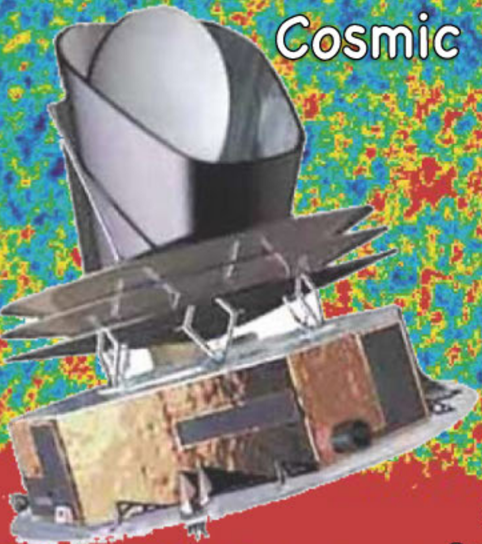
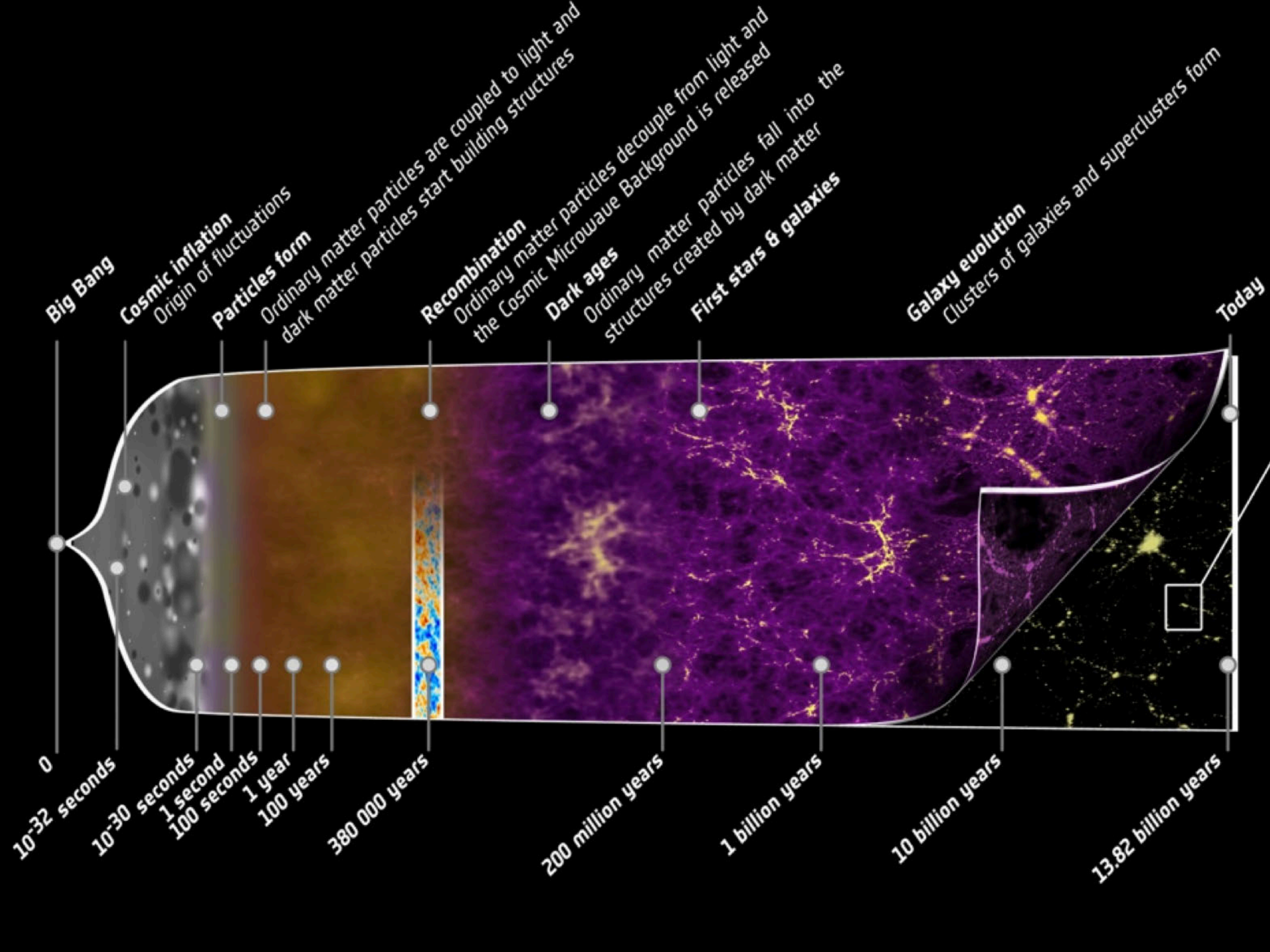
Cosmology with the Cosmic Microwave Background the Planck view

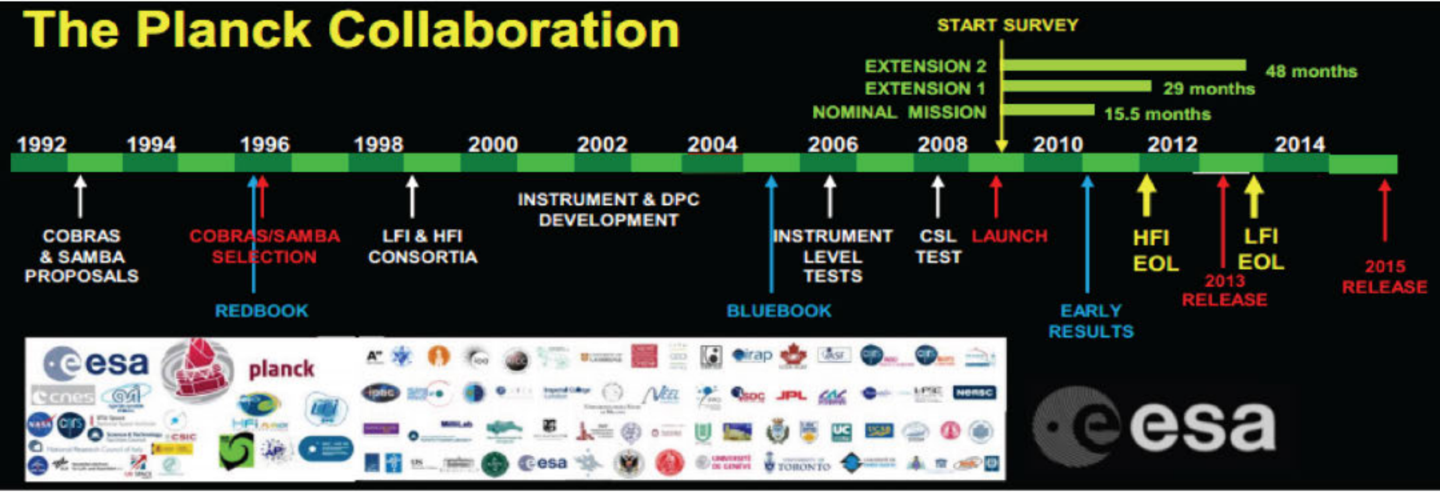


Marina Migliaccio
SSDC – ASI & INFN, Rome, Italy
On behalf of the Planck Collaboration

