Planck 2015 results

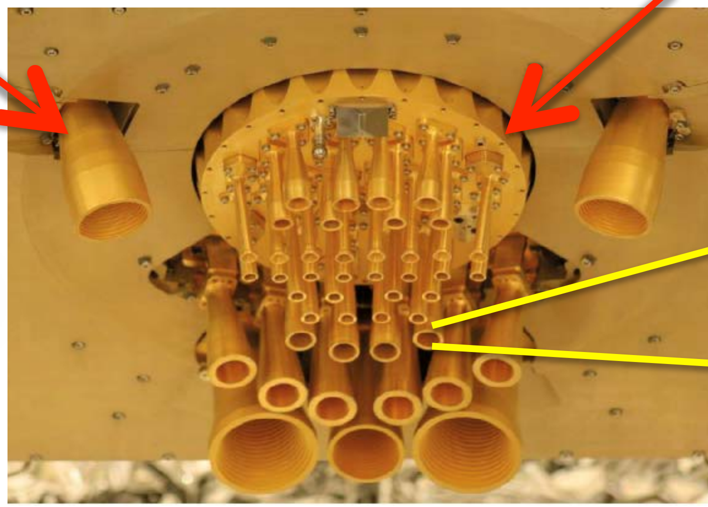
S. Henrot-Versillé on behalf of the
Planck Collaboration

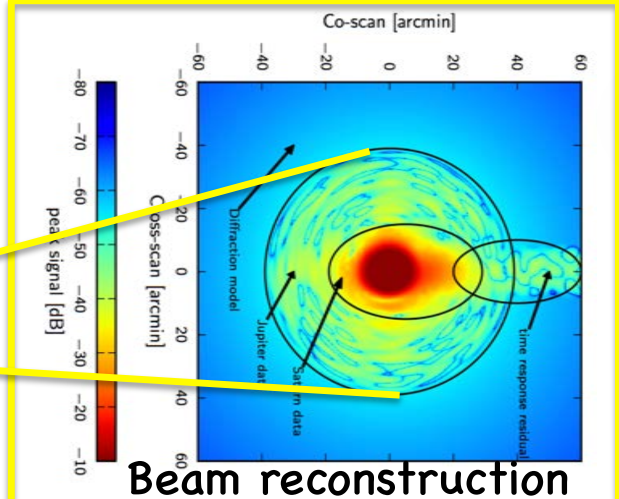
- 2015: what's new in the data ?
  How do we extract the cosmological parameters ?
- Results on the "base" ΛCDM Model,
  - Robustness with the Statistical method
  - Ω_{cdm} & SUSY
- Beyond ΛCDM :
  - the sum of the neutrino mass
  - the effective number of relativistic degrees of freedom
  - the gravitational waves and Bicep2/Keck Array and Planck

Otherwise explicitly stated, the results come from:
"Planck 2015 results. XIII. Cosmological parameters" arXiv:1502.01589

What are the improvements ?

Reminder: there are 2 instruments on board:
LFI (Low Frequency Instrument) + HFI (High Frequency Instrument)





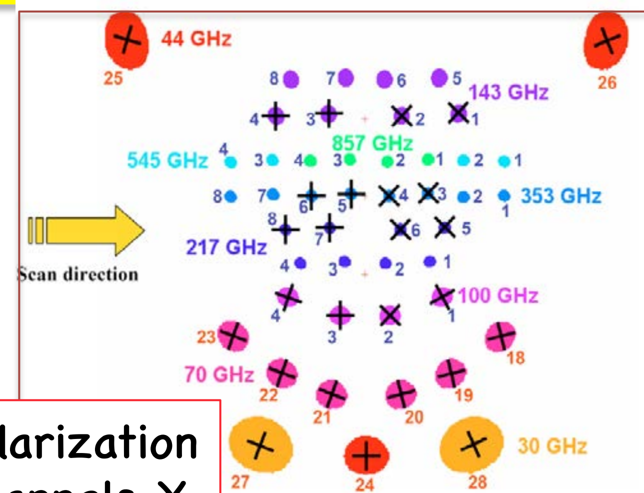
Beam reconstruction

Beam = Spatial resolution

Improvements:

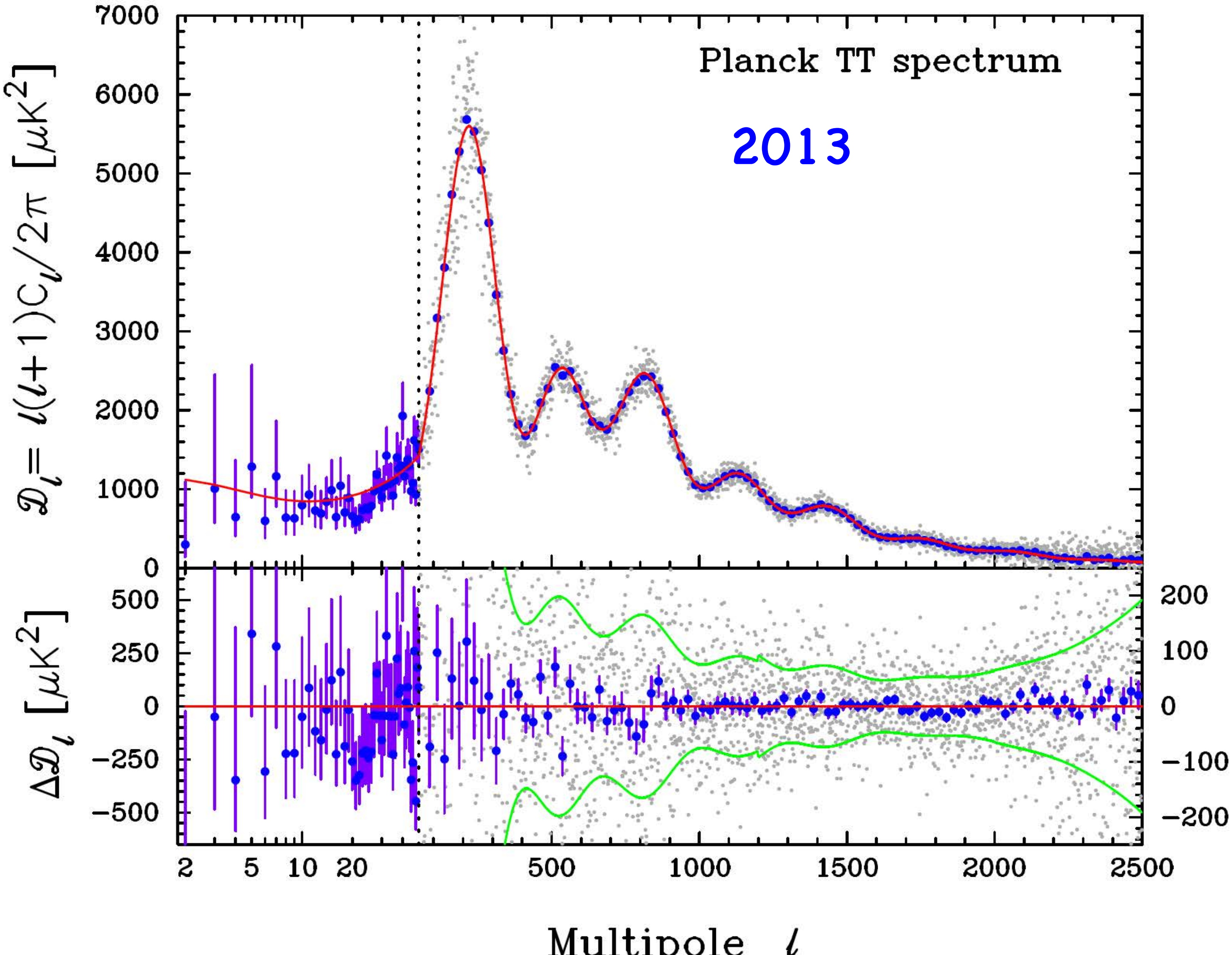
- ➡ data calibration
- ➡ better control of systematics
- ➡ better beam characterization (see above)
- ➡ full mission data: increase of statistics
- ➡ Polarization

No need of Wmap@LowL
we have LFI for Polarisation (LowP) !

