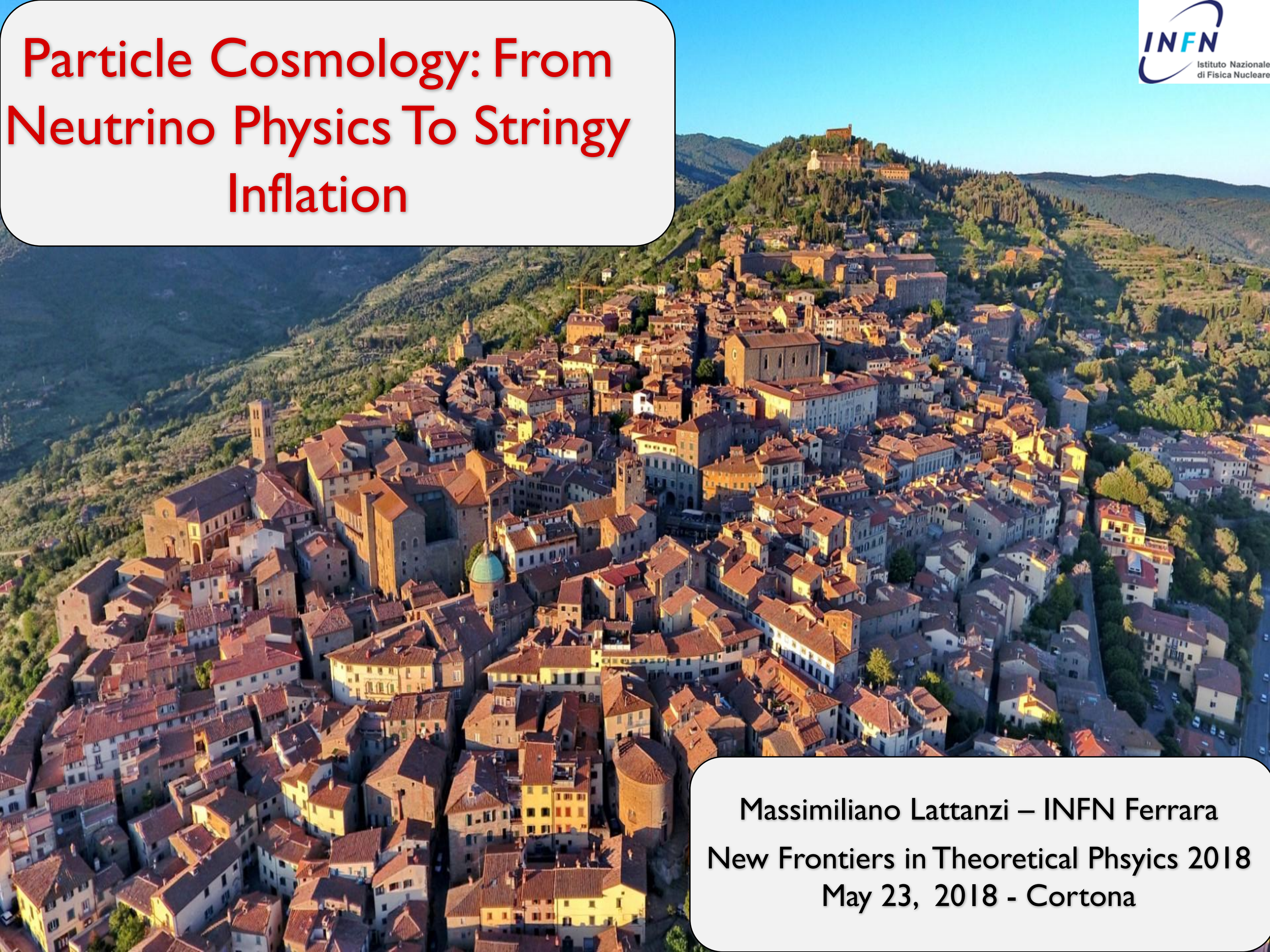
Particle Cosmology: From Neutrino Physics To Stringy Inflation



Massimiliano Lattanzi – INFN Ferrara

New Frontiers in Theoretical Phsyics 2018
May 23, 2018 - Cortona

Cosmology is a powerful probe of particle physics

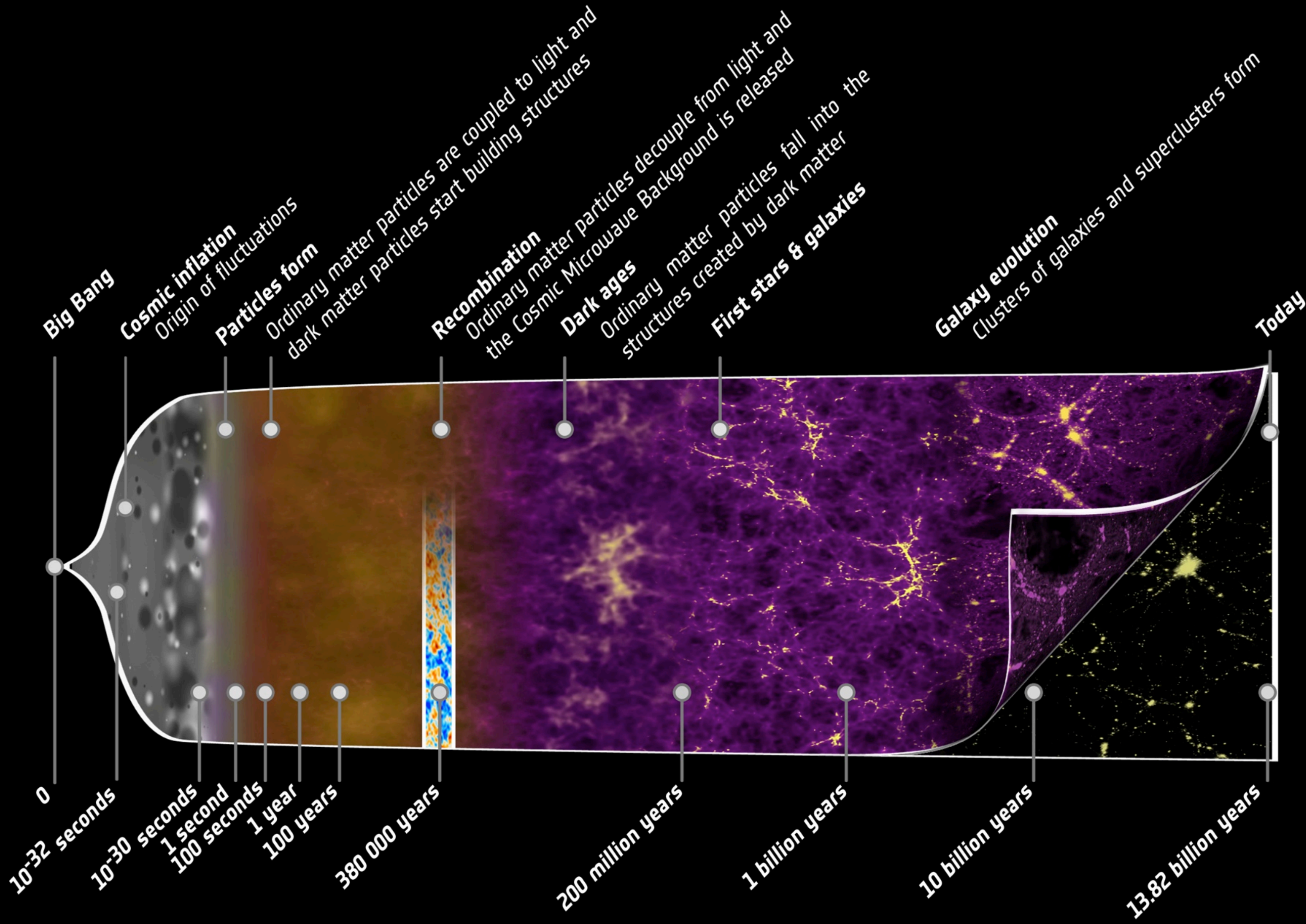
- probes energy scale that are unaccessible from the lab;

- the Universe is a "simple" (i.e., highly symmetric) system;

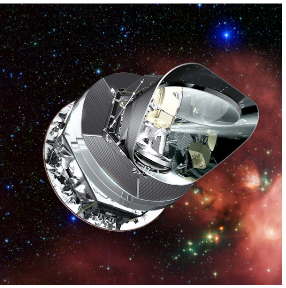
BUT

- no control over experimental conditions (we do 'observations', not 'experiments')

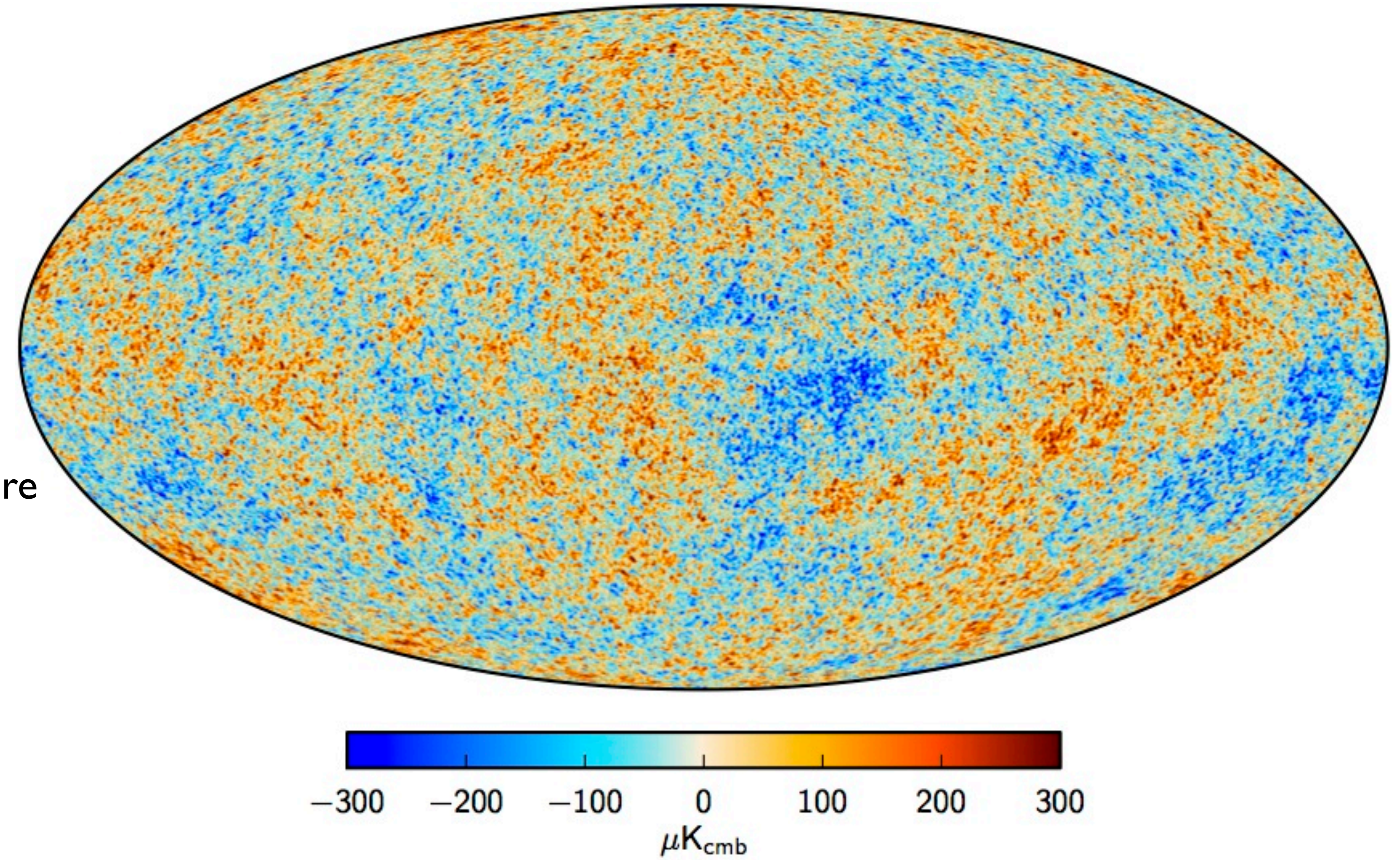
- model dependence can be an issue


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

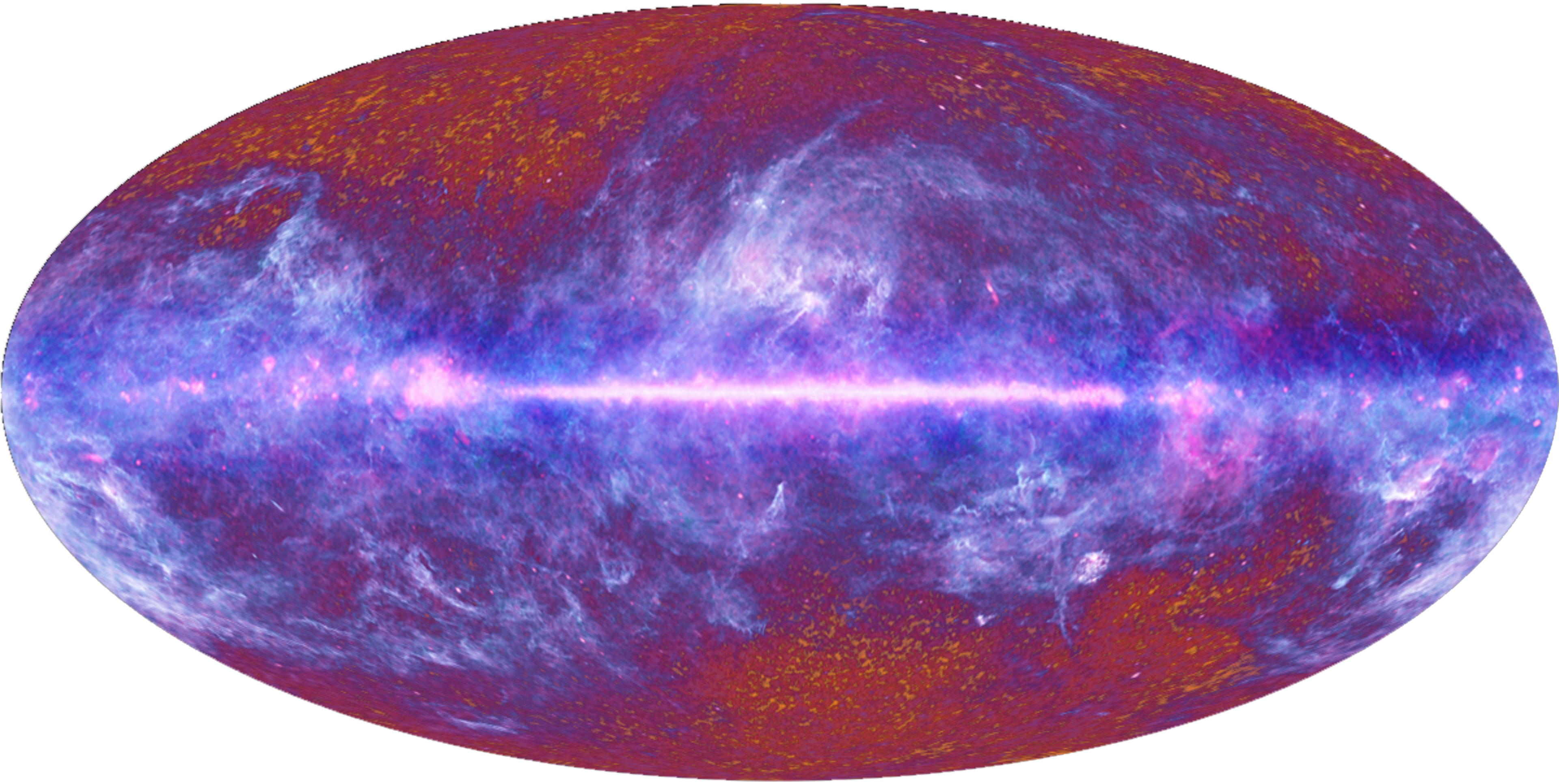


Full sky temperature map from Planck (2015)



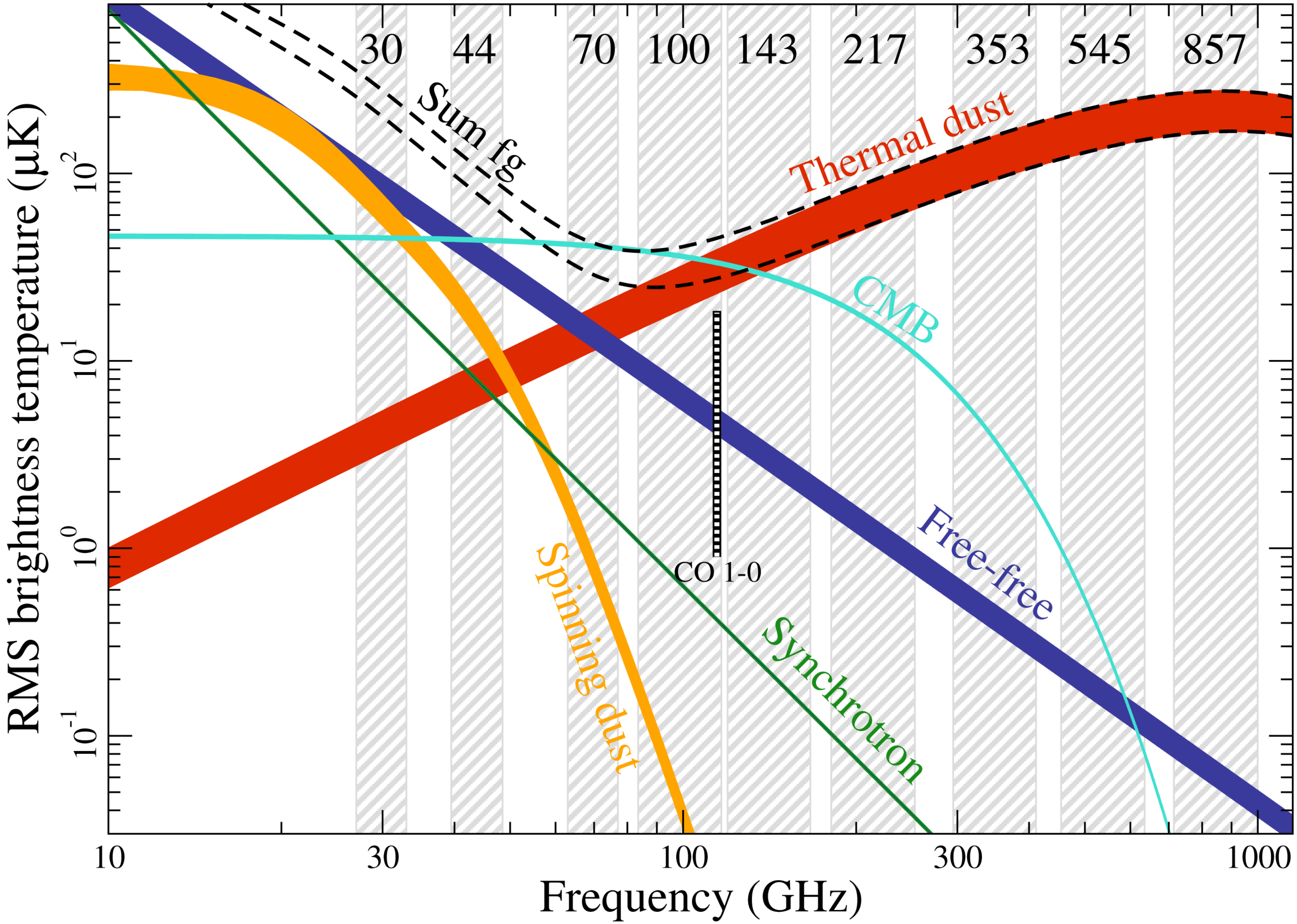
The CMB is a blackbody radiation with T=2.7 K extremely uniform across the whole sky; it is the relic radiation emitted at the time the nuclei and electrons recombined to form neutral hydrogen, when the Universe was ~ 400,000 years old (the so-called last scattering surface, LSS).

Its tiny (~ 10^{-5}) temperature and polarization anisotropies encode a wealth of cosmological information.

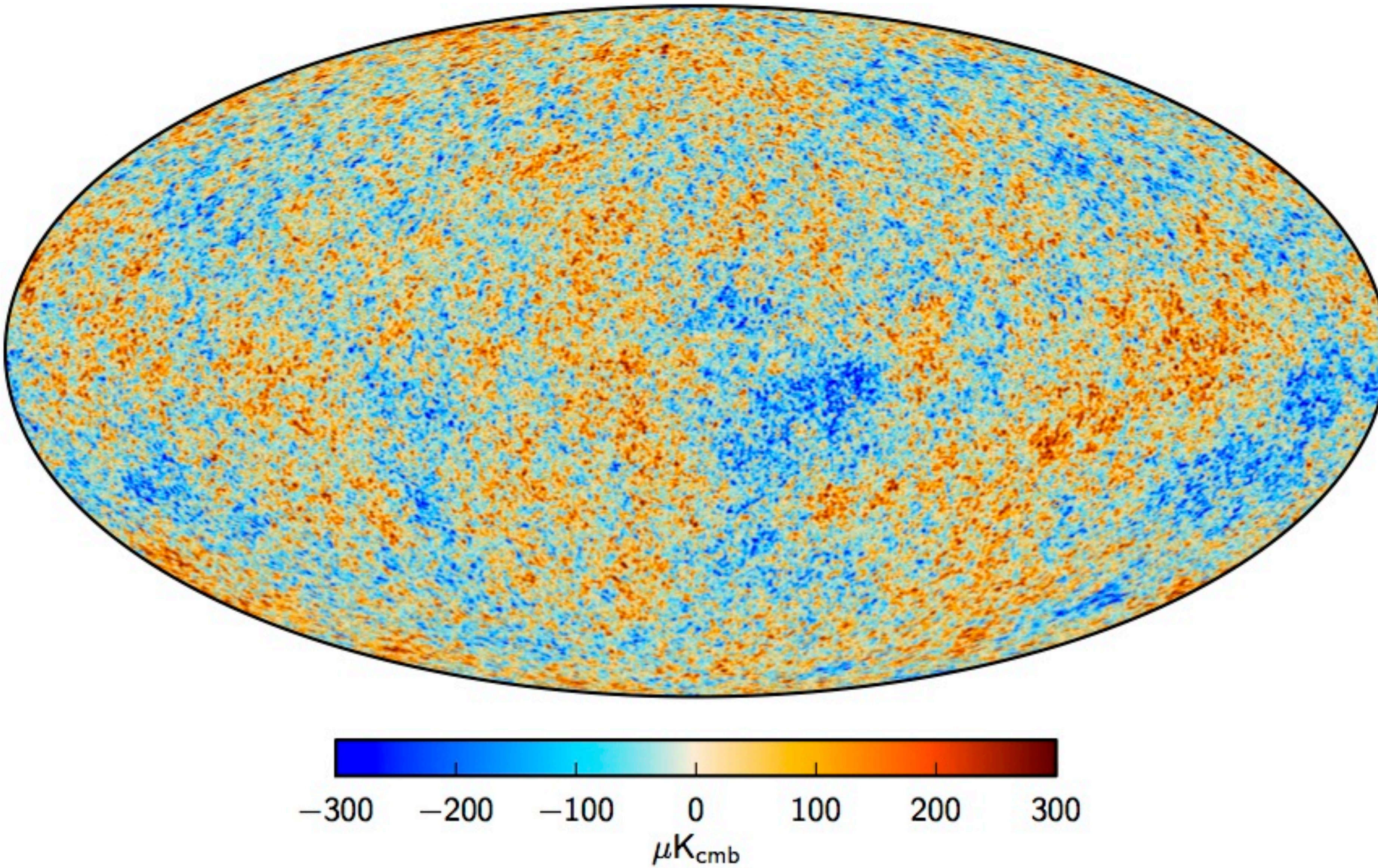


This is how the microwave sky actually looks like!

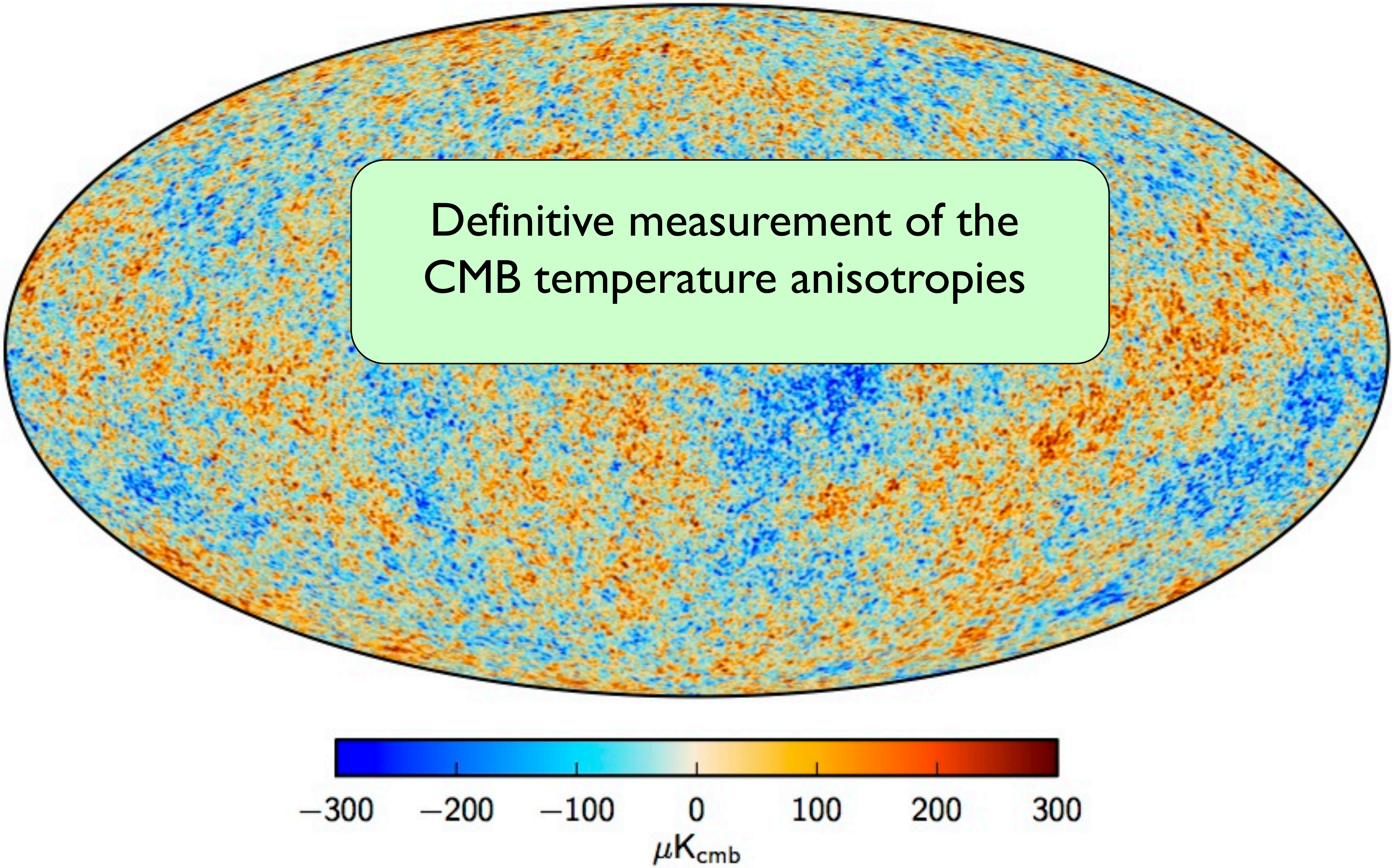
Frequency spectrum of RMS brightness temperature: CMB vs. astrophysical foregrounds



Planck: Temperature Anisotropies

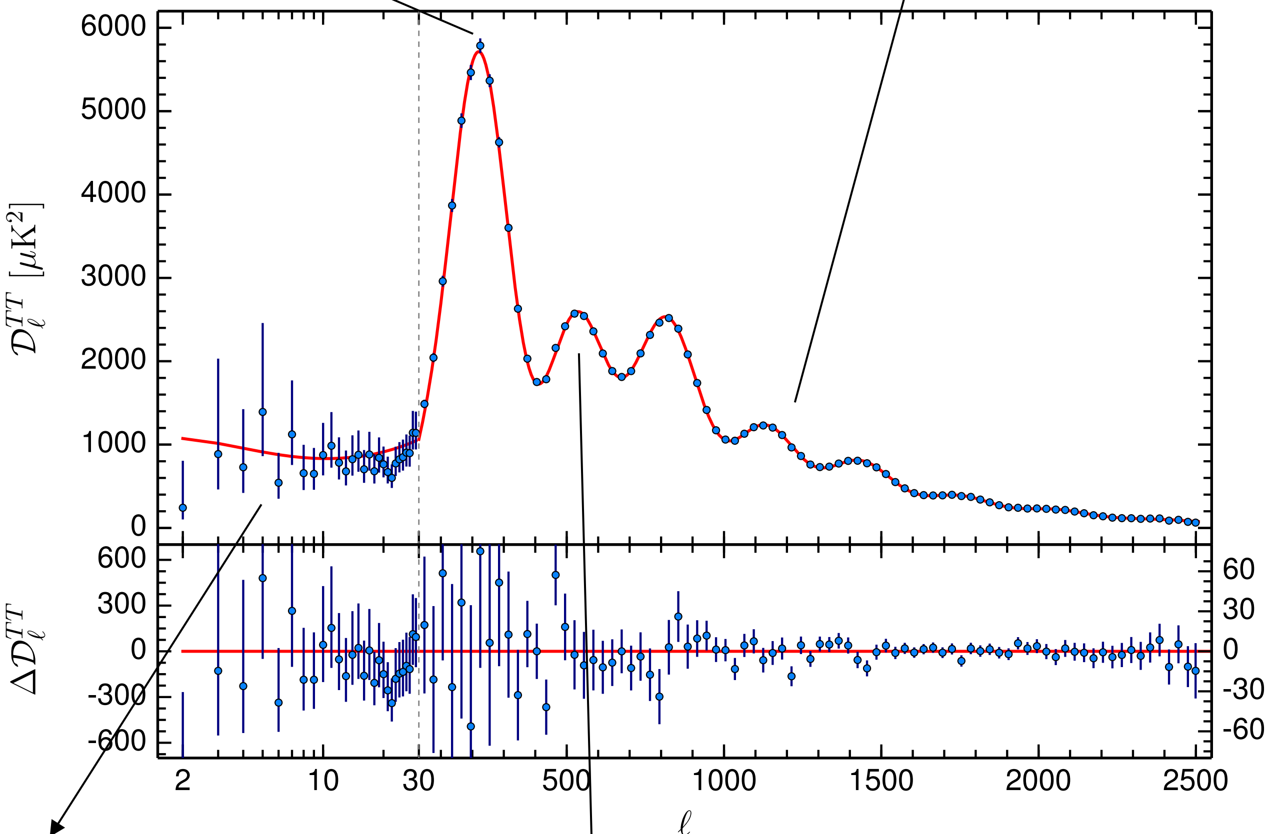


PLANCK: TEMPERATURE ANISOTROPIES



spatial curvature
relative abundance of matter and radiation
distance to the last scattering surface
$\mathbf{H_0}$, $\mathbf{\Omega_m}$, Ω_k

