First Stars VI: abstract book

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S1: Population III stars: formation, IMF, multiplicity and evolution

Formation of First Star with Various Masses

Shingo Hirano (Invited Talk)

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I will present the formation mechanism of first stars with different masses, in especially considering dependence on the environmental properties of the star-forming region. Theoretically, previous studies have well pictured the outline of the first star formation with considering dynamical, thermal, and radiative processes of the star-forming region from the cosmological large-scale to stellar small-scale. However, it is still far from the theoretical derivation of the initial mass function of first stars, which plays a vital role in the early Universe by determining the initial phase of the chemical evolution. The formation mechanisms and final fates of first stars strongly depend on the physical conditions of the circumstances; e.g. physical states of the star-forming cloud, fragmentation, magnetic effects, external radiation sources, cosmological dynamics, and particle nature of dark matter. Because of dependence of the typical mass and mass range of first stars, we must consider such “first star family” to construct the initial mass function. Interestingly, recent observations suggest the existence of low- to high- mass stars in the early Universe; e.g. relic abundances in extremely metal poor stars, close massive binary blackholes detected by gravitational waves, and supermassive blackholes at high-z Universe. This talk will summarize the current understandings of the first star formation in relationship to the observational results and remaining issues for future studies.

The initial mass function of Population III stars: where do we stand?

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The formation of the first stars, the so-called Population III or Pop. III stars, was a key event in the history of our Universe. These first stars had a profound effect on their surroundings in the form of radiative, mechanical and chemical feedback, and understanding the details of Pop. III star formation is crucial for understanding the initial conditions for later generations of star formation. The form of the Pop. III initial mass function (IMF) is of particular importance. Its upper mass limit and slope help determine the amount of feedback produced by a given amount of Pop. III star formation, while its lower mass limit determines whether it is possible for any Pop. III stars to survive until the present day. In this talk, I will review our current state of knowledge of the Pop. III IMF, focussing on the most important open questions and our prospects for placing observational constraints on it in the near future.

The influence of streaming velocities and Lyman-Werner radiation on the formation of Pop. III stars

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The first stars form in small galaxies, so-called minihaloes. In order to host Pop. III stars, they have to cross a minimum mass threshold in the range of a few 10^5 $M_\odot$ − 10^7 $M_\odot$, depending on the large scale streaming velocity in their creation region. A second effect, Lyman-Werner radiation, influences the minimum and average halo mass for star formation as well. With hydrodynamical simulations, we tested which of the two effects is dominant, and find streaming velocities to play a bigger role than Lyman-Werner radiation. In my talk, I will give an overview of my numerical results and provide a physical explanation thereof. Only by understanding the combination of these effects, observational signatures like the 21-cm signal can be interpreted correctly.

Primordial & Extremely Metal-poor high-mass star formation in the early universe

Takashi Hosokawa (Highlight Talk)

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I present our recent efforts toward understanding the high-mass star formation that occurs in the early universe.

The disk fragmentation is a possible process leading to the formation of stellar multiple systems including binaries. However, numerical simulations show diverse fates of the fragments; some evolve into binaries and others merge away with a central star. I first show that the key physics behind such diversity is well understood postulating that the orbital angular momentum is removed by (i) the gravitational torque, and (ii) tidal disruption (Chon & Hosokawa 2019). I also show the binaries generally expand while accreting the disk gas. I demonstrate that such features are also observed in our latest radiation-hydro simulations using a AMR code, showing that massive primordial stellar multiple system appears under the protostellar radiative feedback (Sugimura et al. in prep.).

Extremely metal-poor (EMP) environments are realized soon after massive primordial supernovae. The subsequent star formation has been studied, but mostly focusing on the possible formation of low-mass (< 1 $M_\odot$) EMP stars caused by the fragmentation. I also show our recent 2D simluations that follow the formation of **massive** EMP stars under the protostellar radiative feedback (Fukushima et al. in prep.). The results show that, even at $Z = 10^{-2}$ $Z_\odot$, the star accretes the gas of $\simeq 190$ $M_\odot$ until terminated by the stellar UV feedback as in the primordial cases. I argue that the massive star formation even in nearby metal-poor galaxies should occur under the radiative feedback which is similar to that expected for the primordial star formation.

The impact of magnetic field strength on the primordial initial mass function

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Magnetic fields have been long proposed to play a potentially vital role in setting the primordial initial mass function. Using the AMR code FLASH with the primordial chemistry network from KROME, we carry out 200 3D MHD simulations of turbulent magnetized primordial cloud collapse under the influence of different randomly oriented magnetic field strengths that produce more than 1000 first stars. All the simulations have sufficient resolution for the small-scale dynamo to operate and amplify the field beyond flux-freezing. We show a clear tendency towards the formation of more massive first stars as stronger magnetic fields are introduced even before the onset of radiation feedback, primarily due to the formation of magnetically-supported discs that suppress further fragmentation. Naturally, this completely changes clustering and multiplicity properties of primordial clouds. Further, we analyze the density and velocity power spectra and PDFs of the collapsing clouds and compare them to contemporary star formation models as well as studies of isolated turbulence in a box simulations. These comparisons reveal that the magnetic field strength has a vital role in defining the low density characteristics of primordial clouds, however, have no impact on the high density regions whose characteristics are governed by gravity. Nonetheless, there is an apparent bimodality in the density PDF where the second peak changes position with time as the disk around the first star expands. The driving force behind turbulence goes through a sequence of episodes where it can either be driven by magnetic fields (solenoidal modes) or gravitational collapse (compressive), with clear differences in the turbulent Mach numbers traced by the two. This analysis provides an exciting new window to not only understand the physics of primordial star formation but also test theories of contemporary star formation and magnetized turbulence in more realistic setups.

Radiation feedback in a high resolved Population III star formation

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First models of Population III star formation proposed that the radiation from the first stars can easily escape molecular accretion disks and affect their surroundings through ionization and heating of the gas. This feedback has an important effect on the resulting stellar initial mass function in the primordial Universe. To address this problem, we employ detailed radiation-hydrodynamic simulations and follow a collapse of isolated minihalos for $700-750$ kyr until their central dense gas regions fragment and form multiple stars. We model the subsequent star-disk system evolution by zooming in on the minihalos' innermost 3.9 pc. Radiation produced by the new stars si performed using the innovative radiation transfer code SPRAI. Our results show that future simulations should treat the onset of the ionizing radiation near the first stars with special care. Low resolution and choice of the simple sub-grid models can lead to qualitatively different outcomes. In the talk, I will introduce our different simulation setups and show their final IMFs. Furthermore, I will discuss how the accretion disk gas properties near the most massive stars influence the escaping radiation and expanding HII regions.

Number of population III stars per minihalo

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The numerical studies on the mass accretion phase of pop. III star formation in the last decade suggest that they could be $< 1\ M_{\odot}$ because of the disk fragmentation. In fact, those stars are formed as a member of a multiple system in a minihalo. In order to investigate the fragmentation process in detail, we perform a set of numerical simulations on the collapse of the gas in the minihalo. We find that the average number of stars is roughly proportional to $t^{0.3}$, where t is the elapsed time since the formation of the first protostar. In this talk I will show the latest results on this issue in which the elapsed time is much longer than the previous calculation (Susa 2019, ApJ 877:99).

S2: Transition to second-generation star formation

Is there significance to the critical metallicities?

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It is understood that the radiative cooling provided by heavy elements is crucial to the transition from Pop. III to Pop. II star formation. Classically, two critical metallicities have been identified as the minimum amount of metal required to allow collapsing gas to cool and fragment where metal-free gas cannot. For heavy elements in the gas phase, the critical metallicity is roughly $10^{-3.5}$ $Z_{\odot}$. However, for metals in dust grains, the critical abundance is 100 to 1000 times lower. Simulations have shown that metals in excess of each of these critical abundances can lead to fragmentation in the respective density/temperature regimes where they operate. This would suggest that the lower, dust-related critical metallicity is the true value of importance for forming the first low mass stars. Yet, the vast majority of metal-poor stars observed have total metallicities that exceed the higher critical metallicity. I will present results from simulations that follow the enrichment, collapse, and fragmentation of star forming gas within a cosmological context. In these simulations, metal-enriched star formation occurs at various metallicities and via different enrichment scenarios. I will characterize this diversity of star formation outcomes and connect them with observed metal-poor stars in order to understand what role the critical metallicities truly play.

The mass transition from Population III to Population II stars

Gen Chiaki (Invited Talk)

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The standard Lambda-CDM model suggests that firstly smaller structures form and grow in their mass through merger of dark matter halos. The first Population III stars form in the pristine gas without elements heavier than Helium hosted by the least massive structures (minihalos). It is considered that the first stars are majorly massive ($10-1000$ $M_{\odot}$) because the pristine gas clouds collapse stably against fragmentation. Whereas, long-lived ($\sim$ Hubble time) and low-mass (< 1 $M_{\odot}$) metal-poor (Population II) stars have been observed in the Local Group. The critical condition for the transition of stellar mass scale from massive Population III stars to low-mass Population II stars is still unknown. In this talk, I review the efforts of researchers to disclose this problem.

Metal mixing in primordial minihaloes

Mattis Magg (Highlight Talk)

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The most metal-poor stars in the Milky Way are thought to have formed from the ejecta of one or of a few Population III stars. Comparing the modeled yields of primordial supernovae to the abundance patterns of extremely metal-poor stars is one of the few currently available pathways to constrain the properties of the first stars. However, this abundance fitting often only considers the abundance ratios, and does not consider how the expected outcome depends on the explosion energy and total yields of the supernovae. In this talk I will discuss recent advances in modeling the metal-mixing and fall-back occurring after the first supernovae, with a particular focus on the dilution of metals and the expected metallicities.

Metallicity Dependence of Massive Star Formation

Kei Tanaka

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We are theoretically and observationally investigating massive star formation at various metallicities. Massive stars play a lot of essential roles in a wide range of astrophysical settings throughout cosmic history. Therefore, it is crucial to understand how the process of massive star formation depends on galactic environmental conditions. We developed the first model of massive star formation, including multiple feedback processes, i.e., MHD disk wind, radiation pressure, photo-ionization, and stellar winds (Tanaka et al. 2017; 2018). We find that the feedback does not set the upper mass limit of stellar birth mass at any metallicity. At the solar metallicity, unlike the conventional perspective, the MHD disk wind is the dominant feedback to determine rather than radiative feedback even in the formation of very massive stars with $> 100\ M_\odot$ (see also Staff, Tanaka et al. 2019). On the other hand, photo-evaporation is found to be the dominant feedback at low metallicity of $< 10^{-2}\ Z_\odot$ due to the lack of dust absorption, decreasing the star formation efficiencies from prestellar cores. To test our theoretical model, we are also conducting high-resolution ALMA observations of massive protostars in the Milky Way and the Magellanic Clouds (Zhang, Tanaka et al. 2019; Shimonishi+Tanaka et al., submitted; etc.). In the talk, we will also introduce our theoretical study, which predicted that the binary system formation is more frequent at lower metallicity of $10^{-5}-10^{-3}\ Z_\odot$ (Tanaka & Omukai 2014). This prediction is consistent with what suggested by recent observations (Moe et al. 2019). Our studies raise a question on the common assumption of the universal IMF with a truncated at $100\ M_\odot$.

Star-cluster formation in low-metallicity massive clouds under radiative feedback

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Star formation in star-forming clouds proceeds under UV feedback from massive stars. Recent observations of nearby galaxies showed that massive clouds were disrupted within dynamical time (~ 10 Myr) after star formation started (e.g., Kruijssen et al. 2019). They indicated that photoionization feedback was responsible for inducing the disruption of clouds. However, it is still unclear how the photo-ionization feedback regulates the star formation and destroy clouds in different physical properties, e.g., cloud mass, compactness, and metallicity. For example, the strength of photoionization feedback is likely to depend on the metallicity because dust grains absorb ionizing photons in HII regions. In this talk, using 3D radiative hydrodynamics simulations of star-forming clouds at various metallicities, we study the metallicity dependence on star formation efficiencies (SFEs) and lifetimes of clouds. We use turbulent clouds with masses of $10^4-10^5\ M_\odot$ and surface densities of $10-300\ M_\odot\ pc^{-2}$ as the initial conditions. We show that the dust makes the photo-ionization feedback less significant and the SFE decreases as the metallicity increases: 16 % for $Z = Z_\odot$ and 7 % for $Z = 0.01\ Z_\odot$ at $80\ M_\odot\ pc^{-2}$. The duration time of star formation is regulated to the expansion time of HII regions, which nicely matches the observations. In addition, we discuss the dependencies of cloud mass and compactness on SFEs.

