A Survey of Neutrinoless Double Beta Decay Experiments

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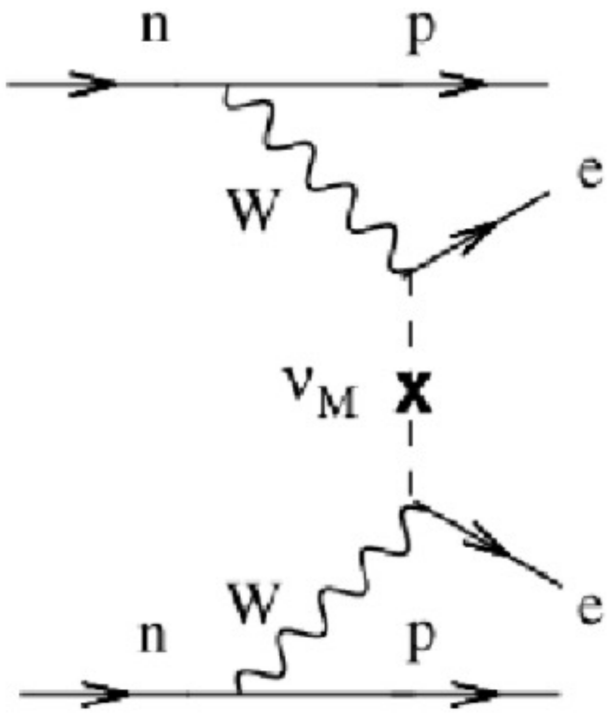
Disclaimer...

I do not work on neutrinoless double beta decay experiments!

This might make me “unbiased” ...
... but I may not have deep expertise!...
(and apologies if I don't zoom in on your fave)

Neutrinoless Double Beta Decay

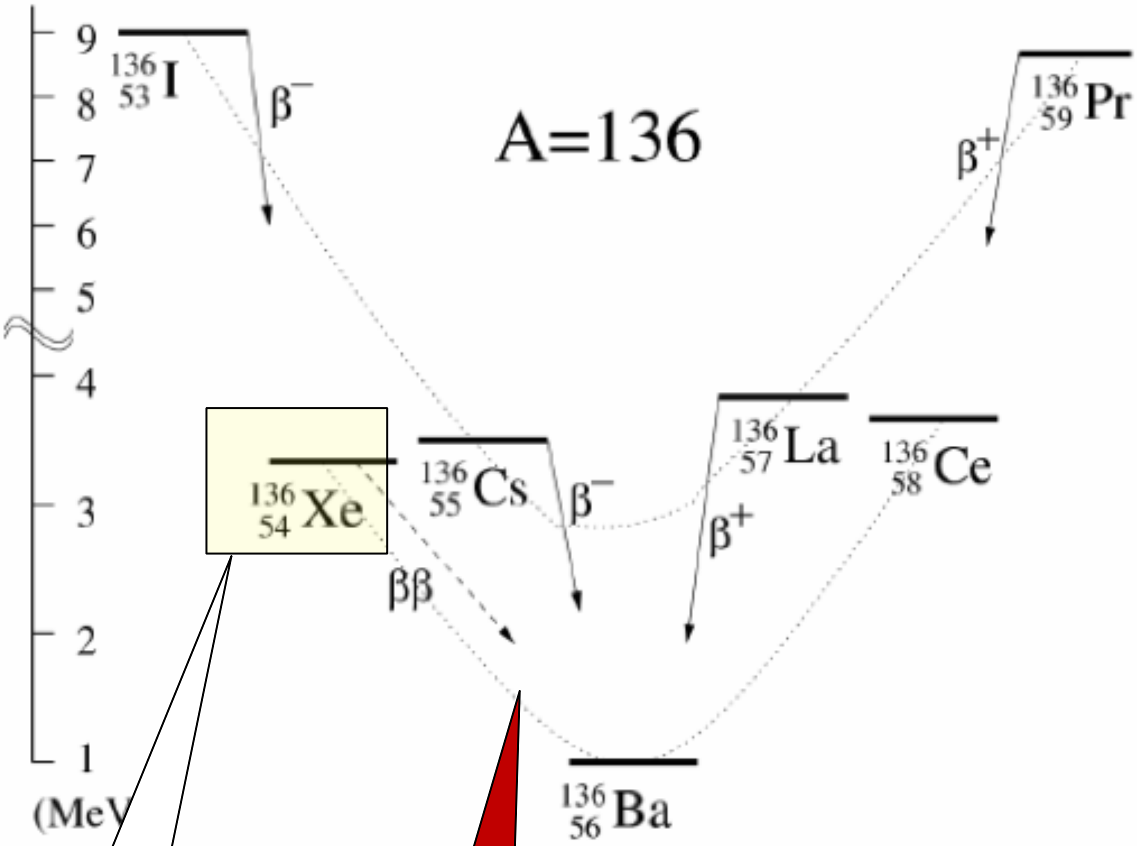


- observation would indicate:
    - **neutrinos are Majorana**
    - antimatterless matter is created

- light neutrino mediator is the nominal 3-flavor explanation
    - but can have other mediators in BSM scenarios

Experimental searches are based on nuclides for which NLDBD is energetically possible, *and* which cannot α, 1β decay

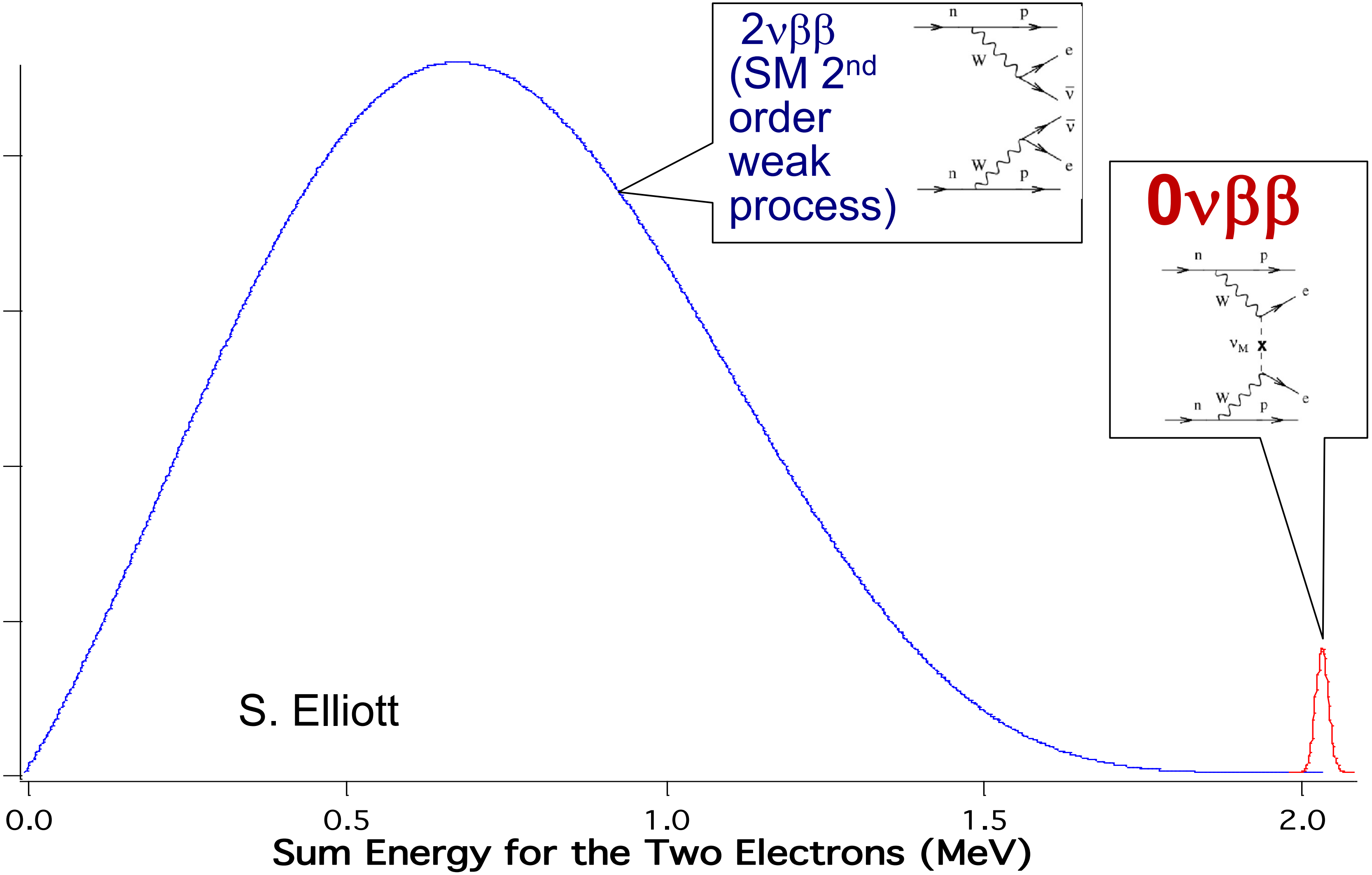
For example:



Stable against ordinary β^- decay

But can decay via $\beta^- \beta^-$

Experimental strategy: look for **peak in the two-electron spectrum** corresponding to neutrinoless final state



$2\nu\beta\beta$ (SM 2^{nd} order weak process)

$0\nu\beta\beta$

S. Elliott

The list of **special NLDBD isotopes** currently being pursued

Isotope	Daughter	$Q_{\beta\beta}$[a] [keV]	f_{nat}[b] [%]	f_{enr}[c] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91

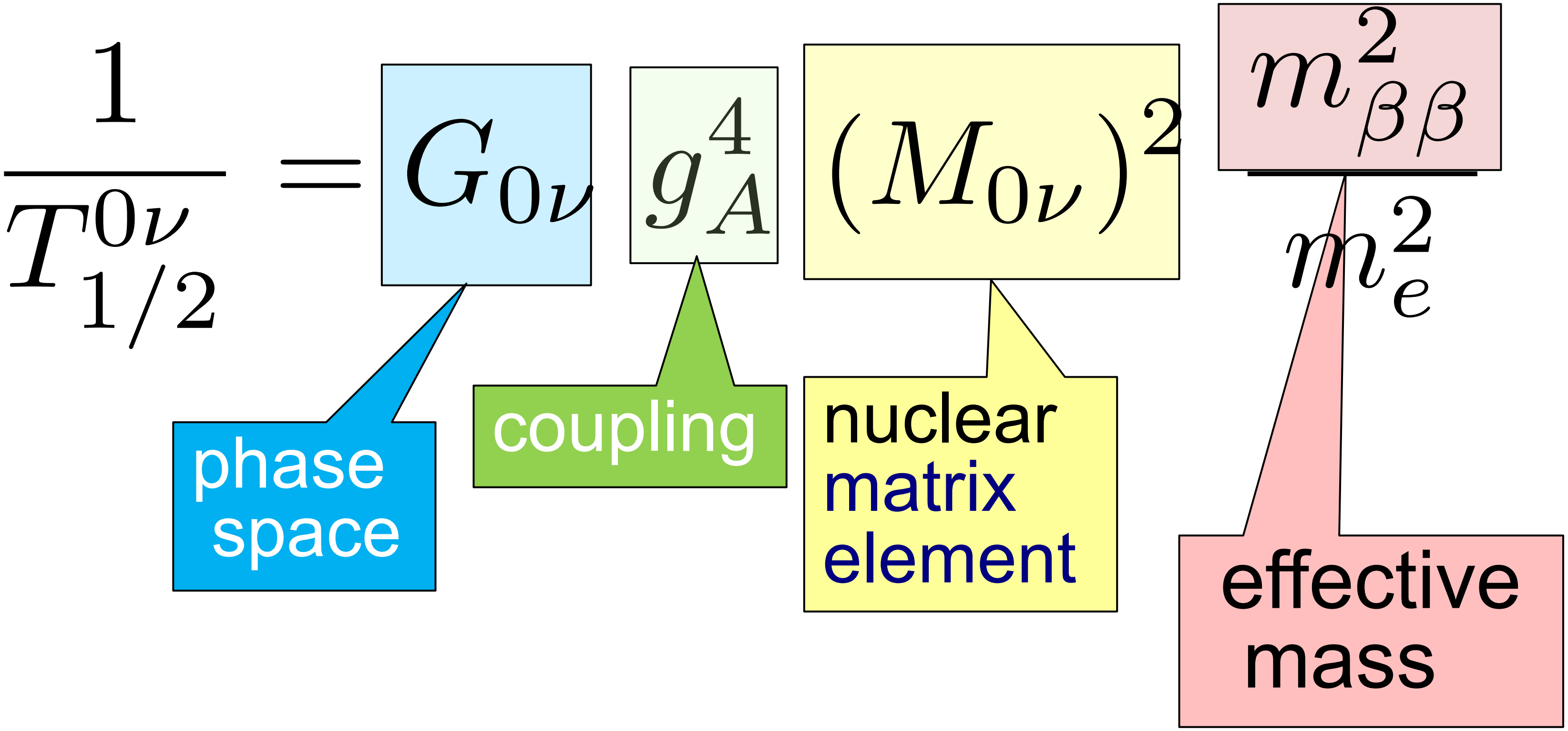
want large Q value!

want high natural abundance!

or at least, ability to enrich...

Agostini, Benato, Detwiler, Menéndez & Vissani, RMP 2022, arXiv:2202.01787 🙏

Observed half-life:



$$\frac{1}{T^{0\nu}_{1/2}} = \boxed{G_{0\nu}}\,\boxed{g_A^4}\,\boxed{(M_{0\nu})^2}\,\frac{\boxed{m_{\beta\beta}^2}}{m_e^2}$$

$$m_{\beta\beta} = |\sum_{i=1}^{3} |U_{ei}^2| e^{i\phi_i} m_i|$$

Effective mass depends on the mixing matrix parameters

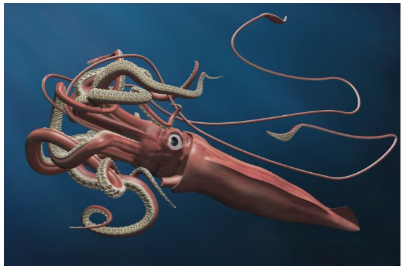
Observed half-life:

$$\frac{1}{T^{0\nu}_{1/2}} = \underbrace{G_{0\nu}}_{\text{phase space}}\ \underbrace{g_A^4}_{\text{coupling}}\ \underbrace{(M_{0\nu})^2}_{\text{nuclear matrix element}}\ \frac{\overbrace{m_{\beta\beta}^2}^{\text{effective mass}}}{m_e^2}\ ^{*}$$

