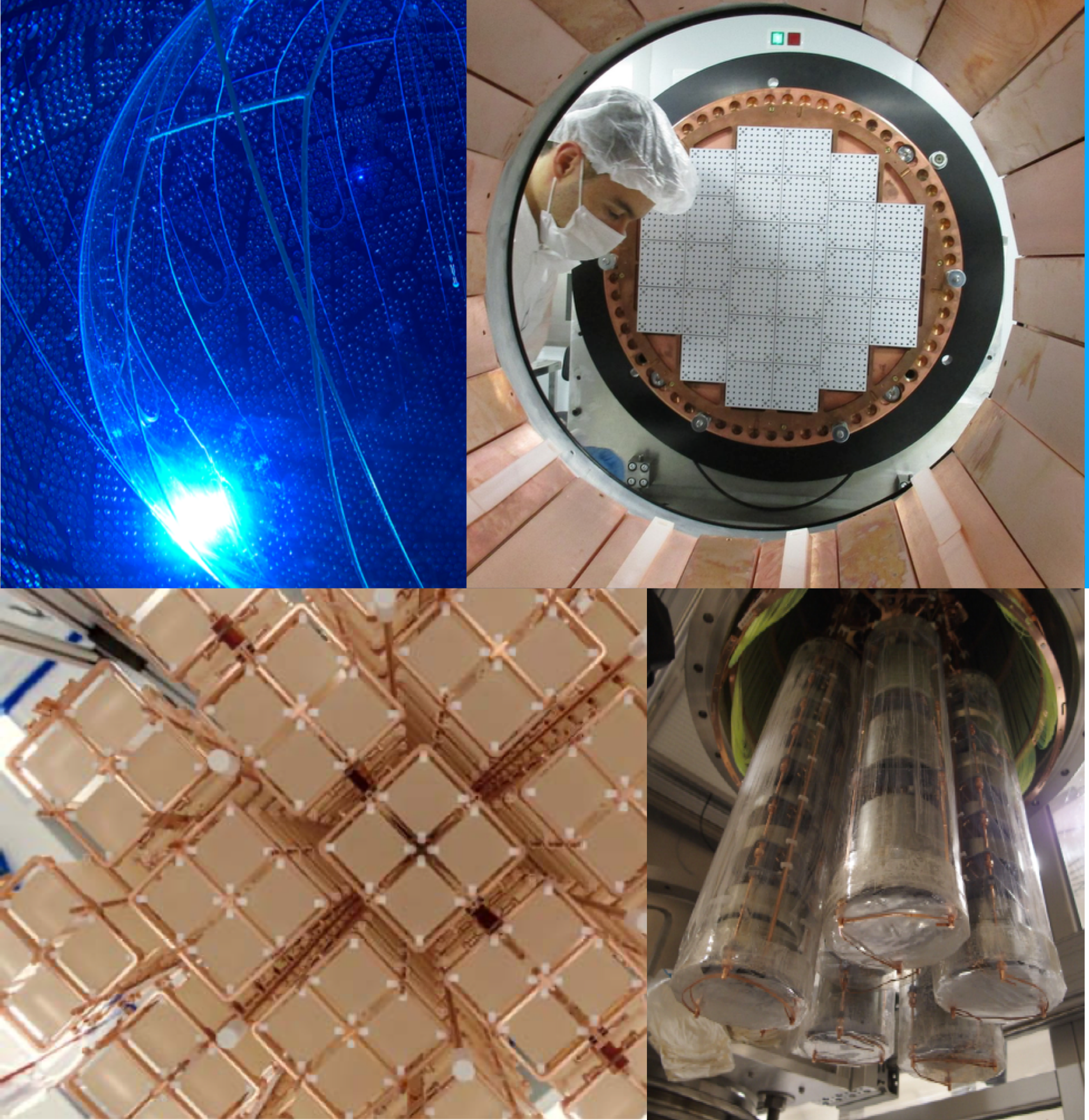


THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

Neutrinoless Double-Beta Decay: To the Ton Scale and Beyond

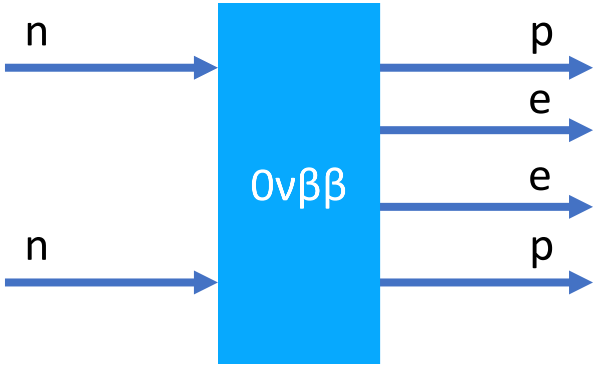
Julieta Gruszko
University of North Carolina at Chapel Hill

SNOWMASS Community Planning Meeting
October 7, 2020

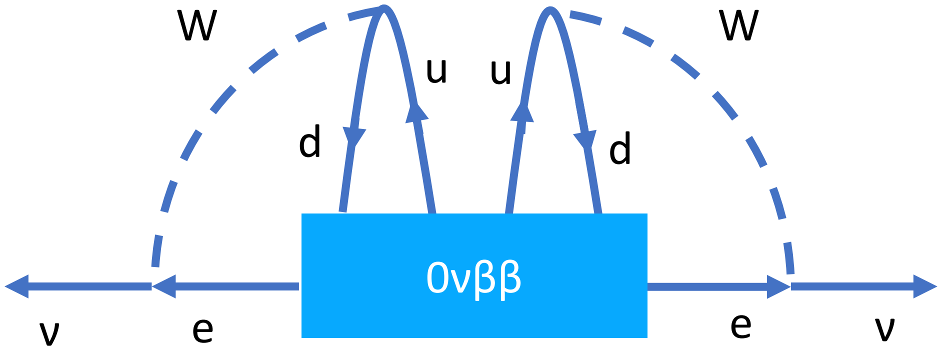
A Caveat

- Most of the materials in these slides are courtesy of the various experimental collaborations
- For much more information, see the materials shown at the mini-workshop on 0νββ experiment (I)
- Thank you to all who all who I borrowed materials from!

0νββ: A Portal to BSM Physics



(A, Z) → (A, Z+2) +2e-

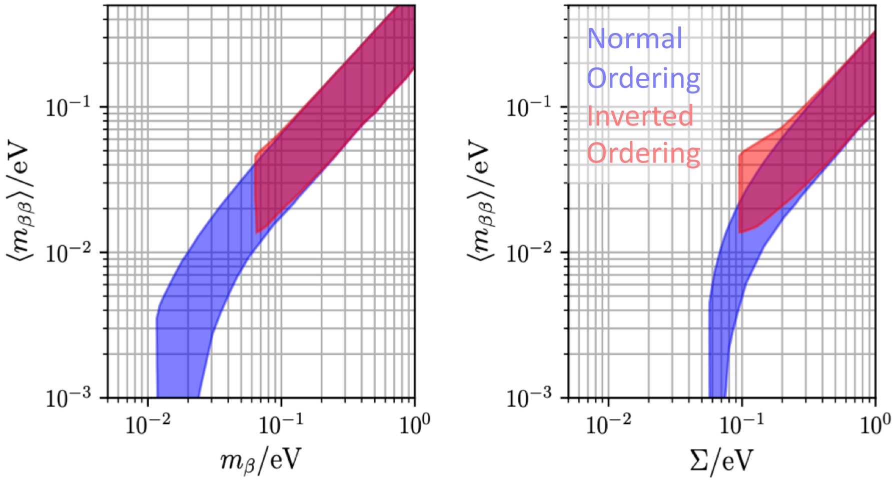


(A, Z) → (A, Z+2) +2e-

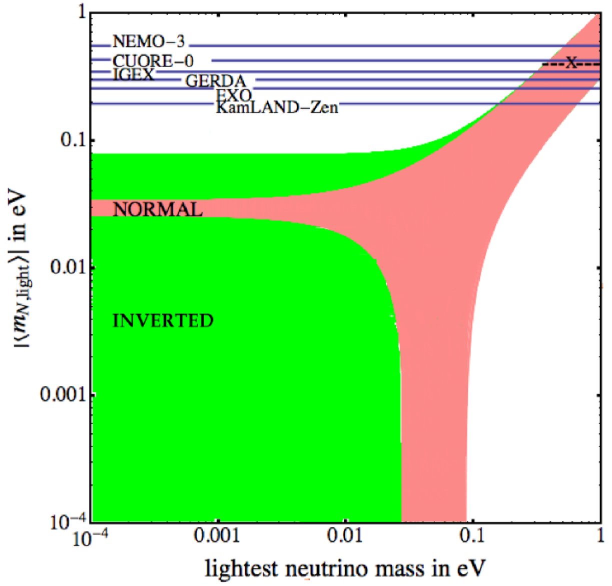
Model-independent implications of 0νββ:

- Lepton number violation
- Neutrino-antineutrino oscillation, implying a non-zero Majorana mass term

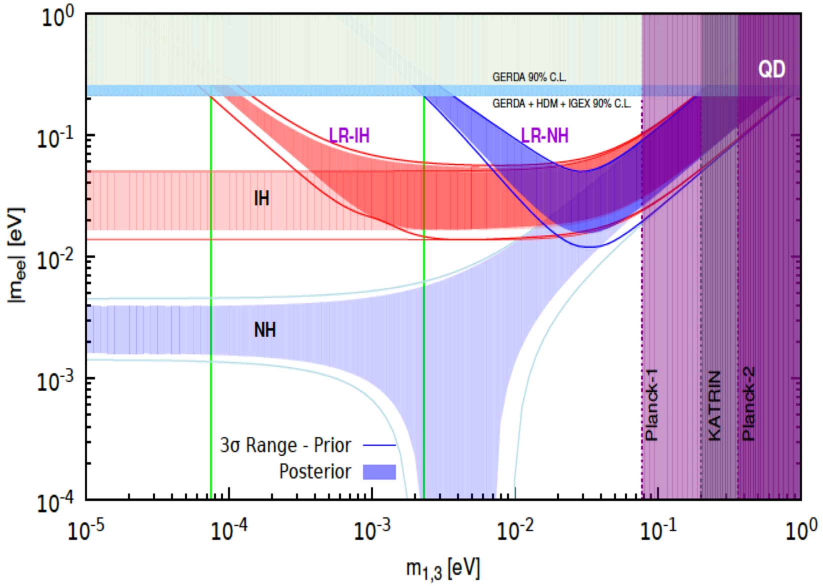
0νββ Rate and New Physics



3 Neutrino Paradigm



Light sterile neutrino contribution
An example: PRD92, 093001 (2015)



Left-Right symm., Type II contributions
From J. HEP 10, 077 (2015)

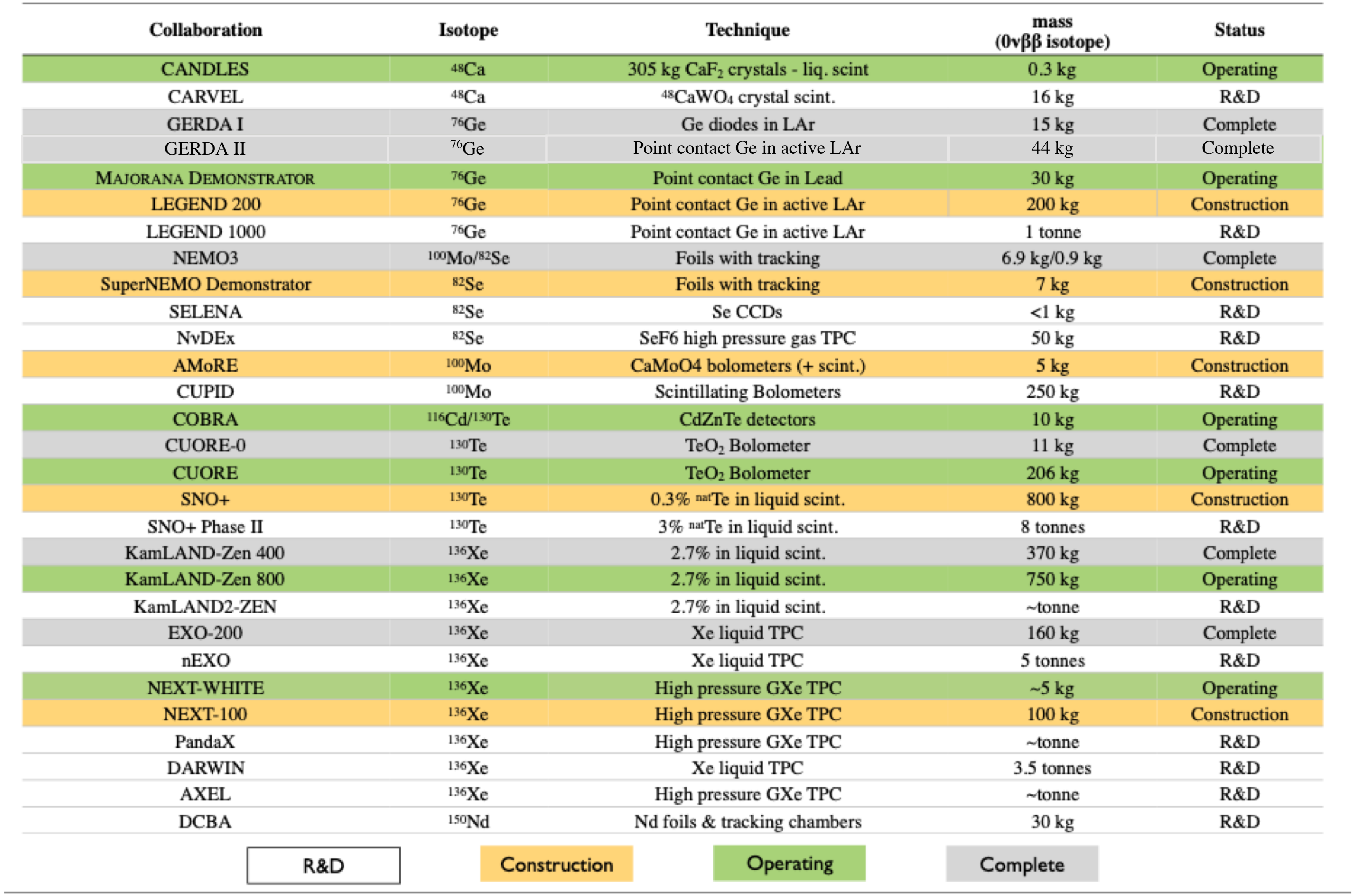
<u>Many physics possibilities alter the 3ν paradigm conclusions.</u>

Necessary measurement regardless of upcoming conclusions on ordering.