Photon diffusion length at recombination
Slope of the primordial spectrum
$\mathbf{N_{eff}}$, Ω_b, $\mathbf{Y_p}$, $\mathbf{n_s}$



+ Overall power
$\mathbf{A_s\, e^{-2\tau}}$

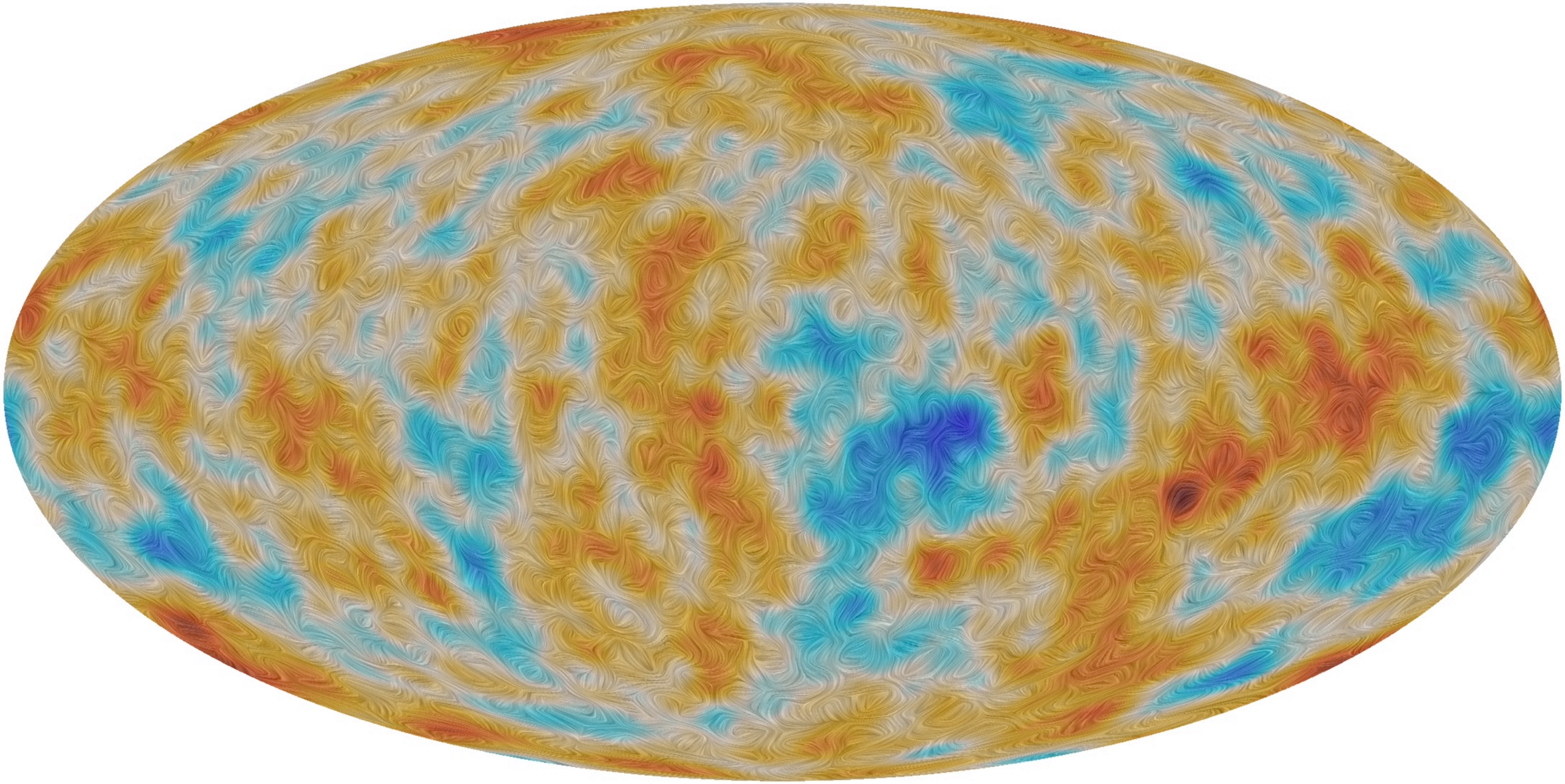
+ low-ell
polarization
(not shown)
Reionization
history
τ

Primordial power spectrum
late time expansion
$\mathbf{A_s}$, Ω_Λ

Baryon abundance
$\mathbf{\Omega_b}$

Planck 2015 XI

Planck 2015 Polarization map



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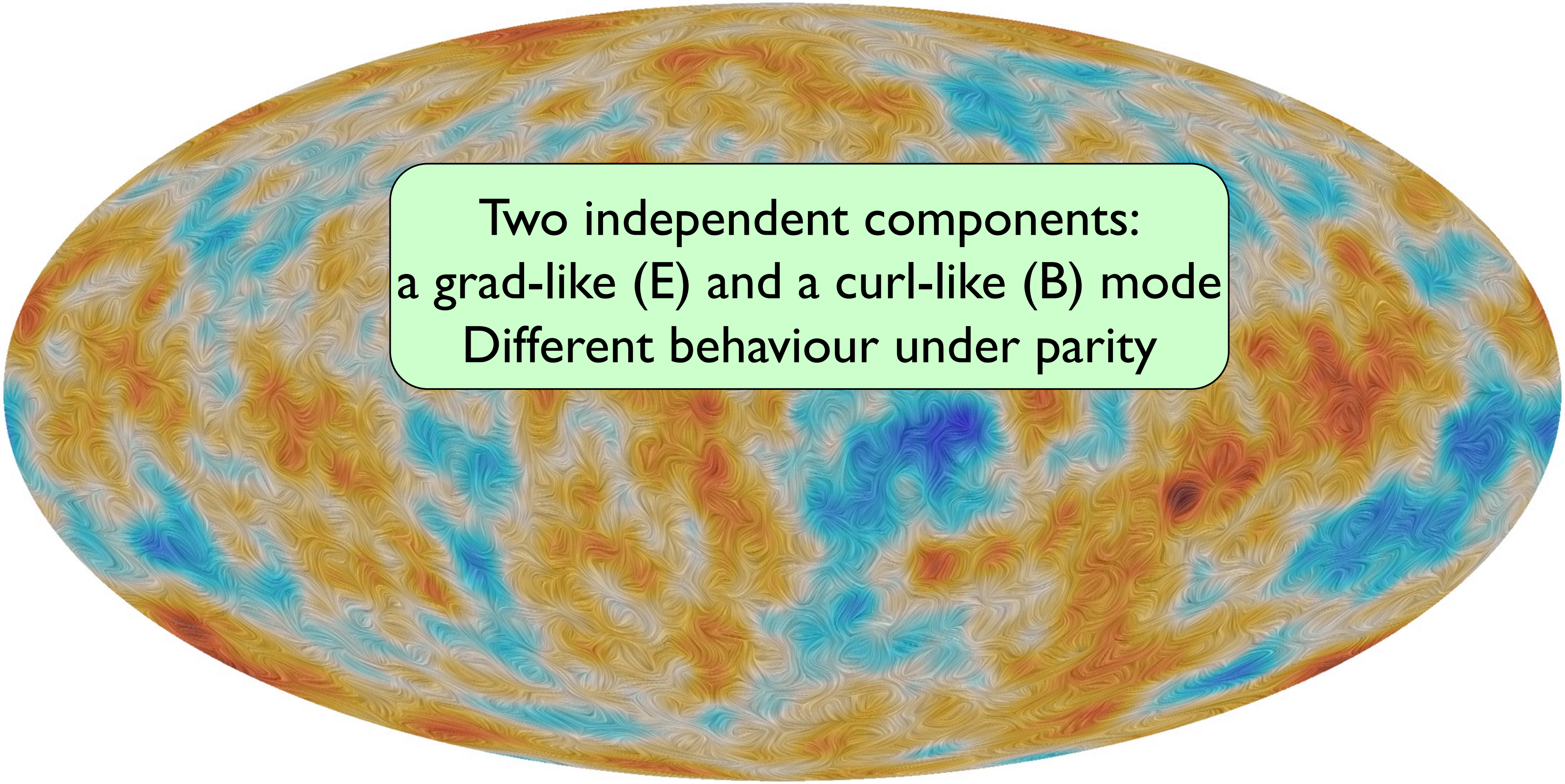

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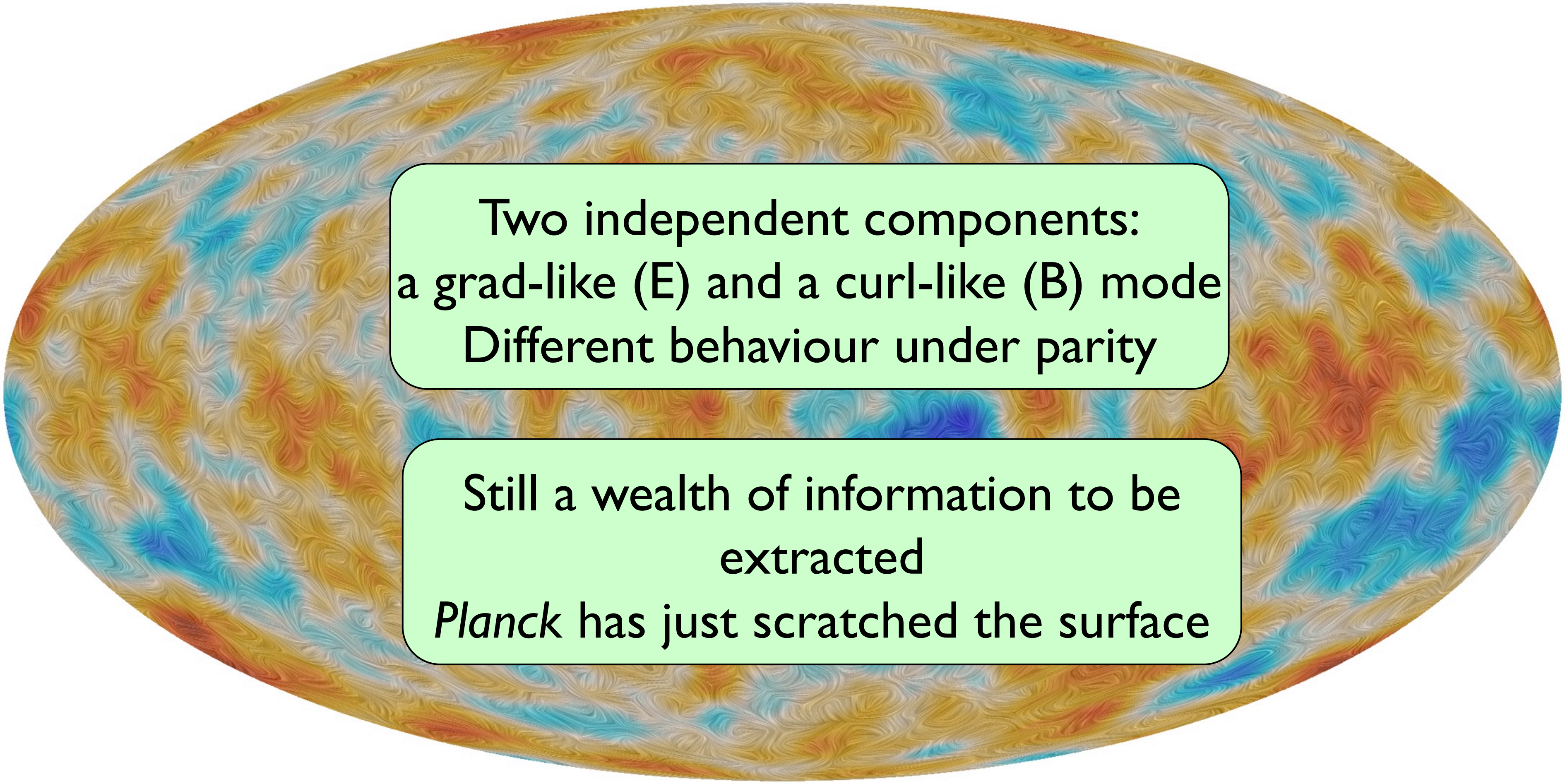
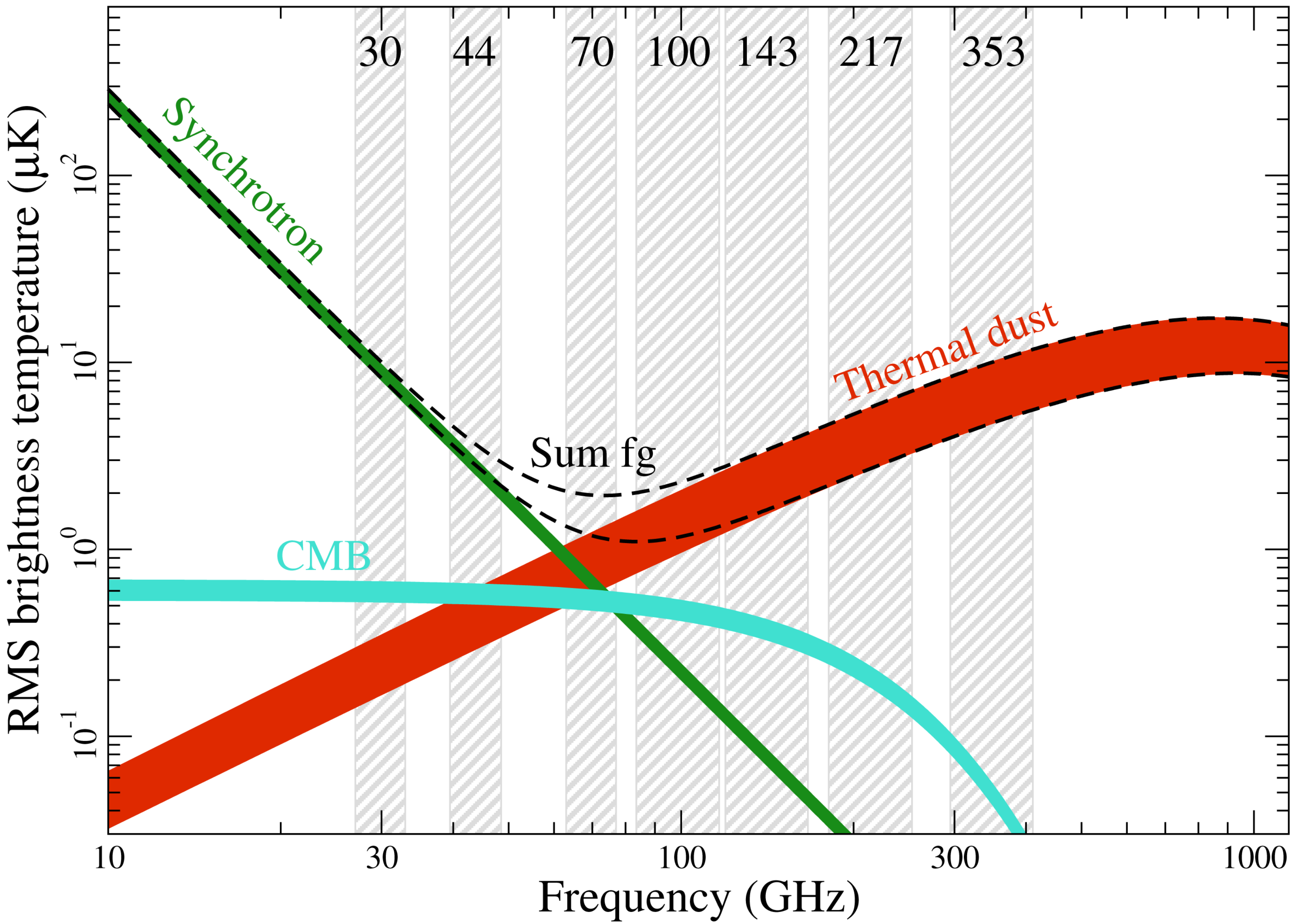


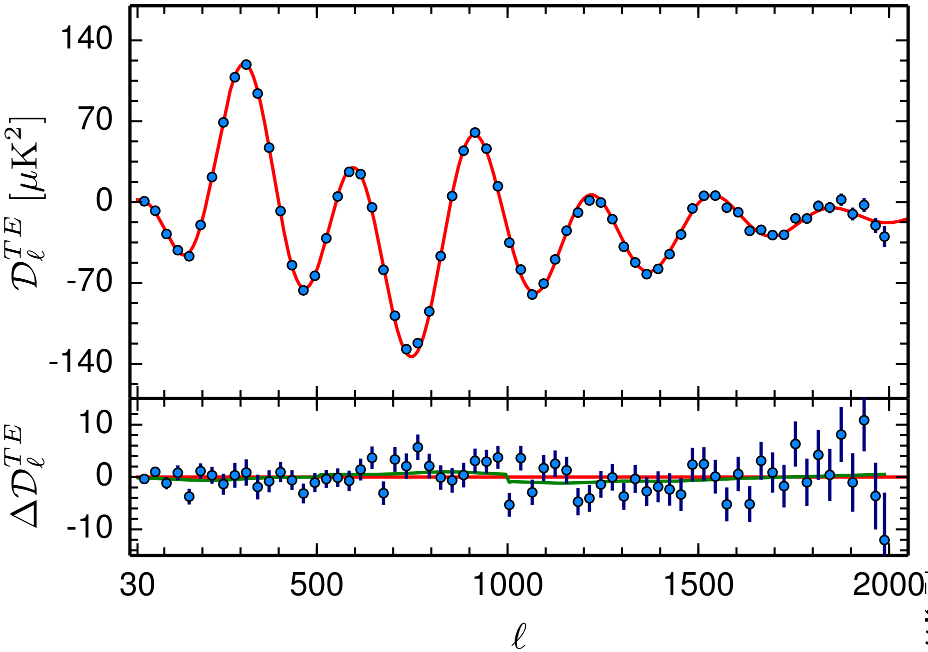
Two independent components:
a grad-like (E) and a curl-like (B) mode
Different behaviour under parity

Still a wealth of information to be extracted
Planck has just scratched the surface

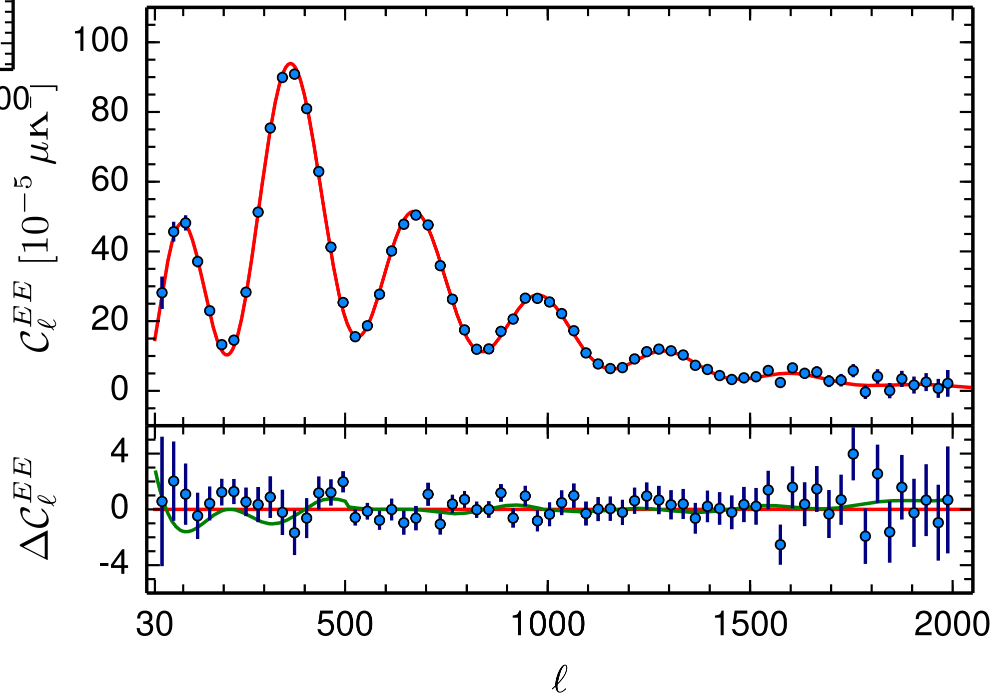
Frequency spectrum of RMS brightness polarization intensity: CMB vs. astrophysical foregrounds



TE and EE angular power spectra



Red curves are fitted to the TT spectrum only!! (without accounting for T to P leakage)



Green lines in the residuals are fits to the T-P leakage model

Planck 2015 XI

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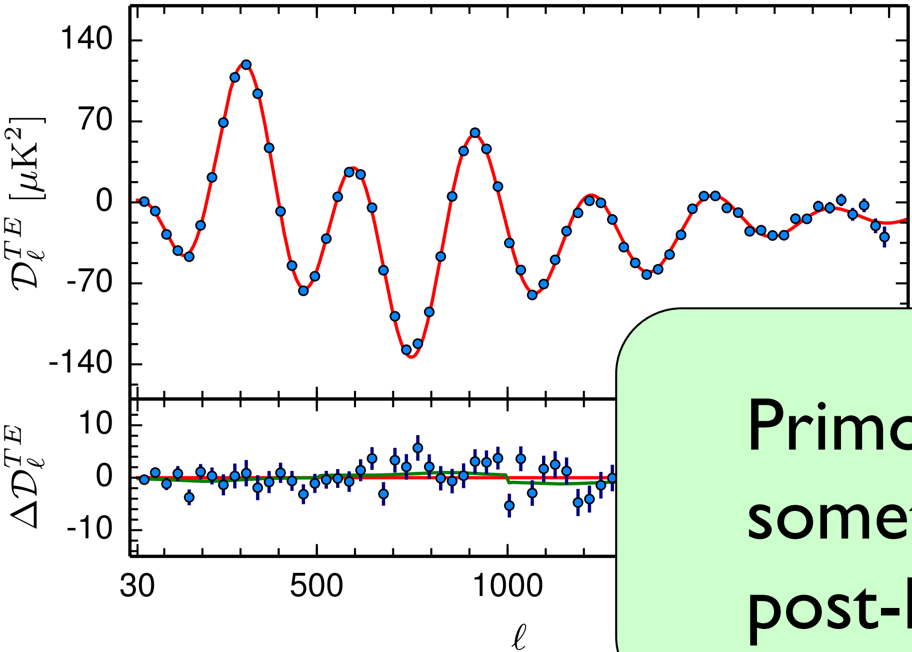

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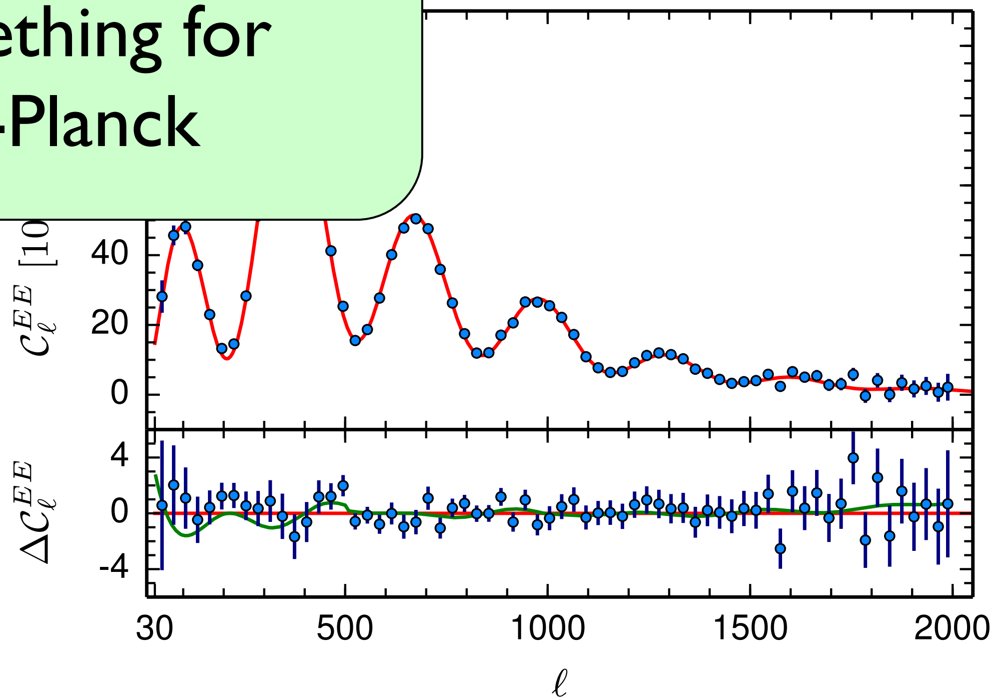
Primordial BB is something for post-Planck



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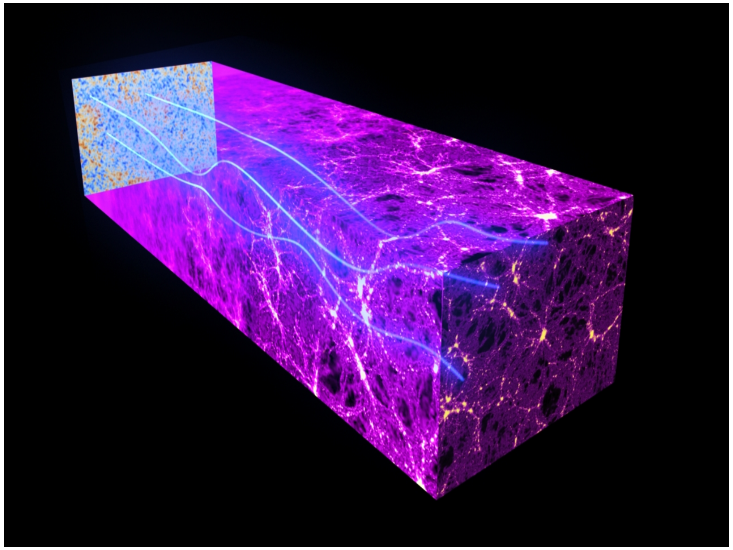
Planck 2015 XI

CMB is sensitive to the late-time density field, too….

