ΛCDM extensions and likelihood tests from Planck

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On behalf of the Planck collaboration

Rencontres du Vietnam 2015, Quy Nhon, 20 August 2015

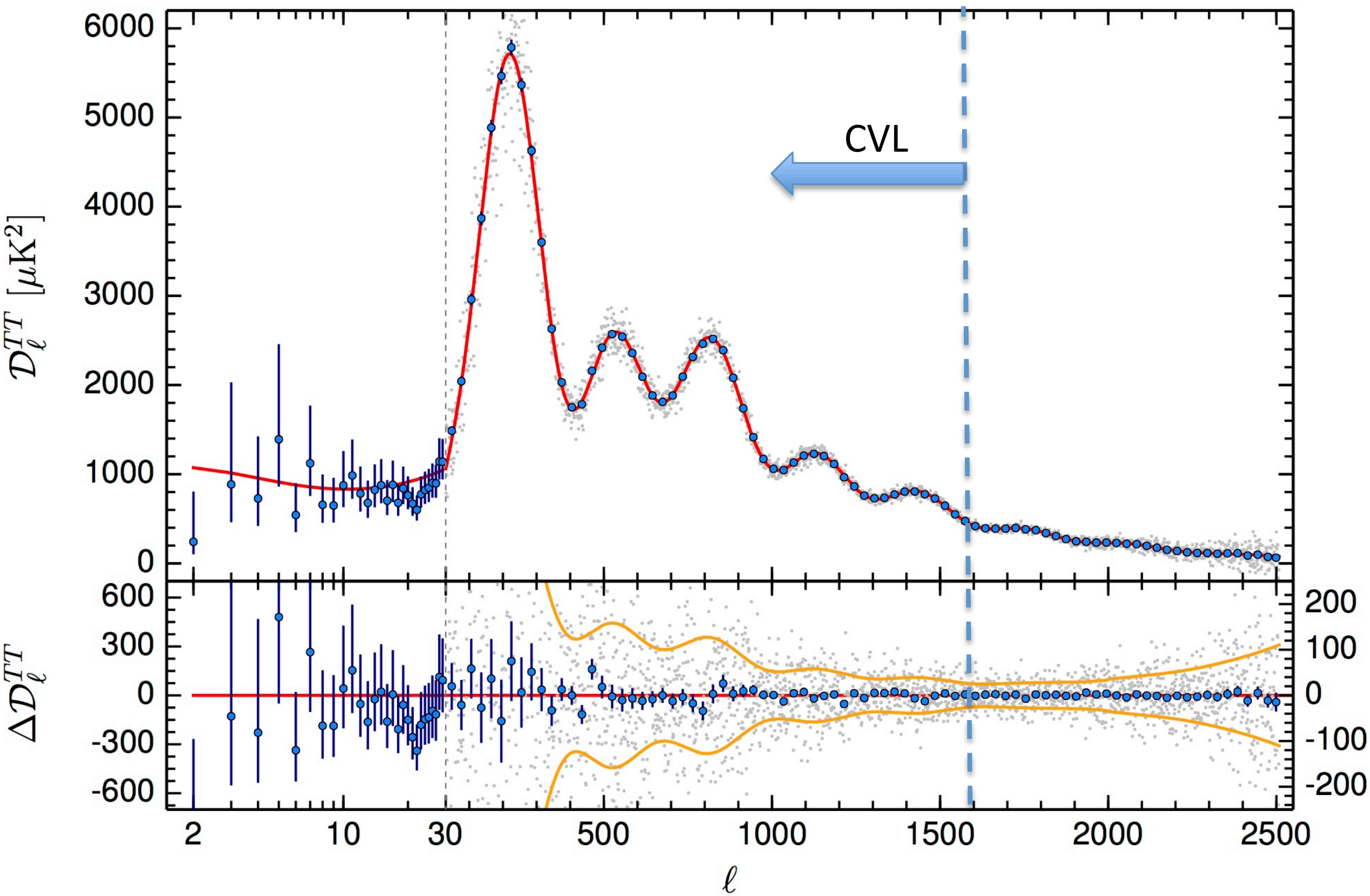
Outline

- The ΛCDM model: understanding the differences between WMAP and Planck

- Extensions of ΛCDM: results on neutrino physics and dark matter annihilation.

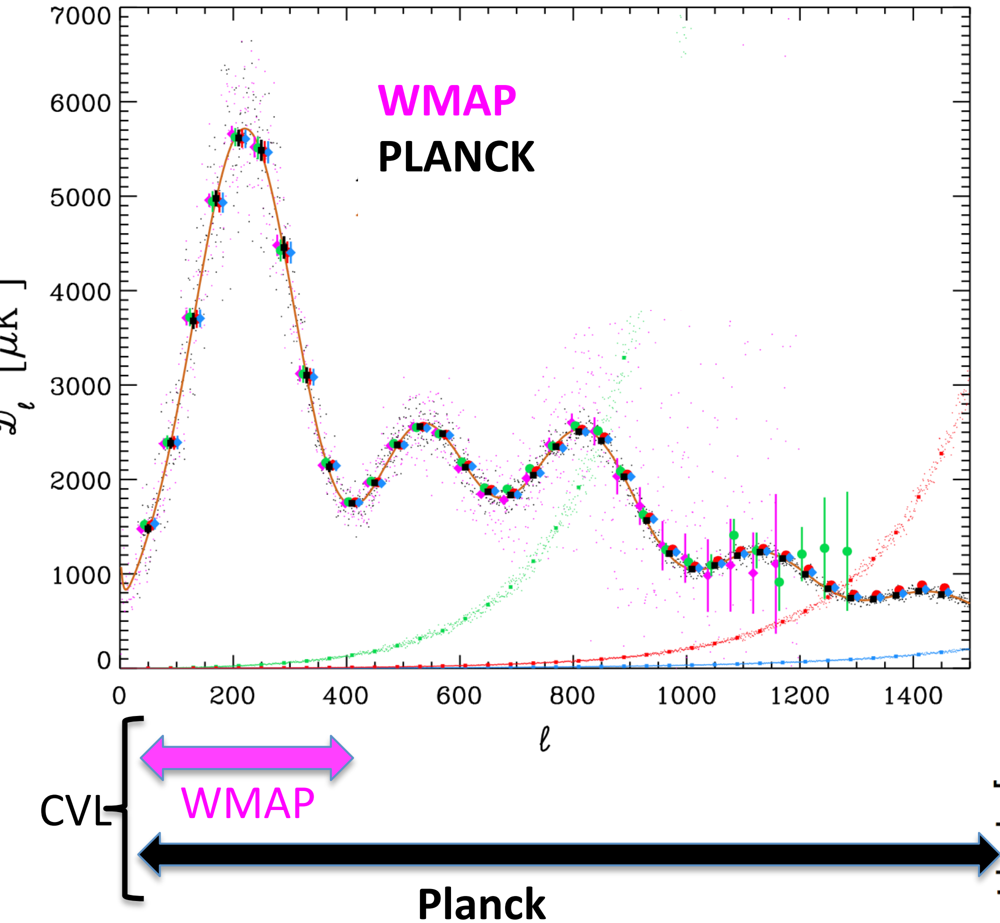
This talk will cover only a very small part of the Planck 2015 results, mostly in the Cosmological Parameters and Likelihood papers (Planck 2015 results XI, XIII).

Planck TT power spectrum

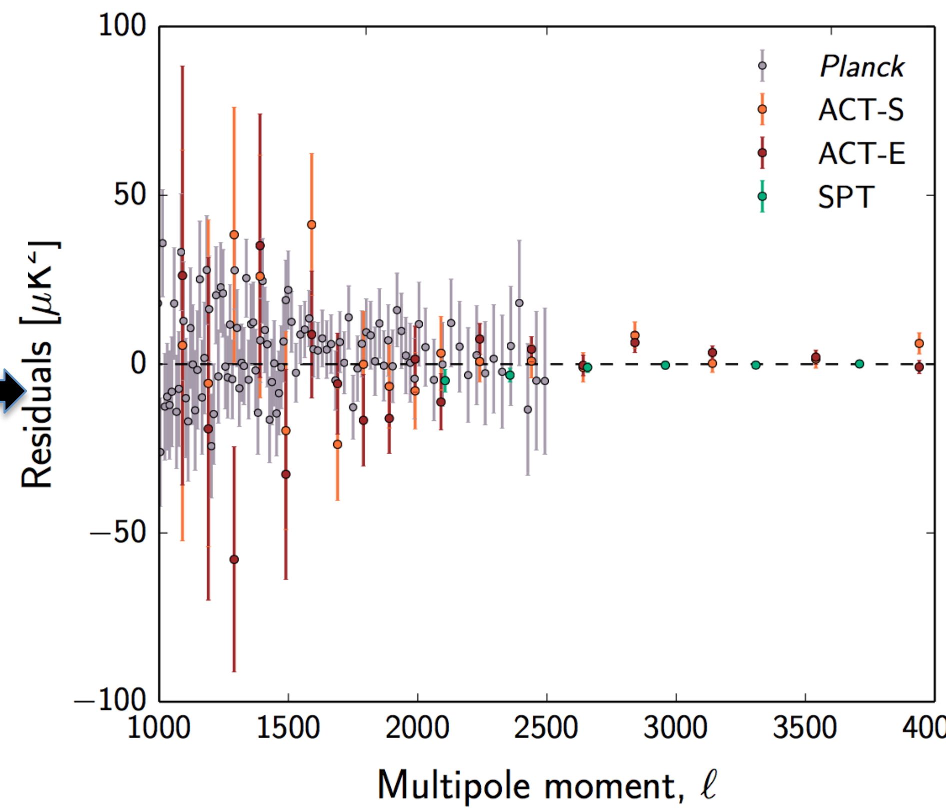


Temperature power spectrum cosmic variance limited till l~1600, on 40-70% of the sky.

Other experiments

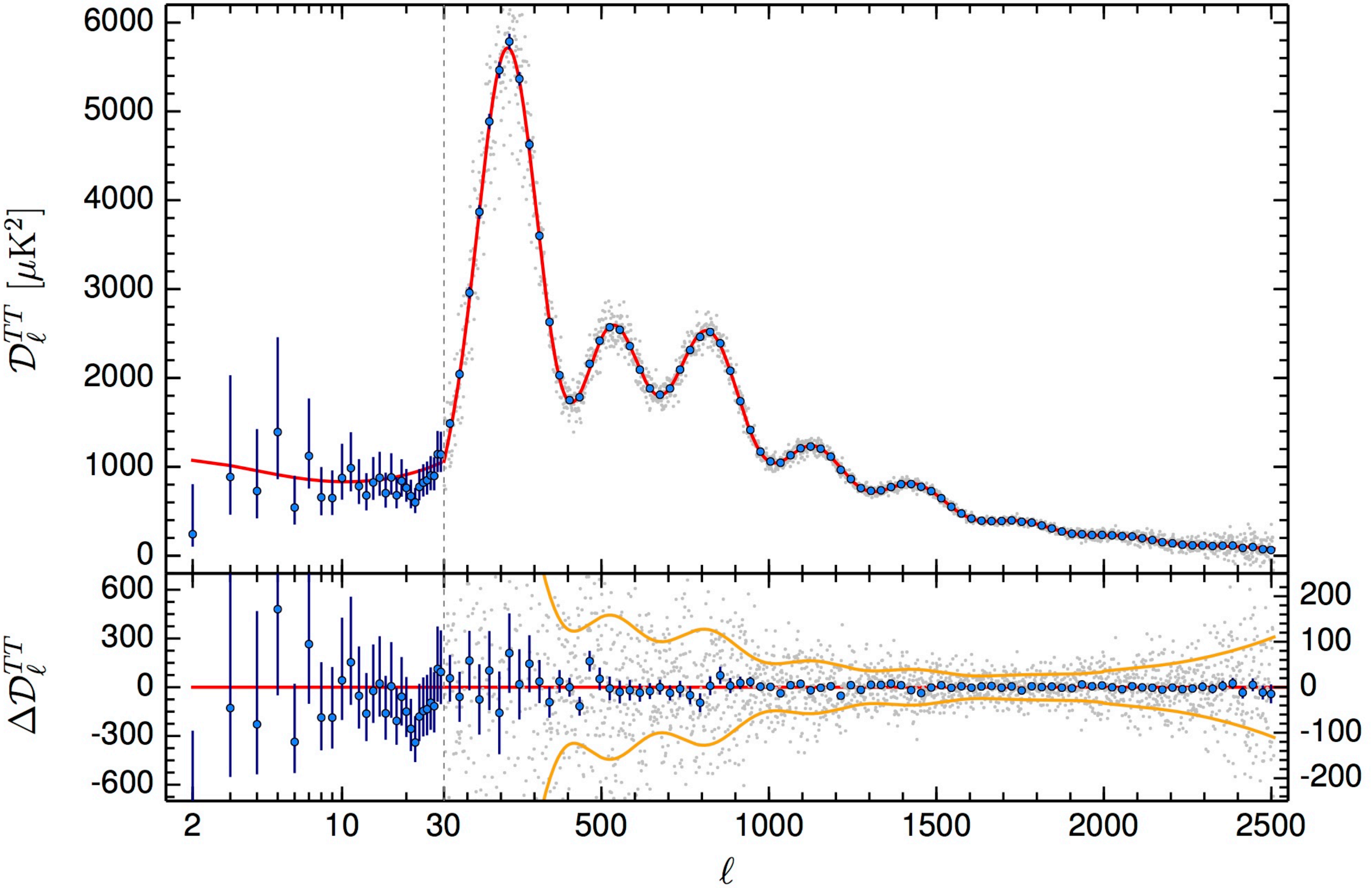


WMAP cosmic variance limited till l~400
(data points till l~1200)