- Additional neutrinos
- Heavy neutrino exchange
- Right handed currents
- R-parity violating SUSY
- Various heavy particle proposals (short-range physics)

If ββ is seen, the qualitative conclusions are profound, but observations in several nuclei will be required to fully understand the underlying physics.

A Rich Experimental Landscape

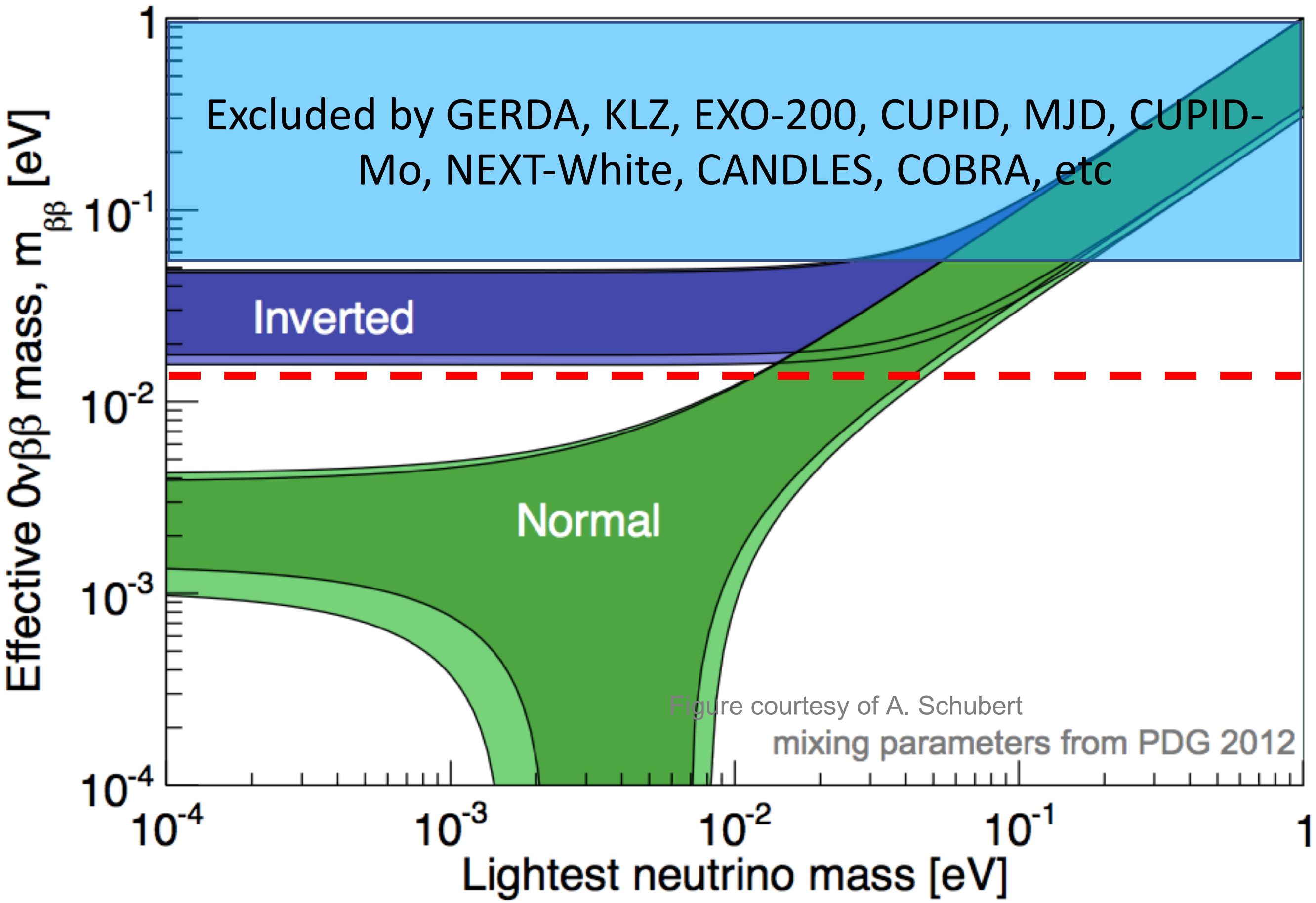


Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	^{48}Ca	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	^{48}Ca	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	^{76}Ge	Ge diodes in LAr	15 kg	Complete
GERDA II	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
Majorana Demonstrator	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
NEMO3	^{100}Mo/^{82}Se	Foils with tracking	6.9 kg/0.9 kg	Complete
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF6 high pressure gas TPC	50 kg	R&D
AMoRE	^{100}Mo	CaMoO4 bolometers (+ scint.)	5 kg	Construction
CUPID	^{100}Mo	Scintillating Bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE-0	^{130}Te	TeO_2 Bolometer	11 kg	Complete
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
SNO+ Phase II	^{130}Te	3% ^{nat}Te in liquid scint.	8 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scint.	750 kg	Operating
KamLAND2-ZEN	^{136}Xe	2.7% in liquid scint.	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	Xe liquid TPC	3.5 tonnes	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DCBA	^{150}Nd	Nd foils & tracking chambers	30 kg	R&D

R&D Construction Operating Complete

From J. Wilkerson

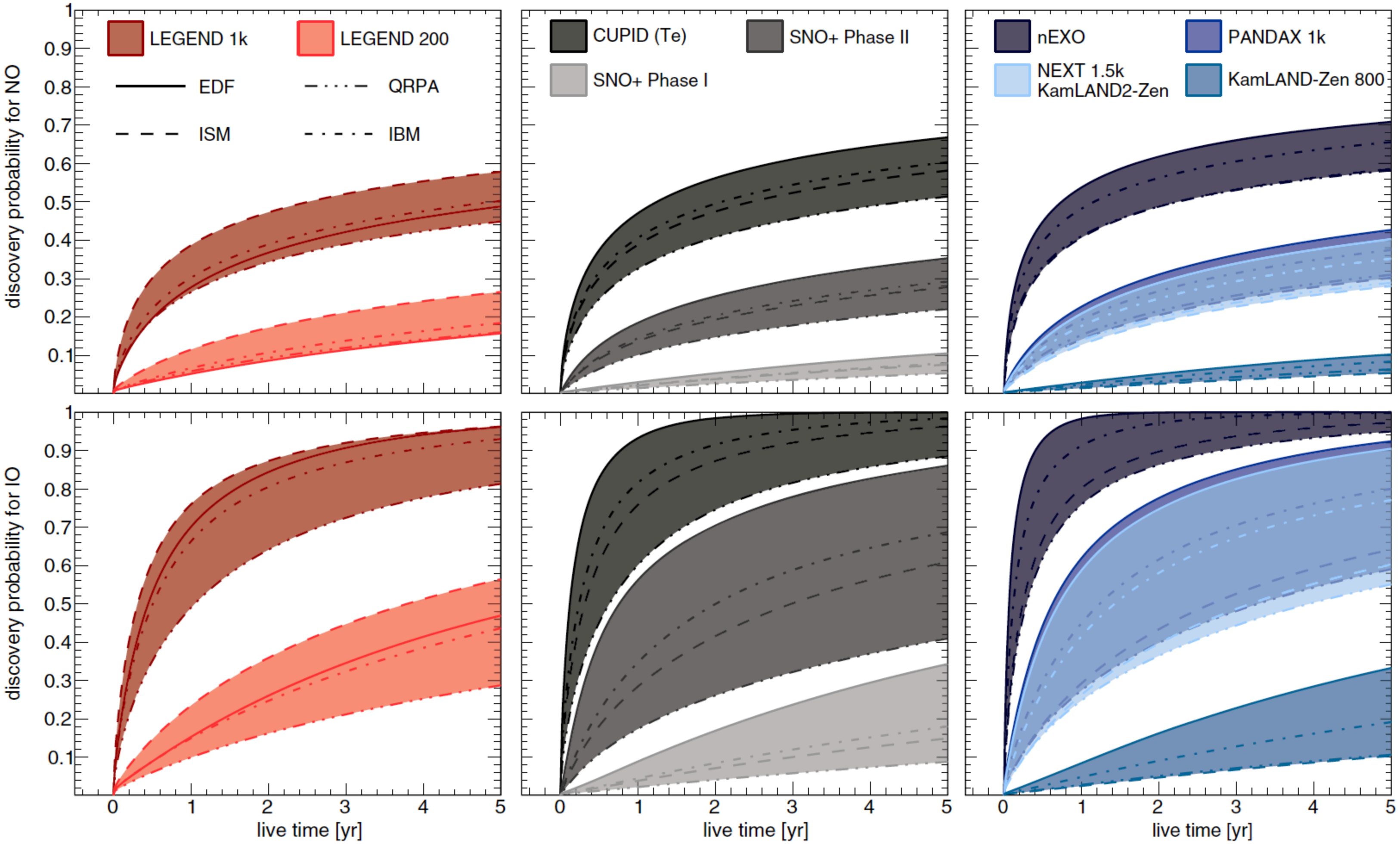
Setting Half-Life Goals for the Next Generation



- Simple light neutrino exchange model is used to set goals for future experiments
- Currently-running experiments have reached half-life sensitivities of 10^{26} yrs
- Next generation plans to reach $m_{\beta\beta}$=17 meV, the value needed to cover the inverted ordering region

Discovering 0νββ at the Ton Scale

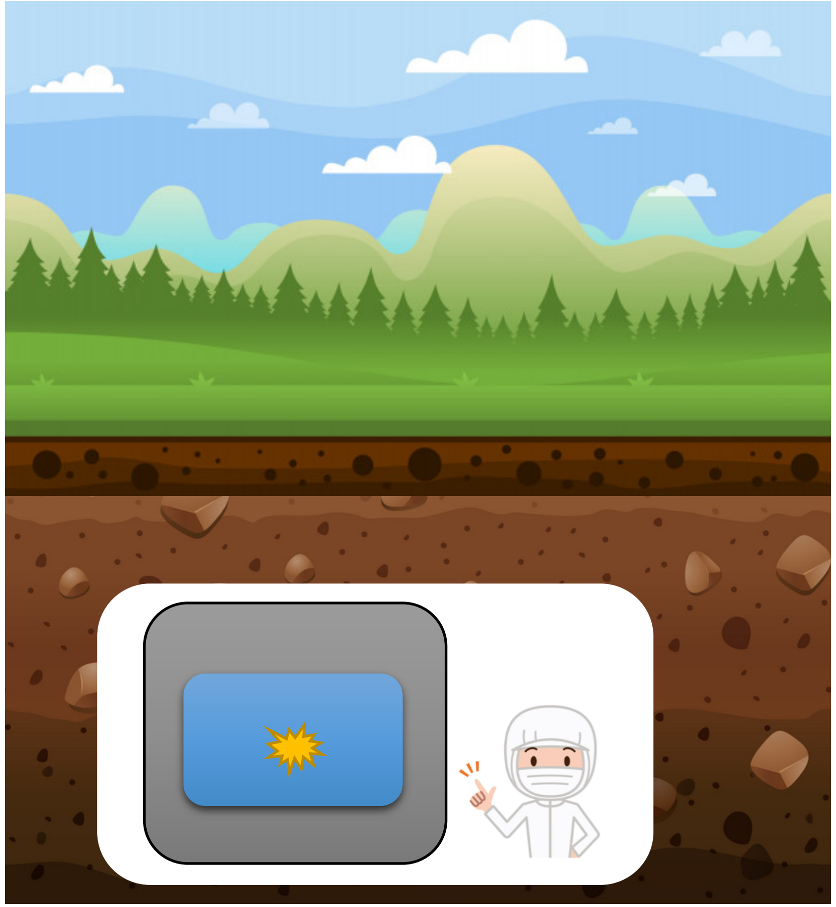
- The goal of ton-scale experiments is discovery
- Discovery sensitivity: the value of $T_{1/2}$ for which an experiment has a 50% chance to observe a signal above background with 3σ significance
- The good news: next-generation experiments have a significant chance of discovering 0νββ regardless of the neutrino mass ordering!
- Discovery goal places additional demands on background levels and energy resolution

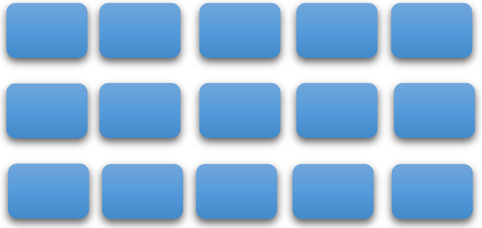


Example analysis from PRD 96, 053001 (2017)

