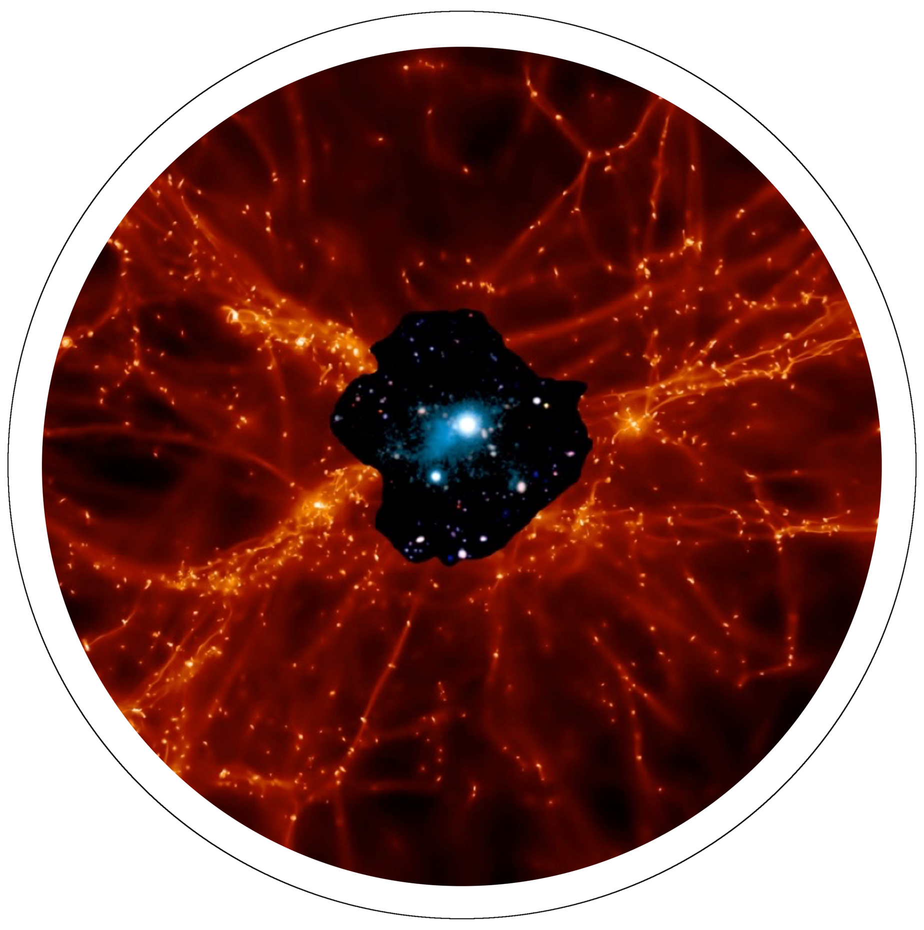
ETH zürich
Department of Physics
Institute for Particle Physics and Astrophysics

