Astronomy 730

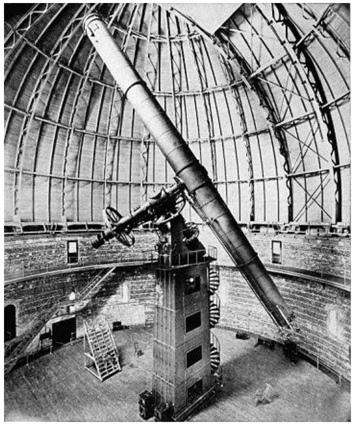
Overview

Outline

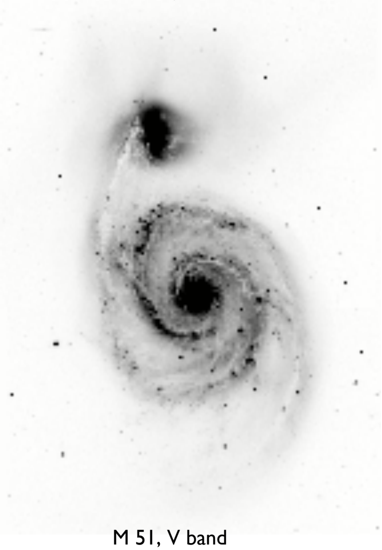
- Introduction to Galaxies
  - History of the field: *establishing standard candles*
  - Properties of individual galaxies
    - Morphology & classification
    - Variations
    - Physical attributes
  - * Statistical properties of galaxies: *distribution functions*
  - Sample surveys
- A Really Brief History of the Universe
  - Big Bang → Creation of primordial elemental abundances
  - → Recombination → Reionization
    - * When did reionization occur?
  - → Structure Formation and Evolution
    - * Where are all the baryons?

History

- At end of 19th century – Yerkes was just being built
  - Stars were "fixed" points on the sky – proper motion on the cusp of discovery
  - Clusters and nebulae were fuzzy blobs Messier cataloged in late 1700's from down-town Paris – to be avoided by comet-hunters
  - Clusters: Open (e.g. Pleiades), and Globular
  - Nebulae:
    - "planetary nebulae": disk-like with central star
    - Giant clouds
    - "spiral nebulae"
- What were the "spiral nebulae"?
  - Kant: "island Universes" – things like the Milky Way just farther away
  - Laplace: solar systems in formation (ever seen M51?)
- Types of matter in the universe
  - Not a lot was known because spectroscopy was hard
  - Spectra of the "fixed" stars looked like the Sun
  - Spectra of the "nebulae" like Orion looked funny – lots of emission lines
  - "spiral nebulae" – not quite right: a little bit of both
- Missing: ***distances***



Yerkes, 1897

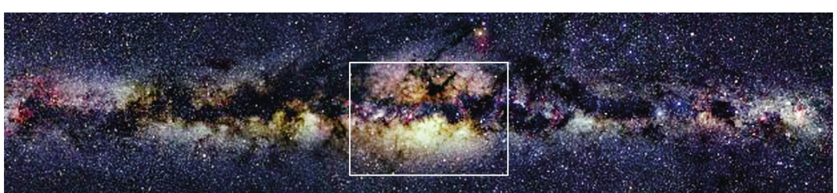


M 51, V band

Spiral Nebulae

NGC 891 observed with WIYN

MW



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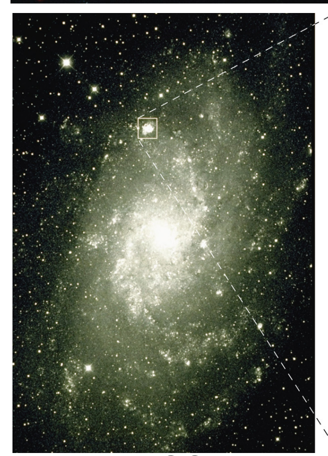
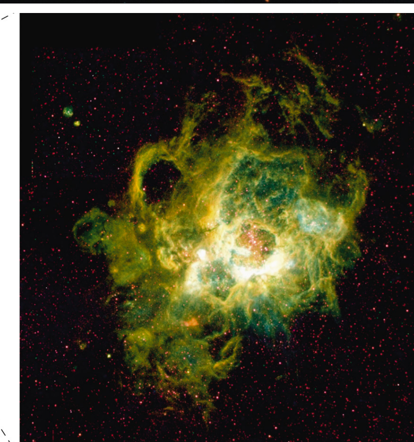


M33



Star-forming nebula in M33

- dust lanes and bulge…a clue?

Early Distances

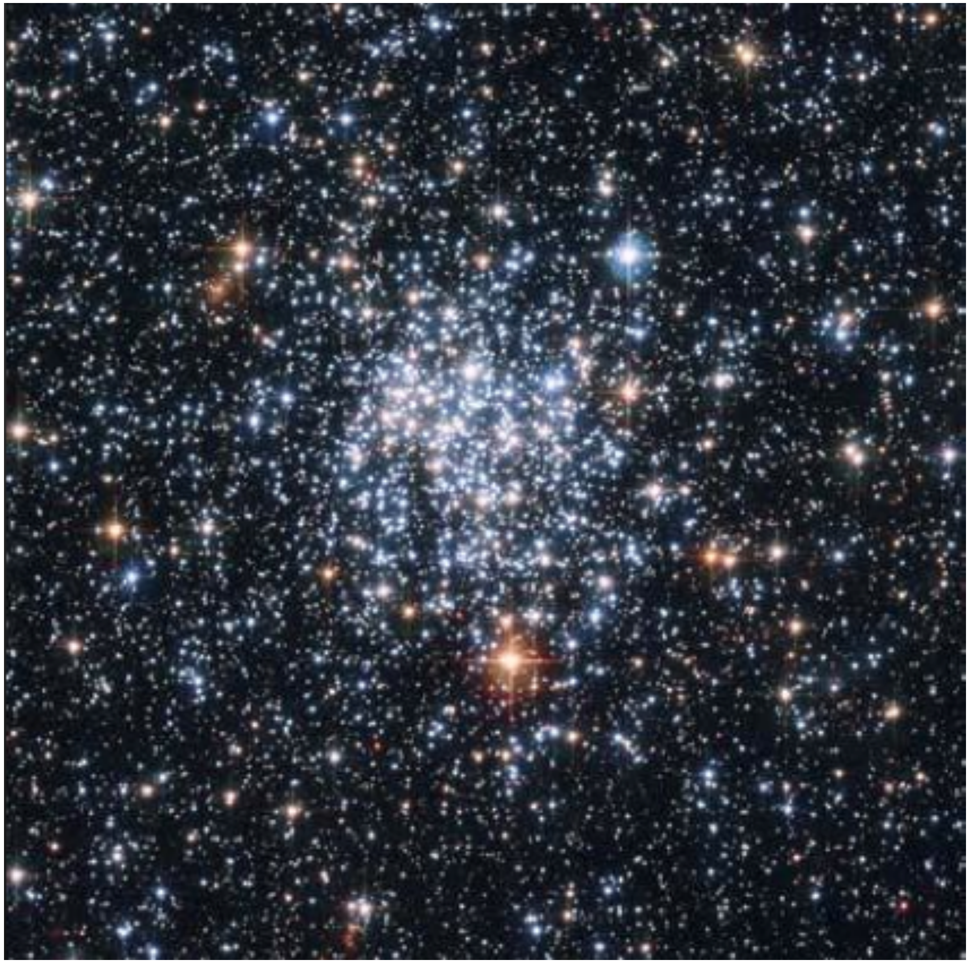
- Trigonometric Parallax
  - D(pc) = 1/θ (arcseconds)
  - In 1900 this was good out to 30 pc (1 pc = 3.1×10^{18} cm)
  - Hipparcos satellite went out to about 200 pc; GAIA satellite (2014) is extending to ~10 kpc (*)
- Other distance indicators needed
  - Statistical parallax (for clusters) – using vertex motion
  - Spectroscopic parallax
  - Variable stars
    - Henrietta Levitt (Harvard) looking for variable stars discovered the brightness of Cepheid variables (in LMC) was proportional to the period.
- Measure period, get brightness, get distance (Cepheids as "standard candles")
- Continues to this day: Cepheids used by HST to measure H_0
- Supernovae (Sne) and galaxies (via scaling-relations) used as standard candles at even larger distances

* See: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=26

Cepheid Variables

- Most stars have constant luminosities...(within limits)
- Some vary…
  - Binaries – orbital eclipsing
  - Novae - mass-accreting white dwarves (WD) or neutron stars
  - Supernovae (SNe) – exploding massive stars or critical-mass WDs
  - Mira variables – asymptotic giant branch stars (ABG) of intermediate mass; red, long term pulsation (100 days)
  - RR Lyrae: low-mass giants (evolved stars), short periods (~day), fainter luminosities, lower mass stars (Horizontal Branch, HB)
  - Cepheids: evolving, luminous massive stars (> $3M_{\odot}$); blue, w/ periods of 10-100 days, easy to find w/ sufficient resolution and timing
- Clusters: young vs old
- Magellanic Clouds – all Cepheids at the same distance, so the period-luminosity relationship really shows up

