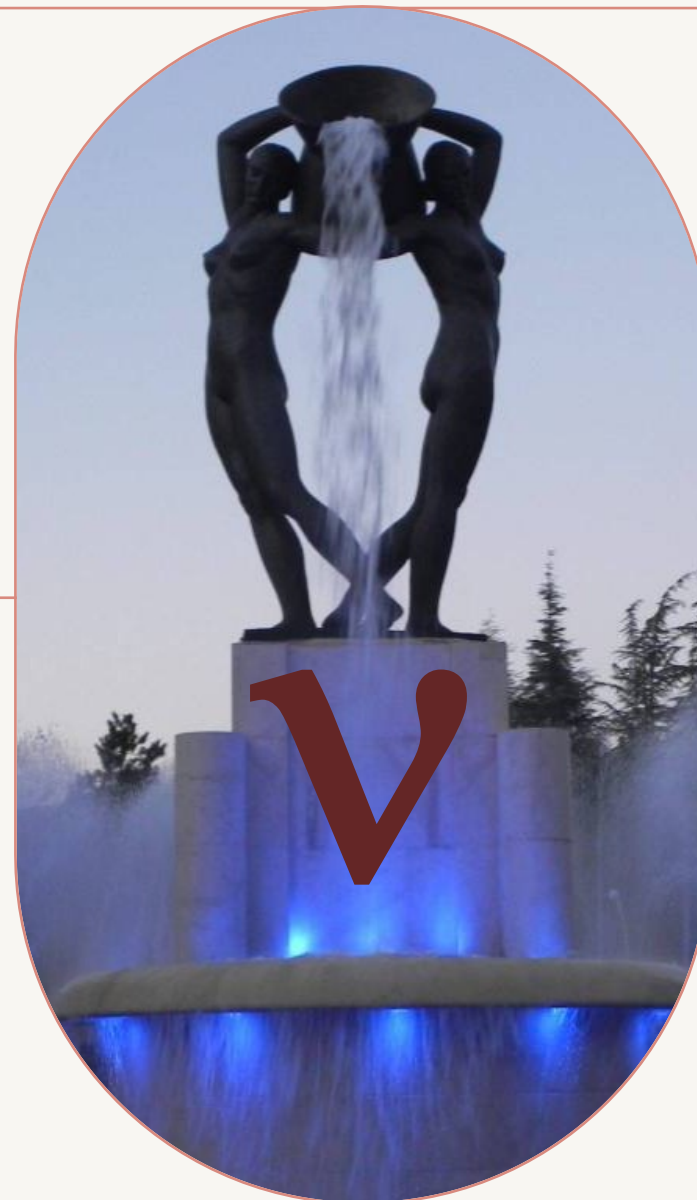


The 3ν paradigm

NAT-NET Meeting
WP1 «Standard Neutrino framework»

- Daniele Montanino
- Francesco Vissani

L'Aquila, July 18, 2023



WP1: Standard neutrino framework

The goal: Investigation of the remaining unknowns of the three-neutrino framework (absolute masses and their ordering, Dirac/Majorana nature, CP phases); refinement of our understanding of neutrino oscillations in vacuum, in matter and with self-interactions; neutrinoless double beta decay with light Majorana neutrinos: constraints on its nuclear model uncertainties and connections with cosmological bounds

Standard 3ν framework and notation

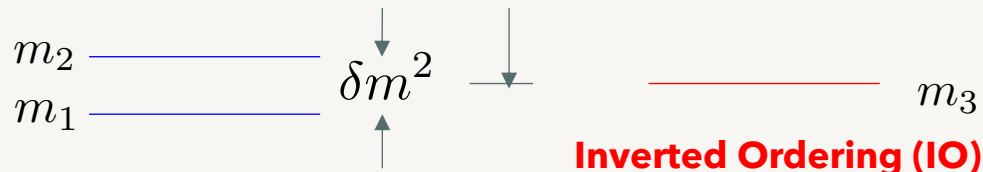
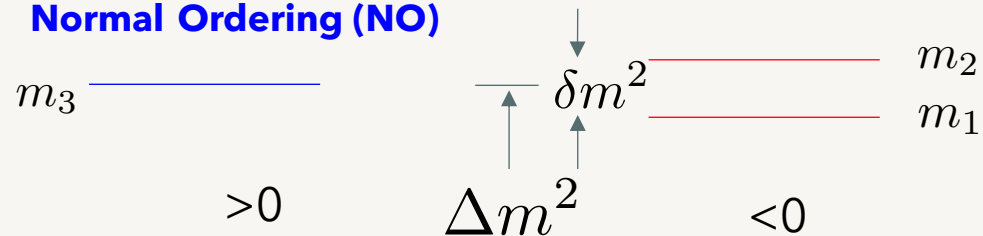
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \cdot \begin{bmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} = \cos \theta_{ij}$ etc.

CP-violating phase

"Majorana" phases
(effective only if neutrinos are Majorana particles)

Normal Ordering (NO)



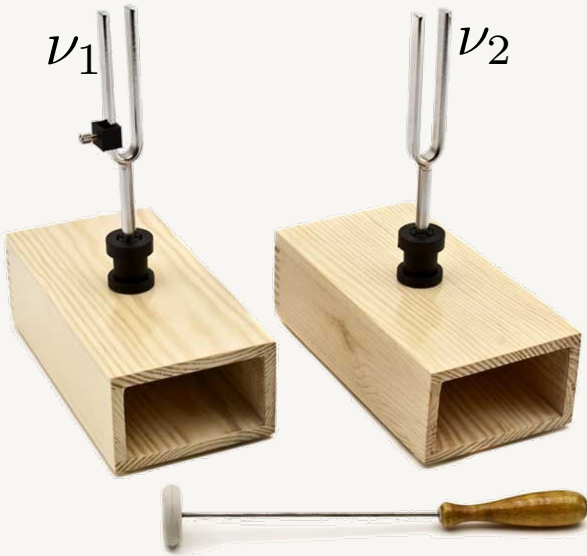
Inverted Ordering (IO)

$$\delta m^2 = m_2^2 - m_1^2$$

$$\Delta m^2 = m_3^2 - \frac{m_1^2 + m_2^2}{2}$$

Neutrino oscillations

- Oscillations are due to interference (beats) among mass eigenstates wavefunctions which propagates with different wavelengths



$$P(\nu_\alpha \rightarrow \nu_\beta; x) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 x}{4E} \right) \quad \alpha \neq \beta$$

$$\Delta m^2 = m_2^2 - m_1^2$$

- Matter can induce an index of refraction on ν_e (MSW effect) affecting oscillation probability

Neutrino oscillations

- For 3 generations the oscillation formula is more complicated

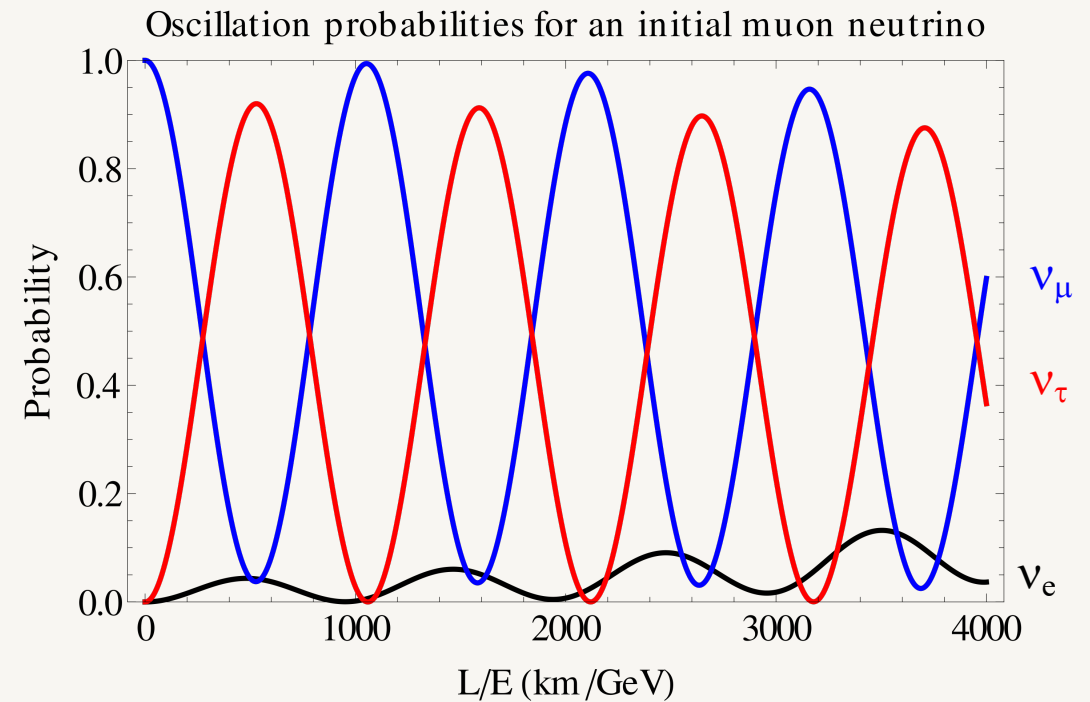
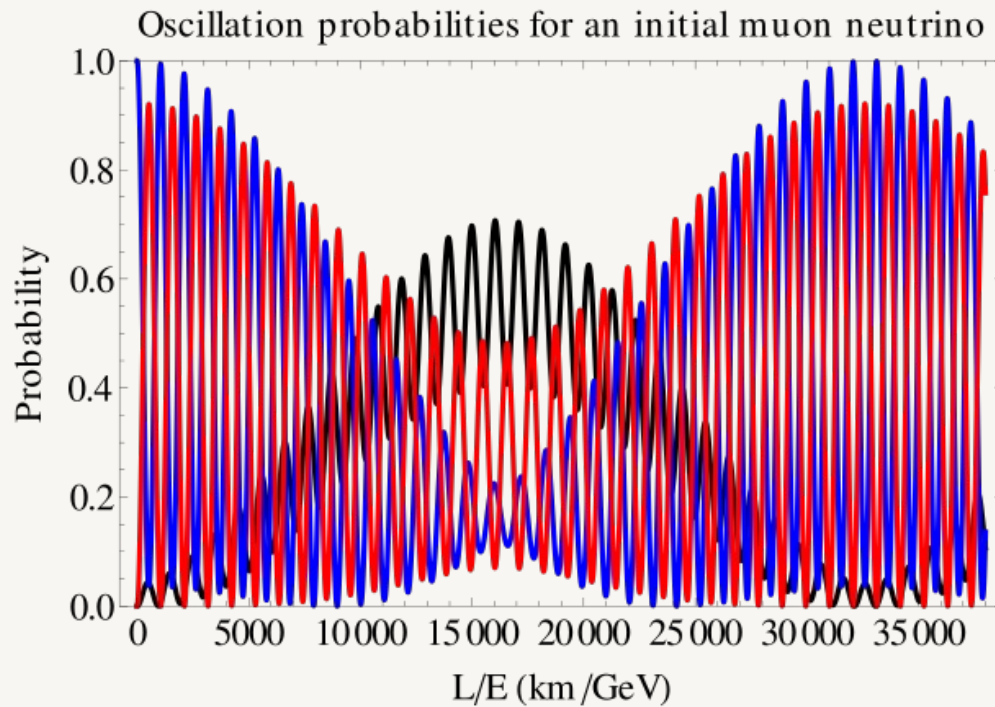
$$P(\nu_a \rightarrow \nu_b; x) = \delta_{ab} - 4 \sum_{j>k} \mathcal{R} [U_{aj}^* U_{bj} U_{ak} U_{bk}^*] \sin^2 \left(\frac{\Delta m_{jk}^2 x}{4E} \right) \quad \text{CP even}$$

$$+ 2 \sum_{j>k} \mathcal{I} [U_{aj}^* U_{bj} U_{ak} U_{bk}^*] \sin \left(\frac{\Delta m_{jk}^2 x}{2E} \right) \quad \text{CP odd}$$

$$\begin{aligned} P(\nu_a \rightarrow \nu_b; x) - P(\bar{\nu}_a \rightarrow \bar{\nu}_b; x) &= 4 \sum_{j>k} \mathcal{I} [U_{aj}^* U_{bj} U_{ak} U_{bk}^*] \sin \left(\frac{\Delta m_{jk}^2 x}{2E} \right) \\ &= J \sin \left(\frac{\Delta m_{12}^2 x}{4E} \right) \sin \left(\frac{\Delta m_{13}^2 x}{4E} \right) \sin \left(\frac{\Delta m_{23}^2 x}{4E} \right) \end{aligned}$$

$$J = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin \delta$$

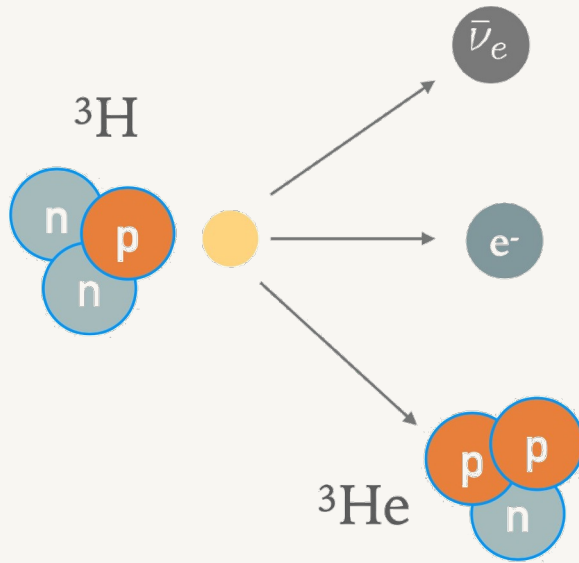
3ν oscillation probabilities



$$s_{13}^2 = 0.1 \quad , \quad s_{23}^2 = 0.97 \quad , \quad s_{12}^2 = 0.861 \quad , \quad \delta = 0$$
$$\Delta m^2 = 23.4 \times 10^{-4} \text{eV}^2 \quad , \quad \delta m^2 = 0.759 \times 10^{-4} \text{eV}^2$$

