Constraining Fundamental Physics with Fundamental Cosmology (with three fundamental examples).

MFC2015 Santander

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Example I: Neutrino Perturbations

Cosmological Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1 MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

That, for a relativistic neutrinos translate in a extra radiation component of:

$$\Omega_\nu h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^\nu \Omega_\gamma h^2$$

Standard Model predicts:

$$N_{eff}^\nu = 3.046$$

Probing the Neutrino Number with CMB data

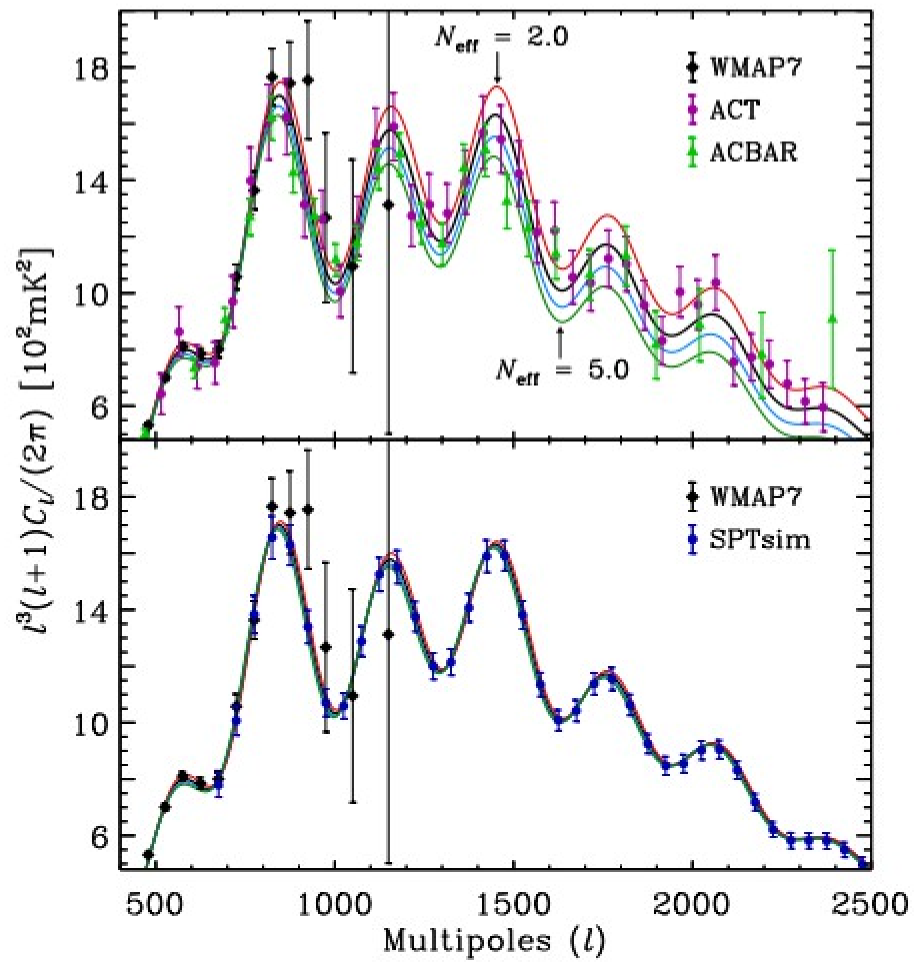
Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}.$$

and the damping scale at recombination:

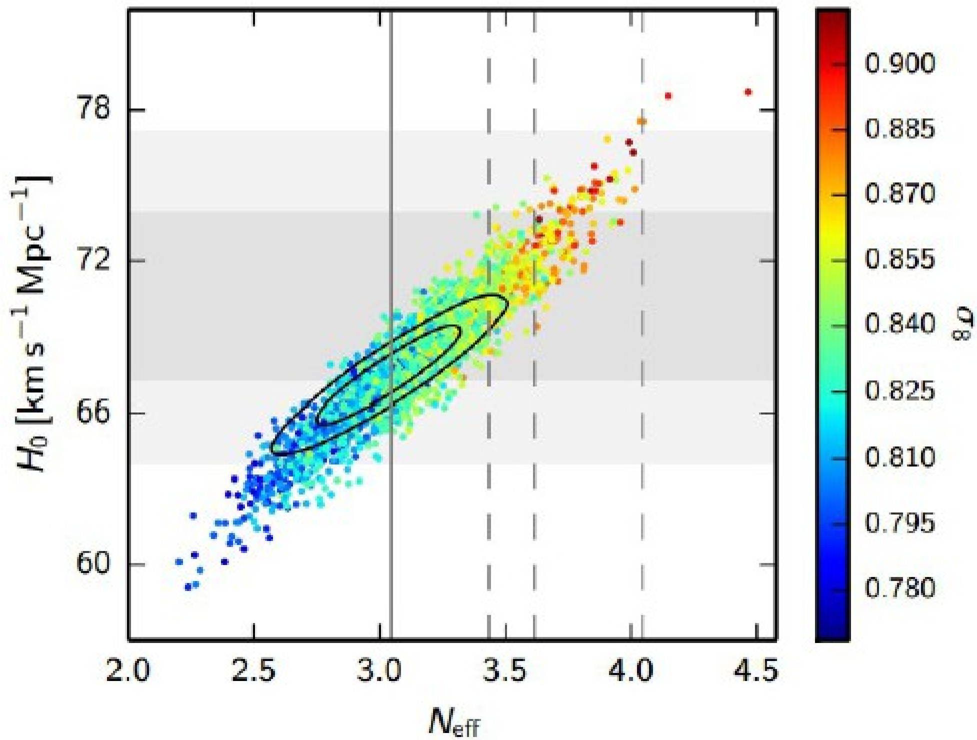
$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

$$\theta_s = \frac{r_s}{D_A} \qquad \theta_d = \frac{r_d}{D_A}$$



Moreover increases early ISW at Recombination (phase shift)

Hou et al, 2011



Planck 2015 is
in very good agreement
with standard
3 neutrinos
framework:
we can further
test neutrino
physics

$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP};$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO};$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP};$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP{+}BAO}.$$

Planck collaboration 2015

Planck “parameters” paper, arXiv:1502.01589, 2015

Further test: Neutrino Perturbations

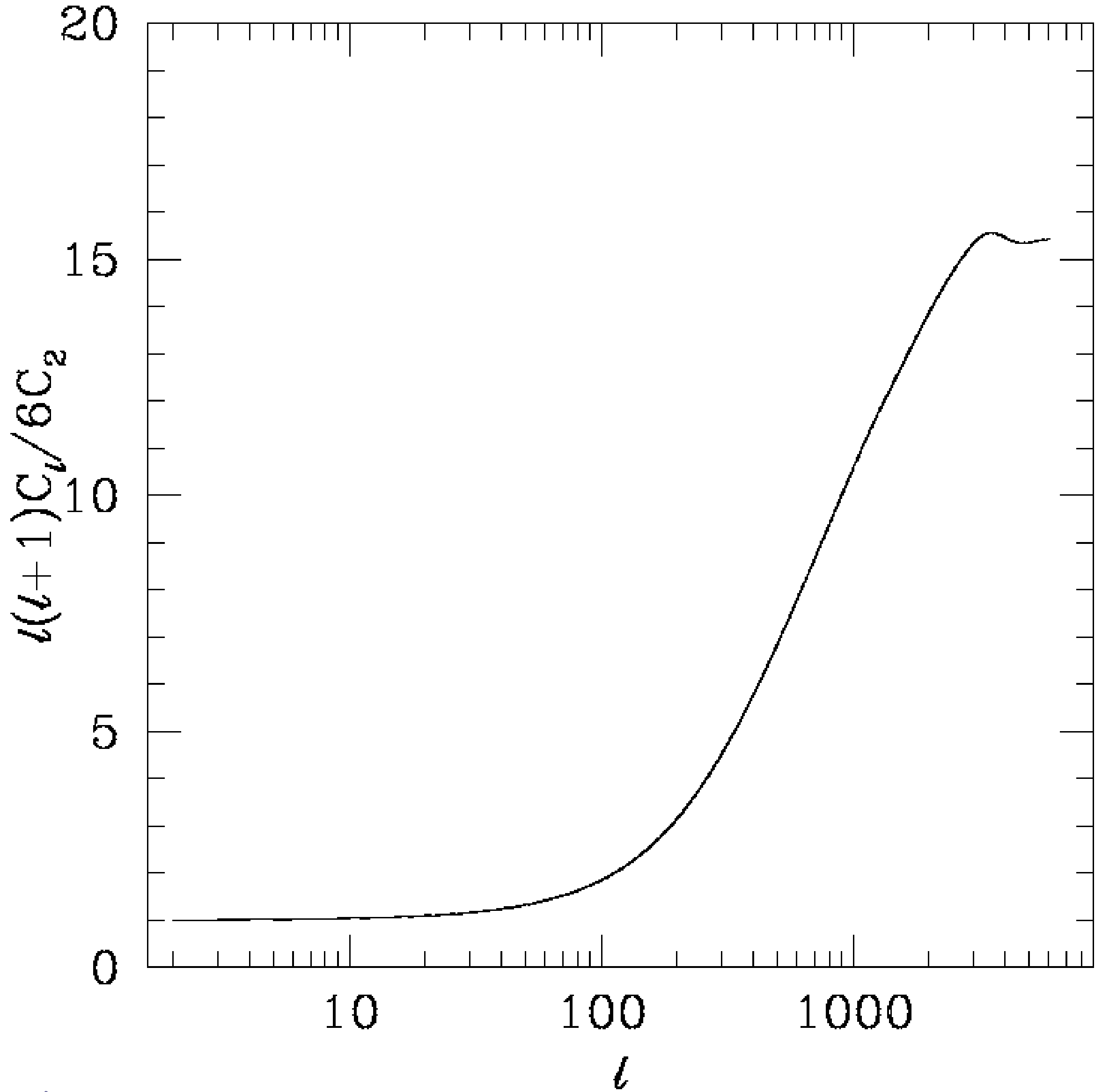
Massless neutrinos, like photons, have perturbations and anisotropies which follow a set of differential equations:

$$
\begin{aligned}
\dot{\delta}_\nu + k\left(q_\nu + \frac{2}{3k}\dot{h}\right) &= \frac{\dot{a}}{a}(1-3c_{\rm eff}^2)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) \\
\dot{q}_\nu + \frac{\dot{a}}{a}q_\nu + \frac{2}{3}k\pi_\nu &= c_{\rm eff}^2\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right), \\
\dot{\pi}_\nu + \frac{3}{5}kF_{\nu,3} &= 3c_{\rm vis}^2\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right), \\
\frac{2l+1}{k}\dot{F}_{\nu,l} - lF_{\nu,l-1} &= -(l+1)F_{\nu,l+1},\ l \geq 3,
\end{aligned}
$$

For the standard massless neutrino case:

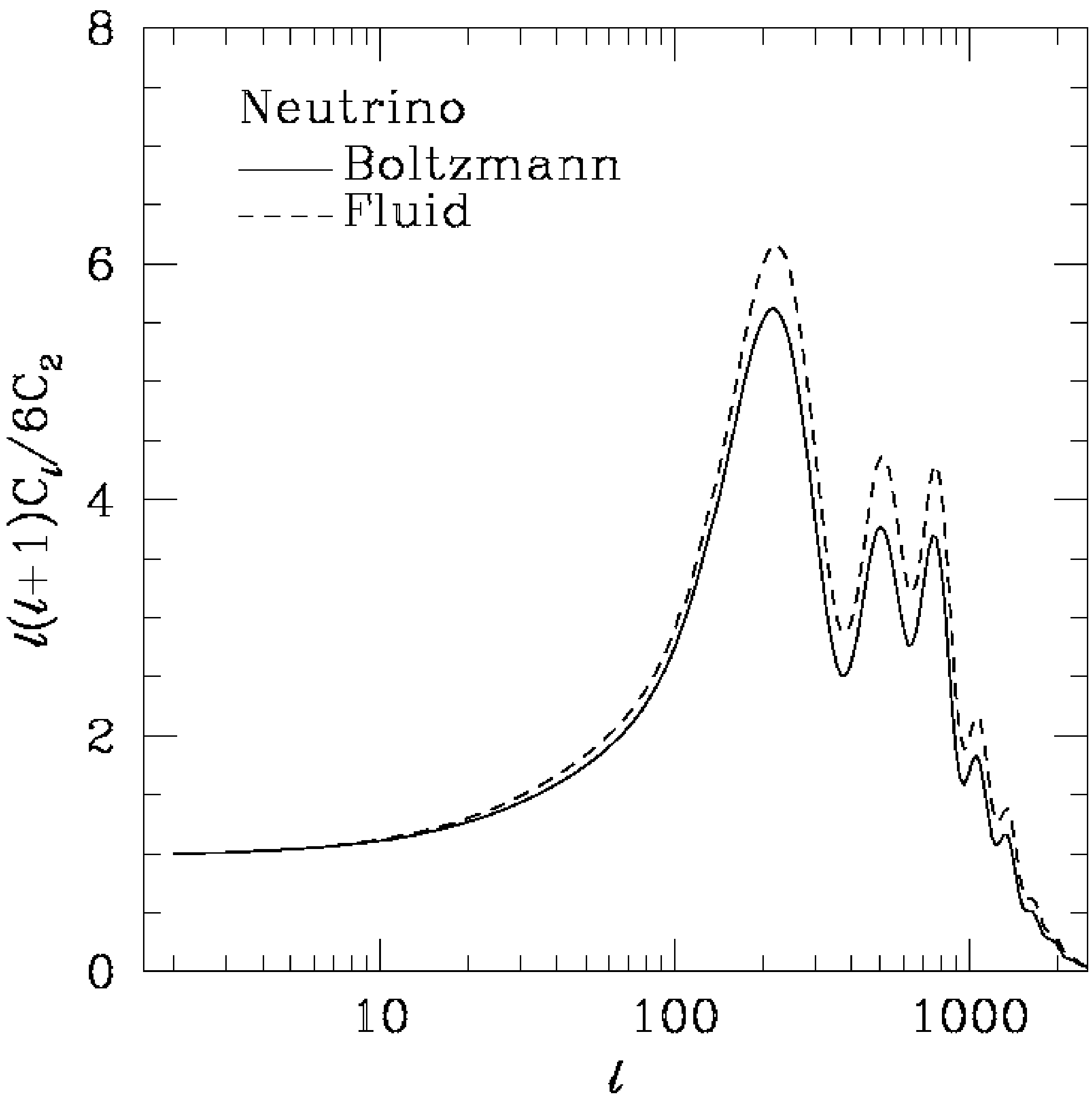
$$c_{eff}^2 = c_{vis}^2 = \frac{1}{3}$$

Can we see them ?



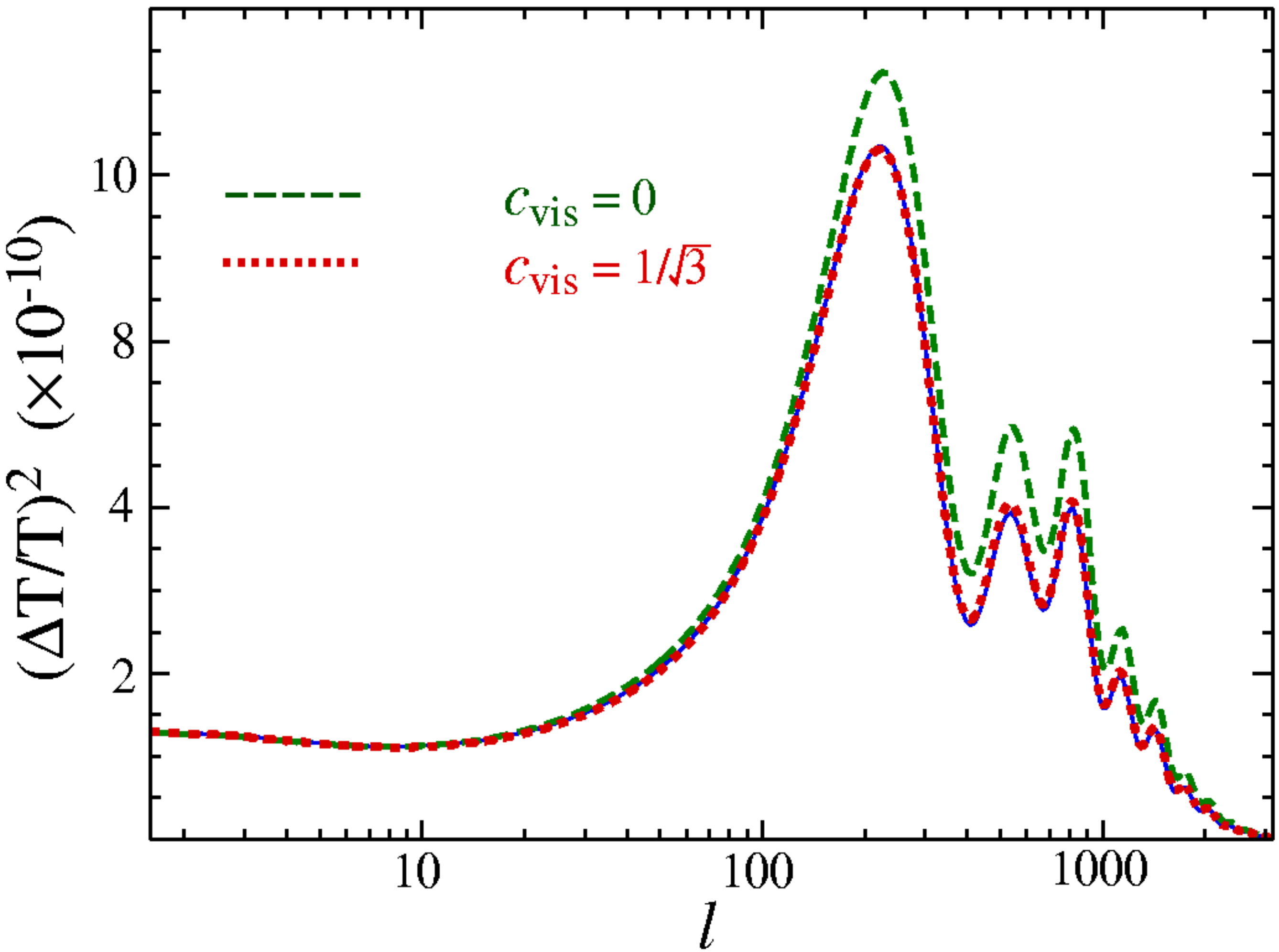
Hu et al., astro-ph/9505043

Not directly!
But we can see the effects on the CMB angular spectrum !
CMB photons see the NB anisotropies through gravity.

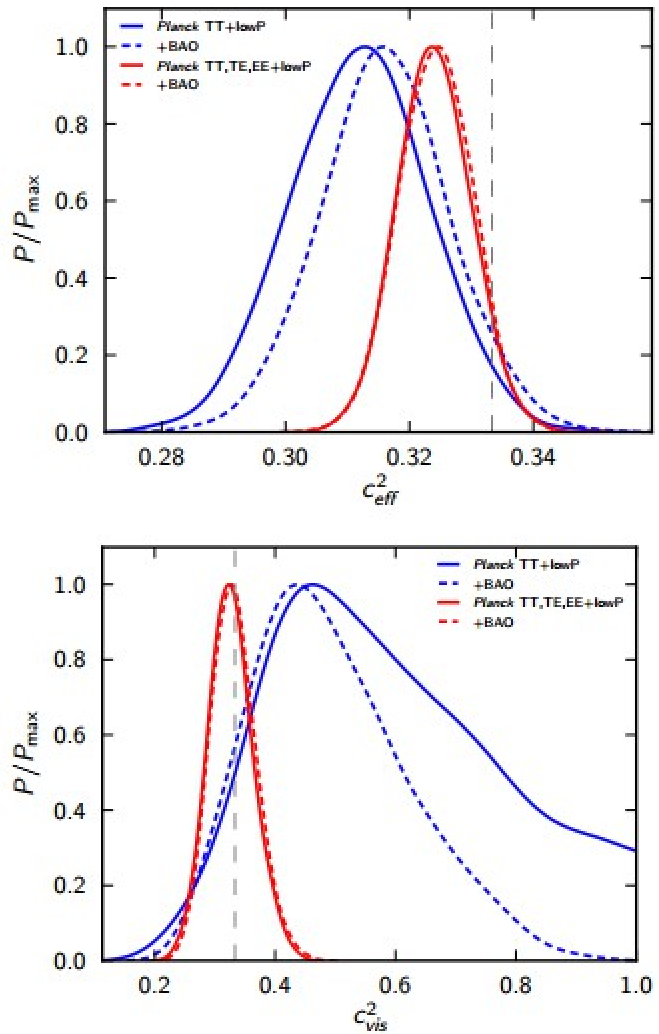


Hu et al., astro-ph/9505043

The Neutrino anisotropies can be parameterized through the "speed viscosity" c_{vis}, which controls the relationship between velocity/metric shear and anisotropic stress in the NB.



Hu, Eisenstein, Tegmark and White, 1999



$$\left.\begin{array}{l} c_{\rm eff}^2 = 0.312 \pm 0.011 \\ c_{\rm vis}^2 = 0.47^{+0.26}_{-0.12} \end{array}\right\} \textit{Planck}\ \text{TT+lowP},$$

$$\left.\begin{array}{l} c_{\rm eff}^2 = 0.316 \pm 0.010 \\ c_{\rm vis}^2 = 0.44^{+0.15}_{-0.10} \end{array}\right\} \textit{Planck}\ \text{TT+lowP+BAO},$$

$$\left.\begin{array}{l} c_{\rm eff}^2 = 0.3240 \pm 0.0060 \\ c_{\rm vis}^2 = 0.327 \pm 0.037 \end{array}\right\} \textit{Planck}\ \text{TT,TE,EE+lowP},$$

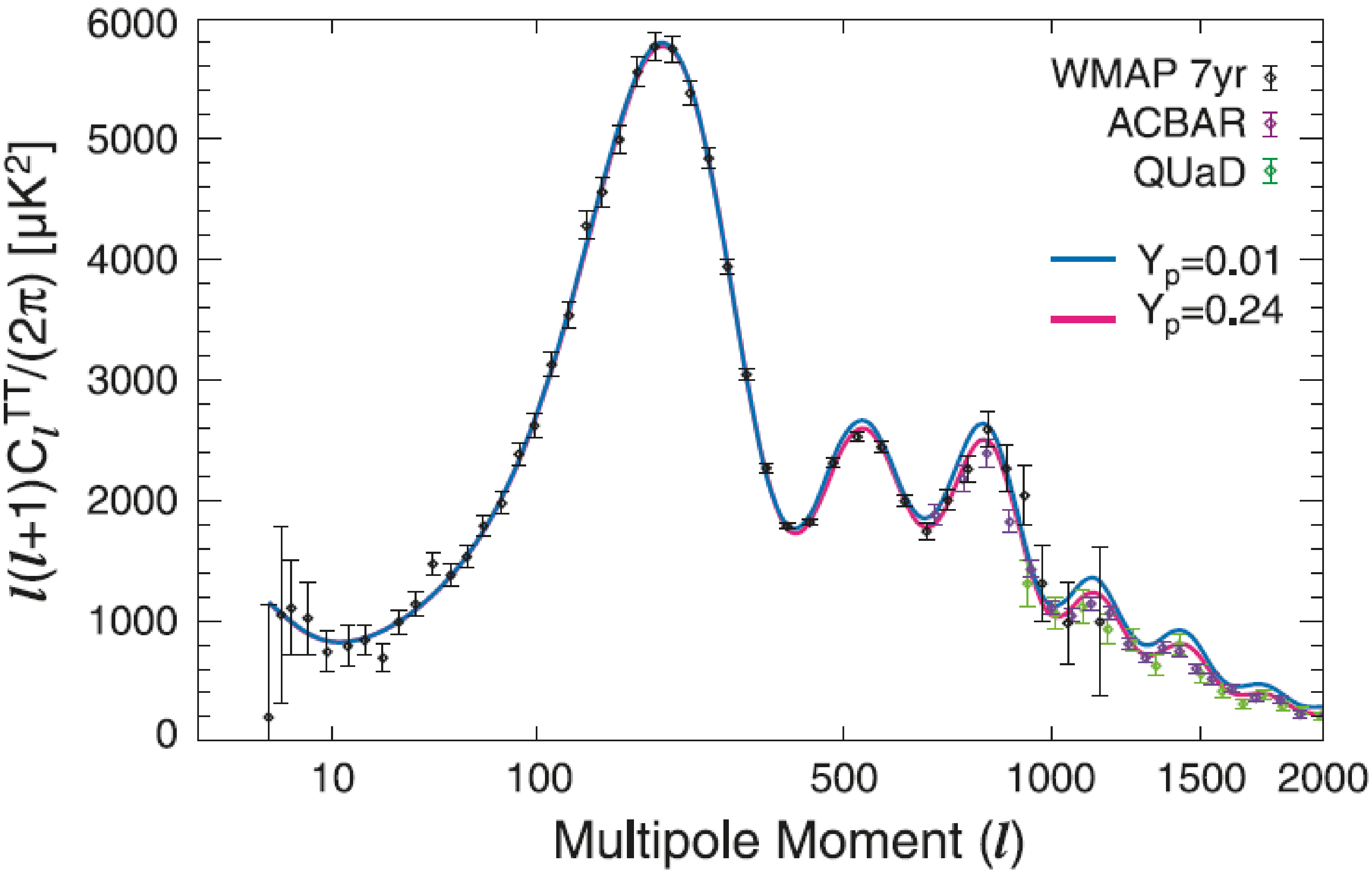
Results consistent with standard model.

Polarization data strongly improves the constraints (by a factor 5 !)

Planck “parameters” paper, arXiv:1502.01589, 2015

Example II: BBN and nuclear rates

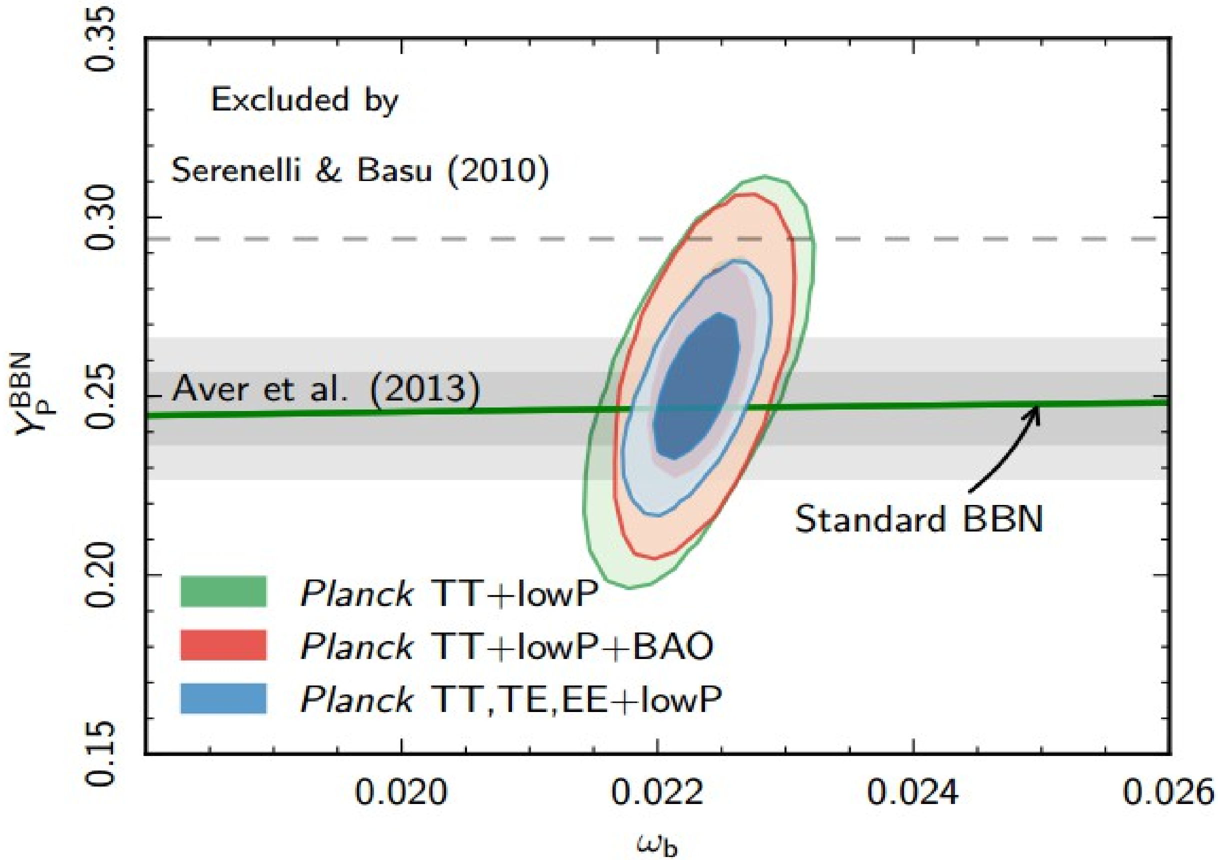
Small scale CMB can probe Helium abundance at recombination.



See e.g.,

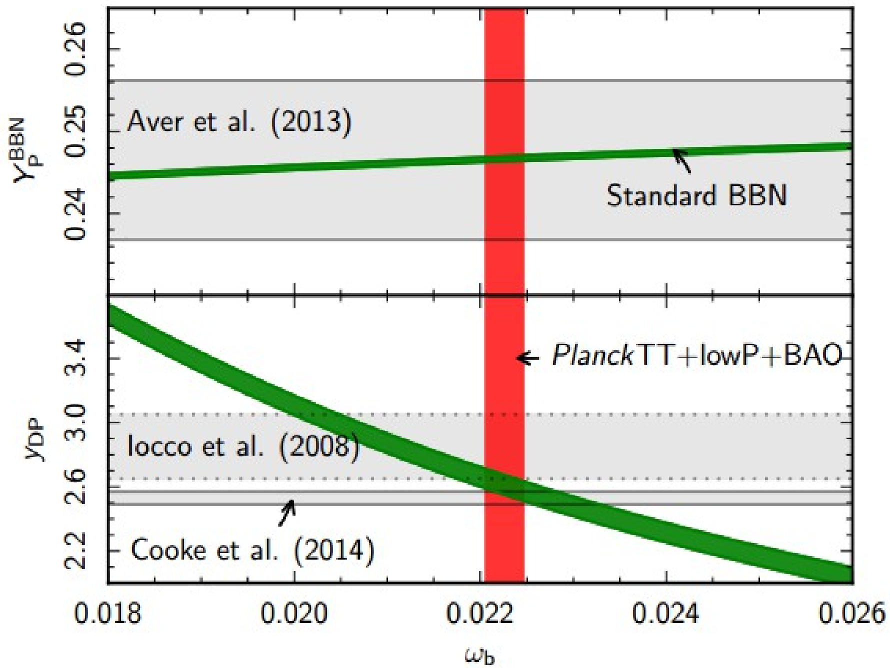
K. Ichikawa et al., Phys.Rev.D78:043509,2008

R. Trotta, S. H. Hansen, Phys.Rev. D69 (2004) 023509



$$
Y_{\rm P}^{\rm BBN} = \begin{cases} 0.253^{+0.041}_{-0.042} & \textit{Planck}\ \text{TT+lowP}\,; \\ 0.255^{+0.036}_{-0.038} & \textit{Planck}\ \text{TT+lowP+BAO}\,; \\ 0.251^{+0.026}_{-0.027} & \textit{Planck}\ \text{TT,TE,EE+lowP}\,; \\ 0.253^{+0.025}_{-0.026} & \textit{Planck}\ \text{TT,TE,EE+lowP+BAO}\,. \end{cases}
$$

Planck "parameters" paper, arXiv:1502.01589, 2015



Abundances can also be derived indirectly by combining CMB observations of the baryon density with standard BBN codes.

Planck determination of the baryon density is now so precise that
uncertainties in BBN rates
(i.e. neutron lifetime for Helium)
have a major impact !

$$Y_P^{BBN} = \begin{cases} 0.24665^{+(0.00020)\ 0.00063}_{-(0.00019)\ 0.00063} & \textit{Planck}\ \text{TT+lowP}, \\ 0.24667^{+(0.00018)\ 0.00063}_{-(0.00018)\ 0.00063} & \textit{Planck}\ \text{TT+lowP+BAO}, \\ 0.24667^{+(0.00014)\ 0.00062}_{-(0.00014)\ 0.00062} & \textit{Planck}\ \text{TT,TE,EE+lowP}, \\ 0.24668^{+(0.00013)\ 0.00061}_{-(0.00013)\ 0.00061} & \textit{Planck}\ \text{TT,TE,EE+lowP+BAO}, \end{cases}$$

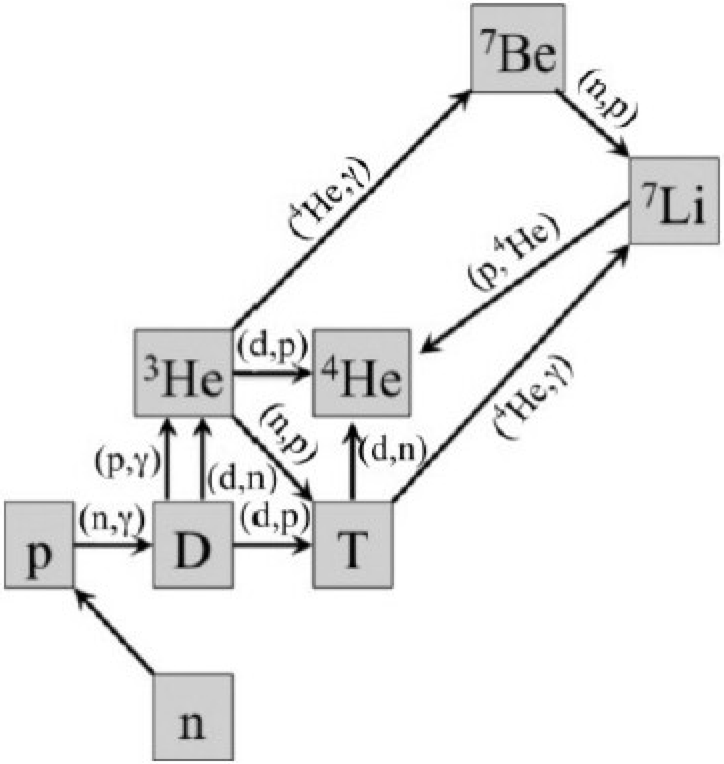
$$y_{DP} = \begin{cases} 2.620^{+(0.083)\ 0.15}_{-(0.085)\ 0.15} & \textit{Planck}\ \text{TT+lowP}, \\ 2.612^{+(0.075)\ 0.14}_{-(0.074)\ 0.14} & \textit{Planck}\ \text{TT+lowP+BAO}, \\ 2.614^{+(0.057)\ 0.13}_{-(0.060)\ 0.13} & \textit{Planck}\ \text{TT,TE,EE+lowP}, \\ 2.606^{+(0.051)\ 0.13}_{-(0.054)\ 0.13} & \textit{Planck}\ \text{TT,TE,EE+lowP+BAO}. \end{cases}$$

$d(p;\gamma)^3He$

The main uncertainty for standard BBN calculations of ^{2}H comes from the rate R_2 of the radiative capture reaction $d(p;\gamma)^3He$, measured from nuclear experimental data.

Reaction	Rate Symbol	$\sigma_{^2H/H} \cdot 10^5$
$p(n,\gamma)^2H$	R_1	± 0.002
$d(p,\gamma)^3He$	R_2	± 0.062
$d(d,n)^3He$	R_3	± 0.020
$d(d,p)^3H$	R_4	± 0.013

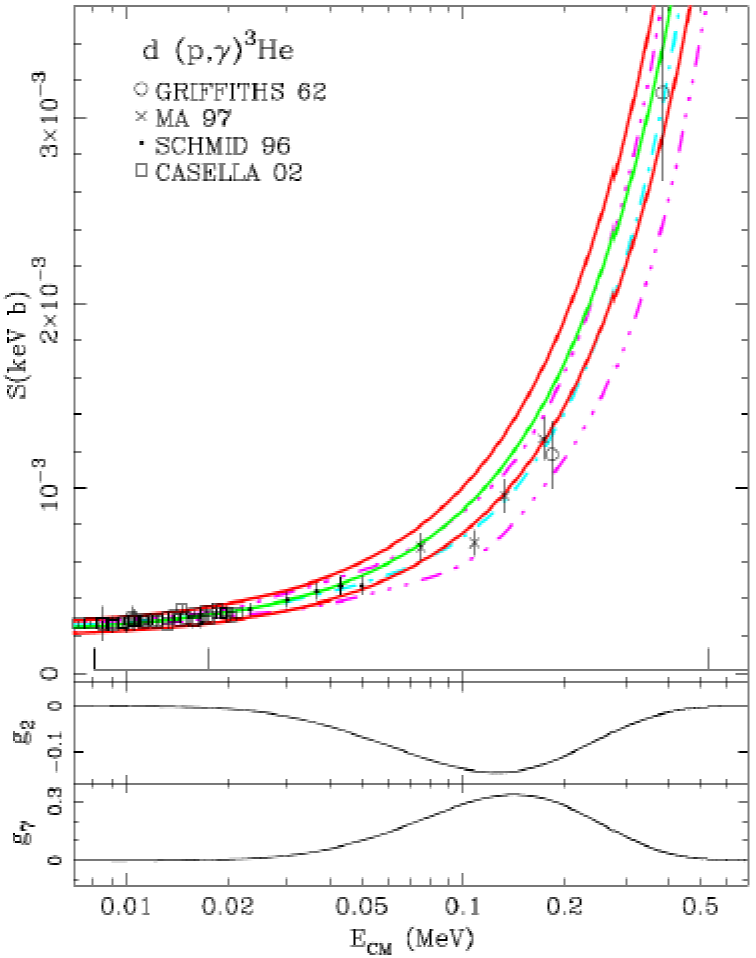
TABLE I: List of the leading reactions and corresponding rate symbols controlling the deuterium abundance after BBN. The last column shows the error on the ratio ^{2}H/H coming from experimental (or theoretical) uncertainties in the cross section of each reaction, for a fixed baryon density $\Omega_b h^2 = 0.02207$.



$d(p;\gamma)^3He$

The main uncertainty for standard BBN calculations of ^2H comes from the rate R_2 of the radiative capture reaction $d(p;\gamma)^3He$, measured from nuclear experimental data.

A reliable *ab initio* nuclear theory calculation of this cross section is systematically larger than the best-fit value derived from the experimental data in the BBN energy range *[30-300 keV]*. Further data on R_2 in the relevant energy range might be expected from experiments such as LUNA.



Assuming the standard cosmological model, following E. Di Valentino et al., Phys. Rev. D90 (2014), 023543, we can combine

- the Planck data
- the direct deuterium abundance measurements in metal-poor damped Lyman-alpha systems

and have independent information on the cross section of the radiative capture reaction $d(p;\gamma)^3He$ converting deuterium into helium.

d(p;γ)^3*He*

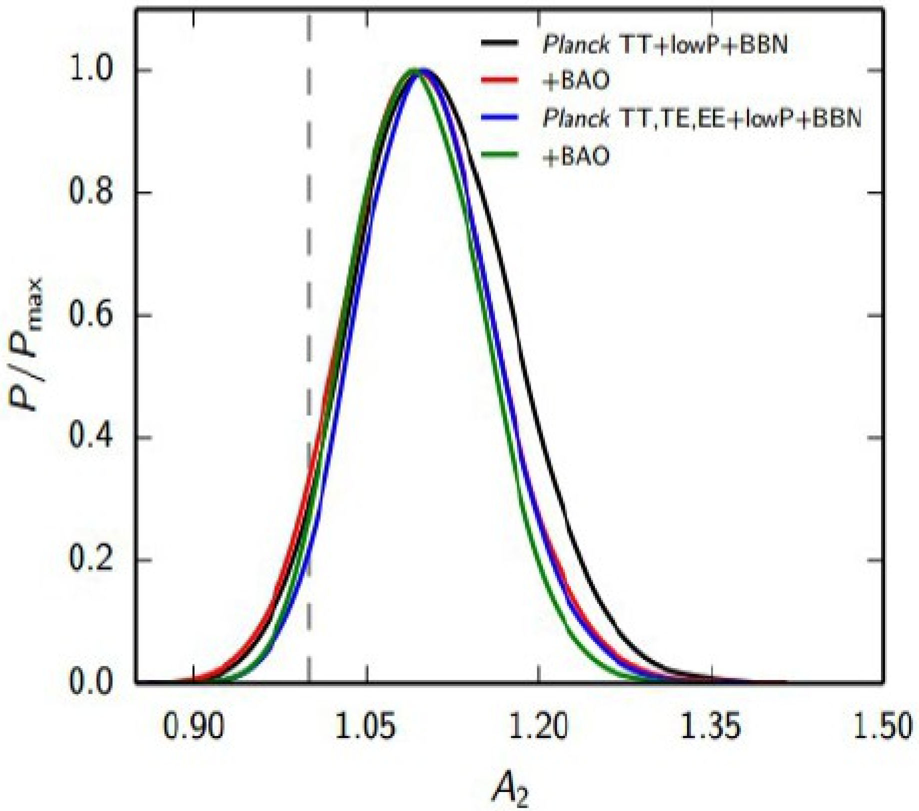
We analyzed the Planck data considering the rate of the radiative capture reaction *d(p;γ)*^{3}*He* as a free input parameter.

Actually the present CMB data (combined with primordial D measurements) are powerful enough to provide information on nuclear rates.

<u>We find that our results give independent support to the theoretical calculation: the rate of the radiative capture reaction *d(p;γ)*^{3}*He* is larger than measured from the nuclear experiments.</u>

We parametrize the generic $R_2(T)$ in terms of an overall rescaling factor A_2

$$R_2(T) = A_2\, R_2^{ex}(T)$$



$$
\begin{aligned}
A_2 &= 1.106 \pm 0.071 \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,, \\
A_2 &= 1.098 \pm 0.067 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,, \\
A_2 &= 1.110 \pm 0.062 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP}\,, \\
A_2 &= 1.109 \pm 0.058 \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP{+}BAO}\,.
\end{aligned}
$$

Planck collaboration 2015

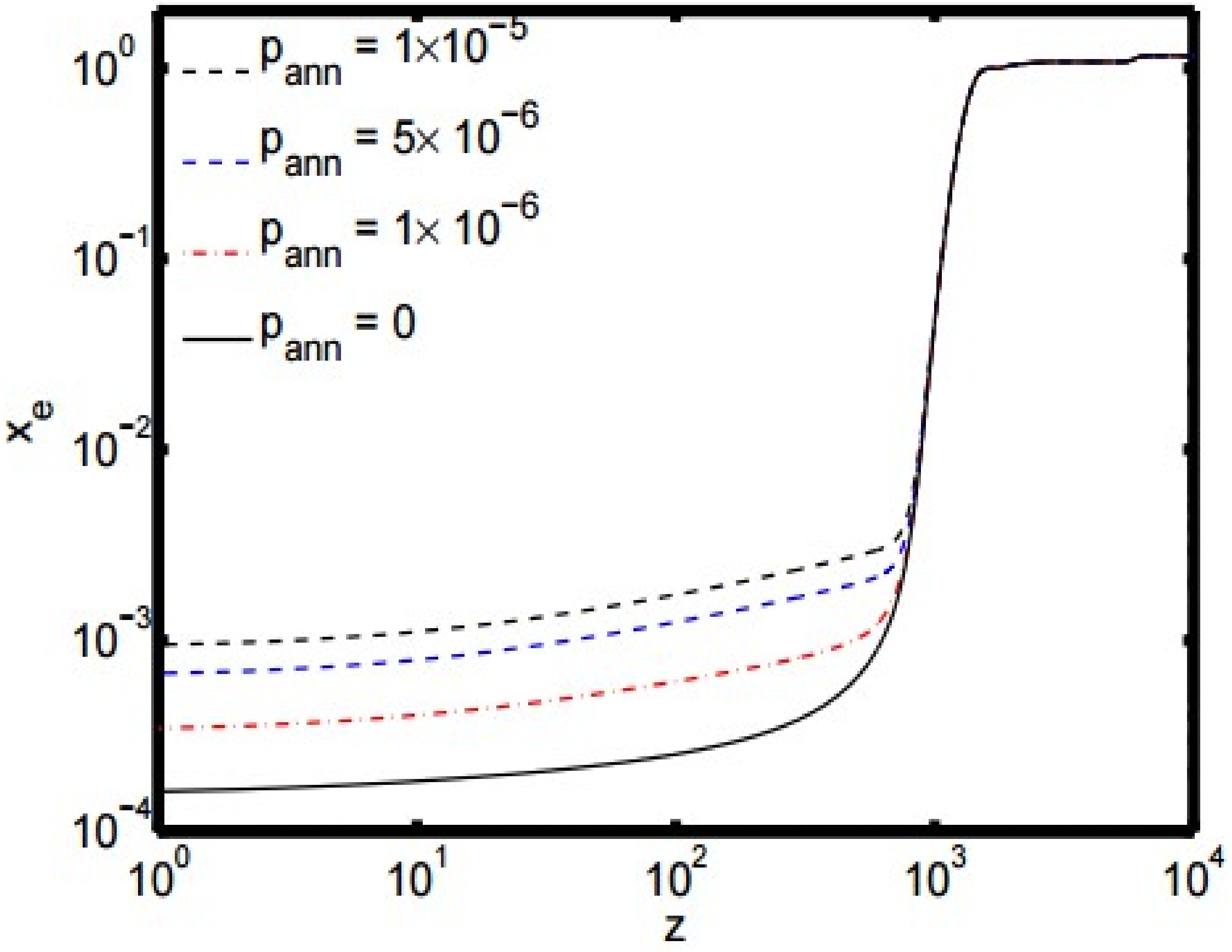
Example III: Dark Matter Annihilation

The rate of energy release per unit volume from annihilating Dark Matter is given By (see Chen and Kamionkowksy 2004):

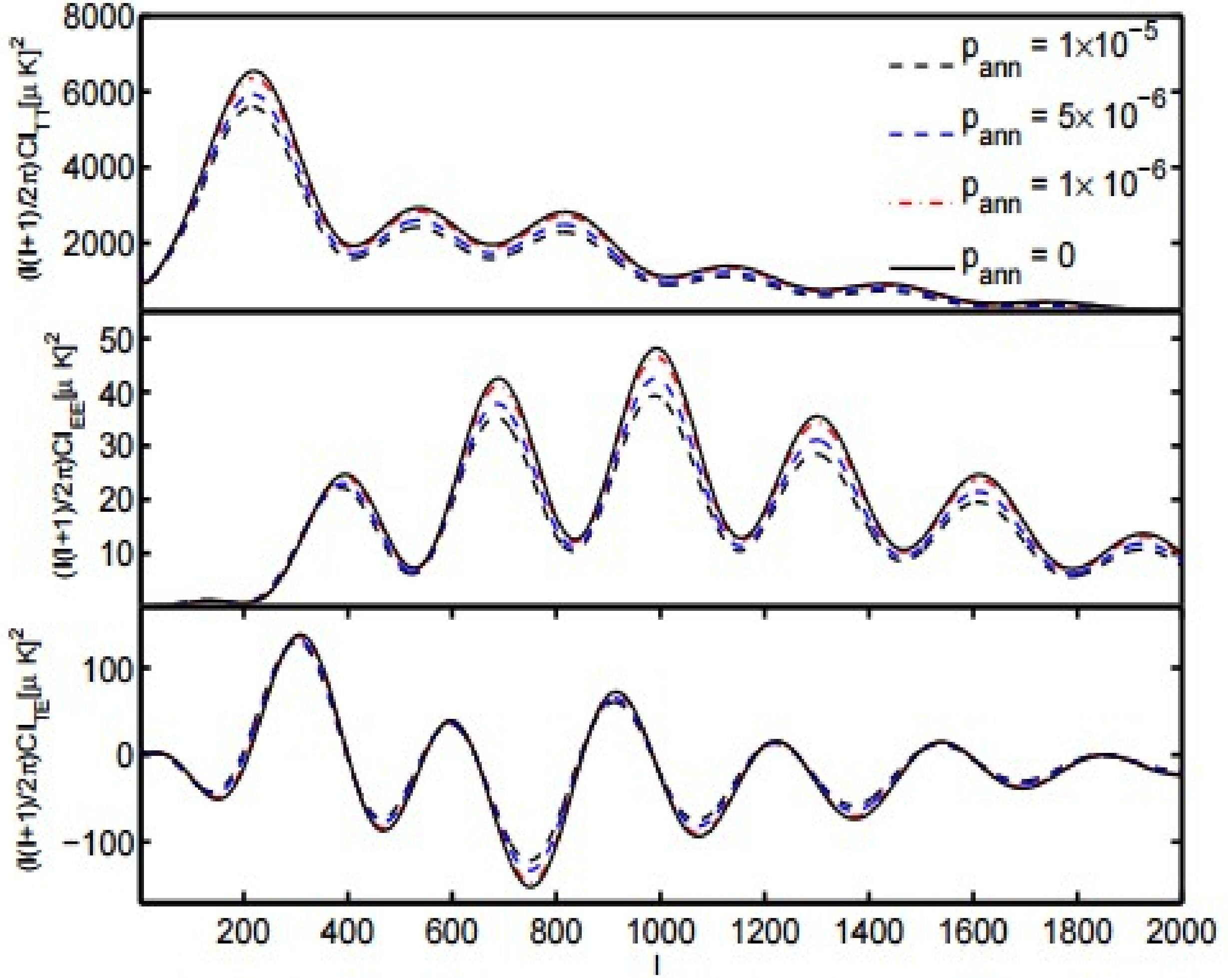
$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 f(z) \frac{<\sigma v>}{m_\chi}$$

Where ρ_c is the critical density of the Universe today, Ω_{DM} is the density of cold dark matter today, $<\sigma v>$ is the thermally averaged cross section of self-annihilating dark matter, m_χ is the dark matter mass, f(z) is the fraction of the overall annihilation energy absorbed by the medium (ionization, lyman-alpha, heating).
We assume f(z) constant with redshift with $f(z)=f_{eff}$.
The whole DM annihilation process can be parametrized by a single parameter:

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

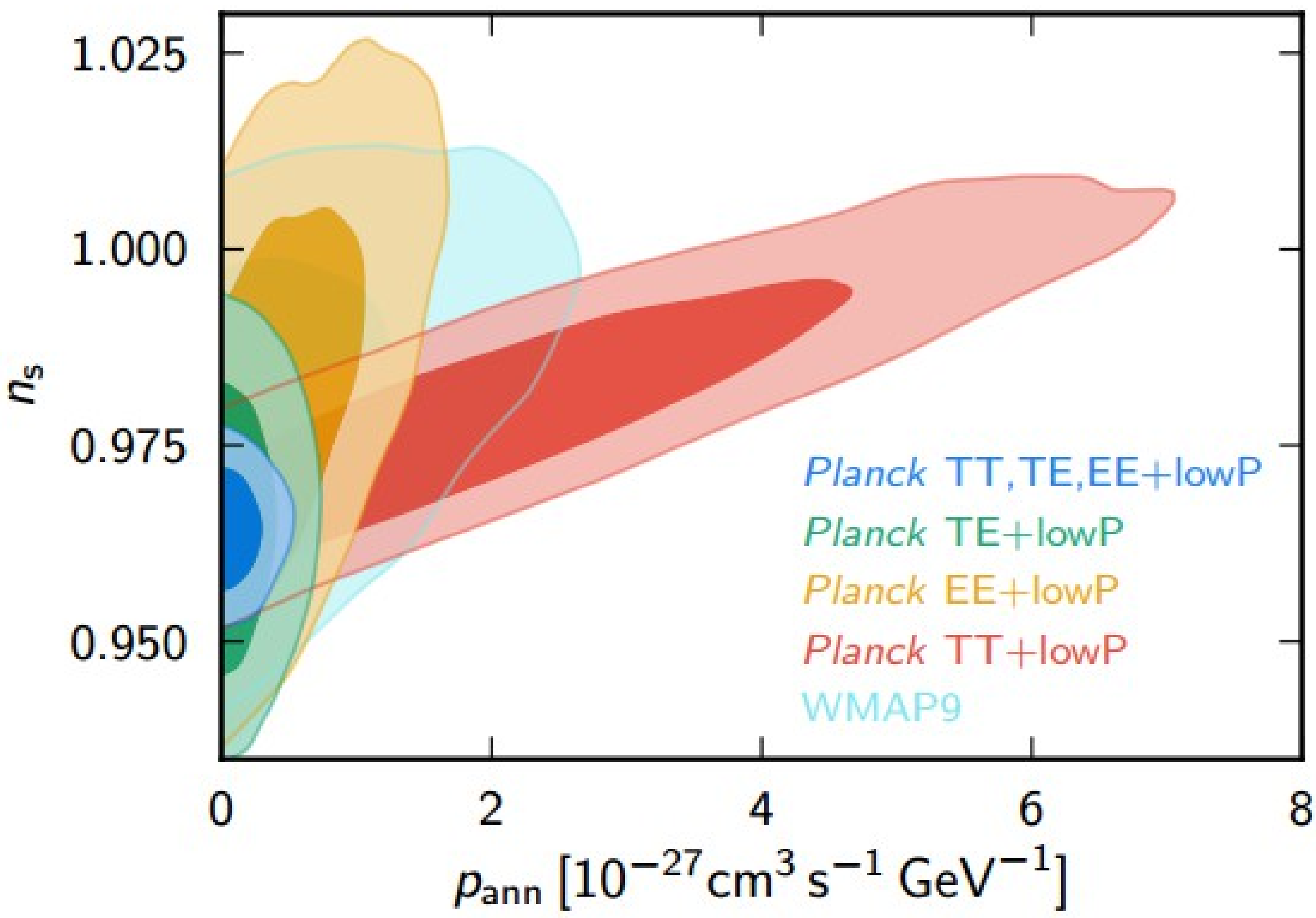


DM annihilation heats, ionizes and excites the primordial plasma leading to a delayed recombination...

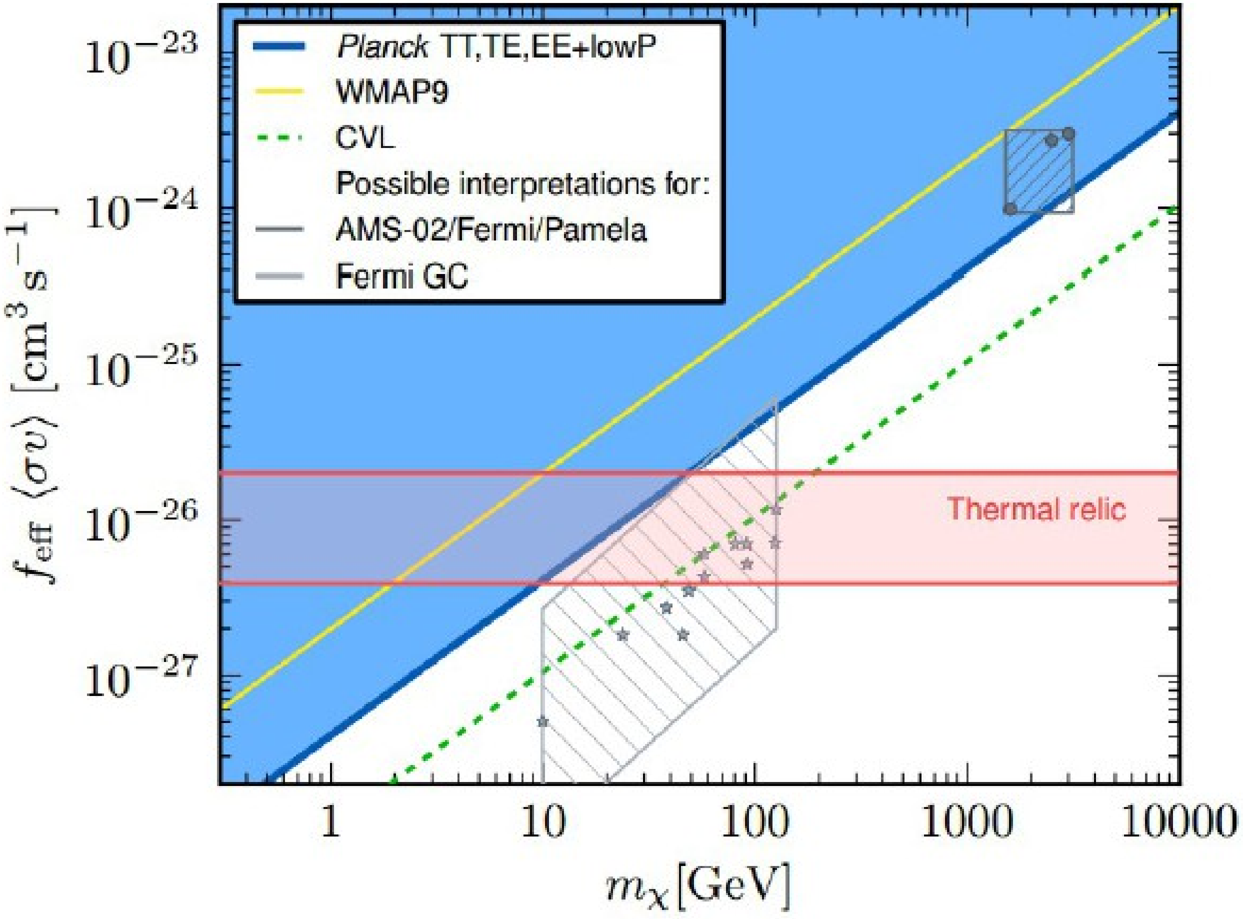


...and to a change in the positions and amplitudes of the CMB peaks.

See e.g. Bean et al, 2007, Galli et al 2009, Galli et al 2011.



Planck “parameters” paper, arXiv:1502.01589, 2015



Most of parameter space preferred by AMS-02/ Pamela/Fermi ruled out at 95%, under the assumption <σv>(z=100)=<σv>(z=0) (s-wave annihilation)

In case of Sommerfield enhancement <σv>~1/v so constraints can be even stronger for today !

For p-wave annihilation <σv>~v^2 and constraints “today” are weaker.

Planck “parameters” paper, arXiv:1502.01589, 2015

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.

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