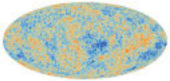
PACIFIC 2018 – 18th February 2018



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

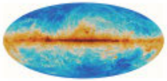


May 2009: Launched from Kourou



Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data — 32 papers

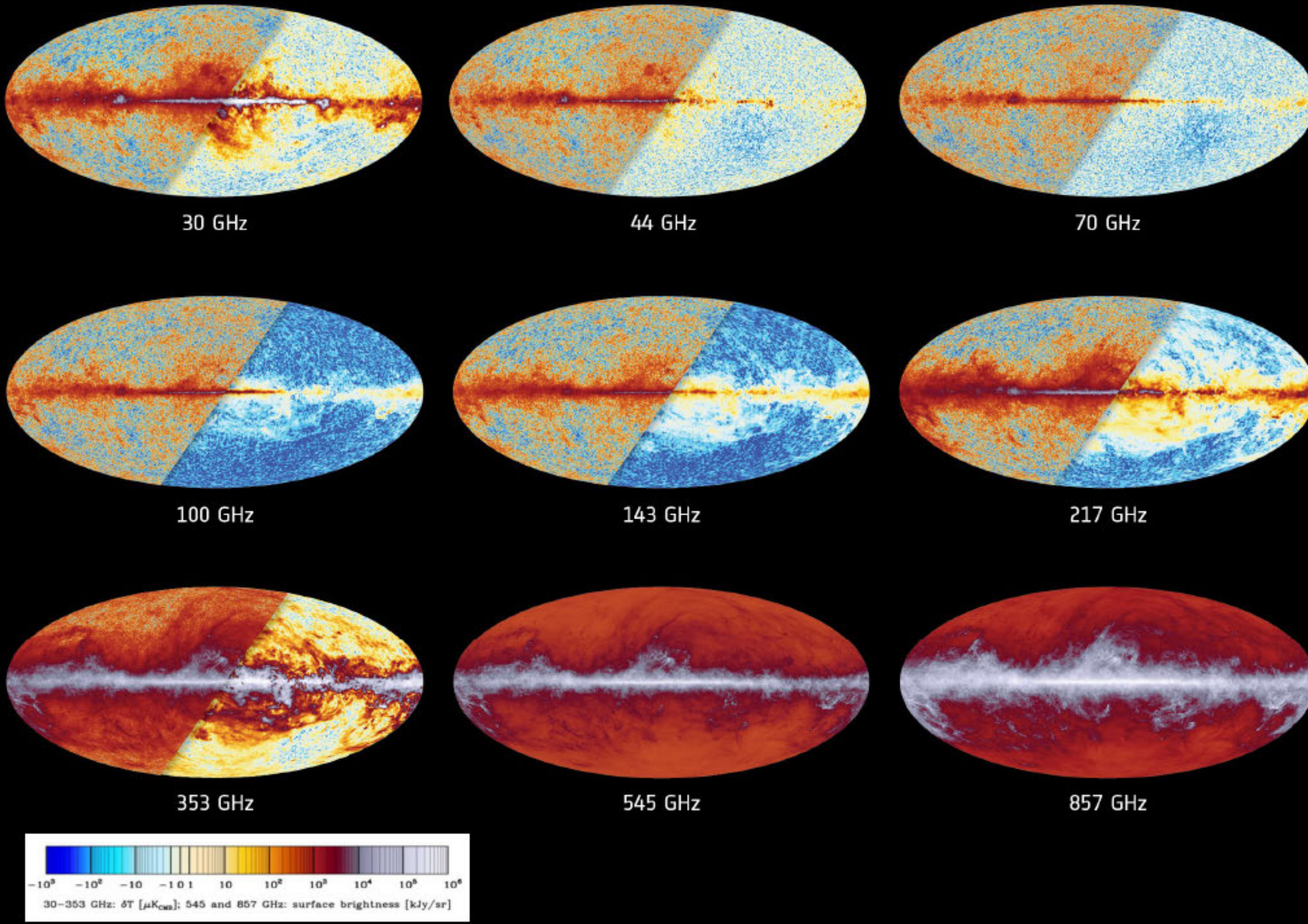
Oct 2013: Planck 'Shut Down' — 55 papers / intermediate results



Feb 2015: Data Release and Cosmology Results
Full Mission Temperature and (preliminary) Polarization data — 28 papers

