Evidence for Dark Matter

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Overview

- The primary evidence for dark matter is that
  - calculations show that many galaxies would fly ap[illegible] would not have formed or move as they do, if they d[illegible] ount of unseen matter.[2]

Other lines of evidence include

- observations in gra[illegible]
- from the c[illegible] ound,
- f[illegible] ations of the observable universe's current structure,
- [illegible] ion and evolution of galaxies,
- [illegible] ass location during galactic collisions
- from the motion of galaxies within galaxy clusters.

⇒ there is FIVE TIMES as much DM in the Universe as "ordinary matter"

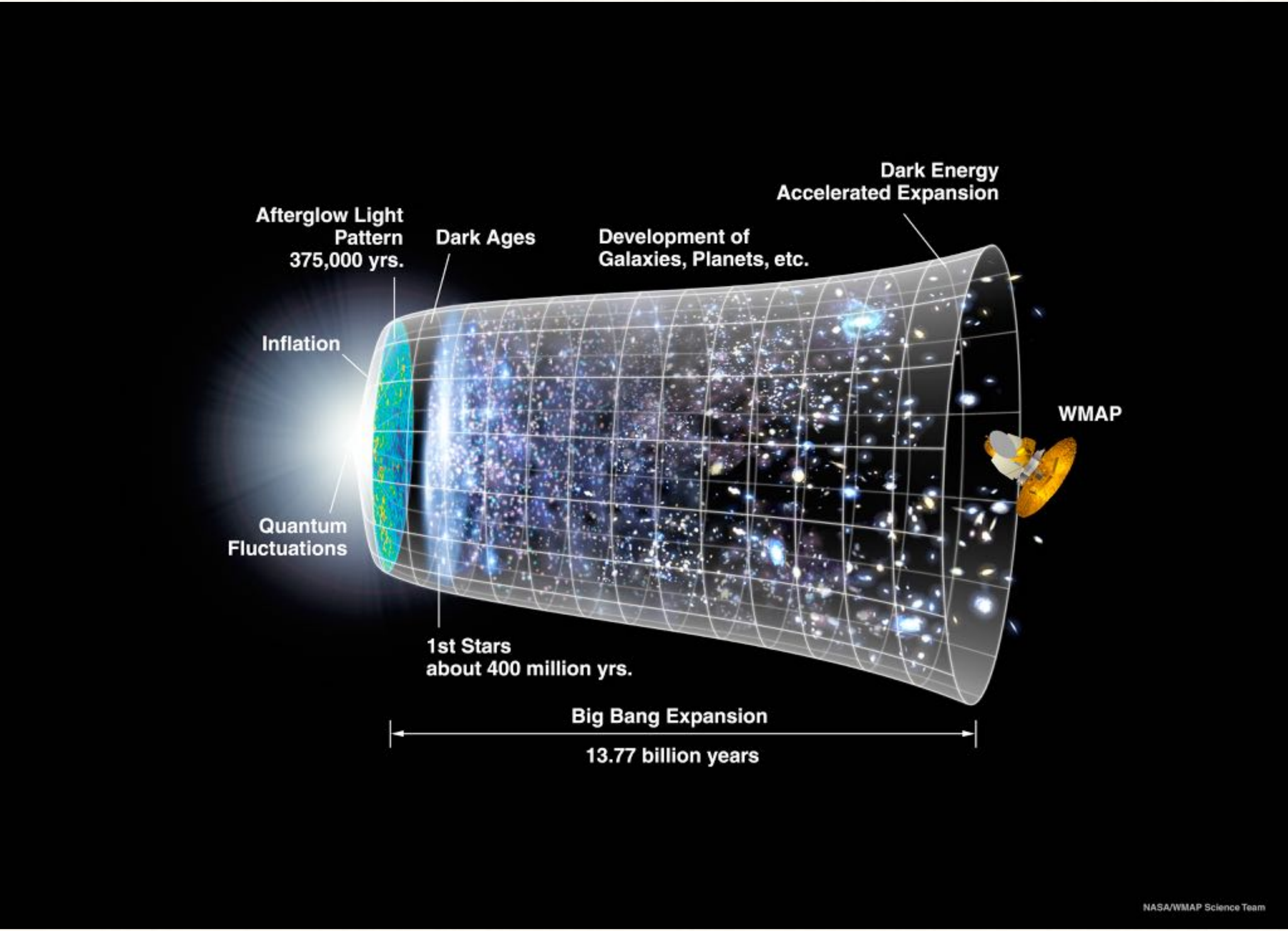
[Wikipedia]

Overview

- *But wait!* On the other hand…
    - Nobody has ever 'directly' detected or produced dark matter
    - We really only know what it apparently is *not* rather than what it is
    - It can apparently pass through the Earth without hindrance
- *Begs the question*: is DM just the current-day Luminiferous Aether? A theoretician's *kludge*?

Cosmological Probes of DM

Lectures 3 & 4


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

Cosmological Probes of DM

$$w = \frac{p}{\rho}$$

Equation of state for a perfect fluid; w is the EOS parameter

Cosmological Probes of DM

$$a = \frac{1}{1+z}$$

a is the scale factor (in the FRW metric)

$$h \equiv \frac{H}{100\ \text{km/s/Mpc}}$$

Cosmological Probes of DM

$$FRW: \quad \rho \propto a^{-3(1+w)}$$

`cold dust'

$$w = 0 \quad \rho \propto a^{-3}$$

ultra-relativistic fluid

$$w = \frac{1}{3} \quad \rho \propto a^{-4}$$

cosmological constant

$$w = -1 \quad \rho = const$$

CMB and Structure Formation

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- Origin of the density fluctuations is tight coupling *before recombination* between radiation and charged p^+ and e^- in the plasma; the radiation and baryons oscillate in phase
- Three competing effects to consider in the hydrodynamics: i) gravitational contraction; ii) density dilution due to Hubble flow; and iii) radiation pressure felt by the charge particles

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$$\frac{\delta\rho}{\rho}$$

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- The growth of structure over the history of the Universe constitutes a probe of the properties of the dark matter

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- Matter-radiation equality happens at T_{CMB} ~ 1 eV but recombination happens at a slightly later time of T_{CMB} ~ 0.3 eV (at t_{cosmo} ~ 380,000 years)

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- The CMB tells us that, at recombination, structure had already started to grow — so this means that, whatever sort of matter was causing the growth of structure, it could not be like $p^+ + e^- + \gamma$ fluid

CMB and Structure Formation

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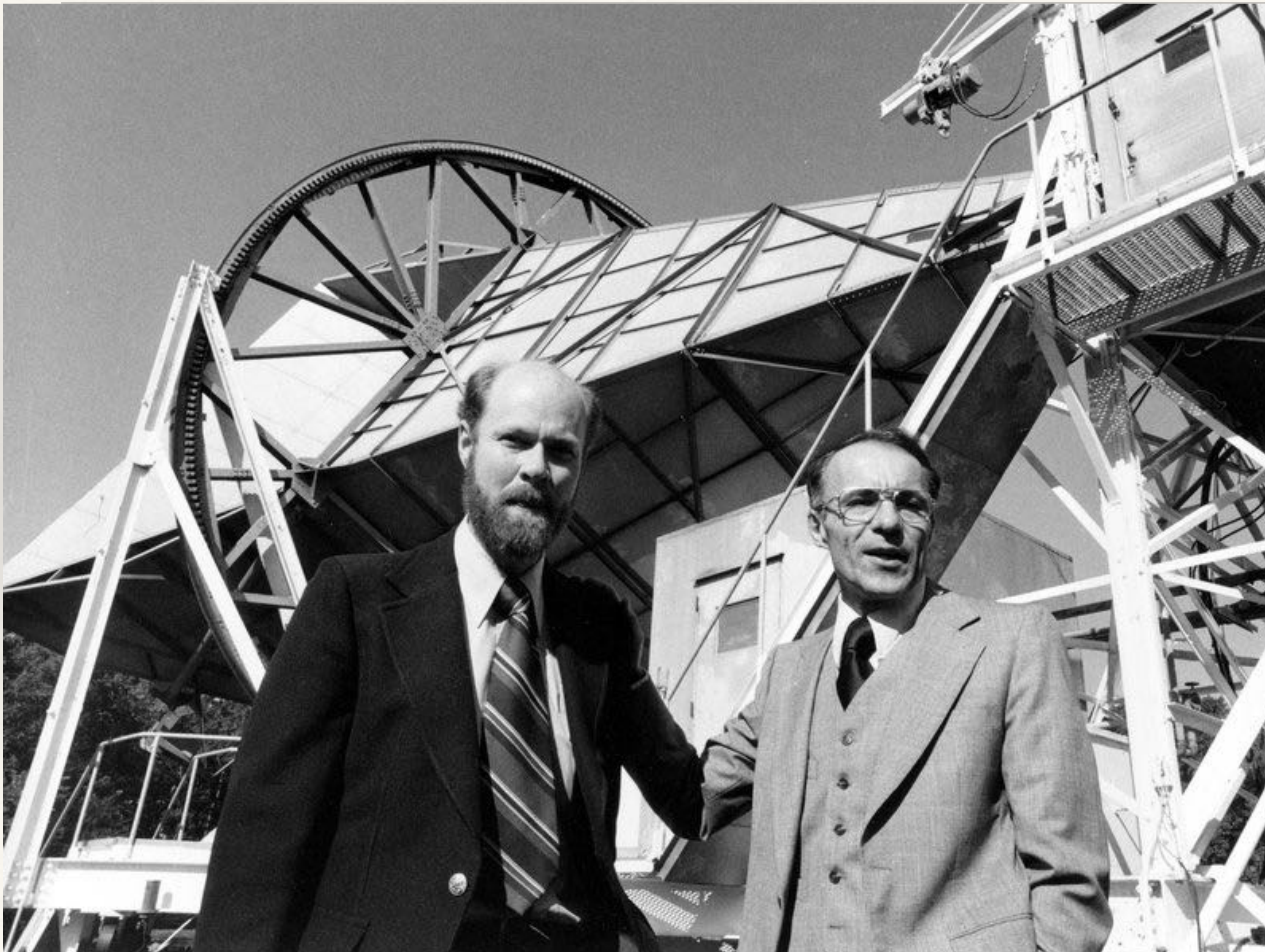
- Note that at recombination the radiation pressure vanishes

Cosmic Microwave Background Radiation

CMB



Penzias & Wilson

CMB signal detected 1964

Nobel Prizes 1978

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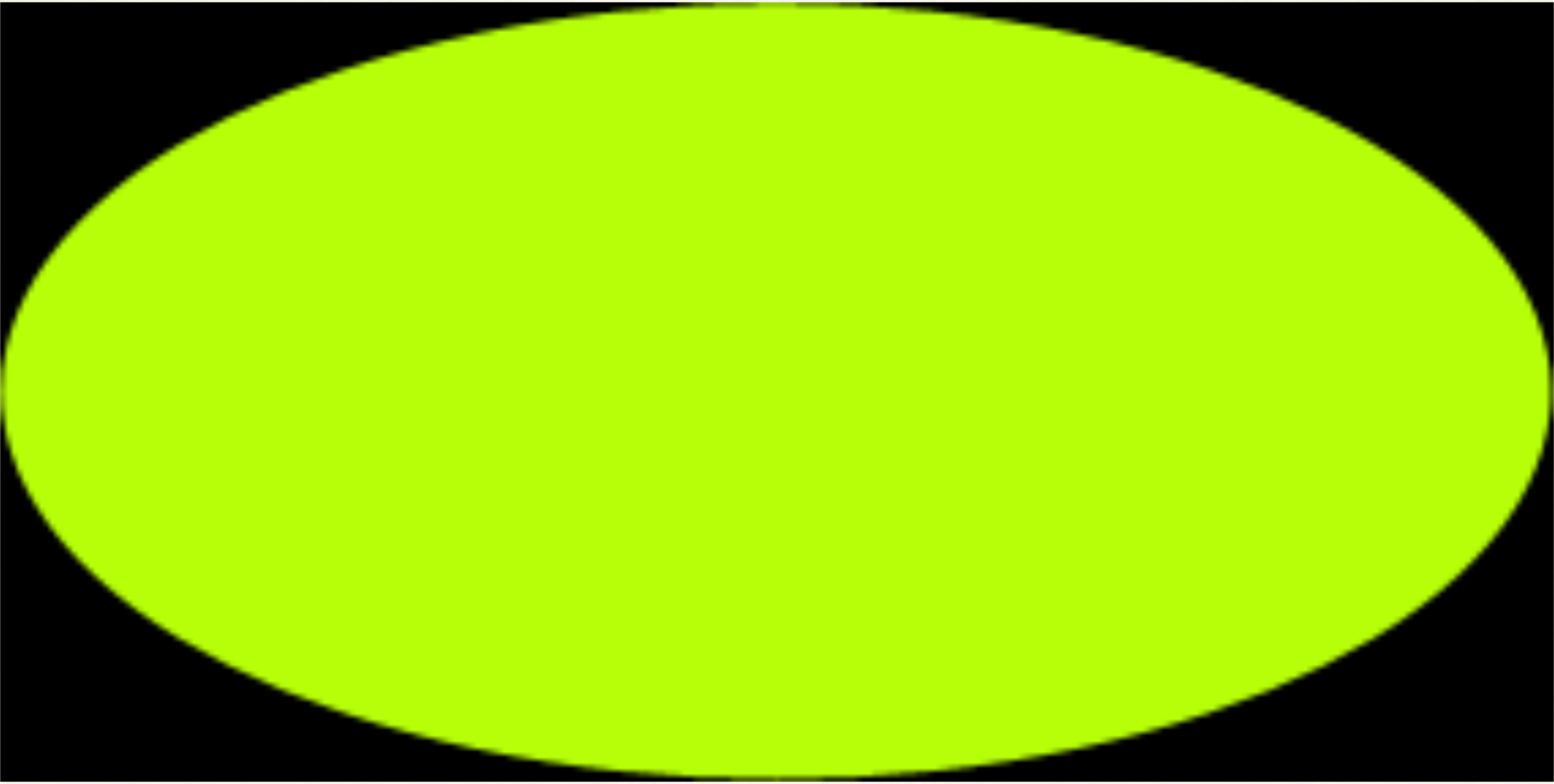
CMB: 2.73 K blackbody



