European Strategy
for Particle Physics

Open questions in (neutrino) physics

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23-27 **JUNE** 2025 **Lido di Venezia**

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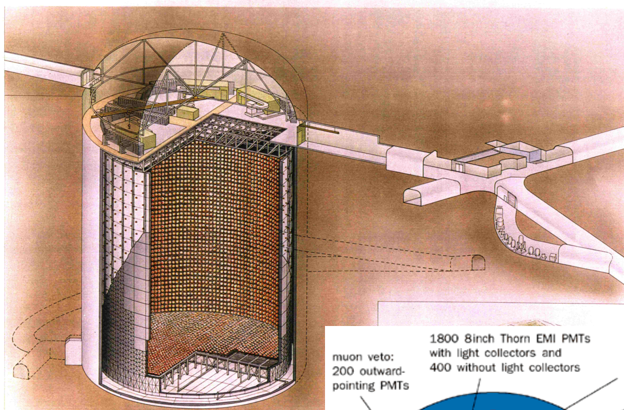
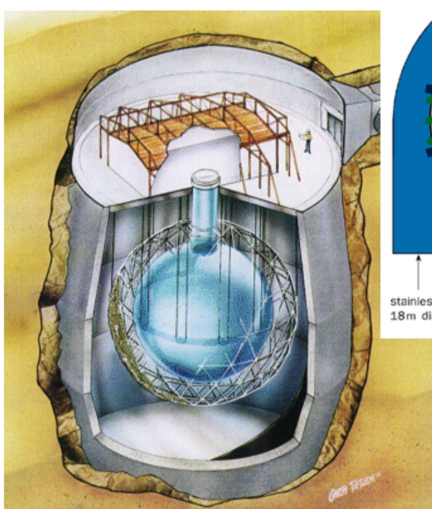
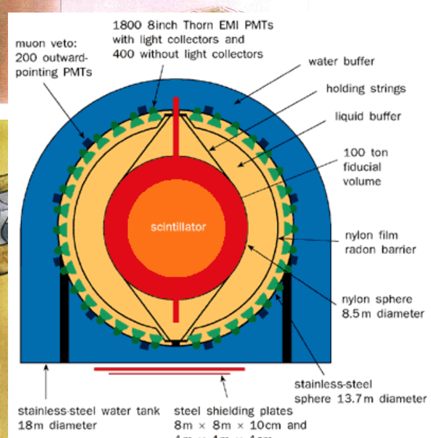
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN
GENERALITAT VALENCIANA Conselleria d'Innovació, Universitats, Ciència i Societat Digital
AsYmmetry Essential Asymmetries of Nature

>20 years of neutrino experiments have revealed neutrino masses and a complex lepton flavour sector

SuperKamiokande



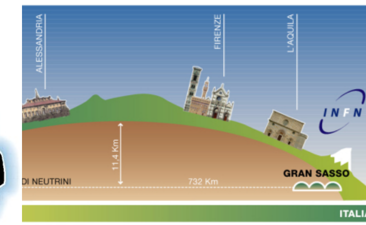




SNO

Borexino

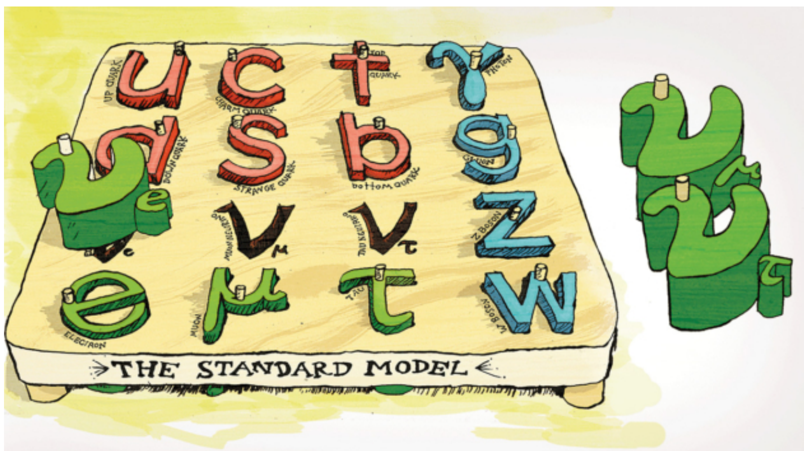
MINOS, Opera

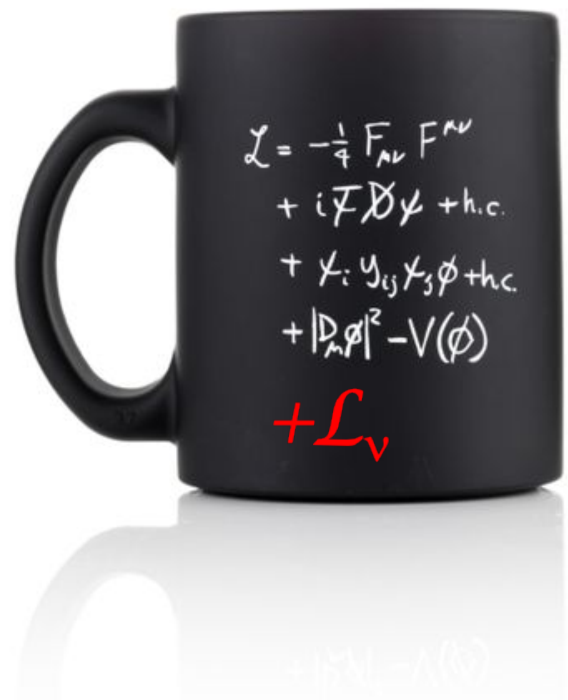


...and many more

Open Questions in Physics

Neutrino physics = νSM in the making





$\mathcal{L}_\nu$ = new Higgs-Lepton couplings+…

Open Questions in Physics

- Missing pieces in the SM puzzle: neutrino masses and mixings

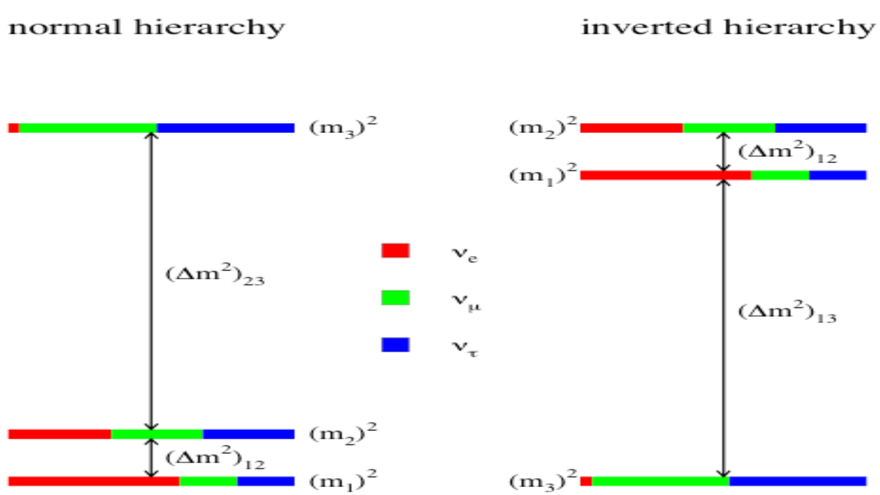
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{12} \sim 34^\circ$

$\theta_{23} \sim 42^\circ$ o 48°

$\theta_{13} \sim 8.5^\circ$

$\delta \sim\ ?$



NO/NH

IO/IH

$7.5 \cdot 10^{-5}\mathrm{eV}^2$

$2.5 \cdot 10^{-3}\mathrm{eV}^2$

Open Questions in Physics

- Missing pieces in the SM puzzle: the input from many experiments in global fits is giving few % precision in most parameters except CP

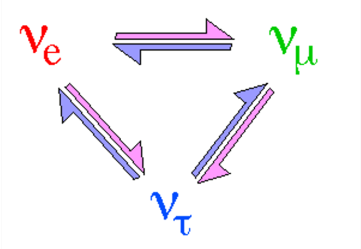
NuFit 6.0, JHEP 12 (2024) 216

IC24 with SK atmospheric data

	Normal Ordering (best fit)		
	bfp $\pm 1\sigma$		3σ range
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	3.7%	$75 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	2.1%	$63 \to 35.95$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	5.0%	$35 \to 0.585$
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	3.1%	$.3 \to 49.9$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	2.3%	$30 \to 0.02388$
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	1.3%	$19 \to 8.89$
$\delta_{CP}/^\circ$	212^{+26}_{-41}	16.4%	$24 \to 364$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	2.5%	$92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	0.8%	$51 \to +2.578$

See also F. Capozzi et al., Phys. Rev. D 104, 8, 083031

5 P. F. de Salas et al., JHEP 02, 071 (2021) 16/06/2025



Major open questions for oscillation experiments:

