

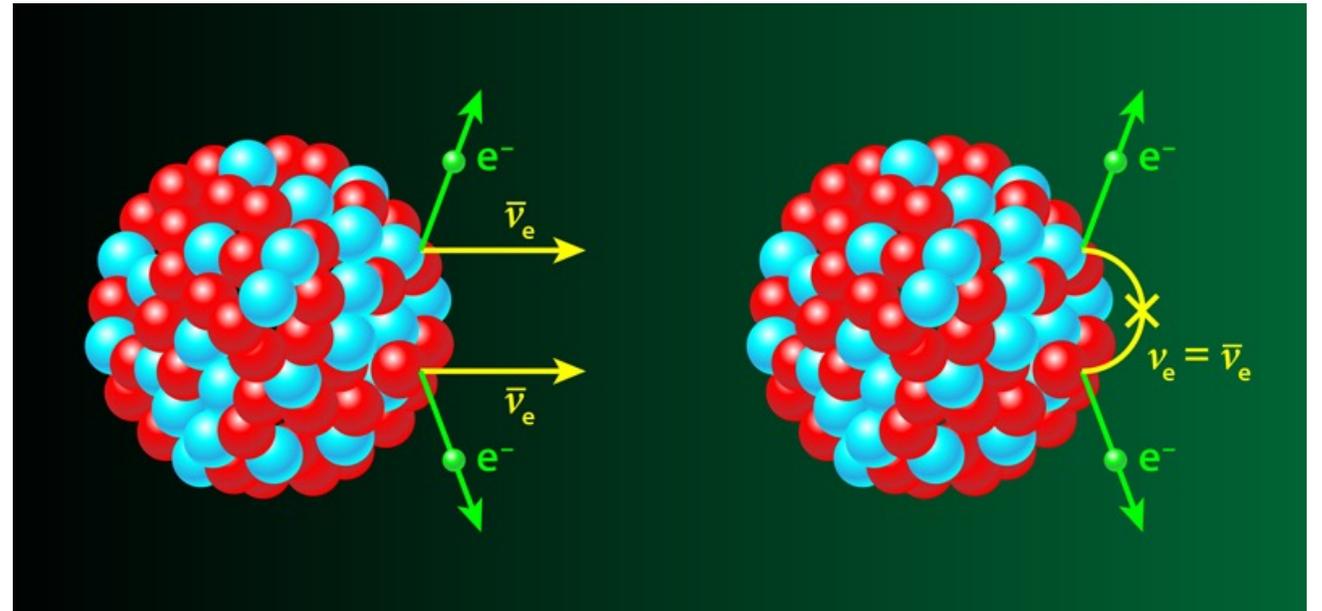
Double Beta Decay review (theory & experiment)

David Moore

Wright Lab, Yale University

TAUP 2023

August 29, 2023



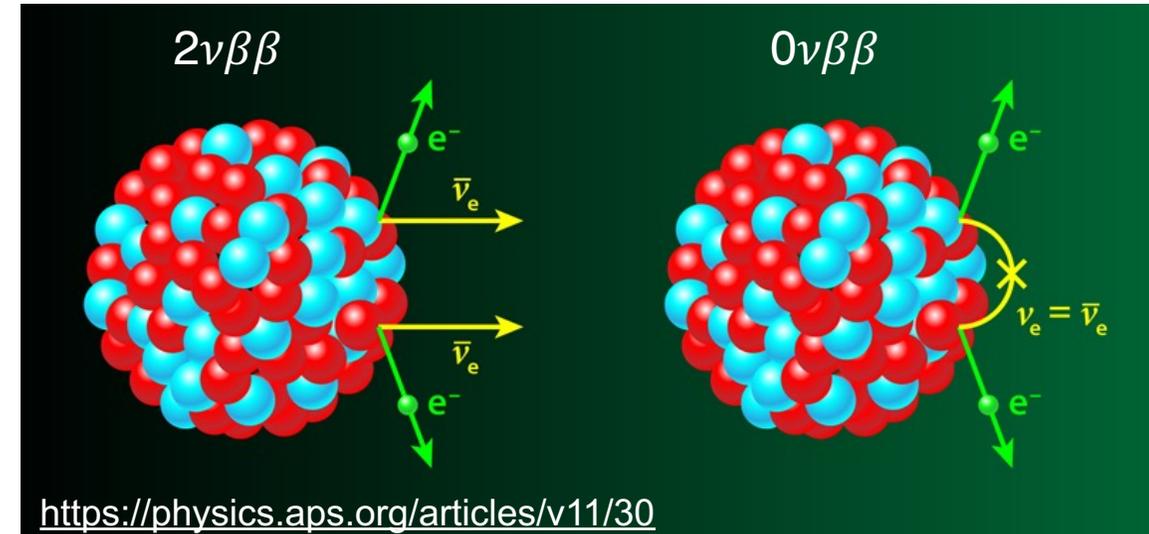
Yale

 Wright
Laboratory

Neutrinoless double beta decay ($0\nu\beta\beta$)

- Searches for $0\nu\beta\beta$ are a powerful experimental probe of lepton number violation (LNV) and other beyond-the-SM physics
- Observation of $0\nu\beta\beta$ would provide key input to explaining the nature and origin of neutrino mass
- Detection of this rare decay would:
 - Demonstrate that neutrinos are Majorana fermions
 - Provide a process where matter particles are created without antimatter (LNV)
 - Complement information from other measurements of the ν mass scale

Schematic of $\beta\beta$ decay processes:

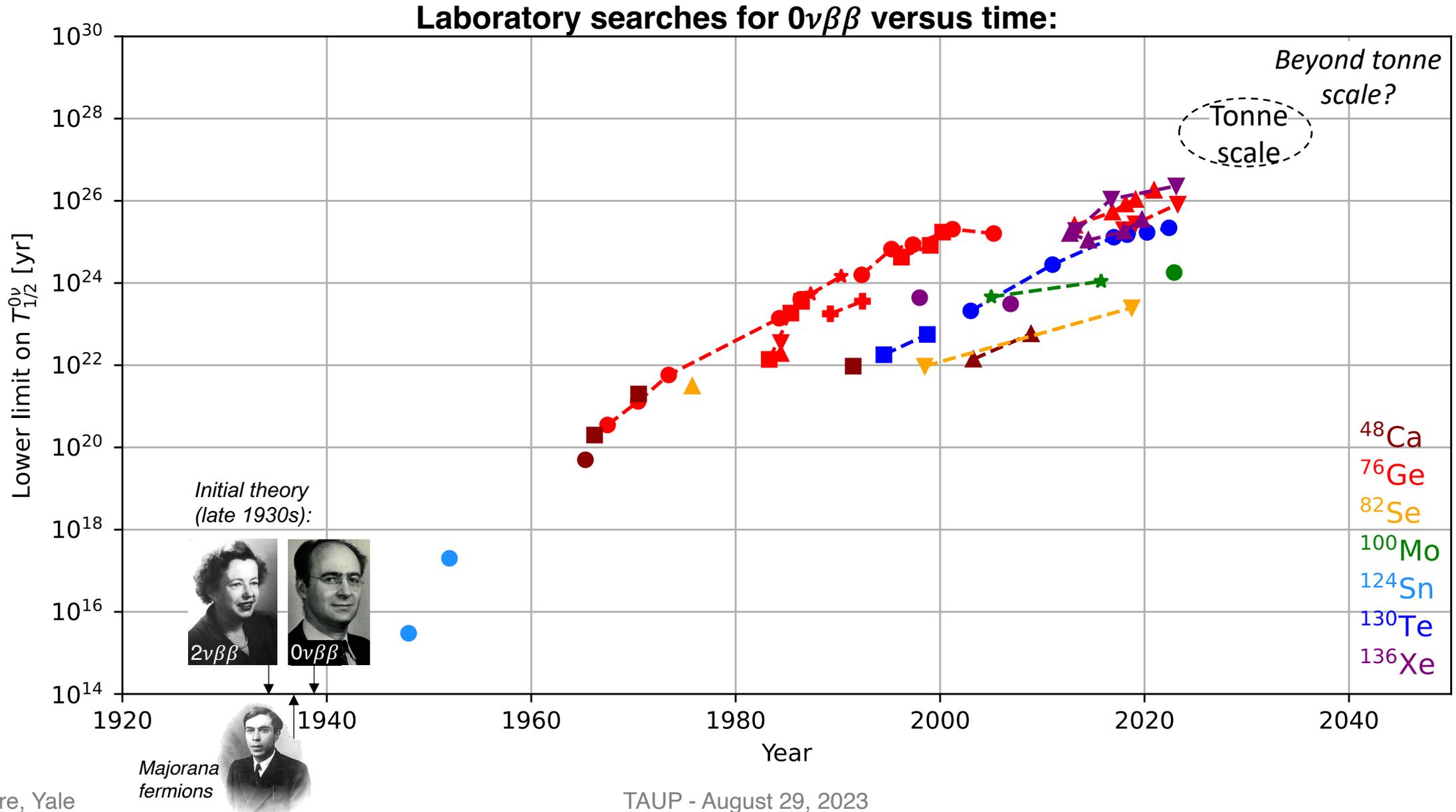


$$2\nu\beta\beta: (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

$$0\nu\beta\beta: (A, Z) \rightarrow (A, Z+2) + 2e^-$$

Rapid experimental and theoretical progress may put observation of this beyond the Standard Model process within reach in the coming years!

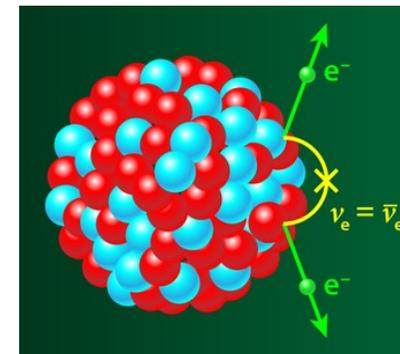
Sensitivity vs. time:



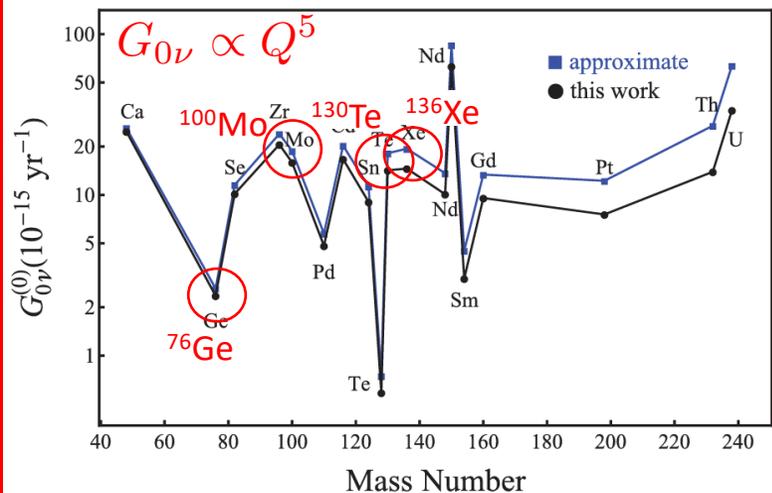
Decay rate

“Standard Mechanism” (light Majorana ν mediates decay):

$$(T_{1/2}^{0\nu})^{-1} = \left[G_{0\nu} \right] \left[g_A^4 |M^{0\nu}|^2 \right] \left[\frac{\langle m_{\beta\beta} \rangle^2}{m_e^2} \right]$$

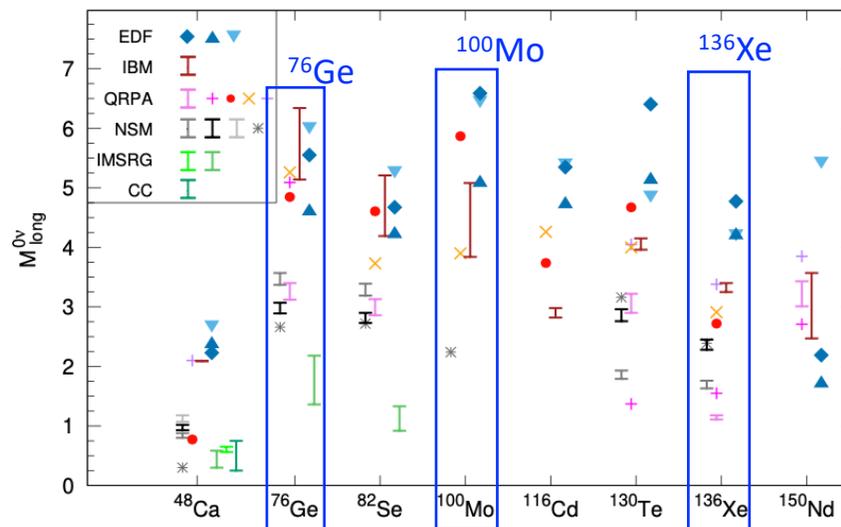


Phase space
(accurately calculated):



Phys. Rev. C 85, 034316 (2012)

Nuclear Matrix Element
(significant theory uncertainty):



Rev. Mod. Phys. 95, 025002 (2023)

Effective Majorana Mass
(assumes “standard” mechanism):

$$\langle m_{\beta\beta} \rangle = \left| \sum |U_{ei}|^2 e^{i\phi_i} m_i \right|$$

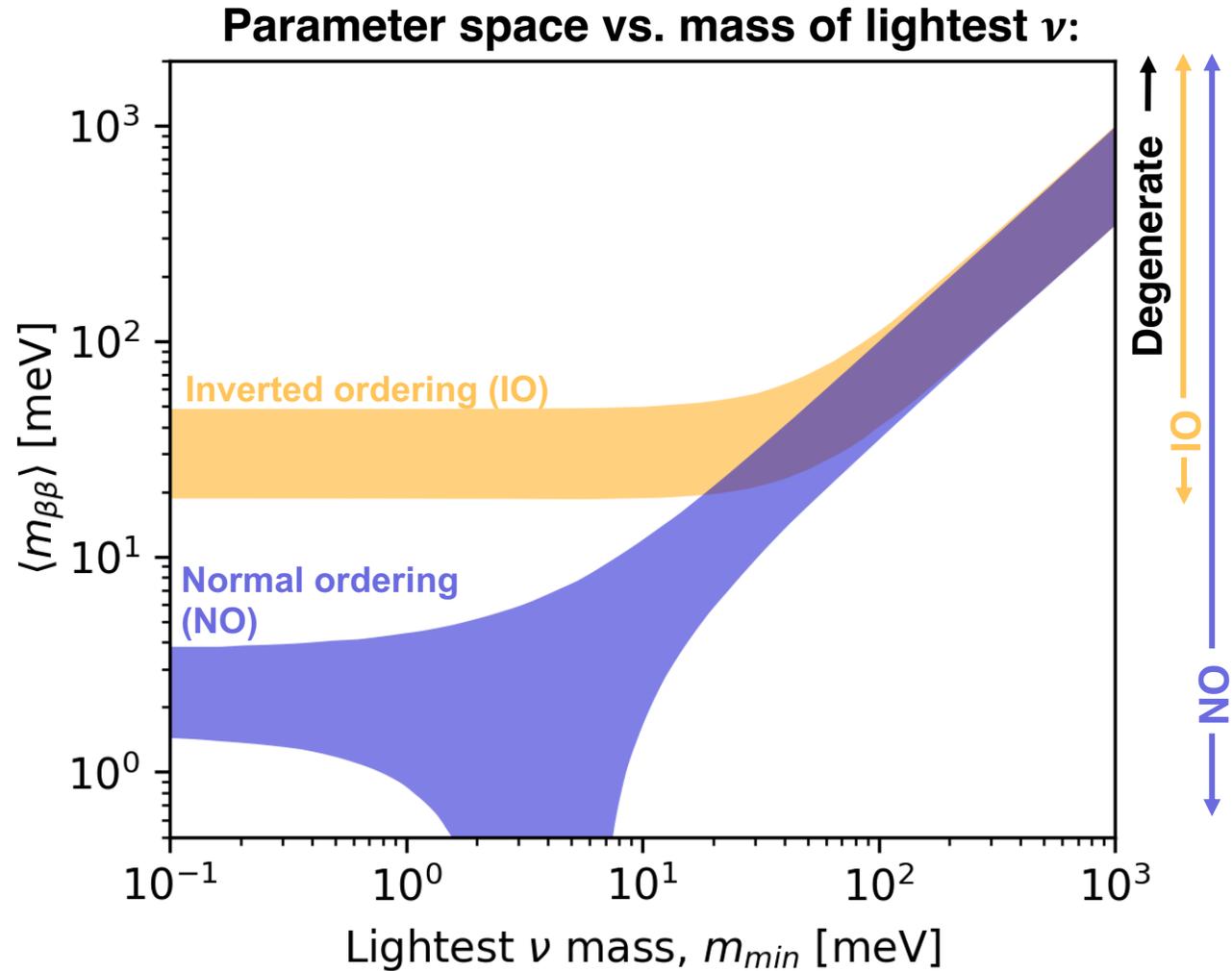
$$= |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}|$$

α, β are unknown Majorana phases

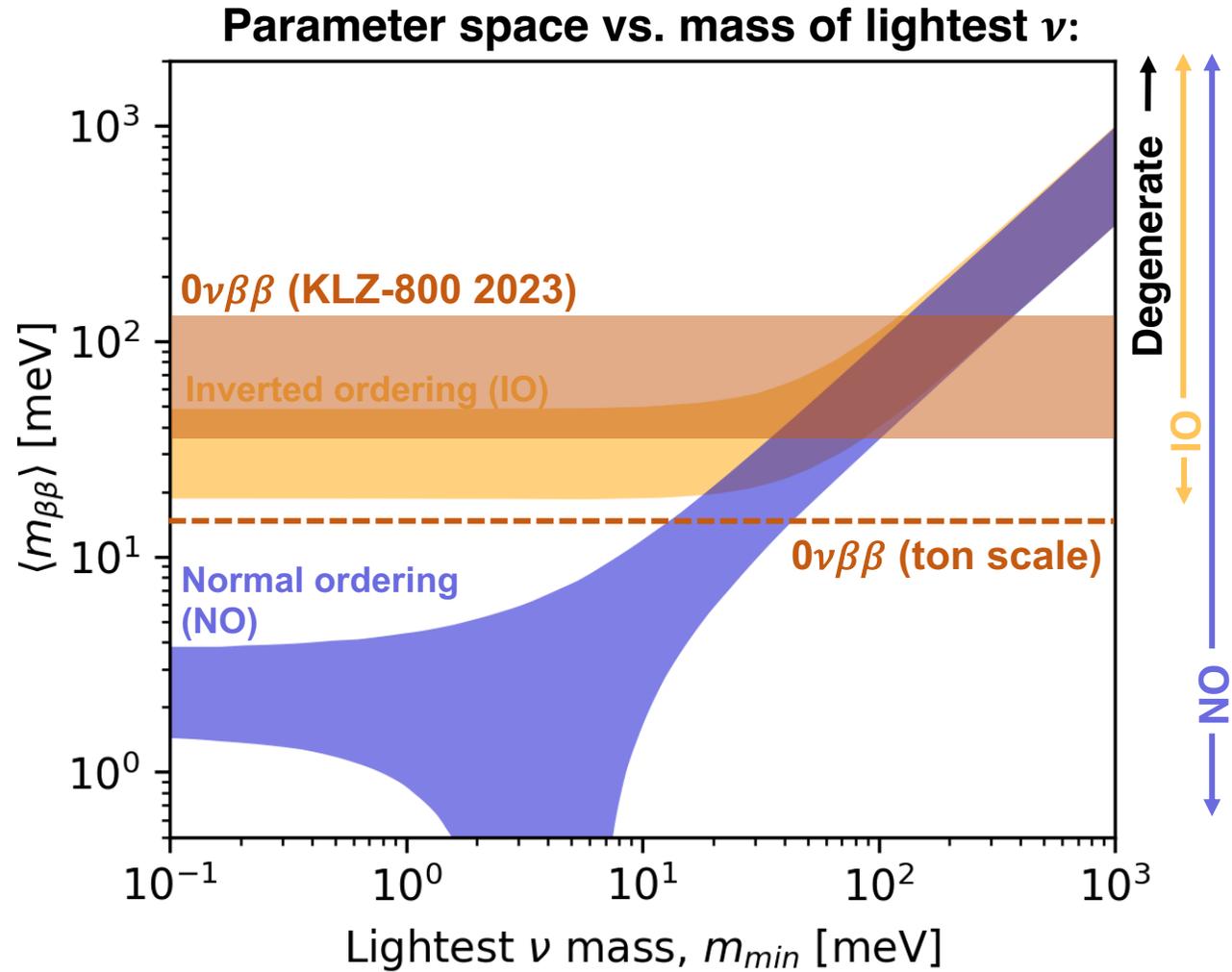
↳ Not measurable in oscillation experiments

This is only one model -- other LNV physics also possible!

