

OBSERVATIONAL COSMOLOGY

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OUTLINE

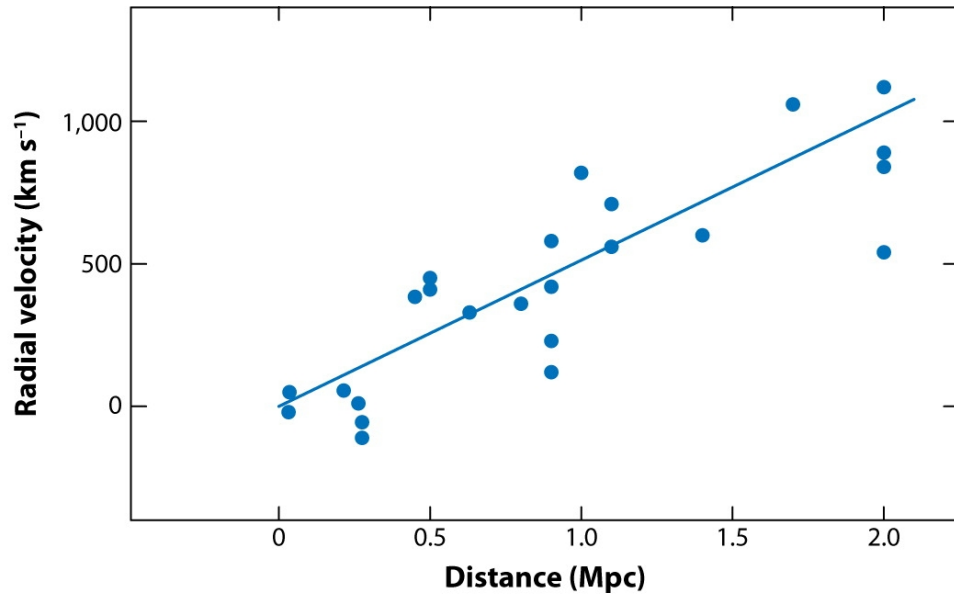
- Observational cosmology: The big questions.
- The expanding Universe.
- Big Bang Cosmology.
- A (very) brief history of the Universe.
- Big Bang Nucleosynthesis
- The Cosmic Microwave Background.
- How do galaxies form ?
- Dark matter and dark energy.
- The Λ CDM cosmological model.

THE BIG QUESTIONS

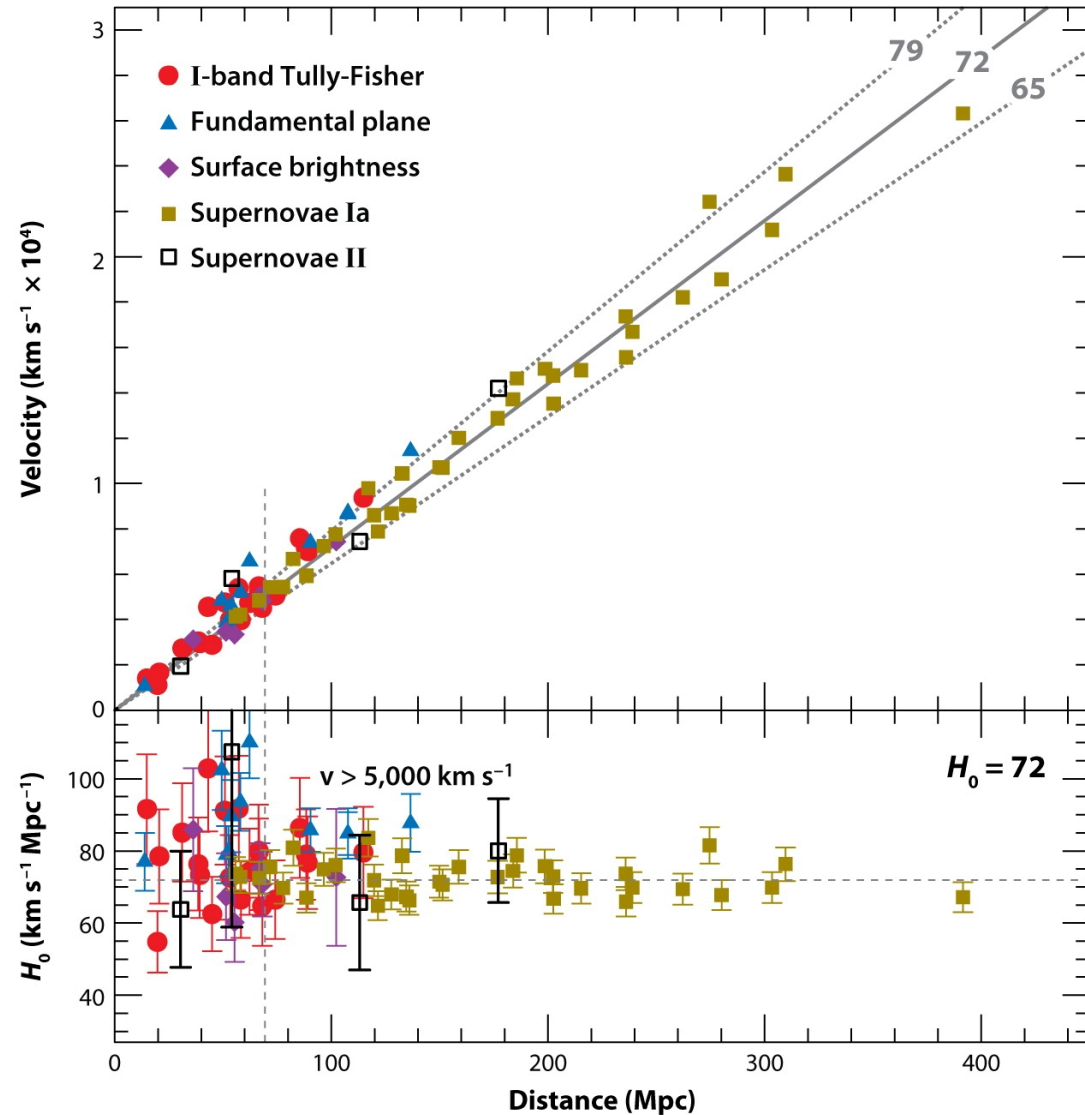
- Theoretical model for the Universe's evolution.
- The constituents of the Universe.
- Structure formation: How do galaxies form and evolve ?

THE EXPANDING UNIVERSE

(Hubble 1929)



(Freedman & Madore 2010)



- The Universe is expanding!

- Hubble's law: $V = H_0 D$
 $H_0 \approx 70 \text{ km/s/Mpc}$.

- *Not* due to physical motion of galaxies: *Stretching* of space!

- Wavelengths are *redshifted*: $\lambda_{obs} = \lambda (1+z)$

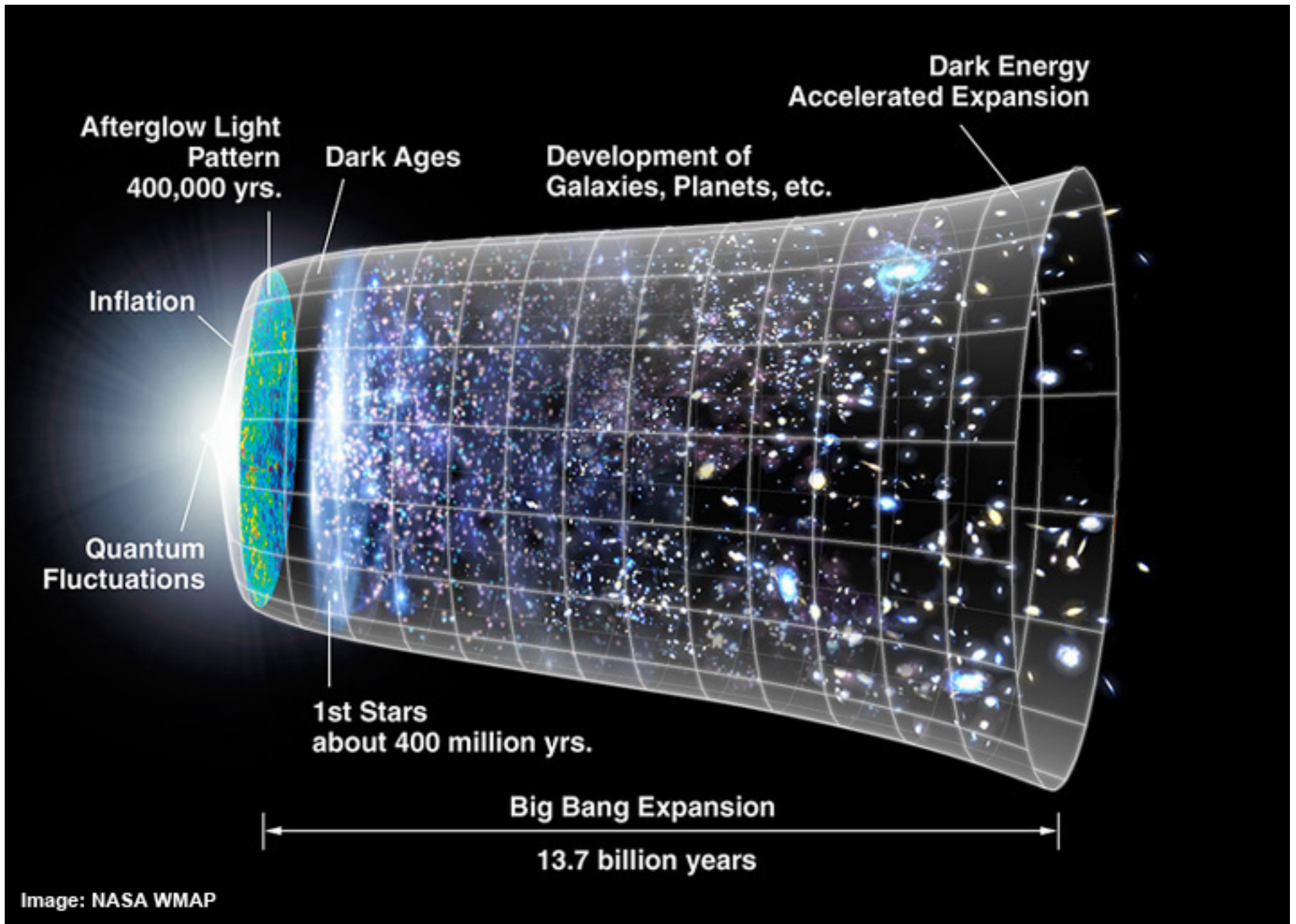
BIG BANG COSMOLOGY

- Theoretical model: General Relativity.
- For an isotropic & homogenous Universe, two Friedmann equations for the “scale factor” $a(t)$:
$$\begin{aligned}(\ddot{a}/a) &= -(4\pi G/3) (\rho + 3p) \\(\dot{a}/a)^2 &= (8\pi G/3)\rho - k/a^2\end{aligned}$$
- p and ρ are the pressure and the energy density, with $p = w\rho$. For non-relativistic matter, $w = 0$. For radiation, $w = 1/3$.
- For ($w > -1/3$), $3p < \rho \Rightarrow (\ddot{a}/a)$ negative! Deceleration due to work done against the gravitational force!
- Cosmological constant, $p = -\rho \Rightarrow (\ddot{a}/a)$ positive !!! *Acceleration!*
- Curvature of the Universe, $k = 0$ (flat), $+1$ (closed), -1 (open). For a flat Universe, $\rho = \rho_c \equiv (3/8\pi G)(\dot{a}/a)^2$: the “critical density”.
- Include different constituents on the right side and solve for $a(t)$!

