Neutrinos in Cosmology and Astrophysics

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Neutrinos in Cosmology and Astrophysics

- Outline of the talk

  - Limits on N_{eff}.
  - Limits on neutrino mass.
  - Non-standard neutrinos scenario.
  - Conclusion

Neutrino effects on observables

BBN:

- neutrinos mantain neutron to proton equilibrium until its decoupling. Remaining neutrons form ^{4}He nucleus (and other things).

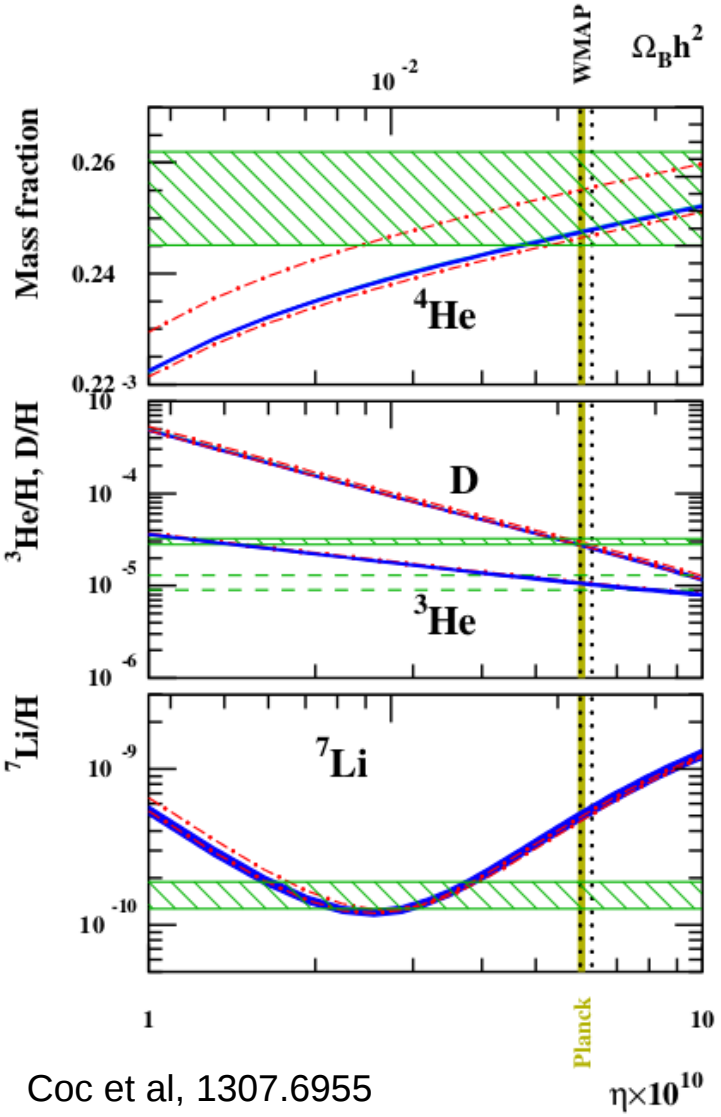
- Any extra radiation speeds-up the Universe expansion, and neutrino decoupling would happen earlier. Extra radiation can be written as a higher neutrino effective number:

$$\rho_R = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

- More neutrons survive, increasing the rate of He4.

Not really neutrino physics (unless we are talking about sterile neutrinos or strong deviations from Fermi-Dirac distribution), but let's continue...

Neutrino effects on observables



Coc et al, 1307.6955

He4 production for Neff going from 3 to 3.7

Earlier work resulted in:
2.89 < Neff < 4.22

Neutrino effects on observables

CMB anisotropies:

- Baryons = Baryons + Electrons
- Coupled baryons + photons fluid feels a pressure given by the photon pressure

P=ρ/3 → Acoustic Osillation

- Sound Horizon: correlation length of each oscillation mode.

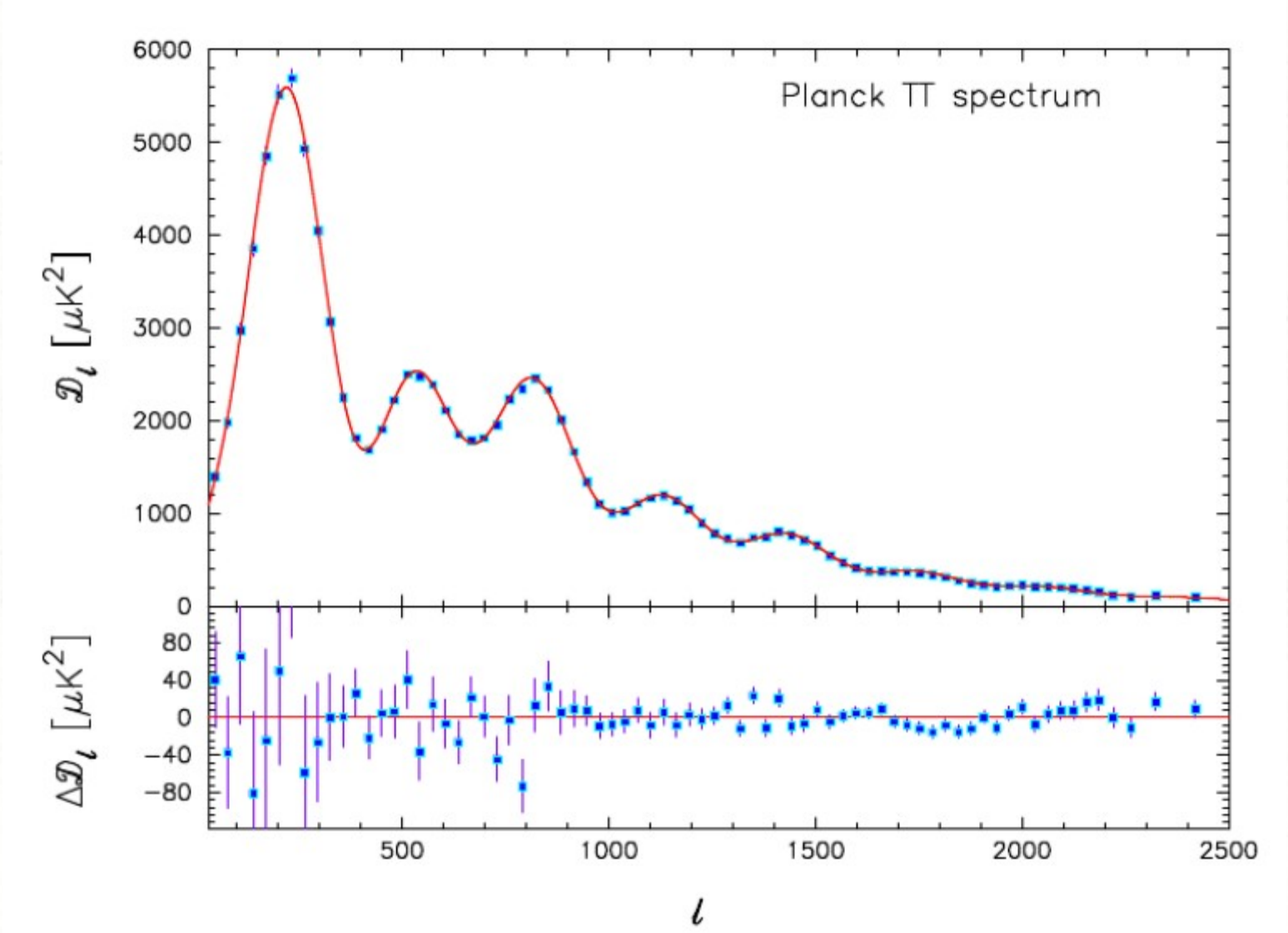
$$r = \int_{t_0}^{t} \frac{c_S\, dt}{a}$$

