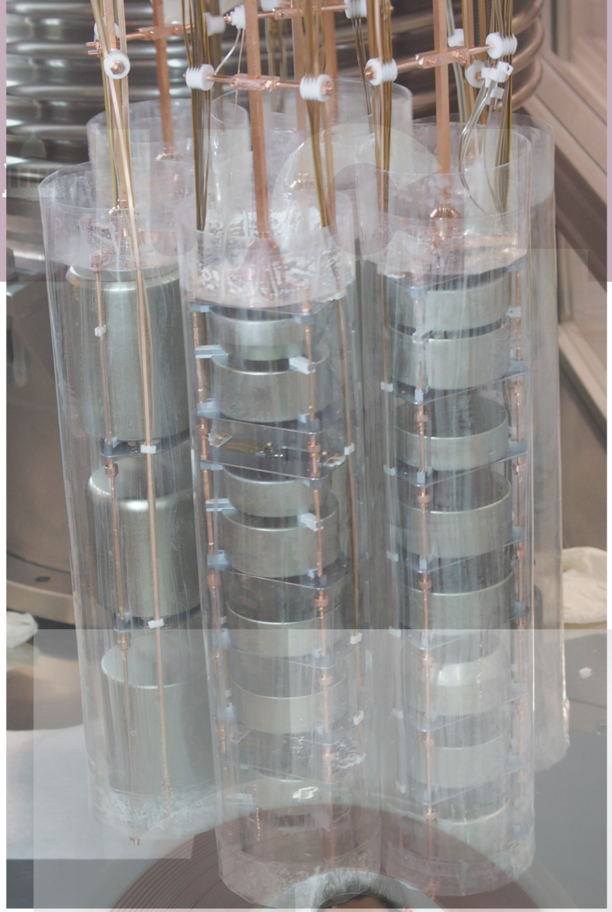
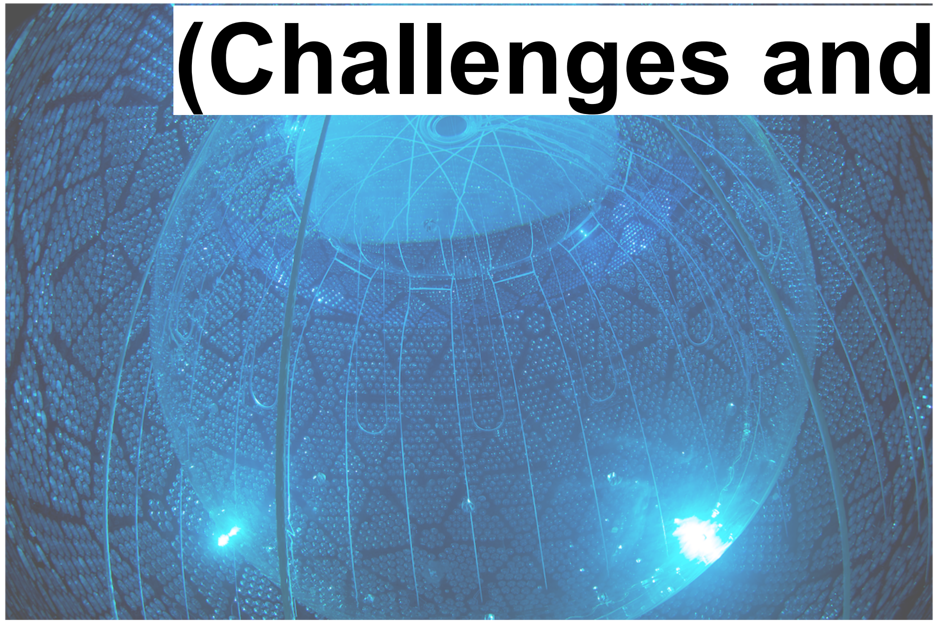




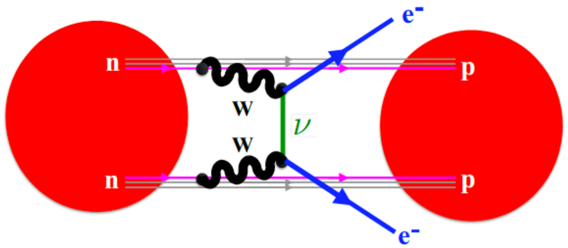
Double Beta Decay Experiments
(Challenges and Opportunities)



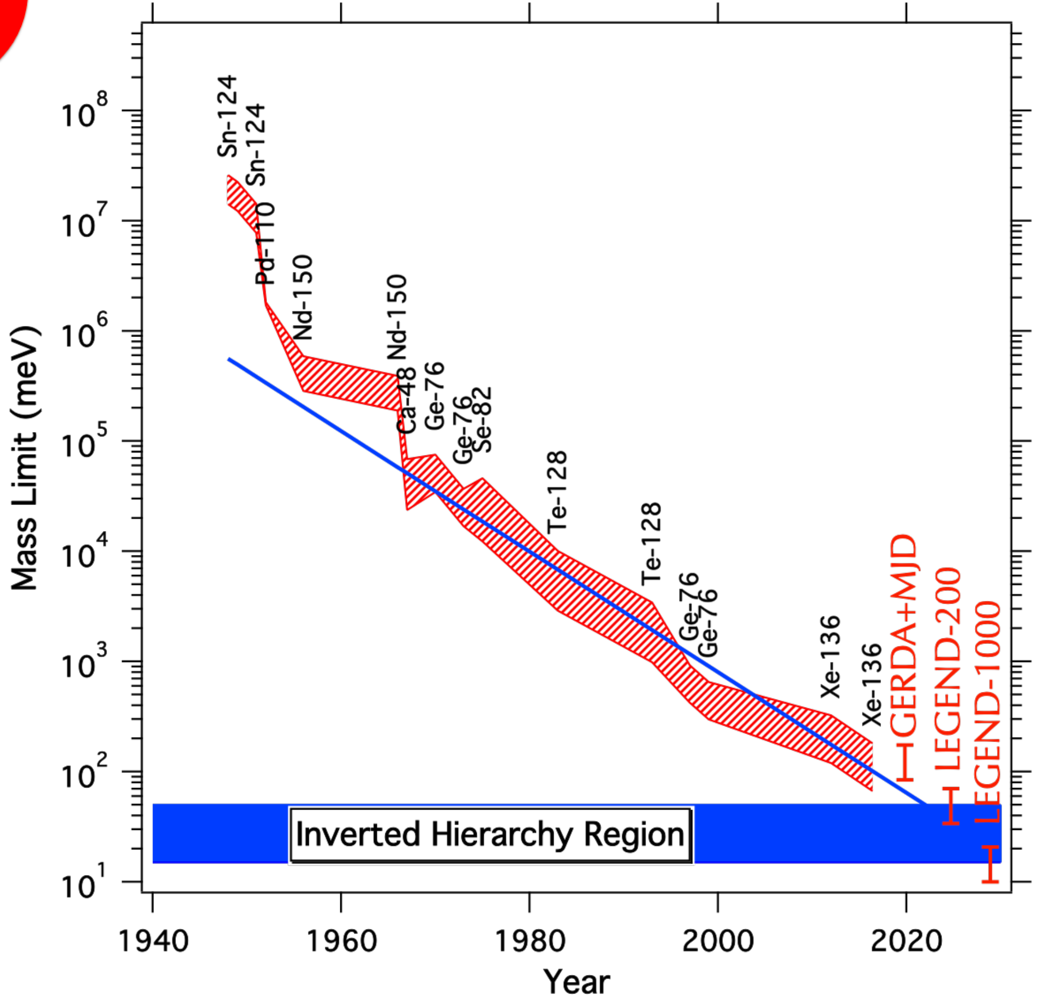
Ruben Saakyan
University College London

GdR-Neutrino
23-Nov-2020

Outline

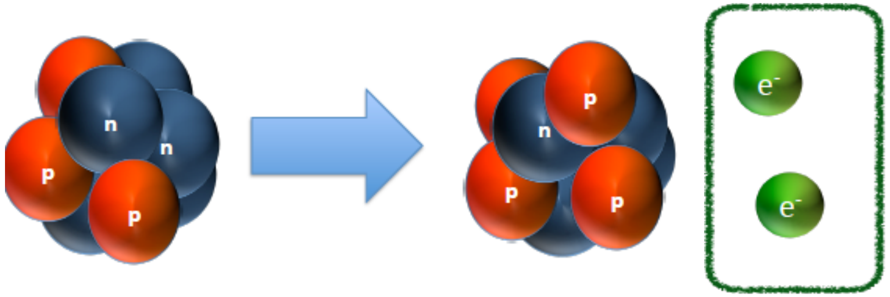


- The Big Picture: Motivation and Context
- Current Constraints and Future Goals
- Challenges and Experimental Approaches
- Summary and Outlook

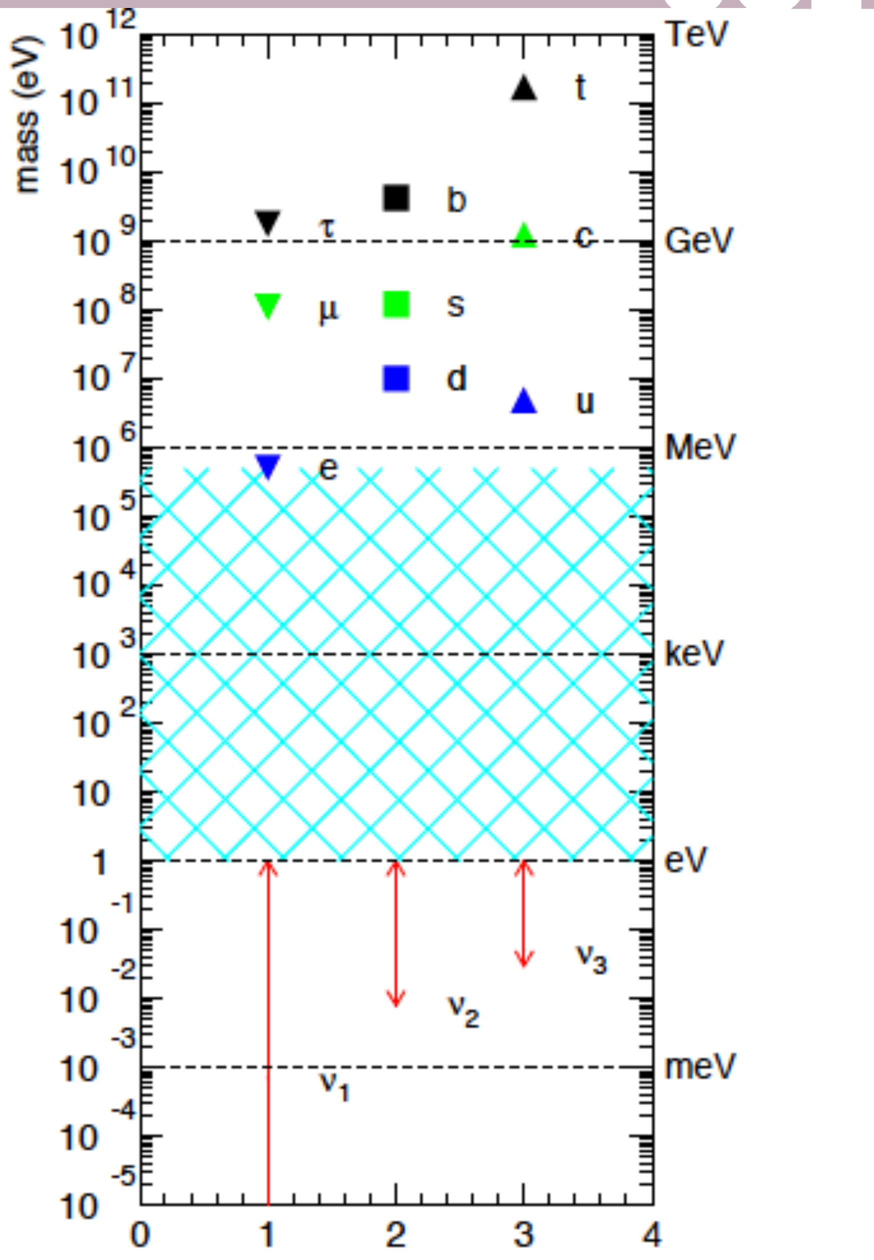


The Big Picture

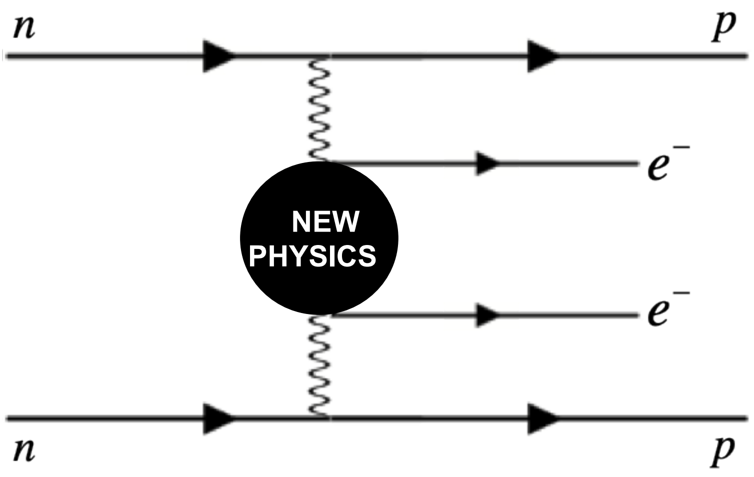
Proton Decay:
"Disappearance" of nucleons



Neutrinoless Double Beta Decay ($0\nu\beta\beta$)
"Creation" of electrons



- Crucial for understanding ***dominance of matter*** over anti-matter
- Crucial for understanding mechanism behind ***ν-mass*** (***Majorana*** vs Dirac)
- $0\nu\beta\beta$ is the most sensitive way to address **L**epton **N**umber **V**iolation ***regardless*** of underlying mechanism



NME:
~~Nasty~~ Nuclear Matrix Element

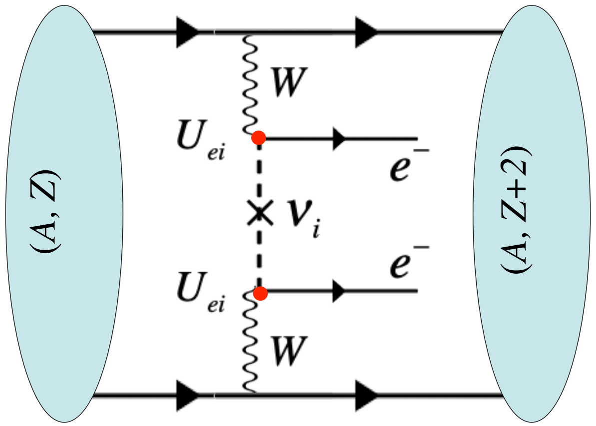
phase space

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \eta^2$$

LNV parameter

η can be due to $< m_{\beta\beta} >$, $V + A$, Majoron, SUSY, *H*⁻⁻, leptoquarks *or a combination of them* → *Connection with collider and neutrino physics*

Most discussed: Light Majorana Neutrino exchange



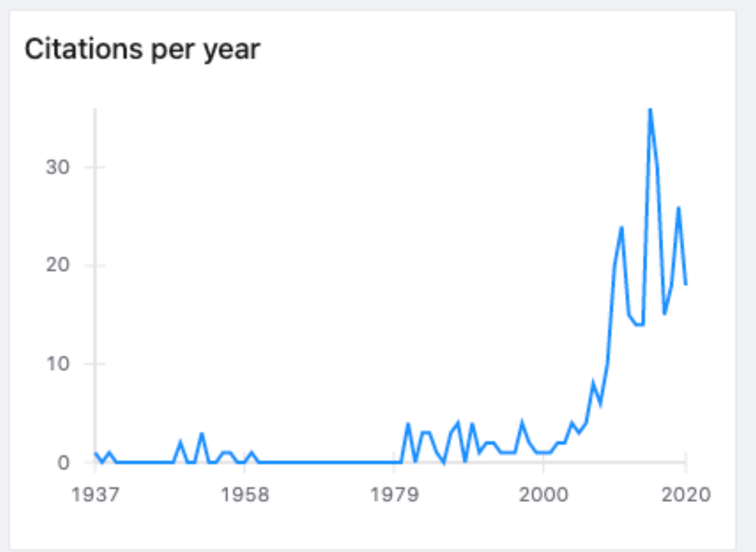
$$\langle m_\nu \rangle = \left|\sum U_{ei}^2 m_i\right| = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}\right|$$

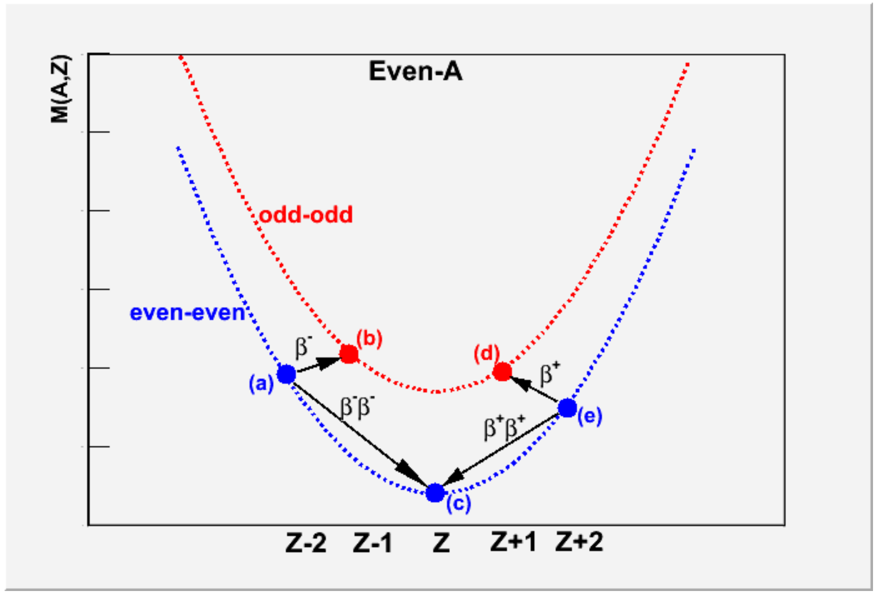
Observation of LNV would have profound implications beyond neutrino physics

