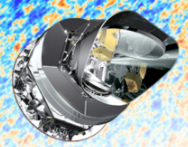


PLANCK

Planck Results

James G. Bartlett

Jet Propulsion Laboratory, California Institute of Technology

Astroparticule et Cosmologie, Université Paris Diderot

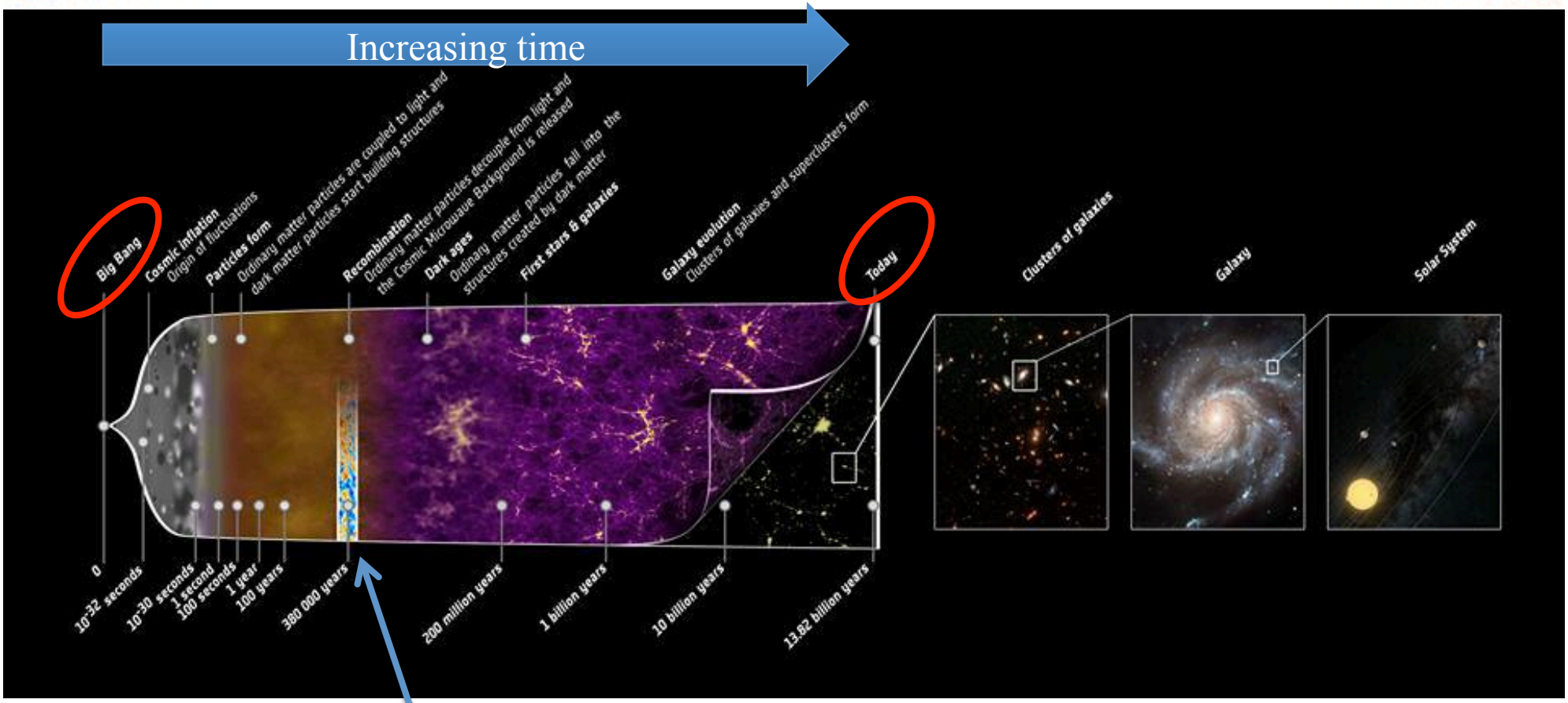
Brookhaven Forum 2015: Great Expectations, a New Chapter

Brookhaven National Laboratory, October 2015

esa

NASA

Vista Point



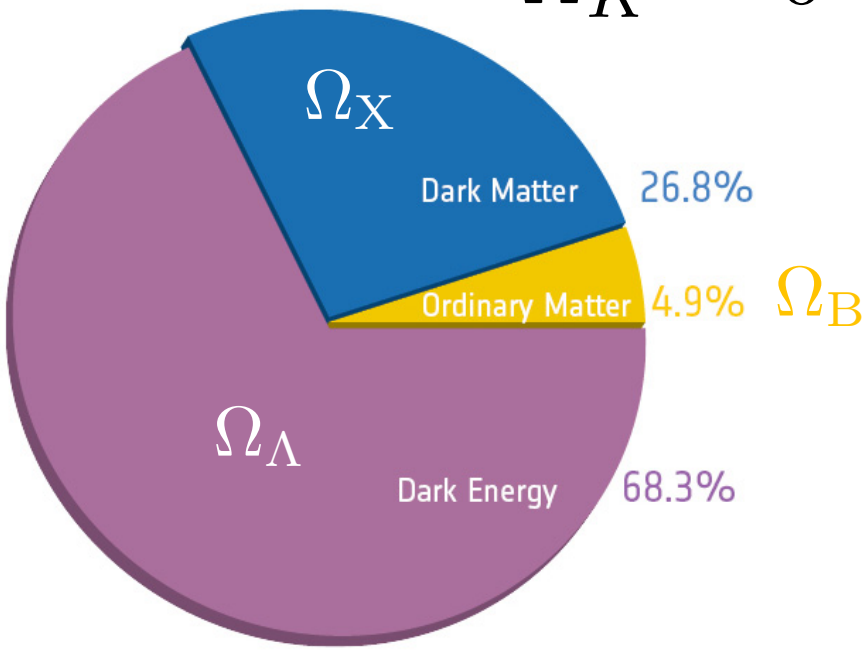
Recombination: "Emission" of cosmic microwave background (CMB)

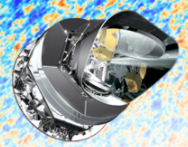
Bottom Line: Flat ΛCDM

- Spectacular success of Flat ΛCDM
  - Six parameters
  - Gaussian adiabatic perturbations
  - Passive evolution
  - Limits on new Physics

- Some curiosities $\lesssim 3\sigma$
  - Tension in large-scale structure
  - Large-scale "anomalies"

$\Omega_K \approx 0$

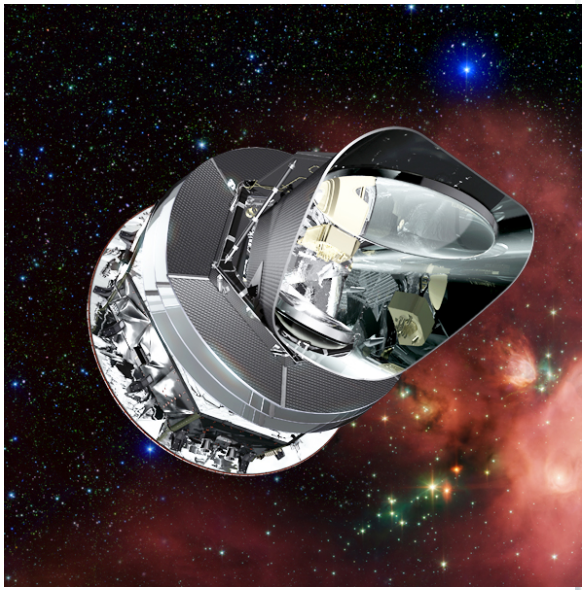




Planck Cosmology Results

- Base ΛCDM
  - Tight constraints
  - Reionization
  - Lensing
  - Consistent with astrophysical measures
  - Curiosities/tensions
- Limits on extensions
  - Curvature
  - Tensors
  - Neutrinos: mass scale, N_{eff}, sterile
  - Dark energy
  - Non-Gaussianity
  - Isocurvature
  - Dark matter annihilation

The *Planck* Mission



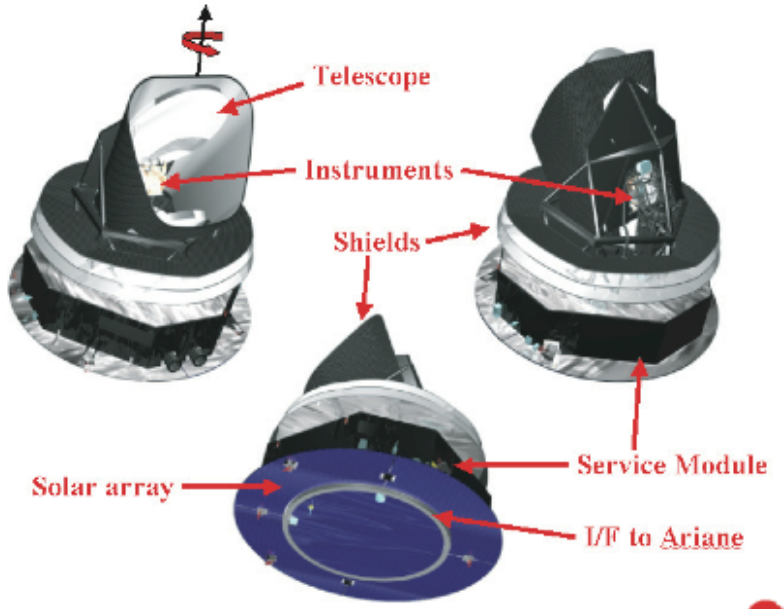
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

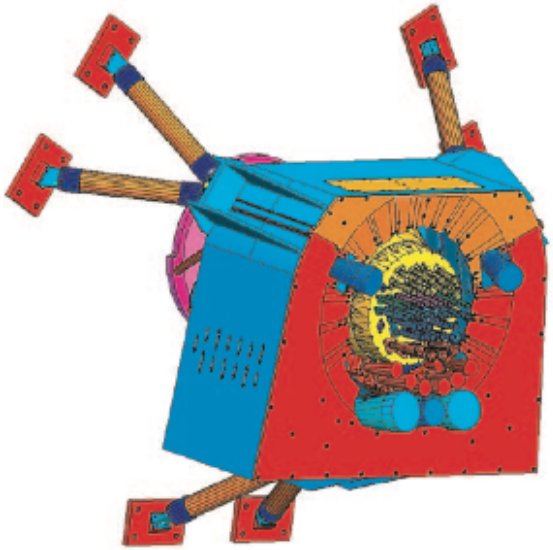
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

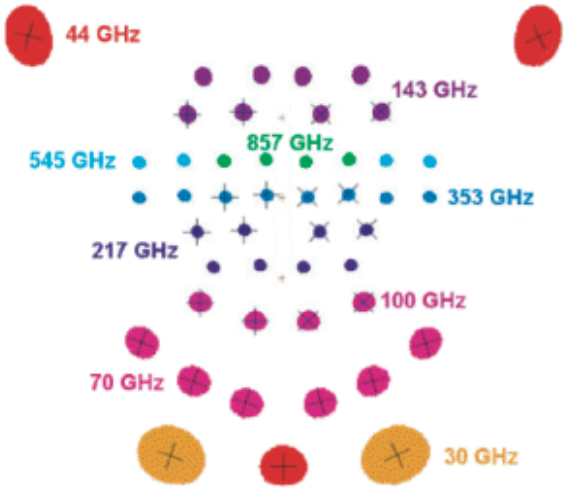
24

Instrument Suite

Two Instruments
- HFI (100-853 GHz)
- LFI (30, 44, 70 GHz)



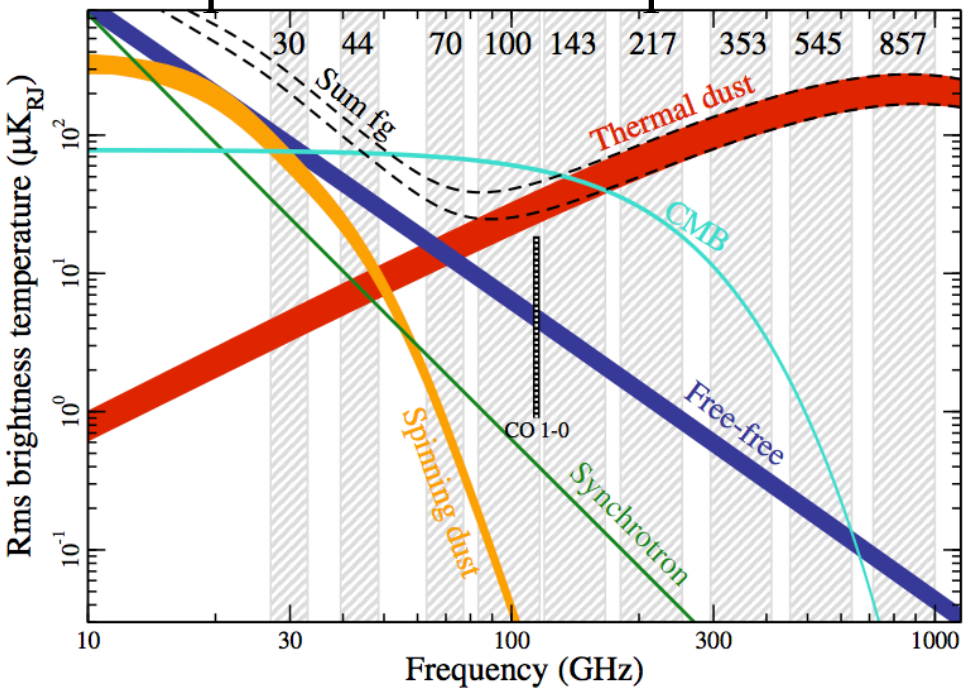




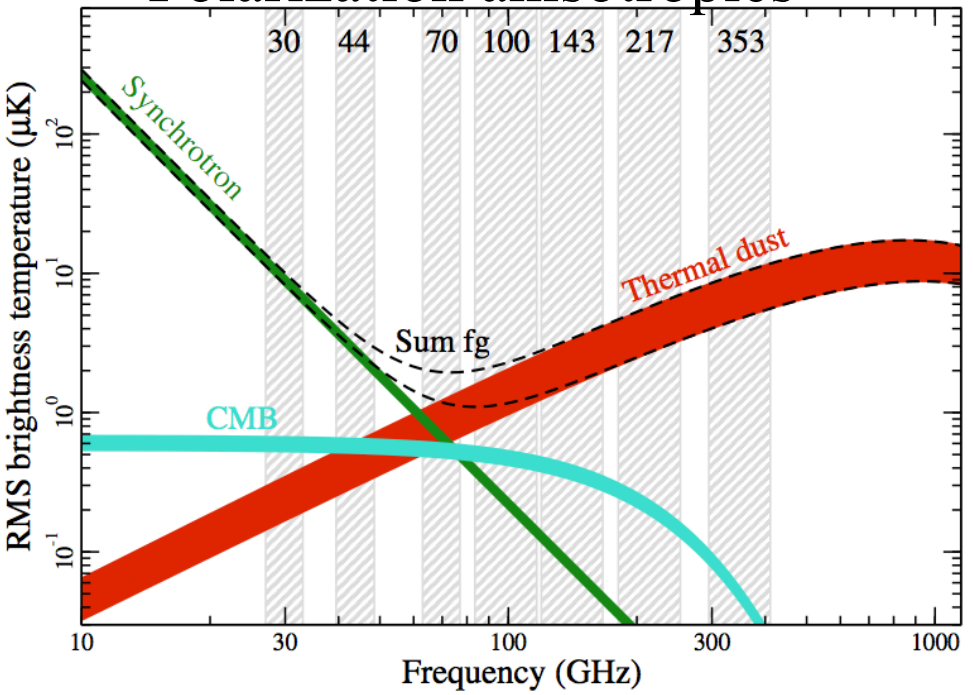
Frequency Coverage: Foregrounds

Planck Collaboration I (2015), Planck Collaboration X (2015)