COSMOLOGICAL EPOCHS

- Distant galaxies are at high redshifts! High z = Early times.
- Expansion causes cooling \Rightarrow Higher temperatures at early times.
- $\rho_{\text{matter}} \propto a^{-3}$, $\rho_{\text{rad}} \propto a^{-4}$ \Rightarrow Radiation dominates at very early times.
 $\rho_{\Lambda} \propto \text{constant}$ \Rightarrow Cosmological constant dominates at late times.
- Important epochs in the history of the Universe:
 - (1) Very early Universe (particle physics epoch): $< \sim 1$ second.
 - (2) Big Bang Nucleosynthesis: ~ 1 second – *few* minutes.
 - (3) Epoch of Recombination, Decoupling: ~ 380000 yrs ($z \sim 1100$).
 - (4) Dark ages (no stars, mainly neutral hydrogen): $z \sim 1100 - 30$.
 - (5) Galaxy formation and evolution: $z \sim 30 - \text{today}$.
 - (6) First stars switch on: $z \sim 30$.
 - (7) The Epoch of Reionization: $z \sim 20 - 6.5$.
 - (8) Dark energy domination, accelerated Universe: $z < \sim 0.5$.

A BRIEF HISTORY OF (NEARLY) EVERYTHING



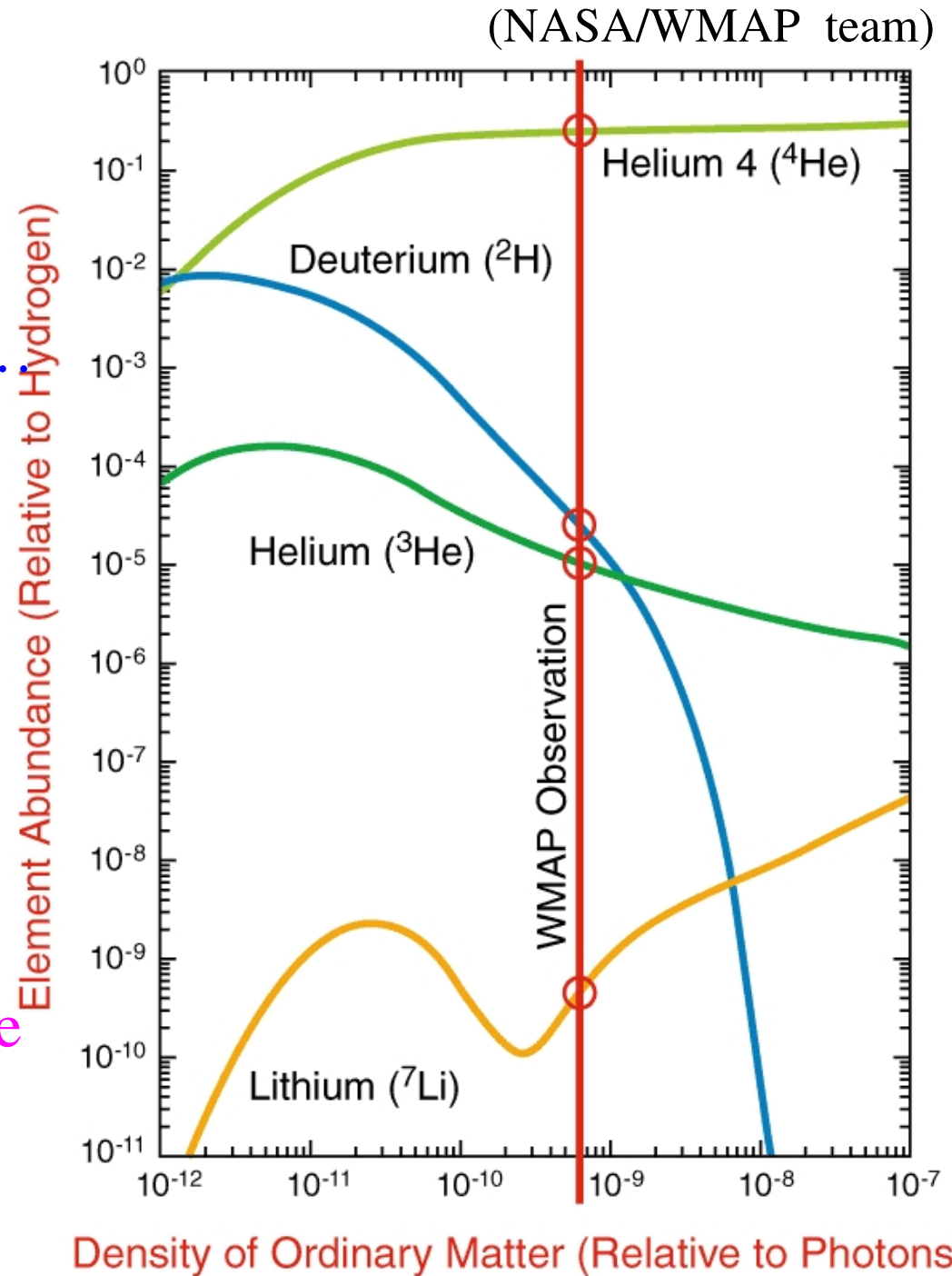
(Courtesy: NASA)

OBSERVATIONAL PROBES

- Big Bang Nucleosynthesis: Abundances of D, ^4He , ^3He , Li.
- The Cosmic Microwave Background: Epoch of “Recombination”.
- Galaxy formation and evolution.
- Galaxy rotation curves: Dark Matter.
- Type Ia supernovae: Dark Energy!
- The Epoch of Reionization.
- ...

BIG BANG NUCLEOSYNTHESIS

- D, ^4He , ^3He , Li *predicted* to be formed in the first few minutes.
(Alpher, Bethe & Gamow 1948)
- The abundances $[\text{D}/\text{H}]$, $[\text{}^4\text{He}/\text{H}]$, ... depend on the expansion rate of the Universe and the baryon density.
- Can measure $[\text{D}/\text{H}]$, $[\text{}^4\text{He}/\text{H}]$, ... via optical or UV spectroscopy of interstellar gas at $z \geq 0$.
- Spectacular agreement between the baryon density inferred from the light element abundances and the independent CMB estimates!



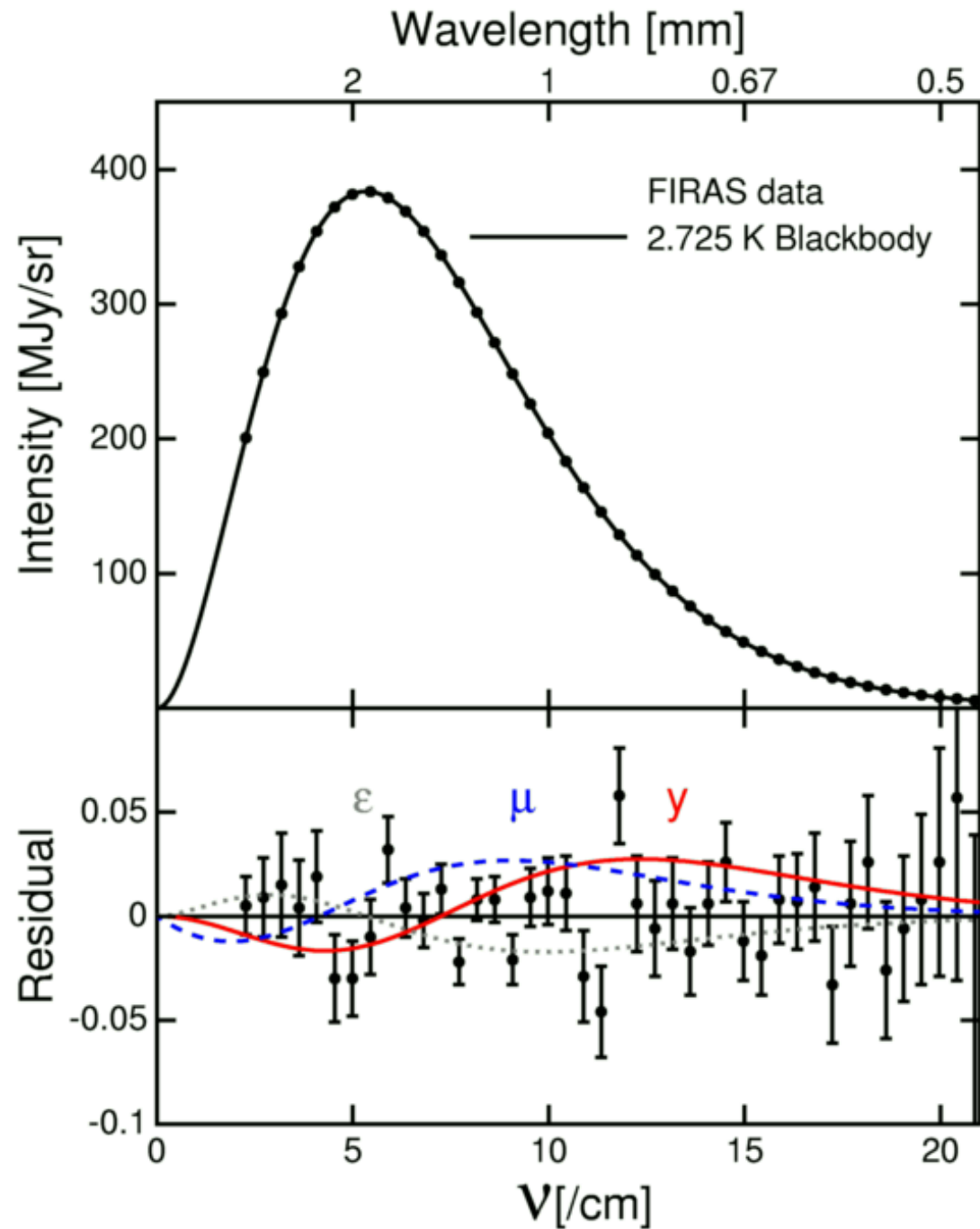
COSMIC MICROWAVE BACKGROUND

- Universe ionized at $z > 1100$
⇒ Radiation “trapped” by scattering off electrons.
- After recombination, few electrons: radiation free-streams away. Predicted to be visible in all directions, with $T \sim 5$ K!
(Alpher & Hermann 1948; Gamow 1948)

- Detected by Penzias & Wilson in 1964, with $T \sim 2.7$ K: Strong evidence for a homogenous, isotropic Universe!
(Penzias & Wilson 1965)

- $T_{\text{CMB}} = 2.725 \pm 0.004$ K
(Mather et al. 1994)