Double Beta Decay

Abstract
From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

M. Goepert-Mayer
***Double beta-Disintegration*, Phys.Rev. 48:512-16 (1935)**





Over **40 nuclei** can undergo **ββ**-decay (including $\beta^+\beta^+$ and 2K-capture)
Only ~**9** experimentally **feasible for** $0\nu\beta\beta$

Isotope	Nat. Abundance (%)	$Q_{\beta\beta}$ (MeV)
Ca48	0.187	4.274
Ge76	7.8	2.039
Se82	9.2	2.996
Zr96	2.8	3.348
Mo100	9.6	3.035
Cd116	7.6	2.809
Te130	34.5	2.530
Xe136	8.9	2.462
Nd150	5.6	3.367

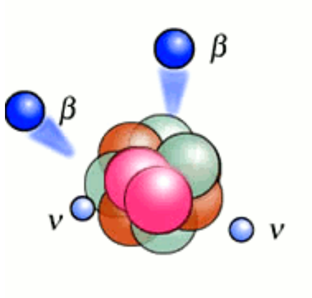
High $Q_{\beta\beta}$ is good for

- Phase Space
- Suppressing natural radioactivity background

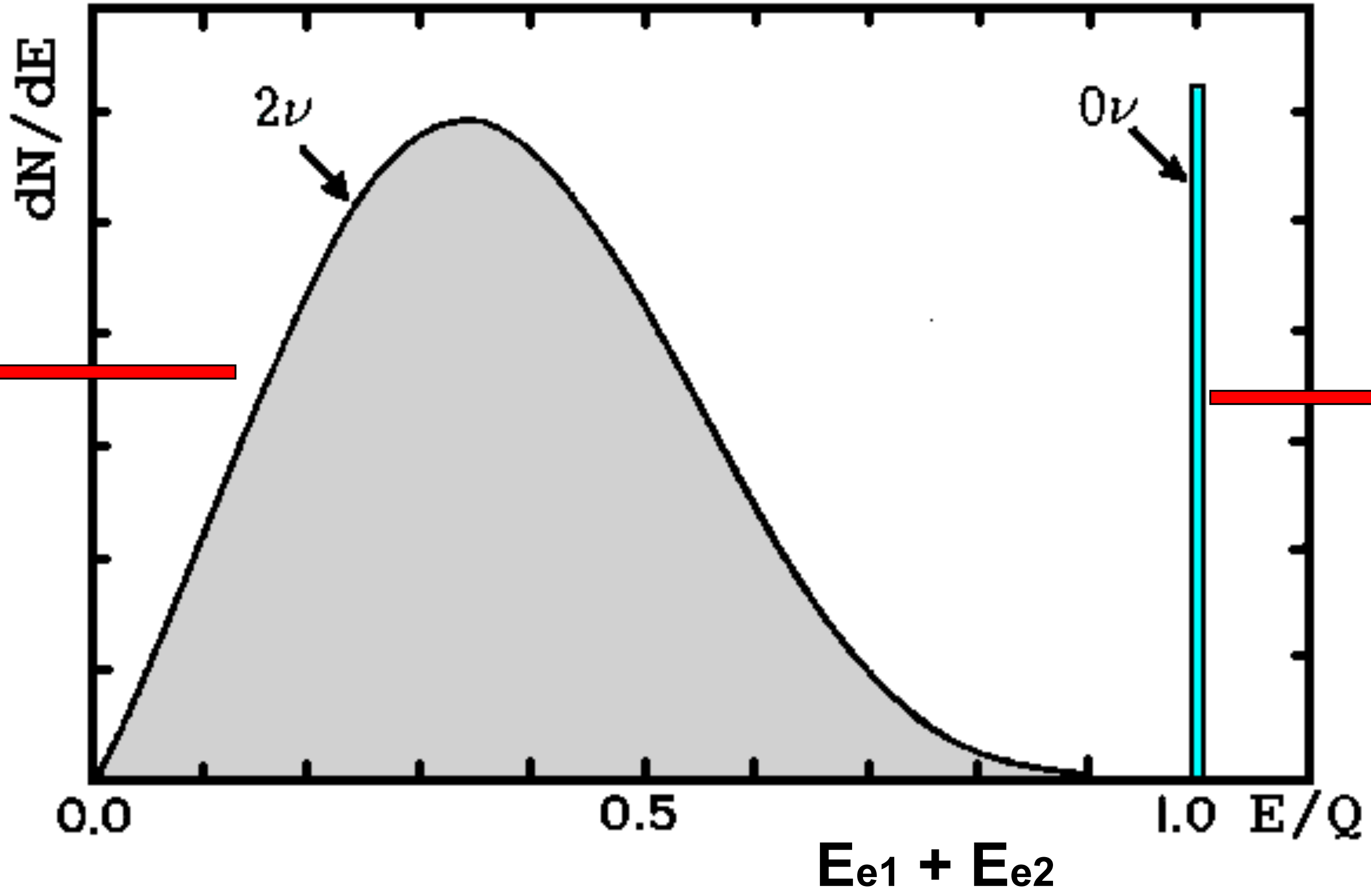
A Very Rare Process. Experimental Observables

$\Gamma^{2\nu} \propto G_F^4$

$T_{1/2} \sim 10^{19} - 10^{24}$ yr!

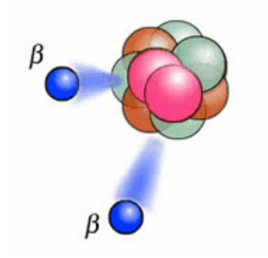


$2\nu\beta\beta(EC/\beta^+)$ has been detected in 13 nuclei!



$\Gamma^{0\nu} \propto G_F^4 \cdot \eta_{LNV}^2$

$T_{1/2} > 10^{26}$ yr!

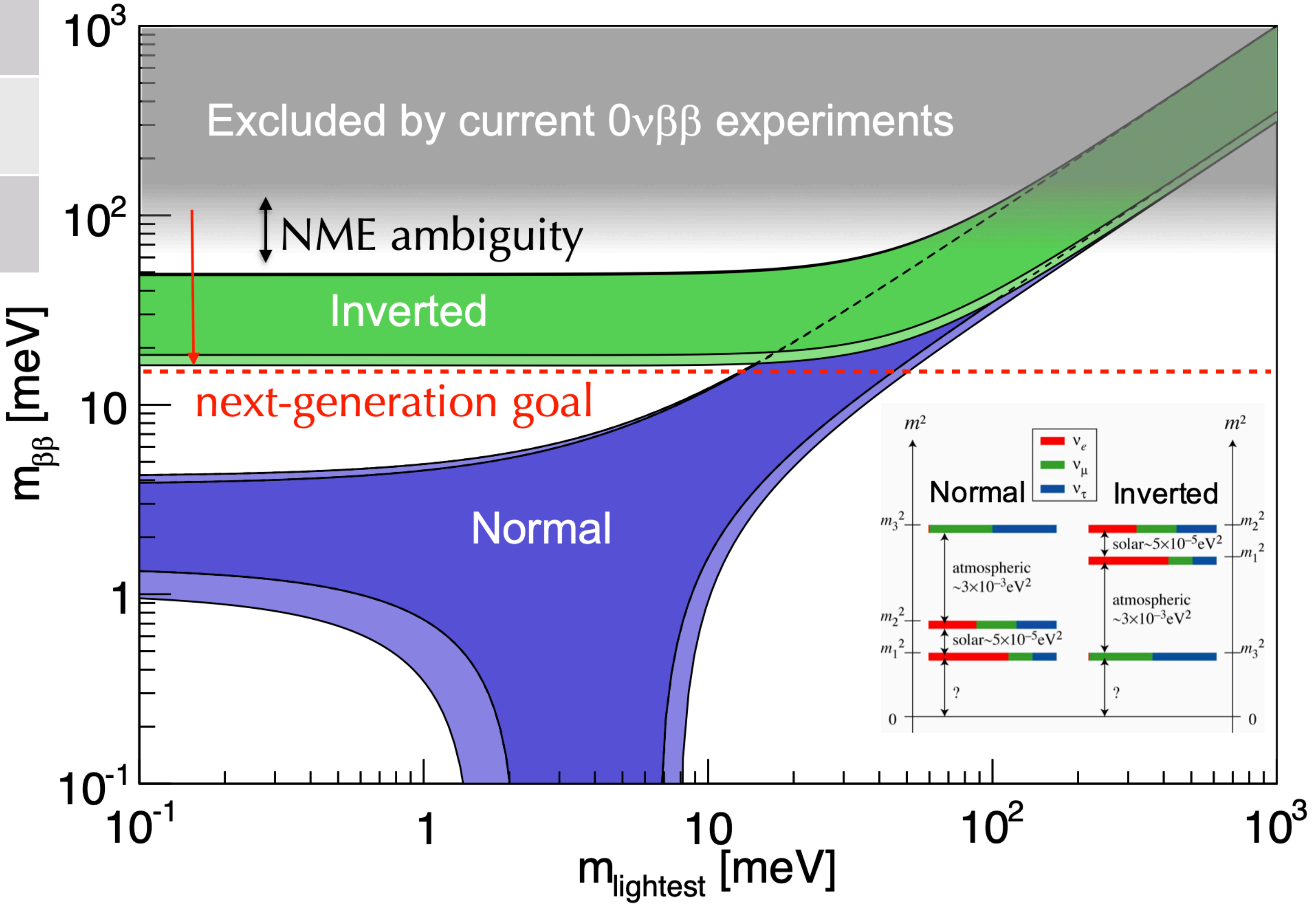


Also: individual electron energies, Ee1, Ee2, and angle θ between them

Current Constraints and Future Goals

Isotope/Exp	$T_{1/2}$ yrs*	$< m_{\beta\beta} >^*$, eV
^{136}Xe, Kamland-Zen	> 10^{26}	< 0.06 – 0.16
^{76}Ge, GERDA	> 1.8 x 10^{26}	< 0.08 – 0.17
^{130}Te, CUORE	> 3.2 x 10^{25}	< 0.08 – 0.35

* 90% CL

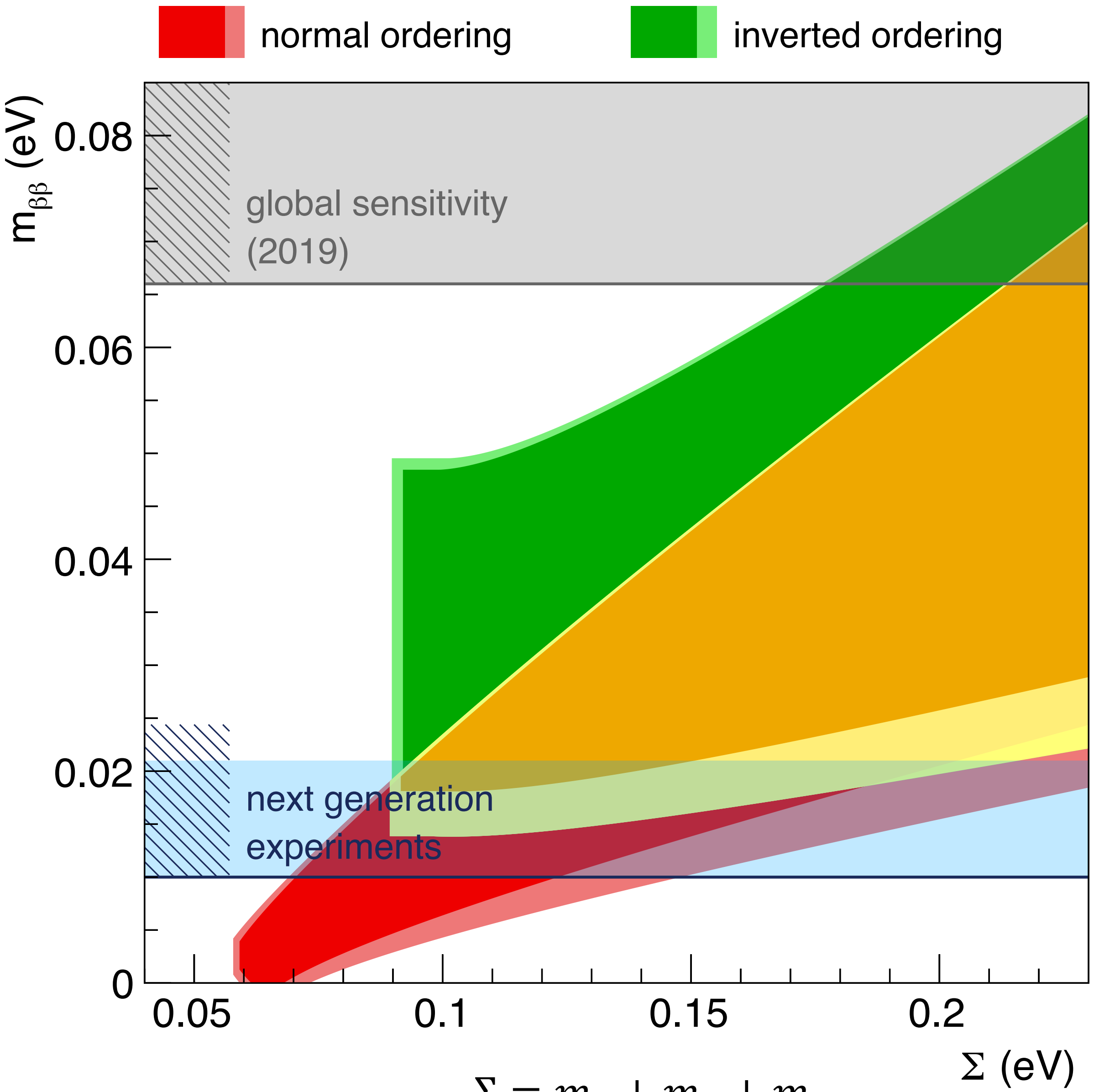


Future Goals:

- ×100 improvement in $T_{1/2}$
- Cover IO with 3σ discovery potential
- Up to 50% of NO

Beware of log scales!

Next generation experiments will have a significant chance of discovering $0\nu\beta\beta$ regardless of mass ordering!

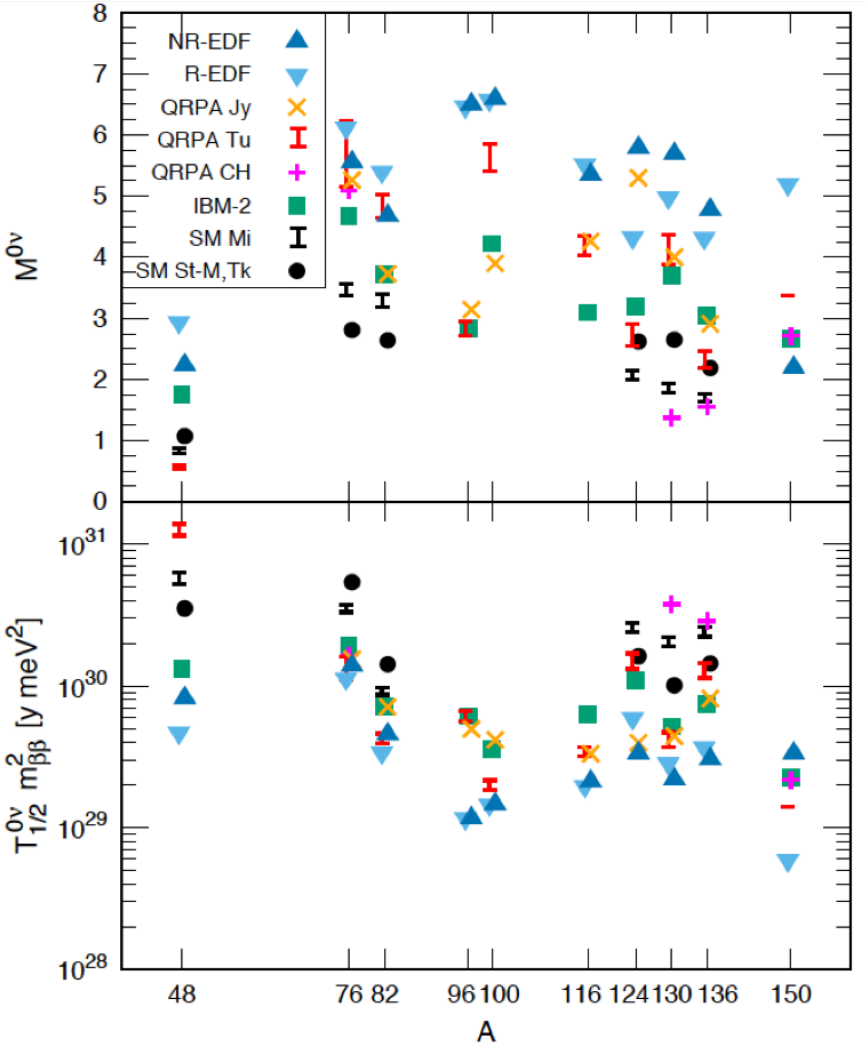


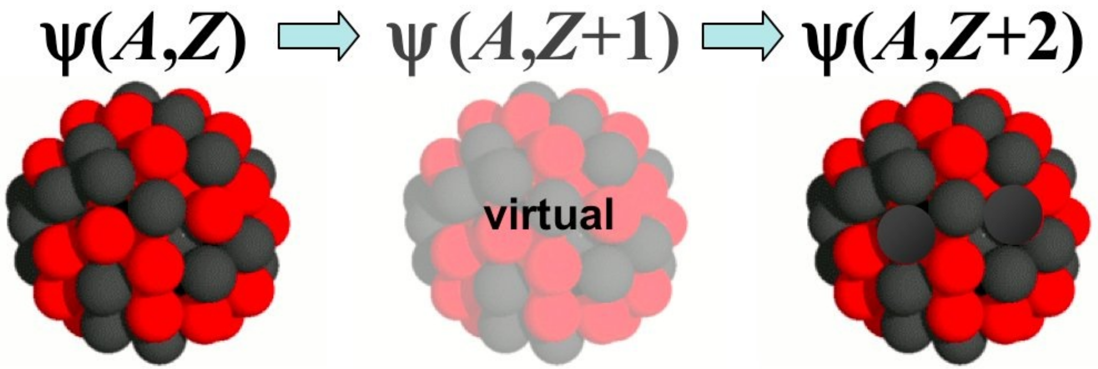
$\Sigma = m_1 + m_2 + m_3$

Challenges

- Backgrounds, backgrounds, backgrounds
  - Radiopurity of components, external background, radon
  - Cosmogenic activation (underground depth)
  - $2\nu\beta\beta$: Energy resolution
  - Particle ID and active shield
- Uncertainties in Nuclear Matrix Elements calculations
- Scalability
- Cost and feasibility

Challenges: Nuclear Matrix Elements.





