Astronomy 330

Lecture 2

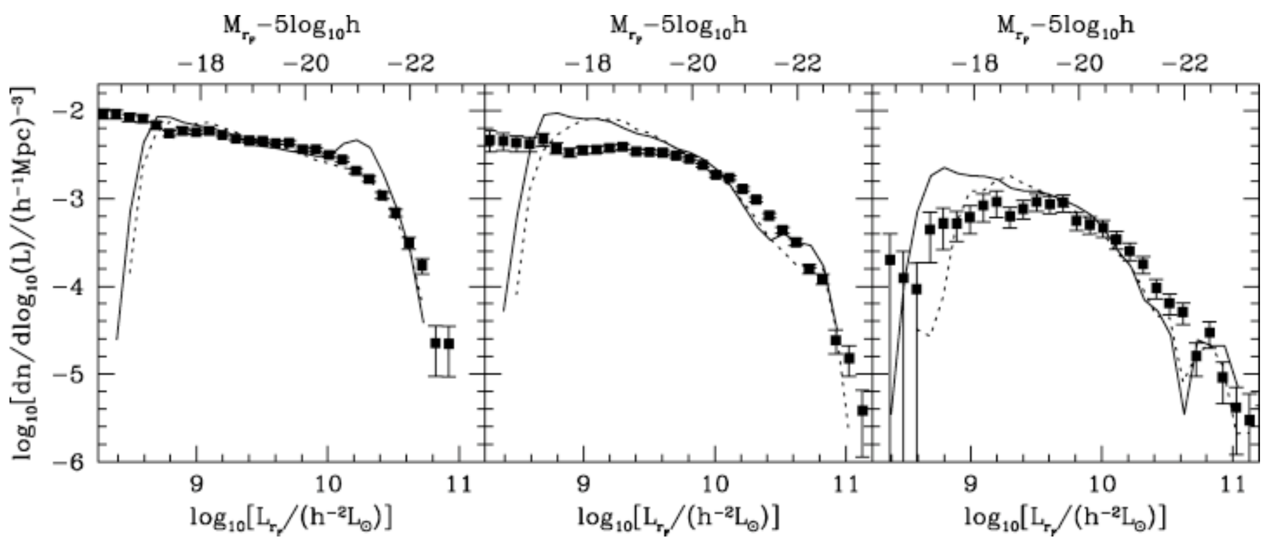
8 Sep 2010

Outline

- Review
- Sloan Digital Sky Survey
- A Really Brief History of the Universe
  - Big Bang/Creation of the Elements
  - Recombination/Reionization
  - Galaxy Formation

Review

- Salient points of the Curtis-Shapley Debate
- Galaxy Morphologies (see tuning-fork diagram)
  - Today, “on average”:
    - Ellipticals(13%), Spirals (61%), Lenticulars(22%), Irr(4%)
- Galaxy Luminosity Function
  - $\Phi(L) = (\Phi^*/L^*)(L/L^*)^{\alpha}\exp(-L/L^*)$



Low-mass ——— environment ——→ High-mass

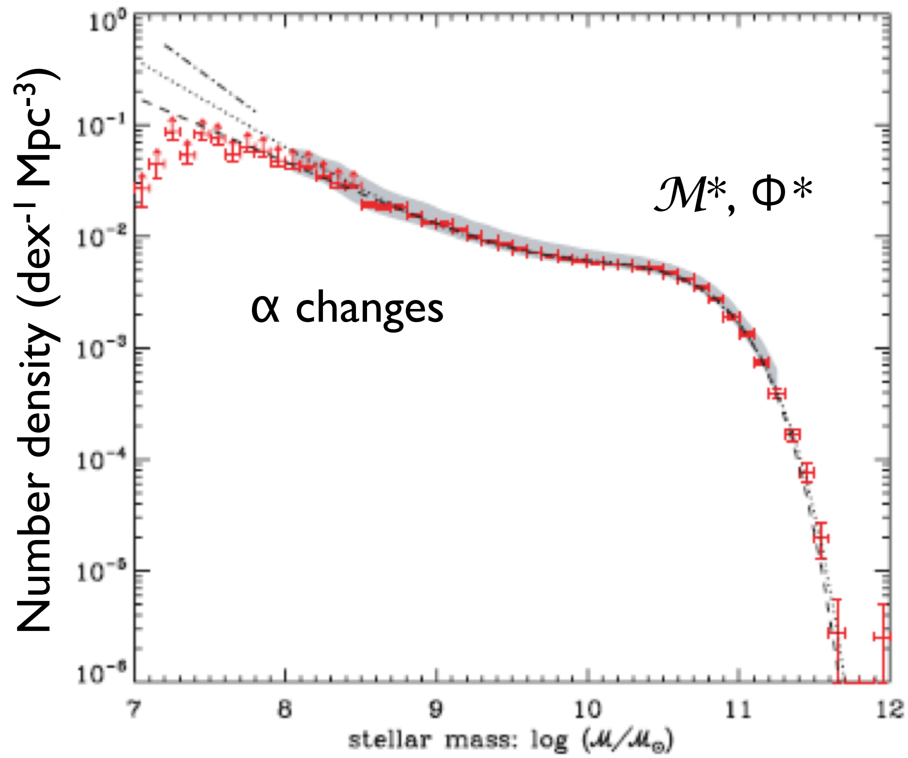
Stellar mass function

Stellar mass estimated from red/near-infrared light assuming a mass-to-light ratio (M/L or Υ), which depends on stellar populations (colors), assumptions about:

- the stellar mass function (IMF)
- neutral and molecular gas content,
- dark-matter

We will discuss these issues.

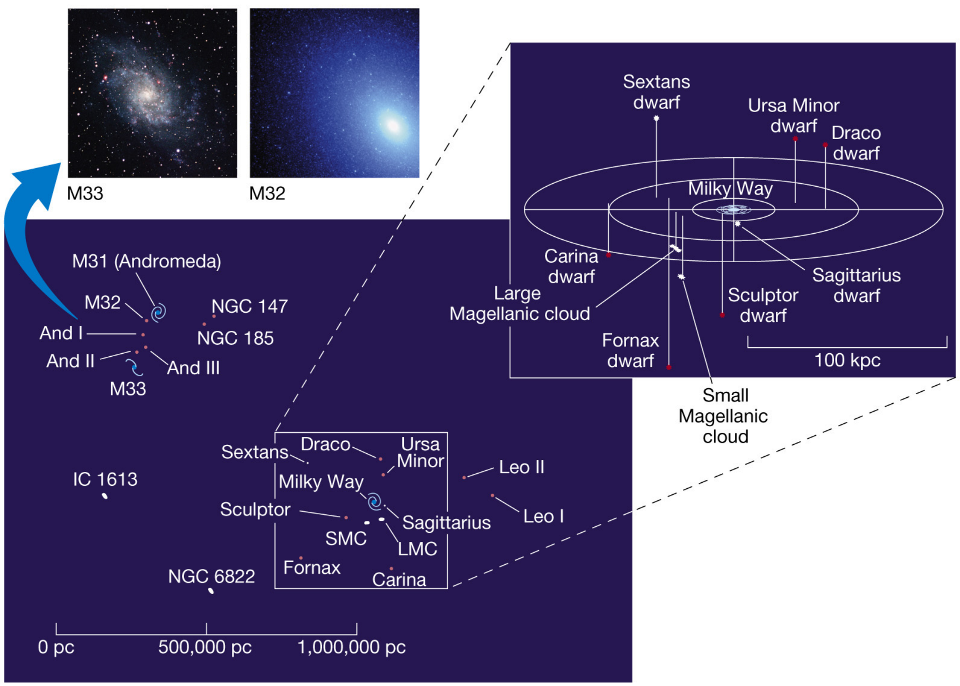
Baldry et al. 2008

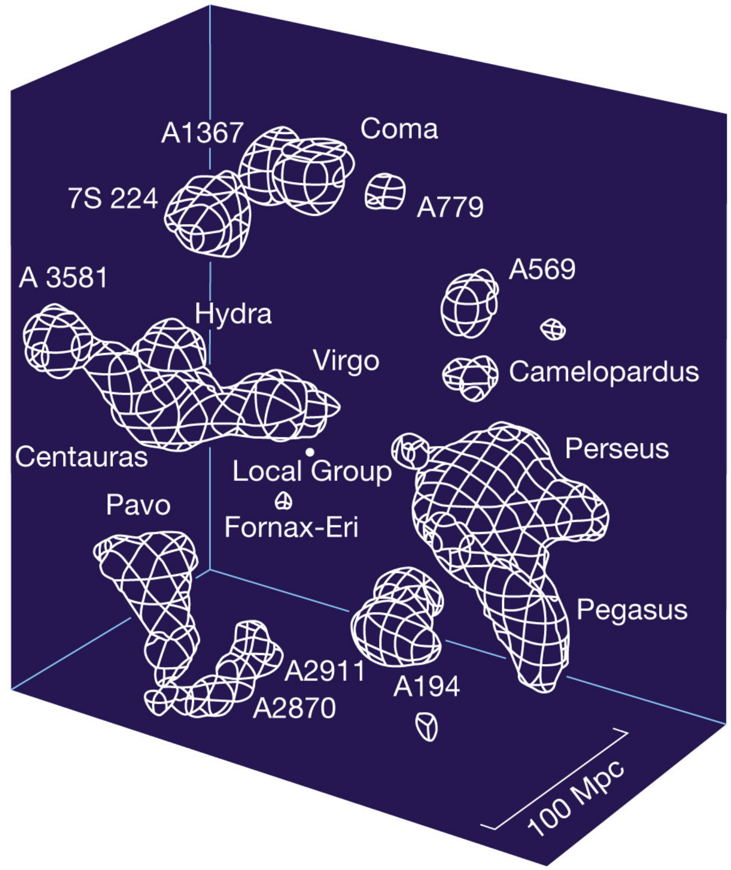


In this case, stellar mass function is modeled as composite of two Schecter functions with different α and ϕ*.