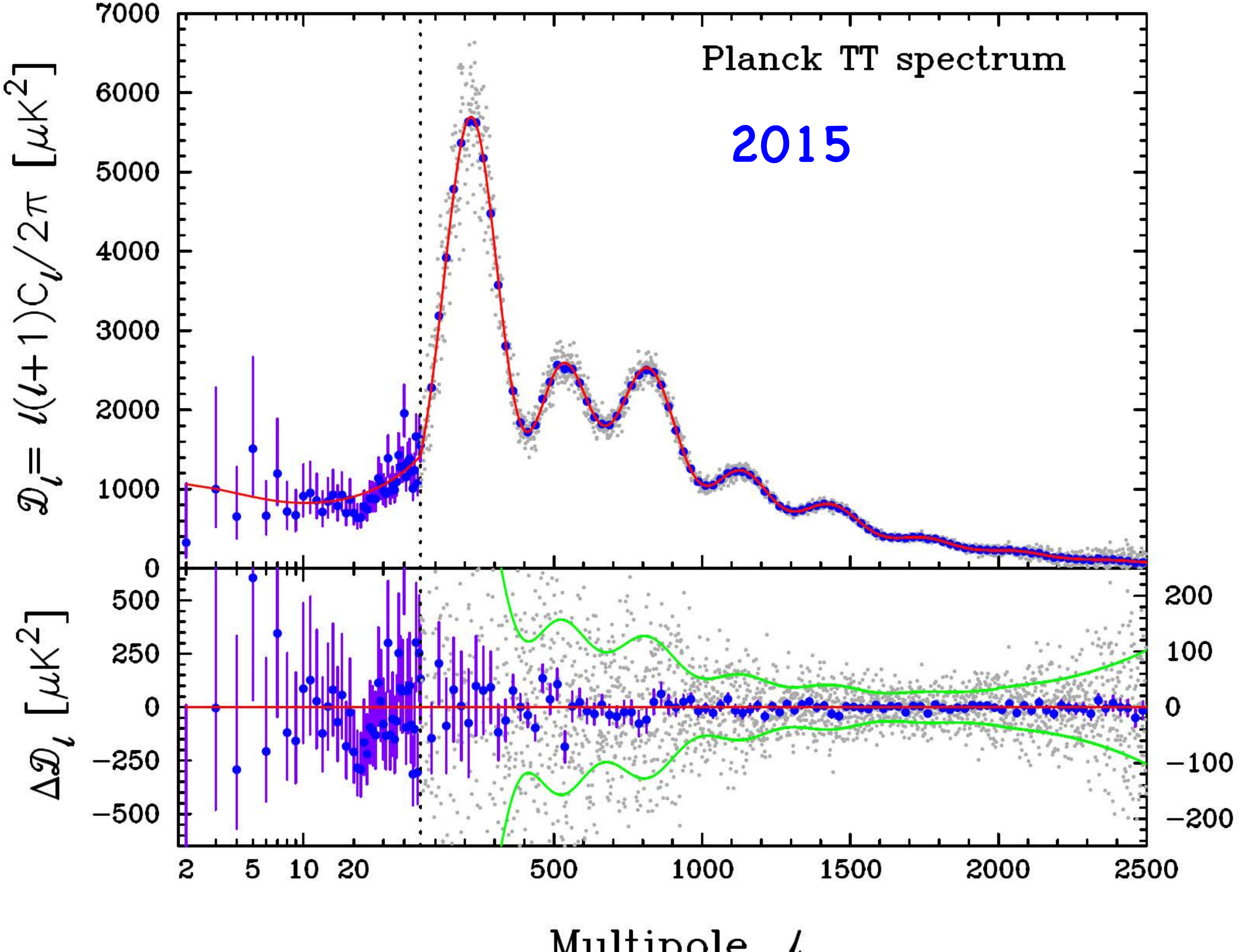


Polarization Channels X

TT (Temperature) spectrum



TT (Temperature) spectrum



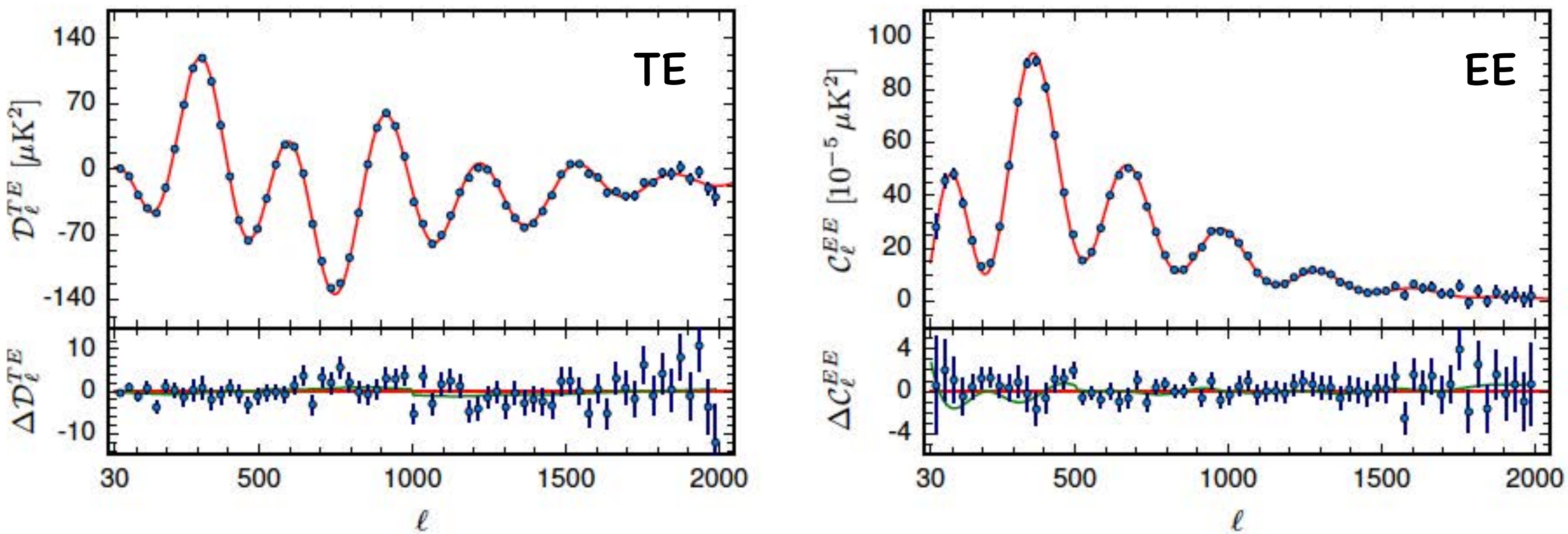
Temperature (T) /Polarization (E)

- E-modes of polarization due to Thomson scattering
- B-modes generated only by primordial tensor modes

(primordial gravitational wave) + lensing of E modes

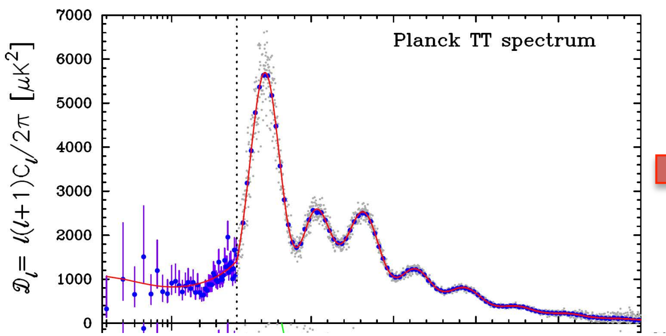
=> Planck was not designed for the B modes of the CMB

Points: data, red line is the best fit model from the TT data only !



From the data to the parameters

e.g. Let's take the high ℓ part of the TT spectrum

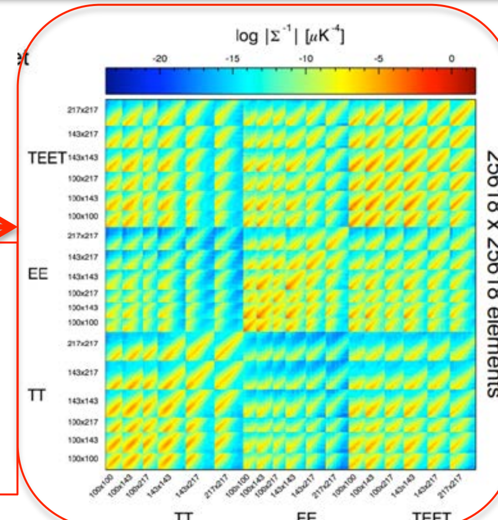


High ℓ: spectrum based likelihood, the measurements are Gaussian BUT correlated ℓ by ℓ (HFI 100/143/217GHz)

$$-2\ln\mathcal{L} = \sum_{\substack{X,Y=T,E\\ X',Y'=T,E}} \sum_{\substack{i,j=100\\ i\le j\\ i',j'=100\\ i'\le j'}}^{217} \sum_{\ell=\ell_{\rm min}^{X_iY_j}}^{\ell_{\rm max}^{X_iY_j}} \sum_{\ell'=\ell_{\rm min}^{X'_{i'}Y'_{j'}}}^{\ell_{\rm max}^{X'_{i'}Y'_{j'}}} \mathcal{R}_\ell^{X_iY_j} \left[\Sigma_{\ell\ell'}^{X_iY_j,X'_{i'}Y'_{j'}}\right]^{-1} \mathcal{R}_{\ell'}^{X'_{i'}Y'_{j'}};$$

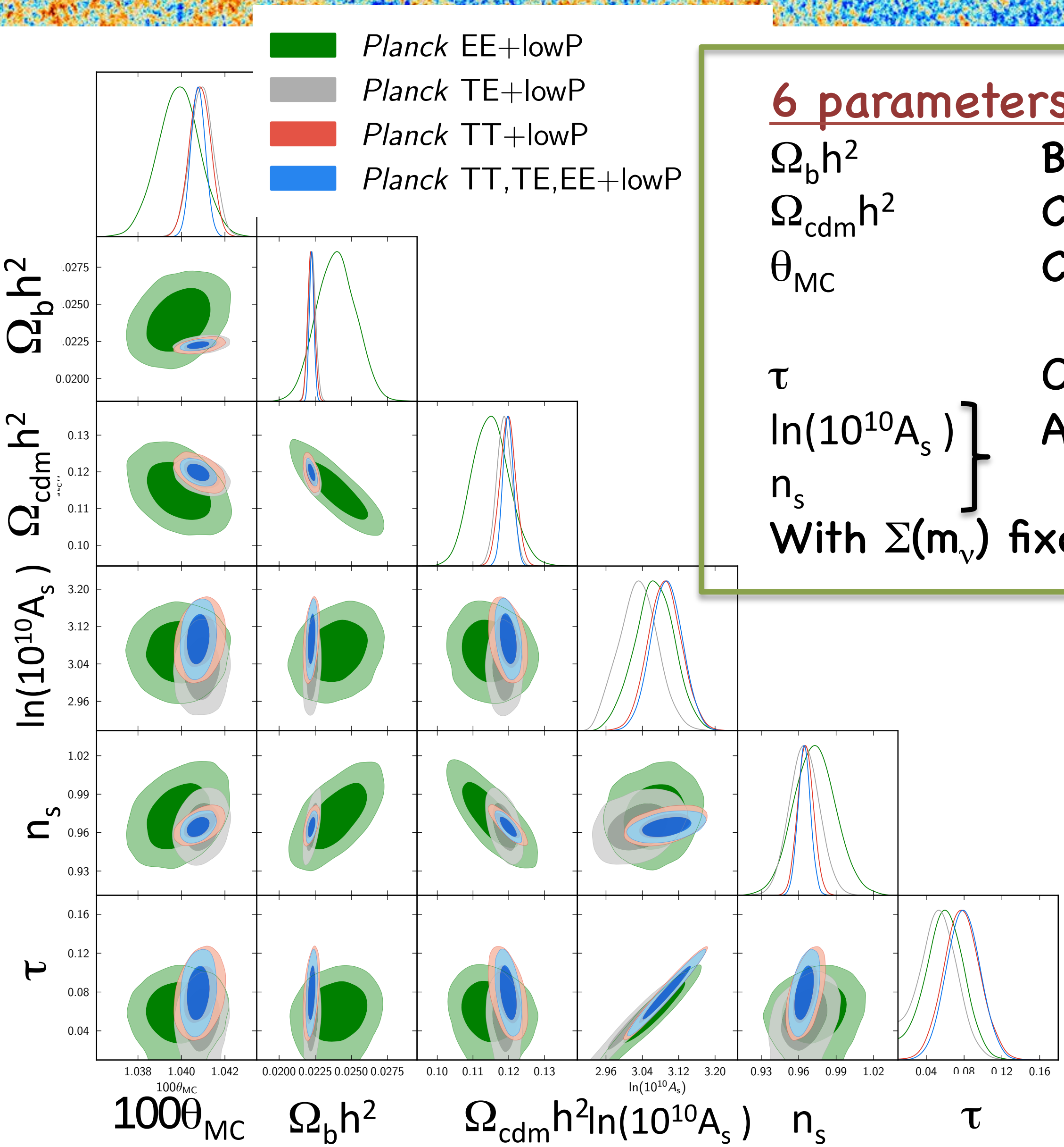
Sum over all the ℓ of all the spectra (per frequencies, and temperature&polarisation)