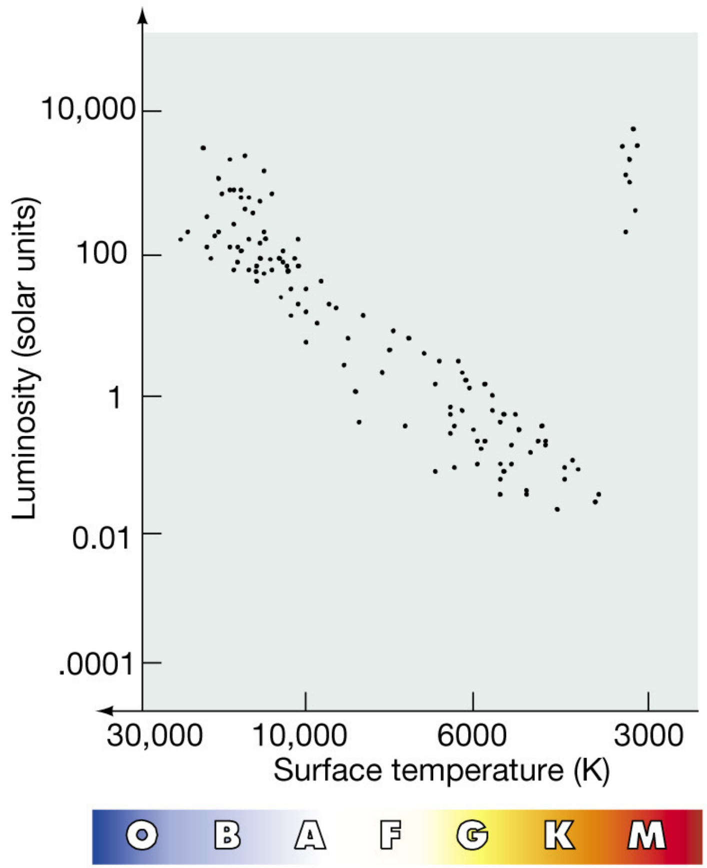
Star Clusters



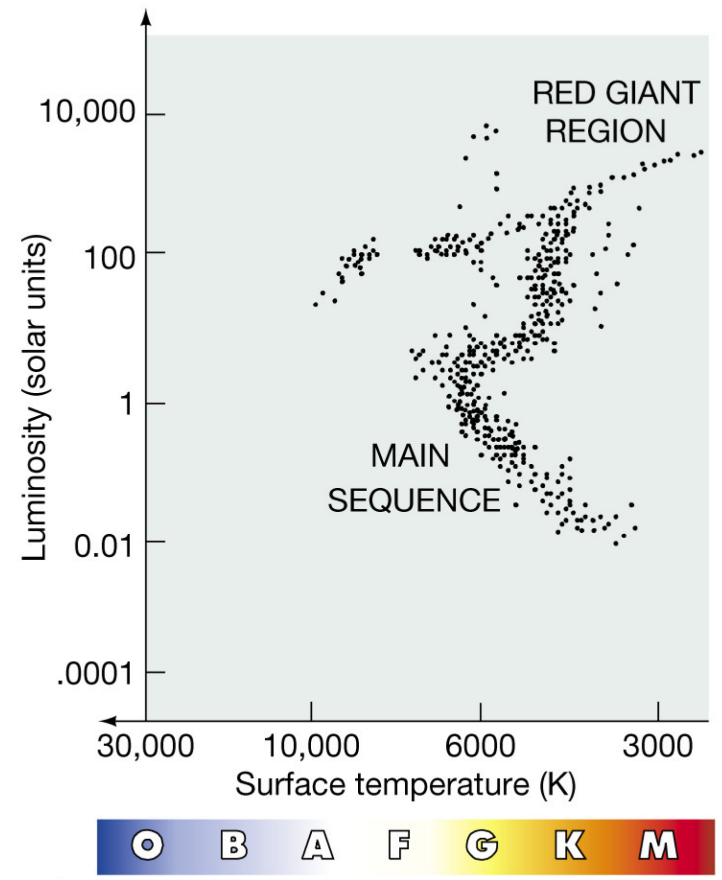
NGC 265 – open cluster in SMC

M80 – MW globular cluster

Star Clusters

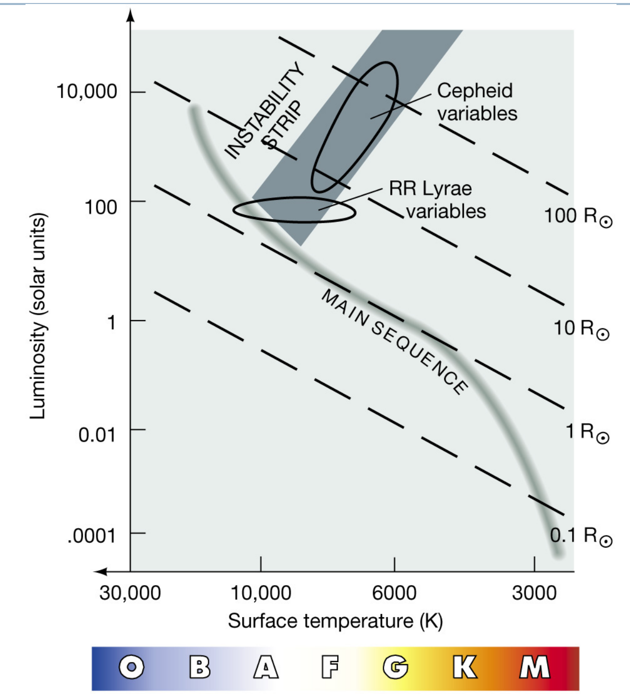


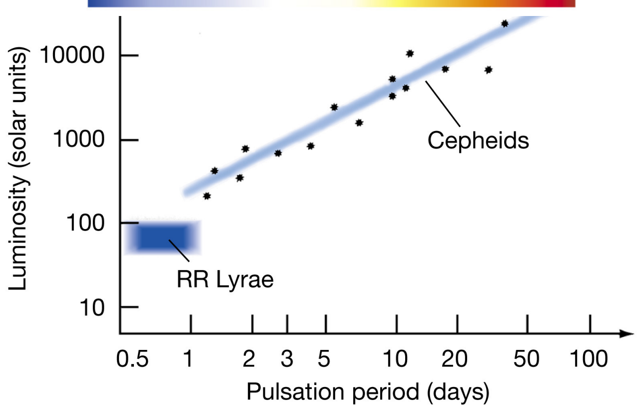
young

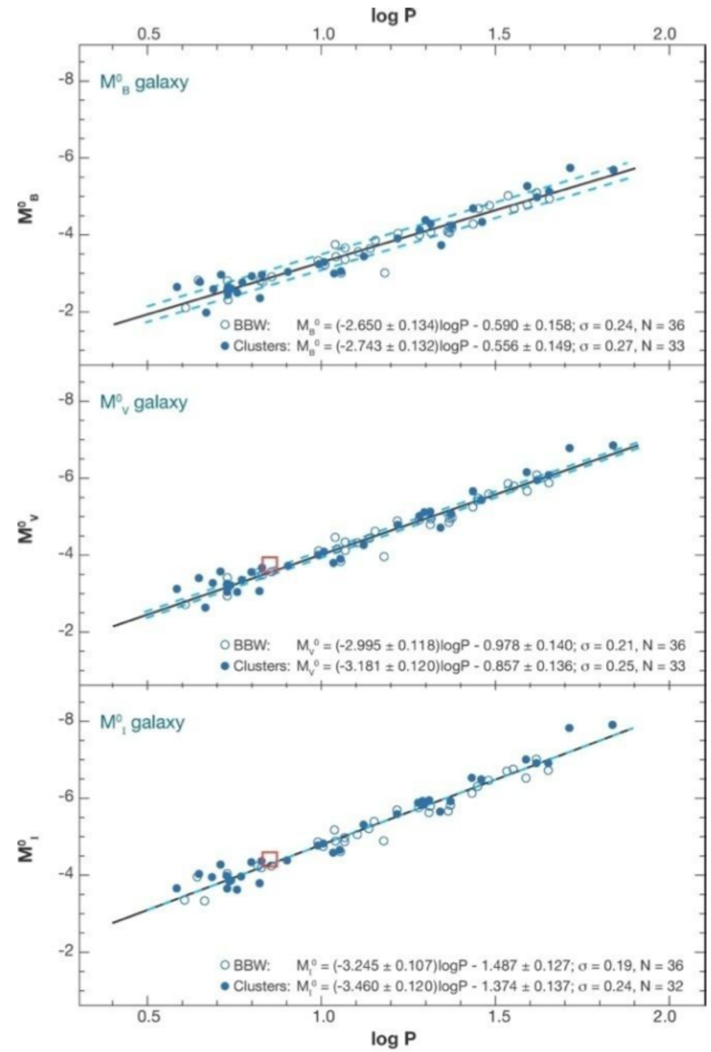


old

Variables & Cepheid P-L relationship





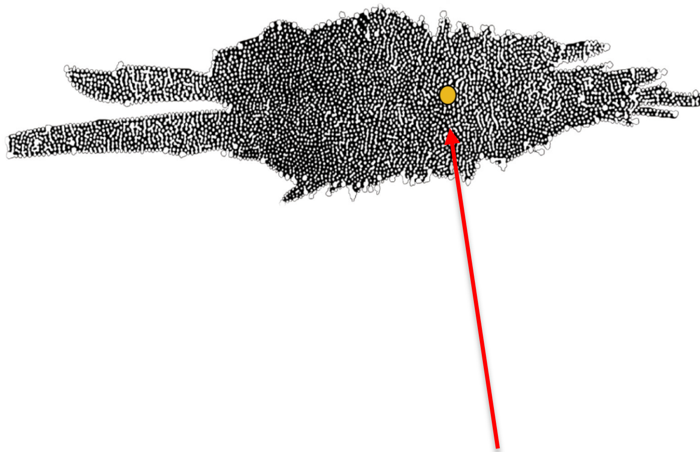


Sandage A, Tammann GA. 2006.
Annu. Rev. Astron. Astrophys. 44:93–140

Shapley

- Shapley applied Cepheid scale to globular clusters…
  - Spherical distribution centered near Sagittarius (we're not at the center any more)
  - Size of the distribution: 100,000 pc (old size based on star-counts was only 8 kpc)
  - Implication: spiral nebulae had to be contained within the Milky Way!
- Mistake
  - Wrong variable stars! They were RR Lyraes!
  - Didn't account for reddening (then again, nobody really did)

Picture of our "universe" pre-Shapley



You were thought to be here

Curtis

- Reported on apparent nova in M31 – derived a distance of 150 kpc (5 times too small, but large enough)
- Radial velocities of spiral nebulae higher than anything else (clue for Hubble)
- Band of dark material seen in some edge-on spiral systems
- Kapteyn used star counts to conclude we live in a flat, heliocentric conglomeration about 15 kpc in diameter (about the same size of M31 if it were 150 kpc away)

Resolution

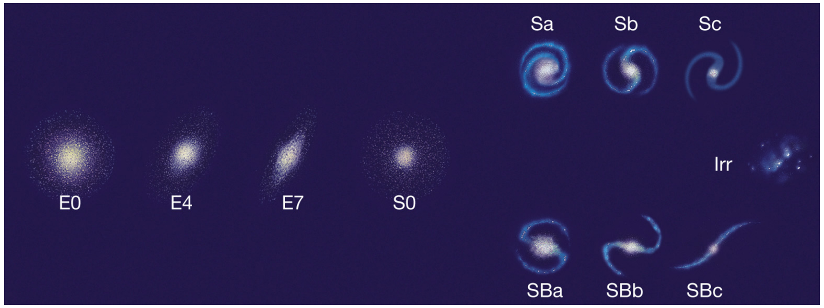
- 1923: Edwin Hubble used the 100-inch telescope at Mt. Wilson
  - Resolved parts of nearby galaxies into stars
  - Detected Cepheids in M31 and measured their periods
  - Used radial-velocity measurements from Slipher at Lowell observatory made with smaller telescopes!
  - Later determined velocity-distance relationship yielding $H_0 \sim 600$ km s^{-1} (bad Cepheid distance calibration)
- Discovery of the ISM
  - Spectra of nebulae showed they were gaseous
  - Stationary absorption lines seen in binary stars
  - Angular diameter vs luminosity distances for Galactic clusters (i.e. open clusters)

Modern times

- 1940-1950's: Understanding of stellar evolution (fusion).
- 1960's: Discovery of CMBR; Big Bang model consolidated.
- 1970's: Distant universe opened by radio astronomy (quasars, radio galaxies); early-universe nucleosynthesis calculated.
- 1980's: modern era of CCD astronomy begins; particle-physics and early-universe meld (unified theories); dark-matter accepted phenomenon.
- 1990's: era of Hubble Space Telescope (HST) and 10m telescopes (Keck, VLT) begins; galaxy evolution confronted; CMBR probed; basic cosmological parameters determined.
- 2000: multi-wavelength satellites, large ground-based surveys, more 10m telescopes than 4m telescopes; dark-energy accepted phenomenon.
- 2020-2030: ALMA, JWST, and ELTs; epoch of reionization and earth-like planets.

Properties of Galaxies: Classification

- Hubble types – quite subjective
  - Ellipticals (E0-E7), where n=10[1-(b/a)])
  - Lenticulars (S0): a transition type
  - Spirals
    - "tightness" of spiral (Sa-Sd)
    - Prominence of central bulge (Sa-Sd)
    - Presence of a "bar" (B, as in SBc)
    - Presence of a ring (r) or lens (s); added by de Vaucouleurs
  - "Morphed" into numerical T types: E = - 5, Sb = 3, Irr = 8-10
    - But note! These are ***not*** quantitative.



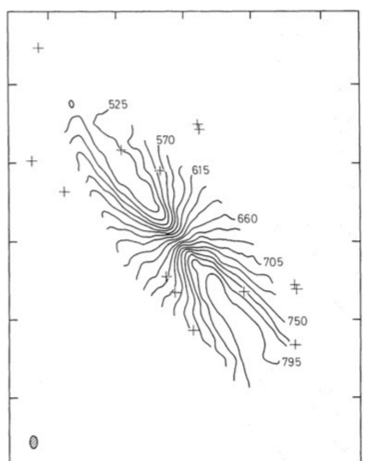
- Other classification schemes
  - Luminosity scale (van den Bergh)
  - Spectral "types" (Morgan)
  - bulge/disk ratio – requires light-profile decomposition (Kent)
  - Structural parameters (image concentration, asymmetry and flocculence)
  - Gas/stellar ratios
  - Kinematic "temperature" (rotational/random velocities)

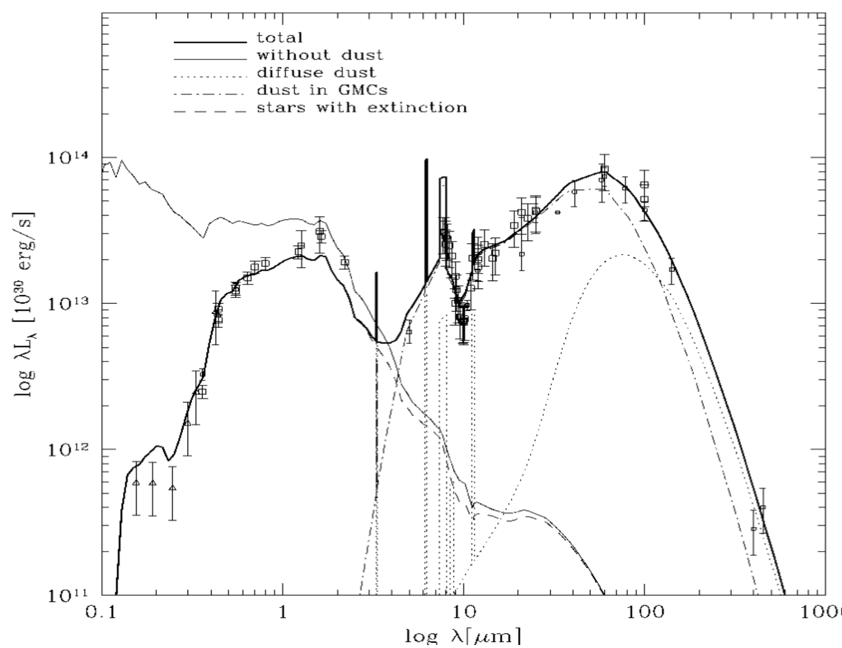
Physical Properties of Galaxies

- Observables

To first order: everything scales with mass

  - Scales: size (s), luminosity (L) (surface-brightness, μ)
  - Shapes: light concentration (c), azimuthal structure ($a_1 \ldots a_n$)
  - Kinematics: rotation (*V*), random motion (σ)
  - Content: spectral energy distributions interpreted as…
    - Stellar populations: age, metallicity, and mass (τ,z, $\mathcal{M}_*$)
    - Dust, gas (all phases): densities (ρ_i





Statistical Properties

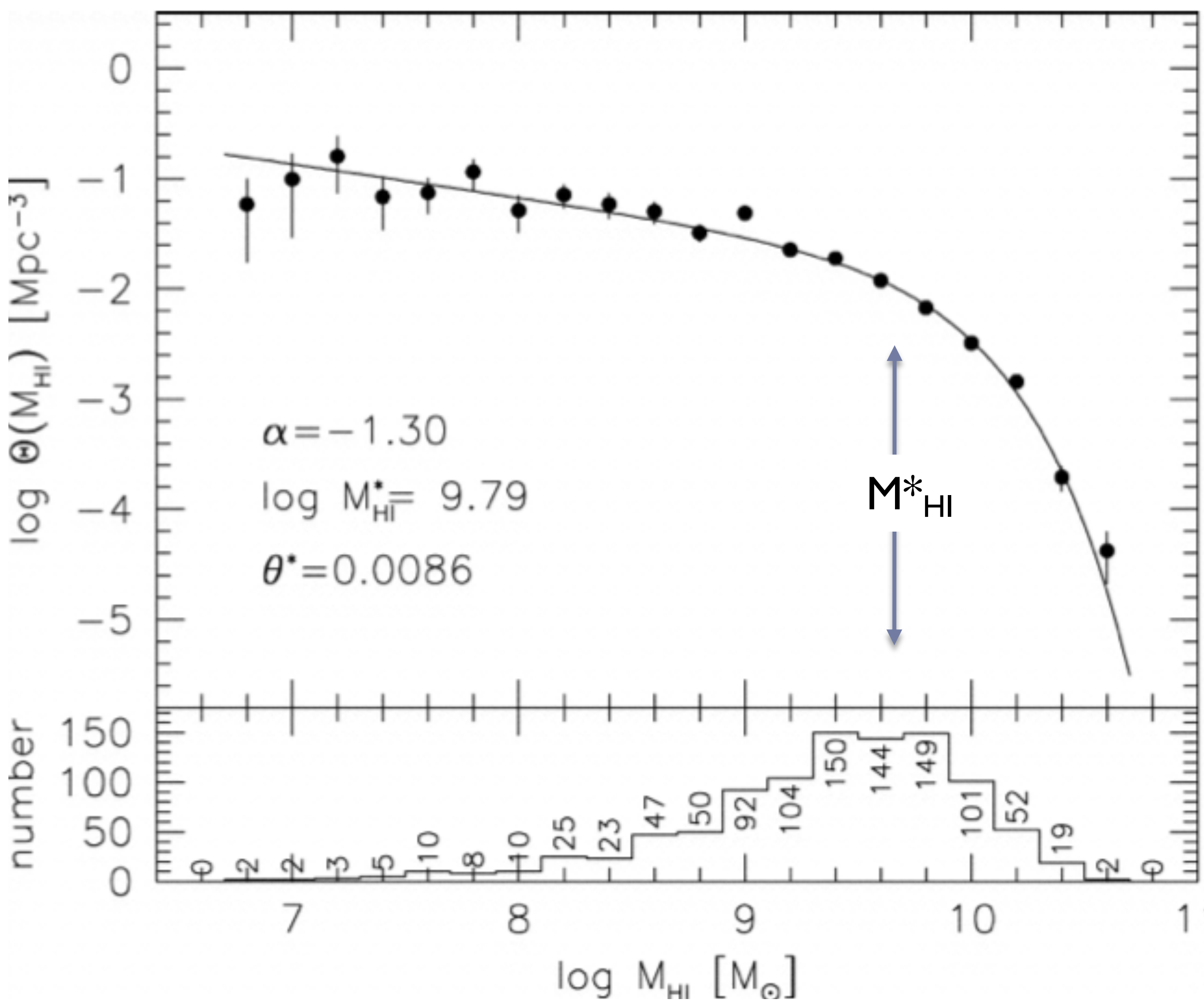
- Crudely defined by the luminosity function (LF)
  - $\int\Phi(M)dM = \nu$, where ν is the total number of galaxies in the magnitude range M, M+dM
  - Need large volume: sample all environments
  - Need unbiased sample (we'll talk about the Malmquist bias later)
  - Convert magnitudes into real luminosities: $m = -2.5 \log 10(L/L_0) + \text{constant}$
- Schecter function
  - $\Phi(L) = (\Phi^*/L^*)(L/L^*)^\alpha \exp(-L/L^*)$
  - L^* is the characteristic luminosity above which the number of galaxies falls off rapidly ($1.2\times10^{10}\ L_\odot$), i.e., the "*knee*"
  - Φ^* = normalization of the galaxy density (0.016 Mpc^{-3})
  - α is the faint end slope (-0.8 to -1.8)

- Both luminosity and mass (HI) functions are reasonably well fit by this near L^*, *but there is substantial variation in the slope and normalization between wavelengths, and that a single Schecter function is not enough.*

