Interplay between Cosmology and Neutrino Physics

International Conference on the Physics of the Two Infinities - Kyoto, 27 Mar 2023

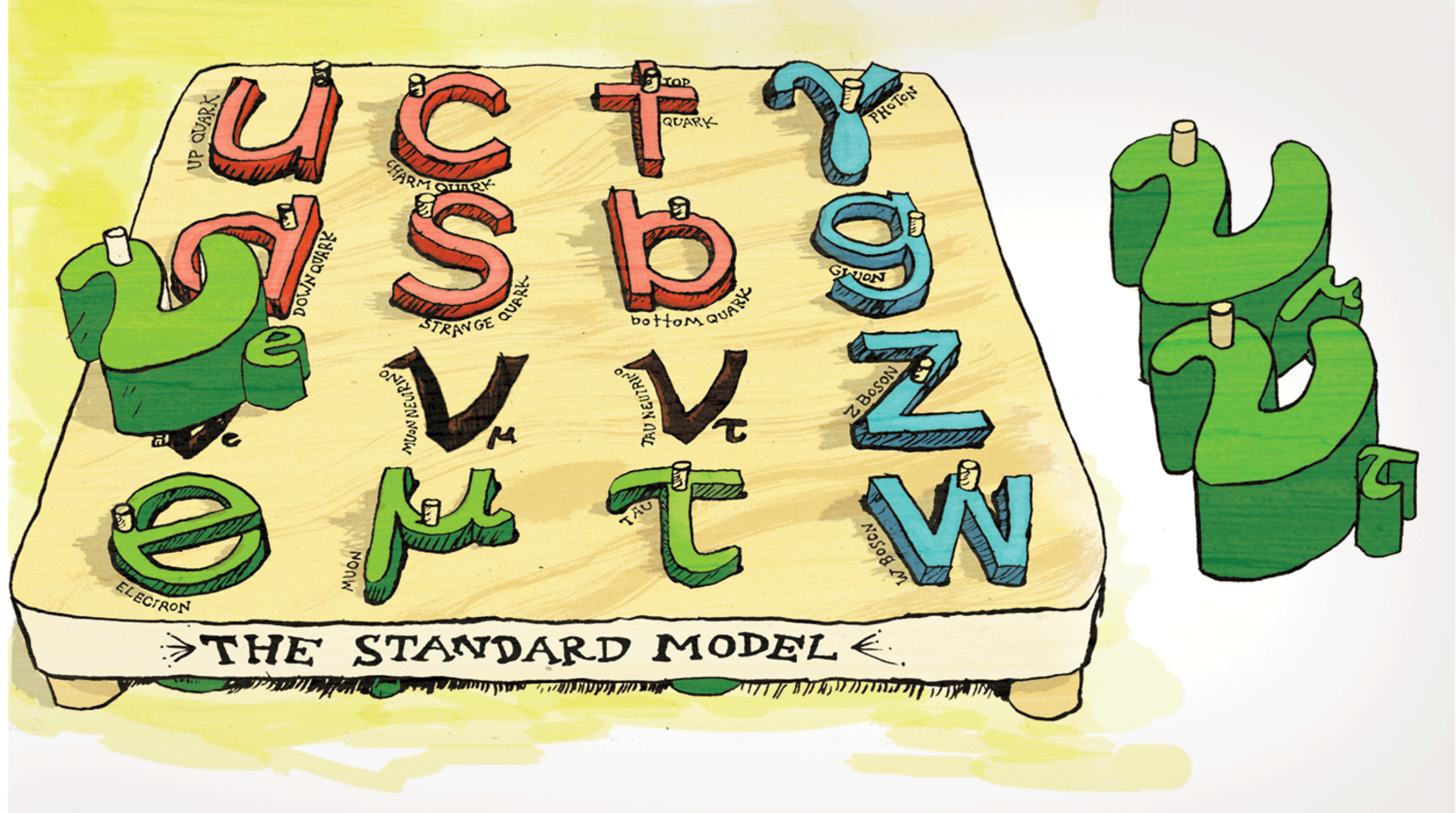
Martina Gerbino - INFN Ferrara

INFN
Istituto Nazionale di Fisica Nucleare

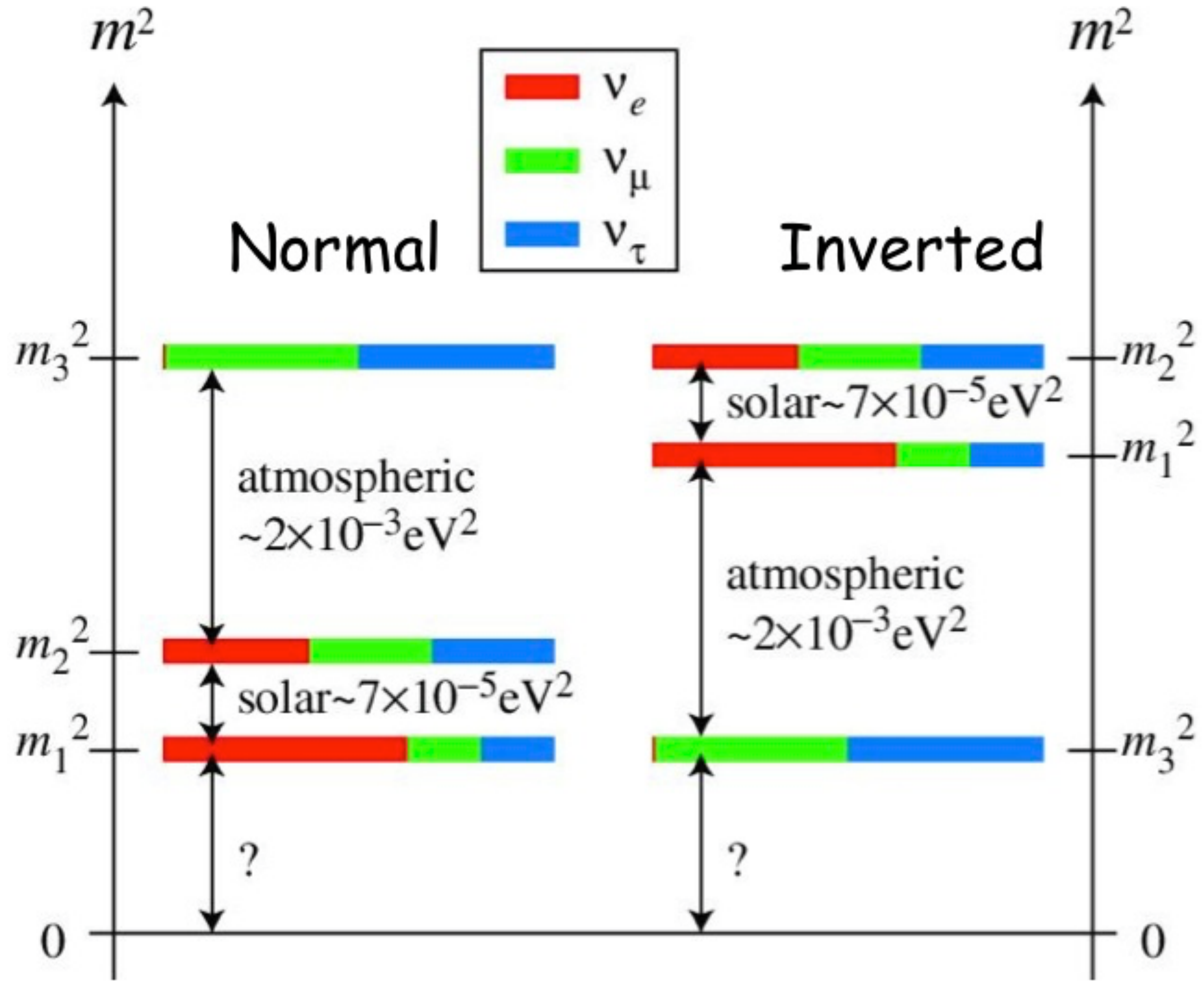
What's in a neutrino?

Neutrino flavour oscillations -> neutrinos have a mass!

Kajita&McDonald 2015 Nobel prize



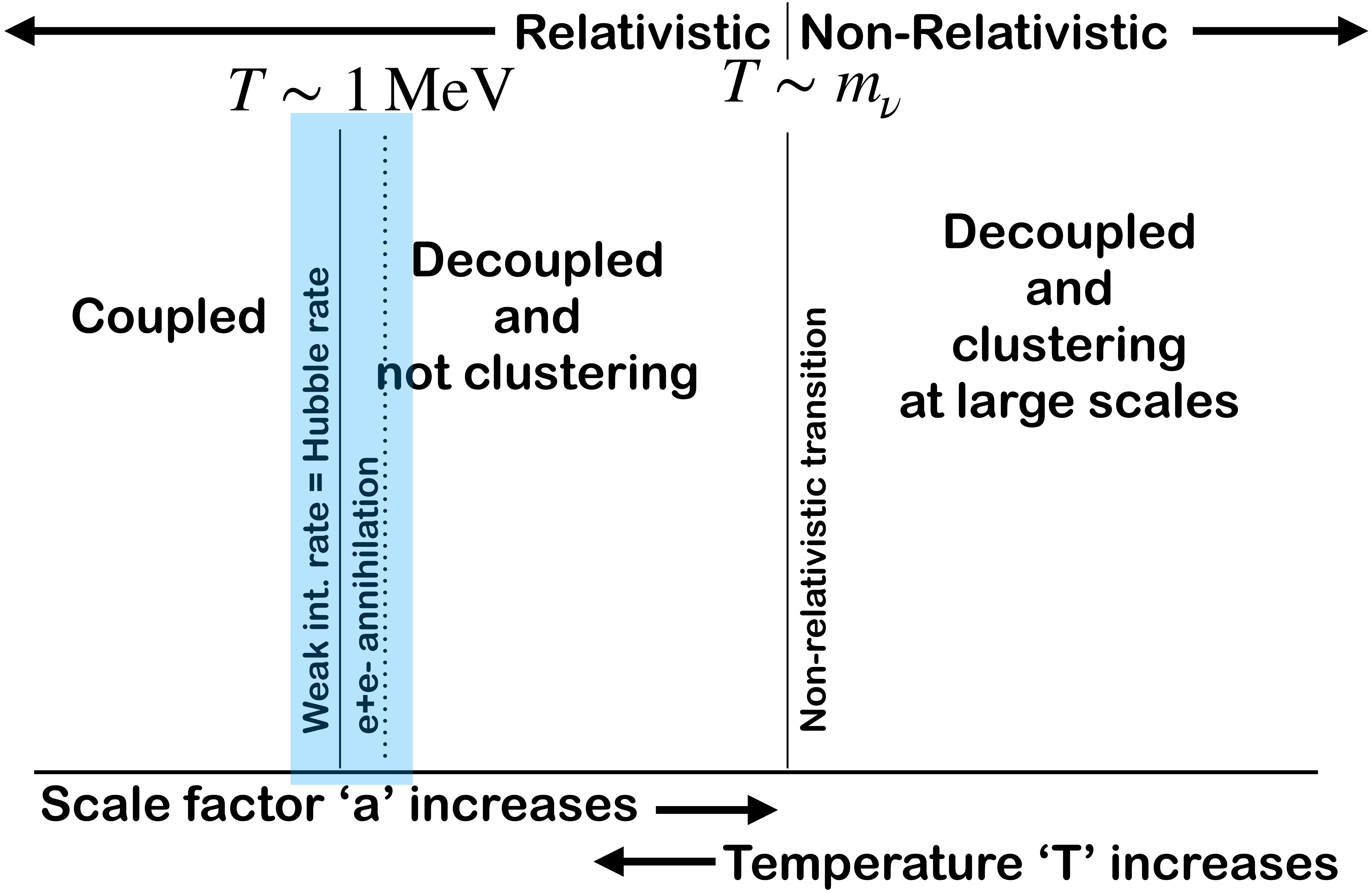
Cannot explain neutrino mass with SM content



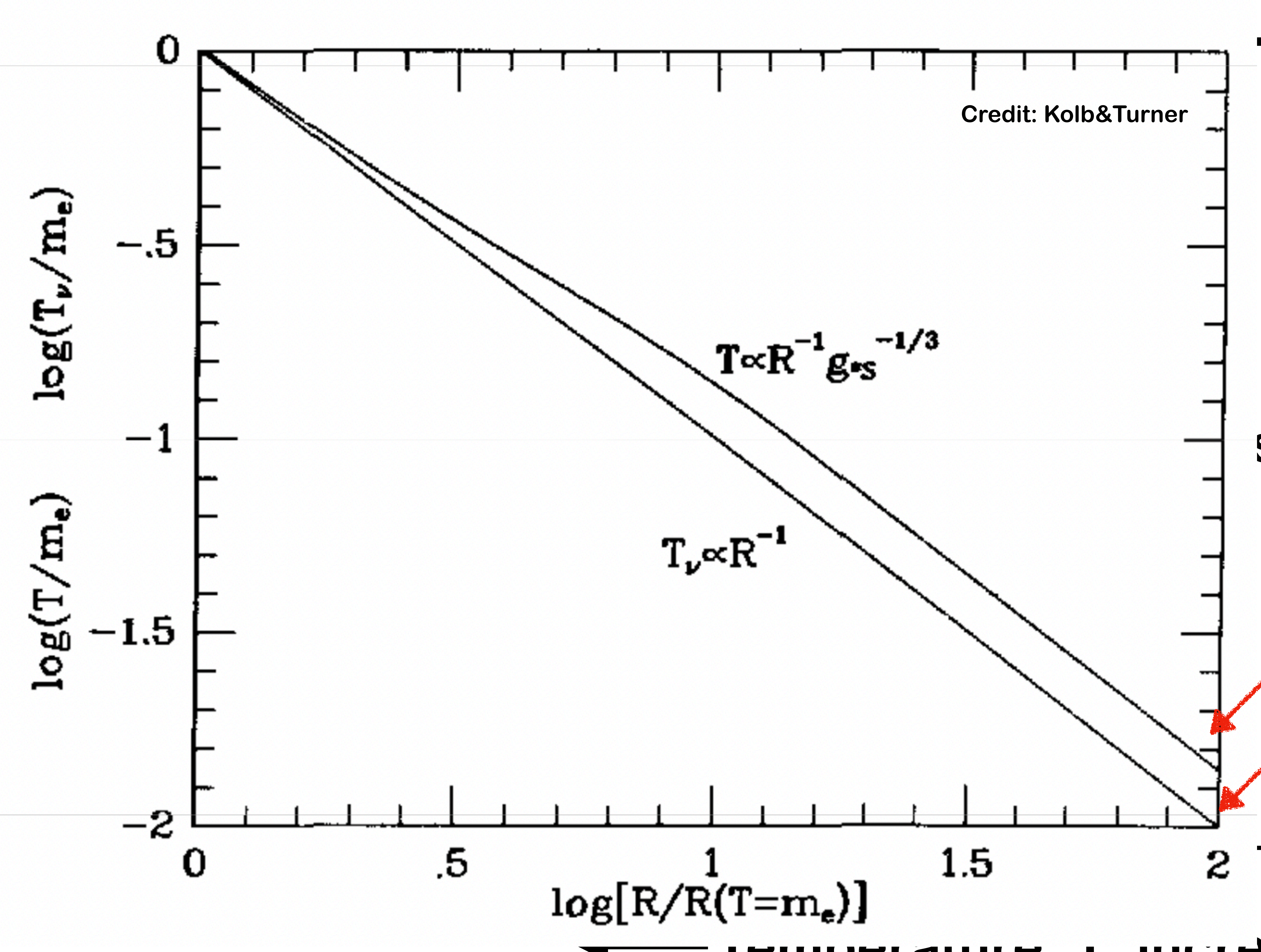
$$0.06\,\mathrm{eV} < \Sigma m_\nu < 2.4\,\mathrm{eV}$$

