Future Physics with Germanium:

Where are we now and what do we need for $0\nu\beta\beta$ and dark matter (from 1t to 100t)

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COSMS INSTITUTE

TUNL

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Questions

- Where are we now for $0\nu\beta\beta$?
- Is there a preferred $0\nu\beta\beta$ isotope in terms of sensitivity?
- What levels of backgrounds and exposure are required for future $0\nu\beta\beta$ experiments to cover the inverted ordering region?
- What are considerations for future ton scale $0\nu\beta\beta$ experiments?
- What is needed to build a ton scale ^{76}Ge Experiment?
- Costs & International prospects?
- Beyond the ton scale?
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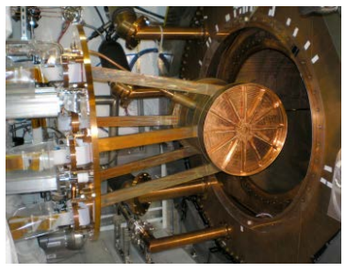
0νββ decay Experiments - Efforts Underway

CUORE

EXO200

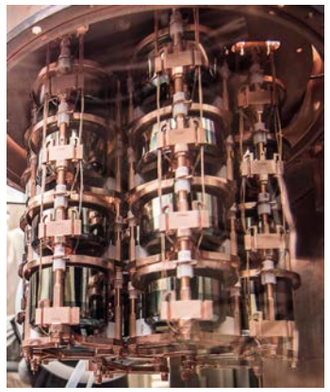


KamLAND Zen

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.	~ tonne	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
II		Point contact Ge in LAr	30-35 kg	Commissioning
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	30 kg	Commissioning
Ton Scale Ge	Ge-76	Point contact	~ tonne	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	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	CaMoO4 scint. bolometer	50 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
COBRA	Cd-116	CdZnTe detectors	10 kg 183 kg	R&D
CUORICINO	Te-130	TeO_2 Bolometer	10 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
CUPID	Te-130	TeO_2 Bolometer & scint.	~ tonne	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	360 kg	Operating
		2.7% in liquid scint.	800 kg	Upgrade
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	Construction
EXO200	Xe-136	Xe liquid TPC	160 kg	Operating*
nEXO	Xe-136	Xe liquid TPC	~ tonne	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA



SNO+

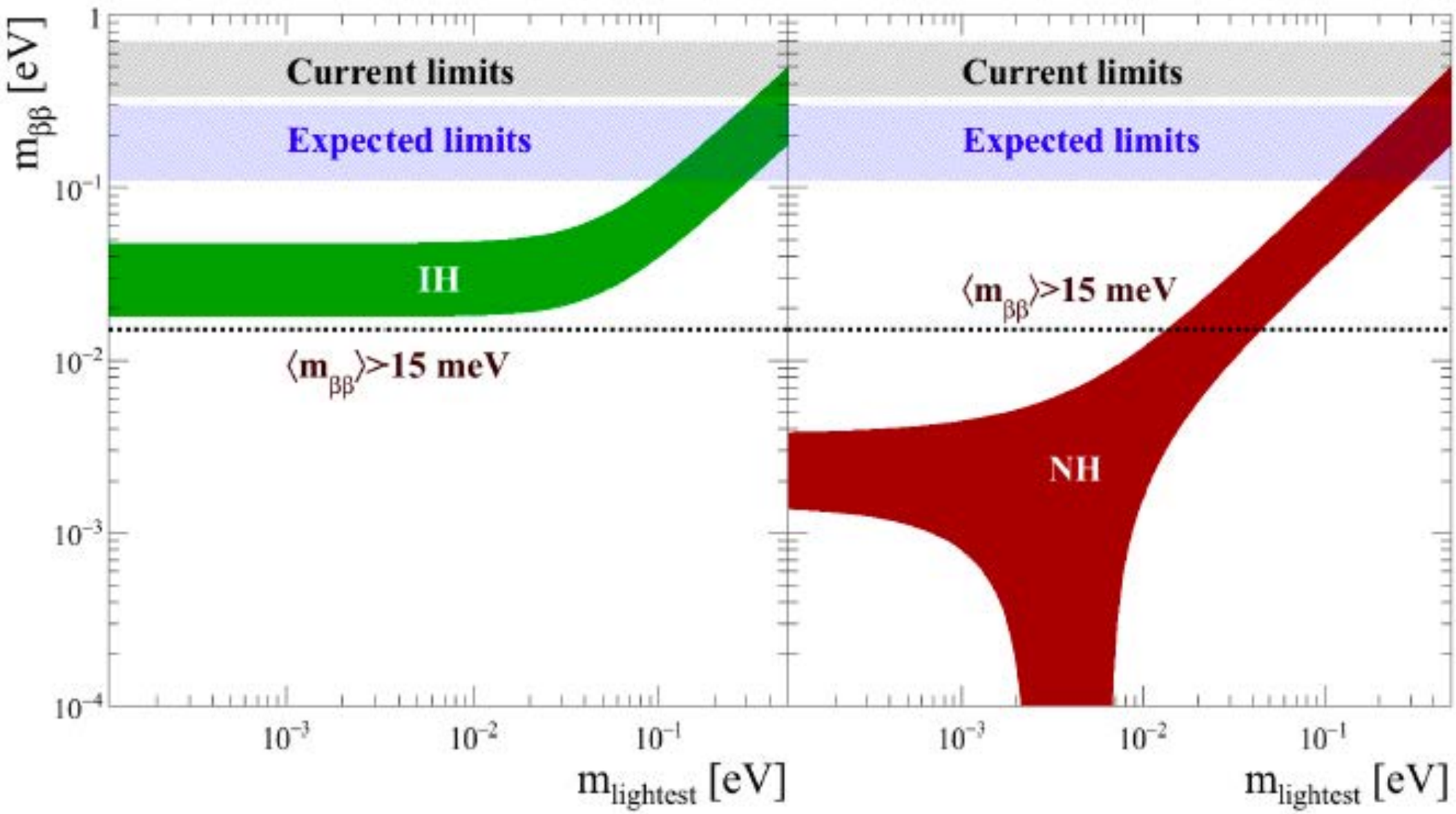
* expect to resume operations in 2016

0νββ Decay and <mββ>

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

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



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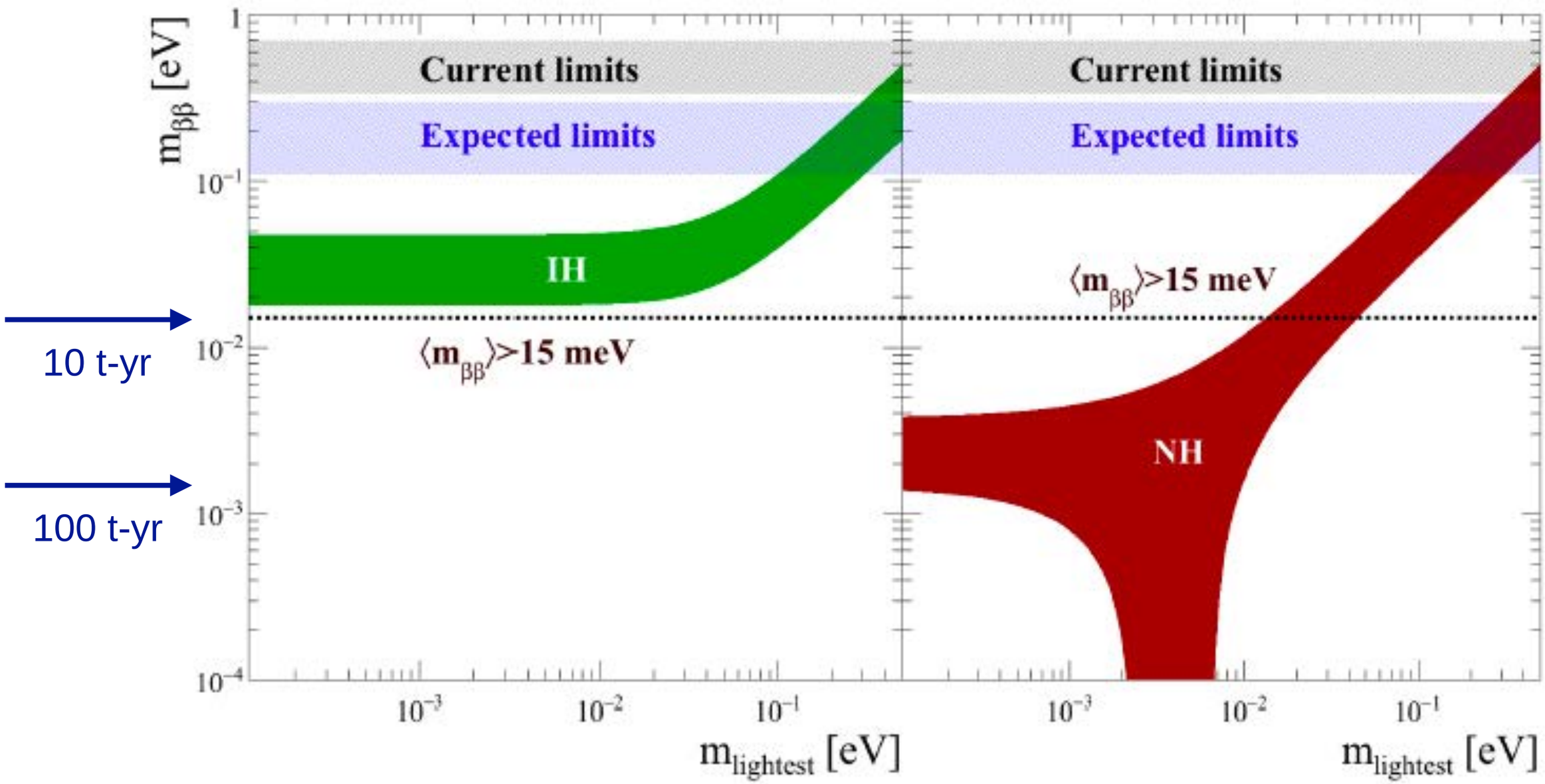

Questions

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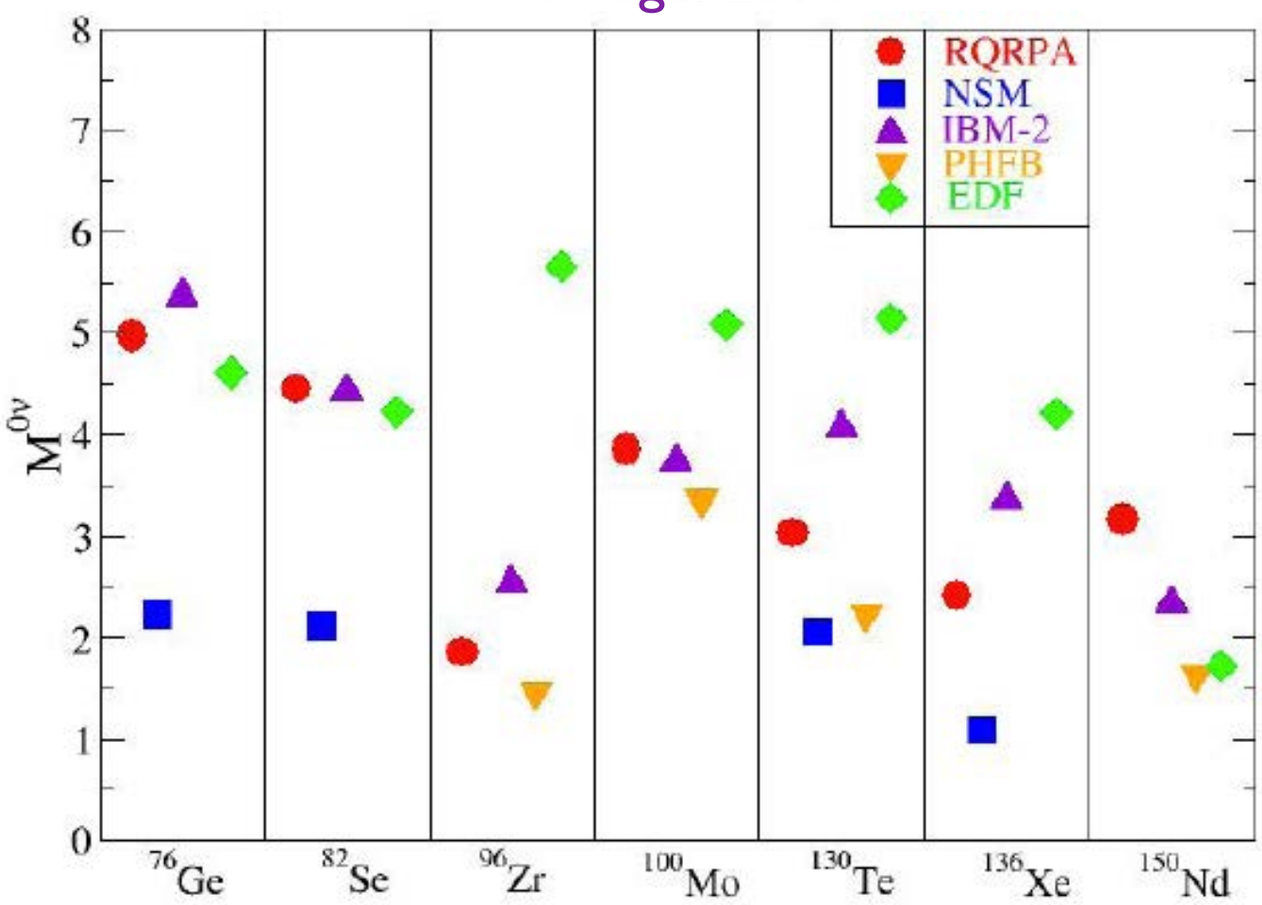
Nuclear matrix elements - $M^{0\nu}$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

- Available model results differ by factors of 2-3
- Discovery goals set by taking "pessimistic" matrix elements
- Improvement is highly desirable: the matrix elements are essential for interpretation — Recently funded theory initiative in the U.S. with goal of quantifying uncertainties.

P. Vogel 2014



Matrix elements for "standard mechanism"

Sensitivity to <$m_{\beta\beta}$> per atom

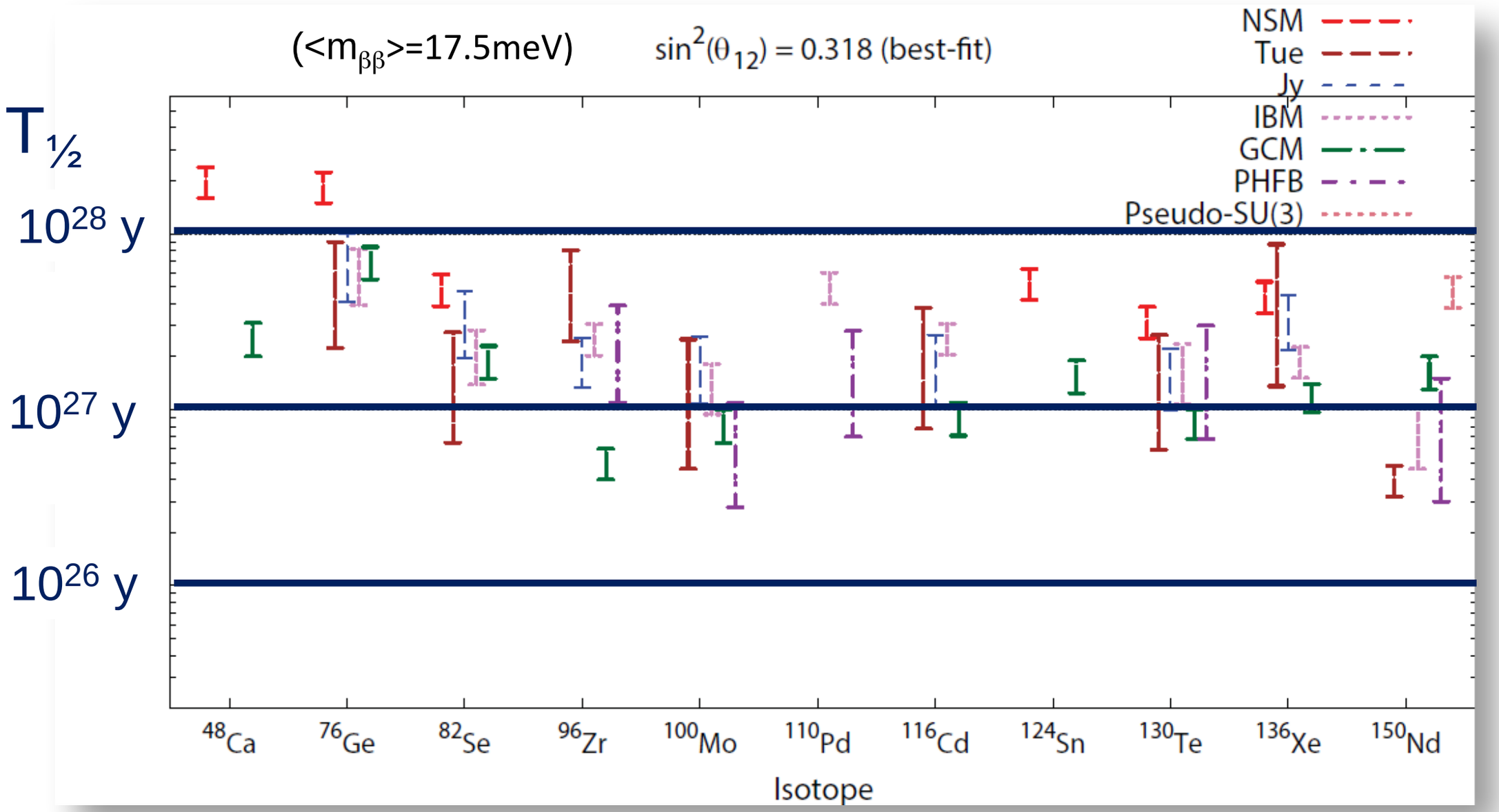


Figure source: A. Dueck, W. Rodejohann, and K. Zuber, Phys. Rev. D83 (2011) 113010.

Rates (sensitivity) per unit mass

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

Typically phase space is expressed in activity per atom, not per unit mass.

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

The phase space $G_{0\nu}$ is in activty per atom

$$\lambda_{0\nu}\frac{N}{M} = \frac{\ln(2)N_A}{Am_e^2} G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$$\equiv H_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

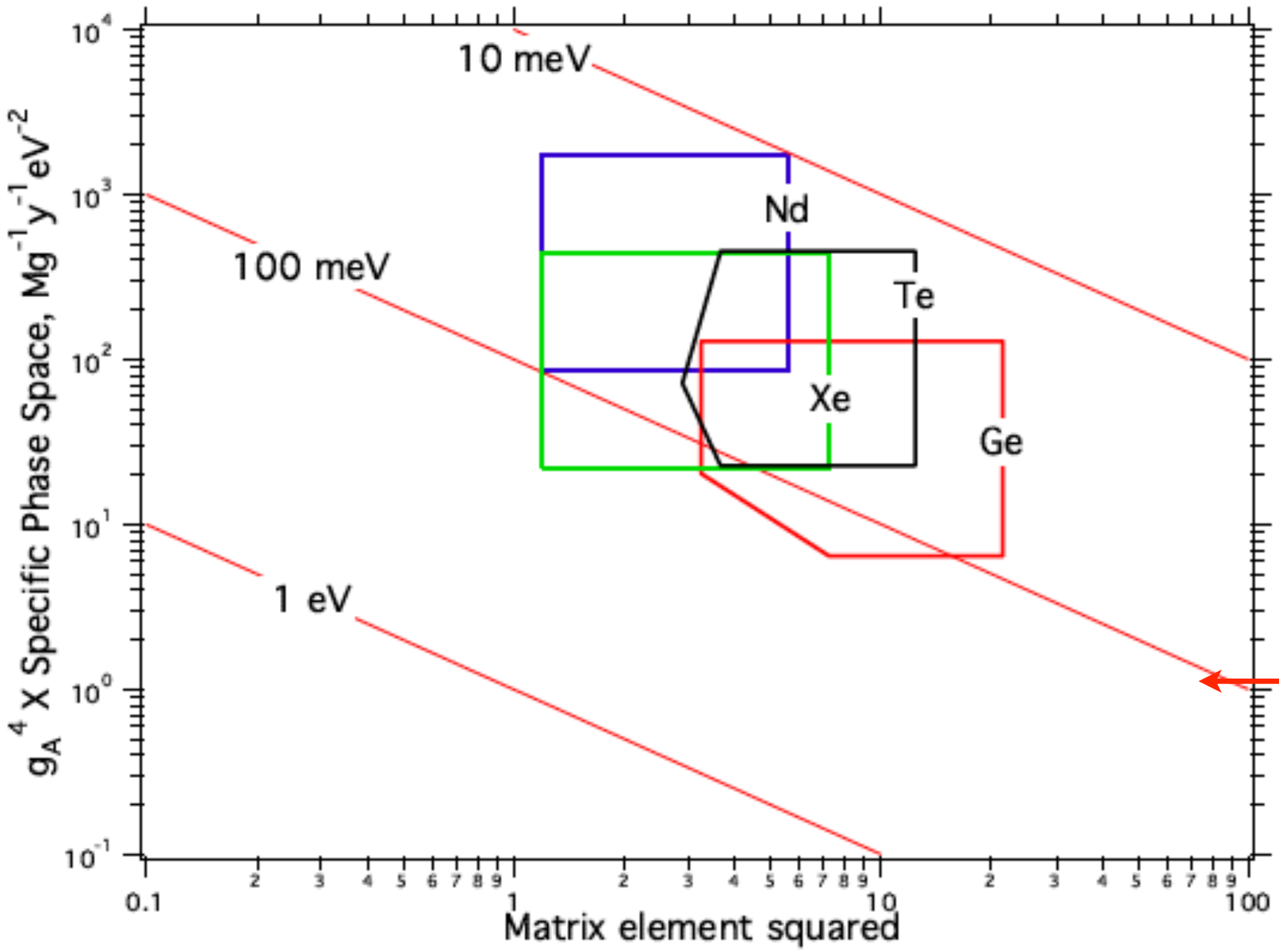
The specific phase space $H_{0\nu}$ is in activity per unit mass