2018: Legacy Data & Paper Release

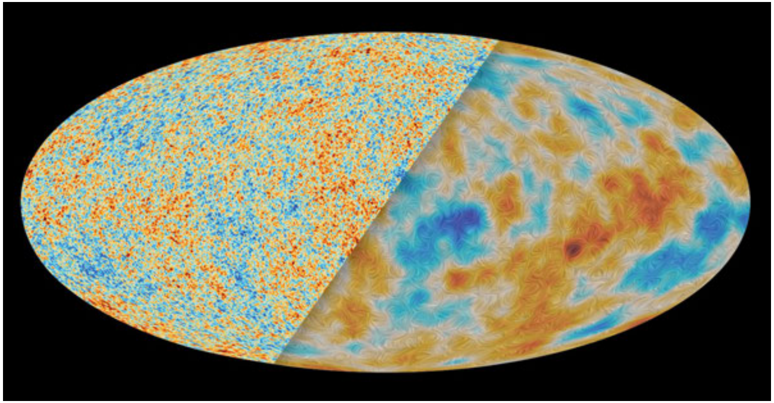
THE SKY AS SEEN BY PLANCK

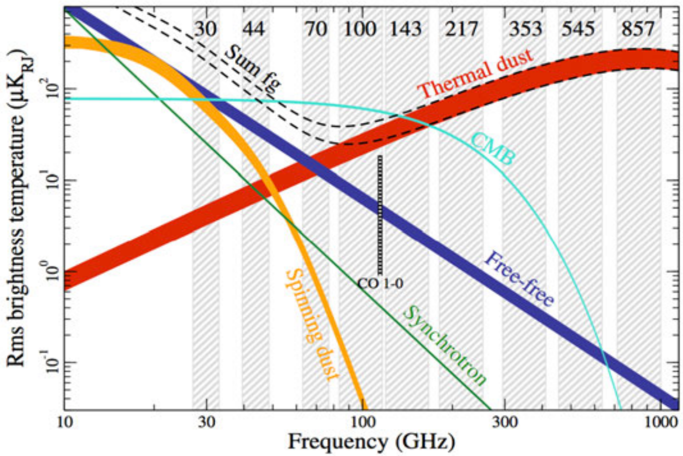


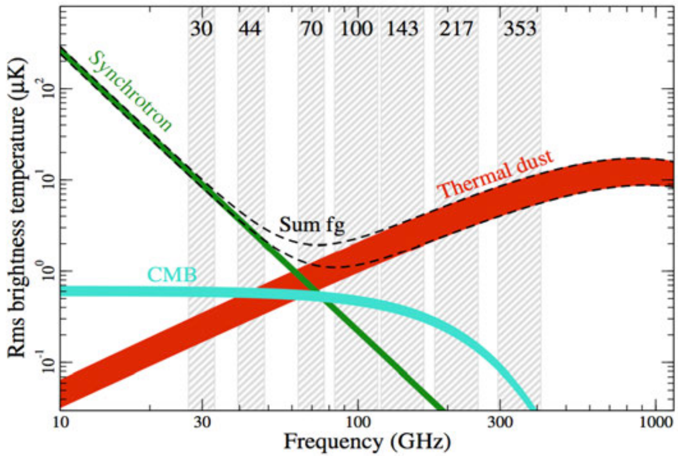
European Space Agency

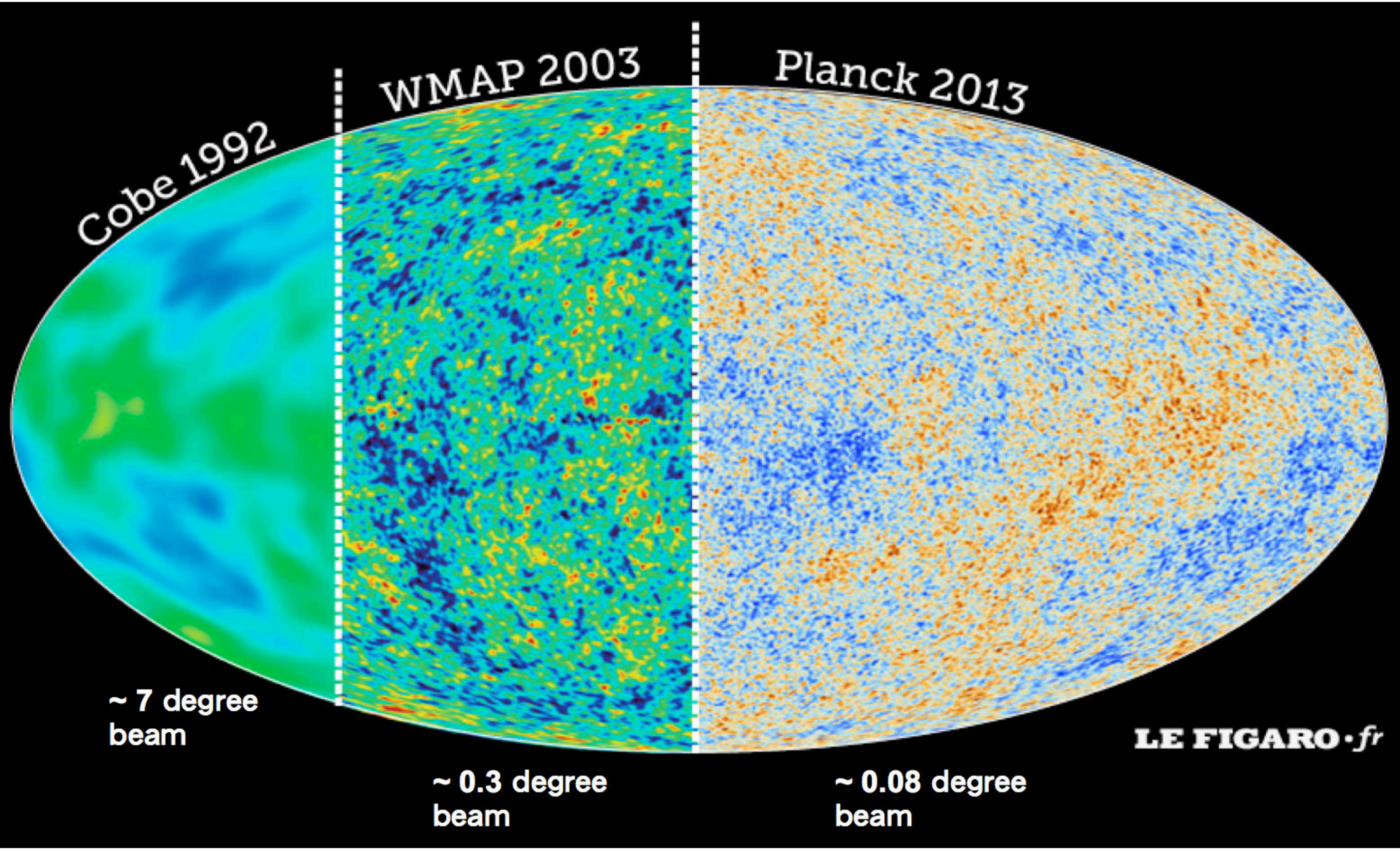
UNVEILING THE CMB SKY

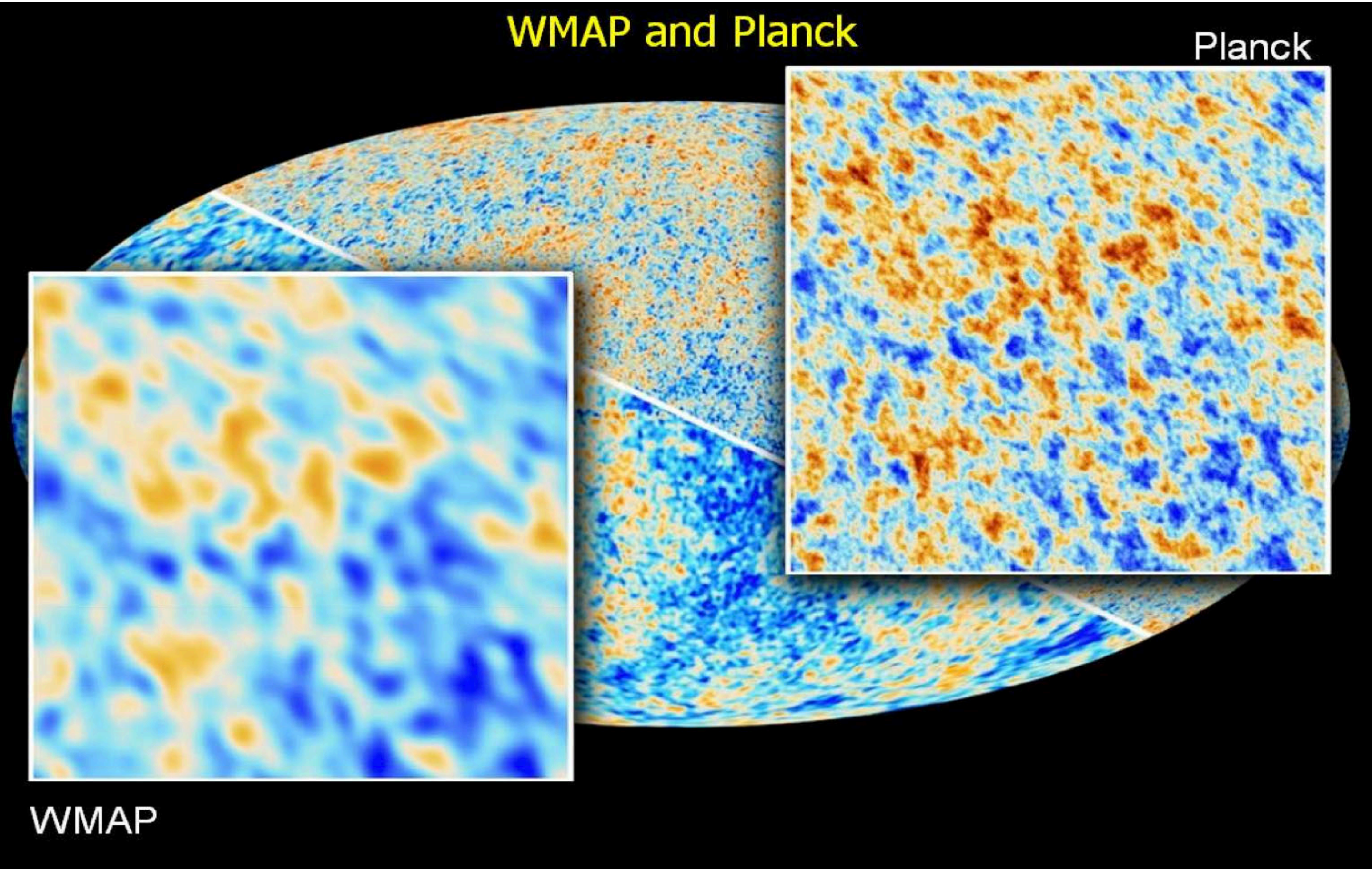
The *ultimate* measurement of the CMB temperature anisotropy field



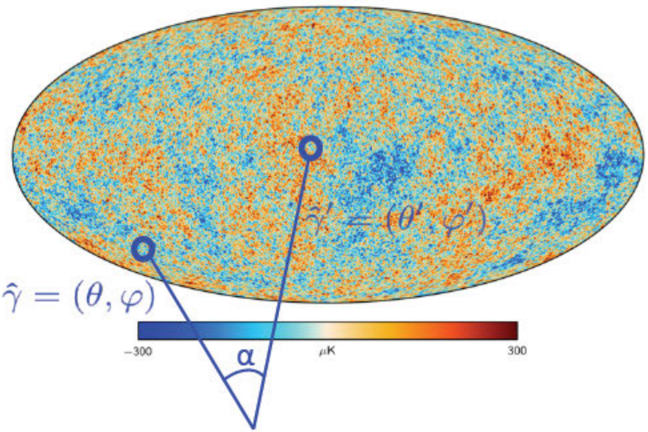





Cobe 1992
WMAP 2003
Planck 2013
~ 7 degree
beam
~ 0.3 degree
beam
~ 0.08 degree
beam
LE FIGARO·fr


WMAP and Planck
Planck
WMAP

STATISTICAL DESCRIPTION – AT SMALL ANGULAR SCALES



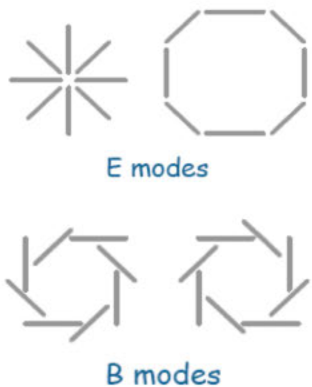
CORRELATION FUNCTIONS

$$C(\alpha) \equiv \left\langle \frac{\Delta T}{T}(\hat{\gamma}) \frac{\Delta T}{T}(\hat{\gamma}') \right\rangle$$ ← from Inflation

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \frac{\Delta T}{T}(\vec{\gamma}'') \right\rangle$$

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \frac{\Delta T}{T}(\vec{\gamma}'') \frac{\Delta T}{T}(\vec{\gamma}''') \right\rangle$$

...



POLARIZATION

$$\mathbf{P}(\hat{\gamma}) = \nabla \mathbf{E} + \nabla \times \mathbf{B}$$

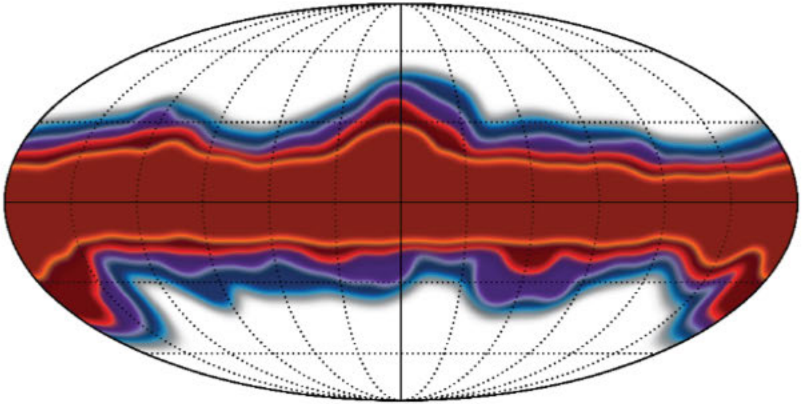
E-modes: even under parity

B-modes: odd under parity

Density perturbations -> E-modes

Gravitational Waves -> E- and B-modes

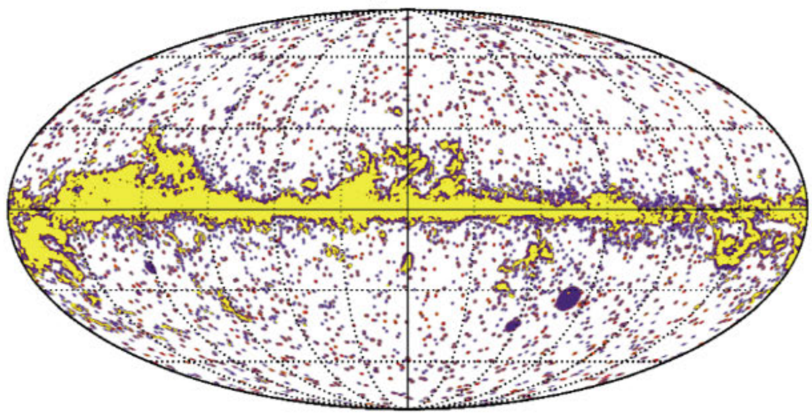
Galactic Masks



Masks used for the high-ℓ analysis.