From oscillations **From b-decay**

Neutrino cosmology



Neutrino cosmology



$T_{\gamma,0} = 2.7255\,\mathrm{K}$

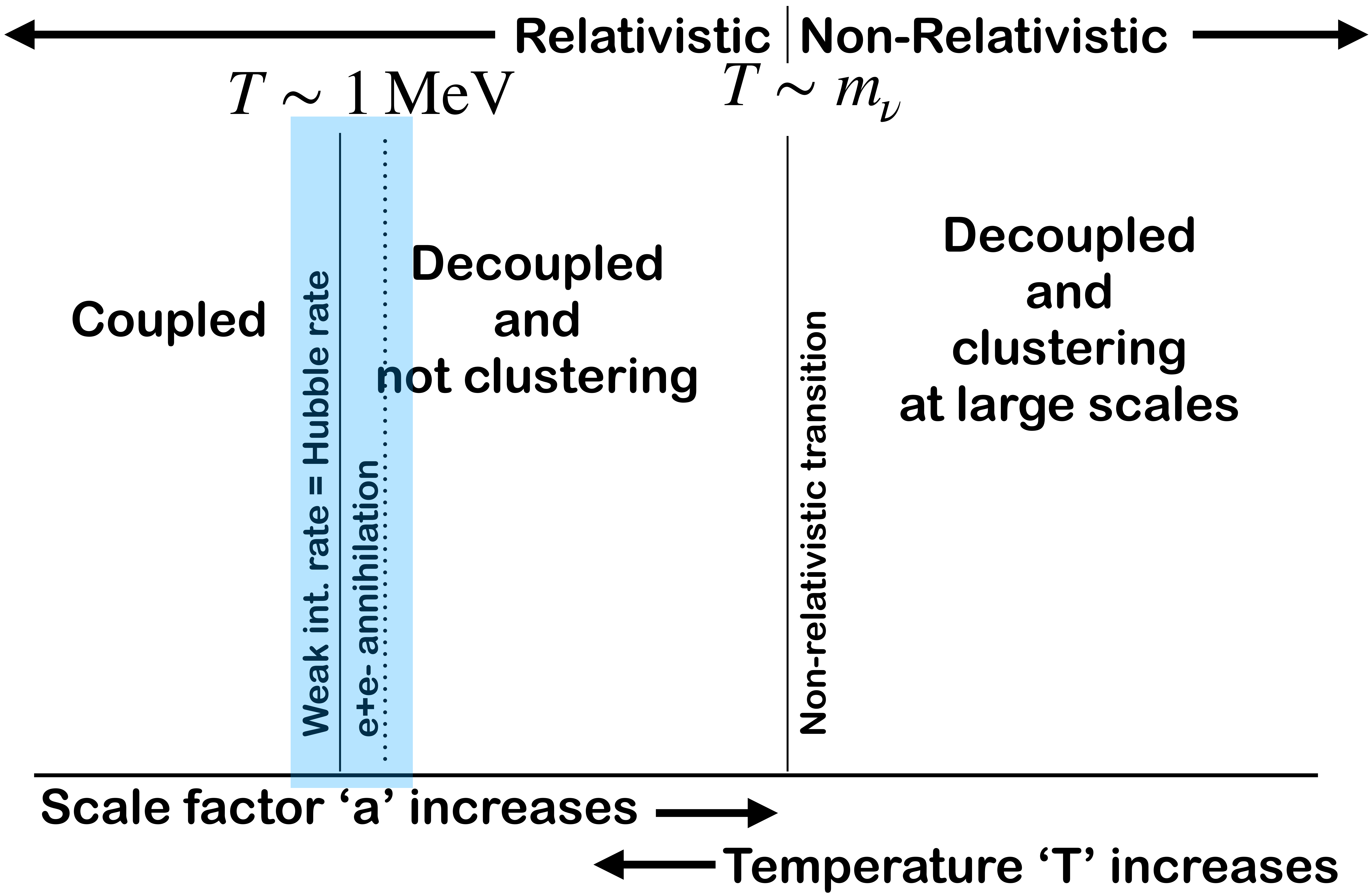
$T_{\nu,0} \simeq 1.9\,\mathrm{K}$

s

S

Temperature T increases

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**

Neutrinos and Cosmology

Pioneering and stringent bounds on neutrino properties from Cosmology already competitive with lab

$$m_\nu < 400\,\mathrm{eV} \qquad (\rho_\nu < \rho_{\rm tot})$$

$$m_\nu < 8\,\mathrm{eV} \qquad (\rho_\nu < \rho_{\rm DM})$$

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

+ lower bounds for very heavy neutrinos
Szalay&Marx(1976)
Hut; Lee&Weinberg; Sato&Kobayashi(1977)

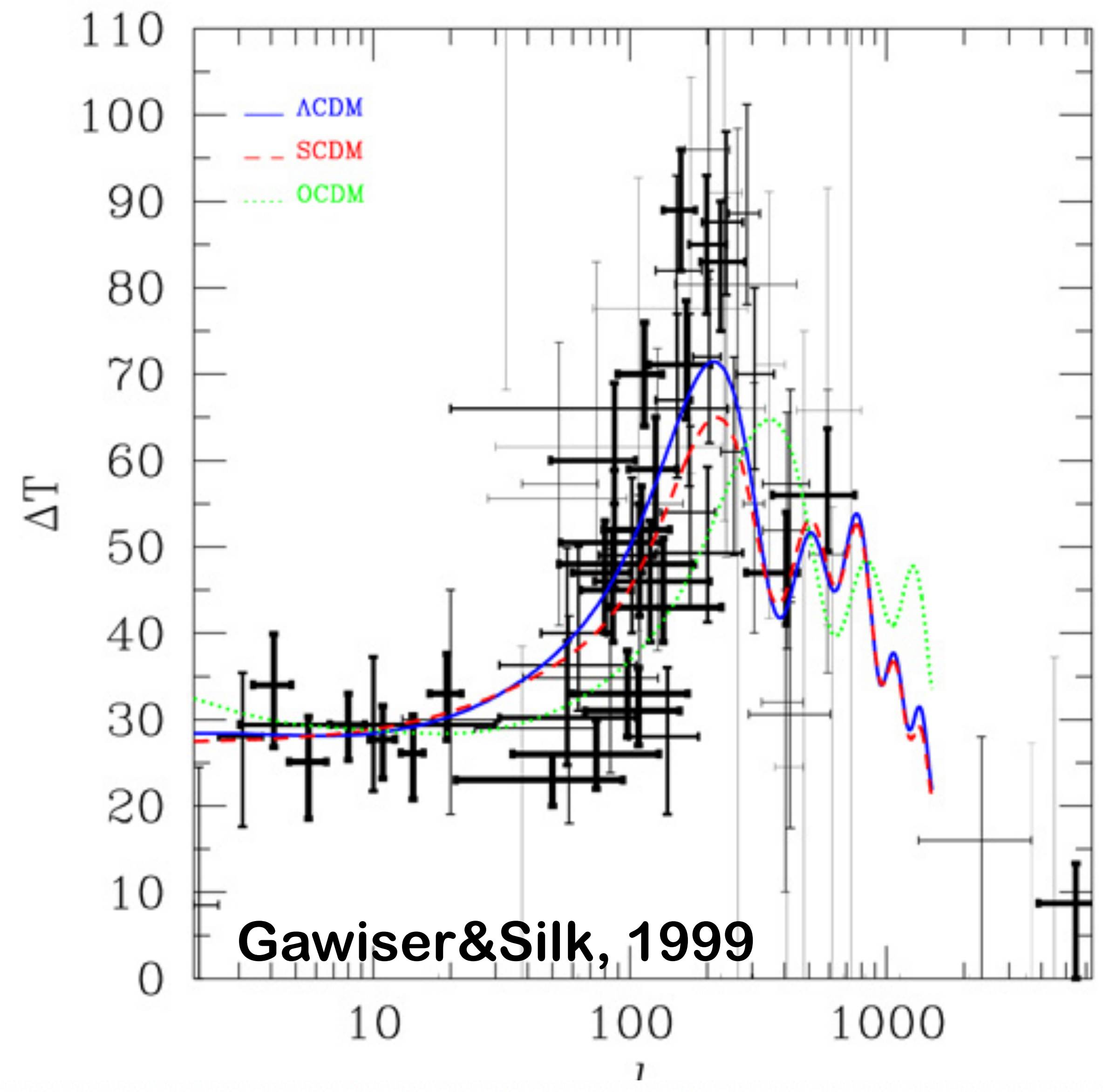
+ from numerical sims
structure formation with hot DM is top-down, incompatible with observations (1980s)

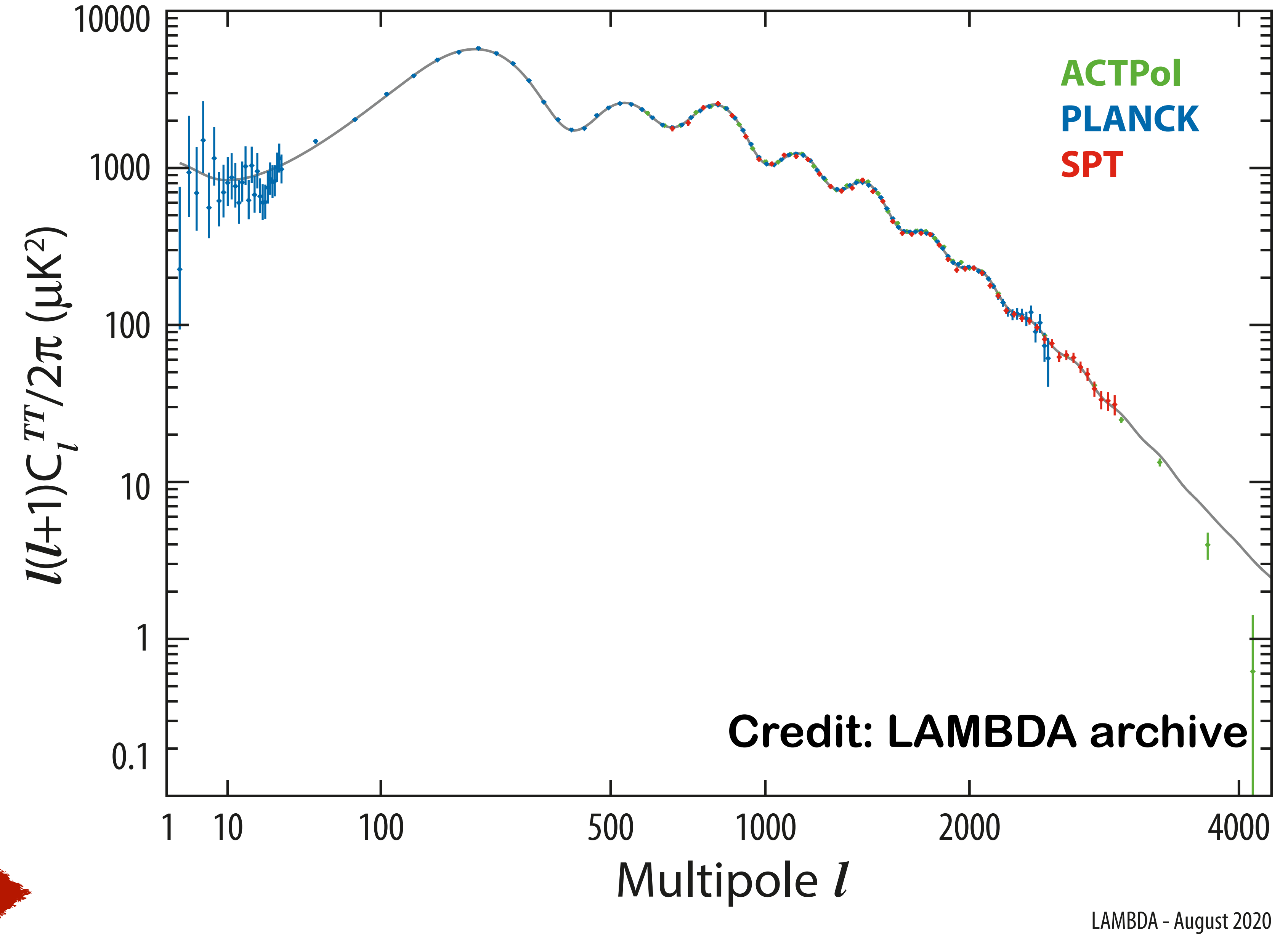
$$N_\nu < 4$$

Schramm&Kawano (1989)
Olive+ (1990)

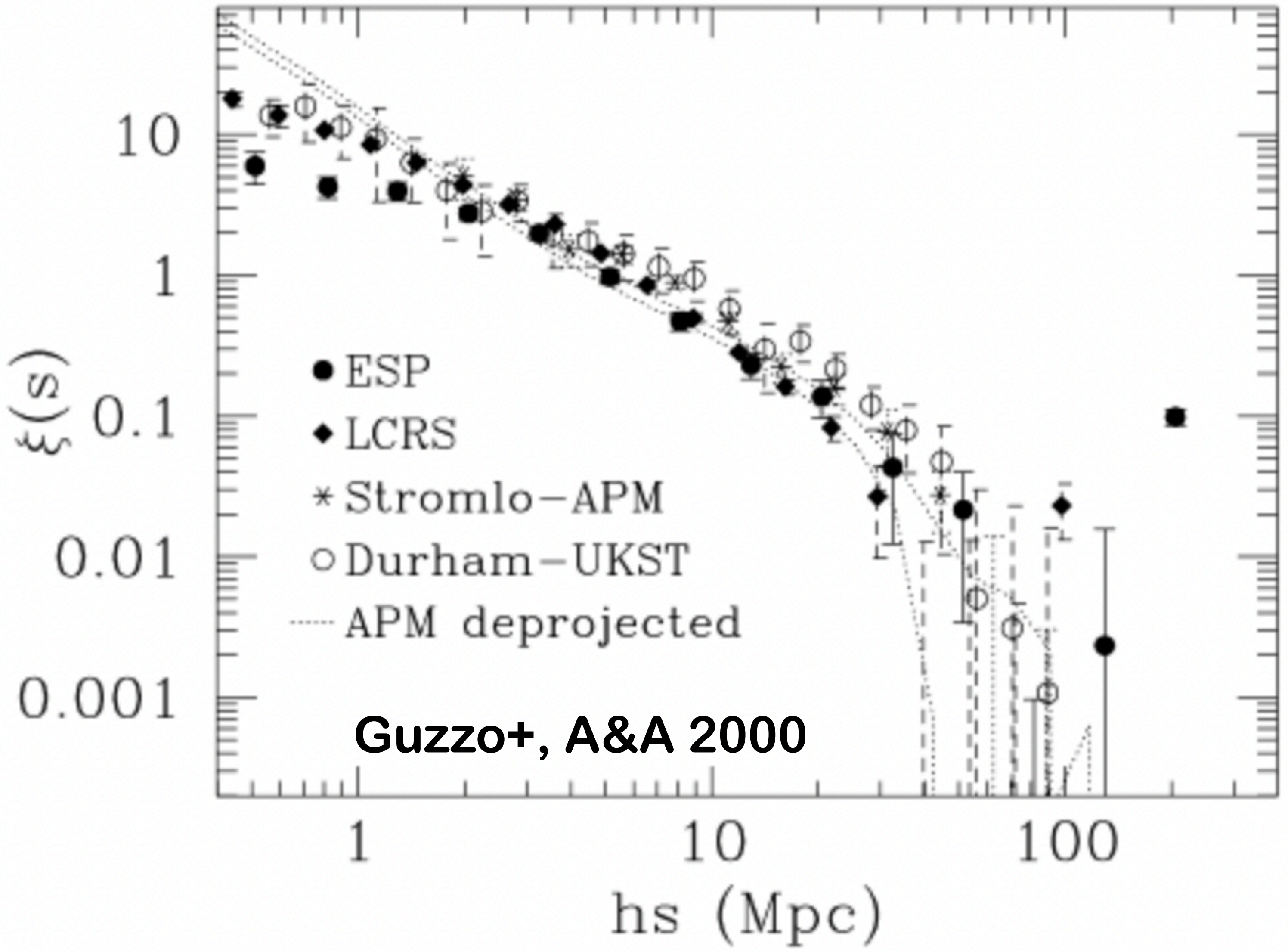
(Stringent) bound on the family number required not to spoil BBN