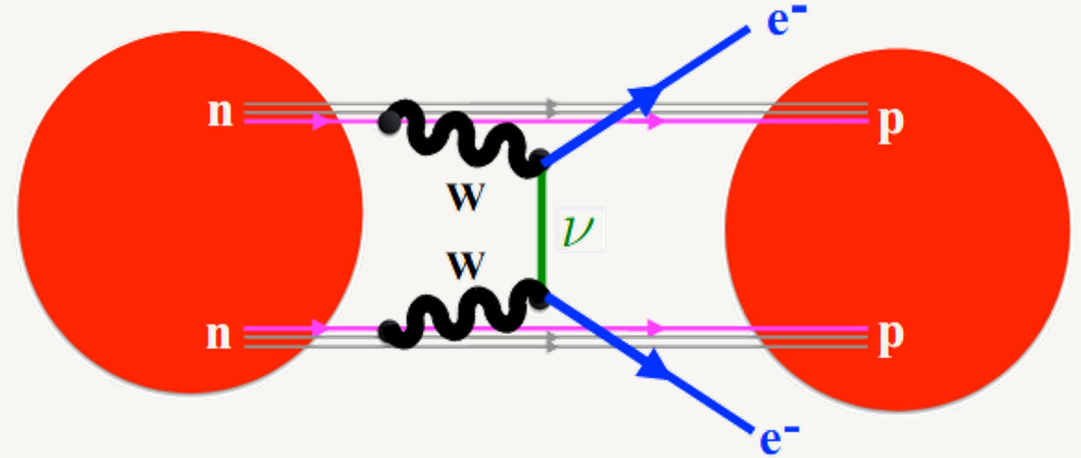
Non oscillatory data

- Tritium Beta decay



$$m_\beta = [c_{12}^2 c_{13}^2 m_1^2 + s_{12}^2 c_{13}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

- Neutrinoless double beta decay



$$m_{\beta\beta} = |c_{12}^2 c_{13}^2 e^{i\phi_1} m_1 + s_{12}^2 c_{13}^2 m_2^{i\phi_2} + s_{13}^2 m_3|$$

- Cosmology $\Sigma = m_1 + m_2 + m_3$

Known and unknown in the 3ν scenario

➤ Known

- ✓ The mass square differences $|\Delta m^2|$ and δm^2 😊
- ✓ The mixing angle θ_{12} 😊
- ✓ The mixing angle θ_{13} 😊
- ✓ The mixing angle θ_{23} and the octant 🤔

➤ Unknown

- ✓ The sign of Δm^2 (mass hierarchy) 😐
- ✓ The delta-CP phase 😐
- ✓ The absolute mass scale 😞
- ✓ The Dirac or Majorana nature of ν 's 😞
- ✓ Majorana phases 😭
- ✓ Other crazy characteristics of ν 's (sterile, NSI, decoherence...) 🤪

3ν global analysis

[1] F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo, *Unfinished fabric of the three neutrino paradigm*, Phys. Rev. D **104**, no.8, 083031 (2021)

The unfinished fabric of the three neutrino paradigm

Francesco Capozzi,¹ Eleonora Di Valentino,² Eligio Lisi,³
Antonio Marrone,^{4,3} Alessandro Melchiorri,^{5,6} and Antonio Palazzo^{4,3}

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In the current 3ν paradigm, neutrino flavor oscillations probe three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), one CP-violating phase δ , and two independent differences between the squared masses m_i^2 , that can be chosen as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$, where $\text{sign}(\Delta m^2) = +(-)$ for normal (inverted) mass ordering. Absolute ν masses can be probed by the effective mass m_β in beta decay, by the total mass Σ in cosmology and—if neutrinos are Majorana—by another effective mass $m_{\beta\beta}$ in neutrinoless double beta decay. Within an updated global analysis of oscillation and nonoscillation data, we constrain these 3ν parameters, both separately and in selected pairs, and highlight the concordance or discordance among different constraints. Five oscillation parameters ($\delta m^2, |\Delta m^2|, \theta_{12}, \theta_{23}, \theta_{13}$) are consistently measured, with an overall accuracy ranging from $\sim 1\%$ for $|\Delta m^2|$ to $\sim 6\%$ for $\sin^2 \theta_{23}$ (due to its persisting octant ambiguity). We find overall hints for normal ordering (at $\sim 2.5\sigma$), as well as for $\theta_{23} < \pi/4$ and for $\sin \delta < 0$ (both at 90% C.L.), and discuss some tensions among different datasets. Concerning nonoscillation data, we include the recent KATRIN constraints on m_β , and we combine the latest ^{76}Ge , ^{130}Te and ^{136}Xe bounds on $m_{\beta\beta}$, accounting for nuclear matrix element covariances. We also discuss some variants related to cosmic microwave background (CMB) anisotropy and lensing data, which may affect cosmological constraints on Σ and hints on $\text{sign}(\Delta m^2)$. The default option, including all Planck results, irrespective of the so-called lensing anomaly, sets upper bounds on Σ at the level of $\sim 10^{-1}$ eV, and further favors normal ordering up to $\sim 3\sigma$. An alternative option, that includes recent ACT results plus other independent results (from WMAP and selected Planck data) globally consistent with standard lensing, is insensitive to the ordering but prefers $\Sigma \sim \text{few} \times 10^{-1}$ eV, with different implications for m_β and $m_{\beta\beta}$ searches. In general, the unfinished fabric of the 3ν paradigm appears to be at the junction of diverse searches in particle and nuclear physics, astrophysics and cosmology, whose convergence will be crucial to achieve a convincing completion.

3ν global analysis – state of the art analysis

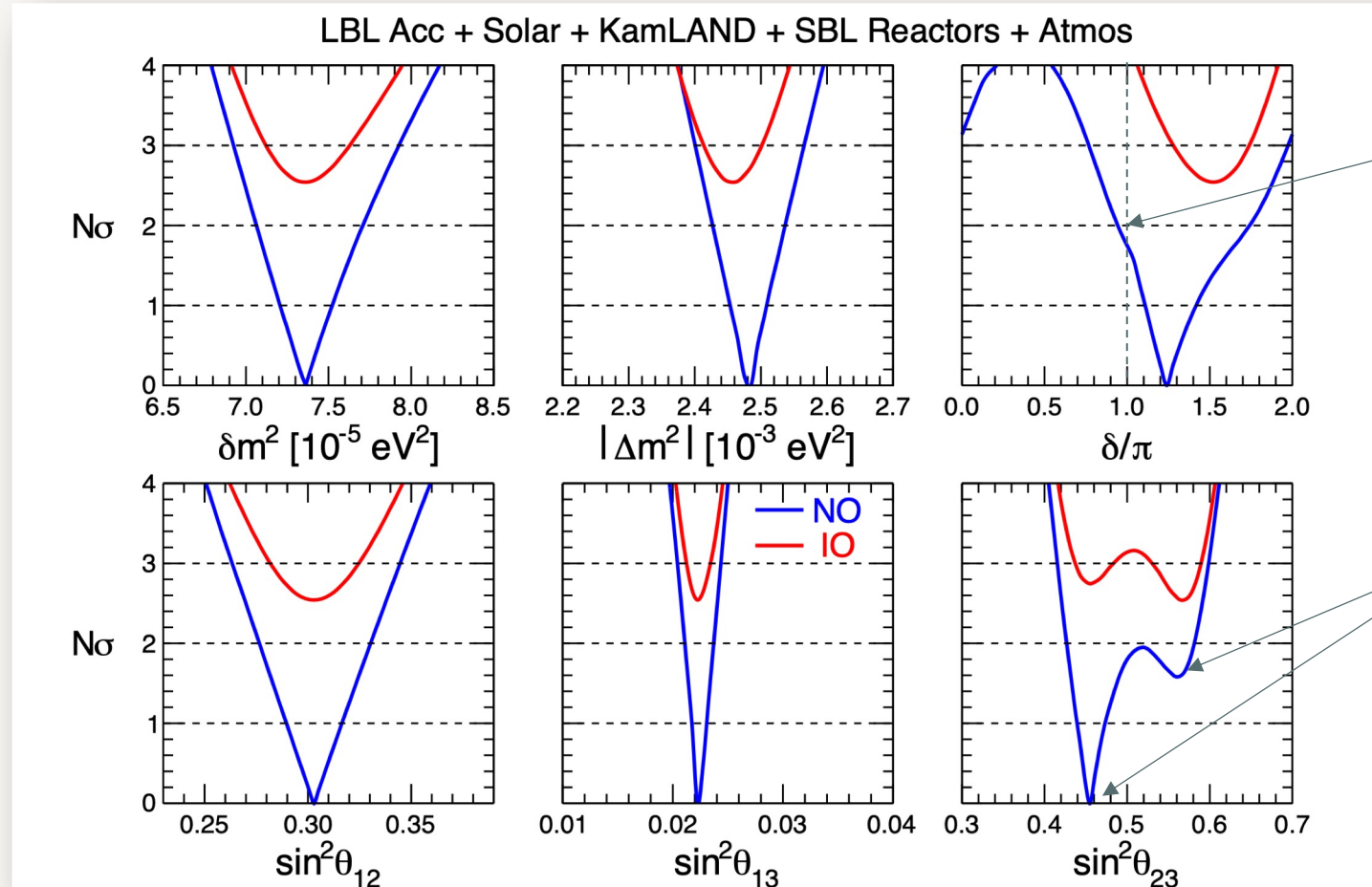
➤ Oscillatory data

- ✓ Solar (SK, SNO, Borexino, older radiochemical experiments) + KamLand
- ✓ Atmospheric (SK)
- ✓ Reactor short baseline (Daya Bay, RENO, Double Chooz)
- ✓ Long baseline accelerators (T2K, NOvA)

➤ Non oscillatory data

- ✓ Beta decay (KATRIN)
- ✓ Double beta decay (GERDA, CUORE, MAJORANA, KamLandZEN, EXO-200)
- ✓ Cosmology (PLANCK + other cosmological data)

Results on single oscillation parameters



No CP-violation
not excluded @ 2σ

Octant
degeneracy

Results on single oscillation parameters

TABLE I: Global 3ν analysis of oscillation parameters: best-fit values and allowed ranges at $N_\sigma = 1, 2$ and 3 , for either NO or IO, including all data. The latter column shows the formal “ 1σ fractional accuracy” for each parameter, defined as $1/6$ of the 3σ range, divided by the best-fit value and expressed in percent. We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that $\delta \in [0, 2\pi]$ (cyclic). The last row reports the difference between the χ^2 minima in IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	“ 1σ ” (%)
$\delta m^2/10^{-5} \text{ eV}^2$	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2 \theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$ \Delta m^2 /10^{-3} \text{ eV}^2$	NO	2.485	2.454 – 2.508	2.427 – 2.537	2.401 – 2.565	1.1
	IO	2.455	2.430 – 2.485	2.403 – 2.513	2.376 – 2.541	1.1
$\sin^2 \theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.30	2.11 – 2.37	2.04 – 2.44	3.0
	IO	2.23	2.17 – 2.29	2.10 – 2.38	2.03 – 2.45	3.1
$\sin^2 \theta_{23}/10^{-1}$	NO	4.55	4.40 – 4.73	4.27 – 5.81	4.16 – 5.99	6.7
	IO	5.69	5.48 – 5.82	4.30 – 5.94	4.17 – 6.06	5.5
δ/π	NO	1.24	1.11 – 1.42	0.94 – 1.74	0.77 – 1.97	16
	IO	1.52	1.37 – 1.66	1.22 – 1.78	1.07 – 1.90	9
$\Delta\chi^2_{\text{IO-NO}}$	IO-NO	+6.5	$\Leftarrow$IO disfavoured @2.6σ			