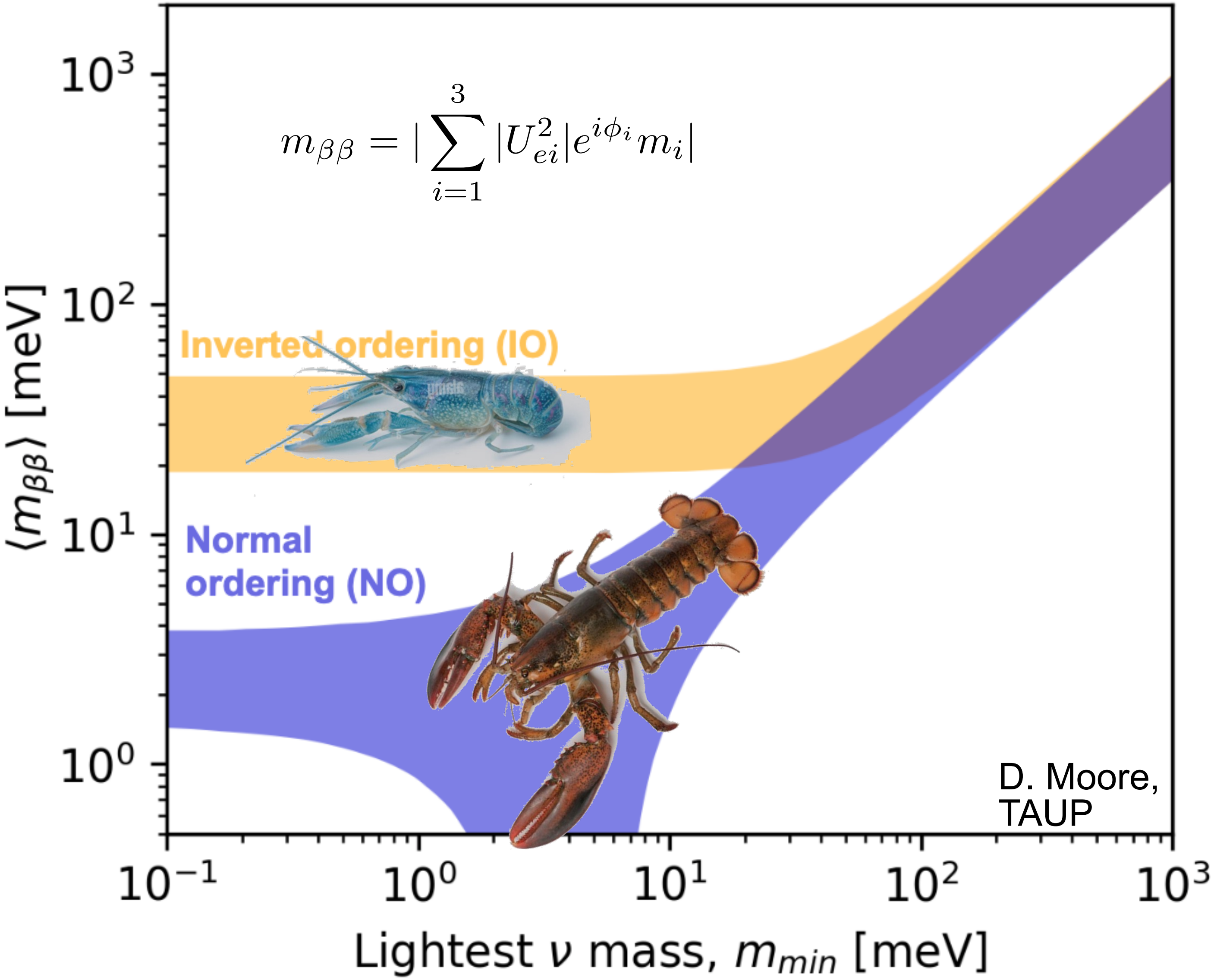
$$m_{\beta\beta} = |\sum_{i=1}^{3} |U_{ei}^2| e^{i\phi_i} m_i|$$

Effective mass depends on the mixing matrix parameters

*Caveat: BSM physics can be hiding!



The Lobster Plot



***If* neutrinos are Majorana*, experimental results must fall in the shaded regions**

Extent of the regions determined by uncertainties on mixing matrix elements and Majorana phases

*and standard 3-flavor picture, light-neutrino exchange mechanism

Neutrino mixing parameters

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

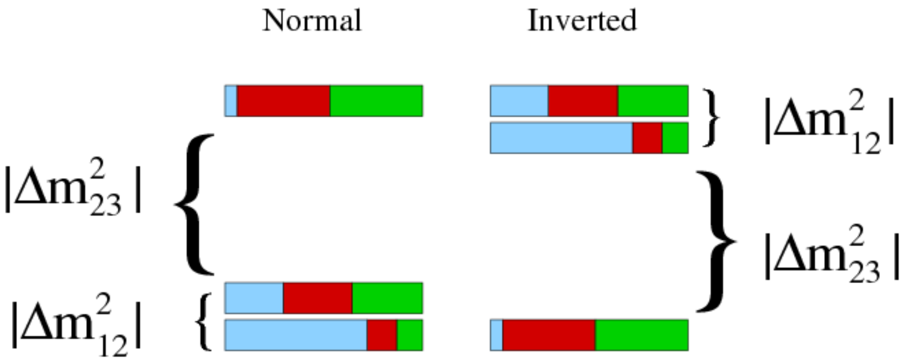
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$

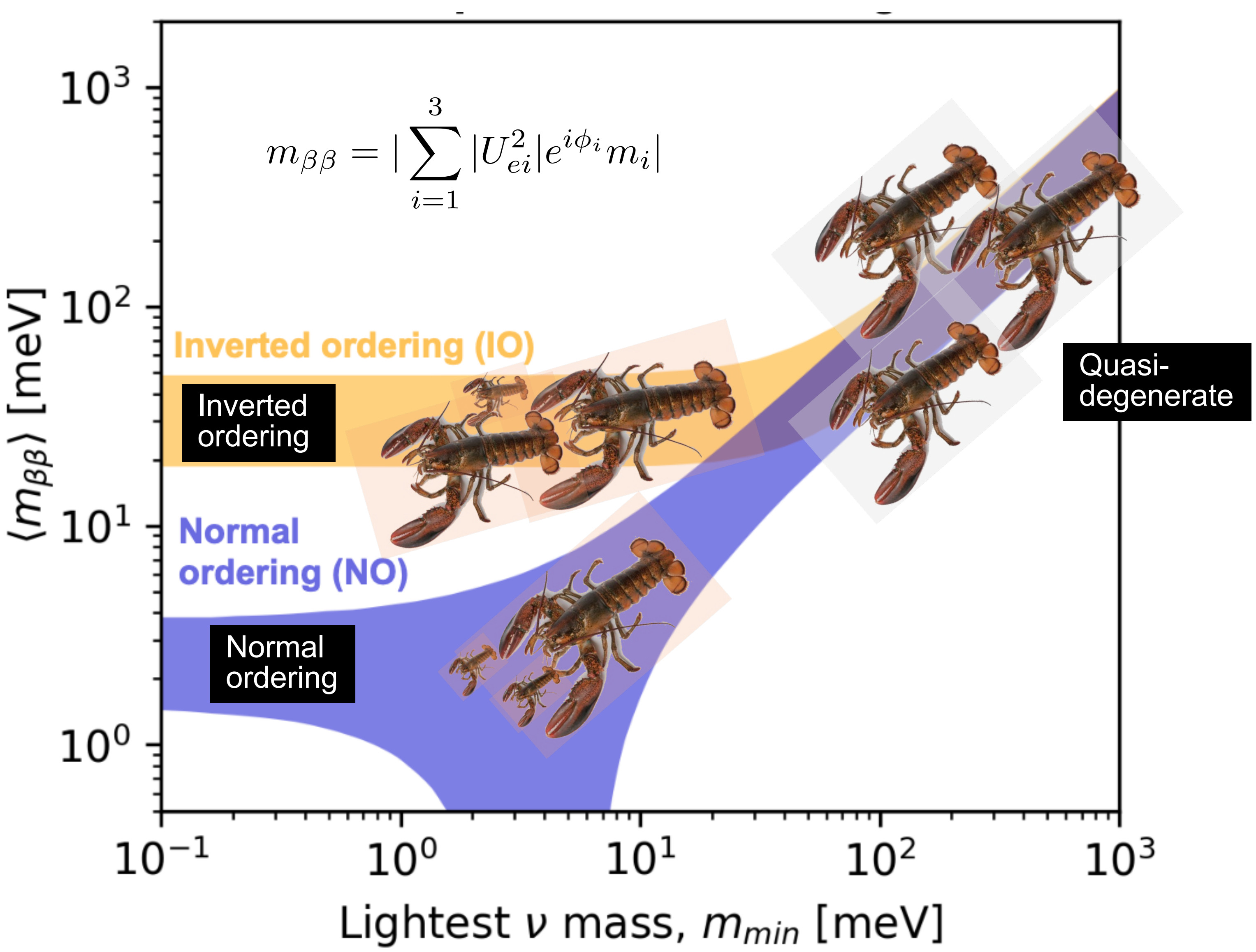
3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

Majorana phases do not affect oscillations



Observables in oscillation experiments

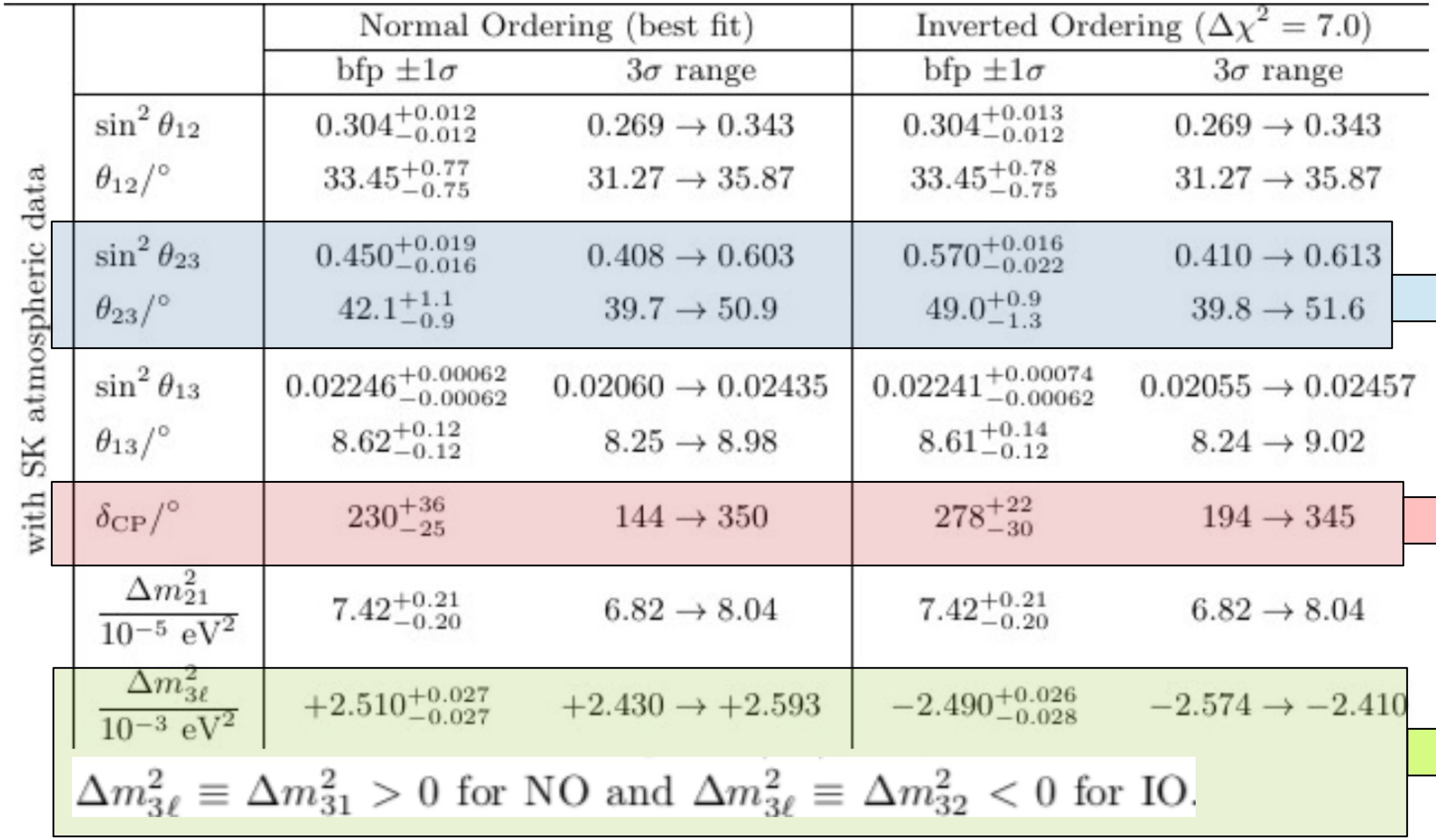
Assuming 3 flavors, light-neutrino exchange mechanism for NLDBD:



Clearly the **mass ordering matters** a lot for interpretation of NLDBD results

Remaining oscillation unknowns in the 3-flavor paradigm

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{\rm CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

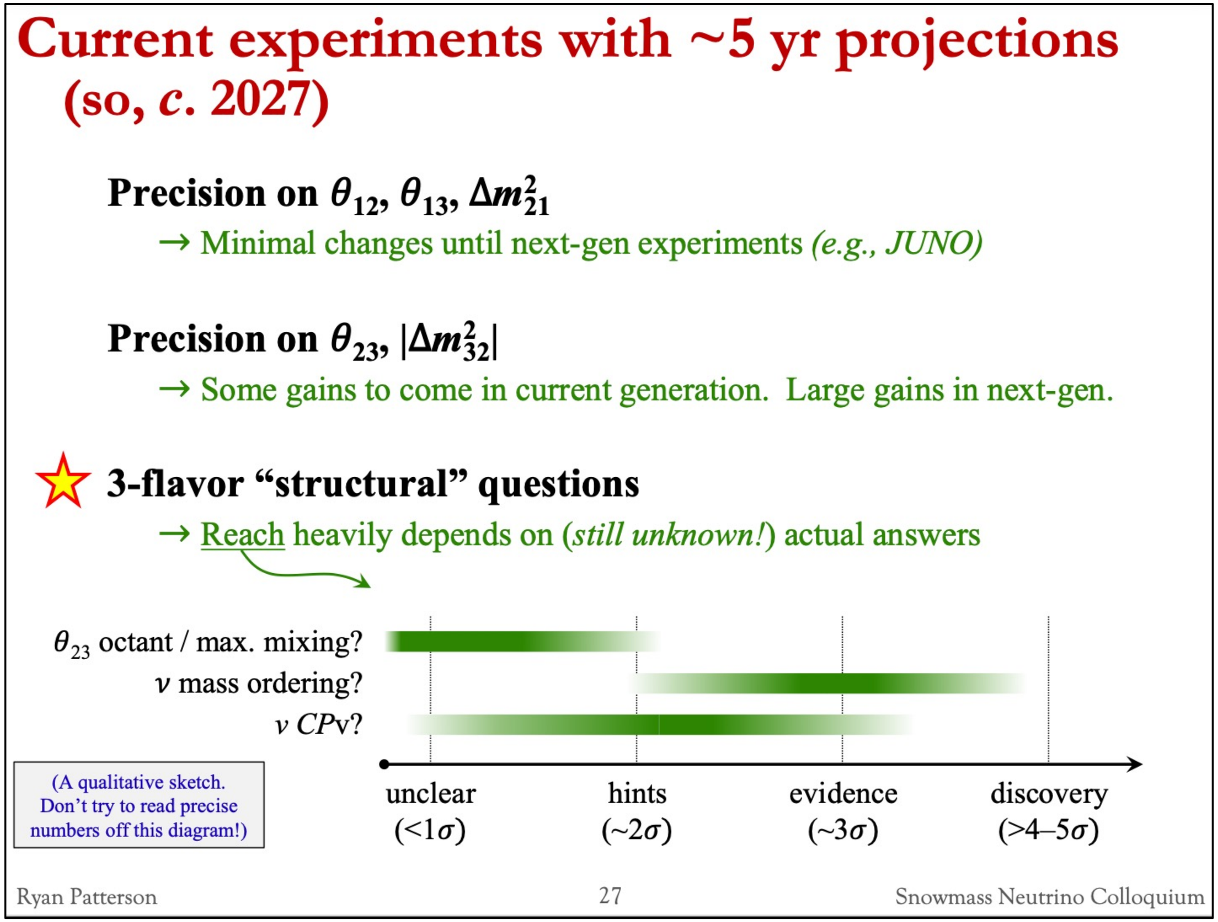
Is θ_{23} non-negligibly greater or smaller than 45 deg?

poor knowledge

sign of Δm^2 unknown (ordering of masses)

More and better info to come from:
beams [LBL], burns [solar, JUNO],
bangs [SNe]... **what will we know about mass ordering?**
(... it's smelling like normal, but inverted is not ruled out...)

