Neutrino cosmology from Planck 2014

J. Lesgourgues (CERN, LAPTh) on behalf of the Planck Collaboration

- Have we detected the Cosmic Neutrino Background
  - through its average density ?
  - through its perturbations/anisotropies ?

- Have we detected something more than the CNB (extra light relics) ?

The Cosmic Neutrino Background (CNB)

Predicted in 1953 with correct temperature ($T_\nu = (4/11)^{4/3}\, T_\gamma$) by *Alpher, Follin & Herman*:

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*,†

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61 years later…

… are we sure that it exists?

1. Probing the CNB *average* density

Alpher et al.'s prediction with refined neutrino decoupling at ~ 1 MeV, and update to 3 ν□s, leads to :

$$\omega_R = \omega_\gamma \left(1 + N_{eff} \times 7/8\ (4/11)^{4/3}\right) \quad \text{with } N_{eff} = 3.046$$

in relativistic regime, and contribution to matter density for $T_\nu < m_\nu$:

$$\omega_M = \omega_b + \omega_{CDM} + (\Sigma\, m_\nu) / 93.14\ \text{eV}$$

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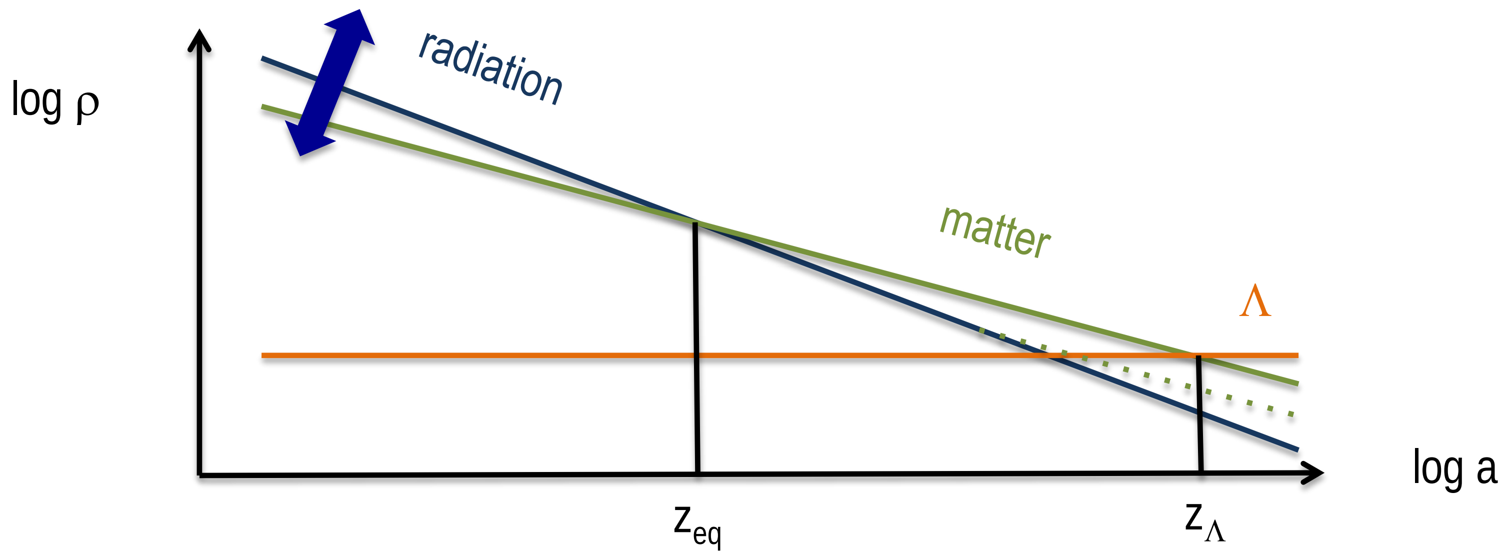
Impact on d_{Arec}, θ_s can be compensated by decreasing H_0
Impact on Late ISW below cosmic variance
} no evidence so far

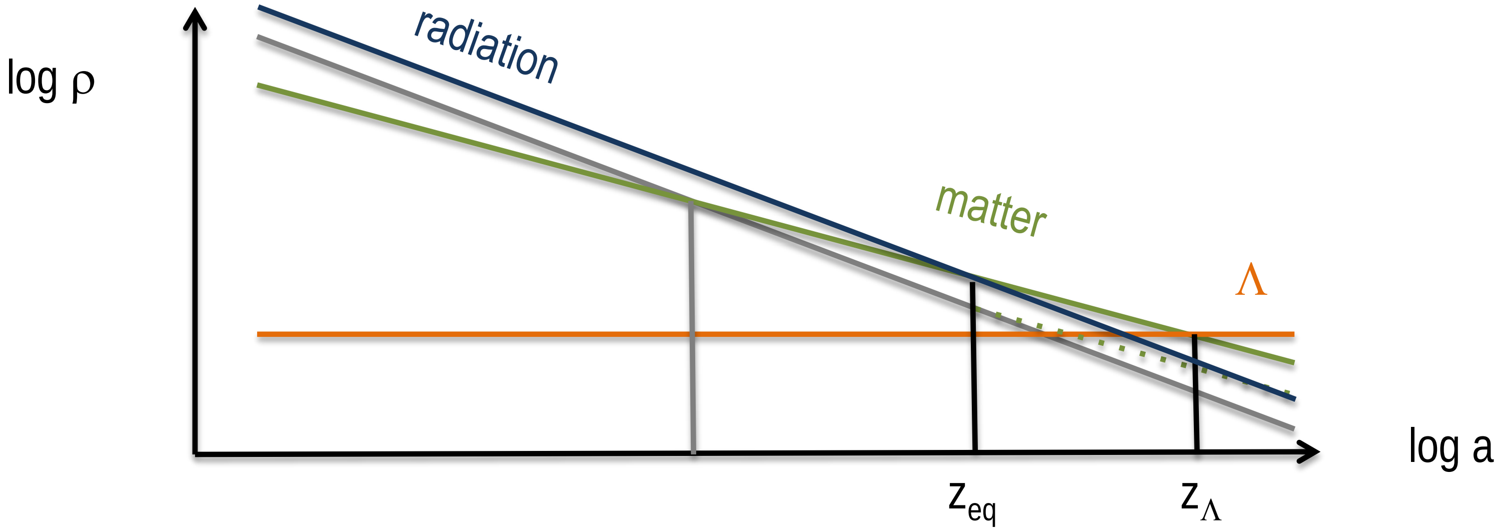
1. Probing the CNB *average* density

- How can we test the density of radiation?



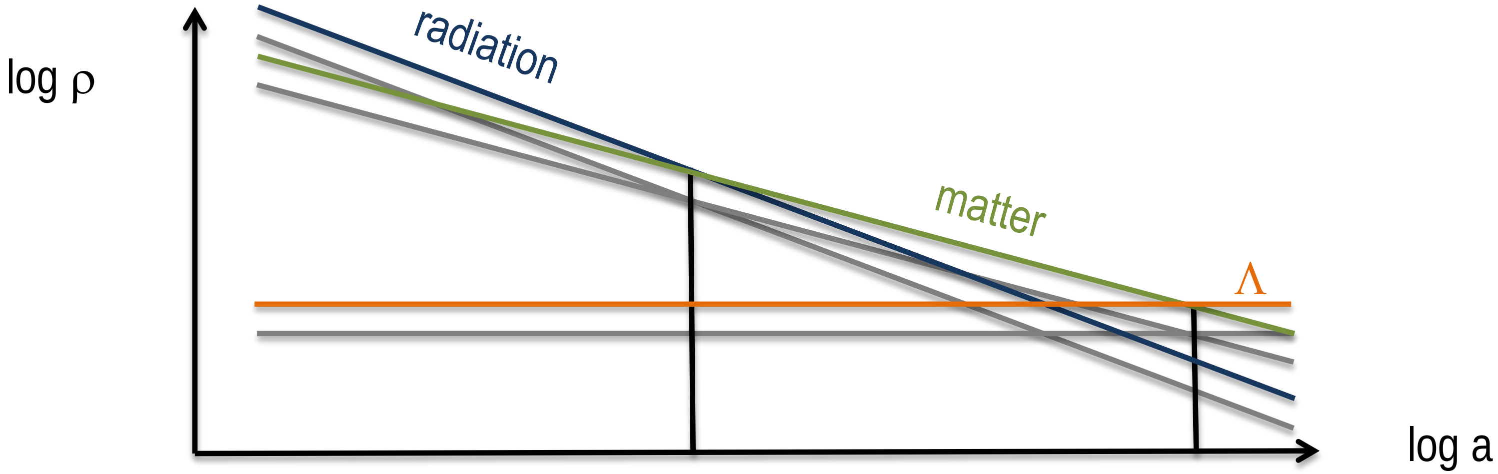
1. Probing the CNB *average* density

- An increase of radiation only would have obvious consequences:



1. Probing the CNB *average* density

- An increase of *all densities* is more subtle to detect:

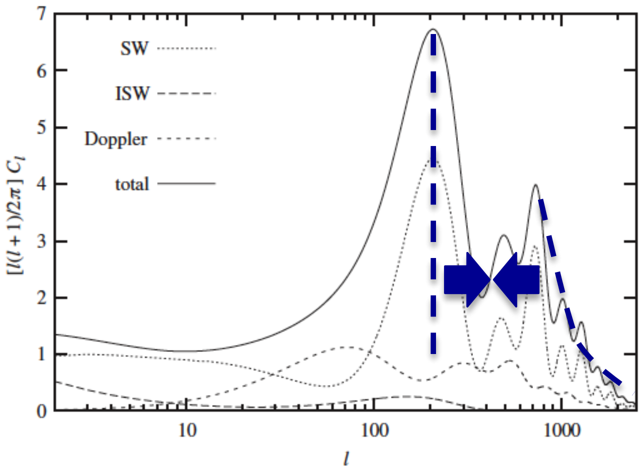


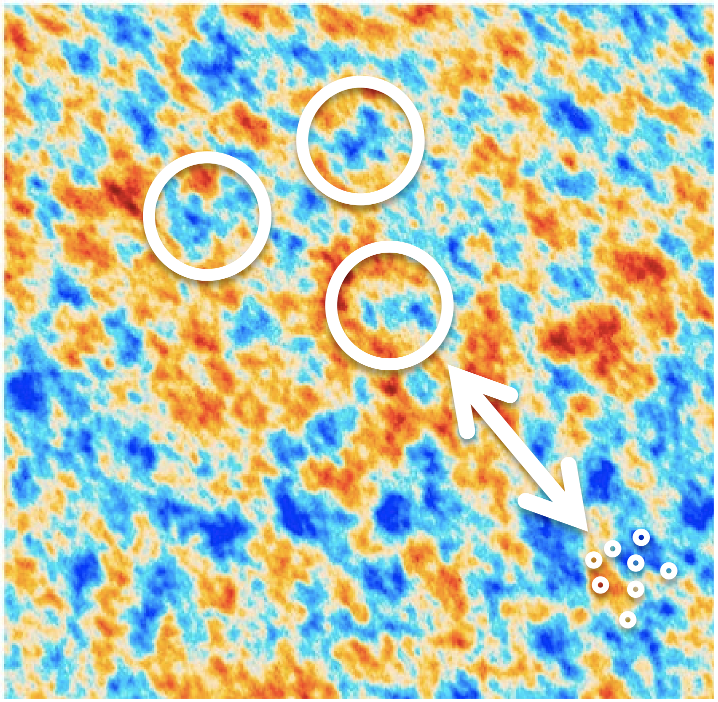
- Or in other word, a simultaneous increase of (H_0, N_{eff}), with Ω_b, Ω_{cdm}, Ω_Λ fixed

1. Probing the CNB *average* density

- Keeping Ω_i fixed and increasing (H_0, N_{eff}) preserves all characteristic redshifts
- But increase in H_0 changes peak-scale-to-damping-scale ratio !

larger (H_0, N_{eff}), more damping





1. Probing the CNB *average* density

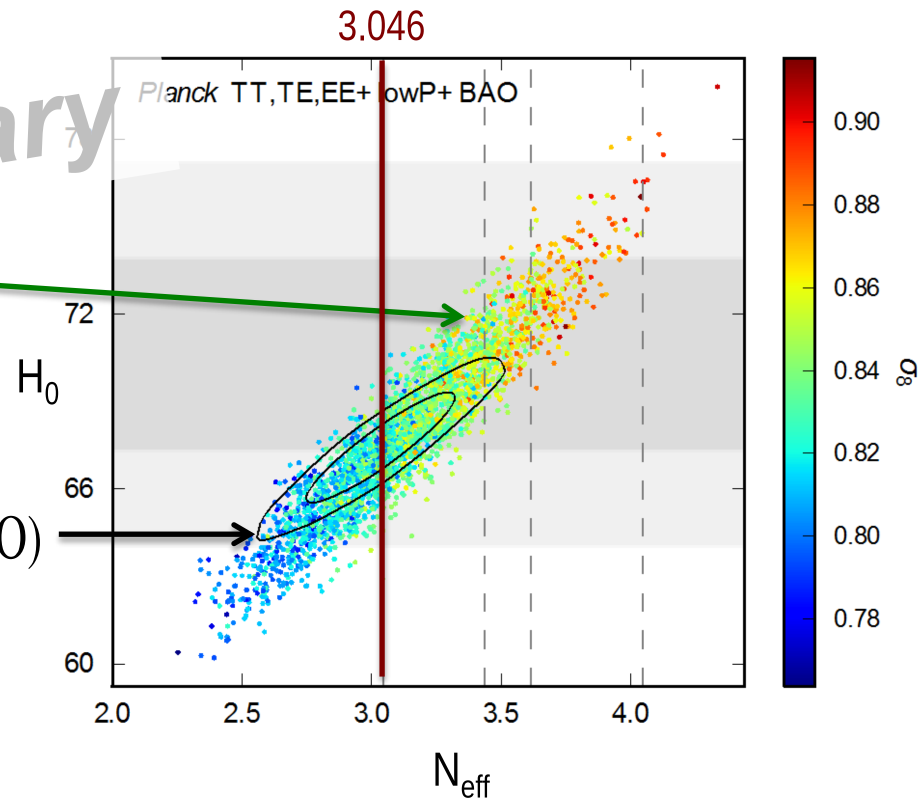
$N_{\rm eff} = 3.13 \pm 0.32$ (*Planck* TT+lowP)

$N_{\rm eff} = 3.15 \pm 0.23$ (*Planck* TT+lowP+ BAO)

$N_{\rm eff} = 2.98 \pm 0.20$ (*Planck* TT,TE,EE+lowP)

$N_{\rm eff} = 3.04 \pm 0.18$ (*Planck* TT,TE,EE+lowP+BAO)

(all at 68% CL, BAO from *6dFGS, SDSS-MGS, BOSS-LOWZ, BOSS-CMASS-DR11*)



1. Probing the CNB *average* density

Preliminary

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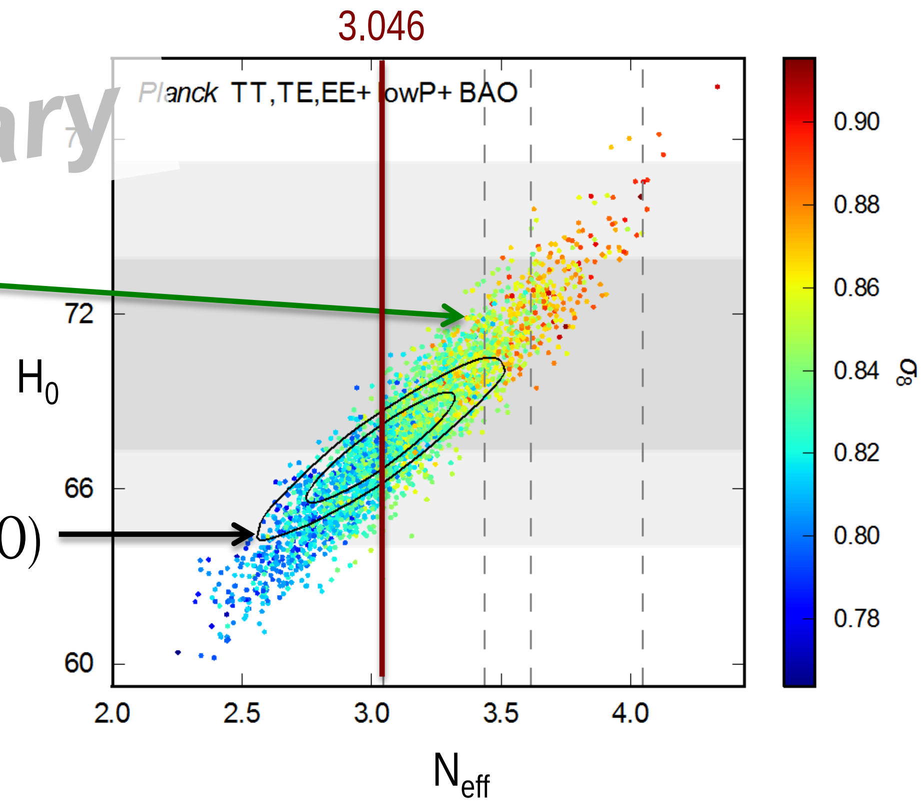

