Acknowledgements: the EXO-200 and nEXO collaborations,
& V. Cirigliano, J. Engel, C. Hall, J. Wilkerson

The Search for Neutrinoless Double Beta Decay

The EXO-200 and nEXO Experiments

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Physics Theory Seminar
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Outline

- Discovery of neutrino mass reinvigorates an old question
- Double Beta Decay and Lepton Number Violation
- Theoretical Underpinnings
- The Experiments and their Challenges
- EXO-200: the Immediate Past
- nEXO: the Near Future
- Outlook and Summary

Disclaimer:
Theory is at student level!

Massive Neutrinos

A Model of Leptons: $SU(2)_L \times U(1)_Y$

$e^-, \mu^-, \tau^- \Rightarrow Q = -e;$

$\nu_e, \nu_\mu, \nu_\tau \Rightarrow Q = 0$

$$\begin{pmatrix} \nu \\ \ell^- \end{pmatrix}_L \quad \ell^-_R \quad \nu_R$$

$$\pm\tfrac{1}{2} \quad 0 \quad 0 \Rightarrow T_3$$

$$\boxed{Q = T_3 + Y/2}$$

$Y_{\nu_L} = -1$ $\quad \boxed{Y_{\nu_R} = 0}$

Right-handed neutrino has no gauge interactions

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Chirality $\equiv \frac{1 \pm \gamma^5}{2} \equiv P_{L,R}$

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(or ultra-relativistic limit)

helicity = chirality

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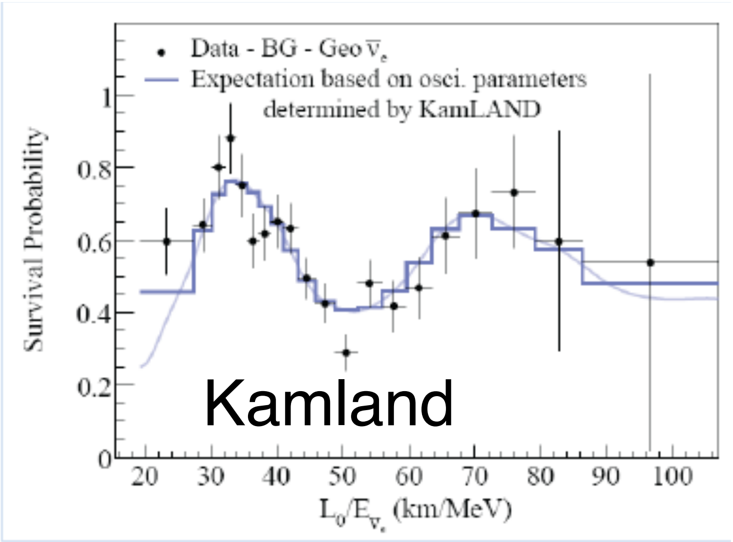
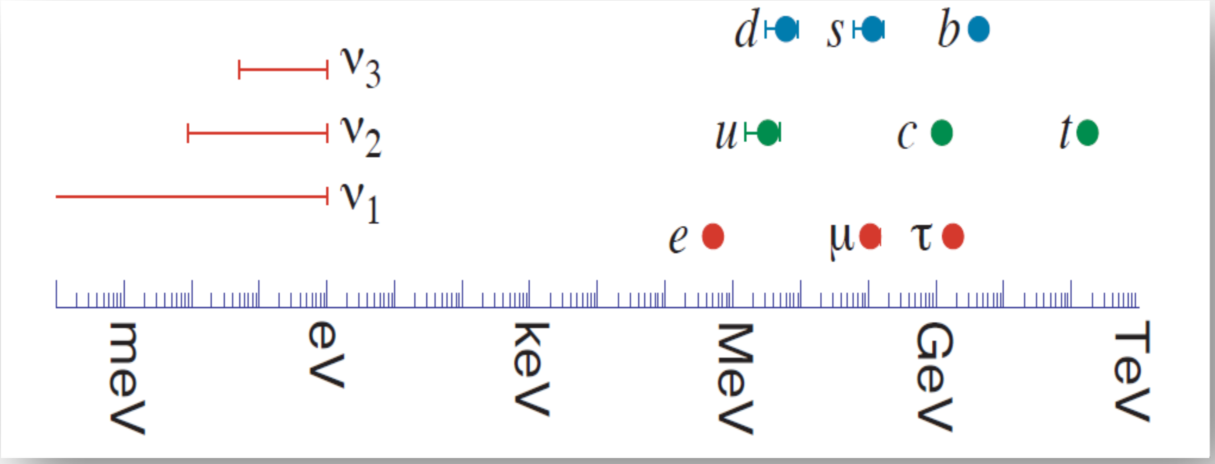
For a massless particle (or ultra-relativistic limit) → **helicity = chirality**

Original formulation of the Standard Model:
ν massless and no right-handed state

Postulate the Massive Right-Handed Neutrino



- Why is neutrino mass so small?
- How small is it?
- What is the mass generating mechanism?
- And…



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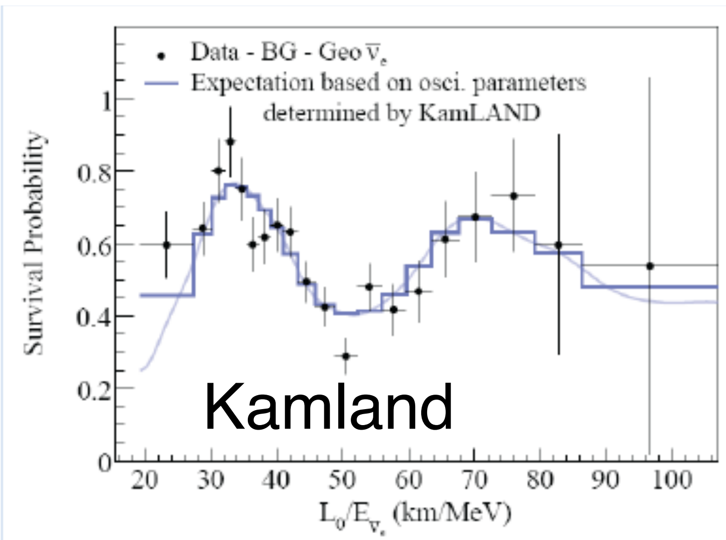

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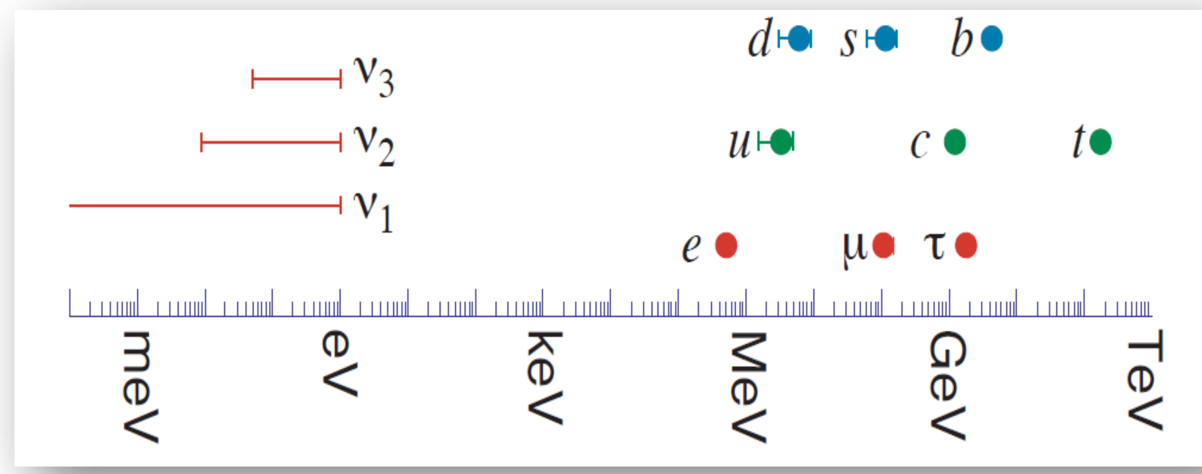
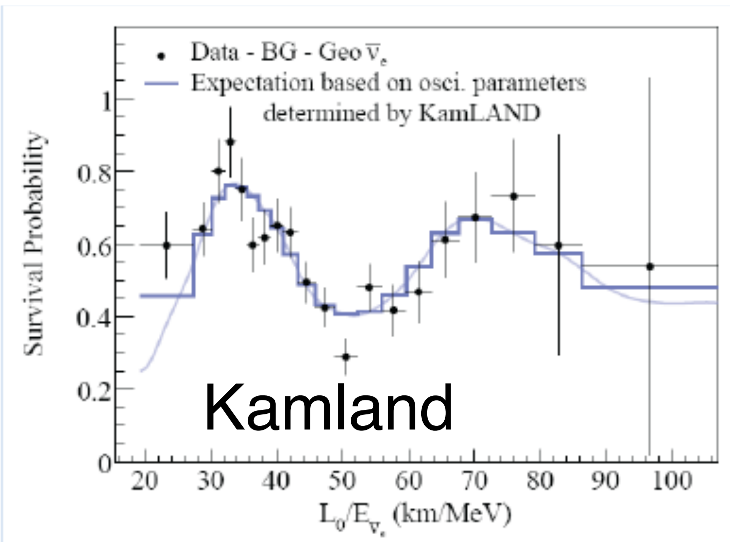


