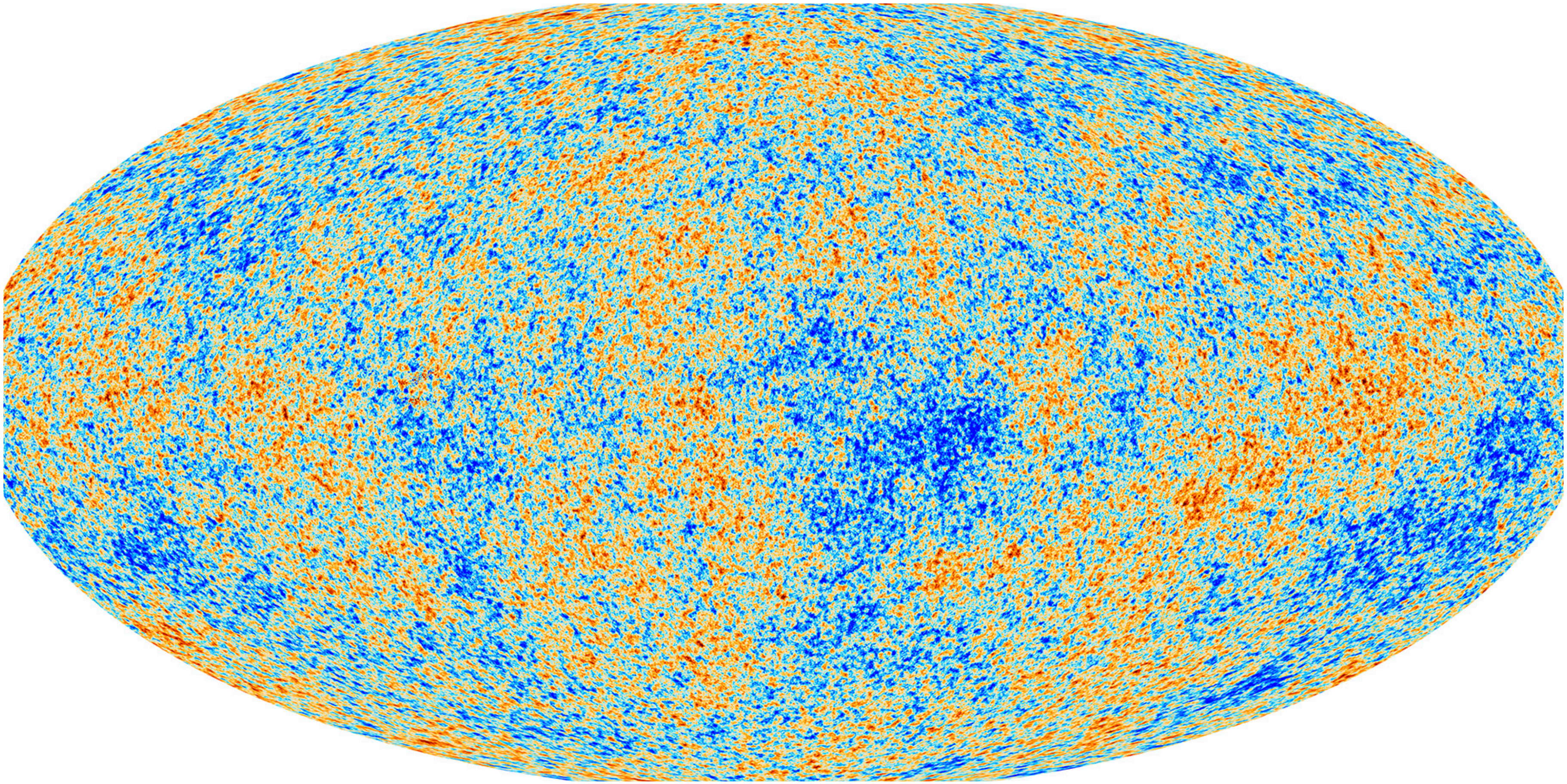
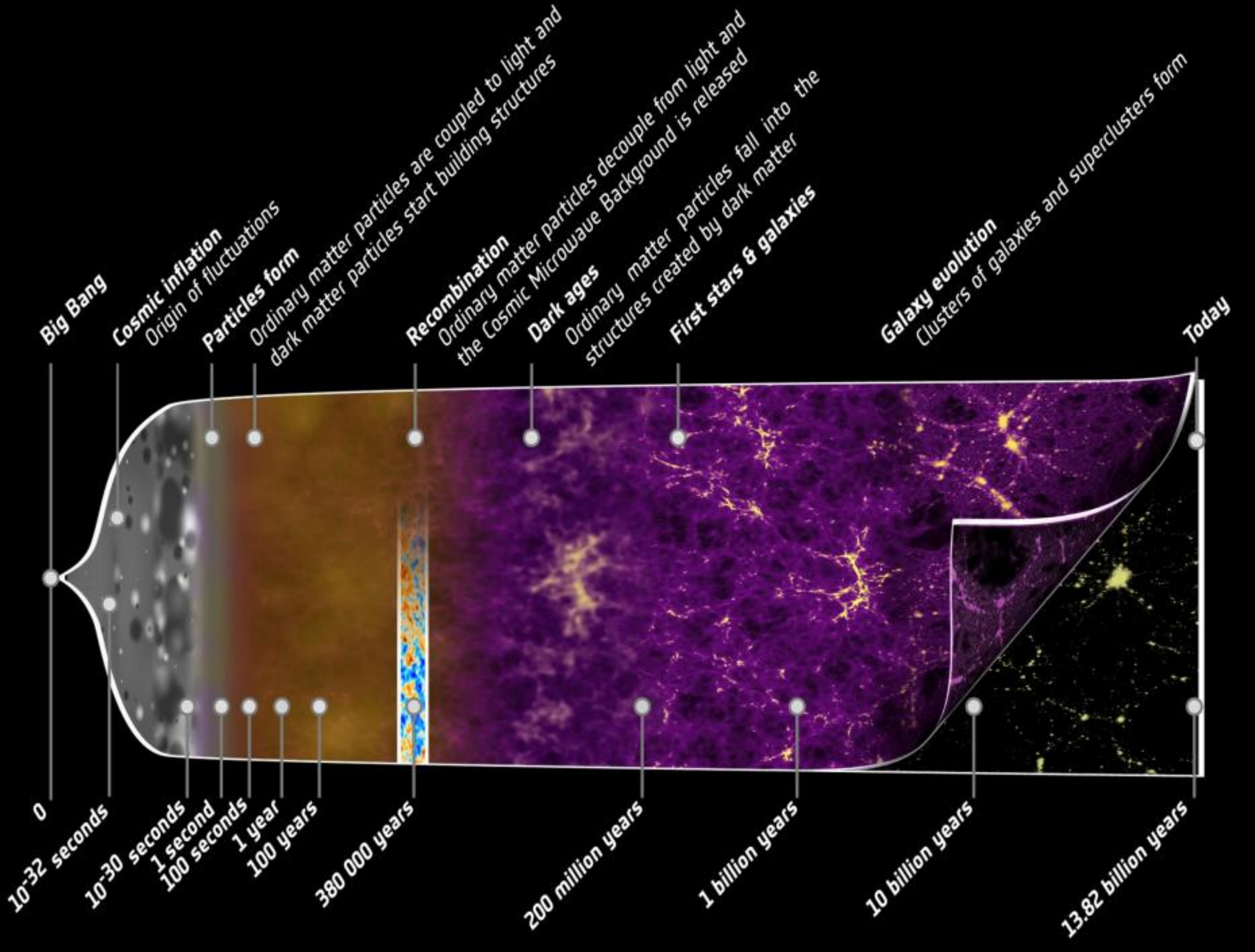
The LCDM model and possible alternatives (extensions)



Alessandro Melchiorri

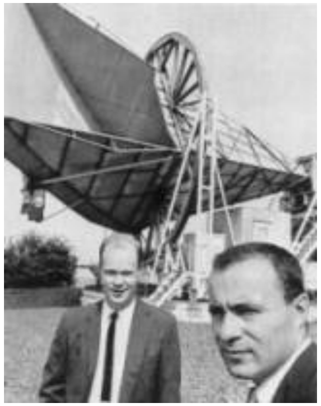
University of Rome La Sapienza



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

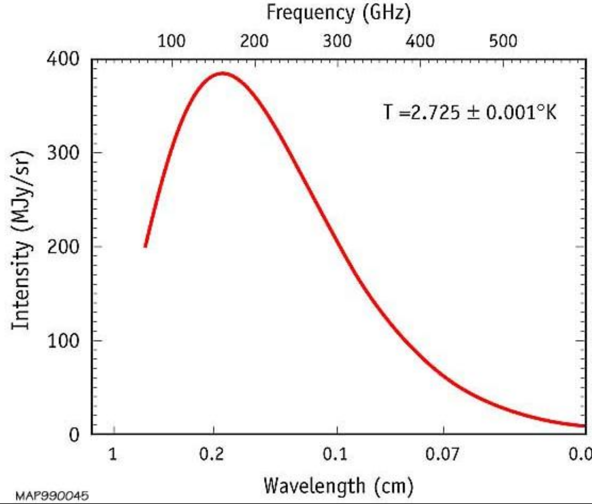
The Cosmic Microwave Background

Discovered By Penzias and Wilson in 1965.



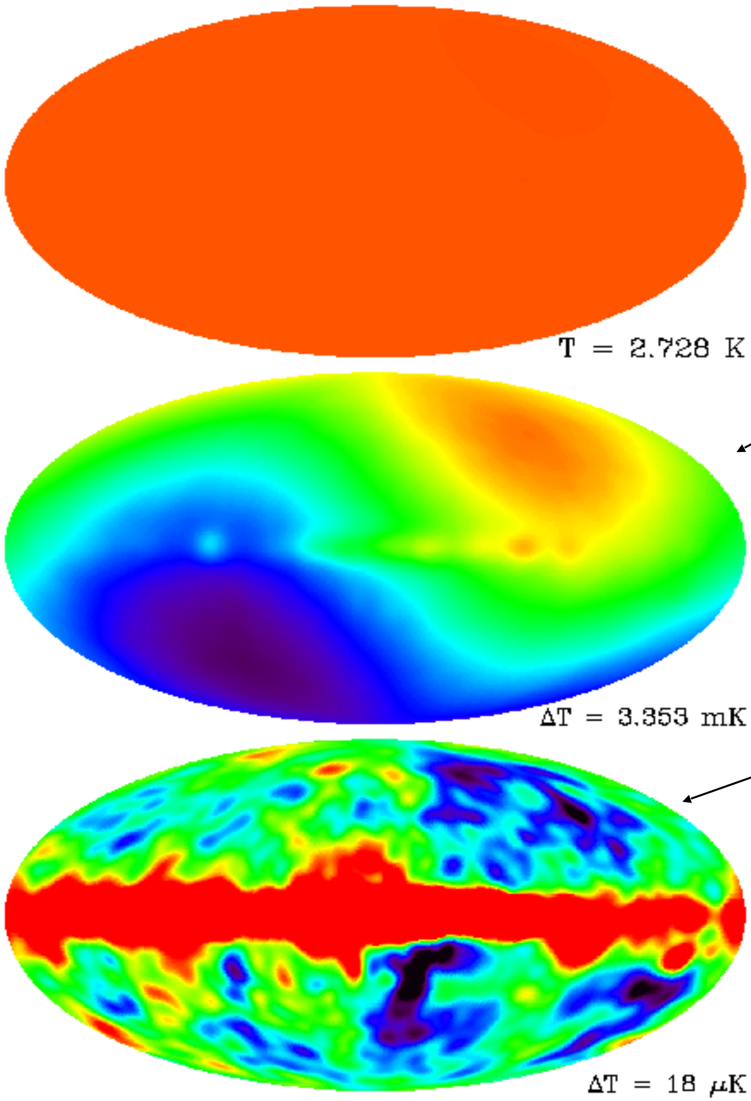
It is an image of the universe at the time of recombination (near baryon-photons decoupling), when the universe was just a few thousand years old (z~1000).

The CMB frequency spectrum is a perfect blackbody at T=2.73 K: this is an outstanding confirmation of the hot big bang model.



The Microwave Sky

COBE (circa 1995) @90GHz

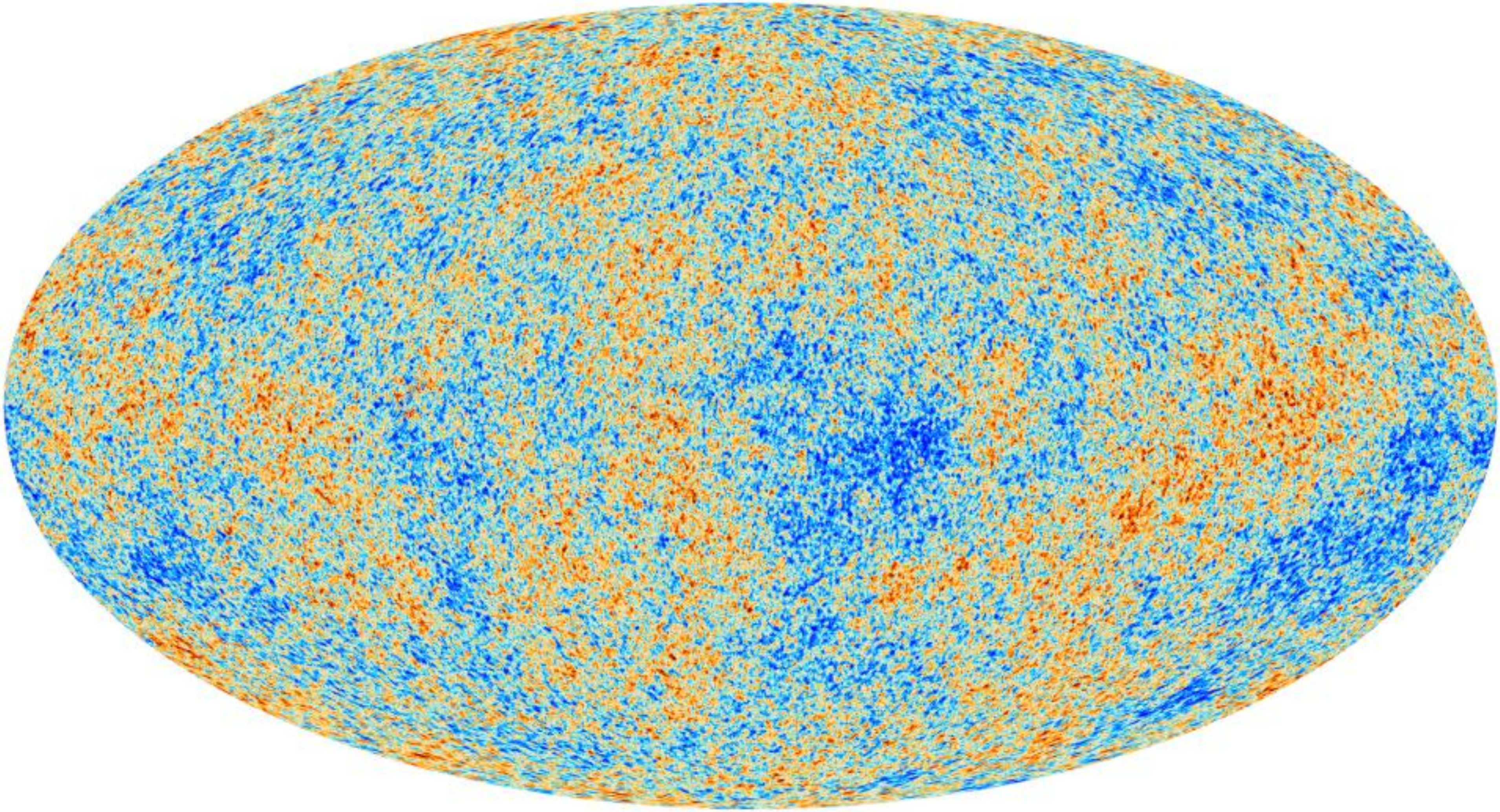


Uniform…

First Anisotropy we see is a Dipole anisotropy:
Implies solar-system barycenter has velocity v/c~0.00123 relative to 'rest-frame' of CMB.

If we remove the Dipole anisotropy and the Galactic emission, we see anisotropies at the level of $(\Delta T/T)_{rms} \sim 20\ \mu K$ (smoothed on ~7° scale).
These anisotropies are the imprint left by primordial tiny density inhomogeneities (z~1000)..

Planck 2013 CMB Map

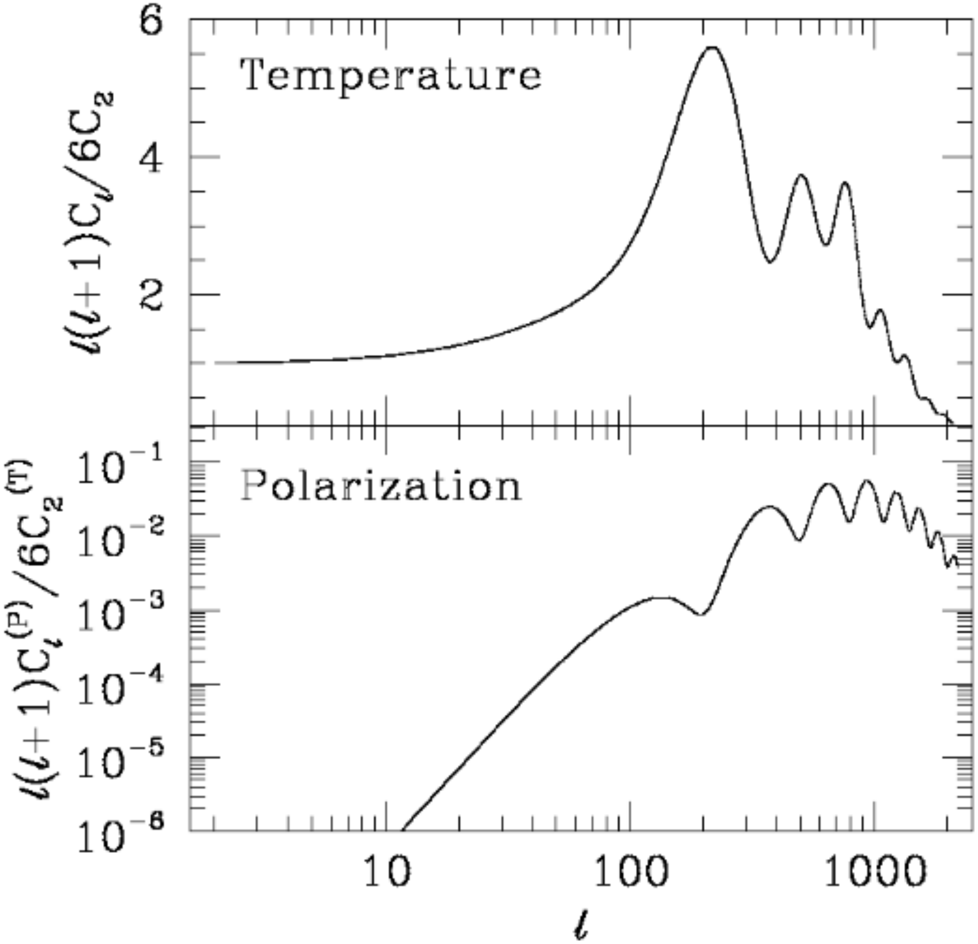


The CMB Angular Power Spectrum

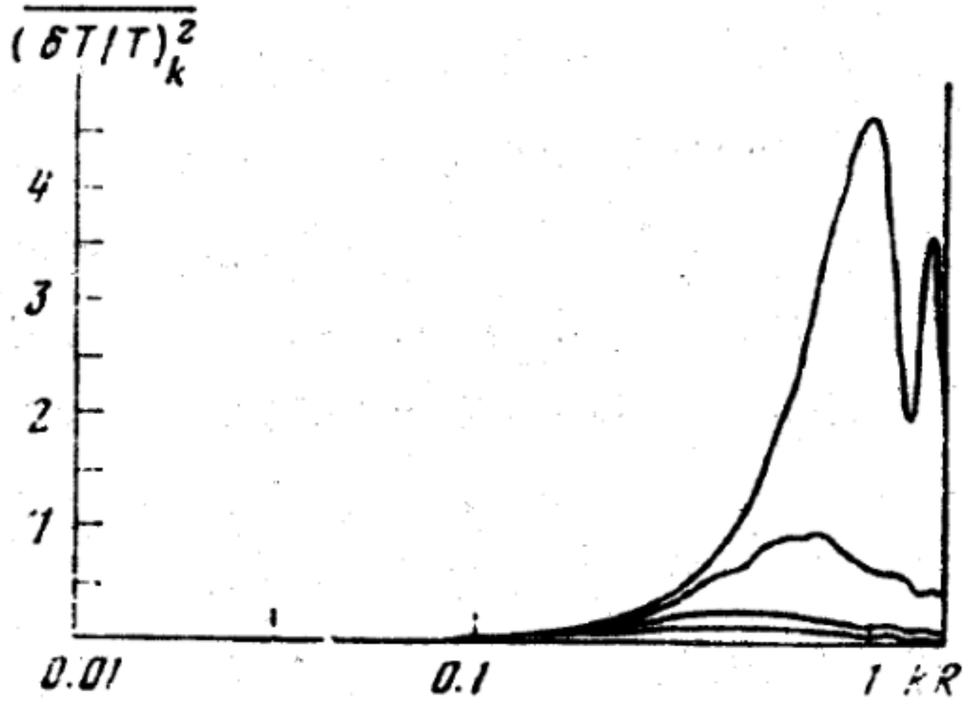
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)\,C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

R.m.s. of $\Delta T / T$ has $l(l+1)C_l / 2\pi$ power per decade in l:

$$\left\langle (\Delta T / T)^2 \right\rangle_{rms} = \sum_l \frac{(2l+1)}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d\ln l$$



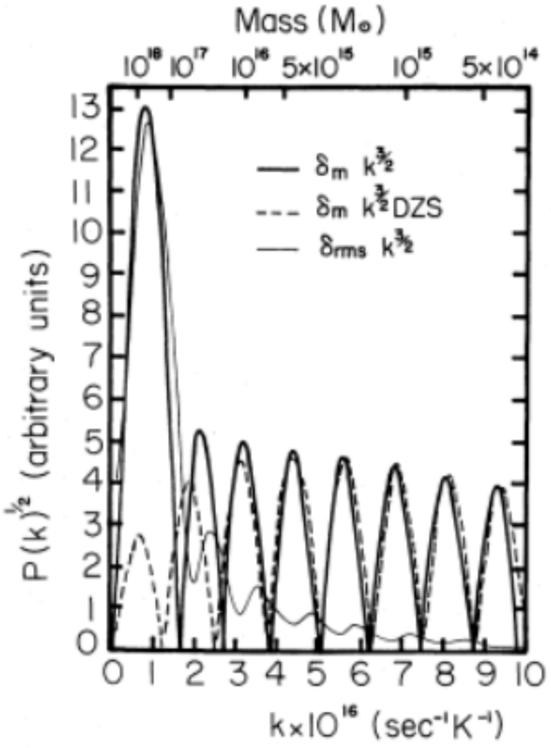
A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



Doroshkevich, A. G.; Zel'Dovich, Ya. B.; Syunyaev, R. A.

Soviet Astronomy, Vol. 22, p.523, 1978

A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



Wilson, M. L.; Silk, J., Astrophysical Journal, Part 1, vol. 243, Jan. 1, 1981, p. 14-25.
1981

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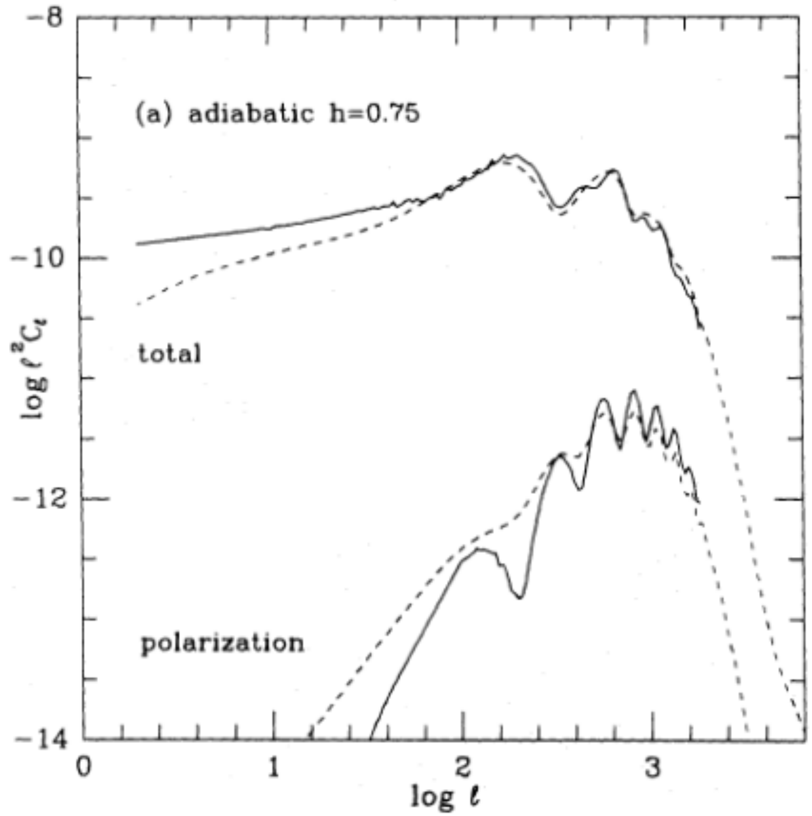
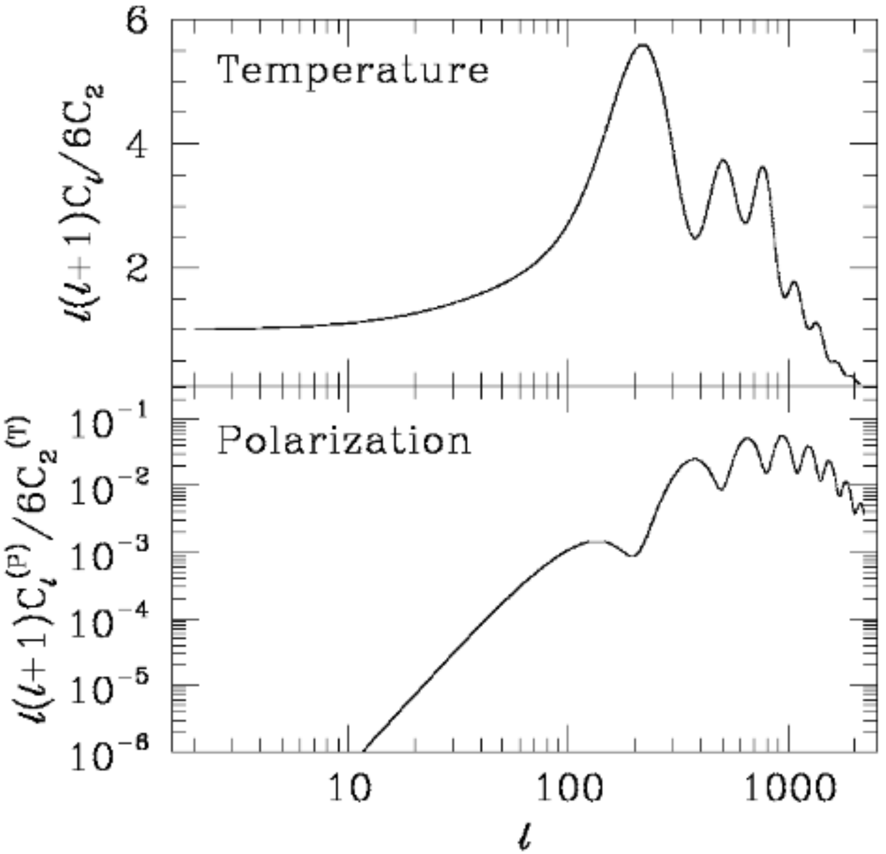


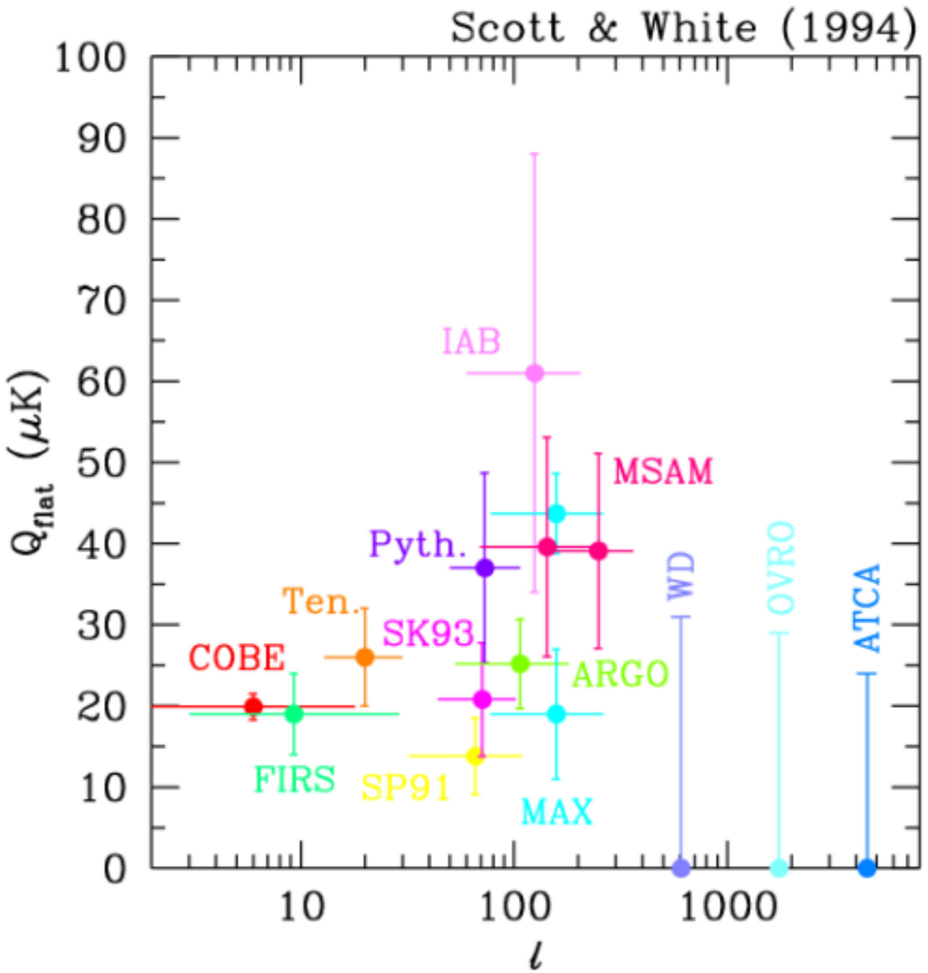
Bond, J. R.; Efstathiou, G.; Royal Astronomical Society, Monthly Notices (ISSN 0035-8711), vol. 226, June 1, 1987, p. 655-687, 1987

A Brief History of the CMB Anisotropies Angular Spectrum (Theoretical predictions)



Hu, Wayne; Scott, Douglas; Sugiyama, Naoshi; White, Martin.
Physical Review D, Volume 52, Issue 10, 15 November 1995, pp.5498-5515

A Brief History of the CMB Anisotropies Angular Spectrum (Experimental Data)



In 1995 Big Bang Model was nearly dead…

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News and Views

Nature **377**, 99 (14 September 1995) |

Big Bang not yet dead but in decline

John Maddox

The latest measurements of the Hubble constant make the Big Bang account of the origin of the Universe more dependent on the coincidence of numbers than it has so far been. But it remains the only theory in the field.

▲ Top

Is there a crisis in cosmology, or is it that the latest measurement of the Hubble constant is yet another of those numeri-cal disagreements that plague the field from time to time? That is the question inevitably prompted by last week's article by N.

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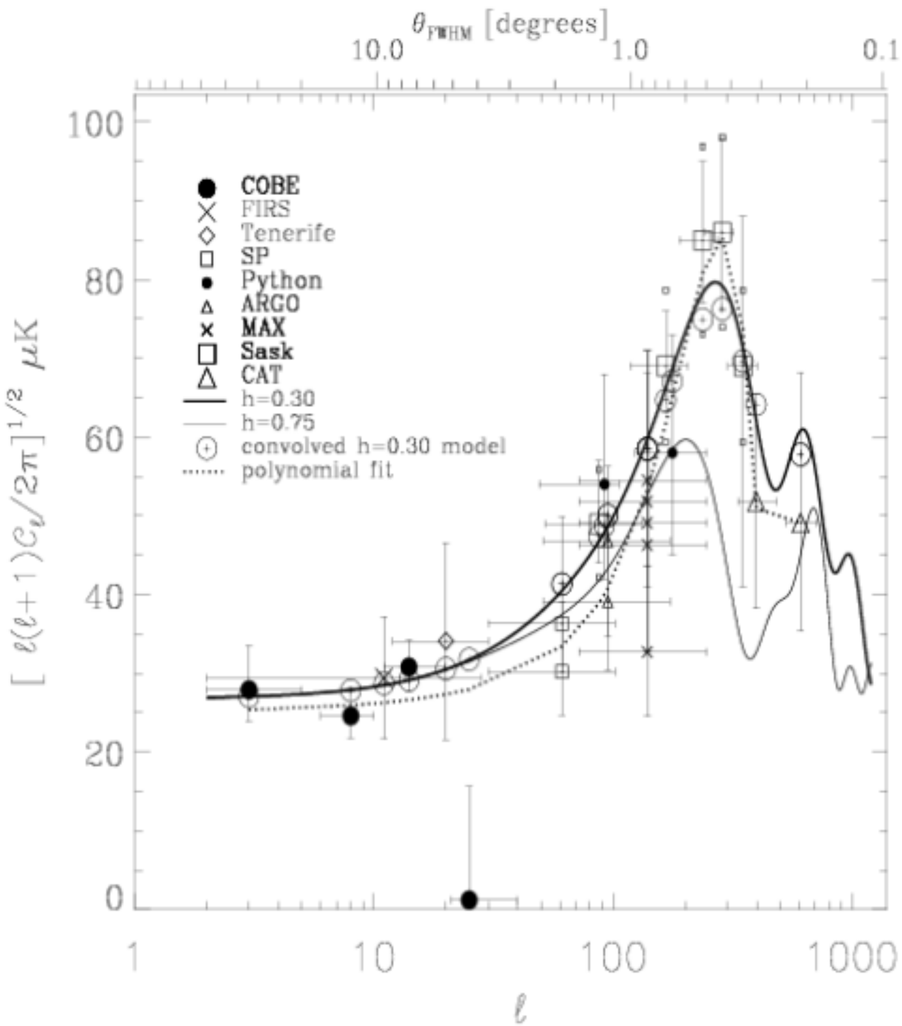
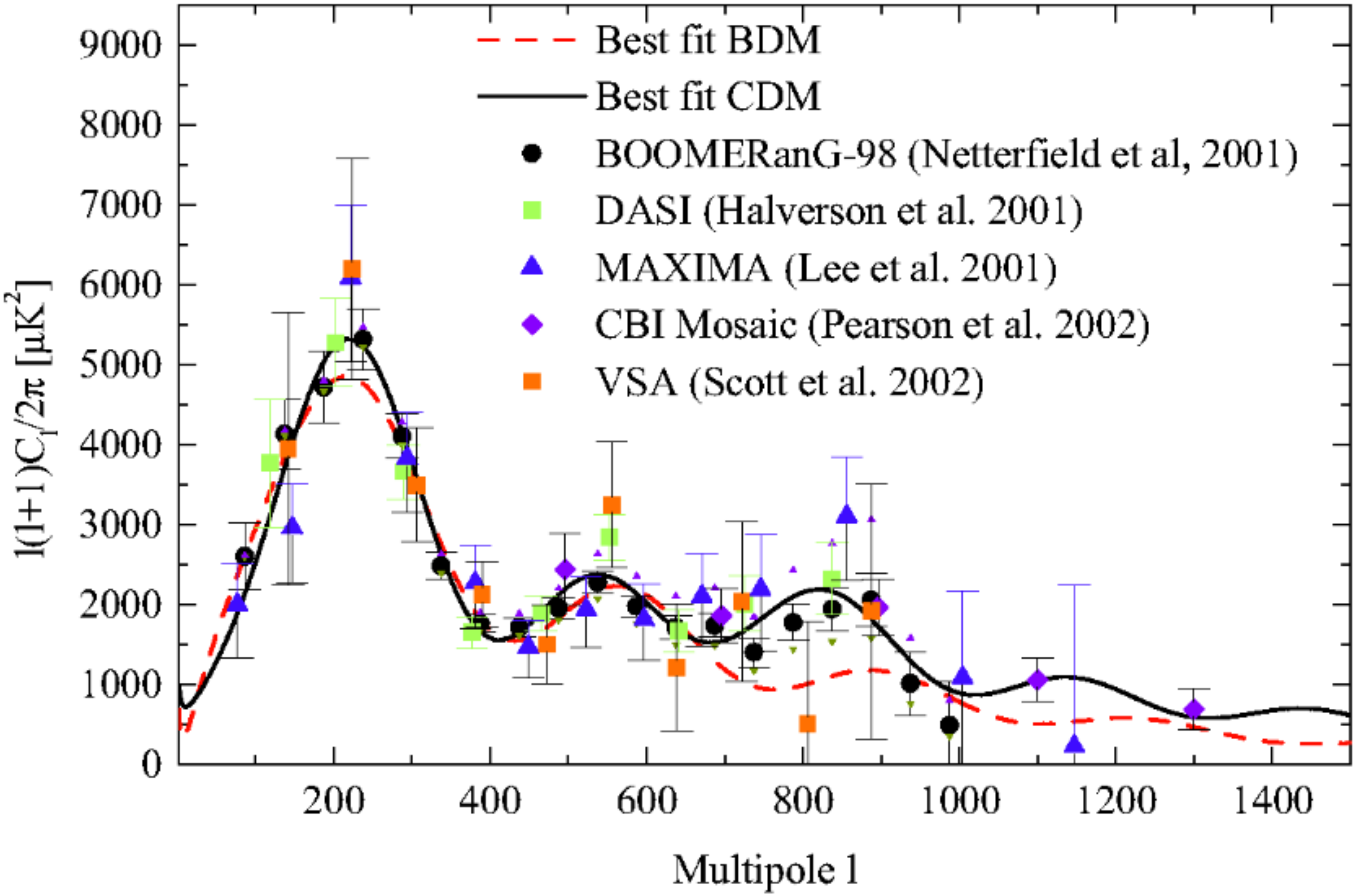
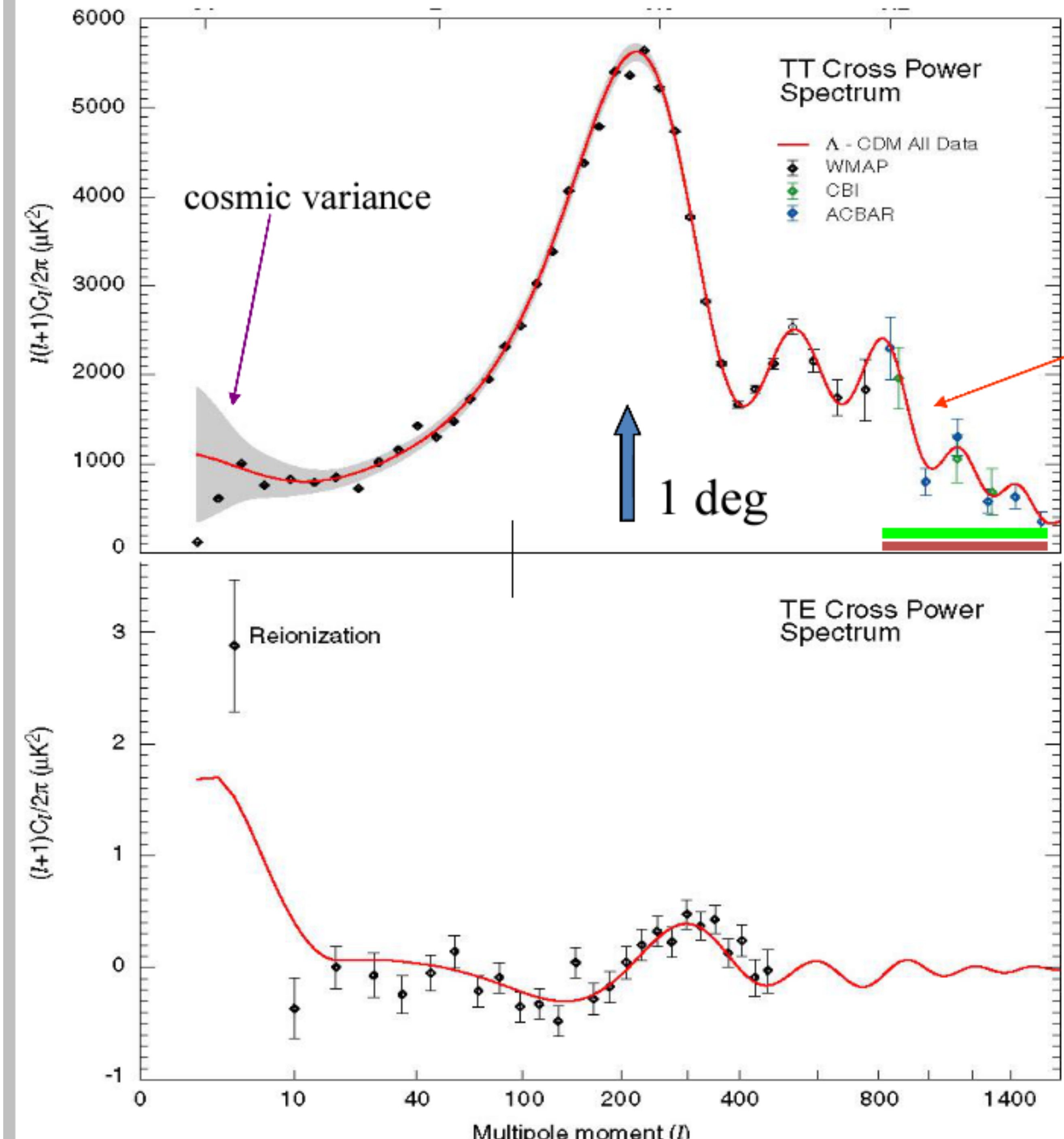
A Brief History of the CMB Anisotropies Angular Spectrum (Experimental Data)



Collection of CMB anisotropy data from C. Lineweaver et al., 1996

CMB anisotropies pre-WMAP (January 2003)





Temperature

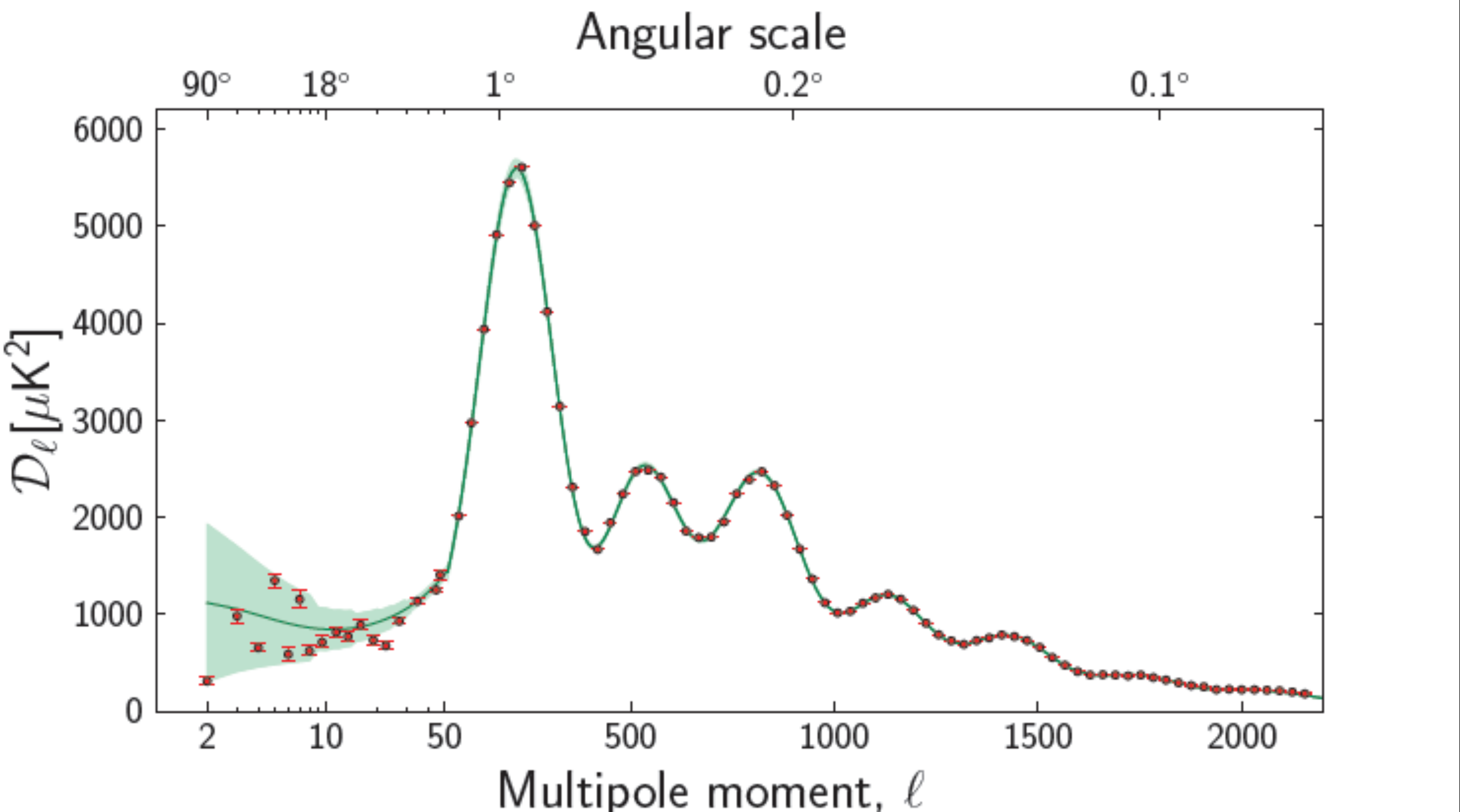
85% of sky

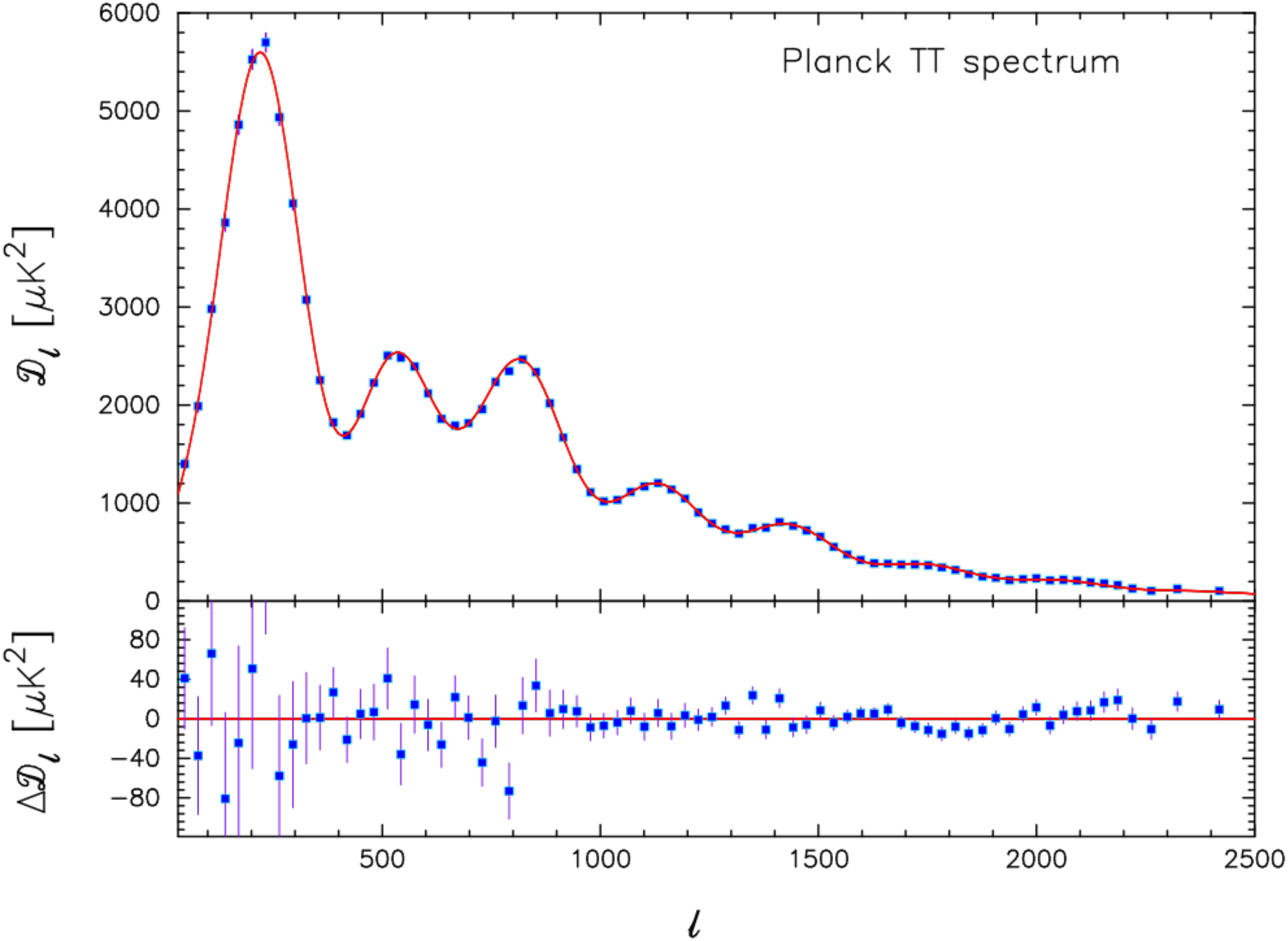
Best fit model

Spergel et al, 2003

Temperature-polarization

Planck 2013 TT angular spectrum



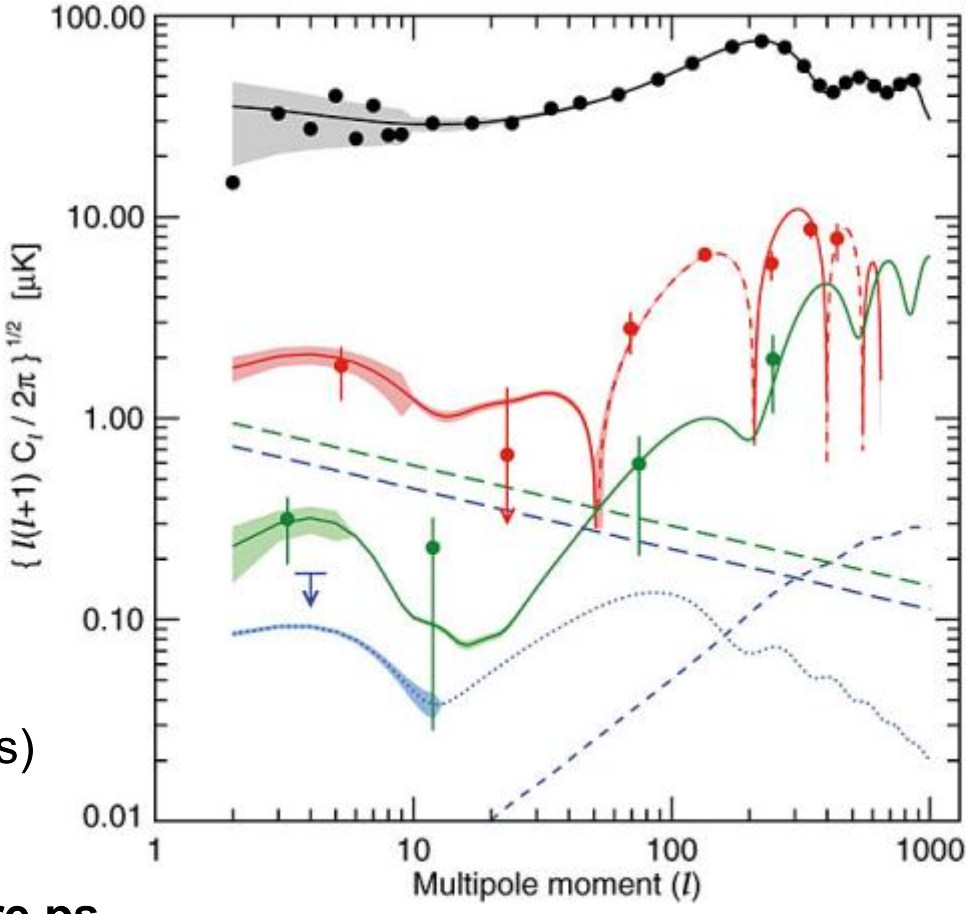


Planck TT spectrum
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell$ [μK^2]
80
40
0
−40
−80
$\Delta\mathcal{D}_\ell$ [μK^2]
500
1000
1500
2000
2500
ℓ

The CMB Angular Power Spectrum

R.m.s. of $\Delta T / T$ has $l(l+1)C_l / 2\pi$ power per decade in l:

$$\left\langle (\Delta T / T)^2 \right\rangle_{rms} = \sum_l \frac{(2l+1)}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d \ln l$$

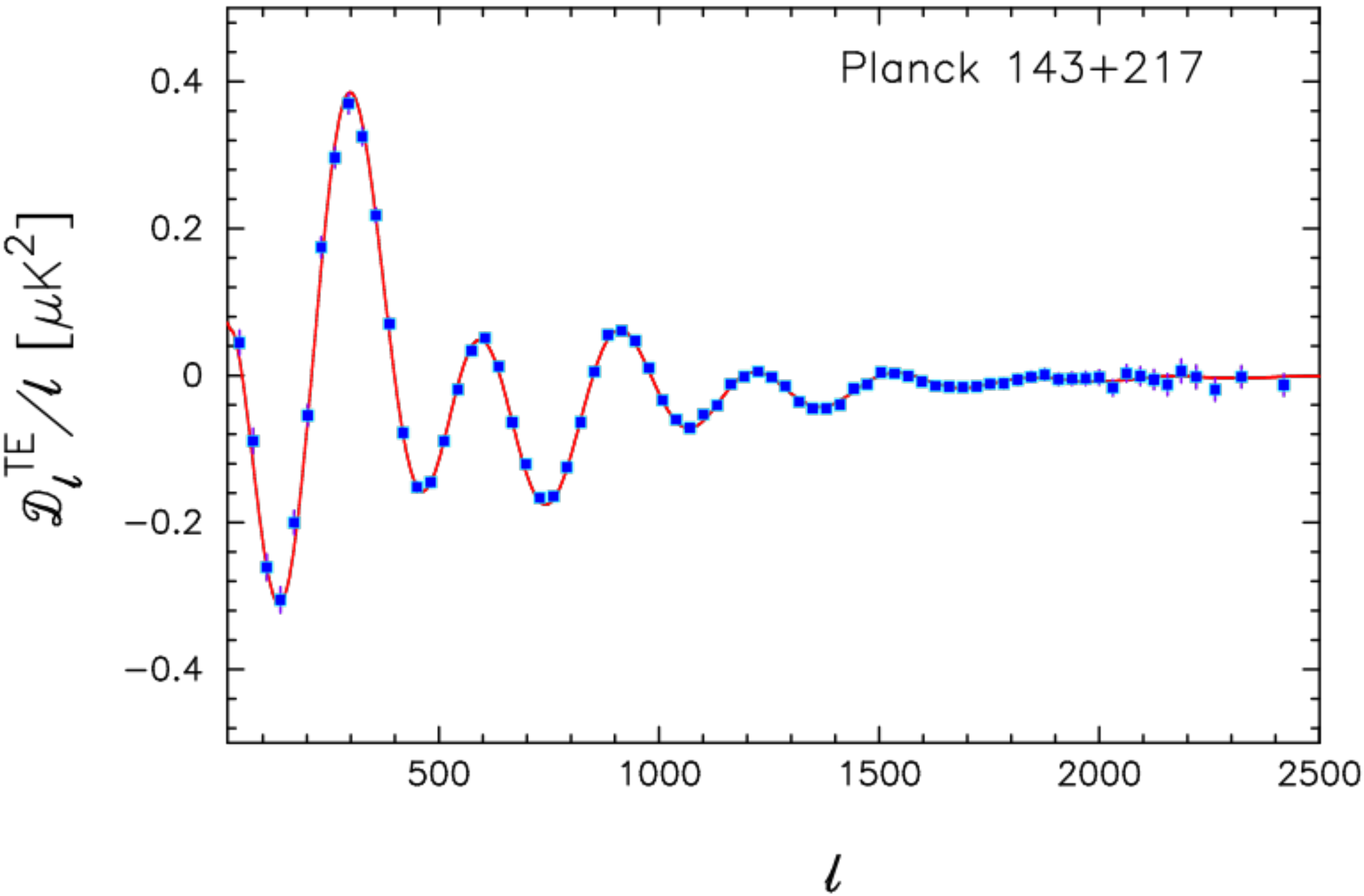


We can extract 4 independent angular spectra from the CMB:

- Temperature
- Cross Temperature Polarization
- Polarization type E (density fluctuations)
- Polarization type B (gravity waves)

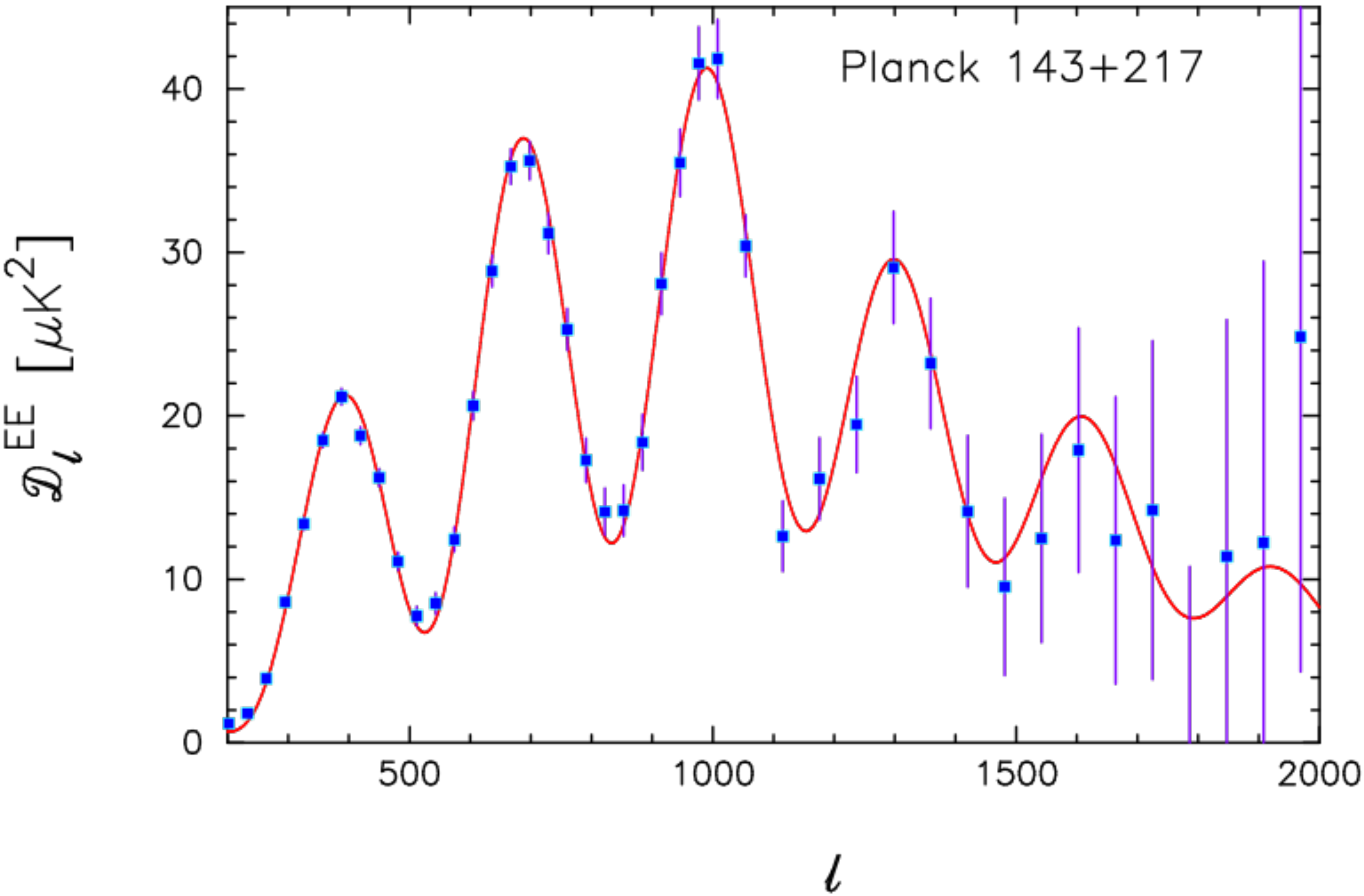
Planck 2013 release is only temperature ps.

Cross Temperature-Polarization spectrum (not present in this release)



Red line: best fit model from the temperature angular spectrum !!!

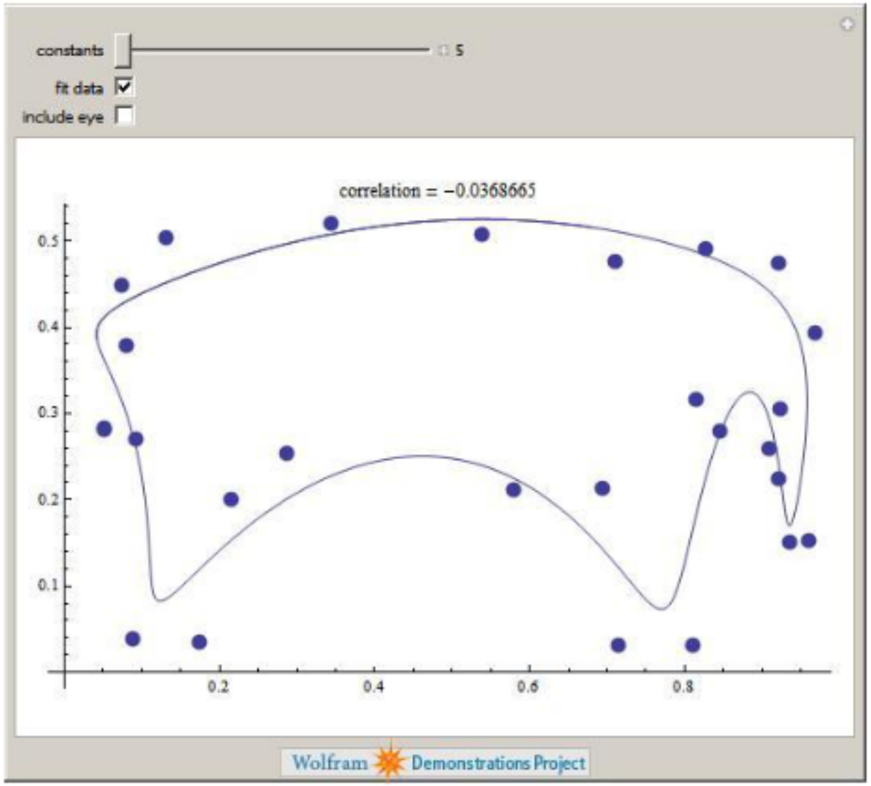
Polarization spectrum
(not present in this release)

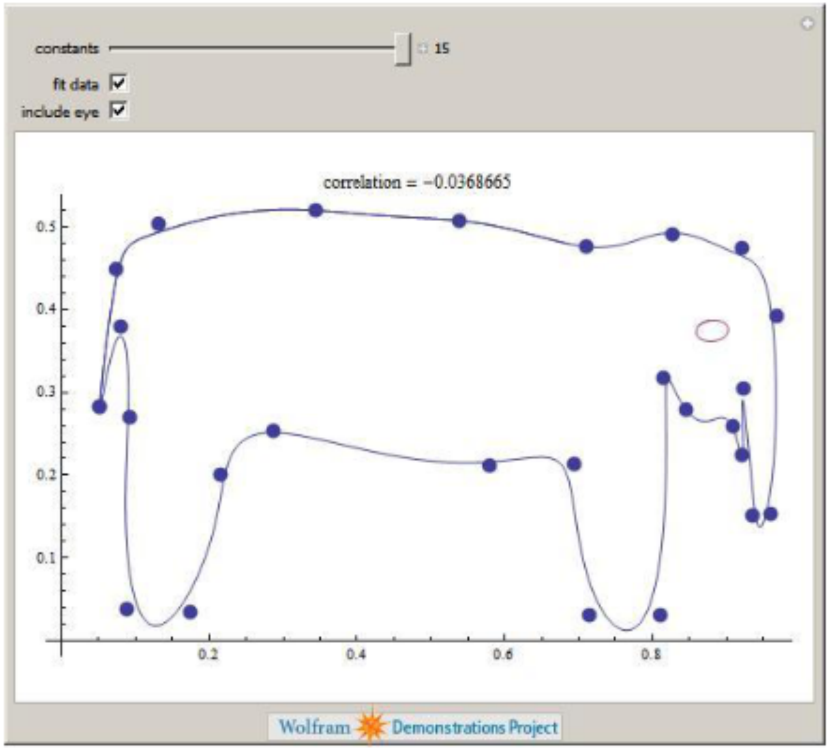


Red line: best fit model from the temperature angular spectrum !!!

How many parameters are needed to describe the CMB anisotropies ?

Enrico Fermi:"I remember my friend Johnny von Neumann used to say, 'with four parameters I can fit an elephant and with five I can make him wiggle his trunk.'"





The standard cosmological model

- Assumes General Relativity, Inflation, Adiabatic and Scalar Perturbations, flat universe.

- Friedmann-Robertson-Walker (or Friedmann-Lemaitre) metric. Hubble Constant (+1)

$$H_0 = 100h\ km/s/Mpc$$

- 3 Energy components: Baryons, Cold Dark Matter, Cosmological Constant (+3). Flat Universe (-1).

$$\omega_b = \Omega_b h^2 \quad \omega_{CDM} = \Omega_{CDM} h^2$$

- Initial conditions for perturbations given by Inflation: Adiabatic, nearly scale invariant initial power spectrum, only scalar perturbations. Two free parameters (+2): Amplitude and Spectral index.

$$P(k) \approx A_S \left(\frac{k}{k_0} \right)^{n_S}$$

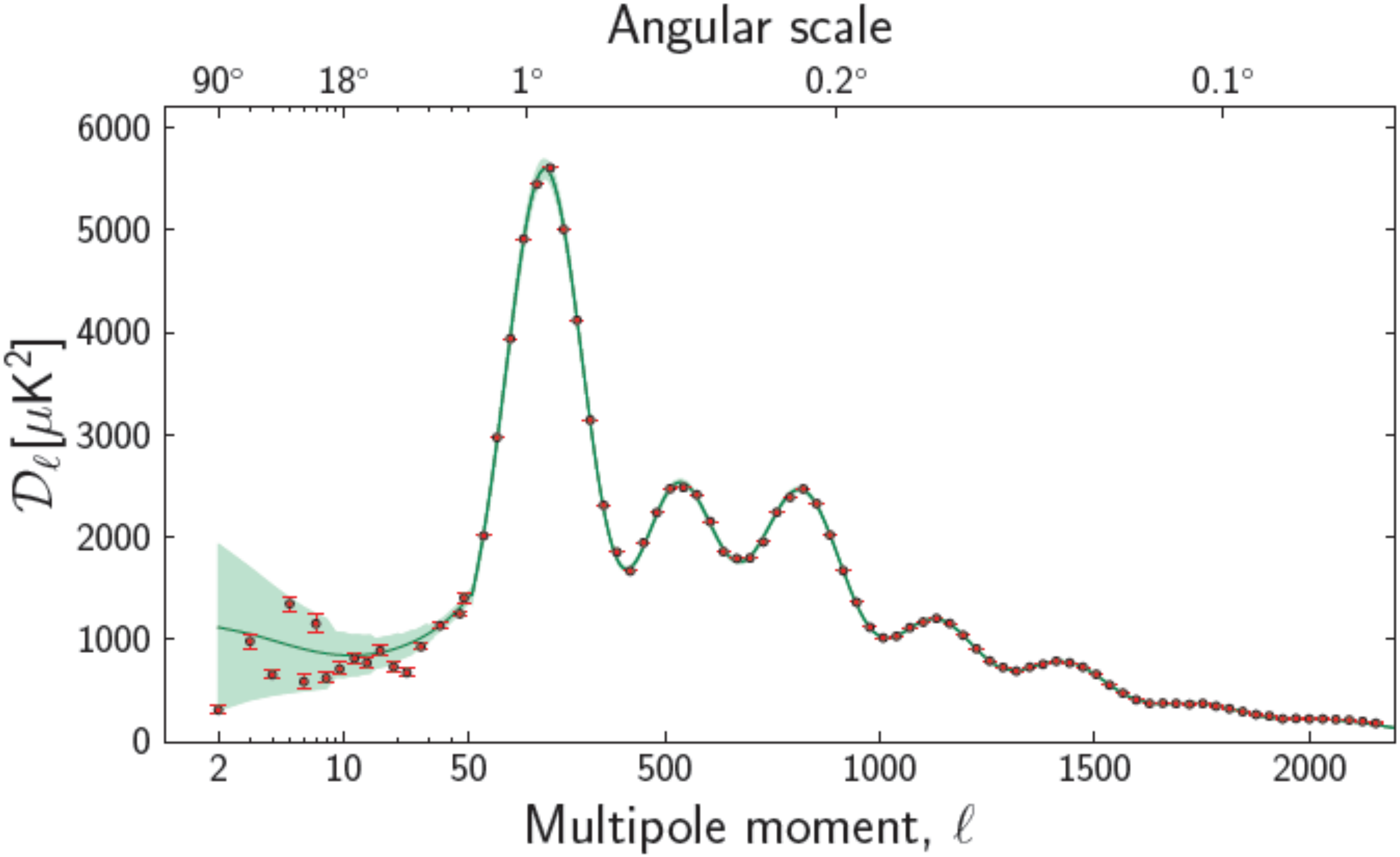
Pivot scale is usually fixed to:

$$k_0 = 0.002\ \ hMpc^{-1}$$

- Late universe reionization characterized with a single parameter(+1) : optical depth τ or reionization redshift z_r.

Total: 1+3-1+2+1= 6 parameters.

Planck 2013 TT angular spectrum



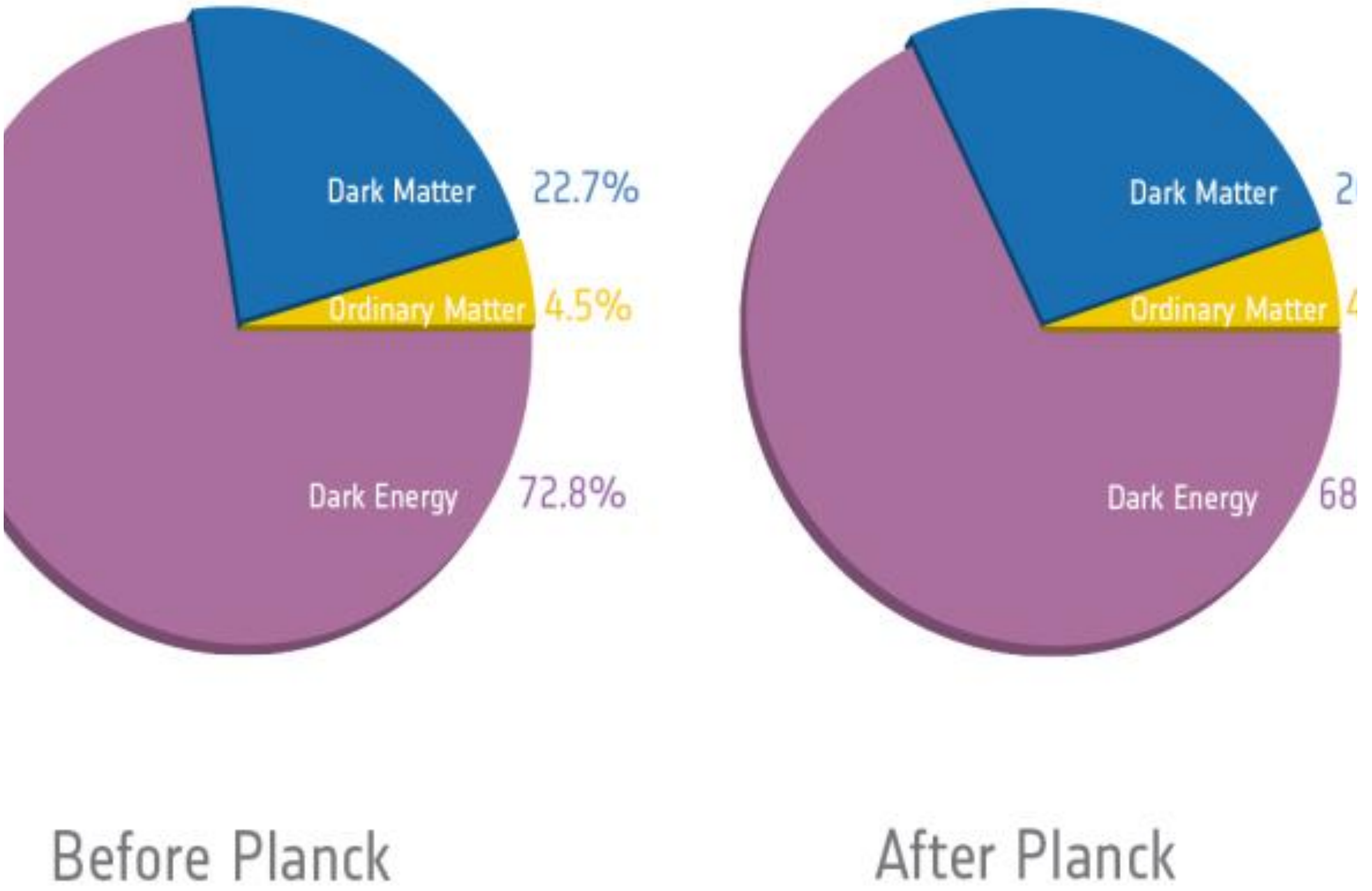
The LCDM model provides an excellent fit to the CMB data !

Constraints

Parameter	*Planck*		*Planck*+lensing		*Planck*+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2

CMB needs Dark Matter at more than 40 standard deviations !
Caveat: CDM must be non relativistic at recombination.
Masses m>10eV would be OK.

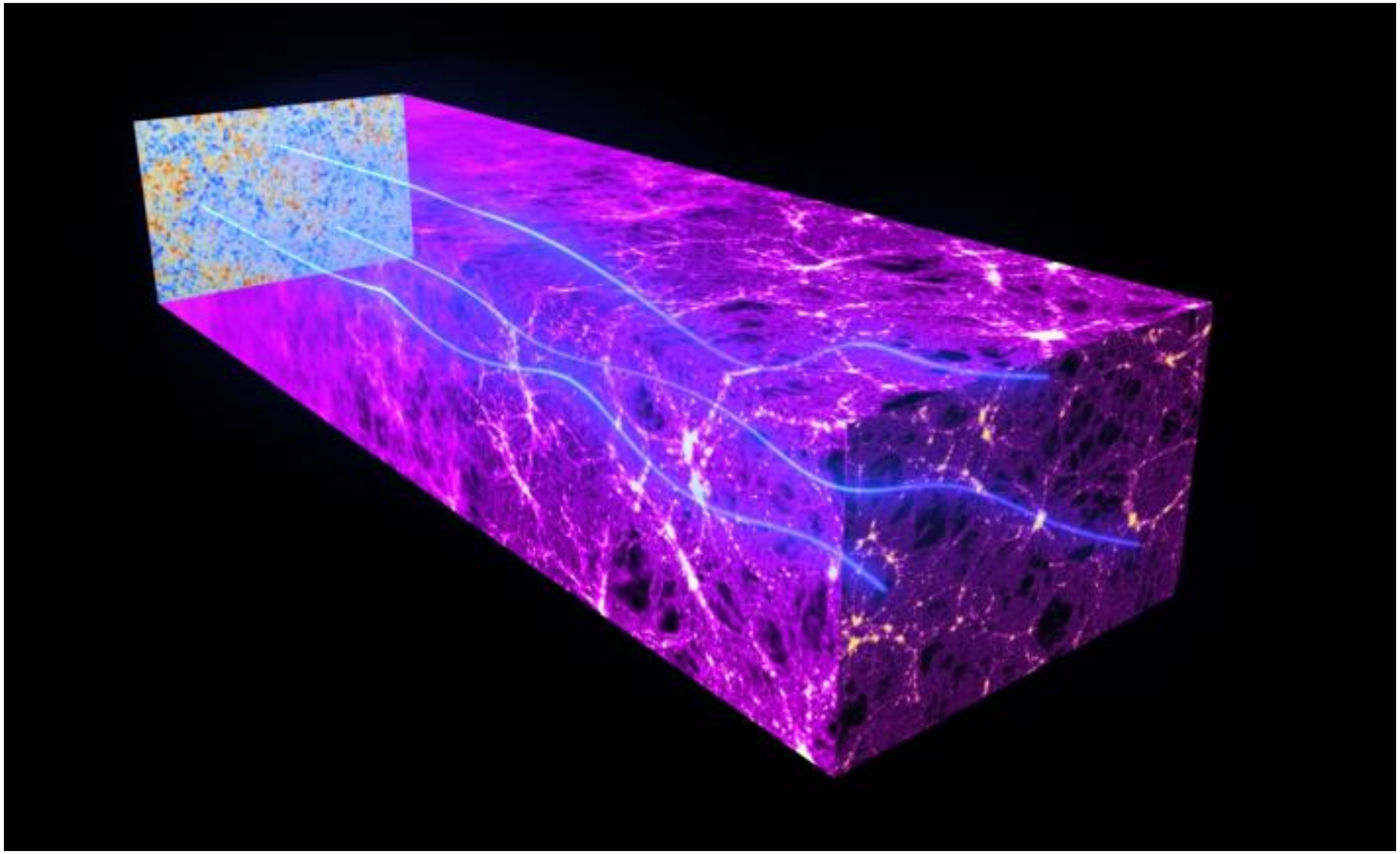
The basic content of the Universe



Cosmology needs new physics !!!!

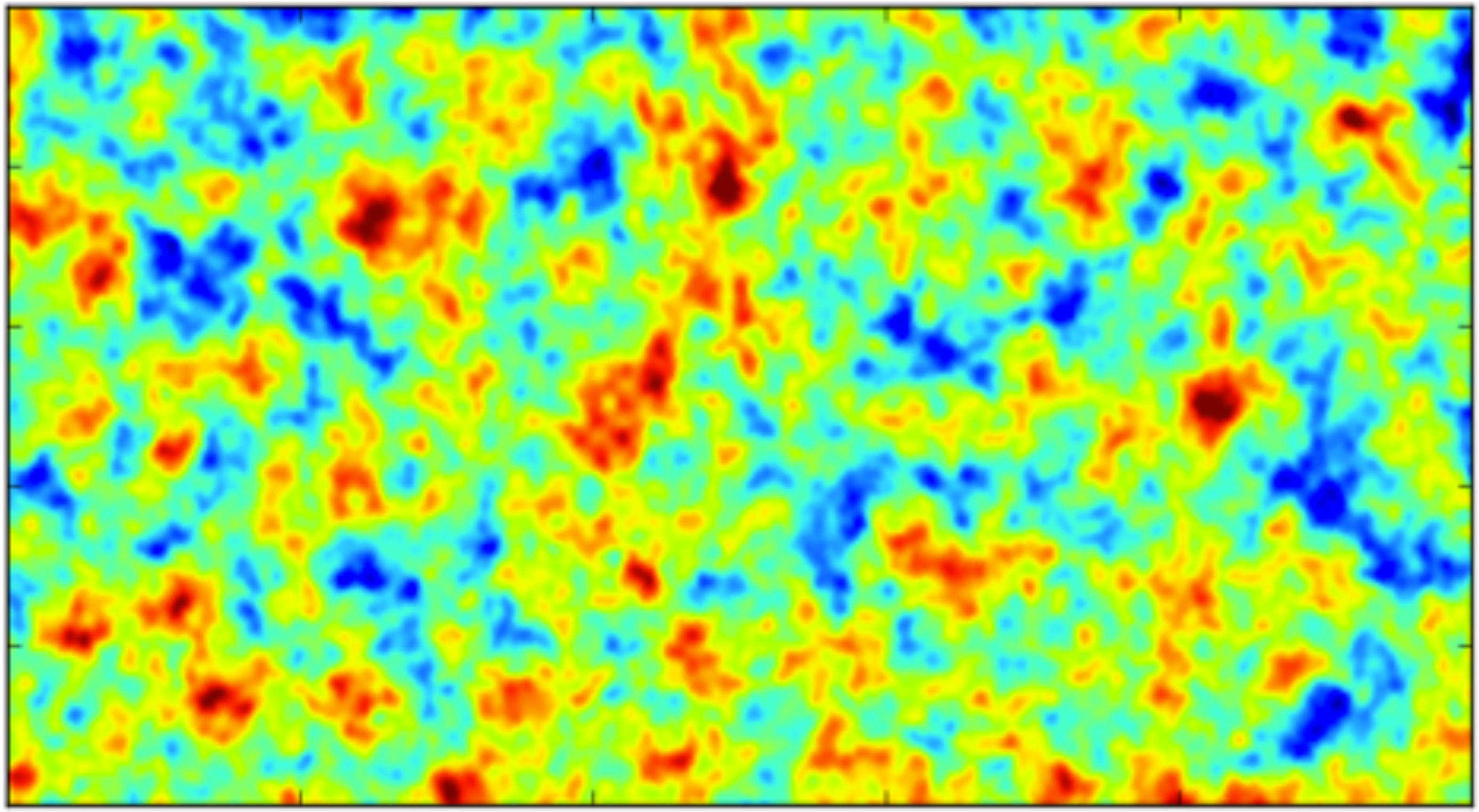
Gravitational Lensing

The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB



Gravitational Lensing

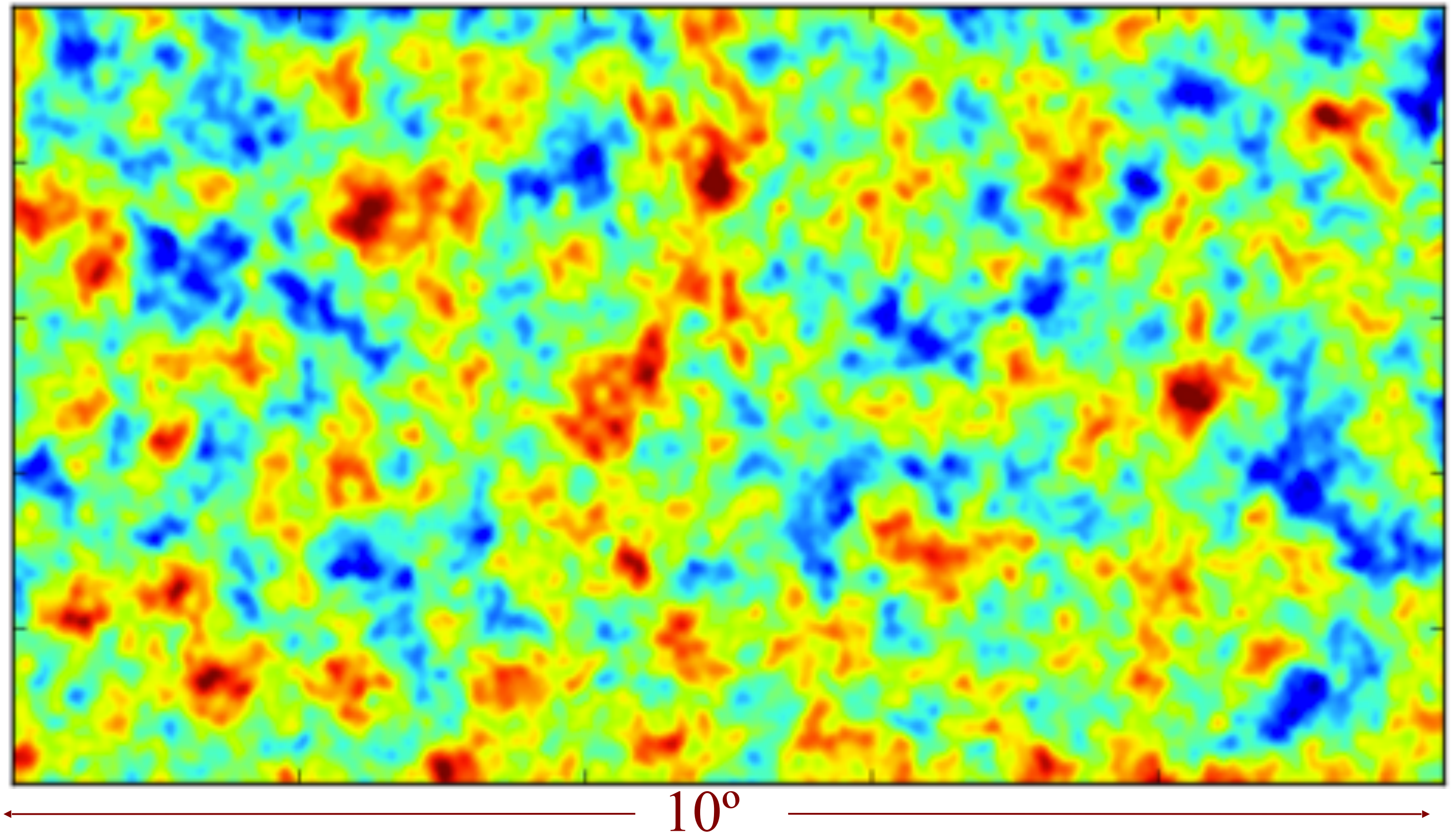
A simulated patch of CMB sky – **before lensing**



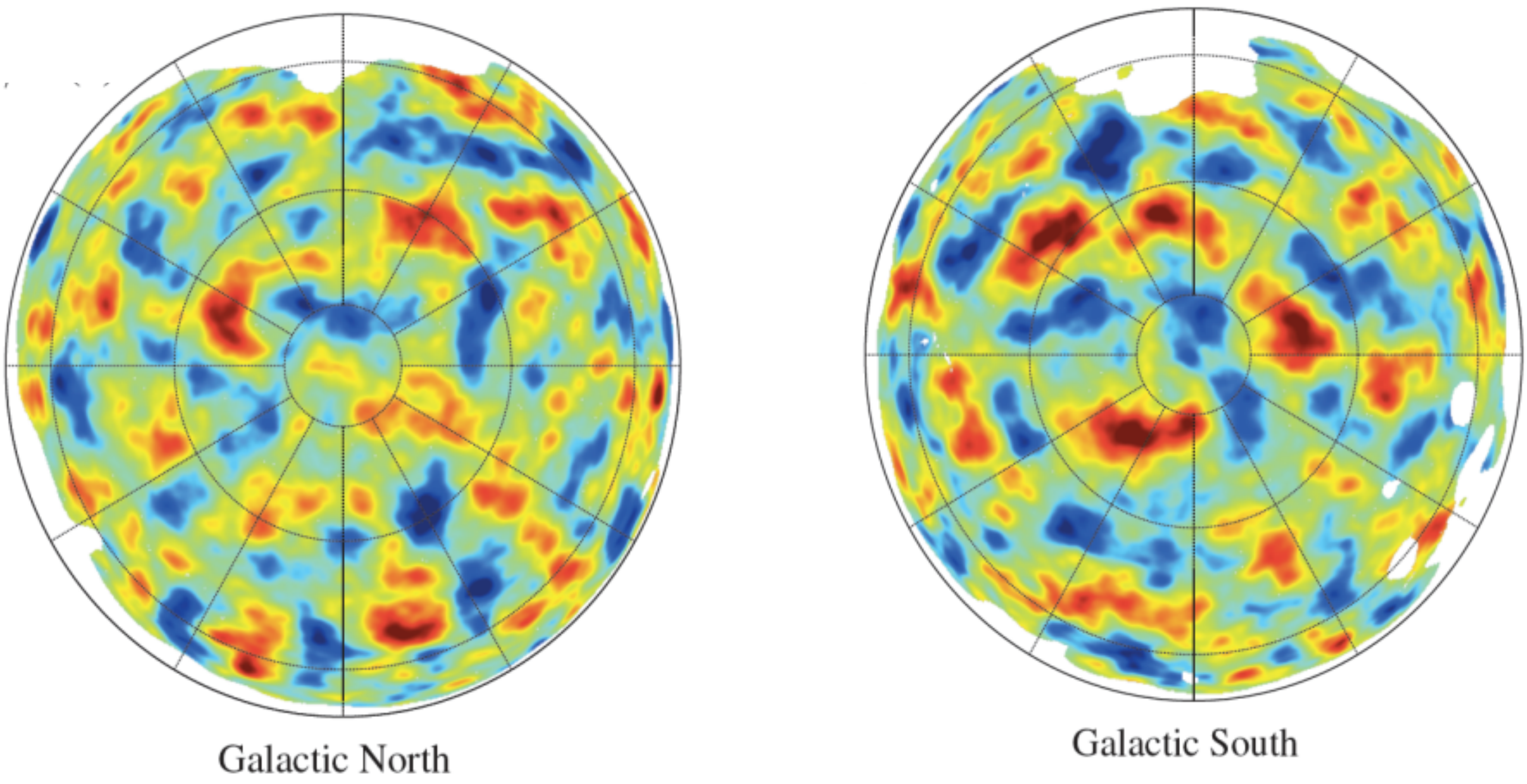
10º

Gravitational Lensing

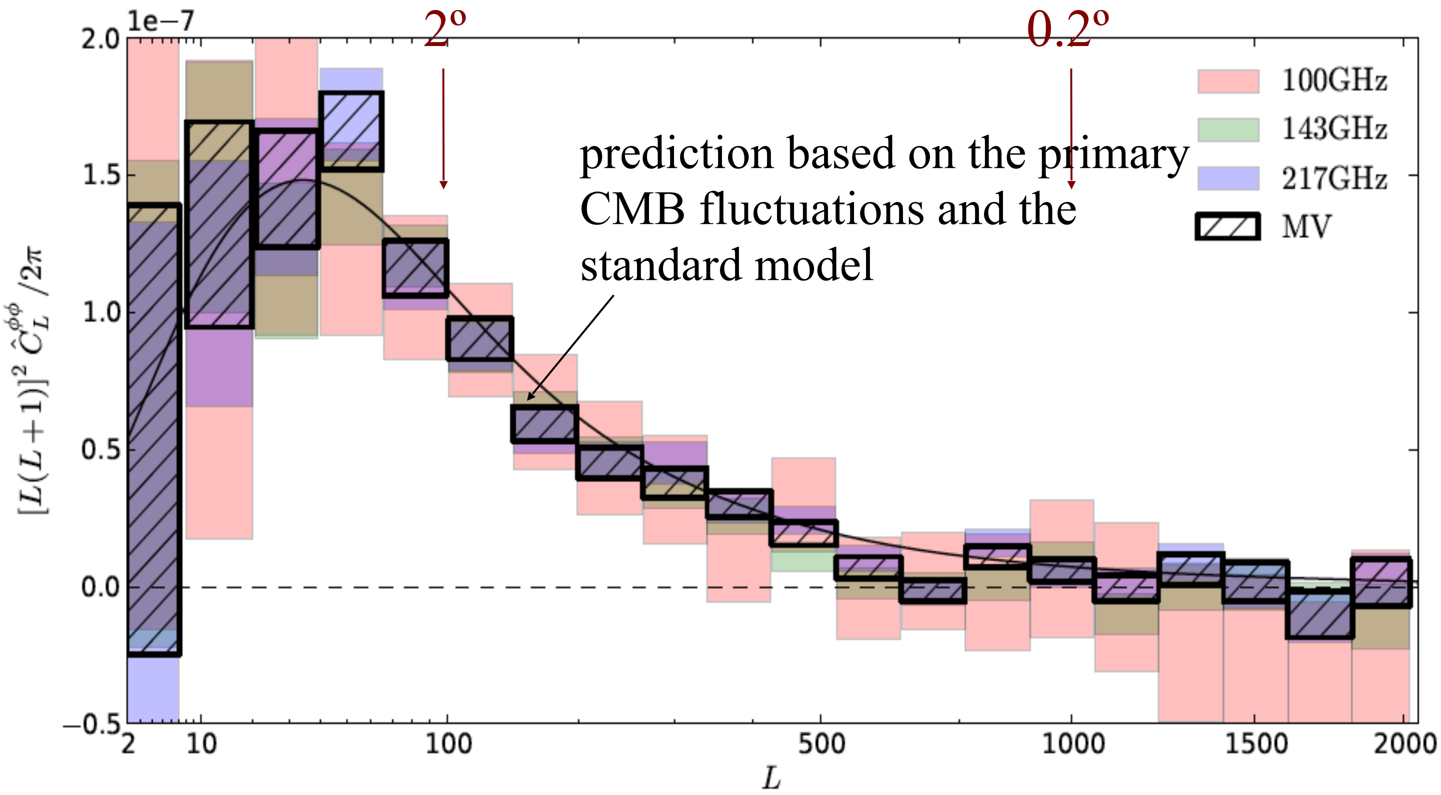
A simulated patch of CMB sky – **after lensing**



Planck dark matter distribution throught CMB lensing



PLANCK LENSING POTENTIAL POWER SPECTRUM
Measured from the Trispectrum (4-point correlation)

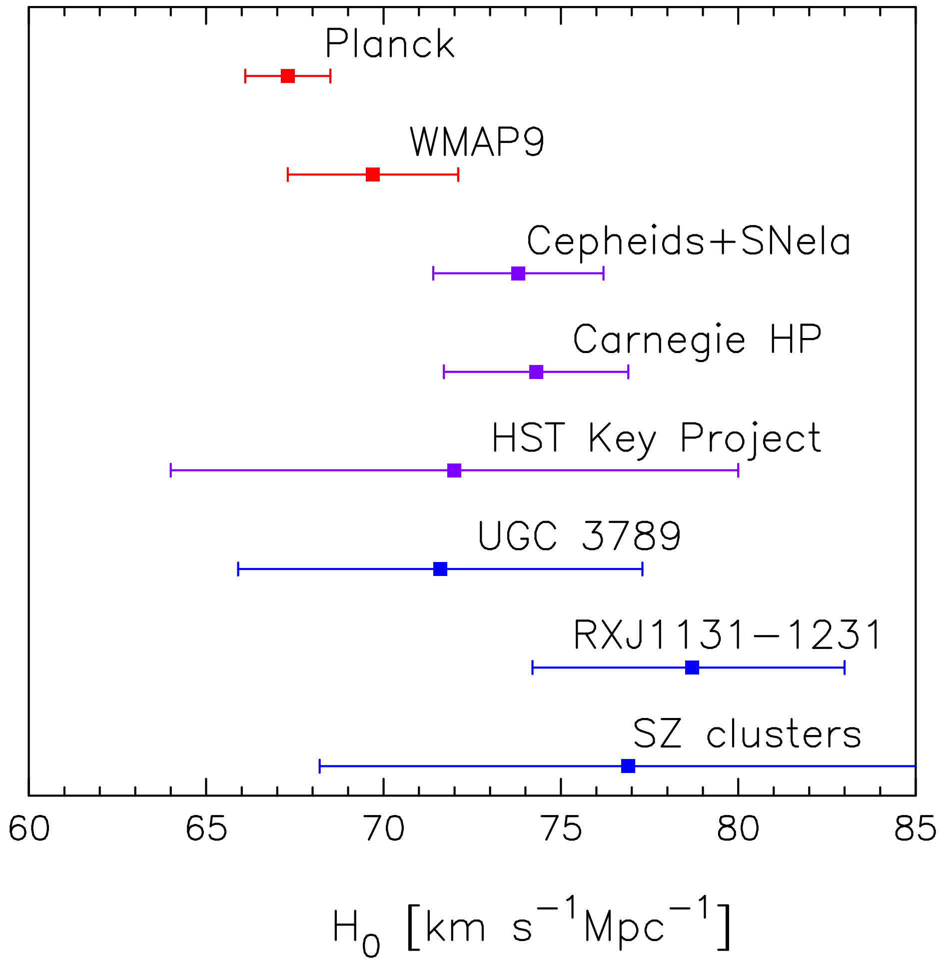


It is a 25 sigma effect!!
This spectrum helps in constraining parameters

Lesson from Planck: the LCDM provides an almost perfect description of the CMB anisotropies.
Dark matter and dark energy are badly needed to explain the observations.

Comparison with other datasets: Hubble Constant

The value of the Hubble constant from Planck is in tension with the Riess et al. 2011 result.



$$\text{Planck + WP} \quad H_0 = 67.3^{+1.2}_{-1.1}\ [\text{km/s/Mpc}]$$

$$\text{HST (Riess et al.)} \quad H_0 = 73.8^{+2.4}_{-2.4}\ [\text{km/s/Mpc}]$$

Cosmological (Massless) Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1 MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

for a relativistic neutrino translates in a extra radiation component of:

$$\Omega_\nu h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^\nu \Omega_\gamma h^2$$

Standard Model predicts:

$$N_{eff}^\nu = 3.046$$

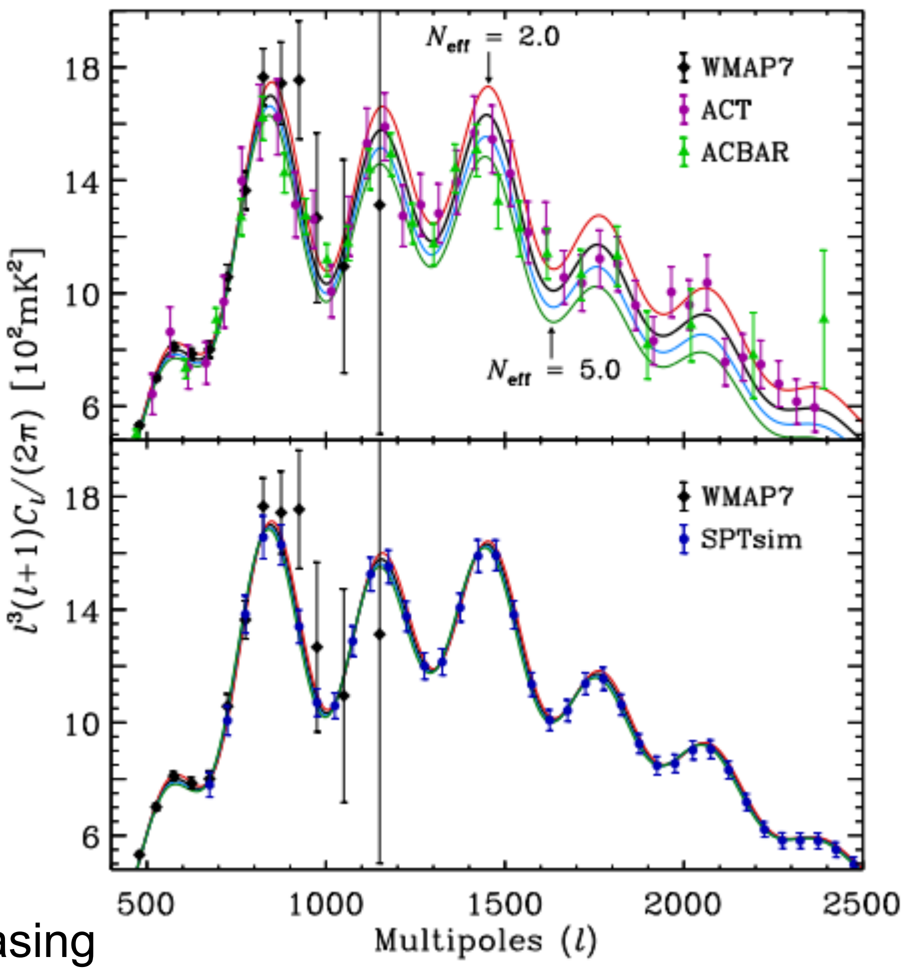
Probing the Neutrino Number with CMB data

Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}.$$

and the damping scale at recombination:

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)}\right]$$



Once the sound horizon scale is fixed, increasing $N_{\rm eff}$ decreases the damping scale and the result is an increase in the small angular scale anisotropy.
We expect degeneracies with the Hubble constant and the Helium abundance.
(see e.g. Hou, Keisler, Knox et al. 2013, Lesgourgues and Pastor 2006).

Constraints from Planck and other CMB datasets (95% c.l.)

$$\text{Planck alone (no pol.)} \quad N_{eff}^{\nu} = 4.53^{+1.5}_{-1.4}$$

$$\text{Planck} + \text{WP} \quad N_{eff}^{\nu} = 3.51^{+0.80}_{-0.74}$$

$$\text{Planck} + \text{WP} + \text{Lensing} \quad N_{eff}^{\nu} = 3.39^{+0.77}_{-0.70}$$

$$\text{Planck} + \text{WP} + \text{highL} \quad N_{eff}^{\nu} = 3.36^{+0.68}_{-0.64}$$

$$\text{Planck} + \text{WP} + \text{highL} + \text{Lensing} \quad N_{eff}^{\nu} = 3.28^{+0.67}_{-0.64}$$

Conclusions:

- $N_{eff}=0$ is excluded at high significance (about 10 standard deviations). We need a neutrino background to explain Planck observations !

- **No evidence** (i.e. > 3 σ) for extra radiation from CMB only measurements.

- $N_{eff}=4$ is also consistent in between 95% c.l.

- $N_{eff}=2$ and $N_{eff}=5$ excluded at more than 3 σ (massless).

Constraints from Planck + astrophysical datasets (95% c.l.)

$$\text{Planck} + \text{WP} + \text{BAO} \qquad N_{eff}^{\nu} = 3.40^{+0.59}_{-0.57}$$

$$\text{Planck} + \text{WP} + \text{SNLS} \qquad N_{eff}^{\nu} = 3.68^{+0.77}_{-0.78}$$

$$\text{Planck} + \text{WP} + \text{Union2} \qquad N_{eff}^{\nu} = 3.56^{+0.77}_{-0.73}$$

$$\text{Planck} + \text{WP} + \text{HST} \qquad N_{eff}^{\nu} = 3.73^{+0.54}_{-0.51}$$

Conclusions:

- When the BAO dataset is included there is a better agreement with Neff=3.046.

- When luminosity distance data are included (supernovae, HST) the data prefers extra «dark radiation». Systematics in luminosity distances or new physics ?

- With HST we have extra dark radiation at about 2.7 σ. This is clearly driven by the tension between Planck and HST on the value of the Hubble constant in the standard LCDM framework.

Can we combine Planck and HST ?

Planck and HST give very different values for the Hubble constant (68% c.l.):

$$\text{Planck} + \text{WP} \qquad H_0 = 67.3^{+1.2}_{-1.1}\ [\text{km/s/Mpc}]$$

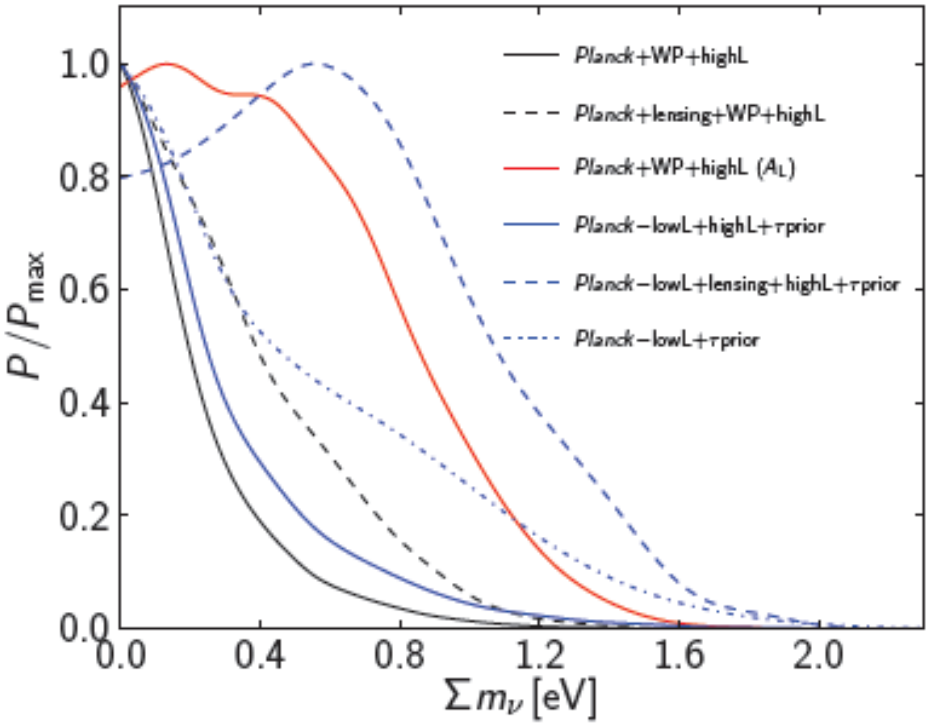
$$\text{HST (Riess et al.)} \qquad H_0 = 73.8^{+2.4}_{-2.4}\ [\text{km/s/Mpc}]$$

But the Planck result is obtained under the assumption of N_{eff}=3.046.
If leave N_{eff} as a free parameter we get:

$$\text{Planck} + \text{WP} \qquad H_0 = 70.7^{+3.0}_{-3.2}\ [\text{km/s/Mpc}]$$

That is now compatible with HST (but we now need dark radiation).
The CMB determination of the Hubble constant is **model dependent**.

Constraints on Neutrino Mass (standard 3 neutrino framework)



$$\sum m_\nu < 0.66\,\mathrm{eV} \quad (95\%;\ Planck\text{+WP+highL}).$$

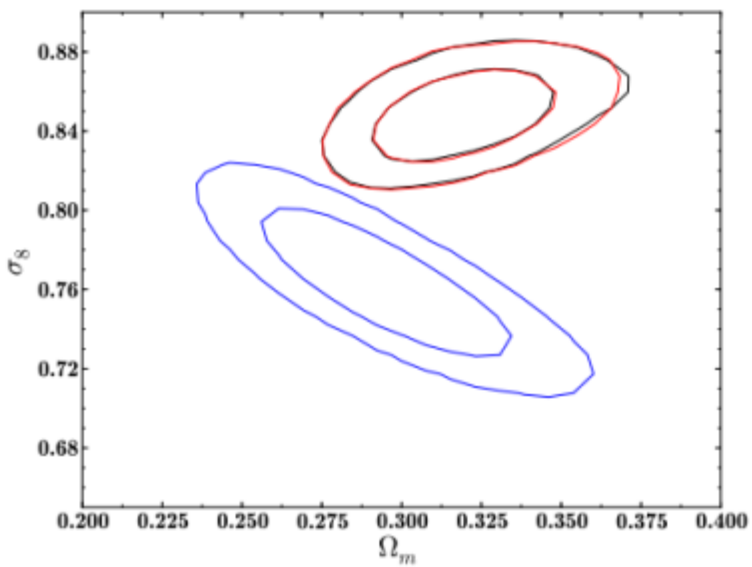
$$\sum m_\nu < 1.08\,\mathrm{eV} \quad [95\%;\ Planck\text{+WP+highL}\ (A_\mathrm{L})],$$

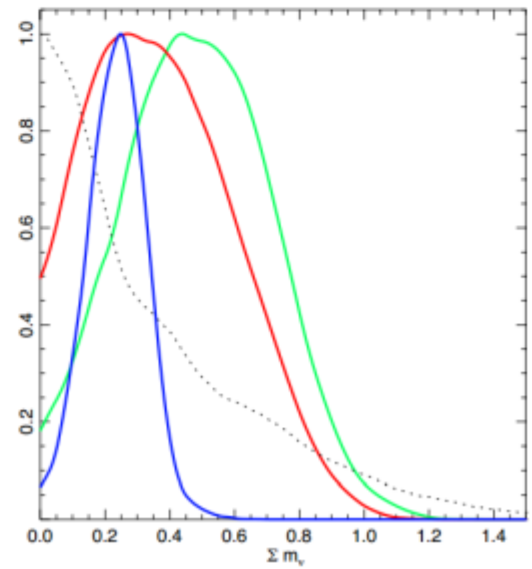
$$\sum m_\nu < 0.85\,\mathrm{eV} \quad (95\%;\ Planck\text{+lensing+WP+highL}),$$

$$\sum m_\nu < 0.23\,\mathrm{eV} \quad (95\%;\ Planck\text{+WP+highL+BAO}).$$

- Planck strongly improves previous constraints on neutrino masses.
- Planck TT spectrum prefers a lensing amplitude higher than expected (A_{LENS}=1.2).
- Inclusion of lensing from TTTT weakens the Planck constraint by 20%
- Including BAO results in the best current constraint on neutrino masses of 0.23 eV

Evidence for a Neutrino mass from SZ Clusters counts ?





Dashed:
Planck CMB

Red:
Planck CMB+SZ
(1-b)=[0.7,1]

Green:
Planck CMB+SZ
(1-b)=0.8

Blue:
Planck CMB+SZ+BAO
(1-b)=[0.7,1]

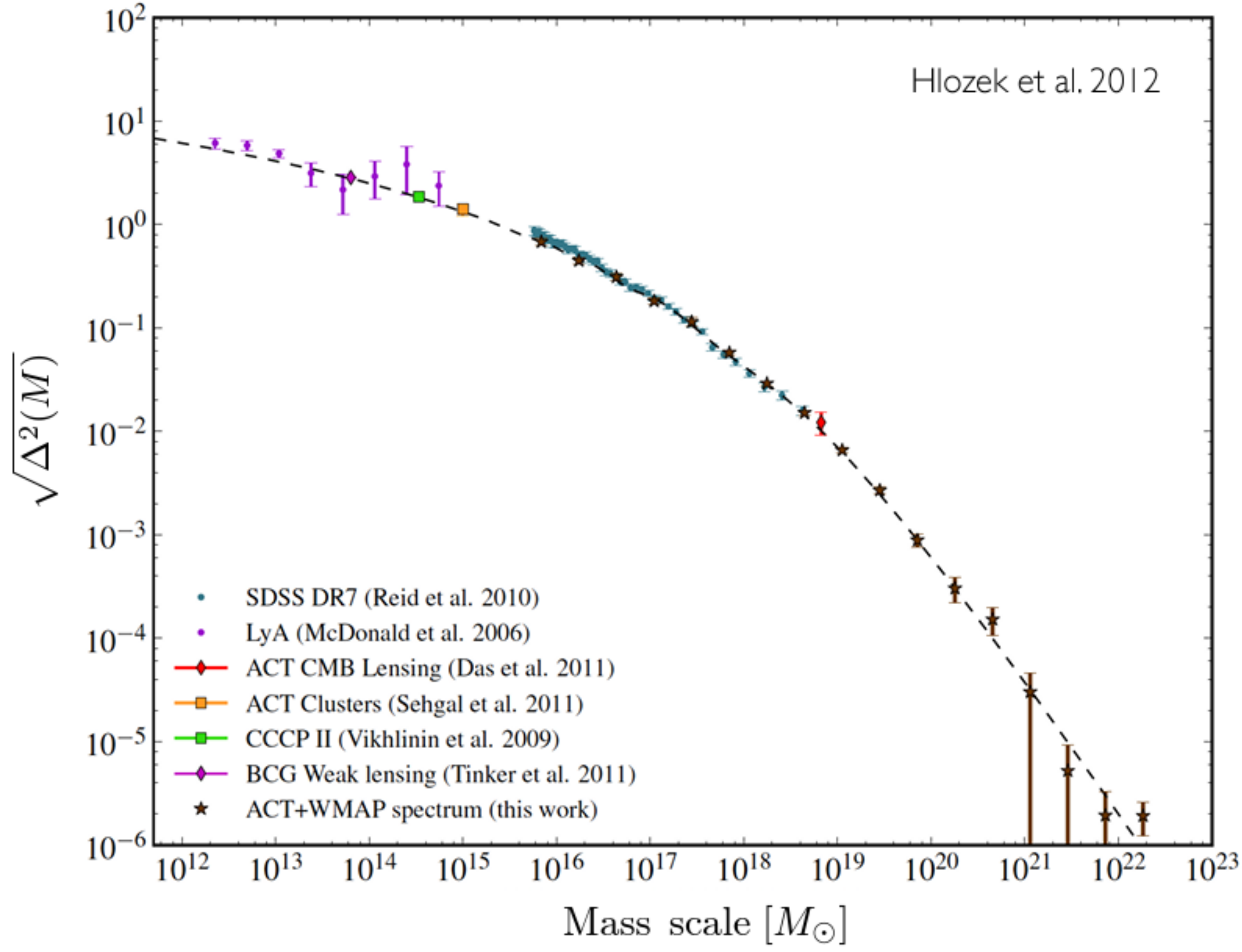
- Cosmological parameters as σ_8 and Ω_m derived from Planck SZ clusters number counts are in strong tension with the parameters derived from CMB TT measurements.
- Massive neutrinos could solve the tension.
- Cluster counts results are however affected by a bias b between the X-ray determined mass and the true mass. Assuming a flat prior of [0.7,1] on (1-b) we have from Planck+BAO+SZ (68% c.l):

$$\sum m_\nu = (0.22 \pm 0.09)\,\mathrm{eV}.$$

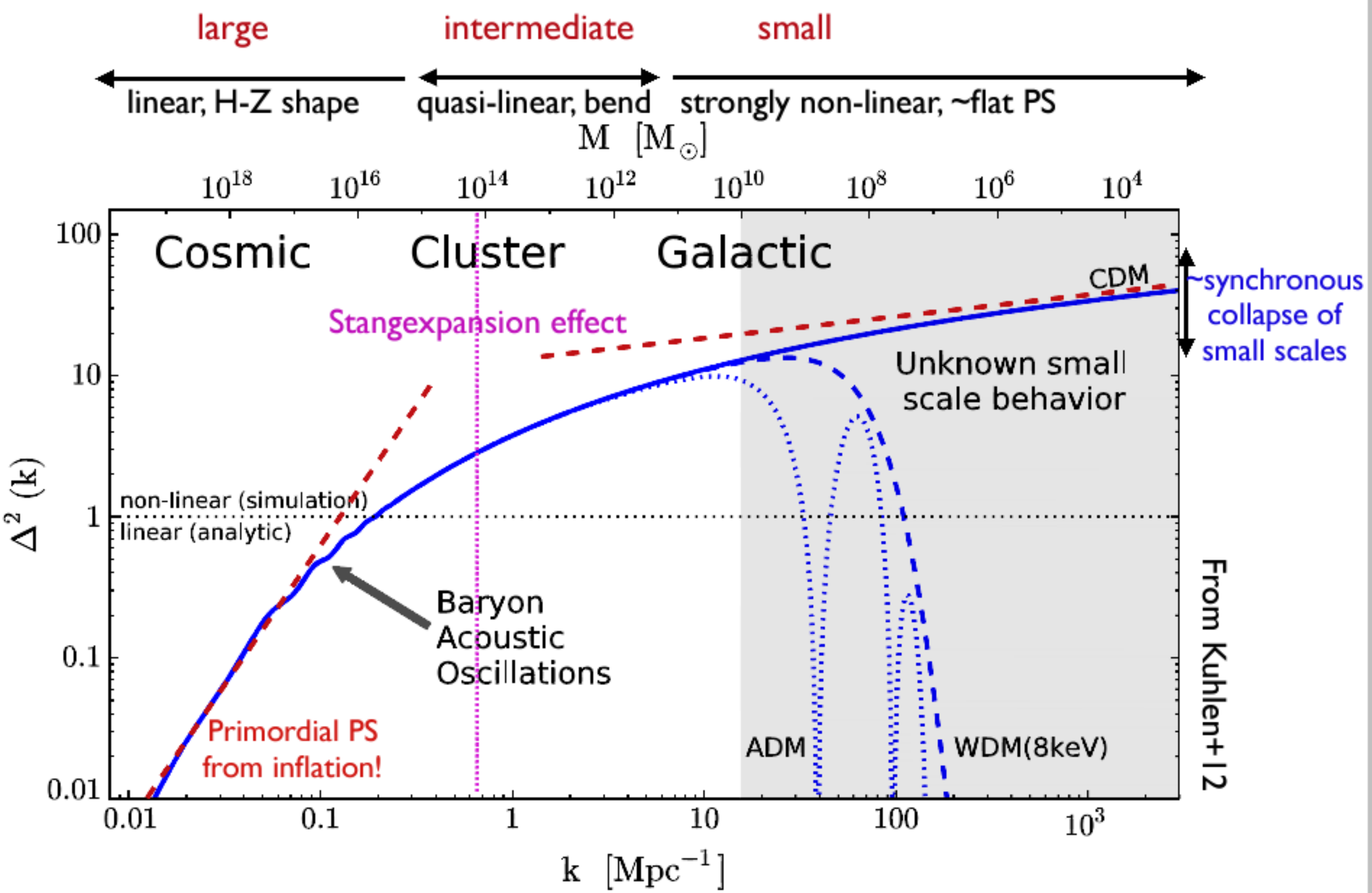
- Agreement could also be obtained by assuming (1-b)=0.55, a bias that is difficult to reconcile with numerical simulations and X-ray/weak lensing comparisons (see discussion in Paper XX).

Lesson number 2 from Planck: we still have room for additional relativistic species. Detection of the neutrino absolute mass scale is possibly around the corner.

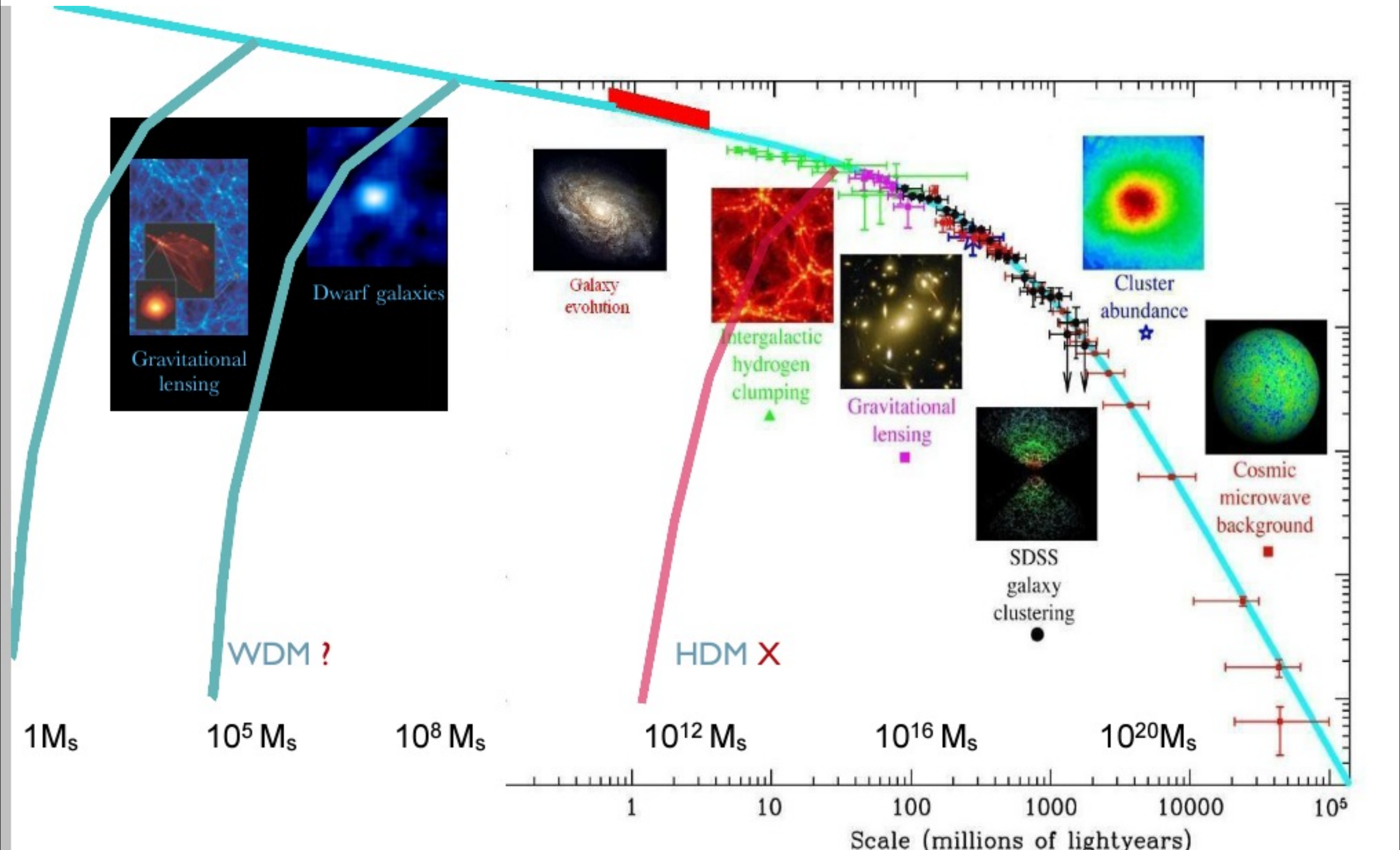
ΛCDM: a remarkably successful theory on large scales



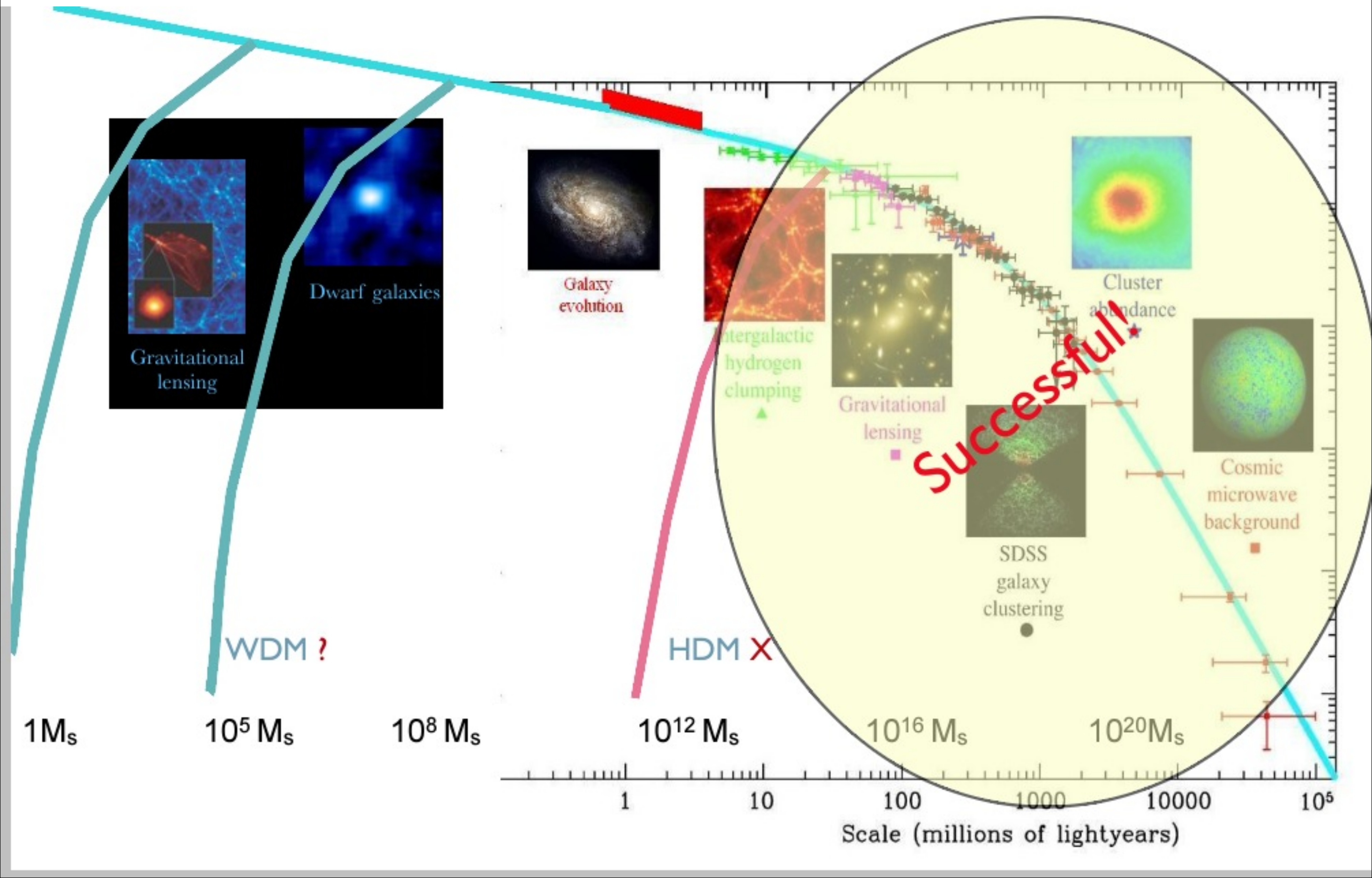
Genetic code for cosmic structure formation: scales



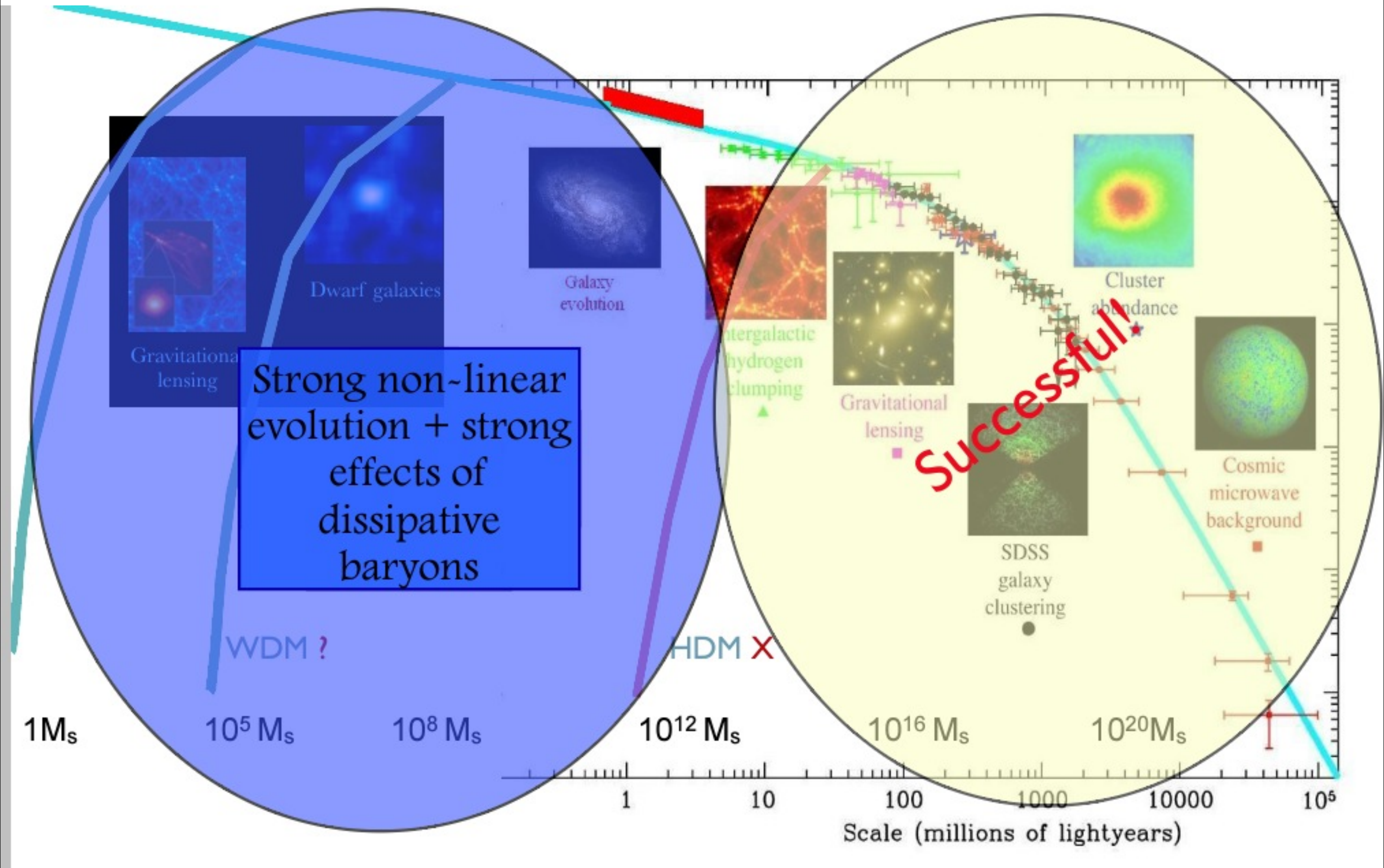
$\Delta^2(k) \equiv 4\pi(k/2\pi)^3 P(k)$, the linear power spectrum of density fluctuations at $z = 0$. The solid line is the canonical cold DM



Gravitational lensing
Dwarf galaxies
Galaxy evolution
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
SDSS galaxy clustering
Cosmic microwave background
WDM ?
HDM X
1Ms
10^5 Ms
10^8 Ms
10^12 Ms
10^16 Ms
10^20Ms
1
10
100
1000
10000
10^5
Scale (millions of lightyears)



Gravitational lensing
Dwarf galaxies
Galaxy evolution
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
Cosmic microwave background
SDSS galaxy clustering
Successful!
WDM ?
HDM X
1Ms
10^5 Ms
10^8 Ms
10^12 Ms
10^16 Ms
10^20Ms
1
10
100
1000
10000
10^5
Scale (millions of lightyears)



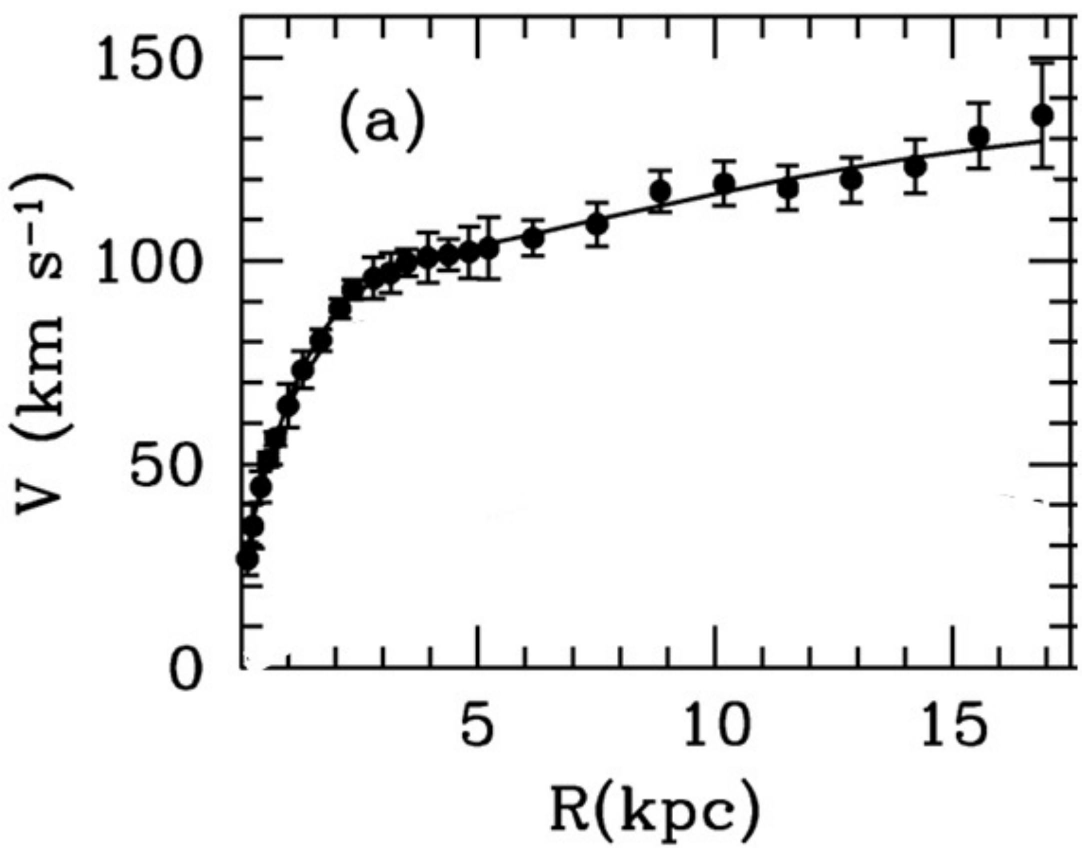
Gravitational lensing
Dwarf galaxies
Galaxy evolution
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
Cosmic microwave background
SDSS galaxy clustering
Strong non-linear evolution + strong effects of dissipative baryons
Successful!
WDM ?
HDM X
1Ms
10^5 Ms
10^8 Ms
10^12 Ms
10^16 Ms
10^20 Ms
1
10
100
1000
10000
10^5
Scale (millions of lightyears)

Problems of LCDM on small scales
Cusp vs Core in galaxies

Local Group galaxy M33

Problems of LCDM on small scales
Cusp vs Core in galaxies

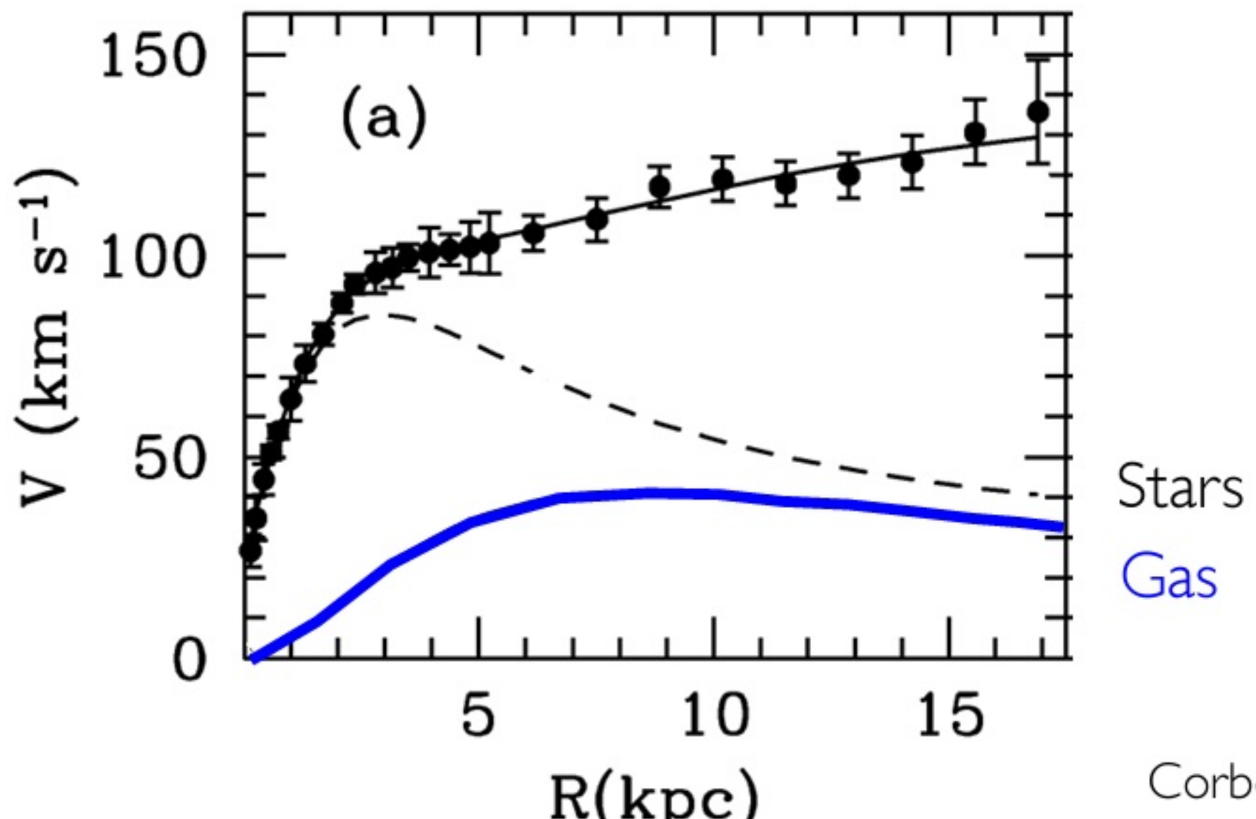
Local Group galaxy M33



Corbelli 2003

Problems of LCDM on small scales
Cusp vs Core in galaxies

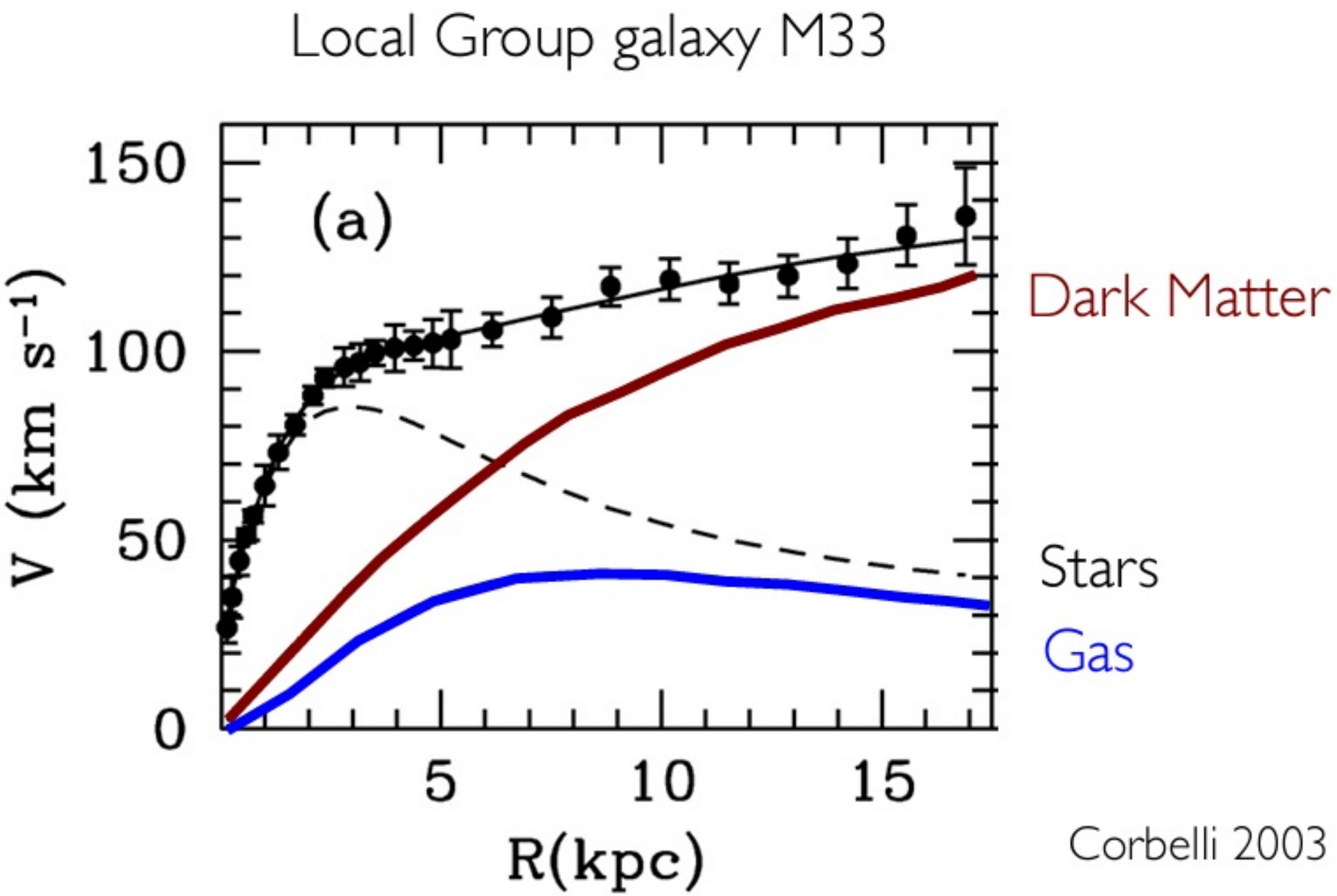
Local Group galaxy M33



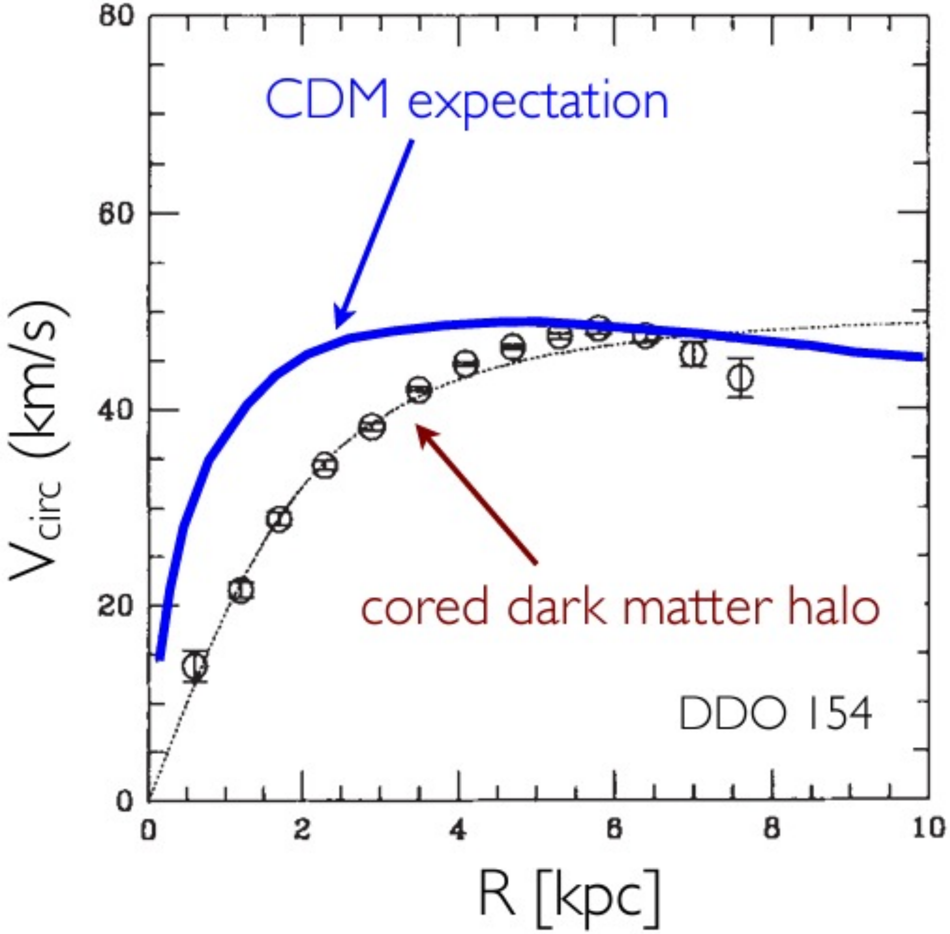
Corbelli 2003

*in context of Newtonian dynamics

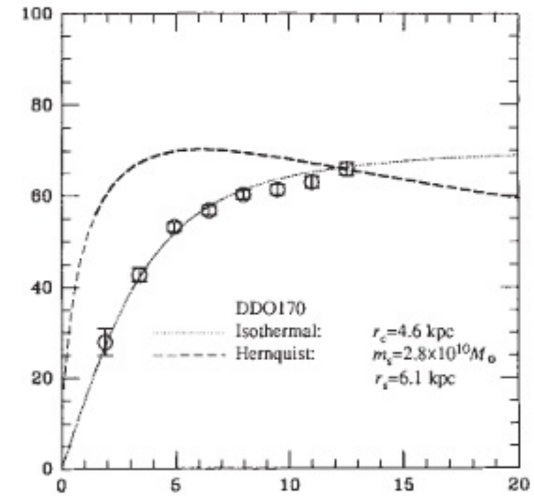
Problems of LCDM on small scales
Cusp vs Core in galaxies

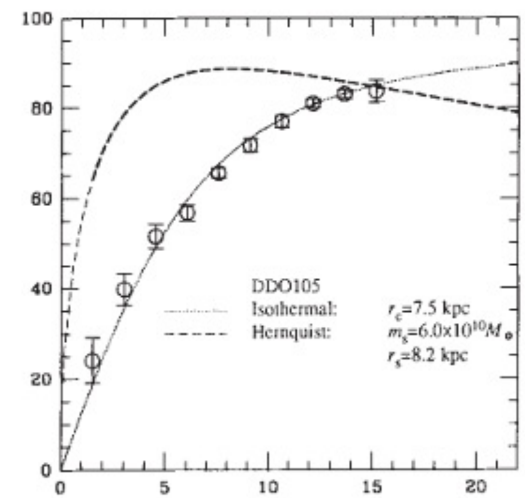


Problems of LCDM on small scales
Cusp vs Core in galaxies



Moore (1994); also Flores & Primack (1994)



