SAIFR-ICTP Summer School 2018

Sao Paulo, 18th - 29th June 2018

Particle Physics & the Early Universe

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Outline

- Lecture 1: Standard Cosmology & the cosmological parameters
- Lecture 2: Inflation & the CMB
- Lecture 3: Thermal Universe and Big Bang Nucleosynthesis
- Lecture 4: Structure Formation & Dark Matter
- Lecture 5: Baryogenesis

Lecture 3: Outline

- Basics of Thermodynamics
- Reheating after inflation
- Neutrino decoupling & BBN
- Thermal relics:
  - Neutrinos & Dark Radiation
  - Planck results and CMB

Basics of thermodynamics

Basic formulas

Relativistic particles with p >> m

$$\rho = \xi_\rho \, g \frac{\pi^2}{30} \, T^4 \qquad \xi_\rho = 1 \; (B) \text{ or } 7/8 \; (F)$$

$$\zeta(3) = 1.202$$

$$n = \xi \, g \frac{\zeta(3)}{\pi^2} \, T^3 \qquad \xi = 1 \; (B) \text{ or } 3/4 \; (F)$$

Non-relativistic particles with m >> p

$$\rho = m \, n$$

$$n = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-\frac{m-\mu}{T}}$$

Maxwell Boltzmann
same for B and F !

Basic formulas II

Entropy density for relativistic species:

$$s = \frac{\rho + p}{T} = \frac{4\rho}{3T} = \frac{2\pi^2}{45} g_S \, T^3$$

$$g_S = \sum_B g_B \left(\frac{T_B}{T}\right)^3 + \sum_F g_F \frac{7}{8} \left(\frac{T_F}{T}\right)^3$$

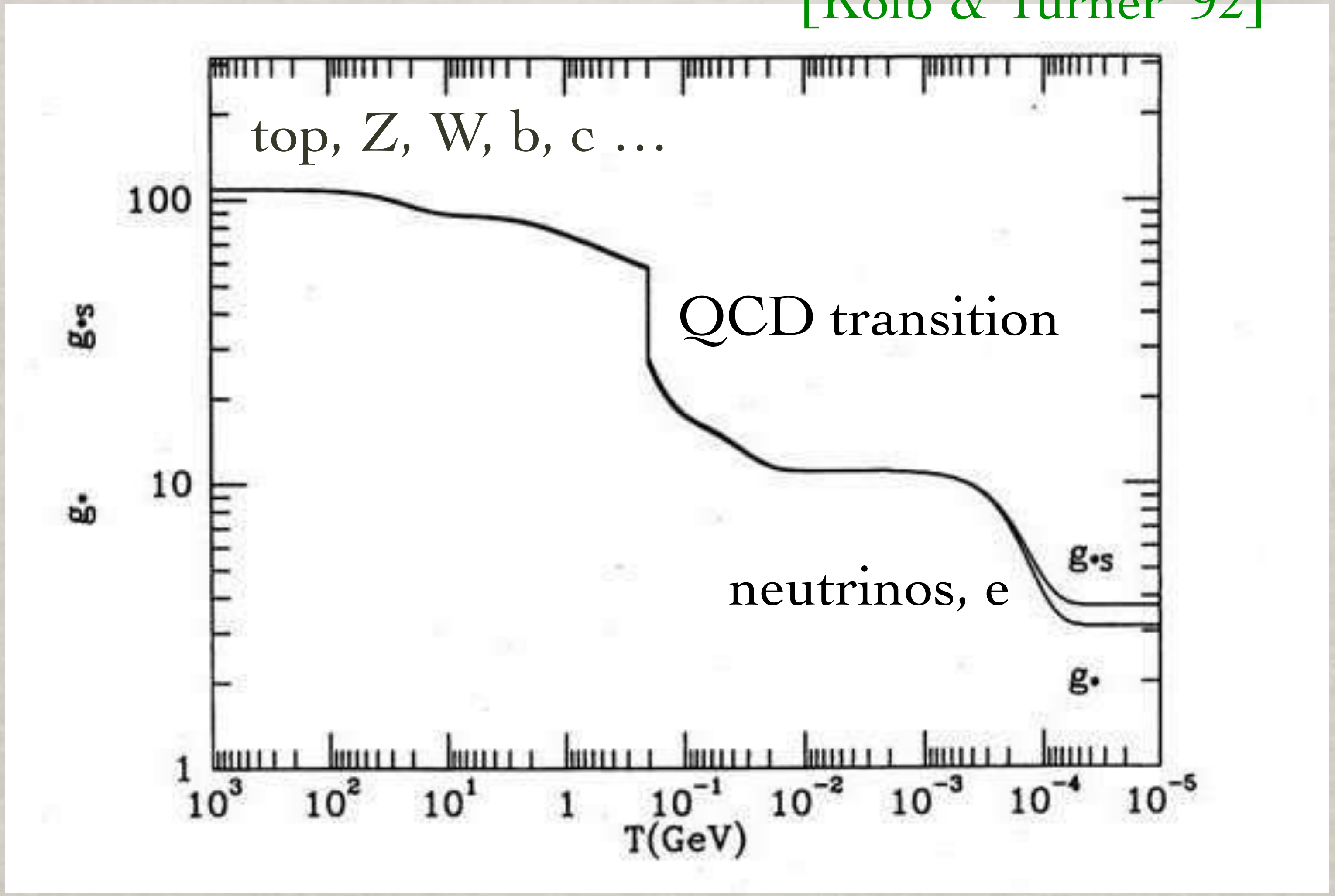
Non-relativistic particles:

$$s = \frac{mn}{T} = g \, m \left(\frac{m}{2\pi T}\right)^{3/2} e^{-\frac{m-\mu}{T}} \sim 0$$

The entropy is stored practically into radiation !

Degrees of freedom

[Kolb & Turner '92]



Reheating after inflation

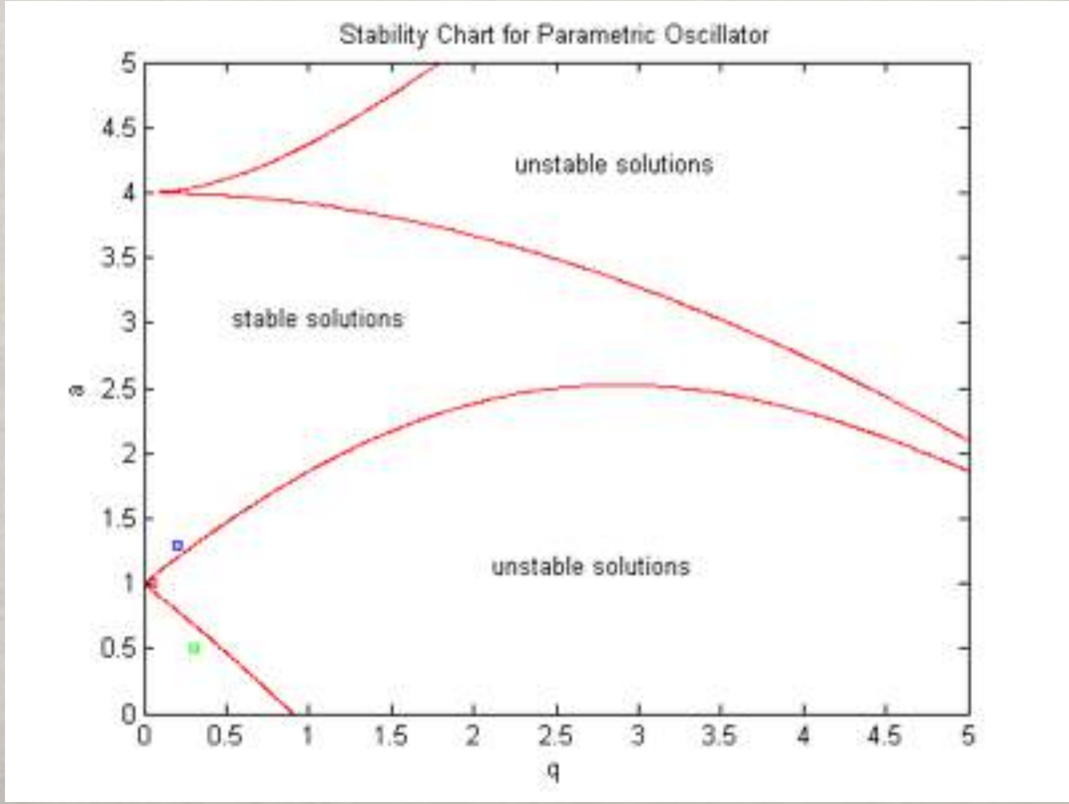
Preheating

[Kofman, Linde & Starobinski '92]

Due to the interaction with the oscillating inflation, fields can have a time dependent mass, even negative:

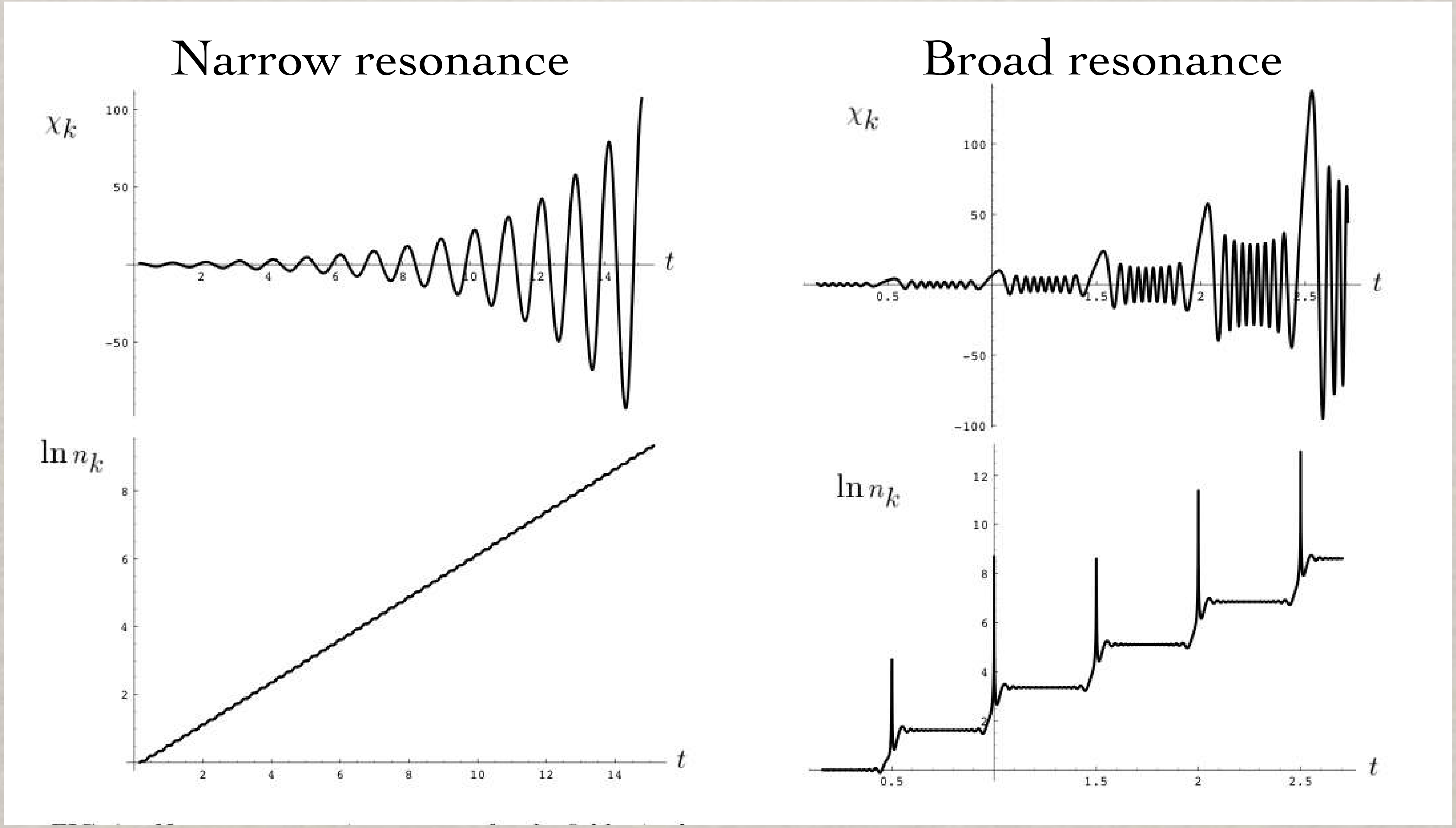
$$\ddot{\chi}_k + (k^2 + m_\chi^2 + 2g^2 A \sin m_\phi t)\chi_k = 0$$

Mathieu equation: $\chi_k'' + (a - 2q\cos 2z)\chi_k = 0$



Preheating II

[Kofman, Linde & Starobinski '92]

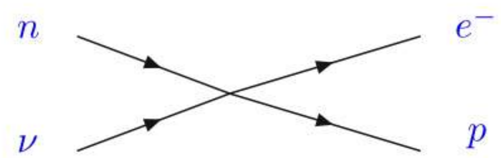


Neutrino decoupling and BBN

Big Bang Nucleosynthesis

After the QCD phase transition at $T \sim 200$ MeV the baryonic matter are $p, n, \pi^0, \pi^\pm, \Lambda, \ldots,$ but at $T \simeq 1$ MeV only the stable one p and the very long-lived n survive. Their number density is not suppressed by $e^{-m/T} \simeq e^{-10^3}$ due to the presence of a chemical potential related to baryon number μ_B. Proton and neutron have the same chemical potential and are still in equilibrium via the reactions

$$n + \nu \leftrightarrow p + e^- \qquad p + \bar{\nu} \leftrightarrow n + e^+$$



$$G_F = \frac{\pi \alpha_w}{\sqrt{2} M_W^2}$$

So the chemical equilibrium gives

$$\frac{n_n^{eq}}{n_p^{eq}} = \exp\left(-\frac{\Delta m + \mu_\nu - \mu_e}{T}\right) \simeq e^{-\frac{\Delta m}{T}} \qquad \text{where} \quad \Delta m \sim 1.29 \text{ MeV}$$

How long do neutrons track equilibrium ??? As long as

$$\langle \sigma(n\nu \to pe) v \rangle \sim \# G_F^2 T^5 \qquad \geq \qquad H = \sqrt{\frac{8\pi G \rho_{rad}}{3}} \sim 1 s^{-1} \left(\frac{T}{1\text{MeV}}\right)^2$$

So freeze-out happens at $T_* \simeq 0.84$ MeV $\qquad \Rightarrow n_n^{eq} \simeq 0.21\, n_p^{eq}.$

But final neutron to proton ratio strongly dependent on H(T) !

