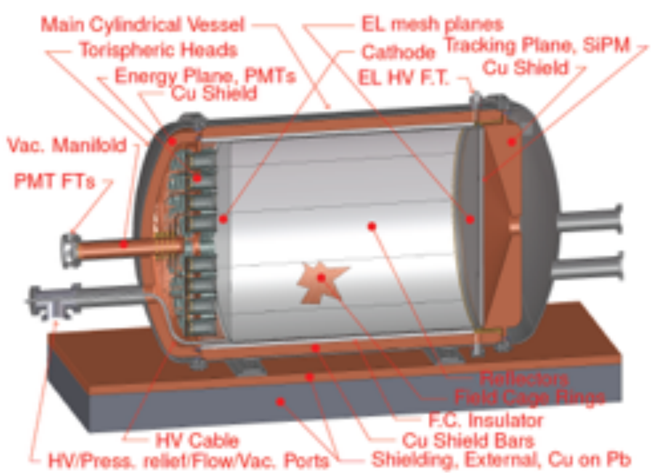
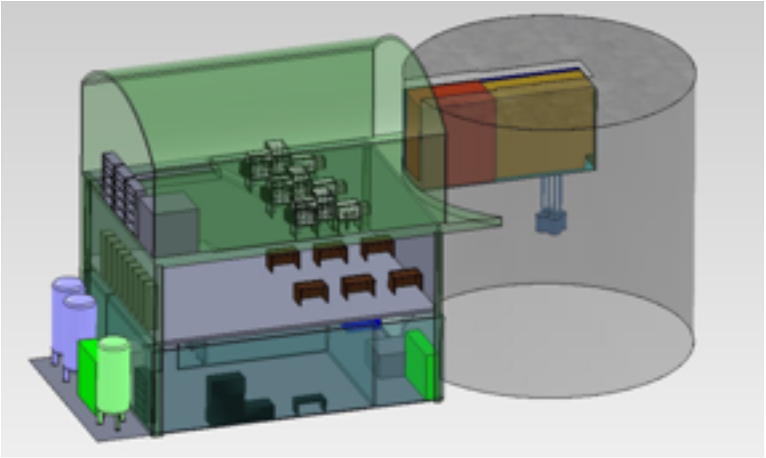
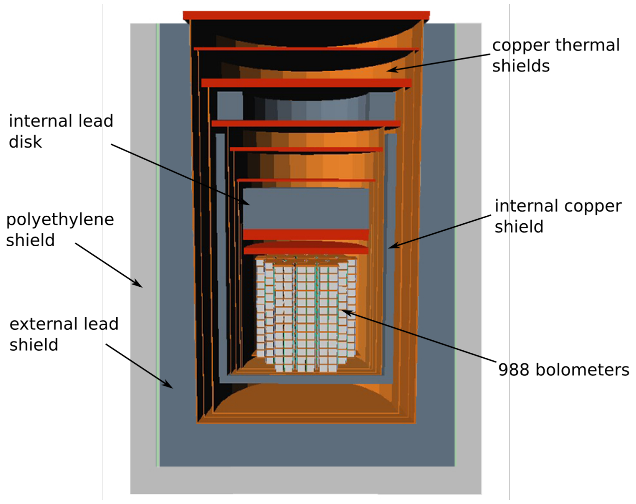
Considerations for future neutrinoless double beta decay experiments

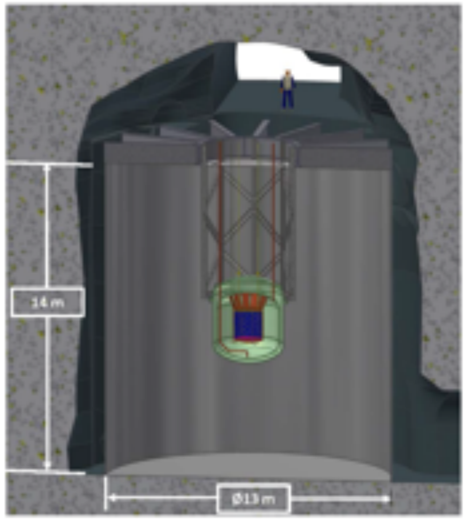
J. F. Wilkerson

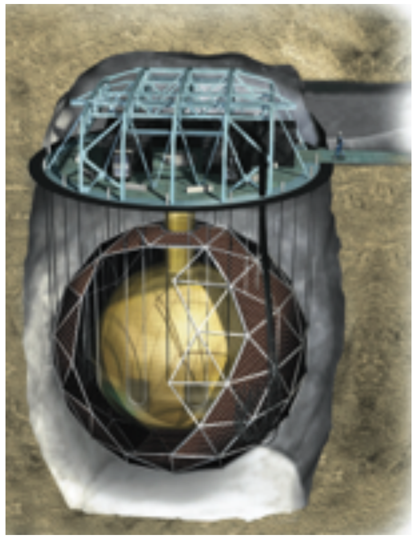
AFCI Neutrino Mass Workshop
December 14, 2015

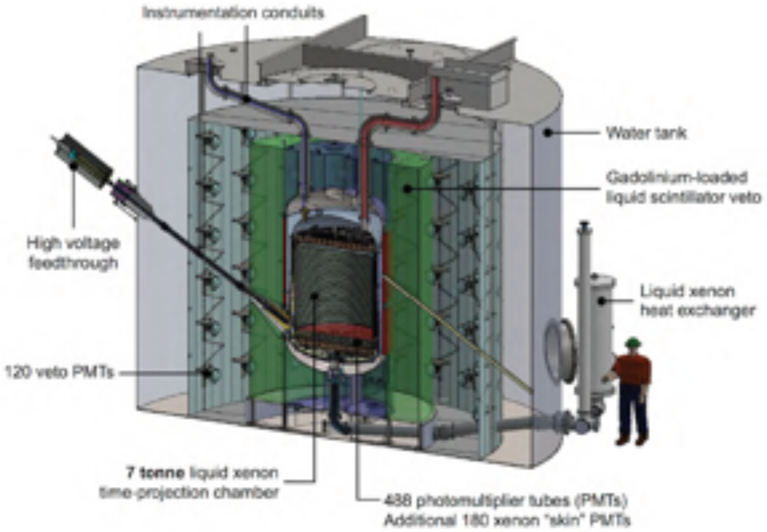












THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

COSMS INSTITUTE

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

Outline

- Brief overview of $0\nu\beta\beta$ and sensitivity to neutrino mass.
- 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 prospects and considerations for future ton scale $0\nu\beta\beta$ experiments?
- Relationship to other measurements?
- Summary

Outline

- **Brief overview of 0νββ and sensitivity to neutrino mass.**
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0νββ decay

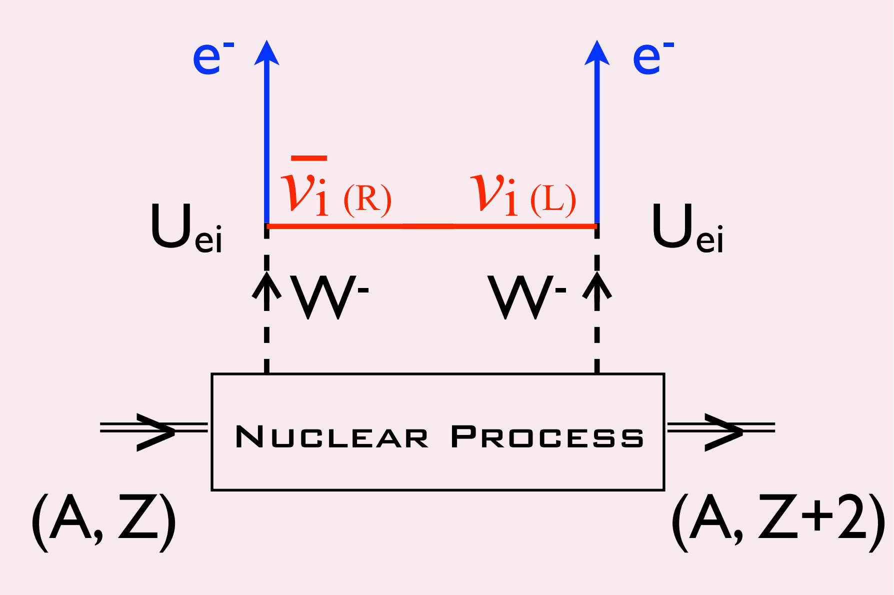
Requires:

- neutrino to have non-zero mass
  - "wrong-handed" helicity admixture ~ m_i/E_{ν_i}

Any process that allows 0νββ to occur requires Majorana neutrinos with non-zero mass.
Schechter and Valle, 1982

- Lepton number violation
  - No experimental evidence that Lepton number must be conserved

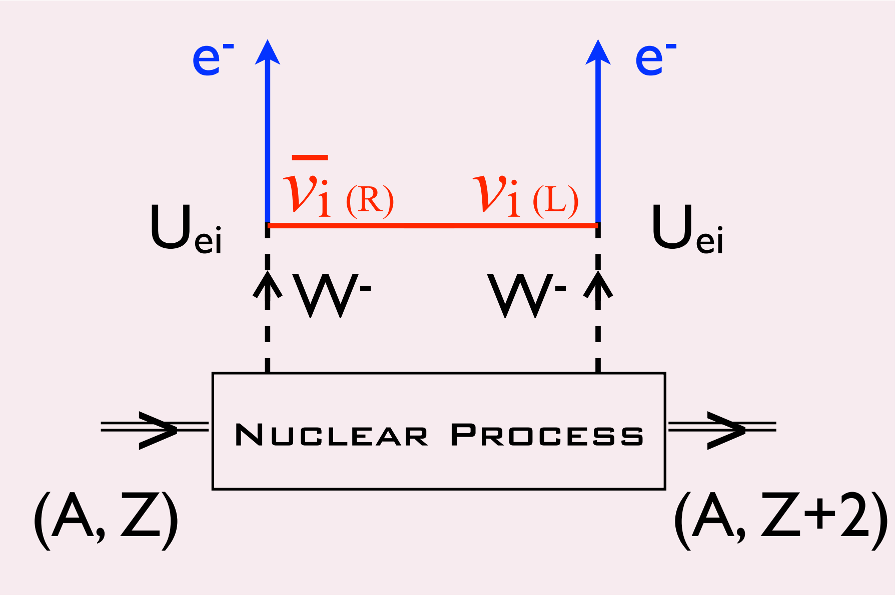
(i.e. allowed based on general SM principles, such as electroweak-isospin conservation and renormalizability)



If 0νββ decay is observed ⇒ neutrinos are Majorana particles
lepton number is violated

0νββ and ν mass

Observable (decay rate) depends on nuclear processes & nature of lepton number violating interactions (η).



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}(\eta)\right|^2 \eta^2$$

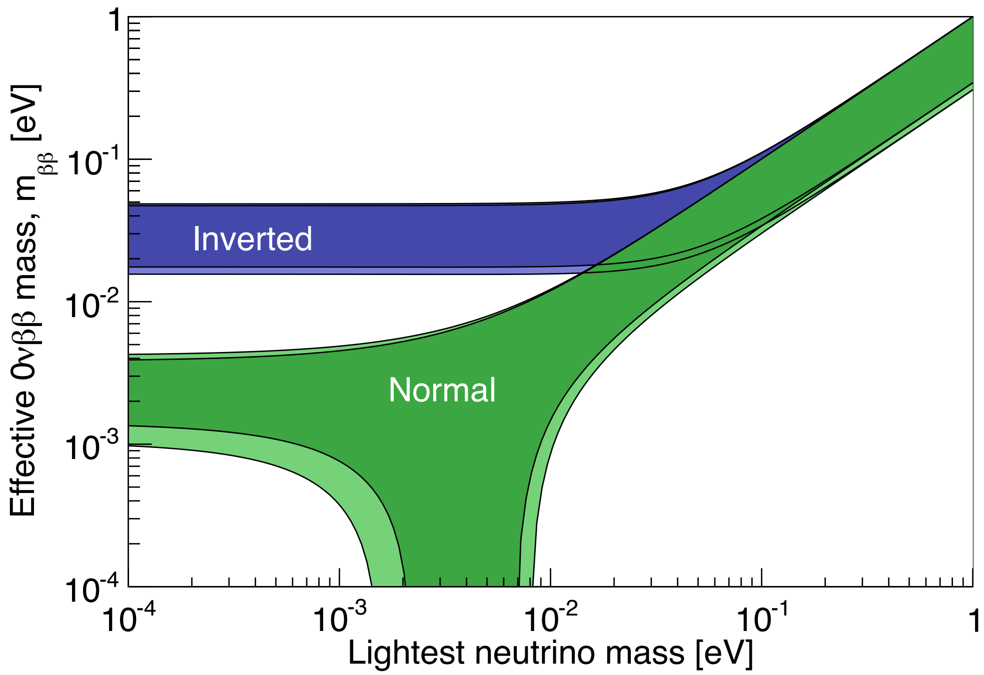
$$\Downarrow$$

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

- Phase space, $G_{0\nu}$ is calculable.
- Nuclear matrix elements (NME) via theory.
- Effective neutrino mass, $\langle m_{\beta\beta}\rangle$, depends directly on the assumed form of lepton number violating (LNV) interactions.

Extracting ν mass from observed 0νββ rates

- Requires a lepton number violating (LNV) mechanism (model)
  - In the "usual" model – light Majorana neutrino and SM interactions – $\langle m_{\beta\beta} \rangle$ depends on mass hierarchy, lepton matrix mixing values, & Majorana phases.
    - The combination of certain θ_{ij}, m_i, and phases ϕ_k values cancel out and could yield no observable decay.