Large Scale Structure

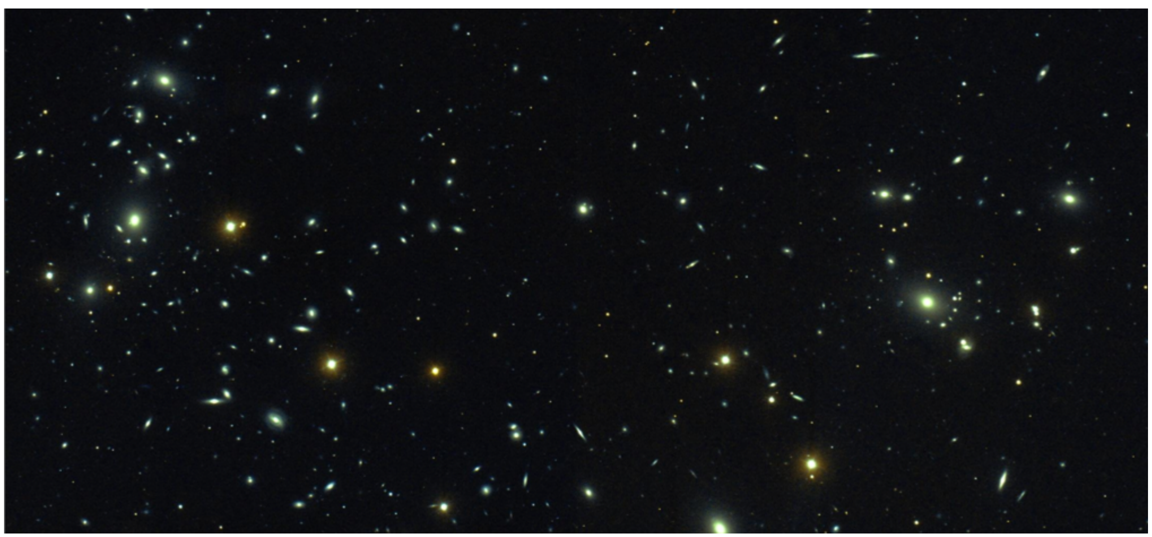
- What's bigger than a galaxy?
- Groups: where most galaxies live
  - Local Group:



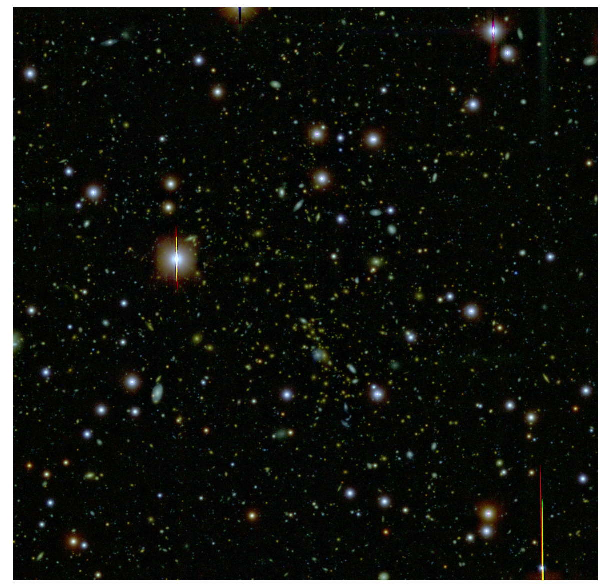


Large Scale Structure

- Bigger still: Clusters
  - Giant Clusters
    - > 1000 galaxies
    - D ~ 1-2 Mpc
    - 1-3 giant elliptical galaxies residing at the center
- High fraction of elliptical galaxies
- Most have copious diffuse X-ray emission
  - Most of the observed mass in clusters is in hot gas
- Huge M/L ratios (~100) ➔ dark matter dominated
  - Gravitationally bound



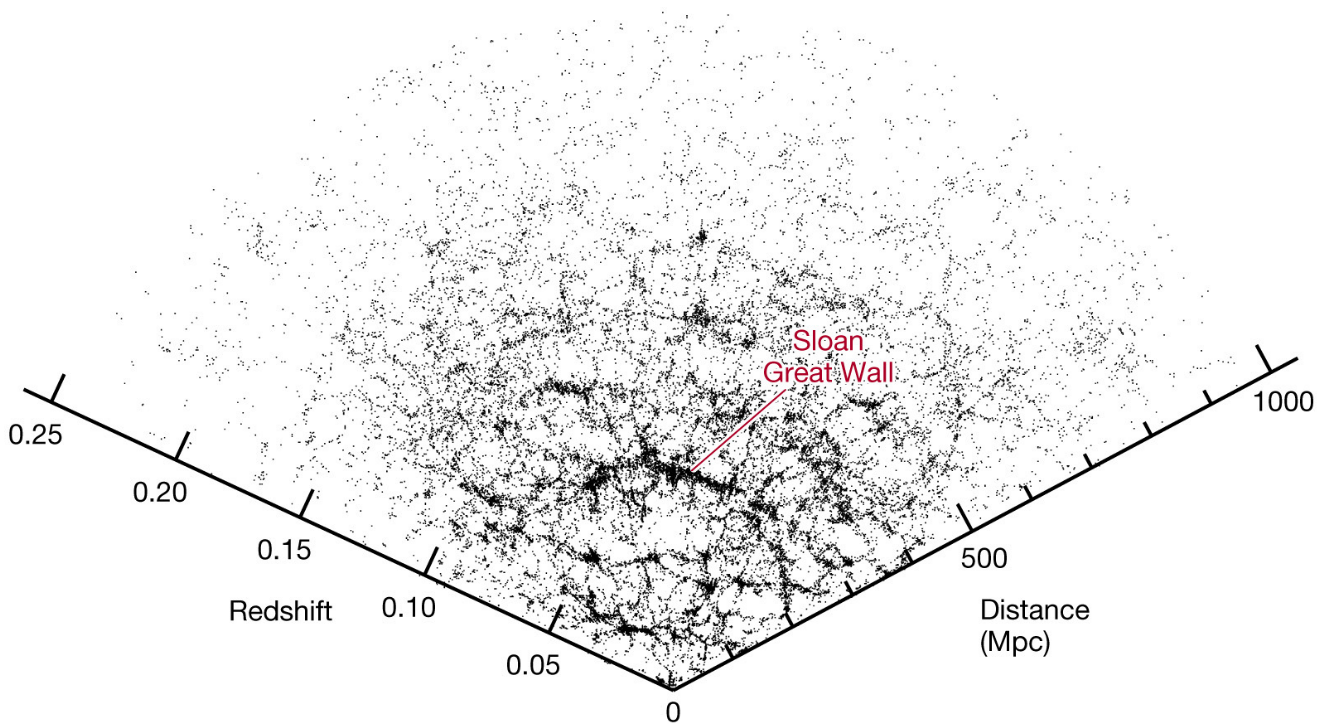
Abell 98 nearly next door



MS0415 at z = 0.54

Large Scale Structure

- Filaments and voids
  - Great Attractor
  - Characteristic scales: 40-120 Mpc



Surveys

- Palomar Sky Survey (POSS) – blue/red photographic imaging (all sky)
  - digitized version (DSS)
- Sloan Digital Sky Survey (SDSS) – modern multi-band optical CCD imaging *and spectroscopy*
  - www.sdss.org
- 2-Micron All-Sky Survey (2MASS) – J,H,K band imaging (all sky)
  - http://www.ipac.caltech.edu/2mass/
- GALEX – UV all-sky survey
  - http://www.galex.caltech.edu/
- IRAS – all sky survey (old satellite: http://irsa.ipac.caltech.edu/IRASdocs/iras.html)
- FIRST/NVSS
  - http://sundog.stsci.edu
  - www.cv.nrao.edu/nvss}
- Arecibo Surveys (ALFALFA)
  - egg.astro.cornell.edu/alfalfa}
- Various "Deep Fields"
  - Hubble Deep Fields (HDF): north and south
  - Chandra (X-ray), Spitzer (IR) have deep fields and various surveys of galaxies
  - ATCA is doing a radio deep field
- Ever-increasing chunks of sky, multiple wavelengths

Adopt-A-Galaxy

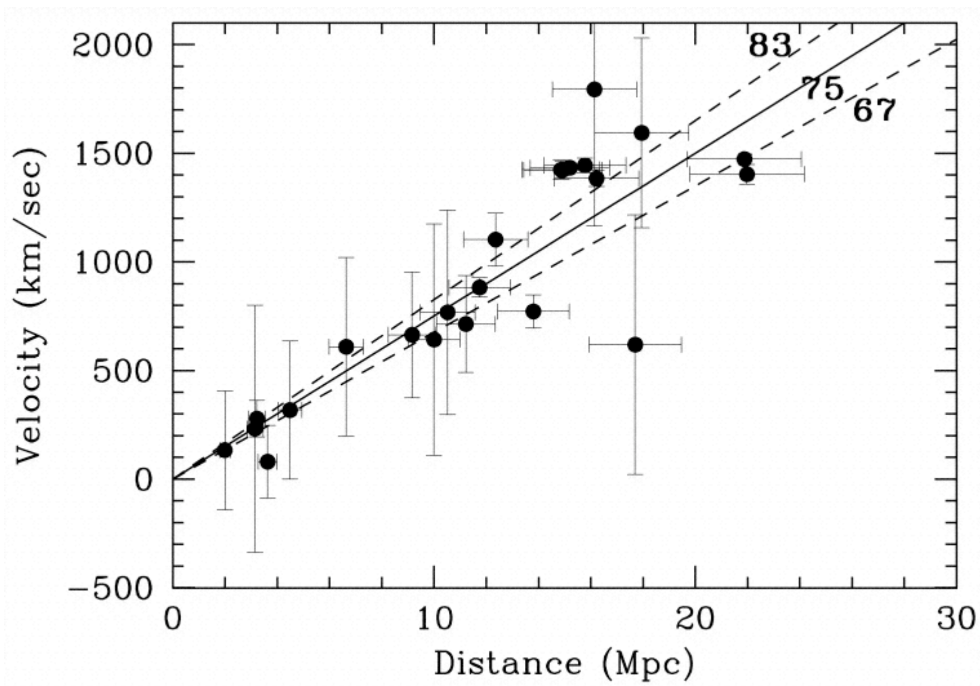
- I Zw 18 – Matthew K.
- NGC 4449 – Nick M.
- NGC 6166 – Ali B.
- NGC 4594 – Megan J.
- NGC 5128 – Nick P.
- NGC 3115 – Elise L.
- NGC 1300 – Cody G.
- NGC 3370 – Sara S.
- NGC 7742 – Hanna H.
- NGC 1512 – Capri P.
- NGC 1569 – Rob G.
- NGC 3949 – Justin S.