Frequency [GHz]	Mask	
	Temperature	Polarization
100	T66	P70
143	T57	P50
217	T47	P41

CO and Compact Source Mask



PARAMETRIC MODEL

$$-\ln \mathcal{L}(\hat{\boldsymbol{C}}|\boldsymbol{C}(\theta)) = \frac{1}{2}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right]^{\mathsf{T}} \mathsf{C}^{-1}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right] + \text{const.}$$

16 spectra in total

$$\hat{\boldsymbol{C}} = \left(\hat{\boldsymbol{C}}^{TT}, \hat{\boldsymbol{C}}^{EE}, \hat{\boldsymbol{C}}^{TE}\right)$$

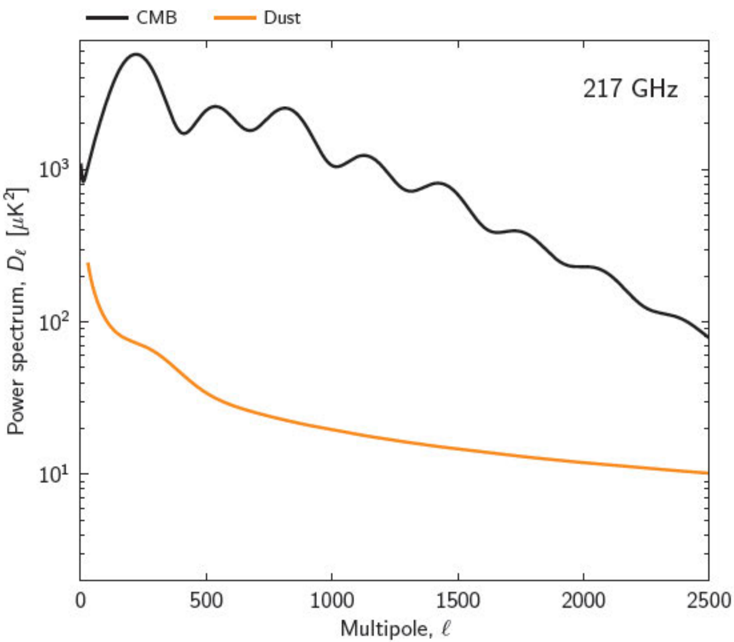
$$\hat{\boldsymbol{C}}^{TT} = \left(\hat{\boldsymbol{C}}^{TT}_{100\times100}, \hat{\boldsymbol{C}}^{TT}_{143\times143}, \hat{\boldsymbol{C}}^{TT}_{143\times217}, \hat{\boldsymbol{C}}^{TT}_{217\times217}\right)$$

$$\hat{\boldsymbol{C}}^{EE} = \left(\hat{\boldsymbol{C}}^{EE}_{100\times100}, \hat{\boldsymbol{C}}^{EE}_{100\times143}, \hat{\boldsymbol{C}}^{EE}_{100\times217}, \hat{\boldsymbol{C}}^{EE}_{143\times143}, \hat{\boldsymbol{C}}^{EE}_{143\times217}, \hat{\boldsymbol{C}}^{EE}_{217\times217}\right)$$

$$\hat{\boldsymbol{C}}^{TE} = \left(\hat{\boldsymbol{C}}^{TE}_{100\times100}, \hat{\boldsymbol{C}}^{TE}_{100\times143}, \hat{\boldsymbol{C}}^{TE}_{100\times217}, \hat{\boldsymbol{C}}^{TE}_{143\times143}, \hat{\boldsymbol{C}}^{TE}_{143\times217}, \hat{\boldsymbol{C}}^{TE}_{217\times217}\right)$$

$\boldsymbol{C}(\theta)$ = CMB theoretical spectra plus physically motivated templates for the foregrounds
θ = {cosmological and nuisance (foreground and instrumental) parameters}

PARAMETRIC FOREGROUND MODEL



Galactic Dust Model

$$\left(C^{XY,\mathrm{dust}}_{\nu\times\nu'}\right)_\ell = A^{XY,\mathrm{dust}}_{\nu\times\nu'} \times C^{XY,\mathrm{dust}}_\ell$$

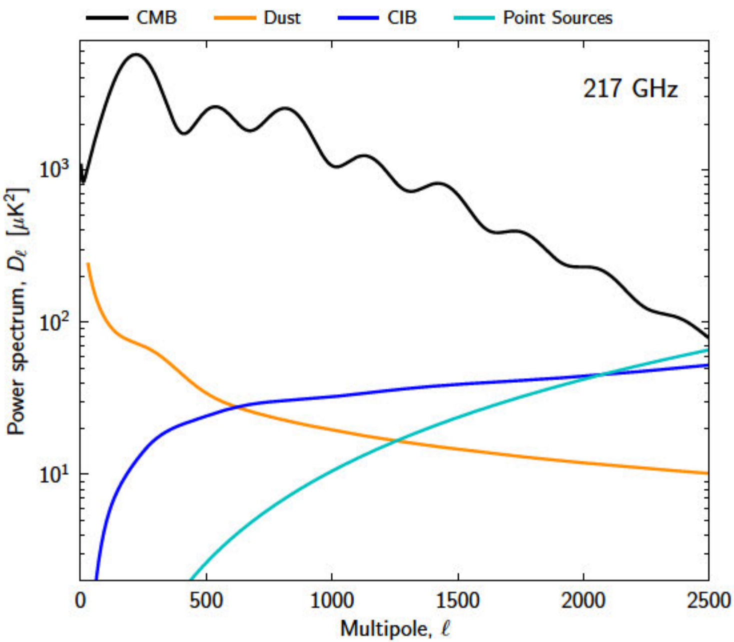
Temperature

C_ℓ^{dust} from 545 GHz, 4 A^{dust} parameters

Polarization

C_ℓ^{dust} from 353 GHz, 12 A^{dust} parameters

PARAMETRIC FOREGROUND MODEL



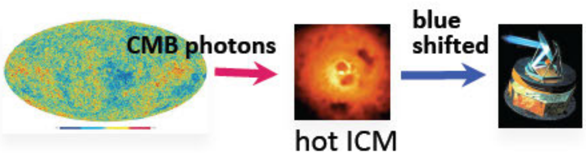
Unresolved Extragalactic Sources

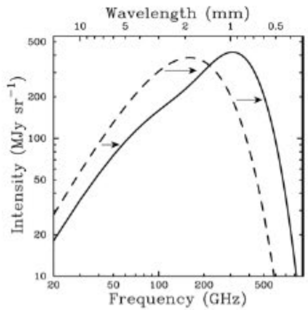
- Shot noise from Poisson fluctuations in the number density of point sources. C_ℓ^{PS} and 4 A^{PS} parameters

- Power due to clustering of high-redshift dusty star forming galaxies that trace large-scale structures: Cosmic Infrared Background (Planck Collaboration XXX. 2014,A&A, 571, A30). C_ℓ^{CIB} and 1 A^{CIB} parameter

SUNYAEV-ZEL'DOVICH EFFECT

Thermal SZ: Signal caused by inverse-Compton scattering of CMB photons (~ 3 meV) by the hot plasma in clusters of galaxies (~ a few keV). C_ℓ^{tSZ} from Efstathiou & Migliaccio 2012, 1 A^{SZ} parameter.



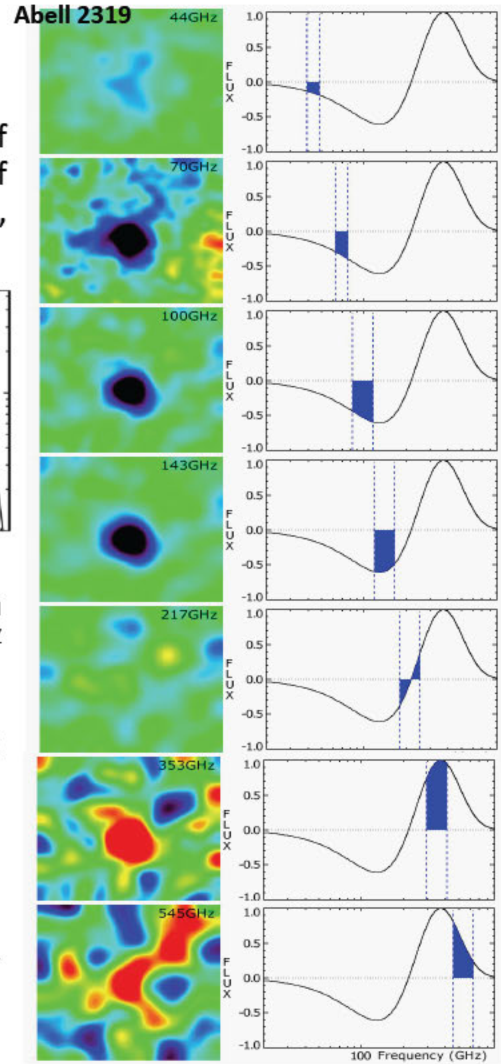


Kinetic SZ: CMB photons are scattered by electrons in bulk motion. C_ℓ^{kSZ} from Trac, Bode & Ostriker 2011, 1 A^{kSZ} parameter.