S3: First supernovae and gamma-ray bursts; Pop. III star fates; abundance patterns at high redshift

The First cosmic explosions

Daniel Whalen (Invited Talk)

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Pop. III supernovae could be the ultimate cosmic lighthouses, some of which will be observable at cosmic dawn at z > 20. Detections of primordial transients could constrain the properties of the first stars, their formation rates, and even the channels of formation of the first quasars. I will review the final fates of Pop. III stars according to their masses, discuss the central engines of their explosions, and their prospects for detection in both deep, narrow surveys by JWST and ELTs on the ground and by wide-field NIR surveys by Euclid and WFIRST in the coming decade.

Rotations of first stars: need of a theory anchored on present-day observational constraints

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Transport processes in stars have a very important impact on the evolution of both single and multiple stars. Indeed, these transport processes govern the distribution of the chemical elements in the interior, have an impact on the surface properties (surface rotation, surface abundances, luminosities, temperatures, gravities, mass loss rates, magnetic fields), determines the angular momentum content of the core at the end of the evolution and thus have an impact on the physics of the core collapse and the outcome of the possibly associated supernova event. In this talk, we shall first provide a brief description of the different transport processes presently available and their advantages/disadvantages when confronted to observational constraints. Then, we shall discuss the impact on Pop. III and very metal-poor stars of different treatments of these transport processes showing their impact on nucleosynthesis, possibly also on their final outcome.

State-of-the-art of chemodynamical simulations: The origin of elements and their evolution in galaxies

Chiaki kobayashi

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State-of-the art of chemical evolution modeling has provided deeper understanding of the origin of elements as well as the evolution of galaxies. We have been running hydrodynamical simulations of galaxies including detailed chemical enrichment from core-collapse supernovae, Type Ia supernovae, AGB stars, super AGB stars, and neutron star mergers. Unlike classical 'one-zone' models, in chemodynamical simulations, chemical enrichment takes place inhomogeneously, which results in a significant contribution from long time-delay sources (e.g., AGB stars) in metal-poor environments. Because of this inhomogeneous effect, the observed N/O-O/H relations in nearby star-forming galaxies can be well reproduced

without rotation of stars. However, even with this effect, it is not possible to explain the observed distribution of rapid-neutron capture elements with neutron star mergers only, and a significant contribution from magneto-rotational supernovae is necessary. With recent observational techniques, the maps of metallicities and elemental abundances can be obtained also for external galaxies. These are in good agreement with our predictions from cosmological simulations with feedback from super-massive black holes that originate from the First Stars. We also predict the evolution of elements that can be explored with James Webb Space Telescope in near future.

Rotation, explosion and nucleosynthesis in early massive stars and the abundances of metal-poor stars

Arthur Choplin

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During the hydrostatic burning phases of early massive stars, rotation is believed to boost the synthesis of light (especially nitrogen) and s-process elements through meridional circulation and shear mixing. Fast rotation is also believed to trigger aspherical jet-like supernova explosions, inducing peculiar explosive nucleosynthesis. By combining 1D stellar models with 2D relativistic hydrodynamical simulations, I will discuss the interplays between rotation, explosion and nucleosynthesis in the early massive stars and investigate the implication on the early chemical enrichment by confronting the model yields with the abundances of observed metal-poor stars.

Chemical abundances in metal-poor quasar absorbtion line systems

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Quasar sightlines through intervening material provide insights into the evolution of gaseous reservoirs within and surrounding galaxies across cosmic time. With the advent of high resolution spectrographs on 8m class telescopes, quasar absorption line systems are excellent probes of the chemical evolution of neutral gas, providing an orthogonal approach to detailed stellar abundances in the Local Group. In this talk I will present recent work focusing on using both damped and sub-damped Lyman alpha systems to study the chemical enrichment of the Universe from the XQ-100 survey between redshifts 2 and 4. I will highlight past and ongoing efforts to search for the chemical signatures of the first stars in these gas-rich quasar absorbers to compliment chemical abundance studies at lower redshifts.

Searches for Population III pair-instability supernovae with upcoming near-infrared transient surveys

Takashi Moriya (Highlight Talk)

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Probing the high redshift Universe with Long Gamma-Ray Bursts

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Because they can be detected up to very high redshift, Long Gamma-Ray Bursts (LGRBs) are seen as a unique probe of structure formation in the early Universe. Yet, their apparent excess-rate beyond $z \sim 3$ relative to standard predictions based on cosmic star formation challenges our understanding between LGRBs and massive stars. I will report on recent progress toward the characterization of the environments where LGRBs take place, mostly based on new data obtained at long wavelengths (ALMA, VLA, GMRT). In particular I will discuss the debated hypothesis on the physical origin of the bias that exists between LGRB hosts and galaxies of the field at low redshifts (i.e., metallicity, stellar density, ...), and I will show that the current number of GRBs identified at $z > 4$ is however too low to investigate the relevance of such a bias at high redshift. In this context, I will finally present future GRB-dedicated projects like SVOM and THESEUS, which will provide new insights into GRBs at cosmic dawn, and open a new window on the early Universe complementary to that afforded by cosmological surveys.

Discrimination of heavy elements originating from Pop. III stars in z = 3 intergalactic medium

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We investigate the distribution of metals in the cosmological volume at $z = 3$, in particular, provided by massive population III (Pop. III) stars using a cosmological N-body simulation in which a model of Pop. III star formation is implemented. Owing to the simulation, we can choose minihalos where Pop. III star formation occurs at $z > 10$ and obtain the spatial distribution of the metals at lower-redshifts. To evaluate the amount of heavy elements provided by Pop. III stars, we consider metal yield of pair-instability or core-collapse supernovae (SNe) explosions of massive stars. By comparing our results to the Illustris-1 simulation, we find that heavy elements originating in Pop. III stars can be discriminated from galactic ones in low-density regions. The median value of the volume-averaged metallicity is log $Z/Z_{\odot} \sim -4.5 - -2$ at the regions. Spectroscopic observations with the next-generation telescopes are expected to detect the metals imprinted on quasar spectra.

S4: Gravitational waves as a new probe of the high-z Universe

Remnants of first stars for gravitational wave sources.

Tomoya Kinugawa (Invited Talk)

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We showed that the typical mass of binary black holes (BH-BHs) whose origin is the first star is 30Msun and mergers of Pop III BH-BH can have sufficiently long merger times to occur in the nearby universe before GW150914 (Kinugawa et al. 2014). The detection rate of the coalescing Pop III BH-BHs is 200 events/yr. This result predicted the gravitational wave events of massive BH-BHs like GW150914 and LIGO paper said 'recently predicted BBH total masses agree astonishingly well with GW150914 and can have sufficiently long merger times to occur in the nearby universe (Kinugawa et al. 2014)' (Abbot et al. ApJL 818,22 (2016)). Thus, there is a good chance to check indirectly the existence of Pop III massive stars by gravitational waves. In this talk, I will summarise the Pop III binary evolutions and the features of Pop III BH-BHs and the detectability of Pop III BH-BHs by the gravitational detectors including future plans.

Exploring new frontiers with gravitational waves from massive black holes

Tilman Hartwig (Highlight Talk)

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Observations of black holes at high redshift are currently limited to the tip of the iceberg. Future space-borne gravitational wave detectors will overcome this limitation by probing the black hole population to higher redshifts and lower masses. This will provide unique probes of supermassive black hole seeding and growth scenarios. I will summarise current model predictions for gravitational waves from massive black holes and their main uncertainties. I will discuss the expected detection rate of binary black hole mergers and how we can maximise the scientific information gain from the upcoming data.

Gravitational wave signals of Pop. III-seeded binary black holes formed by dynamical capture

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We use cosmological hydrodynamic simulations to study the gravitational wave (GW) signals from high-redshift ex-situ binary blackholes (BBHs) formed by dynamical capture during mergers of their host haloes/galaxies. We particularly focus on BHs originated from the remnant of the first generation of massive metal-poor stars (so-called Pop. III stars). These BHs can also be born into binary systems from Pop. III binary stars (i.e., in-situ BBHs), whose GW signals have been intensely studied. Our fiducial simulation produces a local intrinsic rate density of GW events for ex-situ BBHs as $0.01-0.1$ per year per cubic Gpc, and a all-sky occurrence rate of $1-570$ per yer within $z < 5$, depending on the sub-grid model for the stellar environments of ex-situ BBHs. Our rates are comparable to or even higher than the rates predicted for in-situ BBHs, showing that the ex-situ channel of binary BH formation is at least as important as the in-situ channel for producing GWs. We also use the simulated BBHs to predict the detectability of BH-BH merger events for future planned GW instruments such as the Einstein Telescope and deci-hertz detectors.

S5: Stellar archeology as a powerful probe of the high-z Universe

The SkyMapper Extremely Metal-Poor Star Program

David Yong (Invited Talk)

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Chemical abundances in the oldest, most metal-poor stars provide an observational window into the early Universe. Those data enable us to test and refine our understanding of the earliest chemical enrichment events (e.g., supernovae, AGB stars). I will present an update of our high-resolution spectroscopic follow-up of halo metal-poor star candidates from the SkyMapper Telescope as well as the implications and insights into their progenitors.

Looking for the first stars: back to the Lithium plateau.

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In the past few decades an important effort has been made looking for the most metal-poor stars. Those stars are invaluable fossil records and their chemical signatures provide crucial information about the early Universe and the formation and evolution of the Milky Way. Finding these extremely rare objects is challenging and multiple approaches have been attempted.

Spite et al. (1982), found that the lithium abundance in metal-poor stars exhibited an approximately constant value, the so-called "lithium plateau", suggesting it corresponded to the primordial value. This result was later confirmed by Rebolo et al. 1988. More recently and in the context of Λ-CDM model, cosmological observations with the Wilkinson Microwave Anisotropy Probe (WMAP) indicated a primordial lithium abundance that is larger by a factor $3-4$ compared with the observations of metal-poor stars (Spergel et al. 2003). This discrepancy is known as the "Cosmological Lithium Problem". The analysis of a few stars with even lower lithium abundance, the "meltdown" of the plateau, pointed to an explanation that stars are depleting lithium. However, with the discovery of the unevolved star J0023+0307 at [Fe/H] $<$ -6.1 (Aguado et al. 2019a), lying on the plateau, the lithium problem is back. In addition to it a brief description of both methodologies to find these stars with spectroscopic searches (Aguado et al 2016, 2017) and photometric ones (Starkenburg et al. 2017, Youakim et al. 2017) will be discussed together with the main results of 3-years follow-up spectroscopic EMP candidates selected from the Pristine survey, (Aguado et al. 2019c).

Interpreting spectroscopic survey data for metal-poor stars with supernova yield models

Miho Ishigaki (Highlight Talk)

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With the advent of recent large spectroscopic surveys of metal-poor stars in our Milky Way Galaxy, unprecedentedly large data sets of elemental abundances in the atmosphere of metal-poor stars are now available. Statistical properties of the measured elemental abundances have put useful constraints on nucleosynthetic yields of supernovae of different generations of stars as a function of cosmic time. I would like to present highlight results from our studies of the systematic comparison between observed elemental abundances in metal-poor stars and theoretical supernova yield models including those of the first (Pop. III) stars. Issues and prospects for planned future large spectroscopic surveys will also be discussed.

A search for the oldest stars in the inner galaxy with the Pristine survey

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Old, metal-poor stars are not only expected to be present in the Milky Way halo and the dwarf galaxies. Cosmological simulations predict that the fraction of stars that are both very old and metal-poor is highest towards the centers of galaxies: in their bulges. I will present the Pristine Inner Galaxy Survey (PIGS), which is building towards an unprecedented large sample of very metal-poor stars in the bulge region using metallicity sensitive photometry followed by low-/intermediate resolution spectroscopy.

Specifically, I will present new results on the carbon-enhanced metal-poor (CEMP) fraction of the stars in this region. Previous work by the SkyMapper team found a much smaller CEMP fraction in the inner Galaxy when compared to the halo. Our narrow-band photometric filter is narrower than the SkyMapper filter and is less biased by the large amounts of carbon some of these stars have. Consequently, we can provide a more unbiased estimate of the CEMP fraction. Comparing this fraction between the halo and the inner Galaxy has interesting scientific implications for differences in the contributions of both binary stars and first stars ejecta to very metal-poor stars in these environments.

Accurate abundances at the lowest detected iron abundance: SMSS 1605-1443

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We recently announced the discovery of SMSS 1605-1443, a red giant star in the Milky Way's halo that has the lowest detected iron abundance of any star at [Fe/H] = -6.2 (1D LTE) but is strongly carbon enhanced with [C/Fe] = 4. Its chemical composition agrees well with predictions for Population III stars of just 10 solar masses exploding in low-energy fallback-and-mixing supernovae (from Heger & Woosley 2010). Preliminary results from follow-up UVES spectroscopy as well as accurate 3D NLTE spectrum synthesis calculations support these results.

