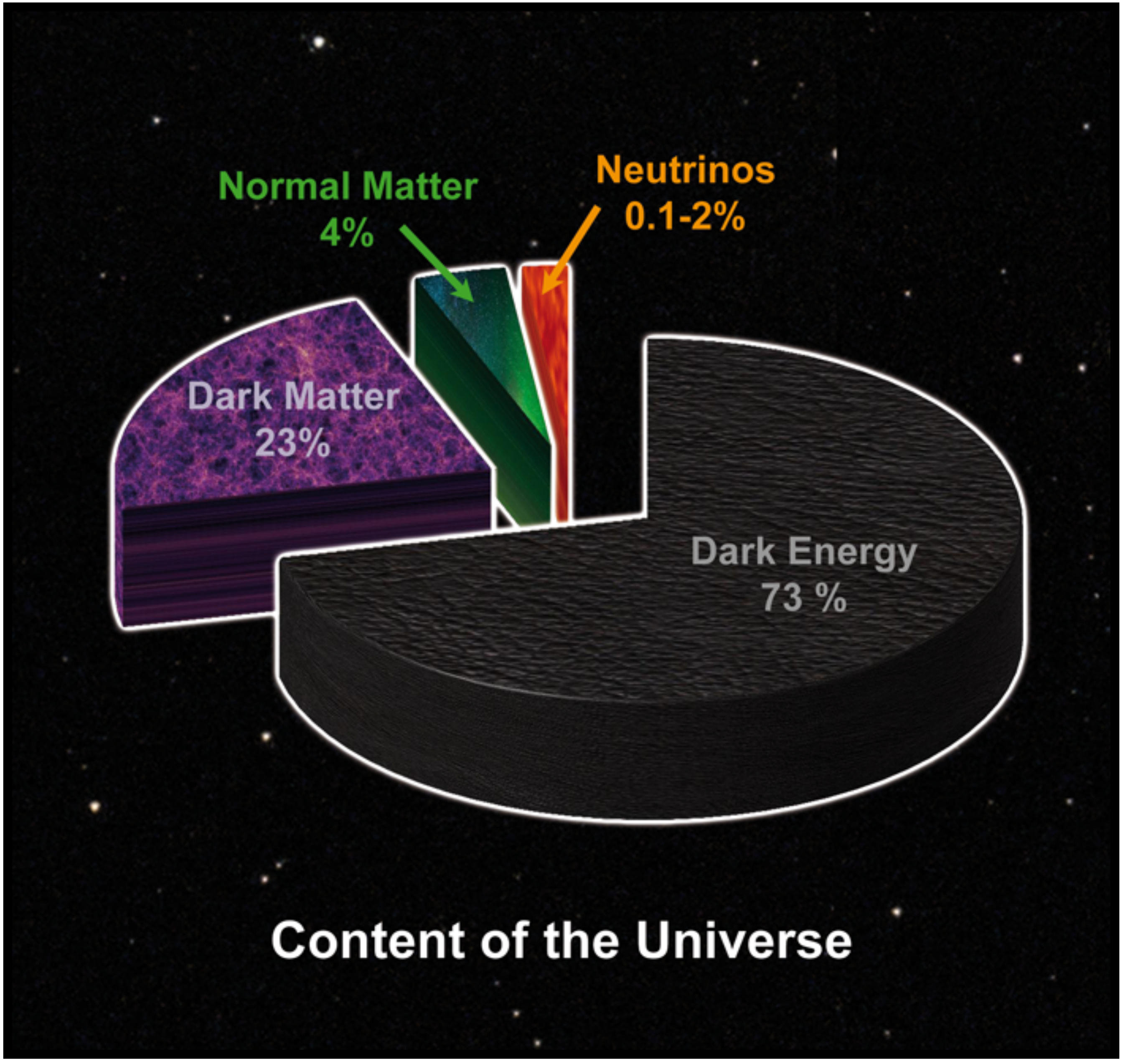
Neutrino mass variables in 3 active and 2 sterile neutrino model

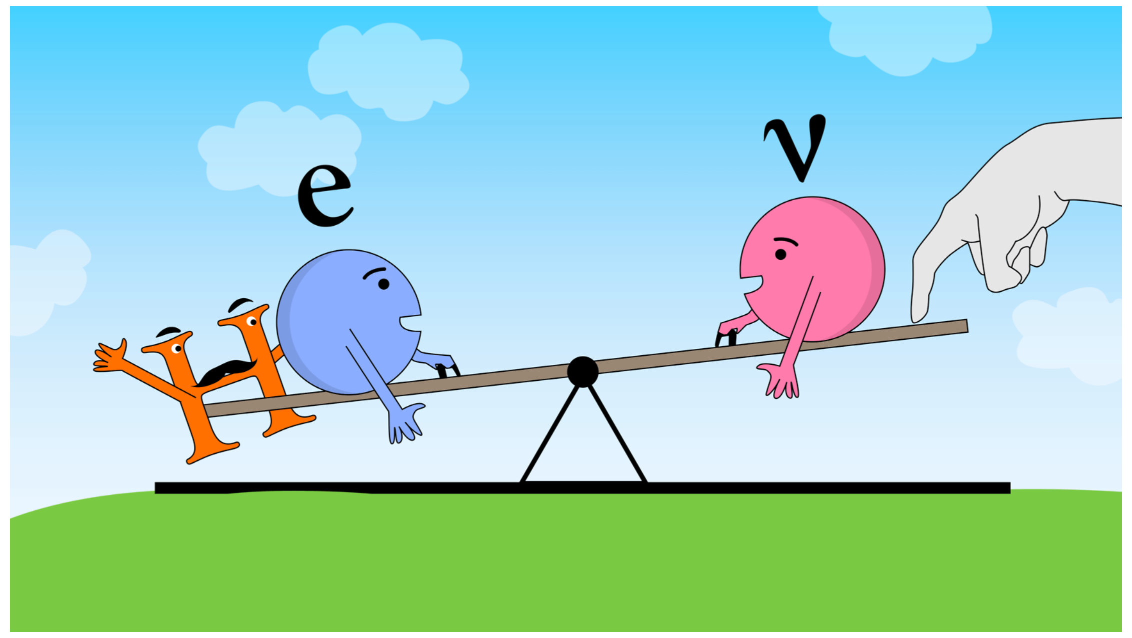
N Rajeev

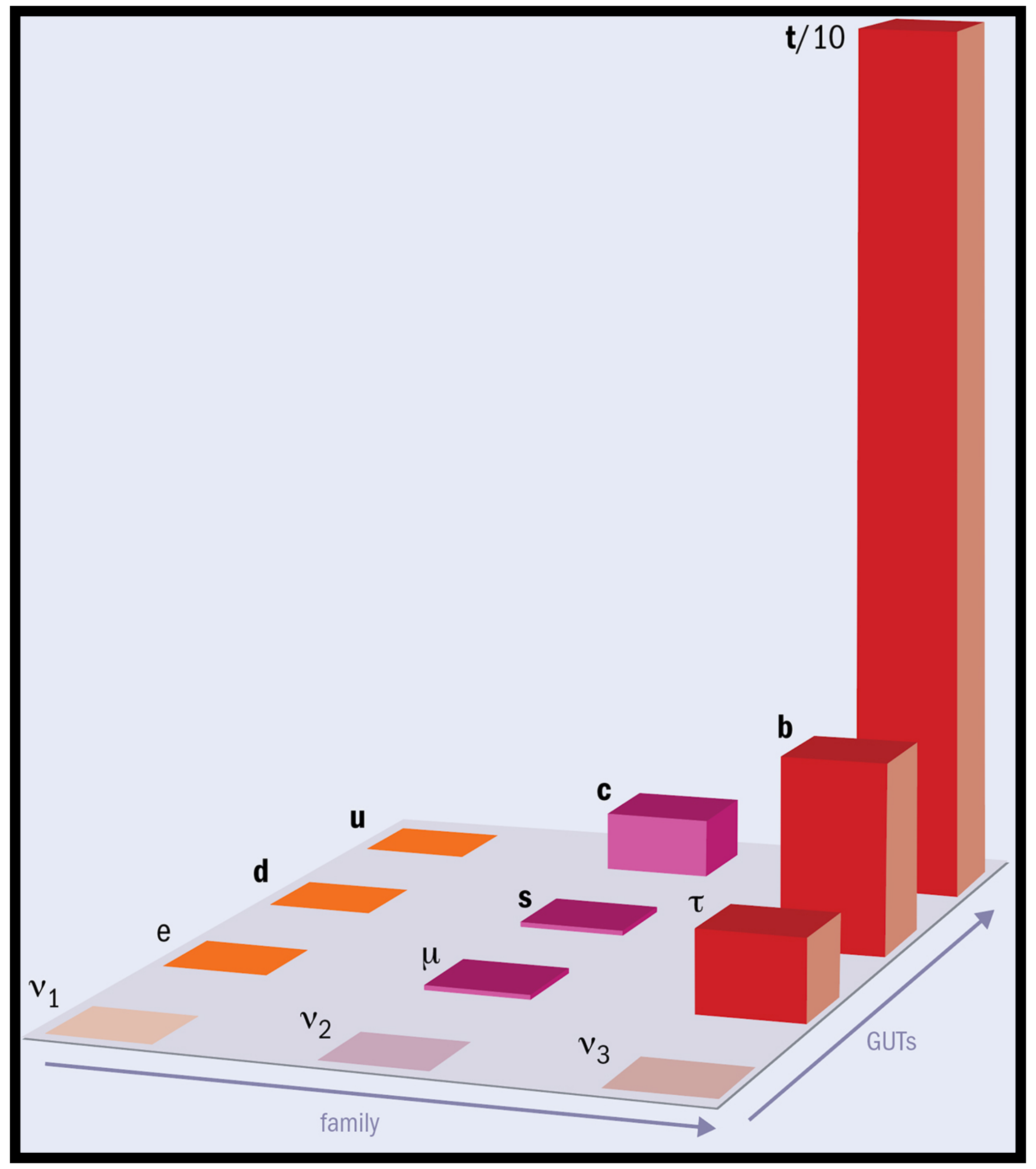
This work is done with Prof. Srubabati Goswami, Hemanth M., and Debashis Pachhar

