NEUTRINOS ACROSS FRONTIERS

ANL-HEP Seminar
July 8th, 2020

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Results presented in this talk are based on works
2007.01650 [astro-ph.CO]; 2003.02289 [astro-ph.CO] in collaboration with:
M. Lattanzi, K. Freese, G. Kane, J. Valle, S. Hagstotz, P. de Salas, S. Gariazzo, S. Vagnozzi, S. Pastor

PUZZLING NEUTRINOS

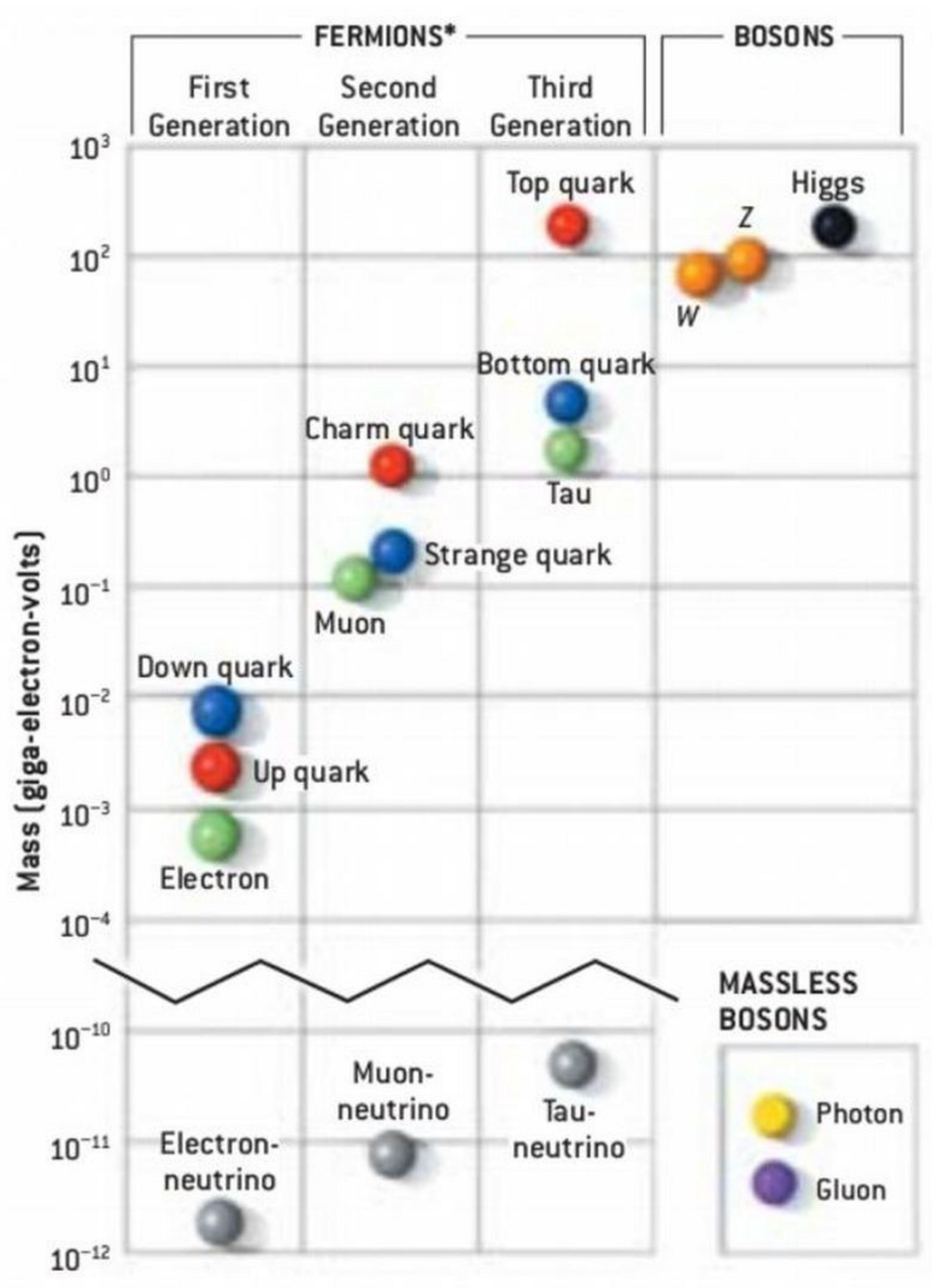


Image credit: G. Kane

Neutrinos are part of the standard model of particle physics….

… however their properties might be related to physics beyond the SM

Many open questions to date:

-absolute mass scale?
-origin of (small) masses?
-origin of mixing pattern?
-mass hierarchy?
-Majorana or Dirac?
-CP violation?

THREE-NEUTRINO MIXING SCENARIO

Flavor state — Mass state

Neutrino flavour eigenstates
are superpositions of the mass eigenstates

$$|\nu_\alpha >= \sum_i U^*_{\alpha i} |\nu_i >$$

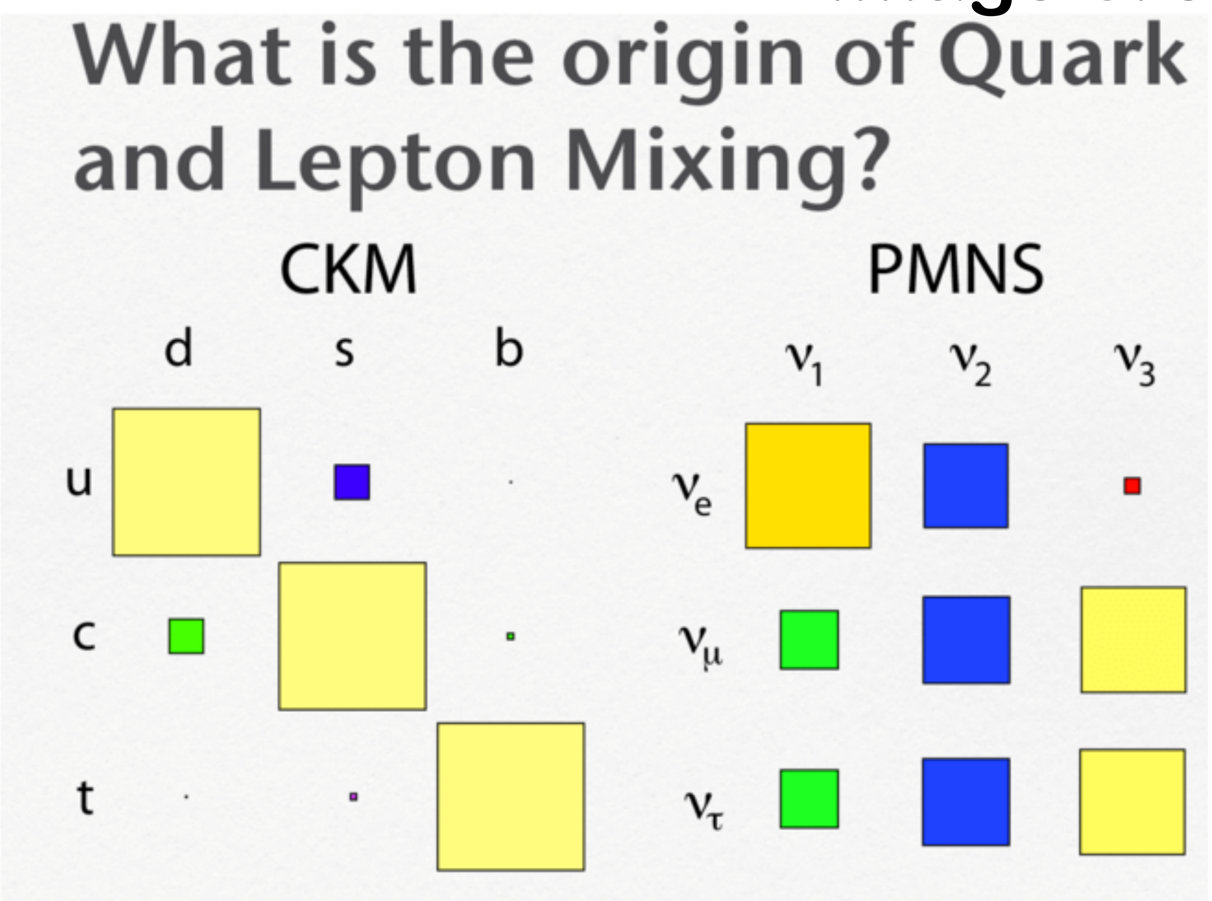
PMNS mixing matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$\times \, \mathrm{diag}(1, \; e^{i\frac{\alpha_{21}}{2}}, \; e^{i\frac{\alpha_{31}}{2}}) \; .$$

Journal of Physics: Conference Series **631** (2015) 012005 doi:10.1088/1742-6596/631/1/012005

Image credit: S.King



3 mixing angles
1 CP-violating Dirac phase
2 CP-violating Majorana phases

+ 3 masses (1 mass scale, 2 mass differences)