Sensitivity to $<m_{\beta\beta}>$

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

For Ge, Te, Xe, Nd

uncertainty on NME^2

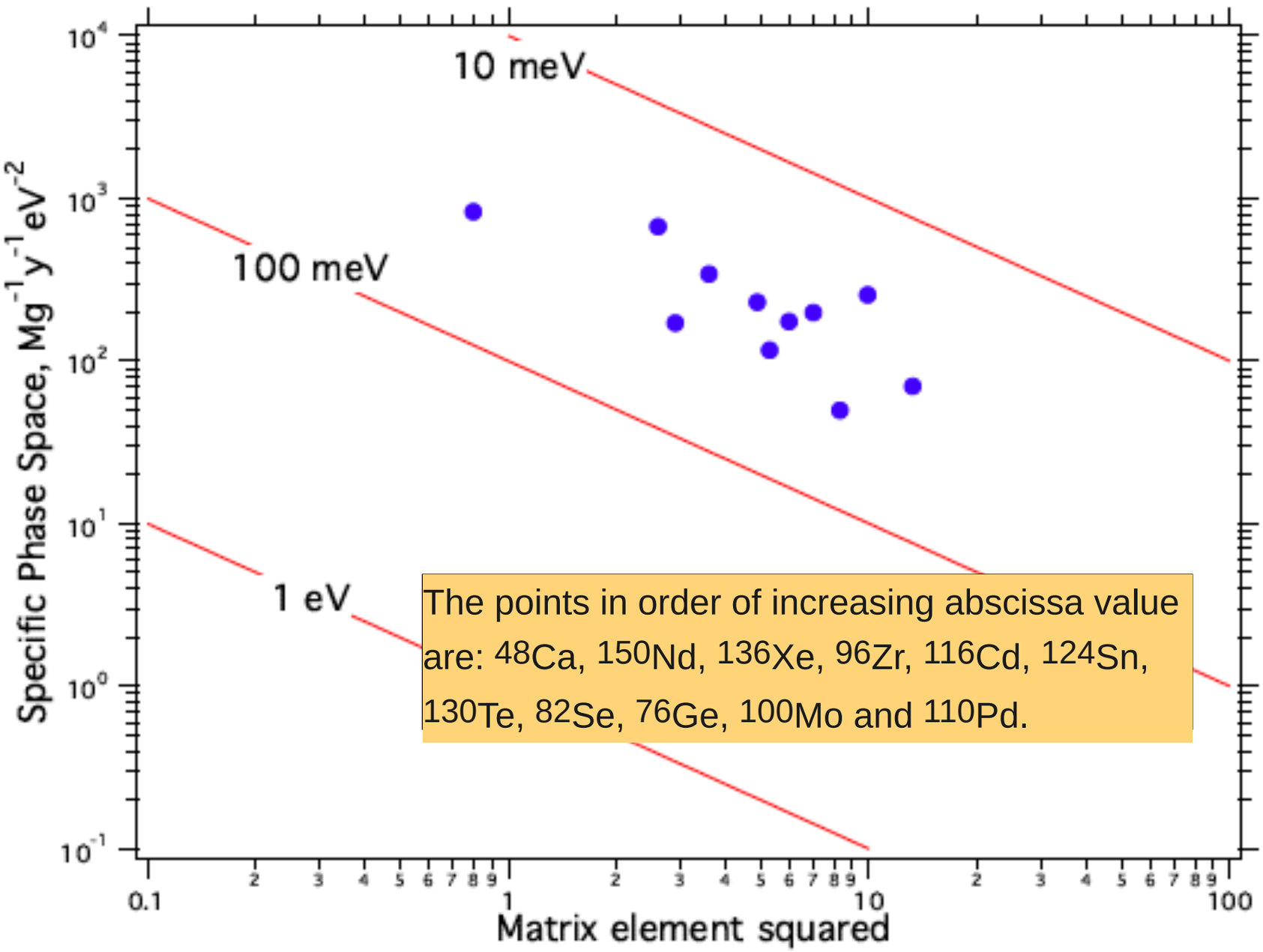


uncertainty on value of g_A^4

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



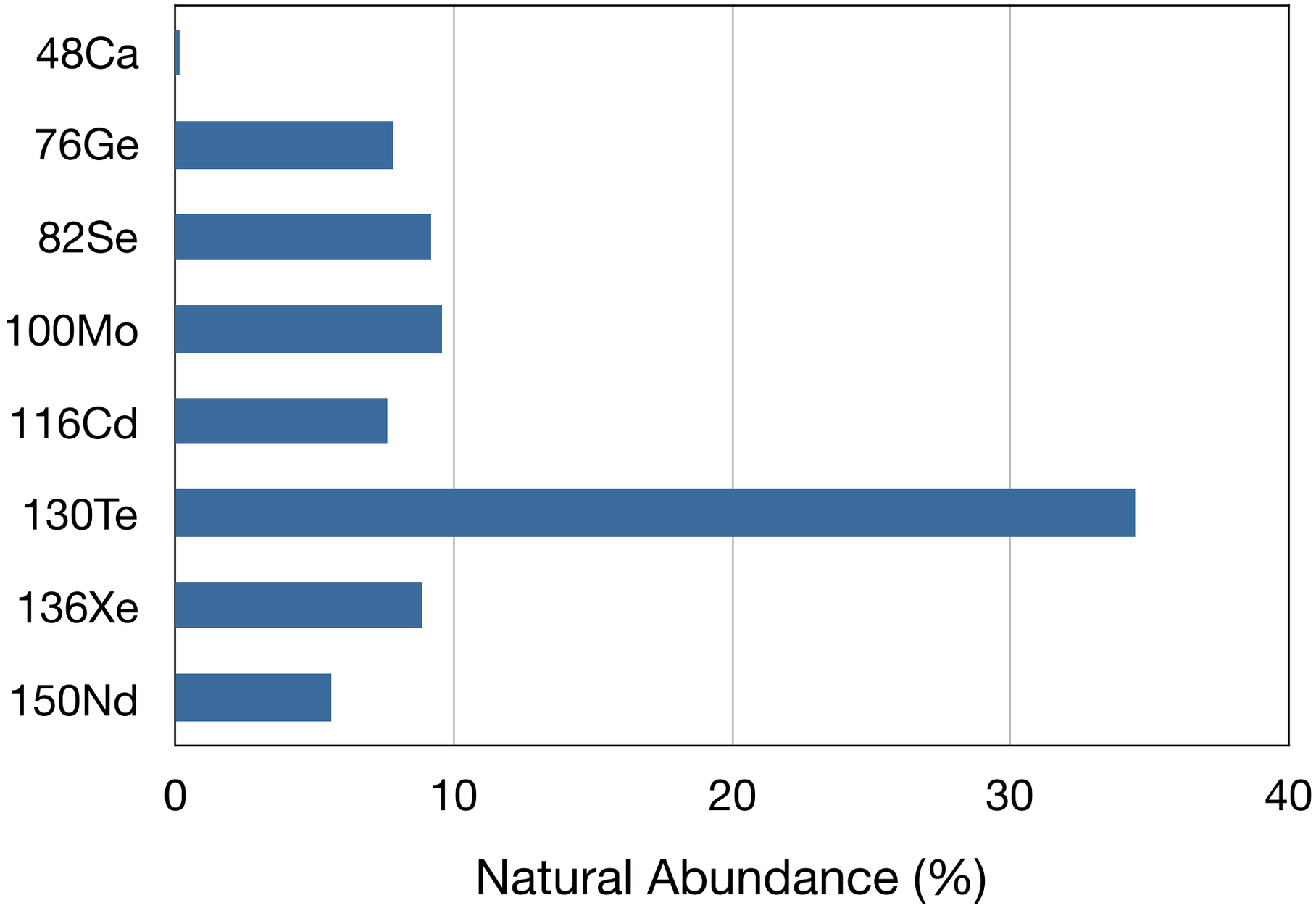
The points in order of increasing abscissa value are: ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo and ^{110}Pd.

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

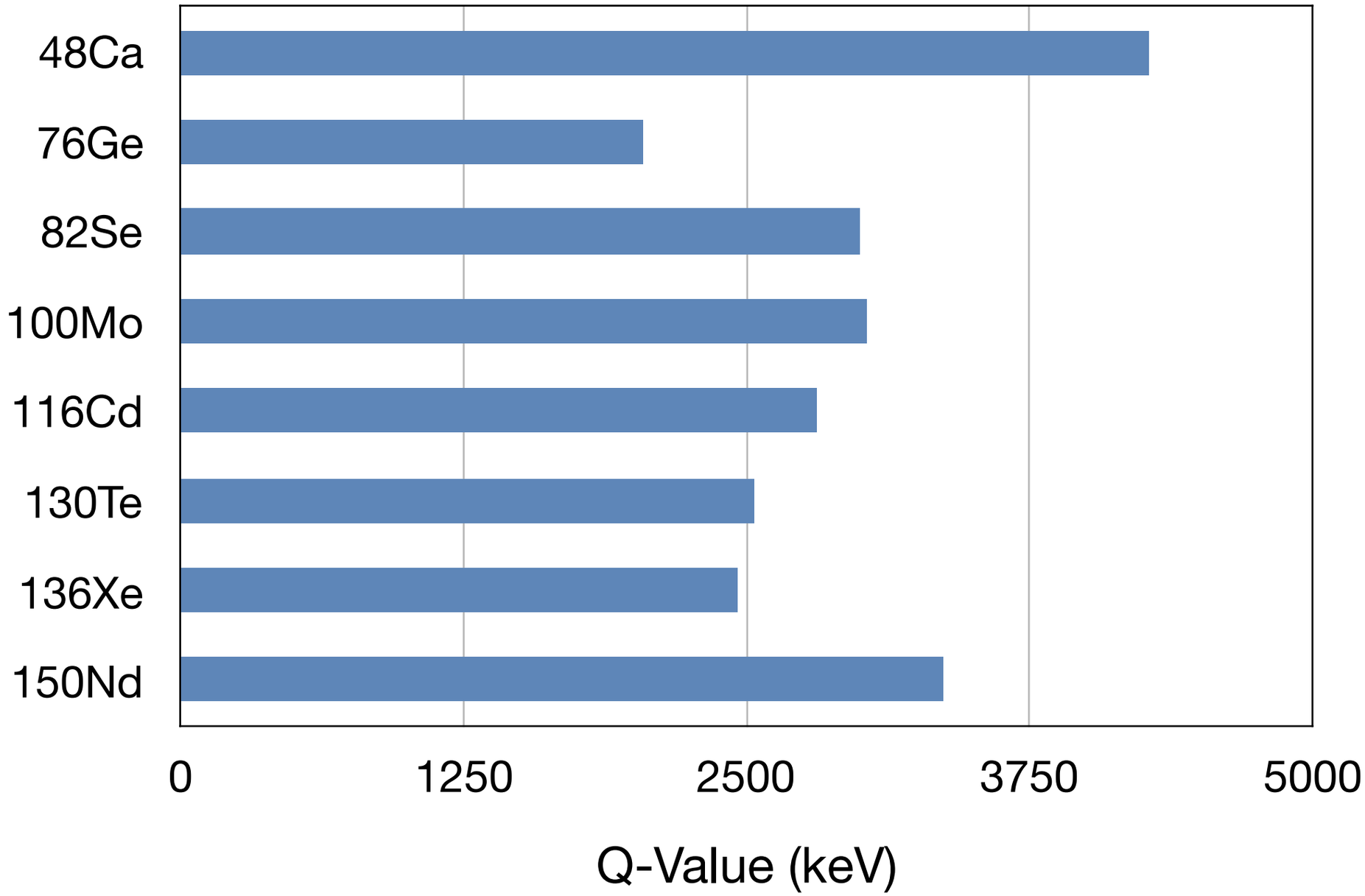
0νββ Isotopes : Natural Abundances



ββ Isotope	Natural Abundance
^{48}Ca	0.187
^{76}Ge	7.8
^{82}Se	9.2
^{100}Mo	9.6
^{116}Cd	7.6
^{130}Te	34.5
^{136}Xe	8.9
^{150}Nd	5.6

Clearly ^{130}Te has an advantage.
For the others, Isotopic enrichment ($s) is needed

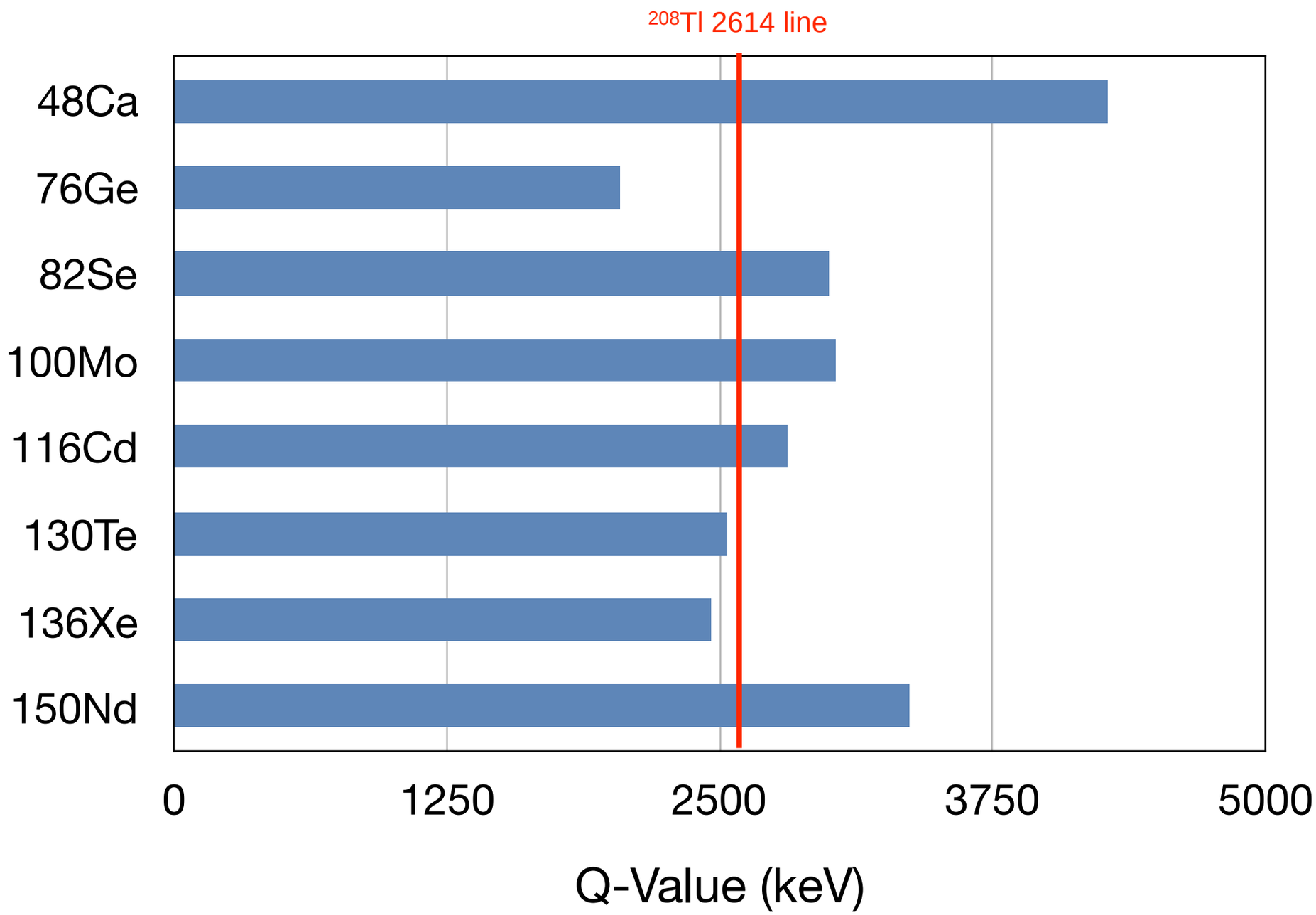
0νββ Isotopes : Q-Values



ββ Isotope	Q-Value
^{48}Ca	4273.7
^{76}Ge	2039.1
^{82}Se	2995.5
^{100}Mo	3035
^{116}Cd	2809.1
^{130}Te	2530.3
^{136}Xe	2457.8
^{150}Nd	3367.3

- Higher Q-value will result in the ββ-decay signal being above potential backgrounds.

0νββ Isotopes : Q-Values



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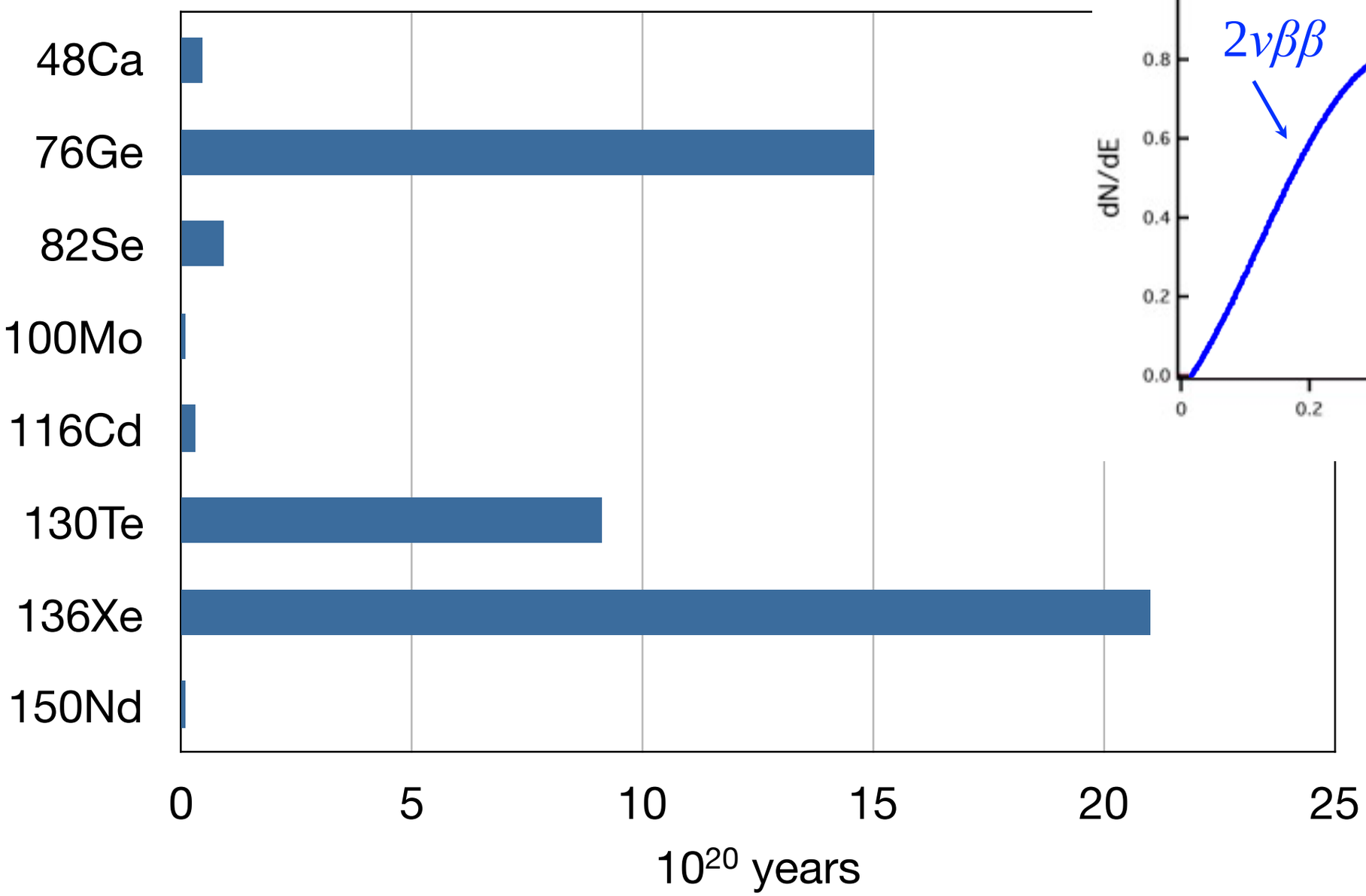
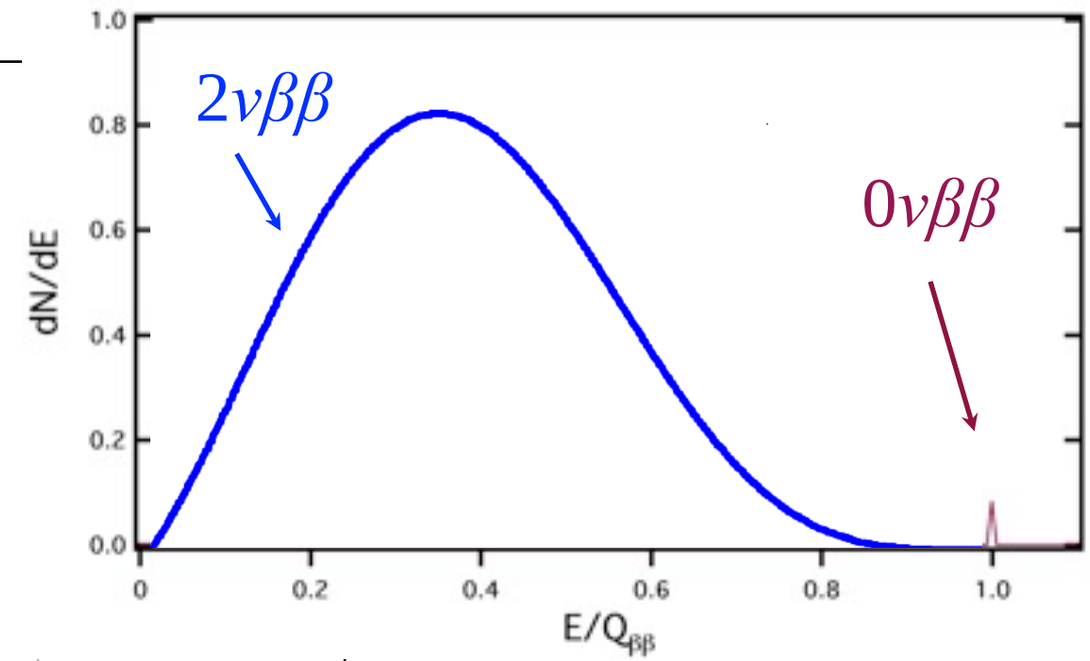
0νββ Isotope : 2νββ $T_{1/2}$





ββ Isotope	2νββ $T_{1/2}$ 10^{20} years
^{48}Ca	0.44
^{76}Ge	15
^{82}Se	0.92
^{100}Mo	0.07
^{116}Cd	0.29
^{130}Te	9.1
^{136}Xe	21
^{150}Nd	0.08

Longer 2νββ $T_{1/2}$ (better) ⇒ lower rate

Irreducible background ⇒ minimize with good resolution

A preferred $0\nu\beta\beta$ isotope in terms of sensitivity?

