Probing the neutrino sector with the CMB

Erminia Calabrese
Cardiff University

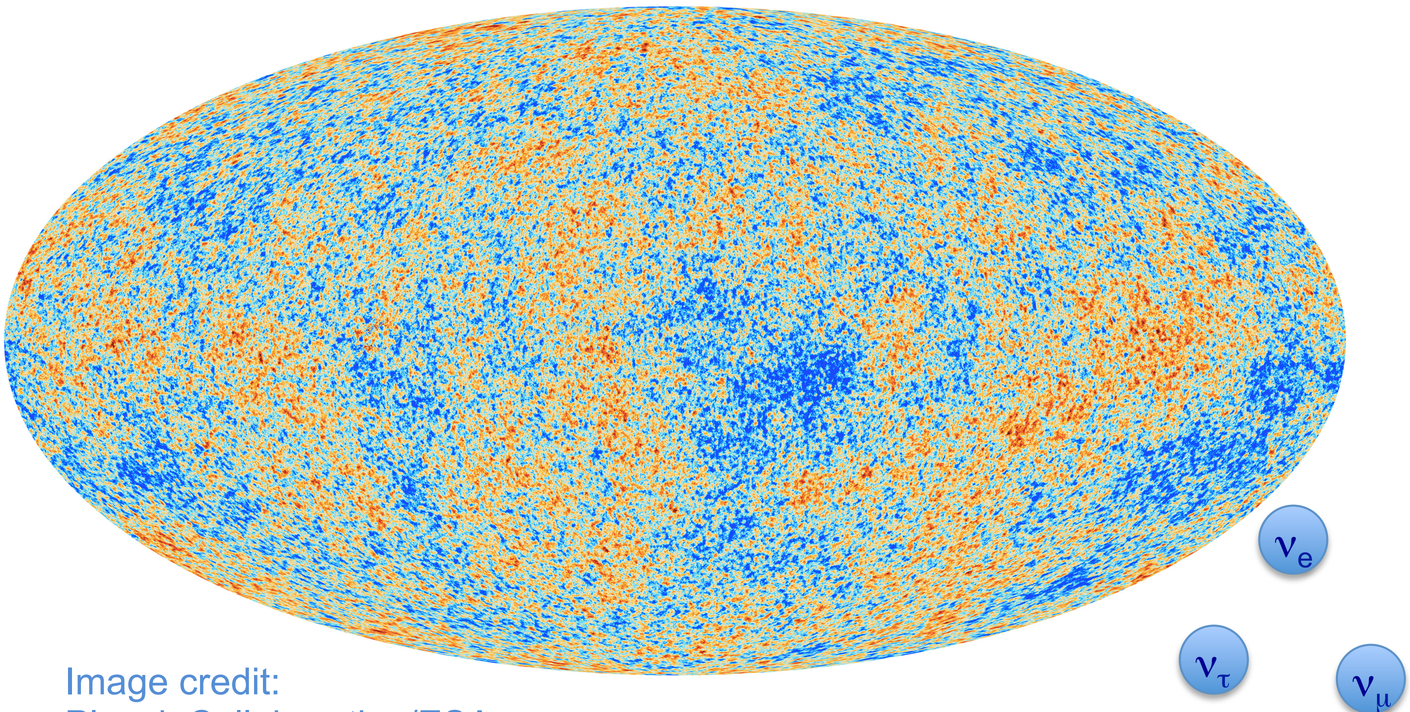
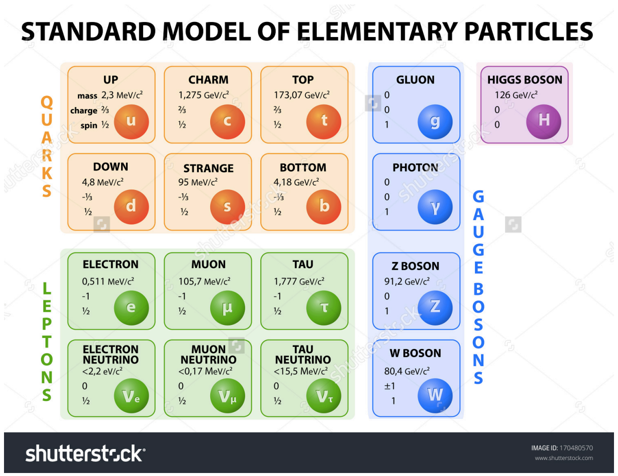


Image credit:
Planck Collaboration/ESA

Towards the coordination of the European CMB programme – Florence, September 6th 2017

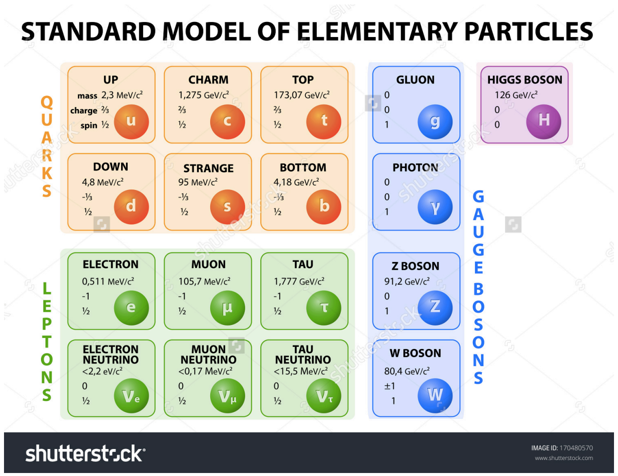
The cosmic neutrino background



- Abundant, very light, weakly interacting particles – hard to detect
- Three oscillating flavors
- Generated via β-decays, nuclear reactions
- Searches in labs or in cosmo

Number (active, sterile), mass, speed, chirality…

The cosmic neutrino background



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Low-energy neutrinos relic of the Big Bang

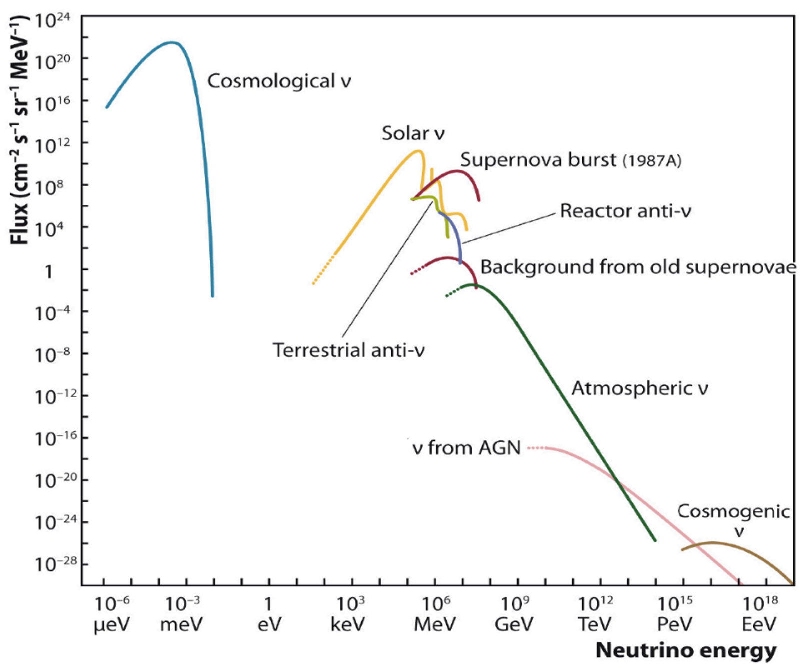
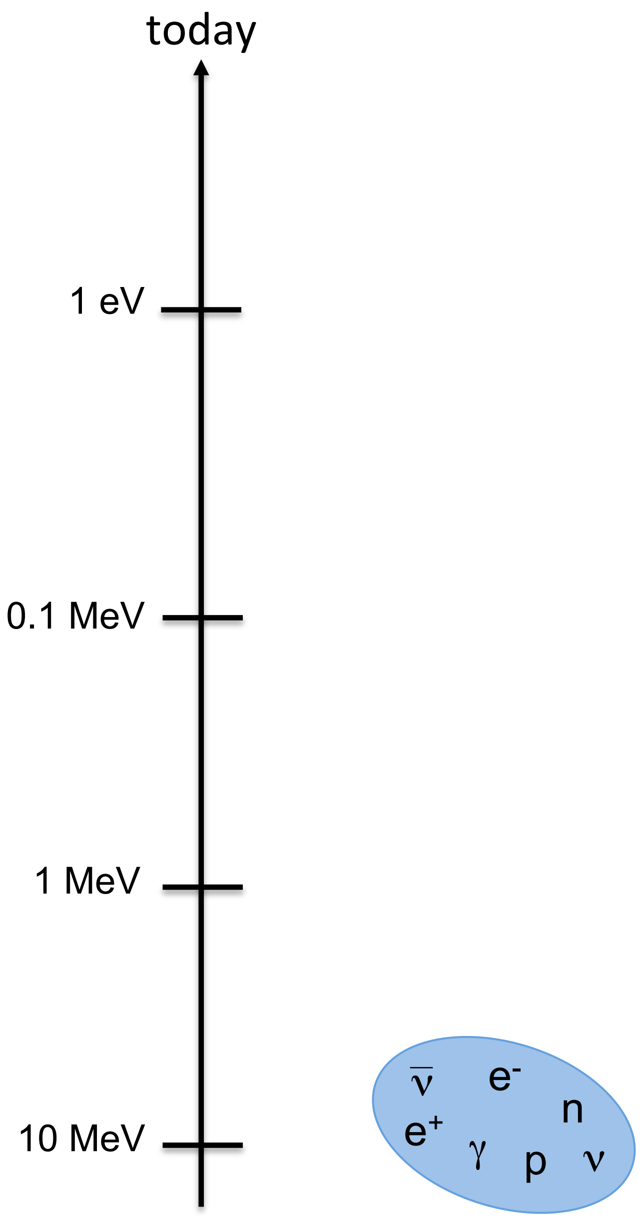