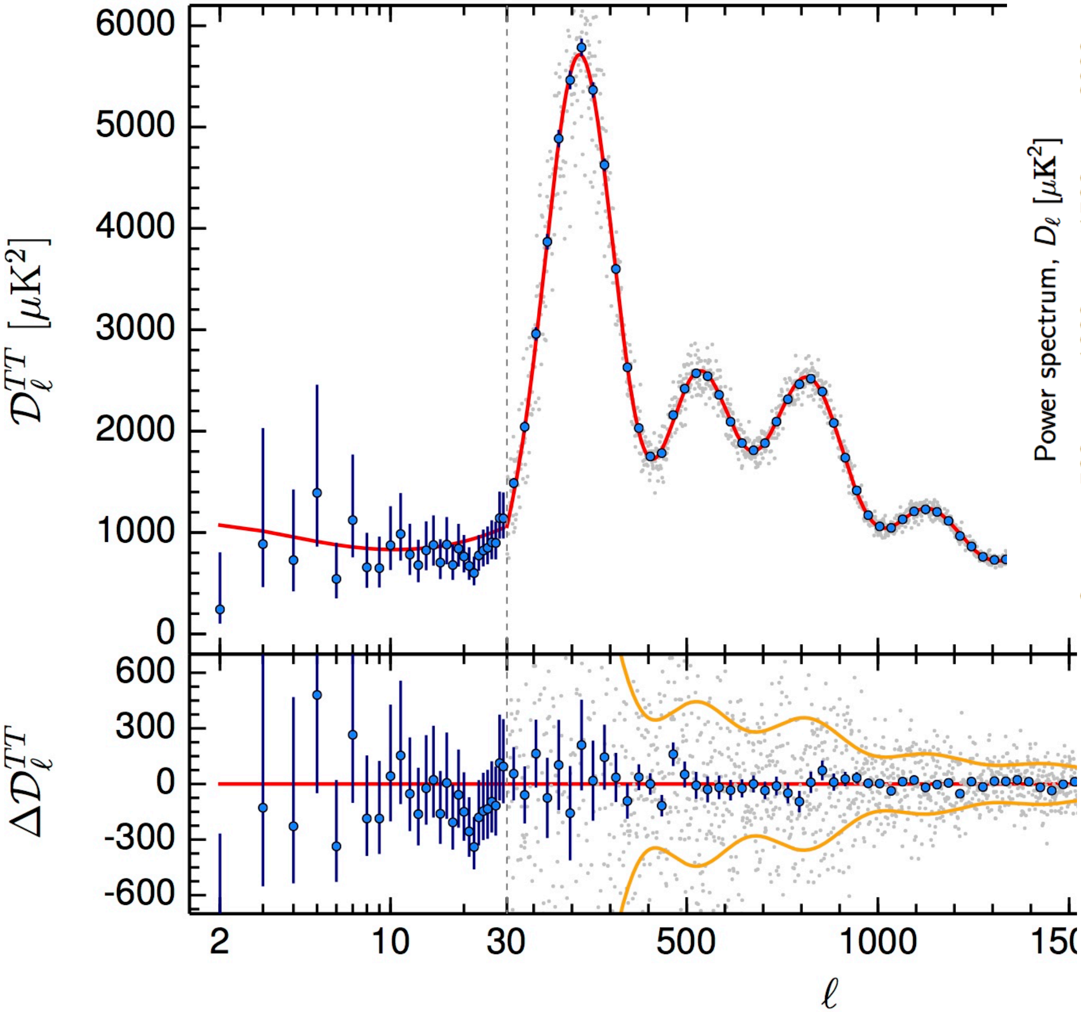


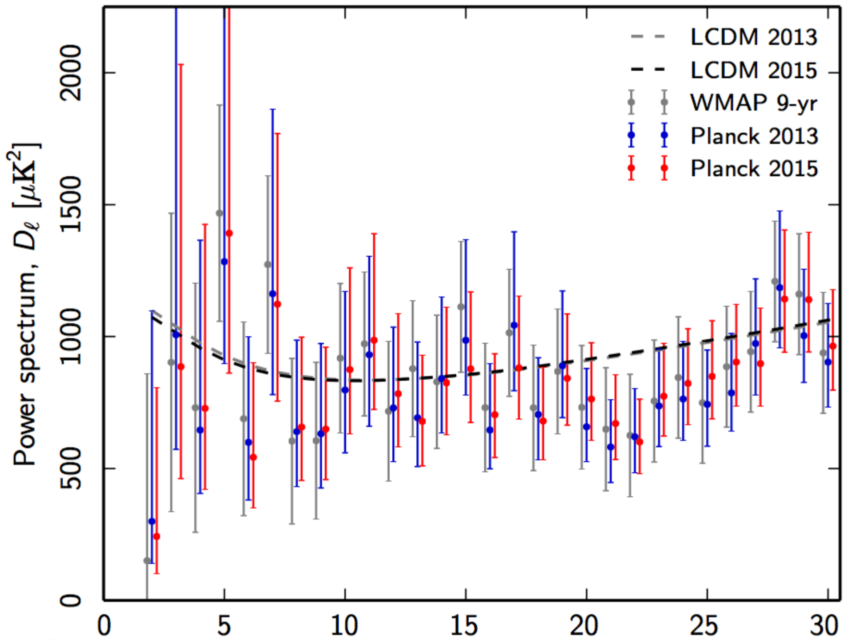
ACT and SPT use < 5% of the sky vs 40-70% in Planck=> sample variance more than 3 times larger than Planck!

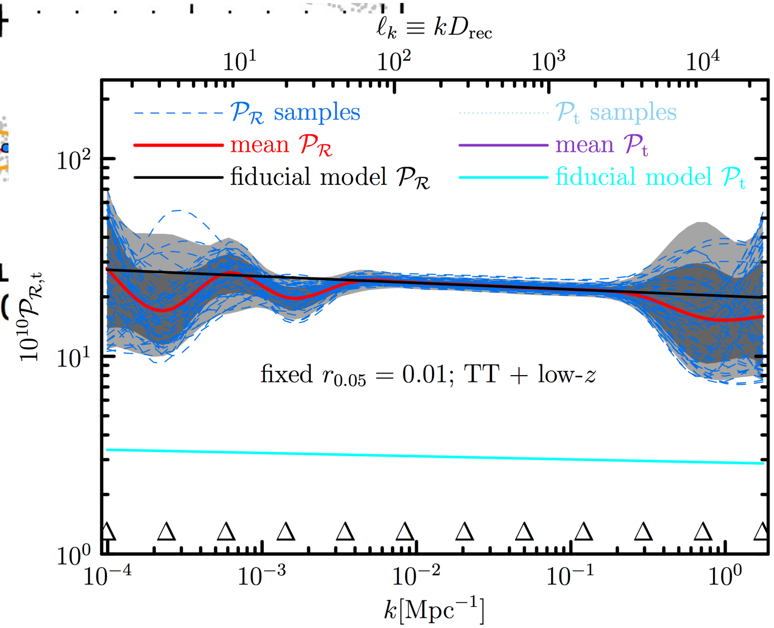
Planck TT power spectrum



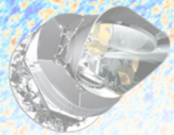
Planck TT power spectrum

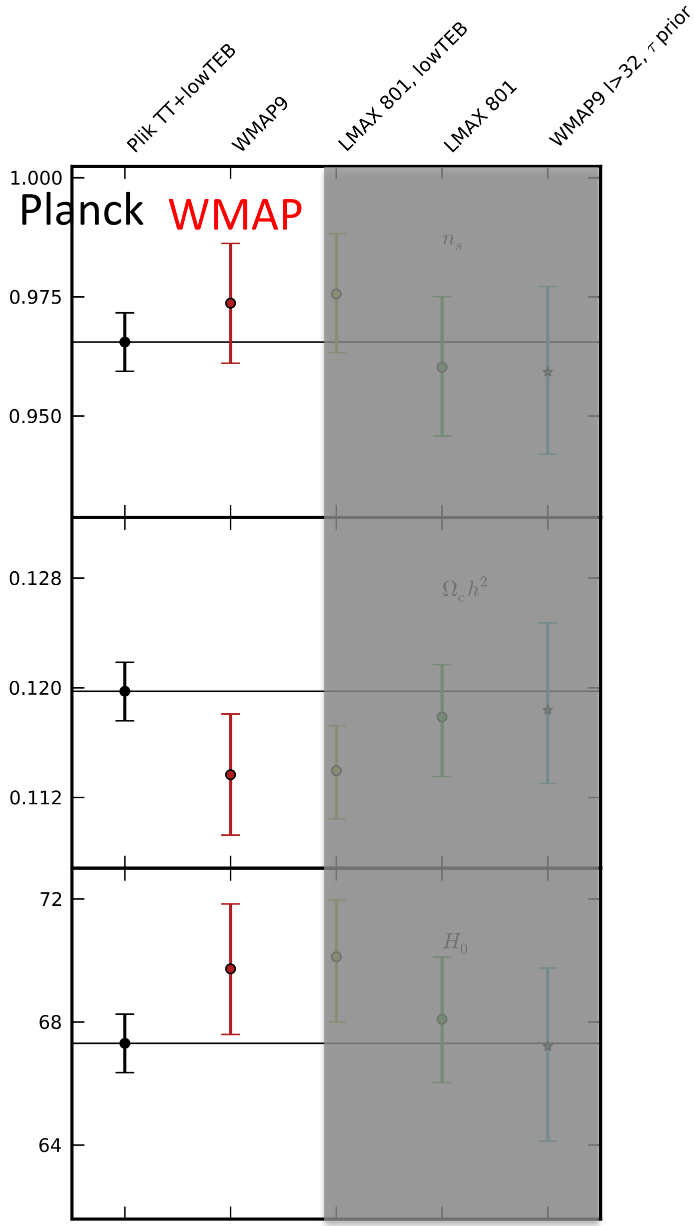


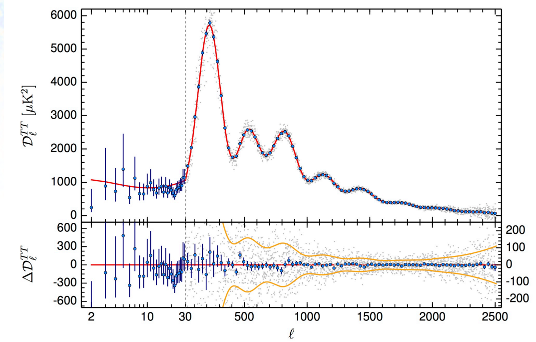




See also Hannestad 03, Shafieloo 03,
Bennet et al. 2011, Mortonson et al. 2009 and many others







- Wmap and Planck parameters differ by ~1 sigma.
- WMAP error bars factor 2 larger.
- N_s and H_0 are larger in WMAP, while $\Omega_c h^2$ is smaller.

(NB: For Planck, we use TT only at high-l and TT and pol at low-l. For WMAP, we use all the TT and pol data available. Few of the runs ran with PICO/CAMB, might give small differences.)