Experimental Techniques

Most Experiments



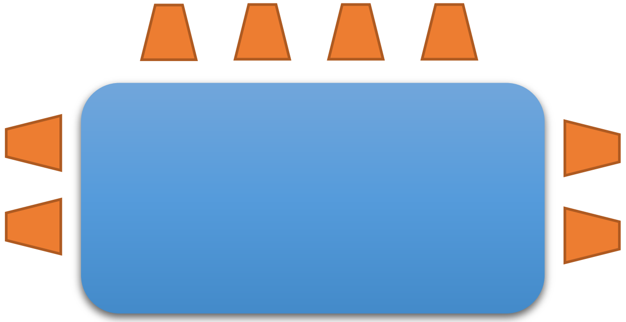


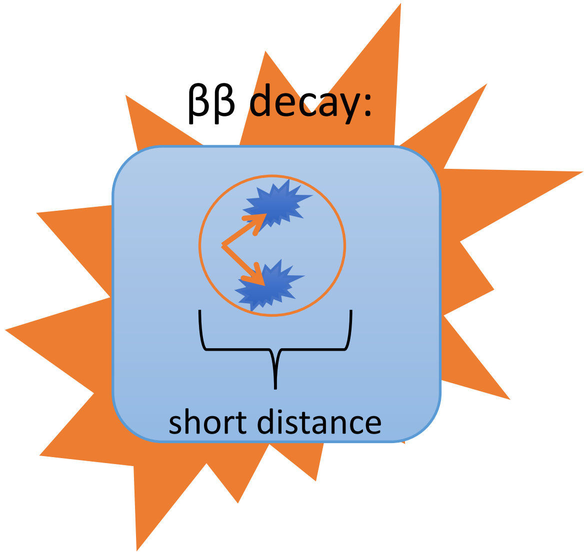
Granular Detectors

- Bolometers and semiconductors
- E.g. CUPID, LEGEND

Most experiments rely on additional background-rejection techniques:

- Event topology
- Particle discrimination
- Fiducialization
- Daughter isotope tagging

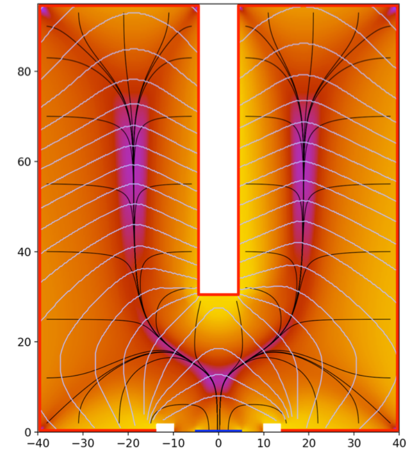




Monolithic Detectors

- Scintillators and TPCs
- E.g. KamLAND-Zen, SNO+, THEIA, nEXO, NEXT

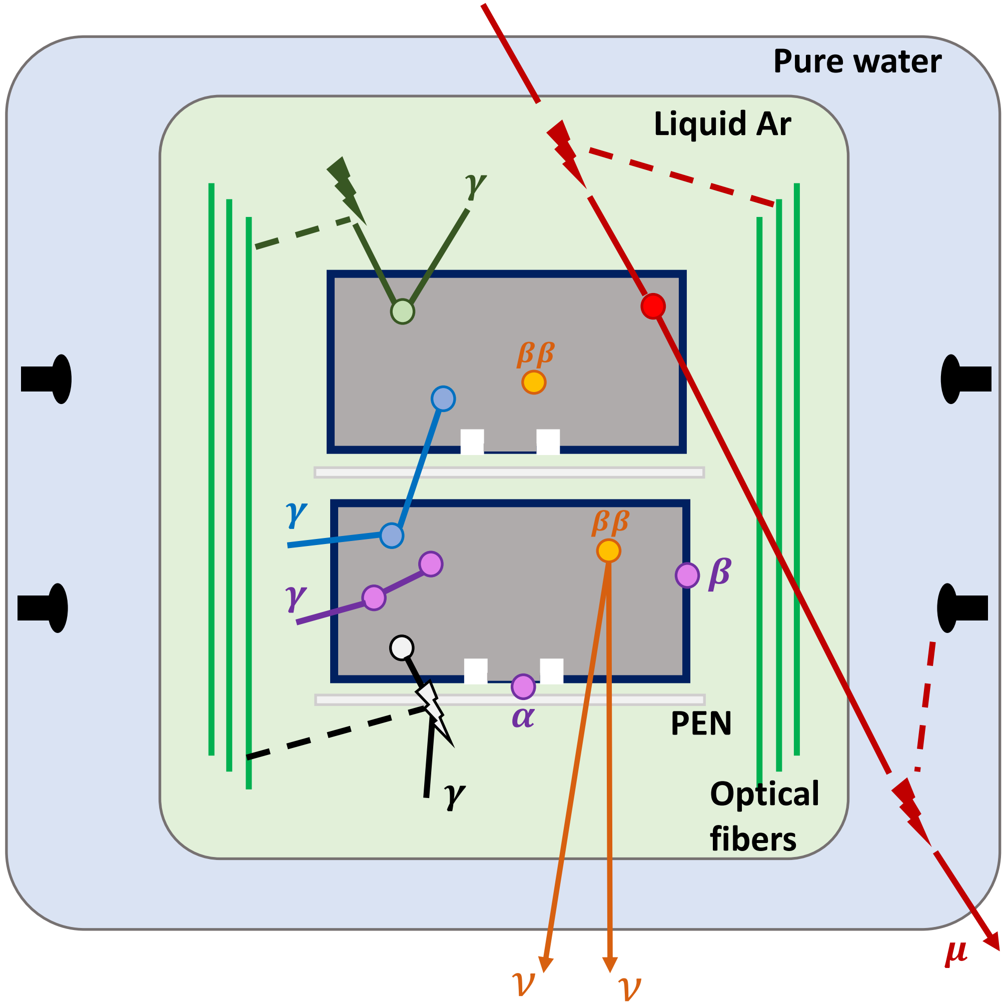
The LEGEND Concept



HPGe point-contact detectors:

- Event topology and fiducialization
- Excellent (~0.1%) energy resolution

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



Pulse shape discrimination (PSD) for multi-site and surface α events

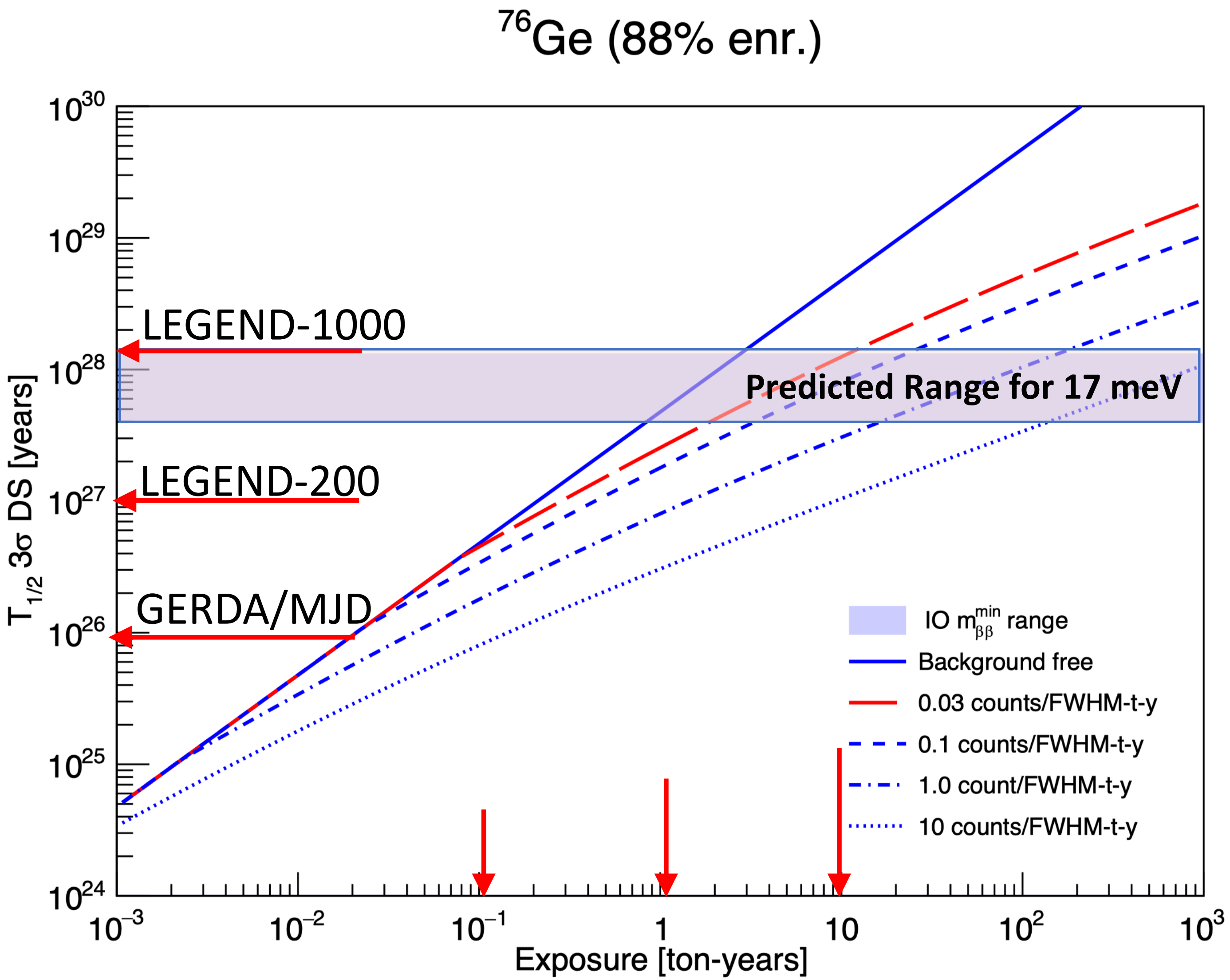
Ge detector anti-coincidence

Scintillating PEN plate holder (under test)

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and/or plastic scintillator

LEGEND Background and Sensitivity Goals



Staged approach with 2 major phases

LEGEND-200:

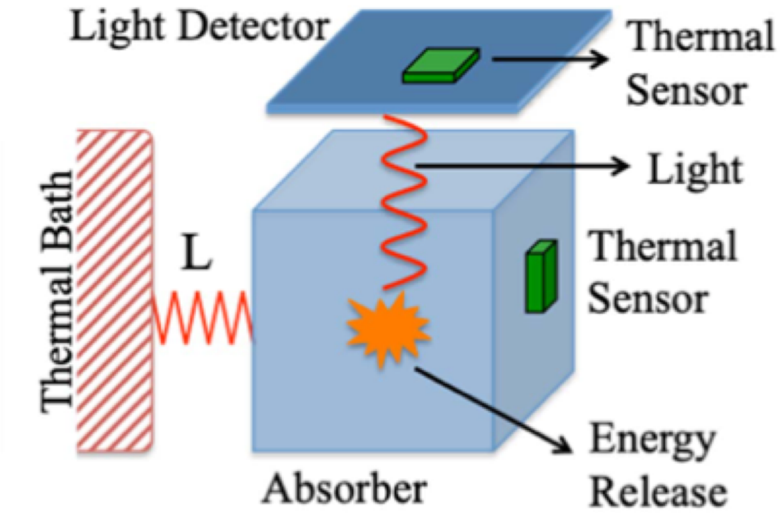
- 200 kg in upgrade of existing GERDA infrastructure at Gran Sasso
- Background goal <0.6 cts/(FWHM t yr) <2x10^{-4} cts/(keV kg yr)
- Data start ~2021

LEGEND-1000:

- 1000 kg, staged via individual payloads (300-500 detectors)
- Background goal <0.03 cts/(FWHM t yr),<1x10^{-5} cts/(keV kg yr)
- Location and timeline TBD

The CUPID Concept

- Tonne-scale bolometer approach demonstrated in CUORE
- Scintillating bolometer technique demonstrated in CUPID-Mo and other experiments
- Scintillation light allows for α rejection
- Mo-100 0νββ Q-value is higher in energy than most other backgrounds
- Switch from CUORE crystals to scintillating bolometers with light readout