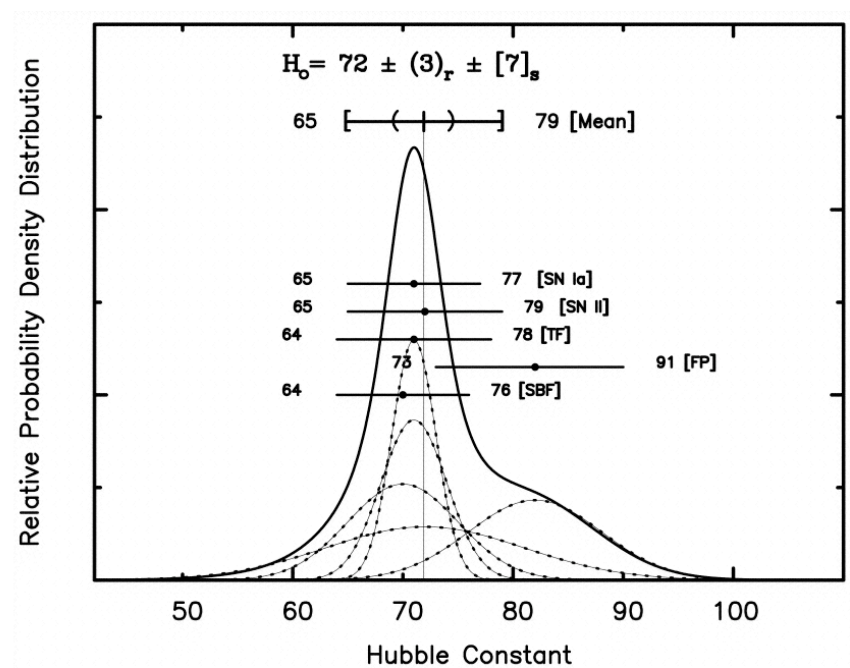
Big Bang / Creation of Matter

- The Expansion
  - Hubble (1929) discovered correlation between recessional velocity and distance
    - $V = H_0 \times D$ (distance in Mpc, V in km s^{-1}, H_0 in km s^{-1} Mpc^{-1})
    - We measure the "redshift", z, as $1+z = (\lambda_{obs}/\lambda_{em})$
    - Best fit from Cepheid data (HST):
      - H_0= 72 km $s^{-1}Mpc^{-1}$ (Freedman et al 2001)
- But is the expansion static?

Measuring H_0: the Hubble "Constant"

- Freedman et al. 2001, ApJ, 553, 47
  - Recall large-scale structure: GR notion of constant expansion (in space) at given time requires assumption of isotropy and homogeneity to be valid.





Big Bang / General Relativity

- Einstein's Field Equation:

$$G_{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

  - $G_{\mu\nu}$ is the Einstein tensor
  - $R_{\mu\nu}$ is the Ricci tensor, R is the Ricci scalar
  - $T_{\mu\nu}$ is the stress-energy tensor

  - In words, think of the field equation as a gravitational analogue of Poisson's equation describing how the space-time ("field") responds to the presence of sources terms (matter, energy, pressure) in $T_{\mu\nu}$.
  - Very difficult to do anything without some simplifying assumptions.

Big Bang / World Models

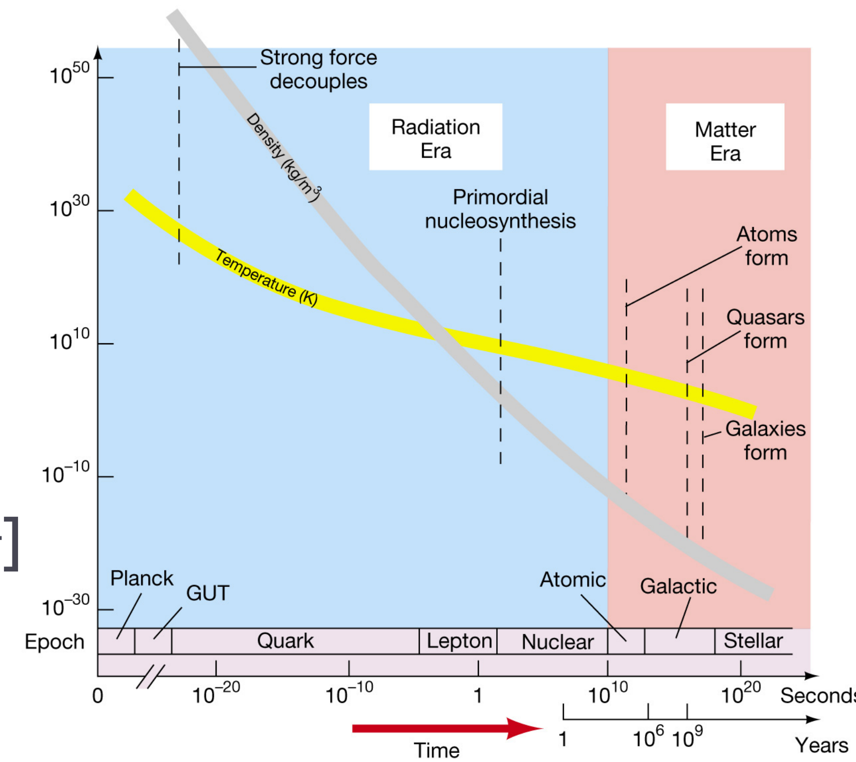
- Friedman equations: isotropic, homogeous universe
  - $\dot{R}^2 = [(8\pi G \rho)/3]R^2 - (c^2/\mathcal{R}^2) + [(1/3)\Lambda R^2]$
  - $\ddot{R} = -4\pi G/3\ R(\rho + 3p/c^2) + [(1/3)\Lambda R]$
    - R is the scale factor (i.e., dimensionless size): $R = 1/(1+z)$
    - $\mathcal{R}$ is the radius of curvature,
    - ρ is the density of matter and energy
    - Λ is the cosmological constant invoked originally to make universe static, and this now looks like "dark energy"
- $H(t) = \dot{R}/R$ by definition, i.e., H varies with time ($\dot{R} = dR/dt$)
- Distances: evluate $D = \mathcal{R} \sin(r/\mathcal{R})$, where $dr = -c\ dt/R(t)$
- Times: evaluate the integral of dz/dt

The Early Universe

- Run the movie backwards…get one big fireball

  ➔ the "Big Bang"

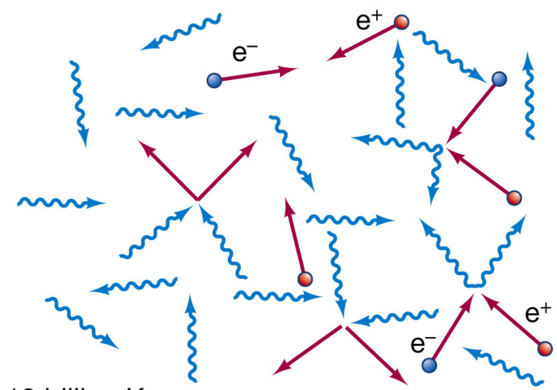
- Universe goes from being radiation dominated to matter dominated; expanding and cooling along the way
  - $\rho_r / \rho_m = \sigma T^4(z) / [\Omega_o \rho_{crit} (1+z)^3 c^2]$
  - for z > 4000, the Universe is radiation dominated
- Milestones along the way….



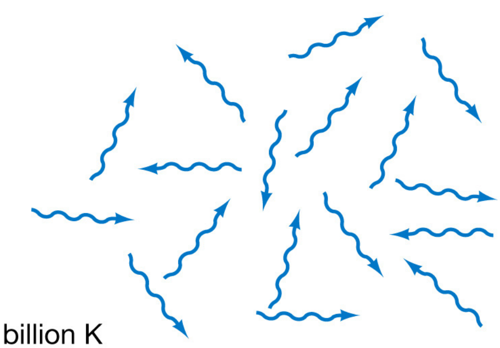
Particle Genesis

- Boltzmann equation: rate change in the abundance of a given particle is difference between rates for producing and destroying particle. Production is energy dependent, destroying depends on ratio of particle to anti-particle. When Universe cooled below kT = 13 MeV, proton production ceased, annihilation got rid of anti-protons, and we're left with protons….
- …ditto for neutrons
- … and for electrons, except kT = 0.5 MeV
- What about neutrinos?

  - Cosmic Mystery #1: Why were there slightly more protons than anti-protons?

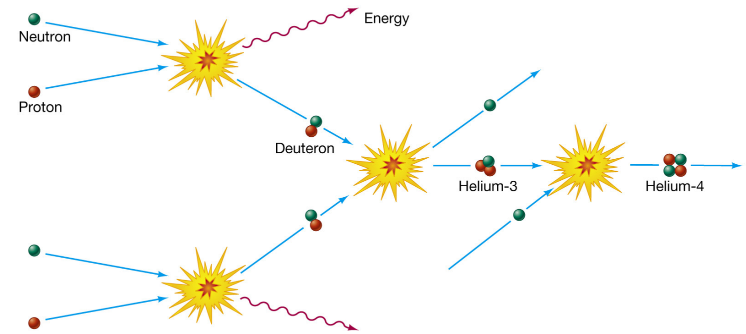


(a) 10 billion K


(b) 1 billion K

Big Bang Nucleosynthesis (BBNS)

- Weak interactions control proton/neutron ratio via following reactions
  - $p + \nu \leftrightarrow n + e+$
  - $p + e- \leftrightarrow n + \nu$
  - $n \leftrightarrow p + e- + \nu$ - beta decay

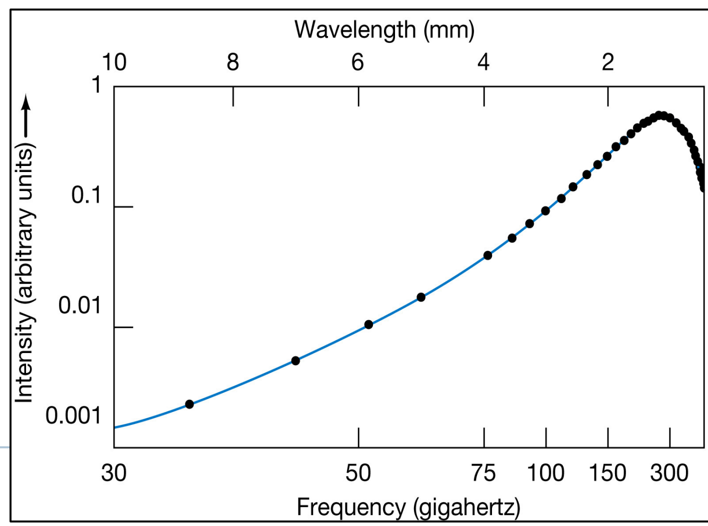


- $n/p = e^{-Q/kT}$ where $Q = (m_n - m_p)c^2 = 1.3$ MeV
- Once kT is below 0.8 MeV, n/p is set…

- If all the neutrons get together with a proton, we get the primordial He abundance, which is about 24% by mass ➔ key test of Big Bang cosmology