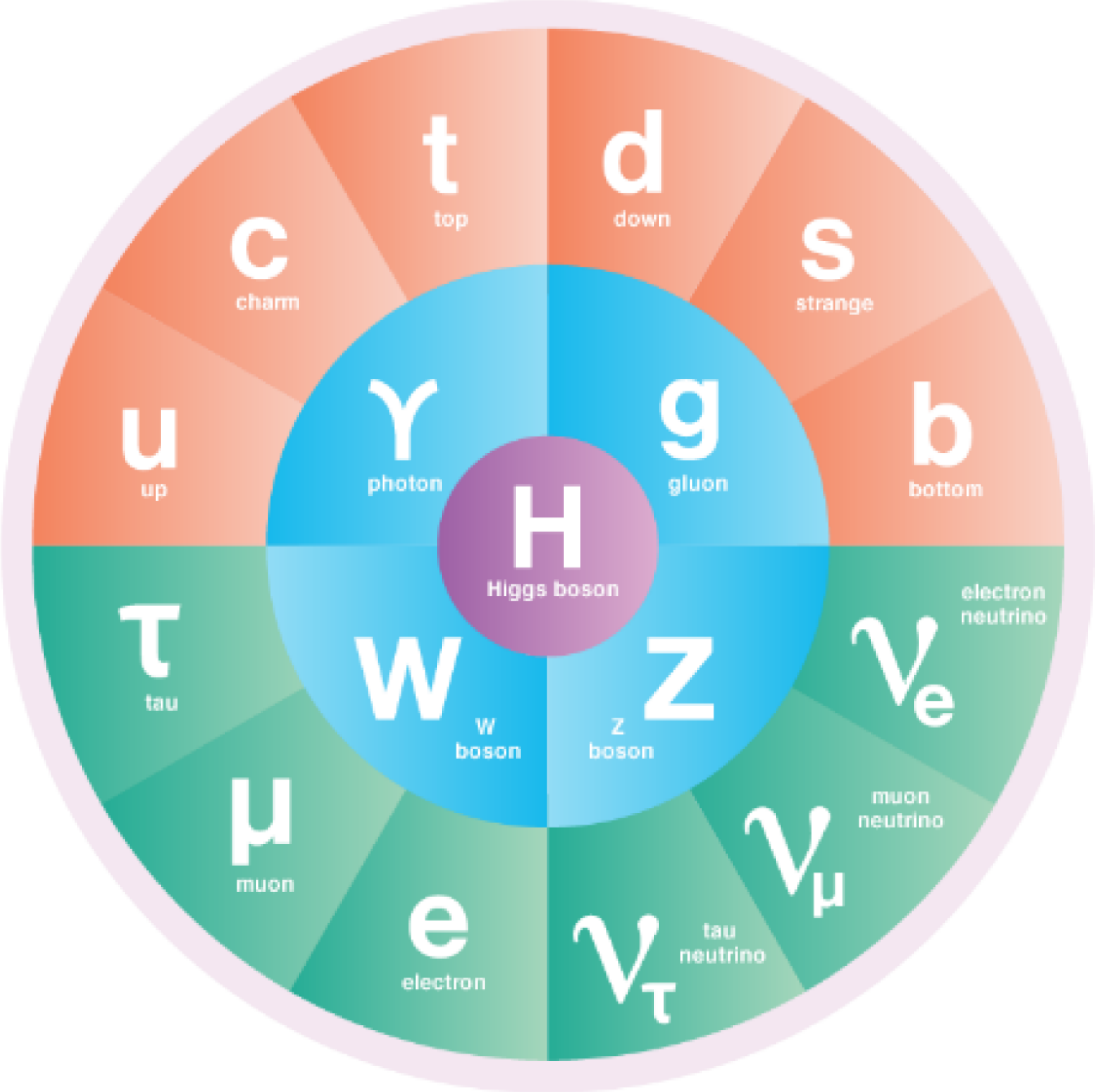
Outline

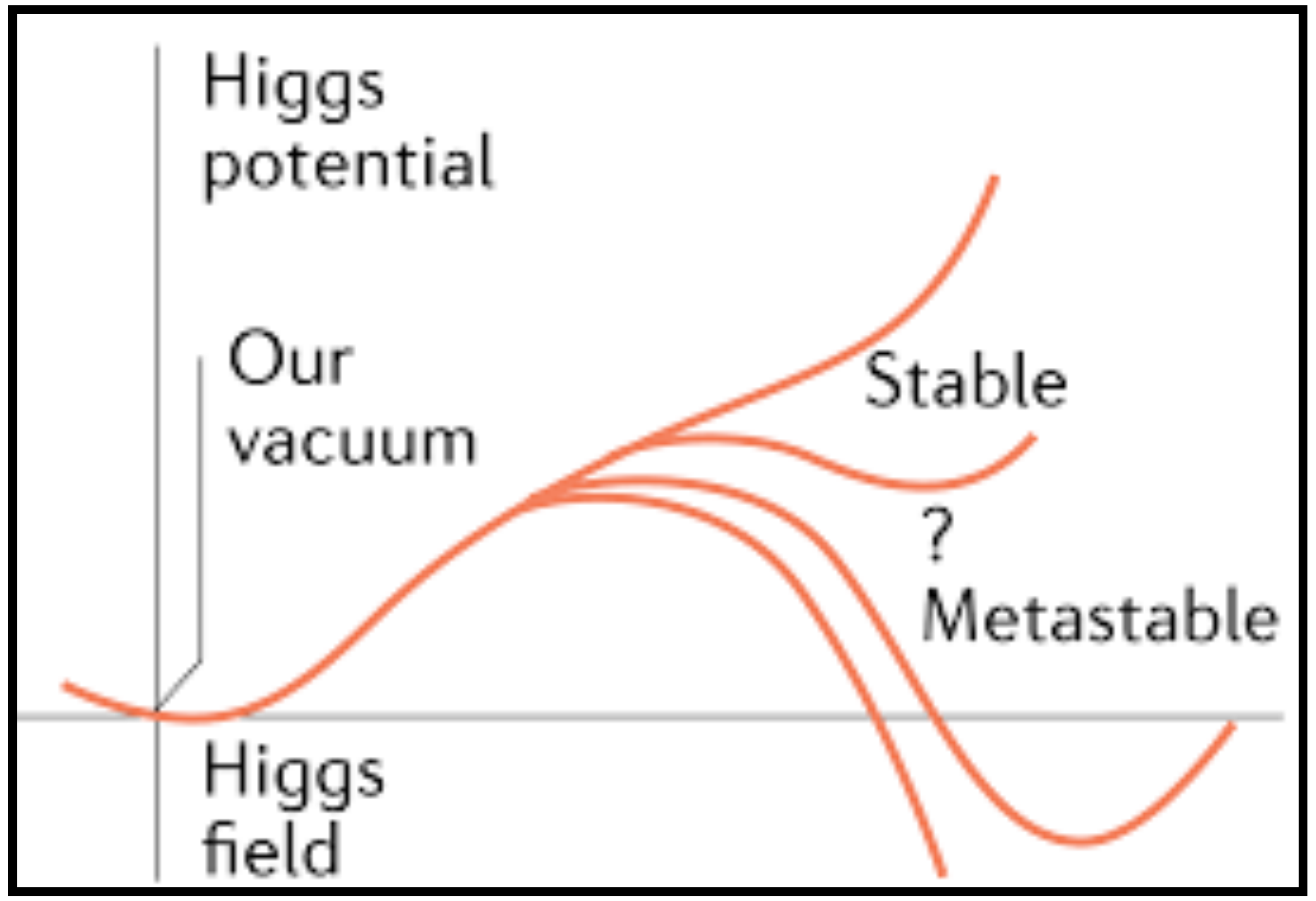
- SM and its Limitations
- Neutrinos and their Anomalies
- Sterile Neutrinos
- Classification of mass ordering in 3 + 2 sterile neutrino framework
- Mass Constraints on 3+2 Sterile Neutrinos
- Summary

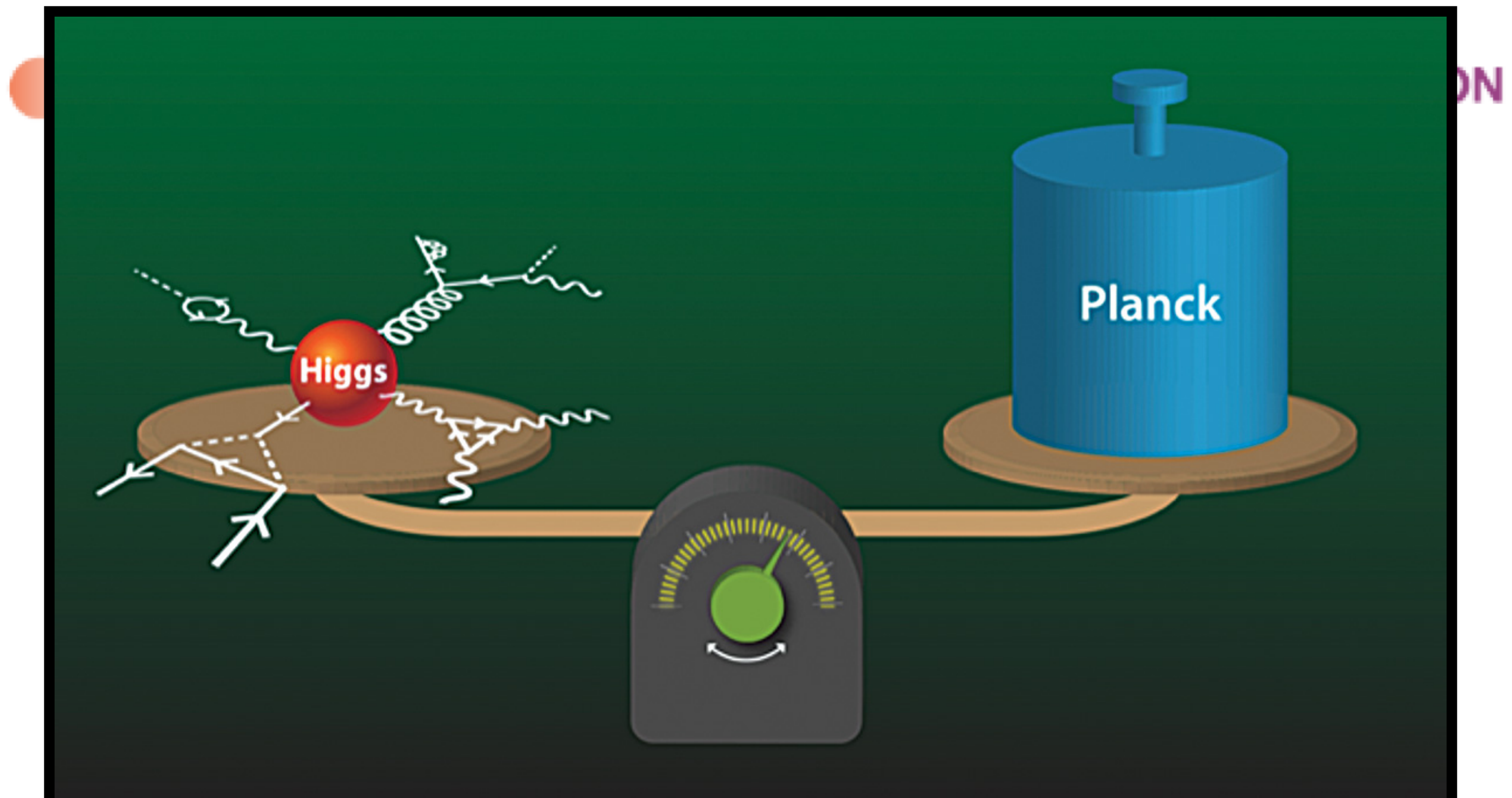

Normal Matter
4%
Neutrinos
0.1-2%
Dark Matter
23%
Dark Energy
73 %
Content of the Universe