The route to precision cosmology

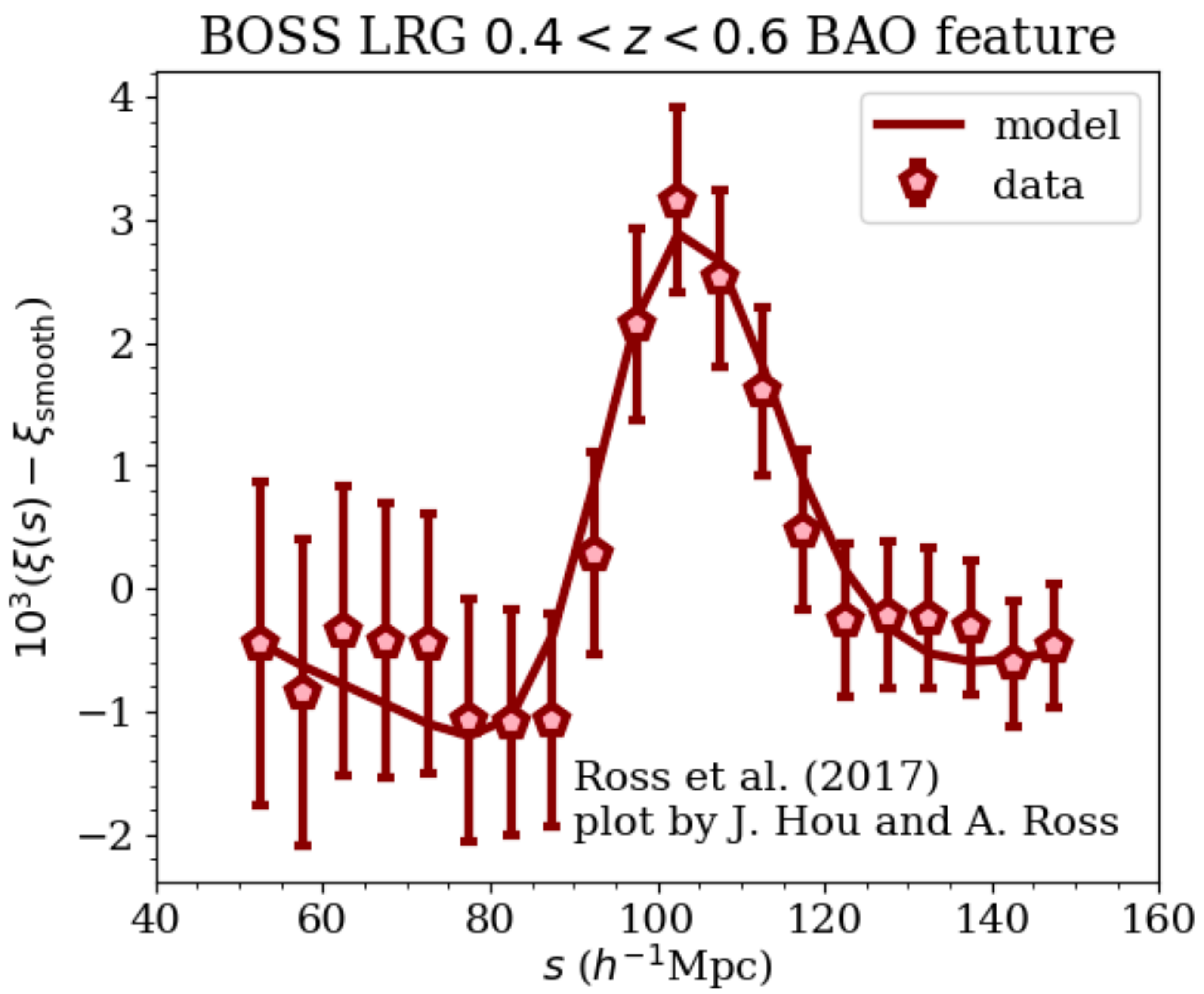




From late 1990s
to today

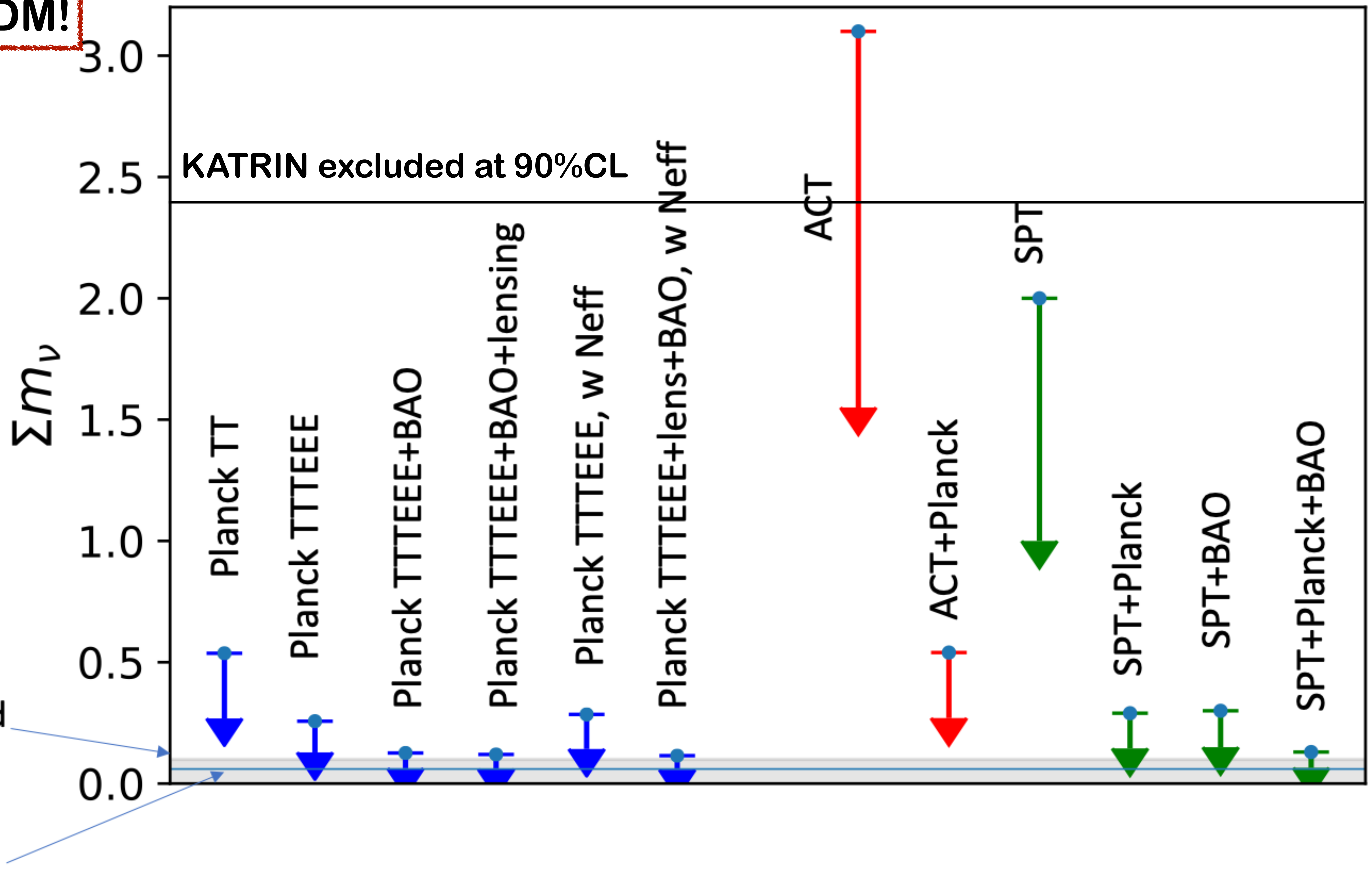


Percent-accuracy observations
Precise theoretical predictions
Improved statistical analysis



Current limits on the mass sum

NOTE: this assumes LCDM!

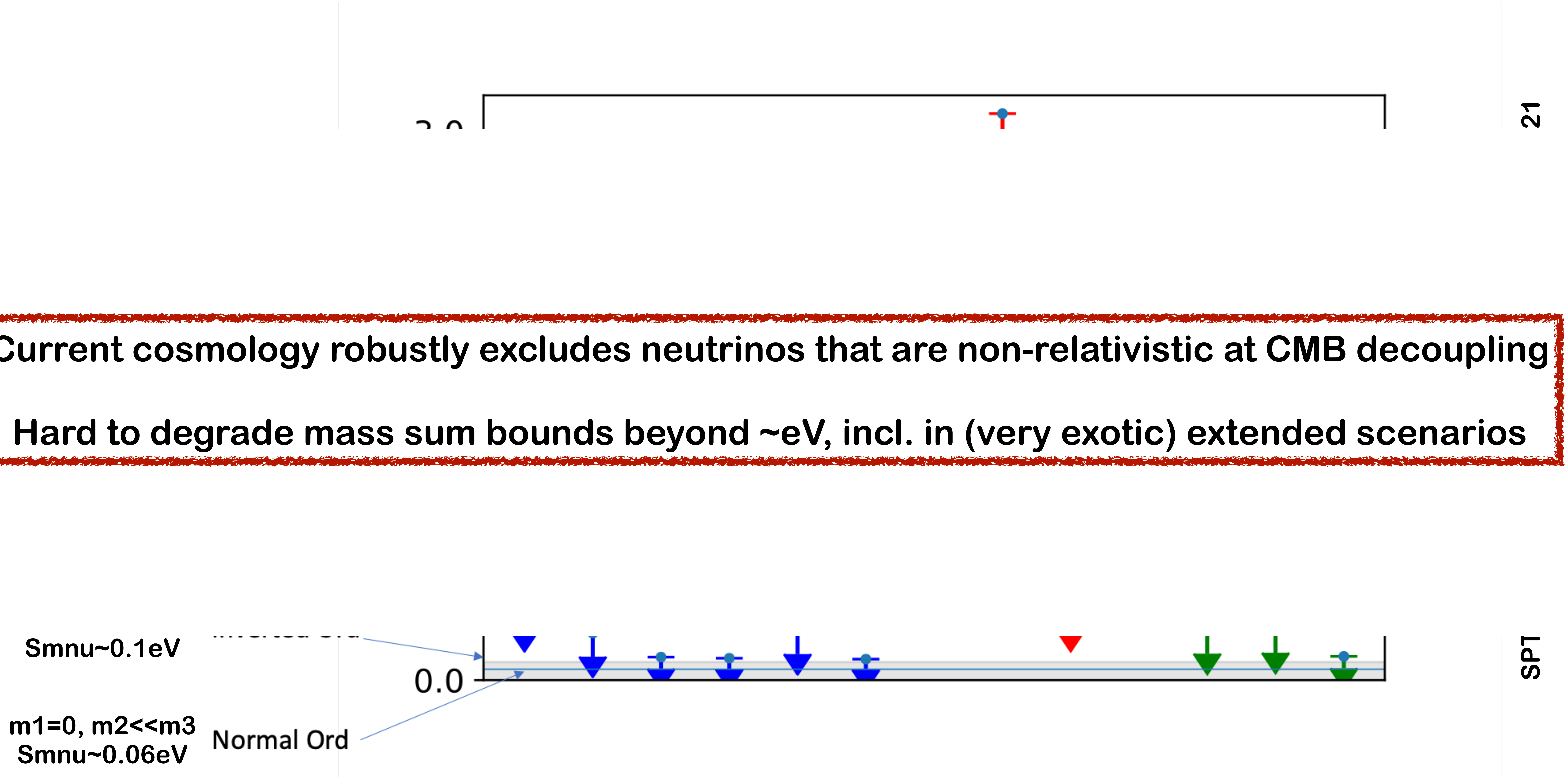


m3=0, m1~m2
Smnu~0.1eV

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

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

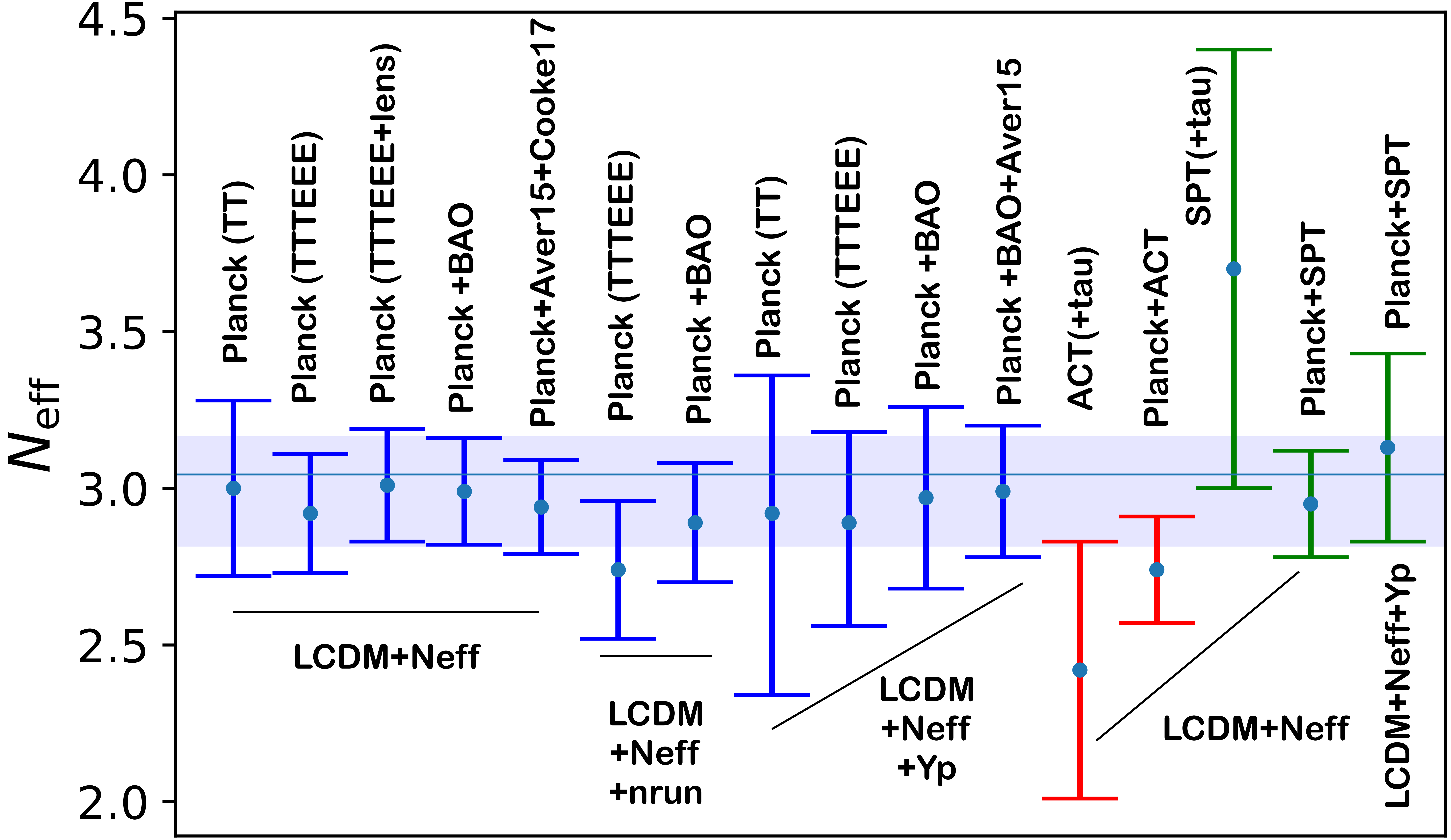
Current limits on the mass sum



Current cosmology robustly excludes neutrinos that are non-relativistic at CMB decoupling

Hard to degrade mass sum bounds beyond ~eV, incl. in (very exotic) extended scenarios

Current limits on Neff



Planck collaboration, VI 2018
ACT Collaboration (Aiola+), 2020
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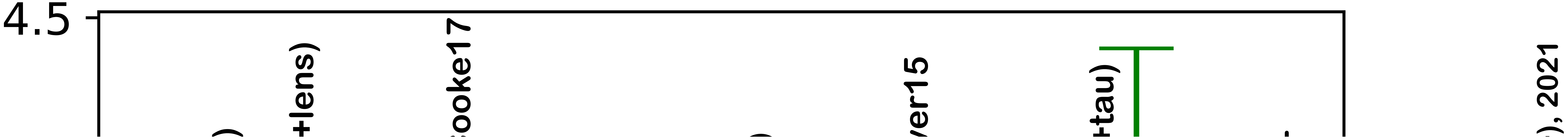
Current limits on Neff



Current cosmology in agreement with standard neutrino decoupling

Extra species thermalising after QCD-PT excluded at high significance (e.g., light sterile neutrino)