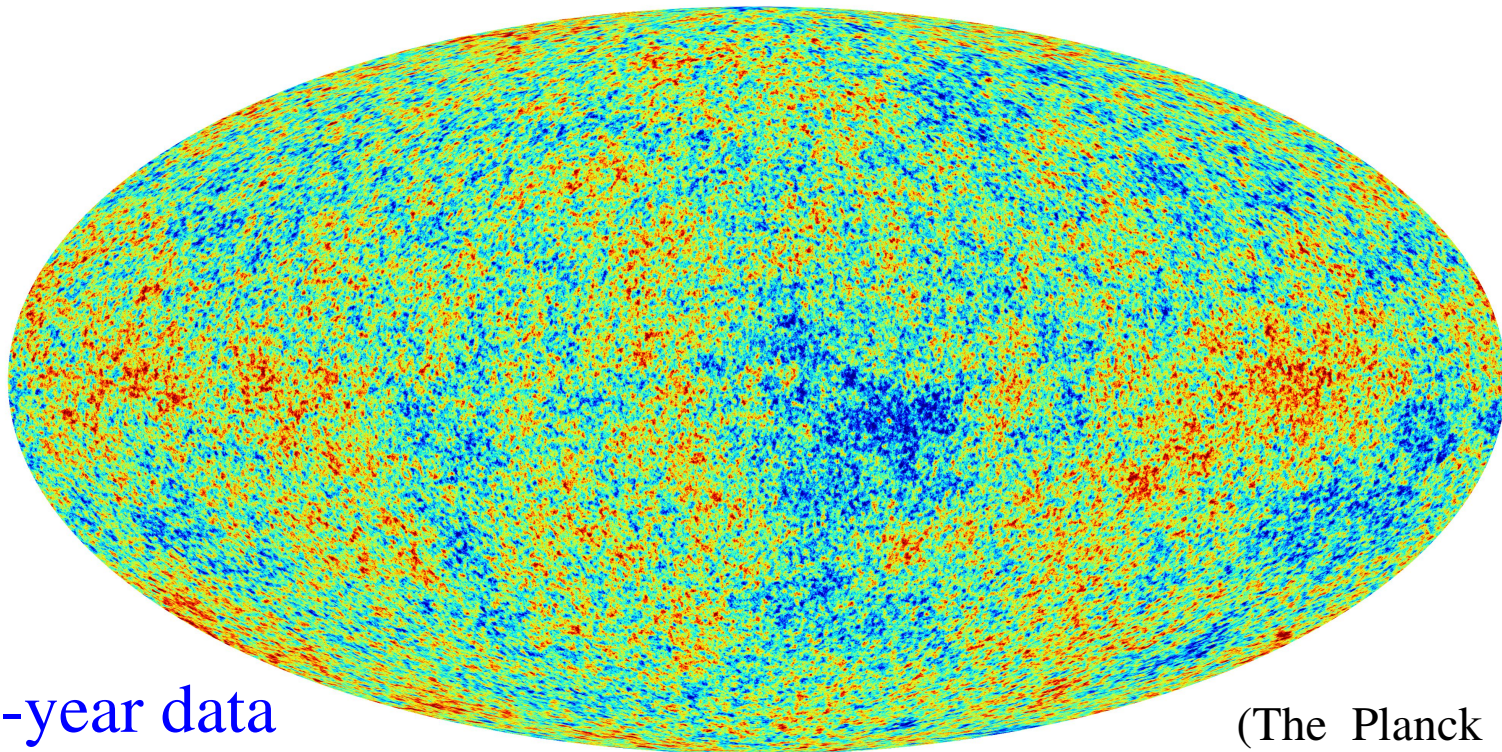
- Best known black body in the Universe!



(Mather et al. 1994)

CMB ANISOTROPIES

- Anisotropies in the CMB trace density inhomogeneities at the epoch of recombination ! First detected by the COBE satellite in 1992!
(Smoot et al. 1992)
- Today: Detailed modelling of CMB anisotropies gives the best constraints on the cosmological model (e.g. WMAP, Planck...).
- $-200 \mu\text{K} - +200 \mu\text{K}$: Extremely low anisotropies, 1 part in 10,000!



Planck 2-year data

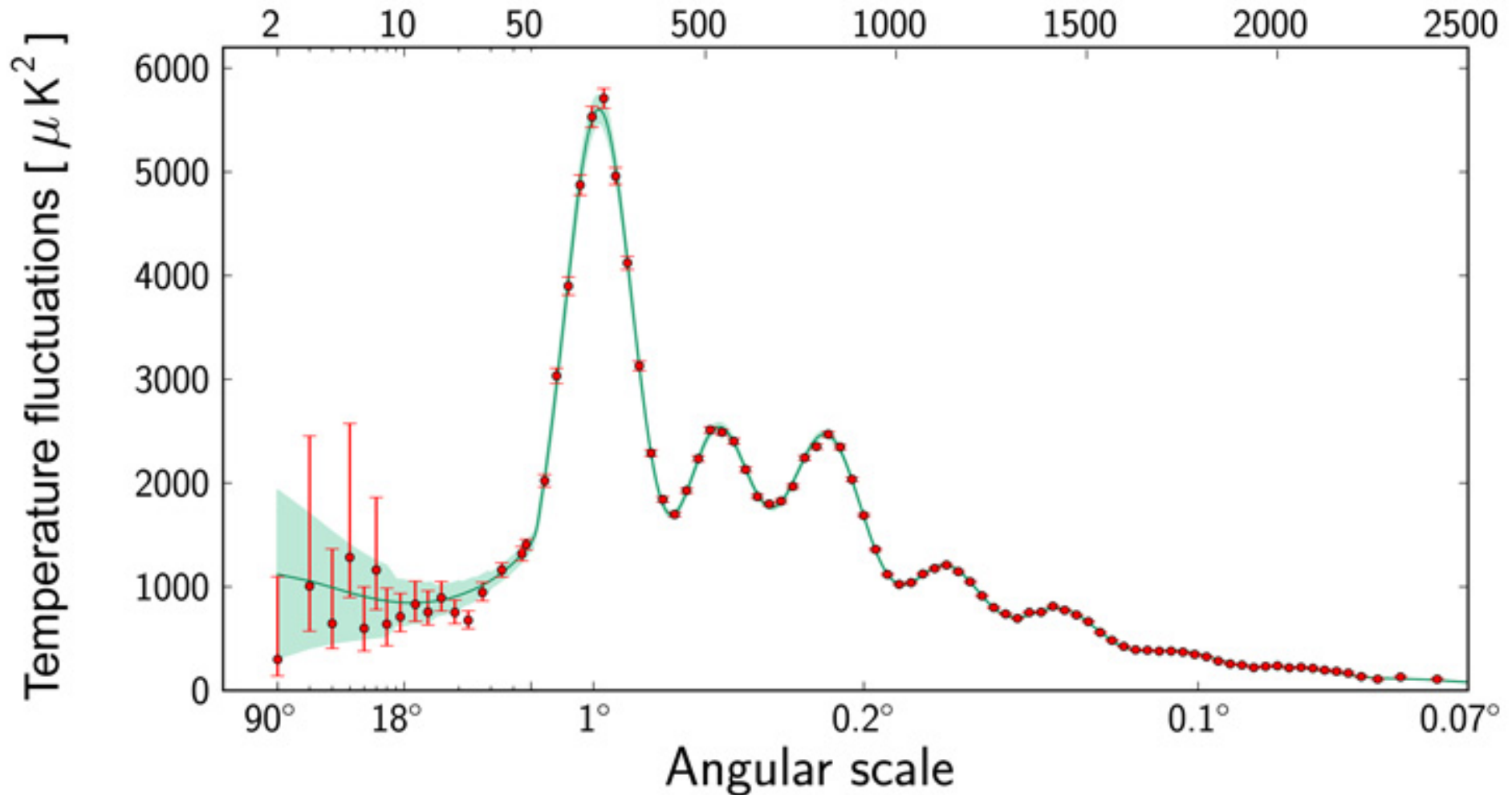
(The Planck collaboration)



CMB ANISOTROPIES

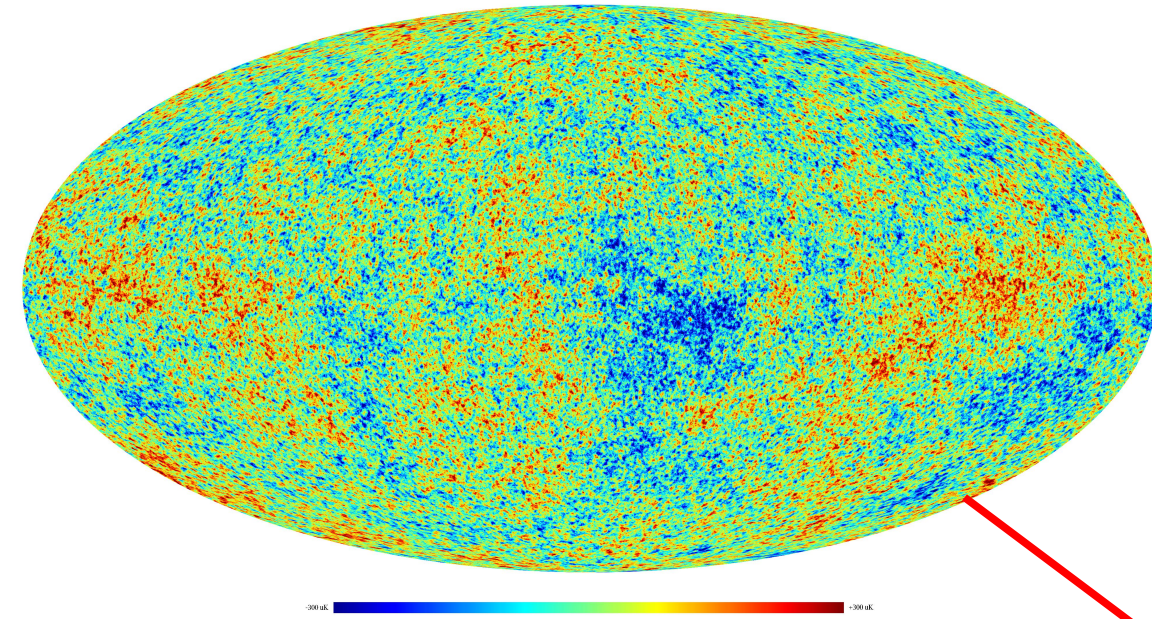
Multipole moment, ℓ

(The Planck collaboration)



- “Acoustic” peaks, due to oscillations in the photon-baryon fluid!
- The “standard” flat Λ CDM cosmology gives an excellent fit!

