High Redshift Universe

- Background radiation
- Star formation: Jeans mass, cooling
- The first stars
- Re-ionization
- Galaxy formation
- Semi-analytical models
- Cosmic downsizing
Background radiation

- CMB is truly diffuse – redshifted radiation from $T \sim 3000\text{K}$ gas.
- Define radiation component as “background” if isotropic
- Other radiations due to unresolved sources
  - what sources and at what redshift?
  - resolve background with more sensitive telescopes with better angular resolution
- Energy in CMB is much larger than other backgrounds
Infrared background

- CIB is hard to measure due to thermal emission of detectors and foregrounds of interplanetary dust and ISM in Milky way.
- Find lower limits on CIB from galaxy counts, upper limits from flux measurements.
- Constraints from $\gamma + \gamma \rightarrow e^+ e^-$, cutoff in spectra of high $z$ gamma-ray sources.
- CIB is mainly due to dusty, star-forming galaxies over a range of redshifts.
- ESA's Herschel satellite now operating, will further resolve CIB.
X-ray background

- CXB discovered in 1962 in same rocket flight that discovered first extrasolar X-ray source.
- Spectrum is hard in `standard' X-ray band (2-10 keV), has exponential cutoff at ~40 keV
  - \( I(E) \sim E^{-0.3} \exp(-E/E_{\text{cut}}) \)
- ROSAT resolved 80% of CXB in 0.5-2 keV band into unobscured AGN.
- Spectra of unobscured AGN are too steep, \( I(E) \sim E^{-0.7} \), to make CXB spectrum.
- Truly diffuse origin for CXB ruled out by CMB spectrum (no SZ effect on large scales)
• Chandra satellite designed specifically to resolve X-ray background in 2-10 keV band.
• About 80% of CBX resolved in deepest images.
• AGN are harder than those found by ROSAT.
• Starting to see normal and starburst galaxies (X-rays from binaries) appear.
X-ray background

- Difference between type-I and type-II AGN is obscuration.
- Absorption column density, $N_H$, has strong effect in X-ray band (above $N_H = 10^x$ cm$^{-2}$).
- X-ray reflection produces bump around 30 keV.
- Harder X-ray sources are those that are more obscured.
- Redshifts peak at $z \sim 1$, have a tail extending to $z \sim 7$.
- NuSTAR satellite now imaging in 5-80 keV band, looking for strongly obscured AGN.
Gravitational collapse

- Stars (and galaxies) form via collapse of gas clouds. How large a cloud is needed?
- Gas cloud radius $R$, mass $M \sim \rho R^3$, baryonic mass $M_b$, $\rho =$ average density of universe.
- Binding energy $\sim -G M M_b / R$
- Kinetic energy $\sim$ thermal energy of baryons $\sim v^2 m N \sim v^2 m (M_b/m) \sim v^2 M_b \sim c_s^2 M_b$
  - where $c_s^2 \sim k T_b / \mu m$, $m =$ proton mass
- For sufficiently large $M$, will have $|\text{binding energy}| > \text{kinetic energy}$
  - $M > (\pi^{5/2}/6) (c_s^2/G)^{3/2} \rho^{-1/2}$ this is the “Jeans mass”
Jeans mass versus redshift

- Average density of universe $\rho(z) = \rho_0 (1+z)^3$

- Baryon temperature:
  - For $z > z_t = 140$, baryons coupled to radiation via free electrons (gas 99.99% neutral)
    - Baryon $T_b = $ radiation $T = T_0 (1+z)$
    - Recall $c_s^2 \sim kT_b$, so $M_J \sim (c_s^2)^{3/2} \rho^{-1/2} \sim (1+z)^{3/2} (1+z)^{-3/2} \sim 1$
    - $M_J = 1.4 \times 10^5 \ M_{\text{Sun}}$ independent of $z$.