The most metal-poor stars in the Large Magellanic Cloud

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The chemical abundances of the most metal-poor stars in a galaxy can be used to investigate the earliest stages of its formation and chemical evolution. Differences between the abundances of the most metal-poor stars in the Milky Way and in its satellite dwarf galaxies have been noted and provide the strongest available constraints on the earliest stages of general galactic chemical evolution models. However, the masses of the Milky Way and its satellite dwarf galaxies differ by four orders of magnitude, leaving a gap in our knowledge of the early chemical evolution of intermediate mass galaxies like the Magellanic Clouds. To close that gap, we have extended the Best & Brightest survey to the Magellanic

Clouds using the mid-infrared metal-poor star selection of Schlaufman & Casey (2014). We have discovered the three most metal-poor giant stars known in the Large Magellanic Cloud (LMC) and reobserved the previous record holder. The stars have metallicities in the range -2.70 $<$ [Fe/H] $<$ -2.00 and three show r-process enhancement: one has [Eu II/Fe] = +1.65 and two others have [Eu II/Fe] = +0.65. The probability that four randomly selected very metal-poor stars in the halo of the Milky Way are as r-process enhanced is 0.0002. For that reason, the early chemical enrichment of the heaviest elements in the LMC and Milky Way were qualitatively different. It is also suggestive of a possible chemical link between the LMC and the ultra-faint dwarf galaxies nearby with evidence of r-process enhancement (e.g., Reticulum II and Tucana III). Like Reticulum II, the most metal-poor star in our LMC sample is the only one not enhanced in r-process elements.

The Oldest Extremely Metal-poor Stars

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It is tempting to assert that the most metal-poor stars in the Galaxy are the direct descendants of the first stars. This is not necessarily the case though, as metal-poor stars form over a range of redshift. Other properties beyond metallicity are therefore necessary to separate the old from the genuinely ancient metal-poor stars. The bulge is the oldest component of the Milky Way, and numerous groups have used simulations to predict that the oldest stars at a given metallicity are found on bulge-like orbits. Tightly bound metal-poor stars have been impossible to find in the inner bulge though, as most metal-poor stars have been discovered using short-wavelength data. These classical techniques fail in the inner bulge due to extreme reddening and extinction. We have used the mid-infrared metal-poor star selection of Schlaufman & Casey (2014) on Spitzer/GLIMPSE data to overcome these problems and discover the most metal-poor stars known in the inner bulge. A comprehensive orbit analysis using Gaia DR2 astrometry and our measured radial velocities confirms that these stars are tightly bound to the Milky Way. We have used high-resolution Magellan/MIKE optical spectra to determine the detailed abundances of each star, and we find a distinct abundance signature in the inner bulge that is not present in halo or dwarf galaxy stars at a similar metallicity. We propose that the distinct abundance signature we detect is a product of a high star-formation rate in the core of the proto-Milky Way that is not realized in dwarf galaxies or the event that produced most of the inner halo.

The Ancient Bulge Globular Clusters

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Bulge globular clusters contain a wealth of information about the formation and evolution of this oldest Galactic component. However, until lately they have been relatively neglected, for good reason: most of the bulge GCs suffer from large and often variable reddening, making traditional optical studies extremely difficult. Many of them have only very basic parameters measured based on crude optical data. We present new results on a number of bulge GCs based on a variety of near-IR techniques, including metallicities and velocities obtained from the VLT FORS2 instrument, deep CMDs from the GEMINI-S GeMS MCAO imager and HST, and first results from CAPOS, a long-term project to investigate detailed chemical abundances in bulge GCs using APOGEE-2S.

The age of Halo metal-poor stars

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The modern, sophisticated models of the chemo-dynamical evolution of the Milky Way need much more stringent observational constraints. Our understanding on the formation and evolution of our galaxy strongly depends on the quality and precision of fundamental stellar properties as distances, kinematics, masses, ages, and chemical composition.

How we can reach such precision, especially in the metal-poor domain? How we can provide precise ages for a big number of field metal-poor stars?

In this talk I will present a sample of 10 Halo metal-poor red giant stars with -3 < [Fe/H] < -1 dex, for which we derived precise element abundances, ages, and kinematics. Our technique combines asteroseimology, high resolution spectroscopy, and Gaia satellite data. We used asteroseismology from past and recent missions (such as CoRoT, Kepler/K2 and TESS) first for analyzing high resolution stellar spectra using the very precise seismic surface gravity. We then combined the spectroscopically derived atmospheric parameters and abundances with the seismic parameters in a Bayesian tool (PARAM) to derive stellar mass, distance, and age. We finally derived stars kinematics using the very precise proper motions from Gaia DR2. The adopted technique has been first presented in Valentini et al. (2019), our pilot study.

With our method we can obtain a precision of < 30 % on age, 15 % in distance, and <0.07 dex in chemical abundances. This sample will help probing the history of the galactic Halo. In particular we will provide an unique insight into its major accretion relics, such as Sequoia and the Gaia-Sausage. We provide not only an informative chemical profile up to Europium, but also precise ages, unveiling when these accretion events happened.

The extreme enhancement in carbon, nitrogen, and oxygen of the iron-poor star J0815+4729

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Low-mass extremely metal-poor stars must have formed from a mixture of material from the primordial nucleosynthesis and matter ejected from the first supernovae. The chemical composition of these stars, especially those still on the main sequence, holds crucial information, such as the properties of the first stars and the early chemical enrichment of the Universe.

We identified the iron-poor dwarf star SDSS J0815+4729 (Aguado et al. 2018a) using the OSIRIS spectrograph at the 10.4m-GTC telescope in La Palma (Canary Islands, Spain). The low-dispersion OSIRIS spectrum revealed already the huge C enhancement in this primitive star with a million times less iron than the Sun.

We have recently acquired high-resolution spectroscopy with HIRES at the 10m-Keck telescope, uncovering the unique abundance pattern of this star (Gonzalez Hernandez et al. 2019, ApJL, in press). We derive [Fe/H] = -5.5 and detect the near-IR OI triplet for the first time in an ultra metal-poor star, confirming the extreme CNO abundances of J0815+4729 with, ratios [X/Fe] > 4. We are unable to detect Li in this star, placing an upper-limit at A(Li)< 1.3 dex, about 0.7 dex below the detection, at the level of the lithium plateau, in J0023+0307 (Aguado et al. 2018b, 2019), and exacerbating the cosmological lithium problem.

Constraining nucleosynthesis in CEMP-s progenitors using Fluorine

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Carbon-Enhanced Metal-Poor (CEMP) stars are among the most important objects for constraining the formation and evolution of the first stellar populations in the Galaxy. CEMP stars with enhancements in slow neutron-capture process (s-process) elements (CEMP-s stars, objects with [Fe/H] $<$ -2, [C/Fe] $>$ 0.7 and [Ba/Fe] $>$ 1) are a significant fraction (as high as 25 %) of all metal-poor stars. Of the proposed formation channels for CEMP-s stars, mass transfer in a binary system from an AGB companion which is now an unseen white dwarf is the most widely accepted scenario. Fluorine production at low metallicity is extremely sensitive to the physical conditions where is produced and probably related to the same nucleosynthetic process responsible for s-process element production in AGB stars during the thermal-pulsating phase. Thus, Fluorine measurements in CEMP-s stars provide a direct test for CEMP-s formation scenarios, nucleosynthesis, and chemical enrichment mechanisms in the early beginnings of the Milky Way. At low-metallicity, $[Fe/H] < -2$, Fluorine have been detected and measured in just 2 stars: HE 1305+0132 and HD 5223. A handful of upper limits also exist. We present Fluorine detections in 2 CEMP-s stars along with a careful comparison with state-of-the-art nucleosynthesis predictions indicating some successes, and shortcomings, of the models.

Life on the fast lane: chemistry of Halo (?) stars on extreme orbits

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One of the least studied population of stars in the Milky Way comprises objects on extremely high energy orbits, barely (if at all) bound to our Galaxy, and reaching deep in the farthest outskirts of the Halo. These objects are expected to include stars accelerated by close encounters in dense stellar systems, remnants of high-energy substructure accretion, and unbound stars entering the MW from intergalactic space. However interesting, until recently only very few of these elusive objects were known. We present a chemical and kinematical analysis of 65 cool evolved stars selected from Gaia DR2 to have extreme Halo (or unbound) orbits. These stars, observed with FORS, show heliocentric velocities in excess of 500 km s^{-1}, apogalactic distances exceeding in some cases 200 kpc, generally low metallicities (-2.5 $<$ [Fe/H] $<$ -1.0) and, at least in some cases, surprisingly young ages. We will present abundances for C, Mg, Ca, Ti, Fe, and Ba, and discuss orbital solutions, integrals of motion and possible origins of these extreme members of our System.

Clues on the lithium meltdown in dwarf stars using the red giant branch stars

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The lithium abundance, A(Li), in the oldest stars is a key element in our understanding of the Big Bang nucleosynthesis. A(Li) remains constant in dwarf stars down to [Fe/H] = -2.8 dex and, at lower metallicity, drops by 0.3 dex. The origin of this lithium meltdown is still unclear: this drop could be primordial (challenging the current models for the primordial nucleosynthesis) or due to (still unknown) settling/diffusion mechanisms in the stellar atmosphere. Red giant branch (RGB) stars below the bump

level (LRGB) are insensitive to diffusion effects occurring in dwarf stars. If the lithium drop observed in dwarf stars is a birthmark, it should be observable in RGB stars as well. I will present the preliminary results of the study of the lithium content in a sample of LRGB stars of in the same metallicity range of the lithium meltdown.

Near-field cosmology with metal-poor stars: Births and deaths of stars in the Magellanic Clouds

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Stars forming (and dying) in nearby metal-poor Galaxies can be studied to a level of detail not afforded in other observations. We summarize our results focusing on the metal-poor stellar populations in star-forming regions of the nearby Magellanic Clouds. We attempt to place it in the context of near-field cosmology, to place constraints on the formation of the first stars and galaxies.

Heavy puzzle pieces: Learning about the i process from Pb abundances

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Abundances of elements heavier than iron are observed in the photospheres of old stars and teach us about nucleosynthesis in the early Universe. The large majority of heavy-elements are formed by the slow (s) and rapid (r) neutron capture processes. However, it has become clear that a neutron-capture process operating at neutron densities intermediate to the s and r process (i process) gives rise to its own characteristic abundance pattern. This i-process pattern is successful at reproducing observed heavy-element abundances that could not be explained previously, e.g. those of carbon-enhanced metal-poor stars that show enrichments of s- and r-process elements (CEMP-s/r, CEMP-i) or Pb-poor post-asymptotic giant branch stars. The required high neutron densities of $n \sim 10^{15}$ cm^{-3} may occur as a result of proton ingestion episodes in metal-poor and metal-free low-mass stars. However, the sites of the i process in nature are as yet unknown.

Comparing theoretical predictions of i-process nucleosynthesis with the observed abundance patterns of CEMP stars and post-AGB stars in the Magellanic Clouds allows us to learn about the thermodynamic properties of possible i-process sites. In this contribution I will present the results of my nuclear-network calculations of i-process nucleosynthesis in comparison to observations.

Spectroscopic follow-up of metal poor candidates from the Pristine survey with Narval at TBL.

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Metal-poor stars, thanks to their old ages are at the heart of near field cosmology. They are nevertheless very rare objects. The Pristine survey, using narrow band photometry centred on the CaII H&K lines, conducted at the CFHT with the wide-field imager MegaCam, allows the determination of the metallicity for a large number of stars, and among them it is possible to have a reliable selection of candidate metal-poor stars. In this talk I will describe the results of follow-up spectroscopy of Pristine metal-poor candidates conducted at the 2m Telescope Bernard Lyot (Pic du Midi) with the Narval Spectrograph. I will also show how the photometric metallicity estimate compares to the spectroscopic metallicity for this and other samples of stars observed in the Pristine spectroscopic follow-up effort. Finally I will discuss how Pristine photometric metallicities can be used to study the metallicity distribution function of metal-poor stars.

S6: From the first galaxies to the epoch of reionization

Probing cosmic dawn with the 21-cm signal

Anastasia Fialkov (Invited Talk)

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Cosmic dawn is one of the least-explored epochs in the history of the Universe illuminated by the very first stars and black holes. One of the potentially powerful probes of cosmic dawn is the predicted 21-cm signal of neutral intergalactic hydrogen. The 21-cm signal is tied to the intensity of radiation generated by the first sources of light, and, thus, can be used to constrain process of primordial star and black hole formation as well as reionization. In my talk I will discuss the status of the field of 21-cm cosmology.

