Cosmic neutrinos and other relics: what remains to be learnt

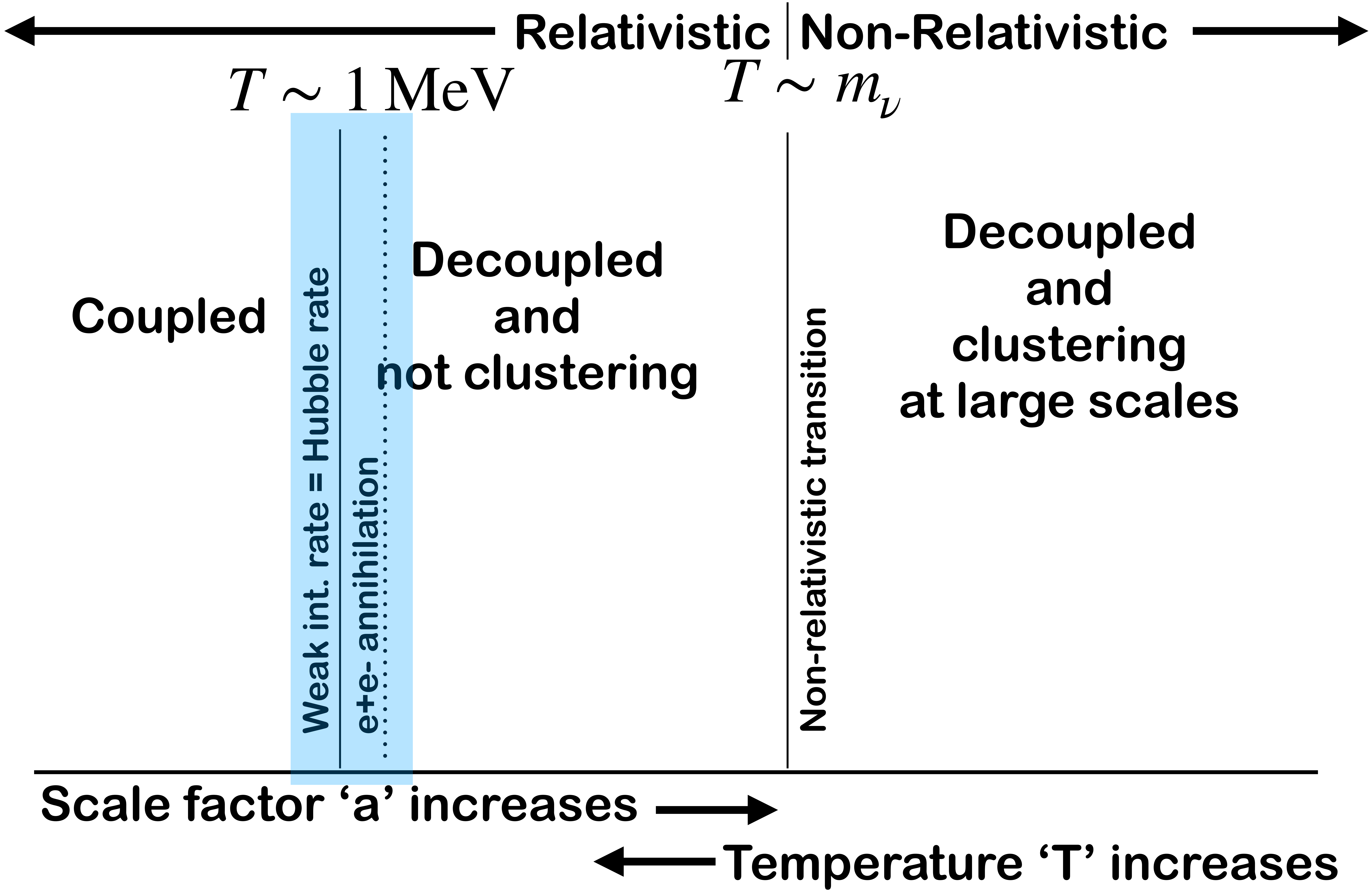
Astroparticle Symposium - Early and Late Universe Cosmology - 7 Nov 2022

Martina Gerbino - INFN Ferrara

Neutrinos and Cosmology

Mature fields, yet treasure trove of discoveries
At the frontiers of research
Groundbreaking results expected in the next decade

Neutrino cosmology



Neutrino cosmology

← Relativistic   Non-Relativistic →

T~m_nu

$$\rho_\nu \propto (T_\nu/T_\gamma)^4 N_{\rm eff}$$

$$\rho_\nu \propto \Sigma m_\nu (T_\nu/T_\gamma)^3$$

$$N_{\rm eff} \equiv \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm st}} = 3.044$$

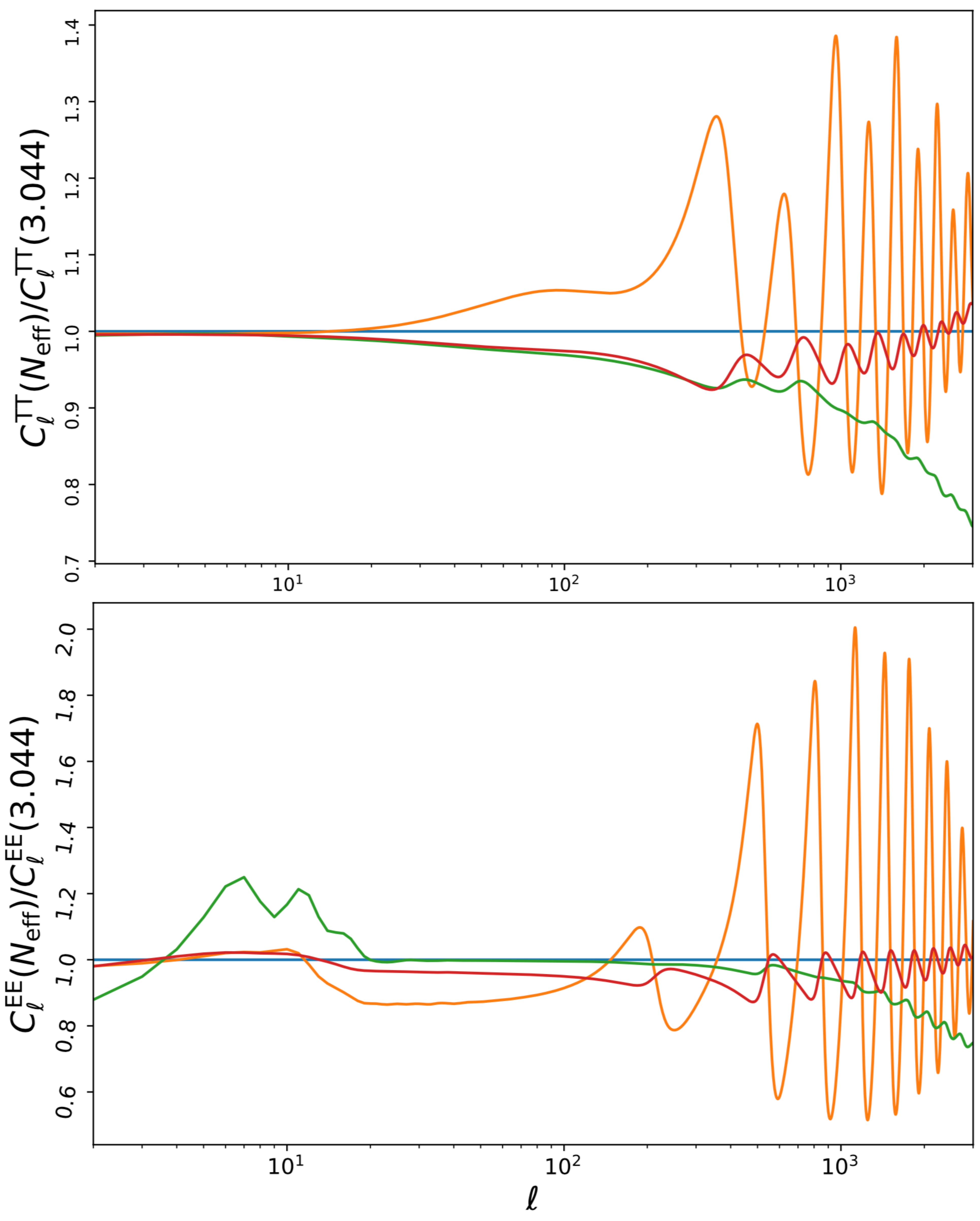
$$\Sigma m_\nu = \Sigma_{i=1,2,3} m_{\nu,i}$$