What next in neutrino cosmology

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

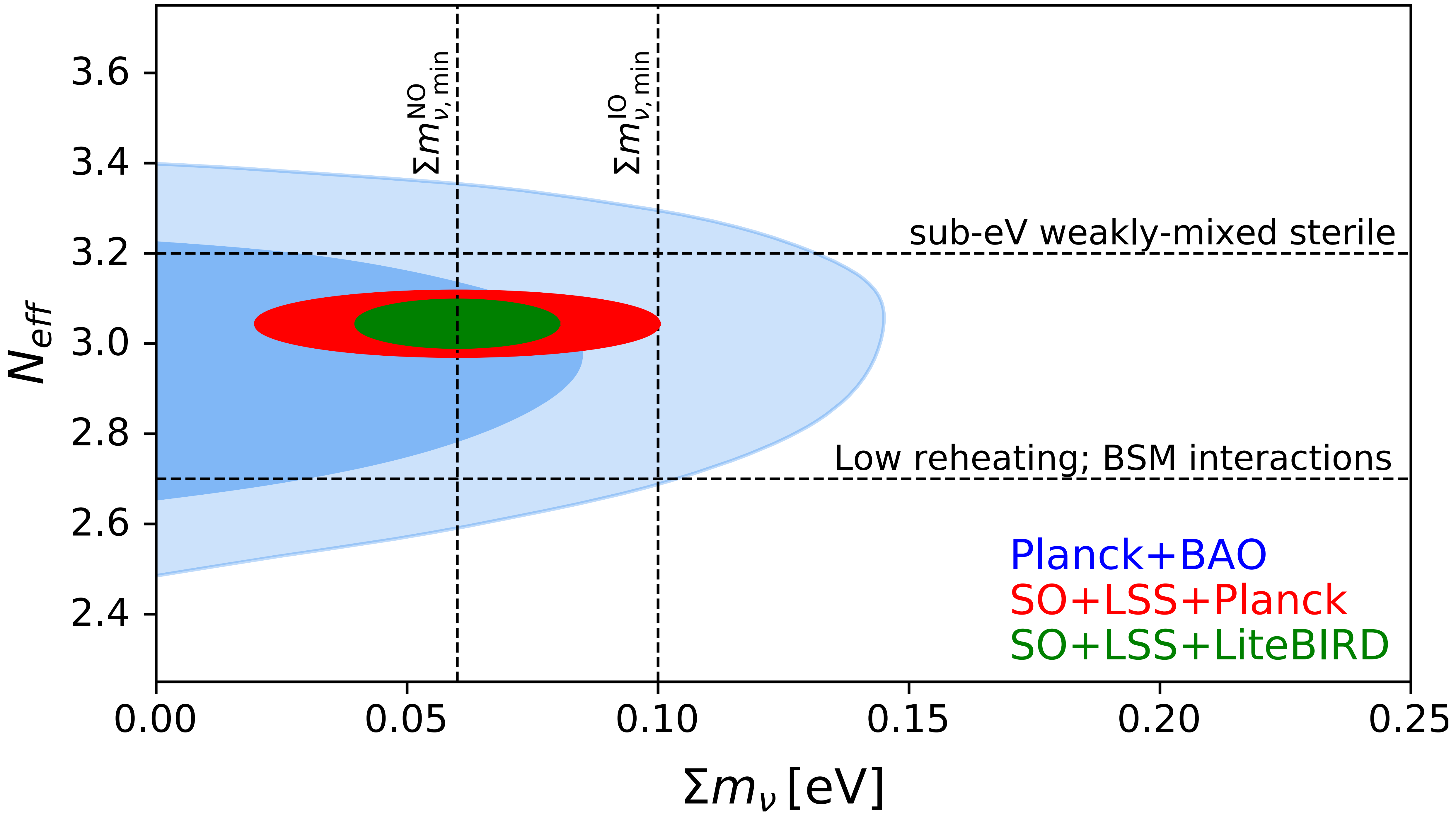
Does it mean that we are moving:

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

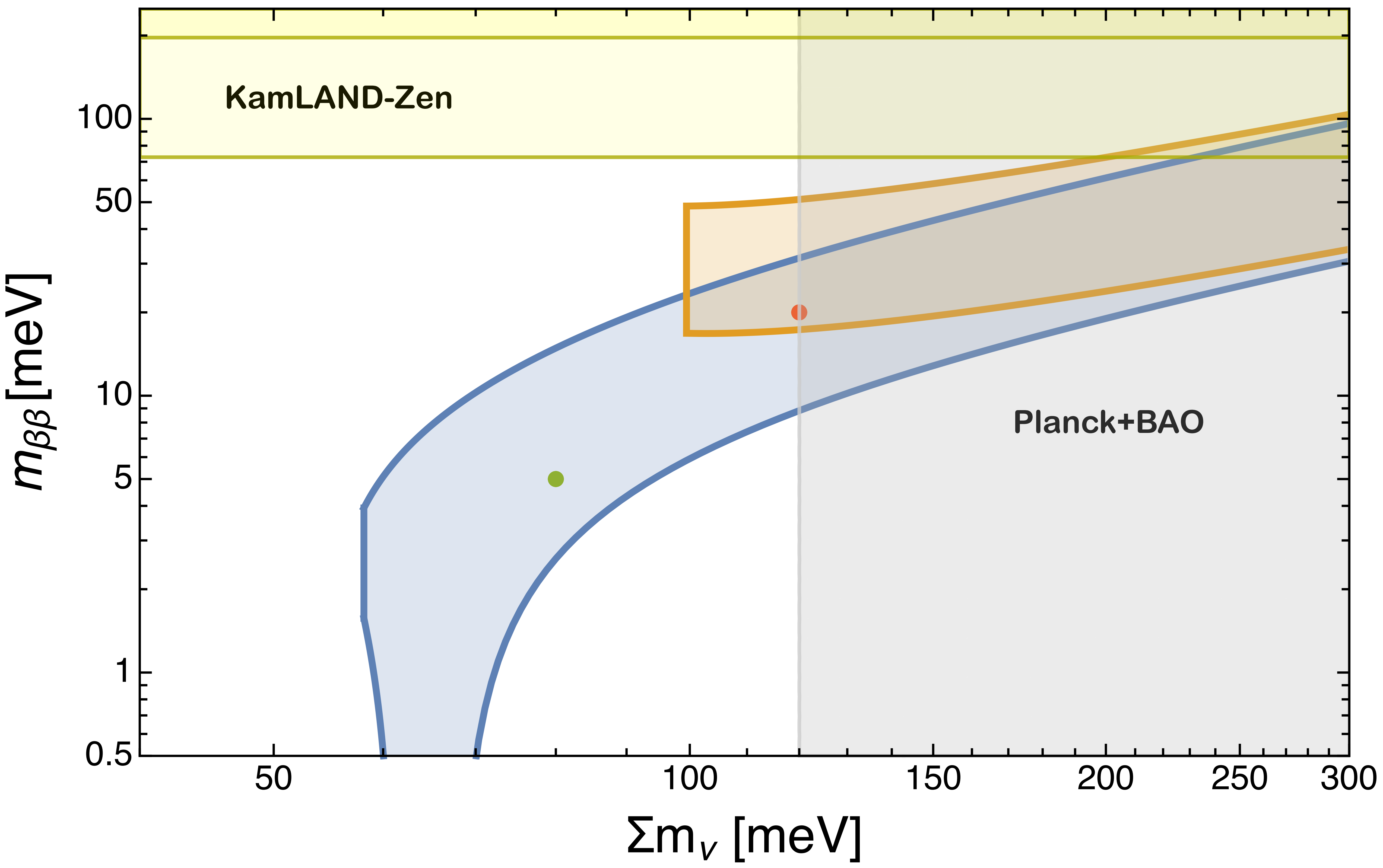
$$\sigma(\Sigma m_\nu) = 0.02\,\mathrm{eV}$$

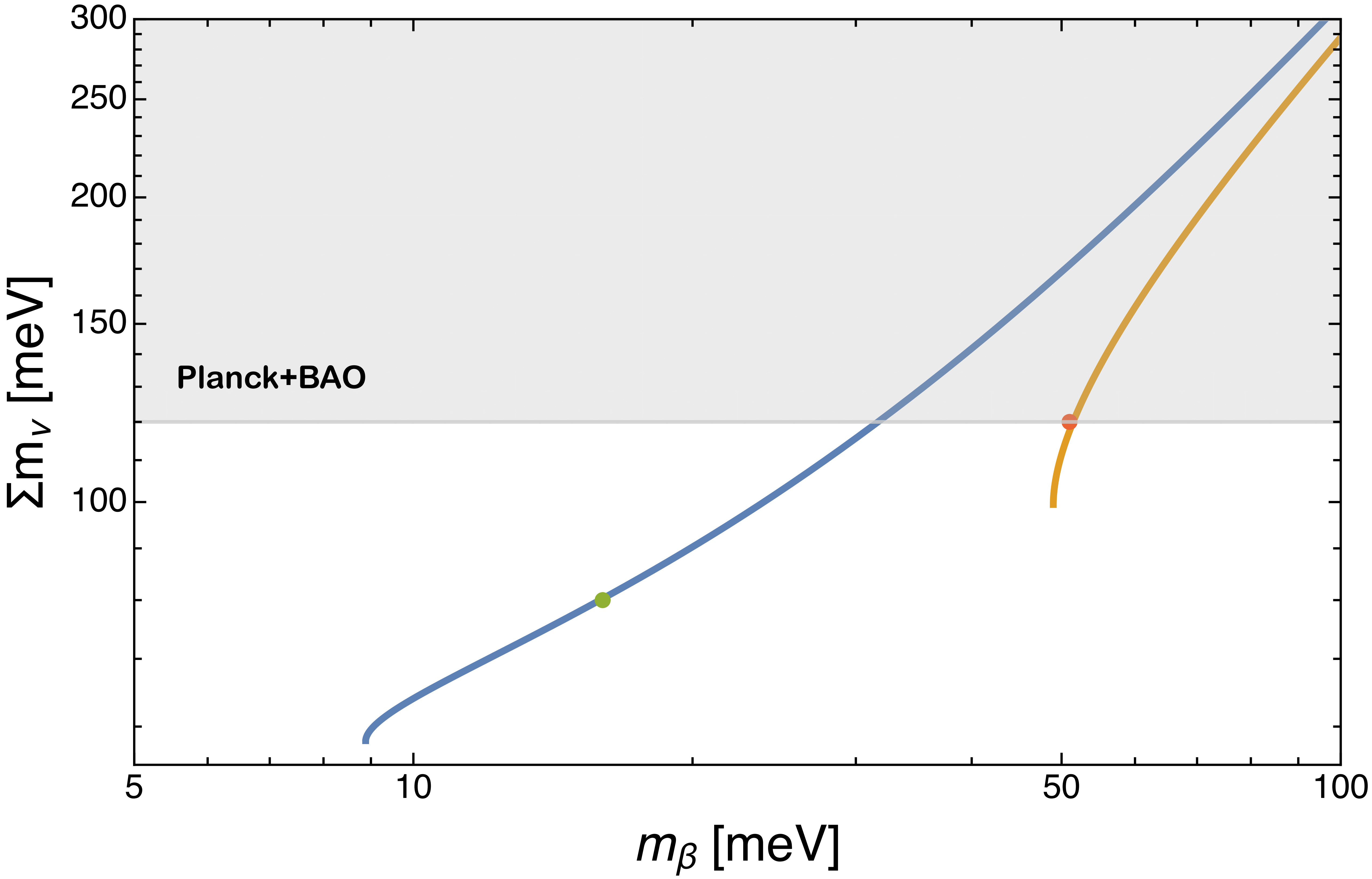
2) **Towards the first probe of the physics of neutrino decoupling, and of BSM content at very early times?**

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



Concordance/discordance scenarios





A joint effort:
synergy between cosmology, 0n2b decay, b-decay and oscillation experiments is key to convince ourselves of the robustness of the results

Gerbino, Grohs, Lattanzi,+, 2022

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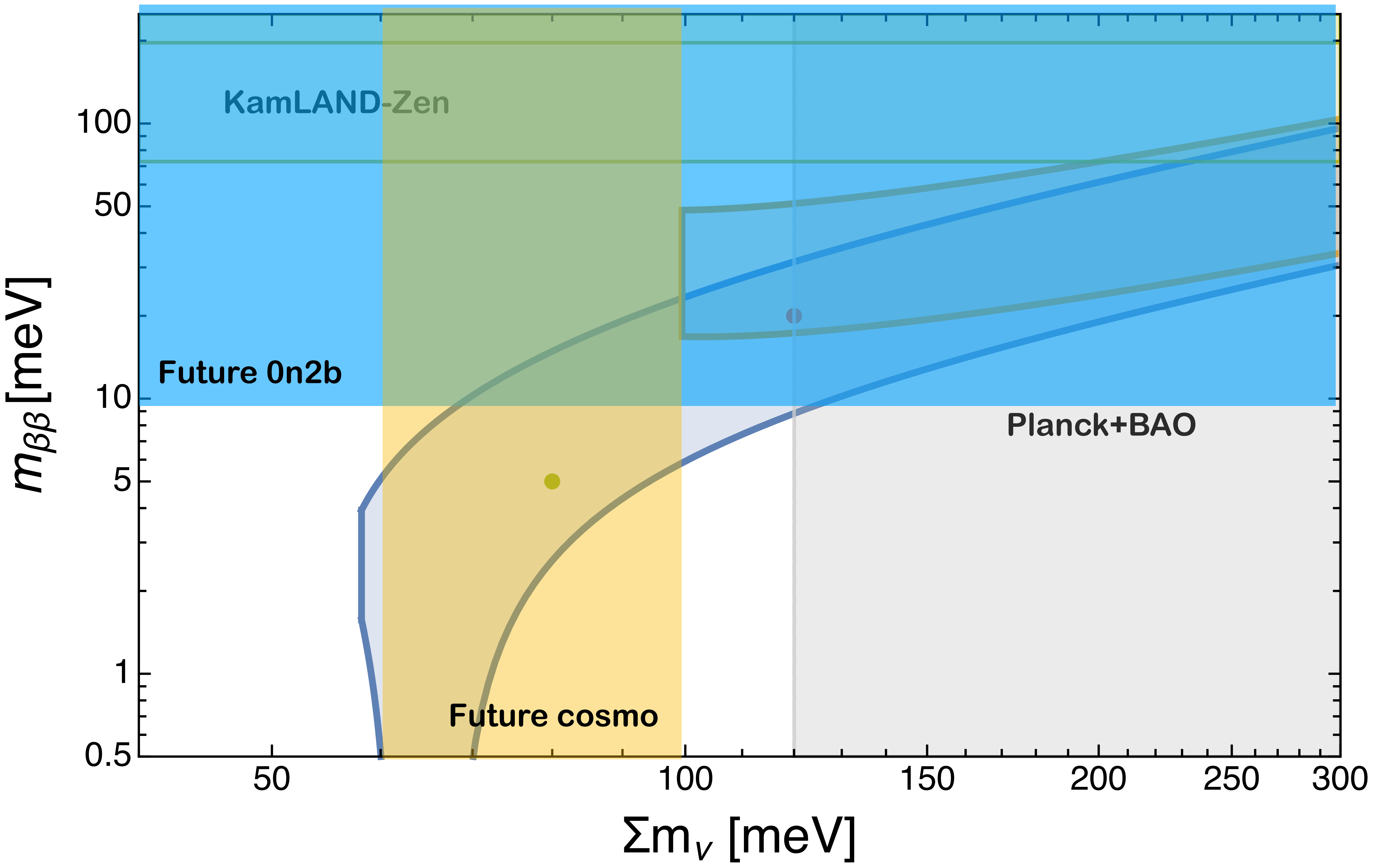