Sound speed

- Temperature map contains information of such sound horizon scale, and can be expanded in spherical harmonics:

$$\frac{\delta T(\hat{n})}{T} = \sum a_{lm} Y_{lm}(\hat{n}) \longrightarrow C_l = < a_{lm} a^*_{lm} >$$

Neutrino effects on observables

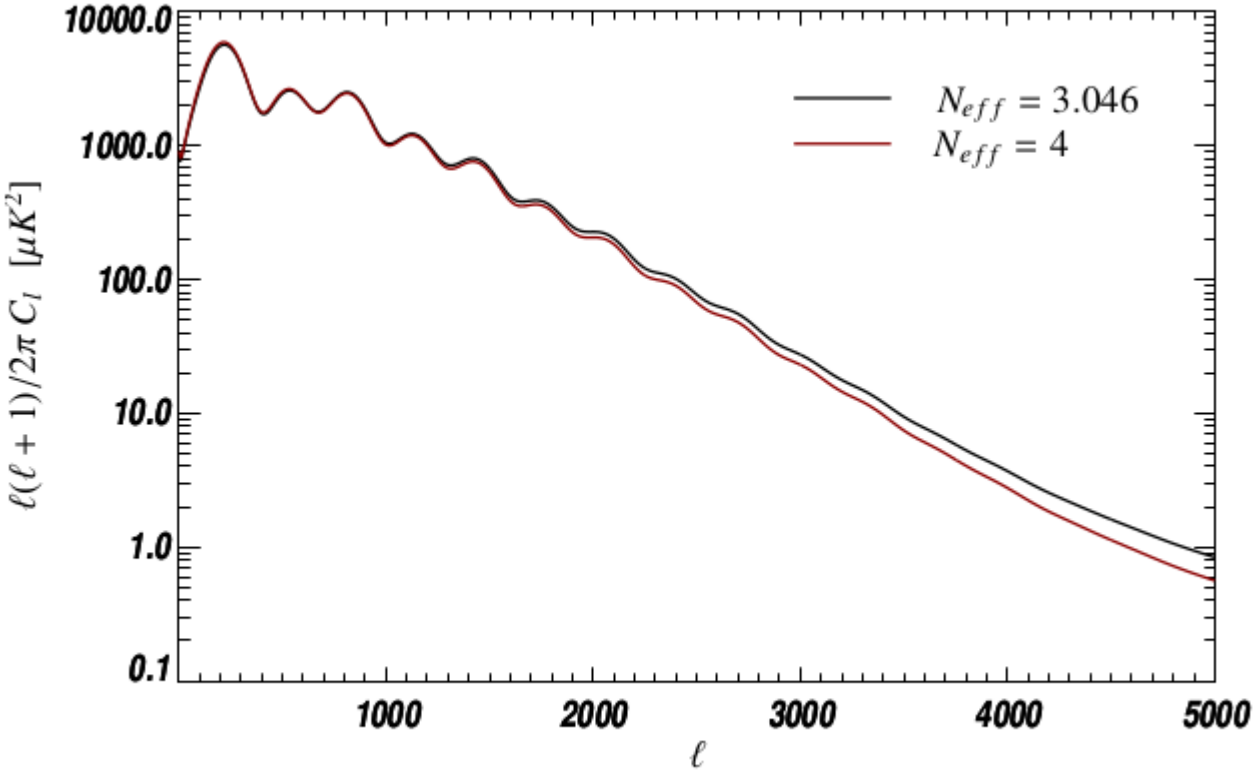


Neutrino effects on observables

Neutrino effects on CMB anisotropies:

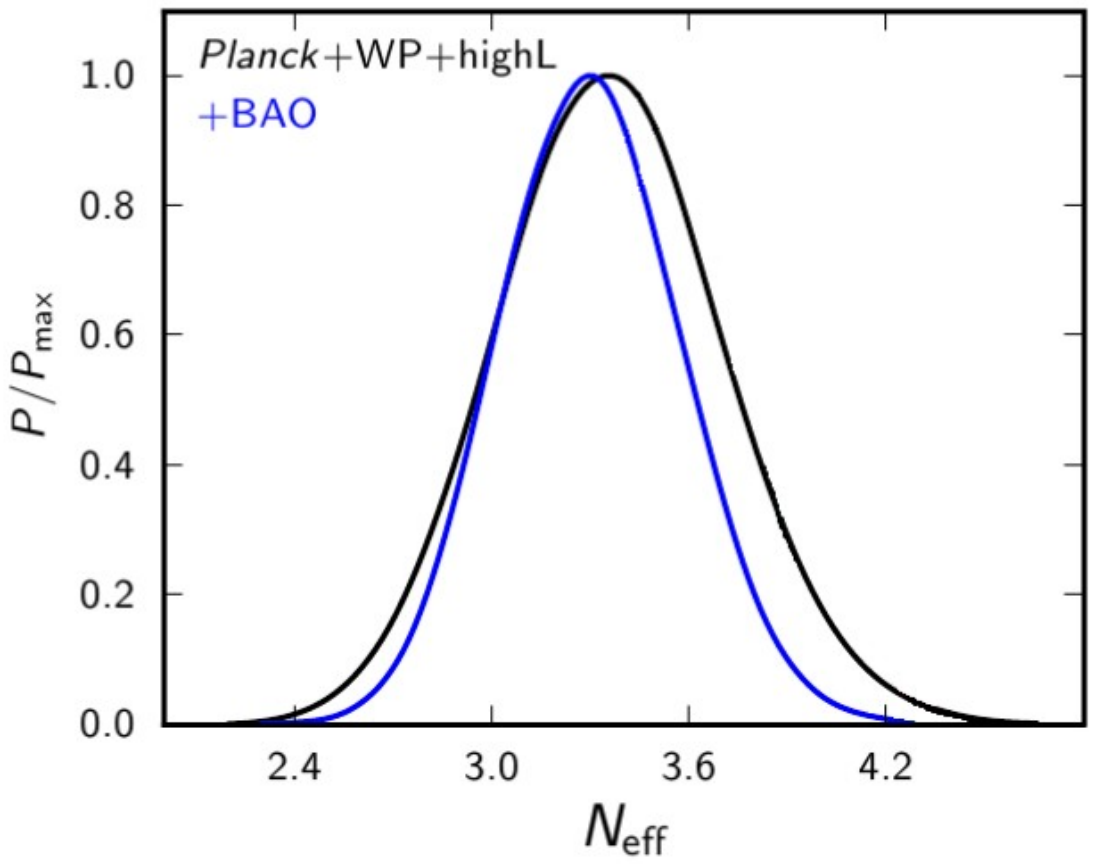
- CMB anisotropies depends on age of transition to matter-dominated universe and amount of non-relativistic matter at such transition.
- Increase in Neff speeds up the Universe cooling, decreasing the age of the Universe at recombination.
- Neutrinos own anisotropies couples gravitationaly to CMB anisotropies.