GALAXY FORMATION AND EVOLUTION



(The Planck Collaboration)

$z_{\text{CMB}} \sim 1100.$

Tiny differences in density:

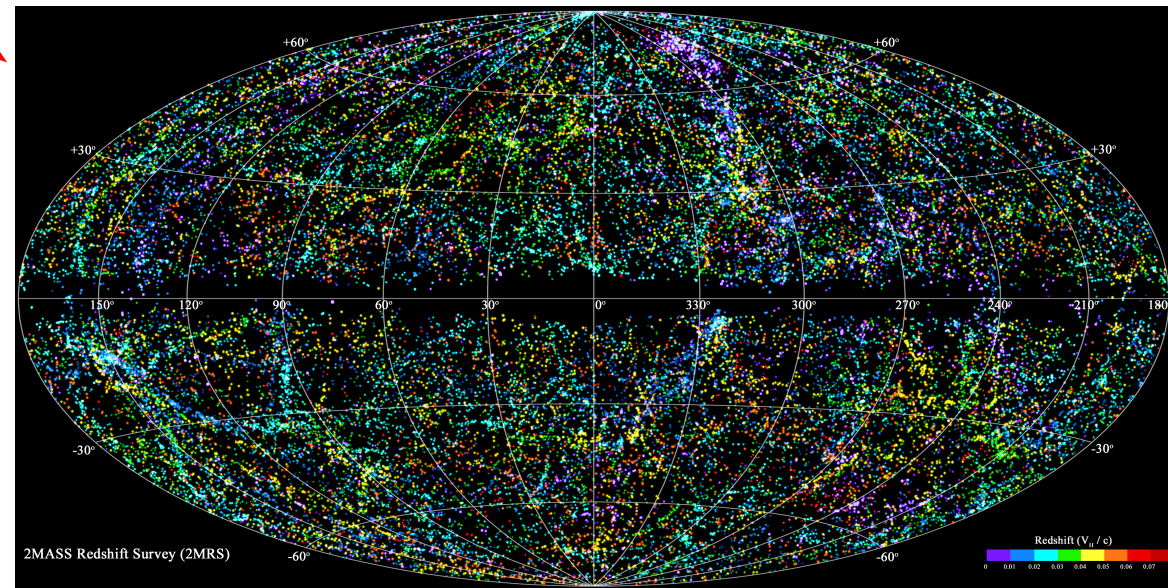
$$\delta = (\rho - \rho_0)/\rho_0 \sim 10^{-4}$$

(Jarrett 2004, PASA)

Large-scale structure at $z \sim 0.$

Huge differences in density:

$$\delta = (\rho - \rho_0)/\rho_0 \sim 10^2 - 10^3$$

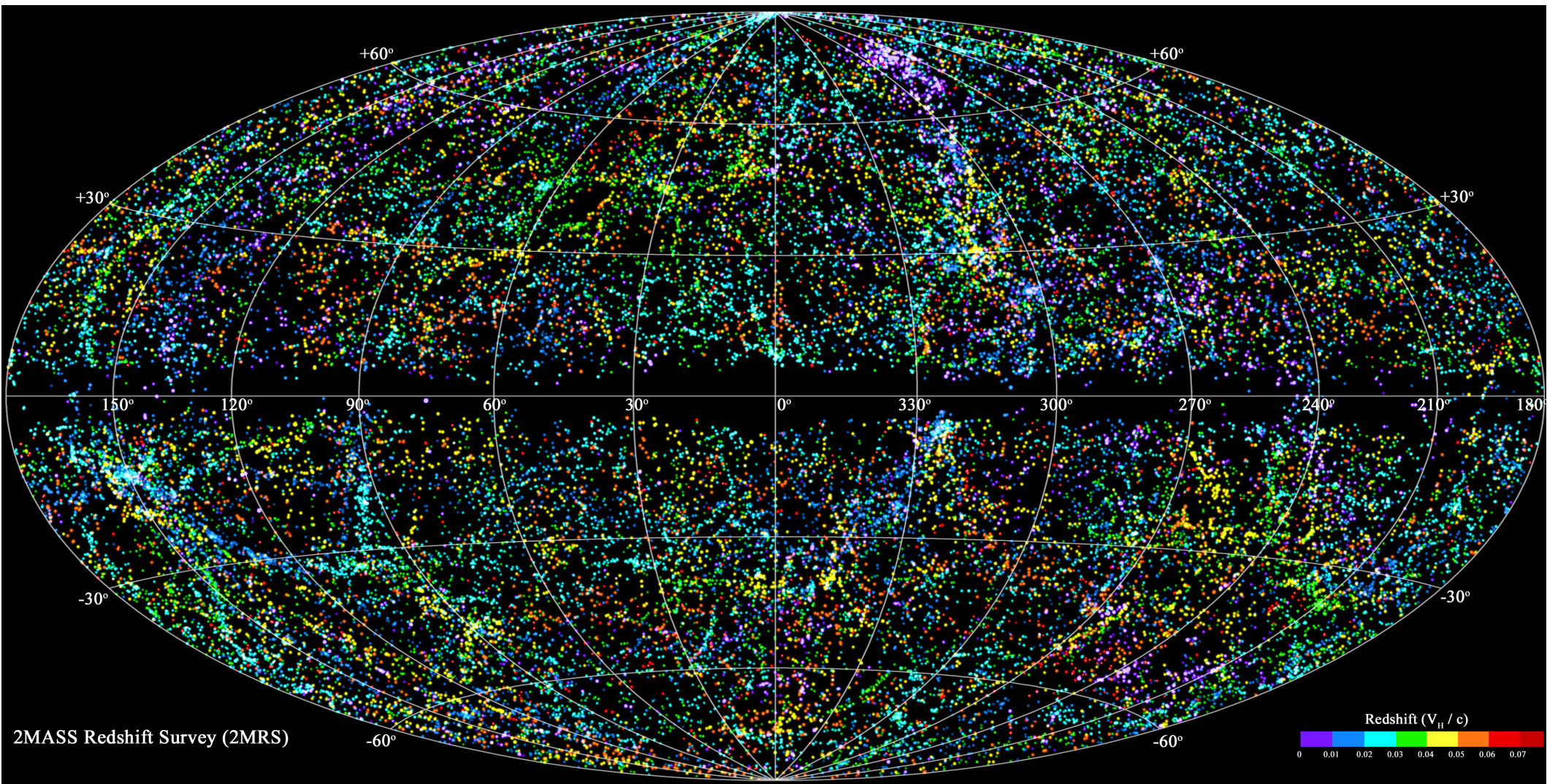


2MASS Redshift Survey (2MRS)

Redshift (V_r / c)

LARGE-SCALE STRUCTURE IN THE UNIVERSE

Nearby ($z < 0.08$) galaxies from the 2-Micron All-Sky Survey



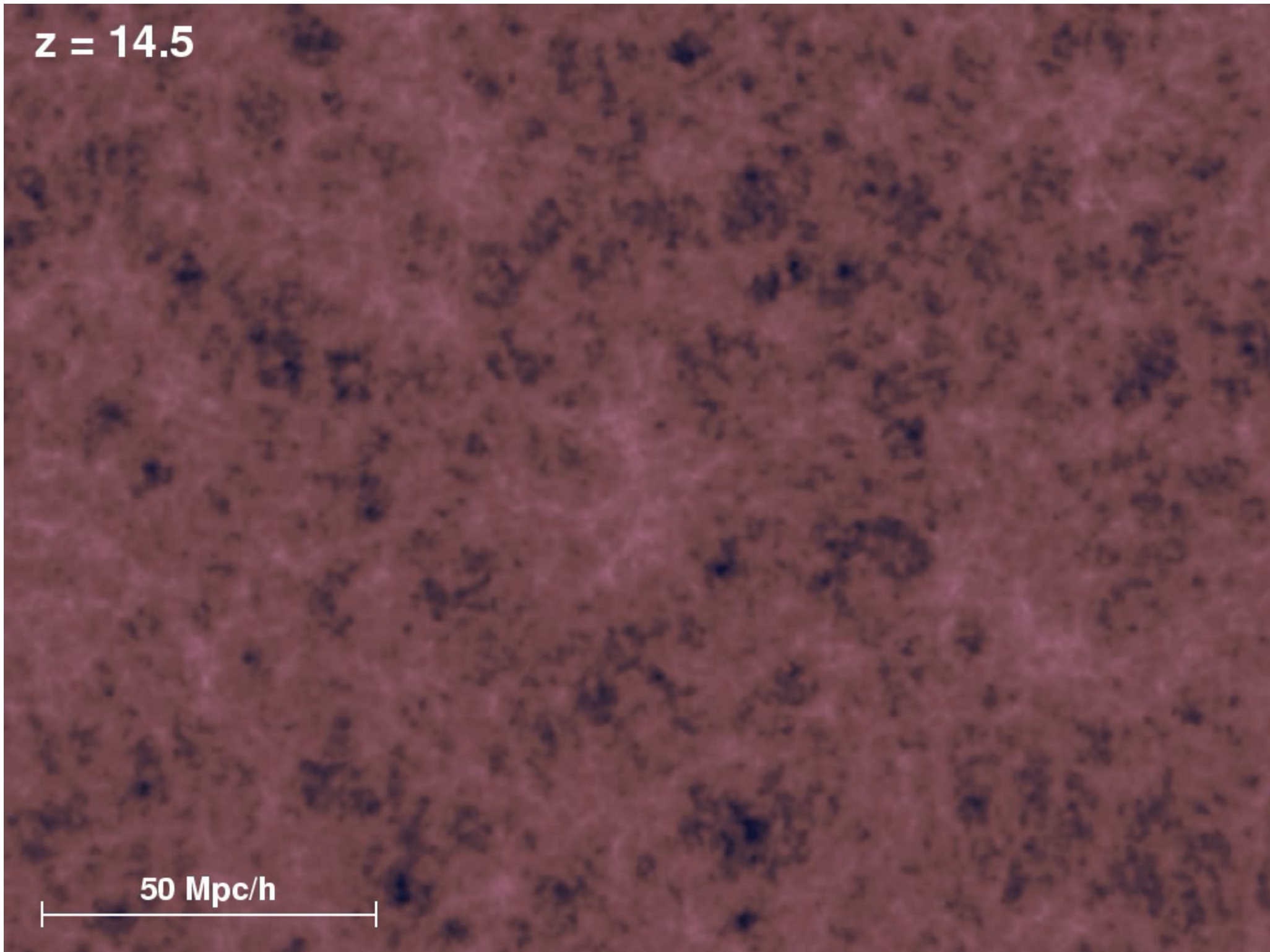
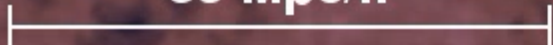
(Jarrett 2004, PASA)

