The Standard Model of Cosmology

- **I. Cosmological Principle**
  homogeneous and isotropic on large scales
- **II. Expansion: kinematics**
  expanding in a way that preserves I. $\rightarrow$ Hubble
- **III. Expansion: dynamics**
  obeys general relativity theory
- **IV. Hot Big Bang**
  hot dense state, dominated by thermal radiation
- **V. Inflation(*)**
  rapid initial ("superluminal") expansion + perturbations
- **VI. The Dark Sector(*)**
  to account for apparent acceleration + large structures

Supporting Observations

“Pillars of Standard Model”

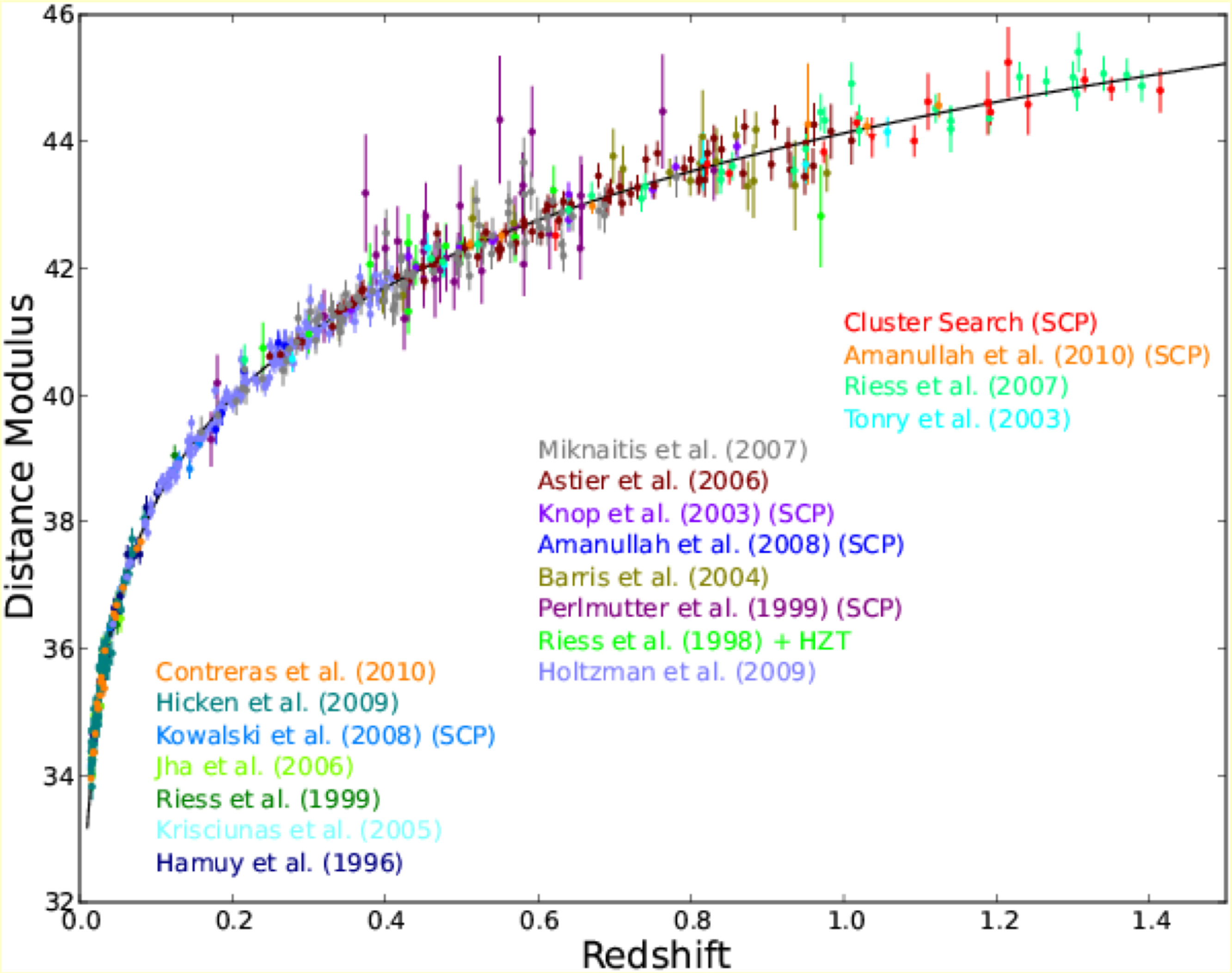
- Expansion history
- Light Element Abundances
- Microwave Background Radiation

other observations

- Homogeneity and Isotropy
- Night Sky is Dark
- Large scale structure measurements

“Linear” Expansion: Supernova Distances

“Hubble diagram” extending out to > 1 Gpc



distance modulus:

$\mu = m - M$

$= -2.5\log(F/F_{10})$

$= 5[\log(d_{pc})-1]$

$\log(d_{pc}) = (5+\mu)/5$

spectroscopic redshift:

$\lambda_{obs} / \lambda_{em} = v/c = 1+z$

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Light Element Abundances

- Observed abundances of light elements

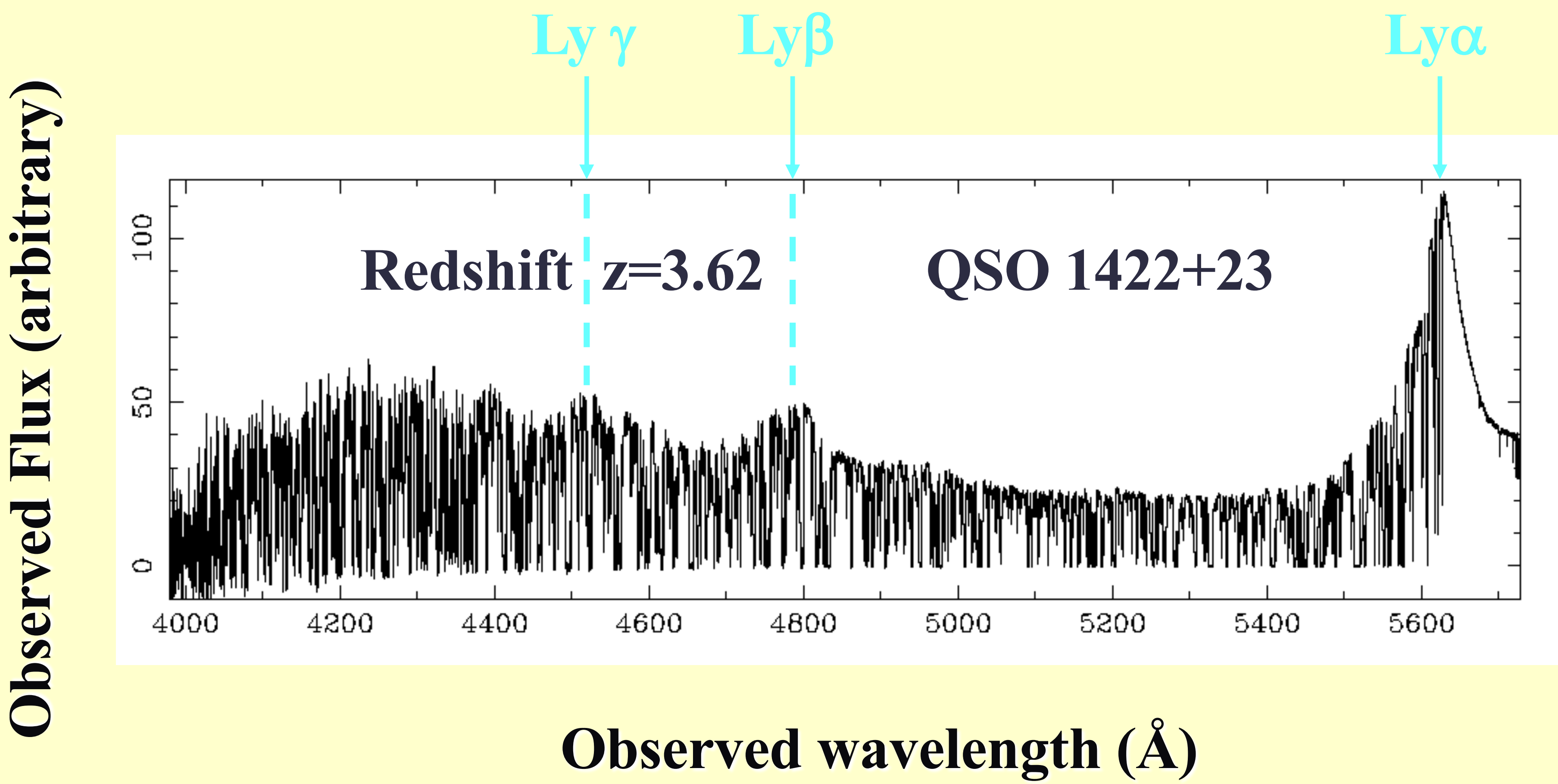
Hydrogen	75%
Helium	24%
Others	1%

- Helium problem:

  - stars would fuse H to He, and He into C, N, O, etc
  - if universe started from 100% hydrogen, we would expect 75% H, 13% He, 12% others
  - problem solved if universe starts out with H + He

Measuring Light Element Abundances

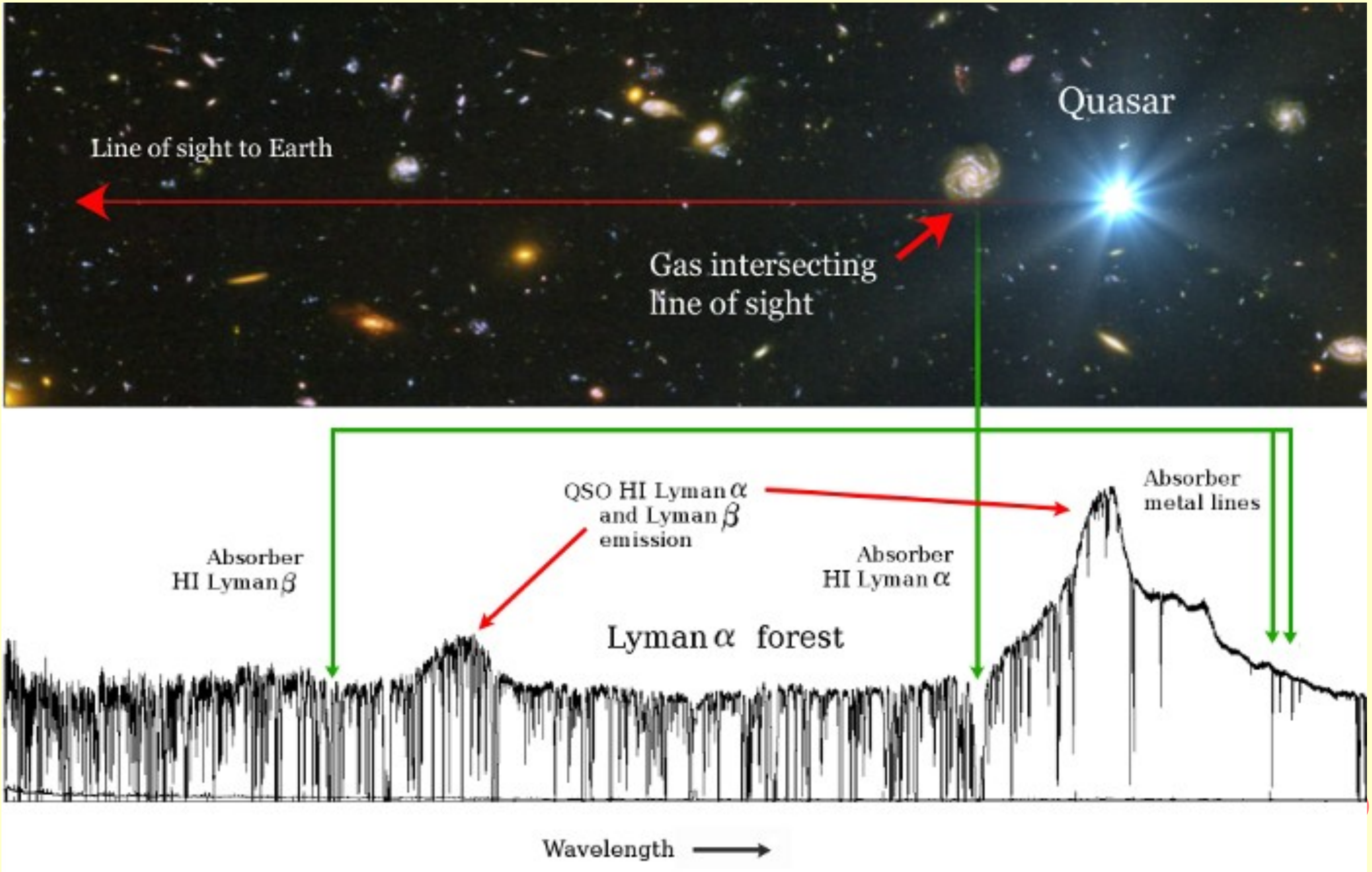
Hydrogen: high-redshift quasar spectra



(Womble et al. 1996)