Limits on m_β

KATRIN 1st campaign



$$m_\beta^2 = 0.1 \pm 0.3 \text{ eV}^2$$

Limits on $m_{\beta\beta}$

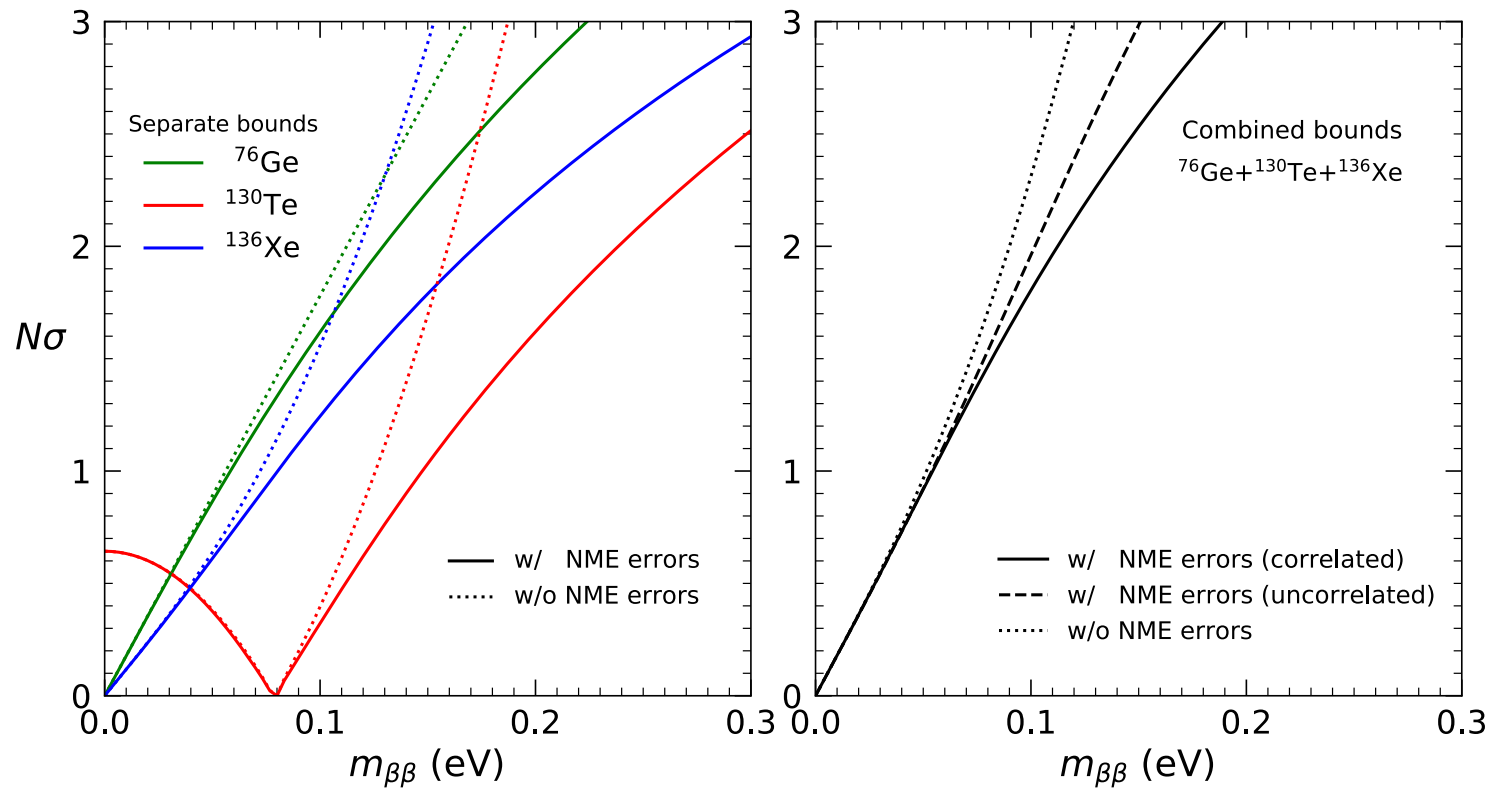
- For the lepton flavor violation decay process $(Z,A)\rightarrow(Z\pm 2,A)+2e^{(\mp)}$ in the 3ν paradigm the parameter $m_{\beta\beta}$ is related to the half-life

$$\frac{1}{T_{1/2}} = G|\mathcal{M}|^2 m_{\beta\beta}^2$$

with G parameter space and $\mathcal{M}$ nuclear matrix element

- Current experiments are compatible with no signal ($T_{1/2}=\infty$)

Limits on $m_{\beta\beta}$



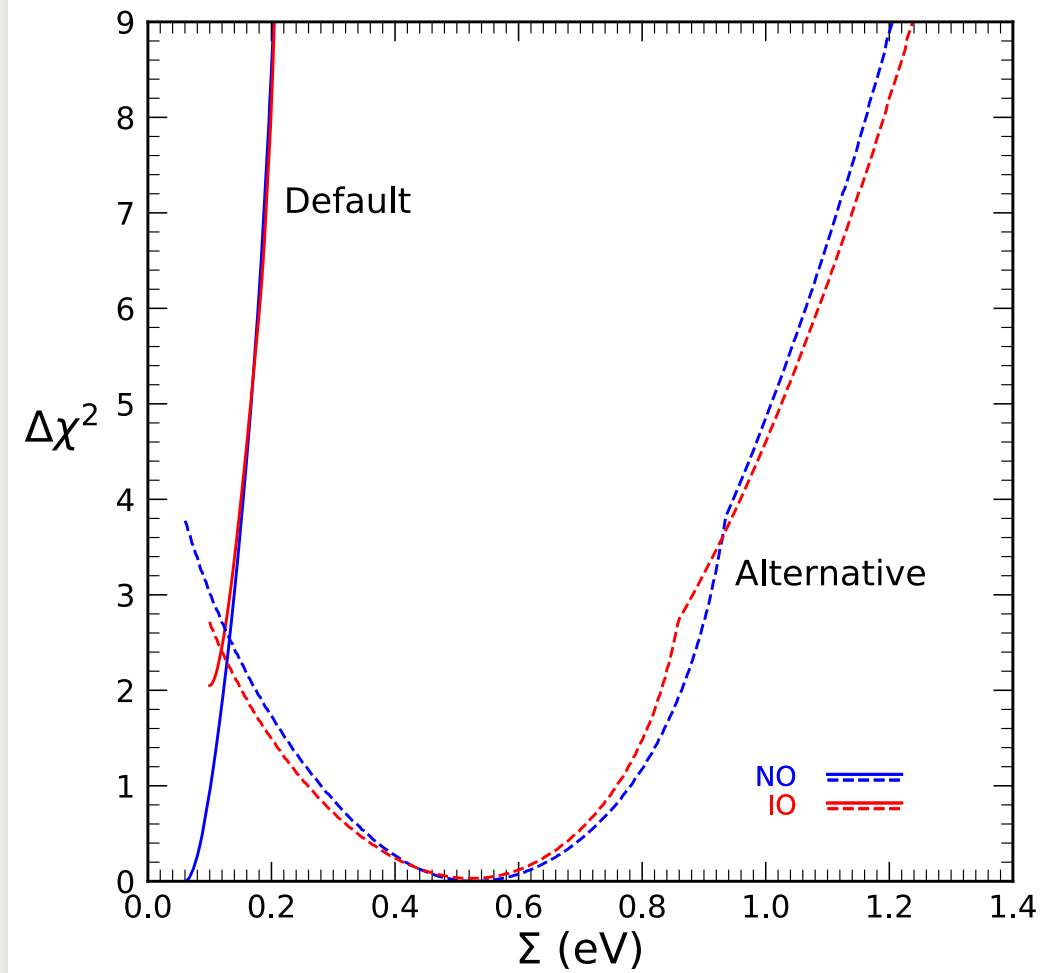
Limits on Σ

«Default»

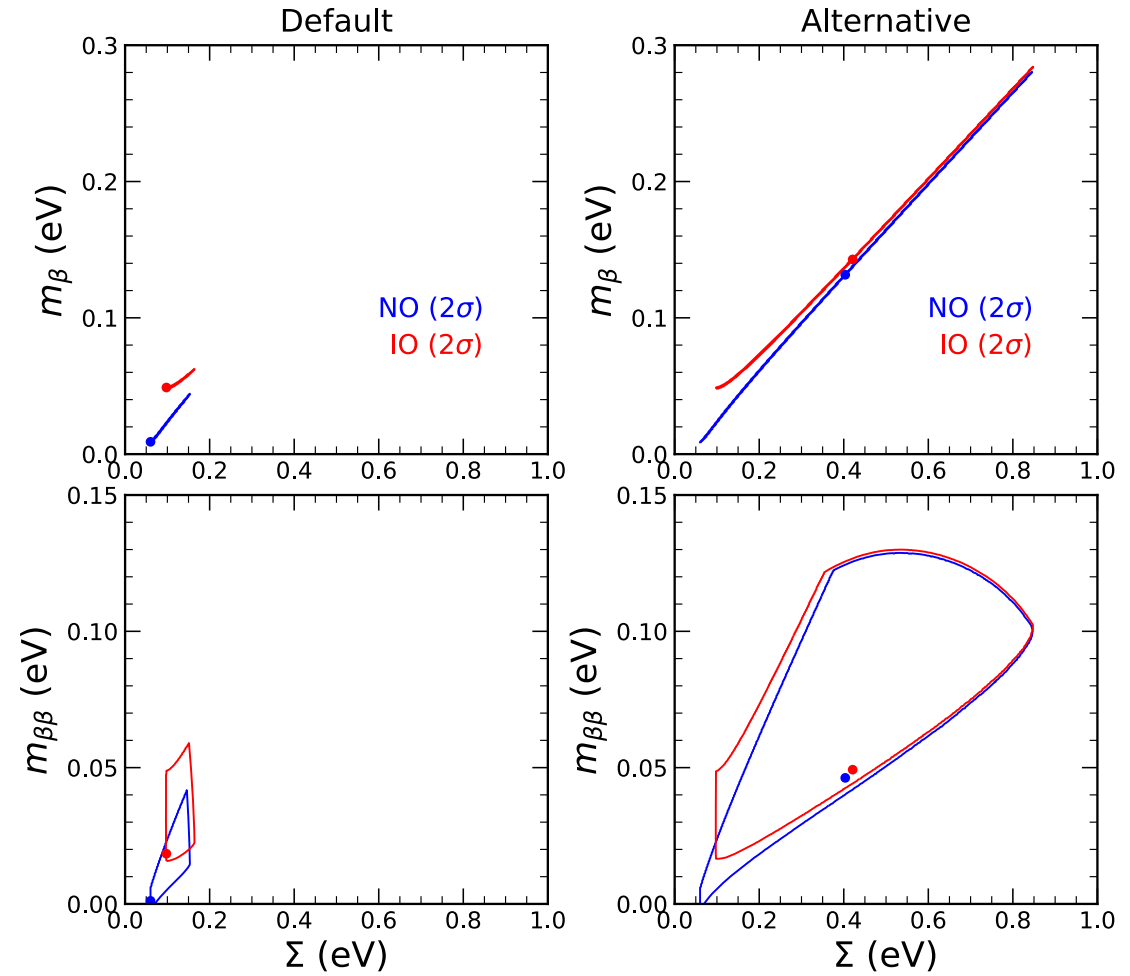
«Alternative»

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + $m_\beta + m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$
0	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing + $H_0(\text{R19})$	< 0.13 eV	3.9	< 0.13 eV	4.0
5	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + $H_0(\text{R19})$	< 0.13 eV	3.1	< 0.13 eV	3.2
6	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing + $H_0(\text{R19})$	< 0.12 eV	3.7	< 0.12 eV	3.8
7	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2
10	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + τ_{prior}	< 1.21 eV	-0.1	< 1.00 eV	0.1
11	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + Planck lowE	< 1.12 eV	-0.1	< 0.87 eV	0.1
12	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