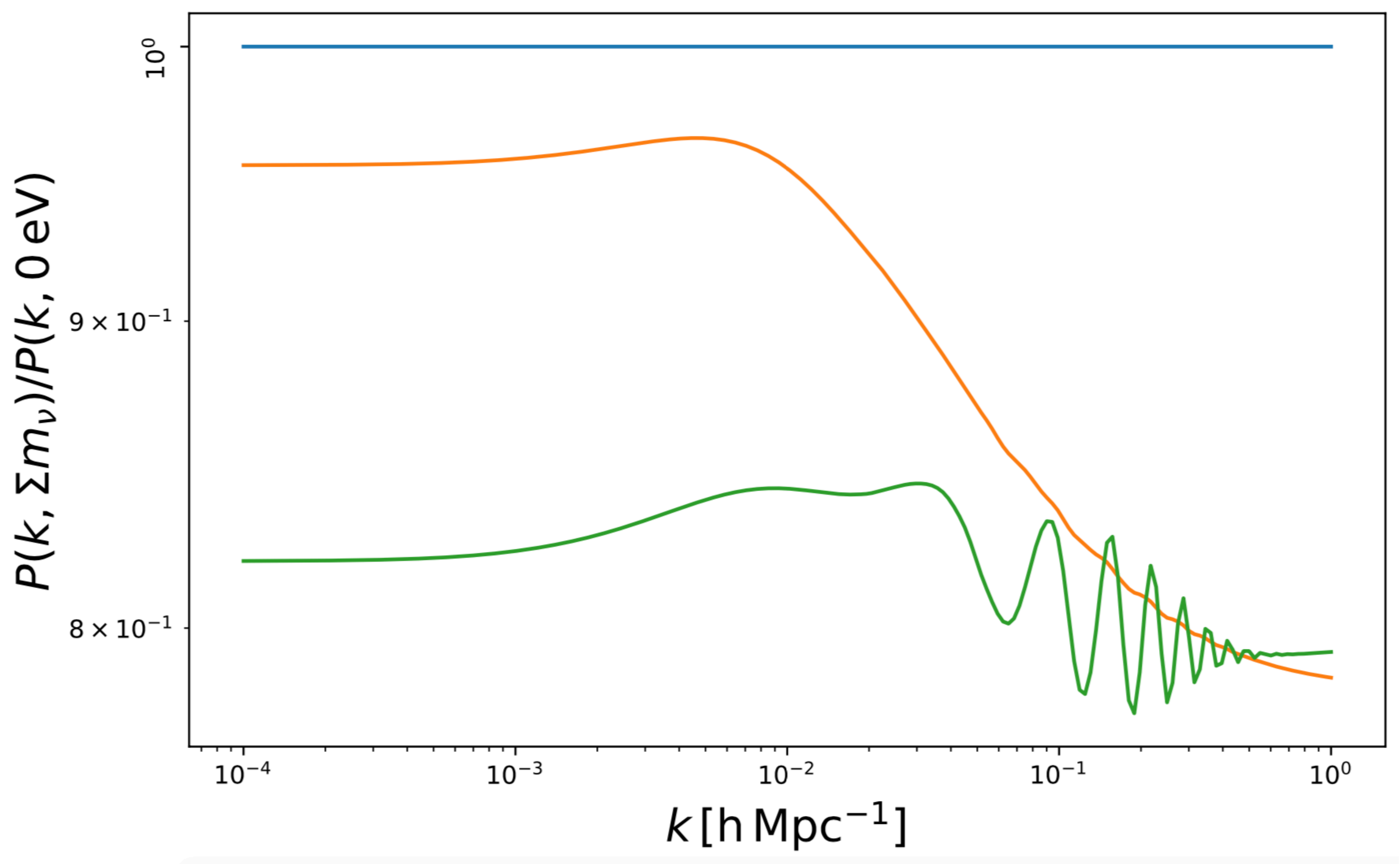
Distorsions due to non-inst decoupling
radiative corrections,
flavour oscillations
Dolgov, 1997, Mangano+,2005
Bennett+2020,Froustey+2020,Akita+2020