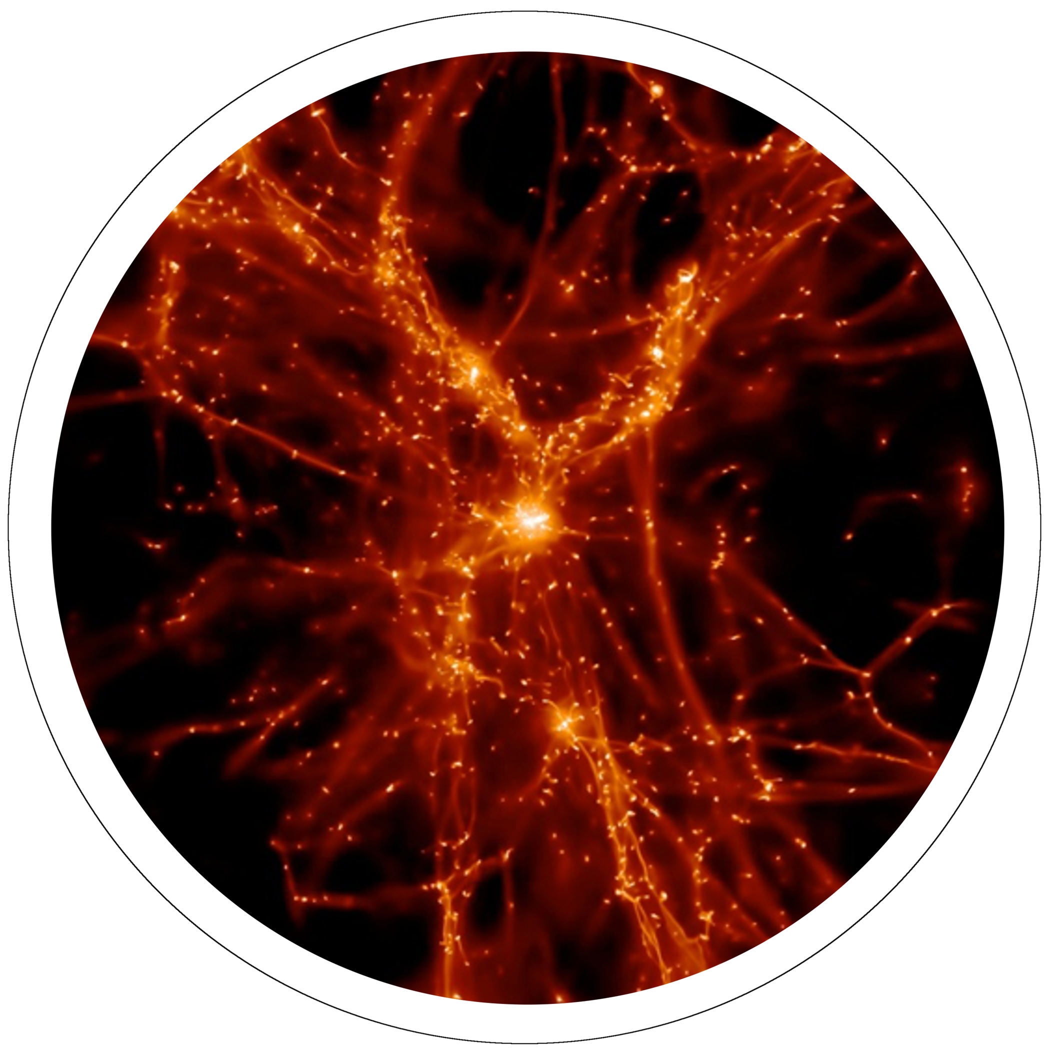
"Cosmic Structure Formation Group"
Group leader: Prof. Dr. Sebastiano Cantalupo

The Bright Universe - Light dominated (Observation)



Illuminating the Dark Universe with Fluorescent Lyα Emission

The Dark Universe - Mass dominated (Simulation)



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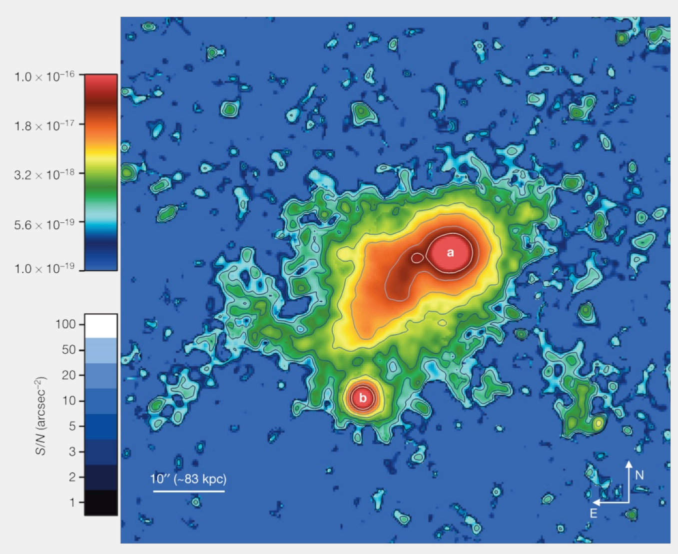
What sets the frequency, size and luminosity of giant quasar Nebulae?