- neutrino ordering
- CP violation
- ≤% precision in all parameters

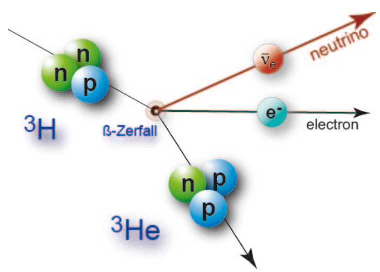
-> M. Scott parallel talk

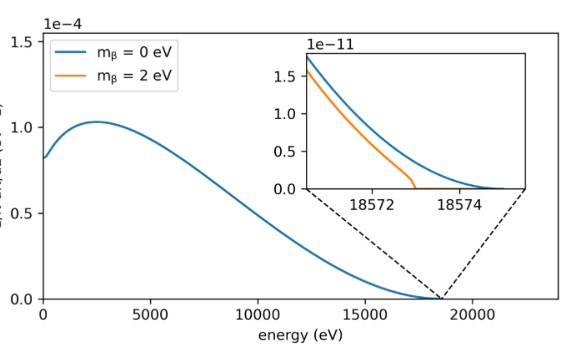
Open Questions in Physics

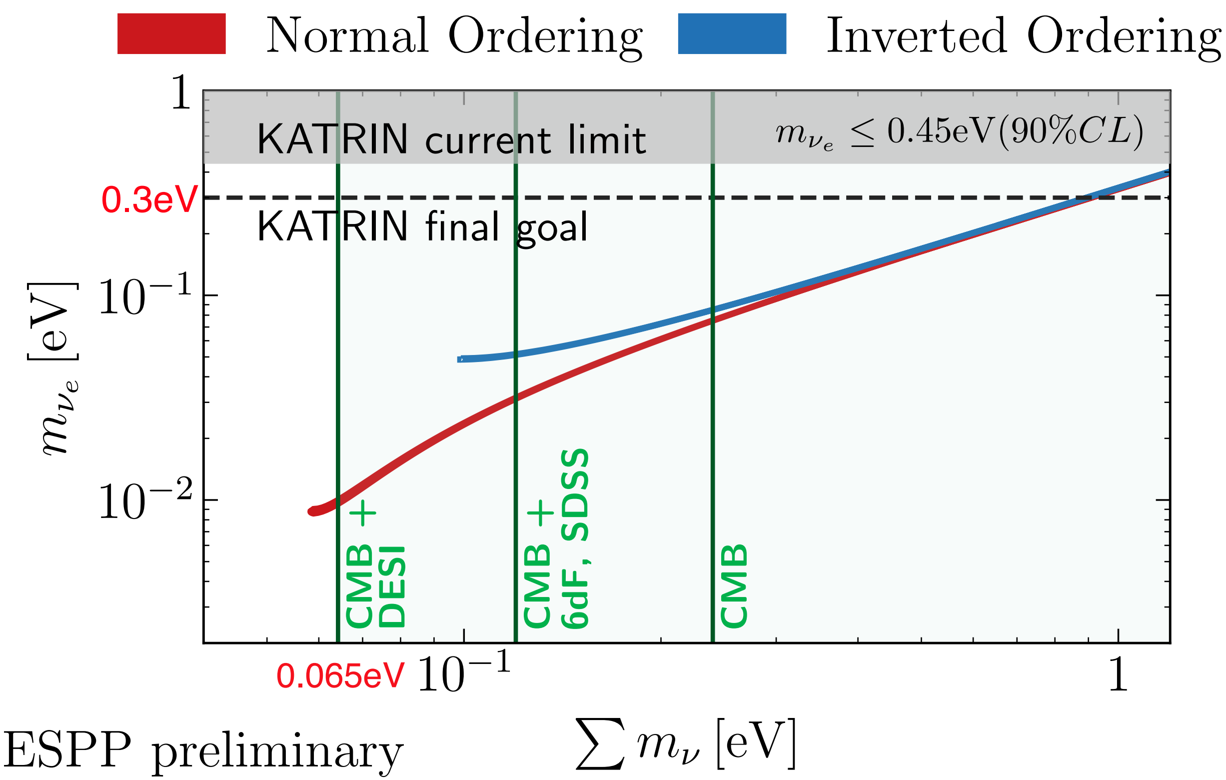
- Missing pieces in the SM puzzle: neutrino mass scale

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

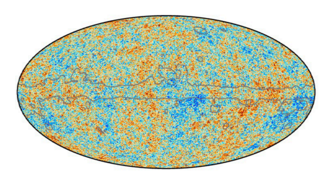
β-decay/e-capture



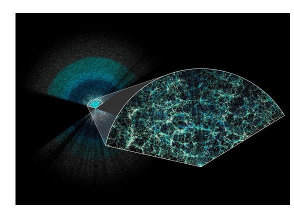




ESPP preliminary



CMB



LSS

-> J. Formaggio parallel talk

Open Questions in Physics

- Understand (subtly) broken symmetries of the SM: flavour, CP, B/L

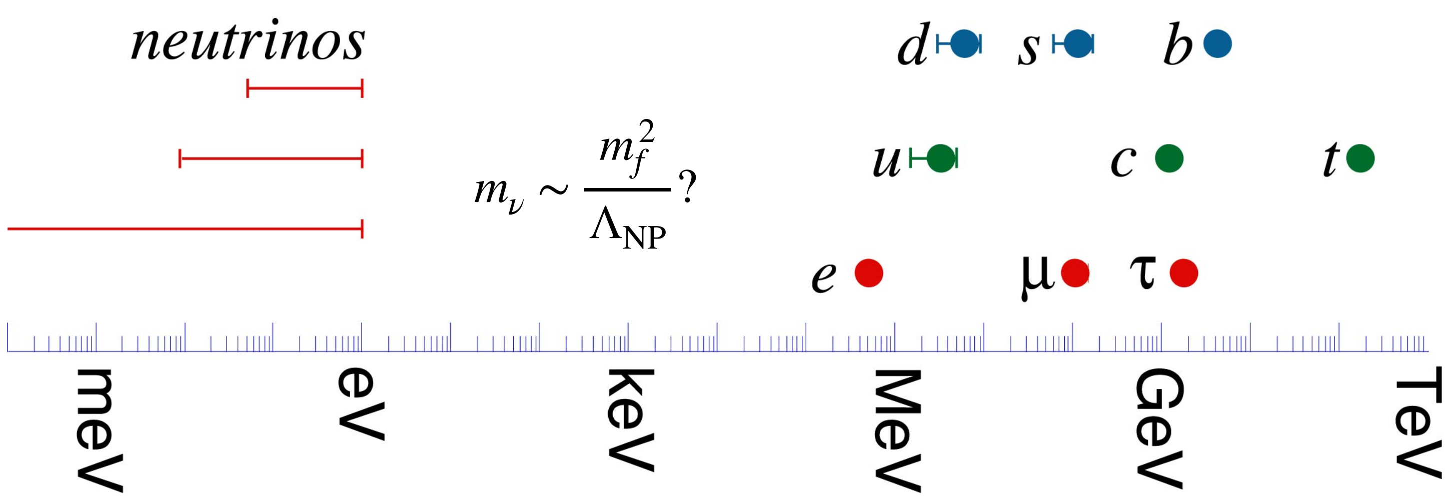
Neutrinos have brought a new perspective to the flavour puzzle

CKM

$$V_{CKM} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PMNS

$$|V_{PMNS}| \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$



$$m_\nu \sim \frac{m_f^2}{\Lambda_{NP}}?$$

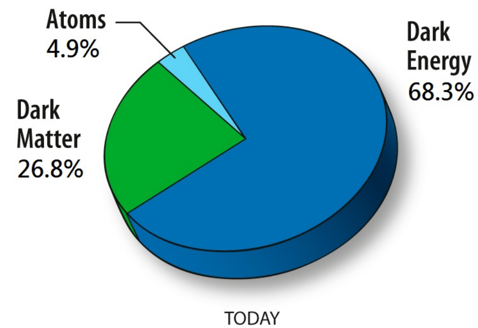
Open Questions in Physics

- The quantum world we don’t understand: gravity and the coexistence of different energy scales

$$M_{\text{Higgs}},\, \Lambda_{\text{NP}}?,\, M_{\text{Planck}}$$

- A Universe we don’t understand:

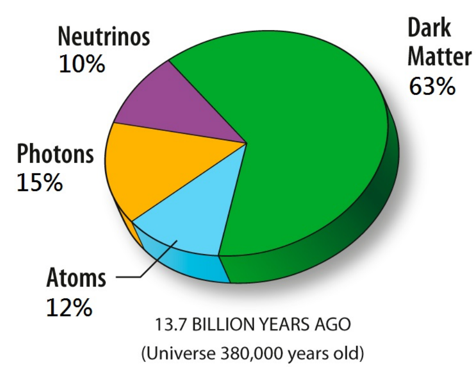
Baryons, Dark Matter, Dark Energy



Baryons <-> matter-antimatter asymmetry

new sources of CP violation+ new non-equilibrium dynamics in the Early Universe (eg. more weakly interacting particles,…) generic in

$$\mathcal{L}_\nu$$

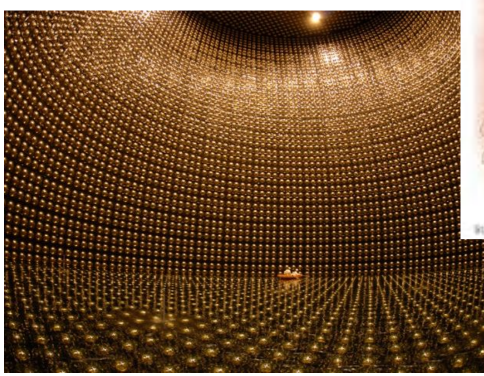


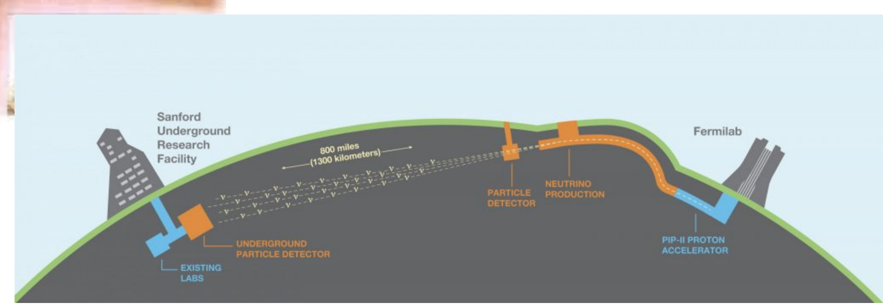
Why are neutrino experiments important in this quest ?

Neutrinos are the most elusives of the SM particles !

Huge detectors + Low Background + Intense Beam Dumps

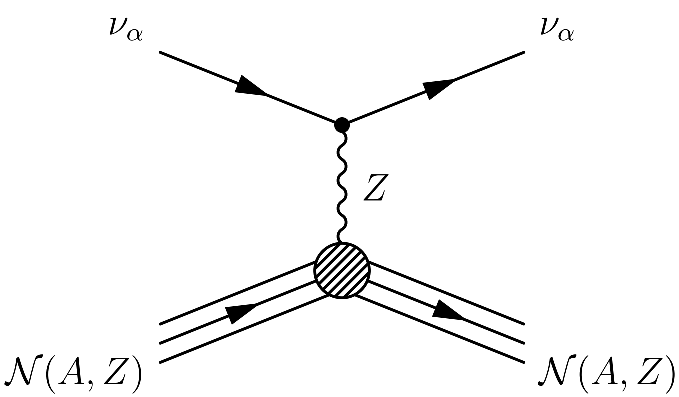
➢ Neutrino experiments = Rare Event Factories !



