AST 541: Collapsed Objects: Clusters of Galaxies and First Galaxies
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Galaxy clusters represent the largest bound and virialized structures in the Universe today. This extreme environment makes them interesting for a variety of cosmology and galaxy formation applications.

- Highest-σ perturbations, probing tail of Gaussian primordial fluctuations.
- Many galaxies within a small volume, allowing observational efficiency for detailed study.
- Contain hot gas near halo virial temperature, allowing an independent probe of cluster properties.
- Often have numerous lensed objects, so serve as a gravitational telescope.
- Their halos are just assembling today (or recently), providing an interesting glimpse into hierarchical mass assembly.

Clusters contain anywhere from tens to many hundreds of $\geq L^*$ galaxies. Live at intersection of LSS filaments.

Famous catalog from Abell: at least 30 galaxies between M_3 and M_3+2 within 1.5 Mpc (physical) radius. That distance is called the Abell radius. Abell Richness class: $R = 0$, $N = 30 - 49$. $R = 1$, $N = 50 - 80$. $R = 2$, $N = 80 - 130$. $R = 5$, $N > 300$.

Galaxy groups are smaller versions of clusters, containing at most a few L^* galaxies. Typically people call groups to be $< 10^{14} M_\odot$ or $< 2 - 3$ keV in virial temperature, but in actuality there is a continuum of objects, with no obvious physical distinction between clusters and groups other than mass. Rare subclass known as "compact groups" (catalogued by Hickson) have several galaxies, spirals or ellipticals, within a very small radius, say 50–100 kpc; likely transient systems, and may include some "projected" groups.

Virgo – a poor cluster ($2 \times 10^{14} M_\odot$), only 18 Mpc away, virial radius about 1.2 Mpc.
Coma – a rich cluster ($10^{15} M_\odot$), about 100 Mpc away, virial radius about 2 Mpc.
Local group – a poor group ($2 \times 10^{13} M_\odot$), < 1 Mpc away, $r_{\rm vir} \sim 0.5$ Mpc (not virialized).

1 Basic properties

Clusters are identified through:
- X-ray emission from hot intracluster medium (ICM),
- Optical selection looking for concentrations of galaxies on the sky,

- Lensing, do large images and look for "strongish" weak lensing,
- Sunyaev-Zel'dovich upscattering of CMB photons from hot ICM e^-'s. (later)

Clusters are rare! $R \geq 1$ clusters have a density of $10^{-5}h^3$ Mpc^{-3}, 1000 times less than L^* galaxies. Most galaxies do not live in clusters (only around 5%). Most galaxies, do, however, live in groups, if one counts all the way down to poor groups like the Local Group.

Clusters are characterized by their:
- Optical richness R,
- Velocity dispersion σ, usually quoted as 1-D,
- X-ray temperature T_X, usually expressed in keV$\approx 10^7$K,
- Dynamical mass M.

The most fundamental is mass, but this is not directly observable except via lensing. Others correlate with mass but not perfectly.

Clusters always have a cD (central dominant) galaxy. It is very massive, up to $10^{12+}M_\odot$ in stars alone. Cluster galaxies orbit cD and are held up by dynamical pressure. cD galaxies typically have an extended envelope of stars beyond de Vauceleurs profile. It is often difficult to separate cD from "intracluster" stars.

Clusters often show substructure, indicating that they are still in the process of forming via merging. However, they are not formed exclusively from merging groups; many isolated galaxies fall in also.

Stars in clusters today are uniformly old and red, with little cold gas. However, there is a strong increase in the amount of blue (star-forming) galaxies in clusters back to $z \sim 1$. This is called the Butcher-Oemler effect.

Clusters are highly clustered. In other words, they show a large bias. The correlation length can be as much as $20h^{-1}$ Mpc, depending on the sample. That's a bias of nearly 4.

Superclusters are also seen, i.e. coherent structures of $\sim$ 100Mpc/h scales with $\delta \sim$few. These are unlikely to be bound objects, but will eventually collapse.