Very big matrix describing all the correlations between the data spectra



Cℓ (data) – Cℓ(model)
Where Cℓ(model) = Cℓ(cosmological parameters)
+ parameterization of foregrounds (nuisance parameters)

The "base" ΛCDM Model



6 parameters:

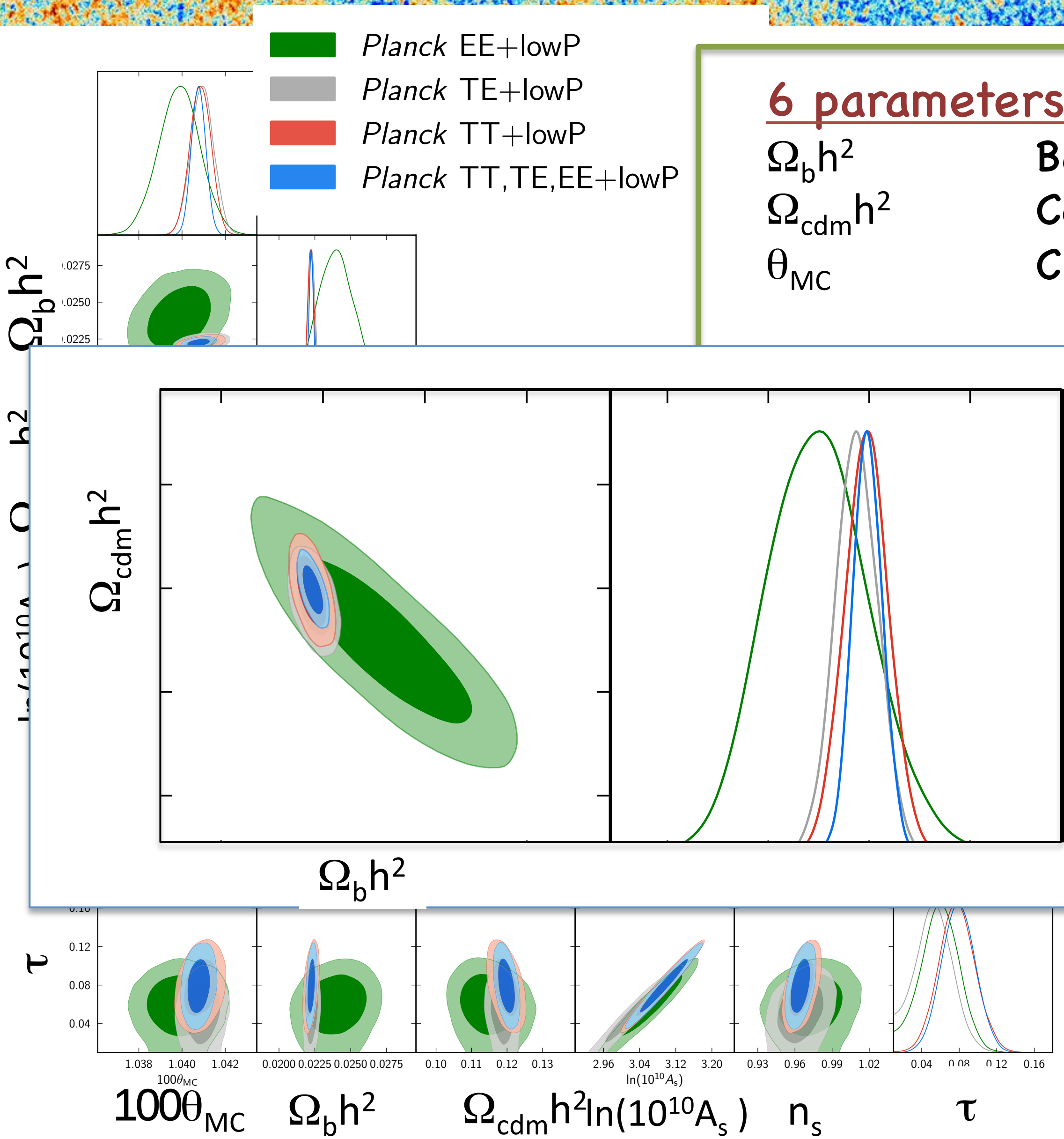
$\Omega_b h^2$	Baryon density
$\Omega_{cdm} h^2$	Cold Dark Matter density
θ_{MC}	Characteristic angular size of the CMB fluctuations
τ	Optical depth to reionization
$\ln(10^{10}A_s)$, n_s	Amplitude and index of primordial fluctuations

With $\Sigma(m_\nu)$ fixed to 0.06eV

Very good agreement between temperature and polarization results !

Parameter	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02230 ± 0.00014
$\Omega_c h^2$	0.1188 ± 0.0010
$100\theta_{MC}$	1.04093 ± 0.00030
τ	0.066 ± 0.012
$\ln(10^{10}A_s)$	3.064 ± 0.023
n_s	0.9667 ± 0.0040

The "base" ΛCDM Model



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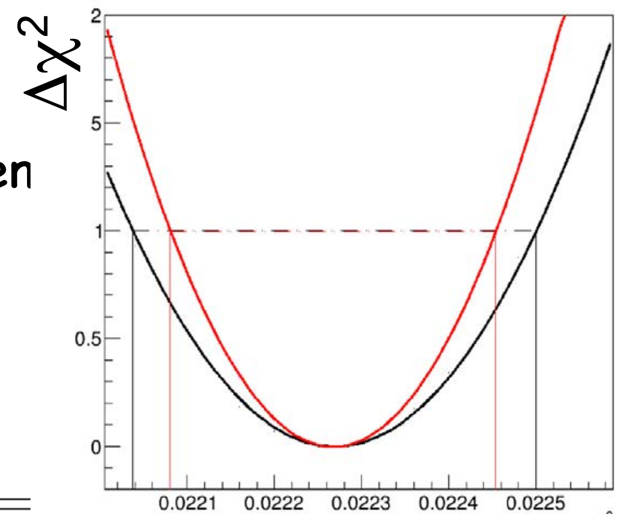
A word on the statistical method

Cosmological parameters determination is mainly done with a Bayesian Analysis and Monte Carlo Markov Chains…

A profile Likelihood analysis has also been performed leading to compatible results
NB: here another Boltzmann solver than the official one has also been used



$\Omega_b h^2$

e.g. for Planck TT (HFI) + LowP (LFI)

Profile Likelihood

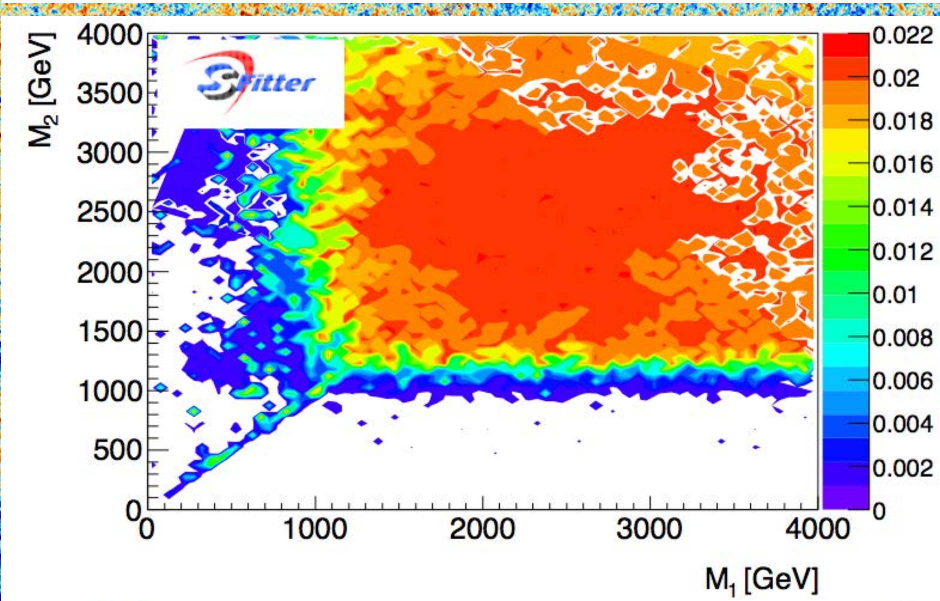
Plik	Parameters
$\Omega_b h^2$	0.02227 ± 0.00023
$\Omega_c h^2$	0.1198 ± 0.0022
$100\theta_0$	1.04184 ± 0.00044
τ	0.082 ± 0.020
$\ln(10^{10} A_s)$	3.098 ± 0.037
n_s	0.9663 ± 0.0063

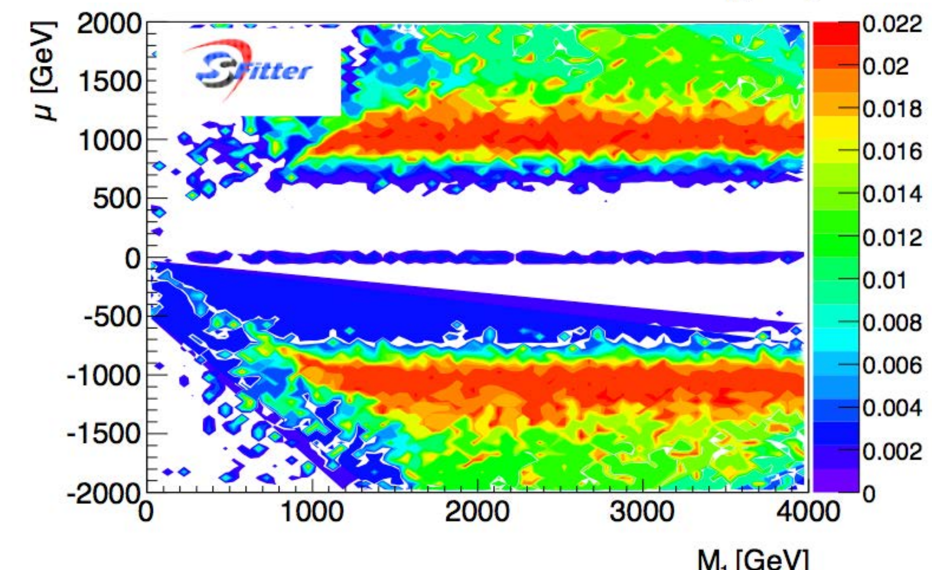
Bayesian Analysis

$\Omega_b h^2$	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

"Planck intermediate results. XVI. Profile likelihoods for cosmological parameters" 2014 A&A 566, A54