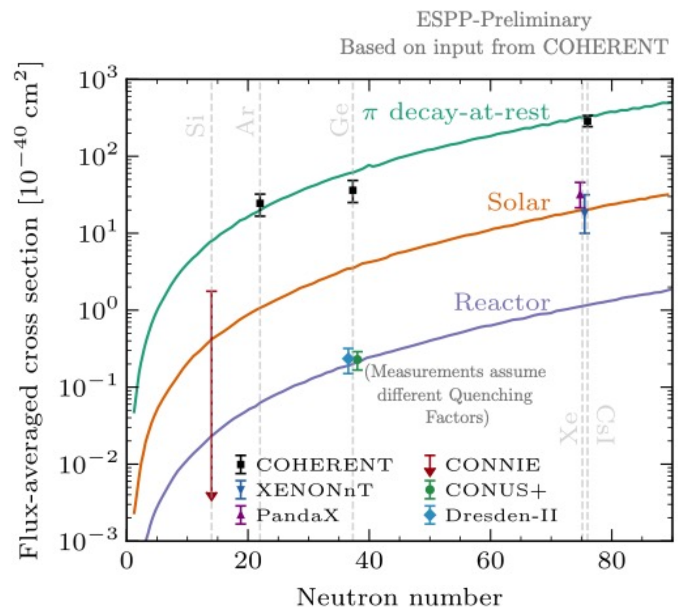


New explorations in neutrino physics

Coherent Neutrino Scattering Eν< 50MeV (nuclear recoils < keV)

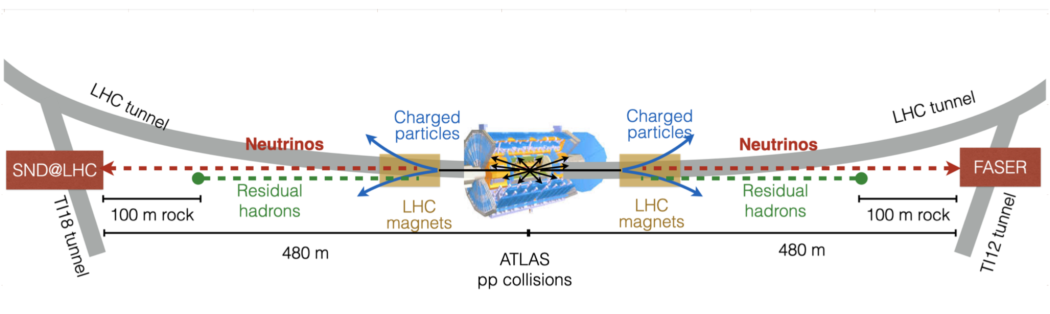


D. Freedman '74



-> I. Esteban parallel talk

O(100 evts) TeV-neutrinos from the LHC detected by FASER & SND



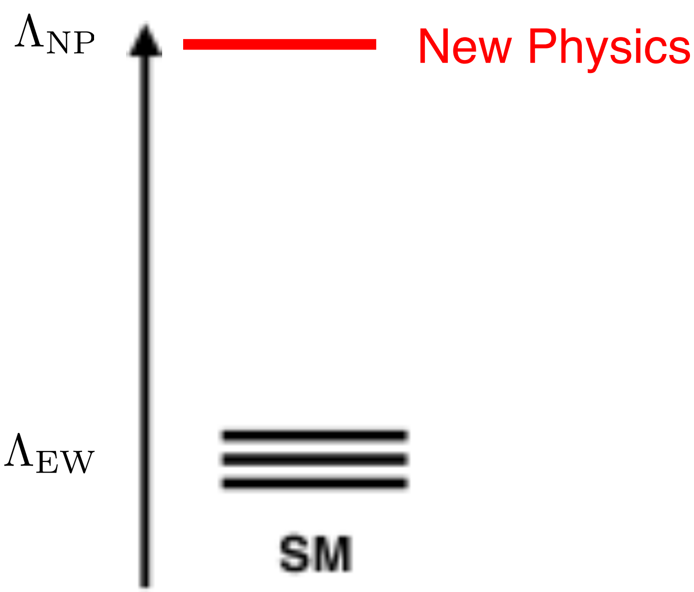
-> I. Esteban & J. Kopp parallel talks

Complementary to Icecube/KM3NET

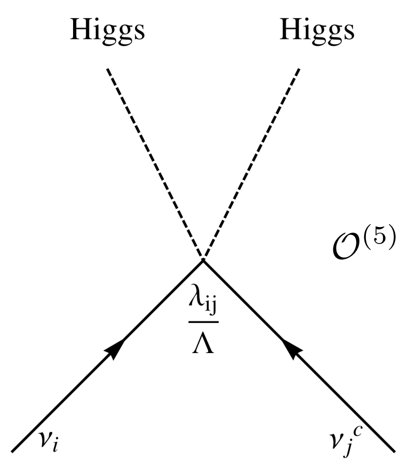
- σ_ν@TeV
- Neutrino flux: forward charm production, gluon PDF
- LFU

Neutrino Exploration of New Physics

$\Lambda_{\text{NP}} \gg E$



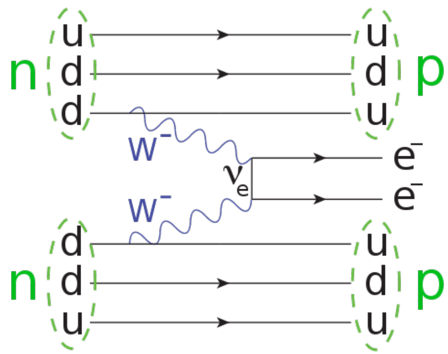
$$\mathcal{L}_{\text{SMEFT}} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)}}_{\text{1 operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}}_{\text{2499 operators(59 B,L,FC)}} + \ldots$$



$$\mathcal{O}^{(5)} = \frac{c_{ij}^{(5)}}{\Lambda} \bar{L}_i H (H L_j)^c + h.c. \rightarrow \bar{\nu}_L \frac{m_\nu}{2} \nu_L^c + h.c.$$

$\beta\beta0\nu$

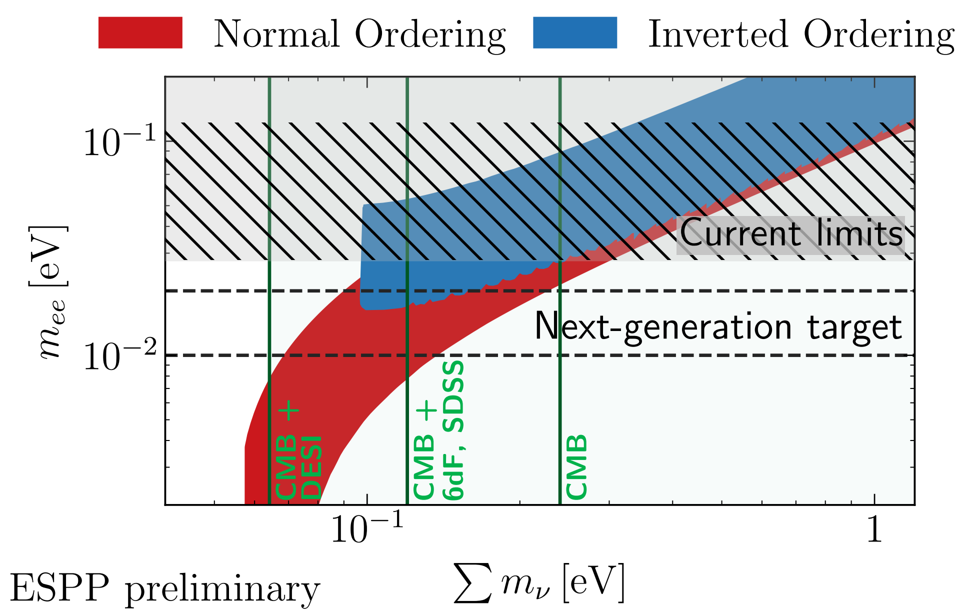
Neutrinoless Double Beta Decay: Λ_{NP}



$$T^{-1}_{2\beta 0\nu} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{NuclearM.E.}} \underbrace{\left|\sum_i \left(V^{ei}_{MNS}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

VALUE (eV)	ISOTOPE	METHOD	DOCUMENT ID	
following data for averages, fits, limits, etc. • • •				
0.028-0.122 eV	^{136}Xe	KamLAND-Zen	[1] ABE	23
< 0.113–0.269	^{76}Ge	MAJORANA	[2] ARNQUIST	23
< 0.48–3.19	^{136}Xe	NEXT	[3] NOVELLA	23
< 0.09–0.305	^{130}Te	CUORE	[4] ADAMS	22A
< 0.8–2.5	^{136}Xe	XENON1T	[5] APRILE	22A
< 0.28–0.49	^{100}Mo	CUPID-Mo	[6] AUGIER	22
< 0.263–0.545	^{82}Se	CUPID-0	[7] AZZOLINI	22
< 0.31–0.54	^{100}Mo	CUPID-Mo	[8] ARMENGAUD	21
< 0.075–0.35	^{130}Te	CUORE	[9] ADAMS	20A
< 0.079–0.180	^{76}Ge	GERDA	[10] AGOSTINI	20B
< 1.2–2.1	^{100}Mo	AMoRE	[11] ALENKOV	19
< 0.093–0.286	^{136}Xe	EXO-200	[12] ANTON	19

PDG24



-> J. Formaggio parallel talk

Additional contributions m_{ee} to are possible from new physics and $\beta\beta 0\nu$ sets competitive bounds !