Physical and observable properties of the first galaxies and black holes

John Wise (Highlight Talk)

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I present results from a suite of cosmological radiation hydrodynamics simulations that focus on massive metal-free stars and the first generations of galaxies. We find that low-luminosity galaxies have UV escape fractions that can exceed 10 per cent during bursts of star formation but is highly variable in both time and angle. We also find that the galaxy luminosity function flattens at absolute UV magnitudes dimmer than -14, arising from internal radiative and supernova feedback. We also calculate the sizes, colors, and typical stellar populations of these first generations of galaxies. We find that a rare set of galaxies form a massive black hole before any star formation, and I present observational predictions for this population that can probe the seeding of supermassive black holes.

Galaxy formation in quasar fields during reionization

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Recent observations have found that many z $\sim$ 6 quasar fields lack galaxies. This unexpected lack of galaxies may potentially be explained by quasar radiation feedback. To accurately model this problem requires both a large cosmological simulation volume and high spatial resolution to resolve galaxies, as well as fully self-consistent radiative transfer (RT). Here I present a suite of 3D radiative transfer cosmological simulations of quasar fields. We find that quasar radiation suppresses star formation in low mass galaxies, mainly by photo-dissociating their molecular hydrogen. Photo-heating also plays a role, but only after $\sim$100 Myr. However, galaxies which already have stellar mass above 10^5 M$\odot$ when the quasar turns on will not be suppressed significantly. Quasar radiative feedback suppresses the faint end of the galaxy luminosity function (LF) within 1 pMpc, but to a far lesser degree than the field-to-field variation of the LF. My study also suggests that by using the number of bright galaxies (M_1500 < -16) around quasars, we can potentially recover the underlying mass overdensity, which allows us to put reliable constraints on quasar environments.

A new formation channel for globular clusters

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The puzzling origins of globular clusters have been greatly debated over the years. I will present a new formation channel for globular clusters, linking them to objects that formed without dark matter in the early Universe in the presence of the stream velocity. This stream velocity (Tseliakhovich & Hirata 2010) arises due to the drop in radiation pressure of baryons from matter-radiation decoupling and induces a phase shift/physical separation between dark matter and baryonic overdensity peaks (Naoz & Narayan 2014). This effect gives rise to gas dominant objects with little to no dark matter. These gas-rich structures, called Supersonically Induced Gas Objects (SIGOs), form naturally outside of dark matter halos as a consequence of the stream velocity. Running hydrodynamic AREPO simulations we find that SIGOs density is high enough to allow stars to form. Then, we model the star formation process and estimate the luminosity of the first star clusters within a SIGO. We find that SIGOs occupy a different part of the luminosity-mass parameter than classical, dark matter halos with gas. SIGOs are dimmer and have globular cluster-like masses. We further adopt a simple model to evolve the SIGOs to current day objects and show that their radius and luminosity is consistent with present-day (local) globular clusters. Since the relative velocity between the baryons and dark matter is coherent over a few Mpc scales, we predict that if this is the dominant mechanism for globular clusters, their abundance should vary significantly over these scales.

Modelling X-ray feedback from binaries at the early universe

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In the early universe XRBs are thought to play a key role in heating and ionizing the intergalactic medium (IGM) . This is due to the fact that X-rays have larger mean free paths than the UV light emitted by the first stars. Consequently, while the latter is responsible for the bulk of the Universe's reionization, the former would have started acting in the IGM at much earlier times, thus having important effects on the 21-cm signal of neutral hydrogen. Despite their significance, the impact of XRBs at high redshifts is still poorly constrained, both due to the uncertainty in their number as well as their SEDs. In my talk I will present an effort to improve the modeling of high-redshift X-ray binaries. We use data from binaries formed within different cosmological Arepo simulations alongside a binary evolution code, Binary_c, to constrain the number of XRBs we expect to be present at each redshift as a function of the underling IMF. By taking this "bottom up" approach we can determine, for each simulation, the XRB number density, the type of each of the binaries (low or high mass) and for how long each pair emits X-rays. Aiming to get better estimates of the influence XRBs' have both on their mother halo and on the IGM we have designed a suitable SED model for each X-ray binary. This new feedback prescription will be publicly available and can be used to improve the treatment of XRBs in future numerical simulations.

Understanding the physical conditions of high-redshift ($z \sim 6$) metal absorption lines

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Dense regions in the high-redshift intergalactic medium (IGM) might be metal enriched. Low-ionization absorption lines can be observable in these regions, particularly during the last phase of reionization. In this work we study these regions by modeling the absorption systems as individual gas clouds heated and ionized by a radiation field to predict its physical conditions (temperature, density, ionization state) and analyze their abundance measurements. We study the properties of these systems (such as column density ratios) to separate them into those where collisional ionization dominates (high temperatures) and those where photoionization dominates (low temperatures). In this talk, I will present the predicted systems by photoionization models and I will show how they compare to low- and high-ionization systems from observations.

Probing Cosmic Dawn : determining the age of the most distant galaxies

Nicolas Laporte (Highlight Talk)

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Determining the period when the first galaxies emerged from a dark intergalactic medium represents a fundamental milestone in assembling a coherent picture of cosmic history. But the so-called 'Cosmic Dawn' period is not accessible yet directly by current ground-based and space telescopes, but it can be constrained following two different methods : simulations of the first population of galaxies or by measuring the age of the most distant galaxies. For the later, a multi-wavelength approach combining photometric and spectroscopic data from the NIR to sub-mm is crucial. This technique allows to estimate the age of very high-redshift galaxies from either the shape of the 4000A break or the amount of dust formed. Our group is conducting deep NIR spectroscopic surveys using X-Shooter/VLT and MOSFIRE/Keck combined with deep ALMA observations to probe the nature and properties (including age, nature, stellar mass, and SFR) of $z > 7$ HST selected galaxies. In this talk, I will describe the latest constraints we obtained on several of the most distant galaxies as well as what we can expect from future facilities.

S7: Dwarf galaxies as a potential probe of the early Universe

Signatures of the First Stars in Relics of the First Galaxies

Alexander Ji (Invited Talk)

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Detection of a spatially extended population of extremely metal-poor stars in the Tucana II ultra-faint dwarf galaxy

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Ultra-faint dwarf galaxies (UFDs) are some of the oldest ($\sim$ 13 Gyr) and most chemically primitive ([Fe/H] $<$ -2.0) systems in the Milky Way halo. Therefore, the chemical abundances of their stars can place strong constraints on early chemical enrichment and the merging and growth of the first galaxies. However, studies of UFDs are limited since (1) generally less than $\sim 10-20$ stars per UFD have been chemically characterized due to their faintness and (2) prior work has largely not searched for member stars outside of two half-light radii due to significant foreground stellar contamination.

Here we bypass the above issues and thereby show that the Tucana II UFD is chemically even more primitive and spatially much more extended than previously assumed. We implement a novel, highly efficient membership selection technique by first deriving photometric metallicities and surface gravities for every star within $\sim$ 10 half-light radii of Tucana II using deep (g $\sim$ 21) SkyMapper photometry. We then identify likely members as metal-poor red giants with Gaia DR2 proper motions consistent with that of Tucana II. By spectroscopically observing these stars, we identify a population of extremely metal-poor ([Fe/H] $<$ -3.0) members located out to $\sim$ 8 half-light radii of the Tucana II UFD, suggesting Tucana II to be the product of one of the earliest galactic mergers. Our observations further show that the Tucana II UFD is the first known extremely metal-poor dwarf galaxy ([Fe/H] $<$ -3.0).

Our result demonstrates that UFDs may principally host spatially extended populations of stars that were missed by previous studies. Indeed, two additional UFDs, Bootes I and Segue 1, already have known individual members at $\sim$ 4 half-light radii. Identifying such populations of stars would be crucial in comprehensively modeling UFDs and plausibly discriminating whether UFDs have a merger history. This, in turn, would be pivotal in understanding the nature of the building blocks of Milky Way sized galaxies.

What conditions shape the Eu abundances of stars in UFDs?

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Two ultra-faint dwarf galaxies (UFDs) are known to be r-process rich. The abundances of europium (Eu) suggest that the origins are likely to be neutron-star mergers (NSMs). However, the diversity in the progenitor system and the environment is not investigated in detail. For example, NSM can happen in the

outskirt of the galaxy, as the binary neutron-stars are expected to receive kick by the anisotropic explosion of two supernovae. We study how the star formation histories of the UFD progenitors and the positions of the merger sites affect the stellar Eu abundance distributions. We use cosmological hydrodynamic simulation to model the r-process enrichment of the UFDs. In this talk, I will demonstrate for the first time how the explosion site and the star formation history of the progenitors affect the observed stellar Eu abundance. I will also discuss the implications of the UFD progenitors and the origin of the r-process elements.

Dwarf galaxies and their hidden treasures

Stefania Salvadori (Highlight Talk)

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Dwarf galaxies are the most common type of systems in the Local Universe and they were even more common at early times, since they were likely the building-blocks of present-day galaxies. After reviewing the most recent observational and theoretical findings for present-day metal-poor stars and galaxies, I will show that Local Group dwarf galaxies are key objects to study the properties of the first stars and the early processes of star-formation. I will demonstrate that these small systems are indeed the best targets to unveil the hidden chemical signatures of the first stars along with their living fossils. I will finally show how upcoming stellar surveys and next generation telescopes will allow us to tightly constrain the first star mass distribution and to successfully link Near- and Far-Field Cosmology.

Constraining the low-mass end of the first stars

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The precise value of the lower-mass limit of Pop. III stars is important in predicting whether any truly metal-free stars could have survived until present-day. Therefore, we investigate the frequency of first stars relics in Ultra-faint dwarf galaxies to limit the low-mass end of the Initial Mass Function (IMF) of the first stars. To this end we develop a theoretical model that follows the formation and evolution of isolated Ultra-Faint dwarf galaxy, particularly focusing on the best studied system: Boötes I. We calibrate the model by comparing our results with available observations (galaxy Luminosity, Metallicity Distribution Function, and Star Formation History) and we detailed studied how the incomplete sampling of the stellar IMF affects the chemical evolution of poorly star-forming Ultra-Fain dwarf galaxies. We explore the impact of different Pop. III IMFs on the expected number of long-living first stars in Boötes I and, by exploiting available data, we provide observational-driven constraints on the minimum mass (M_{min}) of the first stars: we can exclude that Pop. III stars have $M_{min} \leq 0.8\ M\odot$ independently from the shape of the IMF at 68 % confidence level.

Dynamical relics of the ancient galactic halo

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We search for dynamical substructures in the LAMOST DR3 very metal-poor (VMP) star catalog cross matched with Gaia DR2. From 3300 VMP stars with halo kinematics, we are able to recover all the existing substructures such as Gaia-Sausage, Sequoia, and the Helmi Stream. There are also a few new substructures discovered. More interestingly, we found one VMP dominated substructure

Rg5 is dynamically associated with two highly r-process-enhanced stars with [Fe/H] ~ -3. This finding indicates that its progenitor might be an ultra-faint dwarf galaxy that has experienced r-process enrichment from neutron star mergers. This study has taken the first steps in finding dynamical associations between disrupted dwarf galaxies and r-process-enhanced stars, which is crucial for studying their birth environments. This helps us understand the star forming activities, nucleosynthetic events, and chemical evolution in UFDs and other dwarf galaxies in the early universe. The great advantage of studying debris in the nearby halo is that high-resolution spectroscopic observations are much more readily obtainable, so we expect this field of activity to have a rich future in the coming decades.

The stellar populations of high-redshift dwarf galaxies

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(V.Gelli, S.Salvadori, A. Pallottini, A. Ferrara)

We use state-of-art cosmological zoom-in simulations of a typical z $\sim$ 6 Lyman Break Galaxy (LBG) to investigate the stellar properties of its dwarf satellite galaxies. We find six of them residing in the host galaxy halo, their stellar masses ranging from $M_\star \simeq 10^6$ M$\odot$ to $\simeq 10^9$ M$\odot$. All the dwarf satellites properties show no dependence on the distance from the central massive LBG. These systems are mostly spherical, and old and metal-poor stars are located in the inner regions. The SFH and chemical evolution reveal that high-mass dwarf galaxies ($M_\star \simeq 5 \times 10^8$ M$\odot$) form preferably from a pristine gas, experiencing a long history of star formation, characterized by many merger events. Low-mass systems ($M_\star \simeq 5 \times 10^8$ M$\odot$) are instead born from an already chemically enriched gas and have much shorter formation histories due to the strong influence of SN feedback and of the dissociating radiation from the nearby star-forming LBG. All satellites are characterised by high SFRs (typically > 5 M$\odot$ yr^{-1}) and by estimating their emission we found that such high rates make them luminous enough to be detected by upcoming next-generation facilities like James Webb Space Telescope.