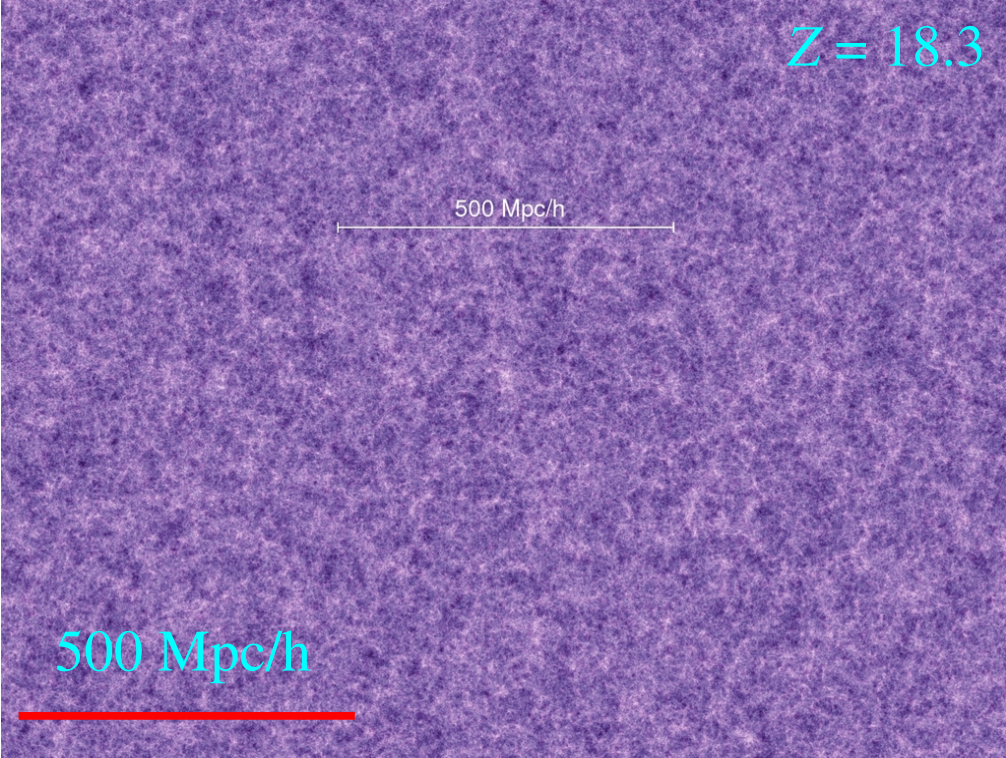
GRAVITATIONAL CLUSTERING

- At early times, the uniformity of the CMB images implies that the Universe was extremely homogenous, to ~ 1 part in 10^4 !
- Small over-densities have slightly higher gravitational attraction and hence become more over-dense with time. Conversely, under-dense regions have lower gravity & become more under-dense with time!
- These tiny over-densities continue to grow with time to become today's galaxies, clusters and superclusters!
- The rate of growth and the nature of the structures formed depend on the constituents of the Universe and are thus an important probe of cosmology!
- E.g. Galaxy surveys + N-body simulations \Rightarrow Cold dark matter!
(Davis et al. 1985)
- Galaxies may have formed “too early” ! Highest redshift, $z \sim 8.6$.
Many candidate galaxies at $z \sim 10$ now being detected with *HST*!
(Lehnert et al. 2010)

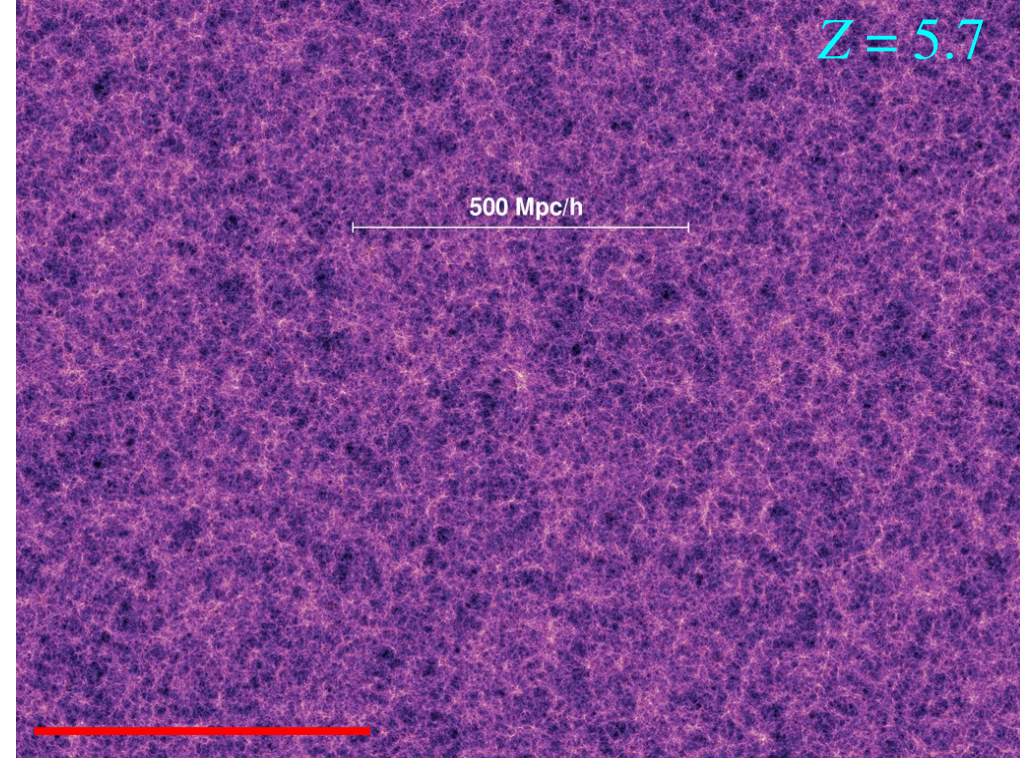
$z = 14.5$

50 Mpc/h

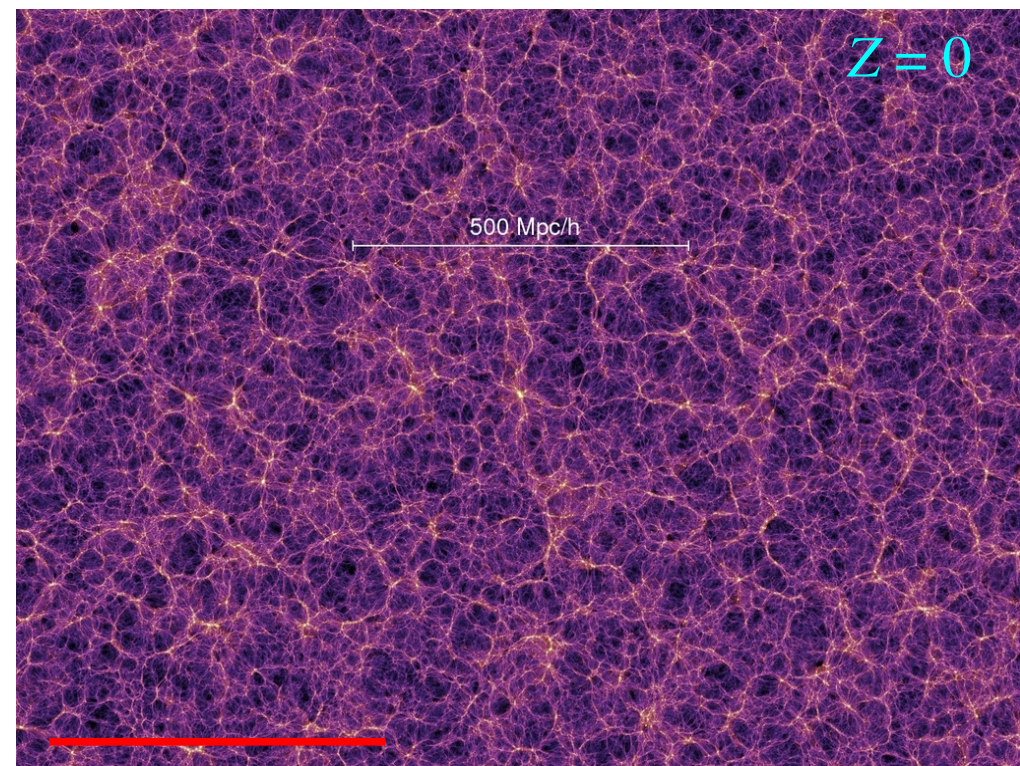
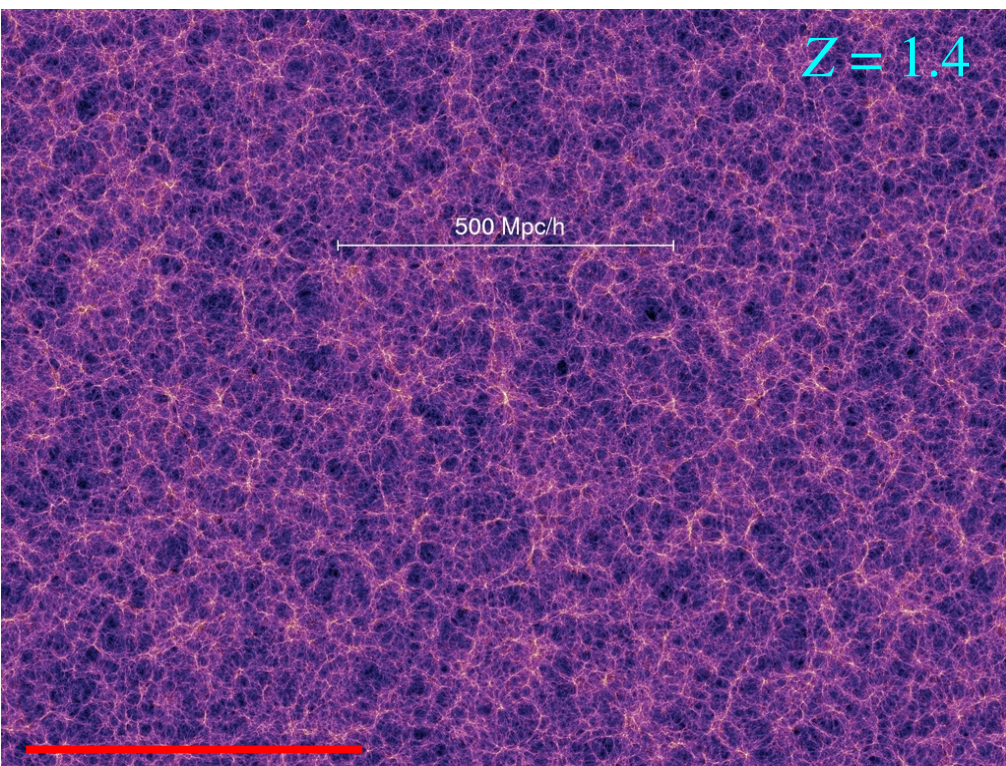