- We really want Φ(all observables):

$$\Phi\ (s, L, c, a_1 \ldots a_n, V, \sigma, \tau, z, \mathcal{M}_*, \rho_i)$$

HI Mass function



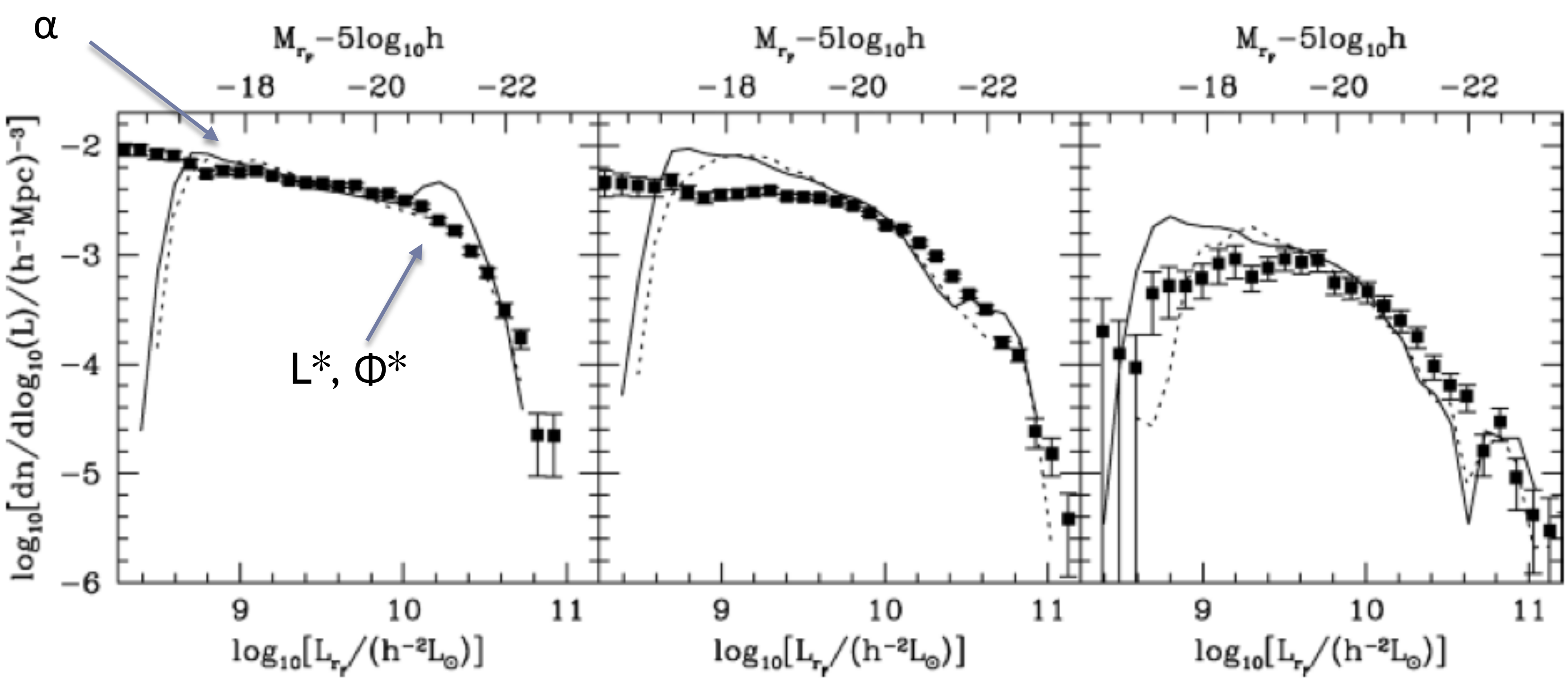
corrected

observed

Optical luminosity functions

As a function of group environment (group total mass): Eke et al. (2004)

$10^{13}\ h^{-1}M_\odot$ $10^{14}\ h^{-1}M_\odot$ $10^{15}\ h^{-1}M_\odot$



Red light (R_F band);
$h = H_0$ / 100 km s^{-1} Mpc^{-1}

Squares: actual data
Solid lines measured from simulations, corrected
Dashed lines measured from simulations, uncorrected

- Φ (s,L,c, $a_1 \ldots a_n$, V, σ, τ, z, $\mathcal{M}_*$, $\rho_{i;}$ e) -- e is environment

Stellar mass function

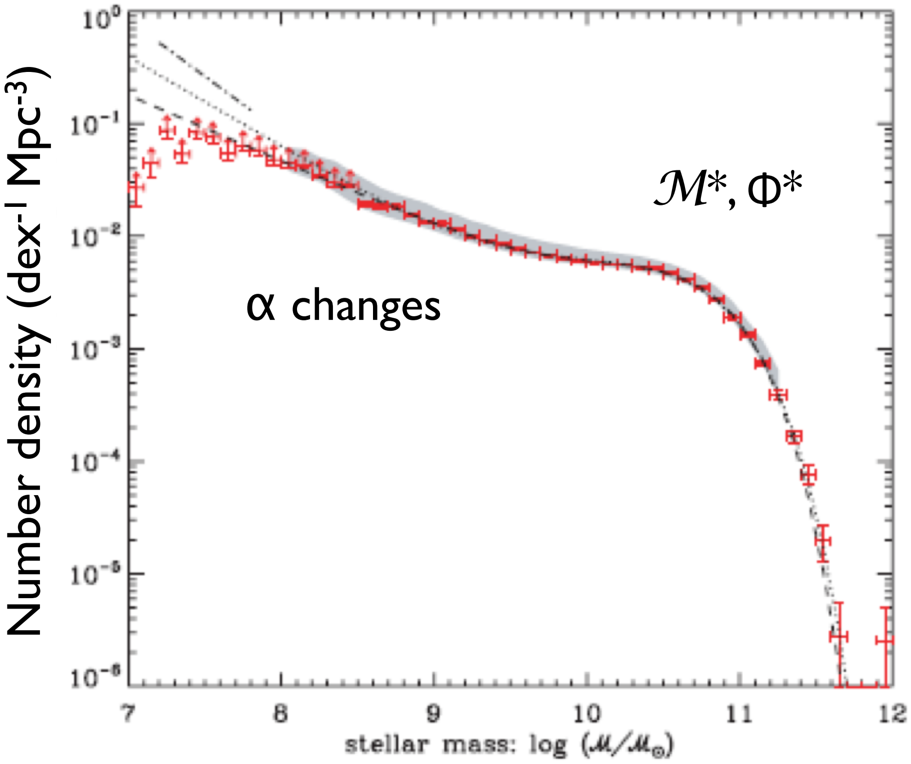
Baldry et al. 2008

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

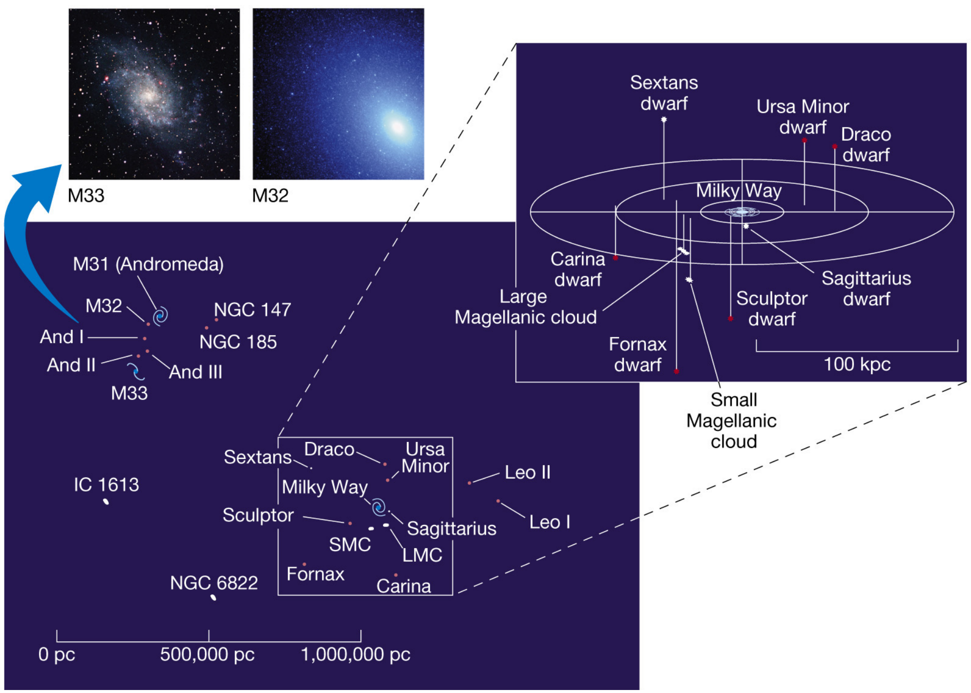
We will discuss these issues.

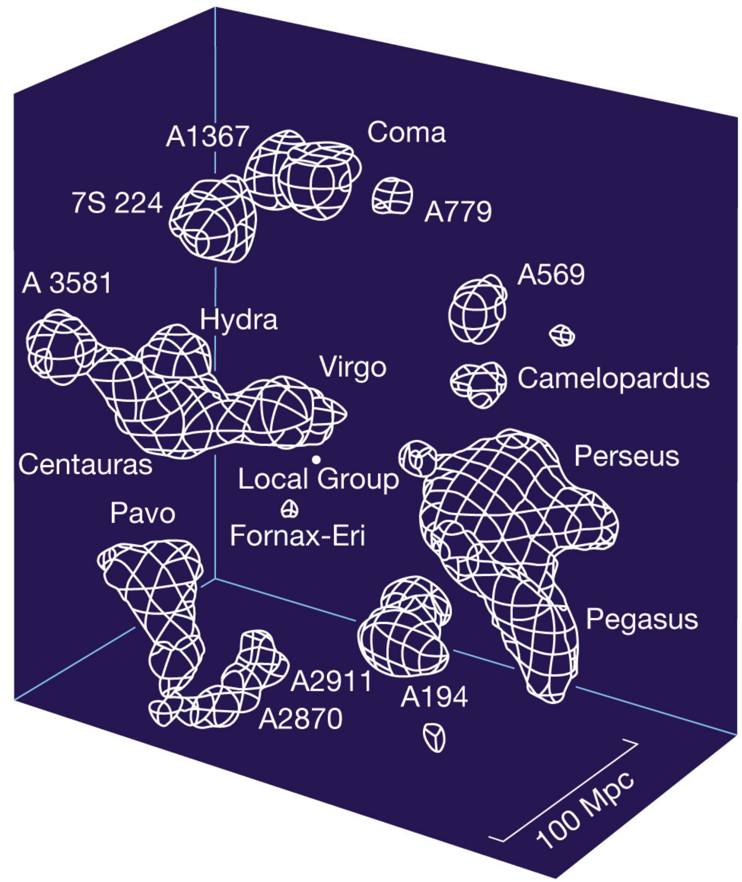
In this case, stellar mass function is modeled as composite of two Schecter functions with different α and φ*.



Large Scale Structure

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



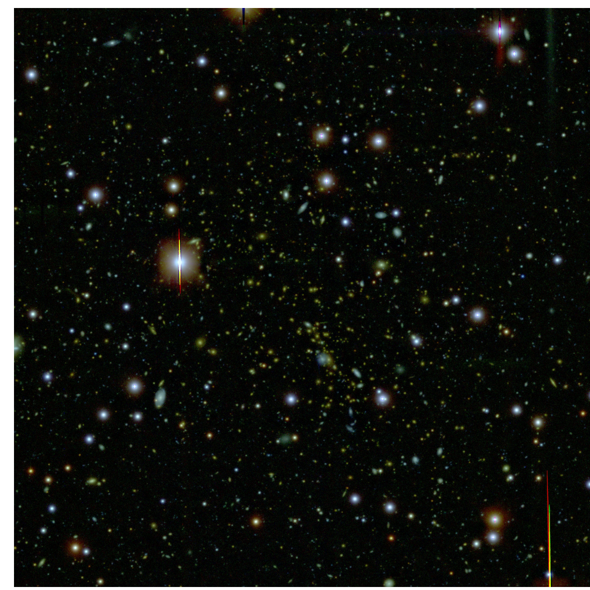


Large Scale Structure

- 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

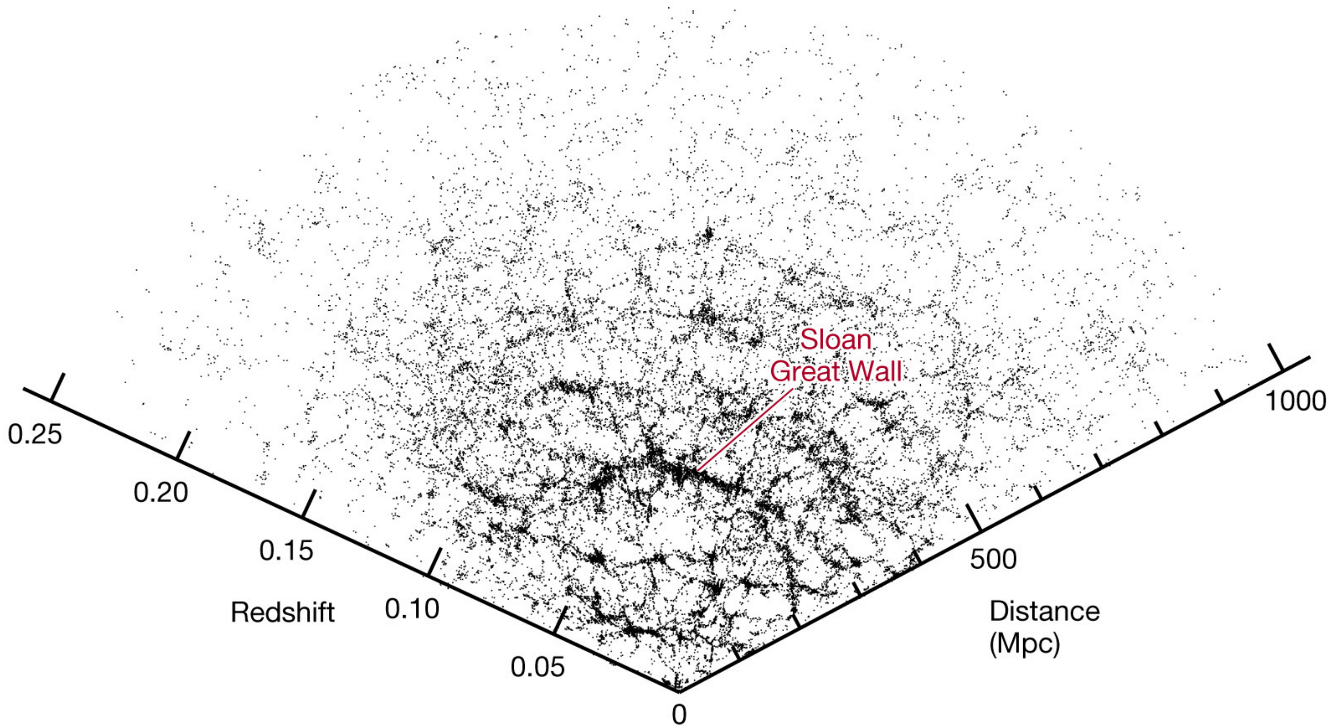
Abell 98 nearly next door



MS0415 at z = 0.54

Large Scale Structure

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



Surveys

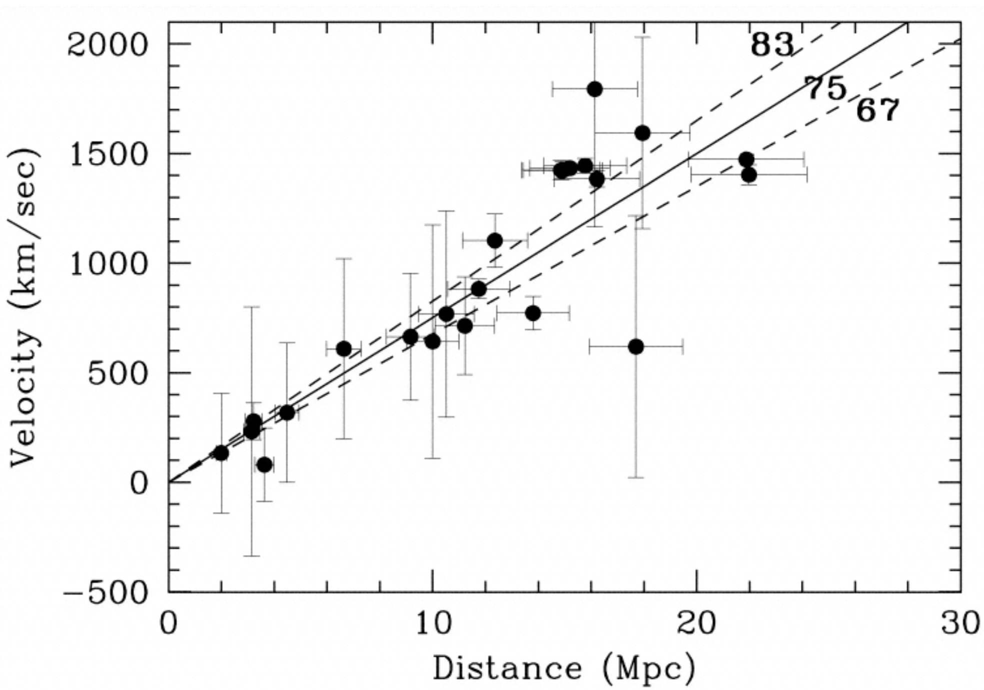
- Palomar Sky Survey (POSS) – blue/red photographic imaging (all sky)
  - digitized version (DSS)
- Sloan Digital Sky Survey (SDSS) – modern multi-band optical CCD imaging *and spectroscopy*
  - www.sdss.org
- 2-Micron All-Sky Survey (2MASS) – J,H,K band imaging (all sky)
  - http://www.ipac.caltech.edu/2mass/
- 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