- Significant effort from different groups and different nuclear models
- ***Question of g_A quenching under study***
- No isotope has clear preference. Choice driven by experimental considerations.
- **Multiple isotope confirmation crucial**
- **Experimental input important**
  - » **2νββ decay**
  - » charge exchange reactions
  - » muon capture

$$\Gamma^{0\nu} = G^{0\nu} g_A^4 \left|M^{0\nu}\right|^2 \langle m \rangle^2$$

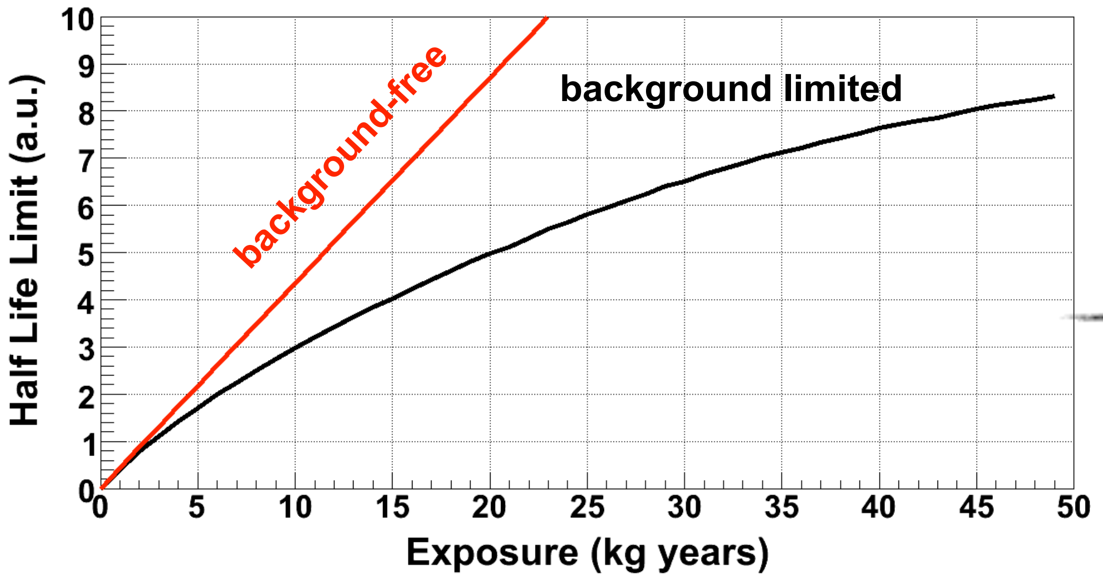
Experimental Challenges

maximise efficiency & isotope abundance

maximise exposure = mass (isotope) × time

$$T_{1/2}^{0\nu}(90\%\ \text{C.L.}) = 2.54 \times 10^{26}\,\text{y}\left(\frac{\varepsilon \times a}{W}\right)\sqrt{\frac{M \times t}{b \times \Delta E}}$$

minimise background & energy resolution



ββ is about **background suppression!**

Backgrounds:

- Cosmic ray muons (**underground lab is a must**)
- **Natural radioactivity** ^{238}U, ^{232}Th, neutrons,…
- **2νββ**

Take Home Message: **$T_{1/2}$~10^{26}yr (<m_ν>~50-100 meV) with 100kg isotope — ~1 event/yr!**

- Large isotope mass
- Superior background suppression
- Good energy resolution

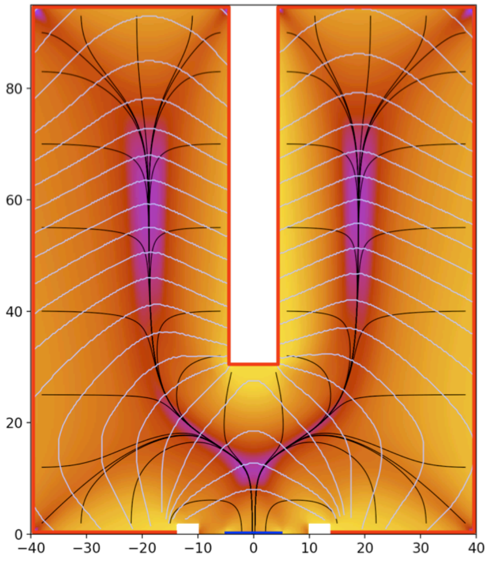
Experimental Approaches

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{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
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	$^{116}Cd/^{130}Te$	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~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
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

- Reach experimental landscape
- Multiple approaches are necessary
  - No isotope a clear winner, NME uncertainties
  - Discovery will constitute a handful of events (at best): need independent verification
  - Discovery with different isotopes may shed light on underlying mechanism

Courtesy of J. Detwiler and J. Wilkerson

Semi-conductors. HPGe. LEGEND Concept

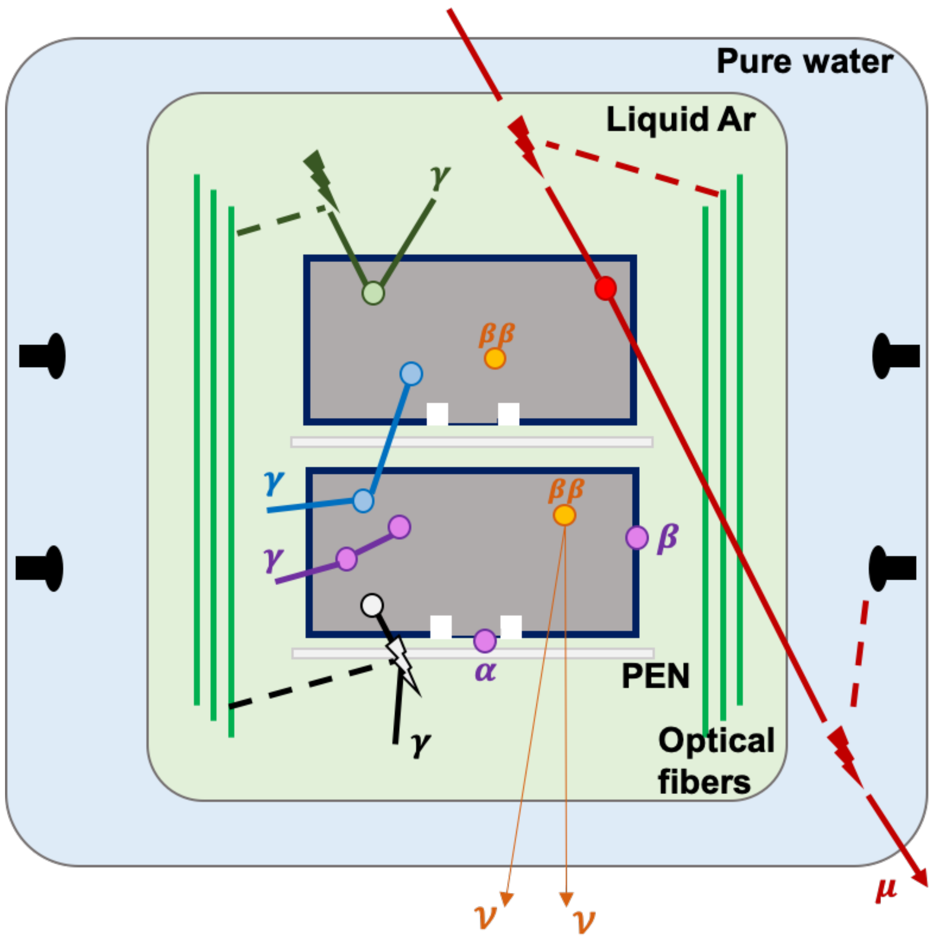


$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume

HPGe point-contact detectors:

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

Background suppression strategy



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

Ge detector anti-coincidence

Scintillating PEN plate holder (under test)

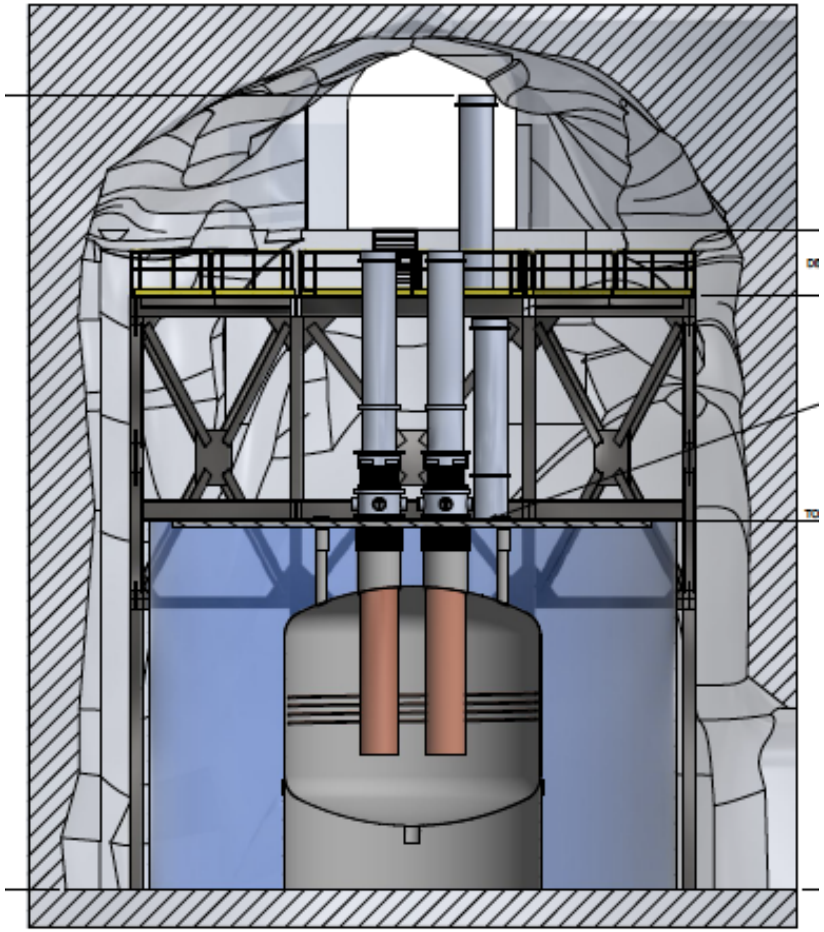
LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and/or plastic scintillator

Built on success of GERDA and Majorana
See talk by C. Wiesinger tomorrow

LEGEND-200:

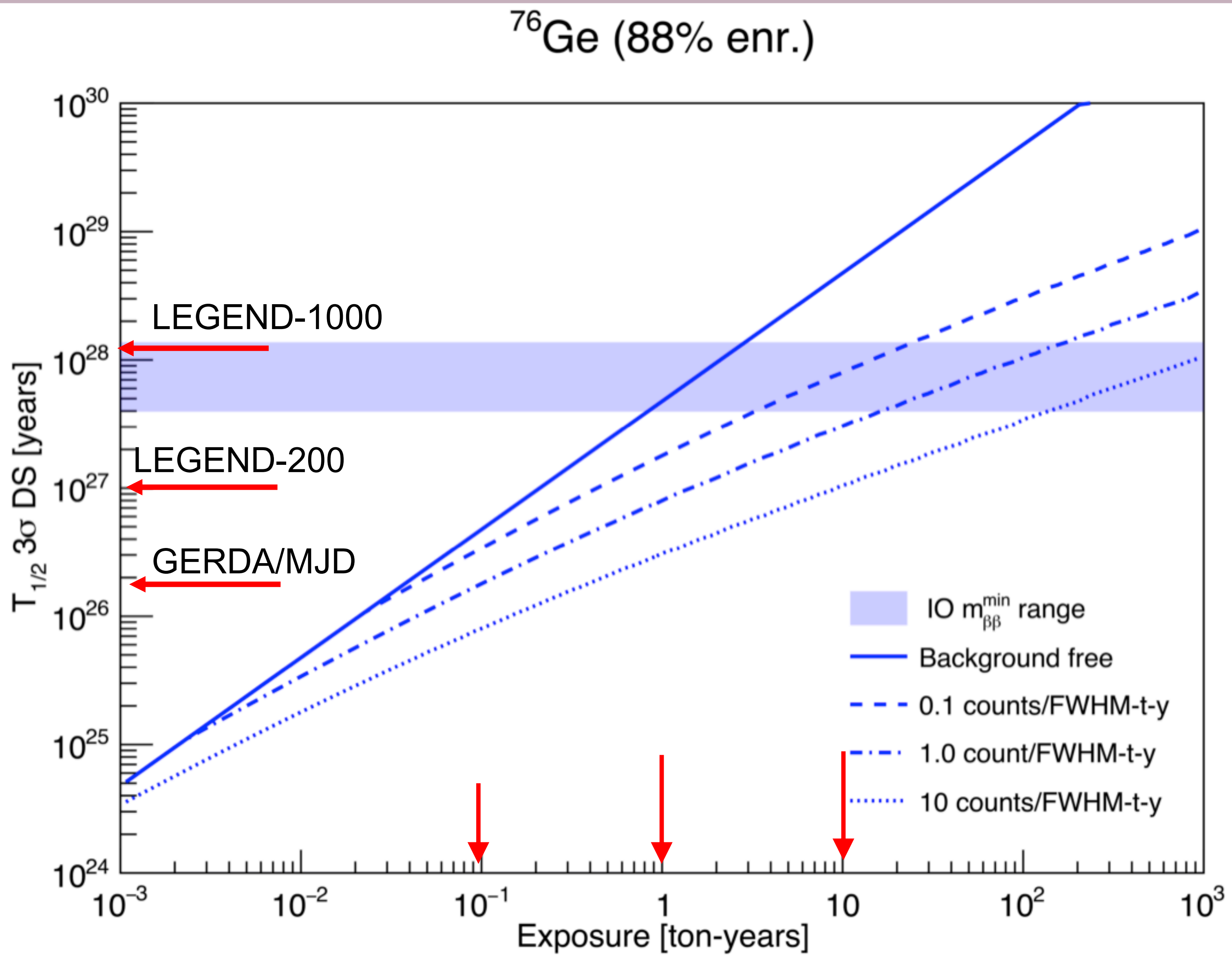
- 200 kg in upgrade of existing infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal
  <0.6 cts/(FWHM t yr)
  $<2\times10^{-4}$ cts/(keV kg yr)
  } Only x3 below GERDA
- Data start ~2021



LEGEND-1000:

- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr), $<1\times10^{-5}$ cts/(keV
- Location to be selected

LEGEND *Discovery* Potential



>10^{28} yr or $m_{\beta\beta}$=17 meV* for worst case matrix element of 3.5 and unquenched g_A.

3-σ *discovery* level to cover inverted ordering, given matrix element uncertainty.