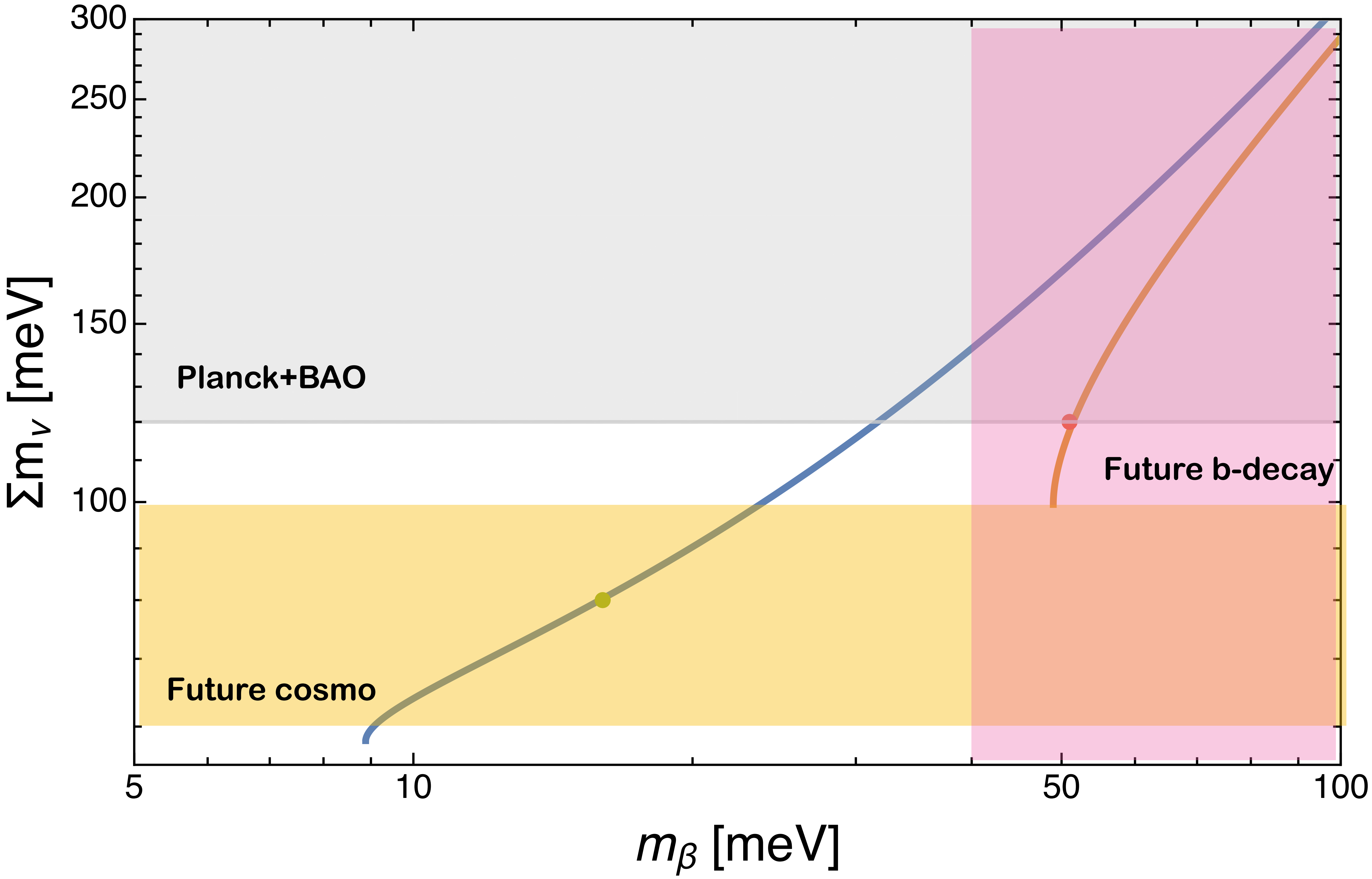

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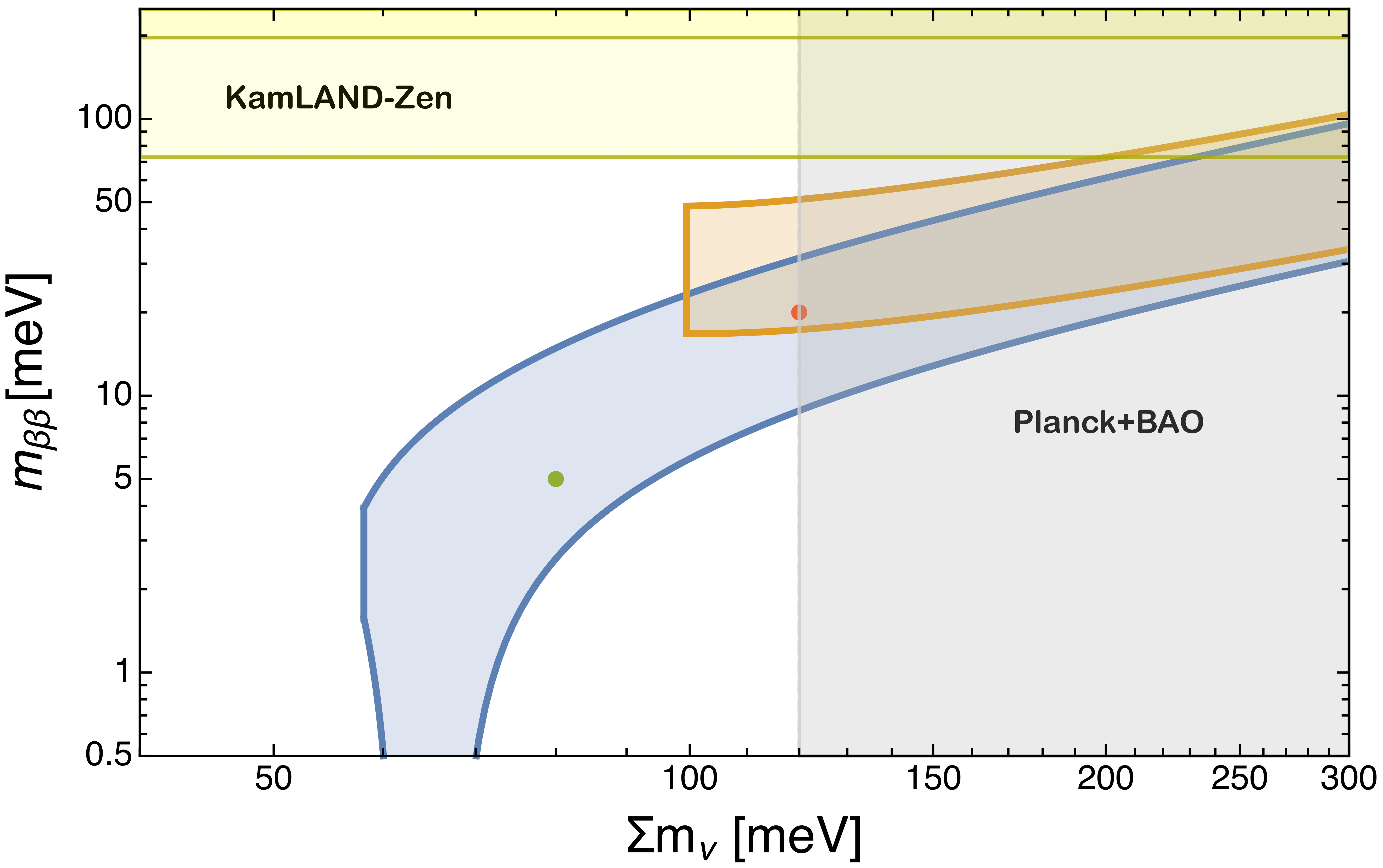

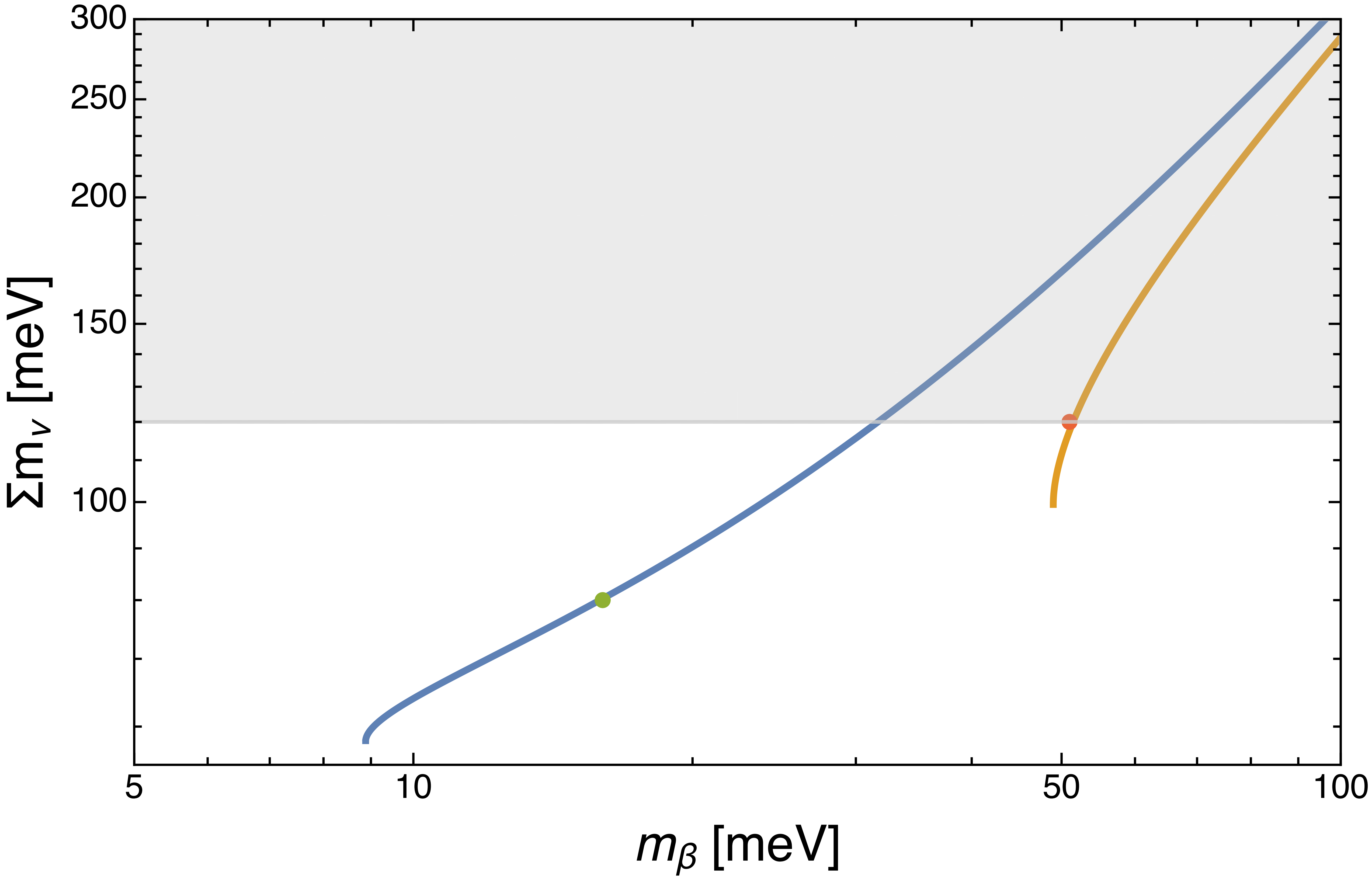

Scenario 1: cosmology and 0n2b measurements

- **Neutrinos are Majorana**
- **If Smnu<0.1eV -> ordering is Normal**
- **If Smnu>0.1eV -> ordering must be inferred from oscillations only**
- **If Smnu>>0.1eV -> expected signal from b-decay expo**

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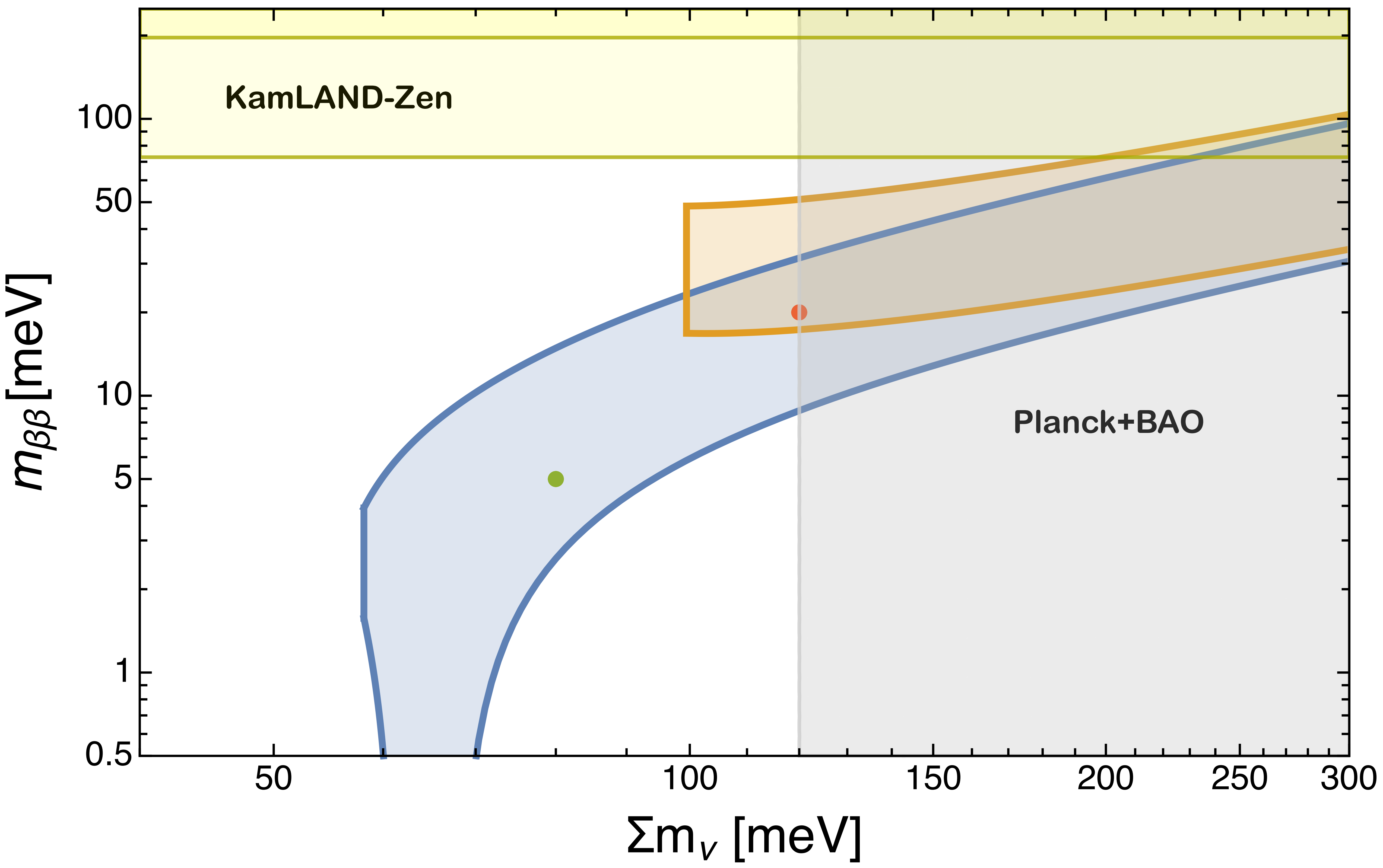
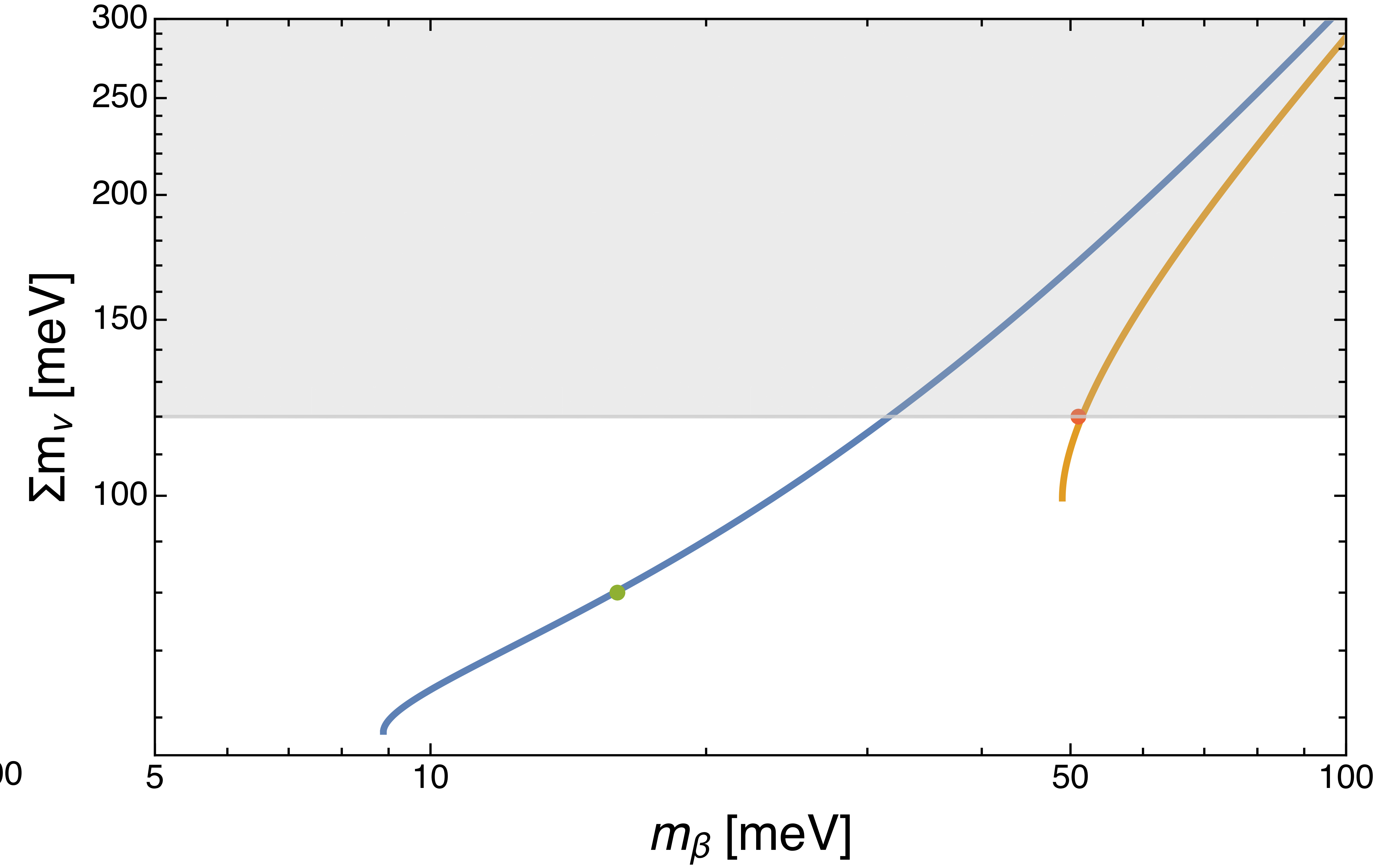
Concordance/discordance scenarios