Allowed parameter space

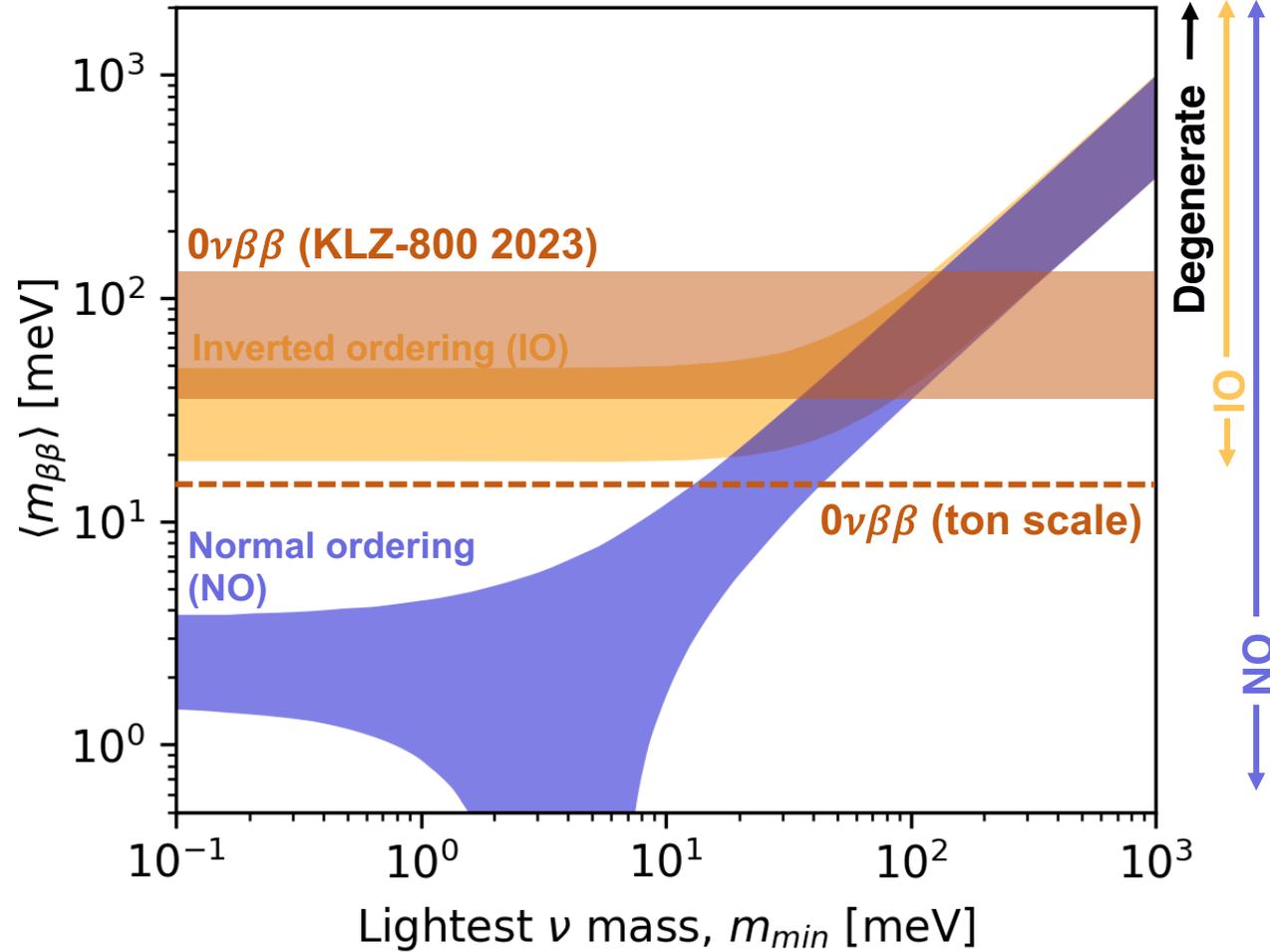


Allowed parameter space

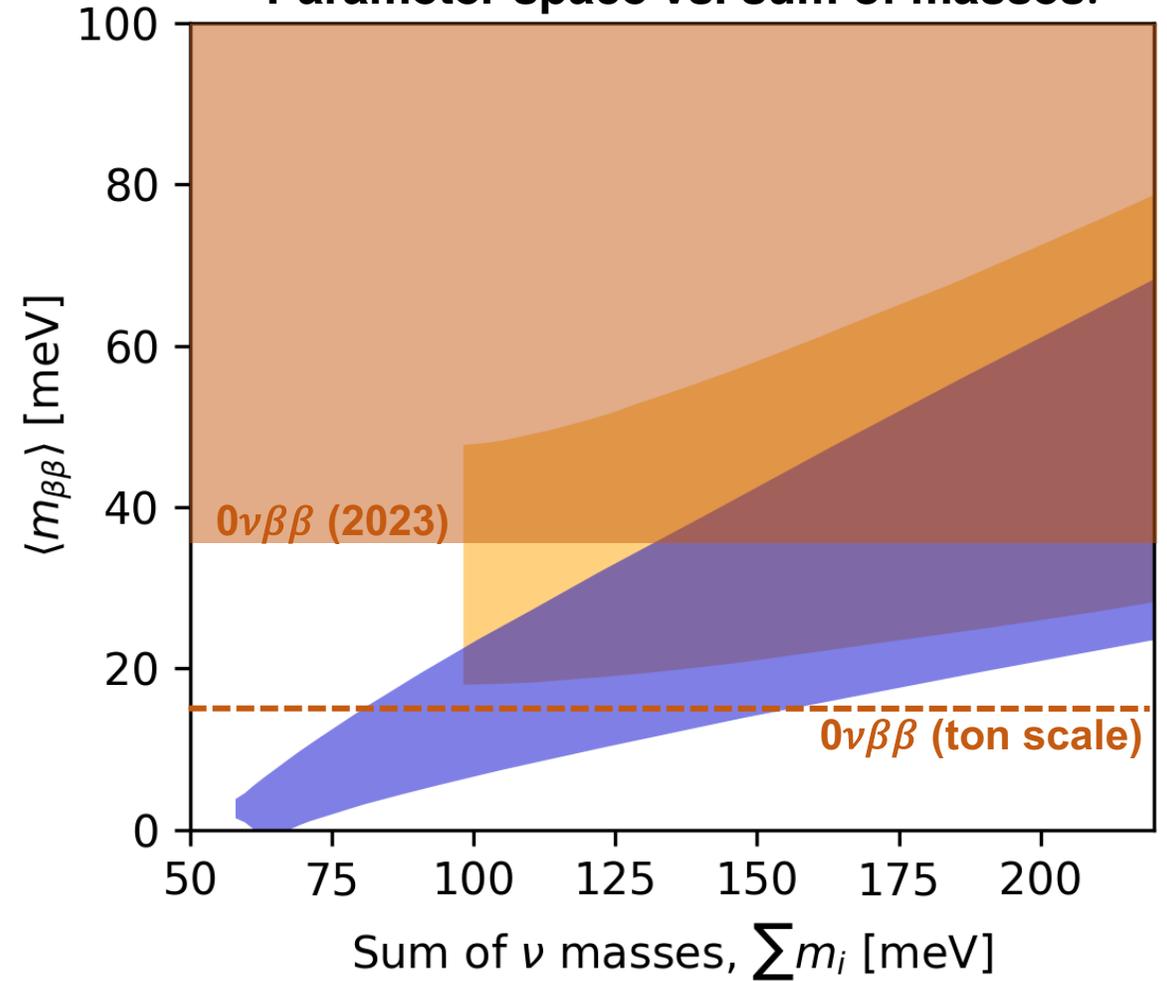


Allowed parameter space

Parameter space vs. mass of lightest ν :

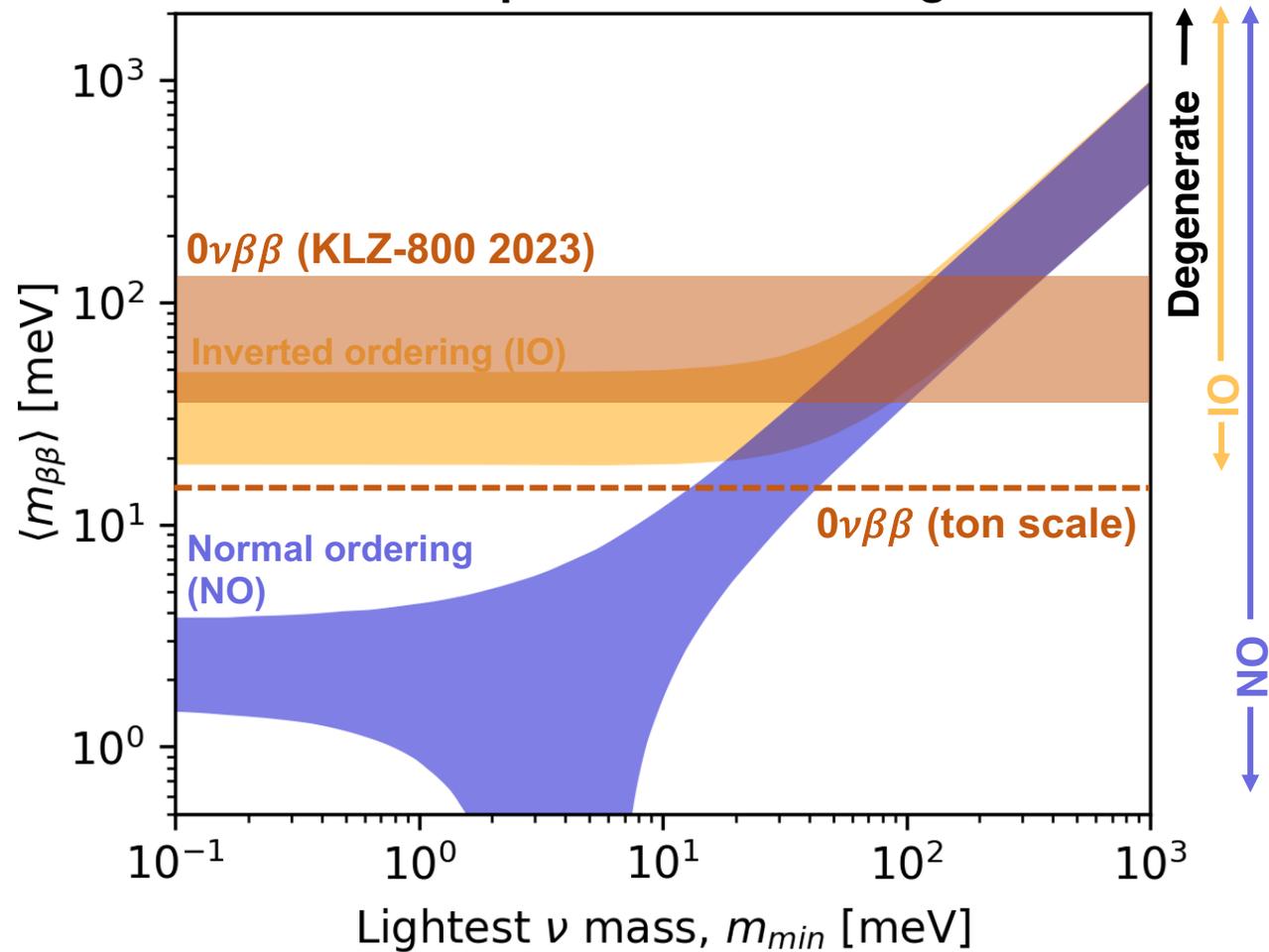


Parameter space vs. sum of masses:

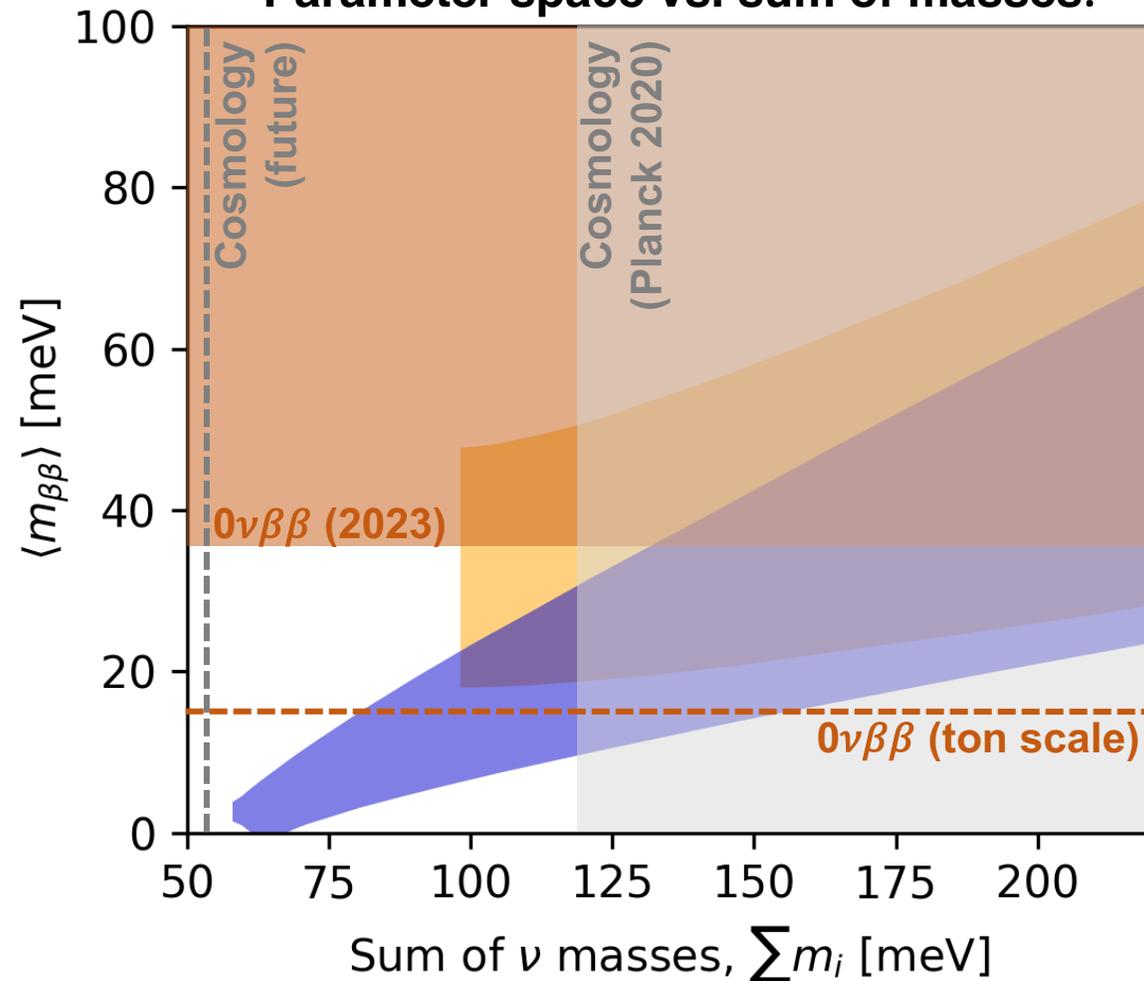


Allowed parameter space

Parameter space vs. mass of lightest ν :