Opportunities: Clear path to bkg-free regime, discovery potential

Challenges: Cost, scaling below 10 meV

$^*m_{\beta\beta}\sim 9-17$ meV

Semiconductors: CMOS imaging detectors

A. Chavarria et al, J. Inst. **12**, P03022 (2017

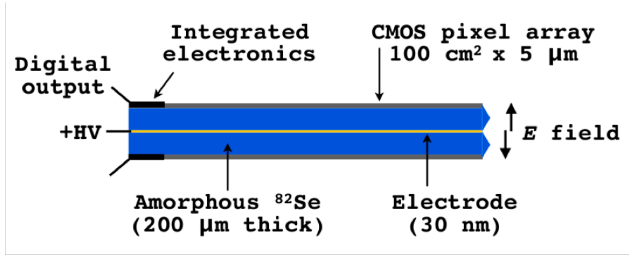
•Amorphous ^{82}Se x-ray detectors readout by CMOS pixel array

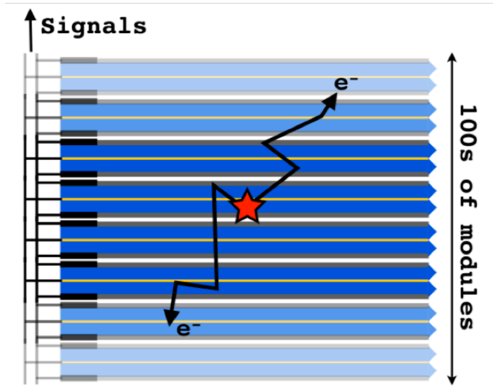
- Stack to achieve high density, high mass array
- 5 μm pixel size gives full track reconstruction

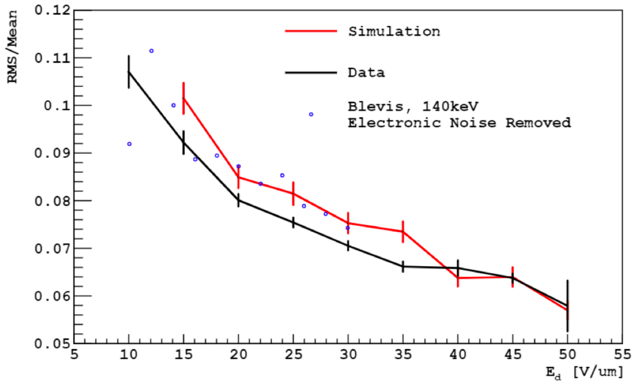
•Estimated background ~0.001 c/(FWHM t y) dominated by natural radioactivity

• **Opportunities**: Industrial production + low background indicates sensitivity to Normal Ordering mass scale

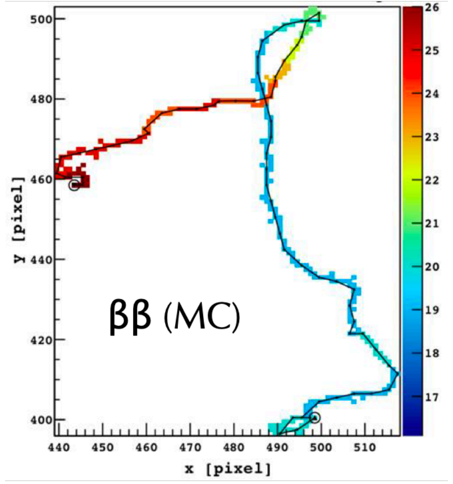
• **Challenges**: energy resolution, maturity for low-bkg applications

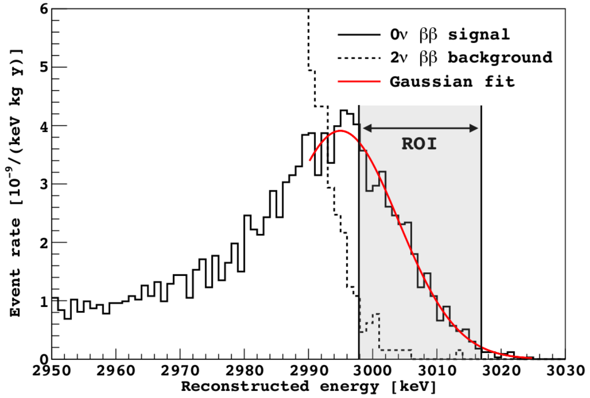




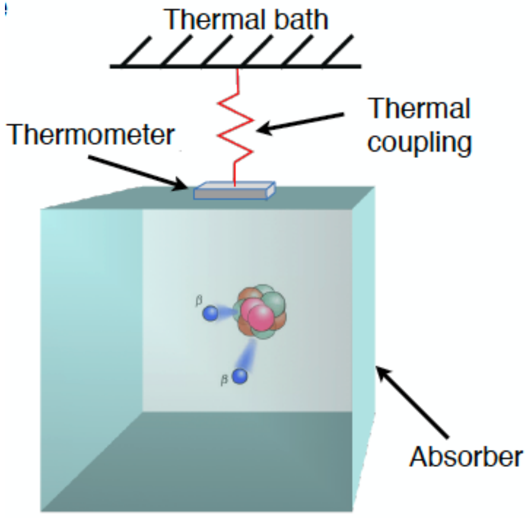


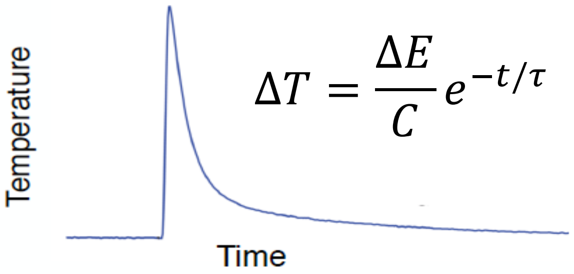
MC: x1000 β rejection with 50% ββ acceptance





Bolometers: CUORE



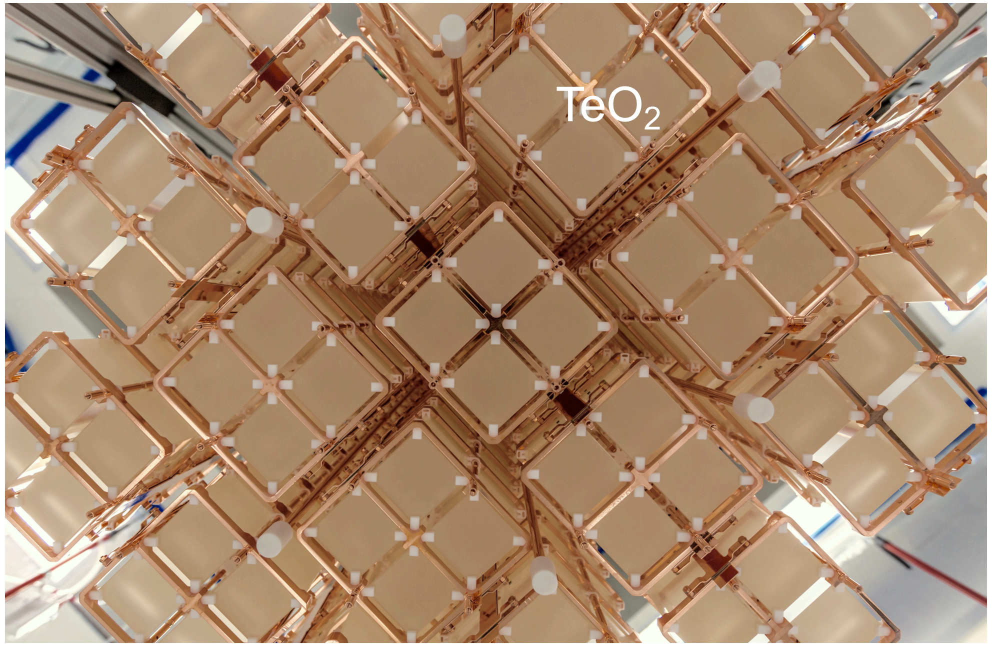


$$\Delta T = \frac{\Delta E}{C} e^{-t/\tau}$$

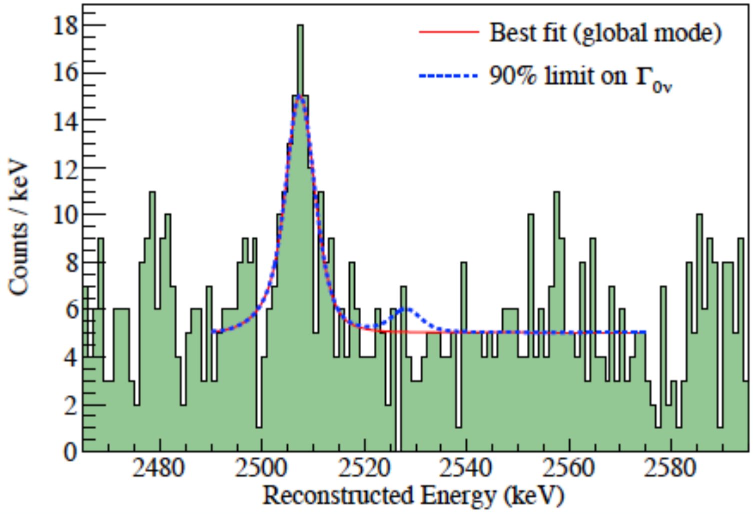
Heat capacity $C \propto T^3$

Typically operated at ~ 10mK

FWHM ~ 0.2-0.3%



CUORE ROI Spectrum



^{130}Te

$372.5\ \mathrm{kg \cdot yr}$

$$T^{0\nu}_{1/2} > 3.2 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$$

$$m_{\beta\beta} < 75 - 350\,\mathrm{meV}$$

Phys. Rev. Lett. 124, 122501 (2020)

Detector Performance Parameters

Background Index

$(1.38 \pm 0.07) \times 10^{-2} \mathrm{cnts/(keV \cdot kg \cdot yr)}$

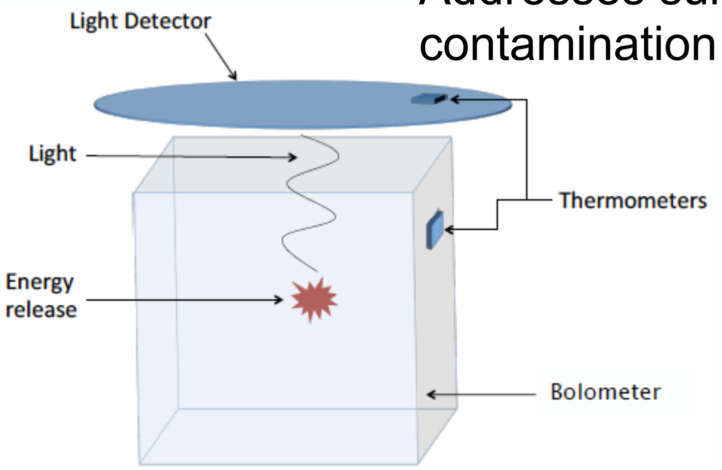
Characteristic FWHM ΔE at $Q_{\beta\beta}$

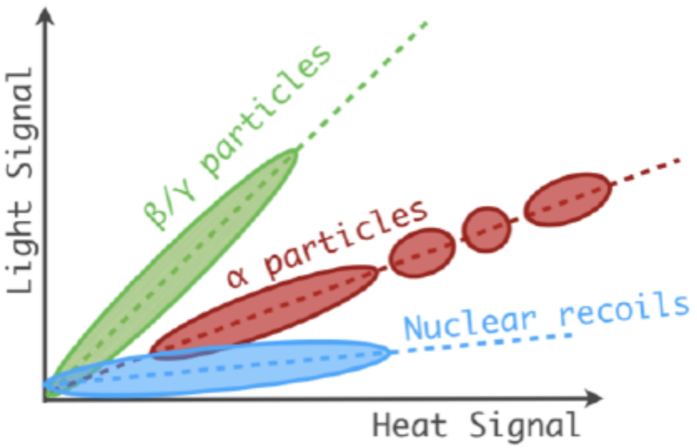
$7.0 \pm 0.3\ \mathrm{keV}$

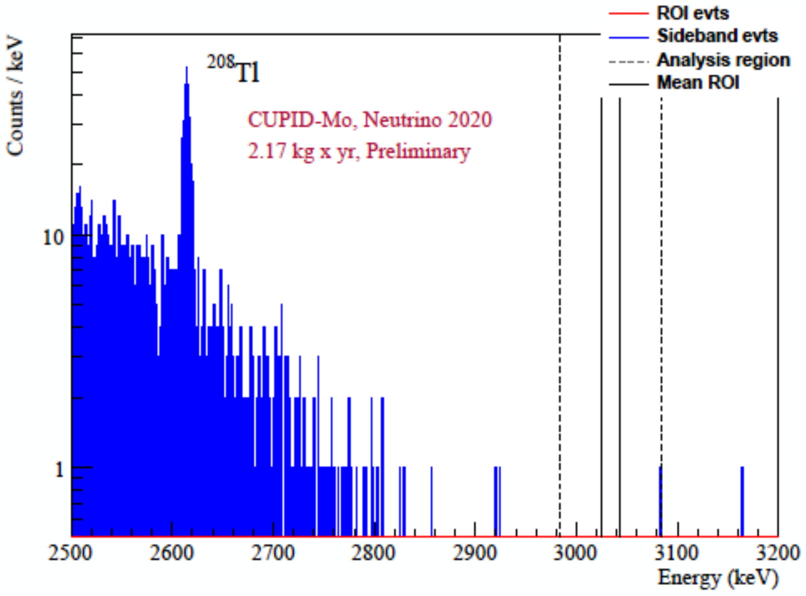
Limiting factor: surface contamination

Bolometers: CUORE → CUPID

Addresses surface contamination







CUPID-Mo Preliminary

$T^{0\nu}_{1/2} > 1.4 \times 10^{24}$ yr (90% c.i)

$m_{\beta\beta} < 310 - 540$ meV

CUPID-Mo Preliminary

$\mathrm{BI} : (4 \pm 2) \times 10^{-3}$ cnts/keV · kg · yr

See next talk by D. Poda

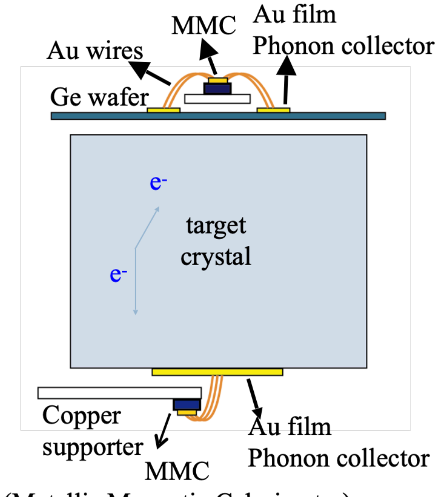
- Particle ID technique robustly demonstrated by **CUPID-0** (ZnSe) and **CUPID-Mo**($Li_2{}^{100}MoO_4$)
  - >99.9% α rejection, >99.9% β/γ acceptance
- CUPID:
  - 250 kg of ^{100}Mo in 1500 Li_2MoO_4 crystals in CUORE cryostat
    - Good *E* resolution from phonons: ~5 keV FWHM at $Q_{\beta\beta}$
    - Scintillation readout rejects background
- Background goal: 0.5 c/(FWHM t y) dominated by 2νββ pile-up and U/Th γ summing
- Discovery sensitivity (10 years): $T_{1/2} > 1.1 \times 10^{27}$ yr, $< m_{\beta\beta} > < 12$-20 meV
- pCDR online, planning for TDR in 2021, followed by 5 years construction at LNGS. 1 ton experiment under consideration

Bolometers: AMoRE

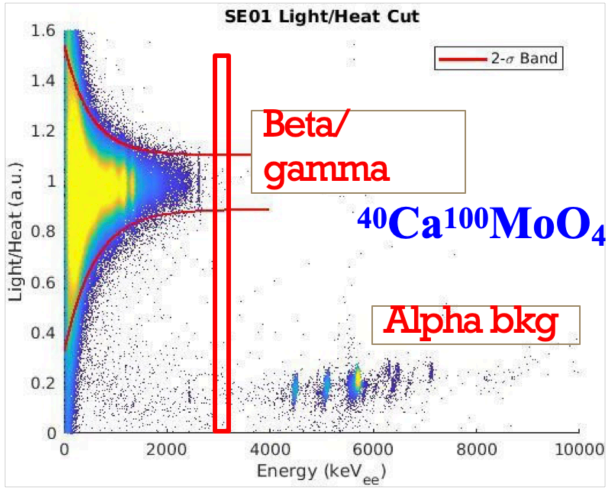
- 100 kg of ^{100}Mo in >95% enriched $Li_2{}^{enr}MoO_4$ crystals
  - Good *E* resolution from phonons
  - Scintillation readout rejects background
- Scaling up from AMoRE-pilot
  - Demonstrated MMC + SQUID readout
  - Switching from $^{40}Ca^{100}MoO4$ crystals
- Background goal: <0.05 c/(keV t y) dominated by 2νββ pile-up
- Limit sensitivity (5 years): $T_{1/2}$ > 8 x 10^{26} yr
- AMoRE-I with 13 $CaMoO_4$ + 5 Li_2MoO_4 (6 kg) scheduled to start in 2020 at Y2L. BG goal: <1.5 c/(keV t y). Full-scale AMoRE-II starts 2022 in YemiLab

Opportunities: Scalability, isotope flexibility

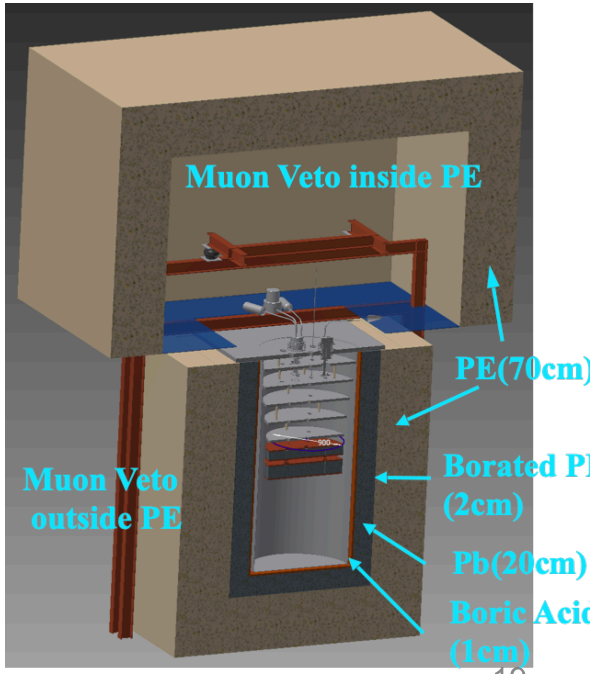
Challenges: Control pile-up and surface bkg, complex operation



(Metallic Magnetic Calorimeter)