Neutrino effects on observables



Neutrino effects on observables

[Planck 2013 results.XVI.]



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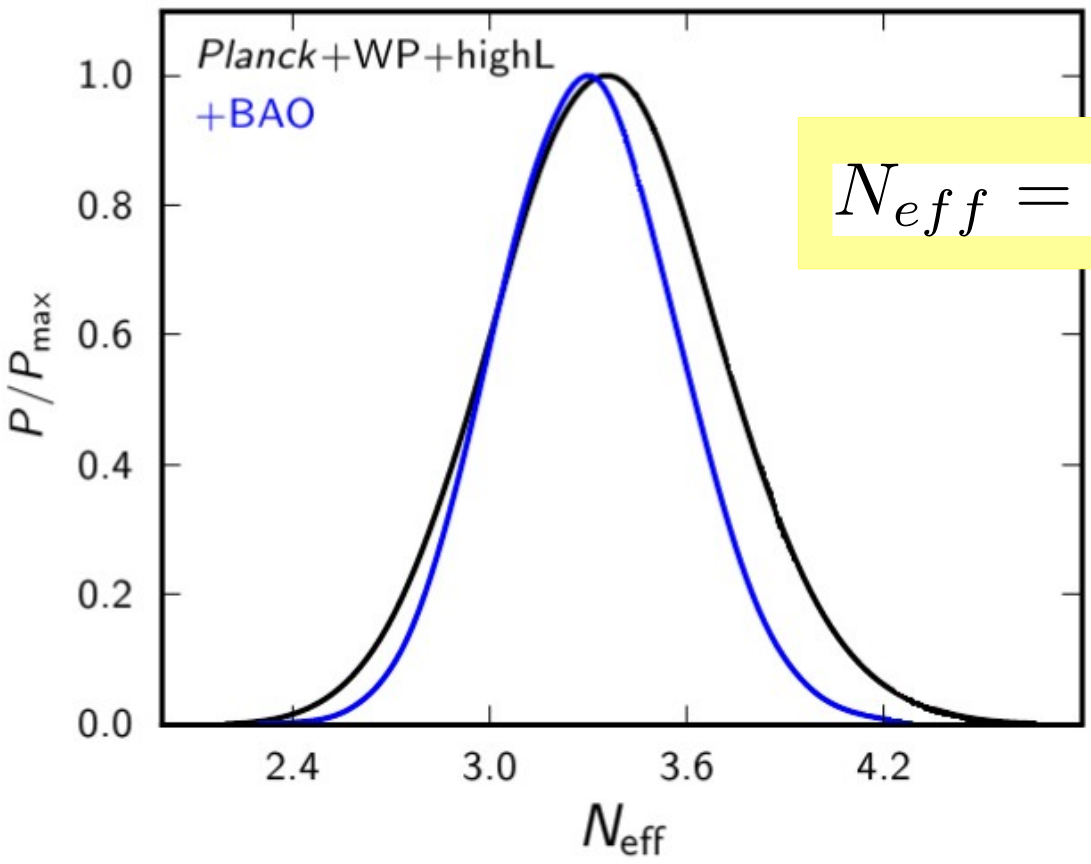


$$N_{eff} = 3.36 \pm 0.34$$

Effects of Neutrino Mass

Effects of Neutrino Mass

or…

When neutrinos became non-relativistic was something important happening?

Neutrino effects on observables

- Recombination:

$$T_\gamma = 0.3 \text{ eV} \quad \rightarrow \quad T_\nu = 0.21 \text{ eV}$$

CMB anisotropies in principle sensible to neutrinos with *m ~ 0.1 eV*.

- Transition to matter-dominated epoch:

$$a = \frac{\Omega_r}{\Omega_m} = 3.4 \times 10^{-4} \rightarrow T_\nu \sim 0.46\,\text{eV}$$

Power Spectrum analysis in principle sensible to neutrinos with *m ~ 0.1 eV*.

Neutrino effects on observables

How to have an intuition of the effect of increasing neutrino mass on cosmological observables? Hard, due to lot of correlations.

- All neutrinos have the same mass, larger than $\sim 10^{-3}$ *eV*, and then are non-relativistic today ($T = 2.34\ 10^{-4}$ *eV*).

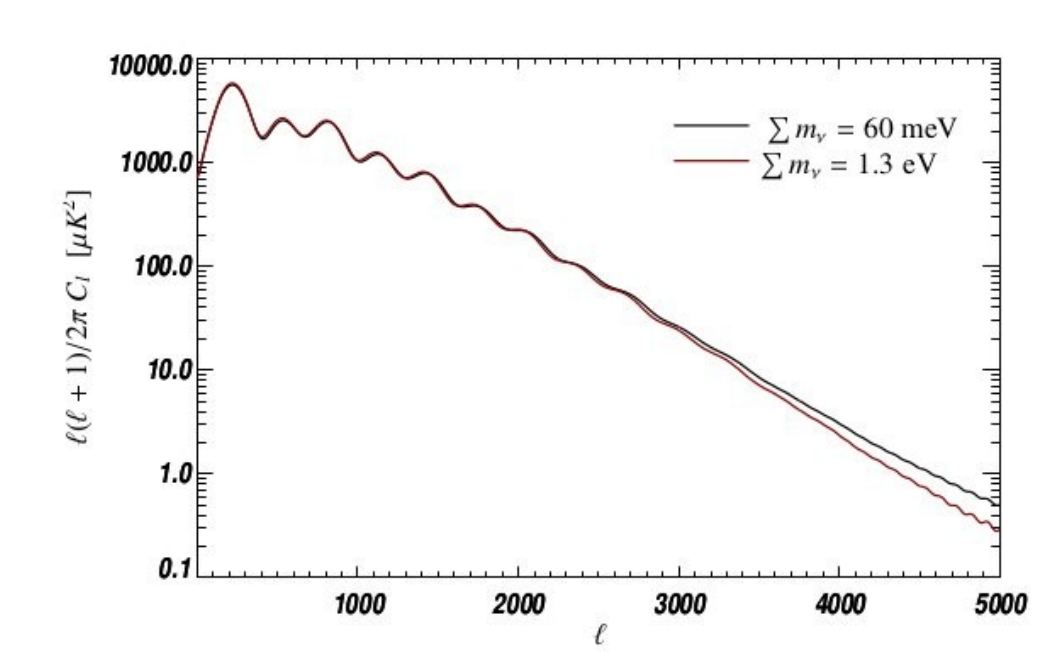
- Let's fix the amount of CDM today, which the neutrinos are part of (the only known fraction of CDM!).

- Neutrinos are non-relativistic today, but were relativistic during Recombination, so the calculations done so far were correct.

- Increasing neutrino mass would then decrease the amount of DM, delaying the matter-radiation equality, causing a similar effect of increasing Neff.