- No preferred isotope in terms of per unit mass - within current uncertainties on NME and g_A.
- Need to enrich ^{130}Te has an advantage
- Backgrounds - higher Q value (especially above ^{208}Th line helps)
- $2\nu\beta\beta$ rate (irreducible background) - ^{76}Ge ^{130}Te, ^{136}Xe are the best.

  - good resolution important

No clear winner. Need to evaluate on case-by-case basis. Backgrounds and resolution are critically important.

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0νββ signals & sensitivity

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

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

Background free

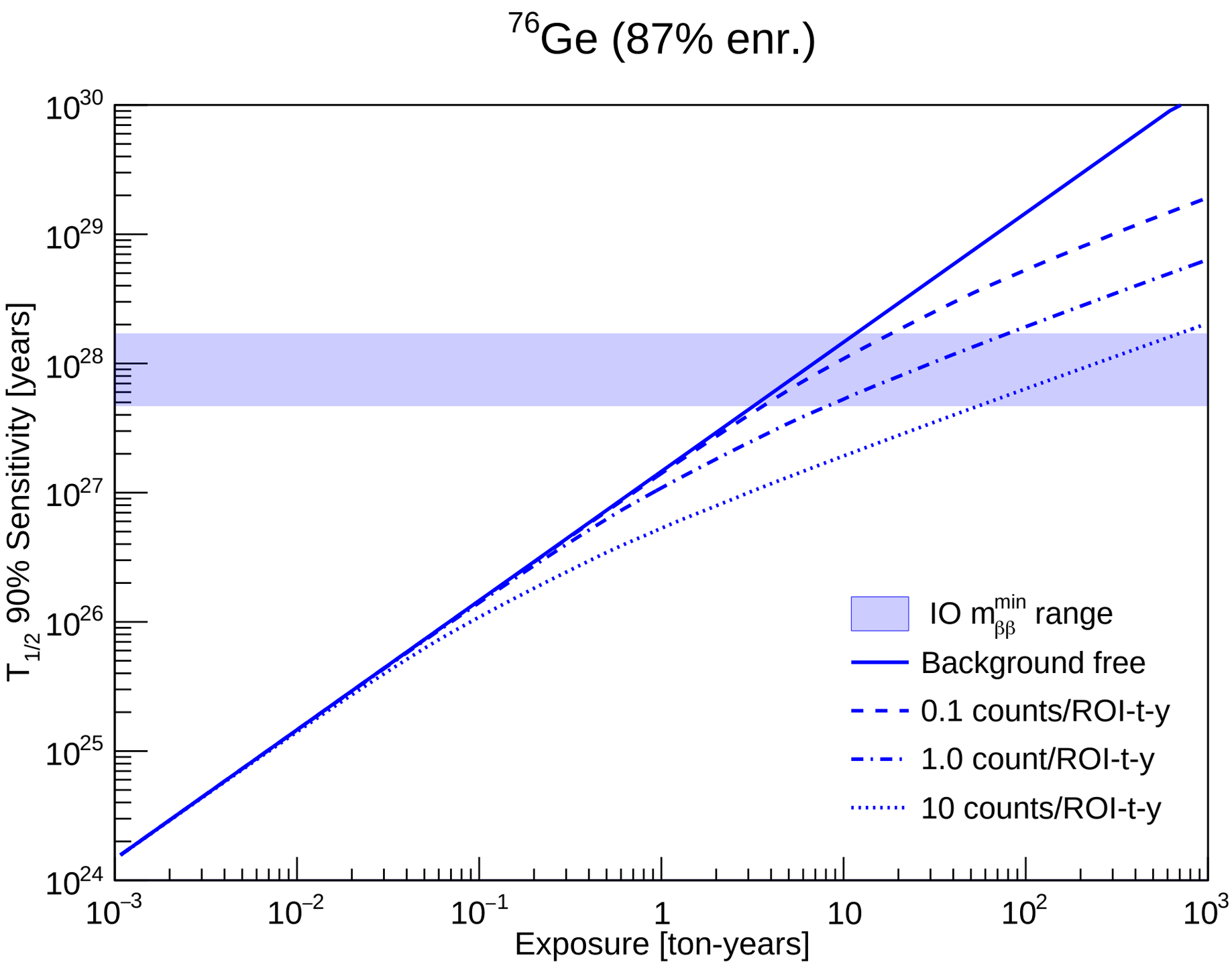
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

Background limited

Note : Backgrounds do not always scale with active detector mass

Sensitivity vs. Exposure ^{76}Ge

J. Detwiler



Inverted Ordering (IO)

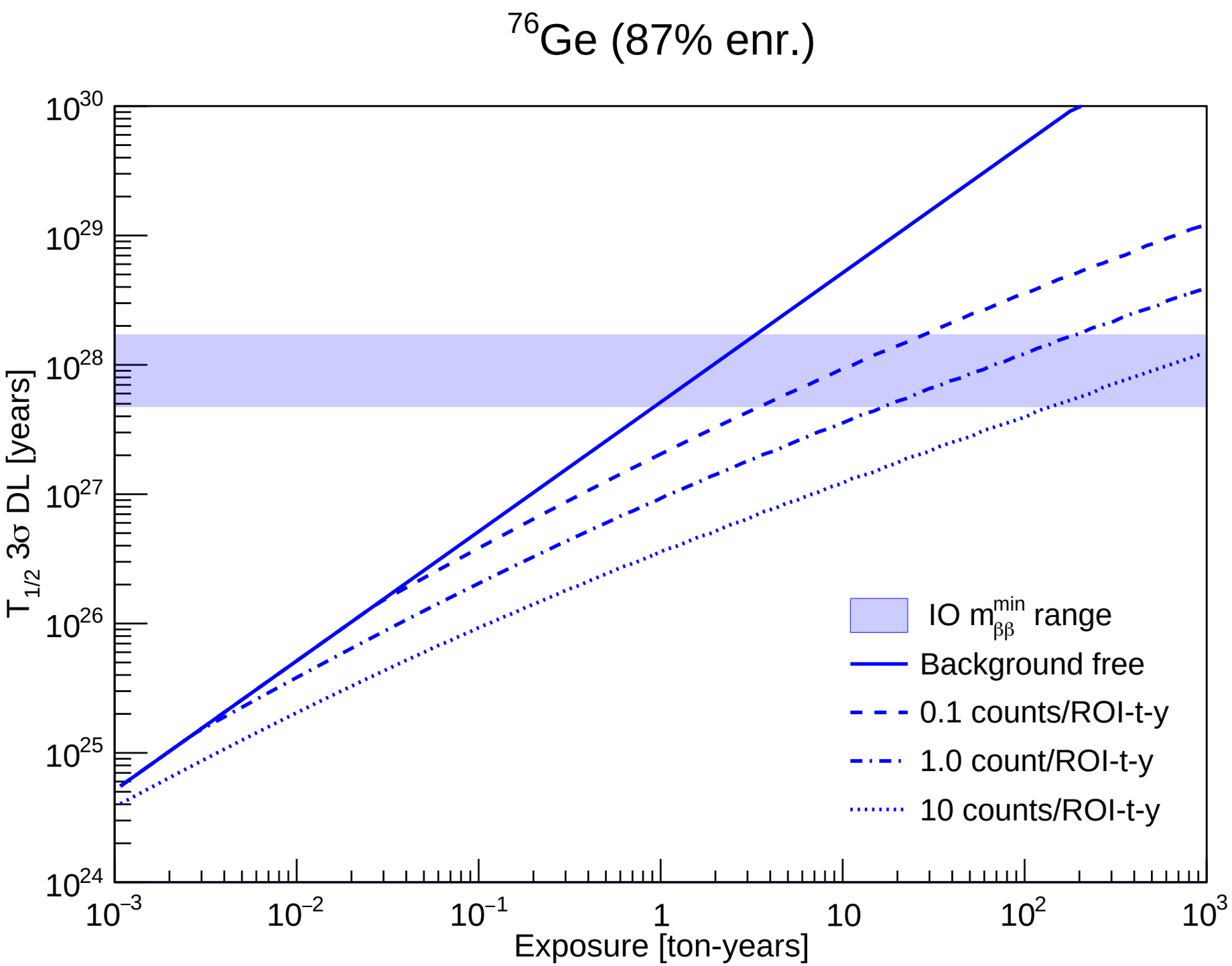
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, ...)

Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

3σ Discovery vs. Exposure for ^{76}Ge

J. Detwiler



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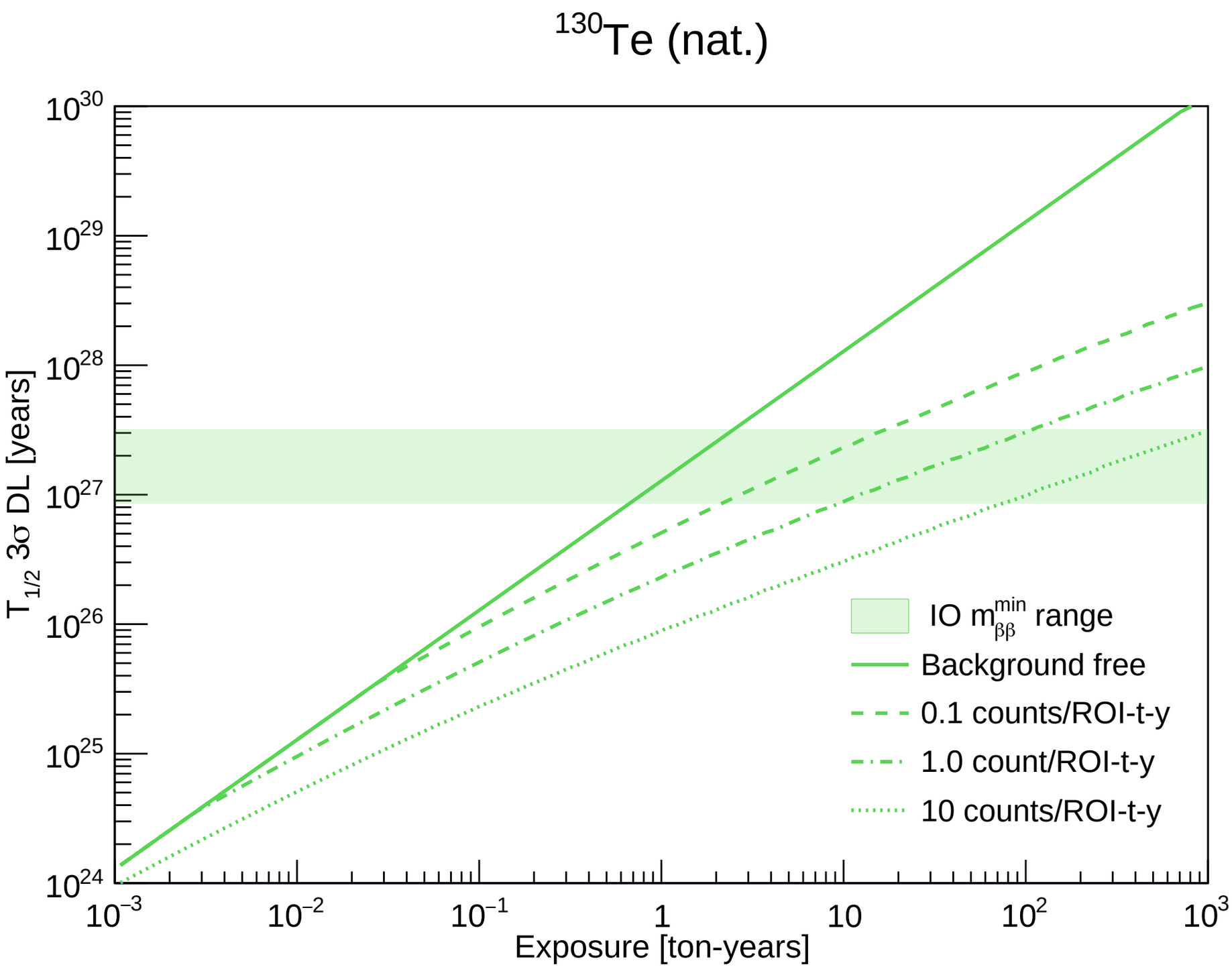
3σ Discovery vs. Exposure for ^{130}Te

J. Detwiler



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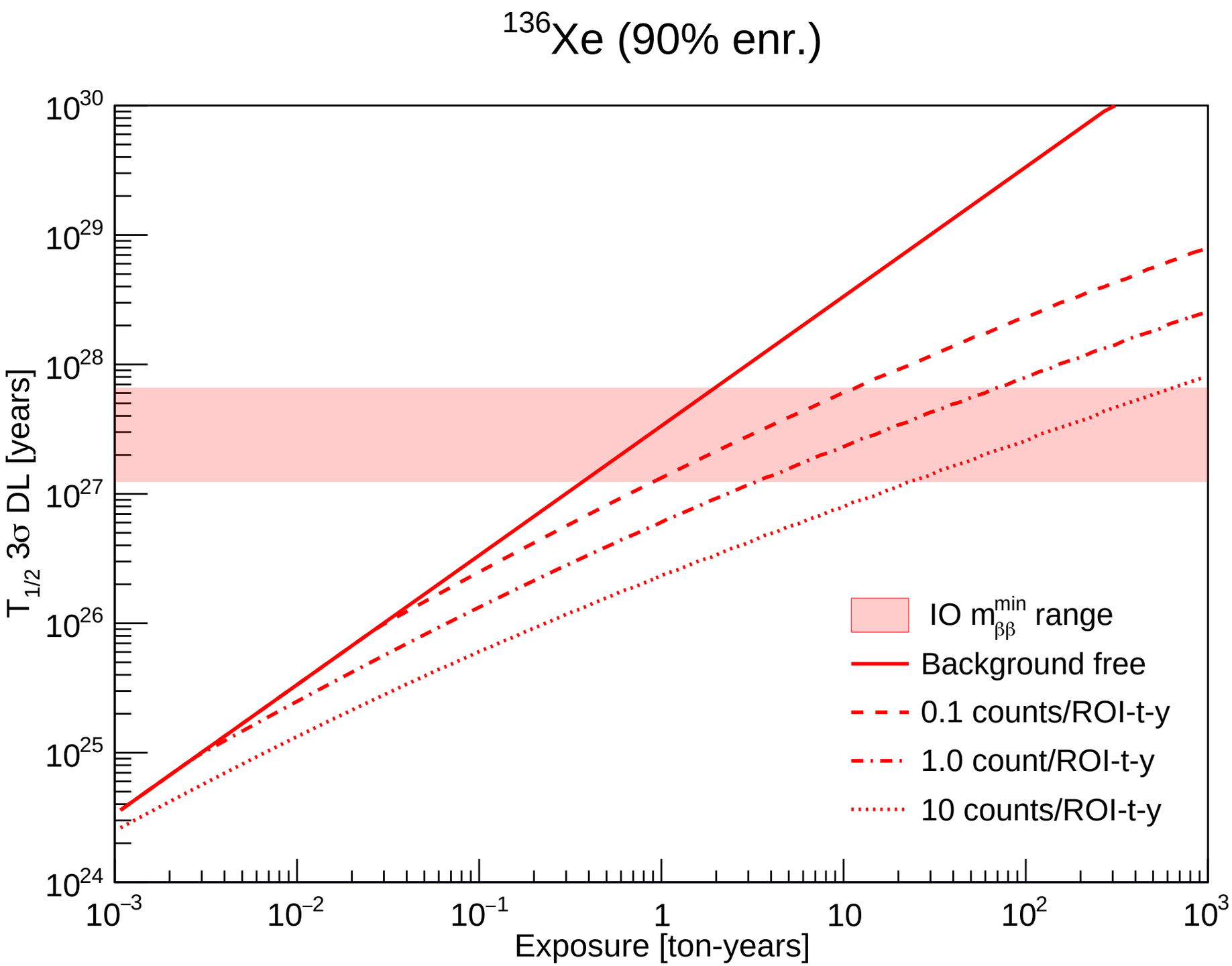
Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, ...)

Assumes 81% efficiency based on CUORE-0. Natural Te is accounted for in the exposure

3σ Discovery vs. Exposure for ^{136}Xe

J. Detwiler



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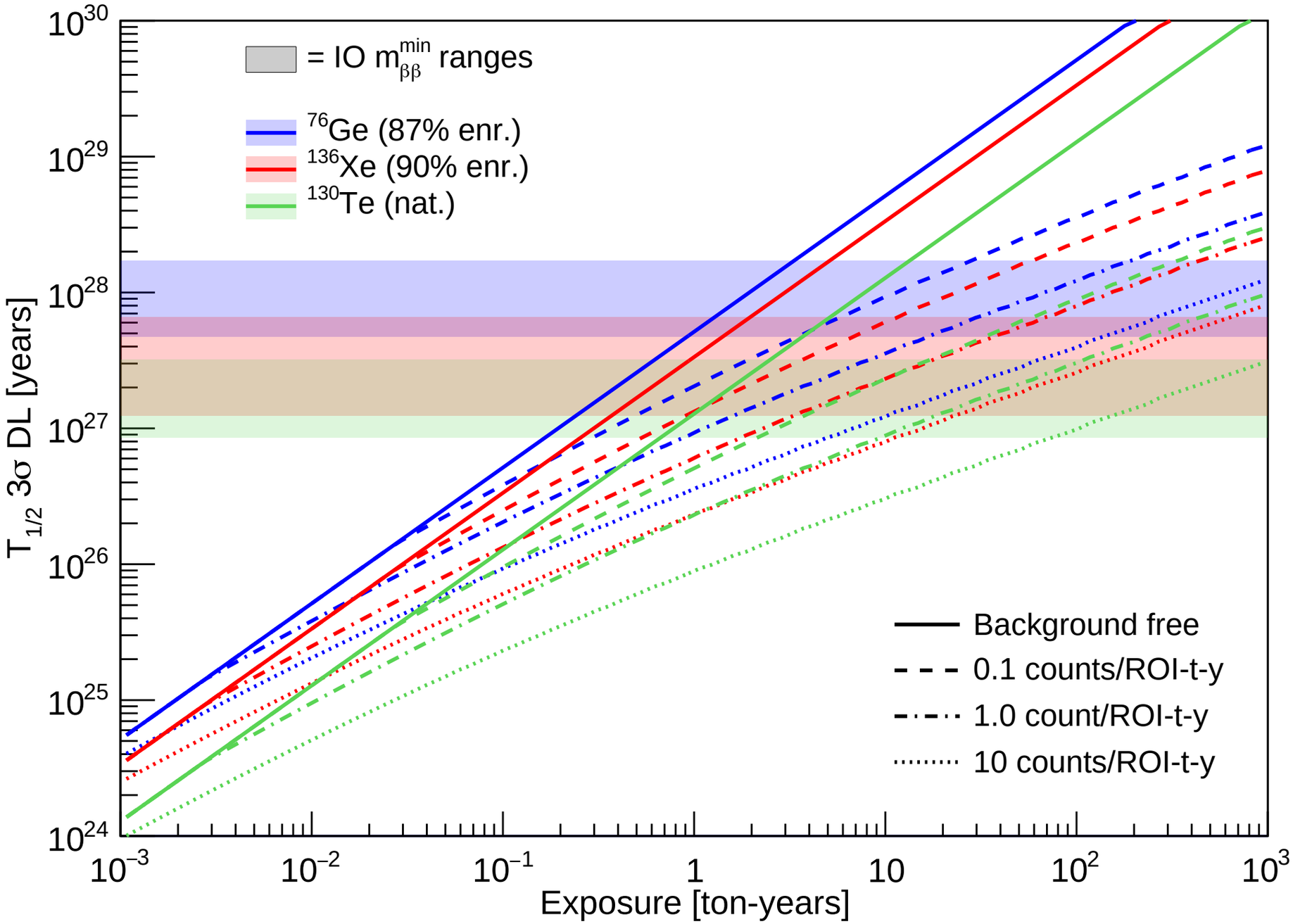
Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

Assumes 84% efficiency based on EXO 200. Enrichment level is accounted for in the exposure