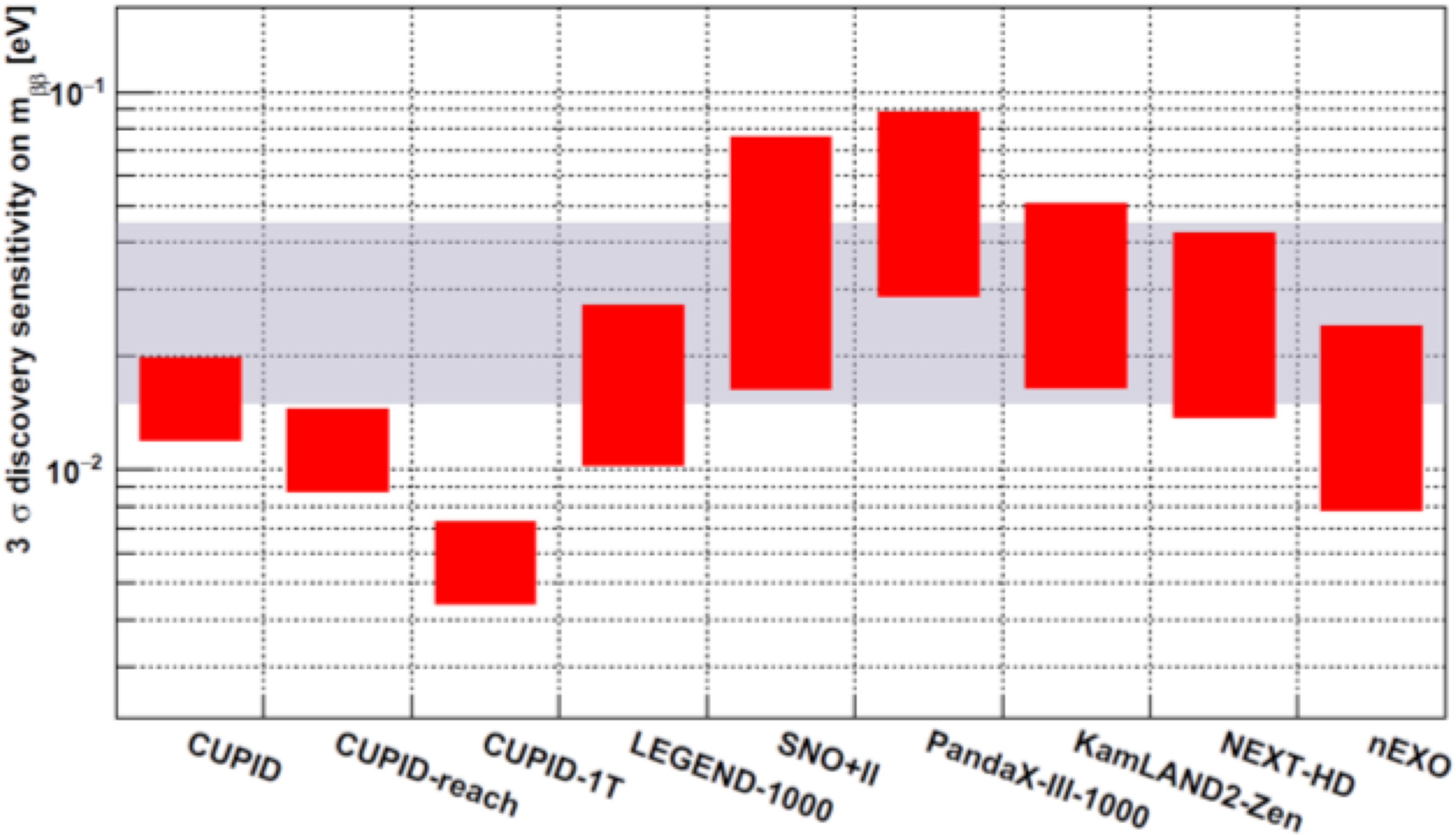


CUPID:

- *enrichment > 95% ⇒ ~250 kg of ^{100}Mo*
  - *~ 1500 crystals, ~300 g each*
  - *ΔE FWHM ~5 keV at $Q_{\beta\beta}$ ~3034 keV*
  - *alpha-particle rejection using light signal*

Slides provided by CUORE, CUPID, CUPID-Mo, and CUPID-0 Collaborations

CUPID Background and Sensitivity Goals



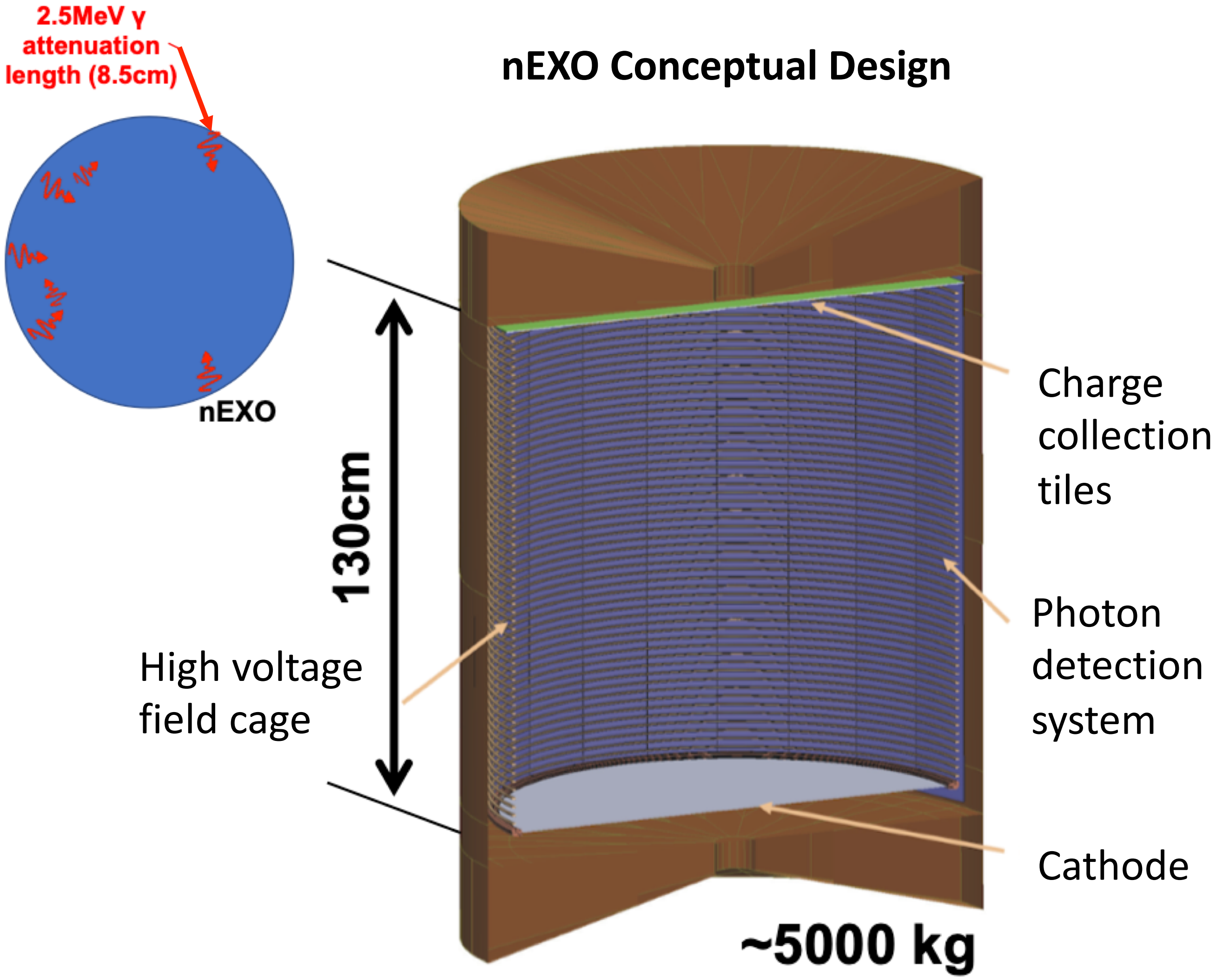
CUPID pre-CDR: exactly what we could start building today: 10^{-4} counts/keV/kg/yr

CUPID reach: assume improvement at reach before construction: $2{\cdot}10^{-5}$ counts/keV/kg/yr

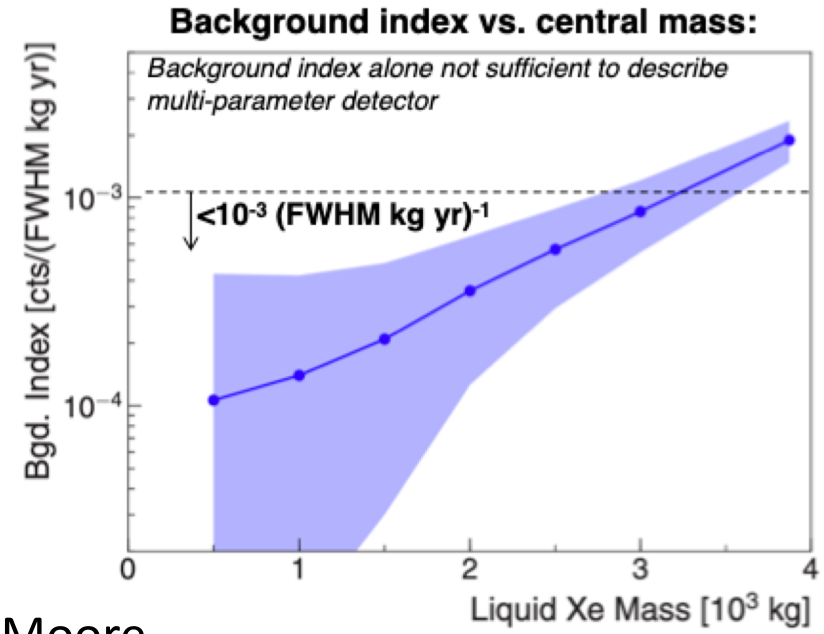
CUPID 1Ton: new, 4 times larger (in volume) cryostat, 1 ton 100Mo : $5{\cdot}10^{-6}$ counts/keV/kg/yr

M. Pavan, CUPID Project Update 13 July 2020

The nEXO Concept

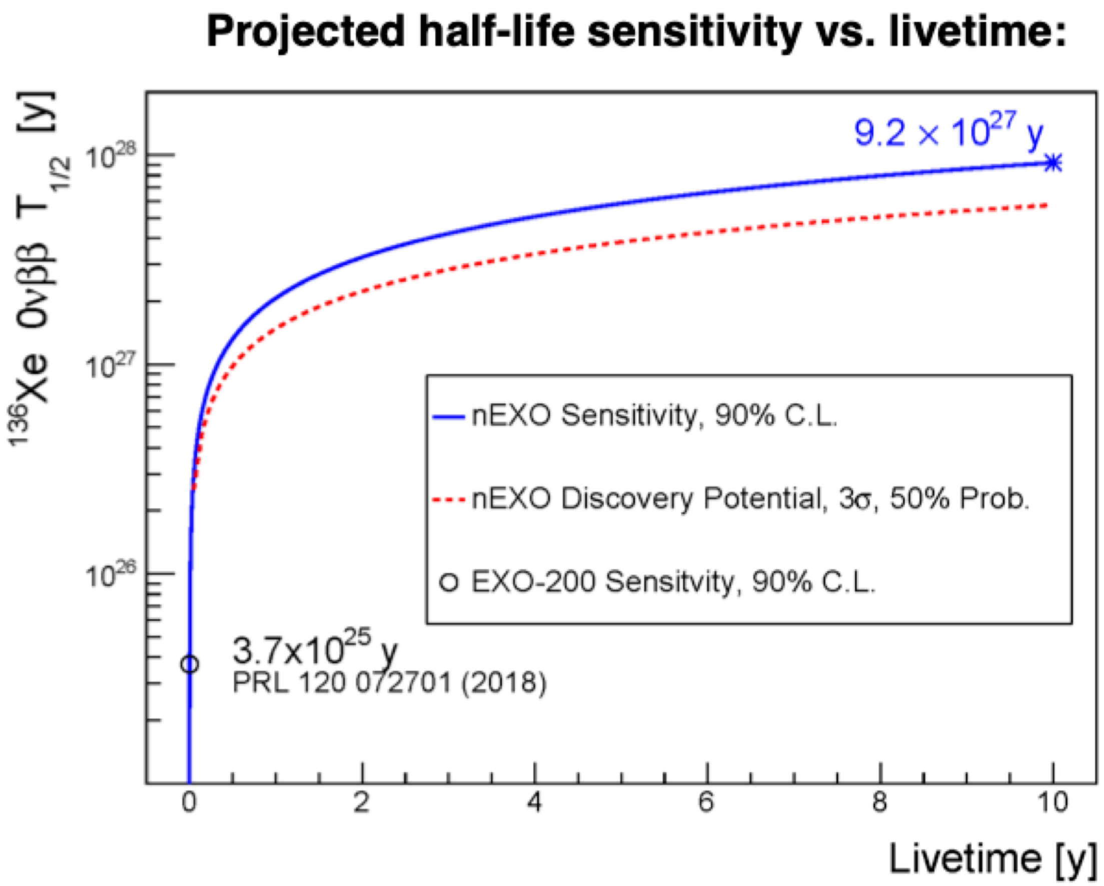


- Large single-phase LXe TPC
- Take advantage of self-shielding, (non-binary) fiducialization, and event topology information to reduce backgrounds

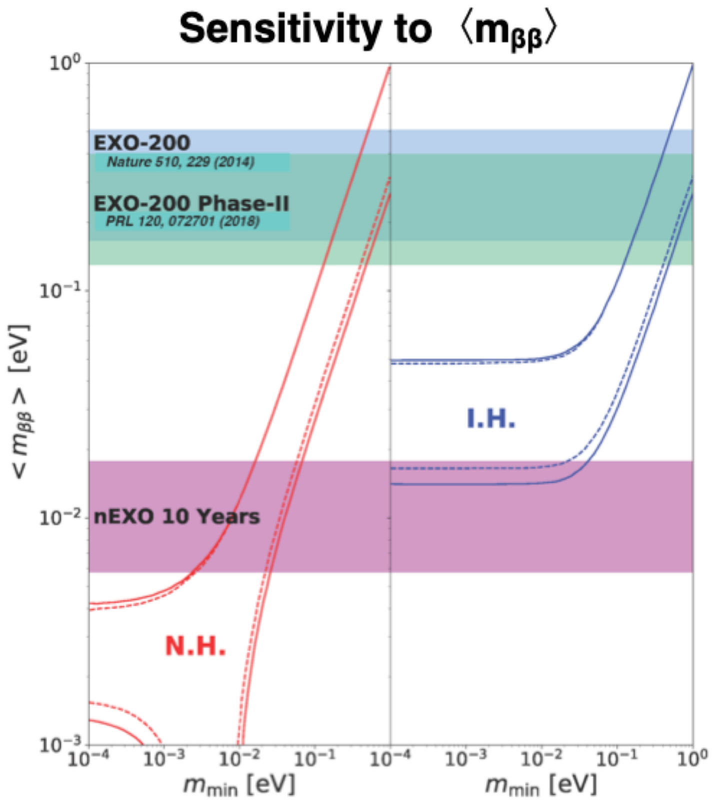


Slides provided by the EXO-200 and nEXO Collaborations, from D. Moore

nEXO Sensitivity Goals



Phys. Rev. C 97, 065503 (2018), arXiv:1710.05075

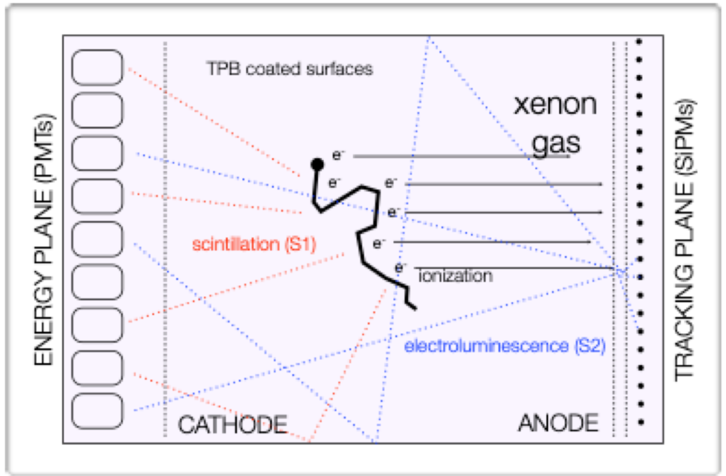


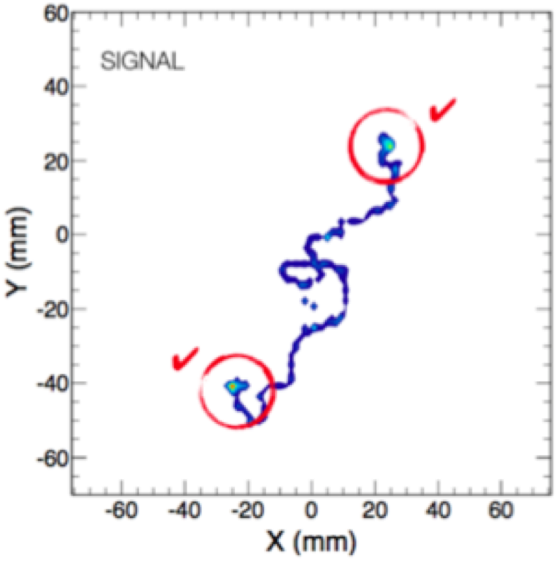
- *Assumes $g_A = g_A^{free} = -1.27$*
- *Bands indicate the envelope of various NME calculations:*
  - *EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)*
  - *ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)*
  - *IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)*
  - *QRPA: F. Šimkovic et al., PRC 87 045501 (2013)*
  - *SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)*

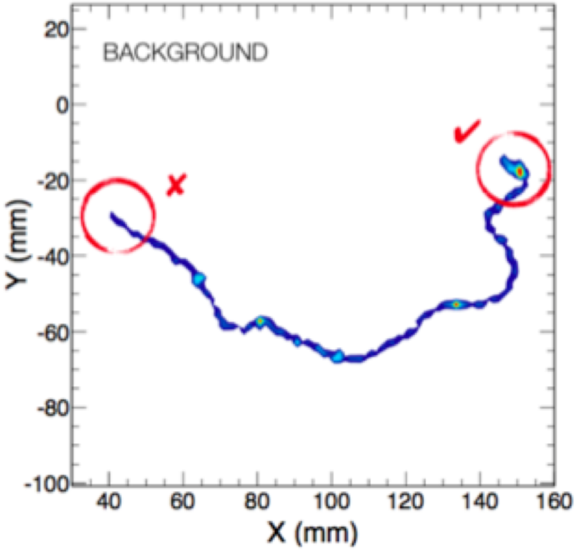
The NEXT Concept

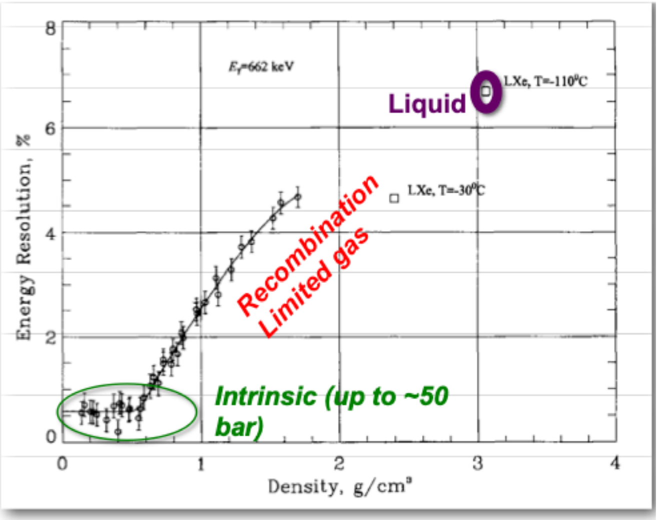
High-pressure gas Xenon time projection chamber:

- High pressure reduces volume for a given mass
- Energy resolution is intrinsically better in gas
- Extensive event topology information, fiducialization, and particle ID







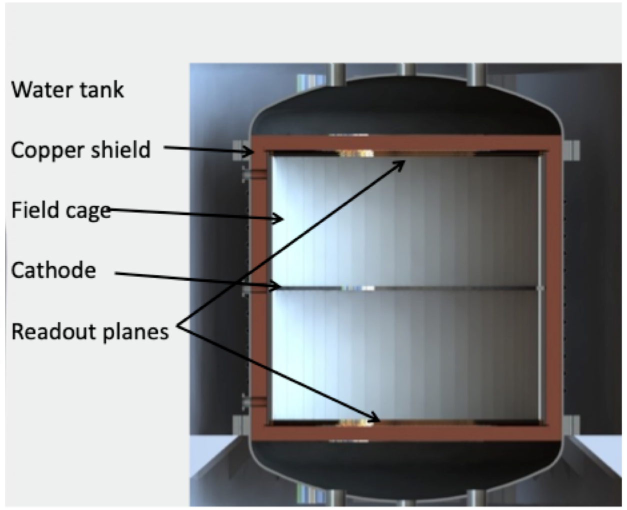


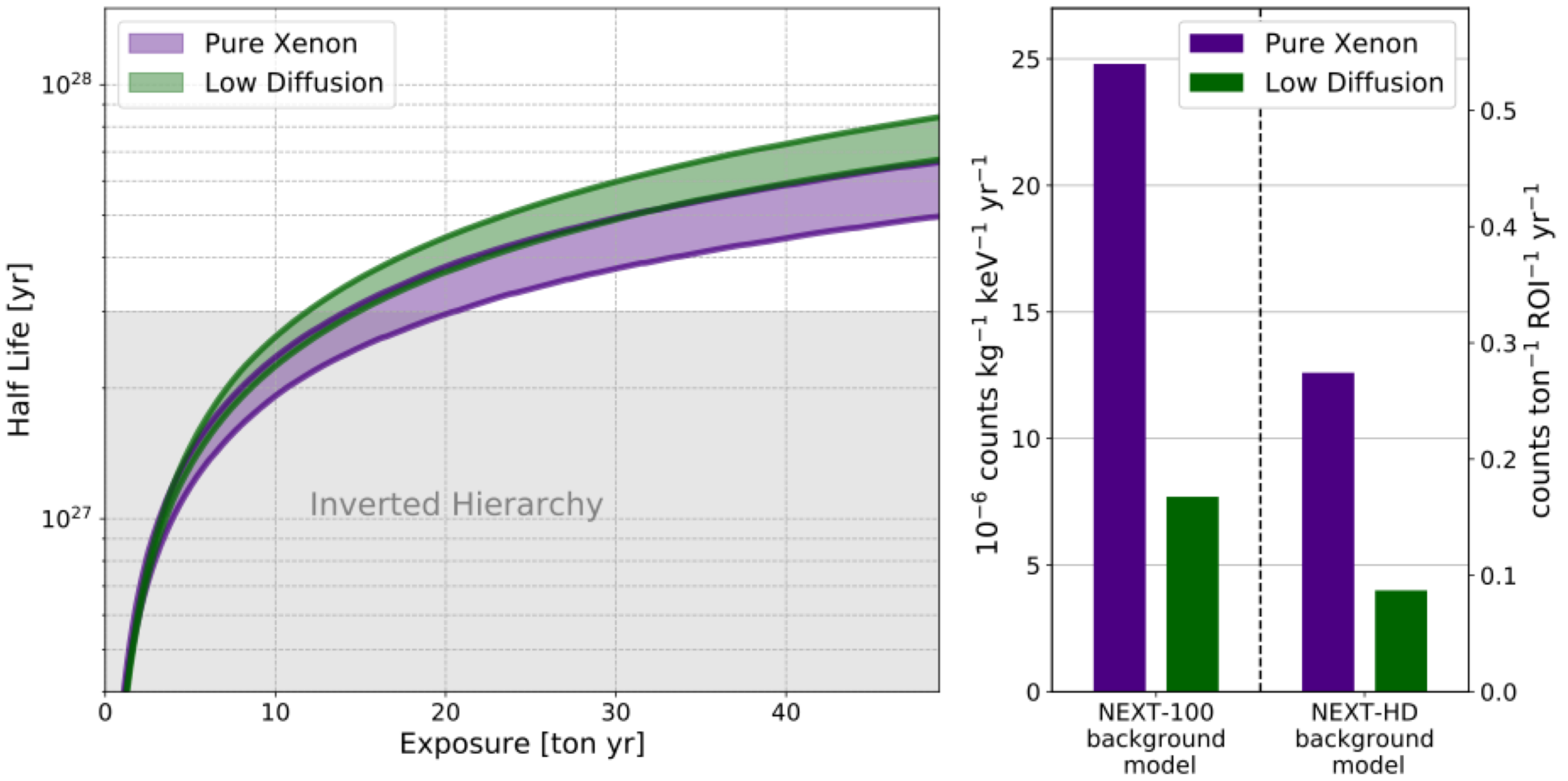
Bolotnikov and Ramsey. "The spectroscopic properties of high-pressure xenon."NIM A 396.3 (1997): 360-370

Slides courtesy of the NEXT Collaboration, from R. Guenette

NEXT Sensitivity Goals

- 1 ton module(s)
- Symmetric detector with 1.3m drift length
- SiPM readout





NEXT Collaboration, arXiv:2005.06467

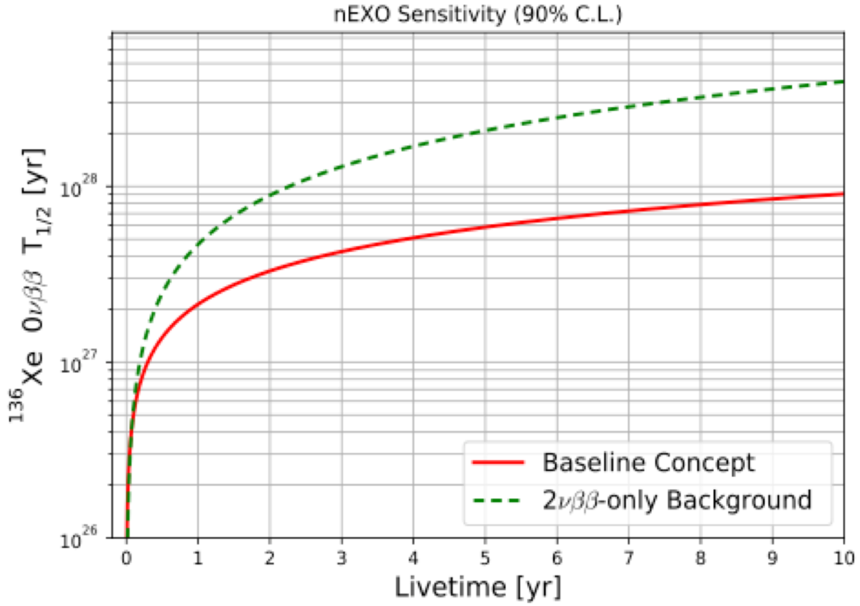
Barium Tagging: A Potential Path to NO

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

"Tagging" Ba daughter has potential to eliminate all but 2νββ backgrounds

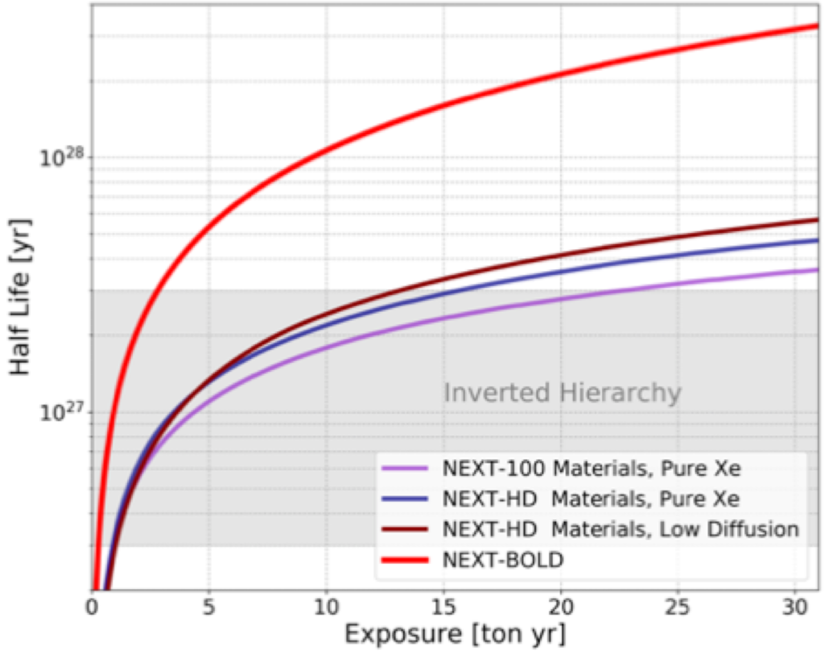
M. Moe, Phys. Rev. C 44, R931 (1991)

In nEXO, eliminating other backgrounds could give up to 4x higher sensitivity



nEXO Collaboration, *Phys. Rev. C* **97**, 065503 (2018)

In NEXT, higher efficiency with Ba tagging and eliminating other backgrounds could provide up to a factor of 6 higher sensitivity

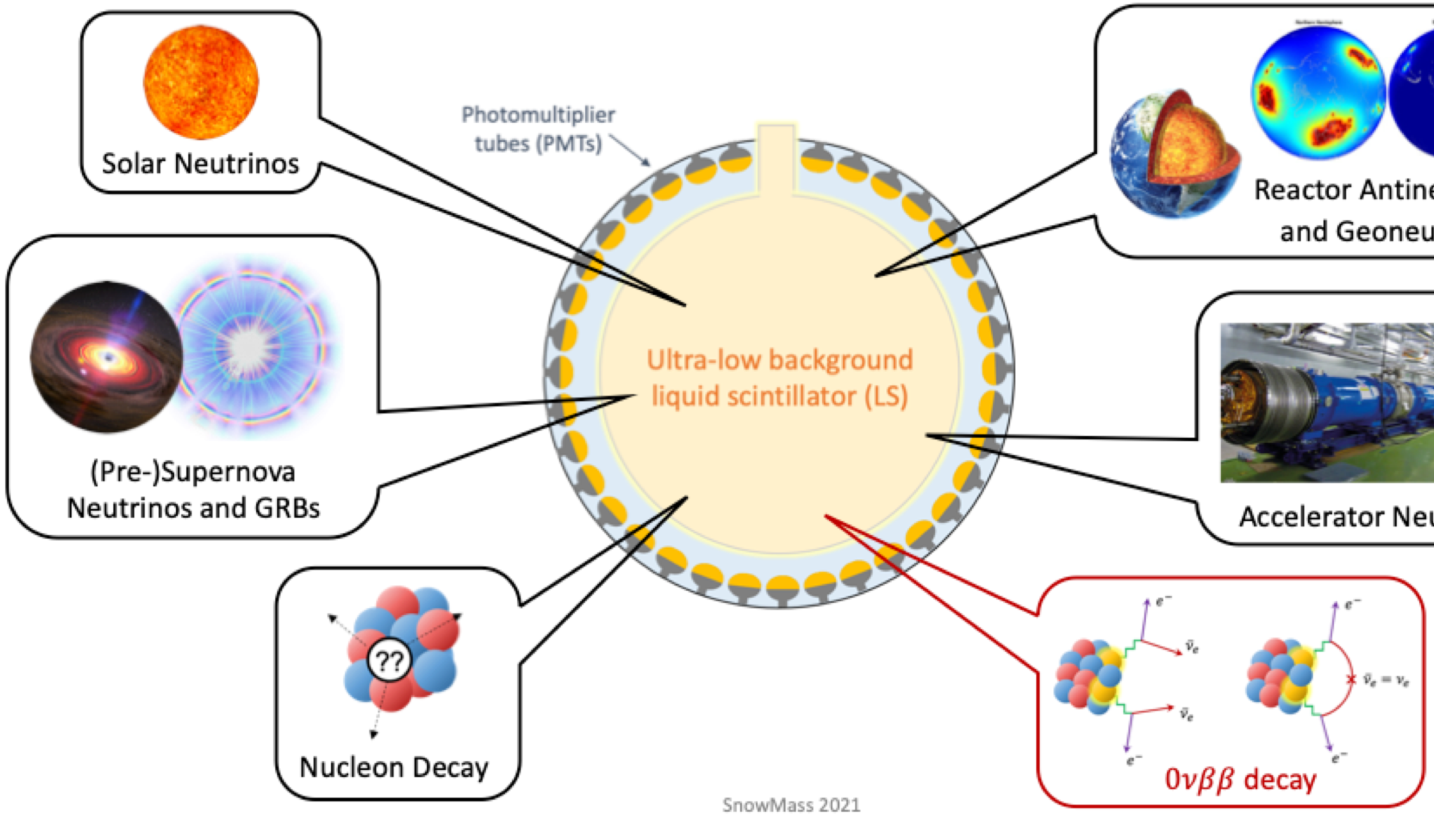


- NEXT and nEXO Collaborations are making progress on a variety of techniques
- Considered a possible upgrade path for the tonne-scale TPC experiments

Could extend sensitivity (further) into the normal ordering region!

Slides courtesy of the NEXT and nEXO Collaborations, from B. Fairbank

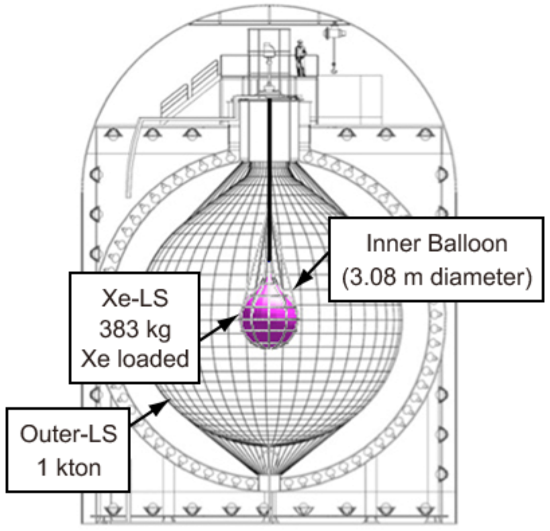
The Liquid Scintillator Concept: SNO+ and KLZ

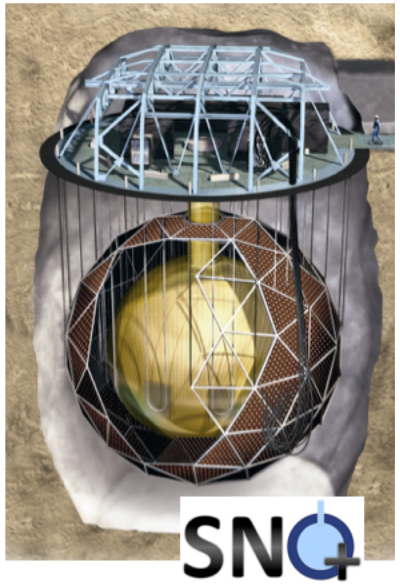


SnowMass 2021

- Self-shielding, fiducialization
- Interior materials can be made extremely pure
- Pursuing R&D for additional event topology and particle ID
- Multi-purpose detector
- Measurement with and without isotope is possible

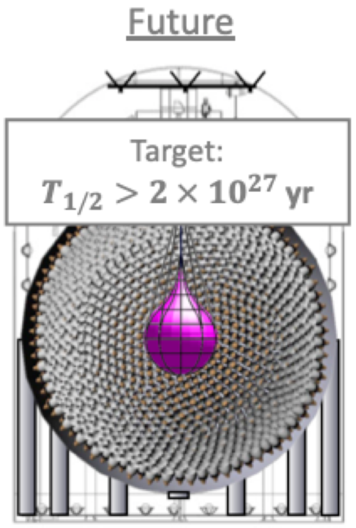
KamLAND-Zen





Slides courtesy of the SNO+, KamLAND-Zen, and Theia Collaborations, from C. Grant and R. Svoboda

Sensitivity of Future Liquid Scintillator Experiments



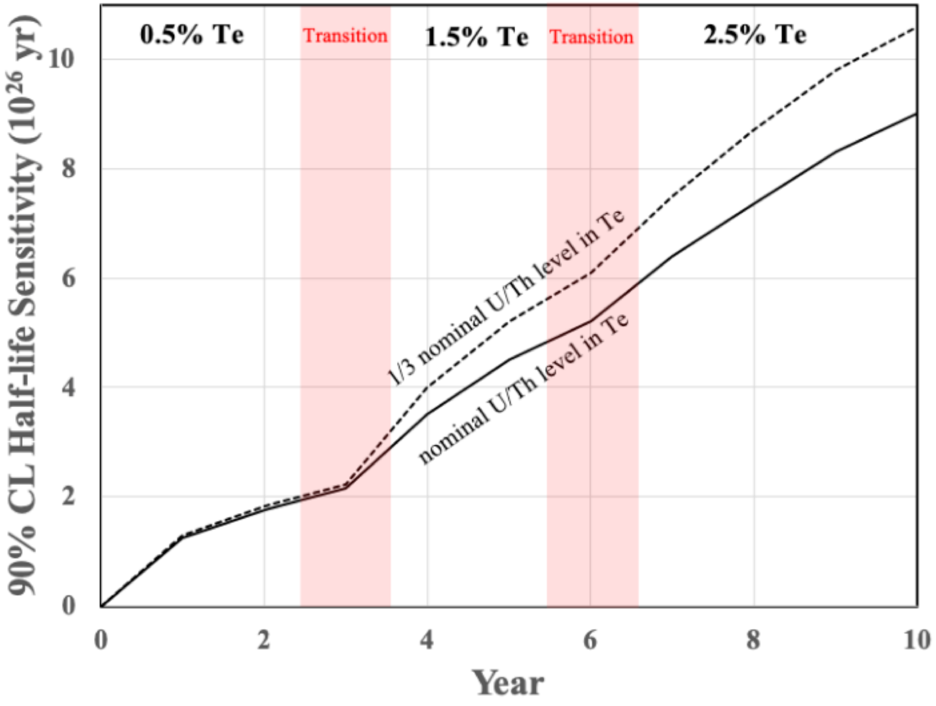
KamLAND2-Zen

Xenon mass ~ 1 ton

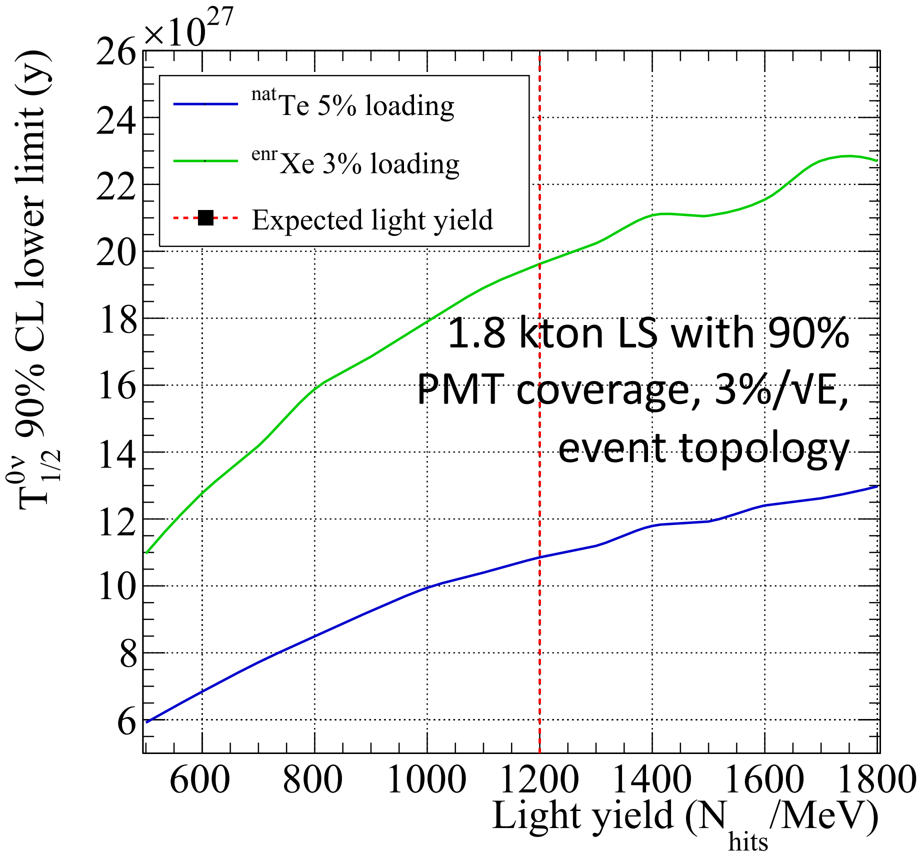
× 5 increase in light collection

Scintillation balloon film

SNO+ Phased Loading Plan (no detector upgrades required)