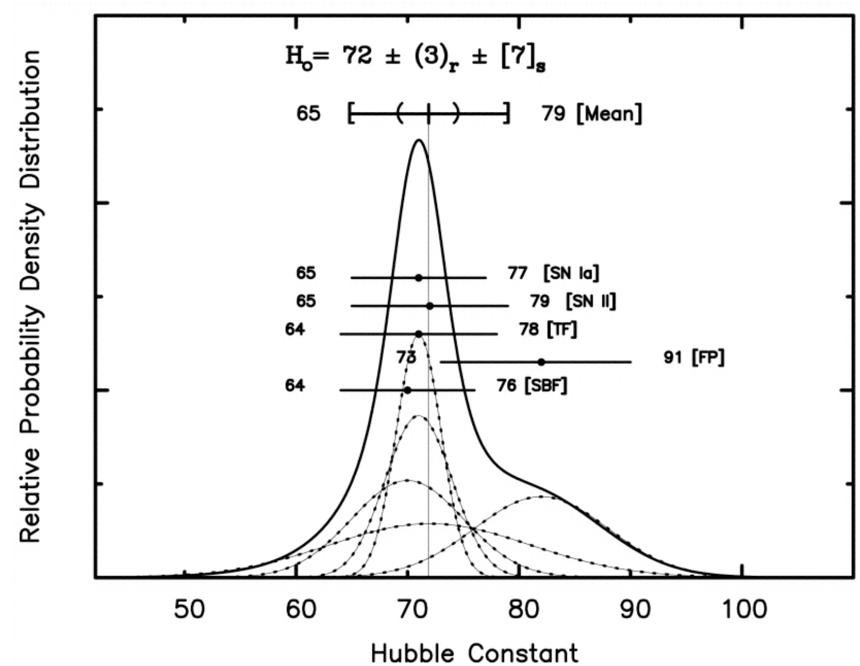
Big Bang / Creation of Matter

- 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:

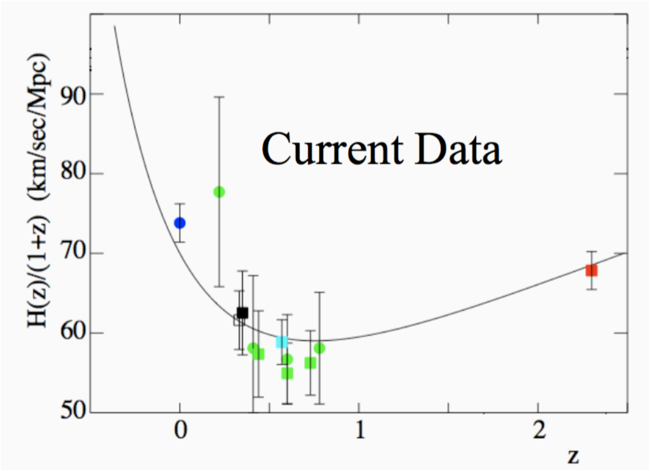
$$G_{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

  - $G_{\mu\nu}$ 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 m
      universe static, and this now looks like "dark energy"



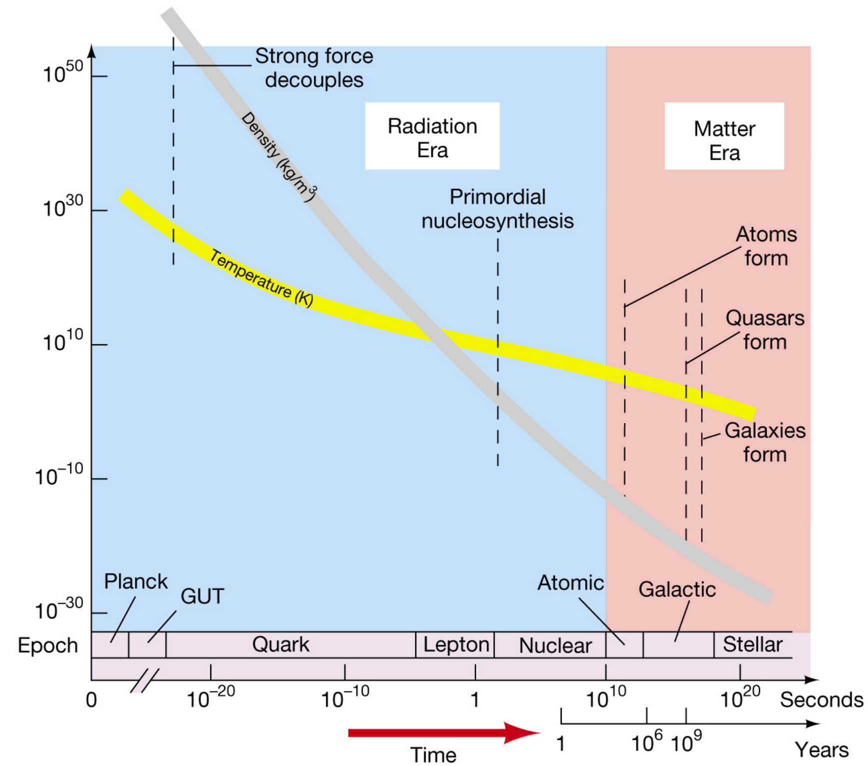
- $H(t) = \dot{R}/R$ by definition, i.e., H varies with time ($\dot{R} = dR/dt$)
- Distances: evaluate $D = \mathcal{R} \sin(r/\mathcal{R})$, where $dr = -c\ dt/R(t)$
- Times: evaluate the integral of dz/dt

The Early Universe

- Run the movie backwards…get one big fireball

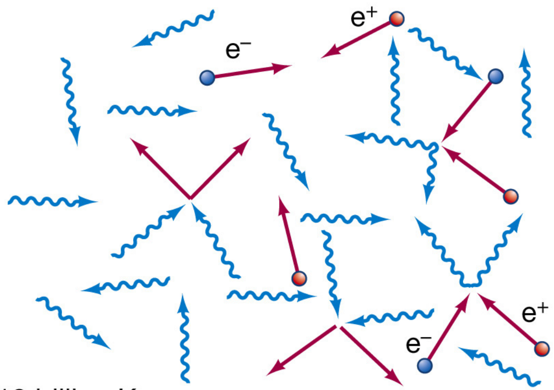
  ➔ the "Big Bang"

- 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….

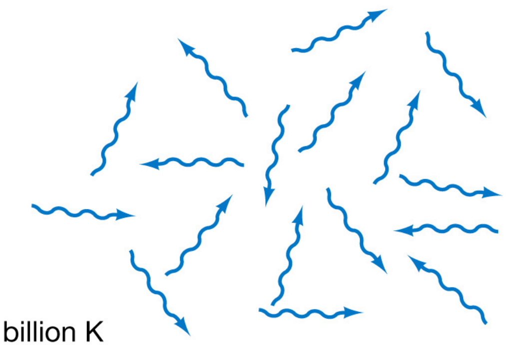


Particle Genesis

- 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?

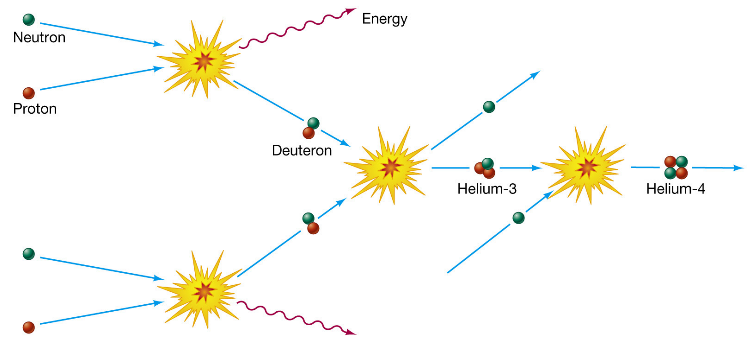


(a) 10 billion K


(b) 1 billion K

Big Bang Nucleosynthesis (BBNS)

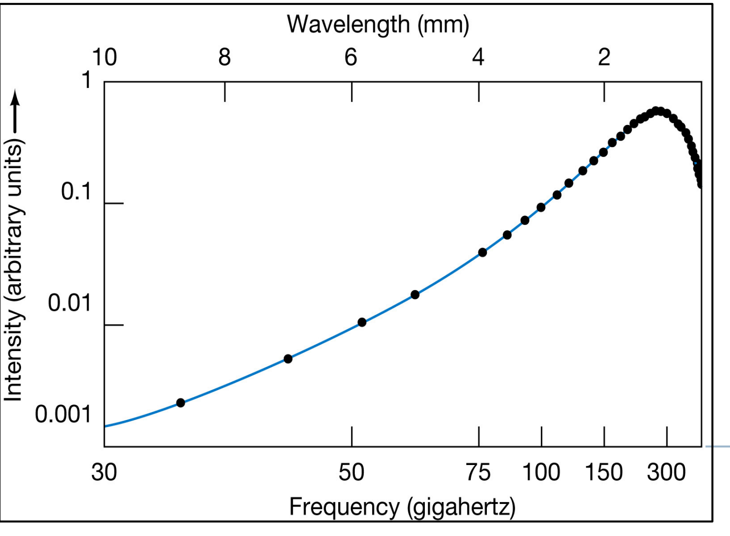
- Weak interactions control proton/neutron ratio via following reactions
  - p+v↔ n+e+
  - p+e- ↔ n+v
  - n ↔ p+e-+v - beta decay



- 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

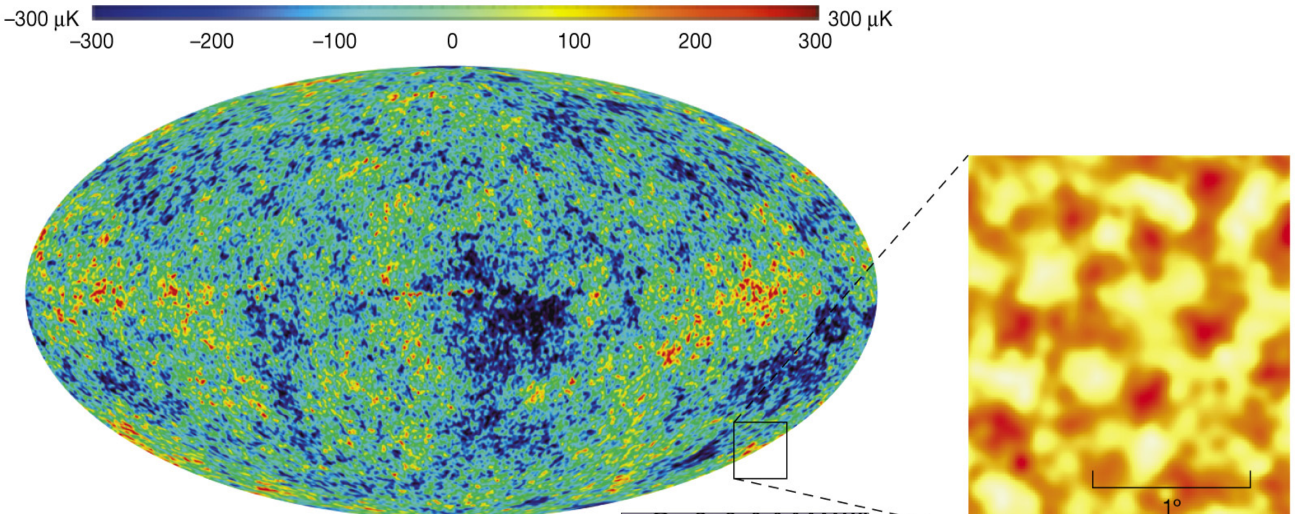
- $T = T_o(1+z)$. At z~1500, T < 4000 K, photons can no longer ionize H, so H recombines… (Saha equation)
- …the Universe becomes transparent to radiation ("surface of last scattering")
- If its 4000 K at z~1500, the temperature now should be 2.7 K ➔ microwave background. Detected by Penzias & Wilson (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) that encode a lot about the physical properties of the Universe.
  - Power spectrum of primordial fluctuations
  - Cosmological model
    - ΛCDM + flat Universe + baryons + radiation + power law fit to power spectrum

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



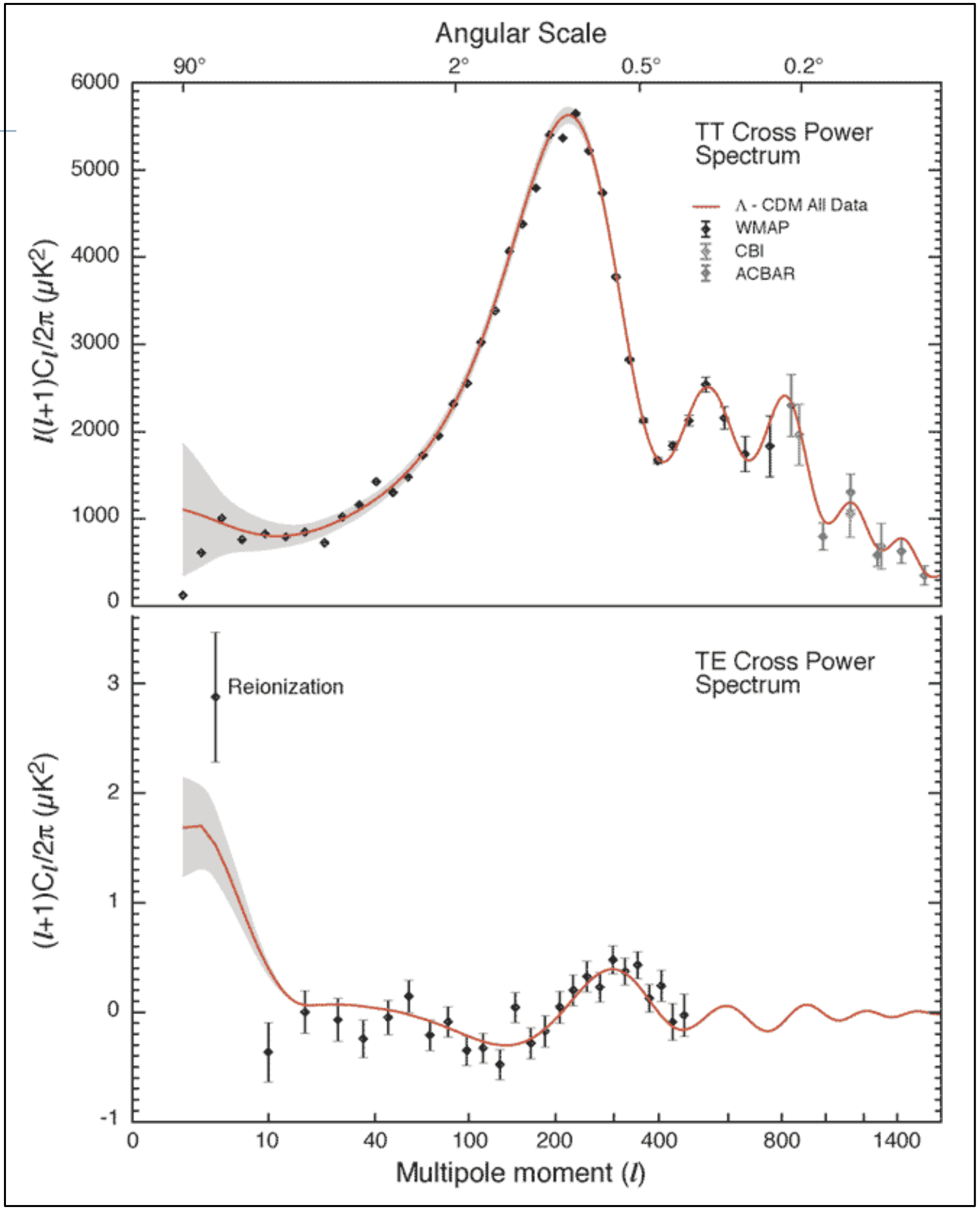
WMAP

- 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)	9yr results*
Amplitude of galaxy fluctuations, σ_8	0.9 ± 0.1	0.821 ± 0.023
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	0.04628 ± 0.0009
Matter density/critical density, Ω_m	0.29 ± 0.07	0.2865 ± 0.009
Age of the universe, t_0	13.4 ± 0.3 Gyr	
Redshift of reionization,[a] z_r	17 ± 5	10 ± 1
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] $l_A = \pi d_C / r_s$.