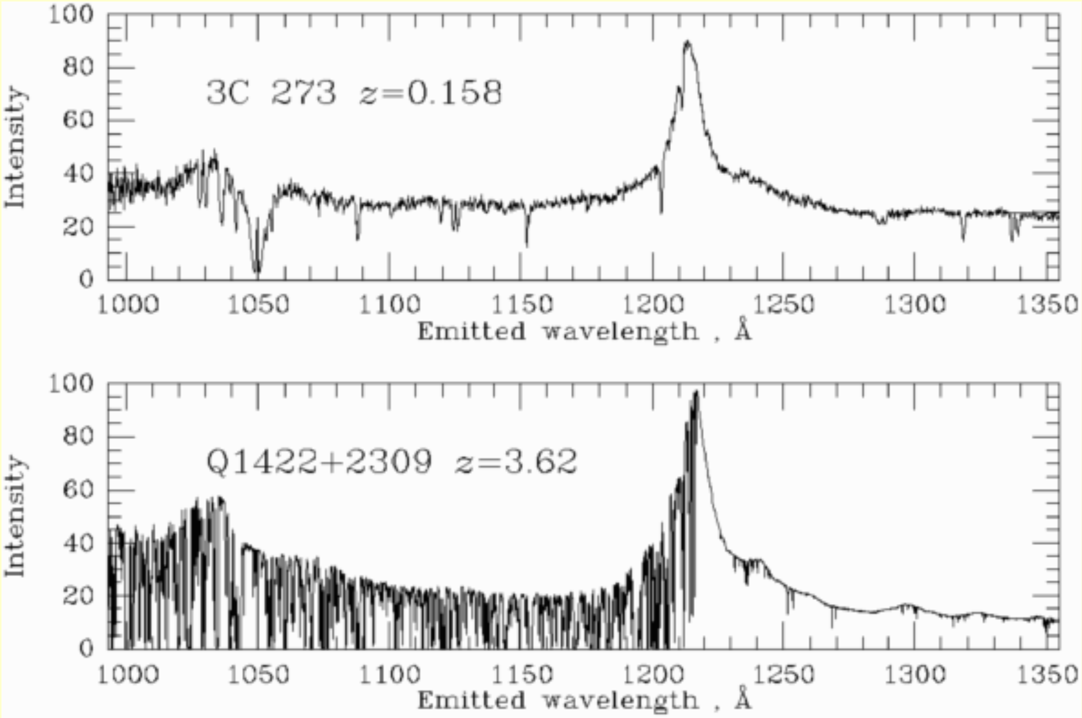
Measuring Light Element Abundances

Metals: Carbon, Nitrogen, Oxygen, Magnesium, Silicon



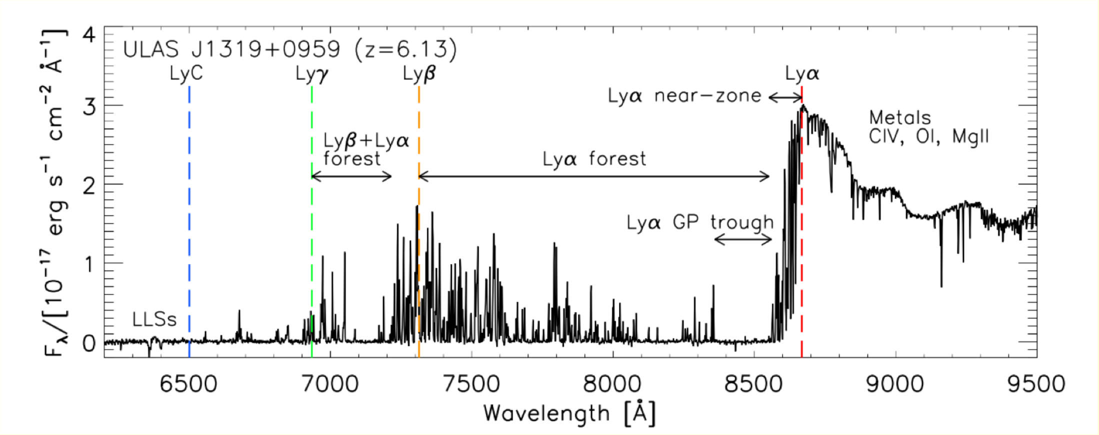
Measuring Light Element Abundances

An aside: universe evolves and gets denser $\rho \sim (1+z)^3$



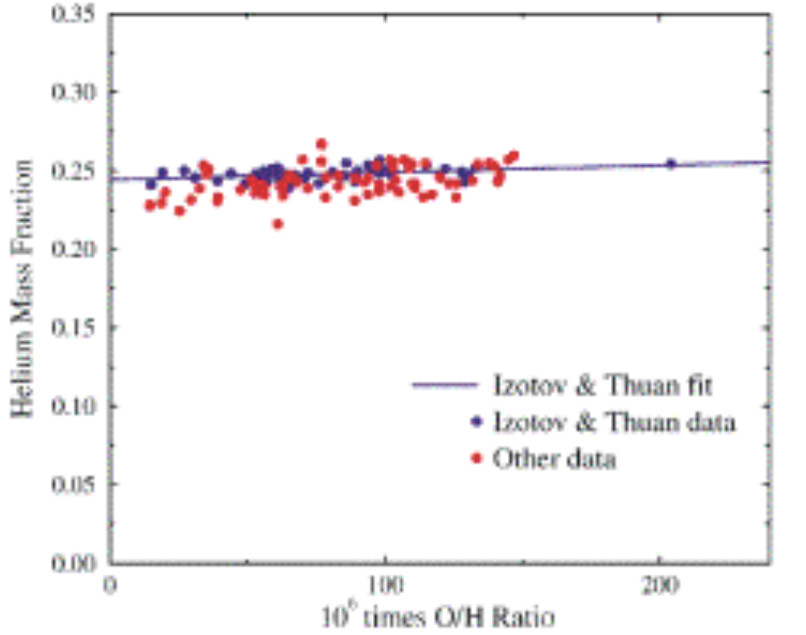
z=0.158

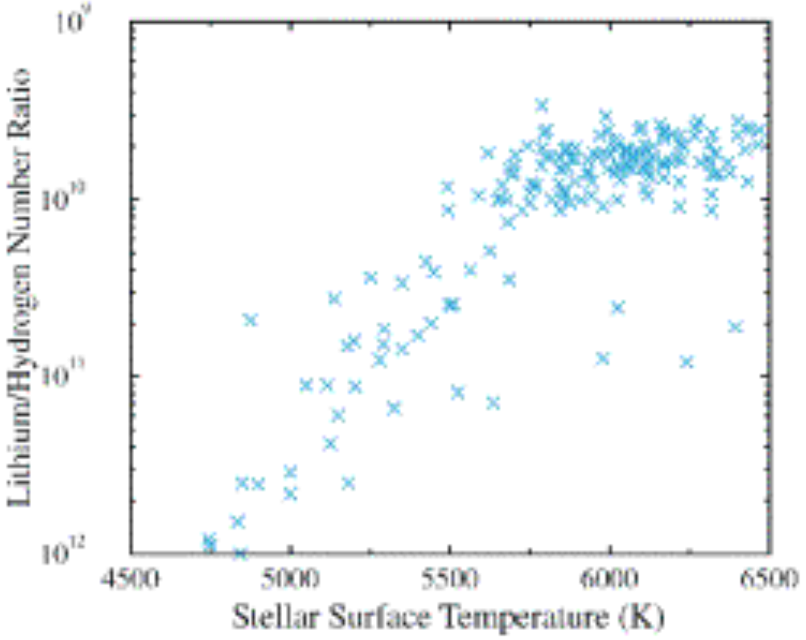
z=3.62



z=6.13

Measuring Light Element Abundances





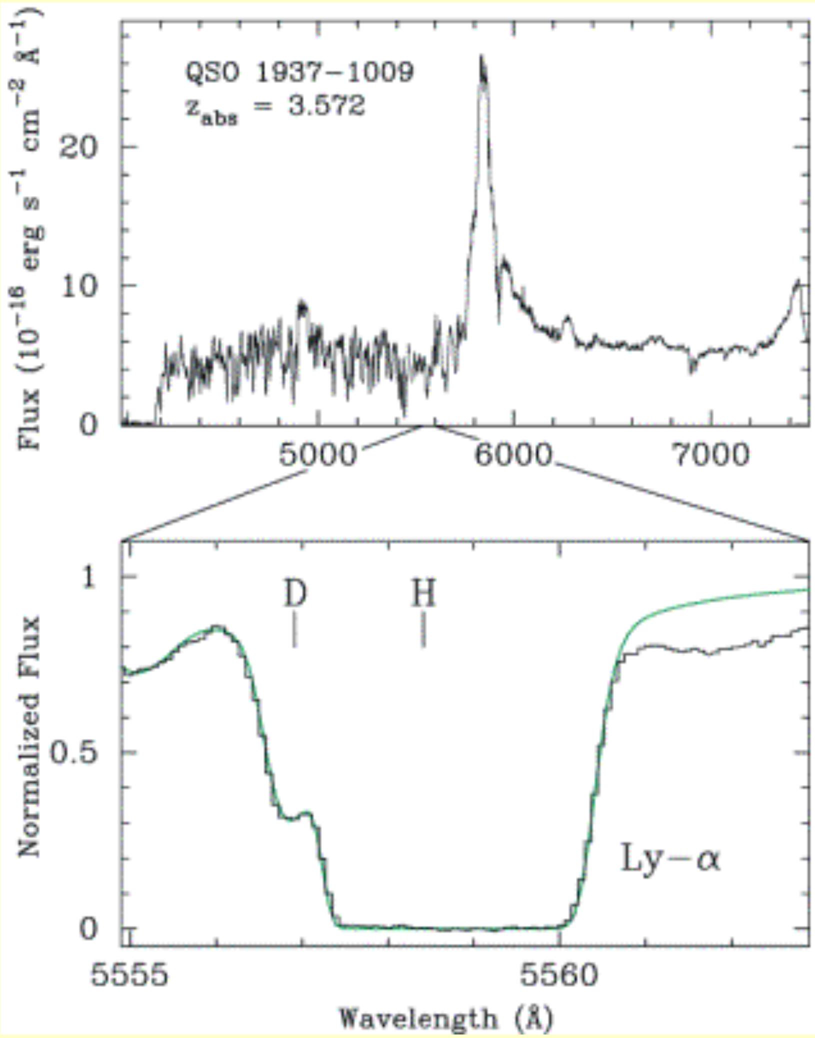
Helium abundance:

- measured in stellar spectra
  (Helium discovered & named after Sun)
- He can be produced in stars, too
- extrapolate to zero metallicity to
  subtract He from stellar nucleosynthesis

Lithium abundance:

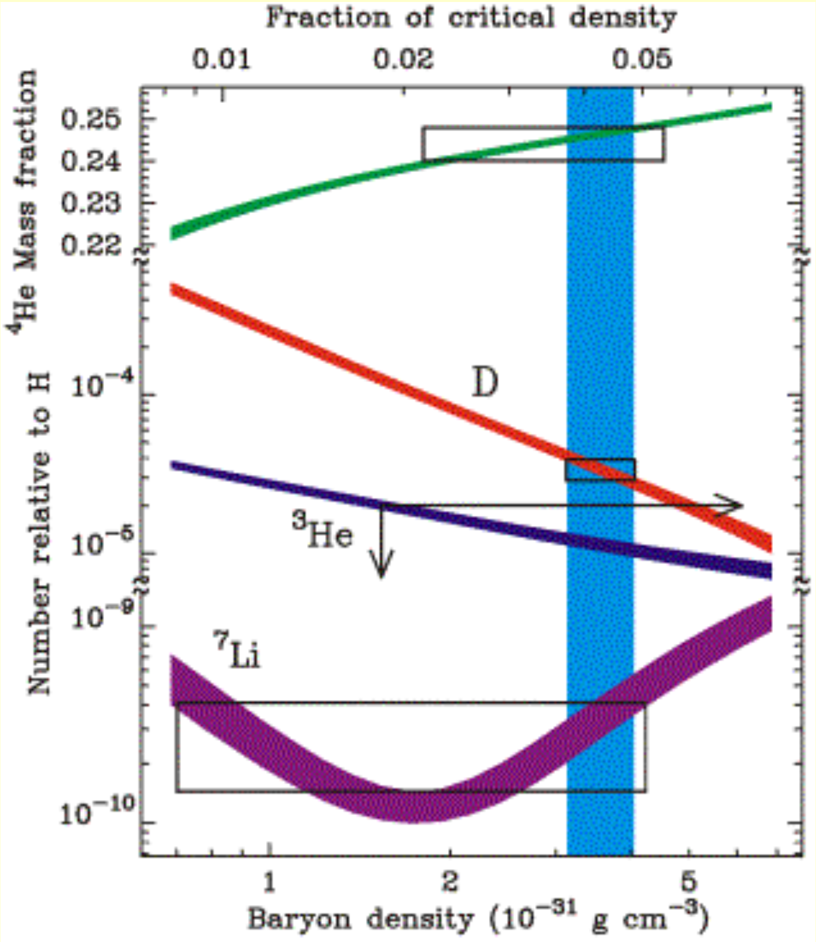
- measured in stellar spectra
- Li is depleted in stars by mixing
- find plateau at high stellar mass
  (these stars have little mixing)

Deuterium Abundance



- **Destroyed easily in stars**
- **Must look for gas that has never cycled through a star**
- **quasar absorption lines:**
  - **low-density gas**
  - **far back in time**
  - **extra neutron makes electron slightly more tightly bound**
  - **possible with 10m telescopes (Keck, VLT)**
  - **D/H = 10^{-5}**

