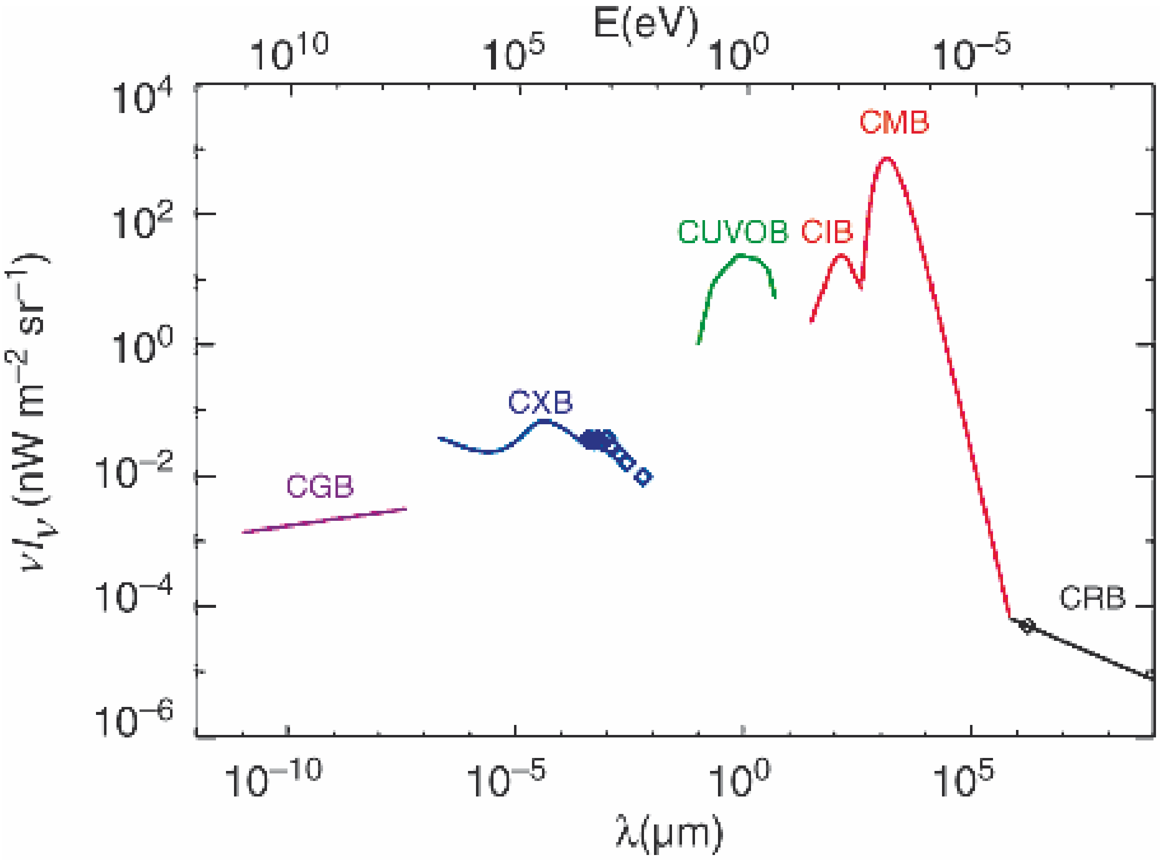
Outline

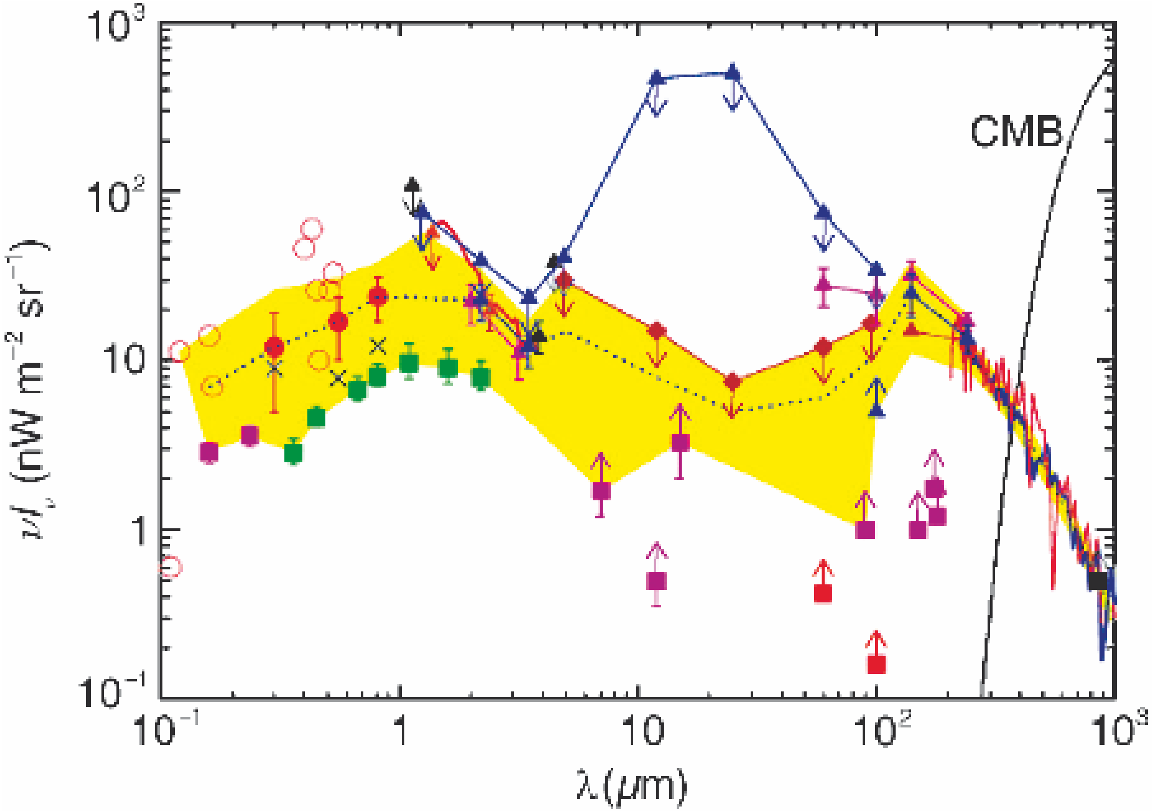
- Go over problem 9.7
- Background radiation
- Star formation: Jeans mass, cooling
- The first stars
- Re-ionization
- Star formation history
- Simulations of structure formation