A Cosmic Web Filament Revealed in Lyman alpha Emission around a Luminous High-Redshift Quasar

(Prof. Sebastiano Cantalupo)

Simulations of structure formation in the Universe predict that galaxies are embedded in a 'cosmic web'1, where most baryons reside as rarefied and highly ionized gas2. This material has been studied for decades in absorption against background sources3, but the sparseness of these inherently one-dimensional probes preclude direct constraints on the three-dimensional morphology of the underlying web. Here we report observations of a cosmic web filament in Lyα emission, discovered during a survey for cosmic gas fluorescently illuminated by bright quasars4, 5 at redshift z≈2.3. With a linear projected size of approximately 460 physical kilopарsecs, the Lyα emission surrounding the radio-quiet quasar UM287 extends well beyond the virial radius of any plausible associated dark-matter halo and therefore traces intergalactic gas. The estimated cold gas mass of the filament from the observed emission—about 1012.0±0.5/C1/2 solar masses, where C is the gas clumping factor—is more than ten times larger than what is typically found in cosmological simulations5, 6, suggesting that a population of intergalactic gas clumps with subkiloparsec sizes may be missing in current numerical models.



[Cantalupo et al. 2017, 2014Natur.506...63C]

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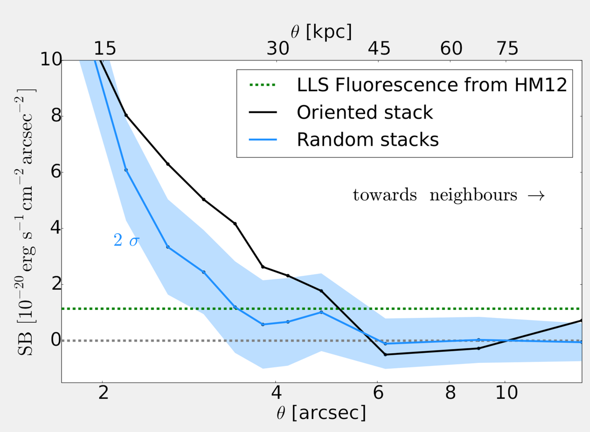
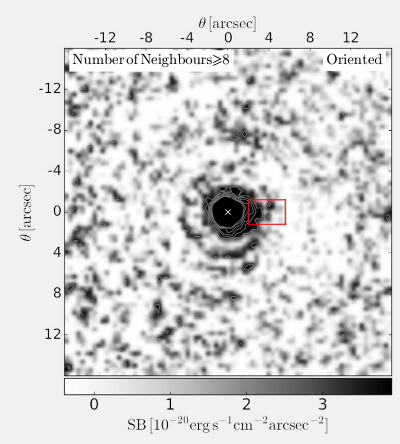
Are galaxies connected by a filamentary "Cosmic Web"?

Stacking the Cosmic Web in Fluorescent Lyman alpha Emission with MUSE

(Sofia Gallego, PhD at D-PHYS - in collaboration)

Most of the matter in the Universe seems to be distributed along filaments connecting galaxies. Fluorescently illuminated by the light of first stars and quasars, the filament expected surface brightness (SB) in Lyα is beyond current observational limits. By using the deepest MUSE/VLT data available, we perform a stacking analysis around Lyα emitting galaxies (LAEs) between 3<z<4, with orientations determined by neighbouring galaxies, reaching a SB sensitivity level bellow the predicted signal. No detectable emission is found on intergalactic scales implying most of our selected regions do not contain filaments given our adopted model. On the other hand, significant emission is found on the circum-galactic medium in the direction of the neighbours, suggesting typically larger gas densities on those directions. The signal is increased around galaxies with a larger number of neighbours but seems independent of any other galaxy properties such as redshift, neighbour distance and luminosity.



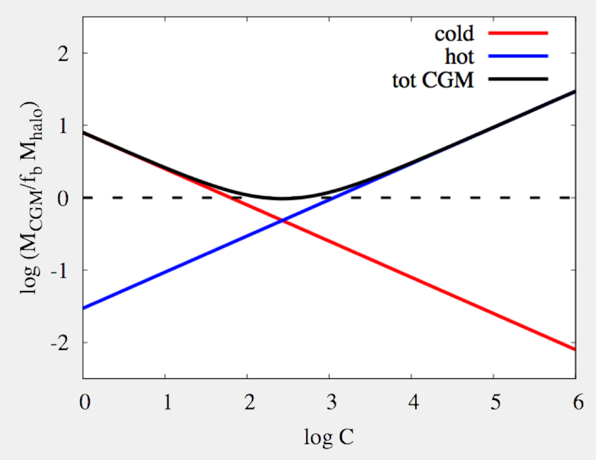


[Gallego et al. 2017, arXiv:1706.03785]