Temperature anisotropies

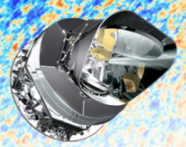


Polarization anisotropies



Launch

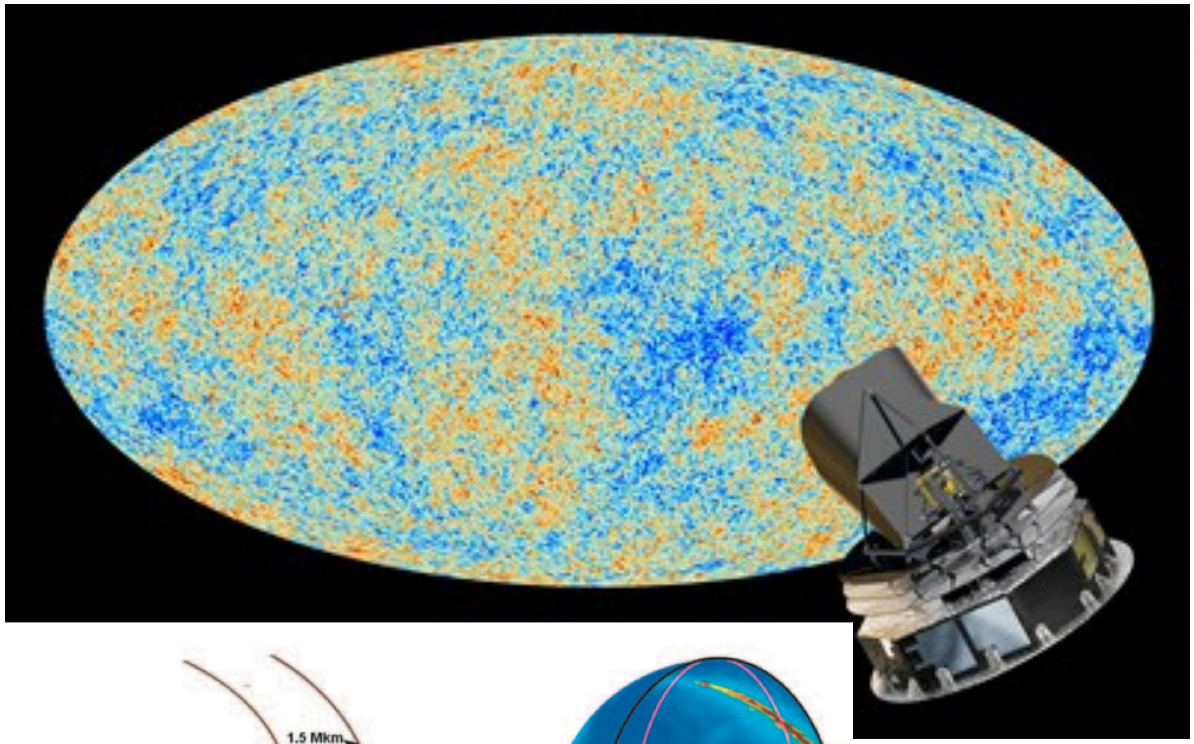
May 14, 2009

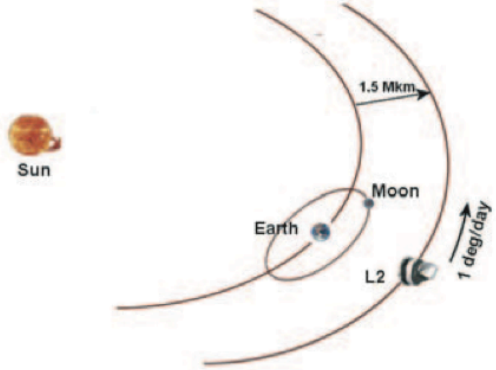


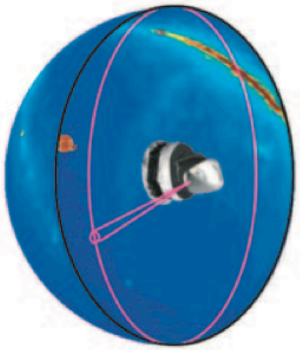
PLANCK

The *Planck* Mission

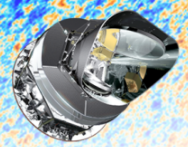
- Launch: 14 May 2009
- Science operations: 12 August 2009
- Early results: 1/2011
- HFI coolant exhausted: 1/2012 – 29 months of science data
- 1st data release: 3/2013 – 15.5 months
- LFI shutdown: 10/2013 – 48 months of science data
- Deorbit L2: 10/2013
- 2nd data release: 2/2015
  - Full mission
  - polarization
- Final data analysis: 2016







esa NASA



PLANCK

Measurements

esa

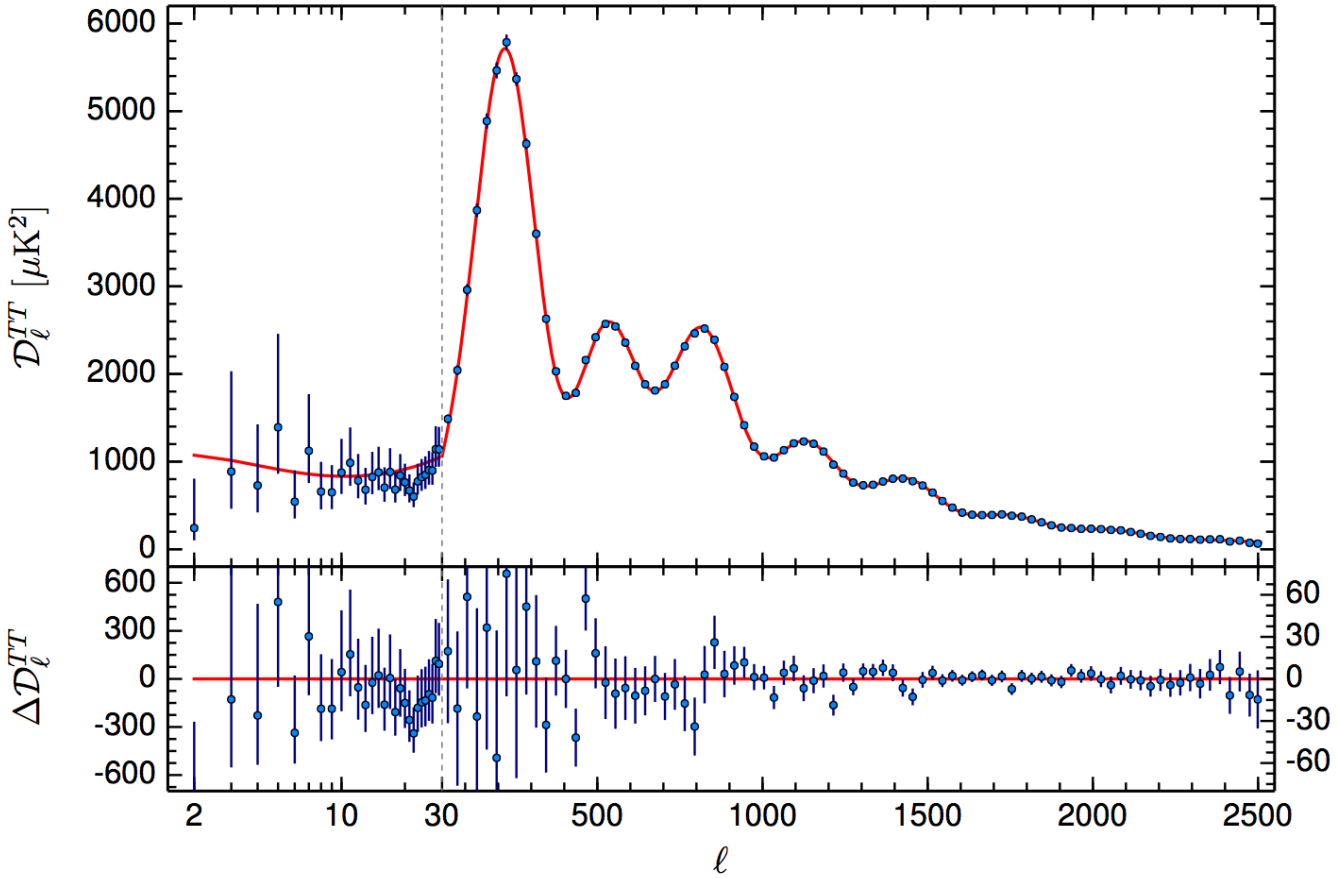
NASA

Planck 2013 ➔2015

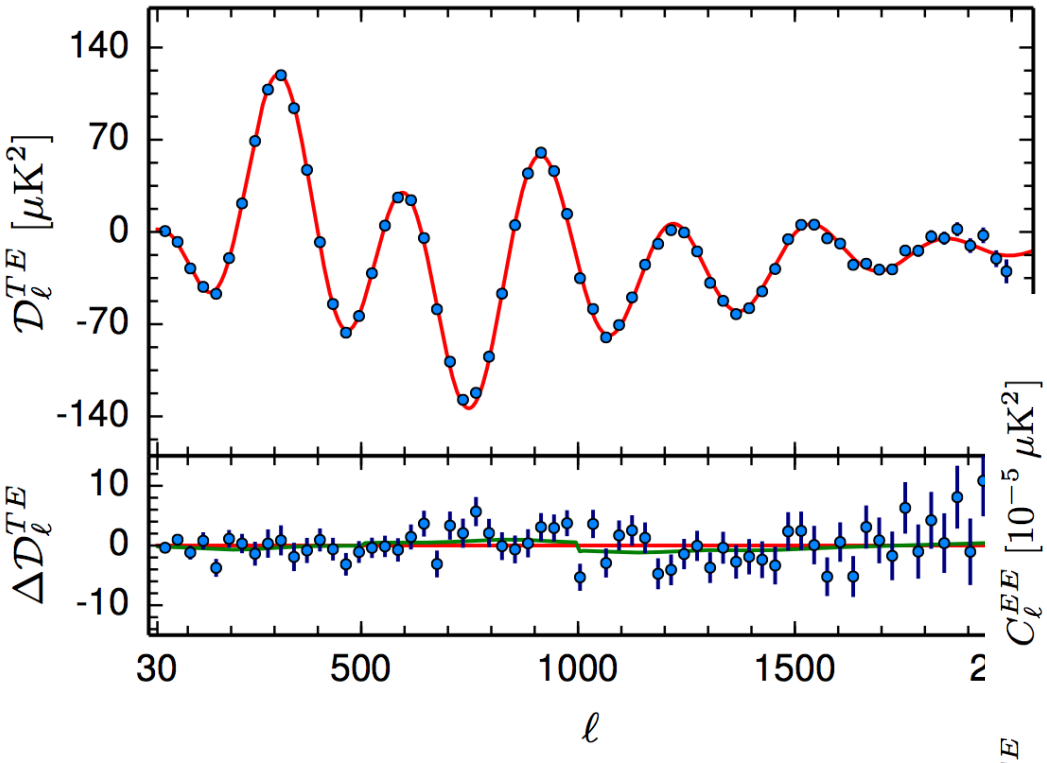
- Absolute calibration (in power) increased
  - Increase by 2% (HFI) and 1.7% (LFI). Both now agree with WMAP to within 0.3%
- Optical depth, τ, decreased
  - 2015 uses *Planck* polarization data: LFI 70 GHz cleaned with 30 and 353 GHz
  - τ = 0.09 (WMAP) ➔ 0.07 $z_{\rm rec} \approx 10$
  - WMAP cleaned with *Planck* 353 GHz now agrees
- More sky used
- Better understanding of systematics

Temperature Power Spectrum

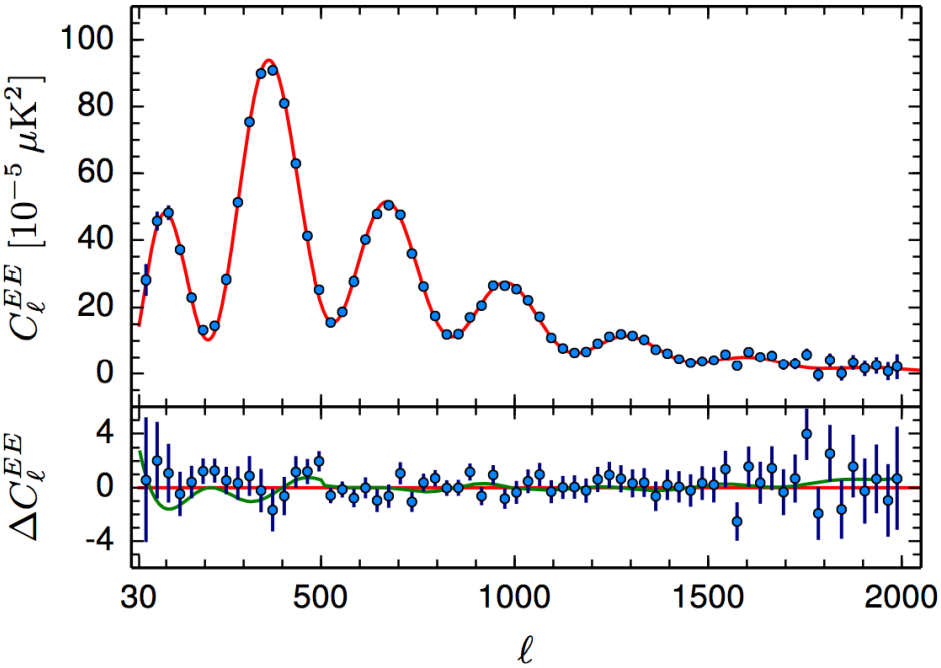
Planck Collaboration XIII (2015)



Polarization Anisotropies



Planck Collaboration XIII (2015)