Measuring the Density of the Universe

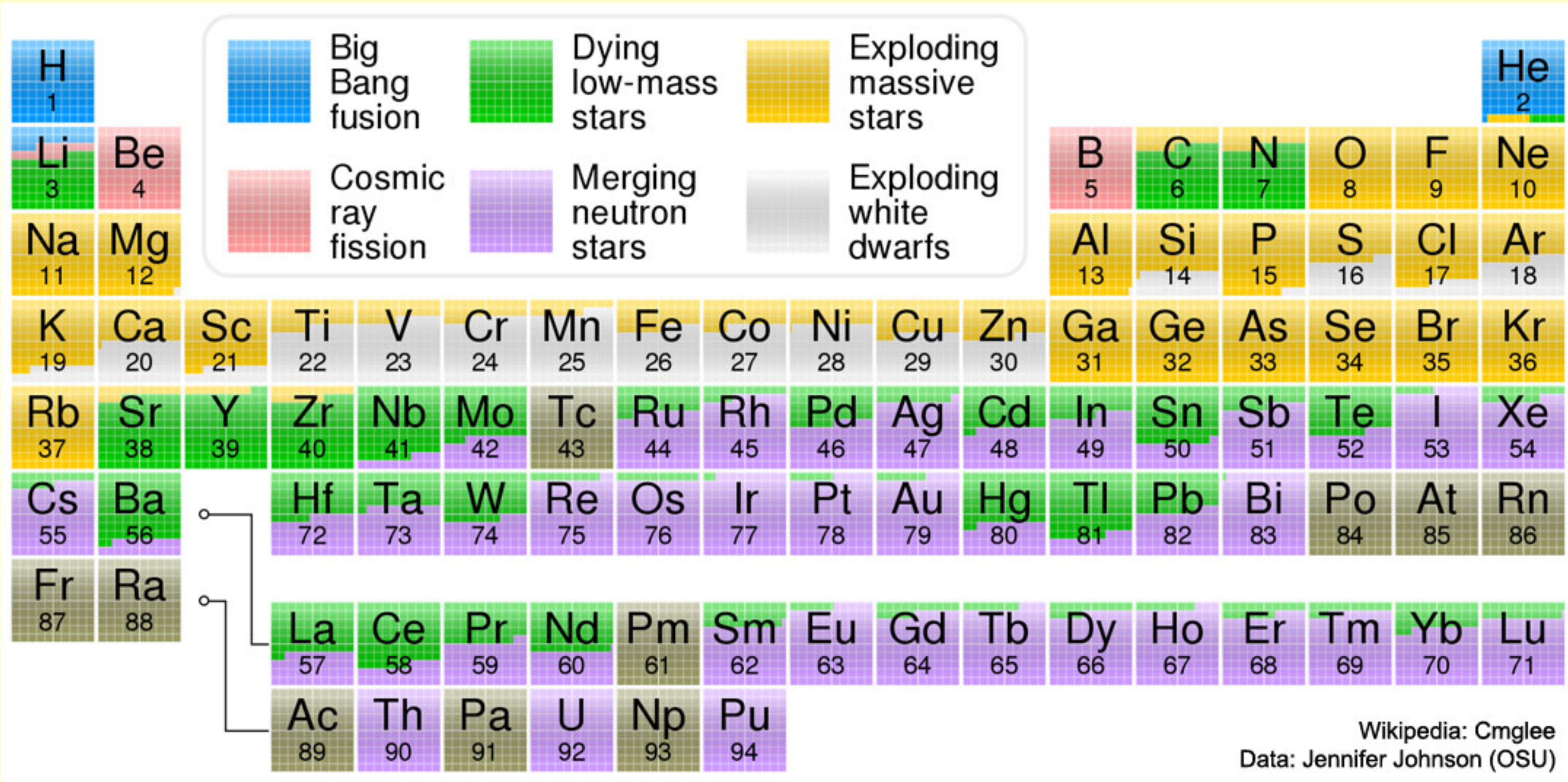


- **Big Bang Nucleosynthesis (BBNS)**
  - **can make precise calculations for relative abundances of light elements**
  - **turns out very sensitive to baryon density**

- **Current results:**
  - **imply 0.2 hydrogen atoms per cubic m**
  - **a small fraction (~4 percent) of the so-called critical density:**

$$\boxed{\Omega(\text{baryons}) \sim 0.04}$$

How about the rest of the elements?



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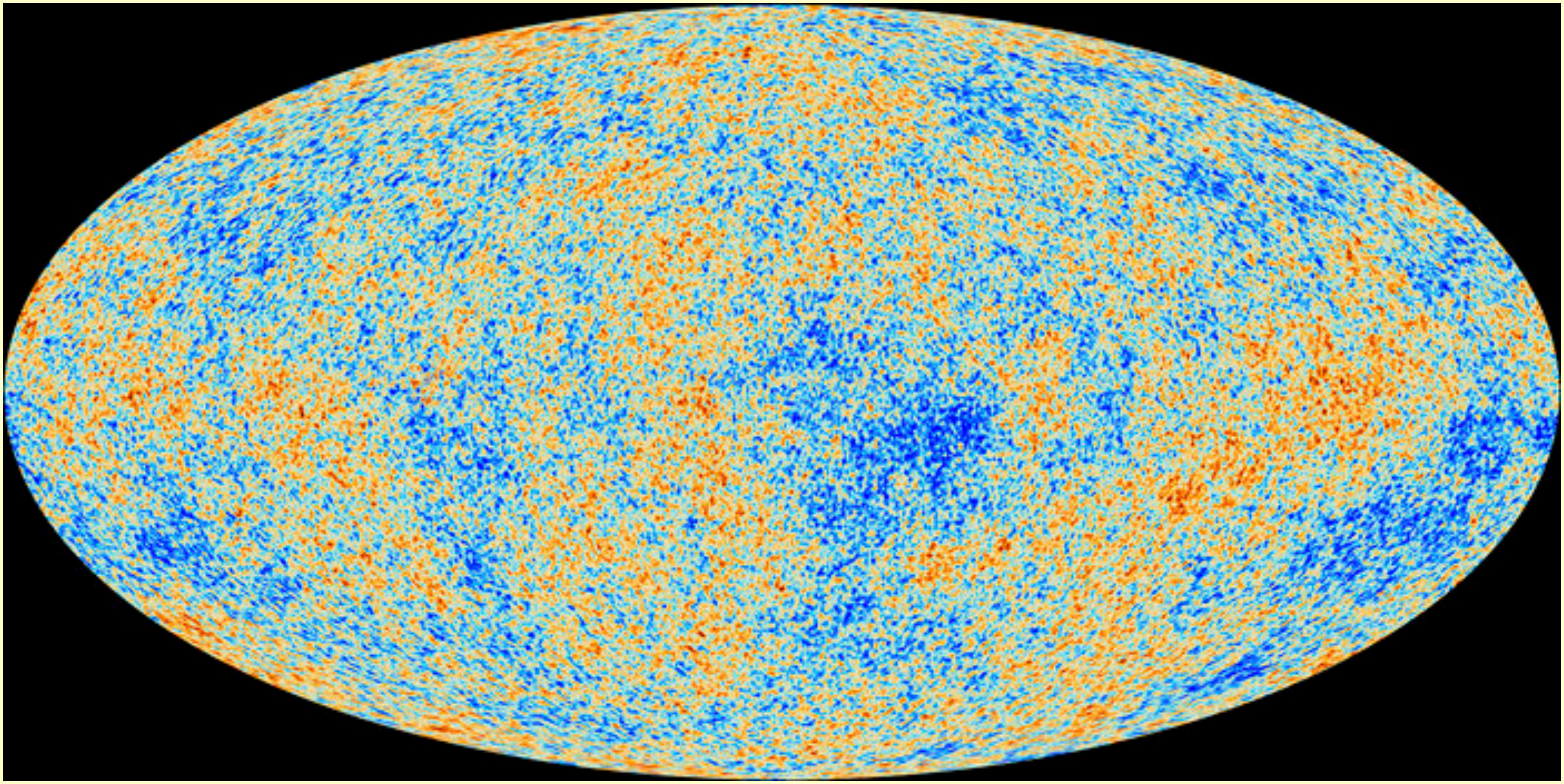
The Cosmic Microwave Background (CMB)



Planck Satellite (2010-2013)

CMB Properties

- Mean temperature: T=2.72548 ± 0.00057 K
- Spectral Deviation: Compton-y parameter

$$y \equiv \int \sigma_T n_e \frac{kT}{m_e c^2} dl \leq 1.5 \times 10^{-5} \quad \text{(COBE 1992)}$$

- Energy Density: $u = a_B T^4 = 4.8 \times 10^{-34}\, g/cm^3$

$$n_\gamma = 420 cm^{-3}$$

$$\langle h\nu \rangle = 6.3 \times 10^{-4} eV$$

$$\Omega_{cmb} = 5 \times 10^{-5}$$

$$n_b / n_\gamma = 5 \times 10^{-10}$$

CMB Anisotropies

- Angular fluctuation power:

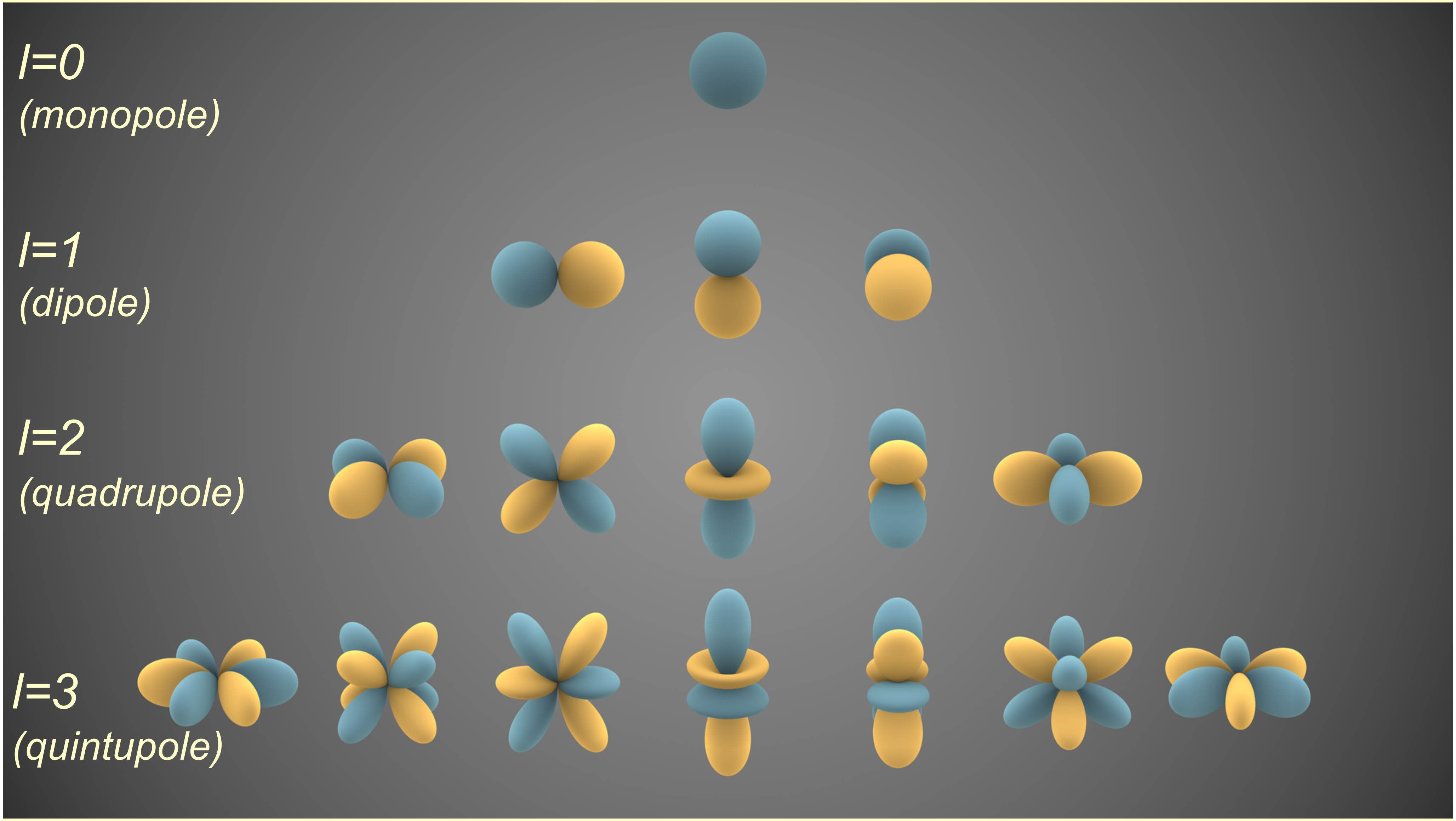
$$\frac{\delta T}{T}\left(\vec{\theta}\right) = \sum_{l,m\in[-l,l]} a_{lm} Y_{lm}\left(\vec{\theta}\right)$$

$$C_l = \left\langle \left| a_{lm} \right|^2 \right\rangle_m$$

- Dipole (*l=1, m=0*):

$$T(\vec{\theta}) = T_0\left(1 + \frac{v}{c}\cos\theta\right)$$

Spherical harmonics



Spherical harmonics

ℓ = 0 [edit]

$$Y_{00} = s = Y_0^0 = \frac{1}{2}\sqrt{\frac{1}{\pi}}$$

ℓ = 1 [edit]

$$Y_{1,-1} = p_y = i\sqrt{\frac{1}{2}}\left(Y_1^{-1} + Y_1^1\right) = \sqrt{\frac{3}{4\pi}} \cdot \frac{y}{r} = \sqrt{\frac{3}{4\pi}} \sin(\theta) \sin\varphi$$

$$Y_{1,0} = p_z = Y_1^0 = \sqrt{\frac{3}{4\pi}} \cdot \frac{z}{r} = \sqrt{\frac{3}{4\pi}} \cos(\theta)$$

$$Y_{1,1} = p_x = \sqrt{\frac{1}{2}}\left(Y_1^{-1} - Y_1^1\right) = \sqrt{\frac{3}{4\pi}} \cdot \frac{x}{r} = \sqrt{\frac{3}{4\pi}} \sin(\theta) \cos\varphi$$

ℓ = 2 [edit]

$$Y_{2,-2} = d_{xy} = i\sqrt{\frac{1}{2}}\left(Y_2^{-2} - Y_2^2\right) = \frac{1}{2}\sqrt{\frac{15}{\pi}} \cdot \frac{xy}{r^2} = \frac{1}{4}\sqrt{\frac{15}{\pi}} \sin^2\theta \sin(2\varphi)$$