$\Omega_{cdm}h^2$ and SUSY (TeV-scale MSSM)





Assumptions:

- all squark masses above LHC actual limits ≈2TeV (except for the stop)
- M_3 is fixed @2TeV
- A_b=0

13 parameters:

tan β<61, M_1<4TeV, M_2<4TeV

$M_{\mu L/R}$, $M_{\tau L/R}$, M_{q3L}, M_{tR}<5TeV

$|A_t|$<4TeV, $|A_\tau|$<4TeV,

m_A<5TeV, $|\mu|$<2TeV

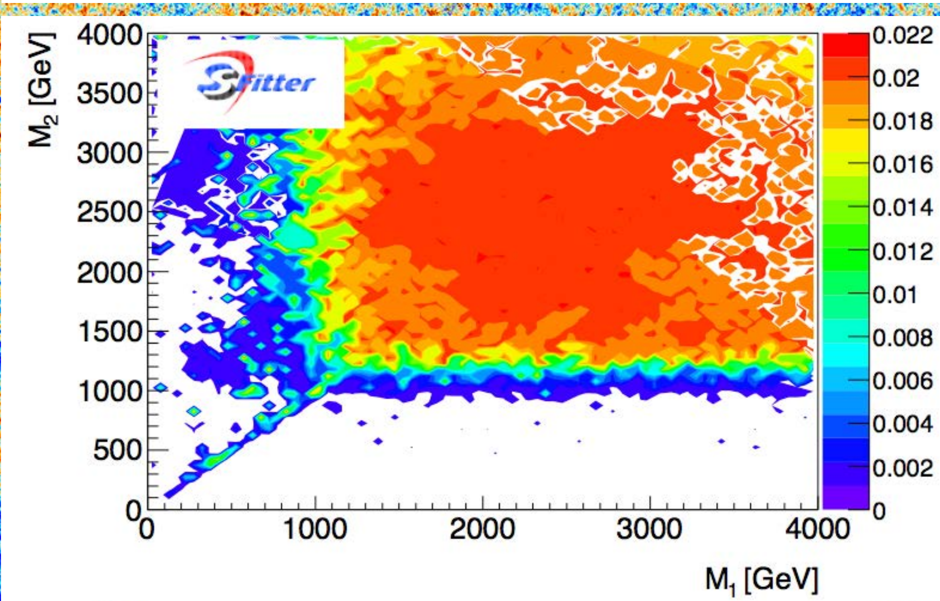
Measurement	Value and error
m_h	$(126 \pm 0.4 \pm 0.4 \pm 3)$ GeV
$\Omega_{cdm}h^2$ Planck (2013)	$0.1187 \pm 0.0017 \pm 0.012$
$\Omega_{cdm}h^2$ WMAP-9year	$0.1157 \pm 0.0023 \pm 0.012$
$BR(B_s \to \mu^+\mu^-)$	$(3.2^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$
$BR(b \to X_s\gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$
$\Delta\mu$	$(287 \pm 63 \pm 49 \pm 20) \times 10^{-11}$
m_t	$(173.5 \pm 0.6 \pm 0.8)$ GeV

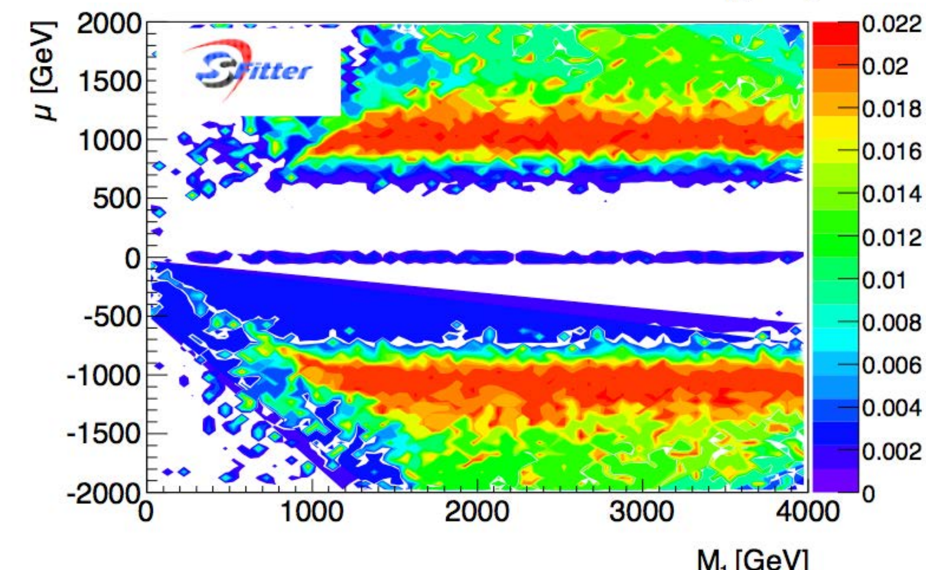
+Xenon100

Phys. Rev. D 89, 055017 (2014)

« Constraining supersymmetry using the relic density and the Higgs boson »

$\Omega_{cdm}h^2$ and SUSY (TeV-scale MSSM)





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$M_{UL/R}$,M...

|A...

m...

Already limited by theoretical errors

Measurement	Value and error
m_h	$(126 \pm 0.4 \pm 0.4 \pm 3)$ GeV
$\Omega_{cdm}h^2$ Planck (2013)	$0.1187 \pm 0.0017 \pm 0.012$
$\Omega_{cdm}h^2$ WMAP-9year	[illegible]
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$\Delta\mu$	$(287 \pm 63 \pm 49 \pm 20) \times 10^{-11}$
m_t	$(173.5 \pm 0.6 \pm 0.8)$ GeV

Meas.±σ(exp)±σ(theo)

+Xenon100

Phys. Rev. D 89, 055017 (2014)

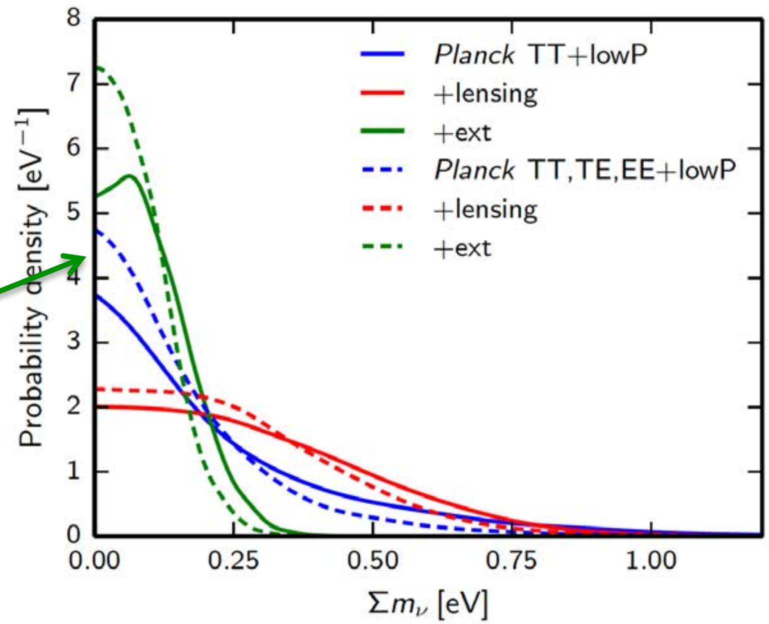
« Constraining supersymmetry using the relic density and the Higgs boson »

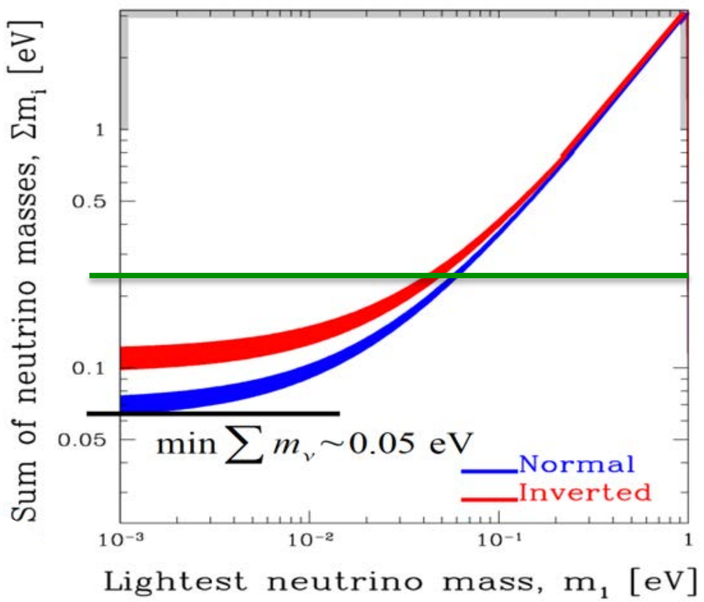
Sum of the Neutrino Masses

⇒ Impact on the first acoustic peak
⇒ + small scales

PlanckTT+LowP+Lensing+BAO+SN/JLA+H0

$\Sigma(m_\nu)<0.23$eV (95%CL limit)





Combined with oscillations measurements
⇒ Starting to test the hierarchy soon ?!?

(cf. yesterday's talk : E. lisi, S. Choubey, T. Johnson,…)

Neff

Neff is the effective number of relativistic degrees of freedom

Under the assumption that ONLY photons and standard light neutrinos contribute to the radiation:

⇒ Neff is the effective number of neutrinos and ≈ 3.046

Any deviation from this value can be attributed to sterile neutrinos, axions, lepton number violation (cf. yesteday J. Heeck's talk) primordial gravitational waves (GW)...