Background radiation



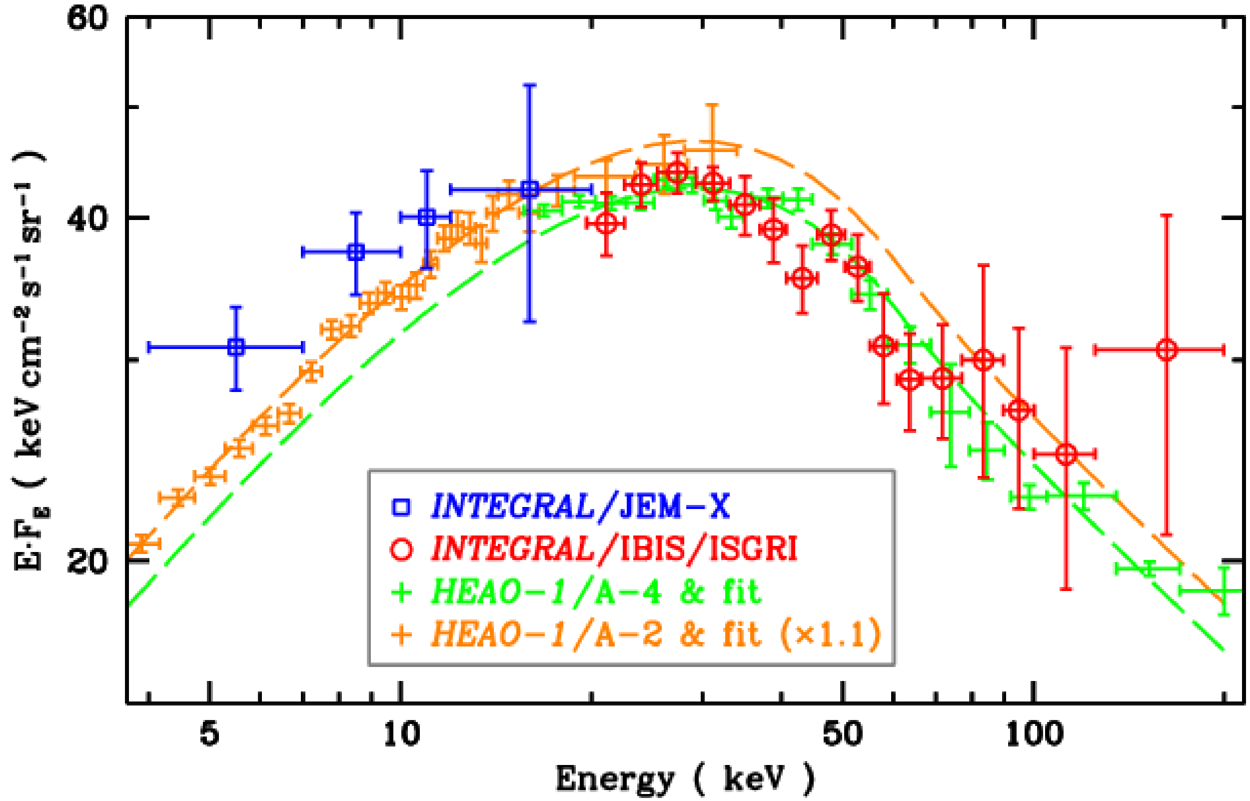
- CMB is truly diffuse – redshifted radiation from $T \sim 3000$K gas.
- Define radiation component as "background" if (roughly) isotropic
- Other radiations due to unresolved sources
  - what sources and at what redshift?
  - resolve background with more sensitive telescopes with better angular resolution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

