Neutrino Cosmology in 2021

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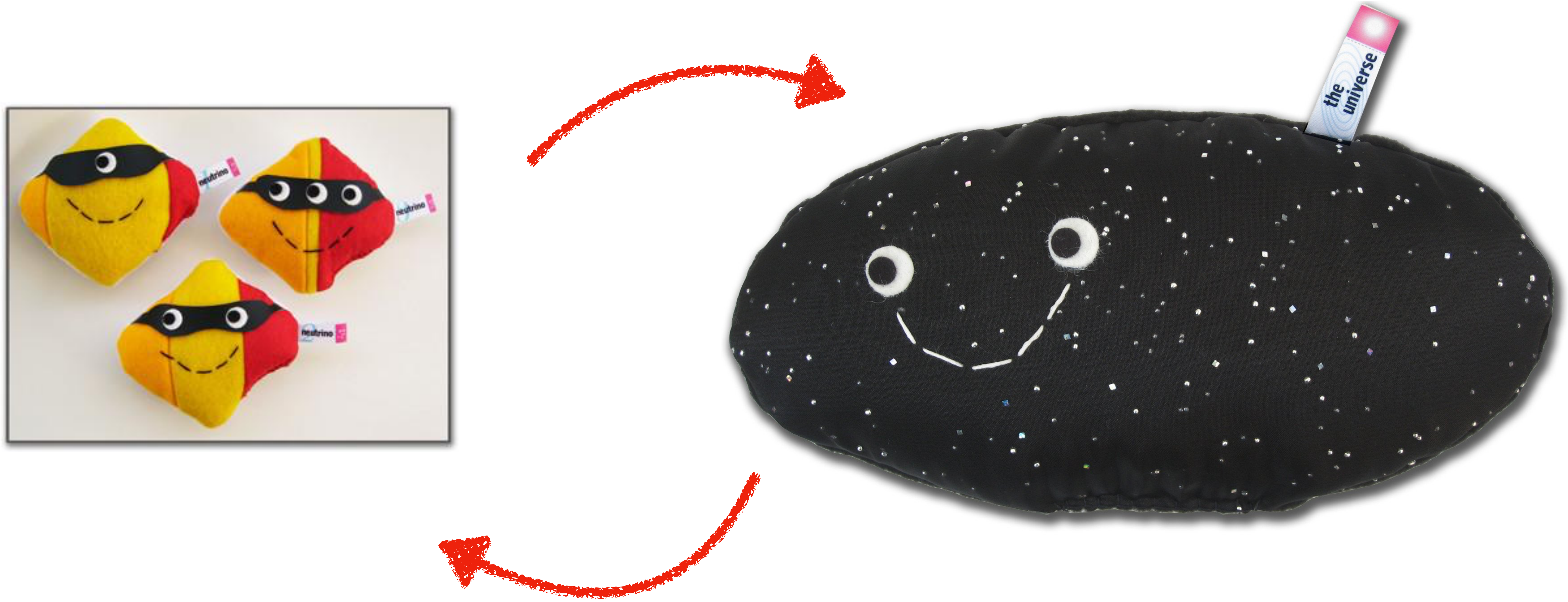
Neutrinos and Cosmology



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

Neutrinos and Cosmology

Neutrinos are essential ingredients of the Standard Cosmological Model
Pioneering bounds on neutrino properties from Cosmology well before lab

$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{93.14\,\mathrm{eV}}$$

$$\Omega_\nu < 1$$

$$\Omega_\nu h^2 < \Omega_m h^2$$

Gershtein-Zeldovich (1966)
Cowsik-McClelland (1972)

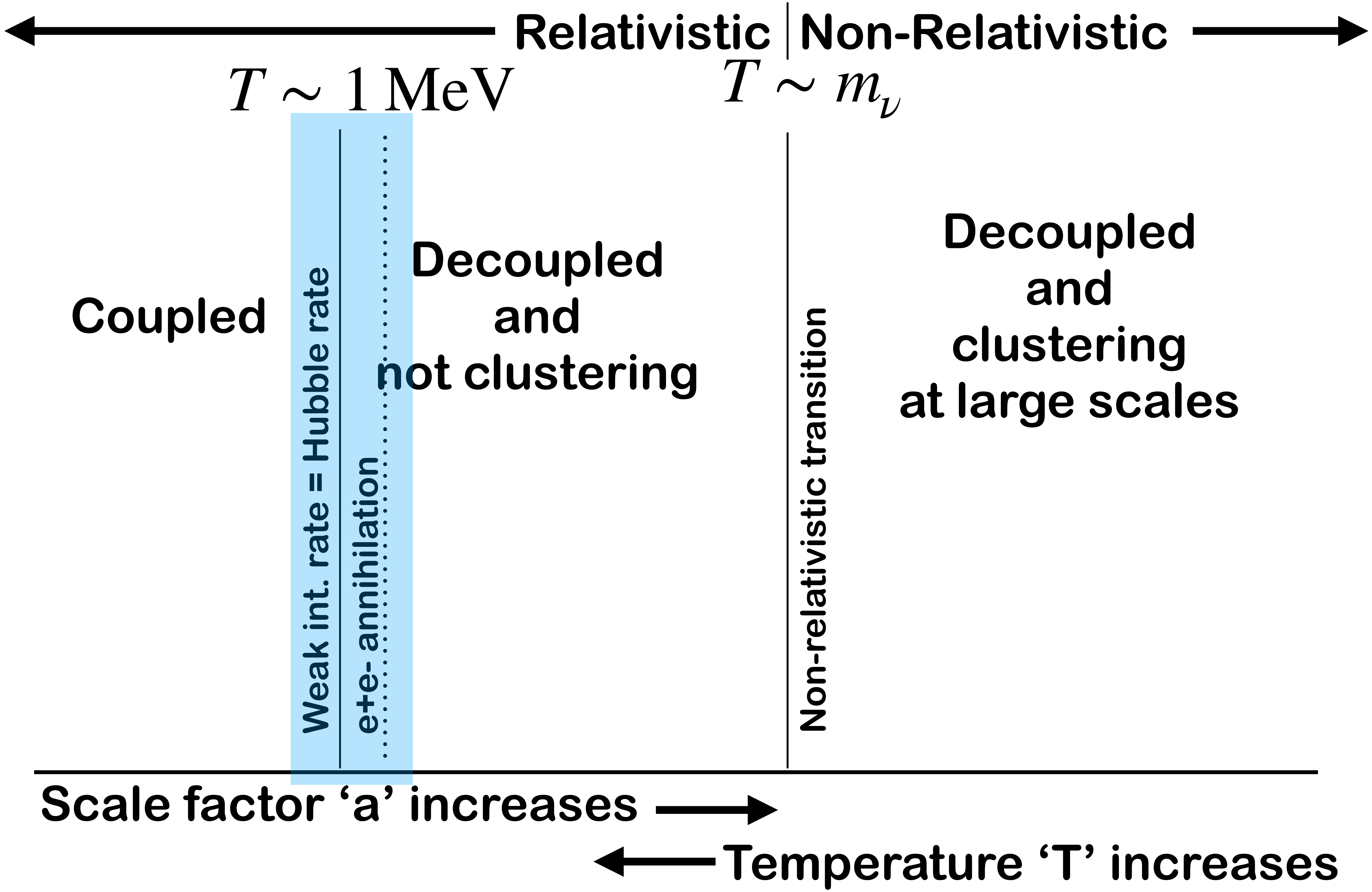
(Stringent) bound on the mass sum required not to over close the Universe