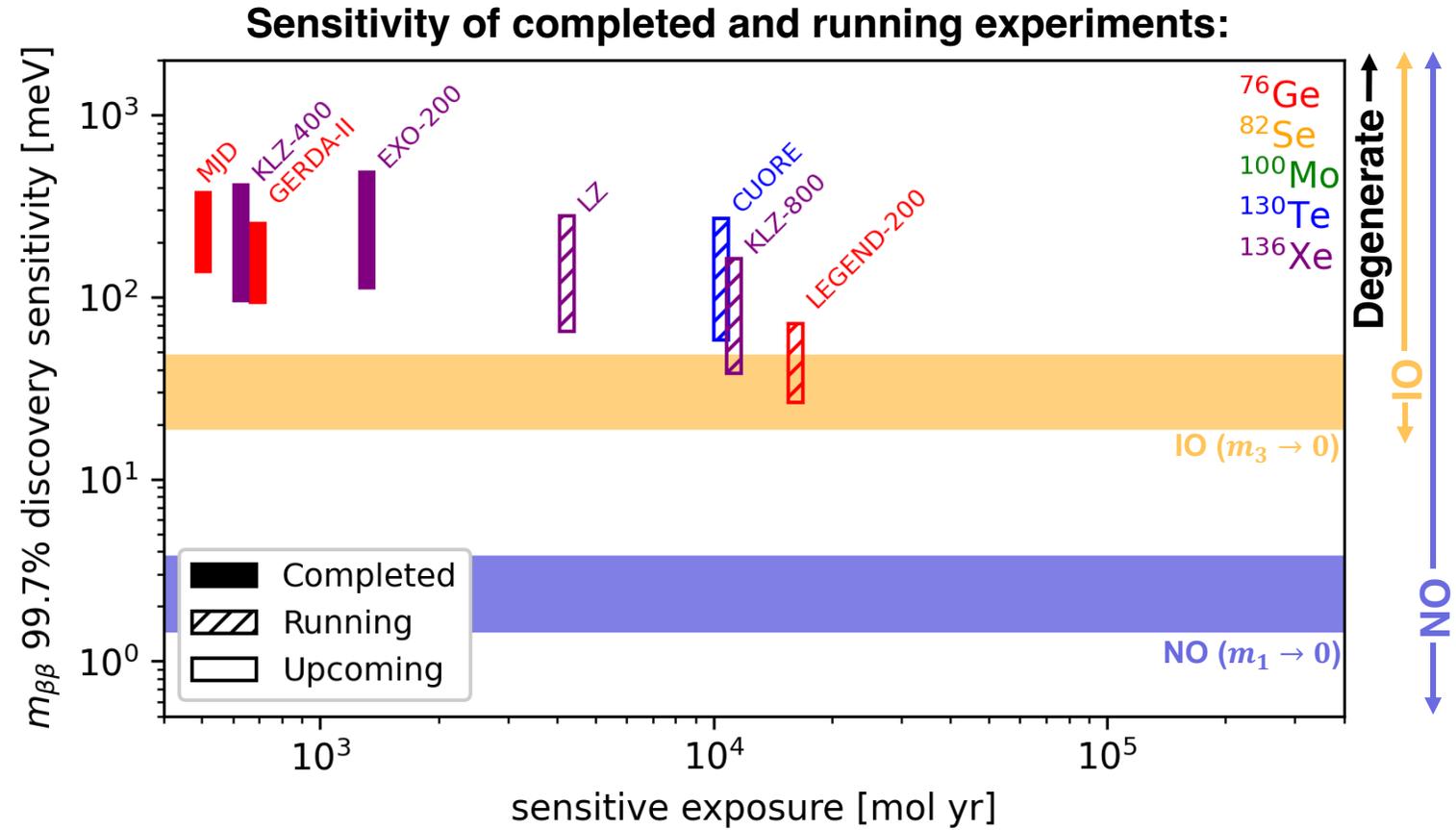
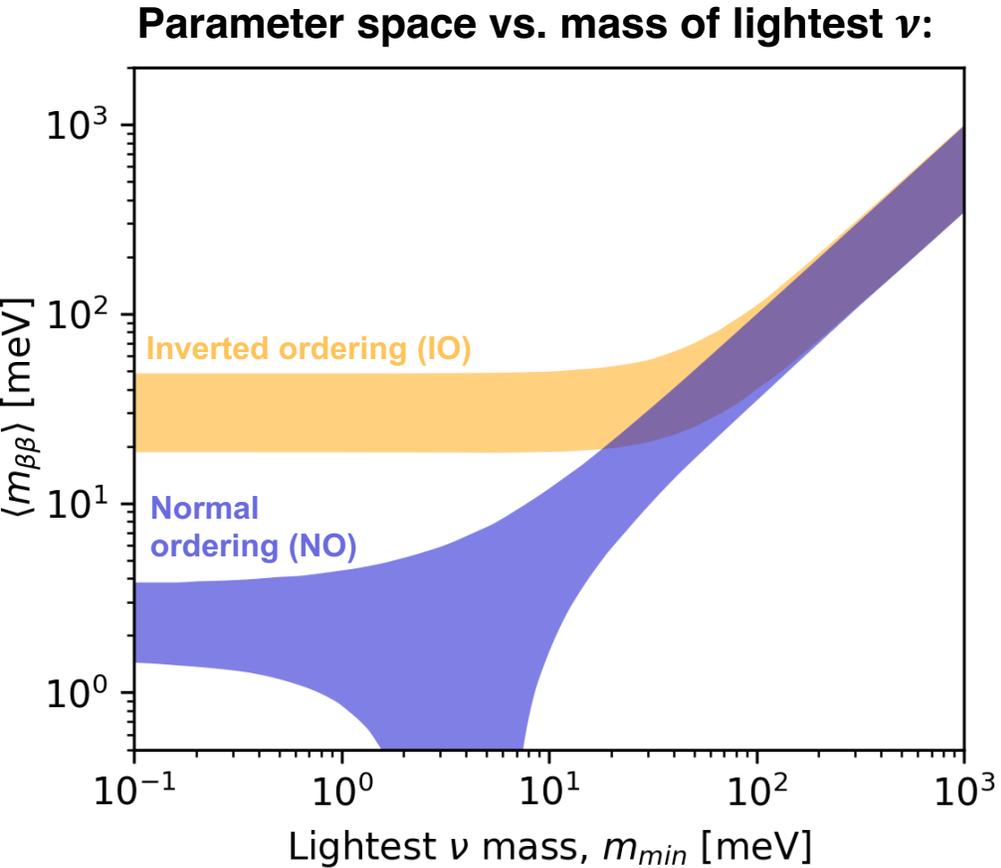


Parameter space vs. sum of masses:



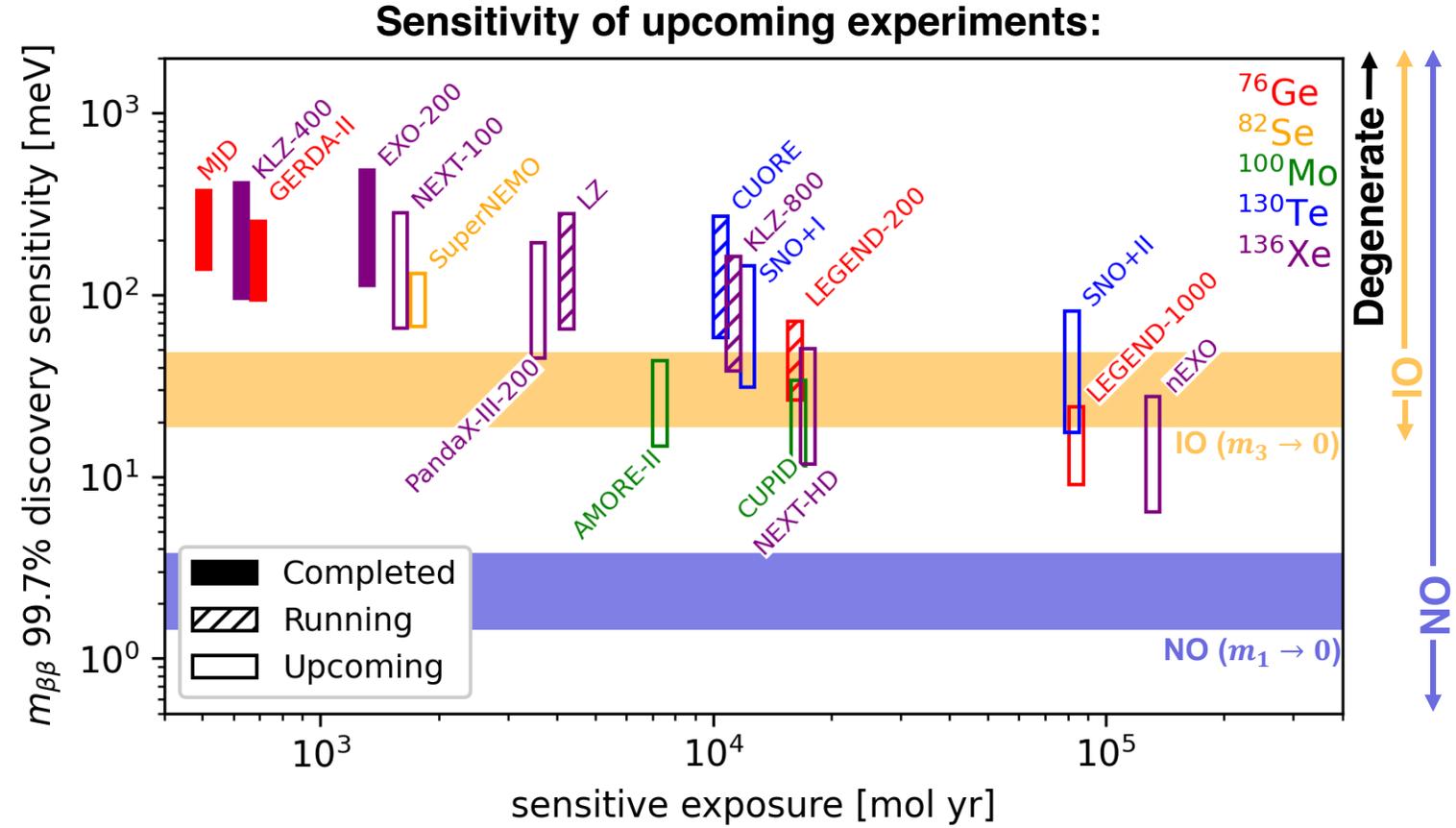
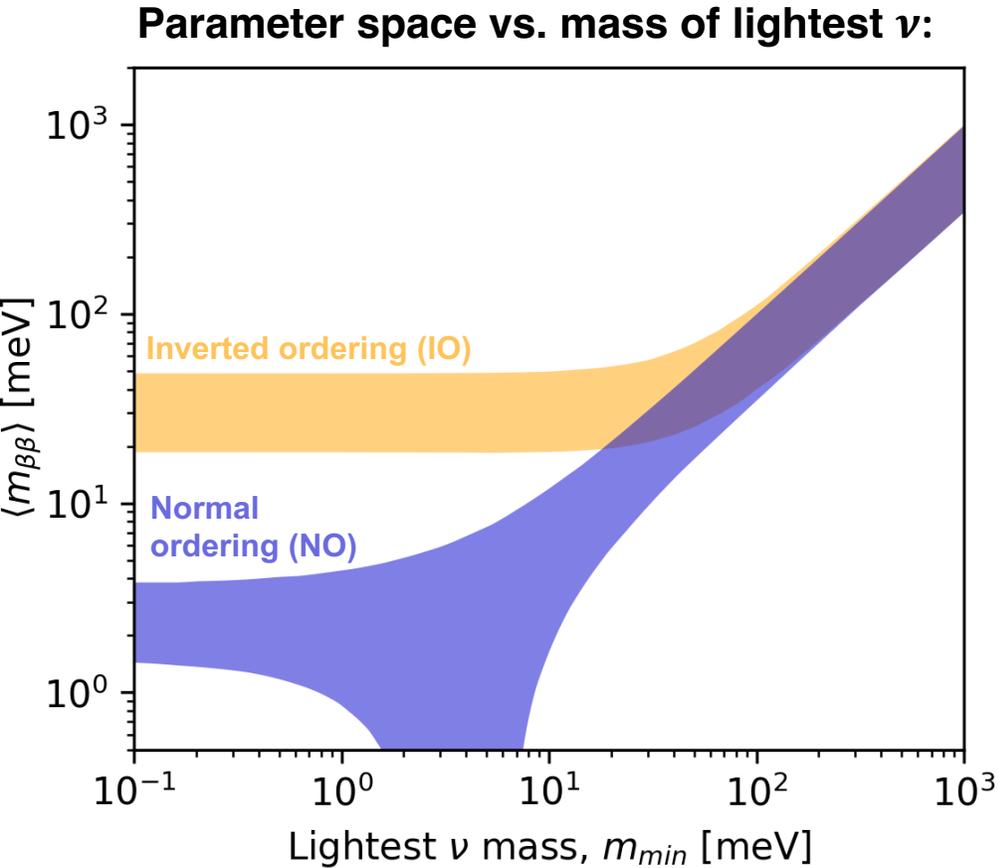
See also constraints from β -decay endpoint (previous talk by Thierry Lasserre): $m_\beta < 0.8$ eV (KATRIN, 2022)

Current sensitivity



Plot adapted from arXiv:2212.11099,
R. Saldanha (private comm.)

Upcoming experiments



Plot adapted from *arXiv:2212.11099*,
R. Saldanha (private comm.)

Presentations at TAUP

	Session:	Title:	Presenter:
Aug 28, 2023	Neutrino and cosmology 1	Synergy between neutrinoless double-beta decay and cosmology towards the discovery of Majorana neutrinos	Stefano Dell'Oro
Aug 29, 2023	Dark matter and Neutrino 1	Exploring New Physics up to the MeV energy scale with XENONnT	Maxime Pierre
		Progress of double-weak decays and solar pp neutrinos in PandaX-4T experiment	Xiang Xiao
		XLZD beyond WIMPs: Neutrino-less double beta-decay and More!	Kimberly Palladino
	Neutrino physics 3A	Latest results from the CUORE experiment	Krystal Alfonso
		Final results of the CUPID-Mo 0 experiment	Léonard Imbert
		Liquid argon light collection and veto modeling in GERDA Phase II	Luigi Pertoldi
		Neutrinoless double-beta decay search with SNO+	Valentina Lozza
		A New ^{82}Se detector for Neutrinoless Double Beta Decay Searches	Emilio Ciuffoli
		Demonstration of TI-208 background reduction using topological information of Cherenkov light and observation of Zr-96 2vbb	Yoshiyuki Fukuda
	Neutrino physics 4A	First results from the CUORE background model	Stefano Ghislandi
		LEGEND-200: From Construction to Physics Data Taking	Michael Willers
		LEGEND-200: First glance at the background in physics data	Katharina von Sturm
		Status of AMoRE-II	Yoomin Oh
		R&D status of the Selena Neutrino Experiment	Alvaro Chavarria
		New prospects in the search for neutrinoless double beta decay of ^{96}Zr	Serge Nagorny
Aug 30, 2023	Neutrino physics 5A	CUPID the next generation $0\nu\beta\beta$ bolometric experiment	Claudia Nones
		Final Results of the MAJORANA DEMONSTRATOR and Improvements in its Background Model	Christopher Haufe
		The MAJORANA DEMONSTRATOR's Search for Double-Beta Decay of ^{76}Ge to Excited States of ^{76}Se	Ian Guinn
		LEGEND-1000: A Ton-Scale Search for Neutrinoless Double-Beta Decay in Ge-76	Vincente Guiseppe
		Discovering the origin of matter with liquid xenon neutrinoless double-beta decay detectors: nEXO and beyond	Samuele Sangiorgio
	Neutrino physics 6A	Final results of the CUPID-0 combined background model	Emanuela Celi
		Result of AMoRE-I Experiment	Han Beom Kim
		NEXT: first neutrino-less double beta decay searches in gaseous Xe and roadmap towards a ton-scale detector	Pau Novella Garijo
		Status of SuperNEMO and Analysis of First Data	Cheryl Patrick
		BINGO: investigation of the Majorana nature of neutrinos at a few meV level of the neutrino mass scale	Vladyslav Berest
		CDEX-300v program for Ge-76 neutrinoless double beta decay search	Prof. Hao Ma
	Neutrino physics 6B	Neutrinoless double beta decay: interplay between nuclear matrix elements and neutrino exchange mechanisms	Antonio Marrone
	Neutrino and Cosmology 3	Low Energy Neutrino Physics with THEIA and EOS	Hans Th. J. Steiger

Posters:	Presenter:
64. Denoising Signals from a High-Purity Germanium Detector using Generative Adversarial Networks with Convolutional Autoencoders	Tianai Ye
114. Constraining the $^{77(m)}\text{Ge}$ Production with GERDA Data and Implications for LEGEND-1000	Moritz Neuberger
118. Projections of discovery potentials for future neutrinoless double beta decay experiments	Manoj Kumar Singh
152. The LEGEND-200 Liquid Argon Instrumentation: From a simple veto to a full-fledged detector	Rosanna Deckert
155. Enhancing Performance for AMoRE-II Detectors Using Lithium Molybdate Crystal Absorber	Jungho So
168. Studies on a deep convolutional autoencoder for denoising pulses from a p-type point contact germanium detector	Mark Anderson
170. Background simulation for AMoRE-II experiment	Jeewon Seo
181. Muon Veto of the LEGEND Experiment	Gina Grünauer
182. Purification of $^{100}\text{MoO}_3$ powder for AMoRE-II crystals' synthesis	Olga Gileva
183. Backgrounds and sensitivity of the CUPID experiment	Pia Loiaza
216. Denoising Algorithms for the CUORE Experiment	Kenny Vetter
233. Impact of marine macroseisms on the response of the CUORE cryogenic calorimeters	Simone Quitadamo
317. Event Reconstruction in the SNO+ Experiment	Tereza Kroupova
323. Optimizing Energy Reconstruction for nEXO	Clarke Hardy
346. SNO+ Tellurium Purification and Loading for Neutrinoless Double Beta Decay Search	Szymon Manecki
347. LEGEND-200 Data Acquisition, Monitoring and Calibration	Brady Bos
372. Development of enhanced light detectors for CUPID experiment	Vladyslav Berest
380. Background Modeling for LEGEND-200	Rushabh Gala
394. Ge Detectors of LEGEND experiment: Production, Characterization, Performance	Valentina Biancacci
446. $0\nu\beta\beta$ Target Out Analysis for the SNO+ Experiment	Benjamin Tam
457. Neutron Veto Instrumentation for LEGEND-1000	Michele Morella
485. Development of cryogenic CMOS ASICs for HPGe detectors for dark matter and neutrino detection experiments	Zhi Deng
515. First Energy Calibration of SuperNEMO's Calorimeter using its Tracko-Calo Technology	Cheryl Patrick
517. Radon contamination measurement in the SuperNEMO demonstrator	Yegor Vereshchaka
557. Analysis techniques for the search of neutrinoless double-beta decay of Te-130 with CUORE	Krystal Alfonso
564. Discovery possibility of new physics beyond the two-neutrinos double-beta decay	Emanuela Celi
628. The Progress of Superconducting Transition Edge Sensor (TES) for Photothermal Detection System in Cupid-China $0\nu\beta\beta$ Experiment	Shasha Lv

>50 talks and posters related to $0\nu\beta\beta$!