S8: Formation, growth and observational constraints on the first supermassive black holes

Life and death of supermassive stars

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Supermassive stars (SMSs) are candidates for being the progenitors of the most massive quasars at redshift $z > 6$. The viability of this formation channel (direct collapse) depends on the properties of the progenitor, whose evolution is dominated by rapid accretion. I will present the most recent models of SMSs, that include accretion and rotation, and discuss their implications regarding the direct collapse scenario and the possible observational signatures of these extreme objects.

The first quasars in cosmological hydrodynamic simulations

Tiziana DiMatteo (Invited Talk)

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Stellar black holes at cosmic dawn

Felix Mirabel (Highlight Talk)

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Theoretical models and observations suggest that large fractions of Pop. III stars end as black holes (BHs) in High-Mass-X-ray Binaries (BH-HMXBs), which are sources of hard X-rays and synchrotron relativistic jets (Microquasars1: MQs). The hard X-rays from these accreting BHs of Pop III have long free paths, pre-heat the Intergalactic Medium (IGM), and produce a smooth end of the re-ionization epoch 2. I will show that the relativistic jets from BH-HMXB-MQs of Pop. III produce a cosmic radio background (CRB) that can account for the excess amplitude and bottom flat absorption of atomic hydrogen at $z \sim 17$ (78 MHz) reported by EDGES3. I will conclude that the Cosmic Radio Background from BH-HMXB-MQs of Pop. III is the smoking gun of Pop. III stars4.

Ezequiel Treister (Highlight Talk)

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Super-Eddington gas accretion onto intermediate-mass seed black holes

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Super-Eddington gas accretion onto seed black holes is an essential formation mechanism of supermassive black holes (SMBHs) with about one billion solar mass discovered at z $\sim$ 7. Wada et al. (2016) investigated the detailed gas structure around SMBHs at the scale of dusty tori or circumnuclear disks (CNDs) based on three-dimensional radiation hydrodynamics (RHD) simulations. However, they just supposed local-AGNs, assuming the solar-abundance gas and constant sub-Eddington accretion. In this study, we, for the first time, explore the feasibility of the super-Eddington growth of intermediate-mass seed BHs in the low-metallicity environments, $Z < 0.1\ Z_\odot$, with 3D RHD simulations, which solve the hydrodynamics, radiative transfer of ionizing photons and thermal emissions from dust grains, and non-equilibrium chemistry self-consistently. Our simulations show that higher gas density and metallicity leads to colder and thinner CNDs, which consequently weakens the photoevaporation of the accreting gas. As a result, we find that the super-Eddington accretion occurs when the metal-enriched gas with Z $> 0.01\ Z_\odot$ goes into the CND regions with the inflow rate of 100 times higher than Eddington. In this talk, based on these results, we will discuss the sites of SMBH formation in the early universe.

Long- and Short-distance relationships with massive black holes

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In the last decade, growth of supermassive black holes in the centers of galaxies and their role in shaping the evolution of galaxies and their star formation histories has become a central topic in cosmology. However, the underlying physics of how a black hole affects the evolution of its host galaxy as well as nearby halos around its vicinity are still not well understood. I will talk about how an accreting black hole can affect the thermodynamics of the interstellar (short-distance) and intergalactic (long-distance) medium and induce/inhibit formation of objects through radiation. I will further provide observational diagnostics for finding the fingerprints of massive black holes in the early universe with forthcoming telescopes such as James Webb Space Telescope.

Formation of massive black hole seeds following collapse and fragmentation of atomic cooling halos

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The observational evidence of Super Massive Black Holes at high redshift (z $\sim$ 7) has lead to the development of models for the rapid formation and growth of massive black hole seeds from pristine gas clouds collapsing inside atomic cooling halos $\sim 10^8\ M_\odot$. The most promising model in terms of the final mass of the black hole seed is the direct collapse of gas clouds in atomic cooling halos yielding products with $\sim 10^5 - 10^6\ M_\odot$ if fragmentation can be efficiently suppressed, however recent numerical simulations show that fragmentation cannot be avoided but still a massive object ($\sim 10^5\ M_\odot$) can be formed if the fragments are able to merge afterwards. In this work we present a model that considers fragmentation during the collapse of the gas clouds by performing direct Nbody + SPH simulations to model a dense cluster of accreting protostars still embedded in their natal gas cloud in order to better understand how the amount of fragmentation affects the final mass of the black hole seed.

Highlights of direct collapse black holes from the past decade

Muhammad Latif (Highlight Talk)

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More than 300 quasars have been observed observed at z¿ 6, they unveil the existence of supermassive black holes of a billion solar mass which pose a challenge for theories of structure formation. How come these monsters grow to such high masses in a very short time is still a mystery. In this talk, I will discuss our current understanding and challenges of forming supermassive black holes. Also show some recent results which suggest that some of them will form in binaries or even multiple systems. In the end I will results from radiation hydrodynamical simulations about the growth of DCBHs.

Formation of the massive seed BHs in the low-metallicity environment

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Recent observation reveals that many SMBHs reside in the early universe, z > 7. Direct collapse (DC) model is one of the promising path to form such SMBHs. Massive seed BHs with 10^5 $M_\odot$ forms out of the clouds with special condition (DC clouds), i.e. very close to a luminous galaxy, which will grow into the high-z SMBHs. In the DC model, the cloud is usually assumed to be completely primordial. The critical metallicity for the massive BH formation is still no consensus so far. Omukai et al. (2008) have found that once a cloud is polluted by heavy elements, the cloud temperature suddenly decreases at the density with $n > 10^{10}$ cm^{-3}, which can induce the violent fragmentation. Whether the fragmentation reduces the final mass of the seed BH or not, should be further investigated by the numerical simulation. We have performed the hydrodynamical simulation, which follows the dynamical evolution of the DC clouds with low-metallicity environment. What we have found is that the existence of the heavy element does not prevent the massive seed BH formation when the cloud metallicity is smaller than 10^{-4} $Z_\odot$. During the initial 10^4 years, the mass of the central star reaches 6000−8000 $M_\odot$ even in the low-metallicity environment. The dust cooling does induce the strong fragmentation, but the central star efficiently grows in mass by the gas accretion and the stellar mergers. In this presentation, I will summarize the results of our calculation and discuss implication for the SMBH formation.

Pulsational instability of very massive stars with various metallicities

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The recent discovery of high-redshift (z > 6) supermassive black holes (SMBH) of 10^{10} $M_\odot$ poses the question of their origin. They require both the formation of massive seed BHs and the subsequent rapid mass accretion within < 1 Gyr after the Big Bang. One plausible scenario for a massive seed BH formation is the so-called stellar merger scenario. In metal-enriched star-forming clouds within a protogalaxy, efficient cooling via metal-line and dust-continuum emission would lead to vigorous fragmentation of the cloud, enabling the formation of dense stellar clusters. Massive seed BHs can be formed, if very massive stars are born through runaway collision in the dense stellar clusters. By combining the cosmological simulation with the N-body simulation, previous studies have shown that very massive stars of 400−1900 $M_\odot$ can be formed in this scenario. It is generally believed, however, that very massive stars are unstable to pulsational instability, which could prohibit massive BH formation, if significant mass-loss is driven by the instability. So far, stability analysis was performed only for zero metallicity and solar metallicity cases, and the stability of slightly metal-enriched stars is not well understood. Here, we study pulsational instability of very massive stars with various metallicities and examine how much fraction of mass is lost during their lifetime.

Making a supermassive star by stellar bombardment

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Approximately two hundred supermassive black holes (SMBHs) have been discovered within the first $\sim$ Gyr after the Big Bang. One pathway for the formation of SMBHs is through the collapse of supermassive stars (SMSs). A possible obstacle to this scenario is that the collapsing gas fragments and forms a cluster of main sequence stars. Here we raise the possibility that stellar collisions may be sufficiently frequent and energetic to inhibit the contraction of the massive protostar, avoiding strong UV radiation driven outflows, and allowing it to continue growing into a SMS. We investigate this scenario with semi-analytic models incorporating star formation, gas accretion, dynamical friction from stars and gas, stellar collisions, and gas ejection. We find that when the collapsing gas fragments at a density of $< 3 \times 10^{10}$ cm^{-3}, the central protostar contracts due to infrequent stellar mergers, and in turn photo-evaporates the remaining collapsing gas, resulting in the formation of $< 10^4$ $M_\odot$ object. On the other hand, when the collapsing gas fragments at higher densities (expected for a metal-poor cloud with $Z < 10^{-5}$ $Z_\odot$ with suppressed H_2 abundance) the central protostar avoids contraction and keeps growing via frequent stellar mergers, reaching masses as high as $\sim 10^5 - 10^6$ $M_\odot$. We conclude that frequent stellar mergers represent a possible pathway to form massive BHs in the early universe.

S9: Current and future surveys and observational facilities

The R-Process Alliance – Progress and Preview

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I report on the progress to date on the R-Process Alliance (RPA), an effort to more than quadruple the number of known highly r-process-enhanced stars (r-II) stars in the Galaxy. These stars are being used to constrain the nature and site(s) of the astrophysical r-process. I also provide a description of how we are dramatically increasing the pace of discovery, using a pre-survey for likely r-I and r-II candidates from MRS spectra obtained by LAMOST, and follow-up of dynamically tagged groups known to have at least one or more r-I and r-II stars.

Big data in Galactic archeology: the future surveys

Elisabetta Caffau (Invited Talk)

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A main concern in the stellar community is to complete the information that will be provided by the Gaia mission. Gyes was conceived in 2010 to complete this information, but, unfortunately, the CFHT board decided not to pursue it. Nevertheless the experience of Gyes was instrumental to spin off subsequent projects like MOONS, 4MOST, and WEAVE. High multiplex (from several hundreds to several thousands spectra per exposure), high resolution spectrographs are going to play a major role in the development of astrophysical knowledge in the next decades.

I will give a biased oversight of the current status of the Gaia follow-up.

Else Starkenberg (Invited Talk)

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Characterizing the origin and properties of the halo r-process star population with data collected by the R-Process Alliance

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Over the last several years, the R-Process Alliance has collected high-resolution spectra of metal-poor giants to systematically identify rare r-process enhanced stars. The combined sample of 380 stars analyzed so far suggests a fraction of 7enhanced stars and 40the Milky Way's halo (Sakari et al. 2018, Hansen et al. 2018, Ezzeddine et al. 2020). Considering the formation history of Milky Way's halo and kinematics of halo stars, it can be expected that these stars did not form in situ but were accreted along with their birth host galaxies as part of the Milky Way's growth over time.

The discovery of the r-process galaxy Reticulum II certainly has shown that small galaxy can experience a neutron star merger or another prolific r-process event that gives rise to a local population of r-process stars (Ji et al . 2016). This provides a this new type of chemical tagging in which the existence of stellar r-process signatures can be used to trace the merger history of the halo. Recent simulations make use of this idea that the frequency of r-process galaxies drives the number of r-process stars ultimately brought into the Milky Way. The majority of the halo r-process star population can indeed be explained as having originated in small dwarf galaxies similar to Reticulum II (Brauer et al. 2018).

This picture is further supported by the kinematics signatures of halo r-process stars which show clustering effects. This shows that is likely that groups of r-process enhanced stars entered the Milky halo together as part of the dissolution of their host galaxies (Roederer et al. 2019)

A global 21-cm Chilean experiment: MIST

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Different experiments around the world are trying to detect the global 21-cm signal from neutral hydrogen in the intergalactic medium during the Dark Ages, the Cosmic Dawn, and the Epoch of Reionization. The EDGES experiment in 2018 was the first to report an absorption feature that departs from theoretical models. Here, we present a Chilean experiment MIST (Mapper of the IGM Spin Temperature) aiming to independently detect the global 21-cm signal that can confirm or discard the EDGES detection in the 50-120 MHz range from the MARI site in northern Chile.

Searching for the first generations of stars at high redshift with JWST

Andrew Bunker (Highlight Talk)

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I will describe future searches for galaxies in the early Universe with the James Webb Space Telescope (JWST). The NIRSpec near-infrared spectrograph on JWST is sensitive out to 5microns, probing the rest-frame optical emission of galaxies out to $z = 7$, and potentially lines such as Lyman-alpha, HeII and [OII] at $z >> 10$. With my colleagues on the ESA NIRSpec Instrument Science Team, we are planning a large GTO survey of galaxies in the high redshift universe, taking advantage of the multiplex available with the microshutter array of NIRSpec to target hundreds of Lyman break galaxies at $z > 5$. By studying line ratios, we can chart the evolution of metallicity, dust extinction and AGN contribution, and coupling with SED fits to the continuum we can determine stellar masses and potentially look for signatures of a different initial mass function (IMF). In particular, the HeII 1640 Ang line might be the signature of a hard ionizing spectrum expected from a top-heavy IMF expected from Population III stars. We will also address the build-up of stellar mass in galaxies at high redshift, and will estimate for the first time the escape fraction of ionizing photons for galaxies at $z > 6$ through comparison of the Balmer lines with the rest-UV continuum. The escape fraction is a critical and unknown quantity in the quest for which sources reionized the Universe at $z \sim 6-9$. JWST will push to even earlier epochs, using the Lyman break to potentially detect the first massive galaxies to form at $z > 10$, and I will present our expected parameter space and sensitivities for our survey.