CPT transformation: *left-handed* particle to *right-handed anti*-particle

Postulate the Massive Right-Handed Neutrino



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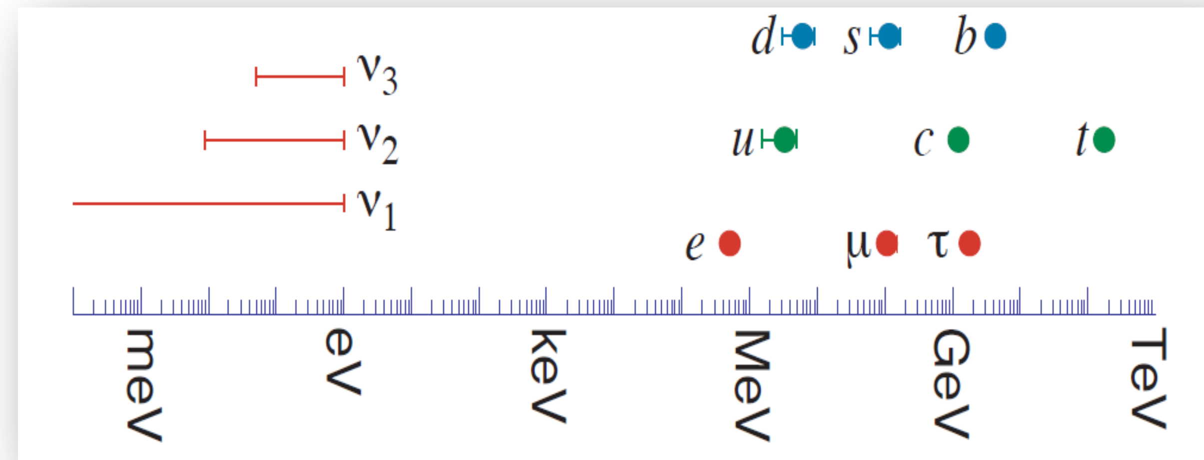
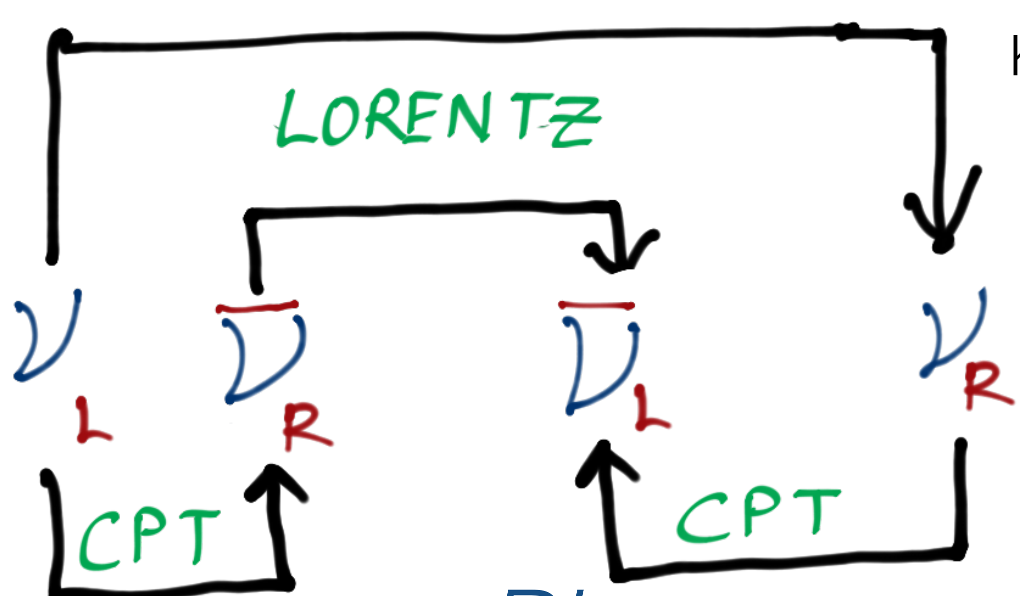
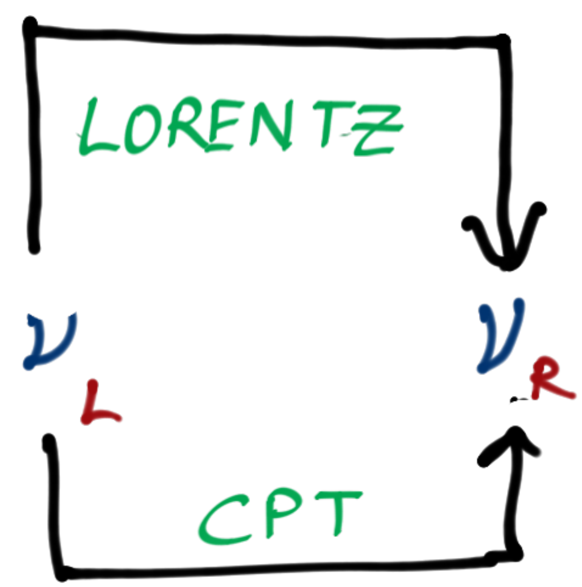


CPT transformation: *left-handed* particle to *right-handed anti*-particle

A profound question:



Kayser '85



Dirac OR *Majorana* Early 1930s

Majorana Particles

In 1928, Dirac discovered the framework to describe relativistic spin-1/2 particles

Dirac 4-spinors are complex fields and naturally explain the existence of anti-particles with opposite quantum numbers

In 1937, Majorana discovered that a simple modification to Dirac's equation leads to the possibility to describe **electrically neutral**, massive spin-1/2 fermions with real fields!

A neutrino can therefore be its own anti-particle

What is the Discovery Experiment?

Neutral Current interactions have subtle differences

Kayser '82

But

Dirac-Majorana Confusion Theorem: the difference between ν_D and ν_M interactions vanishes in the ultra-relativistic limit

Exotic possibilities beyond Standard Model V-A

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The most pragmatic approach to discover the Majorana nature of neutrinos is to search for **Lepton Number Violation (LNV)**

Practically: discover **Neutrinoless Double-Beta Decay** **($0\nu\beta\beta$)**

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Practically: discover **Neutrinoless Double-Beta Decay** **($0\nu\beta\beta$)**

What is this and why do we care so much?

Double Beta Decay and Lepton Number

Baryon and Lepton Number

$p \longrightarrow e^+ \pi^0$

Proton Decay

$B \quad +1 \qquad 0 \quad 0$

Forbidden if B is conserved

Baryon and Lepton Number

$p \longrightarrow e^+ \pi^0$ Proton Decay

B $+1$ 0 0 Forbidden if B is conserved

$n \longrightarrow p e^- \bar{\nu}_e \Rightarrow \bar{\nu}_e p \longrightarrow e^+ n$ but not $\bar{\nu}_e n \longrightarrow e^- p$

L 0 0 $+1$ -1 -1 0 -1 0 -1 0 $+1$ 0

Baryon and Lepton Number

$$p \rightarrow e^+ \pi^0$$

Proton Decay

$$\begin{array}{lcccc} B & +1 & & 0 & 0 \end{array}$$

Forbidden if B is conserved

$$\begin{array}{lcccccccccccc} & n & \rightarrow & p & e^- & \bar{\nu}_e & \Rightarrow & \bar{\nu}_e & p & \rightarrow & e^+ & n \\ L & 0 & & 0 & +1 & -1 & & -1 & 0 & & -1 & 0 \end{array}$$

but not

$$\begin{array}{ccccc} \bar{\nu}_e & n & \rightarrow & e^- & p \\ -1 & 0 & & +1 & 0 \end{array}$$

$$\begin{array}{lcccccccccc} & \pi^+ & \rightarrow & \mu^+ & \nu_\mu & \Rightarrow & \nu_\mu & N & \rightarrow & \mu^- & X \\ L & 0 & & -1 & +1 & & +1 & 0 & & +1 & 0 \end{array}$$

but not

$$\begin{array}{cc} \mu^+ & X \\ -1 & 0 \end{array}$$

Baryon and Lepton Number

$$\begin{array}{lccc} & p & \longrightarrow & e^+ \; \pi^0 \\ B & +1 & & 0 \quad 0 \end{array}$$

Proton Decay

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$$\begin{array}{lccccccccc} & \pi^+ & \longrightarrow & \mu^+ \; \nu_\mu & \Longrightarrow & \nu_\mu \; N & \longrightarrow & \mu^- \; X & \text{but not} & \mu^+ \; X \\ L & 0 & & -1 \; +1 & & +1 \; 0 & & +1 \; 0 & & -1 \quad 0 \end{array}$$

Introduce Lepton Number:

$$L_{e^-} = L_{\nu_e} = -L_{e^+} = -L_{\bar{\nu}_e} = +1$$

This is encoded into the Standard Model Feynman Rules

Conservations Laws consistent with Standard Model

- *Only B-L strictly conserved in the Standard Model*
- *B+L is violated due to anomalies*
- *No fundamental reason to expect B and L to be conserved (assuming only 4 forces in Nature)*

What if CHIRALITY is the key rather Lepton Number?

Neutrinos only interact via the weak interaction, which is parity-violating

$\mu^+ \longleftarrow \pi^+ \longrightarrow \nu_L \quad \Rightarrow \quad \nu_L \longrightarrow \mu^- \qquad \nu_R \longrightarrow \mu^+$

Lepton Number Conservation not required

Dirac and Majorana Masses

If $\nu_R \Longleftrightarrow \bar{\nu}_R$ Majorana Neutrino

L +1 -1

L is violated

No experimental observation precludes this possibility

Most general mass terms for right-handed neutrino:

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$$-g_\nu \bar{l}_L \Phi \nu_R - \frac{m_M}{2} (\bar{\nu}_R)^c \nu_R + h.c.$$

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Most general mass terms for right-handed neutrino:

$$-g_\nu \bar{l}_L \Phi \nu_R - \frac{m_M}{2} (\overline{\nu}_R)^c \nu_R + h.c.$$

After spontaneous symmetry breaking: $m_D \equiv g_\nu \frac{v}{\sqrt{2}}$

$$\mathcal{L}_{D+M} = -\frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

Lepton Number Conservation or Not?

If $\nu \rightarrow e^{i\phi_L}\nu$ m_M term in Lagrangian not invariant

Dirac neutrino: equivalent to demanding L conservation

➡ $m_M = 0$, *one limit of general neutrino mass terms*

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Another limit: A very heavy m_M and a light state $m = \frac{m_D^2}{m_M}$
(See-Saw mechanism)

No SM symmetry precludes m_M from being arbitrarily large

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No SM symmetry precludes m_M from being arbitrarily large

2 self-conjugate states, each with left- and right-handed components

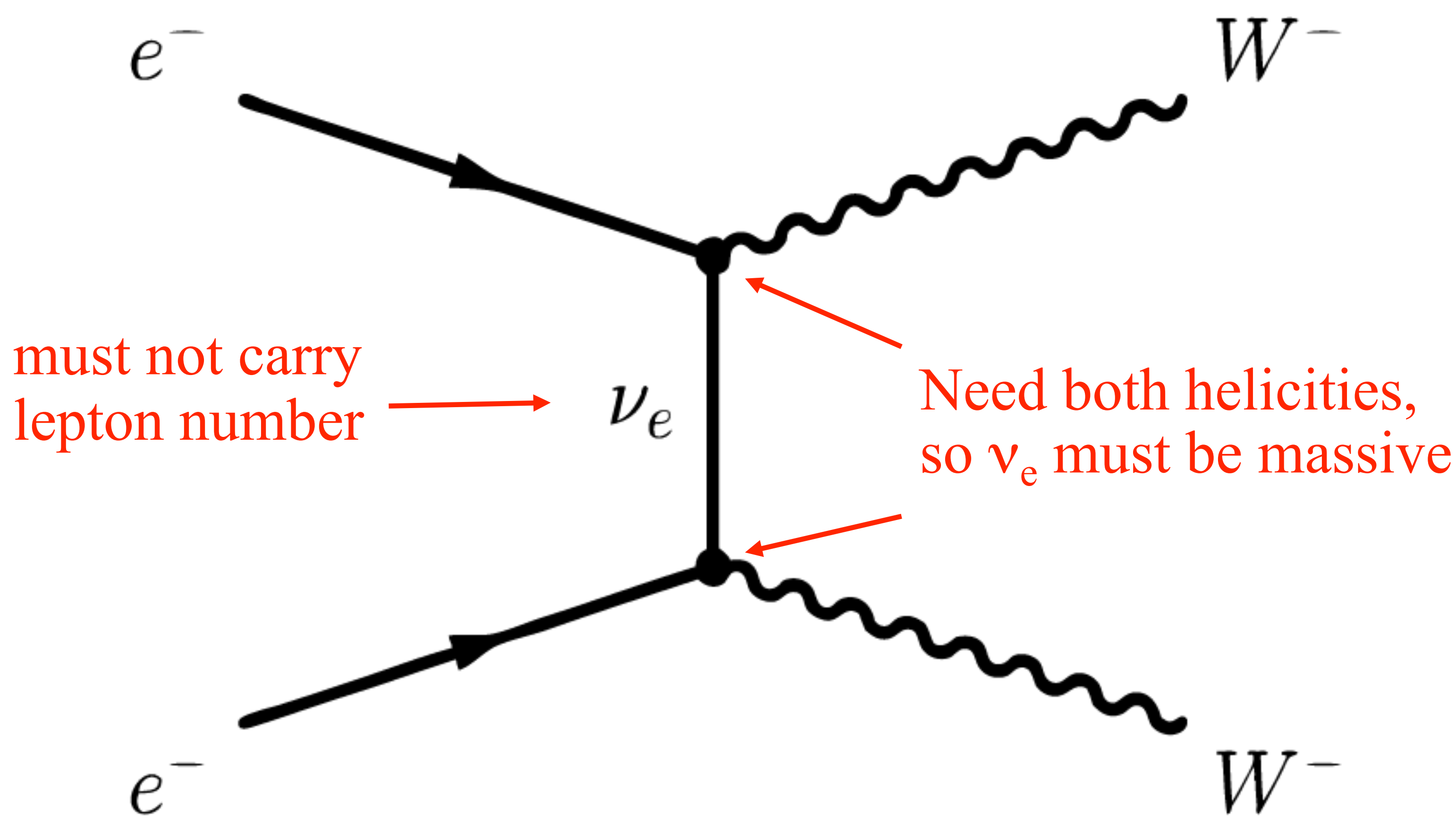
Natural explanation for light neutrino masses

