Astroparticles

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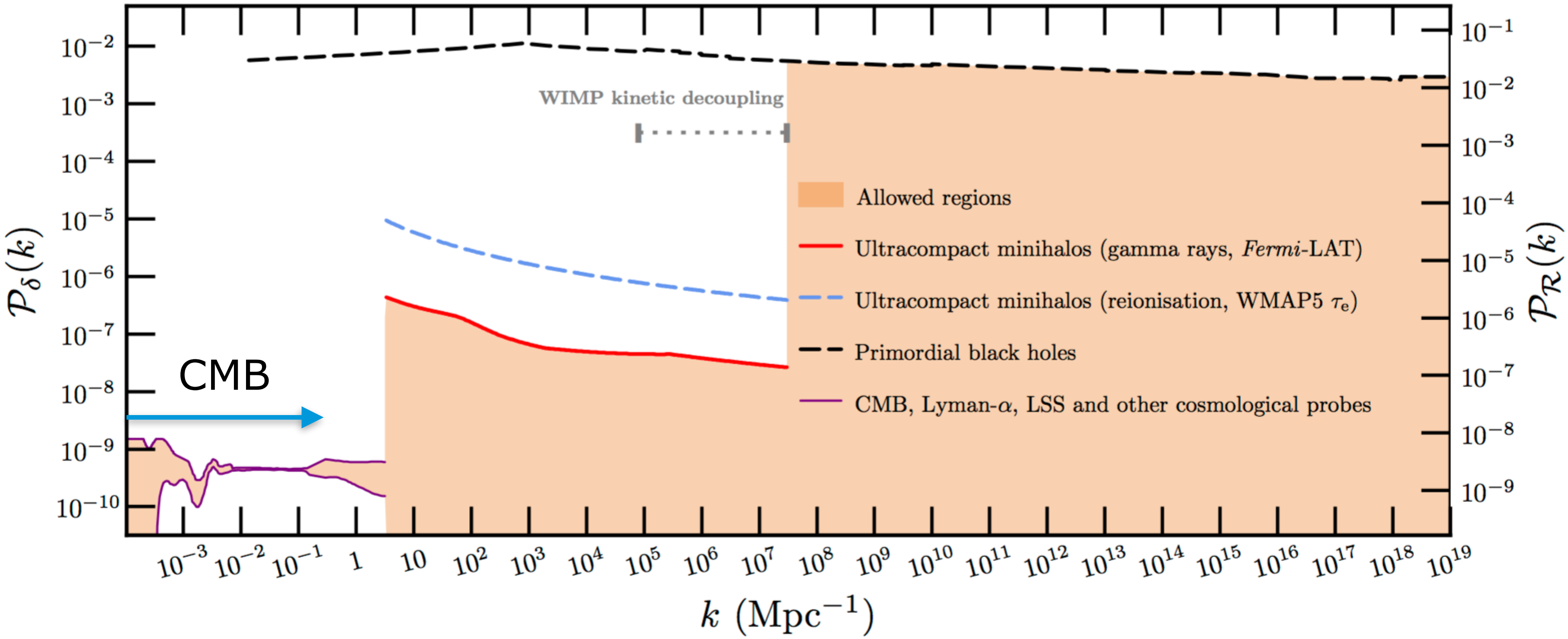
on behalf of the Italian CMB community

CMB anisotropies

CMB anisotropies provide the most stringent constraints on primordial density fluctuations



Bringmann et al.,Phys. Rev. D 85, 125027 (2012)

CMB: how much can we further improve ?

Planck satellite produced the most stringent constraints on cosmological parameters.

There is a fundamental limit to the amount of information we can extract from CMB angular spectra.
This is due to the gaussian nature of primordial fluctuations that induce an unavoidable cosmic noise called cosmic variance.

How far we are from cosmic variance limited ?

Or, how far we are from "scraping the bottom of the barrel" ?

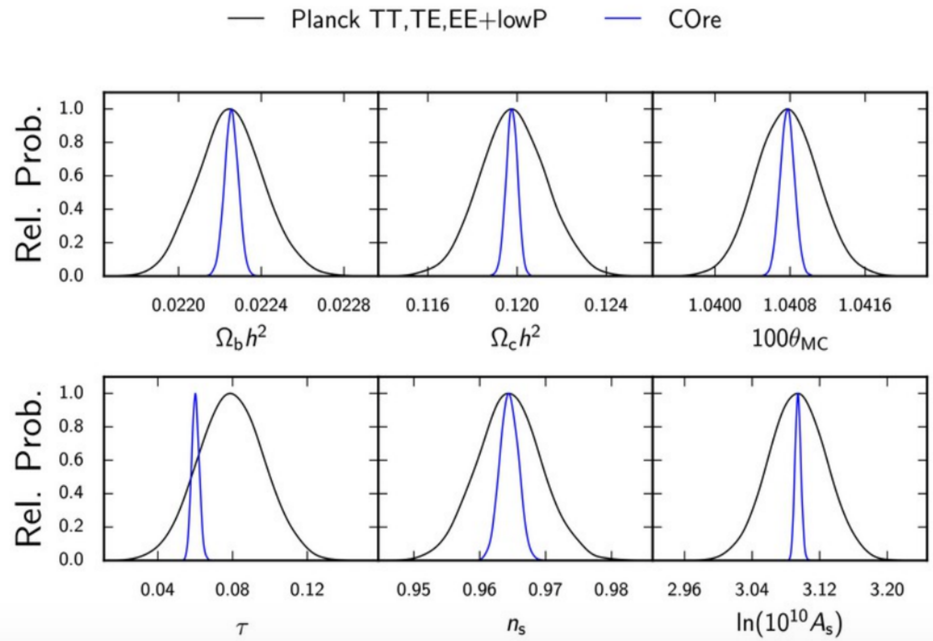
N.B. CV does not affect spectral distortions.