Projections from Snowmass



Current experiments with ~5 yr projections (so, *c.* 2027)

Precision on θ_{12}, θ_{13}, Δm^2_{21}

→ Minimal changes until next-gen experiments *(e.g., JUNO)*

Precision on θ_{23}, $|\Delta m^2_{32}|$

→ Some gains to come in current generation. Large gains in next-gen.

★ **3-flavor "structural" questions**

→ Reach heavily depends on (*still unknown!*) actual answers

θ_{23} octant / max. mixing?

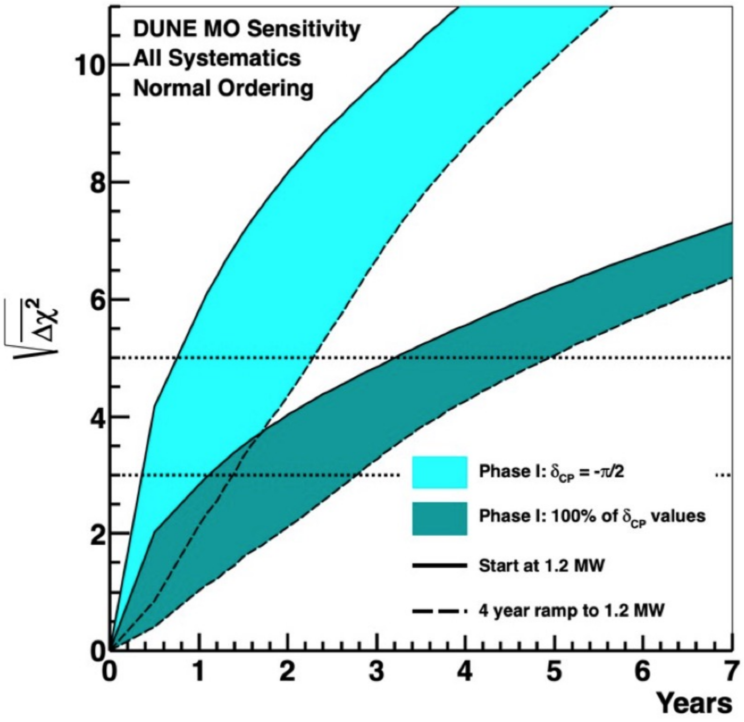
ν mass ordering?

ν *CP*v?

unclear (<1σ) | hints (~2σ) | evidence (~3σ) | discovery (>4–5σ)

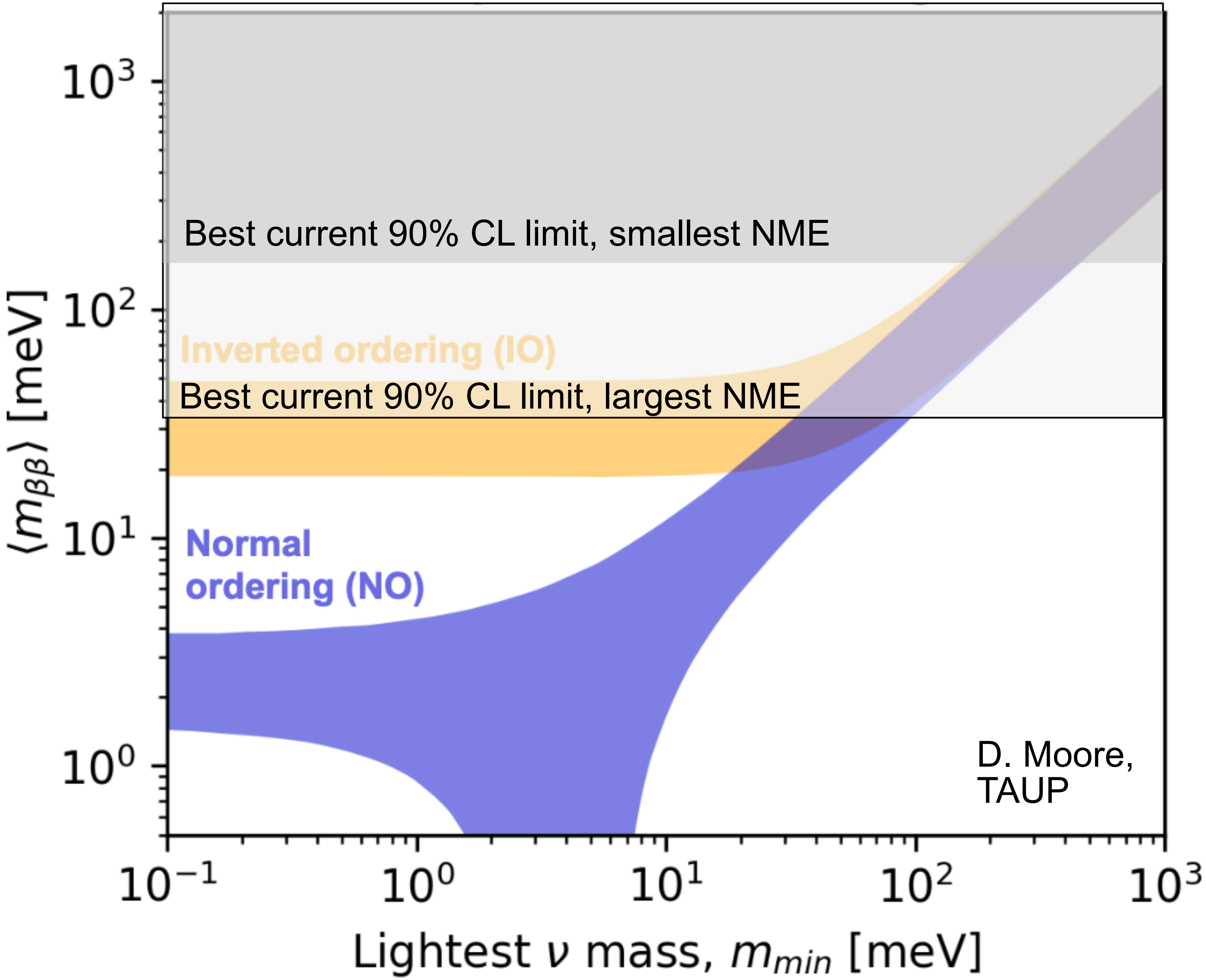
(A qualitative sketch. Don't try to read precise numbers off this diagram!)

Ryan Patterson 27 Snowmass Neutrino Colloquium



- Next ~5 years: maybe ~3σ from T2K + NOvA + JUNO
- DUNE/Hyper-K are next-generation long-baseline experiments
- DUNE will nail the mass ordering very rapidly

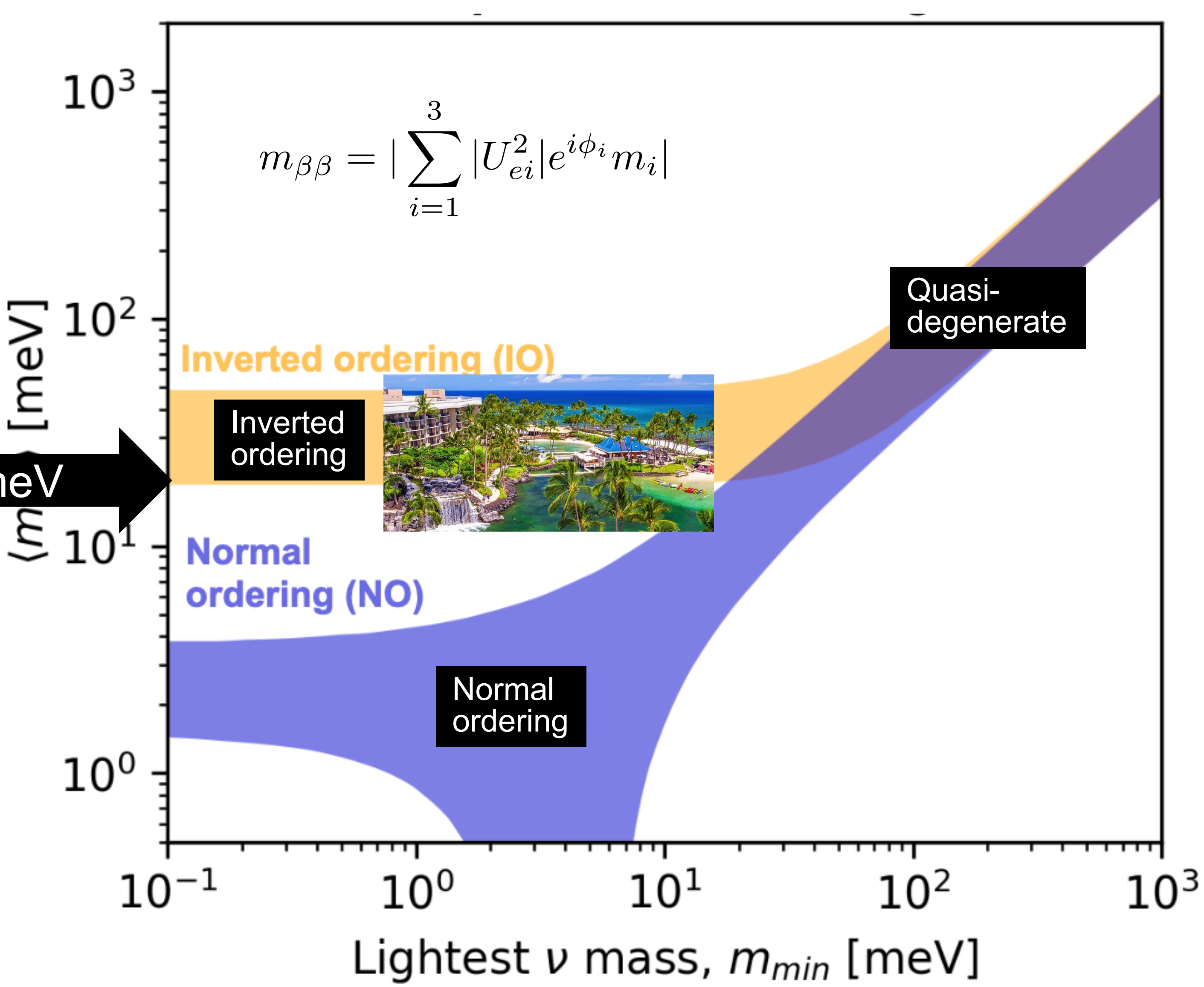
Where we are experimentally for NLDBD



D. Moore,
TAUP

Starting to clip the IO region

Next experimental goal: cover the IO region



$$m_{\beta\beta} = |\sum_{i=1}^{3} |U_{ei}^2| e^{i\phi_i} m_i|$$

18 meV

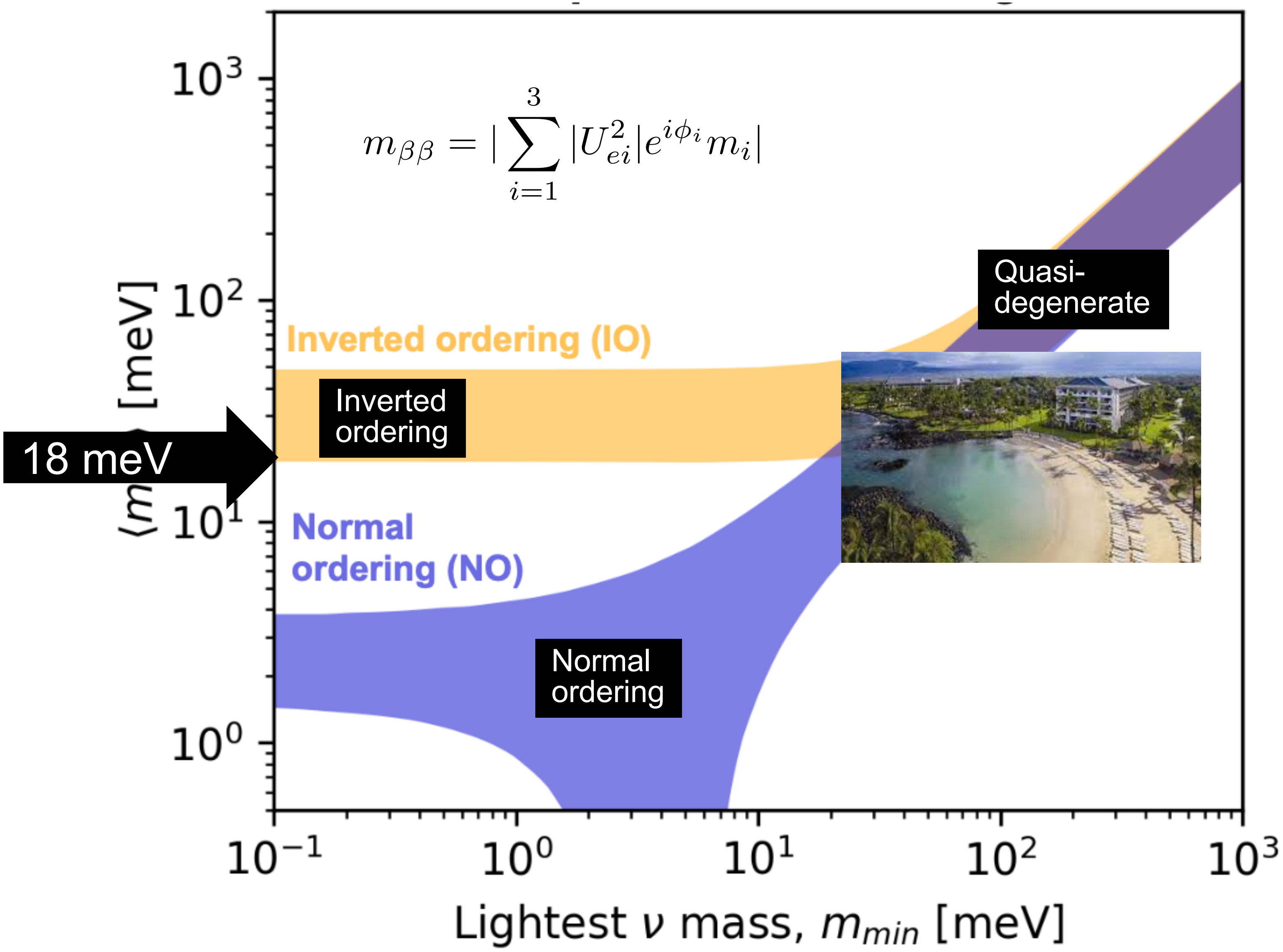
Inverted ordering

Normal ordering

Quasi-degenerate

If ordering is inverted (or QD) we will be in a good place!
Either: discover NLDBD! OR (neutrinos are Dirac OR BSM)