$$N_\nu < 4$$

Schramm&Kawano (1989)
Olive+ (1990)

(Stringent) bound on the family number required not to spoil BBN

Neutrino cosmology



Neutrino cosmology

⟵ Relativistic Non-Relativistic ⟶

T~m_nu

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

$$\rho_\nu \propto \Sigma m_\nu$$

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

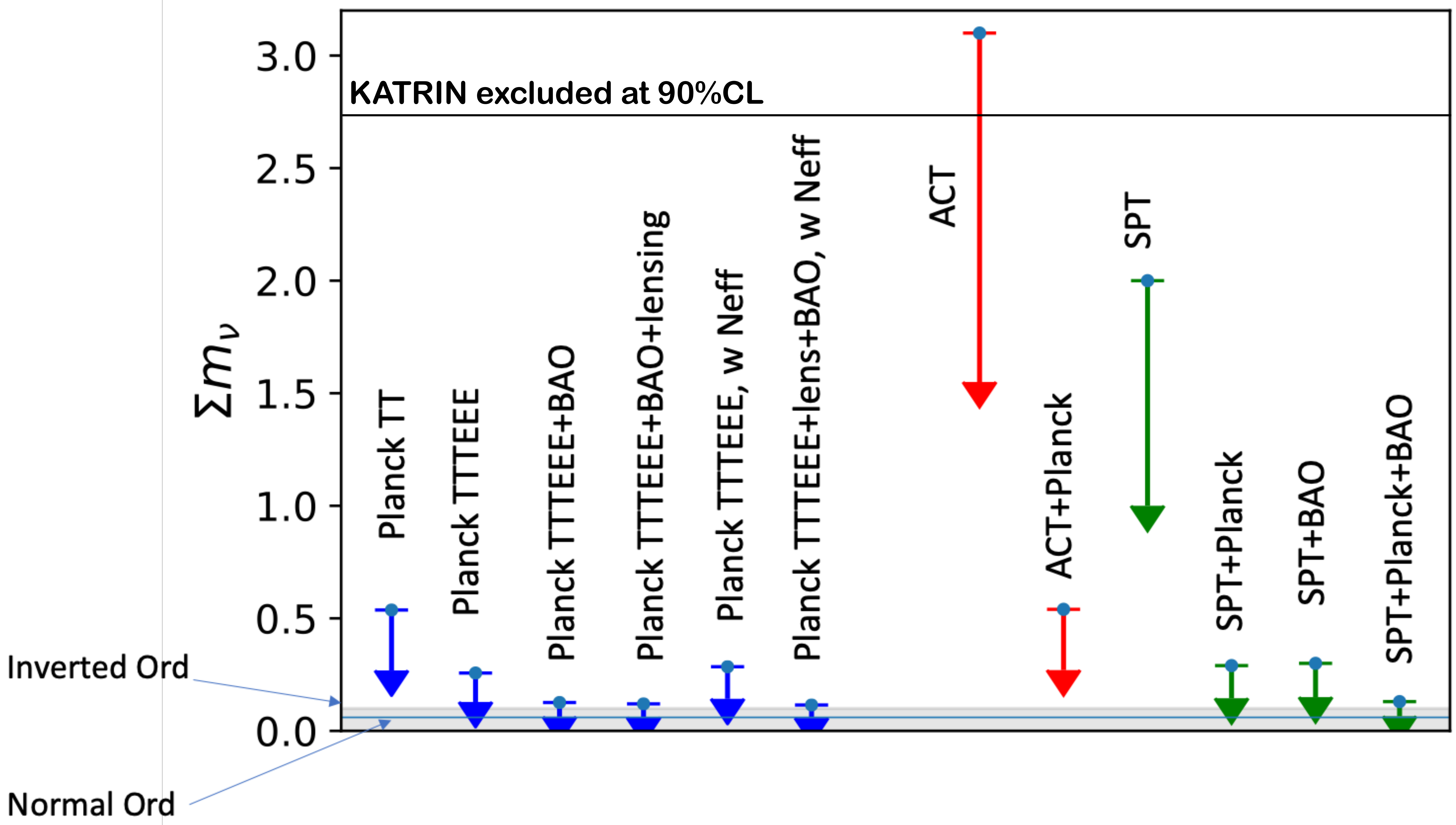
$$\Sigma m_\nu = \Sigma_{i=1,2,3} m_{\nu,i}$$