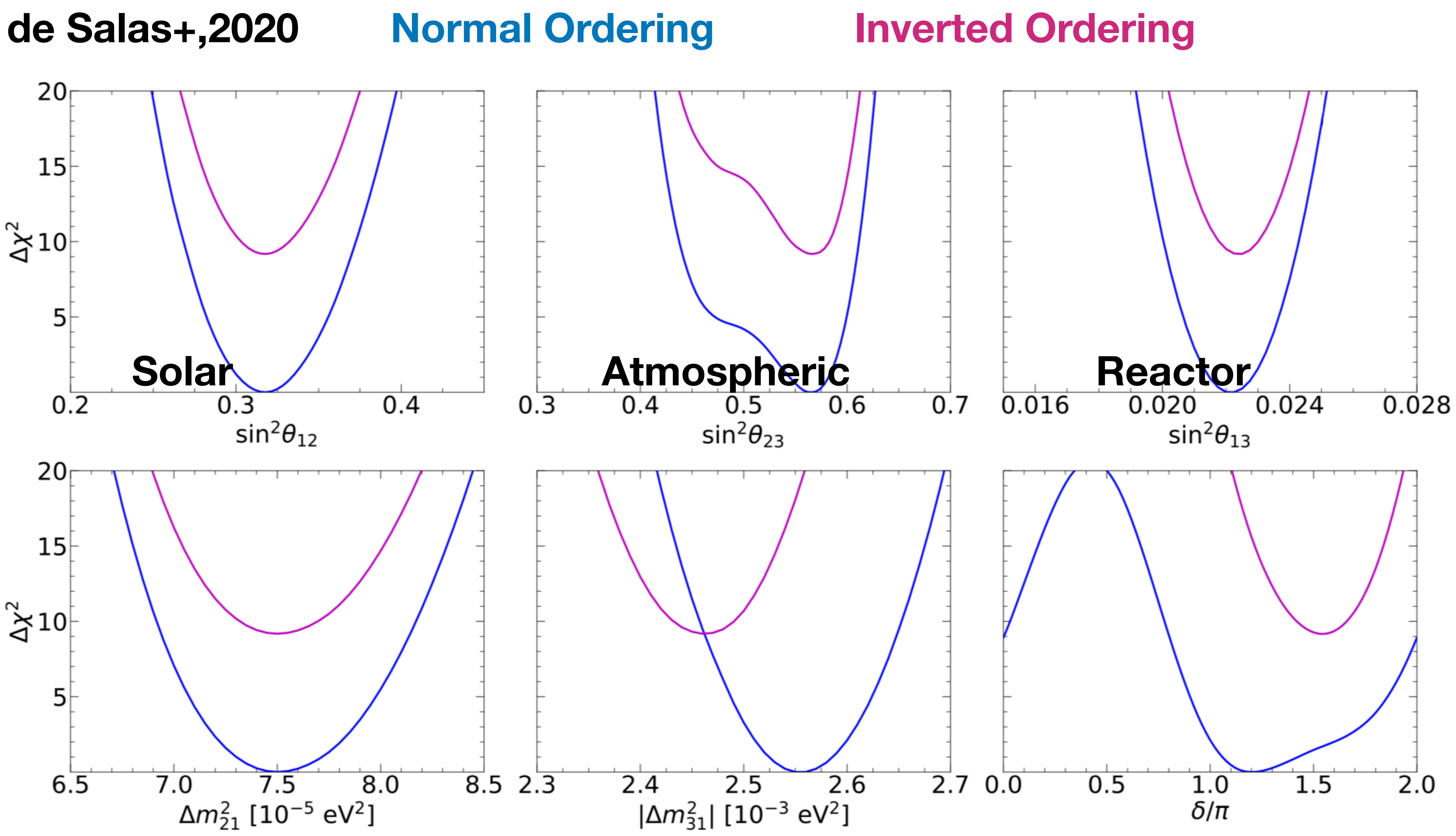
OSCILLATION EXPERIMENTS

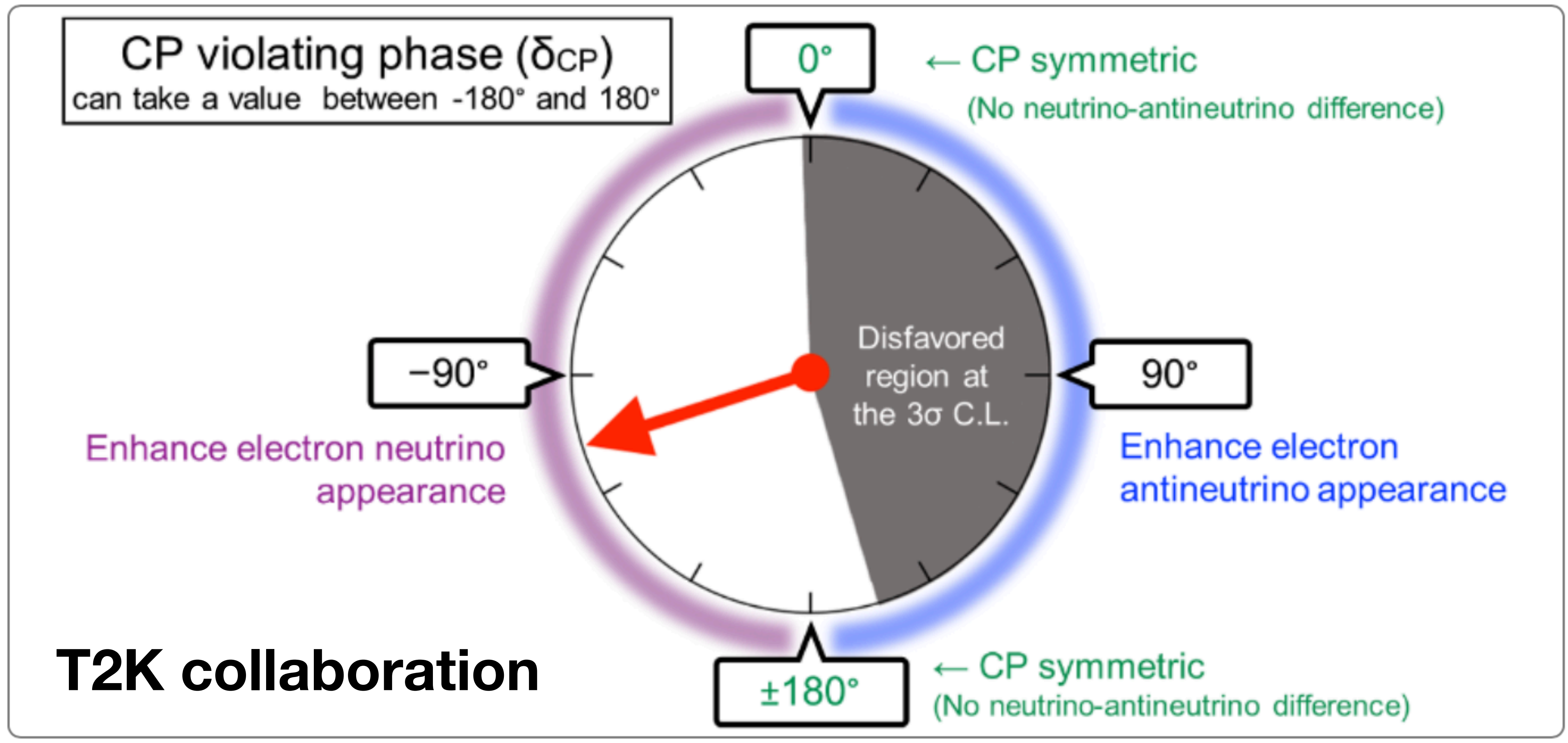
Transition probability in vacuum

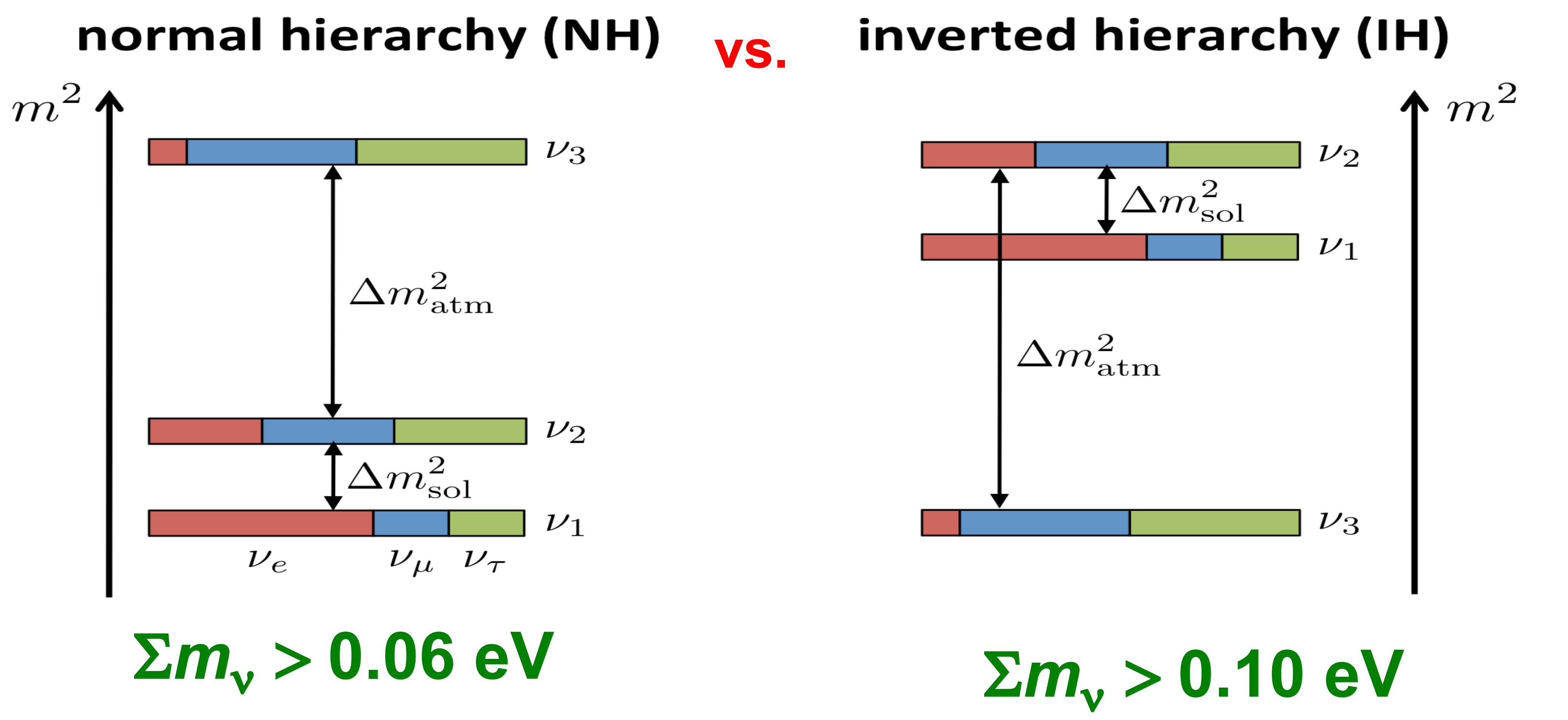
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2 \sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

- Amplitude of oscillations controlled by (quartic product of) mixing matrix elements
- Frequency of oscillations controlled by mass splittings
- Quartic product invariant under rephasing, hence oscillations insensitive to Majorana phases
- CP asymmetry arising from sign of Im(quartic product), which vanishes in survival experiments (alpha=beta). Hence, CP measured only in flavour-changing experiments
- Matter effects important

THREE-NEUTRINO GLOBAL FIT







Most of mixing parameters very well constrained by oscillation experiments
What next: CP phase(s), mass ordering

COSMOLOGICAL SIGNATURES OF ACTIVE NEUTRINOS

Cosmological probes can constrain the sum of the masses and the number of relativistic species via:

Background effects

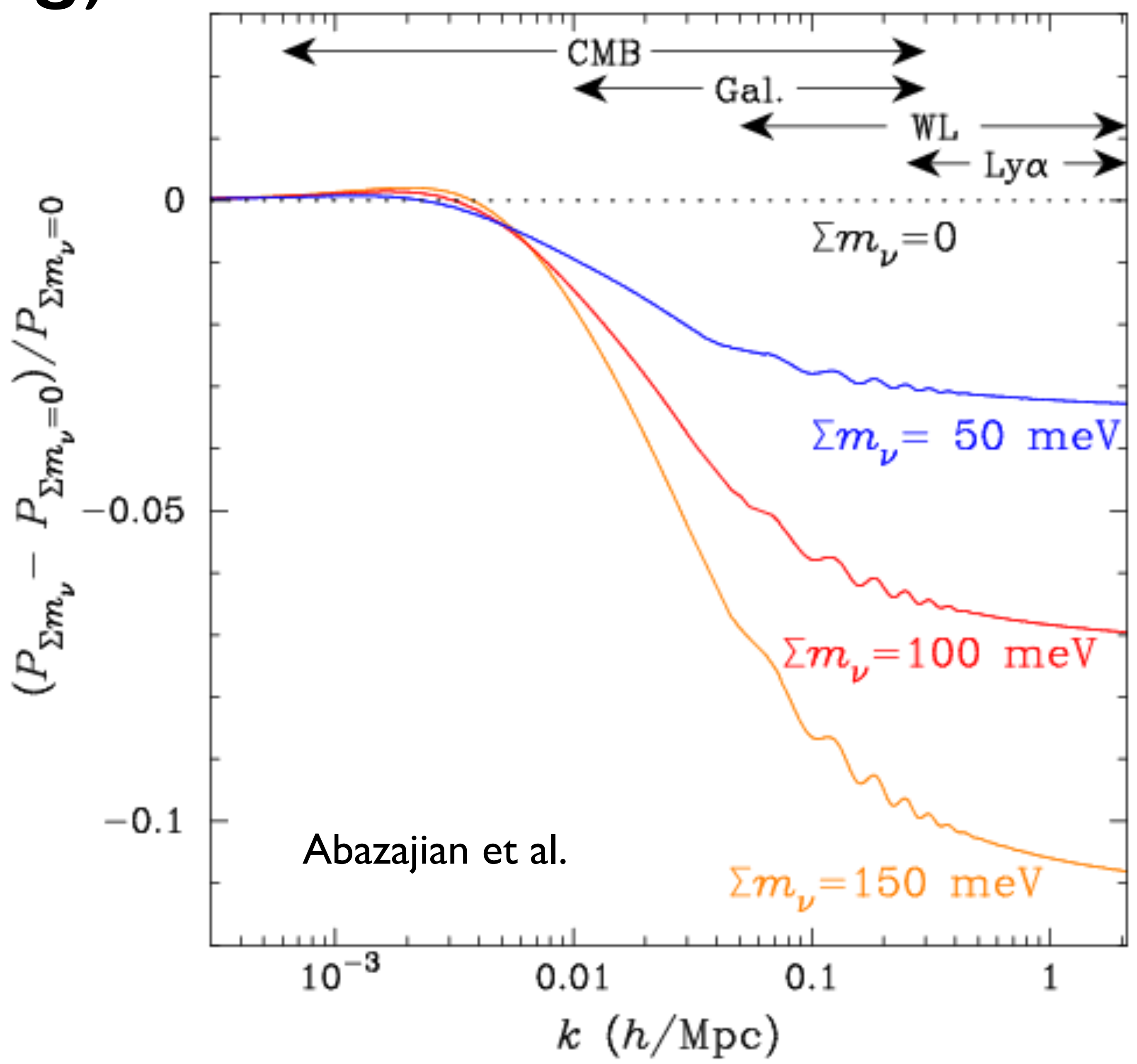
Neutrinos change the expansion rate H(z)
Neutrinos change the epoch of matter-radiation equality