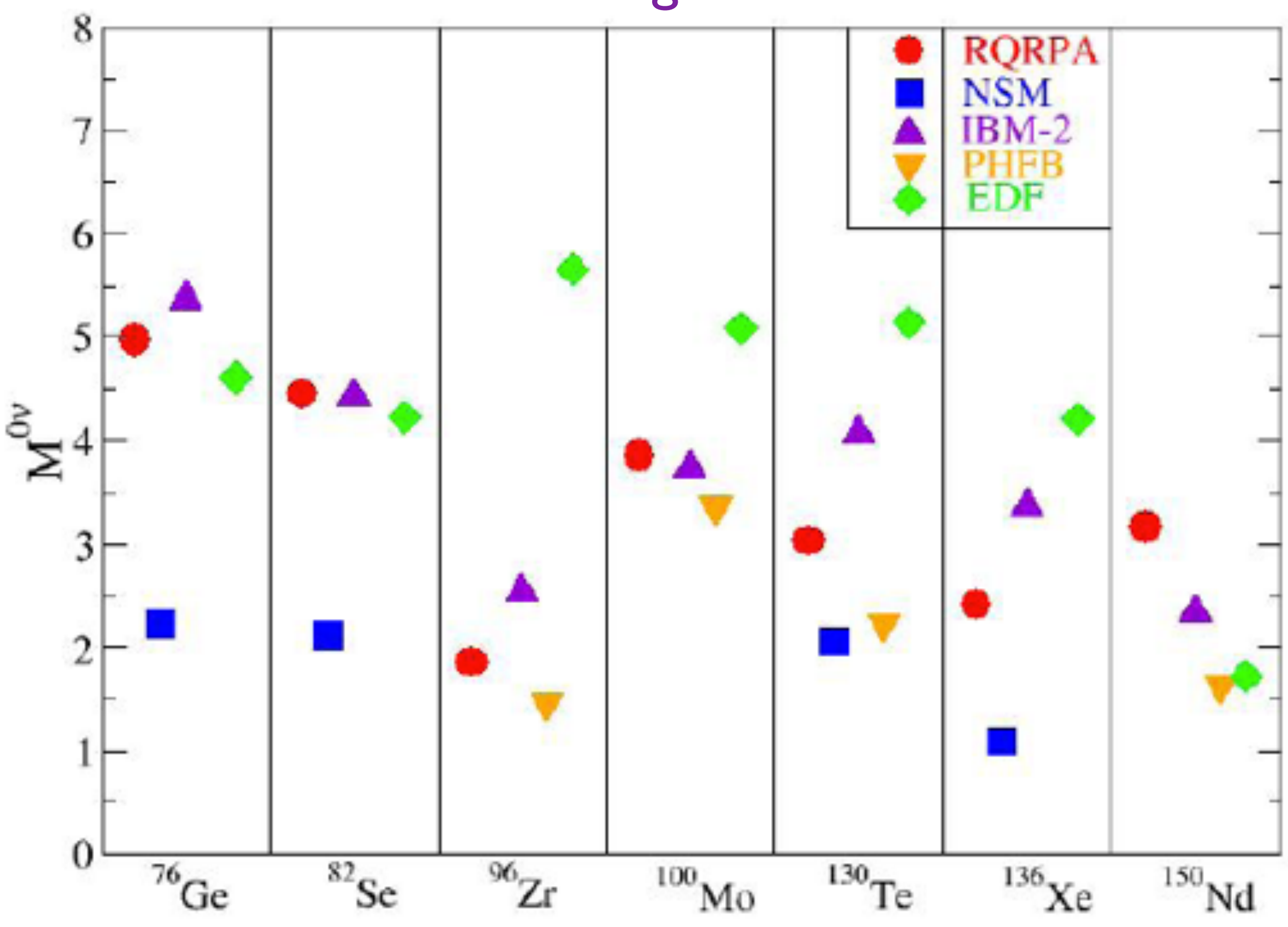
- Requires calculation of reliable theoretical nuclear matrix elements.
  - Advantage of multiple isotopes but one "true" value of $\langle m_{\beta\beta} \rangle$: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{130}Te, ^{136}Xe, ^{150}Nd
  - Potential measurements of excited state decays.
- Knowledge of effective weak-axial coupling constant.

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

P. Vogel 2014



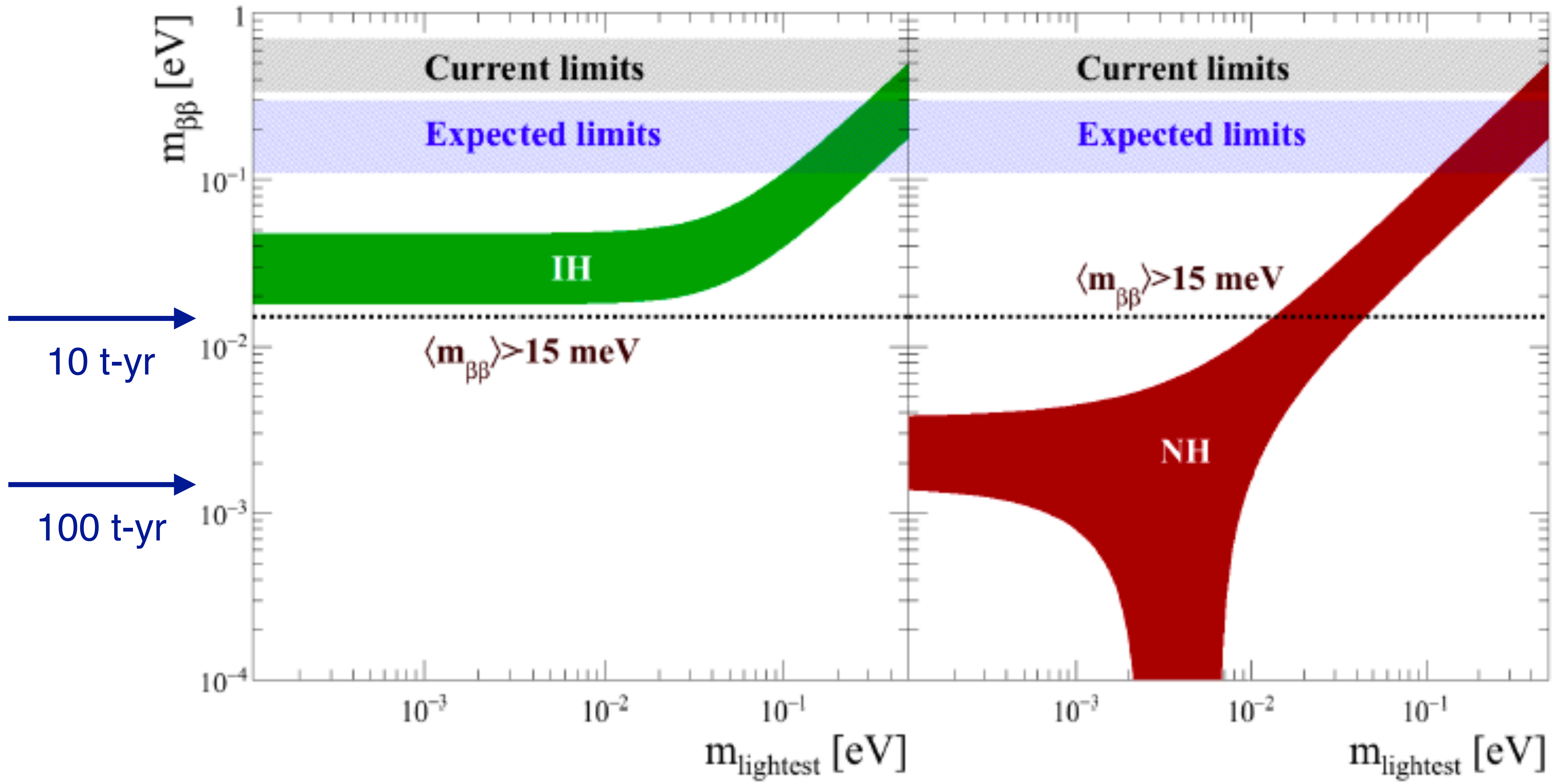
Matrix elements for "standard mechanism"

0νββ Decay and <mββ>

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

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

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



2015 NSAC Long Range Plan for Nuclear Science

Outline

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- **Is there a preferred 0νββ isotope in terms of sensitivity?**
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Sensitivity to <mββ> per atom

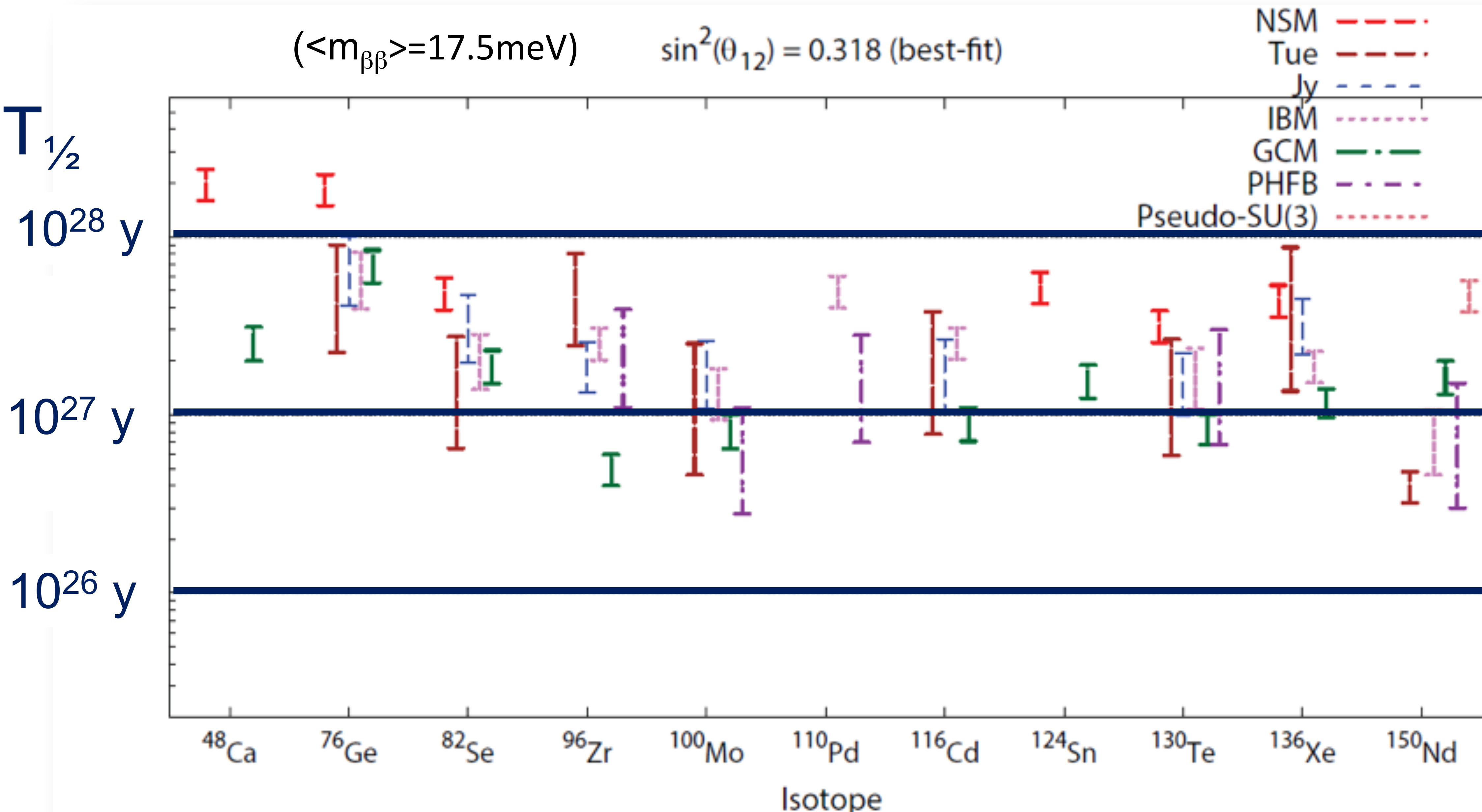


Figure source: A. Dueck, W. Rodejohann, and K. Zuber, Phys. Rev. D83 (2011) 113010.

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

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

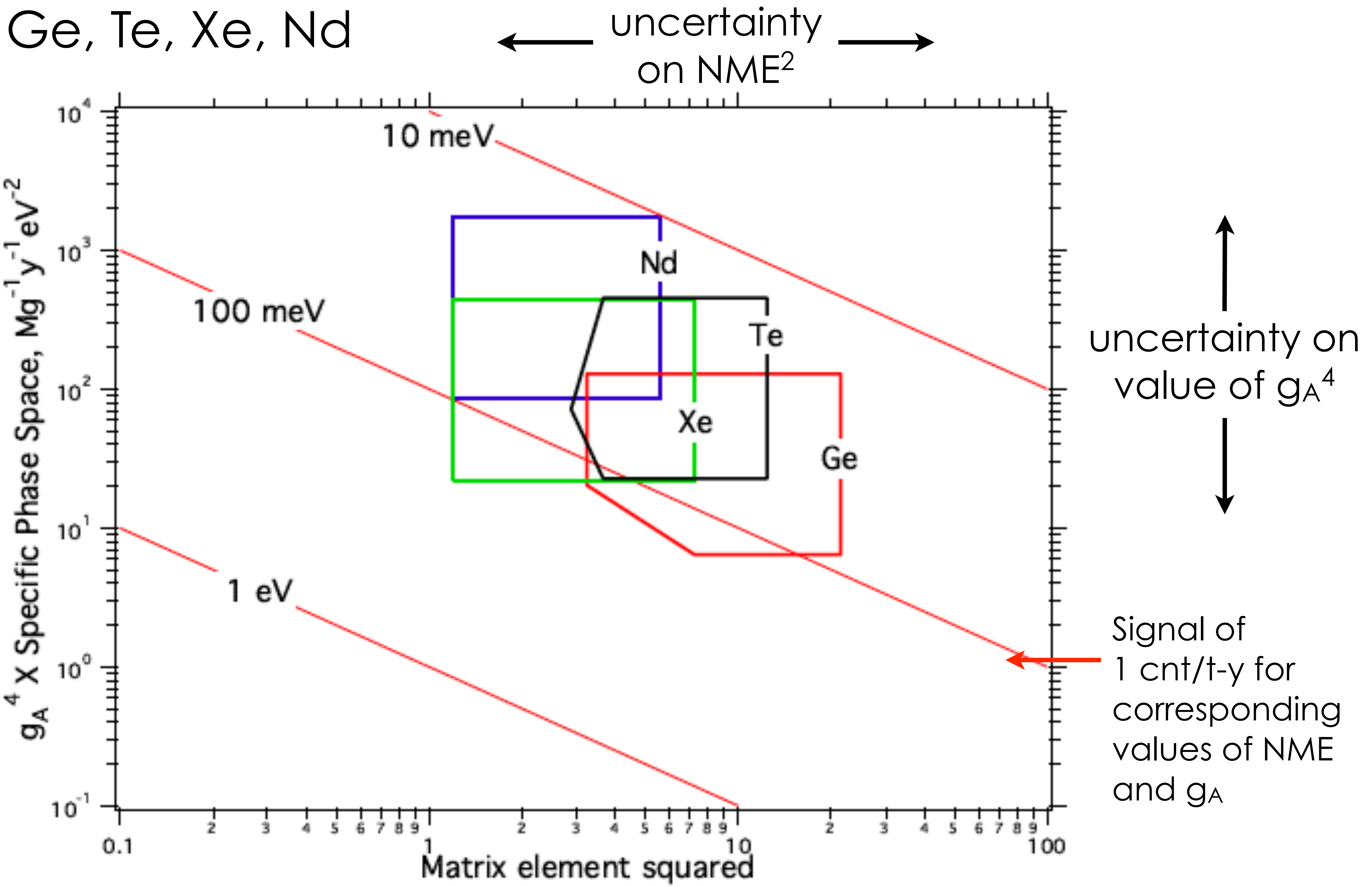
$$\equiv H_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