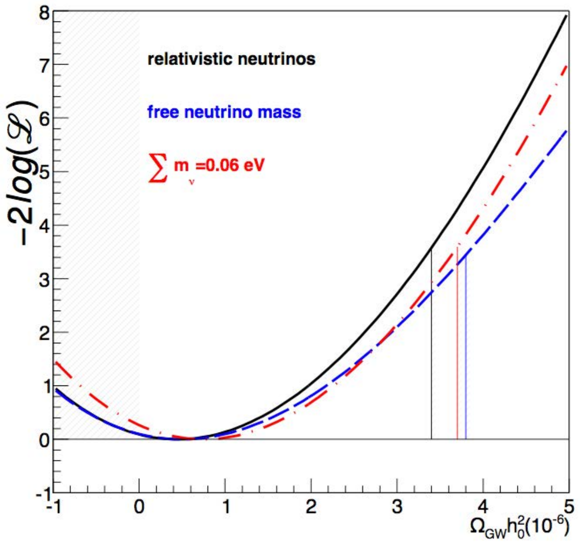
$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,;$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;$$

⇒ No convincing evidence for extra relativistic component

Accuracy with Polarization:

$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}\,;$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}\,.$$

Neff & the stochastic GW bkg



Assuming that any deviation from Neff=3.046 is only due to a primordial Gravitational Wave (GW) background, a limit on the GW energy density can be computed

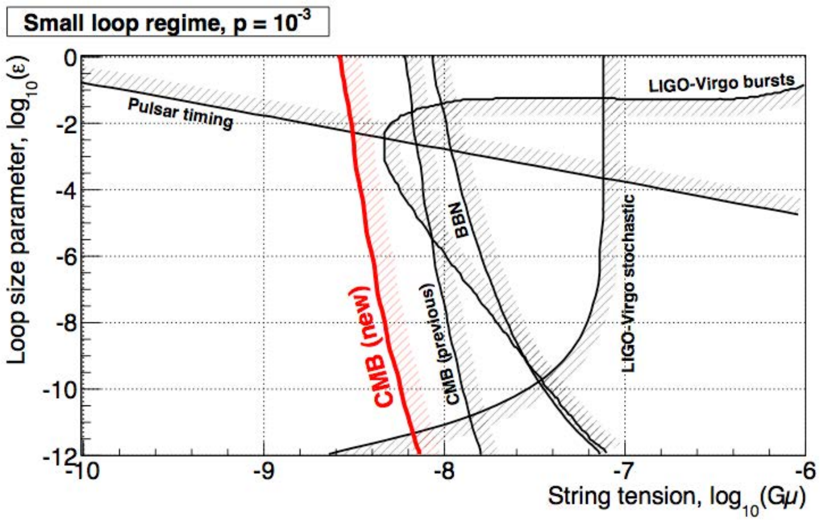
$$\Omega_{\rm GW} \leq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}(N_{\rm eff} - 3.046)\Omega_\gamma \; .$$

Planck2013+WP+HighL+BAO+Lensing:
$\Omega_{GW}h^2 < 3.8\ 10^{-6}$

If the GW can be attributed to a network of cosmic string

⇒ exclusion limits in the strings parameter space

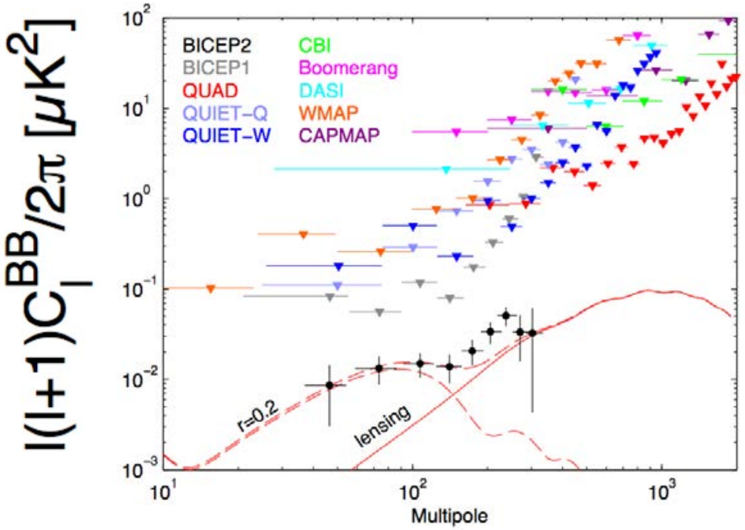
Pushing further the previous constraints…



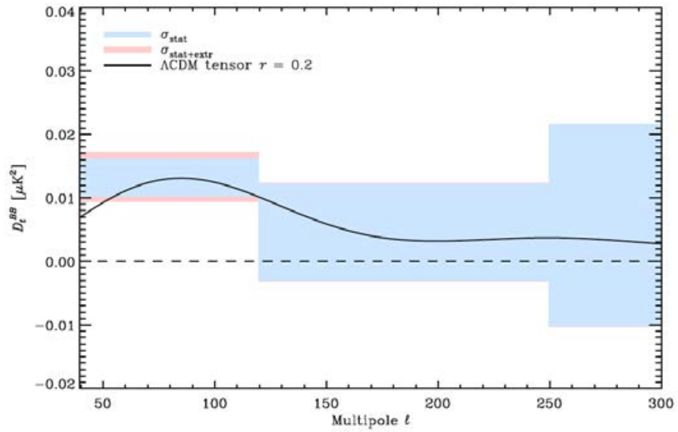
« Improved constraint on the primordial gravitational-wave density using recent cosmological data and its impact on cosmic string models » Class. Quantum Grav. 32 (2015) 045003

Primordial gravitational waves ?

March 2014…Bicep2/Keck Array

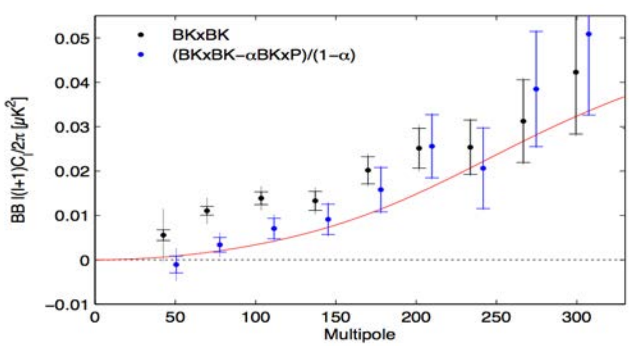


September 2014…answer from Planck



=> The polarized dust contamination cannot be neglected

December 2014… joint Bicep2/Keck Array/Planck analysis



the B-mode excess seen by BICEP2 is consistent with Galactic dust emission, and no significant evidence for primordial gravitational waves is found.

⇒ Upper limit r<0.12 @95%CL

(r is the tensor over scalar ratio)

« A Joint Analysis of BICEP2/Keck Array and Planck Data » arXiv:1502.00612

Summary & Outlook

Planck 2015:

- the first release of all sky polarization data
  (LFI 30,44, 70GHz + 353GHz HFI)
- high quality data (CMB+Lensing) confirming the ΛCDM model with unprecedented accuracy
- permits to test extensions of the ΛCDM models

=> some examples have been given..more in the papers !!
have a look at:

http://www.cosmos.esa.int/web/planck/publications

Next challenge:

- By 2015/2016 targeting a release of HFI 100,143, 217 GHz(CMB) data with an overall improvement of polarization and a lower level of systematics esa

planck

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

CSIC

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
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ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

A" Aalto University

ioa

KICC

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irfu cea saclay

CEFCA

irap

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IASF

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MilliLab

Rutherford Appleton Laboratory

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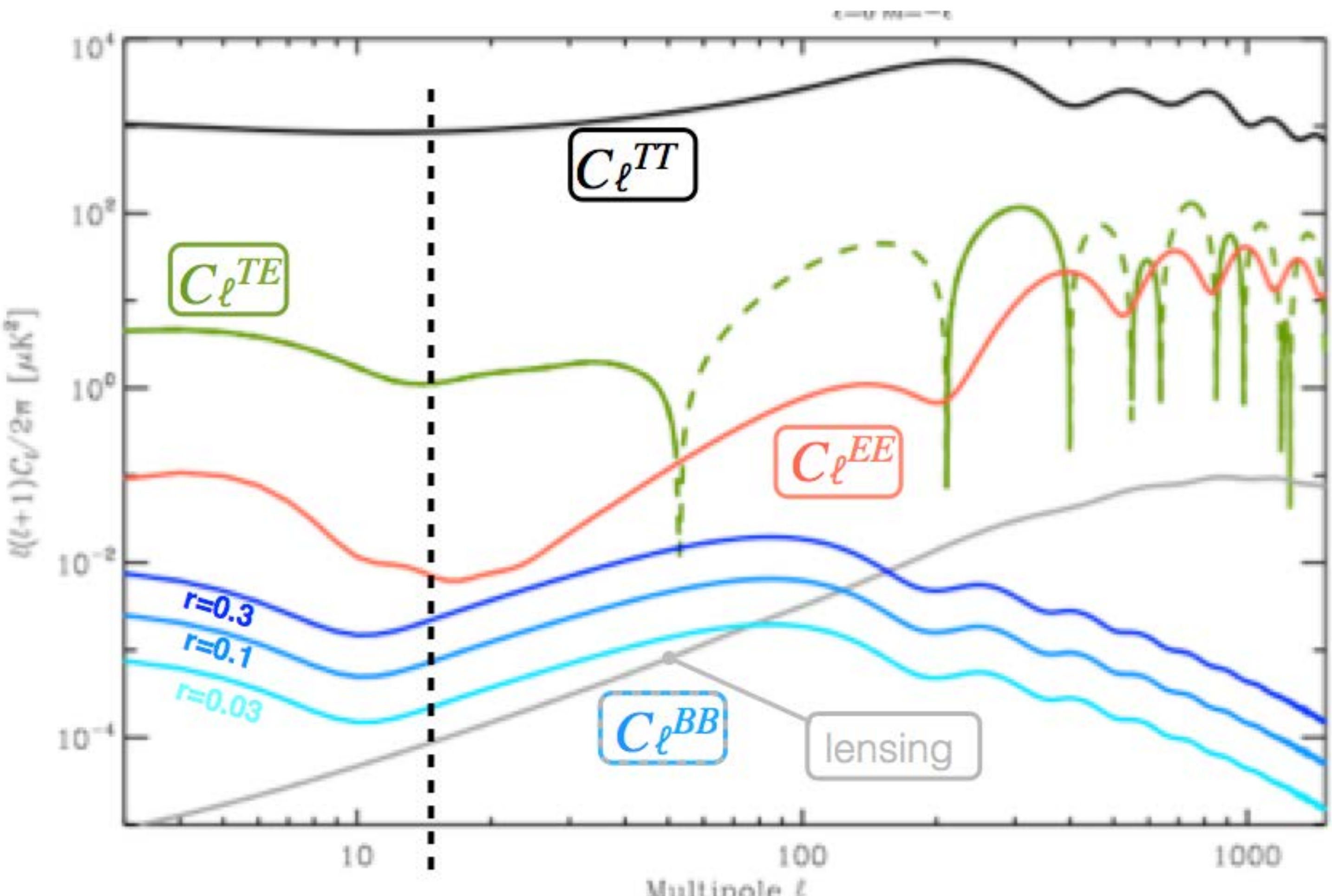
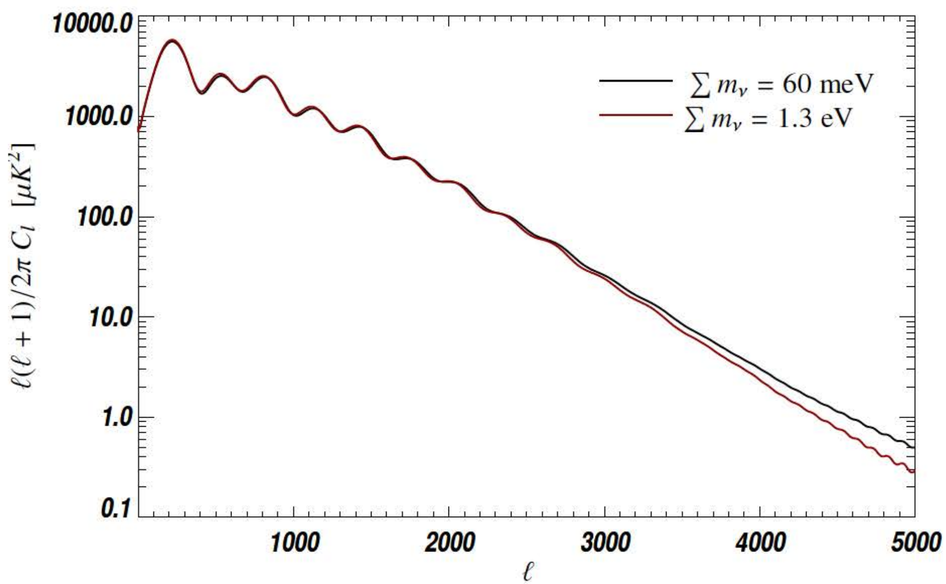