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

Current limits on the mass sum

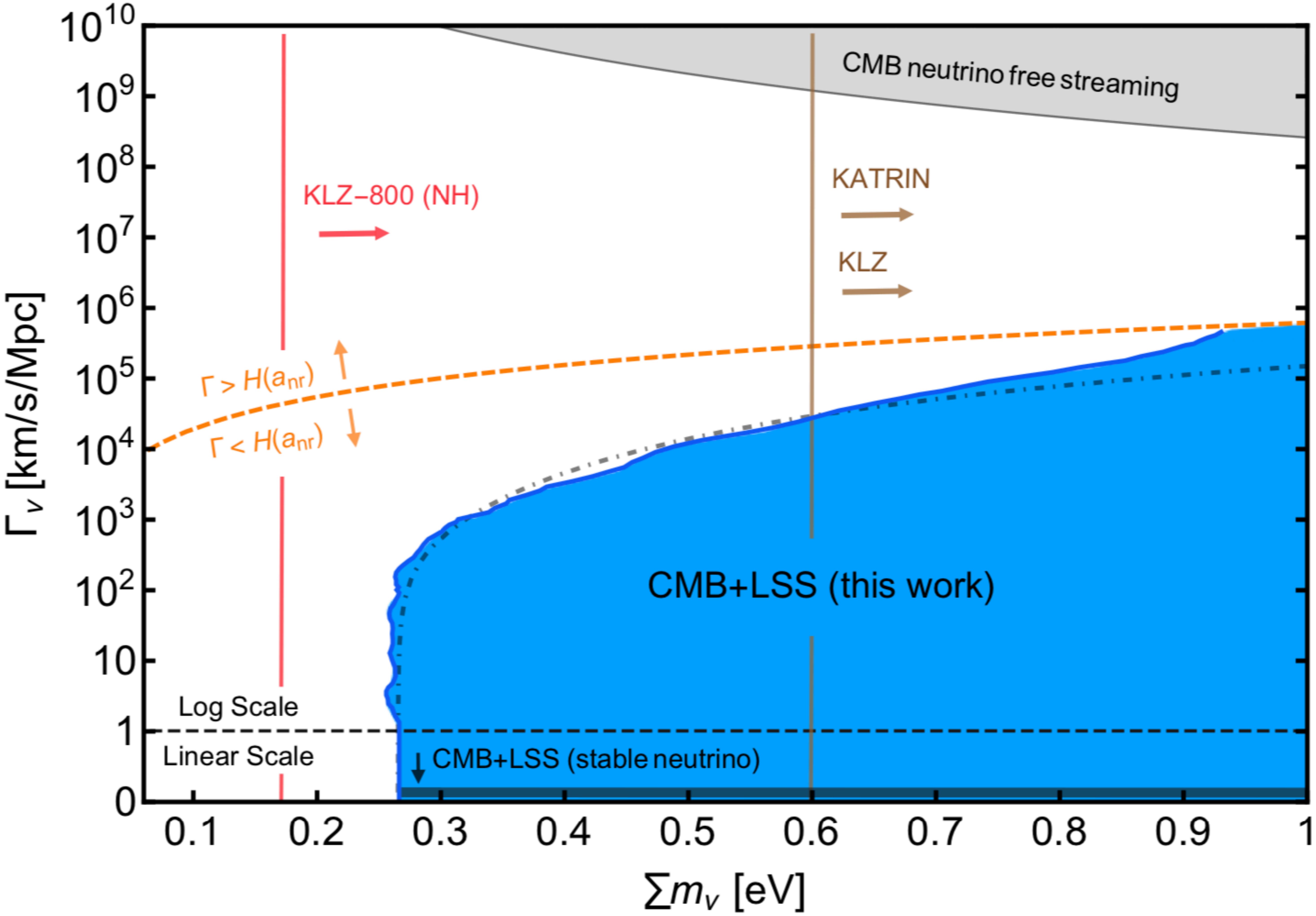


m3=0, m1~m2
Smnu~0.1eV

m1=0, m2<<m3
Smnu~0.06eV

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

Neutrino stability over cosmic times