Scale factor 'a' increases →

← Temperature 'T' increases

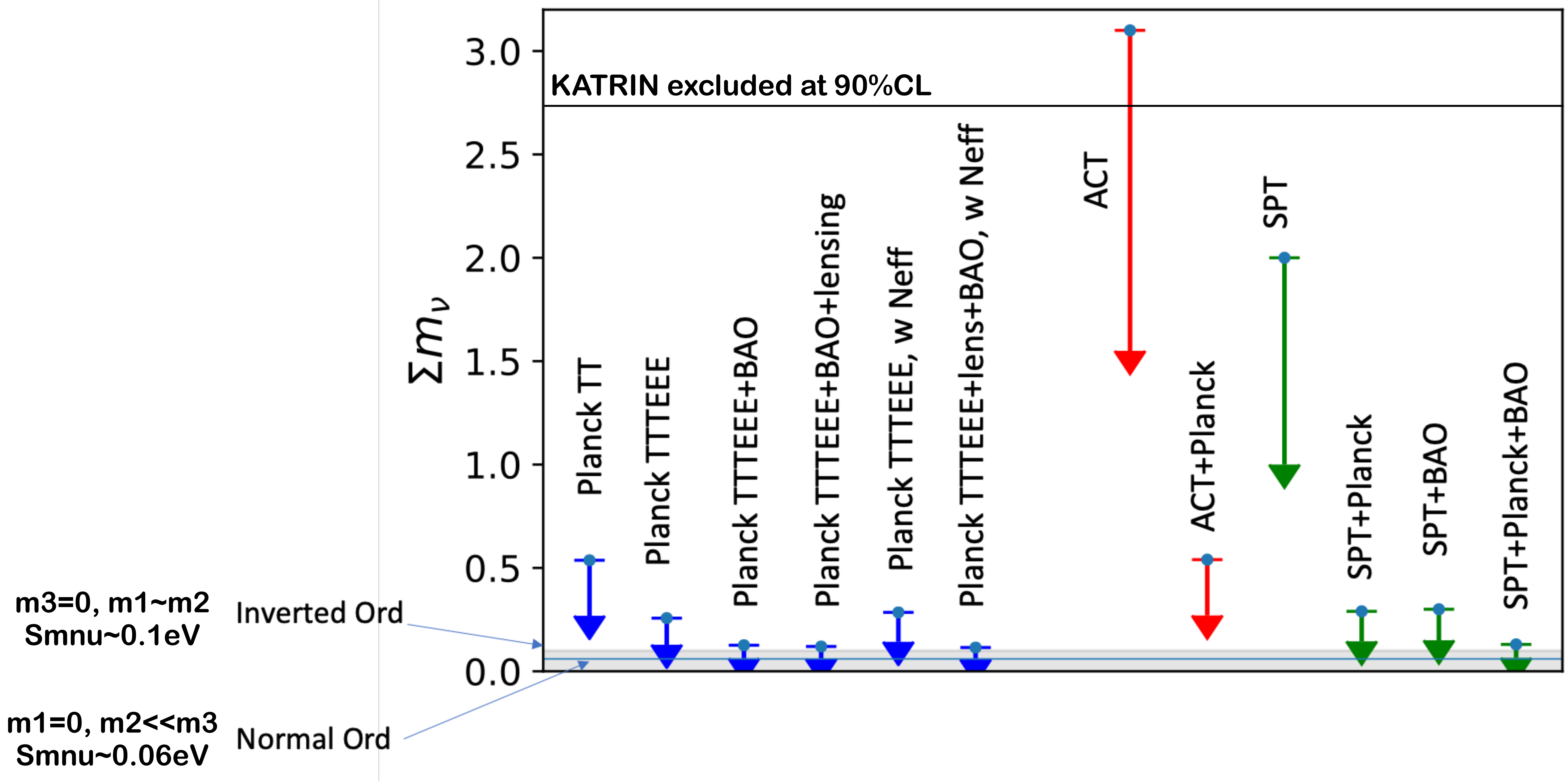
Neutrino imprints





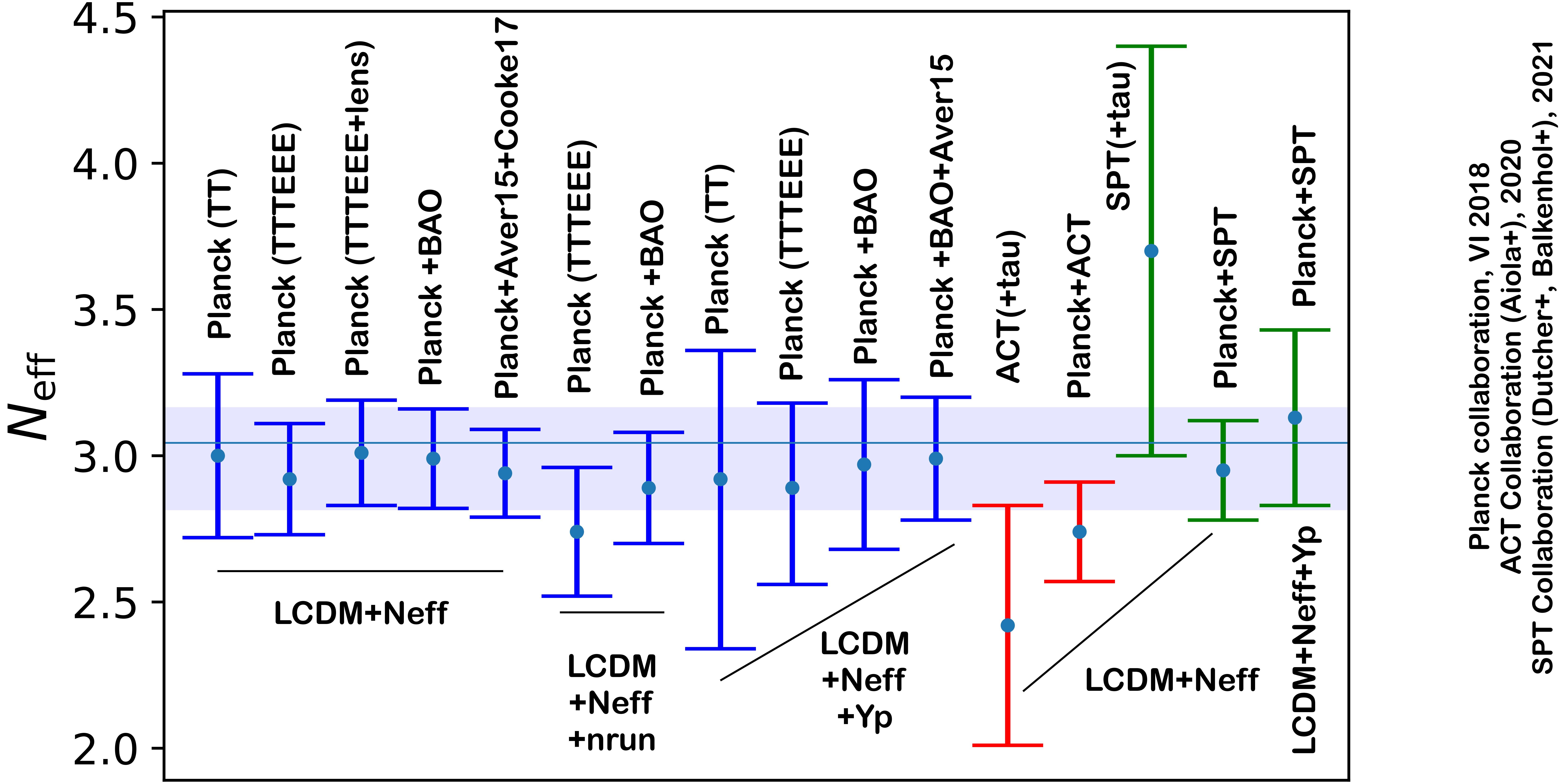
BLUE: ref model
ORANGE: Neff/Sumnu varying
GREEN: fixed matt-rad equality and angular sound horizon
RED: fixed matt-rad equality, angular sound horizon and angular damping scale

