Considerations for Next Generation 0νββ Experiments

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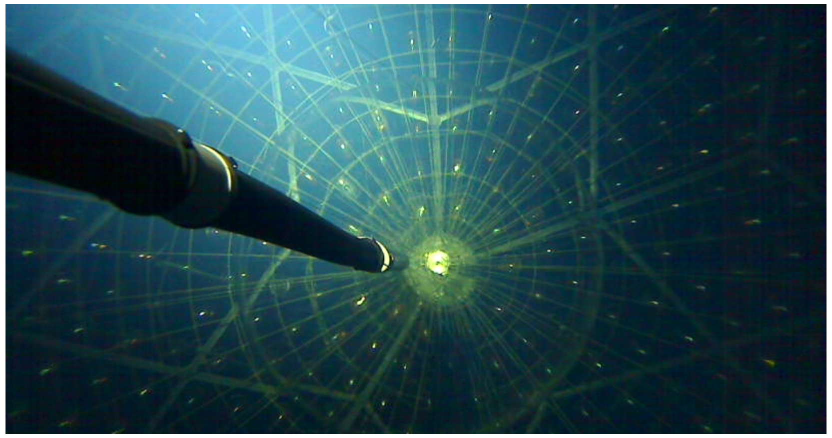
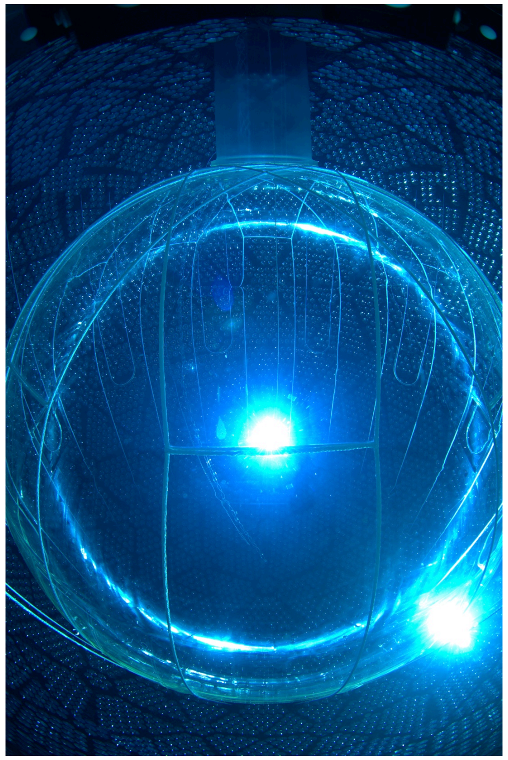
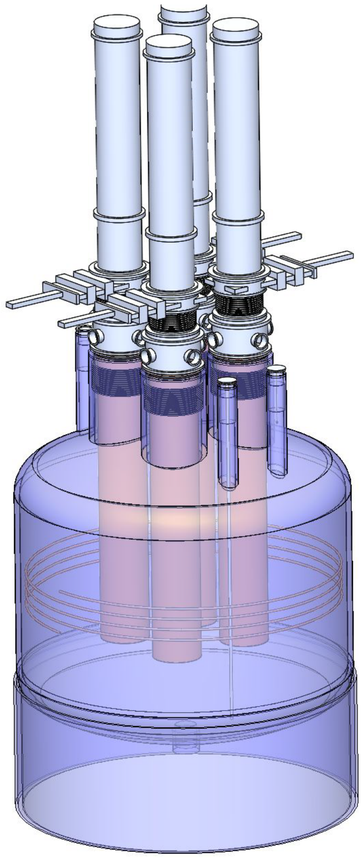
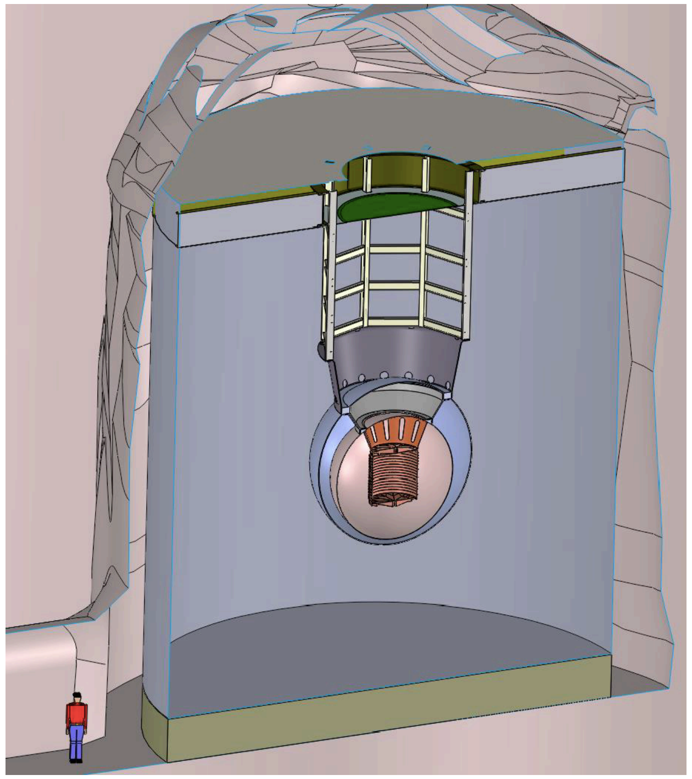
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

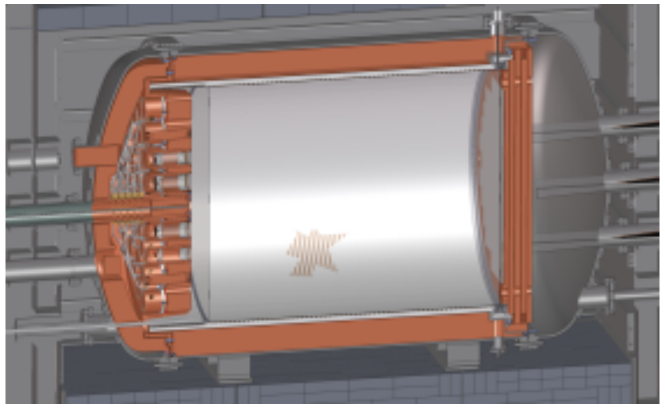
TUNL











INT Workshop on 0νββ
Seattle, WA
June 13, 2017

Searching for 0νββ Decay

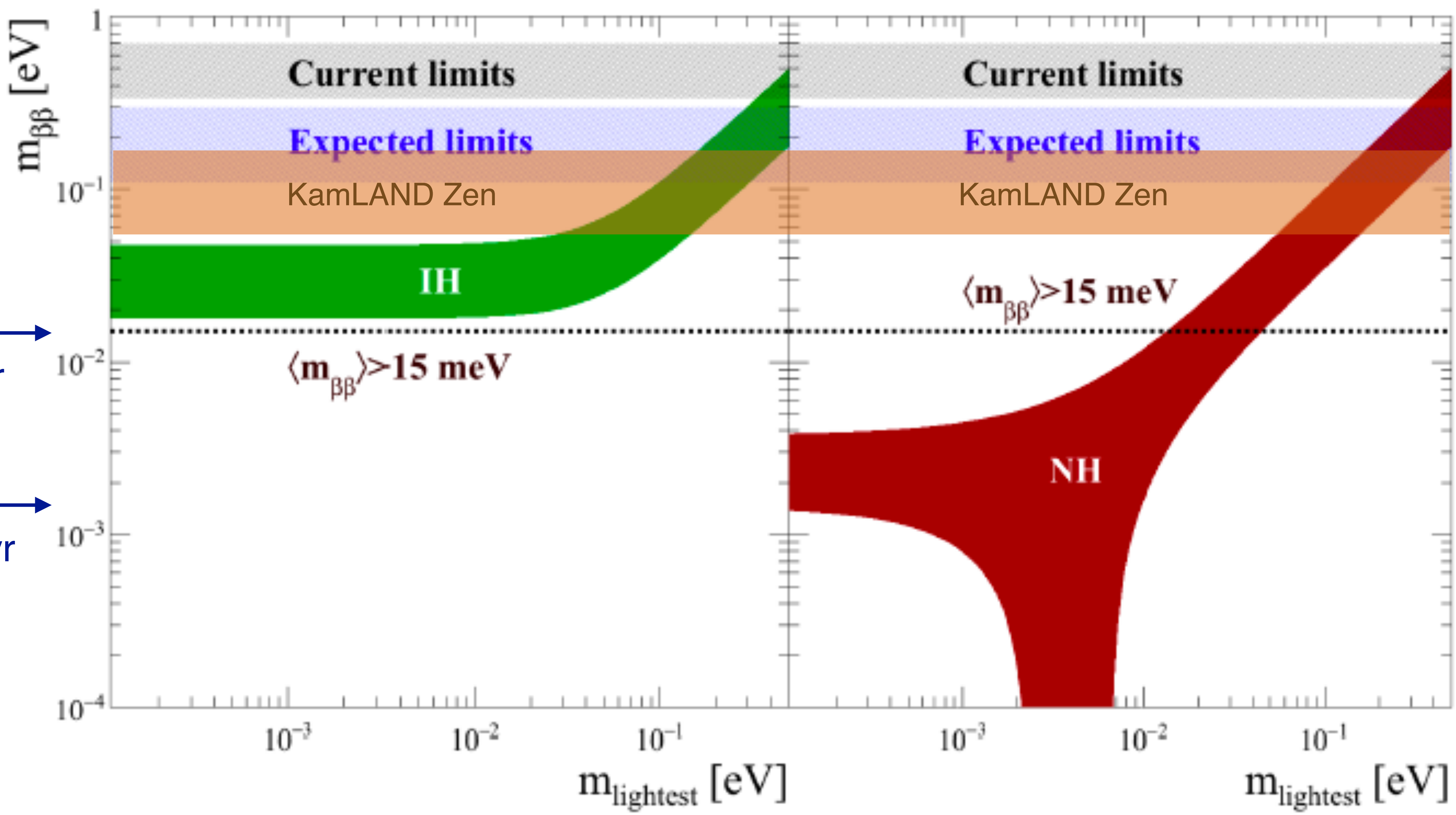
Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2 \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

2015 NSAC Long Range Plan for Nuclear Science

10 t-yr

100 t-yr



Next Generation Considerations

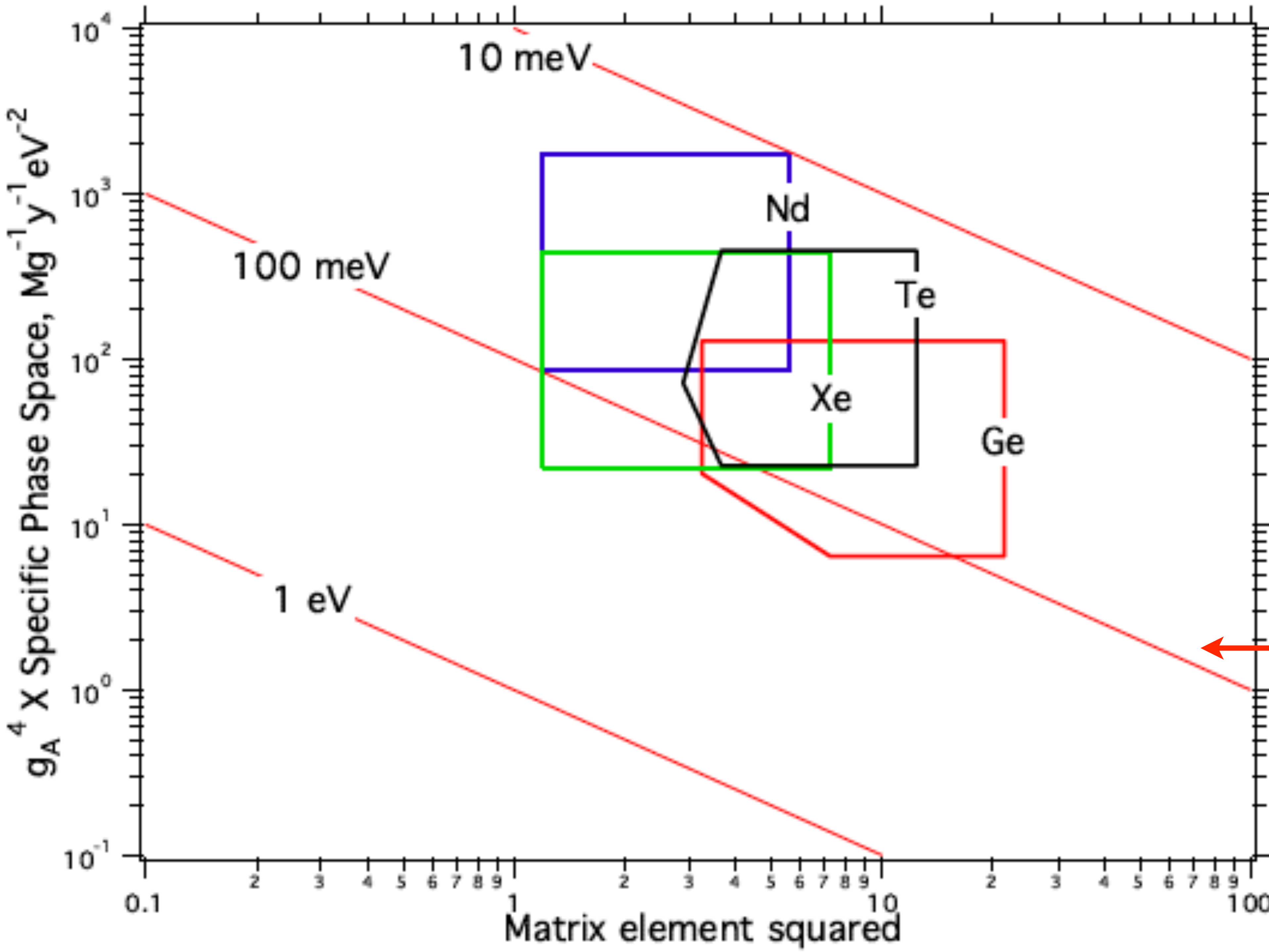
- Is there a preferred $0\nu\beta\beta$ isotope?

Sensitivity to <mββ>

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

For Ge, Te, Xe, Nd

← uncertainty on NME^2 →

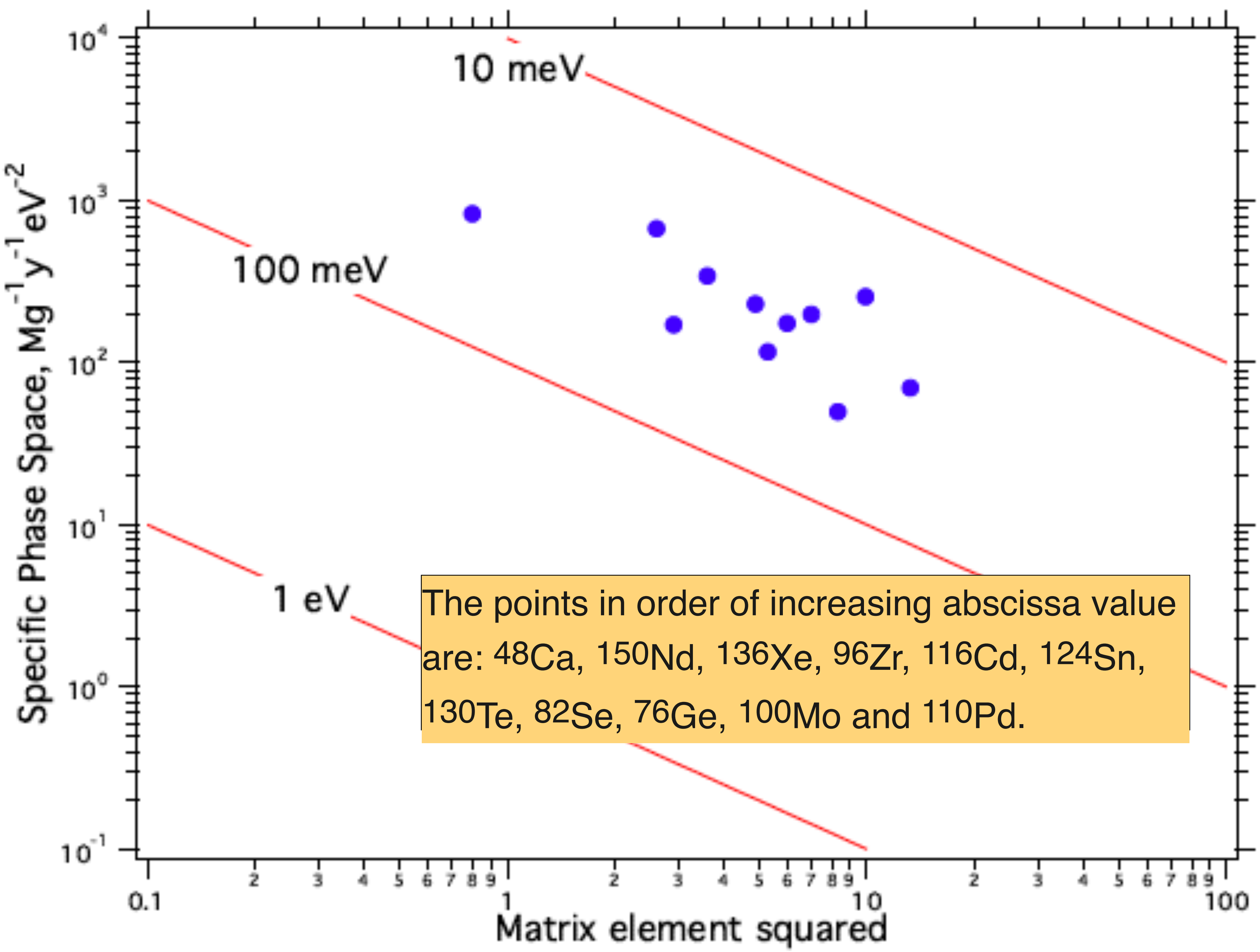


uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

Sensitivity per unit mass of isotope

➡ Isotopes have comparable sensitivities in terms of rate per unit mass



The points in order of increasing abscissa value are: ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo and ^{110}Pd.

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

Inverse correlation observed between phase space and the square of the nuclear matrix element .

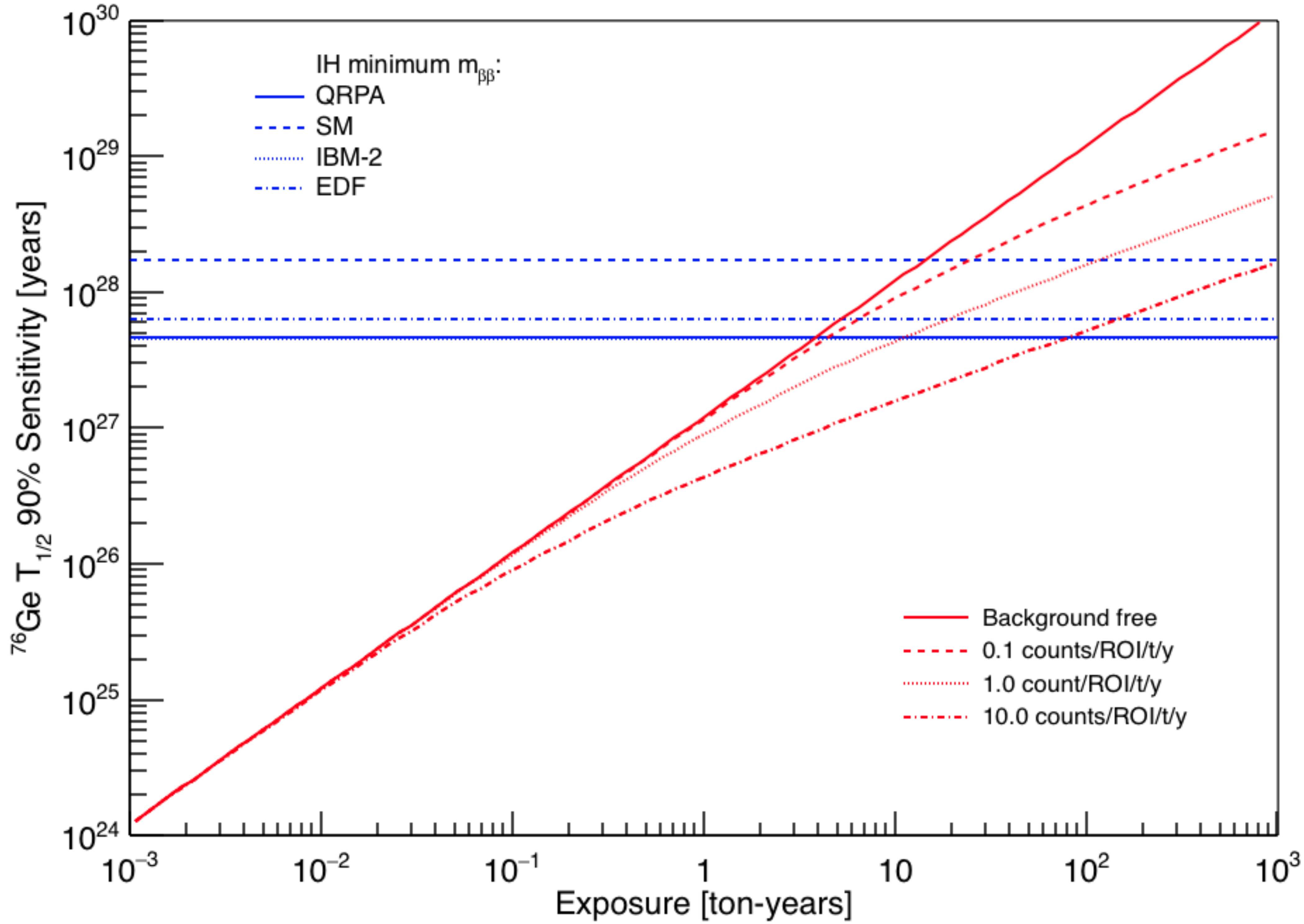
geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1

Next Generation Considerations

- Is there a preferred 0νββ isotope?
  No preferred isotope in terms of per unit mass - ***within current uncertainties on NME and g_A.***
- What is required to cover Inverted Ordering masses?

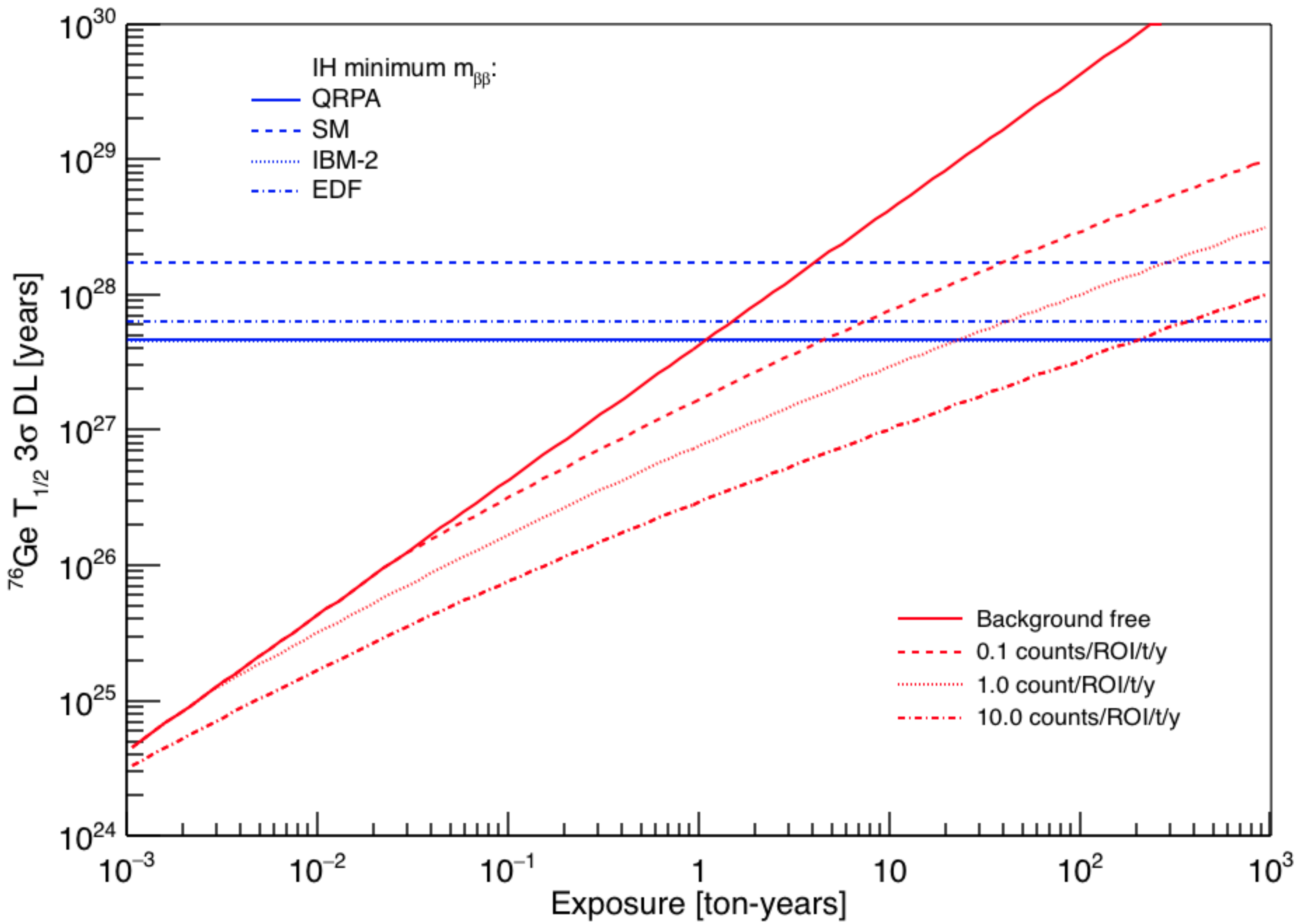
Sensitivity vs. Exposure for ^{76}Ge

$$T_{1/2}^{0\nu}\text{(background free)} \propto MT \qquad T_{1/2}^{0\nu}\text{(backgrounds)} \propto \sqrt{\frac{MT}{b\Delta E}}$$



J. Detwiler

3σ Discovery vs. Exposure for ^{76}Ge

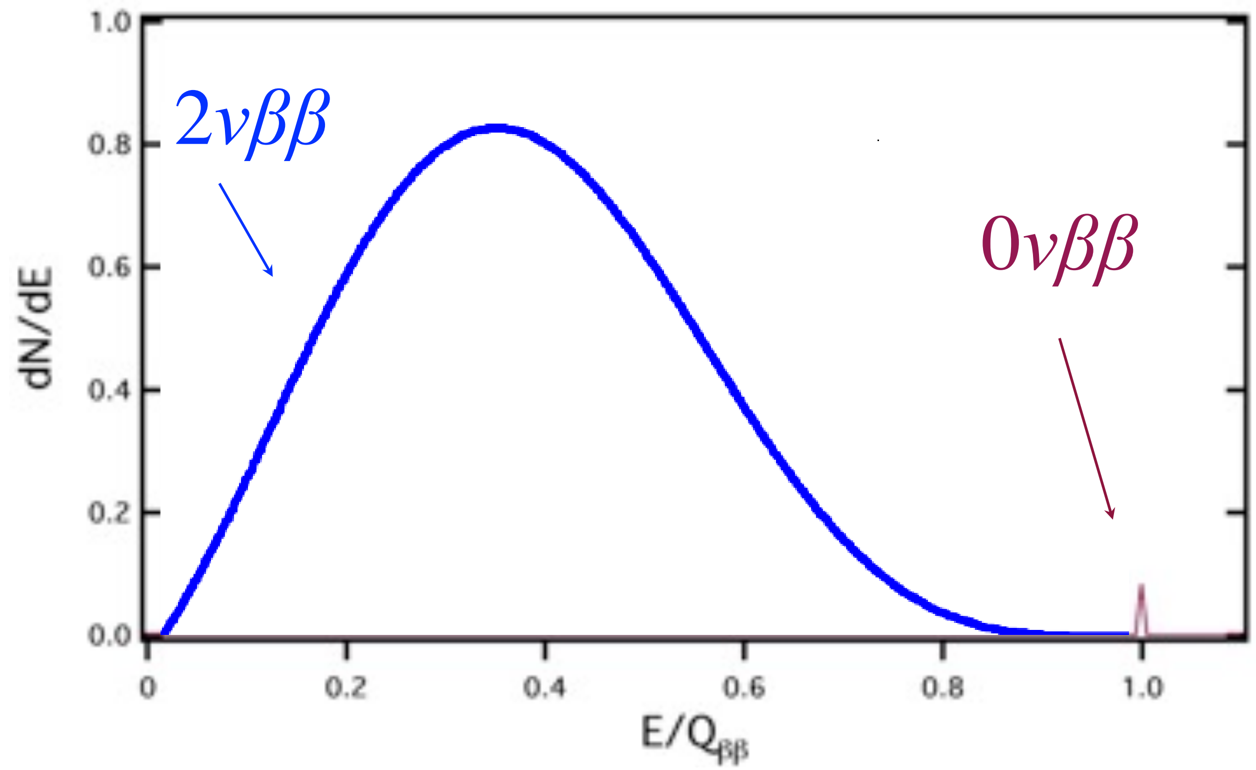


J. Detwiler

Experimental searches for 0νββ-decay

Most sensitive experiments to date using ^{76}Ge, ^{130}Te, and ^{136}Xe have attained results for $T_{1/2} > 5 \cdot 10^{25}$ to 10^{26} years.

(source mass) × (exposure times) of 30 - 125 kg-years



Half life (years)	~Signal (cnts/ton-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1
$>10^{29}$	0.05

Covering IH region requires sensitivities of

0νββ $T_{1/2} \sim 10^{27}$ - 10^{28} years

(2νββ $T_{1/2} \sim 10^{19}$ - 10^{21} years)

Next Generation Expts. aim for background of 0.1 cnts/t-y

Next Generation Considerations

- Is there a preferred 0νββ isotope?
  No preferred isotope in terms of per unit mass - ***within current uncertainties on NME and g_A*****.**
- What is required to cover Inverted Ordering masses?
  For a nearly ideal, background free experiment ~ 10 t-y
- Experimental Considerations

Potential contributions to the background

- Primordial, natural radioactivity in the detector and array components: U, Th, K
- Backgrounds from cosmogenic activation while material is above ground (ββ-isotope or shield specific, ^{60}Co, ^{3}H, ^{39}Ar, ^{42}Ar, …)
- Backgrounds from the surrounding environment:
  external γ, (α,n), (n,α), Rn plate-out, etc.
- μ-induced backgrounds generated at depth:
  Cu, Pb(n,n' γ), ββ-decay specific(n,n),(n,γ), direct μ
- 2 neutrino double beta decay (for 1000 kg, impact depends on resolution)
- neutrino backgrounds (for 1000 kg, can be a contribution)

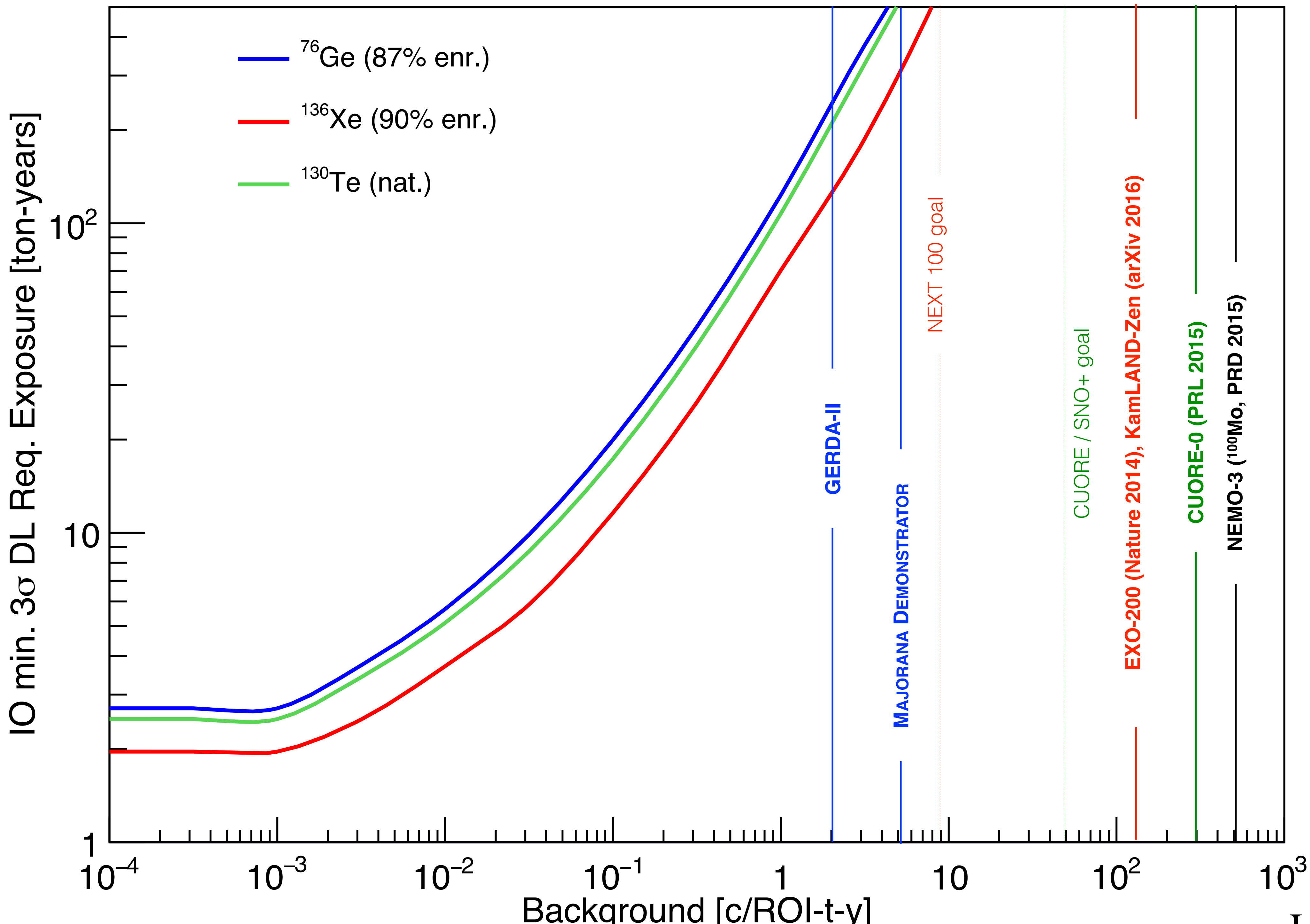
Reducing Backgrounds - Strategies

- Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non “source” materials
  - Clean (low-activity) shielding
  - Fabricate ultra-clean materials (underground fab in some cases)
  - Go deep — reduced μ’s & related induced activities
- Utilize background measurement & discrimination techniques

  $0\nu\beta\beta$ is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions

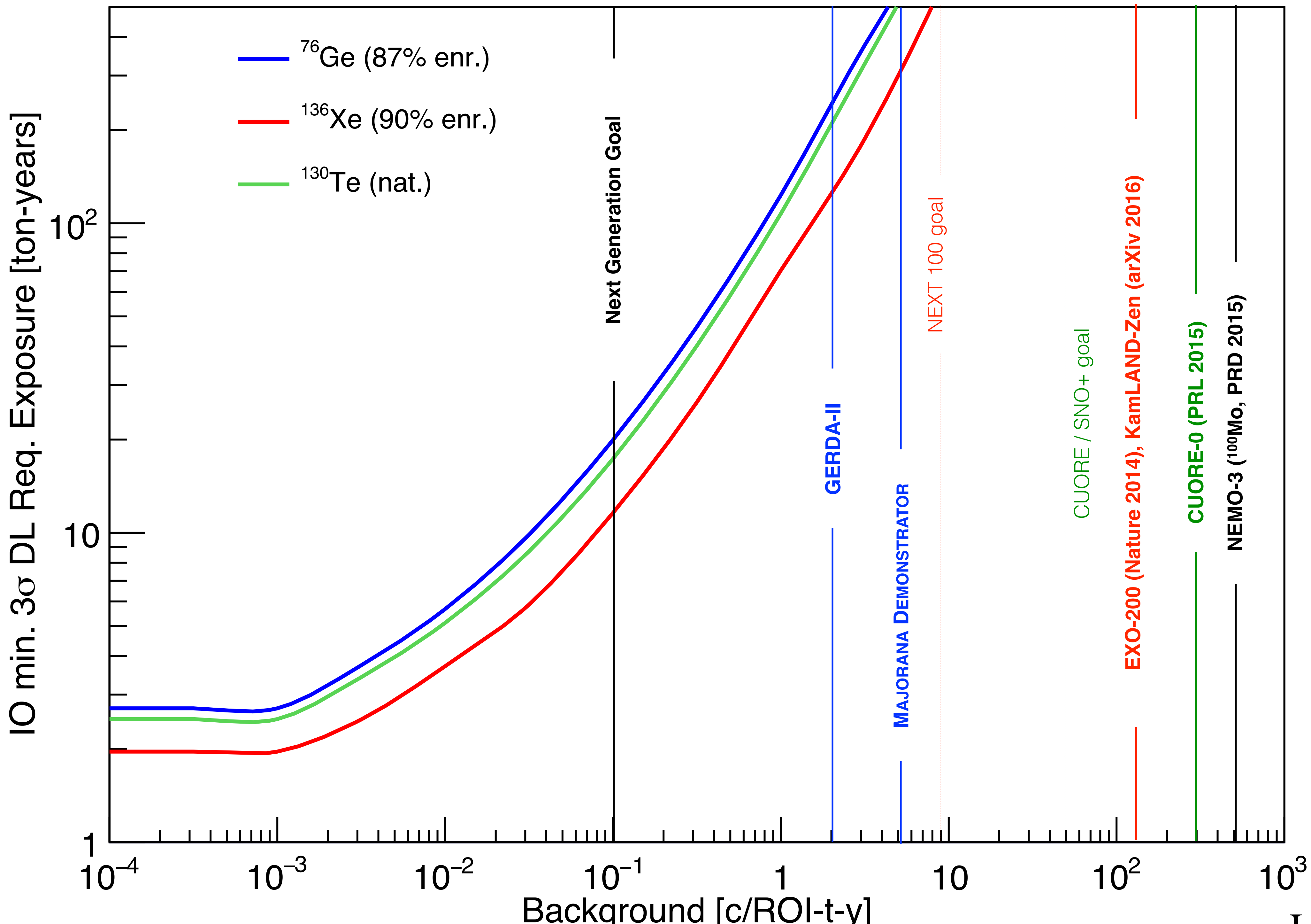
  - Energy resolution
  - Active veto detector
  - Tracking (topology)
  - Particle ID, angular, spatial, & time correlations
  - Fiducial self-consistent fits
  - Single site / multi site fitting
  - Granularity [multiple detectors]
  - Pulse shape discrimination (PSD)
  - Ion Identification

3σ Discovery : Exposure vs. Background



J. Detwiler

3σ Discovery : Exposure vs. Background



J. Detwiler

Next Generation Considerations

- Is there a preferred $0\nu\beta\beta$ isotope?
  *No preferred isotope in terms of per unit mass - **within current uncertainties on NME and g_A**.*
- What is required to cover Inverted Ordering masses?
  For a nearly ideal, background free experiment ~ 10 t-y
- Experimental Considerations
  - *Backgrounds - higher Q value (especially above ^{208}Tl line) is good.*
  - *Enrichment - ^{130}Te (34.5% nat. abundance) has an advantage.*
  - *$2\nu\beta\beta$ rate (irreducible background) - ^{76}Ge ^{130}Te, ^{136}Xe are the best (longest $T_{1/2}$), but impact depends on resolution.*

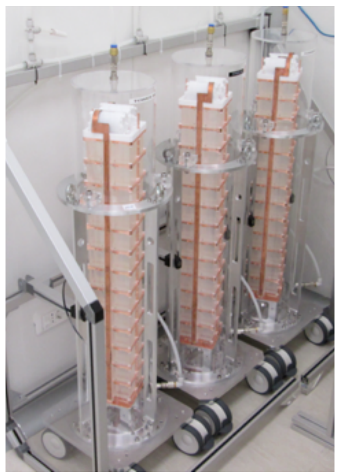
No clear leader. Need to evaluate on expt.-by-expt. basis. Backgrounds and resolution are critically important, in particular for discovery capable measurements.

Discovery of $0\nu\beta\beta$-decay

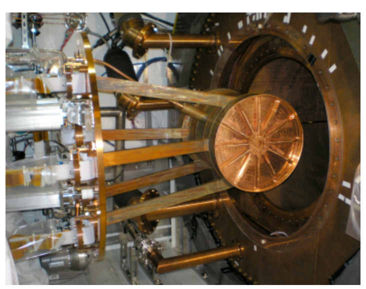
- Evidence : a combination of
  - Correct peak energy
  - Single-site or localized energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Good signal to background (3 σ discovery)
  - Full energy spectrum (backgrounds) understood.
- More direct confirmation : very difficult
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay(s)
- Convincing
  - Observe $0\nu\beta\beta$ in several different isotopes, using a variety of experimental techniques that meet the above definition of evidence

0νββ decay Experiments - Efforts Underway

CUORE



EXO200

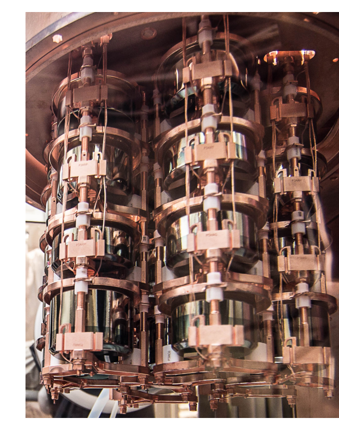


KamLAND Zen

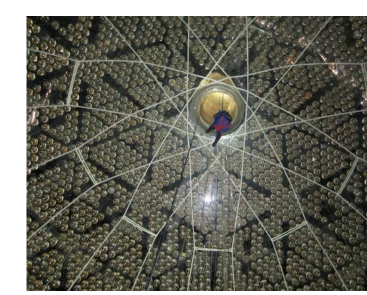
Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

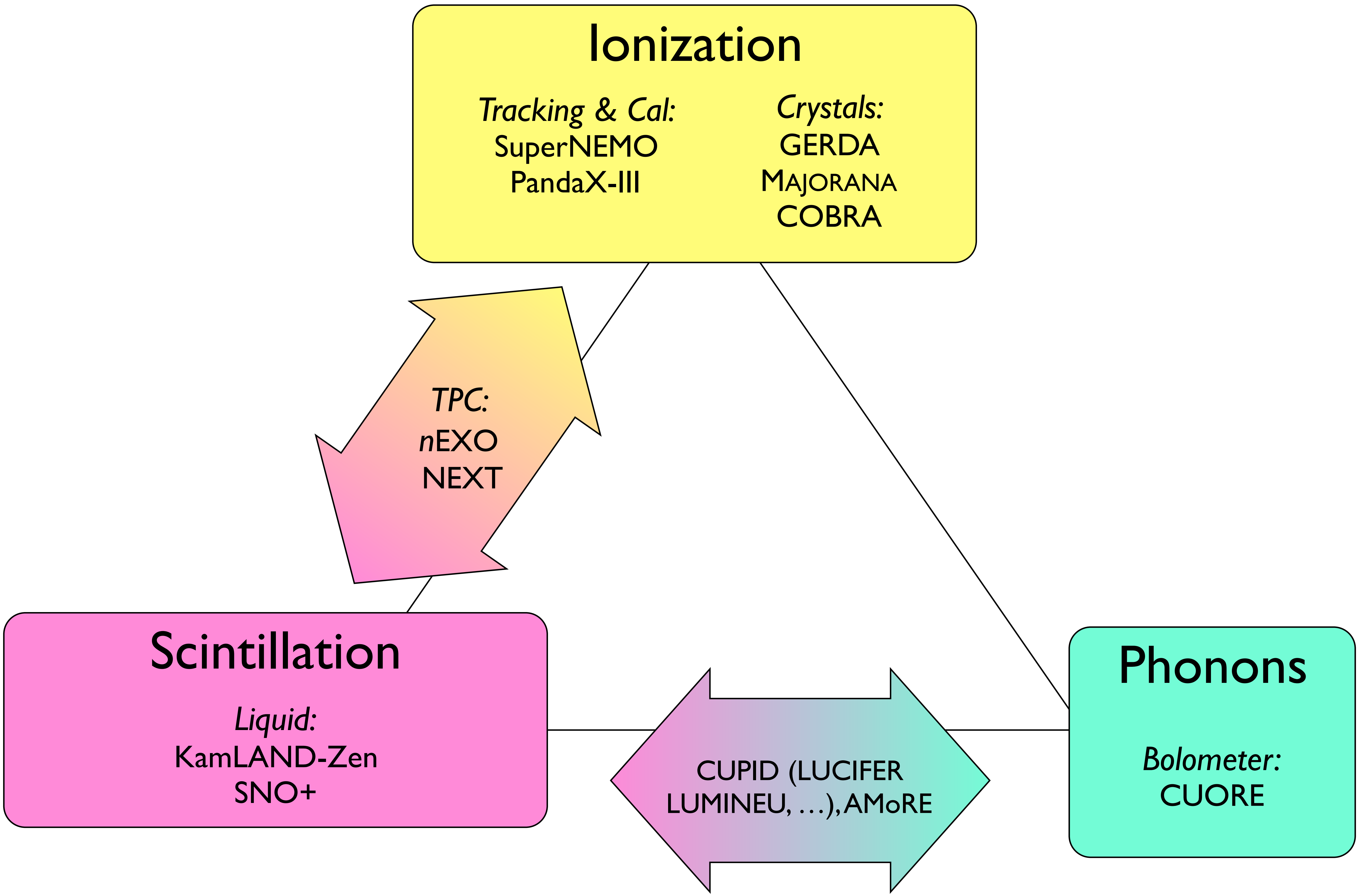
MAJORANA



SNO+



0νββ Detection Techniques



Next generation ton scale experiments

- Active international collaborations building on current efforts.
  - **^{76}Ge : LEGEND**, HPGE crystals, ~ton (builds on GERDA & MAJORANA) Detweiler
  - ^{82}Se : SuperNEMO : Se foils, tracking and calorimeter, 100 kg scale
  - ^{100}Mo : AMoRE : $CaMoO_4$ scint. bolometer, 200 kg scale
  - **^{136}Xe : nEXO** — Liquid TPC, 5 tons Gratta

    NEXT — High pressure gas TPC, ton scale

    PandaX - III — High pressure gas TPC, ton scale

    KamLAND-Zen — ^{136}Xe in scintillator, 800 kg scale

    LZ — ^{nat}Xe liquid TPC, 7 tons, operating 2019
  - **^{130}Te : CUPID (CUORE** with Particle ID) — Bolometer - Scintillation Maruyama

    SNO+ Phase I & II — ^{130}Te in scintillator
- Experiments can be done in a staged (phased) approach. Most are considering stepwise increments.
- Isotope enrichment (^{76}Ge, ^{82}Se, ^{136}Xe) requires time and $s.
- Potential underground lab sites
  - SNOLAB, JingPing, Gran Sasso, SURF, CanFranc, Frejus, Kamioka, ANDES, Y2L

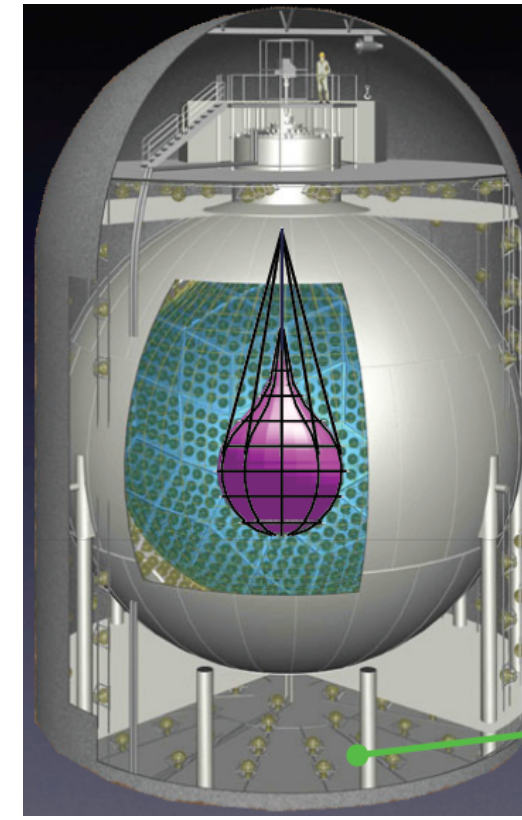
KamLAND-ZEN ^{136}Xe

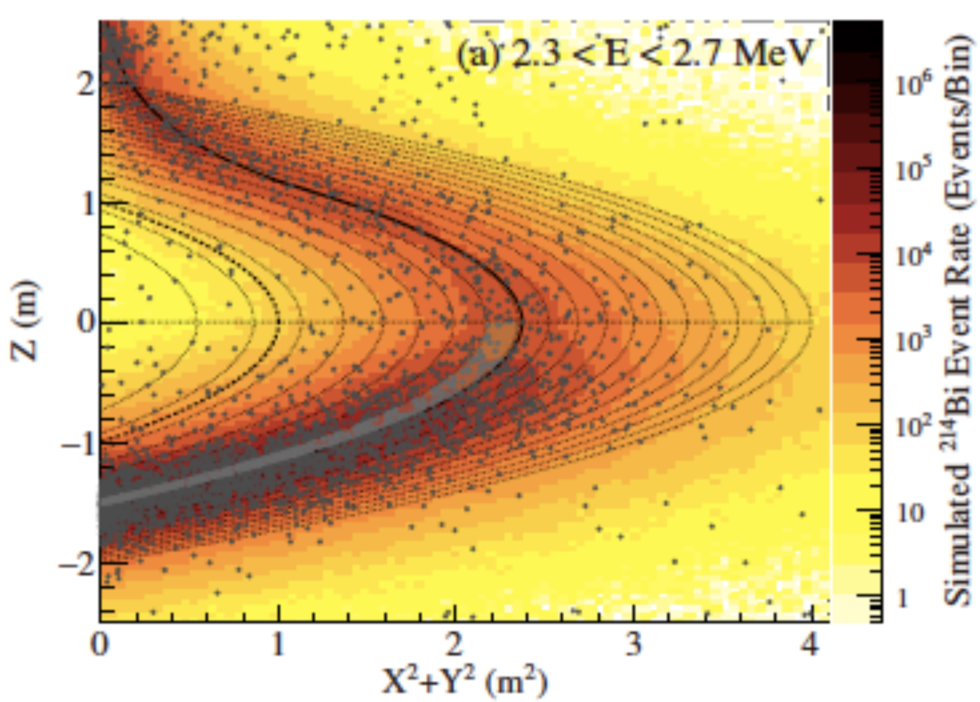
Scintillation

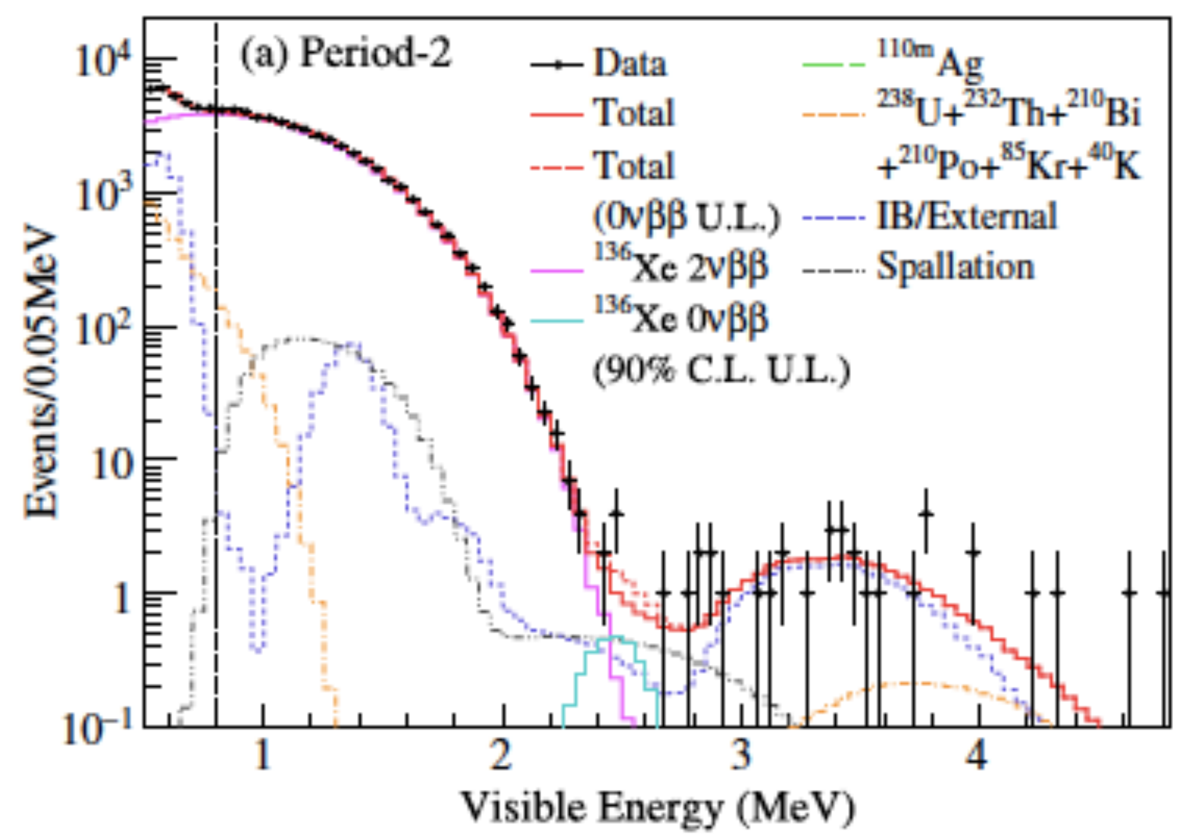
- ^{136}Xe (90% enr) in liquid scintillator, balloon R=1.5 m
- $Q_{\beta\beta}$=2457.8 keV ; σ ~ 114 keV (4.6%)
- Phase II (PRL **117** 082503 (2016))
  - 380 kg (2.96% by Xe wt.)
  - R=1 m fiducial cut
  - 534.5 days, with 126 kg y exposure
  - ^{110m}Ag contamination reduced by x10

  $T_{1/2} > 1.07 \times 10^{26}$ y (90% CL)

Sensitivity $T_{1/2} > 5.6 \times 10^{25}$ y (90% CL)

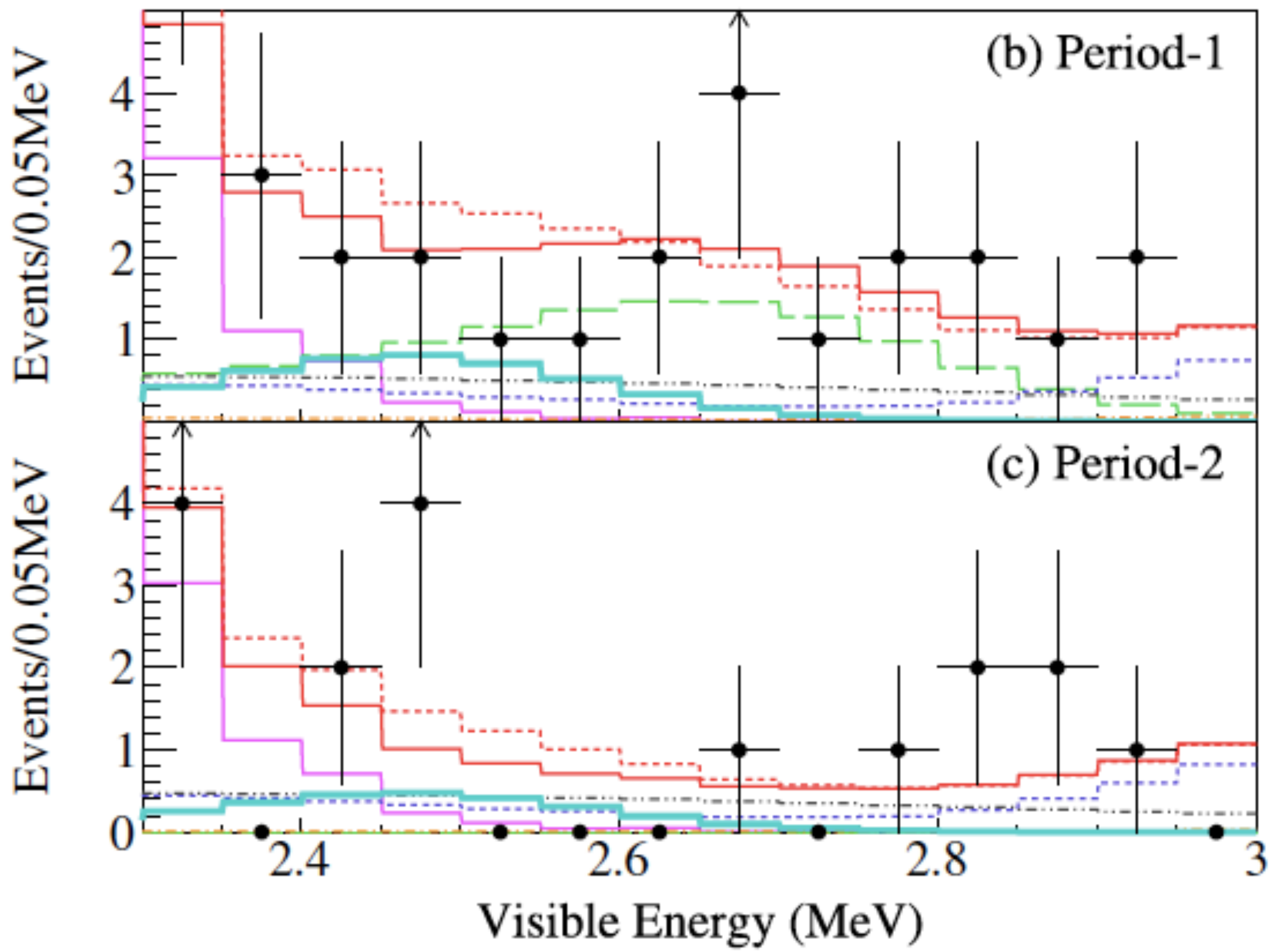


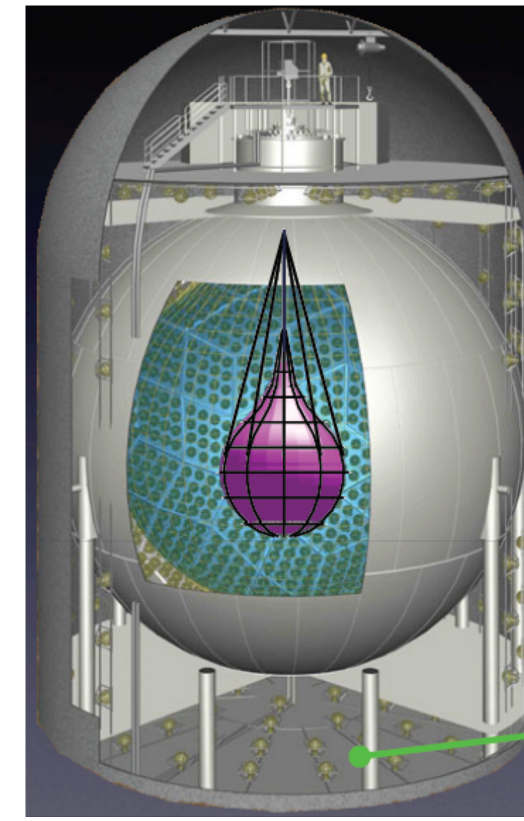


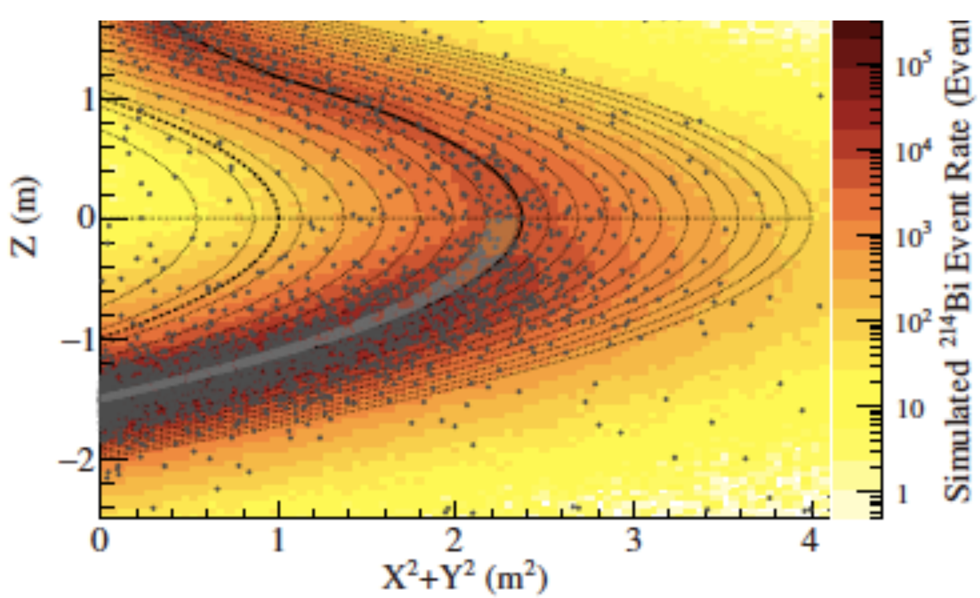


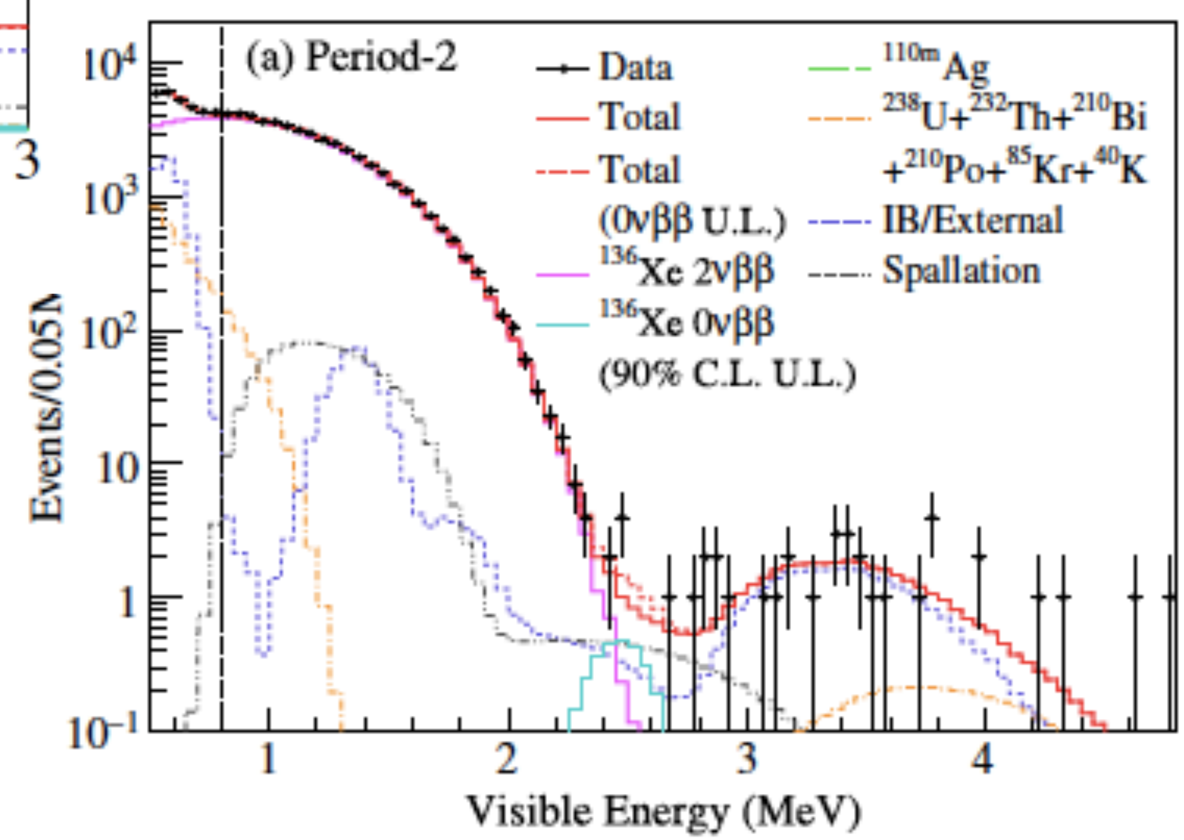
KamLAND-ZEN ^{136}Xe

Scintillation



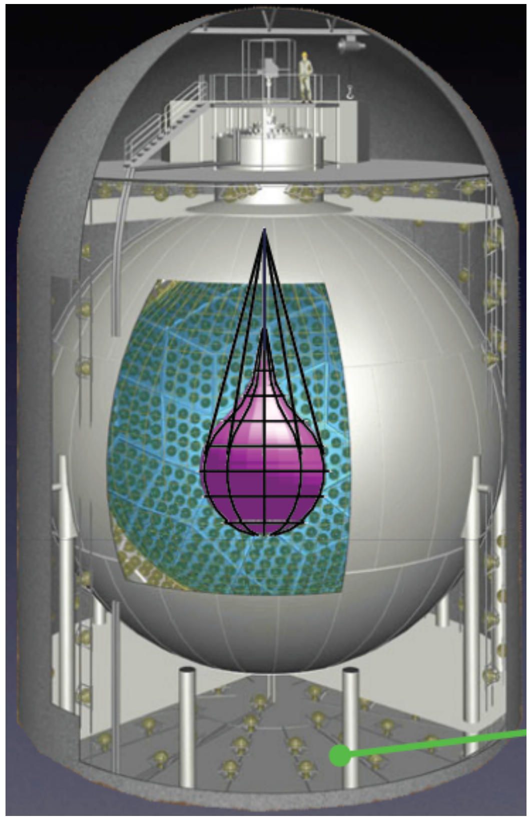






KamLAND-ZEN ^{136}Xe

Scintillation



- ^{136}Xe (90% enr) in liquid scintillator, balloon R=1.5 m
- $Q_{\beta\beta}$=2457.8 keV ; σ ~ 114 keV (4.6%)
- Phase II (PRL **117** 082503 (2016))
  - 380 kg (2.96% by Xe wt.)
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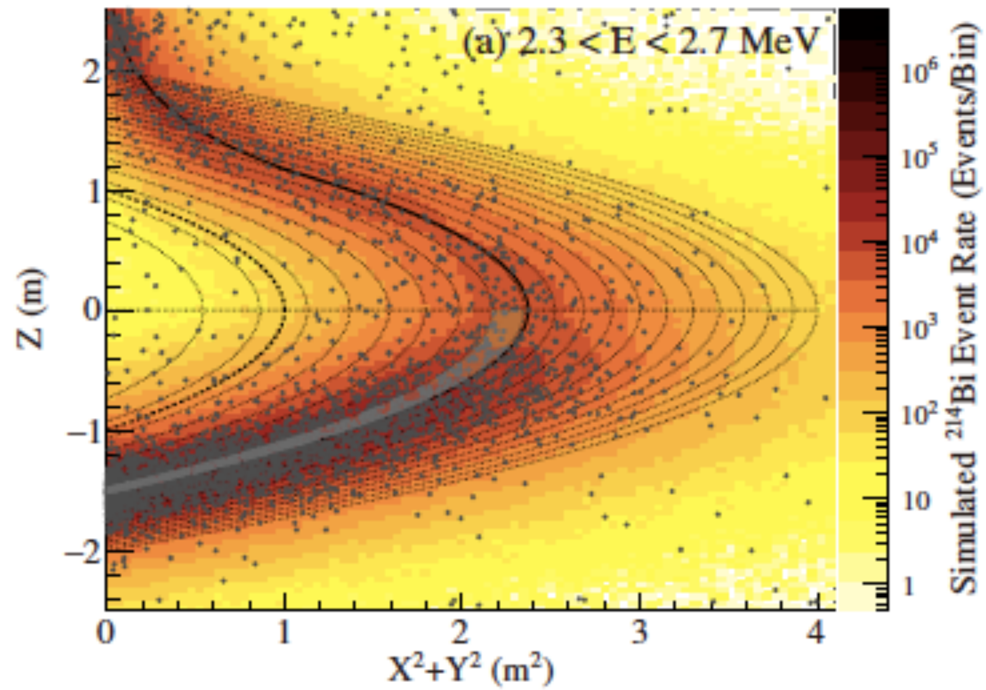


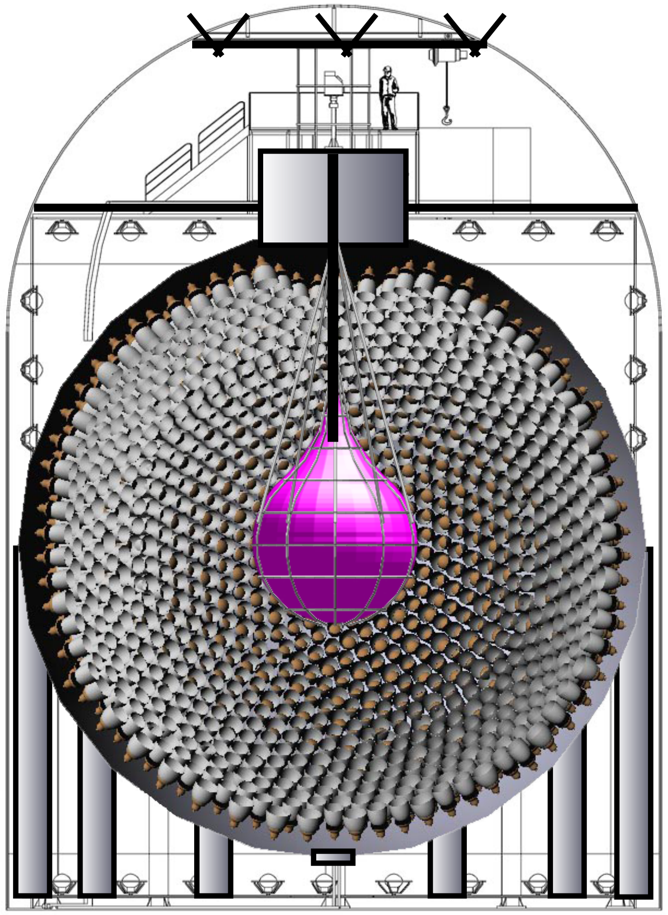
Unsuccessful new larger mini balloon deployment - 2016

Construction and deployment of new mini balloon with improved welding procedure for 800 kg (750 kg_{iso}) phase - 2017

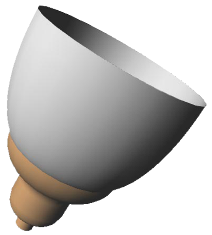
KamLAND-Zen future

Scintillation

Higher energy resolution for reducing 2ν BG ⇨ KamLAND2-Zen



1000+ kg xenon

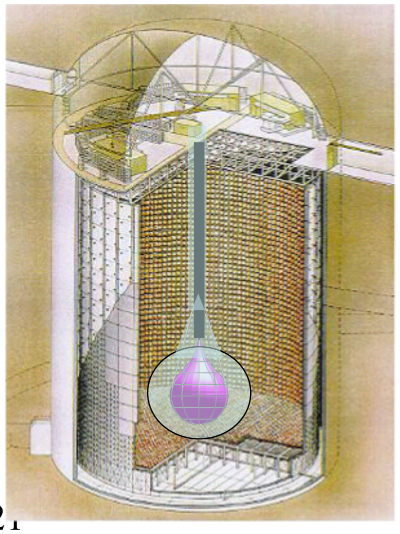


Winston cone	**light collection ×1.8**
high q.e. PMT 17"φ→20"φ ε=22→30+%	**light collection ×1.9**
New LAB LS (better transparency)	**light collection ×1.4**

expected σ(2.6MeV)= 4% → ~2%

target sensitivity: 20 meV

Far future:

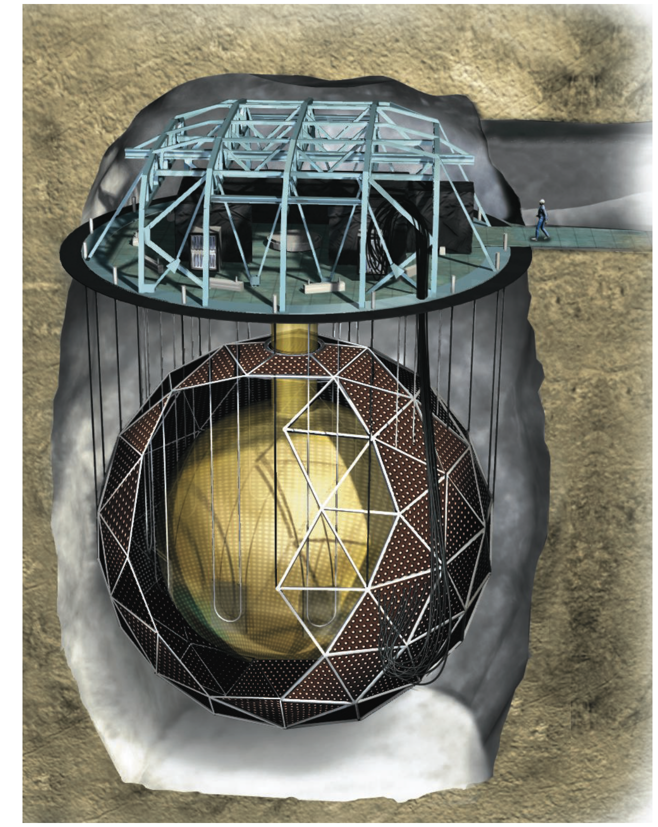


Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV

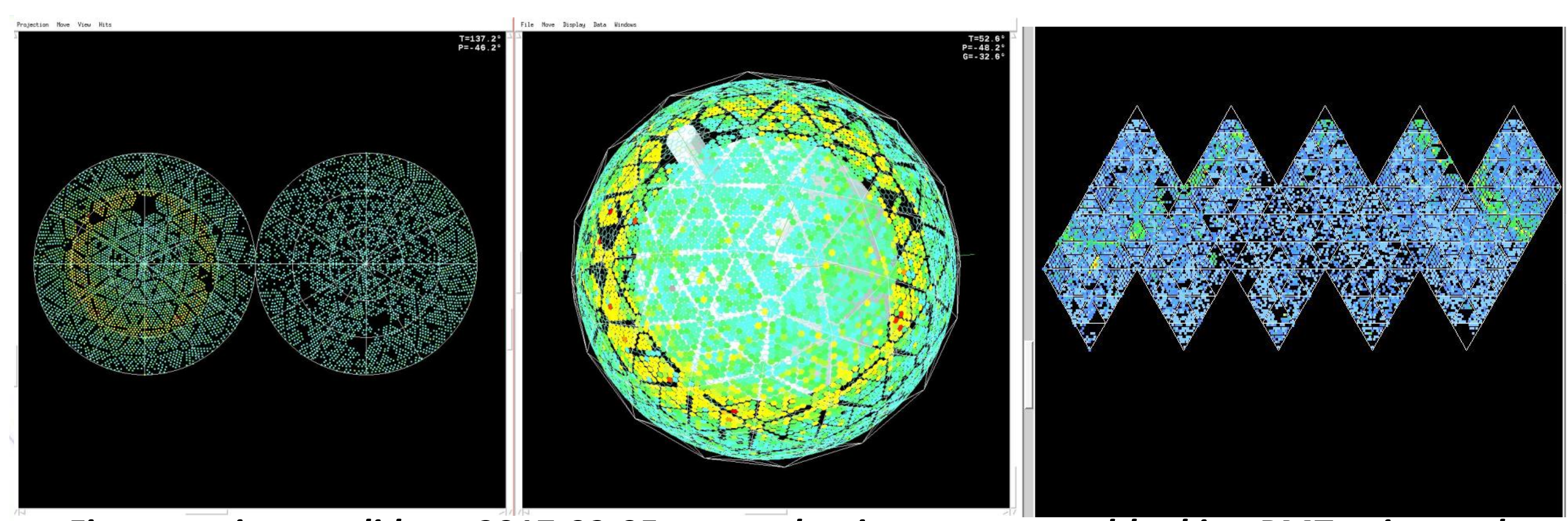
SNO+ ^{130}Te (Phase I)

Scintillation



- 1357 kg ^{130}Te (34.5% nat.) in liquid scintillator, Acrylic Vessel
- $Q_{\beta\beta}$=2530.3 keV ; $\sigma \sim$ 82 keV (4.6%)
- **Present (June 2017)** – water-filled data taking underway
  - measuring backgrounds
  - stable data taking, processing, data flow
  - invisible nucleon decay analysis
- **2017** – scintillator plant commissioning with LAB leading to scintillator filling, end of 2017
- **2018** – tellurium purification and synthesis
  - systems installation completed leading to Te purification and Te loading, late 2018

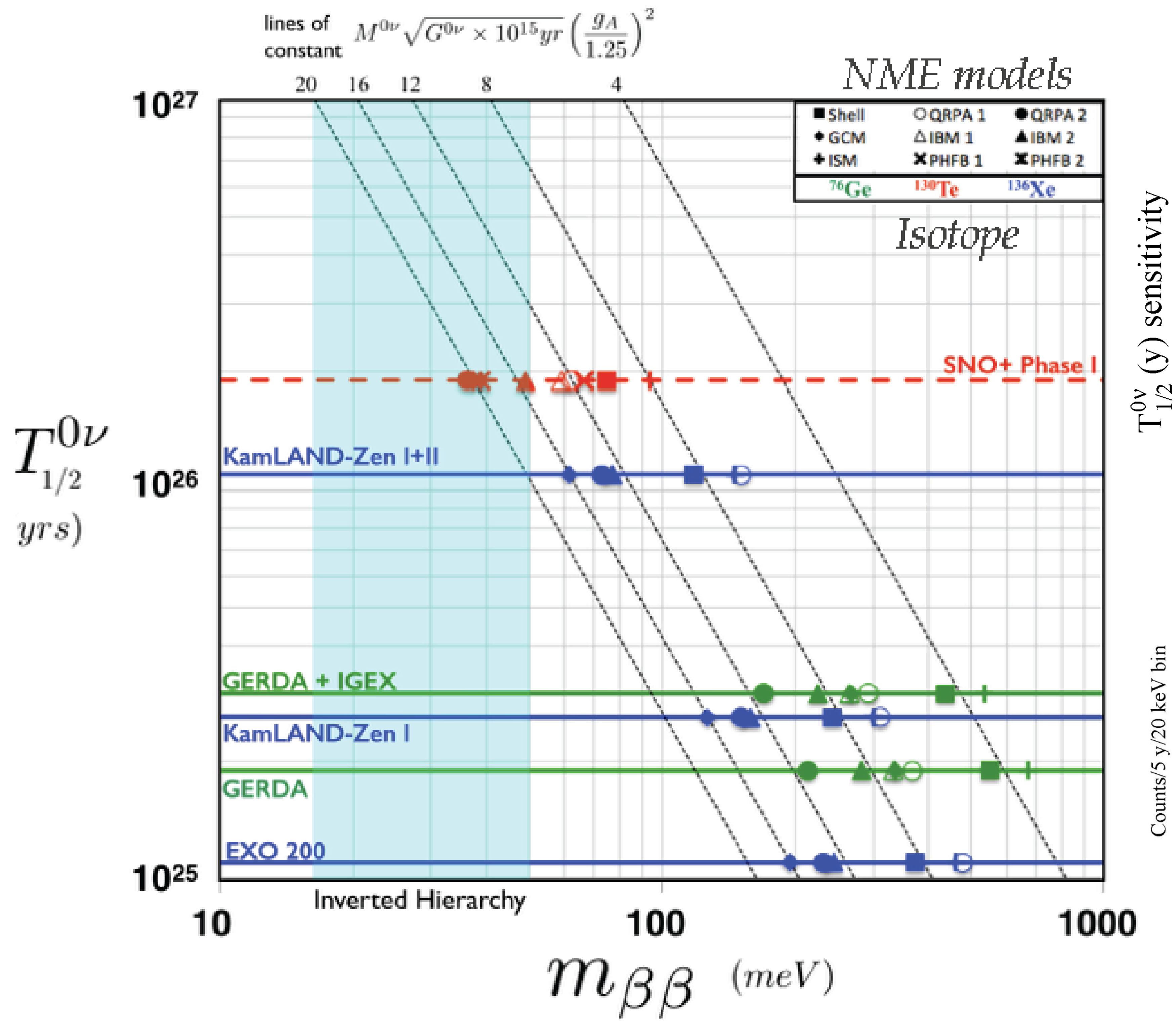
3.8 tonnes Telluric acid UG (half since 01/15); cosmogenic activity decaying

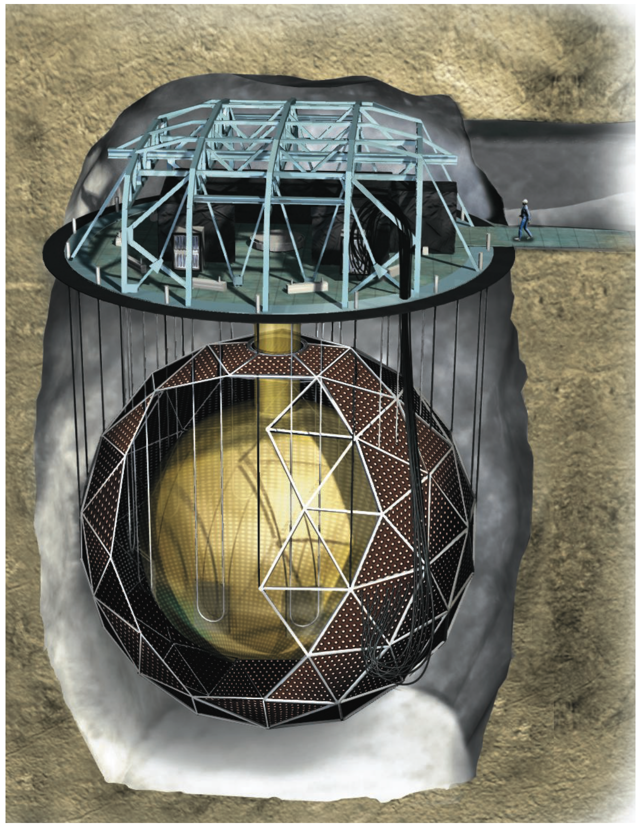


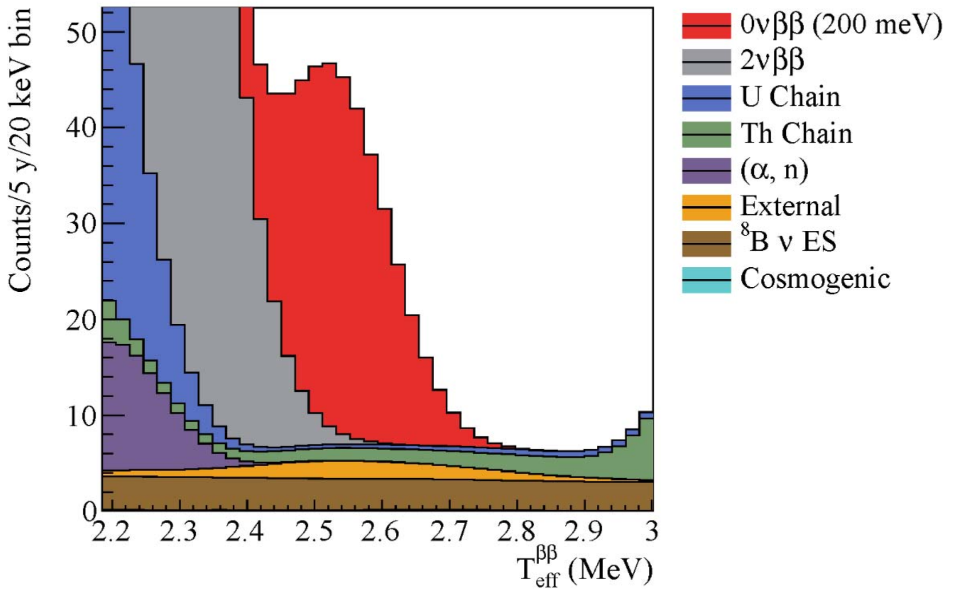
First neutrino candidate: 2017-02-05, upward-going, no outward-looking PMTs triggered

SNO+ ^{130}Te (Phase I)

Scintillation



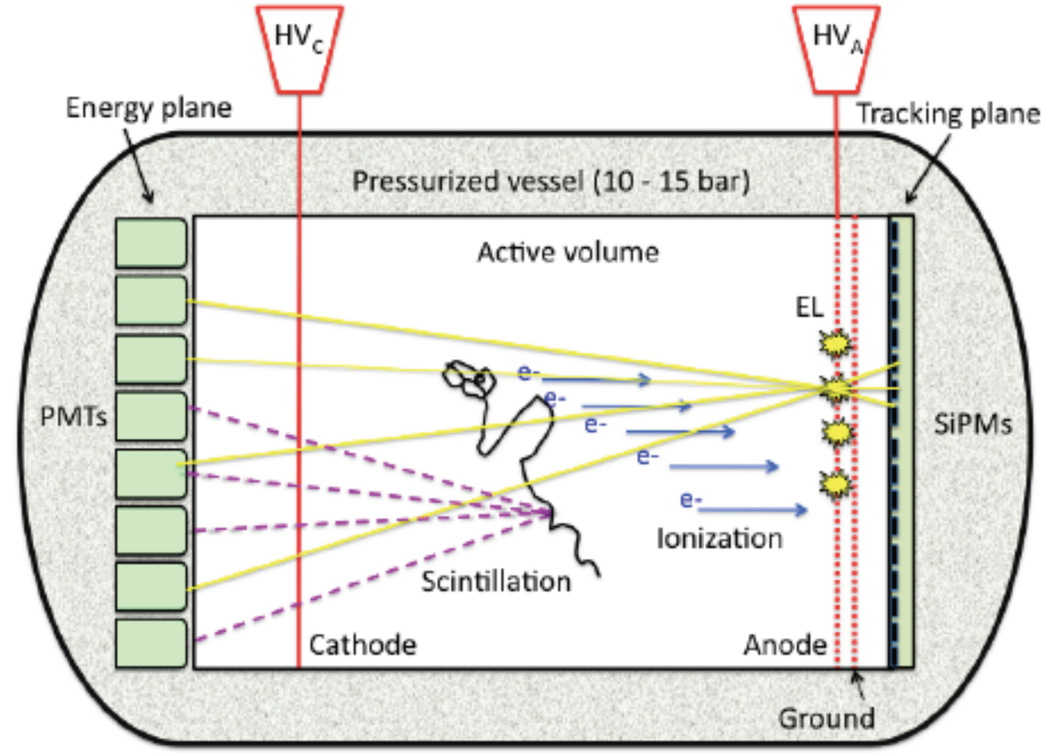




NEXT ^{136}Xe

Scintillation - Ionization

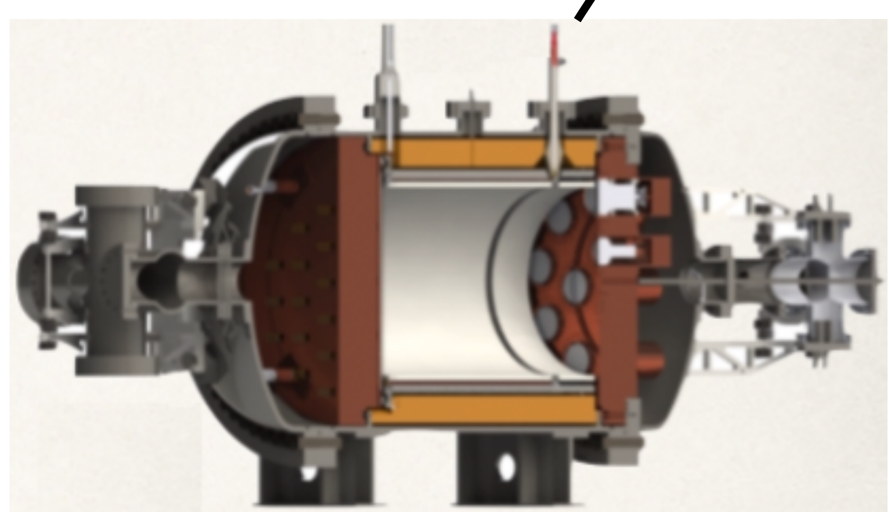
- High pressure (10-15 bar) ^{136}Xe TPC for high E- resolution + tracking capability
- $Q_{\beta\beta}$=2457.8 keV ; σ ~ 7.3 keV (0.3%)
- NEXT-NEW
  - 4.5 kg_{iso}, operating at Canfranc
- Planned : NEXT-100
  - 90 kg_{iso}, b = 44 c/(ROI-t-y)



V. Alvarez et al.,
JINST 7, T06001 (2012),
arXiv:1202.0721

NEXT-100 (~100 kg)
[2018 - 2020's]

Neutrinoless double beta decay searches



NEXT-NEW (~5 kg)
[2015 - 2018]

Underground and radio-pure operations, background, ββ2v

NEXT-tonne (~1000 kg)
[future generation]

NEXT ^{136}Xe

Scintillation - Ionization

- High pressure (10-15 bar) ^{136}Xe TPC for high E- resolution + tracking capability
- $Q_{\beta\beta}$=2457.8 keV ; $\sigma \sim$ 7.3 keV (0.3%)
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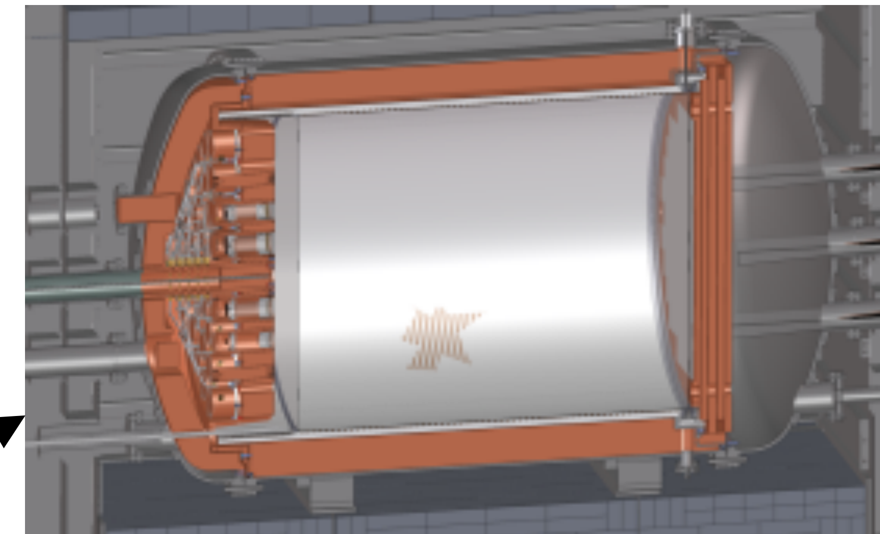

NEXT-100 (~100 kg)
[2018 - 2020's]

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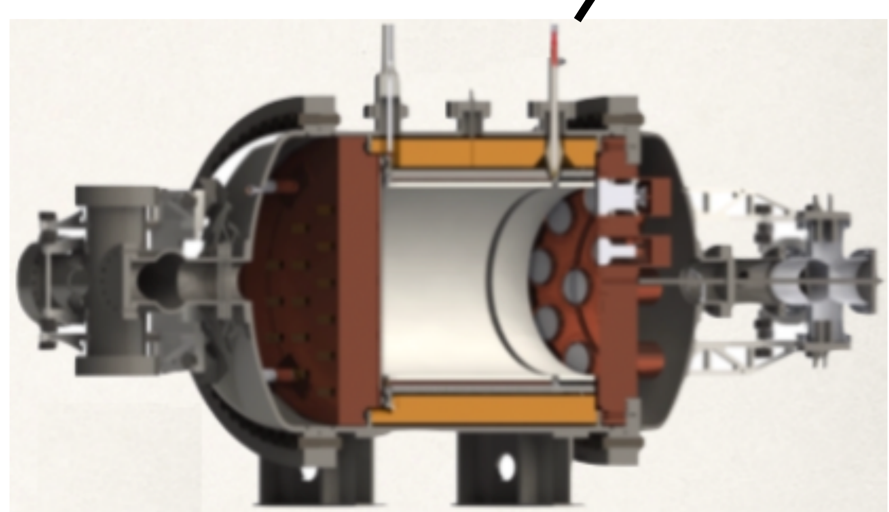
JINST 7, T06001 (2012),
arXiv:1202.0721



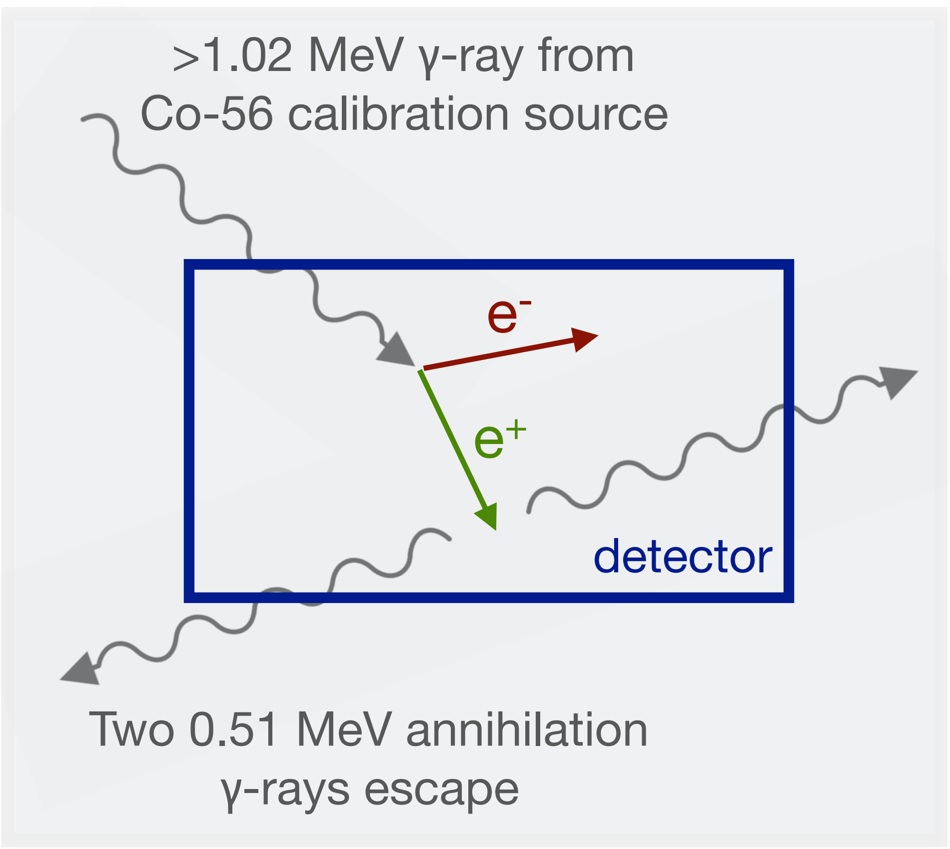
NEXT-NEW (~5 kg)
[2015 - 2018]

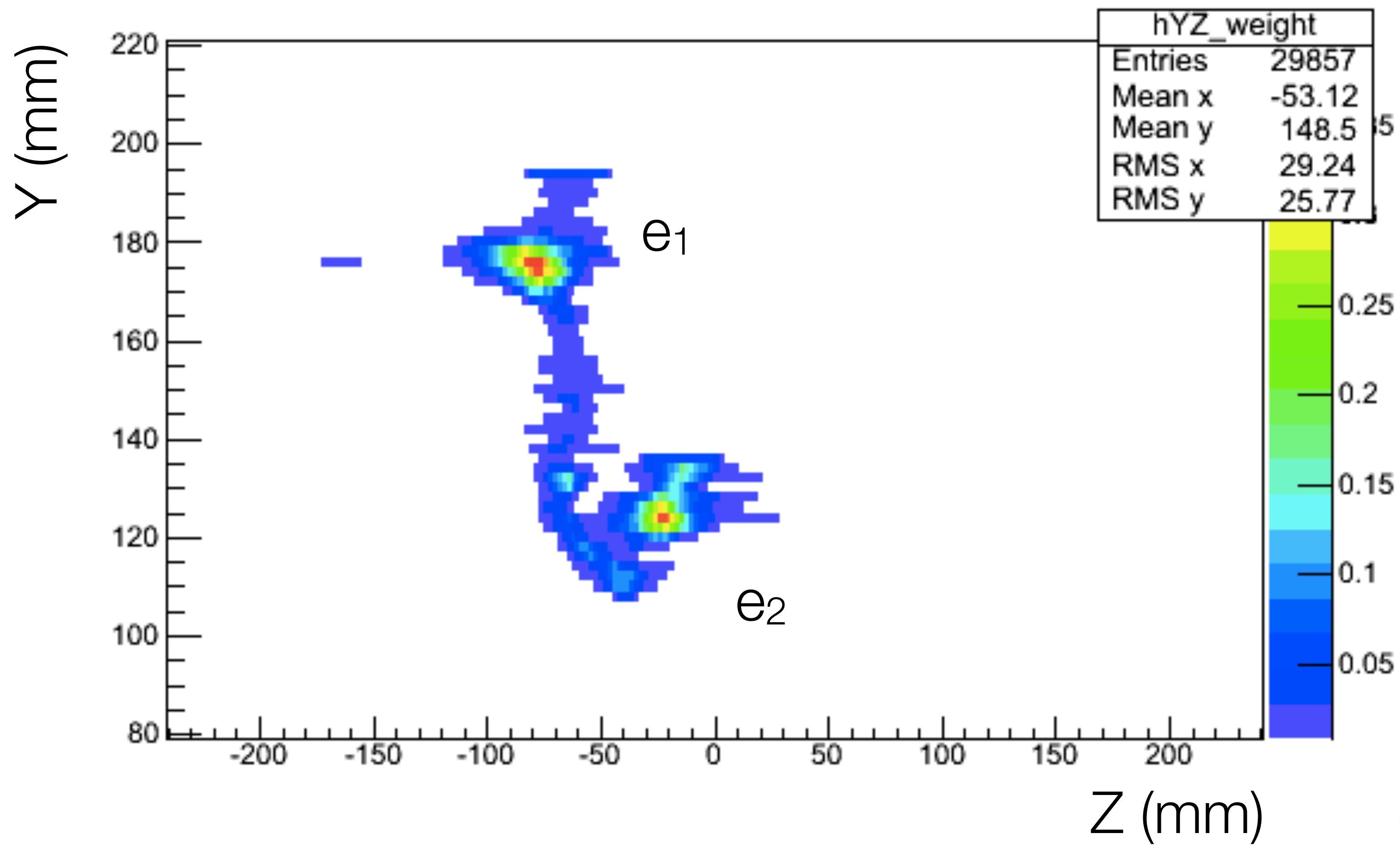
Underground and radio-pure operations, background, ββ2v

NEXT-tonne (~1000 kg)
[future generation]

Topological Reconstruction

- Observe the two stopping electron tracks emitted from common vertex, characteristic of double beta decays
- Powerful handle for single-electron background suppression



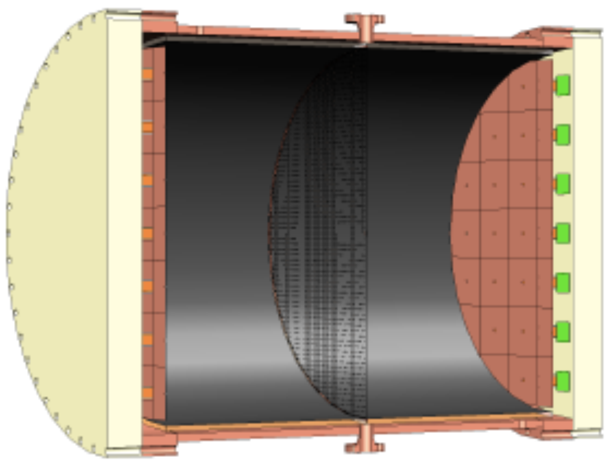


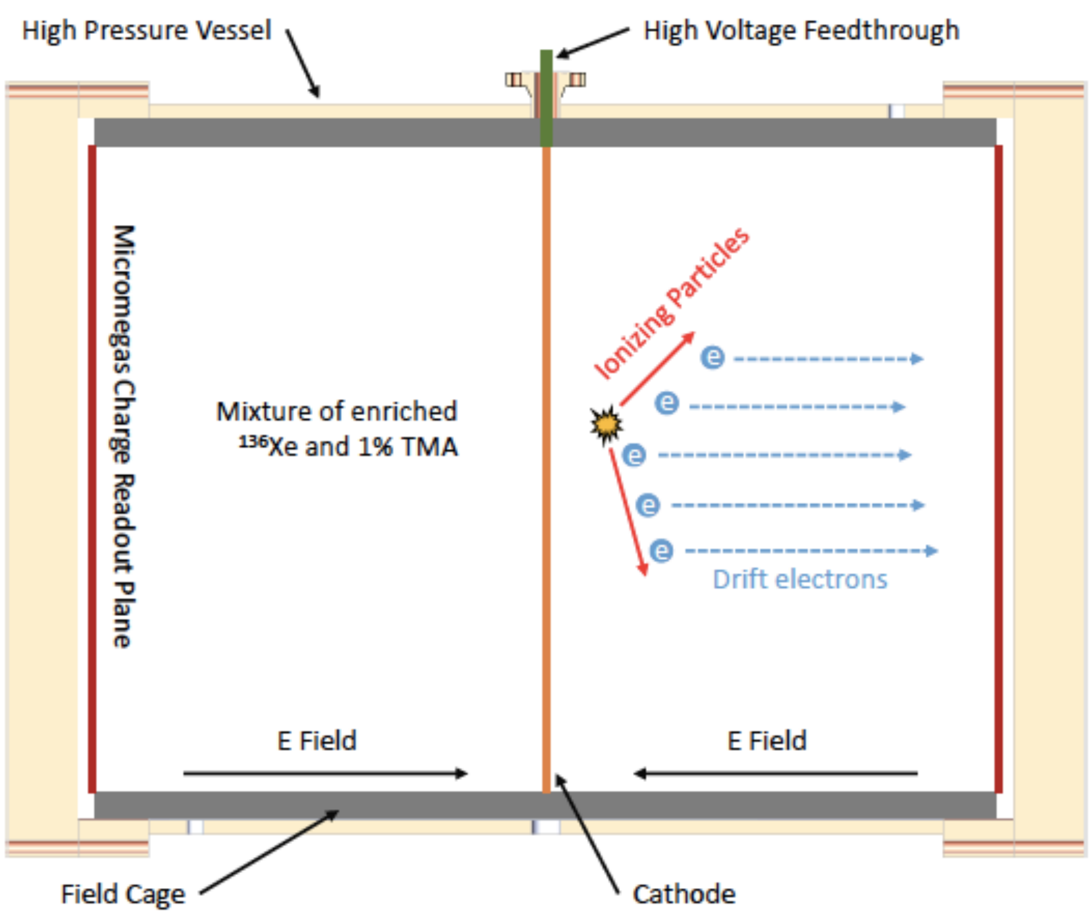
PandaX-III ^{136}Xe

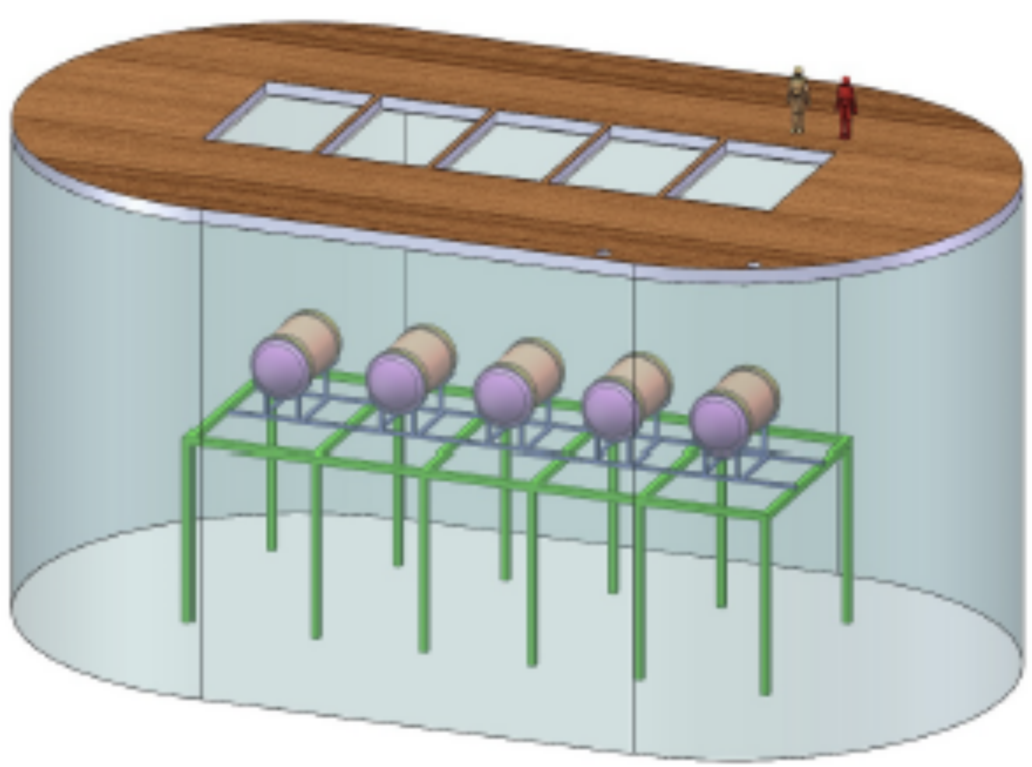
Ionization

X. Chen et al., arXiv:1610.08883

- High pressure (10 bar) TPC using 90% enr ^{136}Xe with Micro-MEsh Gaseous structure readout
- $Q_{\beta\beta}$=2457.8 keV ; $\sigma \sim$ 31 keV (1.3%)
- Five, 180 kg_{iso} modules, in large water shield
- Located at China Jinping Laboratory



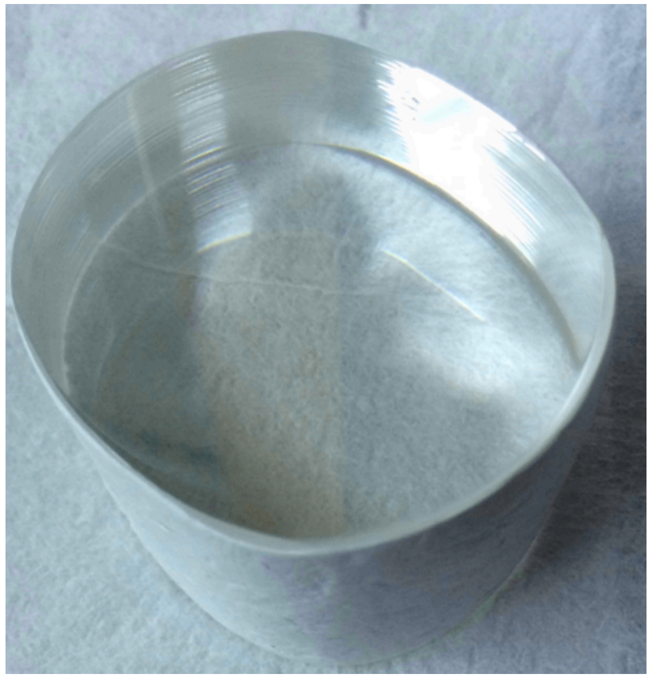




AMoRE ^{100}Mo

Scintillator - Phonons

- $^{40}Ca^{100}MoO_4$ crystals (95% enr. ^{100}Mo, depleted ^{48}Ca) with bolometer (Metallic Magnetic Calorimeter) and light readout.
- $Q_{\beta\beta}$=3034.4 keV
- Phases
  - AMoRE Pilot (1.5 kg) [2016-2017]
    - 6 cyrstals, operating at 8 mK
    - σ (@2.6 MeV) ~ 4.6 - 5.8 keV (0.2%)
  - AMoRE I (4.5 kg) [2017-2020]
  - AMoRE II (200 kg) [2020-2024]
    - Enriched material by 2018
    - Evaluating : Li_2MoO_4 and $Na_2Mo_2O_7$
- AMoRE Pilot and I at Yingyang Undeground Laboratory, AMoRE at new UG lab, Astroparticle Research Facility at Handuk mine.



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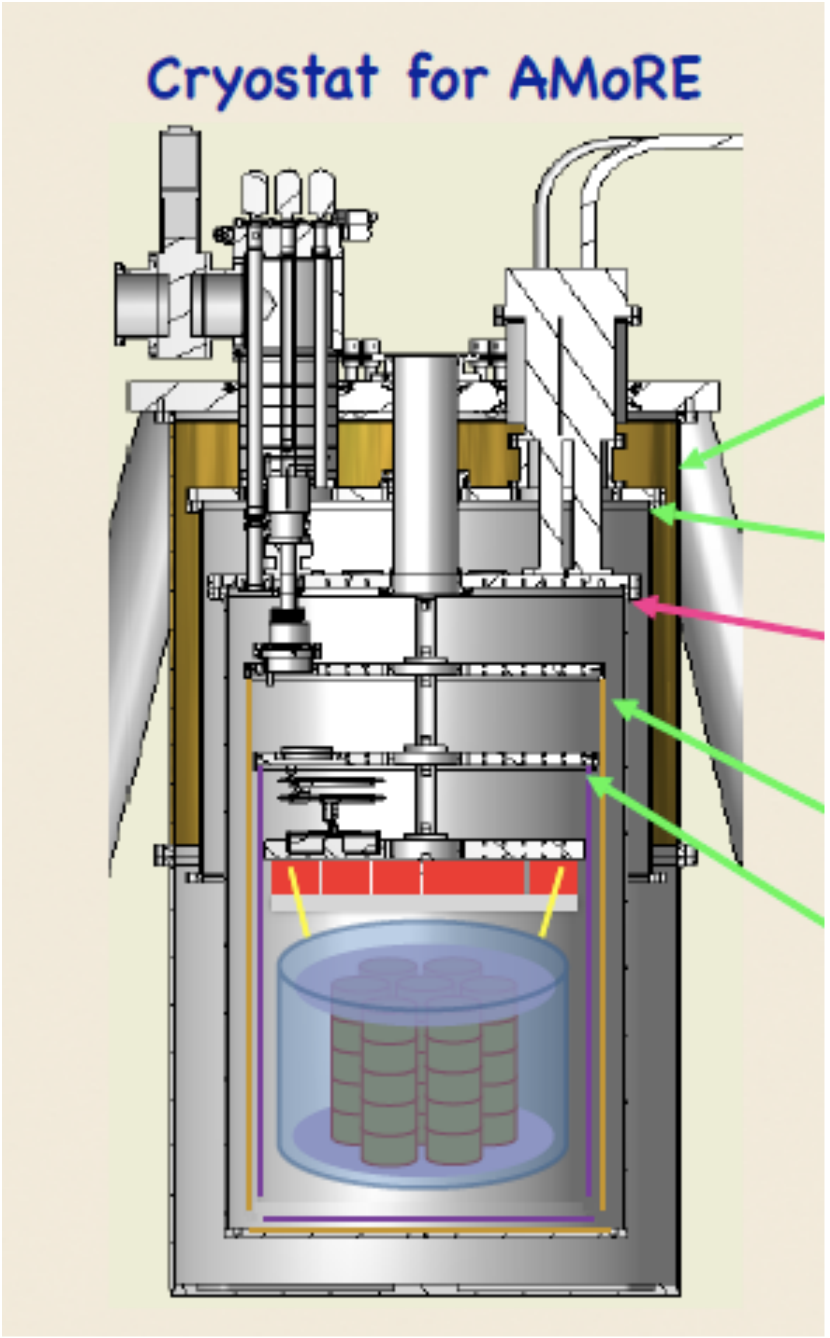
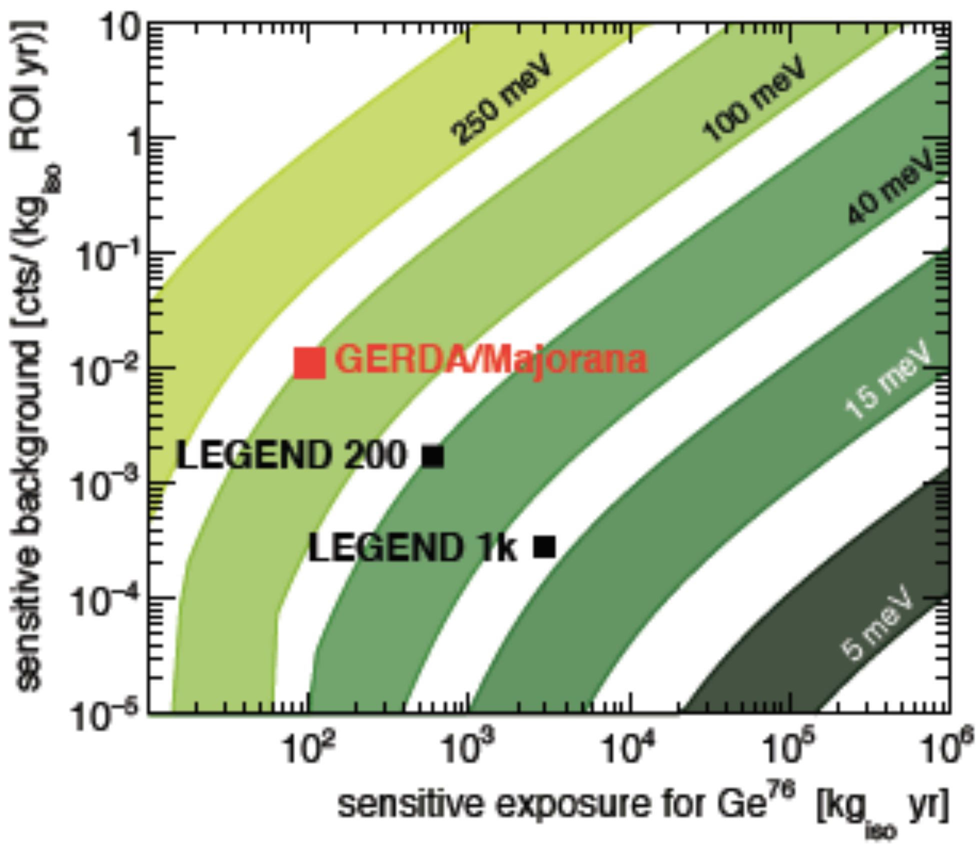


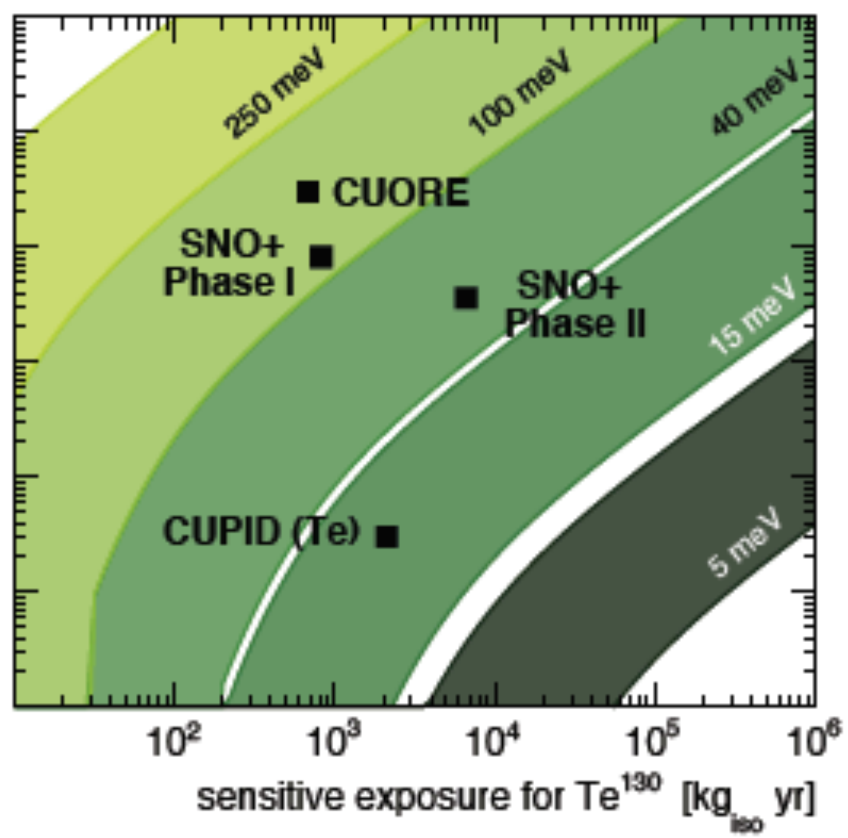
Discovery Sensitivity Comparison

Discovery probability of next-generation neutrinoless double-beta decay experiments
Matteo Agostini, Giovanni Benato, and Jason Detwiler   arXiv:1705.02996v1

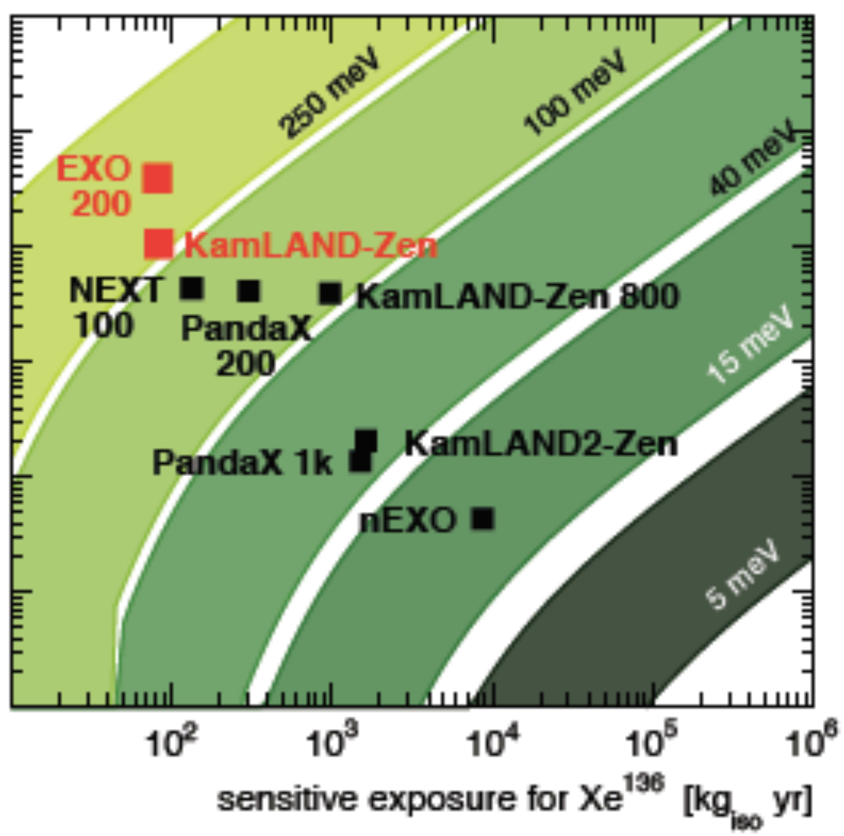
^{76}Ge



^{130}Te



^{136}Xe



Red : Achieved Backgrounds; Black : Projected Backgrounds

Width of bands based on range of NME values

Considerations for Next Gen 0νββ-decay experiments

- Significant experimental progress since the 2015 long range plan.
  - Experiments have attained or are approaching sensitivities of $T_{1/2} > 10^{26}$ years, with substantially reduced backgrounds.
- Large international collaborations are moving forward with next generation experiments based on lessons learned from the current measurements.
- For discovery of 0νββ, experiments require good energy resolution, low backgrounds ("background free") and large exposures (t-y).
- Discovery will require observation by independent experiments, using different isotopes.
- Reduced uncertainties on NME and g_A will have a critical impact on understanding sensitivity and discovery potential.

0νββ INT Workshop Discussions

- Sensitivity in the presence of backgrounds.
- Self-consistent fiducial vol. analysis (e.g. KamLAND-Zen).
- Bayesian vs. Frequentist approaches to sensitivity and discovery level.
- Incorporation of systematic uncertainties into overall estimates of sensitivity.