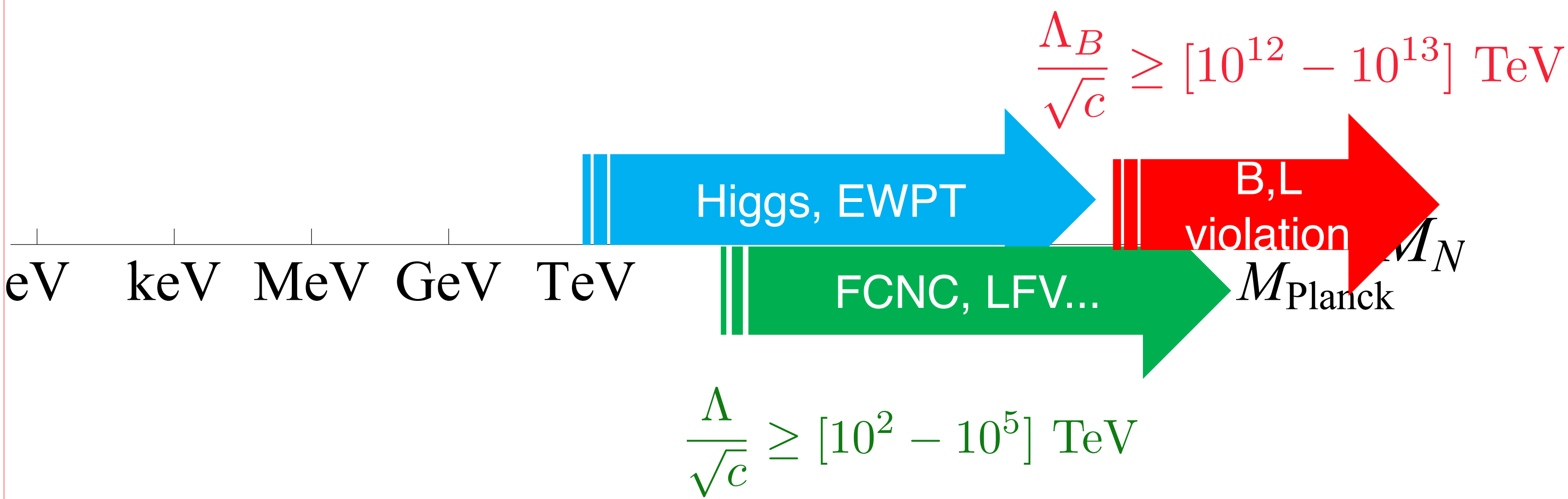
Neutrino Exploration of New Physics

$$\mathcal{L}_{\rm SMEFT} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)}}_{\text{1 operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}}_{\text{2499 operators(59 B,L,FC)}} + \ldots$$

$$\mathcal{L}_{\rm SMEFT} \supset \underbrace{\frac{c^q_{ij}}{\Lambda^2}(\bar{Q}_i\gamma_\mu P_L Q_j)^2}_{\Delta m_K,\Delta m_D,\Delta m_B,\ldots} + \ldots + \underbrace{\frac{c^l_{ij}}{\Lambda^2}\bar{L}_i\sigma_{\mu\nu}\Phi l_j F^{\mu\nu}}_{\mu\to e\gamma,\text{EDMs}\ldots} + \ldots + \underbrace{\frac{c^b_{ijkl}}{\Lambda^2_B}\epsilon_{\alpha\beta\gamma}Q_i^\alpha Q_j^\beta Q_k^\gamma L_l}_{\text{p}-\text{decay}}$$

$$+ \underbrace{\frac{c^\nu_{ijkl}}{\Lambda^2}\bar{L}_i\tilde{H} i\,\partial\!\!\!/(\tilde{H}^\dagger L_j)}_{\text{PMNS Non}-\text{unitarity}} + \ldots + \underbrace{\frac{\tilde{c}^\nu_{ij}}{\Lambda^2}\bar{L}_i\gamma^\mu L_j\bar{Q}_k\gamma_\mu Q_l}_{\text{Non}-\text{standard }\nu\text{ Interactions}} + \ldots$$

Neutrino Exploration of New Physics



Neutrino experiments have provided the most stringent limits to SMEFT via B violating searches: p-decay, n-nbar oscillations,

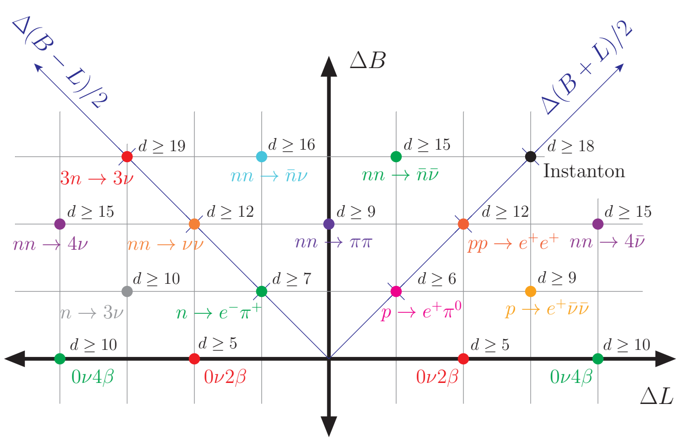


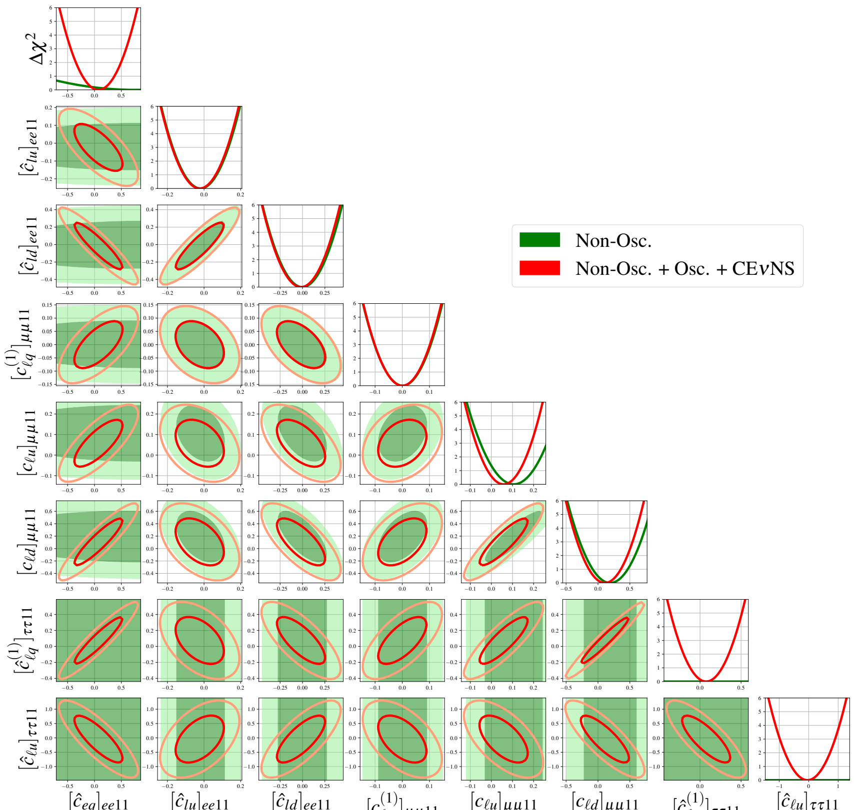
Table 4: Selected baryon number violating searches by Super-Kamiokande.

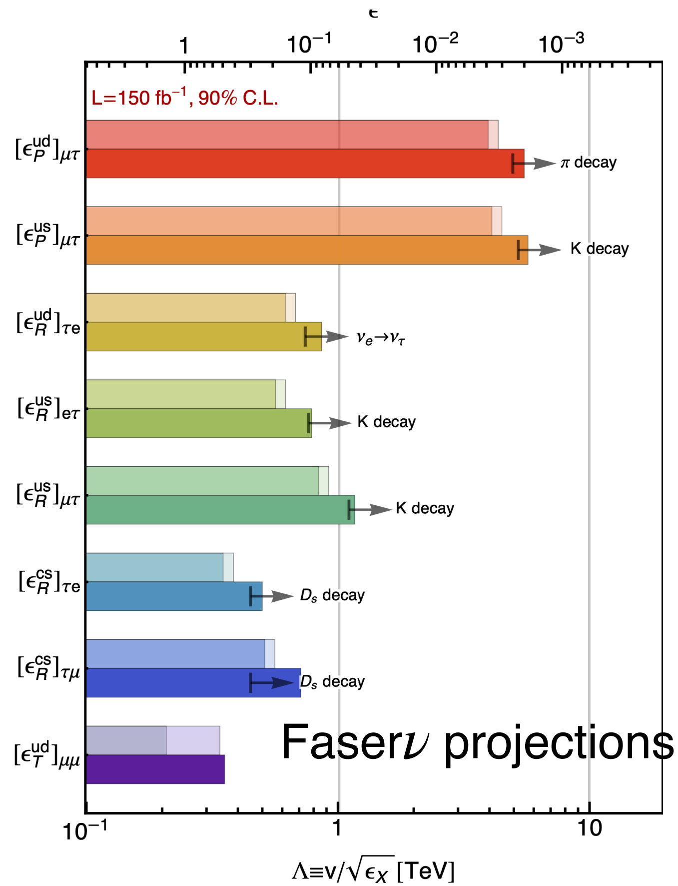
Channel	Comment	Exposure	Limit	Reference
$p \to e^+\pi^0$	$d = 6$ operators, e.g. SU(5)	450 kt·y	2.4×10^{34} y	[55]
$p \to \mu^+\pi^0$	flipped SU(5)	450 kt·y	1.6×10^{34} y	[55]
$p \to \nu K^+$	$d = 5$ SUSY operators	260 kt·y	5.9×10^{33} y	[472]
$p \to \mu^+ K^0$	SUSY SO(10)	173 kt·y	1.6×10^{33} y	[474]
$pp \to K^+K^+$	RPV SUSY	92 kt·y	1.7×10^{32} y	[372]
$p \to e^+e^+e^-$	lepton flavor symmetries	370 kt·y	3.4×10^{34} y	[475]
$n \to \bar{n}$	$\Delta B = 2$	370 kt·y	3.6×10^{32} y	[328]
$np \to \tau^+\nu$	extended Higgs sector	273 kt·y	2.9×10^{31} y	[476]
$n \to \nu\gamma$	radiative	273 kt·y	5.5×10^{32} y	[476]
$p \to e^+\nu\nu$	Pati-Salam	273 kt·y	1.7×10^{32} y	[294]

Dev et al, arXiv:2203.08771

SMEFT: non-standard neutrino interactions

The most general d=6 SMEFT is very complex and constraining it from data under no flavour assumptions a daunting task: neutrino constraints are important !