Perturbations effects

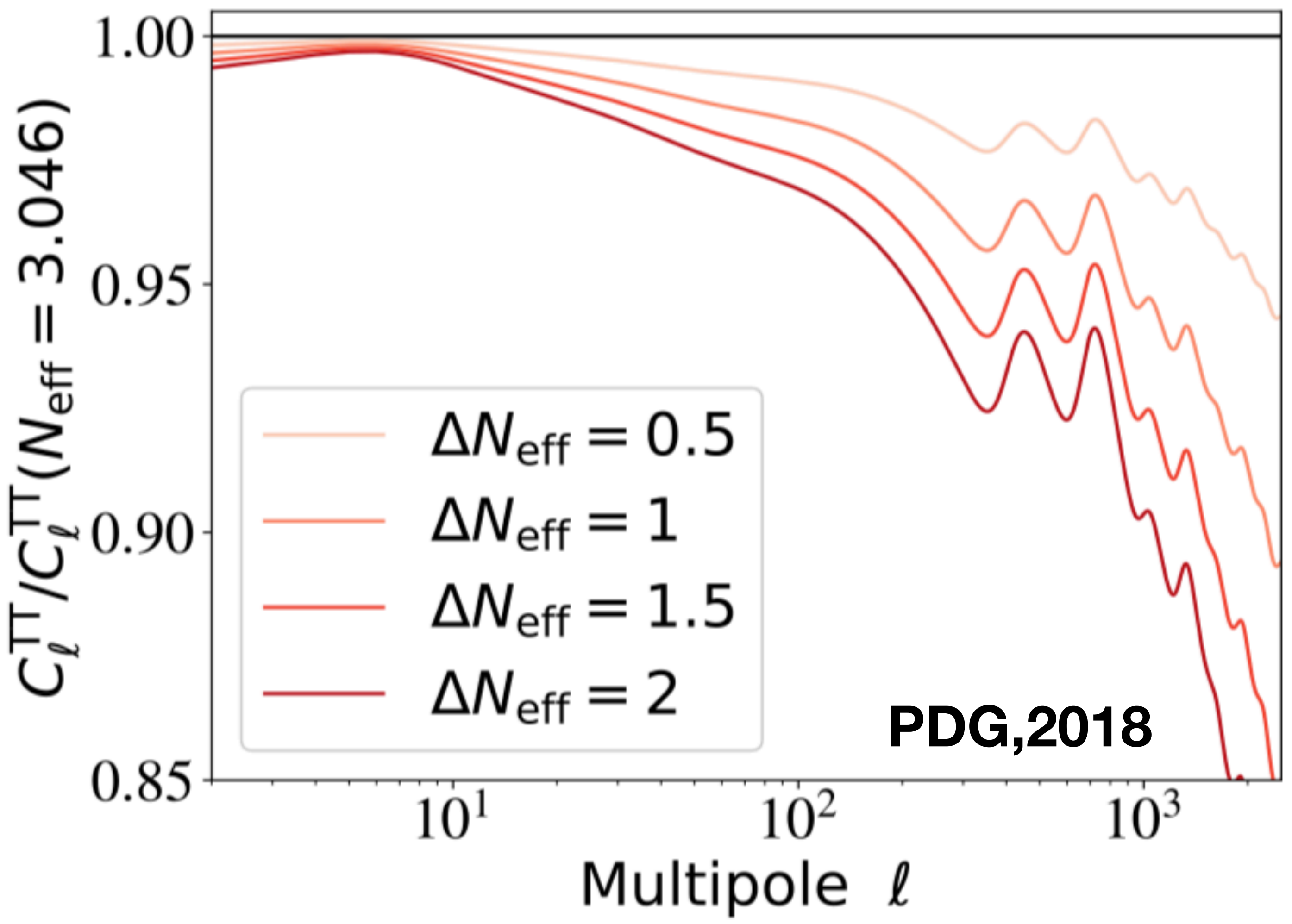
Small-scale density perturbations are suppressed due to collisionless damping (free-streaming).

Neutrinos are collisionless and have large thermal velocities (they have been relativistic for most of the history of the Universe).

They do not cluster below a critical scale, the free-streaming length (corresponding to the scale of the horizon at the time of the nonrelativistic transition)

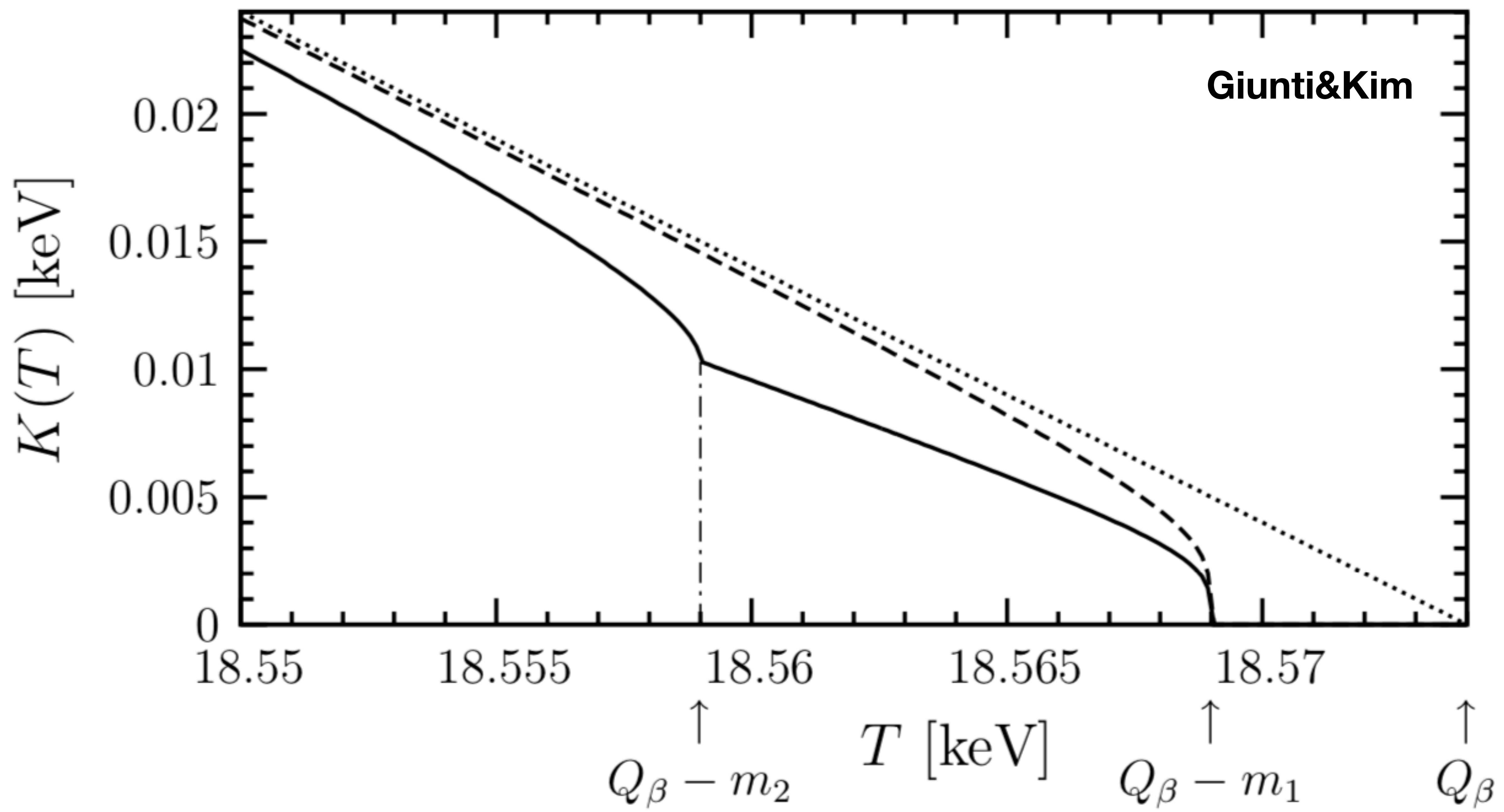


At early times, acoustic oscillations are phase-shifted due to propagation through relativistic neutrinos



LABORATORY SEARCHES OF NEUTRINO MASS SCALE

Beta decay: end-point of the Kurie plot



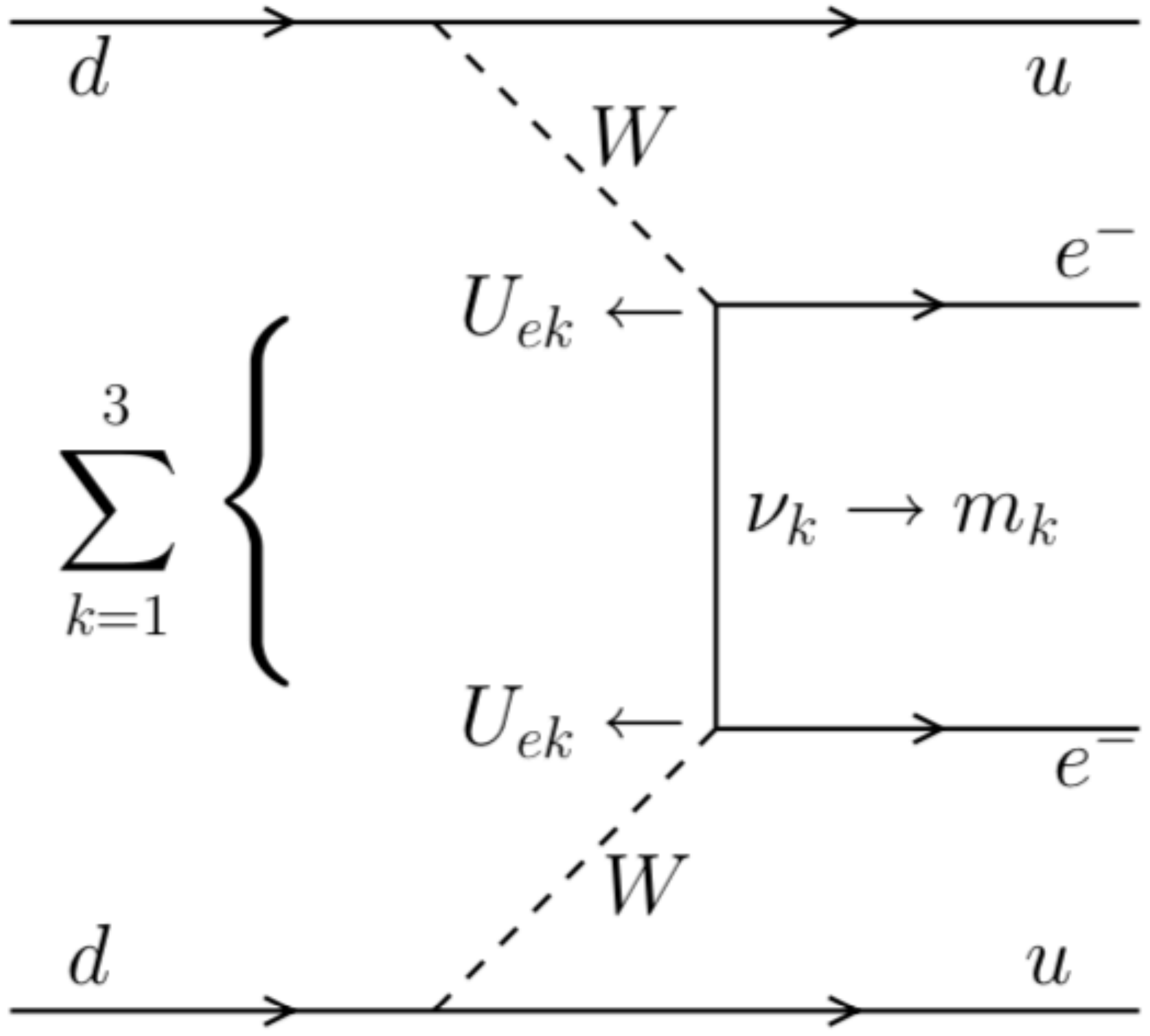
$$K(T) \equiv \sqrt{\frac{\mathrm{d}\Gamma/\mathrm{d}T}{\frac{G_F^2\, m_e^5}{2\,\pi^3}\cos^2\theta_C\,|\mathcal{M}|^2\,F(Z,E_e)\,E_e\,p_e}}$$

$$= \left[(Q_\beta - T)\sqrt{(Q_\beta - T)^2 - m_{\nu_e}^2}\right]^{1/2}$$

Effective electron (anti)-neutrino mass

$$m_\beta \equiv \left[\sum |U_{ei}|^2\, m_i^2\right]^{1/2}$$

Neutrinoless-double-beta decay: half-life



Giunti&Kim

$$[T_{1/2}^{0\nu}(\mathcal{N})]^{-1} = G_{0\nu}^{\mathcal{N}}\,|\mathcal{M}_{0\nu}^{\mathcal{N}}|^2\,\frac{|m_{2\beta}|^2}{m_e^2}$$