N_{eff} compatible with standard model, > 0 at 10 to 17σ

(was ~ 10 to 12σ with Planck 2013)

1. Probing the CNB *average* density

Are we sure that observed N_{eff}~3 comes from neutrinos? Could be anything scaling like radiation:

other light decoupled relics
(axions, gravitinos, etc.)

background of
gravitational waves

scalar field oscillating
in quartic potential

standard neutrinos

neutrinos with exotic interactions
(self-inter., or with dark sector)

other light relics with interactions
(self-inter., or with dark sector)

effects from
modified gravity,
extra dimensions…

1. Probing the CNB *average* density

…ld be anything scaling like radiation:

Standard neutrinos have the strongest theoretical motivations.

Only species giving a definite prediction of N_{eff}~3.

But can we get extra observational evidence?

Maybe at level of perturbations?

gravitational waves

scalar field oscillating
in quartic potential

standard neutrinos

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effects from
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2. Probing the CNB *perturbations / anisotropies*

- Until photon decoupling *neutrino perturbations* governed by Vlasov equation, like any decoupled (*free-streaming*) relativistic relic.
- Their density/pressure perturbations, energy flux and anisotropic pressure/shear act a sources in Einstein equations: *gravitational interactions with photons, baryons*.
- Affects the amount of gravitational boost of CMB acoustic oscillations just after Hubble crossing.
- Controls *amplitude and phase of CMB acoustic oscillations*.

Can we observe these free-streaming effects?

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Can we observe these free-streaming effects?

- later on ($T_\nu < m_\nu$), non-relativistic transition modifies evolution of density perturbations.

Can we see these additional effects of the masses?

2. Probing the CNB *perturbations / anisotropies*

Define two phenomenological parameters changing the perturbation equations:

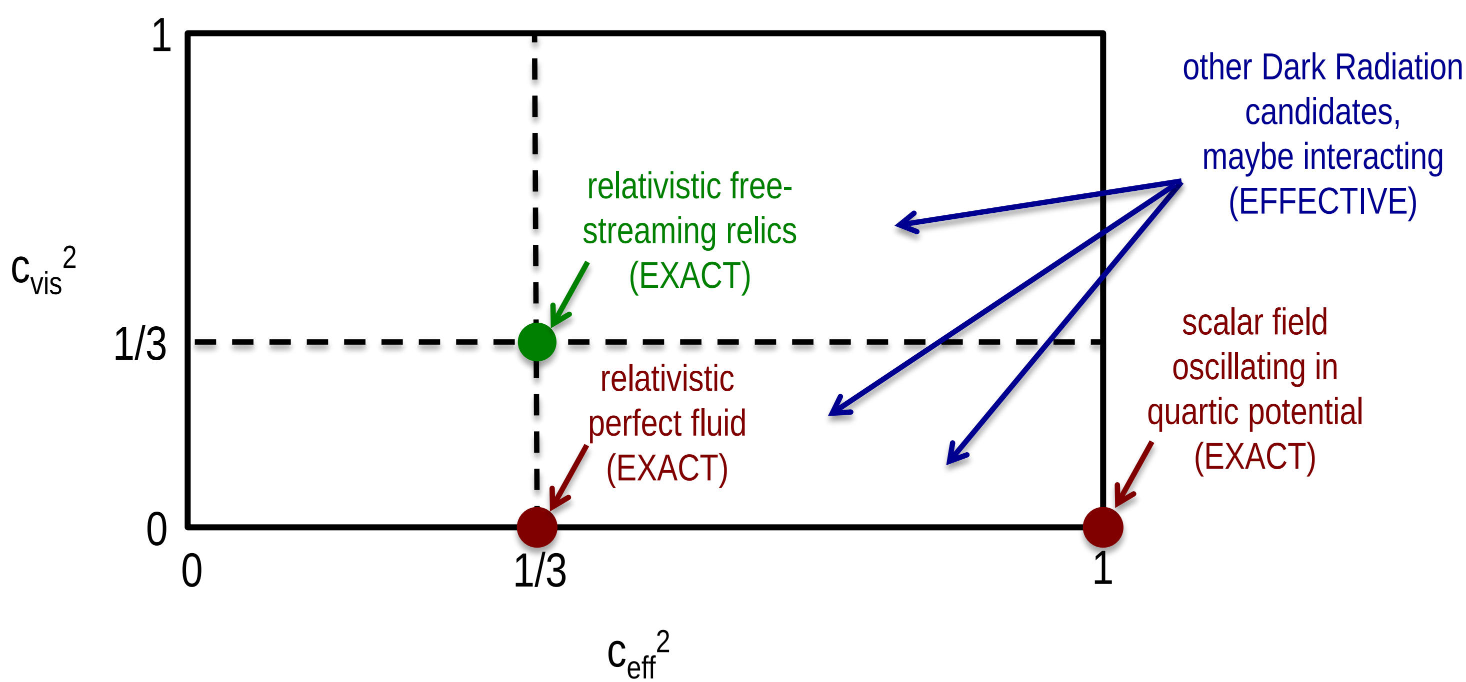
1) Effective *sound speed* : $\delta p = c_{eff}^2 \, \delta\rho$

2) Effective *viscosity speed* c_{vis} controlling the amount of anisotropic pressure / shear

Archidiacono et al. 2011

inspired from *Hu 1998,*

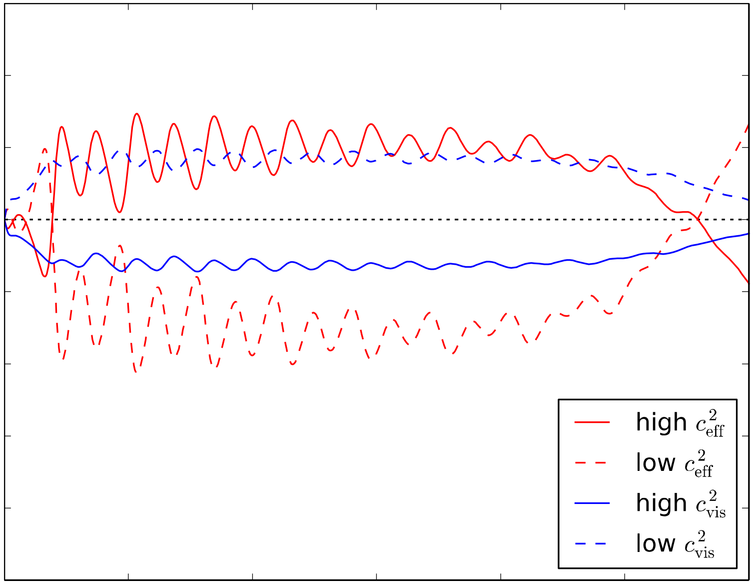
Trotta & Melchiorri 2004…



2. Probing the CNB *perturbations / anisotropies*

Effect of varying (c_{eff}^2, c_{vis}^2) on CMB spectrum:

Temperature



Polarisation

Audren et al., arXiv:1412.xxxx (in preparation)

2. Probing the CNB *perturbations / anisotropies*

If we could prove that $(c_{eff}^2, c_{vis}^2) = (1/3, 1/3)$: evidence for CNB anisotropies (through the CMB ones)

other light decoupled relics
(axions, gravitinos, etc.)