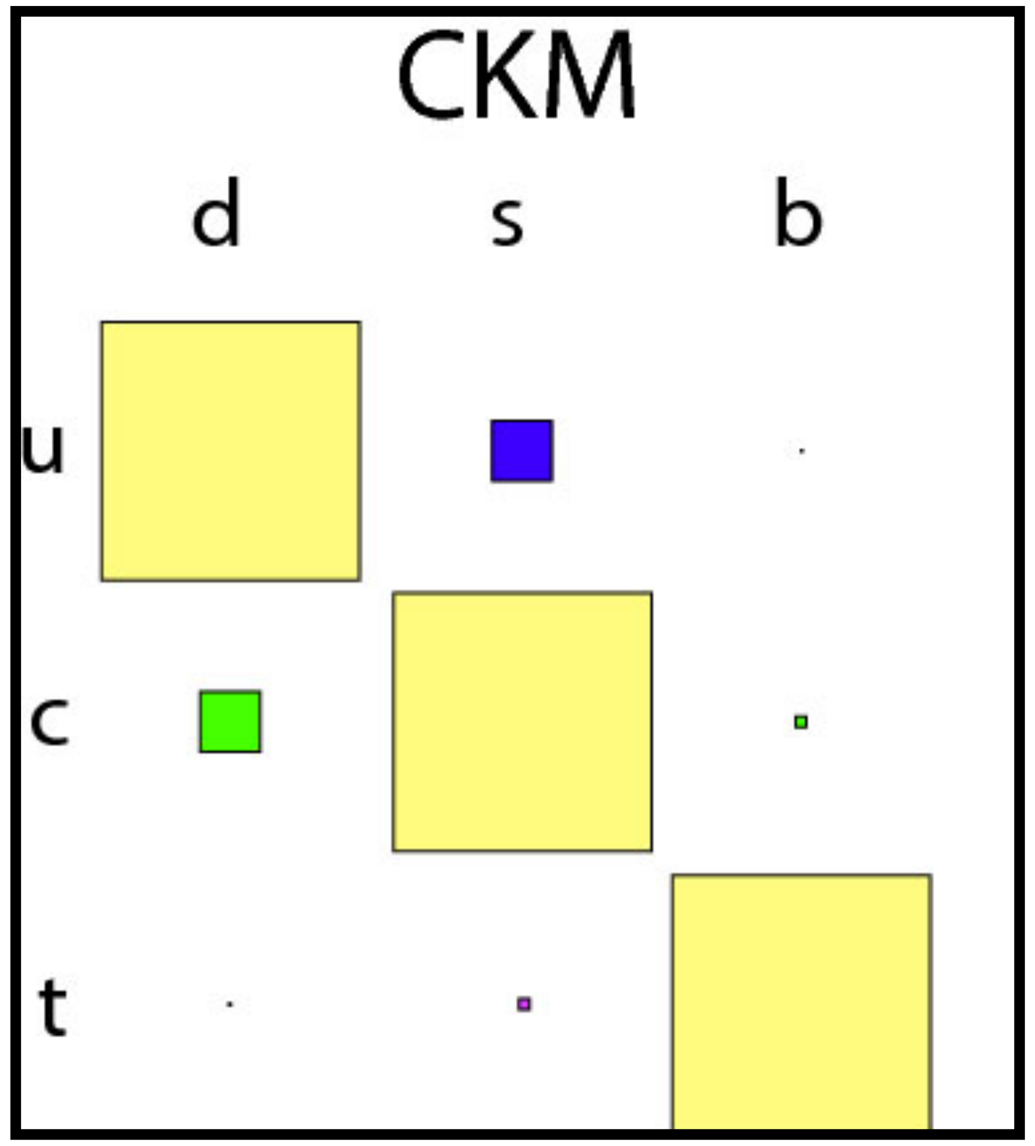

e
ν


t/10
b
c
u
d
e
s
τ
μ
ν_1
ν_2
ν_3
GUTs
family

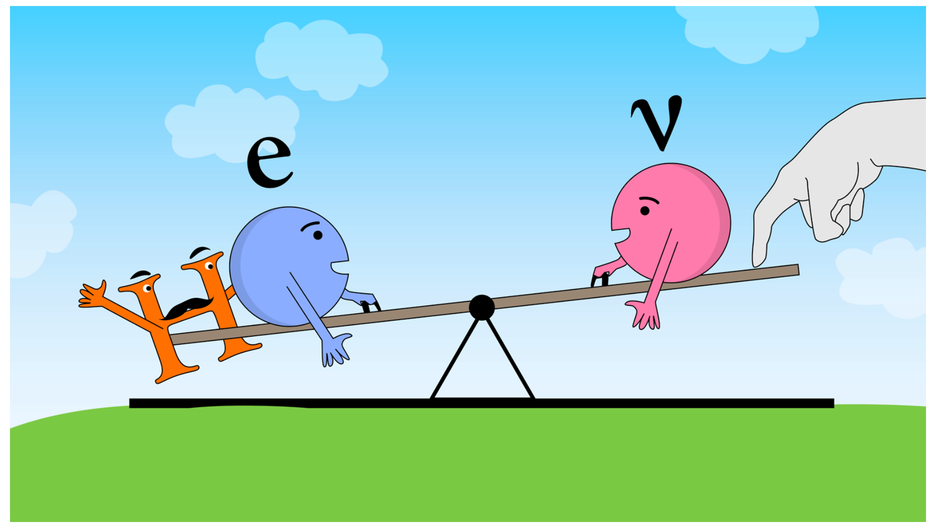

t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
ν_e
electron neutrino
μ
muon
ν_μ
muon neutrino
e
electron
ν_τ
tau neutrino

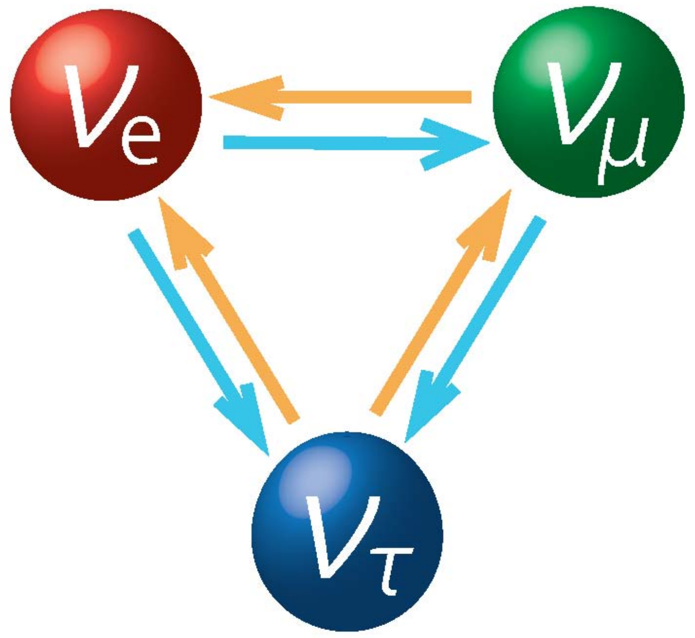

Higgs potential
Our vacuum
Stable
?
Metastable
Higgs field


Higgs
Planck

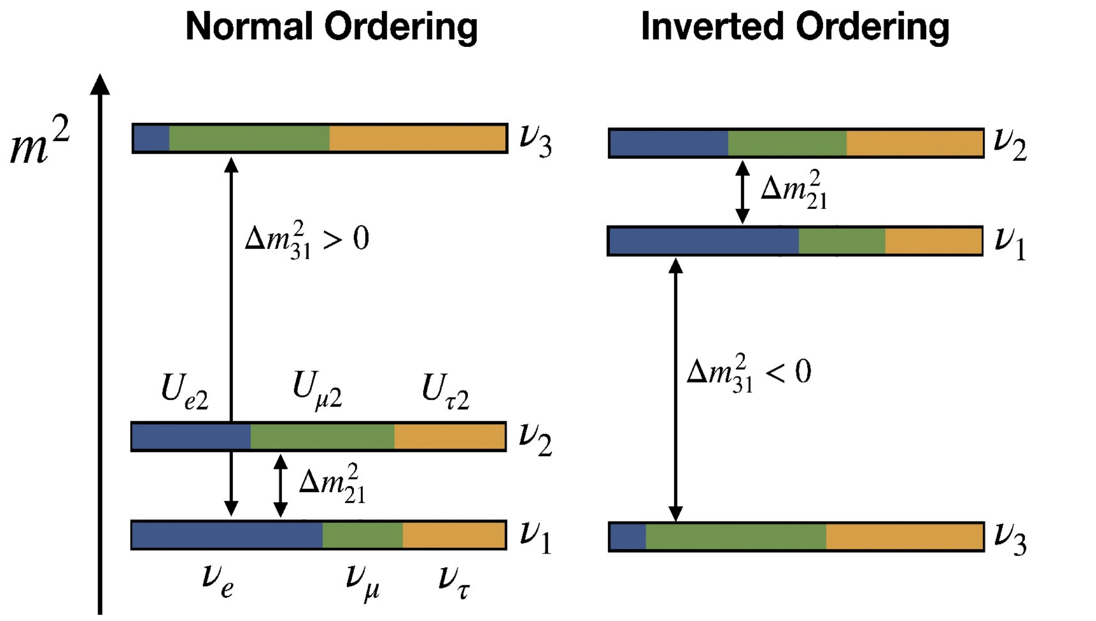

CKM
d
s
b
u
c
t

Neutrinos..!