Current limits on the mass sum



Planck2018, VI
ACT Collaboration (Aiola+), 2020
SPT Collaboration (Dutcher+,Balkenhol+), 2021

Current limits on Neff



What next in neutrino cosmology

A new generation of ultimate cosmological surveys is approaching: Simons Observatory, Euclid, LiteBIRD, CMB-S4, DESI, LSST, SPHEREx, SKA ...

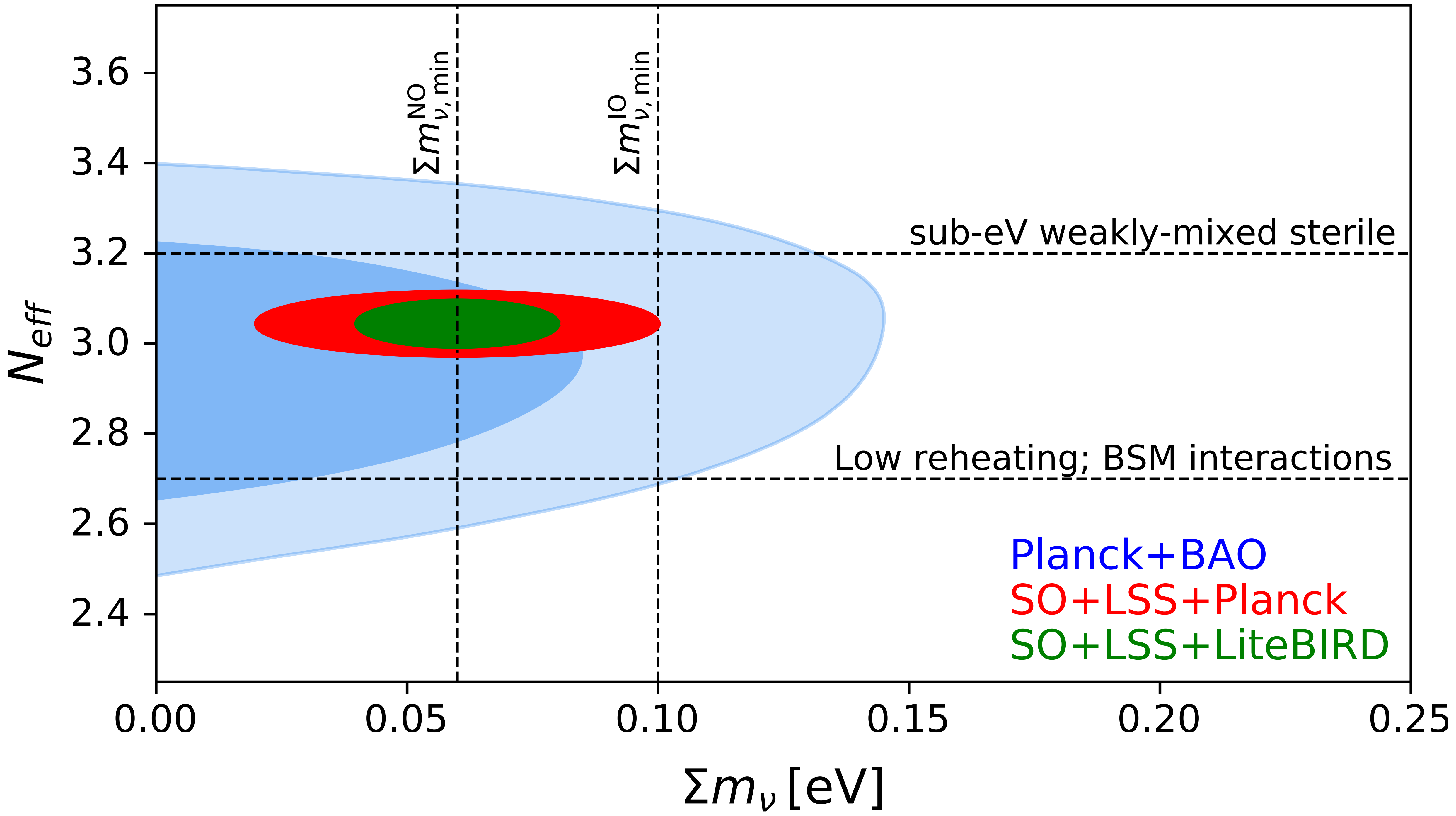
Does it mean that we are moving:

1) **Towards the first detection of the neutrino mass scale?**

$$\sigma(\Sigma m_\nu) = 0.02\,\mathrm{eV}$$

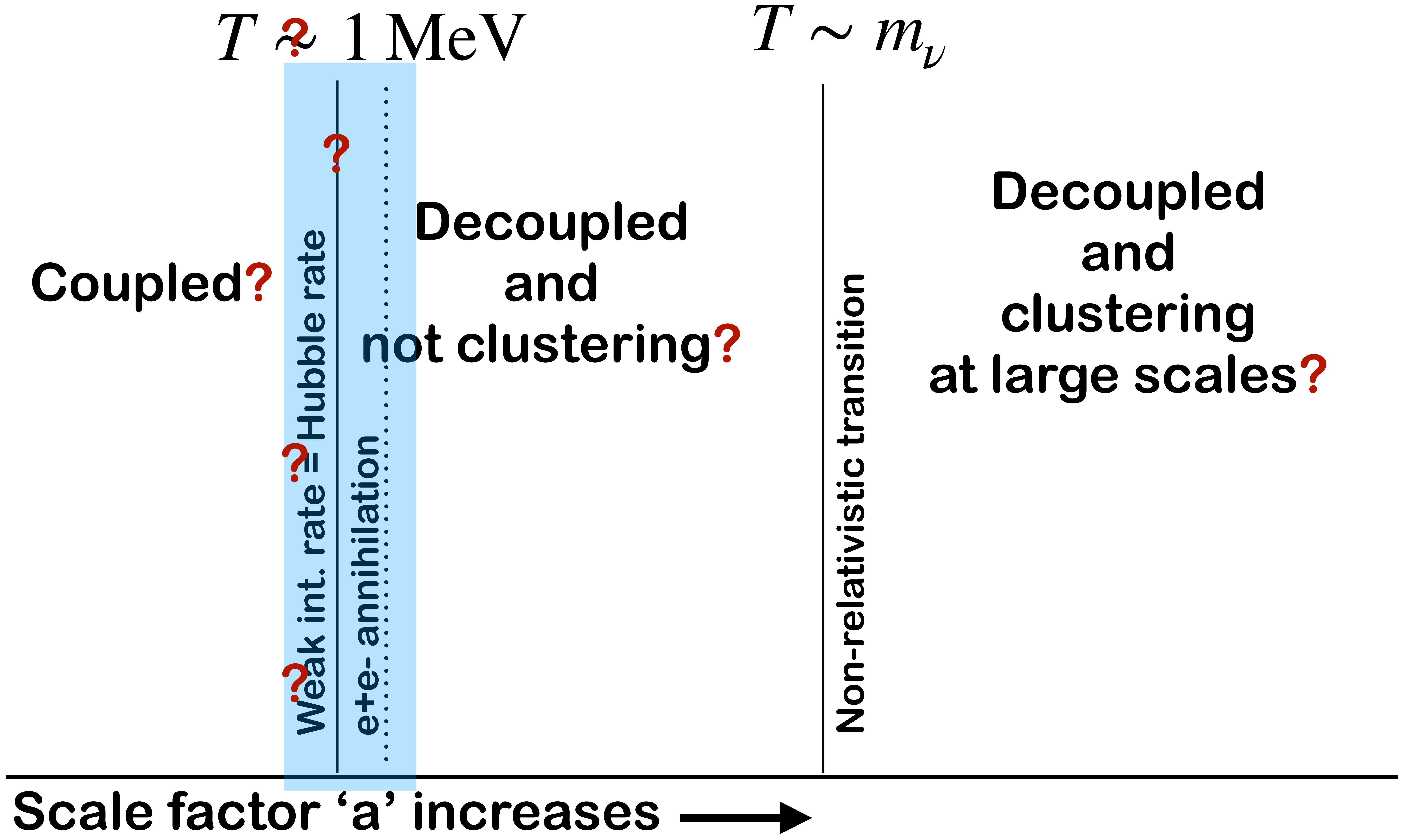
2) **Towards the first probe of the physics of neutrino decoupling, and of BSM content at very early times?**

$$\sigma(N_{\rm eff}) = 0.03$$

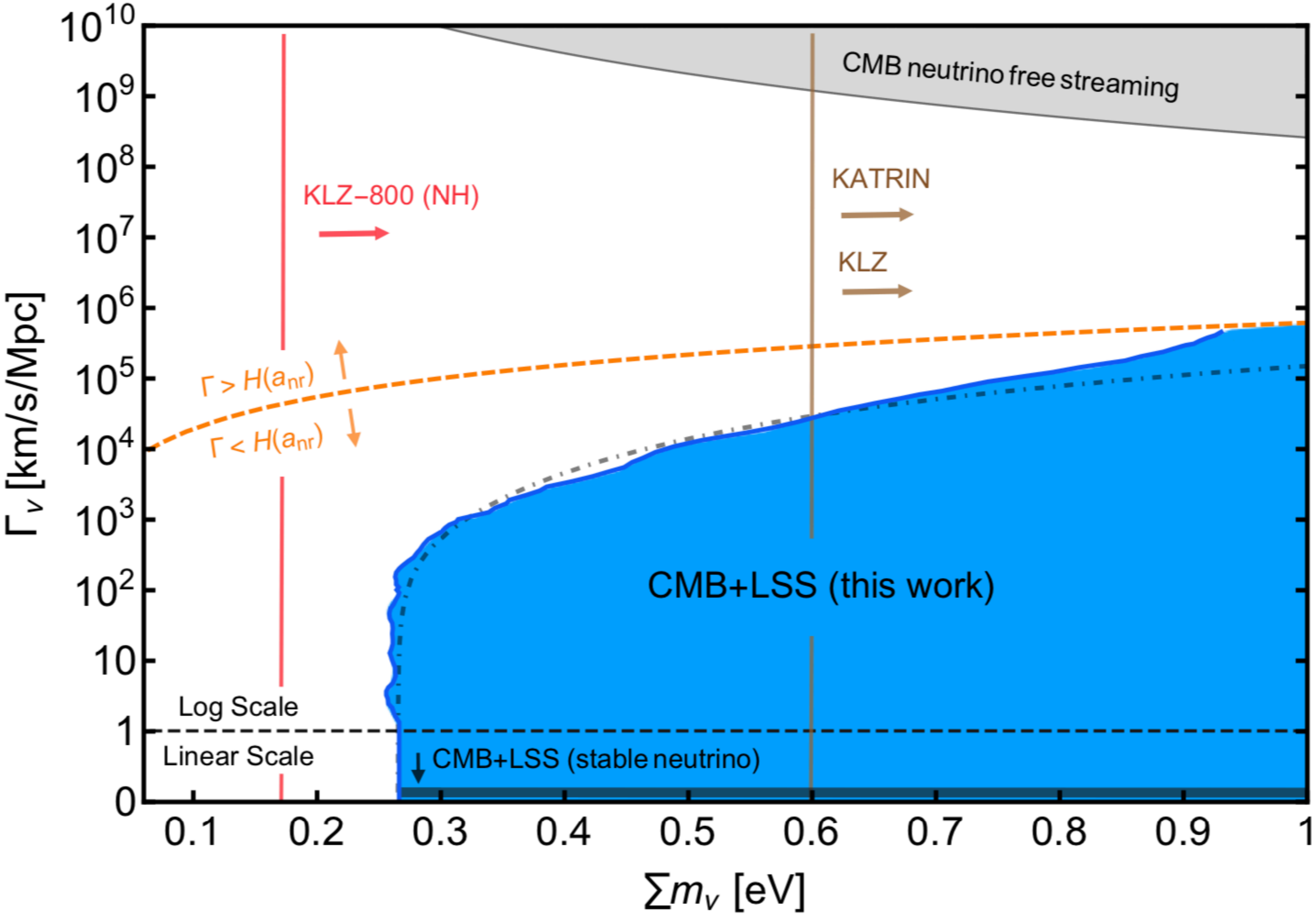


BSM neutrinos?

What if they are not what we think?
(or: how sensitive are we to standard assumptions?)