Majorana mass

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$

The **absolute mass scale** can be measured through:

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2} < 1.1\text{ eV @ 90\%CL} \quad \text{(KATRIN)}$$

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right| < 0.06 - 0.16\text{ eV @ 90\%CL}$$

(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i < 0.12 - 0.24\text{ eV @ 95\%CL}$$

(Planck+…)

The effective **number of relativistic species** is constrained as:

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad @\,95\%\text{C.L.}$$

(Planck2018+…)

BENEFIT OF COMBINED APPROACH

Why a combined-probe approach?

- It allows better constraints of the neutrino parameter space
- It allows for cross-checks
- It may unveil tensions/inconsistencies that might point to new physics

CORNERING QUASI-DEGENERATE NEUTRINOS

Degenerate spectrum of neutrino masses generated via high-energy symmetry breaking (e.g., SO(3), A4)
Mass splittings arise as radiative corrections
(see e.g., Barbieri+,1999; Babu+,2003)

Mass matrix (e.g., from see-saw)

$$\mathcal{M}_\nu = m_0 \begin{pmatrix} 1+2\delta+2\delta' & \delta'' & \delta'' \\ \delta'' & \delta & 1+\delta \\ \delta'' & 1+\delta & \delta \end{pmatrix}$$

→

Mass eigenstates

$$m_1 = m_0 \left|1+2\delta+\delta' - \sqrt{\delta'^2+2\delta''^2}\right|,$$
$$m_2 = m_0 \left|1+2\delta+\delta' + \sqrt{\delta'^2+2\delta''^2}\right|,$$
$$m_3 = m_0.$$

Mass scale (m_0)

Corrections to degenerate spectrum

To fully constrain the model we need:

- **oscillation measurements to constrain mixing angles and mass splittings**
- **cosmology and lab searches (e.g., 0n2b) to constrain mass scale**
- **0n2b (+cosmo?) to constrain Majorana phases**