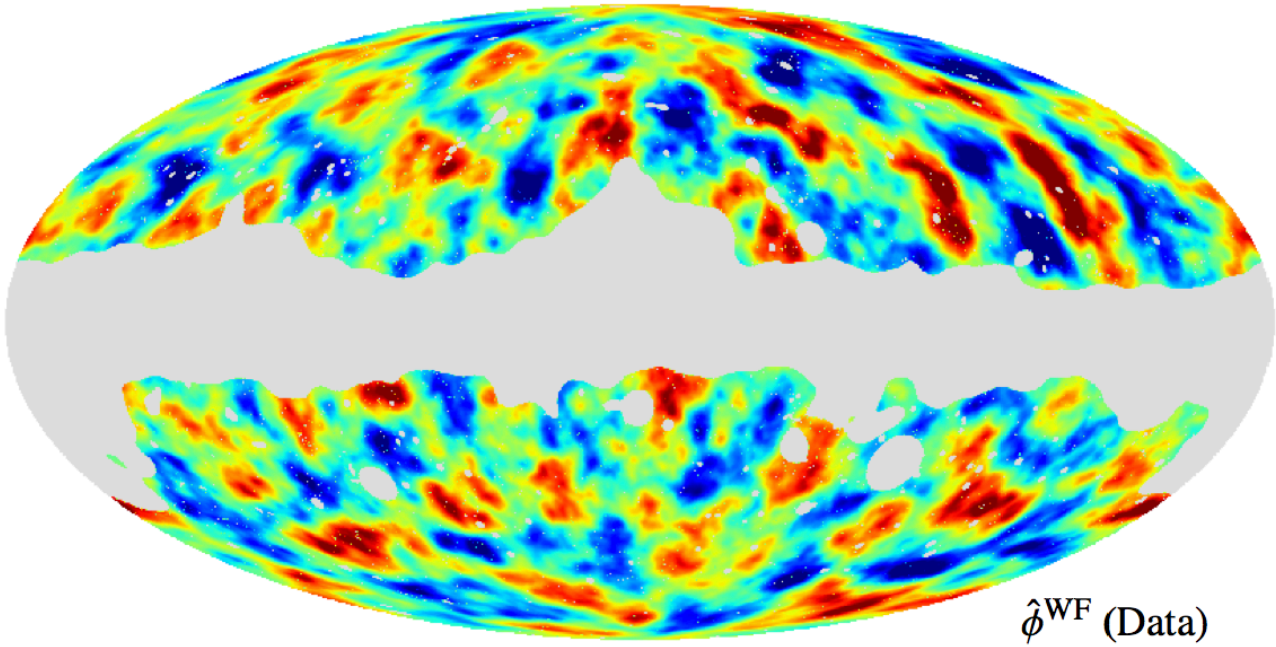


Curves are predictions from *Planck* TT+LowP (i.e., not fits)

CMB Lensing

- Lensing correlates CMB modes (T, E and B)
- Well-defined non-Gaussian signature
- Reconstruct projected matter density

Planck Collaboration XV (2015)

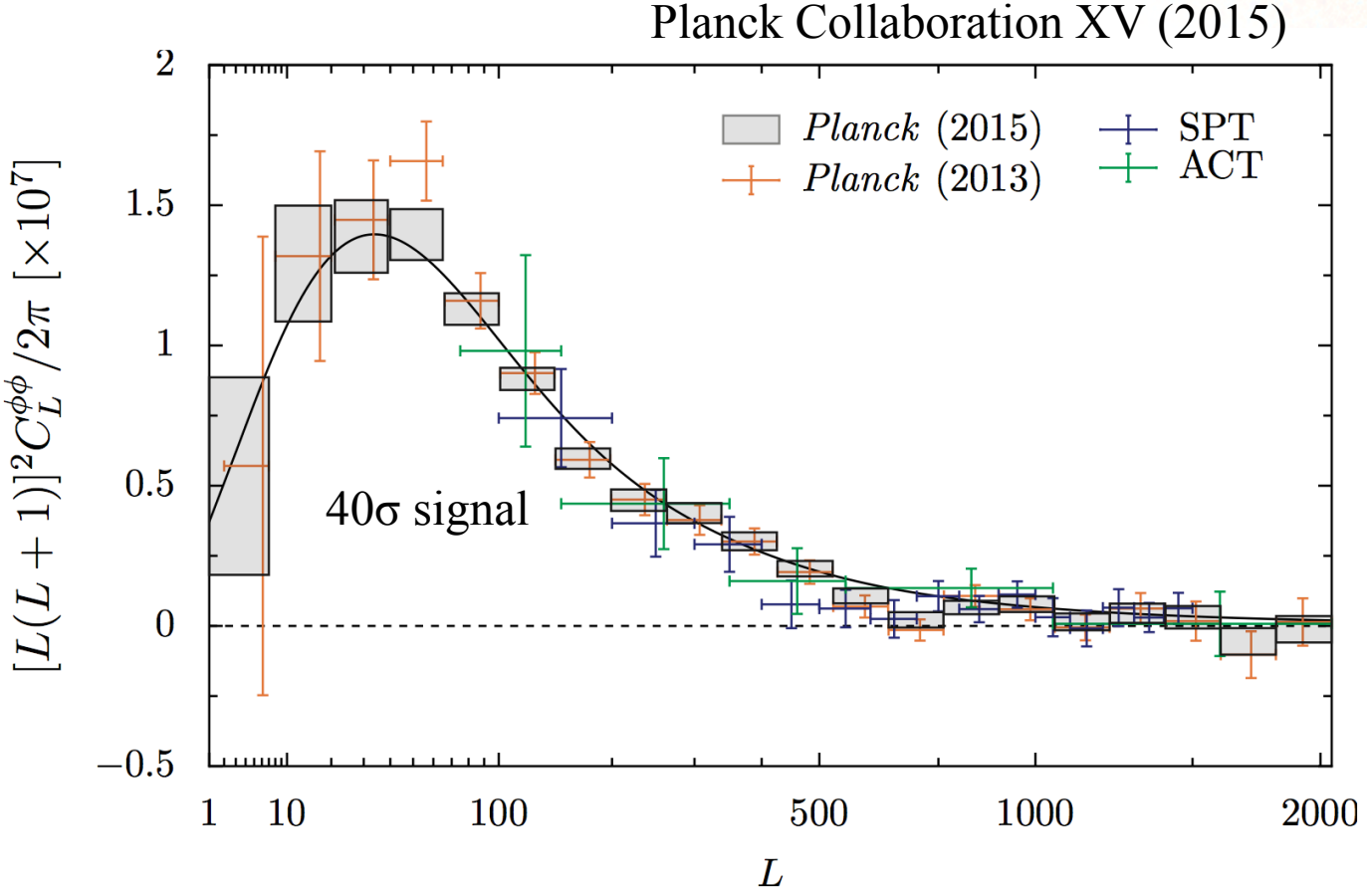


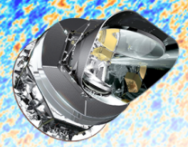
$\hat{\phi}^{\mathrm{WF}}$ (Data)

S/N ~ 1

CMB Lensing

- Lensing correlates CMB modes (T, E and B)
- Well-defined non-Gaussian signature
- Reconstruct projected matter density



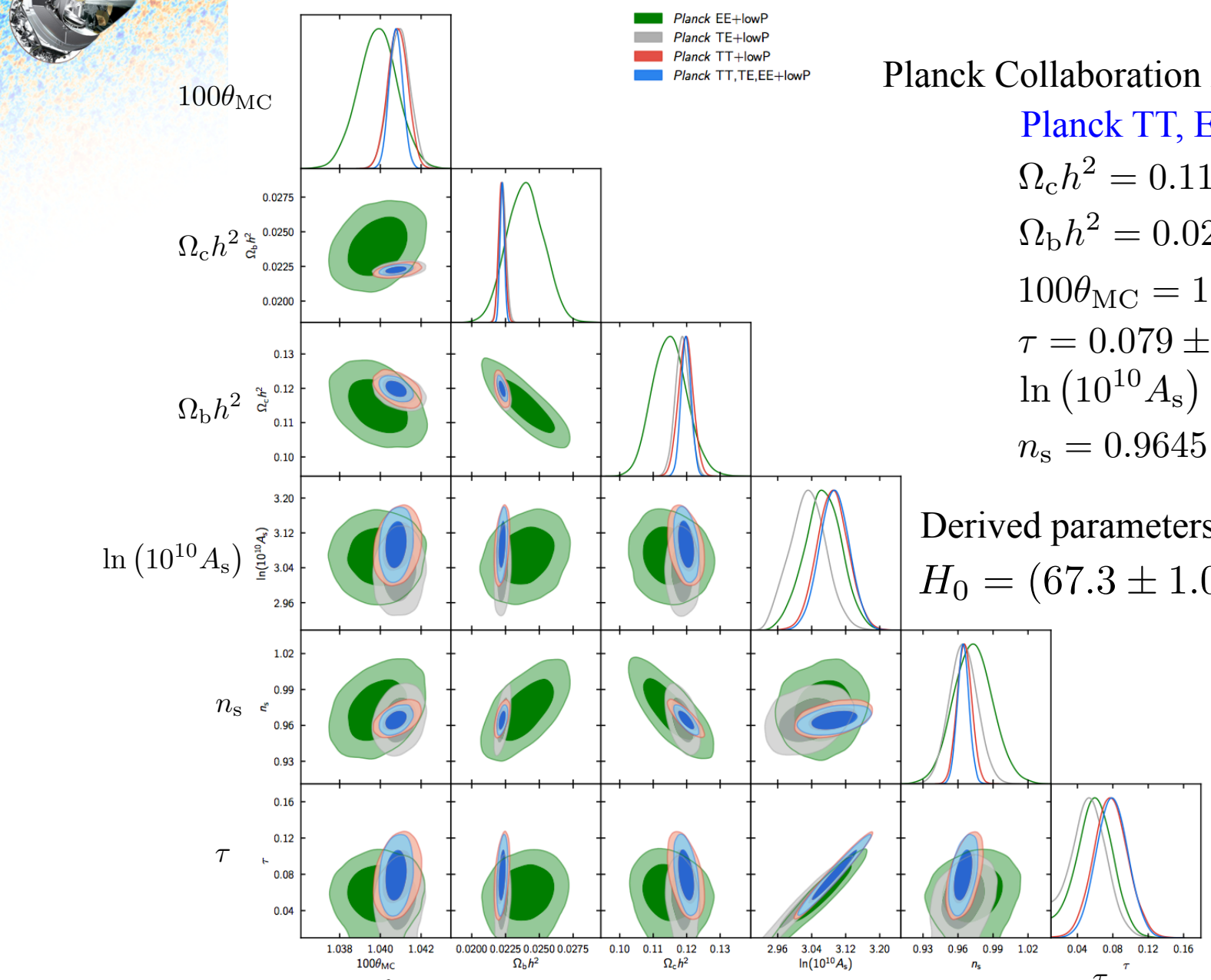


PLANCK

Base ΛCDM Model

esa

NASA



Planck Collaboration XIII (2015)

Planck TT, EE, TE + lowP

$\Omega_{\rm c}h^2 = 0.1198 \pm 0.0015$

$\Omega_{\rm b}h^2 = 0.02225 \pm 0.00016$

$100\theta_{\rm MC} = 1.04077 \pm 0.00032$

$\tau = 0.079 \pm 0.017$

$\ln(10^{10}A_{\rm s}) = 3.094 \pm 0.034$

$n_{\rm s} = 0.9645 \pm 0.0049$

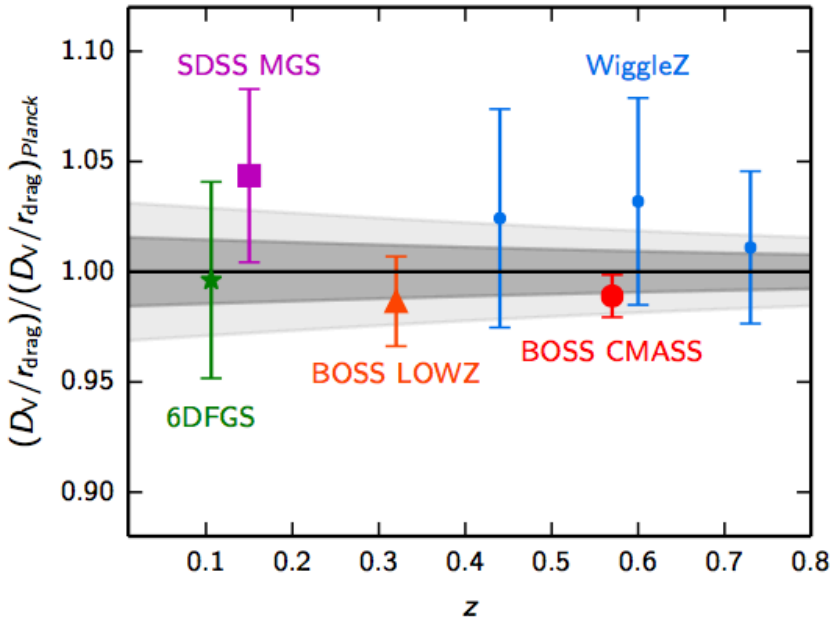
Derived parameters:

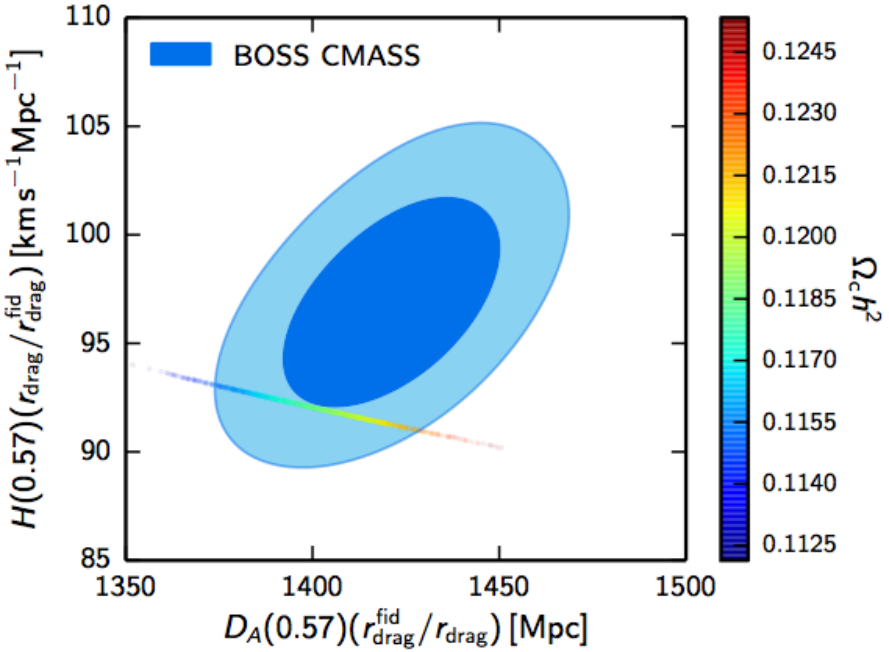
$H_0 = (67.3 \pm 1.0)\,{\rm km\,s^{-1}Mpc^{-1}}$

Fits are statistically good

Comparison: BAO

Planck Collaboration XIII (2015)