- Within the **SM**, neutrinos were originally postulated as exactly **massless** particles, appearing in three copies $(\nu_e, \nu_\mu, \nu_\tau)$ corresponding to each of the charged leptons.
- Lepton number was assumed to be conserved independently for each lepton family.
- The discovery of **neutrino oscillations** demonstrated that neutrinos have tiny but **nonzero** masses and that lepton flavor is **not** a conserved quantity.
- The first evidence came from atmospheric neutrinos observed at Super-Kamiokande and solar neutrinos studied by SNO.
- Followed by confirmation from reactor (KamLAND, Daya Bay, RENO, Double Chooz) and accelerator experiments (K2K, MINOS, T2K, NOvA).
- These observations firmly establish that the three active neutrinos mix via the PMNS matrix, characterized by two mass-squared splittings $(\Delta m^2_{21}, \Delta m^2_{31})$, three mixing angles, and possibly CP-violating phases.
- While the three-flavor oscillation paradigm successfully explains the bulk of experimental data, several anomalies persist which cannot be accommodated within this framework



Known in Standard Picture

$\Delta m^2_{21} = (6.82 - 8.04) \times 10^{-5}\, eV^2$

$|\Delta m^2_{3l}| = (2.42 - 2.59) \times 10^{-2}\, eV^2$

$\sin^2\theta_{12} = (0.275 - 0.344)$

$\sin^2\theta_{13} = (0.023 - 0.024)$

$\sin^2\theta_{23} = (0.407 - 0.620)$

Unknown in Standard Picture

θ_{23} octant : $\theta_{23} > 45^\circ$ / $\theta_{23} < 45^\circ$

Mass ordering : $\Delta m^2_{31} > 0 / \Delta m^2_{31} < 0$

Value of CP phase $(\delta_{CP}) = \delta_{13}$

Absolute mass scale

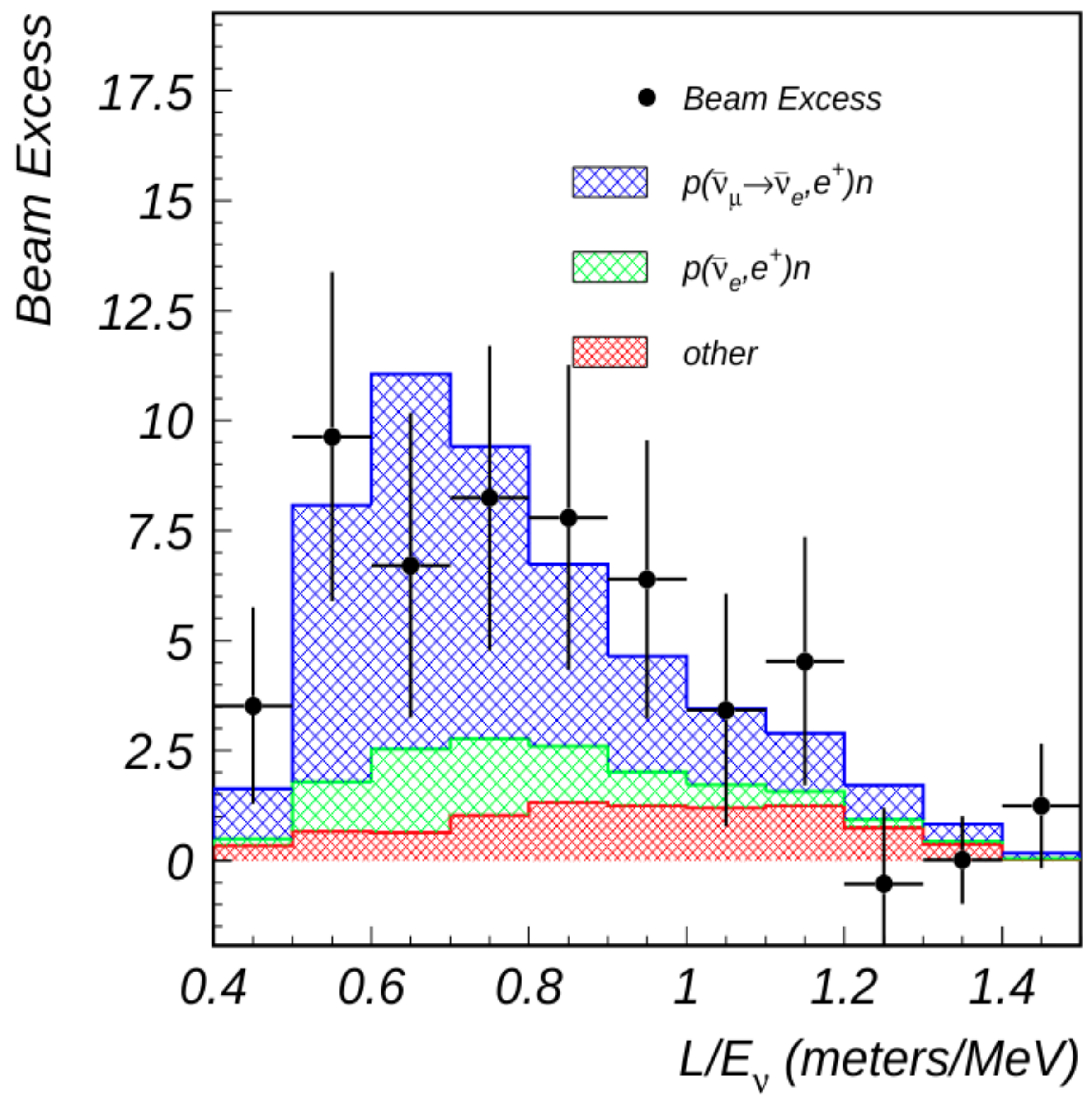
Dirac/Majorana

Neutrino Anomalies..!

LSND Anomaly

- LSND stands for Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory, USA (1993–1998). This base has a length of ~30m and a neutrino energy of ~30 MeV.
- LSND used $\bar{\nu}_\mu$ produced from the muon decay at rest $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
- Looked for $\bar{\nu}_e$ appearance via inverse beta decay $\bar{\nu}_e + p \to e^+ n$
- Found an **excess of** $\bar{\nu}_e$ events over the expected background with statistical significance 3.8σ.
- This suggests oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$ with $\Delta m^2 \sim 1\,\mathrm{eV}^2$ - for larger than solar (7.4×10^{-5}) or atmospheric (2.5×10^{-3}) mass-squared splittings.
- Requires **an additional neutrino state**, since three neutrinos can only provide two independent Δm^2.

LSND

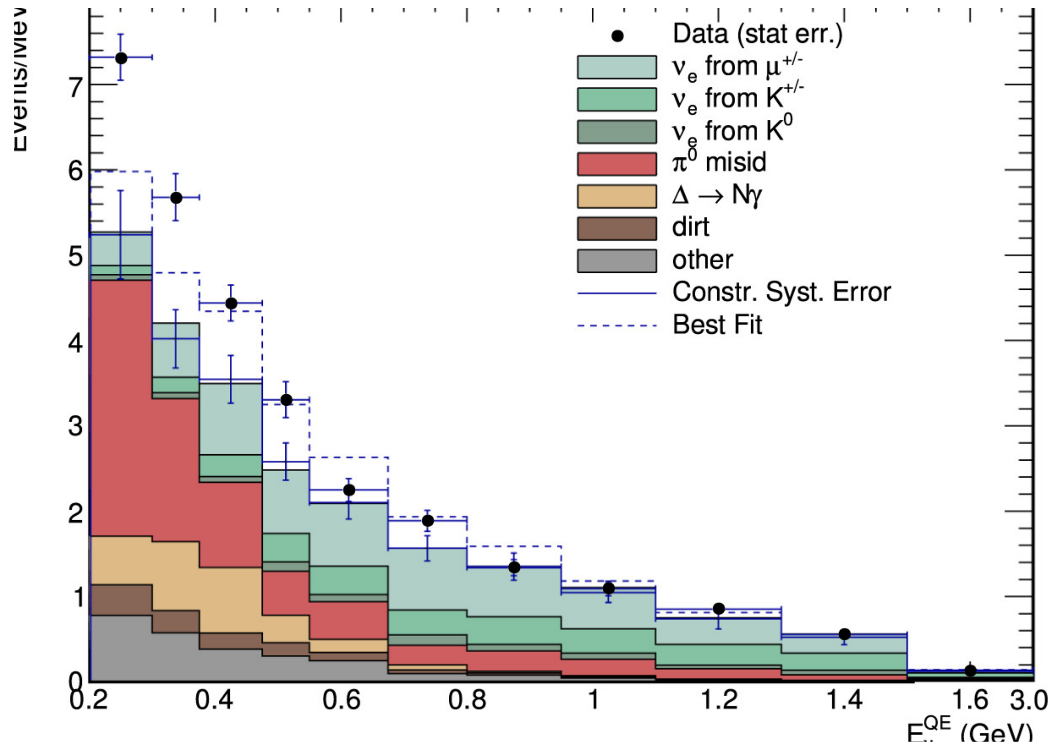


$\bar{\nu}_\mu \to \bar{\nu}_e$ at 3.8σ (C. Athanassopoulos et al , PRL 1995

MiniBooNE Anomaly

- MiniBooNE stands for Mini Booster Neutrino Experiment at Fermilab, USA (2002–2019): baseline: 541 m; Neutrino energy: 200–1250 MeV.
- **The goal was to** test LSND anomaly at higher energy and longer baseline independently.
- Setup: Neutrino beam from pion decay-in-flight, primarily ν_μ.
- MiniBooNE detected an excess of electron-like events in both ν and $\bar{\nu}$ modes.
- Combined excess significance: 4.8σ (2020).
- Consistent with **additional neutrino** oscillations $\nu_\mu \rightarrow \nu_e$ at $\Delta m^2 \sim 1\ \mathrm{eV}^2$
- However, MiniBooNE can't distinguish electrons from single photons — so **photon-like backgrounds (e.g. π⁰ misidentification)** might mimic a signal.
- **MicroBooNE** (2021, LArTPC detector) observed **no evidence for excess** ν_e events, casting doubt on the oscillation interpretation — though it doesn't fully explain MiniBooNE's anomaly.
- The puzzle remains unresolved.