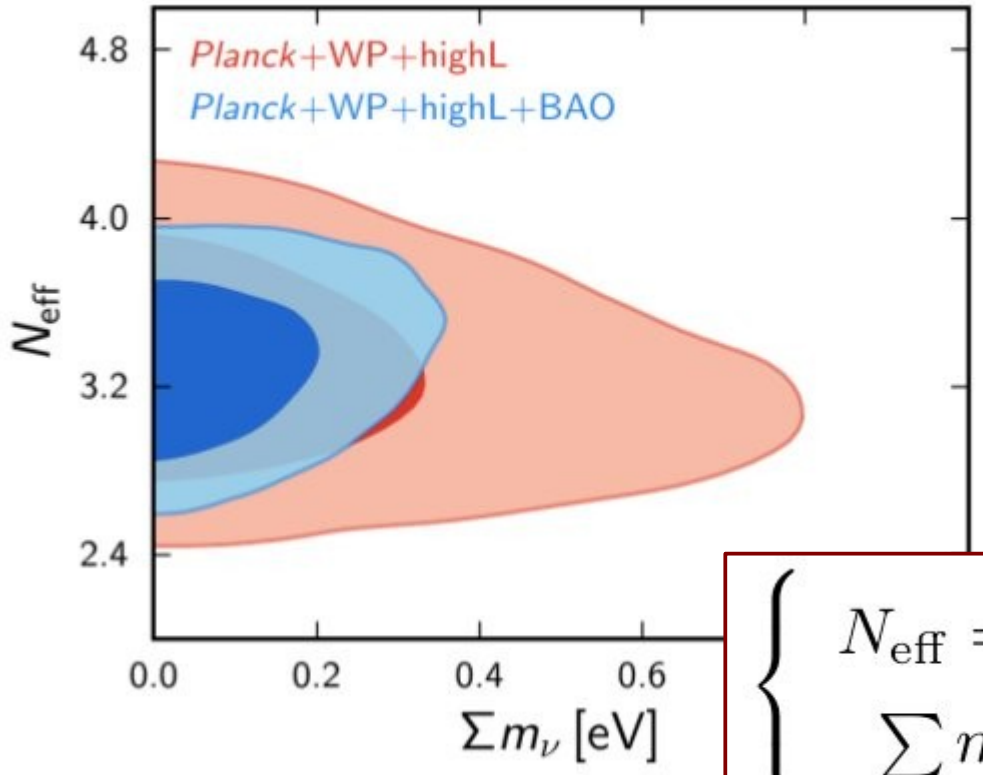
Neutrino effects on observables

➔ Increasing neutrino mass affects amplitutde of first acoustic peak (but is degenerated with other cosmological observables), and supresses damping tail.



Combined Results (Planck+WP+BAO)

[Planck 2013 results.XVI.]



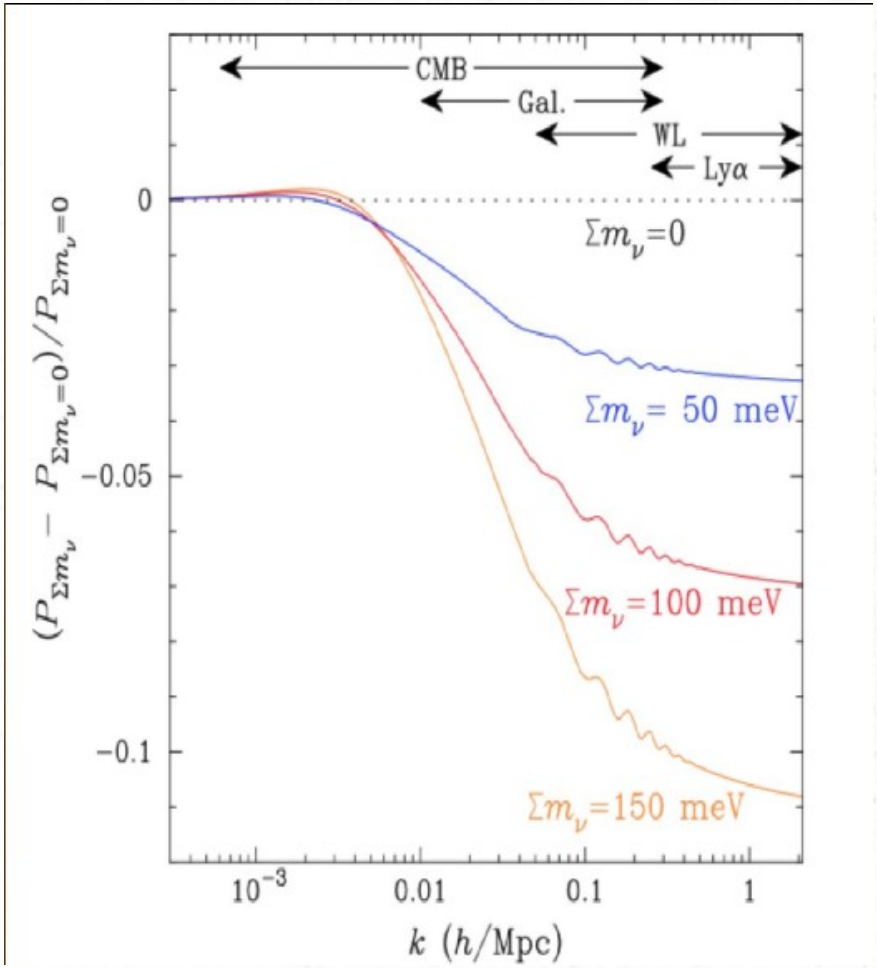
$$\begin{cases} N_{\rm eff} = 3.32 \pm 0.27 \ (68\% CL) \\ \sum m_\nu < 0.28 \ {\rm eV} \ (95\% CL) \end{cases}$$

Neutrino effects on observables

Structure Formation:

- Some of today non-relativistic neutrinos were once fast enough to escape overdense regions, supressing structure growth on small scales → limits on m_ν.
- Massive neutrinos affect also the evolution of universe in latter times, affecting the imprint of primordial perturbations on large scale structures → Baryonic Acoustic Oscillations (BAO)

Neutrino effects on observables



Together with CMB data, provides the stringest limits on neutrino mass.

$$\sum m_i < 0.136\,\mathrm{eV}$$

Arxiv:1507.08665

Sterile Neutrinos

➔ Recently, some short-baseline neutrino experiments presented some tension between the data and the standard neutrino oscillation paradigm.