CMB: how much can we further improve ?

Parameter	Planck TT,TE,EE+lowP	COre
$\Omega_b h^2$	0.02225 ± 0.00016	0.02226 ± 0.00003
$\Omega_c h^2$	0.1198 ± 0.0015	0.1198 ± 0.0003
100θ	1.04077 ± 0.00032	1.04077 ± 0.00007
τ	0.079 ± 0.017	0.060 ± 0.002
n_s	0.9645 ± 0.0049	0.9645 ± 0.0014
$\ln[10^{10} A_s]$	3.094 ± 0.034	3.094 ± 0.003
H_0 [km s^{-1} Mpc^{-1}]	67.27 ± 0.66	67.29 ± 0.10

Errors are improved by a factor 5 (7 in some cases!) respect to Planck 2015.

(results obtained by Cabass, Di Valentino, Gerbino, Giusarma, Pagano, Salvati)



There is still a lot of information to extract !

Volume of parameter space (for LCDM) can be reduced by more than 15000 !

What CMB density fluctuations can (significantly) bound

1. Neutrino mass
2. Neutrino decoupling from primordial plasma
3. Extra Particles (i.e. axions)
4. Dark Matter annihilation
5. Primordial Helium and Neutron Lifetime
6. Modified Gravity
7. …

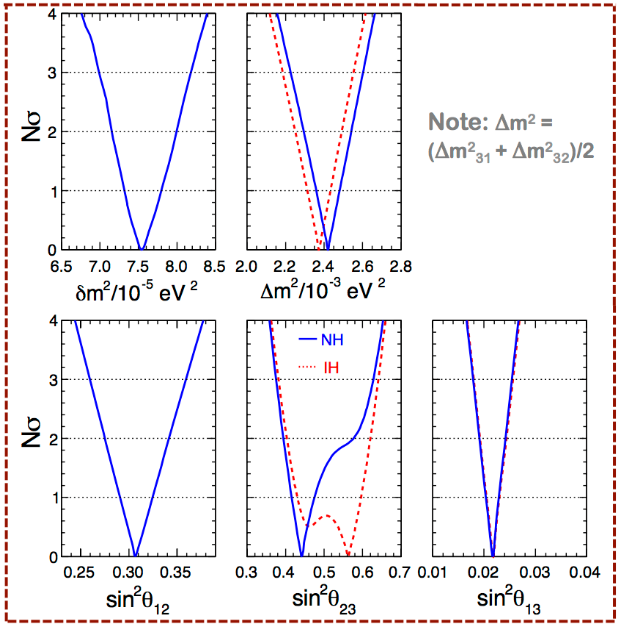
Neutrino Mass

- Current "standard" neutrino model consists of three neutrinos and 9 parameters (3 mass eigenstates, 3 mixing angles and 3 CP violating phases).

- Current experimental data from atmospheric, solar and baseline neutrinos constrain very precisely mass differences (2%) and mixing angles (5-10%).

- One key parameter is lacking: the absolute mass scale !

- Two ways to directly probe it: beta decay and double-beta decay.