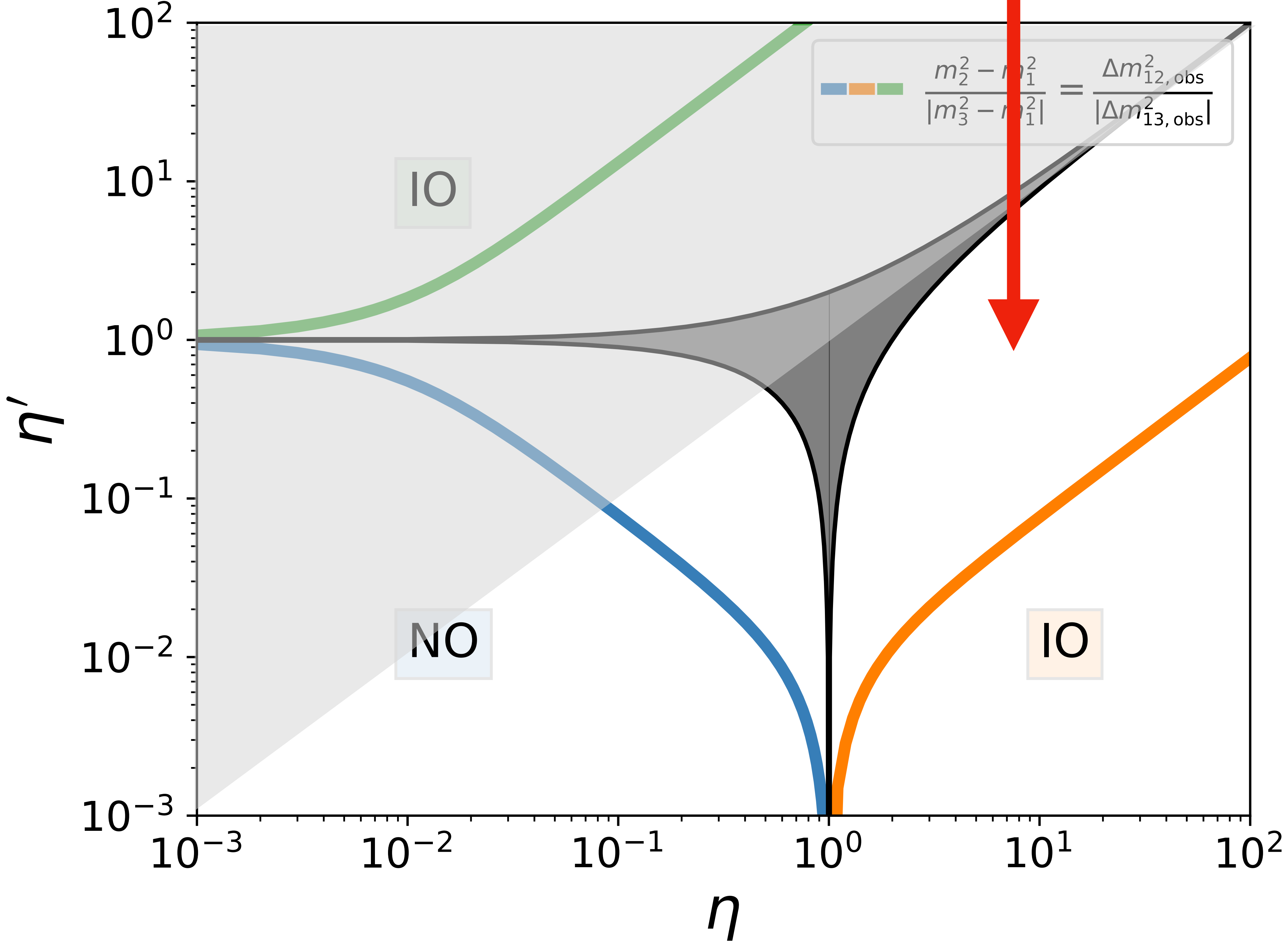
CORNERING QUASI-DEGENERATE NEUTRINOS

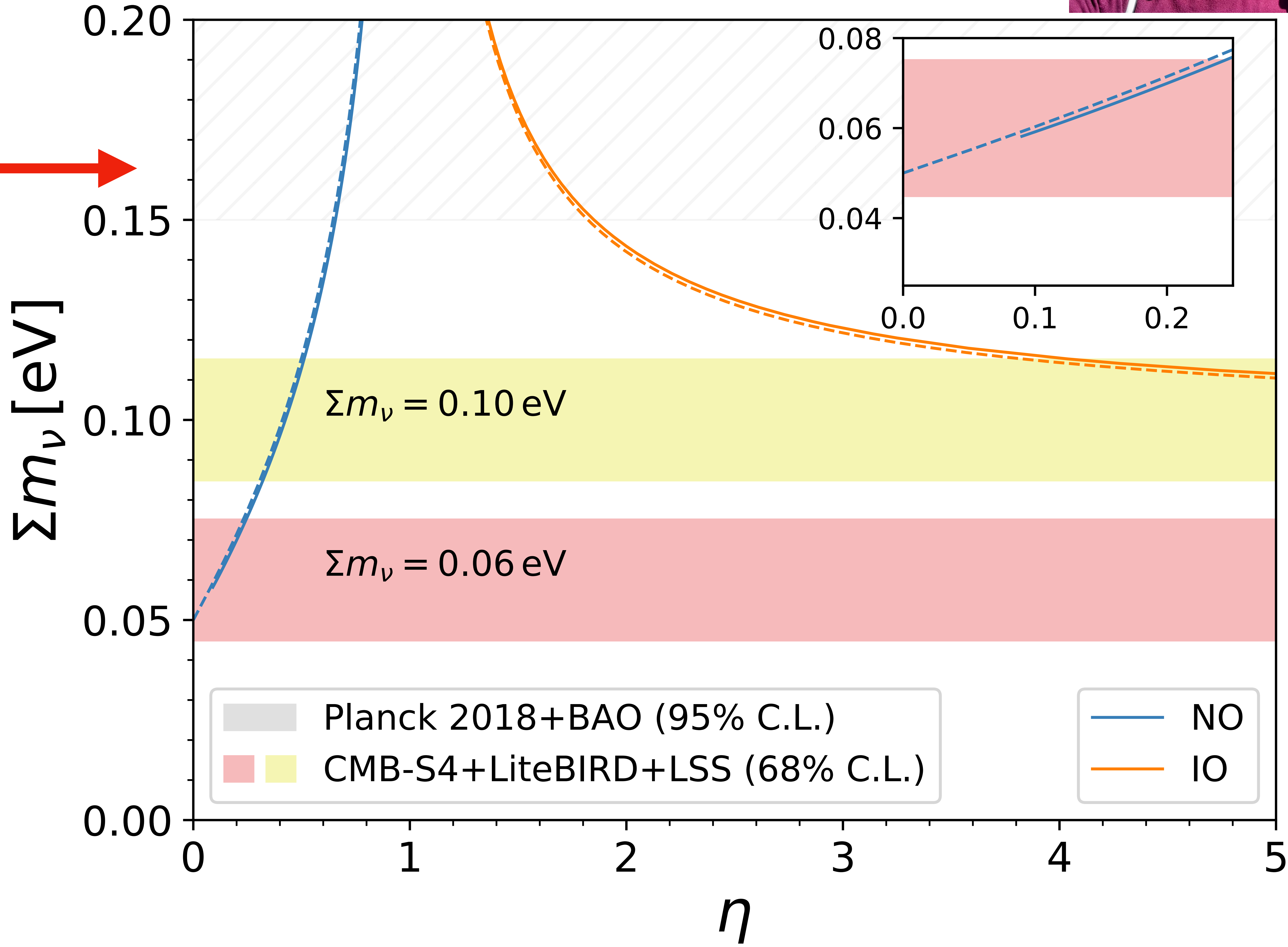
Useful reparametrization

Lattanzi,MG+,2020

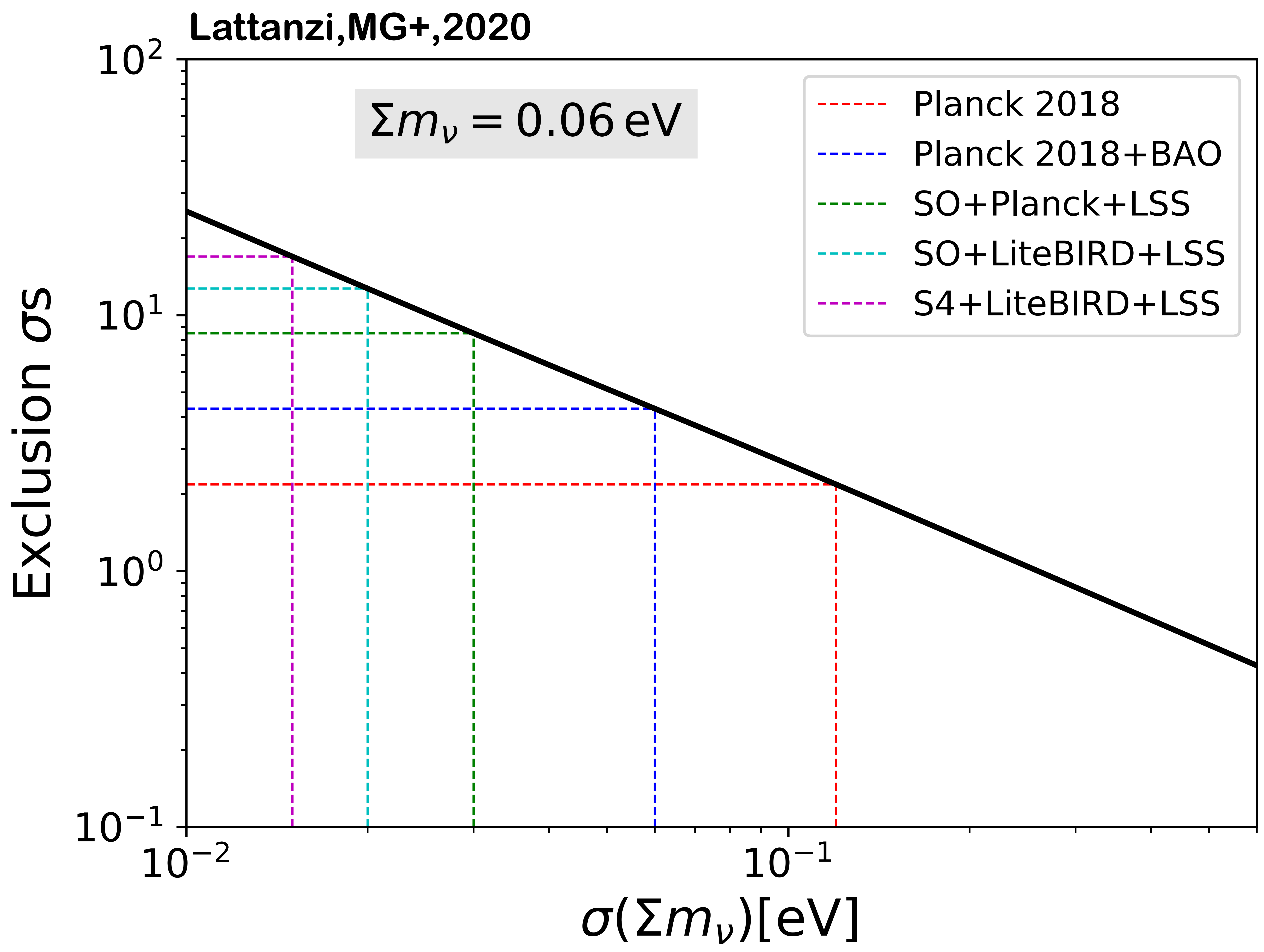
$$m_1 = m_0\,|\eta - \eta'|\ ,$$
$$m_2 = m_0\,|\eta + \eta'|\ ,$$
$$m_3 = m_0\,.$$

Restrict to 1st octant for symmetry





CORNERING QUASI-DEGENERATE NEUTRINOS

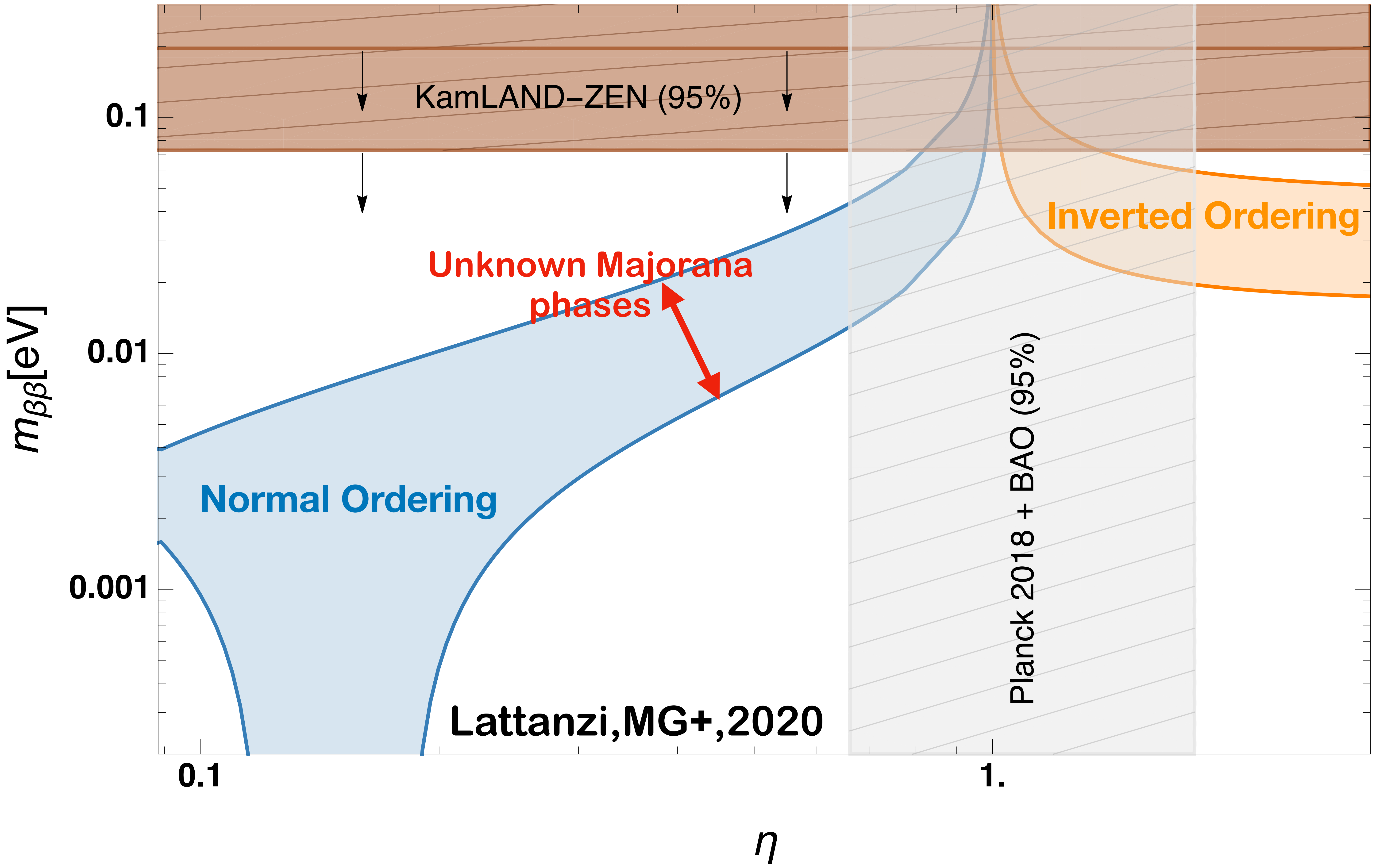


Mass-generation models of quasi-degenerate neutrinos already excluded at >2sigma level within minimal extension of LCDM

Exclusion level increase with future surveys

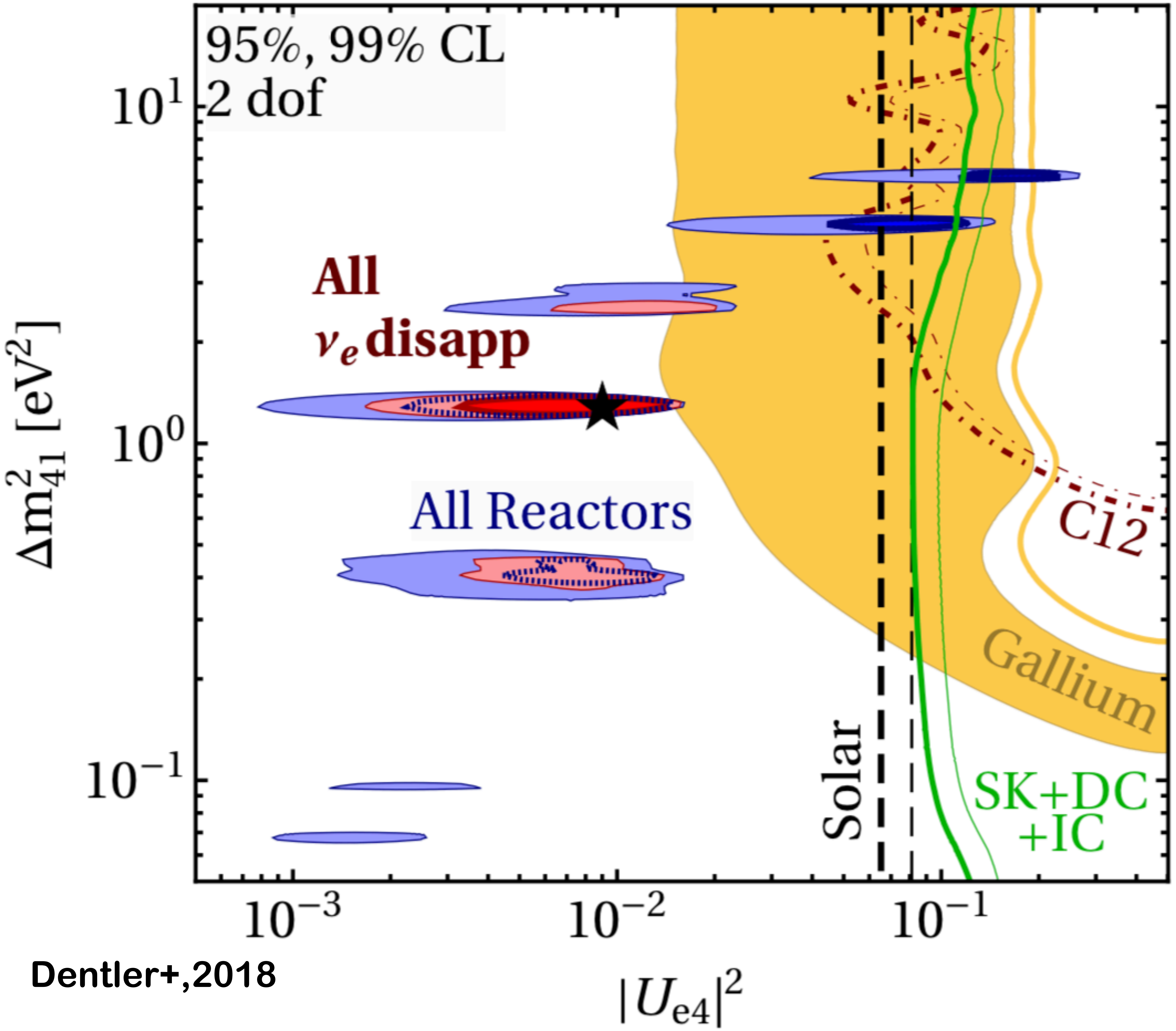
Cosmo+lab can exclude this class of models

CORNERING QUASI-DEGENERATE NEUTRINOS



Combination with lab searches allows to simultaneously constrain mass scale, mixing angles and Majorana phases