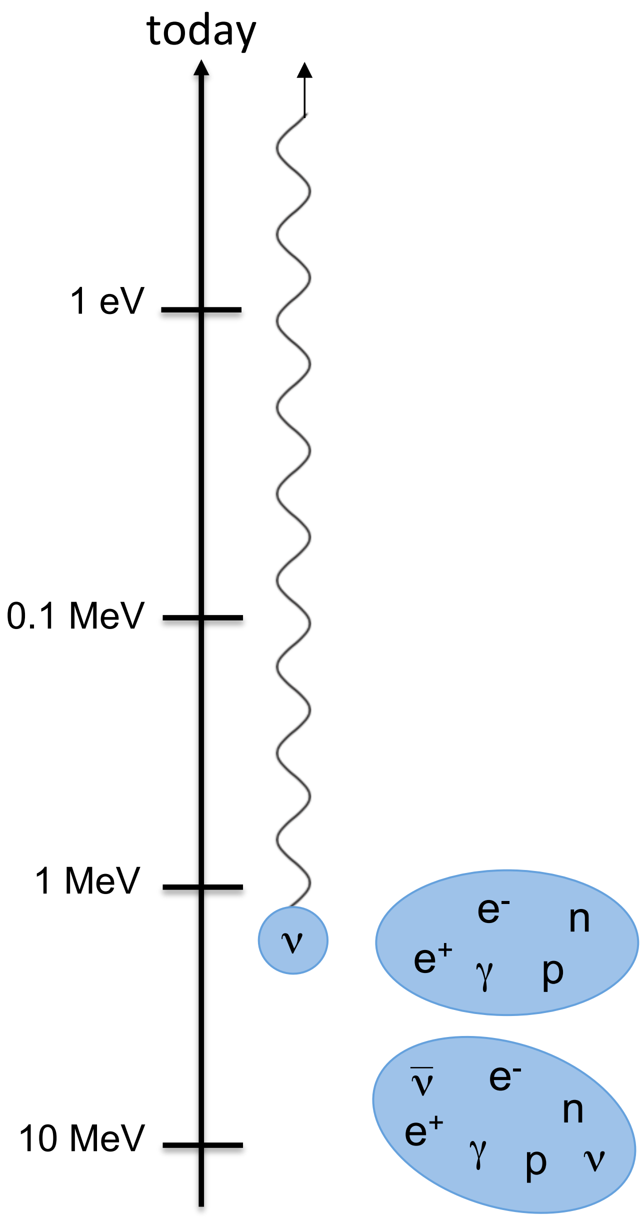
Image credit: IceCube Collaboration

The cosmic neutrino background



Plasma in thermal equilibrium, $T_\nu = T_e = T_\gamma$

The cosmic neutrino background



Equilibrium is maintained until $\Gamma = n\sigma v \approx H$
Neutrinos decouple with $T_\nu = T_\gamma$

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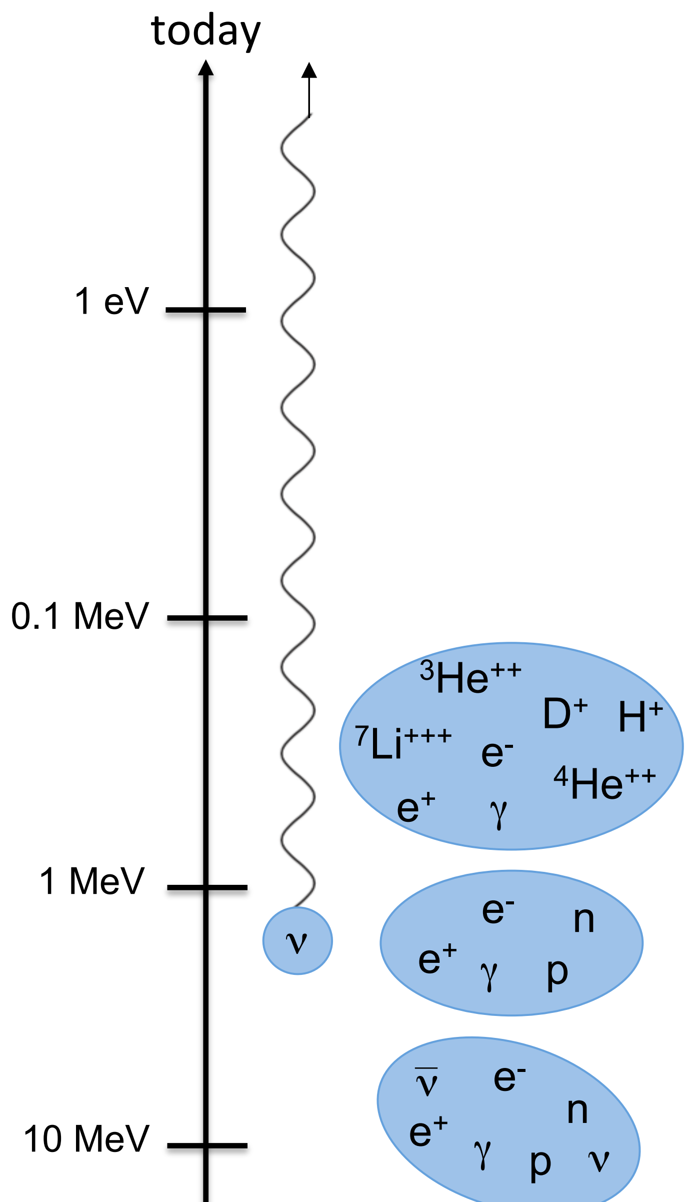

Light elements form during Big Bang Nucleosynthesis
e^+e^- heat the photons, $T_\gamma/T_\nu = (11/4)^{1/3}$