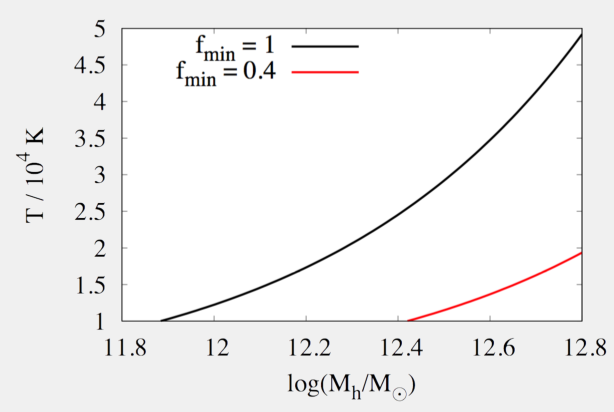
Constraining Feedback Models based on the Number of Baryons in the Circumgalactic Medium (CGM)

(Dr. Gabriele Pezzulli, Post-Doc)

Here is shown the mass of the CGM in our model of the MUSE Giant Lyα nebulae as a function of the clumping factor of the cold gas. The mass is in units of the maximum baryon mass $(\Omega_b/\Omega_m)M_h$, marked as a horizontal dashed line and the fiducial values assumed for halo mass and cold gas temperature are $M_h = 10^{12.3}M_\odot$ and $T = 2\times10^4K$. The red, blue and black lines are for the cold, hot and total gas, respectively. From this follows that viable models require a clumping factor $C \approx 300$ and a total baryon fraction very close to the cosmological value.



Shown in the bottom figure is the minimum total CGM baryon fraction (corresponding to equipartition of the the CGM into the cold and hot phases), as a function of the two model parameters: halo mass and temperature of the cold gas. Low halo masses and high temperatures are inconsistent with cosmology for exceeding the universal baryon fraction. Only the highest halo masses and the lowest gas temperatures are consistent with $f_{CGM} \le 0.4$, as expected for models with strong ejective feedback at high z.



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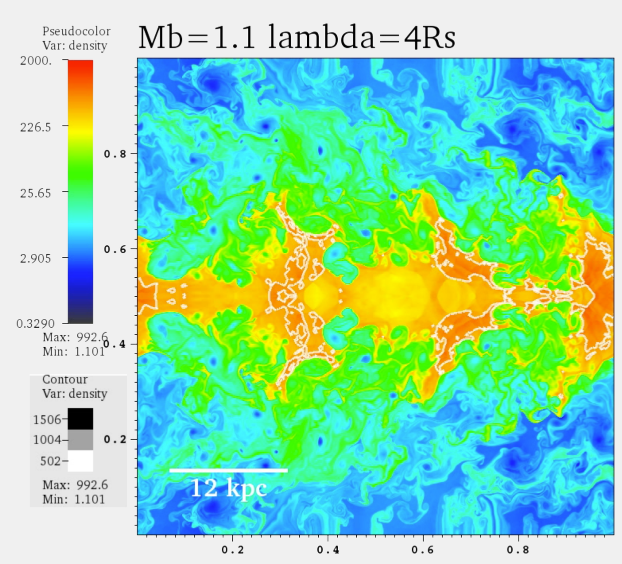
What is the origin of the CGM clumps? Is the CGM multiphase?

Investigating the Origin of Clumps in the CGM using Hydrodynamical Simulations

(Ann-Christine Vossberg, PhD)

In order to understand the dominant processes in accreting filamentary structures and the origin of their physical properties we use 2D idealized high-resolution simulations (RAMSES). This allows us to investigate how different processes effect a filament, its evolution, morphology and its survival. Thermally unstable accreting filaments will not stay laminar but will be subject to KHI and an interplay of cooling and heating. We find that Kelvin-Helmholtz Instability (KHI) in the nonlinear regime may act as a trigger for forming clumps. Additionally KHI has the potential to destroy the filament under certain circumstances. These circumstances largely depend on the Mach-Number of the filament, the perturbation wavelength and the thickness of the interface between the halo and filament. When cooling is introduced the density distribution tail of the filament reaches 14 times the initial filament density and consequently increases the Clumping factor. KHI coupled with radiative cooling may be one reason for the observed high Clumping factor in observations.