- Reactor Neutrino Anomaly: supression of reactor neutrino signal at very close detectors.
- LSND/MiniBoone: appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ flux

➔ Such tension can be alleviated by the inclusion of a fourth neutrino generation, sterile, which mixes with the three active neutrinos.

$$\Delta m_s^2 \sim 1eV^2$$

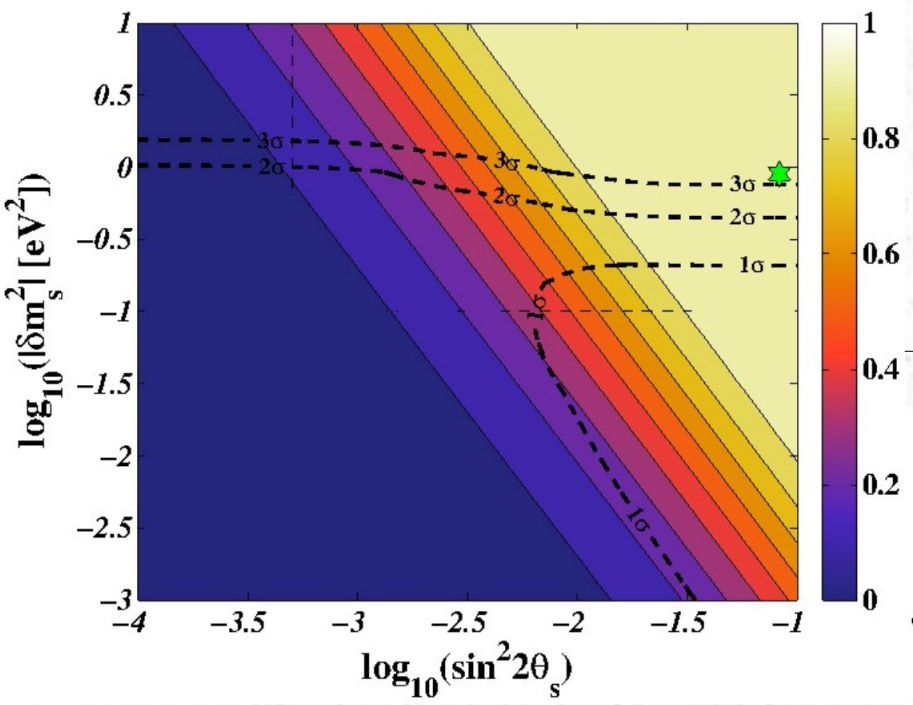
$$sin^2 2\theta_s \lesssim 10^{-1}$$

Does cosmology has something to say about that?

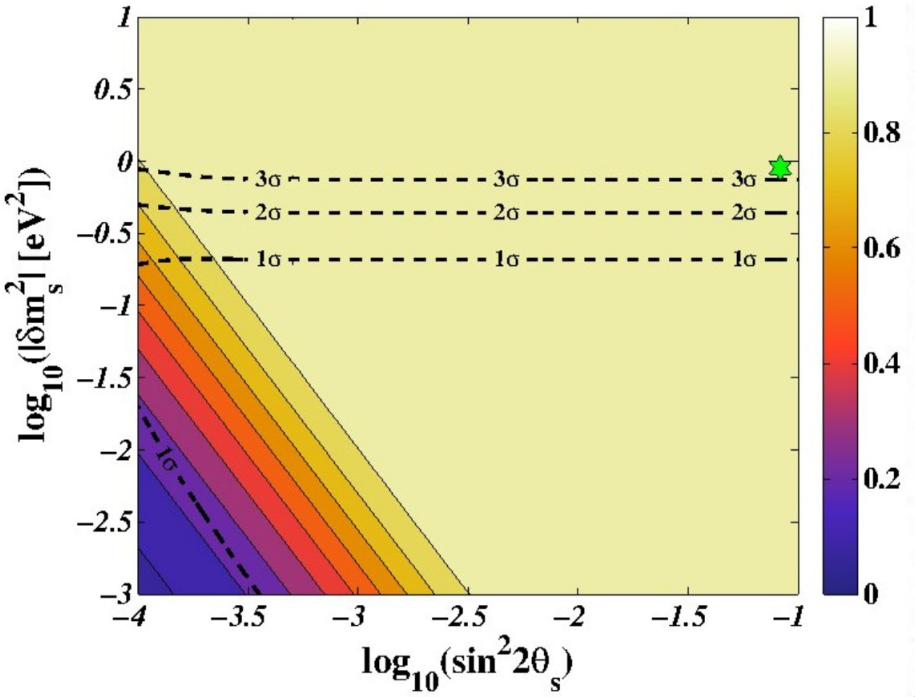
Sterile Neutrinos

→ A new neutrino family would behave as radiation during part of Universe history. Bounds on N_{eff} would apply to such scenario if fourth family are in equilibrium.

Sterile Neutrinos



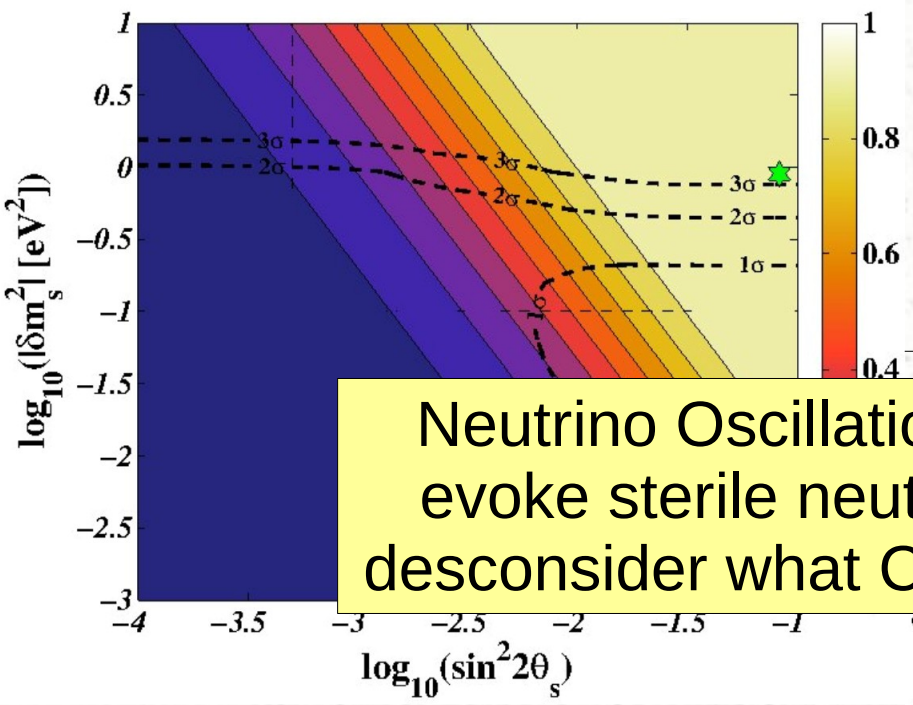
Normal Hierarchy,
non-Resonant Production