3σ Discovery vs. Exposure

J. Detwiler



3σ Discovery vs. Exposure

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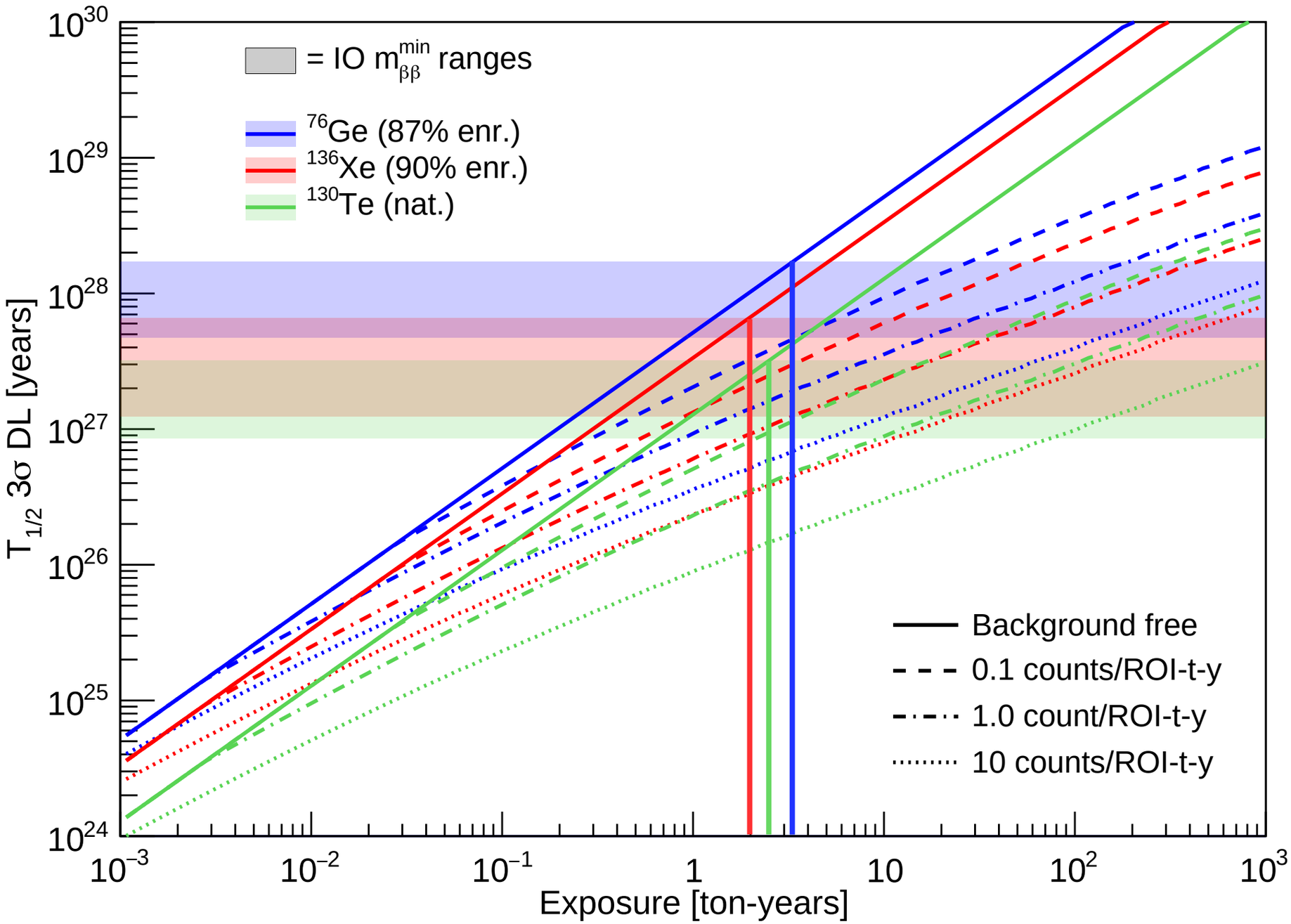
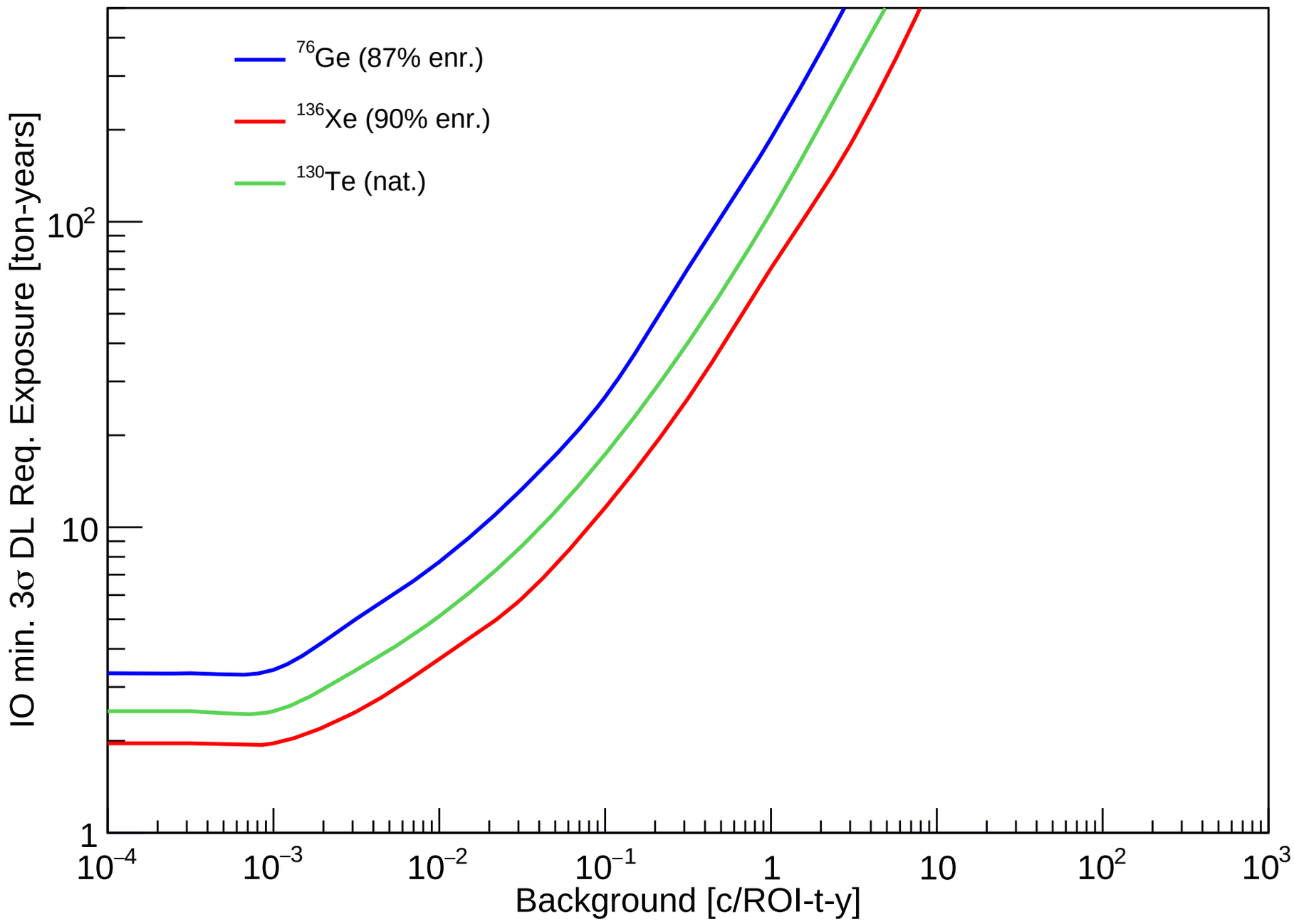


Conclusion:

Based on current knowledge, and planned enrichment levels, isotopes have roughly comparable sensitivities per unit mass, when comparing for the best case of zero backgrounds.

Required 3σ Exposure vs. Background

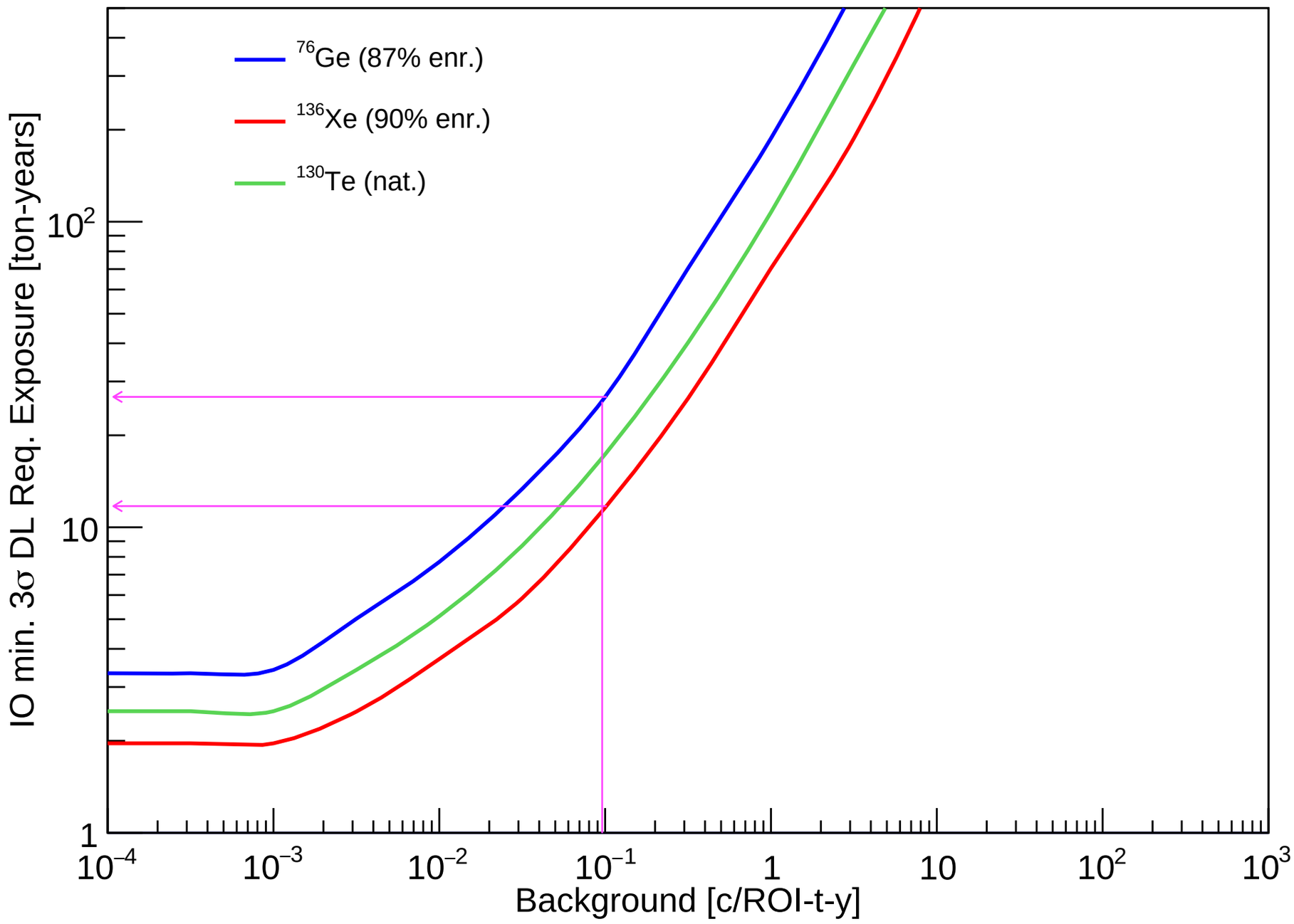
J. Detwiler



"Required" exposure assuming minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Required 3σ Exposure vs. Background

J. Detwiler



"Required" exposure assuming minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Backgrounds in experiments

From NSAC Long Range Plan Resolution Meeting 0νββ talk
V. Cirigliano & J.F. Wilkerson

Experiment		Mass [kg] (total/FV*)	Bkg (cnts/ROI-t-y)†	Width (FWHM)
CUORE0	^{130}Te	32/11	300	5.1 keV ROI
EXO-200	^{136}Xe	170/76	130	88 keV ROI
GERDA I	^{76}Ge	16/13	40	4 keV ROI
KamLAND-Zen (Phase 2)	^{136}Xe	383/88	210 per t(Xe)	400 keV ROI
CUORE	^{130}Te	600/206	50	5 keV ROI
GERDA II	^{76}Ge	35/27	4	4 keV ROI
MAJORANA DEMONSTRATOR	^{76}Ge	30/24	3	4 keV ROI
NEXT 100	^{136}Xe	100/80	9	17 keV ROI
SNO+	^{130}Te	2340/160	45 per t(Te)	240 keV ROI

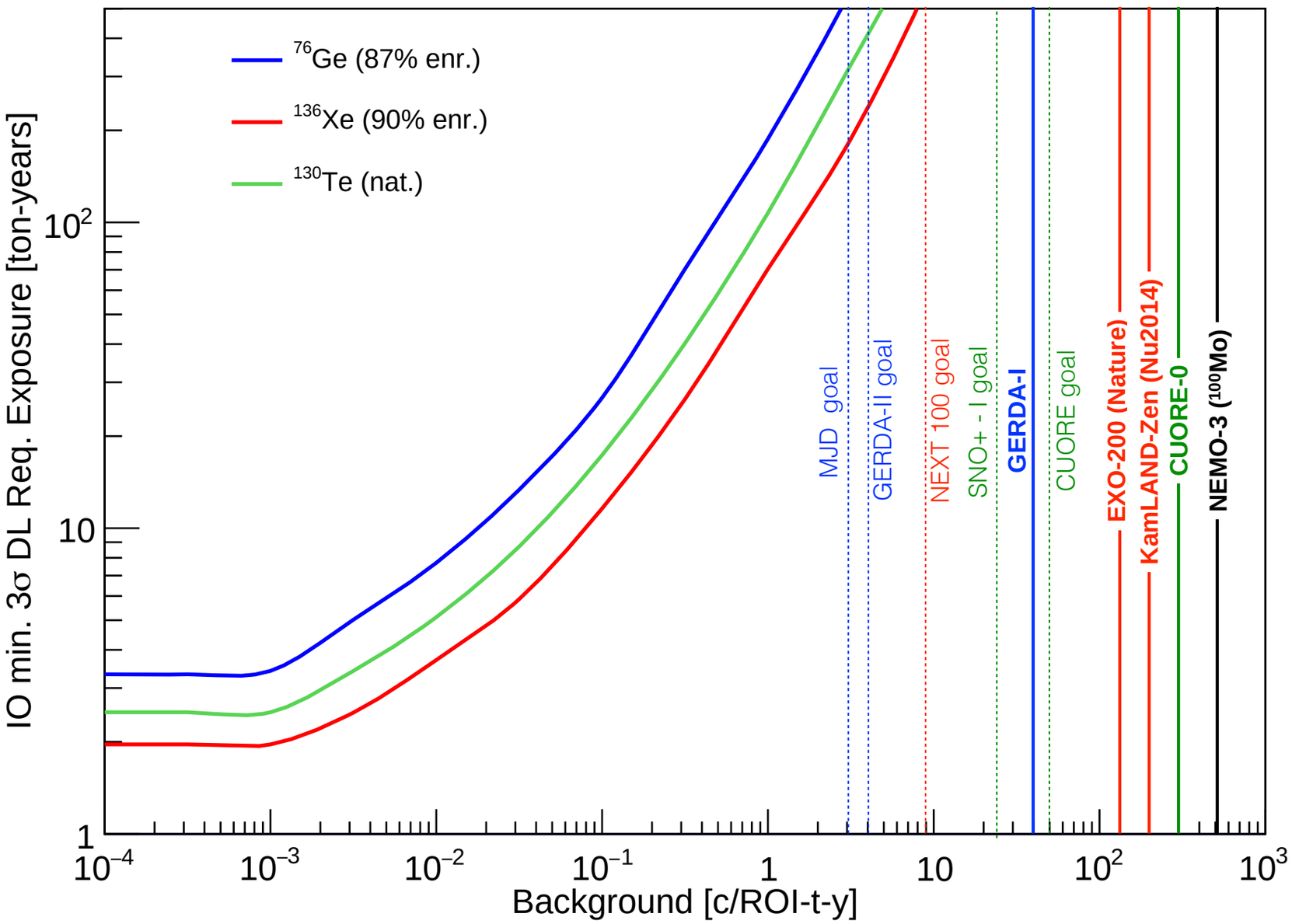
Measured

Projected

* FV = 0νββ isotope mass in fiducial volume (includes enrichment factor)
† Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

3σ Discovery vs. Background

J. Detwiler



3σ Discovery vs. Background

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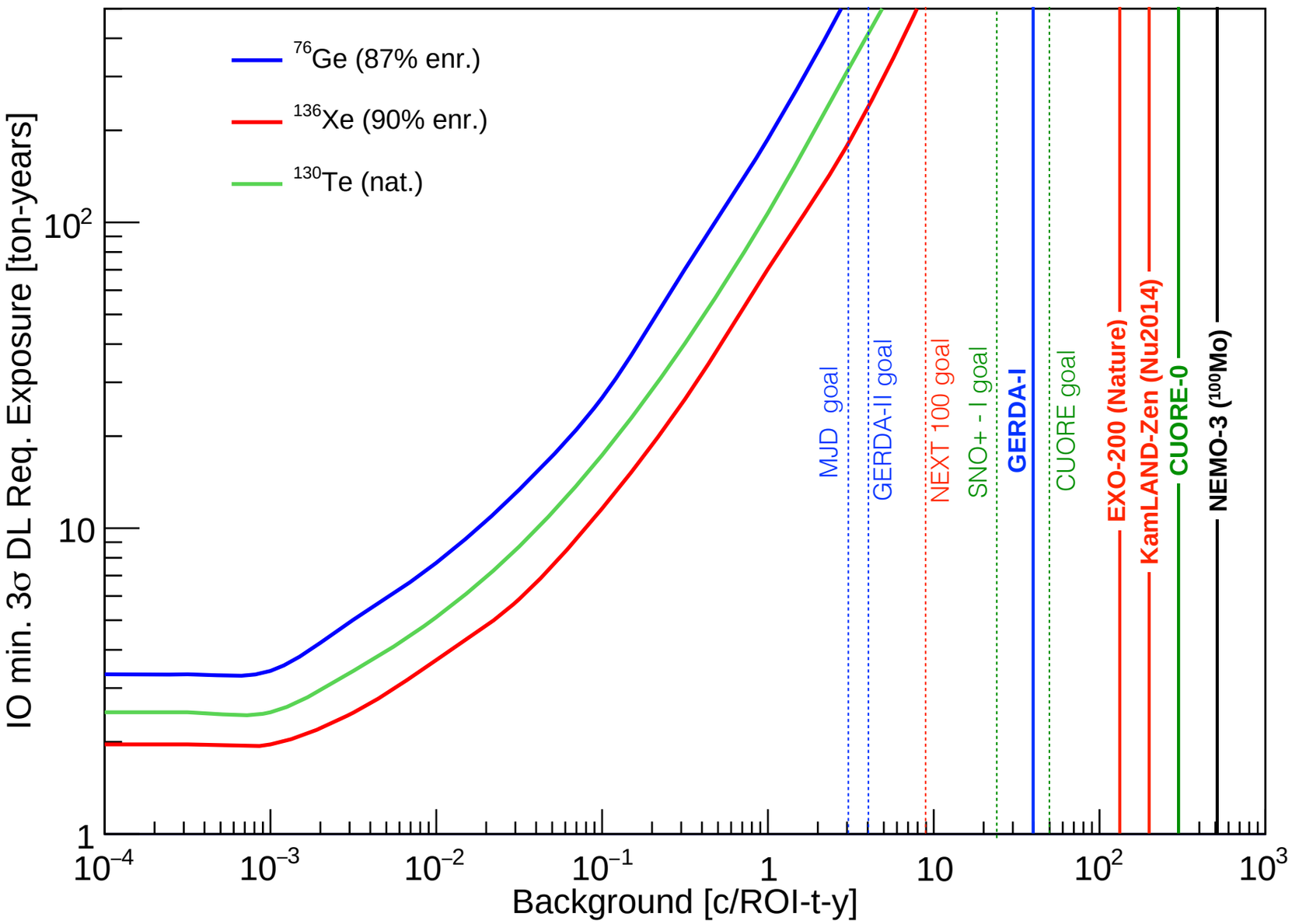

Take away:

Realistically, a next generation experiment should aim for backgrounds at or below 0.1 c/ROI-t-y

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 Fits
  - Granularity [multiple detectors]
  - Pulse shape discrimination (PSD)
  - Ion Identification

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Considerations towards a ton scale $0\nu\beta\beta$

Nuclear Science Advisory Committee (NSAC) — committee of nuclear scientists that advises the Federal agencies involved in nuclear physics — the Department of Energy (DOE) Office of Nuclear Physics and the National Science Foundation (NSF)

In 2013 NSAC established a standing sub-committee on Neutrinoless Double Beta Decay (NLDBD).

- The committee issued its first report in April 2014.
- On October 15, 2015 the committee presented an update on R&D for the ton scale.

See: http://science.energy.gov/np/nsac/meetings/

Major Issue: Background

- For "background-free" experiment, lifetime sensitivity goes as $T_{1/2} \sim M \cdot t_{run}$
  (M= isotope mass)
  → factor of 50 in $T_{1/2}$ needs factor of 50 in M (for constant t_{run})

- For experiment with background, as $T_{1/2} \sim (M \cdot t_{run})^{1/2}$
  → factor of 50 in $T_{1/2}$ needs factor of 2500 in M (for constant t_{run})

- Background reduction is the key to a successful program
  - deep underground
  - radiopurity
  - better E resolution
  - better event characterization

→ **R&D will be crucial**

Bob McKeown
NSAC NLDBD Talk

Simple Background Estimate

NLDBD Rate = N x ln(2) / $T_{1/2}$ (assume $T_{1/2} \approx 10^{28}$ yr)

For 1 Tonne, N=10^6g x 6×10^{23} / MW
(MW= 67, 130, 136 → use MW≈100)

So N≈ 6×10^{27}

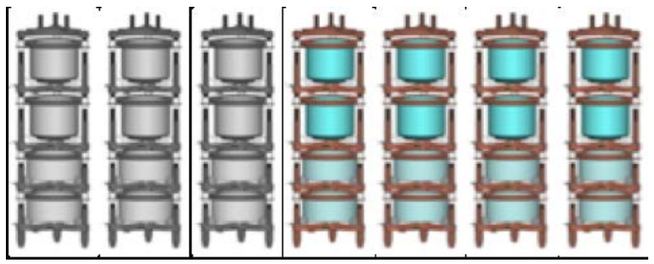
NLDBD Rate = 0.4 /Tonne/yr

Background free → Background < 0.1/Tonne/yr/ROI

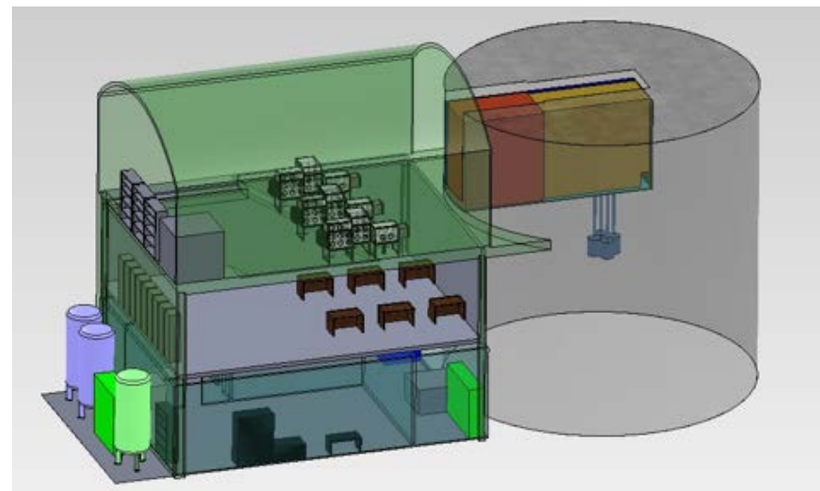
Bob McKeown
NSAC NLDBD Talk

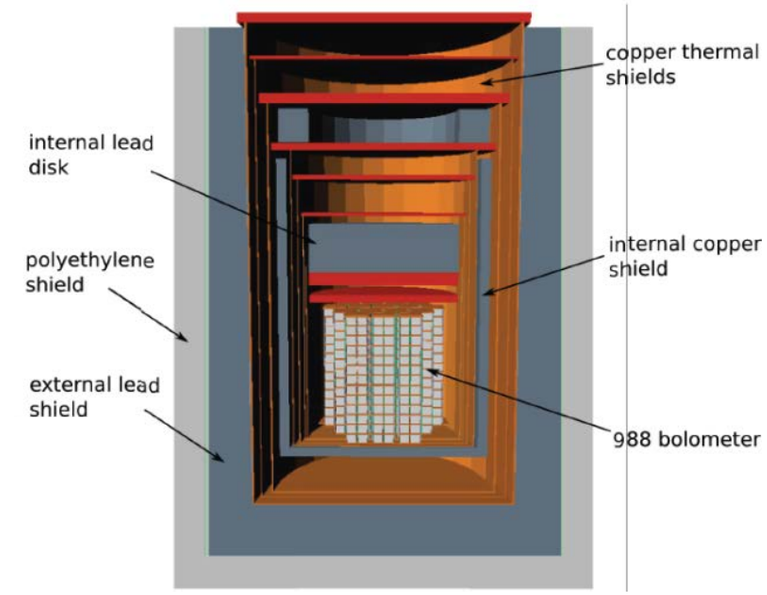
Next Generation Approaches

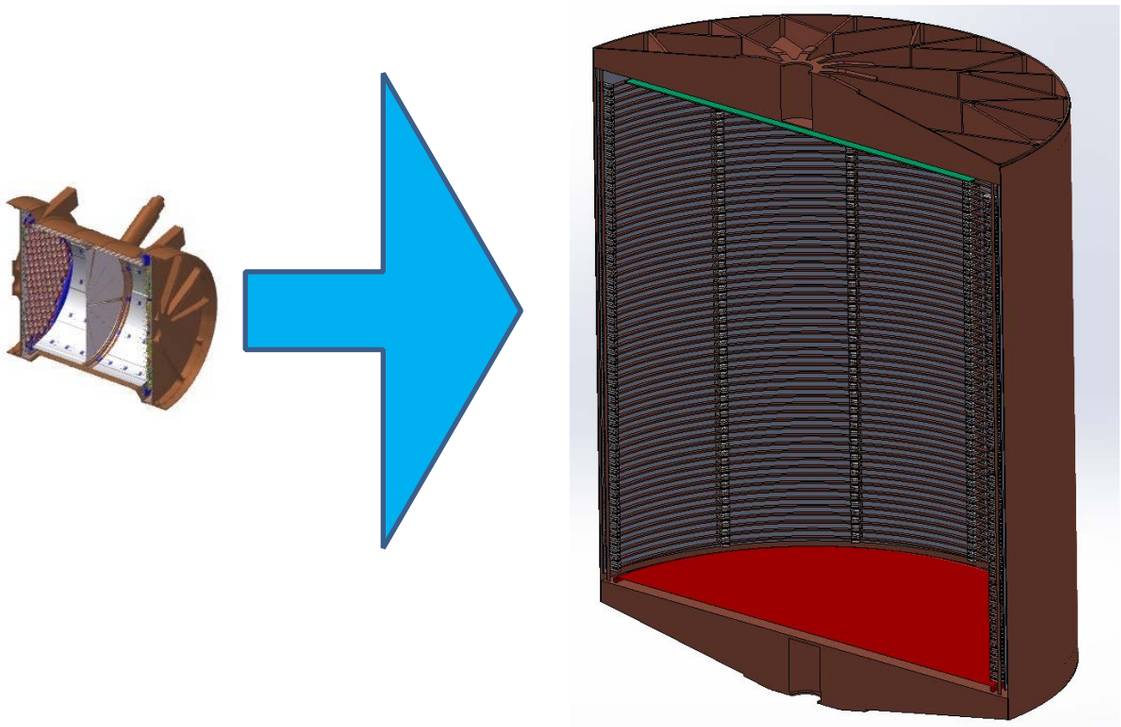
The issue is to scale up to ≥ 1 Tonne with low background.



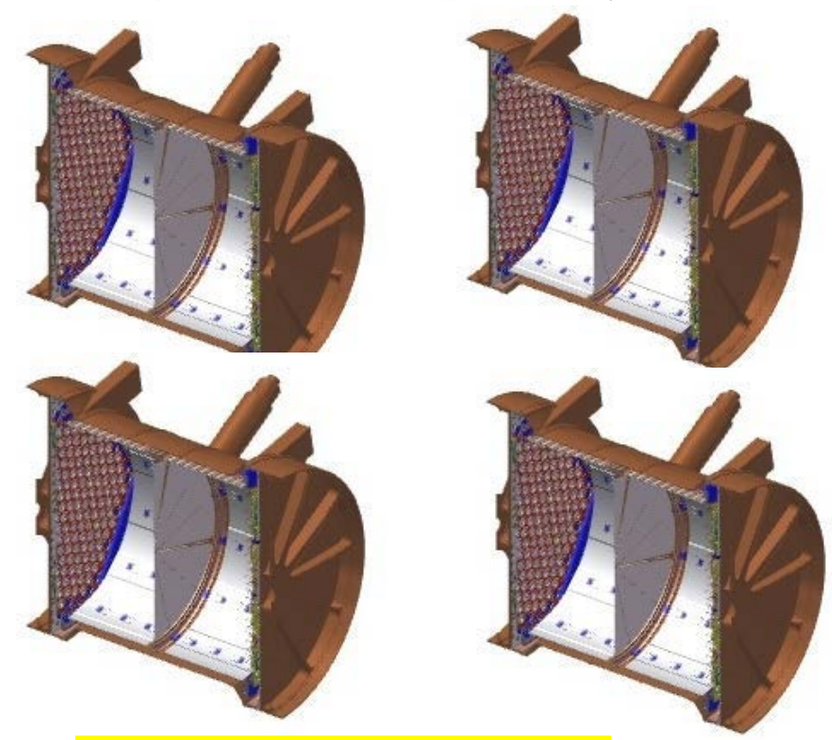
X ~100 →







OR



Bob McKeown
NSAC NLDBD Talk

NSAC NLDBD 2014 "Guidelines"

The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments:

1.) Discovery potential: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter m$\beta\beta$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.

2.) Staging: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.

3.) Standard of proof: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.

NSAC NLDBD 2014 “Guidelines”

4.) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.

5.) International Collaboration: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach

6.) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

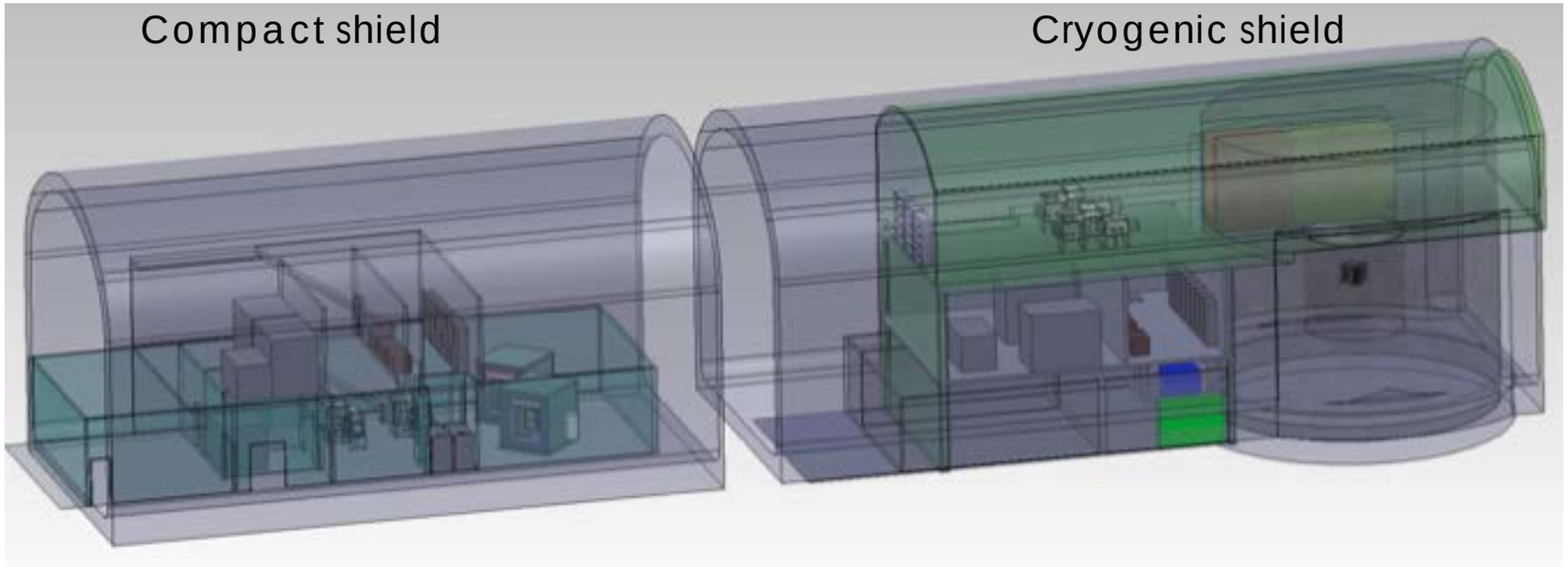
REPORT TO THE NUCLEAR SCIENCE ADVISORY COMMITTEE Neutrinoless Double Beta Decay APRIL 24, 2014

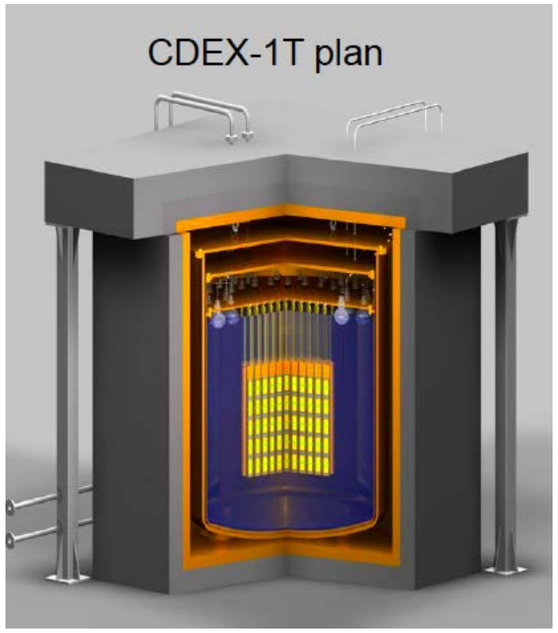
Questions

- Where are we now for $0\nu\beta\beta$?
- Is there a preferred $0\nu\beta\beta$ isotope in terms of sensitivity?
- What levels of backgrounds and exposure are required for future $0\nu\beta\beta$ experiments to cover the inverted ordering region?
- What are considerations for future ton scale $0\nu\beta\beta$ experiments?
- What is needed to build a ton scale ^{76}Ge Experiment?
- Costs & International prospects?
- Beyond the ton scale?
- Ge for Dark Matter?
- Summary

Future ton scale ^{76}Ge

- Moving forward predicated on *demonstration* of projected backgrounds by MJD and/or GERDA, and further reductions at the ton scale.
- CDEX is working towards a ton scale ^{76}Ge experiment at CJPL, the world's deepest underground laboratory
- Realistically there will be one ton scale ^{76}Ge based $0\nu\beta\beta$ experiment. MAJORANA, GERDA, CDEX have all expressed interest towards the establishment of an international ^{76}Ge $0\nu\beta\beta$ collaboration.
- Anticipate down-select of best technologies, lowest background materials.
- Envision a phased, stepwise implementation;
  e.g. 250 → 500 → 1000 kg



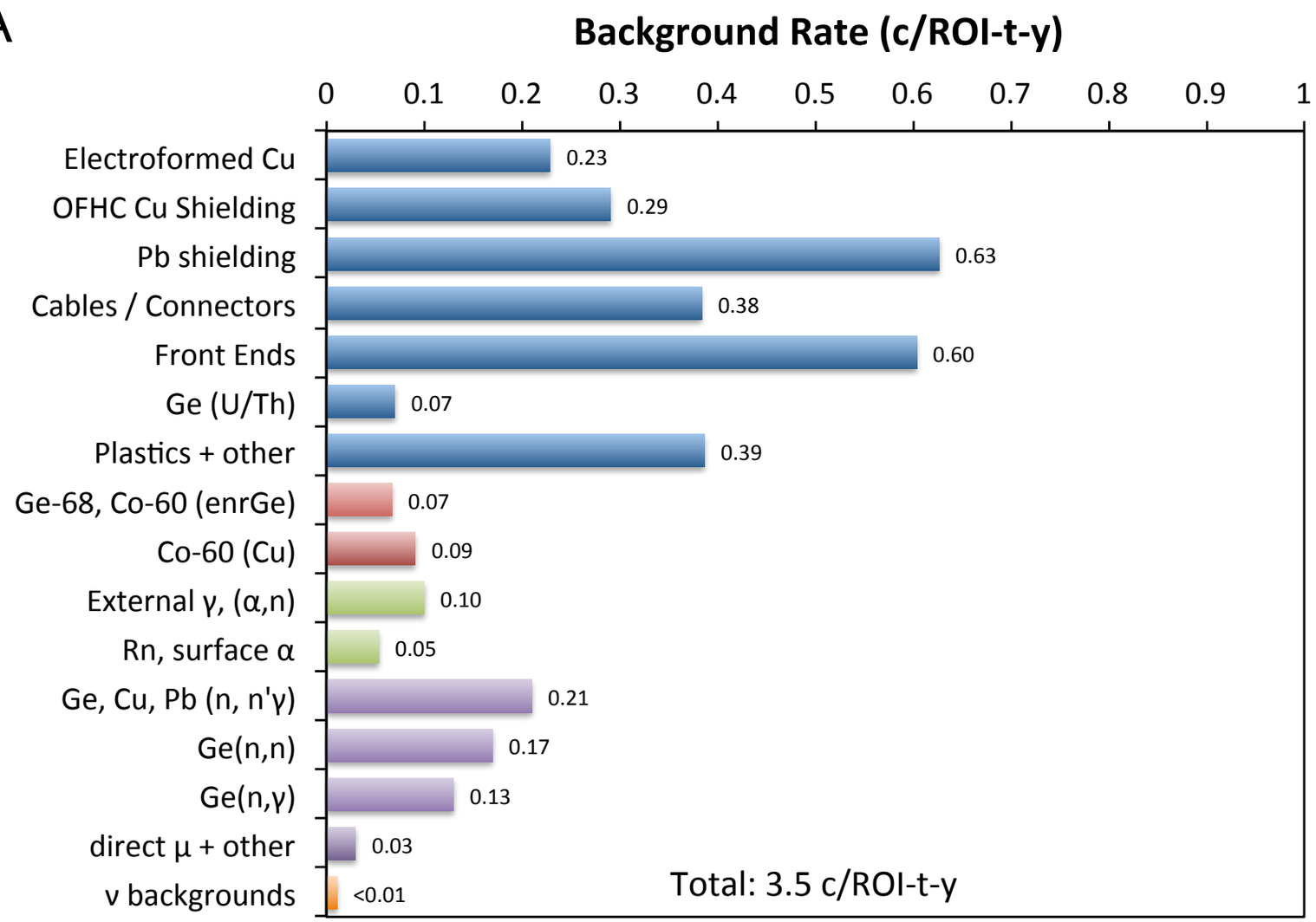


Next generation ^{76}Ge experiment

If MJD and GERDA Phase II reach their background goals of 3-4 c/ROI-t-y, that would scale to 1 c/ROI-t-y for a large scale Ge experiment.

Based on both discovery level and sensitivity considerations, aim is for a total background budget of ≤ 0.1 c/ROI-t-y.

Building on MJD and GERDA how does one get there?



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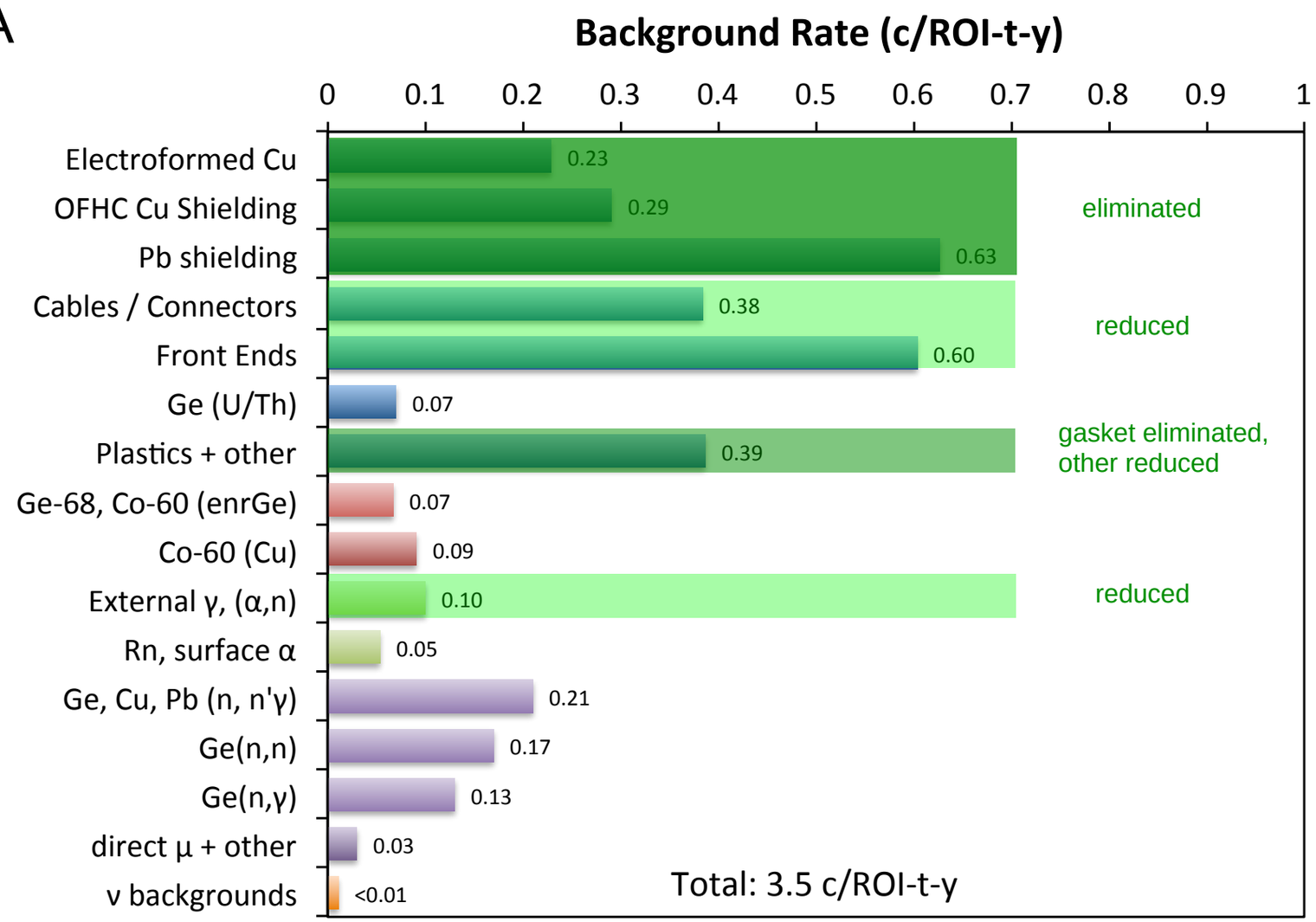
Building on MJD and GERDA how does one get there?

- clean, active shield



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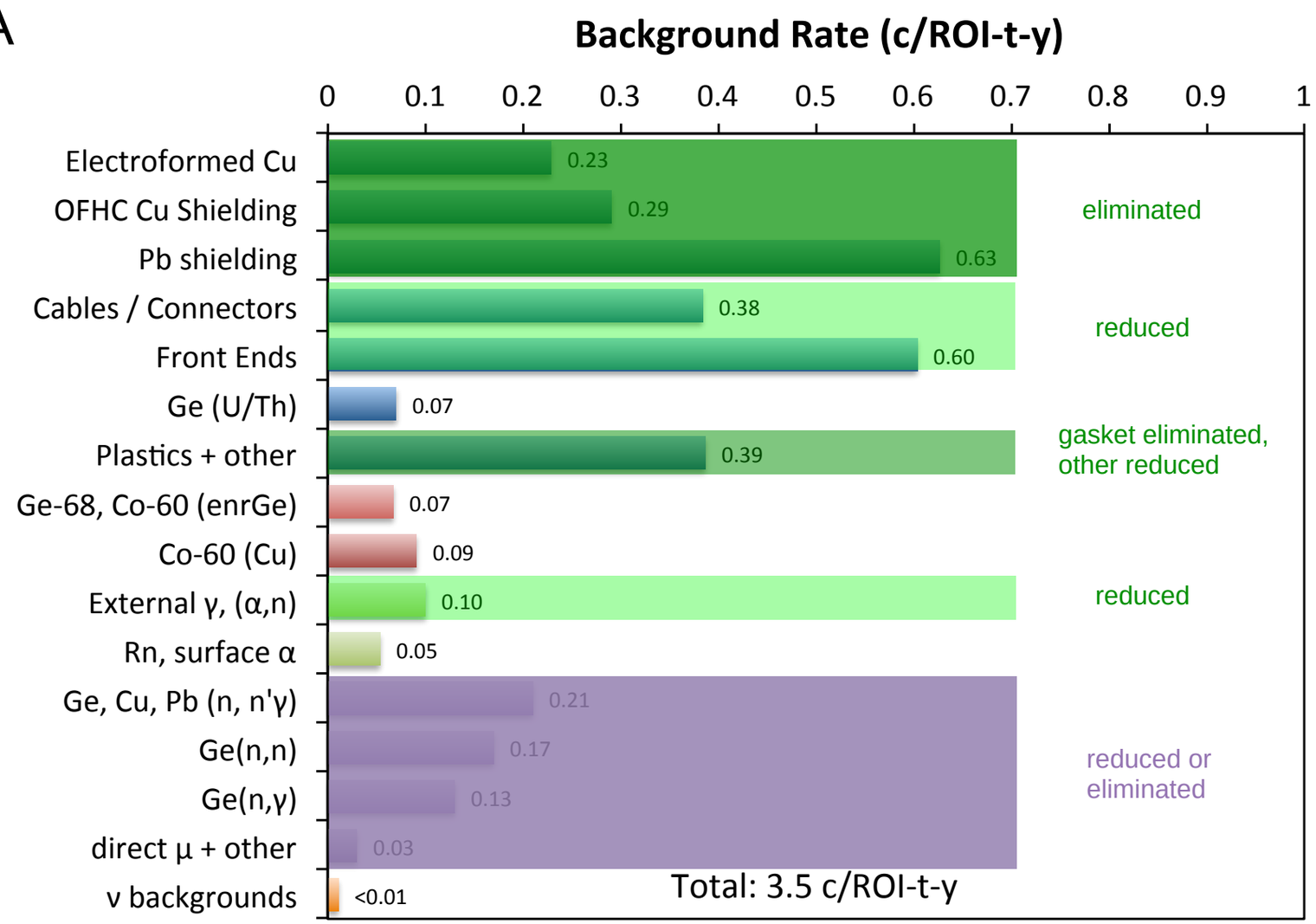
Building on MJD and GERDA how does one get there?

- clean, active shield
- deeper and/or active shield



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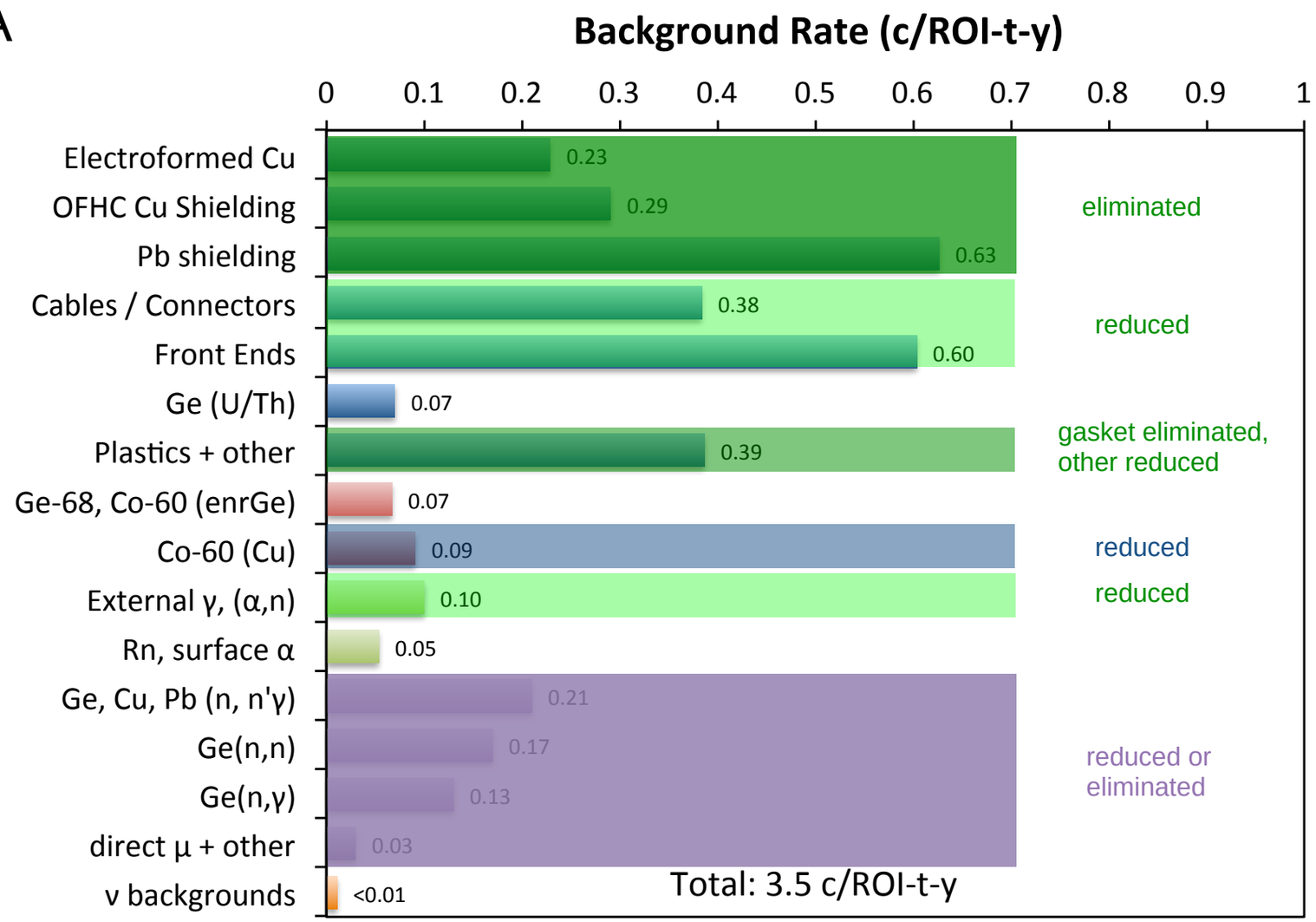
Building on MJD and GERDA how does one get there?

- clean, active shield
- deeper and/or active shield
- EF all Cu underground



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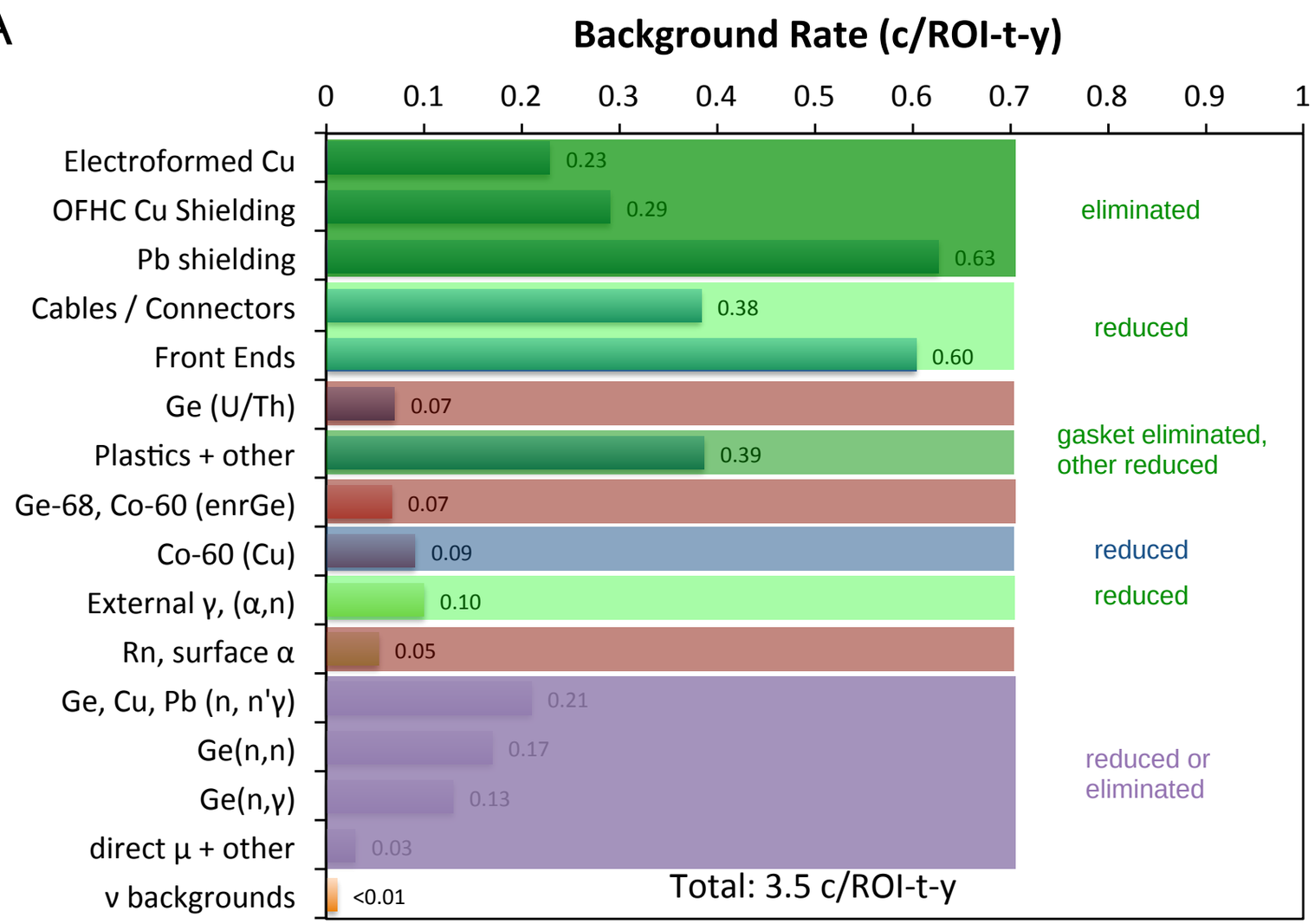
Building on MJD and GERDA how does one get there?

- clean, active shield
- deeper and/or active shield
- EF all Cu underground
- Learn from MJD & GERDA II (values are largely upper limits)



GERDA Challenges beyond Phase II

- Background: for quasi background free operation beyond Phase II need to further reduce backgrounds
  - argon veto & cleaner materials (e.g. Cu, PTFE a la MJD)→ Ra & Th should be ok
  - ^{42}Ar: needs further study e.g. in (existing) test cryostat
    - options: thicker n+ layer, limit volume from which ^{42}Ar is collected, PSD, depleted Ar, ...
  - muon induced background e.g. neutrons → ^{77m}Ge, cut on delayed coincidences

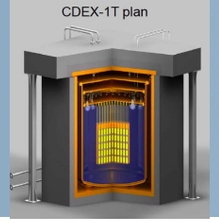
- argon veto: need to detect light produced inside a compact array of detectors,
  - need to reduce radioactivity

- detector operation: in Phase I 2/8 detectors had higher current after 18 months
  - operation, could be cured at LNGS, what fraction in Phase II?

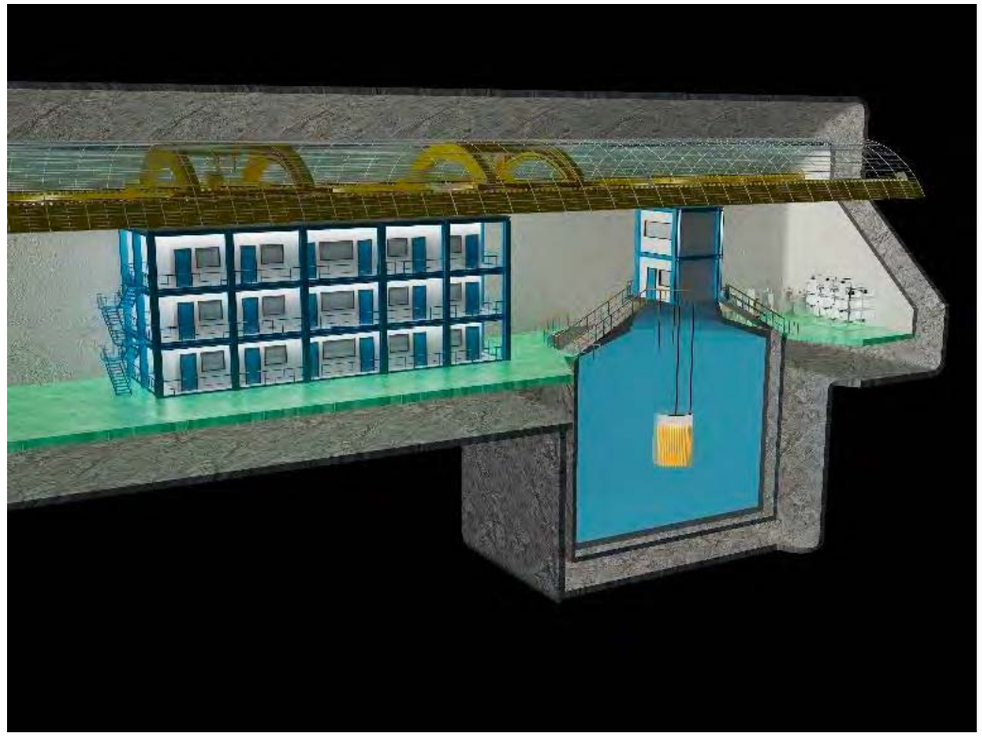
- engineering for large number of detectors (e.g. feedthroughs, cable chains, ...)
  - no fundamental problem, might need iterations → cost + time

Experience from Phase II running extremely important for any future large scale Ge experiment

CDEX Upcoming R&D



- As we heard, CDEX will focus on DM detection experiment, but that some R&D in CDEX would be carried on for $0\nu\beta\beta$.
- Will be building a large cryogenic detector for CDEX-200
- $0\nu\beta\beta$ R&D,
  - Ge-76 Enrichment
  - Ge crystal growth
  - Ge detector fabrication
  - low-background front-end electronics
  - EF-Copper production in CJPL,
  - large UL space and LN/LAr shielding system, are carrying on.



Zhi ZENG/Qian Yue
Tsinghua University

MAJORANA R&D beyond MJD

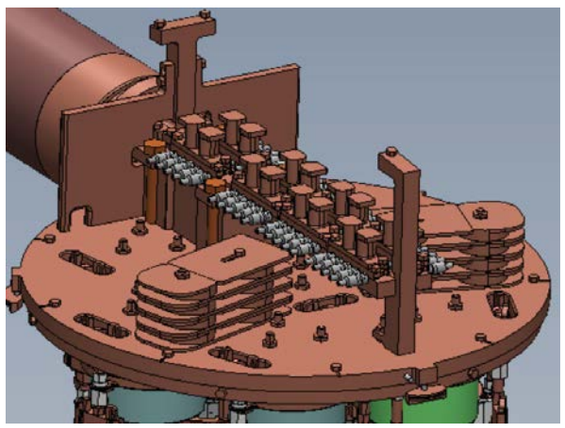
- Robust Signal and High Voltage Connectors
- Ultra-Clean Materials
- Alternative Detector Designs
- Detector Signal Readout
- Cryostat and Detector Mount Designs
- Enrichment
- Cooling and shielding
- Required depth

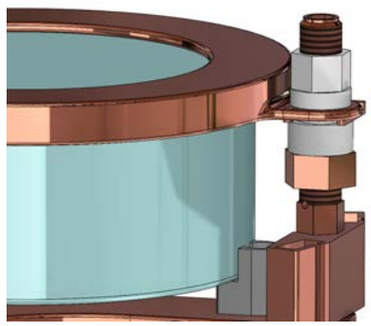
Applicable to any future experiment

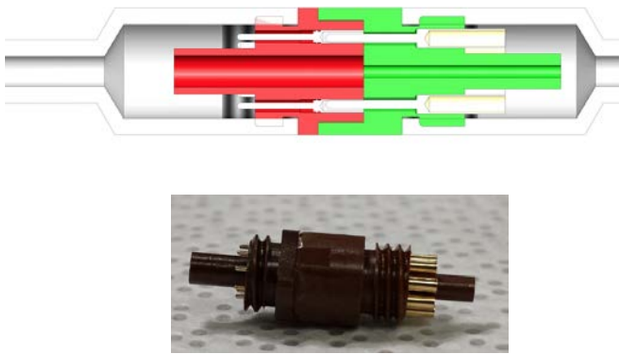
Specific to ^{76}Ge

Robust Signal & High Voltage Connectors

- MJD has produced some of the lowest activity cables and connectors currently in use.
- Tension between low-activity components and robust electrical connections (e.g. clean spring material). Both MJD and GERDA have encountered connection or connector issues.
- Proposed to apply current knowledge to developing next generation cables, working in conjunction with commercial vendors.
  - Connector design
  - High voltage contact design
  - Improve Cu wire radiopurity
- Development times of 18-24 months.
- The outcomes from all of these activities can be applied toward or utilized in all the proposed next generation $0\nu\beta\beta$ and DM experiments.







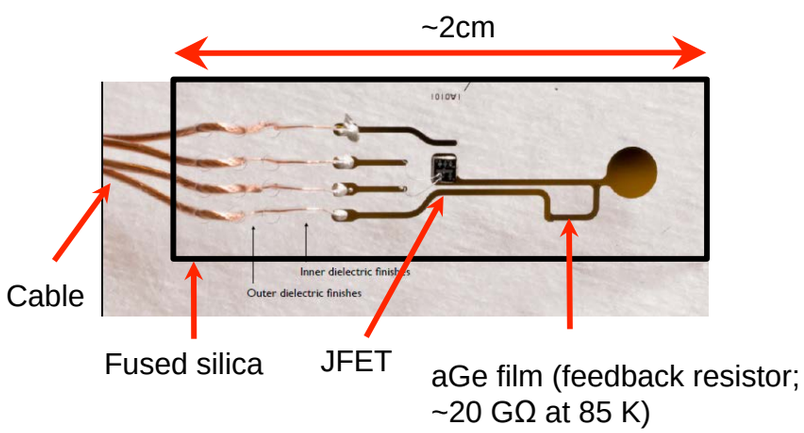
Ultra-Clean Materials

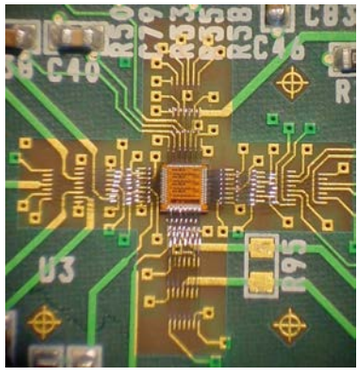
- Build on our success of producing ultra-clean electroformed copper and ultra-sensitive assays for next generation experiments.
- Primary activities.
  - Small parts contamination and associated process control
    - In MJD have observed that small parts have small measurable activity of U & Th (0.2 to 1.0 μBq/kg, while bulk material is at upper limit of sensitivity (≤ 0.1 μBq/kg). This has a negligible impact on MJD, but is important for next generation experiments.
  - Improved electroforming with larger mandrels and improved reliability
    - Larger mandrels would allow for more cost effective production of ultra clean Cu.
    - Would like to optimize process in terms of growth rate.
  - Electroformed alloys
  - Clean welding techniques
    - Much of the ^{60}Co activity is associated with taking the material to the surface for e-beam welding. Would like to develop a method for underground, clean room compatible welding of materials.
- All of these activities have development times of 18-24 months.
- The outcomes from all of these activities can be applied toward or utilized in all the proposed next generation $0\nu\beta\beta$ and DM experiments.

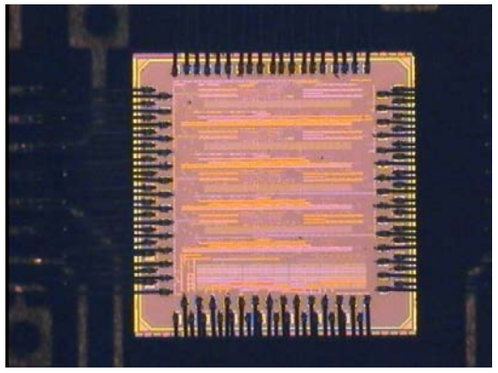
Detectors and readout

- Alternative Detector Designs
  - Larger detectors with thin contacts would use the valuable enriched Ge more efficiently.
  - Larger detectors improve the ratio of Ge mass to readout system mass, reducing backgrounds.
  - Explore alternatives to thick Li contacts, improved improved fiducial volume.
  - Development and testing time scale of 18-24 months

- Detector Signal Readout
  - In current two stage approach, the readout design has reached its limit due to the maximum cable length
  - study feasibility of in-situ amplification with a custom ASIC and improvement to the front-end
  - integrate much of the signal processing into a single ASIC, optimized for in-situ operation at cryogenic temperature.
  - Several year development cycle.

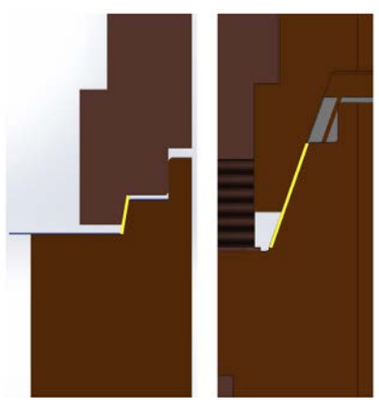


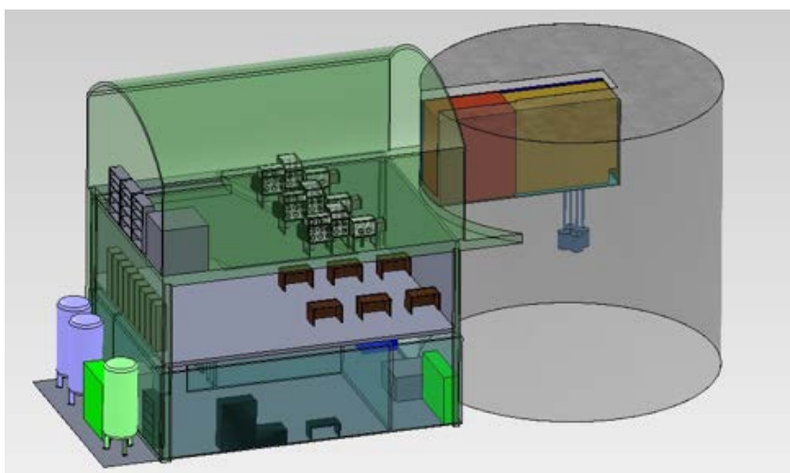




Cryostat and Detector Mount Designs

- Primary activities.
  - Cryostat sealing technologies
    - evaluate new vacuum flange profiles and seal materials for vacuum tightness and radiopurity
  - Alternative detector mount designs
    - maximize the packing density of detectors in a larger cryostat we will likely need to increase the lengths of the detector strings.
  - Development of a prototype liquid cryogen cooled vacuum cryostat
    - investigate a hybrid of the MJD and GERDA experiments, wherein a vacuum cryostat is immersed in a liquid cryogen passive or active shield.
- These activities have development times of between 12-24 months.
- The outcomes from all of these activities can be applied toward or utilized in all the proposed next generation $0\nu\beta\beta$ and DM experiments.





Other Next Generation 0νββ R&D

- Enrichment
  - The scale and cost of U.S. based enrichment is being examined in an ONP Isotopes Program funded study at ORNL (Isotopes group). An alternate enrichment concept is being investigated by an Isotopes Program funded 2-year study at PNNL.
- Cooling and shielding
  - Examining shielding options of a low-Z configuration (GERDA), a high-Z configuration (MAJORANA) and hybrid forms. We have been considering shield designs composed of liquids, cryogens, high-Z materials and alternative shielding materials.
- Required depth
  - Using the DEMONSTRATOR data to learn how neutron and muon interactions produce background as a function of depth. This directly impacts the siting decision of a Next-Generation Ge Experiment.

Questions

- Where are we now for $0\nu\beta\beta$?
- Is there a preferred $0\nu\beta\beta$ isotope in terms of sensitivity?
- What levels of backgrounds and exposure are required for future $0\nu\beta\beta$ experiments to cover the inverted ordering region?
- What are considerations for future ton scale $0\nu\beta\beta$ experiments?
- What is needed to build a ton scale ^{76}Ge Experiment?
- Costs & International prospects?
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- Ge for Dark Matter?
- Summary

Cost for Next Generation 0νββ Experiments

- Next generation experiments estimate total costs range from $50 - $300 M (assuming 50% contingency). Funding profile is typically 5 years (with 2 years of pre R&D funding).
- Most collaborations expect international contributions at a level proportional to participation.
- Enriched isotope costs estimate range from $10 - $100 per g, and total $20 - $120 M.
- ^{76}Ge estimate is $300 M, with $120M for ^{enr}Ge.
- Funding at this scale requires significant community and government support.
  - cooperation between countries' funding agencies
  - advance planning for providing funds

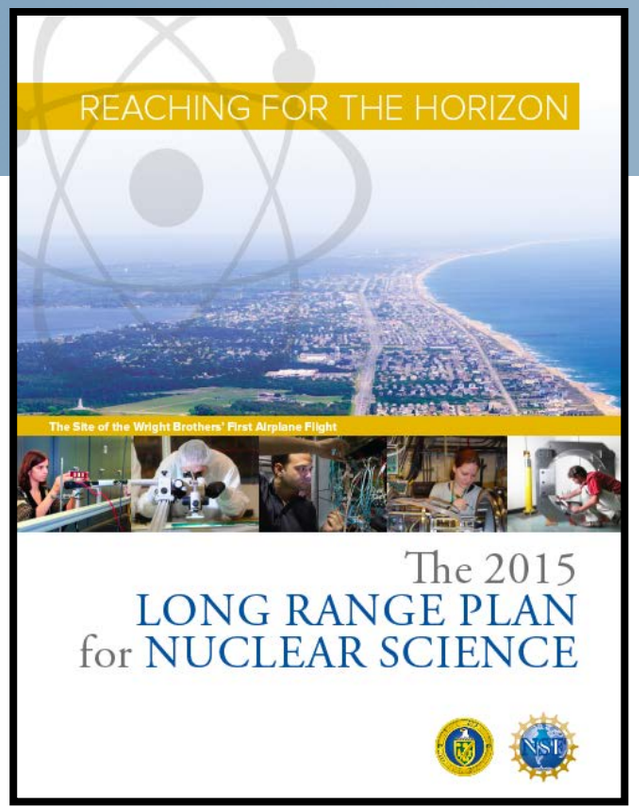
U.S. Process towards a ton scale 0νββ

Nuclear Science Advisory Committee (NSAC) — committee of nuclear scientists that advises the Federal agencies involved in nuclear physics — the Department of Energy (DOE) Office of Nuclear Physics and the National Science Foundation (NSF)

Every 5-7 years, NSAC is charged with developing a Long Range Plan (LRP) for Nuclear Science. Major new initiatives must be endorsed in the LRP in order to go forward. After 18 months of development, with extensive community involvement, the latest LRP was released on October 15, 2015

Link to the LRP: http://science.energy.gov/np/nsac/

NSAC 2015 Long Range Plan



RECOMMENDATION II

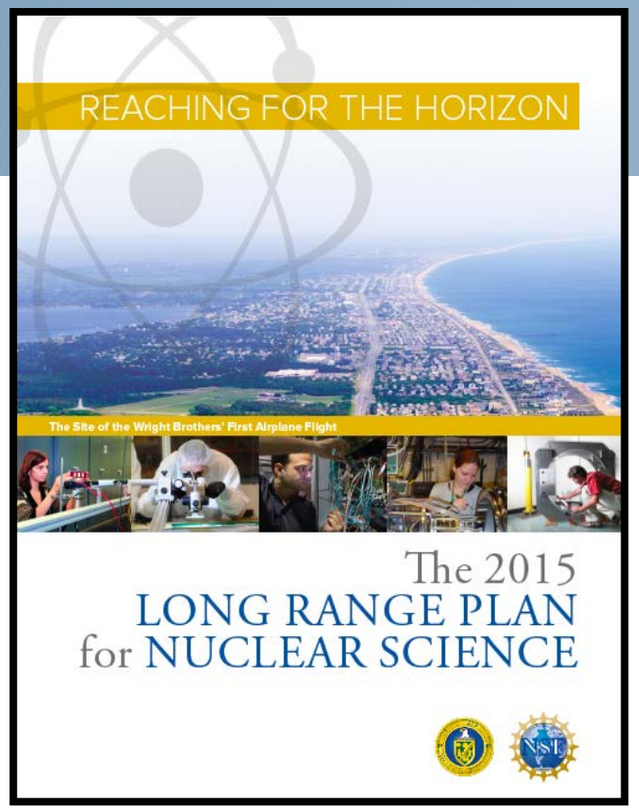
The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.

NSAC 2015 Long Range Plan



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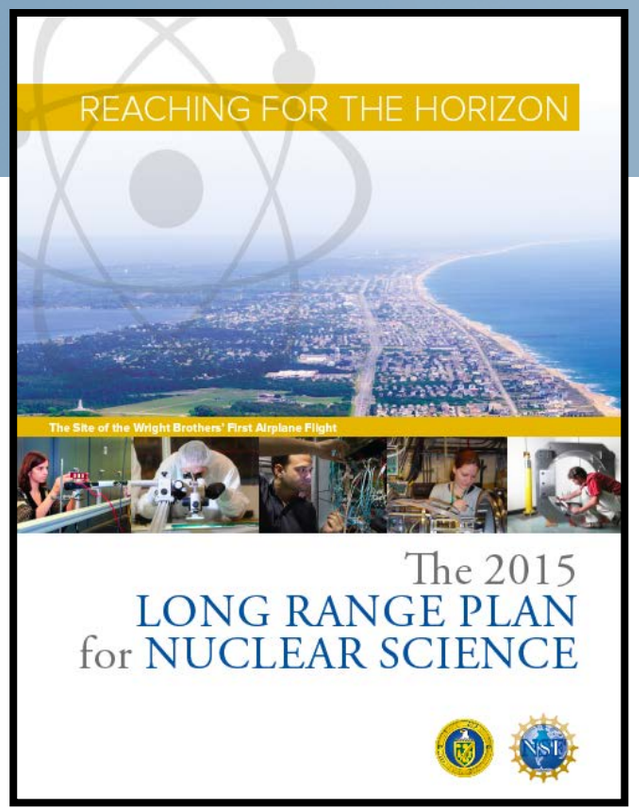
U.S. plan is to make a "down-select" in 2-3 years.
Oct 2015 NSAC NLDBD sub-committee report.

NSAC 2015 Long Range Plan



B: Initiative for Detector and Accelerator Research and Development

U.S. leadership in nuclear physics requires tools and techniques that are state-of-the-art or beyond. Targeted detector and accelerator R&D for the search for neutrinoless double beta decay and for the EIC is critical to ensure that these exciting scientific opportunities can be fully realized.

We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC.

Questions

- Where are we now for $0\nu\beta\beta$?
- Is there a preferred $0\nu\beta\beta$ isotope in terms of sensitivity?
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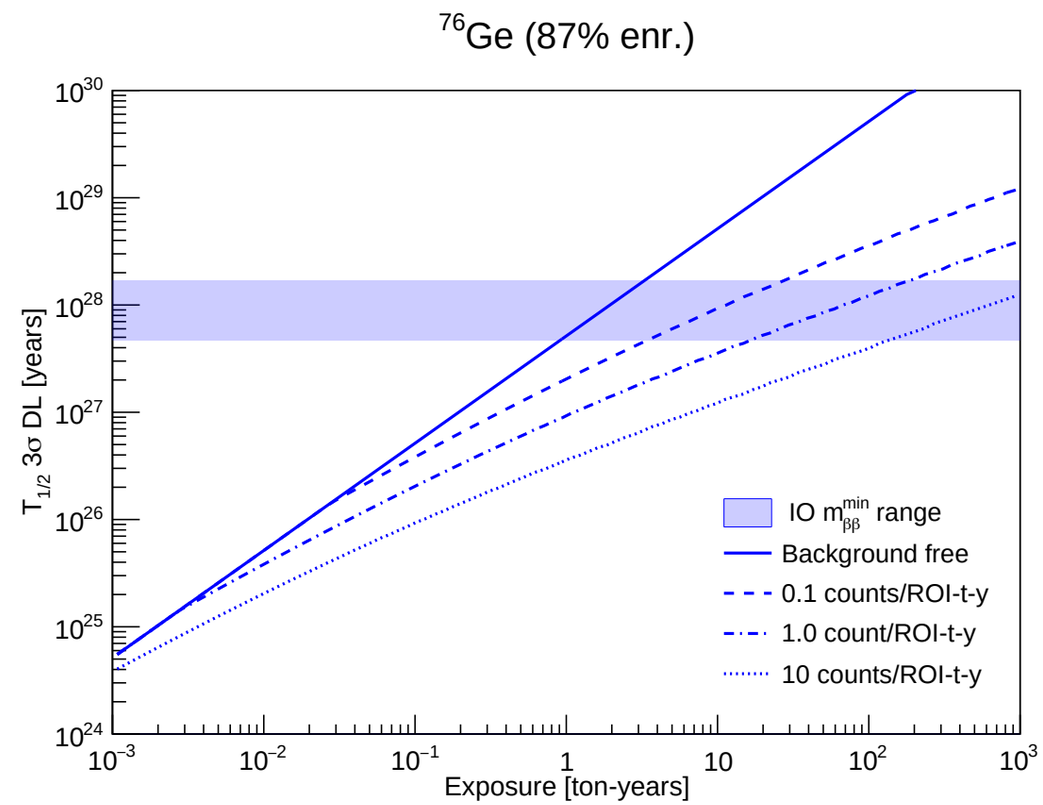
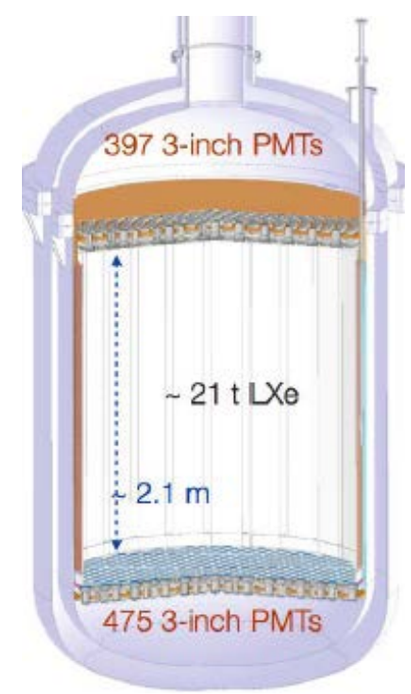
From 1 → 10 → 100 tons?

- What background is required?
- Unique signature
  - single atom tagging?
  - full track reconstruction?
- Does a granular detector make sense at 100 tons?
  - 500 → 5000 → 50000
- Can monolithic large scale (20 ton) next generation DM experiments be competitive for 0νββ measurements?
  - LZ, PandaX IV, ...
- Cost ?





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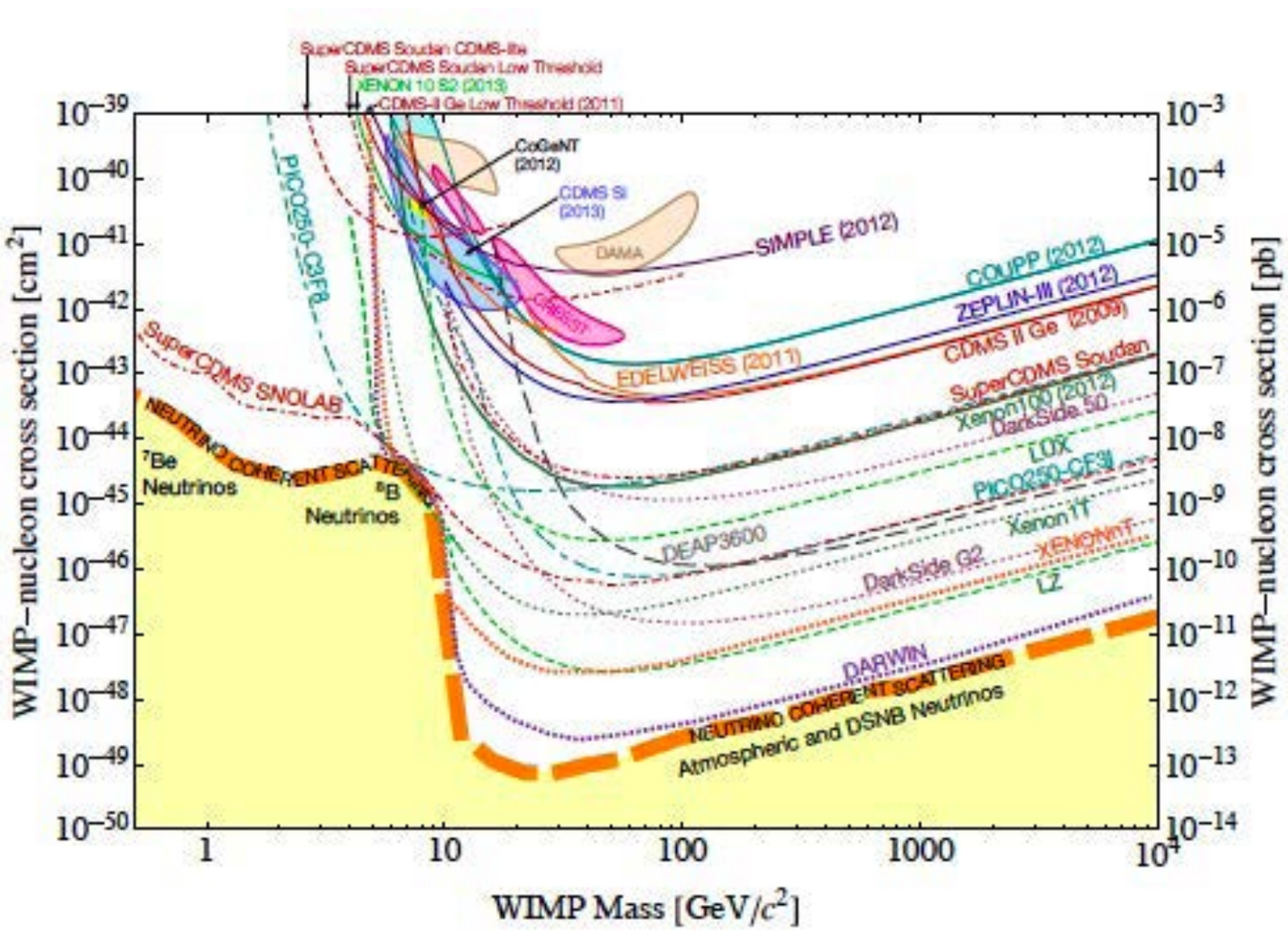
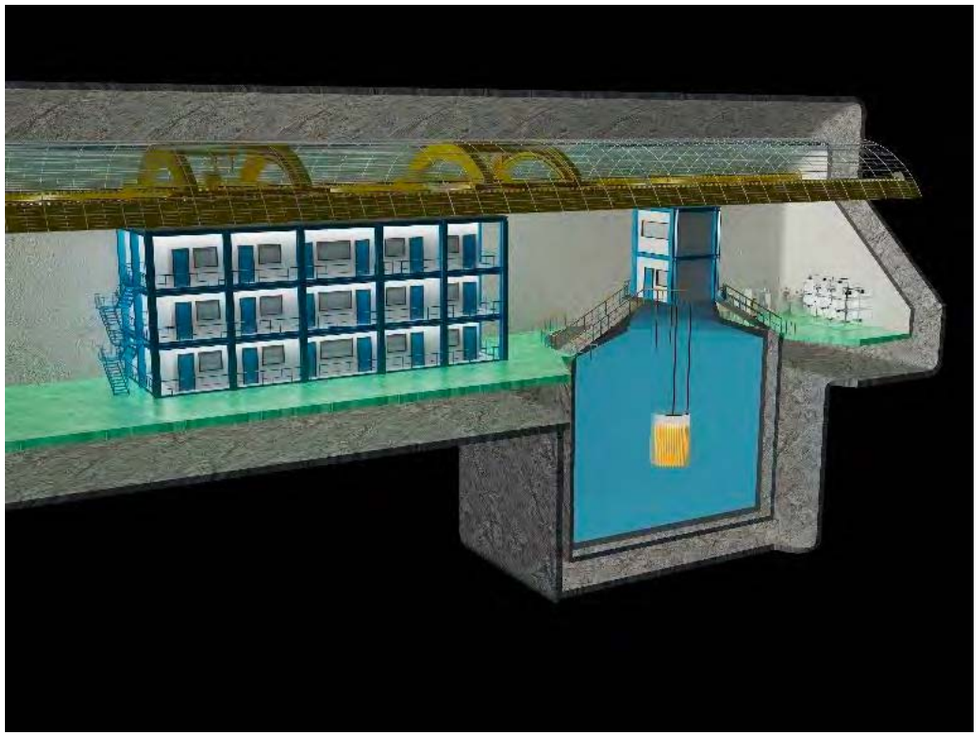
Future Dark Matter and Ge

- Very impressive progress and multiple larger mass experiments going forward.
  - Coherent neutrino scattering by solar neutrinos sets sensitivity goal.
  - Low energy WIMP region being covered by CDEX200, SuperCDMS, CRESST, EDELWEISS.





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- Is there a preferred $0\nu\beta\beta$ isotope in terms of sensitivity?
- What levels of backgrounds and exposure are required for future $0\nu\beta\beta$ experiments to cover the inverted ordering region?
- What are considerations for future ton scale $0\nu\beta\beta$ experiments?
- What is needed to build a ton scale ^{76}Ge Experiment?
- Costs & International prospects?
- Beyond the ton scale?
- Ge for Dark Matter?
- Summary

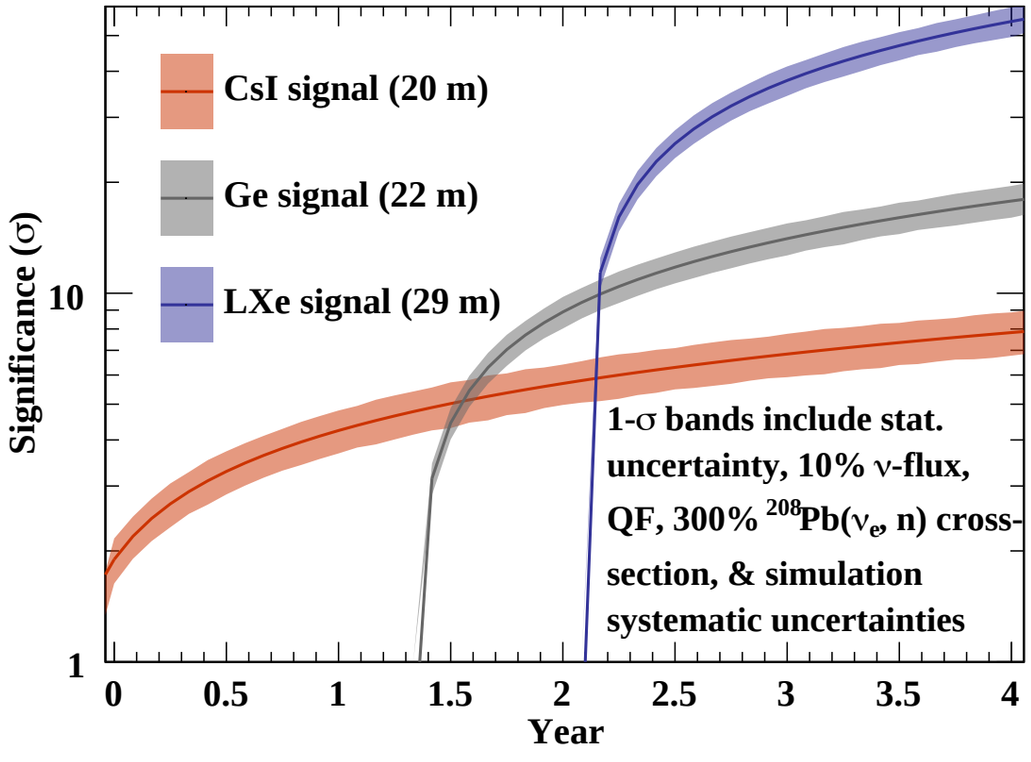
Future Ge 0νββ and Dark Matter Summary

- Large international collaborations are moving forward with designs for next generation 0νββ experiments based on lessons learned from the current measurements.
  - All aim for sensitivity and discovery levels at $T_{1/2} > 10^{27}$ years
  - Requires backgrounds of 0.1 cnt/ton-year or better.
  - An improvement of ×100 over current results.
- The field is rapidly approaching readiness to proceed with ton scale experiments for 0νββ and DM.
  - For 0νββ technical challenges remain that need to be addressed.
- International collaboration is required and will require cooperation not only amongst collaborators but coordination between funding agencies.
  - Time scales - U.S. down select in ~2018.