~~background of gravitational waves~~

~~scalar field oscillating in quartic potential~~

standard neutrinos

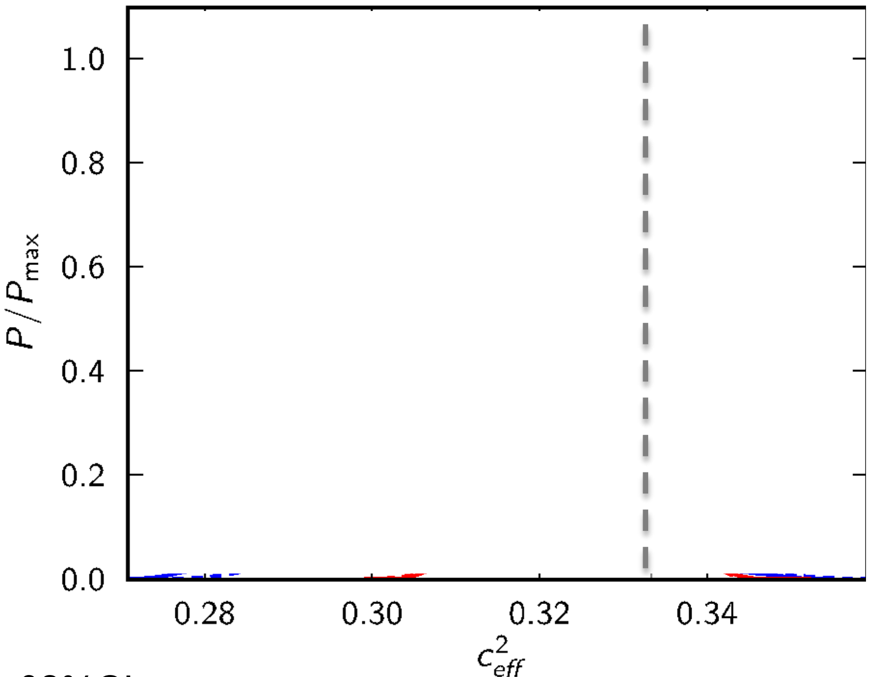
~~neutrinos with exotic interactions (self-inter., or with dark sector)~~

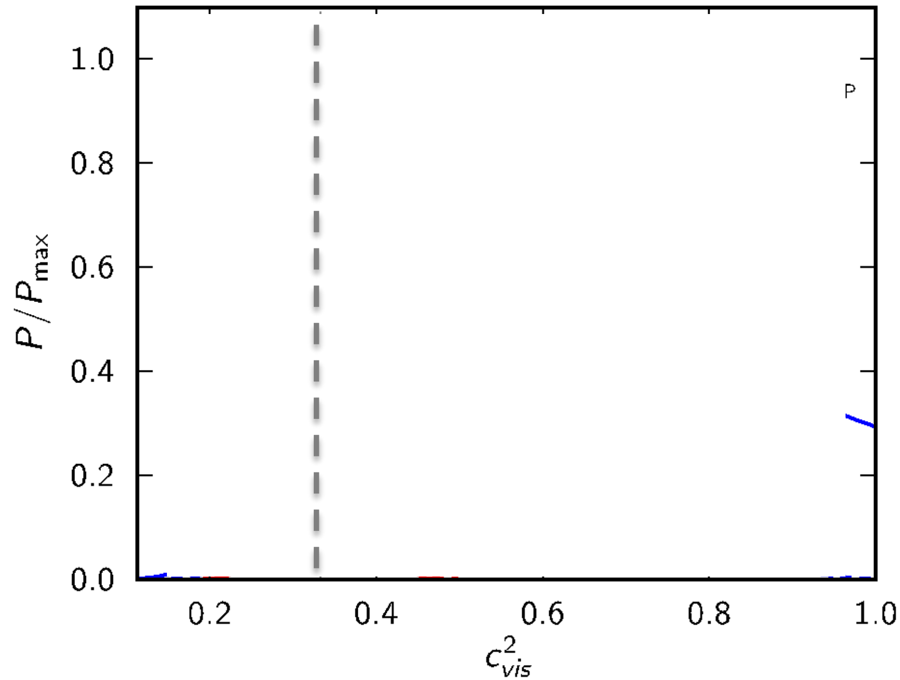
~~other light relics with interactions (self-inter., or with dark sector)~~

~~effects from modified gravity, extra dimensions~~…

If we could prove that $(c_{eff}^2, c_{vis}^2) \neq (1/3, 1/3)$: very strong result in favor of alternative Dark Radiation

2. Probing the CNB *perturbations / anisotropies*

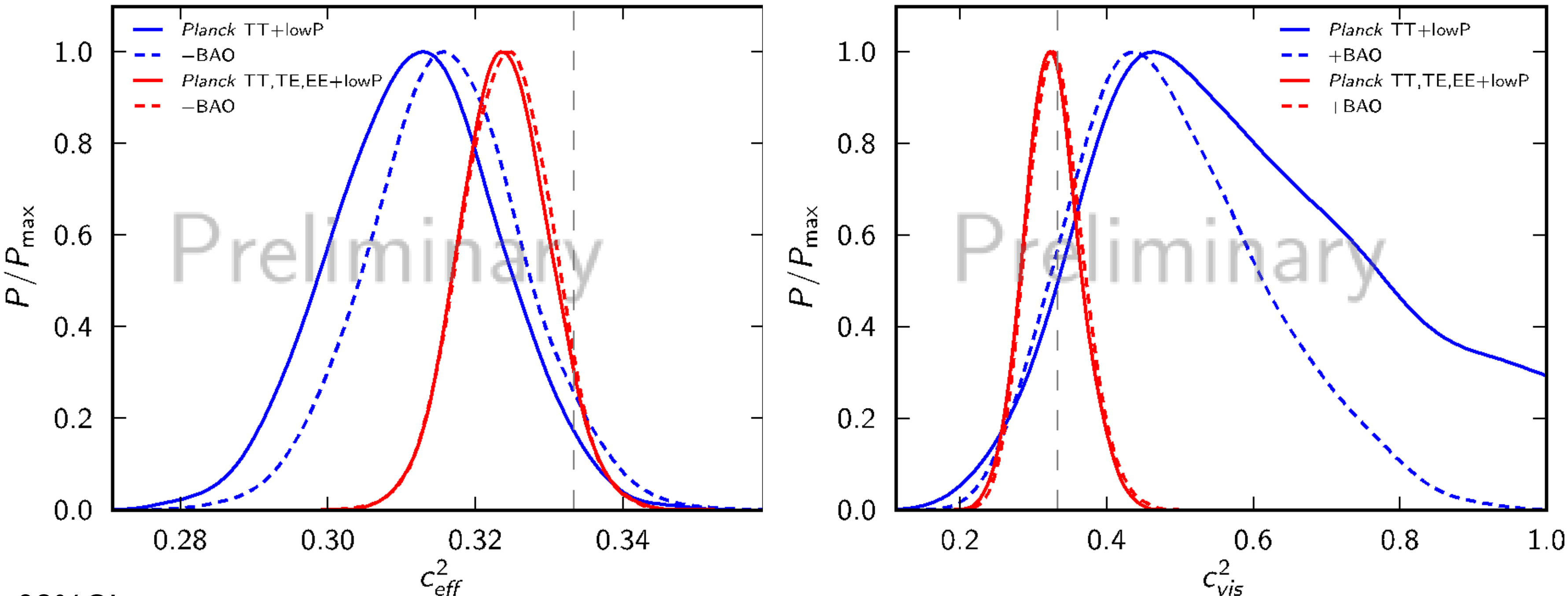




68%CL

Parameter	TT+lowP	TT+lowP+BAO	TT,TE,EE+lowP	TT,TE,EE+lowP+BAO
$c^2_{\rm vis}$				
$c^2_{\rm eff}$				