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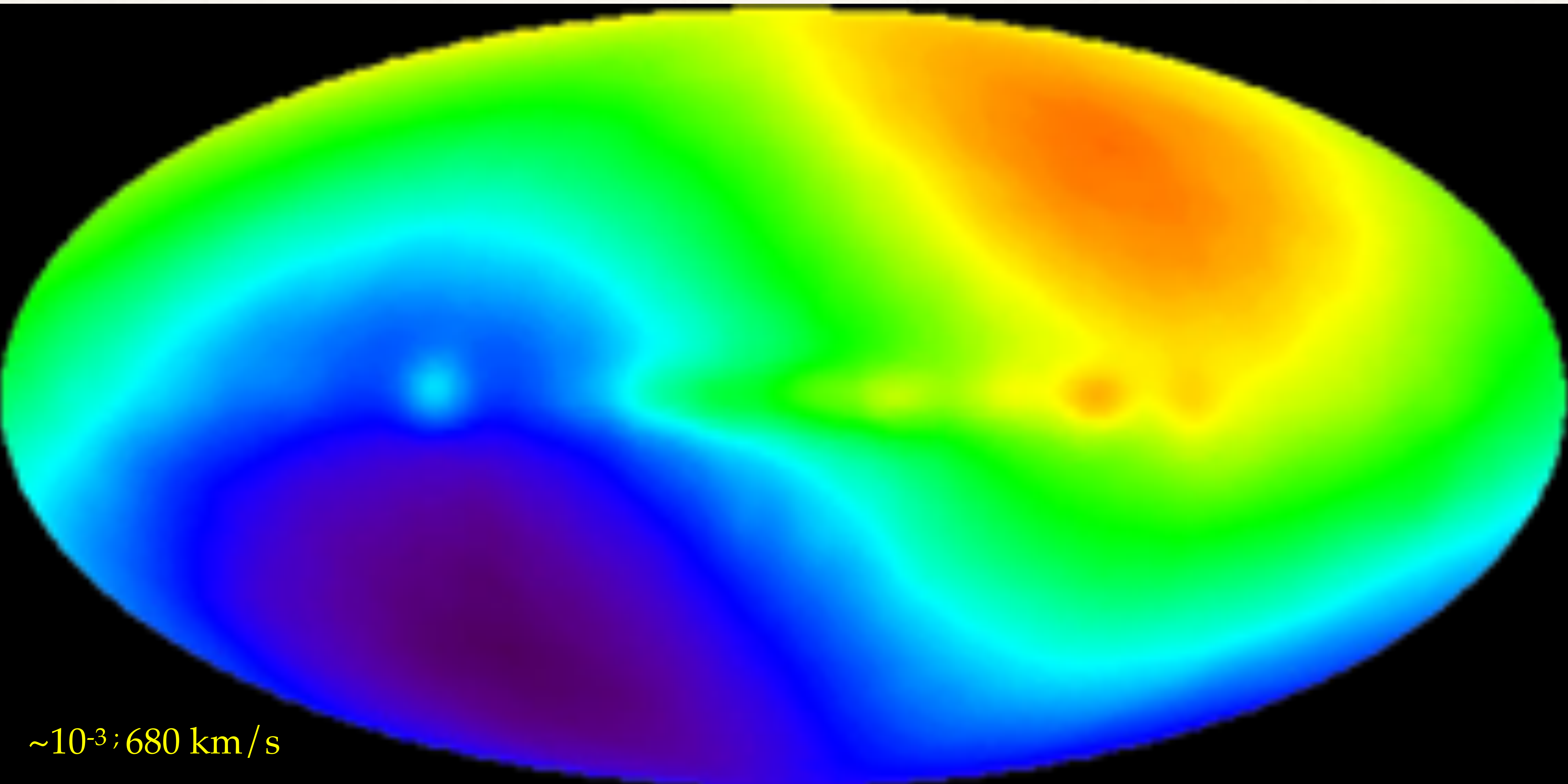
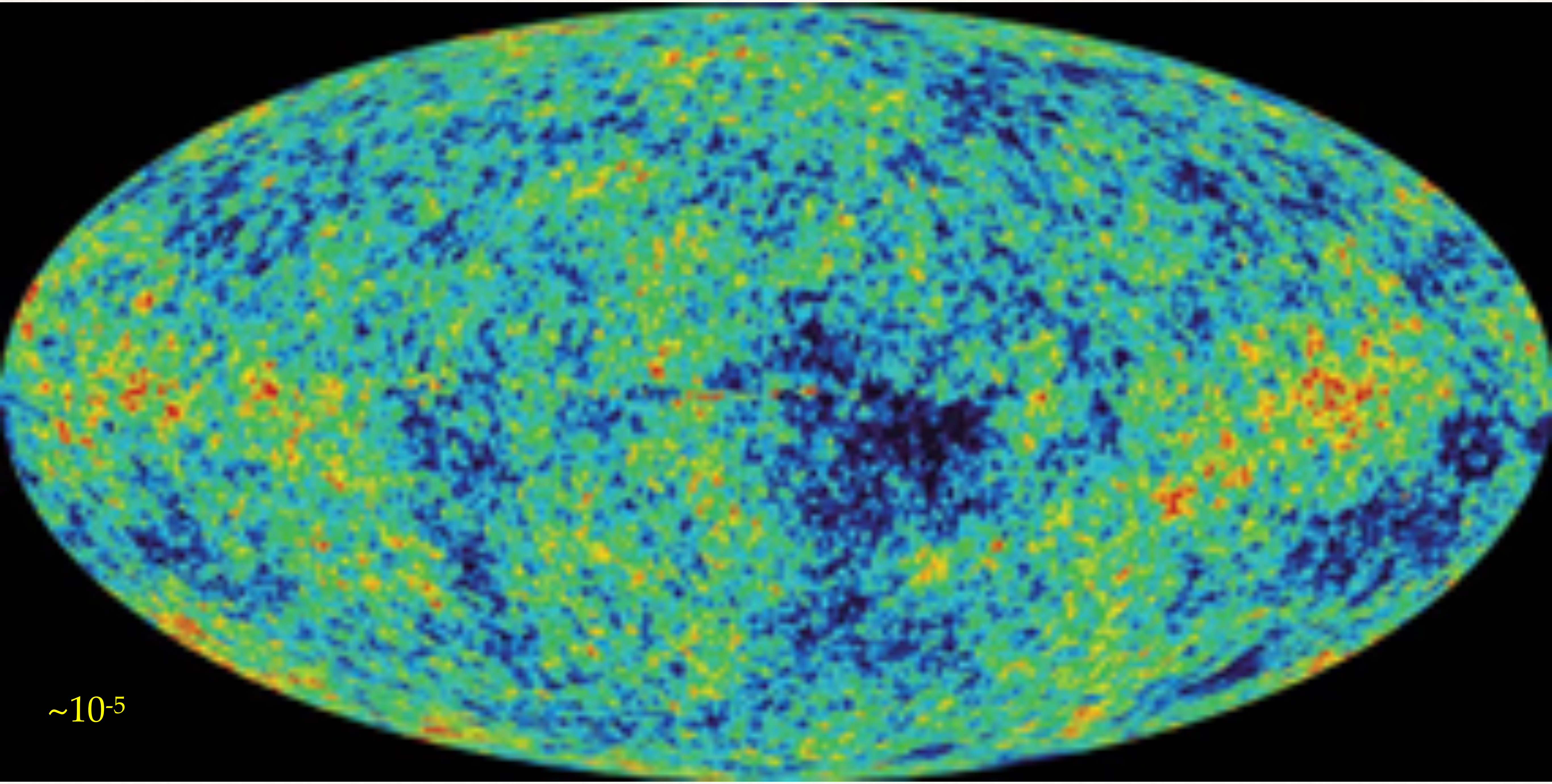
- but there are temp anisotropies that COBE and subsequent experiments could detect with increasing accuracy

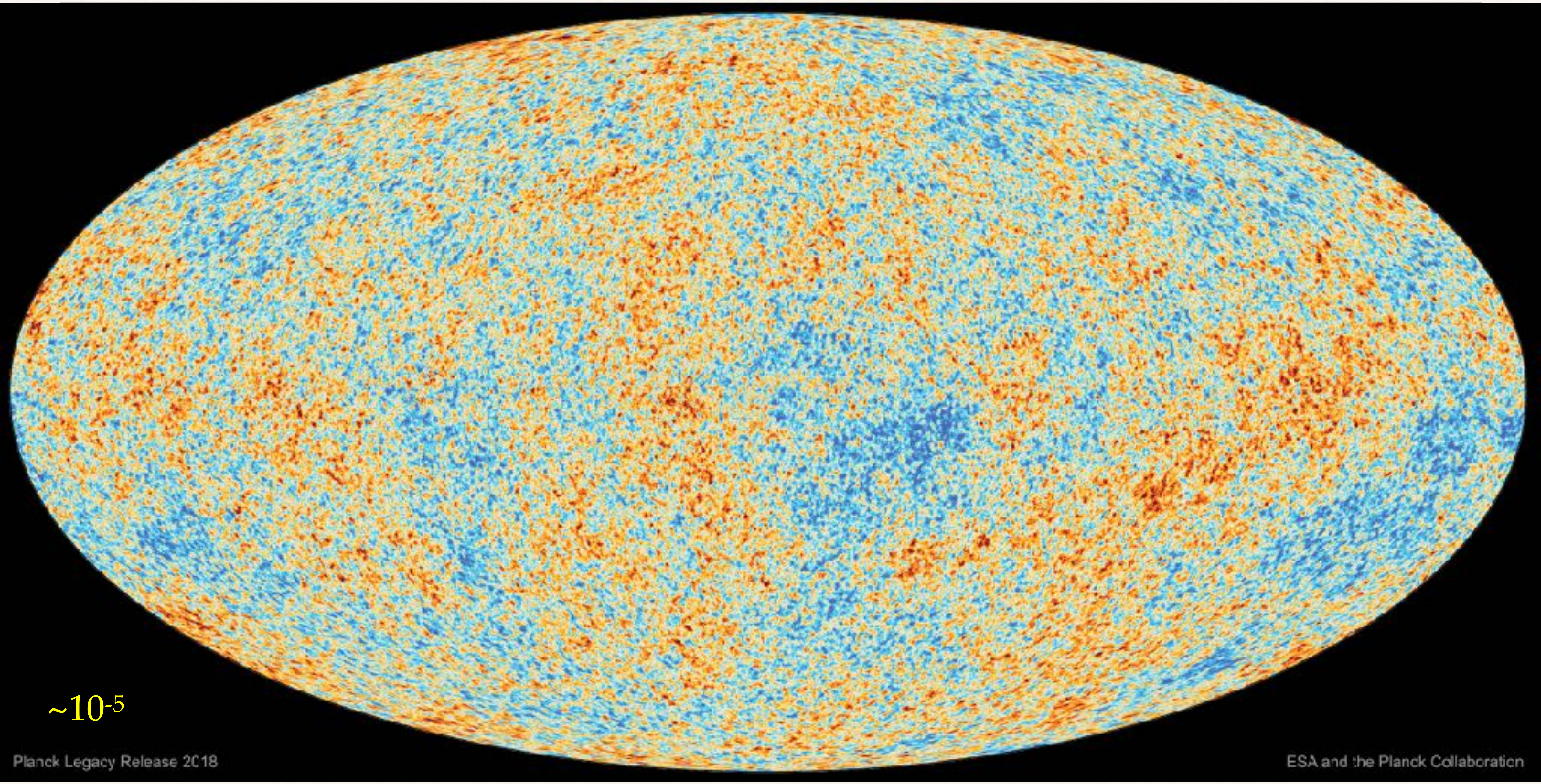
CMB dipole



CMB as seen by WMAP (Galaxy and dipole modelled out)



CMB as seen by Planck



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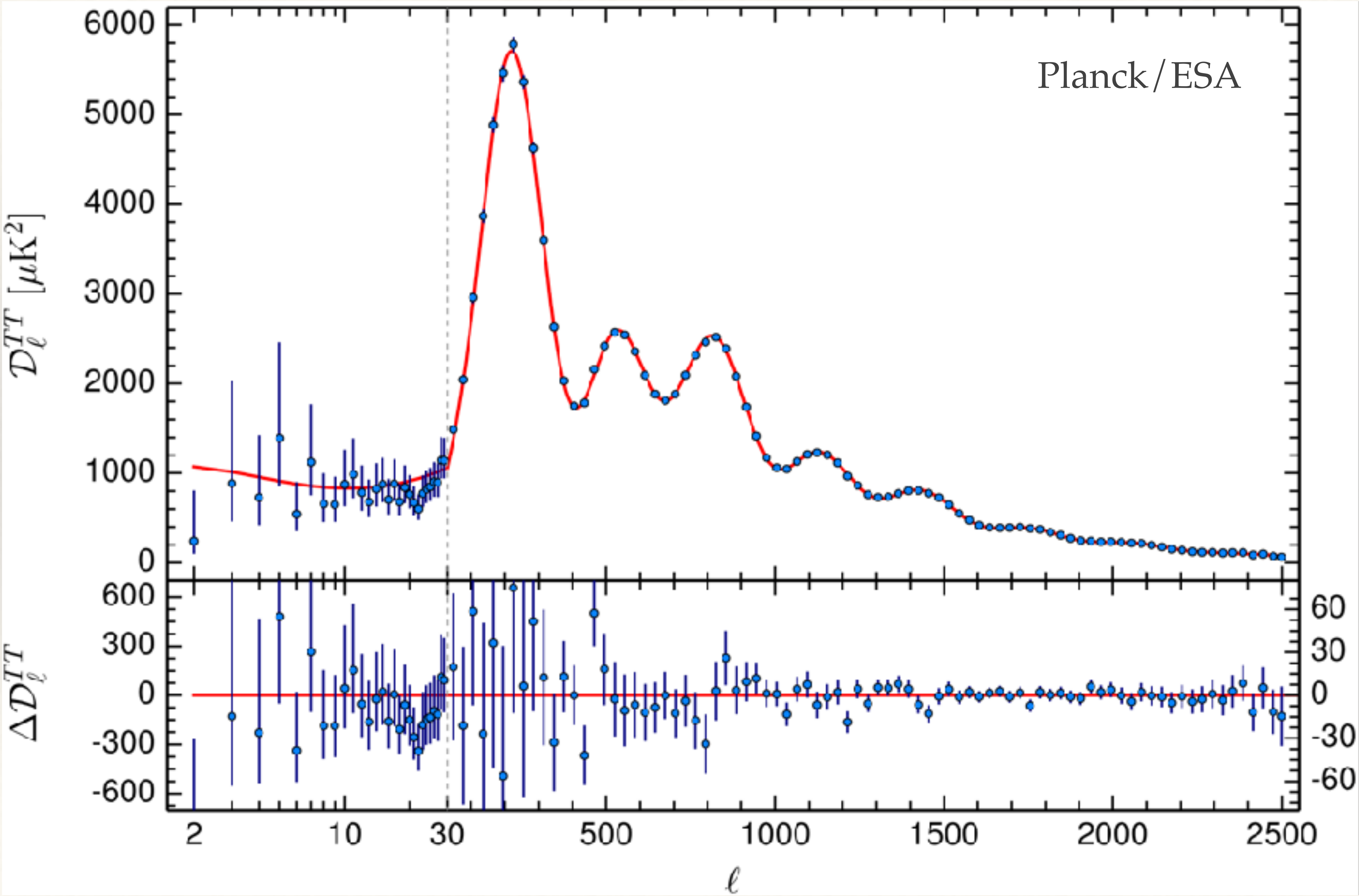
- there are also polarization anisotropies
- anisotropies inform both the total and the bayonic matter content of the Universe as well as the overall geometry