Infrared background



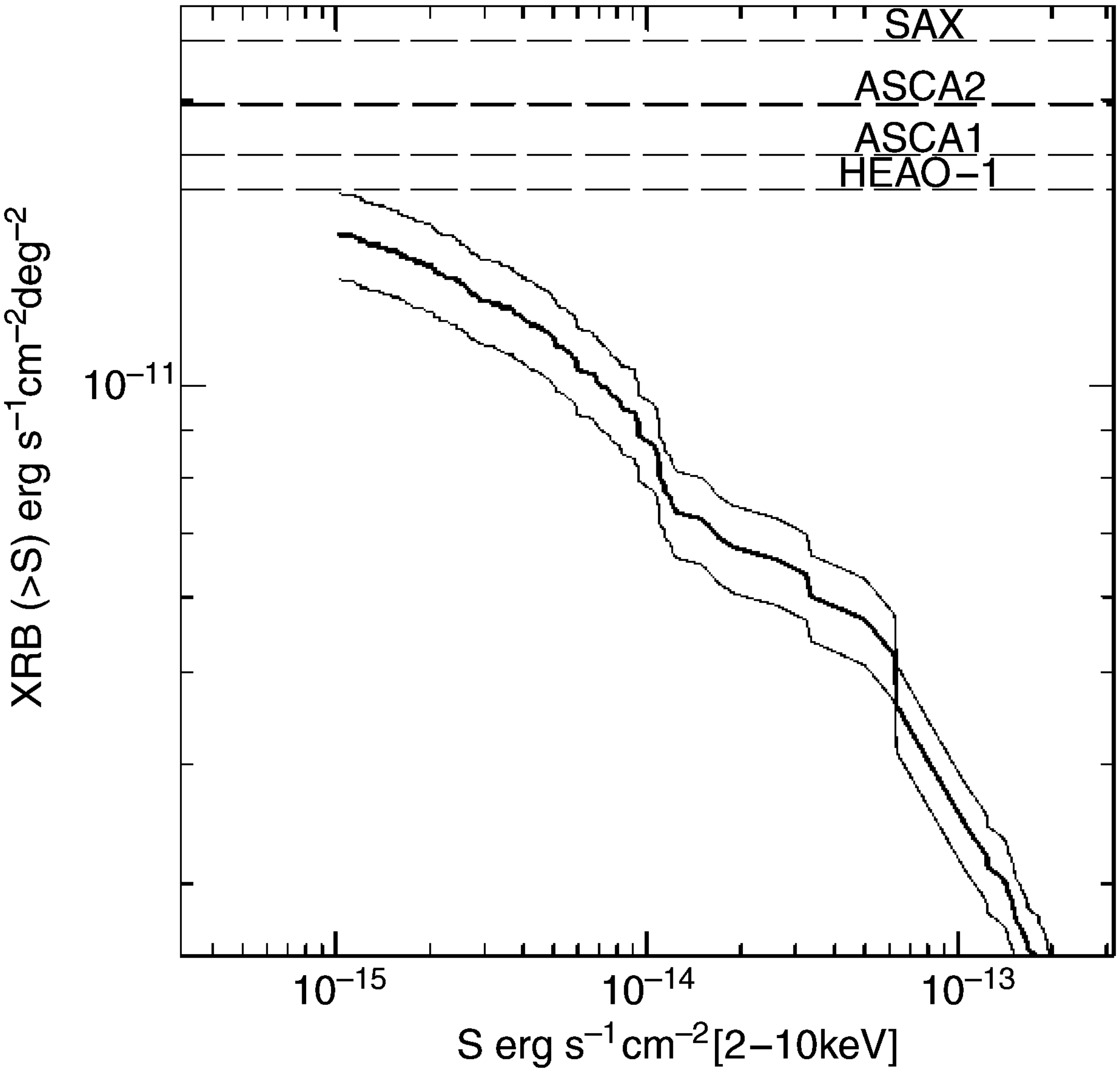
- CIB is hard to measure due to thermal emission of detectors and foregrounds of interplanetary dust and ISM in Milky way.
- Find lower limits on CIB from galaxy counts, upper limits from flux measurements.
  - Goal is to resolve CIB into sources
- Constraints from $\gamma + \gamma \rightarrow e^+ e^-$, cutoff in spectra of high *z* gamma-ray sources
- CIB is mainly due to dusty, starforming galaxies over a range of redshifts.

X-ray background



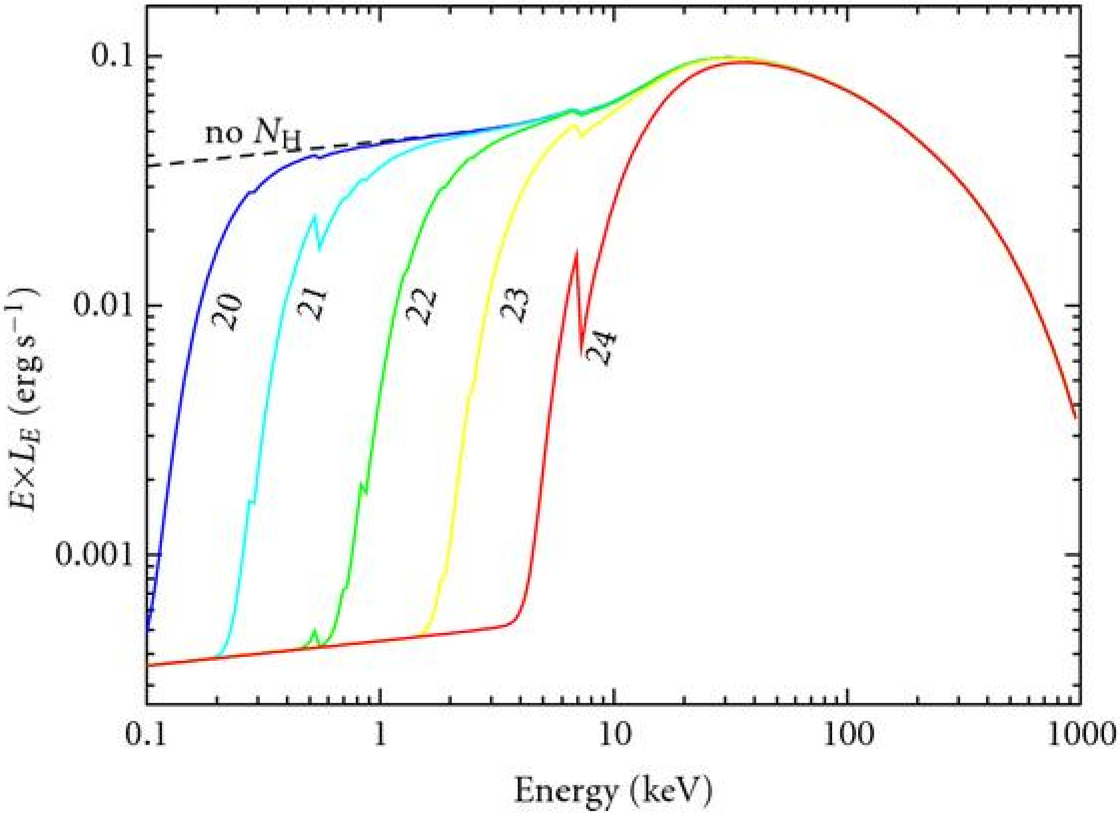
- CXB discovered in 1962 in same rocket flight that discovered first extrasolar X-ray source.
- Spectrum is hard in `standard' X-ray band (2-10 keV), has exponential cutoff at ~40 keV
  - $I(E) \sim E^{-0.3} \exp(-E/E_{\rm cut})$
- ROSAT resolved 80% of CXB in 0.5-2 keV band into unobscured AGN.
- Spectra 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)