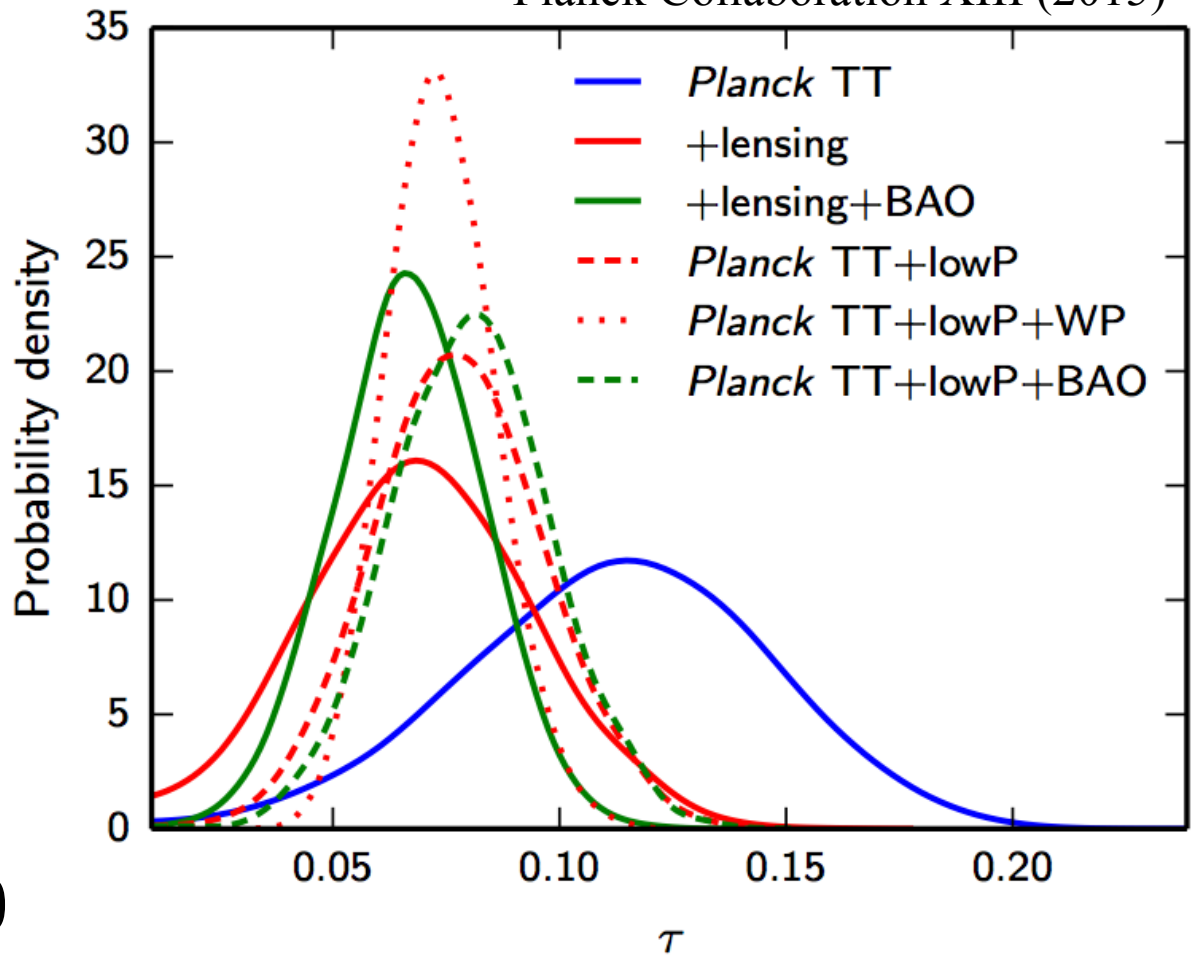




Good consistency: can combine datasets

Reionization

Planck Collaboration XIII (2015)

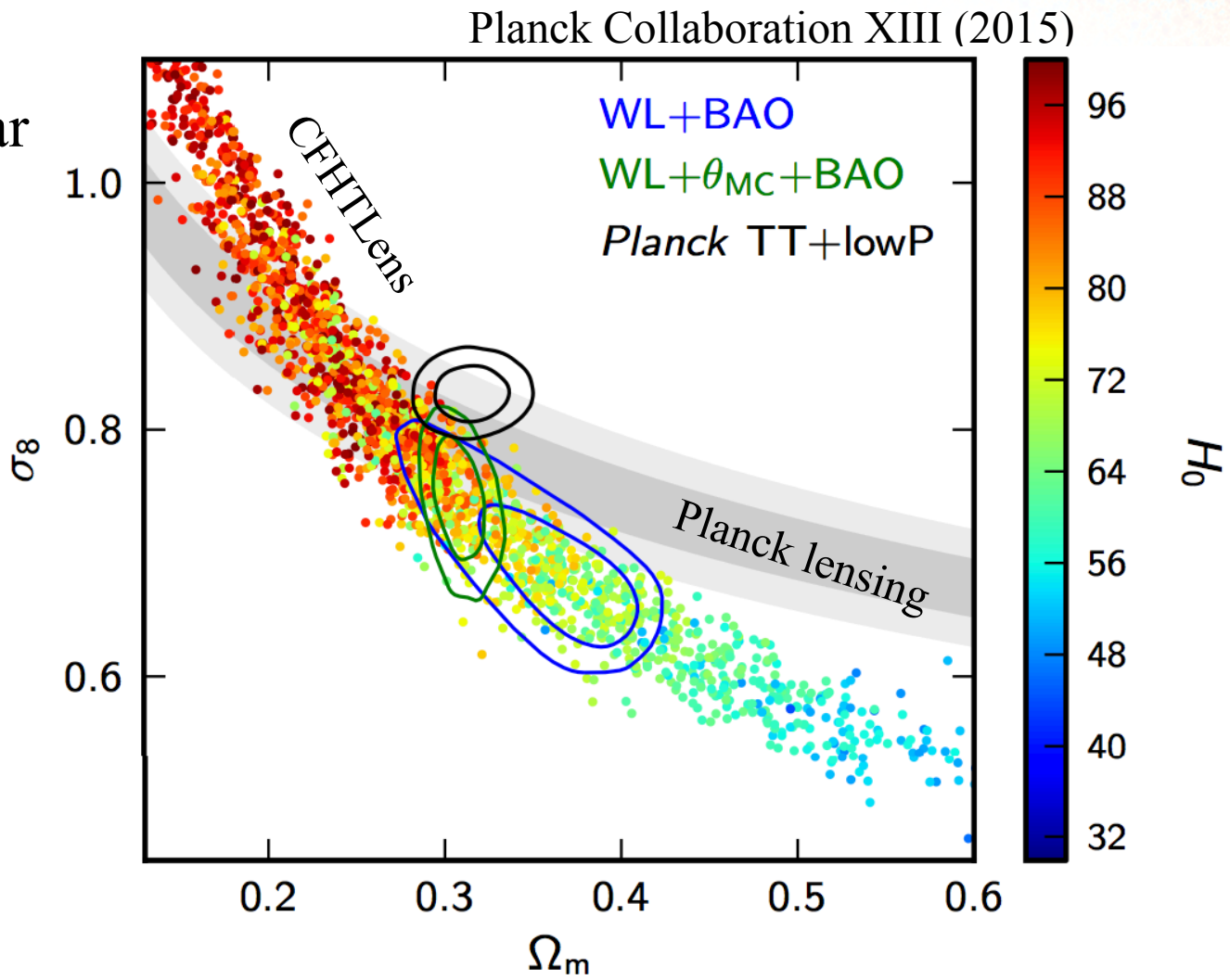


$z_{\rm rec} \approx 10$

LSS Tension: Shear

CFHTLens cosmic shear (Heymanns et al. 2013)

Non-linear/baryon effects in shear measurement?



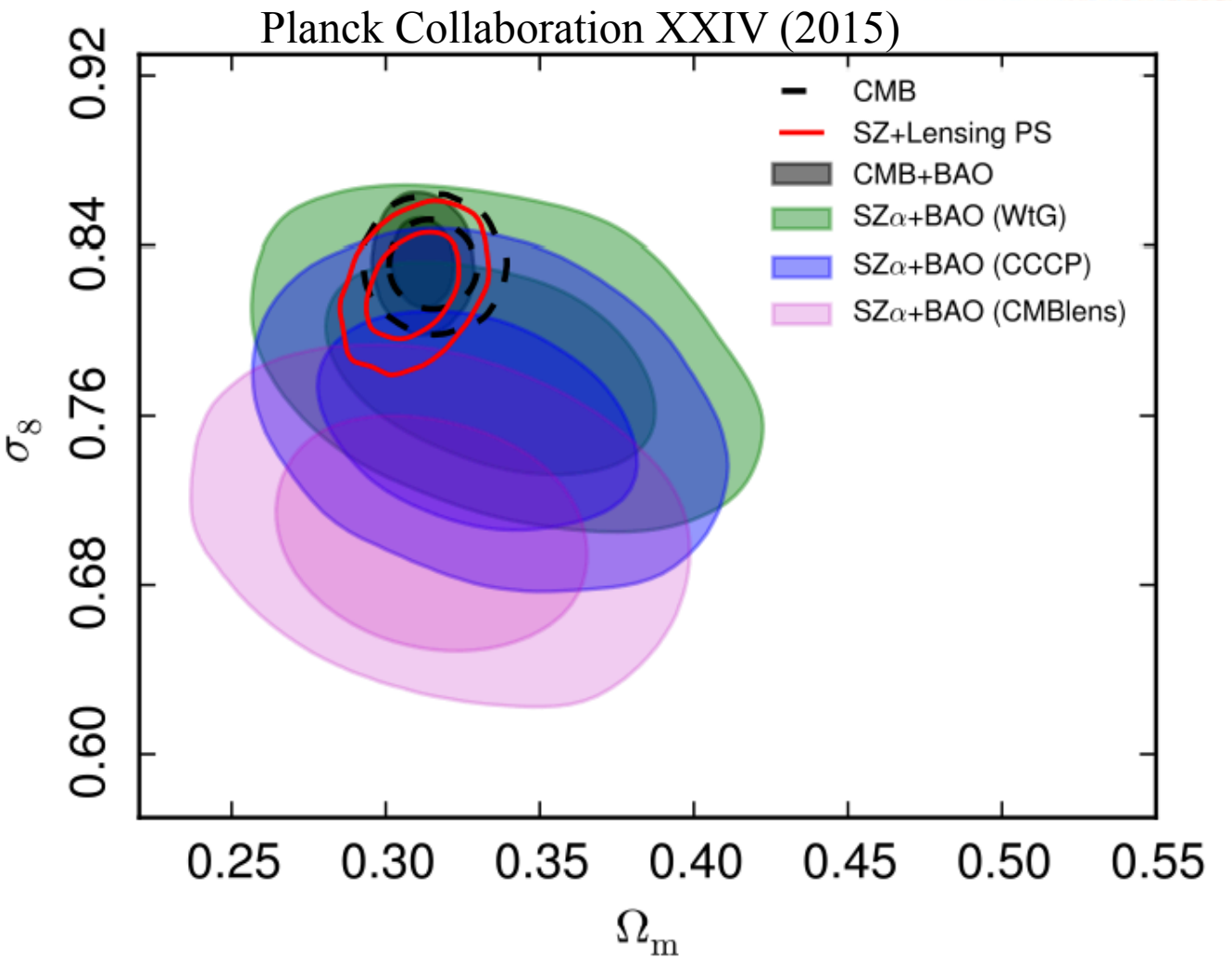
LSS Tension: SZ Clusters

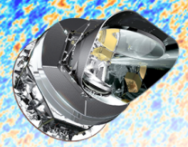
SZ + BAO (CCCP)