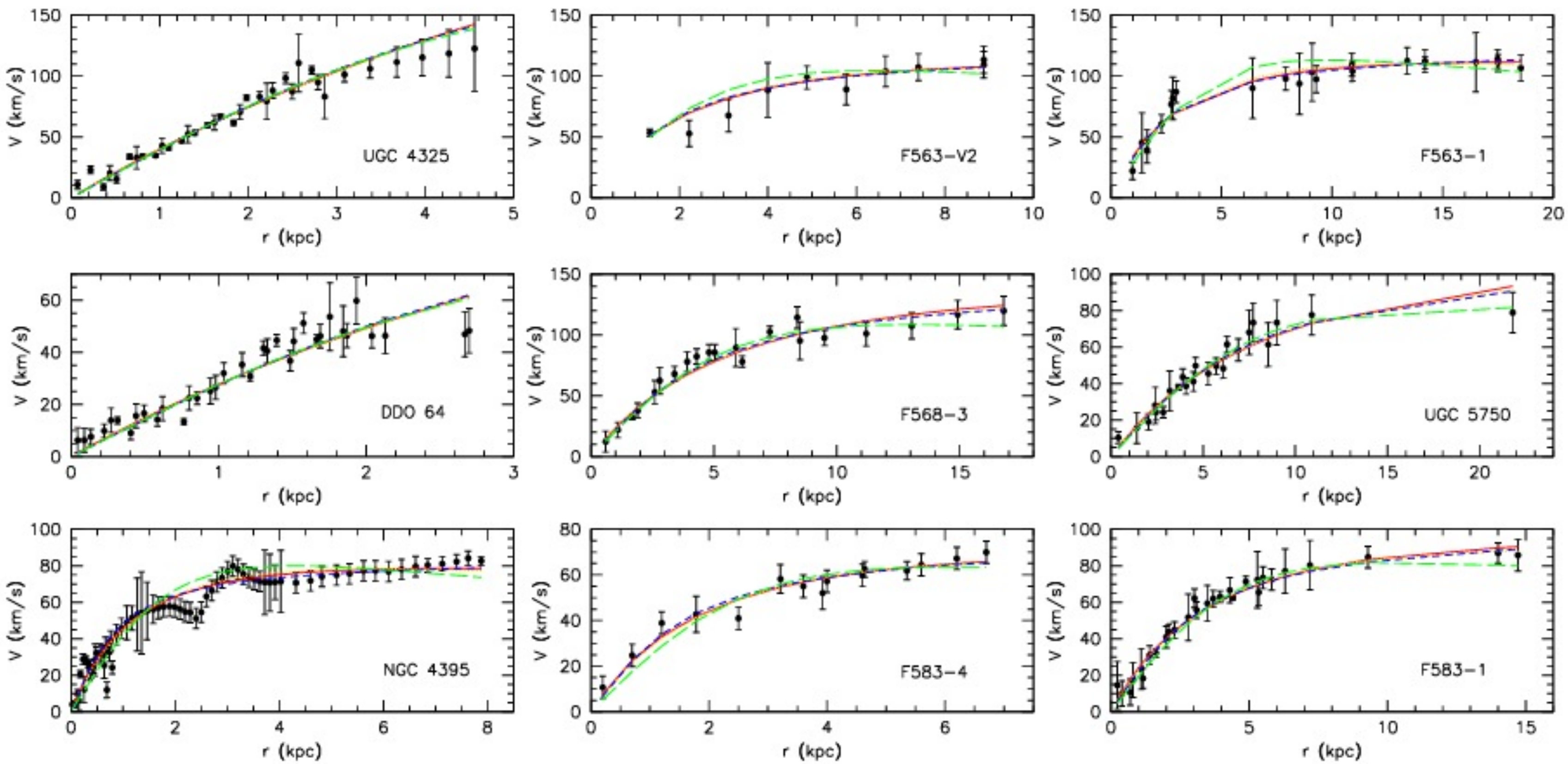


Problems of LCDM on small scales
Cusp vs Core in galaxies

$$\rho \propto r^{-\alpha} \rightarrow V_{\rm circ} \propto r^{1-\alpha/2}$$

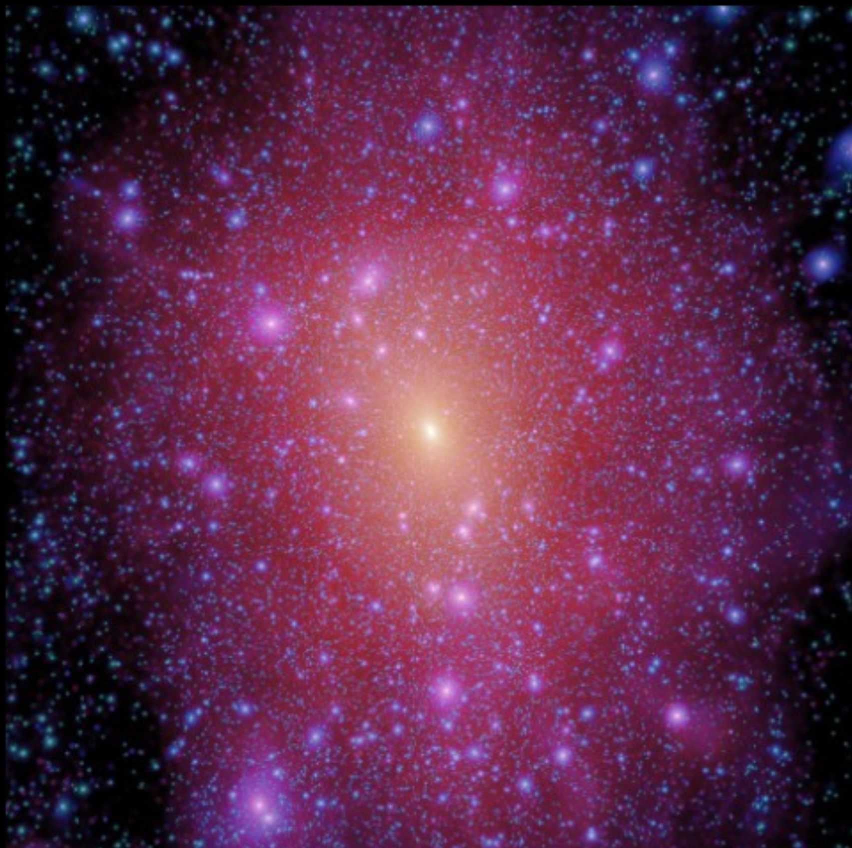
$\rightarrow \alpha = 0 : V_{\rm circ} \propto r$

$\rightarrow \alpha = 1 : V_{\rm circ} \propto r^{0.5}$



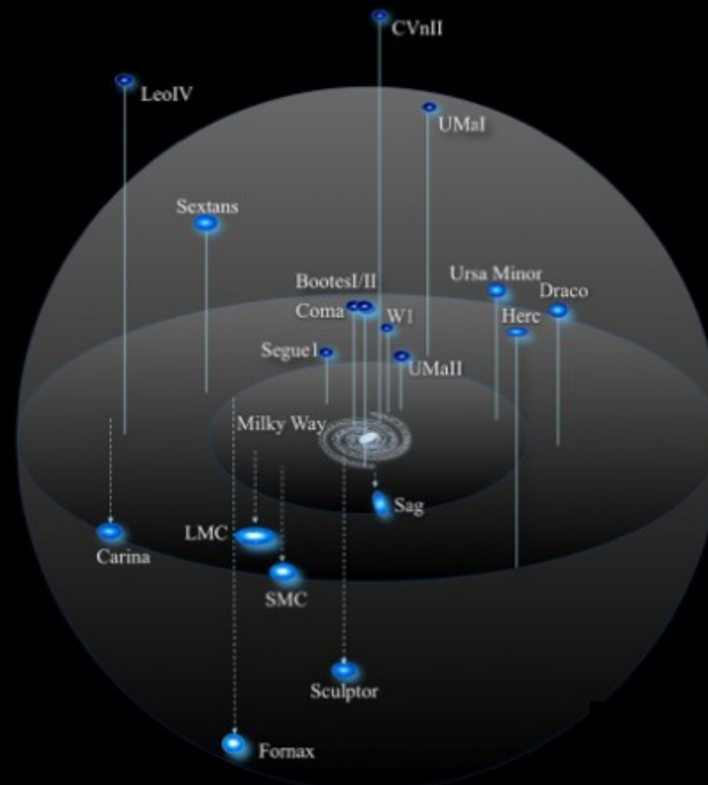
Kuzio de Naray et al. (2010)

Problems of LCDM on small scales
Missing Satellite Galaxies



$>10^5$ identified subhalos

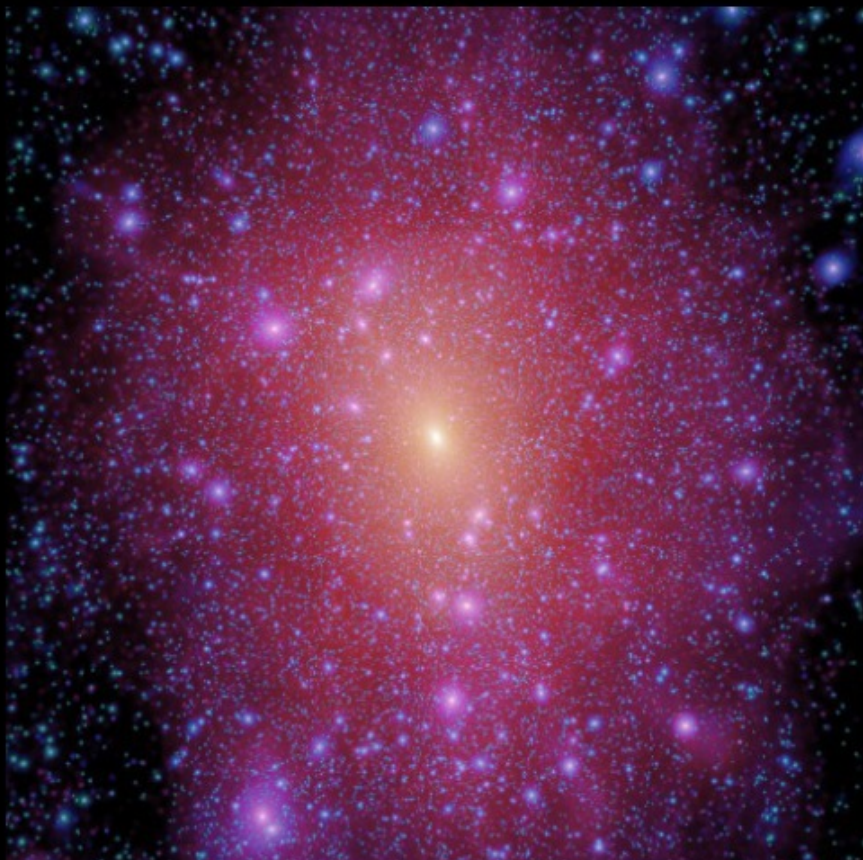
V. Springel / Virgo Consortium

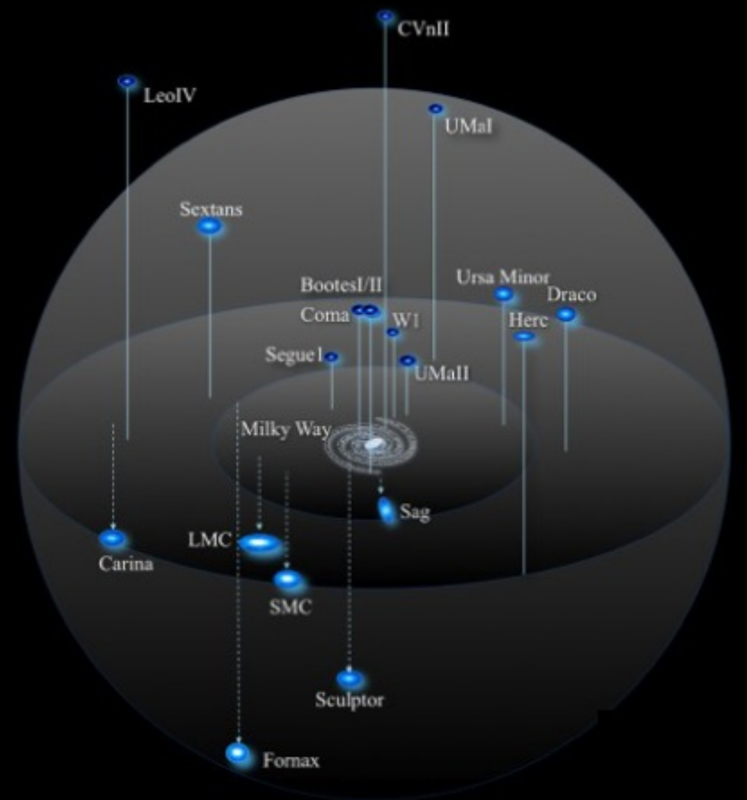


12 bright satellites $(L_V > 10^5 L_\odot)$

J. Bullock

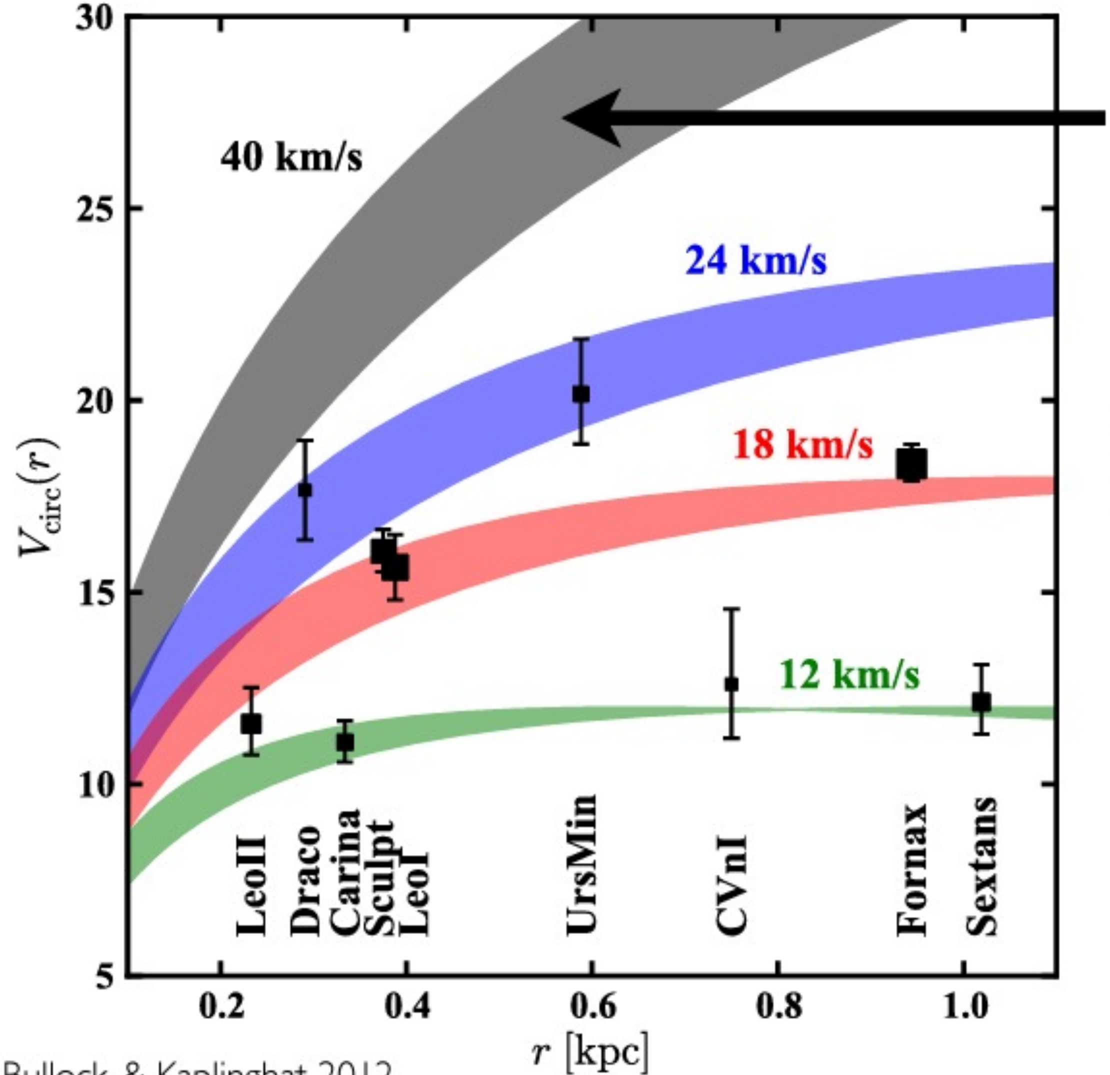
Problems of LCDM on small scales
Missing Satellite Galaxies





Number mismatch: maybe explained through (1) additional ultra-faint satellites and (2) galaxy formation processes (supernova feedback, reionization)?

Problems of LCDM on small scales
Why only small mass in the MW ?



Biggest predicted satellites:
$M_{halo} \sim 10^{10}$ M_{sun}

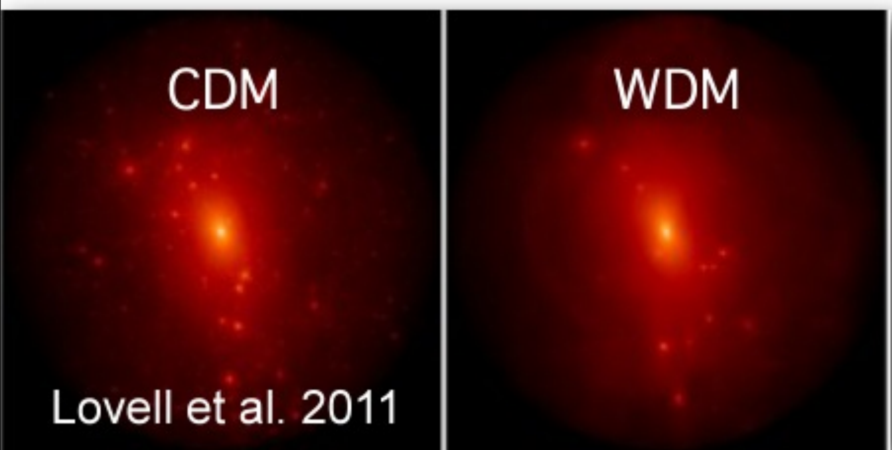
Bright spheroidal satellites:
$M_{halo} = 10^8 - 10^9$ M_{sun}

Similar results found for isolated, low-mass galaxies
(Ferrero, Abadi, Navarro + 2012)

MBK, Bullock, & Kaplinghat 2012

Two possible candidates to solve these problems (if real)

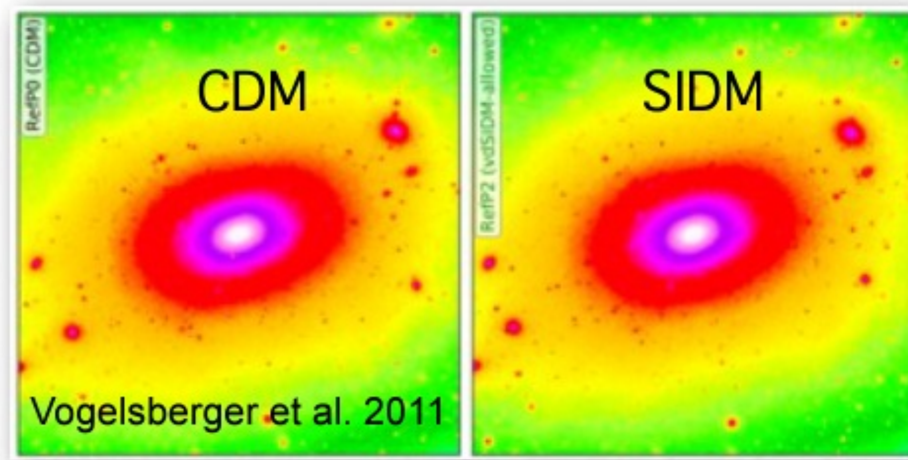
Warm Dark Matter:



$$m_{\rm dm} \sim {\rm keV}$$

Lovell et al. 2011

Self-interacting Dark Matter:



$$\sigma / m_{\rm dm} \sim 1\,{\rm cm}^2/g$$

Vogelsberger et al. 2011, 2012;
Rocha et al. 2012; Peter et al. 2012;
Spergel & Steinhardt (2000)

Phenomenology of SIDM vs. WDM

CDM SIDM WDM

Dark Matter physics?

- WDM: struggles w/ satellite counts, ly-a forest, reionization. No big cores.
- **SIDM** with **σ/m ~ 0.5-1 cm^2/g** can do it.

Conclusions

- CMB and large scale galaxy clustering provide an astonishing confirmation of the LCDM model. The agreement is excellent. There is a clear evidence for new physics beyond the standard model of particle physics (dark matter and dark energy) ! there is no alternative model that can explain those observations.
- CMB also hints to further new physics: an extra relativistic component at recombination is compatible with the data and is suggested when the data is combined with HST measurement of the Hubble constant. In a couple of years this issue will be clarified.
- A "measurement" of the absolute neutrino mass scale is around the corner. Hints for a 0.3-0.2 eV total mass scale from some observables (SZ clusters counts).
- On galactic scales the agreement is less good and actually there are significant discrepancies (cores, number of satellite galaxies, too big to fail etc)
- The situation is controversial: comparison requires N body simulations and accurate treatment of astrophysics. Observations are few and difficult.
- If the problem at small scales persists then we need an alternative to CDM as WDM or SIDM or more... but there is a long way to go....