Scenario 2: cosmology measurement, no 0n2b measurement

- **If Smnu small and ordering is normal from oscillations -> neutrinos could be Majorana**
- **If Smnu large and ordering is inverted from oscillations -> neutrinos are Dirac**

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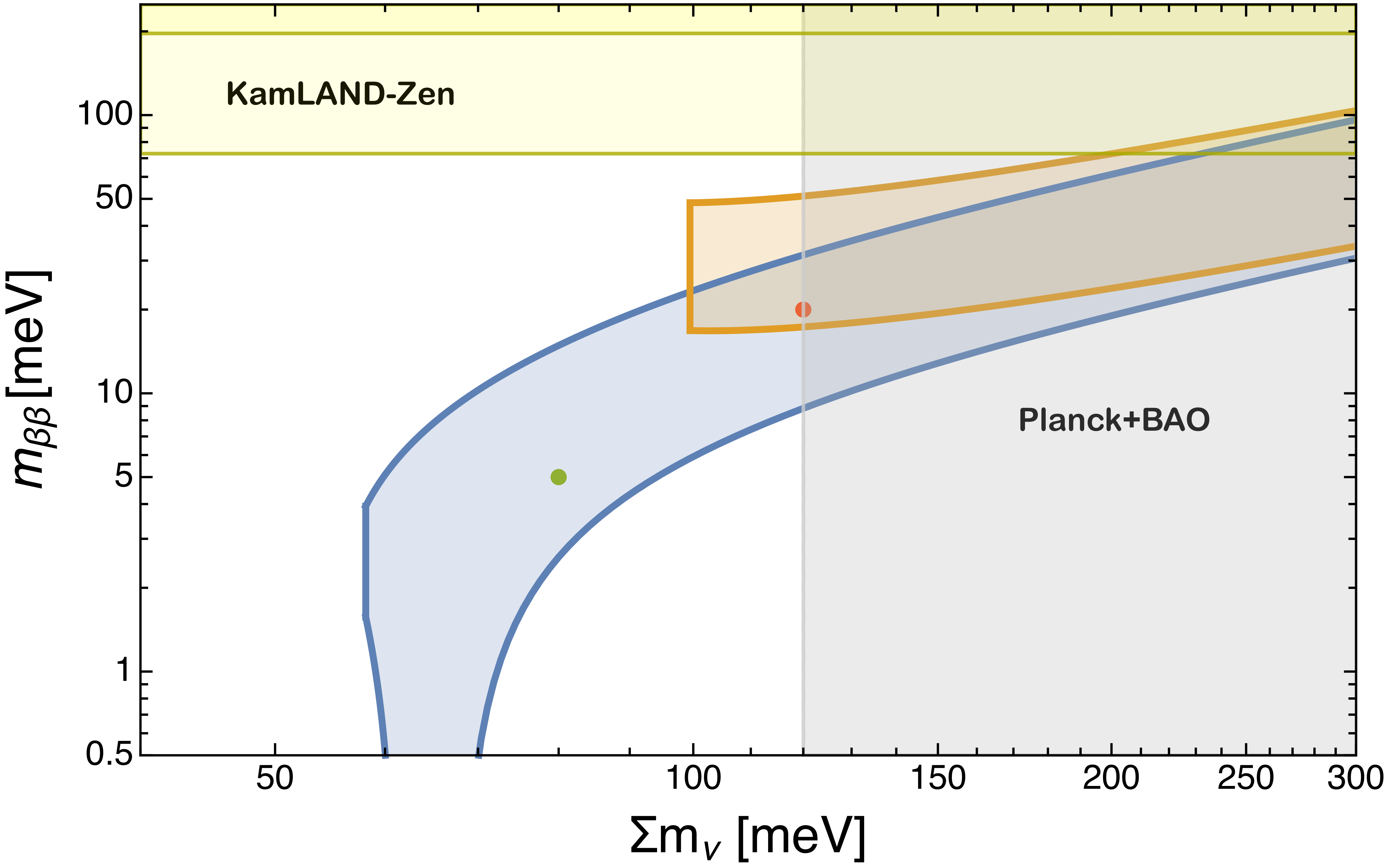
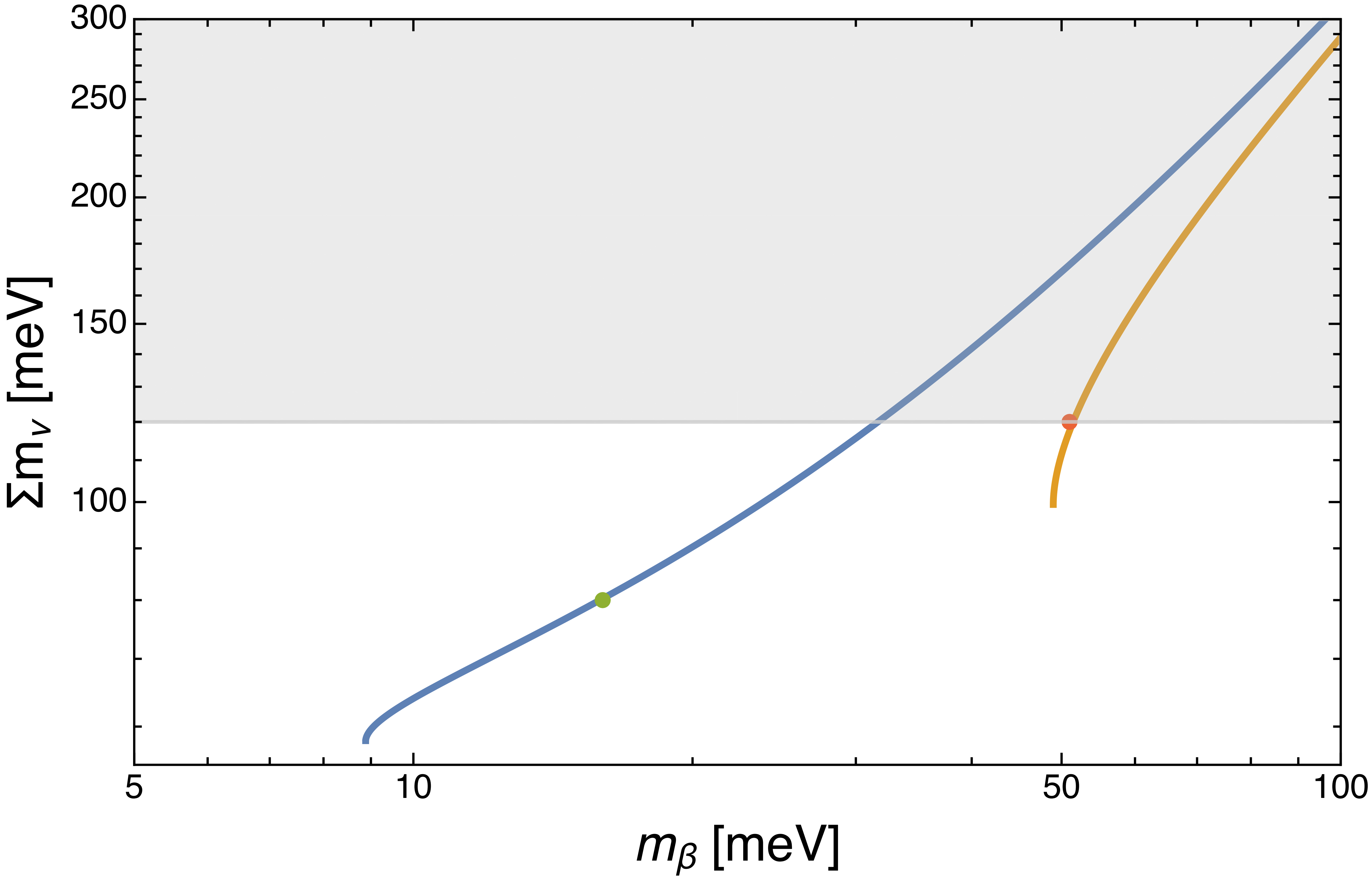
Concordance/discordance scenarios





Scenario 3: 0n2b measurement, no cosmology measurement

- **LCDM model could be wrong: modifications to cosmology? Modifications to cosmic neutrino properties? New interactions, unstable neutrinos?**

Scenario 4: discordant cosmo, 0n2b, b-decay measurements

- **LCDM and/or 0n2b predictions wrong? New physics?**

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Conclusions

Cosmology is a well established route to discoveries in the neutrino sector

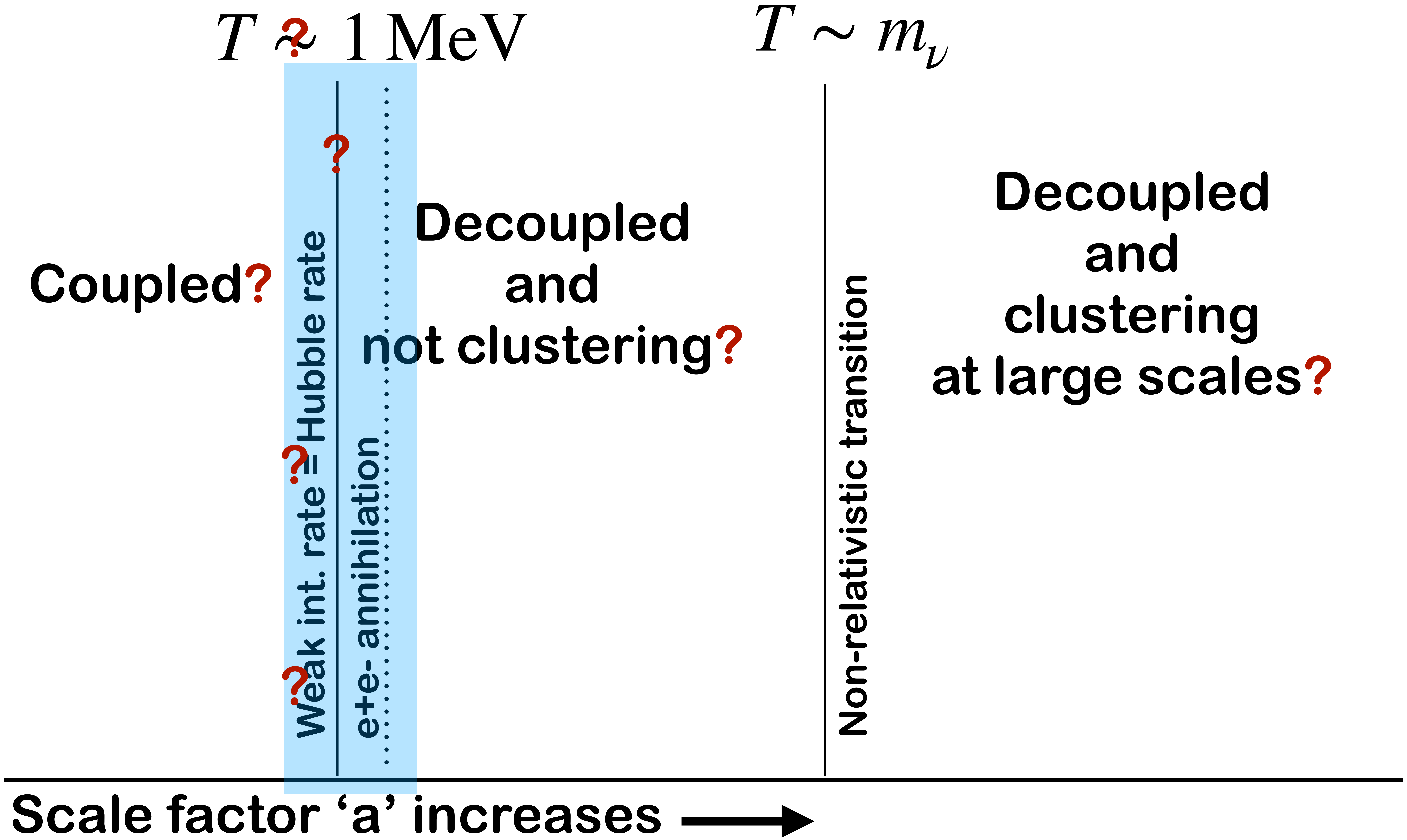
Data are coming soon that can lead to first-ever measurement of the mass sum

Synergy with lab-based experiments is key to robust discoveries

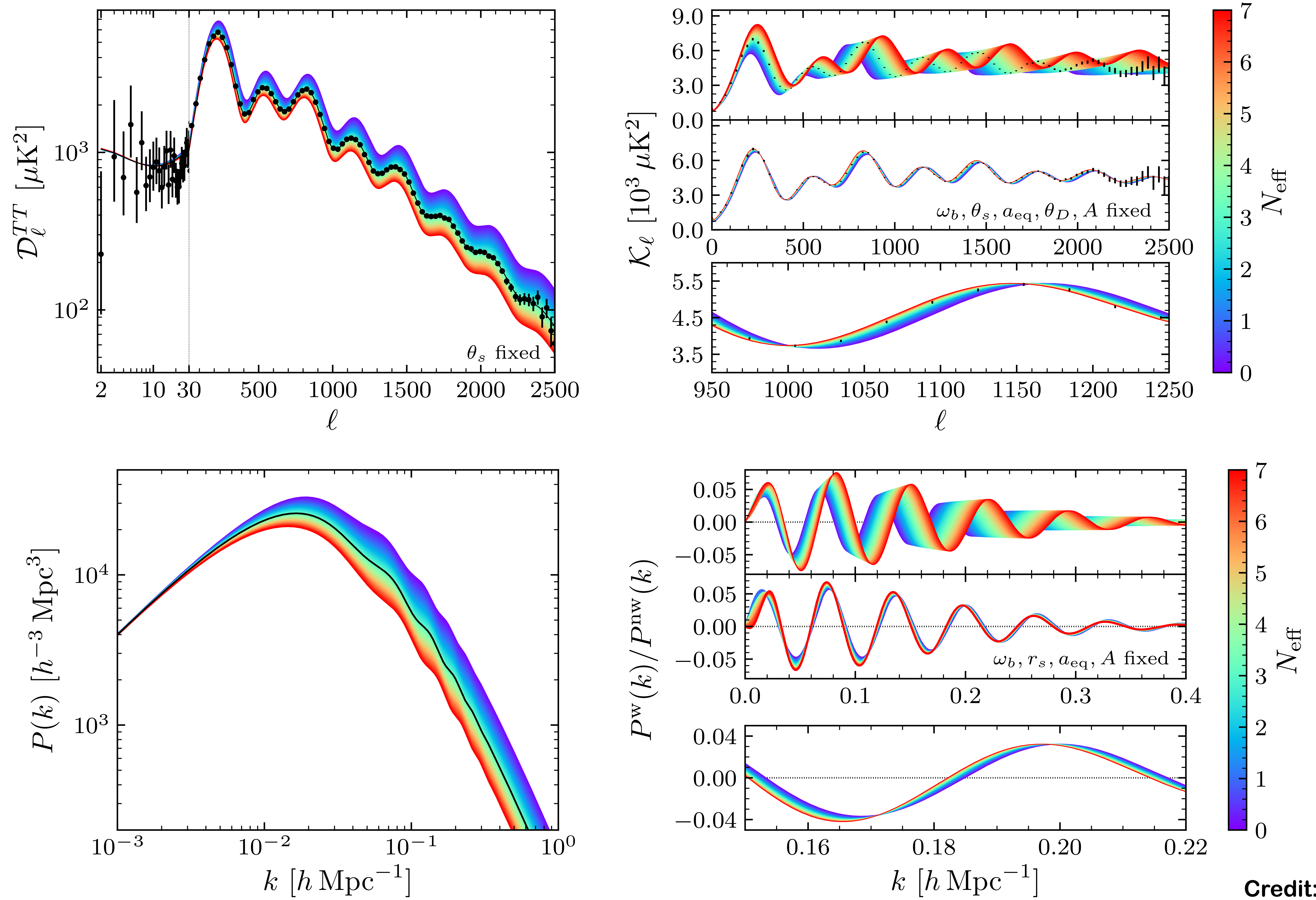
BACK-UP

BSM neutrinos?