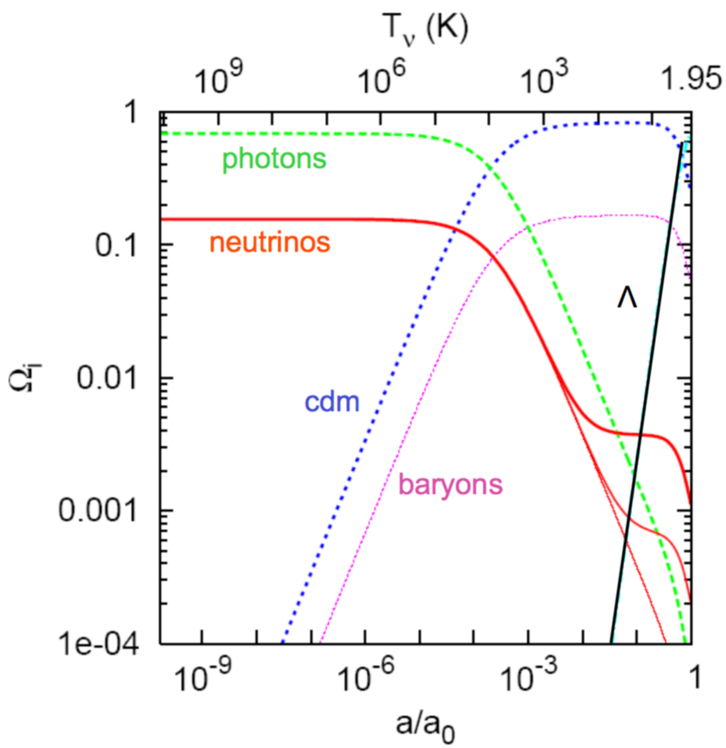
Katrin experiment

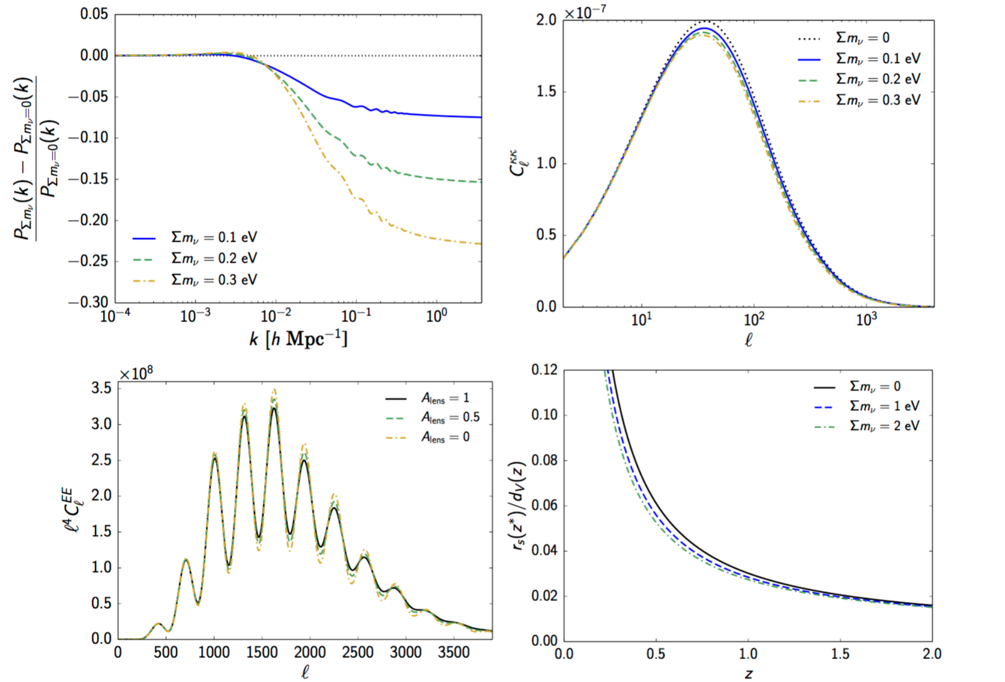
Katrin: beta-decay experiment.

Will probe neutrino mass down to 0.2eV (90% c.l.).

Neutrino Mass from Cosmology

The total neutrino mass (sum of mass eigenstates) can be probed by cosmology !



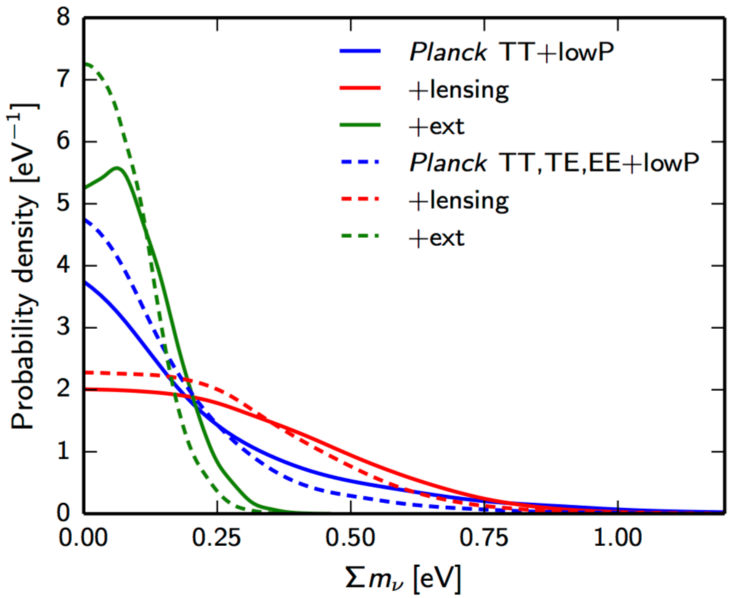


Allison et al., Phys. Rev. D 92, 123535 (2015)

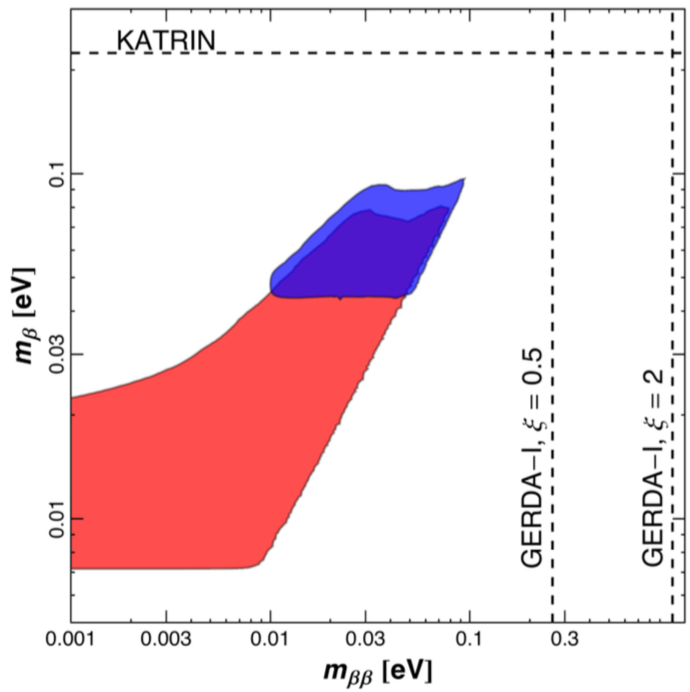
If neutrino have sub-eV masses then they change from relativistic to non relativistic after recombination (the only known particle to do this!). This damps perturbations on clusters and galactic scales.