2. Probing the CNB *perturbations / anisotropies*



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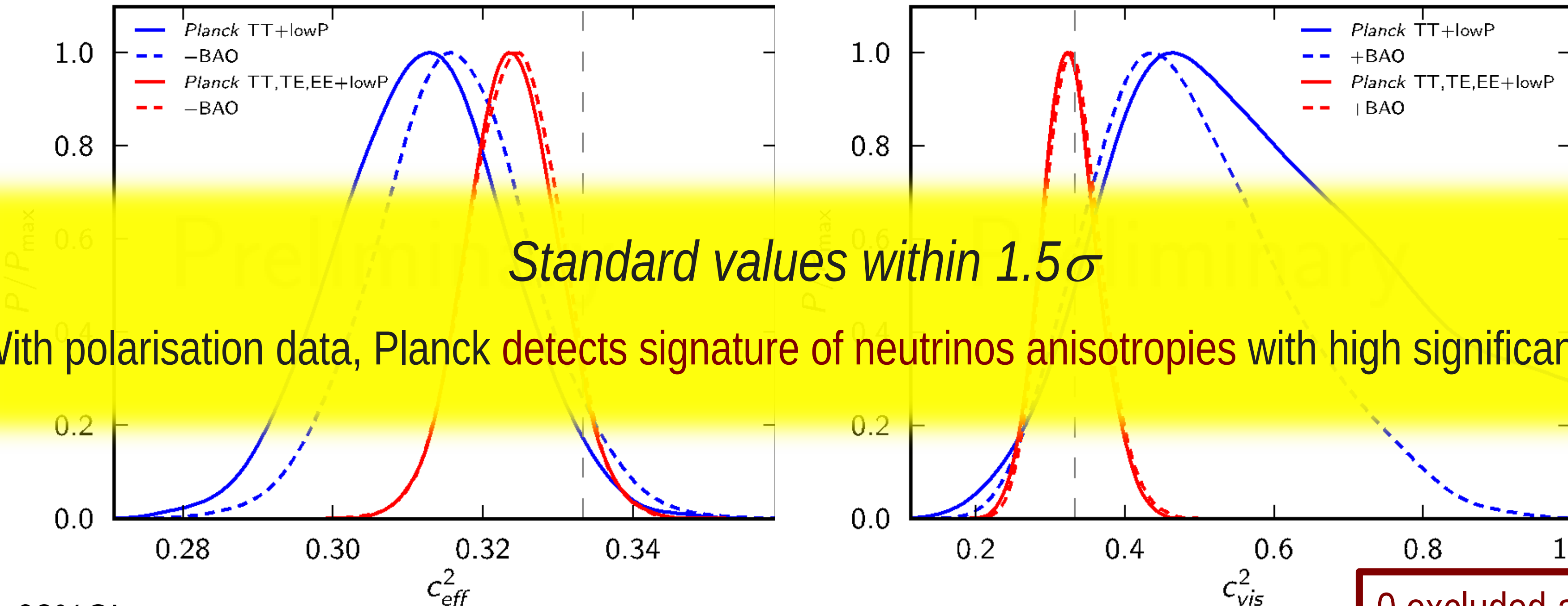
Parameter	TT+lowP	TT+lowP+BAO	TT,TE,EE+lowP	TT,TE,EE+lowP+BAO
$c^2_{\rm vis}$	$0.47^{+0.26}_{-0.12}$	$0.44^{+0.15}_{-0.10}$	0.327 ± 0.037	0.331 ± 0.037
$c^2_{\rm eff}$	0.312 ± 0.011	0.316 ± 0.010	0.3240 ± 0.0060	0.3242 ± 0.0059

2. Probing the CNB *perturbations / anisotropies*



Standard values within 1.5σ

With polarisation data, Planck detects signature of neutrinos anisotropies with high significance!

0 excluded at 9σ

68%CL

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Can we observe these free-streaming effects? *YES !!!*

- later on ($T_\nu < m_\nu$), non-relativistic transition modifies evolution of density perturbations.

Can we see these additional effects of the masses?

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Can we observe these free-streaming effects? *YES !!!*

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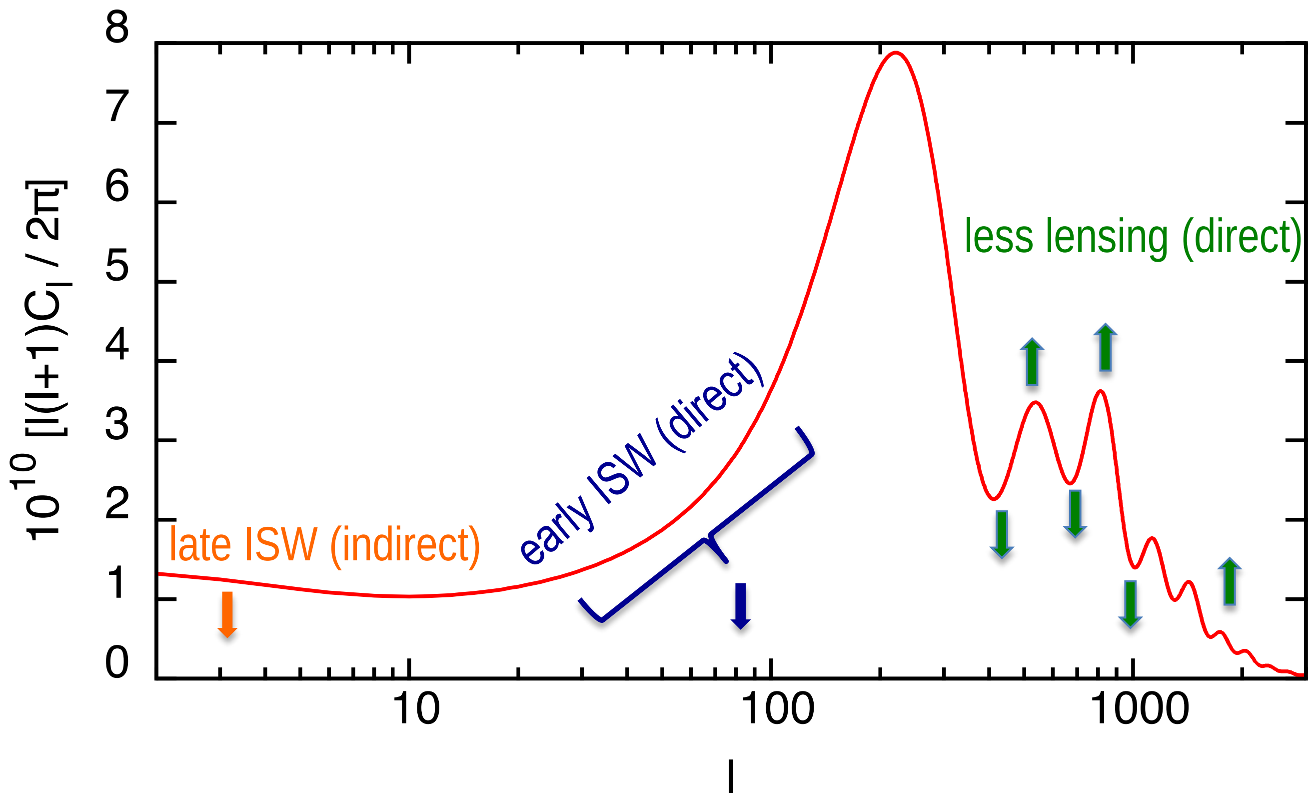
Can we see these additional effects of the masses? *NOT YET*