2 Cluster constituents

Stars make up about 5-10% of the baryonic mass in clusters, with larger clusters having smaller fractions. Clusters have very little cold/neutral gas. So most baryonic matter in clusters is in hot, X-ray emitting gas.

How hot would we expect the gas to be? The galaxies are moving in the cluster at about 1000

km/s; equipartition says gas should be moving similarly.

The kinetic energy density of the particles would be $(3/2)\rho\sigma^2$. If shared into a thermal distribution, the temperature would be $(3/2)nkT$. So $kT = (\rho/n)\sigma^2 = \mu m_p \sigma^2$.

The mean molecular weight is $\rho/n = \mu m_p$. For atomic hydrogen gas, this would be $\mu = 1$. For ionized hydrogen, $\mu = 1/2$. For helium/hydrogen mix, $\mu = 0.59$. So

$$kT = 6.16 \text{ keV} \left(\frac{\mu}{0.59}\right)\left(\frac{\sigma}{1000 \text{ km s}^{-1}}\right)^2$$

That's about 70 million degrees.

3 Simple cluster model

In principle, clusters are very simple entities. To within 10%, they are balls of hot gas sitting in the potential well of the dark matter halo. The hot gas is held up against gravity by thermal pressure gradients. This is known as *hydrostatic equilibrium.*

$$\frac{dp}{dr} = -\frac{GM(<r)\rho}{r^2}$$

$$p = \frac{\rho kT}{\mu m_p}$$

$$\frac{\rho kT}{\mu m_p}\left(\frac{1}{\rho}\frac{d\rho}{dr} + \frac{1}{T}\frac{dT}{dr}\right) = -\frac{GM(<r)\rho}{r^2}$$

$$M(<r) = -\frac{kTr^2}{G\mu m_p}\left[\frac{d(\log\rho)}{dr} + \frac{d(\log T)}{dr}\right]$$

How do we measure these quantities? The temperature can be measured from the X-ray spectrum. The spectrum is not a black-body, but rather is dominated by Bremstrahlung. The spectrum is fairly flat up to a sharp cutoff at $h\nu = kT$:

$$\frac{dE}{dV\,dt\,d\nu} = 6.8 \times 10^{-38} n_e n_i T_K^{-1/2} e^{-h\nu/kT} \bar{g}_{ff} \text{ ergs s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}$$

Integrating over frequency, the total energy radiated per unit volume is

$$\frac{dE}{dV\,dt} = 1.4 \times 10^{-27} T_K^{1/2} n_e n_i \bar{g}_B \text{ ergs s}^{-1} \text{ cm}^{-3}$$

The Gaunt factor is about 1.2.

Givin the temperature, the strength of the emission tells us about the density of the gas. Hence, we can measure ρ and T and generate the mass profile of the cluster.

In doing so, we find that

a) hot gas makes up only about 15% of the cluster's dynamical mass.

b) cluster temperatures are reasonably well matched to the velocity dispersion of the galaxies.

c) clusters are fairly isothermal, but not totally so.

d) the gas density reachs 10^{-2}–10^{-3} cm^{-3} in the centers.

At pressure equilibrium, ρT is a constant. So colder gas has higher ρ and is far more effective at emitting radiation ($\propto \rho^2$). Some clusters seem to have evidence for colder gas in the centers; these are known as "cool core" or "cooling flow" clusters. These are a minority, but exact fraction depends on definition.

4 Estimating Cluster masses

Halo mass is the key parameter for doing cluster cosmology. Basically, the evolution of the halo mass function at the massive end is highly sensitive to cosmological parameters (recall HW problem). However, because the tail is exponential, small errors in mass determination can yield large errors in $n(> M)$. Hence precise mass estimates are required.