Tonne scale program

- In the last 2 years, North American and European agencies have made progress towards coordinating the next-generation “tonne scale” experiments:

North America - Europe Workshop on Future of Double Beta Decay

September 29, 2021 to October 1, 2021
Gran Sasso National Laboratory (LNGS)
Europe/Rome timezone

<https://agenda.infn.it/event/27143/>



<https://indico.cern.ch/event/1242655/>

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<https://agenda.infn.it/event/10000>

2ND INTERNATIONAL MEETING OF NEUTRINO PHYSICS

Apr 27 – 28, 2023
SNOLAB

<https://indico.cern.ch/event/1242655/contributions/5384886/>

Readout from In Camera Sessions

SNOLAB, April 2023

- The international stakeholders in neutrinoless double beta decay research who attended this summit (agencies representing Canada, France, Germany, Italy, UK, and USA) agree in principle the best chance for an unambiguous discovery is an international campaign with multiple isotopes and more than one large tonne-scale experiment implemented in the next decade.
- These stakeholders discussed a scenario that could accomplish the goals of the first bullet by deploying CUPID, LEGEND-1000, and nEXO with one tonne-scale experiment in Europe and one tonne-scale experiment in North America.
- These stakeholders agree on the need for a coordinated effort to efficiently and cost-effectively advance the field for the proposed double beta decay experiments, as well as the future of the field. To that purpose, these stakeholders agree that a structure for international collaboration on this research should be explored. (e.g., an international virtual observatory for neutrinoless double beta decay).
- These funding agencies intend to create a working group to explore how such an international effort could be coordinated. The stakeholders welcome additional international partnerships.

Tonne scale program (CUPID)

CUPID (^{100}Mo):

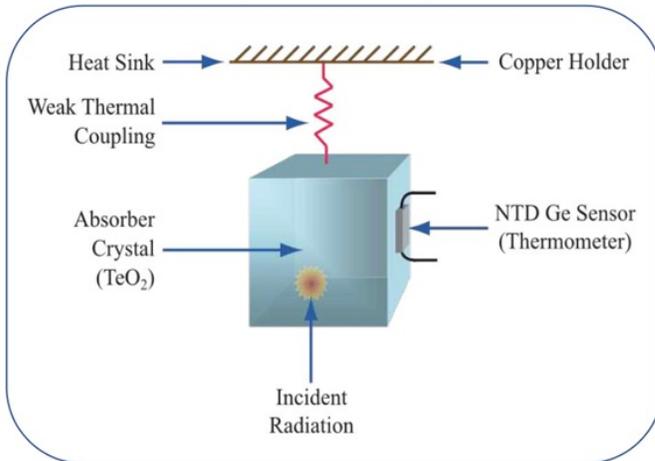
- Builds on CUORE (currently operating), reusing existing infrastructure
- Upgrade detector array with Li_2MoO_4 scintillating bolometers
 - Rejection of α backgrounds and pileup through light signals
 - Higher Q-value of ^{100}Mo avoids γ backgrounds in U/Th chain
- Status:
 - CUPID-Mo demonstrator complete: *Eur. Phys. J. C 82, 1033 (2022)*
 - Conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta} = 12\text{-}20 \text{ meV}$ ($T_{1/2} = 1 \times 10^{27} \text{ yr}$)

Presentations at TAUP:

Léonard Imbert	Final results of the CUPID-Mo 0 experiment	Nu Phys 3A
Claudia Nones	CUPID the next generation $0\nu\beta\beta$ bolometric experiment	Nu Phys 5A
Emanuela Celi	Final results of the CUPID-0 combined background model	Nu Phys 6A
Pia Loiaza	183. Backgrounds and sensitivity of the CUPID experiment	Posters
Vladyslav Berest	372. Development of enhanced light detectors for CUPID experiment	

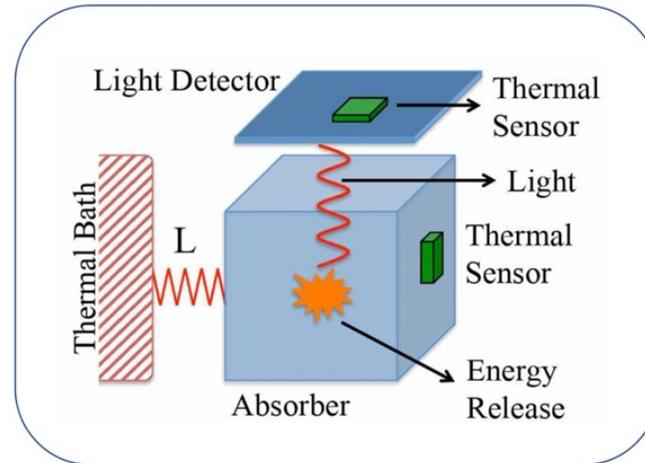
CUORE ^{130}Te

pure thermal detector
(bolometer)

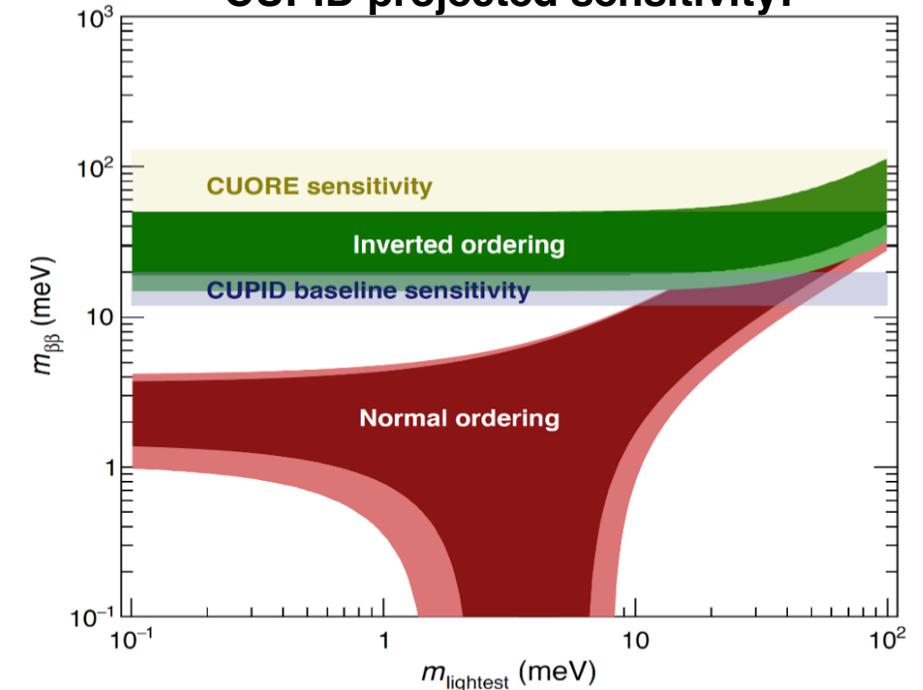


CUPID ^{100}Mo

heat + light
(scintillating bolometer)



CUPID projected sensitivity:



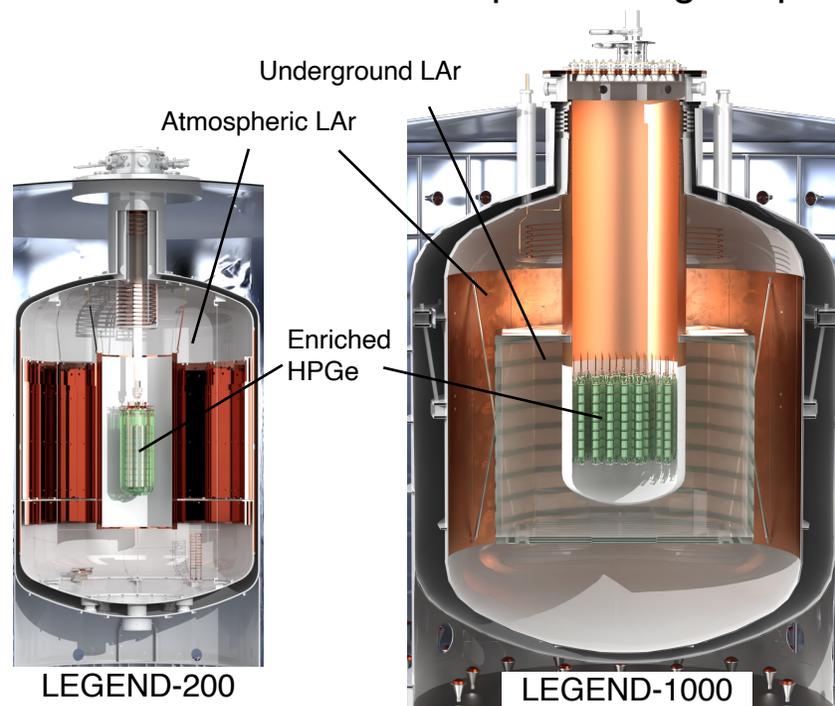
Tonne scale program (LEGEND)

LEGEND (^{76}Ge):

- Builds on the completed MJD and GERDA experiments
- Each stage is designed to increase target mass while decreasing backgrounds
- Status:
 - LEGEND-200:
 - Began stable data taking March 2023 (140 kg), with complete 200 kg array planned early 2024
 - LEGEND-1000:
 - Conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta} = 9\text{-}21 \text{ meV}$ ($T_{1/2} = 1.3 \times 10^{28} \text{ yr}$)

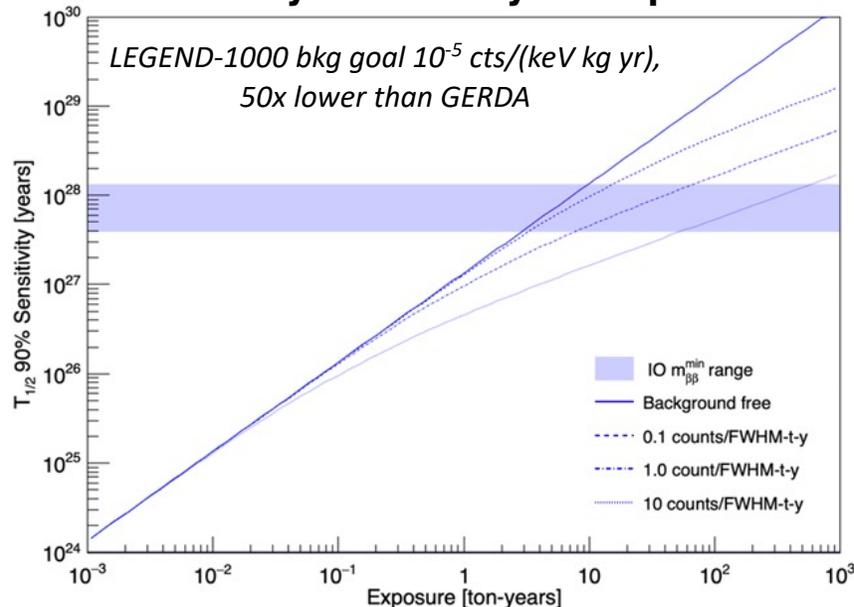
Presentations at TAUP:

Michael Willers	LEGEND-200: From Construction to Physics Data Taking	Nu Phys 4A
Katharina von Sturm	LEGEND-200: First glance at the background in physics data	
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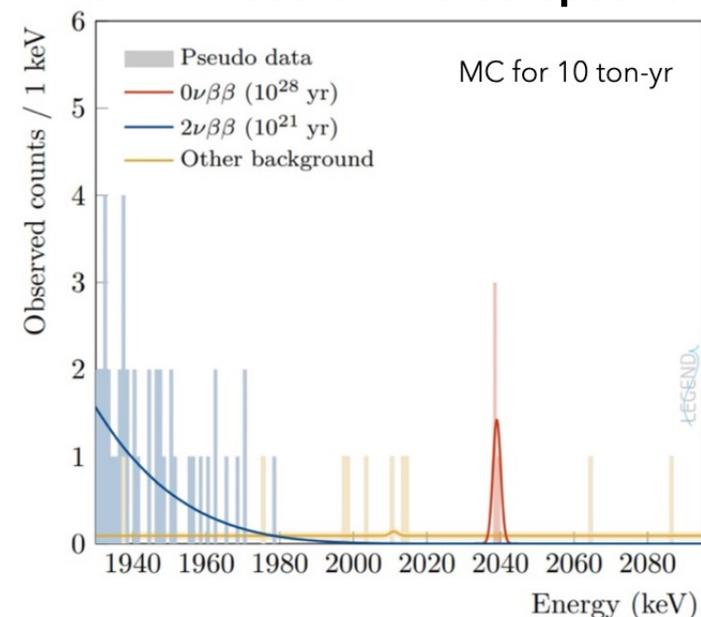
D. Moore, Yale

Discovery sensitivity vs exposure:



TAUP - August 29, 2023

LEGEND-1000 simulated spectrum:



Courtesy S. Elliott and S. Schönert

Tonne scale program (nEXO)

Presentations at TAUP:

Samuele Sangiorgio

Discovering the origin of matter with liquid xenon neutrinoless double-beta decay detectors: nEXO and beyond

Nu Phys 5A

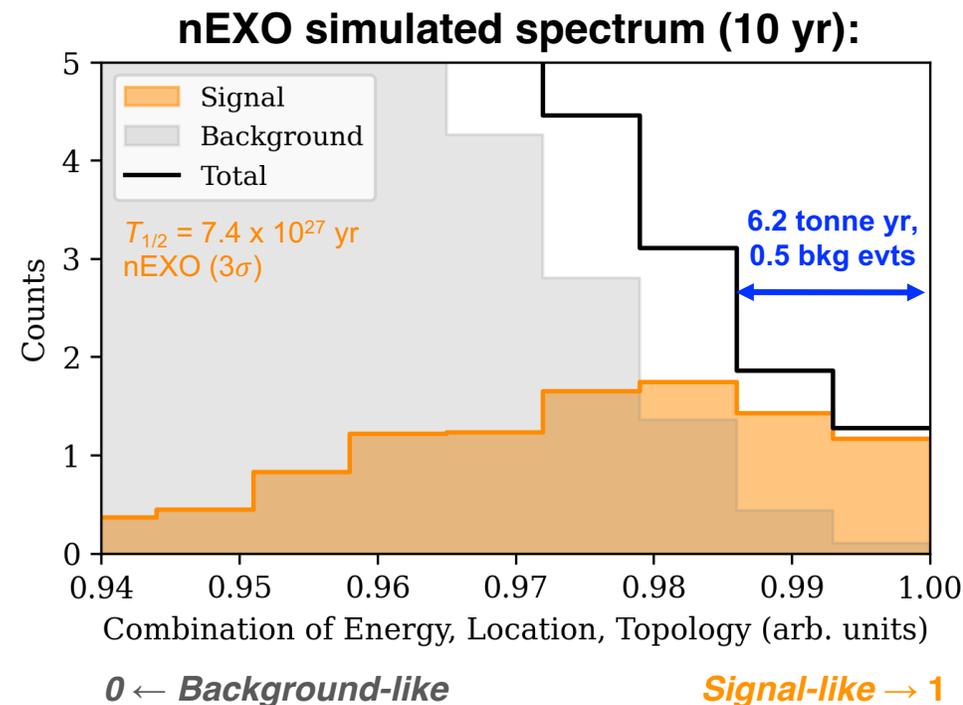
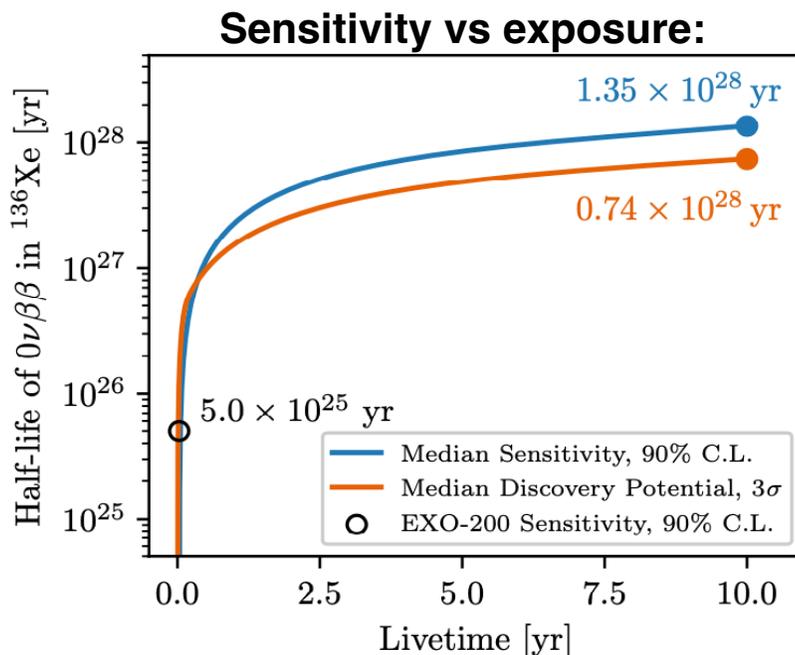
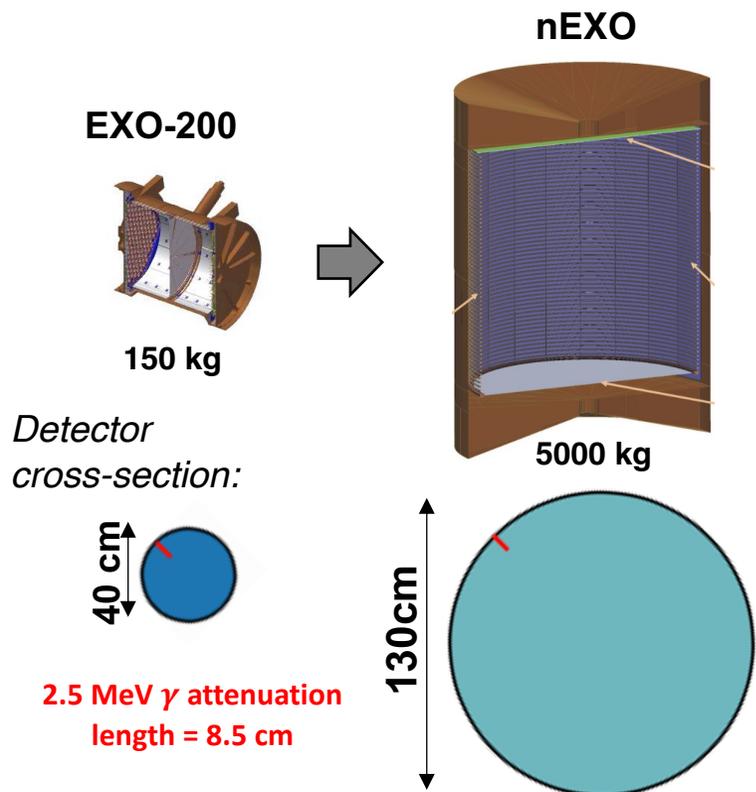
Clarke Hardy