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

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

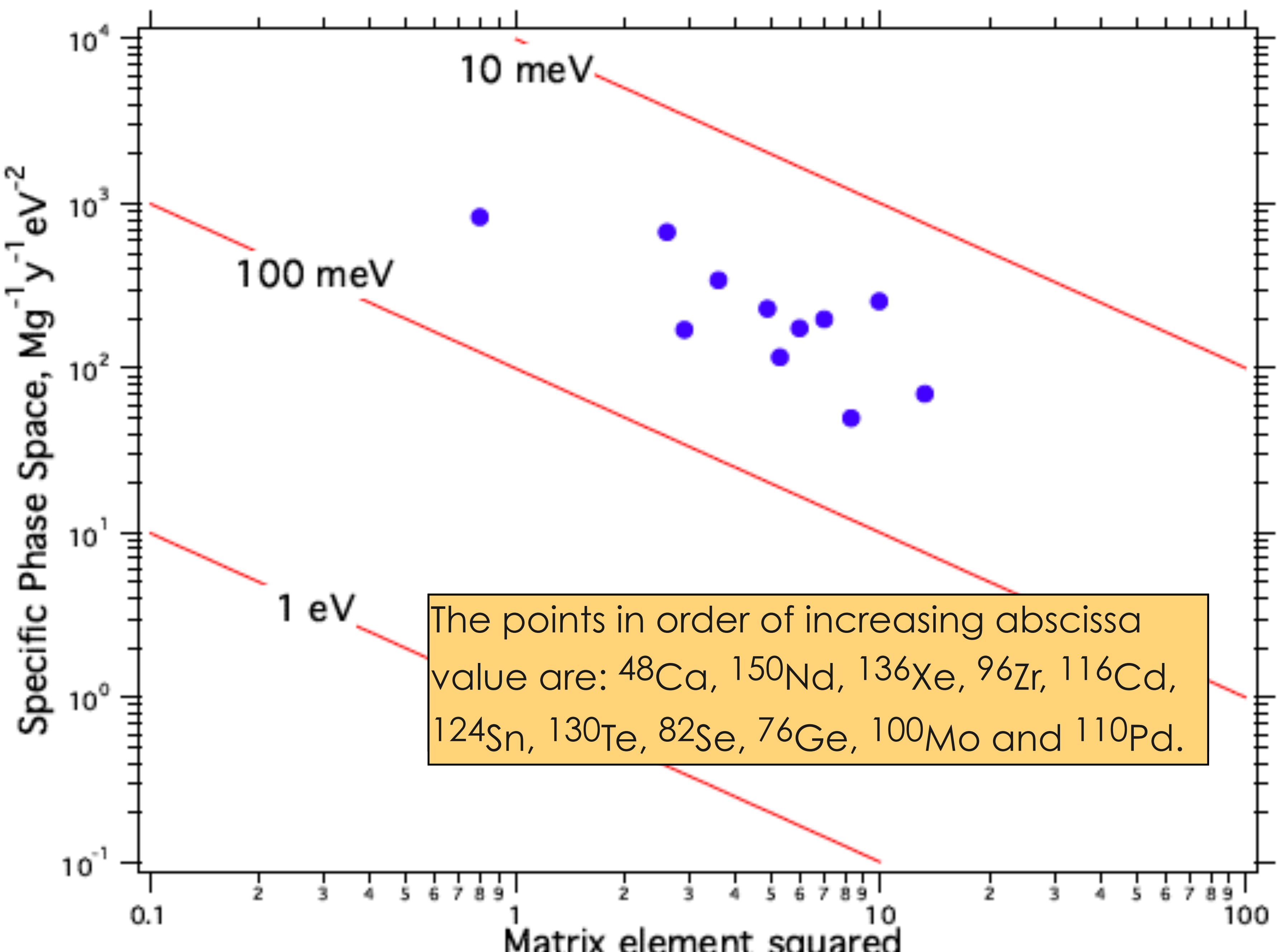
R.G.H. Robertson,
MPL A **28** (2013) 1350021
(arXiv 1301.1323)

For Ge, Te, Xe, Nd



Sensitivity per unit mass of isotope

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



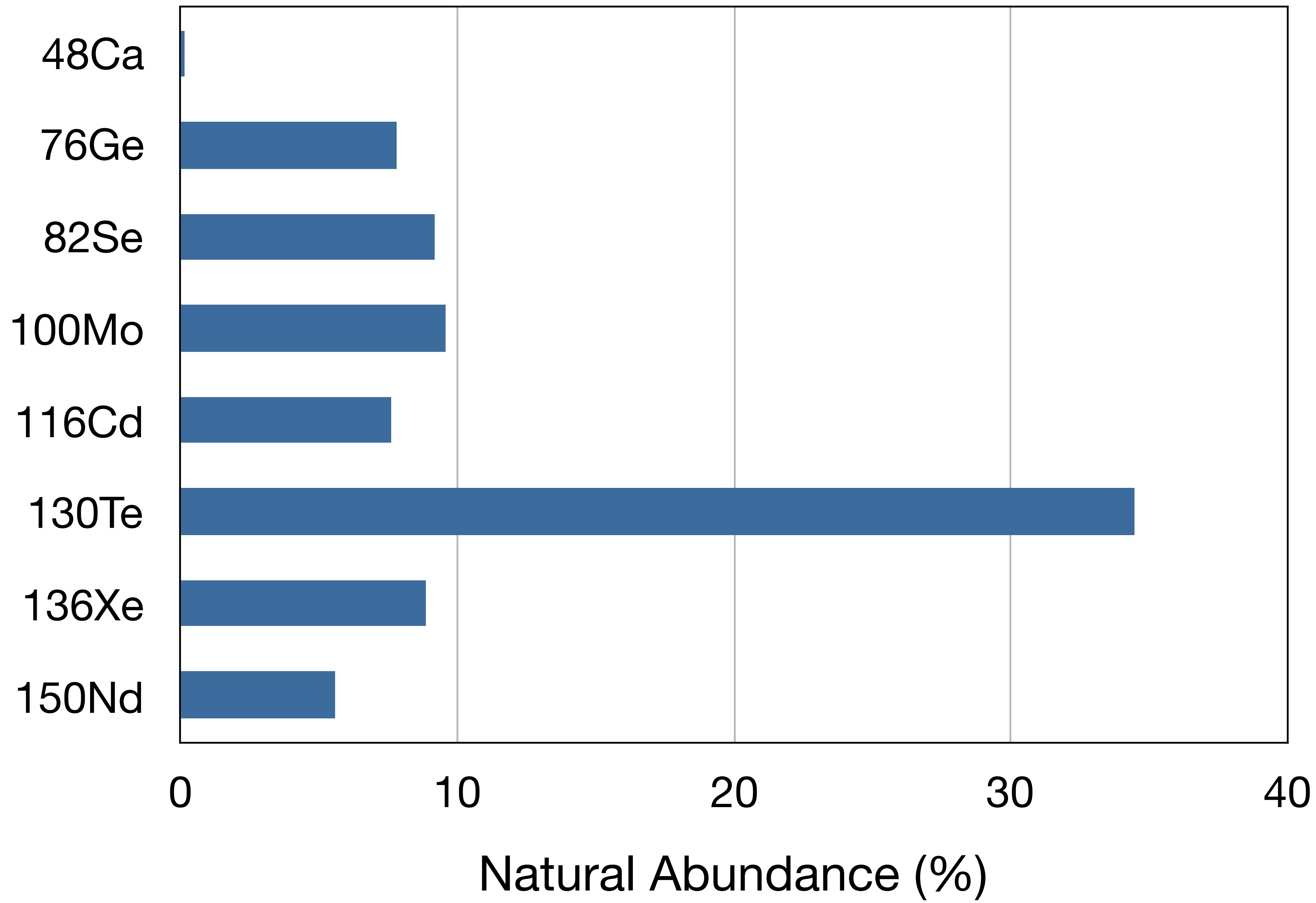
The points in order of increasing abscissa value are: ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo and ^{110}Pd.