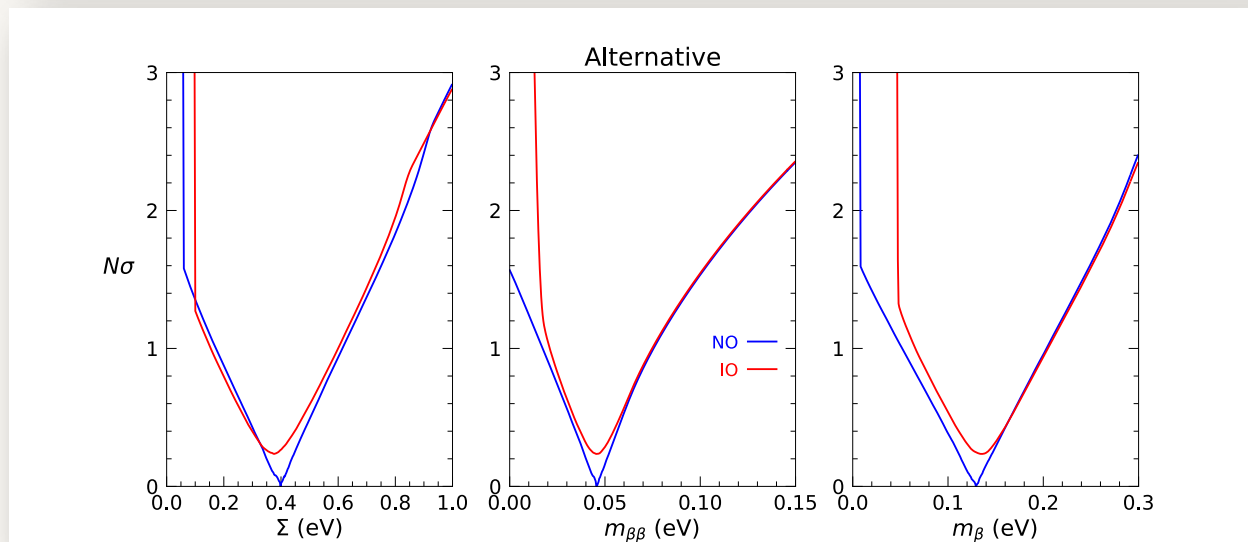
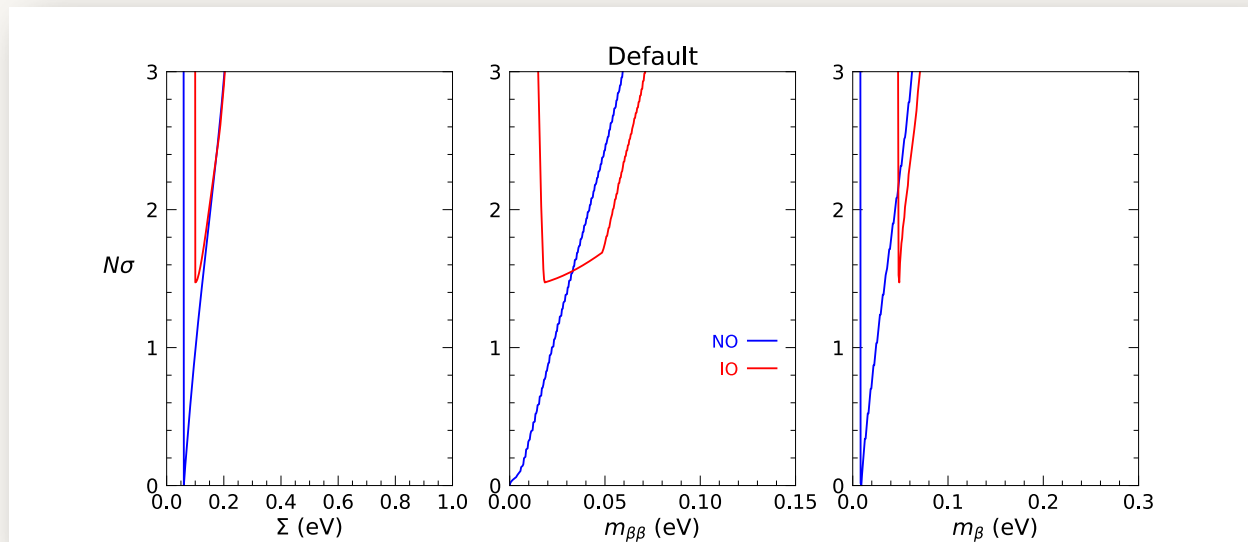
Limits on Σ



Bounds on mass parameters



Bounds on mass parameters



Dependence of $m_{\beta\beta}$ to nuclear matrix elements

[2] E. Lisi and A. Marrone, *Majorana neutrino mass constraints in the landscape of nuclear matrix elements*, Phys. Rev. D **106**, no.1, 013009 (2022)

Majorana neutrino mass constraints in the landscape of nuclear matrix elements

Eligio Lisi¹ and Antonio Marrone^{2,1}

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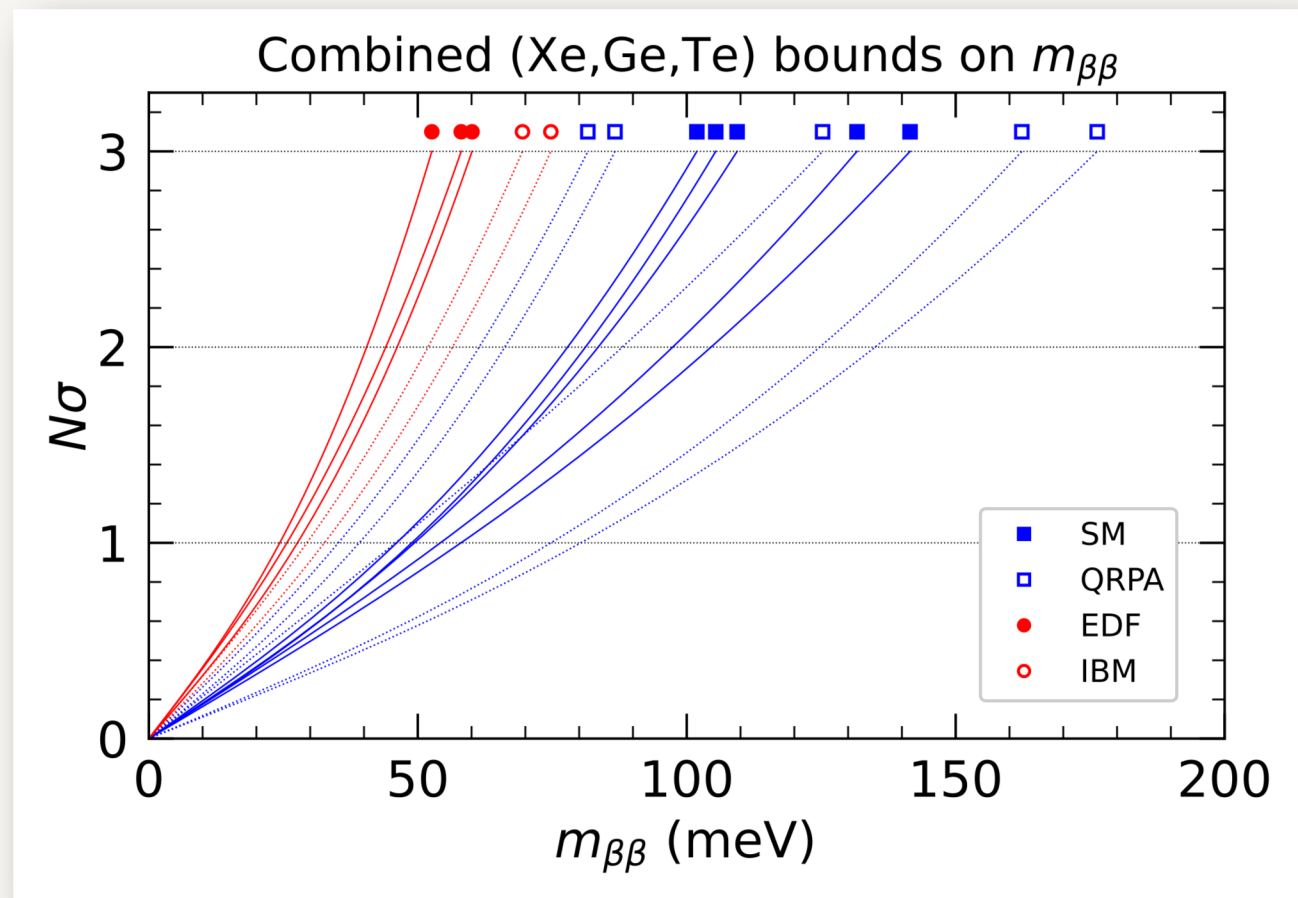
² *Dipartimento Interateneo di Fisica “Michelangelo Merlin,” Via Amendola 173, 70126 Bari, Italy*

We discuss up-to-date constraints on the Majorana neutrino mass $m_{\beta\beta}$ from neutrinoless double beta decay ($0\nu\beta\beta$) searches in experiments using different isotopes: KamLAND-Zen and EXO (^{136}Xe), GERDA and MAJORANA (^{76}Ge) and CUORE (^{130}Te). Best fits and upper bounds on $m_{\beta\beta}$ are explored in the general landscape of nuclear matrix elements (NME), as well as for specific NME values obtained in representative nuclear models. By approximating the likelihood of $0\nu\beta\beta$ signals through quadratic forms, the analysis of separate and combined isotope data becomes exceedingly simple, and allows to clarify various aspects of multi-isotope data combinations. In particular, we analyze the relative impact of different data in setting upper bounds on $m_{\beta\beta}$, as well as the conditions leading to nonzero $m_{\beta\beta}$ at best fit, for variable values of the NMEs. Detailed results on $m_{\beta\beta}$ from various combinations of data are reported in graphical and numerical form. Implications for future $0\nu\beta\beta$ data analyses and NME calculations are briefly discussed.

Dependence of $m_{\beta\beta}$ to nuclear matrix elements

➤ KamLAND-Zen and EXO (^{136}Xe), GERDA and MAJORANA (^{76}Ge) and CUORE (^{130}Te) analysed using different nuclear matrix element calculations:

- ✓ nuclear shell model (SM)
- ✓ quasi-particle random phase approximation (QRPA)
- ✓ energy-density functional theory (EDF)
- ✓ interacting boson model (IBM)



Other “ $m_{\beta\beta} \sim$ related” papers

[3] J. Kostensalo, E. Lisi, A. Marrone and J. Suhonen, *^{113}Cd beta-decay spectrum and g_A quenching using spectral moments*, Phys. Rev. C **107**, no.5, 055502

Interplay between non-interfering neutrino exchange mechanisms and nuclear matrix elements in $0\nu\beta\beta$ decay

Eligio Lisi,^{1,*} Antonio Marrone,^{2,1,†} and Newton Nath^{1,‡}

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² *Dipartimento Interateneo di Fisica “Michelangelo Merlin,” Via Amendola 173, 70126 Bari, Italy*

We revisit the phenomenology of neutrinoless double beta ($0\nu\beta\beta$) decay mediated by non-interfering exchange of light and heavy Majorana neutrinos, in the context of current and prospective ton-scale experimental searches, as well as of recent calculations of nuclear matrix elements (NME) in different nuclear models. We derive joint upper bounds on the light and heavy contributions to $0\nu\beta\beta$ decay, for different sets of NME, through separate and combined data coming from the following experiments (and isotopes): KamLAND-Zen and EXO (Xe), GERDA and MAJORANA (Ge) and CUORE (Te). We further consider three proposed projects that could provide, within current bounds, possible $0\nu\beta\beta$ decay signals at $>3\sigma$ level with an exposure of 10 ton years: nEXO (Xe), LEGEND (Ge) and CUPID (Mo). Separate and combined (Xe, Ge, Mo) signals are studied for different representative cases and NME sets, and the conditions leading to (non)degenerate light and heavy neutrino mechanisms are discussed. In particular, the role of heavy-to-light NME ratios in different isotopes is highlighted through appropriate graphical representations. By using different sets of “true” and “test” NME as a proxy for nuclear uncertainties, it is shown that the relative contributions of light and heavy neutrino exchange to $0\nu\beta\beta$ signals may be significantly biased in some cases. Implications for theoretical models connecting light and heavy Majorana neutrino masses are also briefly illustrated. These results provide further motivations to improve NME calculations, so as to better exploit the physics potential of future multi-isotope $0\nu\beta\beta$ searches at the ton scale.