Current constraints on neutrino masses from Cosmology

Current constraints bound the total neutrino mass to be lower than 0.17 eV at 95 % c.l. !
KATRIN and GERDA should not detect any neutrino mass.



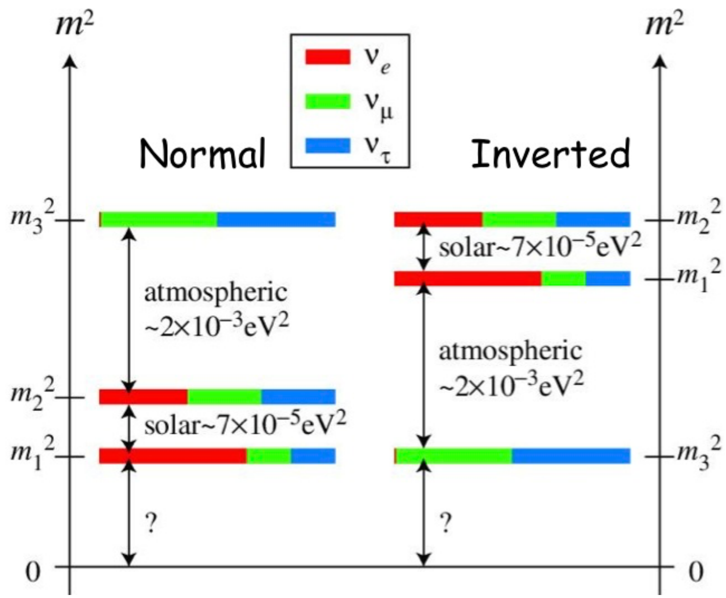
Planck Parameters paper 2015



Gerbino et al., PRD, 2016

Probing neutrino hierarchy

Di Valentino et al., 2016



	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.83^{+0.99}_{-0.98}$
σ_8	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.308^{+0.013}_{-0.013}$
τ	$0.059^{+0.017}_{-0.017}$

Another crucial question is the neutrino hierarchy.
If the total mass is below 0.10 eV then the inverted hierarchy could be excluded. Cosmology is very close in probing this !
The model predict also a minimum for the total mass of 0.06 eV (normal h.)

Future constraints: CMB alone

AdvACTPol × *Planck*
$\sigma(M_\nu) = 53$

SPT-3G × *Planck*
$\sigma(M_\nu) = 66$

Stage-IV × *Planck*
$\sigma(M_\nu) = 44$

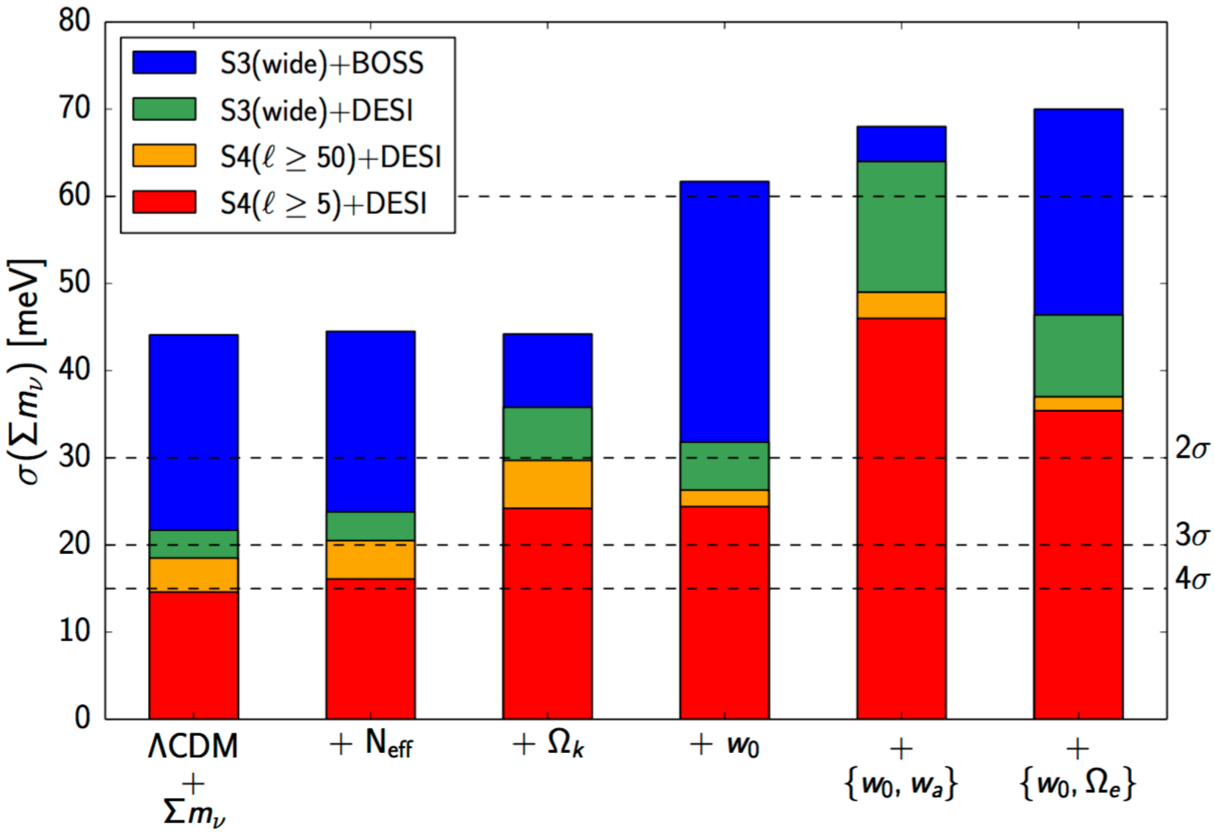
Values are in meV
"Just enough" sensitivity to probe hierarchy.