Neutrino stability over cosmic times



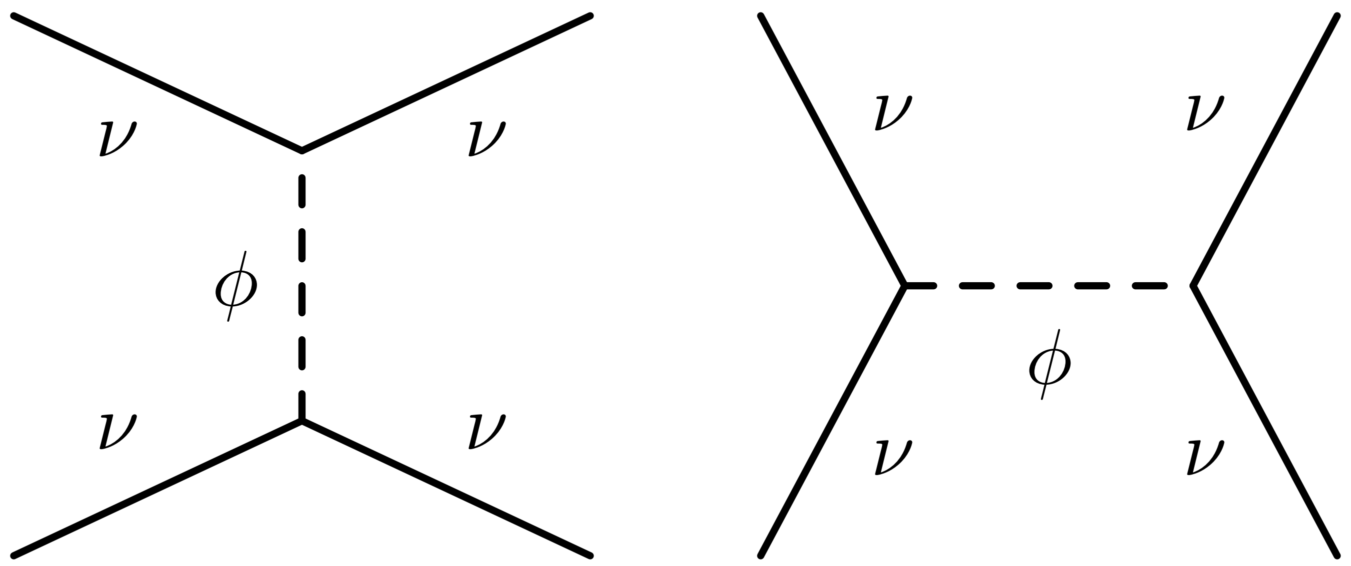
$$\rho_\nu \sim \Sigma m_\nu n_\nu$$

Chacko+,2019;
Chacko+,2021
Abellan+,2022

Mass bounds relaxed for neutrinos decaying when non-relativistic and close to recombination
Updated and improved bounds with more careful treatment (Barenboim+,2021; Chen+,2022)

Neutrino non standard interactions

Neutrinos interact only via weak interactions with other particles
What if new interactions are yet to be discovered?



$$\mathcal{L}_{SM} = -2\sqrt{2}\,G_F\left[(\overline{\nu}_e\gamma^\mu P_L e)\,(\overline{e}\gamma_\mu P_L\nu_e) + \sum_{X,\alpha} g_X\,(\overline{\nu}_\alpha\gamma^\mu P_L\nu_\alpha)\,(\overline{e}\gamma_\mu P_X e)\right],$$

$$\mathcal{L}_{NSIe} = -2\sqrt{2}\,G_F\sum_{\alpha,\beta}\varepsilon^X_{\alpha\beta}\,(\overline{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\,(\overline{e}\gamma_\mu P_X e)\,.$$

Neutrino self-interactions
Forastieri+,2019; Kreisch+,2019; Brinckmann+,2021; Taule+,2022; Kreisch+(ACT),2022; …

Neutrino-electron non-standard interactions
de Salas+,2021; Mangano+,2006; …

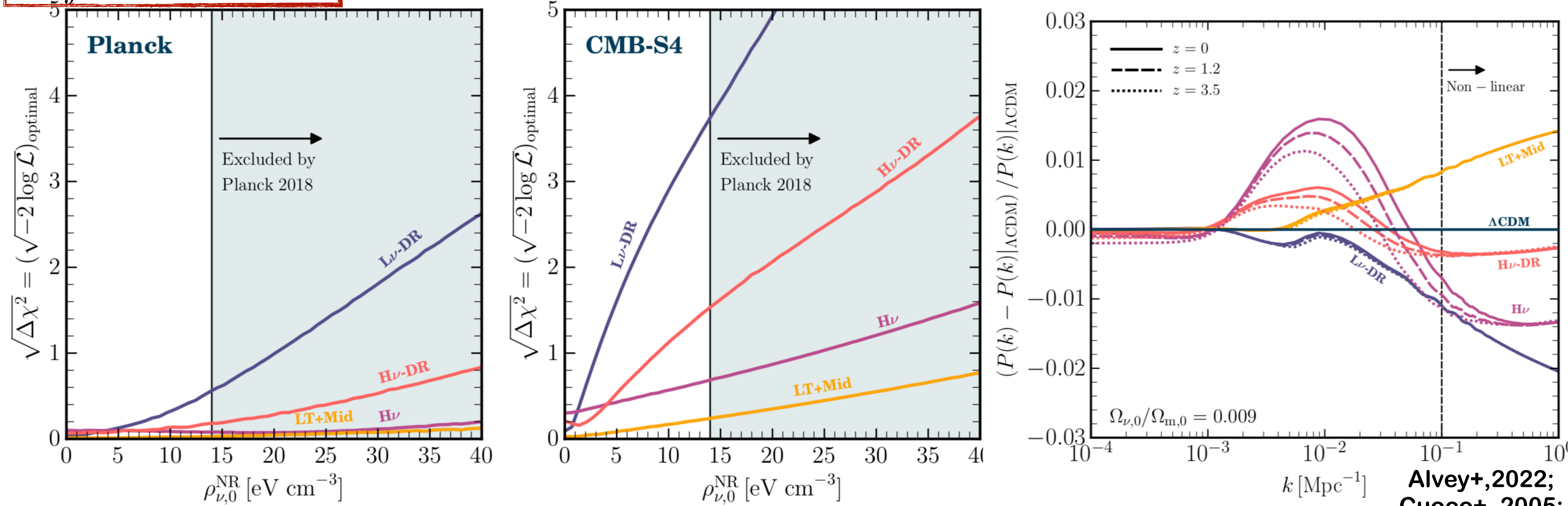
Cosmology can place complementary and competitive bounds to laboratory searches on these NS properties

With current data, no (significant) hints for deviations from the SM.

See Thejs's talk on Tuesday!