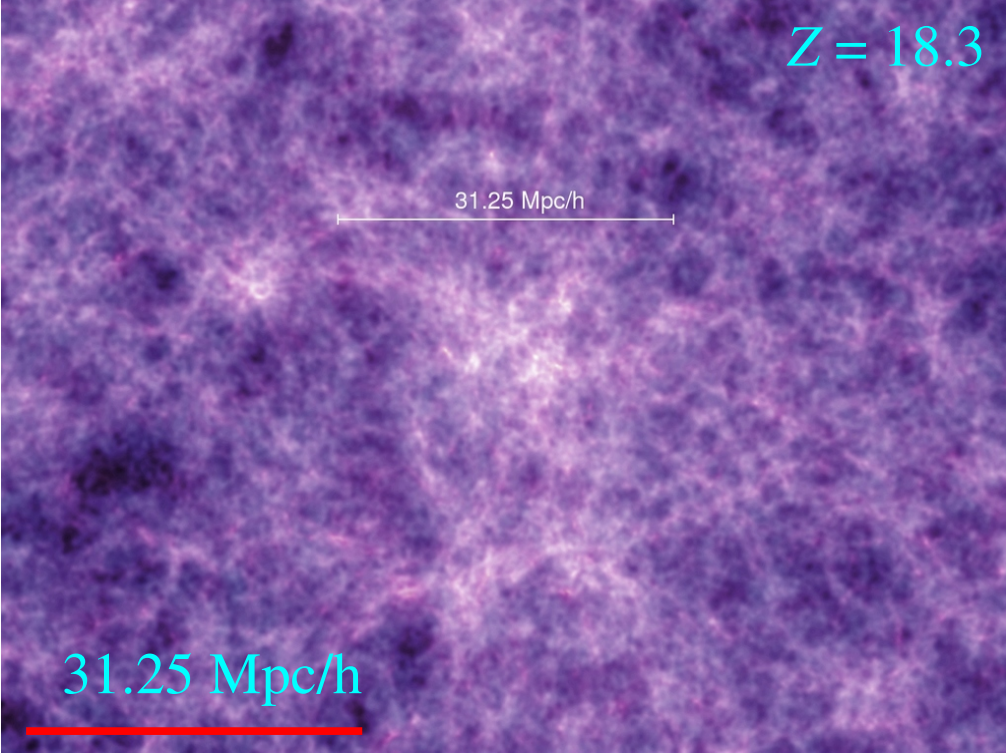


(Millenium Simulation)

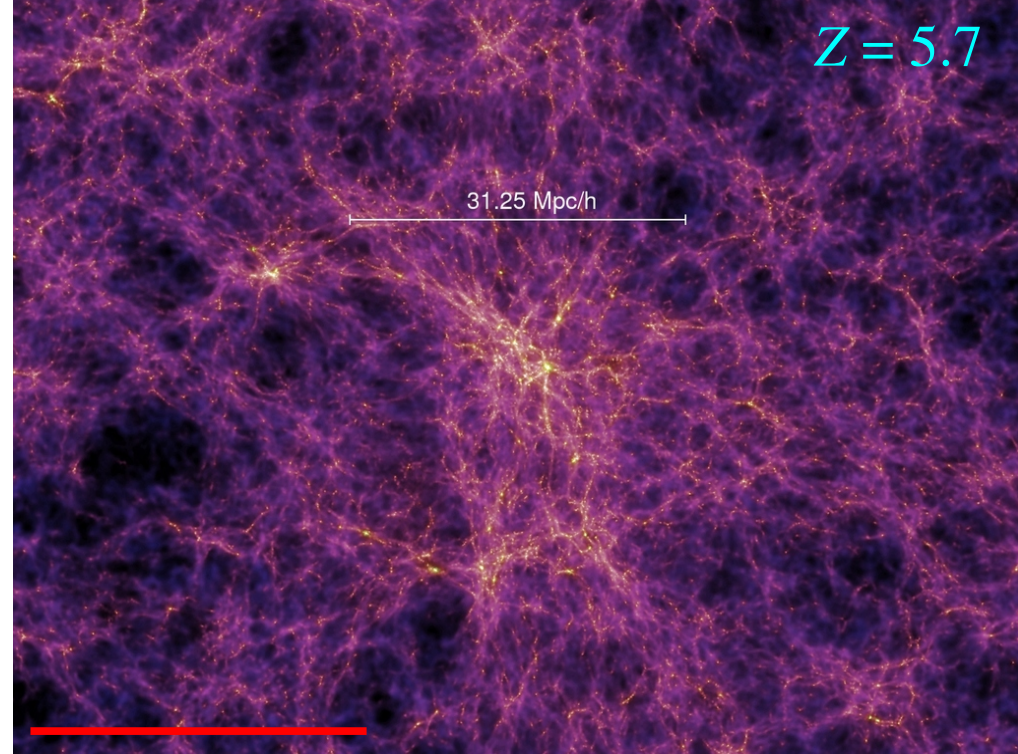


(Courtesy: Volker Springel)

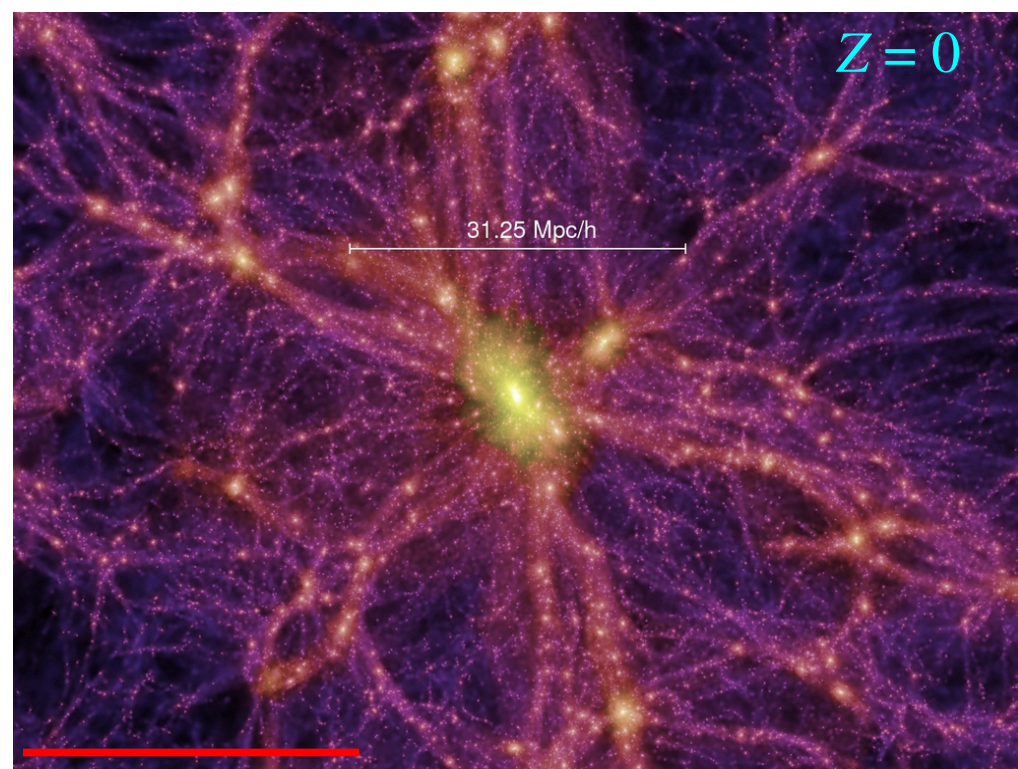
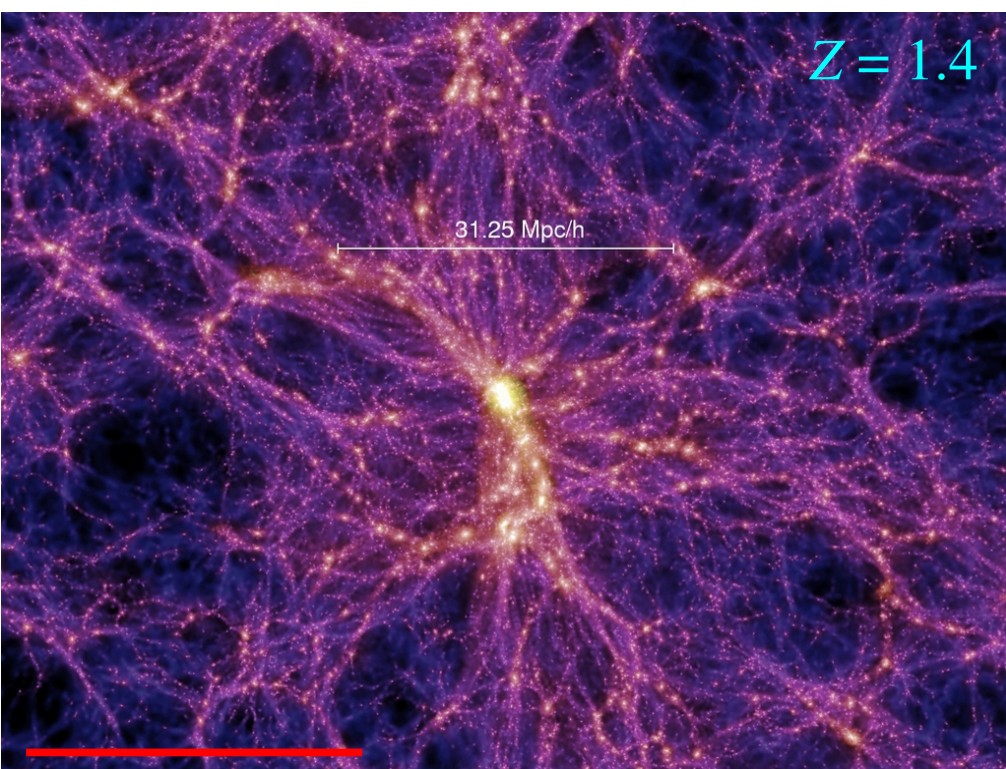