X-ray background



- 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, ρ = average density of universe.
- Binding energy $\sim -GMM_\mathrm{b}/R$
- Kinetic energy ~ thermal energy of baryons $\sim v^2\, m\, N \sim v^2\, m\, (M_b/m) \sim v^2\, M_\mathrm{b} \sim \mathrm{c_s}^2\, M_\mathrm{b}$
  - where $\mathrm{c_s}^2 \sim kT_\mathrm{b}/\mu m$, m = proton mass
- For sufficiently large M, will have |binding energy| > kinetic energy
  - $\mathrm{M} > (\pi^{5/2}/6)\, (\mathrm{c_s}^2/\mathrm{G})^{3/2}\, \rho^{-1/2}$ this is the “Jeans mass”

Star Formation

- When is a gas cloud unstable to collapse?
- Consider a spherical cloud of constant (initial) density and temperature with particles of mean mass *m*. The cloud has a mass *M* and radius *r*, undergoes a radial compression *dr*.
- Gravitational energy:

$$E_g \approx -\frac{GM^2}{r} \rightarrow dE_g = -\frac{GM^2}{r^2}\,dr$$

- Volume decrease $dV = 4\pi r^2 dr$, thermal energy increase $dE_{\mathrm{th}} = PdV$.
- Use equation of state for ideal gas

$$dE_{\mathrm{th}} = nkT\,4\pi r^2\,dr = \frac{M}{\bar{m}\frac{4}{3}\pi r^3}kT\,4\pi r^2\,dr = 3\frac{M}{\bar{m}}kT\frac{dr}{r}$$

Jeans Instability

- Cloud is unstable to collapse if total energy decreases when compressed

$$dE_g + dE_{\mathrm{th}} < 0 \rightarrow 3\frac{M}{\bar{m}}kT\frac{dr}{r} < \frac{GM^2}{r^2}dr$$

- Gives the Jeans mass, radius, and density

$$\rho_J = \frac{3}{4\pi M^2}\left(\frac{3kT}{G\bar{m}}\right)^3 \qquad M_J = \left(\frac{3}{4\pi\rho}\right)^{1/2}\left(\frac{3kT}{G\bar{m}}\right)^{3/2}$$

$$M_J \propto \rho^{-1/2}T^{3/2}$$

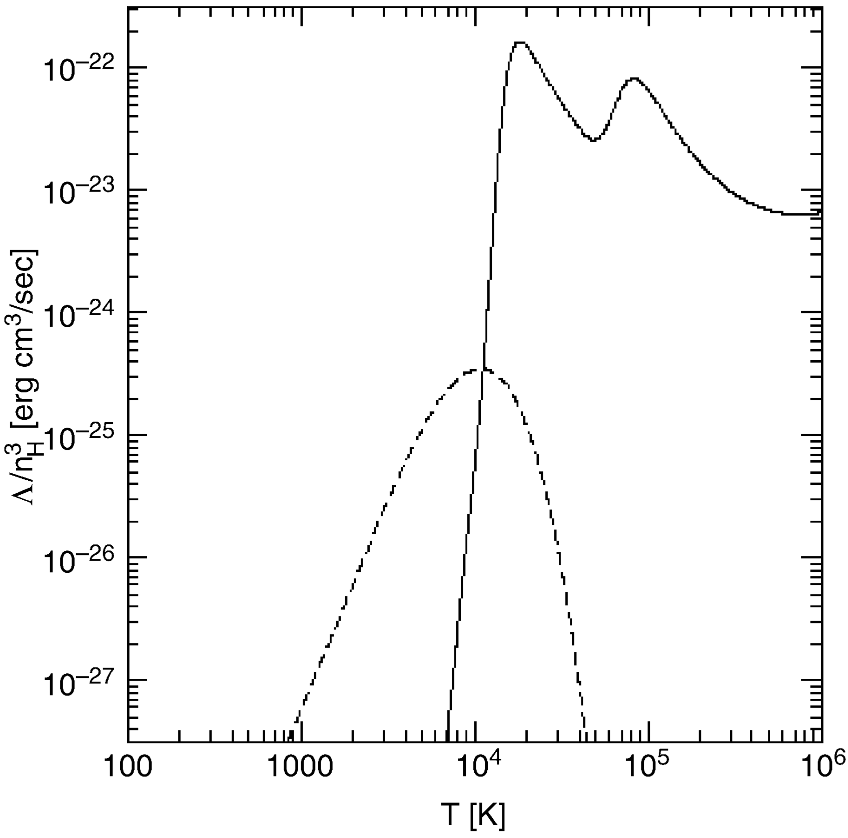
Jeans mass versus redshift

- 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 $T = T_0 (1+z)$
  - Note so $M_J \sim T^{3/2} \rho^{-1/2} \sim (1+z)^{3/2} (1+z)^{-3/2} \sim 1$
  - $M_J = 1.4\times10^5 M_{Sun}$ independent of z.