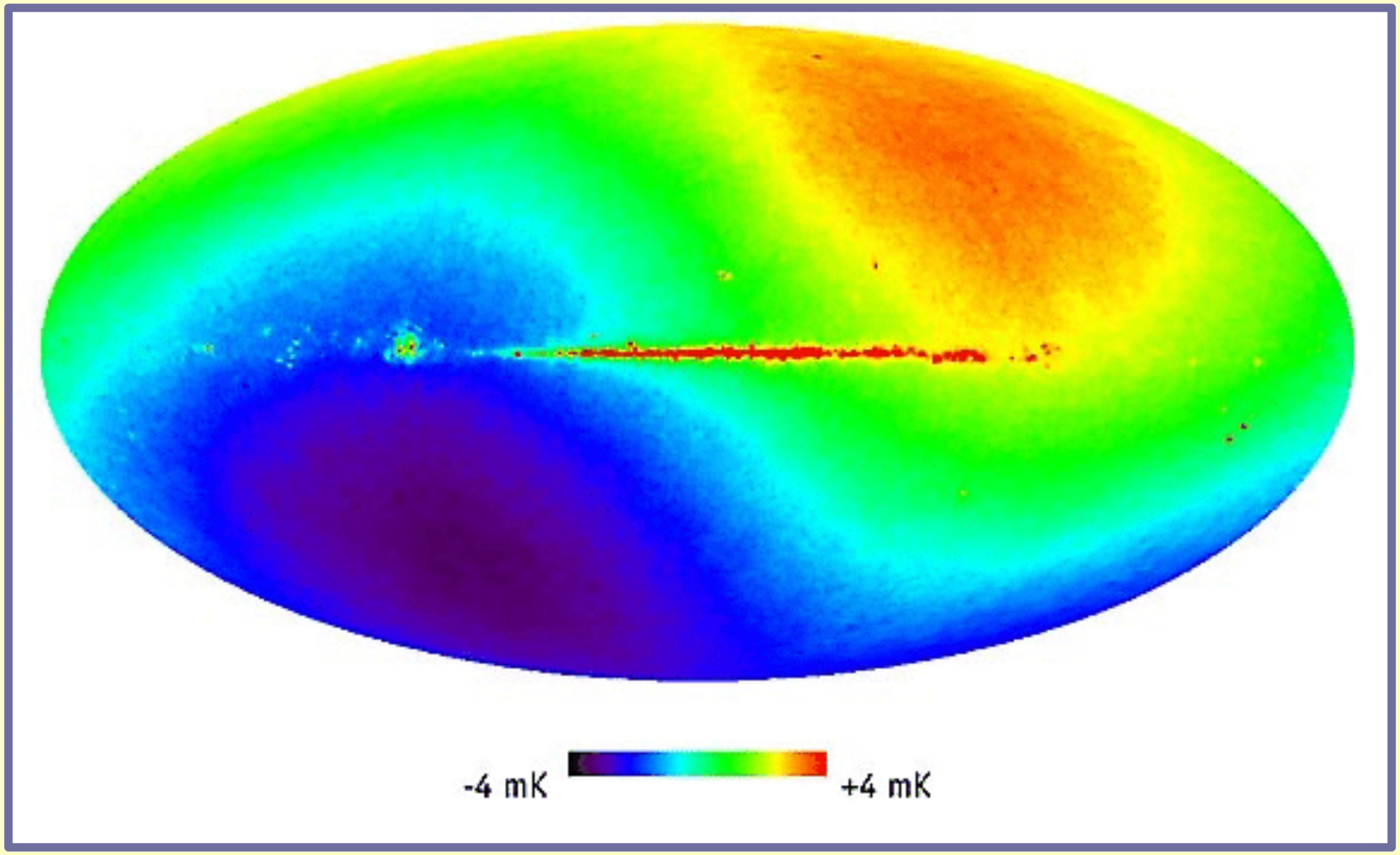
$$Y_{2,-1} = d_{yz} = i\sqrt{\frac{1}{2}}\left(Y_2^{-1} + Y_2^1\right) = \frac{1}{2}\sqrt{\frac{15}{\pi}} \cdot \frac{y \cdot z}{r^2} = \frac{1}{4}\sqrt{\frac{15}{\pi}} \sin(2\theta) \sin\varphi$$

$$Y_{2,0} = d_{z^2} = Y_2^0 = \frac{1}{4}\sqrt{\frac{5}{\pi}} \cdot \frac{3z^2 - r^2}{r^2} = \frac{1}{4}\sqrt{\frac{5}{\pi}}(3\cos^2\theta - 1)$$

$$Y_{2,1} = d_{xz} = \sqrt{\frac{1}{2}}\left(Y_2^{-1} - Y_2^1\right) = \frac{1}{2}\sqrt{\frac{15}{\pi}} \cdot \frac{x \cdot z}{r^2} = \frac{1}{4}\sqrt{\frac{15}{\pi}} \sin(2\theta) \cos\varphi$$

$$Y_{2,2} = d_{x^2-y^2} = \sqrt{\frac{1}{2}}\left(Y_2^{-2} + Y_2^2\right) = \frac{1}{4}\sqrt{\frac{15}{\pi}} \cdot \frac{x^2 - y^2}{r^2} = \frac{1}{4}\sqrt{\frac{15}{\pi}} \sin^2\theta \cos(2\varphi)$$

CMB Dipole

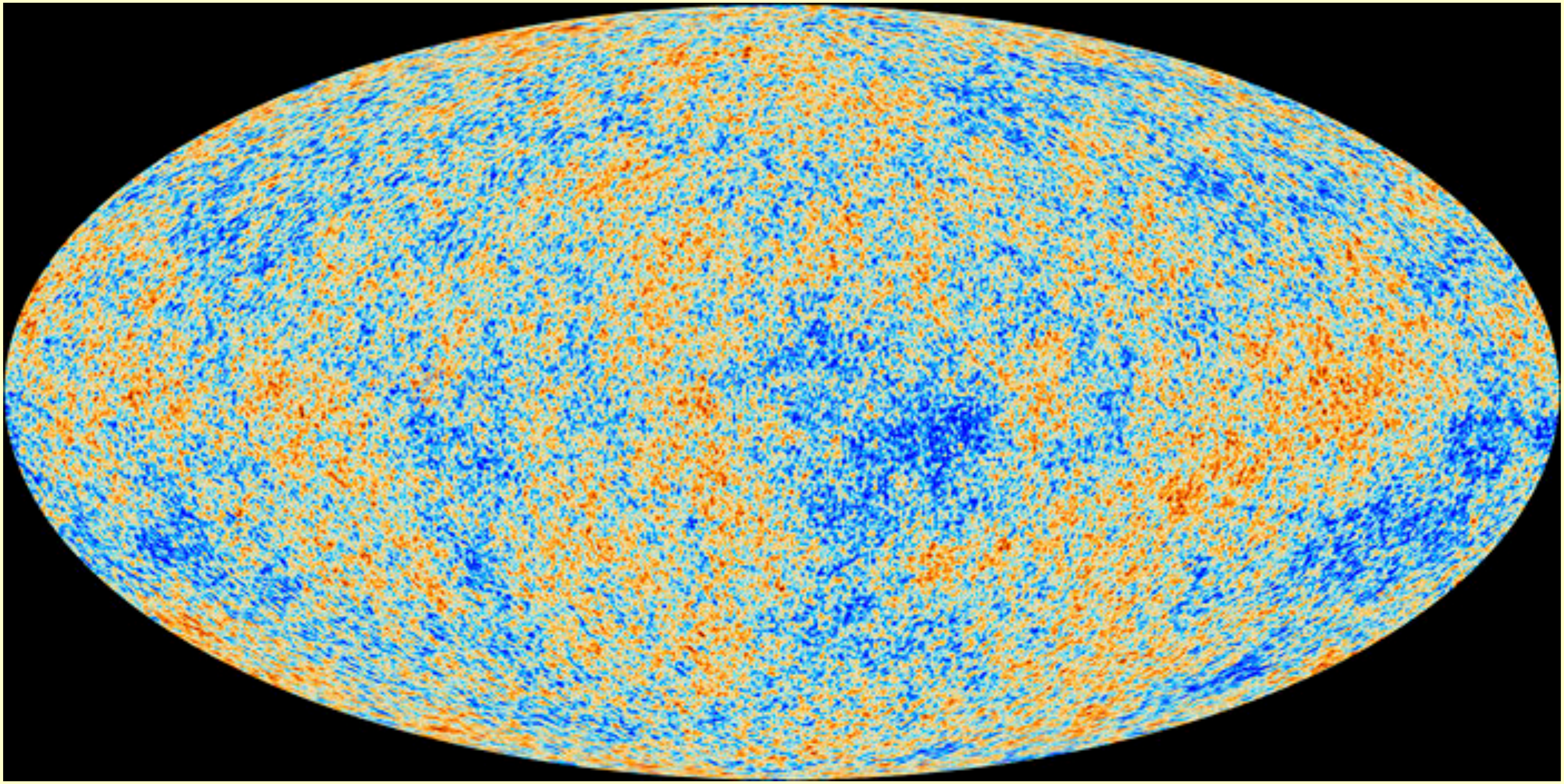


v(sun)-v(CMB)=369.82 ± 0.11 km/s

v(sun)-v(LG) =306 ± 18 km/s

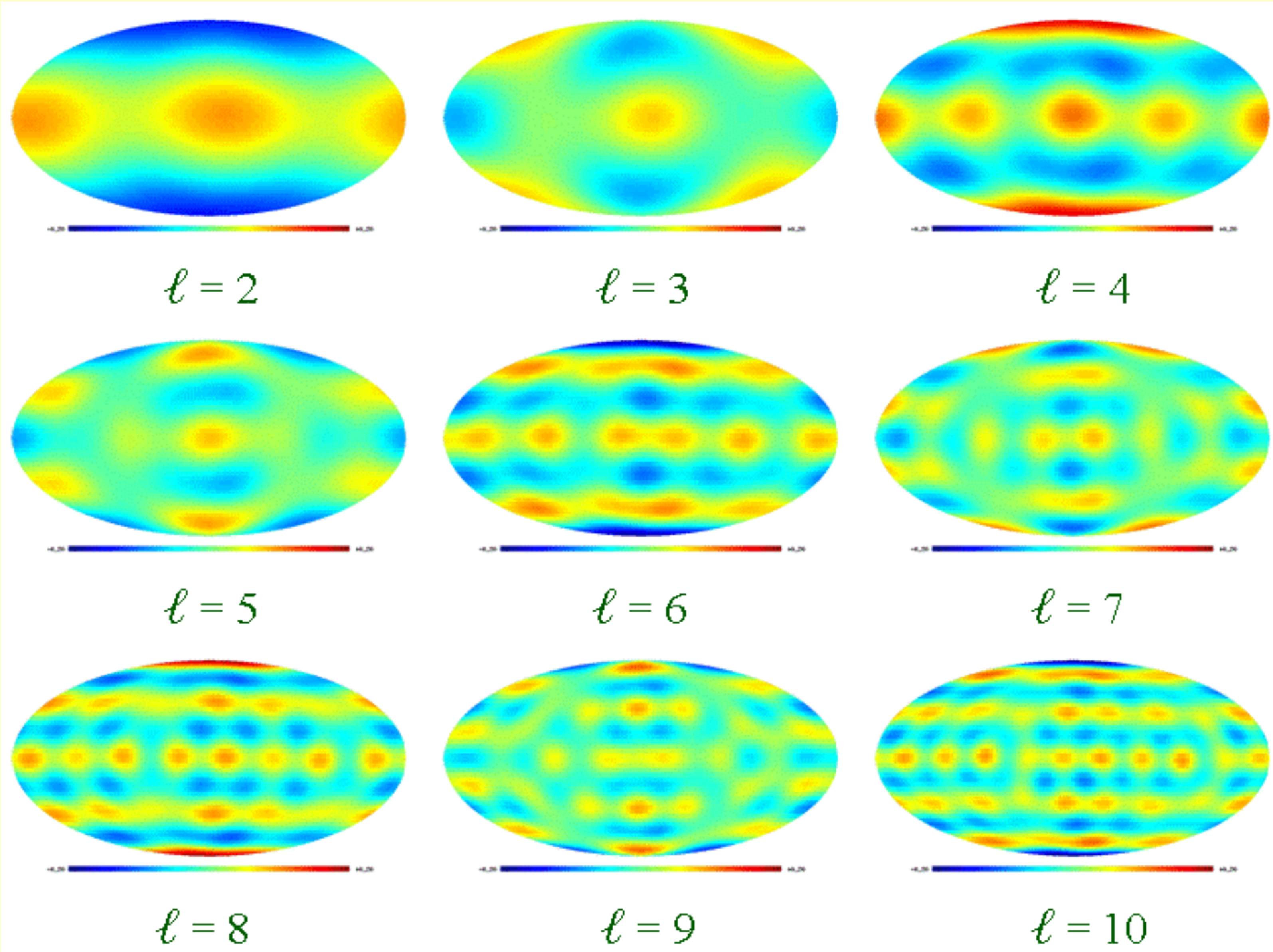
v(LG)-v(CMB) = 627 ± 22 km/s

The Cosmic Microwave Background (CMB)

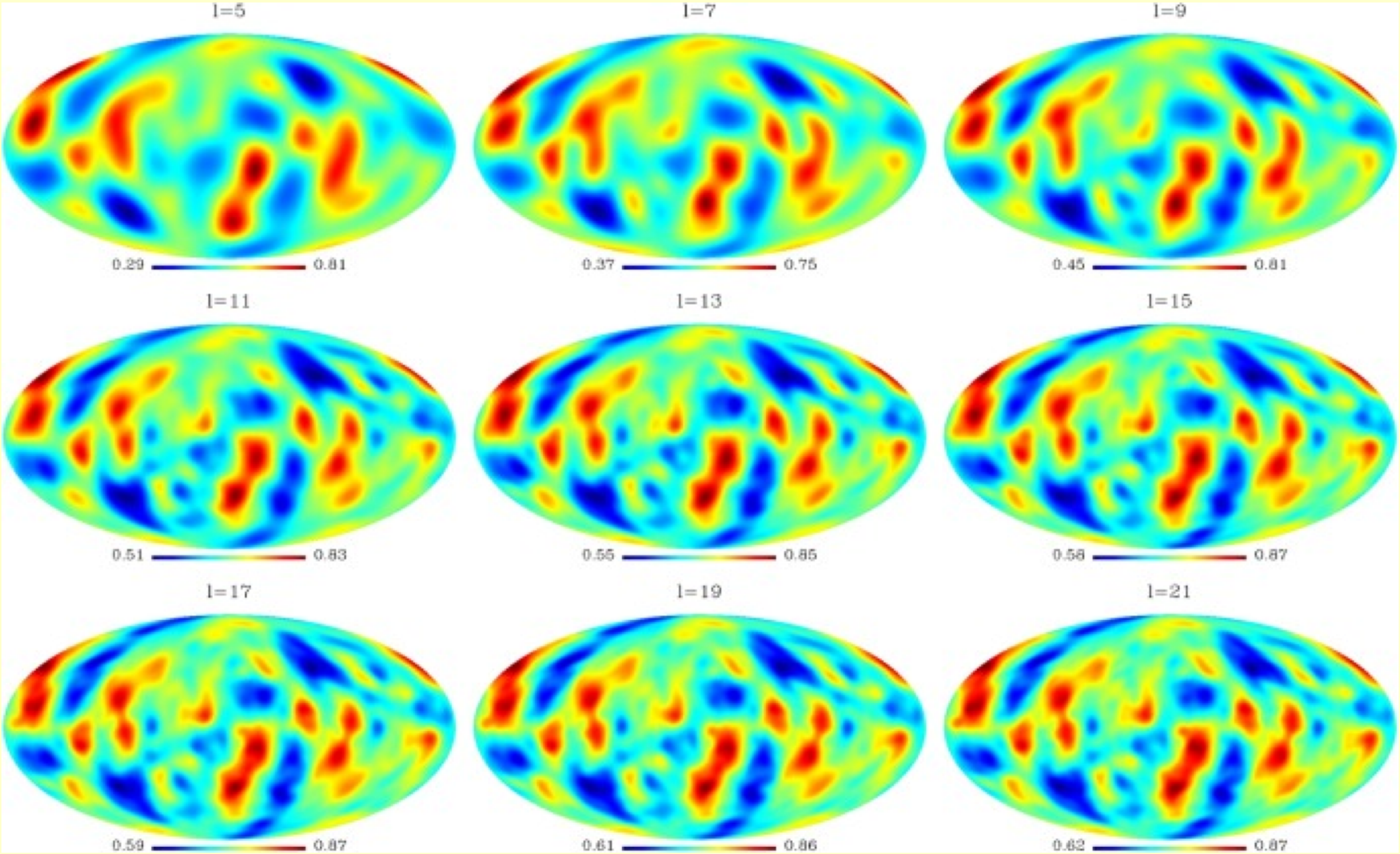


Planck Satellite (2010-2013)