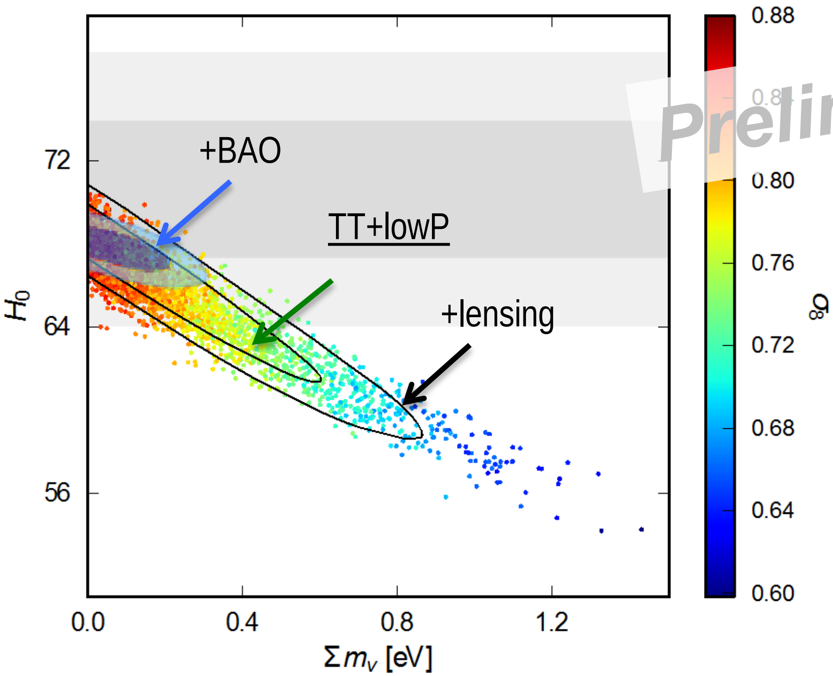
2. Probing the CNB *perturbations / anisotropies*

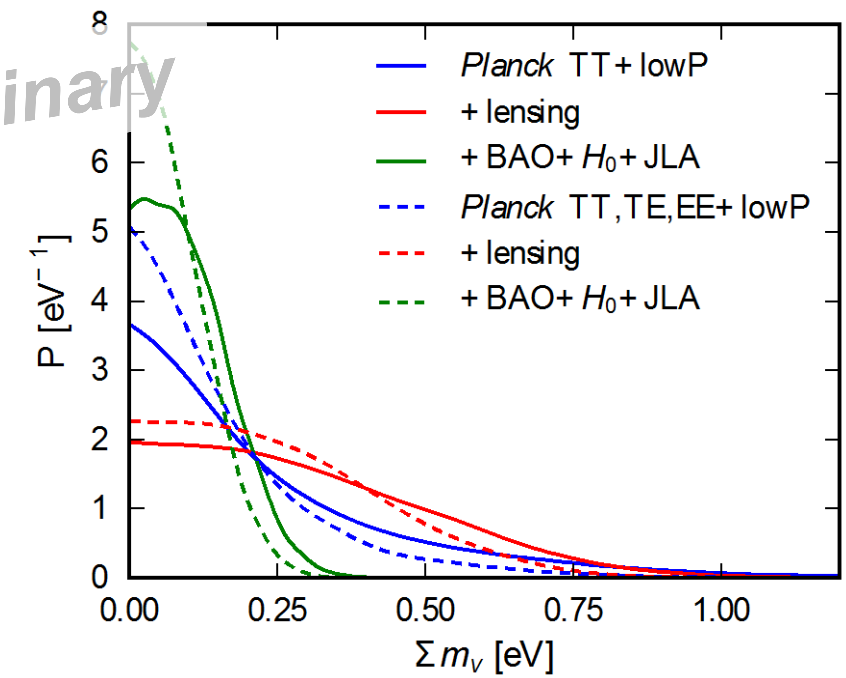
Effect of neutrino masses on CMB Temp. for a constant d_A(dec) and fixed ``early cosmology'' (densites at $T_\nu > m_\nu$) :



Also effects on lensing spectrum probed by lensing extraction: reduction of power on small scales

2. Probing the CNB *perturbations / anisotropies*

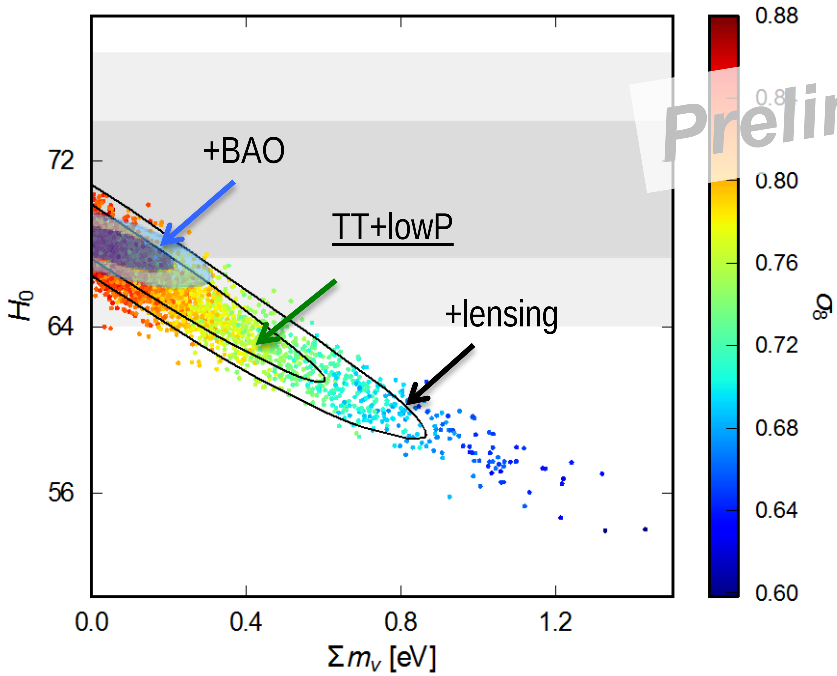


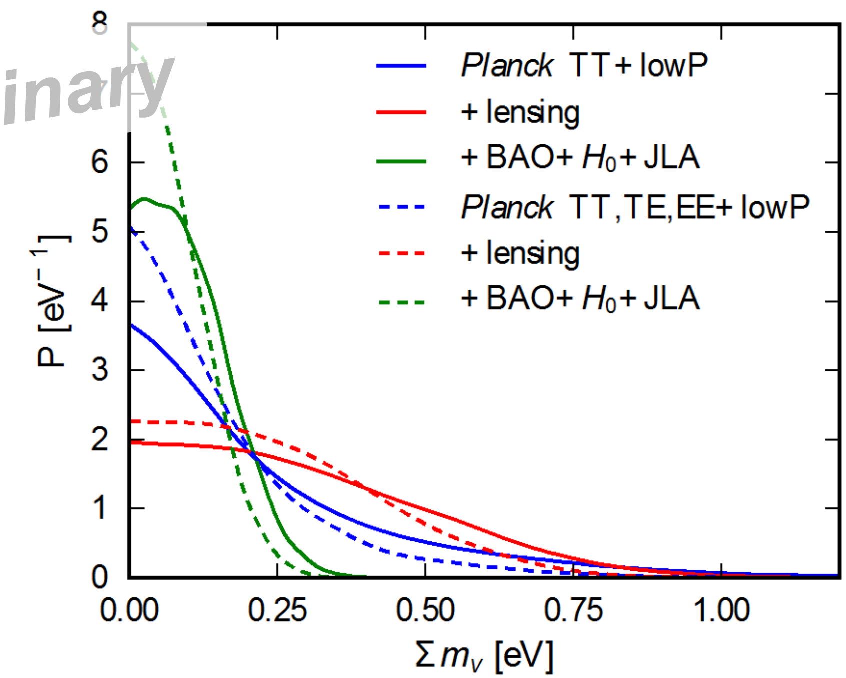


- Without lensing extraction:

X
m⊓ < 0.72 eV (*Planck* TT+lowP)
X
m⊓ < 0.21 eV (*Planck* TT+lowP+ BAO)
X
m⊓ < 0.48 eV (*Planck* TT,TE,EE+lowP)
X
m⊓ < 0.16 eV (*Planck* TT,TE,EE+lowP+BAO). *strongest bound*

2. Probing the CNB *perturbations / anisotropies*





- With lensing extraction:

$\sum m_\nu < 0.70$ eV (95%, *Planck* TT+lowP+lensing).

$\sum m_\nu < 0.58$ eV (95%, *Planck* TT,TE,EE+lowP+lensing).