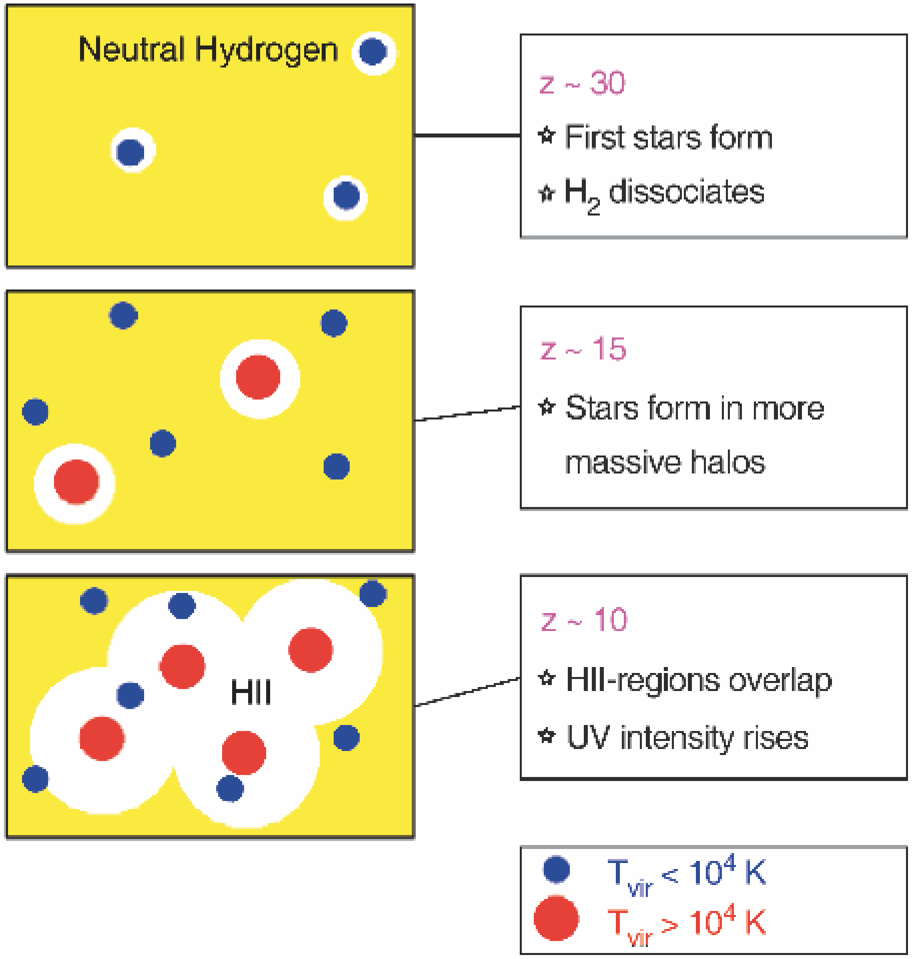
- For $z < z_t$, baryons cool adiabatically due to expansion
  - $T_b \sim \rho_b^{2/3} \sim (1+z)^2$
  - $M_J = 5.7\times10^3 M_{Sun} [(1+z)/10]^{3/2}$

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 $T > 10^4$ K, $kT > 1$ eV.
- Molecular hydrogen cooling is dominant for $T < 10^4$ K, but less efficient.



- As cloud collapses, potential energy is converted to kinetic → virial temperature
- Need $T_{\mathrm{vir}} > 3000$ K to collapse, $M \sim 10^4\, M_{\mathrm{Sun}}$
- Collapse forms Population III star
  - only H, He
  - very hot and massive