Other “ $m_{\beta\beta\sim}$ related” papers

[4] E. Lisi, A. Marrone and N. Nath, *Interplay between non-interfering neutrino exchange mechanisms and nuclear matrix elements in $0\nu\beta\beta$ decay*, [arXiv:2306.07671 [hep-ph]]

^{113}Cd β -decay spectrum and g_A quenching using spectral moments

Joel Kostensalo,¹ Eligio Lisi,² Antonio Marrone,^{3,2} and Jouni Suhonen⁴

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⁴ *Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland*

We present an alternative analysis of the ^{113}Cd β -decay electron energy spectrum in terms of spectral moments μ_n , corresponding to the averaged values of n^{th} powers of the β particle energy. The zeroth moment μ_0 is related to the decay rate, while higher moments μ_n are related to the spectrum shape. The here advocated spectral-moment method (SMM) allows for a complementary understanding of previous results, obtained using the so-called spectrum-shape method (SSM) and its revised version, in terms of two free parameters: $r = g_A/g_V$ (the ratio of axial-vector to vector couplings) and s (the small vector-like relativistic nuclear matrix element, s -NME). We present numerical results for three different nuclear models with the conserved vector current hypothesis (CVC) assumption of $g_V = 1$. We show that most of the spectral information can be captured by the first few moments which are simple quadratic forms (conic sections) in the (r, s) plane: an ellipse for $n = 0$ and hyperbolae for $n \geq 1$, all being nearly degenerate as a result of cancellations among nuclear matrix elements. The intersections of these curves, as obtained by equating theoretical and experimental values of μ_n , identify the favored values of (r, s) at a glance, without performing detailed fits. In particular, we find that values around $r \sim 1$ and $s \sim 1.6$ are consistently favored in each nuclear model, confirming the evidence for g_A quenching in ^{113}Cd , and shedding light on the role of the s -NME. We briefly discuss future applications of the SMM to other forbidden β -decay spectra sensitive to g_A .

Other “ $m_{\beta\beta\sim}$ related” papers

[5] M. Agostini, G. Benato, J. A. Detwiler, J. Menendez and F. Vissani, *Testing the inverted neutrino mass ordering with neutrinoless double-beta decay*, Phys. Rev. C **104** (2021) no.4, L042501

Testing the Inverted Neutrino Mass Ordering with Neutrinoless Double-Beta Decay

Matteo Agostini,^{1,*} Giovanni Benato,^{2,†} Jason A. Detwiler,^{3,‡} Javier Menéndez,^{4,§} and Francesco Vissani^{2,5,¶}

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³*Center for Experimental Nuclear Physics and Astrophysics,*

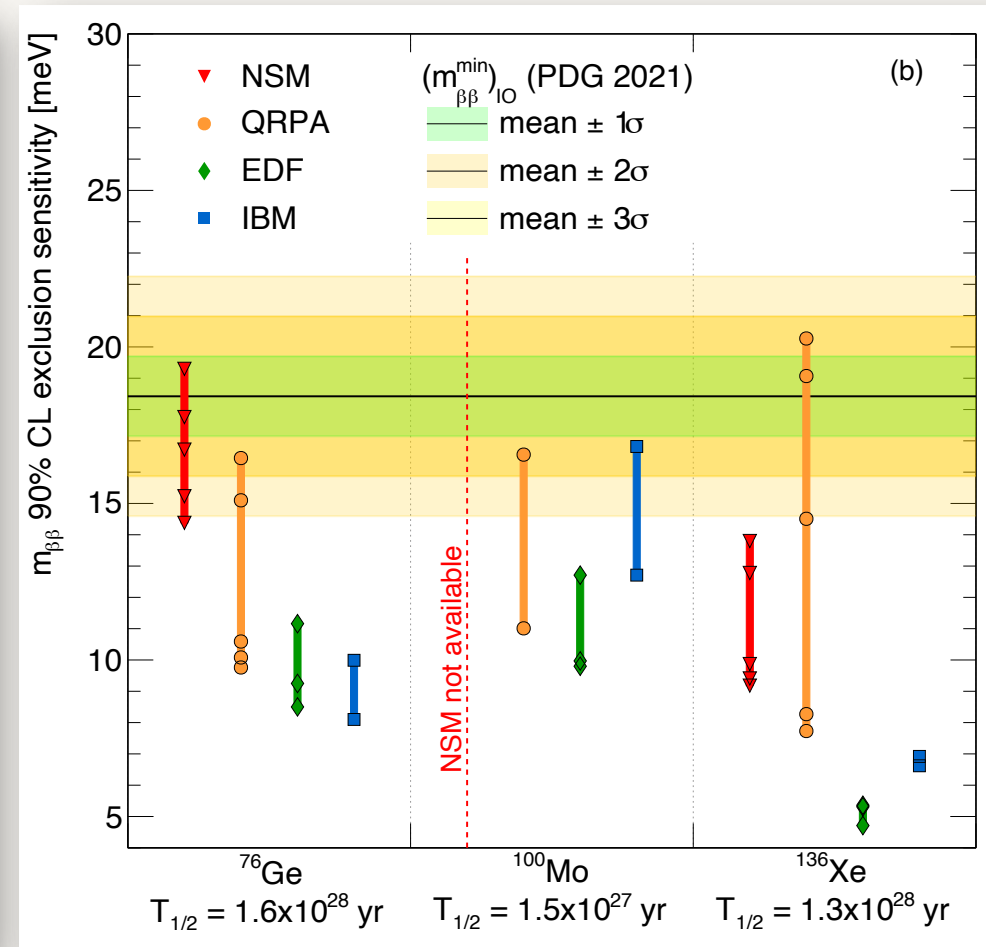
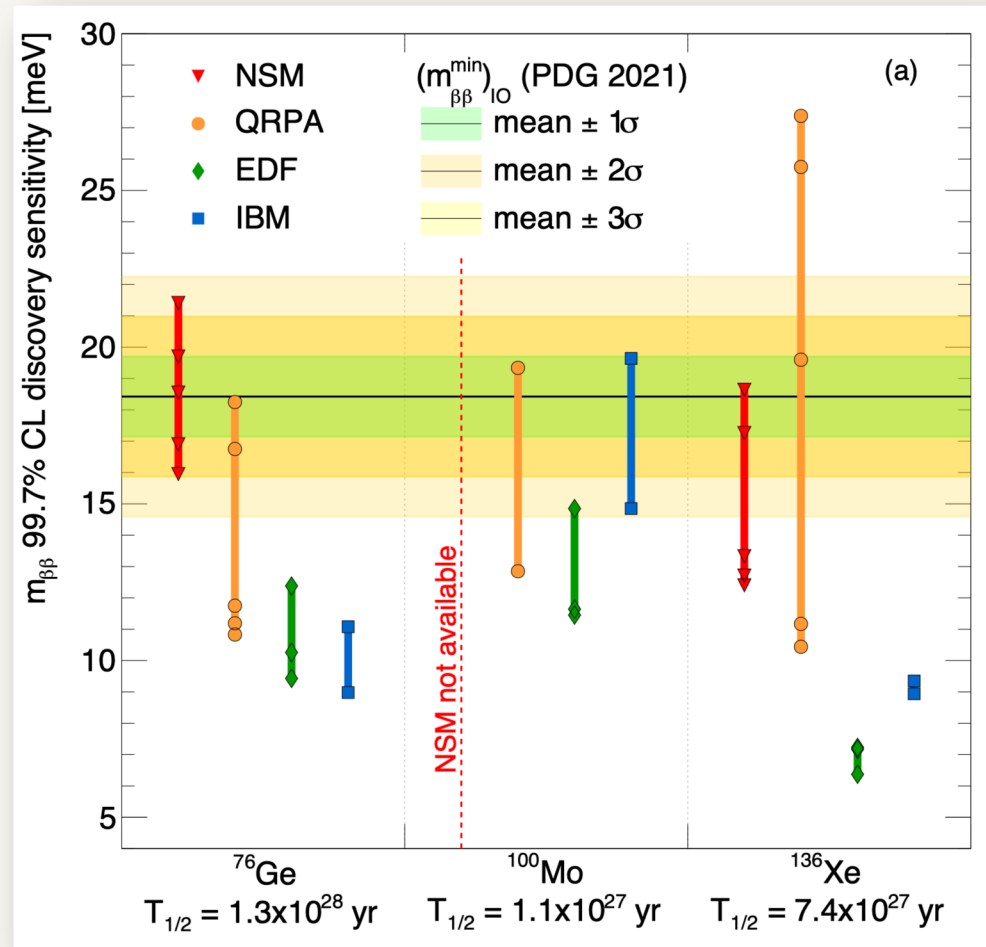
and Department of Physics, University of Washington, Seattle, WA 98115 - USA

⁴*Department of Quantum Physics and Astrophysics and Institute of Cosmos Sciences, University of Barcelona, 08028 Barcelona, Spain*

⁵*Gran Sasso Science Institute, 67100 L'Aquila, Italy*

(Dated: July 13, 2023)

We quantify the extent to which future experiments will test the existence of neutrinoless double-beta decay mediated by light neutrinos with inverted-ordered masses. While it remains difficult to compare measurements performed with different isotopes, we find that future searches will fully test the inverted ordering scenario, as a global, multi-isotope endeavor. They will also test other possible mechanisms driving the decay, including a large uncharted region of the allowed parameter space assuming that neutrino masses follow the normal ordering.



Comparison of $m_{\beta\beta}$ 99.7%-CL discovery and 90%-CL median exclusion sensitivities for different isotopes at stated half-life sensitivities grouped by nuclear many-body frameworks for various matrix element. The horizontal bands show the variation $(m_{\beta\beta}^{\min})_{\text{IO}}$ under variation of the neutrino oscillation parameters

Other “ $m_{\beta\beta} \sim$ related” papers

[6] S. Biondini, S. Dell'Oro, R. Leonardi, S. Marcocci, O. Panella, M. Presilla and F. Vissani,
Complementarity between neutrinoless double beta decay and collider searches for heavy neutrinos in composite-fermion models, [arXiv:2111.01053 [hep-ph]]

Complementarity between neutrinoless double beta decay and collider searches for heavy neutrinos in composite-fermion models

S. Biondini,^{1,*} S. Dell'Oro,^{2,3} R. Leonardi,⁴ S. Marcocci,⁵ O. Panella,⁴ M. Presilla,⁴ and F. Vissani⁶

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(Dated: July 13, 2023)

Composite-fermion models predict excited quarks and leptons with mass scales which can potentially be observed at high-energy colliders like the LHC; the most recent exclusion limits from the CMS and ATLAS Collaborations corner excited-fermion masses and the compositeness scale to the multi-TeV range. At the same time, hypothetical composite Majorana neutrinos would lead to observable effects in neutrinoless double beta decay ($0\nu\beta\beta$) experiments. In this work, we show that the current composite-neutrino exclusion limit $M_N > 4.6$ TeV, as extracted from direct searches at the LHC, can indeed be further improved to $M_N > 8.8$ TeV by including the bound on the nuclear transition $^{136}\text{Xe} \rightarrow ^{136}\text{Ba} + 2e^-$. Looking ahead, the forthcoming HL-LHC will allow probing a larger portion of the parameter-space, nevertheless, it will still benefit from the complementary limit provided by $0\nu\beta\beta$ future detectors to explore composite-neutrino masses up to 12.6 TeV.

Other “ $m_{\beta\beta\sim}$ related” papers

[7] M. Agostini, G. Benato, S. Dell'Oro, S. Pirro and F. Vissani, *Discovery probabilities of Majorana neutrinos based on cosmological data*, Phys. Rev. D **103** (2021) no.3, 033008

Discovery probabilities of Majorana neutrinos based on cosmological data

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(Dated: July 13, 2023)

We discuss the impact of the cosmological measurements on the predictions of the Majorana mass of the neutrinos, the parameter probed by neutrinoless double-beta decay experiments. Using a minimal set of assumptions, we quantify the probabilities of discovering neutrinoless double-beta decay and introduce a new graphical representation that could be of interest for the community.

Published on: [Phys. Rev. D **103**, 033008 \(2021\)](#)

Other “ $m_{\beta\beta}$ ~related” papers

[8] M. Agostini, G. Benato, J. A. Detwiler, J. Menendez and F. Vissani, *Toward the discovery of matter creation with neutrinoless double beta decay*, Rev. Mod. Phys. **95** (2023) no.2, 025002

Review papers

Toward the discovery of matter creation with neutrinoless double-beta decay

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(Dated: July 13, 2023)

The discovery of neutrinoless double-beta decay could soon be within reach. This hypothetical ultra-rare nuclear decay offers a privileged portal to physics beyond the Standard Model of particle physics. Its observation would constitute the discovery of a matter-creating process, corroborating leading theories of why the universe contains more matter than antimatter, and how forces unify at high energy scales. It would also prove that neutrinos and anti-neutrinos are not two distinct particles, but can transform into each other, with their mass described by a unique mechanism conceived by Majorana. The recognition that neutrinos are not massless necessitates an explanation and has boosted interest in neutrinoless double-beta decay. The field stands now at a turning point. A new round of experiments is currently being prepared for the next decade to cover an important region of parameter space. In parallel, advances in nuclear theory are laying the groundwork to connect the nuclear decay with the underlying new physics. Meanwhile, the particle theory landscape continues to find new motivations for neutrinos to be their own antiparticle. This review brings together the experimental, nuclear theory, and particle theory aspects connected to neutrinoless double-beta decay, to explore the path toward — and beyond — its discovery.