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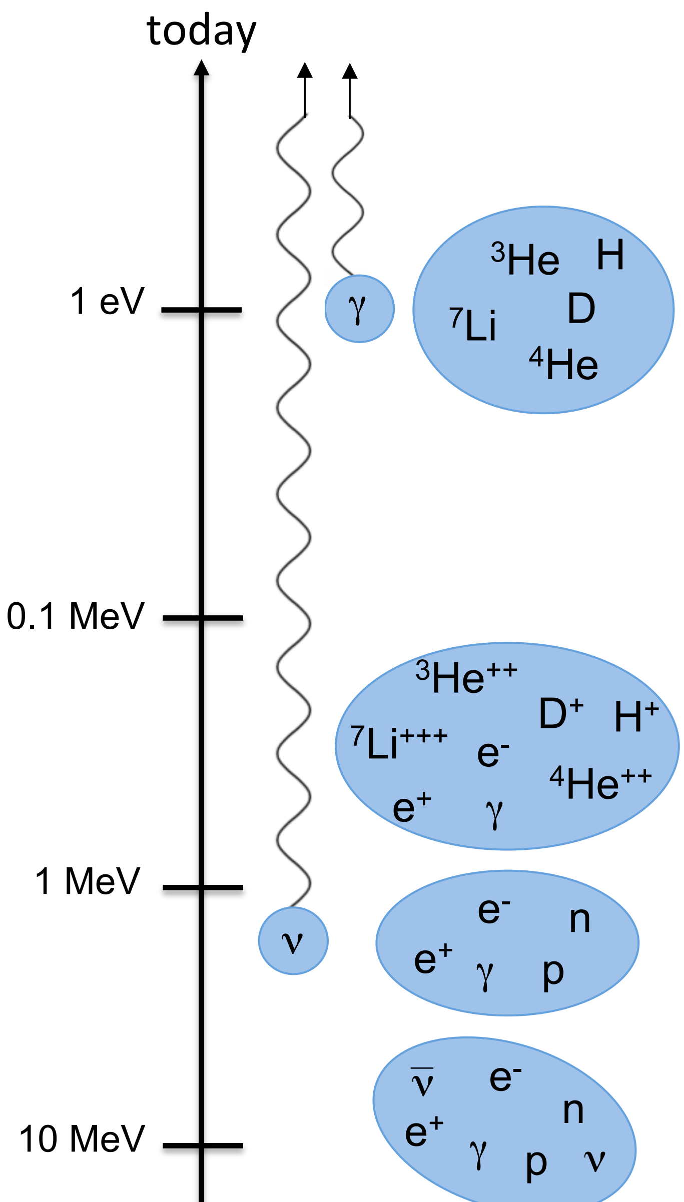

Ions recombine and CMB photons decouple

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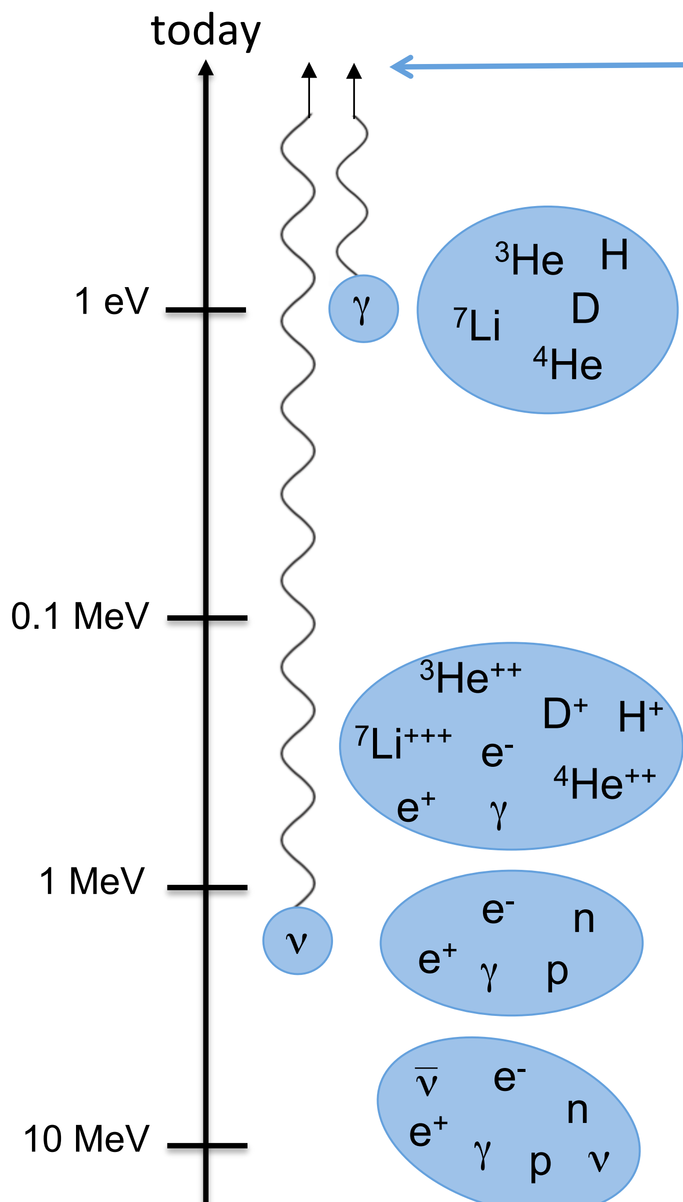
The cosmic neutrino background

Cosmic Microwave Background at 2.7K
and Cosmic Neutrino Background at 1.95K



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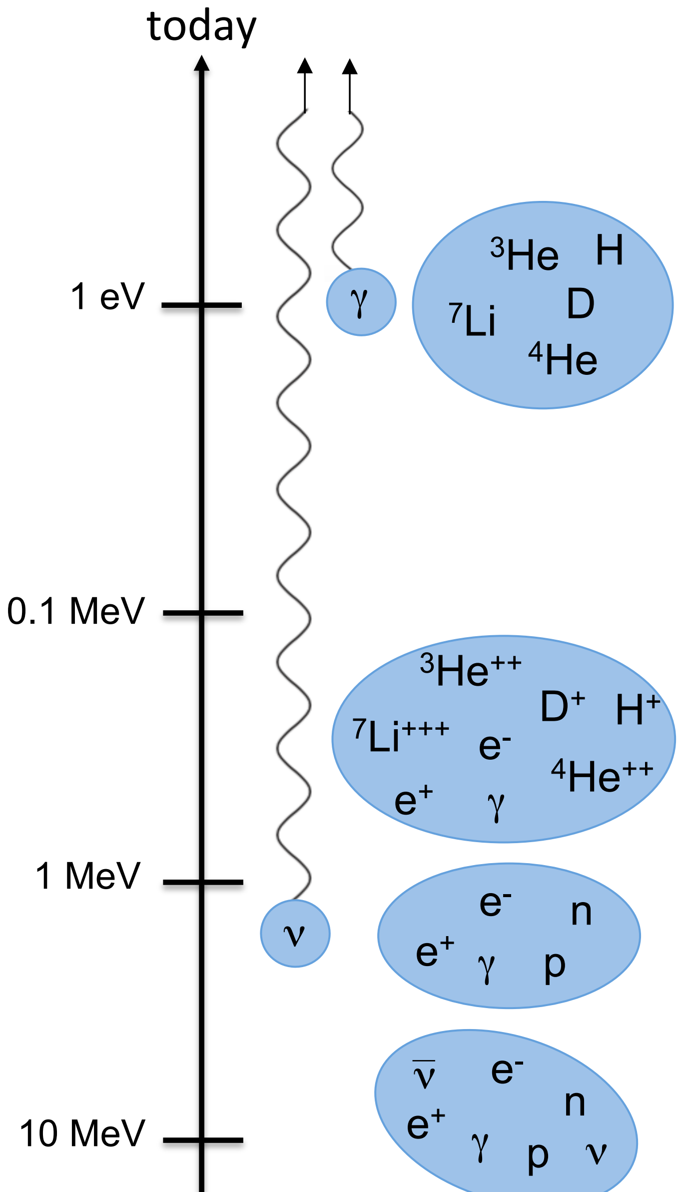
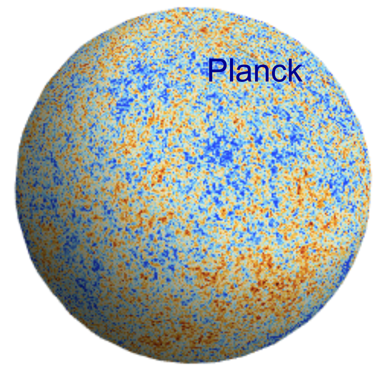
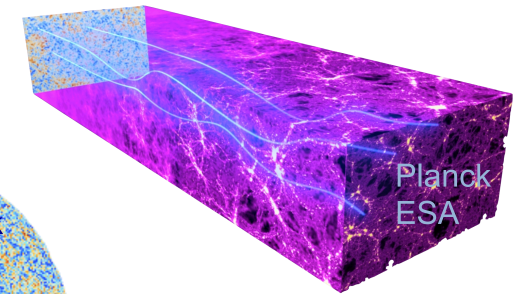
Probing the cosmic neutrino background