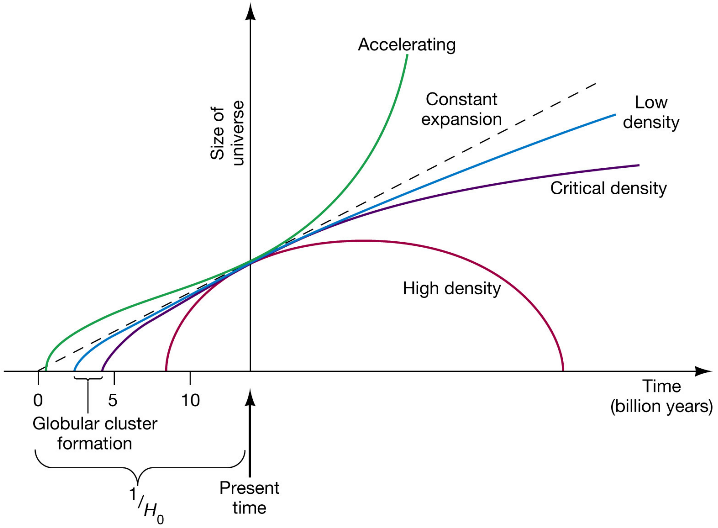
* Bennett et al. 2022 ApJS 208 20

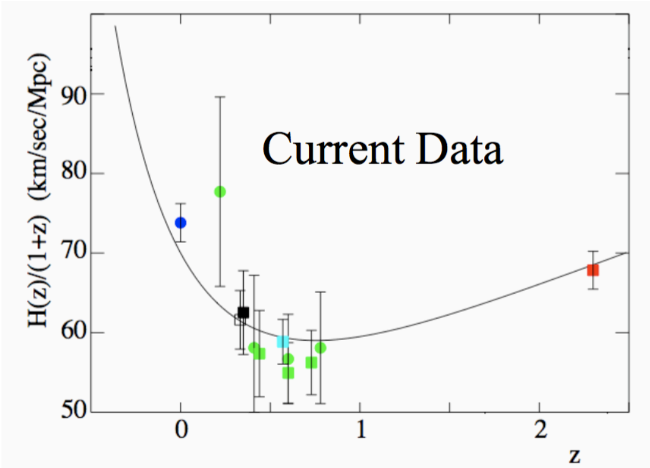
Cosmological Conclusions (delusions?)

- 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 ~9-11.

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~10…
  - But possibly two phases, one early (z>12, and incomplete)
- When did the 1st stars/galaxies form?
  - Gunn-Peterson trough in quasar absorption
  - High redshift objects (JWST)
  - Directly observing 1st stars (NGST, TMT)
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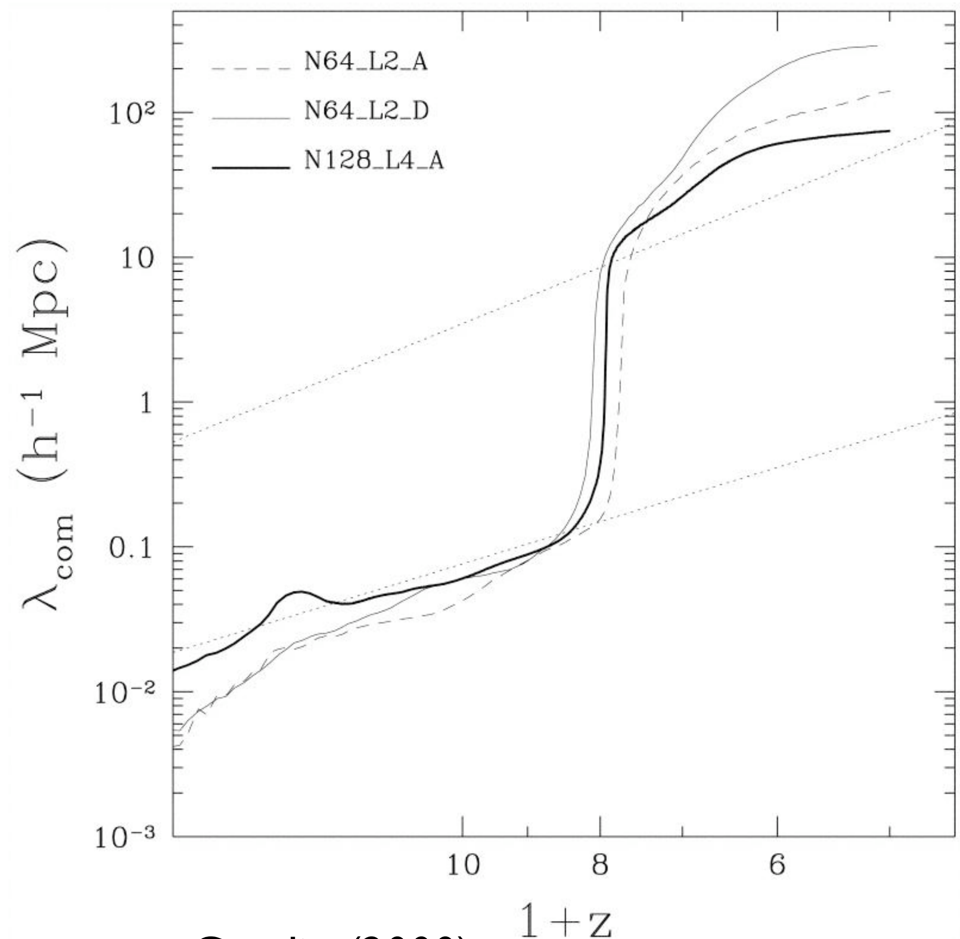
  - Primordial, high redshift black holes (SKA)

Classical Reionization

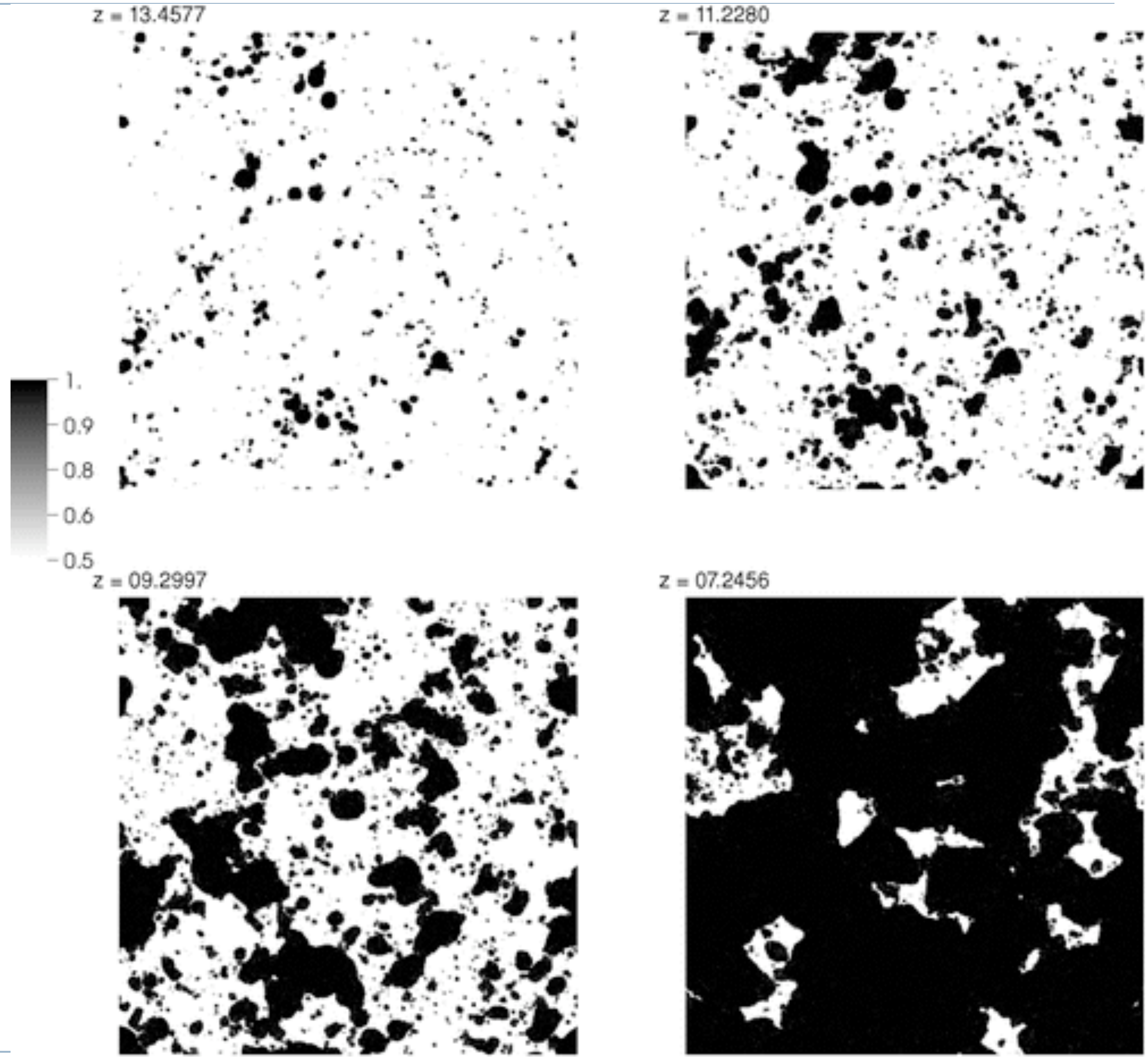
- Individual HII regions overlap ➔ mean free path of ionizing photon increases
- Fast phase transition
- Depends on…
  - Number of sources
  - Ionizing efficiency
  - Clumpiness of IGM



Gnedin (2000)

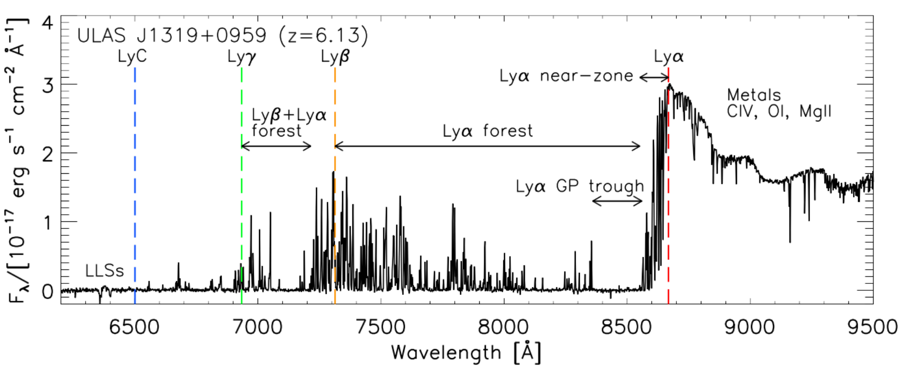
Epoch of Reionization: Simulated

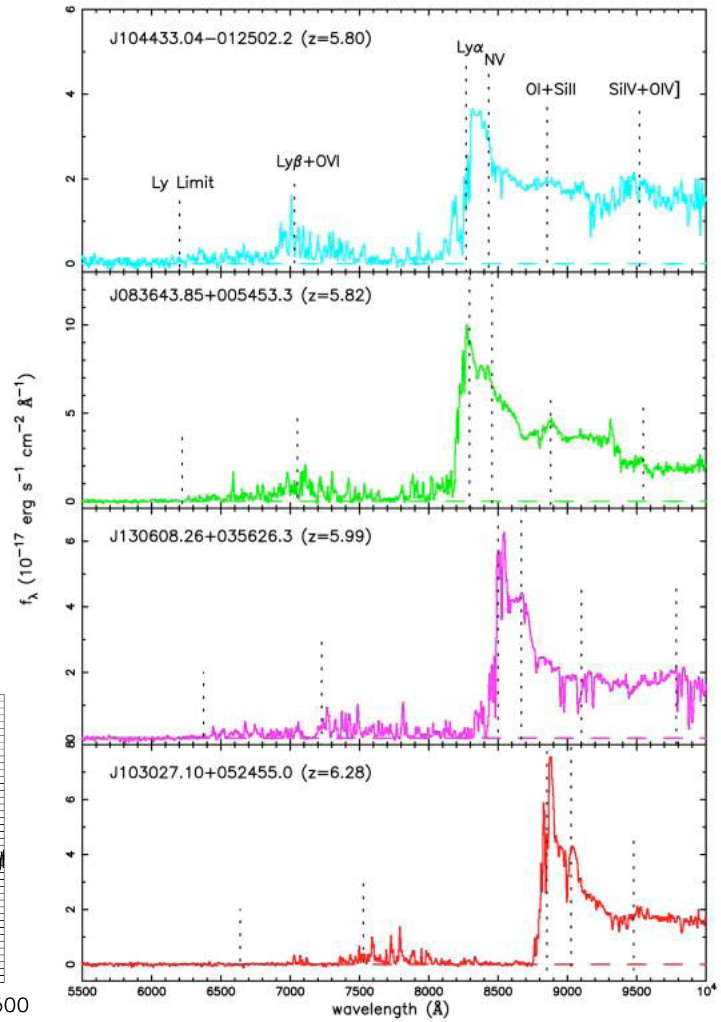
Shin, Trac, Cen (2008)



The High-Redshift IGM

- Neutral between recombination and reionization ➔ hard to study!
- Does the onset of the Gunn-Peterson trough *in high-redshift quasars* imply they lie before the epoch of reionization?
- Consistent with WMAP?