The LAGER survey: Studying Reionization with Ly-alpha emitters

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Reionization of hydrogen in the intergalactic medium (IGM) is a landmark in structure formation. Resonant scattering of Ly-alpha photons is sensitive to neutral hydrogen in the IGM, making Ly-alpha emitters a sensitive, practical, and powerful probe of the central phase of reionization. Redshift $z \sim 7$ is the frontier in Ly-alpha and reionization studies and appears to be in the middle of Reionization.

In the "LAGER" project (Lyman-Alpha Galaxies in the Epoch of reionization), we take deep narrow-band images with DECam (3 deg2 field-of-view) and an optimally designed narrow-band filter to identify Ly-alpha emission at $z \sim 7$. We are conducting a program to observe an area of 24 deg2 in 8 fields with DECam to select 600 LAEs and study reionization with the clustering properties of these Ly-alpha sources.

In this talk I will present the first results from the LAGER survey and the posterior spectroscopic campaign. Up to now, we have observed five DECam fields to full depth. Using instruments in Las Campanas Observatory, we have confirmed 23 Ly-alpha galaxies in the first two fields (COSMOS and CDFS). Based on the spectroscopically confirmed LAEs, we find a significant difference in the bright end of the luminosity functions for the COSMOS and CDFS fields, that could be explained by different local ionization bubbles.

I will describe what we can learn about galaxy evolution and the process of reionization by studying the field to field variation of the Ly-alpha luminosity function at $z \sim 7$, the campaign to test the Reionization bubbles scenario and the tentative detection of a proto-cluster of galaxies at $z \sim 7$.

The 4MOST Milky Way Halo High-Resolution Survey

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4MOST is a wide-field multi-object spectrograph that will start its operations at ESO's 4m VISTA telescope in 2022. With its 2.6 degree diameter field of view and 2400 fibres feeding two low-resolution and one high-resolution spectrographs, it will be able to acquire more than 20 million spectra during the first 5 years of its operation.

The Milky Way Halo High-Resolution Survey is one of the ten 4MOST consortium surveys that will be conducted simultaneously. In this survey, we will study the formation history of the Milky Way, and the earliest phases of its chemical enrichment, with a sample 1.5 million stars at high galactic latitude. Elemental abundances of up to 20 elements with a precision of better than 0.2 dex will be derived for these stars. The sample will include members of kinematically-coherent substructures, which we will associate with their possible birthplaces by means of their abundance signatures and kinematics, allowing us to test models of galaxy formation. Our target catalog will also contain 30,000 stars at a metallicity of less than one hundredth of that of the Sun. This sample will therefore be almost a factor of 100 larger than currently-existing samples of metal-poor stars for which precise elemental abundances determined from high-resolution spectroscopy are available, hence enabling us to study the early chemical evolution of the Milky Way in unprecedented detail.

In my talk, I will give an overview of the characteristics of the 4MOST instrument. I will then present the consortium survey program, focusing in particular on the Milky Way Halo High-Resolution Survey.

POSTERS

Chemodynamical tracers for the formation of dSph - Leo I vs Simulations

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We present a chemo-kinematic analysis of the Leo I satellite of the Milky Way. We are applying the BEACON software to find chemo-kinematic patterns among stars of different stellar populations using their metallicity and radial velocity along the line of sight. We present the detection of 13 possible stream motions with angular momentum distributed randomly in the galaxy. We compare these results with different formation scenarios proposed for the formation of dwarf spheroidal galaxies, specially the dissolving star cluster model which predicts these rotating patterns, showing that this model is in agreement with this observational results.

Investigating Neutral Hydrogen Structures During The Epoch of Reionization using Fractal Dimension

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The clustering and lacunarities in density distributions can be chracterized using fractal dimensions. The generalized fractal dimensions is used to study the neutral hydrogen distribution (HI) during the epoch of reionization. The analysis is done on a simulated data of HI field which is created using a semi-numeric model of the ionized bubbles. We calculate the fractal dimensions for length scales $10h^{-1}$ cMpc. We find that the HI field displays significant multifractal behaviour and is not consistent with homogeneity at these scales when the mass averaged fraction of neutral hydrogen $<= 0.5$. This multifractal nature is completely driven by the shapes and distribution of the ionized regions. The fact that the fractal dimension is sensitive to the neutral fraction implies that it can be used for constraining the reionization history. We also observe that the fractal dimension is relatively less sensitive to the value of the minimum mass of ionizing halos when it is in the range $10^9 - 10^{10}h^{-1}$ $M_\odot$. Interestingly, the fractal dimension is very different when the reionization proceeds inside-out compared to when it is outside-in. Thus the multifractal nature of HI density field at high redshifts can be used to study the nature of reionization.

Detection of the thermonuclear X-ray bursts and dips from the X-ray binary 4U 1323-62

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The results are obtained with the LAXPCs instrument on-board AstroSat satellite by observing the Low Mass X-ray Binary neutron star 4U 1323-62. The observations of 4U 1323-62 observed during the performance verification phase of AstroSat showed six thermonuclear X-ray bursts in a total effective exposure of $\sim$ 49.5 ks over a period of about two consecutive days. Recurrence time of the detected thermonuclear bursts is in accordance with the orbital period of the source $\sim$ 9400 seconds. Moreover,

the light curve of 4U 1323-62 revealed the presence of two dips. We analyzing the individual burst data of AstroSat/LAXPC from the neutron star LMXB 4U 1323−62 in the soft state and present the results from time-resolved spectroscopy performed during all of the six X-ray bursts. In addition, an already known Quasi-periodic oscillation (QPO) at $\sim$ 1 Hz has been detected. However, any evidence of kHz QPO was not found. We have shown the burst profile at different energy ranges. Assuming a distance of 10 kpc, we observed a mean flux $\sim 1.8 \times 10^{-9}$ erg cm^2 s^{-1}. The radius of the blackbody is found to be highly consistent with the blackbody temperature and the blackbody flux of the bursts.

Investigating the 21 cm signal from the reionization epoch

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Due to the formation of a enormous amount of neutral hydrogen during the pre-reionization epoch of Universe, the intergalactic medium (IGM) can be characterized by using the 21-cm line. This powerful tool might allow us to learn about the end of "Dark ages" when the formation of first structures and the first galaxies began. Once the first galaxies emerged the IGM was affected by the associated radiative backgrounds. These objects start emitting ultraviolet radiation that carves out ionized regions around them until hydrogen becomes fully ionized, giving pass to the Reionization era. We calculate the shape of spin temperature and the brightness temperature considering radiative heating. A particular focus of this project will be to consider the contributions from X-ray photons produced by the first massive black holes.

Children of the first star: birth from a Pop III supernova

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The typical timescale for metal-rich outflows to recollapse in dwarf galaxies is tens of millions of years. As massive Pop III stars can have much shorter lifetimes, it is sensible that multiple Pop III stars could enrich a single cluster of metal-poor stars. This poses a problem when trying to observationally extract the masses of their progenitors. Using a suite of magneto-radiation-hydrodynamic simulations to study cloud crushing by a nearby Pop III supernova, we investigate a star formation mechanism that could provide a direct link between individual Pop III stars and metal-poor stellar clusters. Once the blast wave induces gravitational collapse, stars will form on a timescale on the order of millions of years, so the cloud is less likely to be enriched by multiple Pop III supernovae. By varying the density of the cloud, the separation between the cloud and progenitor, the magnetic field, and the mass of the progenitor, we determine the conditions for triggered star formation to occur in the early universe. We model metal transport from the blast wave into the cloud and study how the resultant metallicity of the second generation stars depends on their formation environment and progenitor mass. Depending on the metal mixing efficiency, this may provide a formation mechanism for a subset of Group II or Group III CEMP-no stars.

Interpreting the abundance patterns of metal-poor stars with A-SLOTH

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With current observational technology, the best way to pin down the initial mass function of the first stars is perhaps to look at the abundance patterns of the second generation stars. We implement a modified Population II star formation recipe in the semi-analytical model A-SLOTH. Our approach takes into account star formation in concert with the radiative, mechanical, and chemical feedback from the first and second generation of stars on a star-by-star basis. We utilize A-SLOTH to model the transition from metal-free to metal-enriched star formation and to study the physical properties of their birth clouds inside satellite galaxies of Milky Way-like halos from simulated dark matter merger trees. We compare our results with the observed abundance patterns of metal-poor stars in the Local Group.

Population III Supernovae in The First Galaxies. I. Gas, Metals, and Stars

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Modern cosmological simulations successfully demonstrate that the hierarchical assembly of dark matter halos provided the gravitational wells that nurse the primordial gases to form the first stars and galaxies inside them. One of the most significant objects in the universe, the first galaxies, are naturally regarded as the foundation of early Universe. To examine the effect of Pop III supernova remnants (SNRs) to the first galaxy formation, we perform high-resolution hydro simulations by considering initial Pop III SNRs from different Pop III initial mass functions (IMFs). We follow the mergers of Pop III SNRs with the primordial gas and study the consequent star formation in the first galaxies. We construct 18 models with different halo properties and Pop III SNR compositions. Our results suggest that it is still possible to form Pop III stars inside the first galaxies after the first supernovae, which inject extra metals and change the subsequent Pop II star formation history. We also find that Pop II stellar mass function in our simulated galaxies can be described by power-laws, dN/dMstar proportional to $M^{-\alpha}$, where the exponent α falls in a wide range of 1.46 - 4.76 ($\alpha = 2.35$ for the Salpeter IMF). The mass star distribution are highly sensitive to the previous Pop III supernovae and the properties of the host halos. Our study can provide a channel to correlate the populations of the first stars and supernovae to star formation inside these first galaxies which may be soon observed by the James Webb Space Telescope.

Numerical simulation of astrochemical problems

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Numerical simulation plays a key role in modern astrophysical researches because the characteristic time scale for most of the processes begins from split seconds for some chemical processes and goes up to hundreds of millions of years for galaxies collision processes. In our presentation, we provide a new approach for the numerical simulation of astrophysical and astrochemical processes. This approach is based on combining of both distributed and parallel computing techniques with advanced code vectorization for modern processors architectures such as Skylake-SP/Cascade Lake-SP. Our astrochemical solver is based on a chemical kinetics approach. In our presentation, we will show the result of the numerical simulation of some astrochemical processes in supernovas. This research was supported by the RSCF grant 18-11-00044.

Star formation History in the Outskirt of the SMC

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We present the spatially resolved SFH of a shell-like structure located along the northeast part of the SMC using deep optical photometry from the SMASH survey. We find that the recent activity in the shell-like structure is correlated with the global star formation peak at young ages in the SMC likely due to tidal forces with the LMC and MW.

Stellar collisions in flattened and rotating Pop. III systems

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In the early Universe was found that at low metallicity the fragmentation often occurs in disk-like structures. Stellar collisions may have been a fundamental mechanism in the formation of massive stars and their remnants. Here we investigate the impact of rotation and flattening of dense protostellar clusters on the rate of formation of massive stars through collisions, which will later evolve into massive black holes. We use the Miyamoto-Nagai distribution to represent our model and employ N-body simulations to show, in detail, how flattening and rotation affects the number of collisions and the formation of a more massive object. Our preliminary results suggest that rotation keeps more stars in the system and promotes collisions, i.e. less stars escape and more massive stars are generated by collisions.

Luminosity Functions of Supermassive Black Holes at high redshifts

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Observations found that supermassive black holes weighing up to $\sim 10^9 M_\odot$ are already in place by z$\sim$7, when the universe was $\lesssim$ 1 Gyr old. Such high masses cannot be easily reached in standard accretion scenarios. One possible explanation of the existence of these supermassive black holes is that there was an earlier phase of very rapid accretion onto direct collapse black holes (DCBH) that started their lives with masses $\sim 10^5 M_\odot$. Basu & Das (2019) showed that the mass function of SMBHs in this scenario would be a tapered power law function. Here we use simulation data for the number density and formation rate of DCBH along with models for the growth of the SMBH even after their rapid growth era. These are used to calculate synthetic observable quasar luminosity functions for various redshifts $z \sim 3 - 7$. We show how models can be constrained by observations, and also how the models can allow physical interpretations of the quasar Luminosity functions at higher redshifts that will be observed with future telescopes e.g., JWST.