CROSS-CHECK SCENARIO: LIGHT STERILE NEUTRINO



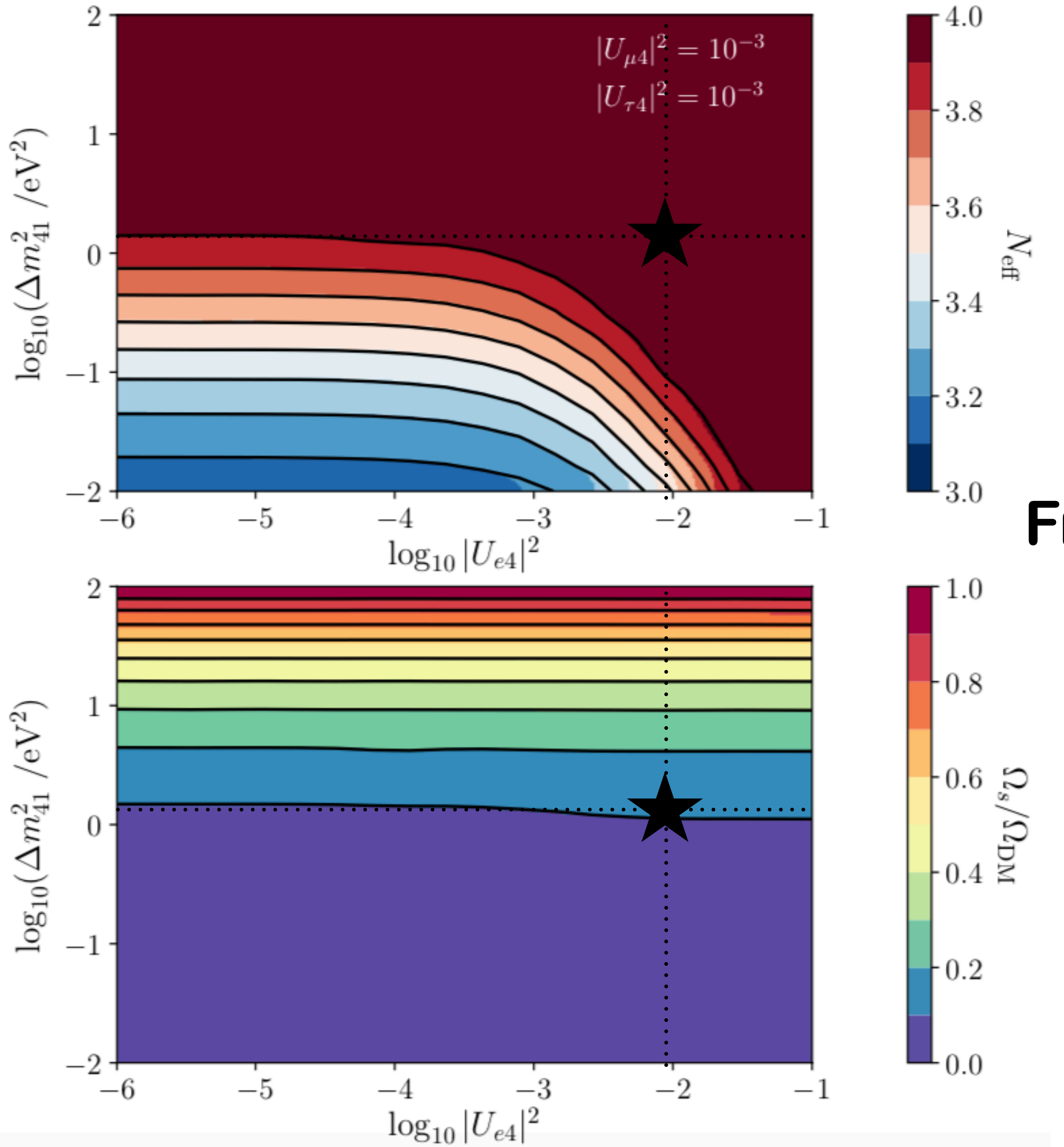
Dentler+,2018

**Possible solution(s)
to anomalies:
existence of a light sterile neutrino
with non-negligible mixing
with electronic nu**

$$\nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau),$$

$$(\nu_{sR})^C = \sum_{k=1}^{N} U_{(3+s)k} \nu_{kL} \quad (s = 1, \ldots, N_s),$$

LIGHT STERILE NEUTRINOS IN COSMOLOGY

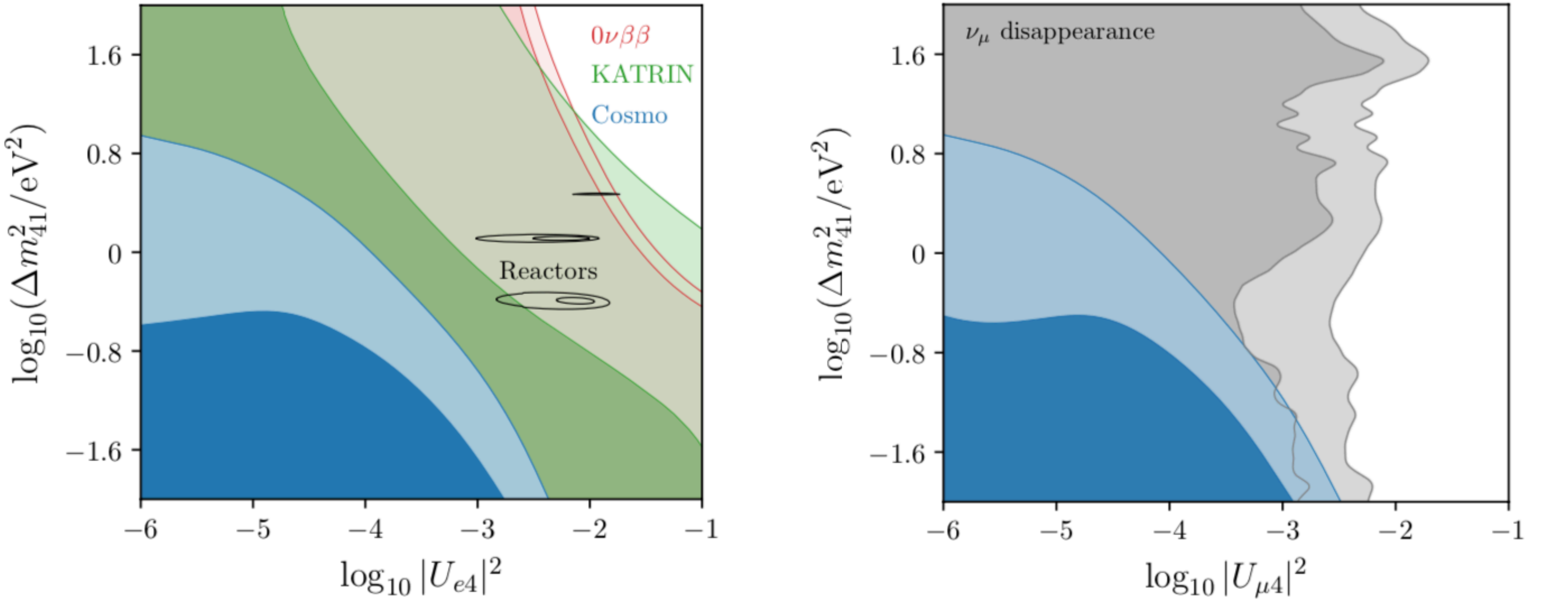


If a light sterile exist,
oscillations in the early Universe
would create a population of sterile
(Dodelson-Widrow)

From the physical mass and the mixing angle
one can compute the sterile contribution
to the total energy density
in radiation, at early times (DNeff);
in matter, at late times (Omega_s)

Hagstotz+(incl.MG),2020

CROSS-CHECK SCENARIO: LIGHT STERILE NEUTRINO



Cosmology robustly exclude region of large sterile mass and mixing params larger than 10^-3 in LCDM extensions

Parameter	experimental upper limit (95%)	cosmological upper limit (95%) $\mathcal{P}(\log \Delta m^2_{14})$	$\mathcal{P}(m_4)$	$\mathcal{P}(\Delta m^2_{14})$
m_4 [eV]	-	1.6	4.4	6.8
$\log_{10}\|U_{e4}\|^2$	-	−3.04	−3.43	−4.0
$\log_{10}\|U_{\mu4}\|^2$	−2.2 (ν_μ)	−3.17	−3.55	−4.16
$\log_{10}\|U_{\tau4}\|^2$	−0.8 (ν_μ)	−3.18	−3.55	−4.19

Light sterile solution to anomalies hard to accommodate

Hagstotz+(incl.MG),2020

Forecast improvements for **absolute mass scale**:

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2} < 0.04 \text{ eV @ 90\%CL}$$

(Project8)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right| < 0.02 \text{ @ 90\%CL}$$

(NEXO)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i$$ 15 meV 1sigma-sensitivity

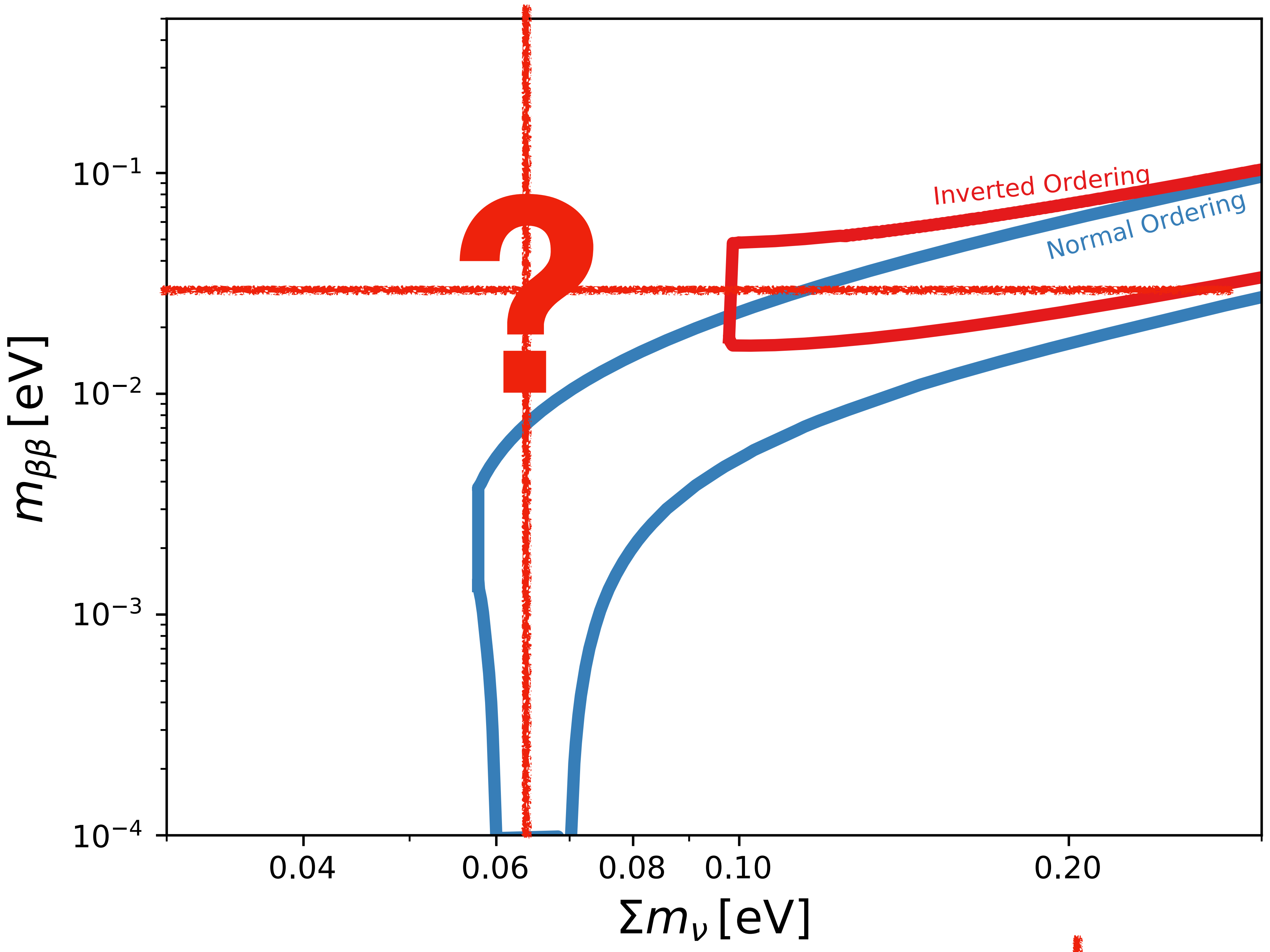
(Stage4 surveys)