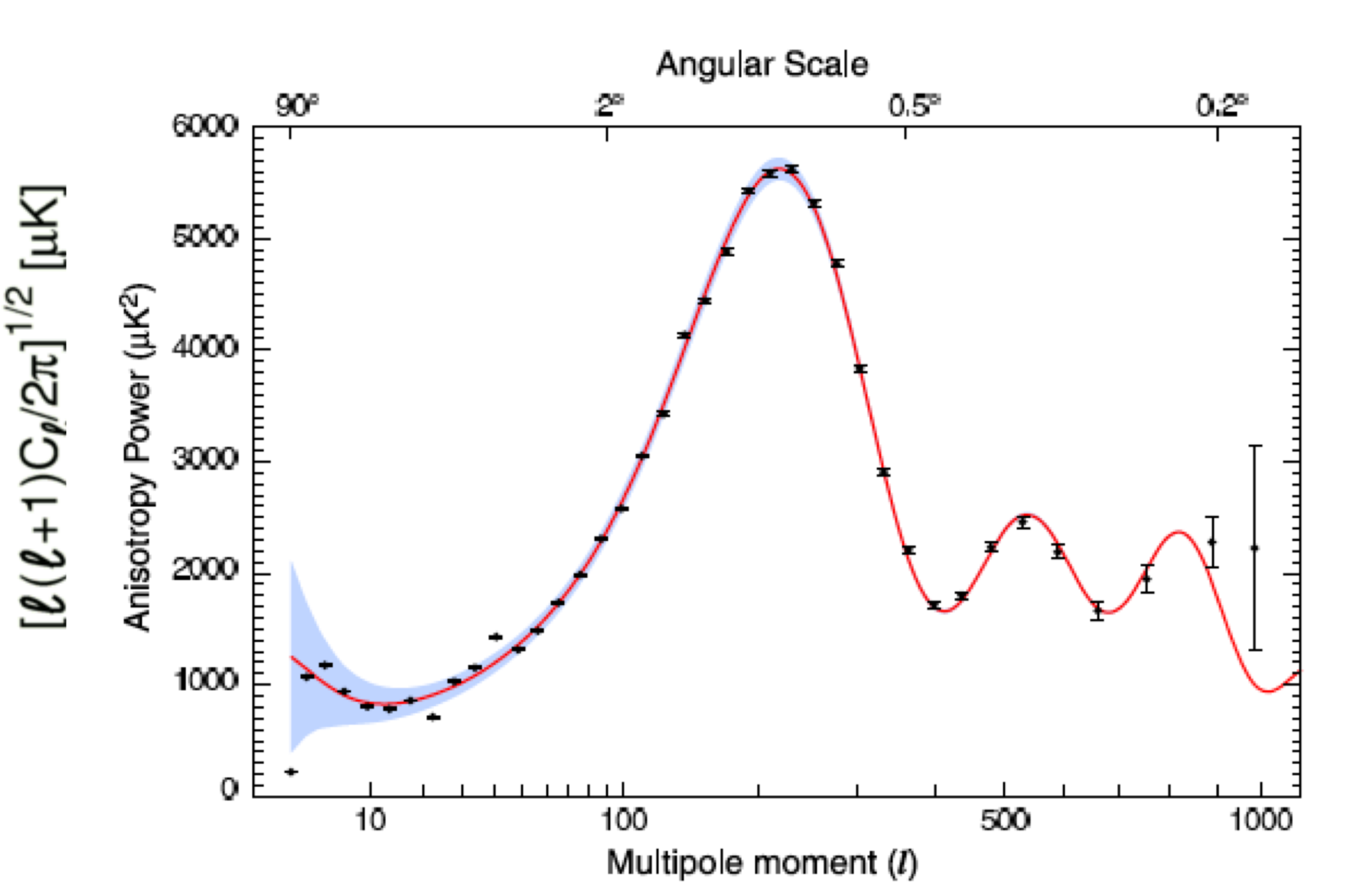
Higher order multipole patterns



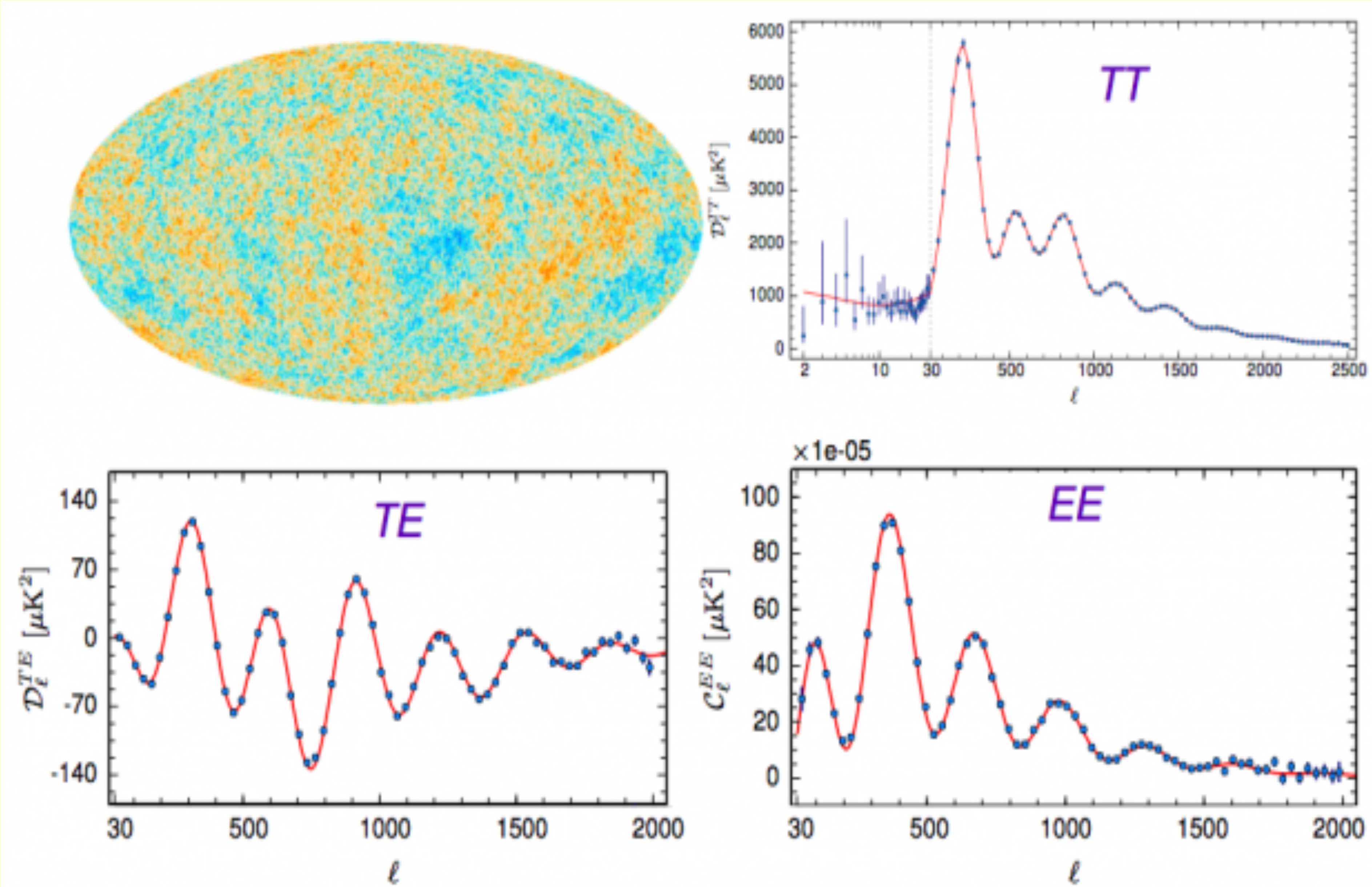
Higher order multipole patterns



CMB Anisotropies



CMB Anisotropies : polarization



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Olbers' Paradox: The Night Sky is Dark

Is this a problem?

- Not if stars are points of light stuck onto a dome

- But yes, in post-Copernican models
  - stars are scattered through space
  - (or galaxies are…)

The Simplest Model

- Universe infinitely large
- Uniformly filled with stars
- Infinitely old

Surface Brightness of the Sky

- Sum over all stars: J is infinitely large

$$J = \frac{1}{4\pi}\int_0^\infty \frac{L}{4\pi r^2} n(4\pi r^2 dr) = \frac{nL}{4\pi}\int_0^\infty dr = \infty$$

- Sum up to the mean free path d=1/(nπR²)

$$J = \frac{nL}{4\pi}\int_0^d dr = \frac{nL}{4\pi}\frac{1}{n\pi R^2} = \frac{L}{4\pi^2 R^2}$$

Still as bright as the disk of an individual star

What does this imply?

- One or more of the assumptions are wrong
  - recognized to be a problem already in 1576 by Thomas Digges (vs Copernicus 1543)
- Obscuring stars by dust does not work
  - proposed as a solution in 1744 by de Chesaux and in 1826 by Heinrich Olbers
- Infinitely old, infinitely large, Euclidean universe is self-contradictory.
  - innocuous-looking puzzle lasts into 20th century until discovery of the expansion of the universe

Resolution in Standard Model

- Finite age / volume
- Frequencies redshift
- Galaxies evolve
- NB: Einstein did not take note problem when trying to maintain static model

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Large-Scale Structure Measurements

Modern Pillars of Standard Model:

based on inhomogeneities

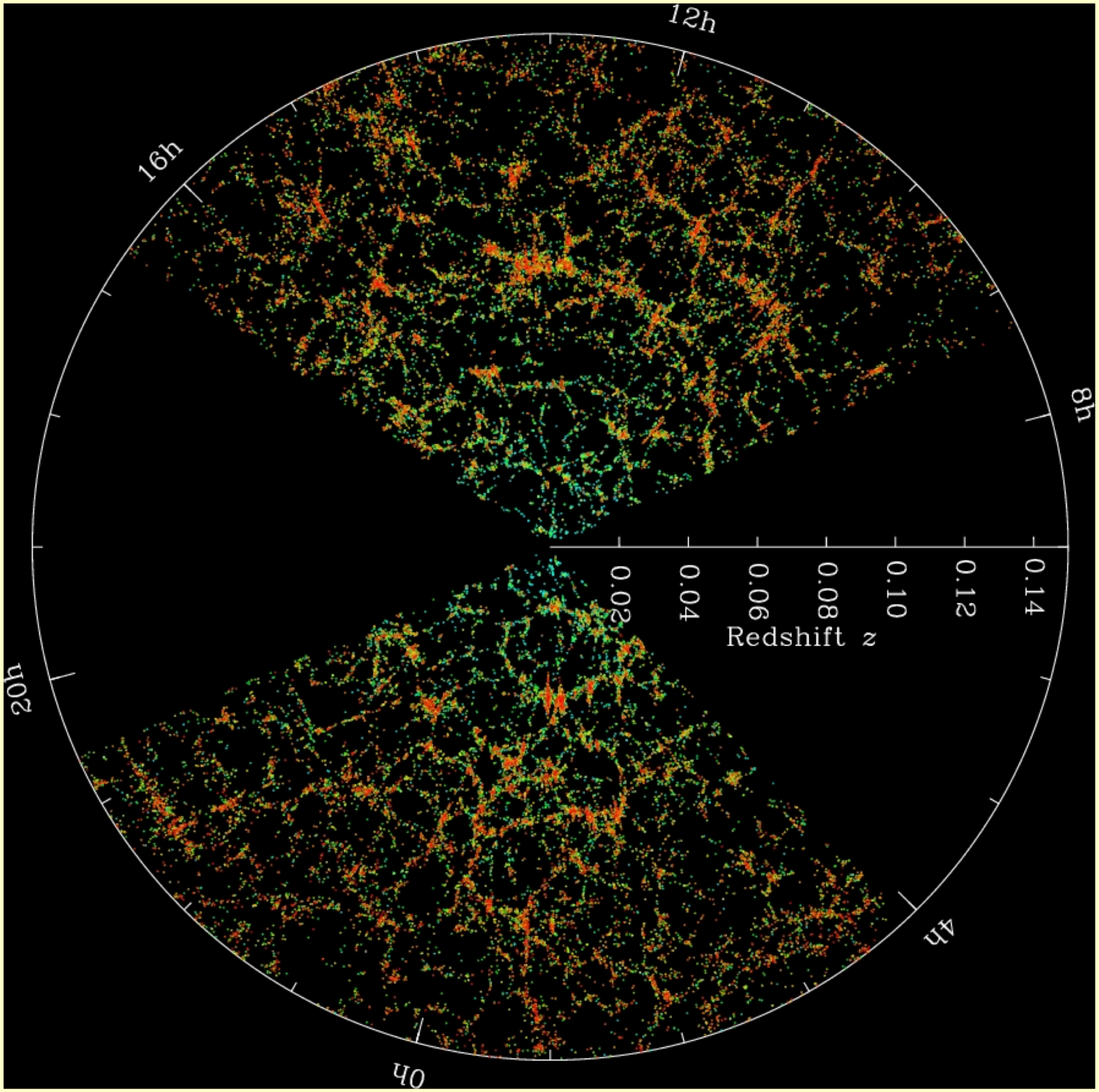
- Galaxy distribution / power spectrum
- Baryon Acoustic Oscillations
- Abundance of nonlinear objects (galaxy clusters)
- Weak gravitational lensing statistics