z ~ 30

- ☆ First stars form
- ☆ H_2 dissociates

z ~ 15

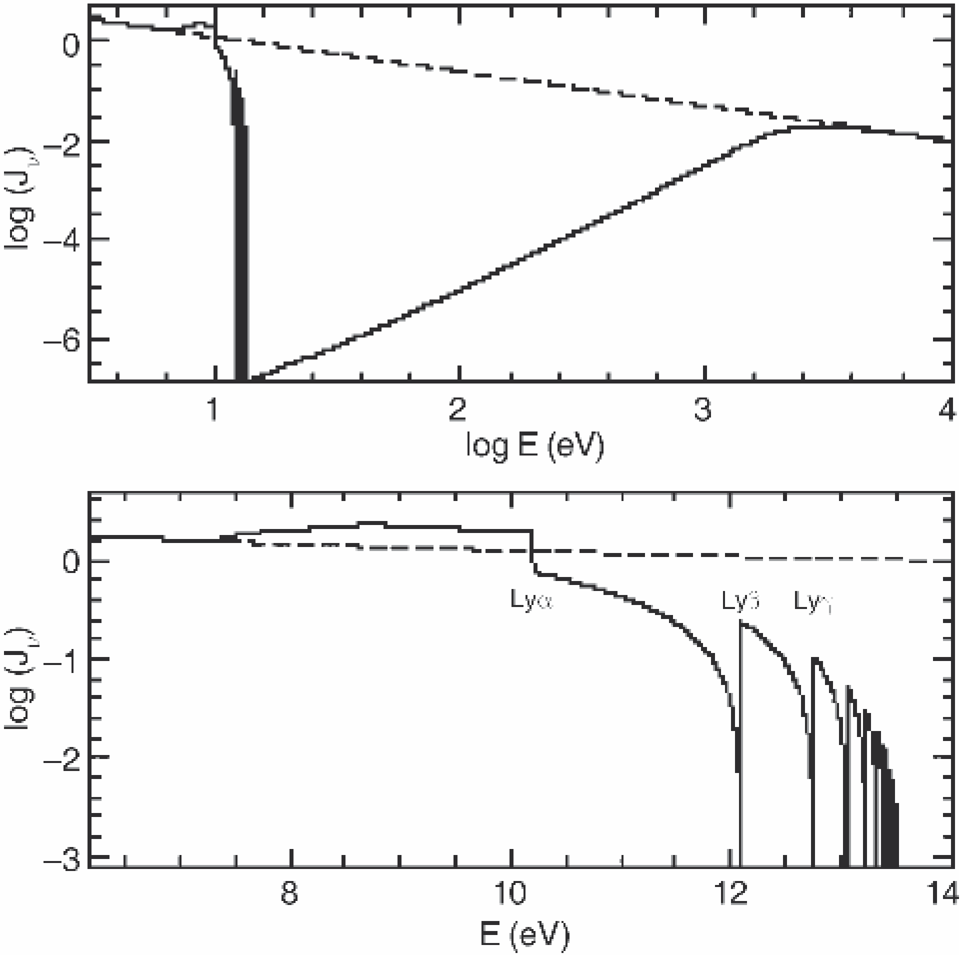
- ☆ Stars form in more massive halos

z ~ 10

- ☆ HII-regions overlap
- ☆ UV intensity rises

● $T_{vir} < 10^4$ K

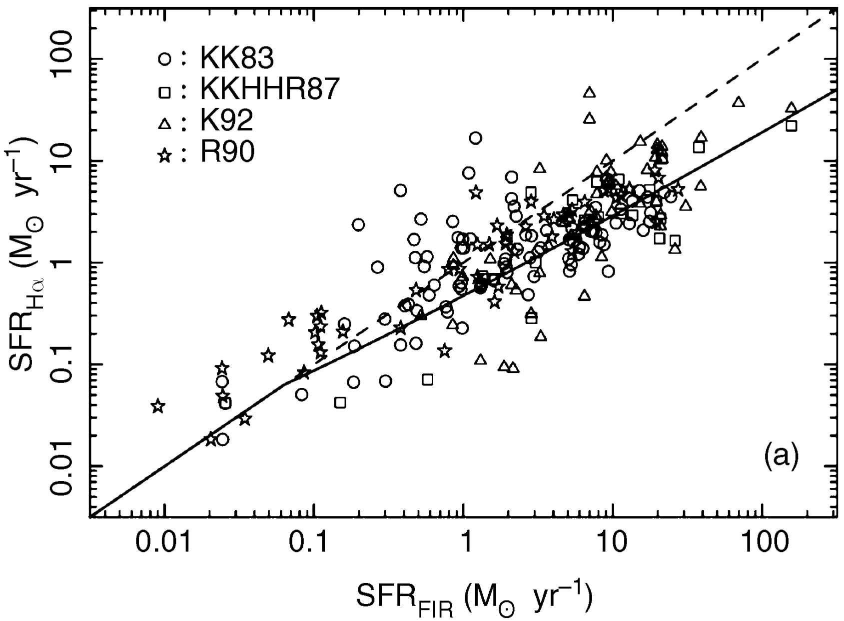
● $T_{vir} > 10^4$ K

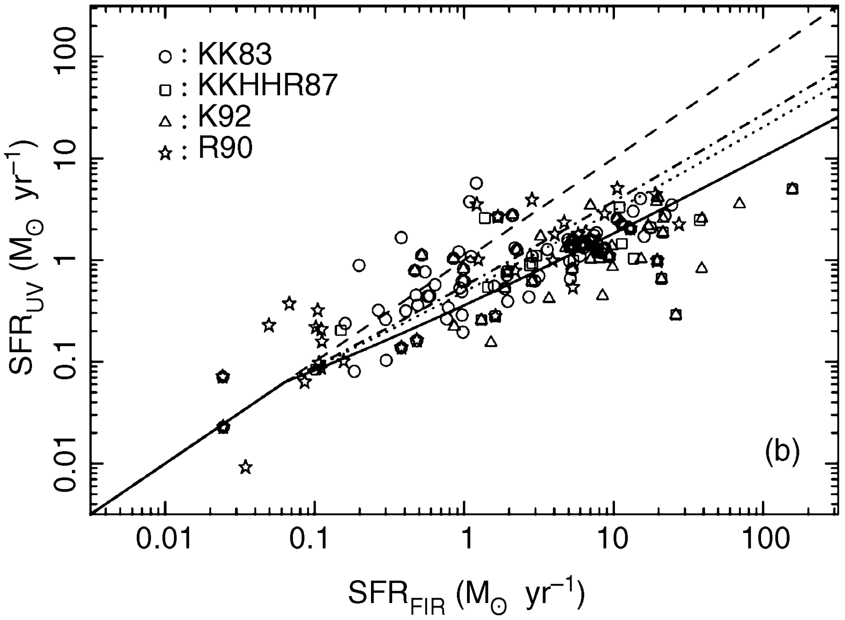


- Pop III stars form in low mass halos, $T_{\mathrm{vir}} \sim 3000$ K, $M \sim 10^4\, M_{\mathrm{Sun}}$.
- Dissociate nearby H_2. Go supernovae, enriching IGM with metals.
- Metals allow cooling at higher temperatures. Stars/galaxies form in higher mass halos.
- Fusion 7 MeV/proton, ionization 13.6 eV/proton, fuse $\sim 2\times10^{-6}$ of protons to reionize.
- Hubble ultradeep field has $10^{12}\, M_{\mathrm{Sun}}$ galaxy at $z \sim 6.5$ with 300 Myr old stars, sufficient to reionize the volume of the HUDF at $z \sim 6.5$.