10^4
10^2
10^0
10^{-2}
10^{-4}
$\ell(\ell+1)C_\ell/2\pi$ [μK^2]
C_ℓ^{TT}
C_ℓ^{TE}
C_ℓ^{EE}
C_ℓ^{BB}
r=0.3
r=0.1
r=0.03
lensing
10
100
1000
Multipole ℓ

$\sum m_\nu$

CMB (sligthly) sensitive to $M_\nu = \sum m_\nu$ (degenerate)



a. effect around first acoustic peak
WMAP: $\sum m_\nu < 1.3$ eV $(95\% CL)$

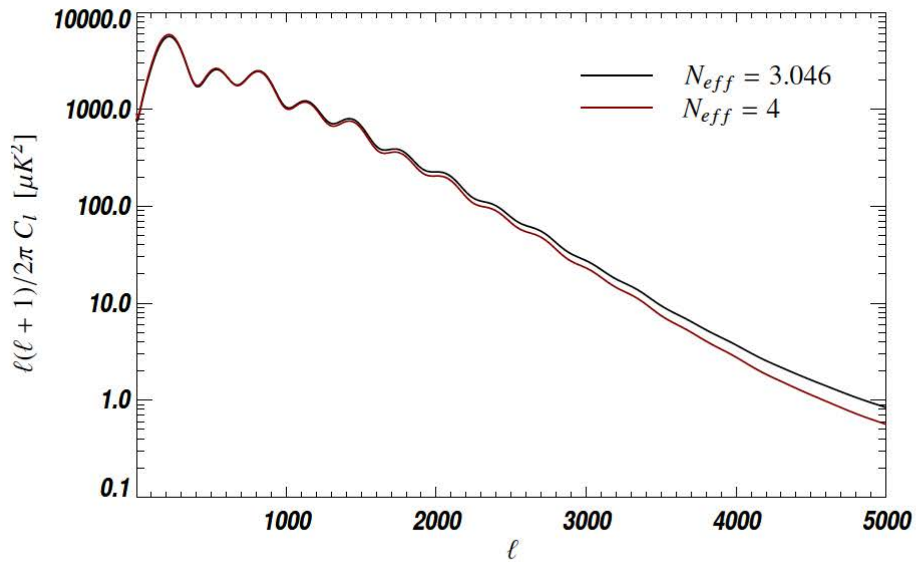
b. Neutrinos free-streaming suppress small scale clustering

$\rightarrow$ effect on CMB lensing potential

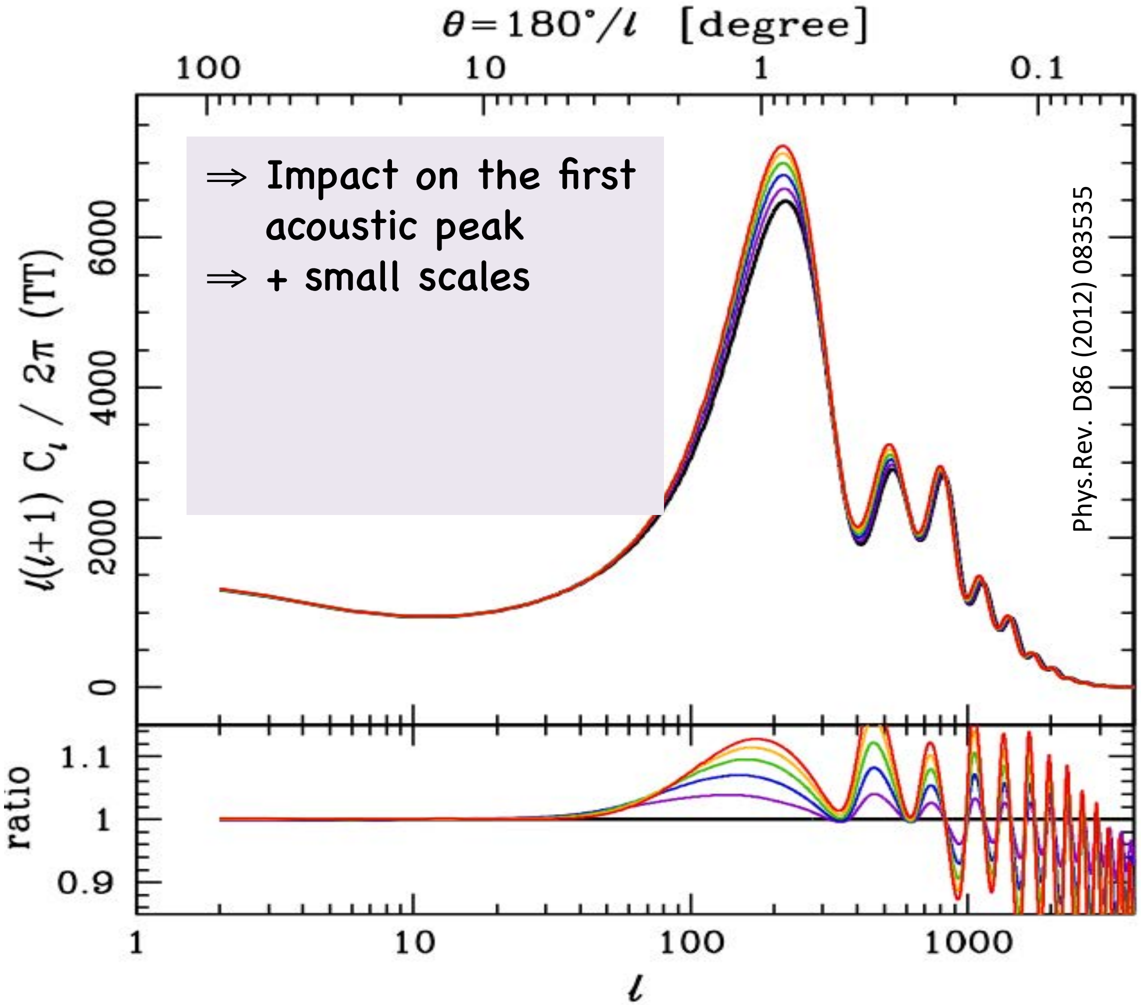
$N_{\rm eff}$

$N_{\rm eff}$ (~massless) degrees of freedom beyond photons relativistic during radiation domination (account for any light relics, GW, etc.)

- $\rho_\nu = N_{\rm eff} \frac{7}{8} (\frac{4}{11})^{\frac{4}{3}} \rho_\gamma$
- standard neutrinos $N_{\rm eff} = 3.046$
- previous hints for $N_{\rm eff} > 3$ from SPT, ACT...



if N_{eff} ⇑, the age of the Universe at recombination ⇓
⇒ **effect on the damping tail**


θ=180°/ℓ [degree]
100
10
1
0.1
⇒ Impact on the first acoustic peak
⇒ + small scales
ℓ(ℓ+1) C_ℓ / 2π (TT)
6000
4000
2000
0
Phys.Rev. D86 (2012) 083535
ratio
1.1
1
0.9
1
10
100
1000
ℓ

Inflation and the Search for Primordial Gravitational Waves Brett Friedman and Advisor: Professor Asantha Cooray