Galaxy Distribution

Number density $n(r)$ of galaxies traces total matter density $\rho(r)$

- 2 large recent surveys: 2dF, SDSS (->BOSS)
- SDSS covers 10,000 sq. degrees
- Approx 1.5 million redshifts

Galaxy distribution



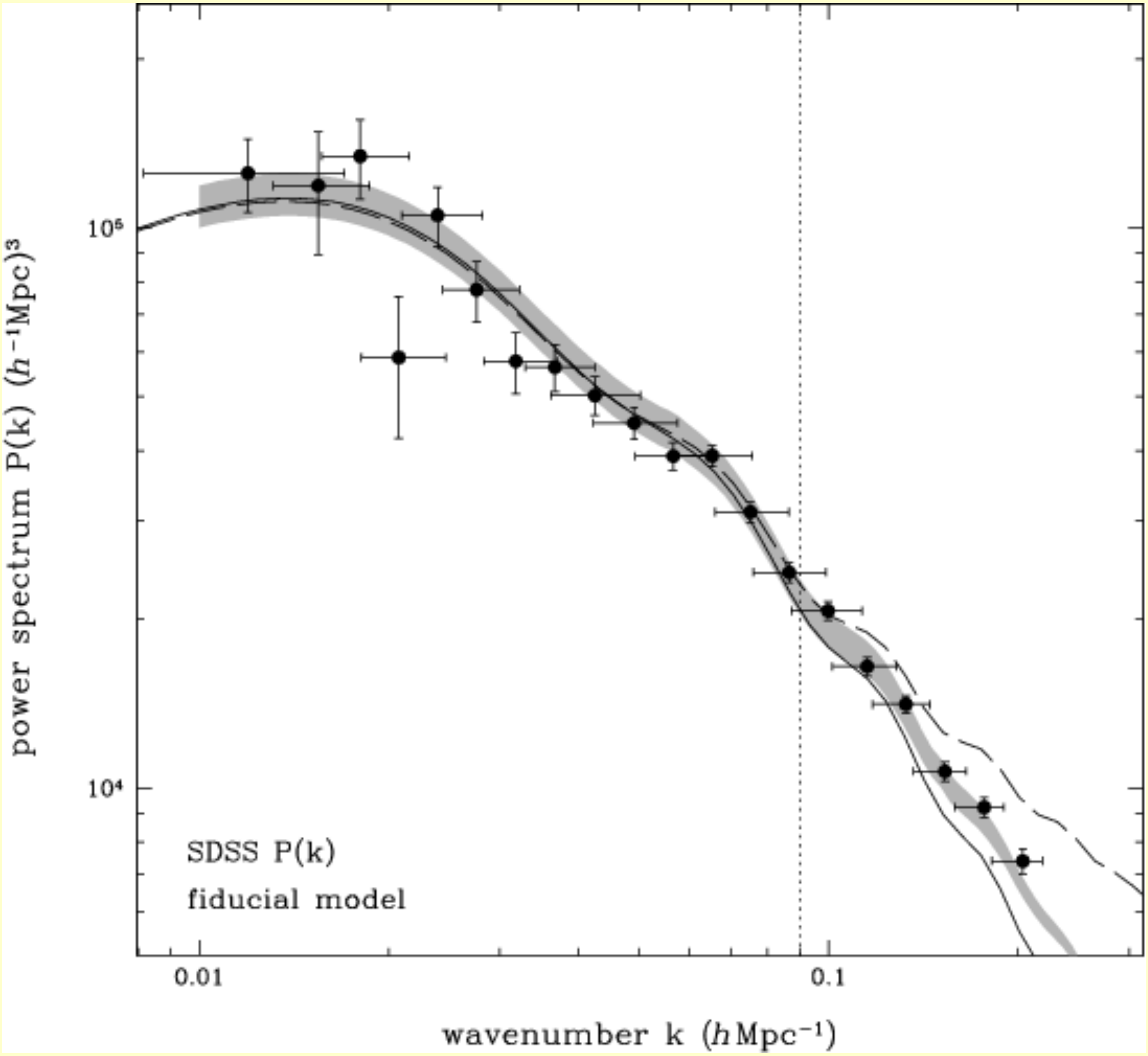
Sloan Digital Sky Survey (SDSS)

www.sdss.org

~10^8 galaxies out to ~1 Gpc

[z~0.2 v~60,000 km/s]

Galaxy Power Spectrum (3D)



power spectrum

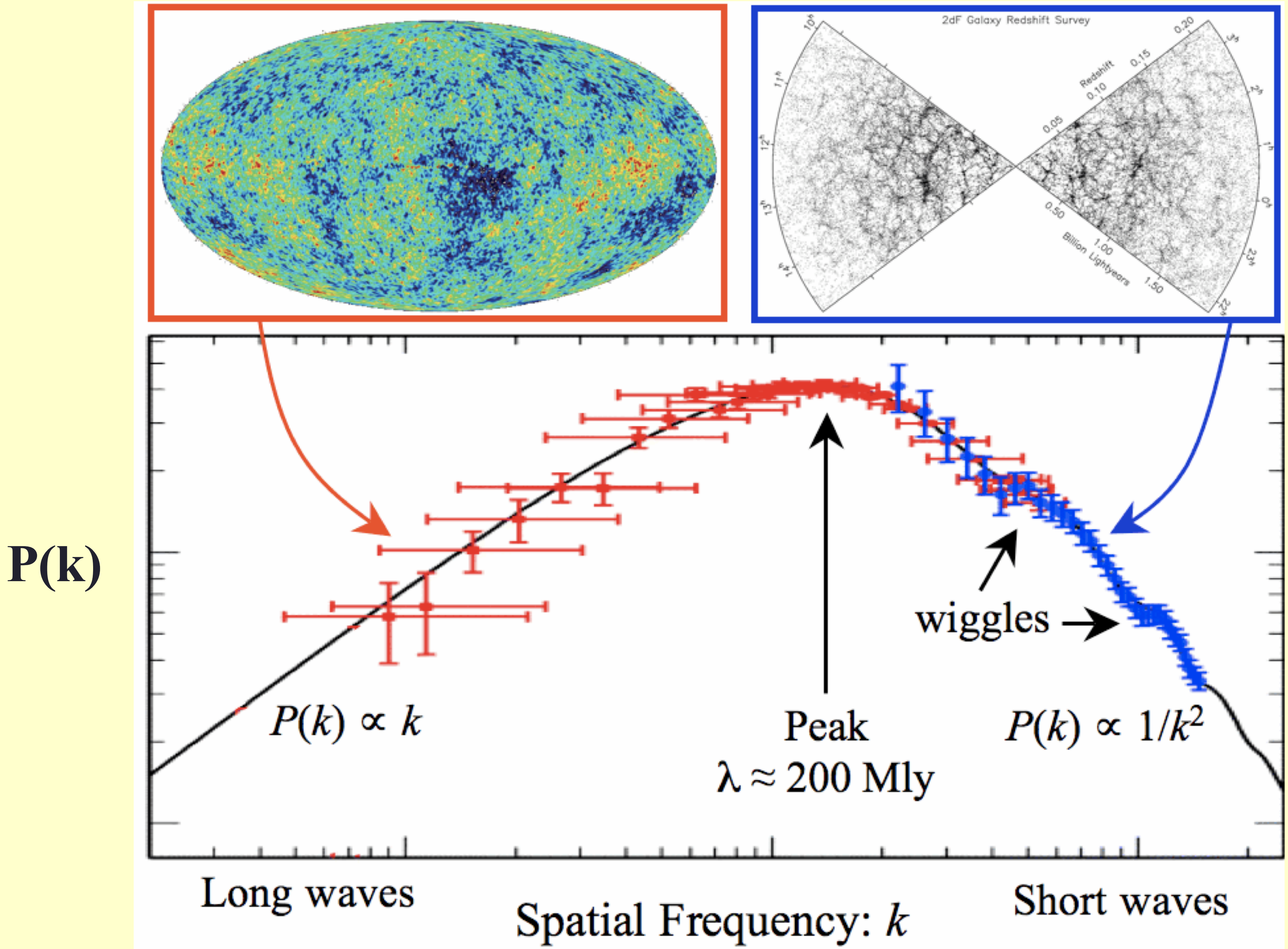
$\langle\delta(\mathbf{k})\ \delta(\mathbf{k'})\rangle =$

$(2\pi)^3 \delta_D\ (\mathbf{k}\text{-}\mathbf{k'}) P(k)$

(assuming the cosmological principle)

SDSS LRGs (Yoo+09)

Galaxy Power Spectrum vs CMB



Large-Scale Structure Measurements

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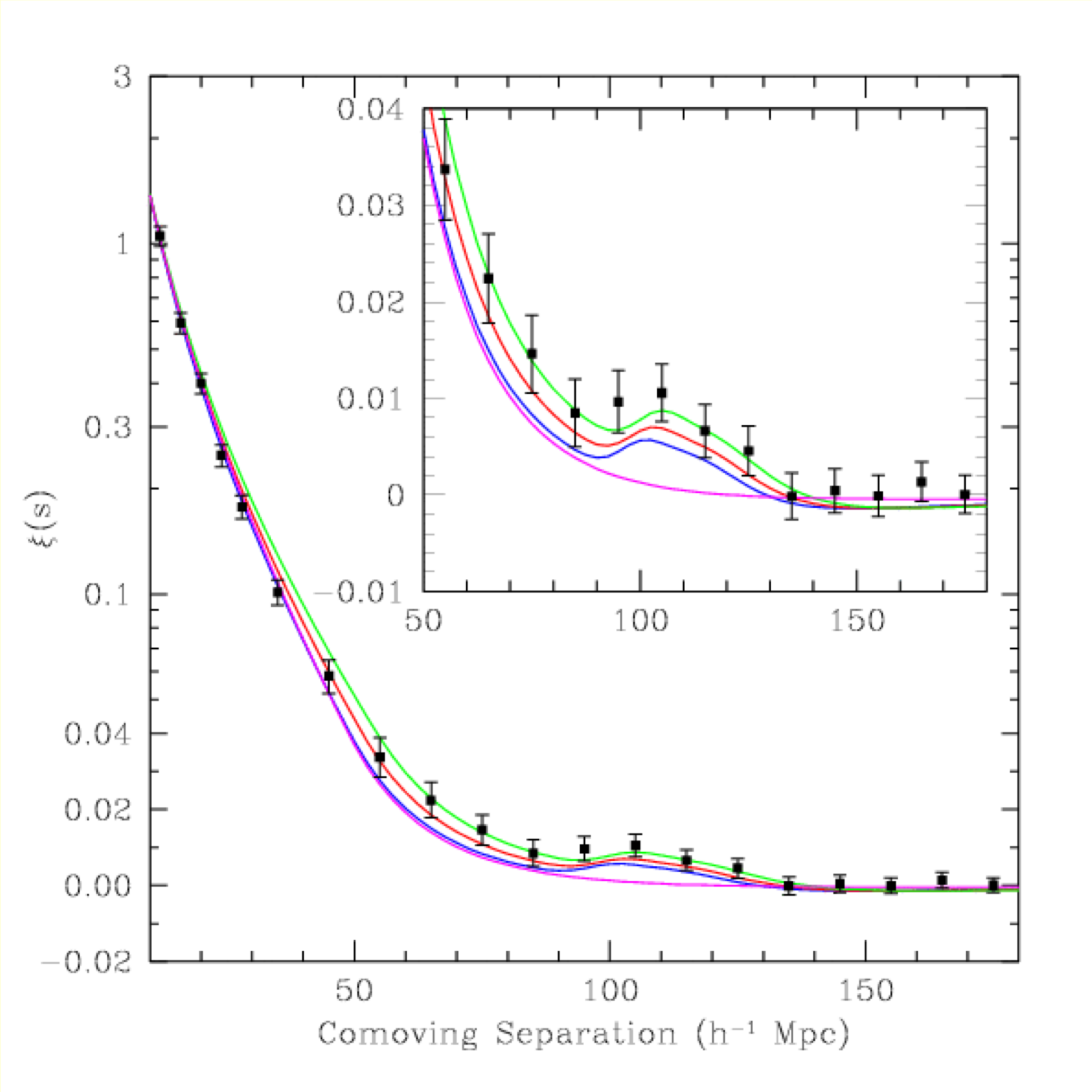
Baryon Acoustic Oscillations ("BAOs")



Feature in galaxy correlation function <n(r)>=<n>[1+ξ(r)]

First measurement based on ~50,000 galaxies in SDSS (Eisenstein et al. 2005)