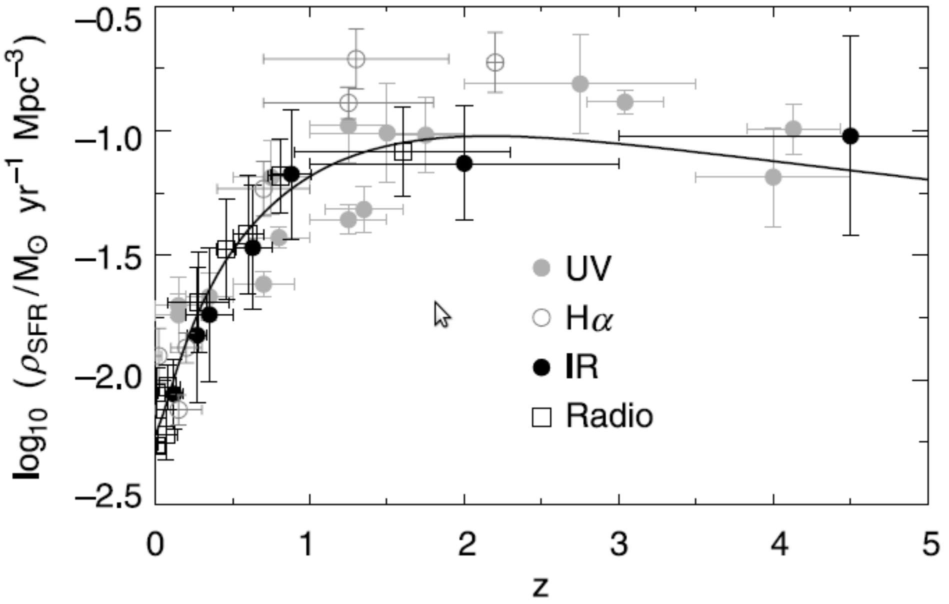
Star formation rate

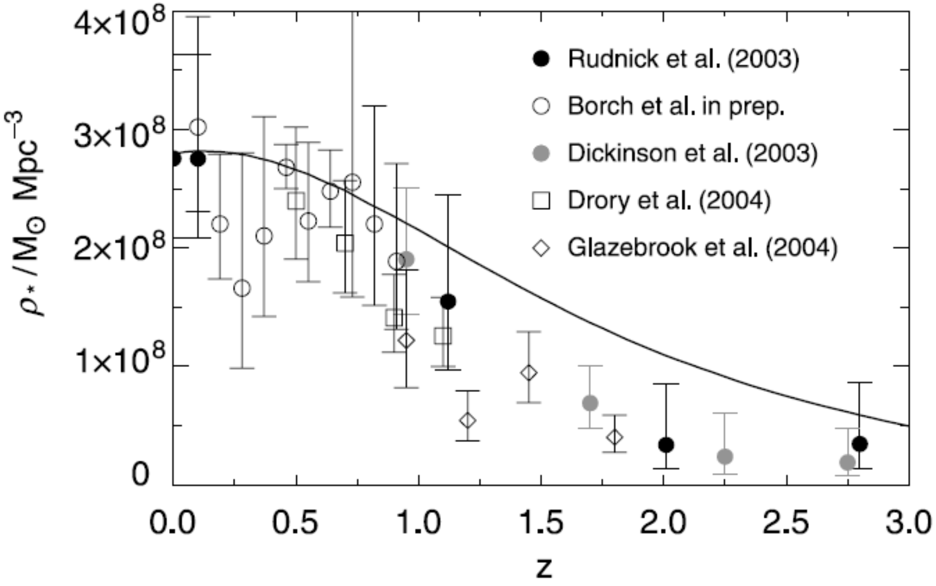
- Star formation rate (SFR) measured in M_{Sun}/year of gas converted into stars.
- Star formation produces emission in a variety of bands, any can be used as SFR indicator, e.g. $\mathrm{SFR}_{\mathrm{FIR}} = \mathrm{L}_{\mathrm{FIR}}/5.8\times10^{9}\,L_{\mathrm{Sun}}$ (M_{Sun}/year)
- Common indicators:
  - UV from young, hot stars
  - FIR from warm dust heated by hot stars
  - Hα 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 stellar initial mass function) and empirically.
- Wide scatter due to absorption, details of environment, different dependence on age of star formation