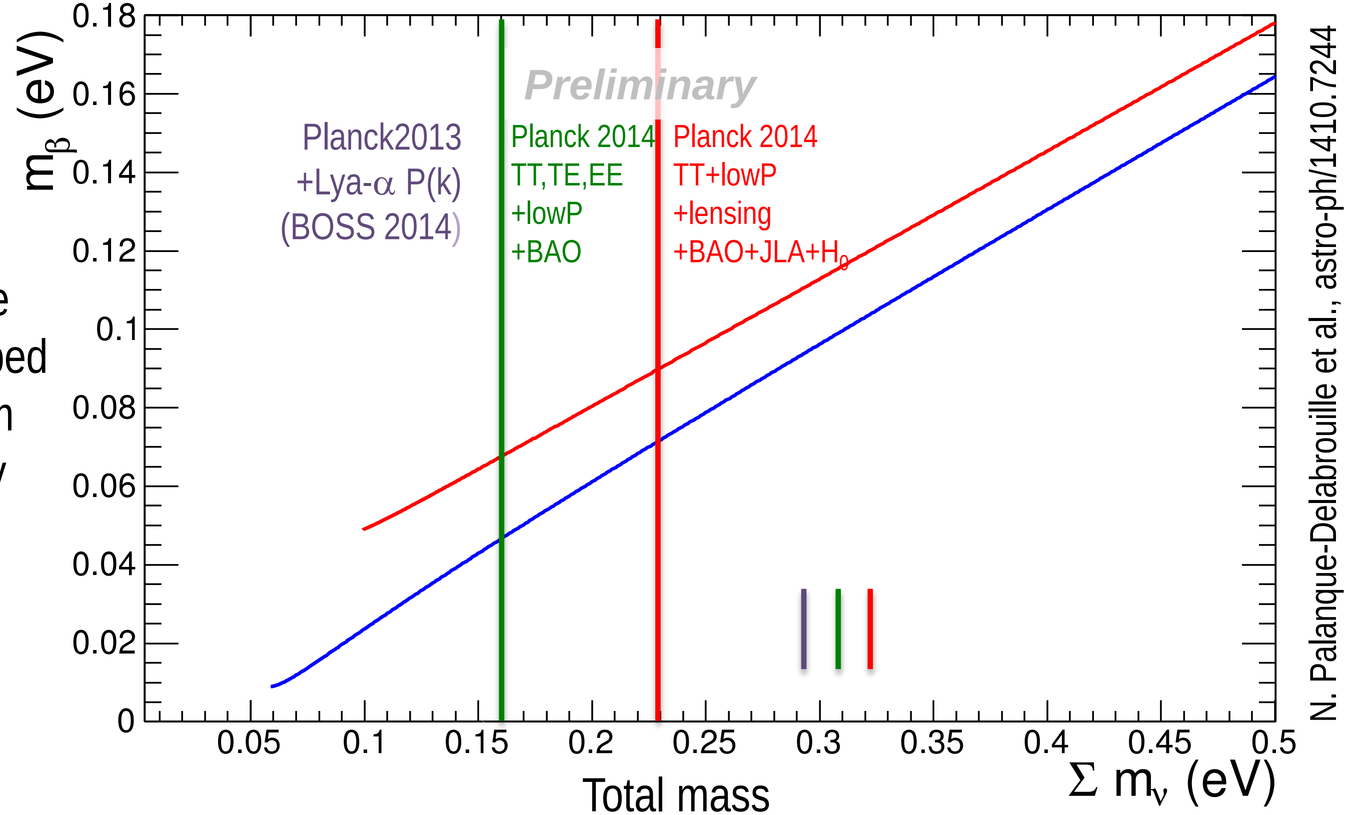
$\sum m_\nu < 0.23$ eV, $\Omega_\nu h^2 < 0.0025$ (95%, *Planck* TT+lowP+lensing+ext).

BAO, JLA, H_0

final conservative bound

2. Probing the CNB *perturbations / anisotropies*

Effective mass probed by tritium β-decay



Total mass

… but small tensions with data prefering a low σ_8 : SZ clusters, galaxy weak lensing, and RSD…

Answer to first question:

We are confident that we have detected the Cosmic Neutrino Background because we can probe with high significance :

1) its background density: N_{eff} ~ 3 matching old theoretical predictions (0 excluded at 17σ)
2) its perturbations in the relativistic regime: $(c_{eff}^2, c_{vis}^2) \sim (1/3, 1/3)$ ($c_{vis}^2=0$ excluded at 9σ)

We don't see yet its perturbations in the non-relativistic regime, but detection of Σm_ν expected to be just around the corner

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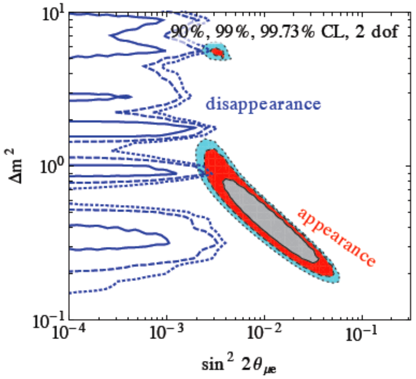
We don't see yet its perturbations in the non-relativistic regime, but detection of Σm_ν expected to be just around the corner

Second question: do we see extra light relics?

3. Are there extra light relics?

- Lots of well-motivated candidates for extra relativistic relics. What does active neutrino mass bounds become in this context?
- These candidates could be light instead of ultra-relativistic. Contribute to both N_{eff} and M_{ν}. What are bounds on their mass?
- Short baseline oscillation anomaly (LSND, MiniBoone, reactor data…)…

Is one light sterile neutrino with m~1eV compatible with Planck?



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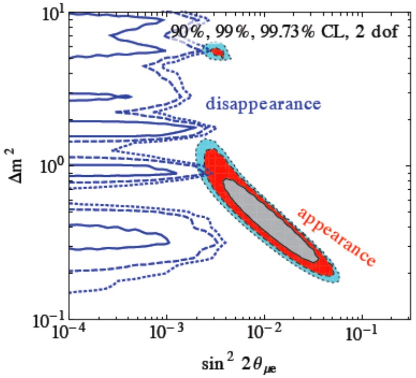
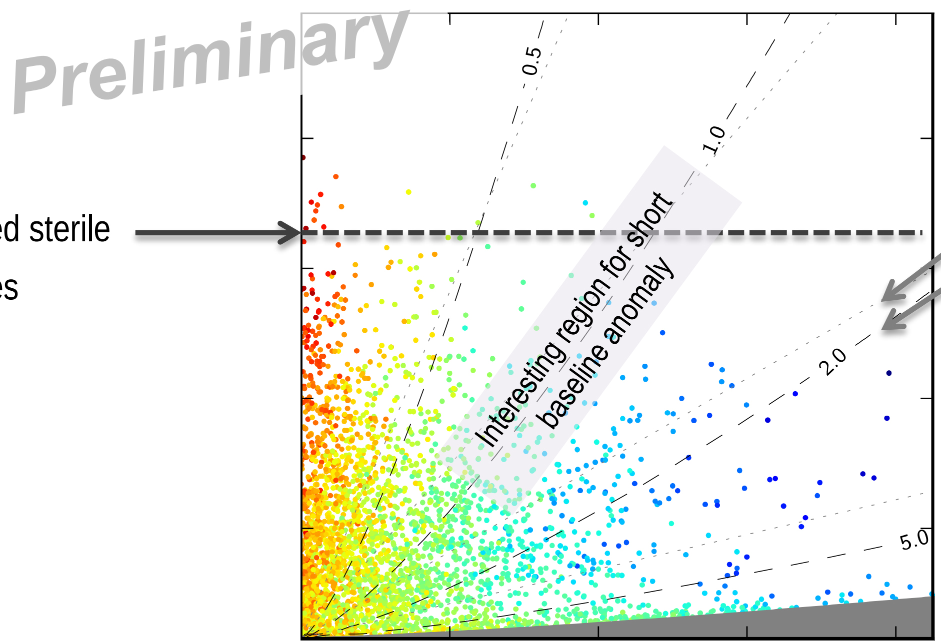


- Model dependent analysis. To catch most of the cases, either exactly or approximately, study one case (one massive extra species) but display results in terms of:
  - N_{eff} : parameter for relativstic density at early times
  - m_{eff} : parameter for non–relativistic mass of HDM today ($\omega_{HDM} = m_{eff}$ / 93.14eV)