Neutrino distribution function

$$\rho \propto \int d^3p \sqrt{p^2 + m^2} f(p)$$



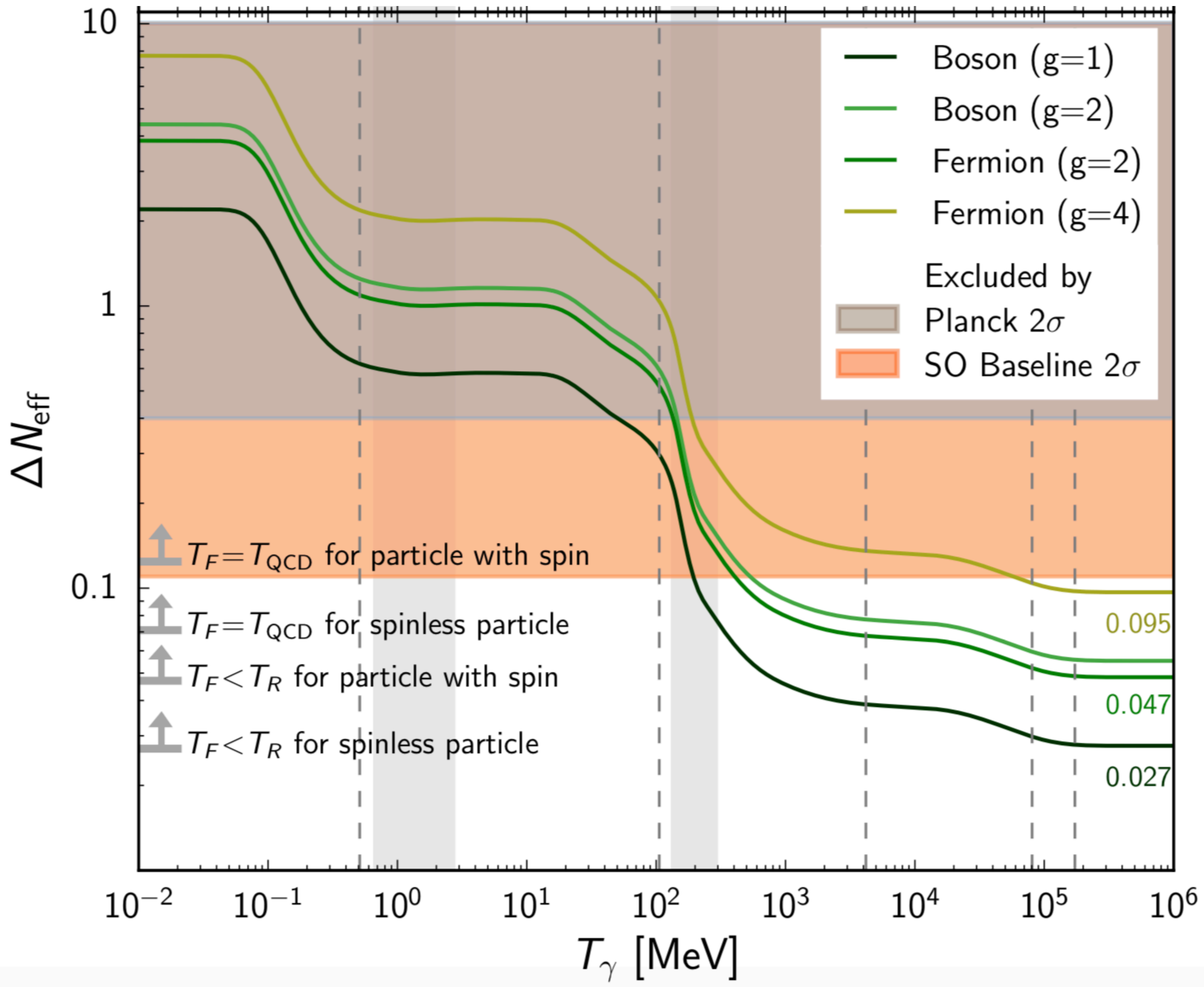
Alvey+,2022;
Cuoco+, 2005;
…

Current CMB is insensitive to details of the distribution function;
future CMB may be mildly sensitive;
LSS surveys may be more sensitive

BSM particle species

Cosmology is (mostly) sensitive to the neutrino contribution to the energy density

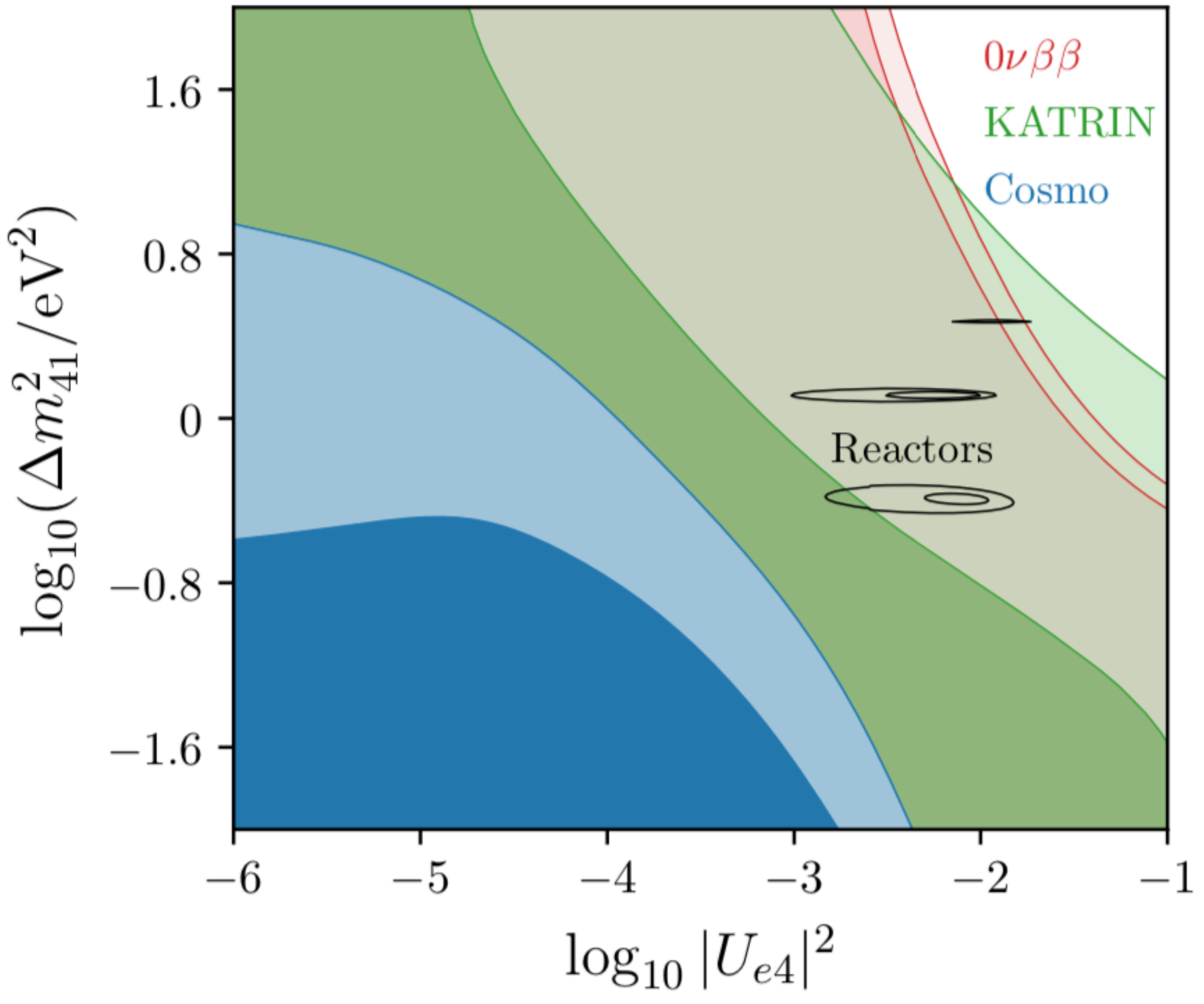
What if there is more than neutrinos contributing to it?