Scalar spectral index ns

Planck	0.9655 ± 0.0062
WMAP	0.974 ± 0.013

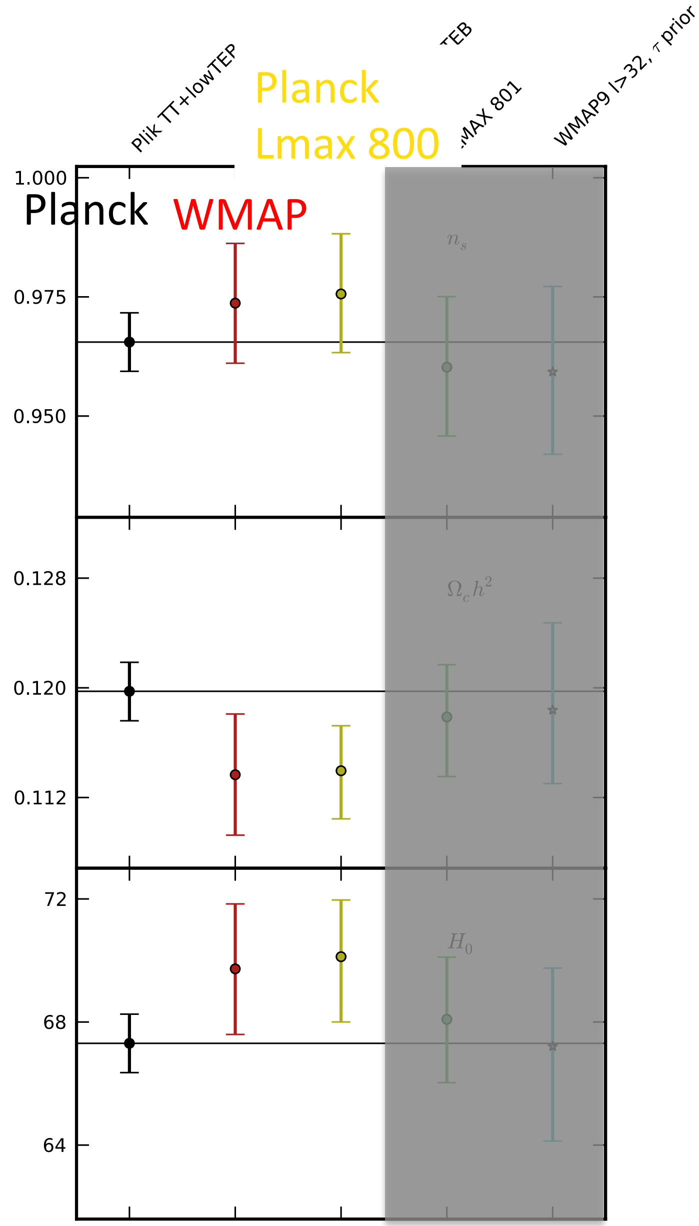
Dark Matter density

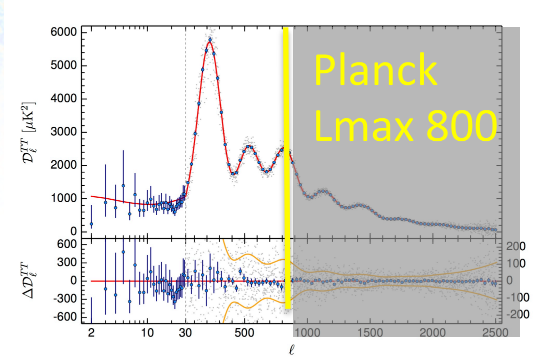
Planck	0.1197 ± 0.0022
WMAP	0.1137 ± 0.0045

Hubble parameter (derived)

Planck	67.31 ± 0.96
WMAP	69.7 ± 2.1

- If we cut Planck data at lmax=800, n_s and H_0 increase while H_0, in good agreement with WMAP.
- Cutting l<800 makes Planck more sensitive to the l~20 deficit, similarly to what happens with WMAP.





Scalar spectral index ns

Dark Matter density

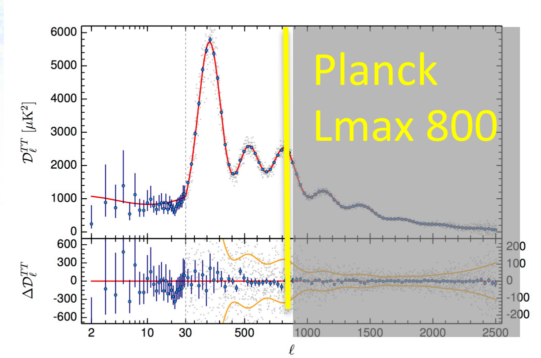
Hubble parameter

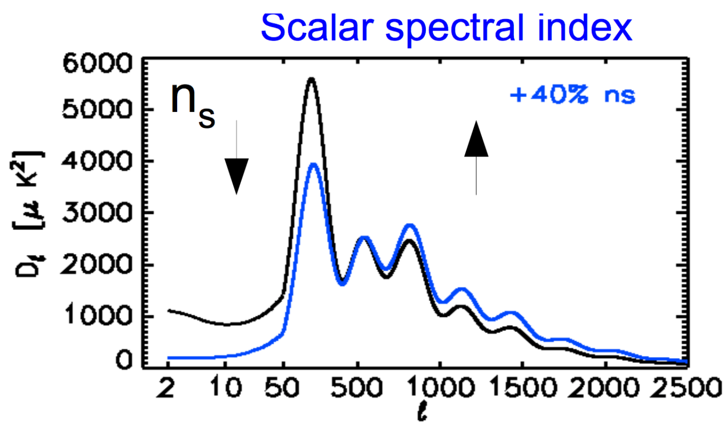
- When we cut at lmax=800, degeneracies in parameters are large. Once can increase ns to better fit for the l=20 deficit (remember the constraining power decreases at lower-l due to cosmic variance)

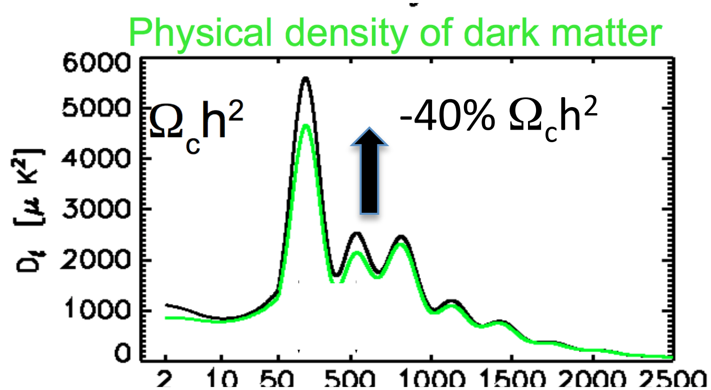
$$\boxed{\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}}$$

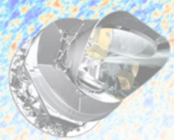
- Since a larger n_s this decreases the first peak, one can compensate by decreasing the value of $\Omega_c h^2$.

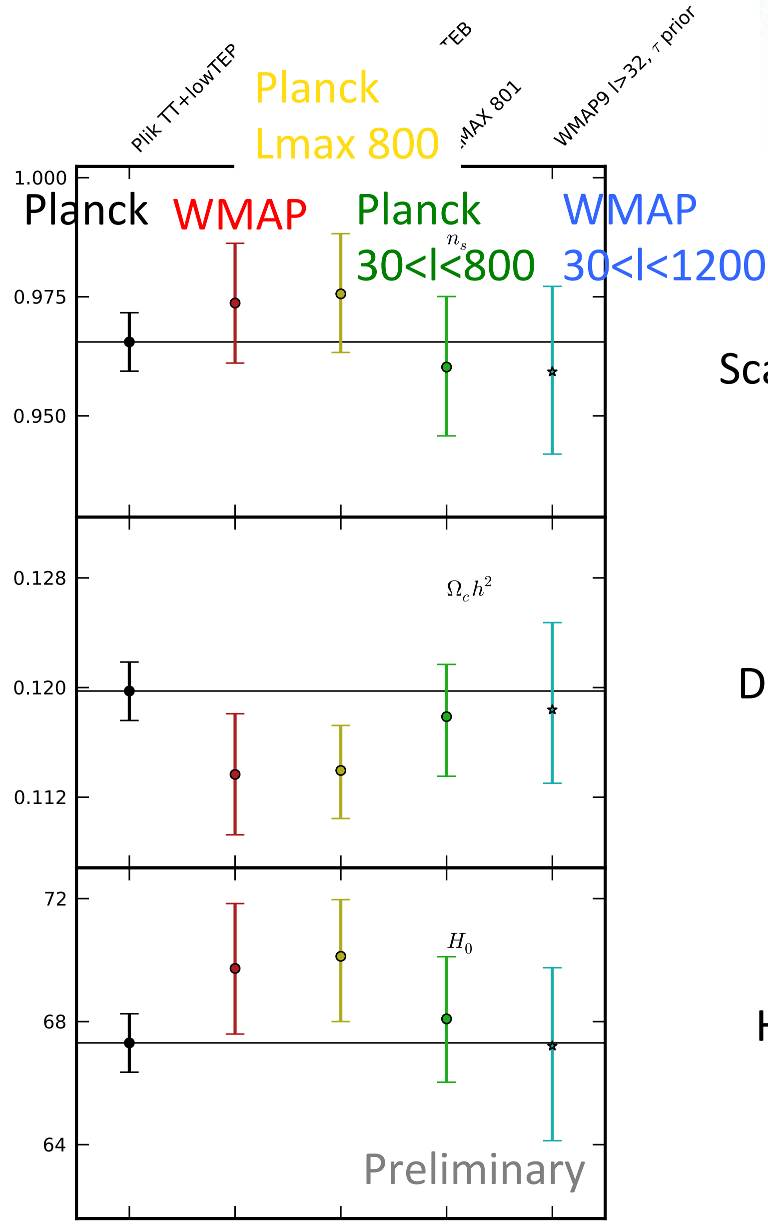
- A smaller $\Omega_c h^2$ requires a larger H0 in order to keep the position of the peaks (e.g. the angular distance to last scattering) fixed.

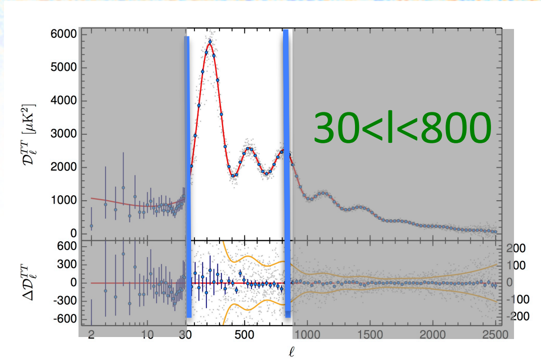












Cutting the TT l<30, we recover the full Planck cosmology both with Planck lmax=800 and with WMAP!