Inverted Hierarchy,
Resonant Production

Hannestad et al., JCAP 1207, 025

Sterile Neutrinos



Normal Hierarchy,
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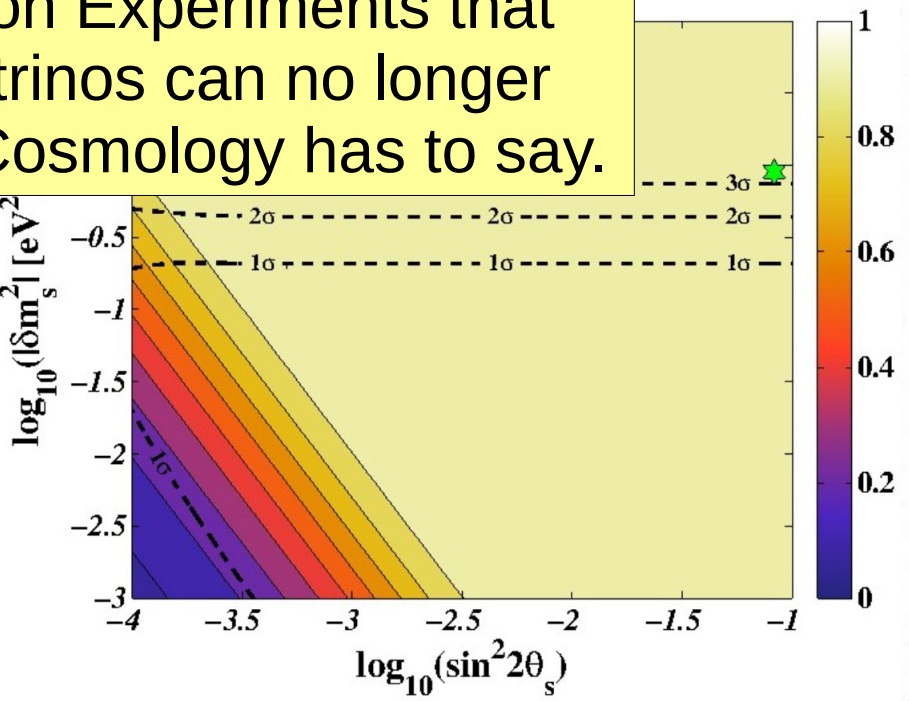
Neutrino Oscillation Experiments that evoke sterile neutrinos can no longer desconsider what Cosmology has to say.



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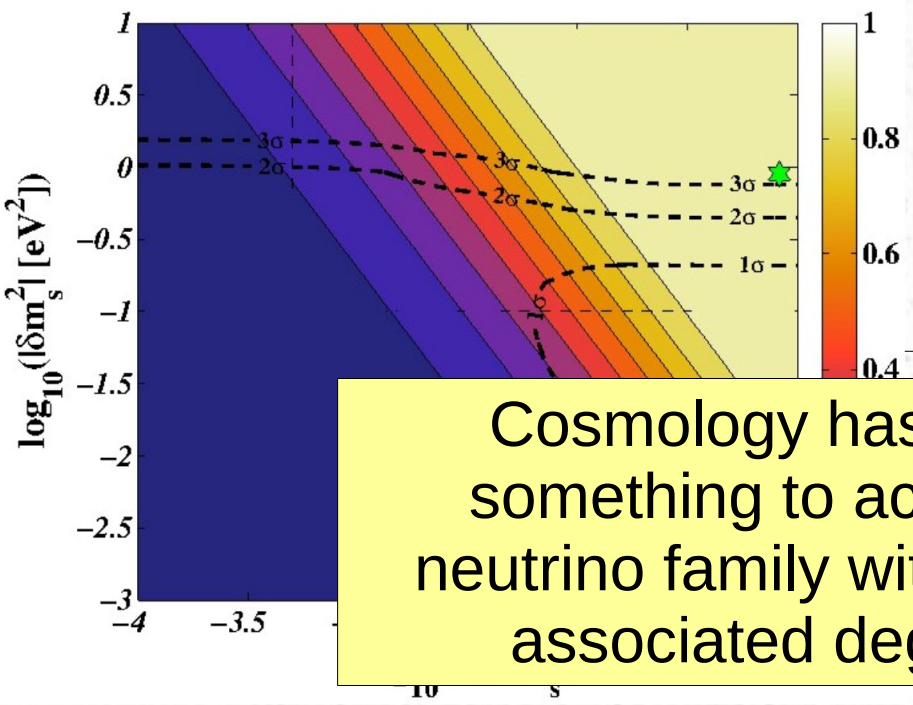
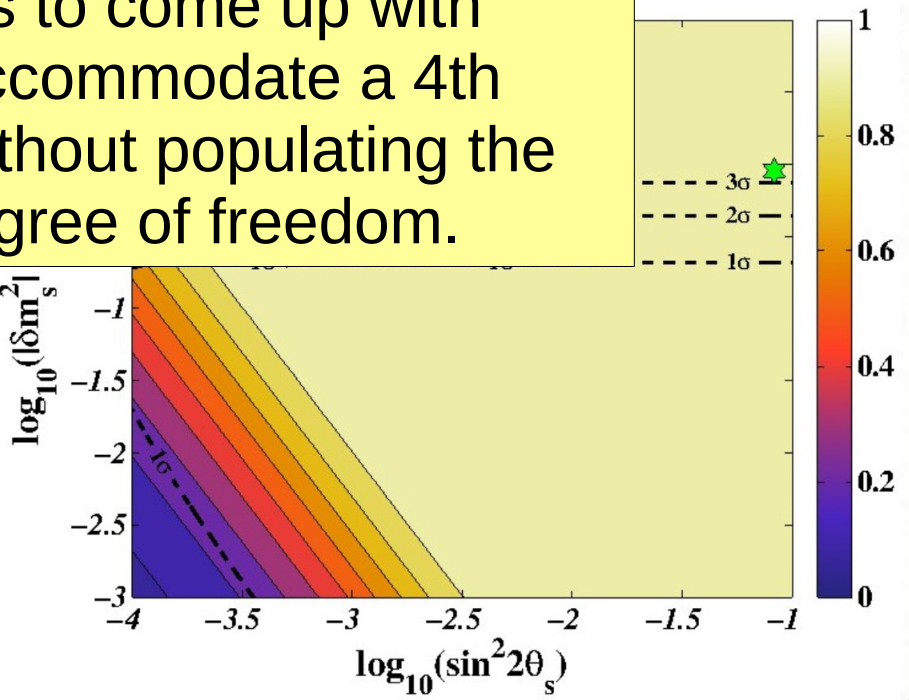


Normal Hierarchy,
non-Resonant Production

Cosmology has to come up with something to accommodate a 4th neutrino family without populating the associated degree of freedom.