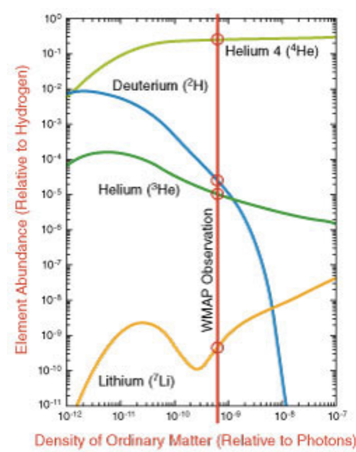




CMB



CMB lensing
LSS



BBN

The cosmic neutrino background

$$\rho_\nu(m_\nu \ll T_\nu) = \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4$$
$$= \rho_\gamma \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}$$
$$\rho_\nu(m_\nu \gg T_\nu) = \frac{\rho_c}{93.14 h^2 {\rm eV}} \Sigma m_\nu$$

Radiation like (very early times)

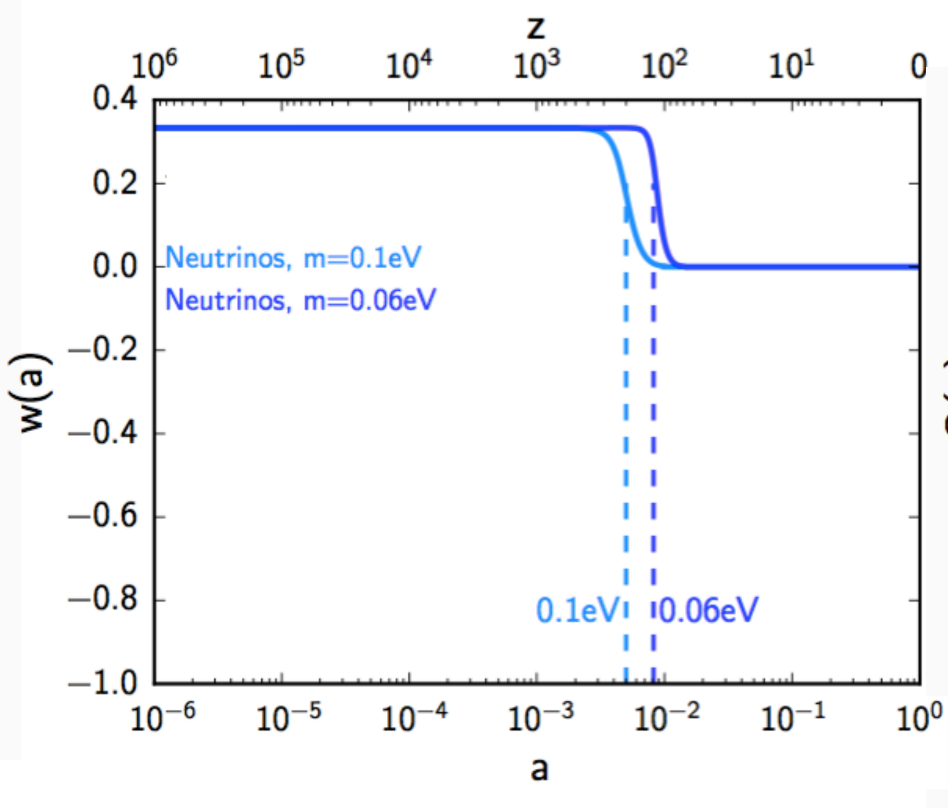
N_{eff}= effective number of relativistic species
= 3.046 (3 active neutrinos + QED corrections) Mangano+ 2001

Matter like (later times)

Σm_ν= total sum of the neutrino masses
> 59 meV from oscillation experiments Particle Data Group 2016

Probing the cosmic neutrino background

w=p/ρ



Ω=ρ/ρ$_c$

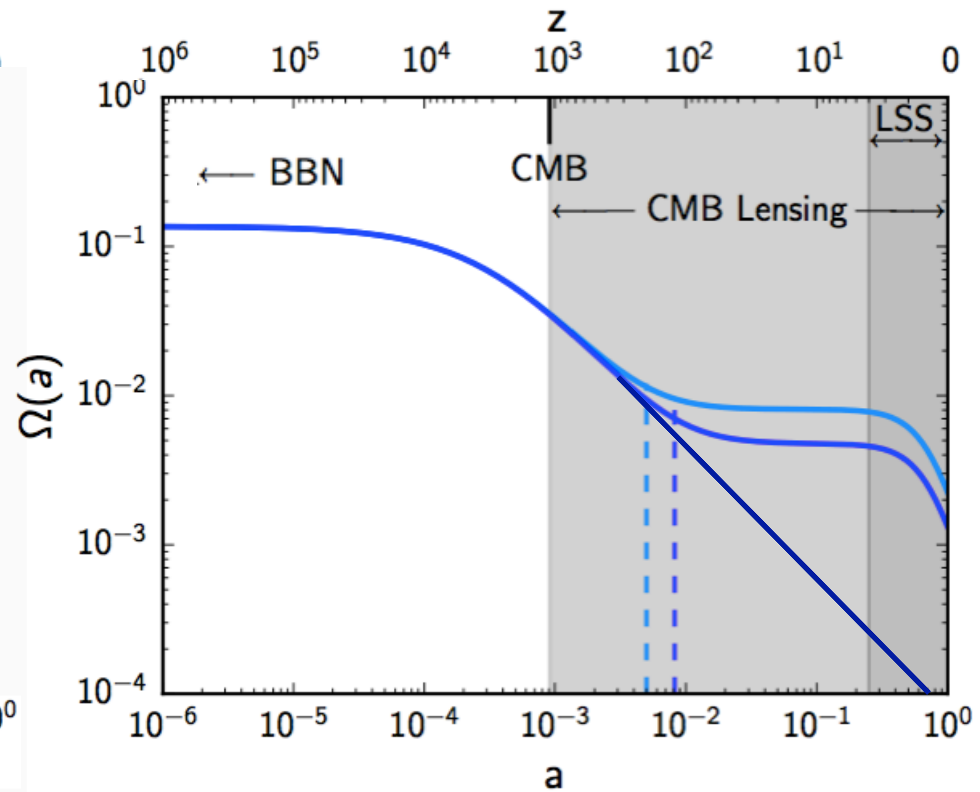


Figure credit: Christiane Lorenz

Probing the cosmic neutrino background

N_{eff} from the expansion rate – counting neutrinos

$$H^2(a) \approx \frac{8\pi G}{3}\Big(\rho_\gamma(a) + \rho_\nu(a)\Big)$$

- Change in the abundance of light elements
- Change in the matter-radiation equality

BBN predictions of Helium and Deuterium
Position, amplitude and damping of CMB acoustic peaks

Σm_ν from the growth of structures – weighing neutrinos

$$\frac{P(k,\Sigma m_\nu) - P(k,\Sigma m_\nu = 0)}{P(k,\Sigma m_\nu = 0)} \approx -0.08\Big(\frac{\sum m_\nu}{1\mathrm{eV}}\Big)\frac{1}{\Omega_m h^2}$$

- Suppression of small-scale density perturbations

Scale dependent suppression of the matter power spectrum, measurable with the CMB lensing signal and the statistics of the large-scale structure

Neutrinos from BBN

The abundance of light element generated during BBN depends on:

- Baryon density
- Expansion rate $H \approx \sqrt{g_* G_N} T^2$

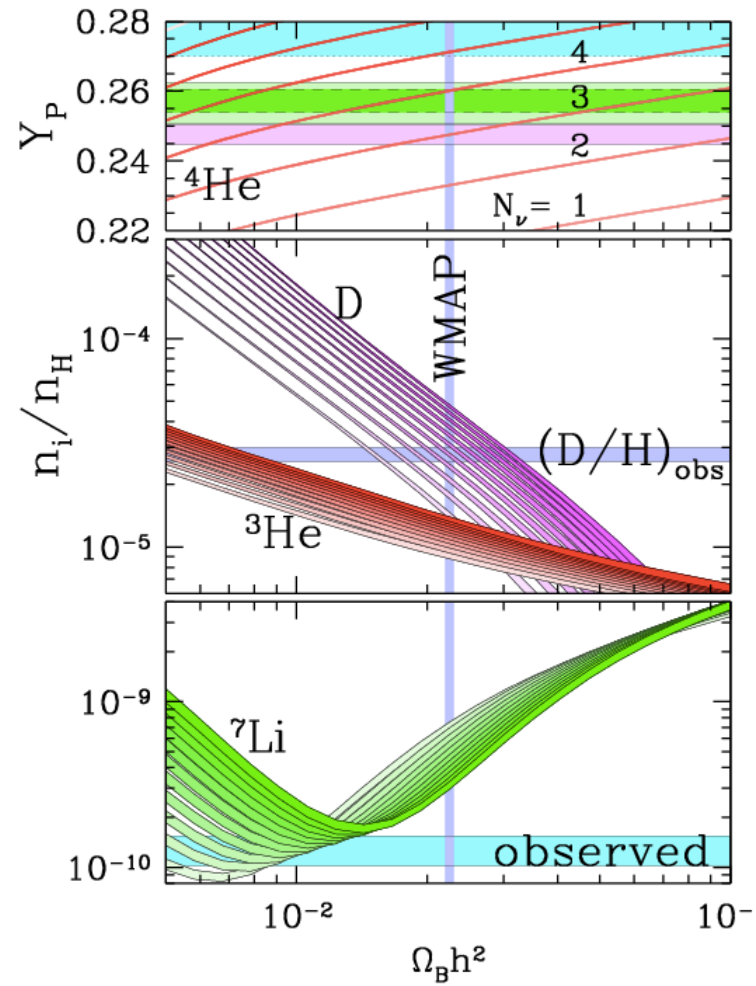
$g_* \propto N_{eff}$

D destroyed in starts, measured value will be a lower limit to the primordial abundance. Data from high-z, low-metallicity QSO absorption line systems.

He^3 produced and destroyed in stars. Data from solar system and galaxies but not used in BBN analysis.

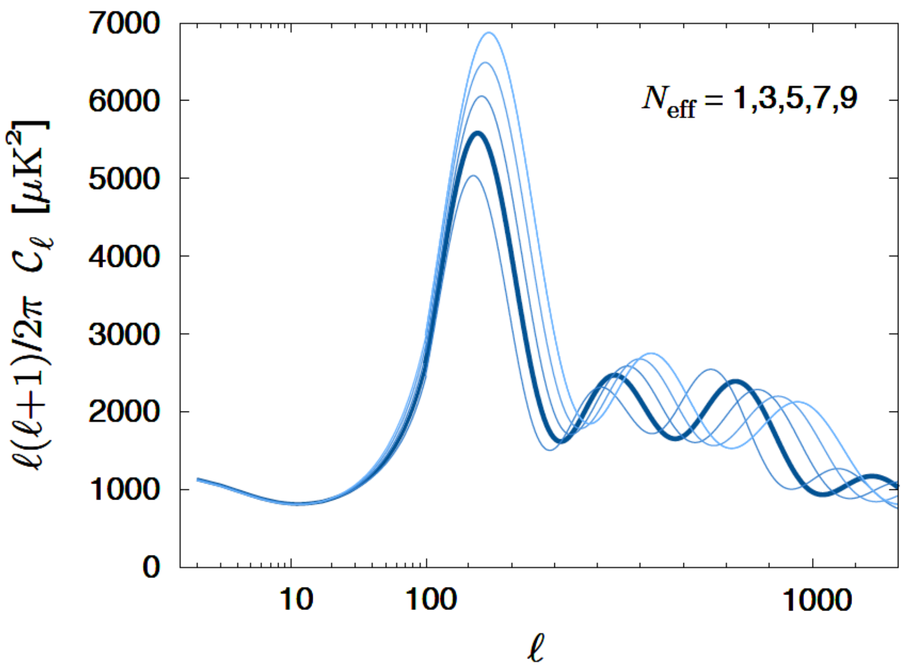
He^4 primordial abundance increased by H burning in stars. Data from low-metallicity, extragalatic HII regions.

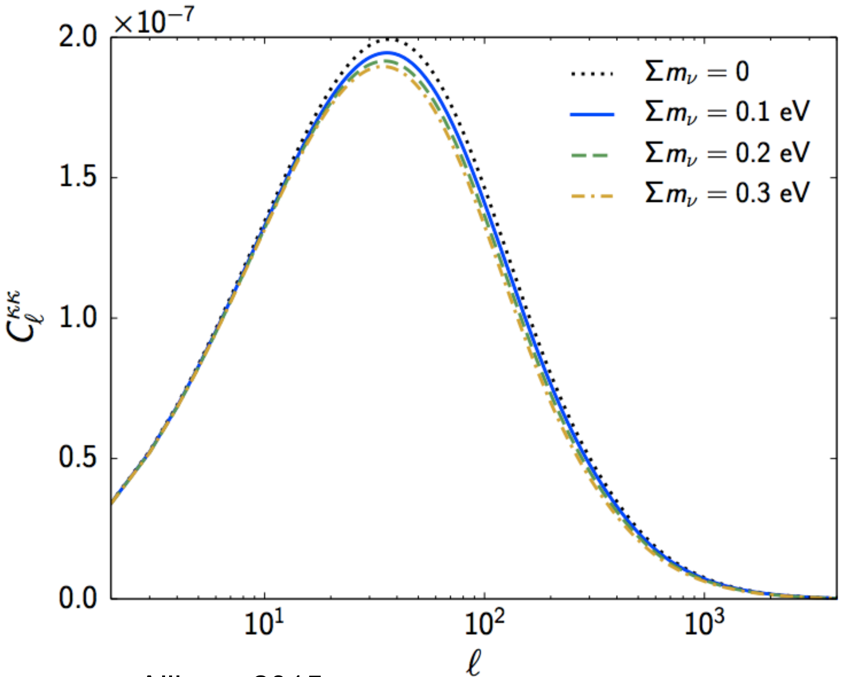
Li^7 destroyed in stars, produced in cosmic ray reactions. Data from oldest, most metal-poor stars in the Galaxy.



Nollett&Holder 2011

Neutrinos from the CMB





Allison+2015

Later matter-radiation equality, higher first peak

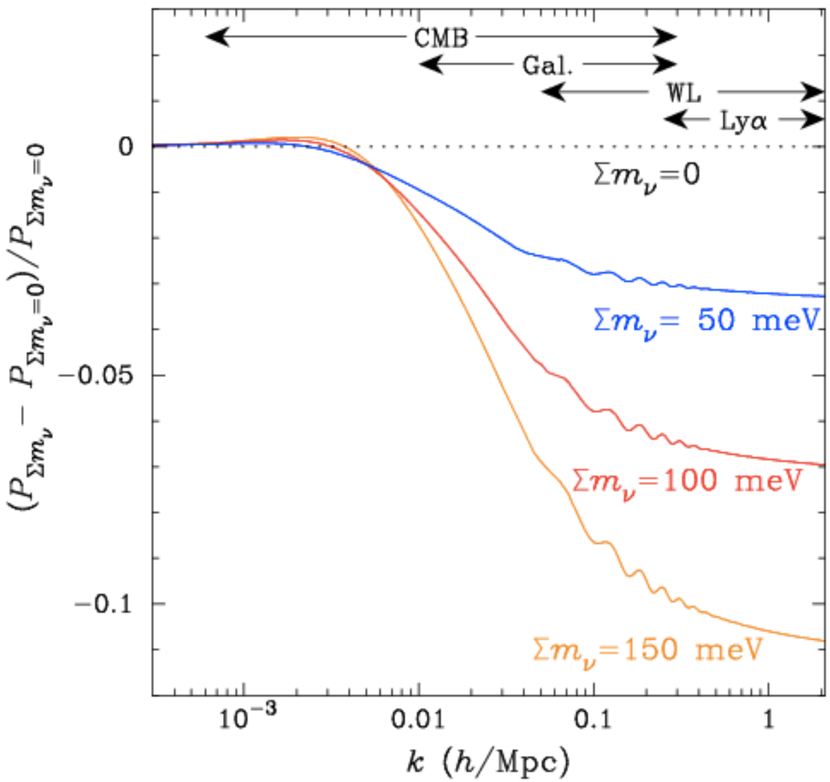
Larger sound horizon, peaks shift to higher l