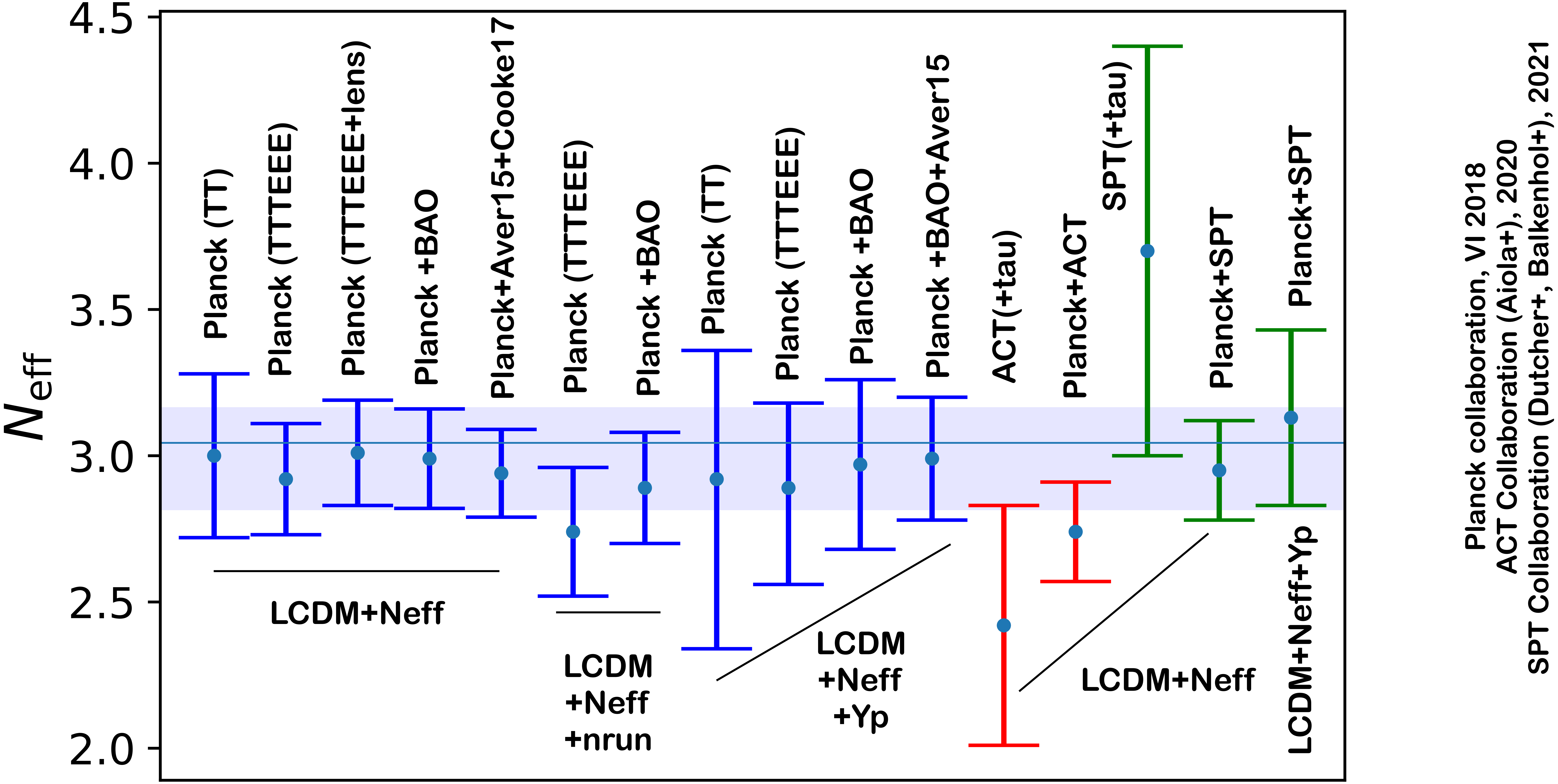


$$\rho_\nu \sim \Sigma m_\nu n_\nu$$

Chacko+,2019

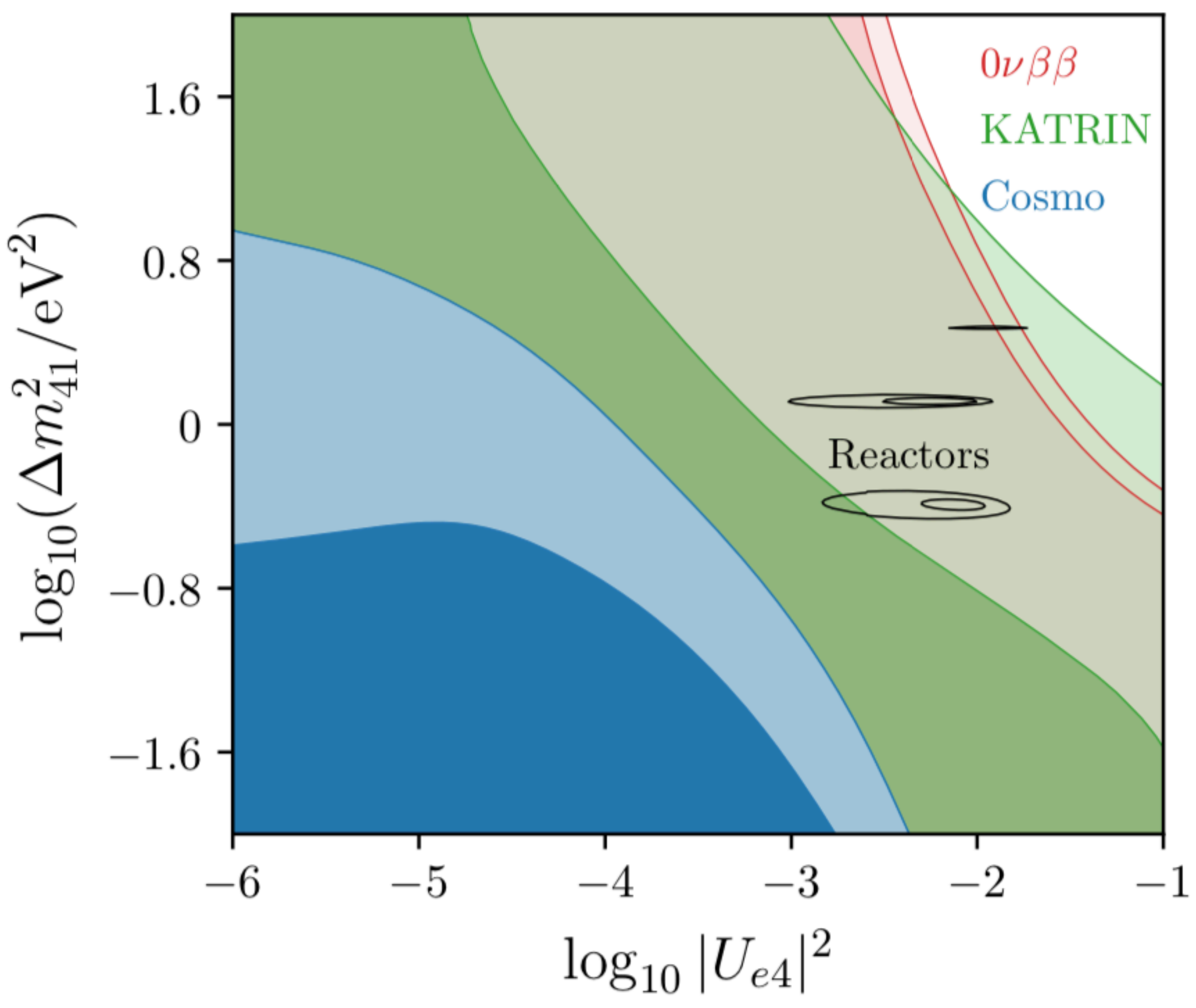
Mass bounds relaxed for neutrinos decaying when non-relativistic and close to recombination
Updated and improved bounds expended with more careful treatment (Barenboim+,2021)