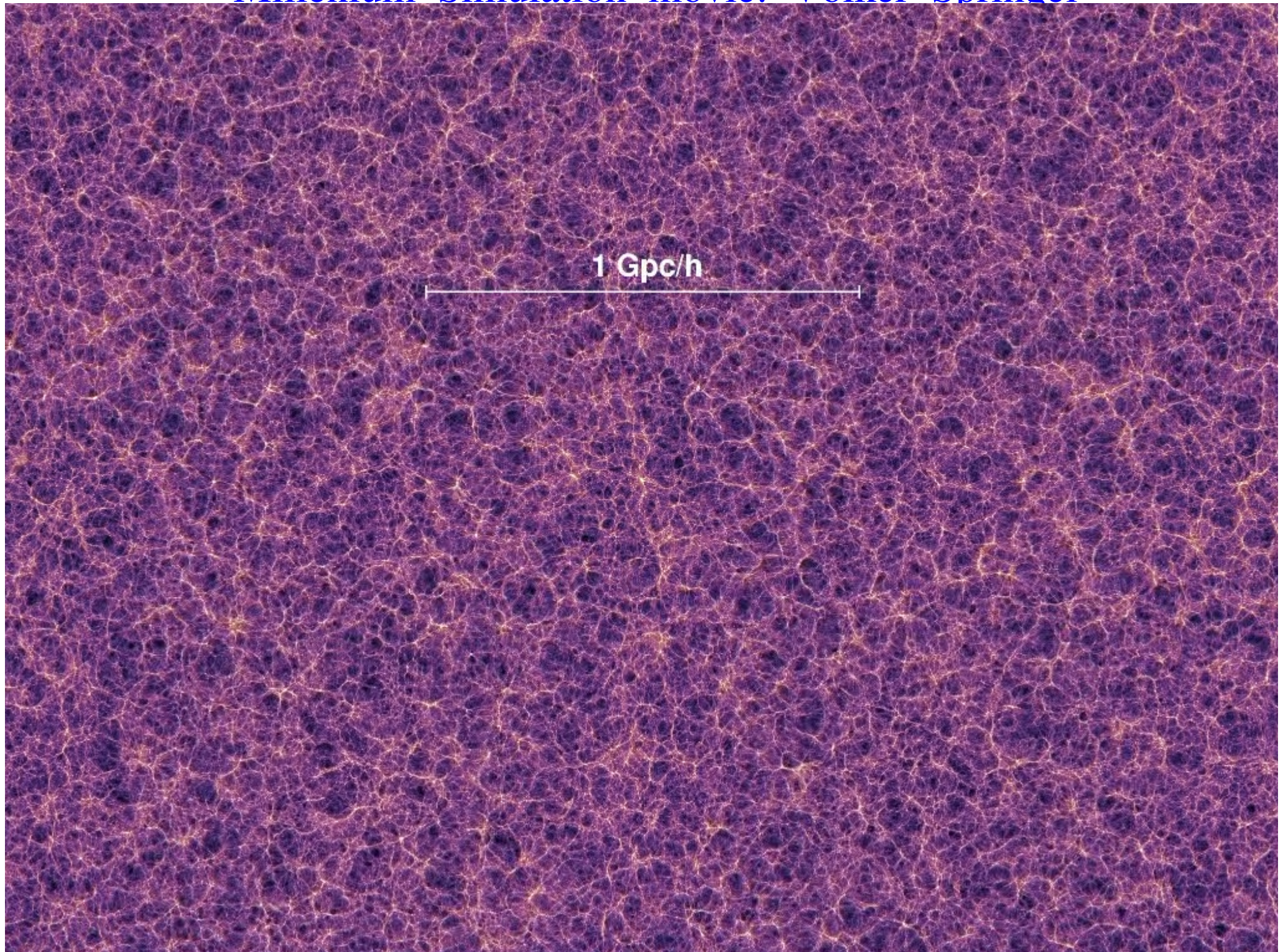
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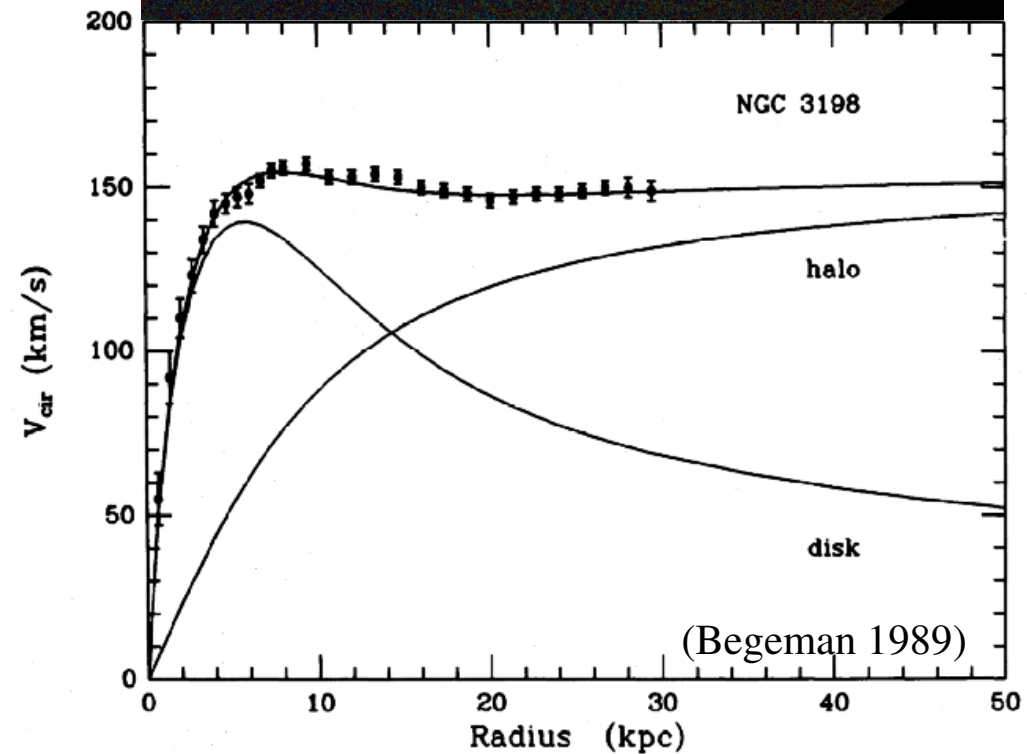
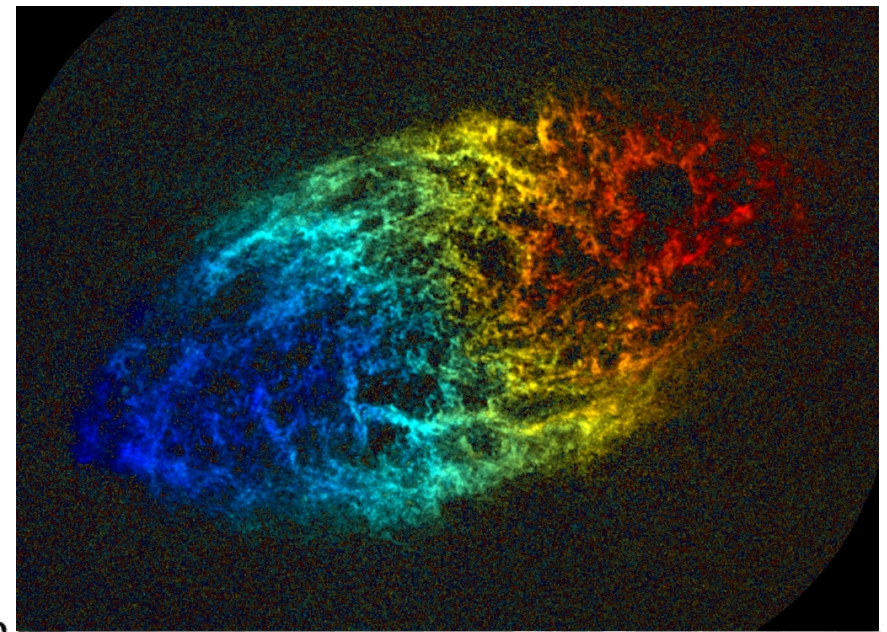
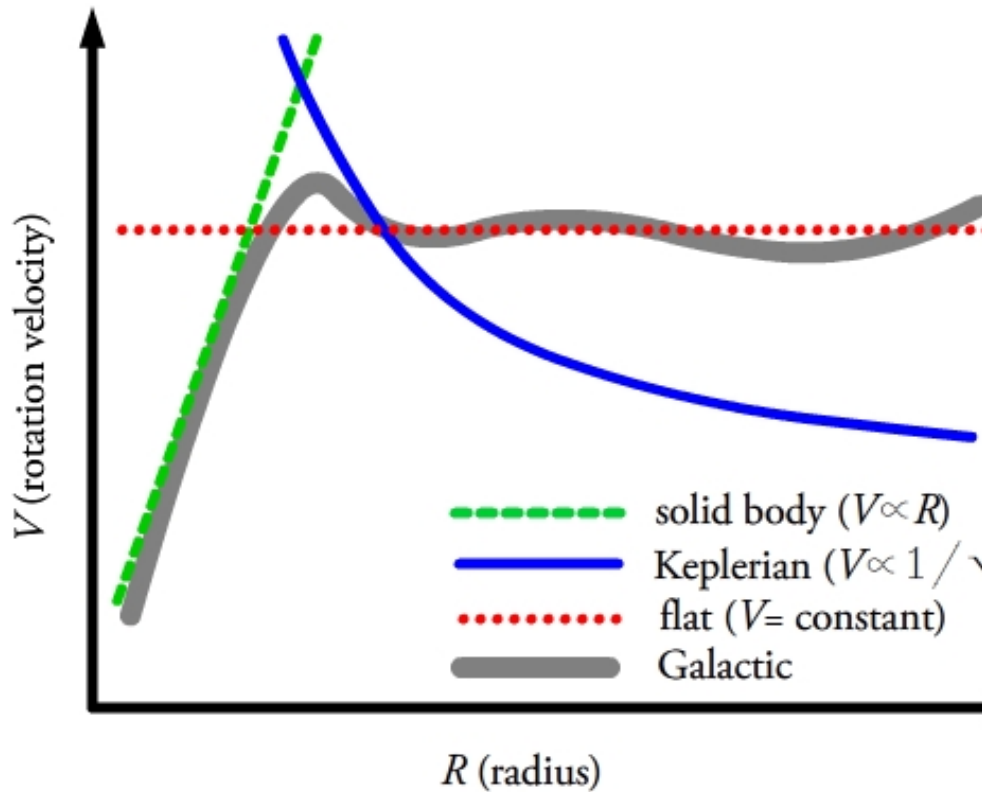


Millenium Simulation movie: Volker Springel



GALAXY ROTATION CURVES

- For circular orbits of gas/stars in a rotating galaxy:
Rotation velocity, $V = [GM/R]^{1/2}$.
 $\Rightarrow V \propto R^{-1/2}$ at large R , as most mass is in the inner regions.