Combination with Planck can be certainly an issue (calibration, systematics, no access to high frequencies from ground etc).

COrE+
$\sigma(M_\nu) = 38$

Cleanest Probe.
Sensitivity at 0.04 eV.
Can rule out inverted hierarchy at 2.5 standard deviations.

Future constraints: CMB+BAO



Allison et al., Phys. Rev. D 92, 123535 (2015)

In principle, S4+DESI could detect the minimum neutrino mass at about 4 standard deviations in LCDM.

Guaranteed discovery.

But:

- It needs Planck (l>5).
- What about foregrounds ?

Expected sensitivity for Core+Euclid: 10 meV. This would detect neutrino mass at 5-6 sigma (LCDM).

Neutrino effective number

CMB is sensitive to the number of relativistic degrees of freedom.

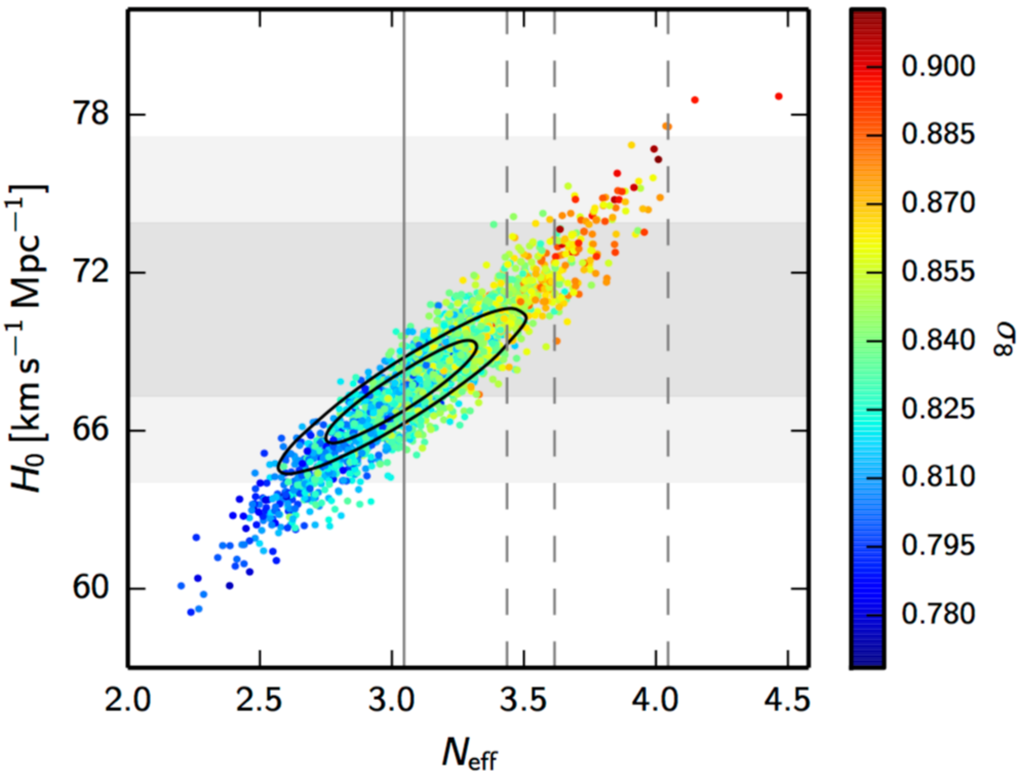
This number, for the standard 3 neutrino framework, is:

$$N_{eff}=3.046$$

A value different from this one could suggest:

- Extra relativistic particles at recombination
- Non standard decoupling
- Inflation reheating temperature close to BBN.
- Extra dimensions
- …..

Neutrino effective number: current constraints



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

No indication for values different from 3.046.
Non-standard models strongly constrained.

Neutrino effective number: future constraints

Stage-IV × *Planck*
$\sigma(N_{\rm eff}) = 0.036$

Improvement of about factor 6 respect to current Planck constraints using CMB data alone.