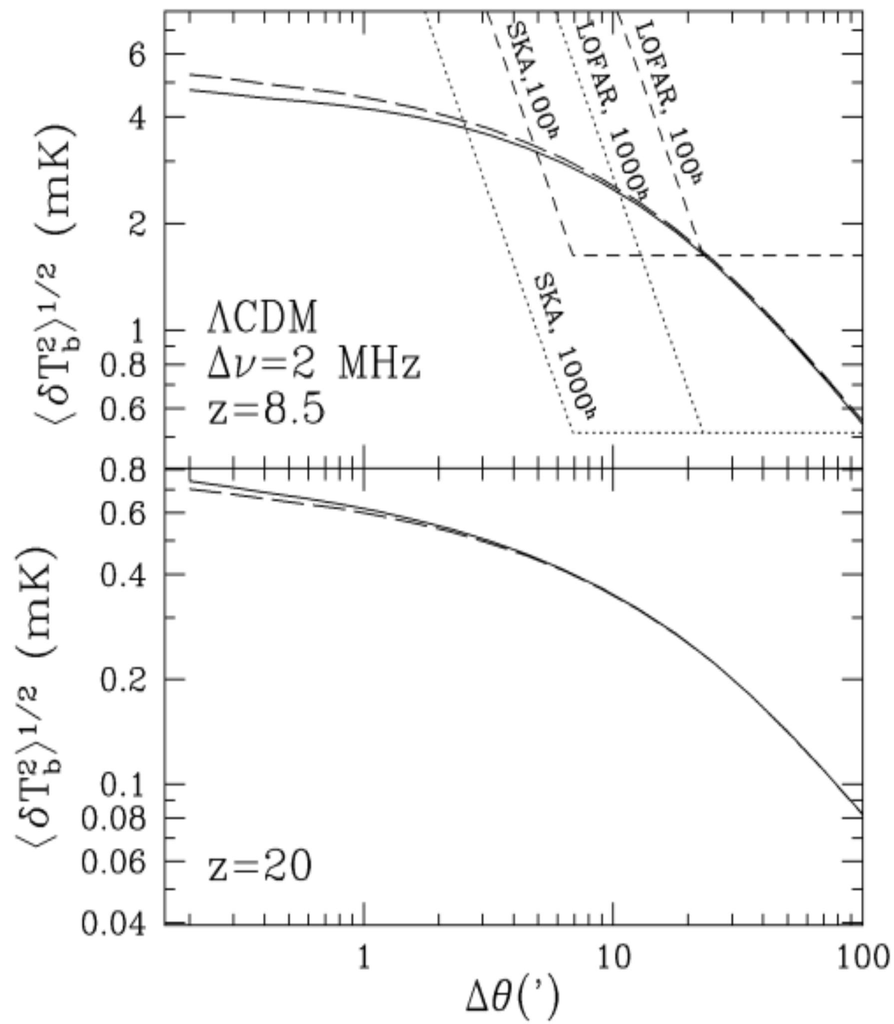


Becker et al 2015

Becker et al 2001

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
- Perhaps a few stronger because of collapsing gas! (Furlanetto & Loeb, in prep)

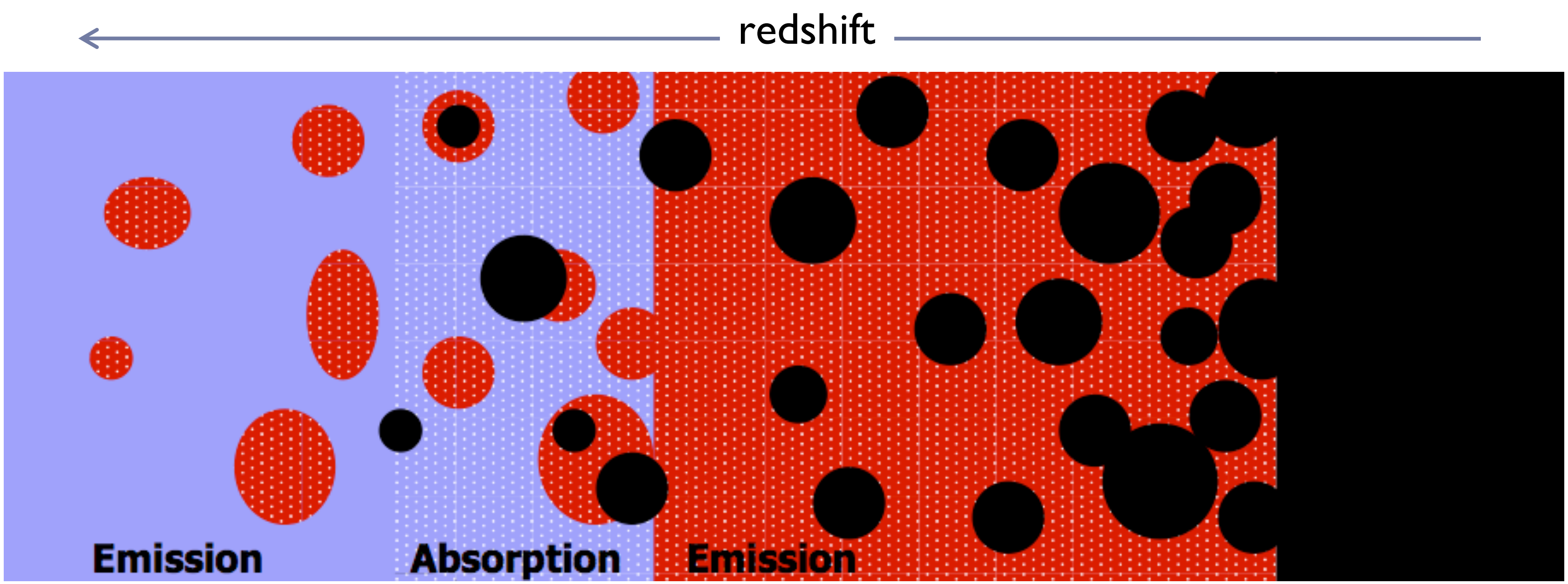


Iliev et al. 2003

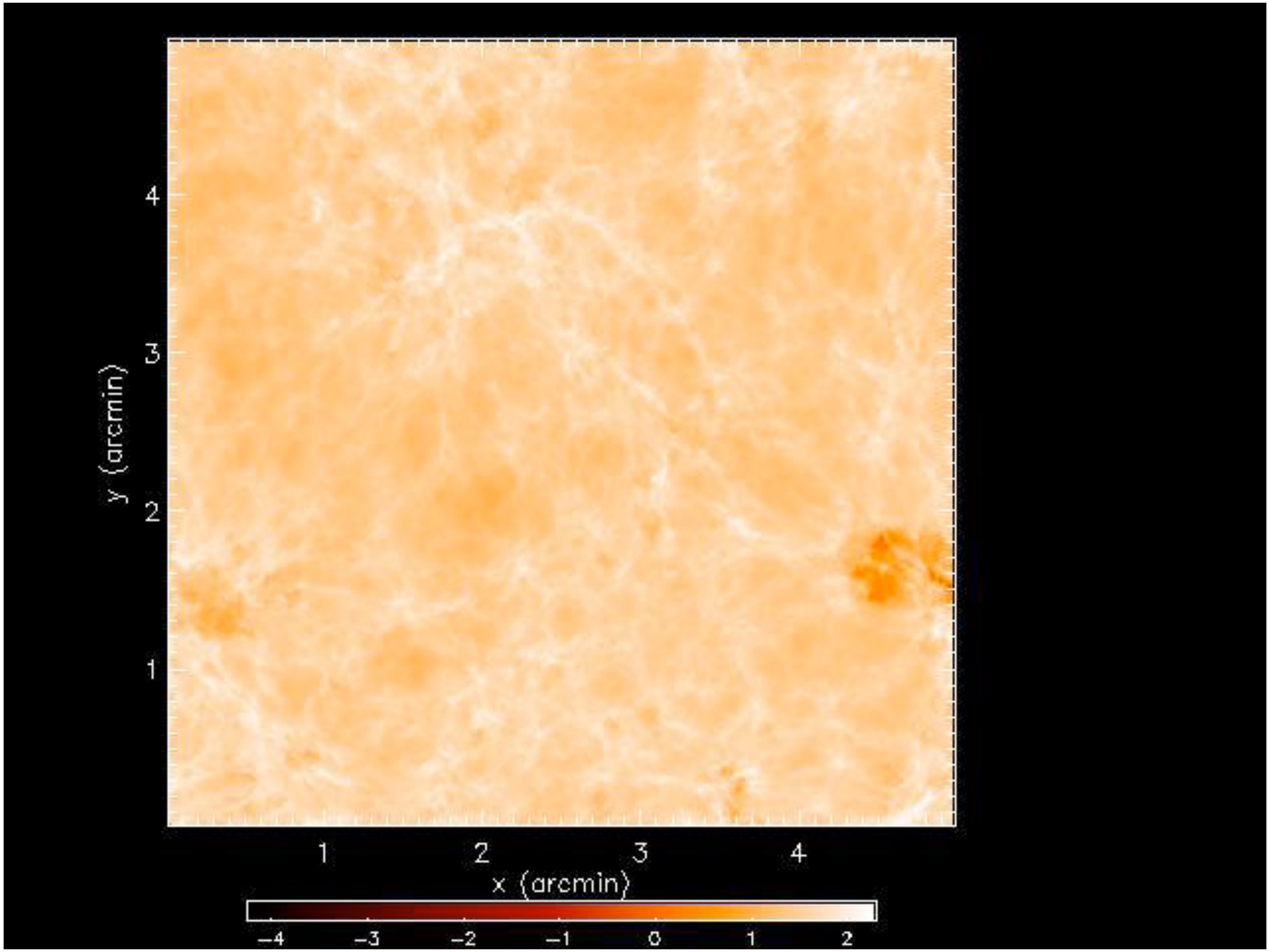
21 cm Toolbox

- 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

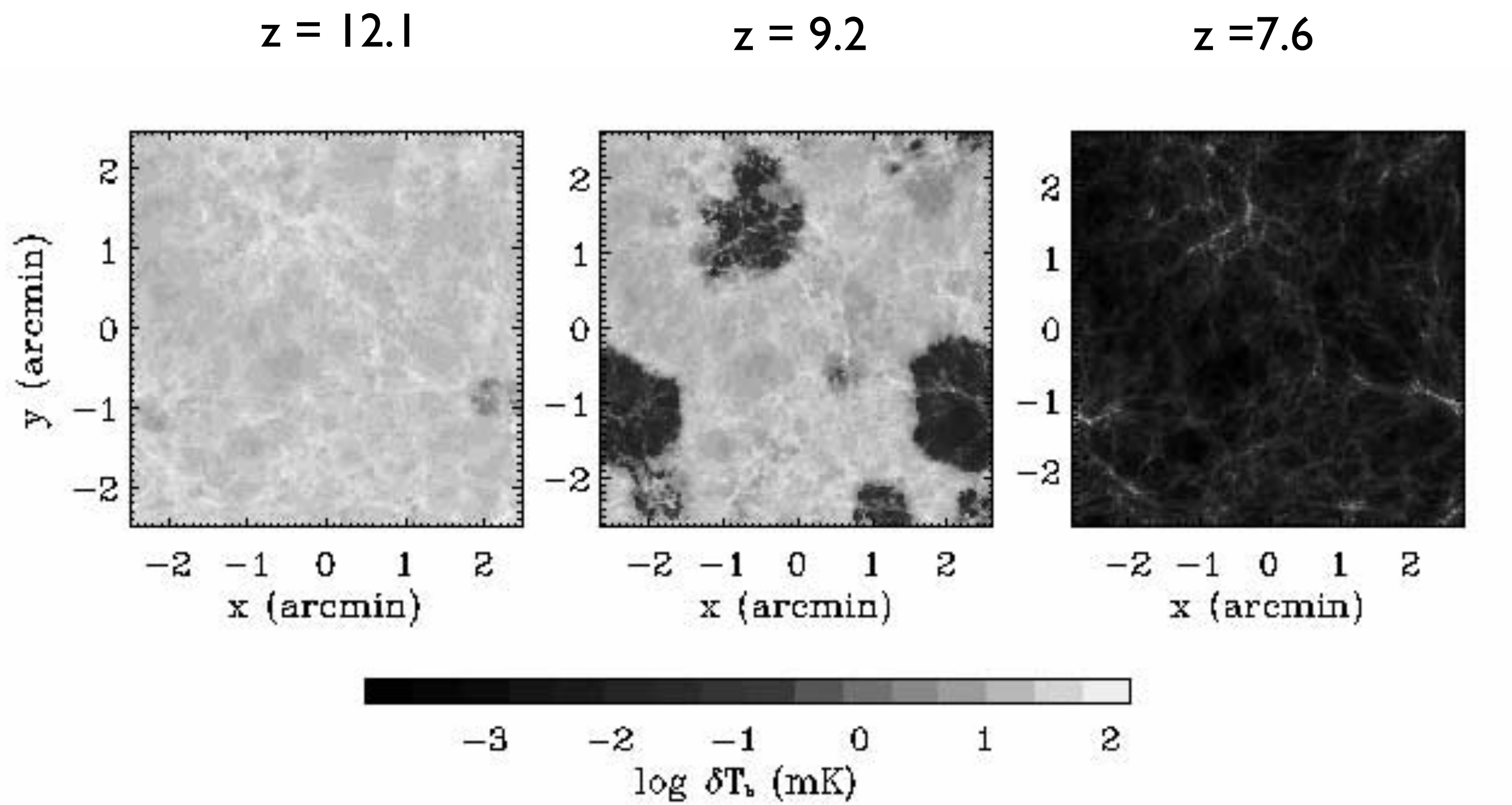


z = 18.3
z = 16.1
z = 14.5
z = 13.2
z = 12.1

10 Mpc comoving
Δν= 0.1 Mhz

Furlanetto et al. 2004

21 cm Observations: Emission



10 Mpc comoving
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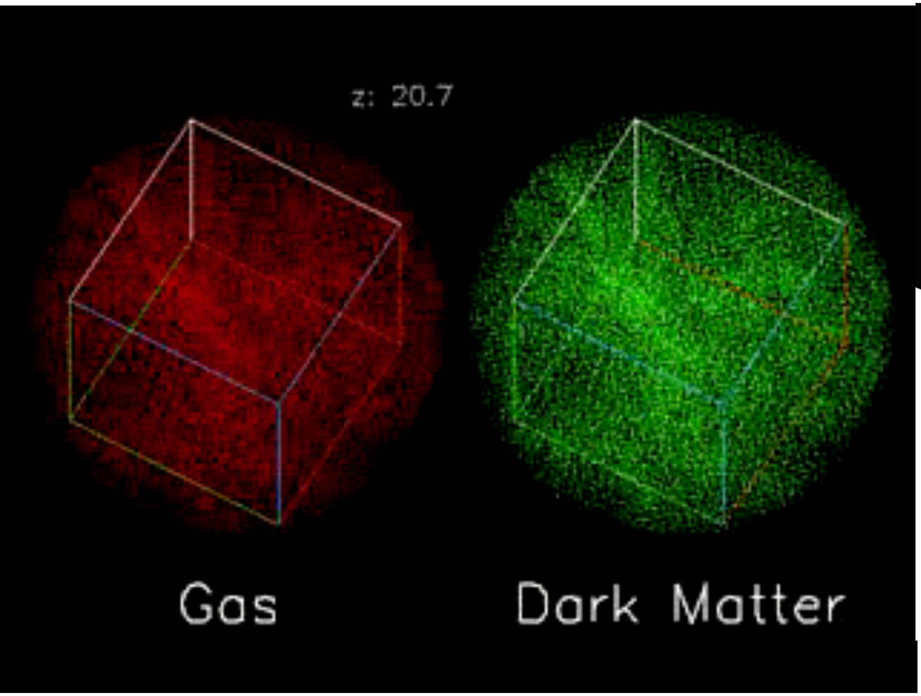
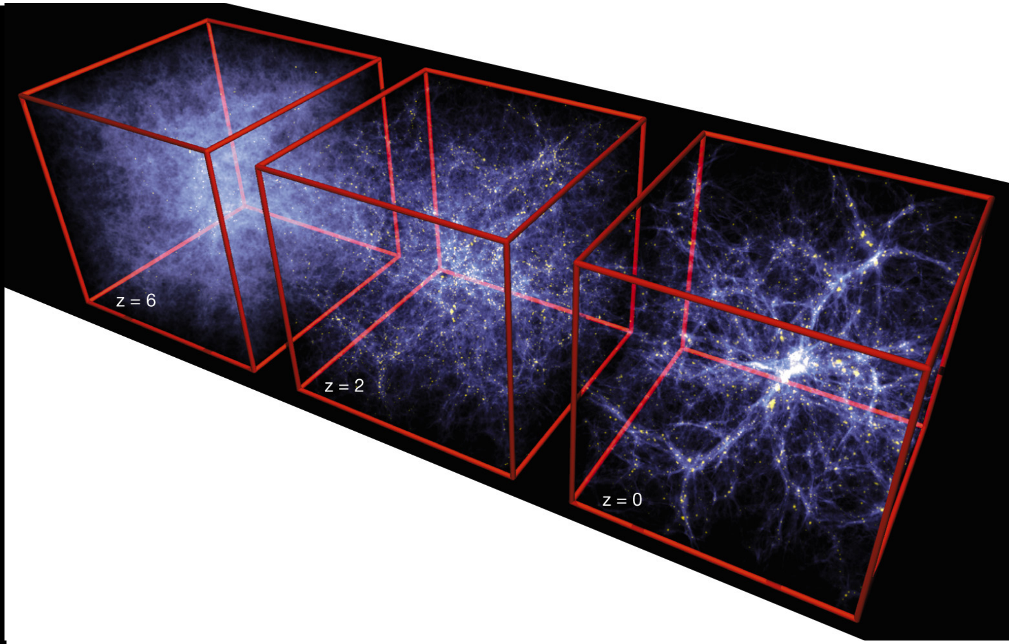
Furlanetto et al. 2004