A new heavy scale for physics beyond the SM

A Gedanken Experiment

L   +1   +1   0   0

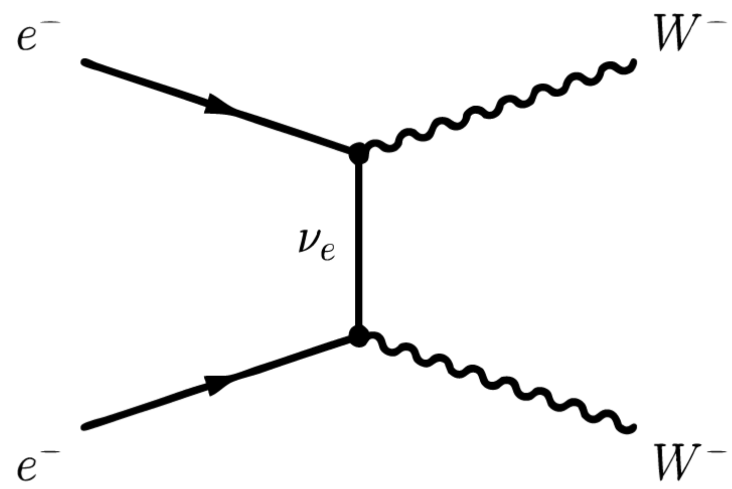
$$e^- + e^- \Longrightarrow W^- + W^-$$



Lepton number changes by two units: $\Delta L=2$

For light neutrinos, this cross-section is unobservably small

Virtual W's Instead



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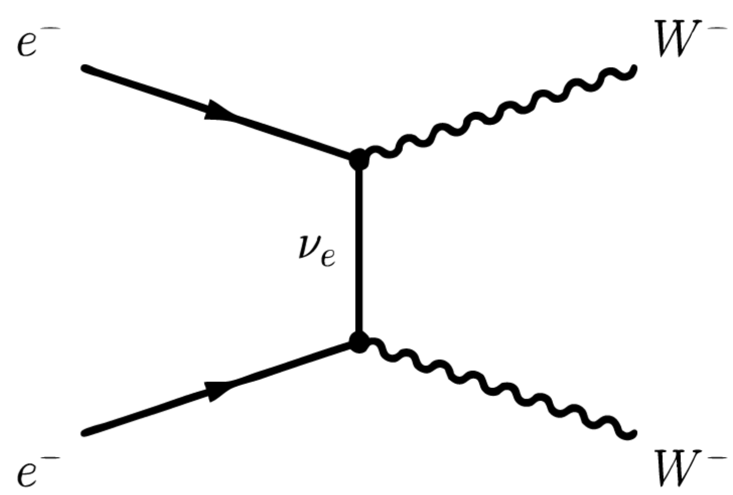
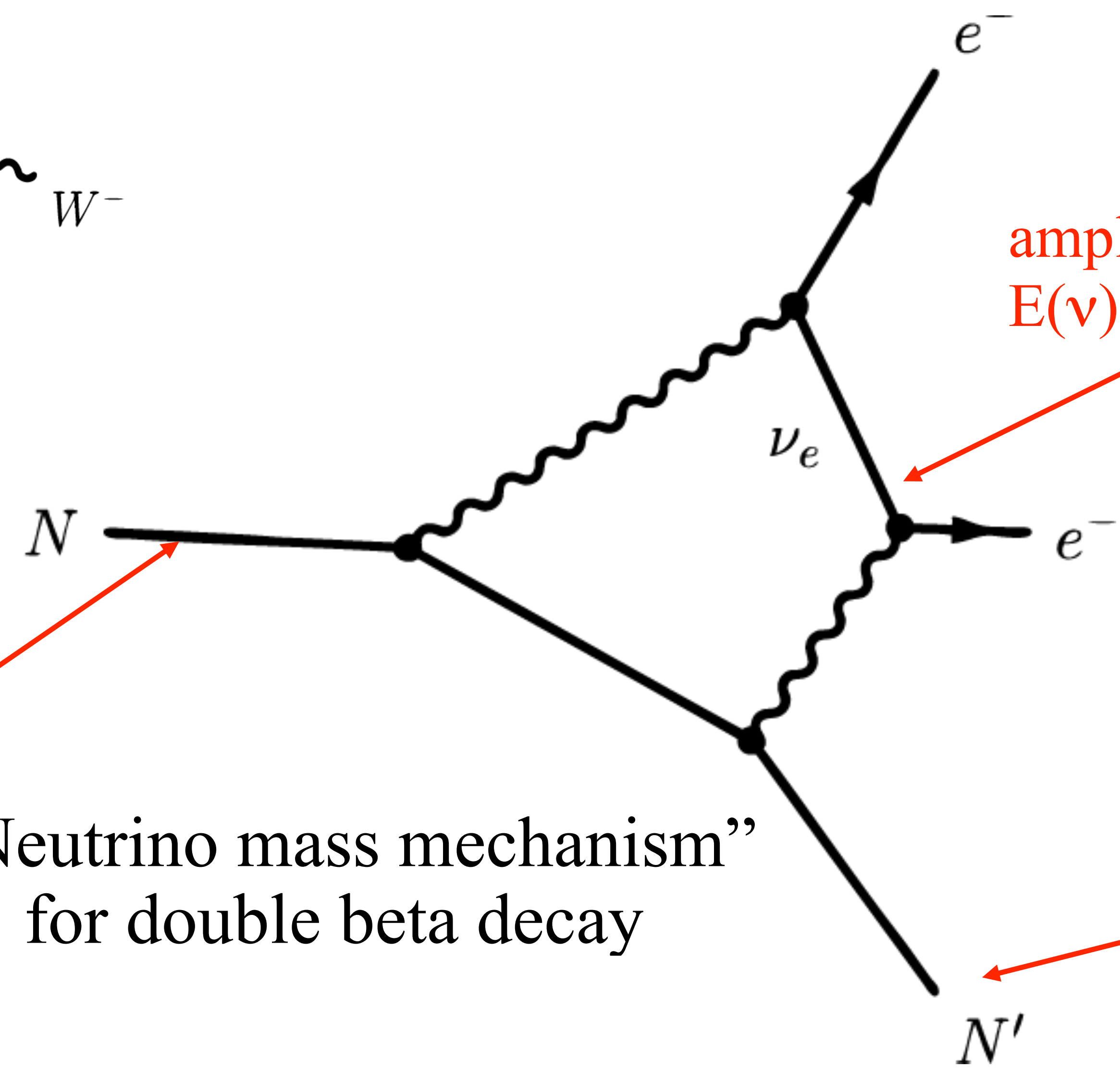


Lepton number changes by two units: ΔL=2

$$(N, Z) \rightarrow (N-2, Z+2) + e^- + e^-$$



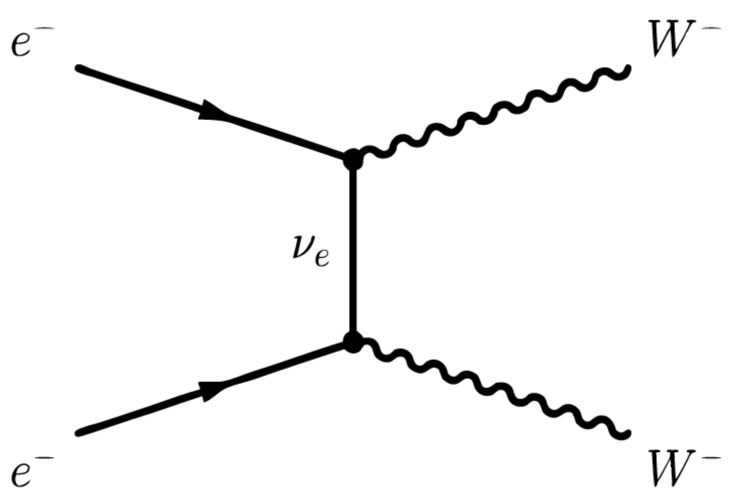
amplitude ~ m(ν)/E(ν),
E(ν) ~ 100 MeV

N(Z,A)

N(Z+2,A)

