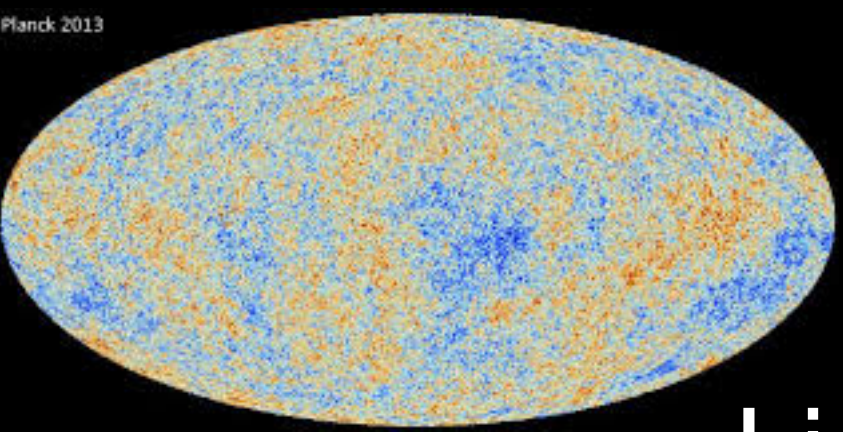
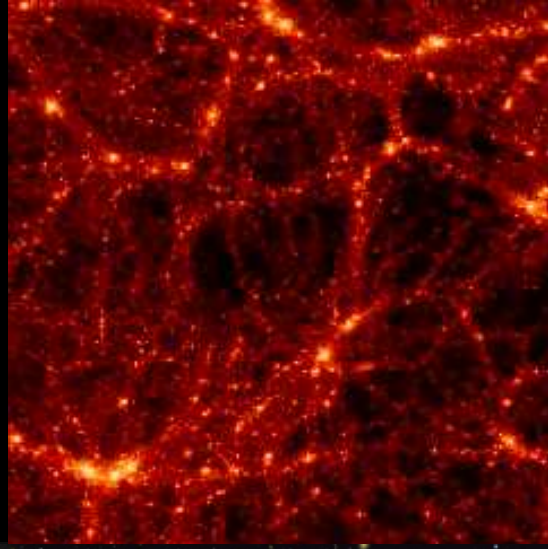




Licia Verde

ICREA & ICC-UB-IEEC
CERN Theory Division

Beyond the standard cosmological model after Planck

http://icc.ub.edu/~liciaverde

Institut de Ciències del Cosmos

First decade of 2000: Precision cosmology

ΛCDM: The standard cosmological model

Just 6 numbers…..

describe the Universe composition and evolution

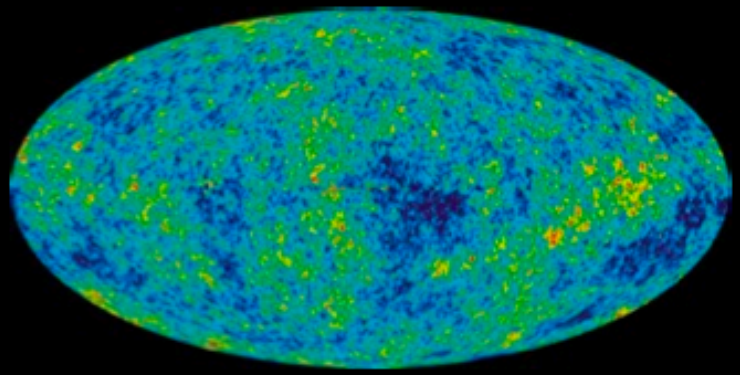
Homogenous background

$$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Λ? CDM?

Perturbations



$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

DISCLAIMER

I am not part of the Planck collaboration

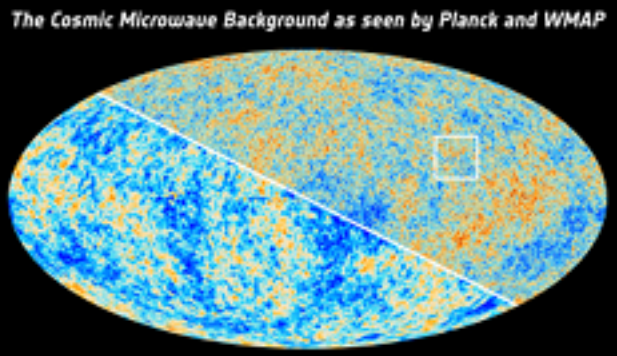
I cannot take any credit for the spectacular results
I have only access to public(published) information
(28 papers, paper XVI of most interest to this audience)

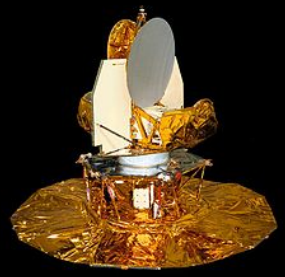
but

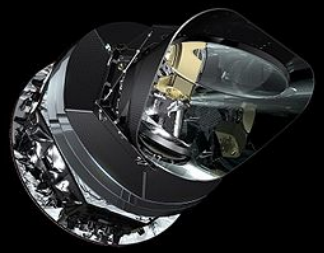
I can give you an external point of view

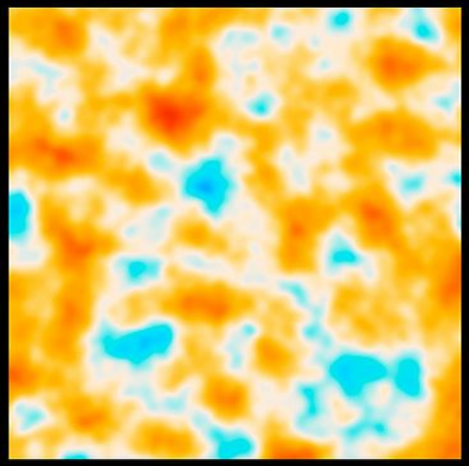
More info at http://www.sciops.esa.int/index.php?project=PLANCK&page=index

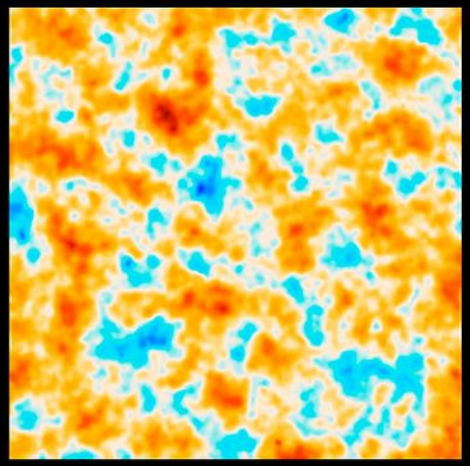
Planck ESA satellite map the Cosmic Microwave Background





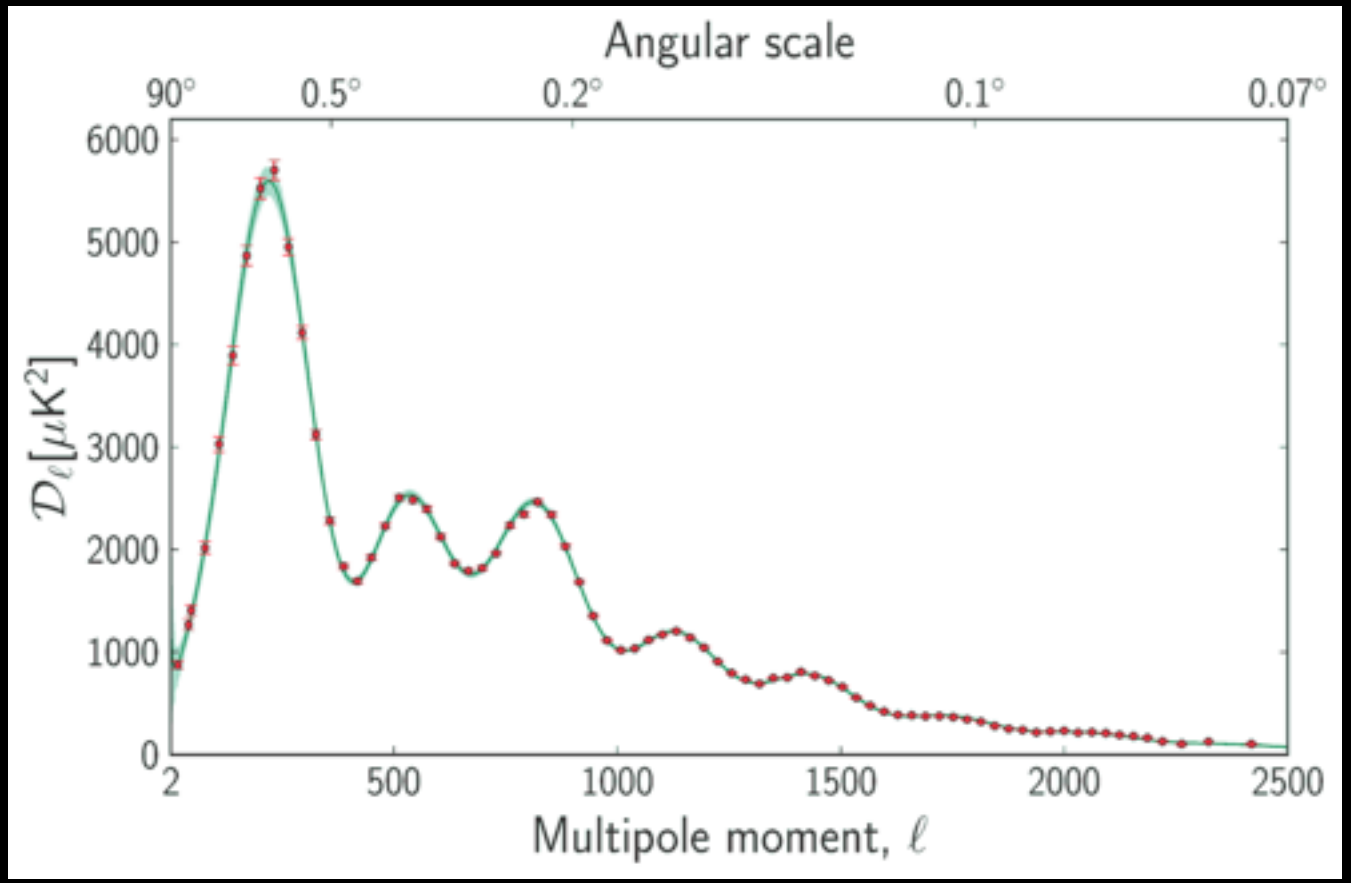






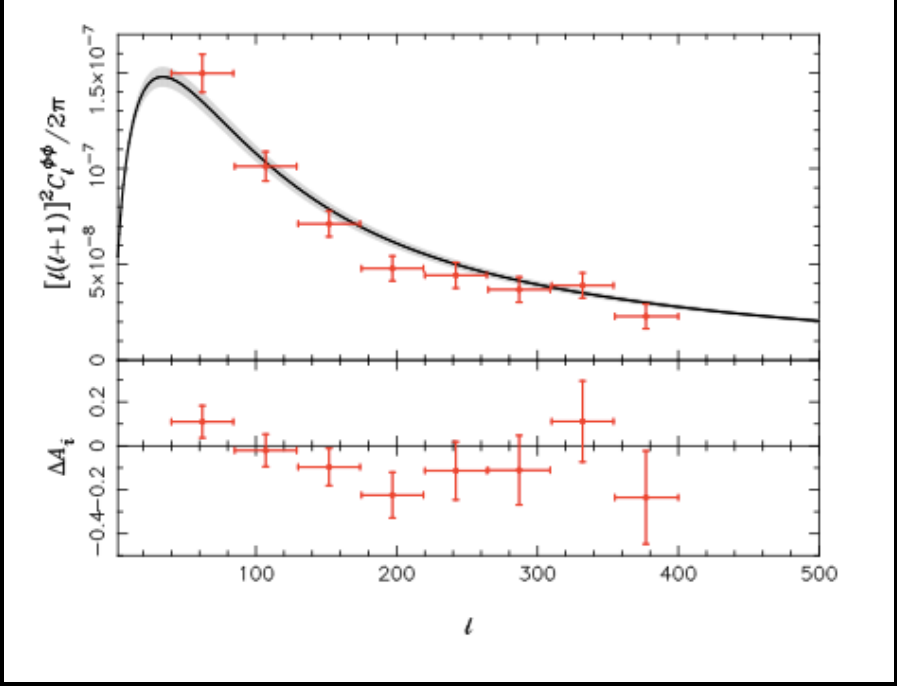
COBE WMAP Planck

Compressing information

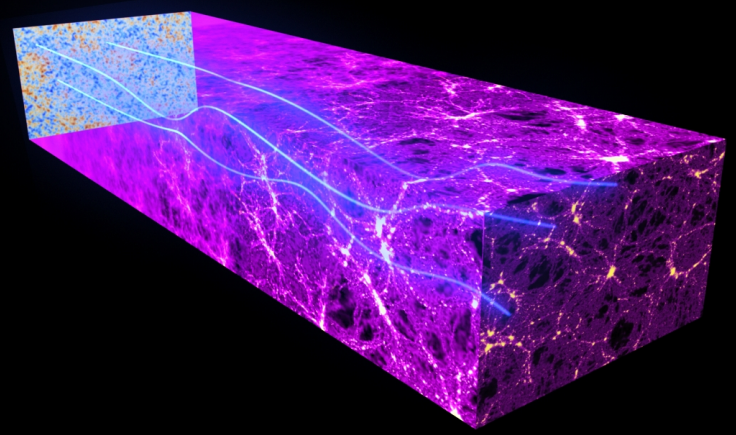


Planck collaboration , 2013, paper XVI

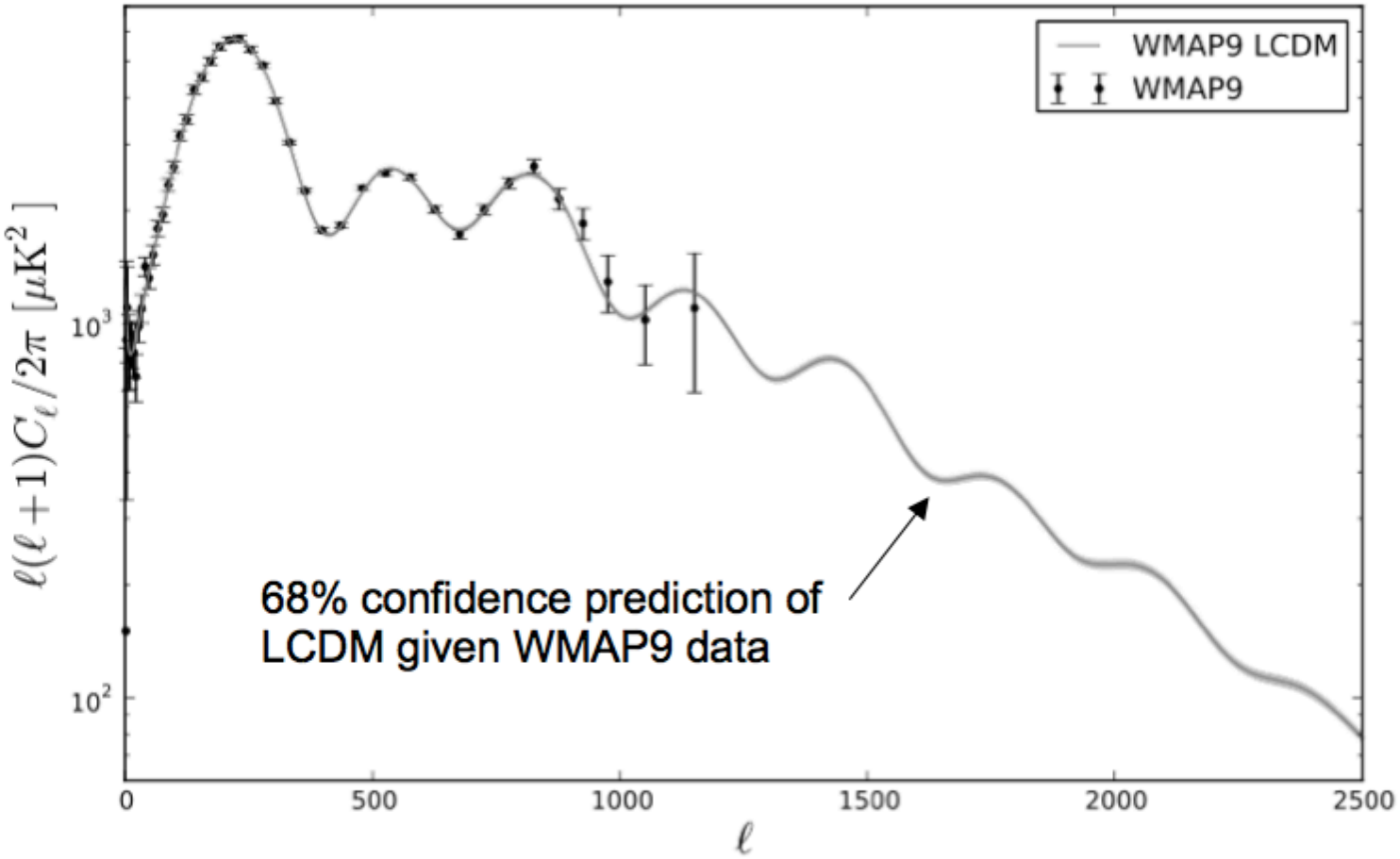
NEW measurement



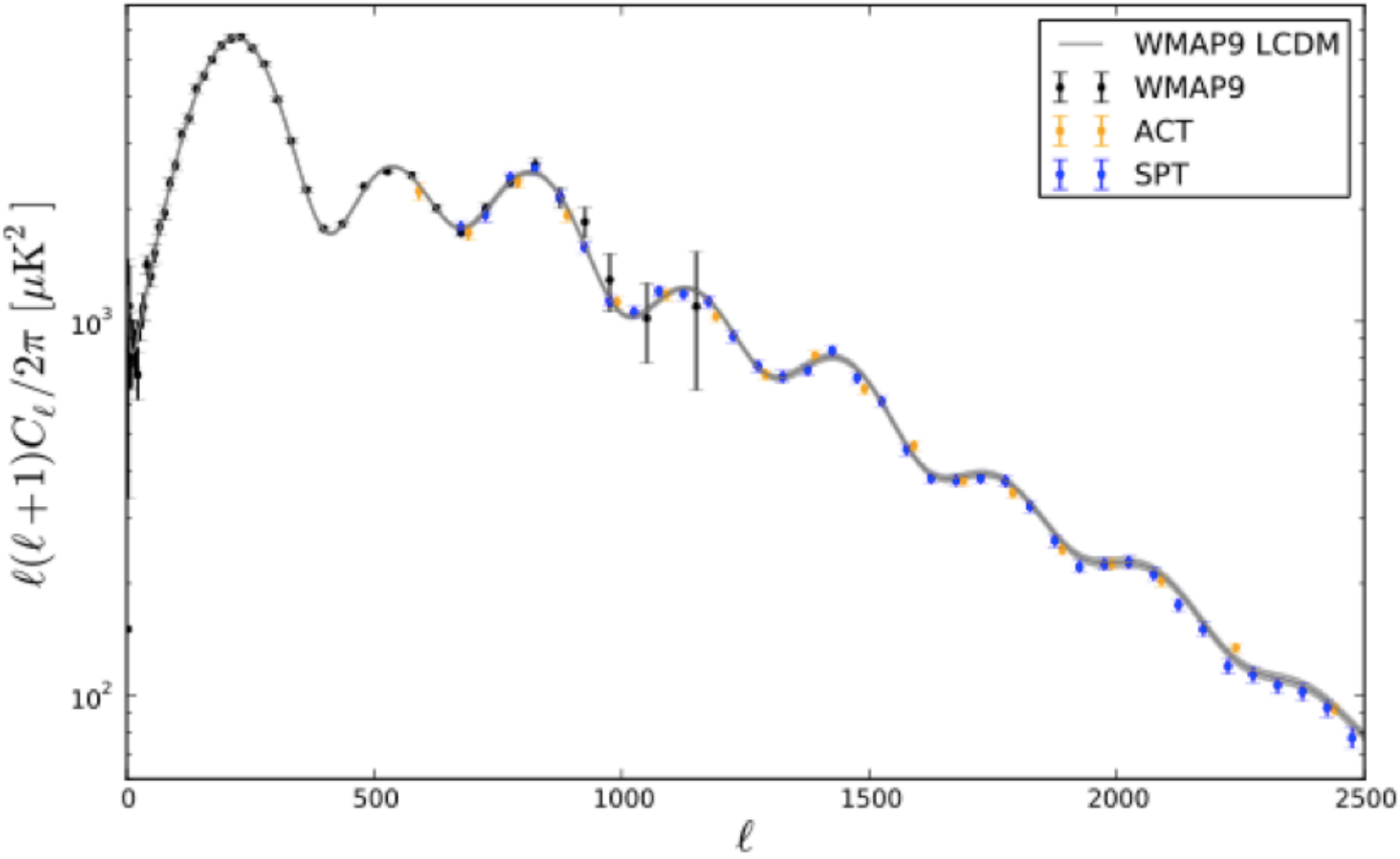
Planck collaboration , 2013, paper XVI



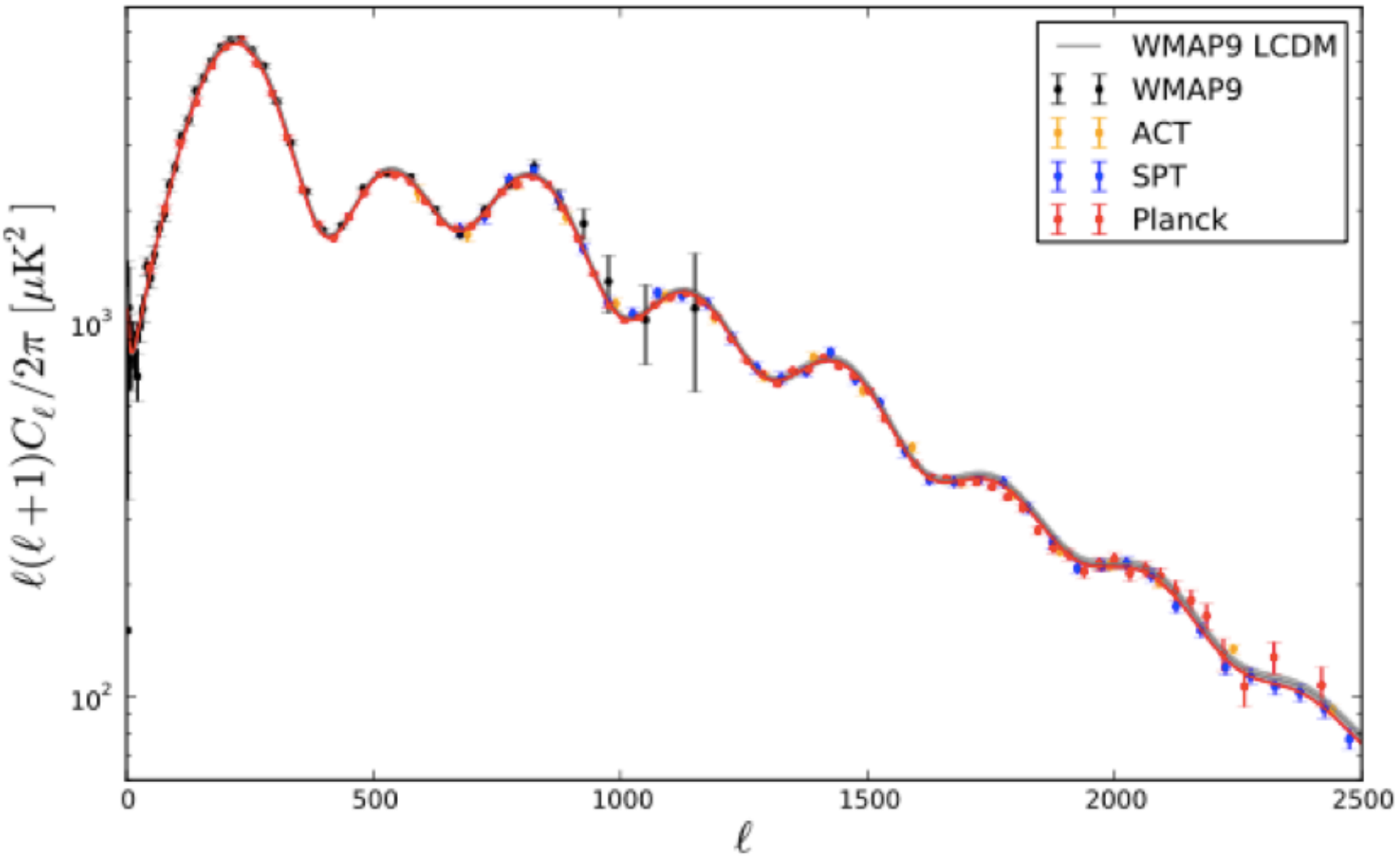
LCDM makes a very precise prediction



Slide credit: M. Millea



Slide credit: M. Millea

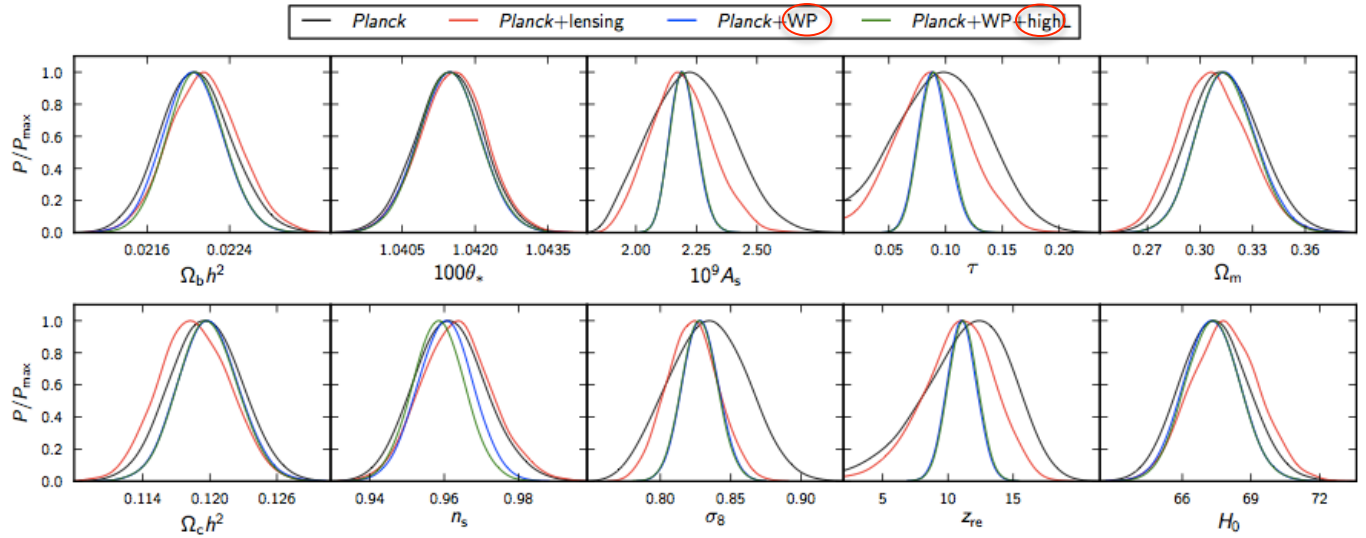


Slide credit: M. Millea

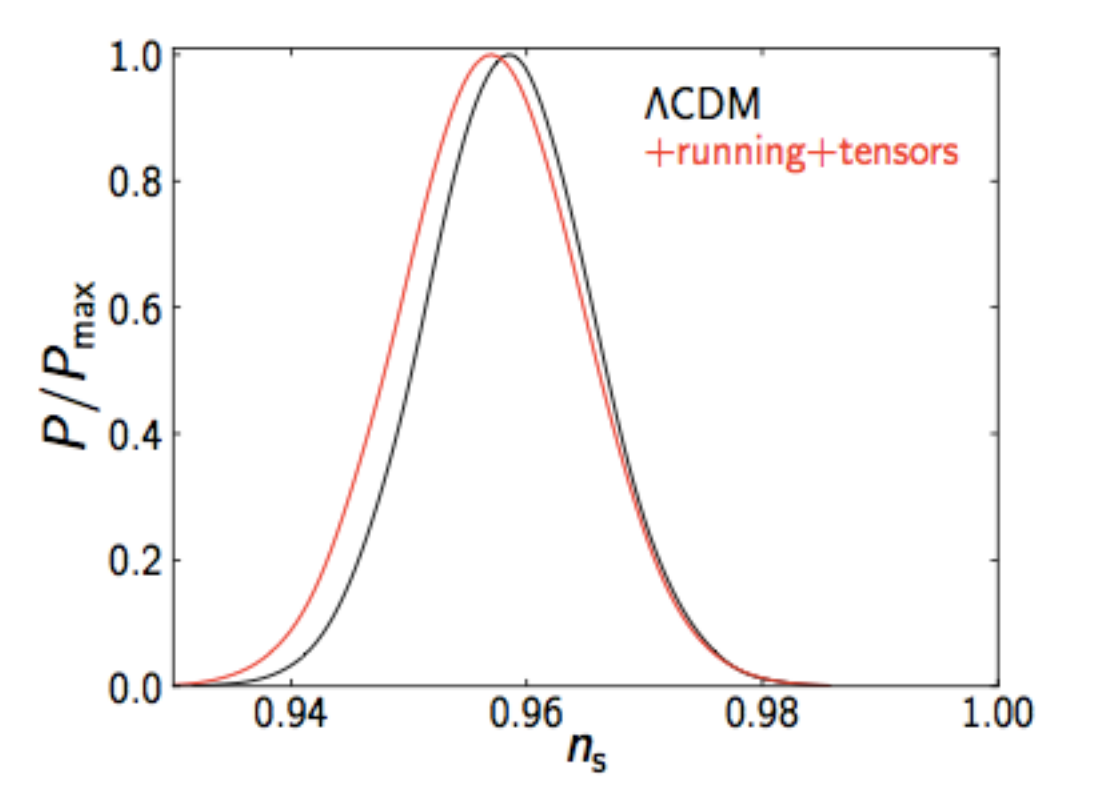
Planck Collaboration: Cosmological parameters

Planck collaboration , 2013, paper XVI

	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45



Not 1 at more than 5 σ → inflation



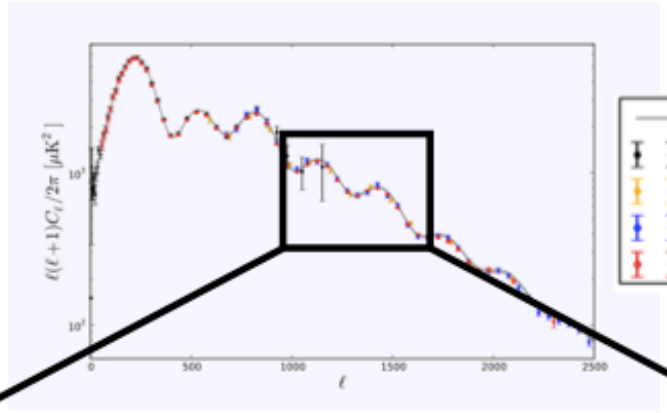
$n_s = 0.959 \pm 0.007$ (68%; *Planck*+WP+highL),

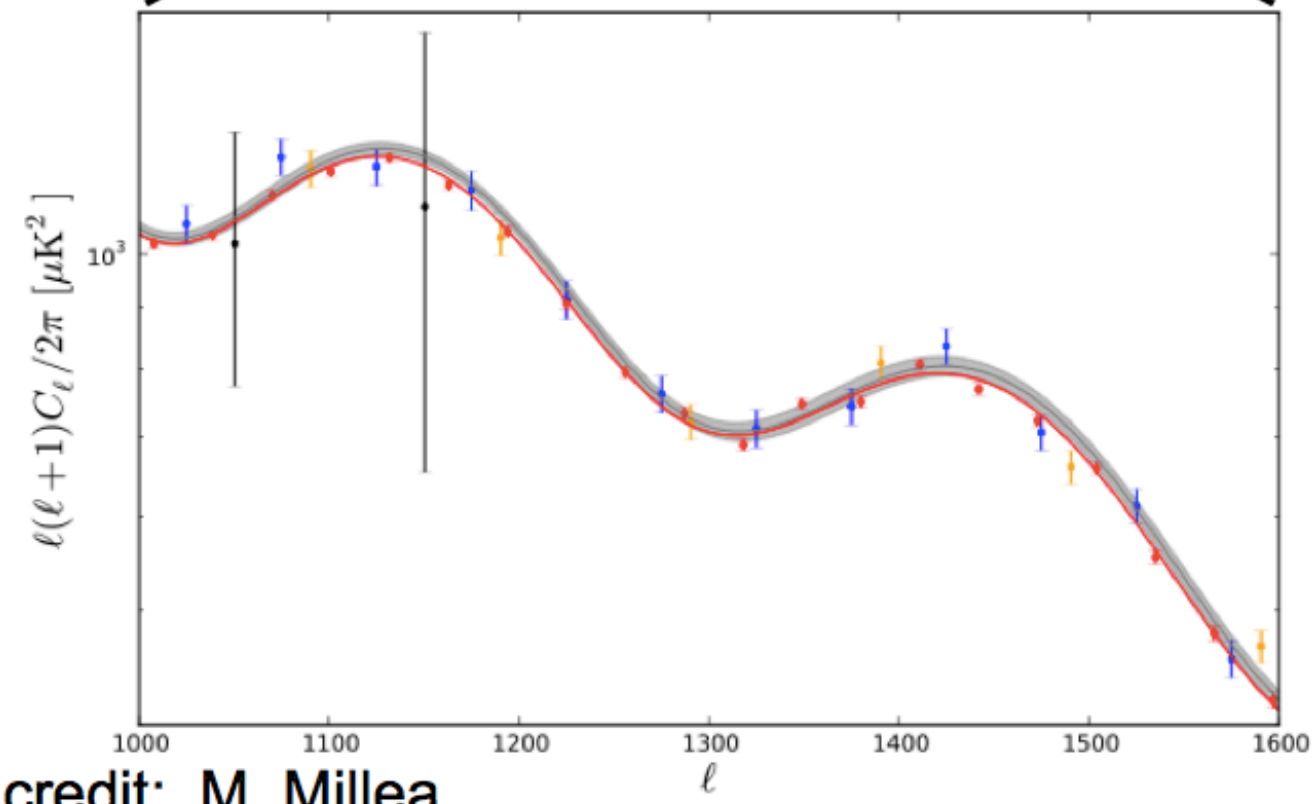
Planck collaboration , 2013, paper XVI

what everybody is talking about

Last Judgment, Vasari, Florence Duomo

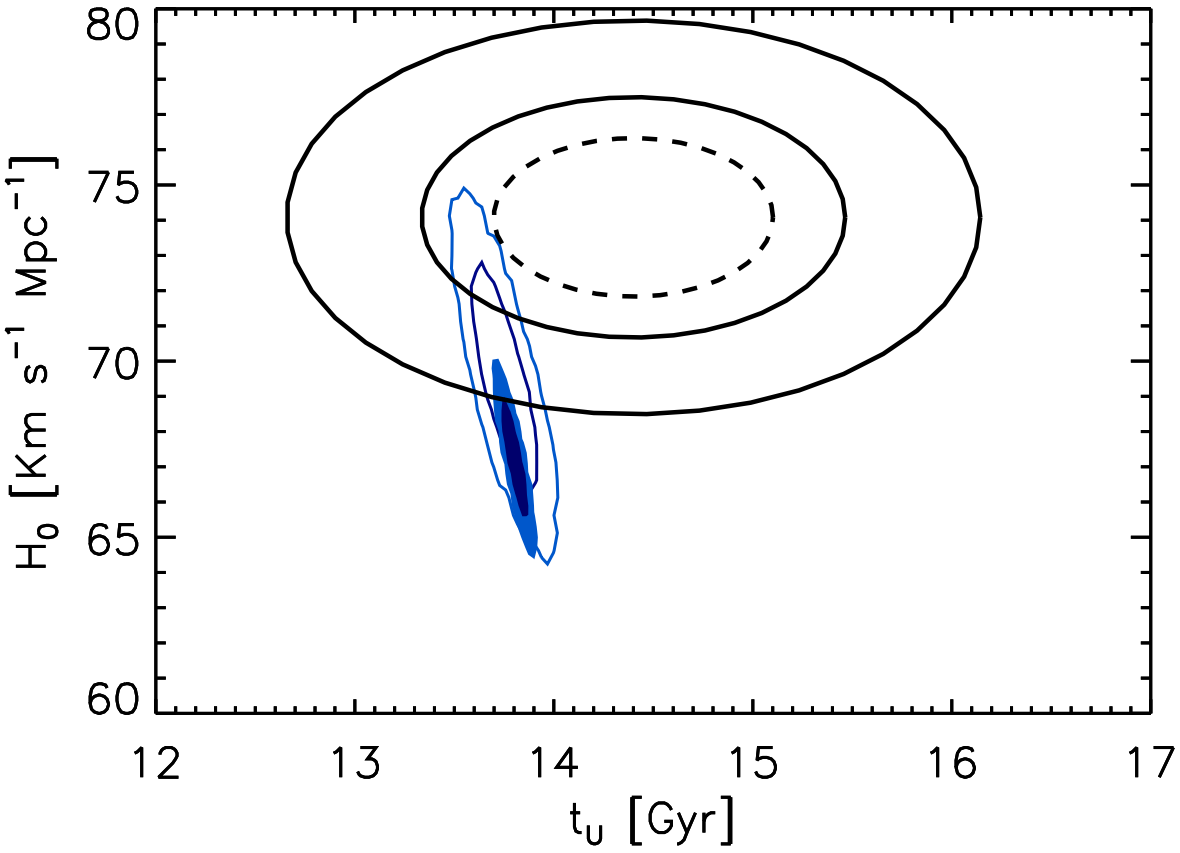
- Here ACT/SPT/Planck are all sample variance limited but Planck has much larger sky coverage





Slide credit: M. Millea

what everybody is talking about



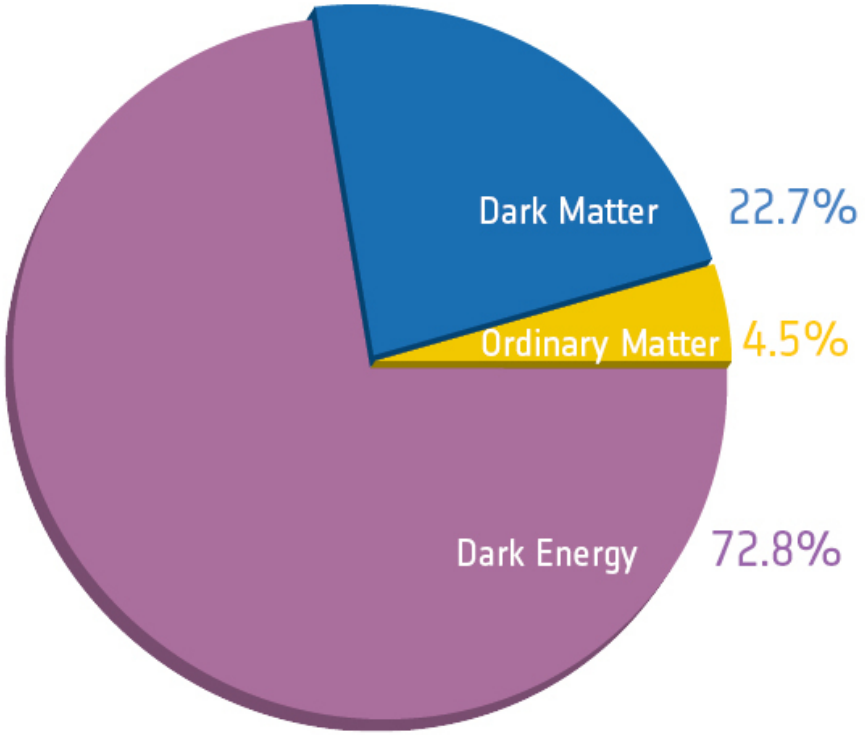
TENSION!!!

Odds: 1:53

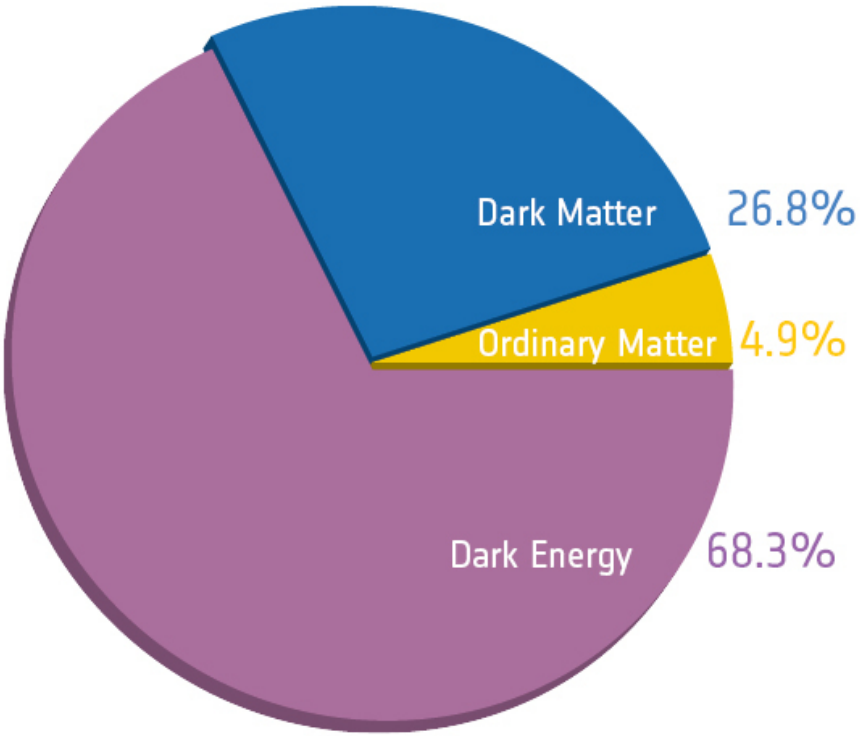
Verde, Protopapas, Jimenez, 2013

what everybody is talking about

Cosmic recipe adjustments

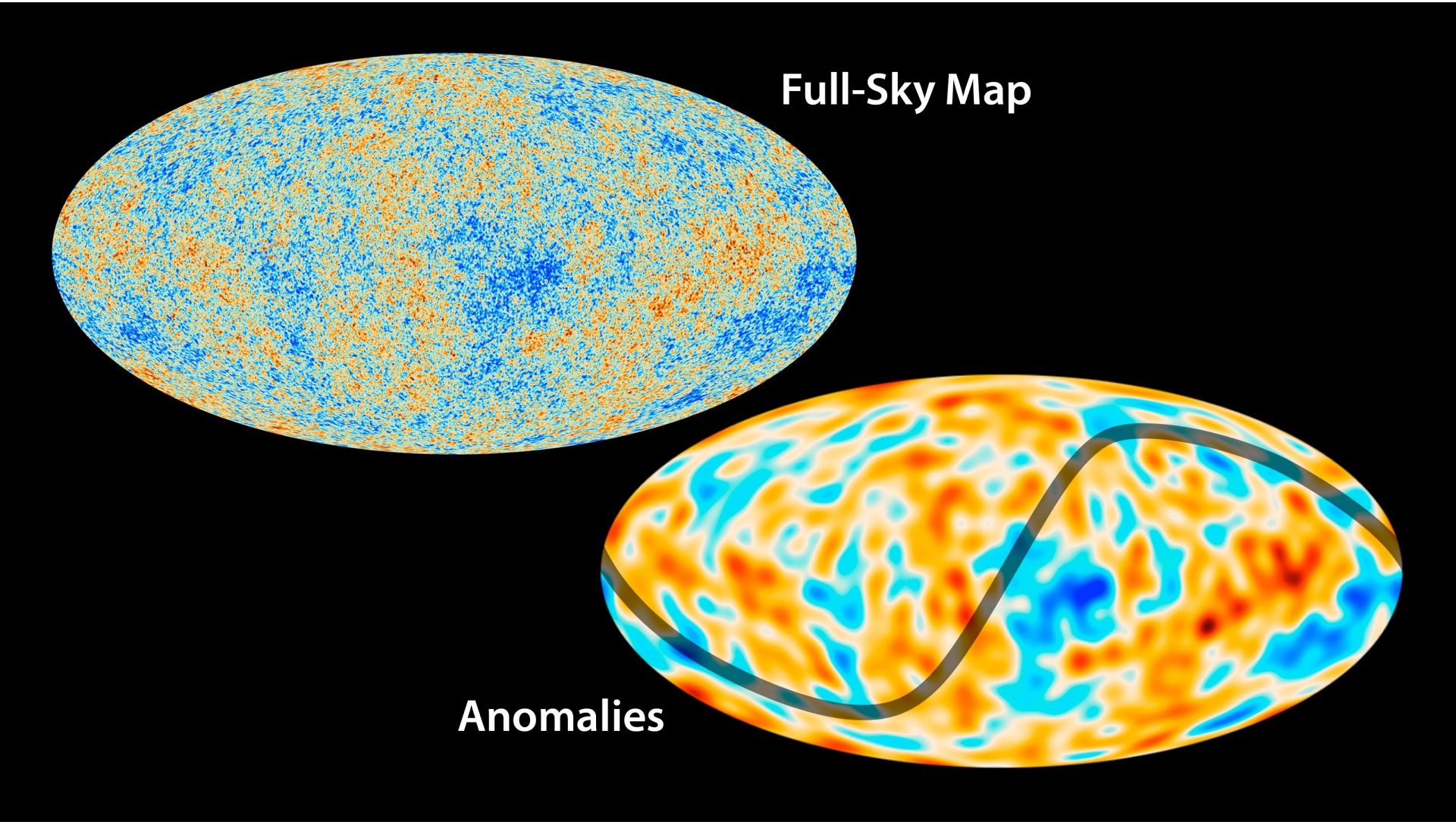


Before Planck



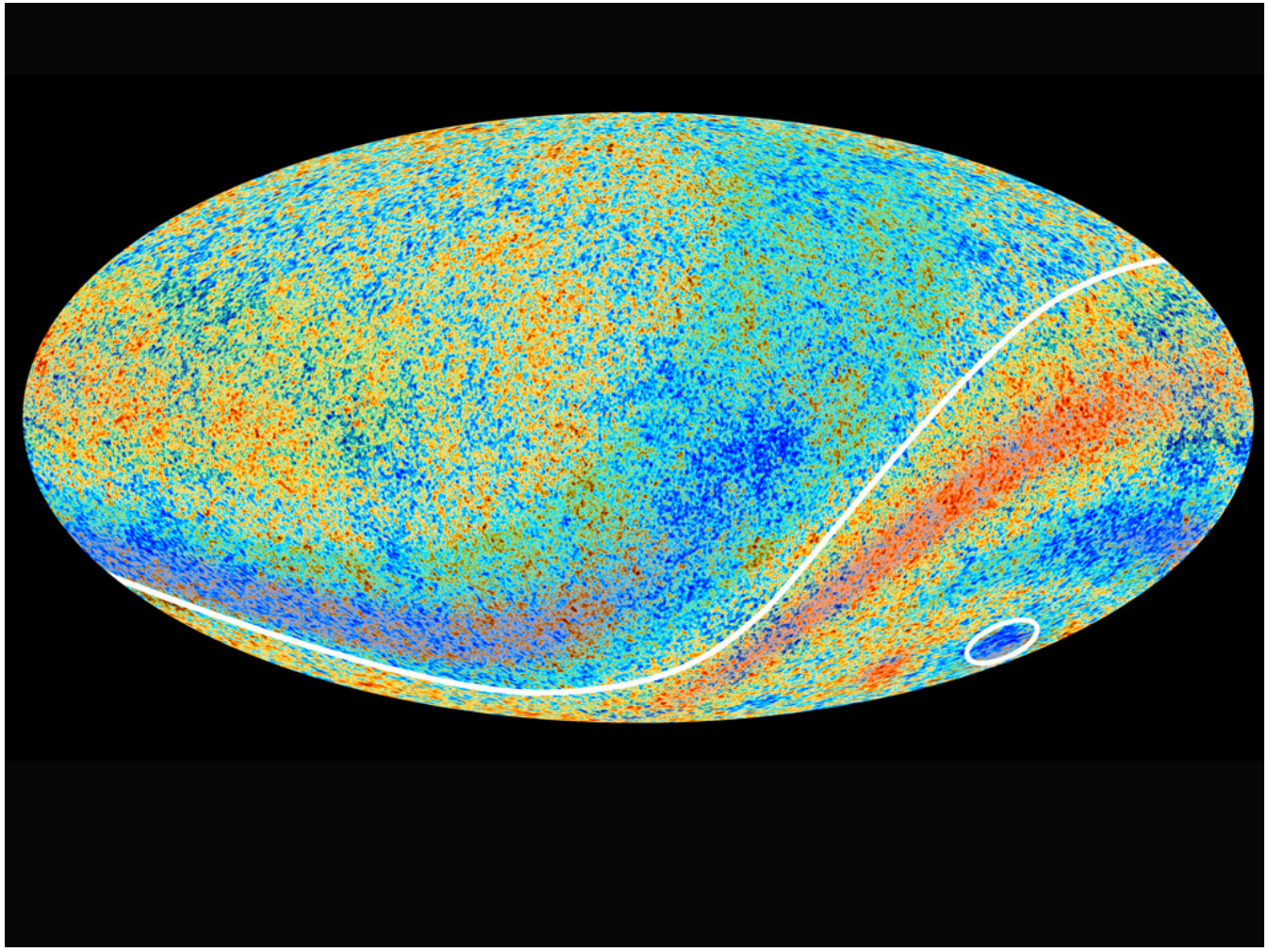
After Planck

what everybody is talking about



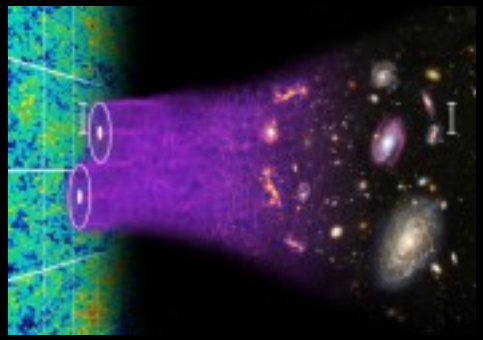
Were there since 2003…..

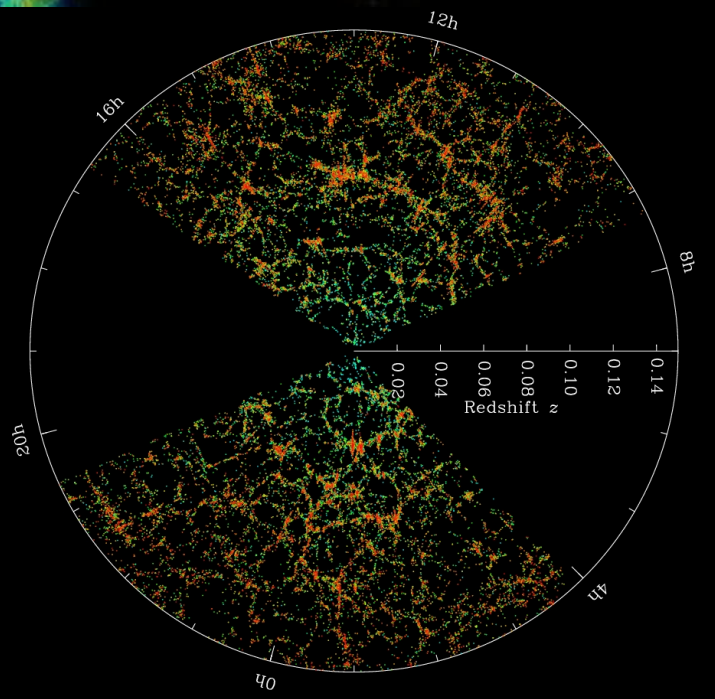
what everybody is talking about



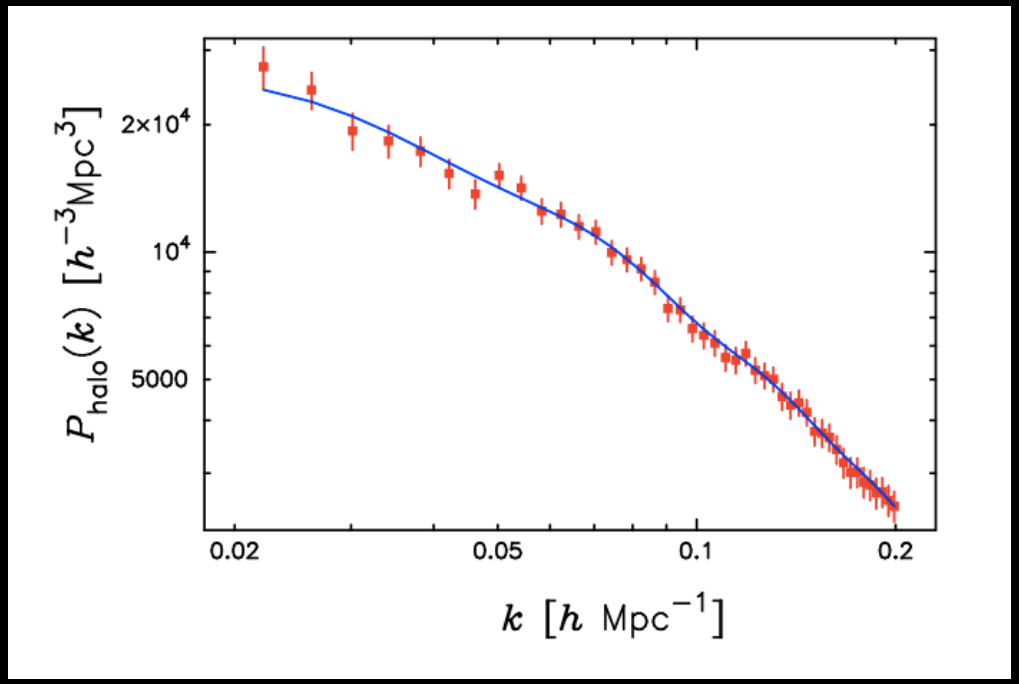
Was there since 2003…..

ΛCDM remains a very good fit to the Universe





SDSS LRG galaxies power spectrum (Reid et al.)



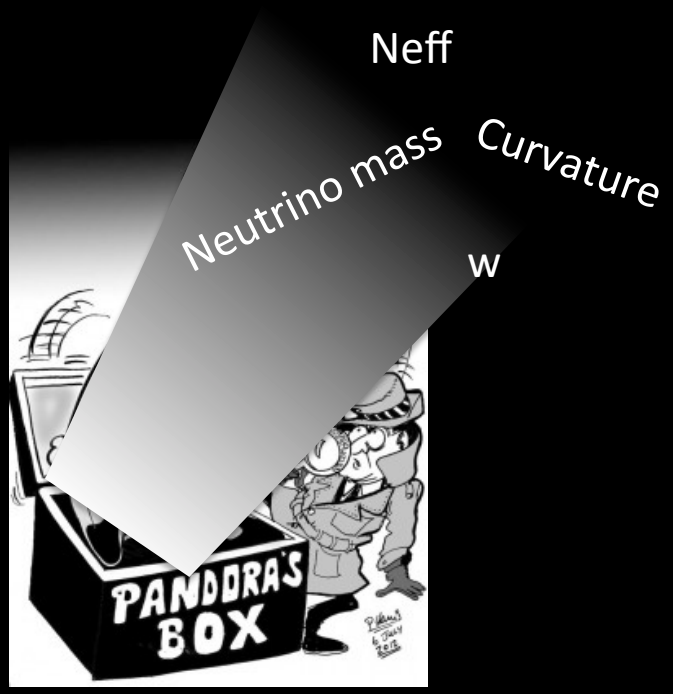
13 billion years of gravitational evolution

STILL….

The model IS incomplete… Neutrinos have mass

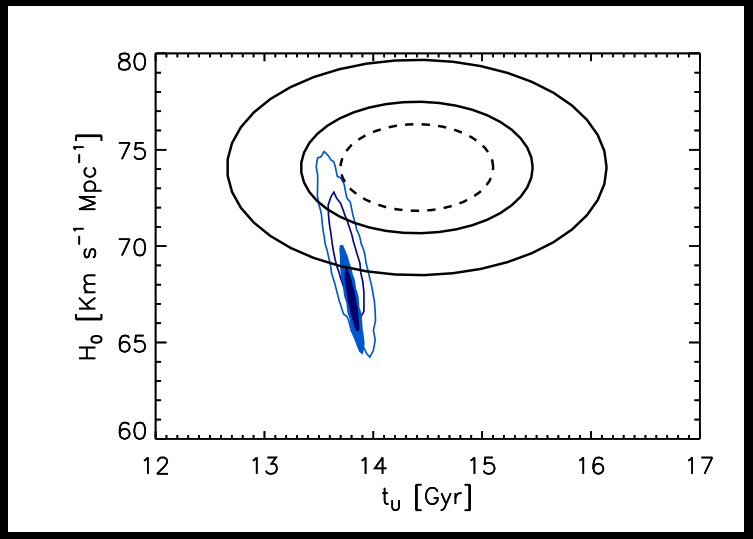
The model is unsatisfactory

The cosmological constant problem
Inflation is more than n_s



TENSION!!!

Is there any model extension that fixes this???



Neutrino mass <0.15 eV for tension not to be highly significant (1:150)

3.4<Neff<4.1 reduce tension to substantial (better than 1:12)
(NO value makes it not significant)

Neff>4.6 makes tension highly significant

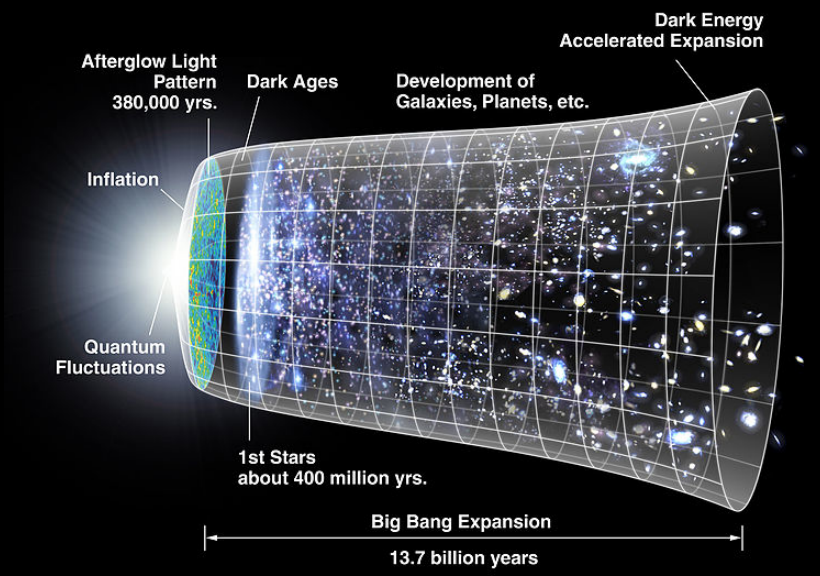
w ~ -1.2 makes tension not significant!

However there are other data out there which do not support this interpretation

LV, Protopapas, Jimenez, 2013

The importance of local measures

- CMB observations predominantly probe the physics of the early Universe up to a redshift of z ~ 1100



- These observations are then interpreted in terms of cosmological parameters defined at z = 0

- This extrapolation is model-dependent

- Immense added value in measuring some of these parameters locally,
in a way that is independent of the cosmological model.

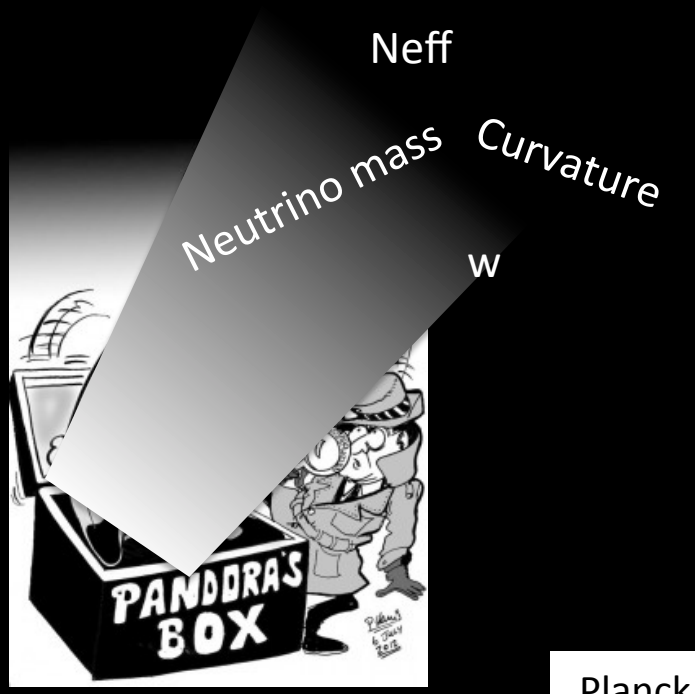
- Examples H_0, age (t_0)

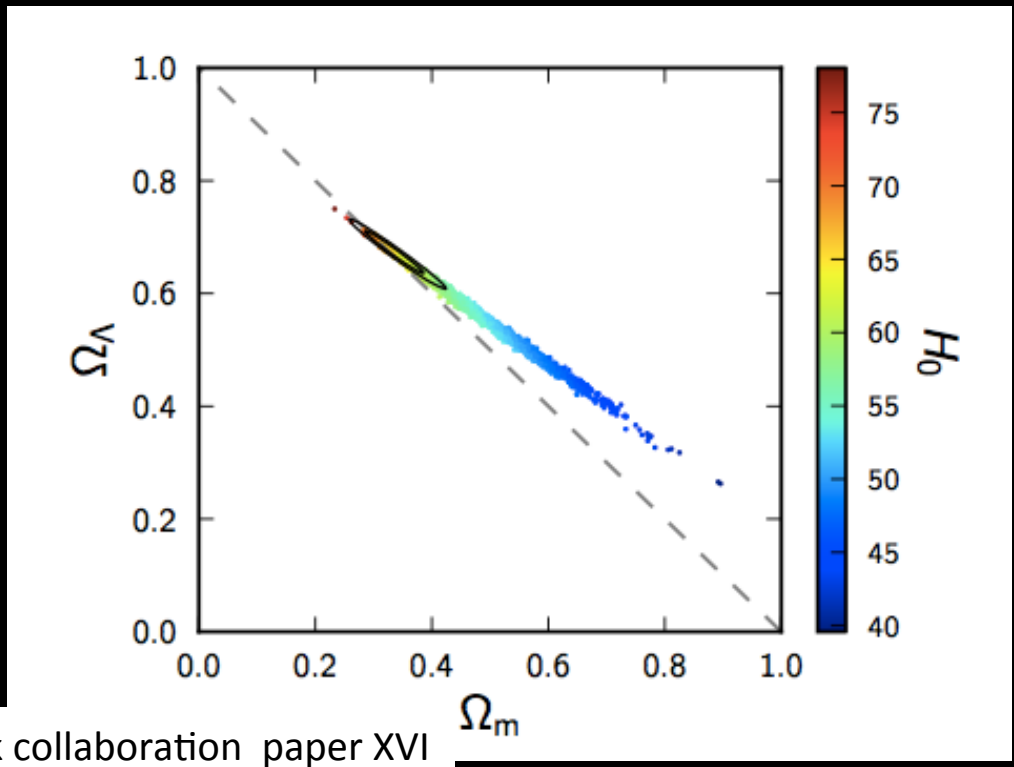
STILL….

The model IS incomplete… Neutrinos have mass

The model is unsatisfactory The cosmological constant problem

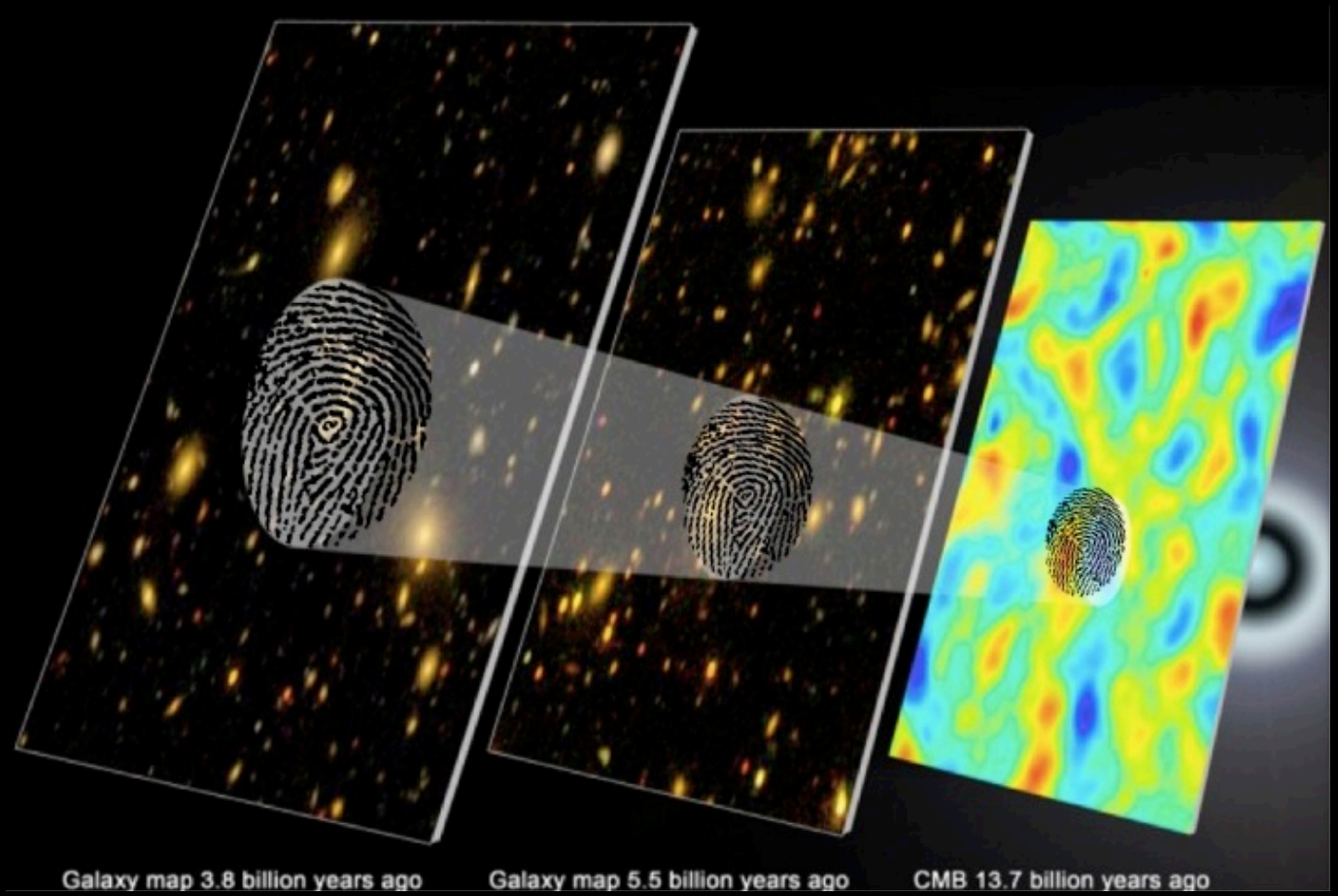
Inflation is more than n_s



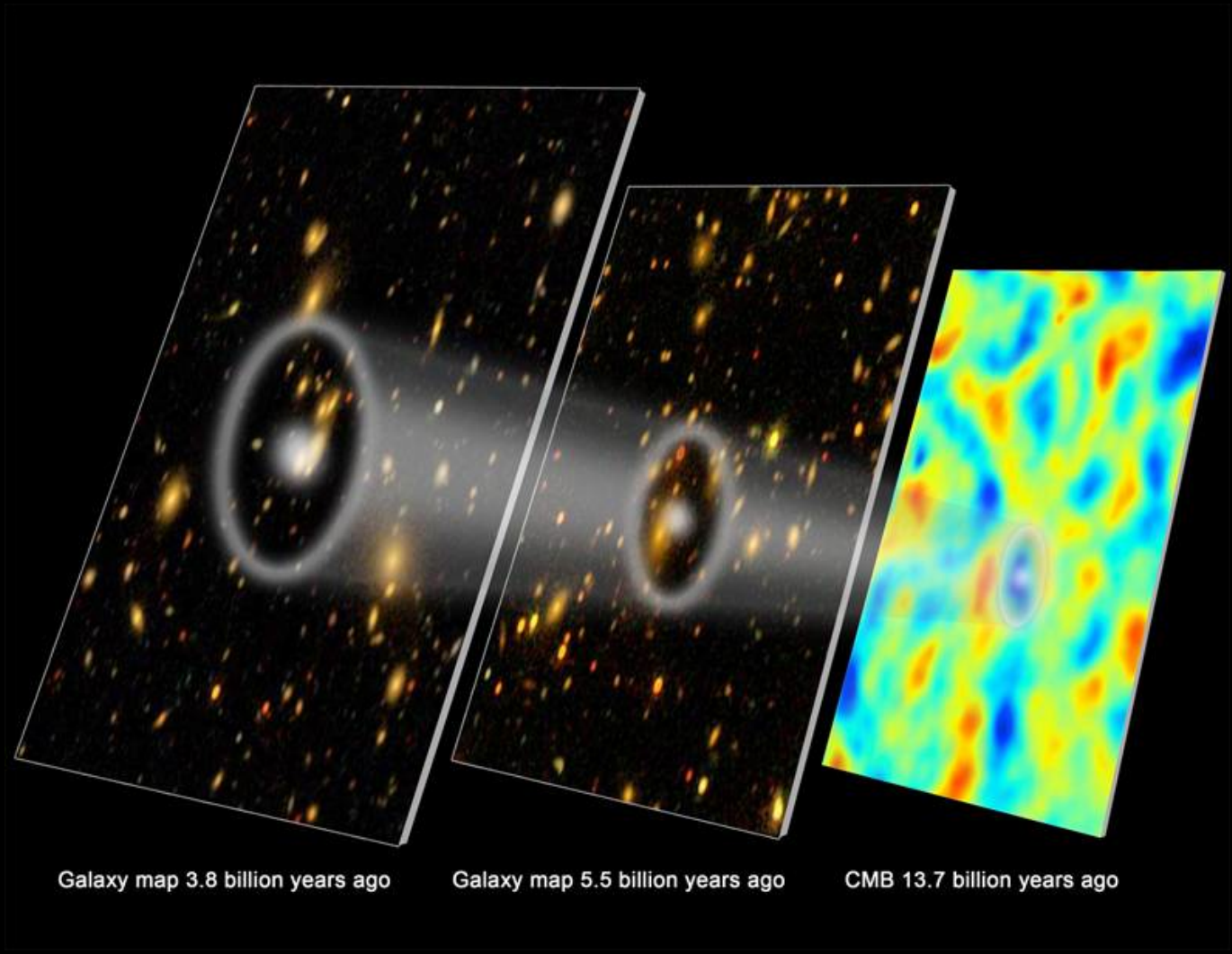


Planck collaboration paper XVI

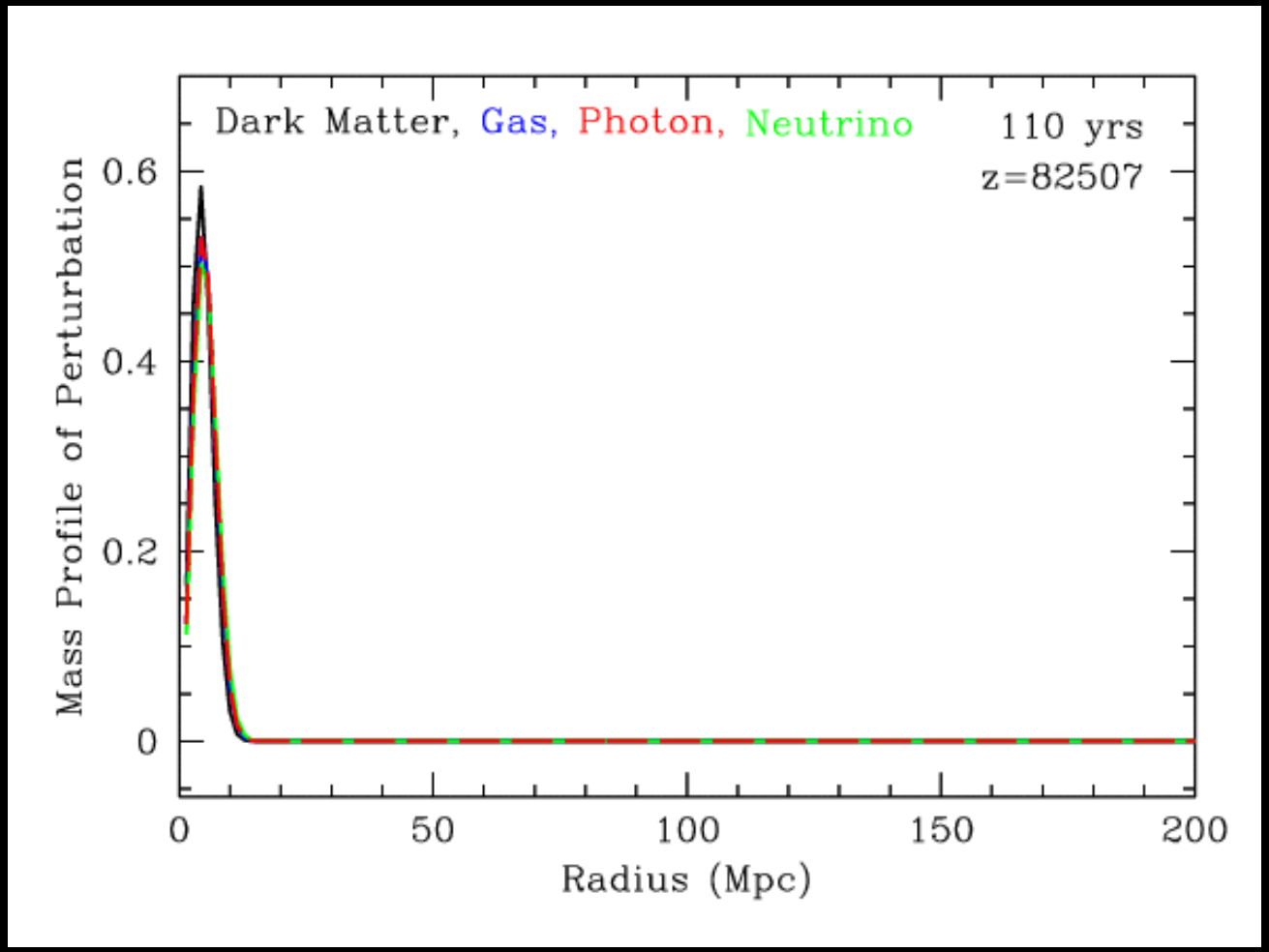
Baryon acoustic oscillations (BAO)



Baryon acoustic oscillations (BAO)



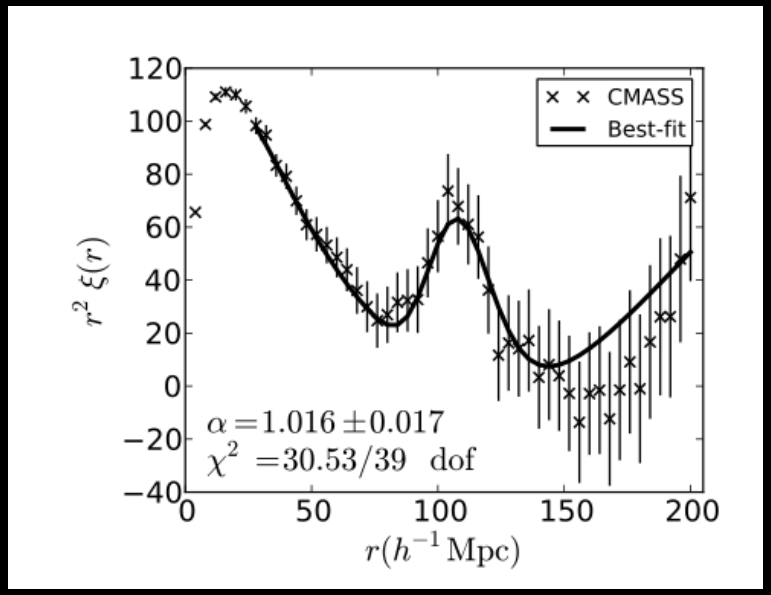
Baryon acoustic oscillations (BAO)

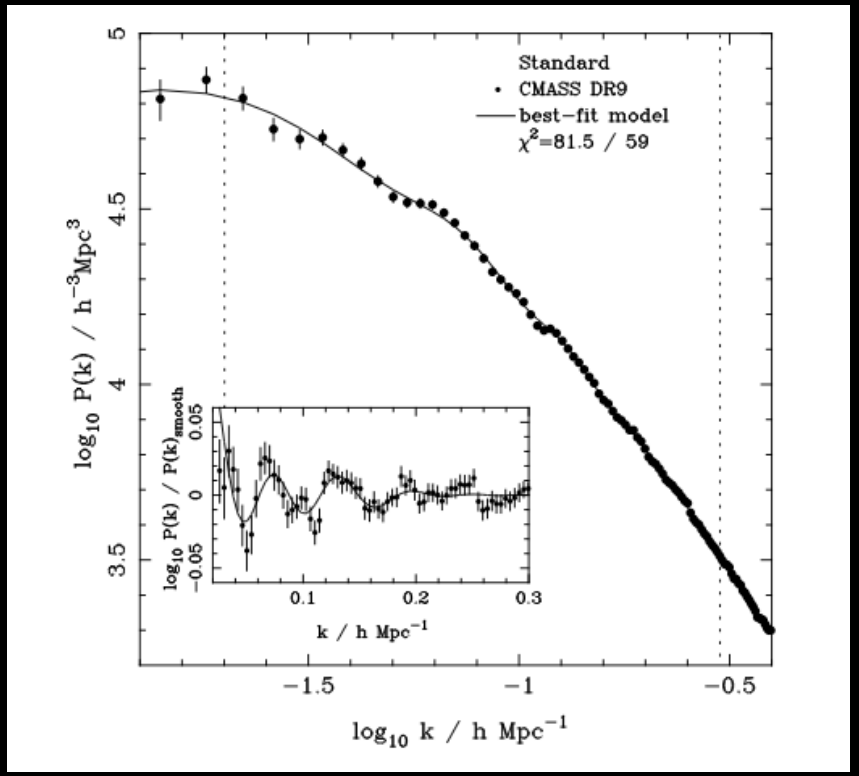


Animation courtesy of D. Eisenstein

Baryon acoustic oscillations (BAO)

Here it is!

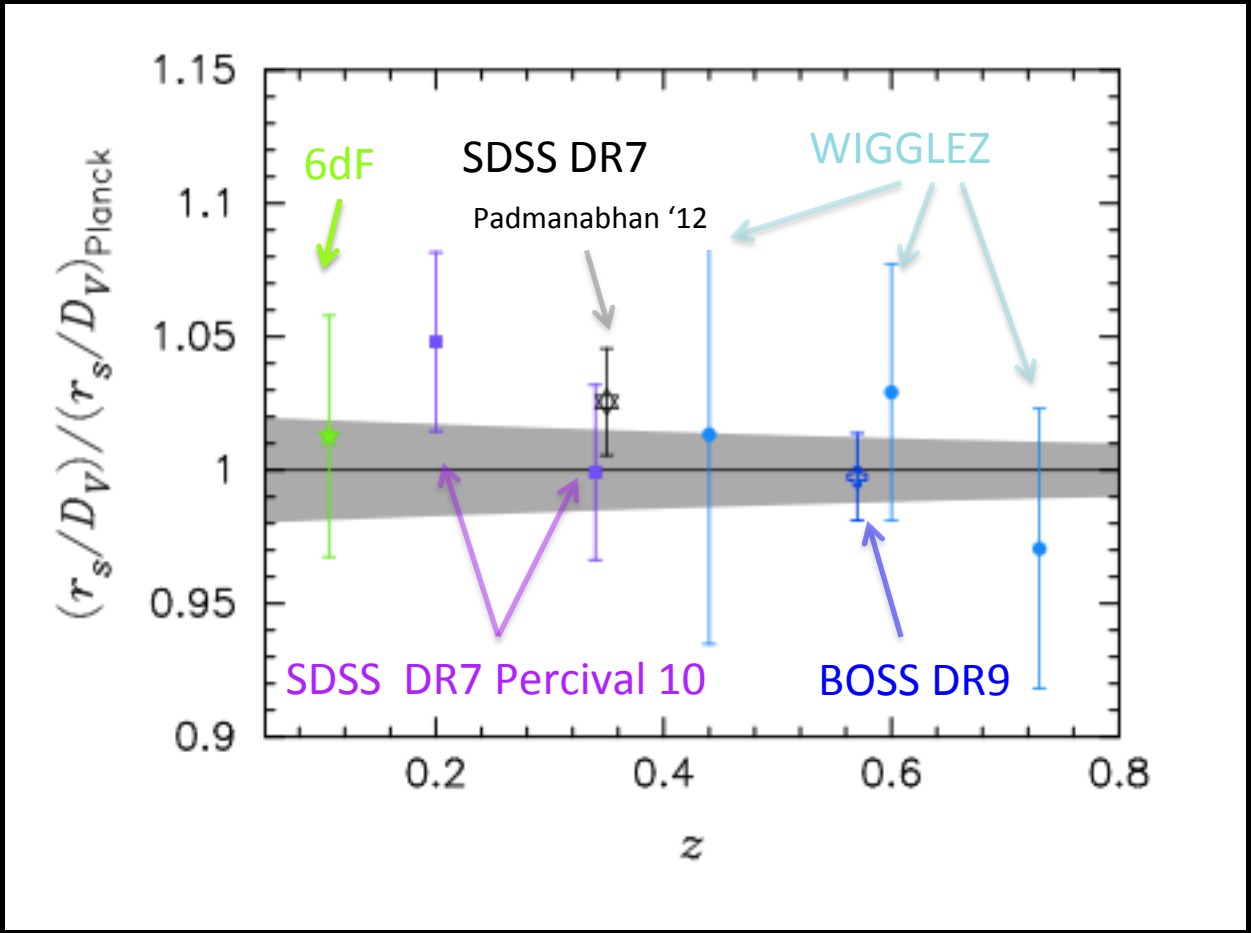




Anderson et al 2012 (BOSS)

The power of BAO

From the Planck cosmological parameters paper: almost the state of the art

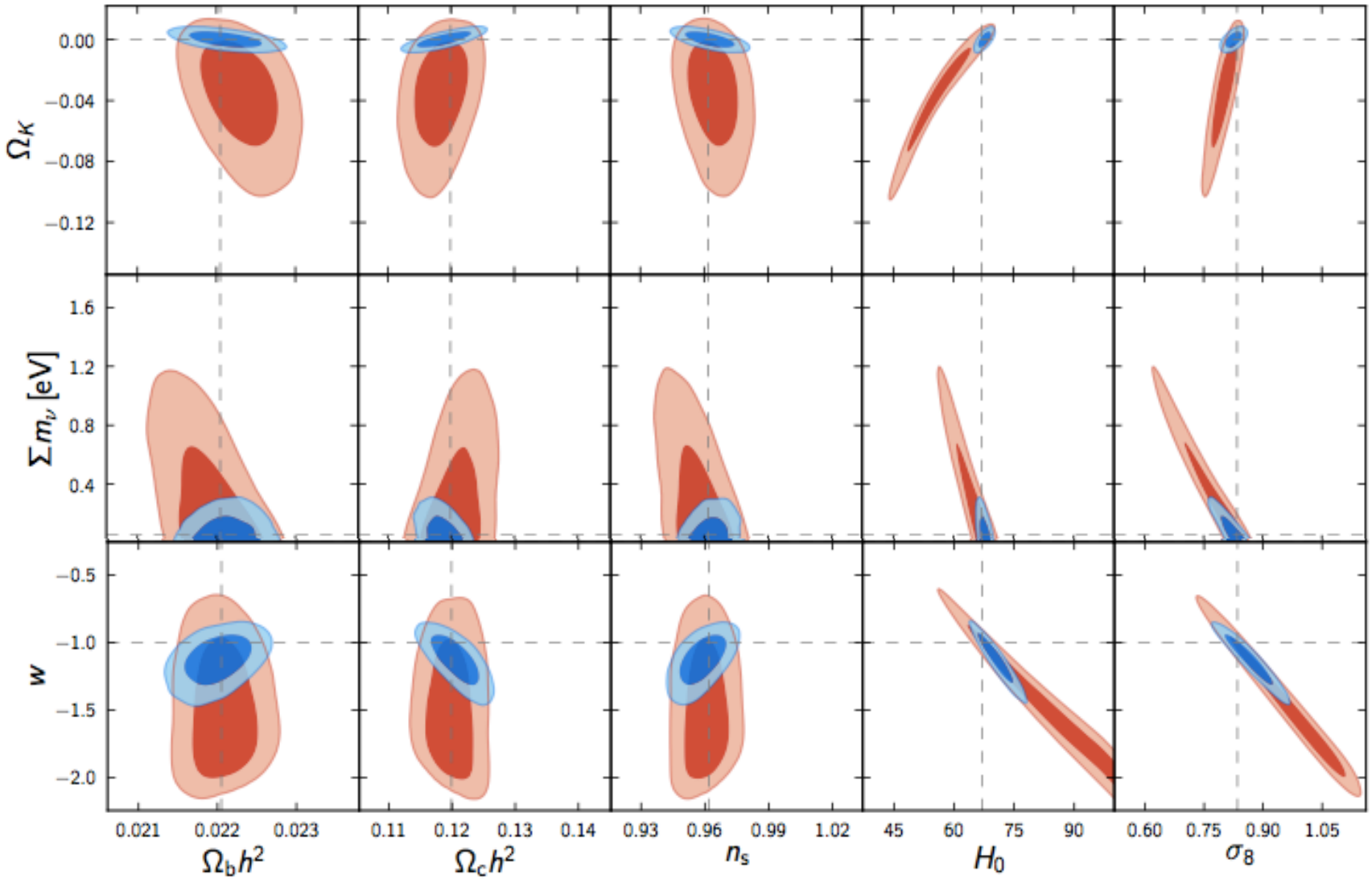


Adapted from Planck collaboration, 2013, paper XVI

The power of BAO

Planck collaboration paper XVI

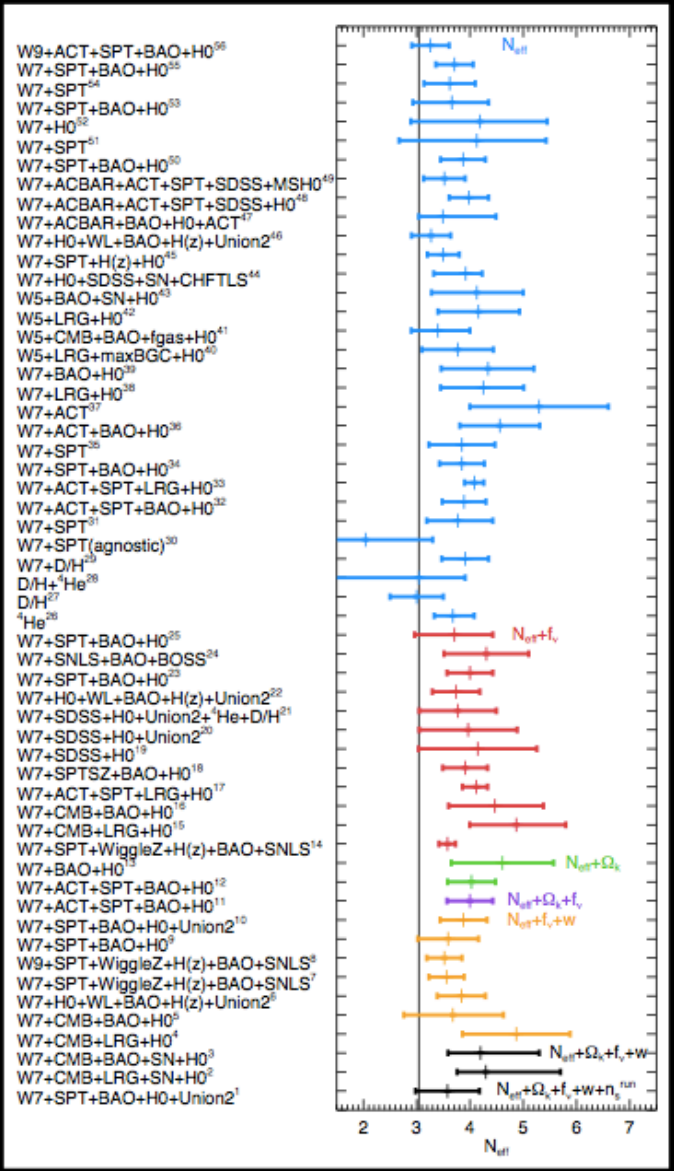
Planck+WP +BAO



Planck collaboration , 2013, paper XVI

Neutrinos beyond the Standard Model?

- Data from particle physics and cosmology imply standard neutrino picture wrong
- Oscillations require neutrino mass
- Cosmological tests hint at >3 species
- Let's concentrate on (effective) number of species (N_{eff}) for now



Riemer-Sørensen et al. [2013]

See also the white paper Abazajian et al. arXiv:1204.5379

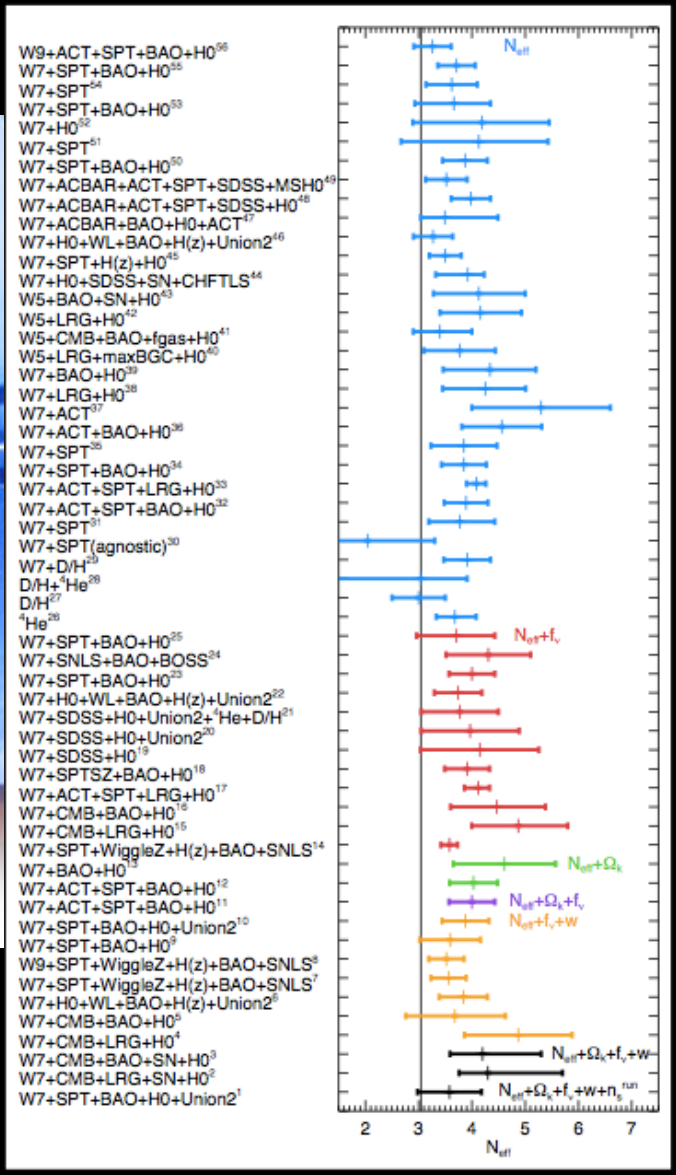
Neutrinos beyond the Standard Model?

Cosmological analyses consistently give best fit values >3.04.

“dark radiation”

But analyses are NOT independent

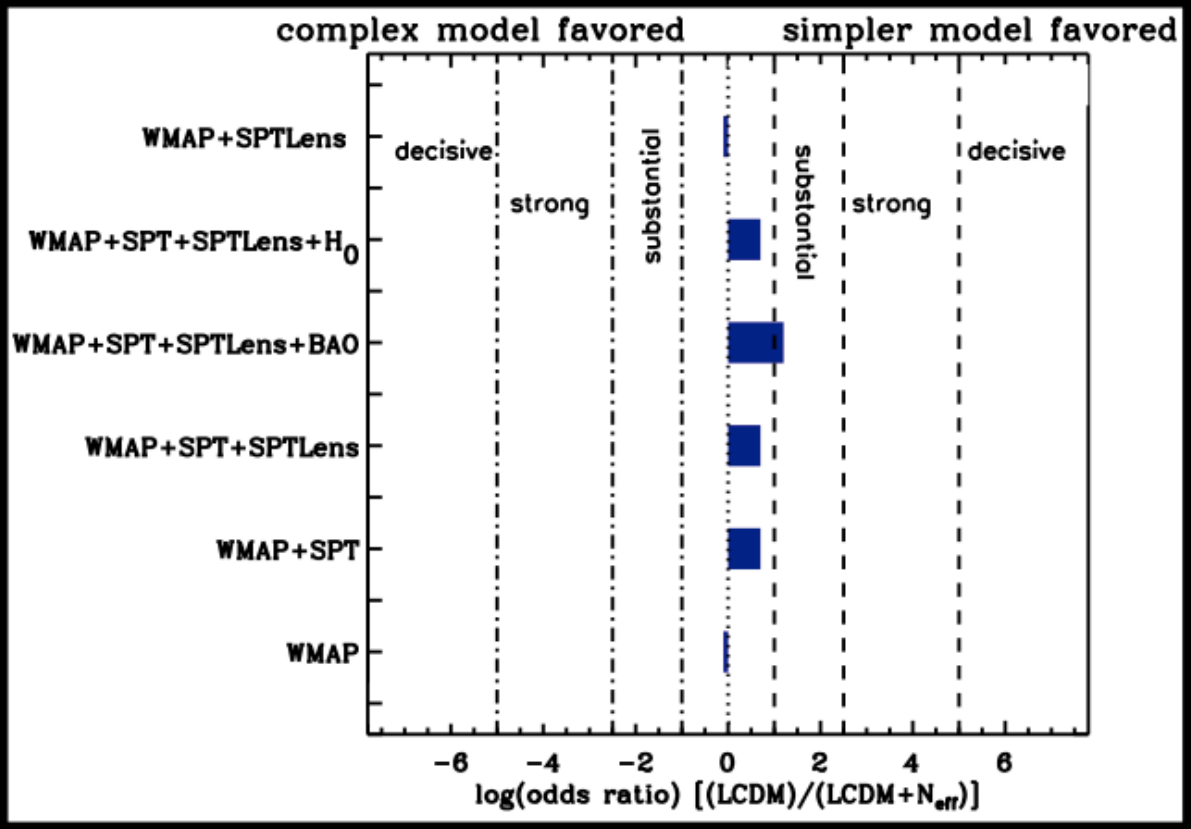
(WMAP is always in common, H0 many times in common)



Riemer-Sørensen et al. [2013]

See also the white paper Abazajian et al. [arXiv:1204.5379]

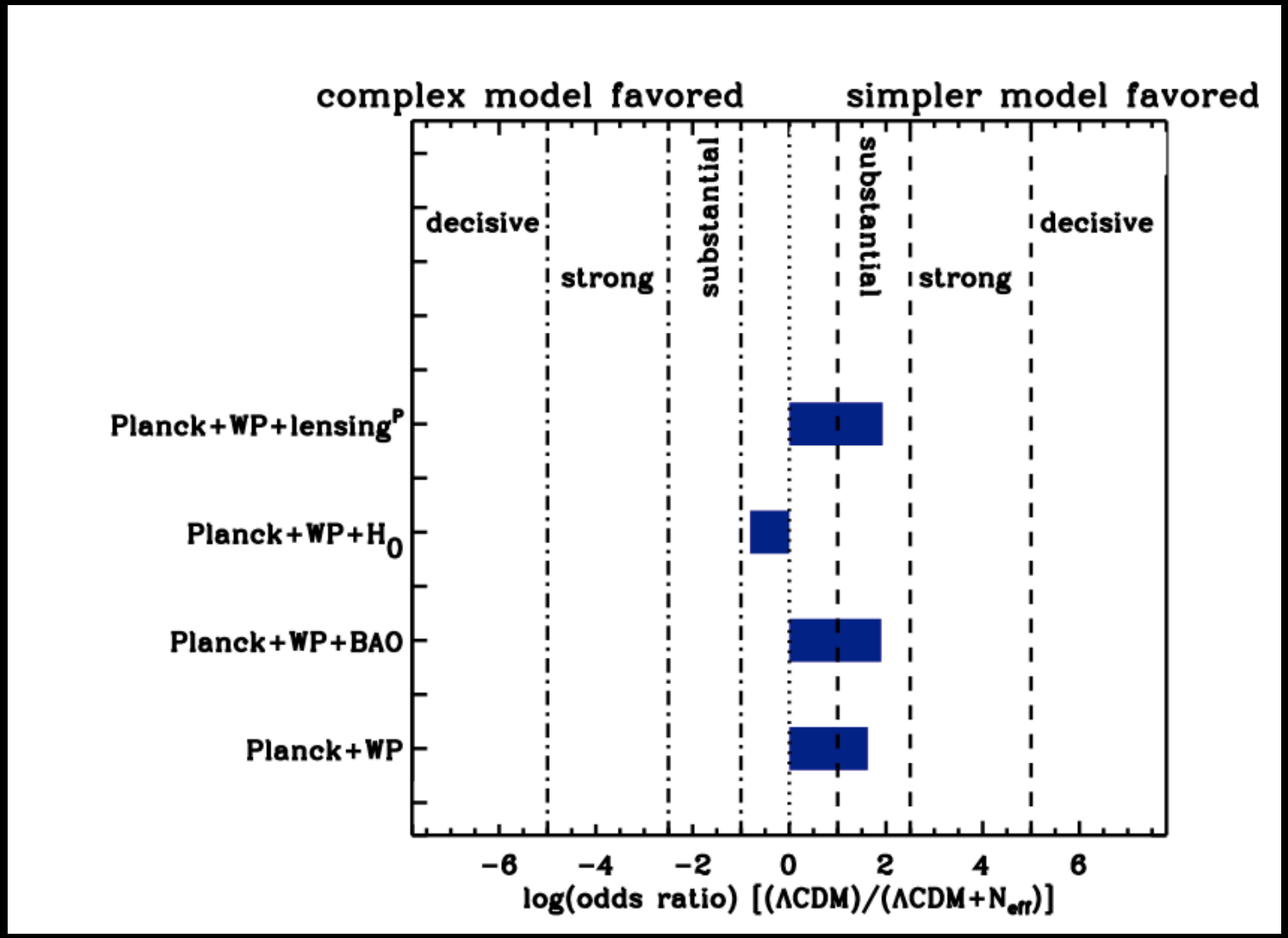
Evidence (pre-Planck)



Feeney, Peiris, Verde, 2013

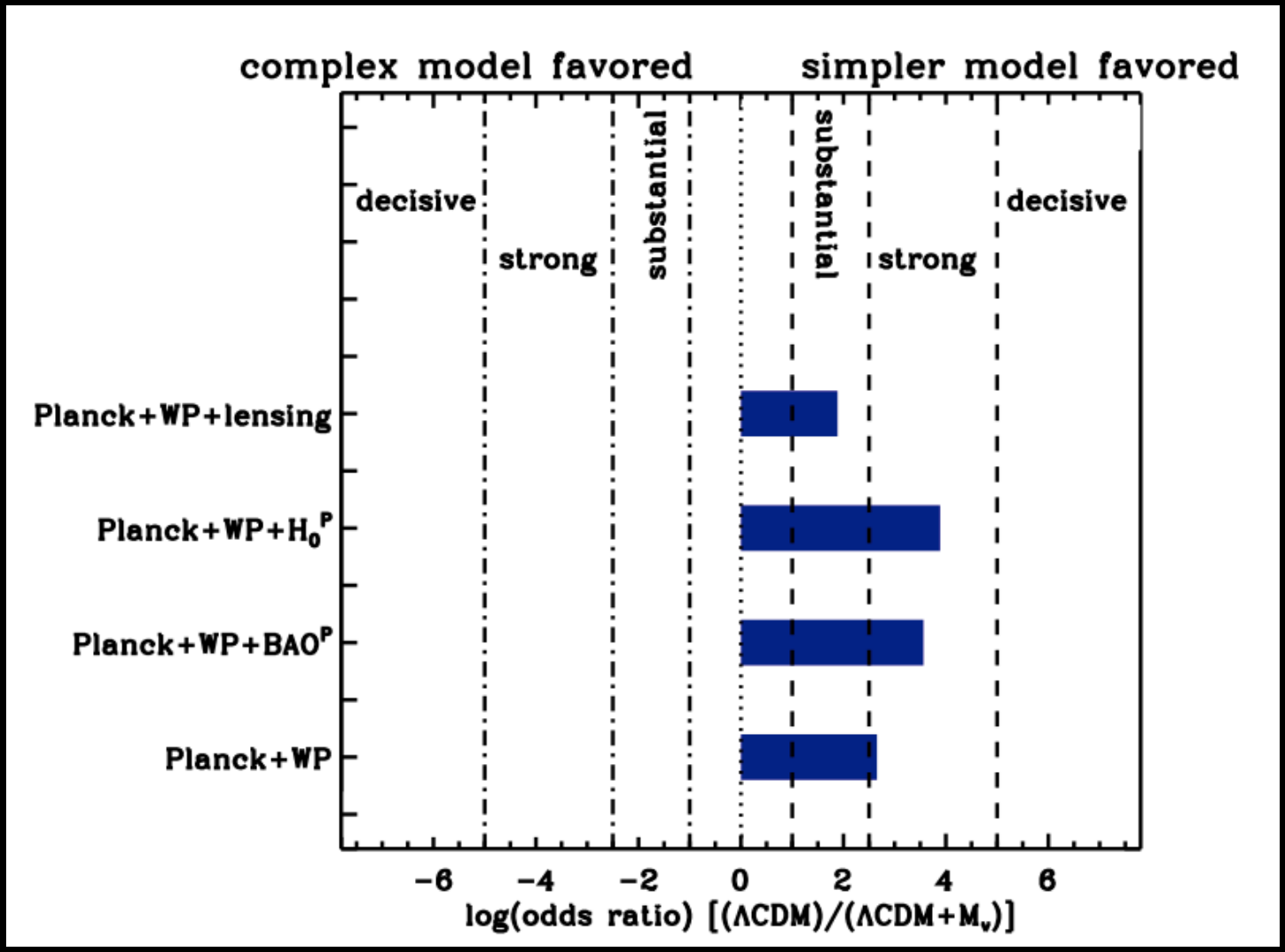
- No evidence for additional neutrinos!
  - odds 3:1 in favour of ΛCDM
- But do we (or do *you*) trust our priors?

Evidence post-Planck Neff



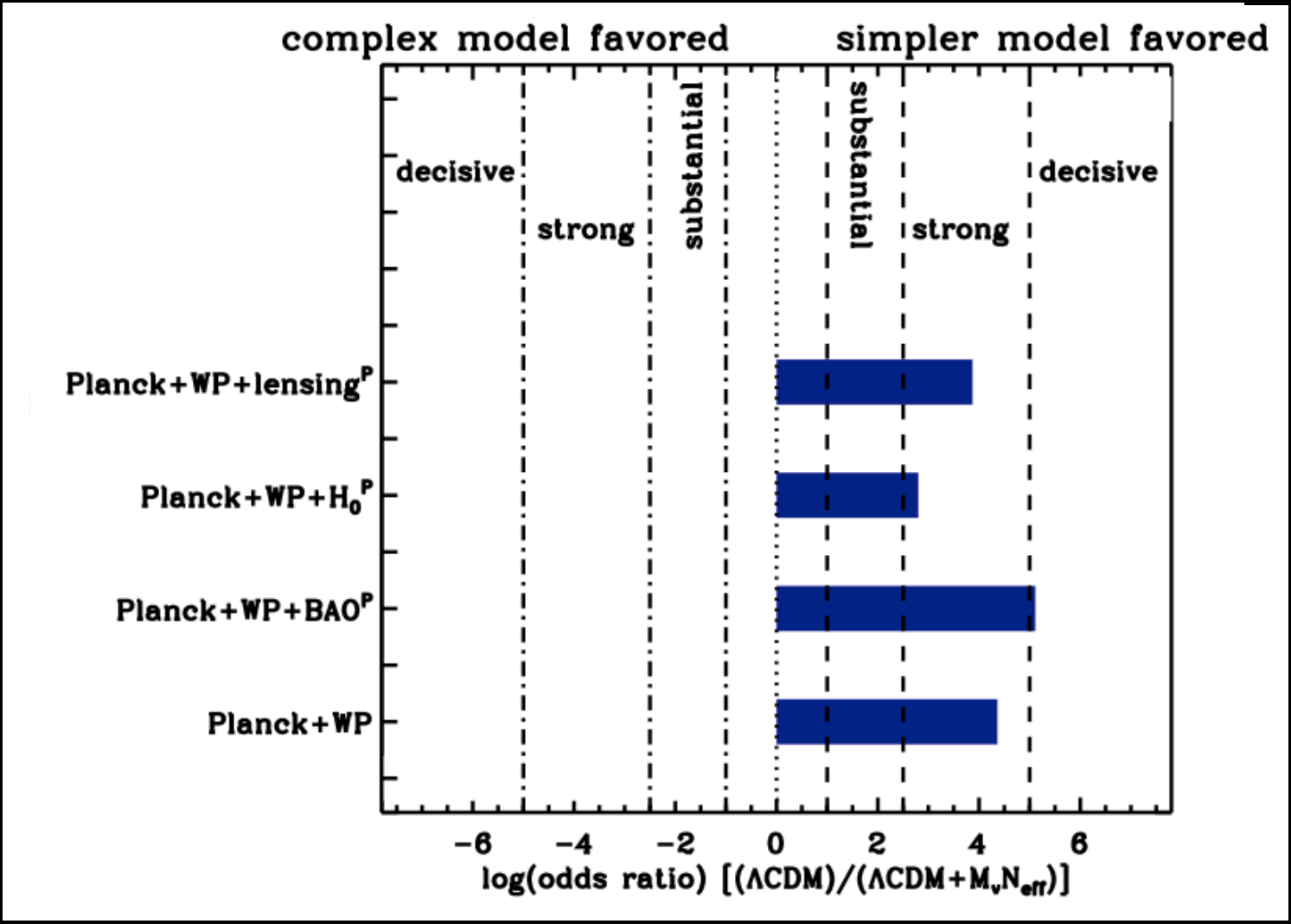
Verde, Feeney, Peiris, Mortlock, 2013

Post-Planck: Mv



Verde, Feeney, Peiris, Mortlock, 2013

Post-Planck: Neff and Mv



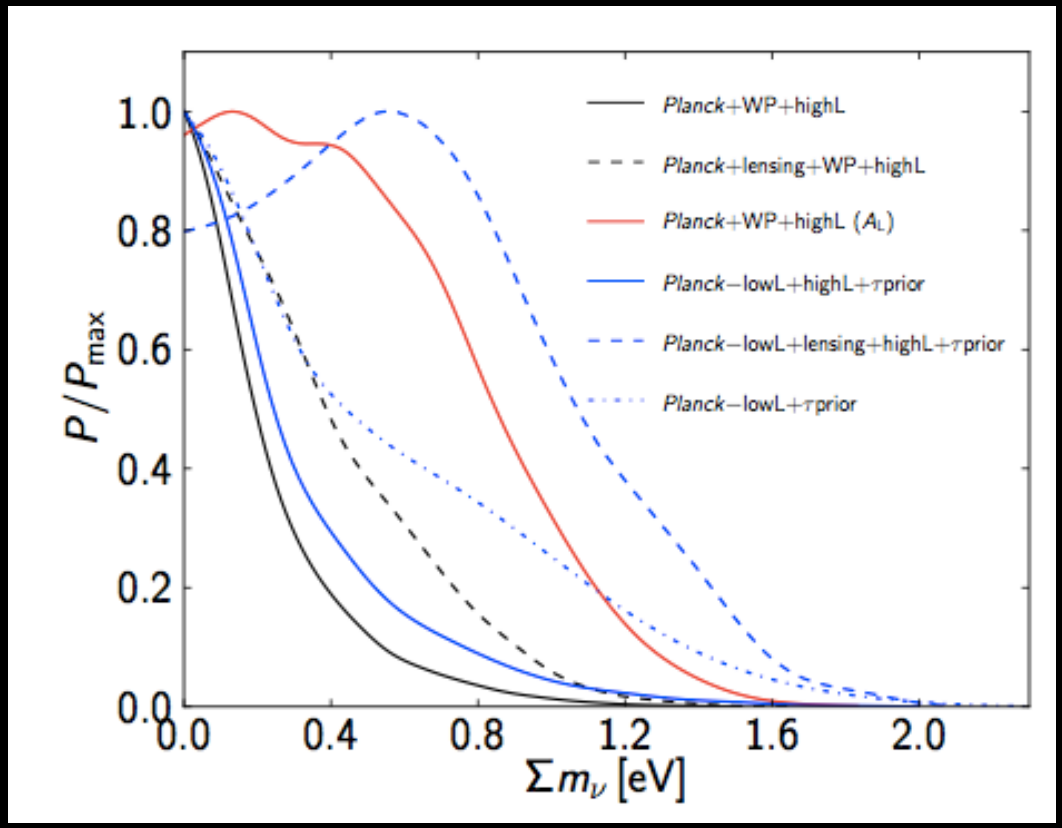
Verde, Feeney, Peiris, Mortlock, 2013

So….

- Yes, profile likelihood confirms it
- Adding more data (Planck) INCREASES the evidence for the simpler (LCDM) model
- if you insist… LCDM vs HZ+Neff undecisive unless BAO or lensing added to Planck , then LCDM is preferred (significant to strong)
- Better lensing and polarization data will be CRUCIAL but have to wait till next year :(

Parameter constraints: Neutrino mass

Planck collaboration, 2013, paper XVI



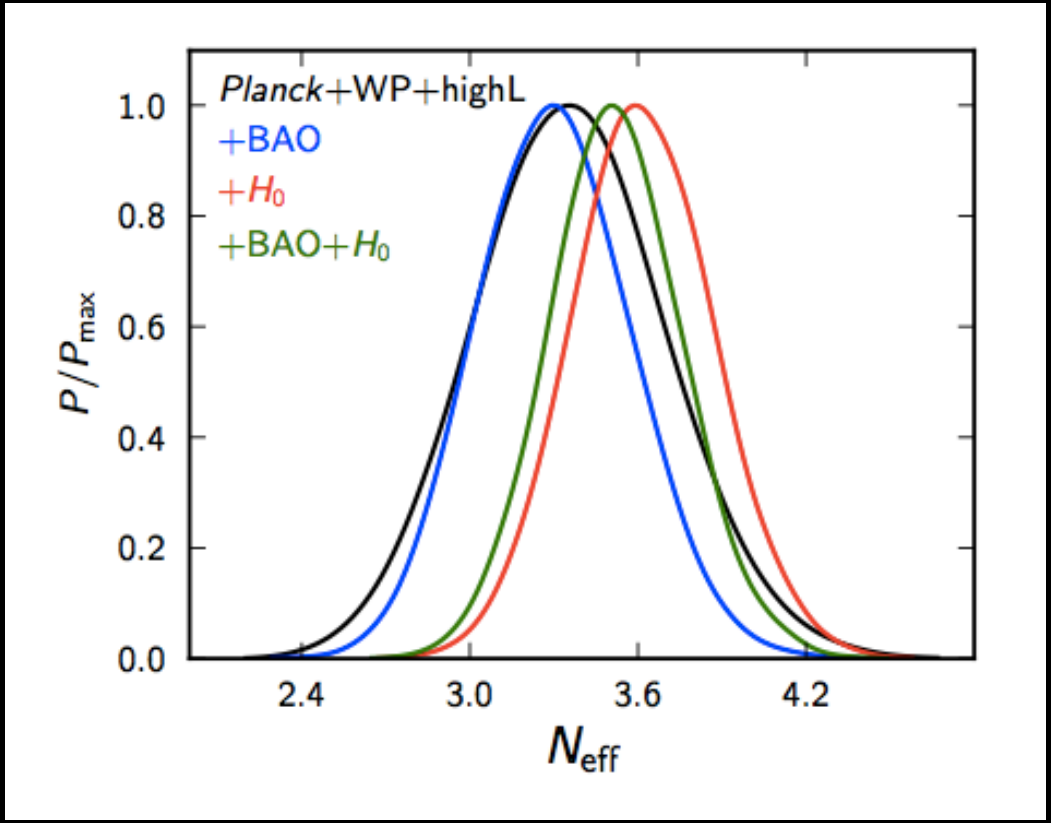
$\sum m_\nu < 0.66\,\mathrm{eV}$ (95%; *Planck*+WP+highL).

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

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

Parameter constraints: Neutrino species

Planck collaboration, 2013, paper XVI

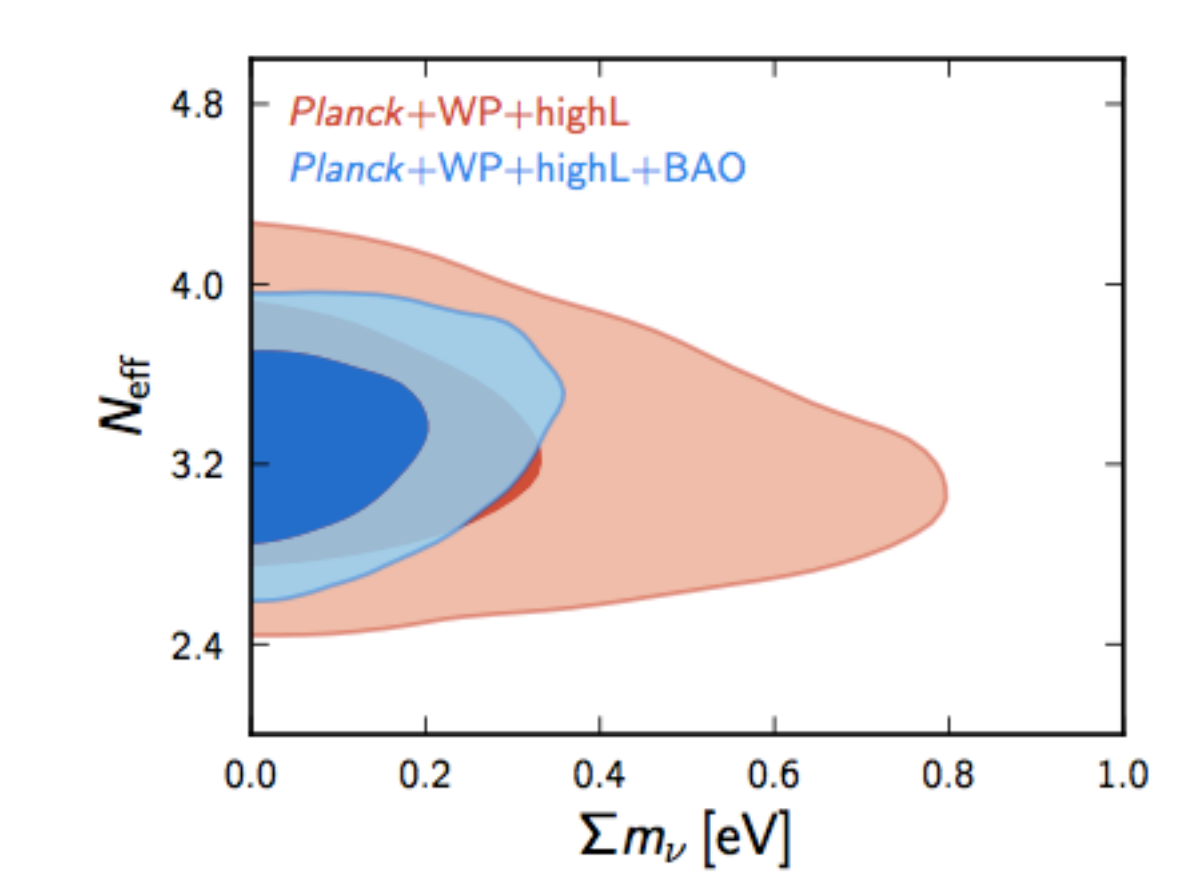


$N_{\rm eff} = 3.36^{+0.68}_{-0.64}$ (95%; *Planck*+WP+highL).

$N_{\rm eff} = 3.30^{+0.54}_{-0.51}$ (95%; *Planck*+WP+highL+BAO).

Parameter constraints:

Neutrino species and total mass



CMB lensing and neutrino mass

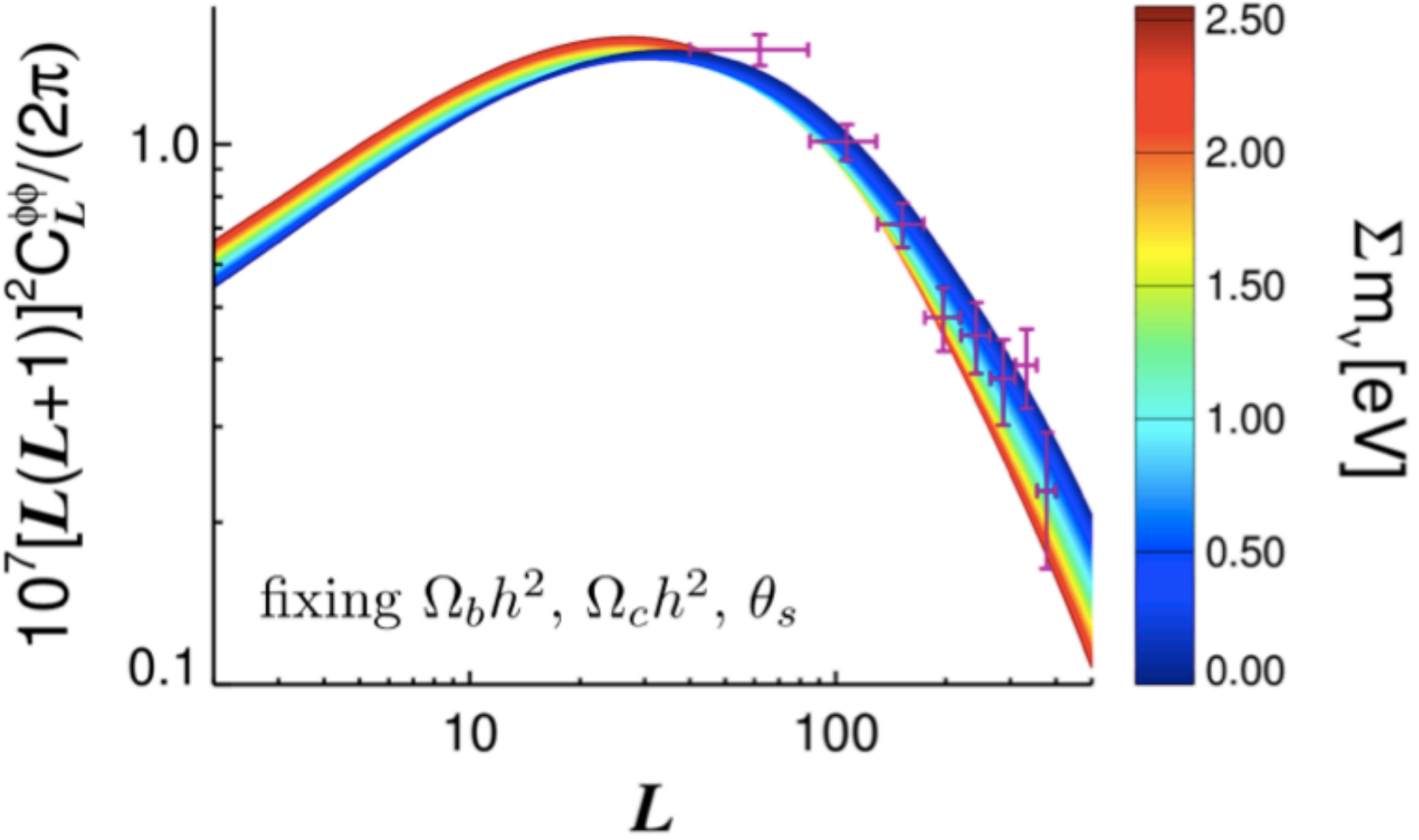
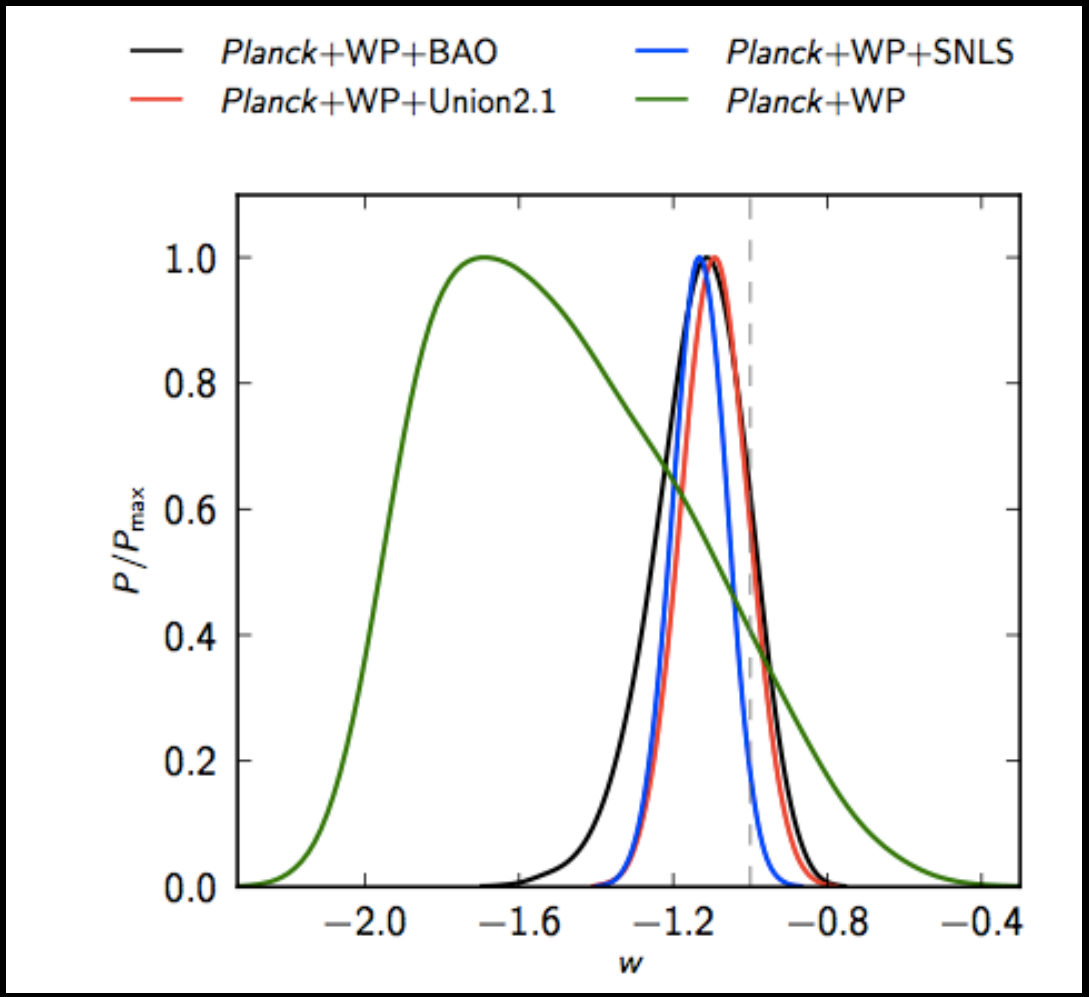


Image credit: Zhen Hou

Data points: Planck XVII

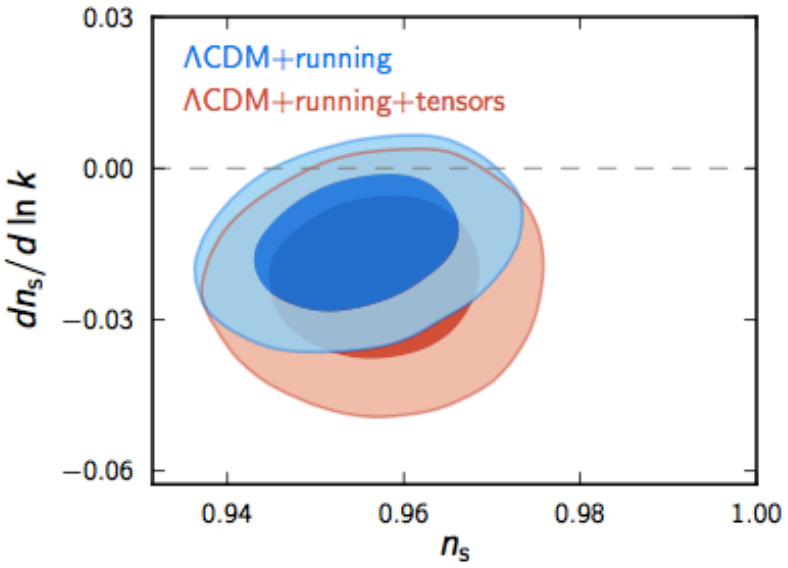
Parameter constraints: Dark energy equation of state parameter:

Planck collaboration, 2013, paper XVI



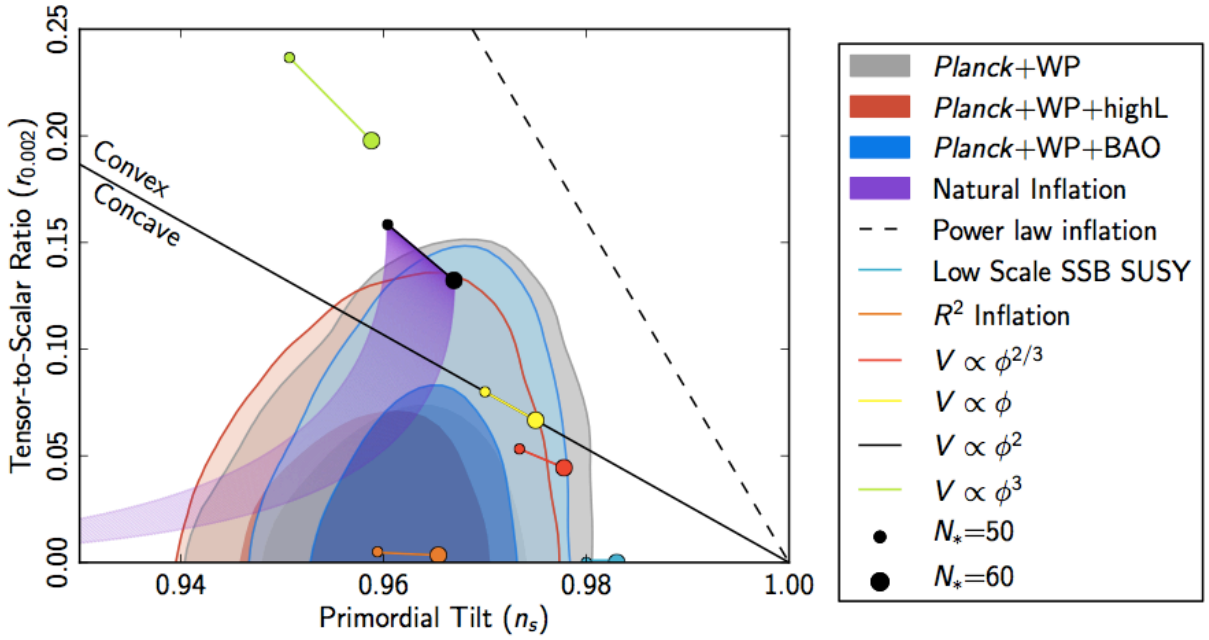
$w = -1.13^{+0.24}_{-0.25}$ (95%; *Planck*+WP+BAO)

inflation



Planck collaboration , 2013, paper XVI

COOL… see next talk

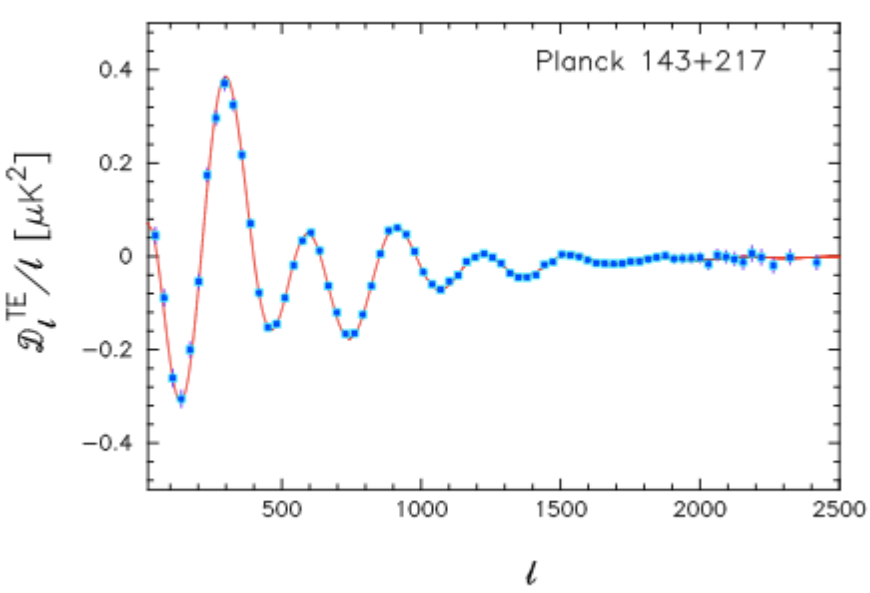


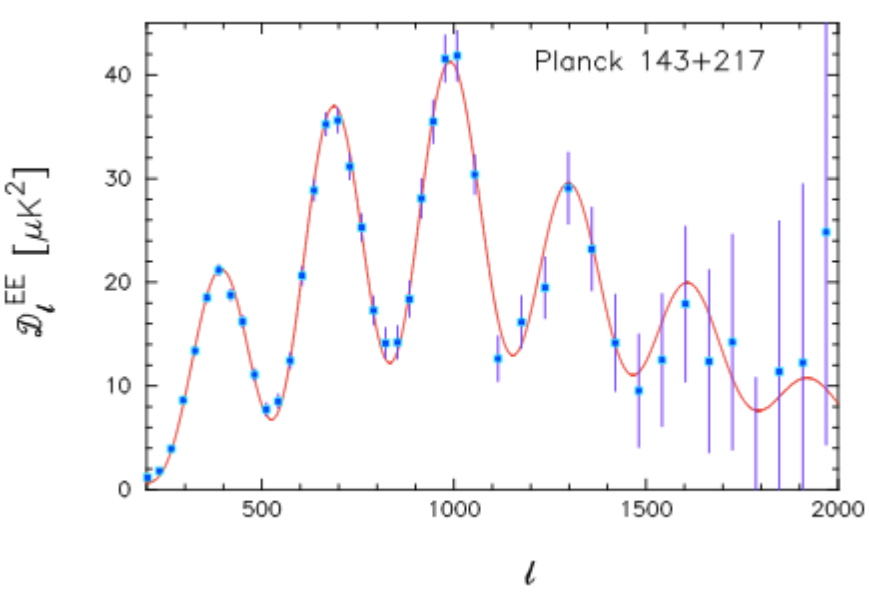
Planck collaboration , 2013
paper XXII

MORE TO COME:

POLARIZATION

Teaser plots



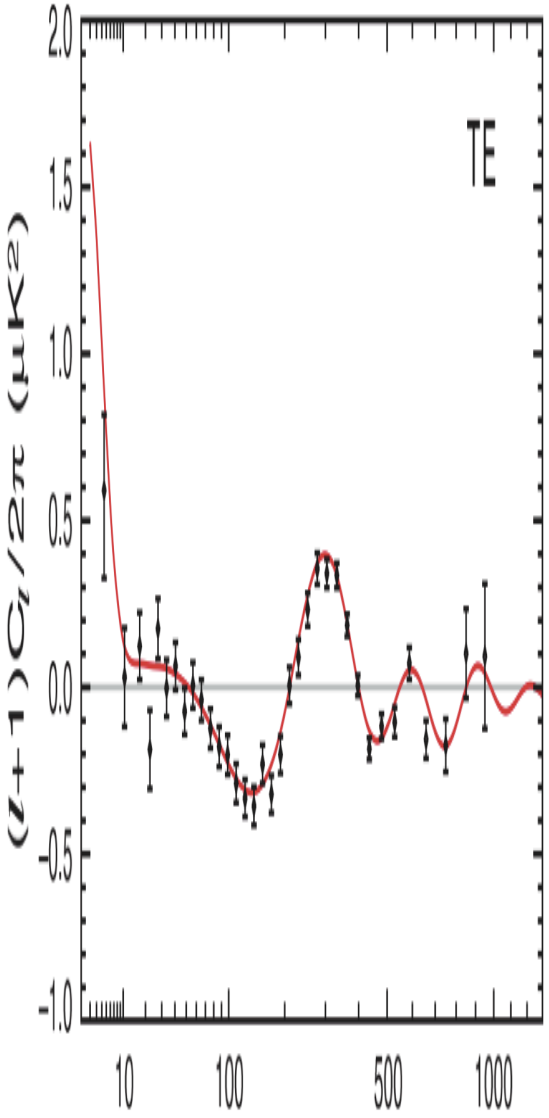


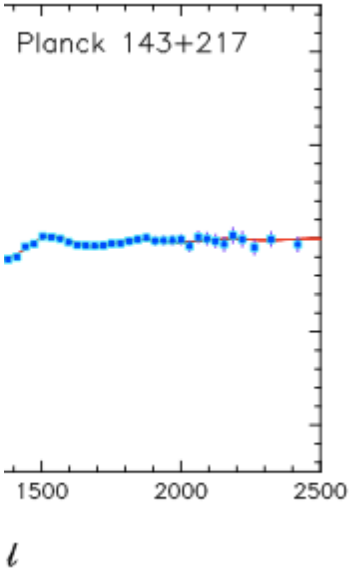
Planck collaboration , 2013, paper XVI

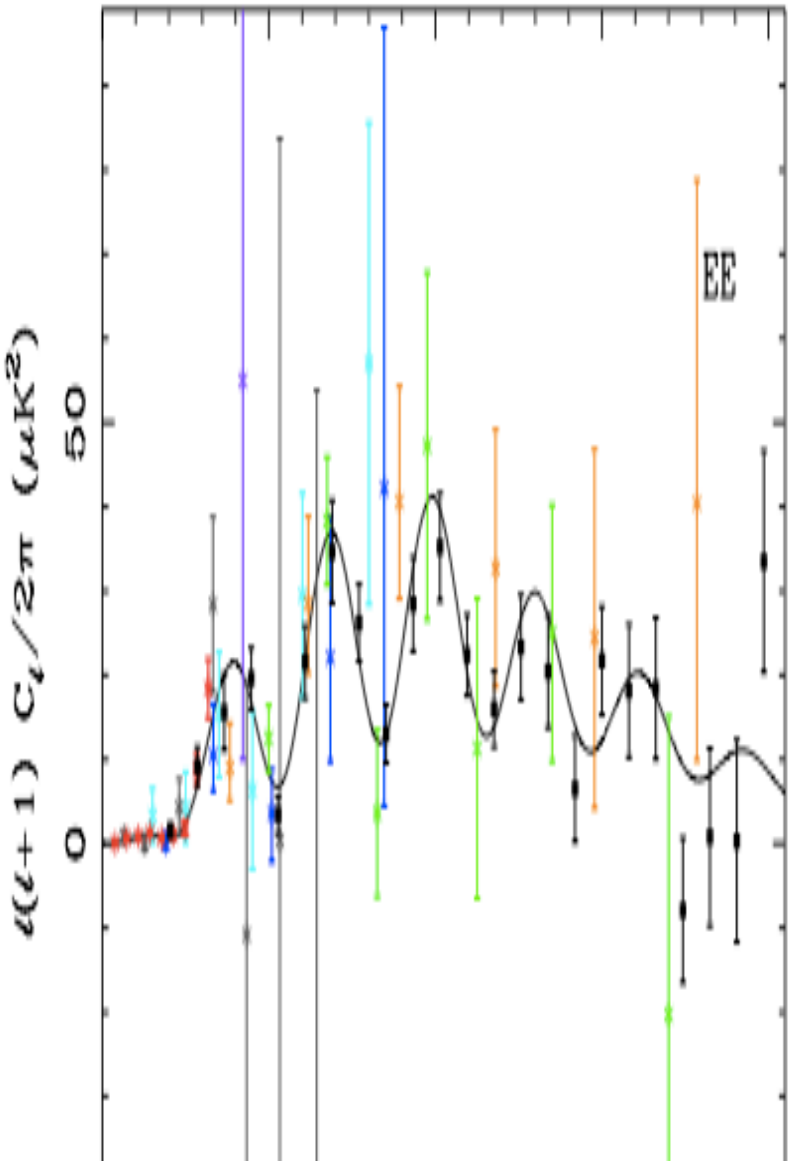
MORE TO COME:

POLARIZAT

Teaser plo

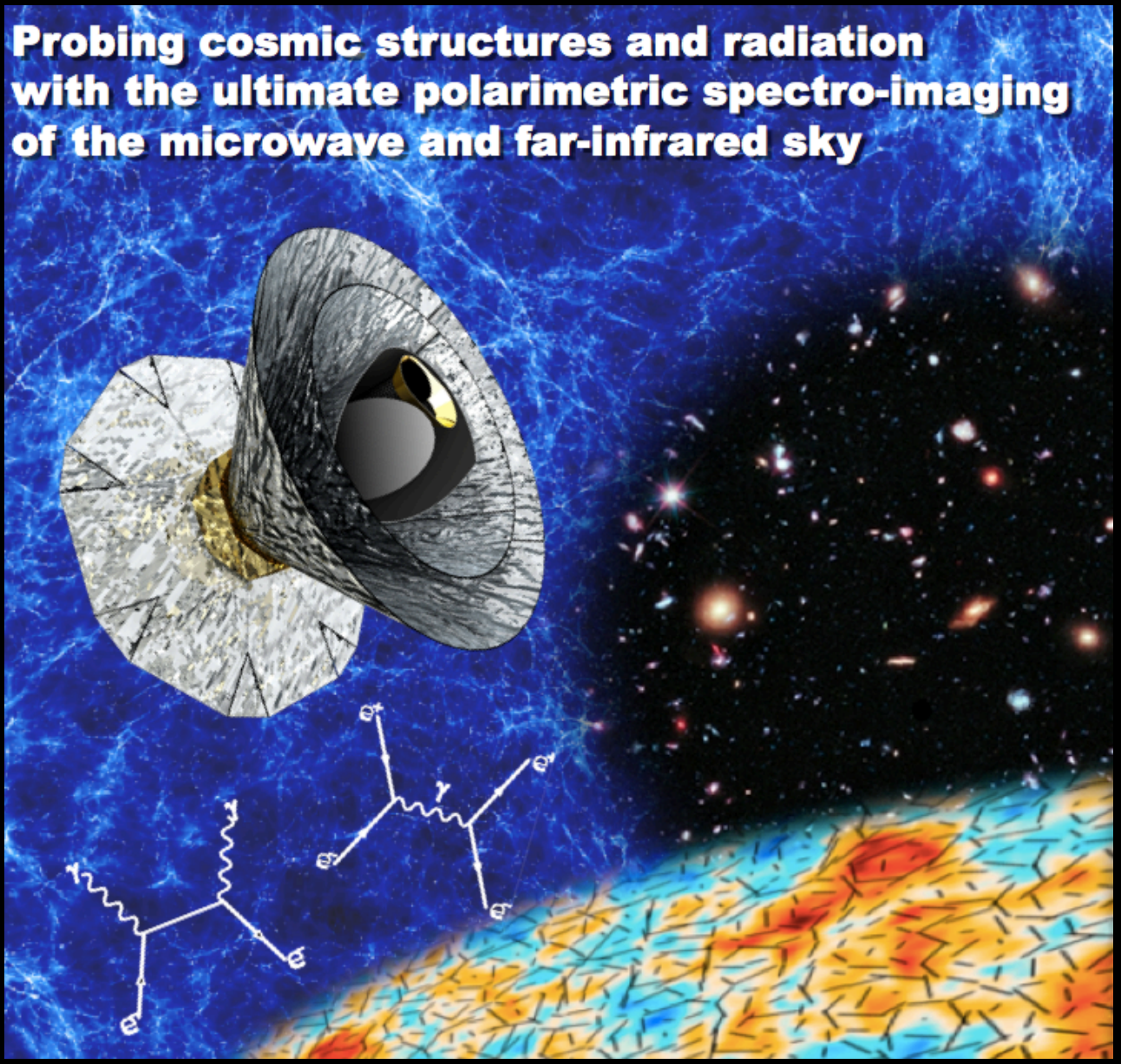






Planck collaborat

More in the future



PRISM

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… the maximally boring universe…

The standard cosmological model has survived ever more stringent tests

Deviations from it are even more constrained

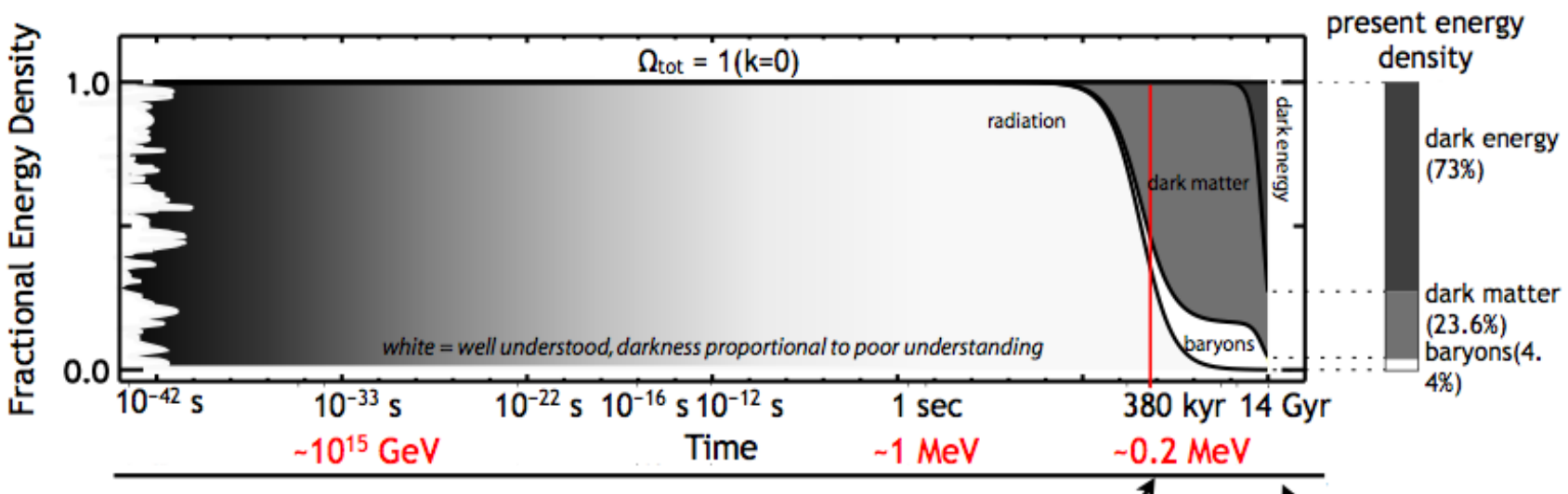
Eventually something will have to give, the model IS incomplete

The point is how much smaller would the observational error bars have to be

Neutrino mass is within the reach of the next generation experiments (large scale structure)

END

Cosmic History / Cosmic Mystery



Planck Energy

GUT symmetry

T=100 TeV (ILC X 100)

nucleosynthesis

Generation of primordial perturbations

Cosmic Microwave Background Emitted carries signature of acoustic oscillations and potentially primordial gravitational waves

non-linear growth of perturbations: signature on CMB through weak gravitational lensing

McMahon adapted by Peiris