- For $z < z_t$, baryons cool adiabatically due to expansion
  - $T_b \sim \rho_b^{2/3} \sim (1+z)^2$
  - $M_J = 5.7 \times 10^3 \ M_{\text{Sun}} [(1+z)/10]^{3/2}$
Cooling

- Jeans criterion is necessary, but not sufficient for collapse.
- For collapse, need to dissipate kinetic energy via radiation = cooling.
- In normal (metallicity) gas, cooling is mostly via metals.
- Atomic hydrogen cools efficiently at high temperatures $T > 10^4 \, \text{K}$, $kT > 1 \, \text{eV}$.
- Molecular hydrogen cooling is dominant for $T < 10^4 \, \text{K}$, but less efficient.
- As cloud collapses, potential energy is converted to kinetic $\rightarrow$ virial temperature
- Need $T_{\text{vir}} > 3000 \, \text{K}$ to collapse, $M \sim 10^4 \, M_{\odot}$
- Collapse forms Population III star
  - only H, He
  - very hot and massive
• Pop III stars form in low mass halos, $T_{\text{vir}} \sim 3000 \text{ K, } M \sim 10^4 M_{\odot}$.
• Dissociate nearby $\text{H}_2$. Go supernovae, enriching IGM with metals.
• Metals allow cooling at higher temperatures. Stars/galaxies form in higher mass halos.
• Fusion 7 MeV/proton, ionization 13.6 eV/proton, fuse $\sim 2 \times 10^{-6}$ of protons to reionize.
• Hubble ultradeep field has $10^{12} M_{\odot}$ galaxy at $z \sim 6.5$ with 300 Myr old stars, sufficient to reionize the volume of the HUDF at $z \sim 6.5$. 
Star formation rate

- Star formation rate (SFR) measured in $M_{\text{Sun}}$/year of gas converted into stars.

- Star formation produces emission in a variety of bands, any can be used as SFR indicator, e.g. 
  $\text{SFR}_{\text{FIR}} = \frac{L_{\text{FIR}}}{5.8 \times 10^9 L_{\text{Sun}}} (M_{\text{Sun}}/\text{year})$

- Common indicators:
  - UV from young, hot stars
  - FIR from warm dust heated by hot stars
  - H$\alpha$ from HII regions around hot stars
  - Radio (1.4 GHz) from e$^-$ in SNR
  - X-rays from accreting compact objects

- Indicators calibrated via models (need IMF) and empirically.

- Wide scatter due to absorption, details of environment, different dependence on age of star formation
Star formation rate

- Once SFR indicators are calibrated, one can use them to measure SFR vs $z$.
- First done by Madau.
- Find galaxies in surveys and then sum SFR in co-moving volume vs $z$.
- Initial estimates done without regard to absorption, showed peak at $z = 1-2$.
- Recent estimates rise to $z = 2$, flat or slight decline at higher $z$.
- Dust enshrouded SF dominates $z > 0.7$.
- Integration of SFR roughly matches measurements of stellar density.
Galaxy searches

• Our knowledge of galaxy evolution is incomplete because we do not have a complete sample of galaxies over all $z$.
• Missing galaxies also make SFR estimates incomplete.
• Galaxies are found through specific searches, e.g. a search for Lyman break galaxies with a particular choice of filters.
• Only galaxies with specific properties are found in specific search, e.g. LGB searches will not find dust-enshrouded SF galaxies.
• Galaxies searches require large telescopes, particularly for spectroscopic follow-up. Now 8-10 m class telescopes exist only on the ground, thus view only in atmospheric bands (e.g. redshift desert $1.3 < z < 2.5$).
• JWST will help solve this problem, especially important is NIR spectroscopy.
Isolated galaxy formation

Formation of a spiral galaxy

1. Stars form gradually within a protogalaxy.
2. Gas not involved in star formation collapses to form a disk.
3. A spiral galaxy results.