$\sigma_8 = 0.76 \pm 0.03$

Planck TT, TE, EE + lowP

$\sigma_8 = 0.831 \pm 0.013$



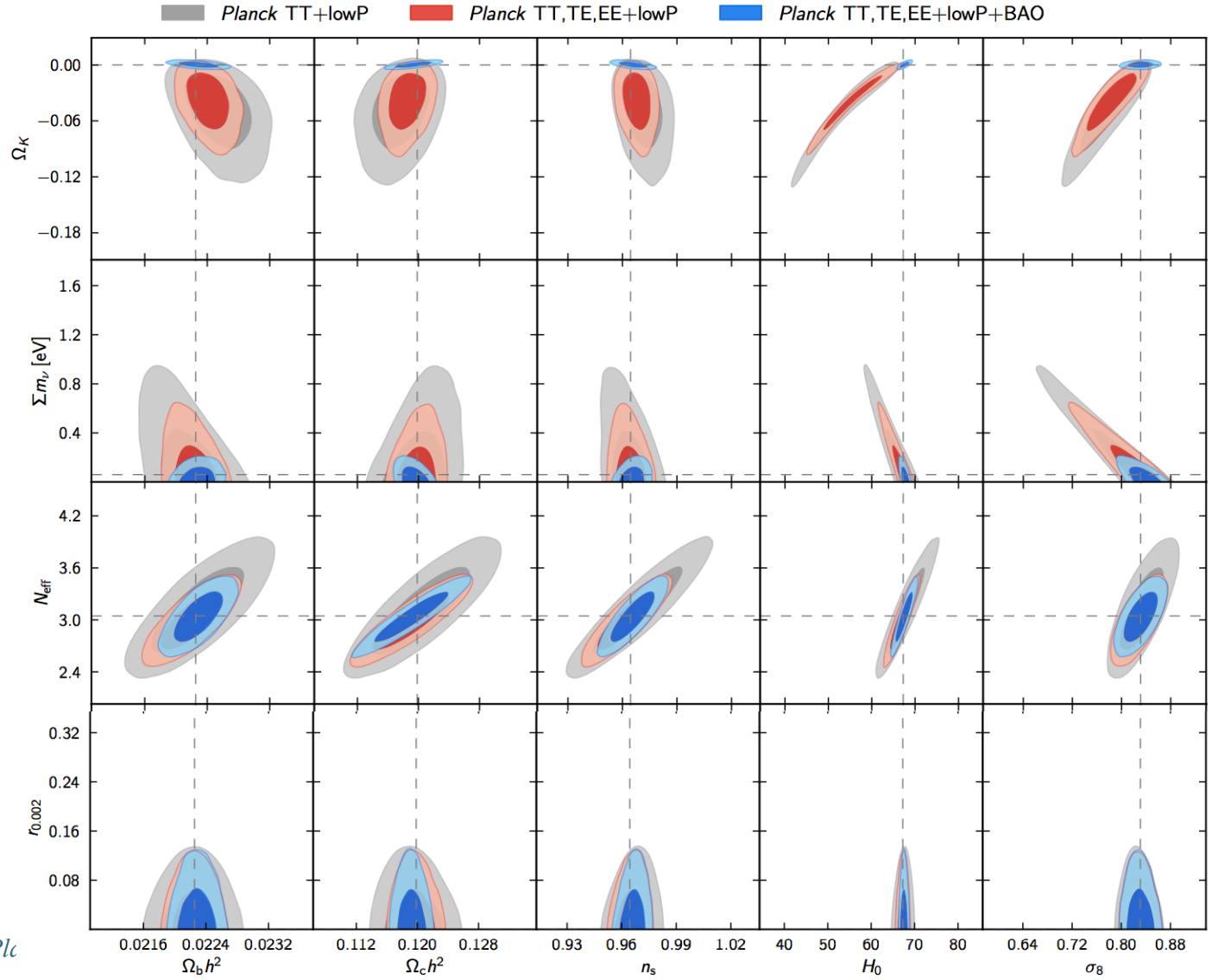


PLANCK

One-Parameter Extensions of Base ΛCDM Model

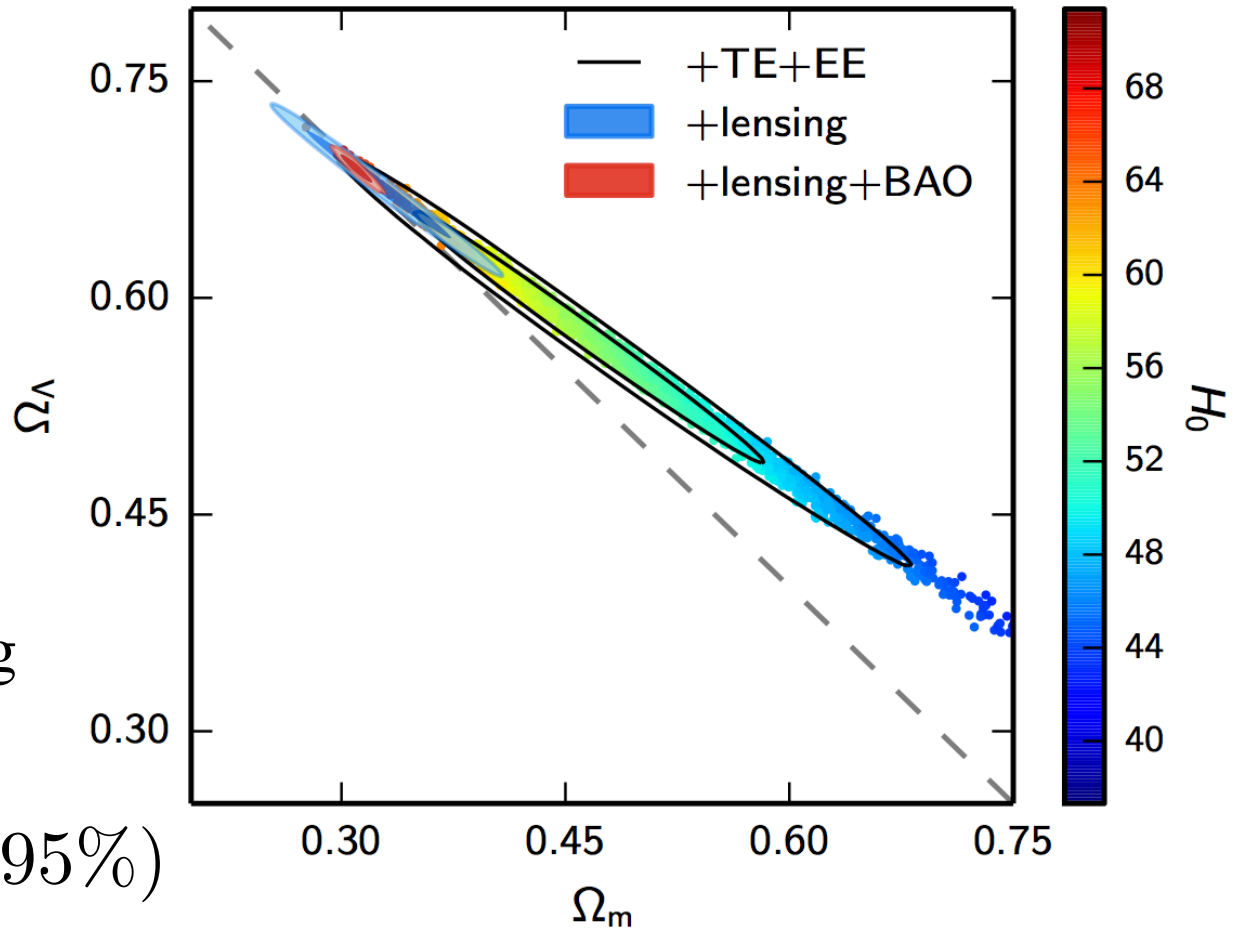
One-Parameter Extensions

Planck Collaboration XIII (2015)



Curvature

Planck Collaboration XIII (2015)

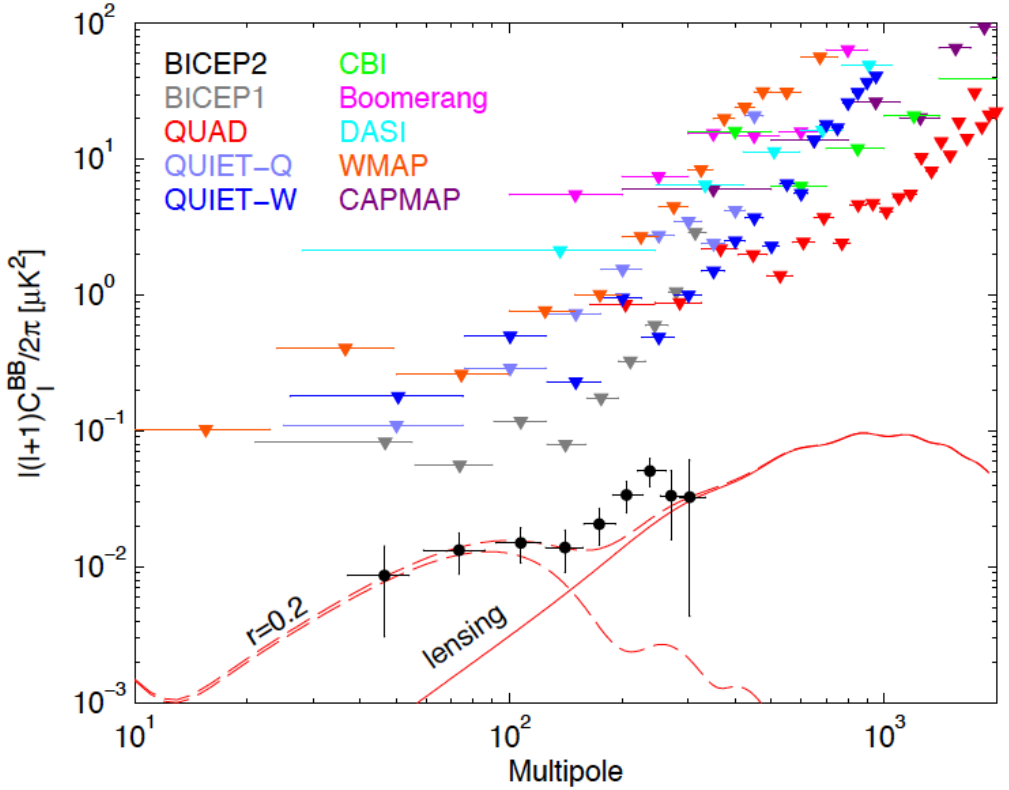


Planck TT+LowP+lensing +BAO

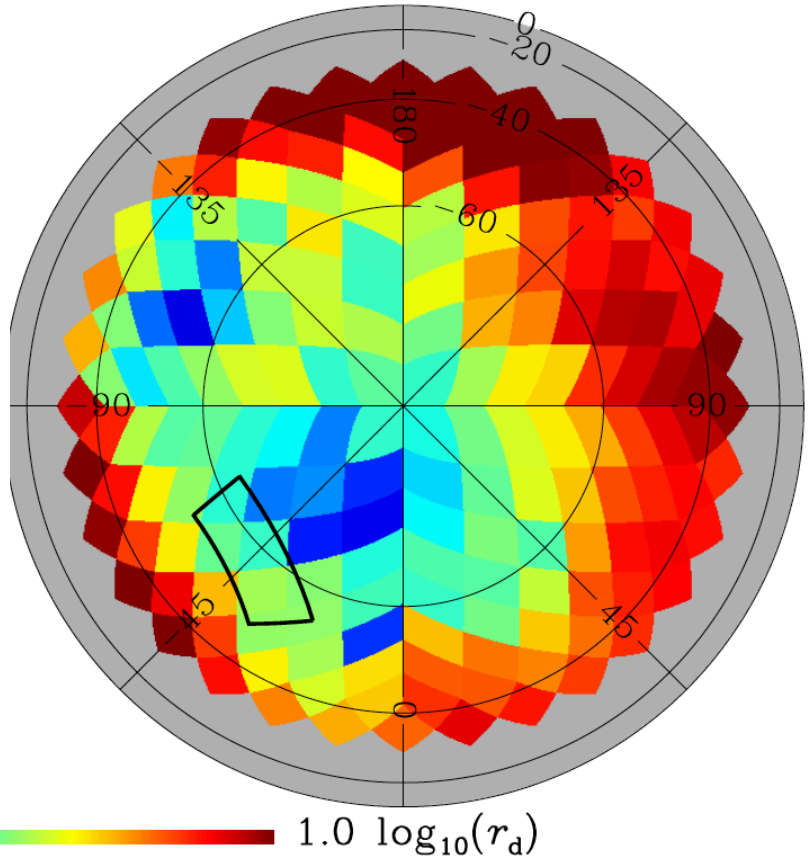
$$\Omega_K = 0.000 \pm 0.005 \ (95\%)$$

Tensors

BICEP2: Ade et al. (2014)

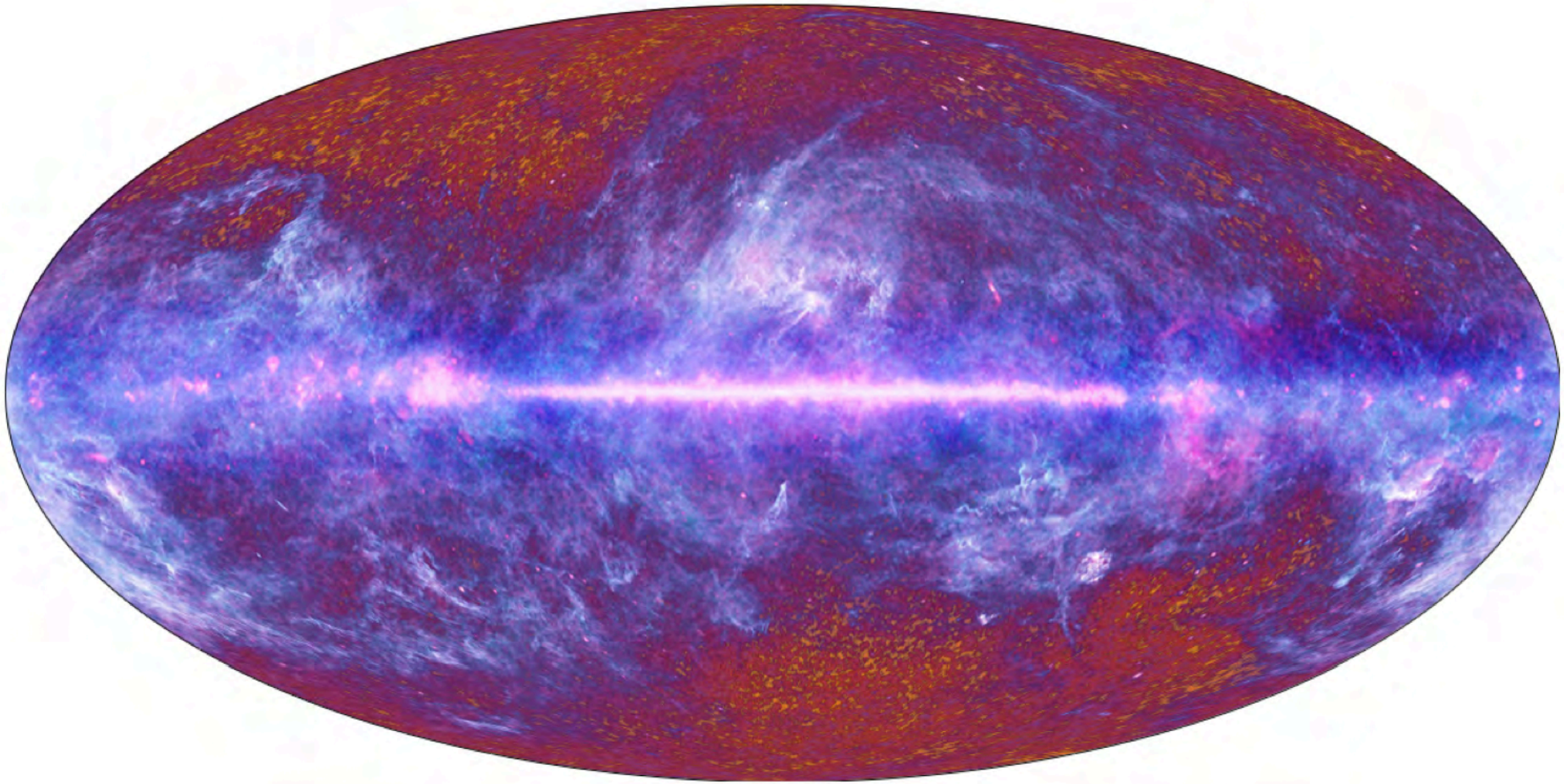


Planck Coll. Int. XXX (2014)



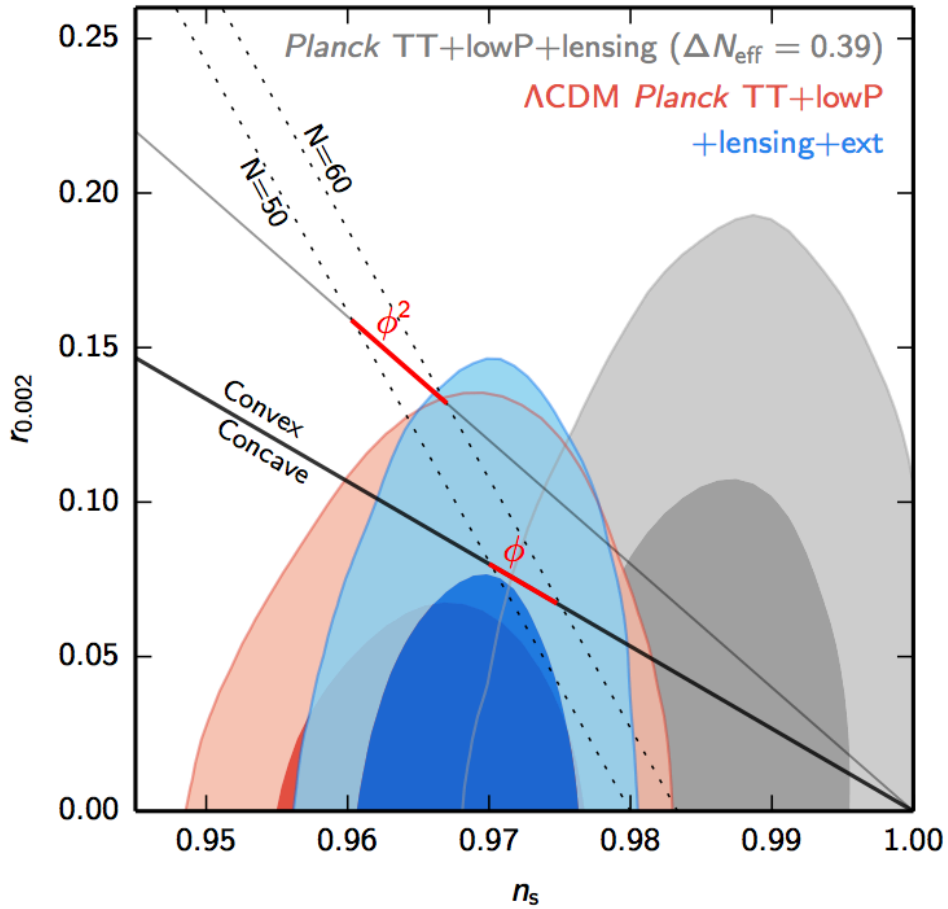
Planck 353 GHz traces dust

Planck's Composite Image



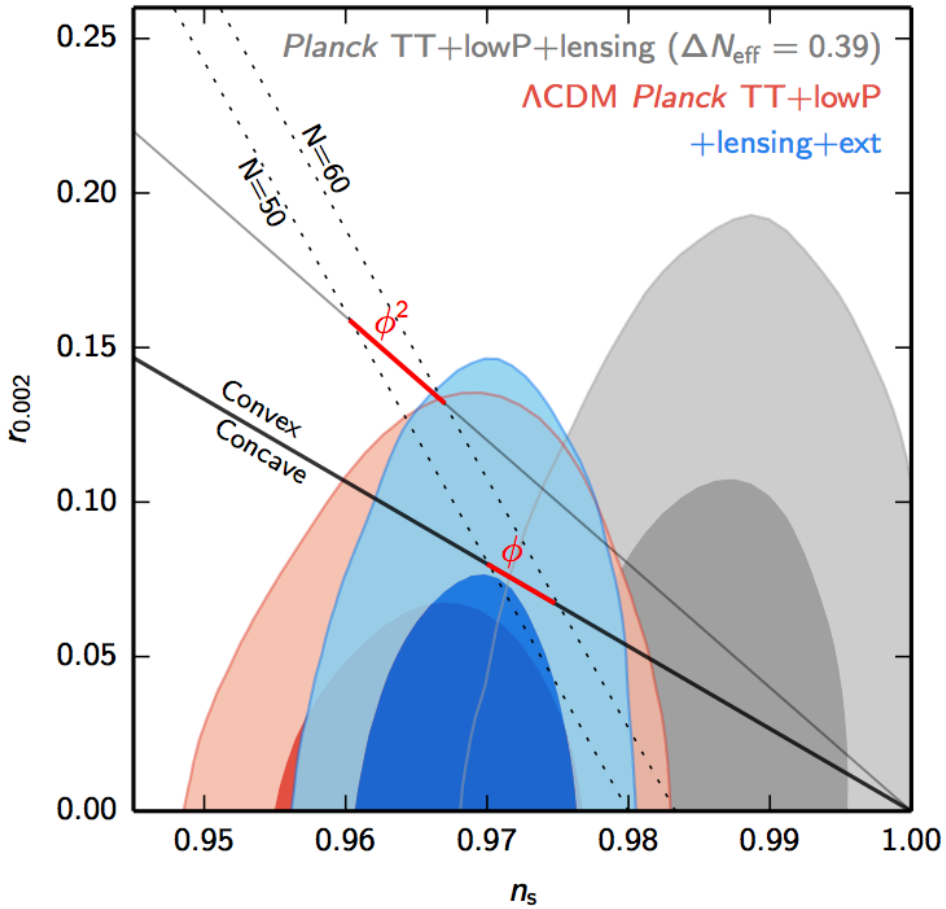
Inflation & Tensors

Planck Collaboration XIII (2015)