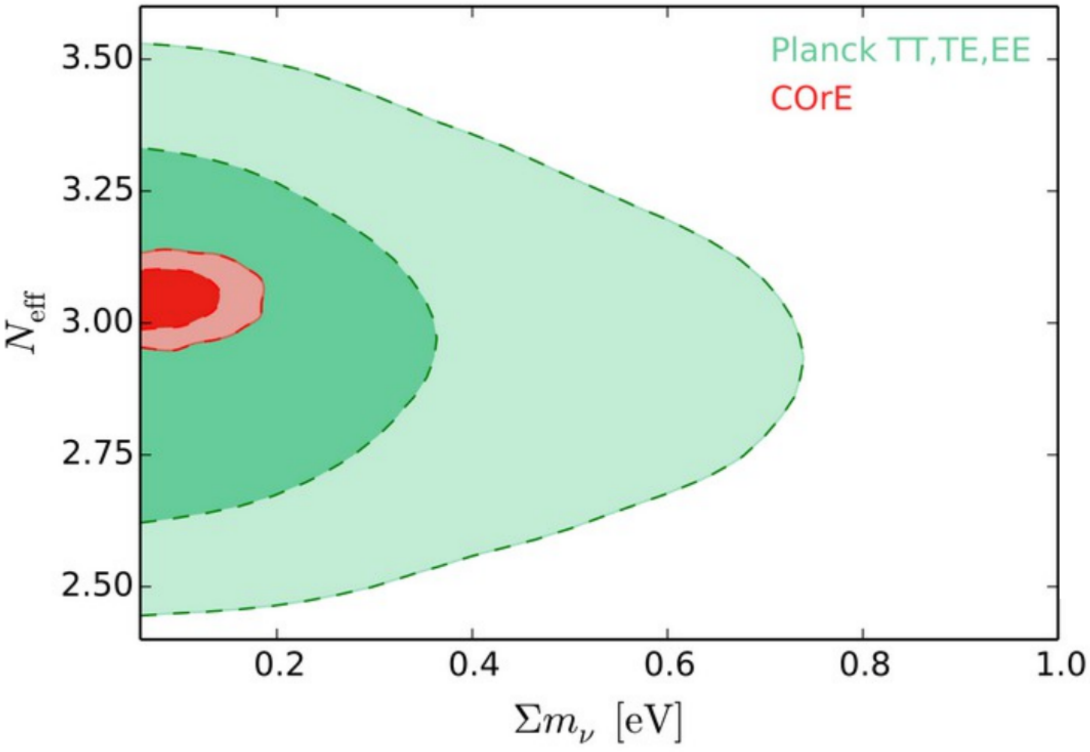
COrE+
$\sigma(N_{\rm eff}) = 0.029$

COrE + Euclid

$\sigma(N_{\rm eff}) = 0.013$

A COrE+Euclid could test neutrino decoupling !

Neutrino effective number+neutrino mass: future constraints



Axions

In the early universe, axions can be produced via thermal or non-thermal processes. If thermal, the axion contributes as an extra hot thermal relic (together with three active sterile neutrinos).

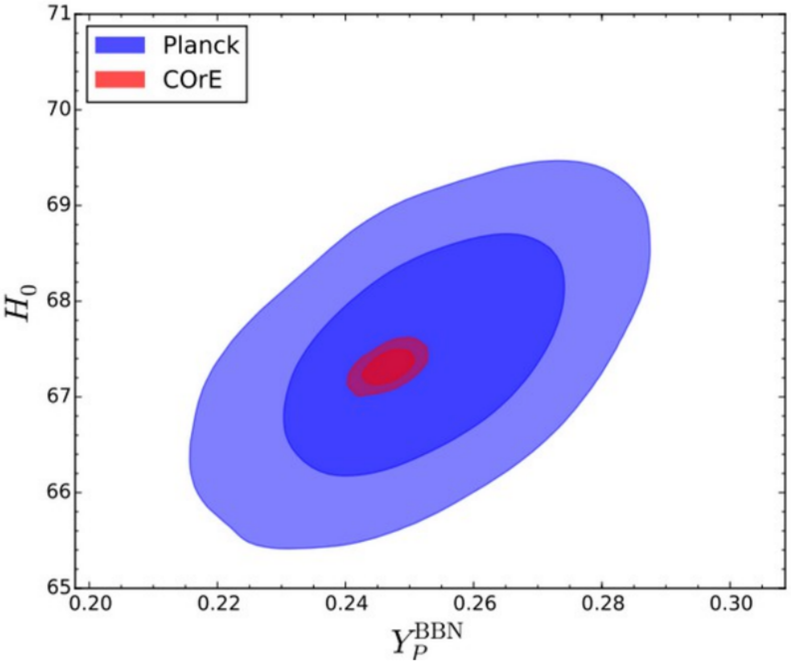
If axions exist and they are produced thermally (with axion-pion interaction), then we expect a minimal axion mass of 0.15 eV leading to:

$$N_{eff} \geq 3.2$$

This number is currently not favored by current observations.

CORE+ can rule out thermal axions at more than 5 standard deviations.

Primordial Helium abundance



Current primordial Helium direct measurements are in tension at about 3 standard deviations.

	Yp
Aver et al. (2015)	0.2449 ± 0.0040
Izotov et al. (2013)	0.254 ± 0.003
Izotov et al. (2014)	0.2551 ± 0.0022

CORE+ can reach a sensitivity to Helium abundance about 2 times better (0.002) than current direct measurements.