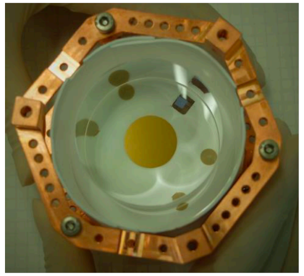


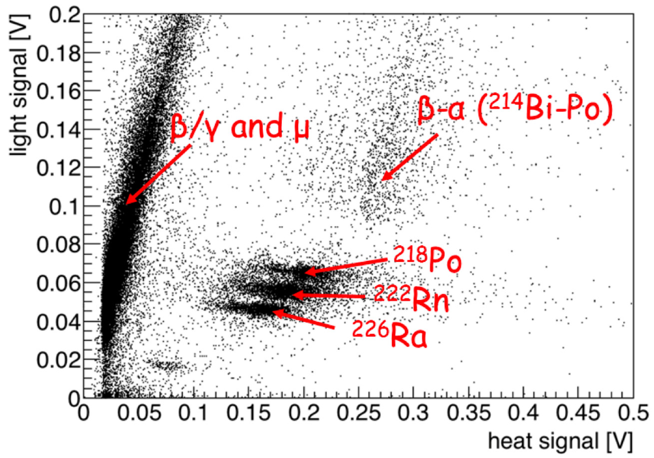
AMoRE-I

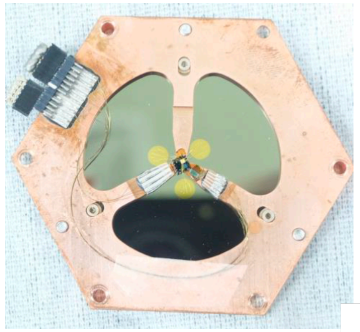


Bolometers: CANDLES

- CaF_2 scintillating crystals
  - Take advantage of ^{48}Ca's high $Q_{\beta\beta}$, "easy" NME
    - But: very low natural abundance (0.19%)
  - CANDLES-III: immerse in liquid scintillator (TAUP 2019: $T_{1/2} > 6\times10^{22}$ y)
  - Next system: operate as scintillating bolometers with MMC phonon readout and Ge wafer for photons
- Crystal performance measurements
  - Good α discrimination
  - E resolution σ = 2% at $Q_{\beta\beta}$ (position uniformity)
  - Purity improved x~10
- ^{48}Ca enrichment: laser isotope separation
  - Proof-of-priniciple complete
  - Scaling up for mass-production

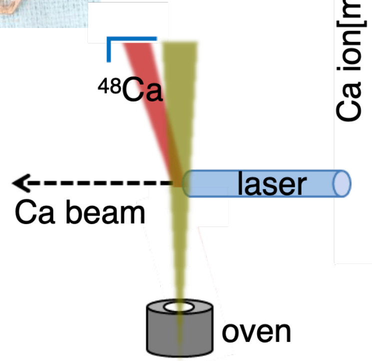


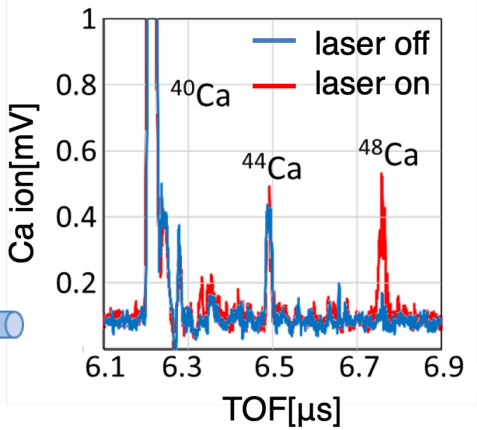




Opportunities: High $Q_{\beta\beta}$, low BG in ROI.

Challenges: E-resolution, scaling up isotope





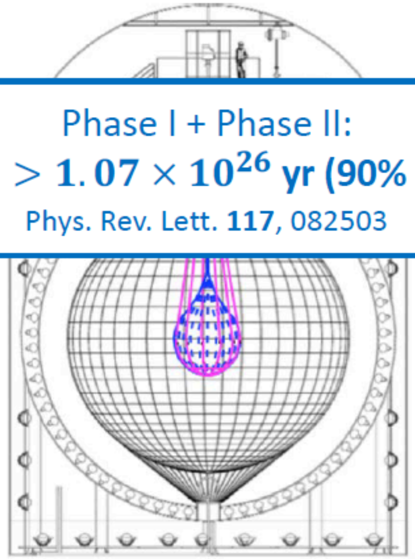
Large Liquid Scintillators: KamLAND-Zen

- Best current constraint on $<m_\nu>$ (0.06- 0.16 eV)

KamLAND2-Zen:

- Background ~2 c/(FWHM t y) dominated by $2\nu\beta\beta$ tail and ^8B solar ν scattering
- Limit sensitivity (5 years): $T_{1/2} > 2 \times 10^{27}$ yr, $m_{\beta\beta} < 12\text{-}53$ meV
- Upgrade preparations underway, will proceed following 5-year run of KamLAND-Zen 800

Past



Phase I + Phase II:
$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)
Phys. Rev. Lett. **117**, 082503

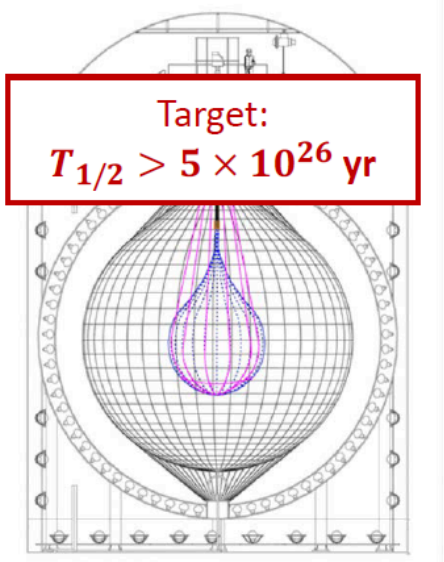
KamLAND-Zen 400

Mini-balloon Radius = 1.54 m

Xenon mass = 320 ~ 380 kg

2011 ~ 2015

Current



Target:
$T_{1/2} > 5 \times 10^{26}$ yr

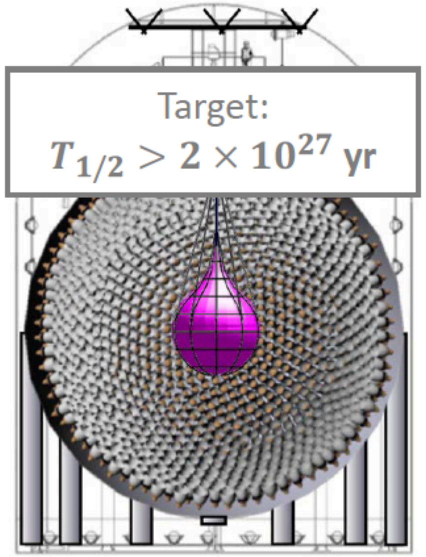
KamLAND-Zen 800

Mini-balloon Radius = 1.90 m

Xenon mass = 745 kg

Started January 2019

Future



Target:
$T_{1/2} > 2 \times 10^{27}$ yr

KamLAND2-Zen

Xenon mass ~ 1 ton

× 5 increase in light collection

Scintillation balloon film

Opportunities: Scalability, cost, simplicity

Challenges: E-resolution, solar neutrinos

Large Liquid Scintillators: SNO+

Phase-I

- Using existing SNO detector and SNO infrastructure
- Water replaced with liquid scintillator (LAB)
- Natural Te loading to commence soon
- Phased approach: from 0.5% loading up
- Phase-I sensitivity: 1.9 x 10^{26} yr

Phase-II

•4 t → 6.5 t ^{130}Te via increased loading in LAB

- Up to several percent with improved light yield
- Can use existing SNO+ Phase I Te loading systems

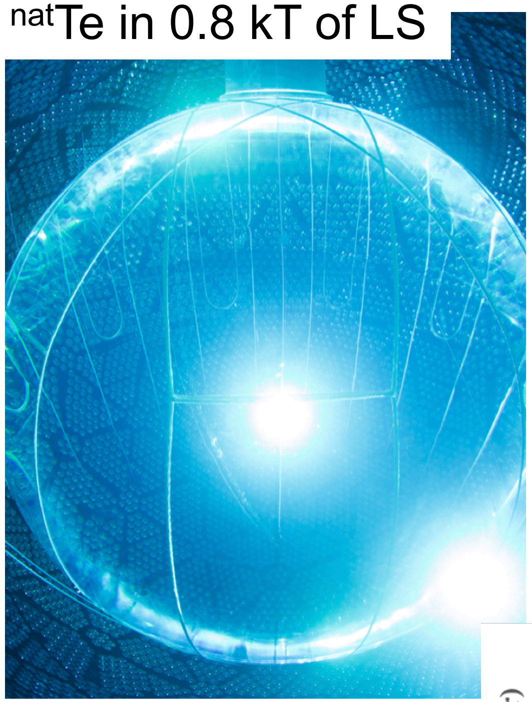
•Inexpensive, no detector upgrade required

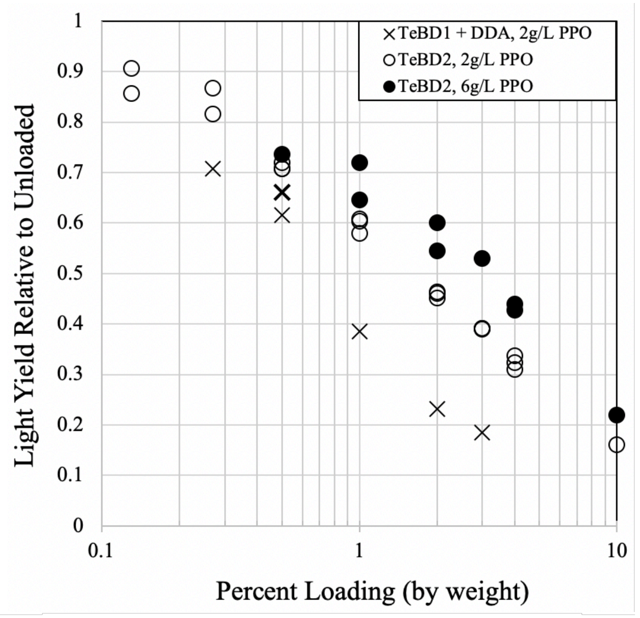
•Background ~10 c/(FWHM t y)
dominated by ^{8}B solar ν scattering

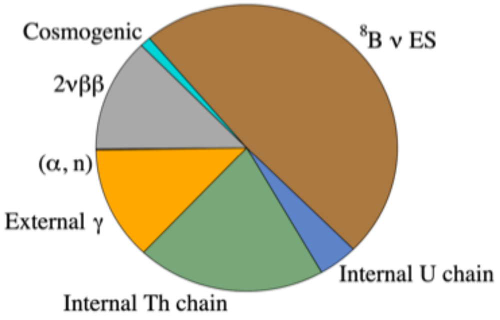
•Limit sensitivity (10 years): $T_{1/2}$ > 10^{27} yr, $m_{\beta\beta}$< 13-63 meV

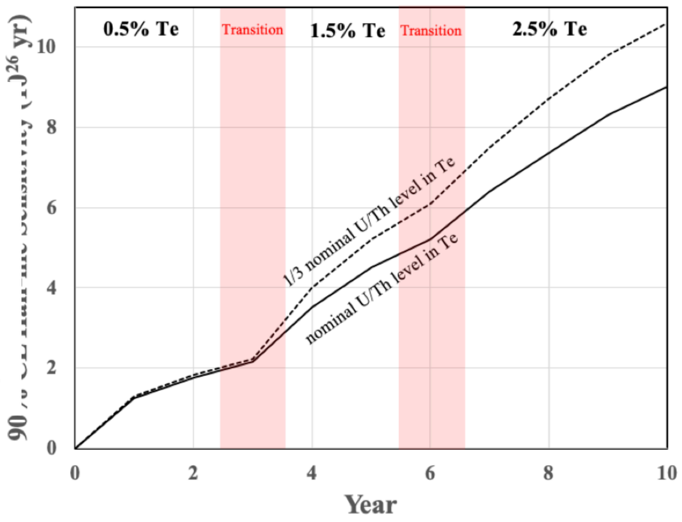
•Plan to increase loading after only 2.5 years of running in Phase I (1.3 t ^{130}Te)

^{nat}Te in 0.8 kT of LS



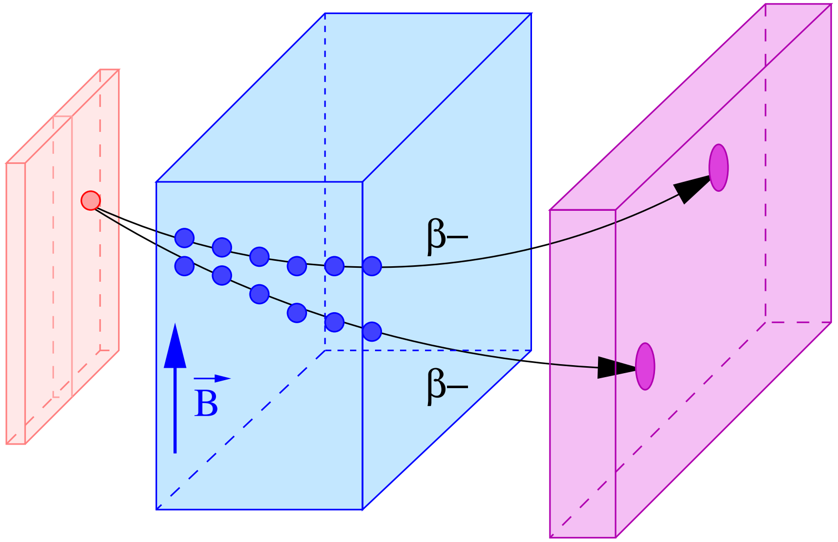






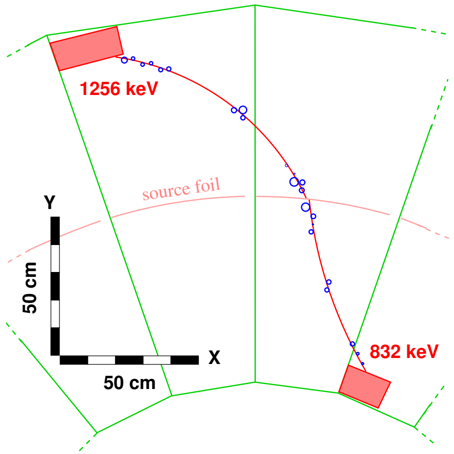
Tracker + ScintCalorimeter: NEMO-3 and SuperNEMO

- Source separated from detector: (almost) any solid isotope can be hosted.
- Full topological event reconstruction including $e^{\pm}$, γ-ray and α-particle identification ➜ strong background control & mechanism probe.
- Successfully exploited by **NEMO-3** experiment: 0νββ limits and 2νββ $T_{1/2}$ for several isotopes.



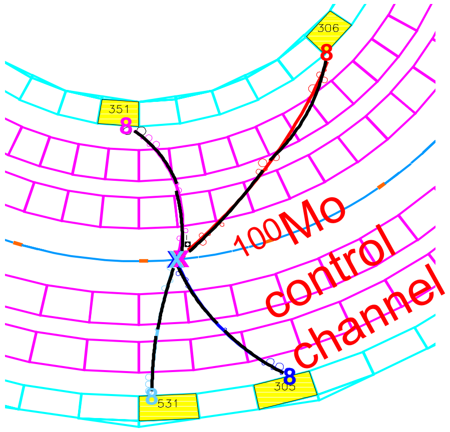
10^{24} year limit with just 7kg of ^{100}Mo

PRD 92, 072011 (2015)



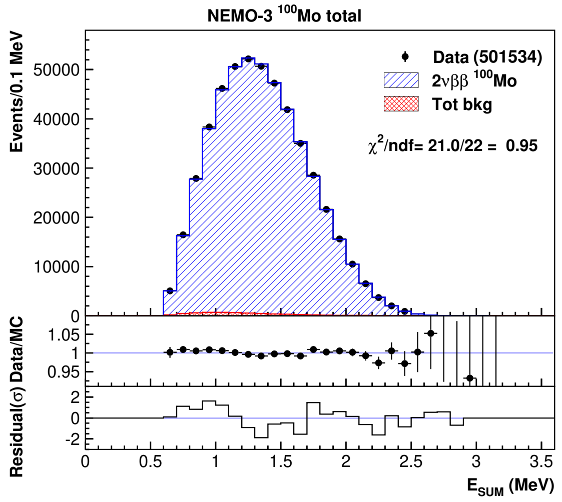
Access unique signatures, e.g. 0v4β

PRL 119, 041801 (2017)



Kinematic probes of DBD mechanism (SSD/HSD)

EPJ C79, 440 (2019)



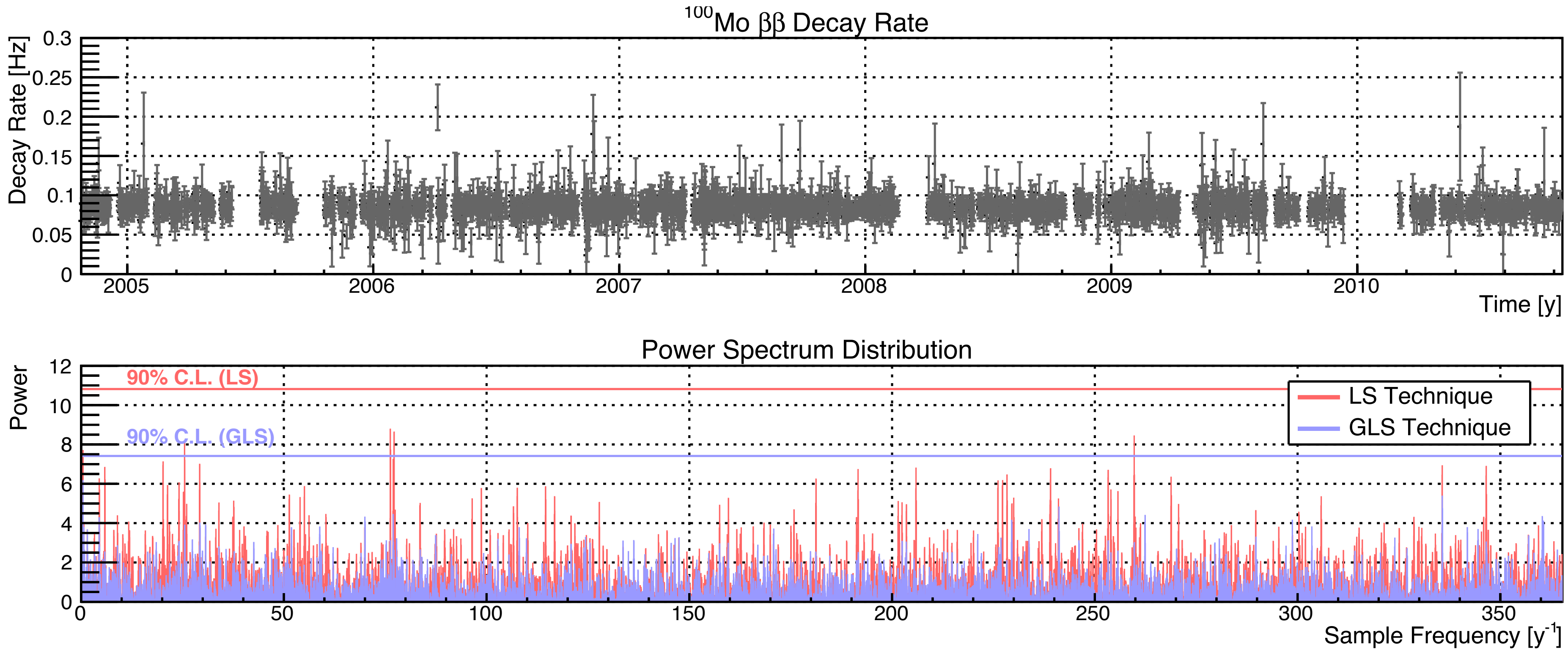
NEMO-3: Lates Physics Results

Many analyses still making use of *unique* approach:

- Search for double-beta decays of ^{82}Se to excited states of ^{82}Kr (2eNγ final state) which can have exceptionally low background.