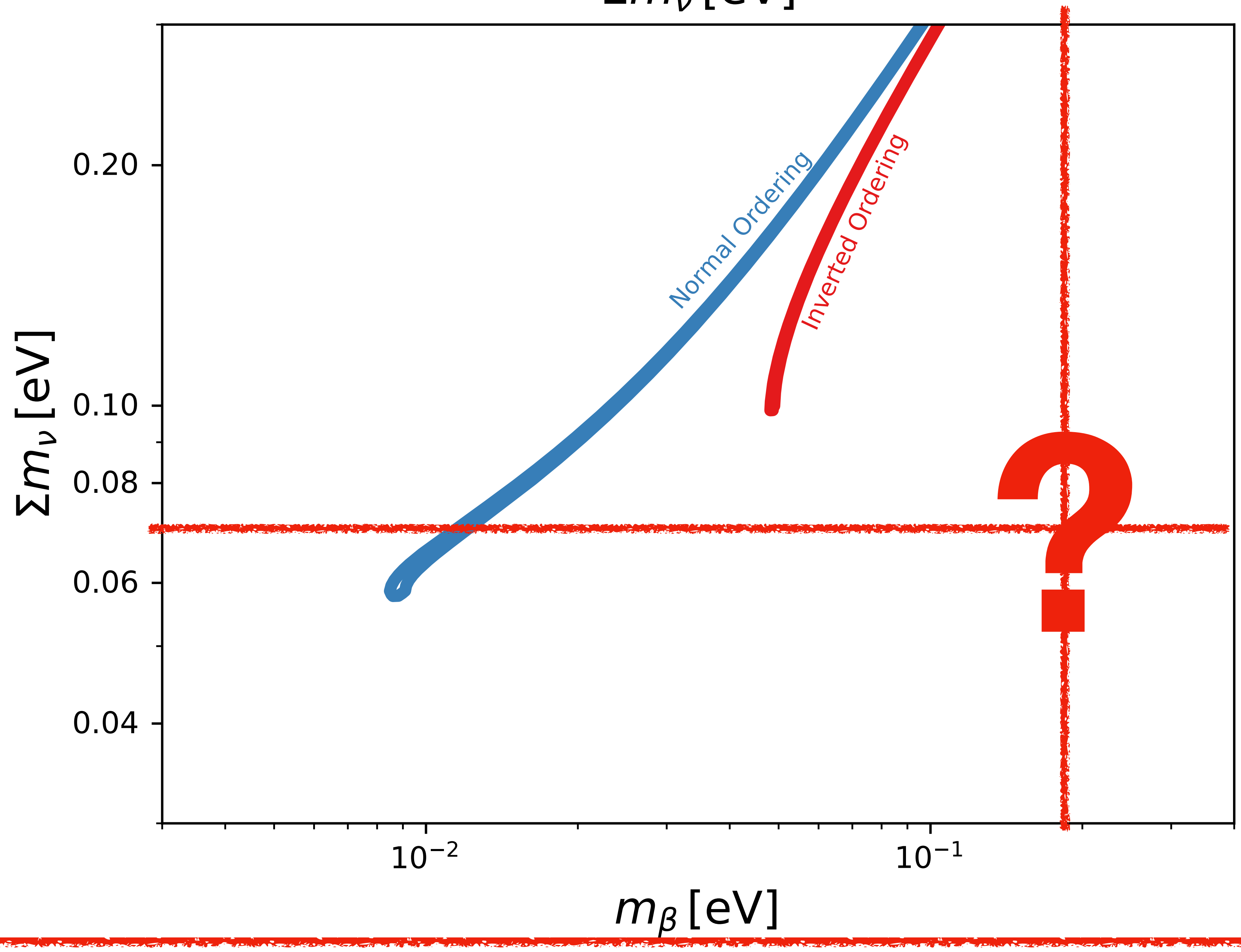
Forecast improvements for number of relativistic species:

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

(Stage4 surveys)

Forecast improvements for oscillation parameters:
- precise measurement of delta-CP and mass ordering **(DUNE)**





CROSS-CHECKS AND SURPRISES

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

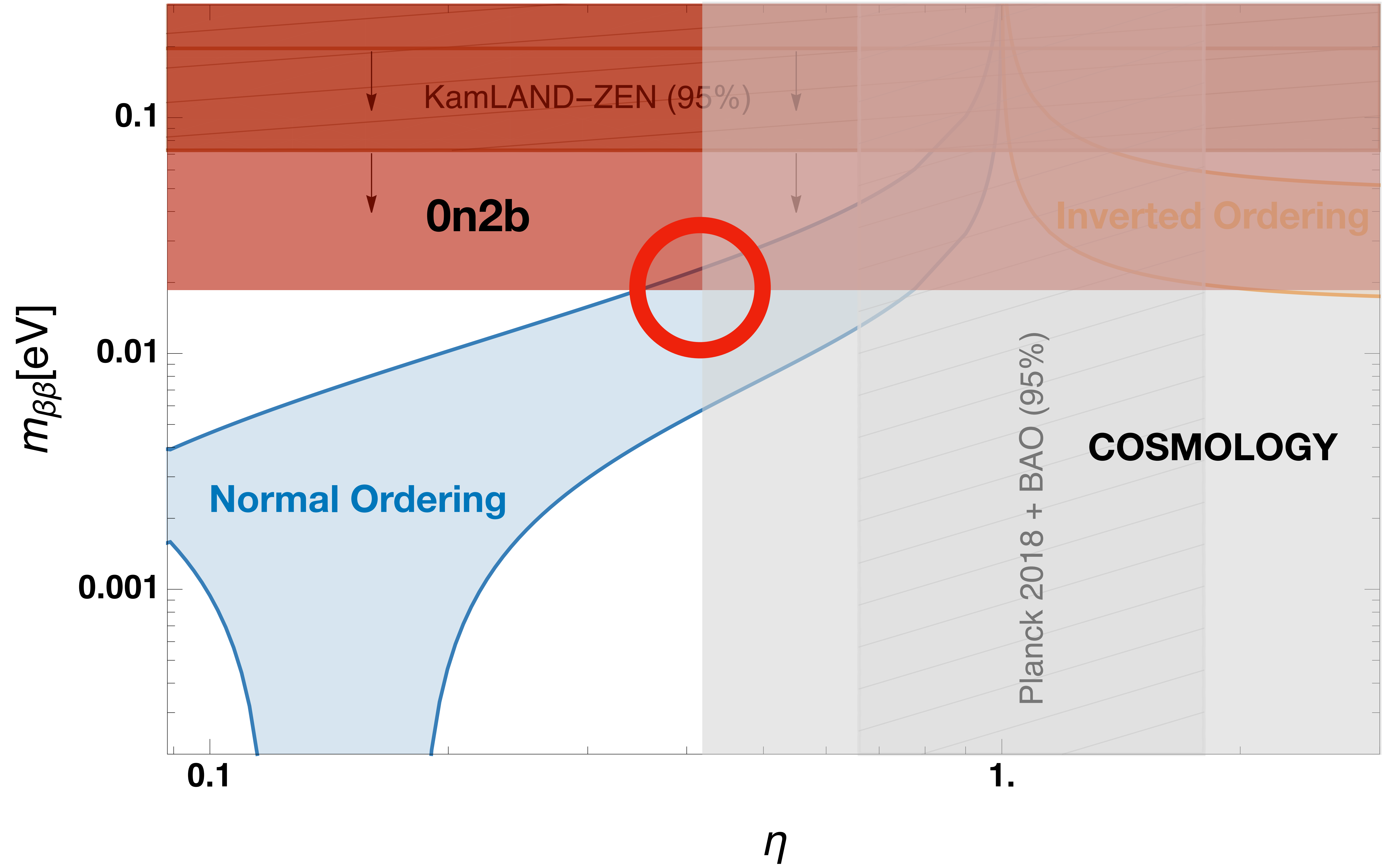
- Concordant signals from both cosmology and 0nu2b. Neutrinos are Majorana. Hierarchy might be determined or not.

- 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?

ENHANCED CONSTRAINING POWER



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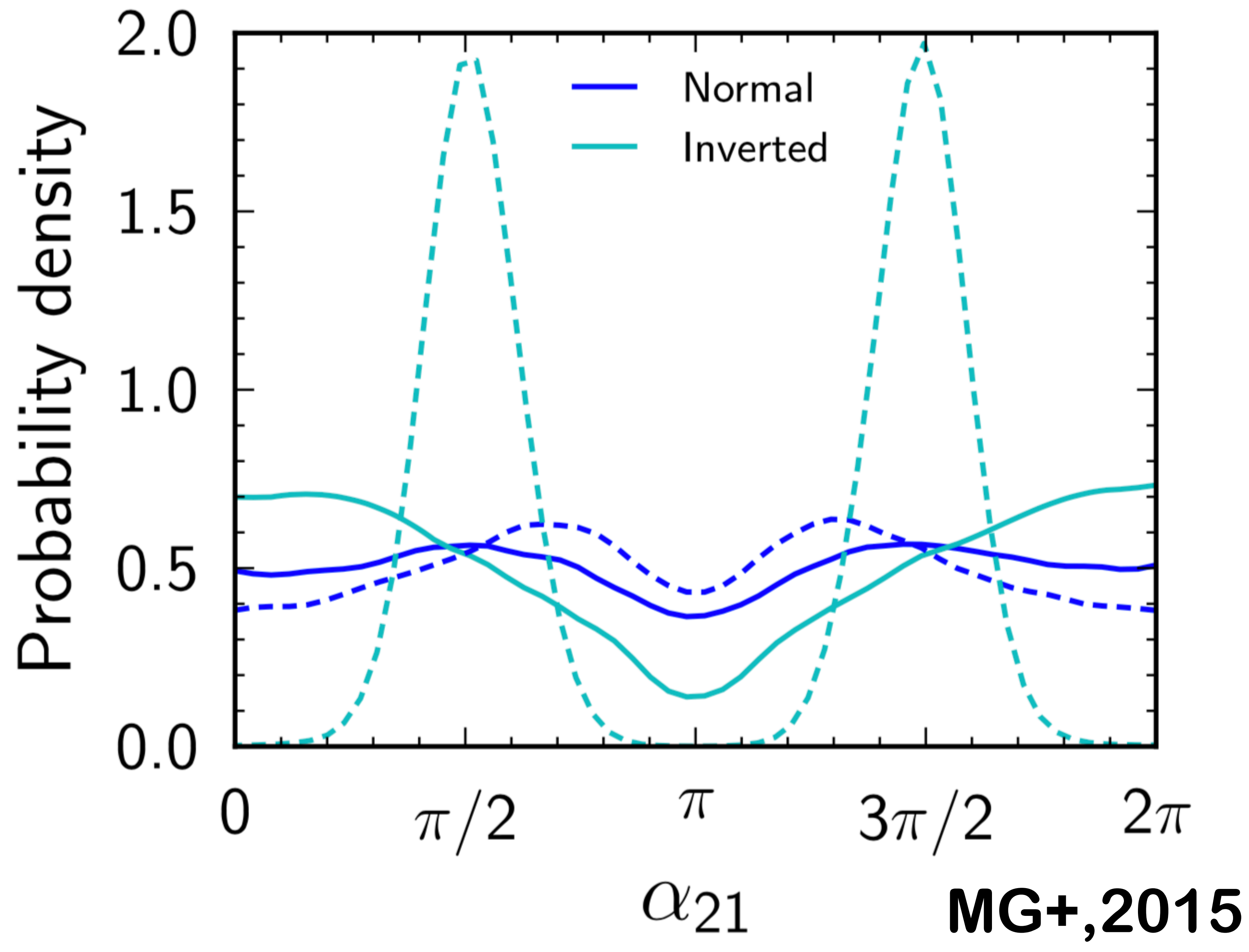
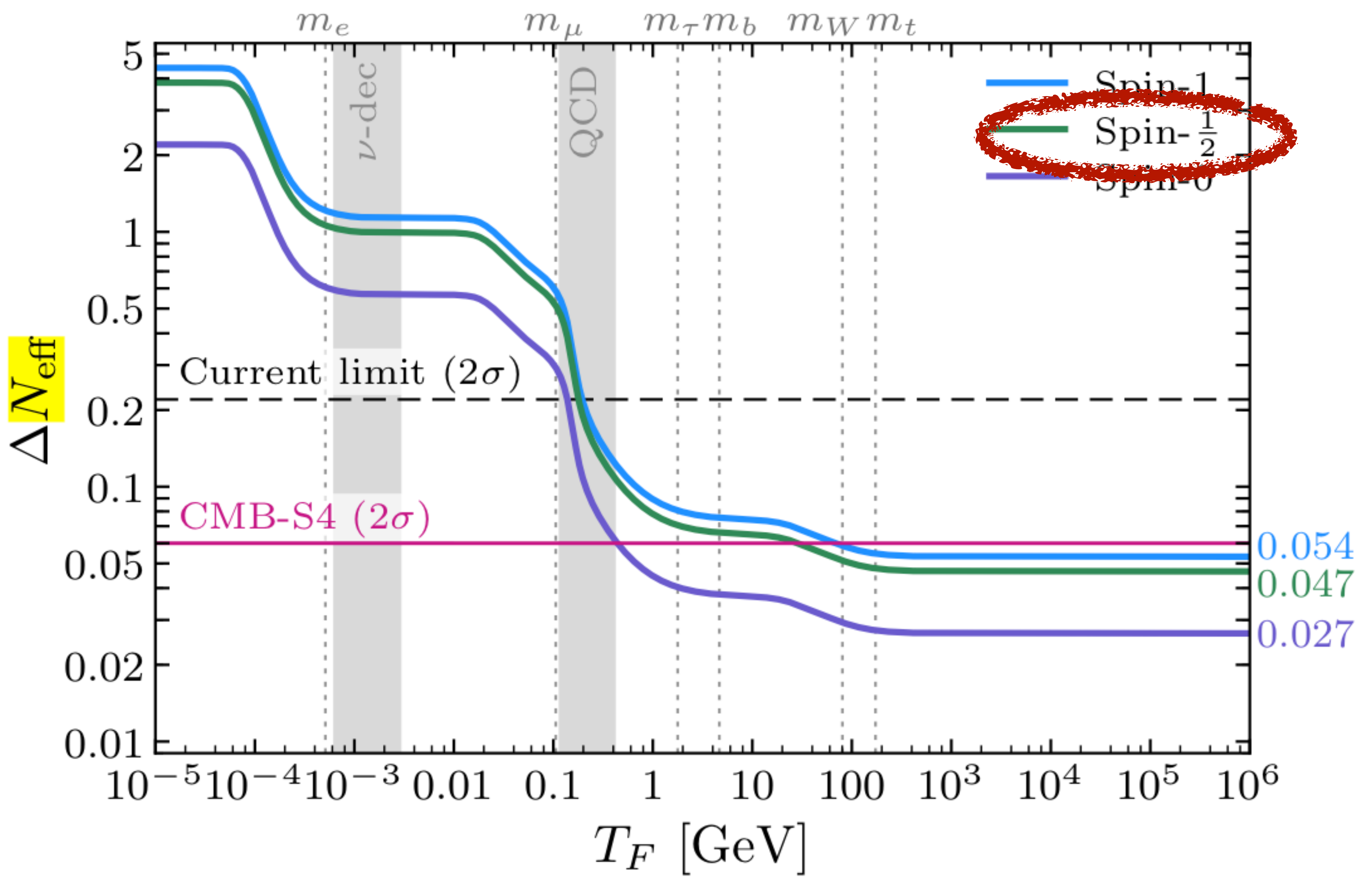