CMB Temperature Power Spectrum

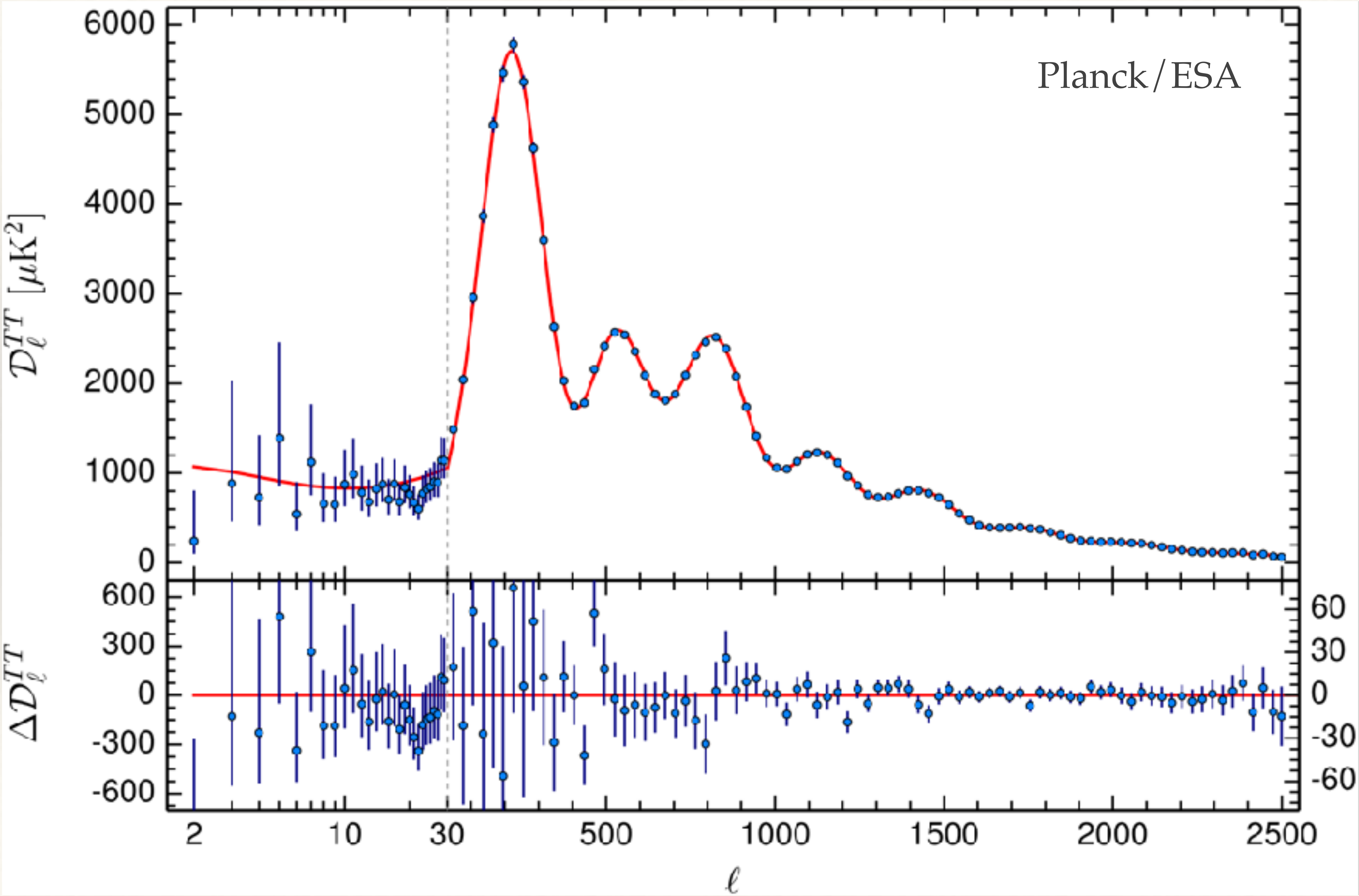


CMB Temperature Power Spectrum

- Before recombination, the combined photon/(ionised) baryon fluid acts like is has an internal pressure
- It therefore supports acoustic waves
- The fluid booms with multiple harmonics like an organ pipe but in a way set by *time* not length
- The power spectrum of the temperature fluctuations reveals the acoustic peaks
- The first peak is the largest sound wave that can undergo a half oscillation over the time from $t_{cosmo} = 0$ at BB to recombination at $t_{cosmo} = 380{,}000$ years
- The waves travel at the relativistic sound speed

$$c_s = \frac{c}{\sqrt{3}}$$

CMB Temperature Power Spectrum



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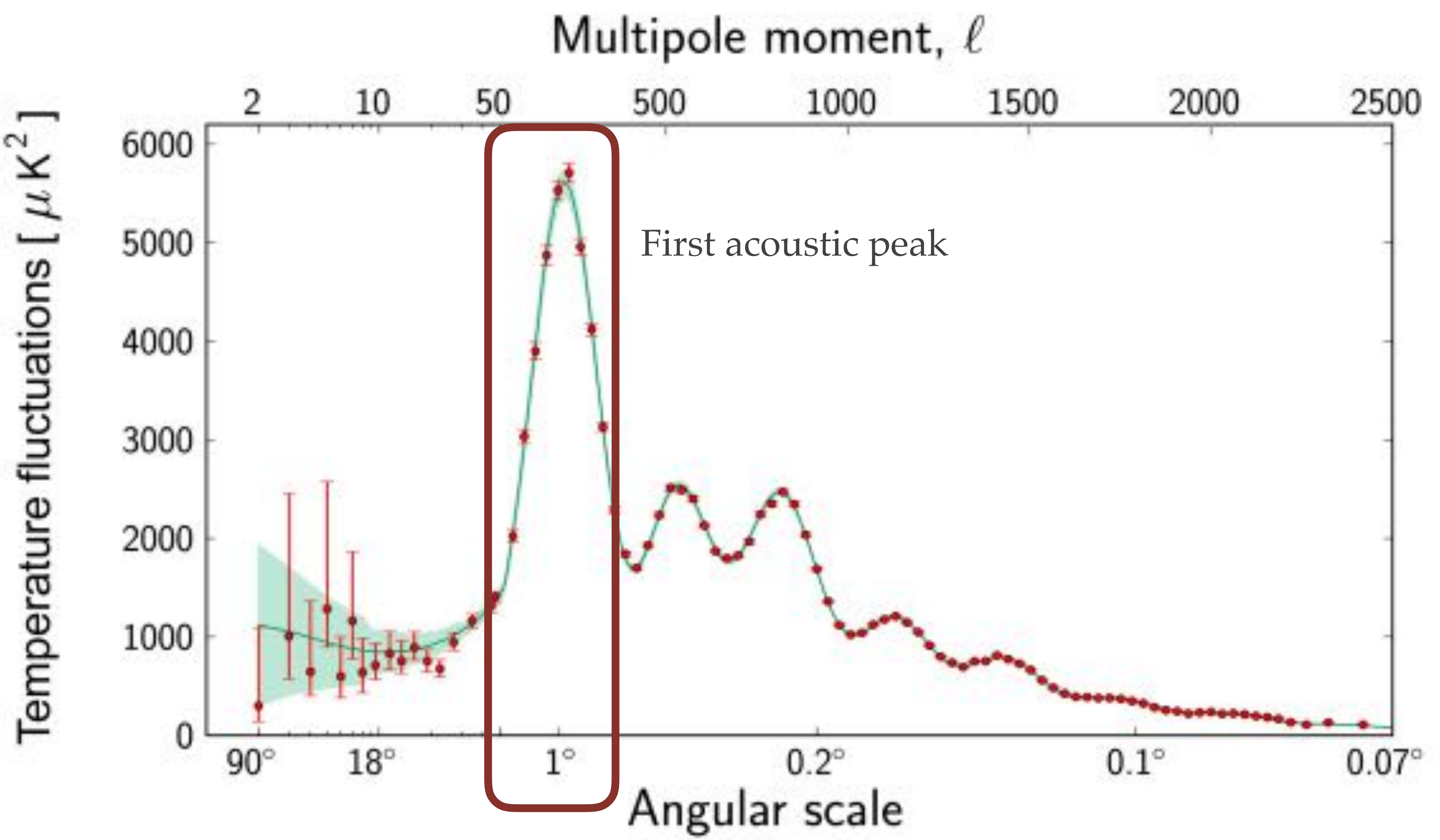

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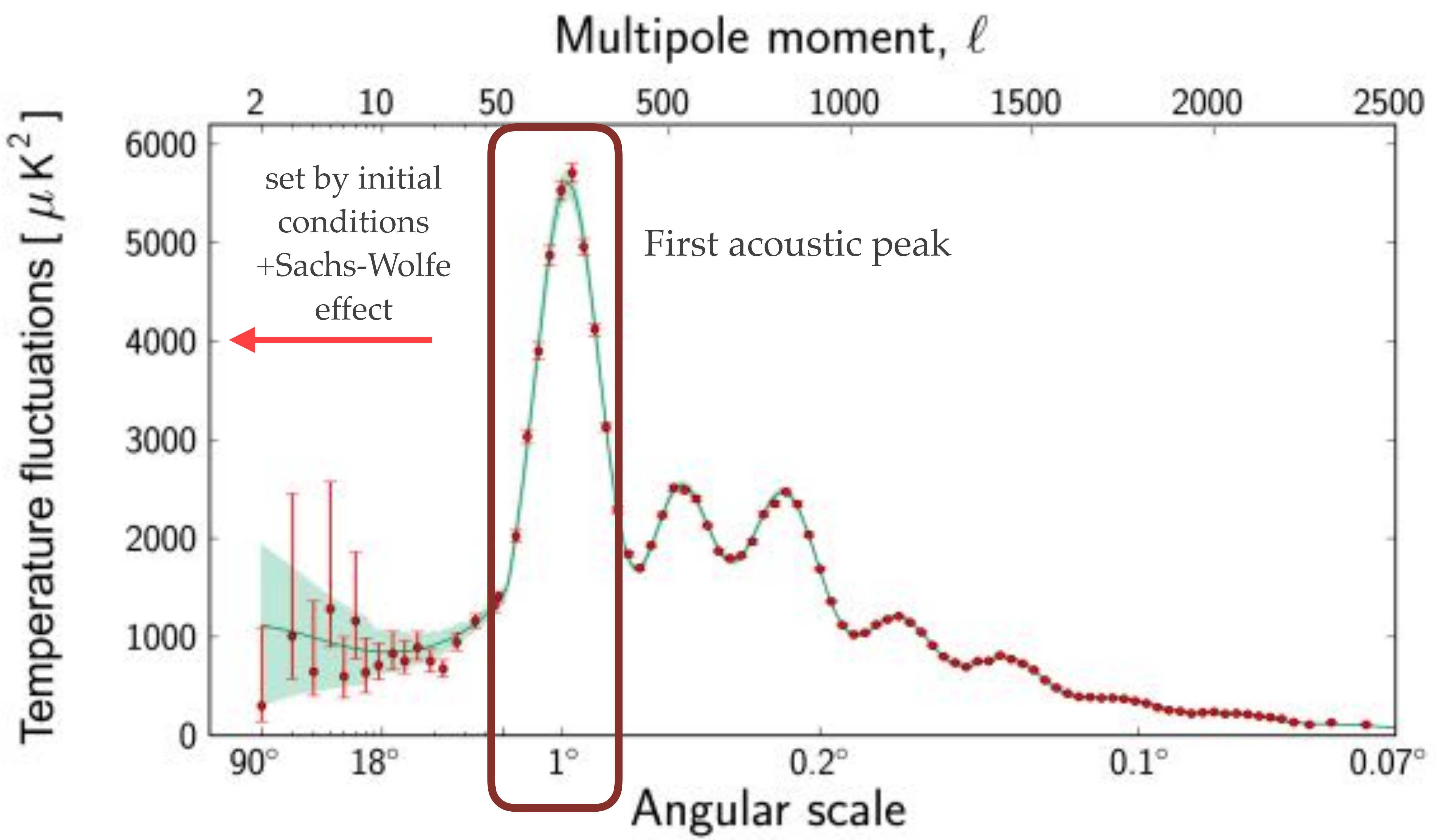
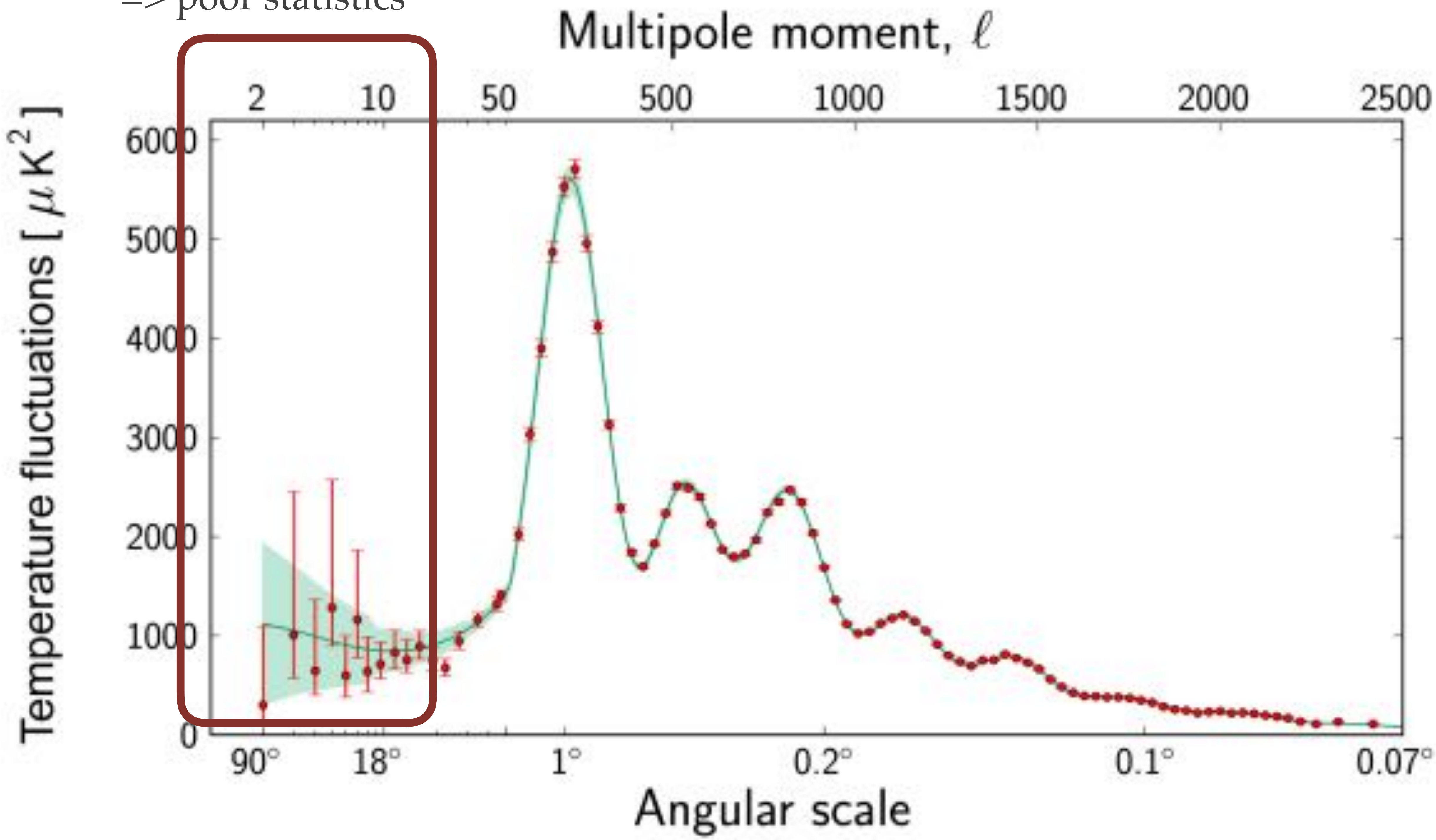