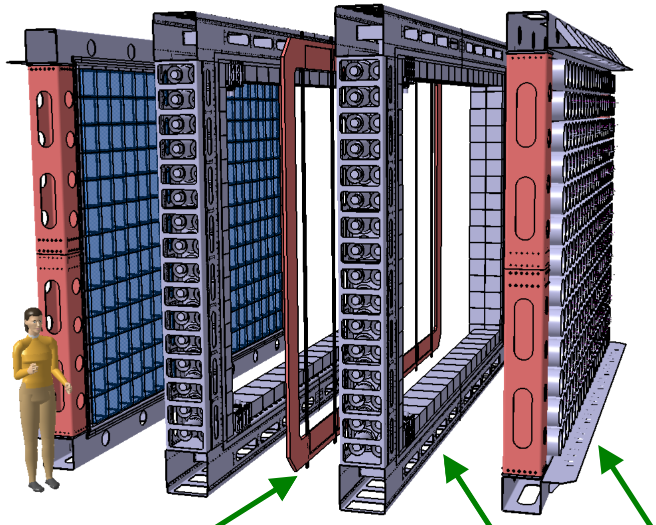
NPA 996, 121701 (2020)

- First ever search for periodic modulations in double-beta decay rate:



Submitted to arXiv last week!

SuperNEMO Status



SuperNEMO Demonstrator Module:

final commissioning in progress

<u>Demonstrator Module (2.5 year run)</u>

<u>17.5 kg × yr initial exposure :</u>

$$T^{0\nu}_{1/2} > 6.5 \times 10^{24}\ \mathrm{yr}$$

$$\langle m_\nu \rangle < 0.20 - 0.40\ \mathrm{eV}$$

- Covid has delayed the turn-on but strong recent progress.
- The **Demonstrator Module** will have a unique physics programme: full event reconstruction of 2νββ **gives access** to nuclear physics : e.g. g_A constraints.
- Can the technique be extended to **confirm a signal anywhere in the IH region? R&D and isotope developments** can point the way.

Opportunities

Challenges
(and opportunities)

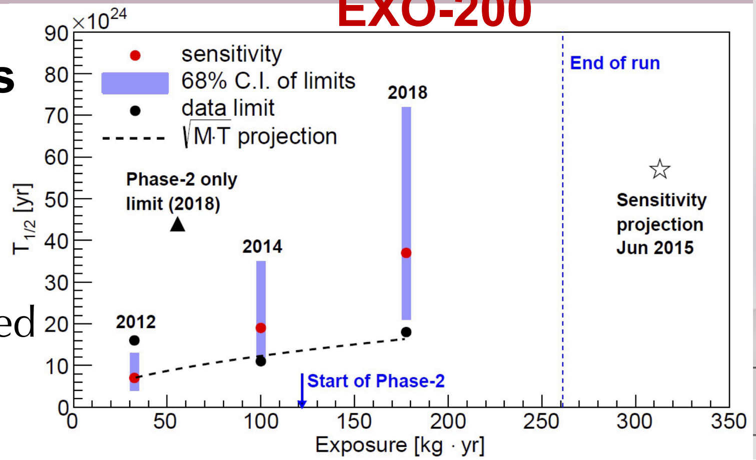
LXe TPC

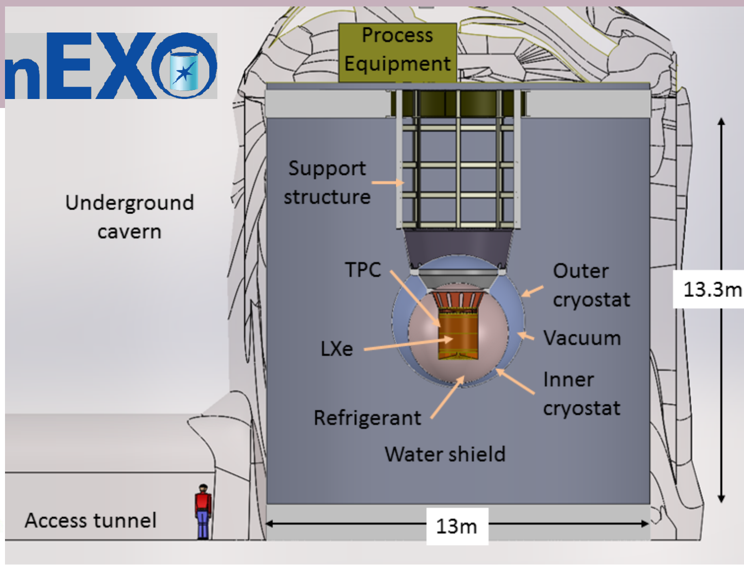
Opportunities

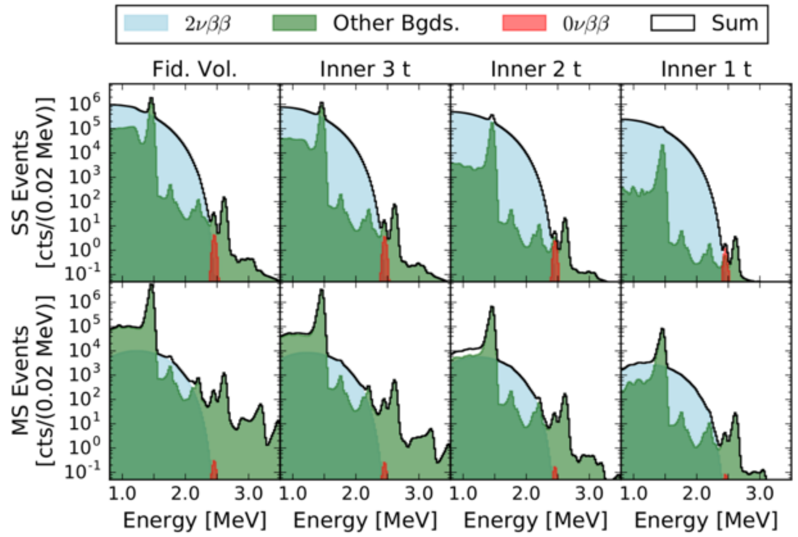
- Charge and light collection
- Scalable, excellent self-shiedling
- PID, position reconstruction
- **nEXO**
    - Upgrade of successful EXO-200 design, Improved light and charge collection
    - Innermost region BG ~0.1 c/(FWHM t y) dominated by natural radioactivity
    - Discovery sensitivity for 10 years livetime (update coming soon):
    $T_{1/2} > 5.7 \times 10^{27}$ yr, $m_{\beta\beta} <$ 7-31 meV
    - PreCDR online. Planning to deploy in SNOLab. Timeline coordinated with US downselect.
- **DARWIN/G3 Dark matter**
    - Dual phase detectors, good E-resolution demonstrated
    - Low background observatory: DM + 0vbb
    $T_{1/2} > 2.4 \times 10^{27}$ yr, $m_{\beta\beta} <$ 11-48 meV

Challenges: E-resolution, BG lines near $Q_{\beta\beta}$

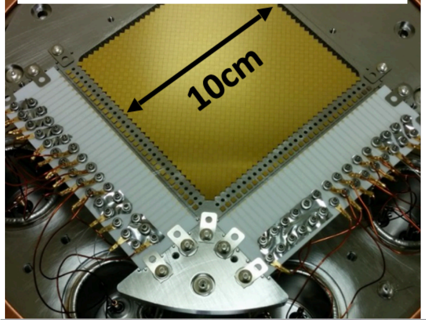
EXO-200



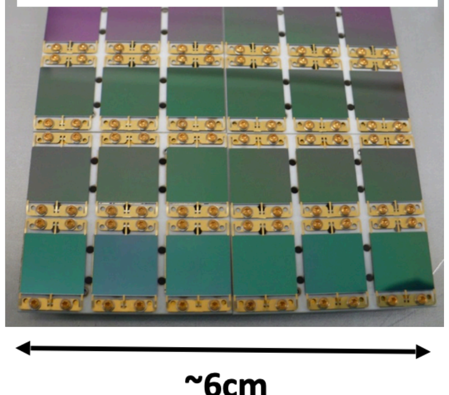




Prototype charge collection tile

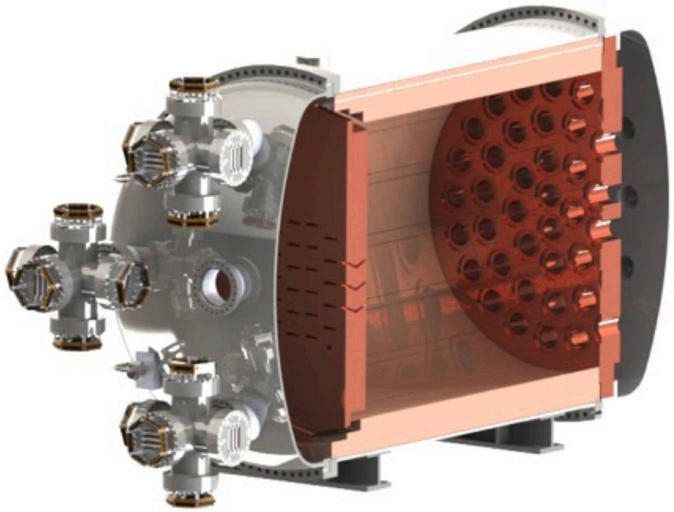


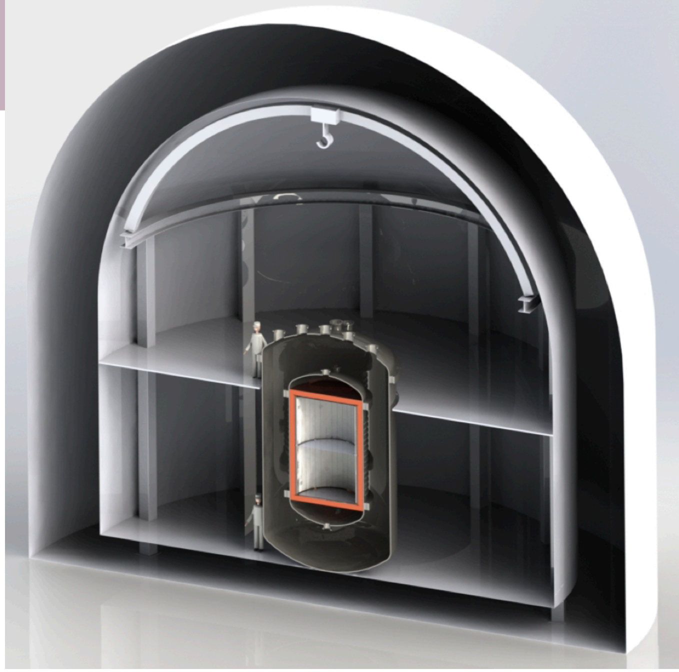
Prototype VUV SiPM array (FBK)

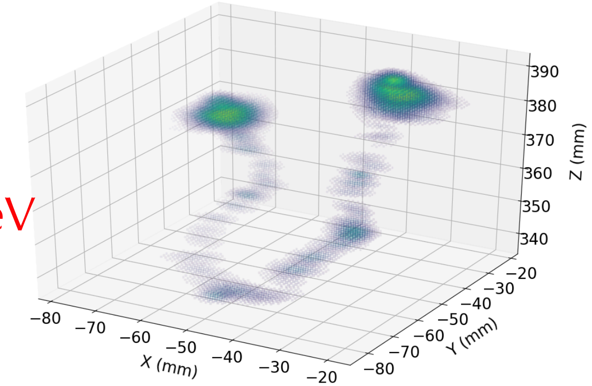


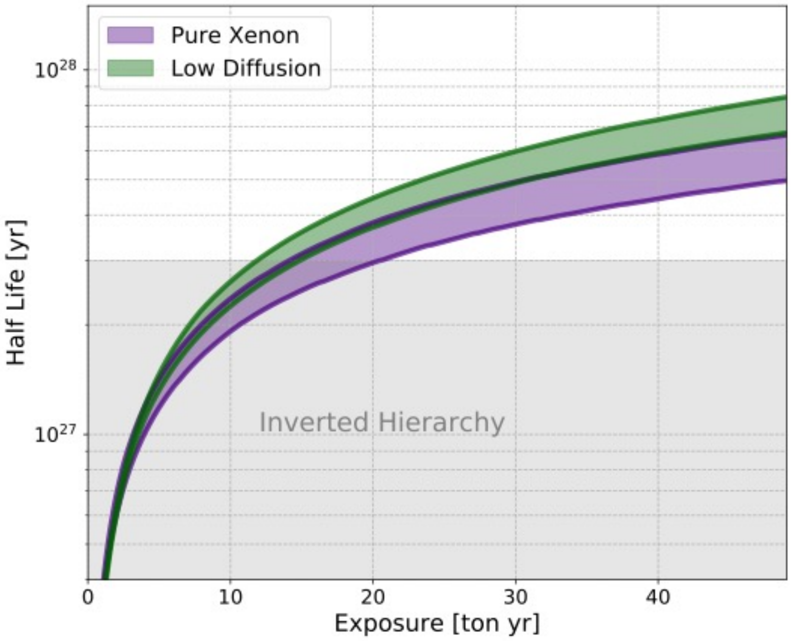
Gas TPC: NEXT-HD

- High-pressure gas EL TPC with 1 ton ^{136}Xe
  - *E* resolution 0.8% FWHM at $Q_{\beta\beta}$
  - Improved tracking over LXe TPC
- Extrapolation of NEXT-100 design
  - PMTs → SiPMs with reduced radioactivity
  - Lower diffusion gas mixture (Xe/He)
- Background ~0.1 c/(FWHM t y) dominated by natural radioactivity
- Limit sensitivity: $T_{1/2}$ > 1.7 x 10^{27} yr, $m_{\beta\beta}$< 13-57 meV
- Will follow NEXT-100 (should start this year)









Opportunities: Energy resolution, topology reconstruction

Challenges: diffusion, modularity vs scalability, maturity for low BG

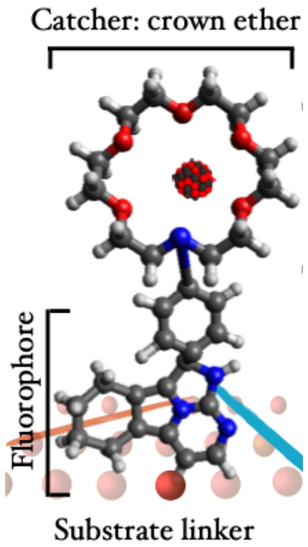
^{136}Xe Daughter Nucleus (^{136}Ba) Tagging

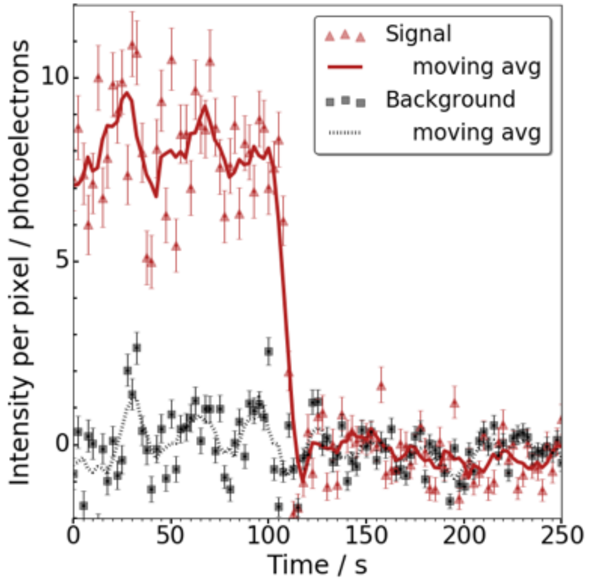
•NEXT: radio frequency carpet sweeps ions to region with switched-fluorescent molecules. Single-molecule sensitivity demonstrated in Xe background.