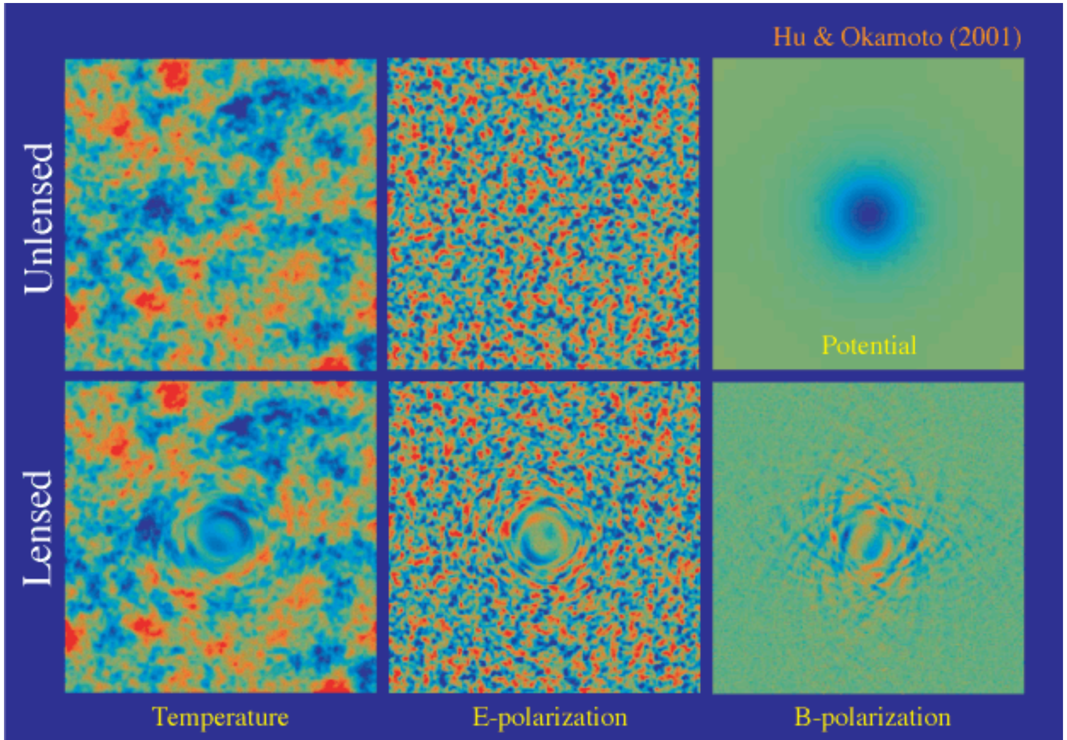


Line-of-sight integral of the gravitational potentials

$$\phi(\hat{n}) = -\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)$$

Deflection field

$$\vec{d} = \vec{\nabla}\phi$$



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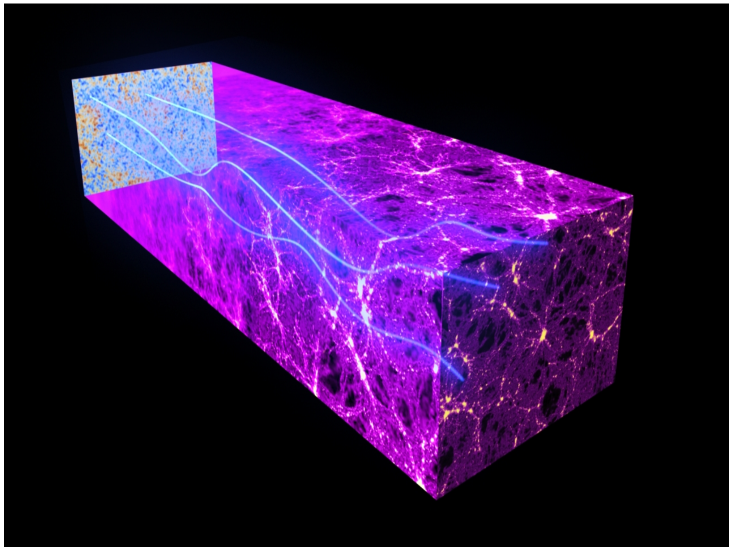

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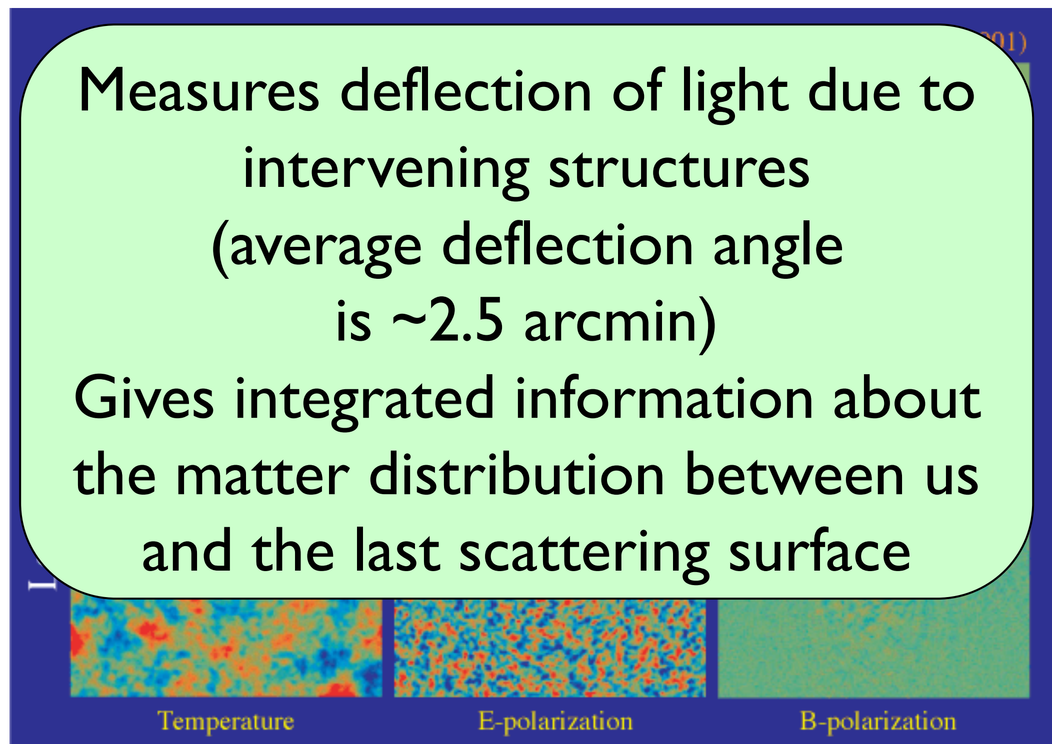
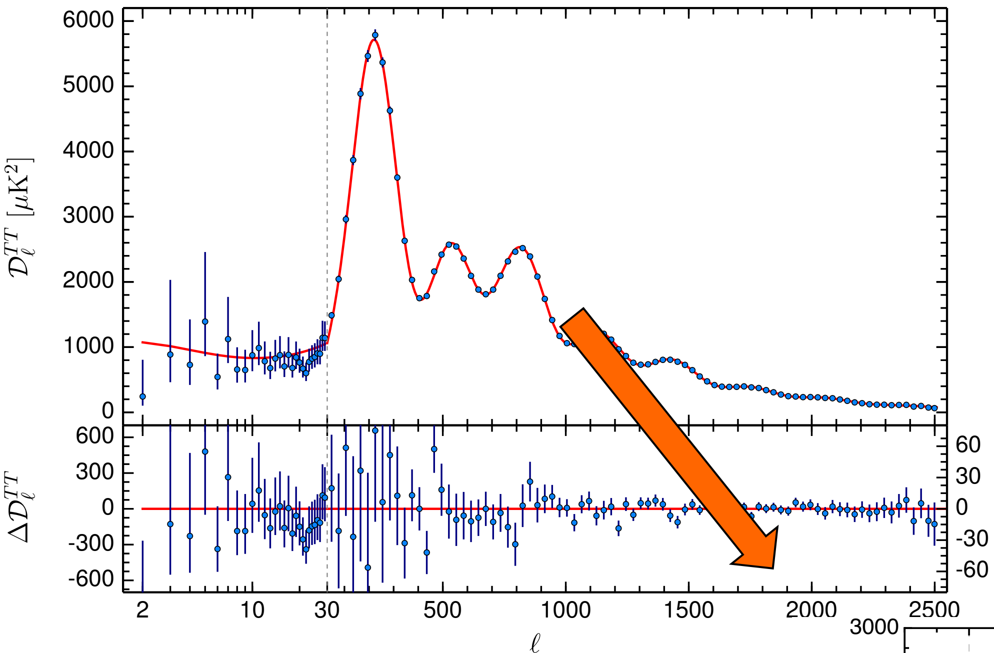
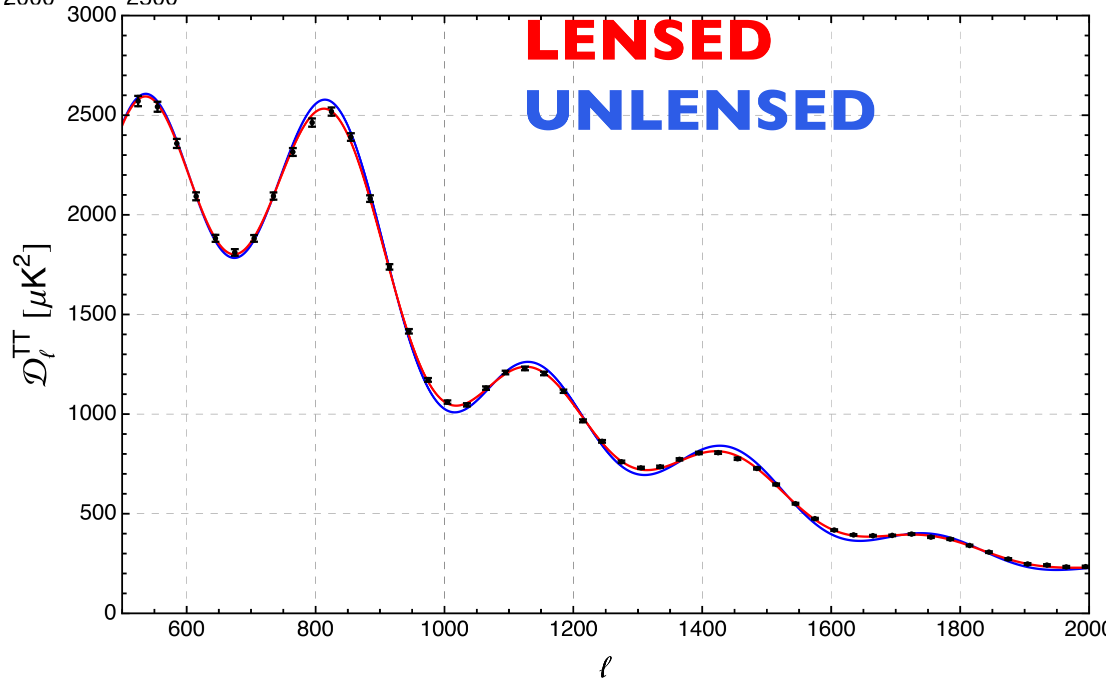


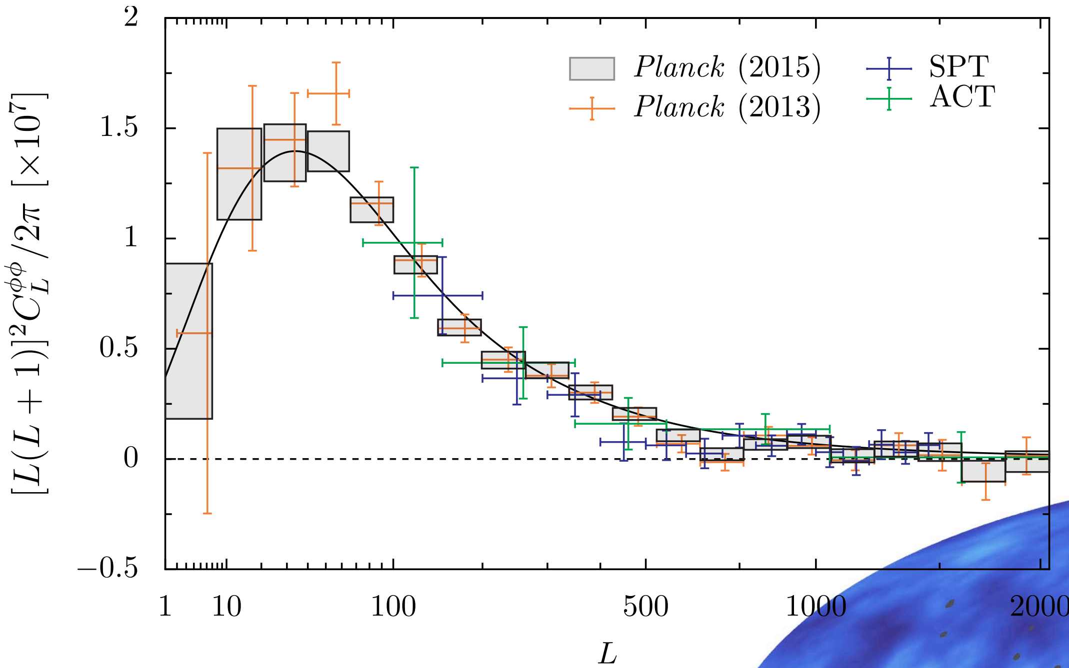
Measures deflection of light due to intervening structures
(average deflection angle is ~2.5 arcmin)
Gives integrated information about the matter distribution between us and the last scattering surface

Lensing smooths the peaks of the CMB power spectrum…
… and introduces nongaussianities in the map (nonzero 4-point c.f.)

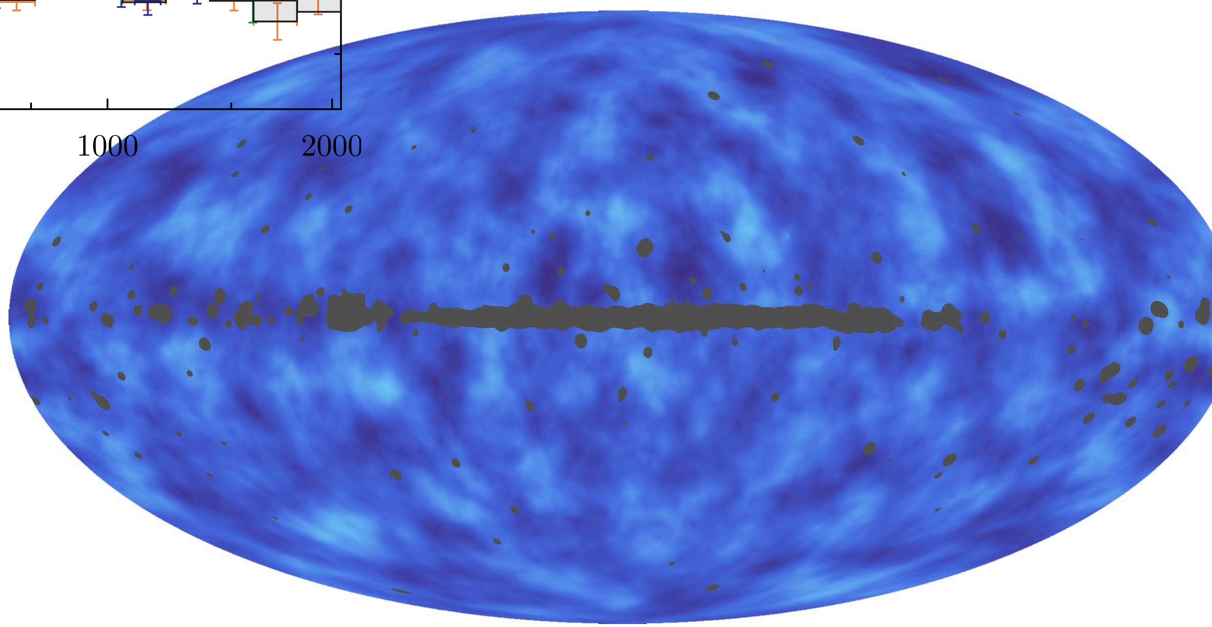




LENSING



Lensing potential estimated from the four-point correlation function



Planck 2015 XXV

LARGE SCALE STRUCTURES

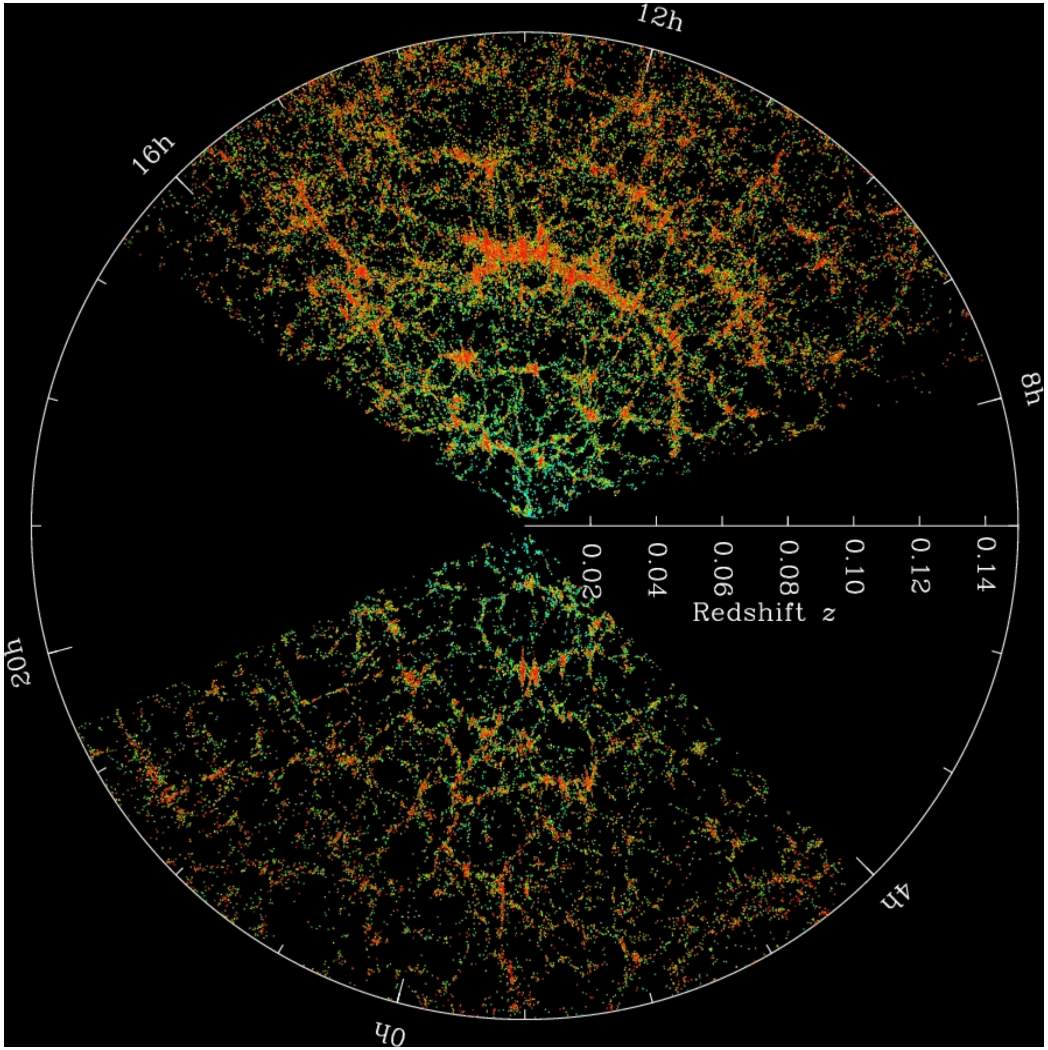
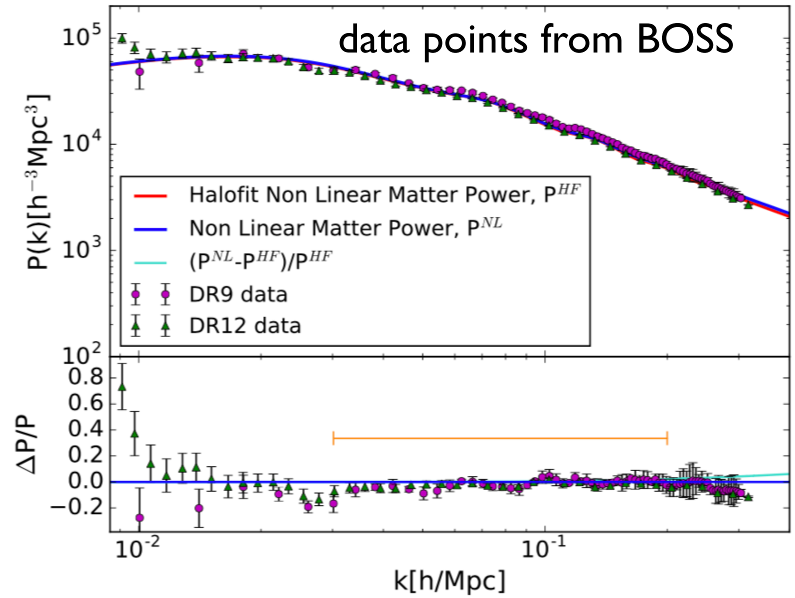
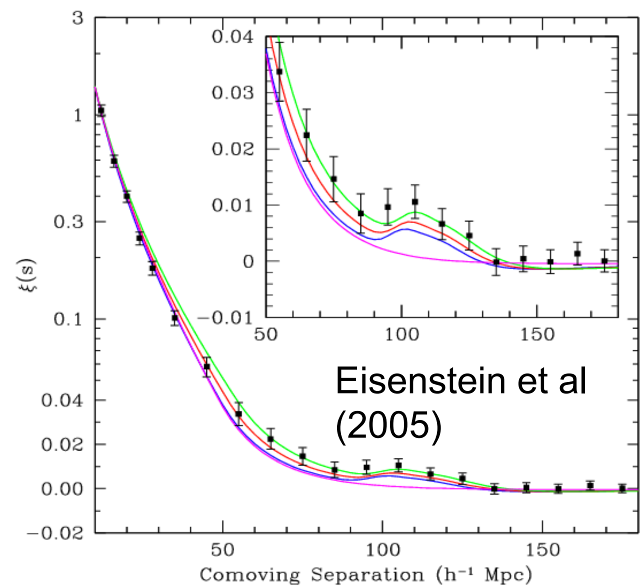


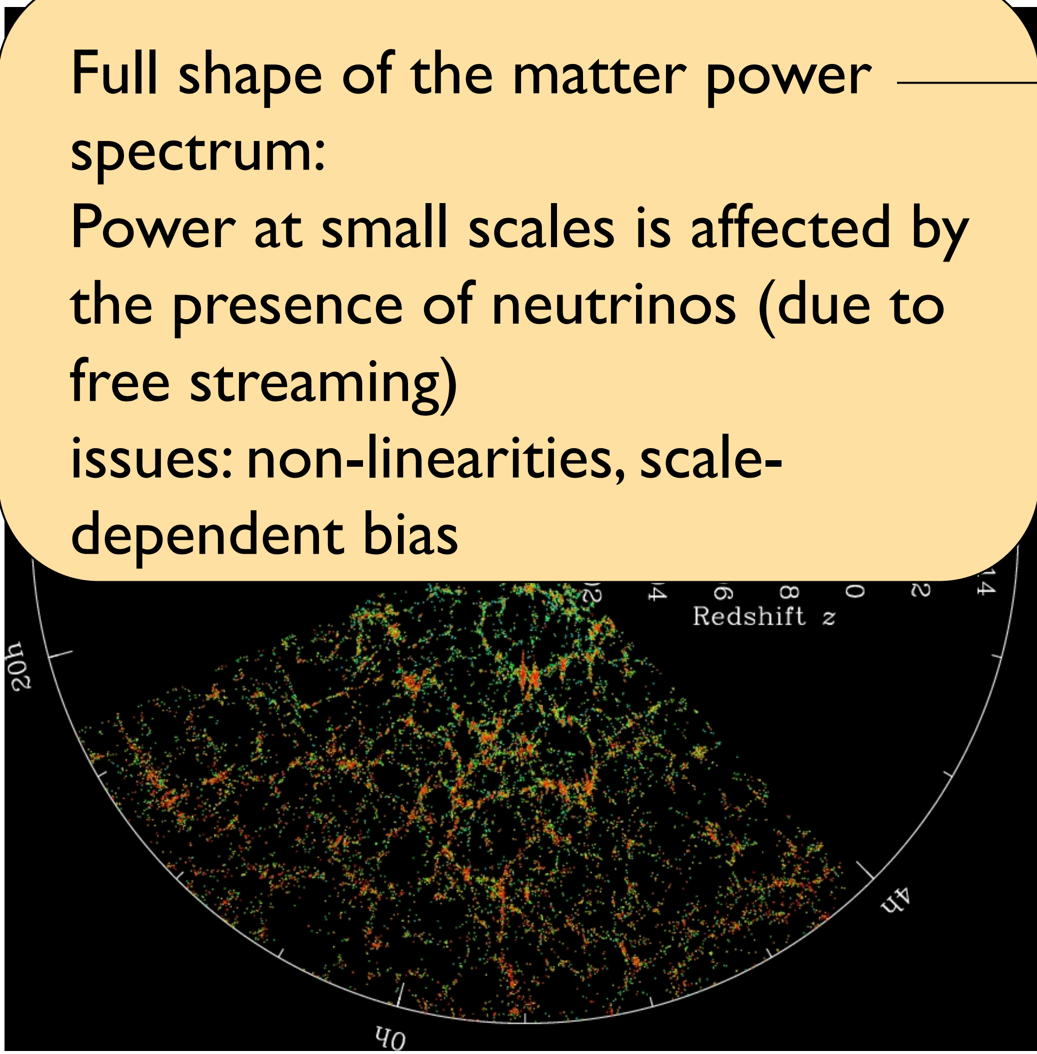
Image Credit: M. Blanton and the Sloan Digital Sky Survey.





LARGE SCALE STRUCTURES

Full shape of the matter power spectrum:
Power at small scales is affected by the presence of neutrinos (due to free streaming)
issues: non-linearities, scale-dependent bias



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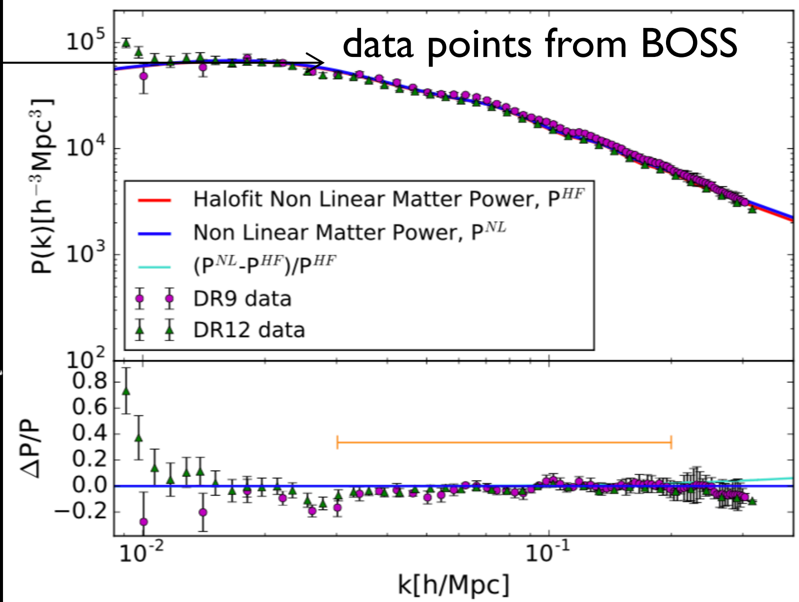

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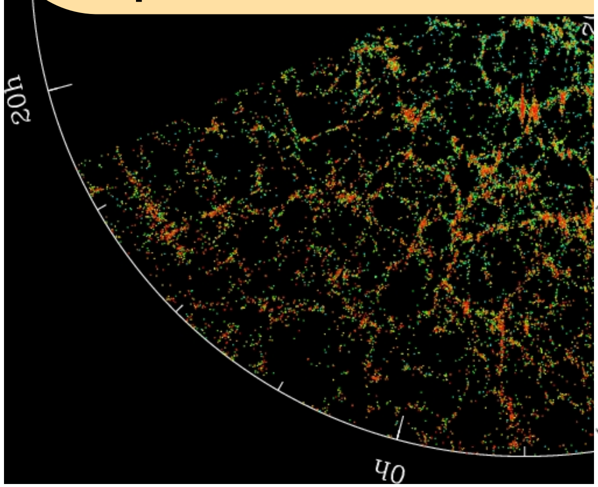

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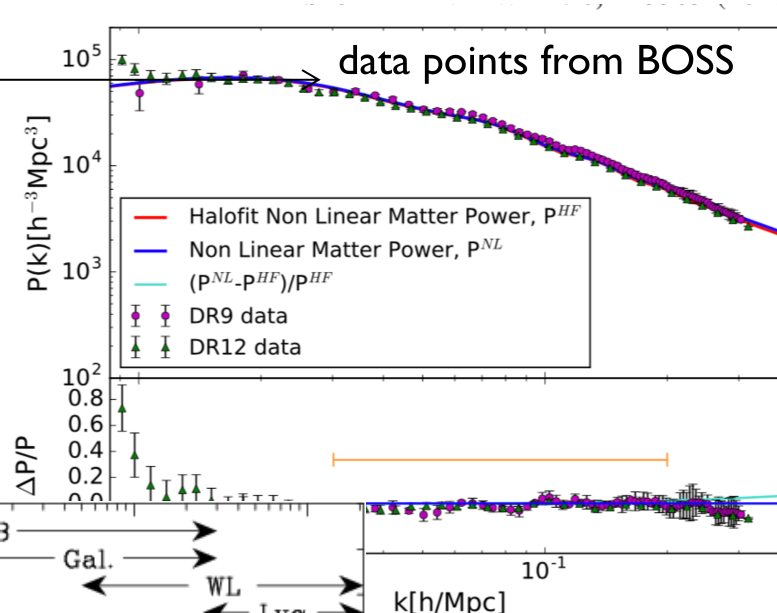
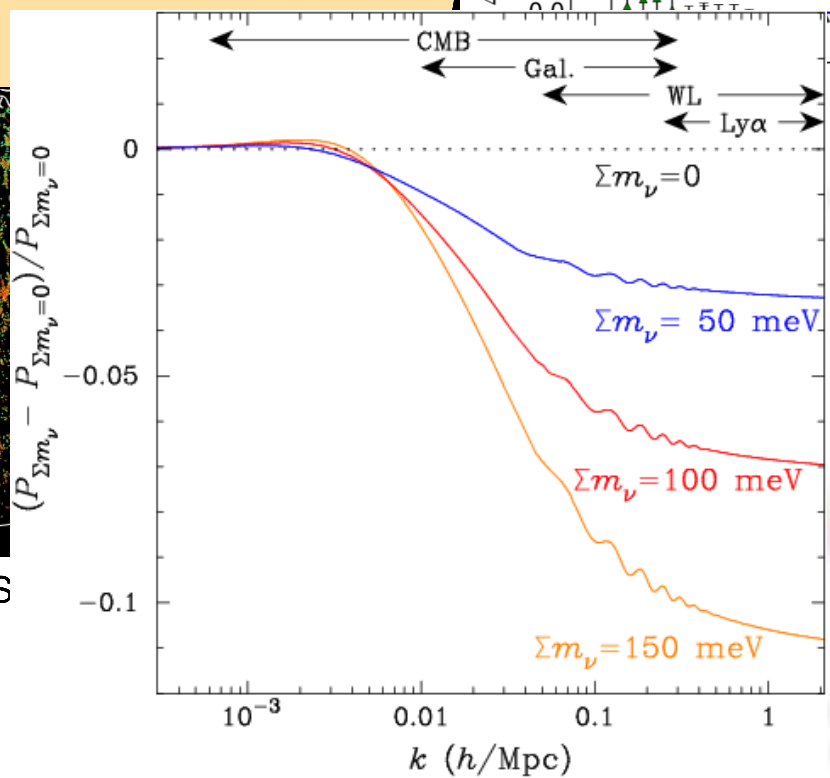
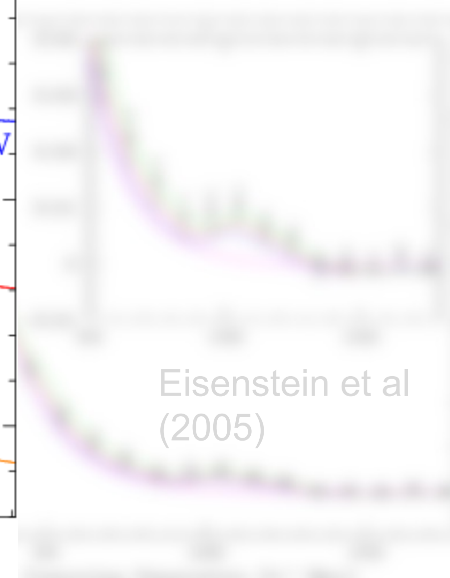