"Neutrino mass mechanism"
for double beta decay

Virtual W's Instead



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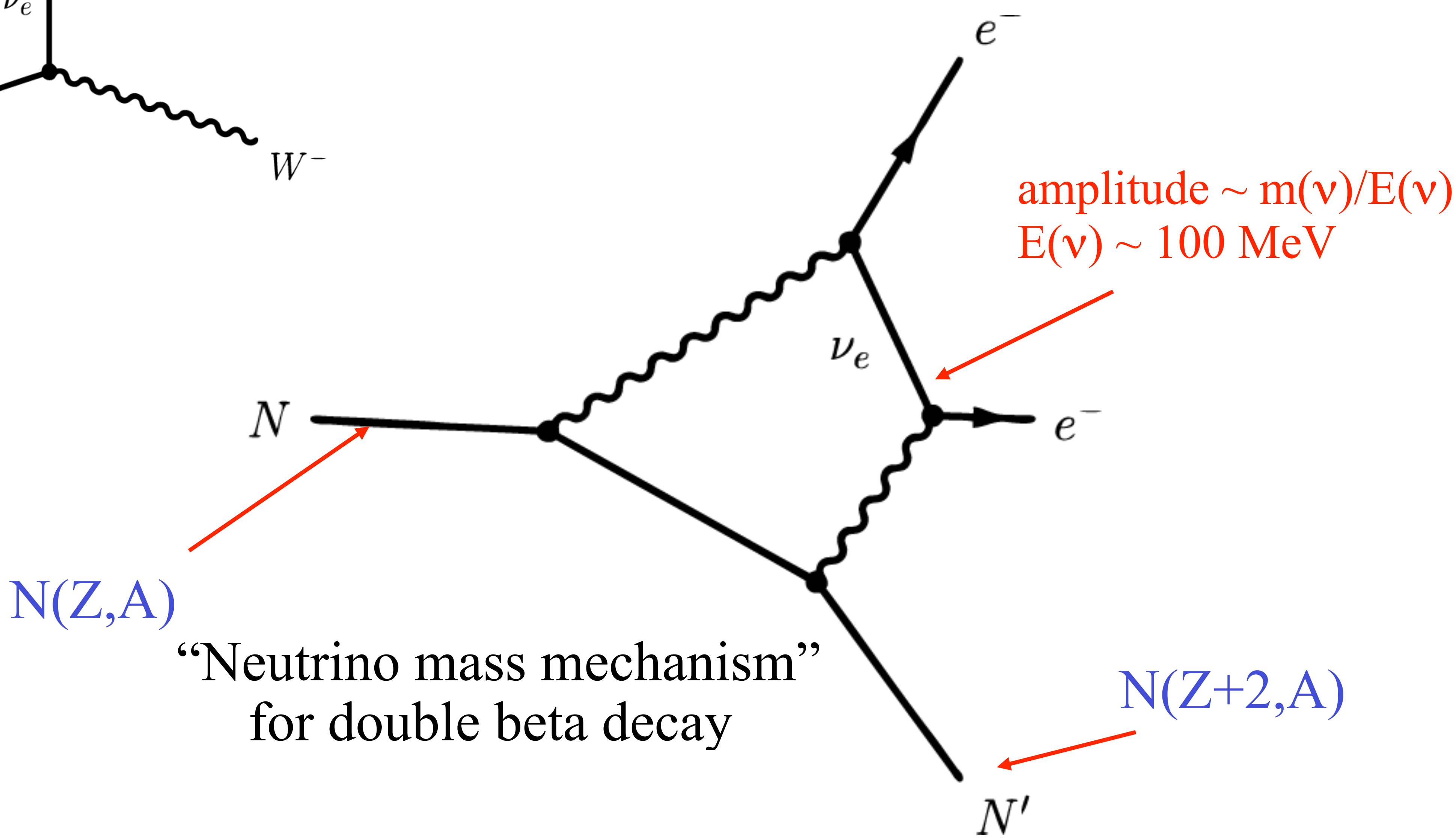
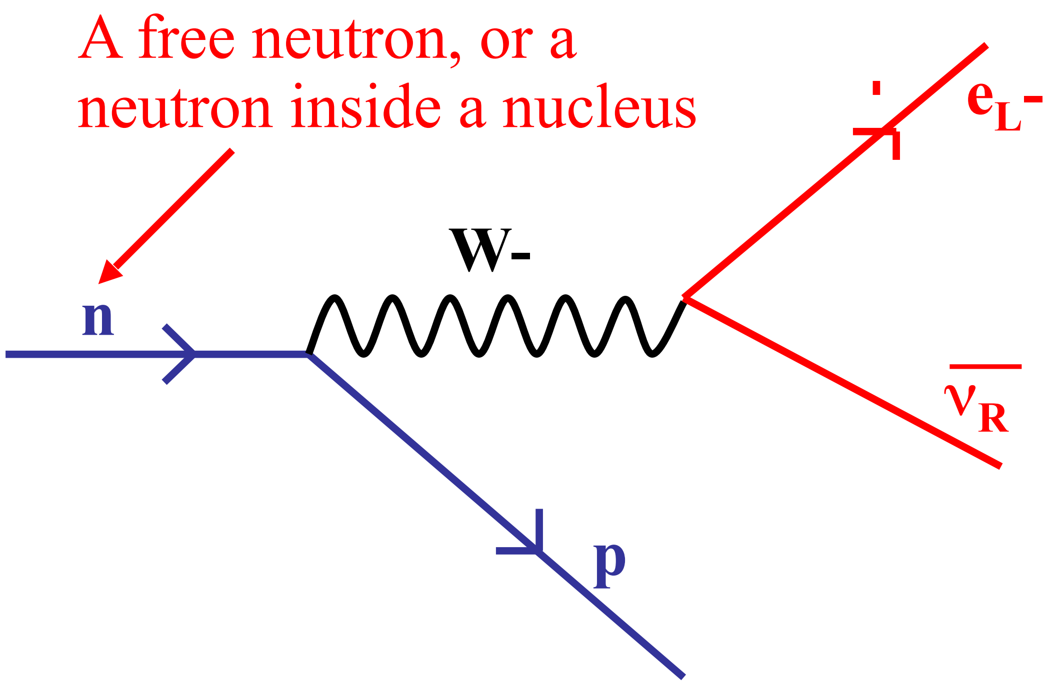


"Neutrino mass mechanism"
for double beta decay

Racah and Furry suggested this was possible for Majorana particles in 1937 soon after Majorana published his theory!

Lepton Number Conserving Standard Model Process

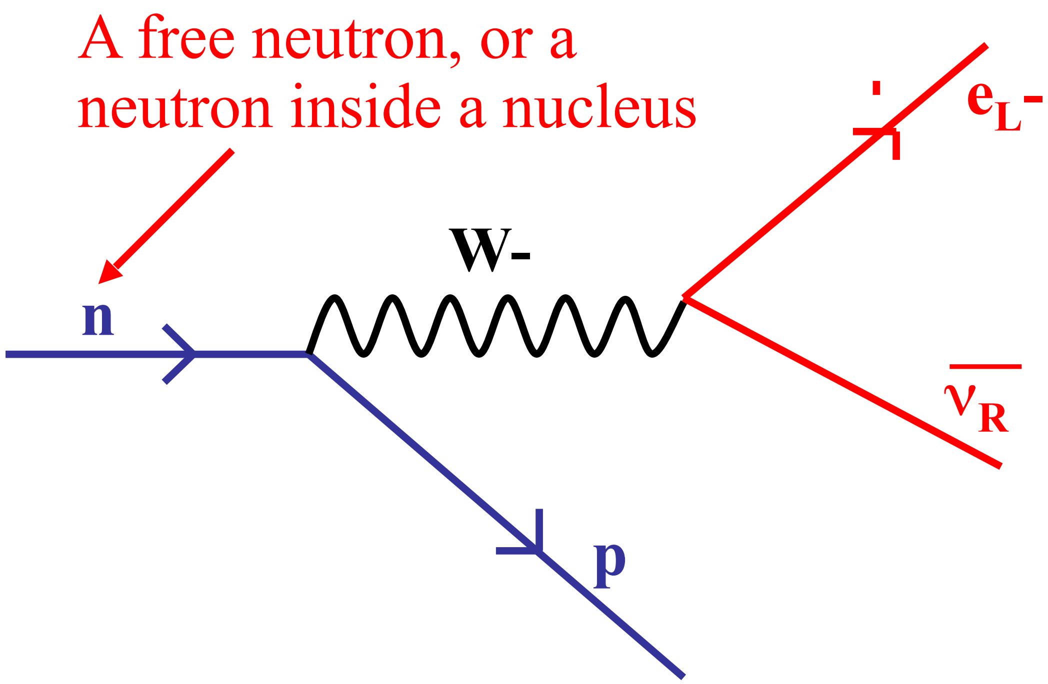
2ν Double Beta Decay



Nuclear Beta Decay

Lepton Number Conserving Standard Model Process

2ν Double Beta Decay



Nuclear Beta Decay

Nuclear Double-Beta Decay with the emission of two neutrinos

Lepton Number Conserving Standard Model Process

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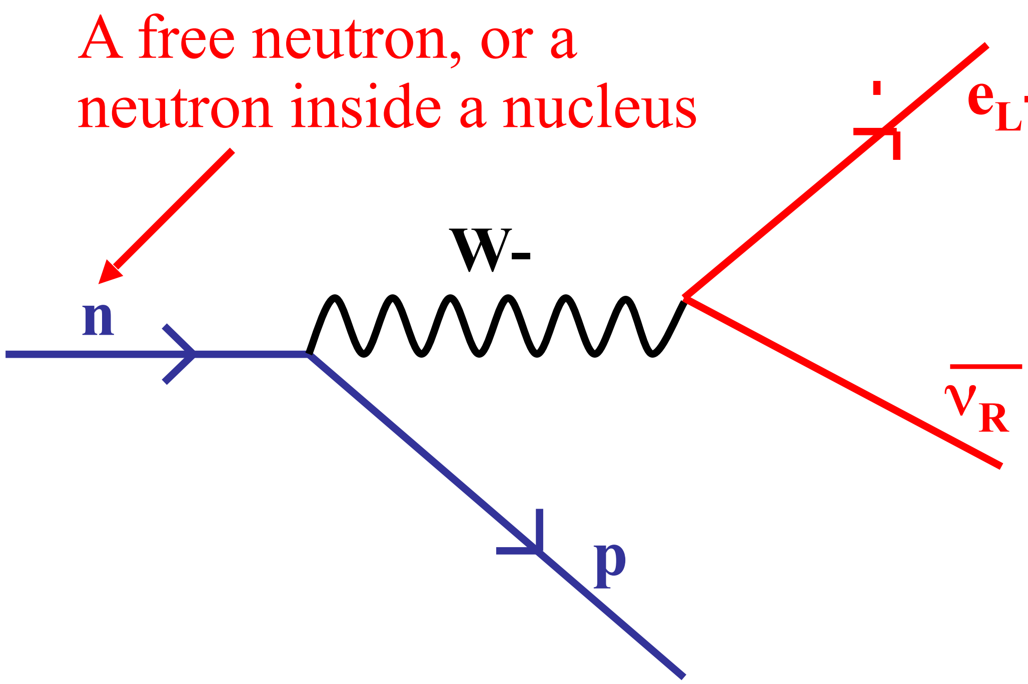
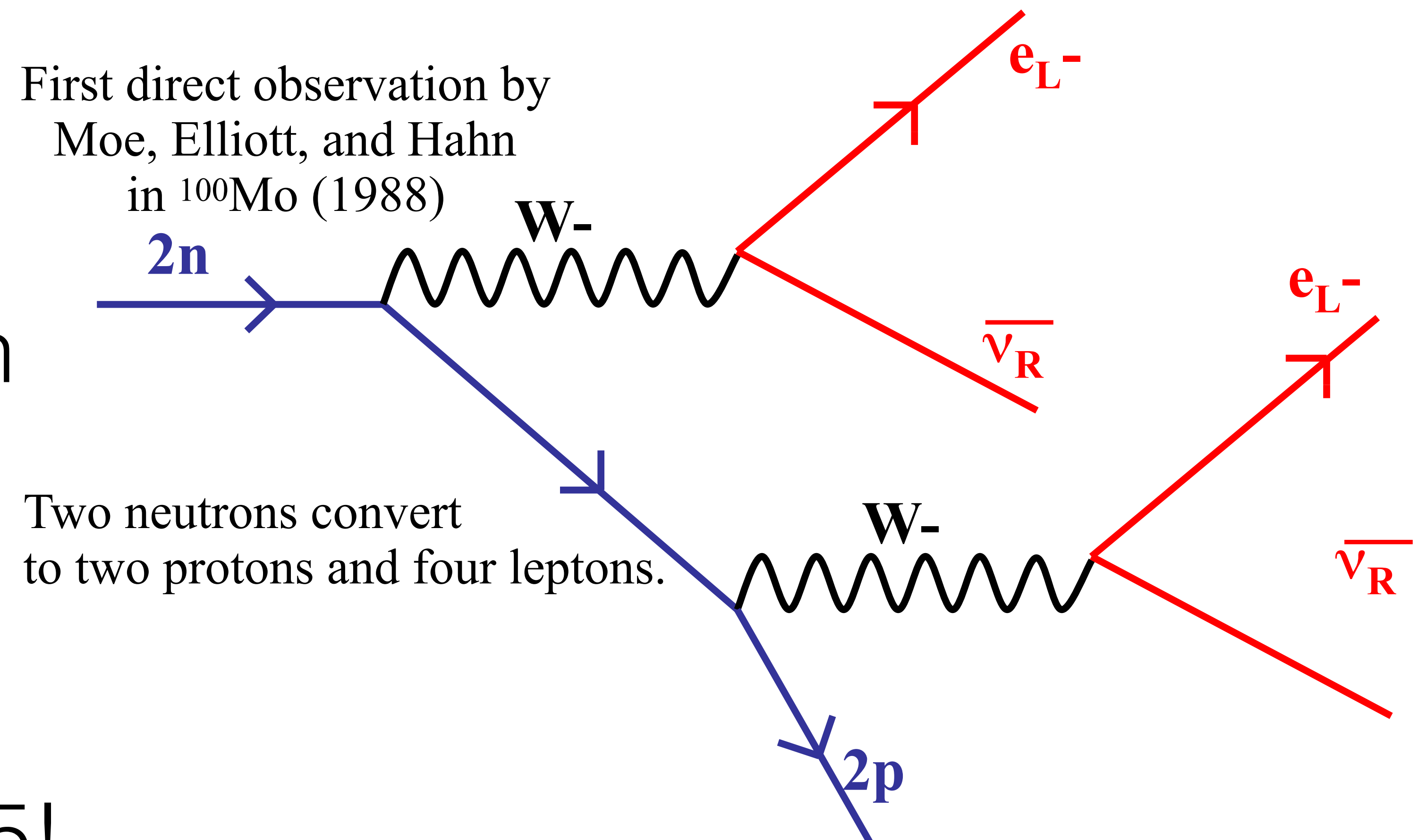