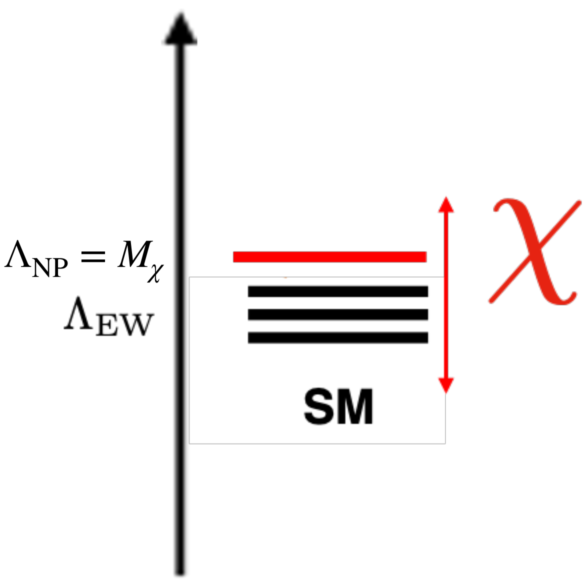
Coloma et al arXiv: 2411.00090
Bresó-Pla et al arXiv: 2301.07036

Falkowski et al arXiv:2105.12136

-> J. Kopp parallel talk

Neutrino Exploration of New Physics

$$g_{\text{NP}-\text{SM}} \ll 1$$



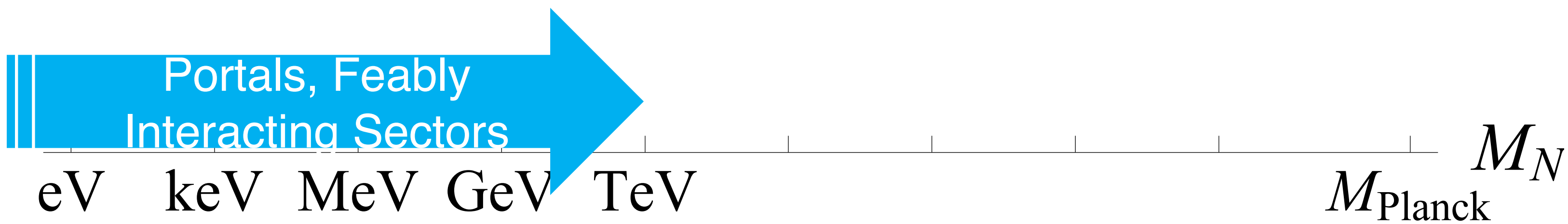
- Feably-interacting particles, long-lived,...

- Model-dependent predictions-> simplified models as benchmarks: Portals

Neutrino Portal

$$\mathcal{L}_{\text{Portals}} \supset \bar{L}\tilde{H}\chi$$

Neutrino Exploration of New Physics



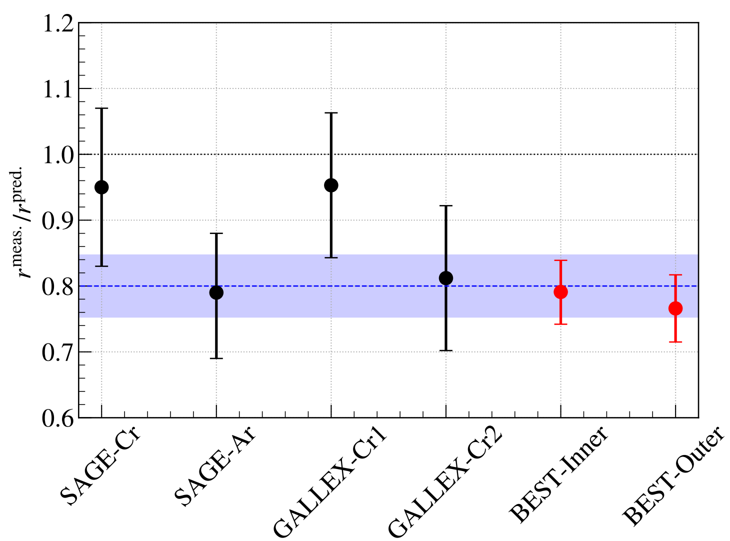
Neutrino Portal = Low-scale Type I Seesaw Model

- Predicts neutrino masses
- Predicts heavy neutrinos at scale (M_N): light sterile neutrinos (participate in oscillations) or Heavy Neutral Leptons (don't), rich phenomenology
- Generation of a matter/antimatter asymmetry, implications in cosmology, stellar evolution, etc

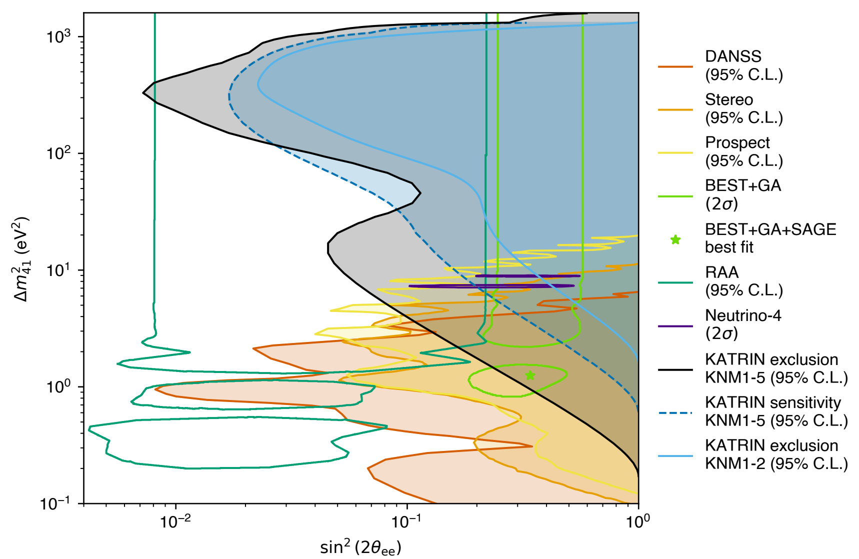
Light Sterile Neutrinos

Standard explanation to neutrino anomalies: LSND/MiniBoone, Reactor, Gallium,...

- MiniBoone/MicroBoone: tensions arising in data (more by SBN@FNAL)
- Reactor anomaly dissolving in flux systematics
- L/E dependence not observed by 5/6 experiments (NEOS, STEREO, PROSPECT, DANSS, SOLID, Neutrino4)
- Gallium anomaly still there but light sterile neutrino explanation excluded by KATRIN !