Usually it is not possible to make a detailed, accurate mass profile from X-ray spectra for a large statistical sample. Furthermore, the assumption of hydrostatic equilibrium may not be applicable in the case of a recently-merged unrelaxed cluster (simulations though indicate that it is ok at the 10-20% level).

Hence others methods are used:

1. Measure X-ray temperature, use $M(< r_{200})$ formula above. In lieu of measuring $\rho(r)$ and $T(r)$, assume it is isothermal or follows NFW profile. Then only need to measure T and r_{200}. Generally, r_{200} is calibrated from simulations, or estimated based on an assumed density profile.

2. Velocity dispersions of the galaxies. Measure the redshifts of many galaxies in the cluster and try to determine the velocity dispersion. Problem: which galaxies are actually in the cluster, and which are just falling in. cf: Fingers of God in redshift surveys.

3. Weak lensing. This has the advantage that it really probes the mass, but the disadvantage that it gets the projected mass along the line of sight. Because large structures are correlated, these masses are typically biased by about 20%. However, this bias can perhaps be calibrated by simulations.

These three methods give similar masses but can differ at the 30% level. This is currently

insufficient for precision cosmology. None are perfect!

5 Sunyaev-Zeldovich effect

CMB photons travelling through the hot ICM are up-scattered (inverse Compton scattering). This produces a deficit of photons at lower frequency and an excess at higher frequency, with a null at 217 GHz. The size of the effect is typically measured by the Compton y parameter, which is

$$y = \int dl\, \sigma_T n_e \frac{k(T_e - T_{cmb})}{m_e c^2}$$

y is related to the shift in intensity $\Delta I(\nu)$:

$$\Delta I(\nu) = \frac{2(kT_{CMB})^3}{(hc)^2} g(x) y$$

where $g(x)$ is the spectral function

$$g(x) = \frac{x^4 e^x}{e^x - 1}\Big[\frac{x(e^x+1)}{e^x-1} - 4\Big]$$

($x = h\nu/kT$), which has a crossover at 217 GHz.

Since the ICM temperature far exceeds the CMB temperature, T_{cmb} is negligible. Hence y is proportional to the integrated gas pressure ($p = knT$ for ideal gas) along the line of sight.

At low frequencies, $\Delta T/T = -2y$. Cores of rich clusters can reach $y \sim 10^{-4}$, which is considerably higher than the primary anisotropies of the CMB.

SZ effect is redshift independent! As long as balls of hot gas are out there, SZ surveys should find them. This is in stark contrast to X-ray and optical surveys whose sensitivity drops rapidly with z.

Combining X-rays and SZ gives powerful probe of cosmology ICM structure. Recall X-ray emission $\propto \rho^2 T^{1/2}$. SZ's $y \propto \rho T$. Hence by obtaining both, one can in principle independently get ρ and T.

One can combine SZ+X-rays to infer the LOS length scale of the cluster, and assuming spherical clusters (on average), one can measure the angular size and infer the angular diameter distance and hence the Hubble constant. This is nice because it is independent of the distance ladder. Currently, technology is insufficient to do this to better than 20-30%, but new radio telescope arrays (particularly at South Pole) will revolutionize this field.

An additional aspect for probing ICM physics is that with sufficient resolution, can get $\rho(r)$ and $T(r)$ independently. This can tell about non-thermal energy injection (will discuss later).

Currently, surveys (e.g. SPT) have found a large number of clusters that were previously X-ray detected.

Kinetic SZ effect: Bulk motion of hot gas, from clusters with non-negligible peculiar velocity, can also cause CMB temperature shifts. The Doppler shift causes an overall temperature shift in the CMB, whose spectral signature is different than thermal SZ. Its amplitude is small. Only hope to measure is to try to measure at 217 GHz, where thermal SZ is zero.

6 Cooling flow crisis

Consider cooling times. The energy density is $(3/2)nkT$, while the cooling rates are proportional to $n^2T^{1/2}$. The ratio gives the amount of time to cool significantly: $t_c \propto T^{1/2}/n$. High density gas will cool in the age of the universe.