Current limits on Neff



Light sterile in cosmology

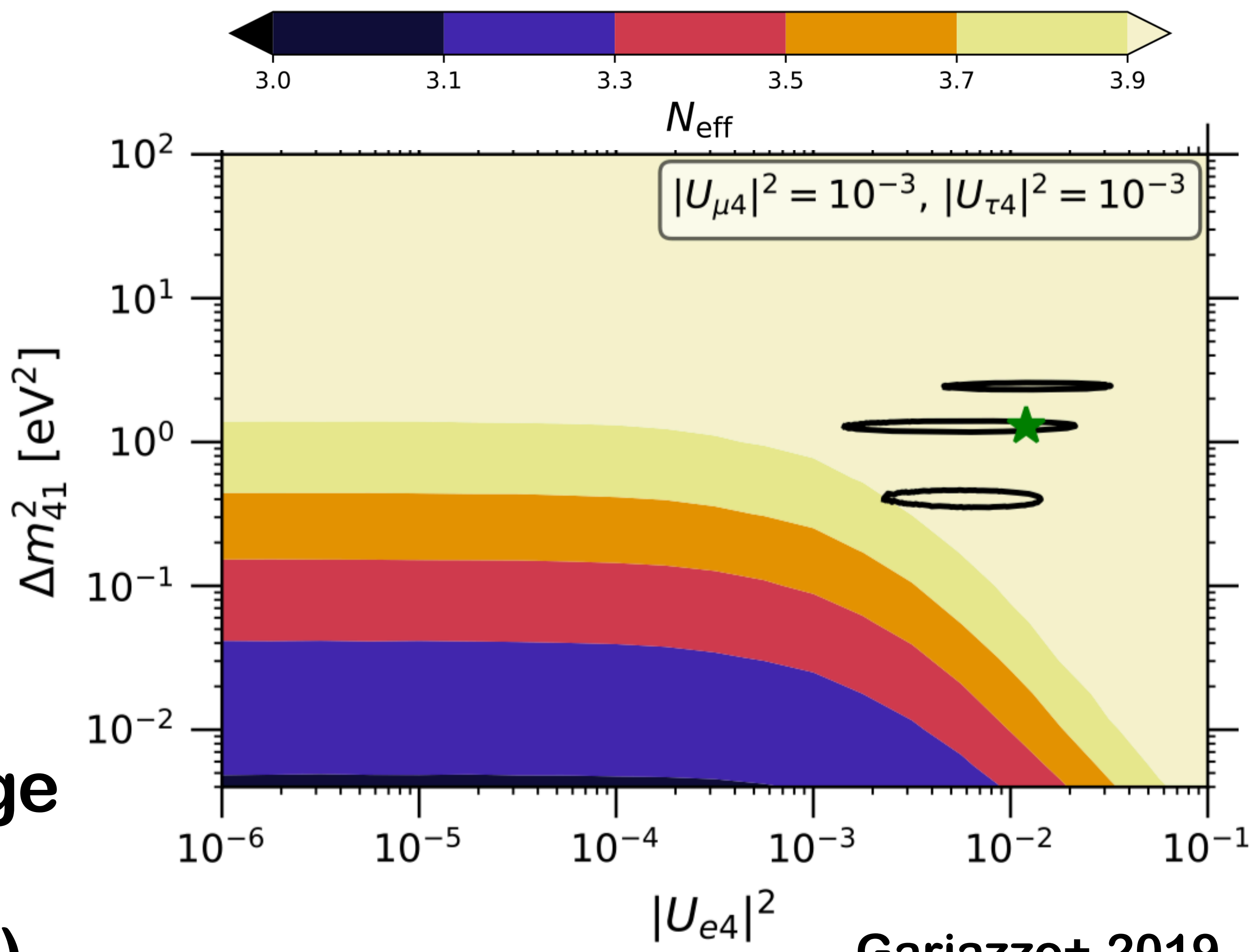
Hagstotz+, 2020; Gariazzo+, 2020



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

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

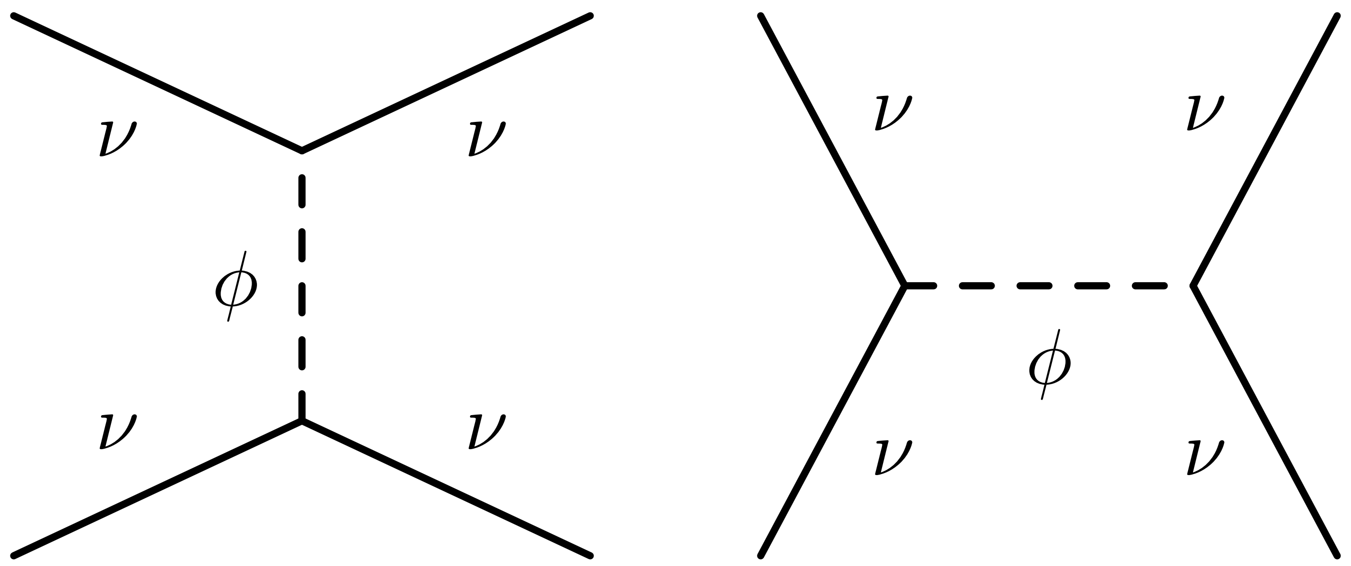


Gariazzo+,2019

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

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; …

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

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

With current data, no hint for deviations from the SM.