CMB Temperature Power Spectrum

low multipole
=> poor statistics



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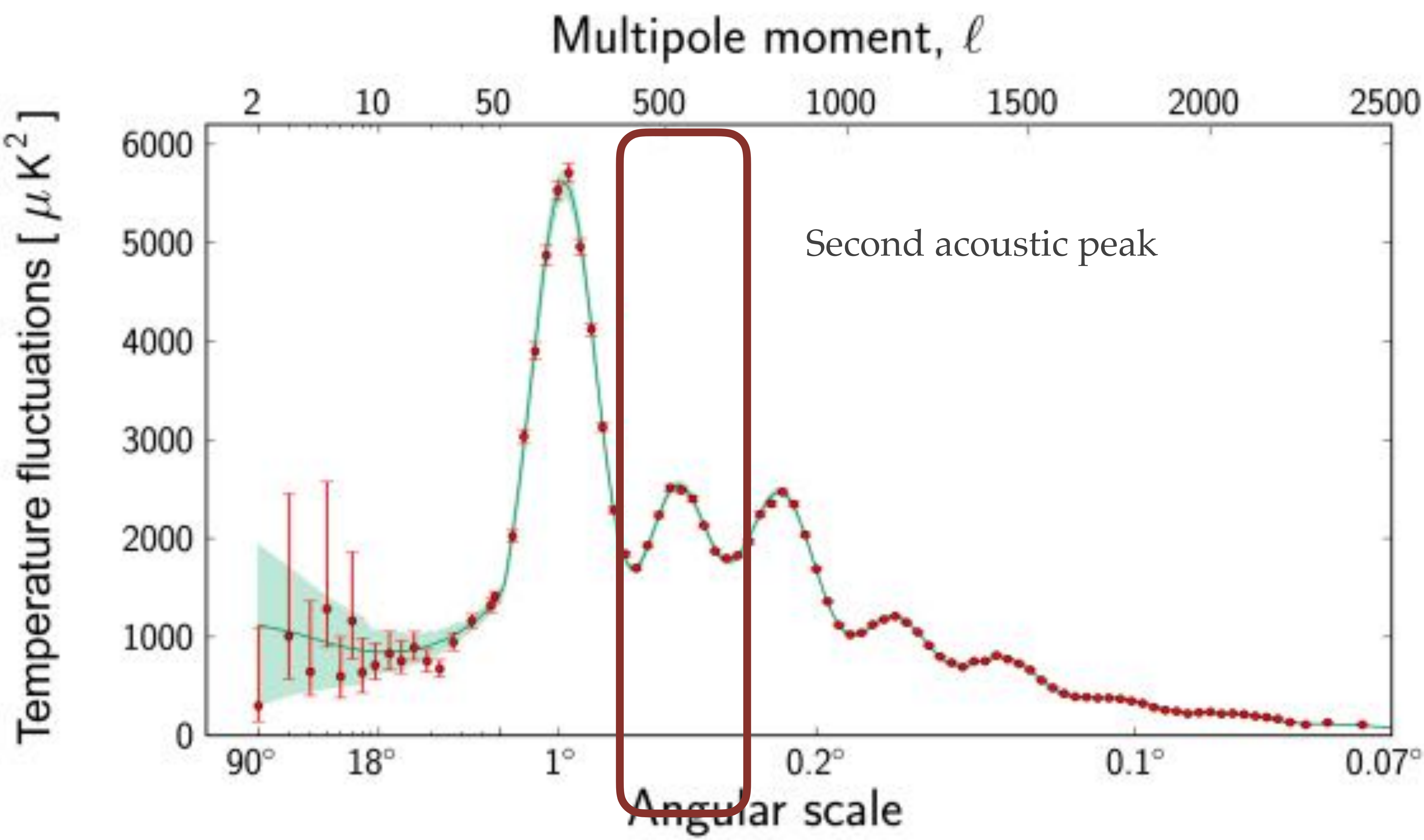

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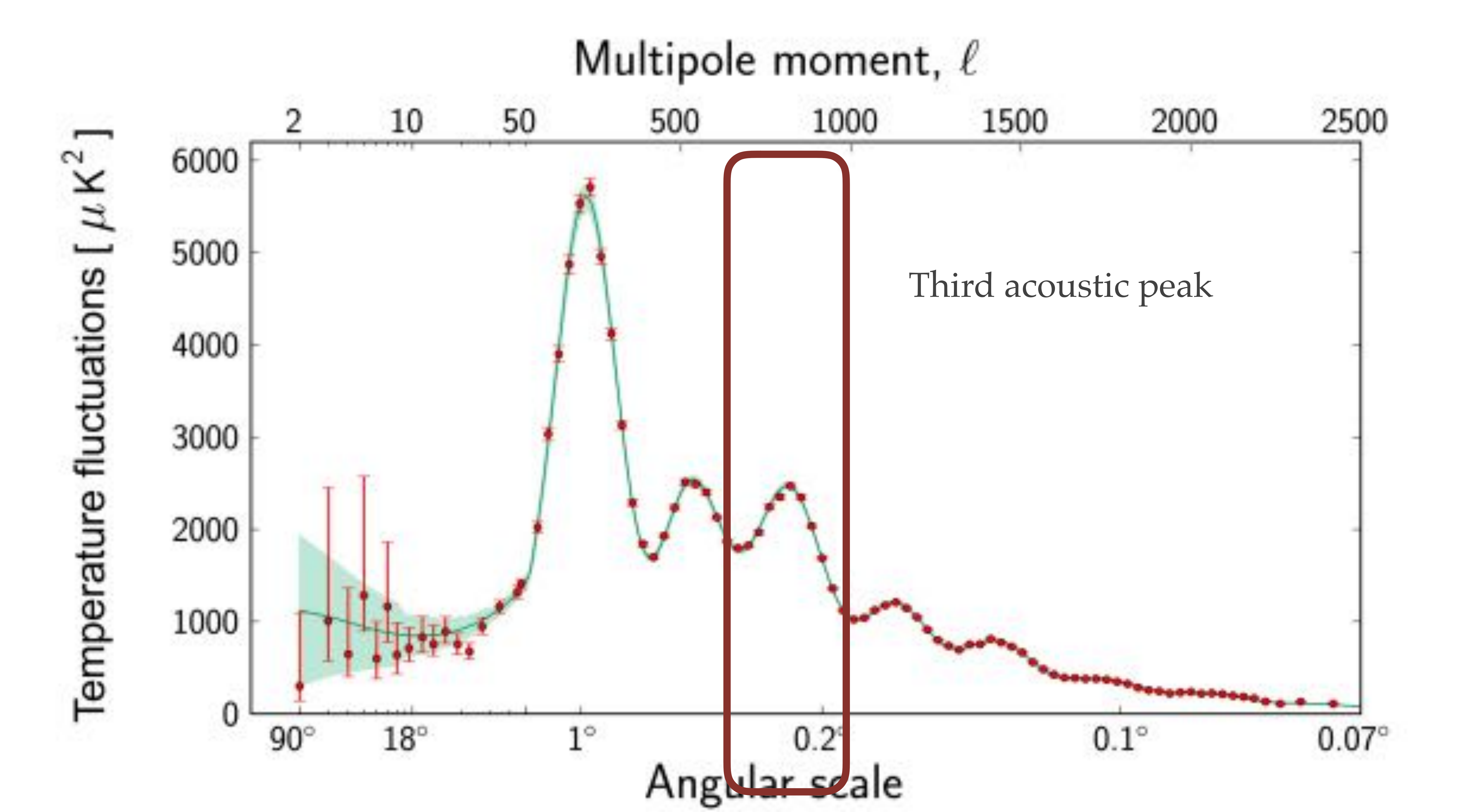

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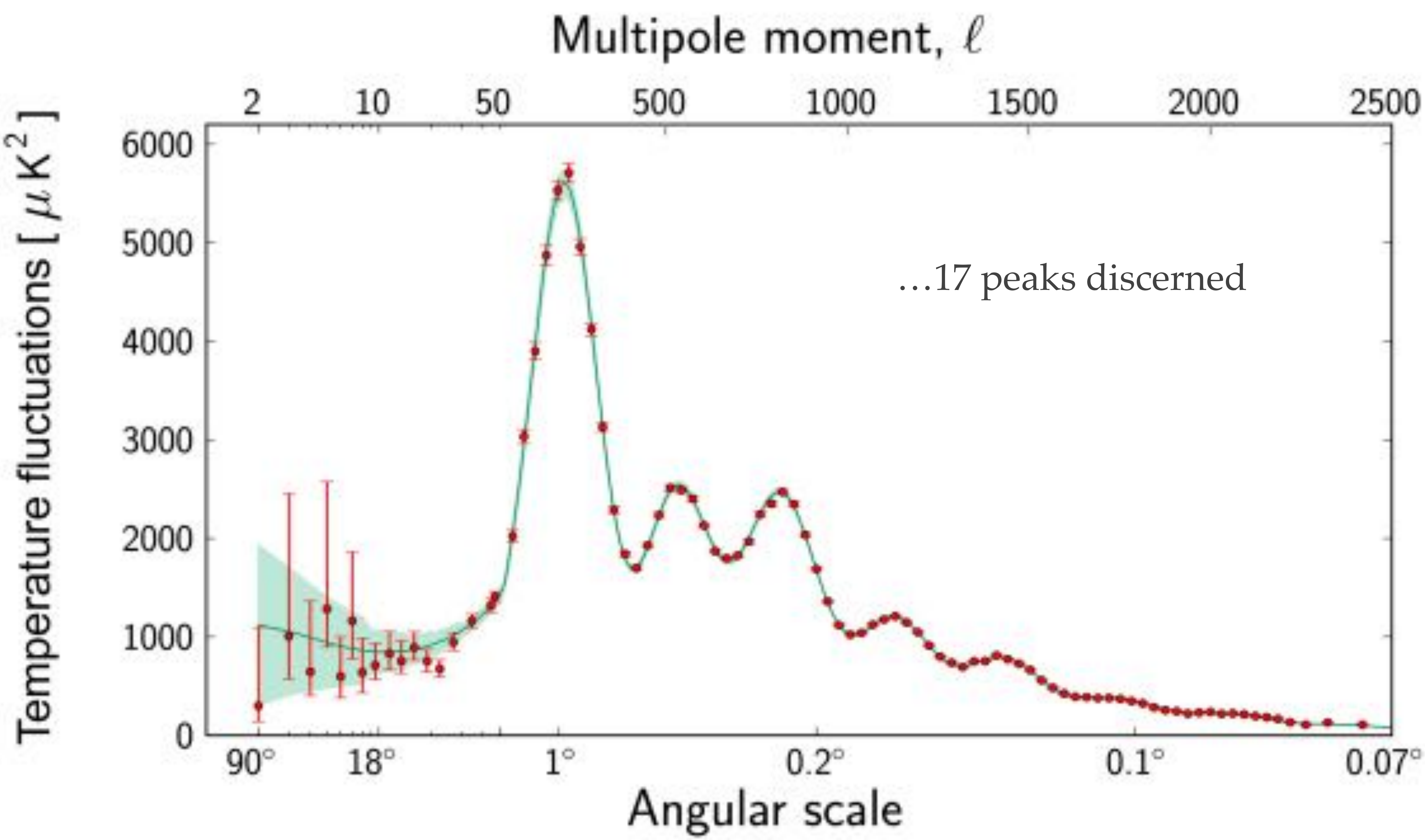
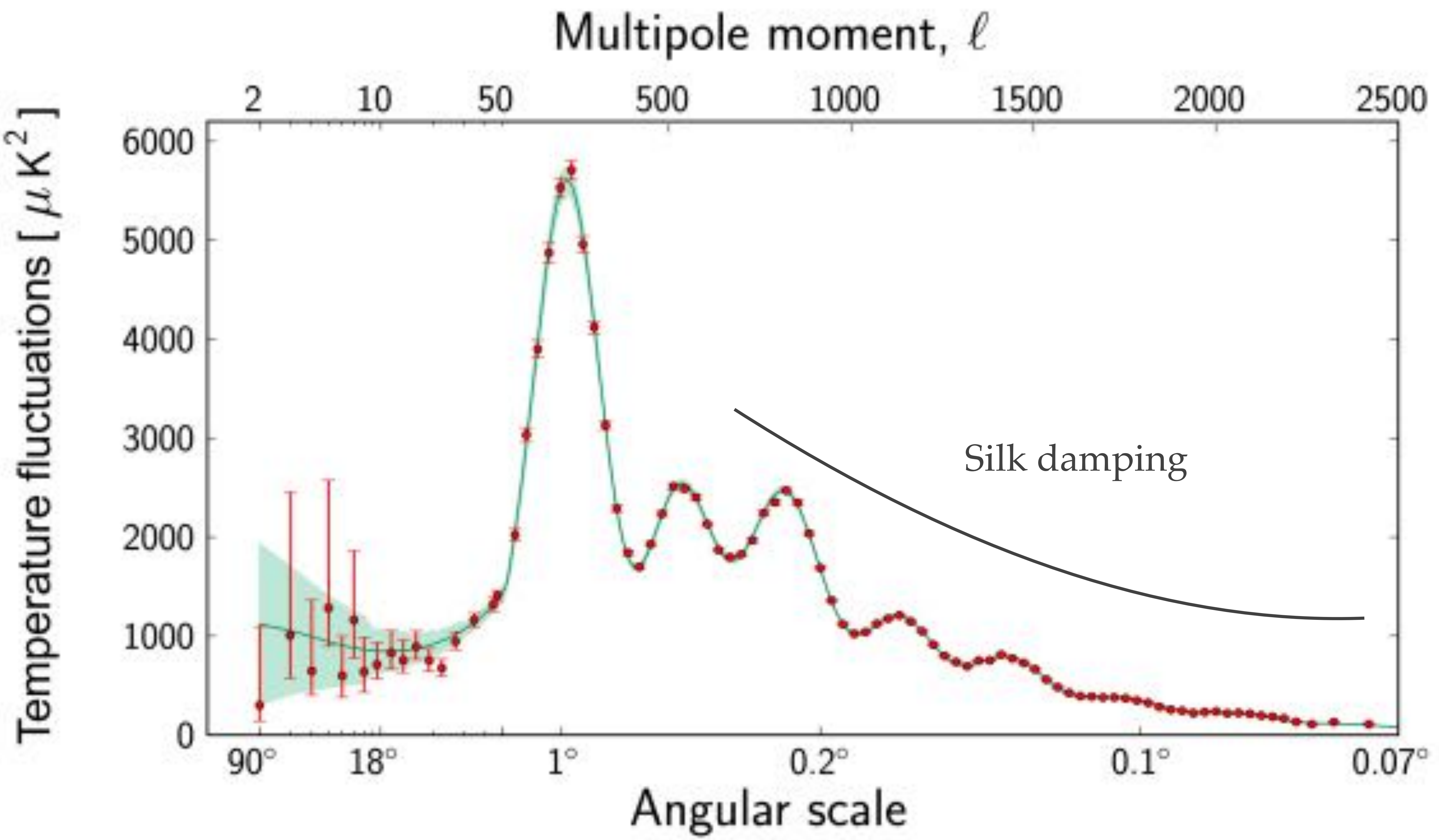