Barinov et al, 2201.07364

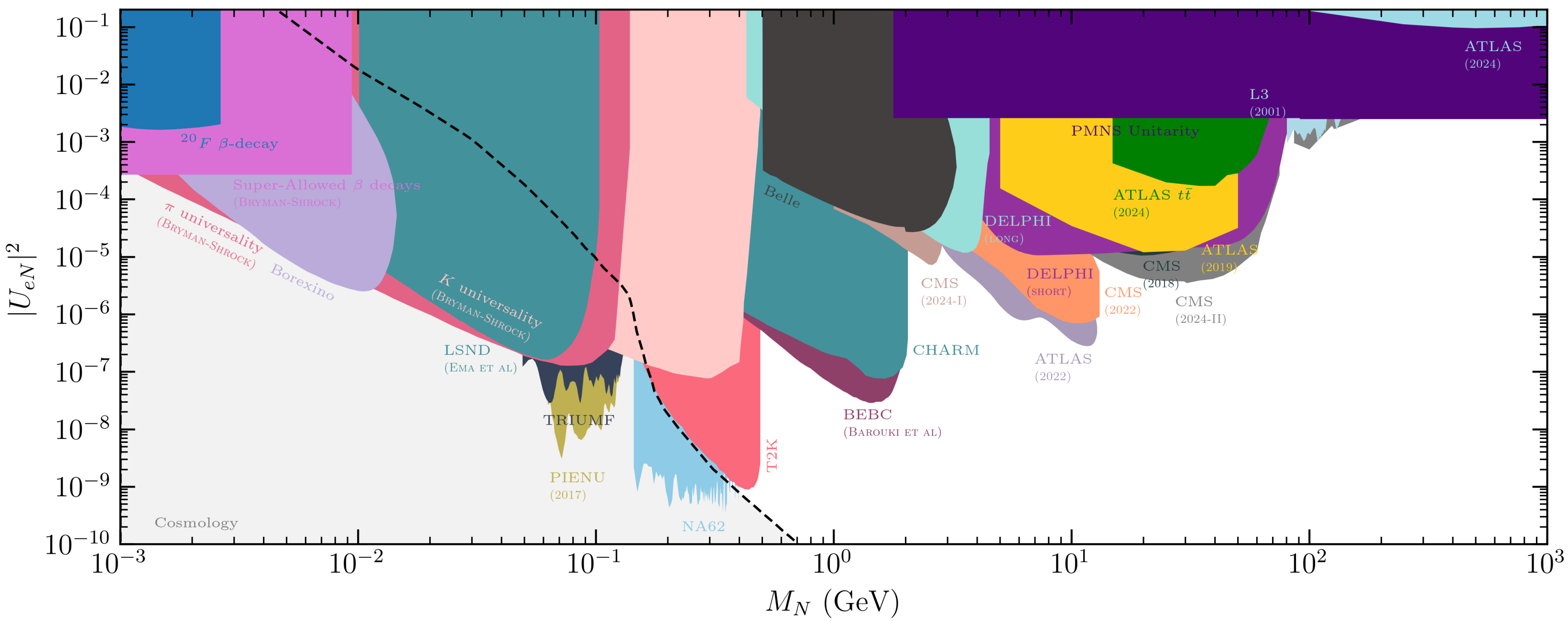


Acharya et al, 2503.18667

Heavy Neutral Leptons

Significant progress in recent years on these searches

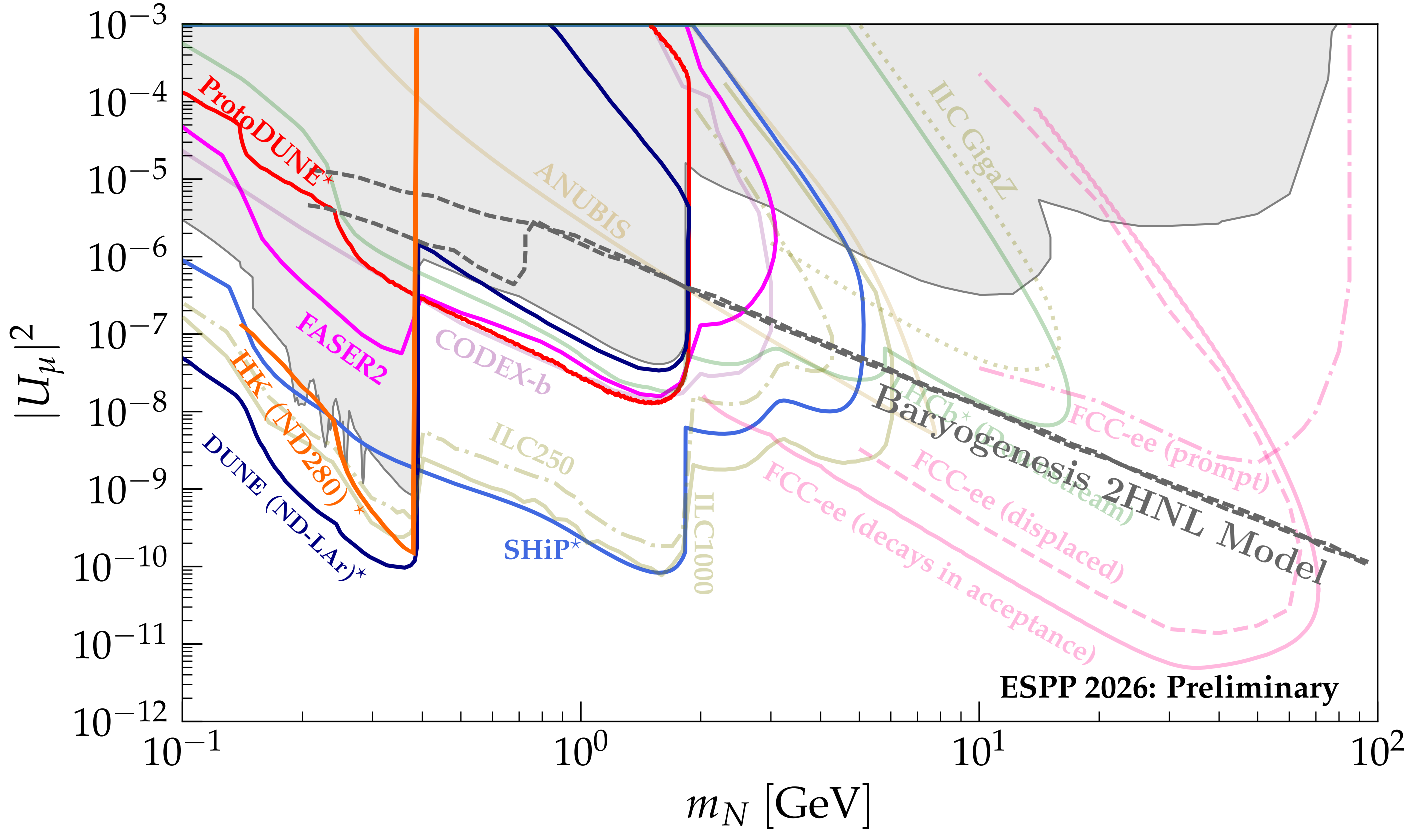
β-decay reactors ββ0ν Meson decays e+e-@Z peak Colliders EWPT/LFV



courtesy J. Hernandez-Garcia , arXiv: 2304.06772

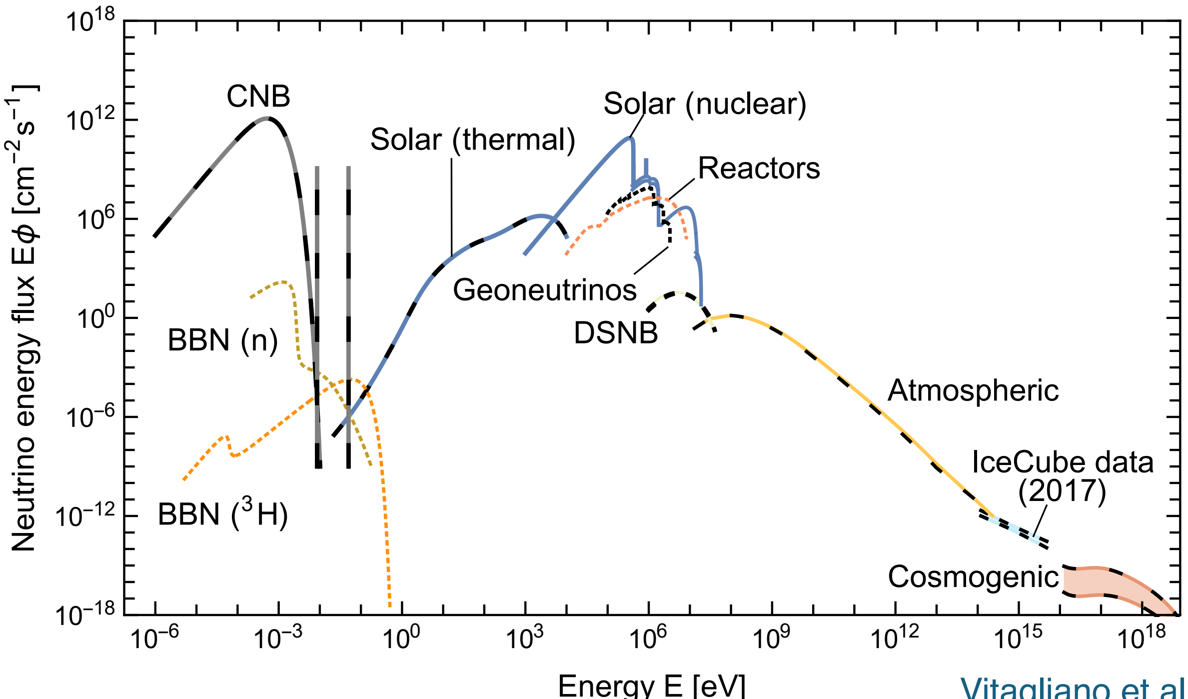
Heavy Neutral Leptons

Future bounds from neutrino and fixed-target experiments very relevant at GeV masses & complementary to colliders (-> BSM WG) within the target space of successful baryogenesis even in the minimal model (2HNL)



Why are cosmic neutrinos important in this quest ?

Neutrinos are ubiquitous in the Universe: learn about ν properties (solar, atmospheric, cosmic ν), probes of complex phenomena in stellar bodies, relics of the most powerful cosmic accelerators, and probes of BSM (eg dark matter annihilations)

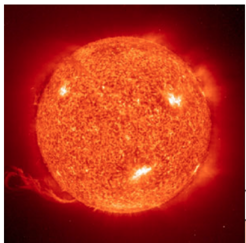


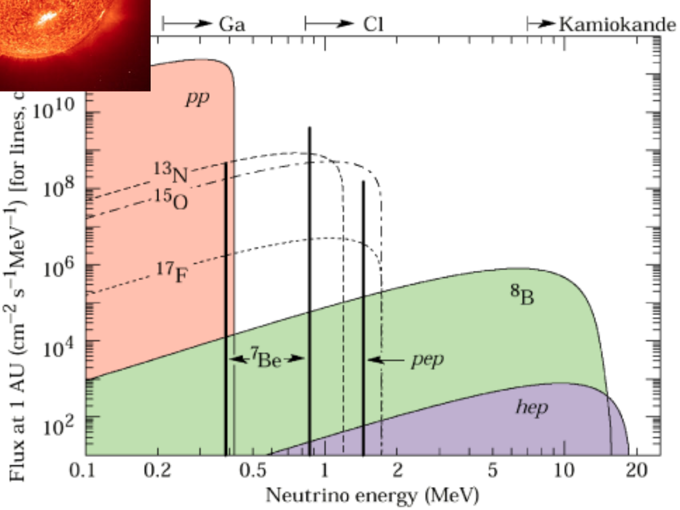
Vitagliano et al, arXiv: 1910.11878

Astro/Cosmo on BSM searches are very relevant and affected by uncertainties that could be reduced if we understand neutrino fluxes !

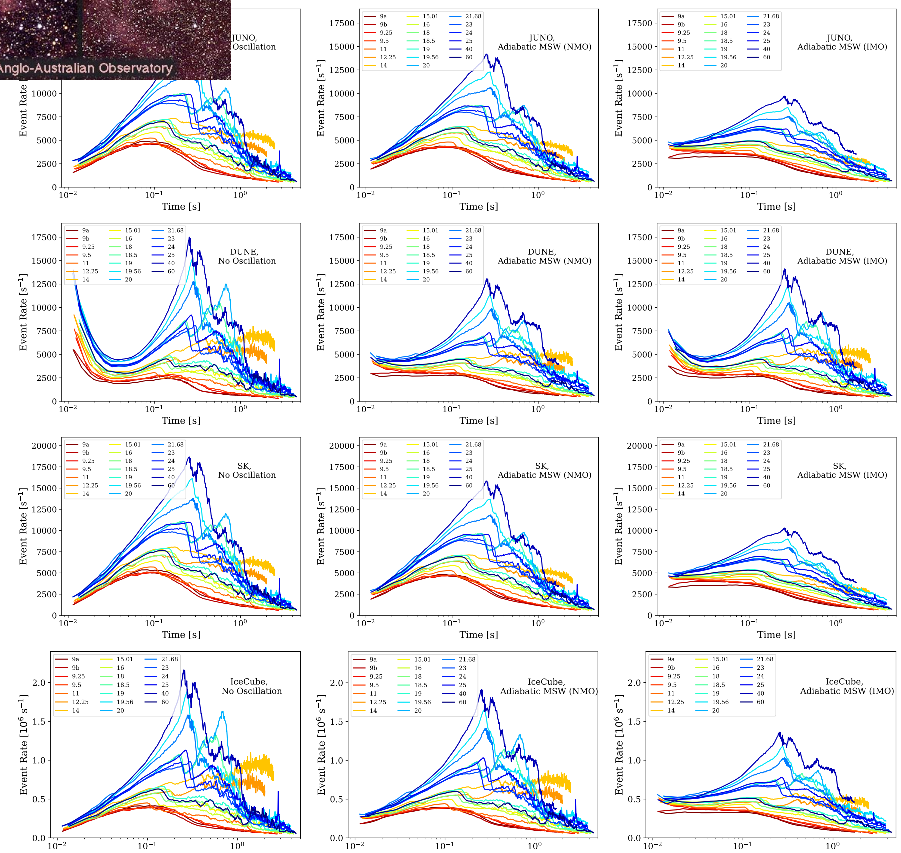
Neutrinos as probes of complex phenomena

From a Standard Solar Model to a Standard Supernova Model ?