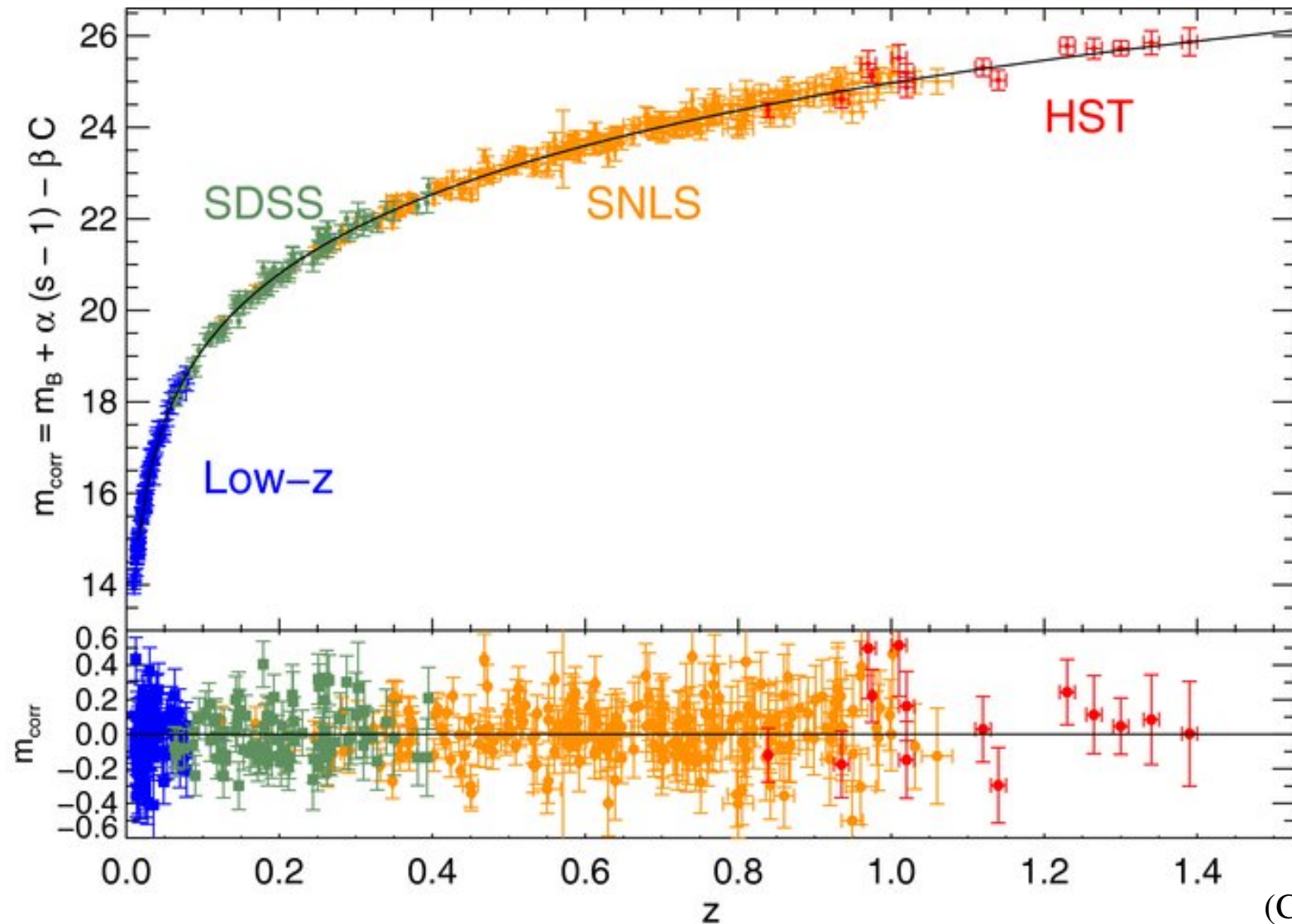


But,... Flat rotation curves \Rightarrow Mass increases with radius!
 \Rightarrow Dark Matter! Non-baryonic!!!

TYPE Ia SUPERNOVAE: DARK ENERGY

- Arise when accretion from a binary companion onto a white dwarf causes the mass to exceed the Chandrasekhar limit.
- Narrow progenitor mass range \Rightarrow Narrow Ia luminosity range!
 \Rightarrow Standard candles! \Rightarrow Distance to the host galaxy!
(Philips 1994)
- Important in local measurements of the Hubble constant!
(e.g. Freedman & Madore 2011)
- Very bright: detectable out to $z \sim 2$! \Rightarrow Can measure the luminosity distance as a function of redshift and test the cosmological model!
(e.g. Riess et al. 2007; Conley et al. 2011)
- High- z type Ia supernovae are *dimmer* than expected from their redshift, for a flat Universe with no dark energy!
 \Rightarrow Larger distances! \Rightarrow Requires an *accelerating* Universe!
(e.g. Riess et al. 1998; Perlmutter et al. 1999)
- $(\ddot{a}/a) = -(4\pi G/3) (\rho + 3p)$. (\ddot{a}/a) positive $\Rightarrow w < -1/3$: *Dark energy!*

TYPE Ia SUPERNOVAE



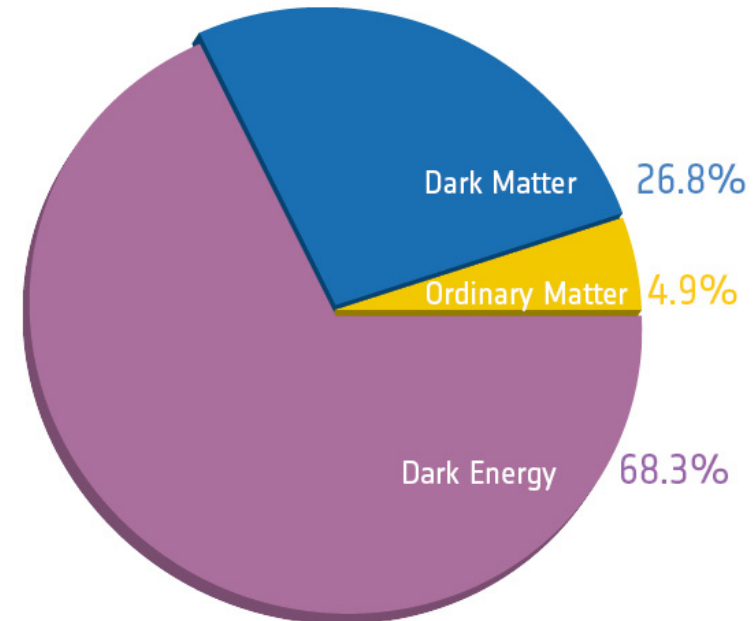
(Conley et al. 2011)

- Present results consistent with a cosmological constant, $w=-1$.
- New surveys (e.g. SNAP, DES): Does w change with time ?!

THE Λ CDM COSMOLOGICAL MODEL

- Best current cosmology: Flat Universe,
 $H_0 = 67 \text{ km/s/Mpc}$, $\Omega_{\text{baryon}} = 0.05$,
 $\Omega_{\text{DM}} = 0.27$, $\Omega_{\text{DE}} = 0.68$, and $w = -1$.

(The Planck collaboration)



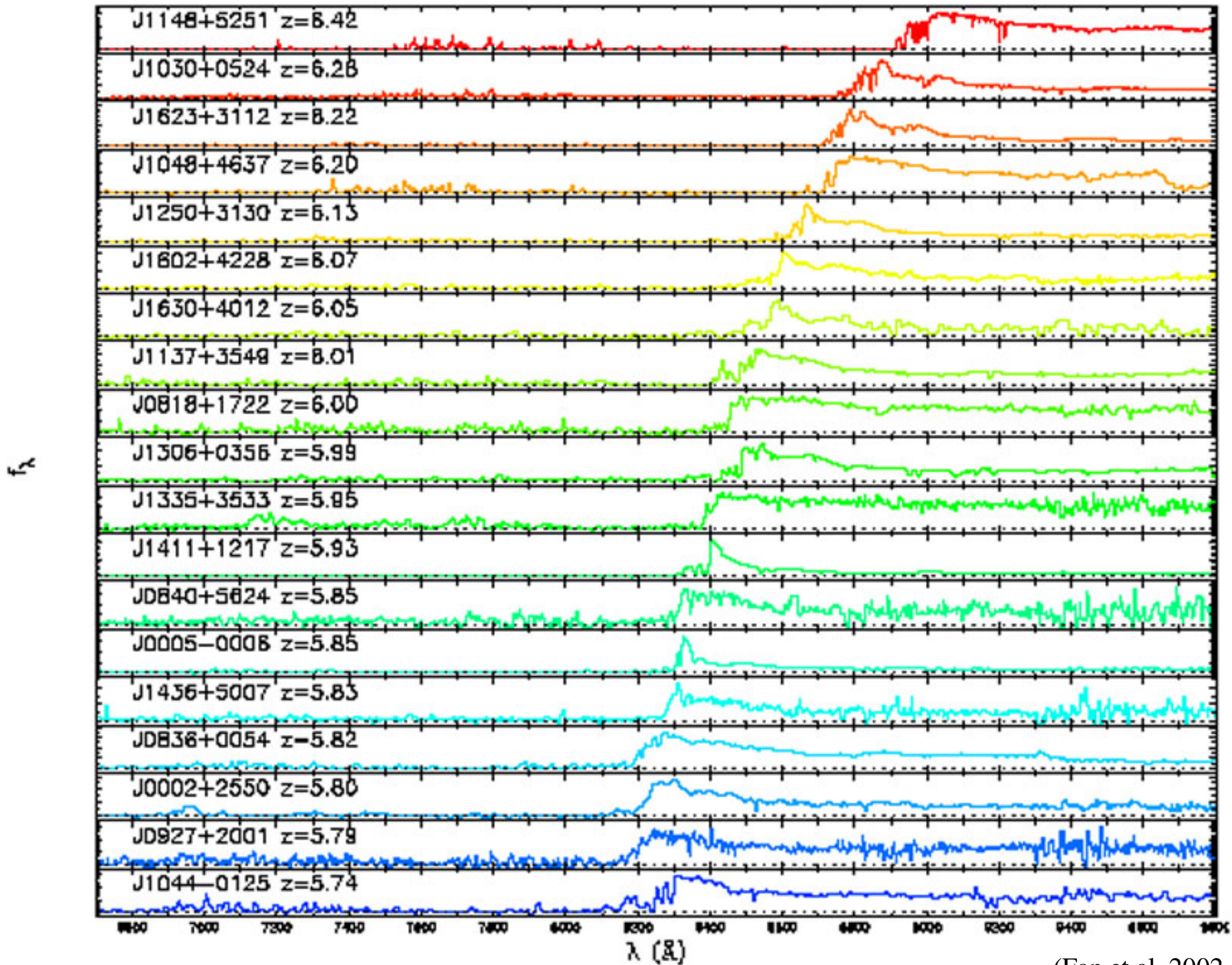
- Some tension in the value of H_0 !
- Is the Dark Energy a cosmological constant, with $w = -1$?
- How do the first stars form and reionize the Universe ?
- Dark matter density profiles ? Predicted to be “cuspy”...
- Fewer dwarf galaxies observed in groups than predicted in the standard Λ CDM cosmology.
- Are there too many big galaxies at high redshifts ?

SUMMARY

- The Universe is expanding! And the expansion is accelerating!
- A homogenous and isotropic model gives an excellent description of the Universe at early times.
- Two Friedmann equations for the “scale factor” $a(t)$:
$$\begin{aligned}(\ddot{a}/a) &= -(4\pi G/3) (\rho + 3p) \\(\dot{a}/a)^2 &= (8\pi G/3)\rho - k/a^2:\end{aligned}$$
- Big Bang Nucleosynthesis predictions for light element abundances in remarkable agreement with observations!
- Cosmic Microwave Background: Best black body in the Universe! Strong evidence for homogeneity and isotropy at $z \sim 1100$! CMB anisotropies: Best probe into the constituents of the Universe!
- Rotation curves: Dark matter! Type Ia supernovae: Dark energy!
- A “flat” Λ CDM cosmology gives an excellent fit to the CMB data!

THE EPOCH OF REIONIZATION

- After recombination at $z \sim 1100$ until $z \sim 30$, the Universe contains mostly neutral hydrogen.
- *If* this neutral hydrogen is present between galaxies at $z \sim 0 - 3$, quasar spectra would show strong Lyman- α absorption at all wavelengths $\lambda < 1215.7 \times (1 + z_{\text{QSO}}) \Rightarrow$ The Gunn-Peterson trough!
(Gunn & Peterson 1965)
- Lack of Gunn-Peterson trough in quasar spectra at $z < 6$: Hydrogen between galaxies is mostly ionized at $z < 6$. Gunn-Peterson trough detected in quasar absorption spectra at $z > \sim 6!!!$
(Fan et al. 2002)
- Reionization by UV photons from first stars/quasars at $z \sim 6.5 - 12$.
Epoch of Reionization: The last phase transition in the Universe!
- Next frontier of cosmology: Multiple radio telescopes currently being used, built, or planned, to study the EoR! Includes the GMRT, LOFAR, MWA, PAPER, SKA...



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