…17 peaks discerned

CMB Temperature Power Spectrum



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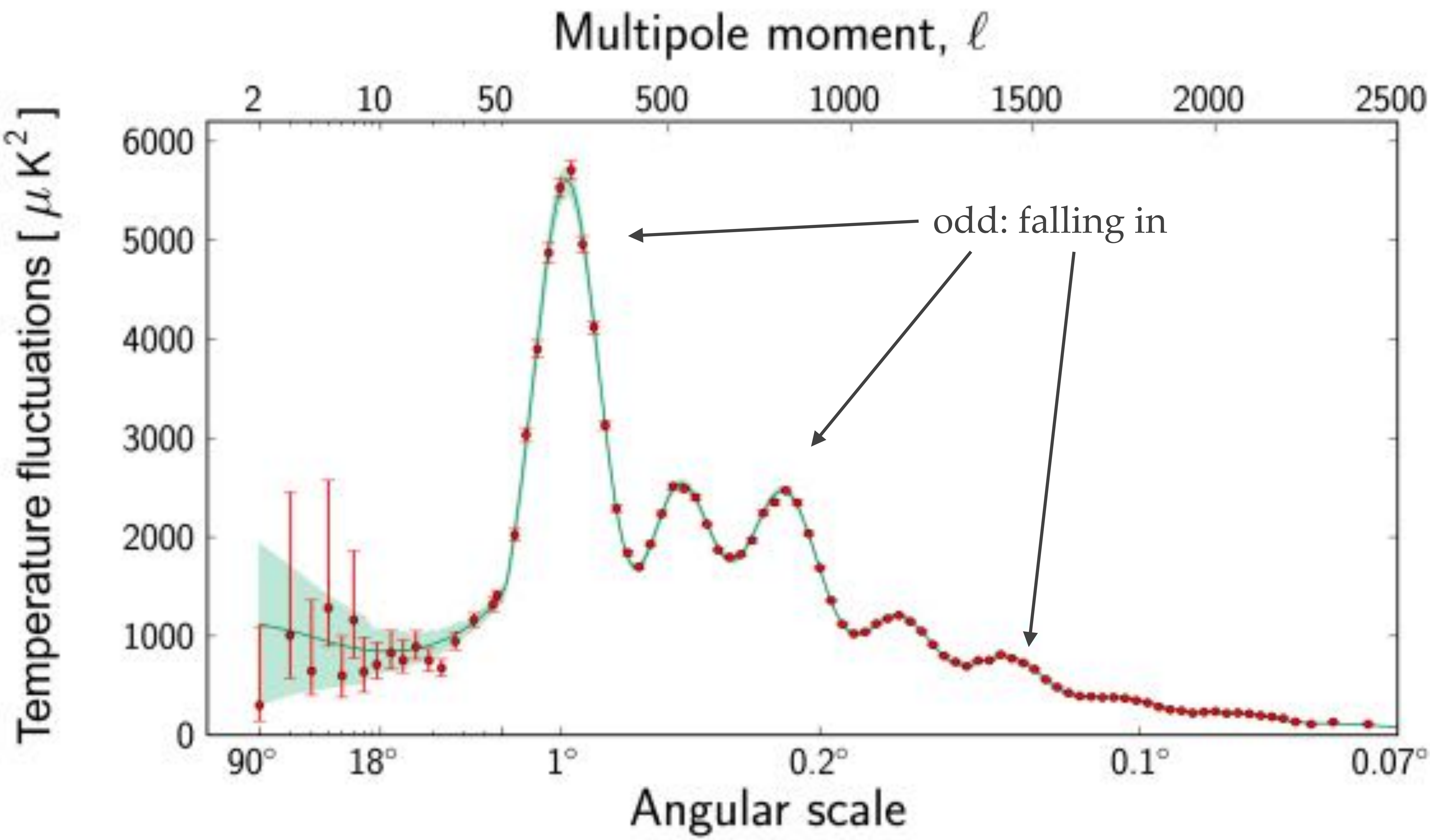

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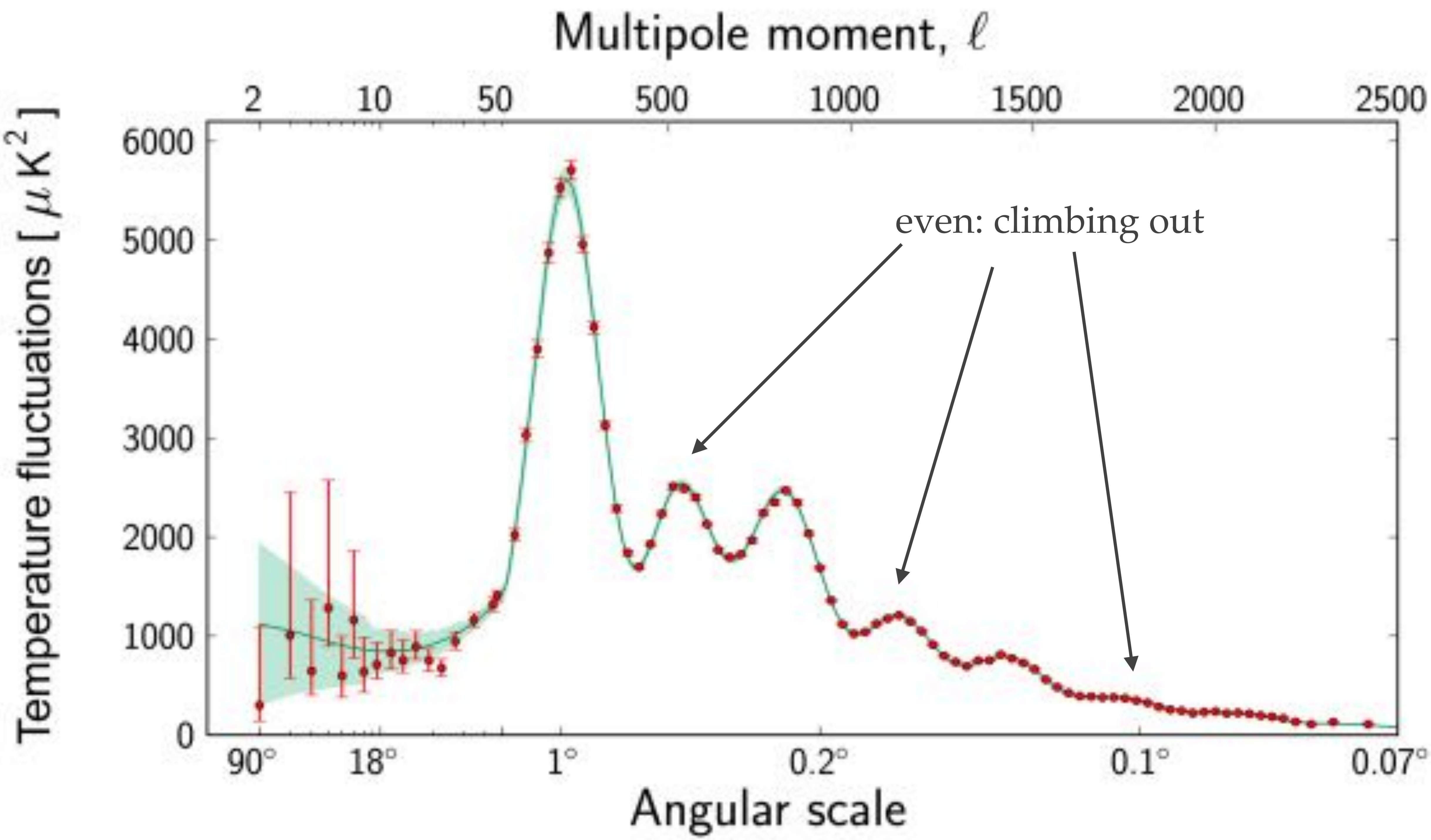
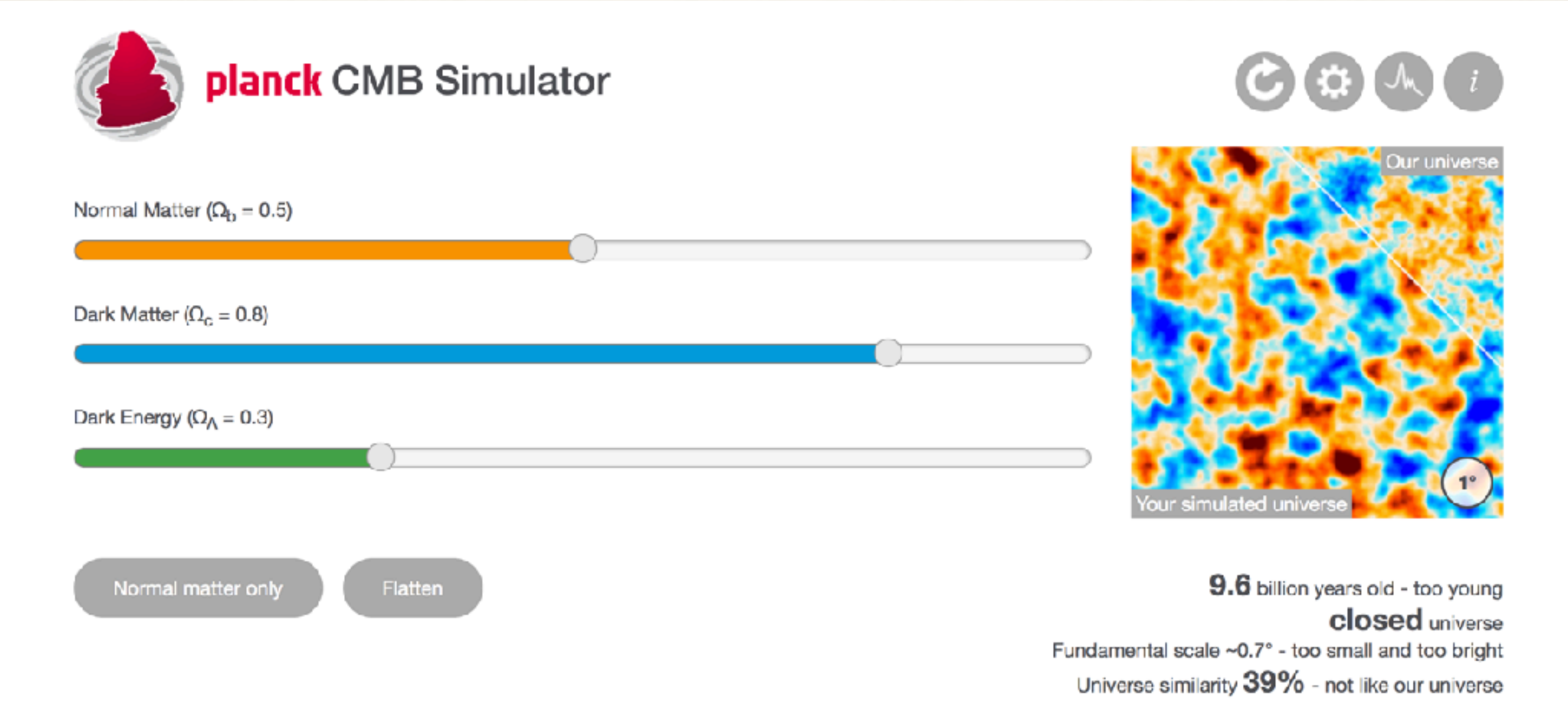


CMB Temperature Power Spectrum

- From detailed examination and self-consistent modelling of the positions and relative amplitudes of the acoustic peaks we can derive a lot of information
- The position of the first peak gives $h^2\,\Omega_m$
- Given independent h measurement we can then determine $\Omega_m = \Omega_{dm} + \Omega_b$
- Ratio of 1st and 2nd acoustic peaks give Ω_{dm} and Ω_b separately
- DM density, Ω_{dm} is around 80% of the total mass density.
- Locally, this corresponds to an average density of dark matter $\varrho_{dm} \approx 0.3$ GeV/cm$^3 \approx 5 \times 10^{-28}$ kg/m^3 at the Sun's location (~10^5 enhancement compared to the cosmological value due to structure formation).