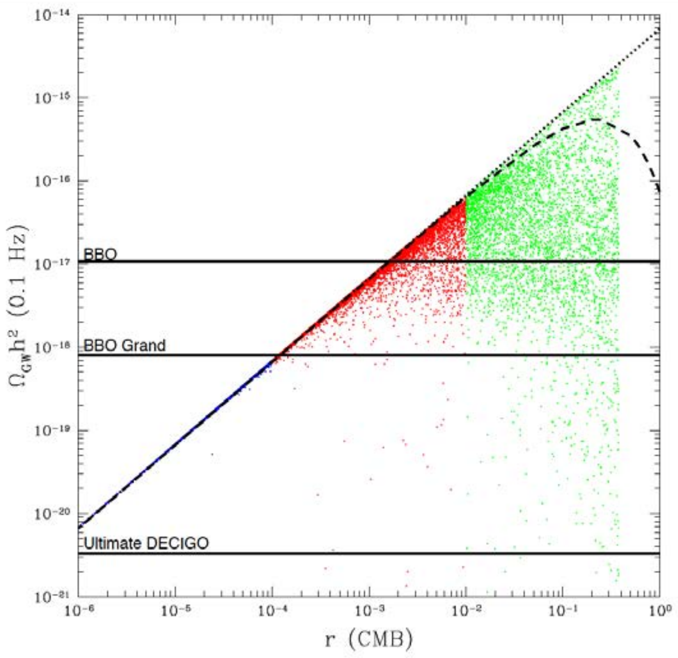
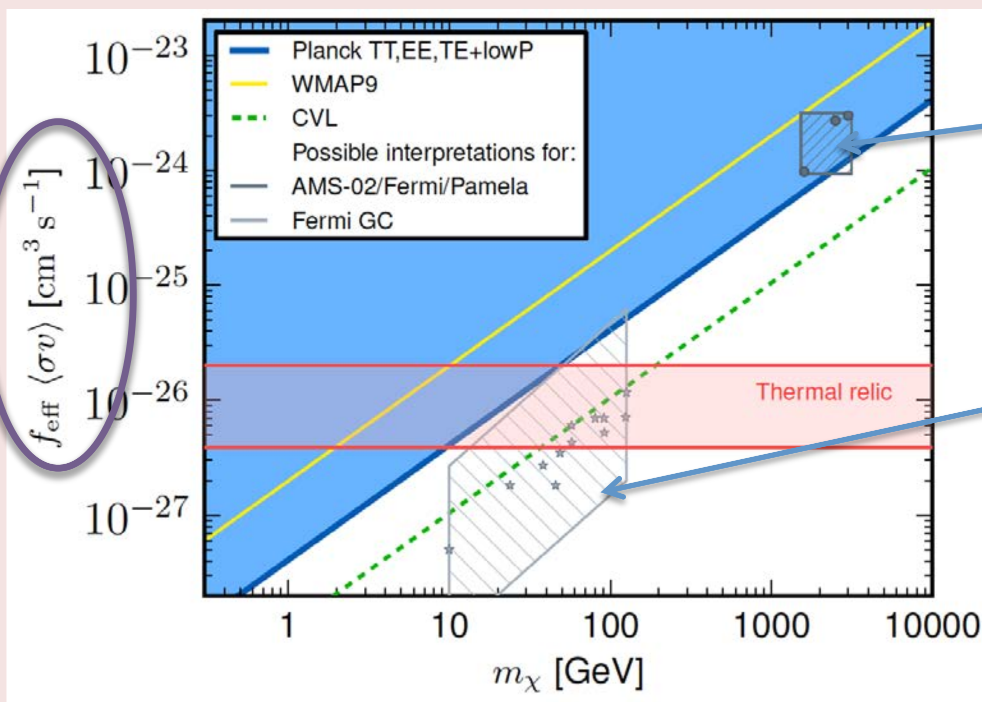


FIG. 6: The amplitude of the gravitational wave background at 0.1 Hz $\Omega_{\rm GW}h^2$ plotted in terms of the tensor-to-scalar ratio at CMB scales ($k = 0.002$ Mpc^{-1}). For reference, I also show the minimum background amplitude that can be detected with a signal-to-noise ratio of unity with BBO, BBO-Grand, and Ultimate DECIGO. The relation between $\Omega_{\rm GW}h^2$ and $r_{\rm CMB}$ is such that one can establish an upper limit on the expected amplitude of the gravitational wave background at a given tensor-to-scalar ratio. The dotted line shows the relation, which I discuss in equation 35. An experiment such as BBO-Grand can probe slow-roll inflationary models with tensor-to-scalar ratios as low as 10^{-4}, lower than what CMB experiments can explore.

Constraint on DM annihilation @ the epoch of recombination

Caveat: Planck and low-redshift anomalies (Pamela,Fermi etc...) can be compared ONLY under the assumption that the annihilation cross-section at the epoch of recombination was THE SAME as today

Thermally averaged annihilation cross-section x the fraction of the annihilation energy that will affect the CMB



The dark gray dots show the best fit DM models for the Pamela/AMS-02/ Fermi cosmic-ray excess as calculated by Cholis and Hooper.

The light gray stars show the best fit DM models for the Fermi galactic center gamma-ray excess as calculated by Calore 2014.

following S.Galli et al. Phys.Rev.D84:027302,2011

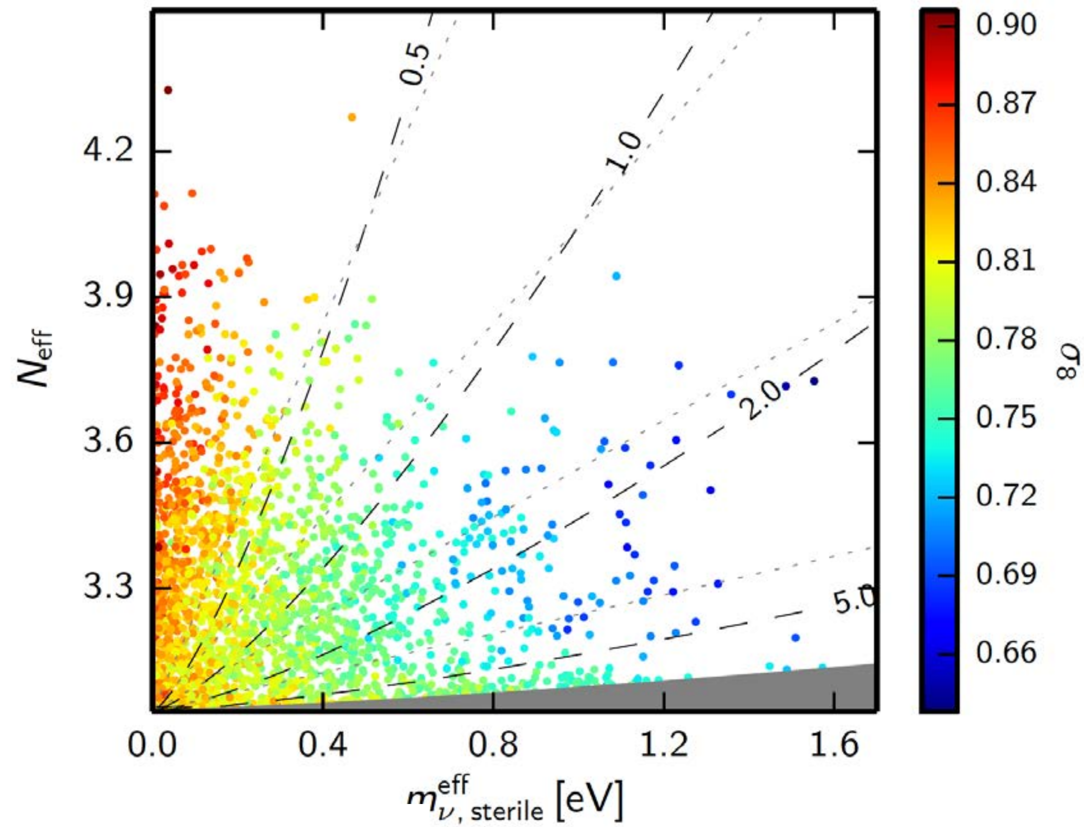
Sterile neutrinos

PlanckTT+LowP

Model:
one massive sterile neutrino

$$m^{\rm eff}_{\nu,\,\rm sterile} \equiv (94.1\,\Omega_{\nu,\rm sterile}h^2)\ \rm eV,$$

In addition to the LCDM
(reminder: 2 massless,
1massive)



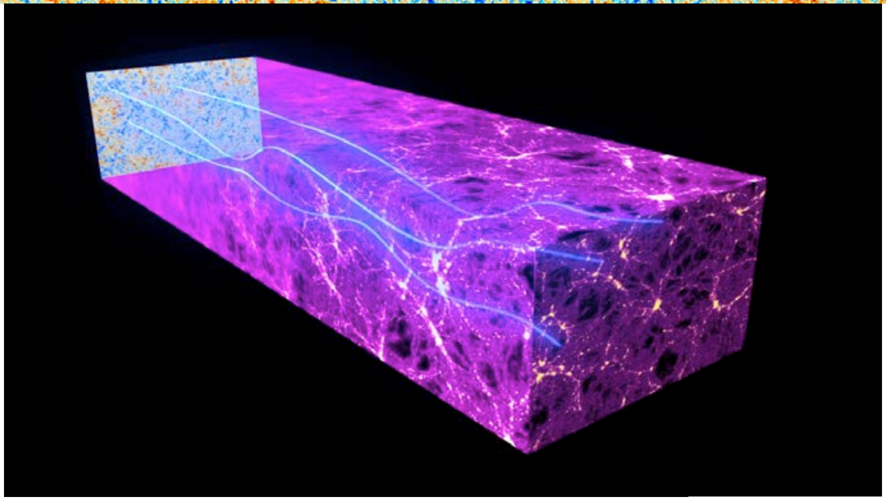
$$m^{\rm eff}_{\nu,\,\rm sterile} = (T_{\rm s}/T_\nu)^3 m^{\rm thermal}_{\rm sterile} = (\Delta N_{\rm eff})^{3/4} m^{\rm thermal}_{\rm sterile}\,,$$

The Planck data strongly disfavour fully thermalized sterile neutrinos with msterile~ 1 eV