Other “ $m_{\beta\beta\sim}$ related” papers

[9] F. Vissani, *What Is Matter According to Particle Physics, and Why Try to Observe Its Creation in a Lab?*, Universe **7** (2021) no.3, 61

What is matter according to particle physics and why try to observe its creation in lab

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The standard model of elementary interactions has long qualified as a theory of matter, in which the postulated conservation laws (one baryonic and three leptonic) acquire theoretical meaning. However, recent observations of lepton number violations - neutrino oscillations - demonstrate its incompleteness. We discuss why these considerations suggest the correctness of Ettore Majorana's ideas on the nature of neutrino mass, and add further interest to the search for an ultra-rare nuclear process in which two particles of matter (electrons) are created, commonly called neutrinoless double beta decay. The approach of the discussion is mainly historical and its character is introductory. Some technical considerations, which highlight the usefulness of Majorana's representation of gamma matrices, are presented in the appendix.

Neutrino~ nucleus coherent scattering

[10] G. Ricciardi, N. Vignaroli and F. Vissani, *An accurate evaluation of electron (anti-)neutrino scattering on nucleons*, JHEP **08** (2022), 212

⇒ See talk by Francesco

An accurate evaluation of electron (anti-)neutrino scattering on nucleons

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We discuss as accurately as possible the cross section of quasi-elastic scattering of electron (anti-)neutrinos on nucleons, also known as inverse beta decay in the case of antineutrinos. We focus on the moderate energy range from a few MeV up to hundreds of MeV, which includes neutrinos from reactors and supernovae. We assess the uncertainty on the cross section, which is relevant to experimental advances and increasingly large statistical samples. We estimate the effects of second-class currents, showing that they are small and negligible for current applications.

Astrophysics & Neutrinos

- Solar neutrinos
- Supernova neutrinos
- High energy neutrinos
- Black hole evaporation
- Cosmology

Solar neutrinos

[11] F. L. Villante and A. Serenelli, *The relevance of nuclear reactions for Standard Solar Models construction*, Front. Astron. Space Sci. **7** (2021), 112



The relevance of nuclear reactions for Standard Solar Models construction

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ABSTRACT

The fundamental processes by which nuclear energy is generated in the Sun have been known for many years. However, continuous progress in areas such as neutrino experiments, stellar spectroscopy and helioseismic data and techniques requires ever more accurate and precise determination of nuclear reaction cross sections, a fundamental physical input for solar models. In this work, we review the current status of (standard) solar models and present a detailed discussion on the relevance of nuclear reactions for detailed predictions of solar properties. In addition, we also provide an analytical model that helps understanding the relation between nuclear cross sections, neutrino fluxes and the possibility they offer for determining physical characteristics of the solar interior. The latter is of particular relevance in the context of the conundrum posed by the solar composition, the solar abundance problem, and in the light of the first ever direct detection of solar CN neutrinos recently obtained by the Borexino collaboration. Finally, we present a short list of wishes about the precision with which nuclear reaction rates should be determined to allow for further progress in our understanding of the Sun.

Supernova neutrinos

[12] K. Rozwadowska, F. Vissani
and E. Cappellaro, *On the rate of
core collapse supernovae in the
milky way*, New Astron. **83** (2021),
101498

On the rate of core collapse supernovae in the Milky Way

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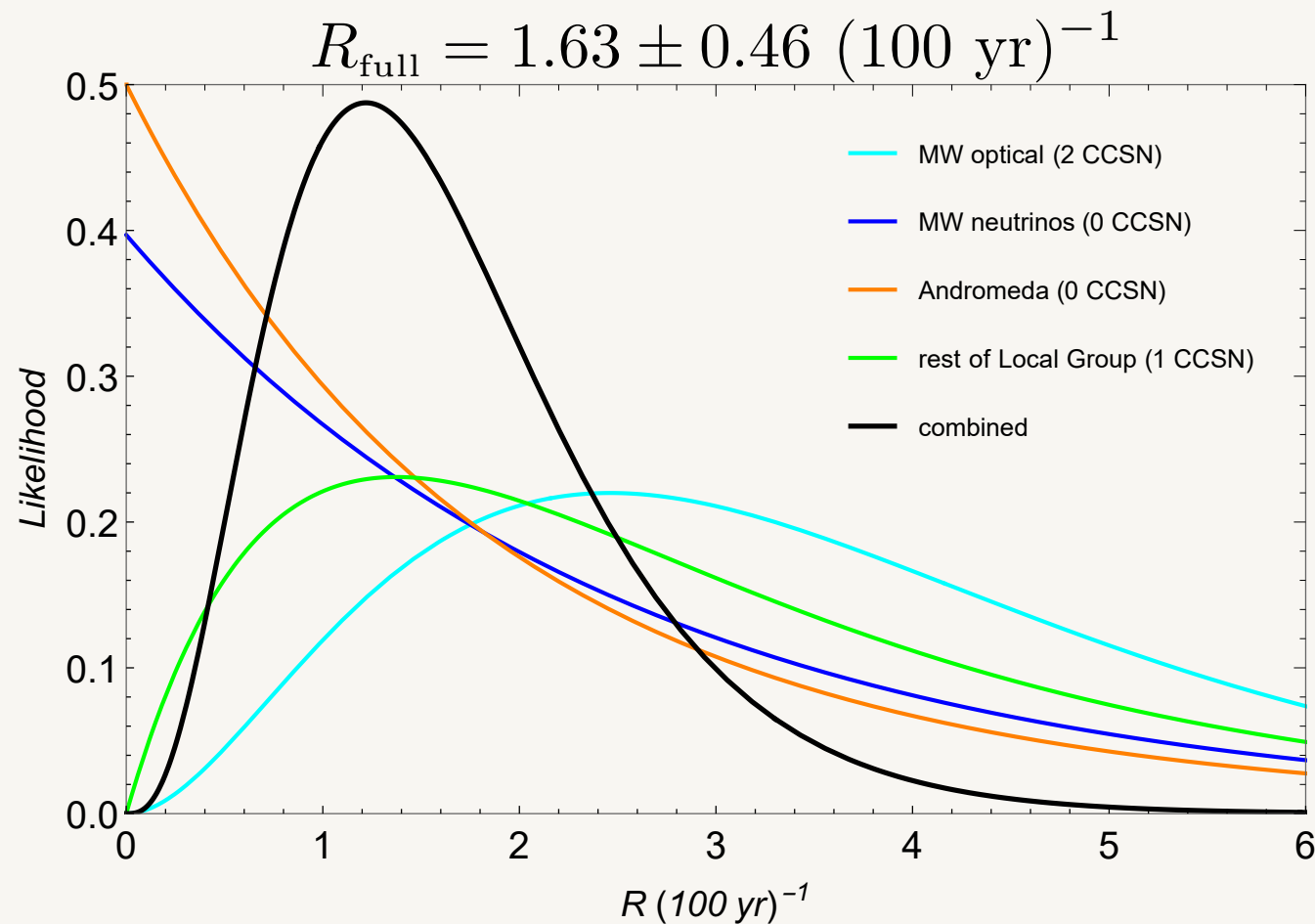
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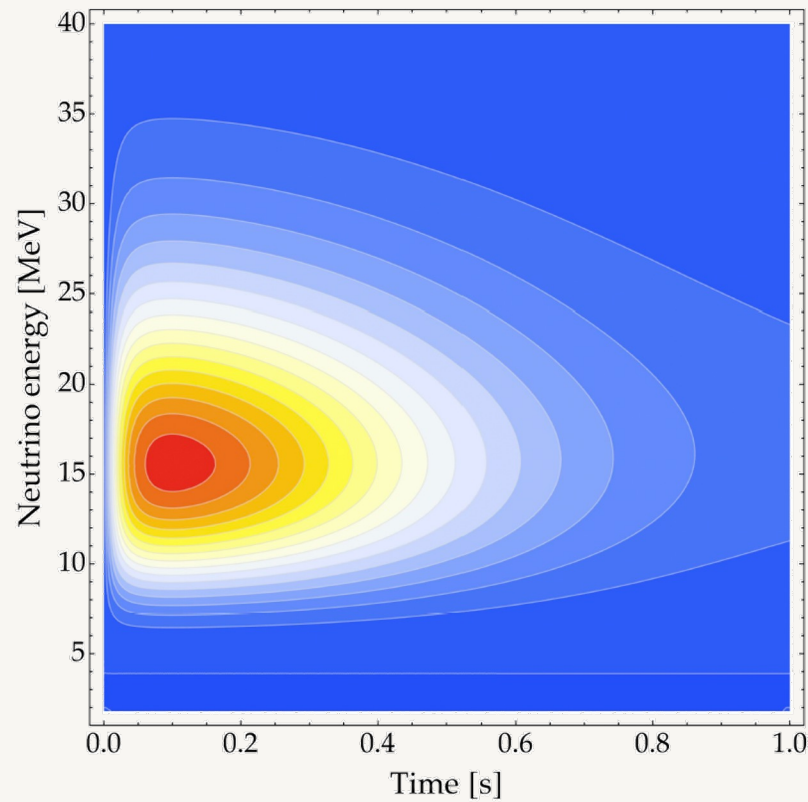
Abstract

Several large neutrino telescopes, operating at various sites around the world, have as their main objective the first detection of neutrinos emitted by a gravitational collapse in the Milky Way. The success of these observation programs depends on the rate of supernova core collapse in the Milky Way, R . In this work, standard statistical techniques are used to combine several independent results. Their consistency is discussed and the most critical input data are identified. The inference on R is further tested and refined by including direct information on the occurrence rate of gravitational collapse events in the Milky Way and in the Local Group, obtained from neutrino telescopes and electromagnetic surveys. A conservative treatment of the errors yields a combined rate $R = 1.63 \pm 0.46 (100 \text{ yr})^{-1}$; the corresponding time between core collapse supernova events turns out to be $T = 61^{+24}_{-14} \text{ yr}$. The importance to update the analysis of the stellar birthrate method is emphasized.

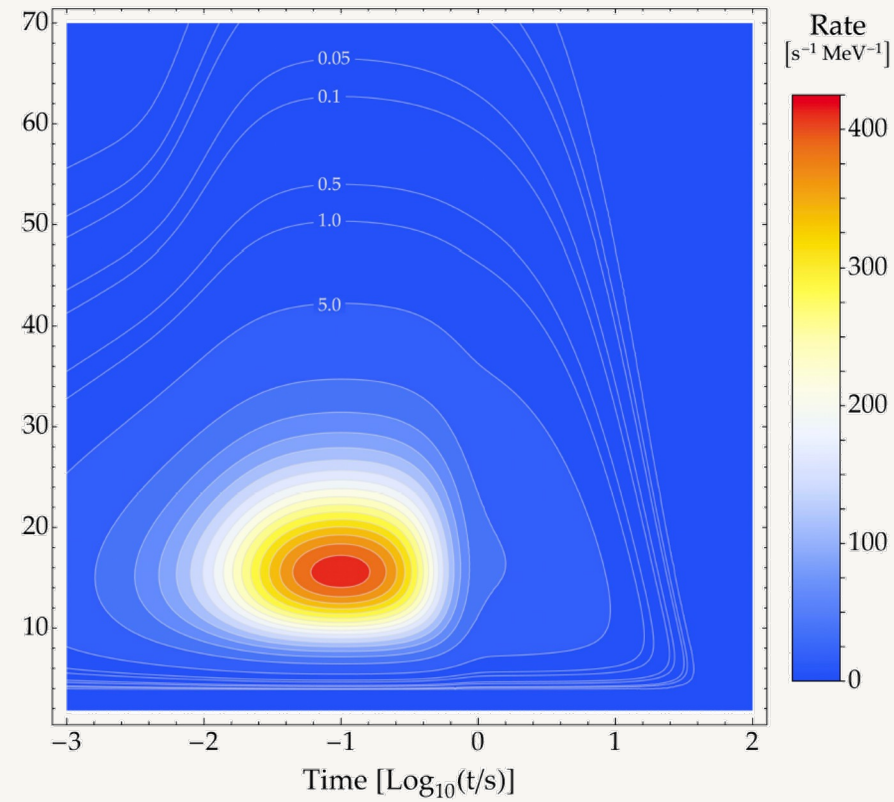
Rate of core collapse SNs in Milky Way



Expected ν counting rate in CC SN explosion



(a) Counting rate up to 1 s.