323. Optimizing Energy Reconstruction for nEXO

Posters

nEXO (^{136}Xe):

- Builds on the completed EXO-200 experiment
- Homogeneous, liquid ^{136}Xe time projection chamber scaled to 5 tonne total mass
 - Dominant external backgrounds exponentially attenuated in central region
- Status:
 - Conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta} = 6\text{-}27\text{ meV}$ ($T_{1/2} = 0.74 \times 10^{28}\text{ yr}$)



Operating/upcoming experiments (cont'd)

- In parallel to the tonne scale program, there is a vibrant worldwide effort exploring other techniques with a variety of isotopes

Summary of $0\nu\beta\beta$ experiments and present status:

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	^{48}Ca	305 kg	$^{nat}\text{CaF}_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300 ν [125]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [126]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [127]	^{82}Se		^{enr}Se , CMOS	Development	
IFC [128]	^{82}Se		ion drift SeF_6 TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	$\text{Li}^{enr}\text{MoO}_4$ scint. bolom.	Prototype	LNGS
AMoRE-I [129]	^{100}Mo	6 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Operation	YangYang
AMoRE-II [129]	^{100}Mo	200 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Construction	Yemilab
CROSS [130]	^{100}Mo	5 kg	$\text{Li}_2^{100}\text{MoO}_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [131]	^{100}Mo		$\text{Li}^{enr}\text{MoO}_4$	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	$\text{Li}^{enr}\text{MoO}_4$ scint. bolom.	Proposal	LNGS
China-Europe [132]	^{116}Cd		$^{enr}\text{CdWO}_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	^{116}Cd		$^{nat}\text{CdTe}$ det.	Development	
TIN.TIN [135]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+ [136]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [137]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe dissolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe dissolved in liq. scint.	Development	Kamioka
LZ [139]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [143]	^{136}Xe	kton	Xe -doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA [145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	

^{48}Ca

^{76}Ge

^{82}Se

^{100}Mo

^{116}Cd

^{124}Sn

^{130}Te

^{136}Xe

Te or Xe

Labs hosting current/future $0\nu\beta\beta$ experiments:



https://indico.fnal.gov/event/43209/contributions/187839/attachments/129296/159530/Heise-UGLabs_Worldwide-Neutrino2020-2020_07_01.pdf

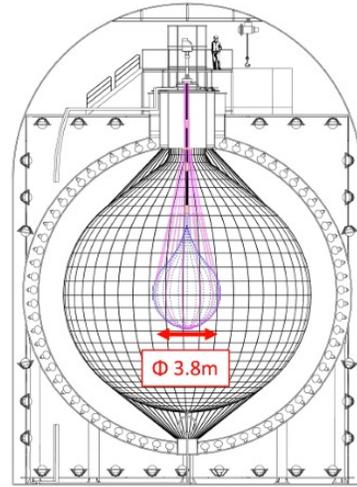
More than 38 experiments in operation, development, or proposed in coming years!

Operating/upcoming experiments (cont'd)

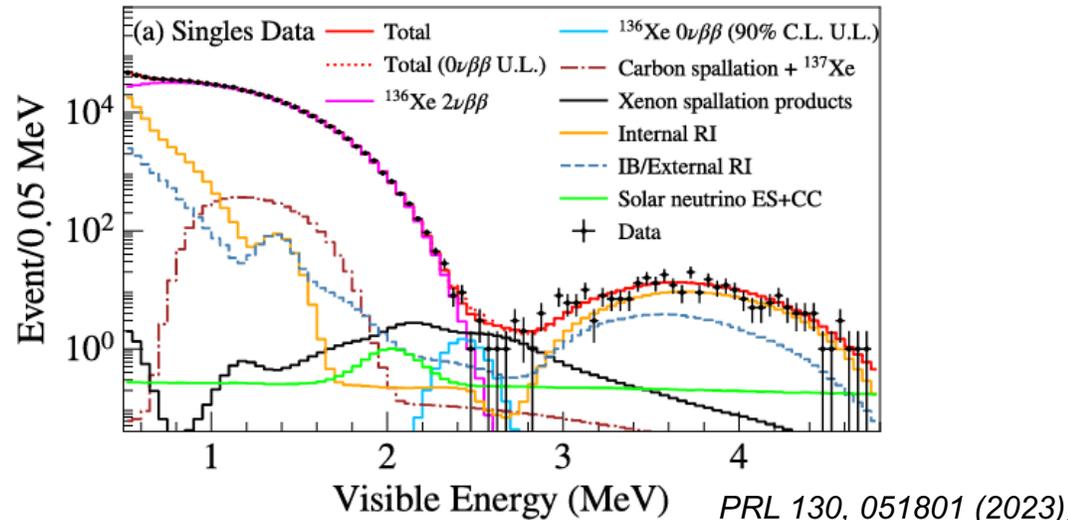
Liquid scintillator detectors:

KamLAND-Zen (^{136}Xe):

- Most sensitive search to date for $0\nu\beta\beta$ ($m_{\beta\beta} < 36\text{--}156\text{ meV}$):
Phys. Rev. Lett. 130, 051801 (2023)
- **KLZ-800:**
 - Mini-balloon with 745 kg of $^{\text{enr}}\text{Xe}$, currently in operation
- **KamLAND2-Zen:**
 - Proposed to improve energy resolution, 1t $^{\text{enr}}\text{Xe}$ mass

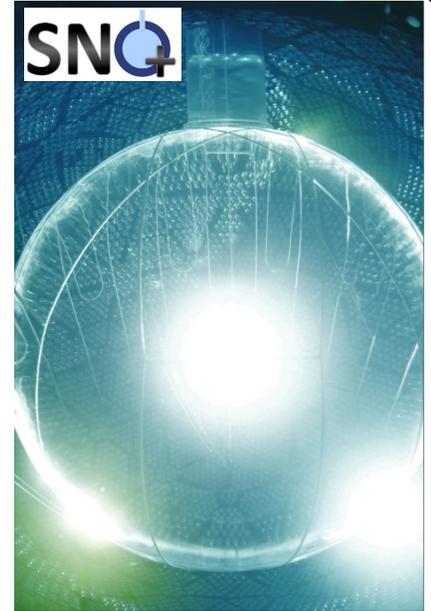


KLZ-800 observed spectrum:

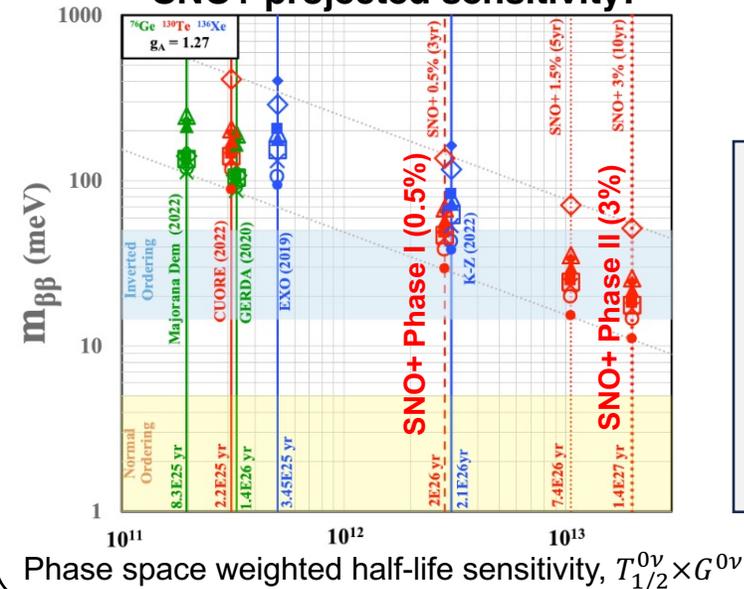


SNO+ (^{130}Te):

- Currently operating with 780 t liquid scintillator, to be loaded with $^{\text{nat}}\text{Te}$
- Status:
 - Water phase complete
 - Pure scintillator phase in progress
 - Phase I Te loading to start 2025:
0.5% $^{\text{nat}}\text{Te} \rightarrow 1.3\text{ t } ^{130}\text{Te}$
 - Planned Phase II with 3% Te to



SNO+ projected sensitivity:



Presentations at TAUP:

Valentina Lozza	Nu Phys 3A
Tanner Kaptanoglu	Nu Phys 7B
Benjamin Tam	Posters
Tereza Kroupova	
Szymon Manecki	

Plots courtesy M. Chen

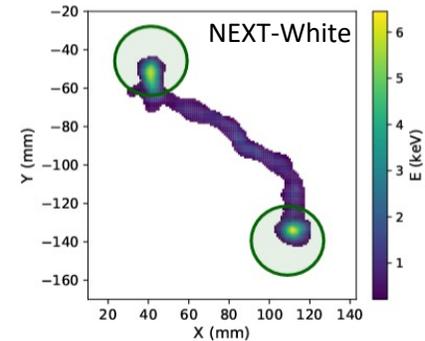
Operating/upcoming experiments (cont'd)

Gas Xe TPCs:

NEXT (^{136}Xe):

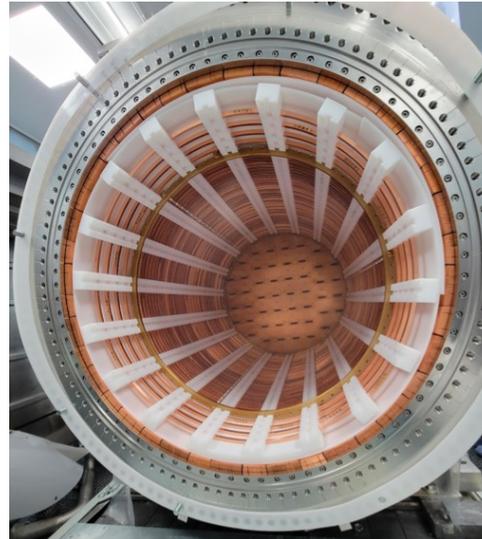
- Energy resolution (0.7% FWHM)
- Topological separation ($\beta\beta$ vs β)
- Status:
 - NEXT-White (10 kg) completed
 - NEXT-100 (100 kg) construction underway at Canfranc
 - NEXT-HD proposed to extend to 1t
 - R&D towards tagging ^{136}Ba daughter (NEXT-BOLD)

Reconstruction of $\beta\beta$ event:

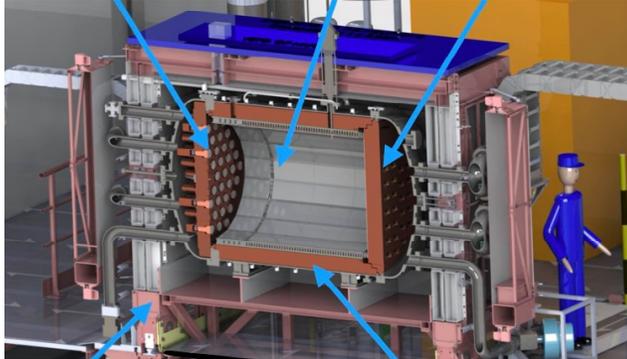


Phys. Rev. C 105, 055501 (2022)

Photo of NEXT-100 TPC:



NEXT-100 detector schematic:



See talk by Pau Novella Garijo Nu Phys 6A

Plots courtesy J. Gomez-Cadenas

LXe DM detectors:

Dual phase LXe TPCs ($^{\text{nat}}\text{Xe}$):

- Multi-ton liquid Xenon TPCs designed for dark matter detection can also search for $0\nu\beta\beta$
 - Sub-percent energy resolution demonstrated at MeV energies
- Currently operating experiments:
 - LZ, XENONnT, PandaX-4T
- Future detectors (e.g. XLZD, Darwin) could reach $>10^{27}$ yr $T_{1/2}$ sensitivity

See talks by:

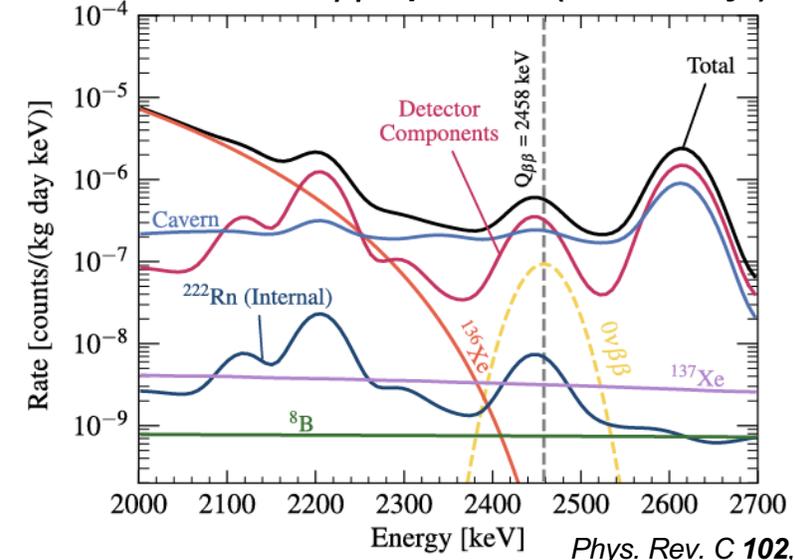
Maxime Pierre

Xiang Xiao

Kimberly Palladino

DM and nu
Inter-track 1

Simulated LZ $0\nu\beta\beta$ spectrum (1.1×10^{26} yr):



Phys. Rev. C 102, 014602 (2020)

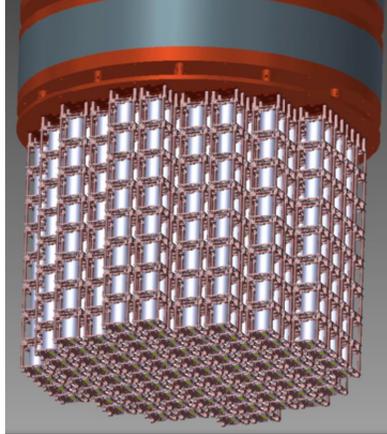
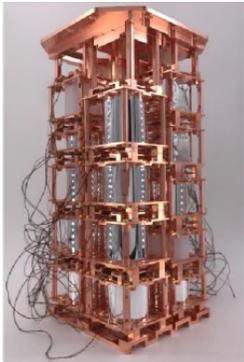
Operating/upcoming experiments (cont'd)

Scintillating Bolometers:

AMoRE (^{100}Mo):

- Scintillating bolometers with $^{\text{enr}}\text{Mo}$
- Sensitivity goal (AMORE-II): $m_{\beta\beta} = 16\text{-}30 \text{ meV}$
($T_{1/2} = 6 \times 10^{26} \text{ yr}$)
- Status:
 - AMoRE-I (currently operating, 6.2 kg)
 - AMoRE-II (under construction, $\sim 180 \text{ kg}$)
 - Over 100 kg of enriched $^{100}\text{MoO}_3$ powder has been purified at CUP

AMoRE-I tower: AMoRE-II concept:



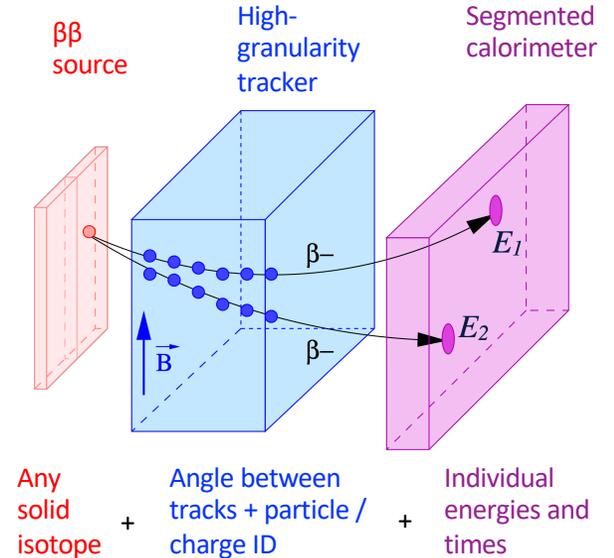
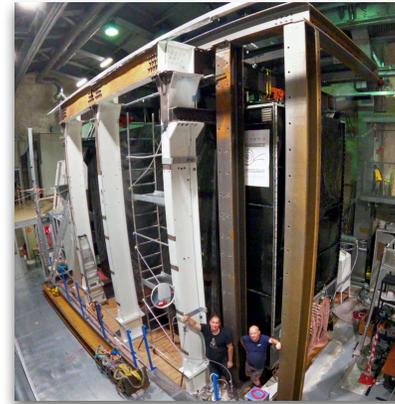
Presentations at TAUP:

Yoomin Oh	Nu Phys 4A
Han Beom Kim	Nu Phys 6A
Jeewon Seo	Posters
Jungho So	
Olga Gileva	

Tracking detectors:

SuperNEMO (^{82}Se , or other isotopes):