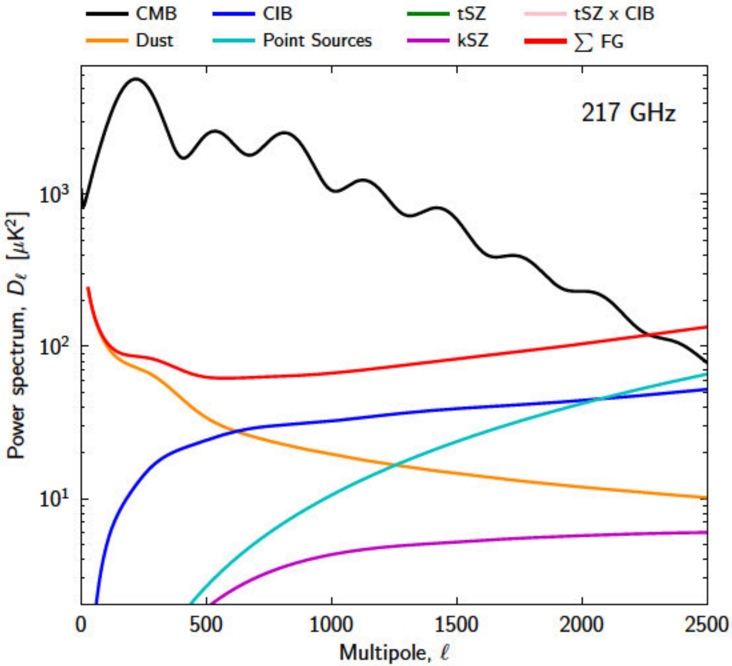
We also impose the 2D prior derived from a joint analysis with ACT and SPT

$$\mathcal{D}_\ell^{kSZ} + 1.6\,\mathcal{D}_\ell^{tSZ} = (9.5 \pm 3)\,\mu\mathrm{K}^2$$

tSZ x CIB: correlation between the tSZ and CIB sources. $C_\ell^{tSZ \times CIB}$ model from Addison et al. 2012. 1 $A^{tSZ \times CIB}$ parameter

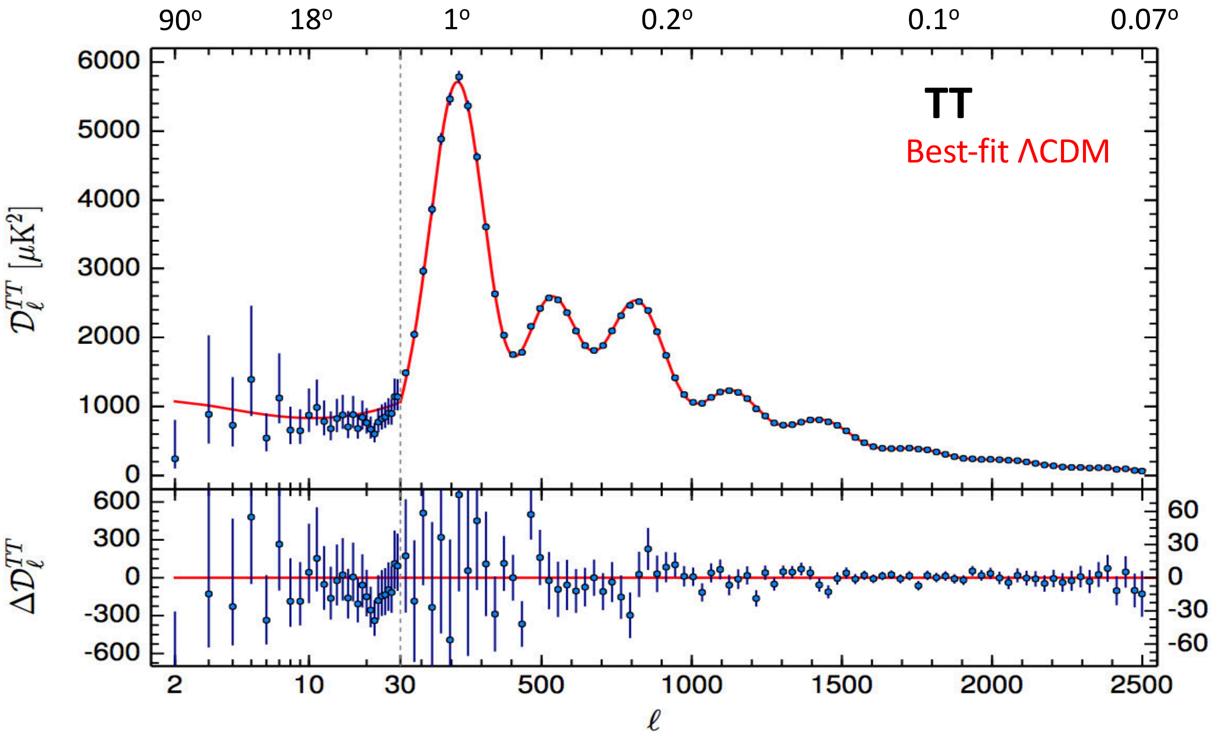


PARAMETRIC FOREGROUND MODEL



After fitting and removing the foreground model to the data, we find a very good agreement among the CMB angular power spectra estimated from different frequencies. Each of them is a good fit to the ΛCDM model.

CMB temperature power spectrum

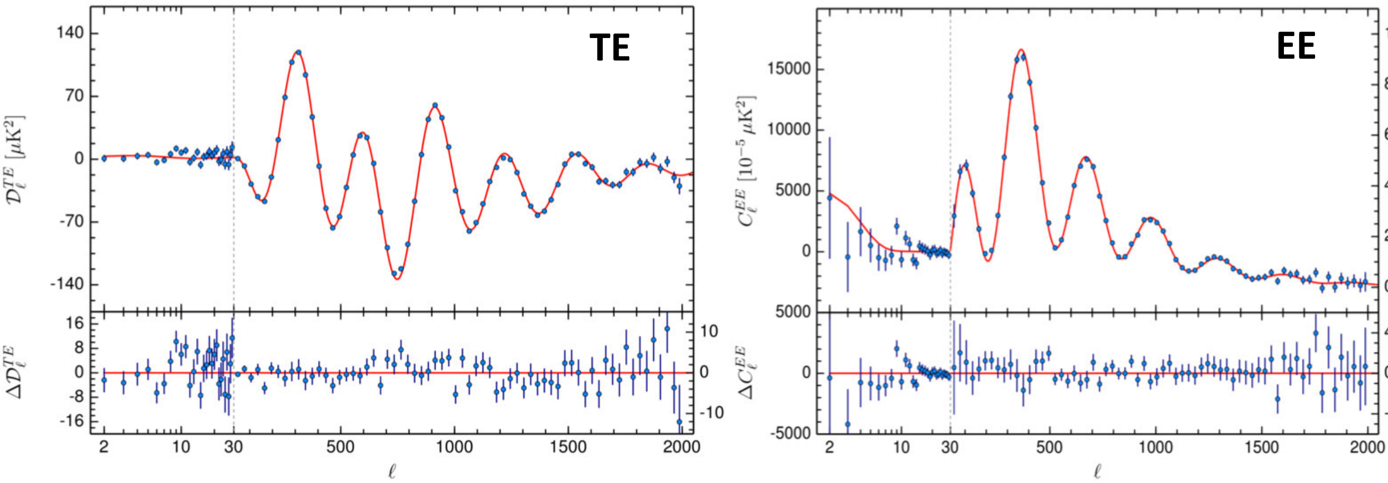


Cosmic Variance Limited up to ℓ =1600, sky fraction =75-40%

As good as it gets for cosmological parameters

ΛCDM is an excellent fit to Planck data: χ^2 = 2545 with 2479 d.o.f. → PTE = 17%

POLARIZATION POWER SPECTRA



Red line is the best-fit cosmology from temperature data: success of the ΛCDM model

Residual low level systematics are still unaccounted for O(1 uK^2) (e.g., T → P leakage,…)

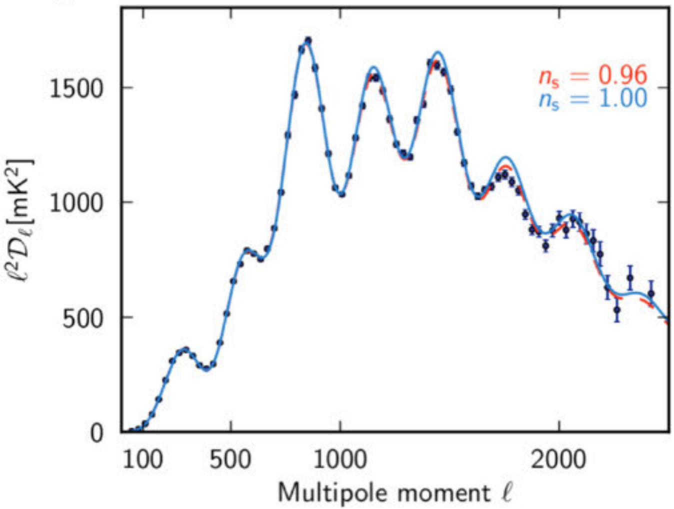
Base ΛCDM

Fully described by 6 parameters

High precision: parameter estimates even better than 1%
Improves on pre-Planck constraints by a factor 1.5 - 2

Parameter	[1] *Planck* TT+lowP	
$\Omega_b h^2$	0.02222 ± 0.00023	Agreement with BBN predictions with 4 times smaller uncertainties
$\Omega_c h^2$	0.1197 ± 0.0022	
$100\theta_{MC}$	1.04085 ± 0.00047	Best measured parameter 0.045% !!
τ	0.078 ± 0.019	Improved constraint expected in 2018
$\ln(10^{10} A_s)$	3.089 ± 0.036	
n_s	0.9655 ± 0.0062	Supports inflationary paradigm: 6σ from scale invariance
H_0	67.31 ± 0.96	
Ω_m	0.315 ± 0.013	
σ_8	0.829 ± 0.014	
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	

$$P(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$



Inflationary Gravitational Waves

Upper limits on primordial tensor modes. The constraints from Planck temperature are already cosmic variance limited.