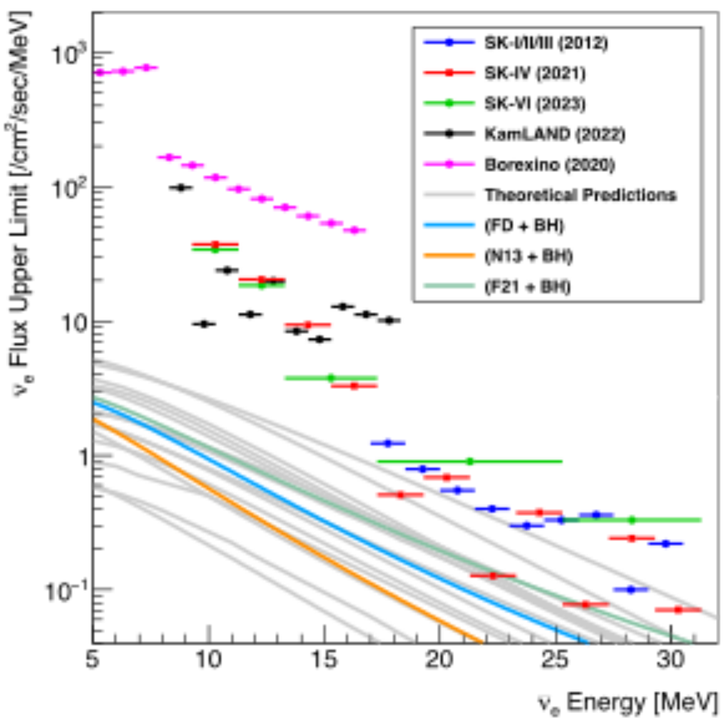


@10kpc

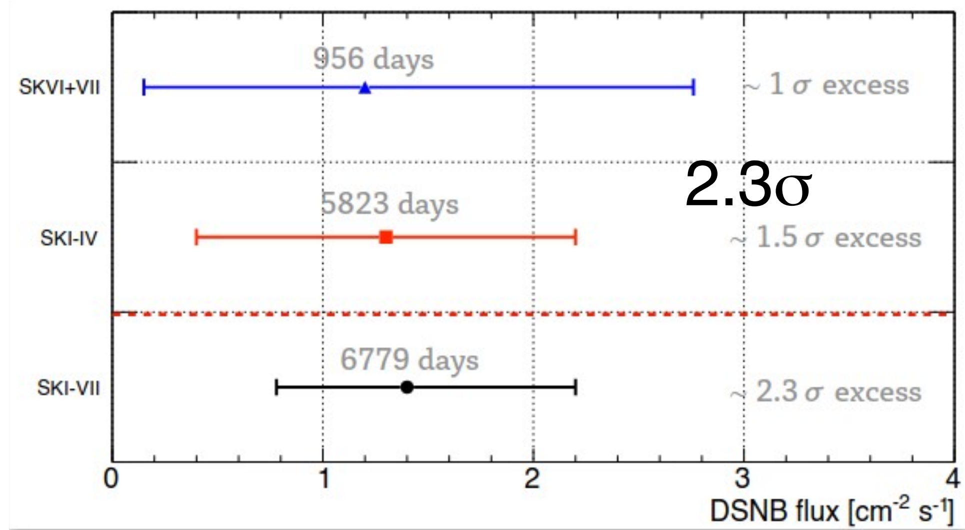


L. Choi et al arXiv: 2503.07531

Diffuse Supernova Neutrino Background around the corner ?



S. Ando et al arXiv: 2306.16076



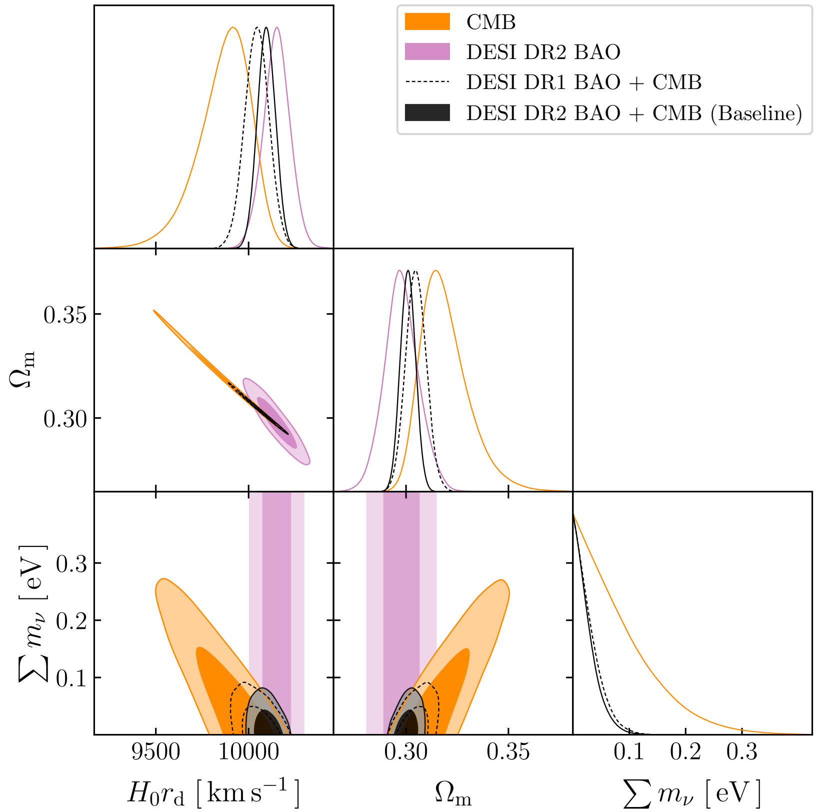
SuperKamiokande Neutrino'24

The neutrino sector is an unfinished endeavour in particle physics and a compelling hint of new physics. An ambitious experimental neutrino program is luckily underway…

BACKUPs

Weighing Cosmological neutrinos

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



$$\sum m_\nu \leq 0.064\mathrm{eV}$$

$$m_l < 0.023\,\mathrm{eV} \quad (95\%; \quad \mathrm{NO\ or\ NO/IO}),$$

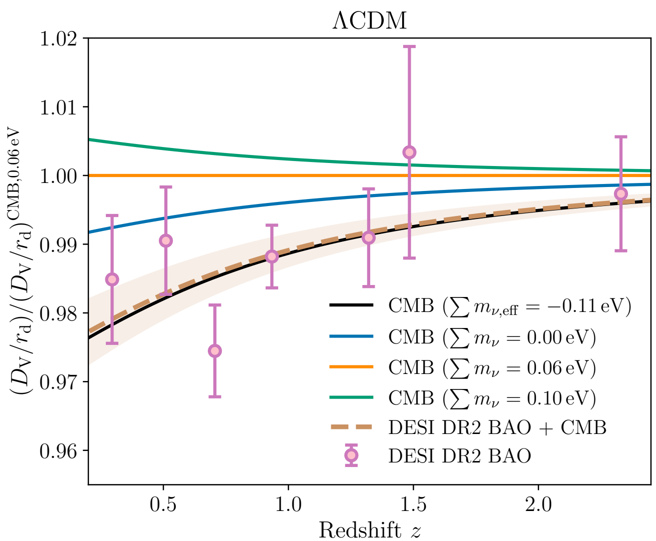
arXiv:2503.14744

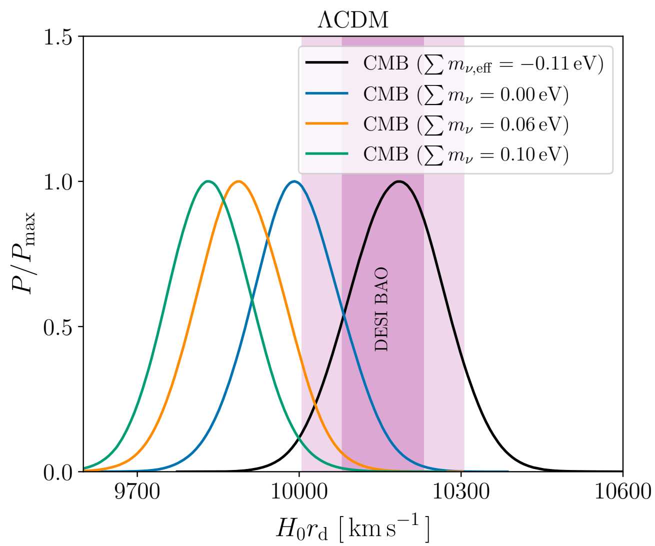
To be compared with the oscillations+Katrin (NuFIT):

$$0.058 \text{ eV} \leq \sum m_\nu \leq 1.2 \text{ eV} \text{ for NO,} \qquad 0.098 \text{ eV} \leq \sum m_\nu \leq 1.2 \text{ eV} \text{ for IO}$$

Weighing Cosmological neutrinos

- 3σ tension between ΛCDM with physical neutrino masses: is the strigent limit a result of inconsistencies in data CMB vs BAO ?