MiniBooNE



$\nu_\mu \rightarrow \nu_e$ at 4.8σ (Aguilar-Arevalo et al.,PRL,2009)

Reactor Antineutrino Anomaly

- Nuclear reactors produce huge fluxes of $\bar{\nu}_e$ from β-decays of fission fragments.
- Detected via inverse beta decay (IBD).
- Around **2011**, updated theoretical models (Huber and Mueller) predicted slightly higher $\bar{\nu}_e$ fluxes than older models.
- When compared to data from ~20 short-baseline reactor experiments (L < 100 m), a deficit of ~6% was observed. Leading to the statistical significance: 2.8σ.
- Could indicate oscillations into **an additional neutrino state** with $\Delta m^2 \sim 1\,\mathrm{eV}^2$ and small mixing angle. However, recent data (DANSS, NEOS, STEREO, PROSPECT) suggest that the anomaly may instead arise from inaccurate reactor flux predictions, especially from U^{235} and Pu^{239}.
- Still debated. The flux-shape distortion ("5 MeV bump") complicates the interpretation.

Gallium (Source) Anomaly

- **GALLEX** and **SAGE** — solar neutrino detectors calibrated using intense radioactive neutrino sources (eg. Cr^{51} and Ar^{37}) with baseline: ~1–2 m; Energy: ~1 MeV.

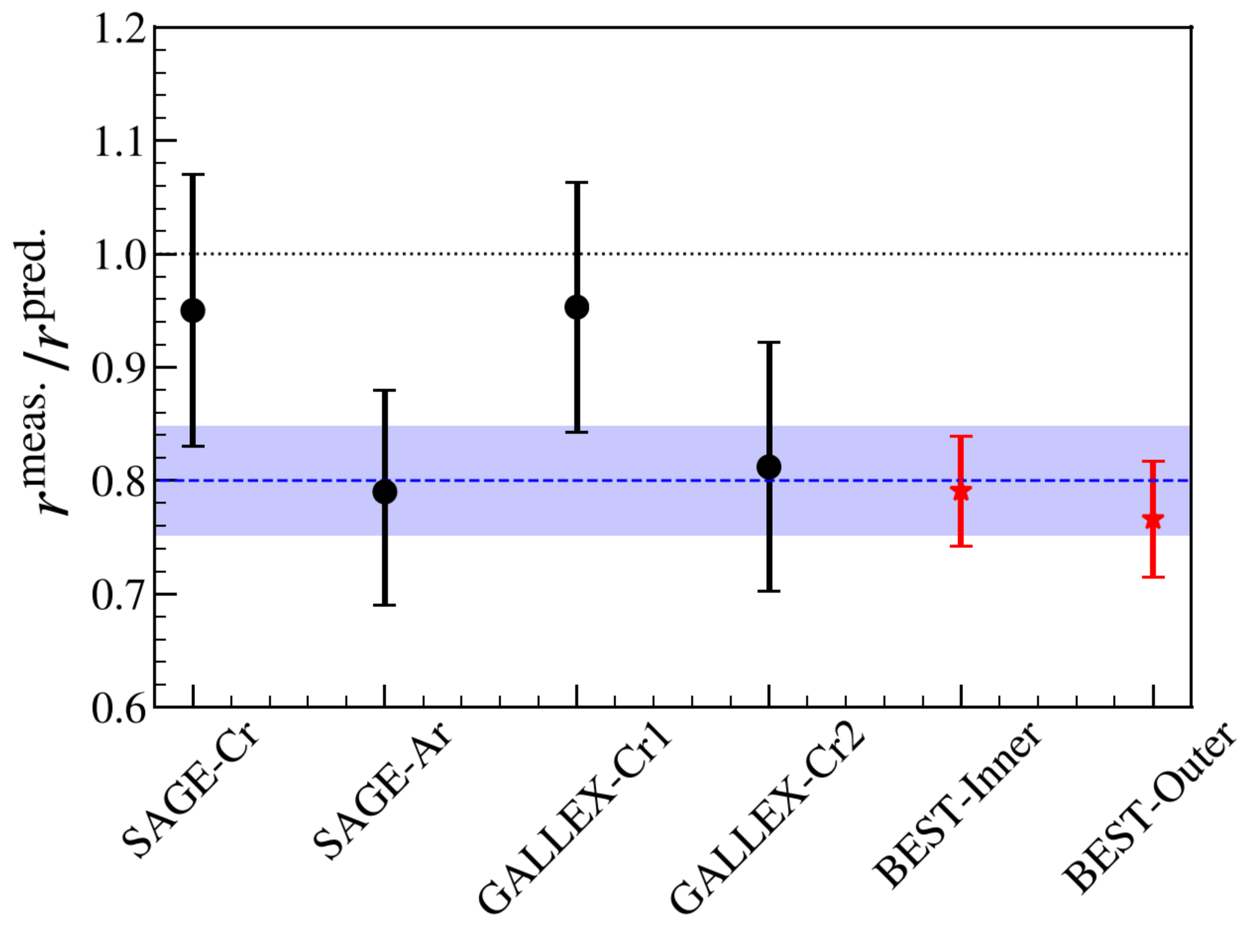
- Measured event rates were **10–20% lower** than predicted. Combined significance: **~2.8σ** deficit.

- This may be due to the short-baseline oscillation $\nu_e \to \nu_s$ with $\Delta m^2 \sim 1\,\mathrm{eV}^2$.

- Same mass range as LSND and MiniBooNE hints — potentially a common **additional neutrino** origin

- Recently, **BEST (Baksan Experiment on Sterile Transitions)** (2022) confirmed the deficit (~20%), strengthening the sterile neutrino interpretation.

Gallium Anomaly



Deficit in ν_e at GALLEX, SAGE, BEST (Barinov et al.,2021)

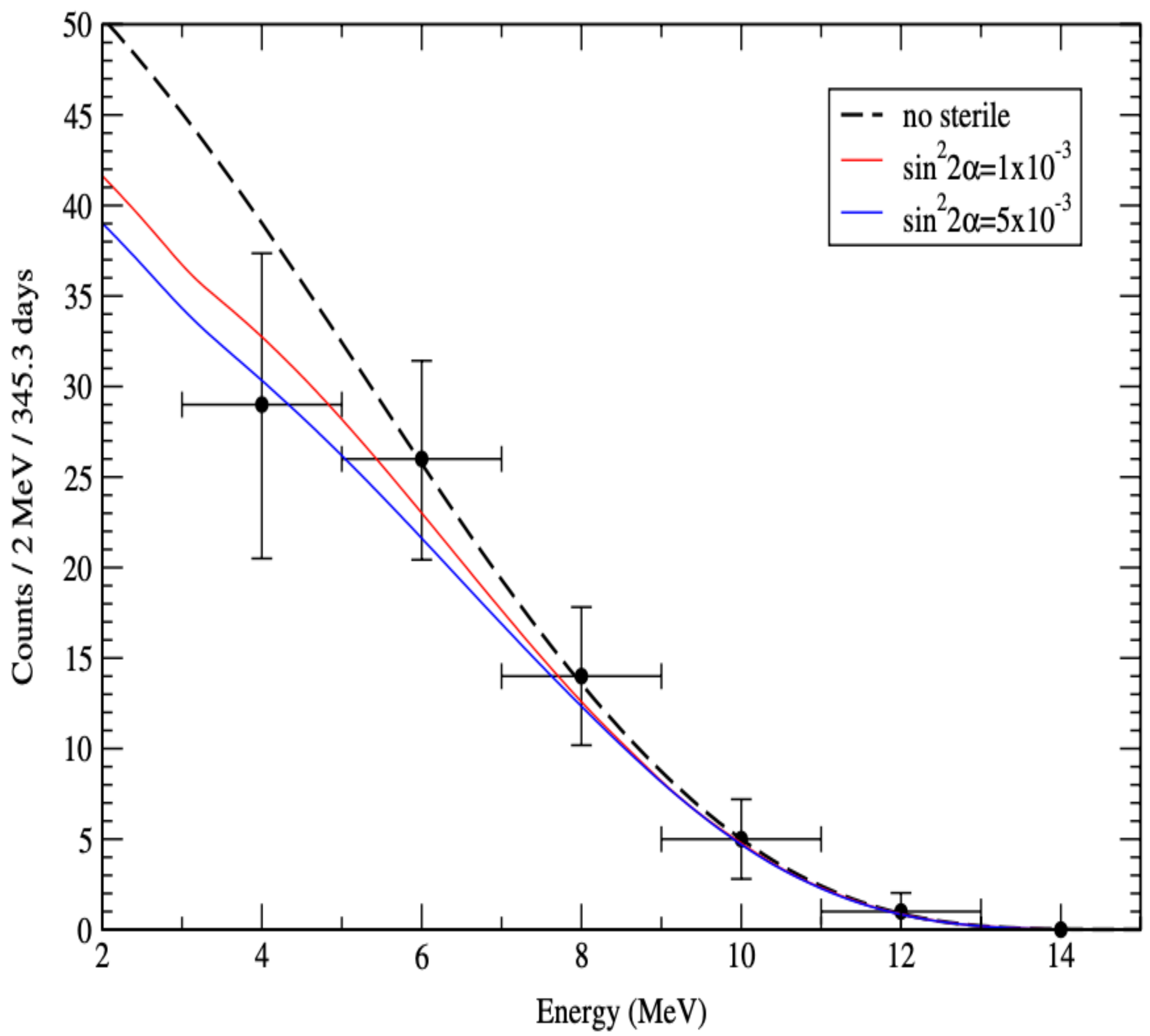
T2K and NOνA Tensions

- T2K (Japan) and NOvA (USA) are long-baseline accelerator neutrino experiments (study $\nu_\mu \rightarrow \nu_e$ appearance).
- **Goal:** Measure CP violation (δ_{CP}), mass ordering, and θ_{23} in the three-flavor framework.
- T2K favors large CP violation, NO and maximal $\theta_{23} \approx 45°$: it observes more ν_e appearance events than NOvA.
- NOvA also prefers NO but δ_{CP} lies near 0 or π and a non-maximal θ_{23}: it observed $\nu_e$appearance is **less** than T2K.
- When both datasets are combined under the **3-flavor framework**, there's a **~2–2.5σ tension** in the preferred values of δ_{CP} and θ_{23}.
- This may be interpreted as either statistical fluctuations or systematic uncertainty.
- If the δ_{CP} or θ_{23} tensions remain even after improved systematics, it could point to: NP - light **additional neutrino states** ($\Delta m^2_{n1} \leq 10^{-2}\,\mathrm{eV}^2$)