Impact of radiation backgrounds on the formation of massive black holes

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The presence of supermassive black holes (SMBHs) of a few billion solar masses at very high redshift has motivated us to study how these massive objects formed during the first billion years after the Big Bang. A promising model that has been proposed to explain this is the direct collapse of protogalactic gas clouds. In this scenario, very high accretion rates are needed to form massive objects early on and the suppression of H2 cooling is important in regulating the fragmentation. Recent studies have shown that if we use a strong radiation background, the hydrogen molecules are destroyed, favoring high accretion rates and therefore producing objects of very high mass. In this work, we study the impact of UV radiation fields in a primordial gas cloud using the recently coupled code GRADSPH-KROME for the modeling of gravitational collapse including primordial chemistry to explore the formation of first SMBHs. We found that to suppress the formation of H2 a very high value of J21 is required, $J21\ 10^5$. As shown in previous work, such strong radiation backgrounds are very rare, so that the direct collapse may be difficult to achieve and therefore this scenario could hardly explain the formation of the first SMBH.

First stars and reionization on ULDM models

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We present results of a semi numerical computation of the process of reionizacion in an ultra light dark matter scenario. Our modelization include standard reionization by population III stars and it's remaining black holes. The predictions of our models are relevant to the interpretation of the EDGES signal.

The Role of Gas Fragmentation During the Formation of Supermassive Black Holes

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We perform cosmological hydrodynamic simulations to study the effect of gas fragmentation on the formation of supermassive black hole seeds in the context of Direct Collapse. Our setup considers different UV background intensities, host halo spins, and halo merger histories. We observe that our low-spin halos are consistent with the Direct Collapse model when they are irradiated by a UV background of $J_{21} = 10000$. In these cases, a single massive object $105M_{\odot}$ is formed in the center of the halo. On the other hand, in our simulations irradiated by a UV background of $J_{21} = 10$, we see fragmentation and the formation of various less massive seeds. These fragments have masses of $103 - 104M_{\odot}$. These values are still significant if we consider the potential mergers between them and the fact that these minor objects are formed earlier in cosmic time compared to the massive single seeds. Moreover, in one of our simulations, we observe gas fragmentation even in the presence of a strong UV intensity. This structure arises in a dark matter halo that forms after various merger episodes, becoming the structure with the highest spin value. The final black hole seed mass is $105M_{\odot}$ for this run. From these results, we conclude that fragmentation produces less massive objects; however, they are still prone to merge. In simulations that form many fragments, they all approach the most massive one as the simulations evolve. We see no uniqueness in the strength of the UV intensity value required to form a DCBH since it depends on other factors like the system dynamics in our cases.

Applying Deep Learning to Super Luminous Supernovae

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Deep Learning has gained great popularity in the last decade due to its success analyzing both images and sequential data, which makes it a powerful tool for time domain astronomy. There are several articles investigating the possibility of using Super Luminous Supernovae (SLSNe) as cosmological beacons to

study the high red shift universe. A better understanding of these objects is necessary to determine whether this exciting prospect is indeed possible. Upcoming surveys such as LSST will provide many more examples of SLSNe, which we will need to catch early on and classify. We present a light curve classifier that uses a deep learning technique called attention and that is capable of distinguishing SLSNe and other rare objects.

Evolution of Accretion Disk around Pop III Star : comparisons between models and simulationsk

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In numerical simulations following Population III (Pop III) star formation, it is broadly observed that the circumstellar disk fragments to form binary and multiple stars. The disk fragmentation is important process because it may change the IMF dramatically and massive tight binaries may evolve into gravitational wave sources. The structure of the Pop III circumstellar disk has been also investigated by semi-analytical models (e.g., Tanaka & Omukai 2014; Matsukoba et al. 2019). In such models, however, steady accretion is assumed and thorough comparisons with numerical results have not been provided. In this work, we develop a non-steady one-dimensional disk model considering the effect of mass supply from the surrounding envelope onto the disk (e.g., Takahashi et al. 2013). We are also able to investigate the structure of the innermost part of the disk, which is often masked in three-dimensional simulations. Our models suggest that the most unstable part of the disk (i.e., radii) changes with varying the angular momentum of the accretion flow onto the disk. Moreover, the validity of the modeling is also confirmed by comparing the results with our latest three-dimensional radiation-hydro simulations (Sugimura et al. in prep.)

Lagrangian coordinates in an Eulerian framework

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We introduce a novel method to follow Lagrangian fluid flows within an Eulerian framework, by creating passive scalar fields which represent each Lagrangian coordinate that are then advected with the fluid. These fields are effectively a coordinate transformation from the Lagrangian to the Eulerian frame. The information from these fields can be combined at any given time to match specific fluid elements across different time outputs and thus, providing a mechanism to reconstruct fluid flows. The accuracy of this method is only limited by that of the underlying the hydrodynamics method governing the fluid itself as the Lagrangian coordinate fields are advected in the same manner as the densities and therefore, provides a natural Eulerian analogue to tracer particles. We implement this method in the AMR magneto-hydrodynamics code Enzo, and demonstrate it's function for select test problems in 1-D, 2-D, and 3-D. Particularly in the 3-D case, we show that the Lagrangian coordinate fields provide additional information about the behavior of the fluid elements, specifically with respect to mixing.

A critical mass for Pop. III stars: dependence on Lyman-Werner radiation, baryon/dark-matter streaming, and redshift

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A critical mass (M_{crit}) for Pop. III stars can be defined as the minimum halo mass which can host sufficient cold dense gas that can lead to the formation of the first stars. The presence of Lyman-Werner radiation that can dissociate molecular hydrogen and baryon-dark matter streaming can delay the formation of Pop. III stars by increasing M_{crit}. Although the delays from both of these effects have been studied individually, their combined effect has not been investigated previously using numerical simulations. In this work, we aim to constrain M_{crit} as a function of F_{LW}, $v_{streaming}$ and z using cosmological simulations with a large sample of halos using the AMR code Enzo. This function would be particularly useful for semi-analytical and analytical models of early galaxy formation. We have measured the z-dependence of M_{crit} and find that it differs from either scaling with the virial temperature or the virial mass of the halo, as sometimes assumed in the past. The measured z-dependence also varies with F_{LW} and $v_{streaming}$. The redshift evolution of M_{crit} has been predicted in many analytical calculations, but not seen previously with numerical simulations with a large number of halos.

The numerical simulation of supernovae Ia by means a new AVX-512 optimizes hydrodynamic code

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The talk presents a new result of numerical modeling of the supernova explosion process of Ia type on massively parallel supercomputers on-base AVX-512-support processors. A hydrodynamic model of white dwarfs closed by the stellar equation of state and supplemented by the Poisson equation for the gravitational potential is constructed. For numerical modeling of the explosion of supernova Ia has used a sub-real physics, where carbon burning is a full numerical simulation. The numerical modeling showed, that burning and explosion of a supernova Ia is nonstandard.

Chemical properties of Blue Compact Dwarf Galaxies: local analogues of high-redshift galaxies

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Blue compact dwarf galaxies (BCDs) are low-metallicity star-forming galaxies found in the nearby Universe, as such they are thought to be excellent local analogues/proxies of high redshift galaxies. By studying the properties of the interstellar medium of these less-evolved local systems, we can probe and predict the properties of the primordial faint galaxies, which are not readily accessible using present technology. This is one of the reasons why BCDs have been the focus of many imaging, spectroscopic and integral field spectroscopic (IFS) studies for over two decades. IFS is the best available technique to study these galaxies hosting star-forming regions, because it not only allows us to access information encoded in the emission lines from the star-forming regions but also enables us to map their distribution and varying properties throughout each system. I use IFS observations from the Gemini North Multi-Object Spectrograph (GMOS-N) to study the H II regions in a sample of BCDs, combine them with large samples of star-forming galaxies from previous studies including BCDs, green peas and low-mass SDSS galaxies, and further explore the observed properties with chemical evolution models. Such studies are imperative to enhance our understanding of the chemical abundance patterns not only in the local Universe but also in the distant Universe, and hence shed light on several secrets of the chemical evolution of the Universe.

Large Scale Dynamo in a Primordial Accretion Flow – An Interpretation from Hydrodynamic Simulation

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Without an existing large scale coherent magnetic field in the early Universe, Population III (Pop. III) stars would likely rotate at or near break-up speed. In this work, focusing on the accretion phase of Pop. III stars, we investigate the possibility of generating a coherent magnetic field through large scale dynamo processes, as well as the corresponding field saturation level. Using results from hydrodynamic simulations, we demonstrate that primordial accretion disks are turbulent with a Shakura-Sunyaev disk parameter $\alpha\mathrm{ss} > 10^{-3}$, and evidence helical turbulence with a dynamo number $|D\alpha\Omega| \gg 10$. The presence of helical turbulence at these levels allows large scale dynamo modes to grow, and the saturation level is determined by the amount of net helicity remaining in the dynamo-active regions (a.k.a. the quenching problem). We demonstrate that, if the accretion could successfully alleviate the quenching problem, the magnetic field can reach approximate equipartition with B/Beq ~ 3.

Public Release of A Sloth: Ancient Star formation and Local Observable by Tracing Haloes

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We will publicly release a semi-analytical model to simulate high-redshift star formation in a cosmological context: Understanding the formation of the first stars, their feedback, and the various observable consequences of their properties is intrinsically a multi-scale problem that exceeds the capability of current numerical simulations. Semi-analytical models are suited to fill this gap and explore the parameter space of these processes. In this poster, we present A SLOTH (Ancient Star formation and Local Observables by Tracing Haloes), our state-of-the-art semi-analytical model. The code runs on dark matter merger trees and includes self-consistent chemical, radiative, and mechanical feedback. We demonstrate that A SLOTH reproduces various independent observables. This model has already been used to investigate the possibility of surviving metal-free stars, gravitational waves from the first stars, the nature of the Lyman-alpha emitter CR7, and to study metal-poor stars in the Milky Way. The versatile A SLOTH code can be used by the community for making various predictions, such as star formation rates, black hole seeding scenarios, or high-z galaxy formation. The code will be made available to the community soon.

Disk fragmentation and intermittent accretion onto supermassive stars

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Supermassive stars, which are hypothesized to form by very rapid gas accretion with its rate exceeding 0.1 $\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$, are promising candidates for the progenitors of supermassive black holes. They are considered to grow by the accretion via the circumstellar disk, but its fragmentation due to gravitational instability can result in intermittent accretion with quiescent period. If such a period is longer than the stellar KH timescale, the forming protostar contracts toward the main sequence star and start emitting copious amount of ionizing photons, shutting off the accretion. Here, we study the formation of supermassive stars by accretion by way of two-dimensional hydrodynamical simulation and examine the time evolution of the accretion rate. Its circumstellar disk fragments vigorously and the accretion rate fluctuates significantly as a result of the clump accretion. The timescale of quiescent phase can be similar to the KH timescale when the central star reaches 10000 $\mathrm{M}_{\odot}$, and the ionization feedback can be important at this moment.

Ionization evolution in low-metallicity star-forming clouds

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Magnetic fields play such roles in star formation as the angular momentum transport in star-forming clouds, thereby controlling circumstellar disc formation and even binary star formation efficiency. The coupling between the magnetic field and gas is determined by the temperature and ionization degree of the gas. Here, we construct the thermal and chemical evolution model for thelow metallicity gas by solving chemical reaction network where (i) all the reactions are reversed and (ii) molecule formation via dust surface reactions are considered for all the molecules. (The results for the primordial has been published as Nakauchi, Omukai and Susa 2019). We find that at $> 10^{16}$ cm^{-3}, the ionization degree becomes > 1000 times higher than the previous results due to the ionization of alkali metals, which has been omitted so far. Among dust surface reactions, only H_2 formation is important in controlling the gas temperature and ionization degree, and those for the other molecules has no such effect. We have also invented minimal reaction network which can treat ionization degree and thus magnetic diffusivity correctly.

Impact of small-scale structure on the cosmic reionization

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Density inhomogeneity in the intergalactic medium (IGM) can boost the recombination rate of ionized gas substantially, affecting the growth of HII regions during reionization. We show that Small-scale density structures hugely boosts the recombination rate until the structures are disrupted by the hydrodynamic feedback after 10−100 Myr. Also, the streaming velocity between baryon and dark matter damps down the recombination boost by suppressing small-scale structures. Given the fluctuations in the streaming velocity at $\sim$100 Mpc scale, we may see a signature of this effect at the late-stage of reionization from 21-cm surveys.

Initial Mass Function (IMF) under the processes of fragmentation and accretion

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We investigate the stellar Initial Mass Function (IMF) in the primordial universe where molecular hydrogen cooling is less efficient and the gas temperature can be higher by a factor of 30. Under such conditions, the gas temperature can be influenced by the environment, metallicity and radiation background. Here we explore if the latter affects the IMF of the stars considering fragmentation and accretion. The fragmentation behavior depends mostly on the Jeans mass and we show that the Jeans mass at the transition point (isothermal to adiabatic phase of collapse) in the equation of state is independent of the initial temperature, and hence the initial mass of the fragments is very similar. Accretion on the other hand is strongly temperature dependent. We show that the latter becomes the dominant process for star formation efficiencies above 5−7 % leading to on average more massive stars.