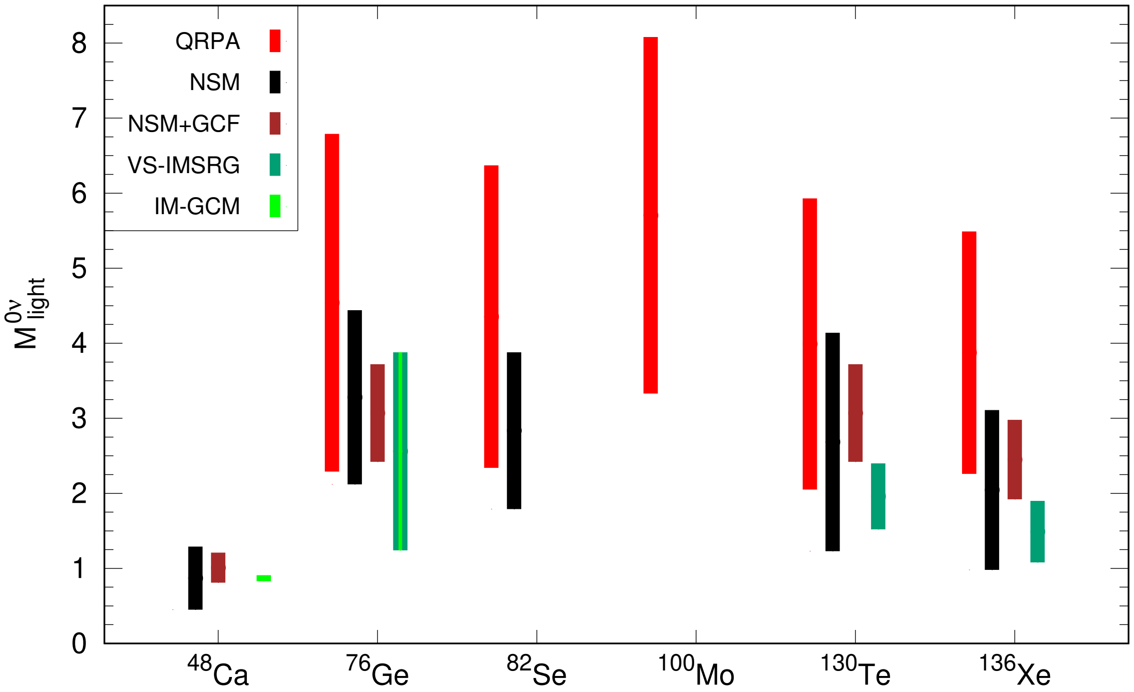
arXiv:2503.14744

- Relaxed limit with physical neutrino masses time-evolving dark energy

$$\sum m_\nu \leq 0.129\mathrm{eV}(95\%)$$

- Much more data from LSS and CMB expected in the near future…

Nuclear Matrix Elements $\beta\beta0\nu$



Wirth et al.
PRL127 242502 (2021)

Belley et al.
arXiv:2307:15156

Belley et al.
PRL132 182502 (2024)

Jokiniemi et al.
PRC 107 044305 (2023)

Weiss et al.
PRC106 065501 (2022)

J. Menéndez, Neutrino 2024

Uncertainties remain but some convergence is observed and better understanding is emerging

PMNS non-unitarity

$$\nu_\alpha = N_{\alpha i}\, \nu_i \,,$$

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(W_\mu^- \bar{\ell}_\alpha \gamma_\mu P_L N_{\alpha i} \nu_i + \text{ h.c.} \right) - \frac{g}{2\cos\theta_W} Z_\mu \bar{\nu}_i \gamma^\mu P_L \left(N^\dagger N \right)_{ij} \nu_j$$

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U$$

90% CL	Averaged ν Oscillations m > 10 eV		Flavour & EWPO [53] m > M_Z	
	Direct	Schwarz	Direct	Schwarz
α_{ee}	8.4×10^{-3} [108]	-	1.2×10^{-3}	-
$\alpha_{\mu\mu}$	1.2×10^{-2} [117]	-	8.6×10^{-5}	-
$\alpha_{\tau\tau}$	2.9×10^{-2} [110]	-	6.0×10^{-4}	-
$\lvert\alpha_{\mu e}\rvert$	1.8×10^{-2} [105]	1.4×10^{-2}	1.9×10^{-5}	5.4×10^{-4}
$\lvert\alpha_{\tau e}\rvert$	6.1×10^{-2} [104]	2.2×10^{-2}	6.2×10^{-3}	1.5×10^{-3}
$\lvert\alpha_{\tau\mu}\rvert$	9.1×10^{-3} [104]	2.6×10^{-2}	6.9×10^{-3}	1.5×10^{-4}

Blennow et al, arXiv: 2502.14980

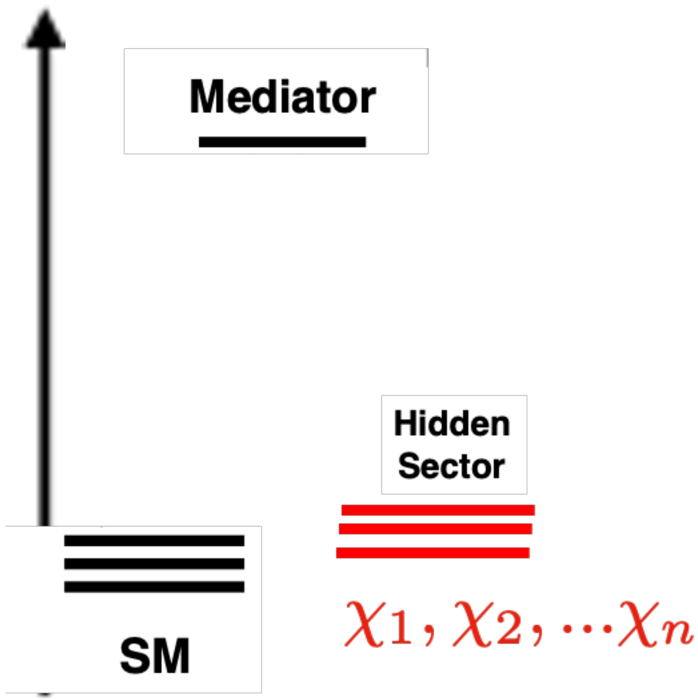
DUNE TDR

Parameter	Constraint
α_{ee}	0.3
$\alpha_{\mu\mu}$	0.2
$\alpha_{\tau\tau}$	0.8
$\alpha_{\mu e}$	0.04
$\alpha_{\tau e}$	0.7
$\alpha_{\tau\mu}$	0.2

Richer Dark Sector Scenarios

or Low-scale Model Building:

Dark sectors could be richer (like the SM) with new gauge interactions, more generations etc and explain DM, neutrino anomalies, etc



•The interactions among dark sectors could be large

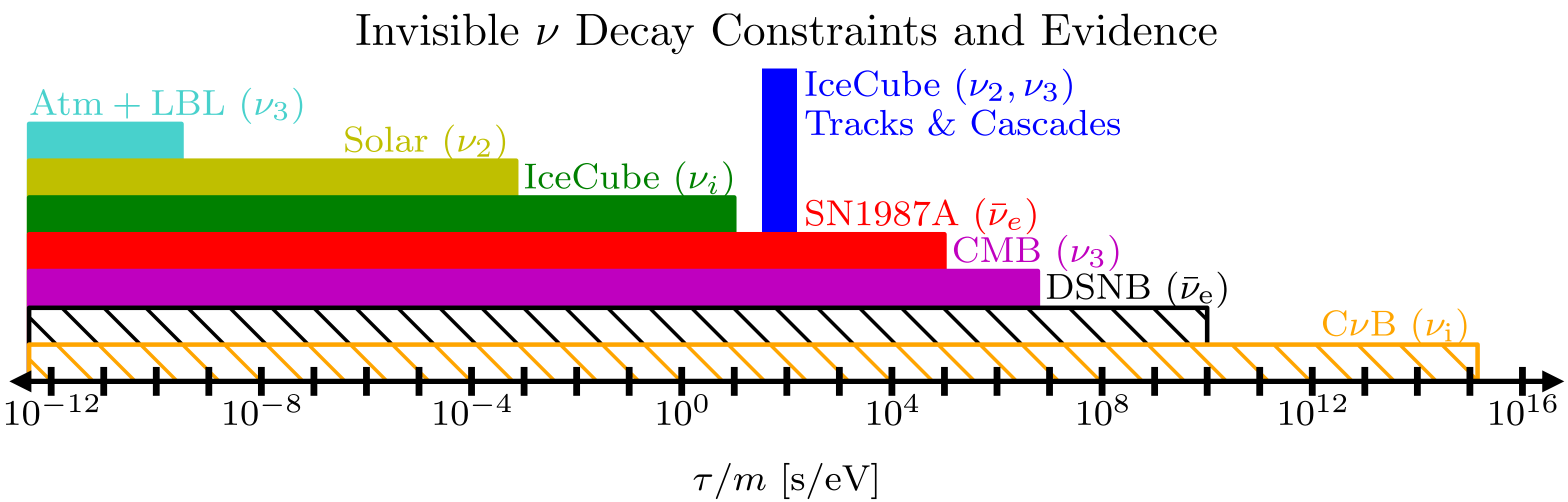
-shorter-lived dark particles
-semi-visible decays
-neutrino decay

Experiments should perform searches in the most model independent way possible

Eg. limits on LLPs as a function of production rate and lifetime or searching for semi-visible decays of LLPs

Neutrino Decay

$$\nu_j \to \nu_i X$$



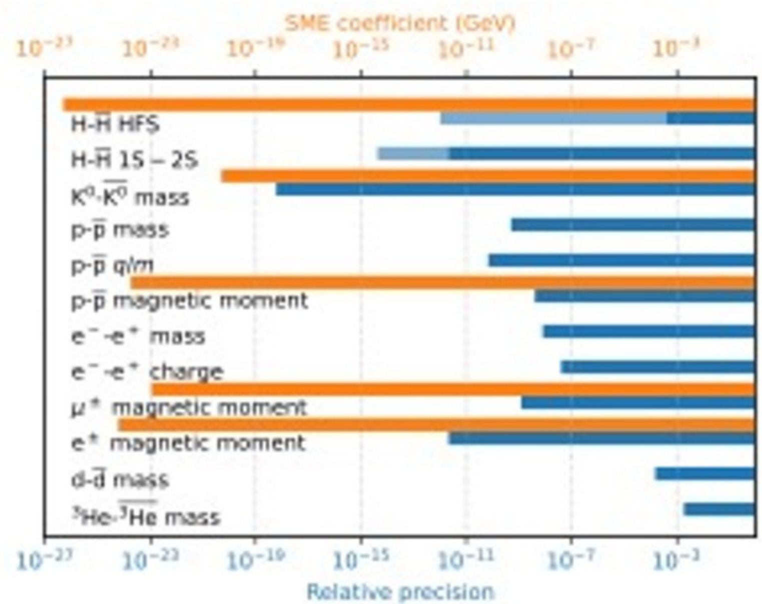
Ackermann et al, arXiv: 2203.08096

Testing fundamental symmetries with neutrinos

Neutrinos are very weakly interacting and might be affected in a more significant way by subtle modifications of fundamental symmetries (CPT, Lorentz, etc)

CPT/LV: difference of particle and antiparticle mass

$$\frac{M_p^2 - M_{\bar{p}}^2}{M_p^2 + M_{\bar{p}}^2} \leq 10^{-n}$$



$$|\Delta m^2_{31(21)} - \Delta \bar{m}^2_{31(21)}| \leq 4 \times 10^{-22(23)} \mathrm{GeV}^2$$