- High granularity tracker + calorimeter
- Full topological reconstruction
 - Background rejection
 - Unique $2\nu\beta\beta$ measurements (nuclear effects, new physics)
 - Ability to probe $0\nu\beta\beta$ mechanism if discovered
- Status:
 - Demonstrator currently taking data ($\sim 6 \text{ kg } ^{82}\text{Se}$)



Presentations at TAUP:

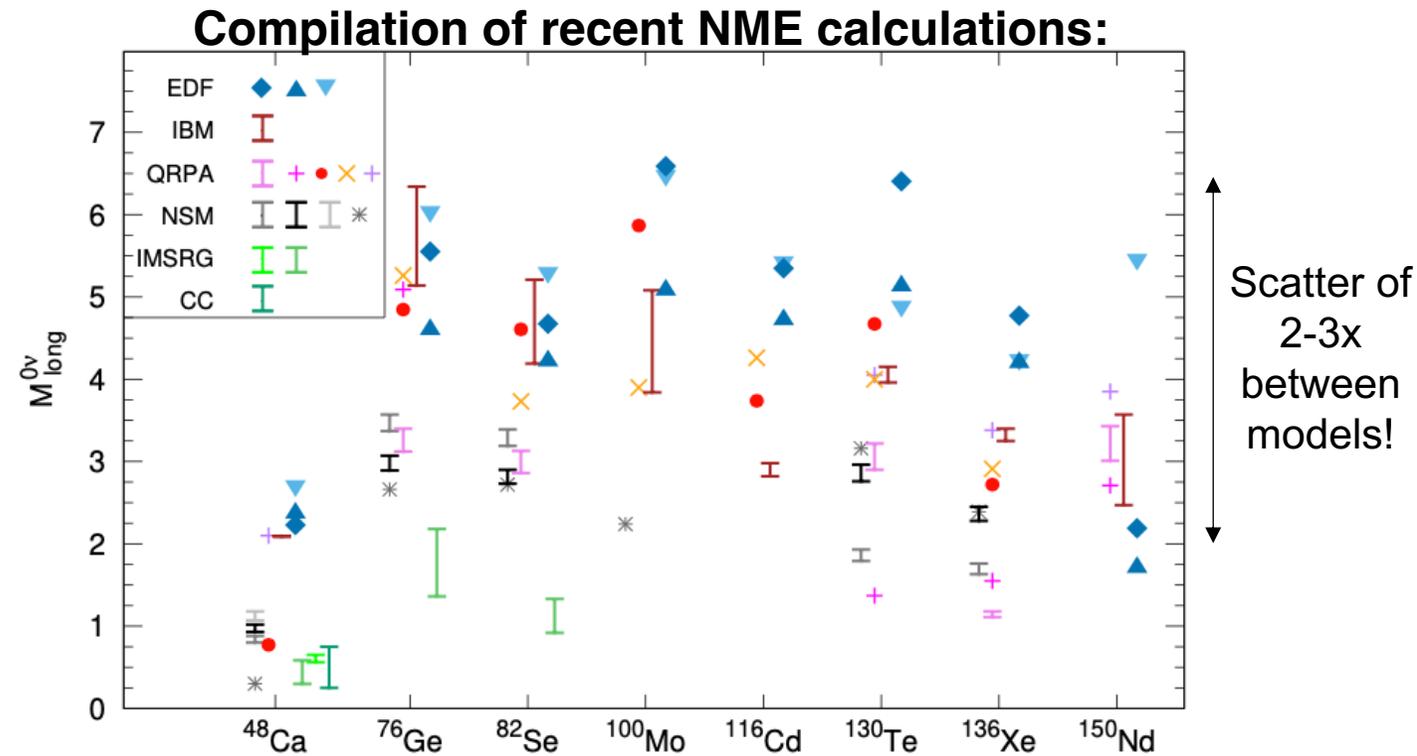
Cheryl Patrick	Nu Phys 6A
Yegor Vereshchaka	Posters
Cheryl Patrick	

Plots courtesy C. Patrick

Nuclear Matrix Elements (NMEs)

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \left[g_A^4 |M^{0\nu}|^2 \right] \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

- NMEs with quantifiable uncertainties are required to accurately plan experiments and interpret results
- Historically, phenomenological models give 2-3x scatter
 - Leads to nearly an order-of-magnitude variation in half-life for a given $\langle m_{\beta\beta} \rangle$
 - Errors are difficult to quantify, and no guarantees true NME lies in range of models
- This is a challenging theory problem, but efforts now underway are starting to move beyond the limitations of phenomenological models!



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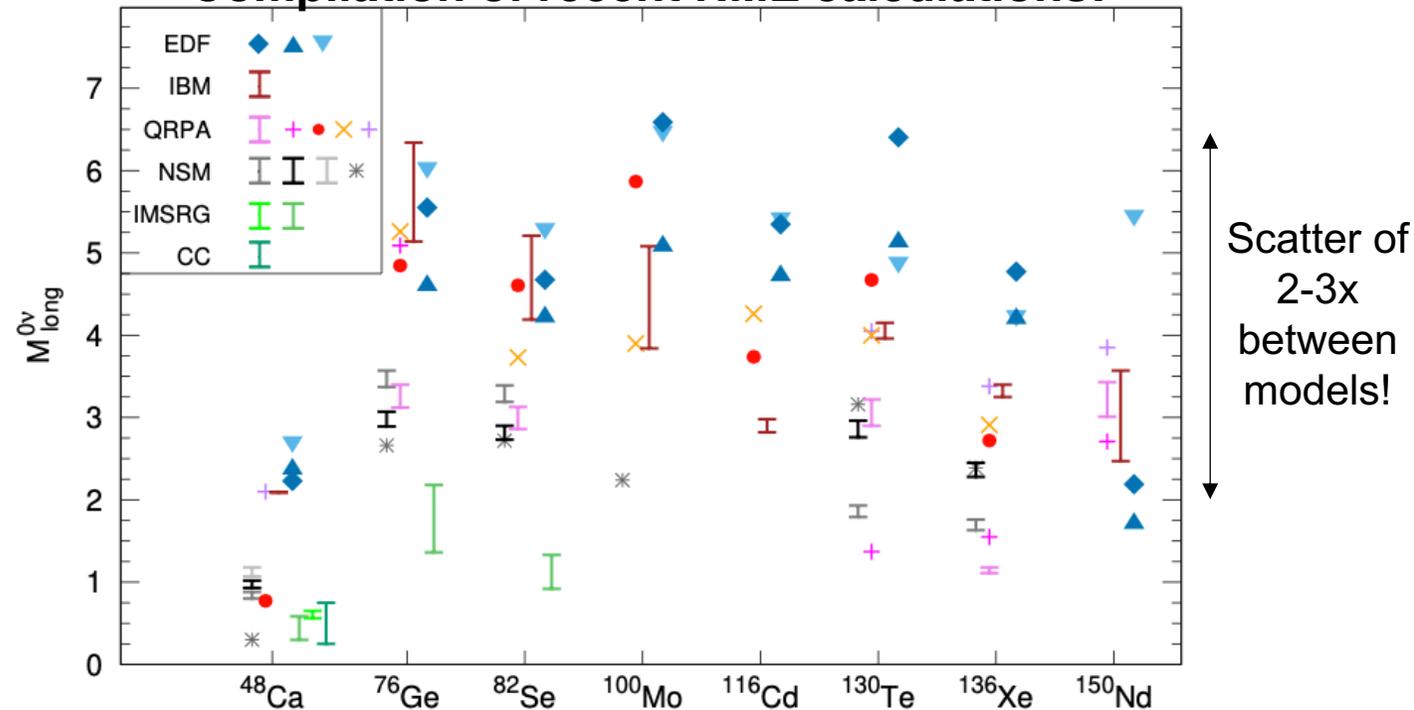
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Updated strategy for NMEs:

1. Quantify the form of the relevant decay operators in EFT
2. Lattice QCD and modeling to constrain coefficients
3. Ab initio nuclear structure calculations to solve the many-body problem
 - ↳ Builds on success resolving “ g_A quenching” for phenomenological models of β decay
4. Develop reliable uncertainty estimates for computed NMEs

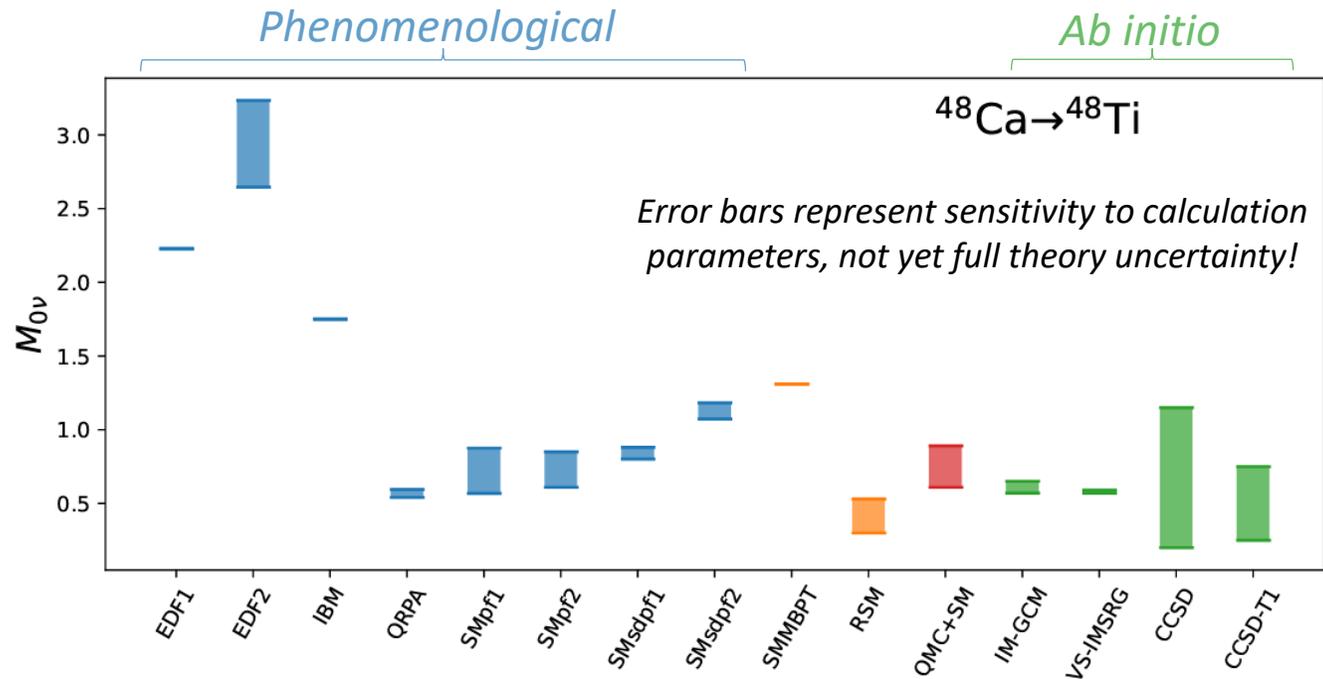
See *J. Phys. G: Nucl. Part. Phys.* 49, 120502 (2022)
 [arXiv:2207.01085] for recent roadmap

Compilation of recent NME calculations:



Ab initio calculations

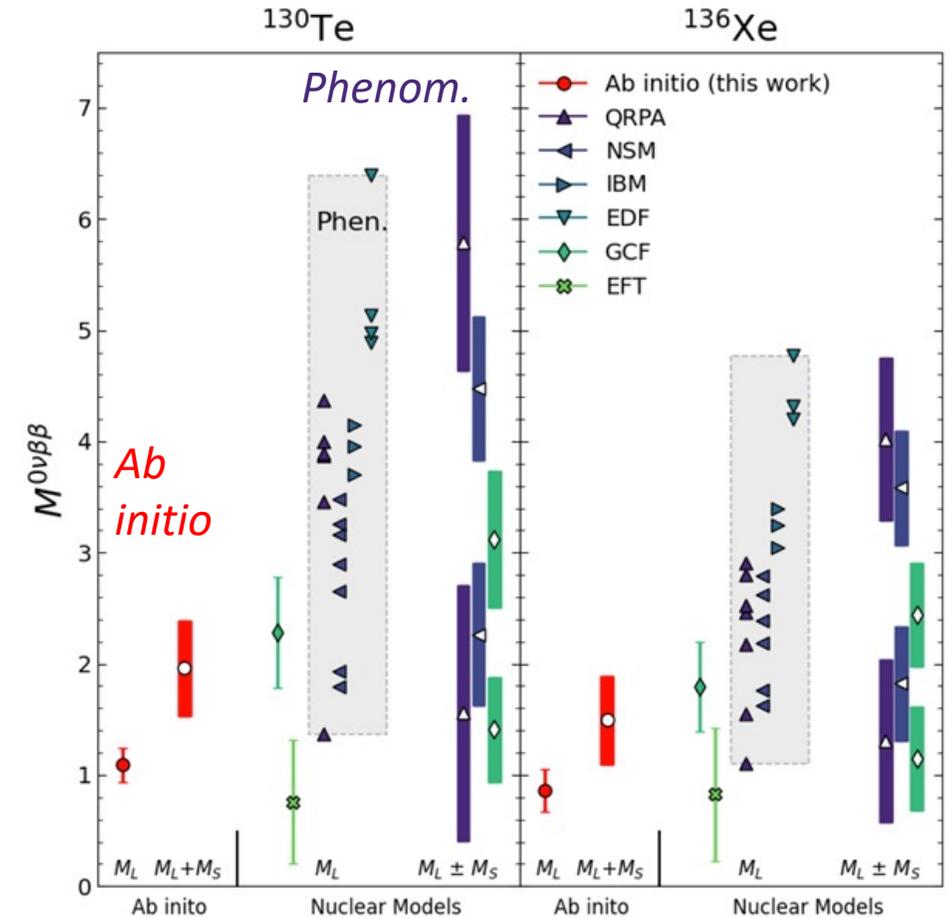
- Initial results from this overall strategy are promising:



arXiv:2212.11099, adapted from J. Phys. G: Nucl. Part. Phys. 49, 120502 (2022)

- Recent work has also extended first *ab initio* calculations to:
 ^{76}Ge , ^{82}Se : Belley et al., Phys. Rev. Lett. 126, 042502 (2021)
 ^{130}Te , ^{136}Xe : Belley et al., arXiv:2307.15156 (2023)

Comparison of *ab initio* to phenomenological NMEs (Te and Xe):



arXiv:2307.15156

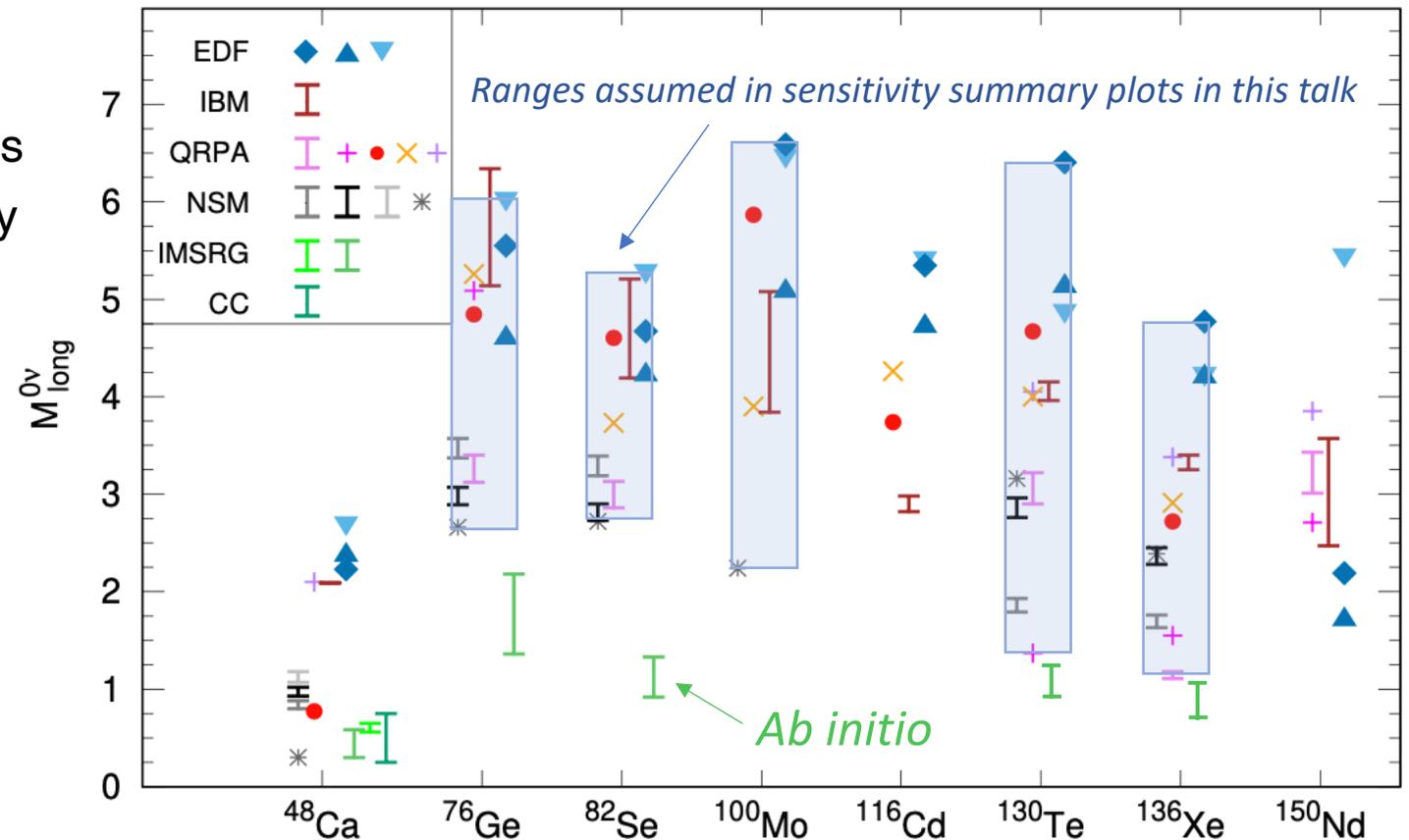
Ab initio calculations (cont'd)

- In general, *ab initio* calculations are coming out near the lower edge of the phenomenological range for isotopes considered
- Nonetheless, may disfavor dramatically lower values (e.g. from naïve extrapolation of “ g_A quenching”)