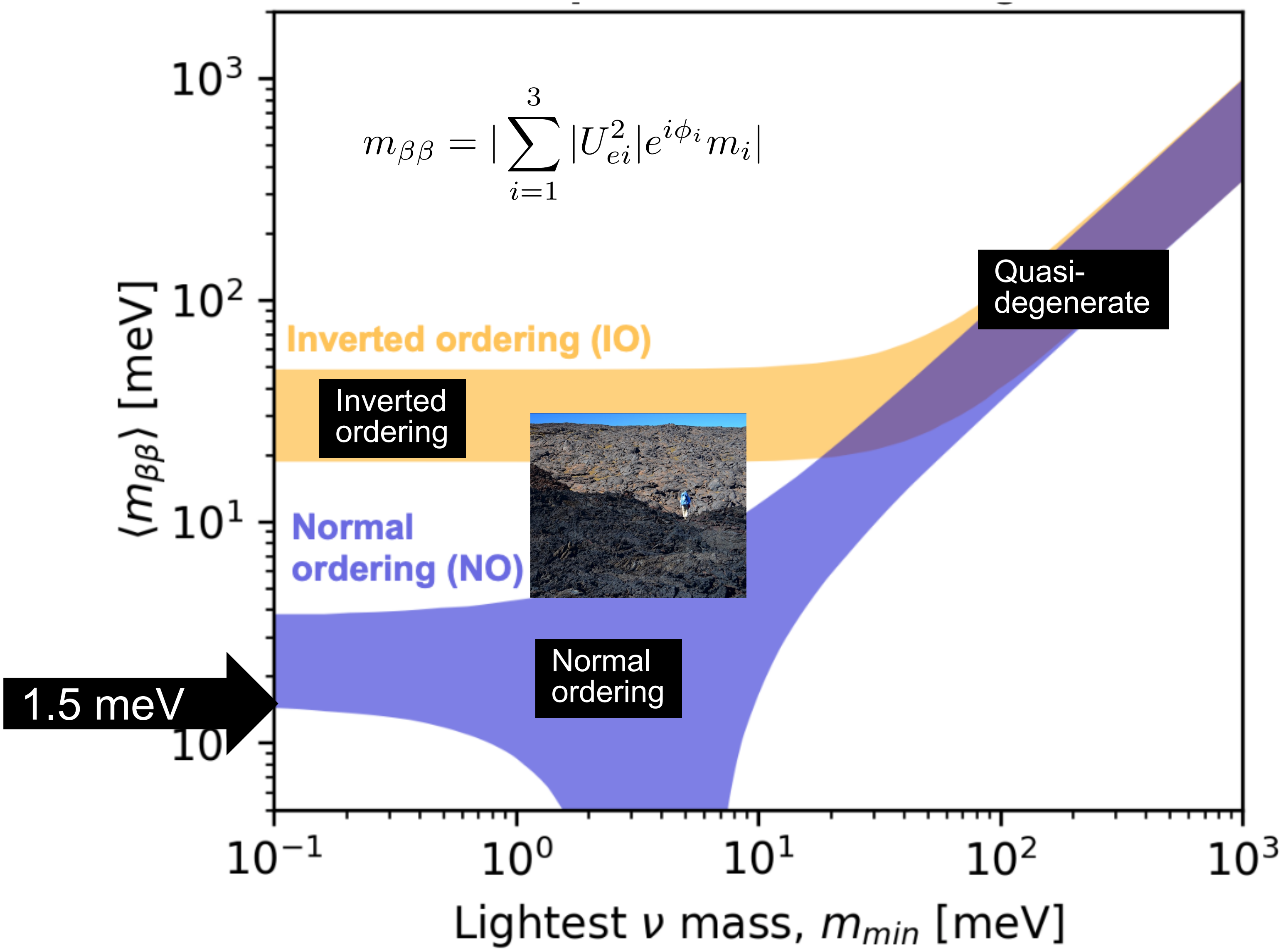
What if the mass ordering is normal?



$$m_{\beta\beta} = |\sum_{i=1}^{3} |U_{ei}^2| e^{i\phi_i} m_i|$$

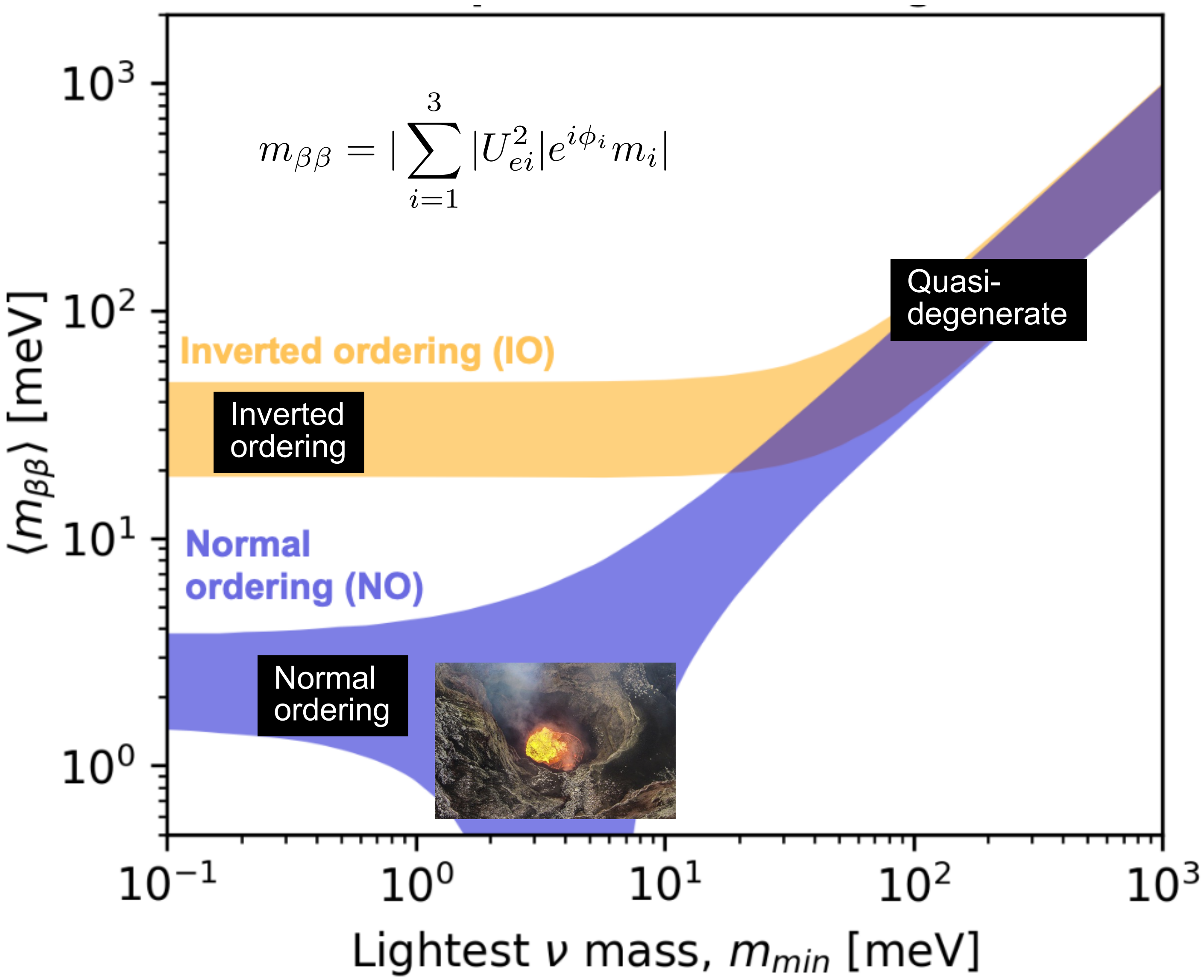
We could also have a high mass scale and discover NLDBD in the next generation ...

What if the mass ordering is normal?



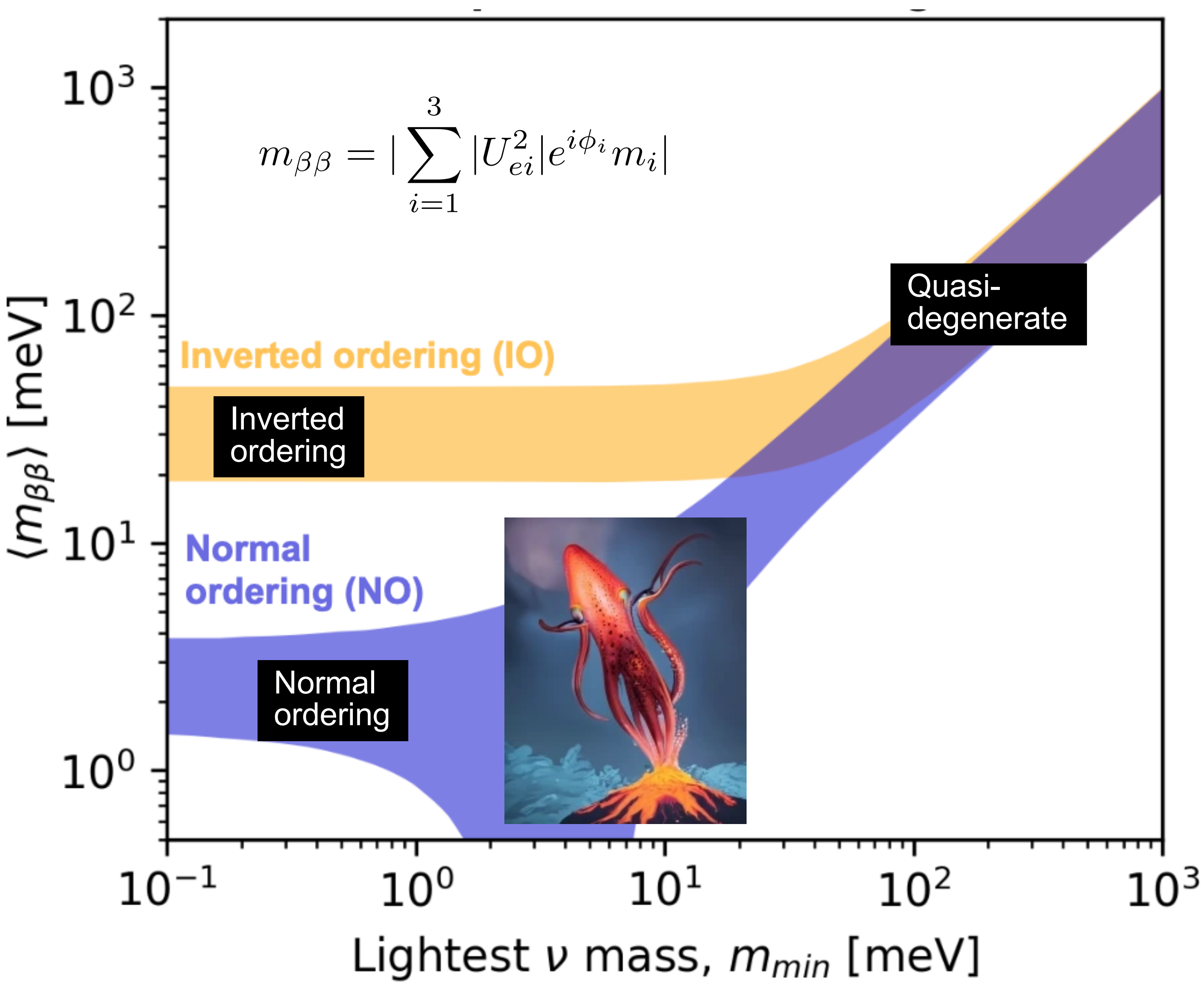
Otherwise, need to go lower...next goal for $m_{\beta\beta}$ is 1.5 meV, normal-ordering floor for $m_1=0$

What if the mass ordering is normal?



But... Nature could have cooked up diabolical parameters and we could end up staring into the funnel of doom...

What if the mass ordering is normal?

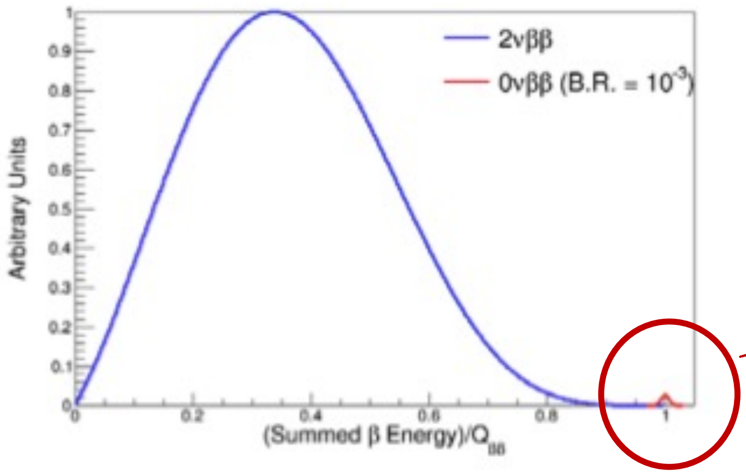


Athough it's still possible BSM could surprise us!

Back-of-the-envelope experimental sensitivity

$$T_{1/2} > \ln 2 \, \frac{\varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE



want lots of signal
and no background
in Region of Interest

Go after the numerator:

$$T_{1/2} > \frac{\ln 2 \; \boxed{\varepsilon \cdot N_{source} \cdot T}}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE

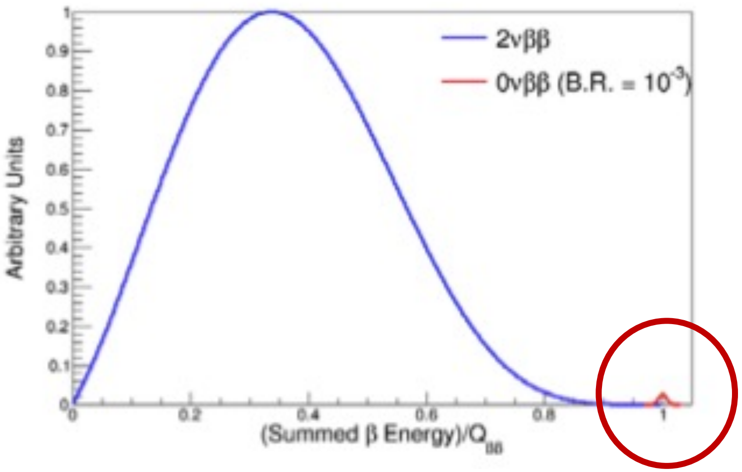
Want lots of candidate isotope!
At lifetime of $10^{26\text{-}27}$ yr (m$_{\beta\beta}$~ 50 meV in IO region)
need ~ 10^4 moles (~ 1 tonne) for 1 count/yr

➔ want high natural abundance, or effective isotope separation

Go after the denominator:

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL\left(\boxed{B(T) \cdot \Delta E}\right)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE

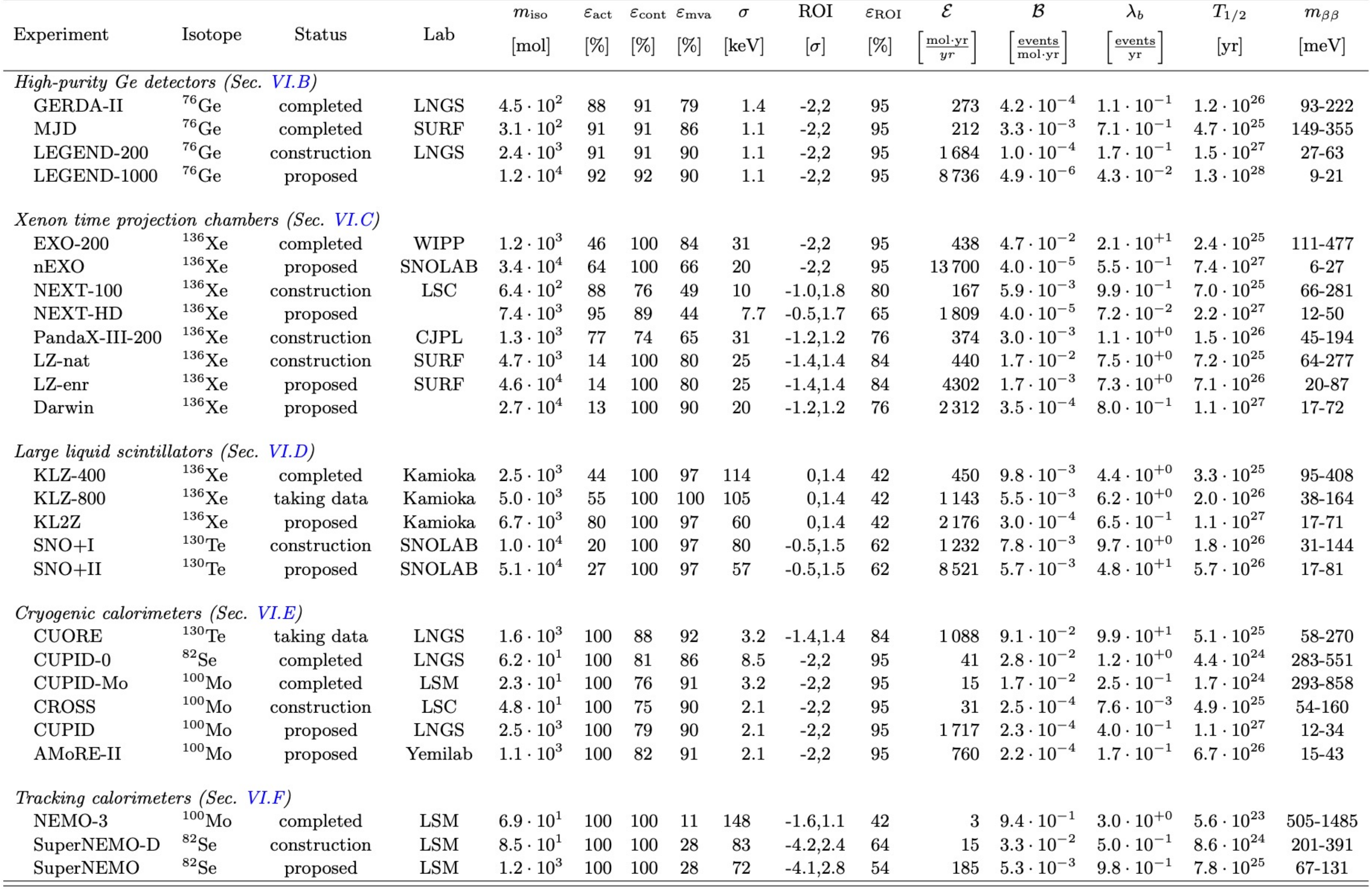


- Want small ΔE to avoid the 2νββ “friendly fire” and exclude other background
- Generally want high Q value to keep away from background
- Beat down all other background ... ultra-cleanliness, underground location needed

Neutrinoless Double Beta Decay Experiments

many, many isotopes and technologies

Recent and future experiments



Experiment	Isotope	Status	Lab	$m_{\rm iso}$ [mol]	$\varepsilon_{\rm act}$ [%]	$\varepsilon_{\rm cont}$ [%]	$\varepsilon_{\rm mva}$ [%]	σ [keV]	ROI [σ]	$\varepsilon_{\rm ROI}$ [%]	$\mathcal{E}$ $\left[\frac{\rm mol\cdot yr}{\rm yr}\right]$	$\mathcal{B}$ $\left[\frac{\rm events}{\rm mol\cdot yr}\right]$	λ_b $\left[\frac{\rm events}{\rm yr}\right]$	$T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
High-purity Ge detectors (Sec. VI.B)															
GERDA-II	^{76}Ge	completed	LNGS	$4.5\cdot10^{2}$	88	91	79	1.4	-2,2	95	273	$4.2\cdot10^{-4}$	$1.1\cdot10^{-1}$	$1.2\cdot10^{26}$	93-222
MJD	^{76}Ge	completed	SURF	$3.1\cdot10^{2}$	91	91	86	1.1	-2,2	95	212	$3.3\cdot10^{-3}$	$7.1\cdot10^{-1}$	$4.7\cdot10^{25}$	149-355
LEGEND-200	^{76}Ge	construction	LNGS	$2.4\cdot10^{3}$	91	91	90	1.1	-2,2	95	1 684	$1.0\cdot10^{-4}$	$1.7\cdot10^{-1}$	$1.5\cdot10^{27}$	27-63
LEGEND-1000	^{76}Ge	proposed		$1.2\cdot10^{4}$	92	92	90	1.1	-2,2	95	8 736	$4.9\cdot10^{-6}$	$4.3\cdot10^{-2}$	$1.3\cdot10^{28}$	9-21
Xenon time projection chambers (Sec. VI.C)															
EXO-200	^{136}Xe	completed	WIPP	$1.2\cdot10^{3}$	46	100	84	31	-2,2	95	438	$4.7\cdot10^{-2}$	$2.1\cdot10^{+1}$	$2.4\cdot10^{25}$	111-477
nEXO	^{136}Xe	proposed	SNOLAB	$3.4\cdot10^{4}$	64	100	66	20	-2,2	95	13 700	$4.0\cdot10^{-5}$	$5.5\cdot10^{-1}$	$7.4\cdot10^{27}$	6-27
NEXT-100	^{136}Xe	construction	LSC	$6.4\cdot10^{2}$	88	76	49	10	-1.0,1.8	80	167	$5.9\cdot10^{-3}$	$9.9\cdot10^{-1}$	$7.0\cdot10^{25}$	66-281
NEXT-HD	^{136}Xe	proposed		$7.4\cdot10^{3}$	95	89	44	7.7	-0.5,1.7	65	1 809	$4.0\cdot10^{-5}$	$7.2\cdot10^{-2}$	$2.2\cdot10^{27}$	12-50
PandaX-III-200	^{136}Xe	construction	CJPL	$1.3\cdot10^{3}$	77	74	65	31	-1.2,1.2	76	374	$3.0\cdot10^{-3}$	$1.1\cdot10^{+0}$	$1.5\cdot10^{26}$	45-194
LZ-nat	^{136}Xe	construction	SURF	$4.7\cdot10^{3}$	14	100	80	25	-1.4,1.4	84	440	$1.7\cdot10^{-2}$	$7.5\cdot10^{+0}$	$7.2\cdot10^{25}$	64-277
LZ-enr	^{136}Xe	proposed	SURF	$4.6\cdot10^{4}$	14	100	80	25	-1.4,1.4	84	4302	$1.7\cdot10^{-3}$	$7.3\cdot10^{+0}$	$7.1\cdot10^{26}$	20-87
Darwin	^{136}Xe	proposed		$2.7\cdot10^{4}$	13	100	90	20	-1.2,1.2	76	2 312	$3.5\cdot10^{-4}$	$8.0\cdot10^{-1}$	$1.1\cdot10^{27}$	17-72
Large liquid scintillators (Sec. VI.D)															
KLZ-400	^{136}Xe	completed	Kamioka	$2.5\cdot10^{3}$	44	100	97	114	0,1.4	42	450	$9.8\cdot10^{-3}$	$4.4\cdot10^{+0}$	$3.3\cdot10^{25}$	95-408
KLZ-800	^{136}Xe	taking data	Kamioka	$5.0\cdot10^{3}$	55	100	100	105	0,1.4	42	1 143	$5.5\cdot10^{-3}$	$6.2\cdot10^{+0}$	$2.0\cdot10^{26}$	38-164
KL2Z	^{136}Xe	proposed	Kamioka	$6.7\cdot10^{3}$	80	100	97	60	0,1.4	42	2 176	$3.0\cdot10^{-4}$	$6.5\cdot10^{-1}$	$1.1\cdot10^{27}$	17-71
SNO+I	^{130}Te	construction	SNOLAB	$1.0\cdot10^{4}$	20	100	97	80	-0.5,1.5	62	1 232	$7.8\cdot10^{-3}$	$9.7\cdot10^{+0}$	$1.8\cdot10^{26}$	31-144
SNO+II	^{130}Te	proposed	SNOLAB	$5.1\cdot10^{4}$	27	100	97	57	-0.5,1.5	62	8 521	$5.7\cdot10^{-3}$	$4.8\cdot10^{+1}$	$5.7\cdot10^{26}$	17-81
Cryogenic calorimeters (Sec. VI.E)															
CUORE	^{130}Te	taking data	LNGS	$1.6\cdot10^{3}$	100	88	92	3.2	-1.4,1.4	84	1 088	$9.1\cdot10^{-2}$	$9.9\cdot10^{+1}$	$5.1\cdot10^{25}$	58-270
CUPID-0	^{82}Se	completed	LNGS	$6.2\cdot10^{1}$	100	81	86	8.5	-2,2	95	41	$2.8\cdot10^{-2}$	$1.2\cdot10^{+0}$	$4.4\cdot10^{24}$	283-551
CUPID-Mo	^{100}Mo	completed	LSM	$2.3\cdot10^{1}$	100	76	91	3.2	-2,2	95	15	$1.7\cdot10^{-2}$	$2.5\cdot10^{-1}$	$1.7\cdot10^{24}$	293-858
CROSS	^{100}Mo	construction	LSC	$4.8\cdot10^{1}$	100	75	90	2.1	-2,2	95	31	$2.5\cdot10^{-4}$	$7.6\cdot10^{-3}$	$4.9\cdot10^{25}$	54-160
CUPID	^{100}Mo	proposed	LNGS	$2.5\cdot10^{3}$	100	79	90	2.1	-2,2	95	1 717	$2.3\cdot10^{-4}$	$4.0\cdot10^{-1}$	$1.1\cdot10^{27}$	12-34
AMoRE-II	^{100}Mo	proposed	Yemilab	$1.1\cdot10^{3}$	100	82	91	2.1	-2,2	95	760	$2.2\cdot10^{-4}$	$1.7\cdot10^{-1}$	$6.7\cdot10^{26}$	15-43
Tracking calorimeters (Sec. VI.F)															
NEMO-3	^{100}Mo	completed	LSM	$6.9\cdot10^{1}$	100	100	11	148	-1.6,1.1	42	3	$9.4\cdot10^{-1}$	$3.0\cdot10^{+0}$	$5.6\cdot10^{23}$	505-1485
SuperNEMO-D	^{82}Se	construction	LSM	$8.5\cdot10^{1}$	100	100	28	83	-4.2,2.4	64	15	$3.3\cdot10^{-2}$	$5.0\cdot10^{-1}$	$8.6\cdot10^{24}$	201-391
SuperNEMO	^{82}Se	proposed	LSM	$1.2\cdot10^{3}$	100	100	28	72	-4.1,2.8	54	185	$5.3\cdot10^{-3}$	$9.8\cdot10^{-1}$	$7.8\cdot10^{25}$	67-131

ABDMV, RMP 2022, arXiv:2202.01787

General NLDBD experiment strategies

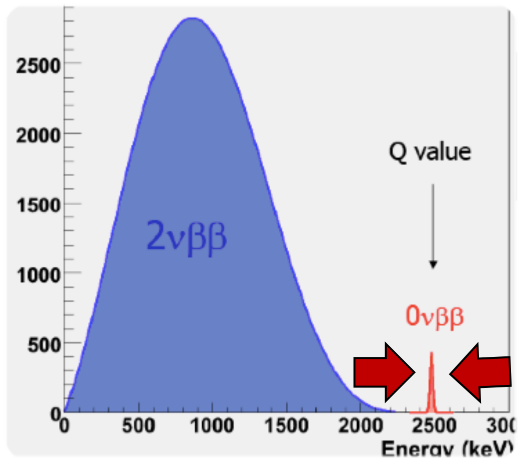
$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

The "Brute Force" Approach

focus on the numerator with a huge amount of material

(possibly sacrificing resolution)

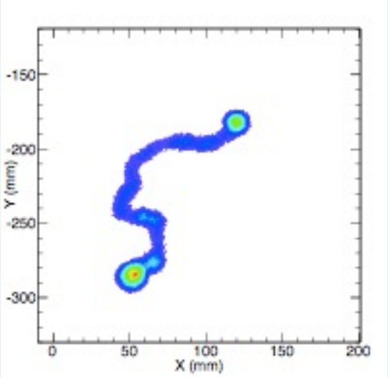
The "Peak-Squeezer" Approach



focus on the denominator by squeezing down ΔE

(various technologies)

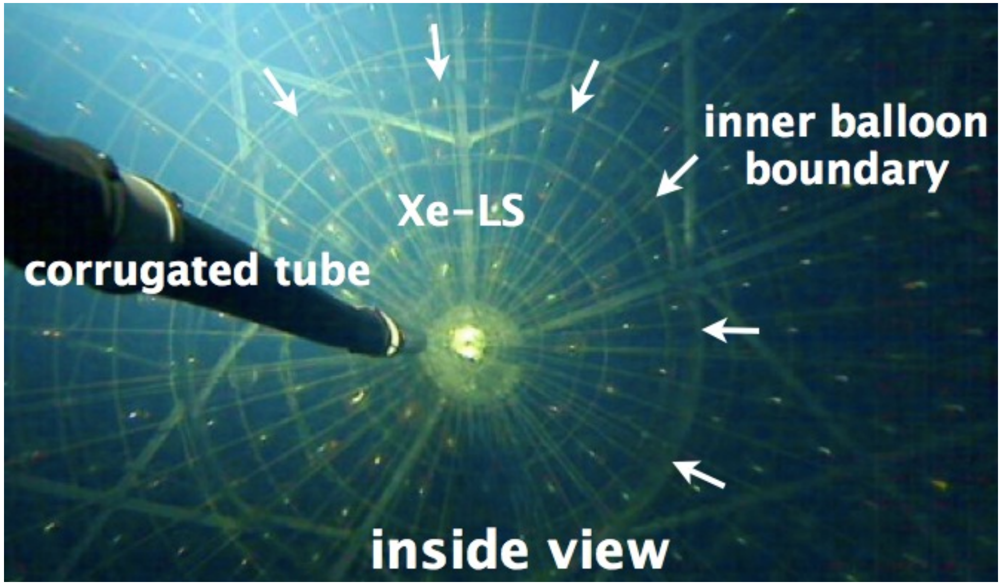
The "Final-State Judgement" Approach

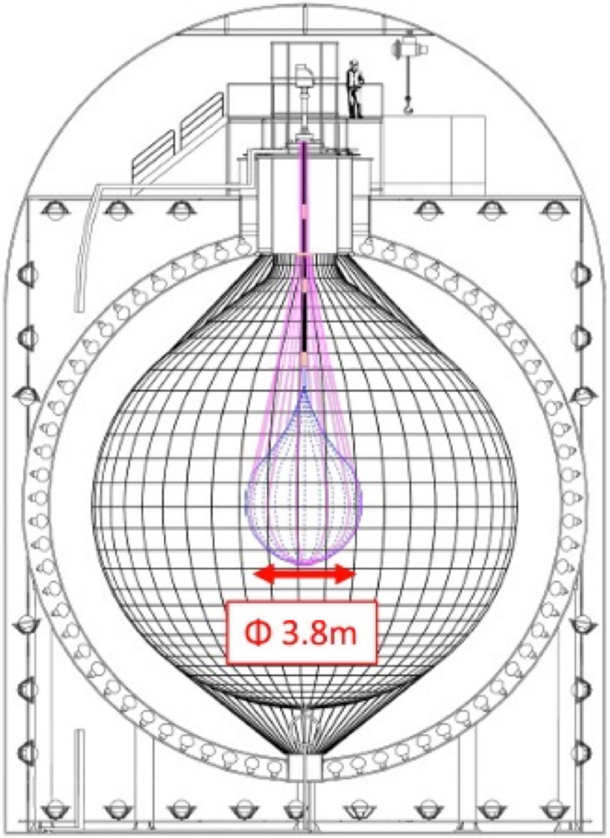


try to make the background zero by tracking or other technique

...and many (most) experiments try to do more than one of these...