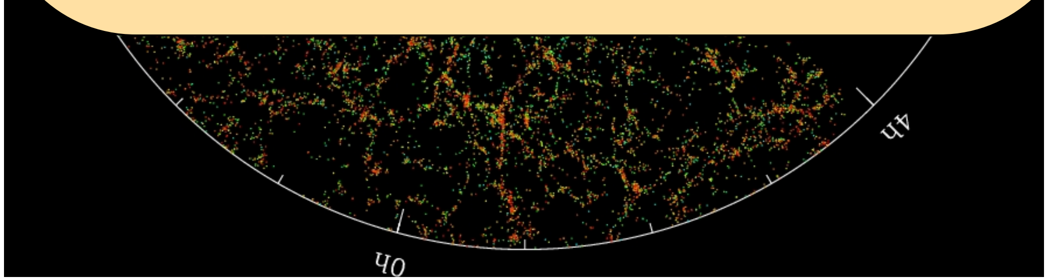


LARGE SCALE STRUCTURES

Baryon acoustic oscillations (BAO): Imprint of a characteristic scale (the sound horizon at the drag epoch) on the matter two-point CF

Standard ruler: BAO allow to constrain the expansion history and solve geometrical degeneracies

Less affected by systematics (e.g. nonlinear evolution)



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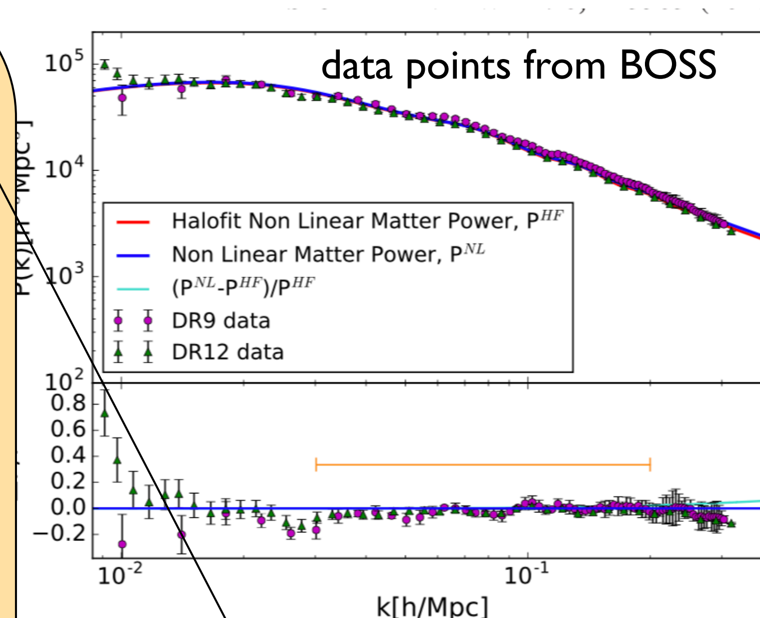
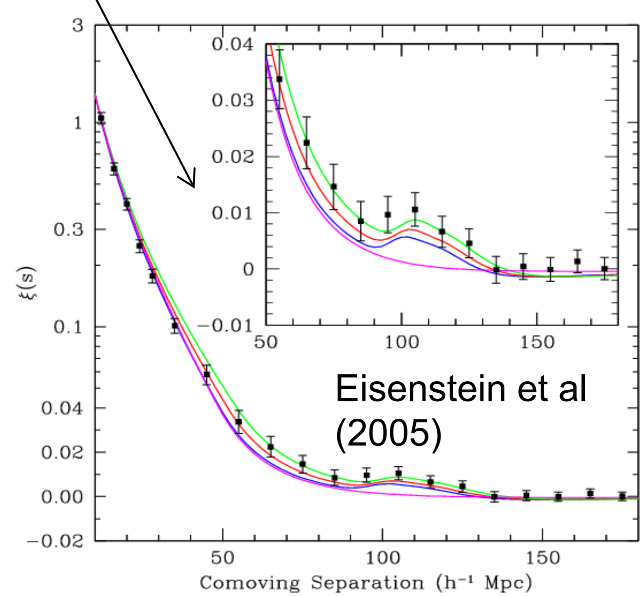
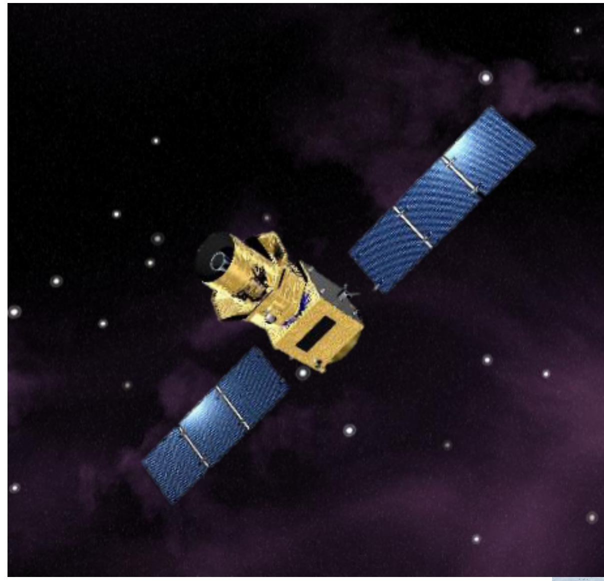




Future experiments



Future experiments

Satellites:
CORE, PIXIE, LITEBIRD

CORE (M5 proposal)**:**
2100 detectors
19 frequency channels
1.7 μK arcmin sensitivity in polarization
angular resolution between 20’ and 2’

Not funded for M5

FUTURE EXPERIMENTS

Ground-based:

Stage 2 & 3 (2016-2020) (~1-10k detectors):
SPT-3G, BICEP3, KECK Array, CLASS, Polarbear, Simons Array, AdvActPol

Stage 4 (2020-?):
~ 500k detectors
30-300GHz
~1 μK arcmin sensitivity over at least 70% of the sky
1 arcmin angular resolution or better

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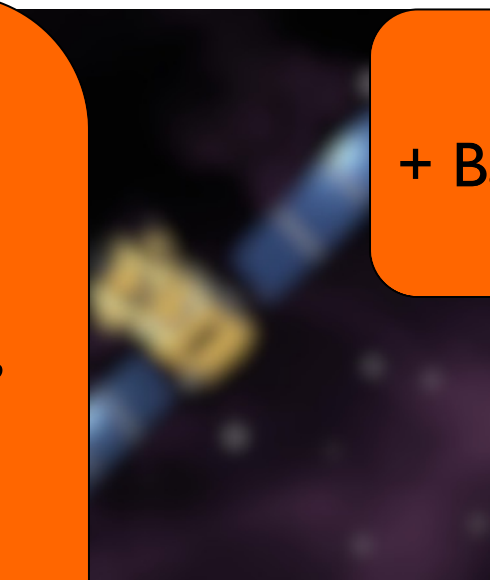
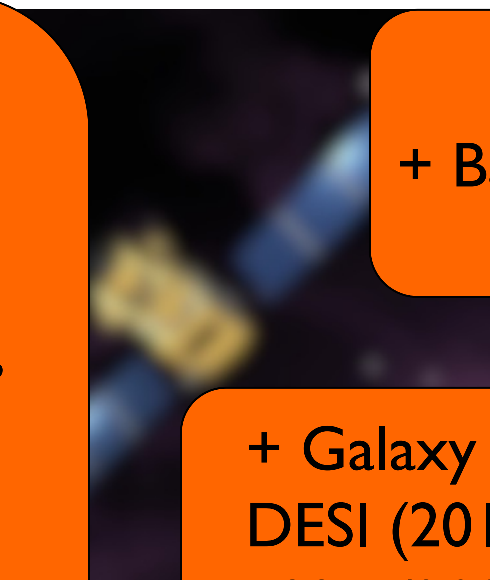
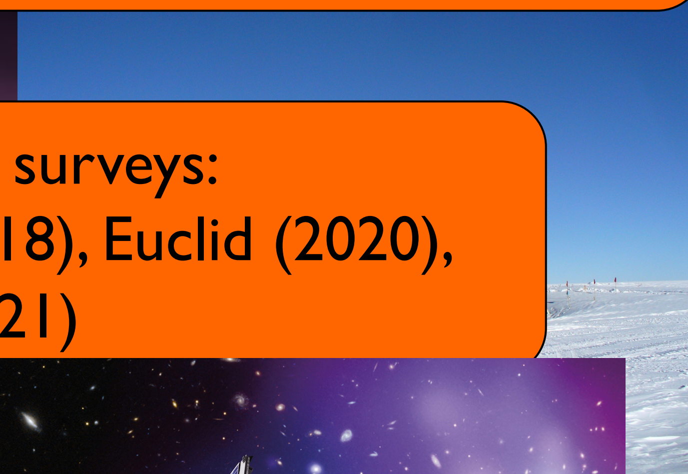
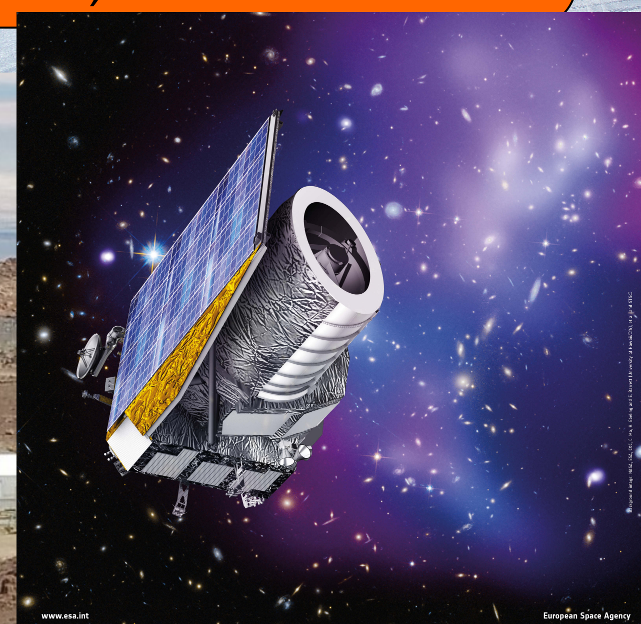


+ Balloon-borne, e.g. LSPE

Future experiments







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\+ Balloon-borne, e.g. LSPE

\+ Galaxy surveys:
DESI (2018), Euclid (2020), LSST (2021)

NEUTRINO COSMOLOGY

Base ΛCDM

Good fit to the data

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

-> Fully described by 6 parameters

Planck 2015 XIII

Base ΛCDM

Good fit to the data

High precision parameter estimates even better than 1%

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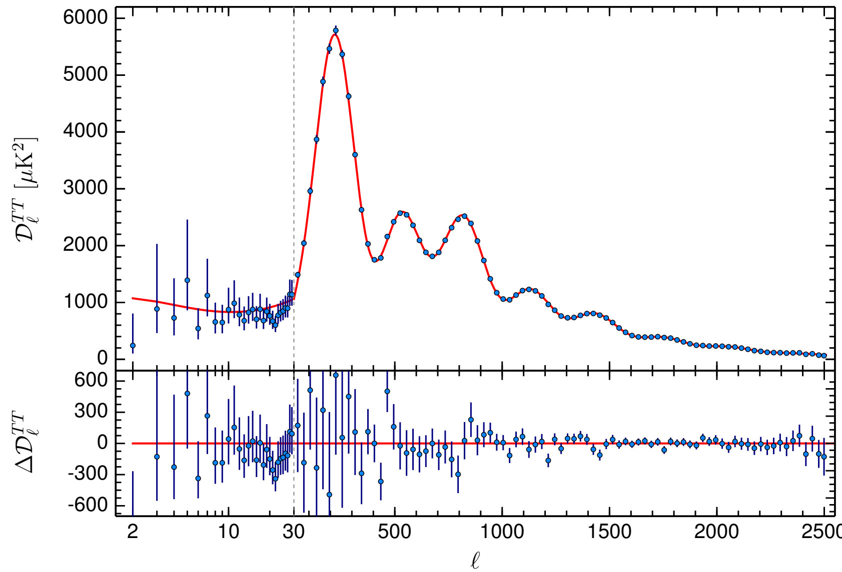
0.03% !!

Sub-% precision ~ 6 - 7σ from scale invariance -> Inflationary Paradigm

Improves on pre-Planck constraints by a factor 1.5 - 2

Planck 2015 XIII

In ΛCDM, the neutrino abundance (relative to the photons) is fixed by GR + SM

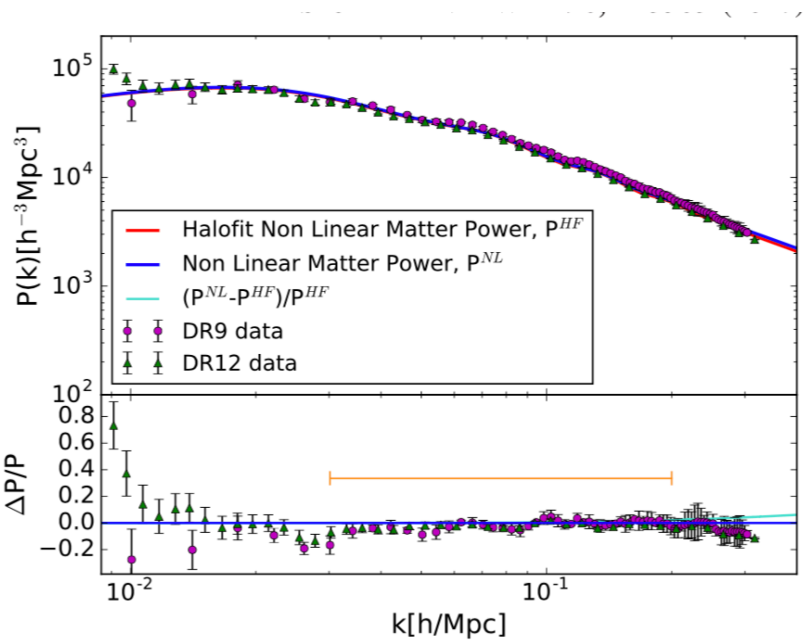


The only free parameter is

$$M_\nu = \Sigma m_i$$

that fixes the present energy density

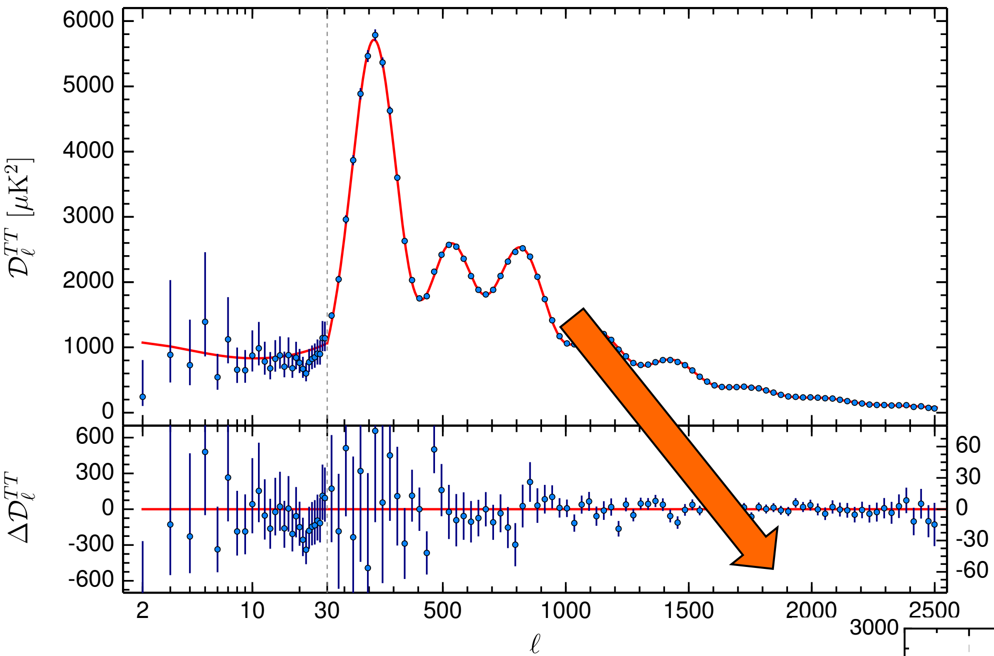
$$\Omega_\nu h^2 \equiv \frac{\rho_\nu}{\rho_c} h^2 = \frac{M_\nu}{93.14\,\mathrm{eV}}$$



The neutrino energy density affects the expansion history (for example changing the relative abundance of matter and radiation)

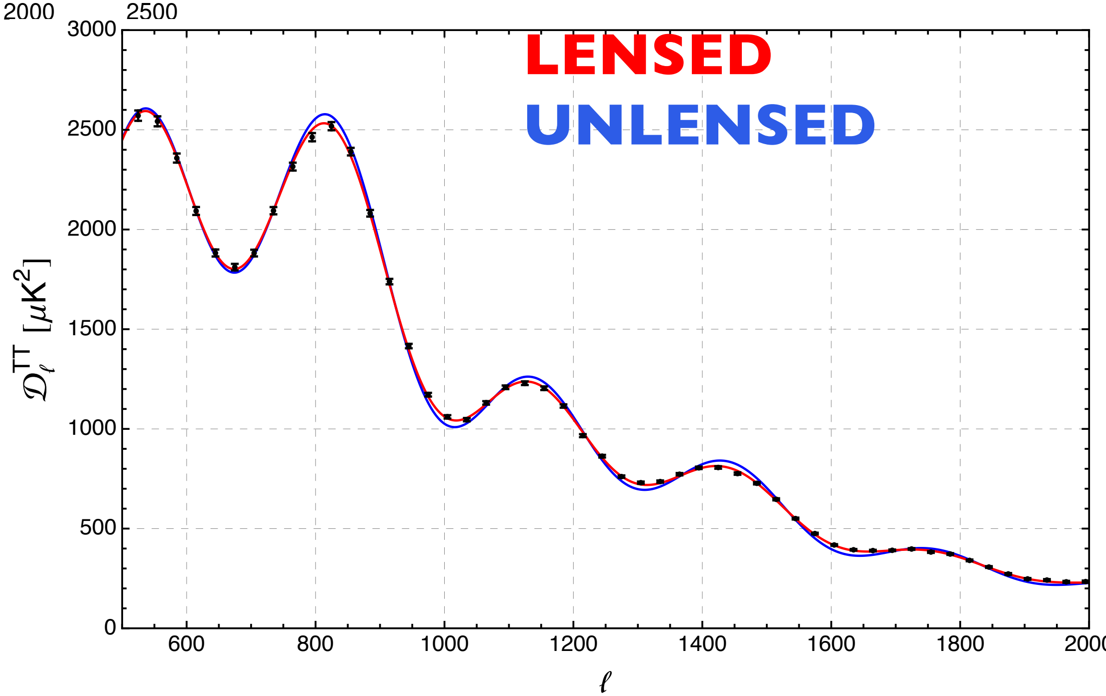
This can be however compensated by tweaking other parameters (e.g. the matter density or the present expansion rate)

Most of the cosmological information on neutrino masses comes from their peculiar effect on the evolution of matter perturbations (also seen in the CMB)



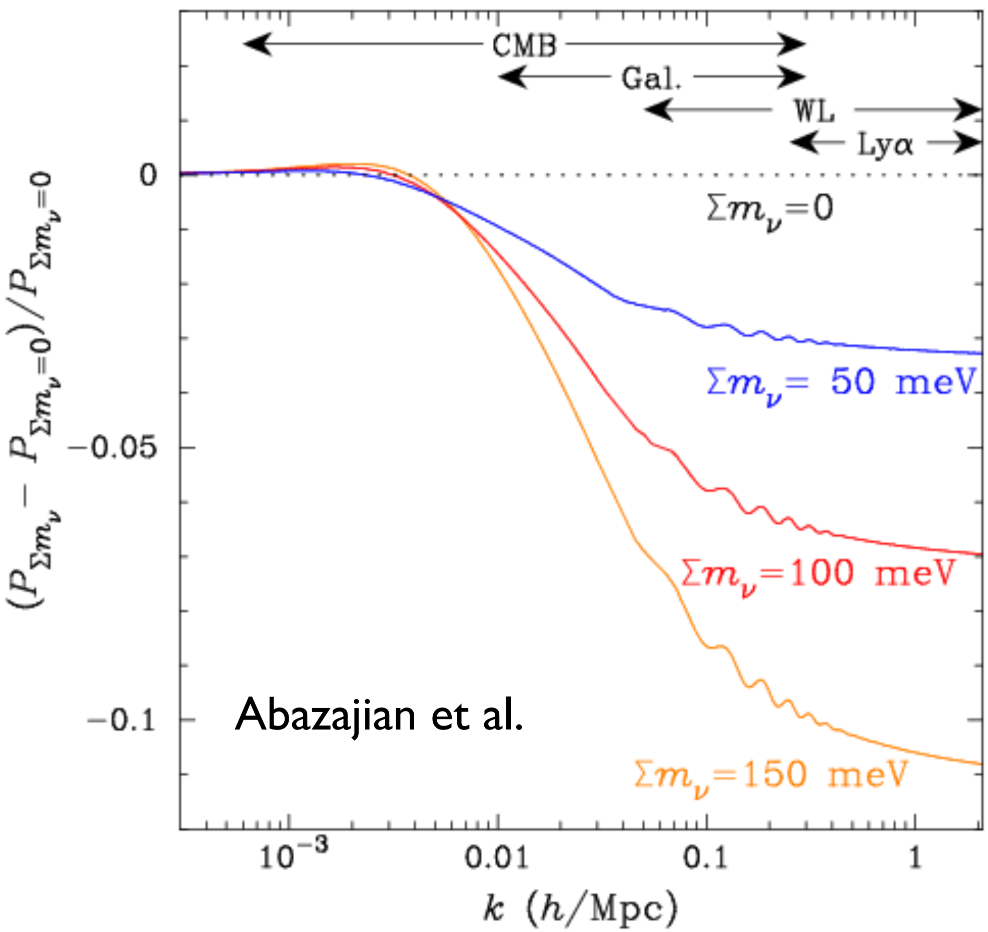
Lensing smooths the peaks of the CMB power spectrum…

… and introduces nongaussianities in the map (nonzero 4-point c.f.)



Neutrino free streaming damps matter perturbations and *reduces* lensing

The effect is proportional to ν energy density



In principle the effect can be seen directly in the matter power spectrum

There are issues however: non-linearities, scale-dependent bias……

In a Universe with neutrinos, small-scale density perturbations are suppressed due to collisionless damping (free-streaming).

Neutrinos are collisionless and have large thermal velocities (they have been relativistic for most of the history of the Universe).

They do not cluster below a critical scale, the free-streaming length (corresponding to the scale of the horizon at the time of the nonrelativistic transition).

At small scales:

$$\frac{P(M_\nu) - P(M_\nu = 0)}{P(M_\nu = 0)} = -8\frac{\Omega_\nu}{\Omega_m}$$

Cosmological constraints on neutrino masses in the ΛCDM model

Dataset	M_ν (95%CL)	Reference
PlanckTT+lowP	<0.72 eV	Planck 2015 XIII
PlanckTT+lowP+lensing	<0.68 eV	Planck 2015 XIII
PlanckTTTEE+lowP	<0.49 eV	Planck 2015 XIII
PlanckTT+lowP+BAO	<0.21 eV	Planck 2015 XIII
PlanckTT+lowP2016	<0.59 eV	Planck Int. Paper XLVI
PlanckTT+lowP+BAO+Pk (BOSS)	<0.16 eV	Alam et al (BOSS coll). 2017
PlanckTT+lowP+Lya	< 0.14 eV	Yéche et al. 2017
PlanckTT+lowP2016+BAO	< 0.15 eV	Vagnozzi et al. 2017
PlanckTT+lowP+BAO+SNIa + galaxy weak lensing	< 0.29 eV	Abbott et al. (DES coll.) 2017

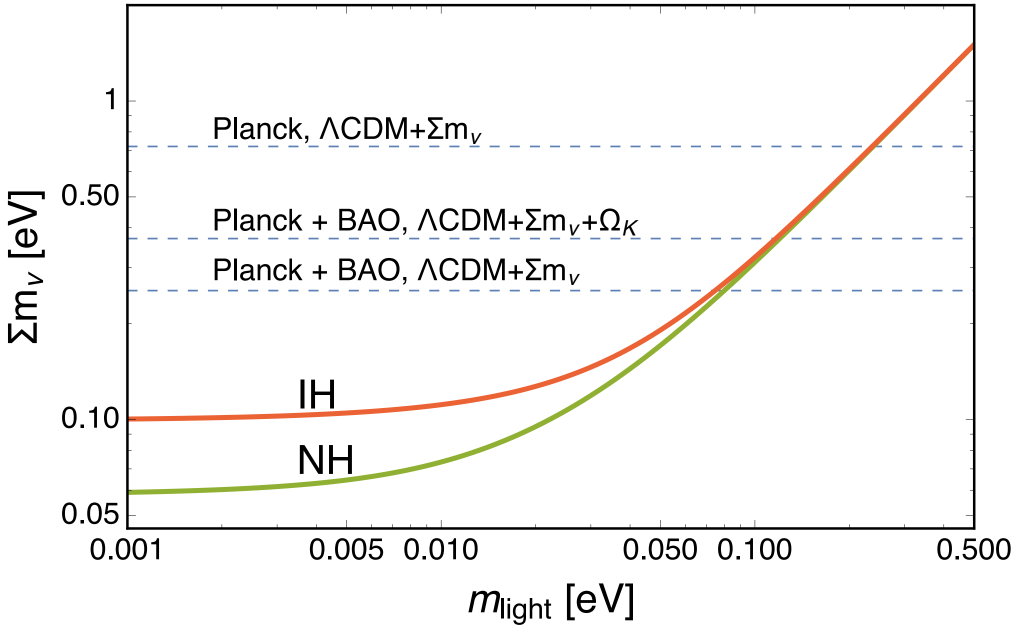
(see Gerbino & Lattanzi 2018 for a review)

The limits reported so far have been obtained in the framework of the standard flat ΛCDM model.
What happens when we give up some assumptions of the model?
Some examples (absolutely not exhaustive!) using PlanckTT+lowP+BAO(+lensing)

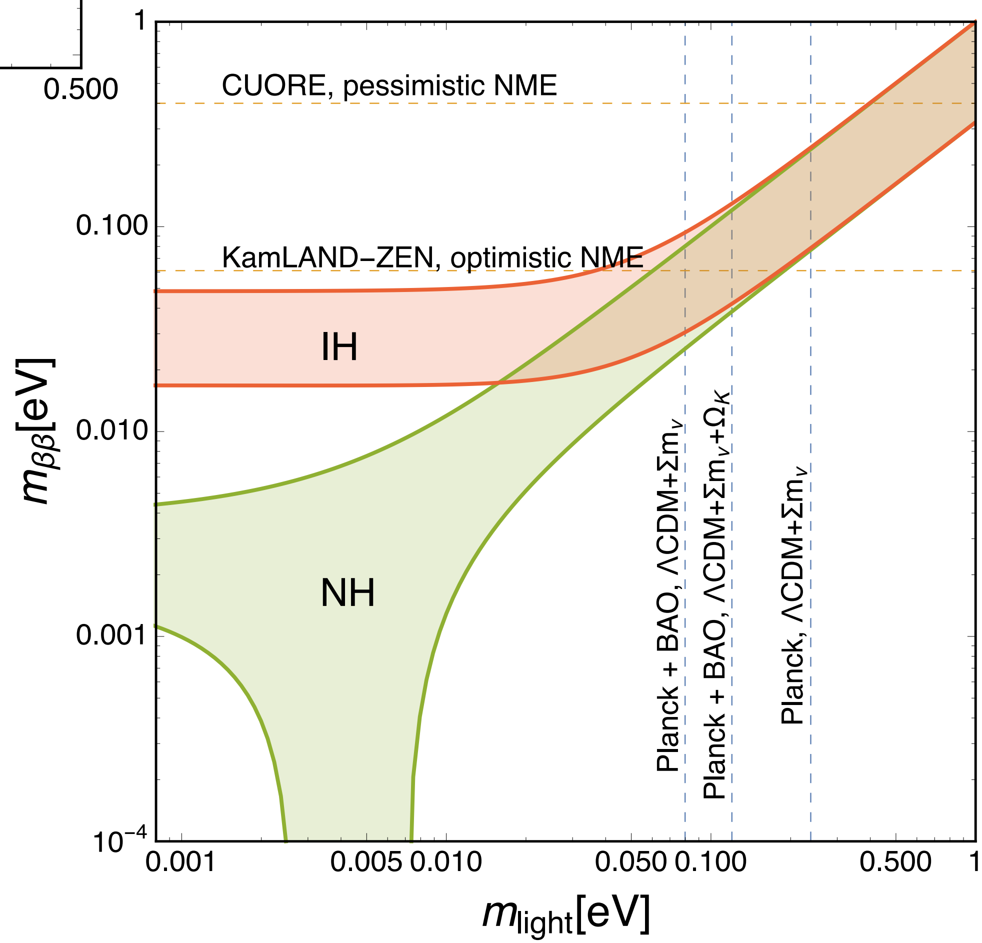
Model	M_ν (95%CL)	Reference
ΛCDM+M_ν	<0.21 eV	Planck 2015 E.S.
+ Curvature	<0.37 eV	Planck 2015 E.S.
+ Dark energy EOS	<0.37 eV	Planck 2015 E.S.
+ extra radiation	<0.32 eV	Planck 2015 E.S.
+ nonstandard lensing amp.	<0.41 eV	Planck 2015 E.S.
+ nonstandard PPS	< 0.26 eV	Di Valentino et al. 2016
+ extended ν parameter space	< 0.36 eV	Nunes & Bonilla 2017