Recombination

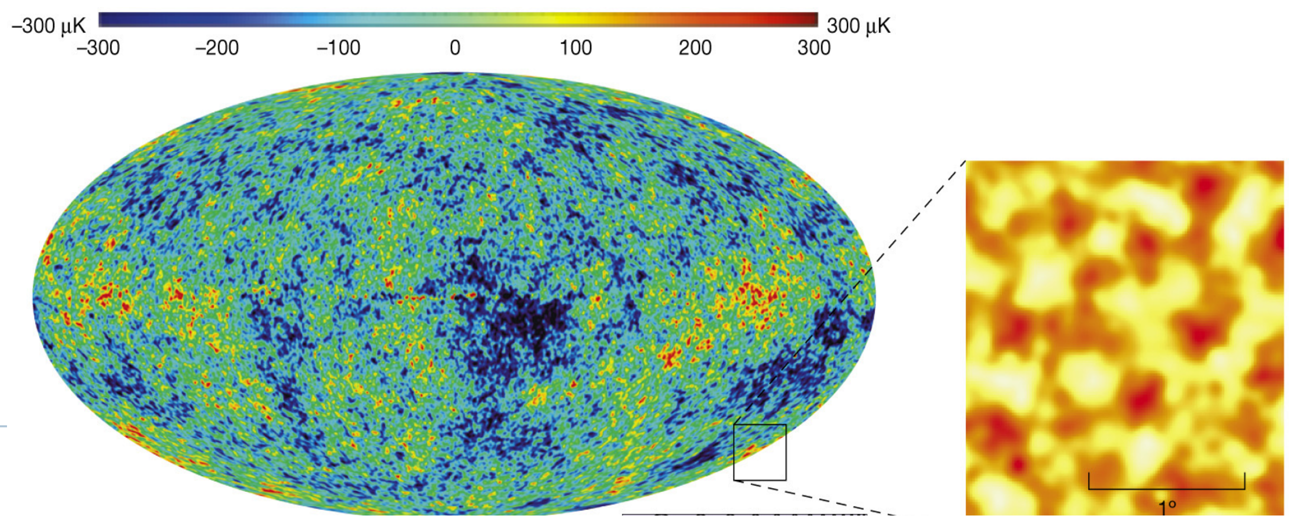
- $T = T_o(1+z)$. At z~1500, T < 4000 K, photons can no longer ionize H, so H recombines… (Saha equation)
- …the Universe becomes transparent to radiation ("surface of last scattering")
- If its 4000 K at z~1500, the temperature now should be 2.7 K ➔ microwave background. Detected by Penzias & Wilson (1965), shown in exquisite detail by the COBE satellite (e.g. Mather et al. 1990 ApJ, 354, L37)



Structure Formation

- Is the MWB really smooth?
- No, there is structure (acoustic peaks) the say a lot about the Universe.
  - Power spectrum of primordial fluctuations
  - Cosmological model
    - Λ CDM + flat Universe + baryons + radiation + power law fit to power spectrum

- WMAP was launched to measure the fluctuations in the microwave background…



WMAP

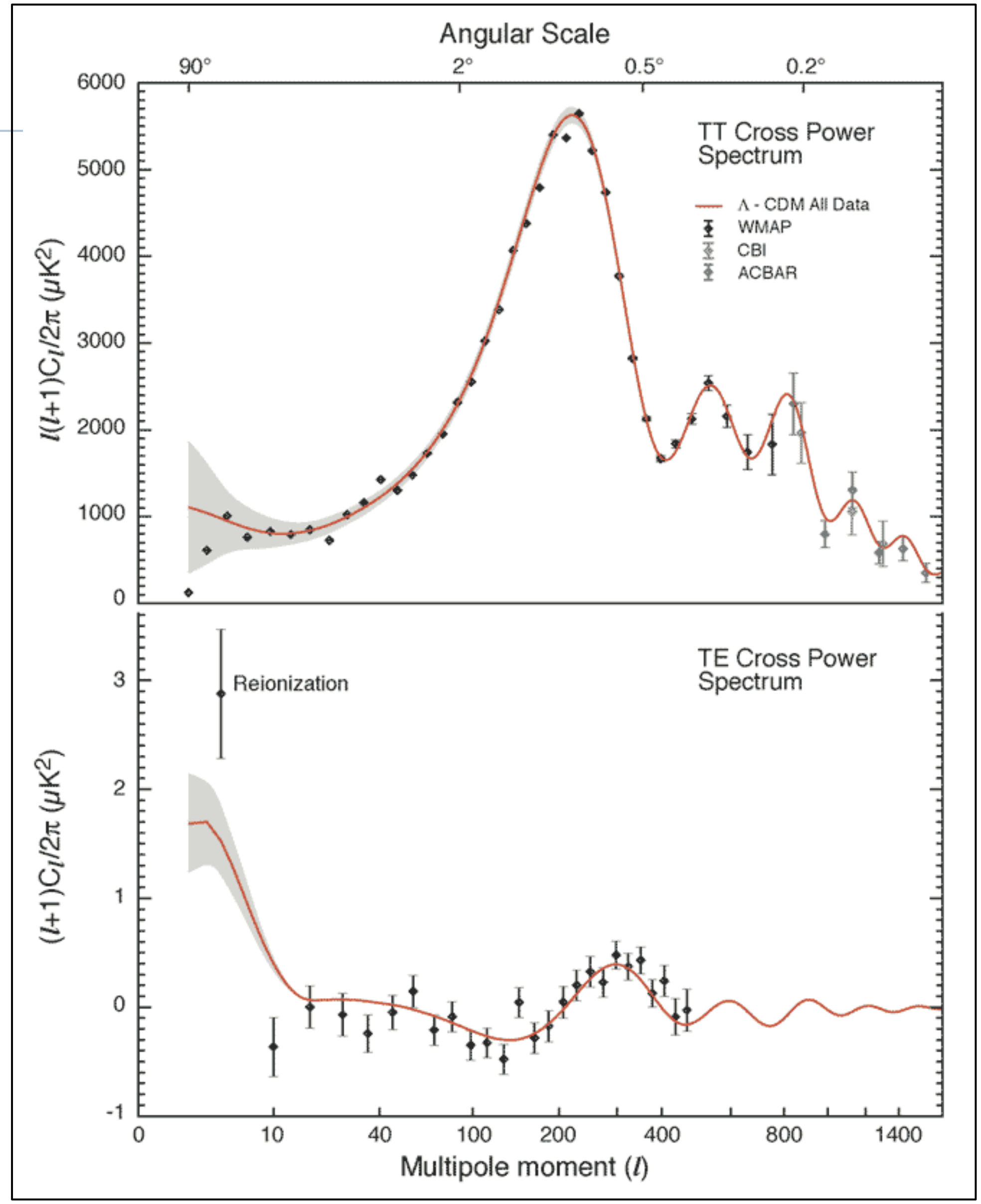
- Spergel et al. (2003,2007)
- Dunkley et al. (2009)

TABLE 1

POWER-LAW ΛCDM MODEL PARAMETERS: *WMAP* DATA ONLY

Parameter	Mean (68% Confidence Range)	Maximum Likelihood
Baryon density, $\Omega_b h^2$	0.024 ± 0.001	0.023
Matter density, $\Omega_m h^2$	0.14 ± 0.02	0.13
Hubble constant, h	0.72 ± 0.05	0.68
Amplitude, A	0.9 ± 0.1	0.78
Optical depth, τ	$0.166^{+0.076}_{-0.071}$	0.10
Spectral index, n_s	0.99 ± 0.04	0.97
$\chi^2_{\rm eff}/\nu$		1431/1342

NOTE.—Fit to *WMAP* data only.



WMAP

WMAP FIRST-YEAR RESULTS: PARAMETERS

TABLE 2

DERIVED COSMOLOGICAL PARAMETERS

Parameter	Mean (68% Confidence Range)
Amplitude of galaxy fluctuations, σ_8	0.9 ± 0.1
Characteristic amplitude of velocity fluctuations, $\sigma_8 \Omega_m^{0.6}$	0.44 ± 0.10
Baryon density/critical density, Ω_b	0.047 ± 0.006
Matter density/critical density, Ω_m	0.29 ± 0.07
Age of the universe, t_0	13.4 ± 0.3 Gyr
Redshift of reionization,[a] z_r	17 ± 5
Redshift at decoupling, $z_{\rm dec}$	1088^{+1}_{-2}
Age of the universe at decoupling, $t_{\rm dec}$	372 ± 14 kyr
Thickness of surface of last scatter, $\Delta z_{\rm dec}$	194 ± 2
Thickness of surface of last scatter, $\Delta t_{\rm dec}$	115 ± 5 kyr
Redshift at matter/radiation equality, $z_{\rm eq}$	3454^{+385}_{-392}
Sound horizon at decoupling, r_s	144 ± 4 Mpc
Angular diameter distance to the decoupling surface, d_A	13.7 ± 0.5 Gpc
Acoustic angular scale,[b] ℓ_A	299 ± 2
Current density of baryons, n_b	$(2.7 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/photon ratio, η	$(6.5^{+0.4}_{-0.3}) \times 10^{-10}$

NOTE.—Fit to the *WMAP* data only.

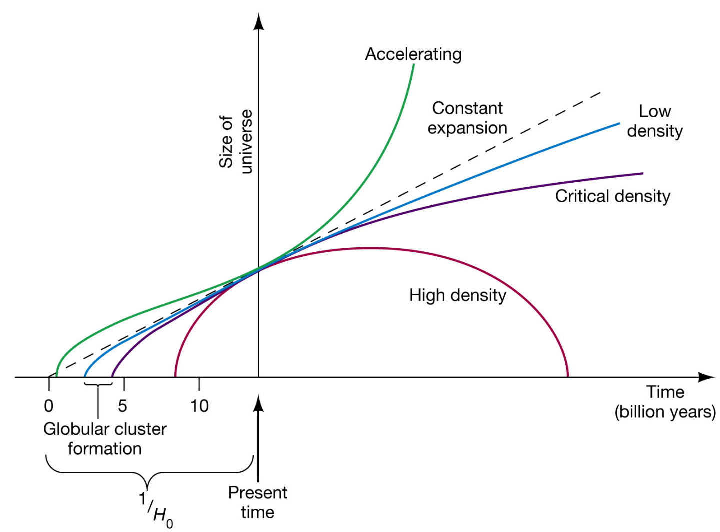
[a] Assumes ionization fraction, $x_e = 1$.

[b] $l_A = \pi d_C / r_s$.

Cosmological Conclusions (delusions?)

- ΛCDM is the best viable model:
  - The Universe is, and always was, spatially flat (Ω=1), but temporally open (Ω_Λ=0.7).
  - Universe of *matter* today is **dark-matter** dominated (Ω_{DM}=0.25, Ω_b=0.05)
    - And its probably cold…(CDM)
  - There's something that behaves like "Dark Energy", maybe.
    - Since z = 1 to 0.7 it has dominated the total mass-energy budget of the Universe, and growing.
  - Reionization happened somewhere between a redshift (z_r) of ~7 and a redshift of ~10-12.