http://planck.cf.ac.uk/cmb-sim



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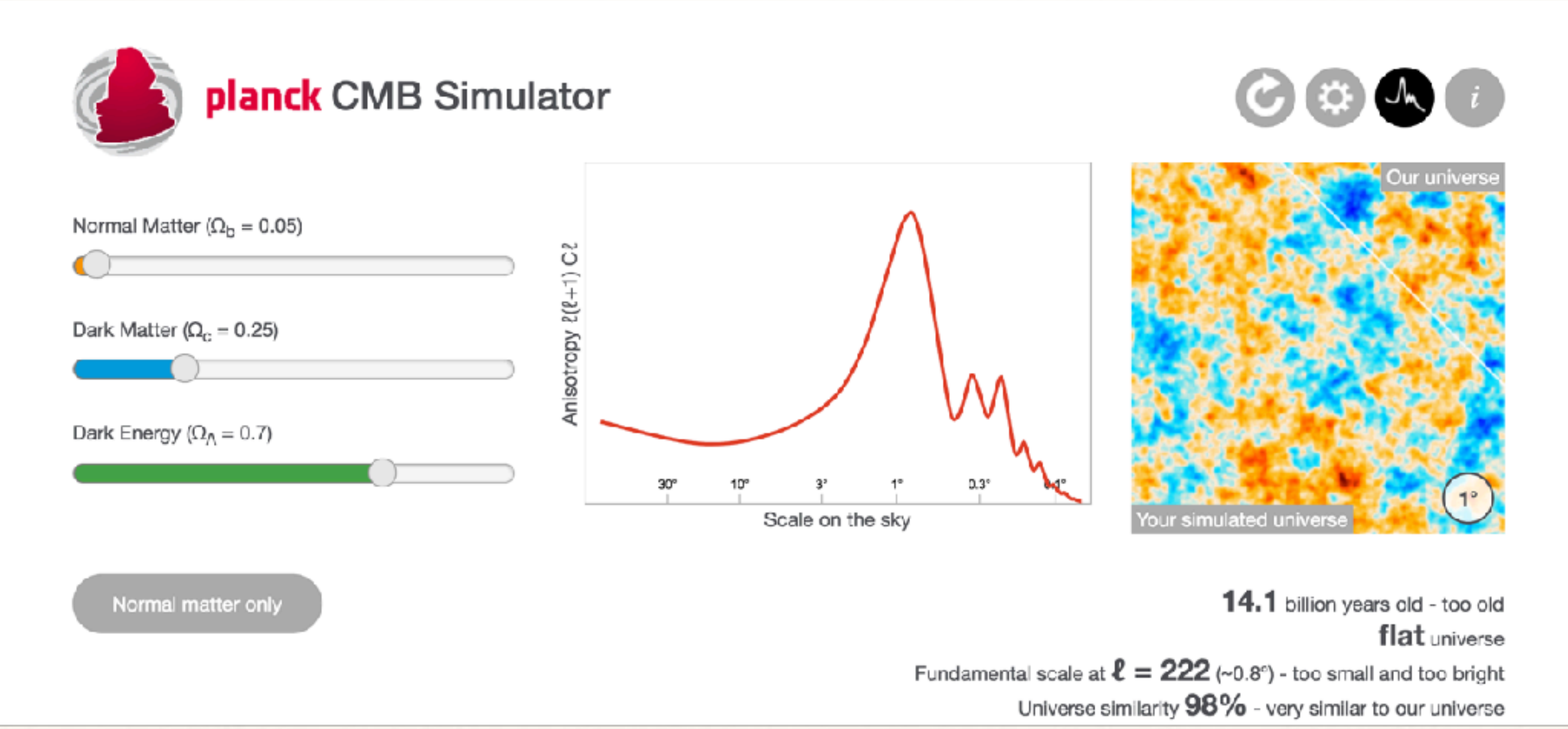

Baryon Acoustic Oscillations

BAO

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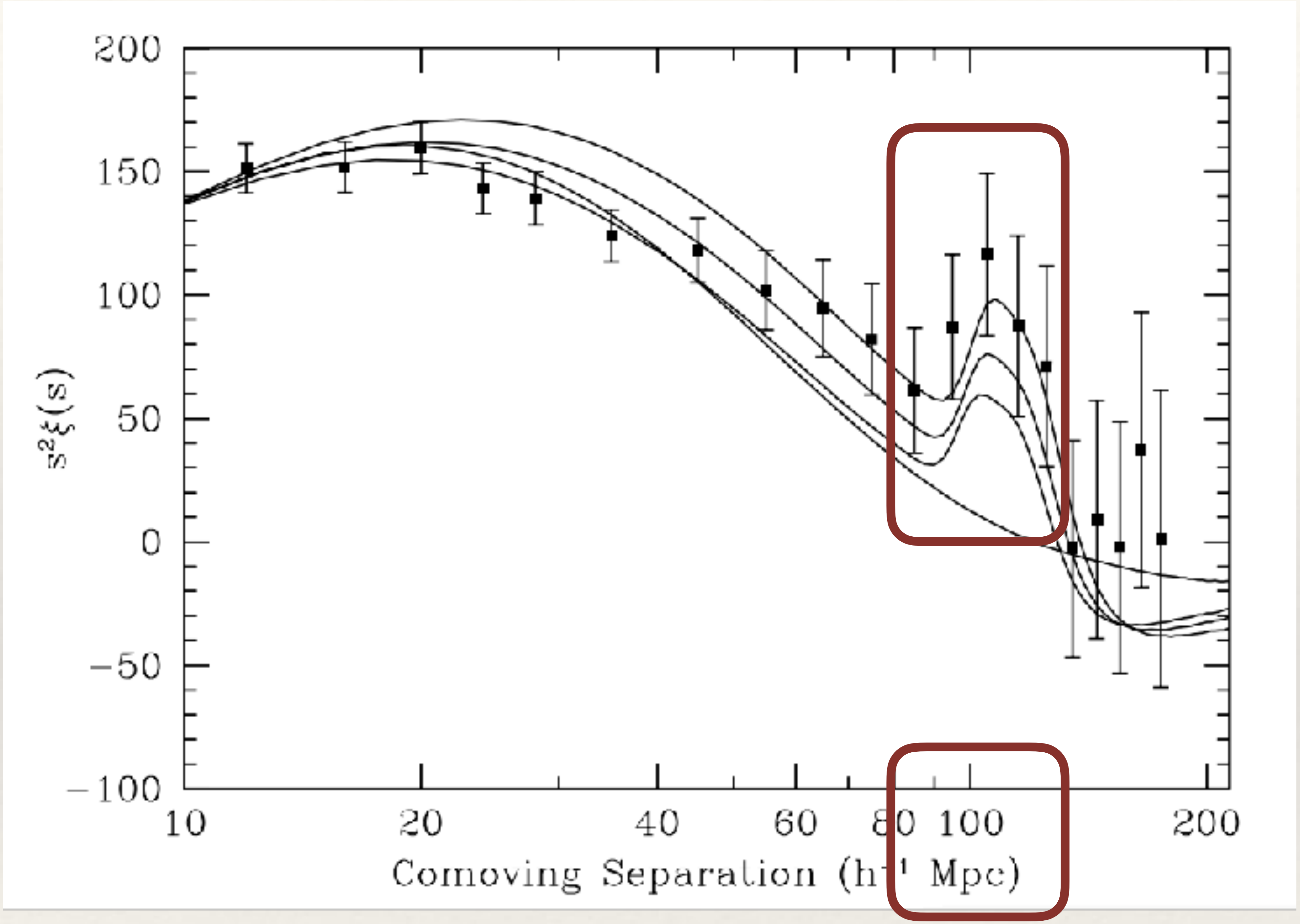
- BAO analysis uncovers a ~150 Mpc characteristic distance between matter clumps

Sloan Digital Sky Survey
Credit: NASA/University of Chicago and Adler Planetarium and Astronomy Museum



current h ~ 0.7, so
spectral peak
at ~150 Mpc comoving

Large-scale redshift-space correlation function of the SDSS LRG sample: Eisenstein+2005

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- hot DM washes out structure and is therefore excluded as the major part of the DM
- cold (hot) means DM is non-relativistic (relativistic) in period of structure formation

Carlos Frenk

Free streaming →

$\lambda_{cut} \propto m_x^{-1}$

for thermal relic

$m_{CDM} \sim 100GeV$

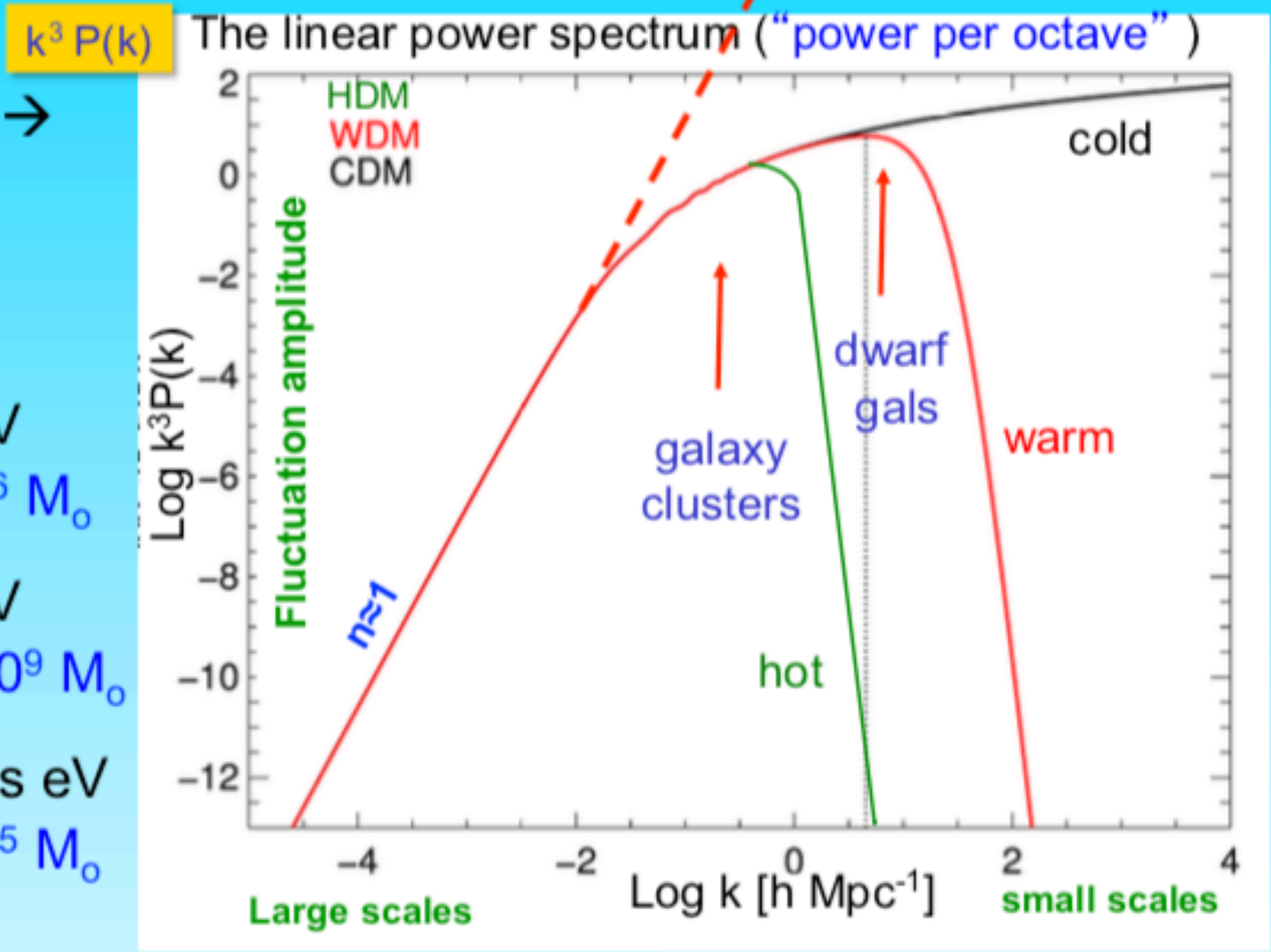
susy; $M_{cut} \sim 10^{-6}\ M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9\ M_o$

$m_{HDM} \sim$ few tens eV

light ν; $M_{cut} \sim 10^{15}\ M_o$



Carlos Frenk

University of Durham

Non-baryonic dark matter candidates

From the 1980s:

Type	example	mass
hot	neutrino	few tens of eV
warm	sterile ν	keV-MeV
cold	axion neutralino	10^{-5}eV - 100 GeV