What next in neutrino cosmology

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

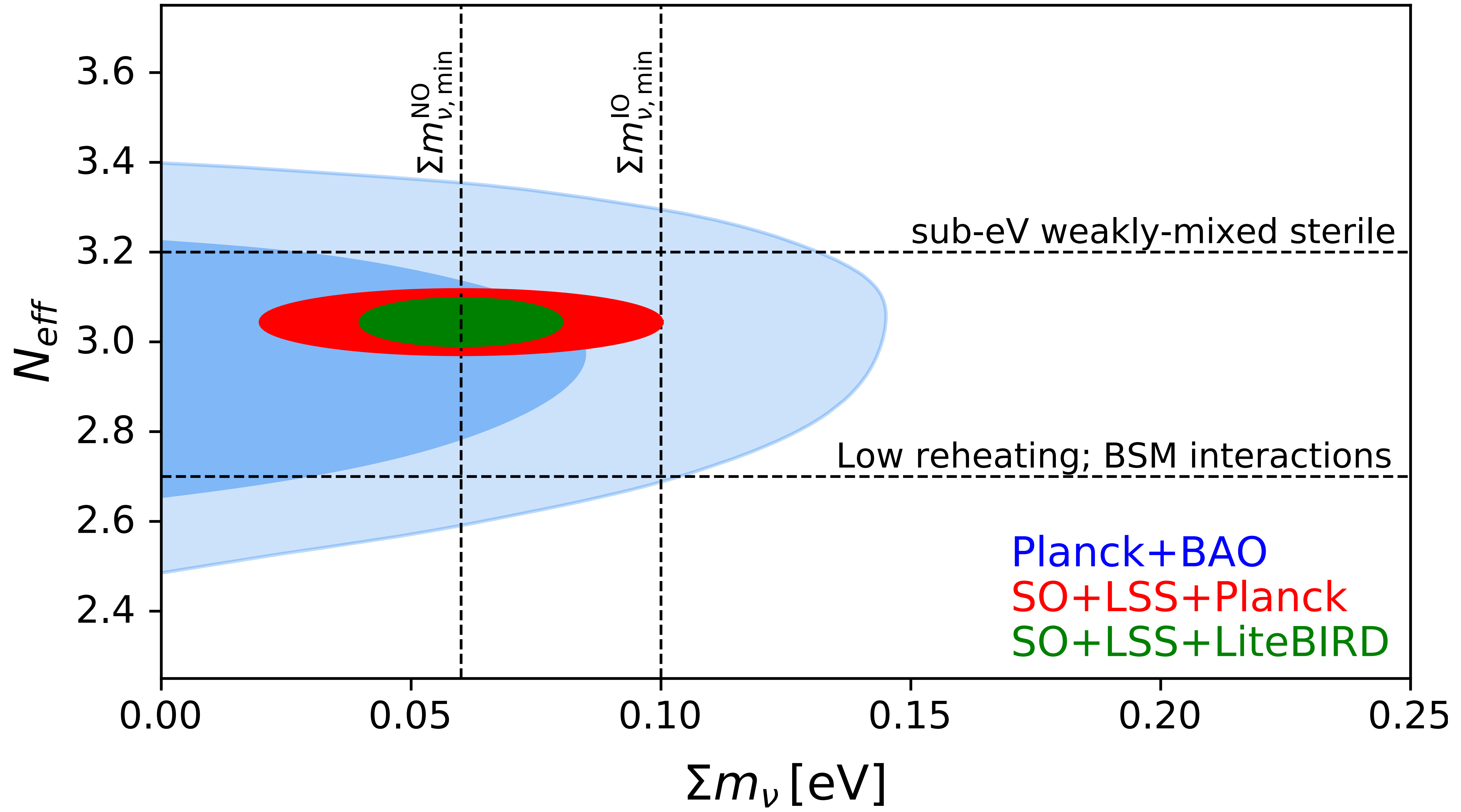
Does it mean that we are moving:

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

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

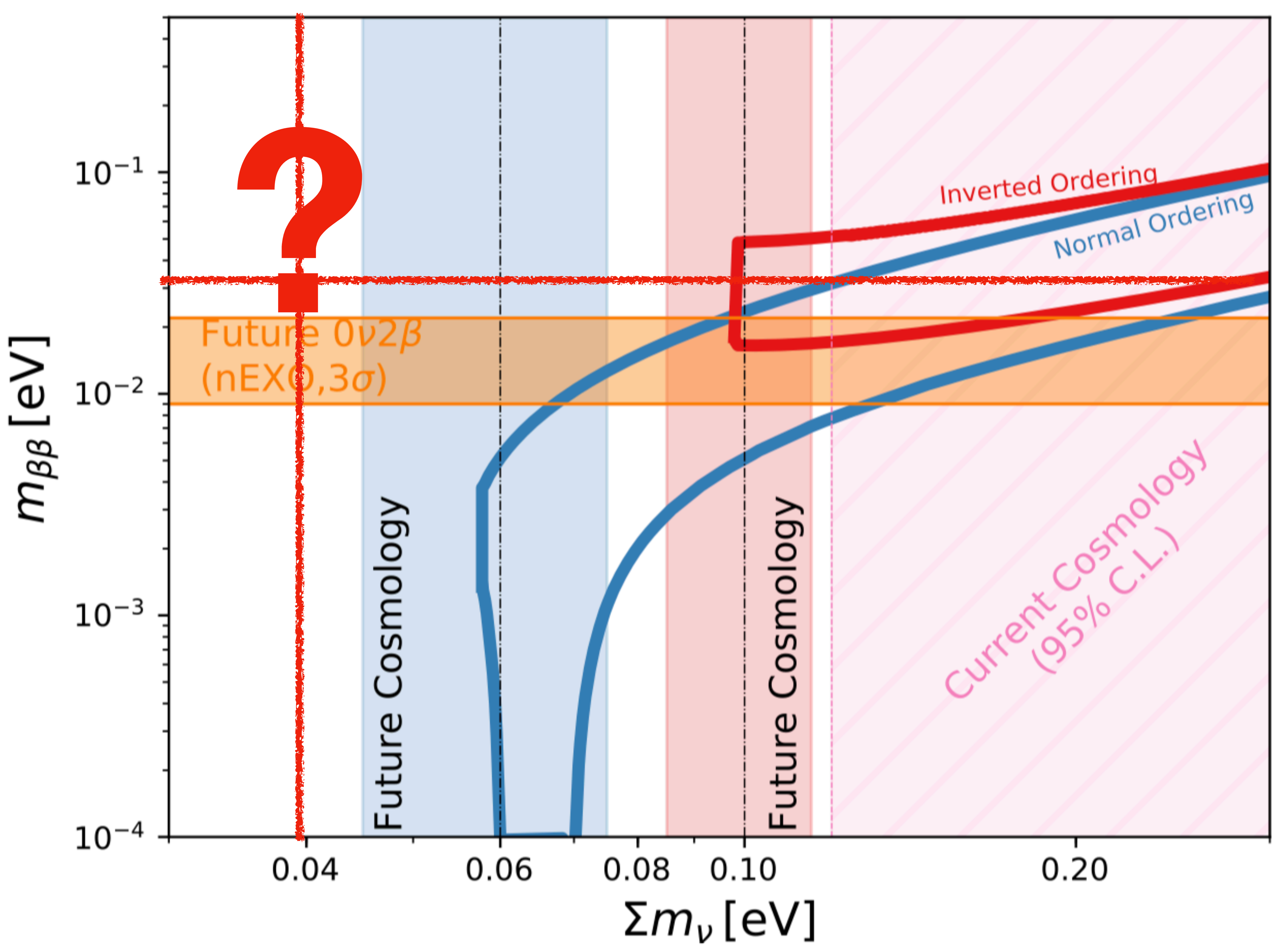
2) **Towards the first probe of the physics of neutrino decoupling, and of BSM content at very early times?**

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



Towards the mass sum: synergy with lab

CMB-S4 Collaboration, 2019



Several interesting scenarios are possible (I am being sketchy here):

- Concordant signals from both cosmology and 0nu2b. Neutrinos are Majorana. Hierarchy might be determined or not.
- Signal from cosmology with Mnu<0.1 eV, no signal from 0nu2b. Hierarchy is normal. Majorana/Dirac undetermined.
- Signal from cosmology with Mnu > 0.1 eV, no signal from 0nu2b. Neutrinos are Dirac. Hierarchy is undetermined.
- No signal from cosmology, signal from 0nu2b. OR we see discordant signals. Neutrinos are Majorana. New physics? E.g. BSM neutrino interactions?

Courtesy of M. Lattanzi

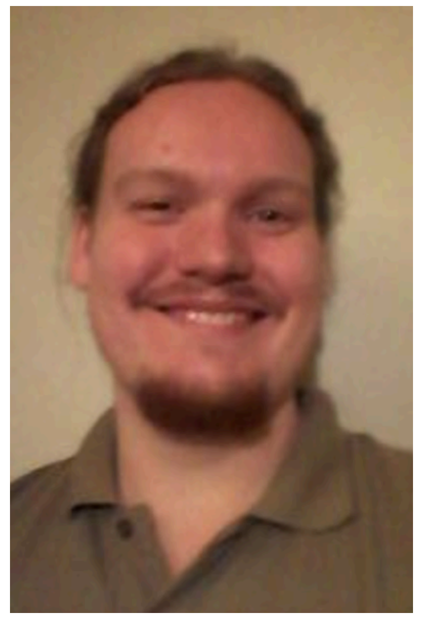
Challenges ahead

- Theory: evolution of cosmic structures at late times (non linear regime)
- Instrument: extreme control of systematics required
- Statistics #1: advanced tools to efficiently combine different (correlated) dataset
- Statistics #2: advanced tools to quantify statistical preference and/or possible bias

The community is aware of these challenges and has already started work against them!

Contributions from CosmoFe:

S. Giardiello



T. Brinckmann

S. Alvi

Conclusions

Cosmology provides competitive and complementary bounds to neutrino (standard and non-standard) properties

At present, no evidence for non-standard neutrino behaviour over cosmological times and scales

Future surveys (~10years) will reach the required sensitivity to allow for groundbreaking results in neutrino physics