Main goal of BOSS

Large-Scale Structure Measurements

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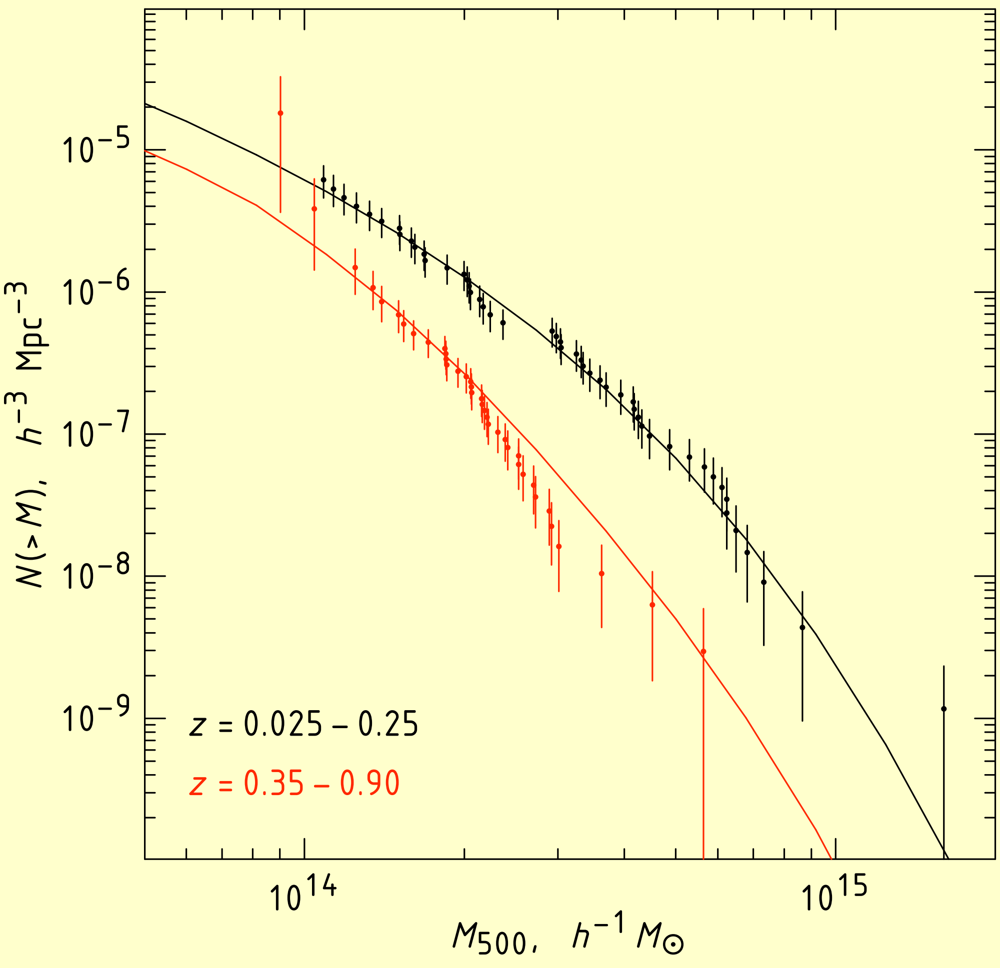
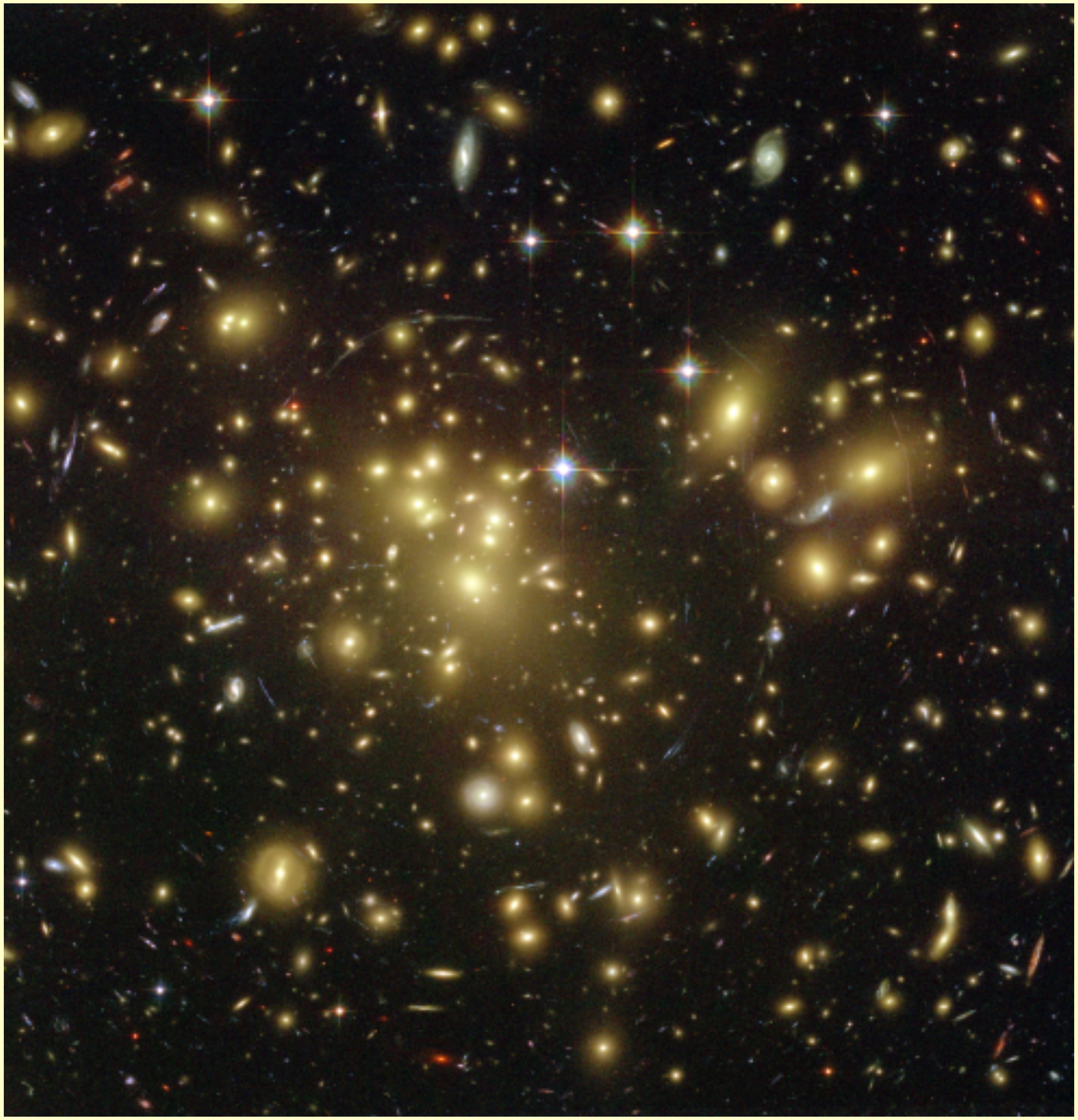
Galaxy Cluster Abundance

Large X-ray survey with Chandra (Vikhlinin et al. 2009)



Gravitational Lensing



Abell 1689

Large-Scale Structure Measurements

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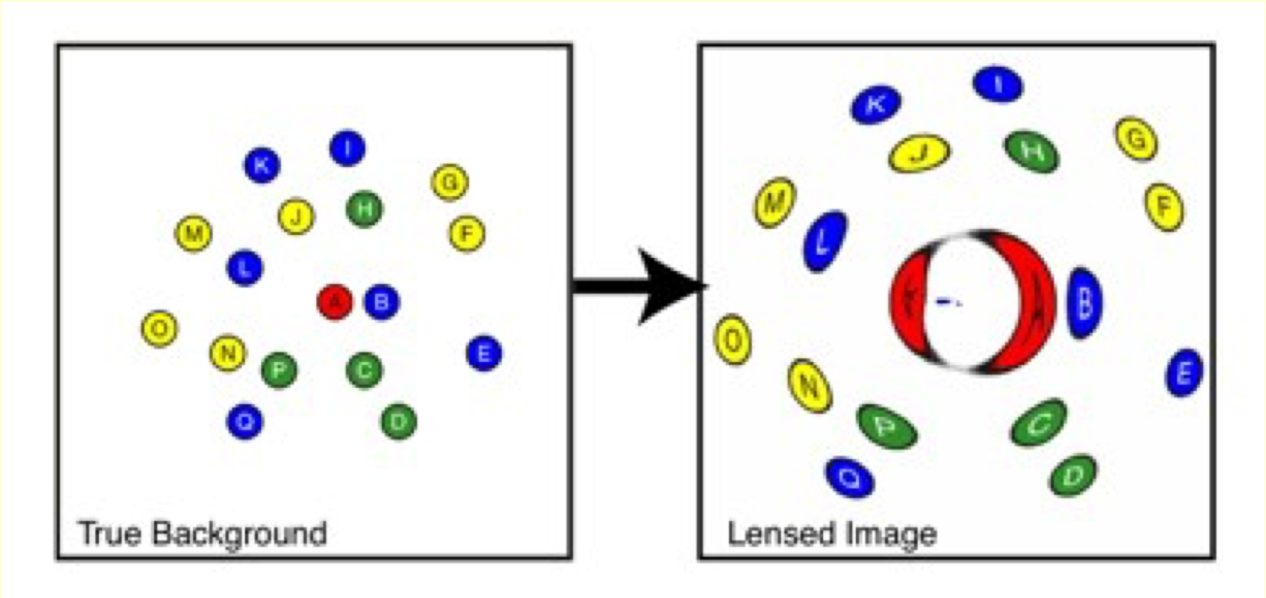
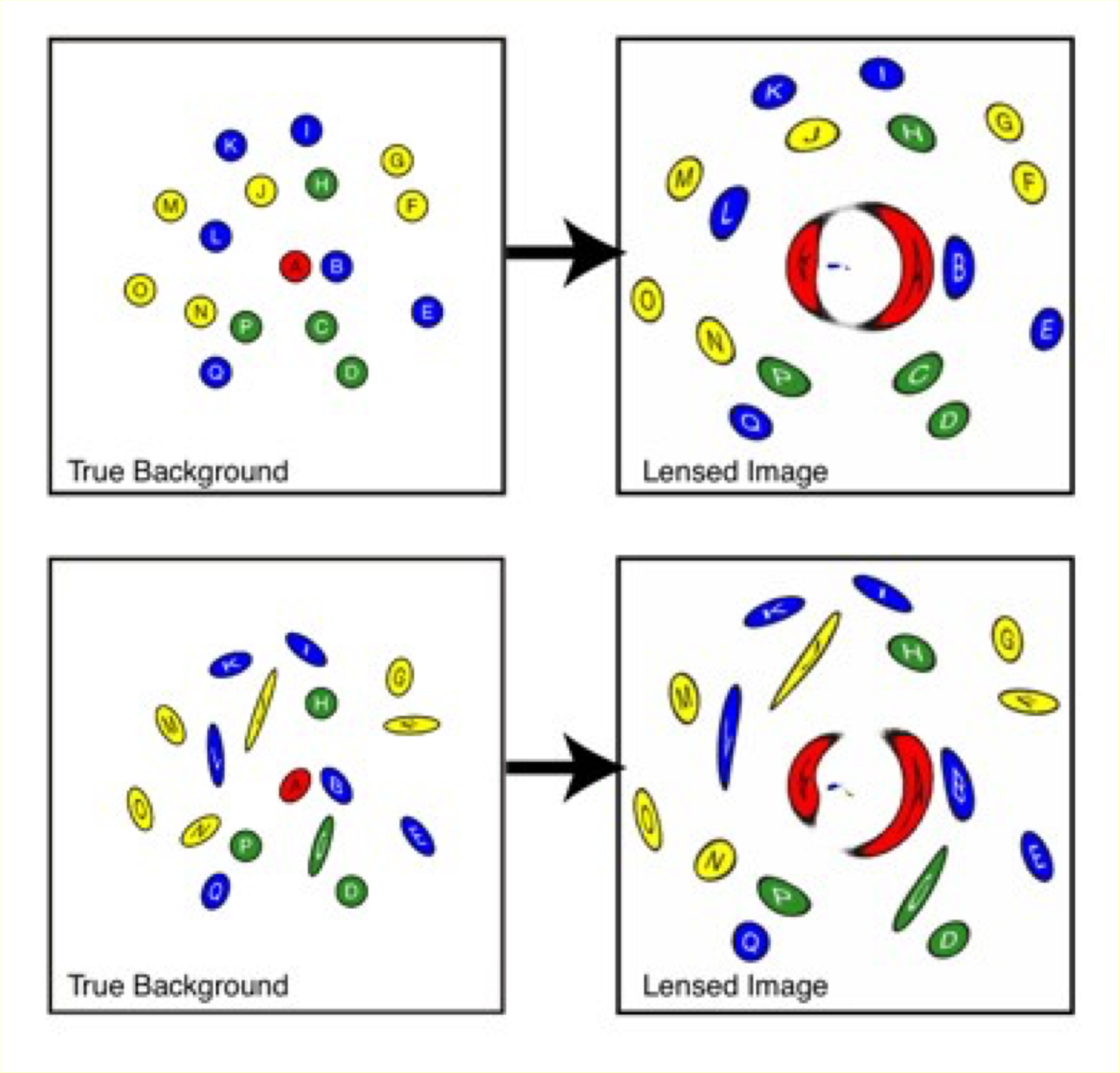
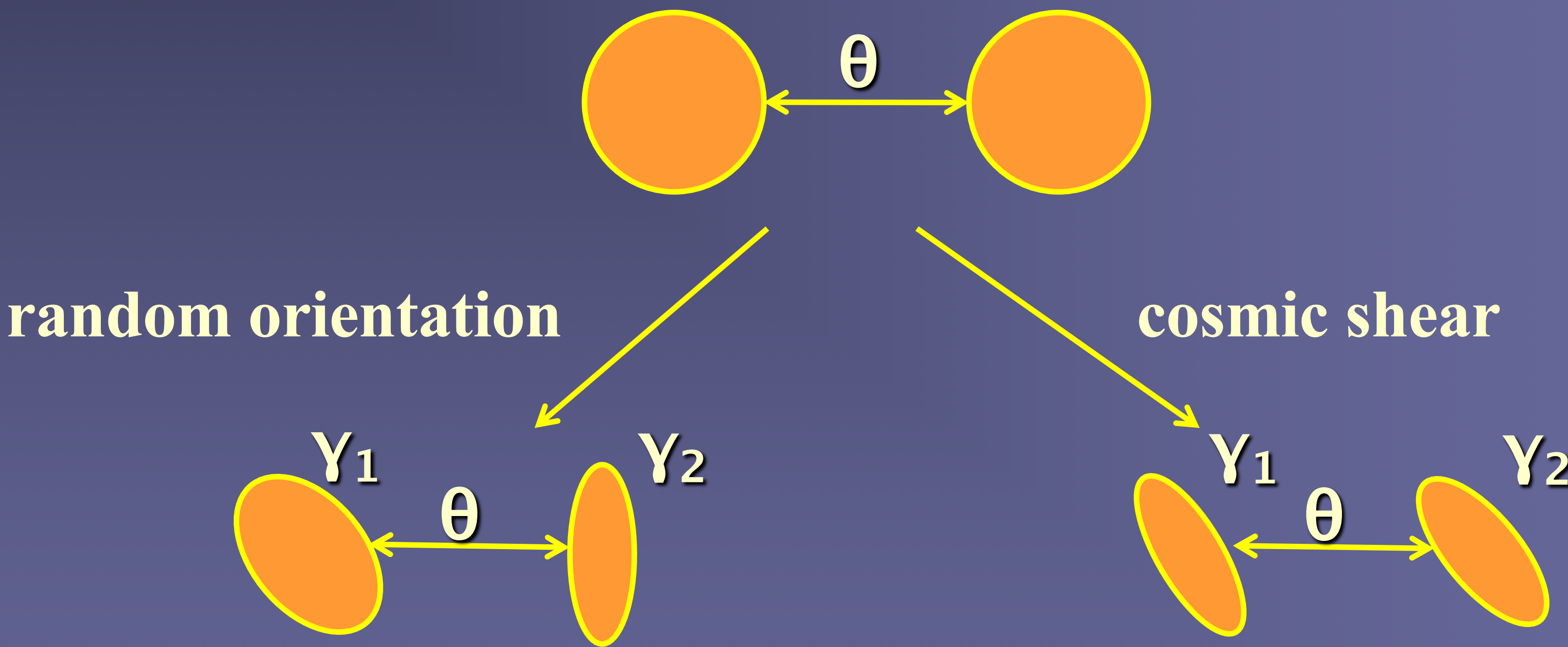
Weak Gravitational Lensing