Anisotropic stresses damp fluctuations during radiation domination, less power at l>200

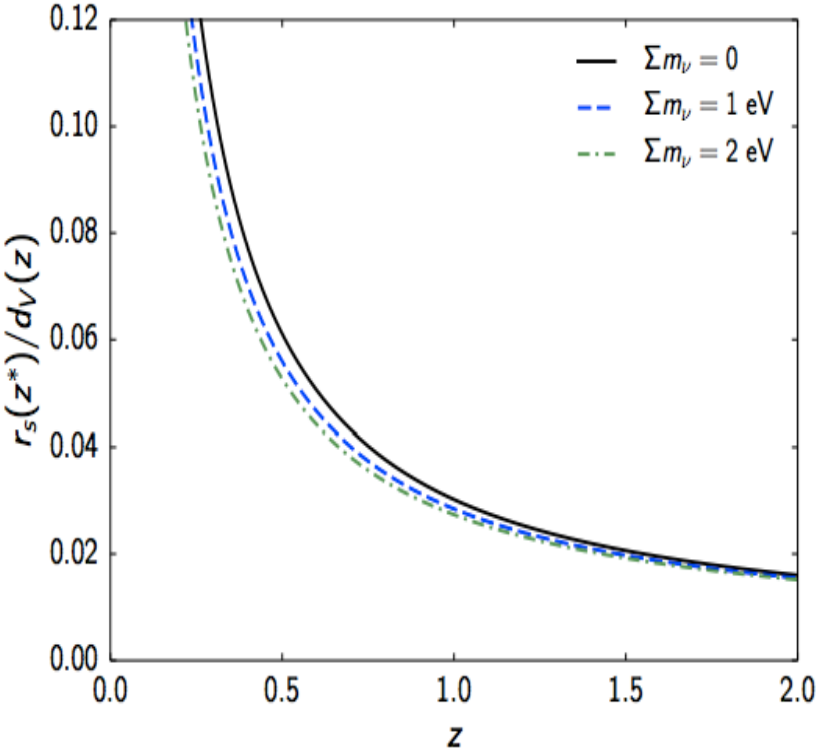
Anisotropies on scales smaller than the photon diffusion length are damped, for fixed peak positions, increasing N_{eff} enhances damping

Effects on the growth of structures changes the amplitude of the CMB lensing signal

Neutrinos from large-scale structure



Abazajian+2014

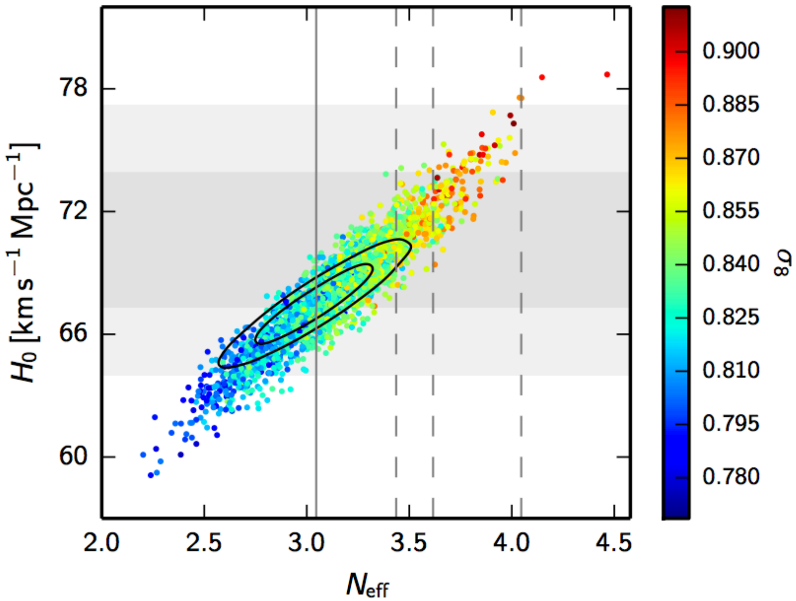


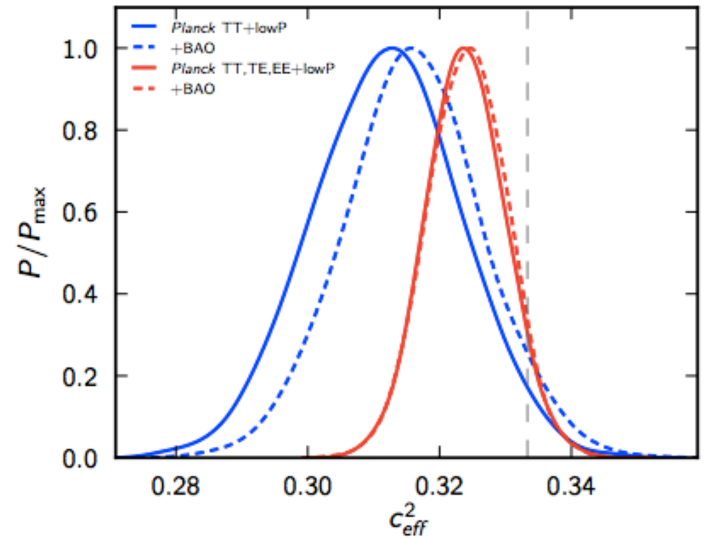
Allison+2015

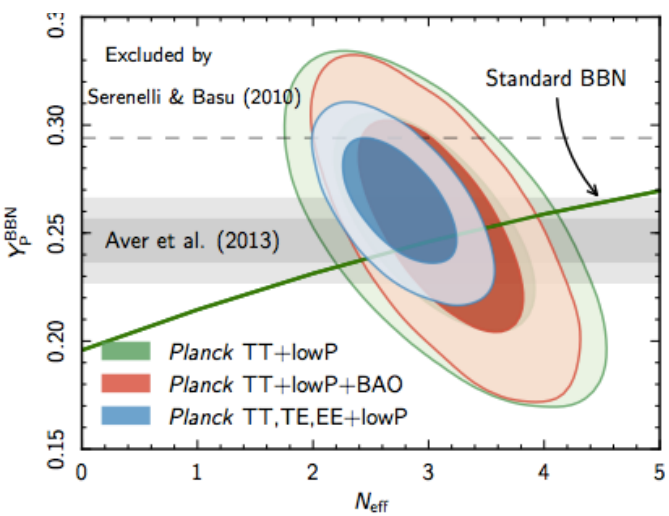
Neutrinos decouple when they are still relativistic suppressing small-scale perturbations