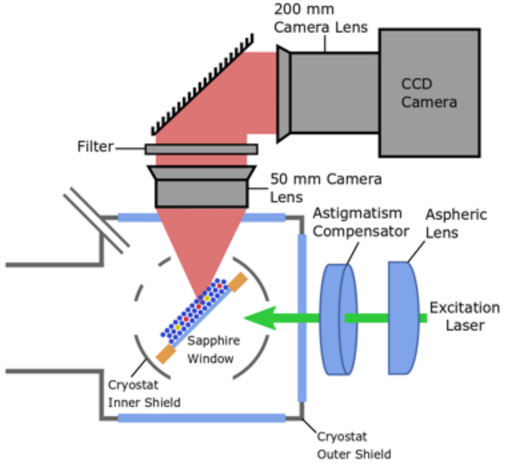
•nEXO: freeze Ba in Xe, transport via probe to imaging stage, lase and image. Single-atom sensitivity demonstrated.

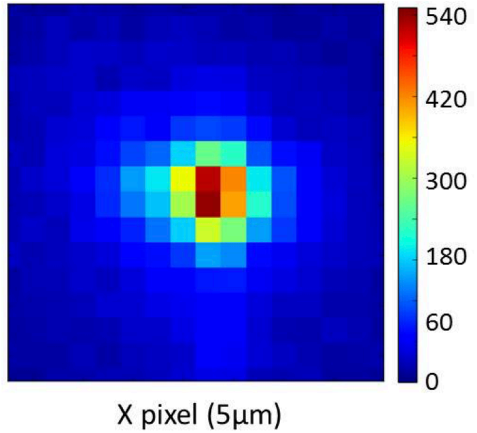
•Enables background-free searches

IF high efficiency can be achieved.









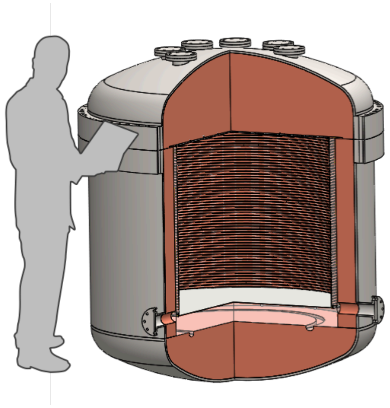
TPCs: PandaX, AXEL, NvDEX

- PandaX
  - PandaX-4T (360 kg ^{136}Xe): upgrade of PandaX-II dual-phase LXe TPC for DM @CJPL, commissioning by end of 2020. 30T upgrade in planning.
  - PandaX-III: 0νββ-focused HPGXe TPC with ~100 kg ^{136}Xe using micromegas readout. Limit sensitivity: $9x10^{25}$ y. Construction underway, commissioning in 2020. 1T upgrade in planning

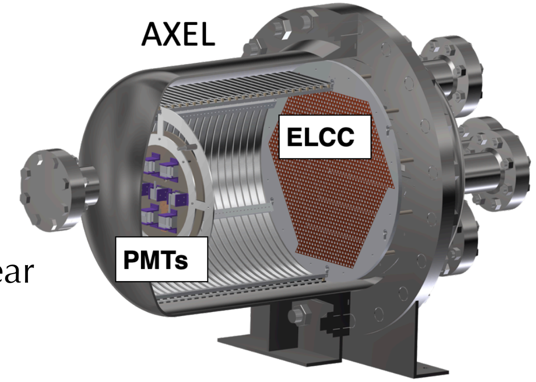
- AXEL
  - HPGXe TPC with Electroluminescence Light Collection Cell (ELCC) readout
  - 10L proof-of-principle demonstrated. 180L prototype under construction at Kyoto U. 40 kg upgrade planned for ~2024.

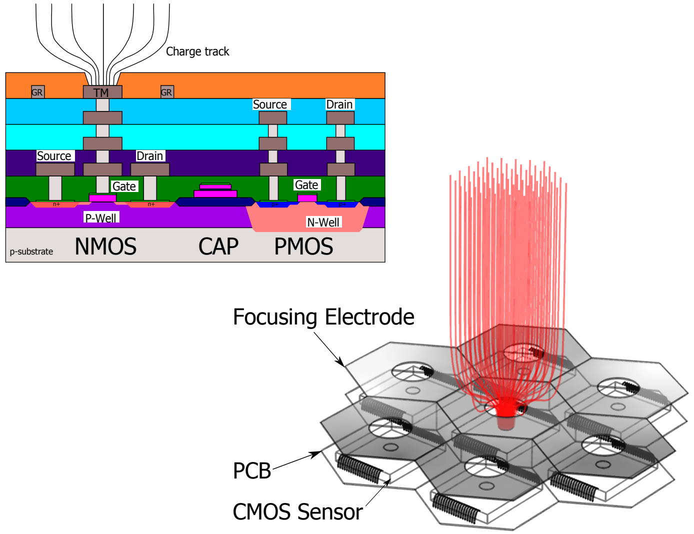
- NvDEX
  - $^{82}SeF_6$ HP gas TPC with Topmetal CMOS readout
  - 100 kg vessel designed, construction at CJPL starting next year

PandaX-4T LXe TPC



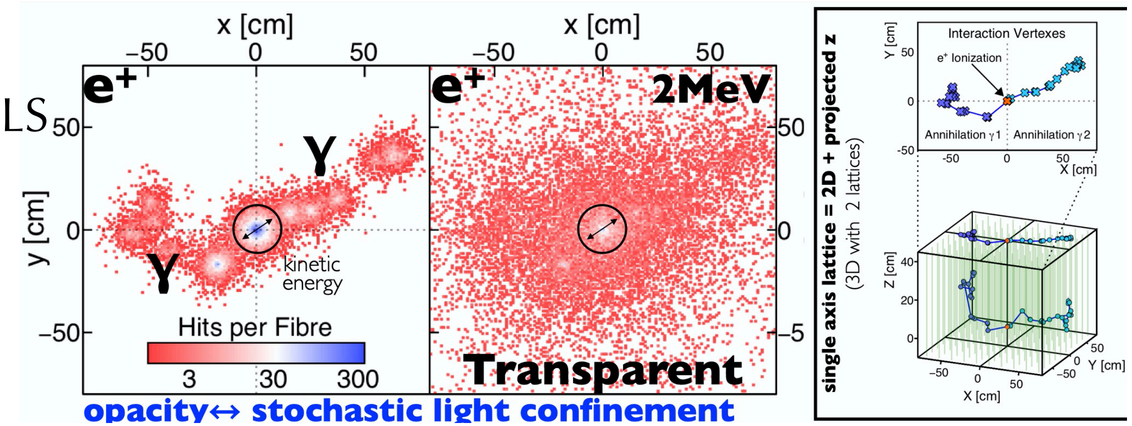
PandaX-III GXe TPC



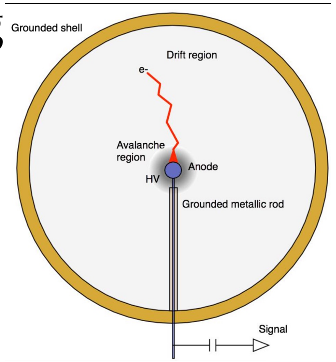


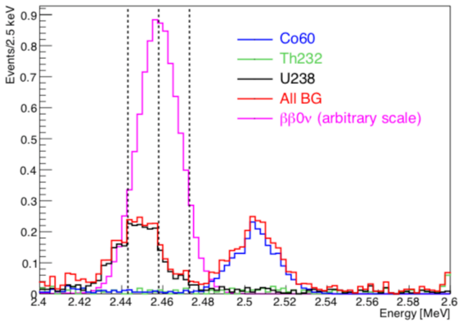
Topmetal CMOS Technology

- LiquidO
  - Opaque loaded LS + WS fibers: tracking / PID in LS with very high loading
  - Protyping underway
  - See arXiv:1908.02859, 1908.03334

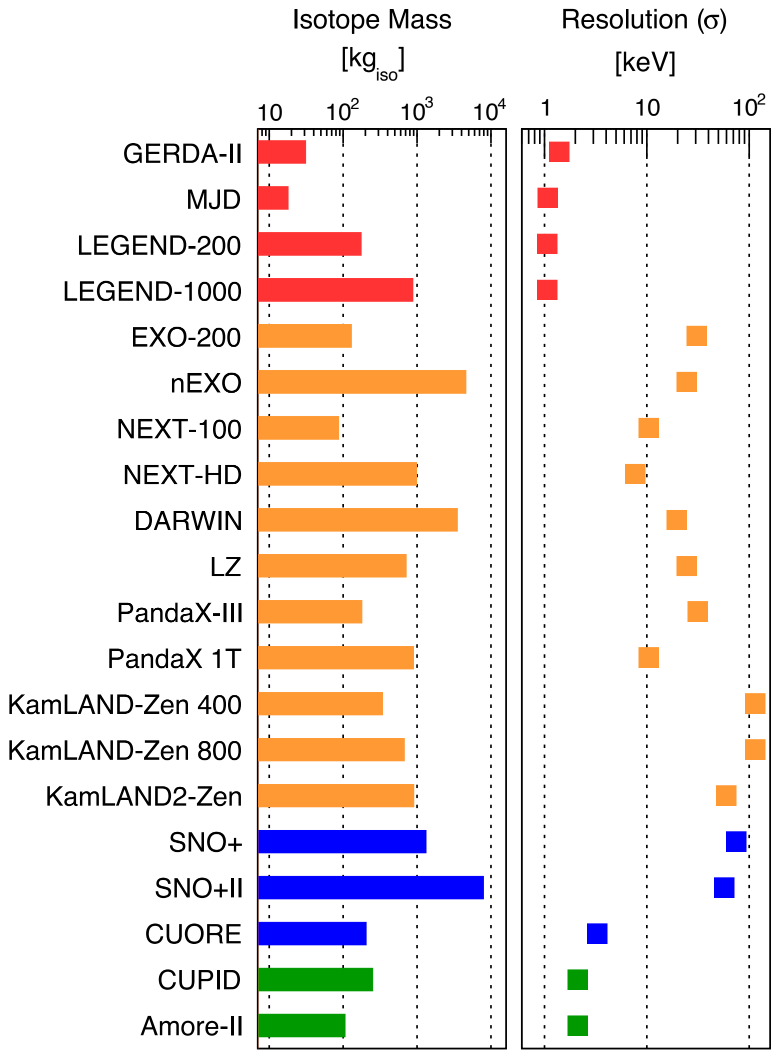


- R2D2
  - Spherical Xenon gas TPC
  - Test ongoing with 8 kg prototype, plans for 50 kg upgrade
  - See JINST **13**, P01009 (2018)





Experimental Outlook



^{76}Ge

^{136}Xe

^{130}Te

^{100}Mo

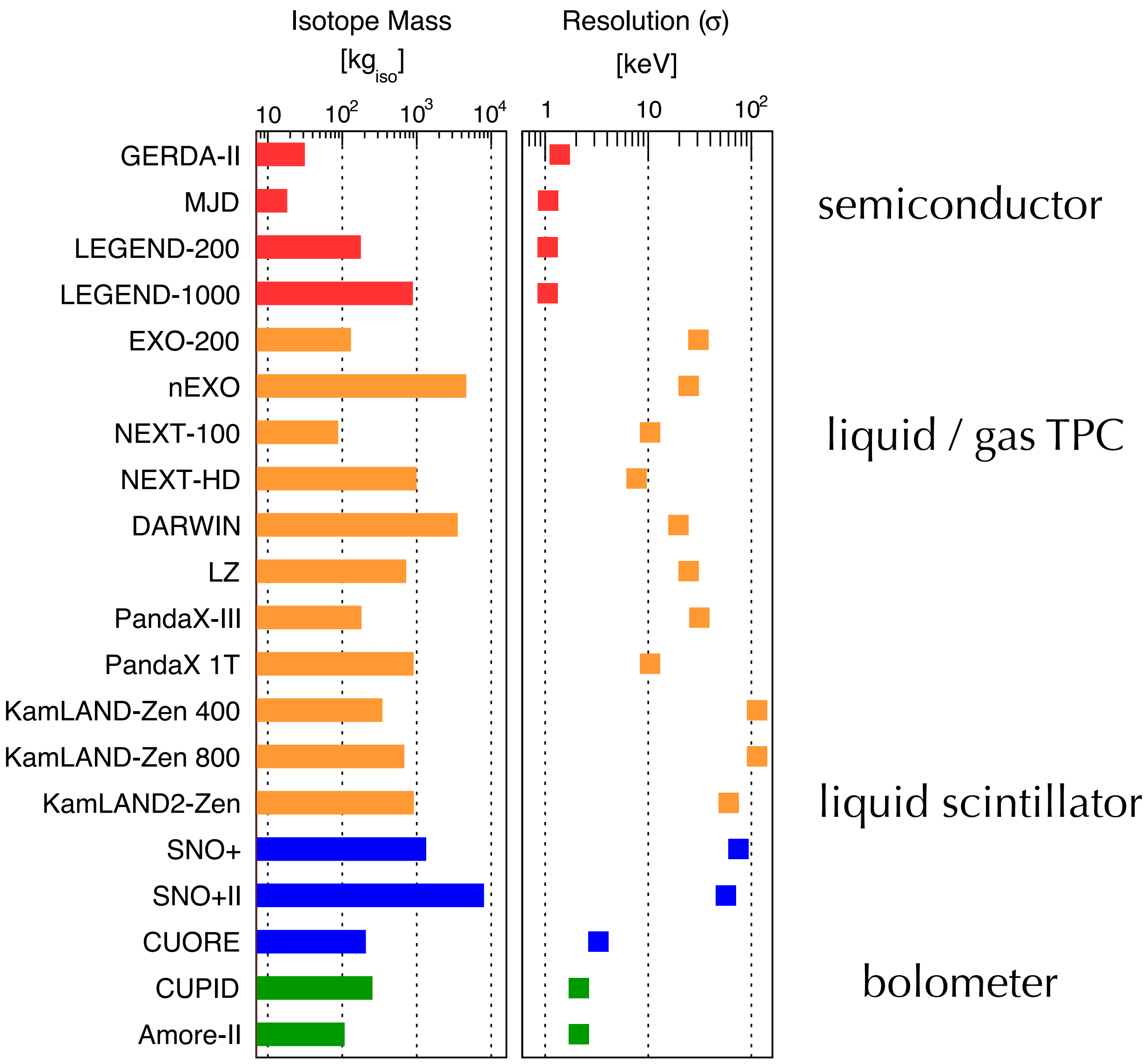
$+ \, ^{48}\mathrm{Ca} + {}^{82}\mathrm{Se} + {}^{96}\mathrm{Zr} \ldots$

$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

$$\mathcal{E} = \epsilon \, m_{iso}^{FV} t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

Agostini, Benato, Detwiler, Menendez, Vissani

Experimental Outlook

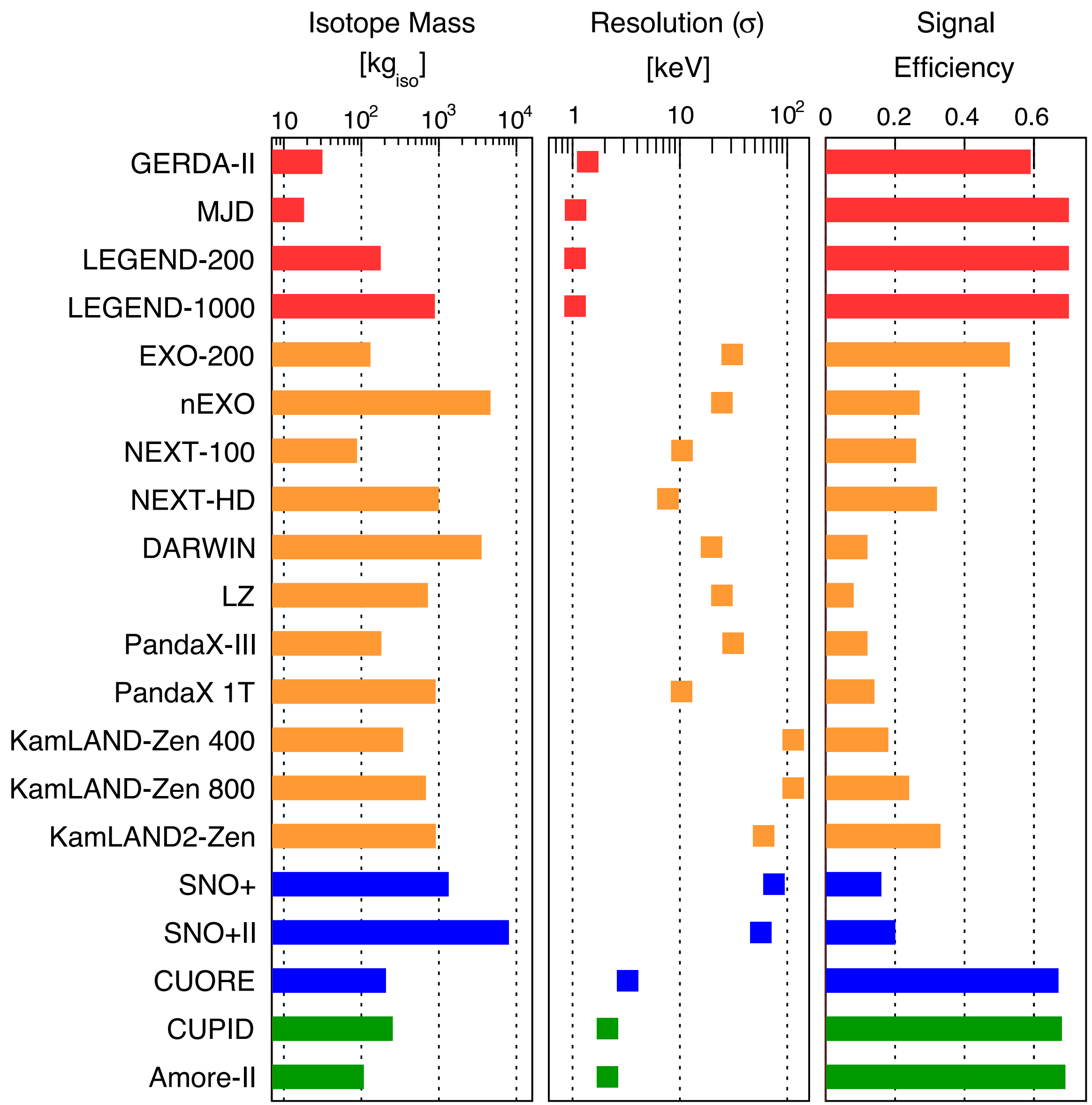


$$T^{3\sigma}_{1/2} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

$$\mathcal{E} = \epsilon\, m^{FV}_{iso}\, t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