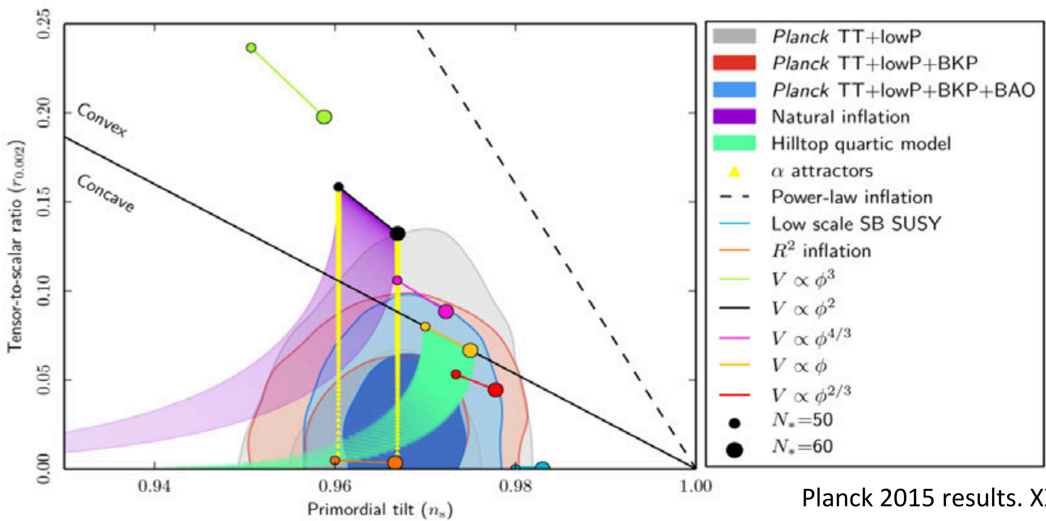
To improve we need direct detection of primordial B-modes.

Bicep2/Keck Array + Planck BB
$r_{0.05} < 0.09$ @95% CL
constraints from B-modes alone are already stronger than temperature

Bicep2/Keck Array + Planck BB & TT
$r_{0.05} < 0.07$ @95% CL

Phys. Rev. Lett. 116 (2016)

$$\frac{A_T}{A_S}$$



Planck 2015 results. XX

Inflationary Gravitational Waves

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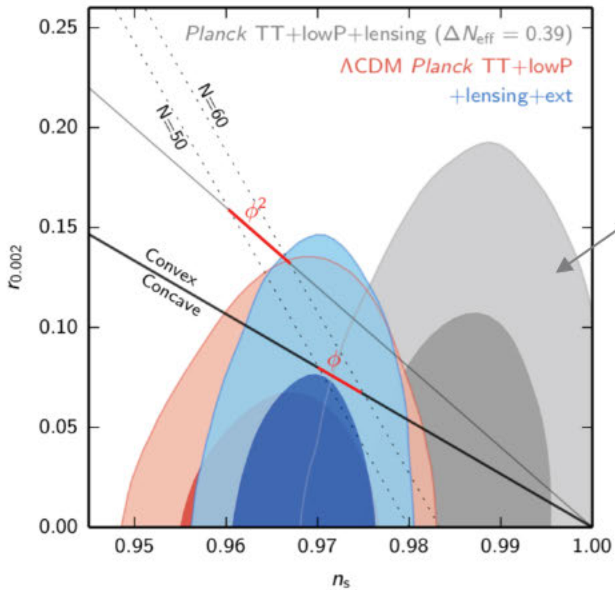
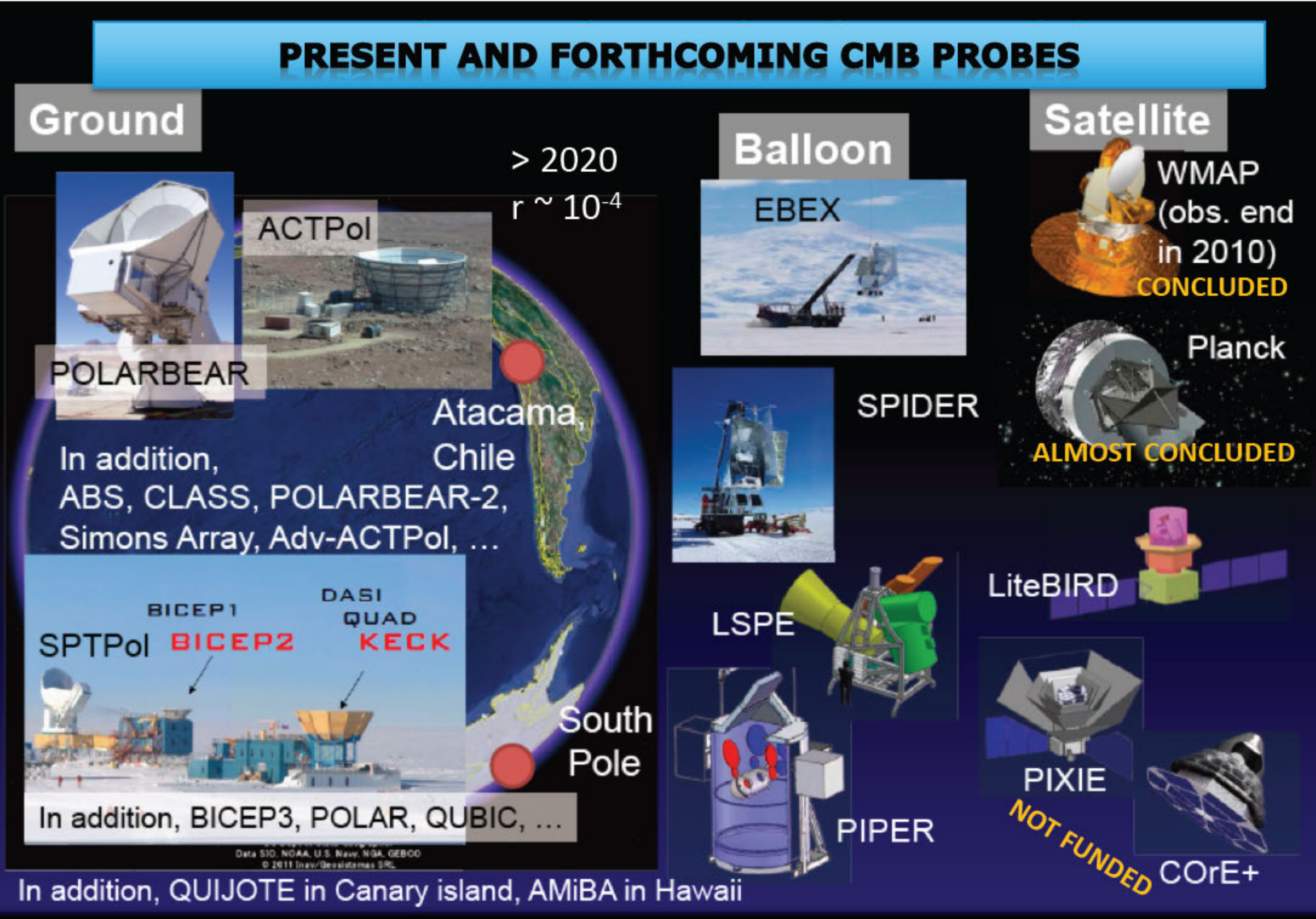
Phys. Rev. Lett. 116 (2016)



Constraints from Temperature are also model dependent.
Disfavoured but not excluded by Planck

Planck 2015 results. XIII


PRESENT AND FORTHCOMING CMB PROBES
Ground
> 2020
r ~ 10-4
ACTPol
POLARBEAR
Atacama, Chile
In addition,
ABS, CLASS, POLARBEAR-2,
Simons Array, Adv-ACTPol, …
DASI
QUAD
BICEP1
SPTPol
BICEP2
KECK
South Pole
In addition, BICEP3, POLAR, QUBIC, …
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2011 Inav/Geosistemas SRL
In addition, QUIJOTE in Canary island, AMiBA in Hawaii
Balloon
EBEX
SPIDER
LSPE
PIPER
Satellite
WMAP
(obs. end
in 2010)
CONCLUDED
Planck
ALMOST CONCLUDED
LiteBIRD
PIXIE
NOT FUNDED
COrE+

Base ΛCDM

Fully described by 6 parameters

High precision: parameter estimates even better than 1%

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

(68% CL)

Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

$$\Omega_k = -0.052^{+0.049}_{-0.055}$$

No evidence for curvature

$$Y_P = 0.252^{+0.041}_{-0.042}$$

In agreement with measurements of primordial abundances and BBN predictions

$$\frac{dn_s}{d\ln k} = -0.008 \pm 0.016$$

Consistent with no running of the spectral index

$$w = -1.54^{+0.62}_{-0.50}$$

Dark Energy EoS compatible with a cosmological constant

Planck TT + LowP (95% Confidence Regions)

Base ΛCDM

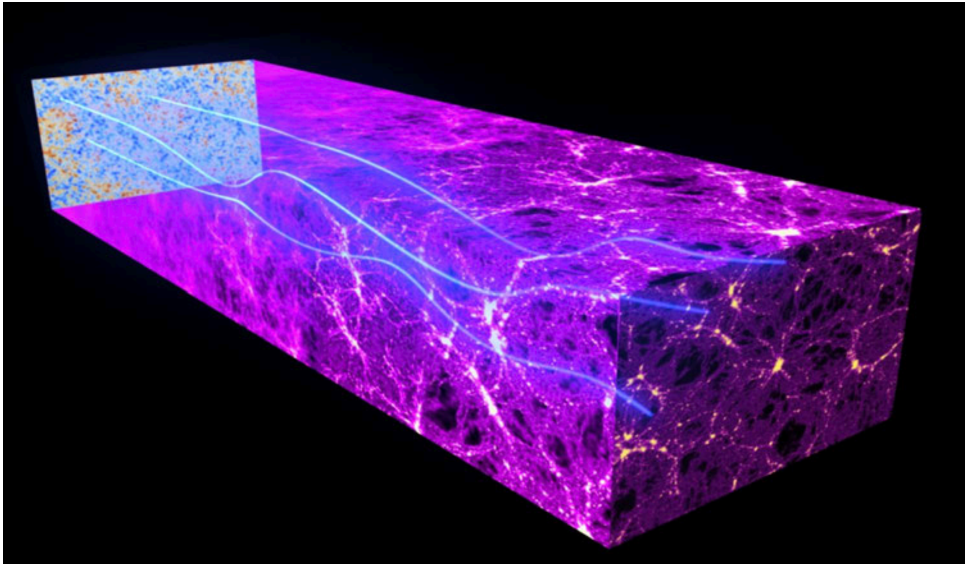
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 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

Almost independent determinations from polarized spectra - **good consistency**
TT → EE at most 1σ shifts
TT → TE at most 0.5σ shifts
TE results are already almost as powerful as TT

The good agreement of the angular power spectra was shown in a previous slide

Gravitational Lensing

The gravitational tug of the intervening large scale structure distorts photon paths. Deflections ~ 2 arcmin, coherent over 2 degree scales. A subtle effect that may be measured statistically with high angular resolution, low-noise observations of the CMB, like those from Planck.



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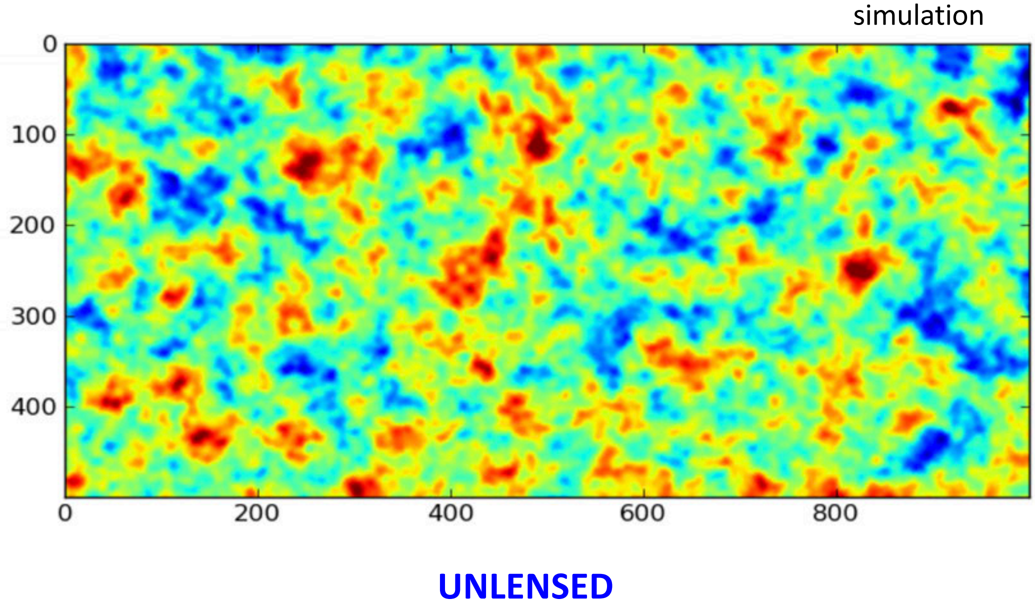
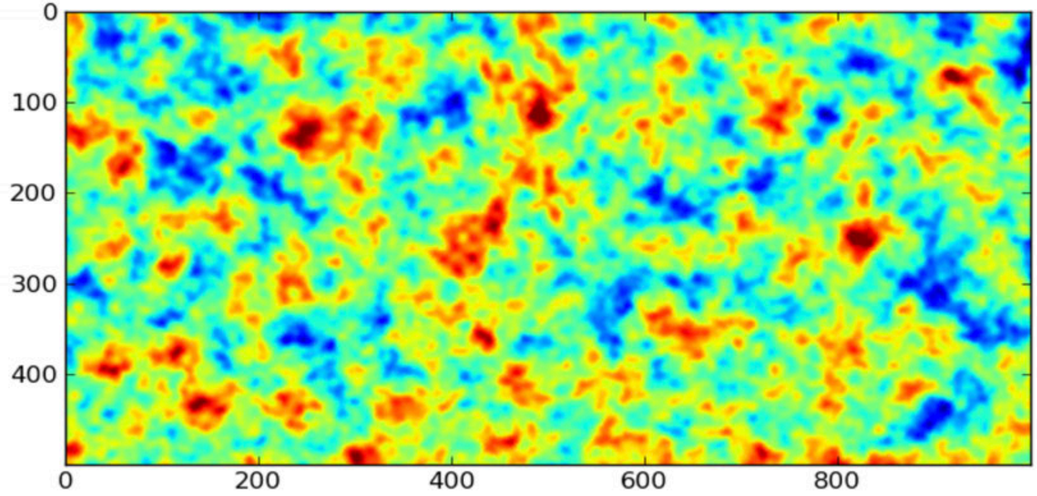


Gravitational Lensing

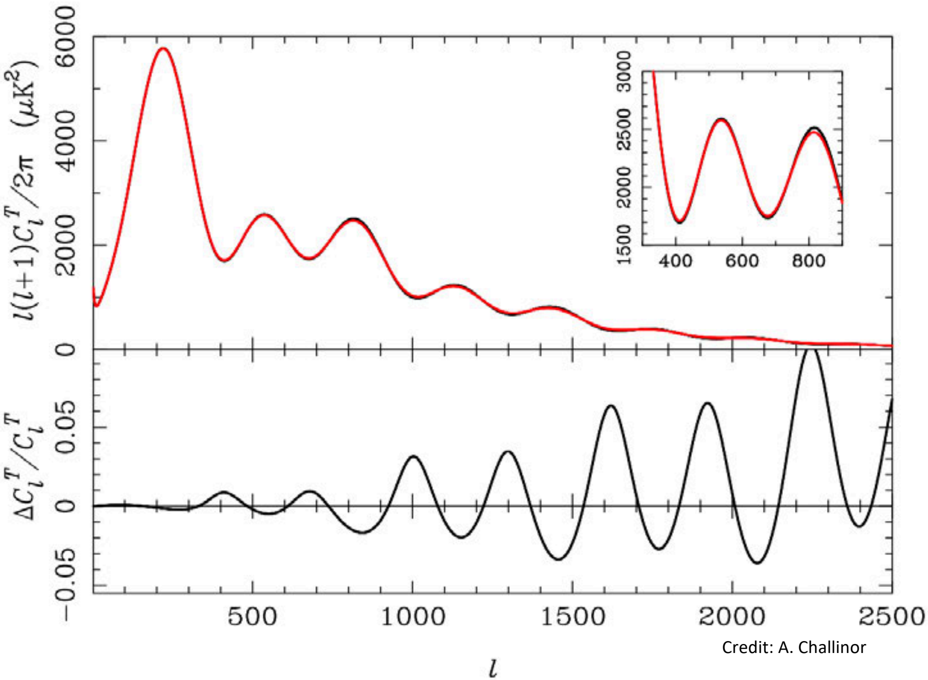
The gravitational tug of the intervening large scale structure distorts photon paths. Deflections ~ 2 arcmin, coherent over 2 degree scales. A subtle effect that may be measured statistically with high angular resolution, low-noise observations of the CMB, like those from Planck.