Star formation rate



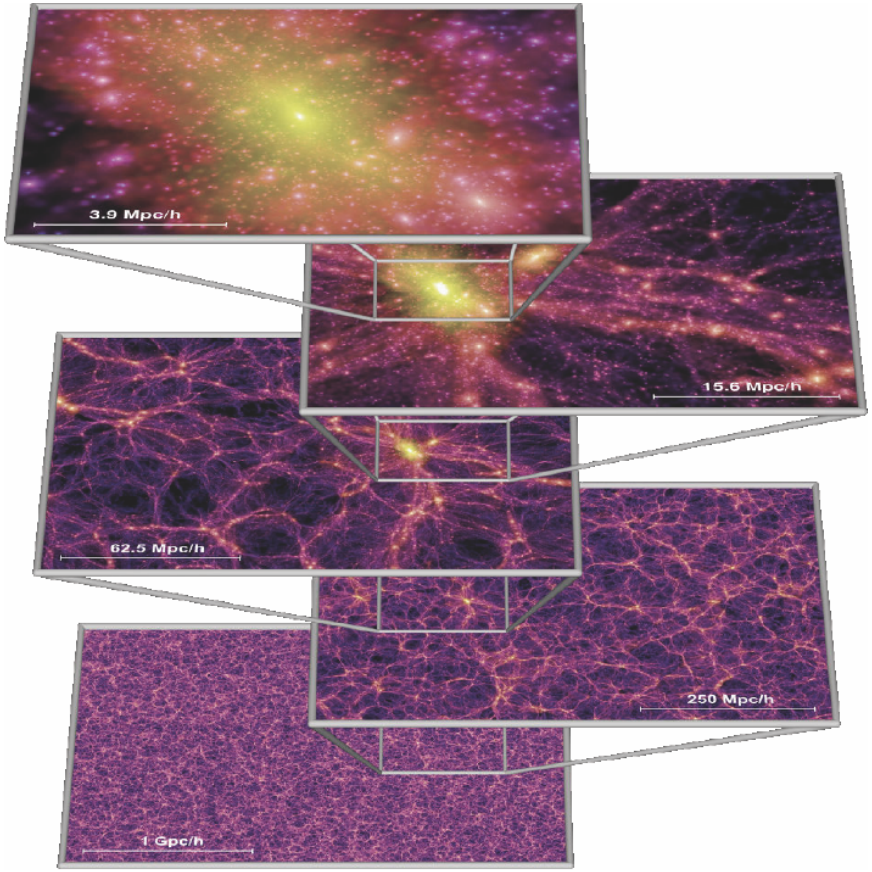


- Once SFR indicators are calibrated, one can use them to measure SFR vs *z*.
- First done by Madau.
- Find galaxies in surveys and then sum SFR in co-moving volume vs *z*.
- Initial estimates done without regard to absorption, showed peak at *z* = 1-2.
- Recent estimates rise to *z* = 2, flat or slight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

- Integration of SFR roughly matches measurements of stellar density.

Numerical simulations

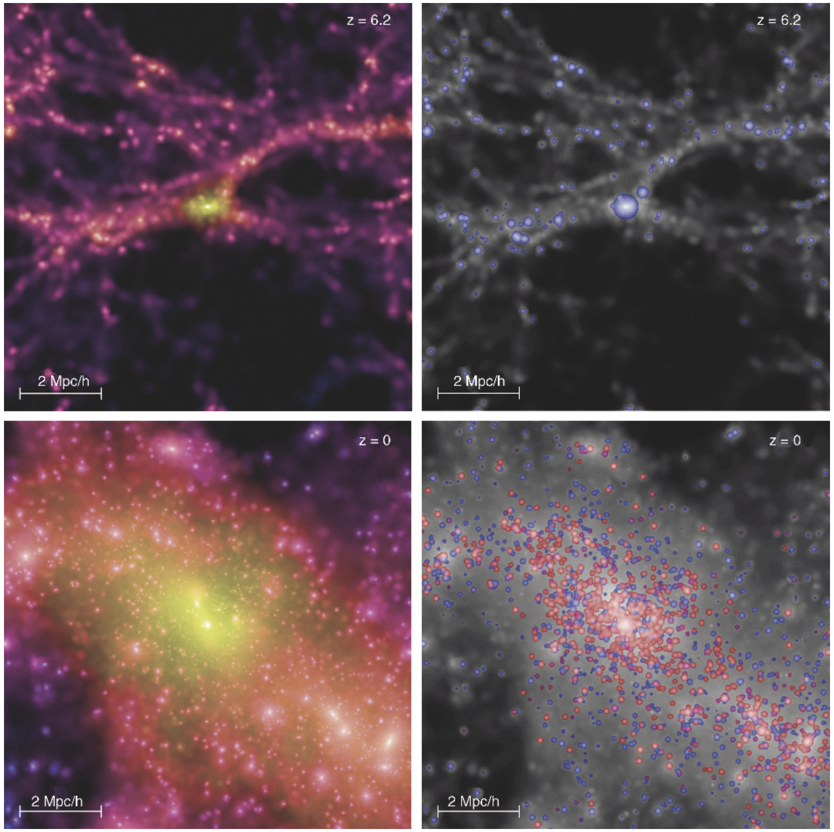
- Would like to extend simulations of structure formation in dark matter to the formation of galaxies.
- Physics of baryons gets in the way. Simulations would require extending down to scales of star formation, i.e. < solar radius, while extending up to scales of 100s of Mpc.
- Instead, graft semi-analytical prescriptions for baryonic processes onto simulations.



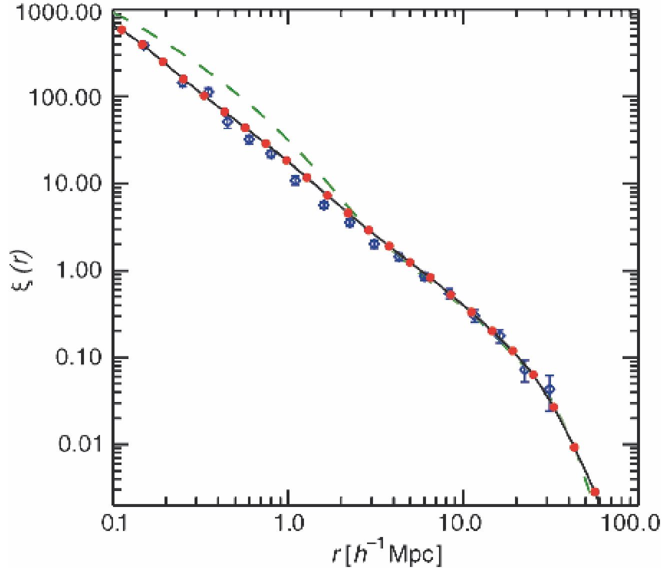
- Cooling and star formation: SFR = A Σ^{β} where Σ = gas surface density. Find A, β from fits to observations or star formation models.
- Feedback: massive stars will supernova, putting energy into ISM and self-regulating SF. Need to model time profile of energy input and fold into simulation.
- UV 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.

Homework

For next class: problems 9.8