Big Bang Nucleosynthesis

Abundances of light elements

After freeze-out the neutrons start to decay with $\tau = 886$ s, i.e. $n_n(t) = n_n(t_*)e^{-t/\tau}$. The lightest composite nucleus is Deuterium, that can be produced in the reaction $p + n \leftrightarrow D + \gamma$

Unfortunately the bounding energy for D is very low $B_D \sim 2.23$ MeV and the number of photons in the Universe above such energy still very large: very easy to dissociate Deuterium !

$$\frac{n_D^{eq}}{n_\gamma} \sim \eta_B X_D \left(\frac{T}{B_D}\right)^2 e^{B_D/T}$$

"Deuterium Bottleneck"

where $\eta_B = n_B/n_\gamma$. So D's abundance start to grow only after $T \leq 0.06$ MeV, i.e. $t \geq 300$ s.

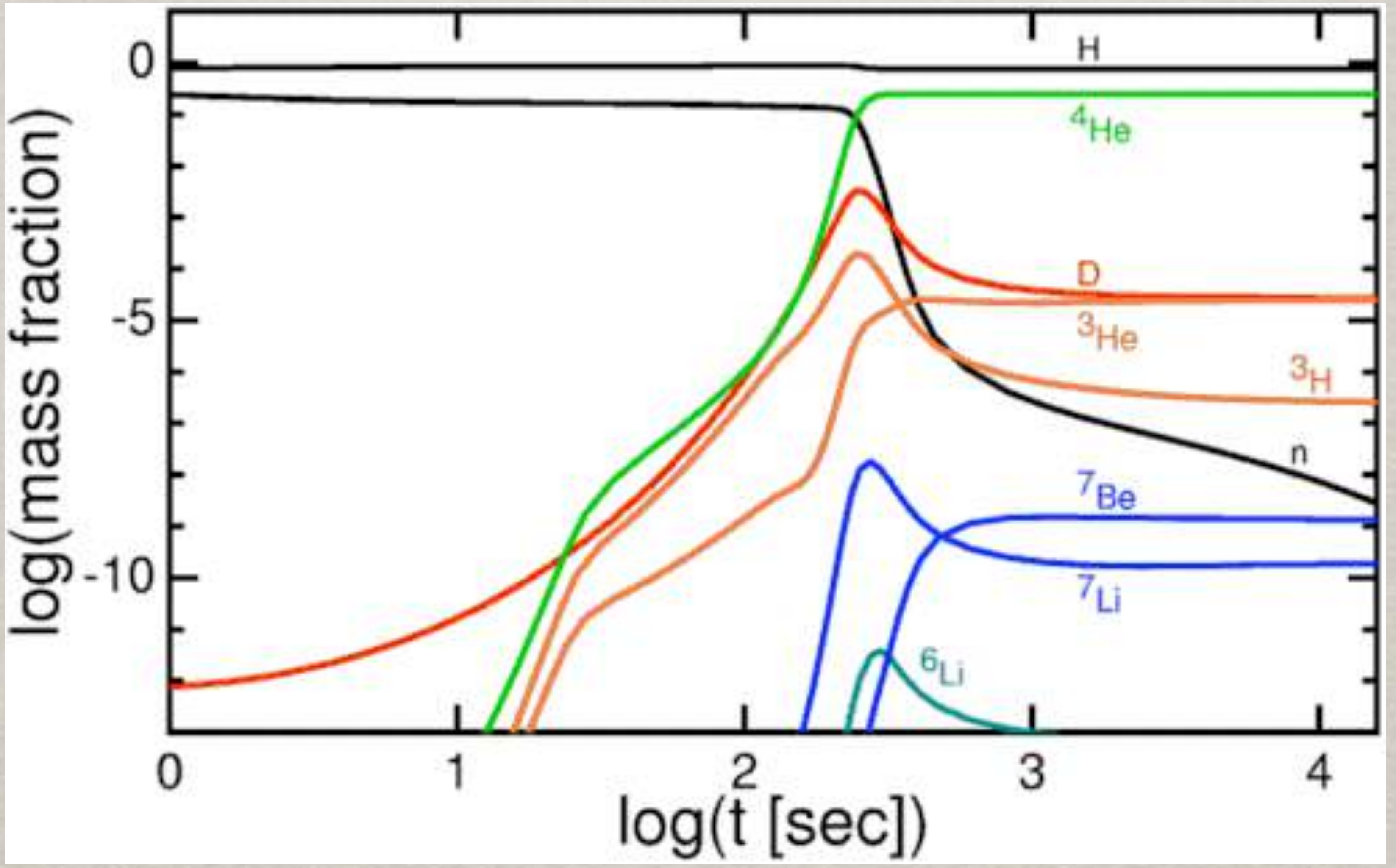
The equilibrium densities of the other light elements are not reached until after this time, since they are all produced starting from D:

$$D + D \leftrightarrow {}^3He + n$$
$$D + D \leftrightarrow {}^3H + p$$
$$D + D \leftrightarrow {}^4He + \gamma$$
$${}^3He + D \leftrightarrow {}^4He + p$$
$${}^3H + D \leftrightarrow {}^4He + n$$

Most of the neutrons end up in ${}^4He$ that is the more strongly bound nucleus, but there remains also a small fraction of Deuterium and ${}^3He$ and some ${}^7Li$ formed from Helium.

Big Bang Nucleosynthesis

Evolution of the light elements abundances in standard BBN



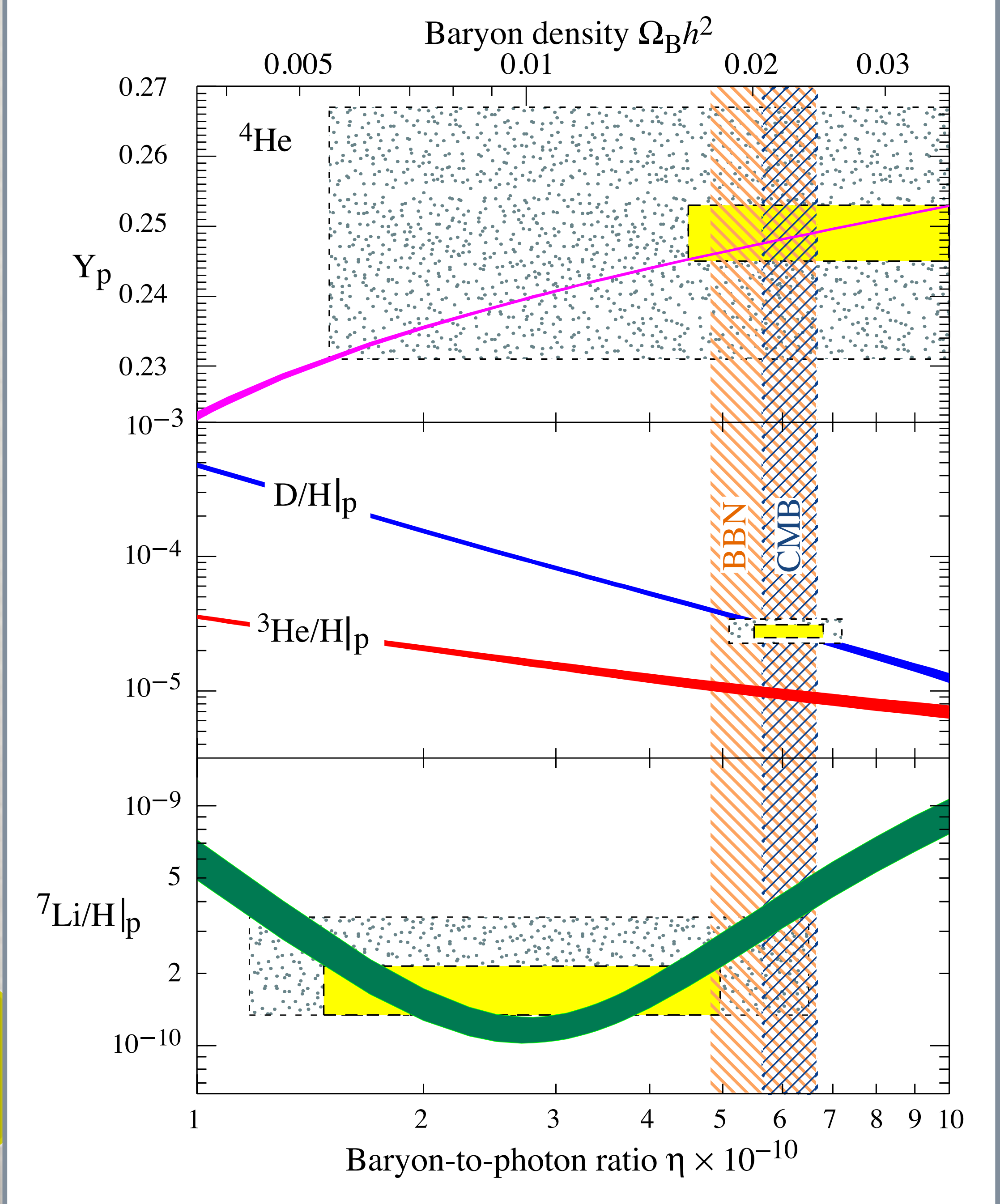
Practically all neutrons end up into Helium

Big Bang Nucleosynthesis

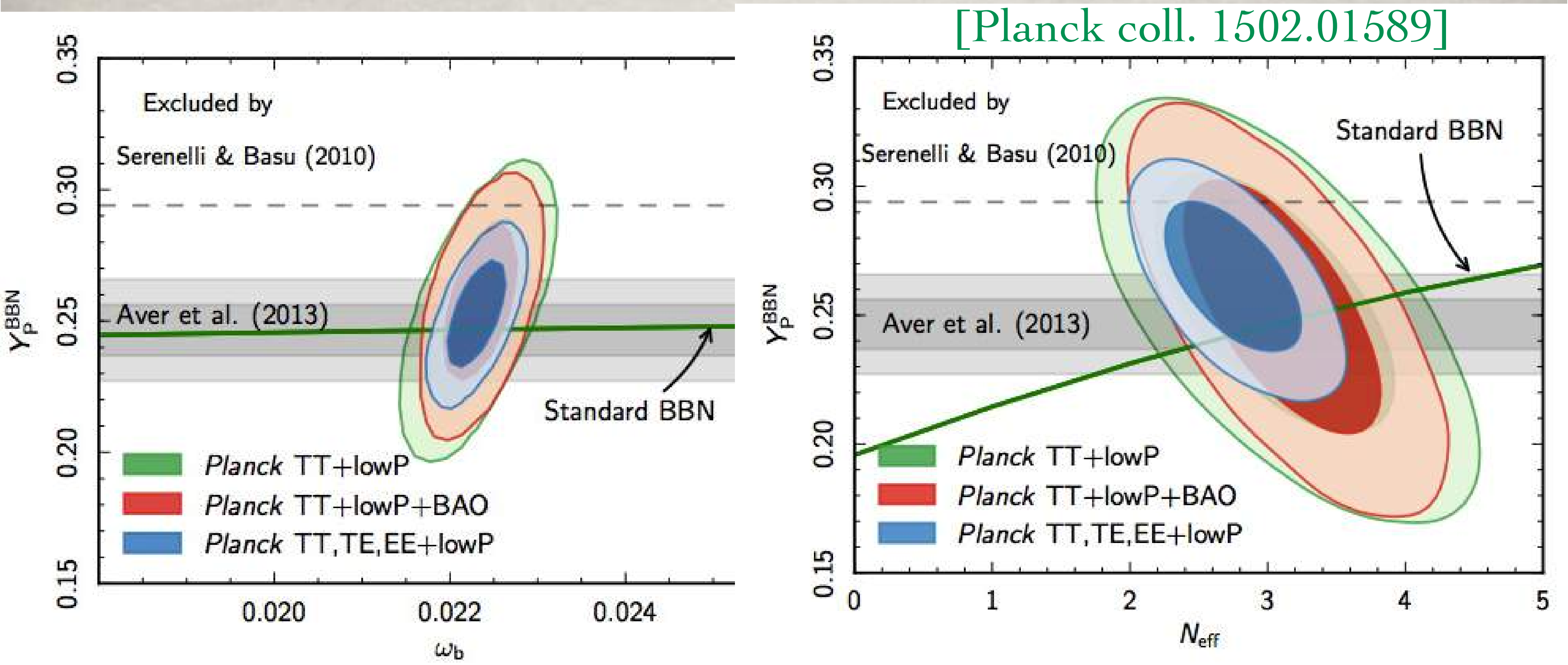
[Fields & Sarkar PDG 07]

- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7

$$\Omega_B h^2 = 0.02 < \Omega_{DM} h^2$$



Planck:Nucleosynthesis

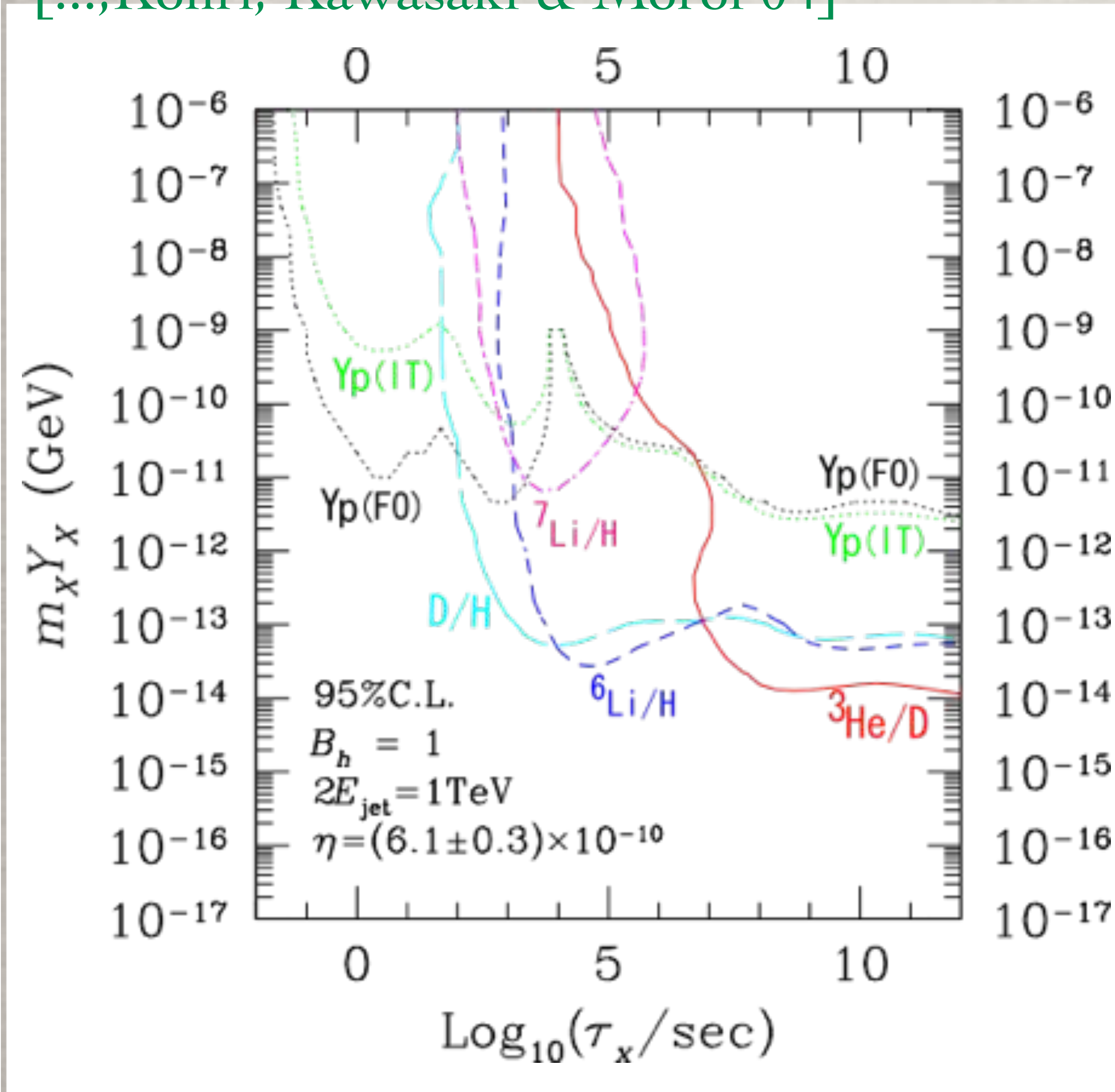


CMB consistent with BBN even fitting both N_{eff} & Y_p .

Note the degeneracy between these two parameters, but orthogonal compared to BBN !

BBN bounds on decays

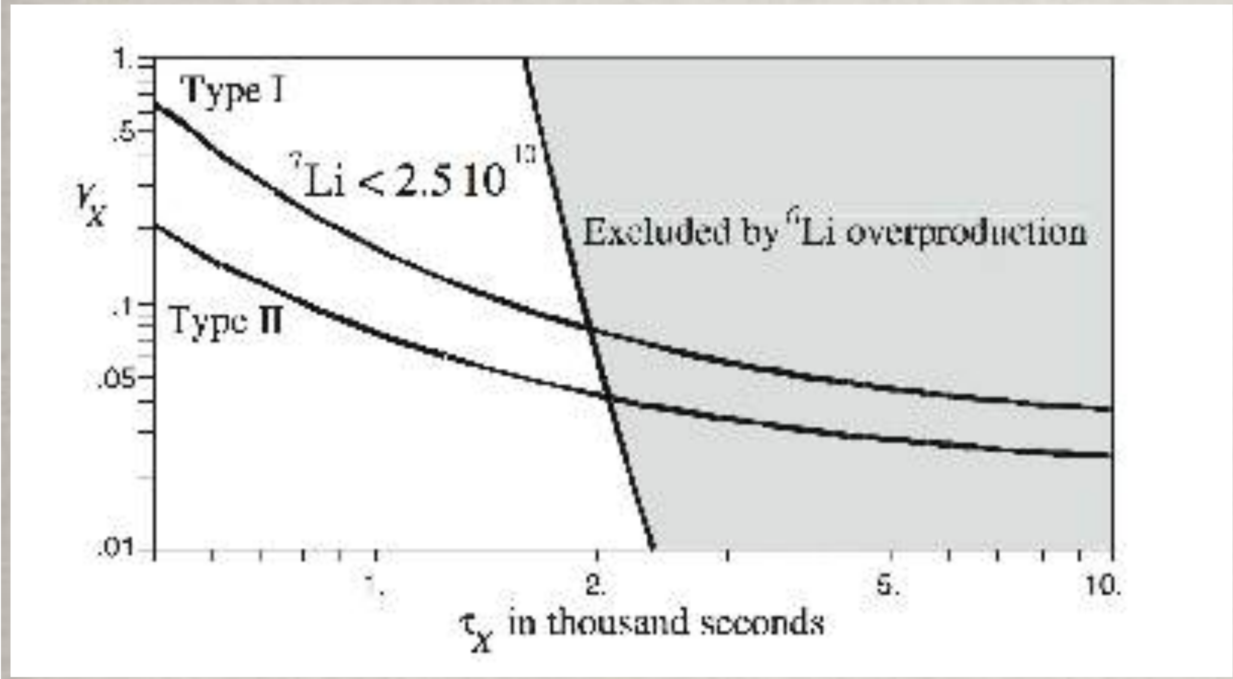
[...,Kohri, Kawasaki & Moroi 04]



Neutral relics:
they can release EM energy and destroy light elements, e.g. D, or if they decay hadronically they can also affect the neutron to proton ratio…
Bounds on the density of any decaying particle !

BBN bounds on decays

[Pospelov 05, Kohri & Takayama 06, Cyburt at al 06, Jedamzik 07,...]



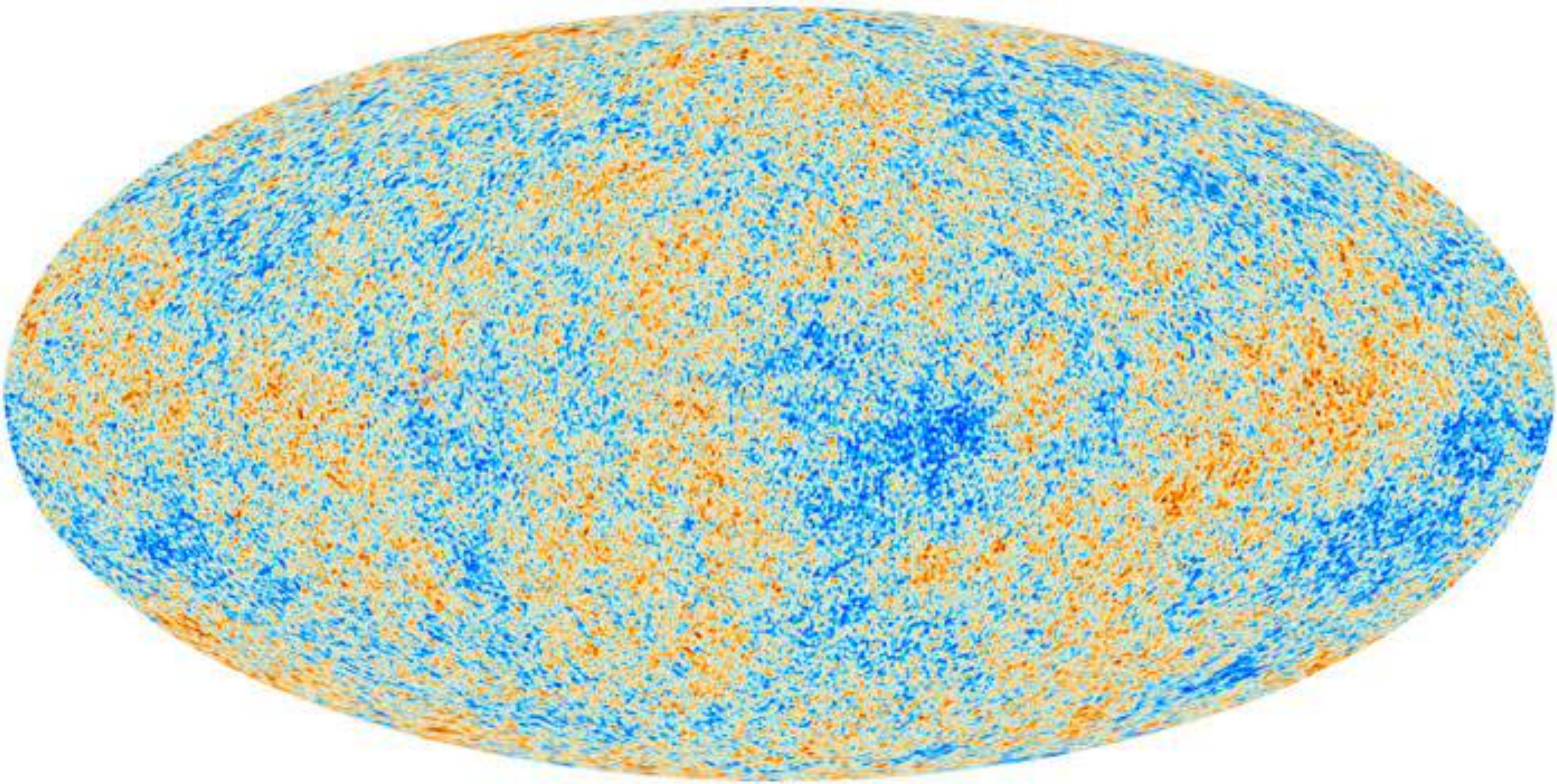
Charged relics:
they can form bounded stated with nuclei and reduce the Coulomb barrier, allowing to speed up some rates, e.g. production of Lithium…

Bounds on the density of any decaying particle !

Planck results and CMB

Planck results 2013-15

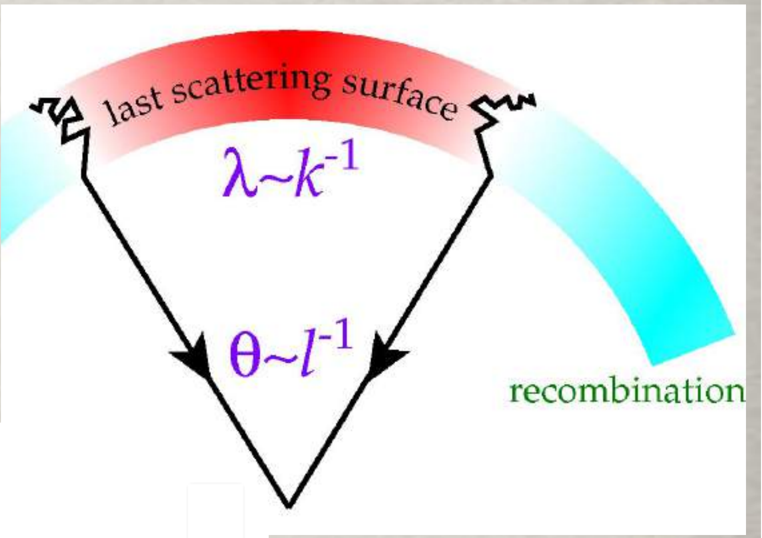
Picture of the CMB anisotropies at recombination



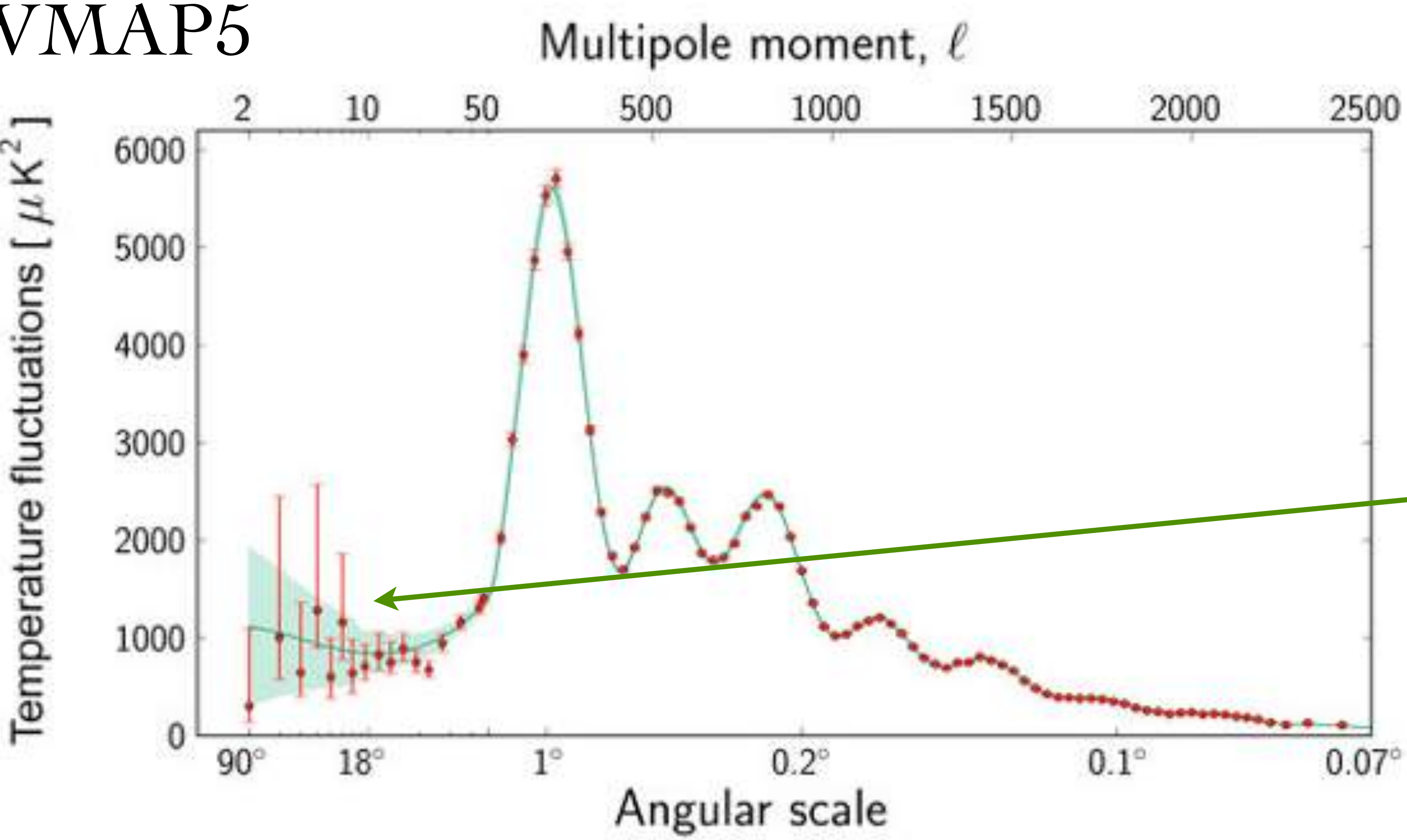
$$\langle T(\theta)T(0)\rangle = \sum_{\ell,m} a_{\ell m} Y_m^\ell(\theta)$$