Large scale structure of the Universe

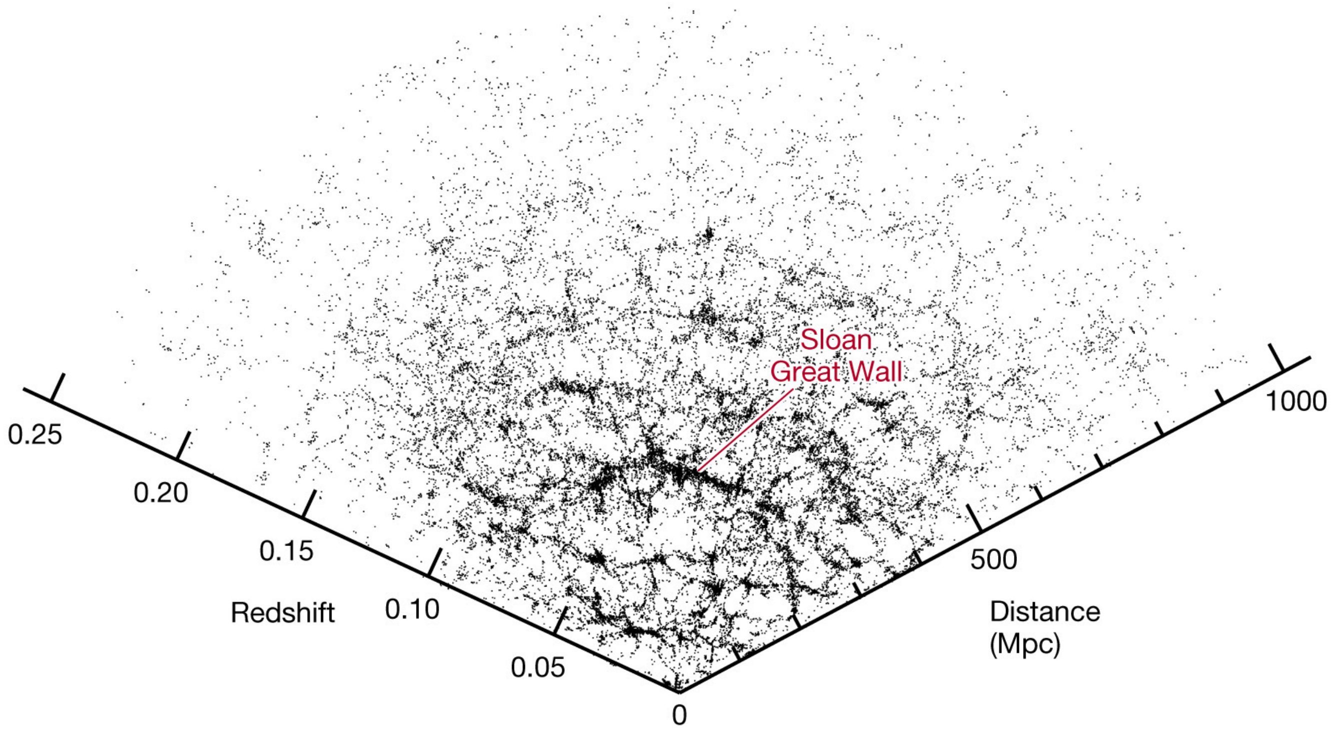
- Fly-through of the Cosmic Web





Large Scale Structure: observed

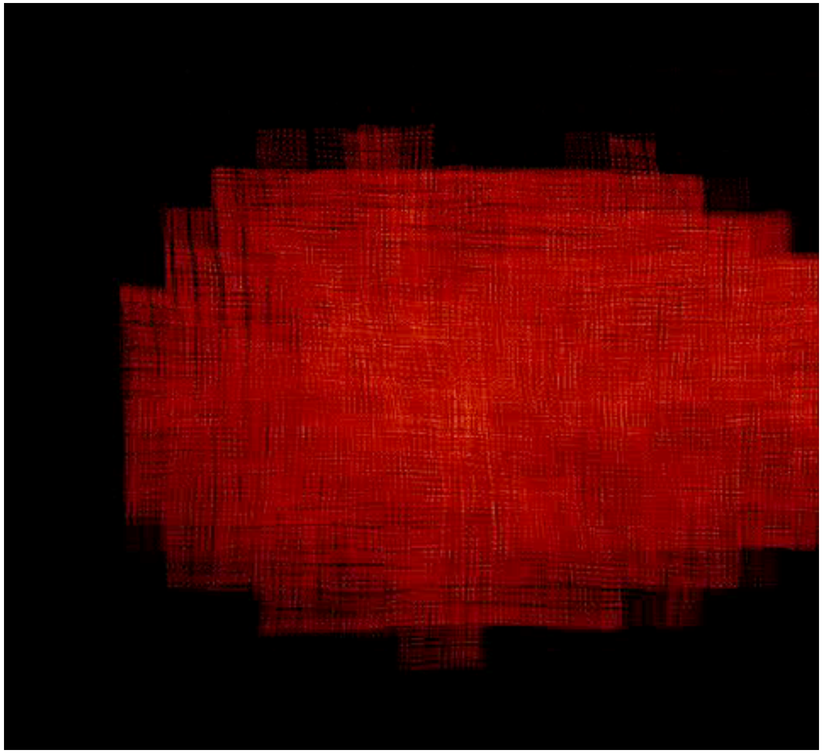
- Filaments and voids
  - Great Attractor
  - Characteristic scales: 40-120 Mpc



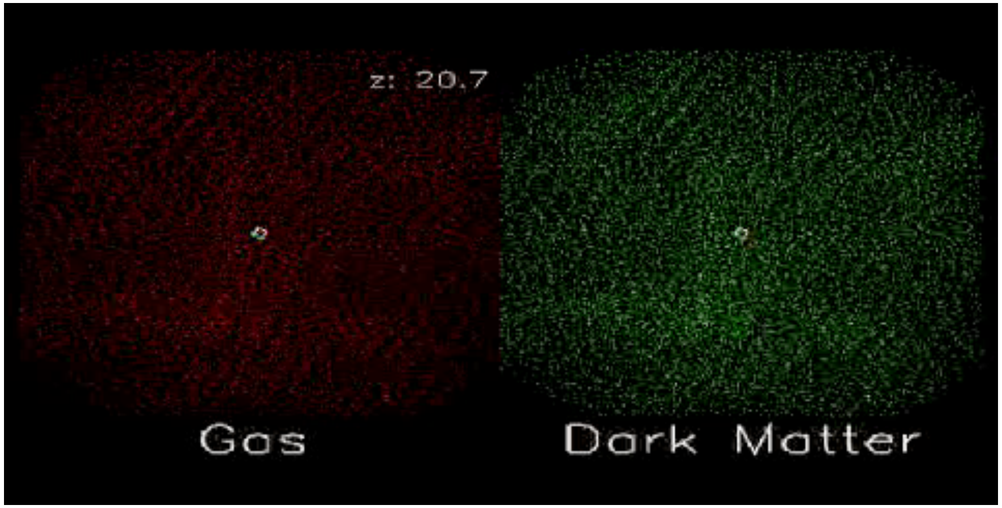
Large scale structure of the Universe

- Structure and Galaxy Formation

elliptical

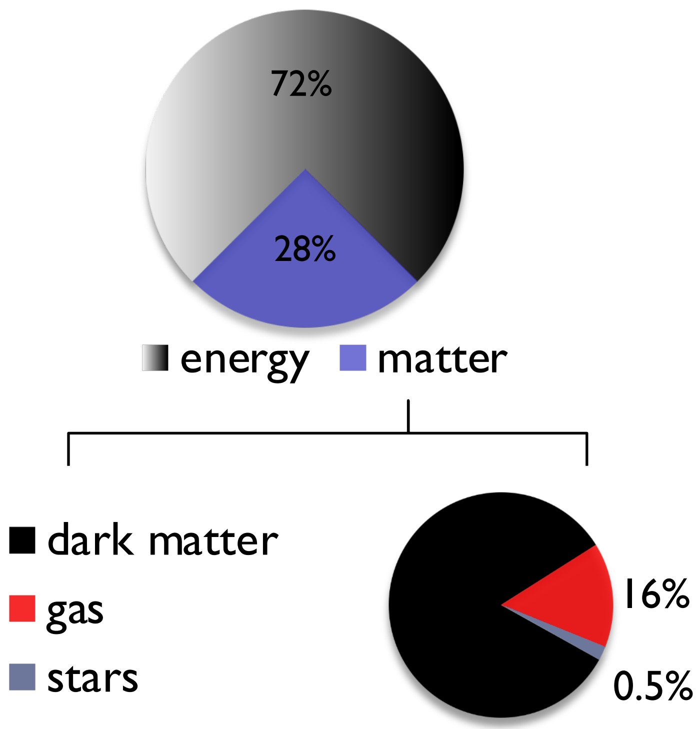


spiral



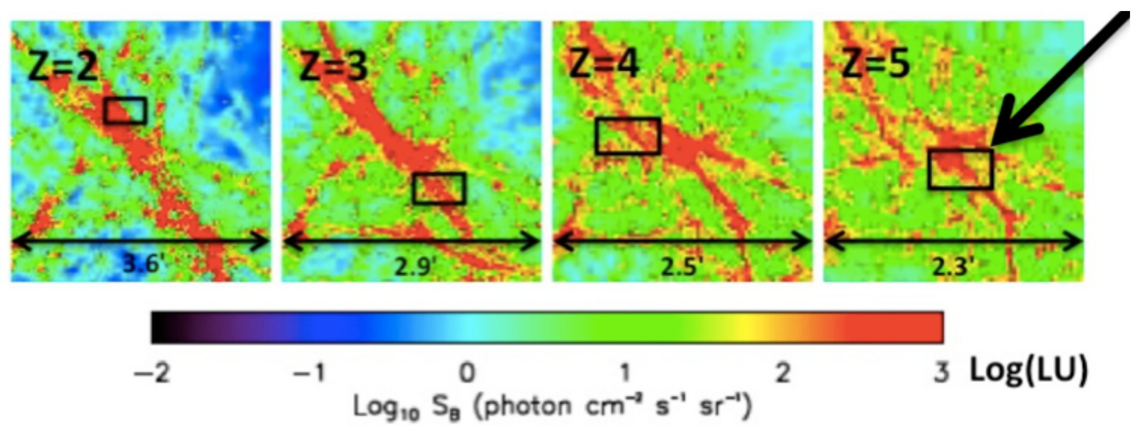
What's missing? The baryons

WMAP (e.g., Bennett et al. '13)



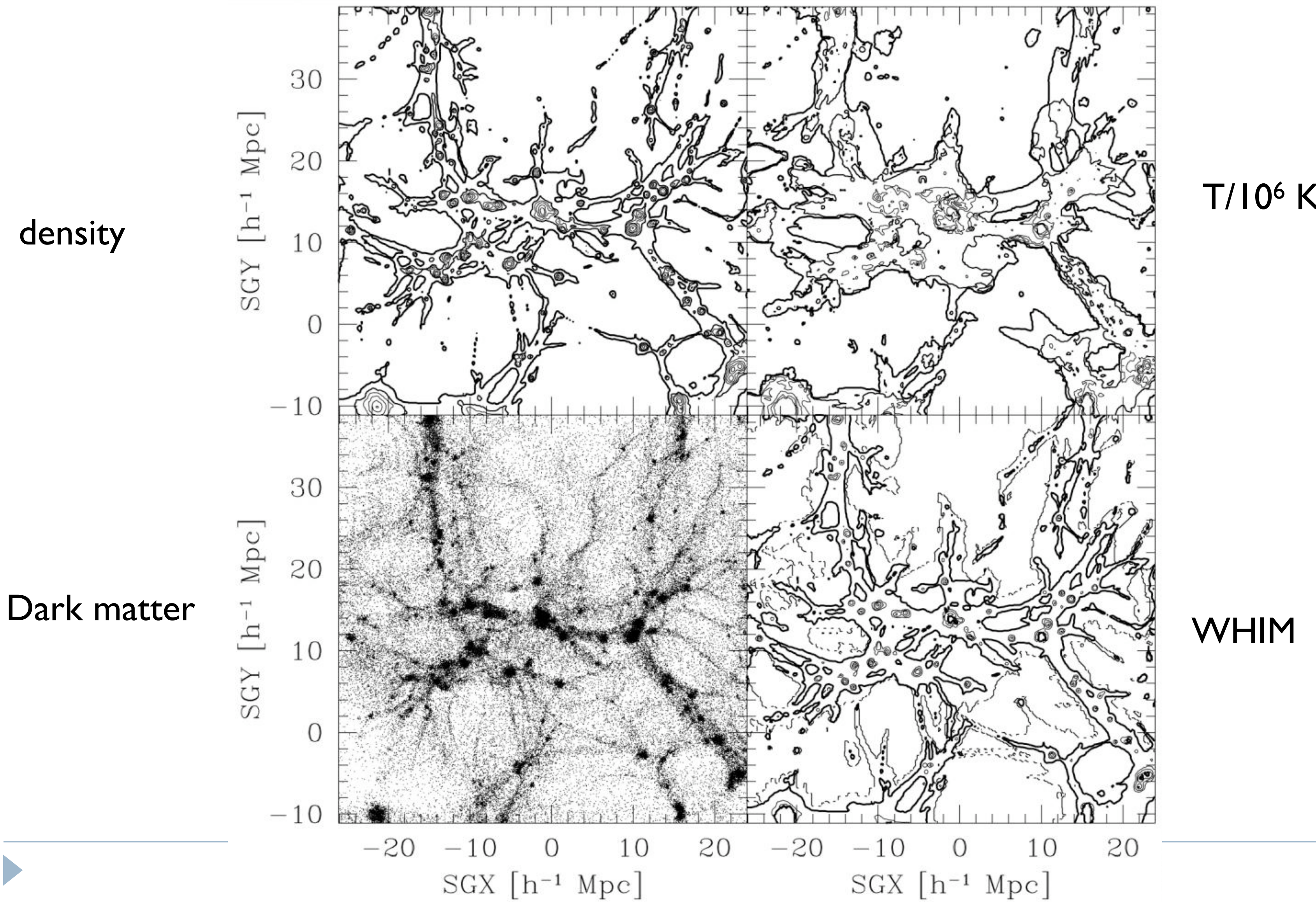
- ~5% of the energy-density
- ~17% of the mass in the universe
- Only ~3% of the baryons are bound in galaxies; the rest is presumably very hot gas in IGM (cosmic web and halos)
  - Stellar Mass Fraction ~ 0.5%

not well known



Lyα and OVI doublet (103.2, 103.8nm; primary coolant for T=3e5K near solar gas, Otte+'03)