SO Collab. (incl MG), 2018

Light sterile in cosmology

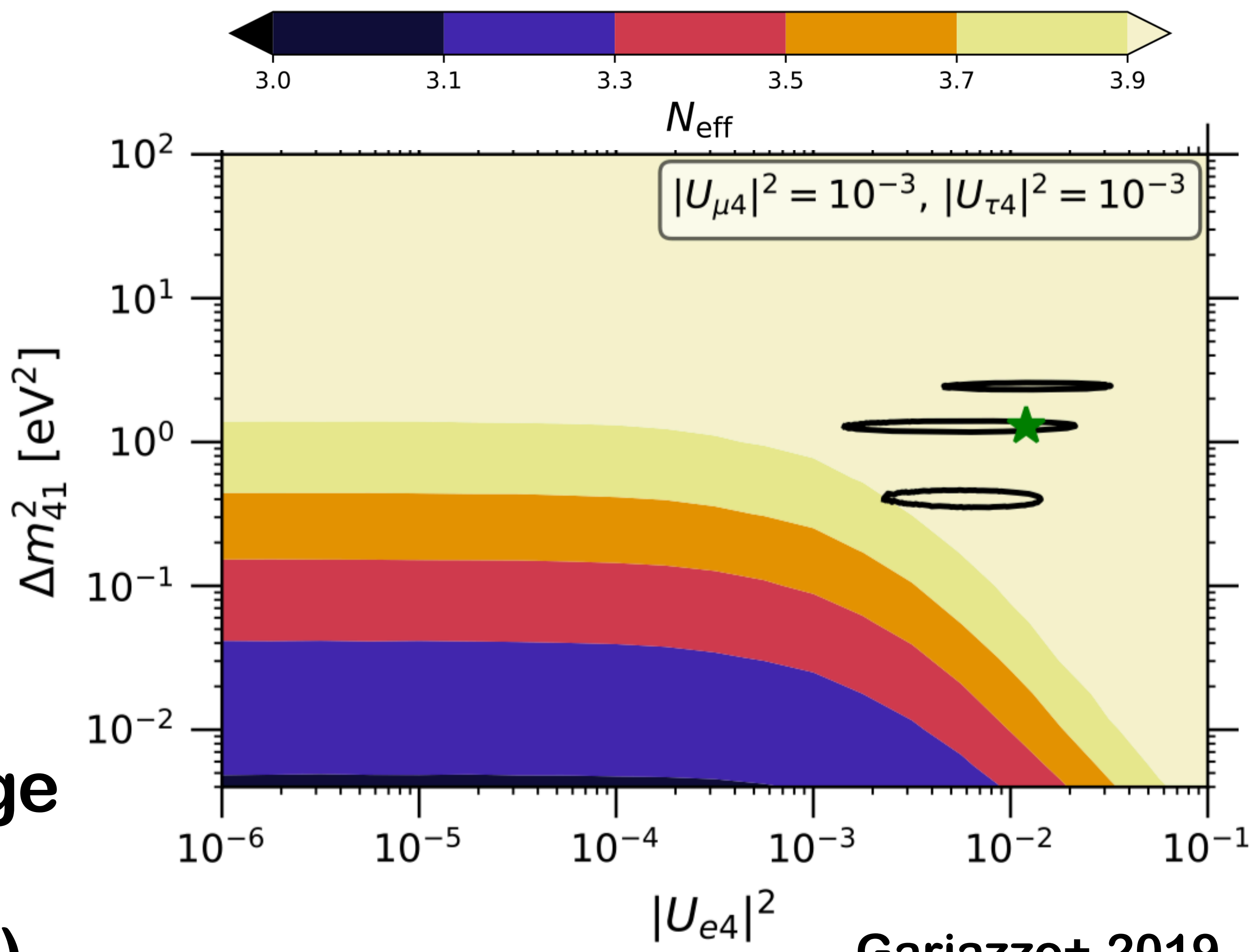
Hagstotz+(incl.MG), 2020; Gariazzo+, 2020



Anomalies in oscillations would require light sterile with large mixing angle.

If they exist, oscillations in the early Universe would create a population of sterile

$$\theta \quad \Delta m^2 \rightarrow \Delta N_{\rm eff} \quad \Omega_{\nu,s} h^2 = \frac{m_{\rm eff}}{94\,\mathrm{eV}}$$



Gariazzo+,2019

Lab best fit is at odds with cosmology: too large contribution to Neff for large mixing angles (quick thermalisation of the sterile with active)

ALPs phenomenology

Caloni, MG,+, 2022

Challenges ahead

THEORY

- cosmology side: modelling of small scales/non-linear scales
- particle physics side: test accuracy&approximations, link theory&phenomenology (what are we really measuring?)
- computational side: can we afford required precision level?

Challenges ahead

INSTRUMENT&DATA

- know your instrument: perfect knowledge of instrumental systematic effects
- know your data: perfect knowledge of what features in the data drive constraints
- combine your data: be coherent (in modelling) and account for (cross)correlations; propagate all (theory&instrument) uncertainties

Challenges ahead

INTERPRETATION

- be statistically accurate and robust (especially if you measure something)

- cosmology is not alone: key comparison&collaboration with complementary avenues (lab, astro, etc)