(the last two rows do not use lensing; the last row uses HST)

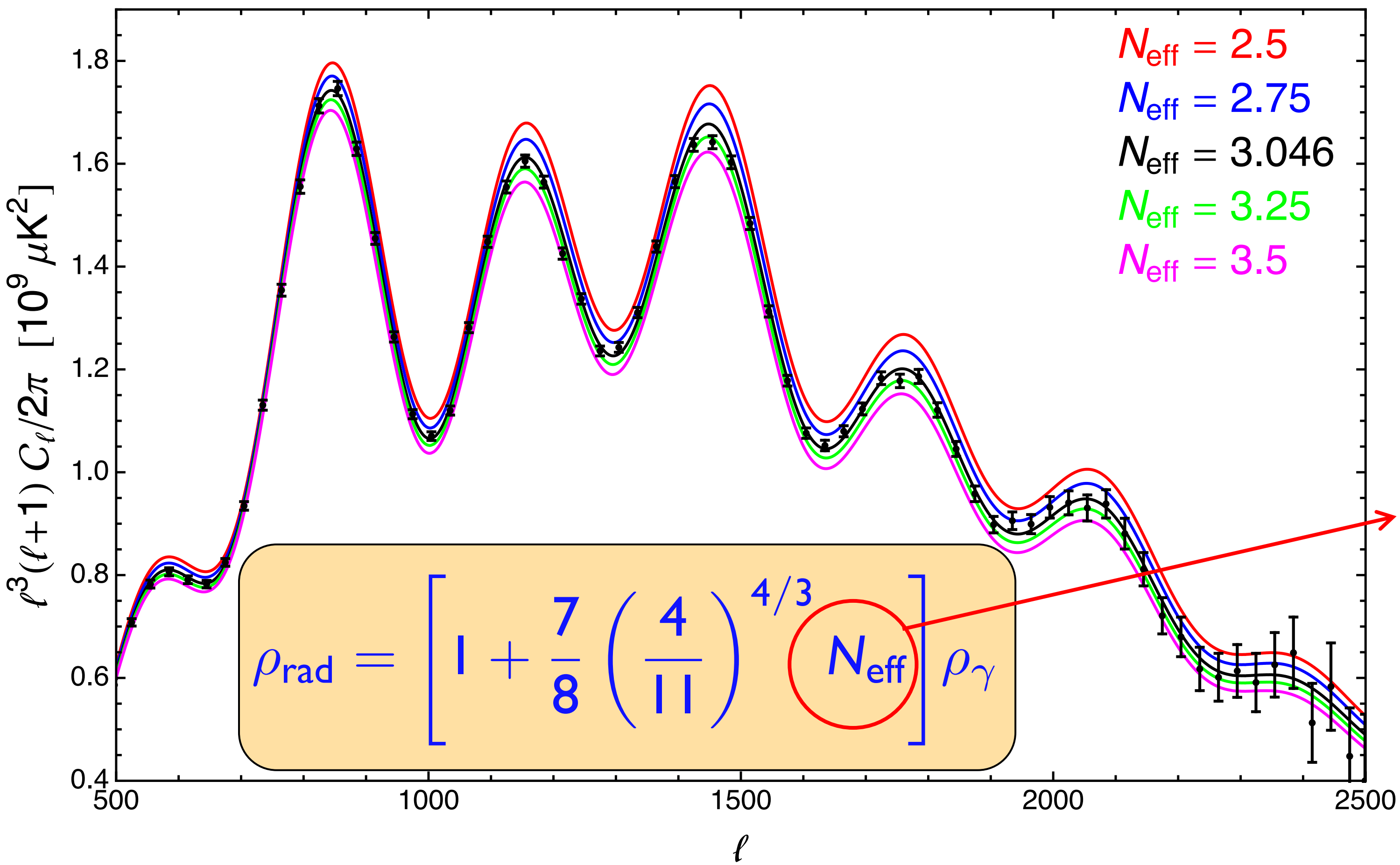
(in some particular models, limits can get tighter: see Vagnozzi et al 2017)



See E. Lisi's talk on Friday



Effective number of relativistic species



$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Due to non-instantaneous decoupling, the standard expectation is **$N_{\rm eff}$ = 3.046** (updated calculation gives $N_{\rm eff}$ = 3.045; see de Salas & Pastor 2016)

(note I am showing ~ $l^4 C_l$, not $l^2 C_l$)

A non-standard value for N_{eff} could be for example due to, :

- Presence of extra, light degrees of freedom: sterile neutrinos, axions, familons, majorons….
- Non-standard physics of neutrino decoupling (e.g., BSM neutrino interactions)
- Lepton asymmetry (non-zero chemical potential)
- Non-thermal active neutrinos (like e.g. in low-reheating scenarios

EFFECTIVE NUMBER OF NEUTRINO FAMILIES

Planck constraints on N_{eff} alone (can be regarded as a massless limit for the sterile)

$$N_{eff} = 3.13 \pm 0.32 \quad \text{(PlanckTT+lowP)}$$

$$N_{eff} = 3.15 \pm 0.23 \quad \text{(PlanckTT+lowP+BAO)}$$

$$N_{eff} = 2.99 \pm 0.20 \quad \text{(PlanckTT,TE,EE+lowP)}$$

$$N_{eff} = 3.04 \pm 0.18 \quad \text{(PlanckTT,TE,EE+lowP+BAO)}$$

(uncertainties are 68% CL)

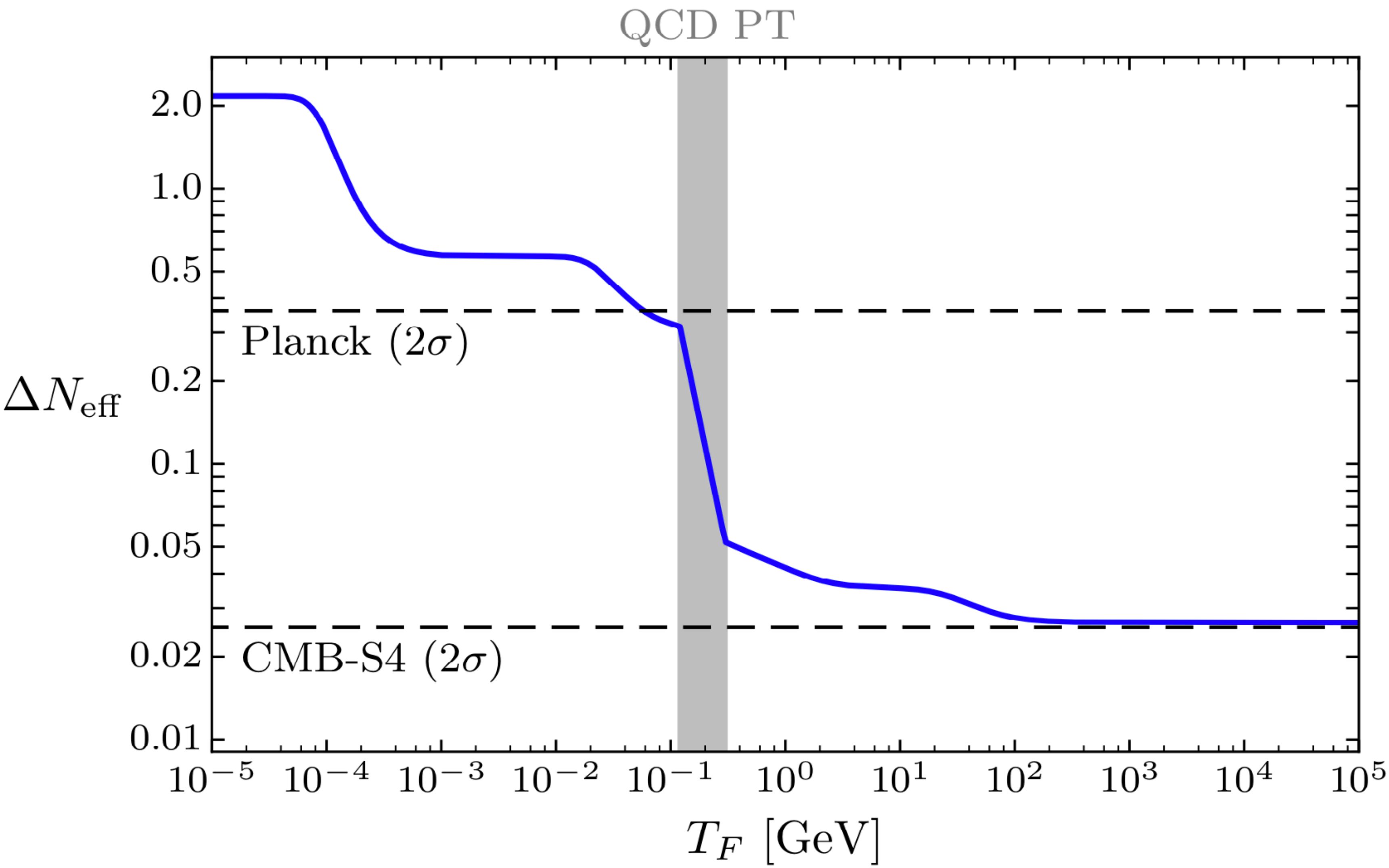
N_{eff} = 4 (i.e., one extra thermalized massless neutrino)
is excluded at between ~ 3 and 5 sigma.

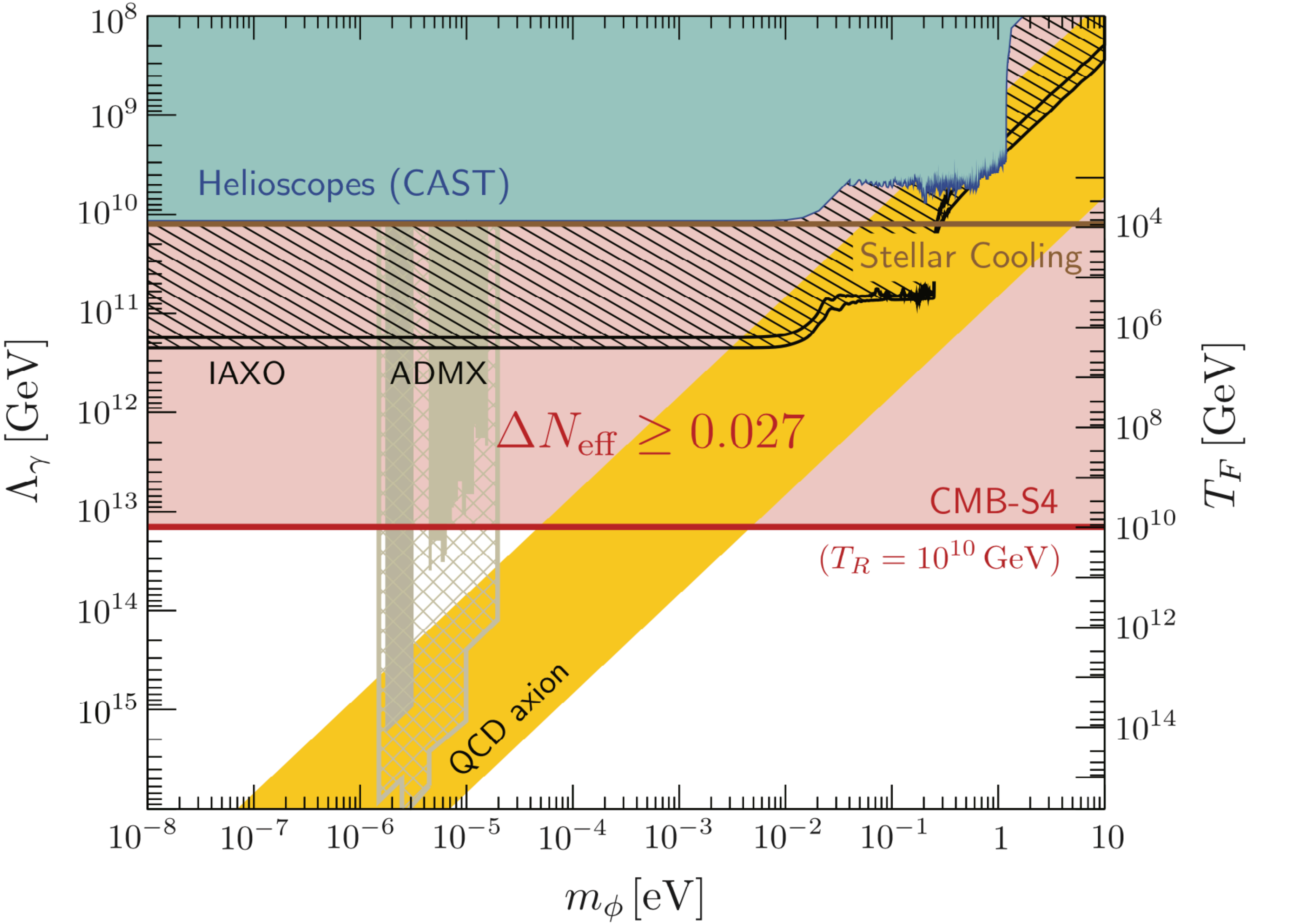
(Planck 2015 XIII)

Future prospects

	$\sigma(M_\nu)$ [meV]	$\sigma(N_{eff})$
CMB Stage IV	45	0.021
CMB Stage IV + DESI BAO	16	0.020
Planck + Euclid	25 - 30	-
CORE	44	0.04
CORE + LSS	15 - 20	0.04

Future observations will have the sensitivity to detect thermal relics up to arbitrarily high decoupling temperatures (Baumann, Green, Wallisch 2017)

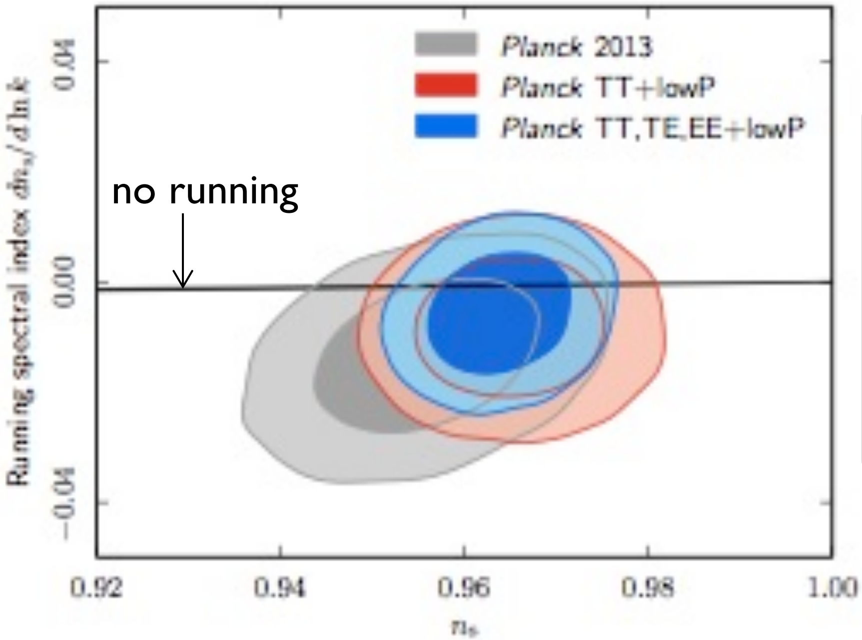




Helioscopes (CAST)
Stellar Cooling
IAXO
ADMX
$\Delta N_{\rm eff} \geq 0.027$
CMB-S4
$(T_R = 10^{10}\ \mathrm{GeV})$
QCD axion
Λ_γ [GeV]
T_F [GeV]
m_ϕ [eV]
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10

LARGE-SCALE ANOMALIES

INFLATION

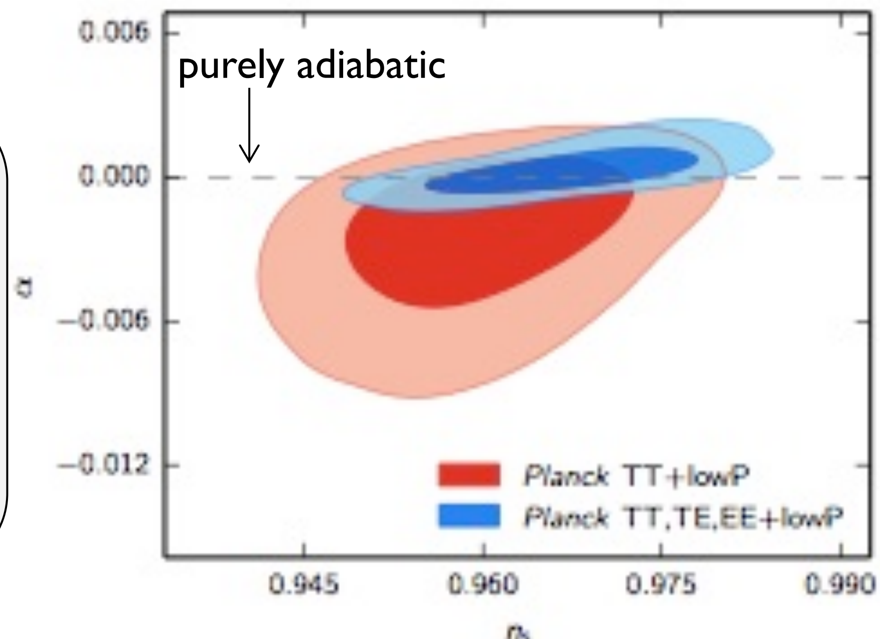


Planck data are consistent with purely adiabatic initial scalar pertubations with a nearly scale-invariant power-law spectrum

Consistent with single-field slow-roll inflation

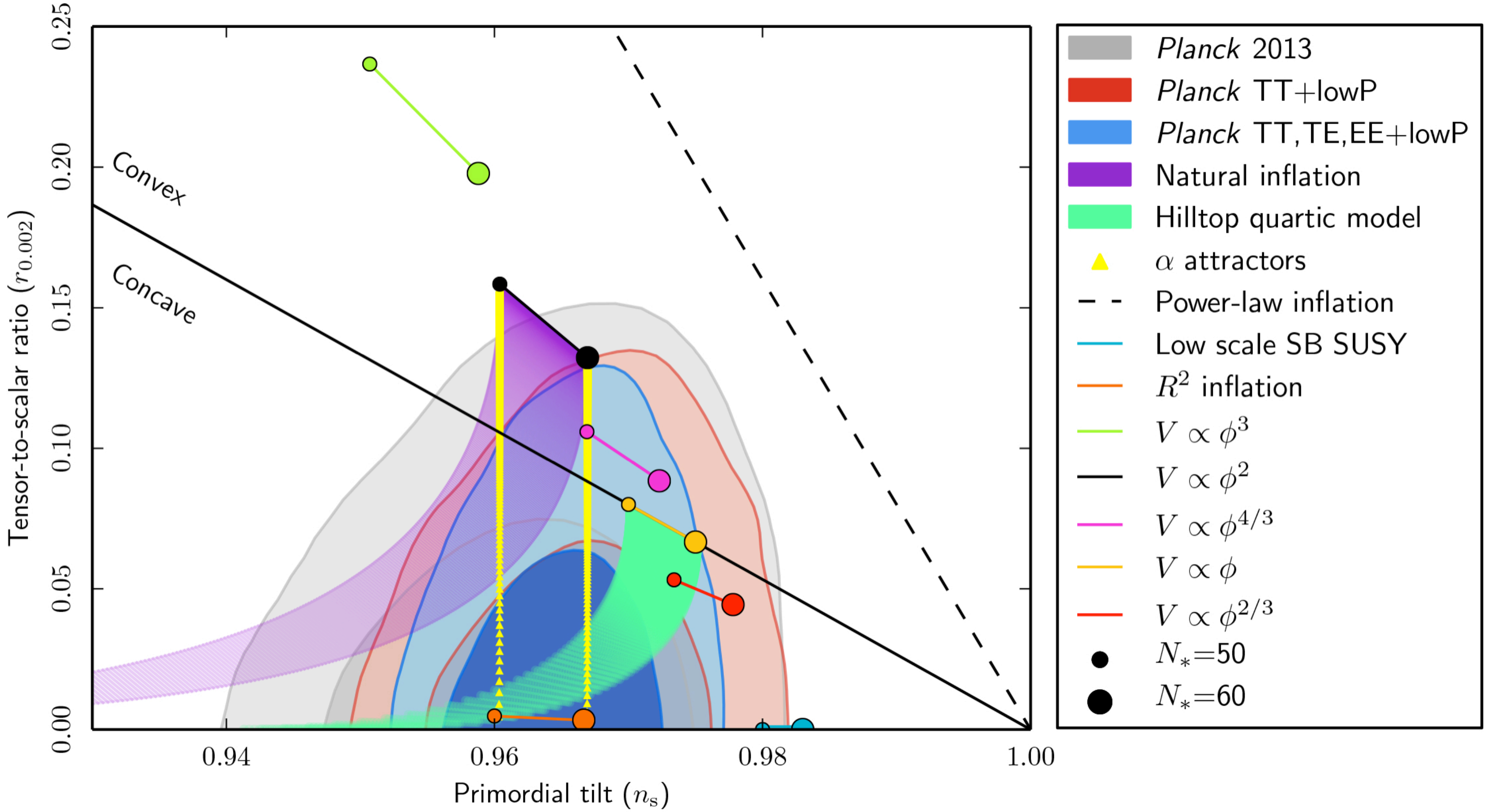
No evidence for

- isocurvature modes
- running of the spectral index
- primordial non-gaussianities
- features in the primordial PS



Planck 2015 XX

INFLATION



Planck TT+lowP+lensing

$n_s = 0.9688 \pm 0.0061$

$r_{0.002} < 0.11$

$\Rightarrow$ $V_{inf} < (1.9 \times 10^{16}\ \text{GeV})^4$

Planck 2015 XX

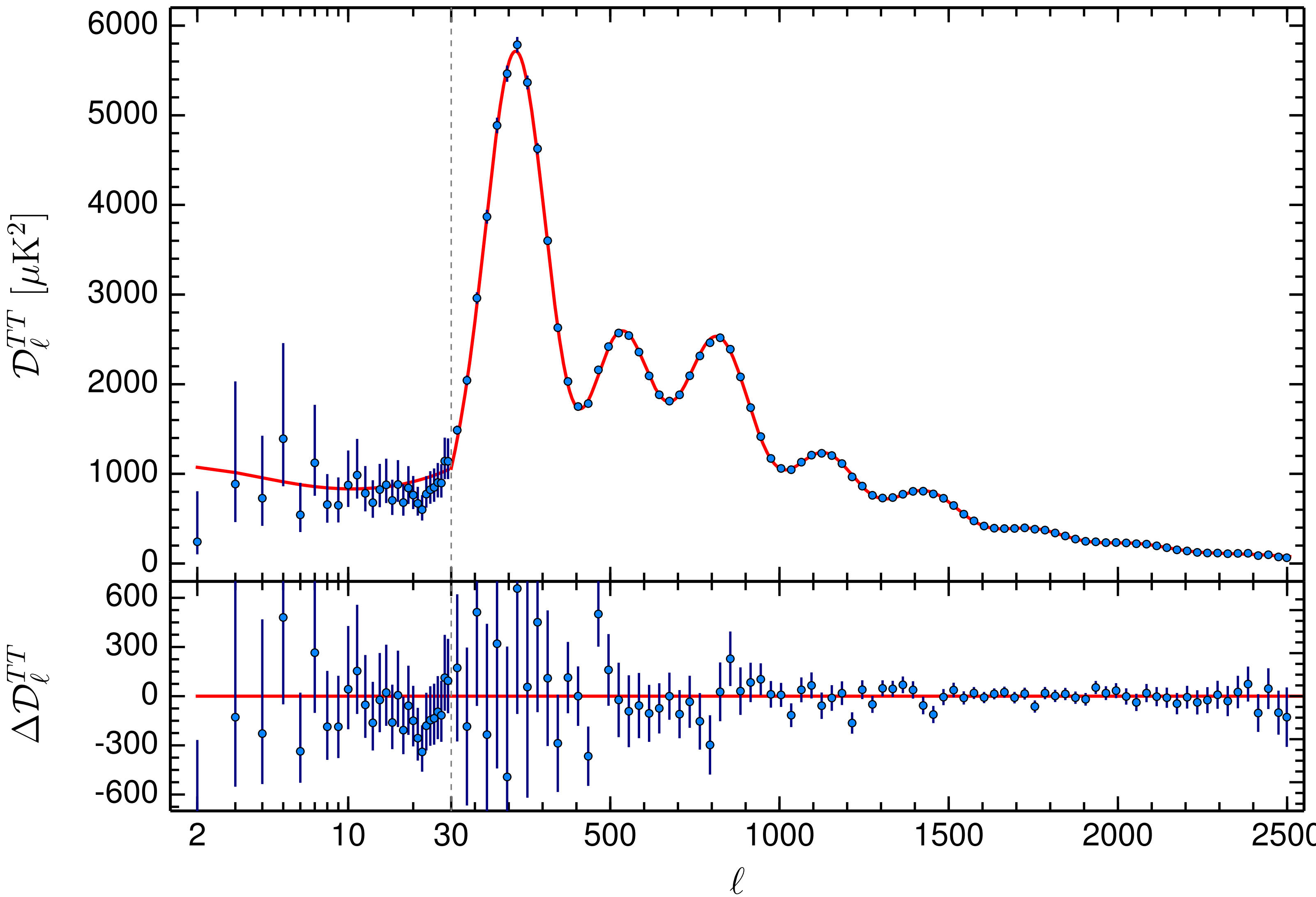
CMB observations are very well explained in the framework of the inflationary LCDM model

However, the microwave sky shows some unexpected, long-standing features ("anomalies") at the largest scales:

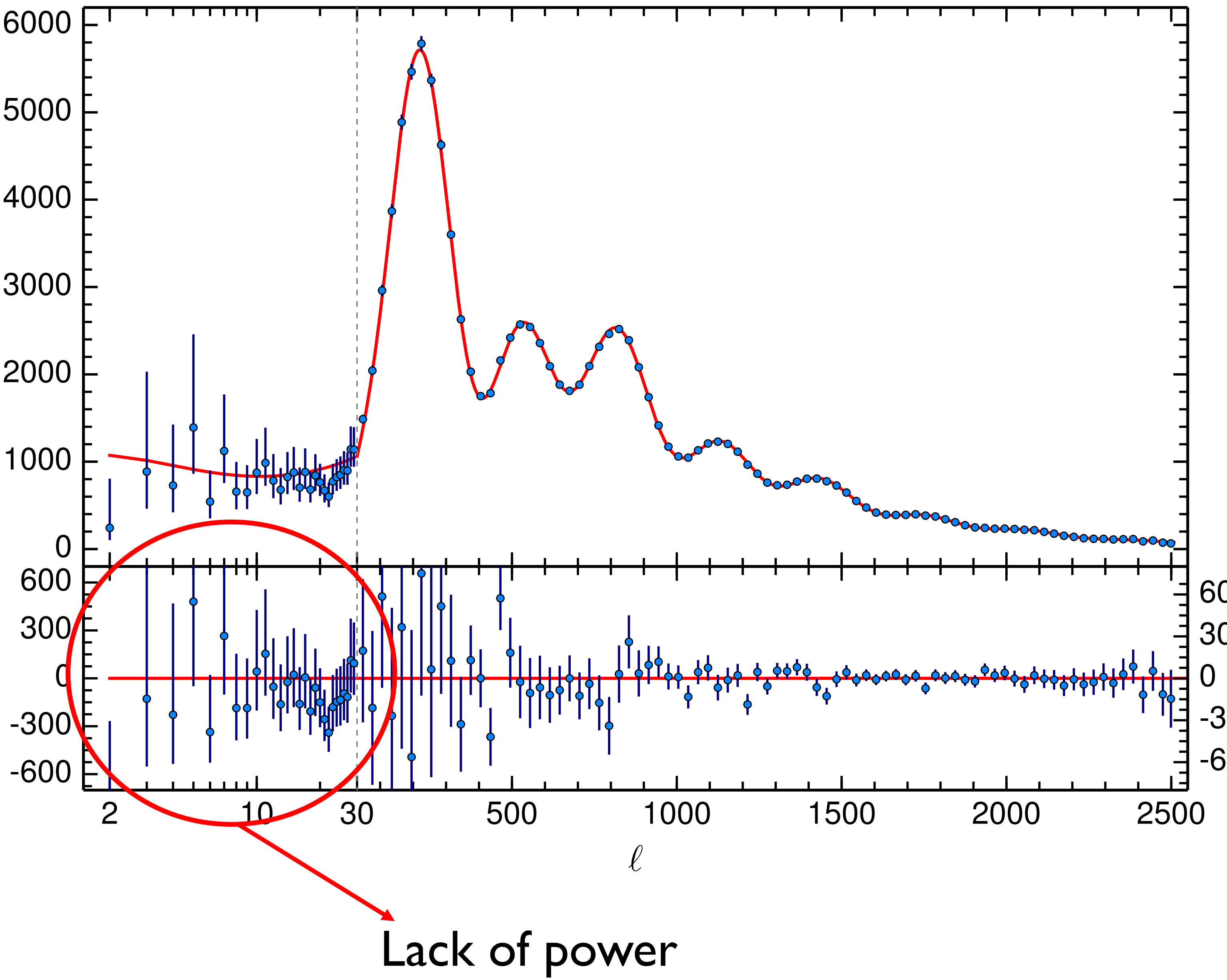
- Low variance
- Lack of correlation (at scales > 60 degrees)
- Quadrupole-octopole alignment
- Hemispherical asymmetry
- Parity (even-odd) asimmetry
- Cold spot

All the anomalies are at the % or ‰ level. However, when combined, their significance is higher (beware that not all of them are stat. ind.)