Brute Force Strategy Example: **KamLAND-Zen**

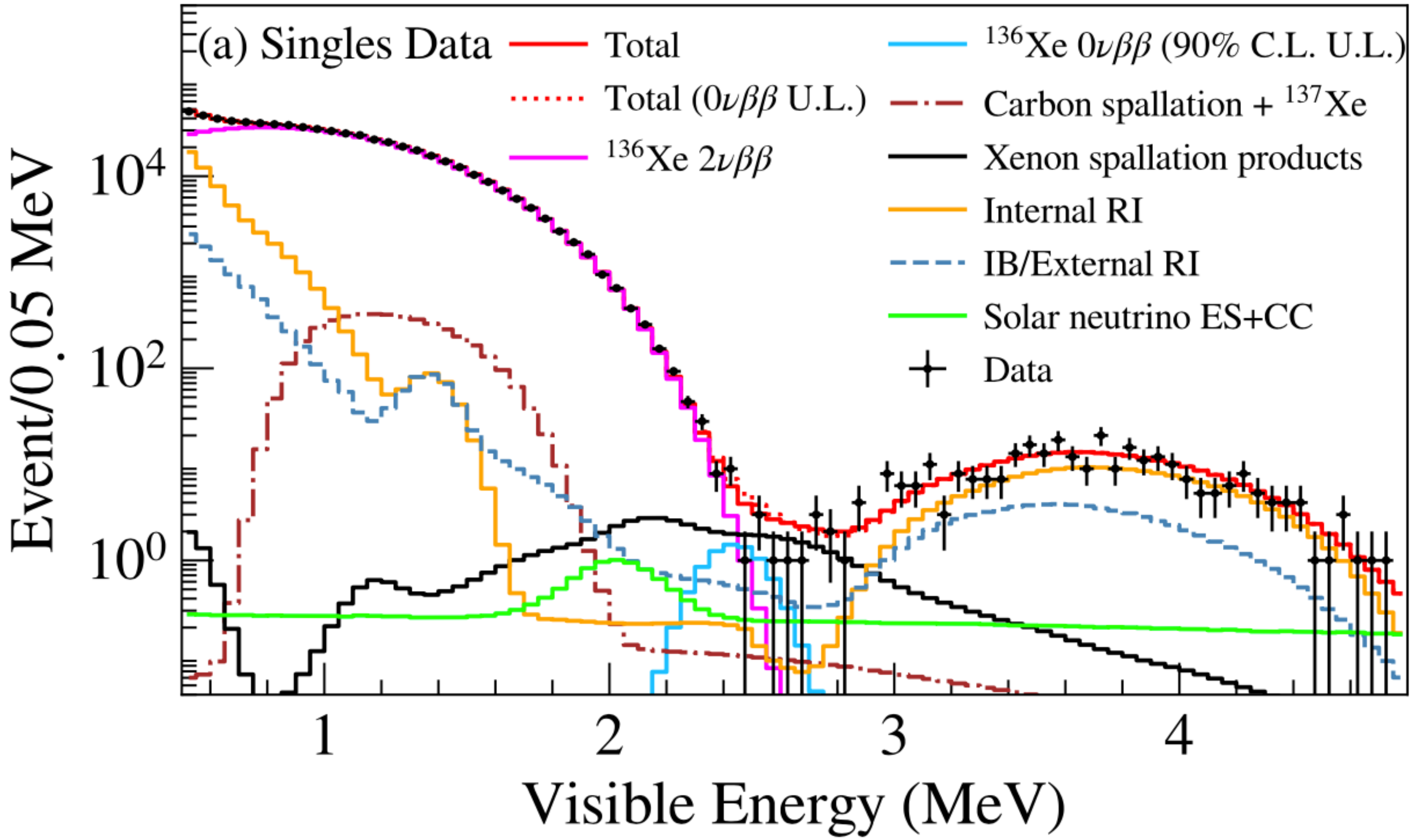




- "KamLAND-Zen 800": mini-balloon w/ 745 kg of ^{enr}Xe-loaded scintillator inside pure scintillator
- Kamioka mine in Japan

KamLAND-Zen Results

PRL **130**, 051801 (2023)

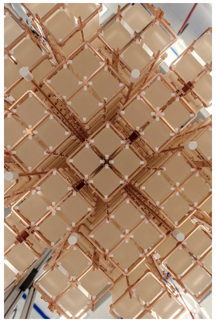


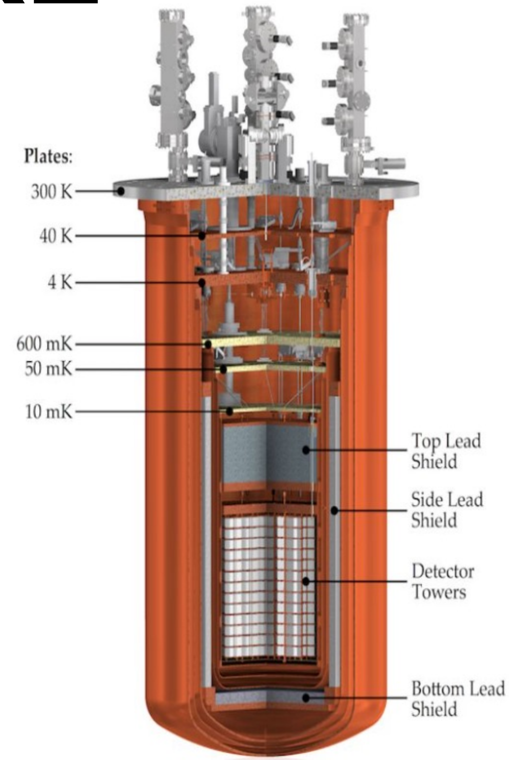
Most sensitive search to date: $m_{\beta\beta} < 36\text{-}156$ meV

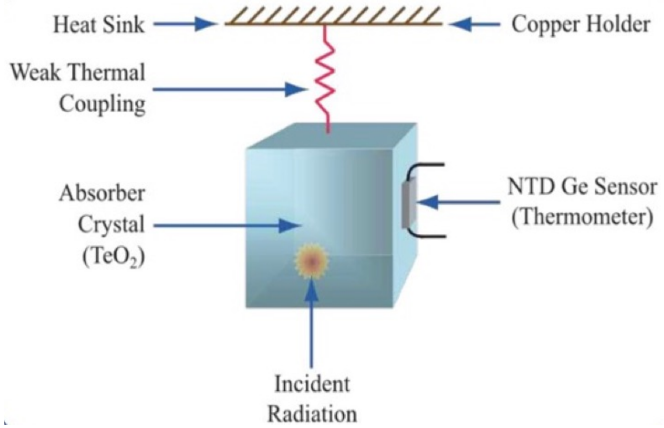
Next plans: improve energy resolution, 1 ton mass

A Peak-Squeezer: **CUORE**

Cryogenic bolometer
w/ $^{nat}TeO_2$ @ LNGS



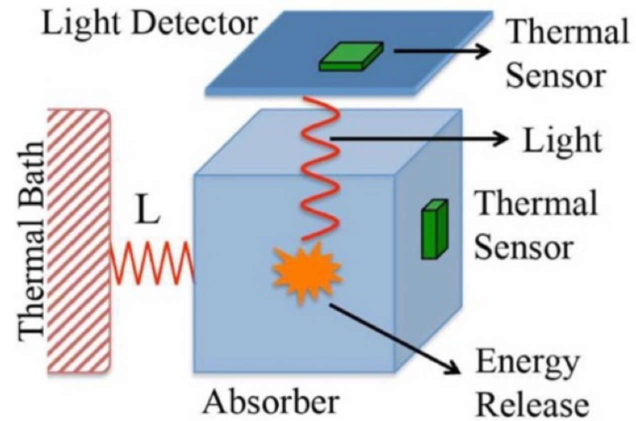




- source = detector
- calorimetric approach w/ high intrinsic energy resolution

Next generation:
CUPID $Li_2{}^{enr}MoO_4$

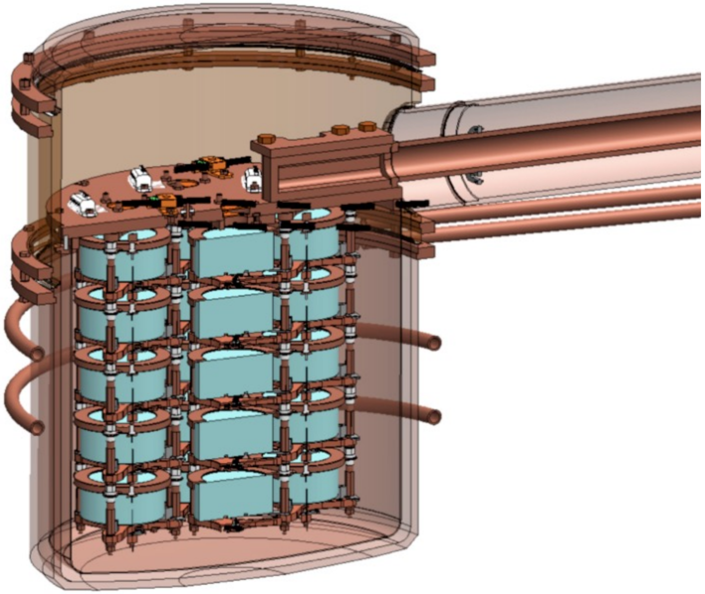
scintillating bolometer
w/ particle id



More Peak-Squeezers: **Germanium**

Germanium diode detectors
enriched in ^{76}Ge; very good energy resolution

MAJORANA DEMONSTRATOR

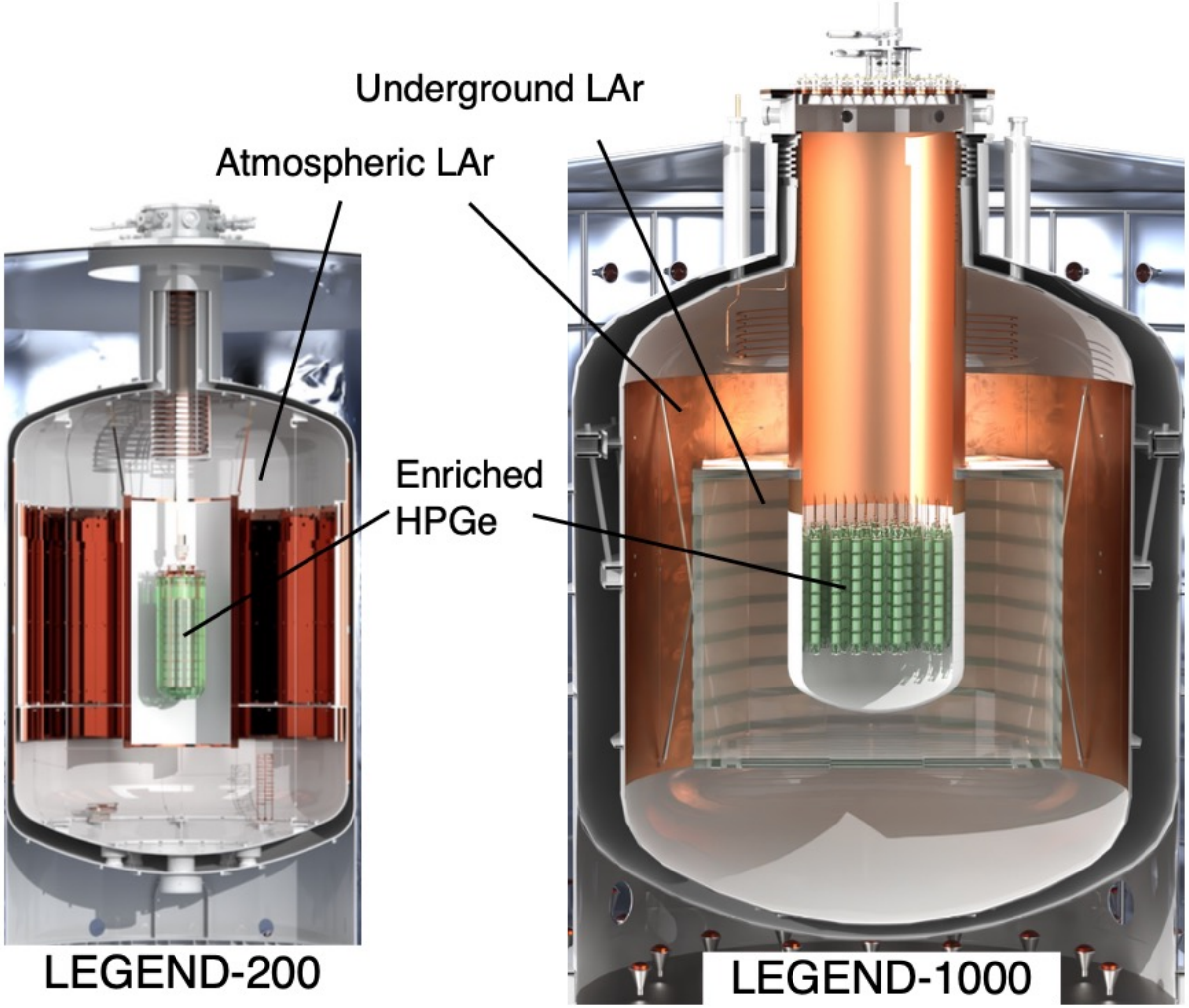


- Sanford Lab in South Dakota
- segmented detector strategy

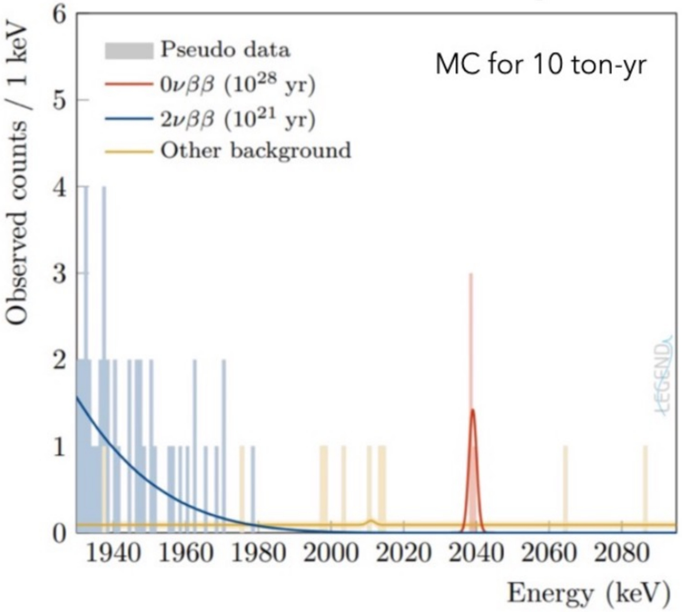
GERDA

- Gran Sasso, Italy
- detectors submerged in LAr

LEGEND tonne-scale program



LEGEND-1000 simulated spectrum:



S. Elliott, S. Schönert

LEGEND-200 @ LNGS

- Physics data-taking March 2023 (140 kg)
- Complete 200 kg array in early 2024

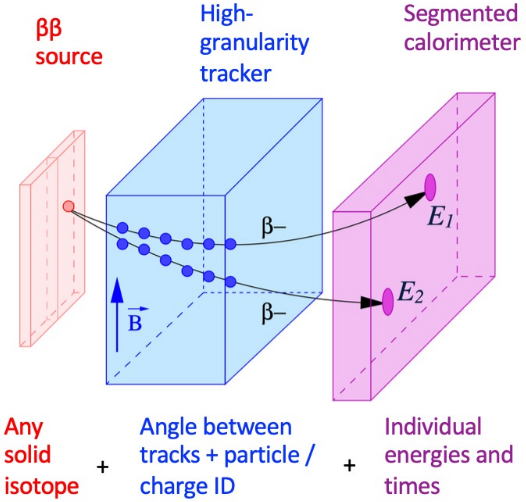
LEGEND-1000

- Site TBD (LNGS or SNOLAB)
- Conceptual design in progress

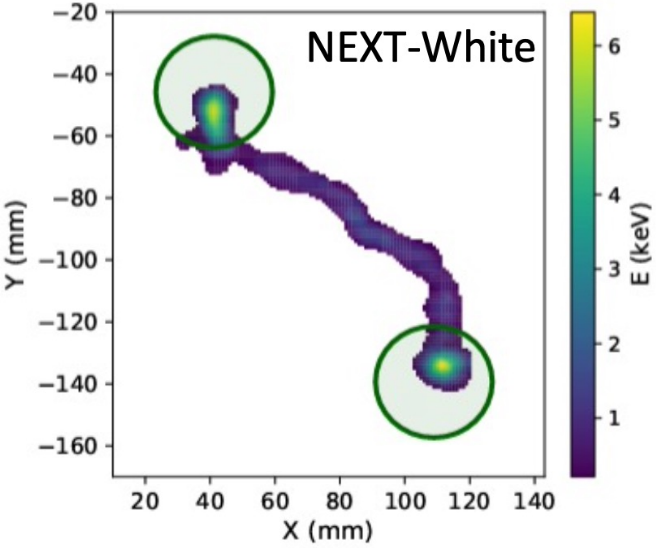
Final-State Judges

Pick out NLDBD signal from the background by precision final-state tracking

Segmented trackers (e.g., SuperNEMO)



Gas Xe TPCs (e.g., NEXT)

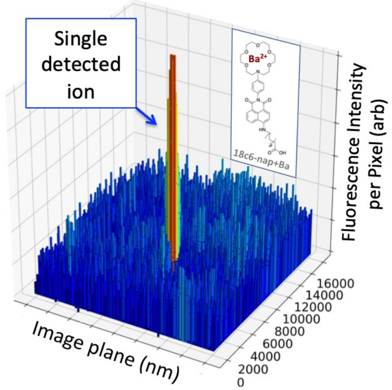


Possibly, pick out DBD signal by final-state-nucleus ID

B. Jones

Barium tagging in xenon liquid or gas

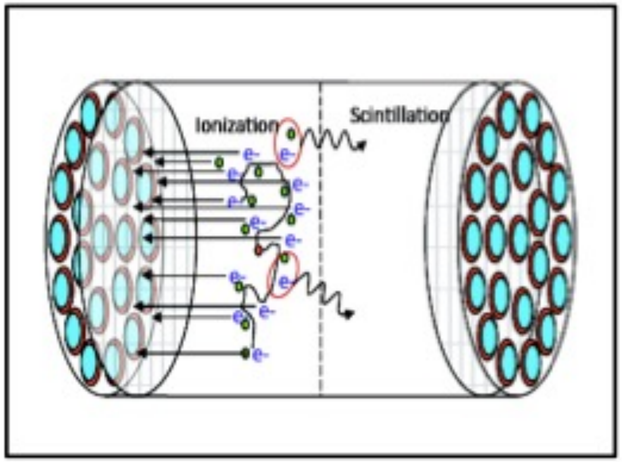
$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e$

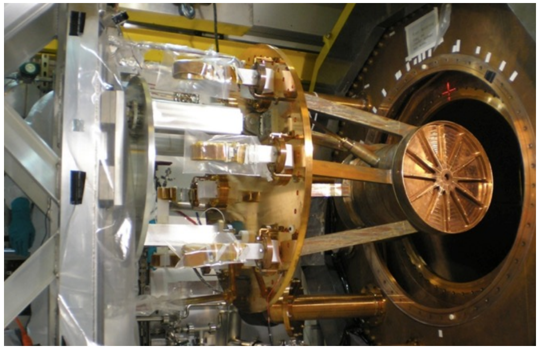


Hybrid peak squeezer/brute-forcer/[final-state judging]

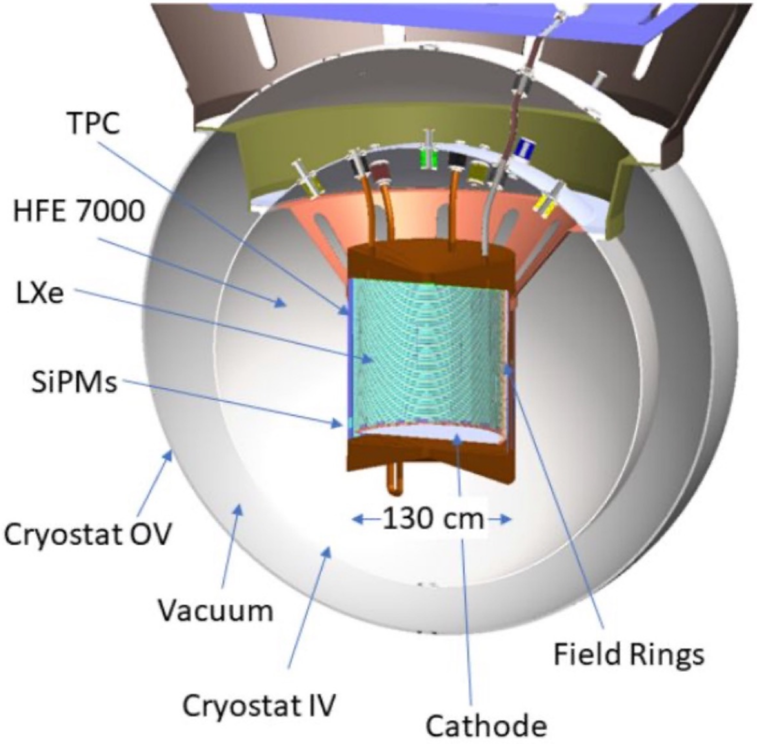
LXe TPCs

EXO-200





nEXO

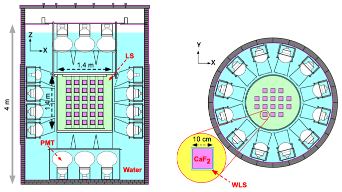


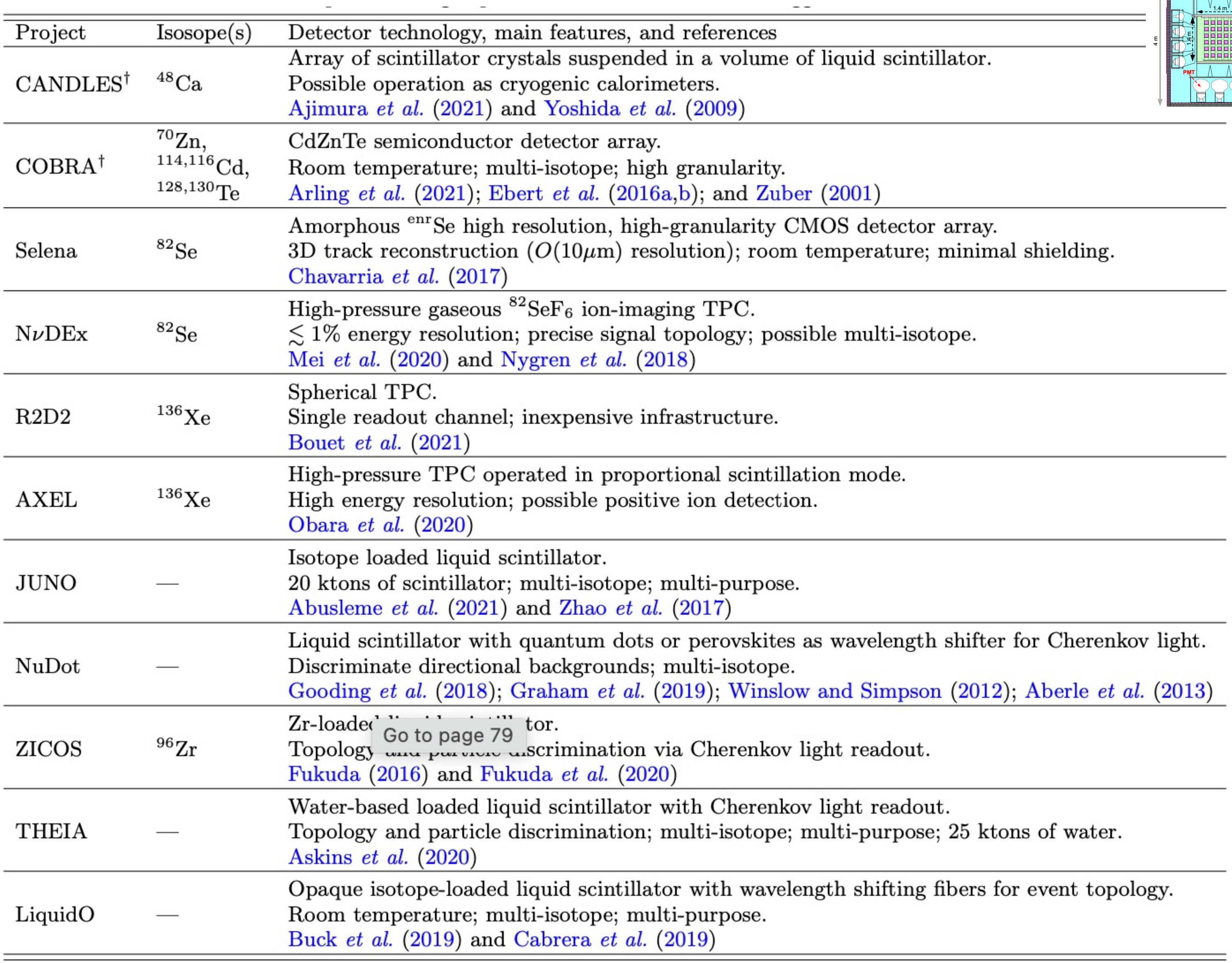
- no tracking, but single (0ν)
  -vs-multisite (bg) selection
- scintillation & ionization
- 80.6% enriched ^{136}Xe

- excellent background rejection by fiducialization

[+...long-term ideas for barium tagging]

And more creative ideas out there!

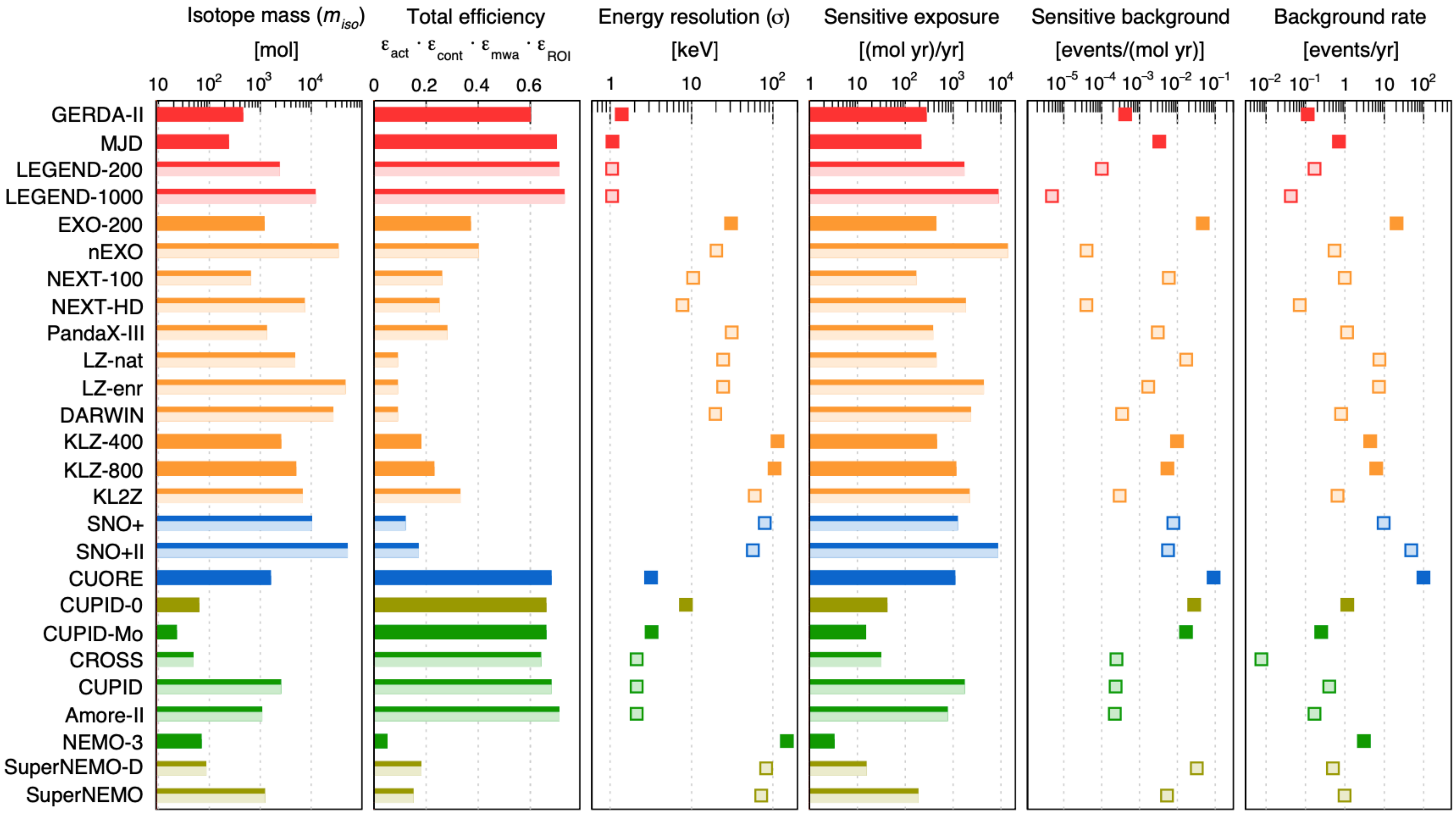




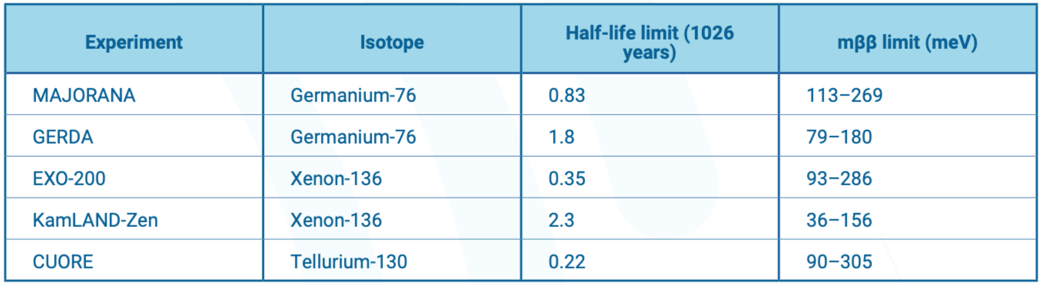
Project	Isosope(s)	Detector technology, main features, and references
CANDLES†	^{48}Ca	Array of scintillator crystals suspended in a volume of liquid scintillator. Possible operation as cryogenic calorimeters. Ajimura *et al.* (2021) and Yoshida *et al.* (2009)
COBRA†	^{70}Zn, ^{114,116}Cd, ^{128,130}Te	CdZnTe semiconductor detector array. Room temperature; multi-isotope; high granularity. Arling *et al.* (2021); Ebert *et al.* (2016a,b); and Zuber (2001)
Selena	^{82}Se	Amorphous $^{\mathrm{enr}}$Se high resolution, high-granularity CMOS detector array. 3D track reconstruction ($O(10\mu\mathrm{m})$ resolution); room temperature; minimal shielding. Chavarria *et al.* (2017)
NνDEx	^{82}Se	High-pressure gaseous ^{82}SeF$_6$ ion-imaging TPC. $\lesssim 1\%$ energy resolution; precise signal topology; possible multi-isotope. Mei *et al.* (2020) and Nygren *et al.* (2018)
R2D2	^{136}Xe	Spherical TPC. Single readout channel; inexpensive infrastructure. Bouet *et al.* (2021)
AXEL	^{136}Xe	High-pressure TPC operated in proportional scintillation mode. High energy resolution; possible positive ion detection. Obara *et al.* (2020)
JUNO	—	Isotope loaded liquid scintillator. 20 ktons of scintillator; multi-isotope; multi-purpose. Abusleme *et al.* (2021) and Zhao *et al.* (2017)
NuDot	—	Liquid scintillator with quantum dots or perovskites as wavelength shifter for Cherenkov light. Discriminate directional backgrounds; multi-isotope. Gooding *et al.* (2018); Graham *et al.* (2019); Winslow and Simpson (2012); Aberle *et al.* (2013)
ZICOS	^{96}Zr	Zr-loaded liquid scintillator. Topology and particle discrimination via Cherenkov light readout. Fukuda (2016) and Fukuda *et al.* (2020)
THEIA	—	Water-based loaded liquid scintillator with Cherenkov light readout. Topology and particle discrimination; multi-isotope; multi-purpose; 25 ktons of water. Askins *et al.* (2020)
LiquidO	—	Opaque isotope-loaded liquid scintillator with wavelength shifting fibers for event topology. Room temperature; multi-isotope; multi-purpose. Buck *et al.* (2019) and Cabrera *et al.* (2019)