(b) Counting rate up to 100 s.

Supernova neutrinos

[13] F. Vissani and A. G. Rosso, *On the Time Distribution of Supernova Antineutrino Flux*, Symmetry **13** (2021) no.10, 1851

Article

On the Time Distribution of Supernova Antineutrino Flux

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Abstract: Neutrino leptonic flavor symmetry violation is the only evidence for physics beyond the standard model. Much of what we have learned on these particles is derived from the study of their natural sources, such as the Sun or core-collapse supernovae. Neutrino emission from supernovae is particularly interesting and leptonic flavor transformations in supernova neutrinos have attracted a lot of theoretical attention. Unfortunately, the emission of core-collapse supernovae is not fully understood: thus, an inescapable preliminary step to progress is to improve on that, and future neutrino observations can help. One pressing and answerable question concerns the time distribution of the supernova anti-neutrino events. We propose a class of models of the time distribution that describe emission curves similar to those theoretically expected and consistent with available observations from the data of supernova SN1987A. They have the advantages of being motivated on physical bases and easy to interpret; they are flexible and adaptable to the results of the observations from a future galactic supernova. Important general characteristics of these models are the presence of an initial ramp and that a significant portion of the signal is in the first second of the emission.

HE neutrinos

[13] S. Aiello et al. [KM3NeT],
Determining the neutrino mass
ordering and oscillation
parameters with KM3NeT/ORCA,
Eur. Phys. J. C 82 (2022) no.1, 26

(NAT-NET people involved in
KM3NeT: Marinelli, Migliozi,
Miele, Pisanti)

Determining the Neutrino Mass Ordering and Oscillation Parameters with KM3NeT/ORCA

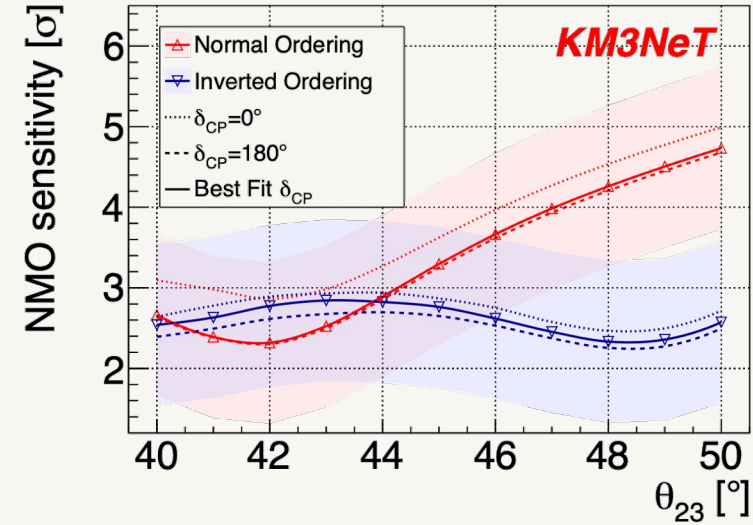


Abstract The next generation of water Cherenkov neutrino telescopes in the Mediterranean Sea are under construction offshore France (KM3NeT/ORCA) and Sicily (KM3NeT/ARCA). The KM3NeT/ORCA detector features an energy detection threshold which allows to collect atmospheric neutrinos to study flavour oscillation. This paper reports the KM3NeT/ORCA sensitivity to this phenomenon. The event reconstruction, selection and classification are described. The sensitivity to determine the neutrino mass ordering was evaluated and found to be 4.4σ if the true ordering is normal and 2.3σ if inverted, after three years of data taking. The precision to measure Δm_{32}^2 and θ_{23} were also estimated and found to be $85 \cdot 10^{-6} \text{ eV}^2$ and $(^{+1.9}_{-3.1})^\circ$ for normal neutrino mass ordering and, $75 \cdot 10^{-6} \text{ eV}^2$ and $(^{+2.0}_{-7.0})^\circ$ for inverted ordering. Finally, a unitarity test of the leptonic mixing matrix by measuring the rate of tau neutrinos is described. Three years of data taking were found to be sufficient to exclude $\bar{\nu}_\tau$ event rate variations larger than 20% at 3σ level.

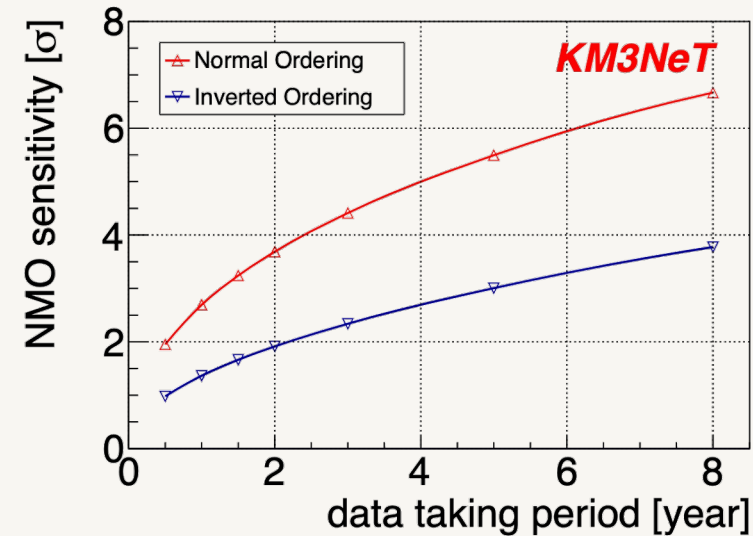
KM3NeT sensitivity

Assumptions

Parameter		Null Hypothesis Values	Constraints
Δm_{21}^2		$7.39 \cdot 10^{-5} \text{ eV}^2$	fixed
θ_{12}		33.82°	fixed
θ_{13}	NO	8.60°	$\pm 0.13^\circ$
	IO	8.64°	
Δm_{31}^2	NO	$2.528 \cdot 10^{-3} \text{ eV}^2$	free
	IO	$2.436 \cdot 10^{-3} \text{ eV}^2$	
θ_{23}	NO	$48.6^\circ, [40^\circ-50^\circ]^\dagger$	free
	IO	$48.8^\circ, [40^\circ-50^\circ]^\dagger$	
δ_{CP}	NO	$221.0^\circ, 0^\circ, 180.0^\circ$	free
	IO	$282.0^\circ, 0^\circ, 180.0^\circ$	



(a)



HE neutrinos

[14] S. Aiello et al. [KM3NeT and JUNO], Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering, JHEP **03** (2022), 055

(NAT-NET people involved in KM3NeT: Marinelli, Migliozzi, Miele, Pisanti)

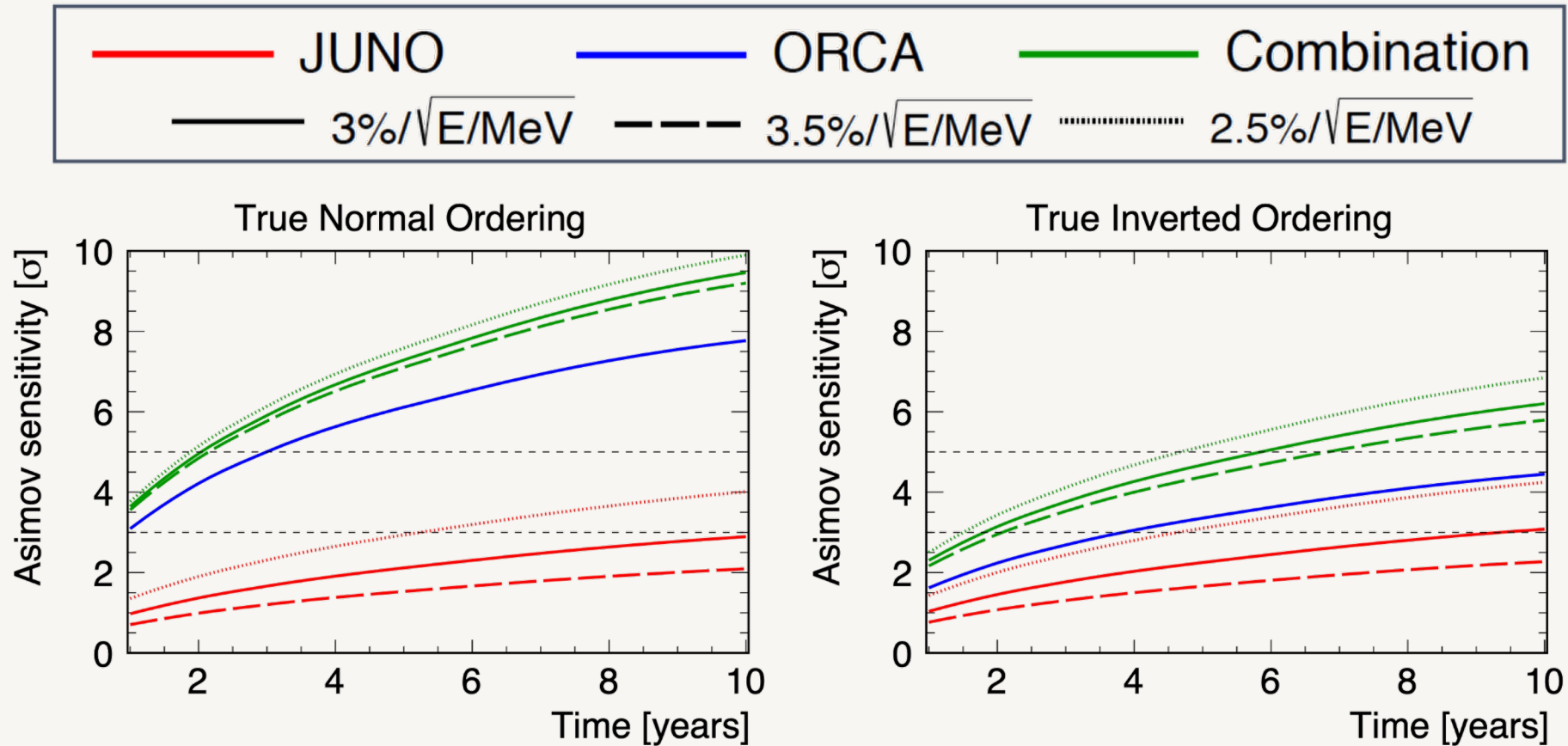
Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering



Abstract

This article presents the potential of a combined analysis of the JUNO and KM3NeT/ORCA experiments to determine the neutrino mass ordering. This combination is particularly interesting as it significantly boosts the potential of either detector, beyond simply adding their neutrino mass ordering sensitivities, by removing a degeneracy in the determination of Δm_{31}^2 between the two experiments when assuming the wrong ordering. The study is based on the latest projected performances for JUNO, and on simulation tools using a full Monte Carlo approach to the KM3NeT/ORCA response with a careful assessment of its energy systematics. From this analysis, a 5σ determination of the neutrino mass ordering is expected after 6 years of joint data taking for any value of the oscillation parameters. This sensitivity would be achieved after only 2 years of joint data taking assuming the current global best-fit values for those parameters for normal ordering.