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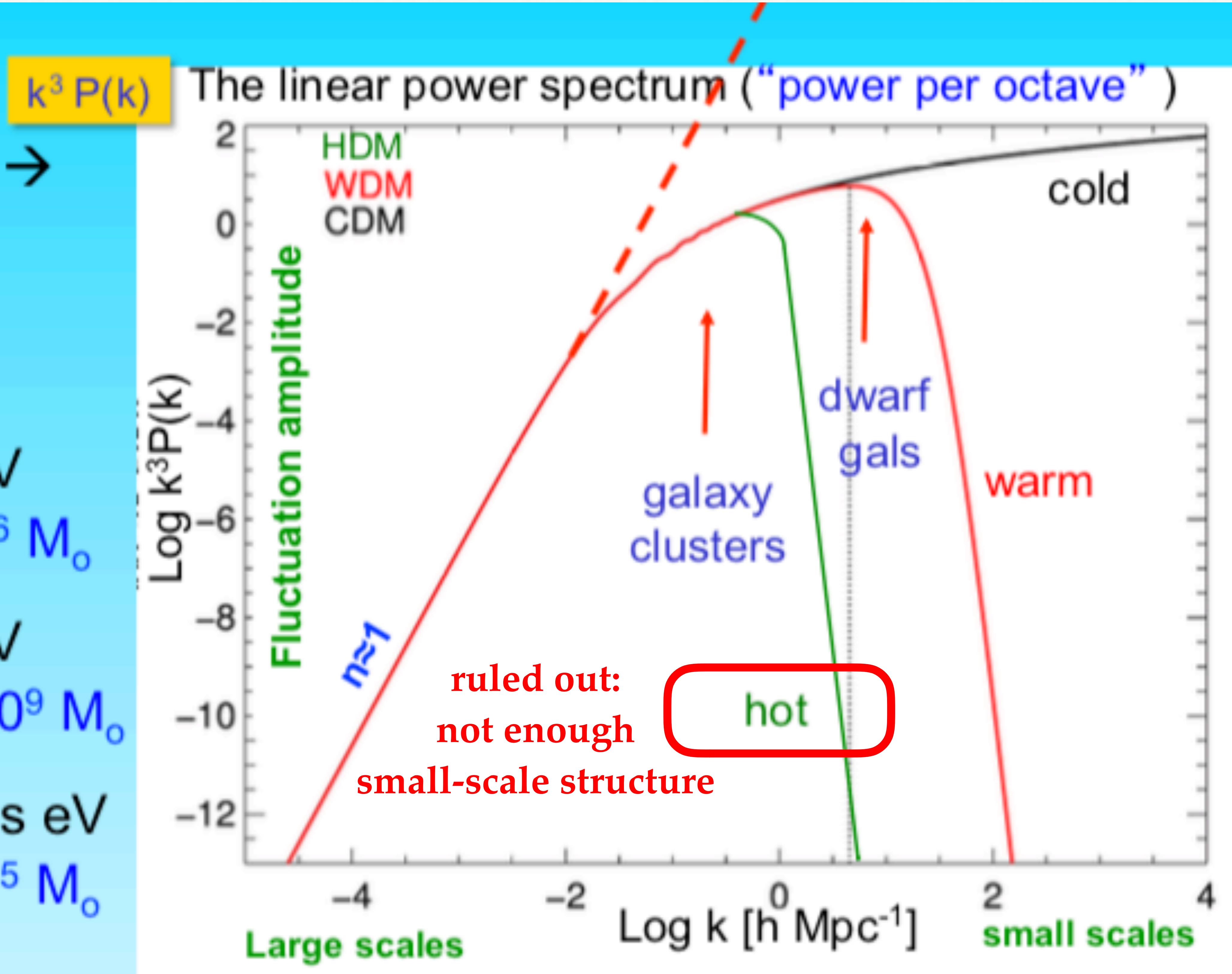
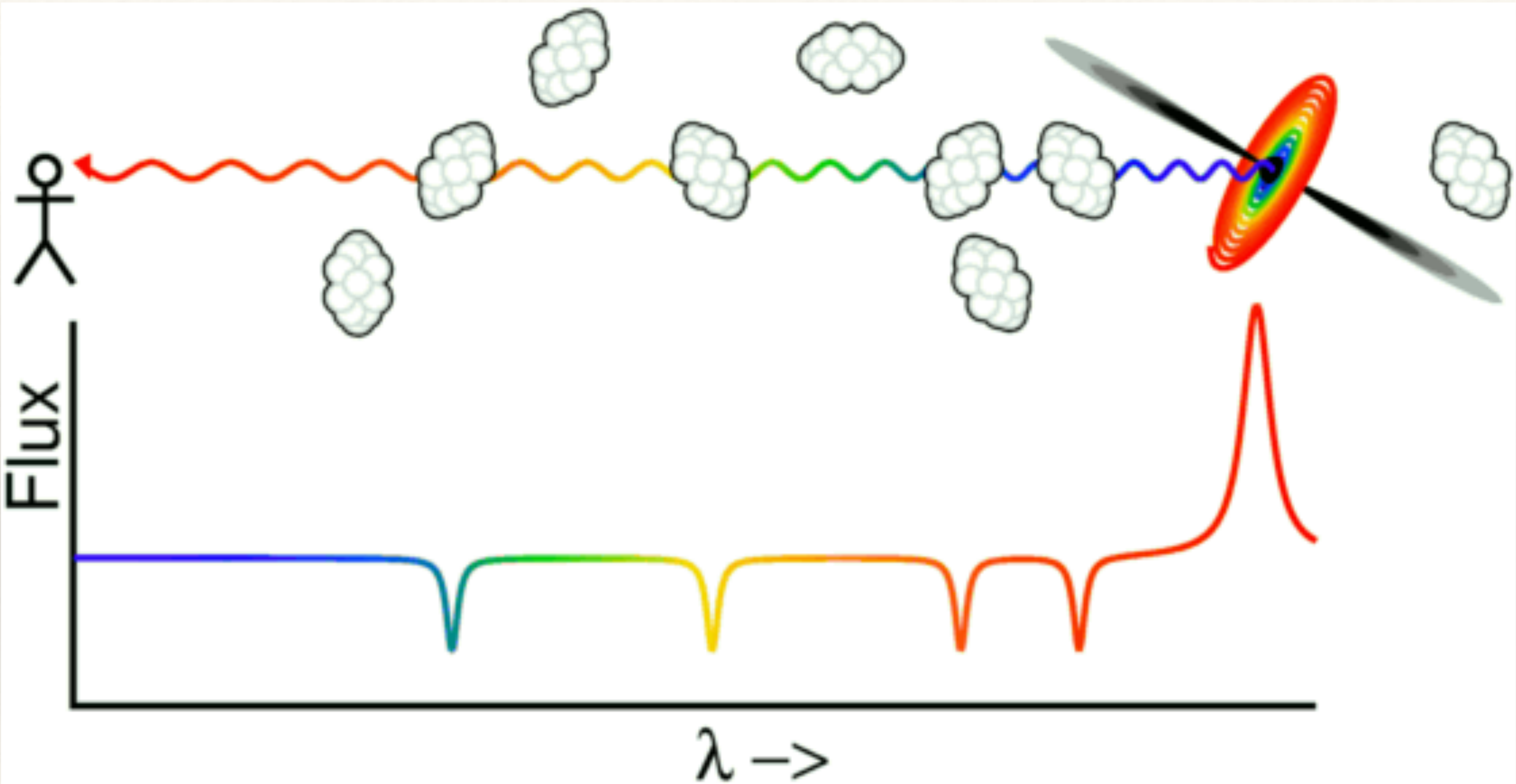


Warm or Cold?

- Both CDM & WDM compatible with CMB & galaxy clustering
- Claims that both types of DM have been discovered:
  - CDM: γ-ray excess from Galactic Center
  - WDM (sterile ν): 3.5 X-ray keV line in galaxies and clusters

Lyman-α Forest Constraints

- The "Lyman-α Forest" is the complex of closely-spaced absorption lines seen in the spectra of distant quasars and galaxies



http://www.astro.ucla.edu/~wright/Lyman-alpha-forest.html

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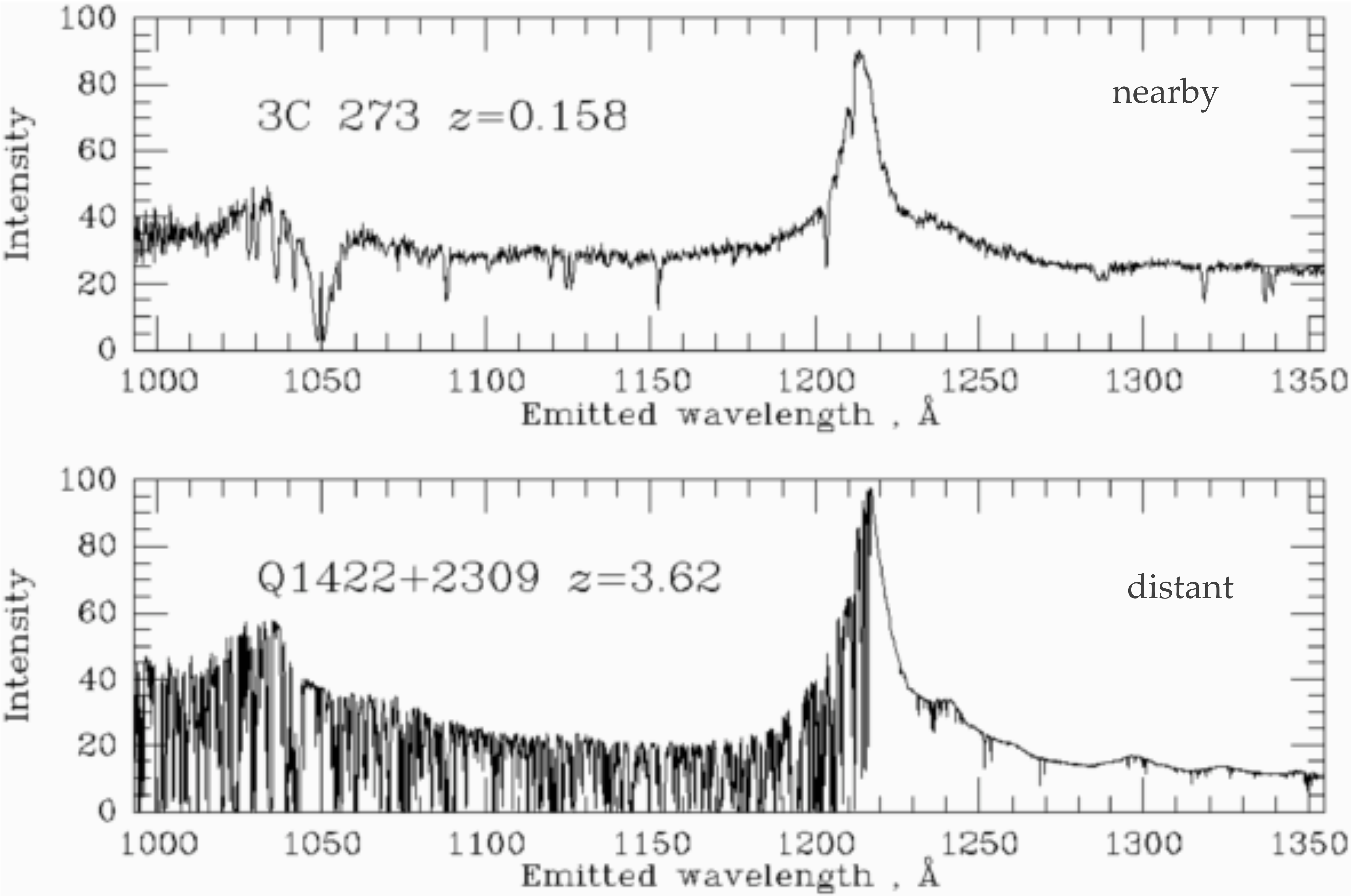

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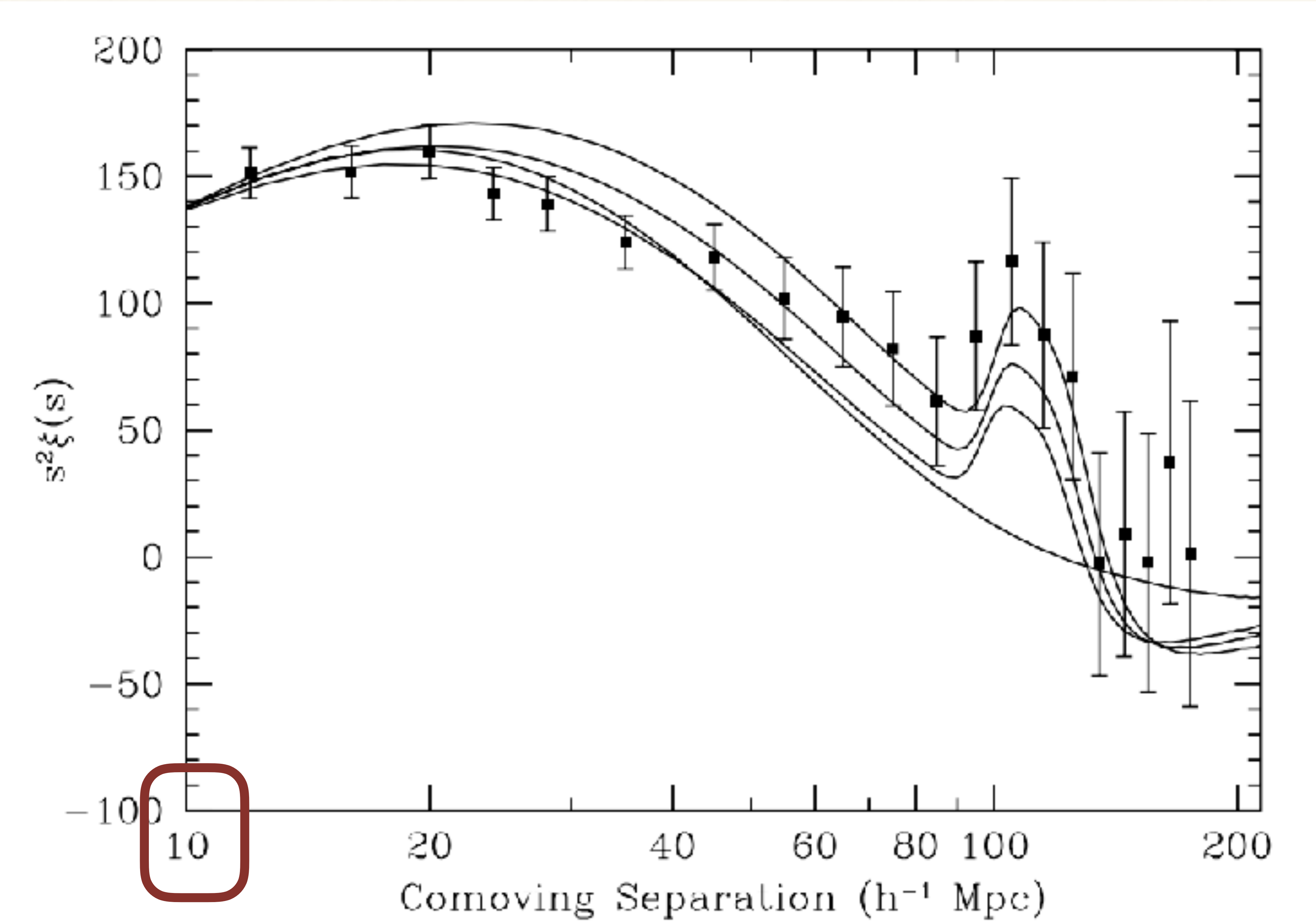
- Essentially, this has to be true in order that we get enough small scale structure to reproduce the Lyman-α Forest
- This constrains the DM mass to be large enough (it cannot be too fast, otherwise it washes out structures on the required small scales) => $M_{DM} > 5$ keV



Ly-α Forest sensitivity at ~10 Mpc

the density perturbations become non-linear on smaller scales: $\frac{\delta\rho}{\rho} \gtrsim 1$

Big Bang Nucleosynthesis

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- BBN proffers constraints on the baryonic matter content of the Universe (and cosmological parameters in general) that is completely orthogonal to those already discussed