(NB: we cut here both the TT and pol data at low-l. We use a prior on tau to break degeneracies)

Scalar spectral index n_s

Dark Matter density

Hubble parameter

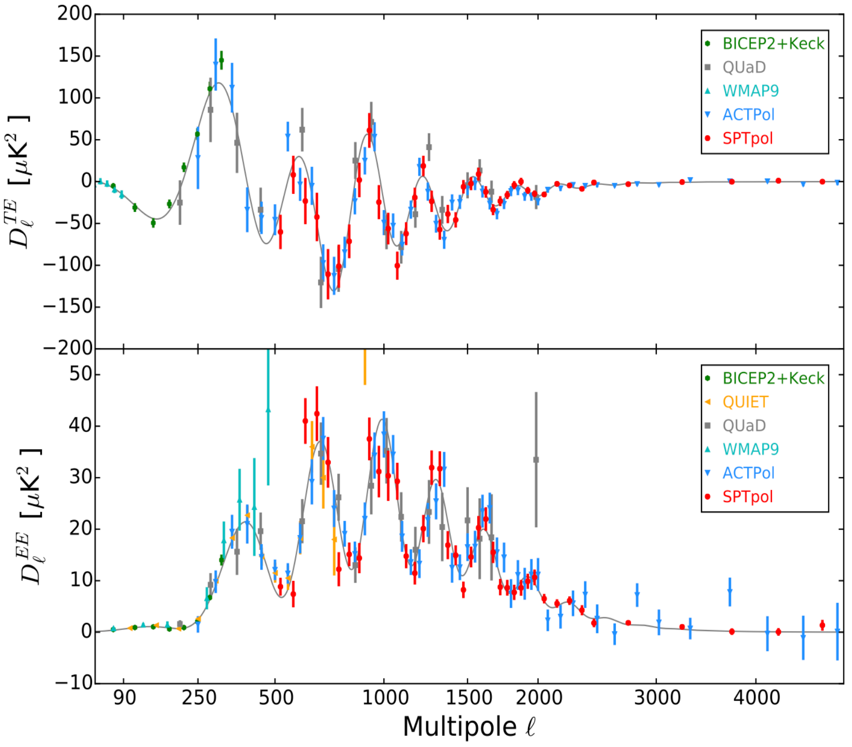
Summary

- Planck and WMAP cosmologies are in very good agreement, in particular when cutting Planck at lmax=800.
- The WMAP and Planck lmax=800 cosmologies are affected by the l~20 deficit: n_s is large to better fit the low-l, $\Omega_c h^2$ is low to compensate for large n_s on the first peak, H_0 increases to keep the position of the peaks (angular diameter distance to last scattering surface) fixed.
- If we cut the l<30, the WMAP and Planck lmax=800 cosmologies are in very good agreement with the full Planck one.
- The full Planck cosmology is less affected by the l~20 deficit thanks to the longer lever arm. However, this deficit still impacts parameters at some level (e.g. Neff, Alens)

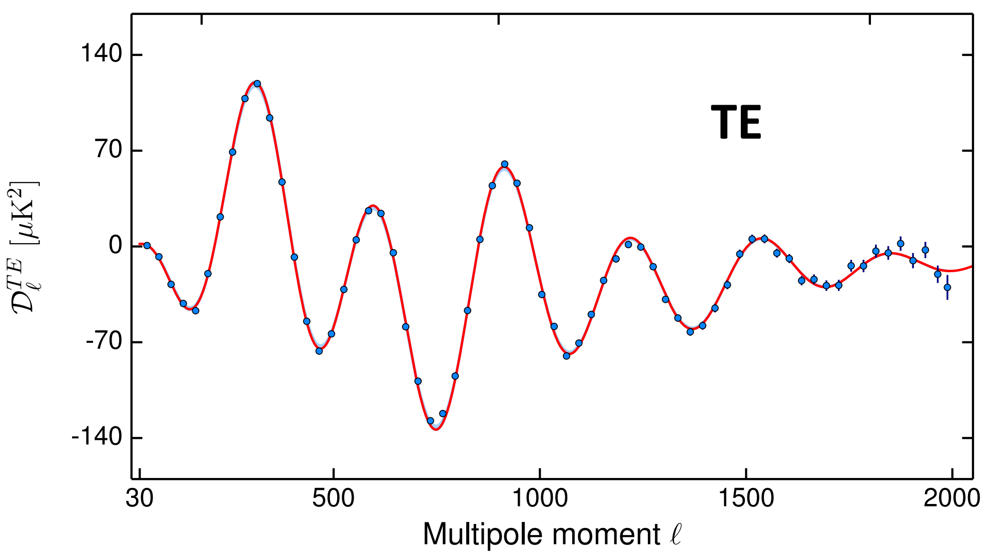
Extensions of ΛCDM

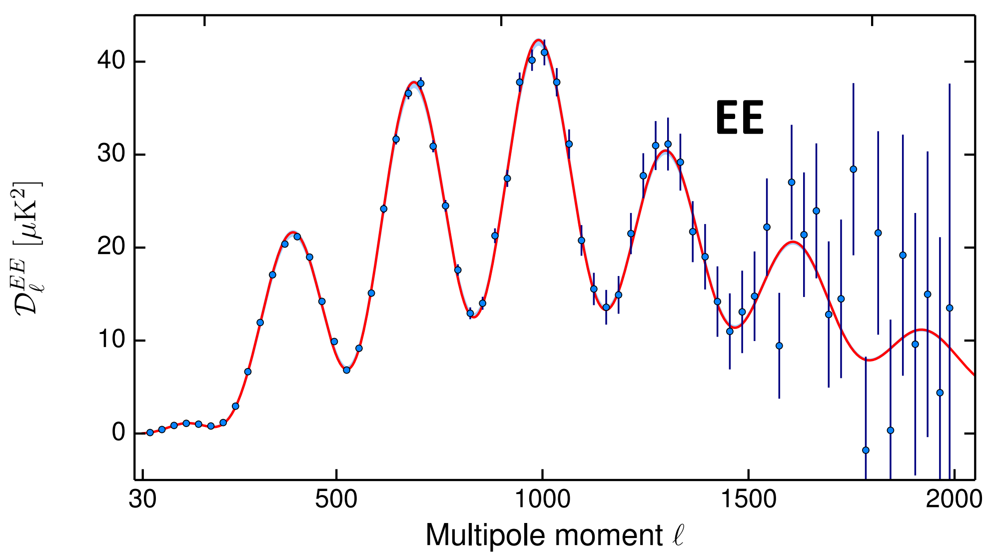
2015 Polarization power spectra

Pre-Planck measurements

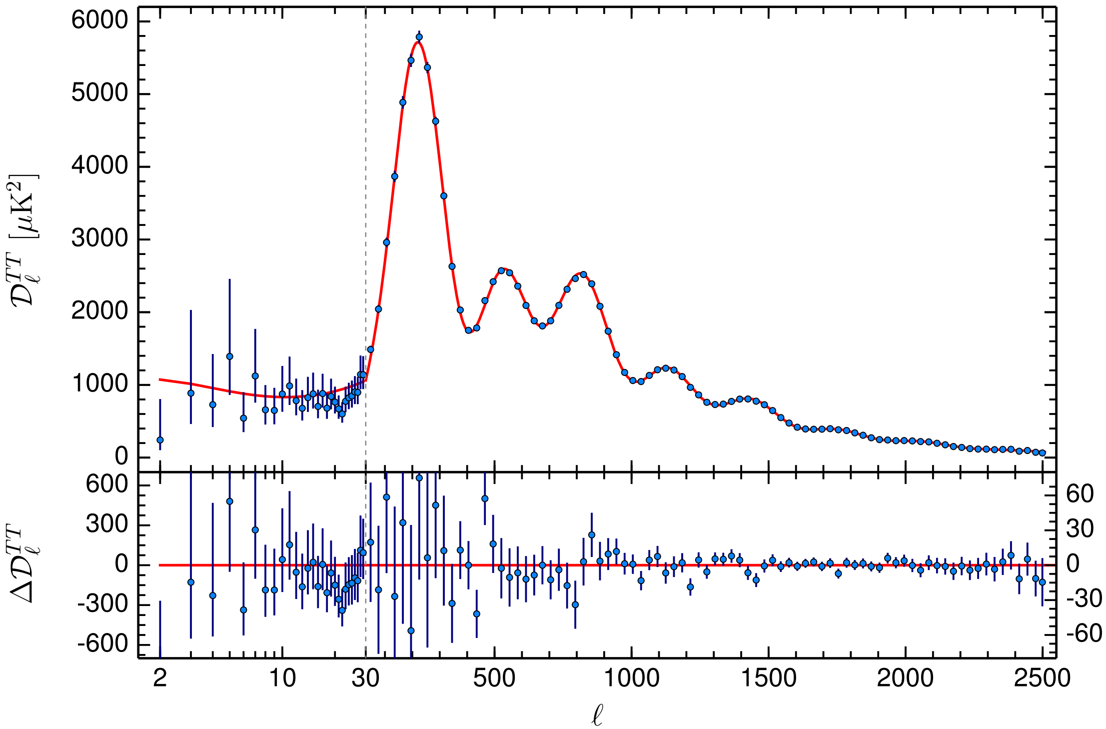


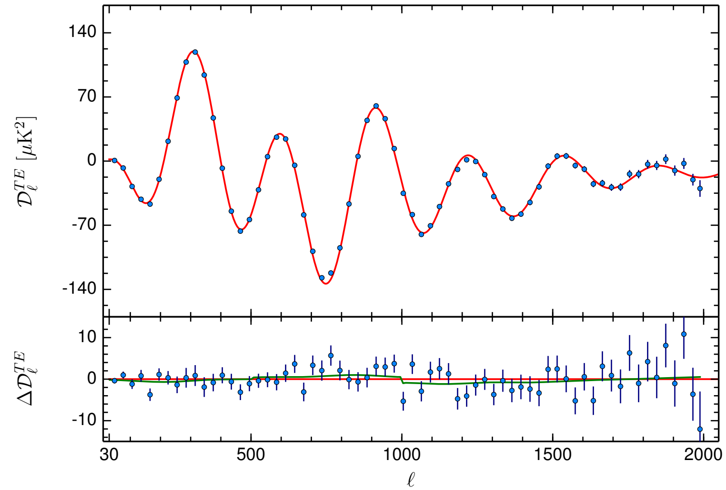
Planck 2015

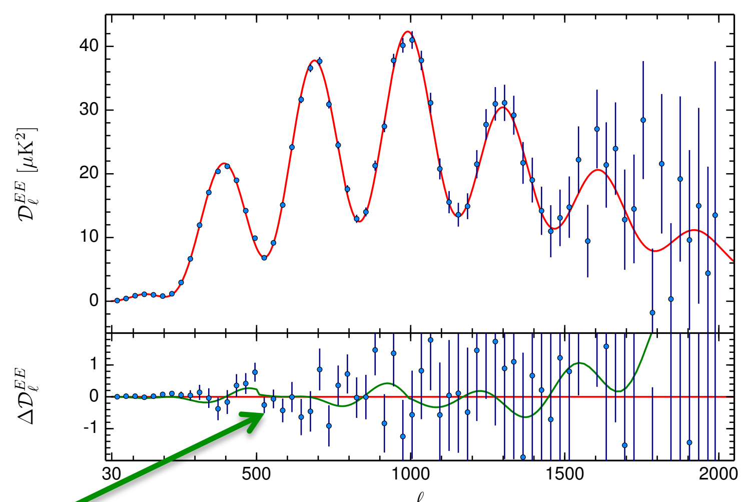




ΛCDM best fit



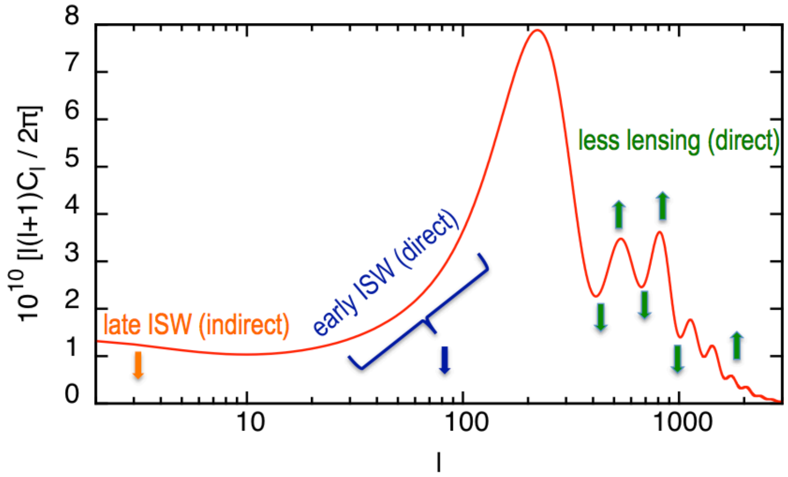




- ΛCDM is very good fit to the data
- Remaining systematics present in polarization spectra, possibly due to unaccounted beam missmatch.

Sum of neutrino masses

- Relativistic at the epoch of recombination, Non-relativistic at late times
- At large scales (T only): changes early and late ISW through changes of expansion rate.
- At small scales: Less lensing, less smoothing of the peaks.



Σm_ν(95% CL) [eV]	2013	2015	2015 +TE,EE
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For 2013, lowP is WMAP polarization
Assumption: 3 degenerate massive neutrinos

- Full mission TT data improve constraints by ~20-40%.
- « Best » estimate from TT+lowP +lensing+ext. Already stronger than expected sensitivity from Katrin (tritium beta decay)!

Number of relativistic species

- CMB is sensitive to radiation density.
- Neff parametrizes the radiation density other than photon). Neff=3.046 (standard).
- Non-standard Neff could be due to additional radiation (sterile neutrino, light relics) or non-standard thermal history.