MO sensitivity as function of Data-Taking time



Primordial Black Holes

[15] R. Calabrese, D. F. G. Fiorillo, G. Miele, S. Morisi and A. Palazzo, *Primordial black hole dark matter evaporating on the neutrino floor*, Phys. Lett. B **829** (2022), 137050

Primordial Black Hole Dark Matter evaporating on the Neutrino Floor

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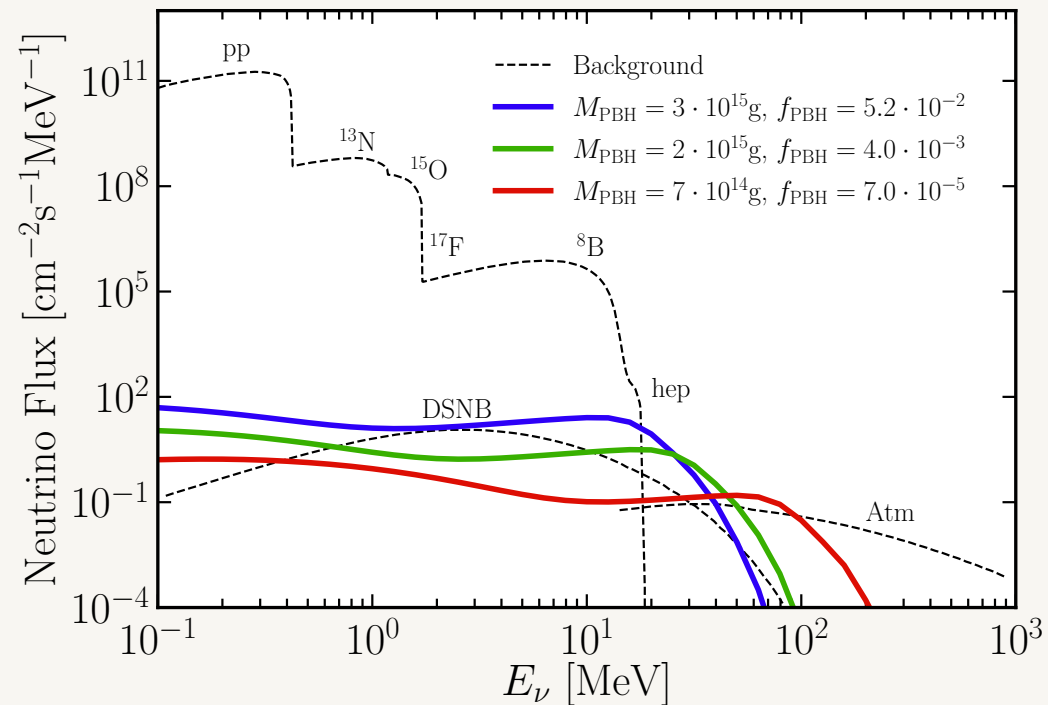
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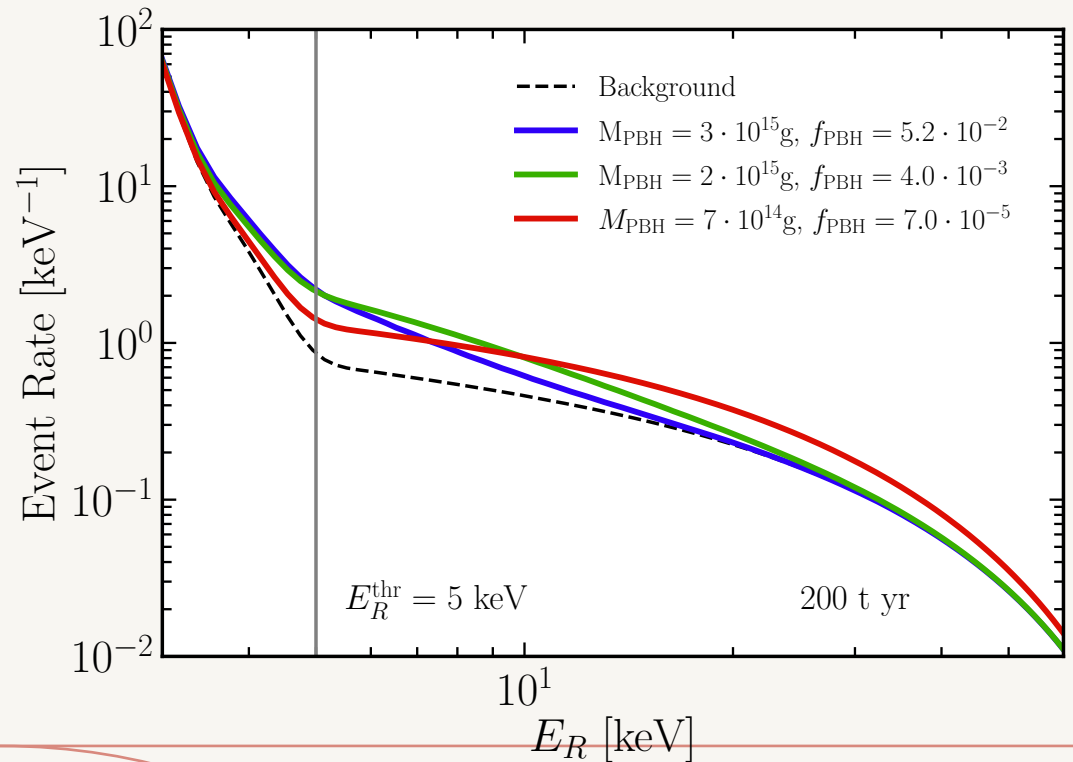
Primordial black holes (PBHs) hypothetically generated in the first instants of life of the Universe are potential dark matter (DM) candidates. Focusing on PBHs masses in the range $[5 \times 10^{14} - 5 \times 10^{15}]g$, we point out that the neutrinos emitted by PBHs evaporation can interact through the coherent elastic neutrino nucleus scattering (CE ν NS) producing an observable signal in multi-ton DM direct detection experiments. We show that with the high exposures envisaged for the next-generation facilities, it will be possible to set bounds on the fraction of DM composed by PBHs improving the existing neutrino limits obtained with Super-Kamiokande. We also quantify to what extent a signal originating from a small fraction of DM in the form of PBHs would modify the so-called “neutrino floor”, the well-known barrier towards detection of weakly interacting massive particles (WIMPs) as the dominant DM component.

Background neutrinos coming from PBH's

- ν flux from BPH's



- Coherent scattering



Cosmology

[15] M. Cielo, M. Escudero, G. Mangano and O. Pisanti, *Neff in the Standard Model at NLO is 3.043*, [arXiv:2306.05460 [hep-ph]]

Neff in the Standard Model at NLO is 3.043

Mattia Cielo,^{1,*} Miguel Escudero,^{2,†} Gianpiero Mangano,^{1,‡} and Ofelia Pisanti^{1,§}

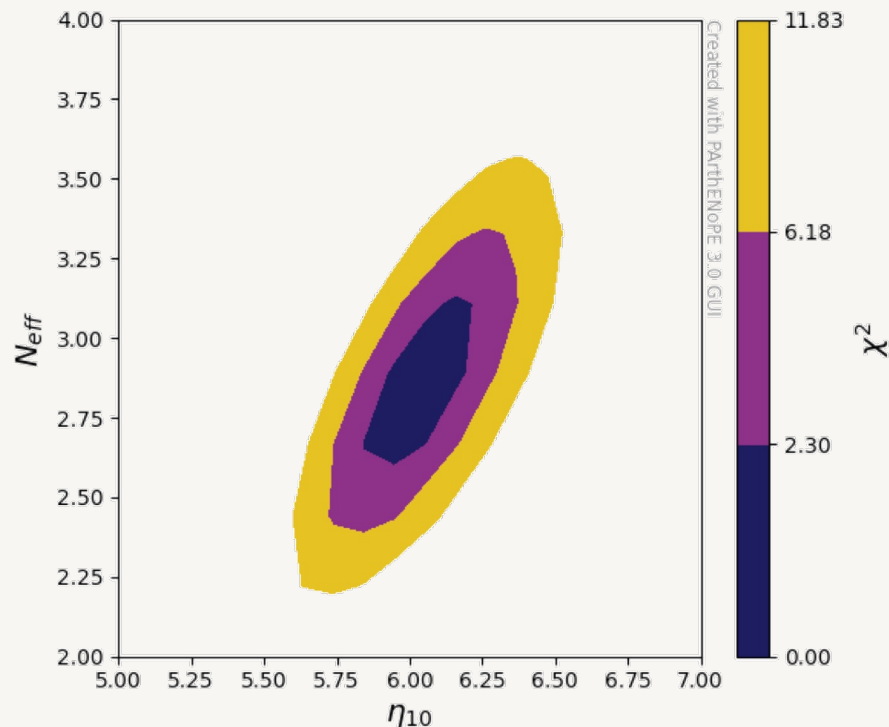
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²*Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

The effective number of relativistic neutrino species is a fundamental probe of the early Universe and its measurement represents a key constraint on many scenarios beyond the Standard Model of Particle Physics. In light of this, an accurate prediction of N_{eff} in the Standard Model is of pivotal importance. In this work, we consider the last ingredient needed to accurately calculate $N_{\text{eff}}^{\text{SM}}$: standard zero and finite temperature QED corrections to $e^+e^- \leftrightarrow \nu\bar{\nu}$ interaction rates during neutrino decoupling at temperatures around $T \sim \text{MeV}$. We find that this effect leads to a reduction of -0.0007 in $N_{\text{eff}}^{\text{SM}}$. This NLO correction to the interaction rates, together with finite temperature QED corrections to the electromagnetic density of the plasma, and the effect of neutrino oscillations, implies that $N_{\text{eff}}^{\text{SM}} = 3.043$ with a theoretical uncertainty that is much smaller than any projected observational sensitivity.

Cosmology

[16] S. Gariazzo, P. F. de Salas, O. Pisanti and R. Consiglio, *PARthENoPE revolutions*, Comput. Phys. Commun. **271** (2022), 108205



PARthENoPE Revolutions

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Abstract

This paper presents the main features of a new and updated version of the program PARthENoPE, which the community has been using for many years for computing the abundances of light elements produced during Big Bang Nucleosynthesis. This is the third release of the PARthENoPE code, after the 2008 and the 2018 ones, and will be distributed from the code's website, <http://parthenope.na.infn.it>. Apart from minor changes, the main improvements in this new version include a revisited implementation of the nuclear rates for the most important reactions of deuterium destruction, $^2\text{H}(p,\gamma)^3\text{He}$, $^2\text{H}(d,n)^3\text{He}$ and $^2\text{H}(d,p)^3\text{H}$, and a re-designed GUI, which extends the functionality of the previous one. The new GUI, in particular, supersedes the previous tools for running over grids of parameters with a better management of parallel runs, and it offers a brand-new set of functions for plotting the results.

Keywords: primordial nucleosynthesis, cosmology, neutrino physics

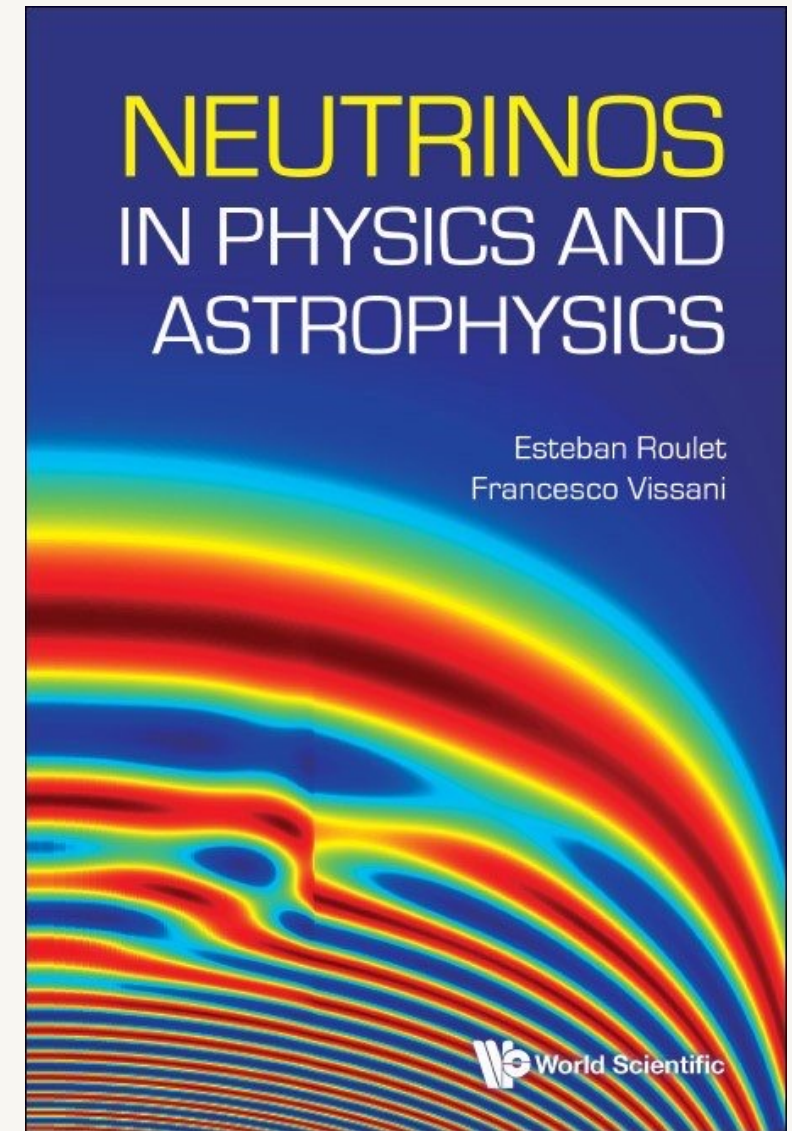
Neutrinos in Physics and Astrophysics

Esteban Roulet, Francesco Vissani

World Scientific Press

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Thanks to everybody



Goodbye and see you again to the Pantheon