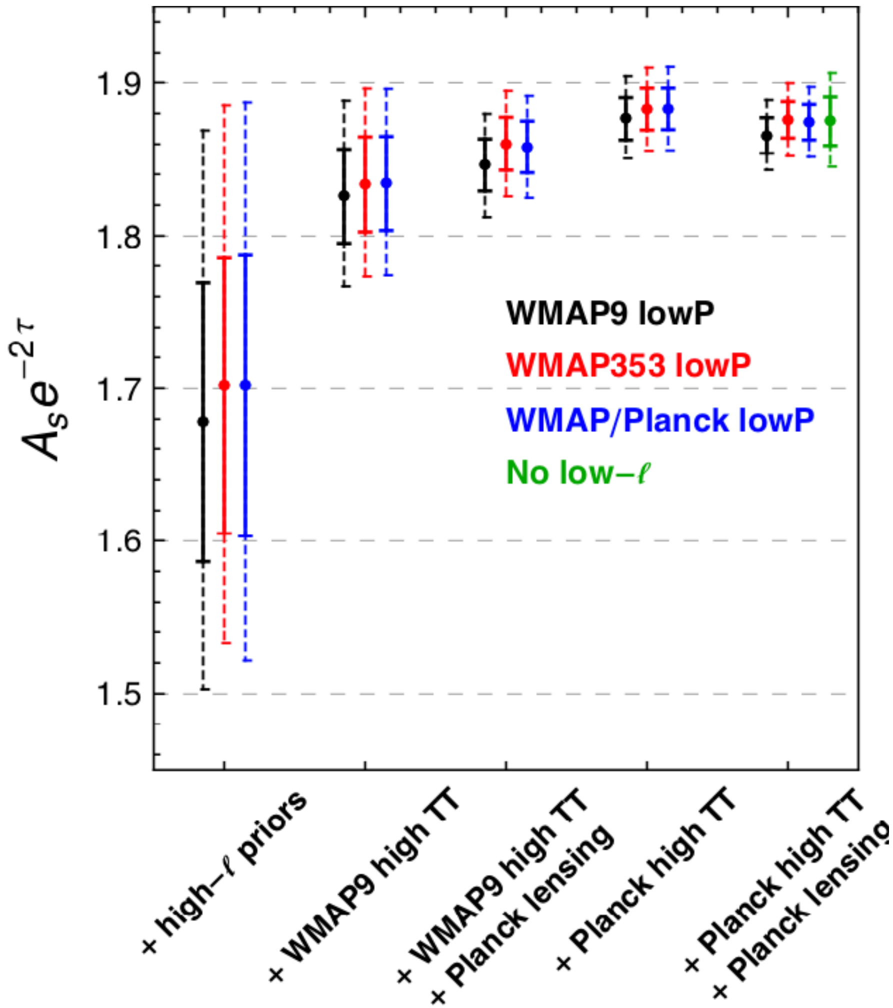
Consistency between WMAP and Planck rules out instrumental effects. Foregrounds? Primordial origin?

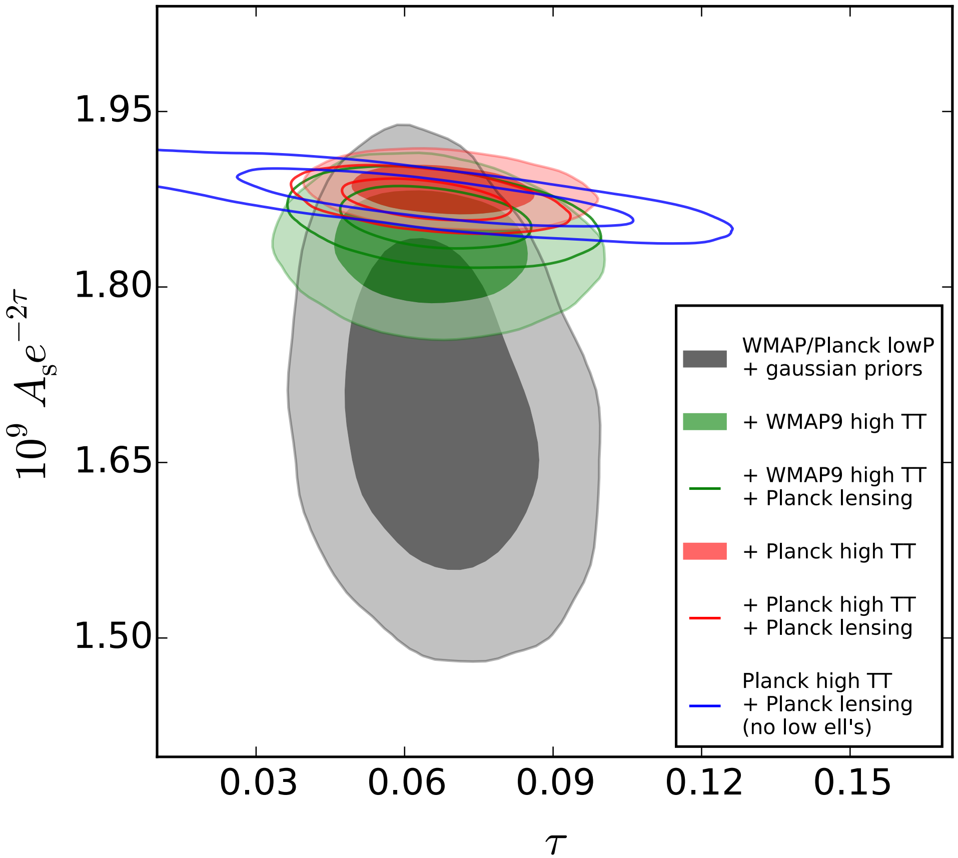


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

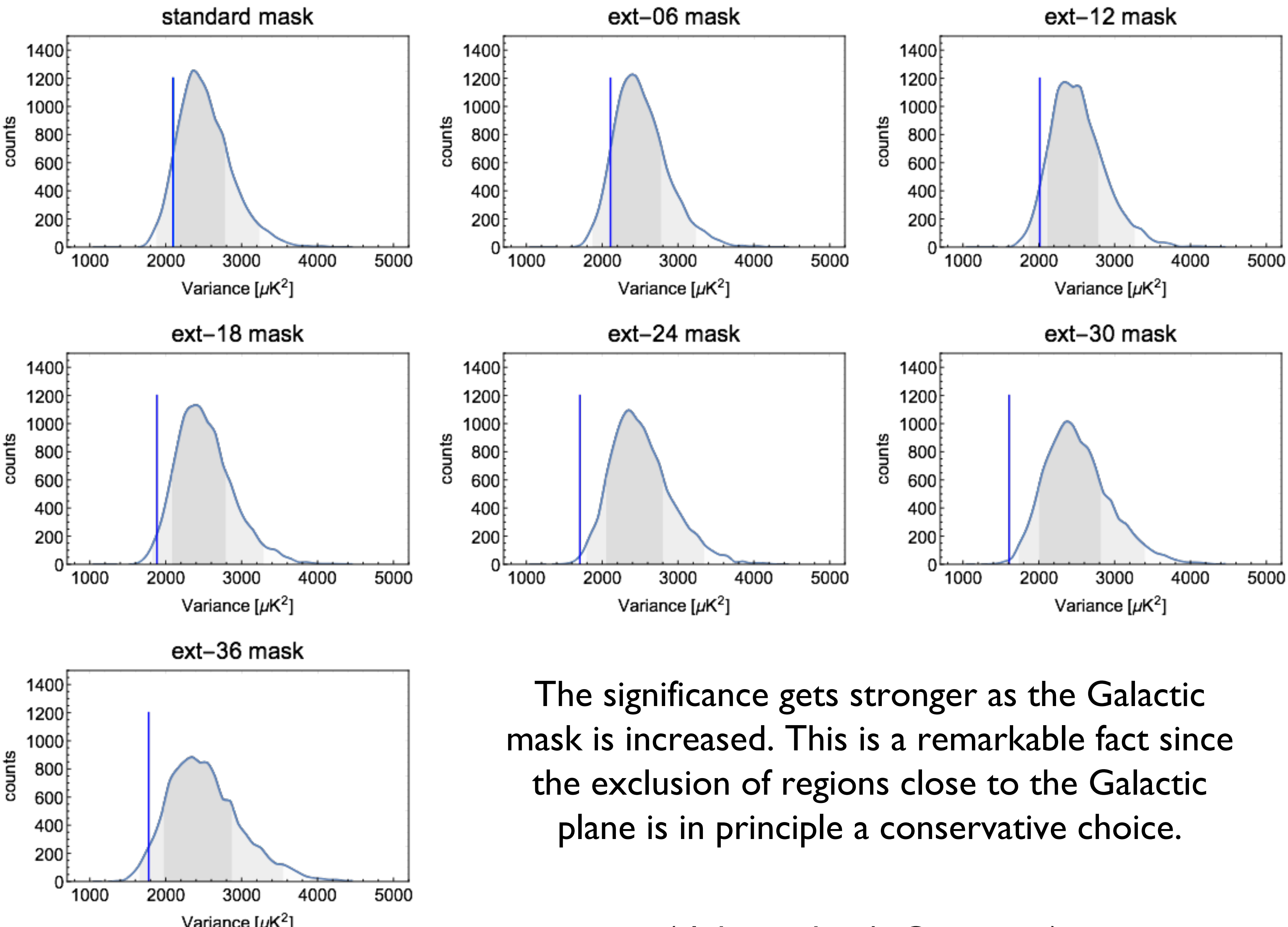


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}\ [\mu\mathrm{K}^2]$
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ
Lack of power





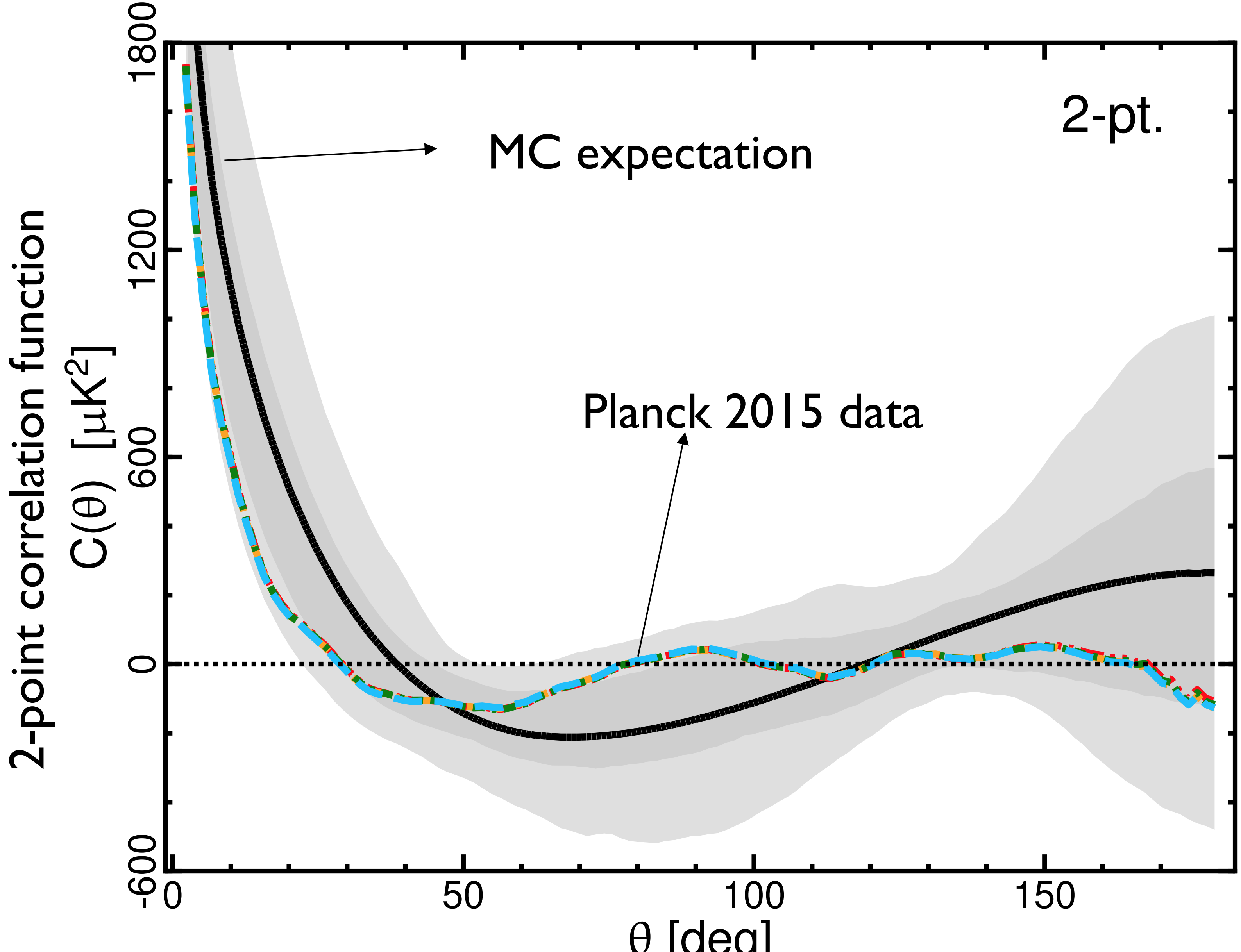
ML, C. Burigana, M. Gerbino. A Gruppuso, N. Mandolesi, P. Natoli, G. Polenta, L. Salvati, T. Trombetta, JCAP 2017



The significance gets stronger as the Galactic mask is increased. This is a remarkable fact since the exclusion of regions close to the Galactic plane is in principle a conservative choice.

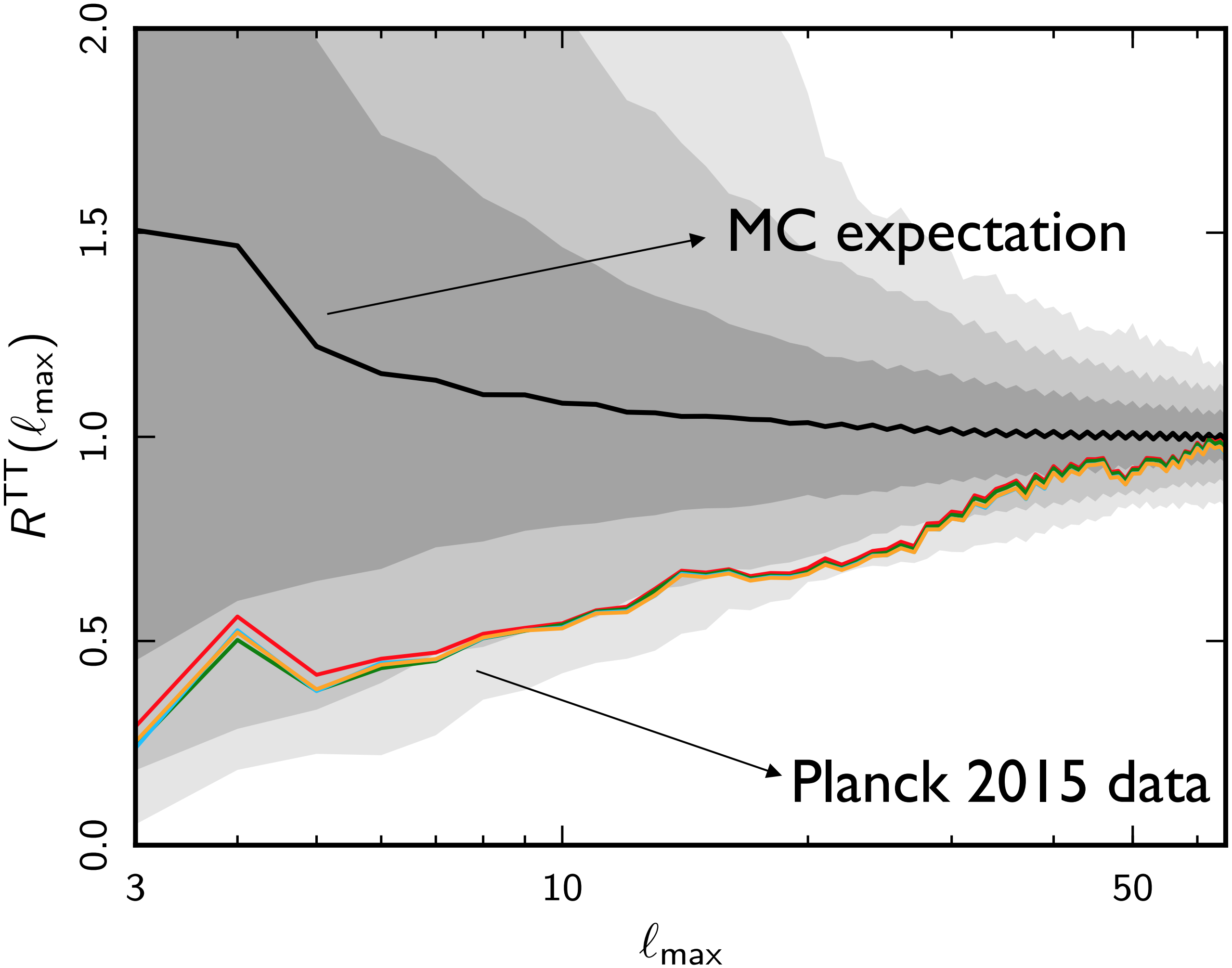
(slide credit: A. Gruppuso)

Lack of large scale correlations



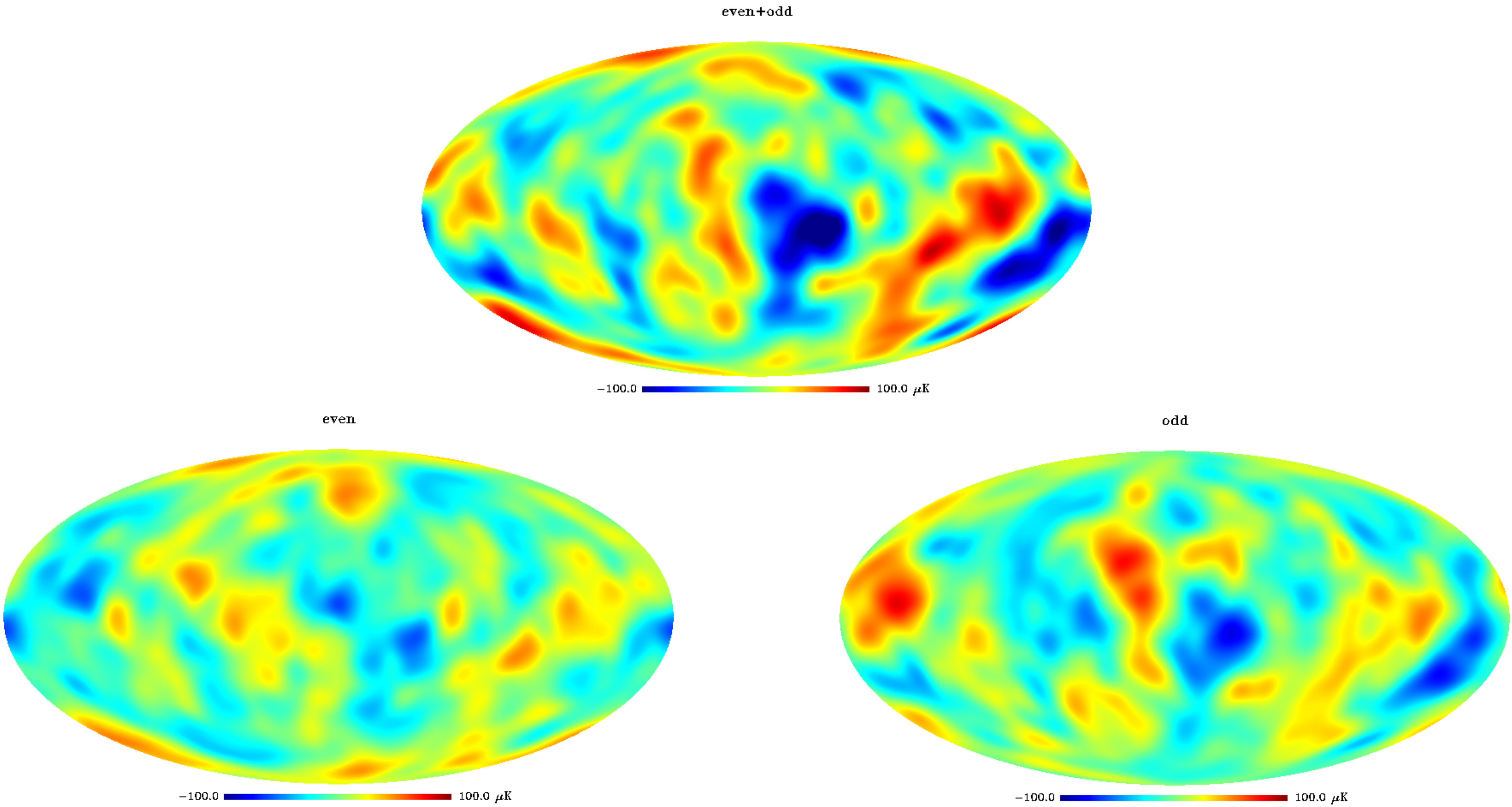
Planck 2015 XVI

Even-odd asymmetry



$$R^{\mathrm{TT}}(\ell_{\mathrm{max}}) = \frac{D_{+}^{\mathrm{TT}}(\ell_{\mathrm{max}})}{D_{-}^{\mathrm{TT}}(\ell_{\mathrm{max}})} \qquad D_{+,-}^{\mathrm{TT}} = \frac{1}{\ell_{\mathrm{tot}}^{+,-}} \sum_{\ell=2,\ell_{\mathrm{max}}}^{+,-} \frac{\ell(\ell+1)}{2\pi} C_{\ell}^{\mathrm{TT}}$$

Planck 2015 XVI



$$\left(\frac{\delta T}{T}(\hat{n})\right)_{\pm} \equiv \frac{1}{2}\left[\frac{\delta T}{T}(\hat{n}) \pm \frac{\delta T}{T}(-\hat{n})\right]$$

A. Gruppuso, N. Kitazawa, ML, N. Mandolesi, P. Natoli, A. Sagnotti 2017

Scale-invariance of the large-scale perturbations is a prediction of single-field, slow-roll inflation.

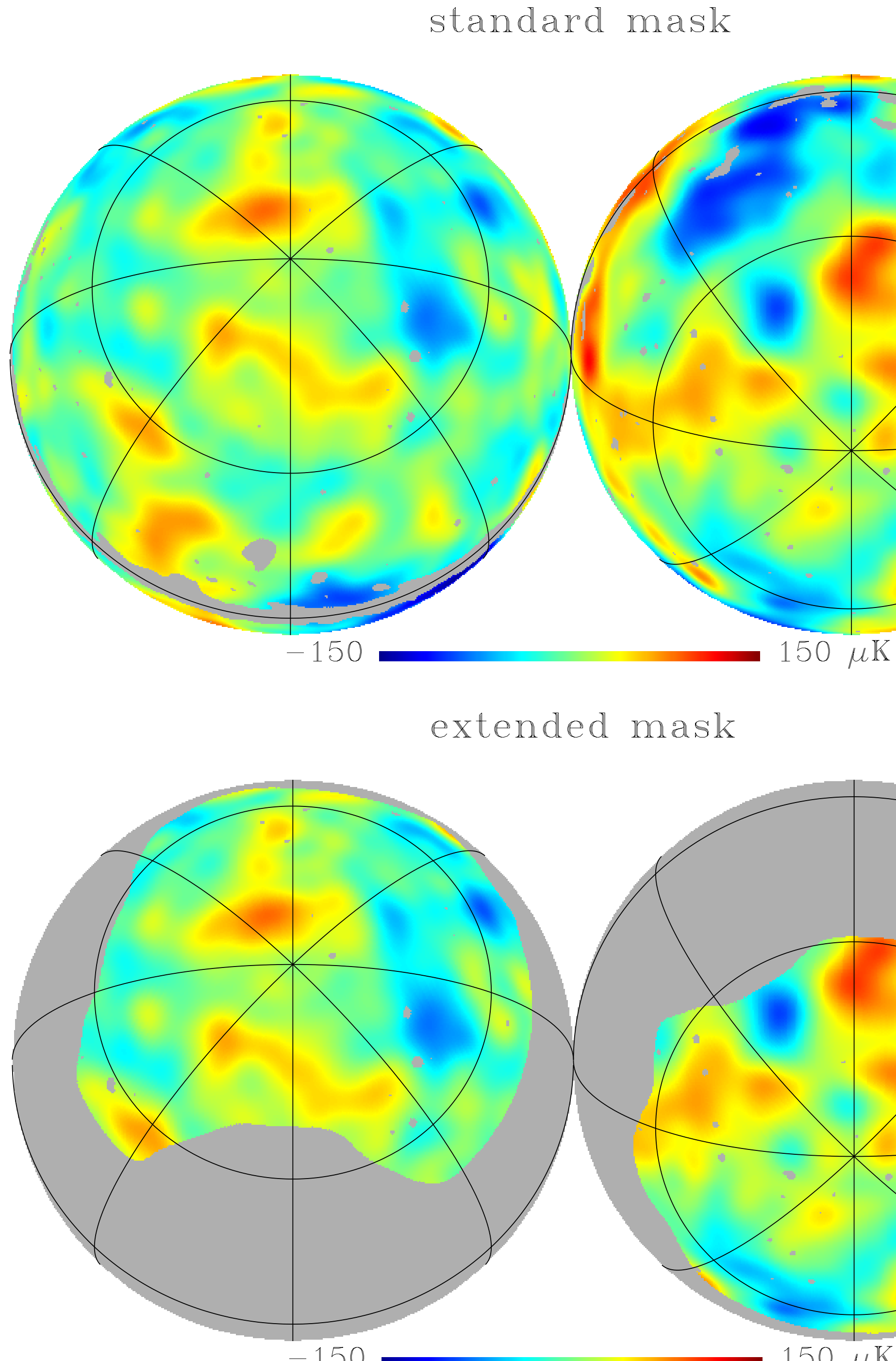
Transition from a pre-inflationary "fast-roll" phase to slow-roll would suppress power in the primordial spectrum.

Are we seeing relics of a decelerating inflaton?