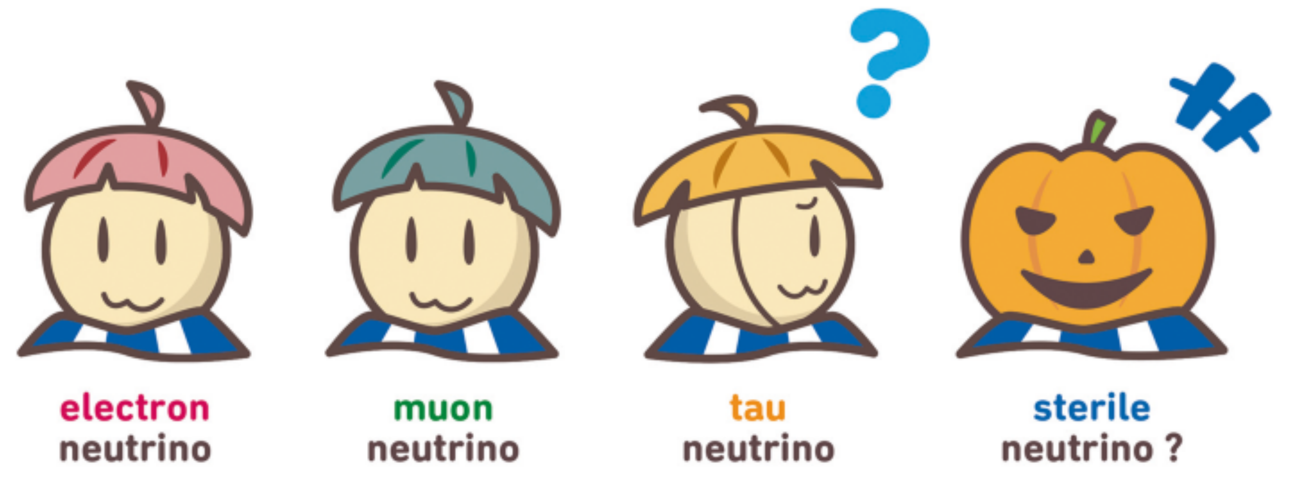
Solar upturn problem

[PhysRevD. 83,113011]

- Solar MSW-LMA predicts a **rise (upturn)** in the electron-neutrino survival probability $P_{ee}(E)$ at low energies (few MeV → sub-MeV), but current data (SNO, Super-K, Borexino) show a **weaker or absent upturn** than predicted.
- Introducing a very light **additional neutrino state** $\Delta m_{01}^2 \sim 10^{-5}$ adds an extra oscillation frequency with a long wavelength comparable to the Sun–Earth scale.
- This modifies the low-energy shape of $P_{ee}(E)$ and can suppress the expected upturn.

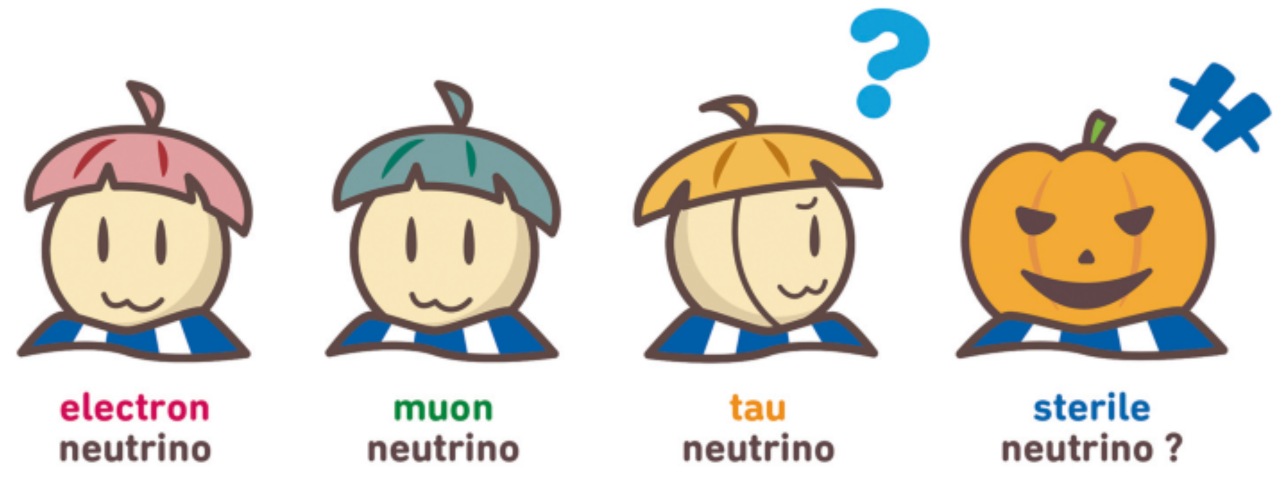


Sterile Neutrinos?



- Sterile neutrinos are hypothetical neutral fermions that **do not interact via the SM weak force** — only through **mixing with the active neutrinos (ν_e, ν_μ, ν_τ)**.
- Why: Since the invisible width of the Z boson measured at LEP constrains the number of light active neutrinos to be three, any additional light states must be “sterile,” i.e., singlets under the SM gauge interactions.
- Additionally, these sterile states must be **non-thermal**: The early Universe’s expansion rate and structure formation depend on the **number of relativistic species** during recombination, quantified by N_{eff}.
- The Standard Model predicts $N_{\text{eff}} \approx 3.046$. A fully thermalized sterile neutrino would increase N_{eff} to ≈ 4.
- Planck (CMB) + BAO data: $N_{\text{eff}} = 2.99 \pm 0.17$, disfavoring such extra species. Also, the total neutrino mass bound $\sum m_\nu < 0.12$ eV is inconsistent with an eV-scale sterile neutrino.
- This interprets: If sterile neutrinos exist, they must be **non-thermal**, **weakly coupled**, or **interacting with a dark sector**, preventing full thermalization.

Sterile Neutrinos?

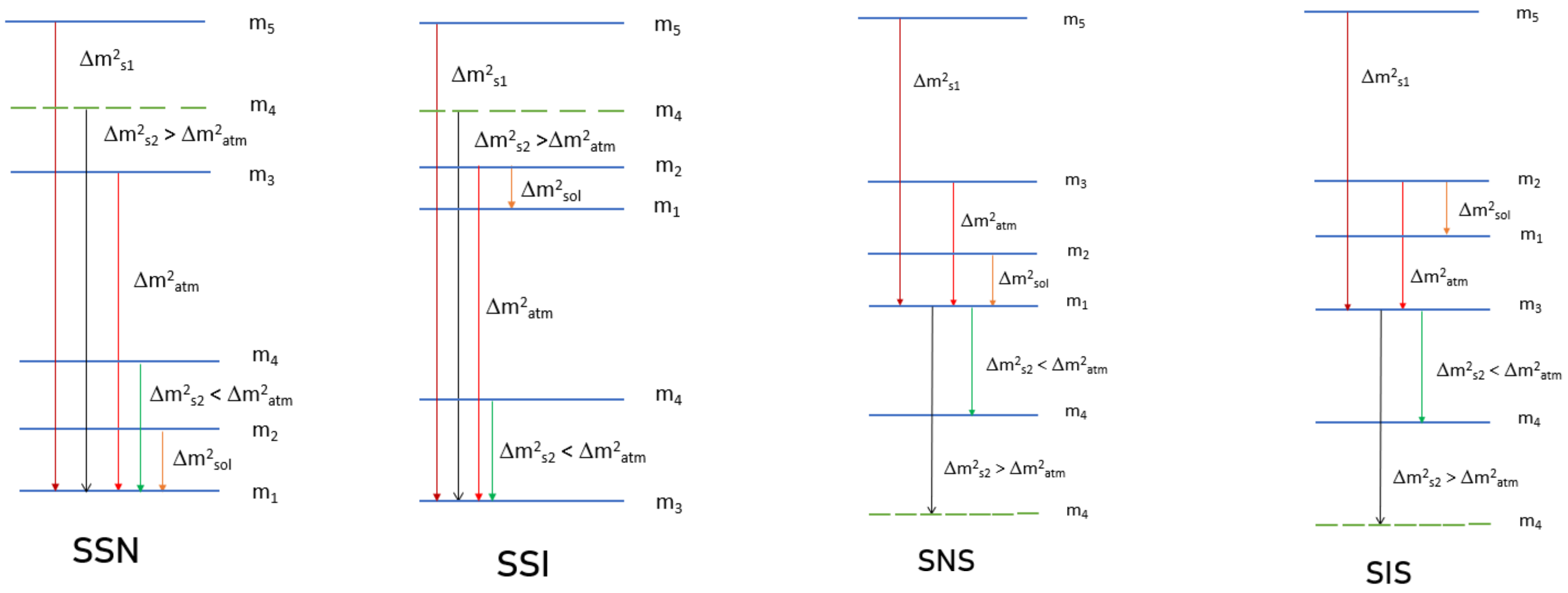


- Naturally appear in many extensions of the SM, e.g. **Type-I Seesaw models** (as right-handed neutrinos).
- Proposed to explain **neutrino anomalies** such as LSND, MiniBooNE, reactor and Gallium deficits. Also, help with tensions in long-baseline data (T2K–NOvA).
- They appear in Oscillations just by expanding the flavor states to include one (or more) sterile states:

$$\nu_\alpha = \sum_{i=1}^{3+N_s} U_{\alpha i}\,\nu_i, \quad \alpha = e, \mu, \tau, s$$

- This led to new mass-squared splittings and mixing angles.
- The extra oscillation frequency can cause **short-baseline appearance/disappearance** or **interference effects** in long-baseline experiments.
- Sterile neutrinos can exist in several mass scales: GeV-TeV (Seesaw), KeV (Warm dark matter), eV (LSND, MiniBooNE anomalies) and sub-eV (T2K–NOvA tension)

Classification of mass ordering in 3 + 2 sterile neutrino framework



Mass Constraints on 3+2 Sterile Neutrino model

Sum of neutrinos Σ

- Direct probes of the absolute neutrino mass scale arise from cosmological observations, which are sensitive to the sum of all neutrino mass eigenvalues,

$$\Sigma = \sum_i m_i.$$

- In the minimal three–neutrino framework, this quantity is determined by the lightest neutrino mass m_{lightest} together with the precisely measured mass-squared differences from oscillation experiments.

NO

$$m_1 = m_{\text{lightest}}, \quad m_2 = \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_{\text{lightest}}^2 + \Delta m_{31}^2},$$

IO

$$m_3 = m_{\text{lightest}}, \quad m_2 = \sqrt{m_{\text{lightest}}^2 + |\Delta m_{32}|^2}, \quad m_1 = \sqrt{m_{\text{lightest}}^2 + |\Delta m_{32}|^2 - \Delta m_{21}^2}.$$

- The Planck 2018 data in combination with BAO measurements impose an upper bound $\Sigma \lesssim 0.12$ eV (95% C.L.)