Neutron Lifetime

Dataset	$Y_{\rm p}^{\rm BBN}$	$\tau_{\bf n}$ [s]
Planck TT, TE, EE + AdvACT	0.2464 ± 0.0065	$\mathbf{879 \pm 32}$
Planck TT, TE, EE + CMB-S4	0.2475 ± 0.0037	$\mathbf{884 \pm 18}$
Planck TT, TE, EE + SPT-3G	0.2487 ± 0.0091	$\mathbf{890 \pm 44}$
COrE	0.2467 ± 0.0023	$\mathbf{880 \pm 11}$
CVL	0.2467 ± 0.0011	$\mathbf{880.7 \pm 5.5}$
Planck TT, TE, EE + Euclid	0.2521 ± 0.0069	$\mathbf{907 \pm 34}$
COrE + Euclid	0.2467 ± 0.0014	$\mathbf{880.3 \pm 6.7}$

Salvati et al, JCAP 2016

Assuming also standard BBN, CMB can constrain the neutron lifetime up to 6 seconds, comparable with current experimental data.

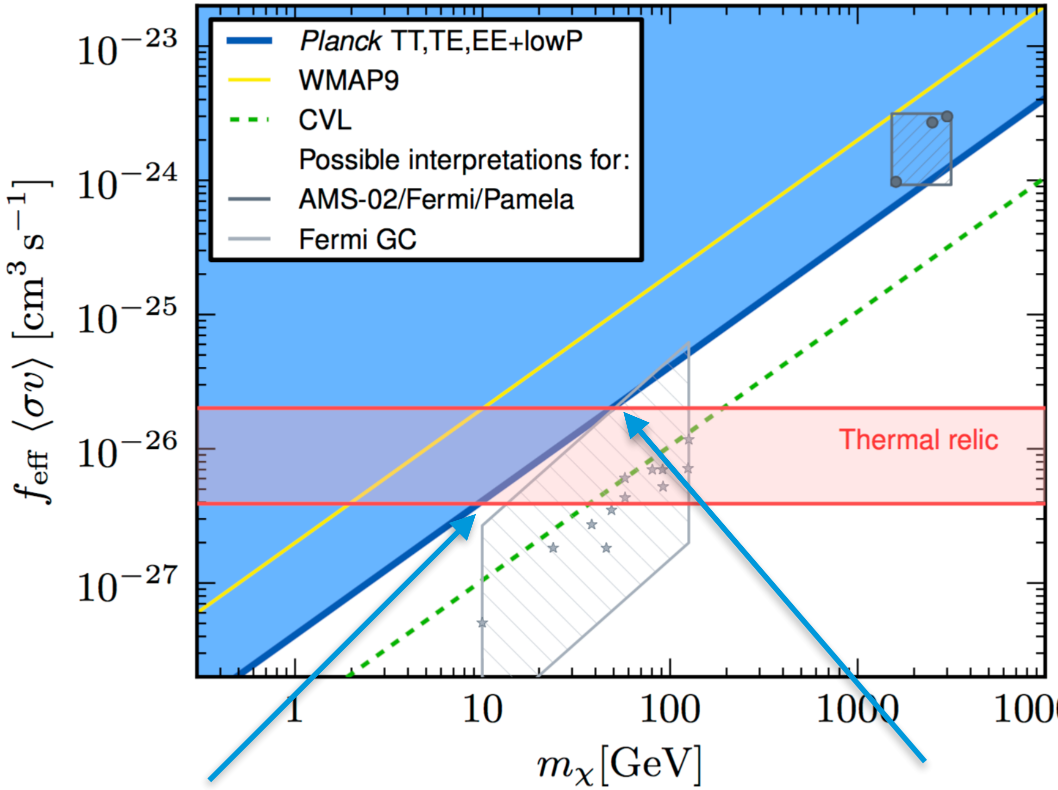
Dark Matter Annihilation

- CMB constrains DM decay at recombination.

- Model dependent

- Constraints can be improved by a factor 3-4 with a CVL limited experiment as CORE+.