Back-up Slides

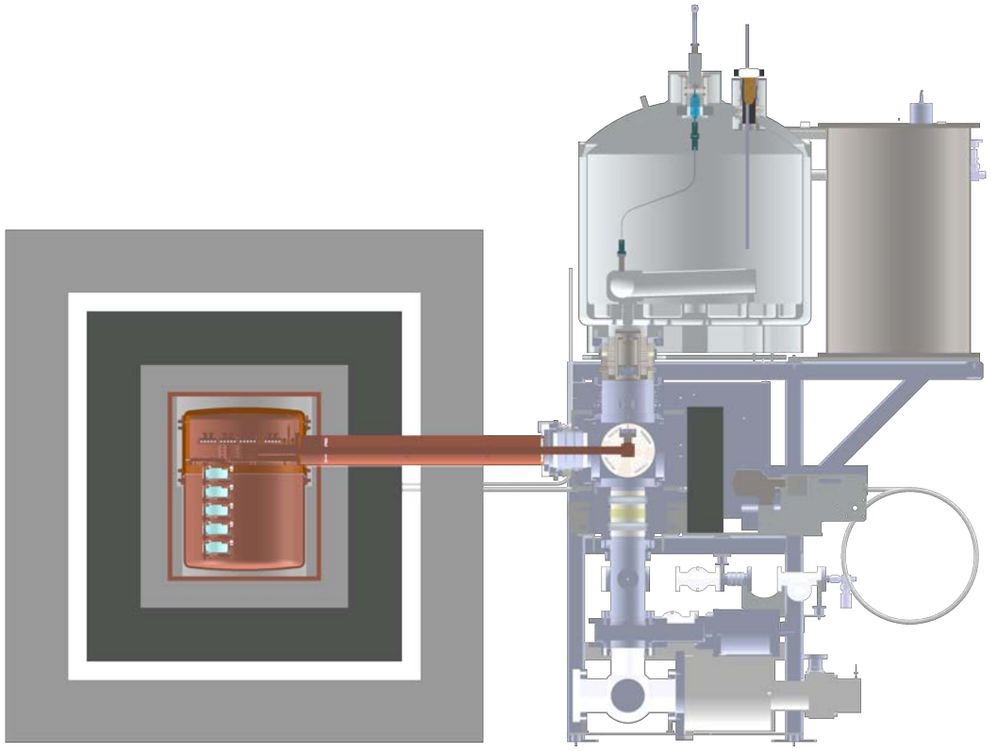
COHERENT: Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) at the SNS

- Exploiting the intense ν flux and pulsed nature of the SNS for an unambiguous first measurement of CEvNS.
- Pulsed timing reduces steady-state backgrounds. Muon-decay νs have characteristic 2.2usec decay time.
- Multi-target approach (CsI, PPC Ge, 2-phase Xe) allows for observation of N^2 cross section dependence, reduction of systematic uncertainties.
- Low-background, short-baseline deployment locations identified. Further background characterization underway.
- CsI target in place, taking data. Deployment of MEPhI-constructed Xe detector supported by ORNL LDRD.



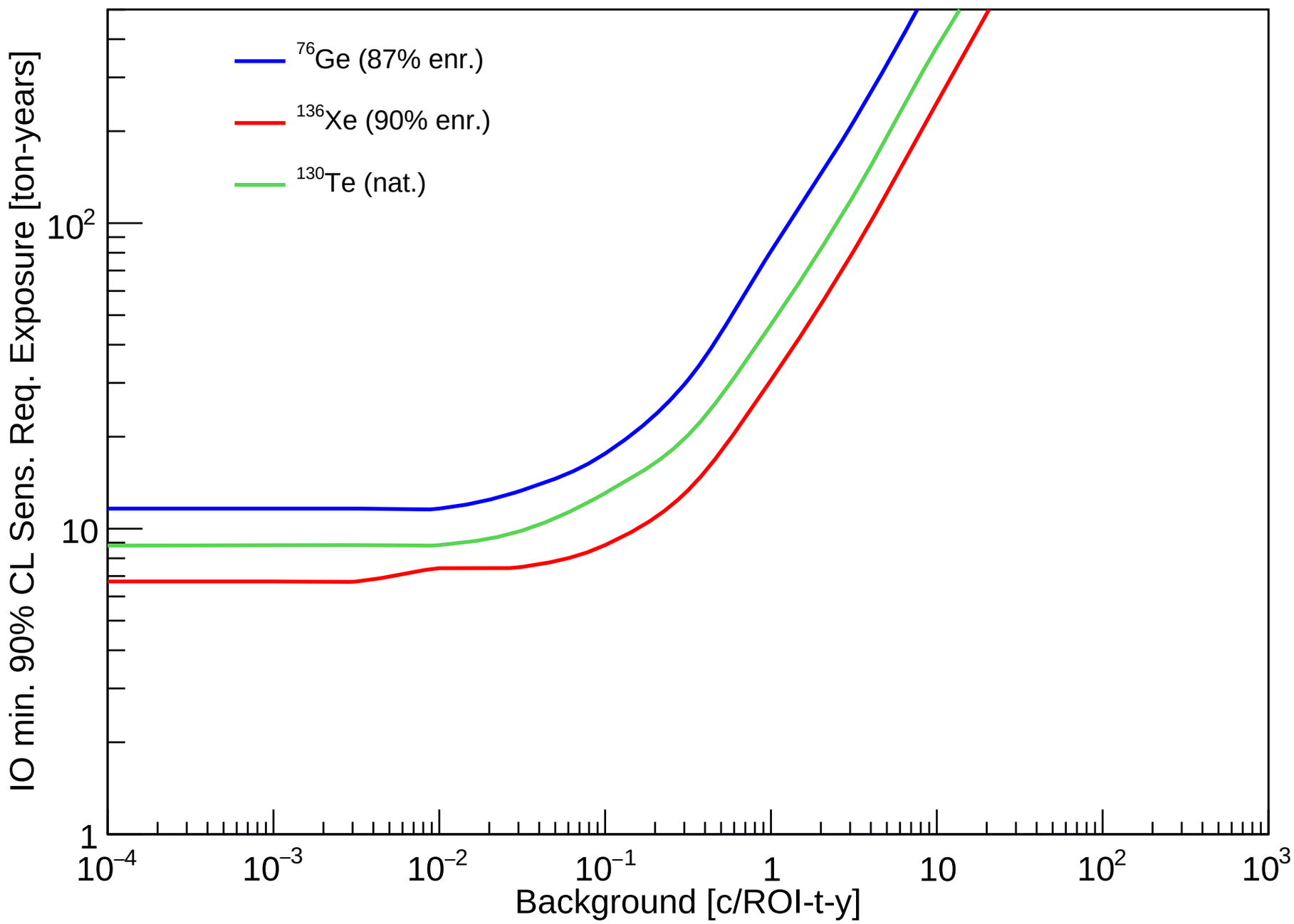
PPC Ge Detector Subsystem

- Repurposed MAJORANA DEMONSTRATOR (MJD) Prototype Module.
- Leverages MJD hardware and software development.
- 15kg PPC detector mass.
- Excellent resolution at low energy.
- Well-measured quenching factor.
- Proposal for support of procurements and deployment submitted to DOE-HEP.



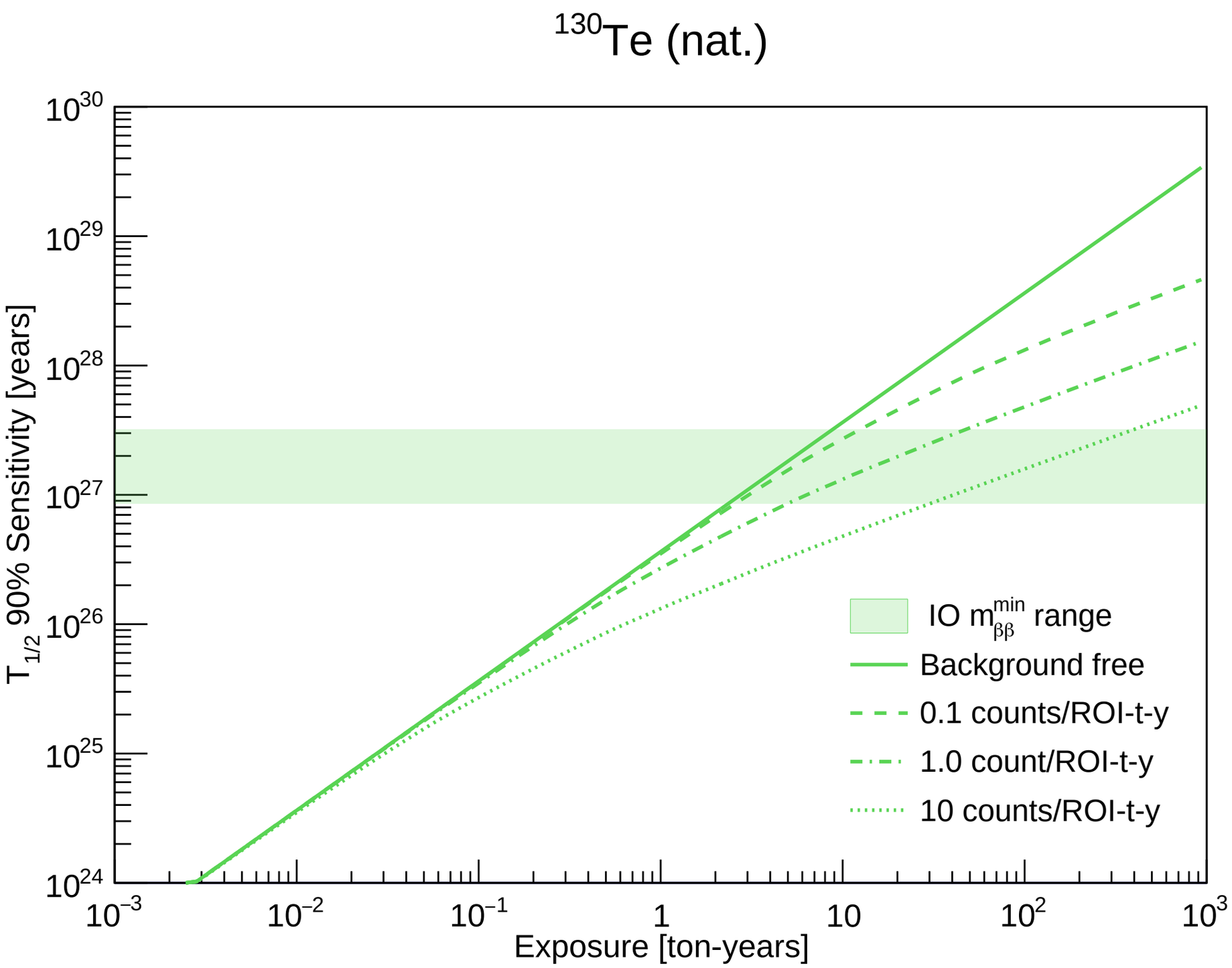
Required Sensitivity vs. Background

J. Detwiler



Sensitivity vs. Exposure for ^{130}Te

J. Detwiler



Inverted Ordering (IO)

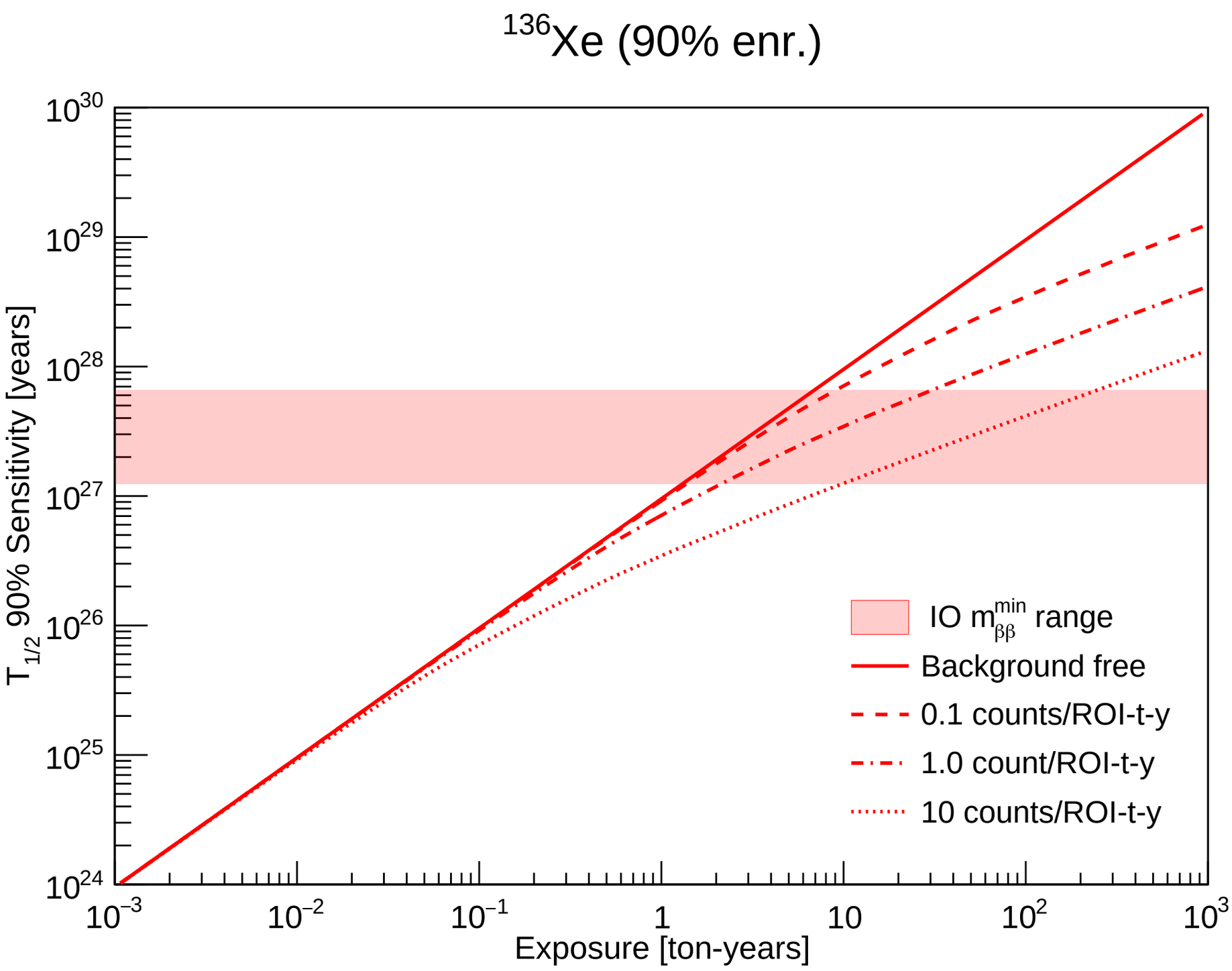
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, ...)

Assumes 81% efficiency based on CUORE-0. Natural Te is accounted for in the exposure

Sensitivity vs. Exposure for ^{136}Xe

J. Detwiler



Inverted Ordering (IO)

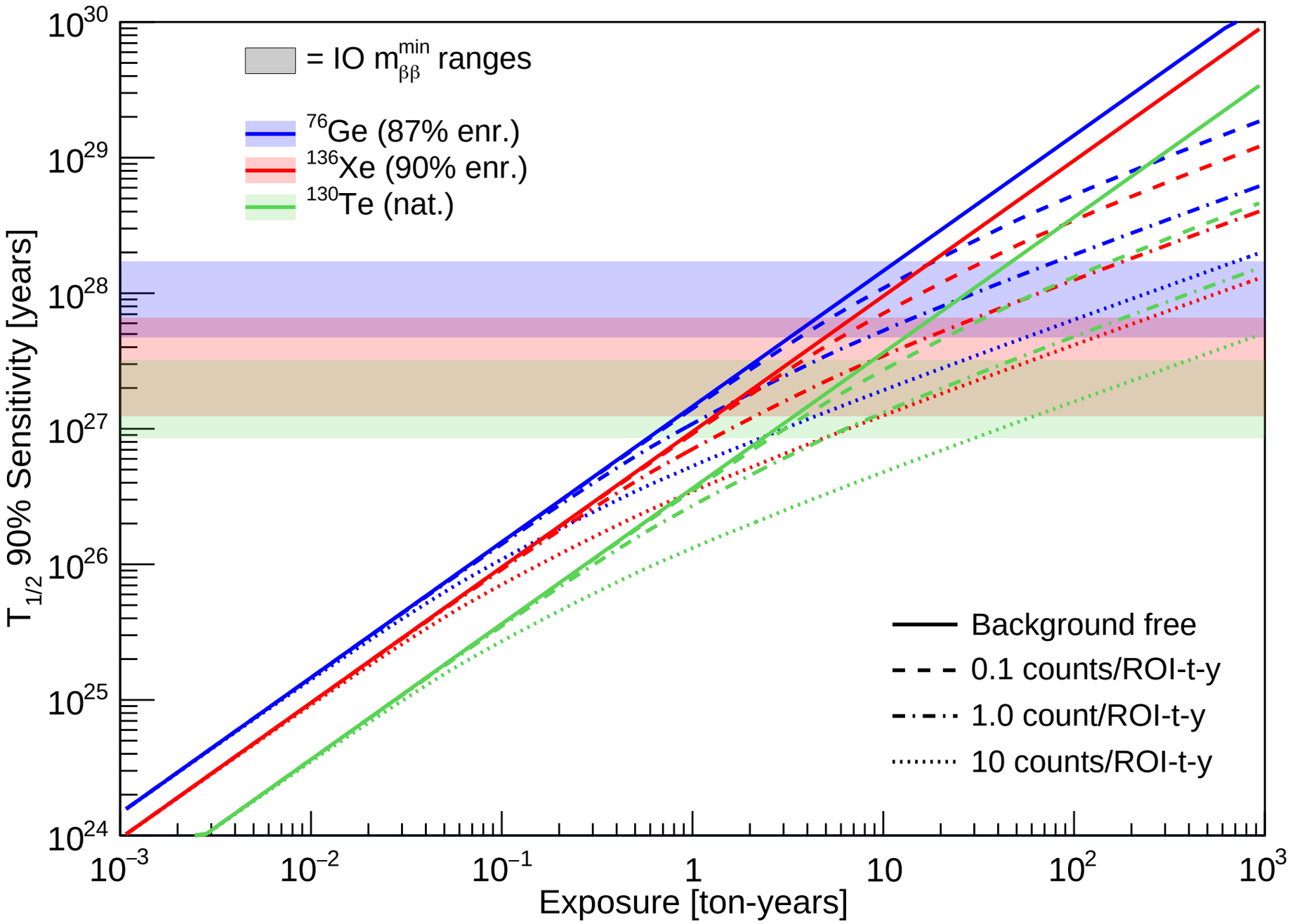
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, ...)

Assumes 84% efficiency based on EXO 200. Enrichment level is accounted for in the exposure

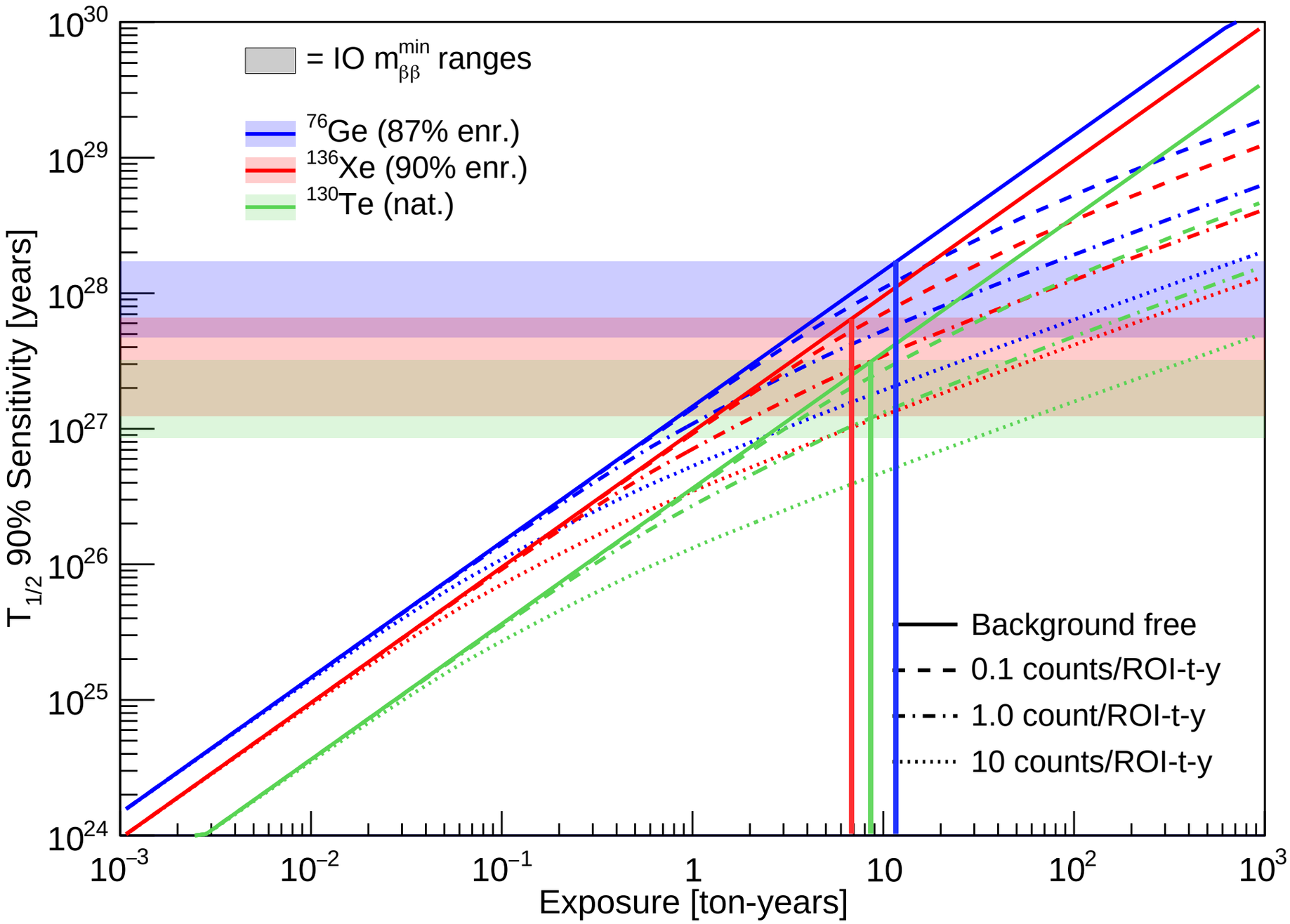
Sensitivity vs. Exposure

J. Detwiler



Sensitivity vs. Exposure

J. Detwiler



Conclusion:

Based on current knowledge, and planned enrichment levels, isotopes have roughly comparable sensitivities per unit mass, when comparing for the best case of zero backgrounds.