Formation of an elliptical galaxy

1. Stars form rapidly within a protogalaxy.
2. Gas is quickly consumed to make stars.
3. A elliptical galaxy results.

The stellar birthrate in galaxies

- Formation of stars in disks in spirals is well understood – gas dissipates energy and angular momentum when forming disk, high density regions collapse into stars.
- Prompt formation of stars in ellipticals and halos is difficult to understand due to lack of dissipation and cooling.
Formation of elliptical galaxies

- Larger ellipticals thought to form in major mergers (between galaxies of comparable mass)
- Major mergers randomize stellar orbits
- One issue is lack of young stars in ellipticals, mergers should trigger star formation.
- Require “dry” mergers – mergers between galaxies with little gas
- Hot IGM in clusters will strip gas from galaxies
- Explanation for Butcher-Oemler effect (decrease in fraction of blue galaxies in clusters with decreasing $z$) and red cluster sequence (no recent star formation in clusters).
- Merger leads to two central SMBH. This is observed as pairs of cores in radio and X-rays, X-shaped morphology of radio jet, orbit of OJ 287.
Numerical simulations

- Would like to extend simulations of structure formation in dark matter to the formation of galaxies.
- Physics of baryons gets in the way. Simulations would require extending down to scales of star formation, i.e. < solar radius, while extending up to scales of 100s of Mpc.
- Instead, graft semi-analytical prescriptions for baryonic processes onto simulations.
- Cooling and star formation: \( SFR = A \Sigma^\beta \) where \( \Sigma = \) gas surface density. Find A, \( \beta \) from fits to observations or star formation models.
- Feedback: massive stars will supernova, putting energy into ISM and self-regulating SF. Need to model time profile of energy input and fold into simulation.
- UV radiation field: intergalactic UV will heat and ionize gas, can prevent infall into low mass halos. Baryon fraction depends on halo mass. Need to calculate and fold into simulation.
- Galaxy mergers: effects on stellar orbits and star formation need to be put in by hand.
Numerical simulations

- Figure shows Millennium simulation augmented with semi-analytical prescriptions for galaxy formation. Massive dark matter halo evolves into massive galaxy cluster.
  - Top $z = 6.2$, bottom $z = 0$
  - Left = dark matter, right = galaxies
  - Same co-moving volume in all panels

- Plot is correlation function:
  - blue = data
  - red/line = galaxies in simulation
  - green = total matter in simulation

- Agreement is quite good, but semi-analytic prescriptions have many parameters.

- Test by comparison with various galaxy scaling relations, galaxy counts, stellar populations, etc.
Cosmic downsizing

• Cold dark matter cosmology is hierarchical with lower mass objects forming first and then being combined into larger mass objects.
• In contrast, high mass galaxies appear to have old stars and in the current universe star formation occurs mainly in relatively low mass galaxies.
  – Star formation appears to be (mostly) restricted to lower mass galaxies with the threshold for star formation decreasing with time – “cosmic downsizing”.
• Also, the most massive galaxies are much less massive than expected from the mass cutoff in dark matter halos.

• Galaxy formation is tied to SMBH formation via M-σ relation.
• AGN produces feedback that heats (galactic and intergalactic) gas and suppresses cooling flows and star formation.
• More massive BHs formed earlier in more massive halos because dynamical time is shorter.
• AGN feedback may explain cosmic downsizing and maximum galaxy mass.
For the rest of the semester

• Read 9.7 and 10.
• Project first full draft on November 28 (Wednesday!)
• Project final draft on December 5 (one week from Wednesday)
• Project presentations on December 5
  – 1:30 pm Brorby and Griffiths, “Searching for Gamma-Ray Blazars in the Infrared”
  – 2:00 pm McCoy and Scheiner, “Correlations between the Cosmic Microwave Background and Infrared Galaxies”
  – 2:30 pm Allured and Marlowe, “Using Infrared Colors to Identify Obscured AGN”
  – 3:00 pm De Pascuale and DeRoo, “Infrared Emission of Supernova Remnants in the LMC”
  – 3:30 pm Butterfield and Savage, “An Infrared View of Compact Galaxy Groups”
  – 4:00 pm Ludovici and Toomey, “Hunting for Blue Compact Dwarfs in the Infrared”