WMAP Hi-z QSOs

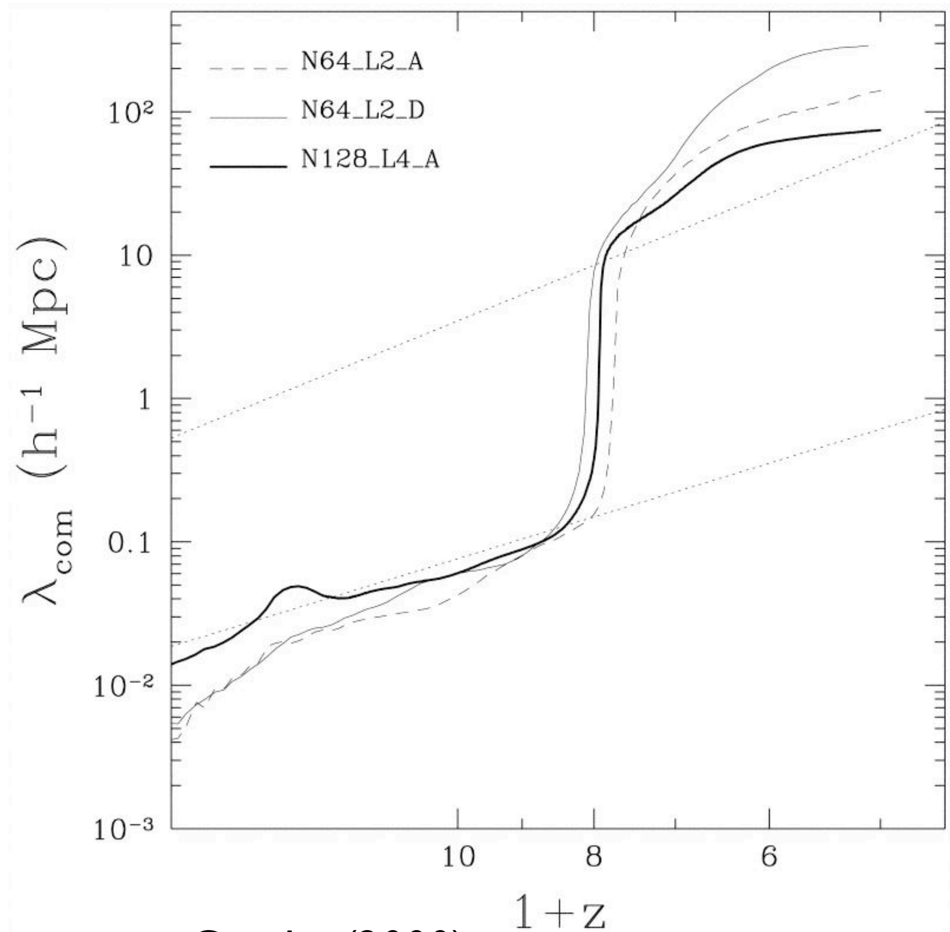


Epoch of Reionization

- Somehow, somewhere stars formed…
- …and ionized the surrounding IGM and the Universe emerged out of the "Dark Ages"
- WMAP says somewhere near z~12…
  - But possibly two phases, one early (z>12, and incomplete)
- When did the 1st stars/galaxies form?
  - Gunn-Peterson trough in quasar absorption
  - Directly observing 1st stars (NGST, TMT)
  - 21 cm line absorption/redshifted emission (SKA)
  - High redshift objects (VLA, GMRT, SKA)
  - Primordial, high redshift black holes (SKA)

Classical Reionization

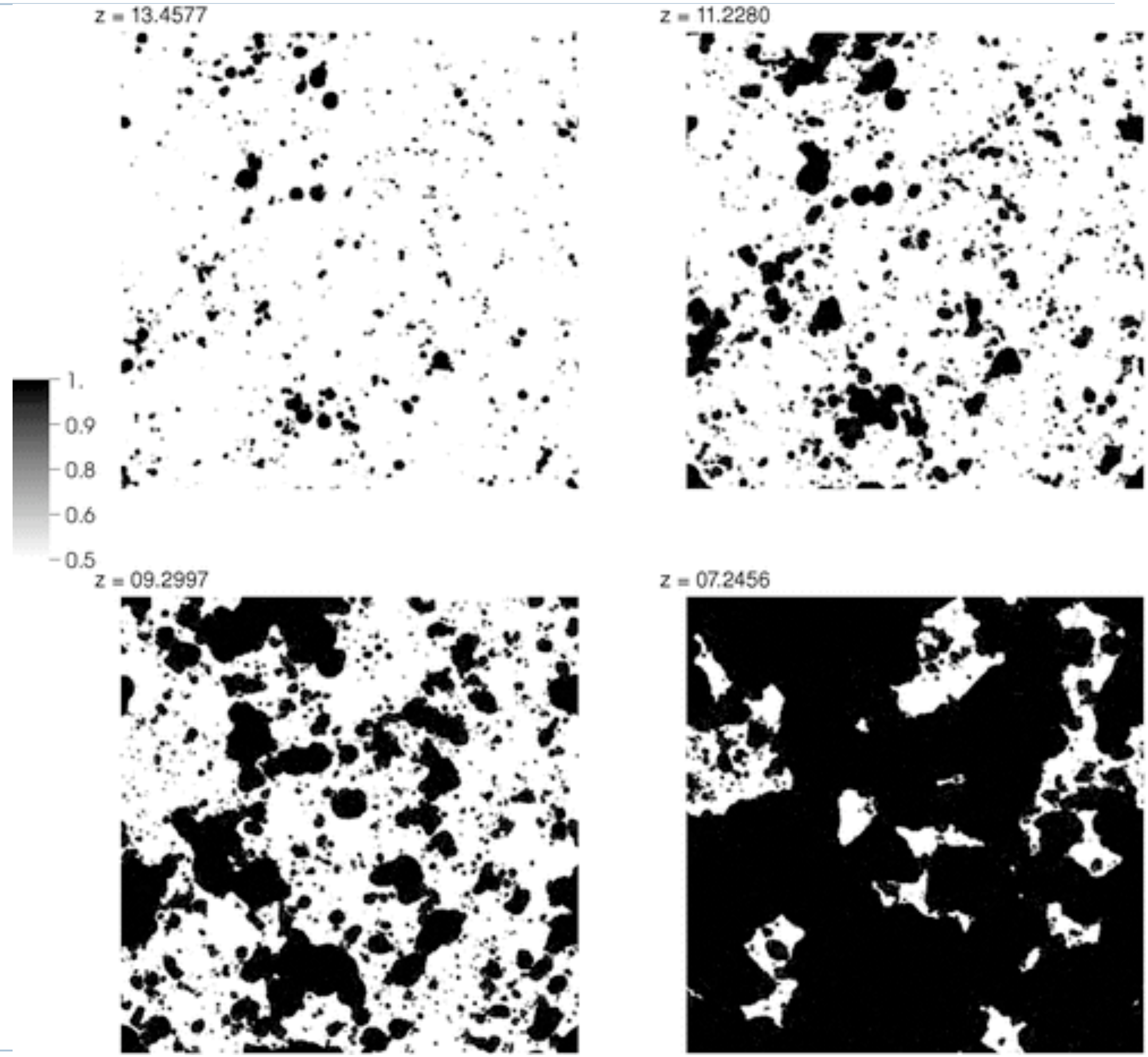
- Individual HII regions overlap ➔ mean free path of ionizing photon increases
- Fast phase transition
- Depends on…
  - Number of sources
  - Ionizing efficiency
  - Clumpiness of IGM



Gnedin (2000)

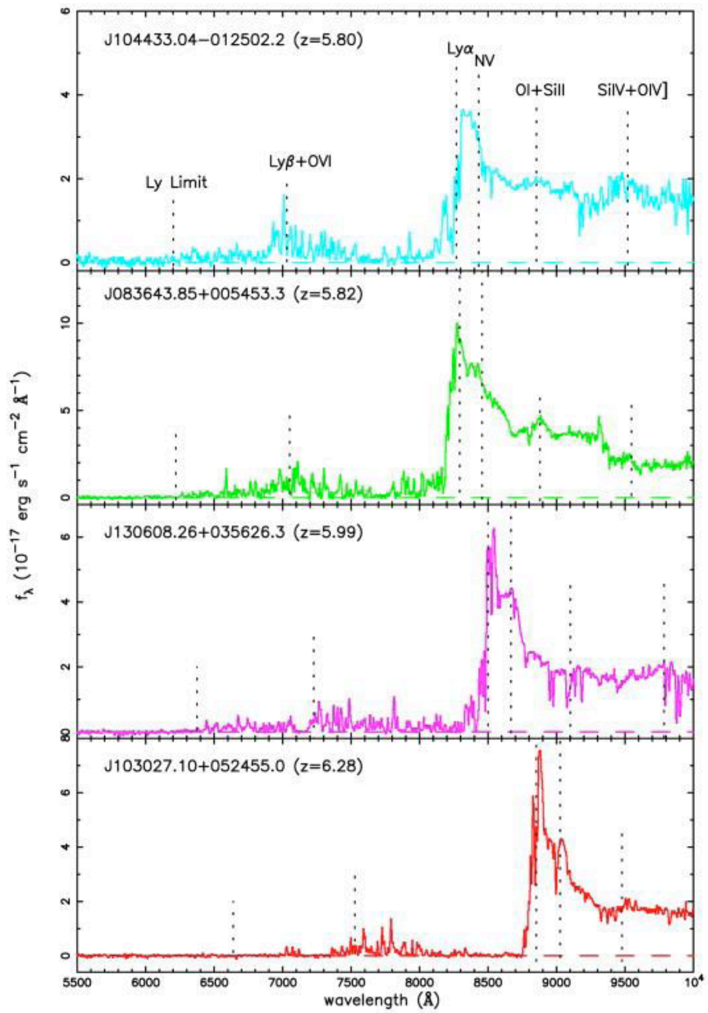
Epoch of Reionization: Simulated

Shin, Trac, Cen (2008)



The High-Redshift IGM

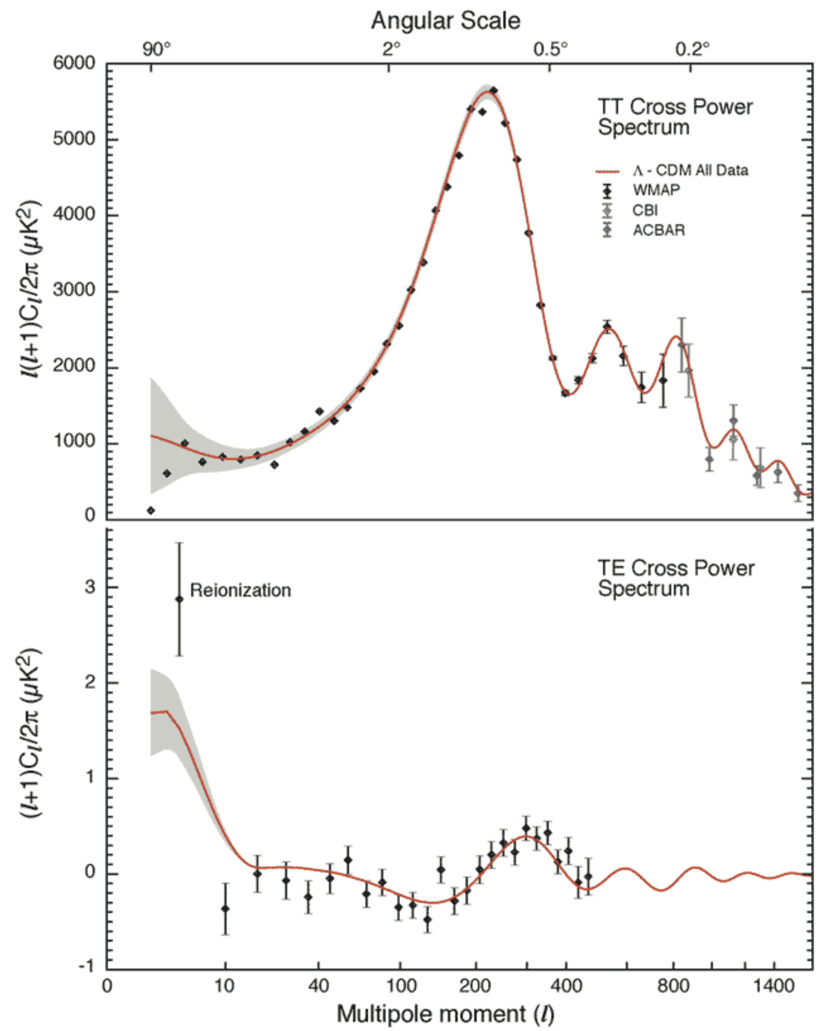
- Neutral between recombination and reionization ➔ hard to study!
- Does a Gunn-Peterson trough imply reionization?