- More work is required:

- Continue to refine calculations and improve accuracy of approximations
- Work towards quantified uncertainty estimates
- Include short-range contributions (likely enhance *ab initio* NME)

Compilation of recent NME calculations:



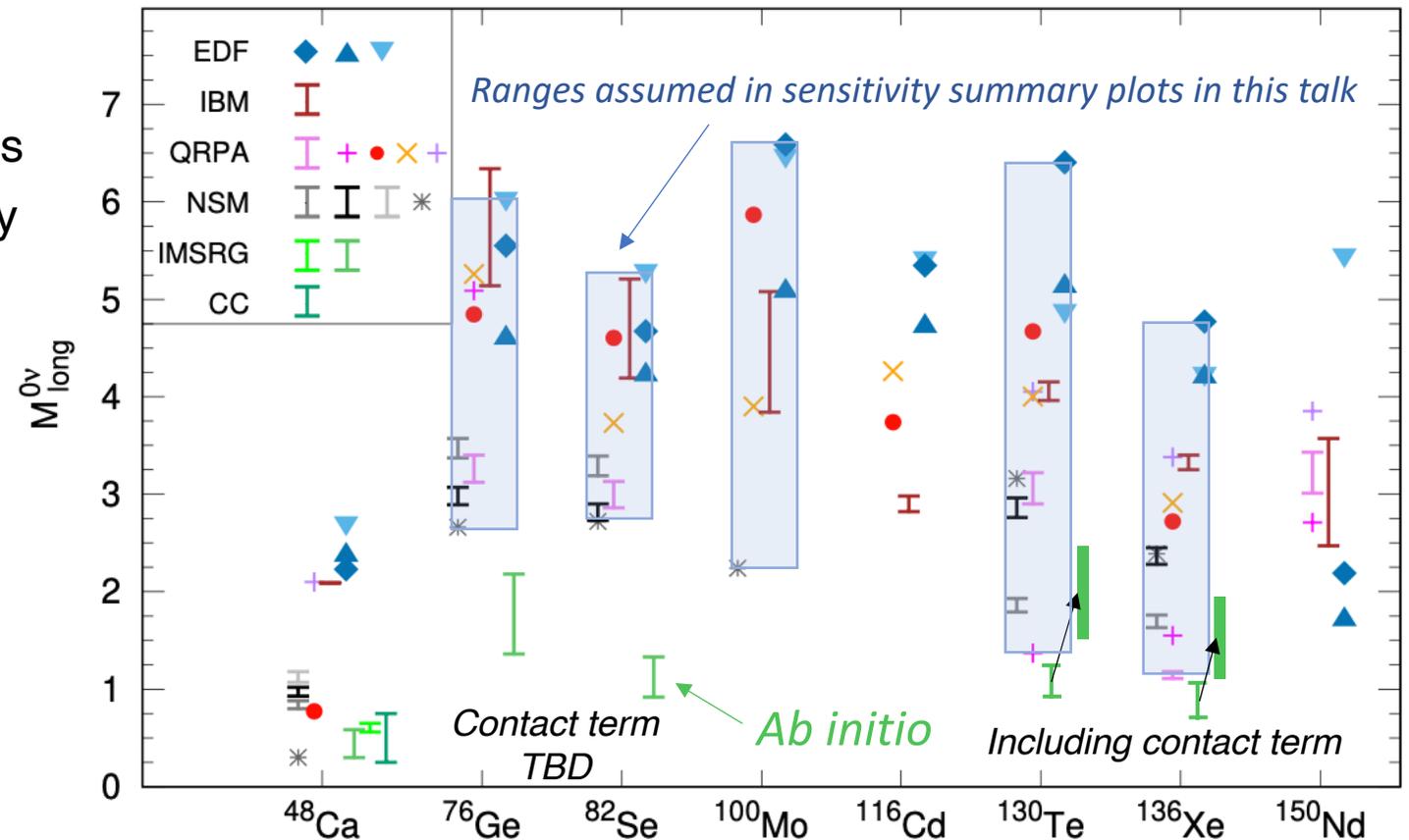
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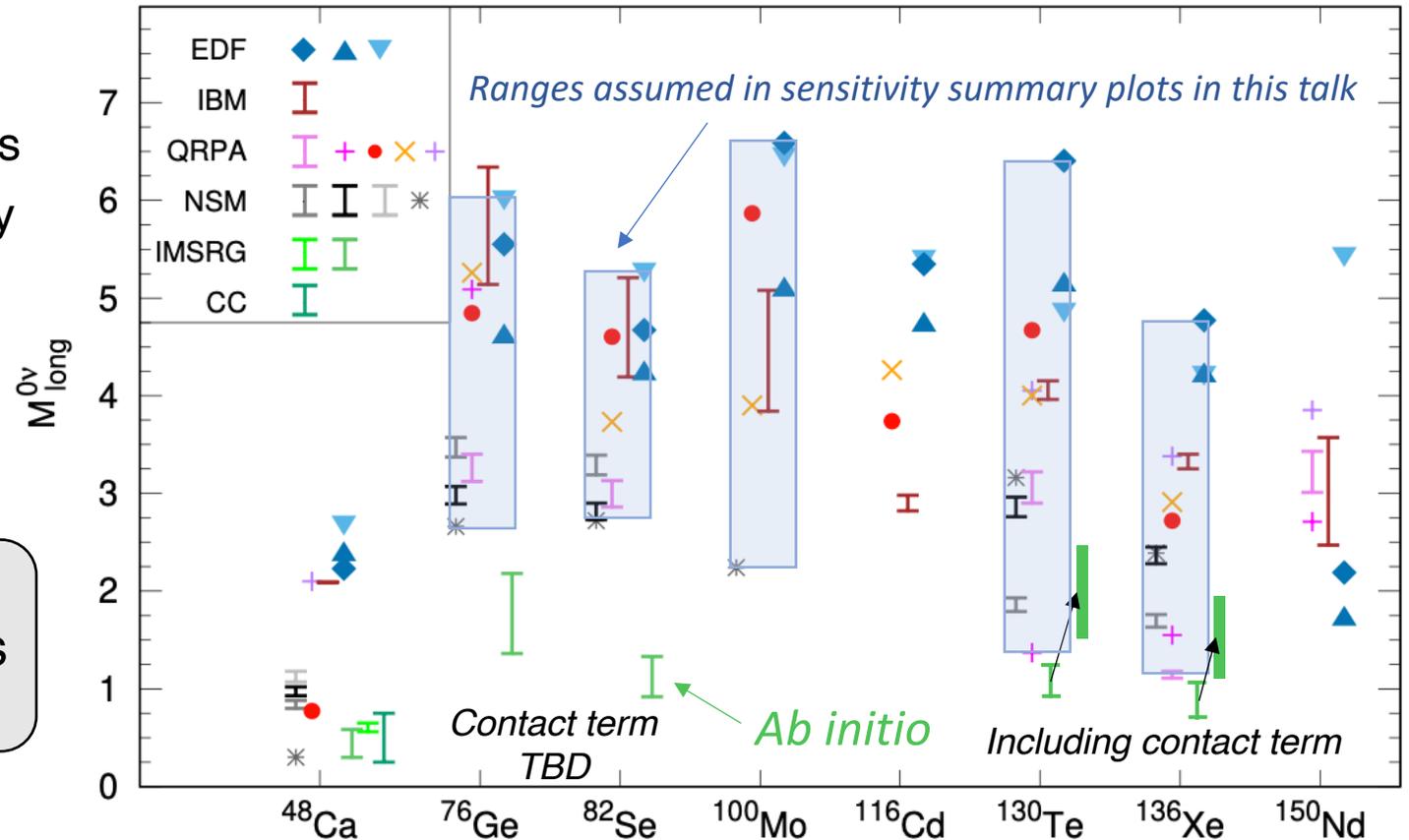
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Still too early to draw definitive conclusions, but a path to reliable NMEs may be in sight!

Compilation of recent NME calculations:

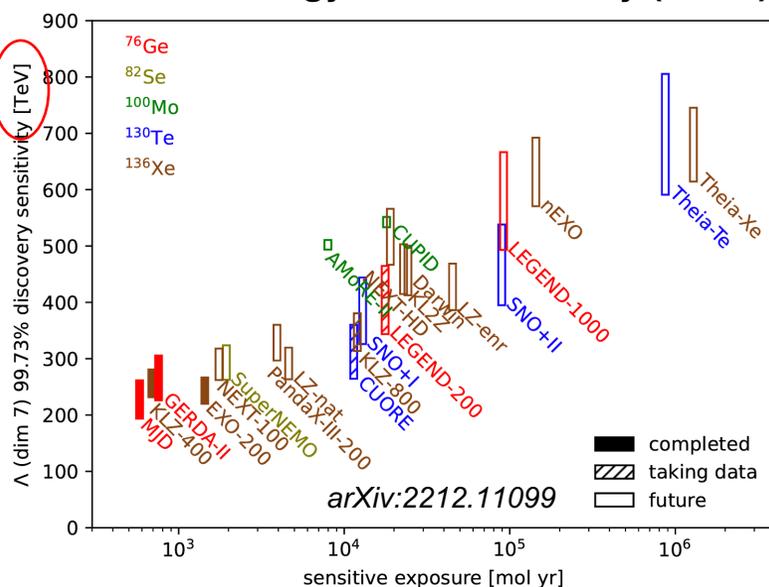


LNV phenomenology

- Searches for $0\nu\beta\beta$ are among the most general probes of LNV for new physics beyond the SM
- There is a vibrant and ongoing theory effort exploring these models and implications for upcoming experiments

*Effective field theory for BSM models
beyond light- ν exchange:*

Effective energy scale sensitivity (dim 7):



Significant complementarity with collider searches!

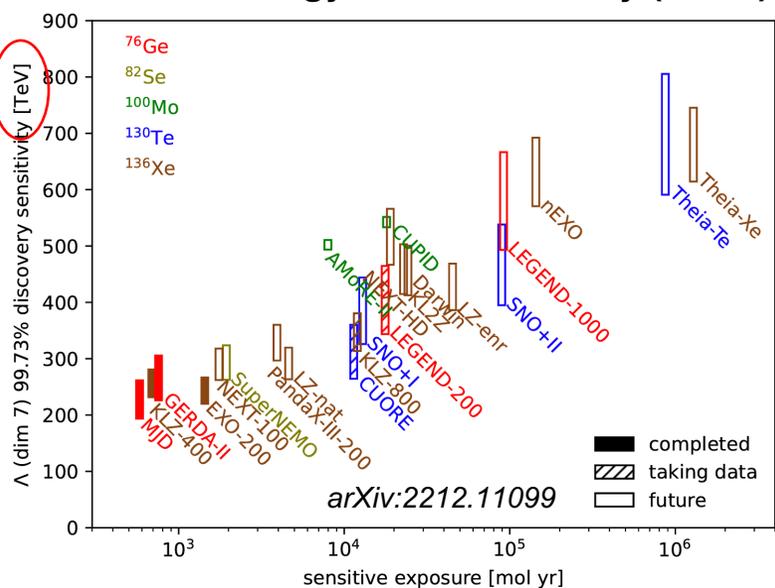
See e.g., *Rev. Mod. Phys.* 95, 025002 (2023) or arXiv:2203.12169 for recent reviews

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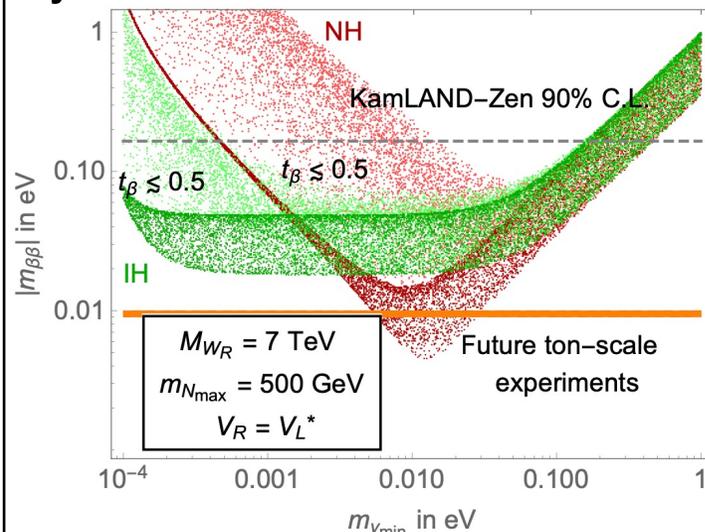


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Implications of specific BSM models for $0\nu\beta\beta$:

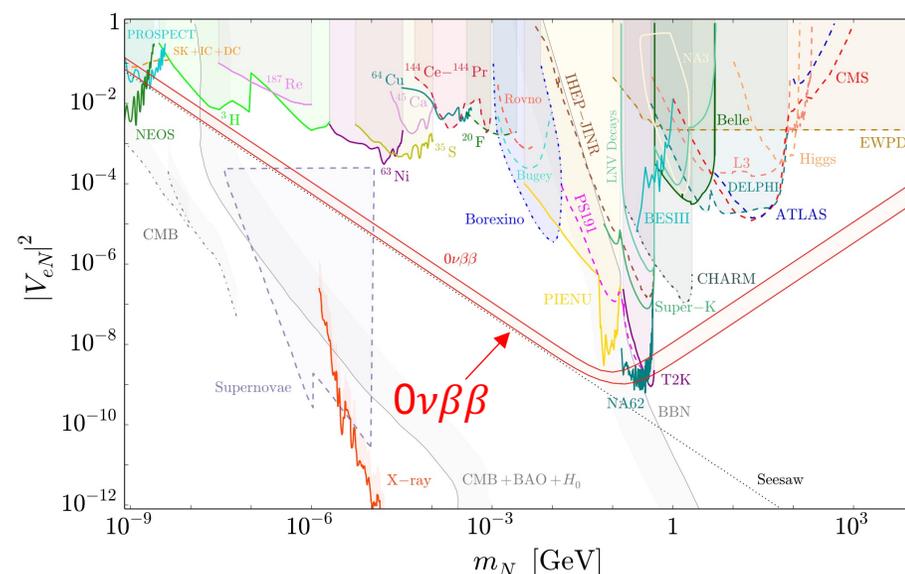
Examples:

$0\nu\beta\beta$ param space in left-right symmetric model:



Li et al., PRL 126, 151801 (2021)

$0\nu\beta\beta$ constraints on mixing with sterile ν :



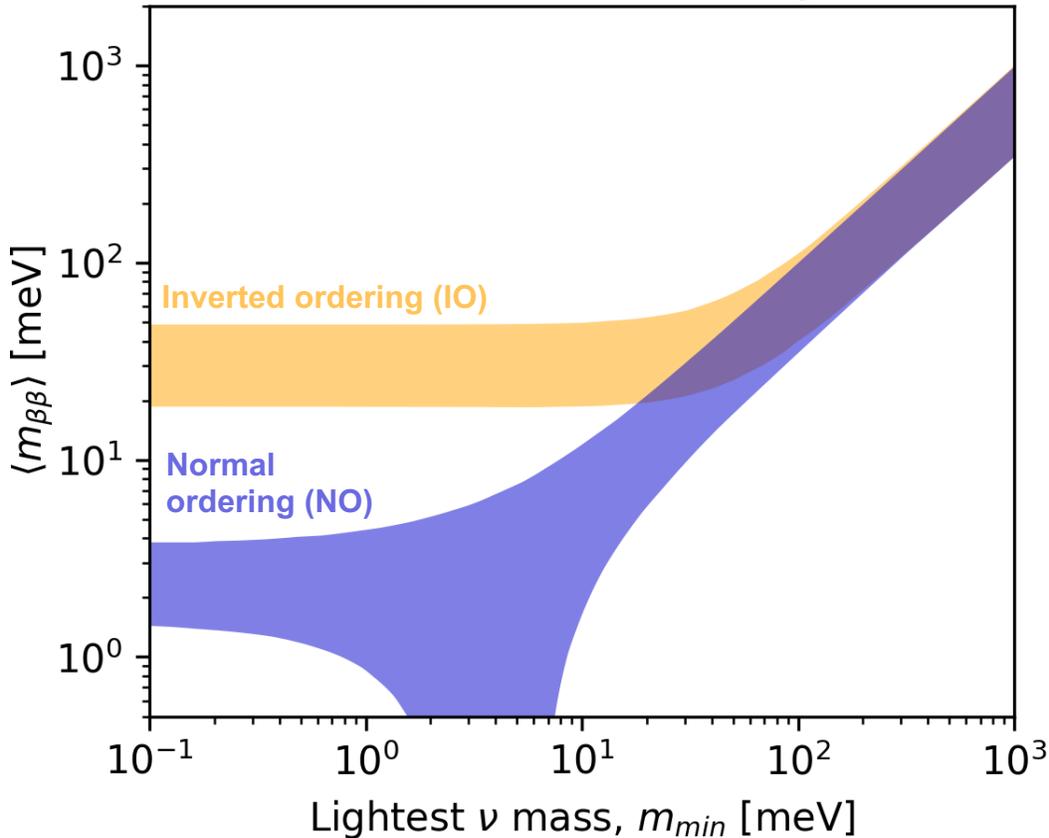
Bolton et al., PRD 103, 055019 (2021)

See e.g., Rev. Mod. Phys. 95, 025002 (2023) or arXiv:2203.12169 for recent reviews