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

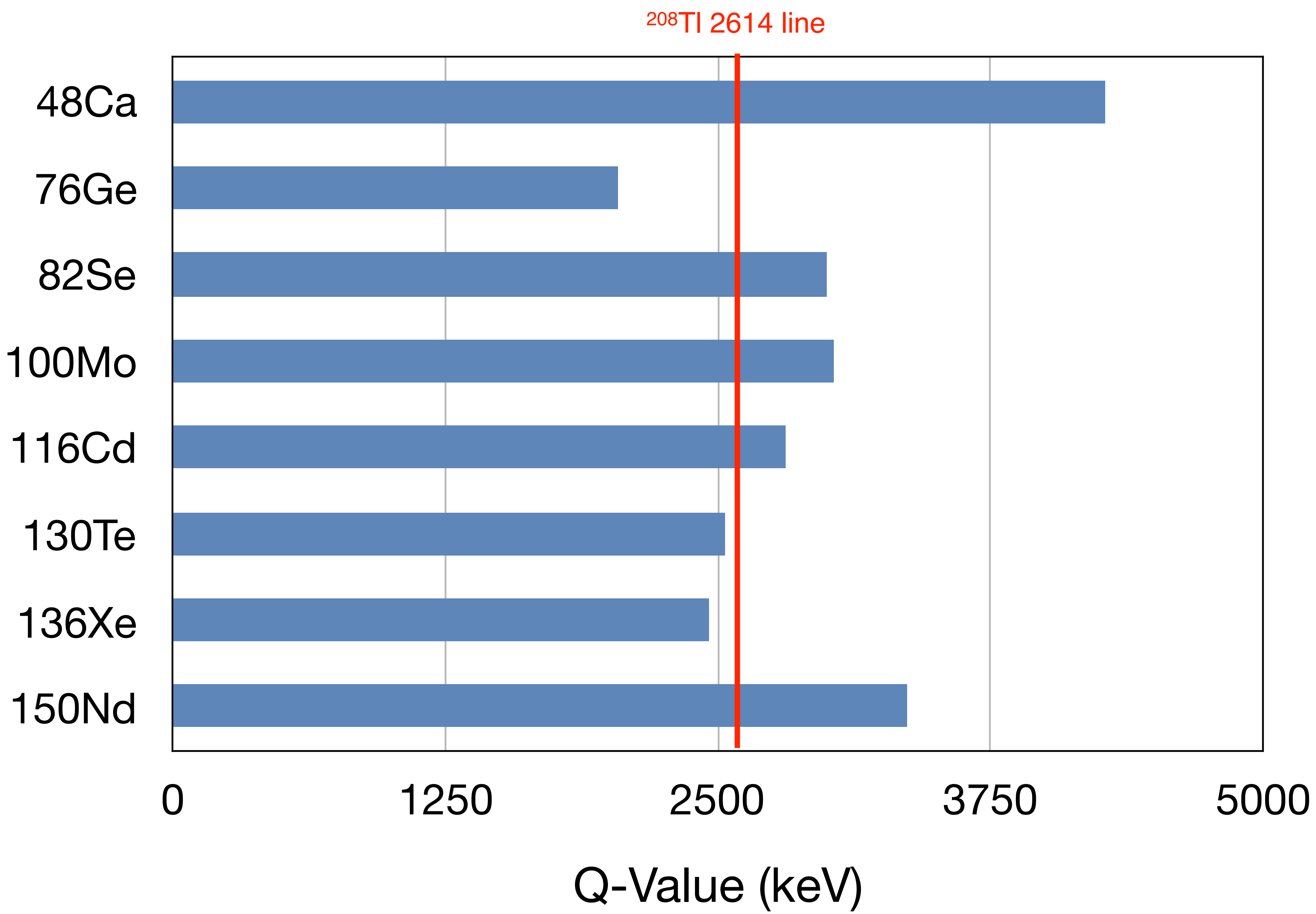
0νββ Isotopes : Natural Abundances



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

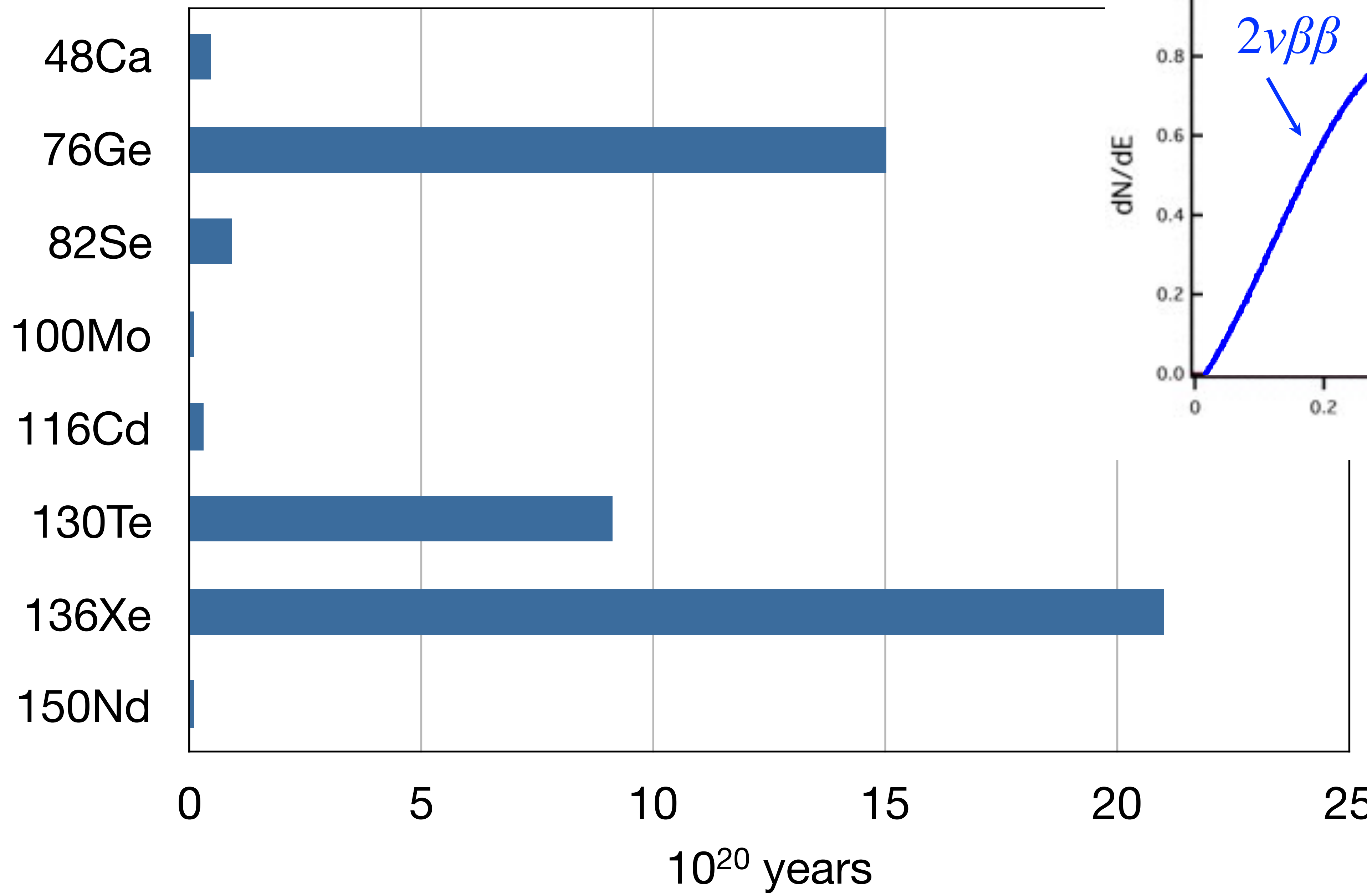
0νββ Isotopes : Q-Values

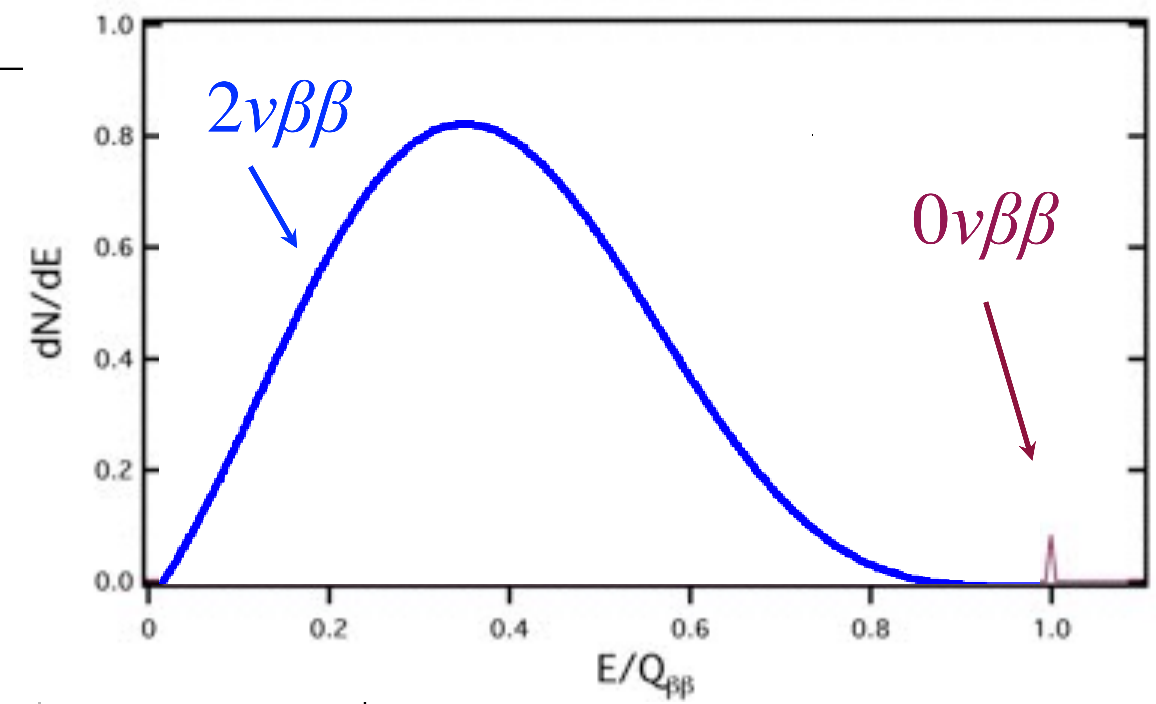


ββ Isotope	Q-Value
^{48}Ca	4273.7
^{76}Ge	2039.1
^{82}Se	2995.5
^{100}Mo	3035
^{116}Cd	2809.1
^{130}Te	2530.3
^{136}Xe	2457.8
^{150}Nd	3367.3

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

0νββ 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}Tl 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

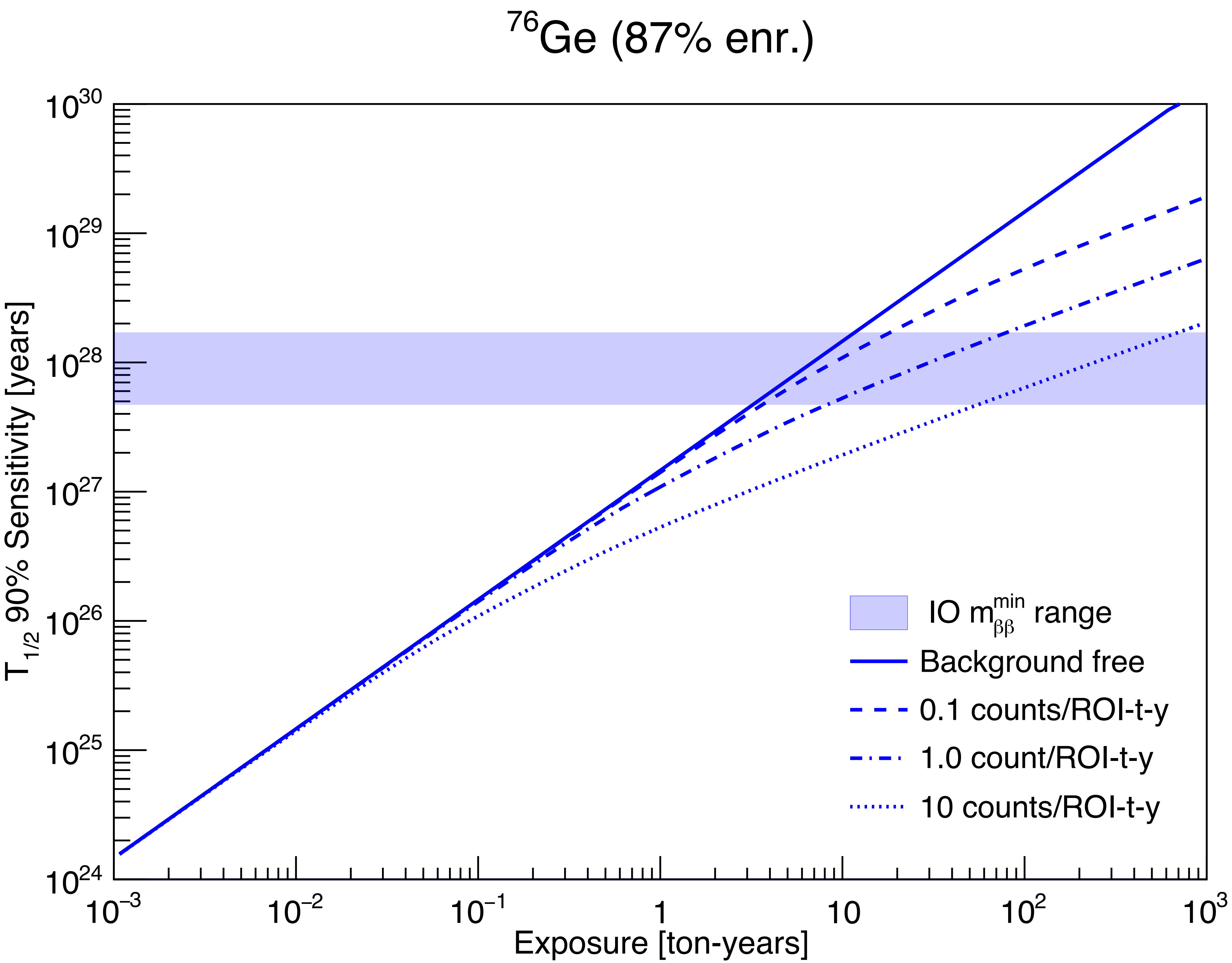
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

Background limited

Note : Backgrounds do not always scale with active detector mass

Sensitivity vs. Exposure ^{76}Ge

J. Detwiler



Inverted Ordering (IO)

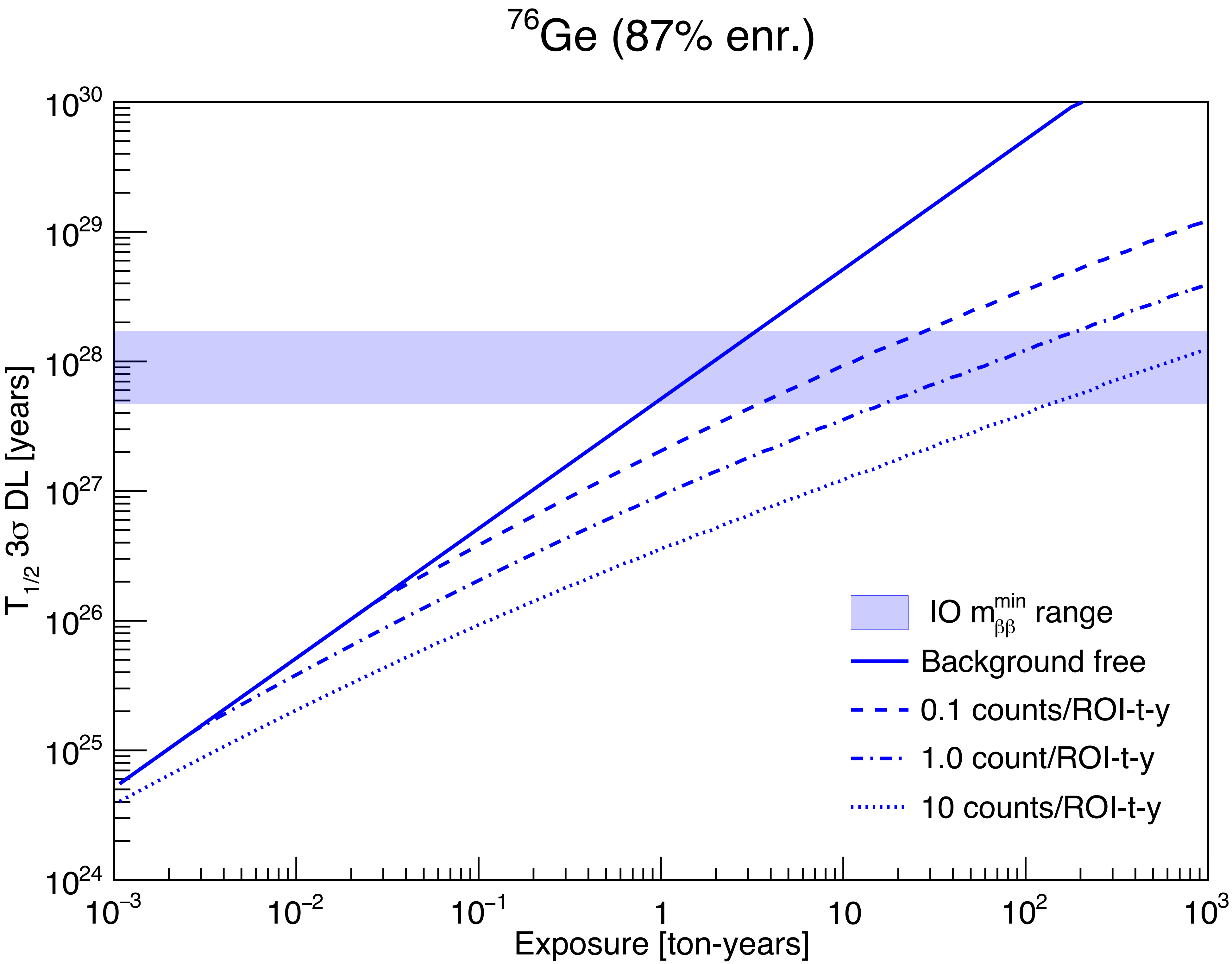
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

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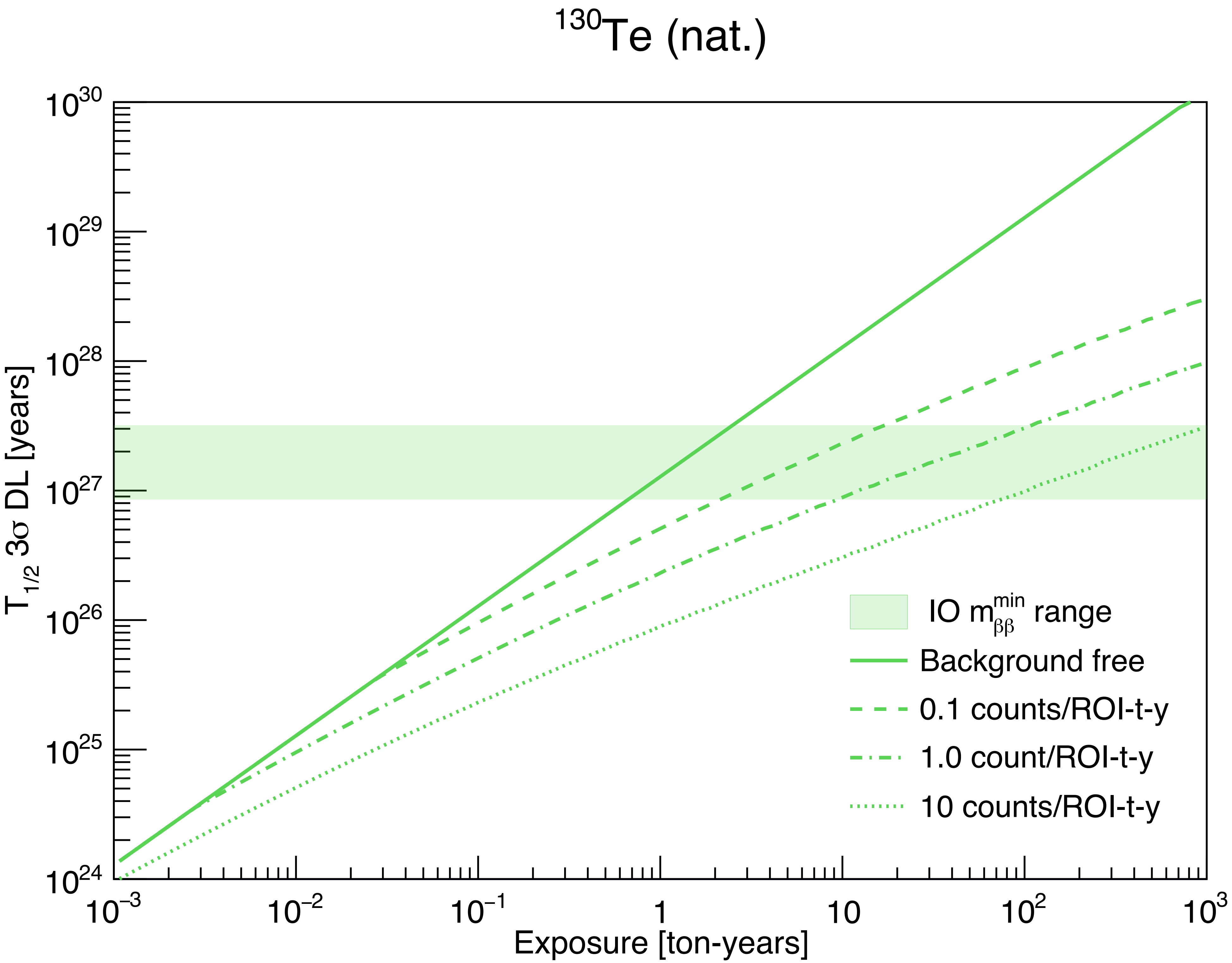
Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

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

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

J. Detwiler



Inverted Ordering (IO)

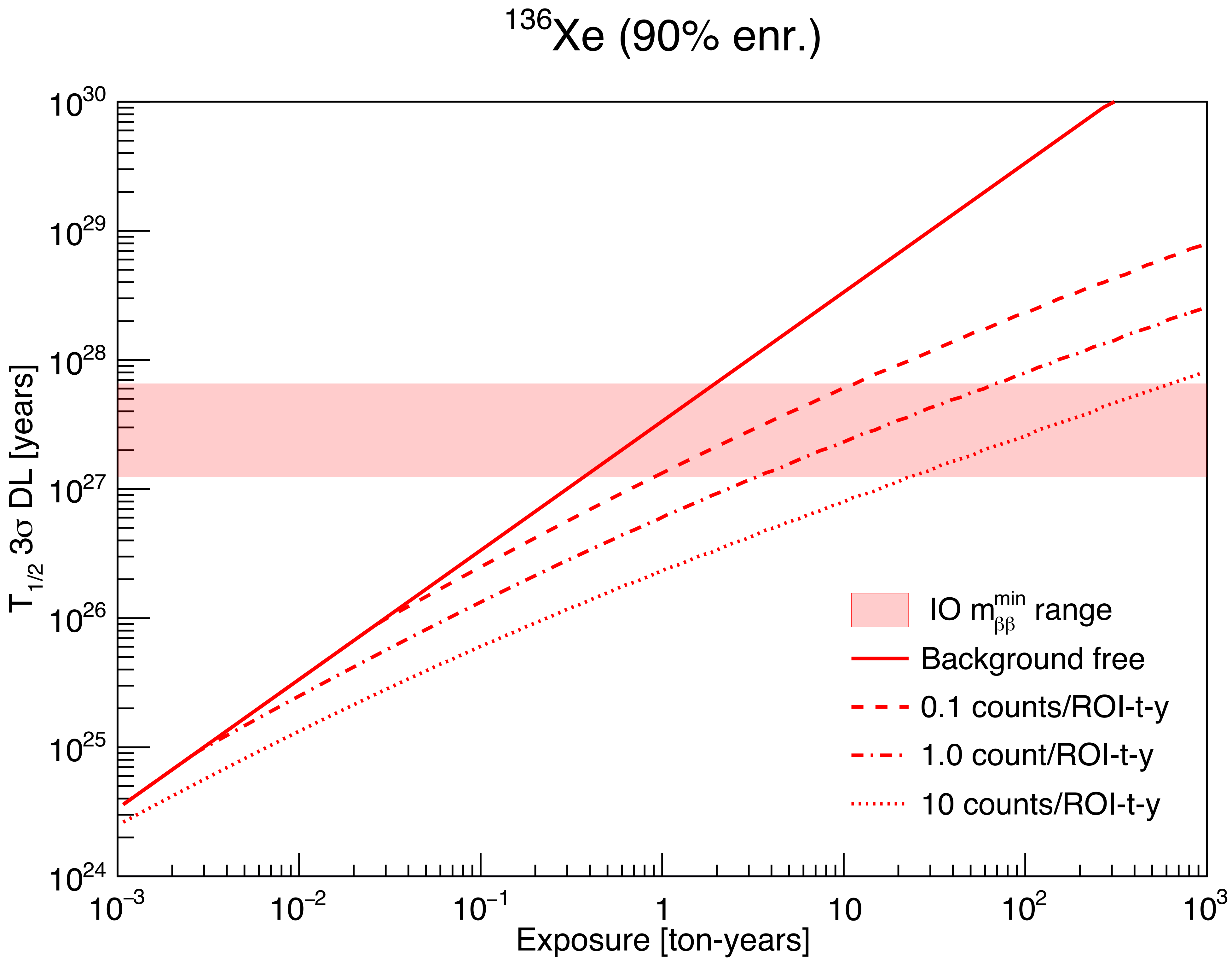
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

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

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

J. Detwiler



Inverted Ordering (IO)

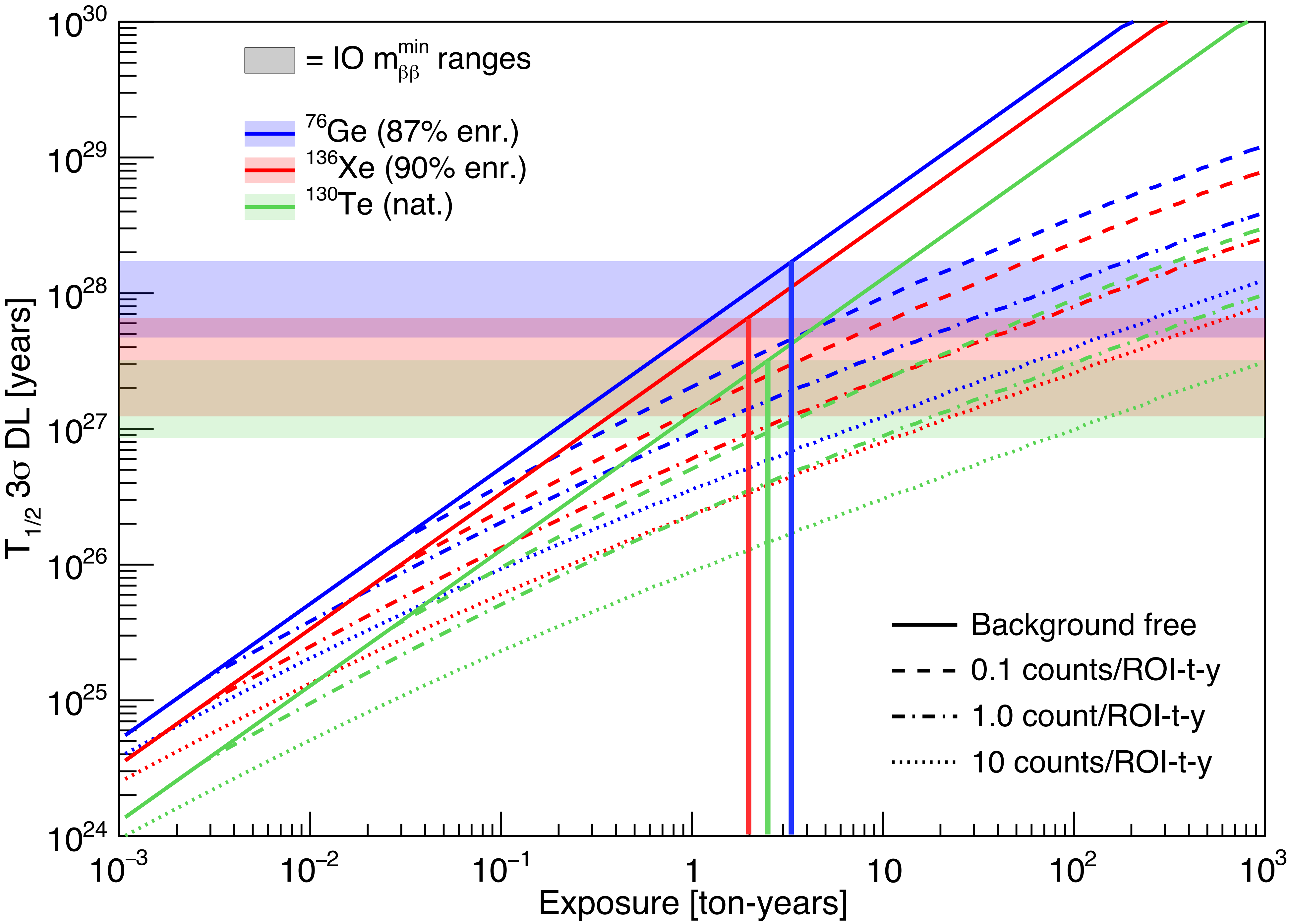
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

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

3σ Discovery vs. Exposure

J. Detwiler

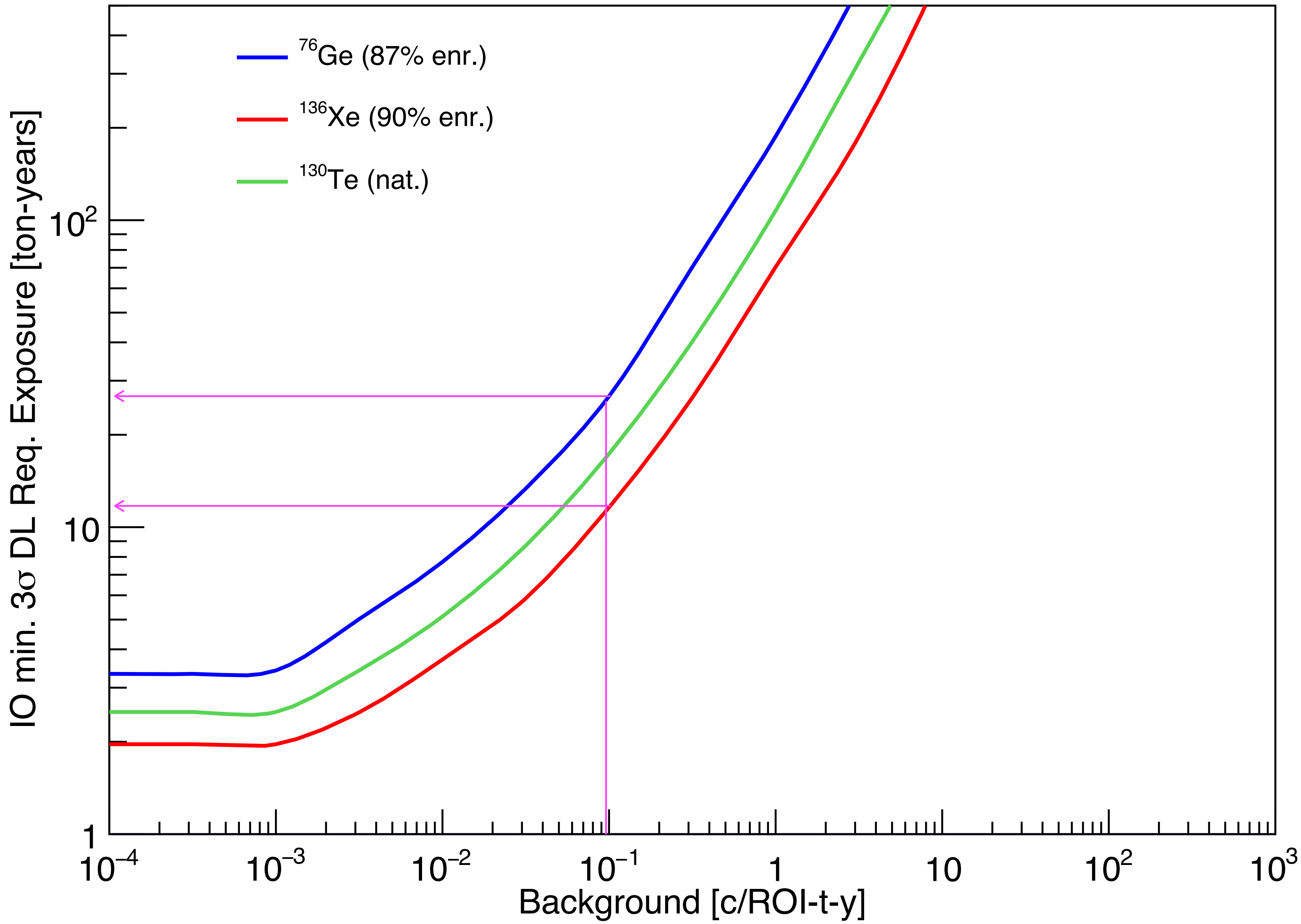


Conclusion:

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.

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

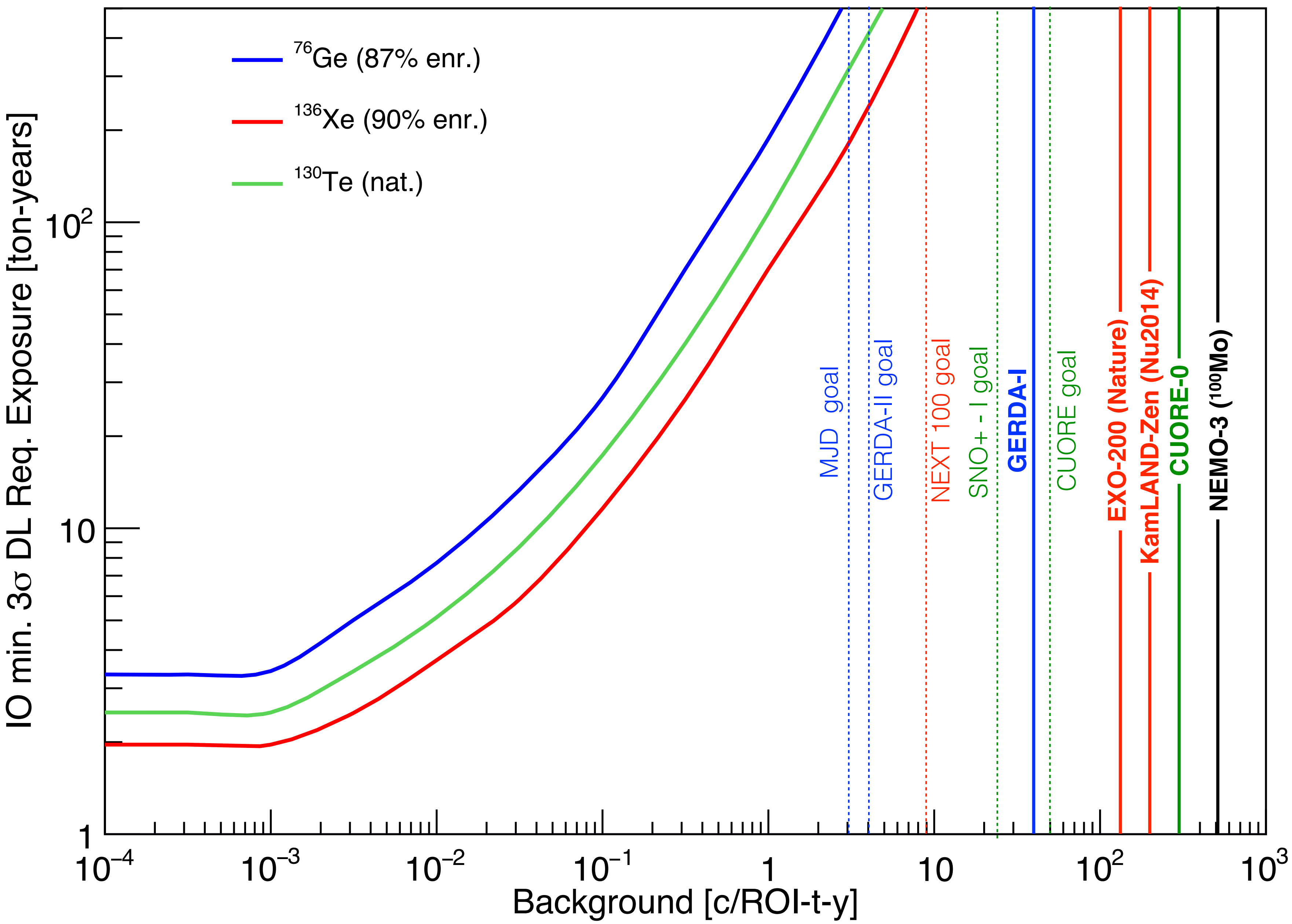
Experiment		Mass [kg] (total/FV*)	Bkg (cnts/ROI-t-y)†	Width (FWHM)
CUORE0	^{130}Te	32/11	300	5.1 keV ROI
EXO-200	^{136}Xe	170/76	130	88 keV ROI
GERDA I	^{76}Ge	16/13	40	4 keV ROI
KamLAND-Zen (Phase 2)	^{136}Xe	383/88	210 per t(Xe)	400 keV ROI
CUORE	^{130}Te	600/206	50	5 keV ROI
GERDA II	^{76}Ge	35/27	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 (CUORE0 – KamLAND-Zen) → ← Projected (CUORE – SNO+) →

* 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



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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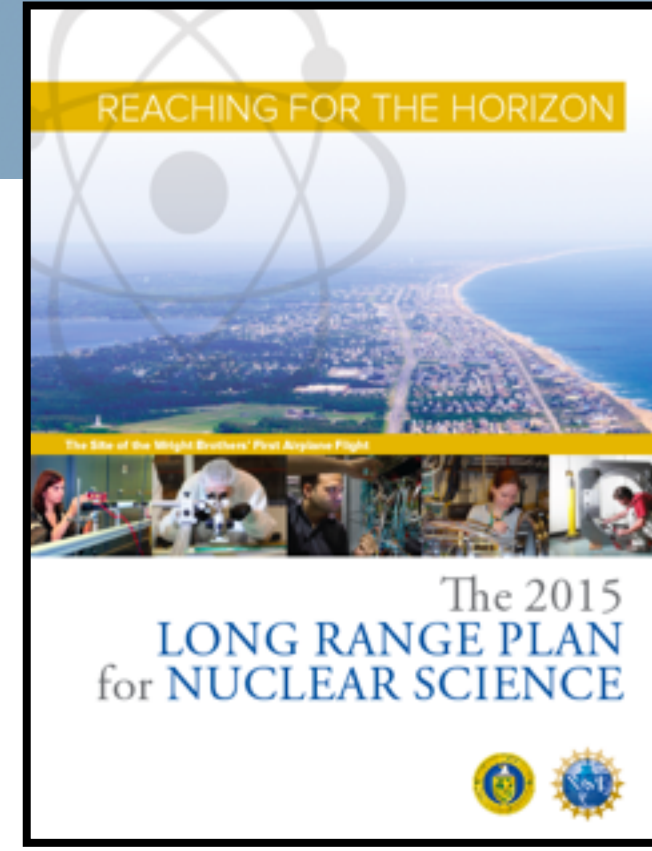
NSAC 2015 Long Range Plan



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.

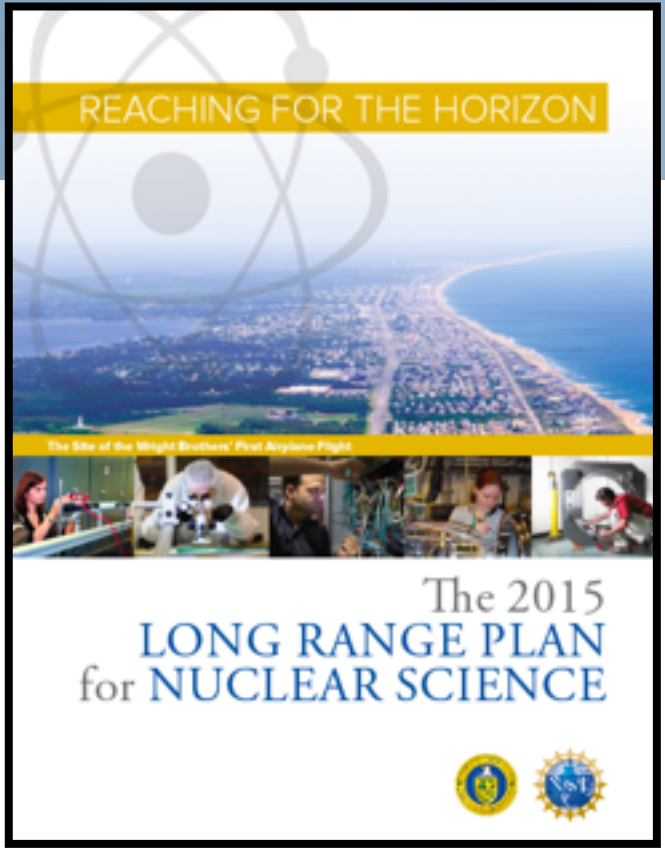
We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

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.

Plan is to make a “down-select” in 2-3 years”
Oct 2015 NSAC NLDBD sub-committee report.

NSAC 2015 Long Range Plan

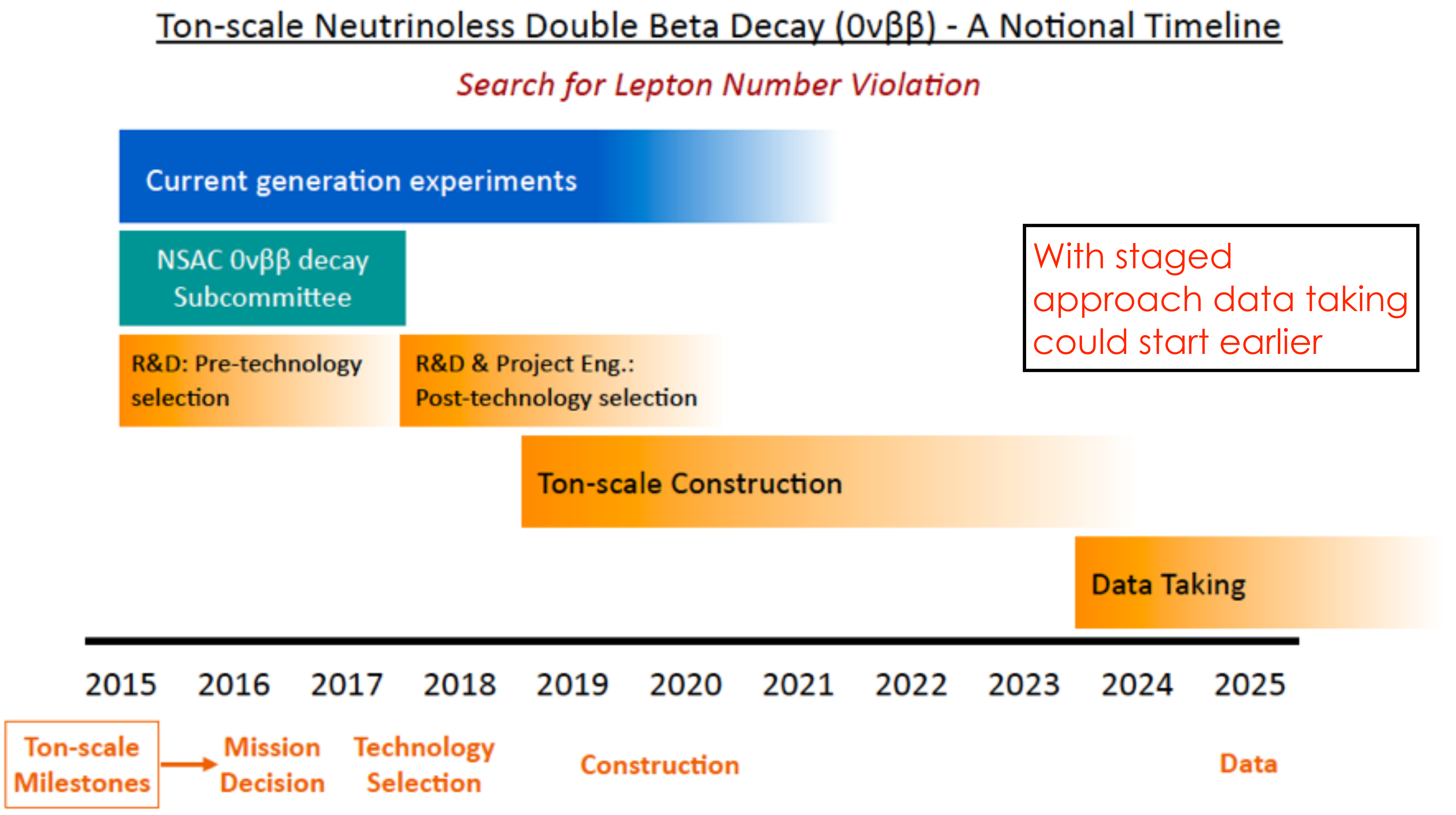


B: Initiative for Detector and Accelerator Research and Development

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.

Next generation 0νββ Timeline



With staged approach data taking could start earlier

2015 NSAC Long Range Plan for Nuclear Science

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 \$50 - \$120 M.
  - Enrichment of large amounts of isotopes will take multiple years
- Funding at this scale requires significant community and government support.
  - cooperation between countries' funding agencies
  - advance planning for providing funds

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

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 $6x10^{23}$ / MW
(MW= 67, 130, 136 → use MW≈100)

So N≈ $6x10^{27}$

NLDBD Rate = 0.4 /Tonne/yr

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

Bob McKeown
NSAC NLDBD Talk

Outline

- Brief overview of 0νββ and sensitivity to neutrino mass.
- Is there a preferred 0νββ isotope in terms of sensitivity?
- What levels of backgrounds and exposure are required for future 0νββ experiments to cover the inverted ordering region?
- What are considerations for future ton scale 0νββ experiments?
- **Relationship to other measurements?**
- Summary

$0\nu\beta\beta$, $\langle m_{\beta\beta} \rangle$, & direct m_β mass meas.

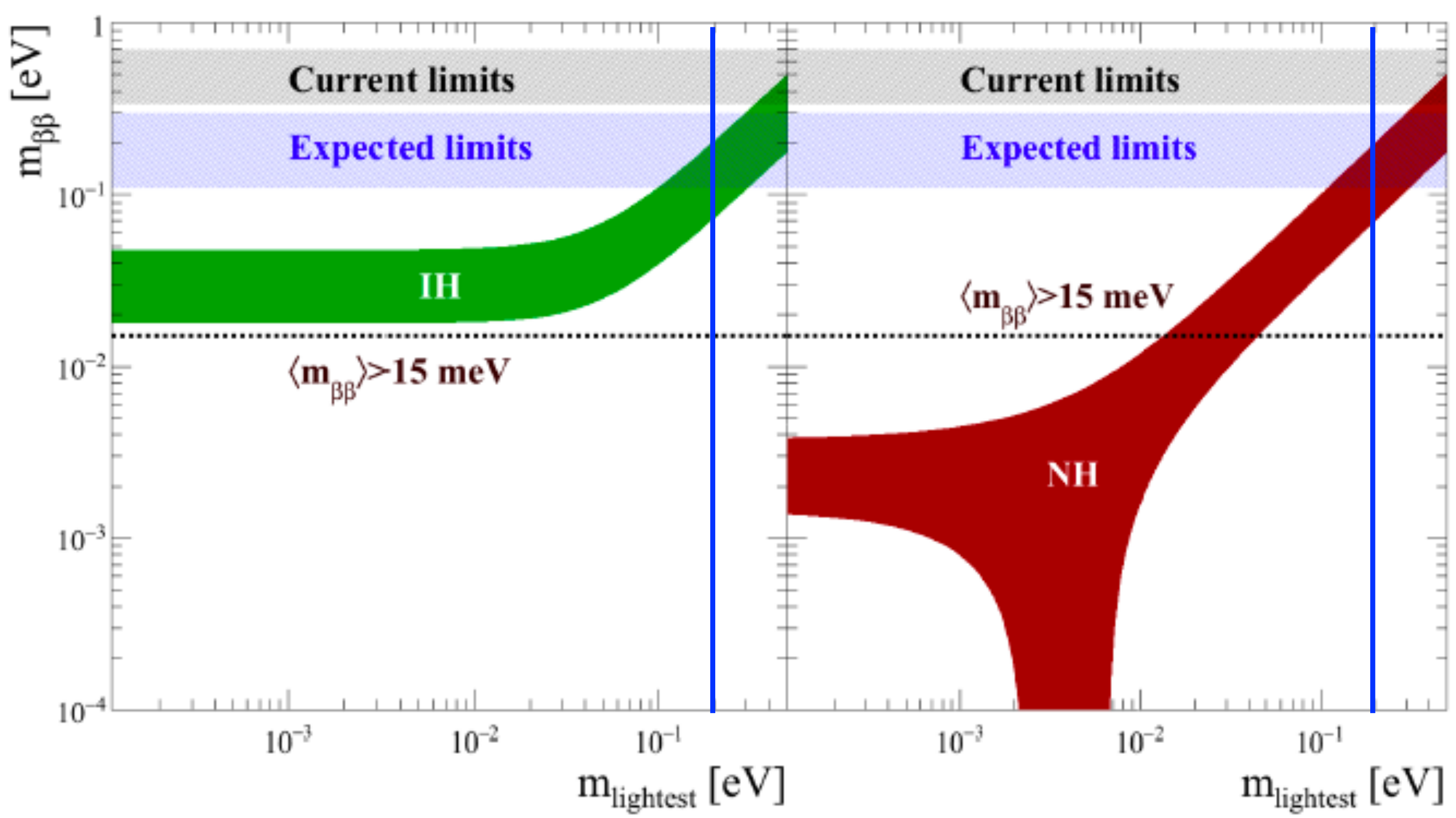
Model Independent

- Current (Mainz & Troitsk) : $m_{\nu e} < 1.8$ eV (90% CL)
- KATRIN : $m_{\nu e} \sim 0.2$ eV (90% CL)
  - could find non-zero value, allowed up to ~ 0.2.
- Future Project 8 : $m_{\nu e} \sim 0.1$ eV (90% CL)
  - below $m_{\nu e} < .06$ eV indicates normal ordering

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)
No sterile neutrinos

10 t-yr

100 t-yr



$0\nu\beta\beta$, $\langle m_{\beta\beta}\rangle$, & cosmological Σm_ν

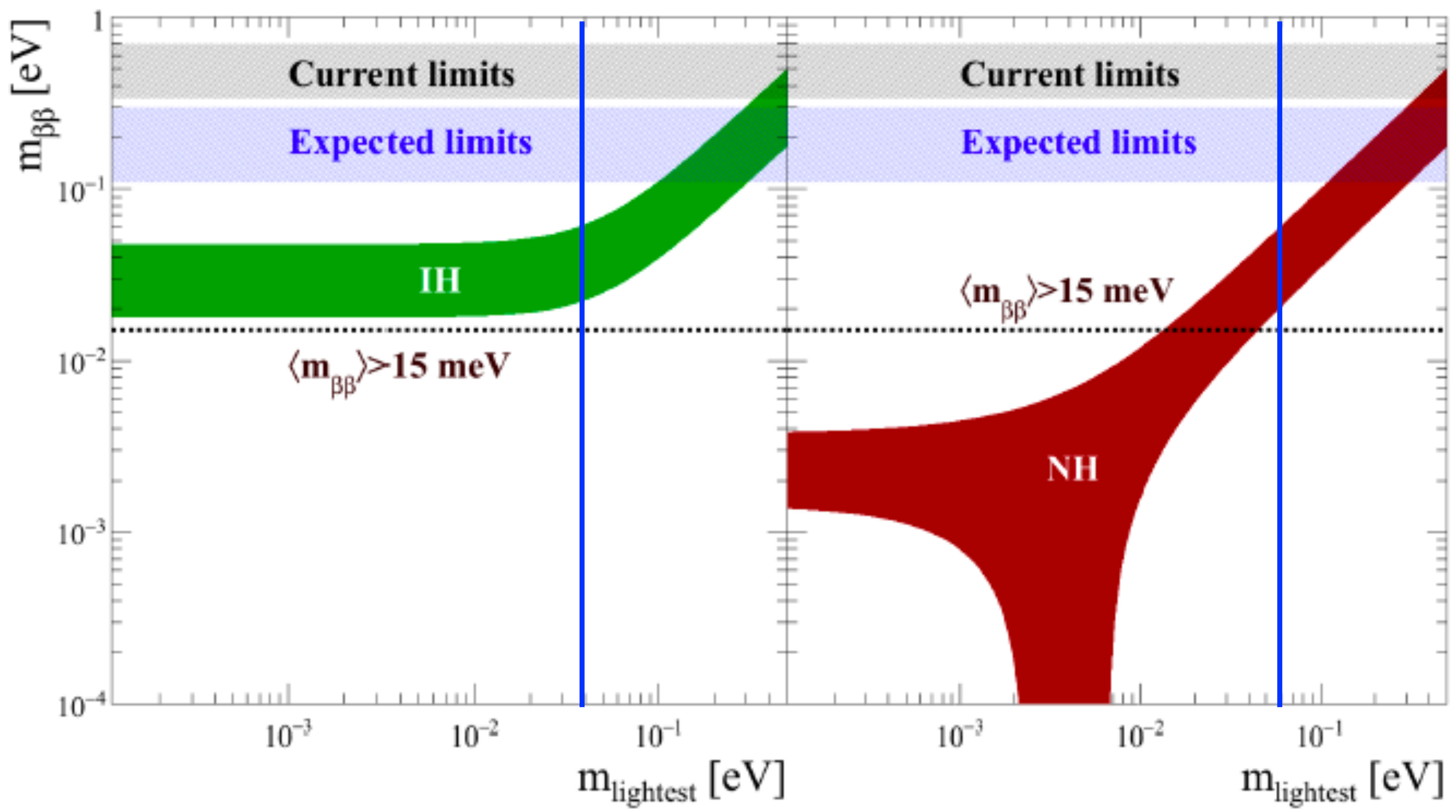
Model Dependencies

- Current cosmological limit : $\Sigma m_\nu < 0.23$ eV (95% CL)
- Future sensitivity : $\Sigma m_\nu \sim 0.02$ eV
  - could find non-zero value, with Σm_ν allowed up to 0.23.
  - sensitive to $m_{lighest} \sim 0$ range, so could rule out inverted & require future $\langle m\beta\beta\rangle$ sensitivity of < 0.05

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)
No sterile neutrinos

10 t-yr

100 t-yr



0νββ, <m$_{\beta\beta}$>, & long baseline osc.

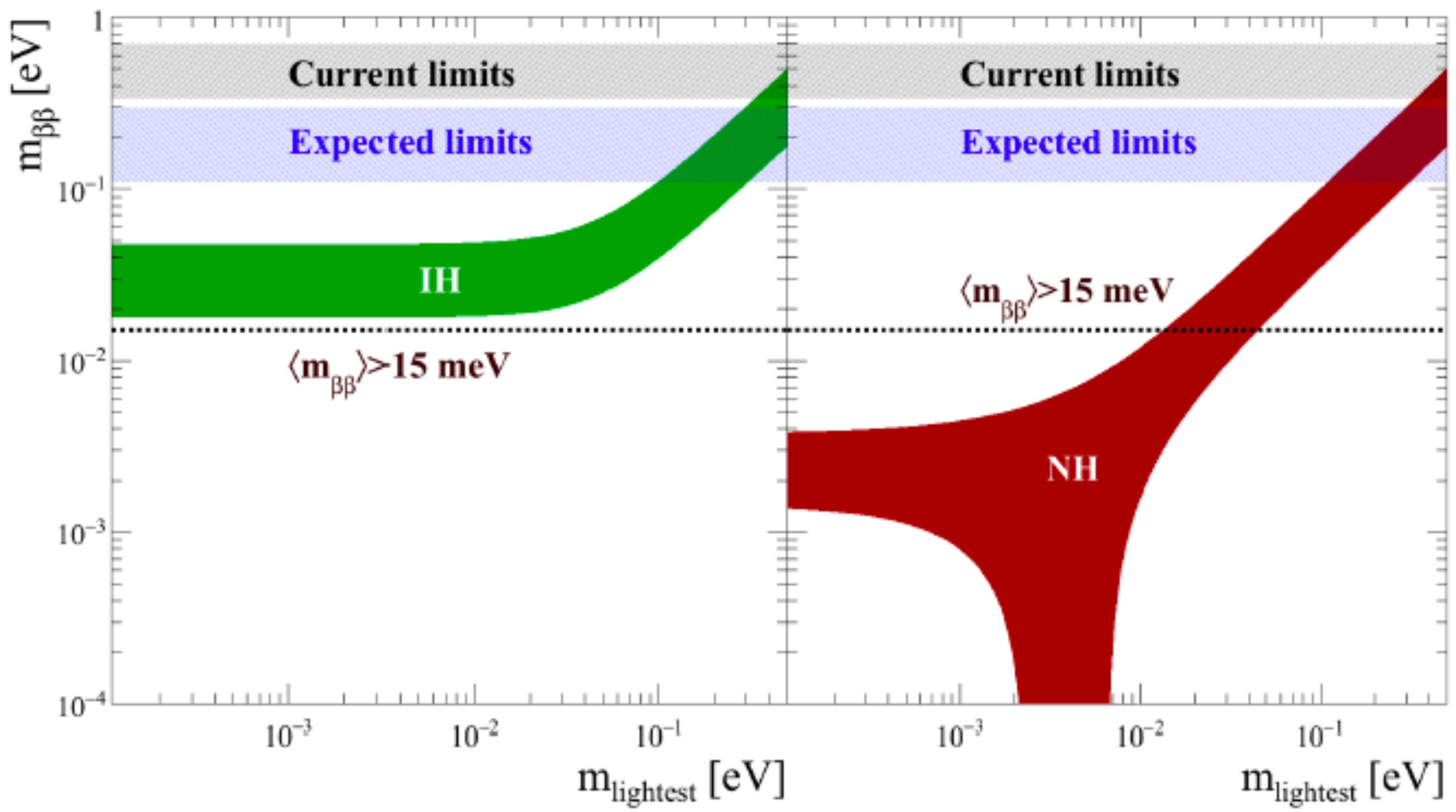
Model Independent

- Future sensitivity : Provide clear determination of inverted or normal ordering.
  - provides no information on absolute masses

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)
No sterile neutrinos

10 t-yr

100 t-yr

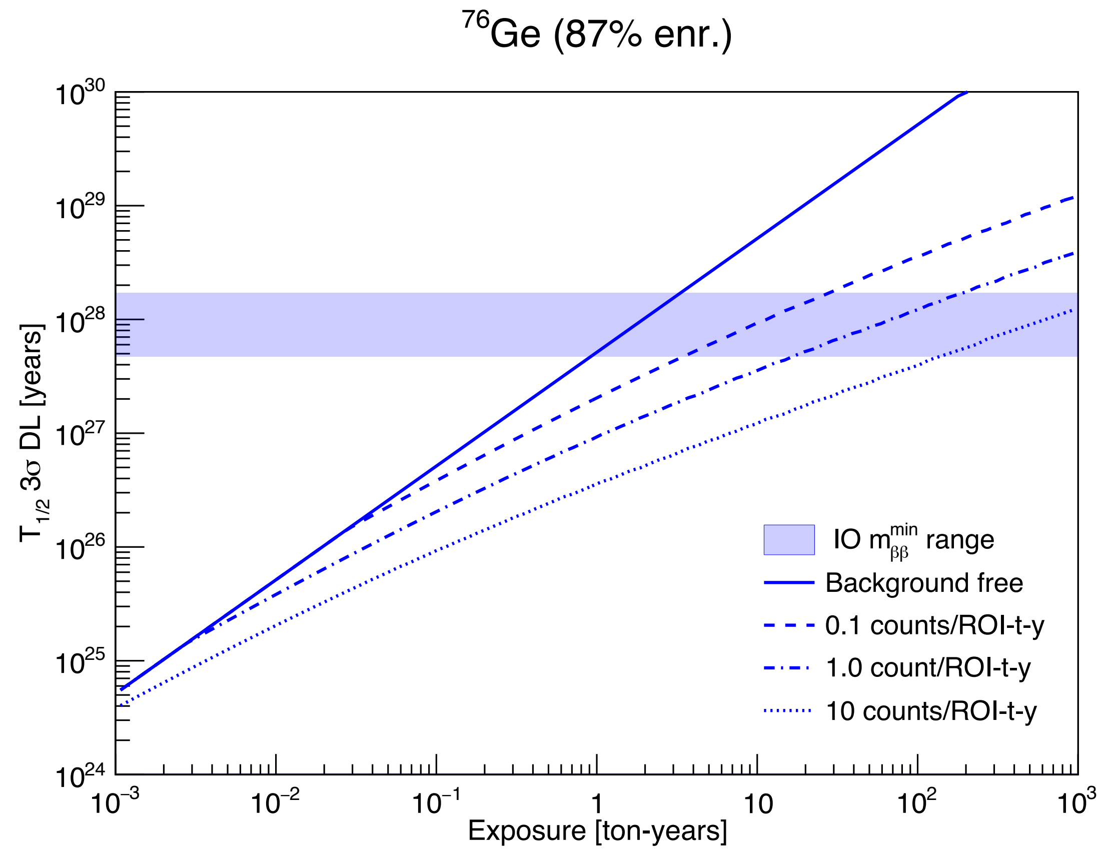


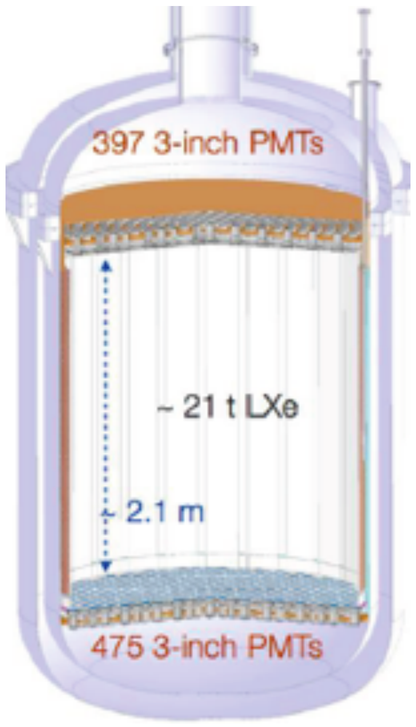
0νββ and other measurements

- Extraction of <mββ> requires:
  - knowledge or assumption of LNV mechanism
  - values (and uncertainties) for NME and g_A
- Determination of ordering by other measurements
  - if inverted ordering, then null 0νββ measurement with sufficient sensitivity, would indicate Dirac neutrinos, assuming LNV mechanism.
  - if normal ordering, a potentially ambiguous situation because of <mββ> "cancellations". Depends on ultimate absolute mass value.
- Determination of mass by other measurements
  - Extremely complementary to 0νββ
  - If very small, indicates major challenge for 0νββ measurements

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 $0\nu\beta\beta$ measurements?
  - LZ, PandaX IV, …
- Cost ?





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- **Summary**

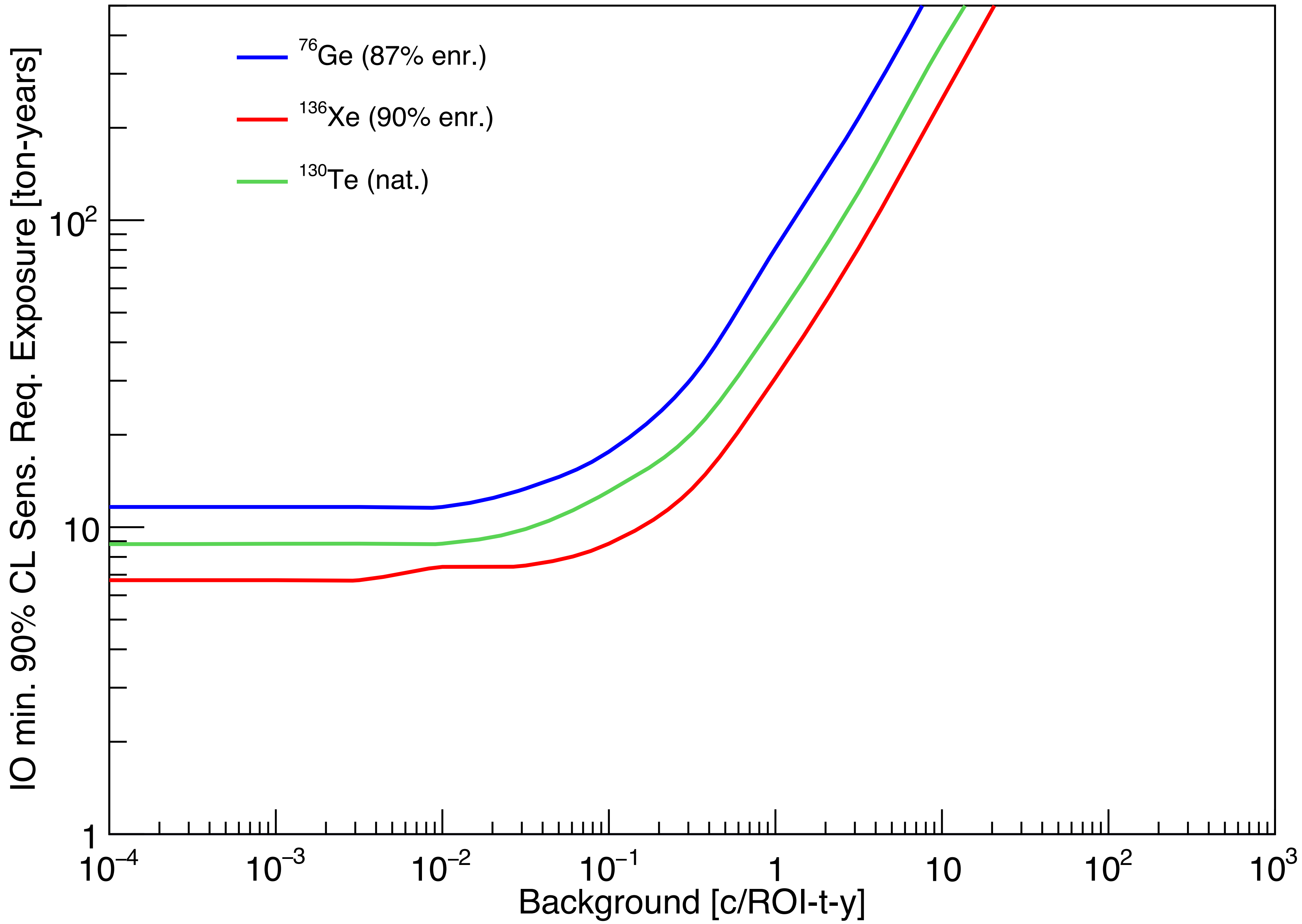
Summary

- Observation of $0\nu\beta\beta$ would signify neutrinos are Majorana particles and Lepton Number Violation.
  - Determination of $\langle m_{\beta\beta} \rangle$ depends on the LNV mechanism plus understanding of NME and g_A.
  - Other neutrino mass and/or LNV measurements would be very complementary to understanding the meaning of observed $\langle m_{\beta\beta} \rangle$.
- Large international collaborations are moving forward with designs for next generation $0\nu\beta\beta$ experiments based on lessons learned from the current measurements.
  - All aim for sensitivity and discovery levels at $T_{1/2} > 10^{27}$ years
  - Require 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 $0\nu\beta\beta$. (Talks on Tuesday)

Back-up Slides

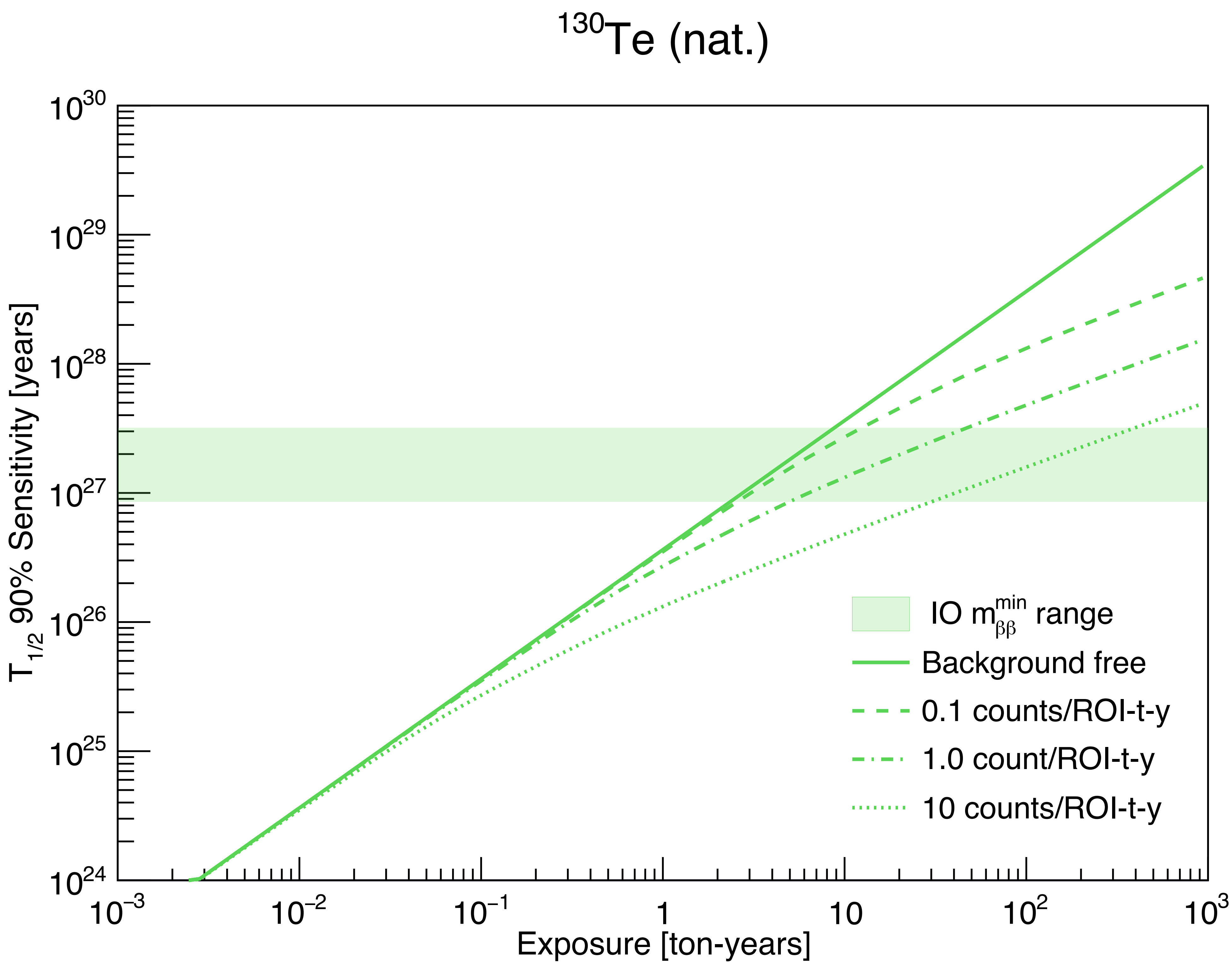
Required Sensitivity vs. Background

J. Detwiler



Sensitivity vs. Exposure for ^{130}Te

J. Detwiler



Inverted Ordering (IO)

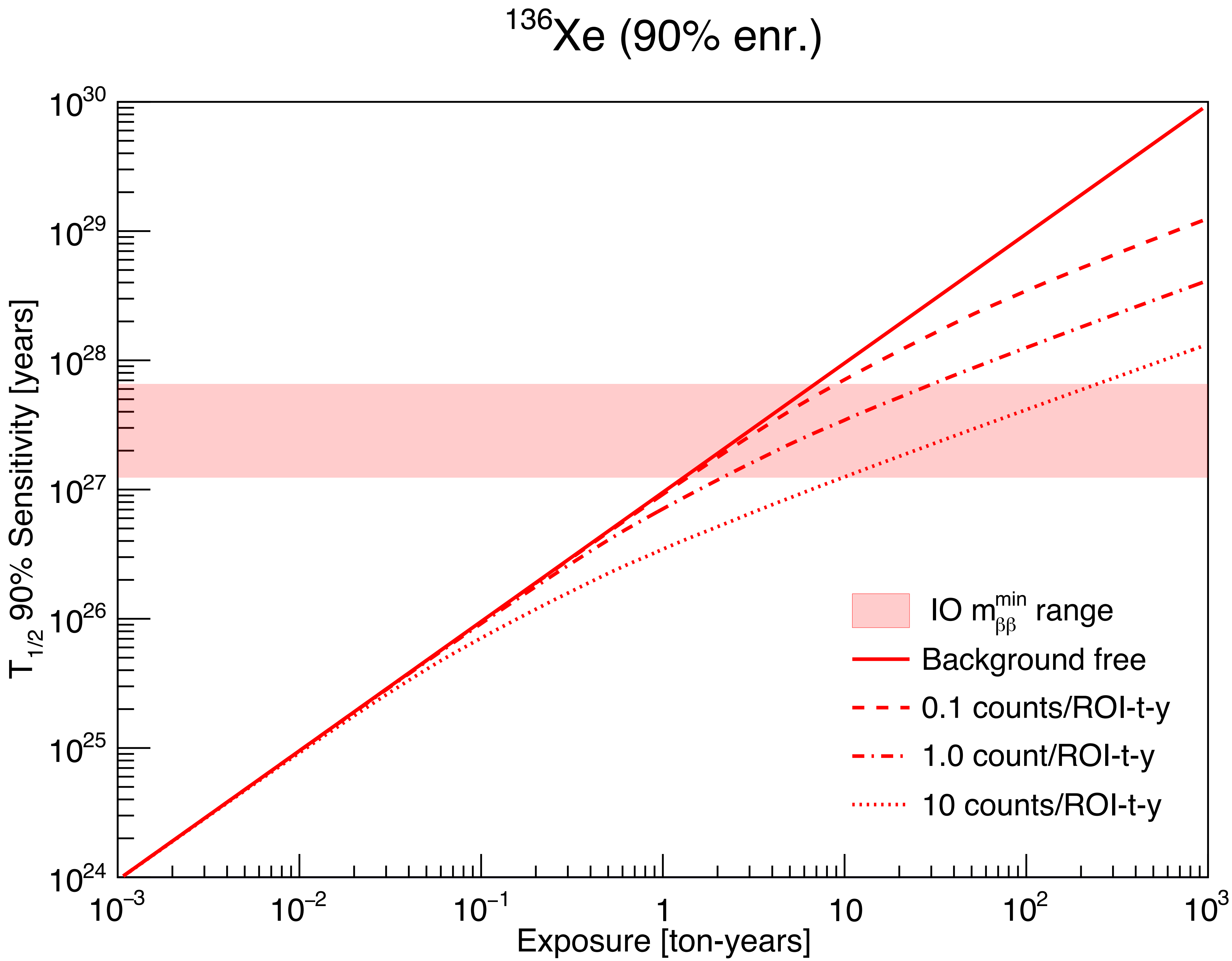
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

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)

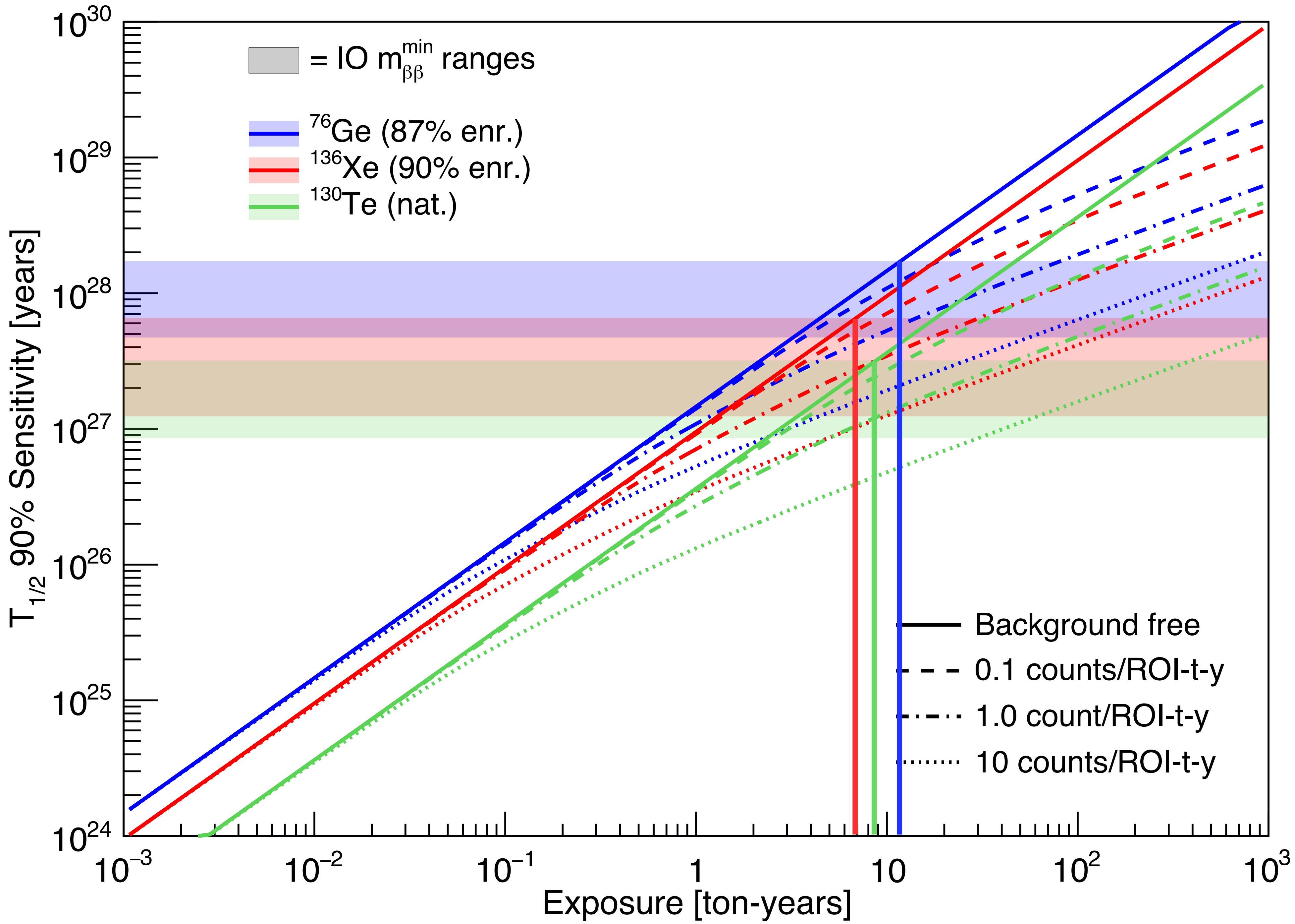
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

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



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.