WMAP and Reionization

- Ionized gas ➔Thomson scattering
- WMAP results imply 14 $< z_r <$ 20

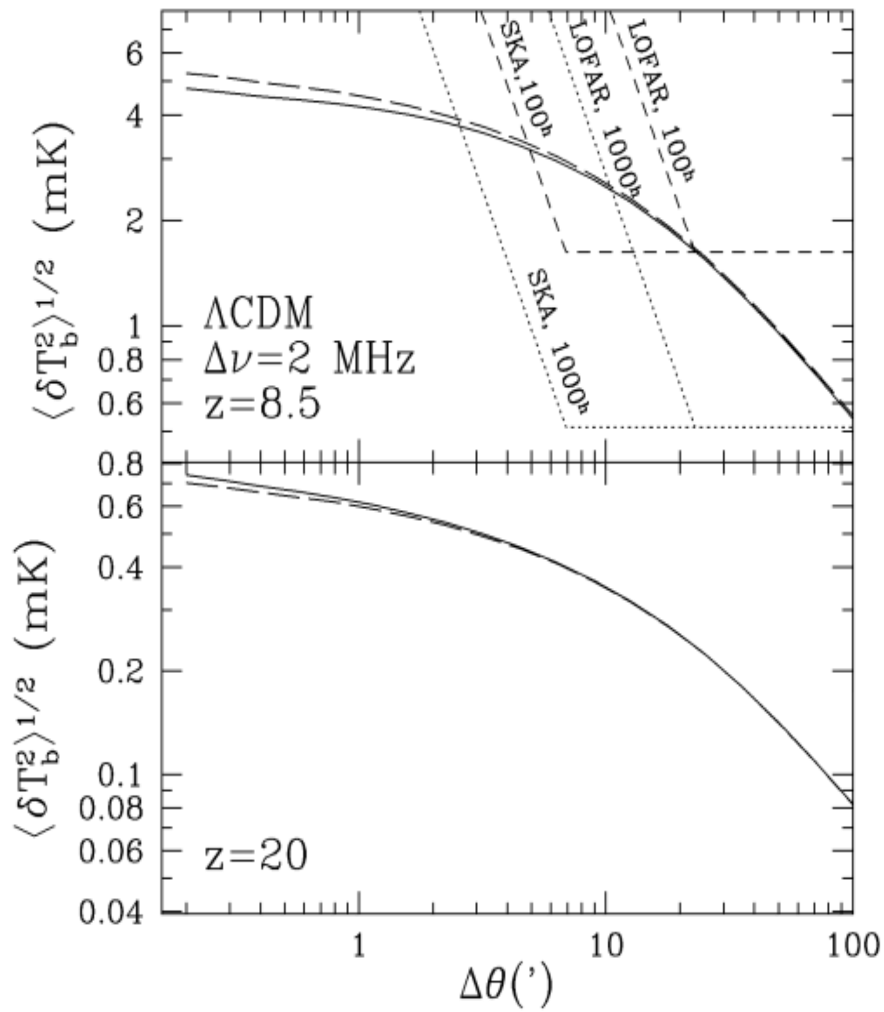
Are these results compatible?



Spergel et al. 2003

Dark Ages: Emission from Over-dense Neutral Gas

- Signal proportional to projected HI mass-variations between beams
- Sensitivity curves in top panel are 3σ in 100 hours
- Extremely hard at z=20 because signal decreases rapidly *and* T_{sky} increases rapidly
- Perhapsa few stronger because of collapsing gas! (Furlanetto & Loeb, in prep)

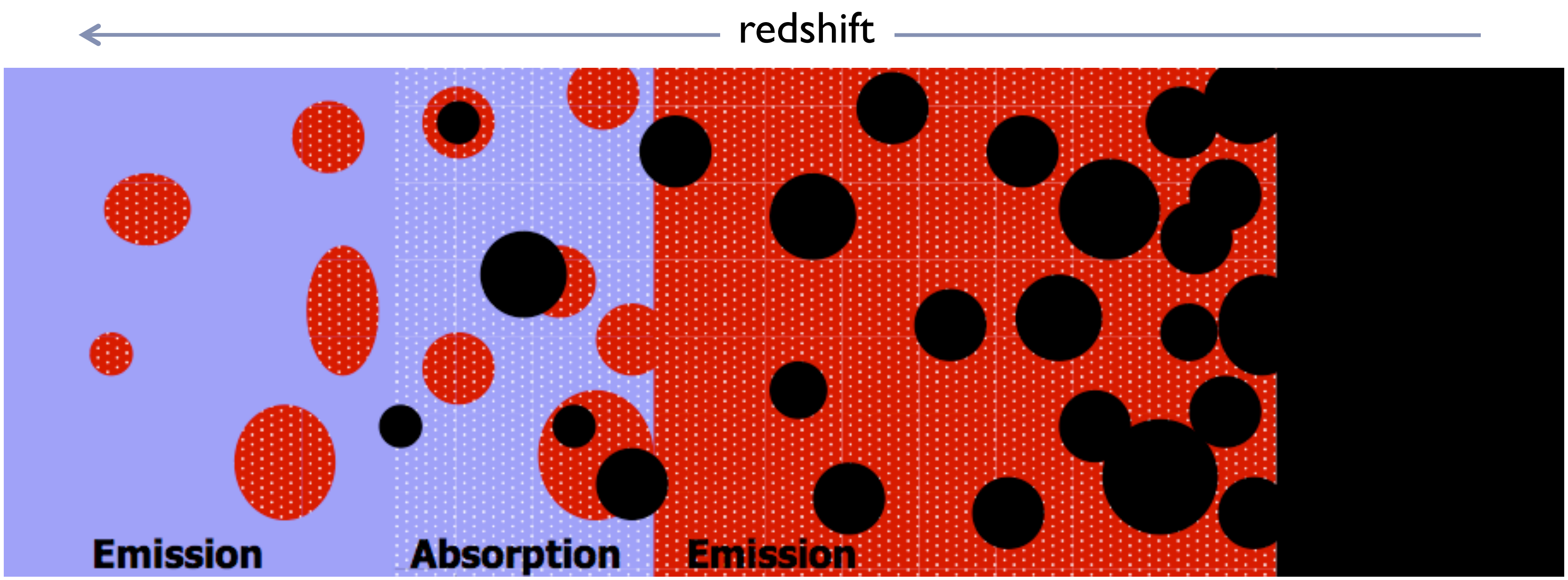


Iliev et al. 2003

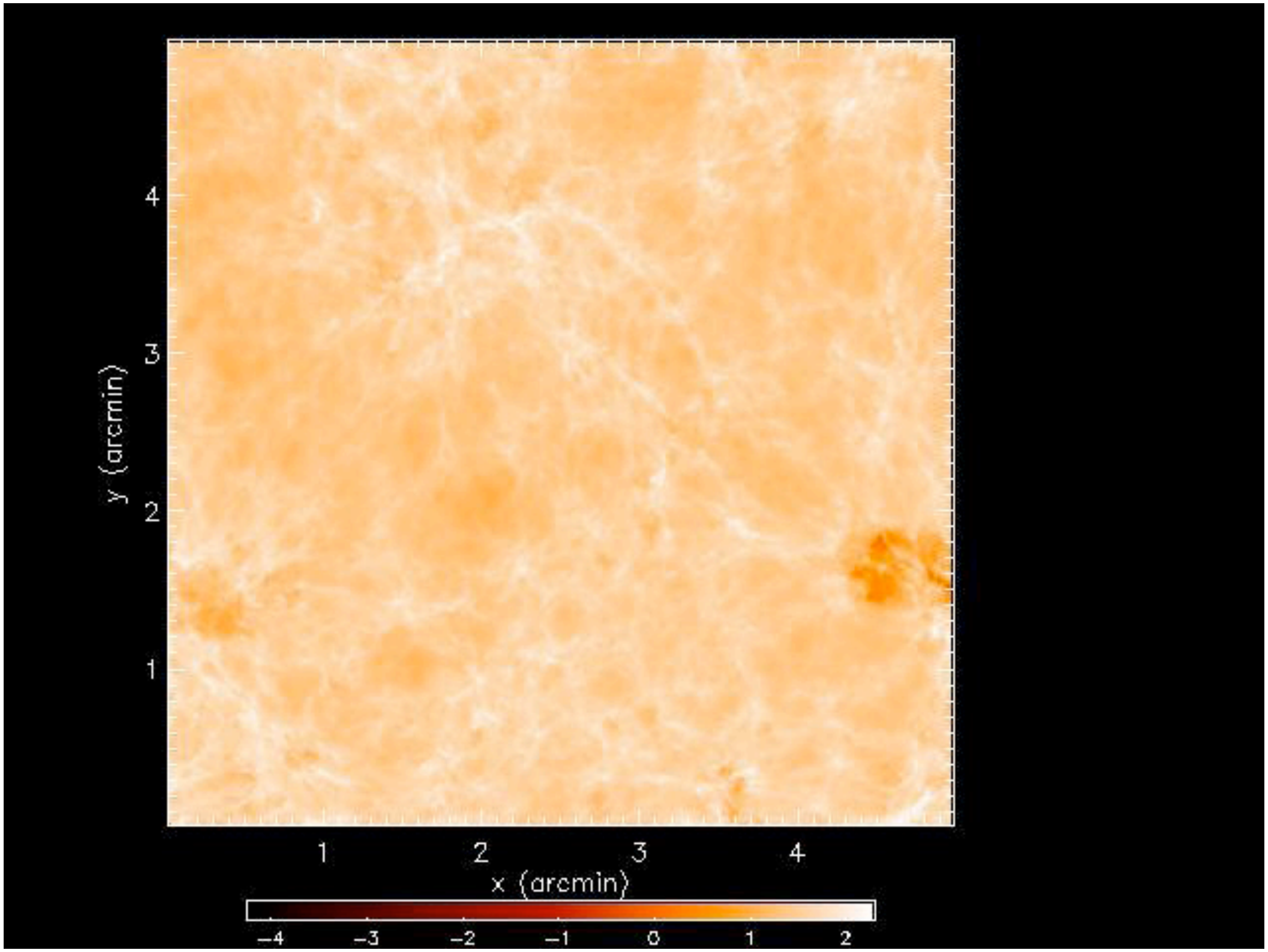
21 cm Toolbox

- X-rays heat diffuse IGM to $T_K > T_{CMB}$
  ➔ signal independent of T_K
- Brightness variations from δ only
- Ionized regions grow