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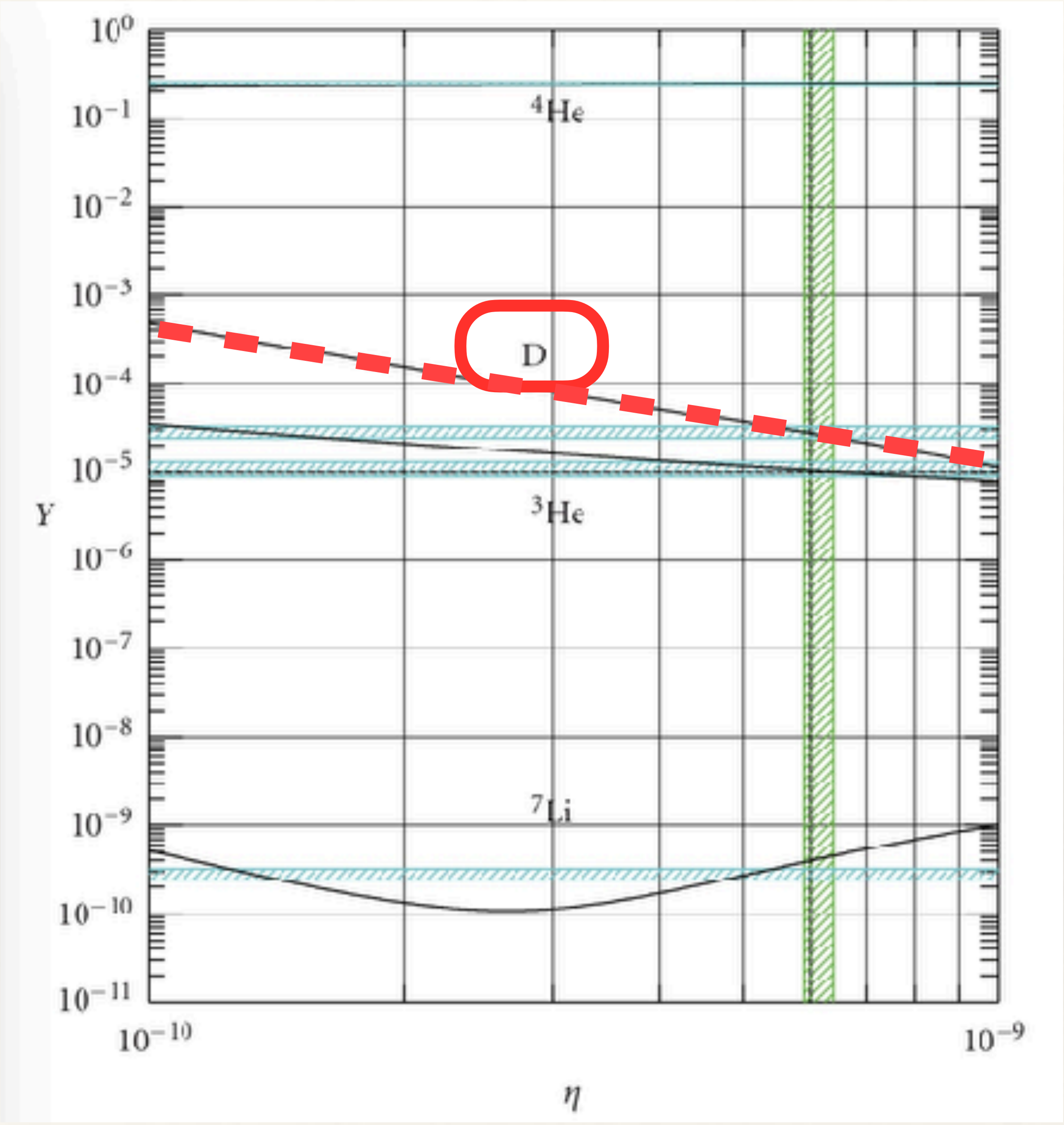
- D/H (and other primordial abundances relative to H) are strongly dependent on the overall baryon to photon ratio:

$$\eta = \frac{B}{\gamma} \simeq 6 \times 10^{-10}$$

← Reminder: the large value of this ratio reflects the very small B-anti B asymmetry of the Universe

Big Bang Nucleosynthesis



the larger η, the more reactions there will be and the more efficiently deuterium will be eventually transformed into helium-4.

To form heavy elements, nucleosynthesis has to proceed before t_{decay} ~ 900 s of free neutrons

But D is delicate:
the average energy of the photons only drops below the D binding energy at t ≳ 10 s

So after this time, we can pass through the D bottleneck to start forming ^{3}He, ^{3}H (Tritium) and then ^{4}He

After about ~20 minutes, densities and temperatures have dropped so much that nucleosynthesis ceases

We end up with ~25% ^{4}He *by mass* and trace amounts of other nuclei (^{4}He highest binding energy per nucleon among light elements)

Big Bang Nucleosynthesis

- CMB measurements give us the number density of photons at all cosmological times; thus for a given η we know the baryon number density too

Big Bang Nucleosynthesis

- CMB measurements give us the number density of photons at all cosmological times; thus for a given η we know the baryon number density too
- By combining both BBN abundance information on η with CMB measurements we can obtain the baryon density

$$\Omega_b \equiv \frac{\rho_B}{\rho_{tot}} \simeq 0.04$$

$$\Omega_b \simeq 0.2 \ \Omega_m$$

Problems for the (Λ)CDM Paradigm?

- Problems, such as they are, are encountered on small scales in the deeply non-linear regime, $l \lesssim$ Mpc and $M \lesssim 10^{11}\,\mathrm{M}_\odot$

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Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '12

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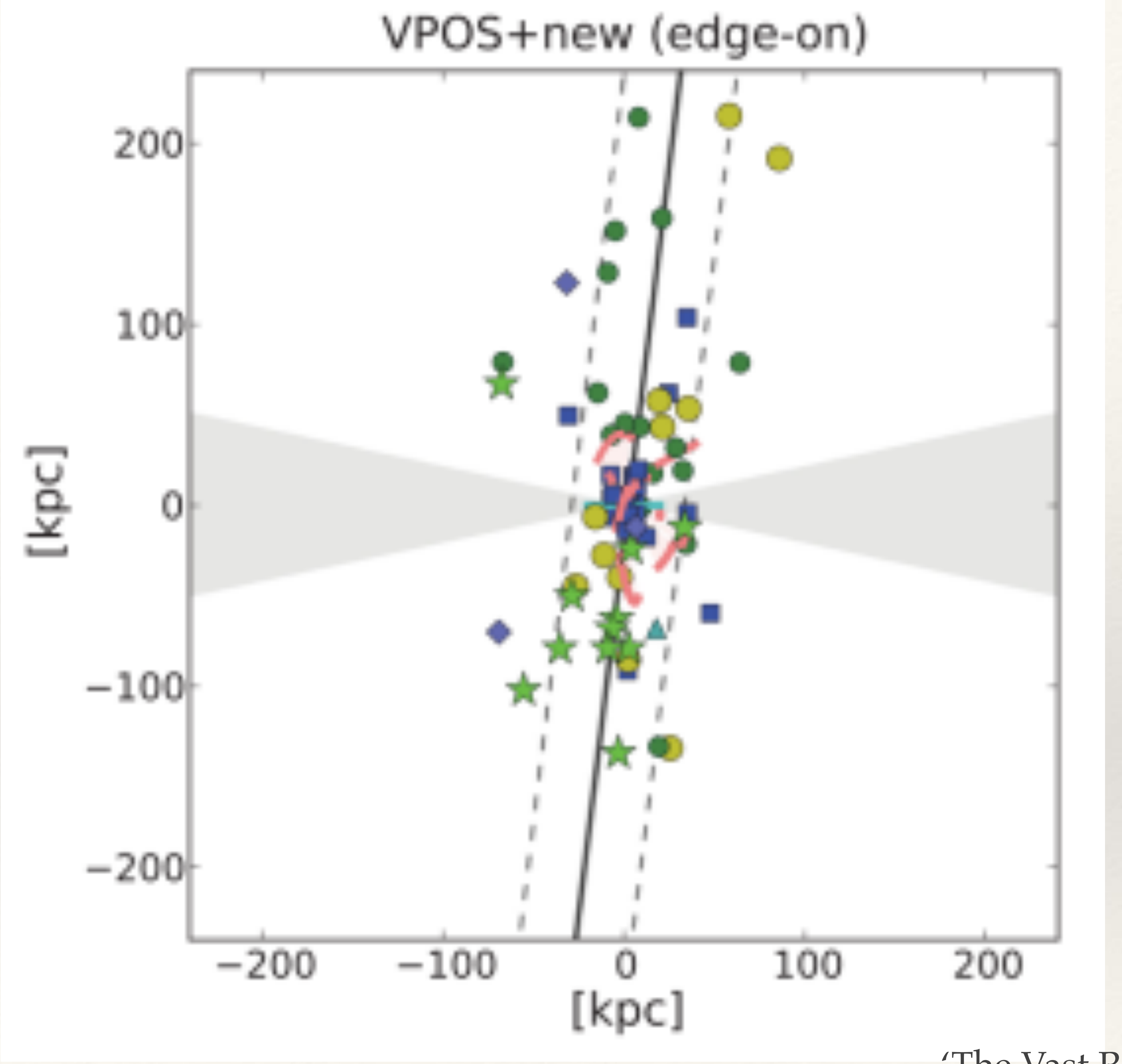

‘The Vast Polar Structure’
Marcel Pawlowski

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see: Small-Scale Challenges to the ΛCDM Paradigm
Bullock & Boylan-Kolchin 2018

Closing Remarks

- Multiple pieces of evidence point to th… DM in our Universe with the f…
  - massive
  - cold

No Standard Model particle meets these requirements so DM seems to point to the need for physics beyond the Standard Model

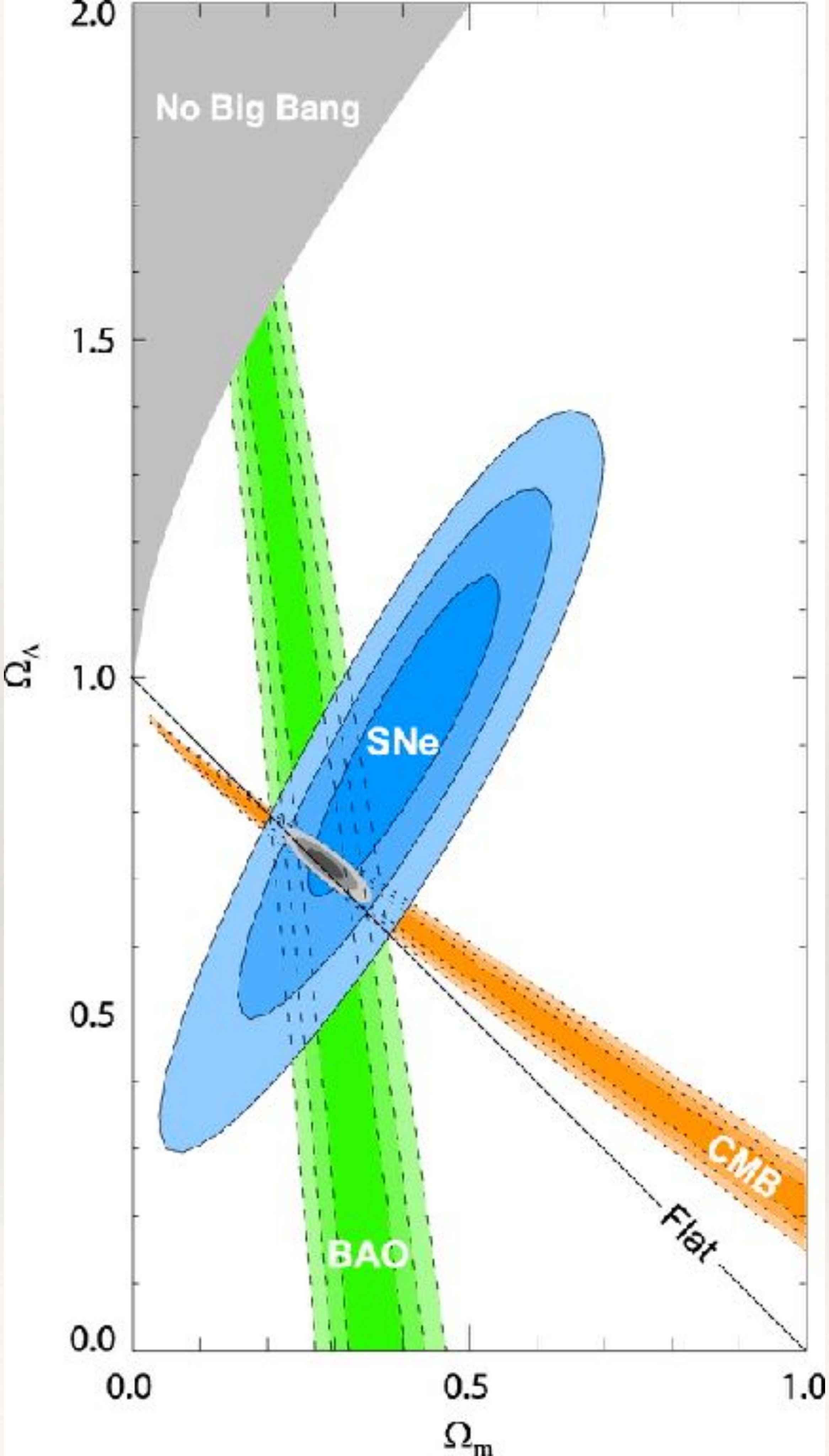
Closing Remarks

- DM is not simply a kludge that addresses a single observational anomaly
- Rather, there is evidence for something acting like CDM (= cold, collisionless, electrically neutral, stable) over the history of the Universe and on many different size scales
- This evidence has been collected by many different — and different types of — experiments
- All these observations point to the requirement for a significant amount of DM in the Universe, at a level ~5x its baryonic matter content
- DM is the most conservative option *we know* that addresses all these pieces of evidence
- That said, CDM is a completely phenomenological model as we don't know what the hell it is!

Closing Remarks

- It is also worth saying that there is a pervasive sense of worry or even crisis amongst DM researchers because none of the theoretically-well-motivated candidates (thermally produced WIMPs, axions, sterile neutrinos) has yet turned up in indirect, direct, or collider searches, and the "natural" parameter space for these candidates is being severely eroded
- See Bertone and Tait 2018

Extra Slides



Kowalski+2008

This video zooms in on the galaxy cluster Abell 1689. Overlaid in purple is the distribution of dark matter in the galaxy cluster. The distribution of normal and dark matter in the lens, the relative geometry of the lens and distant galaxies behind the cluster, and the effect of dark energy on the geometry of the universe, together explain the distorted shapes of some of the galaxies visible here. Astronomers are able to use this relationship to probe the properties of dark energy.

NASA, ESA, ESO/Digitized Sky Survey 2, E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM).