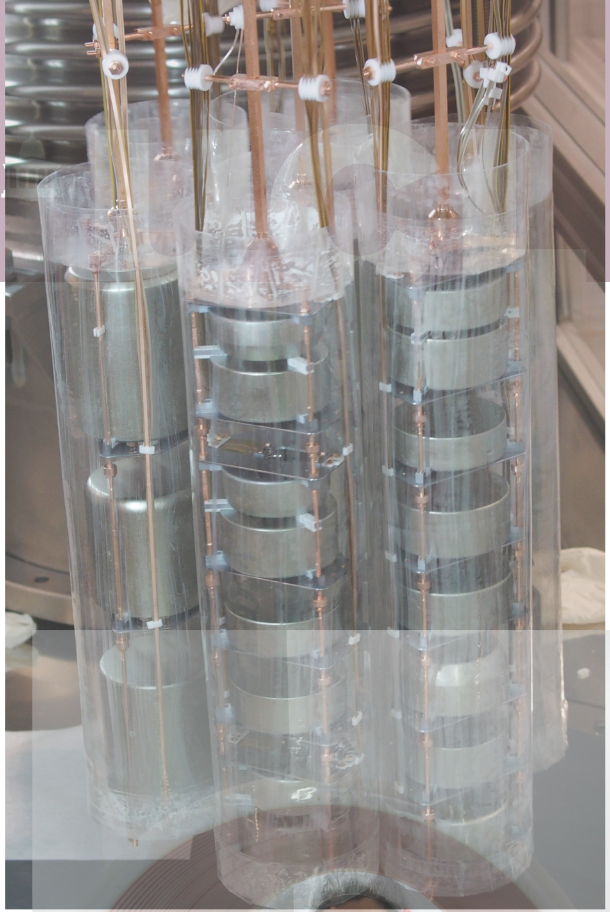
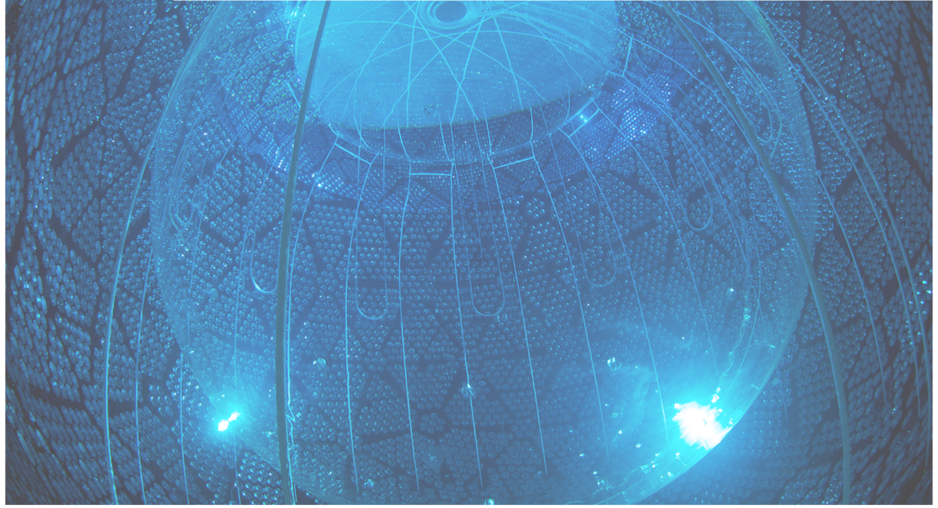


Double Beta Decay Experiments
(Challenges and Opportunities)



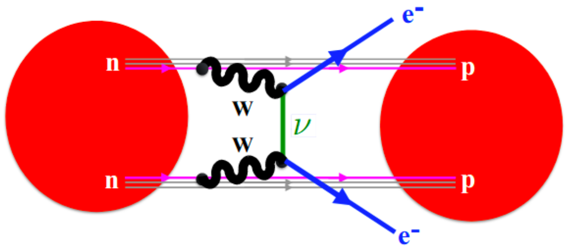
Ruben Saakyan
University College London

ββ-France II Workshop @ IJC laboratory (Orsay)

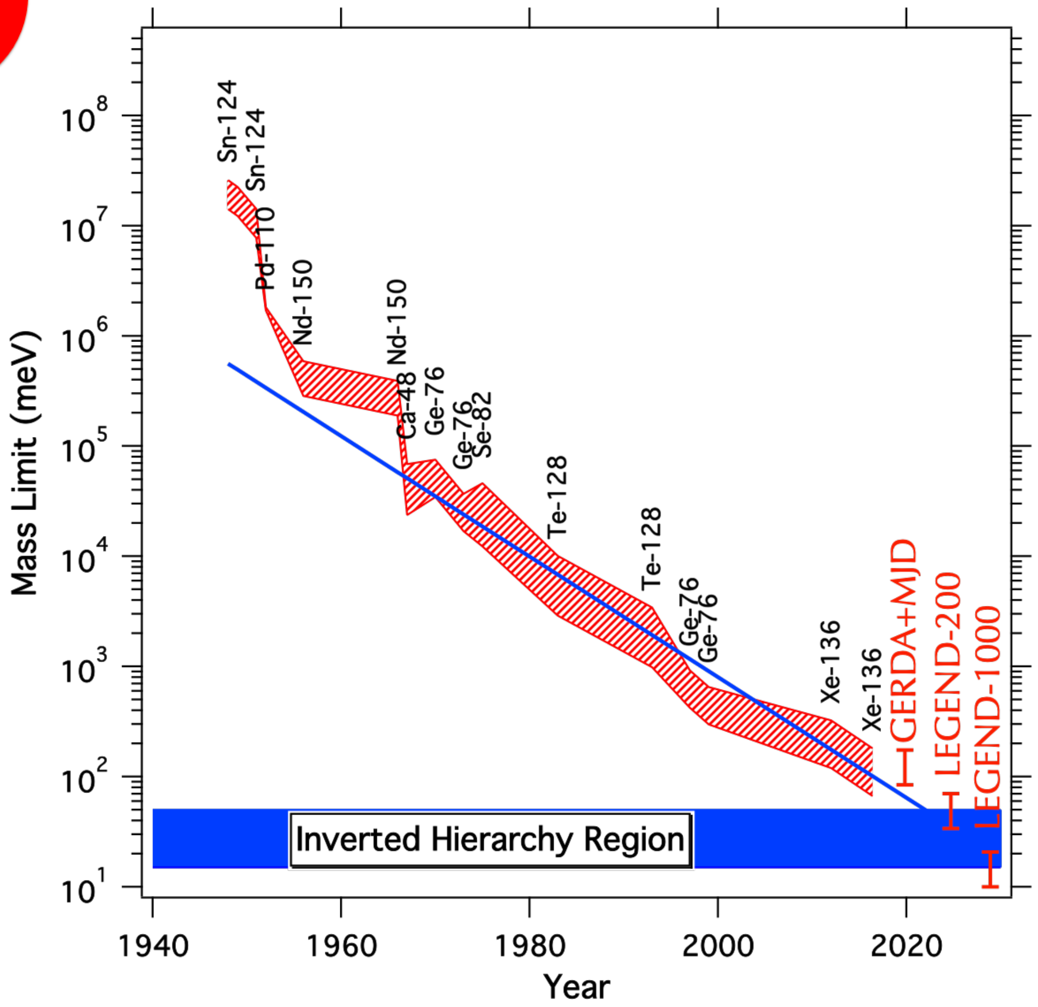
Presented Remotely

16-Oct-2020

Outline

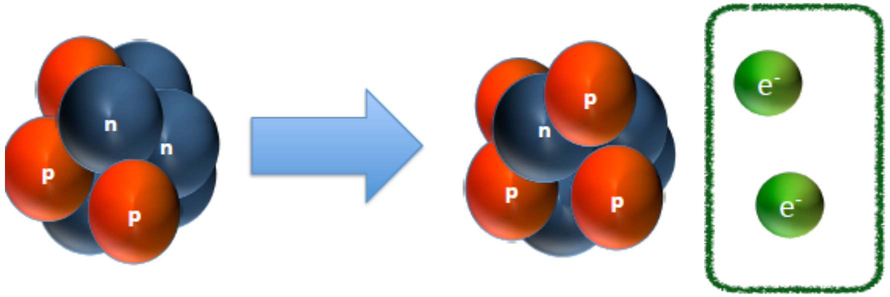


- The Big Picture: Motivation and Context
- Current Constraints and Future Goals
- Challenges and Experimental Approaches
- Summary and Outlook



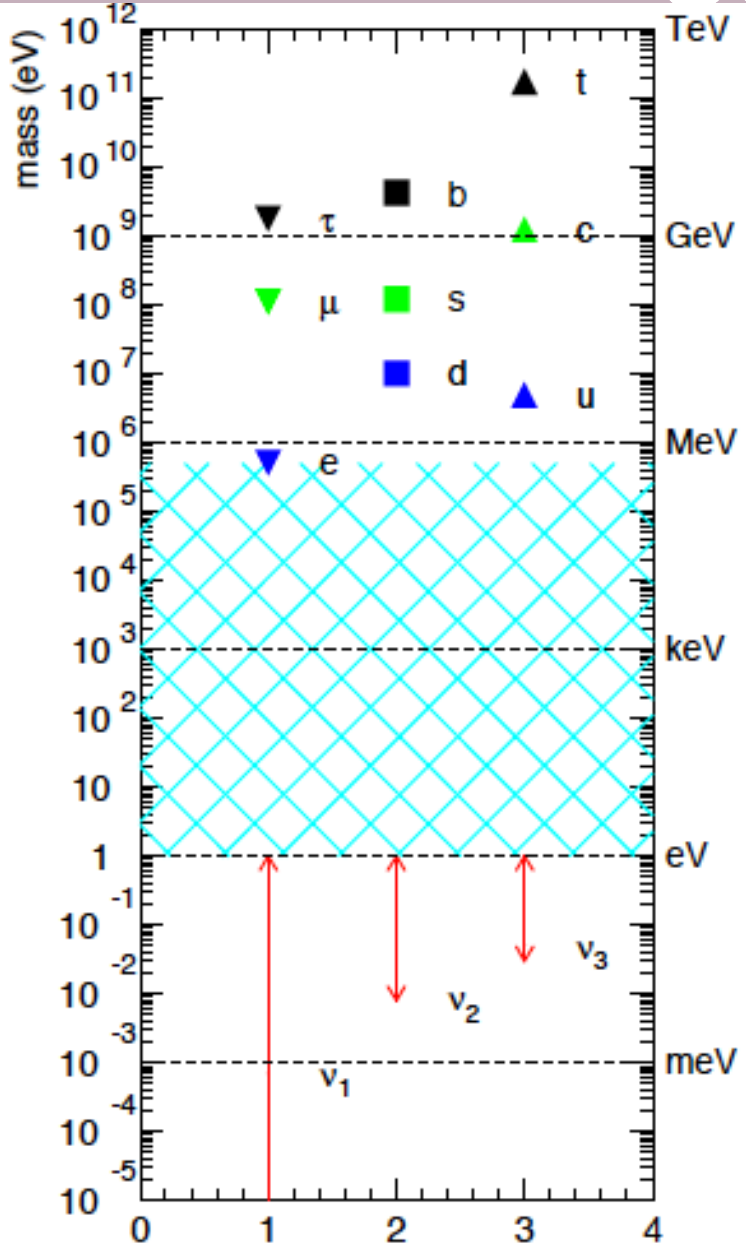
The Big Picture

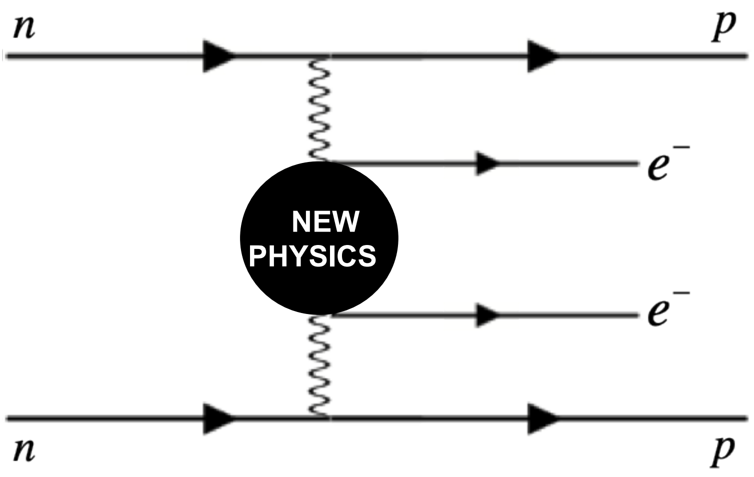
Proton Decay:
“Disappearance” of nucleons



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)
- 0νββ is the most sensitive way to address **L**epton **N**umber **V**iolation ***regardless*** of underlying mechanism





NME:
~~Nasty~~ Nuclear Matrix Element

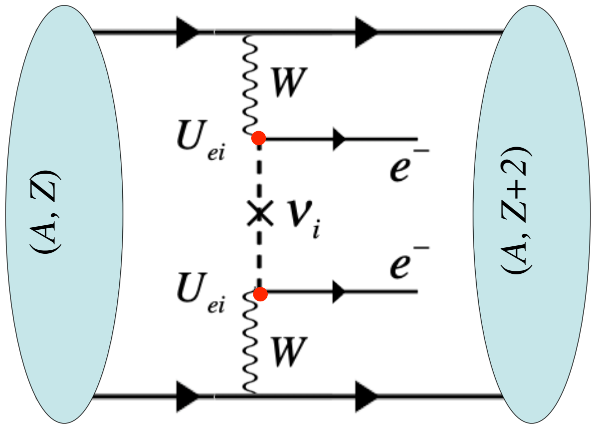
phase space

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

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*

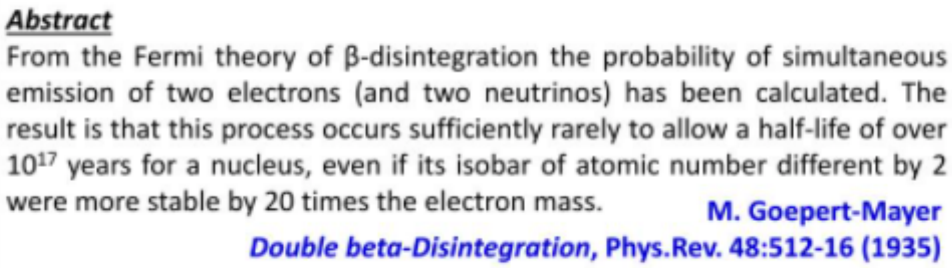
Most discussed: Light Majorana Neutrino exchange

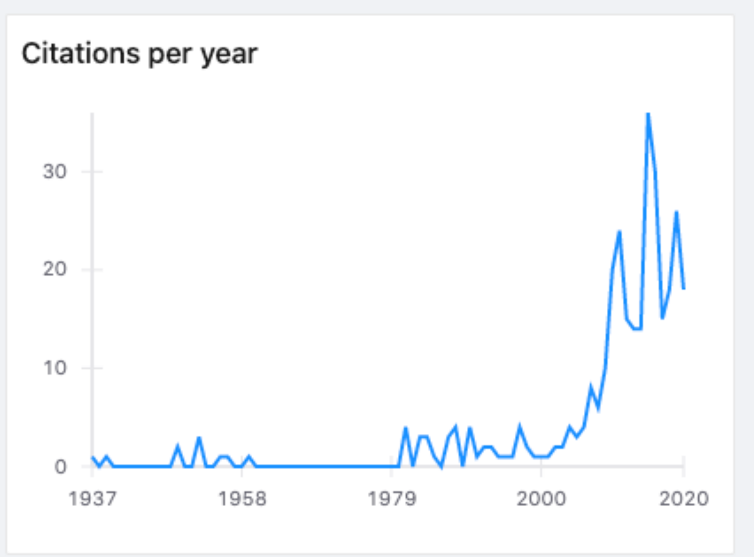


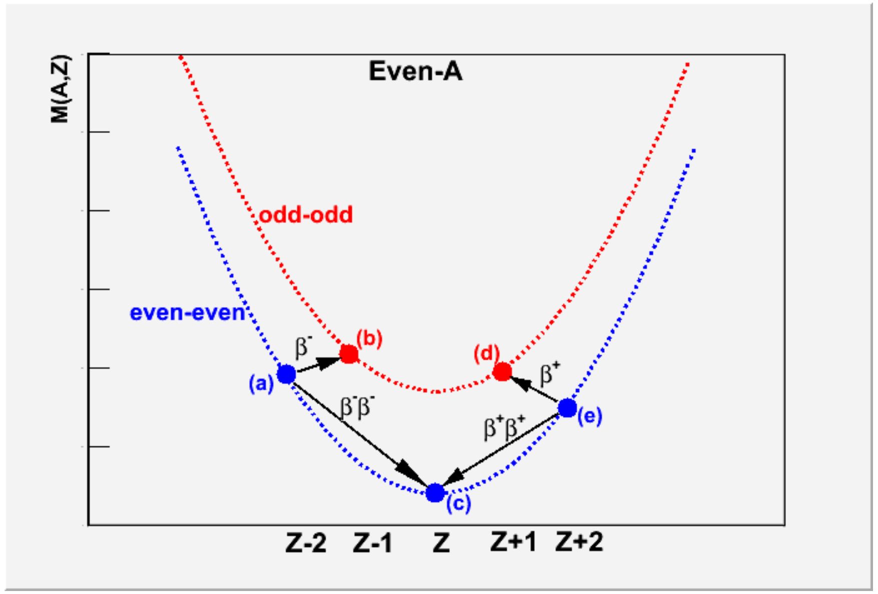
$$\langle m_\nu \rangle = \left|\sum U_{ei}^2 m_i\right| = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}\right|$$

Observation of LNV would have profound implications beyond neutrino physics

Double Beta Decay

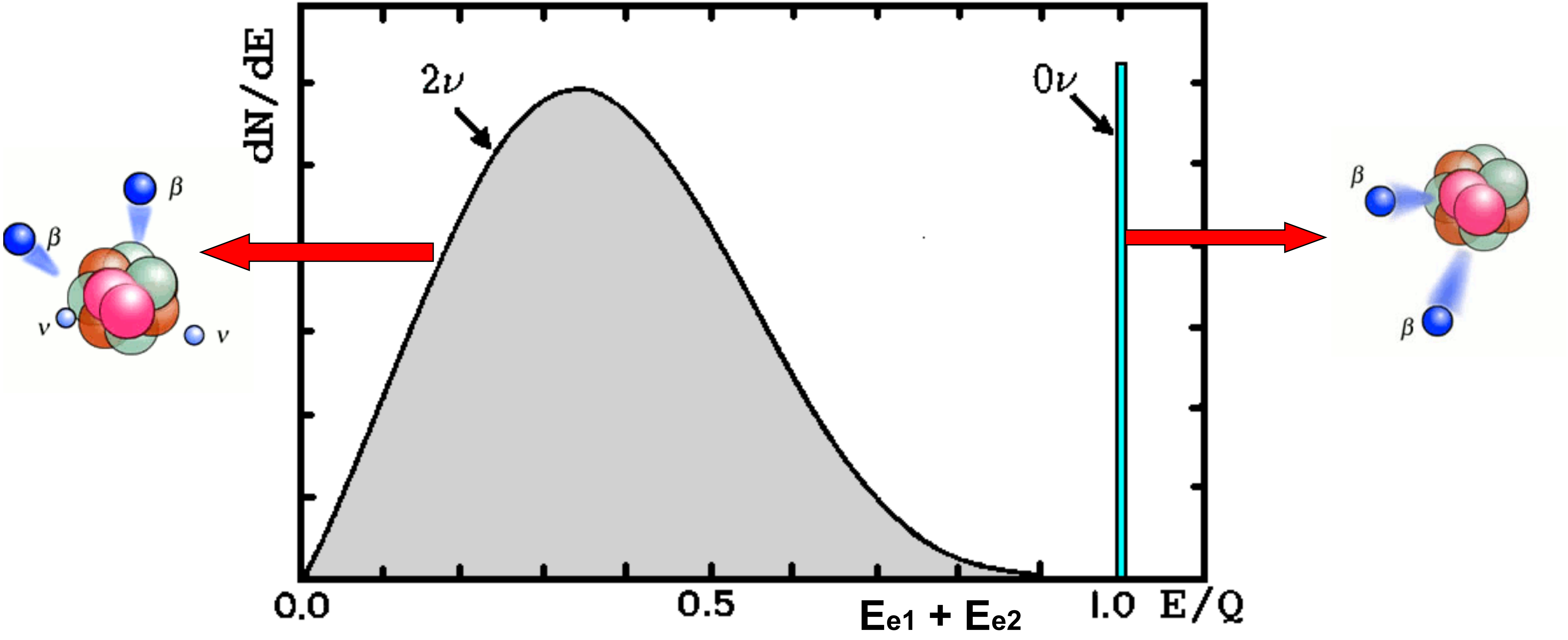






Isotope	Nat. Abundance (%)	$Q_{\beta\beta}$ (MeV)
Ca48	0.187	4.274
Ge76	7.8	2.039
Se82	9.2	2.996
Zr96	2.8	3.348
Mo100	9.6	3.035
Cd116	7.6	2.809
Te130	34.5	2.530
Xe136	8.9	2.462
Nd150	5.6	3.367

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

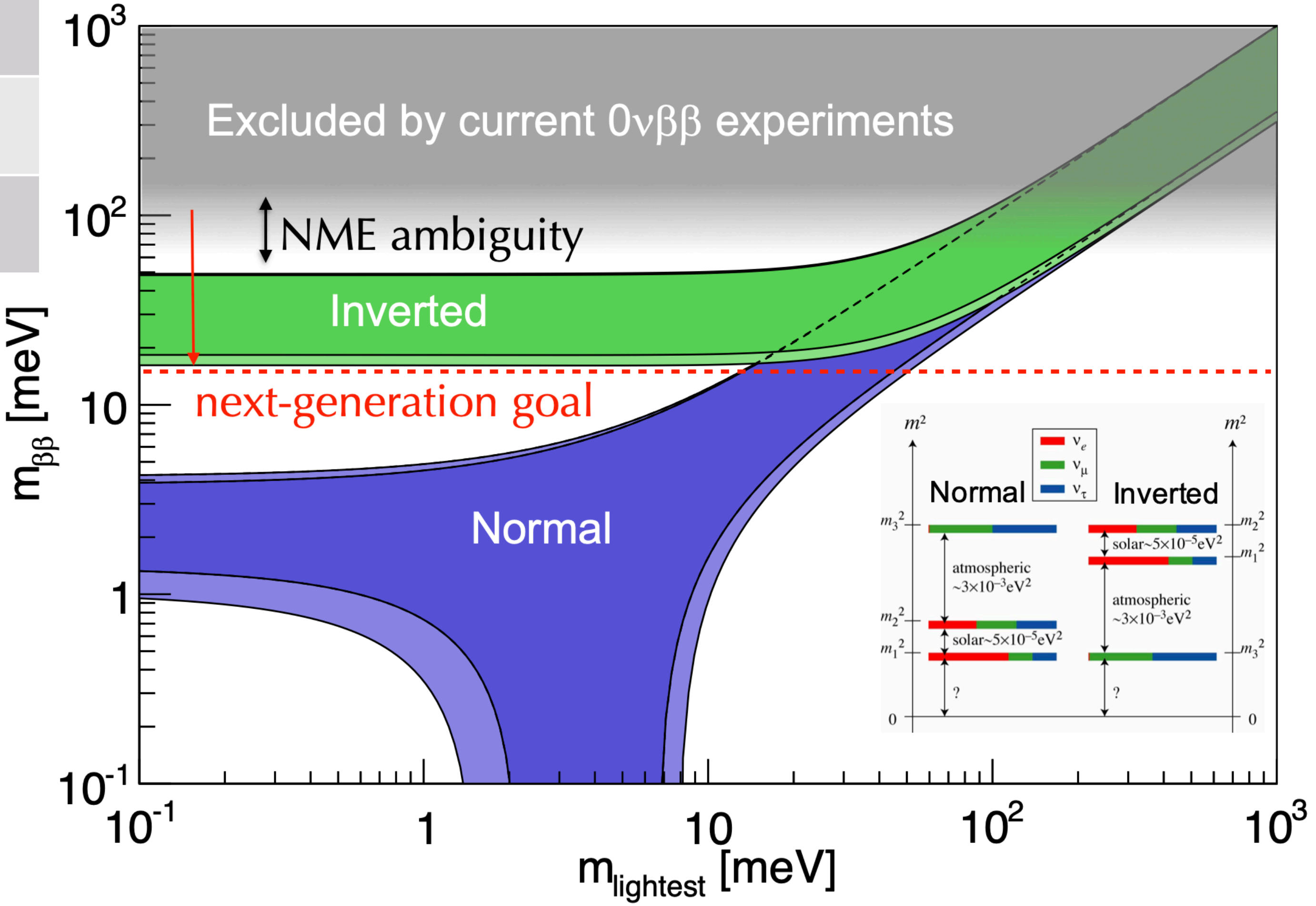


Also: individual electron energies, Ee1, Ee2, and angle θ between them

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	$> 1.8 \times 10^{26}$	< 0.08 – 0.17
^{130}Te, CUORE	$> 3.2 \times 10^{25}$	< 0.08 – 0.35

* 90% CL

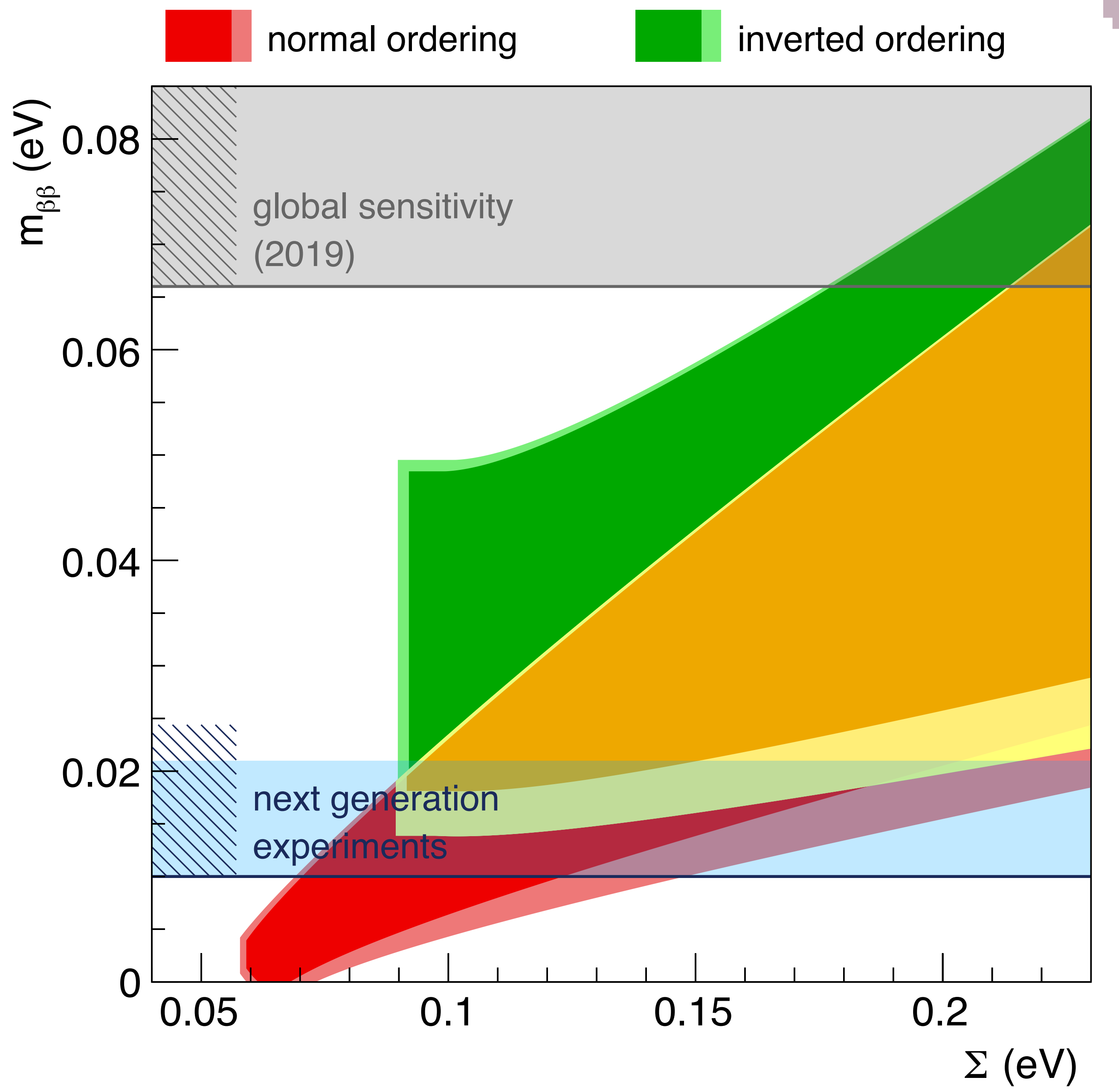


Future Goals:

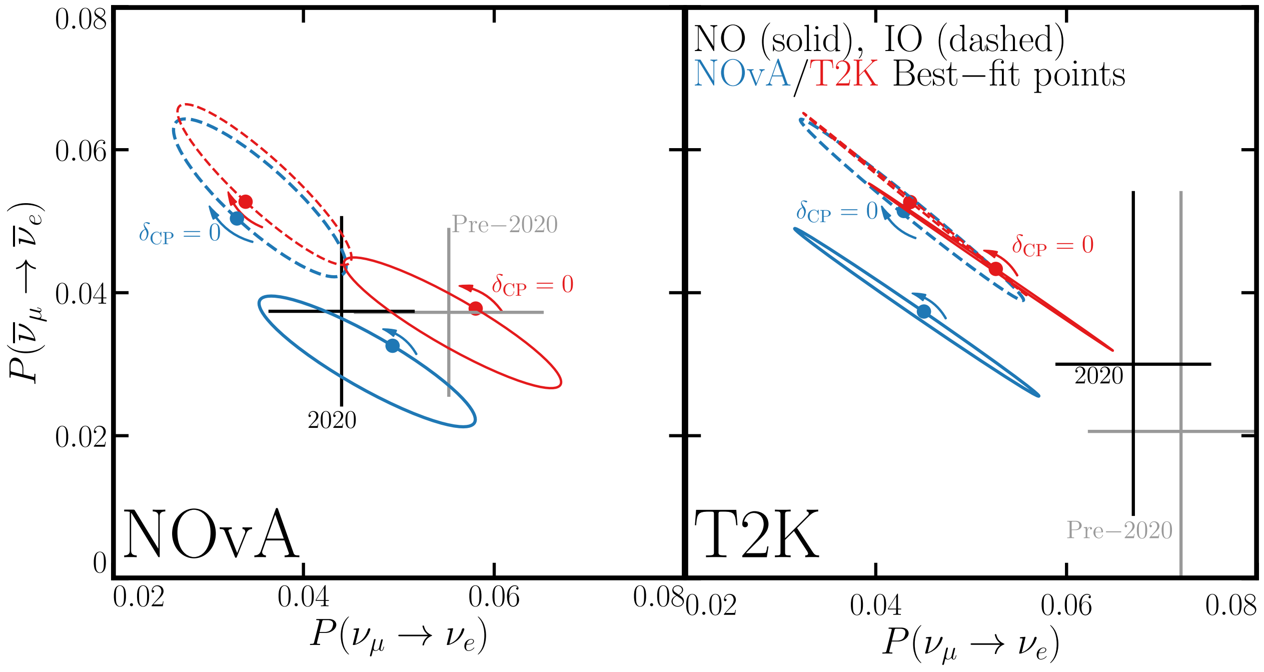
- ×100 improvement in $T_{1/2}$
- Cover IO with 3σ discovery potential
- Up to 50% of NO

Beware of log scales!

Next generation experiments will have a significant chance of discovering 0vbb regardless of mass ordering!



Back to (Mass-)Square(d) One:



Experiment(s)	$\Delta\chi^2_{(NO,IO)}$	$\Delta\chi^2_{CPC}$
T2K	+1.2	2.9
NOvA	+0.13	0.49
SK18/SK20	+3.4/+3.2	0.35/0.81
T2K + NOvA	−1.8	2.2
T2K + SK18	+5.7	3.0
NOvA + SK18	+3.6	0.68
T2K+NOvA+SK18	+2.2	0.35

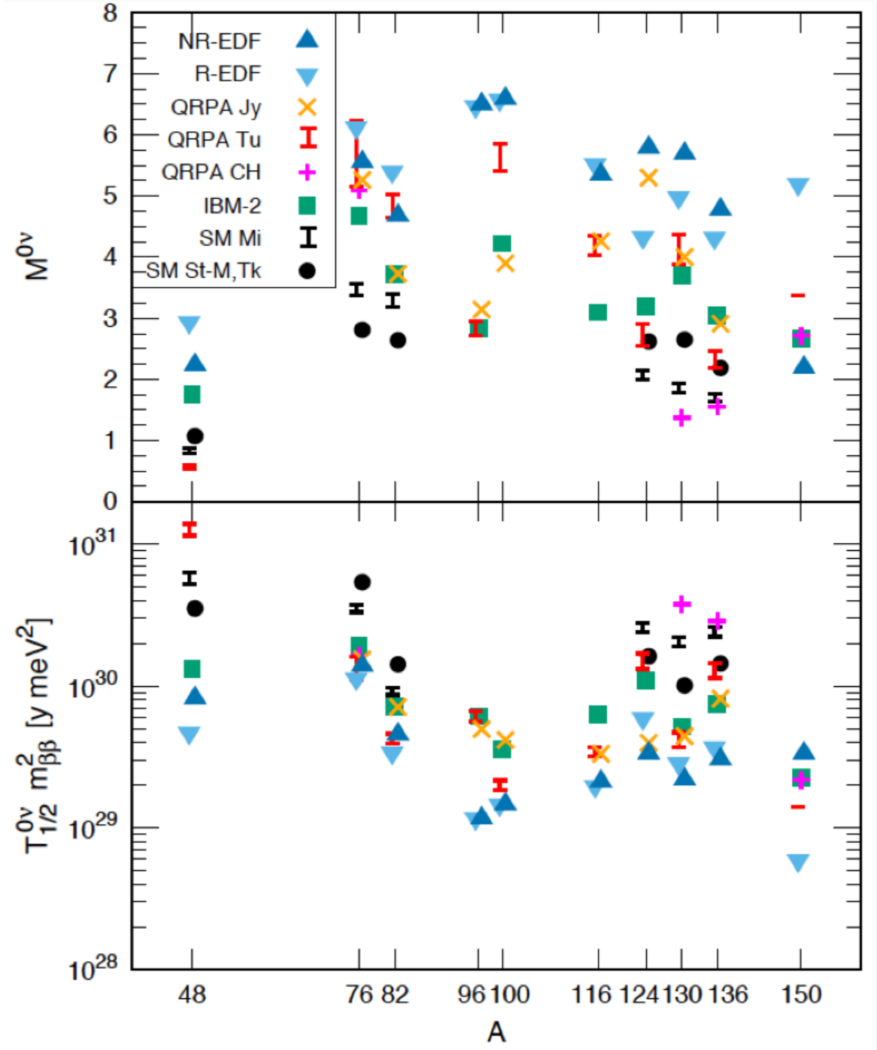
Kelly et al, arXiv:2007.08526v1

"…. We show that, despite previous results giving a strong preference for ***the normal ordering***, with the newest data from T2K and NOvA, this ***preference has all but vanished***. Additionally, we highlight the ***importance*** of this result for non-oscillation probes of neutrinos, including ***neutrinoless double beta decay*** and cosmology…."

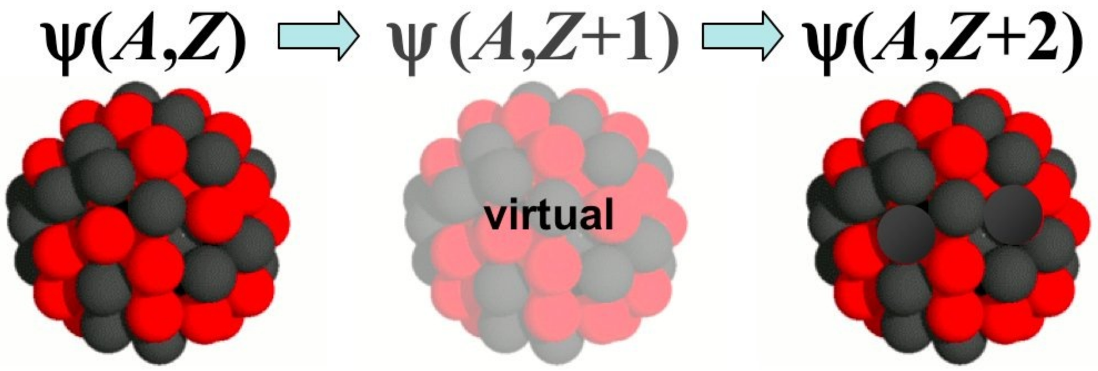
Challenges

- 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.



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



- 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

See J. Menendez talk for (much) more info

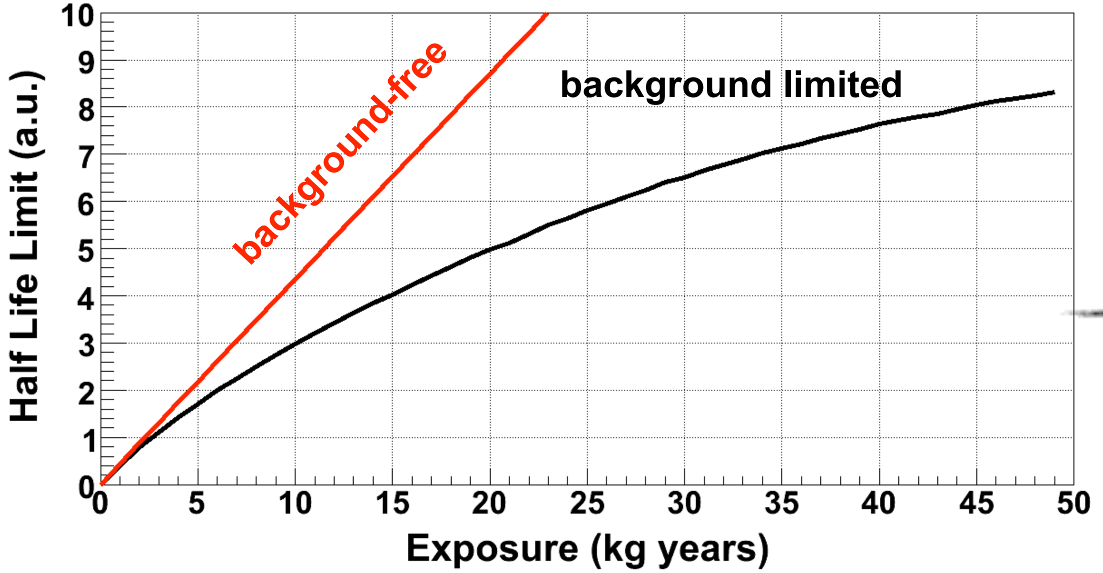
Experimental Challenges

maximise efficiency & isotope abundance

maximise exposure = mass (isotope) × time

$$T_{1/2}^{0\nu}(90\%\ \mathrm{C.L.}) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

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

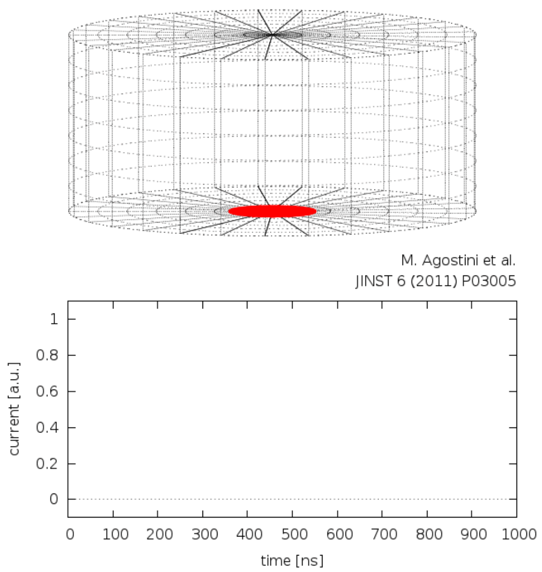
Experimental Approaches

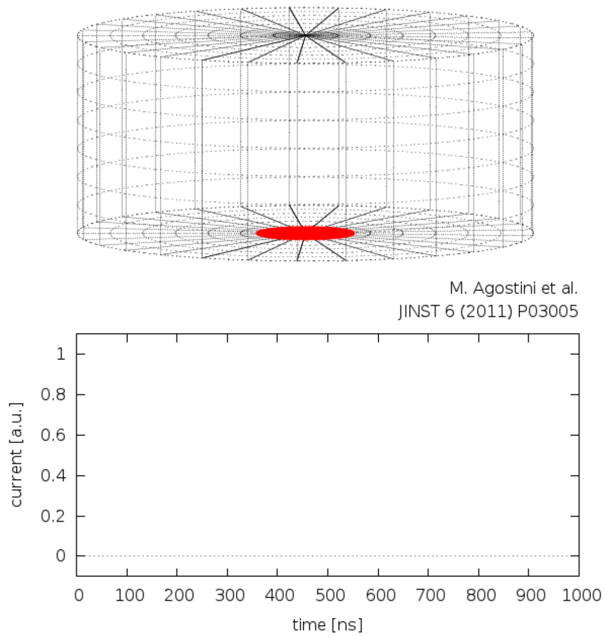
Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
Majorana Demonstrator	^{76}Ge	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

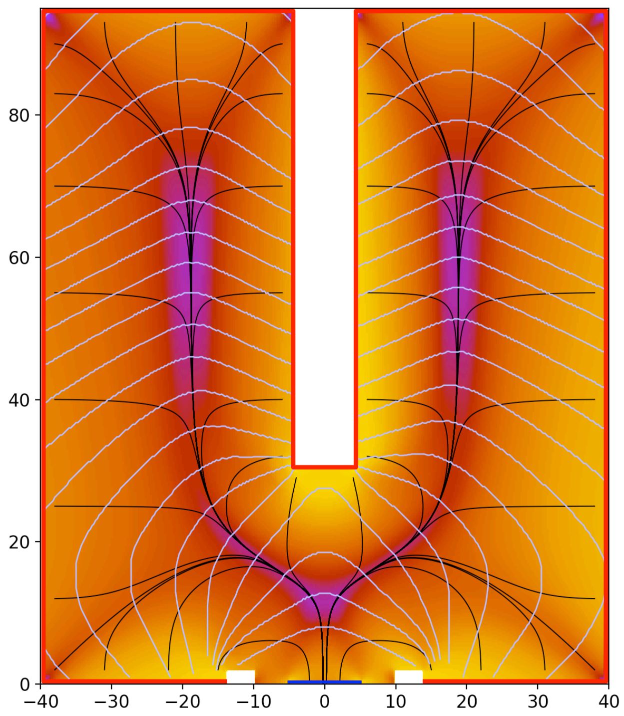
- Reach experimental landscape
- Multiple approaches are necessary
  - No isotope a clear winner, NME uncertainties
  - Discovery will constitute a handful of events (at best): need independent verification
  - Discovery with different isotopes may shed light on underlying mechanism

Courtesy of J. Detwiler and J. Wilkerson

Semiconductors: HPGe





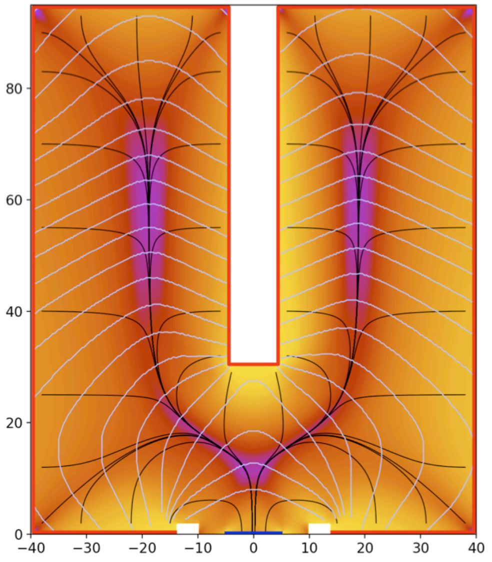


Inverted **C**oaxial **P**oint **C**ontact

- Source = Detector: HP^{76}Ge
- Superb energy resolution ~0.1% at Q_{bb} = 2039 keV
- "Solid state TPC" capabilities: particle ID and background rejection
- Feasibility to reach zero BG regime

{ GERDA, Majorana } → LEGEND-200 → LEGEND-1000

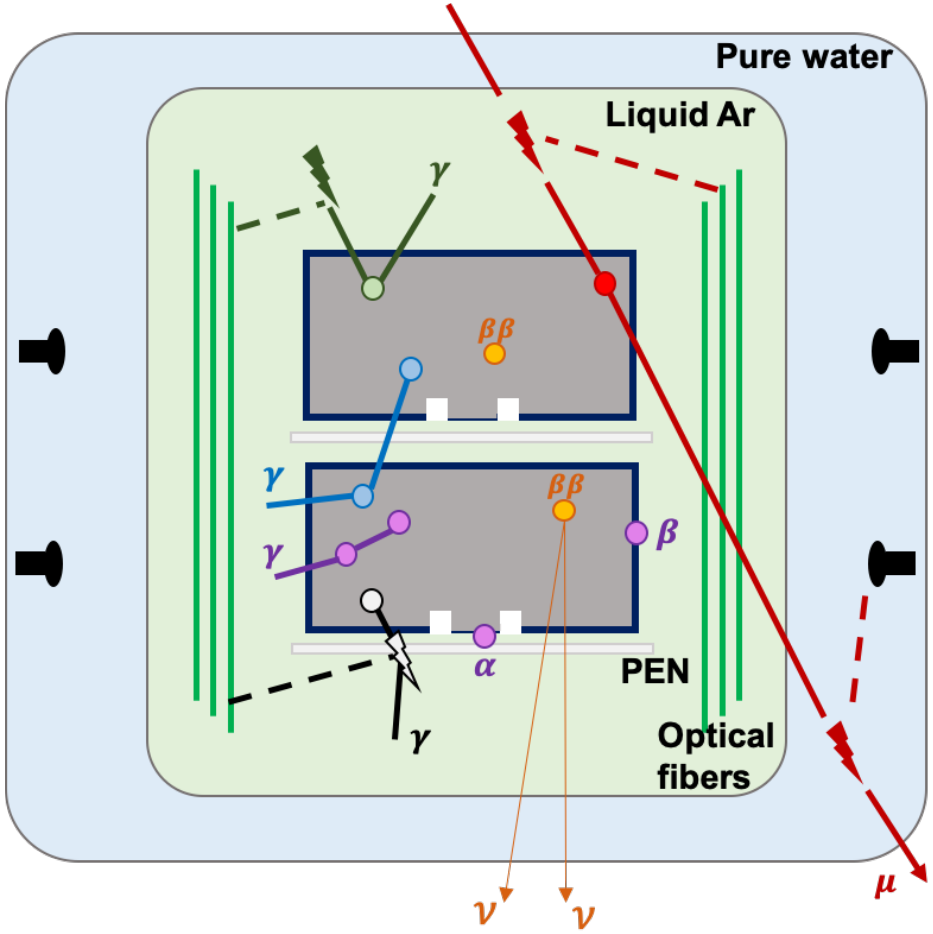
LEGEND Concept



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

HPGe point-contact detectors:

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



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

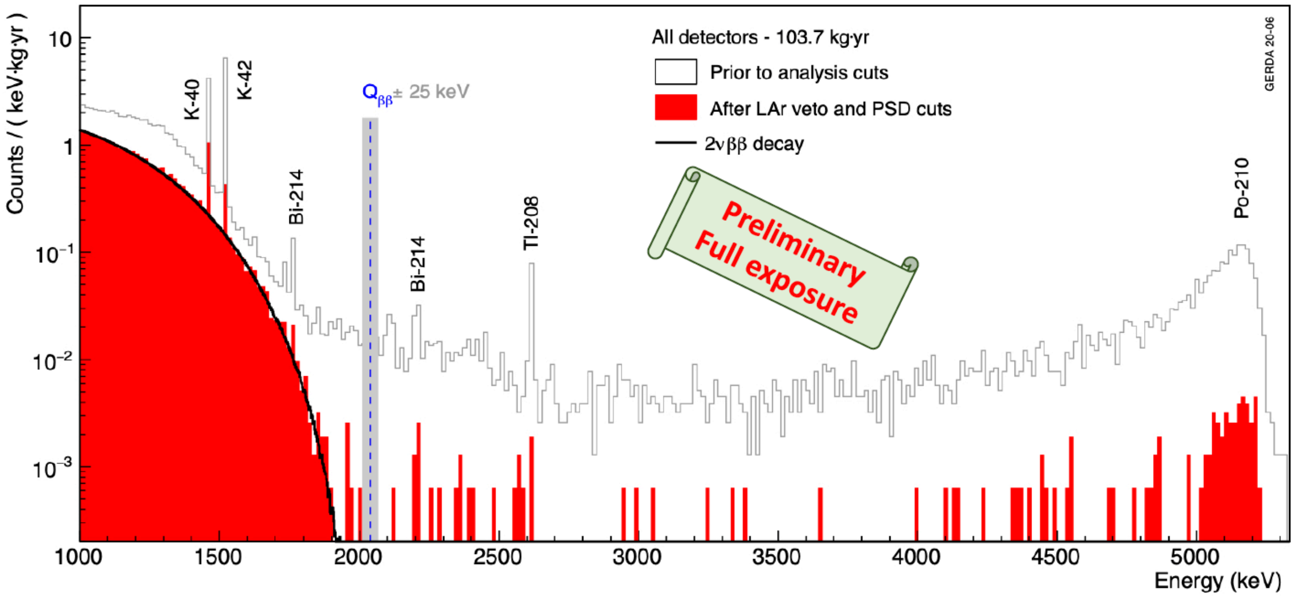
Ge detector anti-coincidence

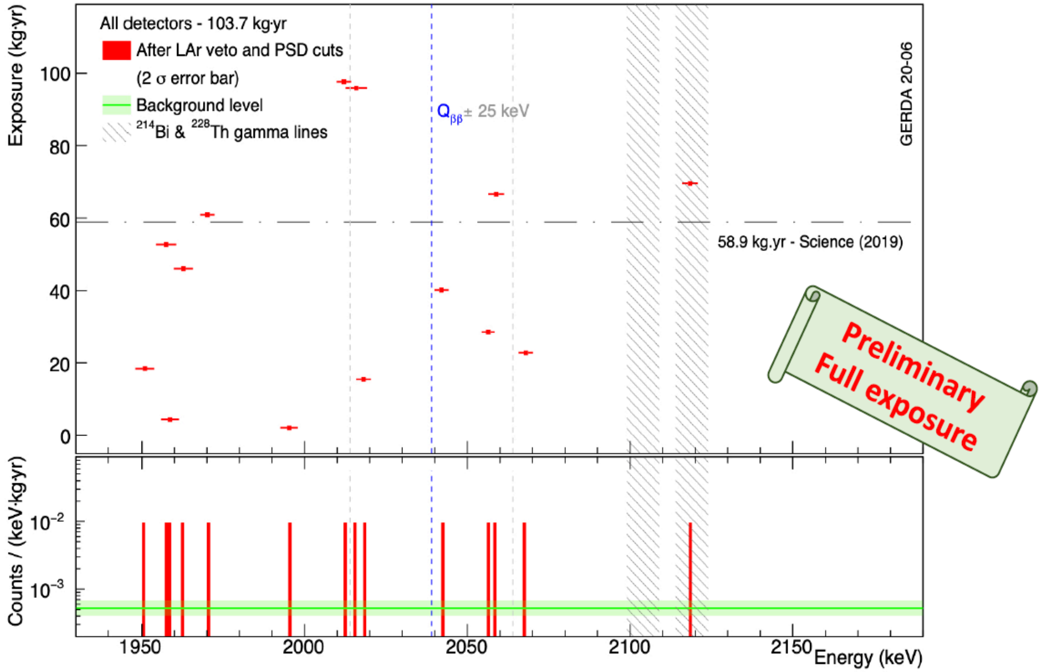
Scintillating PEN plate holder (under test)

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

Muon veto based on Cherenkov light and/or plastic scintillator

GERDA Result at Neutrino2020 (talk by Y. Kermaidic)





Frequentist analysis*:

- Median sensitivity for limit setting:
  $\mathbf{1.8 \times 10^{26}\ yr\ (90\%\ C.L.)}$
  - Best fit → no signal
  - 90% C. L. lower limit:
    $\mathbf{T^{0\nu}_{1/2} > 1.8 \times 10^{26}\ yr}$

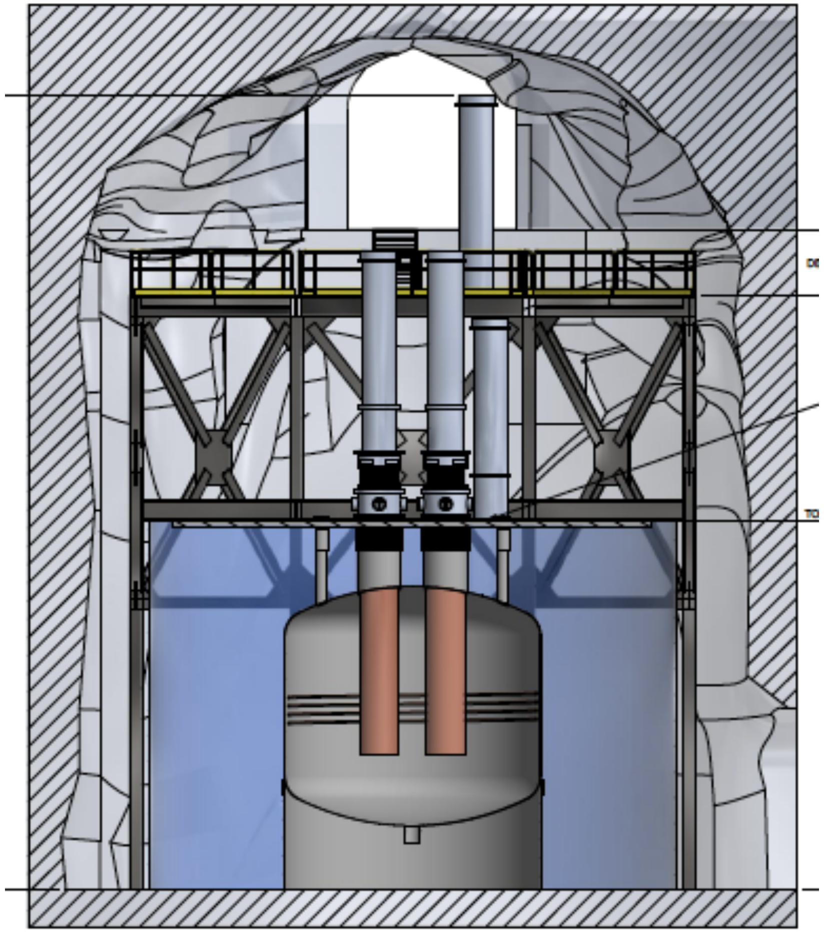
Bayesian analysis with uniform prior*:

- Median sensitivity for limit setting:
  $1.4 \times 10^{26}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$
- $T^{0\nu}_{1/2} > 1.4 \times 10^{26}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$

Longest $T_{1/2}(0\nu\beta\beta)$ limit to date despite only 40kg of isotope!

LEGEND-200:

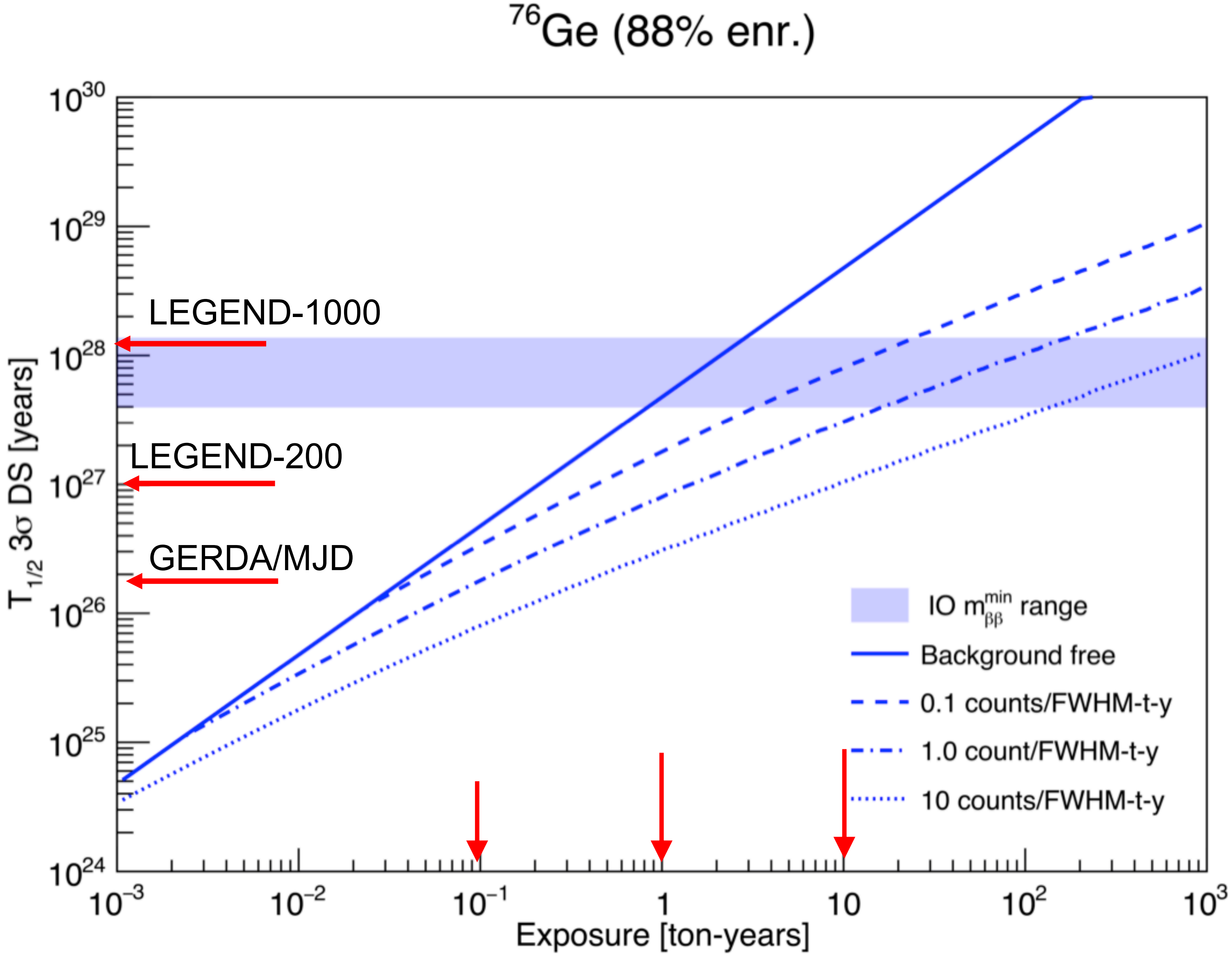
- 200 kg in upgrade of existing infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal
  <0.6 cts/(FWHM t yr)
  <2x10^{-4} cts/(keV kg yr)
- Data start ~2021



LEGEND-1000:

- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr),<1x10^{-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.

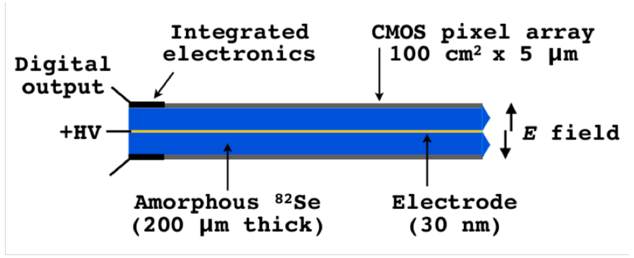
3-σ *discovery* level to cover inverted ordering, given matrix element uncertainty.

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

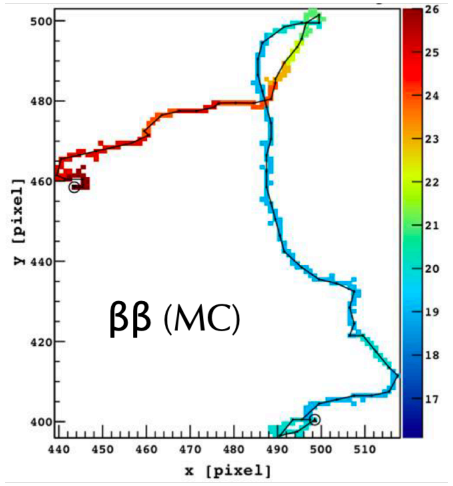
Challenges: Cost, scaling to 10 meV and below

Semiconductors: CMOS imaging detectors

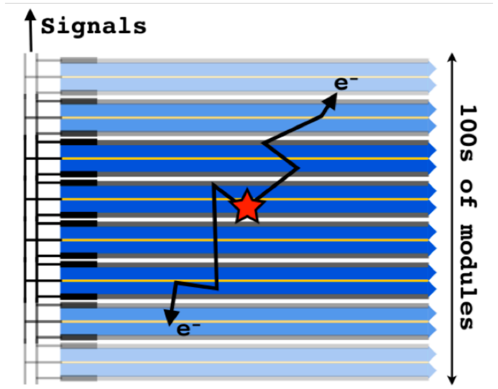
A. Chavarria et al, J. Inst. **12**, P03022 (2017

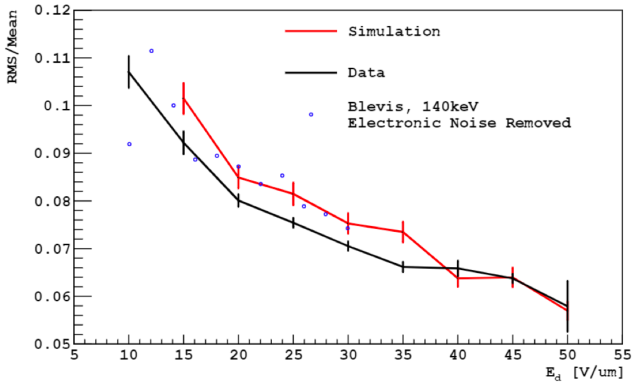


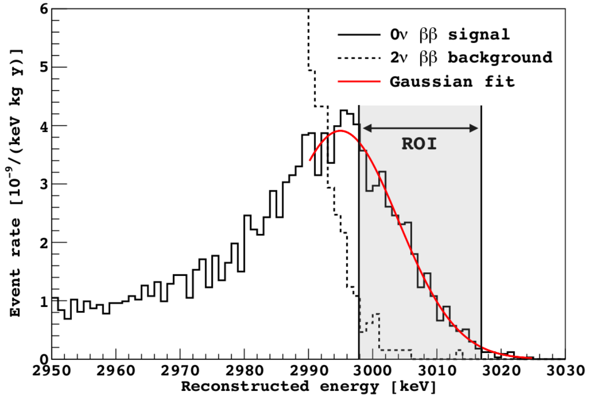
MC: x1000 β rejection with 50% ββ acceptance



- 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



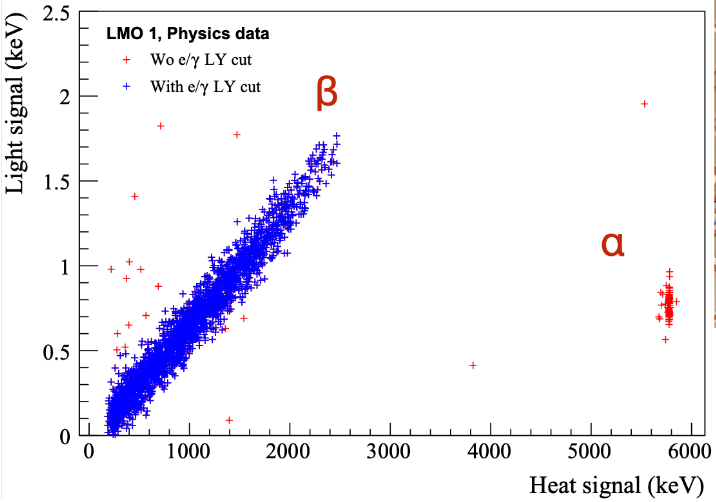


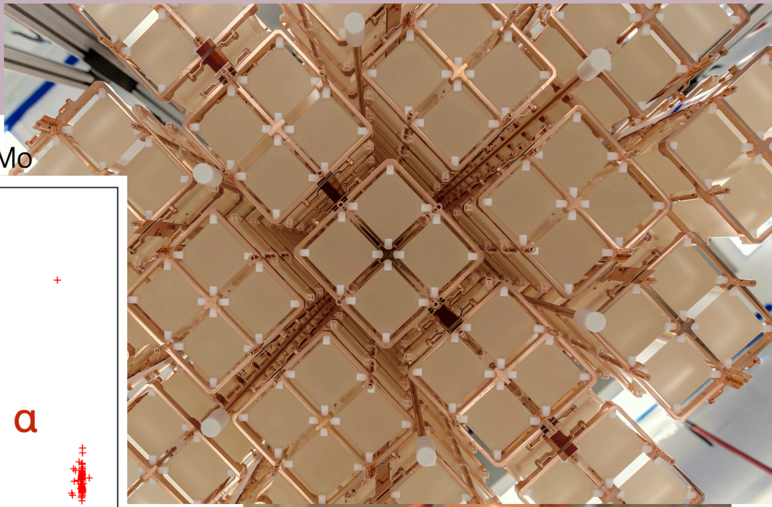


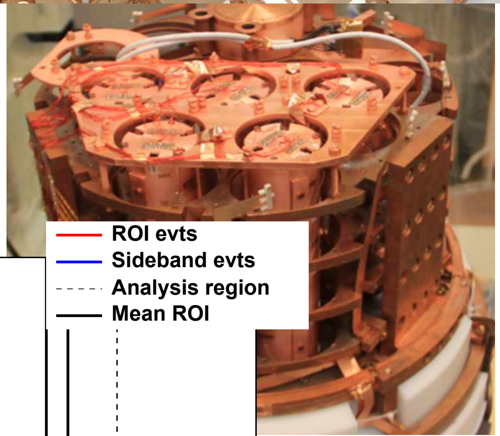
Bolometers: CUORE → CUPID

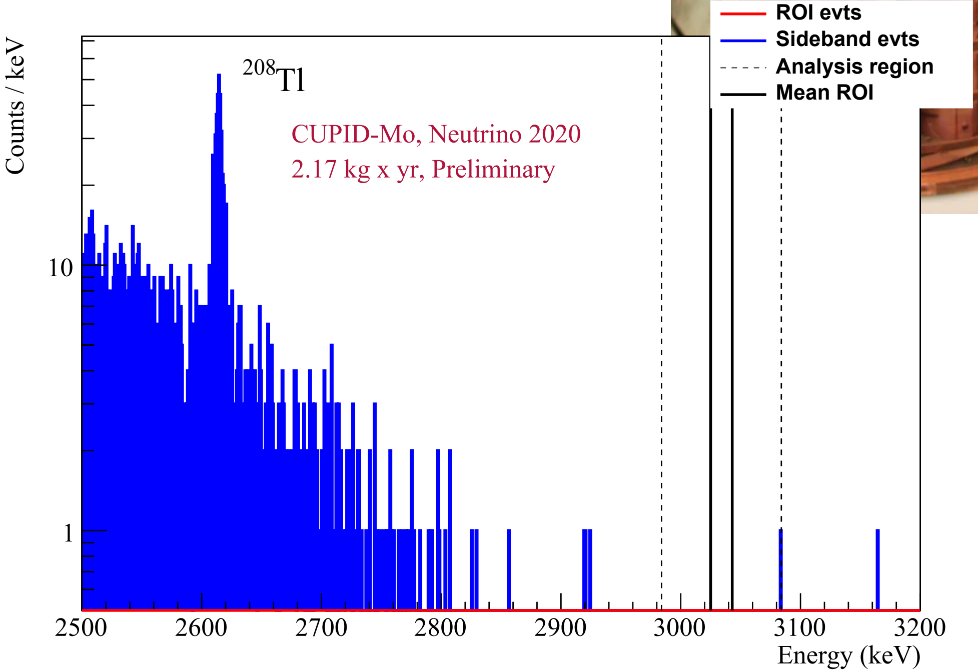
- CUORE
  - Making bolometer a "working horse" of $0\nu\beta\beta$
  - Leading ^{130}Te constraint: > 3×10^{25} yr.
- CUPID:
  - 250 kg of ^{100}Mo in 1500 Li_2MoO_4 crystals in CUORE cryostat
  - Good *E* resolution from phonons: ~5 keV FWHM at $Q_{\beta\beta}$
  - Scintillation readout rejects background
- Particle ID technique robustly demonstrated by CUPID-0 and CUPID-Mo
  - >99.9% α rejection, >99.9% β/γ acceptance
- Background goal: 0.5 c/(FWHM t y) dominated by $2\nu\beta\beta$ pile-up and U/Th γ summing
- Discovery sensitivity (10 years): $T_{1/2} > 1.1 \times 10^{27}$ yr
- pCDR online, planning for TDR in 2021, followed by 5 years construction at LNGS. 1 ton experiment under consideration

Heat/Light separation -CUPID-Mo









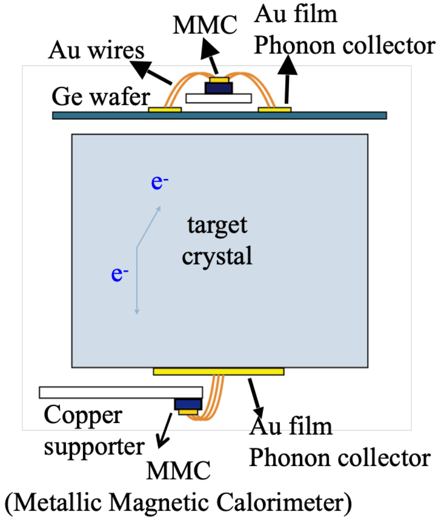
See dedicated talks later today

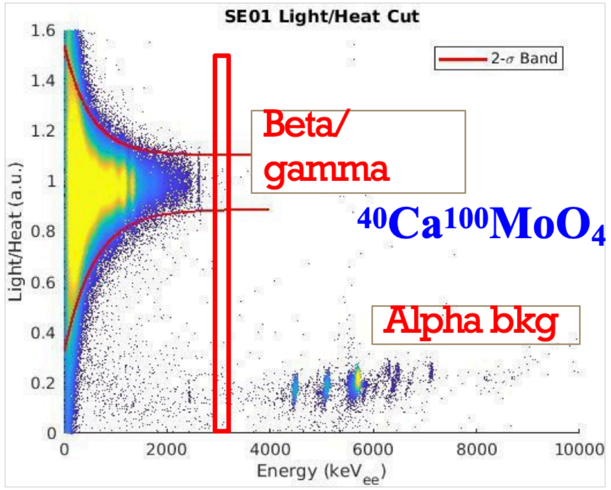
Bolometers: AMoRE

- 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): $T_{1/2} > 8 \times 10^{26}$ 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

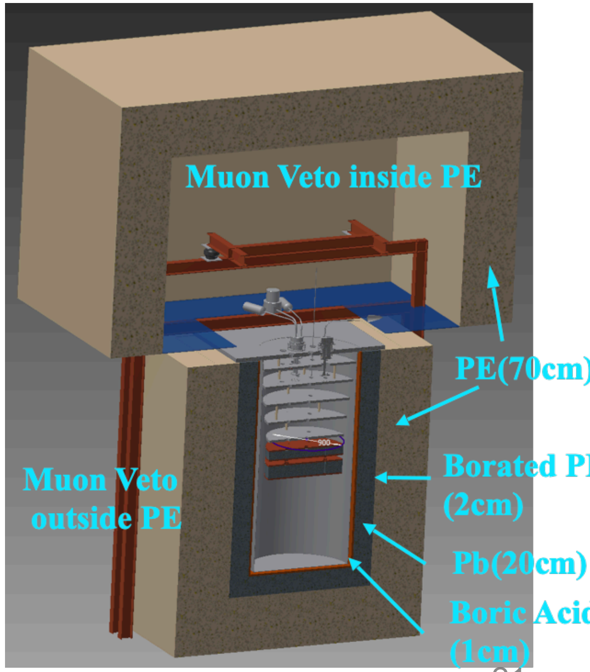
Opportunities: Scalability, isotope flexibility

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





AMoRE-I

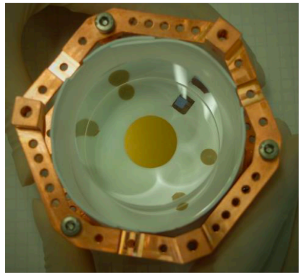


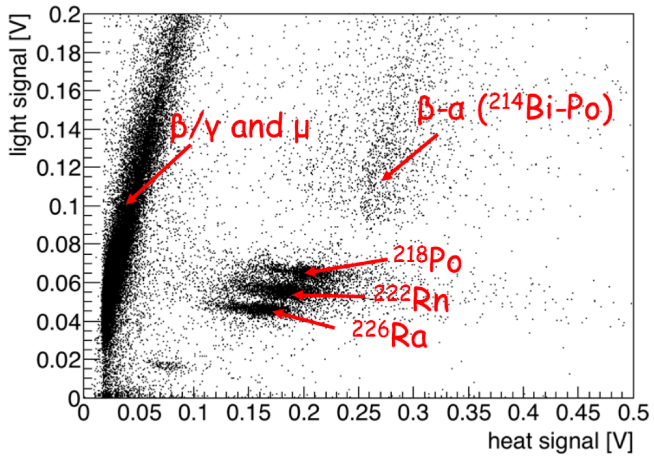
Bolometers: CANDLES

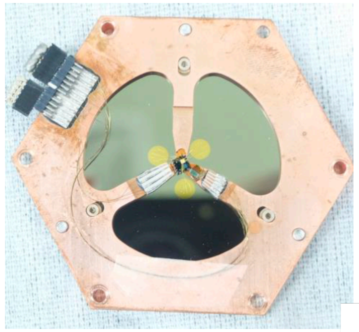
- CaF_2 scintillating crystals
  - Take advantage of ^{48}Ca's high $Q_{\beta\beta}$, "easy" NME
    - But: very low natural abundance (0.19%)
  - CANDLES-III: immerse in liquid scintillator (TAUP 2019: $T_{1/2} > 6\times10^{22}$ y)
  - Next system: operate as scintillating bolometers with MMC phonon 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

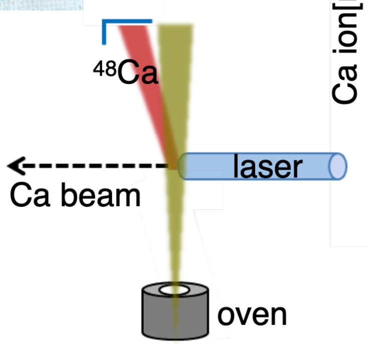
Opportunities: High $Q_{\beta\beta}$, low BG in ROI.

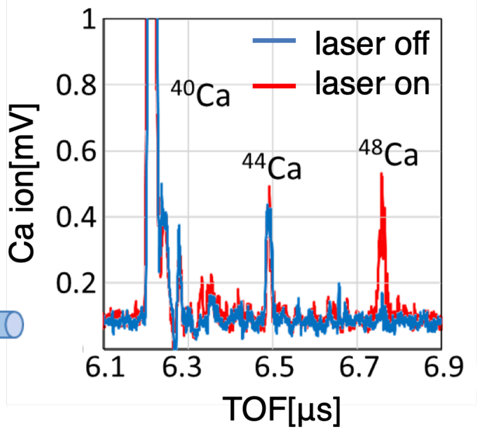
Challenges: E-resolution, scaling up isotope





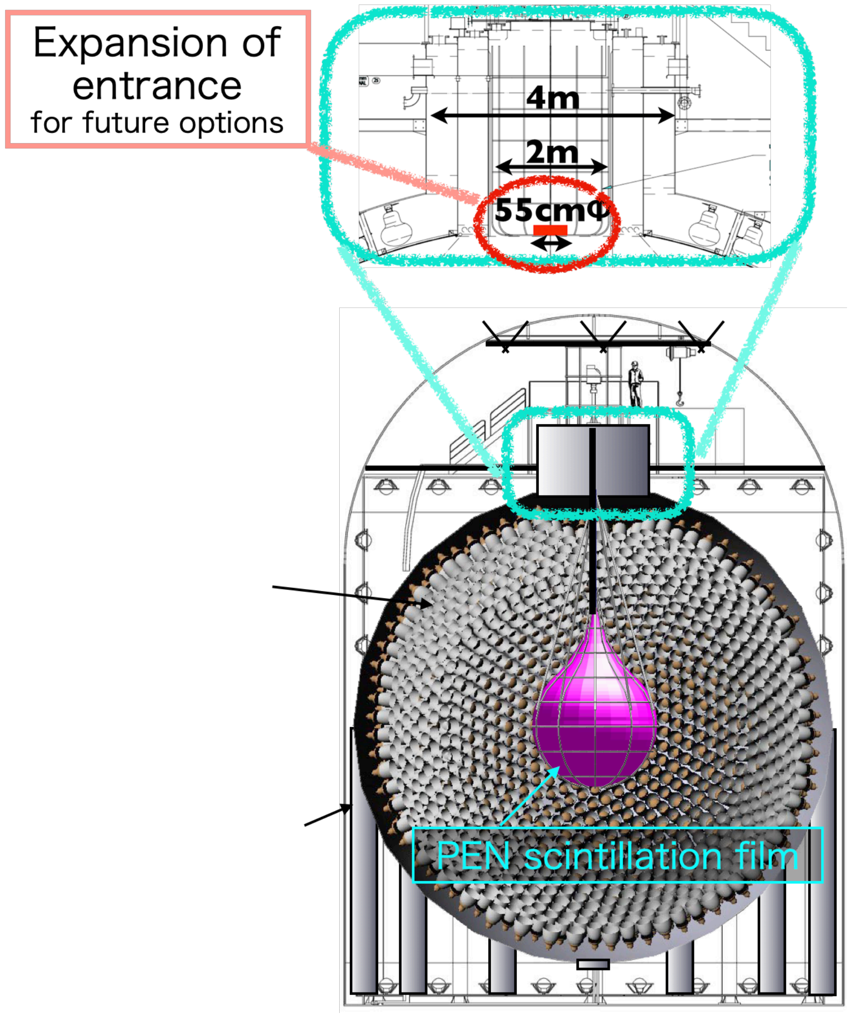






Large Liquid Scintillators: KamLAND2-Zen

- Best current constraint on <m_ν>
- 1000+ kg 90% enriched ^{136}Xe loaded in liquid scintillator (2.7% wt)
  - High exposure, good self-shielding
  - Energy and position reconstructed from number and timing of photons
- Upgrade of successful KamLAND-Zen detector
  - x2 improved resolution: Winston cones, high-q.e. PMTs, LAB LS
  - PEN balloon for active veto of balloon backgrounds
  - Improved electronics, background tagging, PID, possibly pressurized LS
- Background ~2 c/(FWHM t y) dominated by $2\nu\beta\beta$ tail and ^{8}B solar ν scattering
- Limit sensitivity (5 years): $T_{1/2} > 2 \times 10^{27}$ yr
- Upgrade preparations underway, will proceed following 5-year run of KamLAND-Zen 800



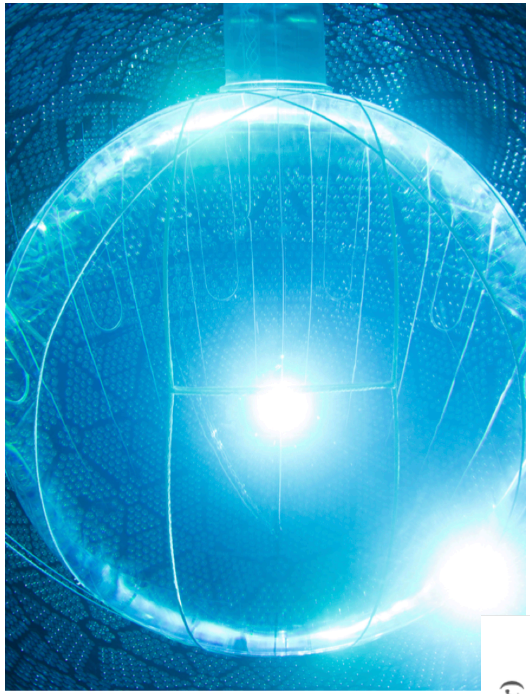
Opportunities: Scalability, cost, simplicity

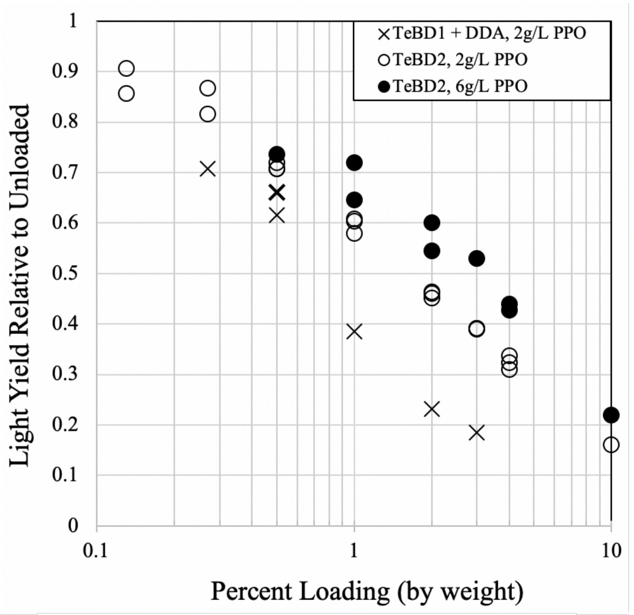
Challenges: E-resolution, solar neutrinos

Large Liquid Scintillators: SNO+

Phase-I

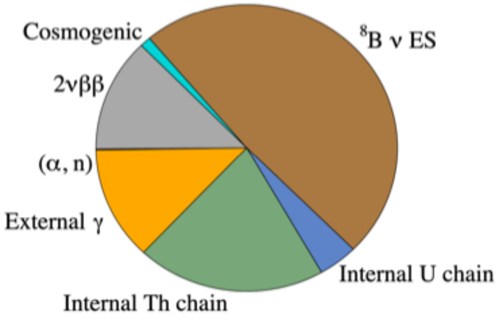
- Using existing SNO detector and SNO infrastructure
- Water replaced with liquid scintillator (LAB)
- Natural Te loading to commence soon
- Phased approach: from 0.5% loading up
- Phase-I sensitivity: 1.9 x 10^{26} yr

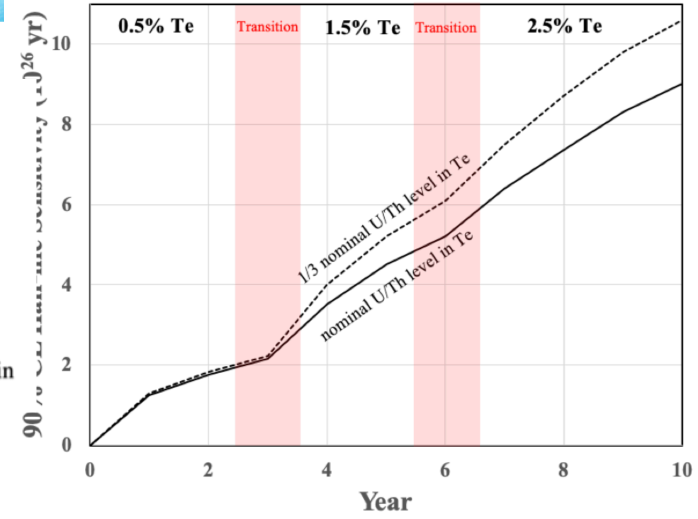




Phase-II

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





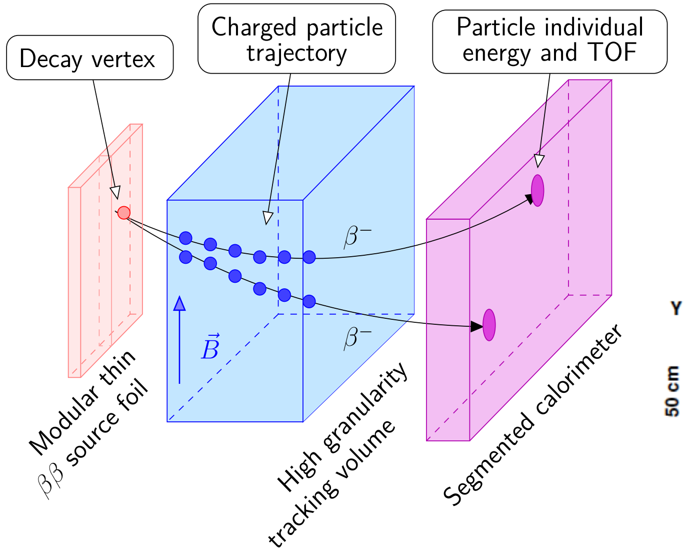
Other large LS, e.g. JUNO: See dedicated talk later today

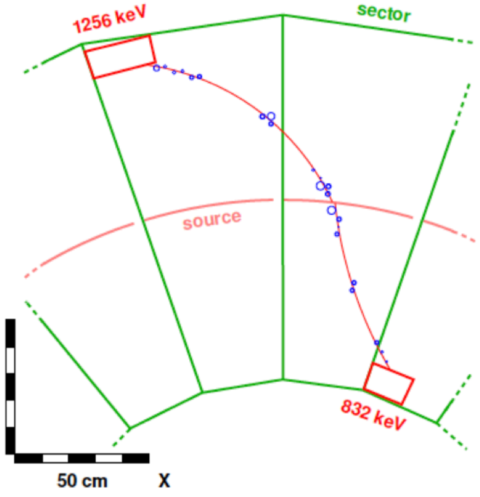
Tracker + ScintCalorimeter: SuperNEMO

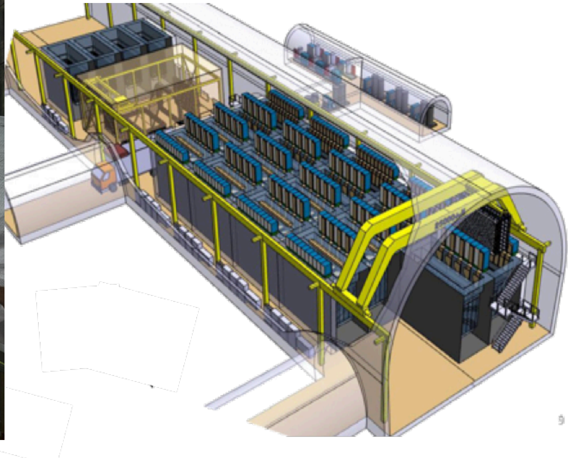
- Foils of isotope viewed by tracker, calorimeter
  - Foils can be made of any ββ isotope (SuperNEMO now ^{82}Se)
  - Full PID(e-, e+, γ and α), ββ kinematics, and topology: E_{single}, E_{sum}, x, y, z, t, cosθ: can be used to probe underlying LNV mechanism
- Builds off of NEMO-3 success: most precise 2νββ measurement for several isotopes
  - Experimental input to NME, g_A, …
  - New physics with 2νββ, Deppisch et al, *arXiv:2003.11836v1*
- SuperNEMO Demonstrator with 6.3 kg ^{82}Se under commissioning at LSM
- Scaling up to 500 kg would provide half-life sensitivity beyond 10^{26} years
- *In the event of <m$_\nu$> ~50 meV discovery is arguably the best to verify result with multiple isotope and understand underlying mechanism of LNV*

Opportunities

Challenges: Scalability, E-resolution,





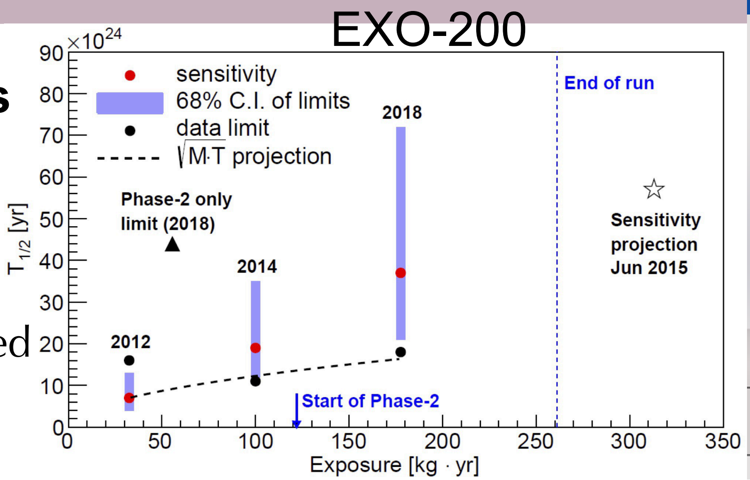


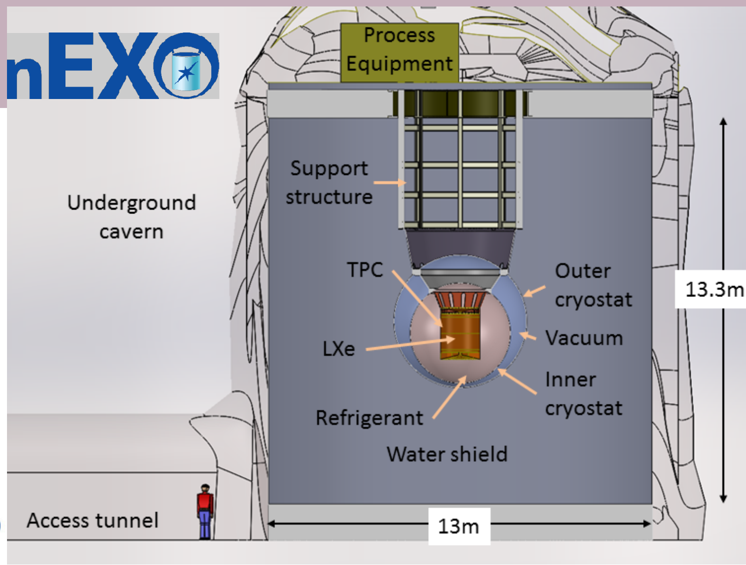
See dedicated talk later today

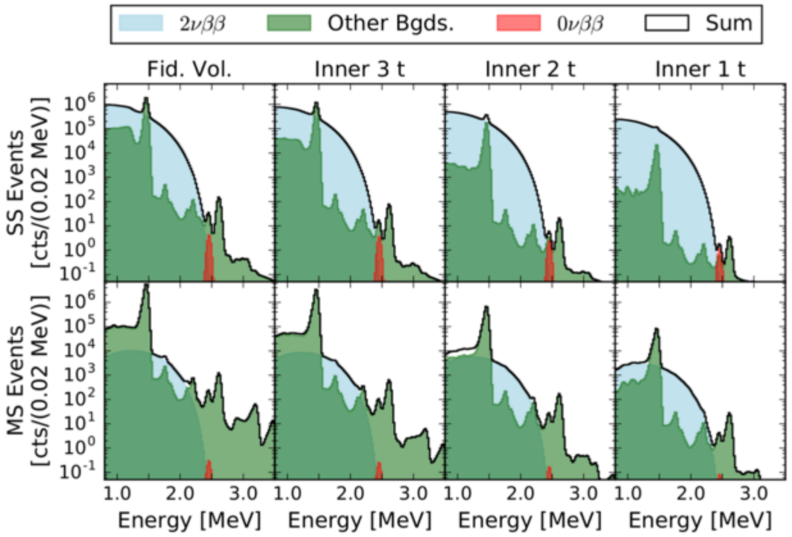
LXe TPC

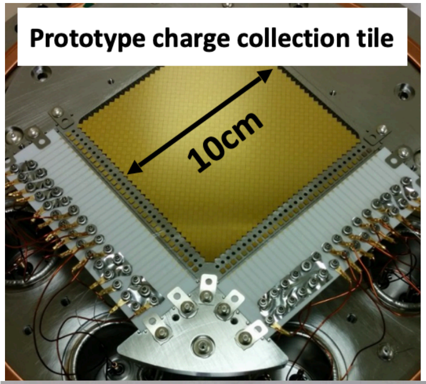
Opportunities

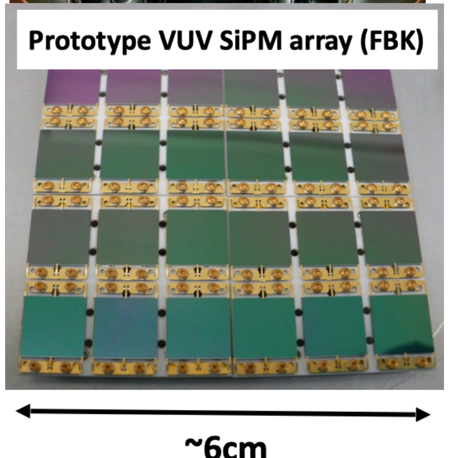
- Charge and light collection
- Scalable, excellent self-shiedling
- PID, position reconstruction
- nEXO
    - Upgrade of successful EXO-200 design, Improved light and charge collection
    - Innermost region BG ~0.1 c/(FWHM t y) dominated by natural radioactivity
    - Discovery sensitivity for 10 years livetime (update coming soon): $T_{1/2} > 5.7 \times 10^{27}$ yr
    - 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







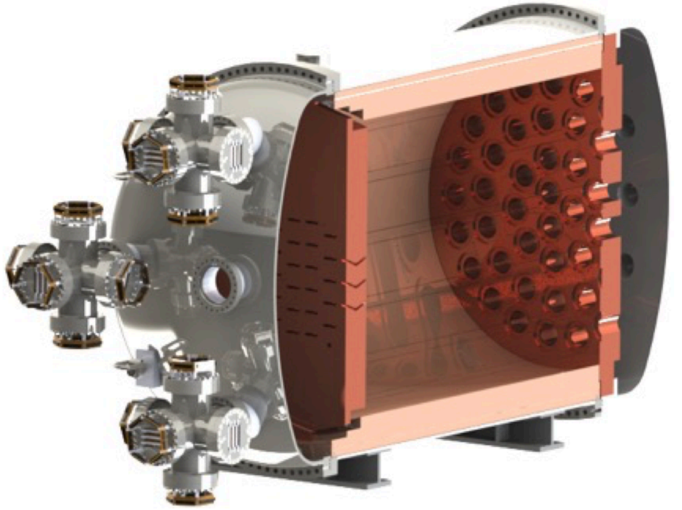


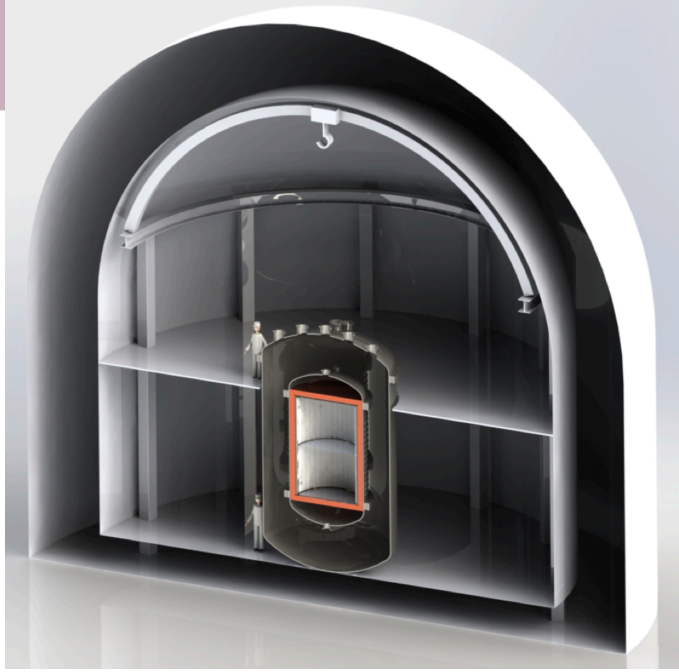


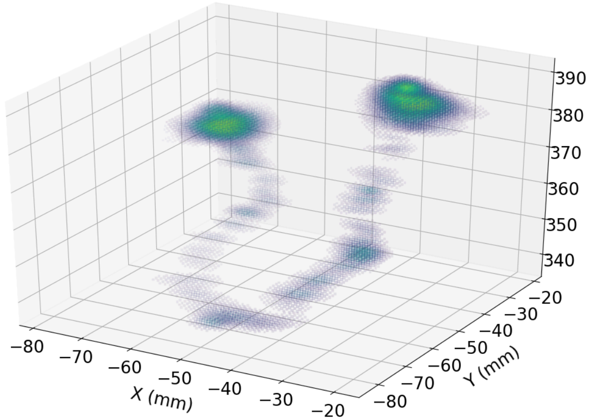
Challenges: E-resolution, BG lines near $Q_{\beta\beta}$

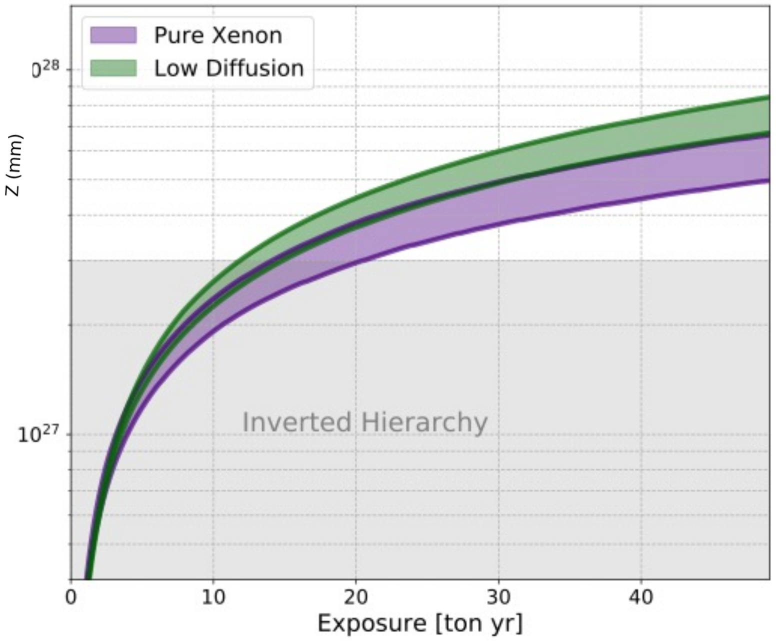
Gas TPC: NEXT-HD

- 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 (10 years): $T_{1/2} > 3 \times 10^{27}$ yr
- Will follow NEXT-100 (should start this year)









Opportunities: Energy resolution, topology reconstruction

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

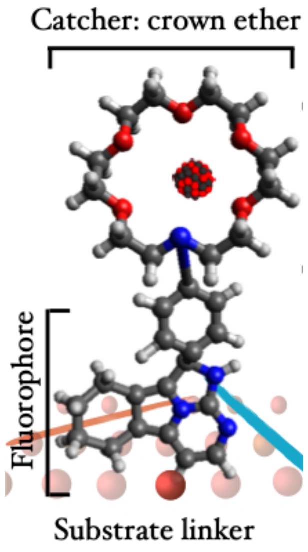
^{136}Xe Daughter Nucleus (^{136}Ba) Tagging

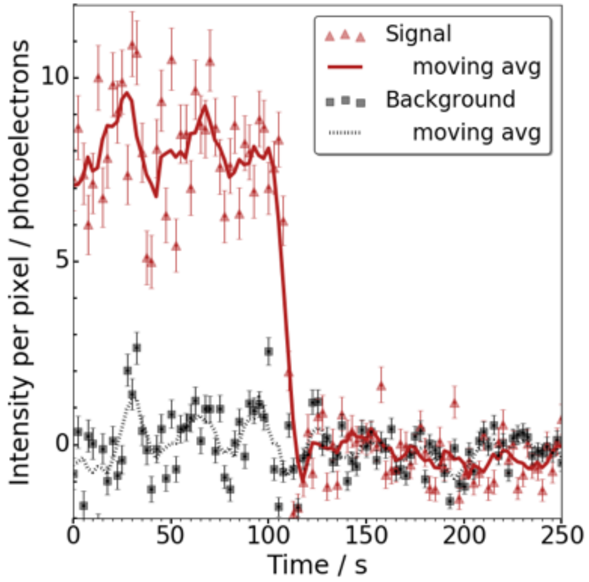
•NEXT: radio frequency carpet sweeps ions to region with switched-fluorescent molecules. Single-molecule sensitivity demonstrated in Xe background.

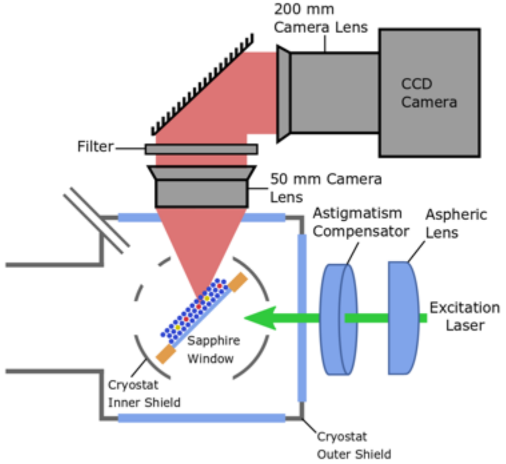
•nEXO: freeze Ba in Xe, transport via probe to imaging stage, lase and image. Single-atom sensitivity demonstrated.

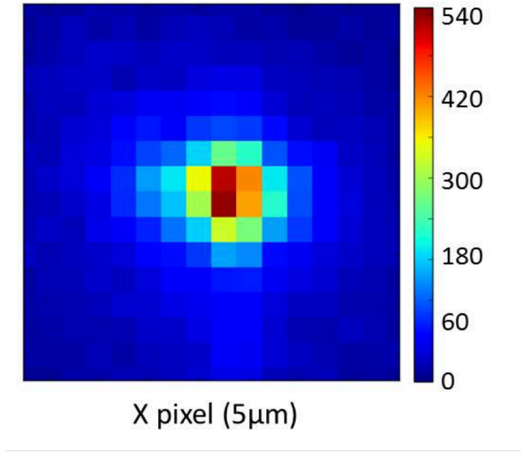
•Enables background-free searches

IF high efficiency can be achieved.





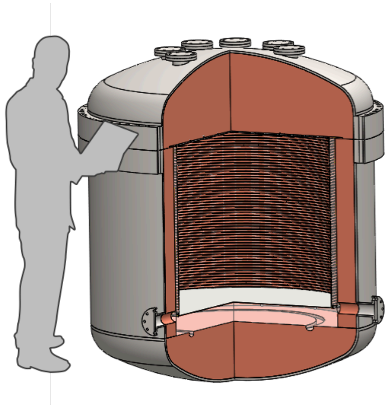




TPCs: PandaX, AXEL, NvDEX

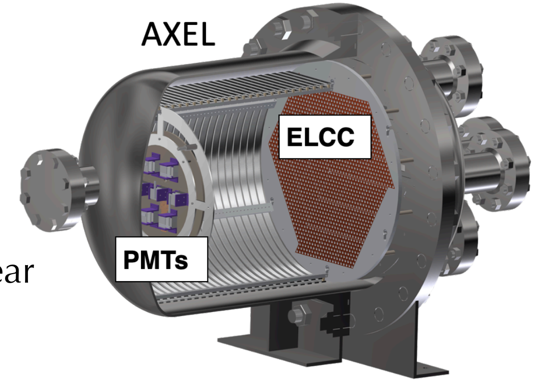
- PandaX
  - PandaX-4T (360 kg ^{136}Xe): upgrade of PandaX-II dual-phase LXe TPC for DM @CJPL, commissioning by end of 2020. 30T upgrade in planning.
  - PandaX-III: 0νββ-focused HPGXe TPC with ~100 kg ^{136}Xe using micromegas readout. Limit sensitivity: $9x10^{25}$ y. Construction underway, commissioning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

PandaX-4T LXe TPC

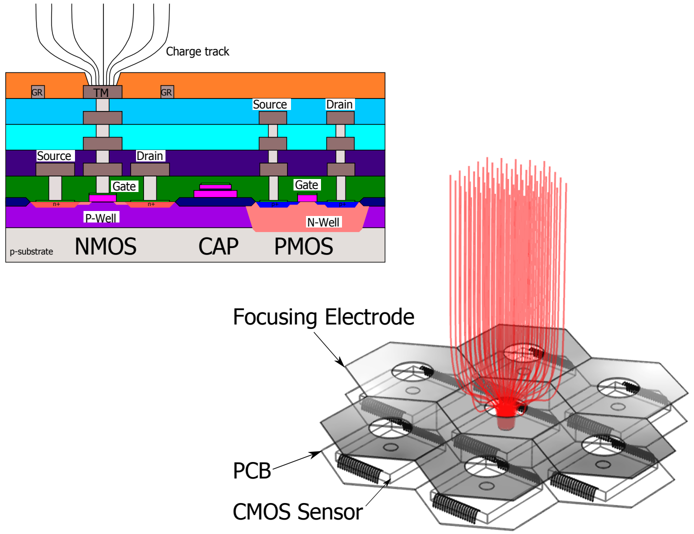


PandaX-III GXe TPC

- 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.



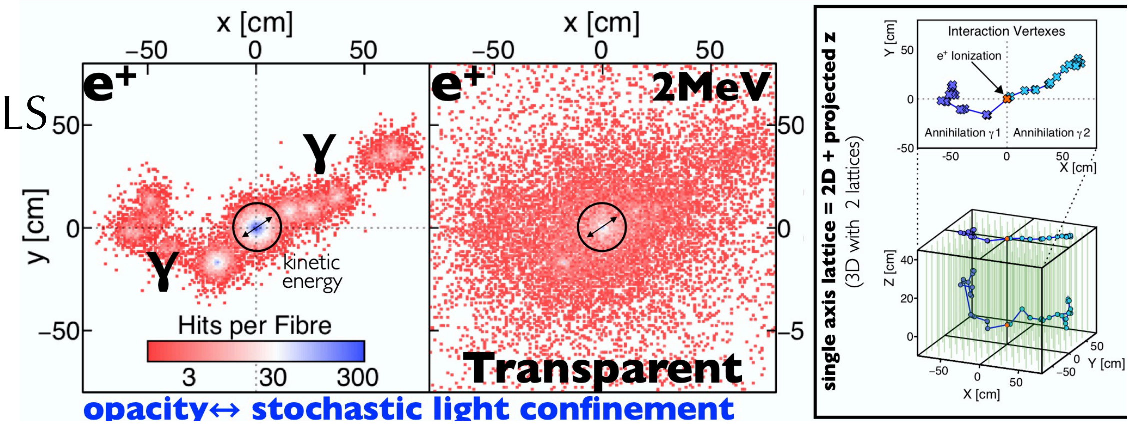
- NvDEX
  - $^{82}SeF_6$ HP gas TPC with Topmetal CMOS readout
  - 100 kg vessel designed, construction at CJPL starting next year



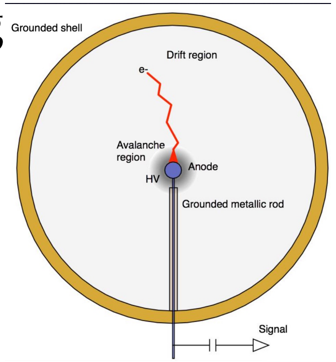
Topmetal CMOS Technology

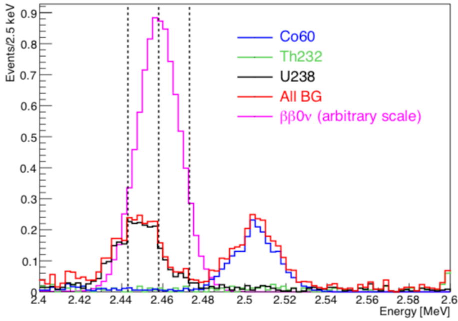
Other exciting R&D underway: LiquidO, R2D2

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



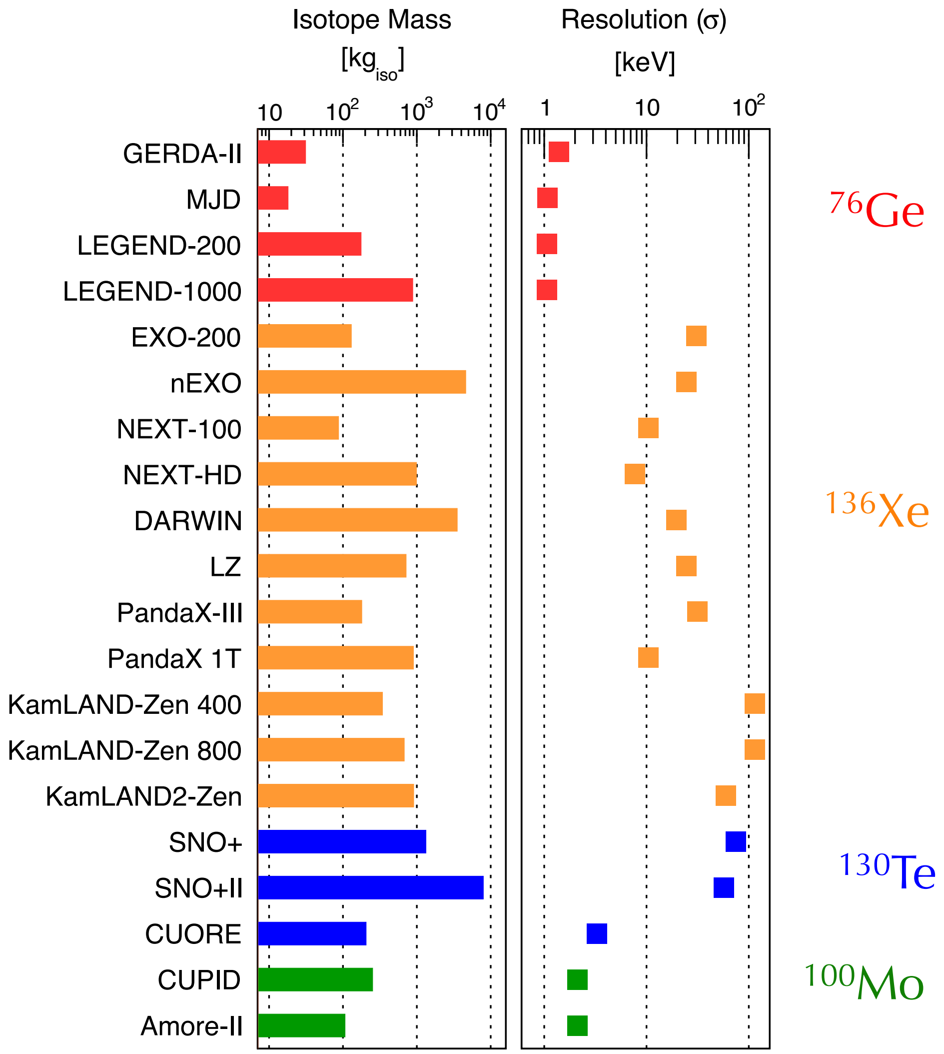
- R2D2
  - Spherical Xenon gas TPC
  - Test ongoing with 8 kg prototype, plans for 50 kg upgrade
  - See JINST **13**, P01009 (2018)





See dedicated talks later today
Apologies for missing others!

Experimental Outlook



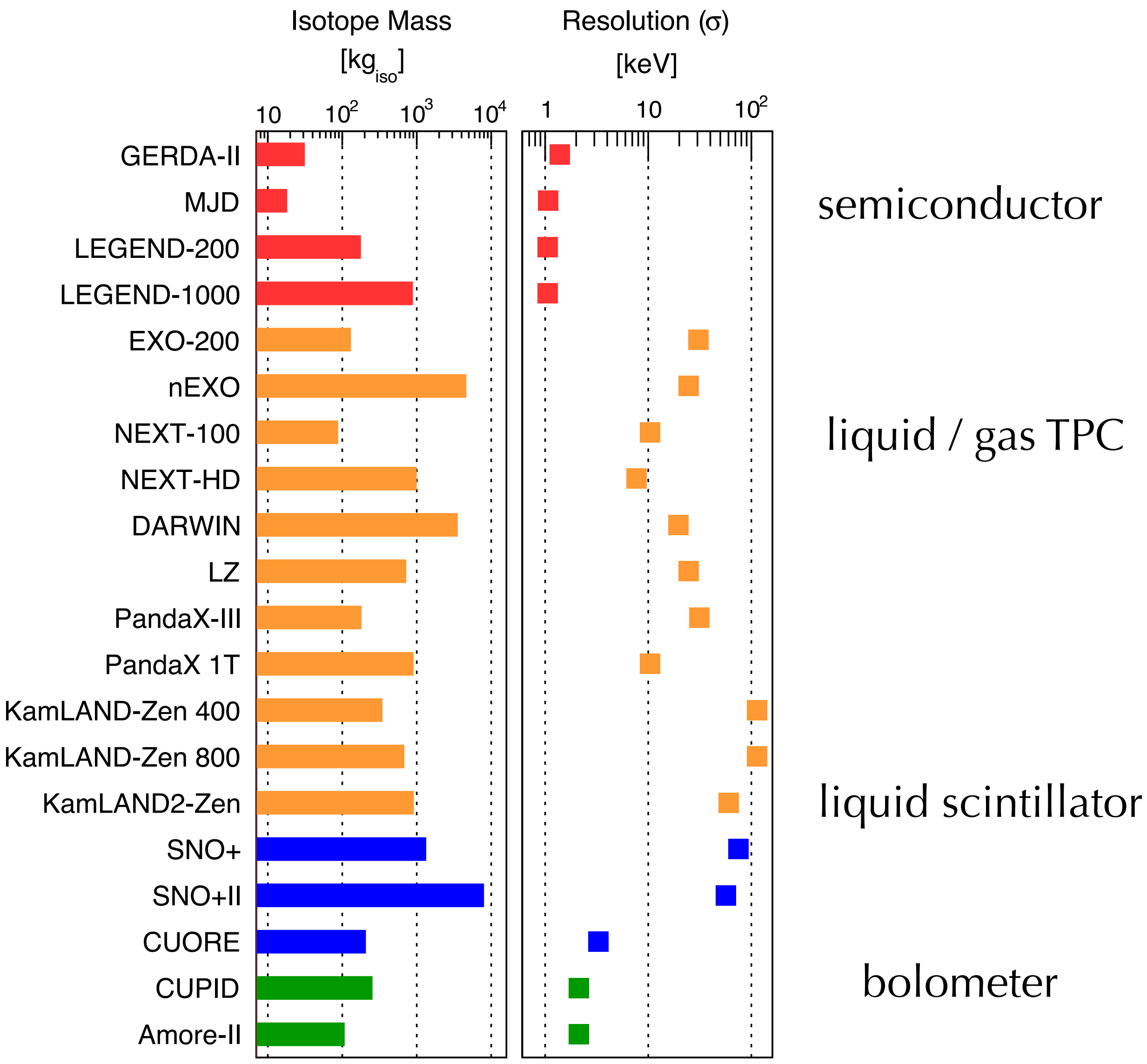
$+\ ^{48}\mathrm{Ca} + \ ^{82}\mathrm{Se} + \ ^{96}\mathrm{Zr}\ \ldots$

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

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

Agostini, Benato, Detwiler, Menendez, Vissani

Experimental Outlook



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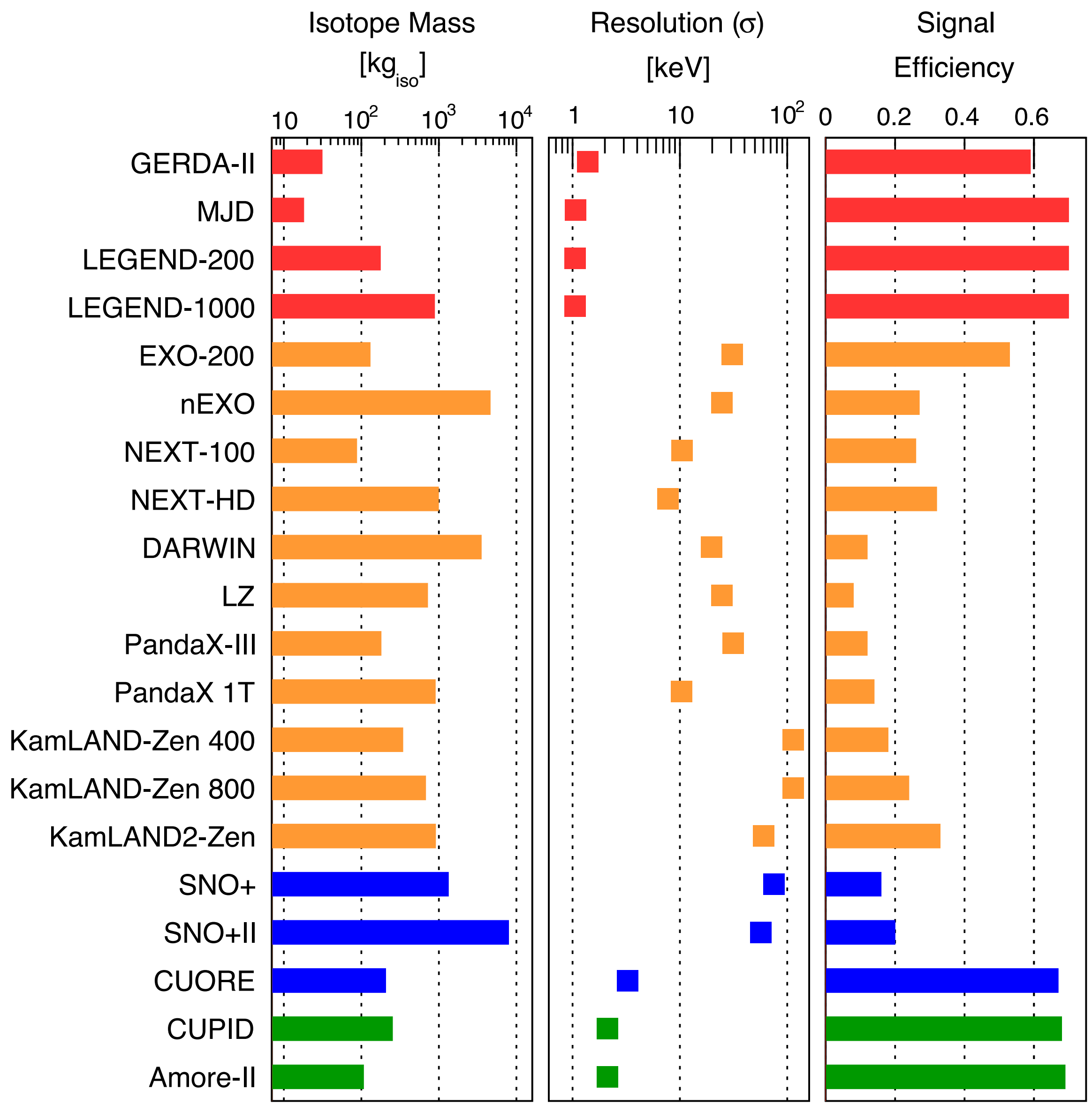
Experimental Outlook



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

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

Lower efficiency due primarily to fiducialization

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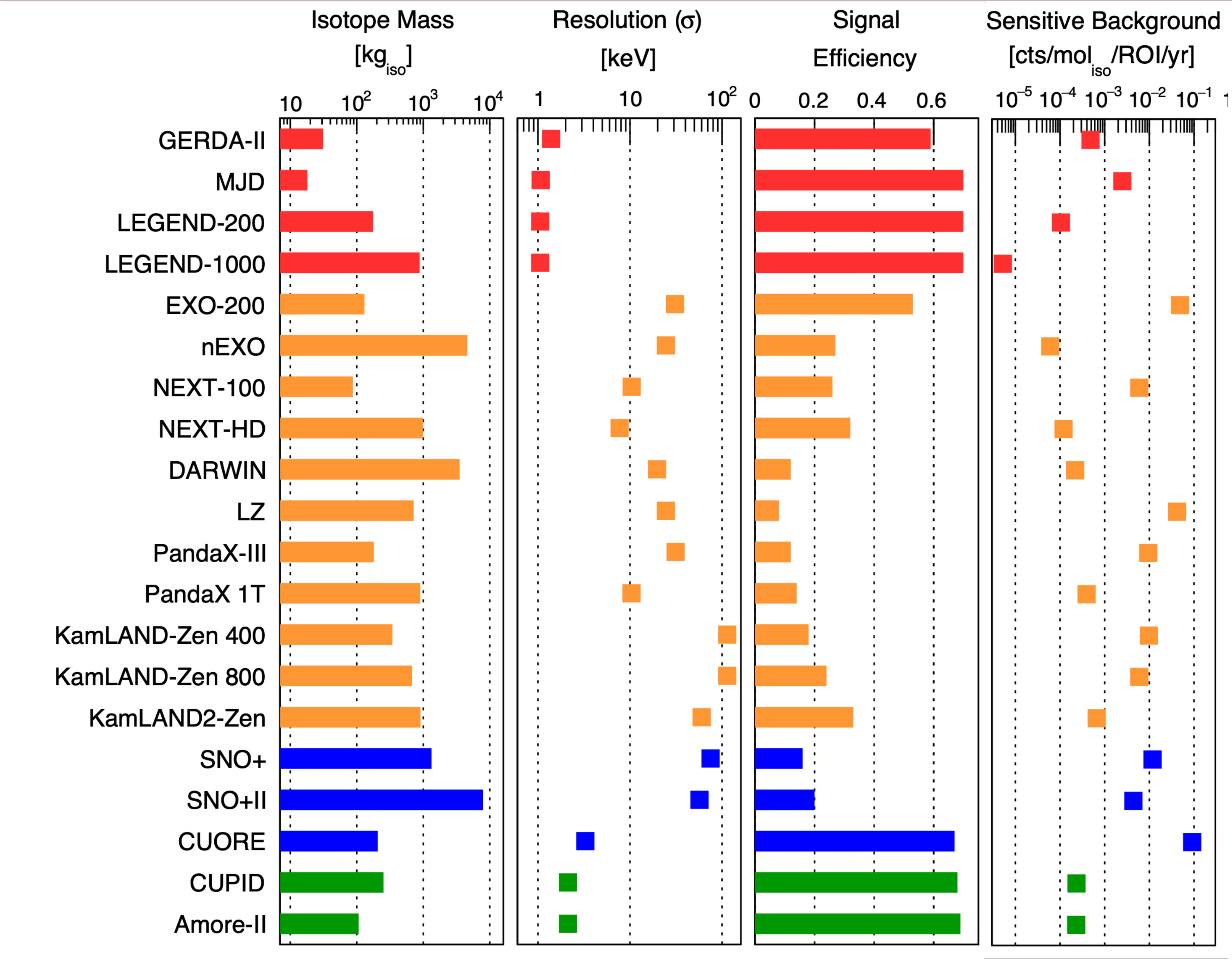
Experimental Outlook



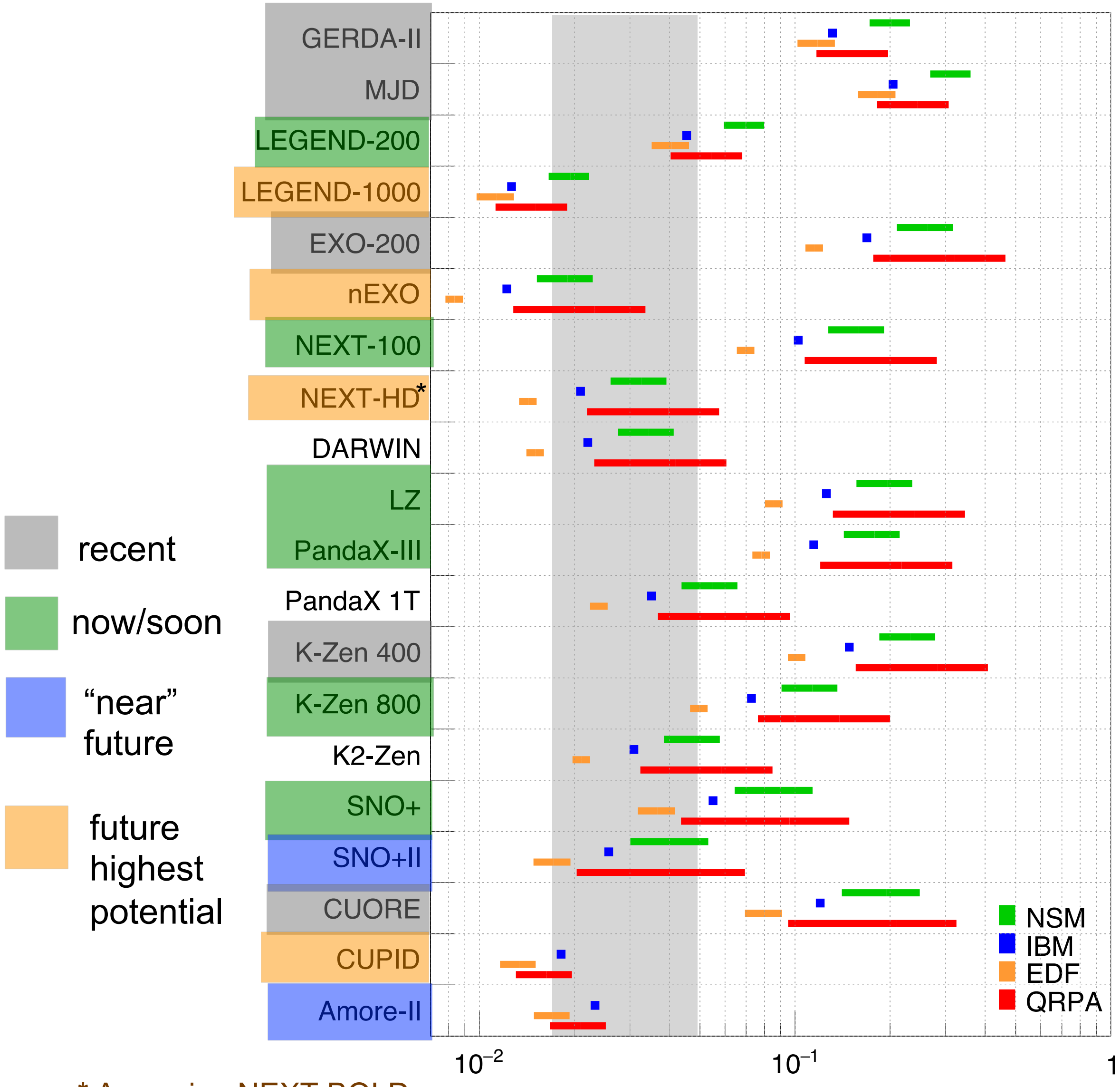
$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

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

Next generation experiments:
<1 bkg count/year

Agostini, Benato, Detwiler, Menendez, Vissani

0vbb Discovery Sensitivity: What lies ahead?



* Assuming NEXT-BOLD

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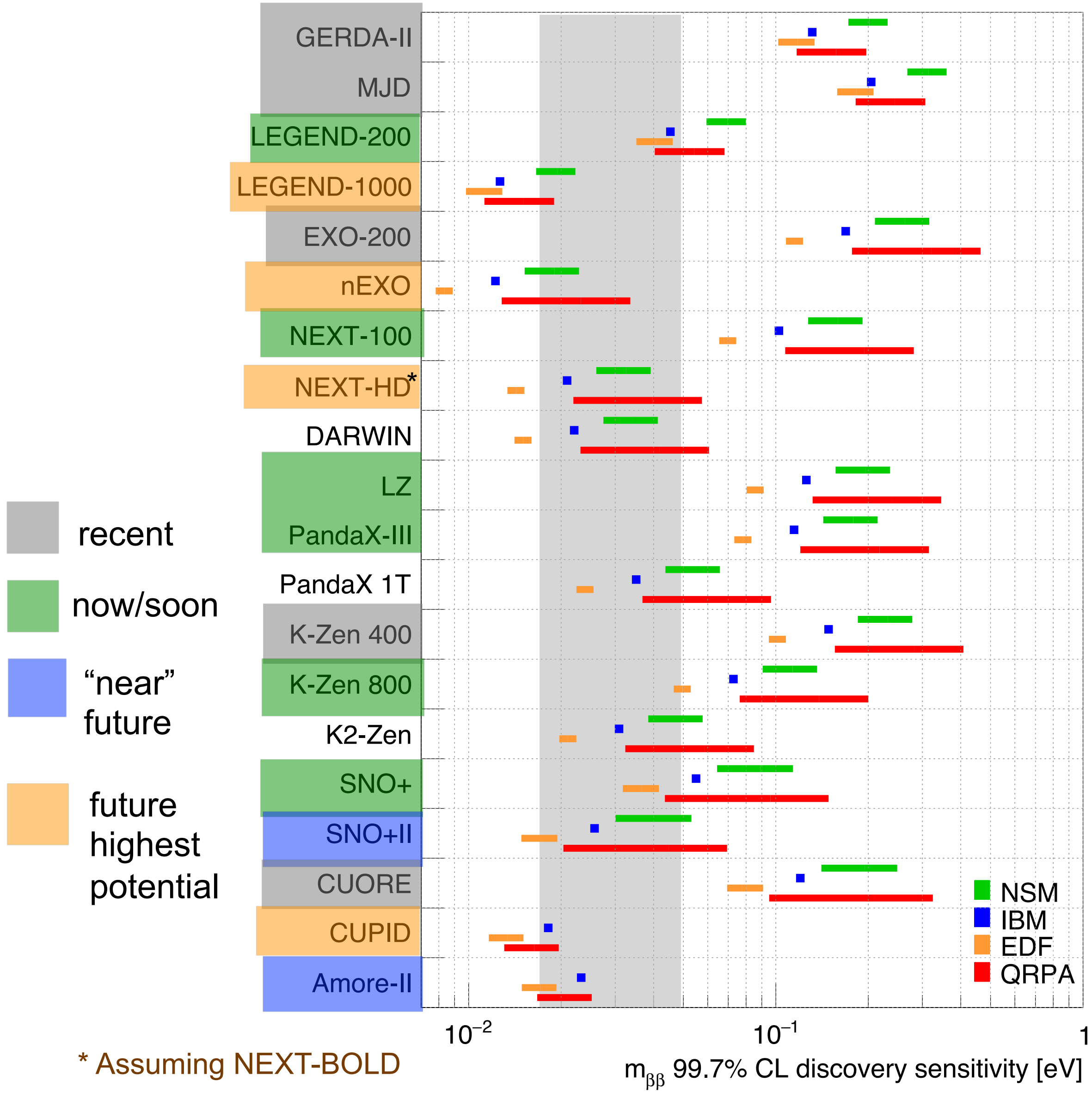
Concluding Remarks

- Upcoming generation of $0\nu\beta\beta$ 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 muti-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 $0\nu\beta\beta$ is clear (to us) but must be continuously made (to everyone else).

0vbb Discovery Sensitivity: What lies ahead?



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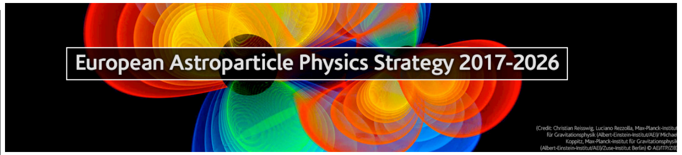
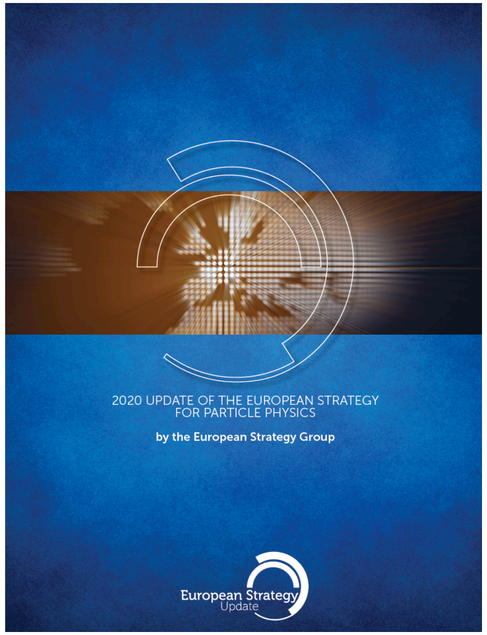
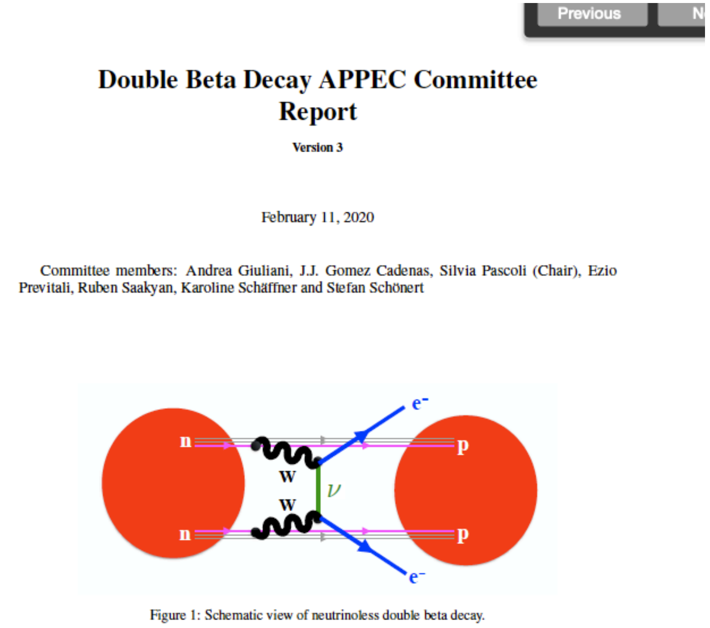
Crucial time for defining future 0νββ strategy







Previous

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.