Planck parameters paper, 2015



Thermal relic annihilating in tau's

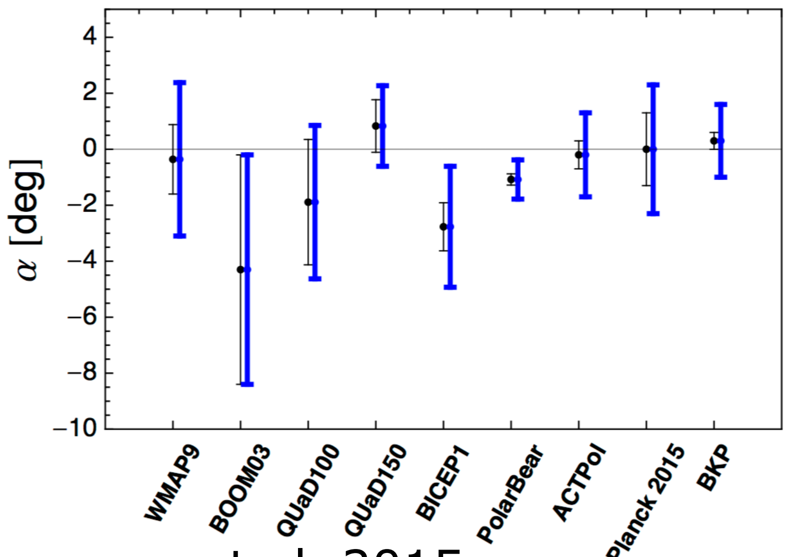
Thermal relic annihilating in e

Cosmic Birefringence

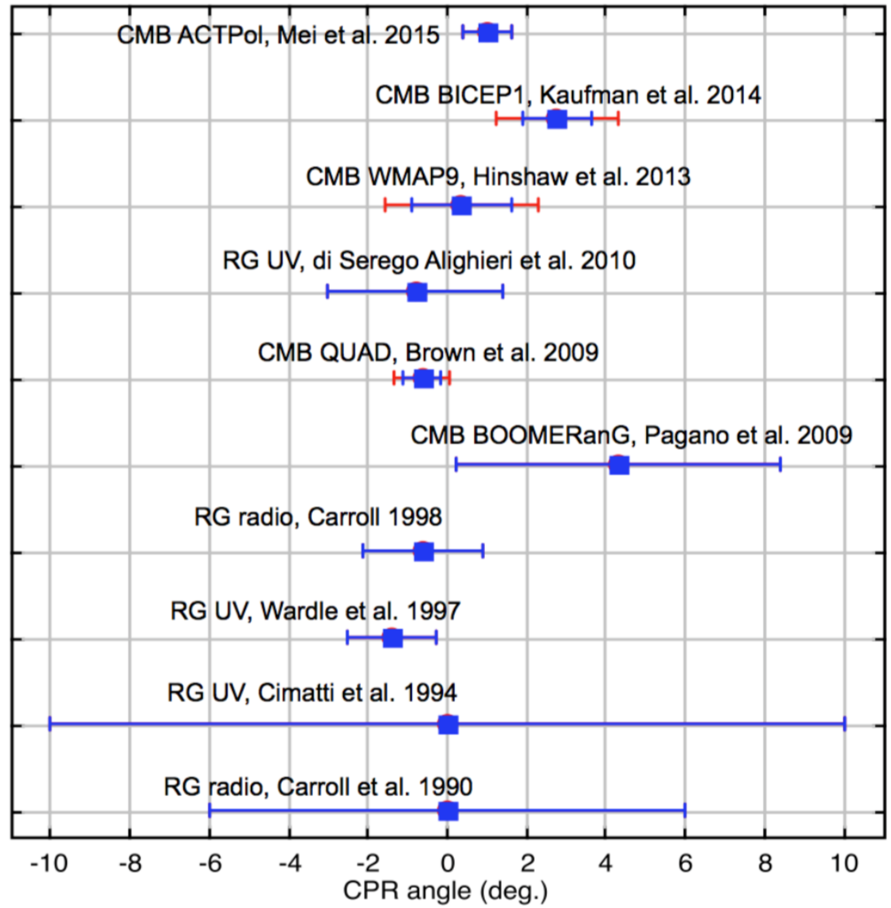
- New Physics in e.m. sector can induce a rotation of the CMB polarization angle.

- Current constraints are dominated by systematics.

- Constraints can be significantly improved.



Gruppuso et al, 2015



S. di Serego Alighieri, 2016

Modified Gravity

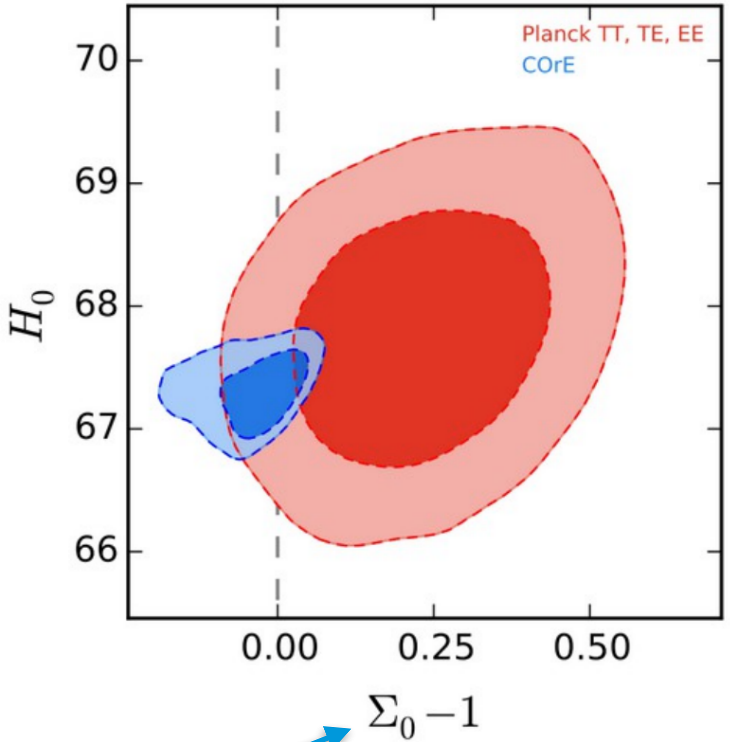
Di Valentino, et al, PRD 2016

- Planck 2015 provides mild hints for anomalies.

- Several exotic physical mechanisms have been proposed to explain these anomalies.

- Among them, modify gravity scenarios.

- CORE will significantly improve the constraints on these models.



“Modified Gravity” parameter.

Conclusions

- Future CMB data will provide a guaranteed discovery: the neutrino mass (or the failure of LCDM).
- We could test the neutrino decoupling.
- Light particles (Axions) can be ruled out.
- Complementary information on DM cross section.
- Neutron Lifetime
- Cosmic Birefringence
- …

The italian CMB community is ready to scientifically exploit in the optimal way future CMB data !

Italy had the co-leaders of the parameters, likelihood, inflation and non-gaussianity Planck papers that are between the most cited papers in physics and astrophysics of 2015.