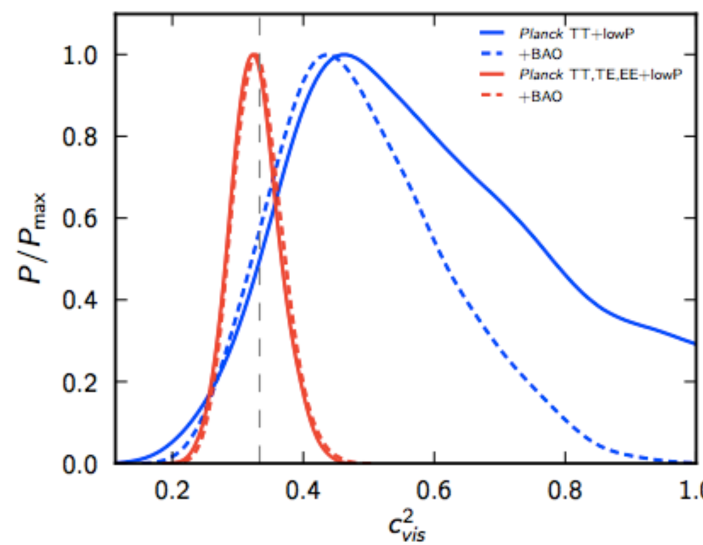
Massive neutrinos behave as additional matter in the BAO redshift range, decreasing the Hubble rate and increasing the volume distance

The neutrino number







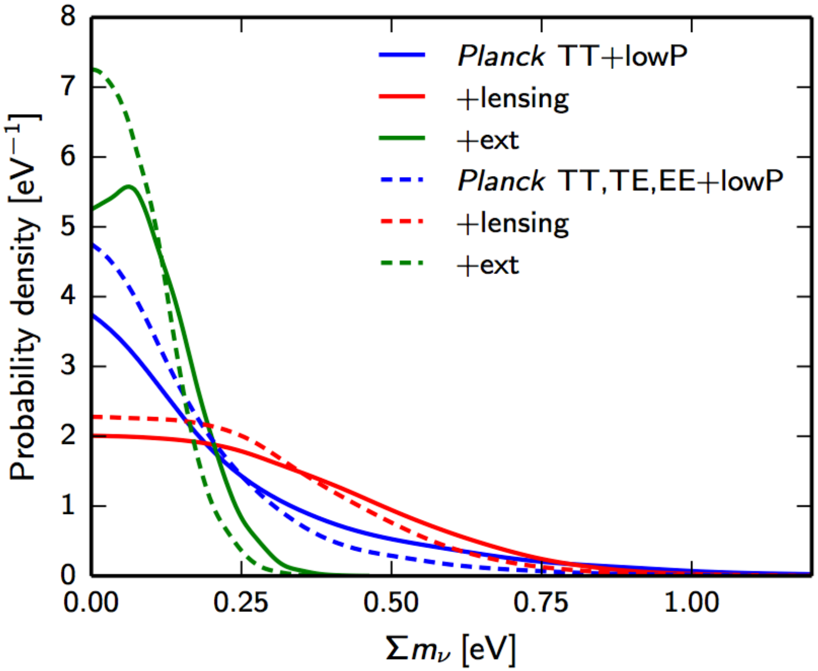


$$N_{\rm eff} = 3.04 \pm 0.18$$

Planck TT, TE, EE+lowP+BAO

Planck 2015 results. XIII

The neutrino mass



$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck}\ \text{TT+lowP};$$
$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck}\ \text{TT+lowP+BAO};$$
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck}\ \text{TT, TE, EE+lowP};$$
$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck}\ \text{TT, TE, EE+lowP+BAO}.$$

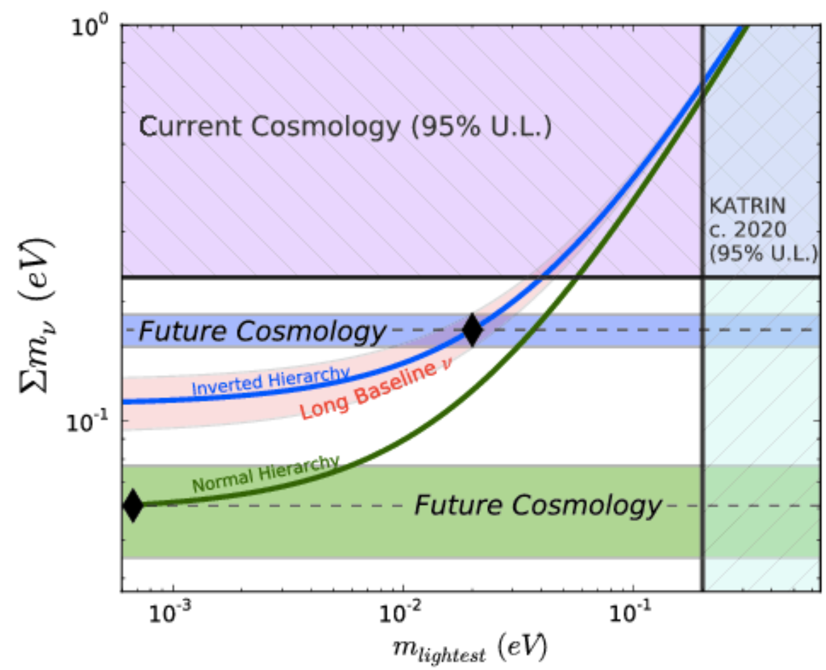
Planck 2015 results. XIII

$$(m_1^2, m_2^2, m_3^2) = \mu^2 + \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm\Delta m^2\right)$$

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

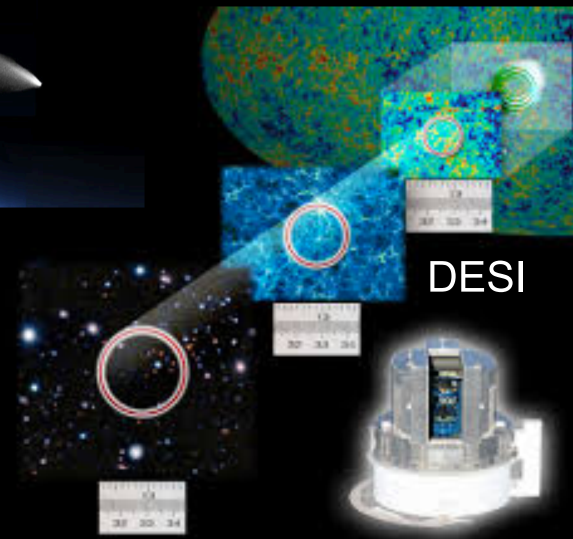
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

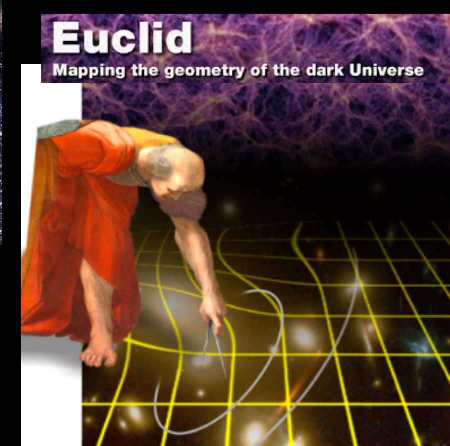
$$\Sigma = m_1 + m_2 + m_3$$



Abazajian+2014

Neutrino cosmology in the next decade





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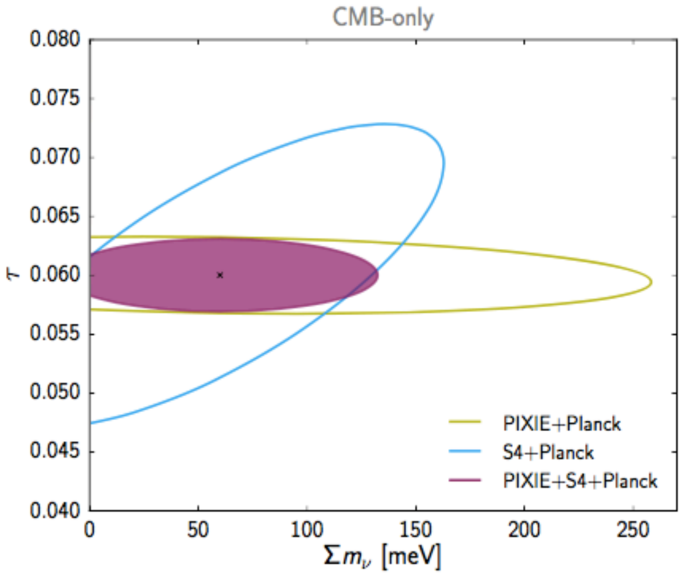