simulation



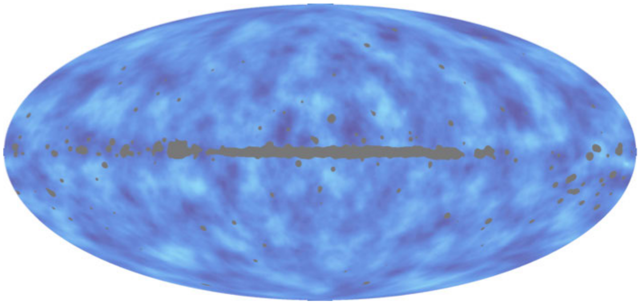
LENSED

Gravitational Lensing



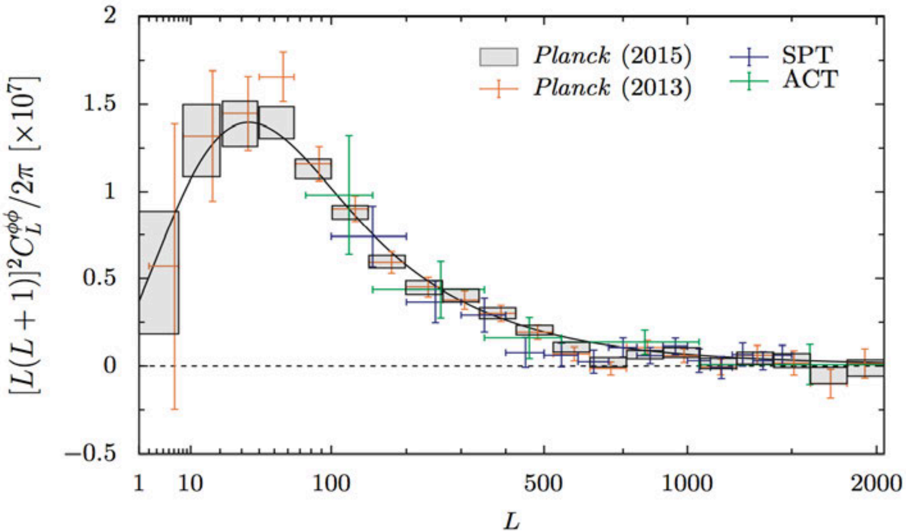
Credit: A. Challinor

Gravitational Lensing



Deflections induce a distinctive non-Gaussianity -> 4pt correlation function -> gravitational potential

Planck 2015 results. XV



Amplitude constrained to ~ 2.5%
40 sigma detection

Breaks degeneracies in constraining: Dark Matter, Large scale structure evolution, Curvature, Neutrino masses, …

ΛCDM: a success story...

Good agreement between Planck CMB Temperature, Polarization and Lensing

Planck measurements consistent with other CMB experiments (e.g. WMAP, ACT and SPT), with Baryon Acoustic Oscillation, Type Ia SN.

Tensions with some low-z observables

PLANCK

$H_0 = 67.31 \pm 0.96$ km $s^{-1}Mpc^{-1}$ (PlanckTT+LFI LowP)

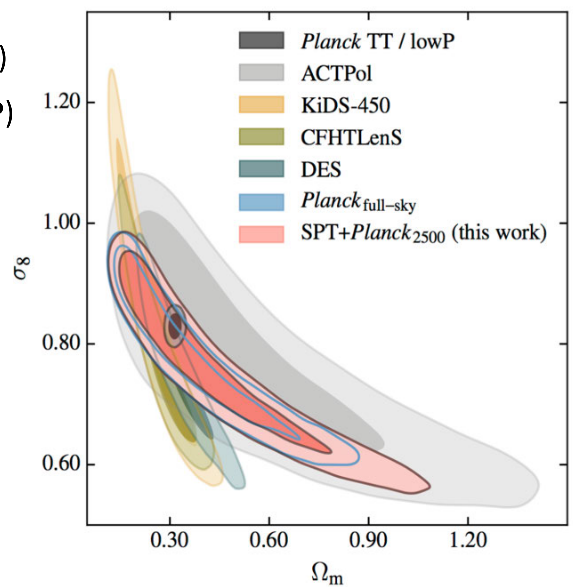
$H_0 = 66.88 \pm 0.91$ km $s^{-1}Mpc^{-1}$ (PlanckTT+HFI LowP)

DIRECT MEASUREMENTS (Riess et al. 2016)

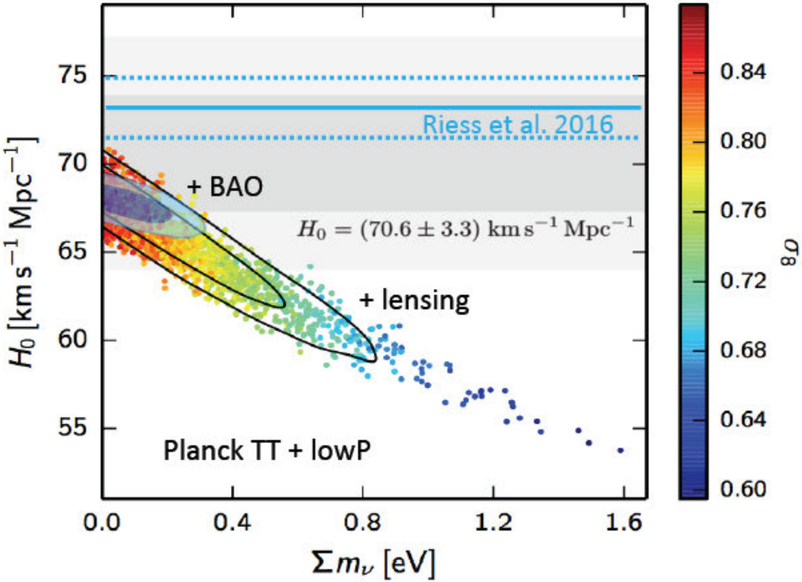
$H_0 = 73.24 \pm 1.74$ km $s^{-1}Mpc^{-1}$

σ_8 from Planck > estimates from optical weak lensing surveys and (possibly) large galaxy clusters number counts.

G. Simard et al. SPT Collaboration 2018



Can deviations in the neutrino sector reconcile the tensions?



Massive neutrinos damp the amplitude of matter fluctuations but are not enough to solve the tension with Large-Scale Structure measurements of σ_8

Larger neutrino masses increase the tension with direct H_0 measurements

Planck TT + lowP	**Planck 2015 + BOSS Lyman-α**	**Planck 2015 + BOSS DR12**
$\Sigma m_\nu < 0.71$ eV (95% CL)	$\Sigma m_\nu < 0.12$ eV (95% CL)	$\Sigma m_\nu < 0.16$ eV (95% CL)
	(Palanque-Delabrouille et al. 2015)	(BOSS collab. 2016)

Can deviations in the neutrino sector reconcile the tensions?

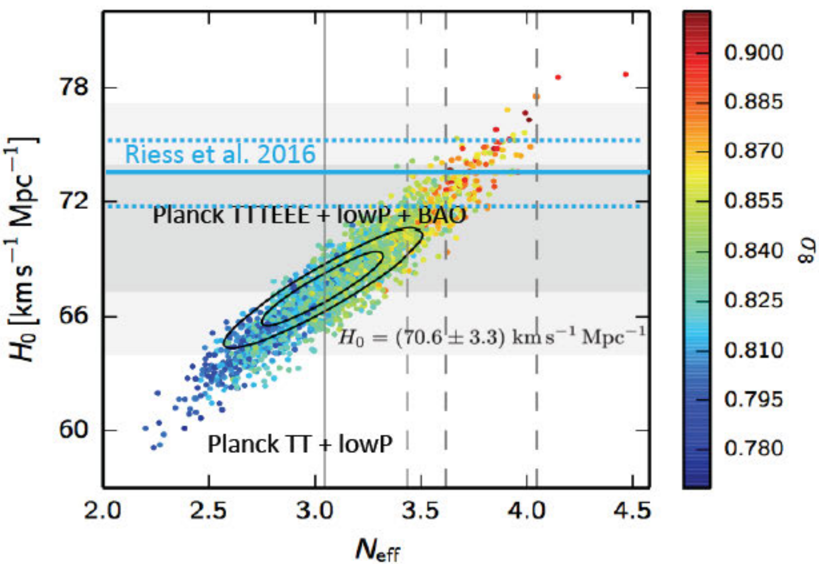
Extra relativistic degrees of freedom in the early Universe. E.g. due to sterile neutrinos, neutrino/antineutrino asymmetry, other dark relics

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

$N_{\rm eff} = 3.04 \pm 0.18$ (PlanckTTTEEE+lowP+BAO)

$N_{\rm eff} > 0$ ~ 15σ detection of the ν background

$N_{\rm eff} = 4$ excluded at ~ 5σ



Higher $N_{\rm eff}$ provides a better agreement with direct H_0 measurements, but increases tension with measurements of σ_8 from Large-Scale Structure

Summary

- ✓ Planck temperature data are more precise than those from any previous CMB experiment -> Ultimate (cosmic variance limited) measurement of CMB anisotropy
- ✓ Main Goal fulfilled: Cosmological parameters determined at unprecedented sub-% precision
- ✓ Opened a new window on polarized foregrounds and CMB polarization science
- ✓ First results from polarization in good agreement with temperature
- ✓ Planck has set the bar high: and yet we find no compelling evidence for new physics beyond the base inflationary ΛCDM model of Cosmology
  –> if there are deviations they ought to be small and challenging to detect
- ✓ There are some tensions with astrophysical low-z measurements, which may or may not hint at new physics. At present, simple extensions to ΛCDM cannot explain all of them.
- ✓ The Planck Legacy Release is approaching (2018)

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