PS: σ_8 is the late time fluctuations amplitude

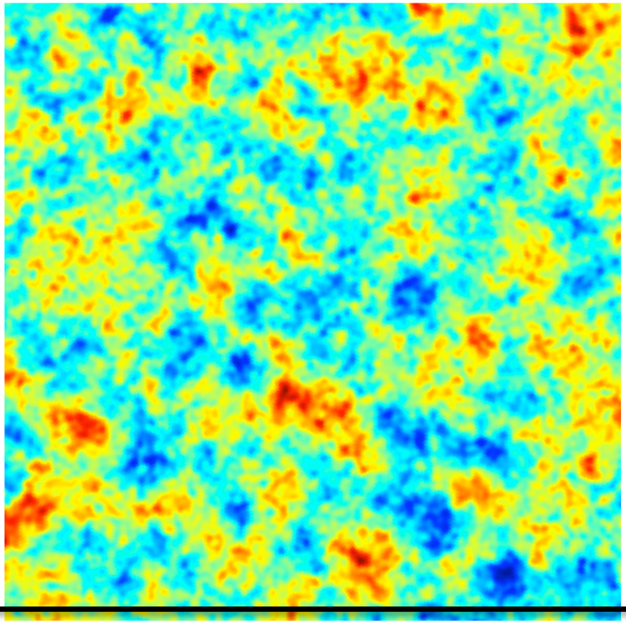
σ_8 = 0 .850 +/-0.015

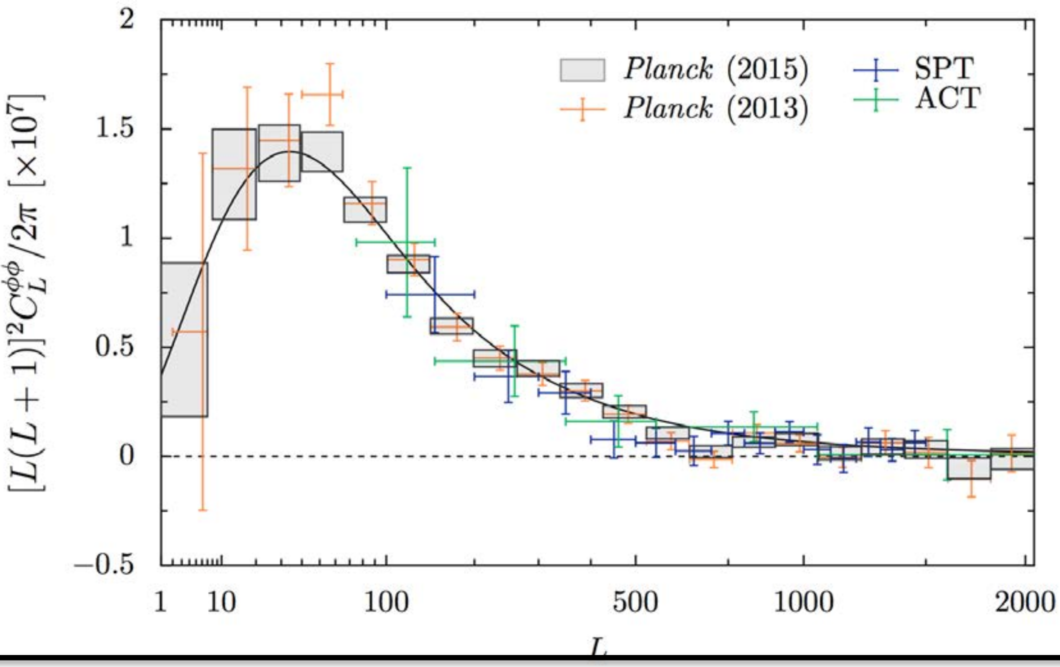
Gravitational Lensing of the CMB



Distorsion of the CMB photon path by the Large Scale Structures

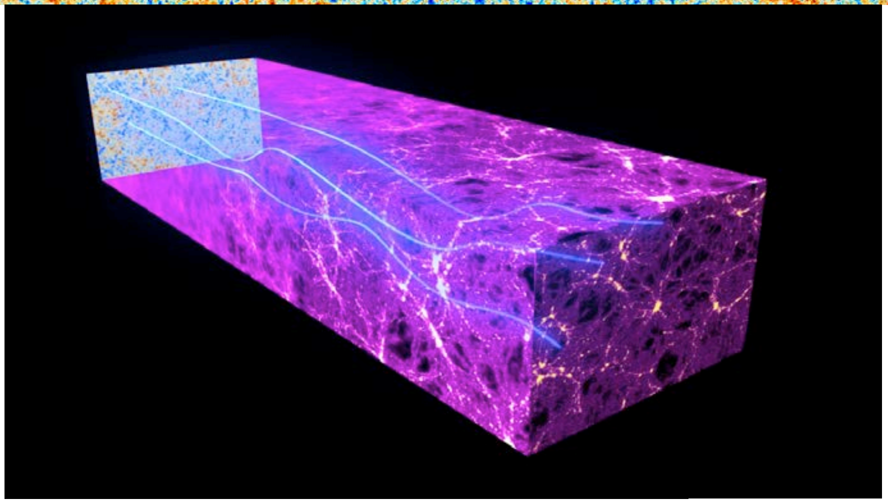
Measured from 4-points correlation function





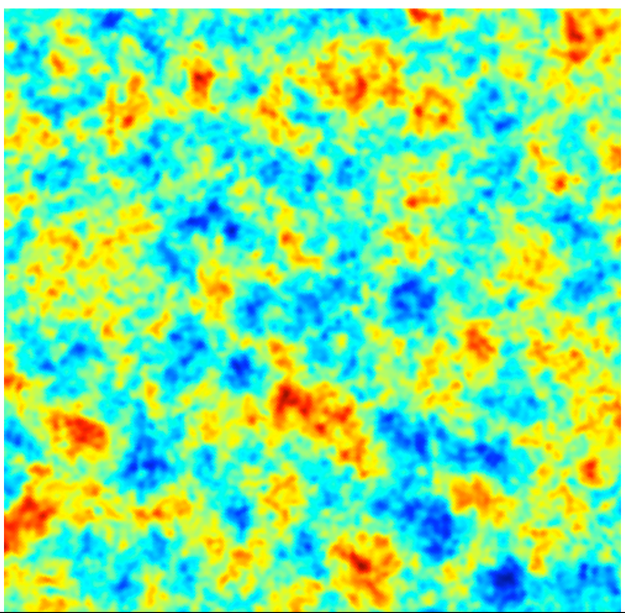
S. Henrot-Versillé

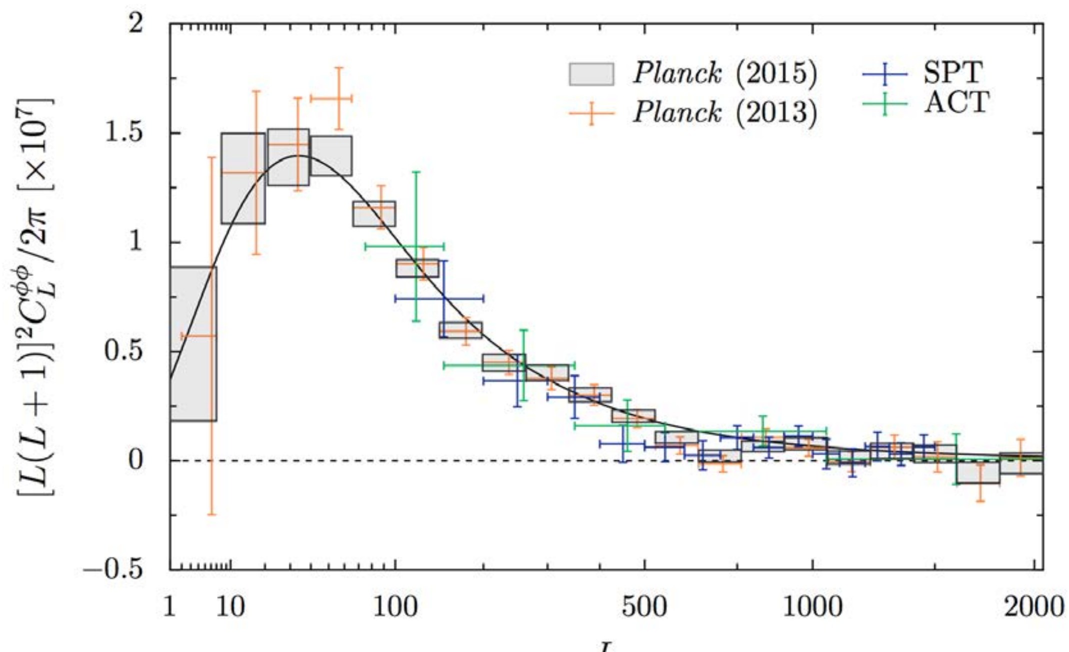
Gravitational Lensing of the CMB



Distorsion of the CMB photon path by the Large Scale Structures

Measured from 4-points correlation function





A word on the statistical method

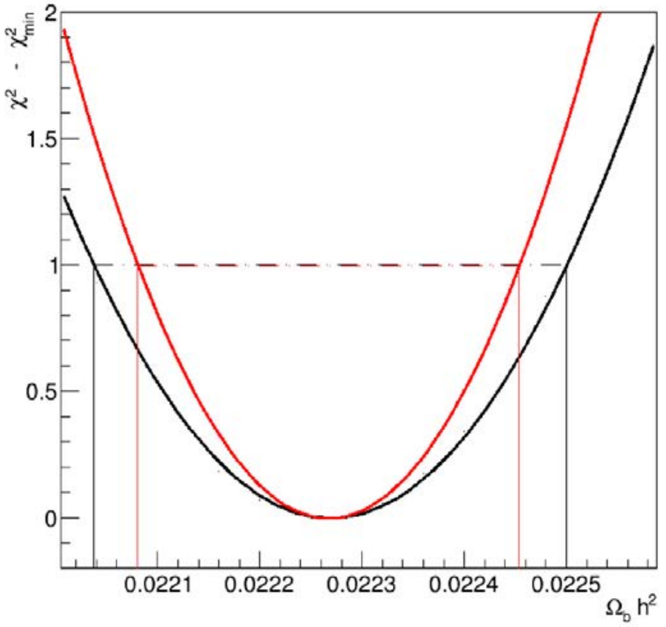


Figure 1. $\chi^2 - \chi^2_{min}$ profile of $\Omega_b h^2$ within the ΛCDM model for Plik: in black is shown the full profile likelihood fit (to get the full error of table 1) and in red the profile likelihood fit when the nuisance are fixed to the ones obtained when maximizing the likelihood function (to get the "sensitivity related" error of table 1).

Parameter	Full Error	'sensitivity related' and 'foreground and instrumental' error
Plik Parameters		
$\Omega_b h^2$	0.02227 ± 0.00023	$0.02227 \pm 0.00019 \pm 0.00014$
$\Omega_c h^2$	0.1198 ± 0.0022	$0.1198 \pm 0.0021 \pm 0.0007$
$100\theta_{MC}$	1.04184 ± 0.00044	$1.04184 \pm 0.00044 \pm 0.00003$
τ	0.082 ± 0.020	$0.082 \pm 0.018 \pm 0.009$
$\ln(10^{10} A_s)$	3.098 ± 0.037	$3.098 \pm 0.034 \pm 0.014$
n_s	0.9663 ± 0.0063	$0.9663 \pm 0.0051 \pm 0.0036$

Parameter	TT+lowP 68 % limits
$\Omega_b h^2$	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