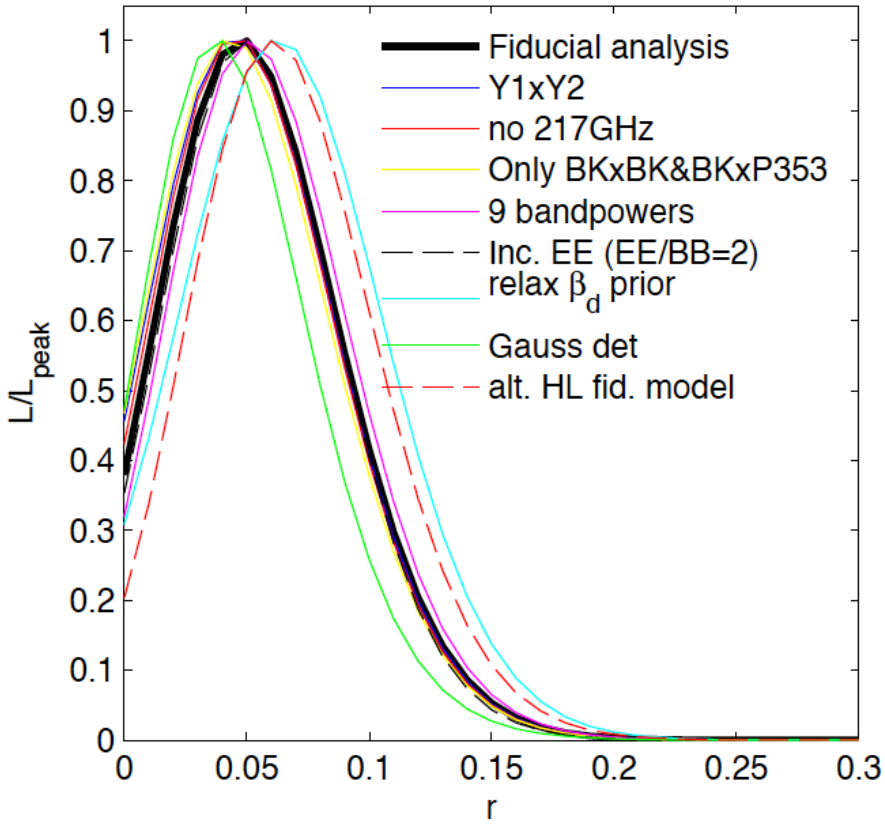


Inflation & Tensors

Planck Collaboration XIII (2015)



BICEP2/Keck/Planck Collabs (2015)



Inflation & Tensors

Planck TT+LowP & $r_{0.002}=0$

$$n_{\rm s} = 0.9655 \pm 0.0062$$

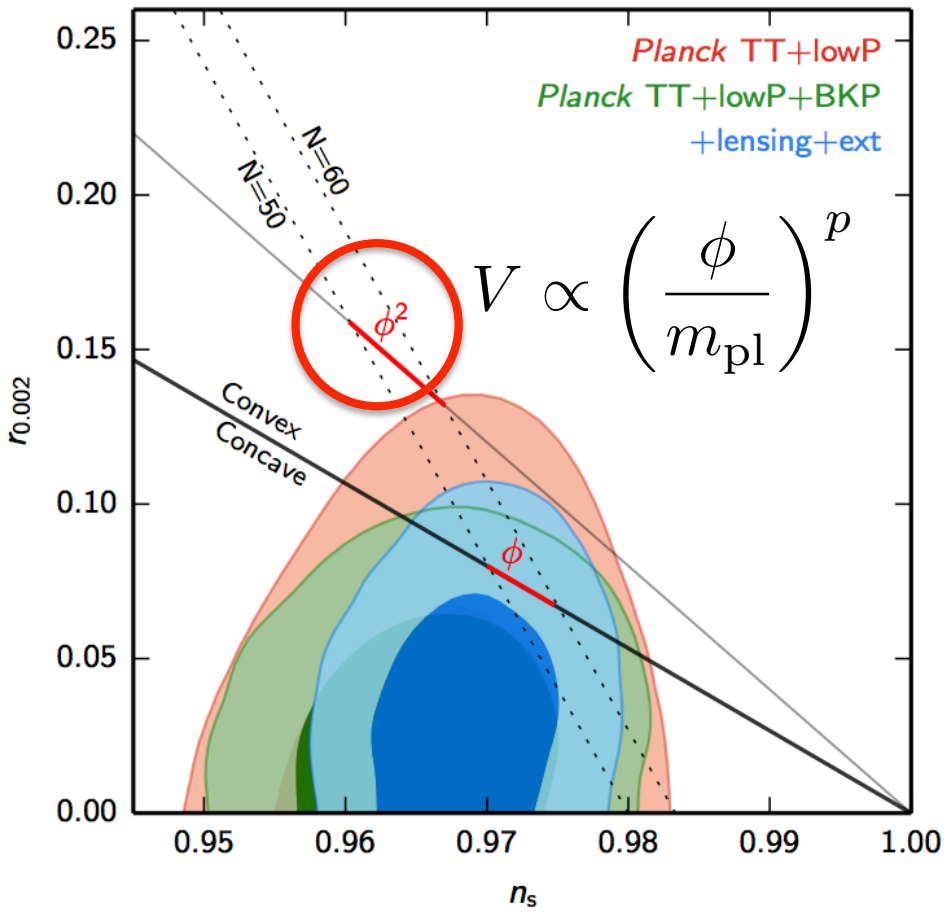
Planck TT+LowP

$$r_{0.002} < 0.10 \ (95\%)$$

Planck TT+LowP+BKP

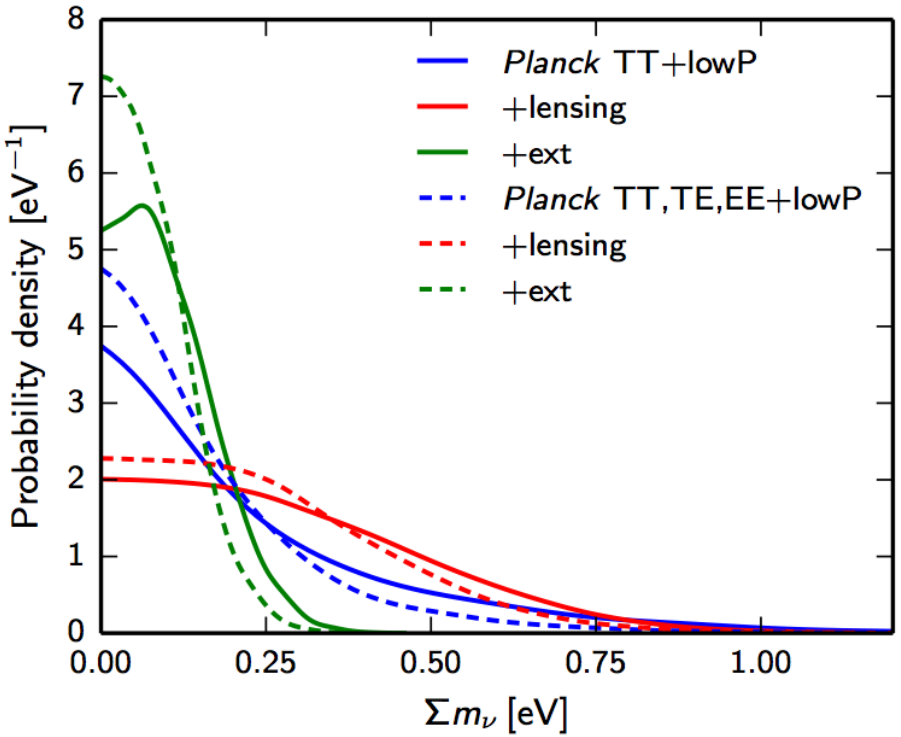
$$r_{0.002} < 0.08 \ (95\%)$$

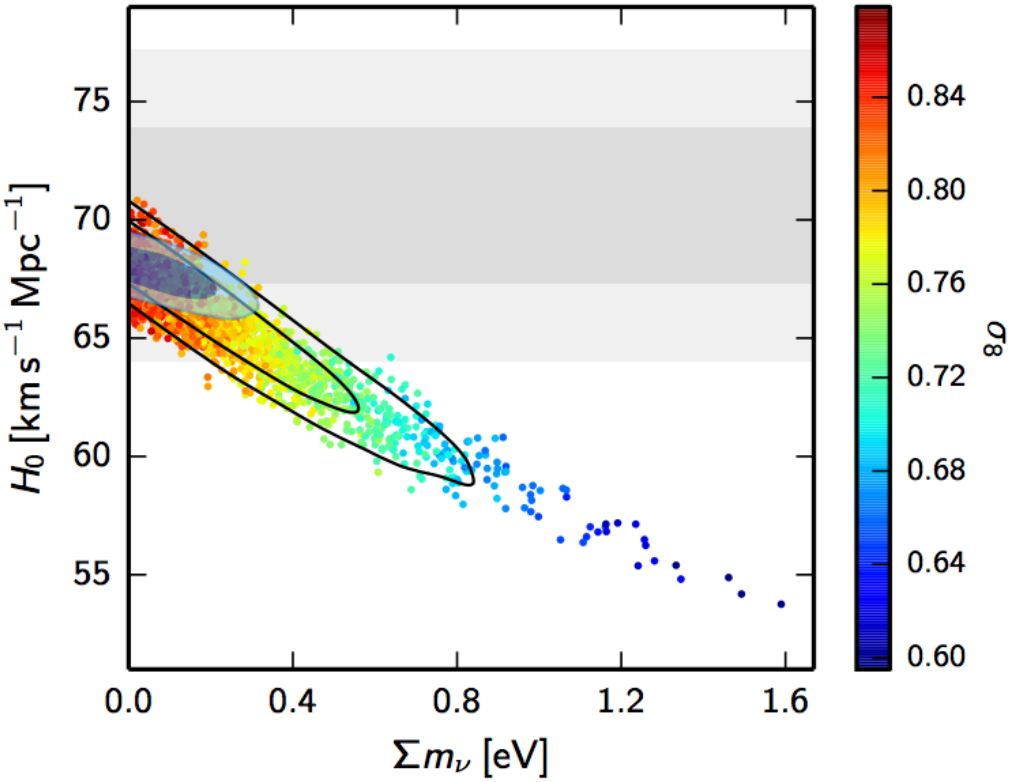
Planck Collaboration XIII (2015)



Neutrinos: Mass Scale

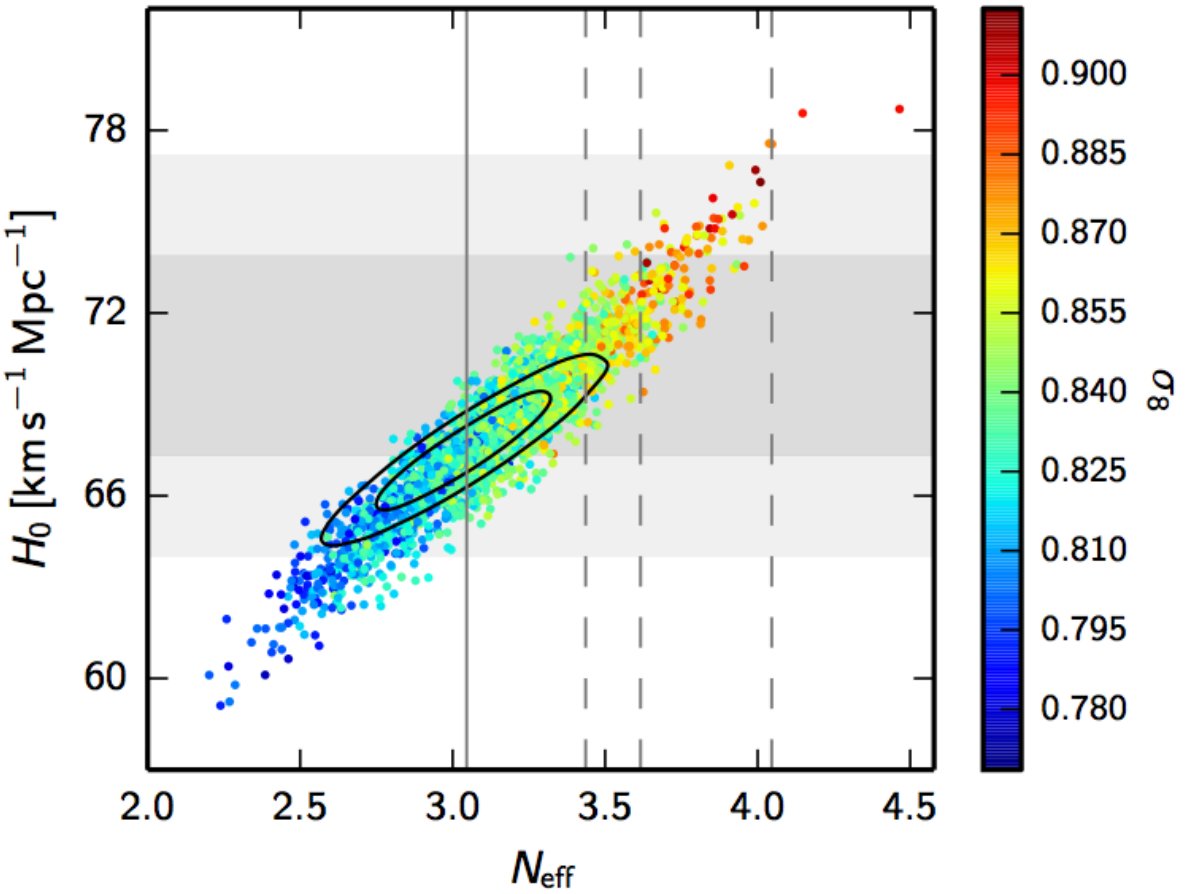
Planck Collaboration XIII (2015)