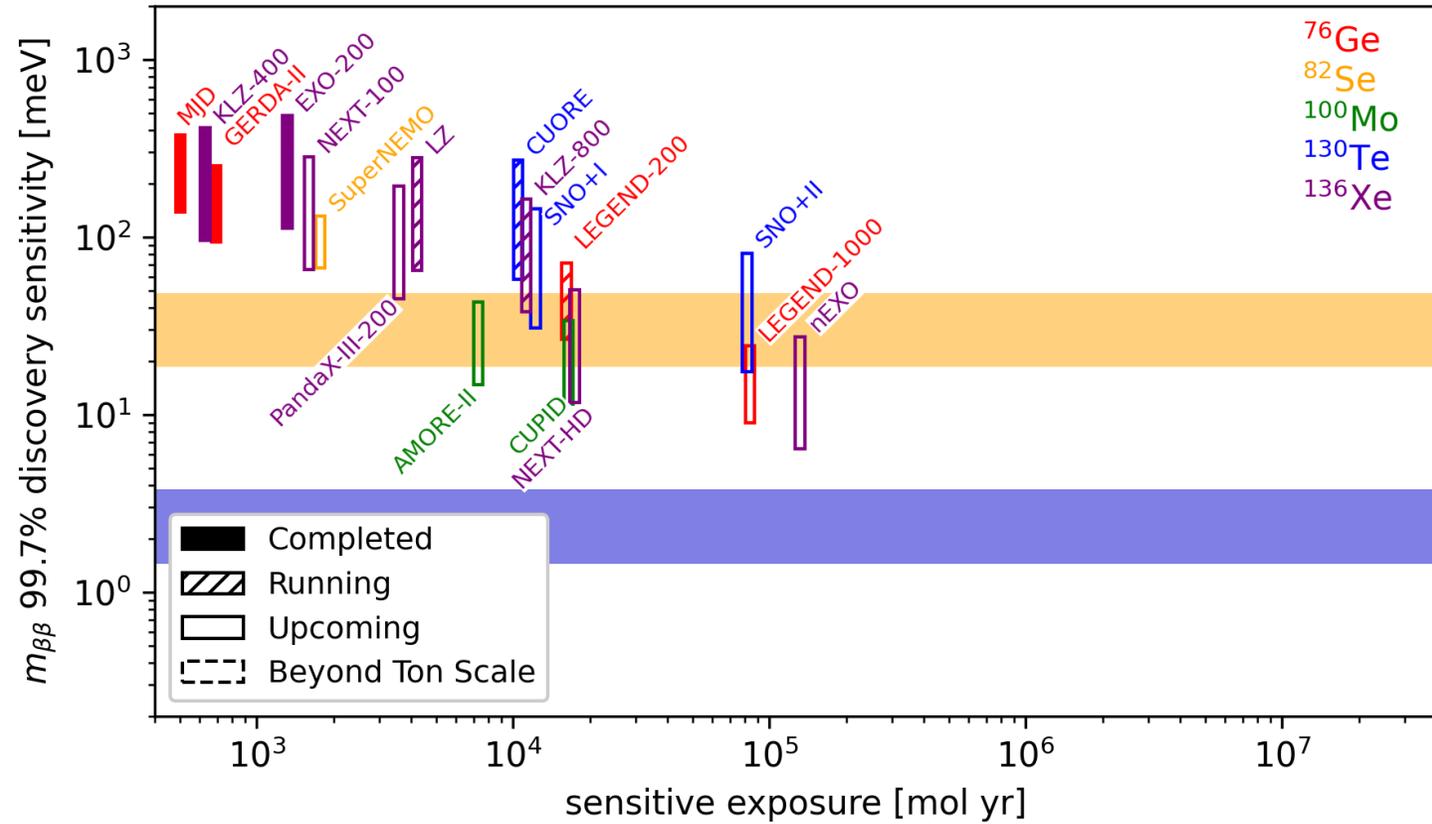
Beyond the ton scale

- While there is significant discovery potential in upcoming experiments, extensions beyond the tonne scale may ultimately be required

Parameter space vs. mass of lightest ν :



Sensitivity of upcoming experiments:

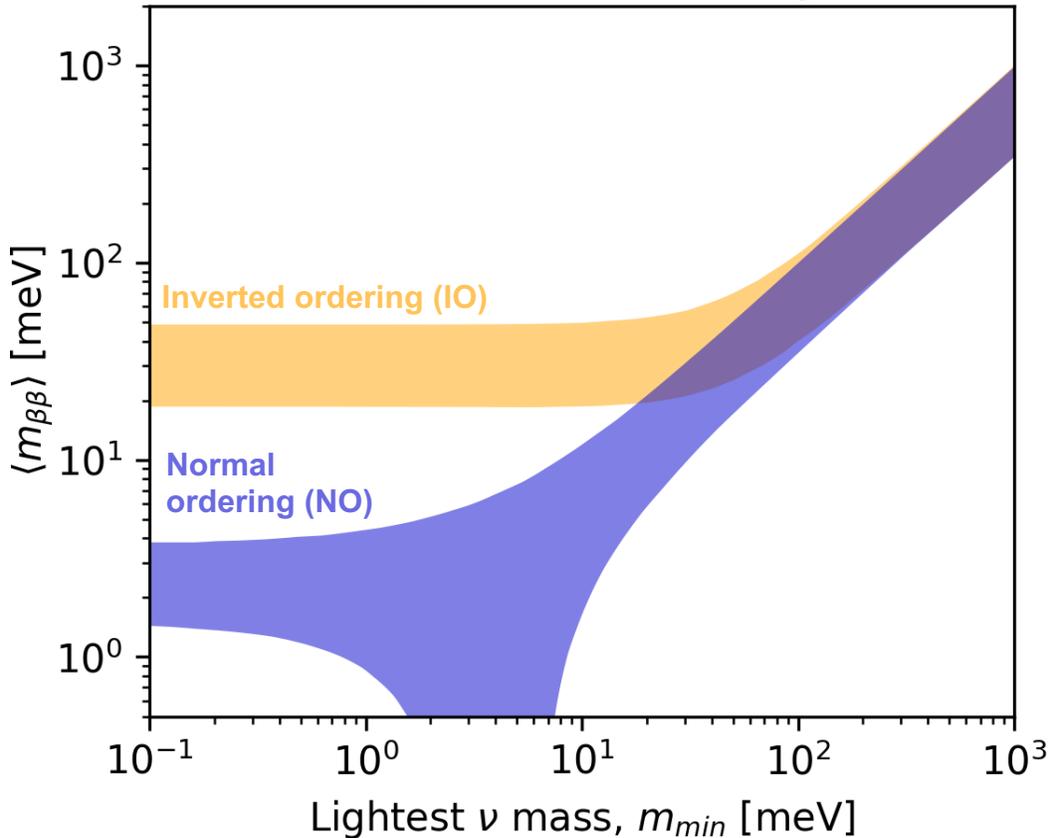


Plot adapted from arXiv:2212.11099,
<https://indico.cern.ch/event/1242655/contributions/5377665/>
 R. Saldanha (private comm.)

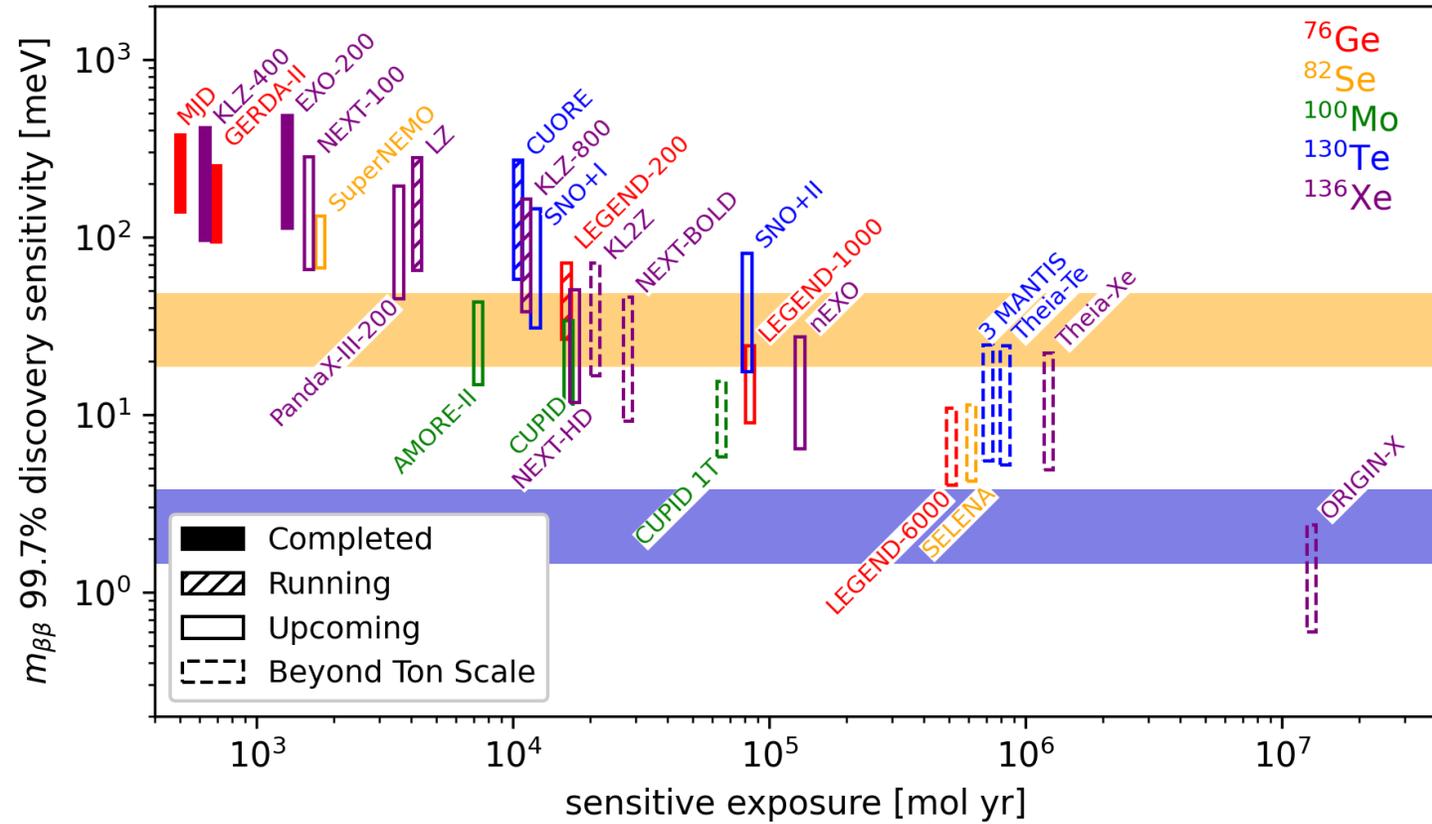
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Parameter space vs. mass of lightest ν :



Sensitivity of proposed beyond ton scale experiments:

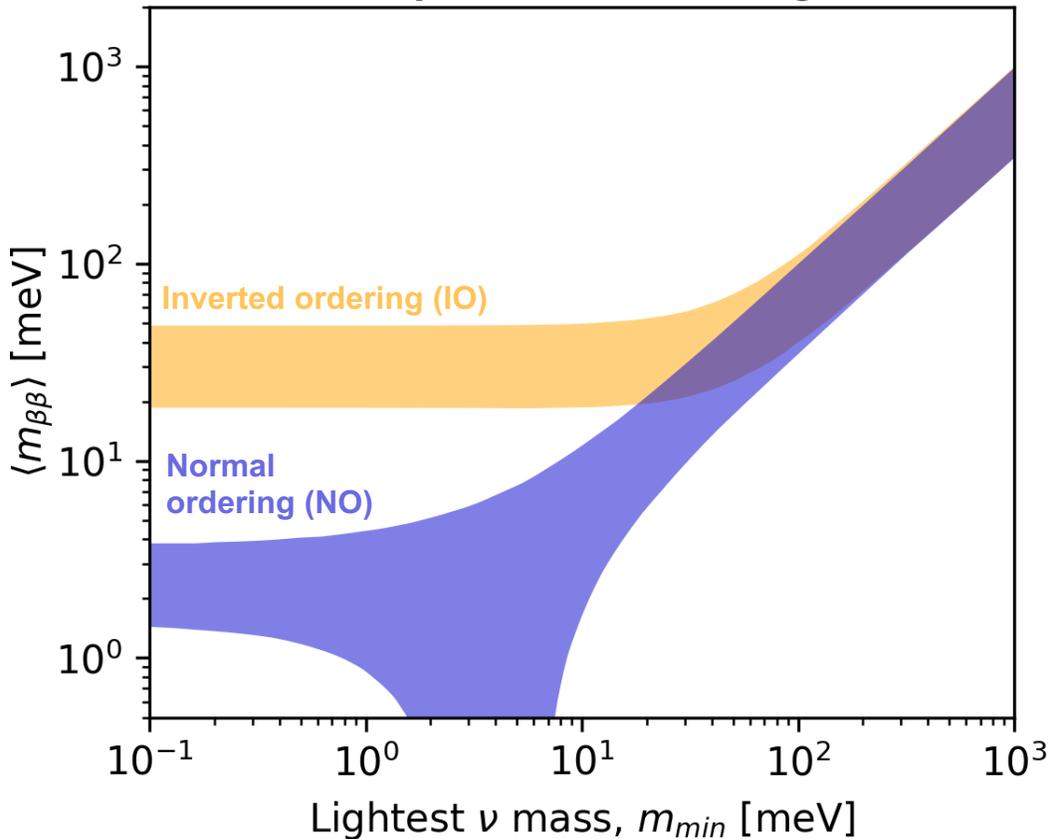


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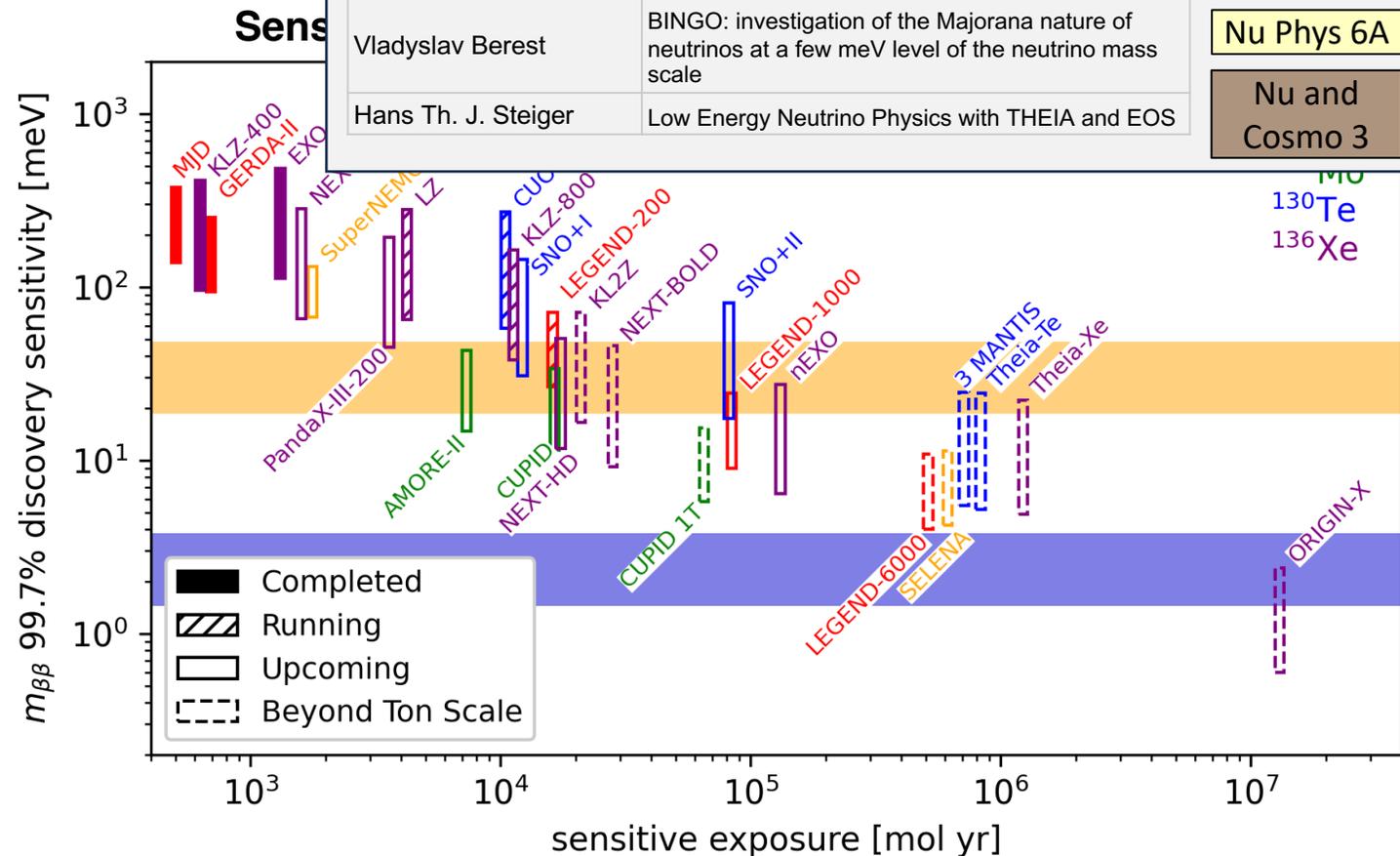
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Parameter space vs. mass of lightest ν :



Presentations at TAUP:

Emilio Ciuffoli	A New ^{82}Se detector for Neutrinoless Double Beta Decay Searches	Nu Phys 3A
Alvaro Chavarria	R&D status of the Selena Neutrino Experiment	Nu Phys 4A
Kimberly Palladino	XLZD beyond WIMPs: Neutrino-less double beta-decay and More!	DM and nu 1
Samuele Sangiorgio	Discovering the origin of matter with liquid xenon neutrinoless double-beta decay detectors: nEXO and beyond	Nu Phys 5A
Vladyslav Berest	BINGO: investigation of the Majorana nature of neutrinos at a few meV level of the neutrino mass scale	Nu Phys 6A
Hans Th. J. Steiger	Low Energy Neutrino Physics with THEIA and EOS	Nu and Cosmo 3



Plot adapted from arXiv:2212.11099,
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 R. Saldanha (private comm.)

Summary

- Searches for $0\nu\beta\beta$ are a powerful probe of LNV in nature and the most sensitive experimental test of whether neutrinos are Majorana particles
- More than 80 years after $0\nu\beta\beta$ was first proposed, upcoming experiments are now approaching the minimal masses expected from oscillation experiments
- There is a vibrant world wide experimental effort pursuing a number of technologies at the ton scale and beyond
- Significant theoretical progress is being made on determining accurate NMEs and LNV phenomenology for $0\nu\beta\beta$
- If neutrinos are Majorana particles, these efforts have substantial potential to discover this beyond the Standard Model process in the coming years!



Experimental signature

- Experimental techniques have been developed to identify the rare $0\nu\beta\beta$ events amidst backgrounds (natural and cosmogenic radioactivity, $2\nu\beta\beta$, ...) based on several parameters