Planck angular power spectrum

$$C_\ell = \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2$$

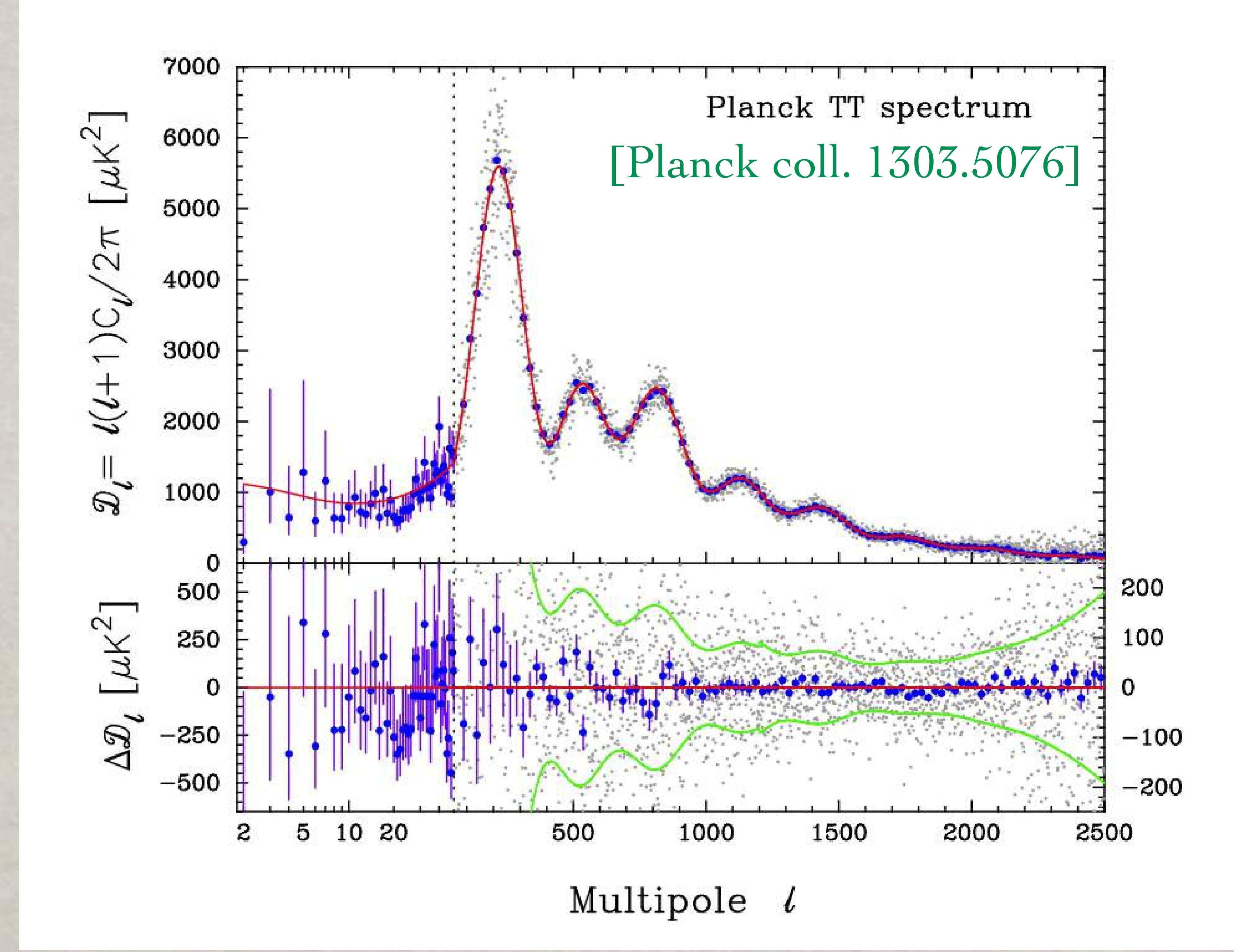


WMAP5



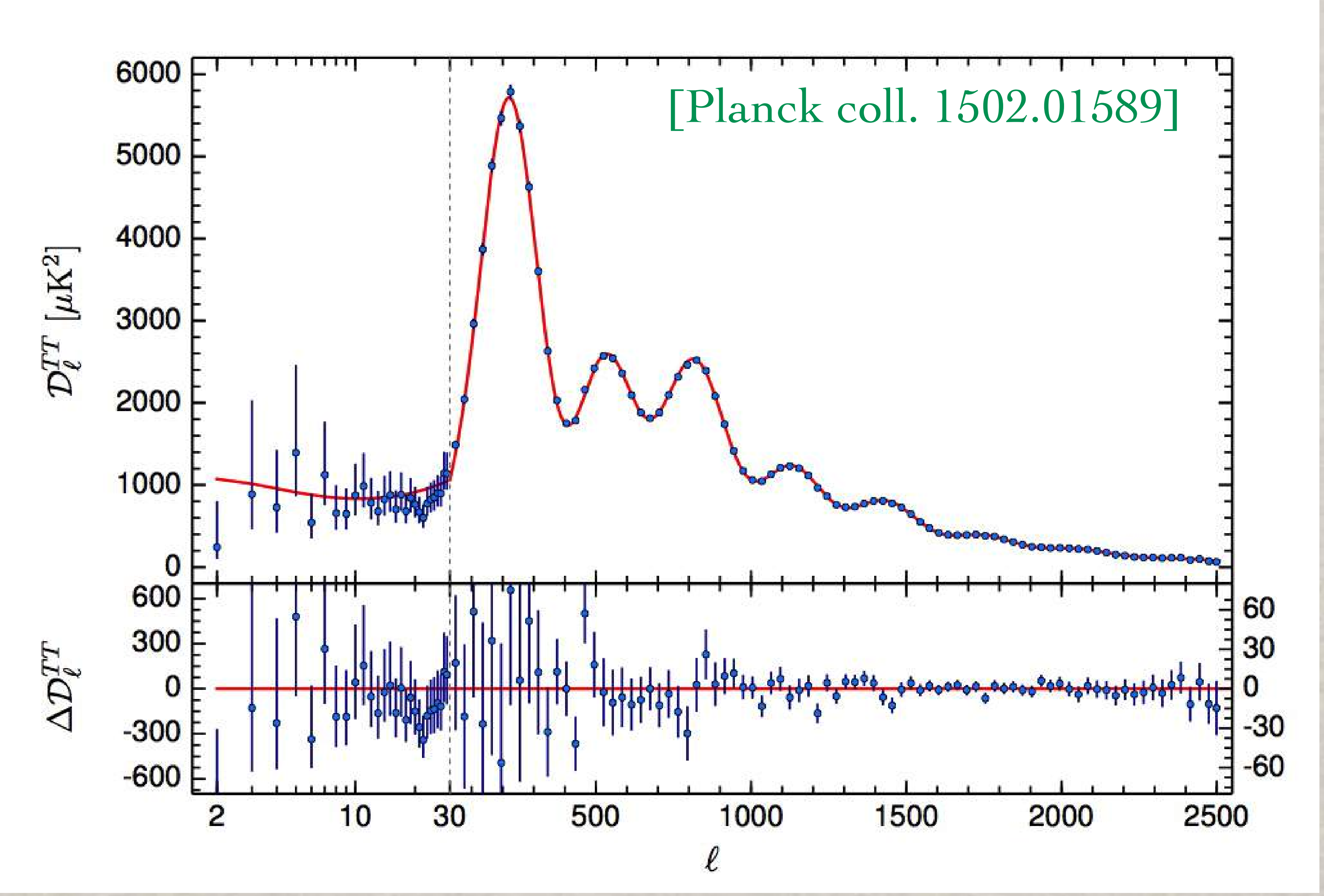
Cosmic variance

Planck TT spectrum



Perfect agreement with 6-parameter ΛCDM model!

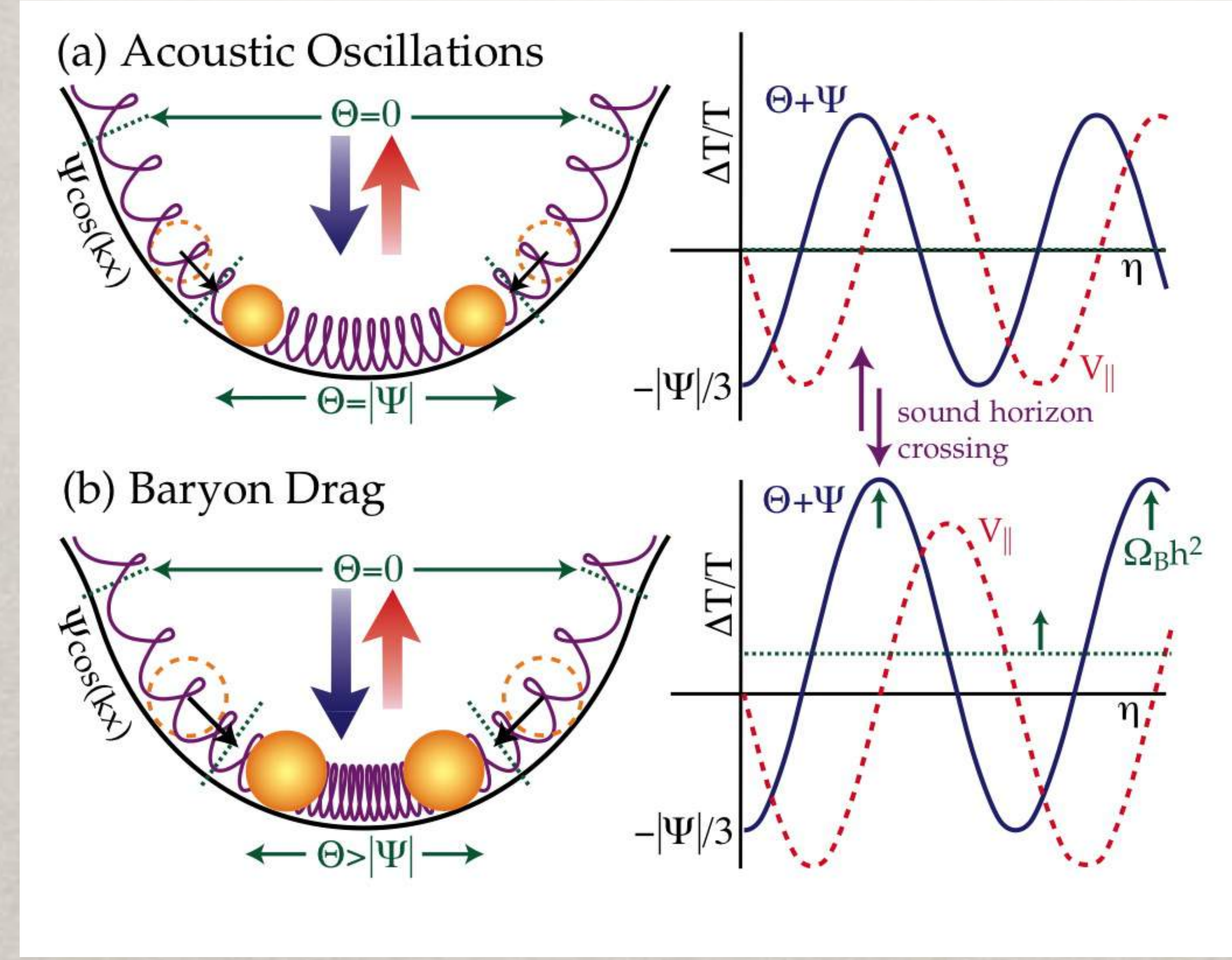
Planck TT spectrum



Perfect agreement with 6-parameter ΛCDM model!