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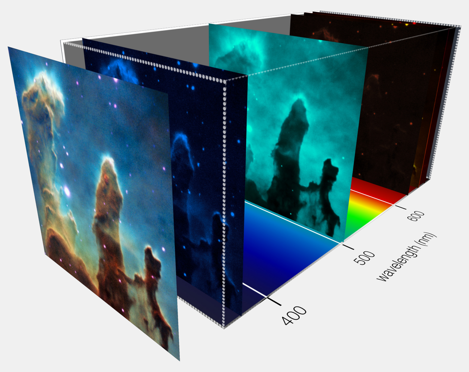
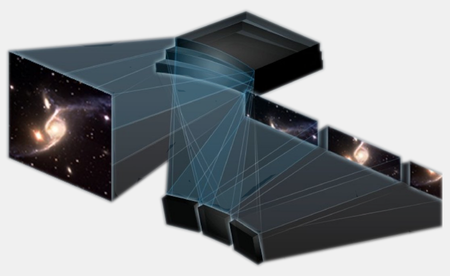
Multi-Unit Spectroscopy Explorer (MUSE)

MUSE is a second generation instrument in development for the Very Large Telescope (VLT) of the European Southern Observatory (ESO). MUSE couples the discovery potential of an imaging device to the measuring capabilities of a spectrograph, while taking advantage of the increased spatial resolution provided by adaptive optics. This makes it a unique and powerful tool for discovering objects that cannot be found in imaging surveys.





The concept of MUSE foresees the splitting of the adaptive optics corrected field of view in 24 sub-fields. Each of these sub-fields is fed into a spectrograph (called Integral Field Unit, IFU). An image slicer in front of each IFU serves as entrance slit, thus producing a spatially resolved spectrum of the full sub-field (from ESO website).

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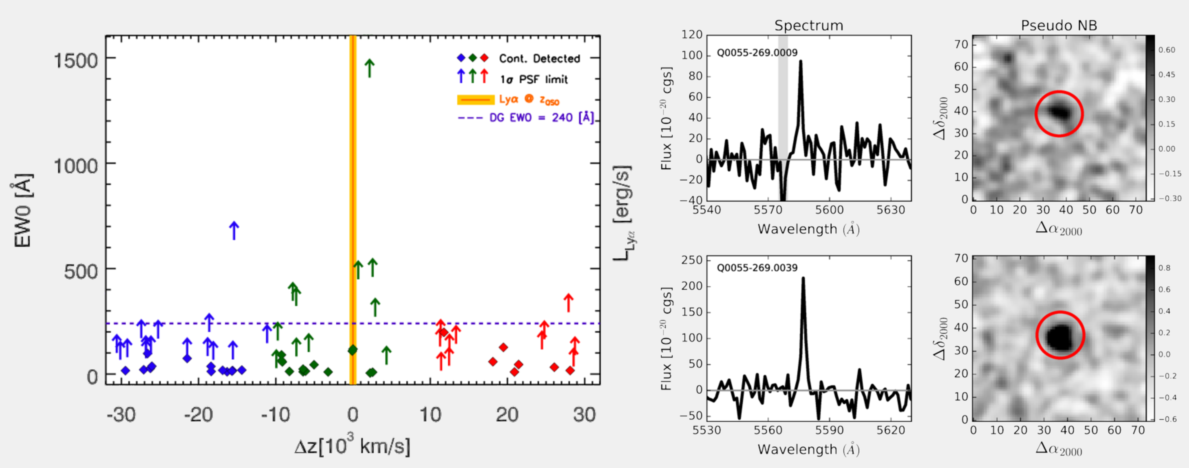
How is gas converted into stars? Is there a dark galaxy phase?