Nuclear Beta Decay

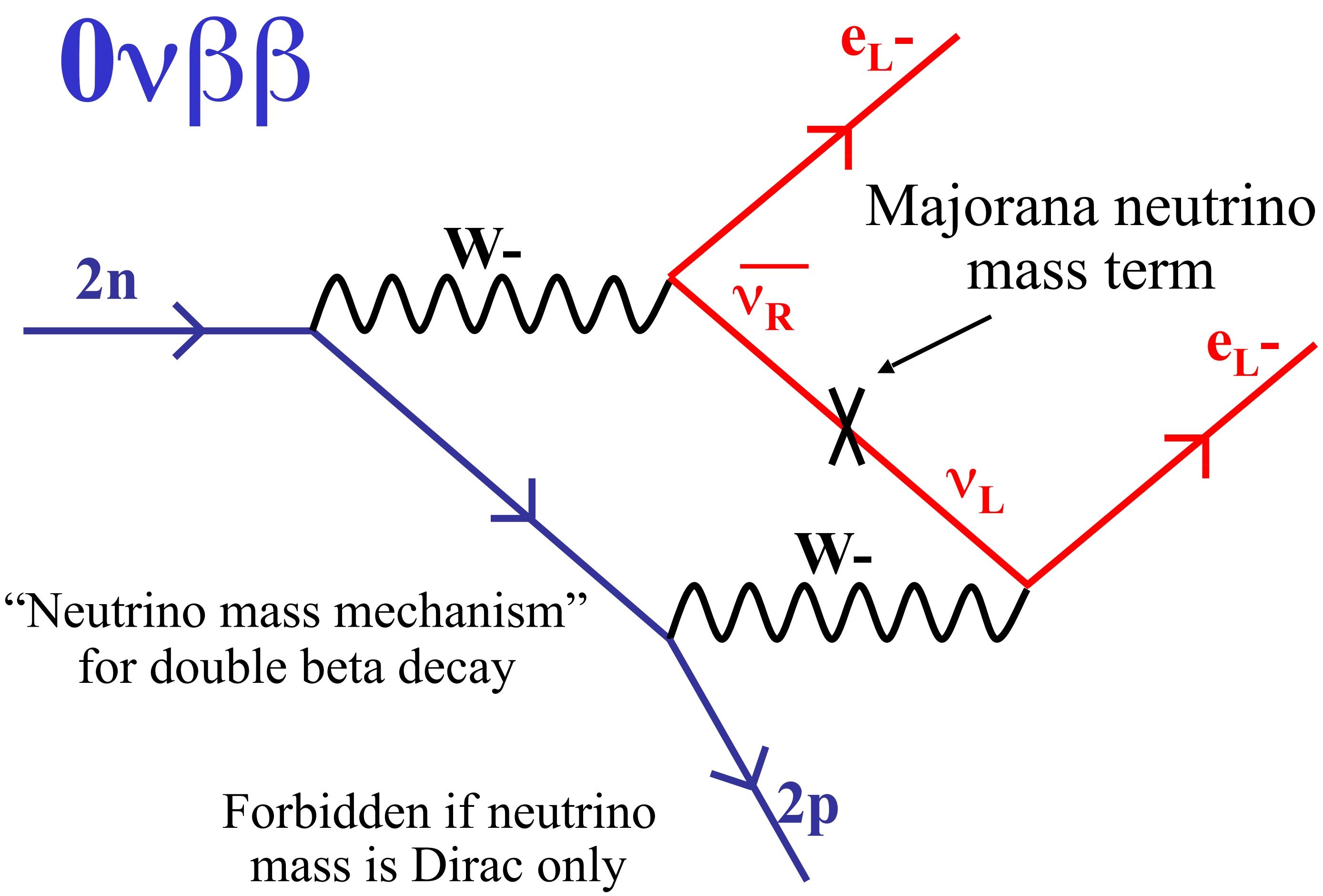


Nuclear Double-Beta Decay with the emission of two neutrinos

Suggested by Maria Goeppert-Mayer in 1935!

0ν Double Beta Decay

$$(N, Z) \rightarrow (N-2, Z+2) + e^{-} + e^{-}$$

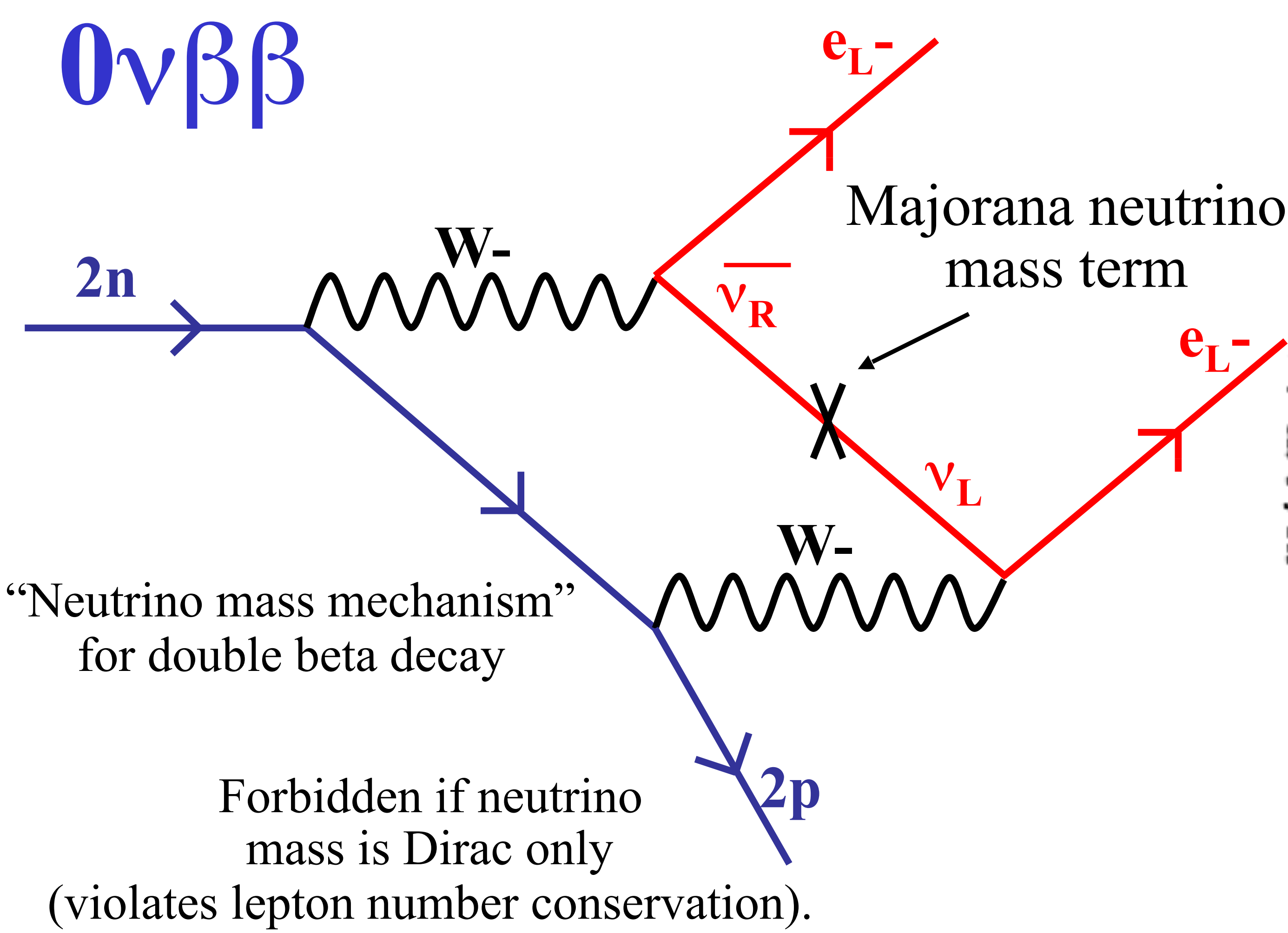


"Neutrino mass mechanism" for double beta decay

Forbidden if neutrino mass is Dirac only (violates lepton number conservation).