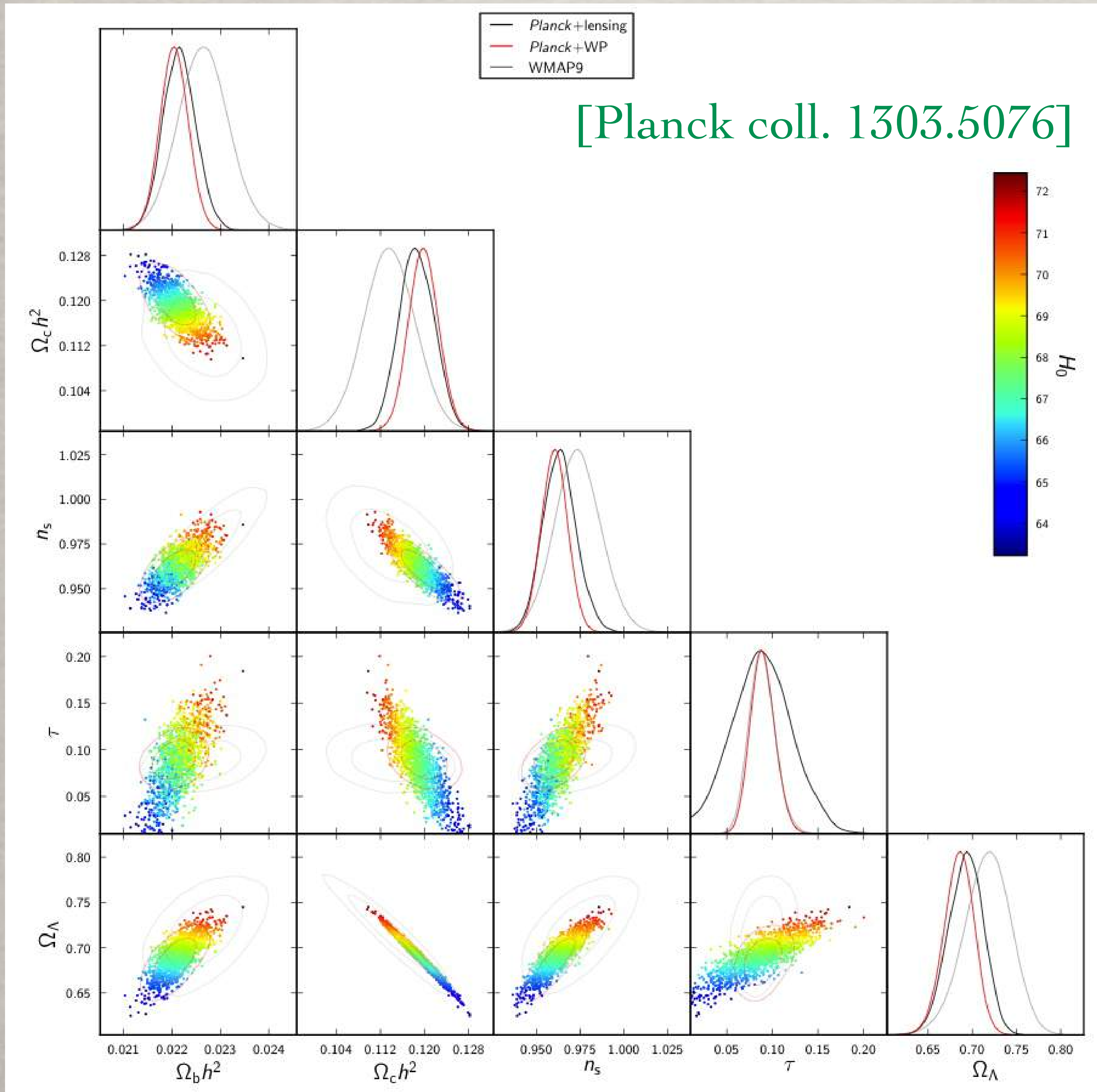
CMB primer

[Wayne Hu's CMB primer at http://background.uchicago.edu/~whu/]



Baryons increase the mass in the plasma and the drag force...

Planck cosmo parameters



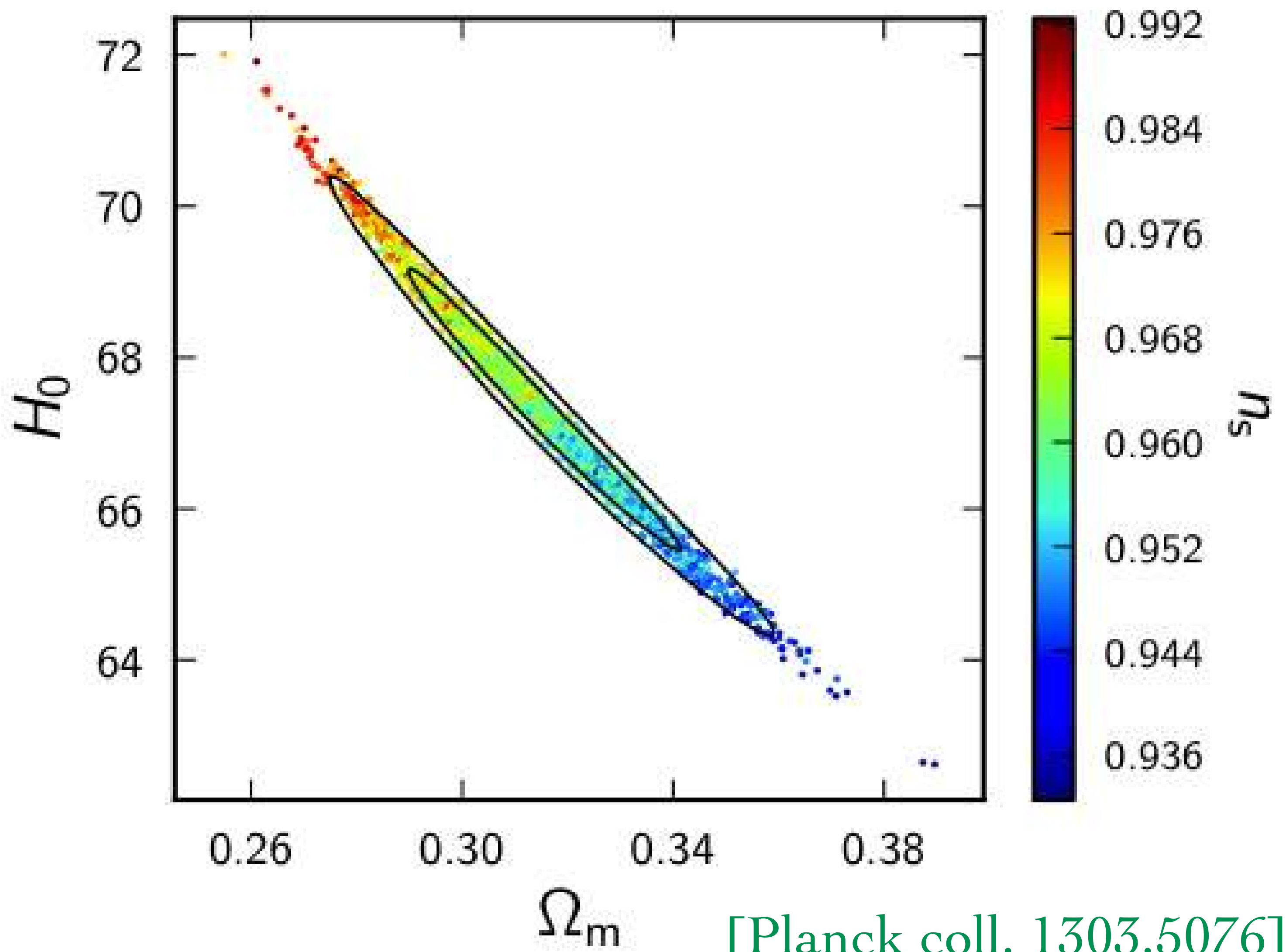
[Planck coll. 1303.5076]

Low value for H_0 (green)preferred !

Therefore slightly larger value for $\Omega_{CDM} h^2$

Otherwise the fit is in good agreement with WMAP9

Planck cosmo parameters

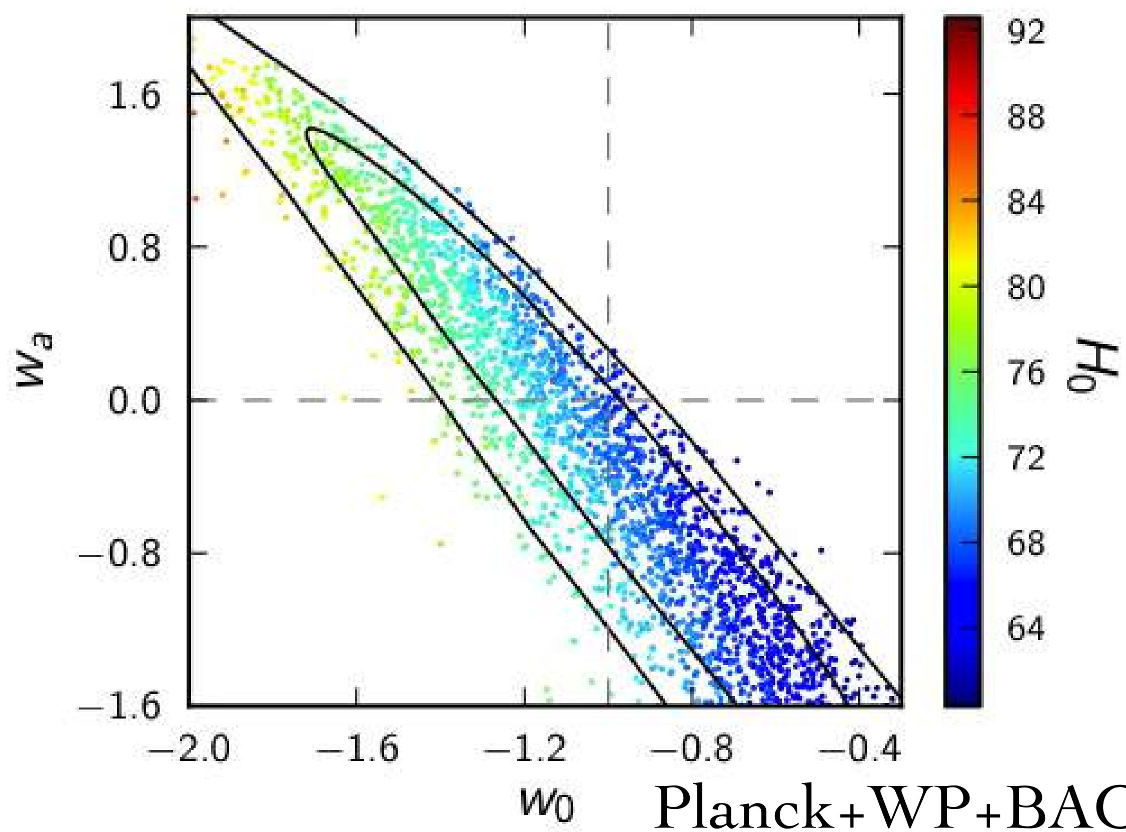


[Planck coll. 1303.5076]

Degeneracy in the plane H_0 vs Ω_m depending on n_s.

Planck: dark energy

[Planck coll. 1303.5076]



Planck+WP+BAO

95% CL Planck+WP+BAO

For constant w

$$w < -1.13^{+0.24}_{-0.25}$$

Instead for

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

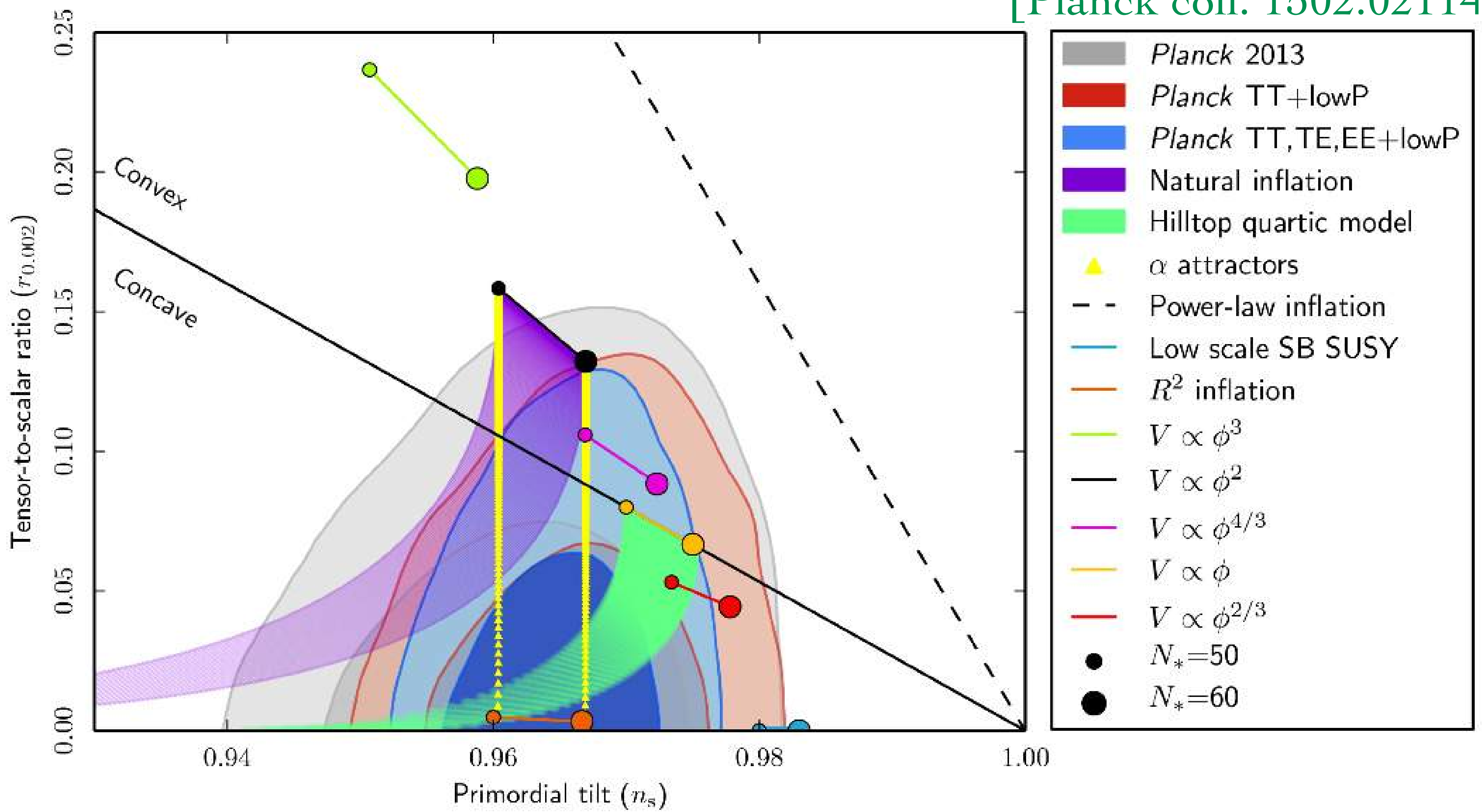
$$w_0 = -1.04^{+0.72}_{-0.69}$$

$$w_a < 1.32$$

Data are consistent with a cosmological constant !