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

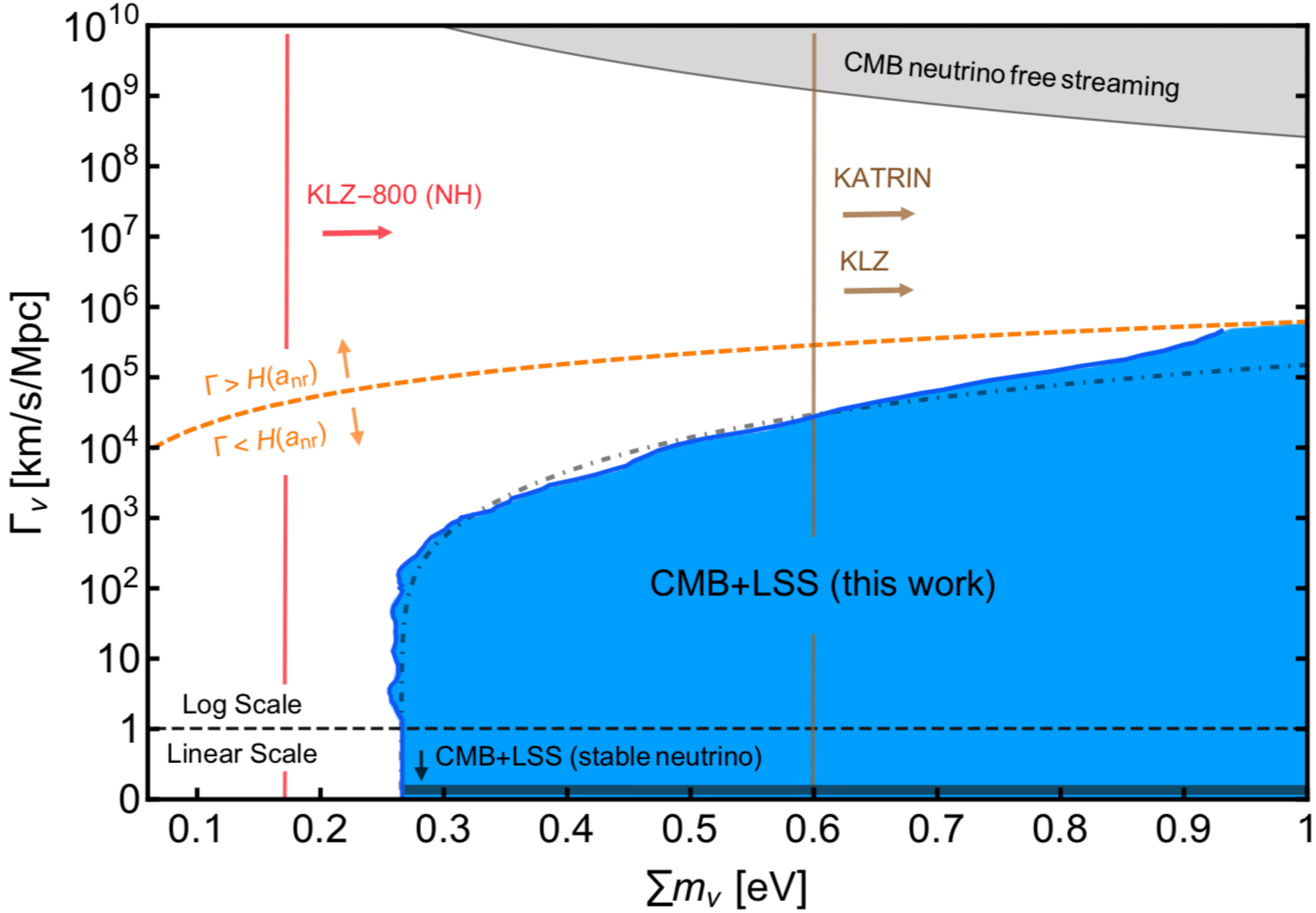


Neutrino effects on CMB and matter PS



Credit: Ben Wallisch, PhD thesis

Neutrino stability over cosmic times



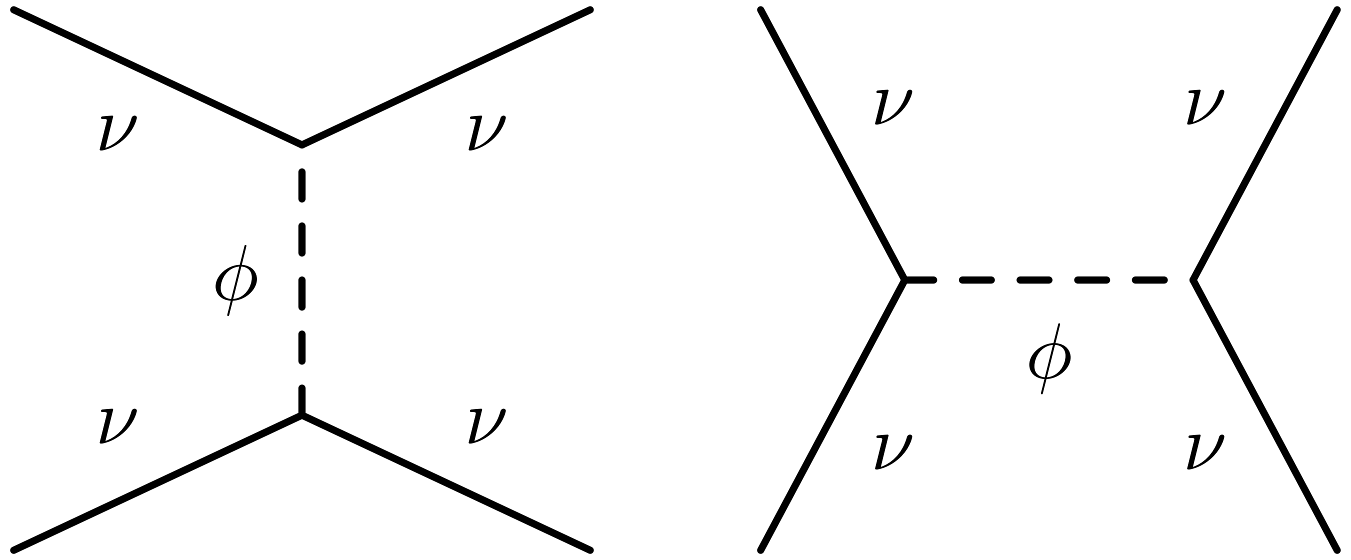
$$\rho_\nu \sim \Sigma m_\nu n_\nu$$

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; ...

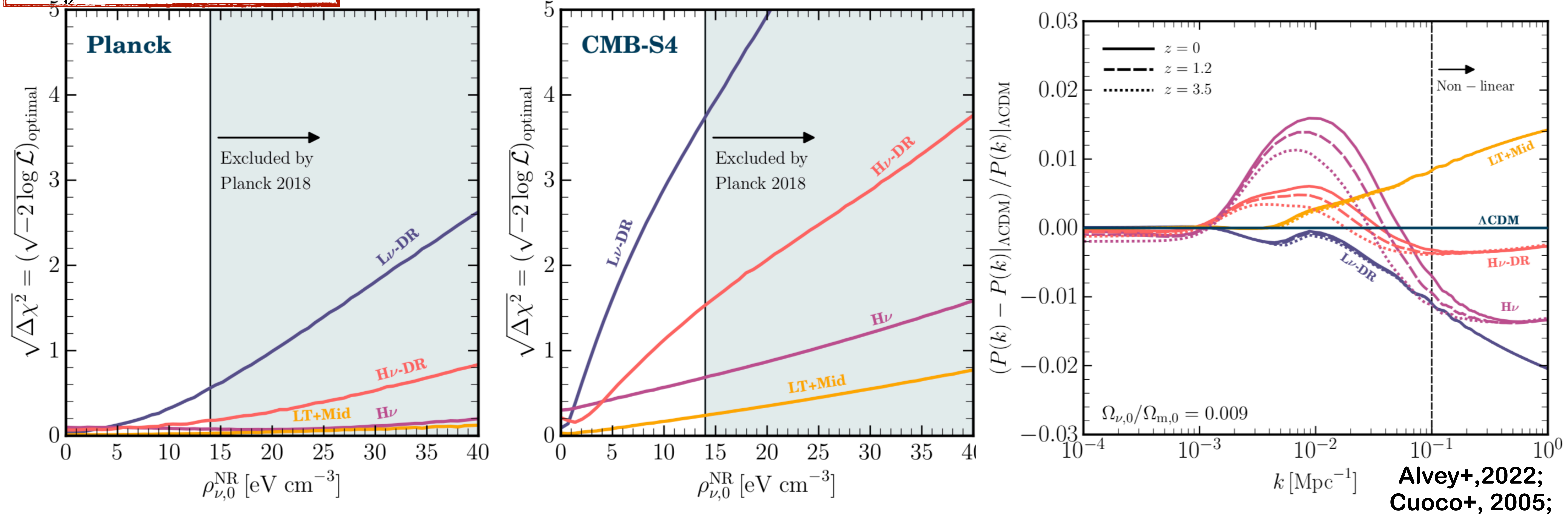
Cosmology can place complementary and competitive bounds to laboratory searches on these NS properties

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

See Thejs's talk on Tuesday!

Neutrino distribution function

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



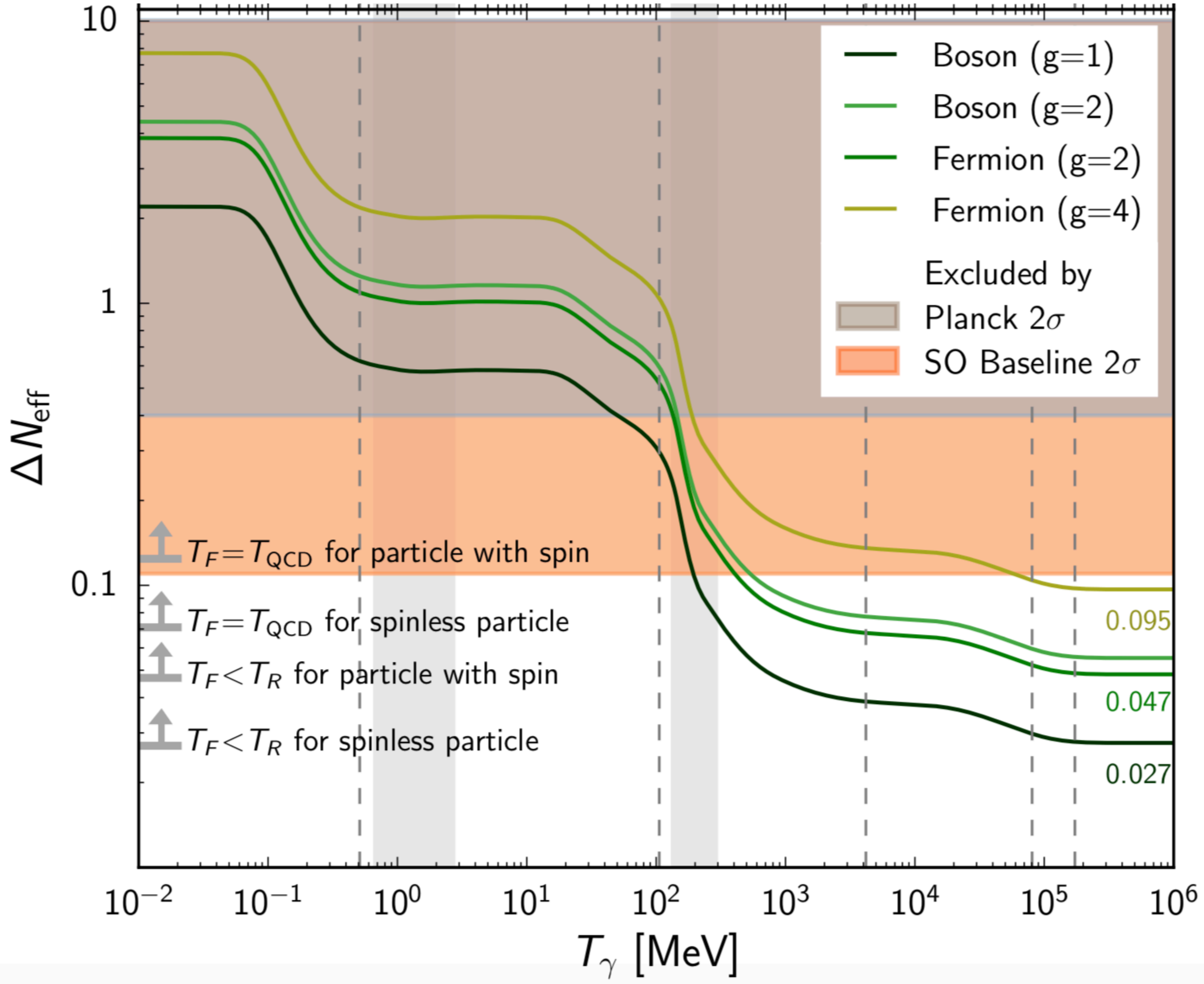
Alvey+,2022;
Cuoco+, 2005;
…

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

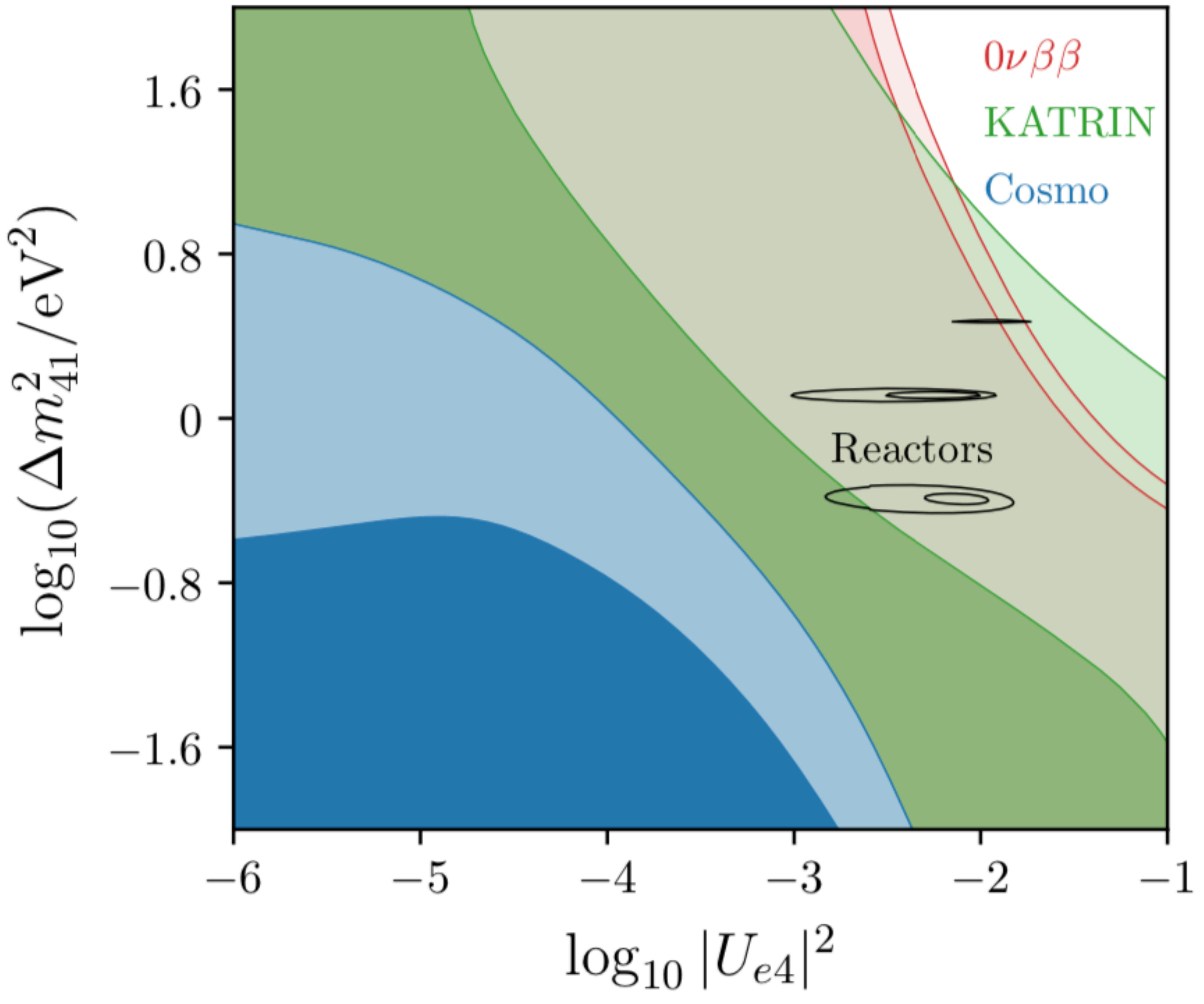
What if there is more than neutrinos contributing to it?