Often, we find that the densities implied in the centers of clusters would allow the gas to cool in a Gyr or less. We also find clusters with extra luminosity and cooler gas in the centers. From estimating t_c, one naively predicts that 100–1000 $M_\odot$/yr of gas is cooling. Yet, we do not see this cool gas: no noticable star formation, no lumps, generally no soft X-ray emission below ~ 1 keV!

What prevents this gas from cooling? Unknown. Popular theory is that AGN activity injects energy periodically in a self-regulating manner. Evidence includes "hot bubbles" seen in X-ray data that appear to coincide with radio emission from AGN jets, and that could contain enough energy to suppress cooling flows. However, exact mechanism remains uncertain.

Another possibility is magnetic conduction. Magnetic fields are seen in clusters at the microgauss level; such fields, if efficiently conductive, could thermalize clusters and prevent cool cores. Generally requires maximally efficient conduction, which is difficult to understand.

Third possibility is that hierarchical accretion transports enough gravitational energy to cluster centers to prevent cooling flows. This is seen in some but not other hydro simulations; it's very difficult to model in quantitative detail.

It is tempting to try to solve both crises with AGN feedback. Not clear if this will work, because feedback is required at late times to prevent cooling flows ("radio mode"), but cluster scaling relations don't evolve much at least out to $z \sim 0.5$.

7 ICM metallicity crisis

ICM gas is not primordial. It has metals, typically 1/3 solar!

How did metals get into the ICM? Unclear. Could be swept out of galaxies via ram pressure stripping when they fall into the cluster medium, or could be blown out of galaxies by supernovae, or could have accreted from IGM at that metallicity.

Probably not latter, as IGM metallicity is much lower, even taking into account metallicity-density relation.

Models for stripping/blowout tend to fall short of required metal budget by $\sim \times 2$. But intracluster stars, i.e. stars that are bound to the cluster potential but not any individual galaxy, can make up as much as half the cluster's stellar mass, and accounting for the metals produced by those stars can alleviate the shortfall. However, IMF variations could also do it.

These various "crises" associated with gastrophysical processes are a significant challenge for using cluster to do precision cosmology. It is clear clusters are not as simple as originally thought. Much like how galaxies were originally used to try to do cosmology, but then cosmology was constrained independently so galaxy evolution became the more interesting question, it seems that clusters will follow a similar track, and that clusters themselves will become more interesting than doing cosmology with them.

8 Clusters and Cosmology

Clusters are proven to be powerful tools for cosmology, examples:

- Measurement of density parameter via mass to light ratio.
- Measurement of density parameter via baryon fraction.
- Measurement of cosmological parameters via dN/dz.
- Measurement of Hubble constant via S-Z.
- Probing non-Guassianity via the most massive systems.
- Understanding dark matter, Bullet cluster.

9 First Galaxies

Two important conclusions from last two weeks of lectures:

- P-S theory tells us when halos at different masses collapse in the universe, how their densities evolve with redshift.
- The competition of cooling and gravity tells us the condition of when galaxies can cool and form stars.

These are the basic elements of galaxy formation. We will discuss the formation of the first galaxies. They are actually simpler questions theoretically, because the lack of significant feedback, this is a well posed question which we can solve from the initial conditions.

10 First Halos in the Universe

Figure (page 19 on the pdf): it shows $\sigma(M)$ and $\delta_{\rm crit}(z)$, with the input LCDM power spectrum. The solid line is $\sigma(M)$ for the cold dark matter model with the parameters specified above. The horizontal dotted lines show the value of $\delta_{\rm crit}(z)$ at $z = 0, 2, 5, 10, 20$ and 30, as indicated in the figure. From the intersection of these horizontal lines with the solid line we infer, e.g., that at $z = 5$ a $1-\sigma$ fluctuation on a mass scale of $2 \times 10^7 M_\odot$ will collapse. On the other hand, at $z = 5$ collapsing halos require a $2-\sigma$ fluctuation on a mass scale of $3 \times 10^{10} M_\odot$, since $\sigma(M)$ on this mass scale equals about half of $\delta_{\rm crit}(z = 5)$. Since at each redshift a fixed fraction (31.7%) of the total dark matter mass lies in halos above the $1-\sigma$ mass, Figure 1 shows that most of the mass is in small halos at high redshift, but it continuously shifts toward higher characteristic halo masses at lower redshift. Note also that $\sigma(M)$ flattens at low masses because of the changing shape of the power spectrum. Since $\sigma \to \infty$ as $M \to 0$, in the cold dark matter model all the dark matter is tied up in halos at all redshifts, if sufficiently low-mass halos are considered.

Figure (page 20 on the pdf): it shows the cooling rates as a function of temperature for a primordial gas composed of atomic hydrogen and helium, as well as molecular hydrogen, in the absence of any external radiation. We assume a hydrogen number density $n_H = 0.045$ cm^{-3}, corresponding to the mean density of virialized halos at $z = 10$. The plotted quantity Λ/n_H^2 is roughly independent of density (unless $n_H > 10$ cm^{-3}), where Λ is the volume cooling rate (in erg/sec/cm^3). The solid line shows the cooling curve for an atomic gas, with the characteristic peaks due to collisional excitation of H1 and He2. The dashed

line shows the additional contribution of molecular cooling, assuming a molecular abundance equal to 1% of n_H. From the curve, it requires T$\sim 10^3$ for molecular H to be important in cooling, and 10^4 for atomic H to be important. Therefore, dark matter halo can't cool at virial temperature less than 1000K. Also note that if the universe were ionized, no H2 therefore things have to wait.

Figures on pages 21, 22 and 23: we show explicitly the properties of collapsing halos which represent $1-\sigma$, $2-\sigma$, and $3-\sigma$ fluctuations (corresponding in all cases to the curves in order from bottom to top), as a function of redshift. No cutoff is applied to the power spectrum. Figure 2 shows the halo mass, Figure 3 the virial temperature (as well as circular velocity. In figures 2 and 3, the dotted curves indicate the minimum virial temperature required for efficient cooling with primordial atomic species only (upper curve) or with the addition of molecular hydrogen (lower curve). Figure 4 shows the binding energy of dark matter halos. The binding energy of the baryons is a factor $\sim \Omega_b/\Omega_m \sim 15\%$ smaller, if they follow the dark matter. Except for this constant factor, the figure shows the minimum amount of energy that needs to be deposited into the gas in order to unbind it from the potential well of the dark matter. For example, the hydrodynamic energy released by a single supernovae, $\sim 10^{51}$ erg, is sufficient to unbind the gas in all $1-\sigma$ halos at $z > 5$ and in all $2-\sigma$ halos at $z > 12$.

At $z = 5$, the halo masses which correspond to $1-\sigma$, $2-\sigma$, and $3-\sigma$ fluctuations are $1.8\times10^7 M_\odot$, $3.0 \times 10^{10} M_\odot$, and $7.0 \times 10^{11} M_\odot$, respectively. The corresponding virial temperatures are 2.0×10^3 K, 2.8×10^5 K, and 2.3×10^6 K. The equivalent circular velocities are 7.5 km s^{-1}, 88 km s^{-1}, and 250 km s^{-1}. At $z = 10$, the $1-\sigma$, $2-\sigma$, and $3-\sigma$ fluctuations correspond to halo masses of $1.3\times10^3 M_\odot$, $5.7\times10^7 M_\odot$, and $4.8\times10^9 M_\odot$, respectively. The corresponding virial temperatures are 6.2 K, 7.9×10^3 K, and 1.5×10^5 K. The equivalent circular velocities are 0.41 km s^{-1}, 15 km s^{-1}, and 65 km s^{-1}. Atomic cooling is efficient at $T_{\rm vir} > 10^4$ K, or a circular velocity $V_c > 17$ km s^{-1}. This corresponds to a $1.2-\sigma$ fluctuation and a halo mass of $2.1\times10^8 M_\odot$ at $z = 5$, and a $2.1-\sigma$ fluctuation and a halo mass of $8.3\times10^7 M_\odot$ at $z = 10$. Molecular hydrogen provides efficient cooling down to $T_{\rm vir} \sim 300$ K, or a circular velocity $V_c \sim 2.9$ km s^{-1}. This corresponds to a $0.81-\sigma$ fluctuation and a halo mass of $1.1\times10^6 M_\odot$ at $z = 5$, and a $1.4-\sigma$ fluctuation and a halo mass of $4.3 \times 10^5 M_\odot$ at $z = 10$.

From these calculations, we see why the first objects, probably cooled by H_2, formed at $z \sim 20$.

11 Fragmentation of the First Gaseous Objects to Stars

As mentioned in the preface, the fragmentation of the first gaseous objects is a well-posed physics problem with well specified initial conditions, for a given power-spectrum of primordial density fluctuations.

11.1 Star Formation

Detailed 3D simulations now can follow the formation process of the first stars in a halo of $\sim 10^6 M_\odot$ by following the dynamics of both the dark matter and the gas components, including H_2 chemistry and cooling (example: pages 23 and 24 of the pdf). The collapsing region forms a disk which fragments into many clumps. The clumps have a typical mass $\sim 10^2$–$10^3 M_\odot$. This mass scale corresponds to the Jeans mass for a temperature of ~ 500K and the density $\sim 10^4$ cm^{-3} where the gas lingers because its cooling time is longer than its collapse time at that point. Each clump accretes mass slowly until it exceeds the Jeans mass and collapses at a roughly constant temperature (isothermally) due to H_2 cooling that brings the gas to a fixed temperature floor.

Simulation shows that the collapse of one of the above-mentioned clumps with $\sim 1000 M_\odot$ and demonstrated that it does not tend to fragment into sub-components. Rather, the clump core of $\sim 100 M_\odot$ free-falls towards the center leaving an extended envelope behind with a roughly isothermal density profile. These calculations indicate that each clump may end as a single massive star; however, it is conceivable that angular momentum may eventually halt the collapsing cloud and lead to the formation of a binary stellar system instead.

As soon as nuclear burning sets in the core of the proto-star, the radiation emitted by the star starts to affect the infall of the surrounding gas towards it. The radiative feedback involves photo-dissociation of H_2, Lyα radiation pressure, and photo-evaporation of the accretion disk. For example, Tan & McKee studied these effects by extrapolating analytically the infall of gas from the final snapshot of the above resolution-limited simulations to the scale of a proto-star; they concluded that nuclear burning (and hence the feedback) starts when the proton-star accretes $\sim 30 M_\odot$ and accretion is likely to be terminated when the star reaches $\sim 200 M_\odot$.

If the clumps in the above simulations end up forming individual very massive stars, then these stars will likely radiate copious amounts of ionizing radiation and expel strong winds. Hence, the stars will have a large effect on their interstellar environment, and feedback is likely to control the overall star formation efficiency. This efficiency is likely to be small in galactic

potential wells which have a virial temperature lower than the temperature of photoionized gas, $\sim 10^4$K. In such potential wells, the gas may go through only a single generation of star formation, leading to a "suicidal" population of massive stars.

Page 25 of the pdf shows the fate of the first stars. The final state in the evolution of these stars is uncertain; but if their mass loss is not too extensive, then they are likely to end up as black holes. The remnants may provide the seeds of quasar black holes. Some of the massive stars may end their lives by producing gamma-ray bursts. If so then the broad-band afterglows of these bursts could provide a powerful tool for probing the epoch of reionization.

Where are the first stars or their remnants located today? The very first stars formed in rare high-σ peaks and hence are likely to populate the cores of present-day galaxies. However, the bulk of the stars which formed in low-mass systems at later times are expected to behave similarly to the collisionless dark matter particles and populate galaxy halos.

11.2 Population III Stars

Currently, we do not have direct observational constraints on how the first stars, the so-called Population III stars, formed at the end of the cosmic dark ages. Pop III stars were proposed at least fifty years ago, but they are expected to be massive, thus short lived.

Population I stars form out of cold, dense molecular gas that is structured in a complex, highly inhomogeneous way. The molecular clouds are supported against gravity by turbulent velocity fields and pervaded on large scales by magnetic fields. Stars tend to form in clusters, ranging from a few hundred up to $\sim 10^6$ stars. It appears likely that the clustered nature of star formation leads to complicated dynamics and tidal interactions that transport angular momentum, thus allowing the collapsing gas to overcome the classical centrifugal barrier. The most important feature of the observed IMF is that $\sim 1M_\odot$ is the characteristic mass scale of Pop I star formation, in the sense that most of the mass goes into stars with masses close to this value. In Figure 6, we show the result from a recent hydrodynamical simulation of the collapse and fragmentation of a molecular cloud core. This simulation illustrates the highly dynamic and chaotic nature of the star formation process.

Still, studies of the so-called Extremely Metal Poor Stars (EMPS) have allows us to probe the environment of the earliest star formation. The recent discovery of stars like SM0313 with a mass of $0.8M_\odot$ and an iron abundance of $[\mathrm{Fe/H}] < -7$ shows that at least some low mass stars could have formed out of extremely low-metallicity gas. These are likely the second generation of stars and their abundance pattern would teach us about the chemical yield of

the first, Pop III stars.

The very first stars, marking the cosmic Renaissance of structure formation, formed under conditions that were much simpler than the highly complex environment in present-day molecular clouds. Subsequently, however, the situation rapidly became more complicated again due to the feedback from the first stars on the IGM. Supernova explosions dispersed the nucleosynthetic products from the first generation of stars into the surrounding gas, including also dust grains produced in the explosion itself. Atomic and molecular cooling became much more efficient after the addition of these metals. Moreover, the presence of ionizing cosmic rays, as well as of UV and X-ray background photons, modified the thermal and chemical behavior of the gas in important ways.

Early metal enrichment was likely the dominant effect that brought about the transition from Population III to Population II star formation. Recent numerical simulations of collapsing primordial objects with overall masses of $\sim 10^6 M_\odot$, have shown that the gas has to be enriched with heavy elements to a minimum level of $Z_{\rm crit} \simeq 10^{-3.5} Z_\odot$, in order to have any effect on the dynamics and fragmentation properties of the system. Normal, low-mass (Population II) stars are hypothesized to only form out of gas with metallicity $Z \geq Z_{\rm crit}$. Thus, the characteristic mass scale for star formation is expected to be a function of metallicity, with a discontinuity at $Z_{\rm crit}$ where the mass scale changes by $\sim$ two orders of magnitude. The redshift where this transition occurs has important implications for the early growth of cosmic structure, and the resulting observational signature.

12 Probing First Galaxies

Observations of the first galaxies is one of the main frontiers of modern astrophysics. Goals of JWST, WFIRST, SKA etc.

- Individual first stars, not really possible.
- First galaxies: objects with $\sim 10^6 M_\odot$, H^2 cooling. Maybe OK with photometric detection of JWST, but beyond spectroscopic capability. The first atomically cooled halos ($10^8 M_\odot$), more likley,
- First SNe: PISNe, early GRBs, possible.
- First AGN: objects with Eddington accretion and $10^6 M_\odot$ BHs, maybe possible with JWST and ATHENA? Interesting case for galaxy CR7.

- Reionzation: a better way to approach this is to study the overall impact of first stars to the IGM, the history of reionization, and the sources that are responsible to it, will take us a lot about first galaxies, topic of next week.