Dark Galaxy Candidates at Redshift 3.5 Detected with MUSE

(Dr. Raffaela Marino, Post-Doc at D-PHYS - in collaboration)

Recent theoretical models suggest that the early phase of galaxy formation involves an epoch when galaxies are gas-rich but inefficient at forming stars: a "dark galaxy" phase. We perform an integral field survey for dark galaxies fluorescently illuminated by quasars at z>3 with MUSE, which provides us a nearly uniform sensitvity coverage over a large volume in redshift space, compared to previous narrow-band imaging surveys. By comparing the rest-frame equivalent width (EW_0) distributions of the Lyα sources detected in proximity to the quasars and in control samples, we detect a clear correlation between the locations of high EW_0 objects and the quasars, not seen in other properties such as Lyα luminosities or volume overdensities, suggesting the possible fluorescent nature of at least some of these objects. Among these, we found 6 dark galaxy candidates with EW_0 limits larger than 240 Angstrom with similar properties to previously detected candidates at z 2.4. Our results also provide a lower limit of 60 Myr on the quasar lifetime.



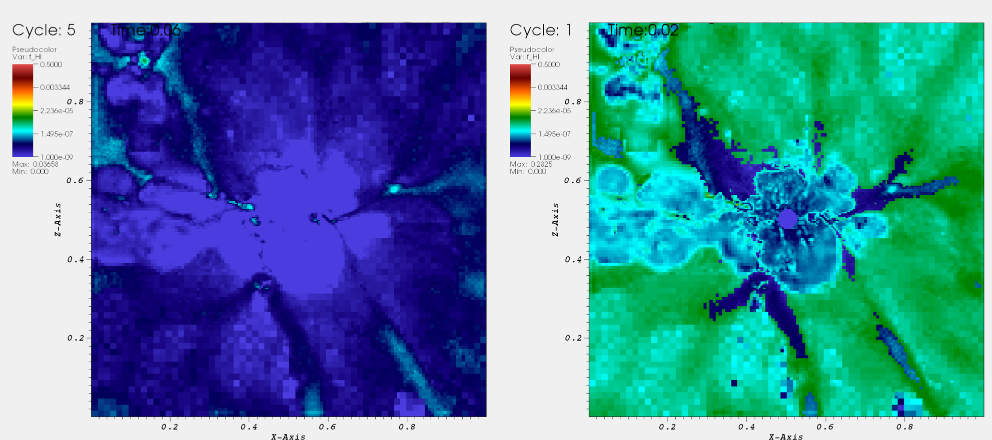
[Marino et al. 2017, arXiv:1709.03522]

Incorporating the Cosmological Radiative Transfer code, RADAMESH with Hydrodynamics

(Saeed Sarpas, PhD)

The advent of supercomputers and the more efficient CPU architectures has enabled cosmologists to simulate the Universe in more detail. So far, Gravity, Hydrodynamics and radiative cooling and heating effects have been included into the cosmological simulations, however still some important parts of the puzzle (such as proper stellar and AGN feedback mechanisms, magneto-hydrodynamics and radiative transfer effects) are either missing or not fully implemented. In the era of high precision cosmology, adding these extra phenomena to cosmological simulation seems crucial, especially to reach the percent accurate results. Our objective is to incorporate cosmological simulations with radiative transfer effects. Presently, these effects are treated in a post-processing state. Considering the active role of radiative hydrodynamics in cosmic structure formation, post-processing these effects might lead to less accurate results. The non-local nature of these effects make them extremely tricky and challenging to be implemented in an efficient way. We accept this challenge with the expectation of getting more precise results especially in the environment of our interest which is circumgalactic medium (CGM) illuminated by a bright quasar.