SO Collab. (incl MG), 2018

Light sterile in cosmology

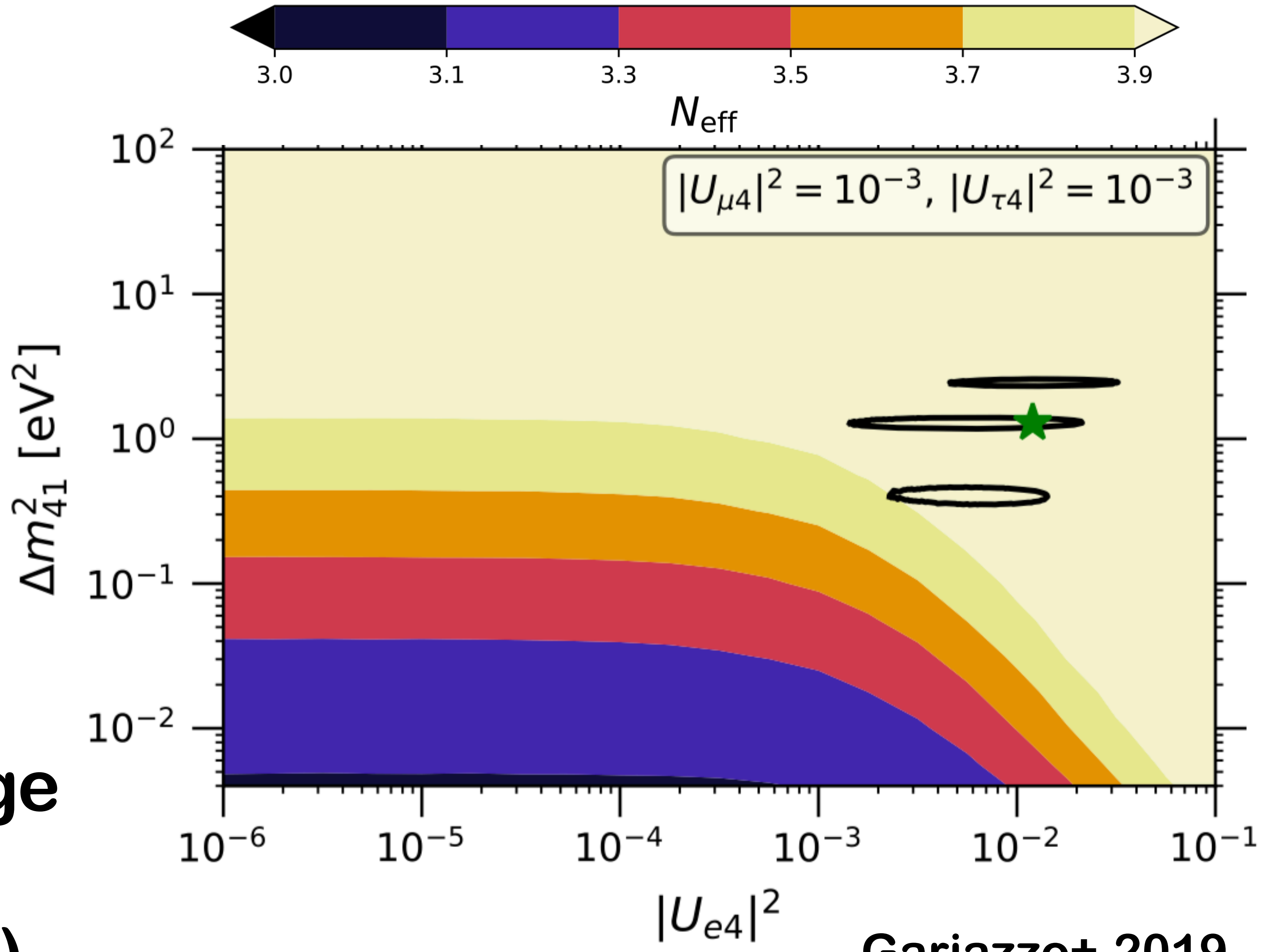
Hagstotz+(incl.MG), 2020; Gariazzo+, 2020



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

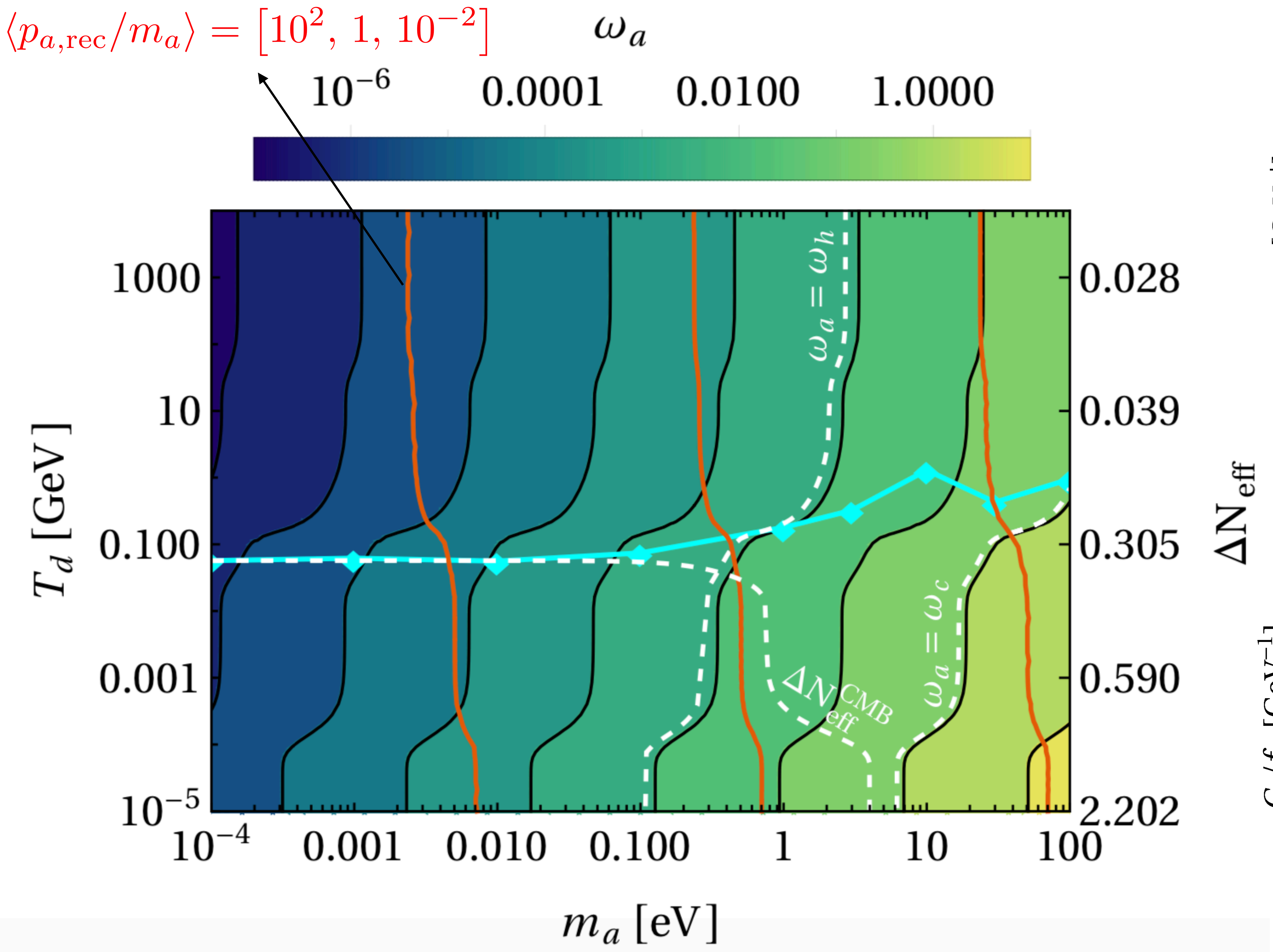
$$\theta \quad \Delta m^2 \rightarrow \Delta N_{\rm eff} \quad \Omega_{\nu,s}h^2 = \frac{m_{\rm eff}}{94\,\text{eV}}$$

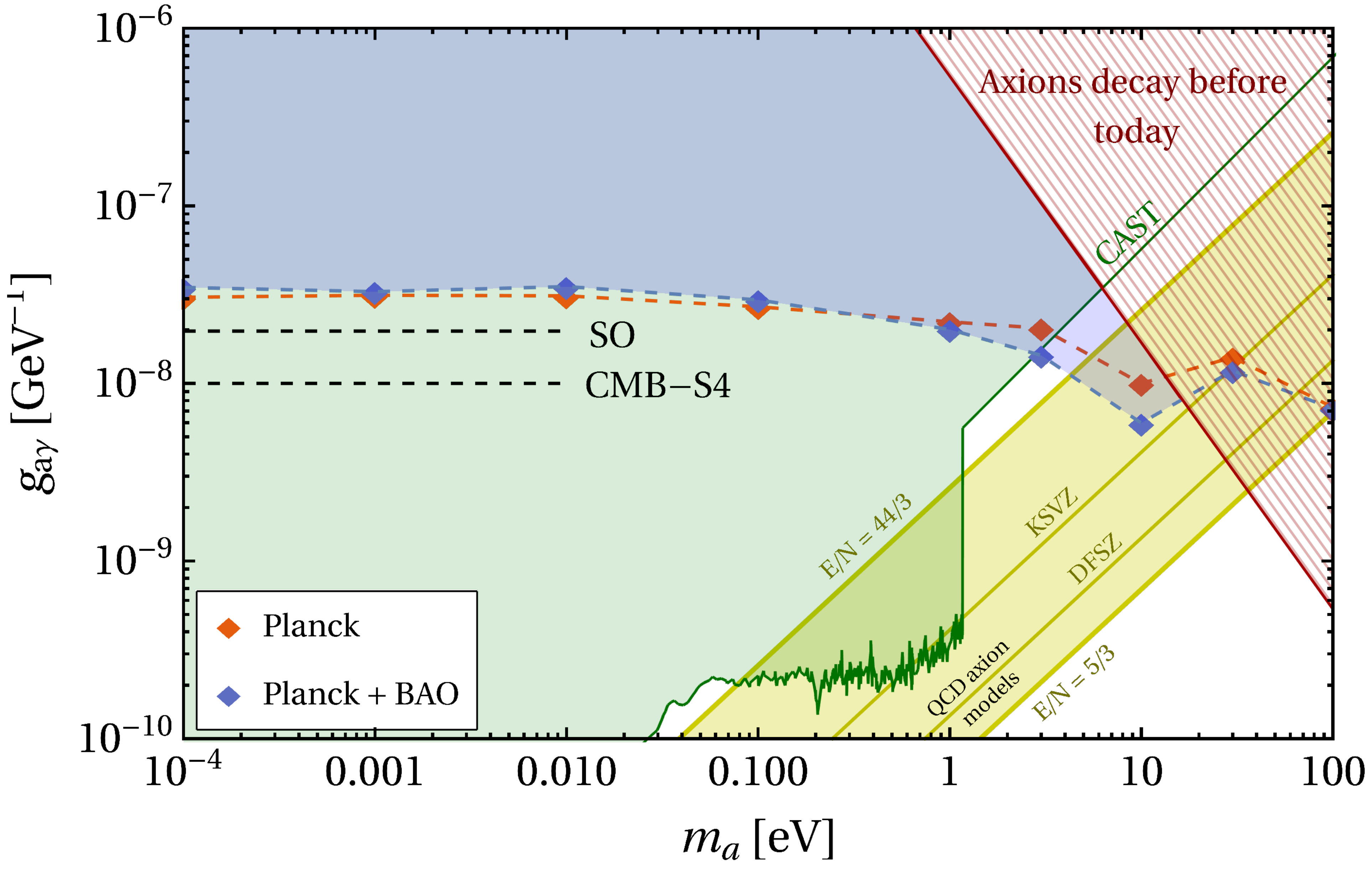


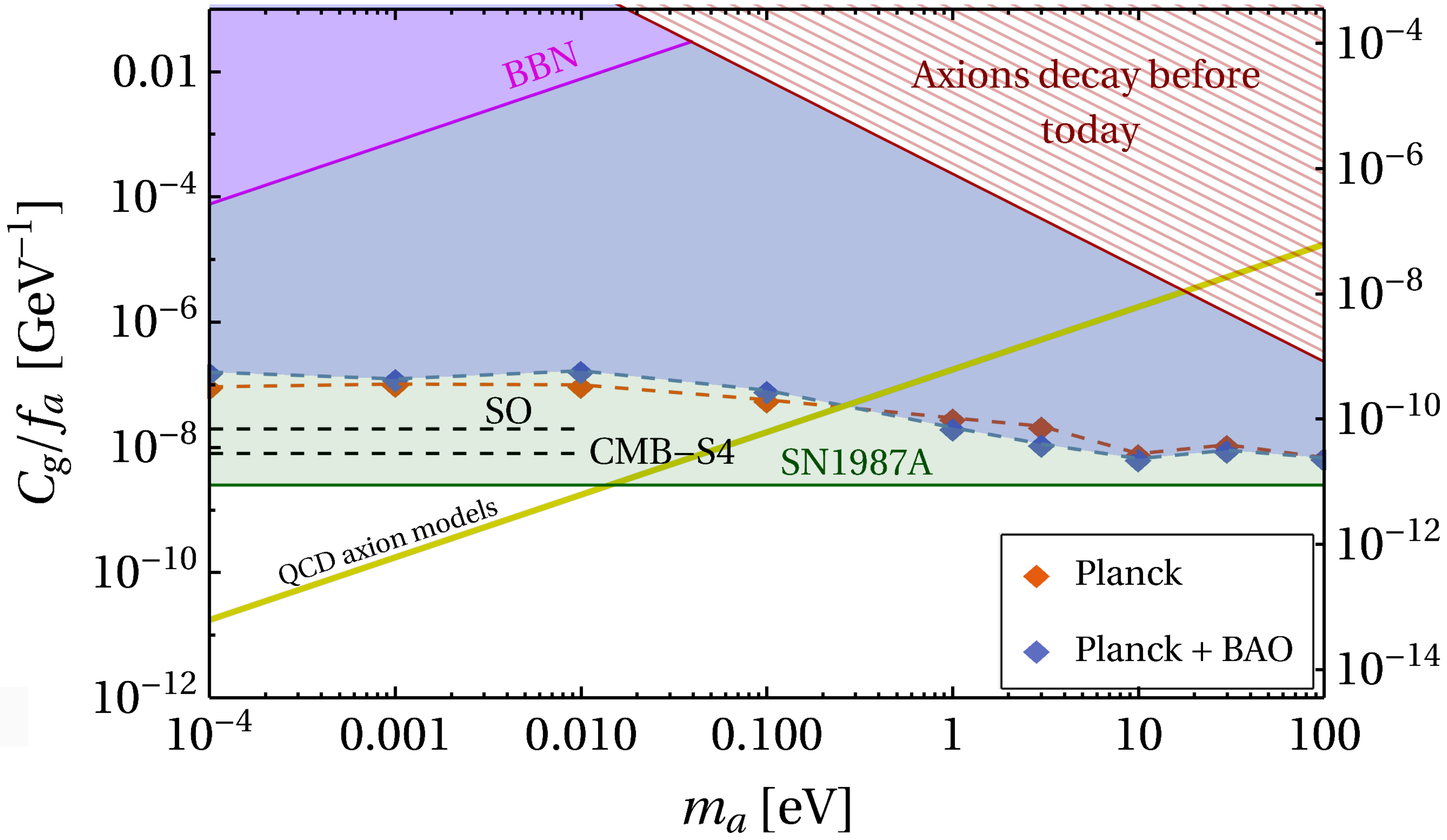
Gariazzo+,2019

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)