3. Are there extra light relics?

One thermalised sterile neutrino species



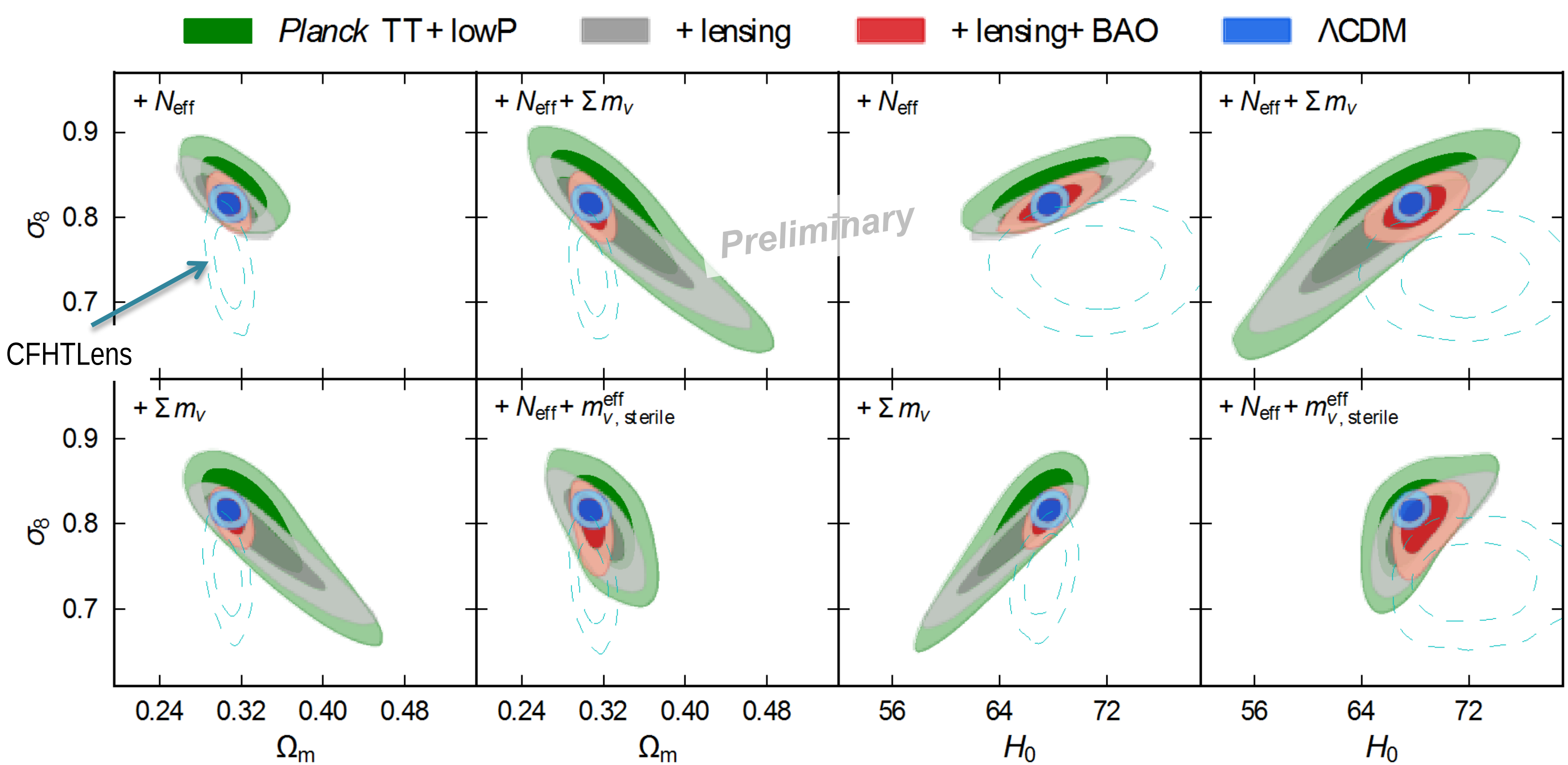
Physical masses

(DW sterile neutrino)

(early decoupled thermal particle)

Prior m < 10eV to avoid degeneracy with CDM

3. Are there extra light relics?



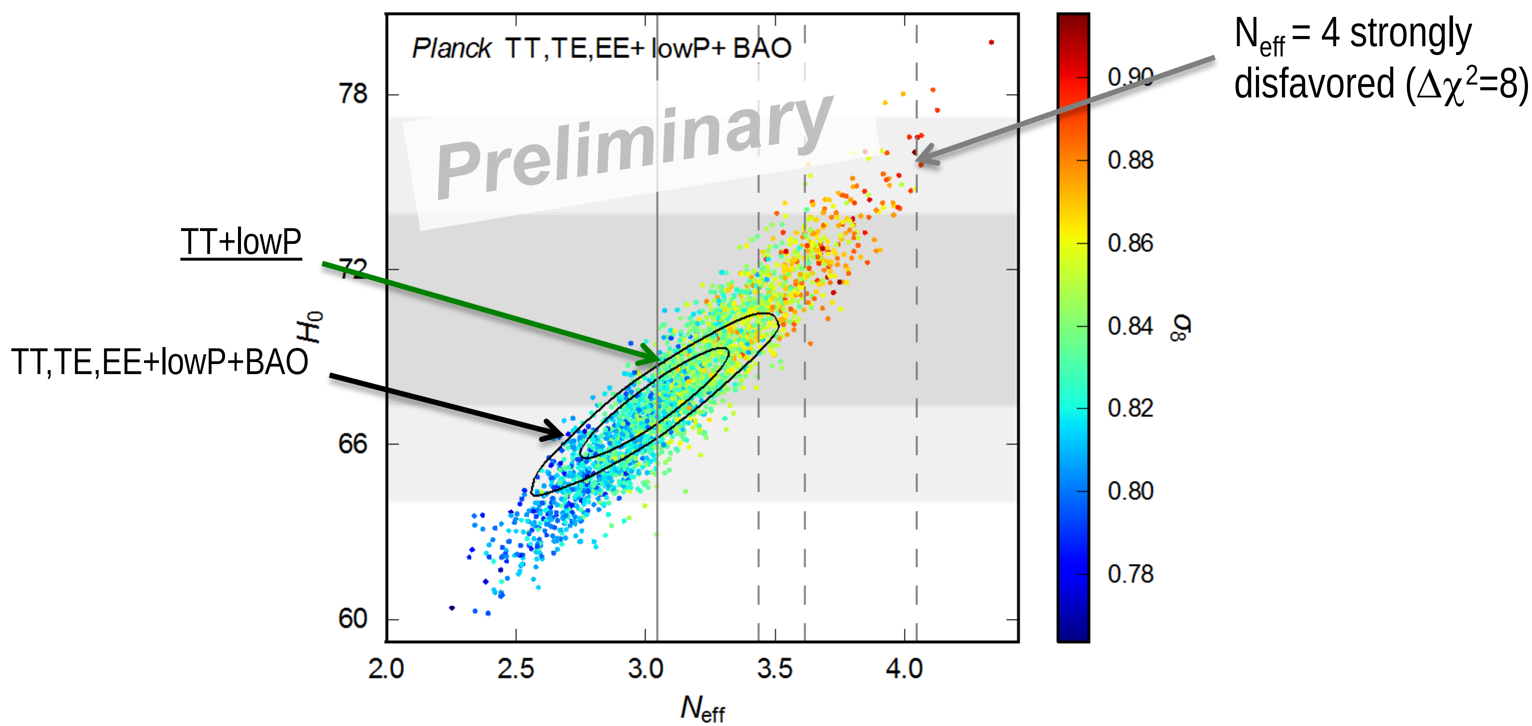
- Several datasets prefer low σ_8 (SZ clusters, galaxy weak lensing, …) but are also sensitive to H_0 and Ω_m.
- Direct measurements of Hubble rate prefer high H_0.

Assuming massive neutrinos and/or extra radiation brings very marginal reduction of tensions.

3. Are there extra light relics?

No convincing evidence, and stronger bounds than in 2013

3. Are there extra light relics?



Still, with high-H_0 prior from LMC and MW cepheids (Efstathiou 2014) :

$$\left.\begin{aligned} N_{\rm eff} &= 3.46 \pm 0.25 \\ H_0 &= 71.1 \pm 2.1 \end{aligned}\right\} \quad (68\%, \textit{Planck}\ \text{TT+lowP+ high}\ H_0)$$