Inverted Hierarchy,
Resonant Production



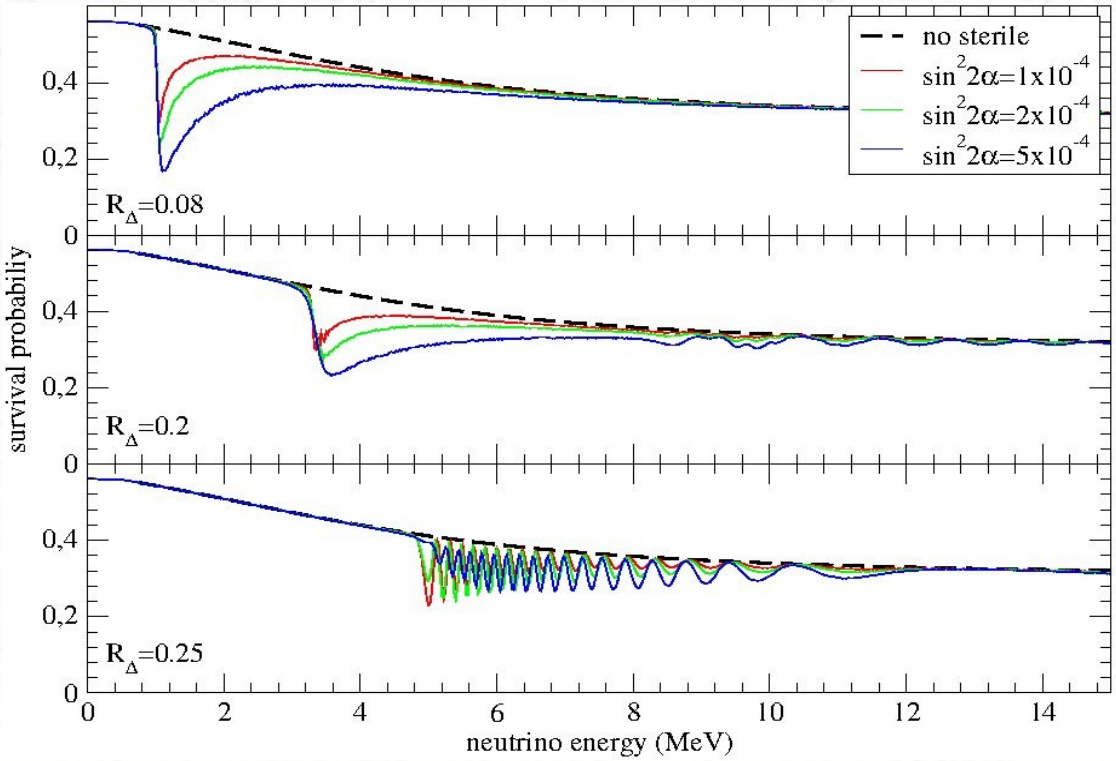
Hannestad et al., JCAP 1207, 025

Sterile Neutrinos

→ But going the other way around, taking the indication of some extra radiation on cosmological data to be a sterile neutrino, what would be the signatures on neutrino oscillation experiments?

Sterile Neutrinos

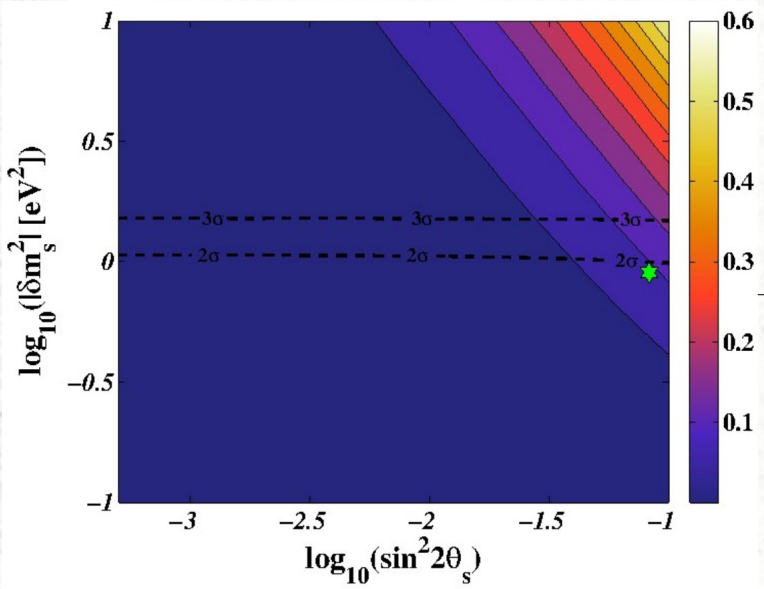
➔ Effect on solar neutrinos, with $m_1 < m_0 < m_2$ (”inverted” hierarchy): supression of survival probability for intermediate energies, increasing quality of fit to solar neutrino data.



PCH and A. Smirnov, Phys.Rev.D83:113011,2011

What about ”non-standard” Sterile Neutrinos?

Large lepton asymmetry: Lepton asymmetry in neutrino sector is not so strongly bounded. $L \sim 10^{-2}$ can supress population of sterile state in early universe, through blocking of sterile neutrino thermalization.



Normal Hierarchy,
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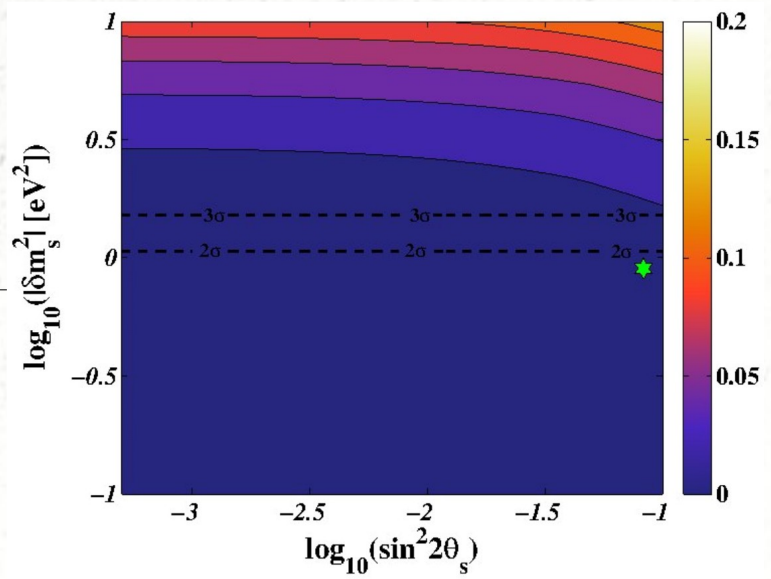


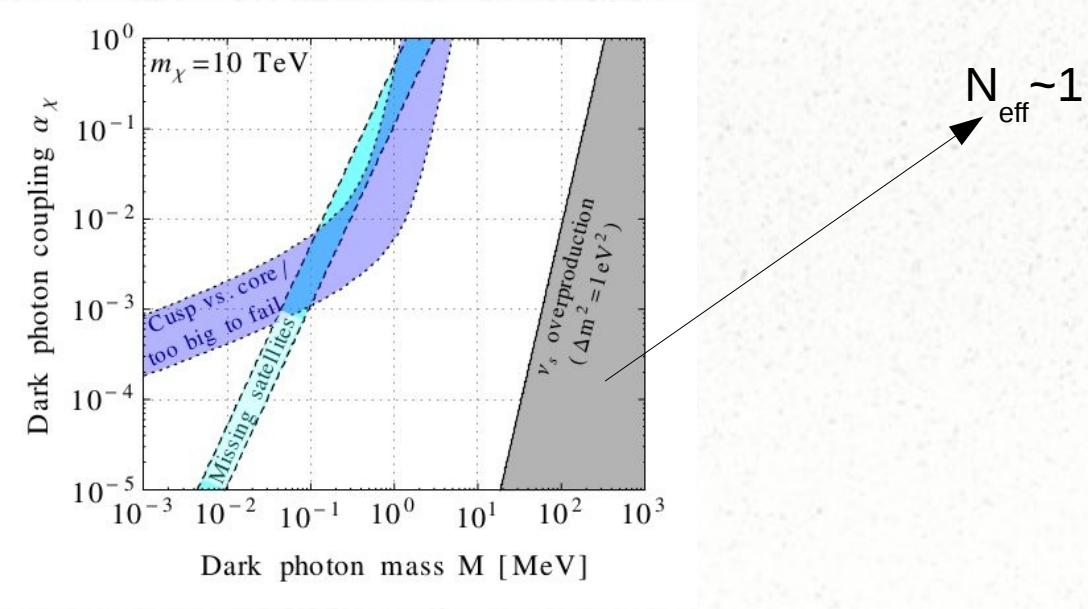
Inverted Hierarchy,
Resonant Production

Hannestad et al., JCAP 1207, 025

Secret Interactions: Sterile Neutrinos can be strongly self-coupled through secret Fermi 4-point interactions:

$$G_X = \frac{g_X^2}{M_X^2}$$

Leading to a new potential term in neutrino Quantum Kinetic Equations. Sterile Neutrino thermalization is supressed.