Planck: Inflation

[Planck coll. 1502.02114]

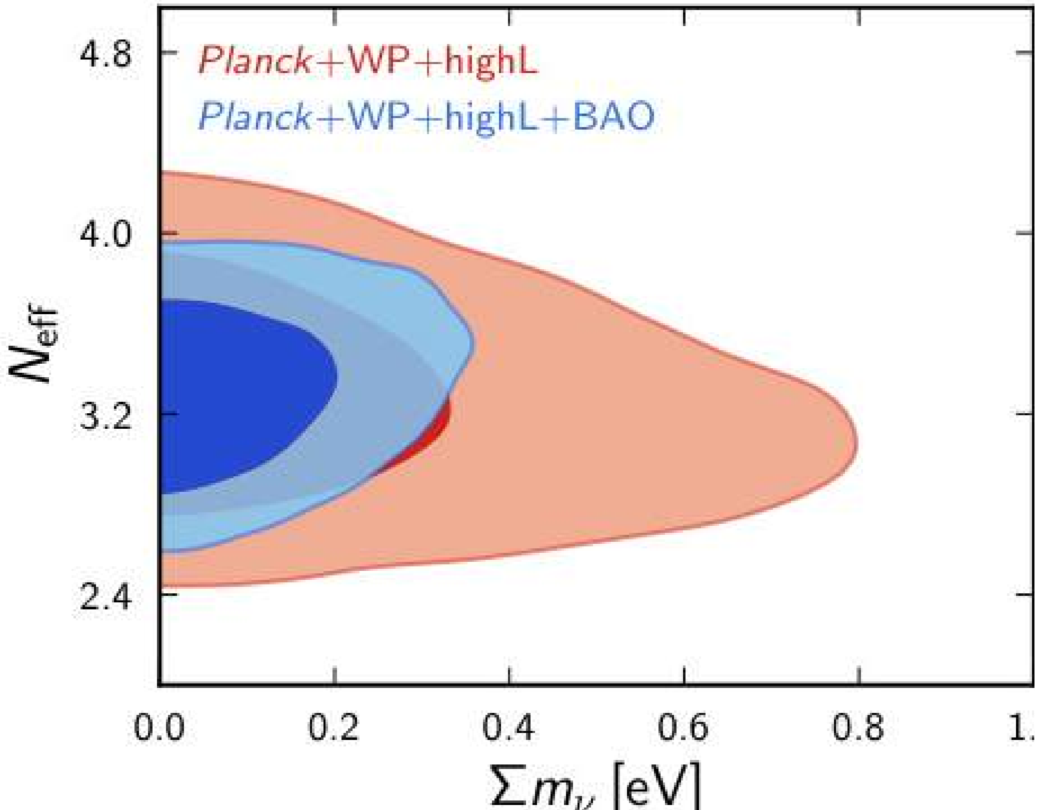


$$n_s = 0.968 \pm 0.006 \qquad r_{0.02} < 0.11(95\% CL)$$

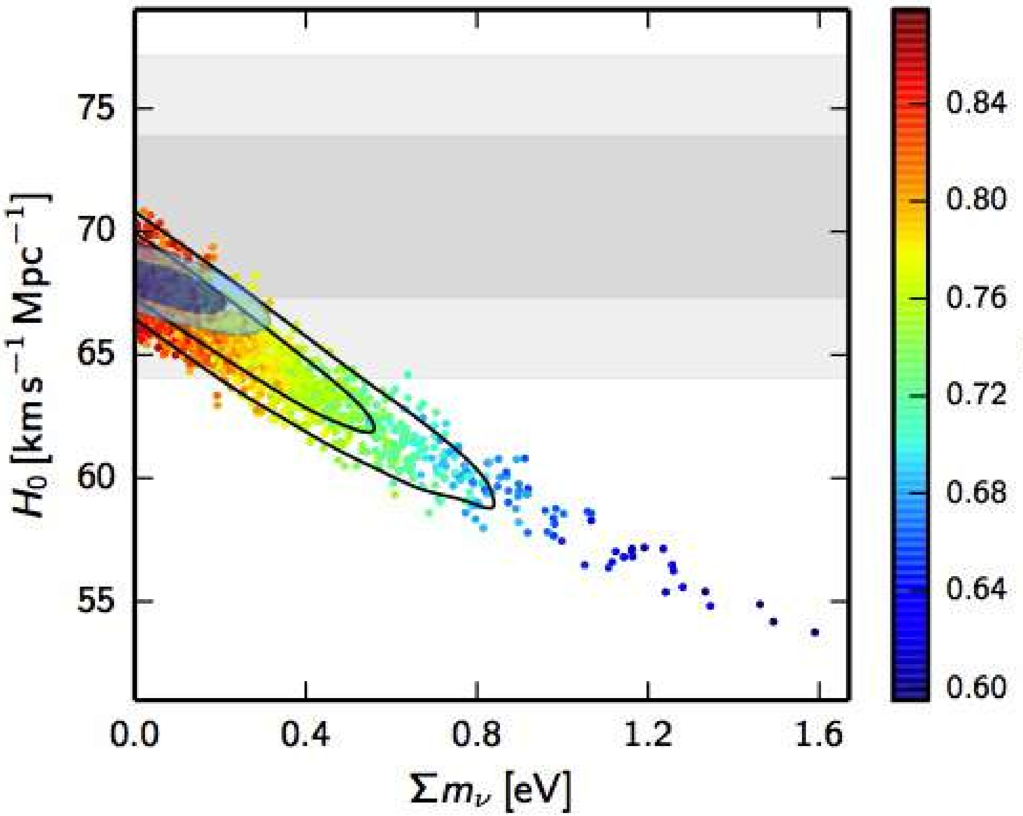
No evidence for running of n_s: $\frac{dn}{d\log(k)} < -0.003 \pm 0.007$

Planck: dark radiation

[Planck coll. 1303.5076]



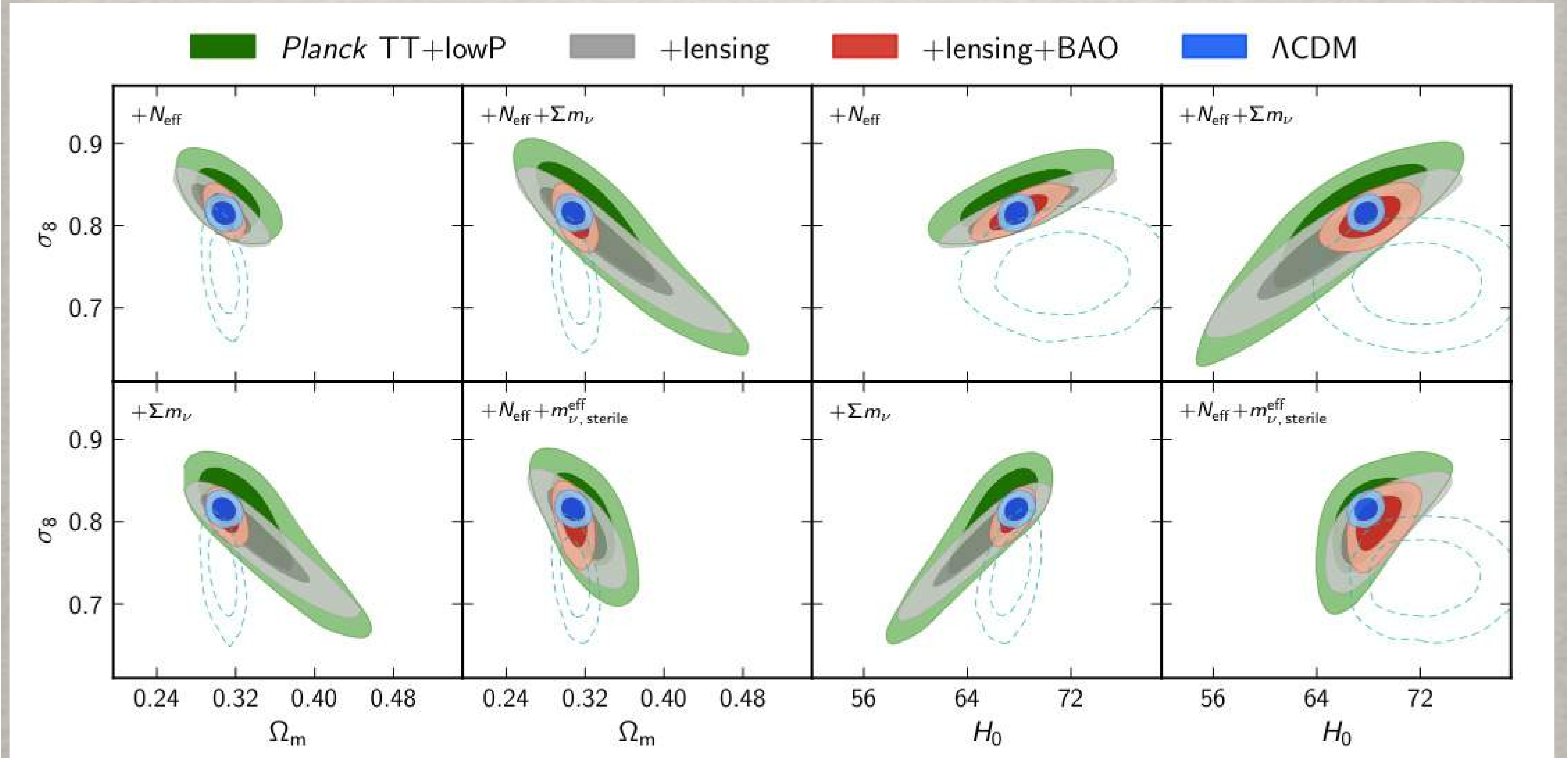
[Planck coll. 1502.01589]



No evidence for dark radiation, Neff =3.046 is within 1 σ.

Also limit on the sum of neutrino masses below the eV !

Planck: DR & sigma_8



Degeneracy between fluctuation growth shown by sigma_8 and neutrino masses/N_eff

Non gaussianity & the bispectrum

If the curvature fluctuations are perfectly gaussian, all the information about their distribution is contained in the two-point correlation and the power spectrum & the odd-point correlations are vanishing. For non-gaussian perturbations we have more correlations to consider...

$$\langle \delta T(x_1) \delta T(x_2) \delta T(x_3) \rangle \;\Rightarrow \delta(k_1 + k_2 + k_3) F(k_1, k_2, k_3)$$

Bispectrum

For a locally non-gaussian field, i.e.

$$\Phi(x) = \phi_g(x) + f_{NL} \left(\phi_g^2(x) - \langle \phi_g^2(x) \rangle \right)$$

we obtain

$$F(k_1, k_2, k_3) \propto f_{NL} \left(P(k_1) P(k_2) + perm... \right)$$

Planck: non-gaussianity

The Planck collaboration looked for non-gaussianities, both in the bispectrum (f_{NL}) and in the trispectrum (τ_{NL}, g_{NL}):

$$\langle \delta T(x_1)\delta T(x_2)\delta T(x_3)\delta T(x_4)\rangle \Rightarrow \delta(k_1+k_2+k_3+k_4)T(k_1,k_2,k_3)$$

$$T(k_1,k_2,k_3) = \frac{25}{9}\tau_{NL}\left[P(k_1)P(k_2)P(k_{13}) + \ldots\right] + 6g_{NL}\left[P(k_1)P(k_2)P(k_3) + \ldots\right]$$

Bispectrum for various shapes

[Planck coll. 1303.5084 & 1502.01592]

$$f_{NL}^{local} = 2.7 \pm 5.8 \quad 0.8 \pm 5$$

$$f_{NL}^{equil} = -42 \pm 75 \quad -4 \pm 43$$

$$f_{NL}^{ortho} = -25 \pm 39 \quad -26 \pm 21$$

Trispectrum

$$g_{NL}^{loc} < (-13 \pm 18) \times 10^4$$

[Feng et al. 1502.00585]

$$g_{NL}^{loc} < (-9 \pm 7.7) \times 10^4$$

[Planck coll. 1502.01592]

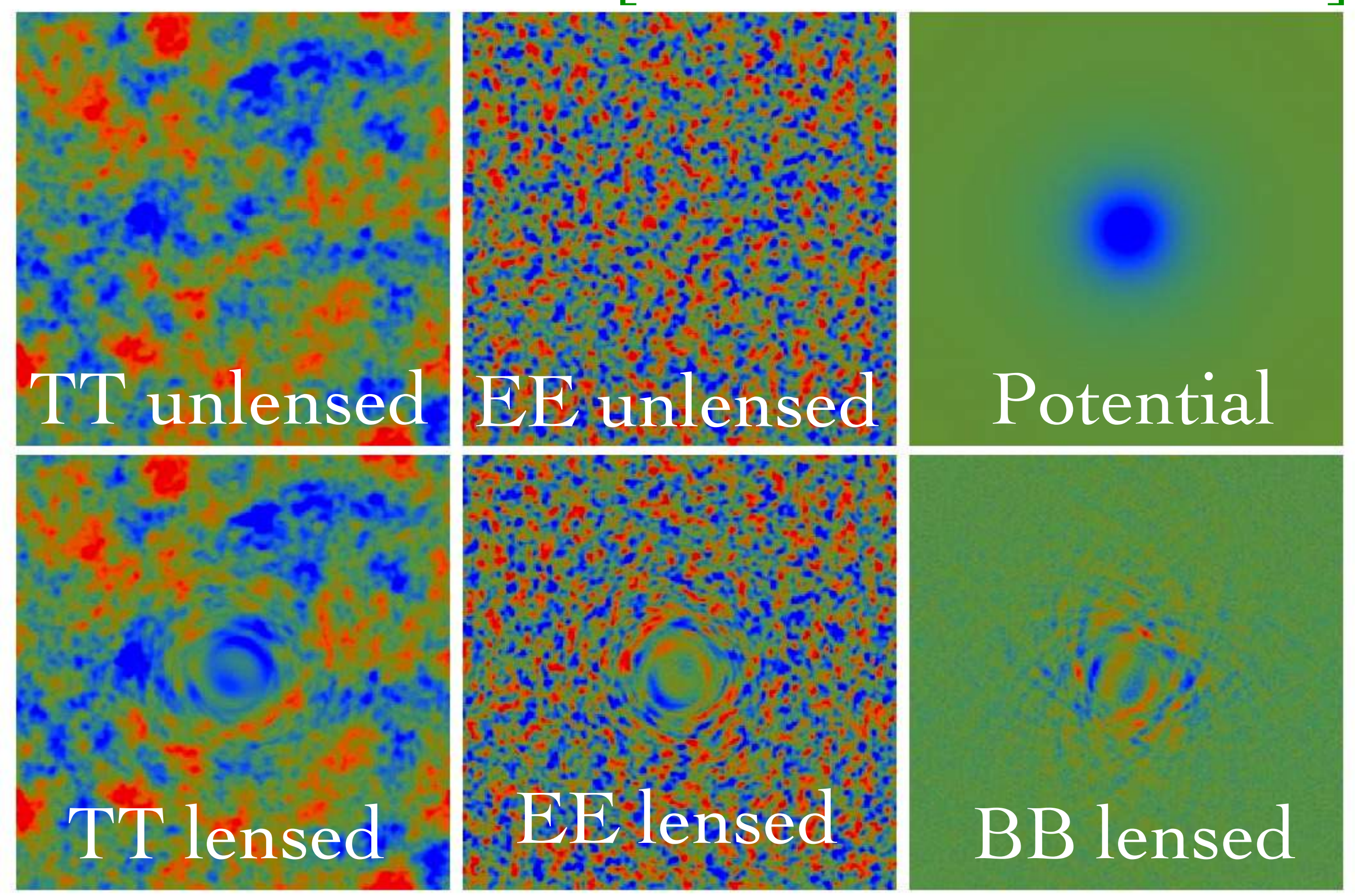
No evidence of non-gaussianities in the primordial fluctuations:

no evidence of multifield models or reduced c_s , etc. .

Note: non-gaussianity from lensing subtracted is at same level !

Planck:CMB lensing

[W. Hu & T. Okamoto 2002]



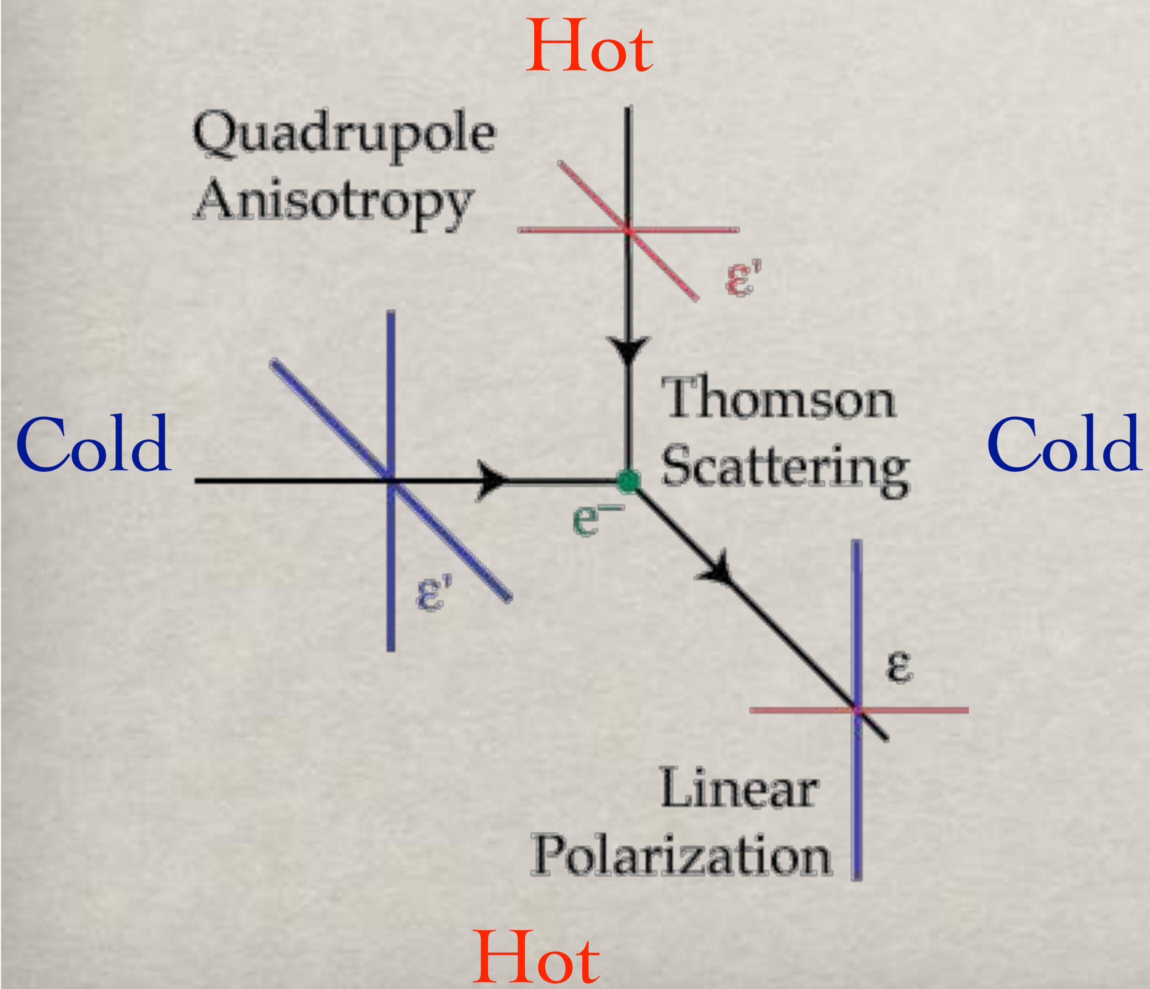
The Planck collaboration has detected the CMB lensing at more than 25 sigma significance !

Unfortunately it introduces late-time non-gaussianity...

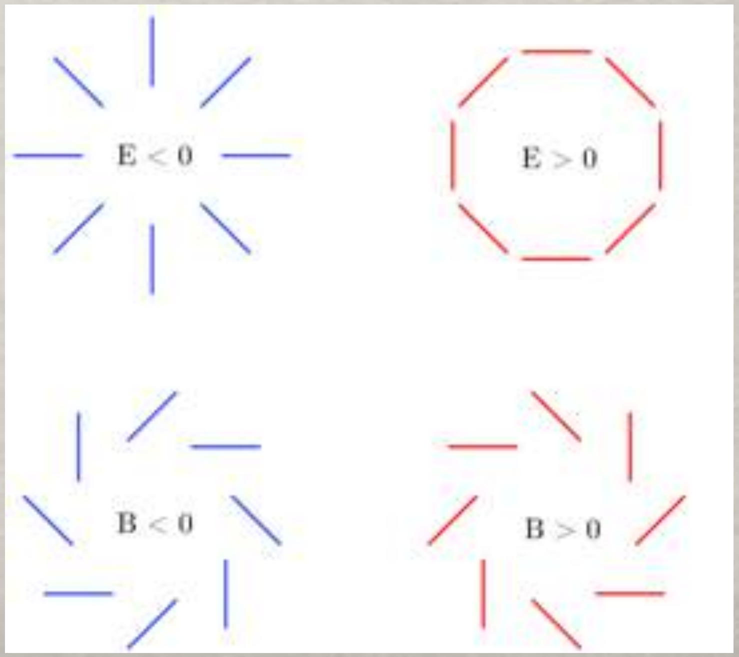
Polarization of the CMB

CMB POLARIZATION

The CMB light comes from Thomson scattering on the last scattering surface and is expected to be about 20% polarized due to quadrupole configurations -> gravitational waves !



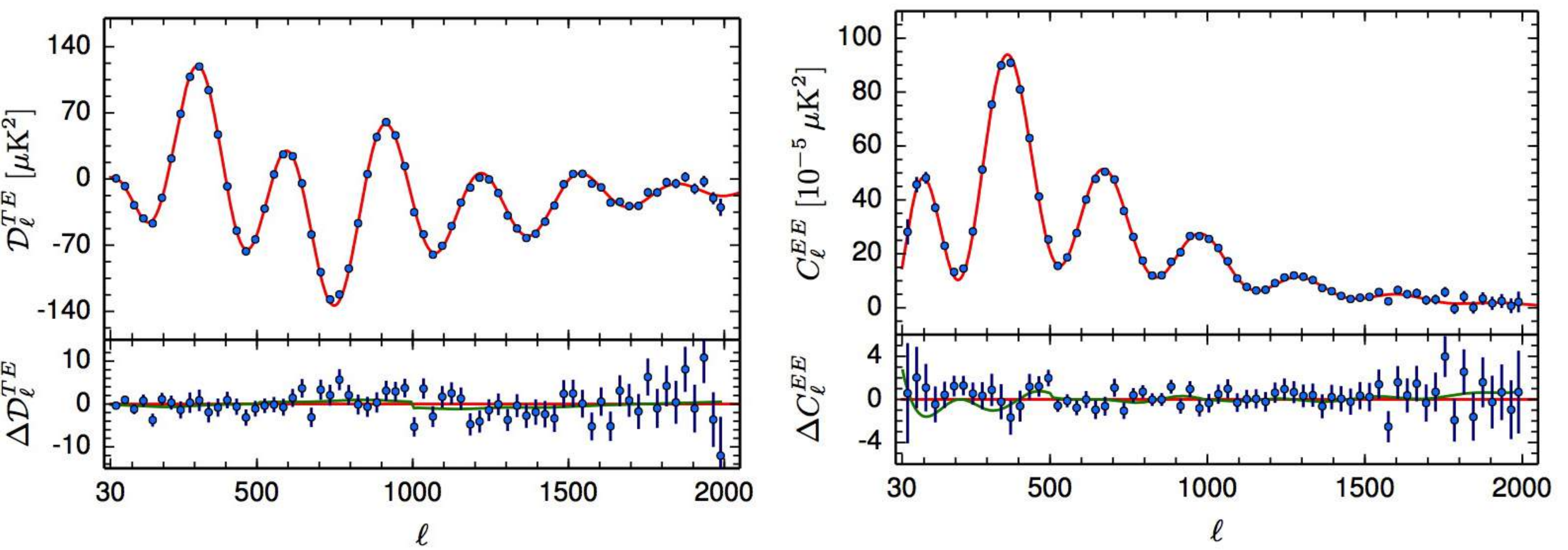
Pattern in the CMB



Planck TE & EE spectrum

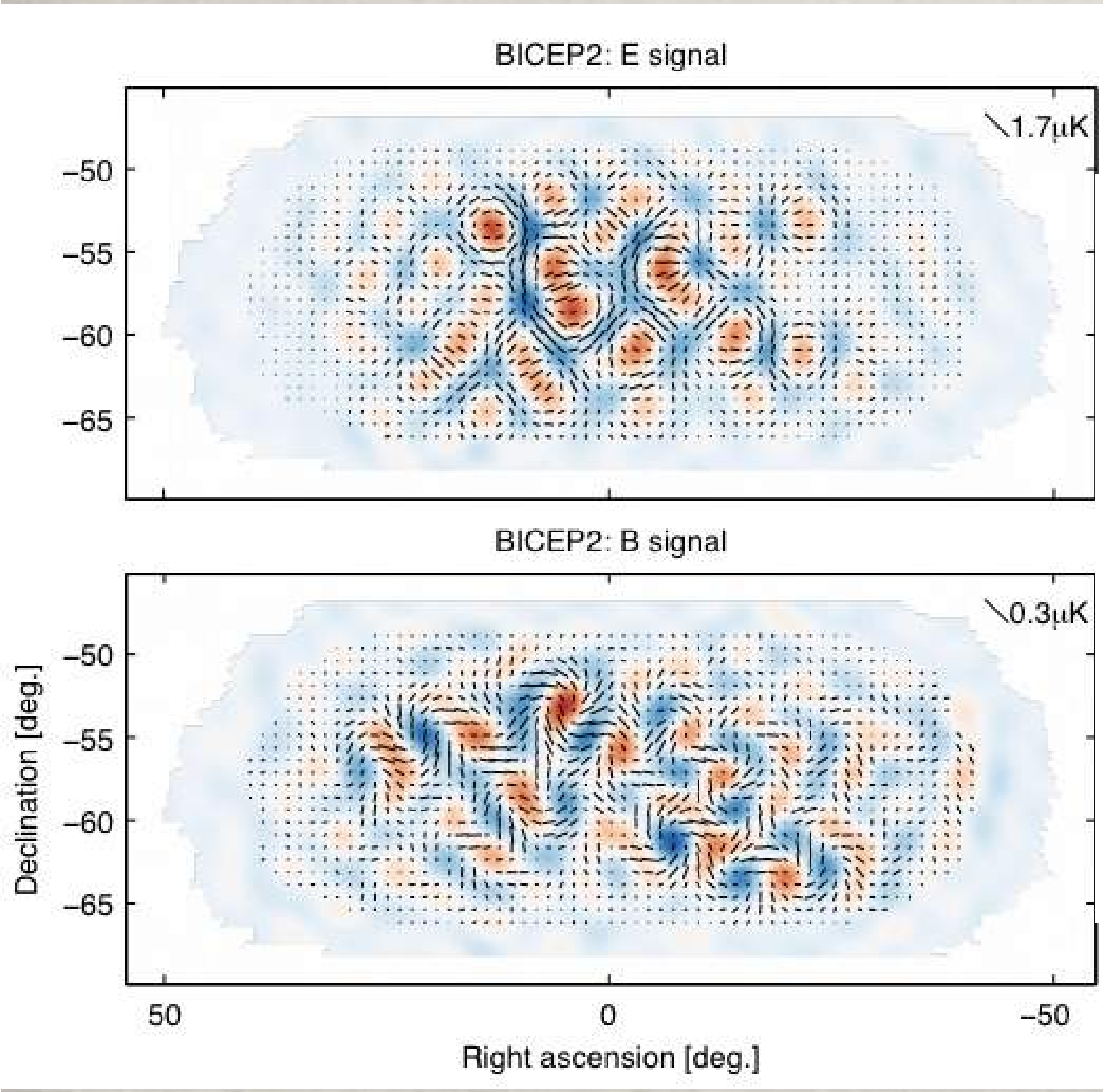
Planck also released results about the measure of the CMB polarization:

[Planck coll. 1502.01589]

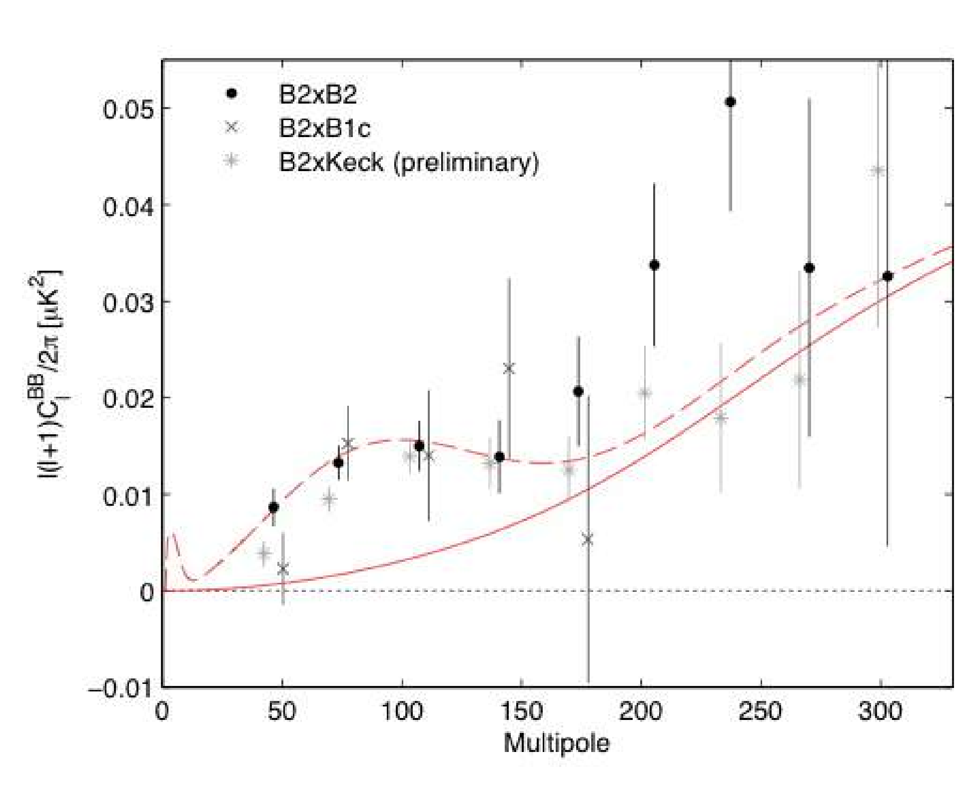


Again perfect agreement with 6-parameter ΛCDM model but some of the degeneracies between parameters are lifted !

BICEP2: POLARIZATION



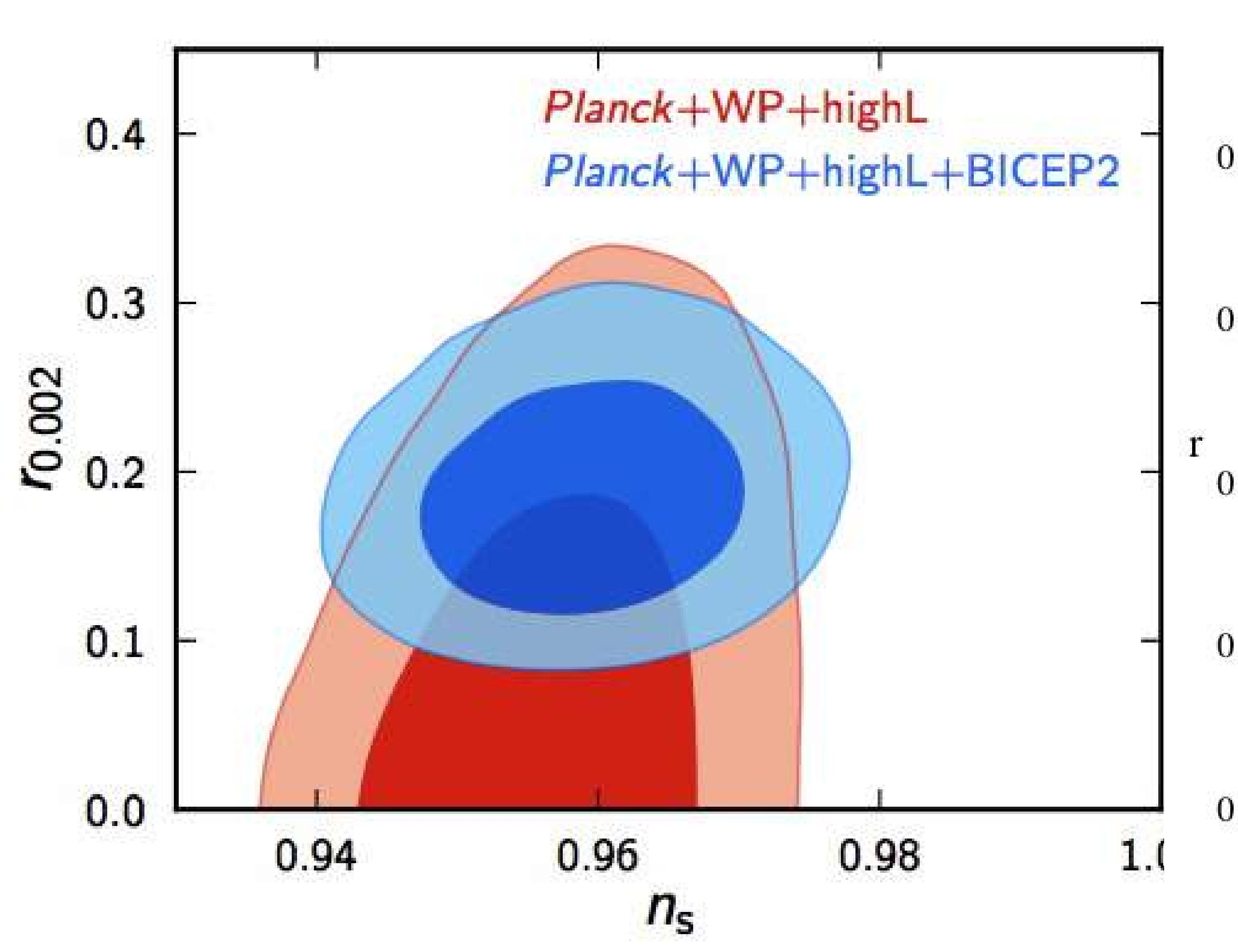
[BICEP2 coll. 1403.3985]



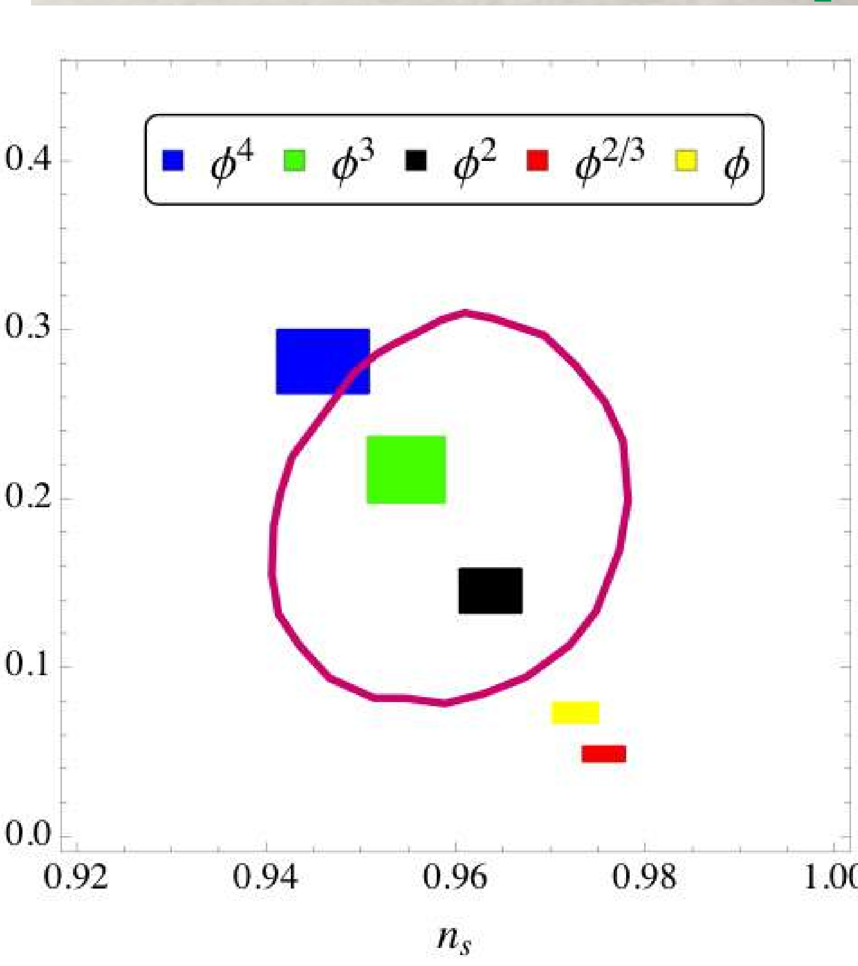
B-modes discovered at 5.2 sigma !?!

BICEP2: POLARIZATION

[BICEP2 coll. 1403.3985]

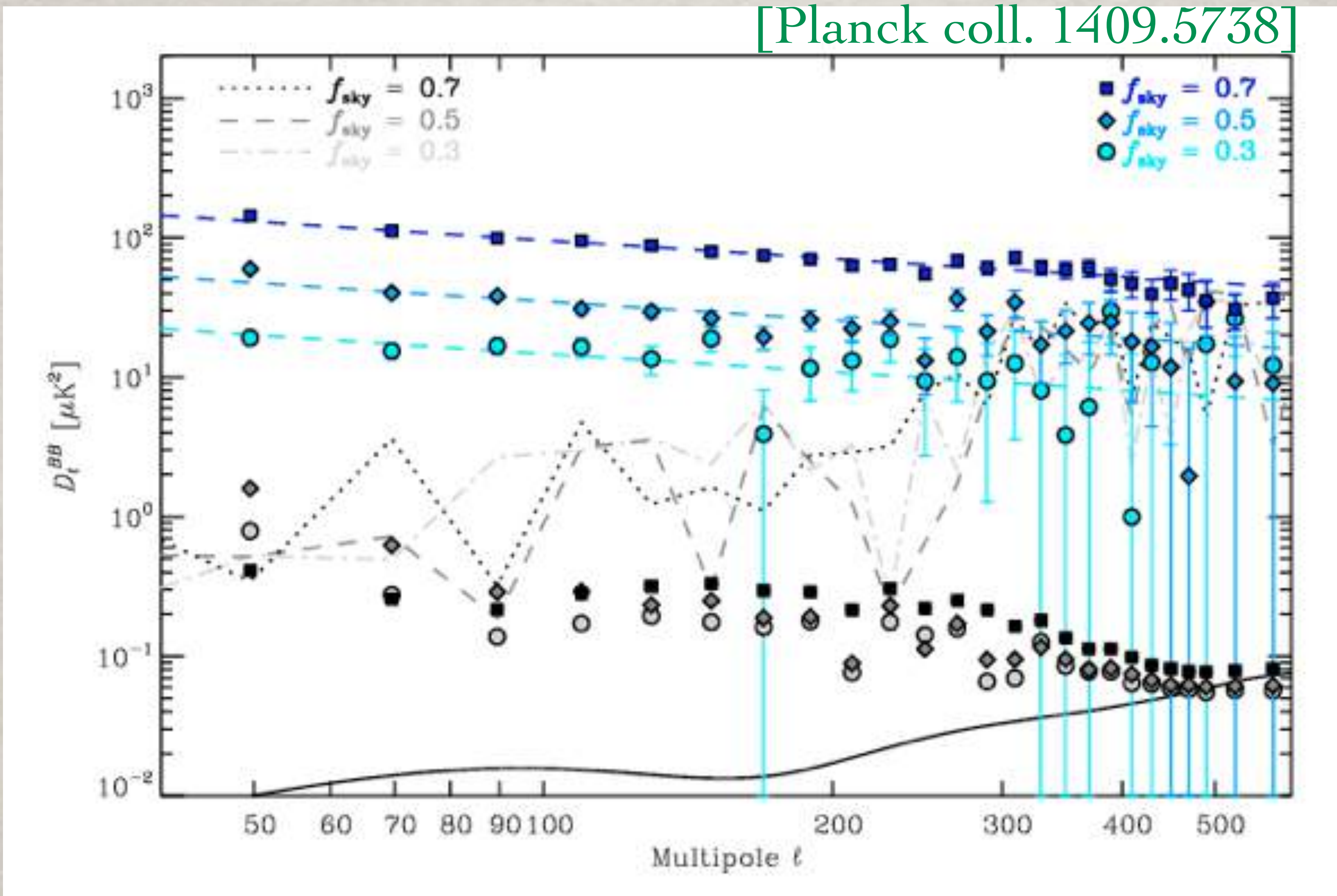


Calmet & Sanz 1403.5100]



Scale of inflation is high, polynomial chaotic inflation seems preferred, Higgs inflation disfavored !

BICEP2 vs Planck



But measurement of dust emission by the Planck satellite show that the level of dust larger than expected...

Outlook

Numerical codes

- CMB anisotropies: CAMB, CMBfast: http://camb.info
- Parameter estimations:
  CosmoMC @ http://cosmologist.info/cosmomc/
- BBN: Parthenope @ http://parthenope.na.infn.it
- Inflation and inflationary perturbations:
  MultiModeCode @ www.modecode.org
- WIMP Dark Matter & beyond:
  DarkSUSY @ www.darksusy.org
  MicrOMEGAs @ https://lapth.cnrs.fr/micromegas/