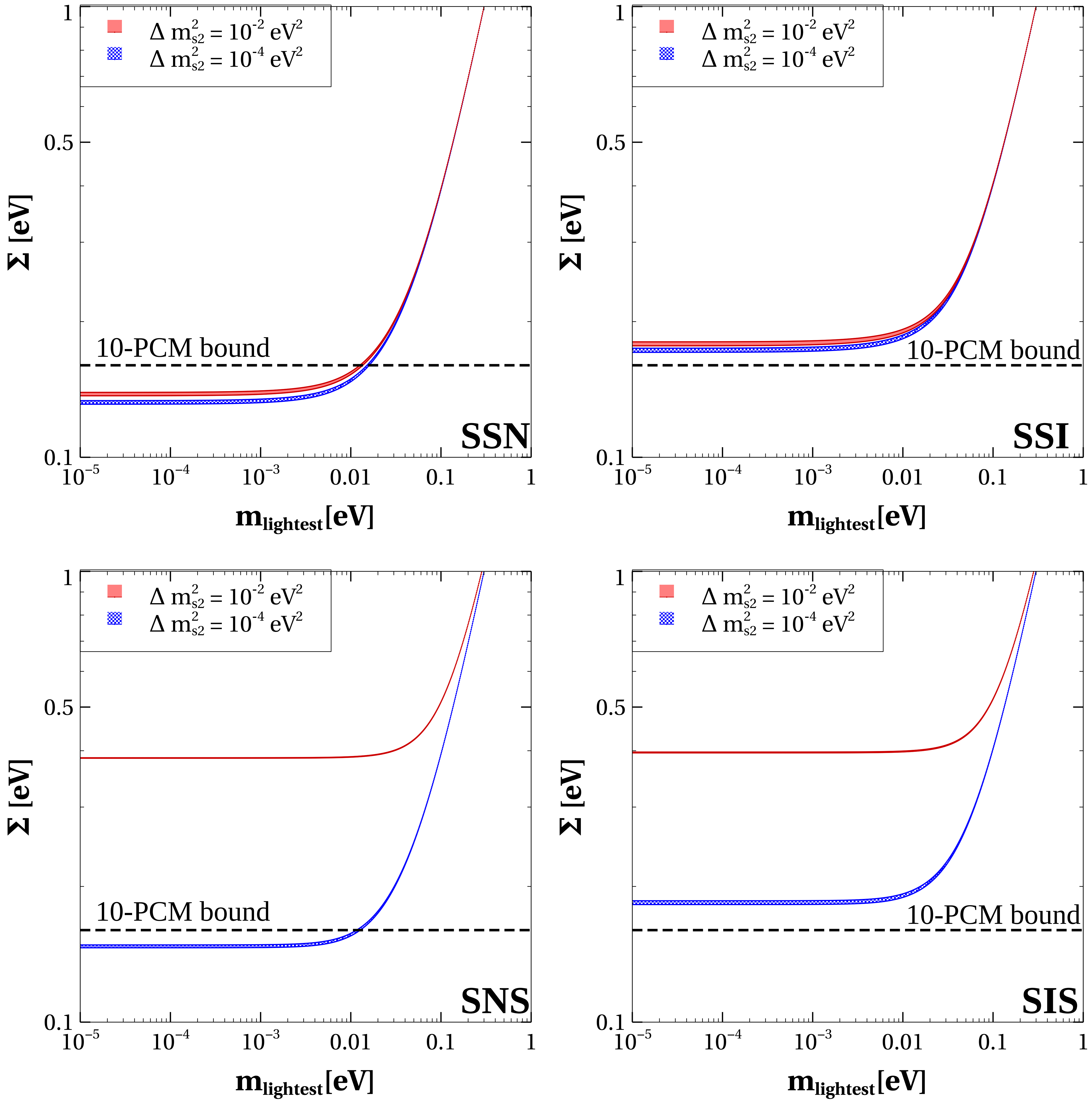
- In the 3+2 framework, we have two additional mass eigenstates m_4 and m_5 which enter the sum.

Cosmological constraint on Σ

- If the active-sterile mixing is large, sterile neutrinos become fully thermalised in the early Universe, following the same Fermi-Dirac distribution as active flavors.
- As a result, they contribute equally to the effective number of relativistic degrees of freedom, N_{eff}, and to the total mass sum, which is enhanced relative to the three-flavor case.
- The precise measurement of CMB by the Planck collaboration constrains the $N_{\text{eff}} = 2.99^{+0.34}_{-0.33} \quad (95\,\%\ CL)$ which ruled out the possibility of an extra sterile state.
- This tension can only be alleviated if the sterile neutrinos are not fully thermalized in the early Universe.
- In such cases, physical masses of the sterile neutrinos do not contribute to Σ.

$$\Sigma^{3+2} = m_1 + m_2 + m_3 + \Delta N_{\text{eff}} \ (m_4 + m_5)\,.$$

Σ vs m_{lightest} in different mass schemes



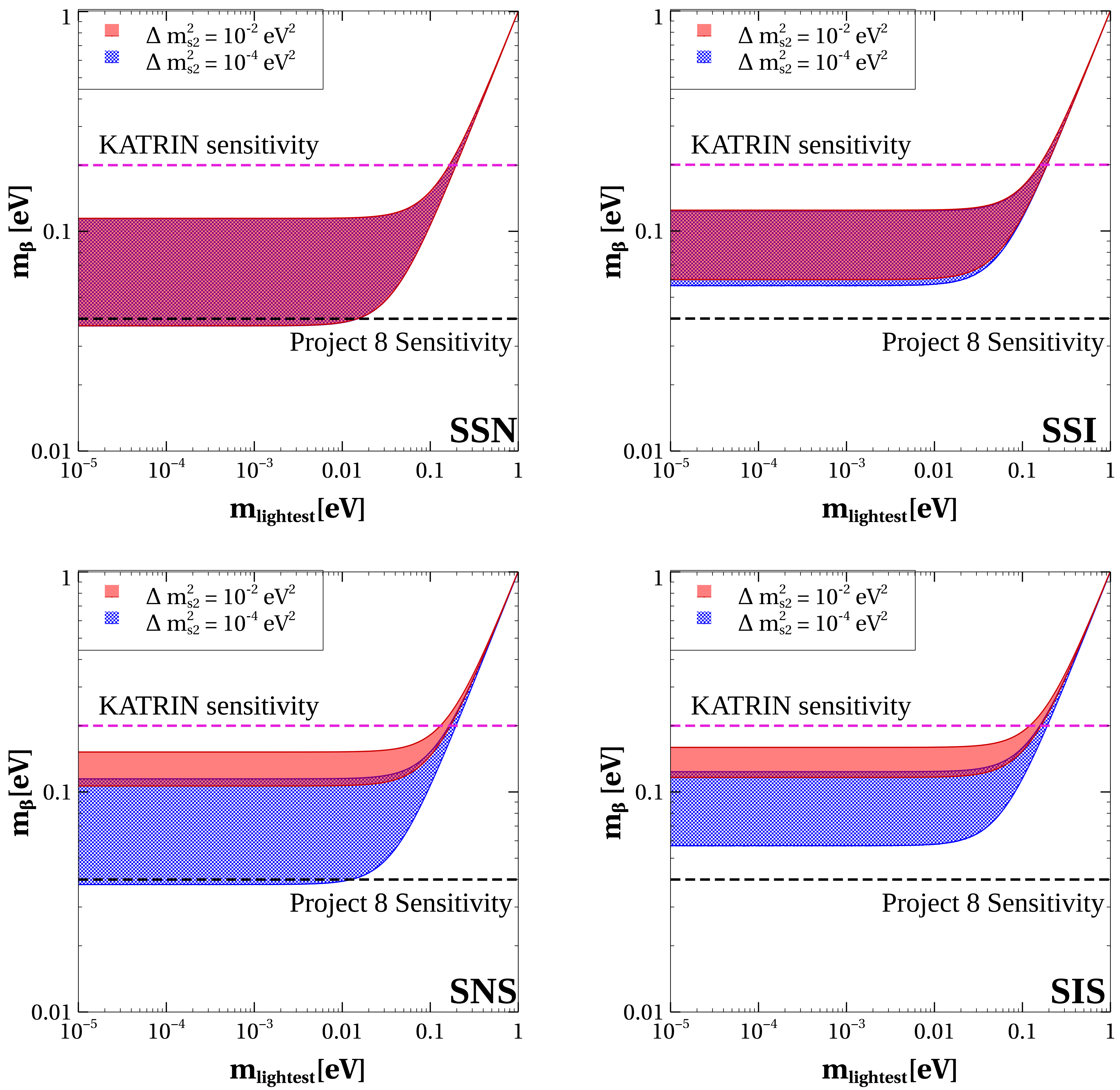
- SSN scenario is favored by 10-PCM bound up to $m_{\text{lightest}} \sim 0.015$ eV for both the mass squared differences, i.e $\Delta m^2_{s2} = 0.01$ & $10^{-4}\,\text{eV}^2$.
- SSI scenario is disfavored by the 10-PCM bound for both the mass squared differences.
- SNS scenarios is disfavored for $\Delta m^2_{s2} = 0.01\ \text{eV}^2$ however, it is allowed for $\Delta m^2_{s2} = 10^{-4}\,\text{eV}^2$ up to $m_{\text{lightest}} \sim 0.010$ eV as of 10-PCM bound is concerned.
- On the other hand, the SIS scenario is completely disfavor by the 10-PCM bound.