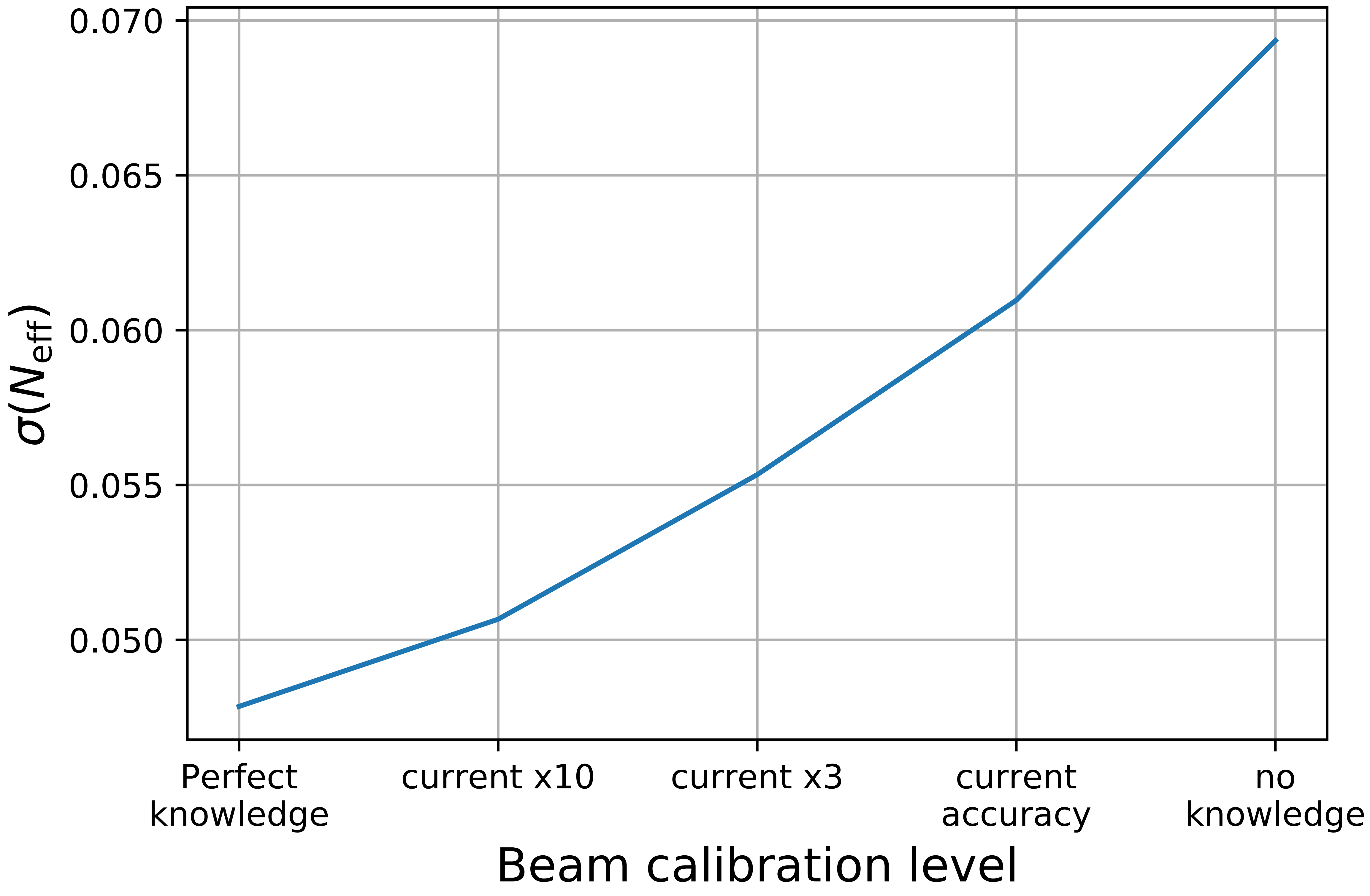
Need to face non-trivial challenges with a clear roadmap

Synergy with laboratory searches will corner neutrino unknowns

What next in neutrino cosmology

Many challenges ahead!

1) Know your instrument!

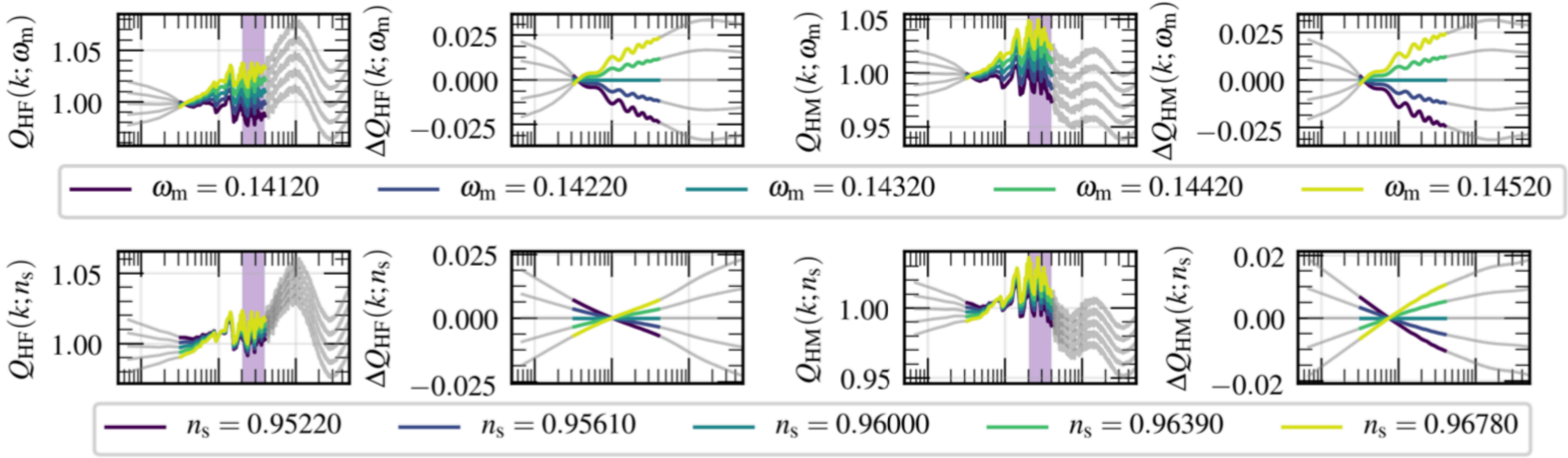


Adapted from
Simons Observatory Coll, 2018

What next in neutrino cosmology

Many challenges ahead!

2) Know your model!



Knabenhans+, in prep.

What next in neutrino cosmology

Many challenges ahead!

3) Know your data!

Combining information from multiple cosmological surveys: inference and modeling challenges
arXiv: 2103.05320

Abstract:
The tightest and most robust cosmological results of the next decade will be achieved by bringing together multiple surveys of the Universe. This endeavor has to happen across multiple layers of the data processing and analysis, e.g., enhancements are expected from combining Euclid, Rubin, and Roman (as well as other surveys) not only at the level of joint processing and catalog combination, but also during the post-catalog parts of the analysis such as the cosmological inference process. While every experiment builds their own analysis and inference framework and creates their own set of simulations, cross-survey work that homogenizes these efforts, exchanges information from numerical simulations, and coordinates details in the modeling of astrophysical and observational systematics of the corresponding datasets is crucial.