The WHIM: Warm-Hot Intergalactic Medium



Physical Properties of the WHIM

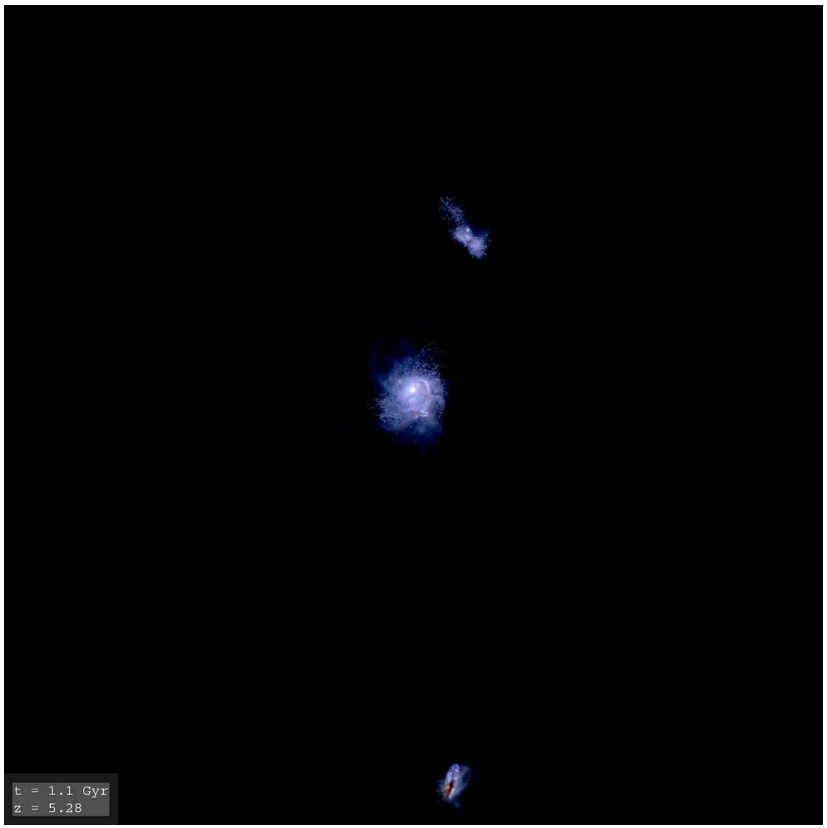
- Detection in: QSO absorption line (HST,FUSE)
  - Limited to individual sightlines – FUSE has < 200 usable sightlines
  - Unknown: ionization fraction, abundance, temperature, filling factor

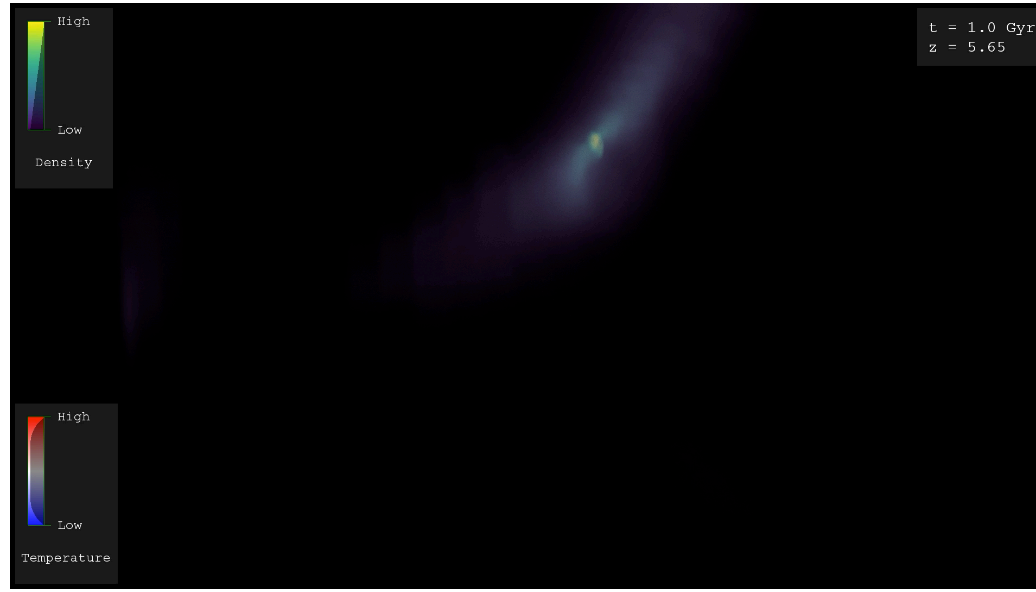
    - Any measure of the physical conditions in the WHIM are dependent on these
    - ***Claimed to contain the bulk of normal matter (baryons) in the universe***

- How was the WHIM produced?
- Is there cold gas too? (how do you detect it?)

Galaxy Formation simulations focusing on multiphase gas and the CGM

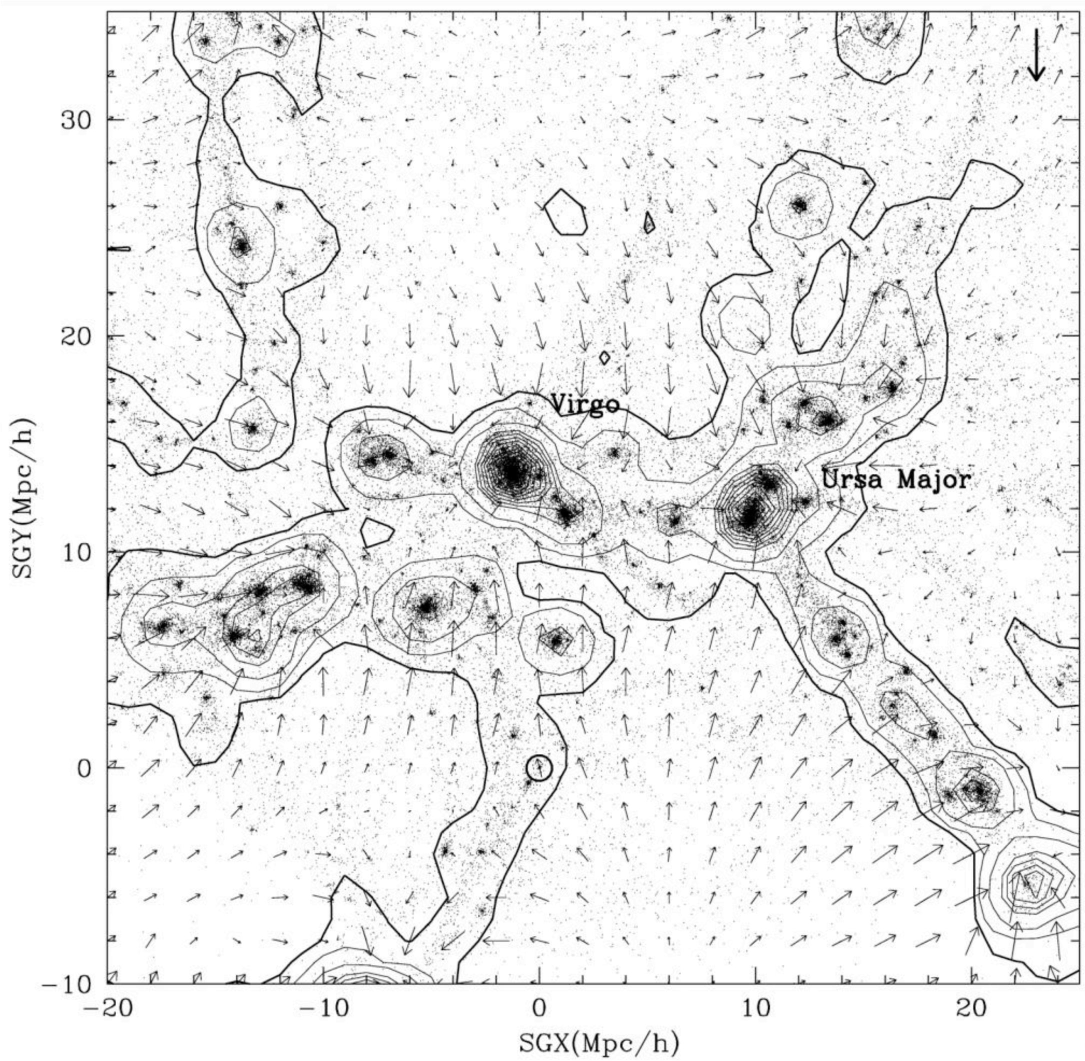
FOGGIE (Peeples et al. 2019)





https://foggie.science/multimedia.html

Cosmic Streaming



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

Klypin et al. 2003

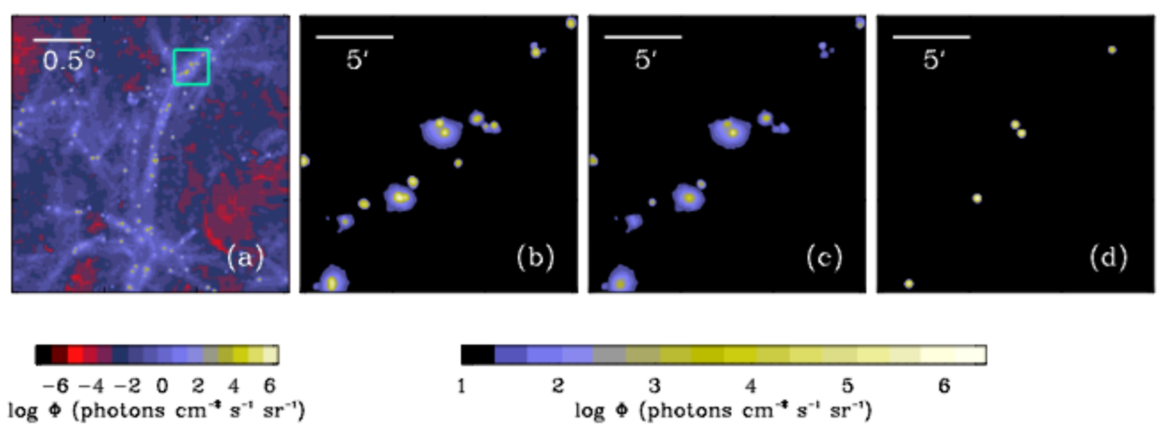
Physical Processes in the Cosmic Web

- 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

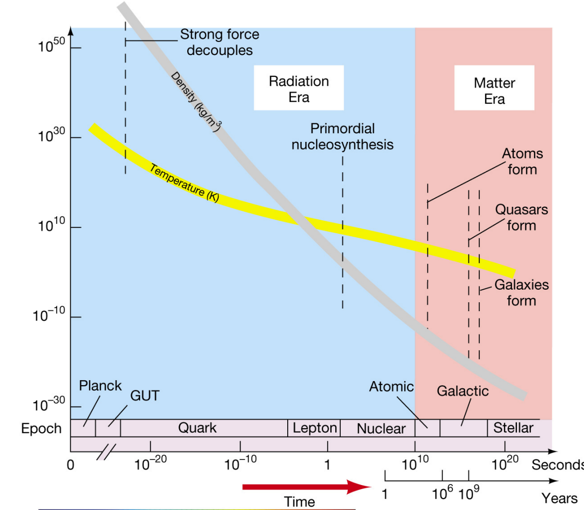


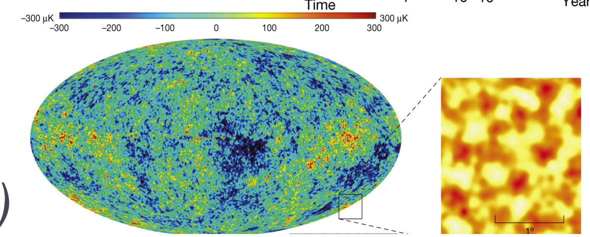
Summary: Big Bang / Creation of Matter

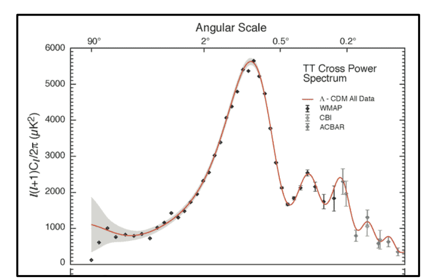
rad^n dom.

- Expansion & evolution: GR and Friedman equations: $R=1/1+z$, $\dot{R},\ddot{R}$
- Early Universe
  - Inflation (10^{-34} sec)
  - Particle genesis (10^{-15} to 1 sec)
  - BBNS (3 minutes) ➔ Cosmic He abundances
  - *Recombination* ($4\text{x}10^5$ yr) ➔ CMBR
- Dark Ages (?)
- *Reionization* and onward
  - When the first stars and AGN formed *(z=12?)*
  - Galaxy formation
  - Evolution of galaxies, their stars and planets

matter dom.



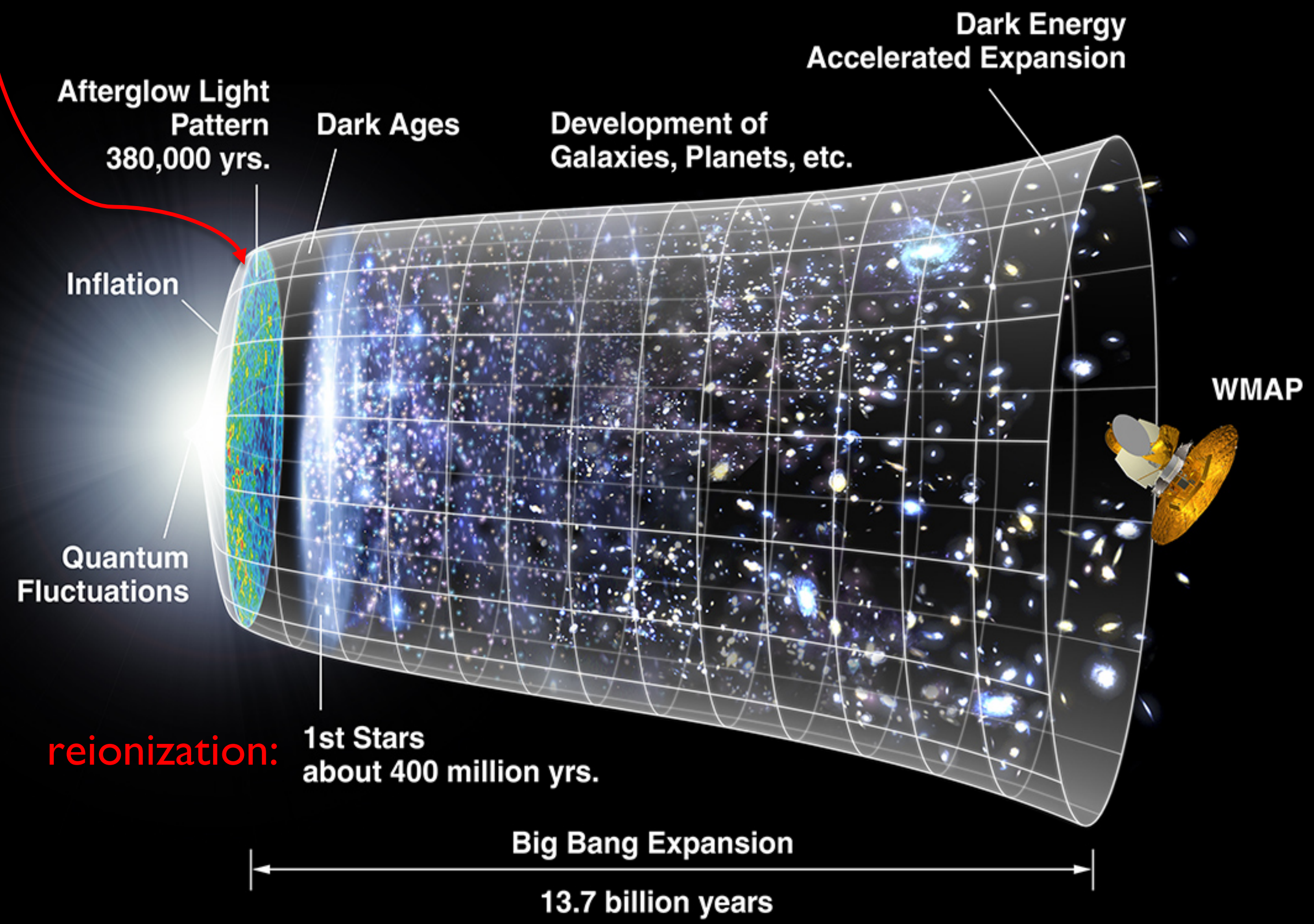




Structure grows via gravity in matter dominated era

precision cosmology & first glimpse of structure

Structure starts growing here



reionization:

NASA/WMAP Science Team

Outstanding Observational Issue: Epoch of Reionization

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  - High redshift objects (JWST, SKA)
  - Primordial, high redshift black holes (SKA)
- Where are the baryons?