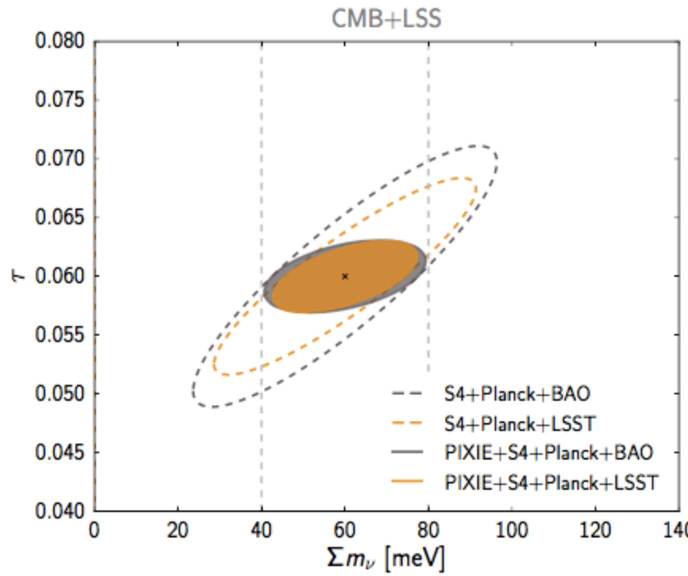

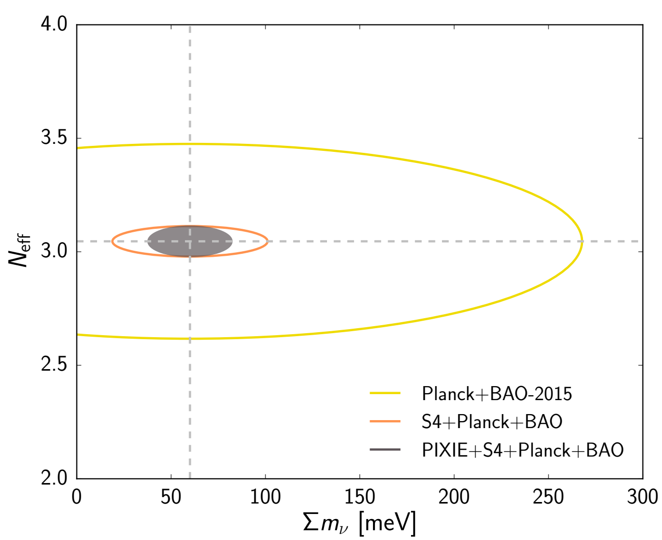

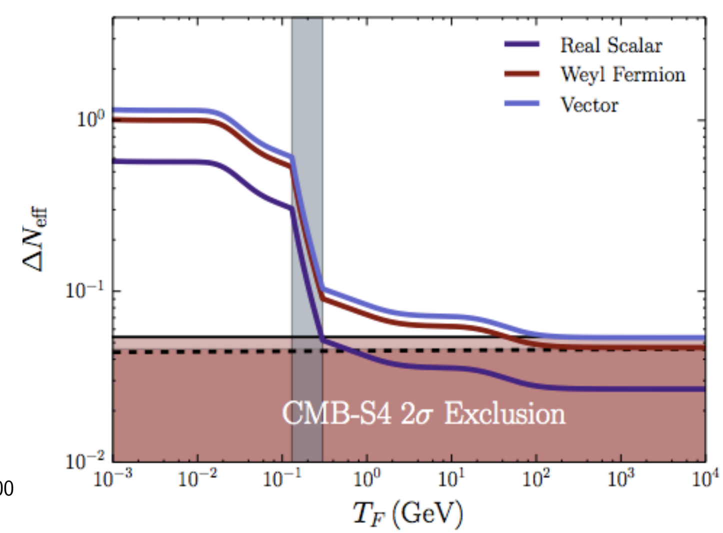

Calabrese+ 2016
Abazajian+2016

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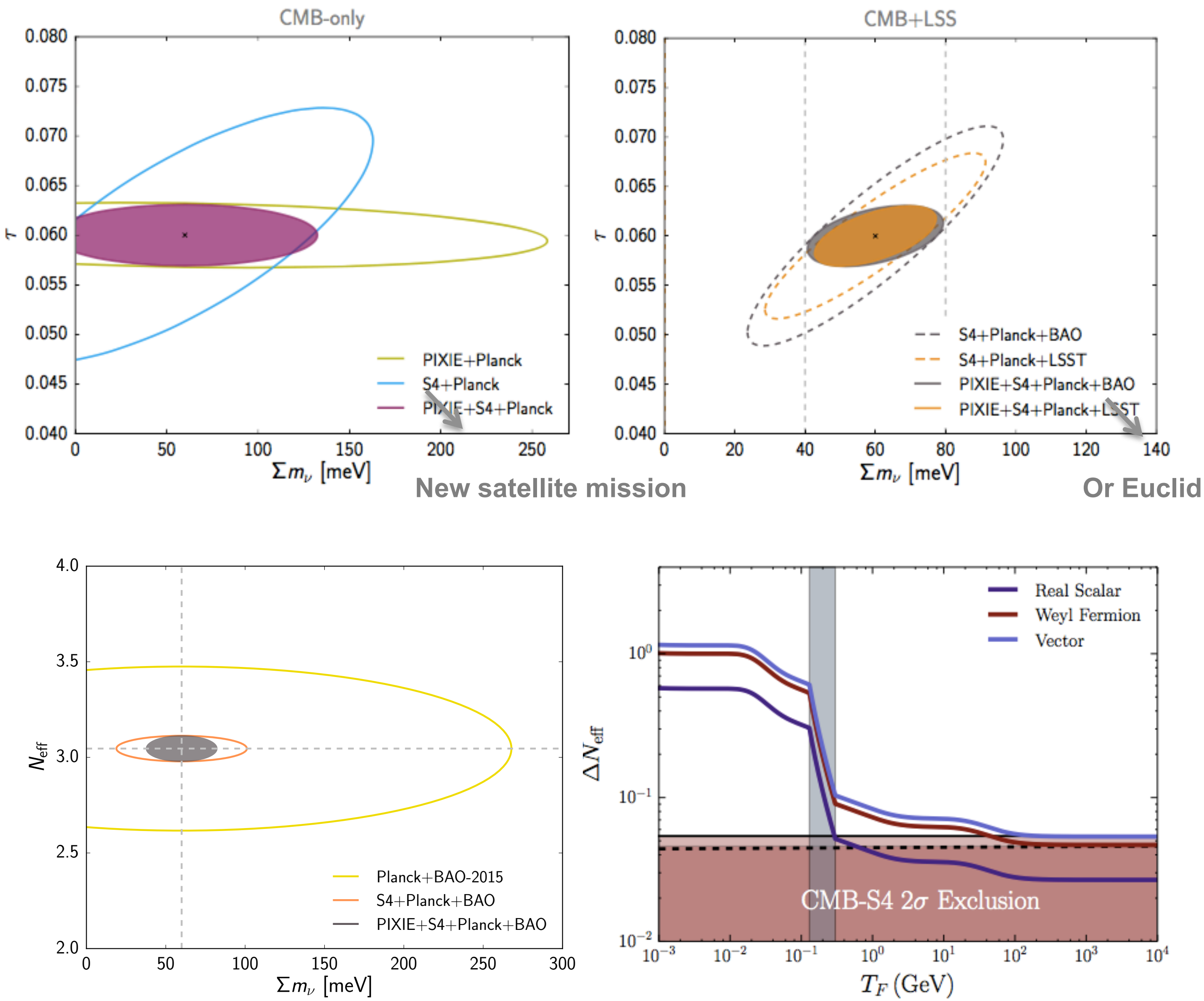

Calabrese+ 2016
Abazajian+2016

Looking for…

1-2% determination of N_{eff} from CMB – ruling out other light relic particles

First cosmological determination of the neutrino mass hierarchy from future CMB combined with large-scale-structure data

First cosmological determination of the neutrino absolute mass from future CMB combined with large-scale-structure data (3-5σ)

Robust determination of the neutrino mass
(under cosmological parameter degeneracies and systematics)