ABDMV, RMP 2022, arXiv:2202.01787

Summary of recent and future experiments



ABDMV, RMP 2022, arXiv:2202.01787

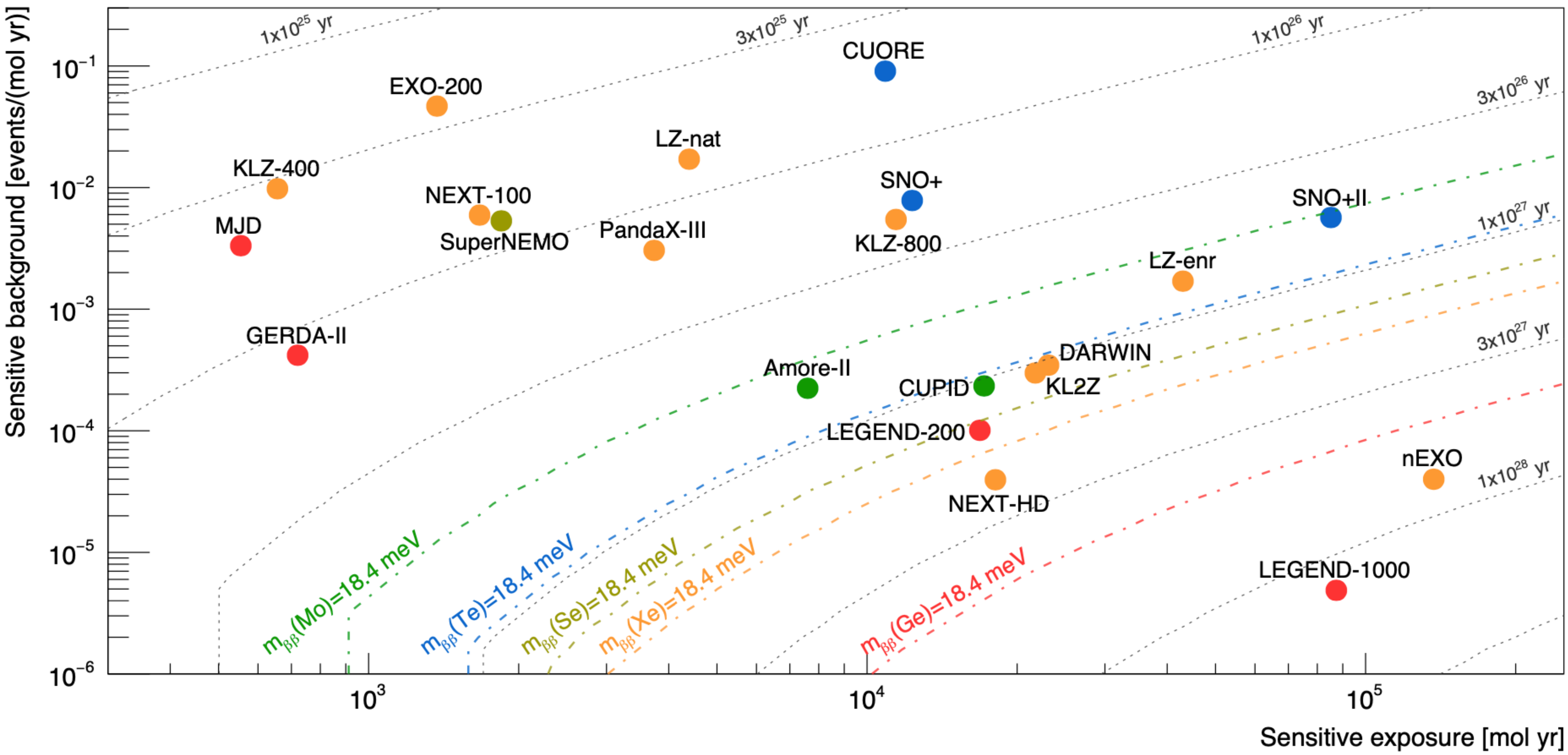


Experiment	Isotope	Half-life limit (1026 years)	mββ limit (meV)
MAJORANA	Germanium-76	0.83	113–269
GERDA	Germanium-76	1.8	79–180
EXO-200	Xenon-136	0.35	93–286
KamLAND-Zen	Xenon-136	2.3	36–156
CUORE	Tellurium-130	0.22	90–305

Up-to-date
limits from LRP

Sensitive background and exposure for recent and future experiments

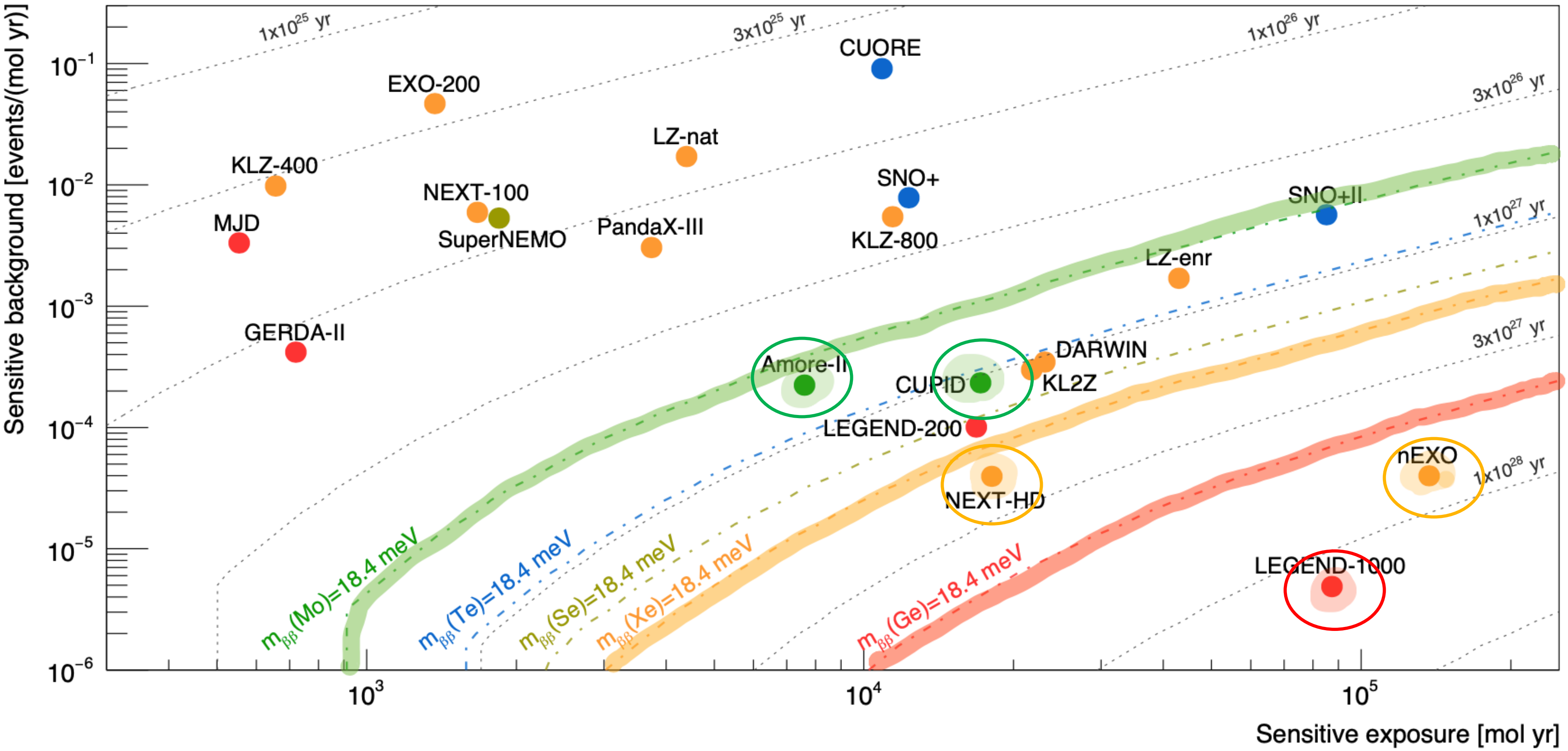
ABDMV, RMP 2022, arXiv:2202.01787



Grey dashed lines: discovery sensitivity on the NLDBD $T_{1/2}$ (isotope-independent)

Sensitive background and exposure for recent and future experiments

ABDMV, RMP 2022, arXiv:2202.01787



Grey dashed lines: discovery sensitivity on the NLDBD $T_{1/2}$ (isotope-independent)
Colored dashed lines: $m_{\beta\beta}$ sensitivities to **get to the bottom of the IO region** for *specific isotopes*, taking into account NME & phase space

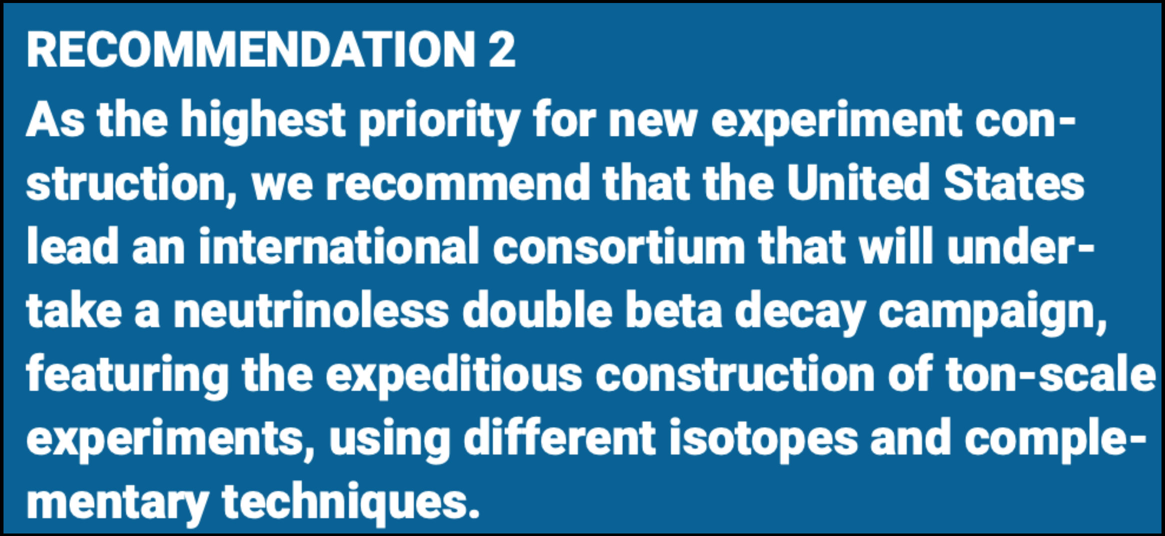
[specific ~optimistic NME assumption] → **want to be to the lower right of *your* colored line!**

NLDBD in the US Long Range Plan

A NEW ERA OF DISCOVERY

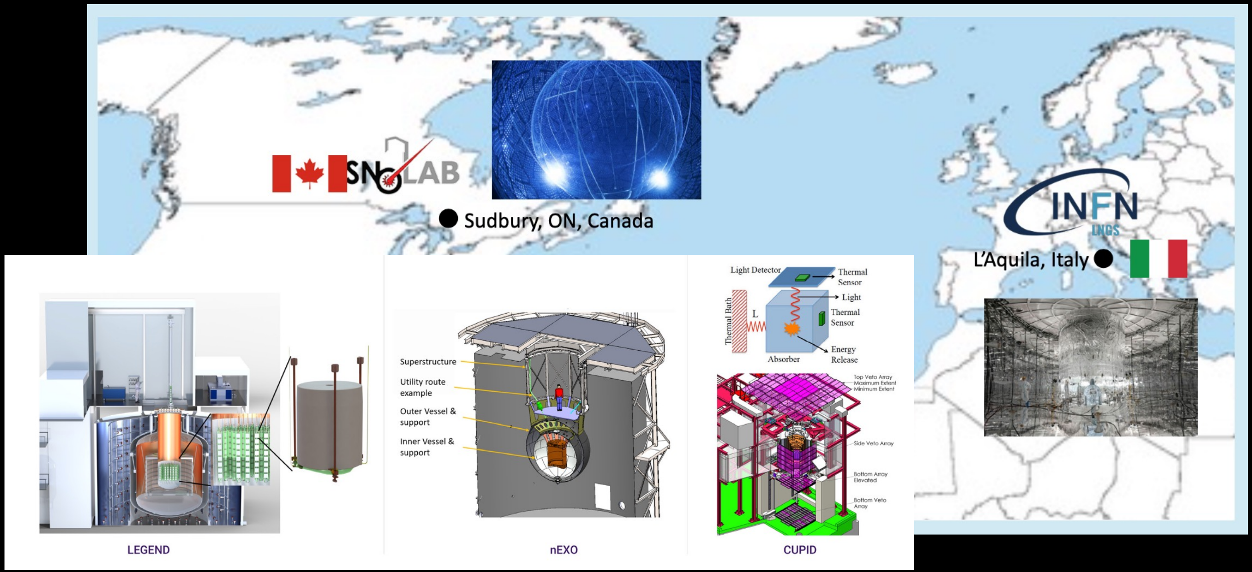
THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

2023 | VERSION 1.3



RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.



CUPID, nEXO, LEGEND @ LNGS & SNOLAB

The future is exciting for NLDBD experiments!

- we're starting to **clip the IO region** (KZ-800)
- **next-generation tonne-scale experiments** will get below it
- lots of activity and ideas

(Don't forget to watch out for giant squids)