Presupernova evolution, explosion and nucleosynthesis of zero and very low metallicity massive stars

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In the last years observations of Fe-poor stars have made possible to have detailed measurements of their surface chemical composition. These objects are the perfect laboratories in which is possible to investigate the differences among the disparate astrophysical sites of element production, from the lightest ones to the neutron capture elements. In fact, iron poor stars probably formed during the very early epochs of the evolution of the Universe, hence the study of their abundance patterns may help to constrain the nucleosynthetic yields of the

rst supernova explosions. Observations allow to divide iron poor stars in a multitude of subclasses. A number of them shows not negligible abundances of neutron capture elements relative to iron (e.g. Sr, Ba, Pb), which are supposed to be produced through the s-process nucleosynthesis. Since the efficiency of this process scales with the initial metallicity, no production of elements heavier than Zn is obtained in classical models of zero and very low metallicity massive stars. This unexpected high presence of s-process nuclei in extremely iron poor stars may be the result of a mass transfer event from an AGB star companion in a binary system, in which is expected an efficient s-process nucleosynthesis even at very low metallicity. On the other hand, iron poor stars may also formed out from gas clouds that were polluted by the supernova yields of rotating massive progenitors. Rotation at low metallicity, in fact, can considerably boost the s-process nucleosynthesis in massive stars through a larger production of neutrons, which is due to additional mixing processes inside the star. The aim of my work is to study of the evolution, nucleosynthesis and explosion of zero and very low metallicity massive stars. In particular, I am focusing on the study of the efficiency of the s-process nucleosynthesis as a function of the initial rotational velocity and of the initial metallicity.

Magnetohydrodynamic effects on first star formation

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We perform three-dimensional MHD simulations of the first star formation ,starting from a dense core until the formation of a protostar ,consistently solving the energy equation with detailed cooling processes and non-equilibrium chemistry. Previous MHD simulations (e.g., Machida et al.2008) have shown magnetic fields can play important roles such as magnetic braking and MHD jet launching also in first star formation, but they adopted a barotropic equation of state obtained from one-zone calculation instead of solving energy equation. Here, I present our simulation results and compare them with the cases with barotropic EoS. In particular, I examine the effect of changes in thermal evolution due to shock heating as well as of delayed collapse by magnetic pressure, and discuss how those effects can alter the nature of forming first stars.

The Pop III disk fragmentation: disentangling the numerical and physical effects

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Pop III stars are likely formed in multiple systems via disk fragmentation. However, numerical simulations show diverse results, and we have no consensus on what the typical multiplicity and binarity of Pop III stars were. In order to disentangle possible physical and numerical effects that may cause the divergent results, we perform a suite of 3D simulations focusing on the disk fragmentation process by using the publicly-available AMR code ENZO. We follow the long-term evolution (t ¿ 1000 yr) after the birth of the embryo protostar with the sink particle technique. We show that the number of protostars (i.e., sink particles) can substantially differ by an order of magnitude depending on different implementation of the sink particles. Nevertheless Susa (2019) recently shows that simulations by different authors may suggest the similar trend that the number of protostars gradually increases with time as $n \propto t^0.3$. We investigate how such scaling may be modified in a variety of situations with different parameters such as angular momentum and EOS of the accreting gas.

Lyman Werner background and Pop. III formation

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The formation of Population III (Pop III) stars is a critical step in the evolution of the early universe. To understand how these stars affected their metal-enriched descendants, the details of how, why and where Pop III formation takes place needs to be determined. One of the processes that is assumed to greatly affect the formation of Pop III stars is the presence of a Lyman-Werner (LW) radiation background, that destroys H2, a necessary coolant in the creation of Pop III stars. Self-shielding can alleviate the effect the LW background has on the H2 within halos. In this work, we perform a cosmological simulation to study the birthplaces of Pop III stars, using the adaptive mesh refinement code Enzo. We investigate the distribution of host halo masses and its relationship to the LW background intensity. Compared to previous work, halos form Pop III stars at much lower masses, up to a factor of a few, due to the inclusion of H2 self-shielding. We see no relationship between the LW intensity and host halo mass. Most halos form multiple Pop III stars, with a median number of four, up to a maximum of 16, at the instance of Pop III formation. Our results suggest that Pop III star formation may be less affected by LW radiation feedback than previously thought and that Pop III multiple systems are common.

Compact Starburst Dwarf Galaxies at 150 MHz: Strong Magnetic Fields in Proxies for Proto-Galaxies

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Compact Starburst Dwarf Galaxies at 150 MHz: Strong Magnetic fields in Proxies for Proto-Galaxies Francisca SOTO-BRAVO(1), Dominik J. BOMANS(1) (1)Astronomical Institute, Ruhr University Bochum, Germany In order to perform a detailed analysis of first galaxies and thus understand the formation and evolutionary process of galaxies in the very early universe, we need the sensitivity and resolution of the next generation telescopes like JWST, E-ELT, and SKA. To overcome this technical barrier now, one can use proxies of these galaxies in the local universe, like compact, strongly starforming dwarf galaxies. Using data from the LOFAR 150MHz LoTSS Survey we probed the radio continuum emission of a sample of 6 compact dwarf starburst galaxies and 10 Green Pea galaxies and derived their magnetic fields (using three different approaches). The analysis of our sample suggests that that magnetic fields may play a major role for the evolution of the low mass early galaxies (e.g. for the structure and evolution of their galactic outflows/winds). It also implies that these galaxies main contributors for the magnetization of the intergalactic medium.

First detection obtained with the ALMA of the [N II]122 μm Line Detection in a QSO−SMG Pair BRI 1202−0725 at z = 4.69

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I report the first detection obtained with the ALMA of the [N II] 122 μm line emission from a galaxy group BRI 1202-0725 at z = 4.69 consisting of a quasi-stellar object (QSO) and a submillimeter-bright galaxy (SMG). Combining this with the detection of [N II] 205 μm line in both galaxies, we constrain the electron densities of the ionized gas based on the line ratio of [N II] 122/205. The derived electron densities are 26-11+12 and 134-39+50 cm^{-3} for the SMG and the QSO, respectively. The electron density of the SMG is similar to that of the Galactic Plane and to the average of the local spirals. However, higher electron densities (by up to a factor of three) could be possible for systematic uncertainties of the line flux estimates. The electron density of the QSO is comparable to high-z star-forming galaxies at z = 1.5−2.3, obtained using rest-frame optical lines and with the lower limits suggested from stacking analysis on lensed starbursts at z = 1−3.6 using the same tracer of [N II]. Our results suggest a large scatter of electron densities on a global scale at fixed star formation rates for extreme starbursts. The success of the [N II] 122 μm and 205 μm detections at z = 4.69 demonstrates the power of future systematic surveys of extreme starbursts at z > 4 for probing the interstellar medium conditions and the effects on surrounding environments.

The formation of Compact Ellipticals in the merger star cluster Scenario

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In the last decades, extended old stellar clusters have been observed. They are like globular clusters (GCs) but with larger sizes (a limit of effective radius R_{eff}) of 10 pc is currently seen as reasonable). These extended objects (EOs) cover a huge range of mass. Objects at the low mass end with masses comparable to normal globular clusters are called extended clusters or faint fuzzies (Larsen & Brodie (2000)) and objects at the high-mass end are called ultra compact dwarf galaxies (UCDs). Ultra compact dwarf galaxies are compact object with luminositys above the brigtest known GCs. UCDs are more compact than typical dwarf galaxies but with comparable luminosities. Usually, a lower mass limit of $2 \times 10^6 M_\odot$ applied. Fellhauer & Kroupa (2002a,b) demostrated that object like ECs, FFs and UCDs can be the remnants of the merger of star clusters complexes, this scenario is called the Merging Star Cluster Scenario. A more concise study was performed by Bruns et al. (2009, 2011). Our work tries to explain the formation of compact elliptical(cE). These objects are a comparatively rare class of spheroidal galaxies, possessing very small R_{eff} and high central surface brightnesses (Faber 1973). cEs have the same parameters as extended objects but they are slightly larger than 100 pc and the luminosities are in the range of -11 to -12 Mag. The standard formation scenario of these systems proposes a galaxy origin. cEs are the result of tidal stripping and truncation of nucleated larger systems. Or they could be a natural extension of the class of elliptical galaxies to lower luminosities and smaller sizes. We want to propose a completely new formation scenario for cEs. In our project we try to model cEs in a similar way that UCDs using the merging star cluster scenario extended to much higher masses and sizes. We think that in the early Universe we might have produced sufficiently strong star bursts to form cluster complexes which merge into cEs. So far it is observationally unknown if cEs are dark matter dominated objects. If our scenario is true, then they would be dark matter free very extended and massive 'star clusters'.

Conditions for detecting Population III galaxies with next-generation telescopes

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Dark matter halos that manage to reach the HI-cooling mass without prior star formation or external metal pollution represent potential formation sites for Population III star clusters (a.k.a. Population III galaxies) and/or direct collapse black holes (e.g. Regan et al. 2019, arXiv:1908.02823). Since Pop. III galaxies are expected to attain total stellar masses of at most 1e6 Msolar (e.g. Visbal et al. MNRAS, 469, 1456), finding such objects in blind surveys of the high-redshift Universe will be very challenging. Which telescope that is most suitable for this endeavour depends on a combination of parameters; the comoving number density of suitable halos, the stellar initial mass function of the Pop. III starburst and the total stellar mass formed in this starburst. While JWST will be unbeatable when it comes to photometric and spectroscopic depth, smaller wide-field survey telescopes like Euclid and WFIRST cover much larger volumes and could in principle beat JWST by picking up rare cases of gravitationally lensed objects. Here, we model the spectral properties and gravitational lensing probabilities of Pop. III galaxies at $z = 6-15$ and identify the parameter regions required for detection with JWST, Euclid and WFIRST separately. The parameter combinations that would allow for detections are also compared to the Pop. III galaxy comoving number densities and total stellar mass predictions favoured by current simulations. We find that there are regions in the Pop. III galaxy parameter space for which WFIRST would indeed allow for detections and JWST would not, Euclid is ruled unable to provide competitive detection prospects.

Heating of Coronal Loops on Low-mass Pop III Stars

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Recent cosmological simulations suggest the existence of low-mass Pop III stars in the current universe, although they have not been detected. In this study, we focus on the radiation from coronae of those stars. To understand the property of stellar atmosphere with low-metallicity, we performed one-dimensional magnetohydrodynamics simulations for the heating of coronal loops with various metallicities. All the simulated loops are heated up to around 10^6 K by the dissipation of Alfven waves, however, the behavior of dynamical evolution and the physical properties of loops are quite different for different metallicity cases. We find that lower-metal stars have hotter and denser corona because of the inefficient radiative cooling. In particular, the density of metal-free corona is more than an order of magnitude higher than that of the solar-metallicity case. As a result, the UV and X-ray luminosities from the metal-free corona are larger than those of the solar-metal corona, which indicates that the radiation from metal-free corona could contribute to the structure formation in the early universe.

Galactic chemical evolution

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Galactic chemical evolution (“GCE”) is a great tool to probe the influence of various astrophysical sites on the observed abundances of stars. We use the high resolution ((20 pc)3 /cell) inhomogeneous GCE simulation tool “ICE” to to answer the most burning question of the GCE of r-process elements: Why do some low-metallicity stars show (high) r-process abundances?

NEI evolution in SNRs

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Mixed morphology supernova remnants (MMSNRs) comprise a substantial fraction of observed remnants, but their origin remains puzzling. Recently, a clue to their nature arose from X-ray evidence of recombining plasmas in some MMSNRs. Recent calculations of remnant evolution in a cloudy interstellar medium that included thermal conduction but not non-equilibrium ionization (NEI) showed promise in explaining observed surface brightness distributions but could not determine if recombining plasmas were present. We present numerical hydrodynamical models of MMSNRs in 2D and 3D, including explicit calculation of NEI effects done via an efficient eigenvalue method. Both the spatial ionization distribution and temperature-density diagrams from the simulations show recombining plasmas created both by adiabatic expansion and thermal conduction, albeit in different regions. Features created by the adiabatic expansion stand out in the spatial and temperature-density diagrams, but thermal conduction also plays a role. Simulated observations from XRISM, Athena, and Lynx with both spatial and spectral input from various regions will also be presented along with initial results on how well the underlying physics can be uncovered from spectral analyses. With the KROME package, we are going to calculate the chemistry and some microphysics in the SNR evolution.