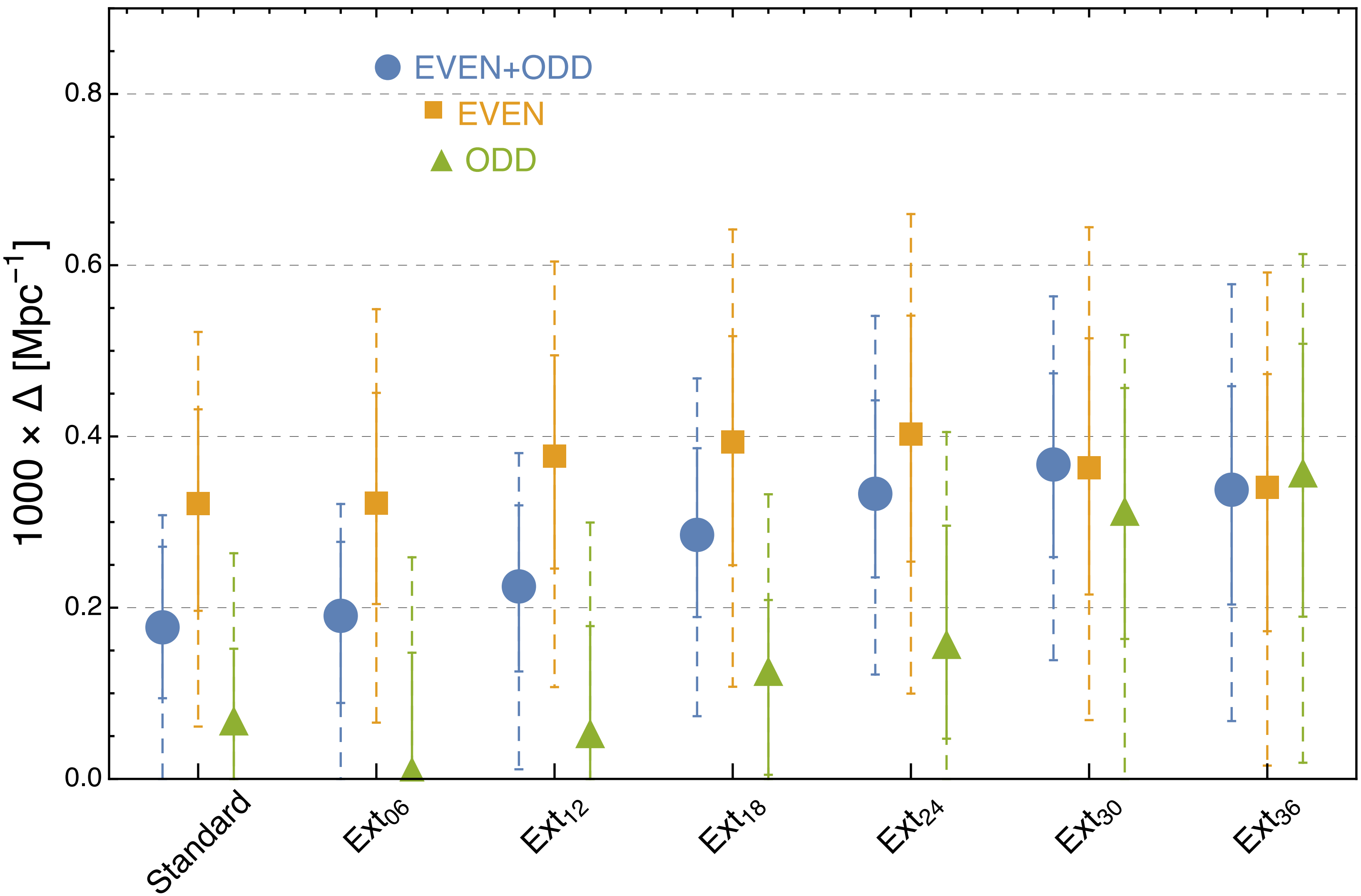
See e.g. Contaldi, Peloso, Kofman, Linde (2003); Destri, de Vega, Sanchez (2010); Dudas, Kitazawa, Patil, Sagnotti (2012); Kitazawa, Sagnotti (2014)

$$P(k) \sim \frac{k^3}{[k^2 + \Delta^2]^{2-n_s/2}} \longrightarrow P(k) \sim k^{n_s - 1}$$

~ scale that enters the horizon at the onset of slow roll


standard mask
−150
150 μK
extended mask
−150
150 μK

Constraints on Δ from Planck 2015



A. Gruppuso, N. Kitazawa, ML, N. Mandolesi, P. Natoli, A. Sagnotti 2017

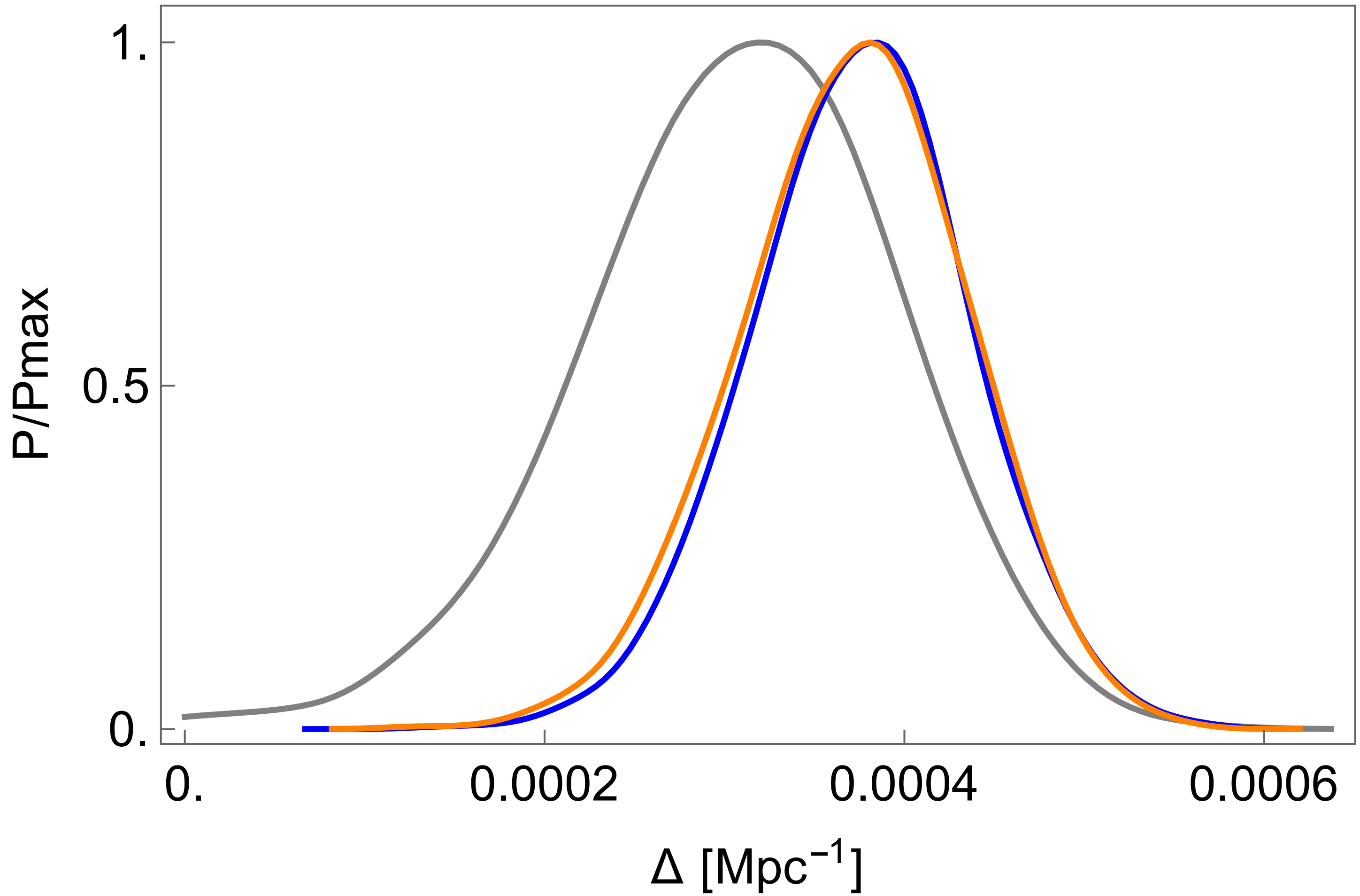
- The even multipoles are consistently lower than the LCDM expectation, independently on the galactic masking

- The odd multipoles are consistent with the LCDM expectation for the smaller masks (more sky). In larger masks (less sky), they are consistent with the even multipoles (and then have low power)

- The power at large scales is concentrated around the galactic plane, in the odd multipoles

- 3.16σ detection of Δ in the Ext30 mask

Forecasted constraints on Δ from future experiments

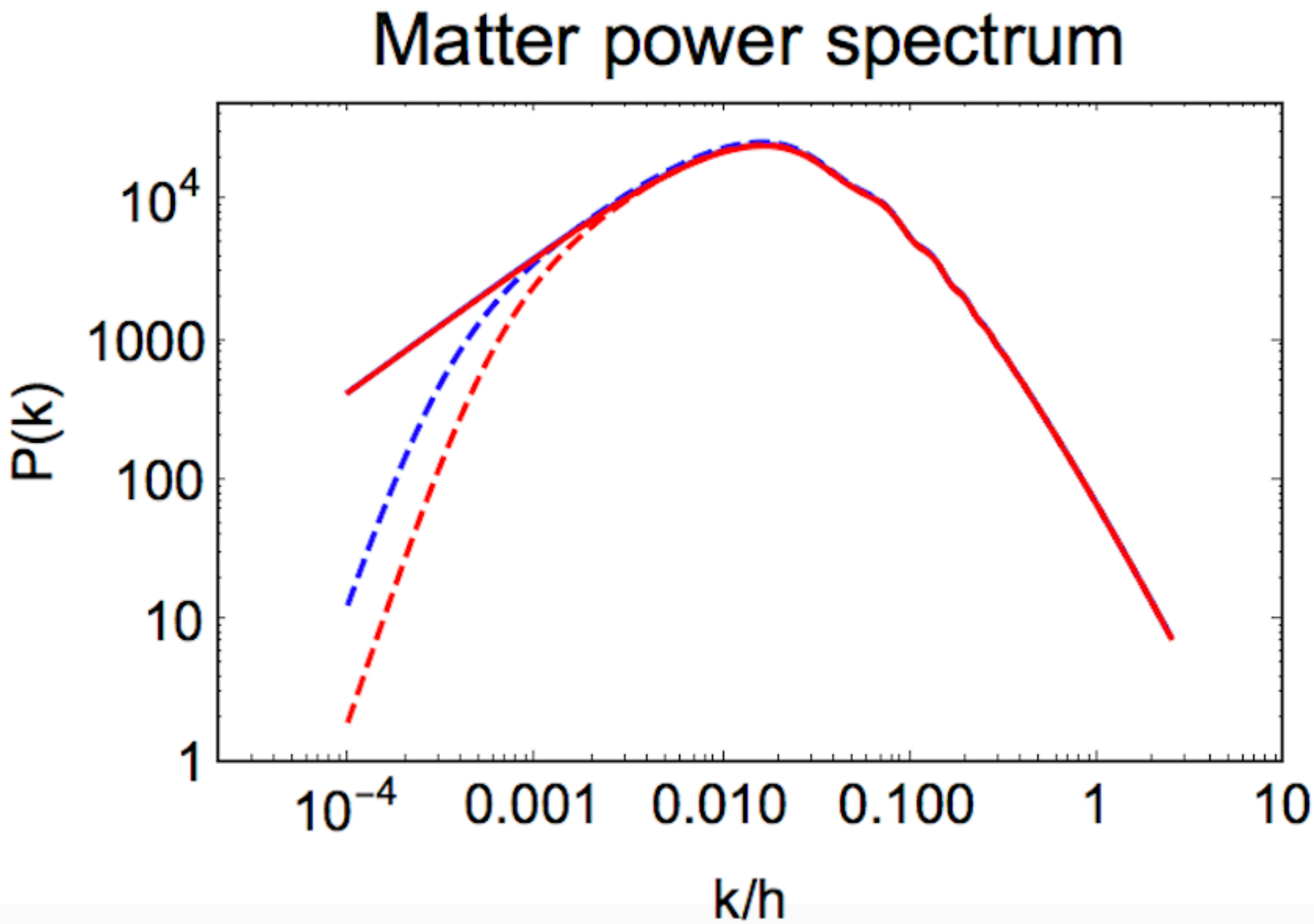


Grey: Planck-like noise, standard masking

Orange: CVL large-scale pol., ext30 mask

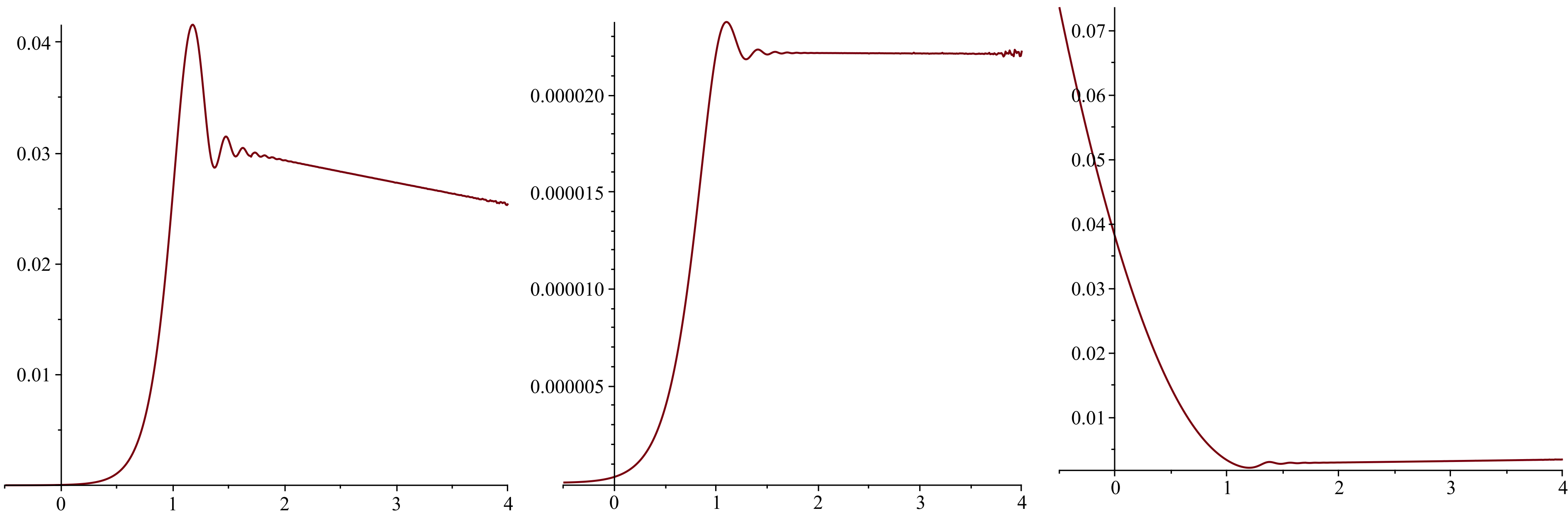
Blue: CVL large-scal pol, full sky

Imprint of Δ on large scale structures



The power suppression is a universal prediction of fast-roll scenarios.
The suppression is accompanied by a peak and oscillations around the transition, which are however more model dependent
Pre-inflationary scenarios also give a prediction for the tensor modes (see e.g. Dudas, Kitazawa, Patil, Sagnotti 2012)
For a Staronbinsky model with critical exponential wall ($V \propto e^{2\phi}$) :

scalar amplitude | tensor amplitude | tensor-to-scalar ratio



Log[k/Δ]

A. Gruppuso, N. Kitazawa, ML, N. Mandolesi, P. Natoli, A. Sagnotti 2017

CONCLUSIONS

- Cosmology is a powerful probe of particle physics
- Current observations already give strong constraints on e.g. neutrino masses or the effective number of neutrino families
- Future observations might allow to probe the neutrino hierarchy…
- … or the presence of thermalized scalar particles
- Lack of power at large scales might be related to an early phase of slow roll and to the onset of fast roll
- Future measurements of CMB polarization might lead to a detection of the cutoff scale associated to fast roll

Thank You

BACKUP SLIDES

THE COSMIC NEUTRINO BACKGROUND

The presence of a background of relic neutrinos (***CνB***) is a basic prediction of the standard cosmological model

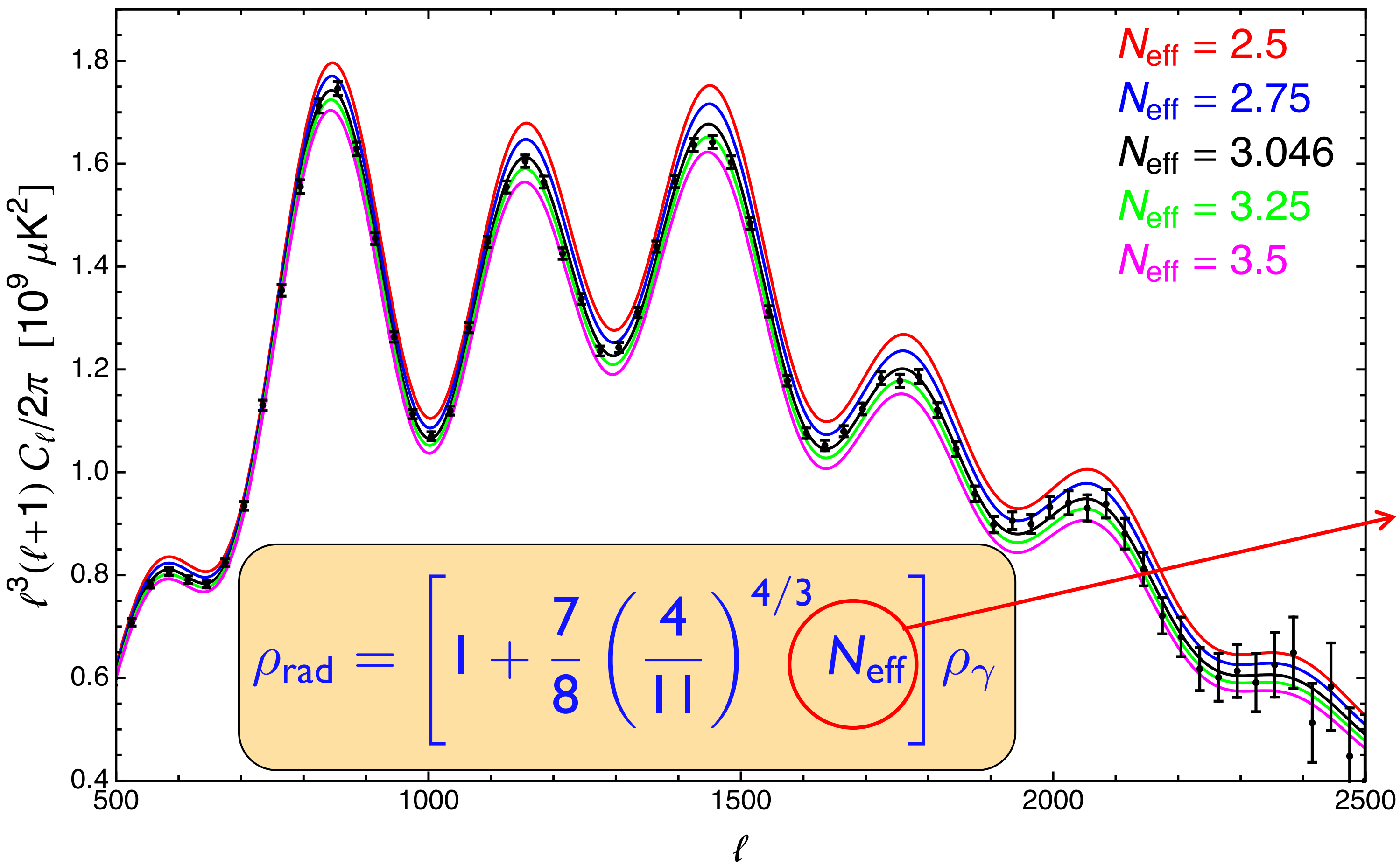
- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until T ~ 1 MeV (z ~ 10^{10});
- Below T ~ 1 MeV, neutrino free stream keeping an equilibrium spectrum:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species

THE COSMIC NEUTRINO BACKGROUND

This picture is consistent with current CMB observations:

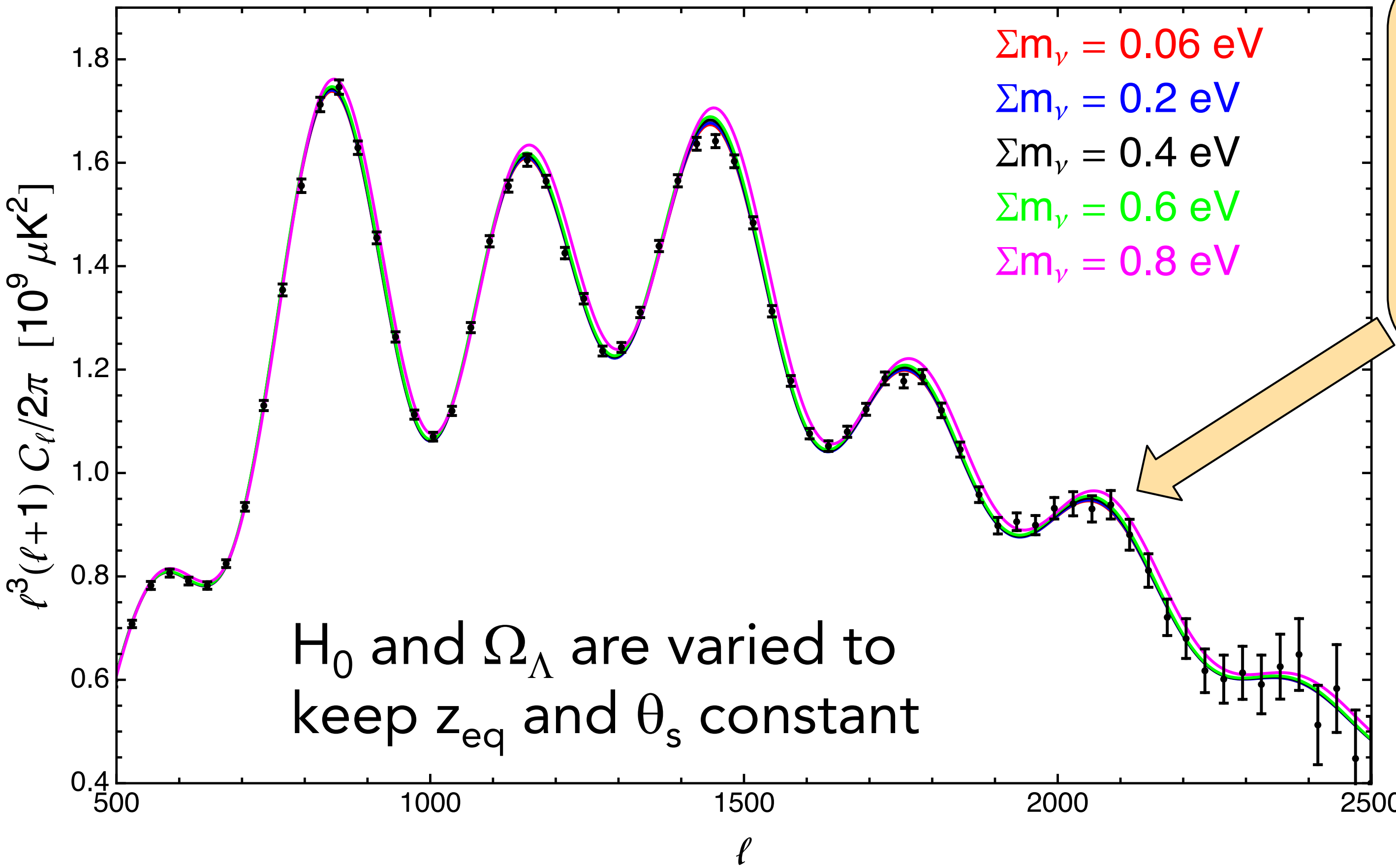


Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Due to non-instantaneous decoupling, the standard expectation is **$N_{\rm eff}$ = 3.046** (updated calculation gives $N_{\rm eff}$ = 3.045; see de Salas & Pastor 2016)

(note I am showing ~ $l^4 C_l$, not $l^2 C_l$)

Neutrino free streaming damps small-scale perturbations

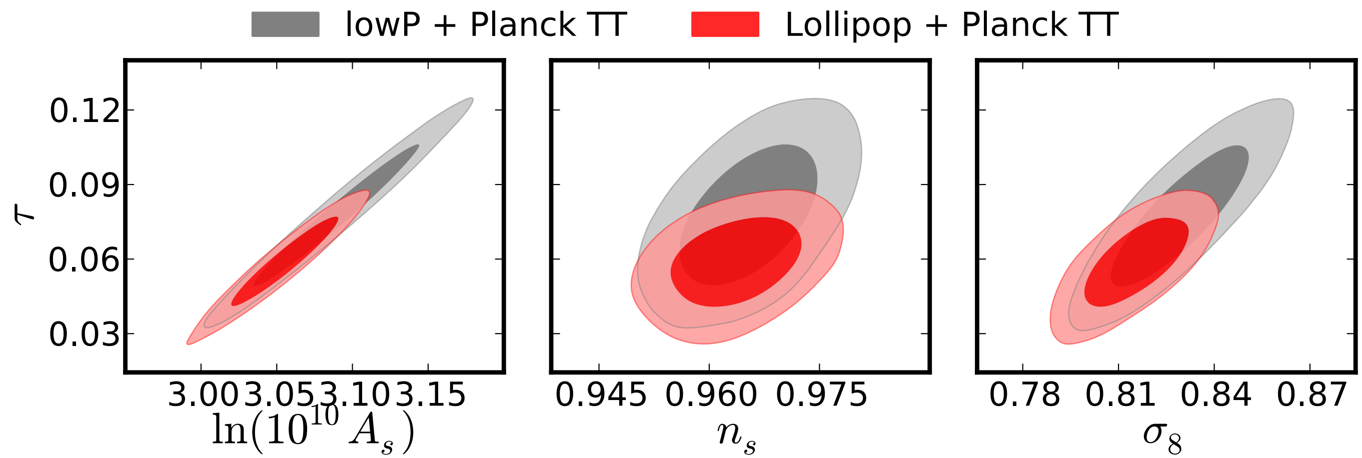


Net effect is to decrease lensing

- proportional to the neutrino energy density
- the effect is larger for larger masses

2016 Polarization data

New large-scale polarization data has been released in May 2016 (Planck int. res. XLVI)



Smaller τ means less overall power (thus smaller fluctuations) and less lensing

Tighter constraints on neutrino mass:

$\Sigma m_\nu < 0.59$ eV (PlanckTT+2016lowP)

$\Sigma m_\nu < 0.34$ eV (PlanckTTTEEE +2016lowP)

Comparison with lab

The absolute mass scale can be measured through:
(numbers on the right are current upper limits)

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

(2.05 – 2.3 eV @ 95%CL)
(Troisk-Mainz)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$

(0.06 – 0.16 eV @ 90%CL)
(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i$$

(0.2 – 0.7 eV @ 95%CL)
(Planck)

U is the neutrino mixing matrix: $|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i>$

Comparison with Lab

The absolute mass scale can be measured through:
(numbers on the right are forecast for future sensitivities)

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

(200 meV @ 68%CL)
(Katrin)

- neutrinoless double beta decay

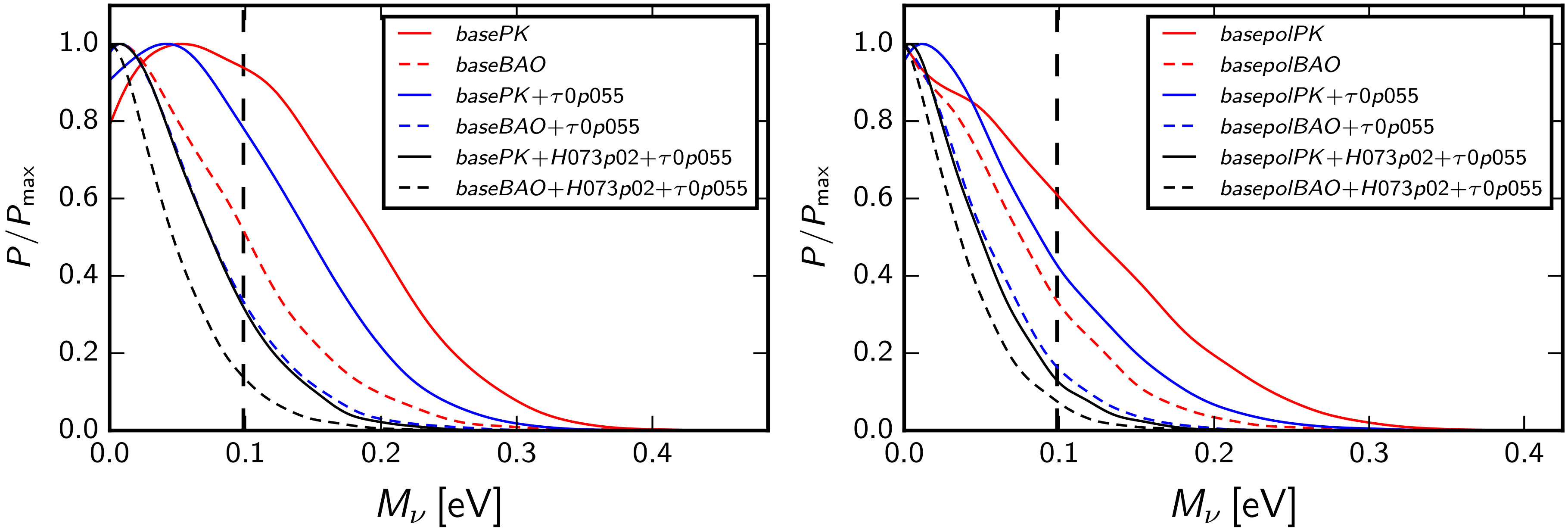
$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$

(8 – 20 meV @ 90%CL)
(nEXO, 5-year exposure)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i$$

(16 – 45 meV @ 68%CL)
(CORE, CORE+LSS)



Update using latest data (limits are 95% CL)

M_ν < 0.19 eV (PlanckTT+lowP+BAO)

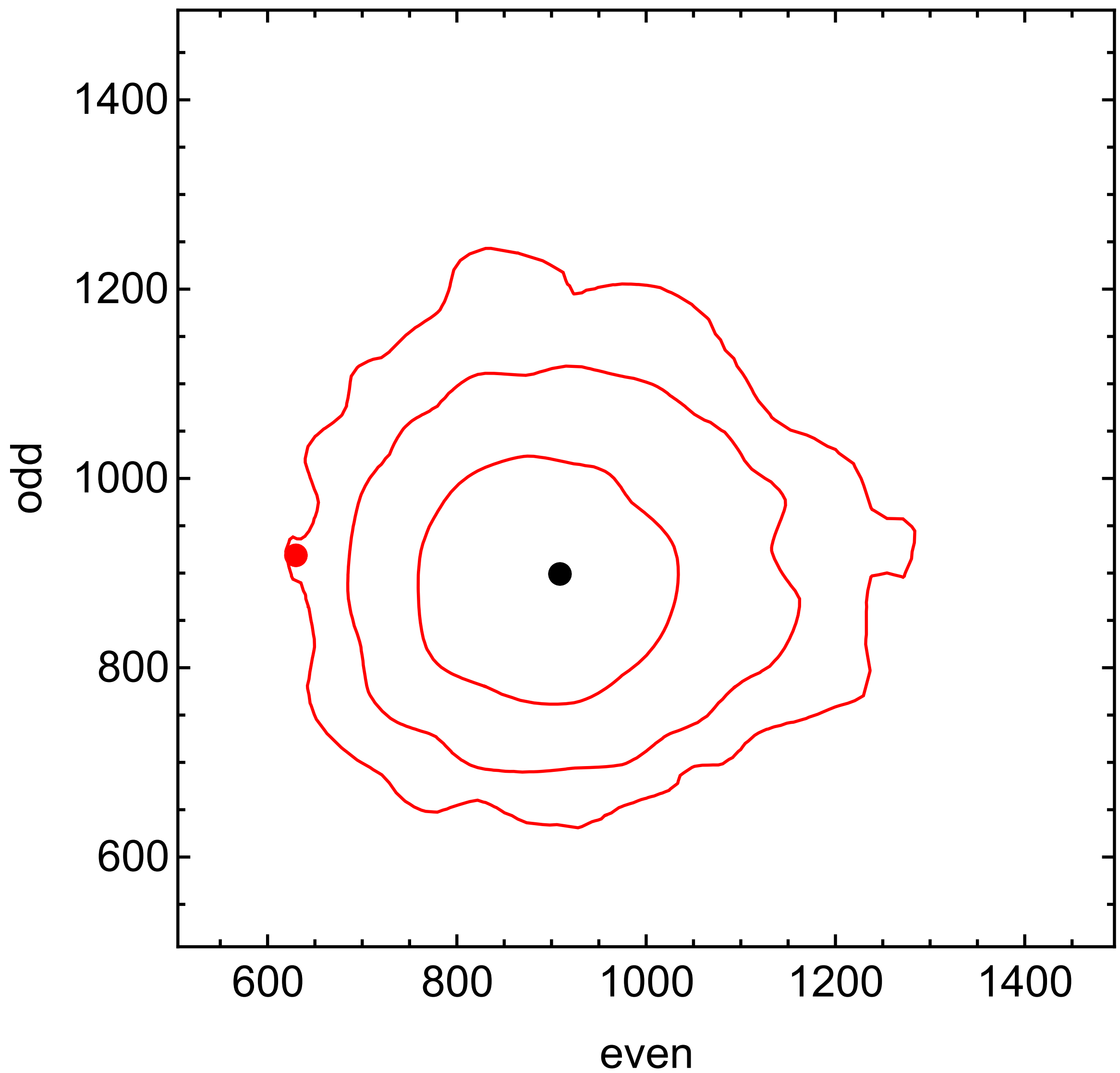
M_ν < 0.15 eV (PlanckTT+lowP2016+BAO)