0ν Double Beta Decay

Experimental Signature



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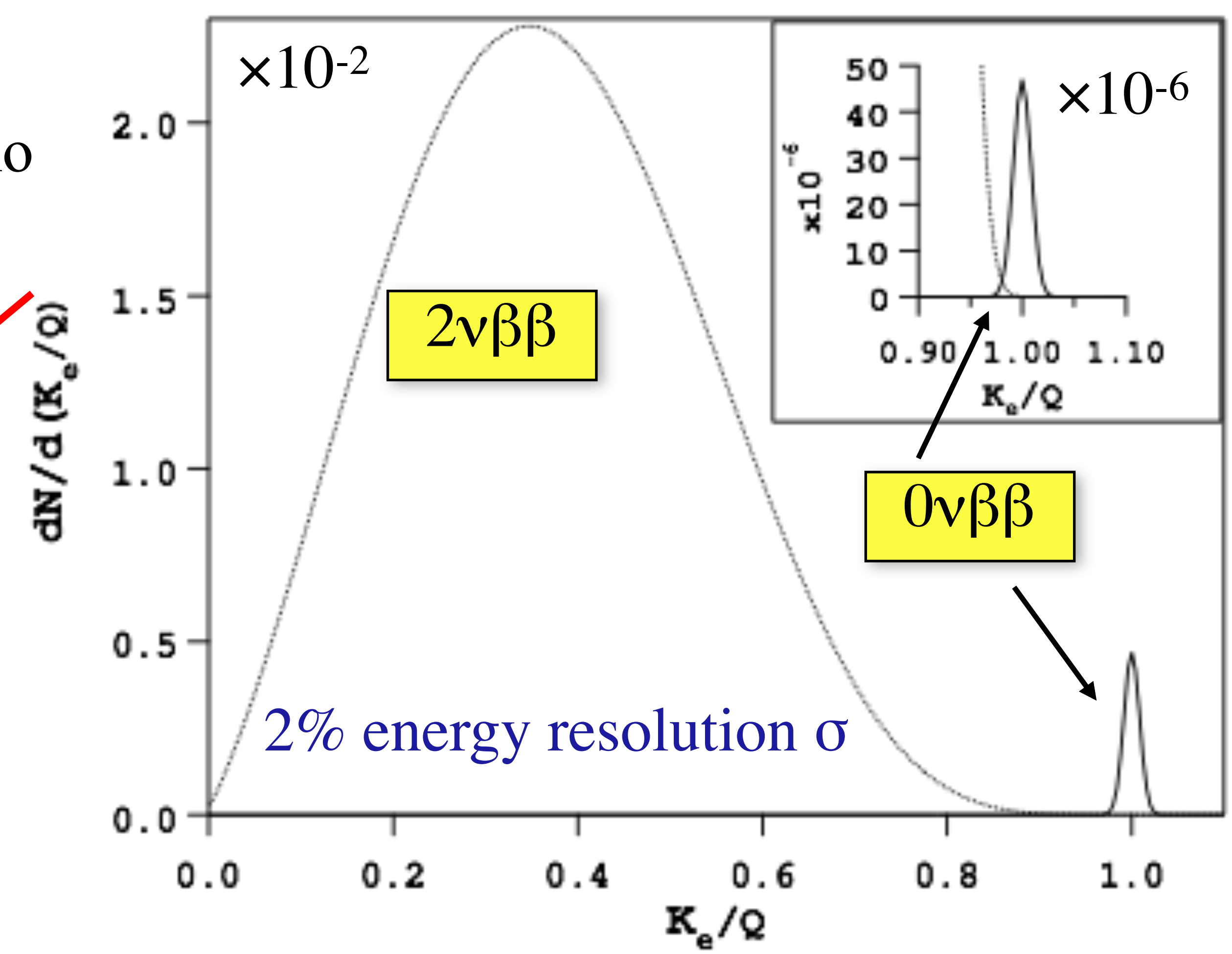
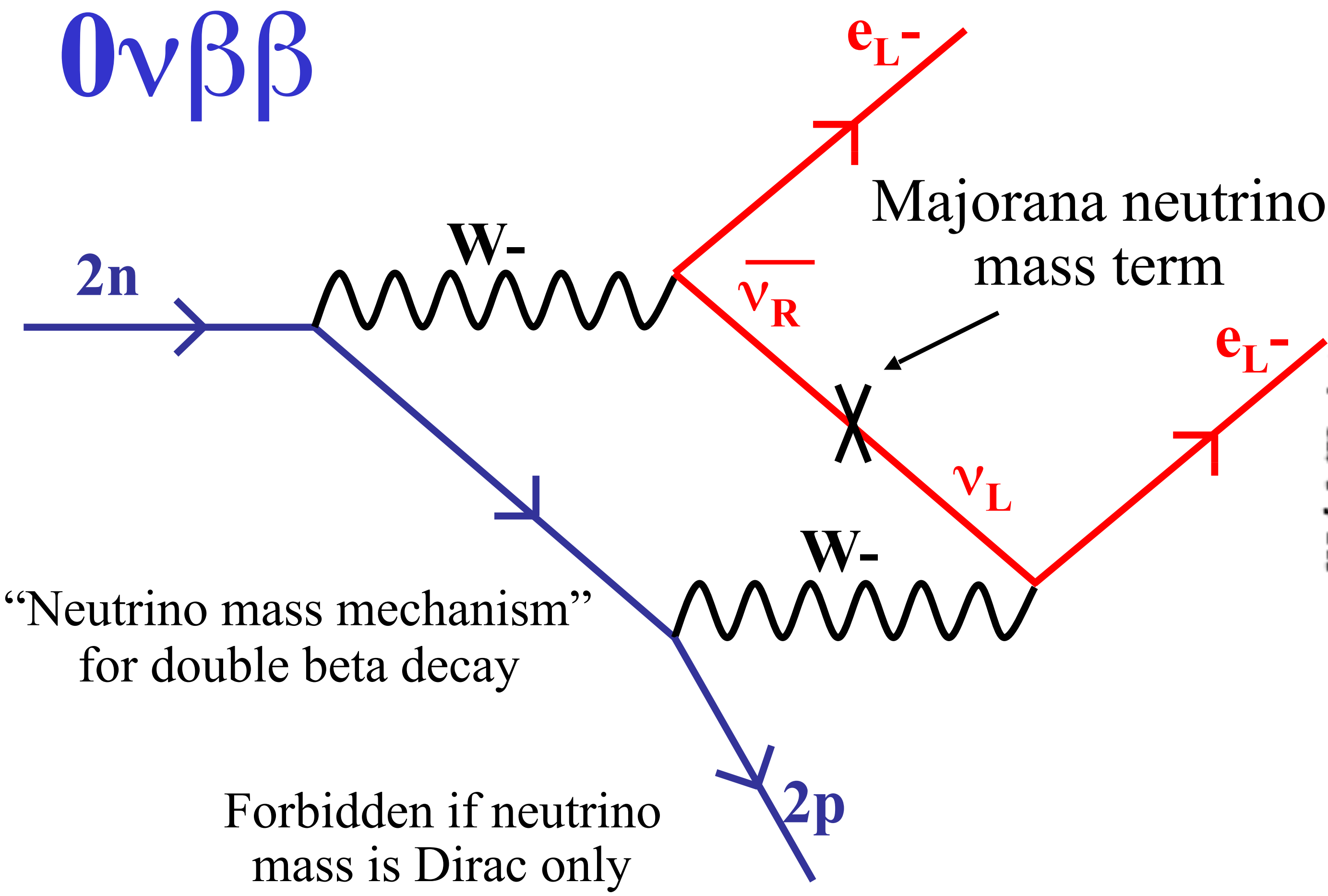


0ν Double Beta Decay

Experimental Signature

$0\nu\beta\beta$



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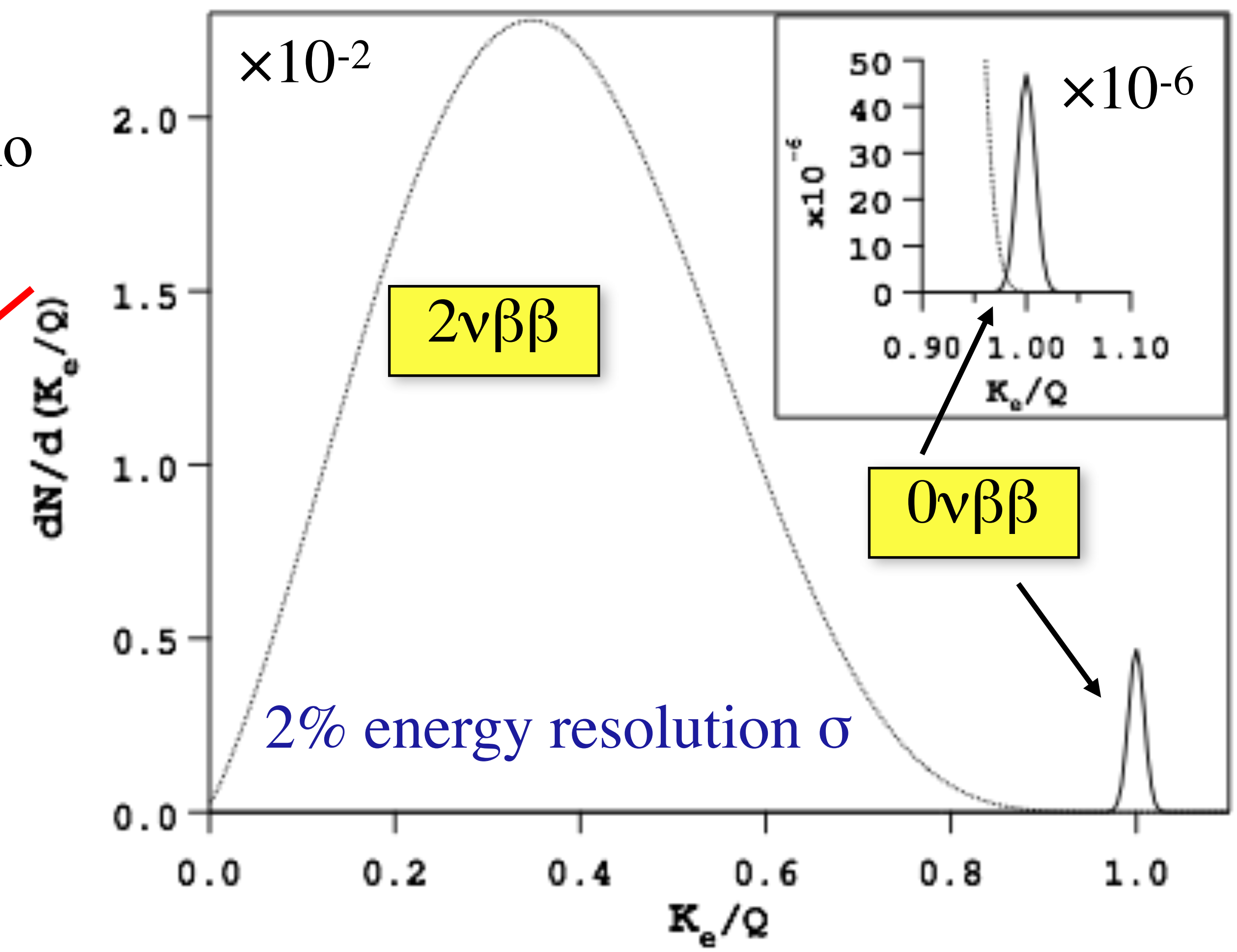
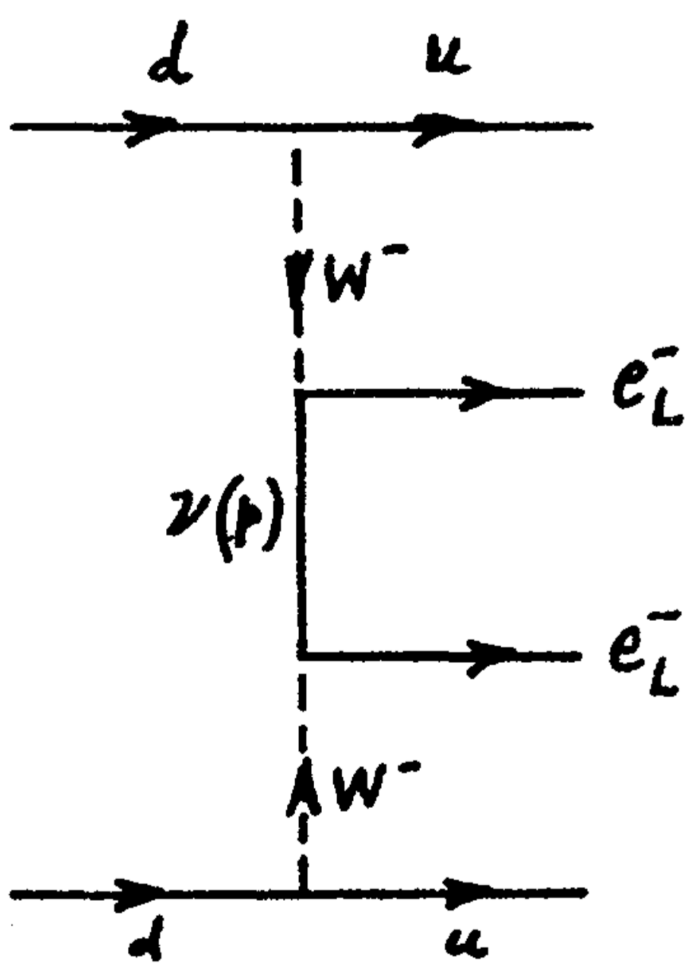