Blue: Cold IGM
Red: Hot IGM
Black: Ionized IGM
Hatch: $T_S \sim T_K$



21 cm Observations: Emission

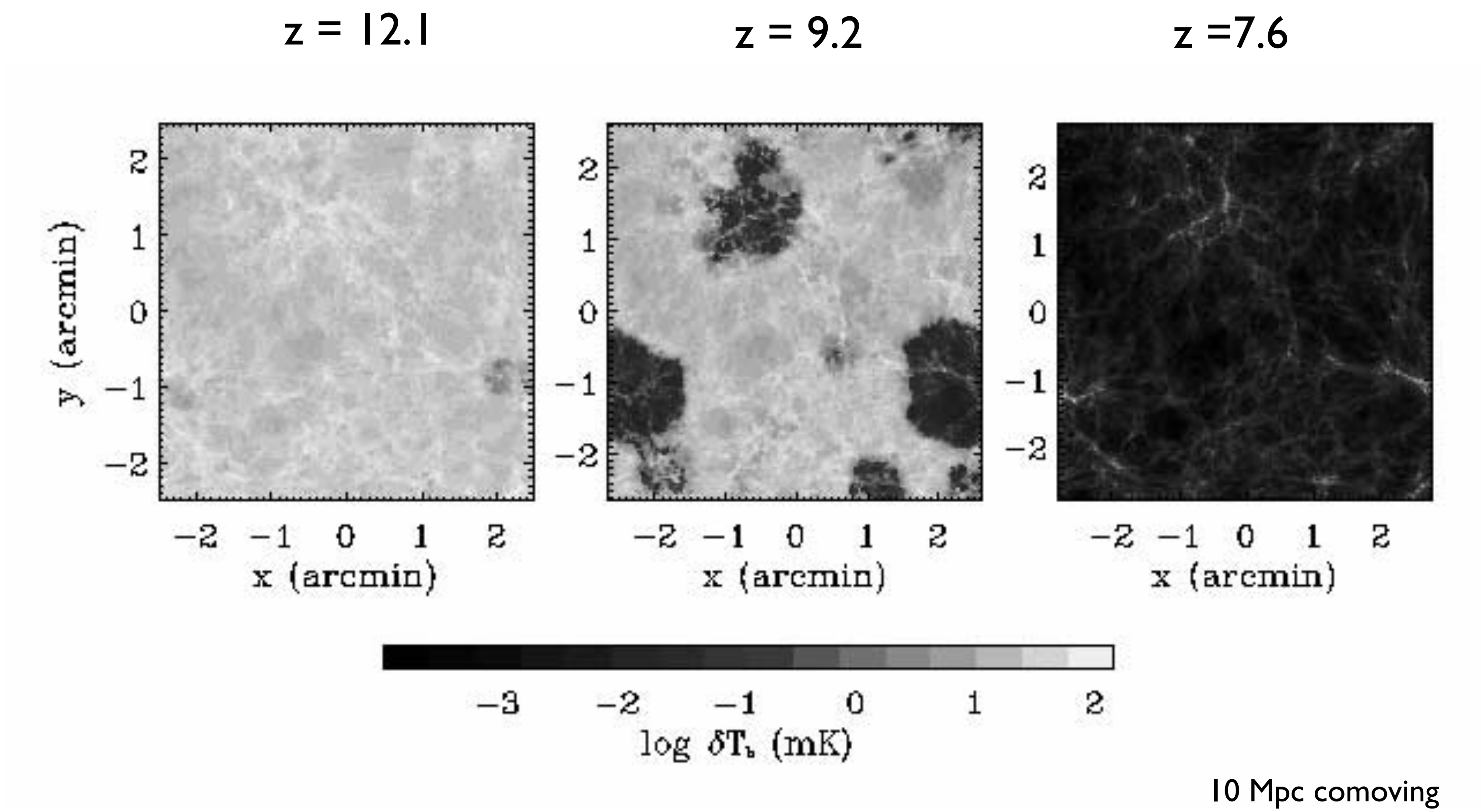


z = 18.3
z = 16.1
z = 14.5
z = 13.2
z = 12.1

10 Mpc comoving
$\Delta \nu$ = 0.1 Mhz

Furlanetto et al. 2004

21 cm Observations: Emission

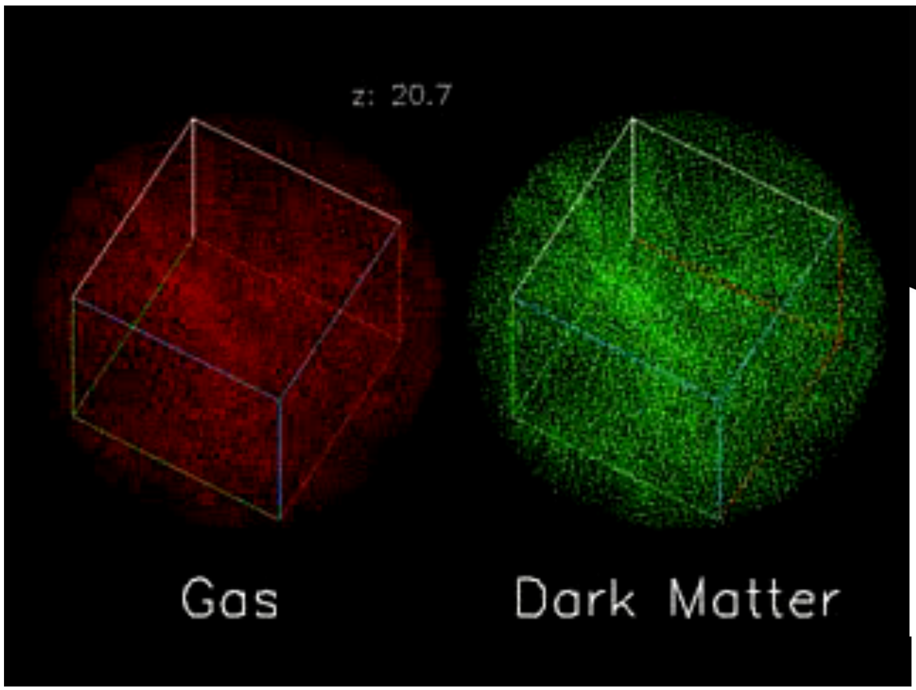


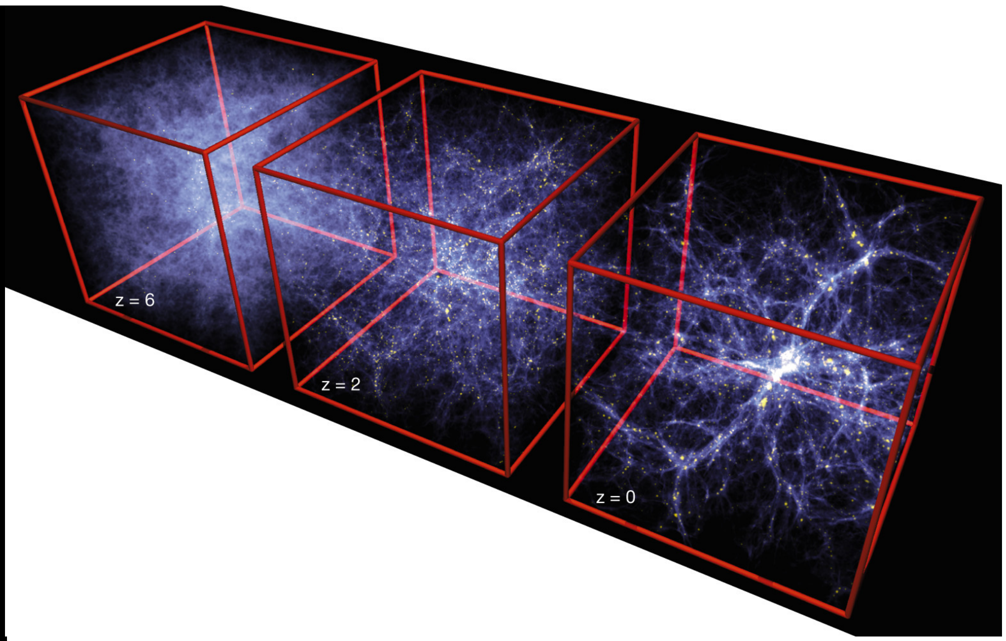
10 Mpc comoving
$\Delta\ \nu$ = 0.1 Mhz

Furlanetto et al. 2004

Large scale structure of the Universe

- Fly-through of the Cosmic Web

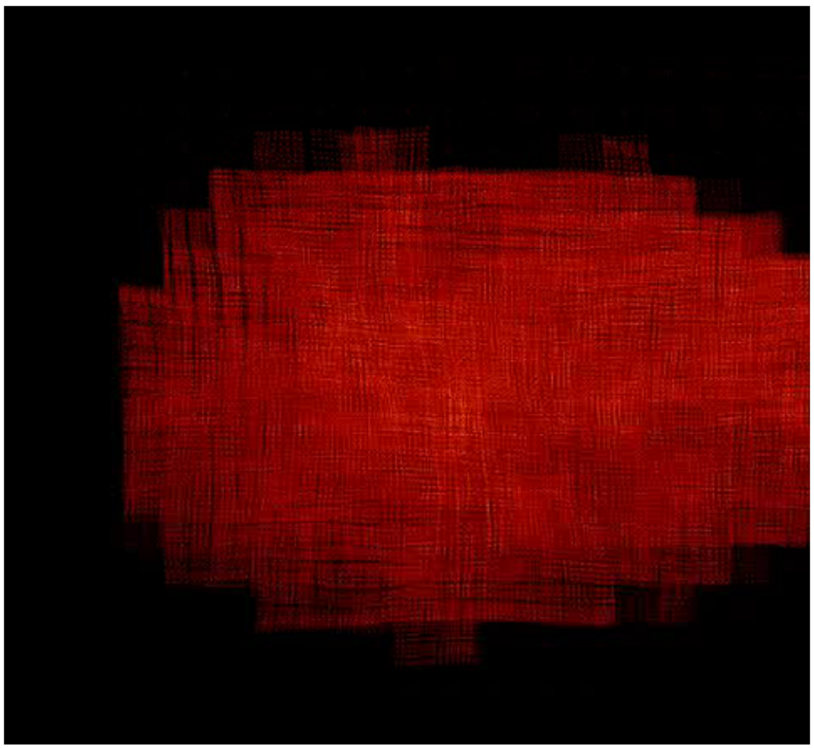




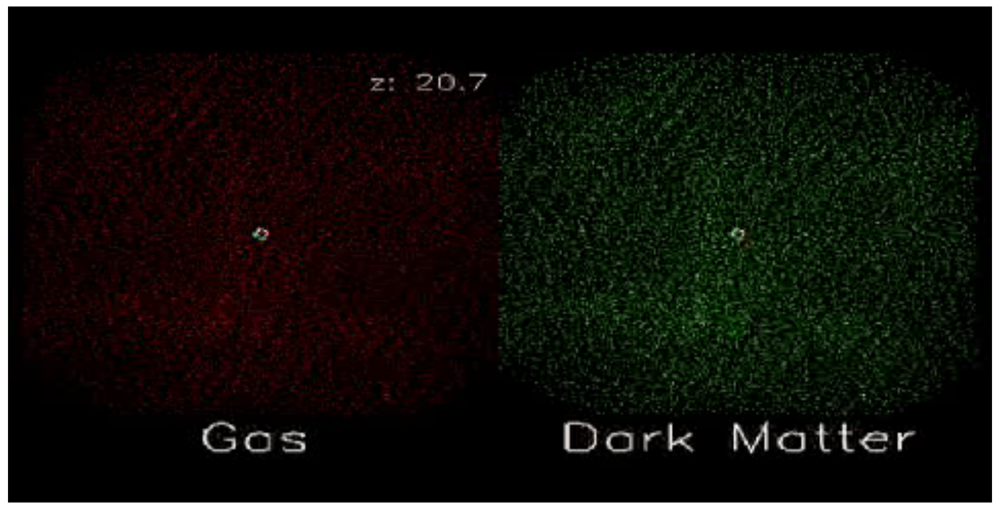
Large scale structure of the Universe

- Structure and Galaxy Formation

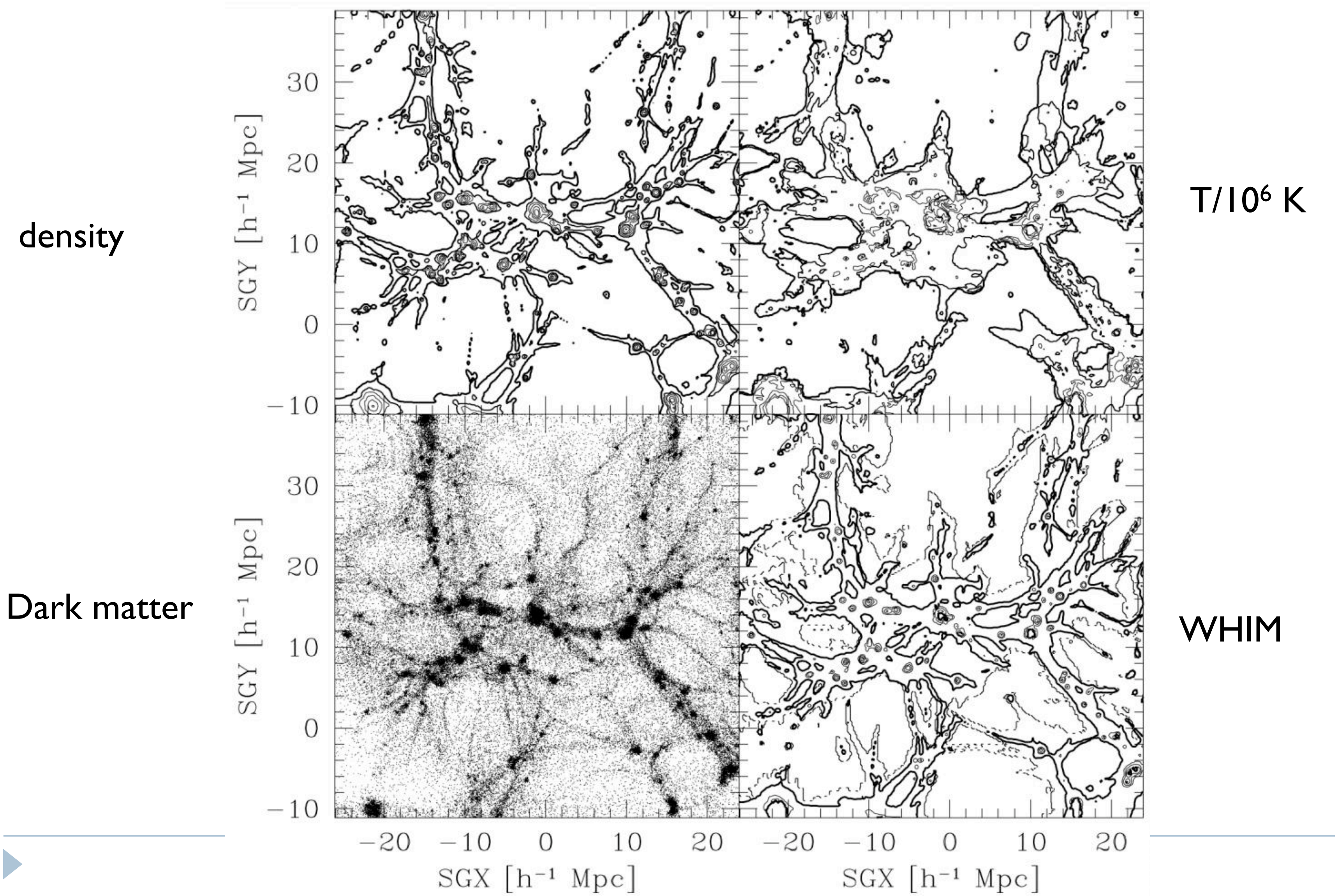
elliptical



spiral



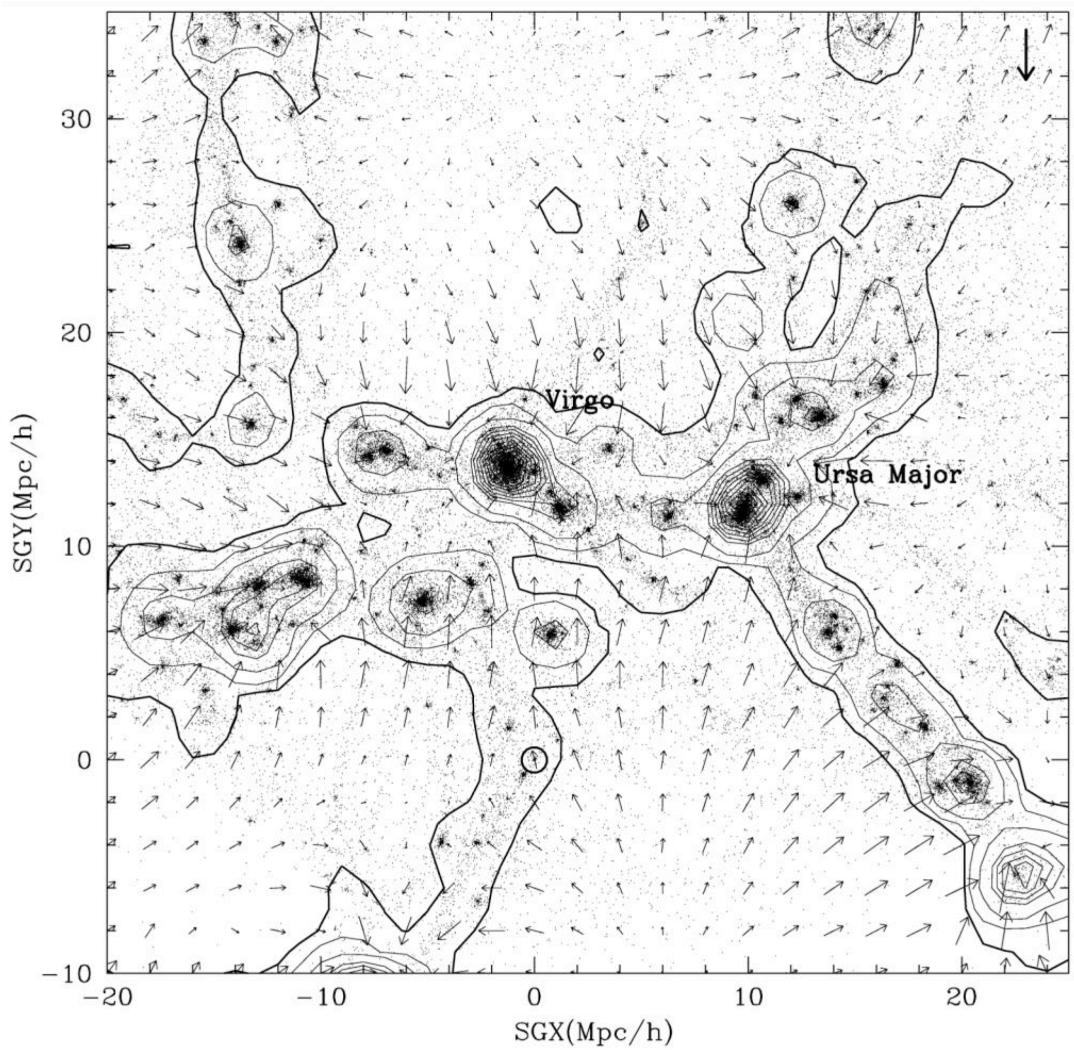
The WHIM: Warm-Hot Intergalactic Medium



Physical Properties of the WHIM

- QSO absorption line (HST,FUSE)
  - Limited to individual sightlines – FUSE has < 200 usable sightlines
  - Unknown: ionization fraction, abundance, temperature, filling factor
    - Any measure of the physical conditions in the WHIM are dependent on these
    - Claimed to contain the bulk of normal matter (baryons) in the universe
- How was the WHIM produced?
- Is there cold gas too? (how do you detect it?)

Cosmic Streaming



- What does H_0 mean?
  - Over what scales (spatial)?
  - What kinematic scales?

Klypin et al. 2003

Physical Processes in the Cosmic Web

- Large scale shocks as baryons accrete onto collapsing structures
- Gas is shock-heated to 10^5-10^7 K
  - WHIM origins, or AGN and star-formation too?
- Shock accelerate particles (cosmic ray ions) to 10^{18}–10^{19}eV
- Inter-cluster B-fields: 10^{-7}–10^{-12} G
  - Origin and amplification?

Mapping the Cosmic Web

- Galaxies are only the high density islands in the web
- Most of the web is in the form of diffuse WHIM
  - Detected primarily via QSO absorption sightlines
  - Fraction of kinetic power converted to radiative energy
- Diffuse emission should be detectable in the optical (nebular line emission, e.g., redshifted Lyα) but suitable instrumentation has yet to be built.
- Diffuse synchotron emission (radio) another possibility
  - Parameters:
    - Infall velocity
    - Density of in-falling baryonic gas
    - Magnetic field strength
    - Efficiency of shock acceleration
    - Fraction of kinetic power converted to radiative energy

Furlanetto et al. 2003:
Ly α surface-brightness