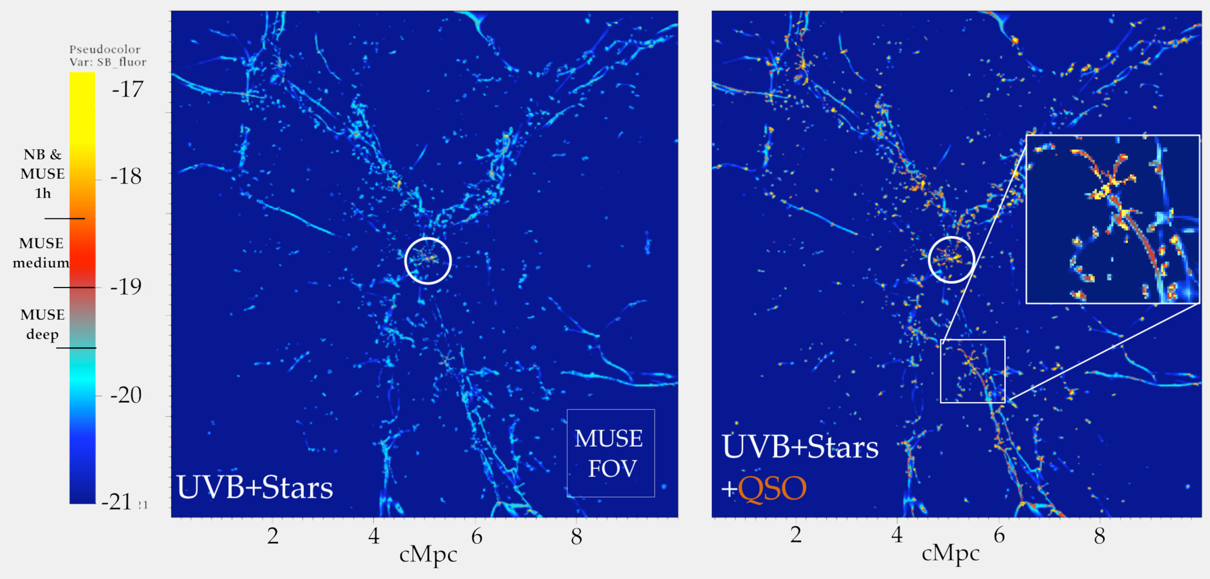
The pictures show how a bright quasar is able to ionize its environment in a comparably short period of time (here the interval between two snapshots is less than 100000 yrs). This result has been generated by post-processing an EAGLE snapshot at $z \approx 3$ using RADAMESH code.



RADAMESH: Cosmological Radiative Transfer for Adaptive Mesh Refinement Simulations

(Prof. Sebastiano Cantalupo)

RADAMESH is a three-dimensional radiative transfer (RT) code, based on a ray-tracing, photon-conserving and adaptive (in space and time) scheme. It uses a novel Monte Carlo approach to sample the radiation field within the computational domain on a "cell-by-cell" basis. Thanks to this algorithm, the computational efforts can be focused where needed most, i.e. within the Ionization-fronts (I-fronts). This results in an increased accuracy level and a huge gain in computational speed with respect to a "classical" Monte Carlo RT, especially when combined with an Adaptive Mesh Refinement (AMR) scheme. RADAMESH is able to adaptively refine the computational mesh in correspondence of the I-fronts, allowing to fully resolve them within large, cosmological boxes. The propagation of ionizing radiation is followed from an arbitrary number of sources and from the recombination radiation produced by H and He. The chemical state of six species (HI, HII, HeI, HeII, HeIII, e) and gas temperatures are computed with a time-dependent, non-equilibrium chemistry solver. Using our AMR scheme, we find that properly resolving the I-front of a bright quasar during Reionization produces a large increase of the predicted gas temperature within the whole HII region.



[Cantalupo & Porciani 2011, 2011MNRAS.411.1678C]

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What is the density distribution of the cold gas in CGM?

Analyzing the CGM in the Massive Dark Matter Halos of Cosmological Simulations

(Marius Tresoldi, Master Student)

In order to better understand the high redshift giant Ly-α nebulae revealed by MUSE, we analyze the properties of the hydrogen gas in the most massive dark matter halos at $z \sim 3$ using hydrodynamical simulations of cosmic structure formation such as the EAGLE and the Illustris project. These large-scale simulations have boxsizes of up to 100 cMpc and thus provide a useful sample of the rare halos of interest with $M > 10^{12.5} M_{\odot}$. Shown are both the phase diagram and the radial temperature distribution of the hydrogen gas in the RefL0100N1504 simulation of EAGLE at $z = 3.01$, where one can clearly distinguish between two phases. First there is the hot gas at $T \sim 10^{6.5}\mathrm{T}$ which corresponds to gas accreted from the intergalactic medium (IGM) that has been shock heated while falling into the gravitational potential well of the dark matter halo. The second phase is the cold CGM gas at $T \sim 10^{4.1}\mathrm{T}$ which is assumed to be responsible for the Ly-α emission observed by MUSE when ionized by a central quasar.