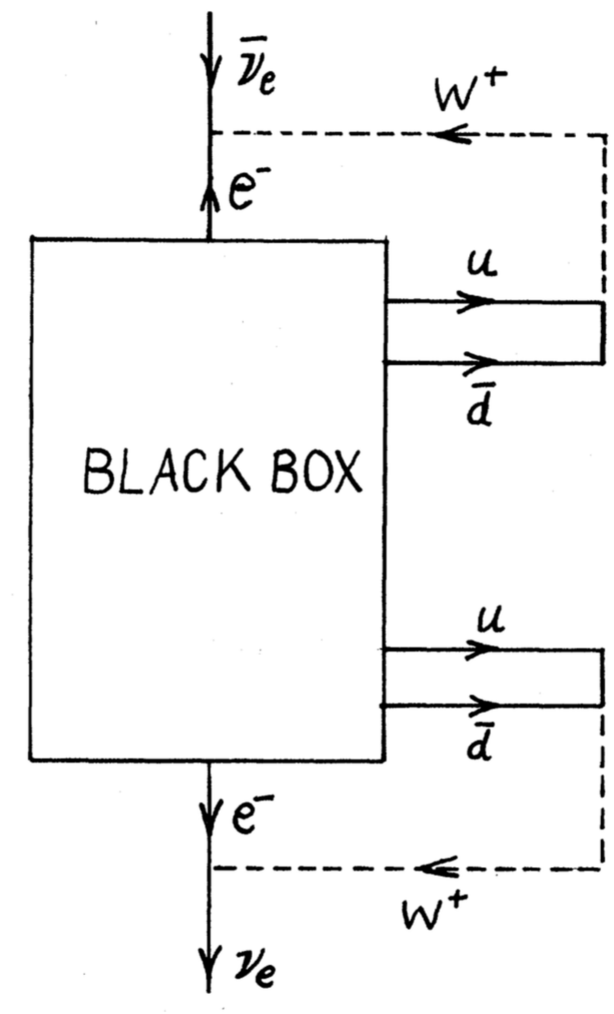
If observed, it would unambiguously signal that Lepton Number is NOT a conserved quantity, and that neutrinos are Majorana particles i.e. their own anti-particles

Schechter and Valle, PRD 25, Vol. 11 (1982)

A Theorem

If neutrinoless double-beta decay occurs, there exists a way to convert an anti-neutrino to a neutrino, a ***Majorana mass*** *amplitude*





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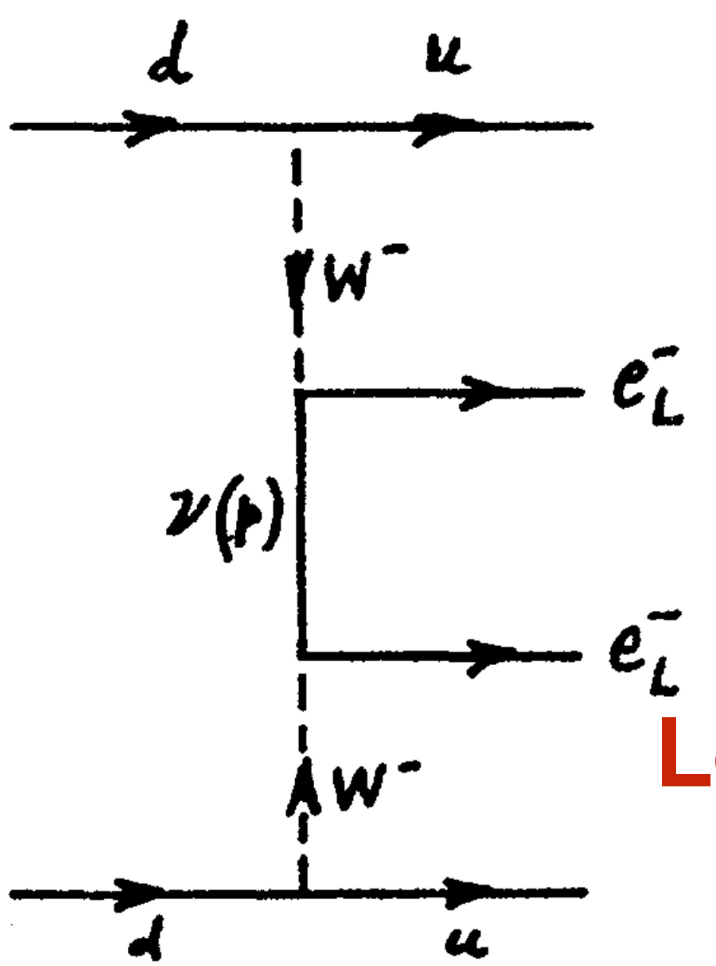
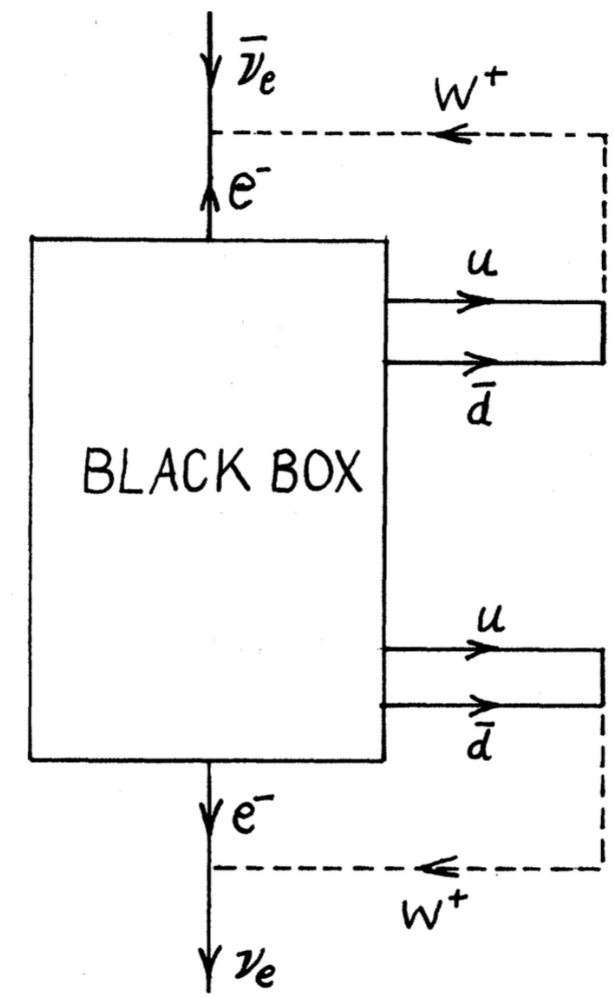


No caveats:

0νββ

Lepton Number Violation
and
Majorana Neutrinos



Theoretical Underpinnings

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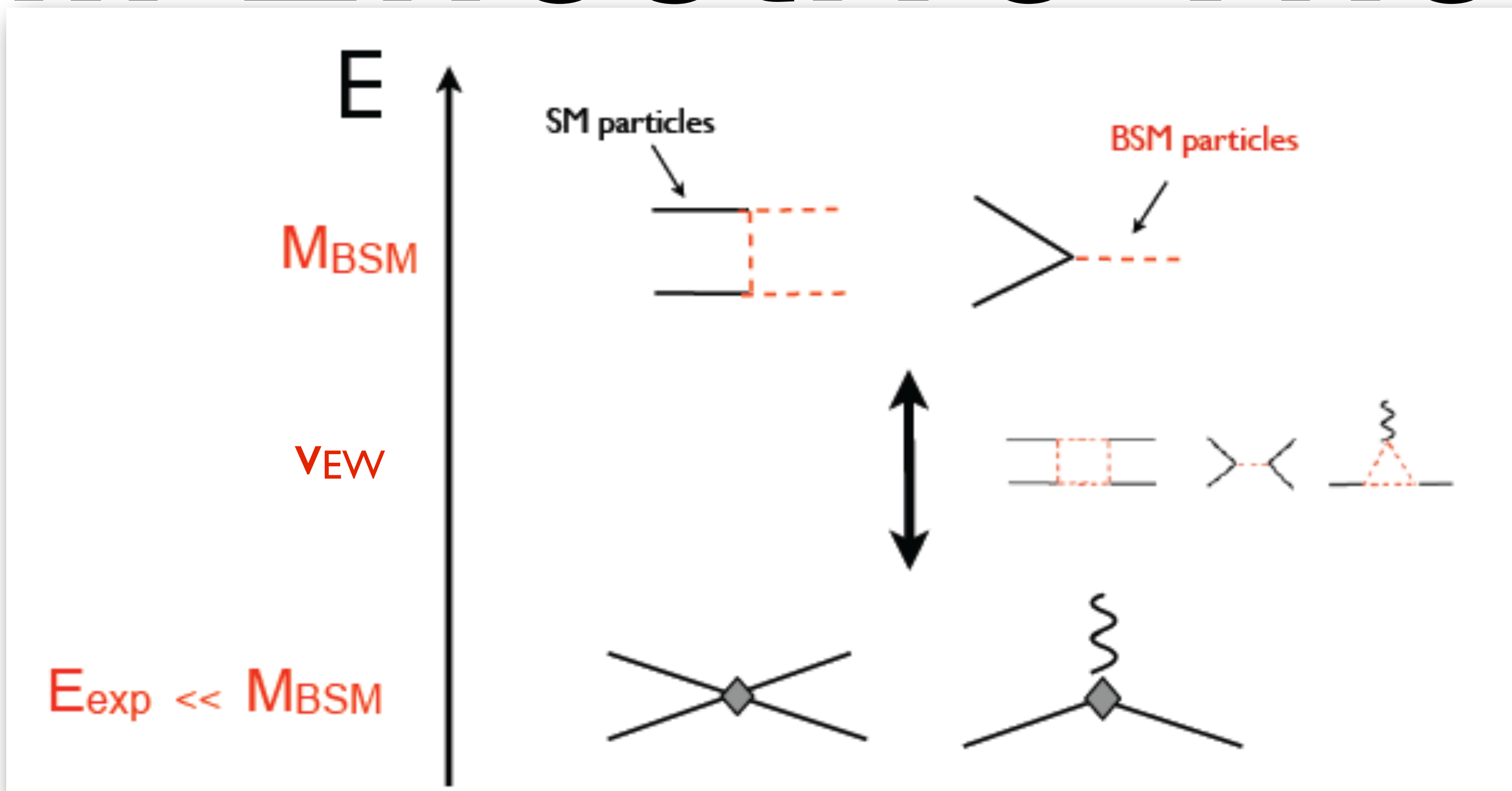
BSM Effective Theory



- EFT expansion in E/M_{BSM}, M_W/M_{BSM}

$$\boxed{\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots}$$

$$\Lambda \leftrightarrow M_{\rm BSM}$$

$$C_i \; [g_{\rm BSM}, \; M_a/M_b]$$

- Each model generates its own pattern of operators: experiments at $E \ll M_{BSM}$ can *discover* and *tell apart* new physics scenarios

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Dimension-5 Operator

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Weinberg 1979

- Dim 5: only one operator

$$\boxed{\hat{O}_{\text{dim}=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell} \qquad C = i\gamma_2\gamma_0$$

- Violates total lepton number (l → $e^{i\alpha}$ l , e → $e^{i\alpha}$e)
- Generates Majorana mass for L-handed neutrinos (after EWSB)

$$\frac{1}{\Lambda}\hat{O}_{\text{dim}=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