Agostini, Benato, Detwiler, Menendez, Vissani

Experimental Outlook



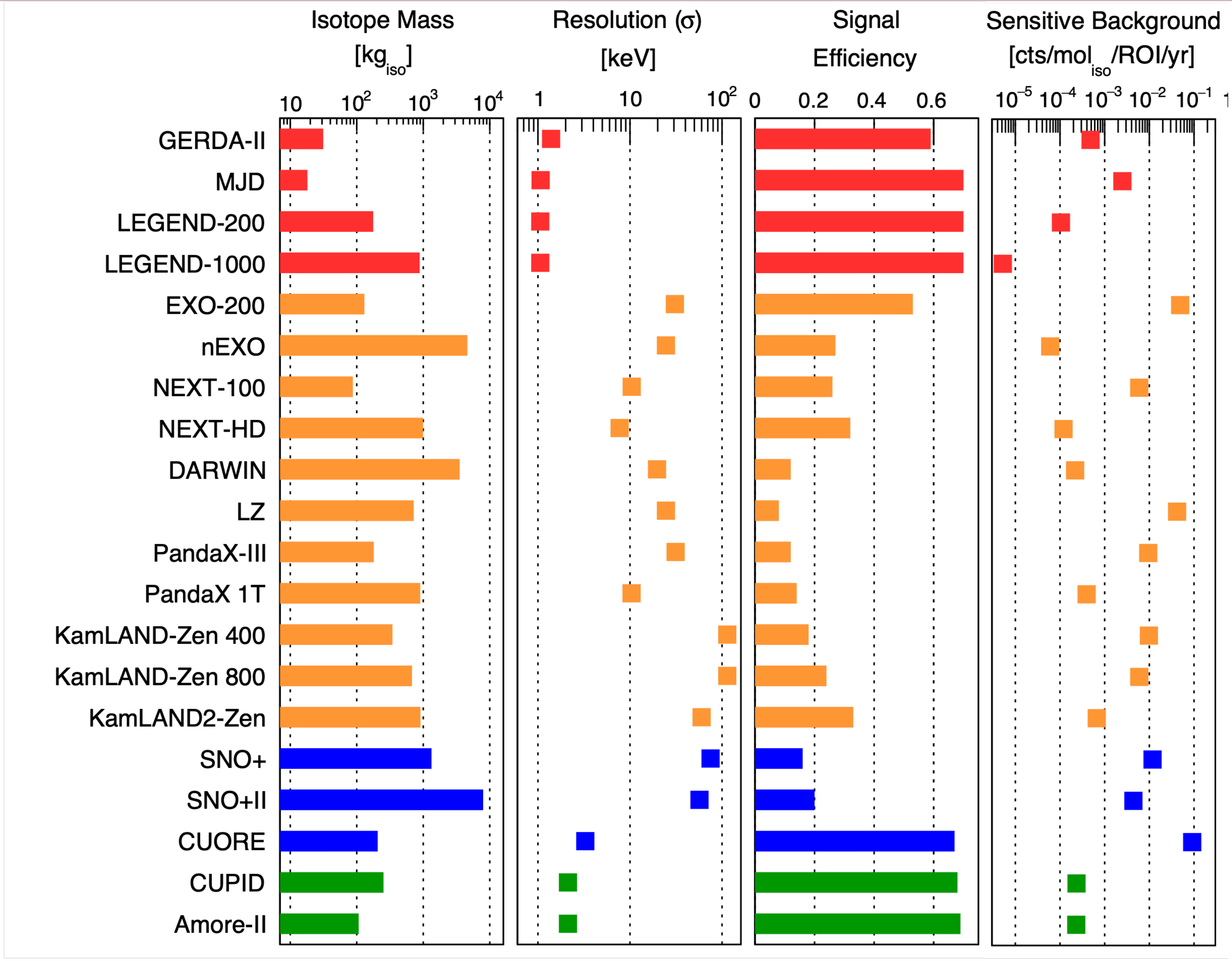
$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{BE})}$$

$$\mathcal{E} = \epsilon \, m_{iso}^{FV} t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

Lower efficiency due primarily to fiducialization

Agostini, Benato, Detwiler, Menendez, Vissani

Experimental Outlook



$$T^{3\sigma}_{1/2} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

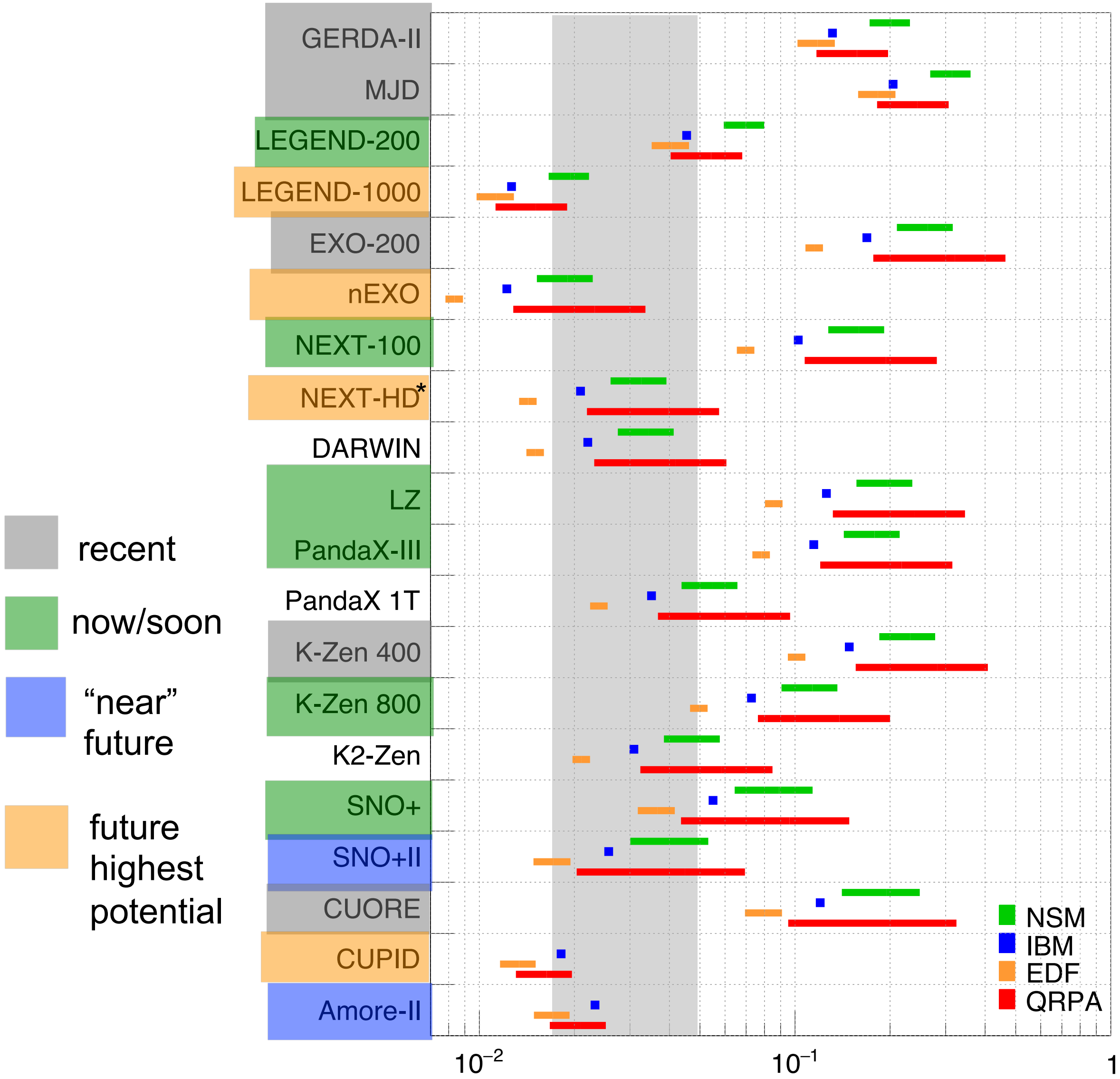
$$\mathcal{E} = \epsilon\, m^{FV}_{iso}\, t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

Next generation experiments: <1 bkg count/year

- Special role of SuperNEMO if $< m_\nu >$ is in 50-100 meV region
  - Underlying mechanism
  - Multi-isotope

Agostini, Benato, Detwiler, Menendez, Vissani

$0\nu\beta\beta$ Discovery Sensitivity: What lies ahead?



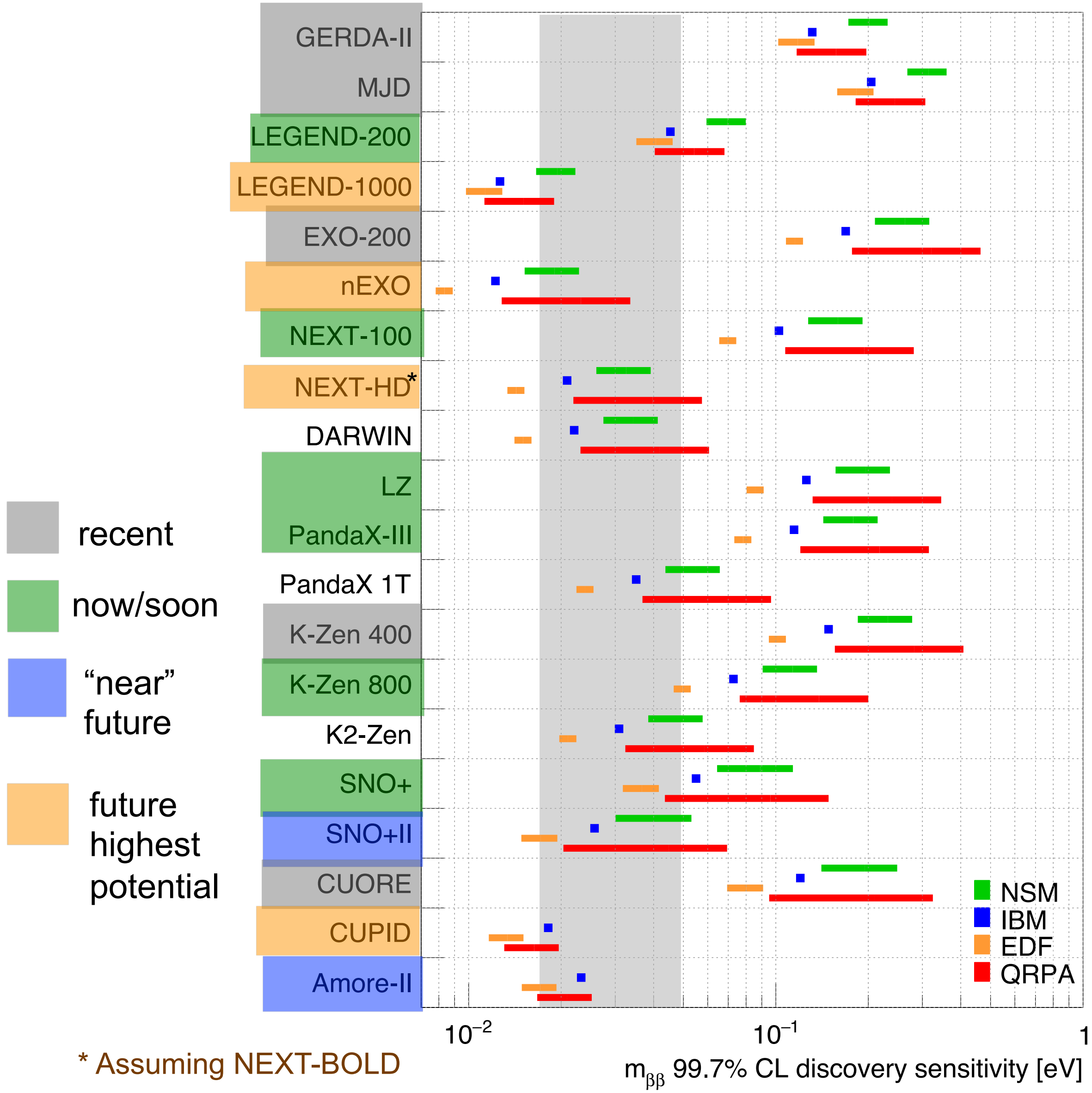
* Assuming NEXT-BOLD

Agostini, Benato, Detwiler, Menendez, Vissani

Concluding Remarks

- Upcoming generation of 0νββ experiments will fully explore IO region
  - Testing new physics at 10-100 TeV scale!
- Focus on discovery (which could come at any time!)
- Must be open-minded about mechanism behind LNV (more than "just" neutrino physics).
- A multi-isotope program exploiting different technologies is necessary
  - Nuclear model uncertainties
  - Signal is just a few events
- R&D underway to reach $m_{\beta\beta} \sim O(1\text{ meV})$
- Difficult balance between diversity and focus of future programme
- The case for 0νββ is clear (to us) but must be continuously made (to everyone else).

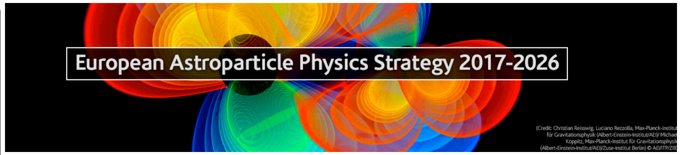
$0\nu\beta\beta$ Discovery Sensitivity: What lies ahead?

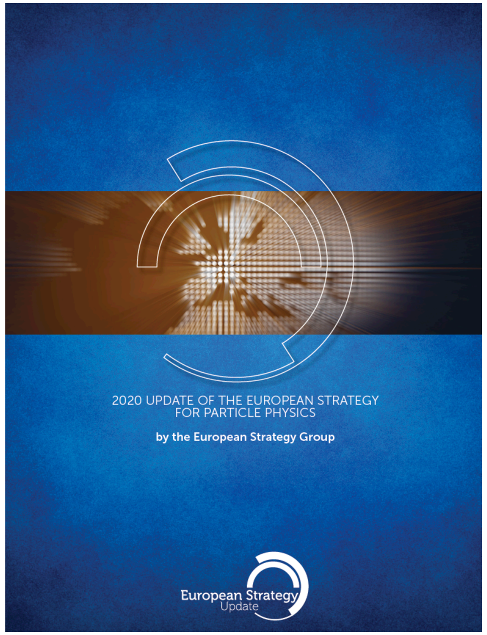


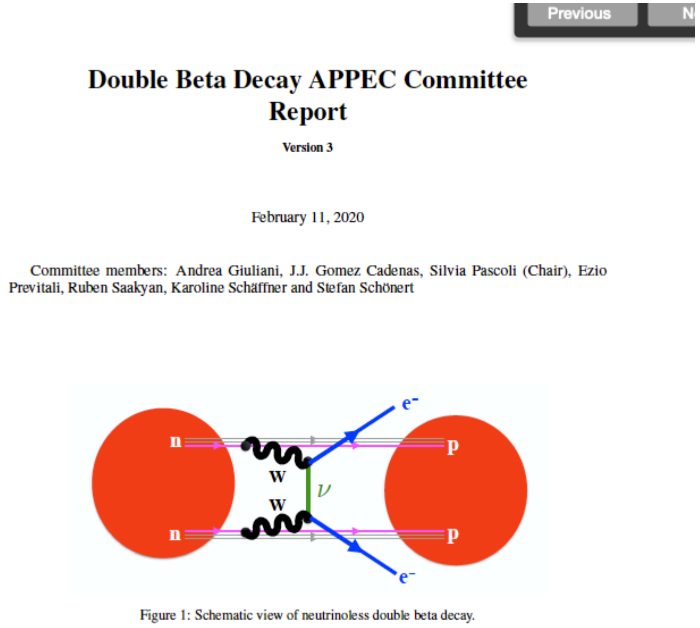
* Assuming NEXT-BOLD

Agostini, Benato, Detwiler, Menendez, Vissani

Crucial time for defining future 0νββ strategy






Double Beta Decay APPEC Committee Report

Version 3

February 11, 2020

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

Figure 1: Schematic view of neutrinoless double beta decay.