Theia Detector Concept

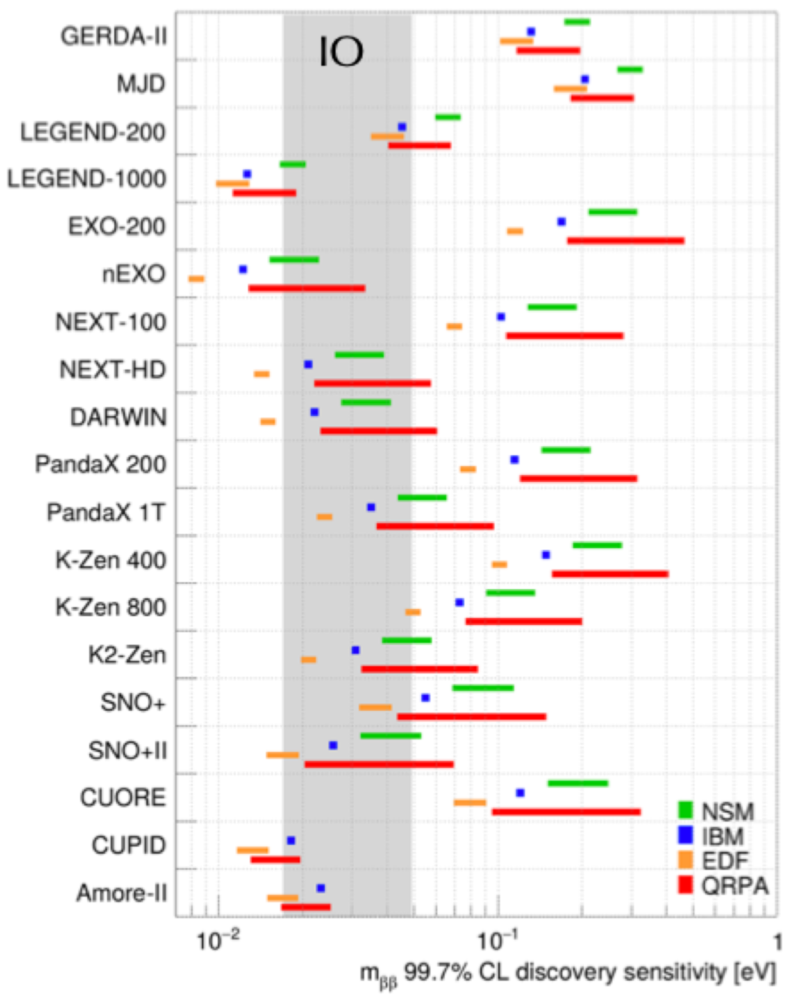


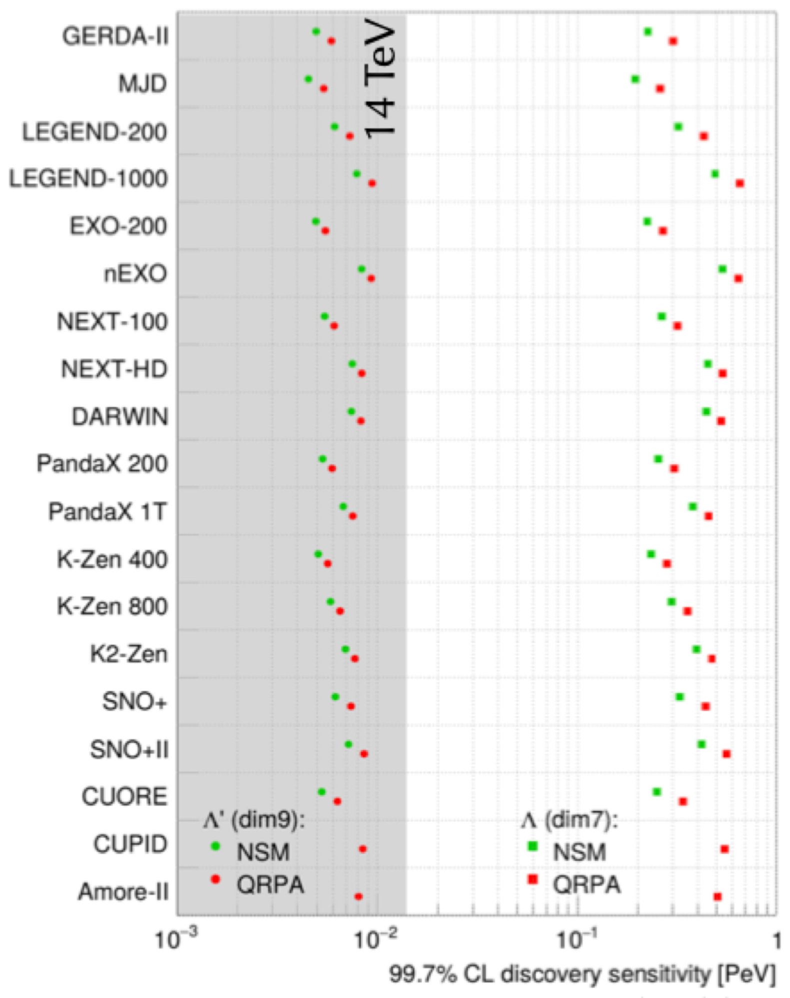
1.8 kton LS with 90% PMT coverage, 3%/√E, event topology

Eur. Phys. J. C (2020) 80:416

- Upgrades to KLZ and SNO+ will reach $T_{1/2} > 10^{27}$
- Theia concept could reach $m_{\beta\beta} < 10$ meV

The Future of 0νββ Searches



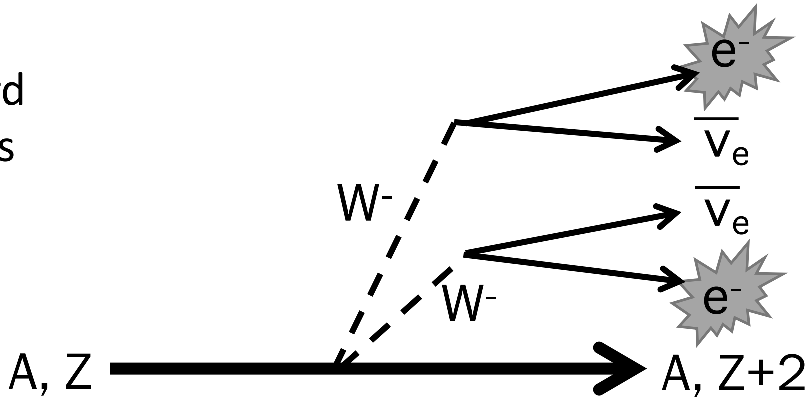


- The coming generation of 0νββ experiments will fully explore the inverted hierarchy region
- Corresponds to searching for new physics at the 10's - 100's of TeV scale!
- R&D is underway to reach $m_{\beta\beta} \sim \mathcal{O}(1\text{meV})$
- Discovery could come at any time!

Agostini, Benato, Detwiler, Menendez, Vissani, paper in prep.

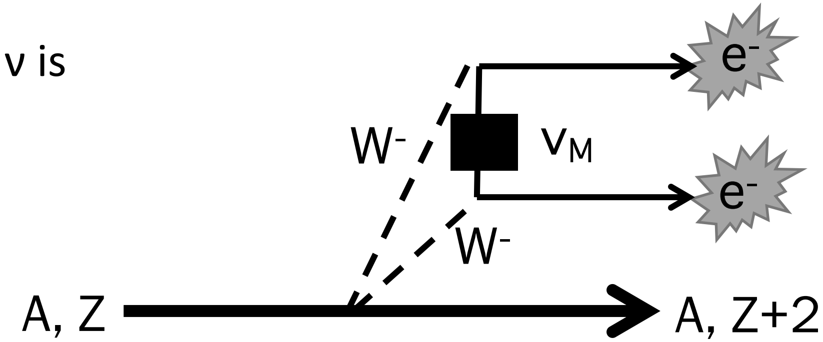
Extra Slides

2νββ: Standard Model process

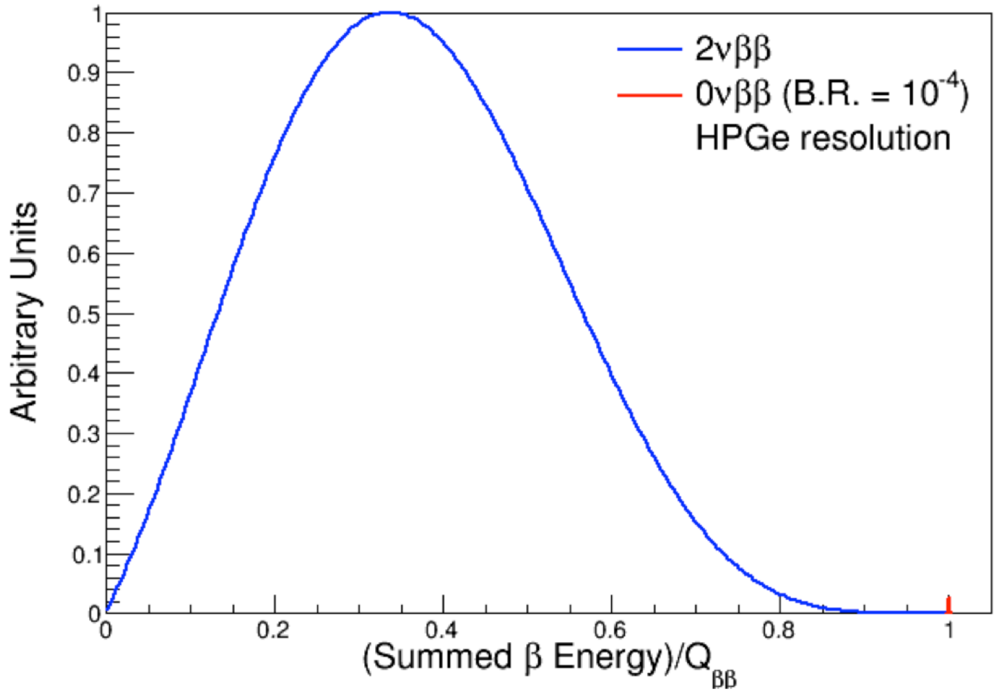


Missing energy

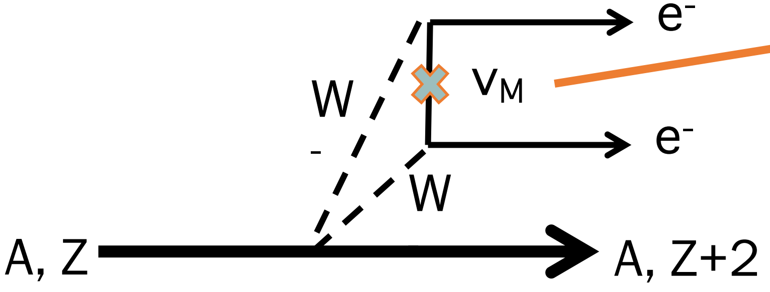
0νββ: Only if ν is Majorana



No missing energy



The 0νββ Rate



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\boxed{\langle m_{\beta\beta}\rangle}}{m_e}\right)^2$$

Effective Majorana mass for light neutrino exchange:

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

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha 1/2} & 0 & 0 \\ 0 & e^{i\alpha 2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

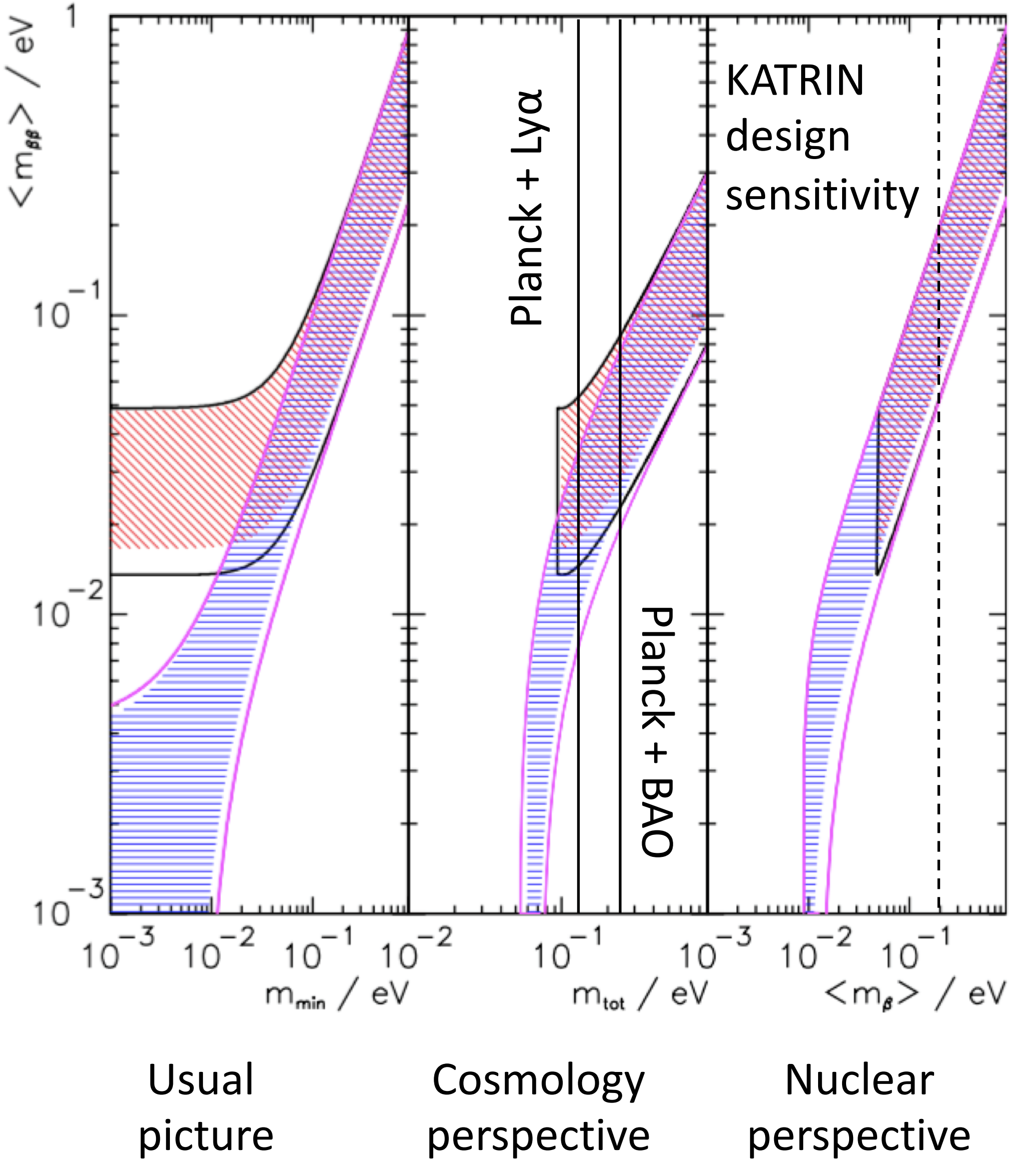
c_{ij} = cos θ_{ij}, s_{ij} = sin θ_{ij}, δ = Dirac CP violation, α_i = Majorana CP violation

Even under the simplest assumptions, the 0νββ rate depends on mixing angles, δ_{CP}, neutrino masses, mass hierarchy, and 2 totally unknown phases