B. Dasgupta and J. Kopp, PhysRevLett.112.031803,
see also Pospelov, PRD84 (2011) 085008

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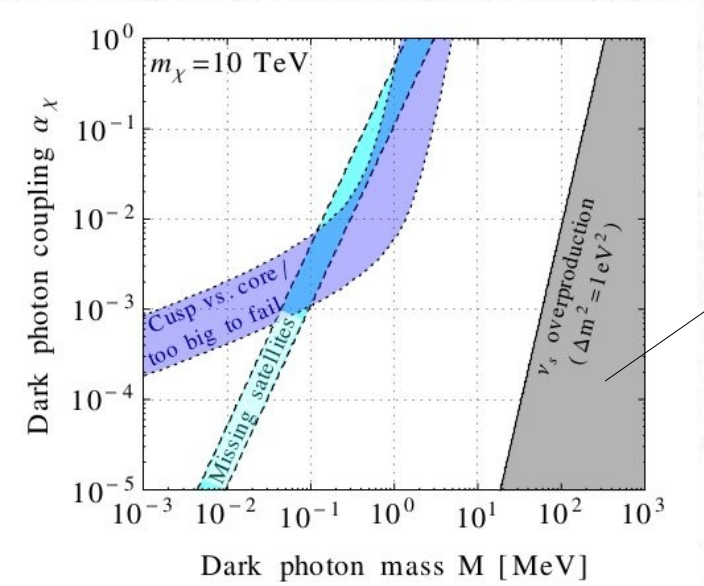
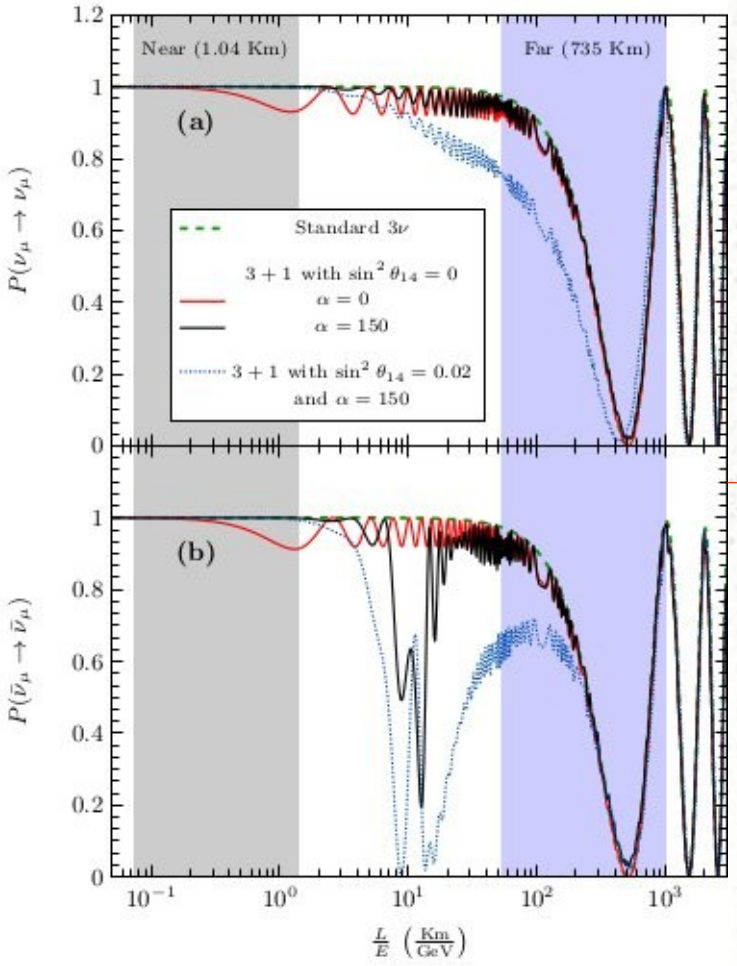


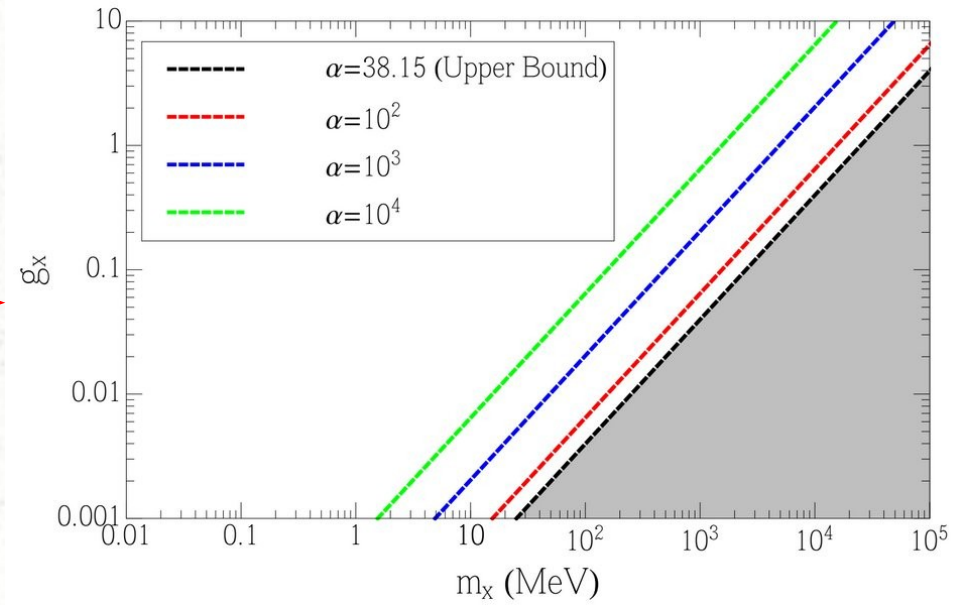
N_{eff}~1

However...

B. Dasgupta and J. Kopp, PhysRevLett.112.031803,
see also Pospelov, PRD84 (2011) 085008

Secret Interactions: Such large interaction could affect also neutrino oscillation probabilities in long-base line experiments, as MINOS.





Orlando Peres and Zahra Tabrizi, preliminary

Pseudo-scalar self-Interactions: (arxiv:1508.02504)

- sterile neutrino secret interactions through a light pseudo-scalar supress sterile neutrino production until after neutrino decoupling.

$$\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4 .$$

- latter production of sterile neutrinos through contact with active neutrinos

- strongly coupled $\phi\nu$ fluid at late times. Rich phenomenology and better fit to cosmological observables.

”(...) it could be another indication that we are seeing the first signs of new, hidden interactions in the dark sector.”

Conclusions