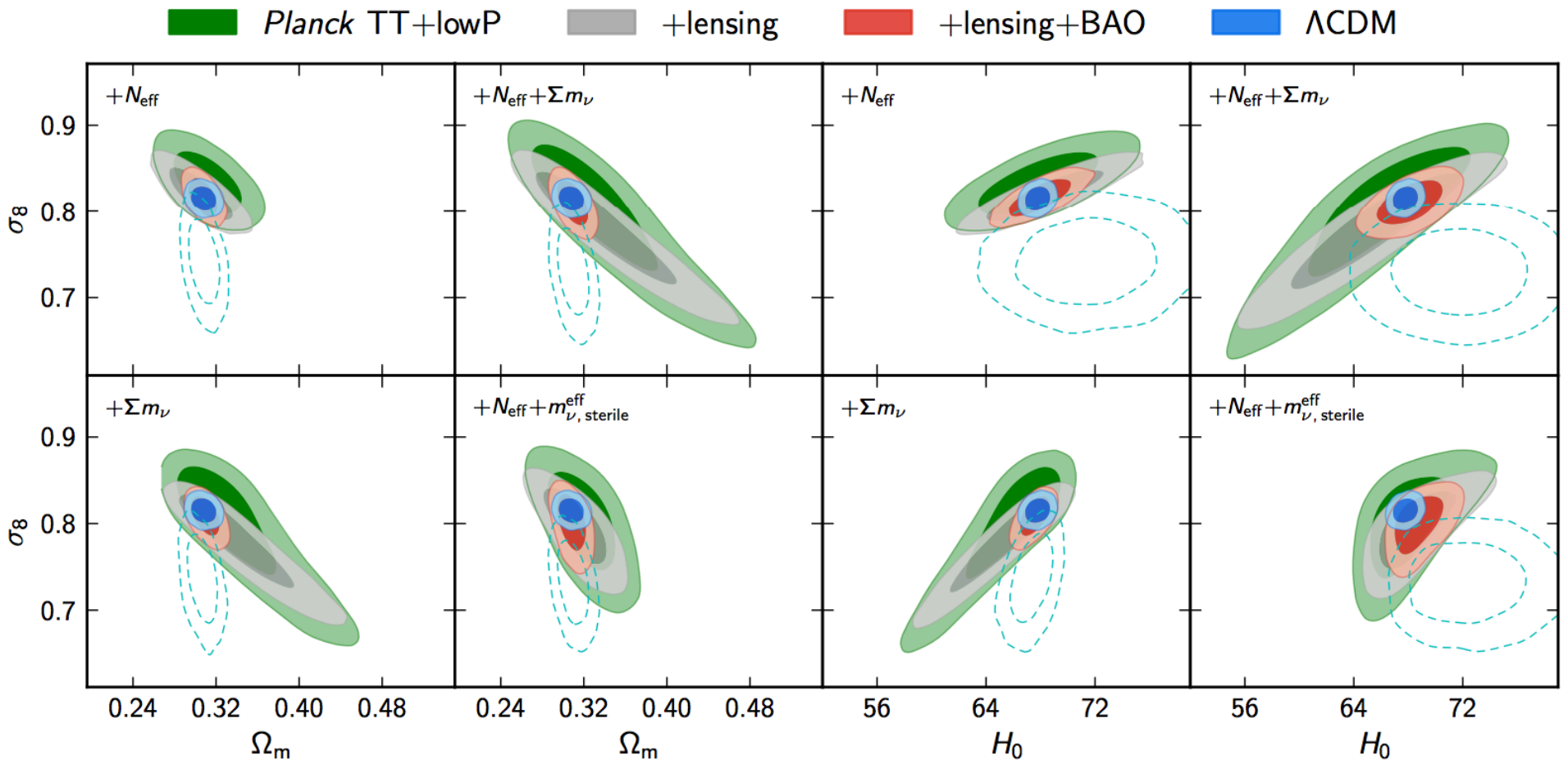
Neutrinos: N_{eff}

Planck Collaboration XIII (2015)



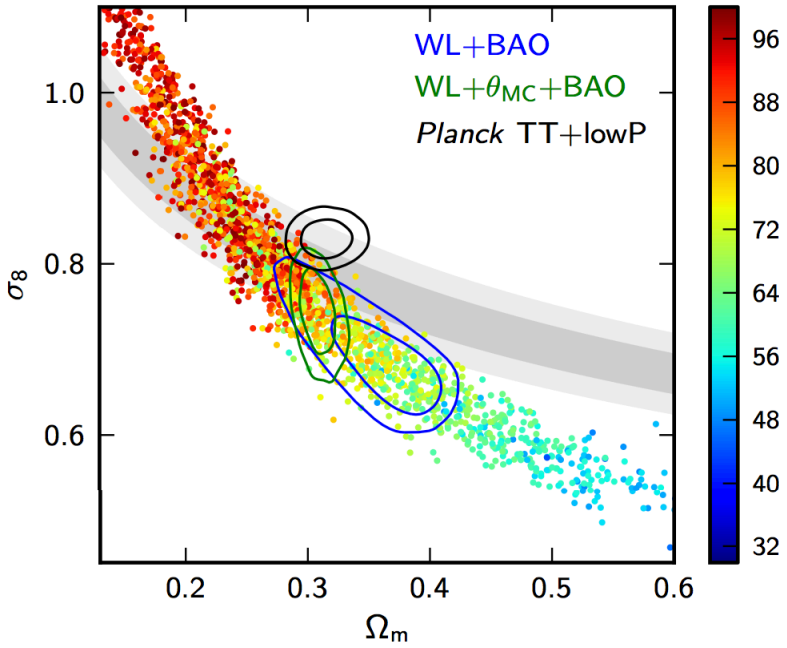
Neutrinos and Shear Tension

Planck Collaboration XIII (2015)

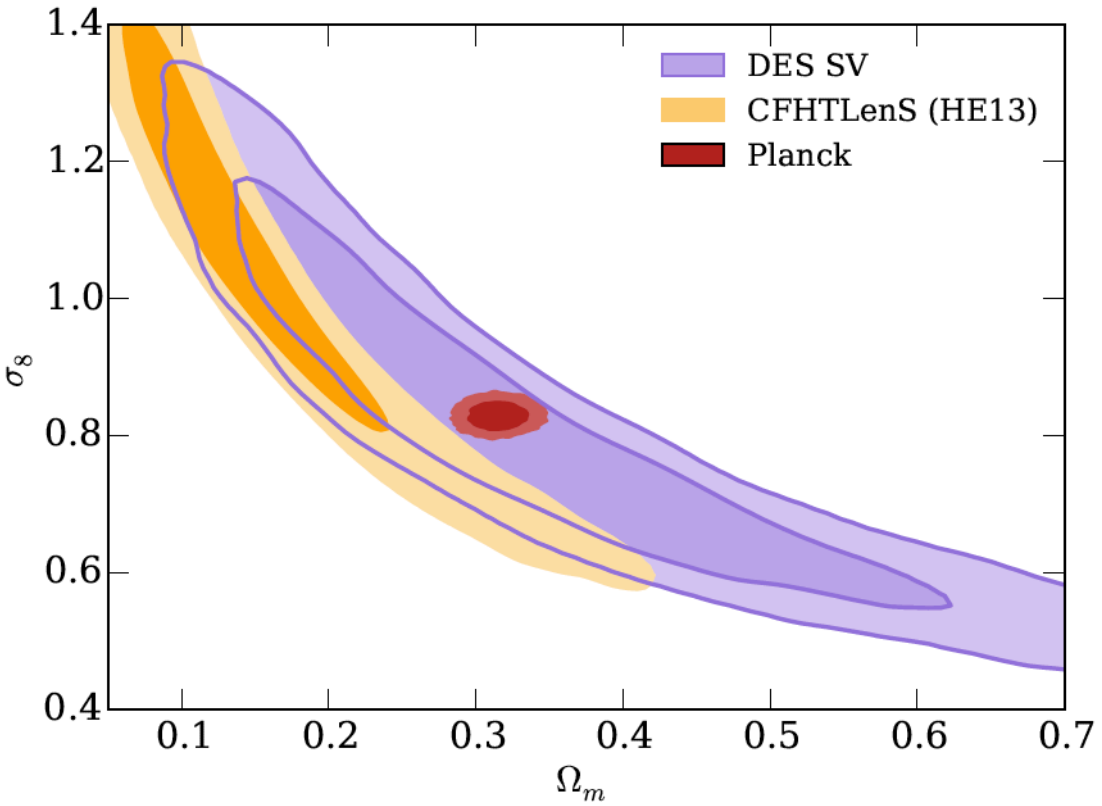


Do not resolve the tension on σ_8

LSS Tension: Shear

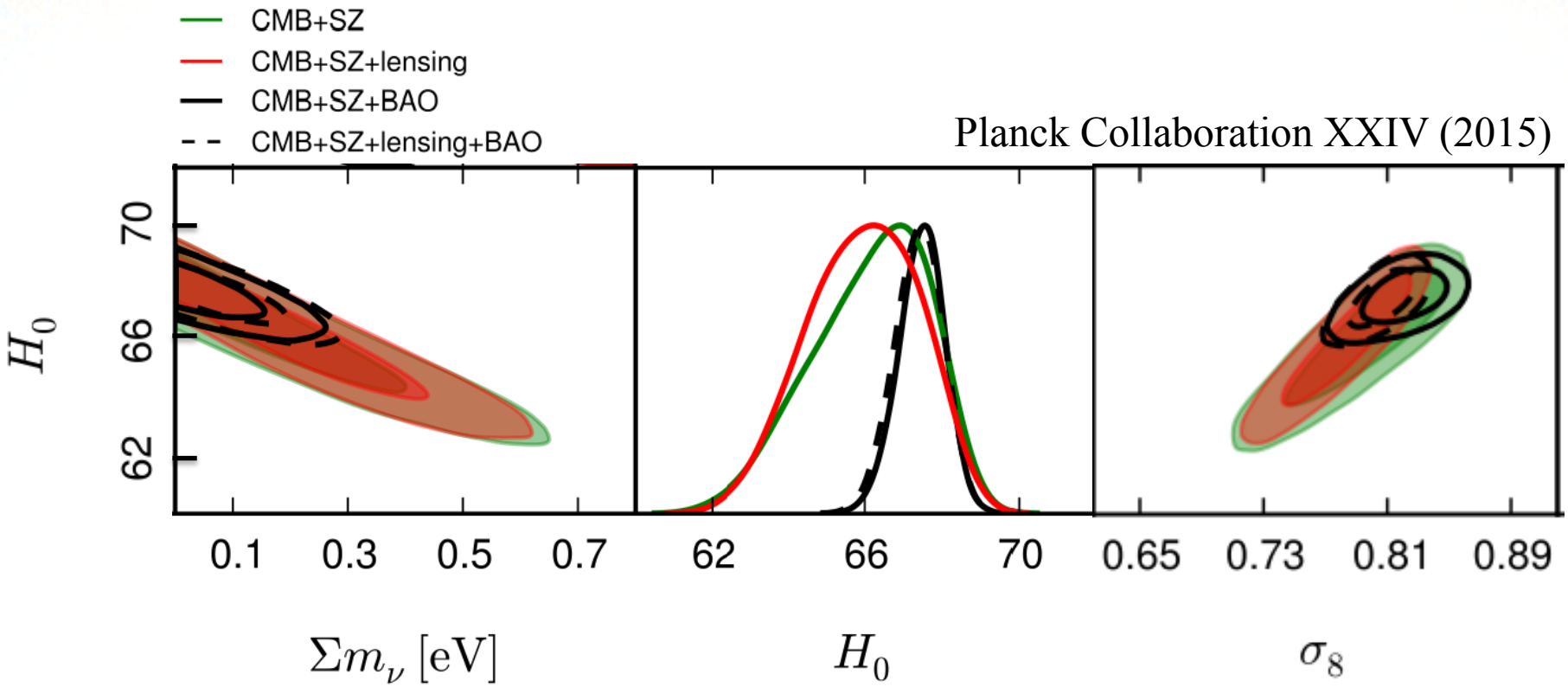


Planck Collaboration XIII (2015)
(WL from CFHTLens)



Dark Energy Collaboration (2015)
Science Verification Data

Neutrinos and SZ Clusters



Planck Collaboration XXIV (2015)

Do not resolve the tension on σ_8
(Cluster mass scale remains an open issue)

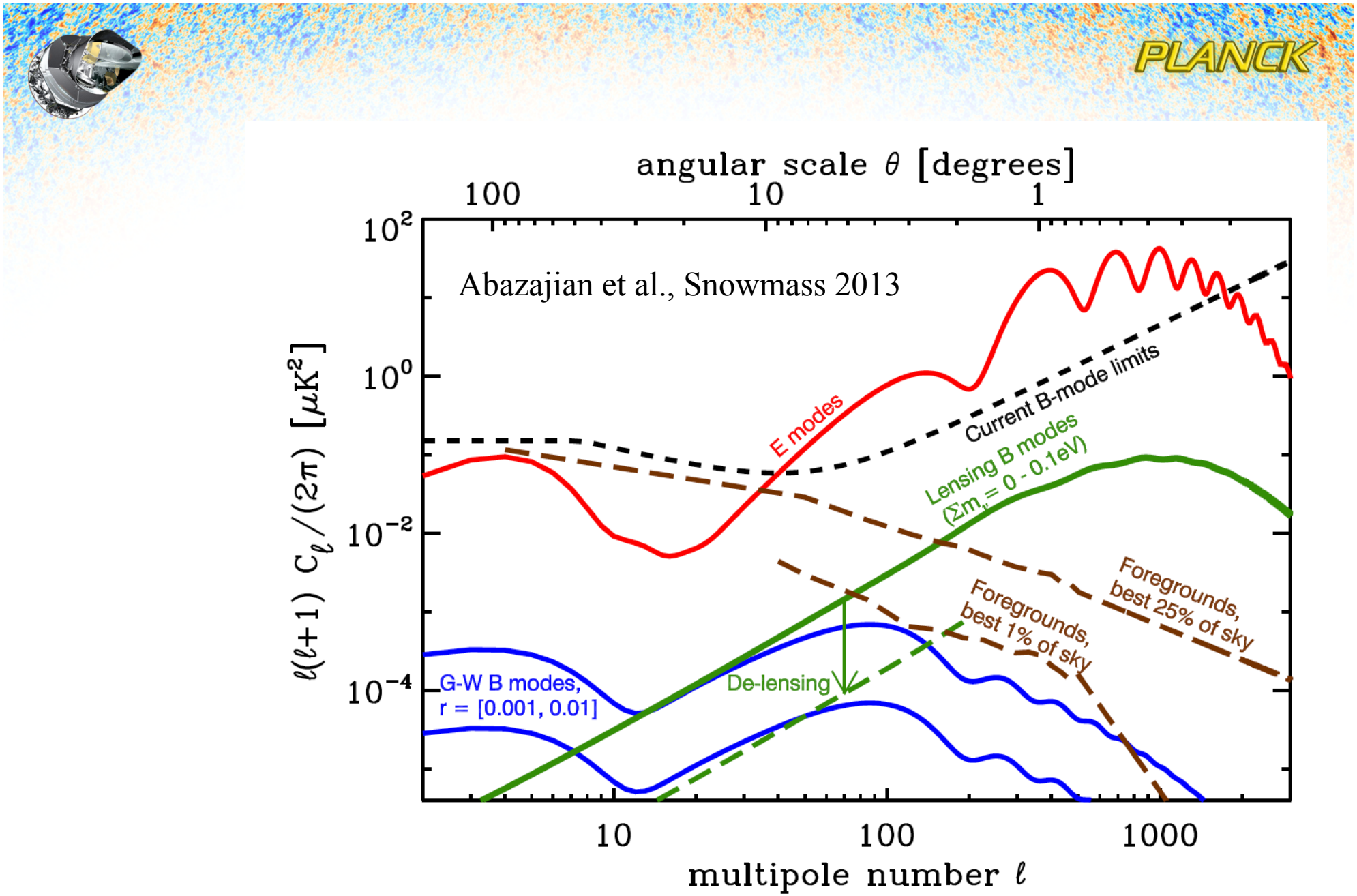
Conclusion

- Flat ΛCDM works extremely well
  - ~1% constraints on base parameters
  - No evidence for new Physics
- Some constraints on extensions:

$r_{0.002} < 0.08 \ (95\%)$ Planck TT+lowP+BKP

$\sum m_\nu < 0.17 \text{ eV} \quad (95\%)$ Planck TT, EE, TE+lowP+BAO

- Future
  - CMB-Stage IV, NASA Explorer/Probe, ESA M5, LiteBIRD
  - Tensors, Neutrino mass
  - Important issues: foregrounds, (de)lensing


angular scale θ [degrees]
100
10
1
Abazajian et al., Snowmass 2013
E modes
Current B-mode limits
Lensing B modes
(Σm_ν = 0 - 0.1eV)
Foregrounds,
best 25% of sky
Foregrounds,
best 1% of sky
G-W B modes,
r = [0.001, 0.01]
De-lensing
ℓ(ℓ+1) C_ℓ/(2π) [μK²]
10²
10⁰
10⁻²
10⁻⁴
10
100
1000
multipole number ℓ

Dark Energy

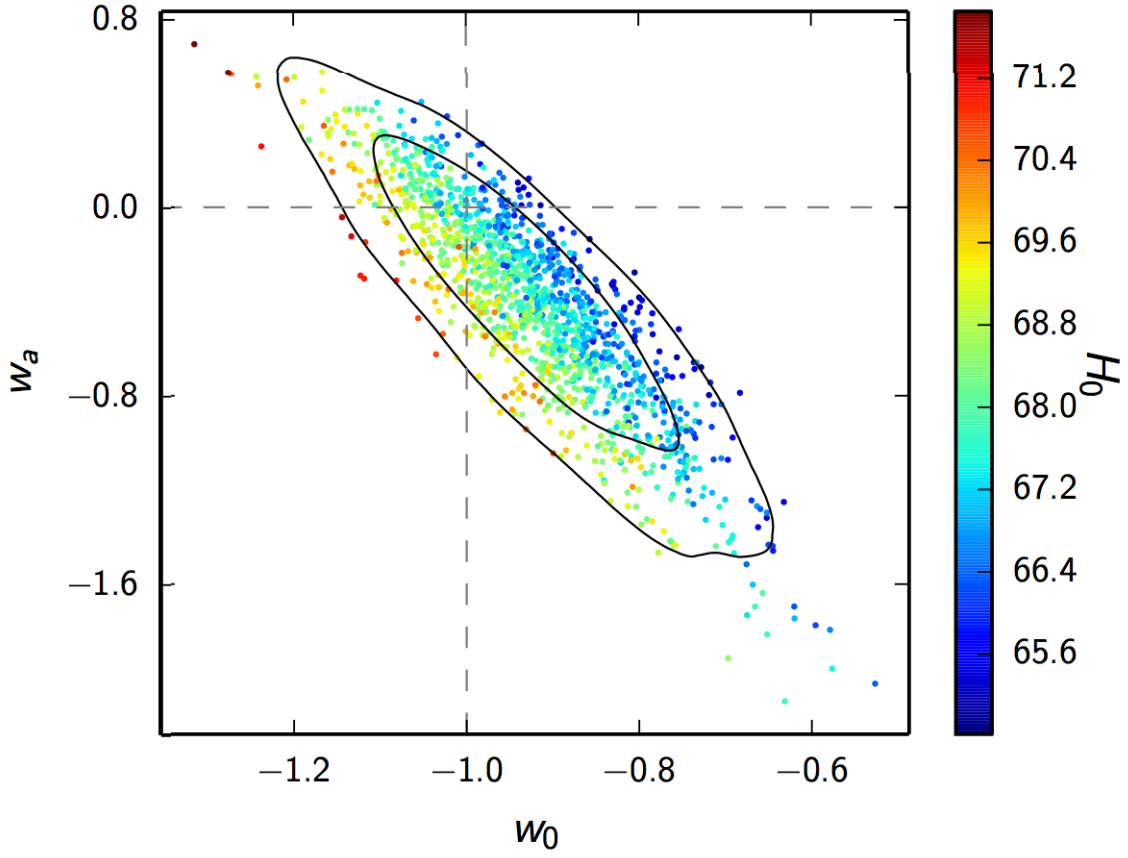
Planck Collaboration XIII (2015), Planck Collaboration XIV (2015)

Constant *w*:

Planck TT, TE, EE+lowP +lensing+BAO+JLA+H_0

$$w < -1.019^{+0.075}_{-0.080}$$

$$w(a) = w_0 + w_a(1-a)$$



Non-Gaussianity

Temperature only

$$f_{\rm NL}^{\rm local} = 2.5 \pm 5.7$$

$$f_{\rm NL}^{\rm equil} = -16 \pm 70$$

$$f_{\rm NL}^{\rm ortho} = -34 \pm 33$$

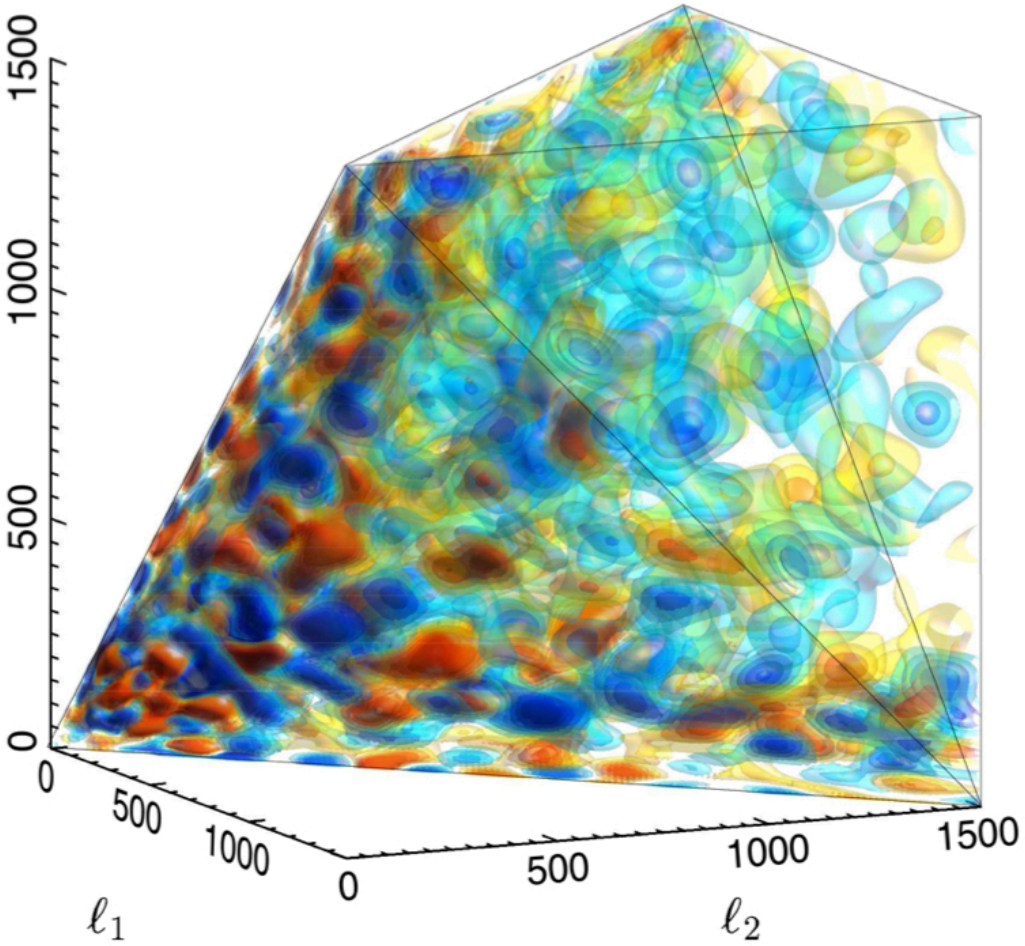
Temperature & polarization

$$f_{\rm NL}^{\rm local} = 0.8 \pm 5.0$$

$$f_{\rm NL}^{\rm equil} = -4 \pm 43$$

$$f_{\rm NL}^{\rm ortho} = -26 \pm 21$$

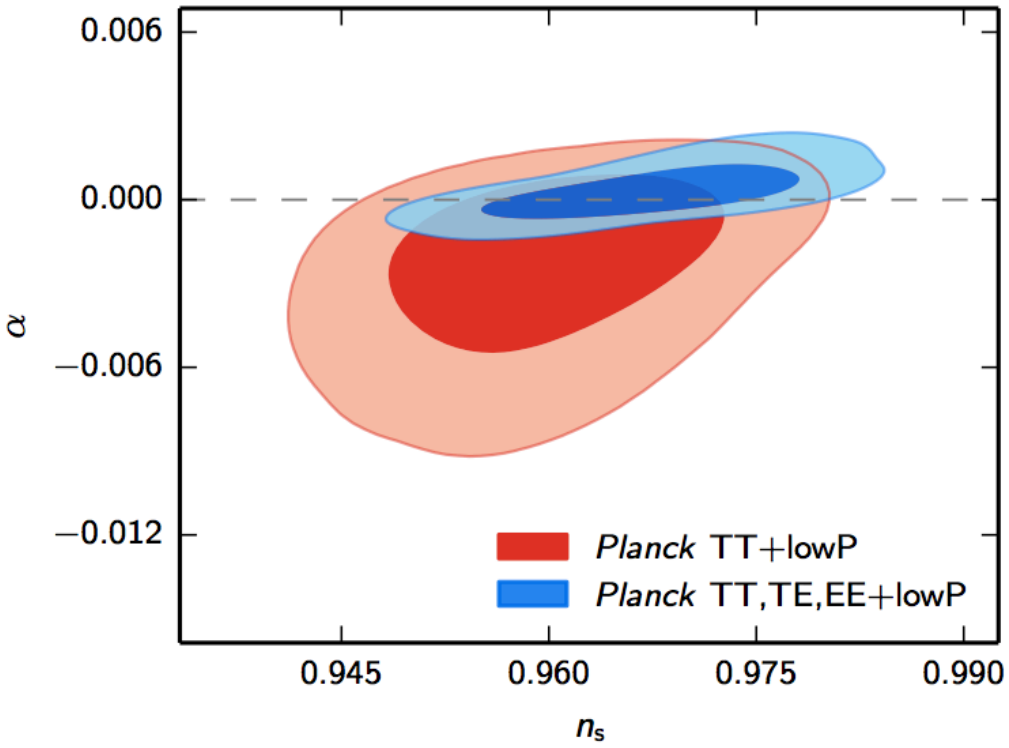
Planck Collaboration XVII (2015)



Temperature bispectrum

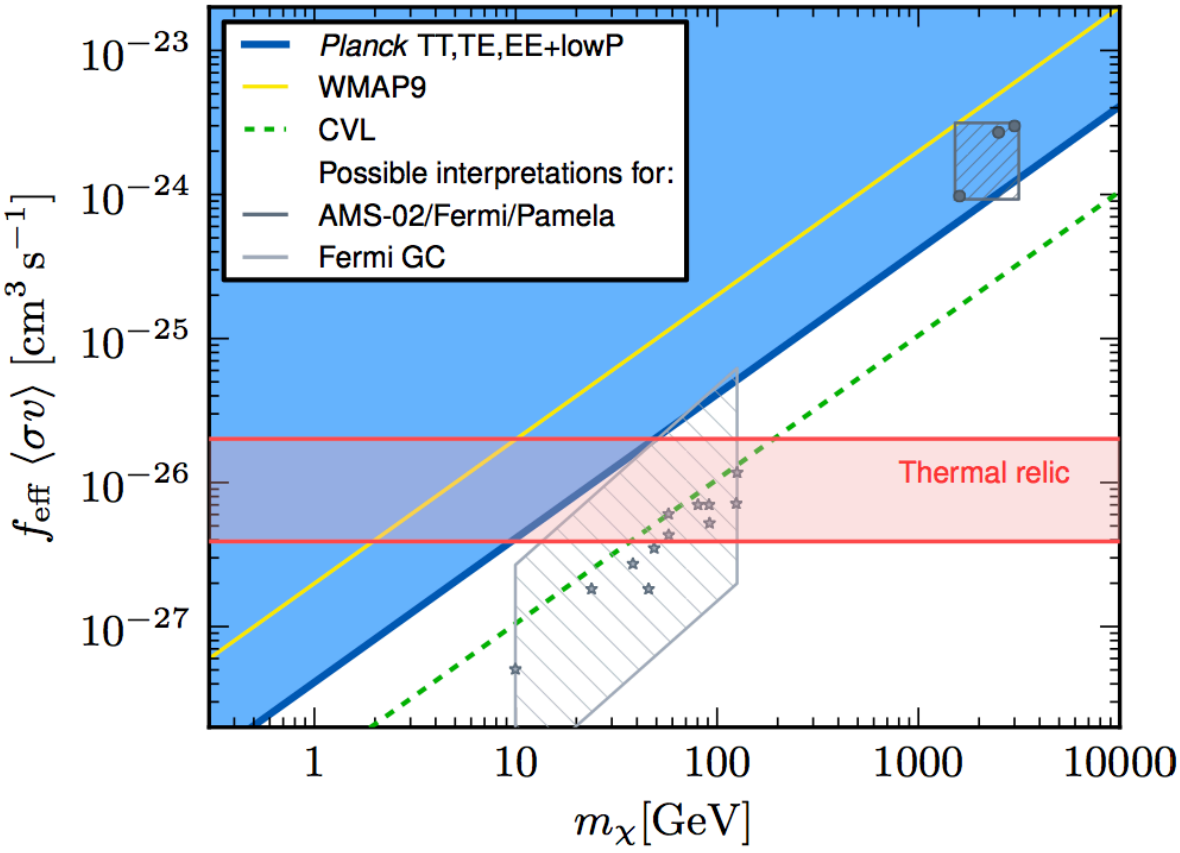
Isocurvature Modes

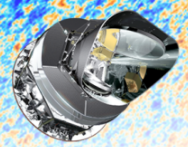
Planck Collaboration XIII (2015)



Dark Matter Annihilation

Planck Collaboration XIII (2015)





PLANCK

The End

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