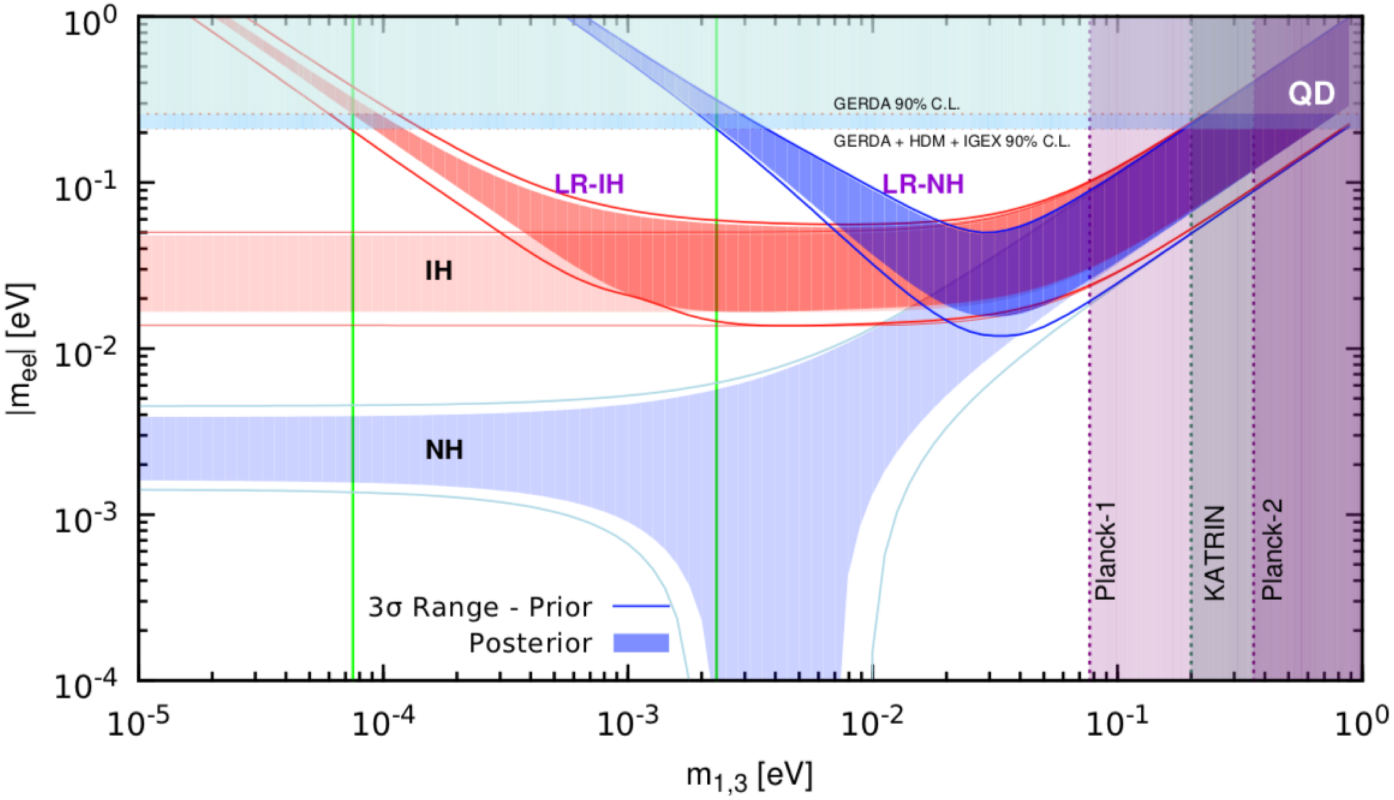
0νββ and Neutrino Masse

- In the usual picture, equal areas give the illusion of equal probability
- But $m_{lightest}$ is shown on a log scale and can go all the way to 0
- Mass measurements don't measure $m_{lightest}$: eventually they will measure something non-zero!
- Switching to this view also shows that there isn't a sudden jump between IH and NH allowed rates of 0νββ
- The situation for 0νββ is not as hopeless as it may first appear!

Fig. courtesy of P. Vogel

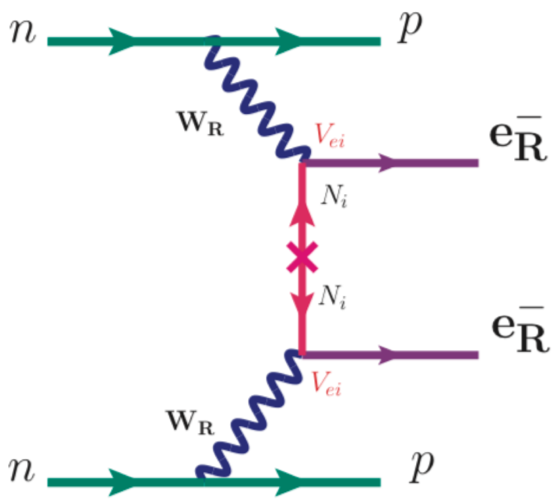


What About the Unknown Unknowns?

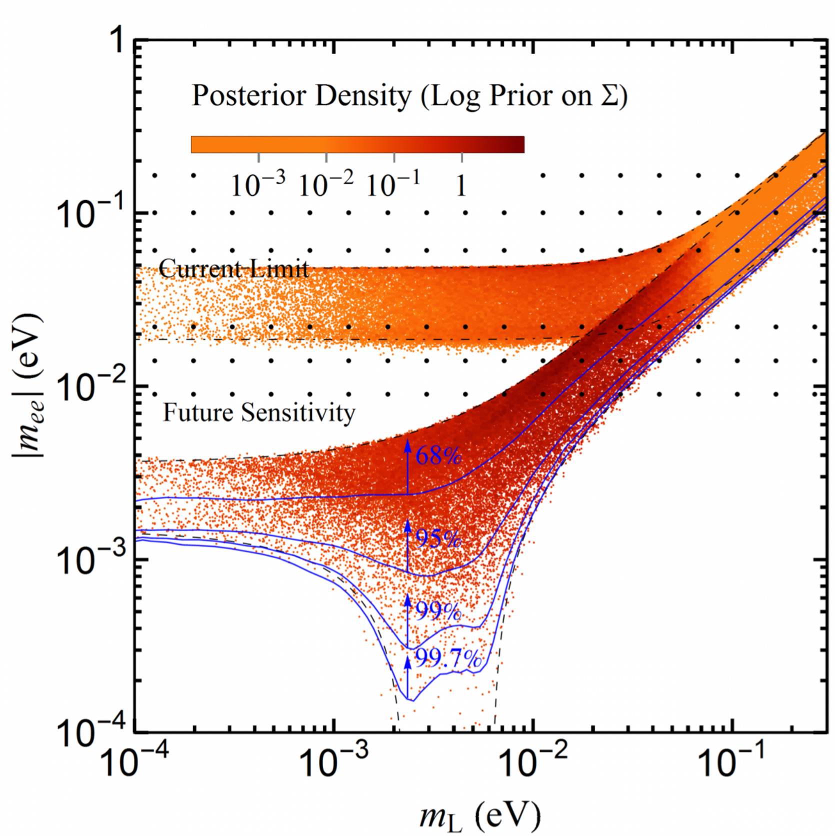


S.-F. Ge, M. Linder, and S. Patra, JHEP 1510 (2015) 077

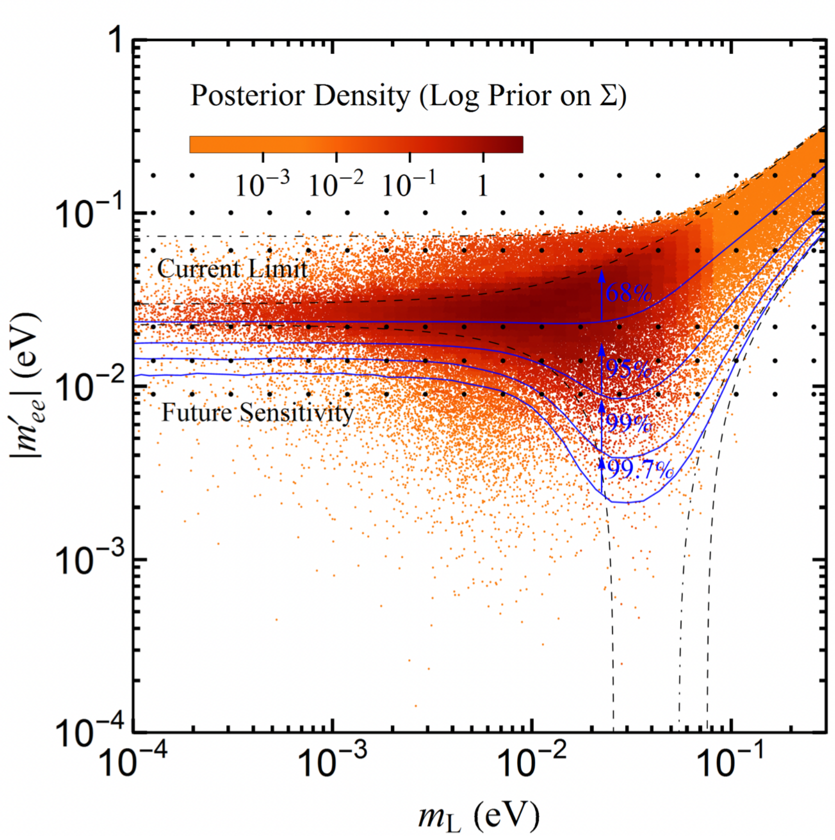
- The situation changes significantly if new physics is at lower scales
- For instance, Type-II seesaw-dominated LRSM



What About the Unknown Unknowns?



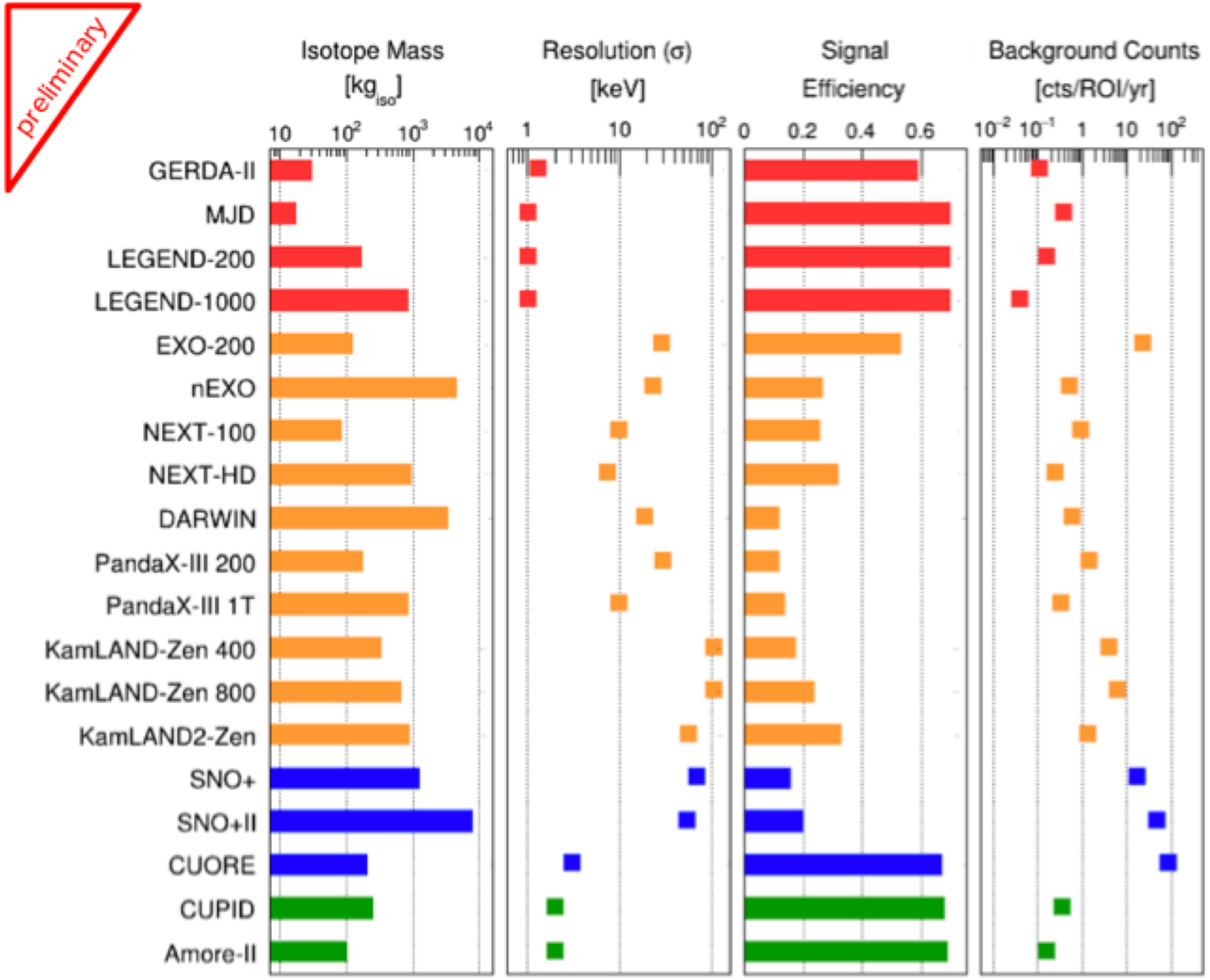
3ν mixing, flat prior on Σm



(3+1)ν mixing, flat prior on Σm
$\Delta m^2_{41} \equiv 1.7$ eV^2 and $\sin^2\theta = 0.019$

- Adding sterile neutrinos also changes the expected rate
- The change depends on the sterile neutrino mass and its mixing

G. Huang, S. Zhou, arXiv: 1902.03839



Next generation experiments:
<1 bkg count/year

J. Detwiler

Agostini, Benato, JD, Menendez, Vissani

preliminary

Discovery Sensitivity Comparison