Weak Gravitational Lensing



Weak Lensing by Large Scale Structure



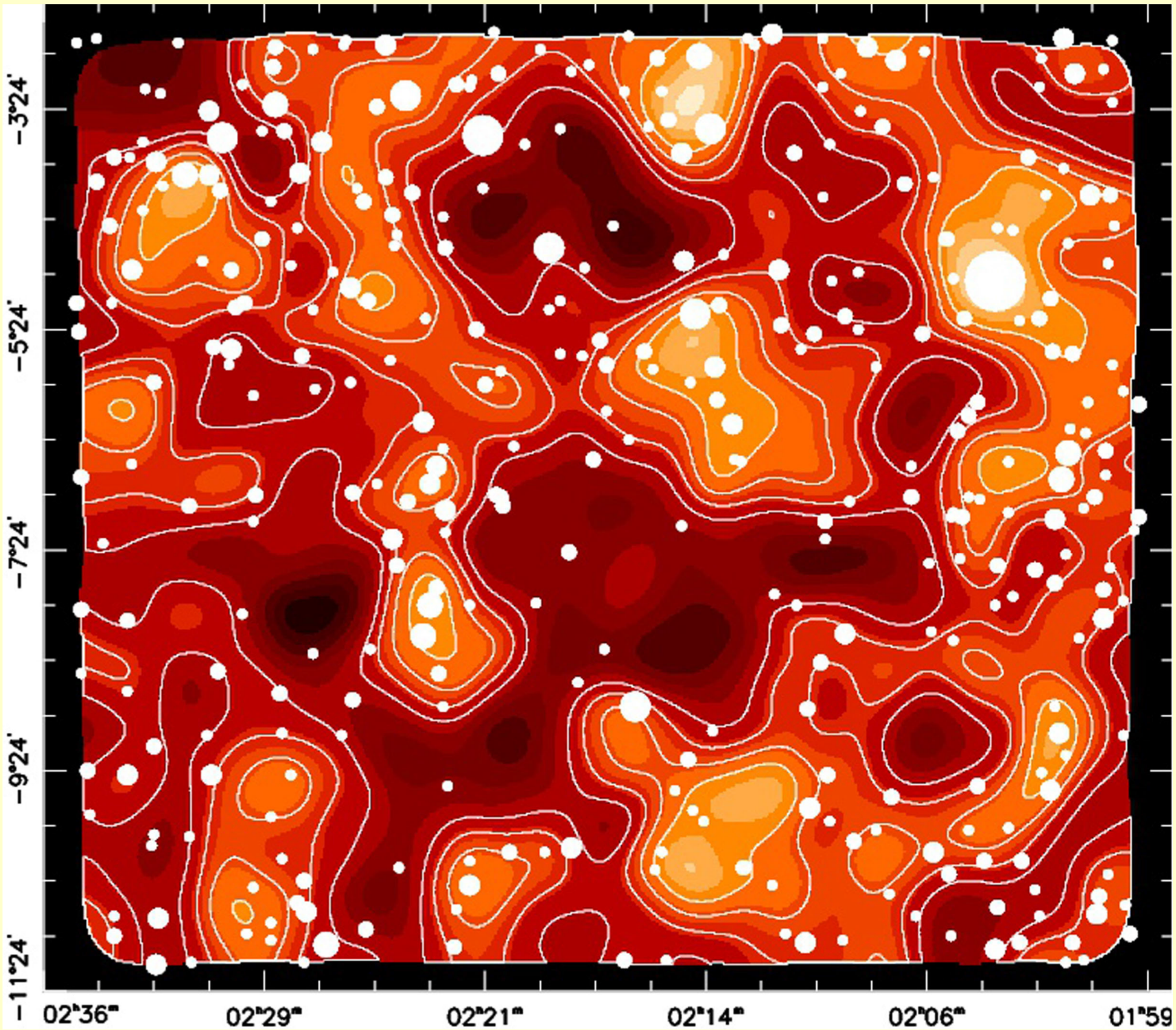
$C(\theta) = \langle \gamma_1 \gamma_2 \rangle = 0$ $C(\theta) = \langle \gamma_1 \gamma_2 \rangle \approx 10^{-4} \neq 0$

signal is weak, must average over many* galaxies

- *$(0.3/\sqrt{900}) = 0.01$ → $10^3 \times 10^4 = 10^7$ galaxies for 1% error on $\gamma \sim 0.01$*
- *→ need ~200 deg^2 for ~10 galaxies $arcmin^{-2}$*

Weak Gravitational Lensing Power Spectrum

First such large survey in 2013 (CFHTLenS) – 7 million galaxies in 154 deg^2



Weak Gravitational Lensing Power Spectrum

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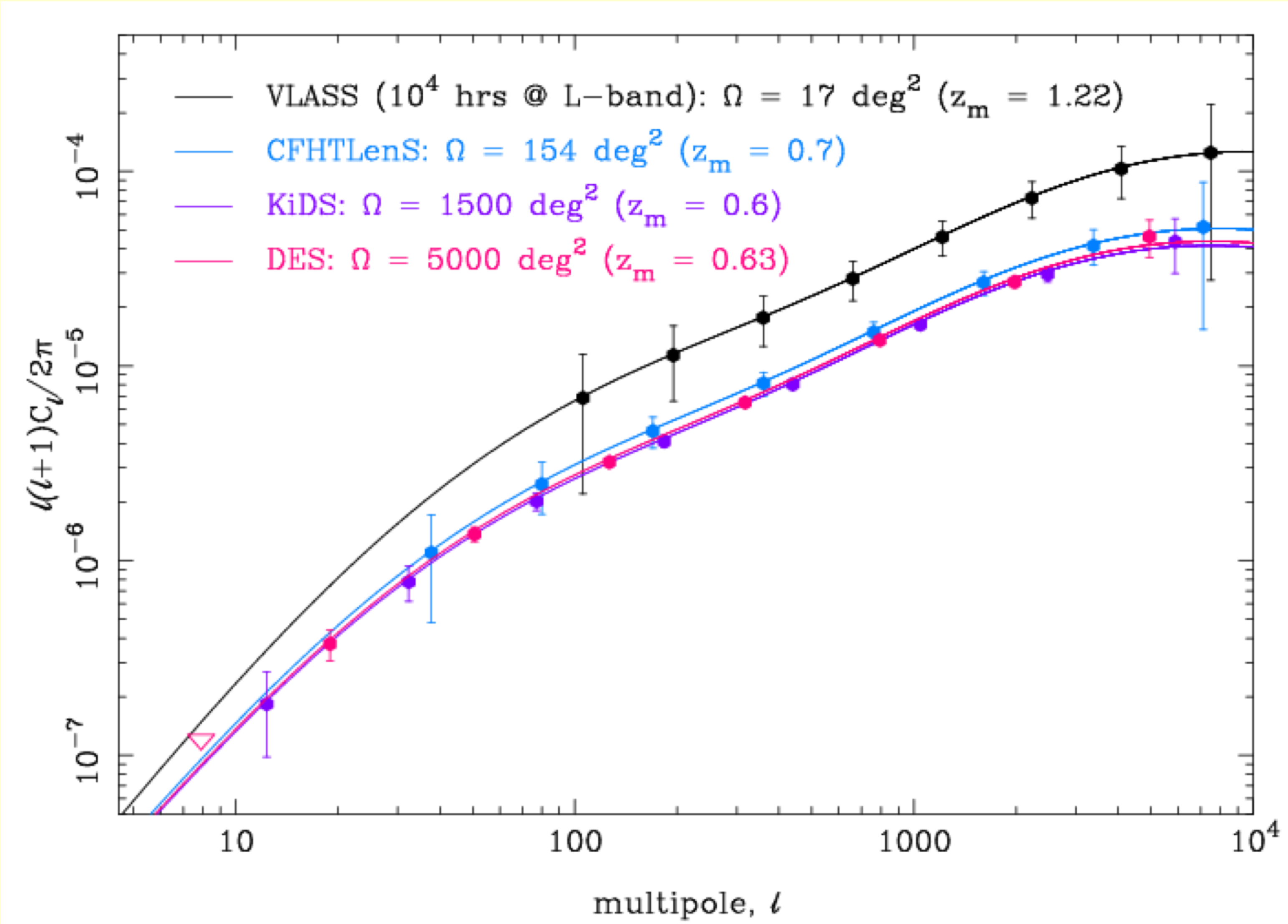
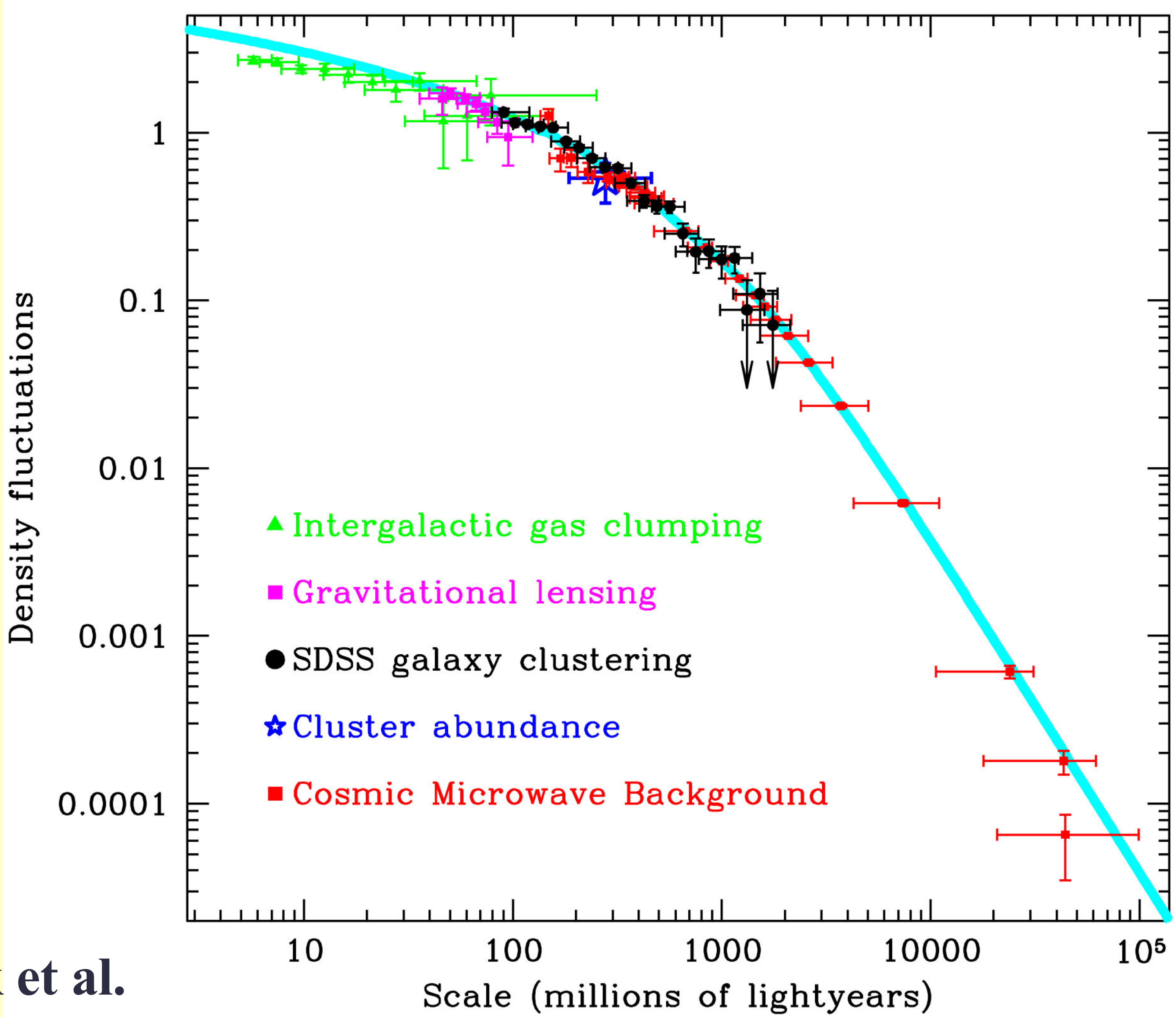


Composite Matter Power Spectrum



Tegmark et al.