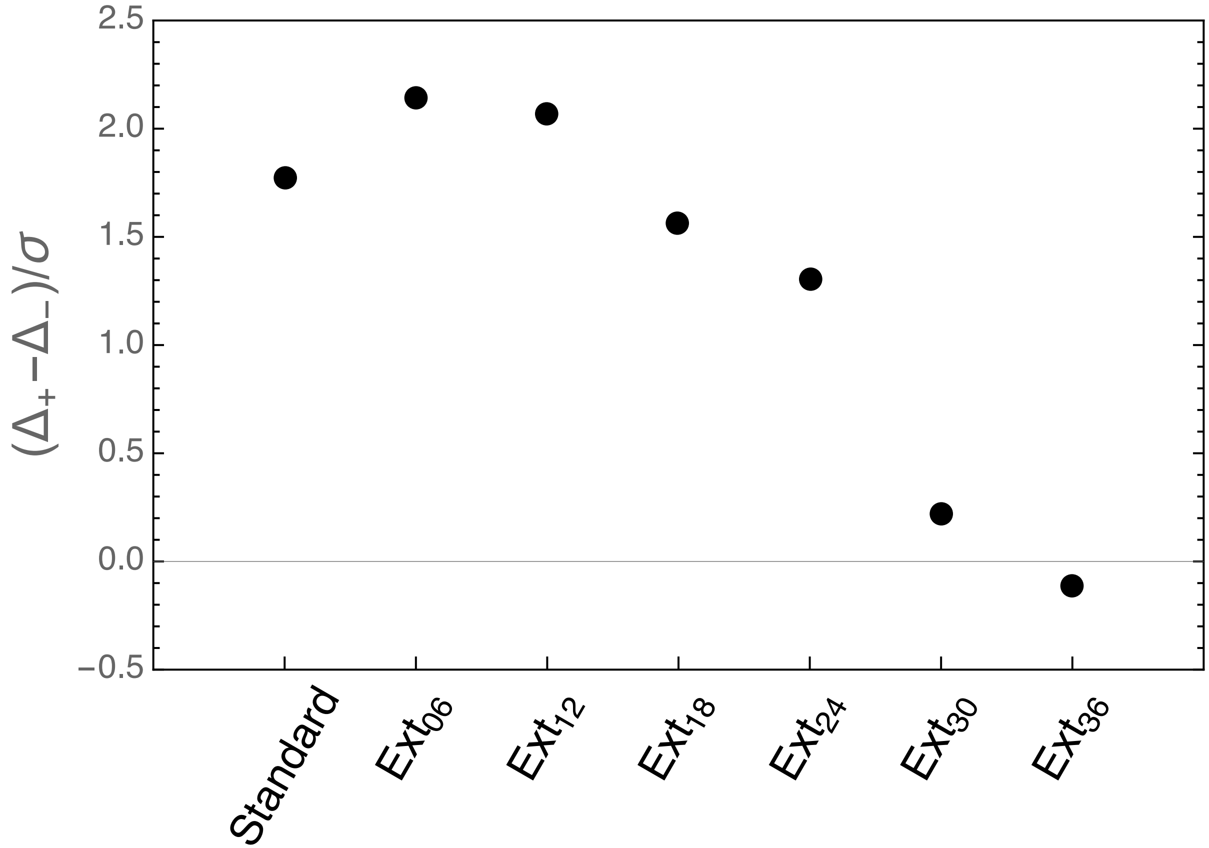
M_ν < 0.09 eV
(PlanckTTTEEE+lowP2016+BAO+H0)

Normal hierarchy is favoured with odds ~3:1 for the most constraining dataset combinations

Vagnozzi et al., arXiv:1701.09172

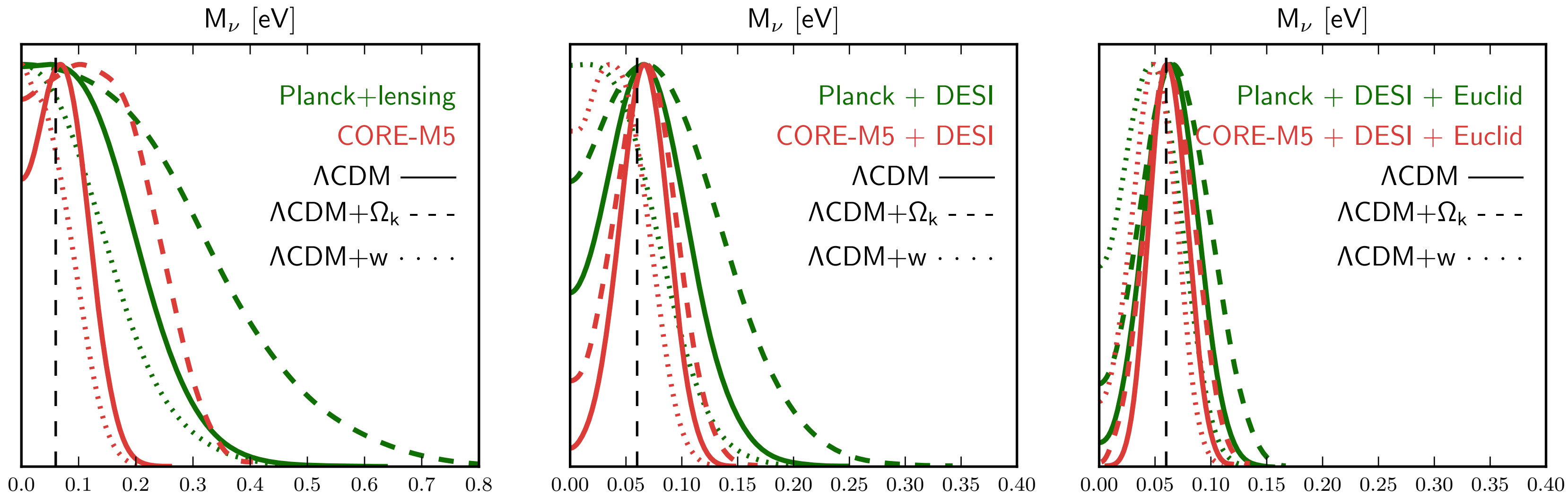
Frequentist analysis





$(\Delta_+ - \Delta_-)/\sigma$
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Standard
Ext_{06}
Ext_{12}
Ext_{18}
Ext_{24}
Ext_{30}
Ext_{36}

Neutrino masses from CORE-M5



Di Valentino et al (CORE collaboration), arXiv:1612.00021

Expected uncertainty on M_ν from CORE (+LSS) in ΛCDM+M_ν

$\sigma(M_\nu)$ = 0.044 (0.016) eV

Uncertainty from CORE+LSS degrades to 0.02 eV in some extended models

In combination with LSS, guarantees at least a 4σ detection

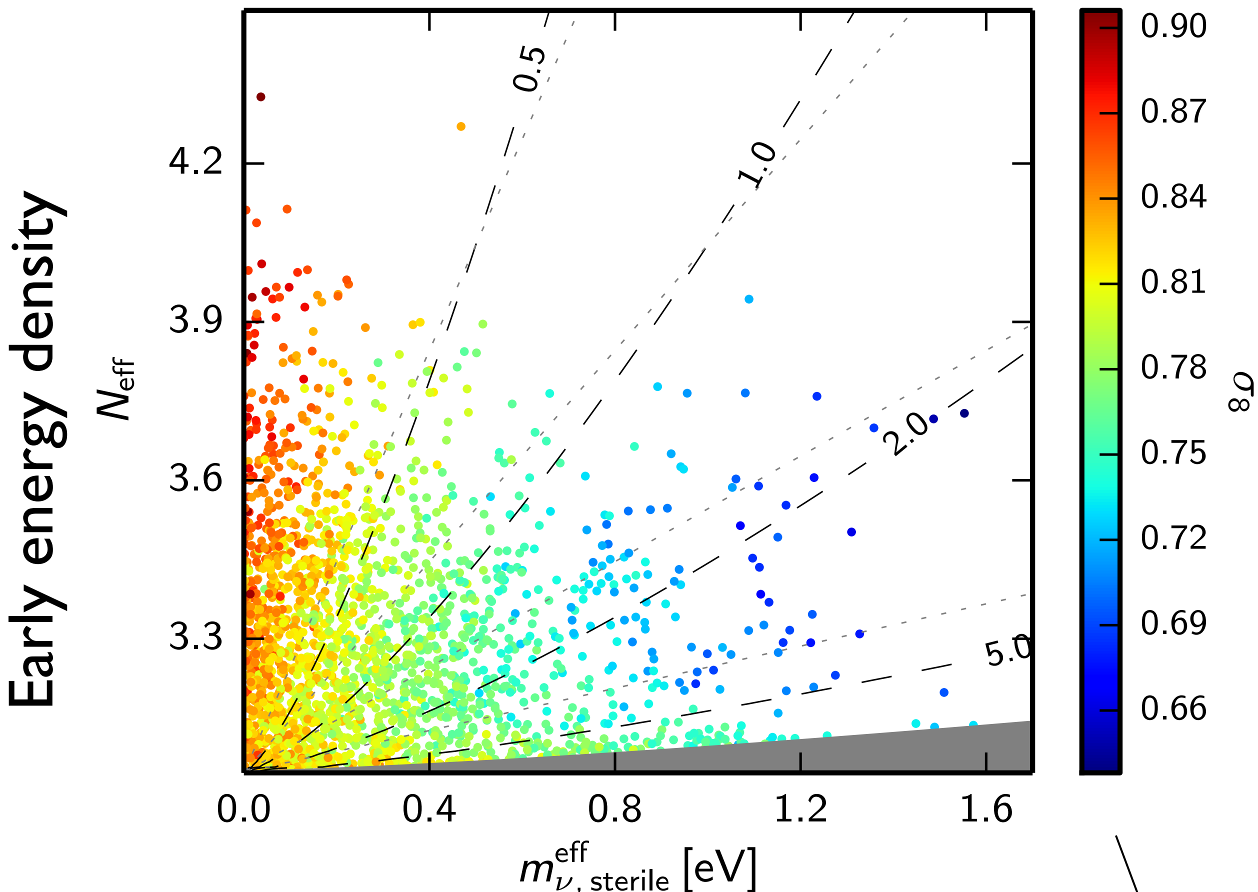
However, beware that all forecast shown here and in the following assume perfect control of systematics

THE FUTURE: GROUND-BASED EXPERIMENTS

Years	Stage	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015–2016	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS SPT clusters)
2017–2020	Stage 3 10,000 detectors	10^{-6}	0.006	0.06	0.06eV (Boss BAO prior)	~300-600 (DES + DESI SZ Clusters)
2021–2023, **Target**	Stage 4 CMB-S4 ~500,000 detectors	**10^{-8}**	**0.0005**	**0.027**	**0.015eV** (DESI BAO $+\tau_e$ prior)	**1250** (DESI +LSST S4 Clusters)

CMB-S4 Science Book (arXiv: 1610:02743)

Planck constraints on massive sterile neutrinos



Present-day energy density

Amplitude of density fluctuations

Planck TT+lowP+ lensing+BAO

$N_{\mathrm{eff}} < 3.7$

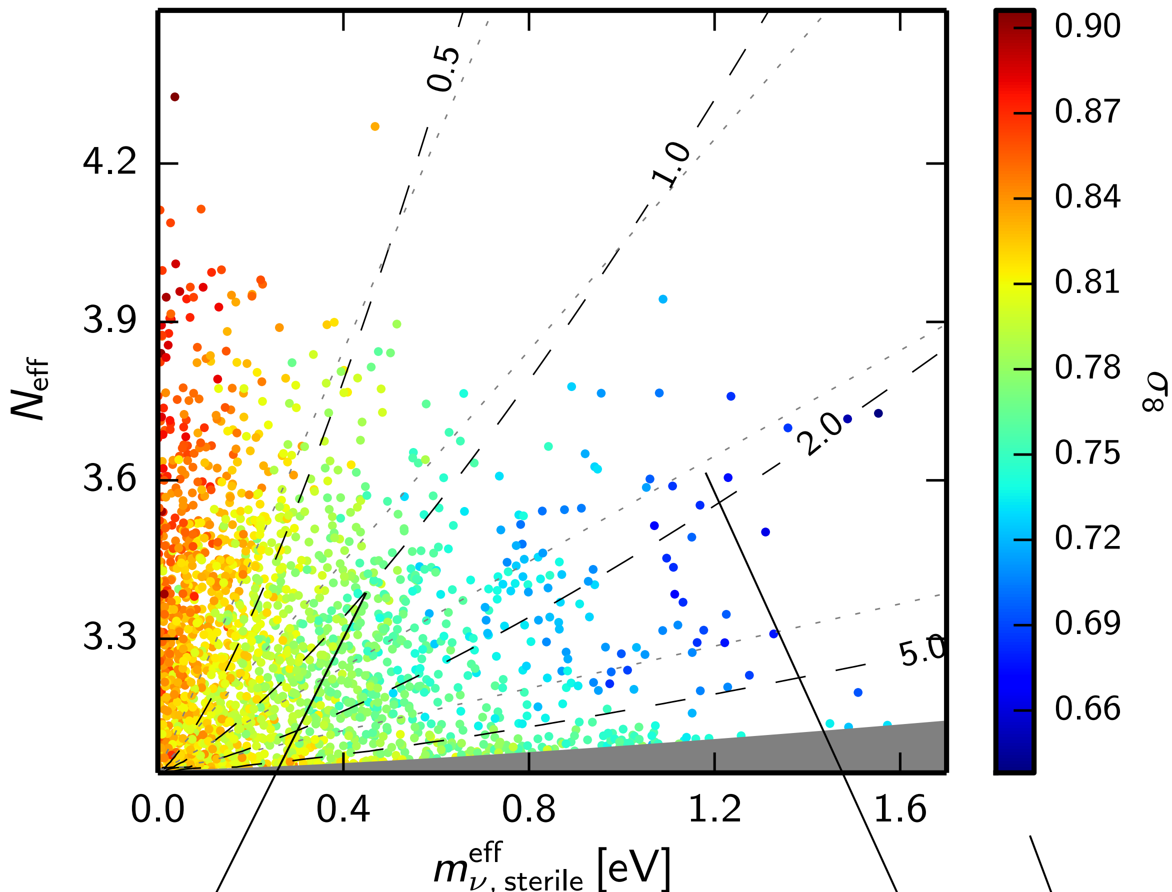
$m^{eff}{}_{sterile} < 0.52$ eV

One sterile eigenstate; total active mass fixed to 0.06 eV

Planck 2015 XVI

Planck constraints on massive sterile neutrinos

Early energy density



Present-day energy density

Planck TT+lowP+lensing+BAO

$N_{\rm eff} < 3.7$

$m^{eff}_{sterile} < 0.52$ eV

One sterile eigenstate; total active mass fixed to 0.06 eV

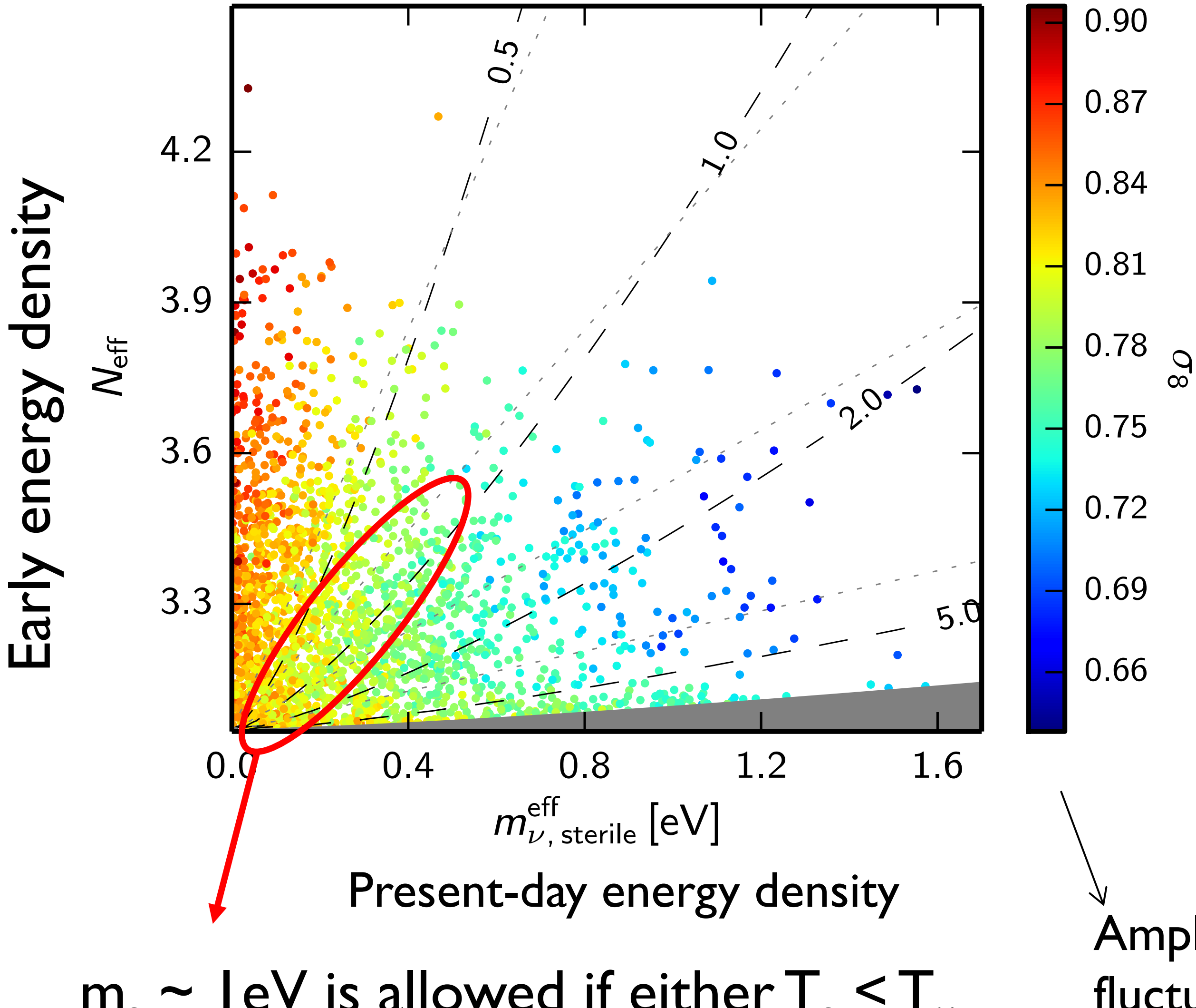
Amplitude of density fluctuations

Lines of constant m_s (thermal)

Lines of constant m_s (DW)

Planck 2015 XVI

Planck constraints on massive sterile neutrinos



Planck TT+lowP+lensing+BAO

$N_{\rm eff} < 3.7$

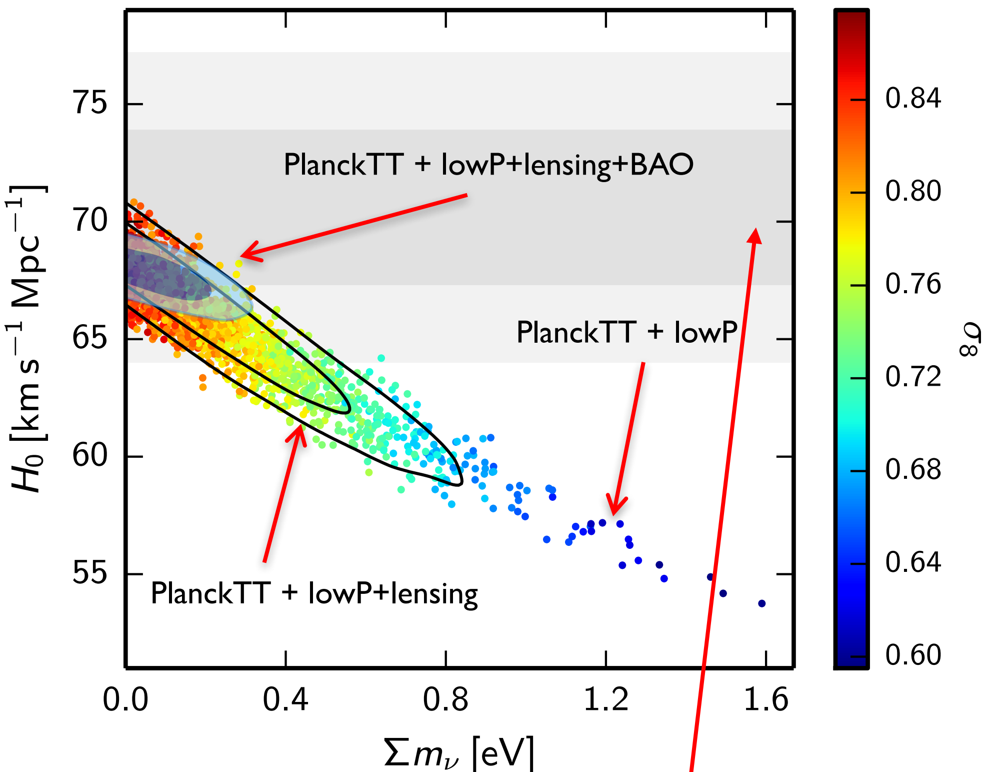
$m^{eff}{}_{sterile} < 0.52$ eV

One sterile eigenstate; total active mass fixed to 0.06 eV

$m_s \sim 1$ eV is allowed if either $T_s < T_\nu$ or if distribution is a gray body

Planck 2015 XVI

Planck 2015 ΛCDM constraints on neutrino mass



Estimate of the lensing p.s. from the 4-point c.f.

PLANCK TT + lowP + lensing
M_ν < 0.68 eV (95%CL)

~ one order of magnitude better than present kinematic constraints already at the same level than near-future expectations for e.g. KATRIN

Inclusion of external data like BAO allows to better constrain the expansion history and reduce degeneracy with H0:

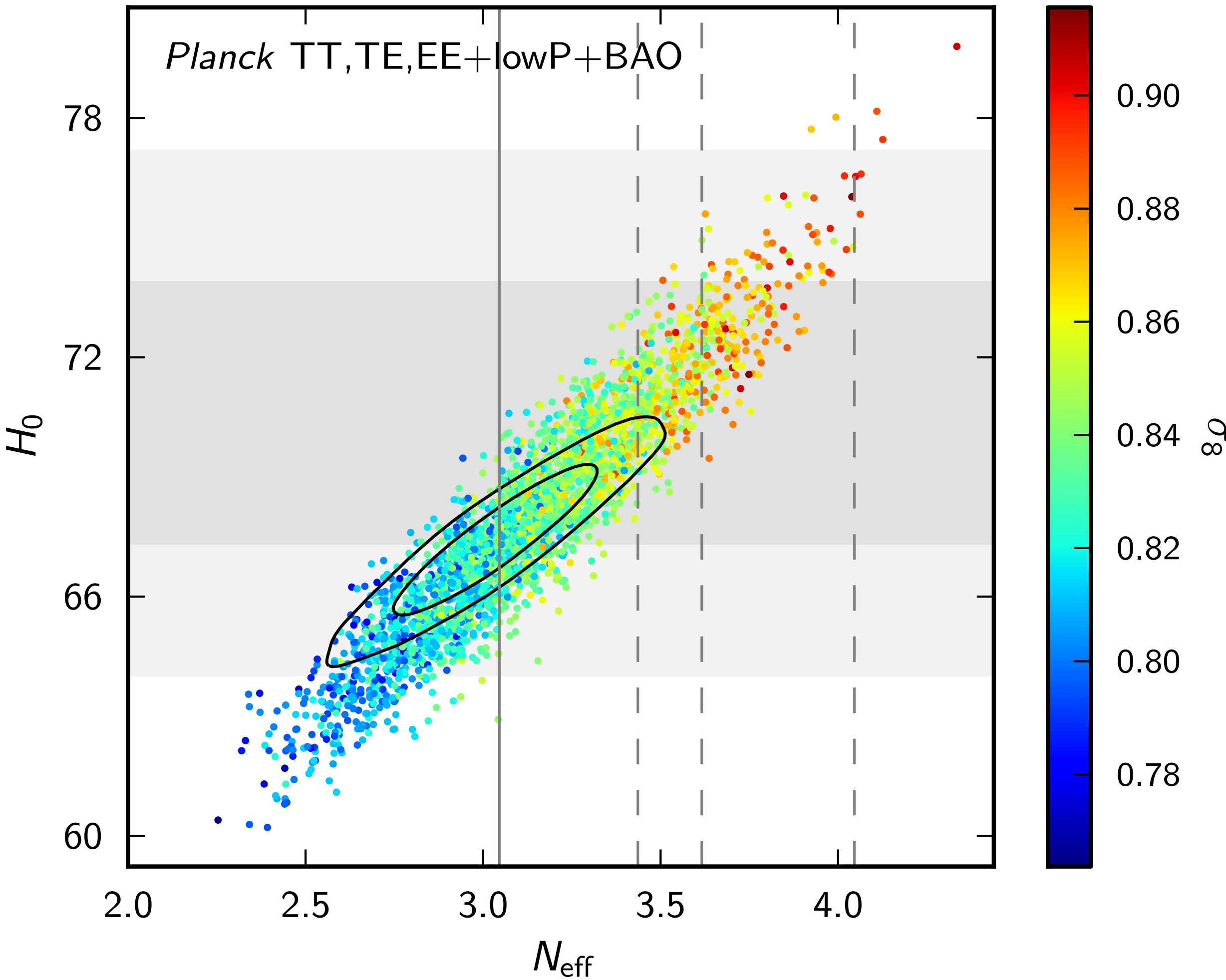
PLANCK TT+lowP+lensing+BAO
M_ν < 0.23 eV (95% CL)

Standard ruler in the galaxy c.f (not affected by nonlinearities)

Note that non-zero neutrino mass does not alleviate tension with direct measurements of H0

(Planck 2015 XIII)

EFFECTIVE NUMBER OF NEUTRINO FAMILIES

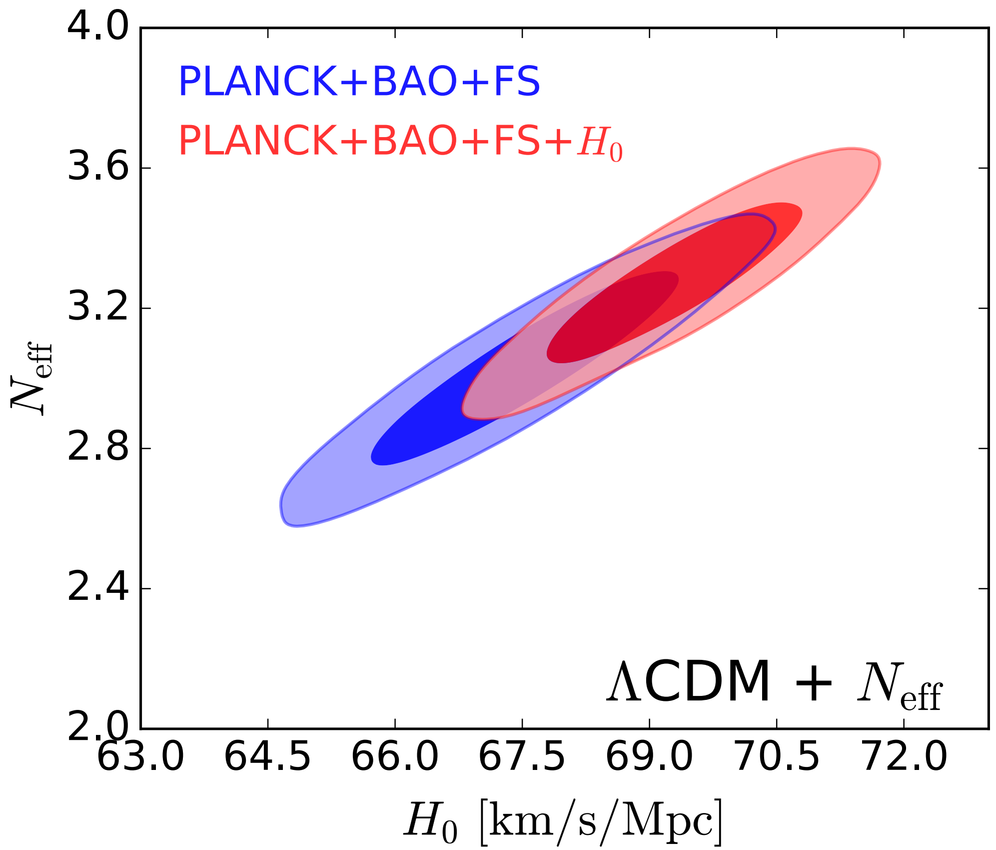


Higher values of N_{eff} can help relieve the tension with astrophysical measurements of H_0

However, they imply a larger σ_8 and thus worsen the tension with LSS probes.

(Planck 2015 XIII)

Effective number of neutrino families



Planck 2015 + BOSS DR12 (BAO+shape):

N_{eff} = 3.03 +/- 0.18

Planck 2015 + BOSS DR12 (BAO+shape) + H_0:

N_{eff} = 3.28 +/- 0.16

(BOSS collab., arXiv:1607.03155)