Mass ordering	$\Delta m^2_{s1} = 1.3\ \text{eV}^2$	
	$\Delta m^2_{s2} = 0.01\ \text{eV}^2$	$\Delta m^2_{s2} = 10^{-4}\ \text{eV}^2$
SSN	< 0.011	< 0.014
SSI	Disallowed	Disallowed
SNS	Disallowed	< 0.010
SIS	Disallowed	Disallowed

Effective Electron Neutrino Mass in Beta Decay

- The **effective electron-neutrino mass** measured in β-decay experiments is given by $m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2},$
- This quantity reflects the **incoherent sum** of neutrino mass contributions to the electron spectrum.
- In tritium β-decay: $^3\mathrm{H} \rightarrow ^3\mathrm{He}^+ + e^- + \bar{\nu}_e$ the **endpoint energy** of the emitted electron depends on the neutrino mass.
- If neutrinos are massive, the **electron energy spectrum near the endpoint** is slightly distorted — the maximum kinetic energy of the electron is reduced by m_β.
- Thus, by precisely measuring this endpoint shape, one can put **a bound on the neutrino mass**, independent of any assumptions about whether neutrinos are Majorana or Dirac.
- KATRIN (2024) put the most stringent direct bound on the effective neutrino mass to date $m_\beta < 0.8$ eV (90% CL). Project 8 (atomic tritium): aims for $m_\beta \sim 40$ meV.
- When a sterile neutrino mixes with ν_e, the β-spectrum gains an **additional component**: it leaves a measurable imprint on the β-spectrum.

m_β vs m_{lightest} in different mass schemes

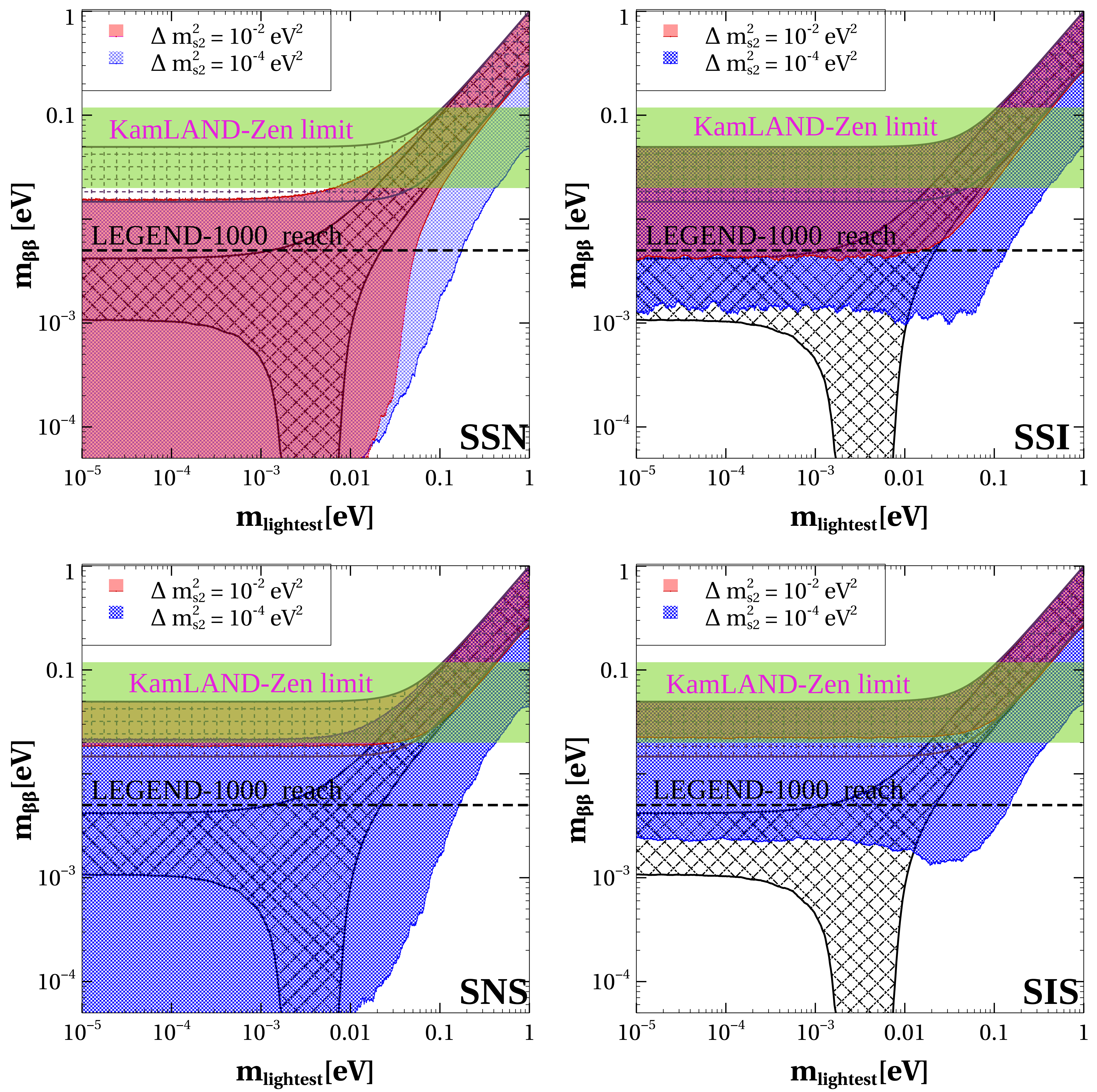


- There is an overlap of both contributions $\Delta m^2_{s2} = 0.01 \,\&\, 10^{-4}\,\mathrm{eV}^2$ in SSN and SSI. This is not the case with SNS and SIS.
- Although the current and projected KATRIN sensitivity ($m_\beta < 0.2$ eV) allows all the mass-ordering schemes considered, they are disfavored once the more stringent Project 8 sensitivity is taken into account.
- In the case of normal ordering, the SSN scenario is consistent with KATRIN up to $m_{\text{lightest}} \sim 0.015$ eV, while the SNS scheme is allowed up to $m_{\text{lightest}} \sim 0.01$ eV.
- $\Delta m^2_{s2} = 10^{-4}\,\mathrm{eV}^2$ contribution can meet Project 8 sensitivity in SNS upon considering the 3σ uncertainties.
- However, the 10-PCM bound on the lightest neutrino mass strongly excludes both inverted ordering schemes (SSI and SIS).

Effective Majorana Mass in Neutrinoless Double Beta Decay

- The effective Majorana mass, $$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 \, m_i \, e^{i\alpha_i} \right|,$$
- Probed in **neutrinoless double-β decay (0νββ)** — sensitive only if neutrinos are **Majorana**.
- Sensitive to phases and cancellations among mass terms: Because $m_{\beta\beta}$ involves coherent summation, the Majorana phases can lead to constructive or destructive interference
- Current limits (KamLAND-Zen, GERDA, CUORE): $$m_{\beta\beta} \lesssim (0.028 - 0.122)\,\mathrm{eV}.$$
- 3+2 sterile neutrinos **can significantly alter** both the magnitude and the interpretation of the 0νββ bounds.
- Next-generation detectors: **nEXO**, **LEGEND-1000**, **CUPID**, **KamLAND-Zen 800**, **NEXT** with target sensitivity $m_{\beta\beta} \sim 10\ \mathrm{meV}.$

$m_{\beta\beta}$ vs m_{lightest} in different mass schemes



SSN

Region	$m_{\beta\beta}^{\text{NO}}$ (eV)	$\lvert t_{14}^2 m_4\rvert$ (eV) ($\Delta m^2_{s2} = 10^{-4}$)	$\lvert t_{14}^2 m_4\rvert$ (eV) ($\Delta m^2_{s2} = 10^{-2}$)	$\lvert t_{15}^2 m_5\rvert$ (eV) ($\Delta m^2_{s1} = 1.3$)
$m_1 \approx 0$	0.001 – 0.004	1.0×10^{-3} – 2.0×10^{-3}	5.0×10^{-6} – 5.0×10^{-5}	1.14×10^{-3} – 1.14×10^{-2}
$m_1 \approx \sqrt{\Delta m^2_{\text{sol}}}$	0.0018 – 0.018	1.319×10^{-3} – 2.638×10^{-3}	5.0×10^{-6} – 5.0×10^{-5}	1.14×10^{-3} – 1.14×10^{-2}
$m_1 \approx 0.1$ eV	0.02 – 0.10	1.005×10^{-2} – 2.010×10^{-2}	7.07×10^{-6} – 7.07×10^{-5}	1.145×10^{-3} – 1.145×10^{-2}

SSI

Region	$m_{\beta\beta}^{\text{IO}}$ (eV)	$\lvert t_{14}^2 m_4\rvert$ (eV) ($\Delta m^2_{s2} = 10^{-4}$)	$\lvert t_{14}^2 m_4\rvert$ (eV) ($\Delta m^2_{s2} = 10^{-2}$)	$\lvert t_{15}^2 m_5\rvert$ (eV) ($\Delta m^2_{s1} = 1.3$)
$m_3 \approx 0$	0.015 – 0.050	1.00×10^{-3} – 2.00×10^{-3}	5.00×10^{-6} – 5.00×10^{-5}	1.140×10^{-3} – 1.140×10^{-2}
$m_3 \approx \sqrt{\Delta m^2_{\text{sol}}}$	0.0018 – 0.018	1.319×10^{-3} – 2.638×10^{-3}	5.02×10^{-6} – 5.02×10^{-5}	1.140×10^{-3} – 1.140×10^{-2}
$m_3 \approx 0.1$ eV	0.02 – 0.10	1.005×10^{-2} – 2.010×10^{-2}	7.07×10^{-6} – 7.07×10^{-5}	1.145×10^{-3} – 1.145×10^{-2}

SNS & SIS

Region	$m_{\beta\beta}$ (eV)		$\lvert t_{14}^2 m_4\rvert$ (eV) ($\Delta m^2_{s2} = 10^{-4}$)	$\lvert t_{14}^2 m_4\rvert$ (eV) ($\Delta m^2_{s2} = 10^{-2}$)	$\lvert t_{15}^2 m_5\rvert$ (eV) ($\Delta m^2_{s1} = 1.3$)
	NO	IO			
$m_4 \approx 0$	0.001 – 0.004	0.015 – 0.050	0	0	1.14×10^{-3} – 1.14×10^{-2}
$m_4 \approx 0.01$ eV	0.017 – 0.055	0.0018 – 0.018	1.00×10^{-3} – 2.00×10^{-3}	5.00×10^{-7} – 5.00×10^{-6}	1.140×10^{-3} – 1.140×10^{-2}
$m_4 \approx 0.1$ eV	0.05 – 0.15	0.02 – 0.10	1.00×10^{-2} – 2.00×10^{-2}	5.00×10^{-6} – 5.00×10^{-5}	1.145×10^{-3} – 1.145×10^{-2}

Summary

- Although the three-flavor oscillation paradigm successfully explains several experimental data, anomalies persist which cannot be accommodated within this framework.
- LSND, MiniBooNE, etc, short-baseline-expt. suggest the need for eV-scale sterile neutrinos.
- T2K and NOvA (long-baseline-expt.) suggest the need for sub-eV scale sterile neutrinos.
- By combining oscillation data, constraints from neutrinoless double beta decay, cosmological considerations and tritium β decay, we aim to delineate the viable parameter space for the 3+2 model.
- 10-PCM bound allows SSN and SNS. KATRIN bound on m_β allows all 4 mass schemes, SSN and SNS show better for the future Project-8 sensitivity on m_β.
- For $m_{\beta\beta}$, eV-scale sterile is dominating, sub-eV sterile for 10^{-4} term becomes comparable to the active contribution, sub-eV sterile for 10^{-2} is subleading. Cancellation is possible depending on the phase.

Thank you for your patience..!