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

	2013	**2015**	**2015 +EE,TE**
PlanckTT+lowP	3.51±0.39	3.13±0.32 (18%)	2.98±0.20 (48%)
PlanckTT+lowP +BAO	3.40±0.30	**3.15±0.23 (23%)**	**3.04±0.18 (40%)**

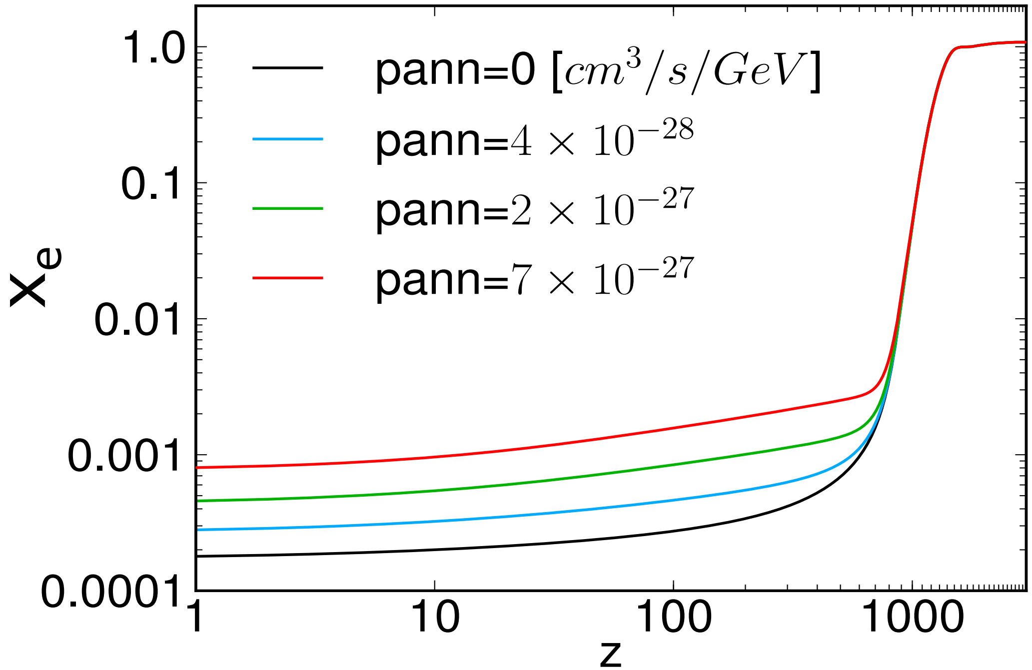
Assumption:
1 massive neutrino at 0.06eV, other massless

(for 2013, lowP is WMAP polarization) (68% C.L.)

- Planck measures $N_{\rm eff}$ in perfect agreement with the standard value, 3.046.
- $N_{\rm eff}$>0 confirmed at ~15-sigma.
- $N_{\rm eff}$=4 excluded at 3-5 sigma!

DM annihilation at the epoch of recombination

$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \underbrace{f_{eff} \frac{<\sigma v>}{m_\chi}}_{p_{ann}}$$



The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.

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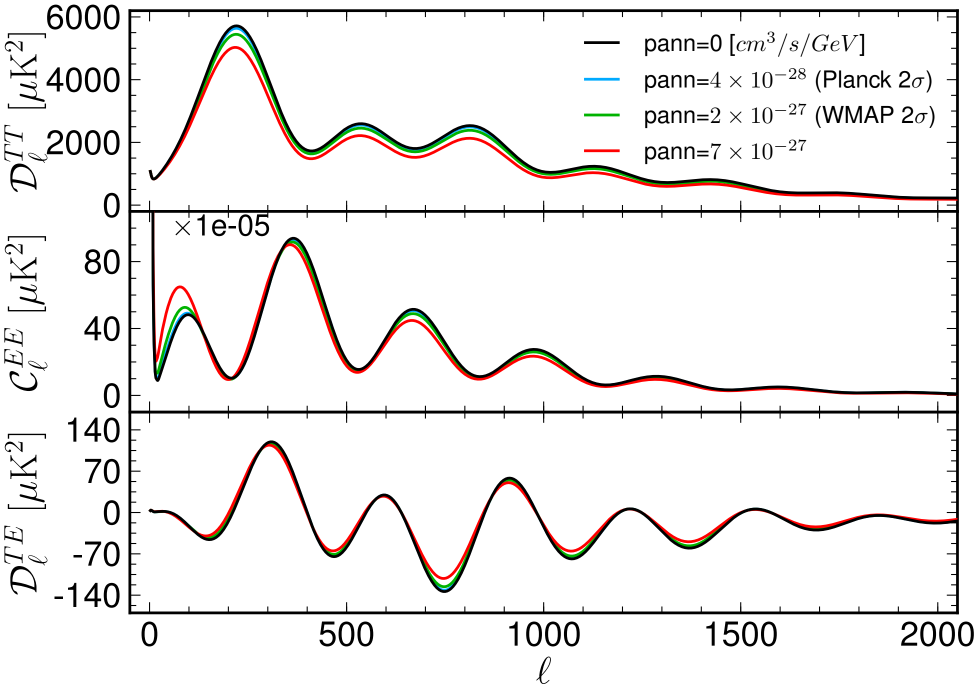
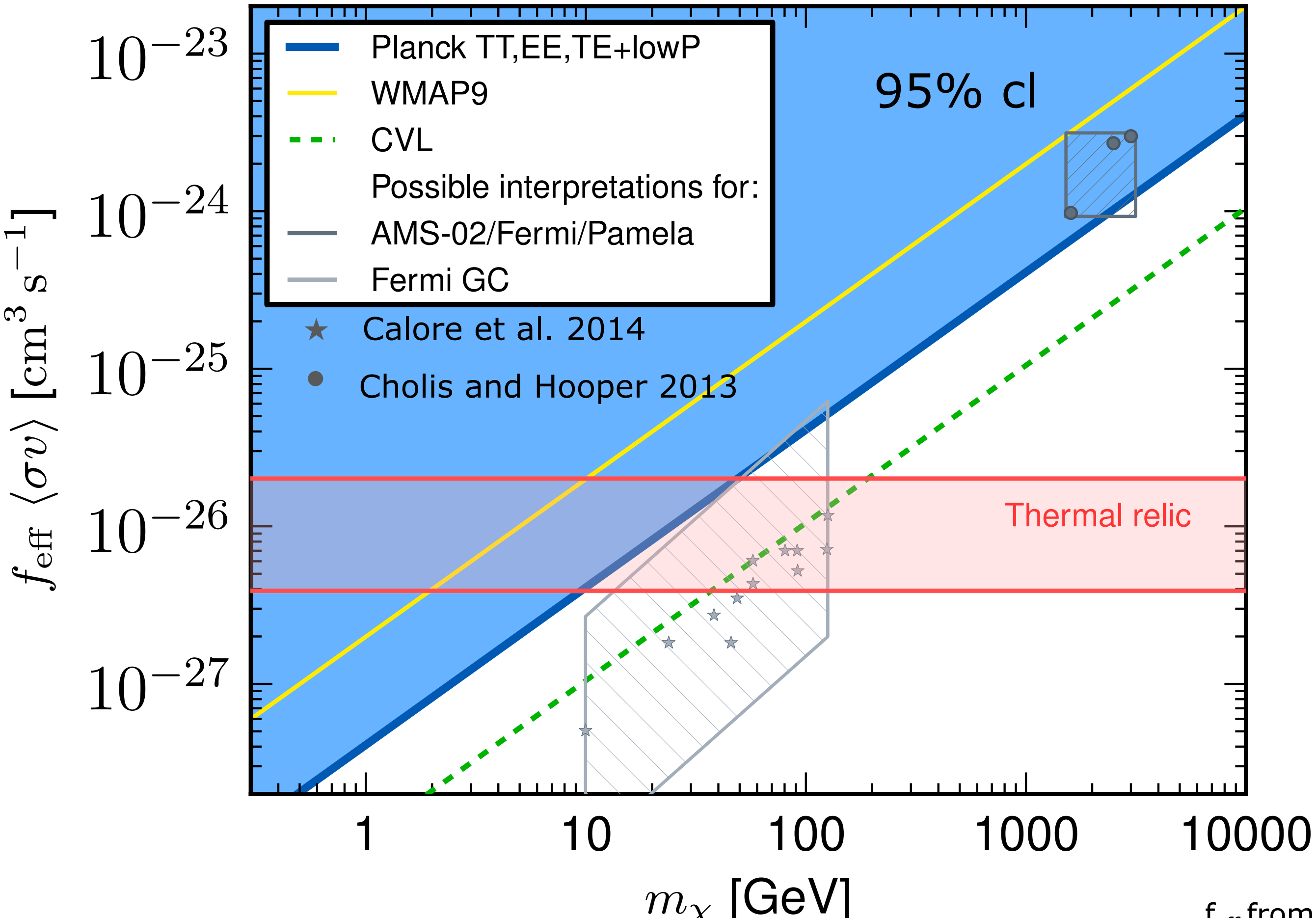


- The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.
- Suppresses the peaks, but enhances polarization at large scales!

Constraints on Dark Matter Annihilation



Most of parameter space preferred by AMS-02/ Pamela/Fermi ruled out at 95%, under the assumption <σv>(z=1000)=<σv>(z=0)

Thermal Relic cross sections at z~1000 ruled out for:

m~<40 GeV (e^-e^+)
m~<16 GeV ($\mu^+\mu^-$)
m~<10 GeV ($\tau^+\tau^-$).

Only a small part of the parameter space preferred by Fermi GC is excluded

$f_{\rm eff}$ from T. Slatyer (Madhavacheril et al. 2013)

Conclusions

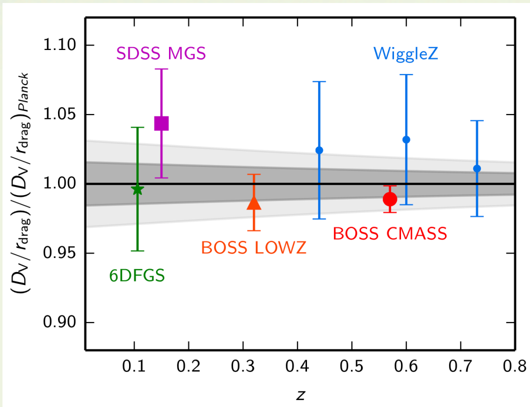
- Good agreement between Planck and WMAP on LCDM parameters. Differences understood.
- Planck 2015 data is powerful to constrain LCDM and extensions.
- Planck polarization can improve spectacularly constraints on a number of models, e.g. DM annihilation.

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.

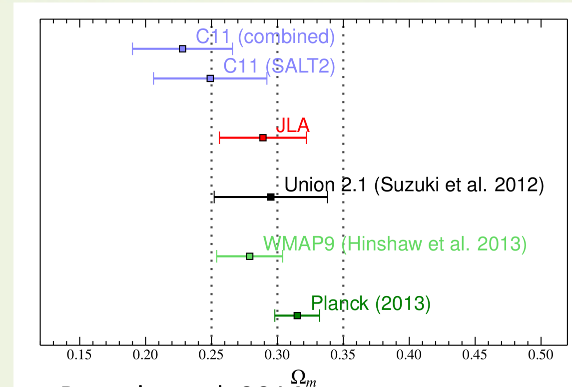
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

Comparison with other datasets:

BAO

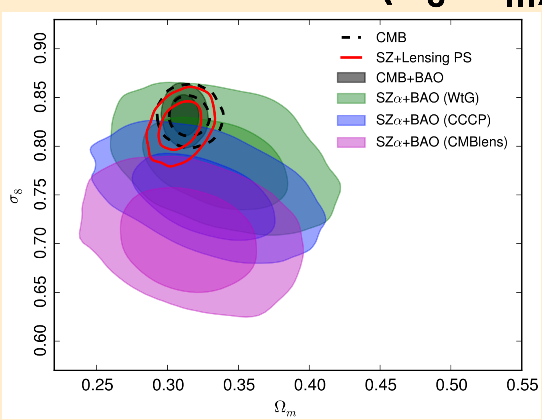


Supernovae (Ω_m)



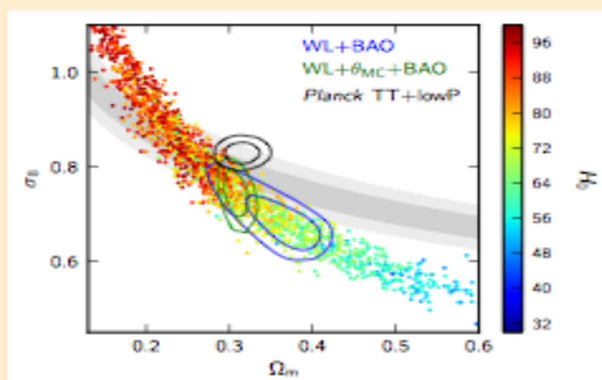
Betoule et al. 2014

Cluster counts (σ_8-Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8-Ω_m)



Direct measurements H_0

H_0=67.8±0.96
(PlanckTT+lowP+lensing)

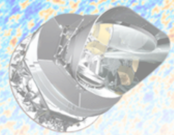
VS

H_0=72.8±2.4 **[2σ tension]**
(Riess+11)

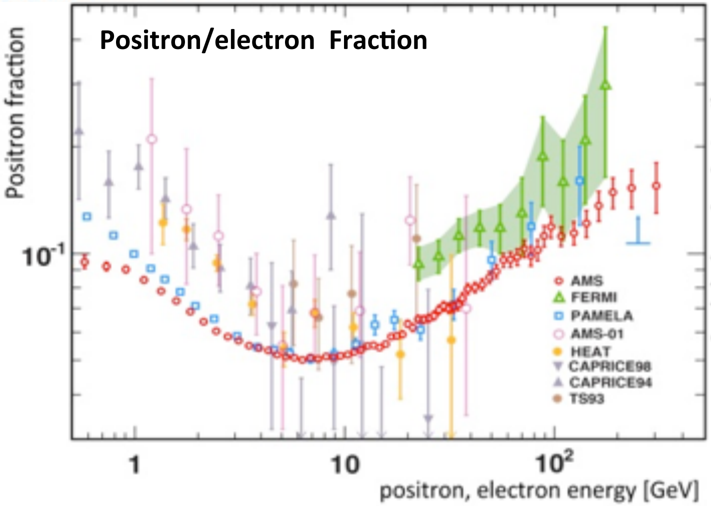
H_0=70.6 ± 3.3 **[1σ tension]**
(Efstathiou+14)

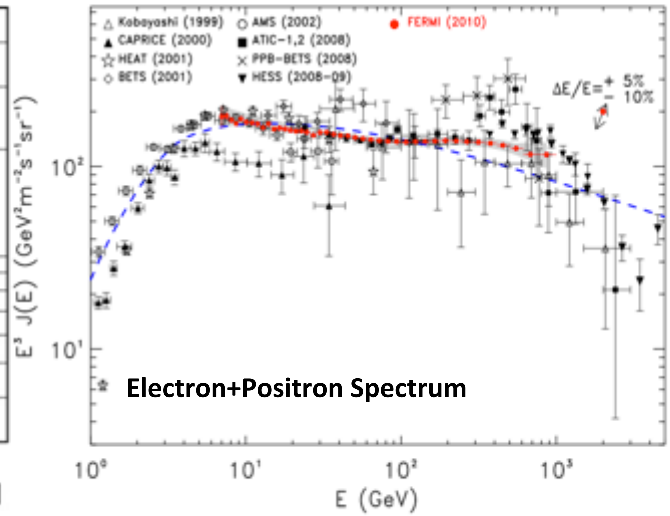
H_0=74.3 ± 2.6 **[2.5σ tension]**
(Freedman+12)

[in Km/s/Mpc]



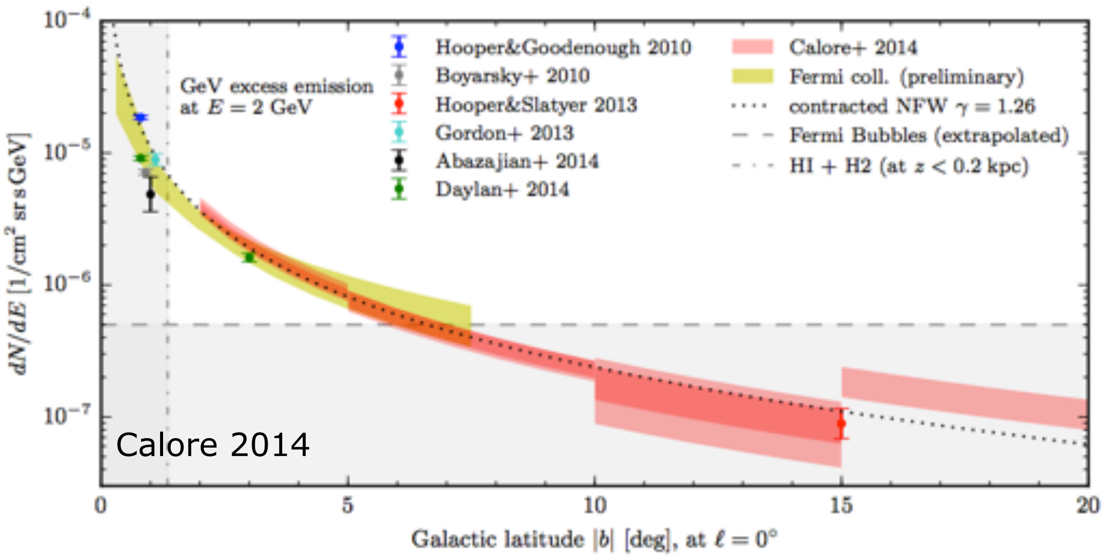
Recent anomalies:
Dark matter annihilation?





Cosmic rays excesses in PAMELA/FERMI/AMS-02

- Leptonic ann.chan.,
- Mass ~ TeV,
- Large cross-section required ($\sim 10^{-23} cm^3/s$).
- Need broken power law in electrons.



Fermi Galactic Center excess

- Many ann. chan. allowed.
- Mass ~ few tens GeV,
- Thermal relic cross section ($\sim 10^{-26} cm^3/s$)

Inflation: n_s and r

- From **Planck TT+lowP:**
  - Almost a **6σ departure** from scale invariance (but model dependent! relaxable when opening Neff)

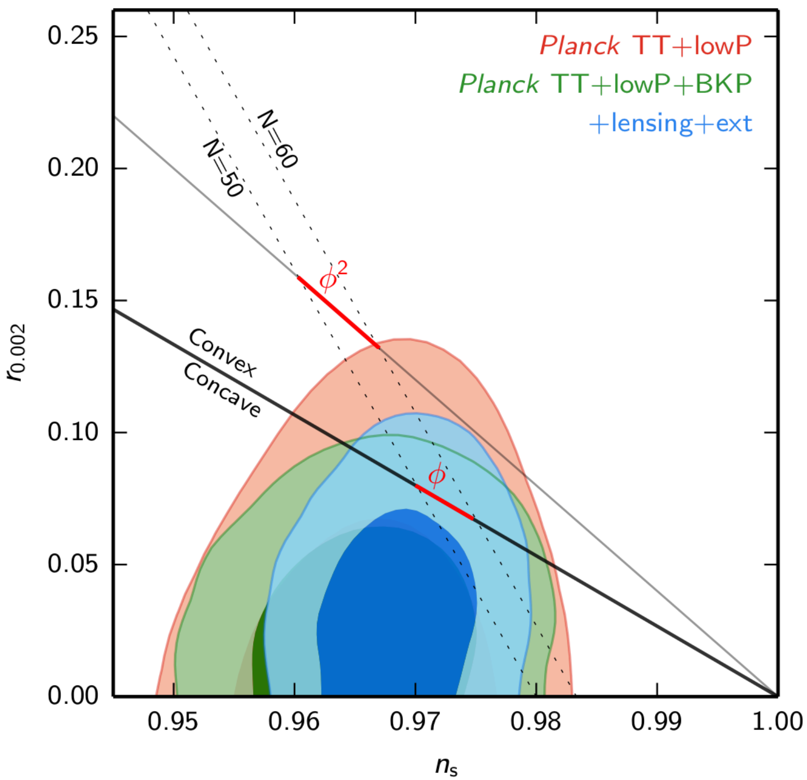
    n_s=0.9655±0.0062

  - Tensor to scalar ratio constrained at 95%c.l.:

    r<0.10

- Adding BB measurements from **BICEP2/KECK**, foreground-cleaned with Planck data (**Planck TT+lowP +BKP**):

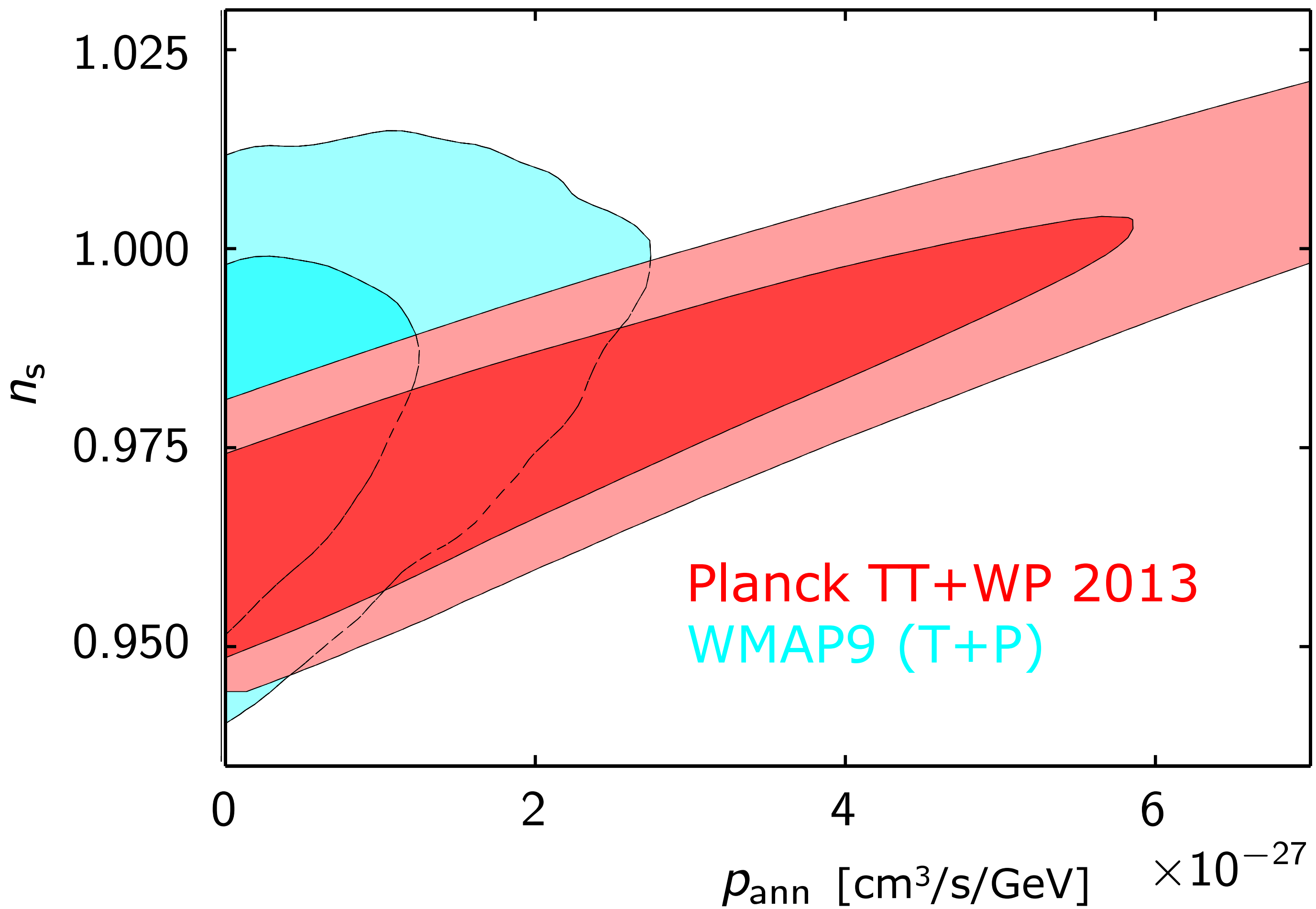
    r<0.08



r=Power in tensor (Grav. Waves)/scalar (density pert.)

ns=spectral index of primordial scalar perturbations

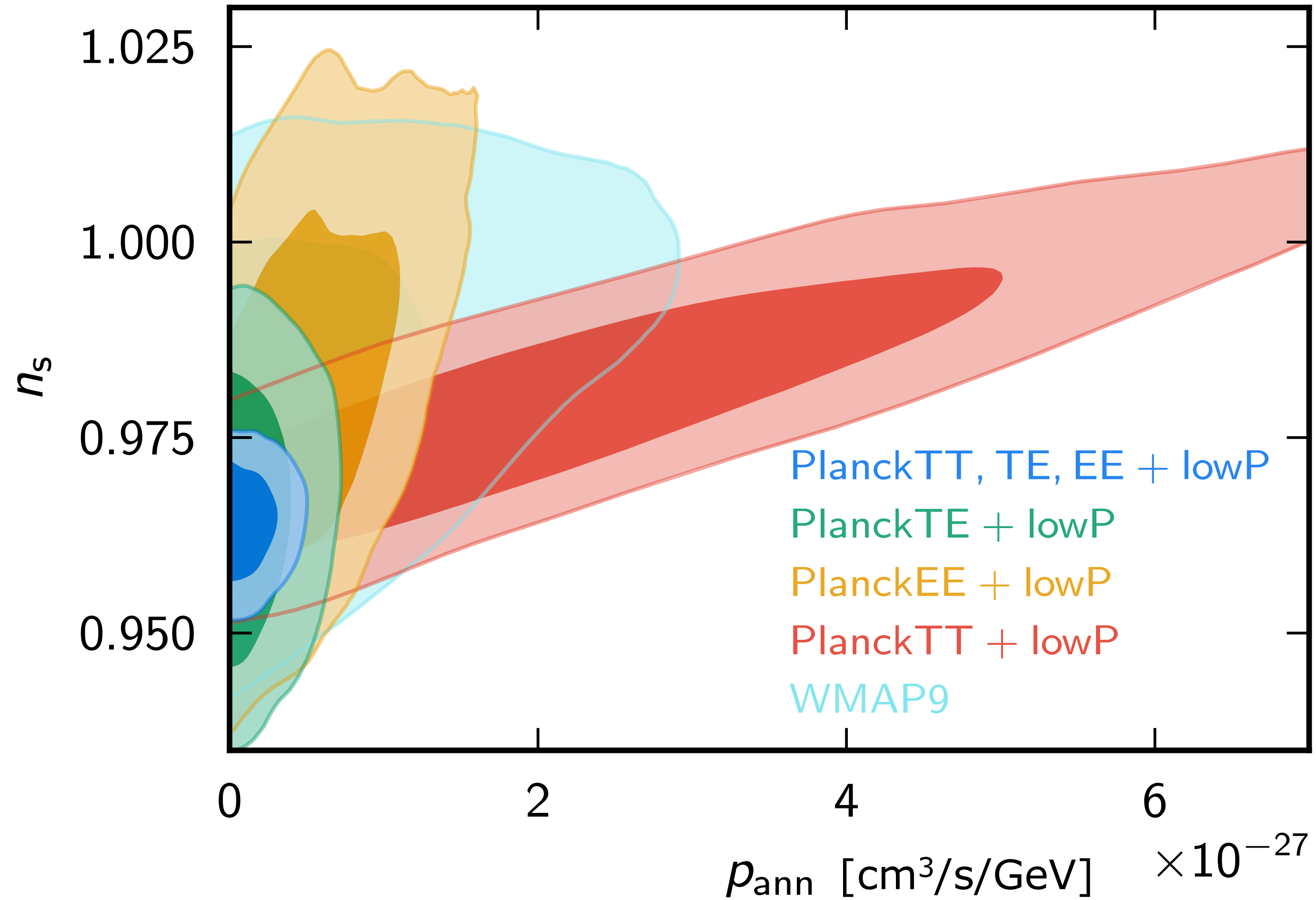
Previous Constraints



Large degeneracies in TT only data.

$$p_{ann} = f_{eff} \frac{<\sigma v>}{m_\chi}$$

Planck 2015 Constraints



Polarization breaks degeneracies!

Planck TT,TE,EE set a constraint 5 times stronger than WMAP9, 4 times stronger than WMAP9+SPT

$$p_{ann} = \boxed{f_{eff} \frac{<\sigma v>}{m_\chi}}$$

Extensions of ΛCDM

Dataset

- **Planck TT**: Planck **TT 2 < ell < 2500**.
- **lowP**: low-l Planck **polarization 2 < ell < 30** (For 2013 results, this will indicate low-l WMAP polarization).
- **Planck TE, EE**: Planck TE and EE high-ell, 30 < ell < 2000
  Small systematics in polarization might still be affecting the results.
- **Lensing**: Planck lensing potential 40 < ell <400 from 4-point correlation function
- **Ext**, external datasets:
  - **BAO** (6dFGS, SDSS-MGS, BOSS-LOWZ, CMASS DR11)
  - **JLA**: Type Ia Supernovae (SNLS +SDSS+low z Sne)
  - **H0**: Hubble constant (Efstathiou 2014 reanalysis of Riess et al. 2011)

➢ Whenever not specified, we assume
Neff=3.046, Σm_ν=0.06eV (1 massive, two massless).

NEUTRINOS

A one-slide overview on neutrinos

- Standard model of particles: 3 active neutrinos
  - *Apperance/disapperance anomalies: additional sterile neutrinos?*
- Neutrino oscillation experiments:
  - $\delta m^2_{sun} = 7.6 \pm 0.6 \times 10^{-5}\ eV^2$, $\delta m^2_{atm} = 2.5 \times 10^{-3}\ eV^2$
  - *Still lacking absolute mass value*

- Standard model of cosmology: relic neutrino background.
  - In thermal equilibrium with plasma via weak interactions.
  - Today at T=1.9K.
  - Relativistic at the epoch of recombination (if $\Sigma m_\nu < 1 eV$), non-relativistic today.

Neutrinos and CMB

Relativistic at early times (Neff):

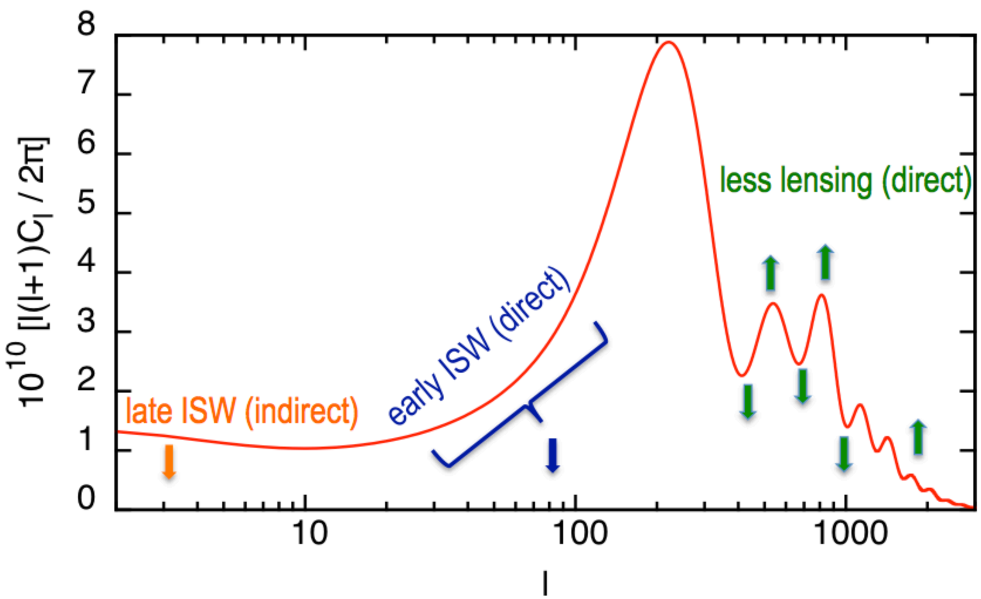
- CMB is sensitive to radiation density.
- Neff parametrizes the radiation density other than photon). Neff=3.046 (standard).
- Non-standard Neff could be due to additional radiation (sterile neutrino, light relics) or non-standard thermal history.

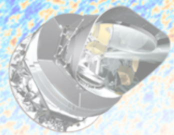
$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Prefactor calculated for standard neutrinos , i.e. Fermions decoupling (instantaneously) before e^+e^- annihilation,today at T=1.9K

Non-relativistic at late times (mnu):

- At large scales (T only): changes early and late ISW through changes of expansion rate.
- At small scales: Less lensing, less smoothing of the peaks.





Sum of neutrino masses

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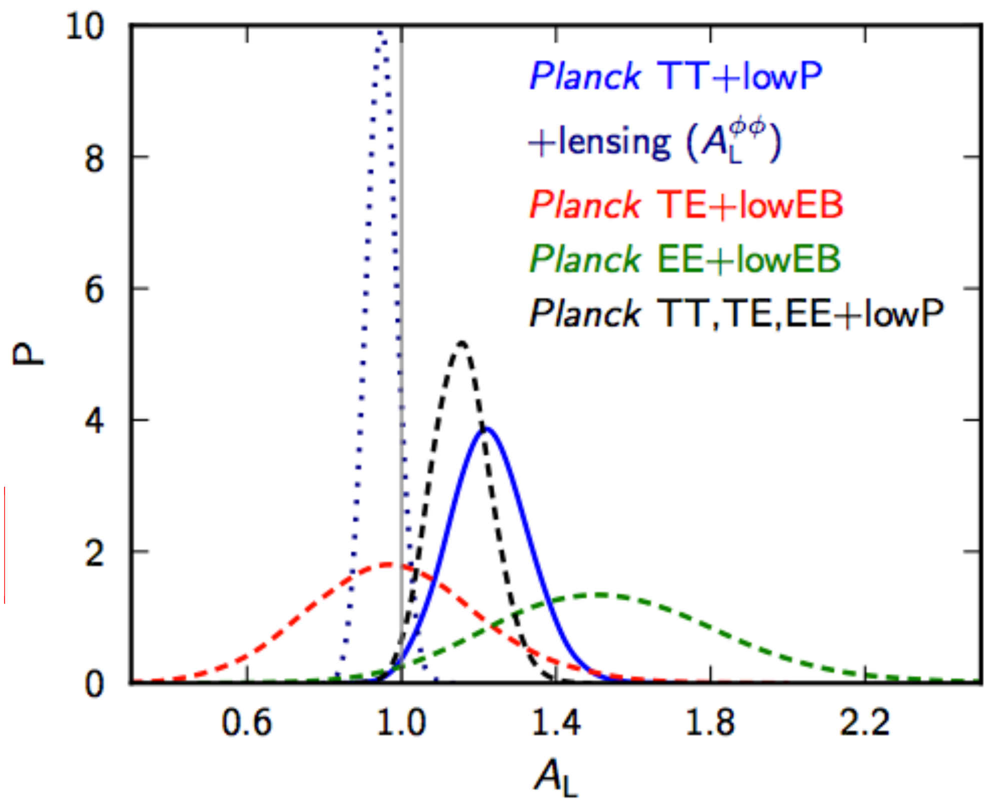
- Full mission TT data improve constraints by ~20-40%.
- Alens problem: CMB prefers a ~2-sigma larger lensing amplitude than LCDM, while lensing reconstruction prefers lower values. This mild tension limits the improvement on neutrino mass in CMB+lensing combination.
- « Best » estimate from TT+lowP +lensing+ext. Already stronger than expected sensitivity from Katrin!

For 2013, lowP is WMAP polarization

Assumption: 3 degenerate massive neutrinos

Sum of neutrino masses



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PlanckTT+lowP +lensing+BAO		**<0.23**	<0.19

- Full mission TT data improve constraints by ~20-40%.
- Alens problem: CMB prefers a ~2-sigma larger lensing amplitude than LCDM, while lensing reconstruction prefers lower values. This mild tension limits the improvement on neutrino mass in CMB+lensing combination.
- « Best » estimate from TT+lowP +lensing+ext. Already stronger than expected sensitivity from Katrin!

For 2013, lowP is WMAP polarization

Assumption: 3 degenerate massive neutrinos

Number of relativistic species

- CMB is sensitive to radiation density.
- Neff parametrizes the radiation density other than photon). Neff=3.046 (standard).
- Non-standard Neff could be due to additional radiation (sterile neutrino, light relics) or non-standard thermal history.

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

	2013	**2015**	**2015 +EE,TE**
PlanckTT+lowP	3.51±0.39	3.13±0.32 (18%)	2.98±0.20 (48%)
PlanckTT+lowP +BAO	3.40±0.30	**3.15±0.23 (23%)**	**3.04±0.18 (40%)**

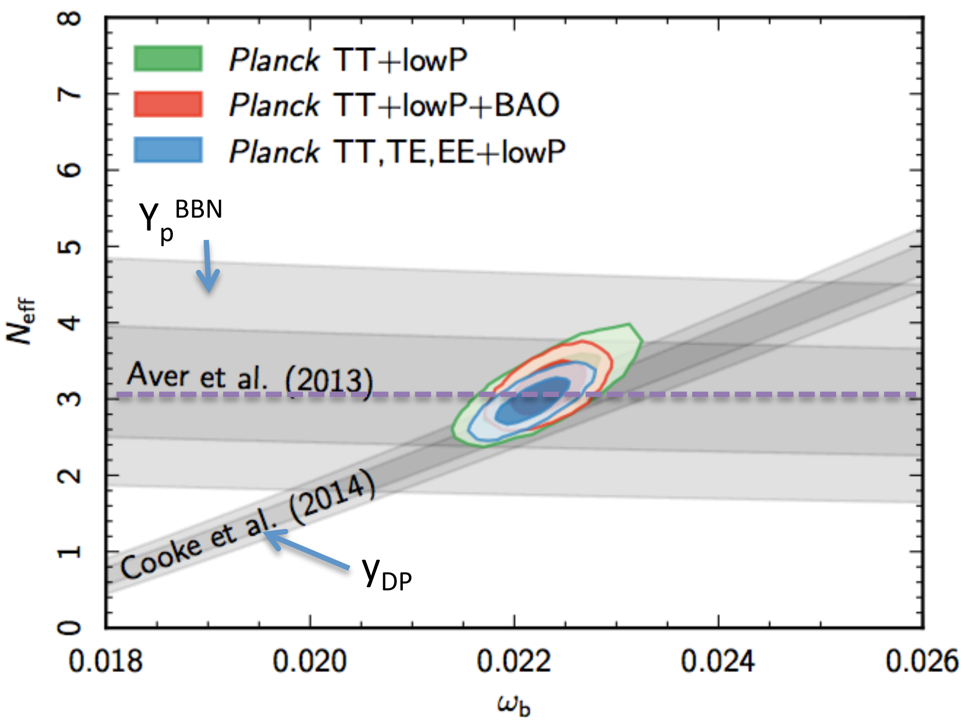
Assumption:
1 massive neutrino at 0.06eV, other massless

(for 2013, lowP is WMAP polarization) (68% C.L.)

- Planck measures N_{eff} in perfect agreement with the standard value, 3.046.
- N_{eff}>0 confirmed at ~15-sigma.
- N_{eff}=4 excluded at 3-5 sigma!

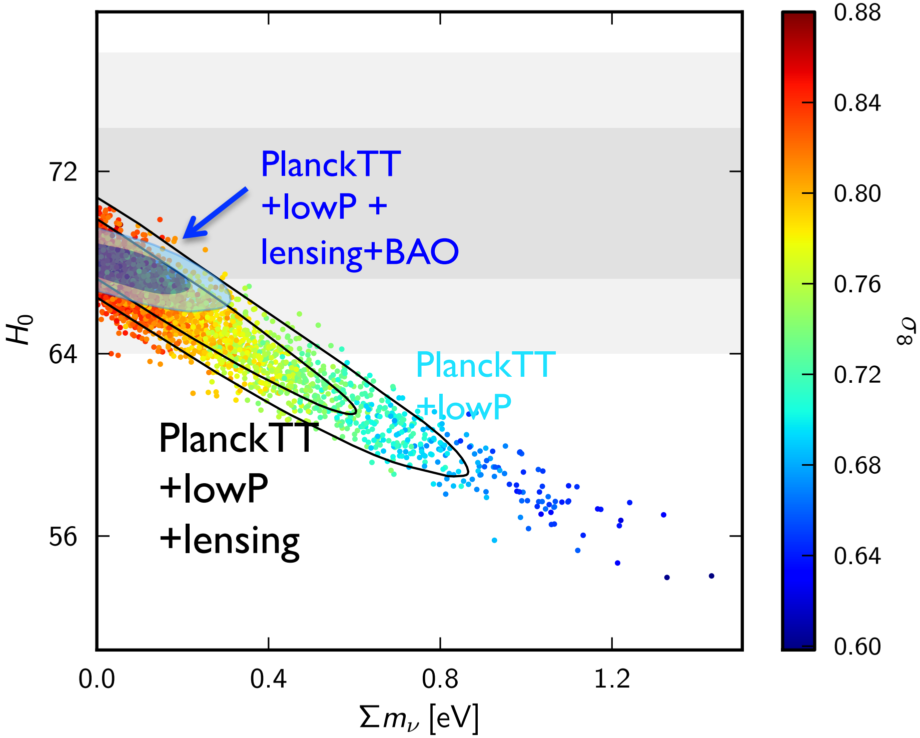
Number of relativistic species: Agreement with BBN

- PArthENoPE code for BBN predictions (Pisanti et al. 2008). From primordial Yhe and deuterium measurements, constraints on N_{eff}-$\Omega_b h^2$
- Great agreement between CMB and primordial abundance measurements, assuming standard BBN!

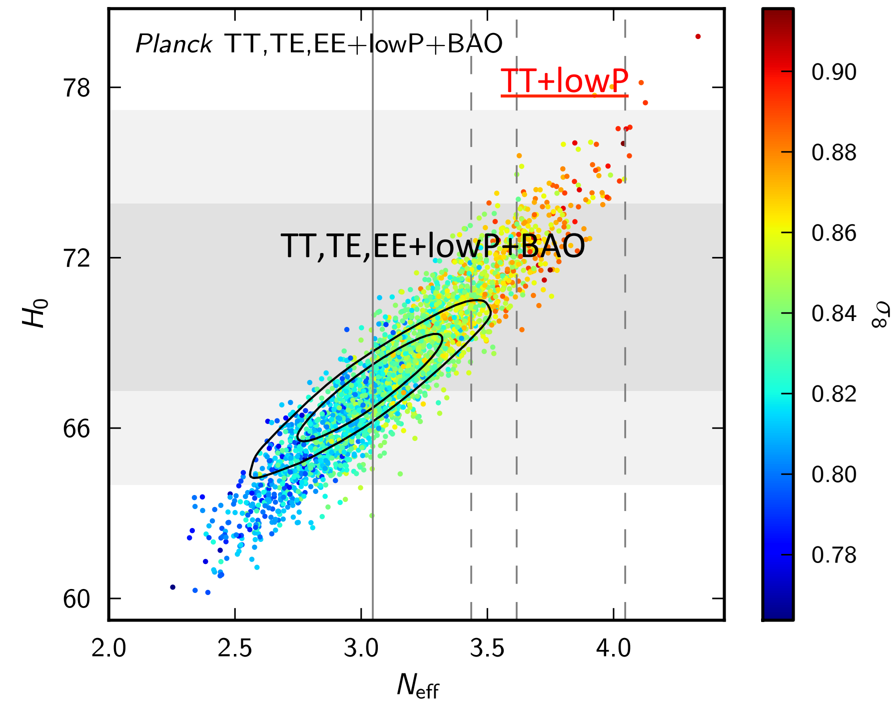


Neutrinos and tensions

σ_8 tension



H_0 tension

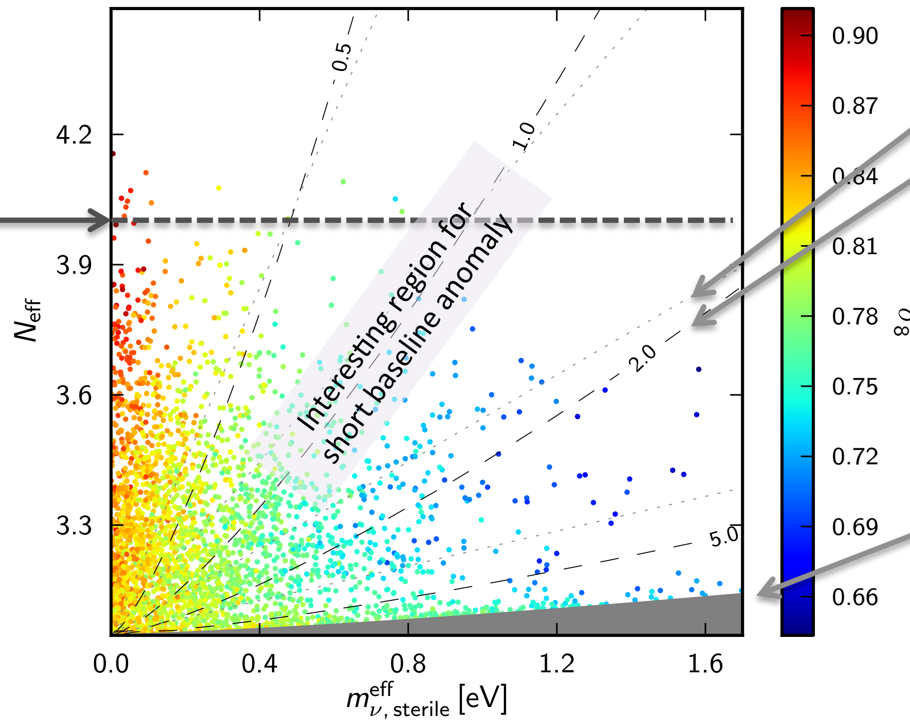


- Neutrino mass alleviates σ_8 tension-> requires low H_0
- Neff alleviates H_0 tension-> requires high σ_8
- Need both to solve tensions(or massive sterile neutrinos).

$$\left.\begin{array}{l} N_{\rm eff} = 3.2 \pm 0.5 \\ \sum m_\nu < 0.32\,\mathrm{eV} \end{array}\right\} \quad (95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}BAO}).$$

Massive sterile Neutrinos

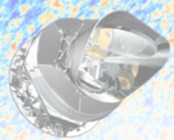
One thermalised sterile neutrino species



Physical masses
(DW sterile neutrino)
(early decoupled thermal particle)

Prior m < 10eV to avoid degeneracy with CDM

$$\left.\begin{aligned} N_{\rm eff} &< 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.59\,{\rm eV} \end{aligned}\right\} \quad (95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO}).$$



Comparison of parameters

Parameter	WMAP9 +ACT+SPT[a]
$100\Omega_b h^2$	2.252 ± 0.033
$100\Omega_c h^2$	11.22 ± 0.36
$100\theta_A$	1.0424 ± 0.0010
τ	0.085 ± 0.013
n_s	0.9690 ± 0.0089
$10^9 \Delta^2_{\mathcal{R}}$	2.17 ± 0.10
$\Omega_\Lambda{}^b$	0.735 ± 0.019
σ_8	0.814 ± 0.018
t_0	13.665 ± 0.063
H_0	71.4 ± 1.6

Parameter	[1] *Planck* TT+lowP	
$\Omega_b h^2$	0.02222 ± 0.00023	
$\Omega_c h^2$	0.1197 ± 0.0022	1.6
$100\theta_{MC}$	1.04085 ± 0.00047	
τ	0.078 ± 0.019	
$\ln(10^{10} A_s)$	3.089 ± 0.036	
n_s	0.9655 ± 0.0062	1.4
H_0	67.31 ± 0.96	1.6
Ω_m	0.315 ± 0.013	
σ_8	0.829 ± 0.014	
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	

Calabrese 2014 et. al

Planck improved constaints by a factor 1.4-2 on most LCDM parameters.

3. Neutrino perturbations

- Standard model of cosmology predicts neutrino perturbations, characterized by effective sound speed and viscosity parameter (isotropic and anisotropic pressure perturbations)
- Standard values for free-streaming particles $(c_{eff}^2, c_{vis}^2) = (1/3, 1/3)$; perfect fluid: (1/3,0)…

Parameter	TT	TT,TE,EE	TT,TE,EE+BAO
c^2_{vis}	0.57 ± 0.16	0.336 ± 0.039	0.338 ± 0.040
c^2_{eff}	0.314 ± 0.012	0.3256 ± 0.0063	0.3257 ± 0.0059

- First constraints from CMB alone.
- Standard free-streaming behaviour in perfect agreement with Planck data

PRELIMINARY