MG+,2015

ENHANCED CONSTRAINING POWER



Changes to neutrino history must not spoil cosmo probes

S4 collaboration, 2019

CONCLUSIONS

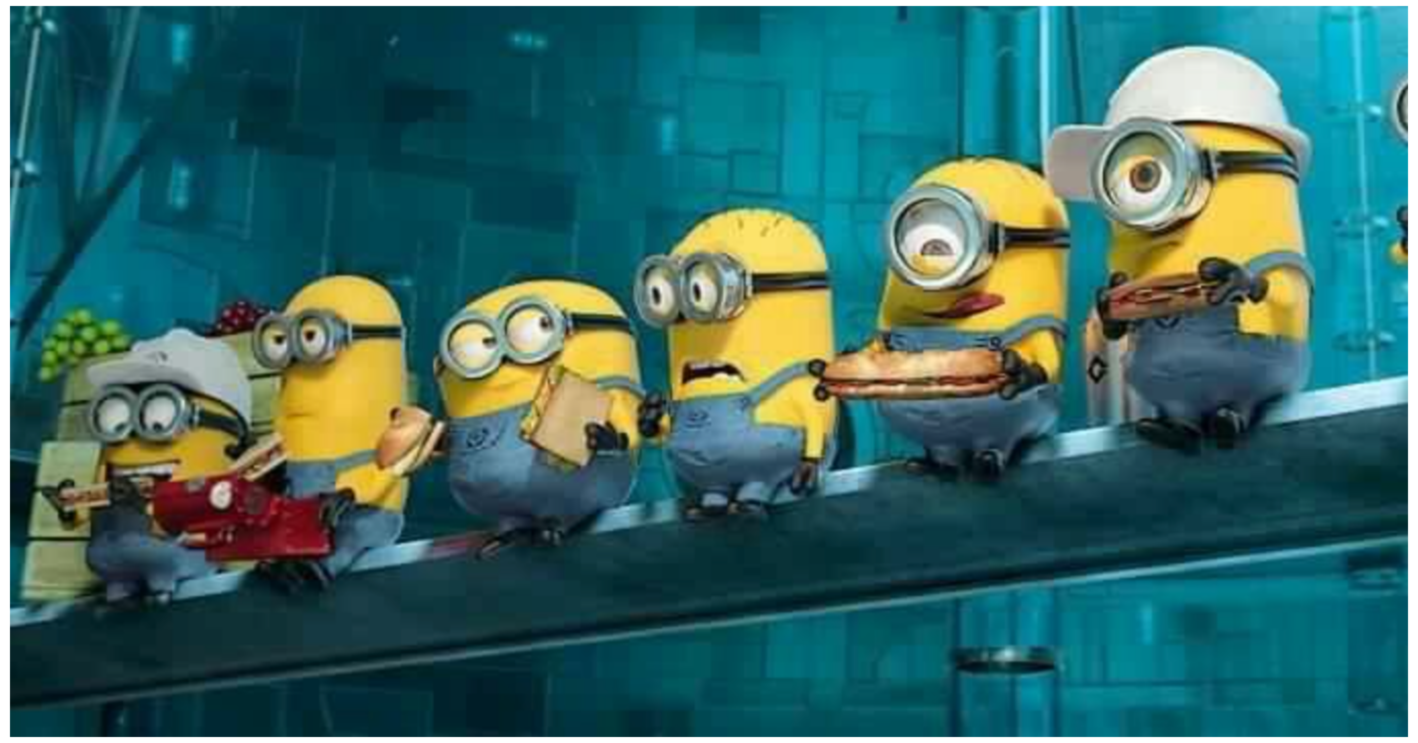
Terrestrial facilities and cosmological surveys are complementary probes of neutrino physics

They are (or will be) competitive in sensitivity

A synergic approach can strengthen constraints on neutrino properties

Or can unveil hints to new physics in the neutrino sector

…and now let's have lunch (or dinner)!



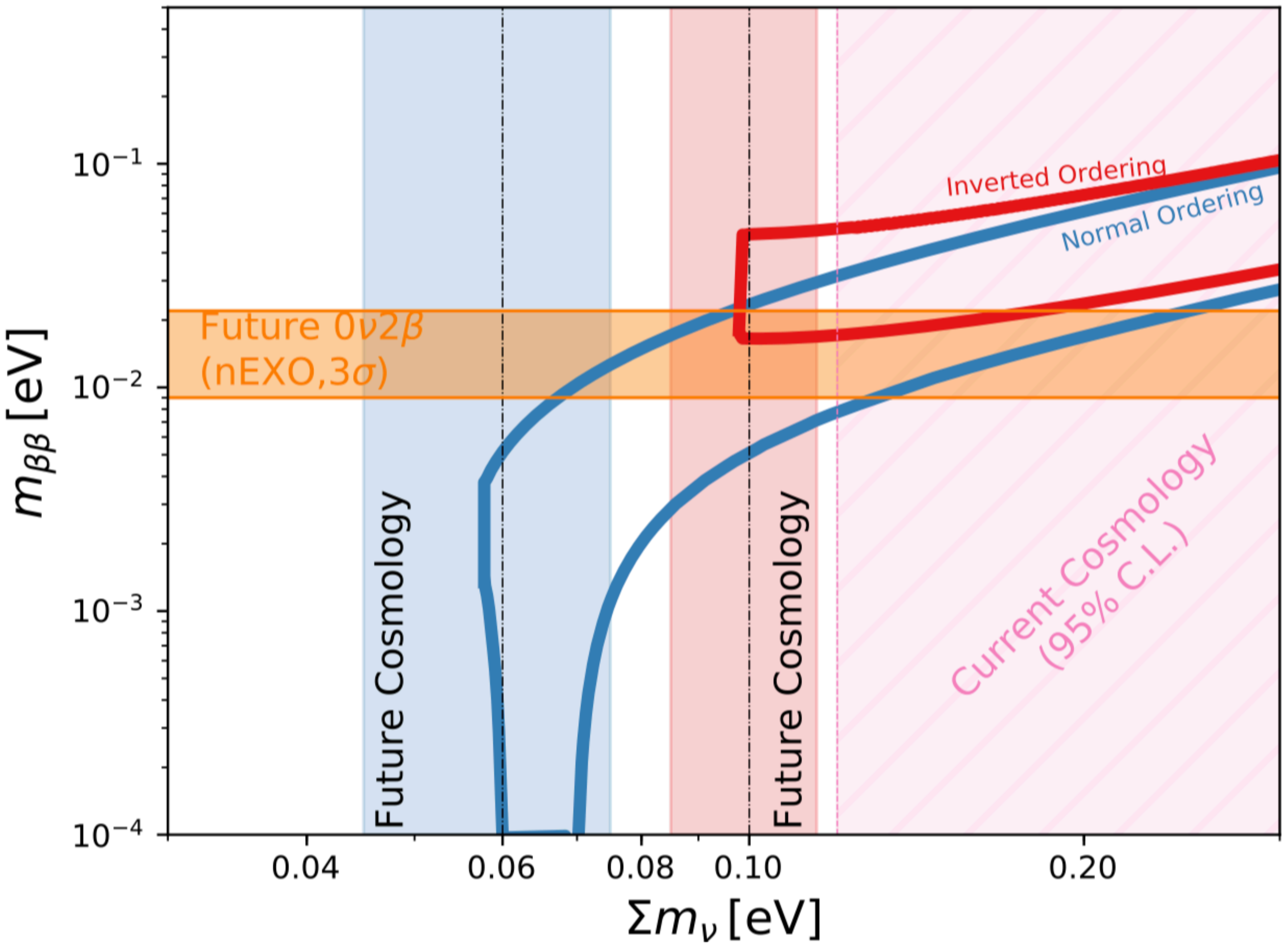
BACK-UP SLIDES

To increase sensitivity to neutrino masses AND reduce model dependency, we need:

- Precise measurement of the CMB lensing signal (both from 2- and 4-point correlation functions)
- Cosmic variance limited measurement of the reionization optical depth
- other CMB probes of structure formation, e.g. SZ galaxy clusters

+ non CMB information

- BAO information to reduce geometrical degeneracies
- Full shape of the matter power spectrum
- CMB/LSS cross correlations



10^{-1}
10^{-2}
10^{-3}
10^{-4}
$m_{\beta\beta}$ [eV]
0.04
0.06
0.08
0.10
0.20
Σm_ν [eV]
Future $0\nu2\beta$
(nEXO,3σ)
Inverted Ordering
Normal Ordering
Future Cosmology
Future Cosmology
Current Cosmology
(95% C.L.)