V. Cirigliano

Dimension-5 Operator

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$$\frac{1}{\Lambda}\hat{O}_{\text{dim}=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

- "See-saw": $m_\nu \sim 1\,\text{eV} \;\rightarrow\; \Lambda \sim 10^{13}\,\text{GeV}$

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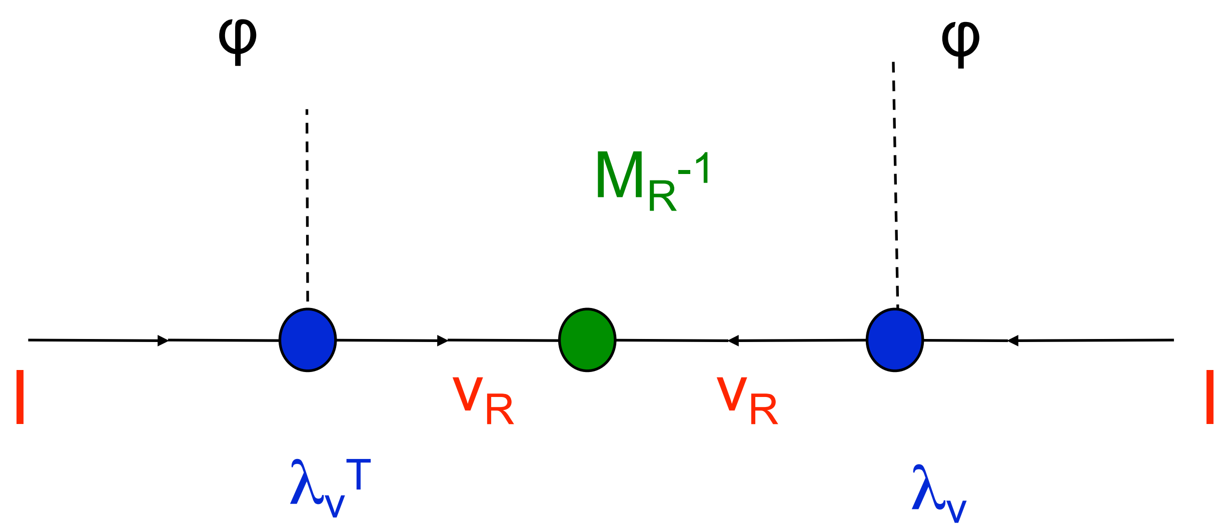
Explicit Realizations

- Models with heavy R-handed Majorana neutrinos



$$\boxed{g \sim \lambda_\nu^T M_R^{-1} \lambda_\nu}$$

$$\mathcal{L}_5 = \; g_{\alpha\beta} \; \ell_\alpha^T C \epsilon \varphi \; \varphi^T \epsilon \ell_\beta$$

V. Cirigliano

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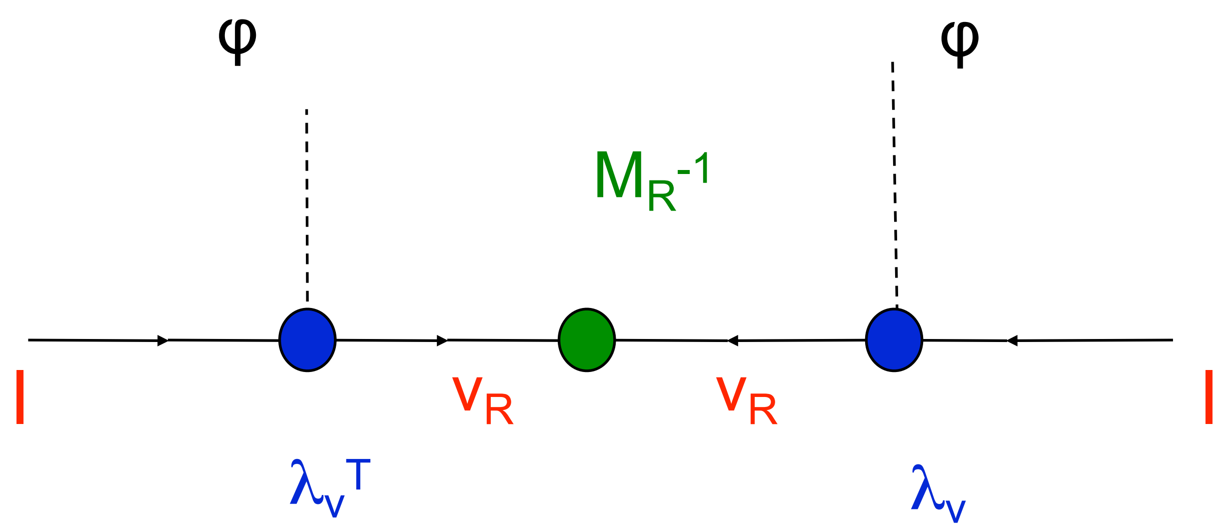
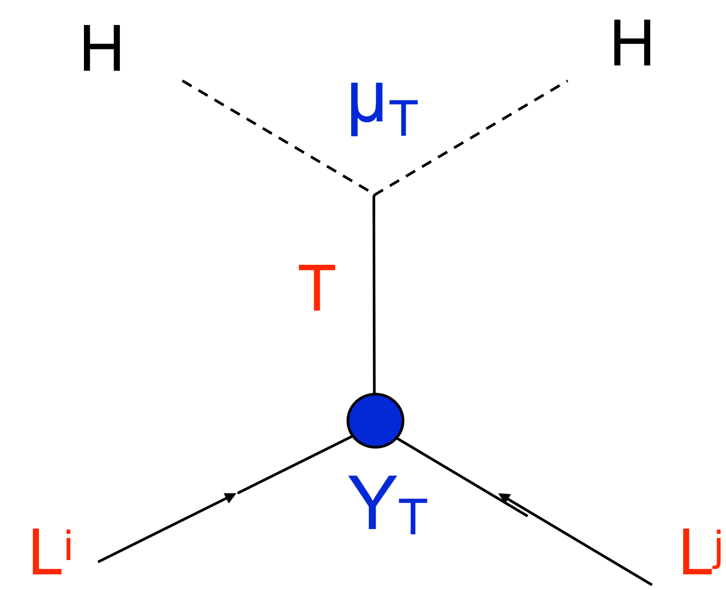
- Models with heavy R-handed Majorana neutrinos



$$g \sim \lambda_\nu^T M_R^{-1} \lambda_\nu$$

$$\mathcal{L}_5 = g_{\alpha\beta}\; \ell_\alpha^T C\epsilon\varphi\; \varphi^T \epsilon \ell_\beta$$

- Or with triplet Higgs field: no heavy neutrinos!



$$g \sim \mu_T M_T^{-2}\; Y_T$$

$$\mathcal{L}_5 = g_{\alpha\beta}\; \ell_\alpha^T C\epsilon\varphi\; \varphi^T \epsilon \ell_\beta$$

V. Cirigliano

What is in the Black Box?

(Classifying sources of LNV: organize discussion by scales)

V. Cirigliano

What is in the Black Box?

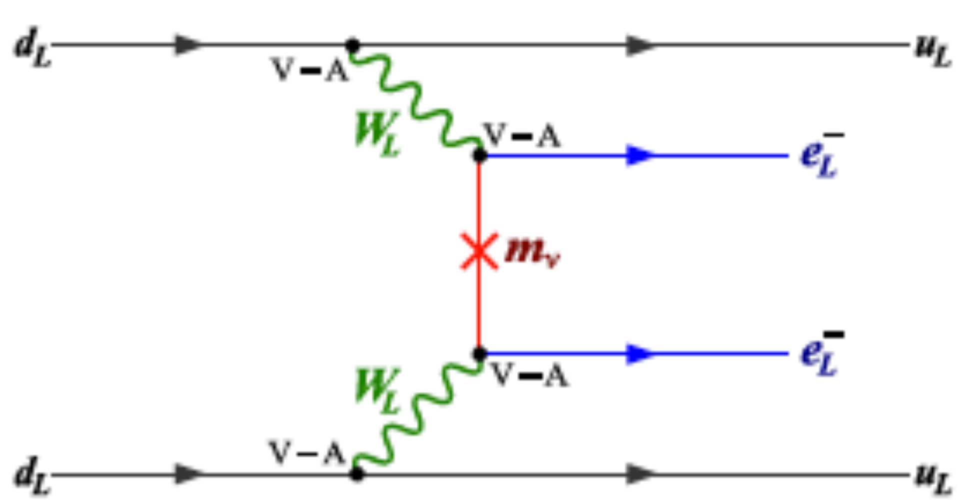
(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale (Λ>> TeV)

Low energy footprints encoded in the leading dim-5 operator

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

This is a Majorana mass term for ν's:
neutrinoless double-beta decay mediated by light ν exchange



Other Possibilities for the Black Box

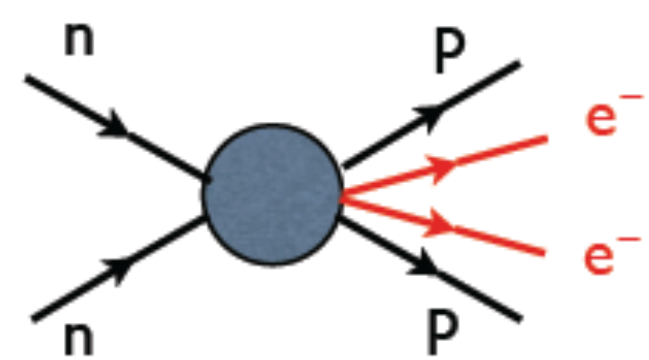
V. Cirigliano

(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale (Λ>> TeV)

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

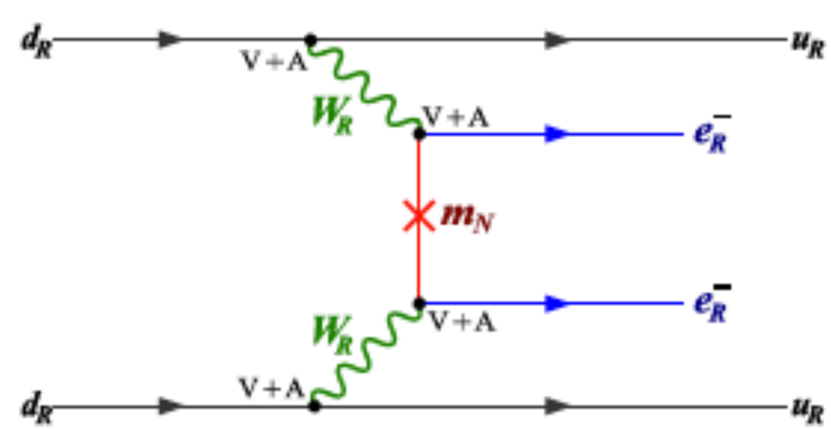
- LNV dynamics at lower scale (Λ~TeV)



Higher dimensional operators become relevant

$$\frac{1}{\Lambda^5}\,\bar{q}q\,\bar{q}q\,\overline{e^c}e$$

Arise in well-motivated models:
Left-Right Symmetric Model,
RPV-SUSY, ...



Other Possibilities for the Black Box

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$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

- LNV dynamics at lower scale (Λ~TeV)

$$\frac{1}{\Lambda^5}\,\bar{q}q\,\bar{q}q\,\overline{e^c}e$$

- LNV dynamics at very low energy (e.g. low-scale seesaw)

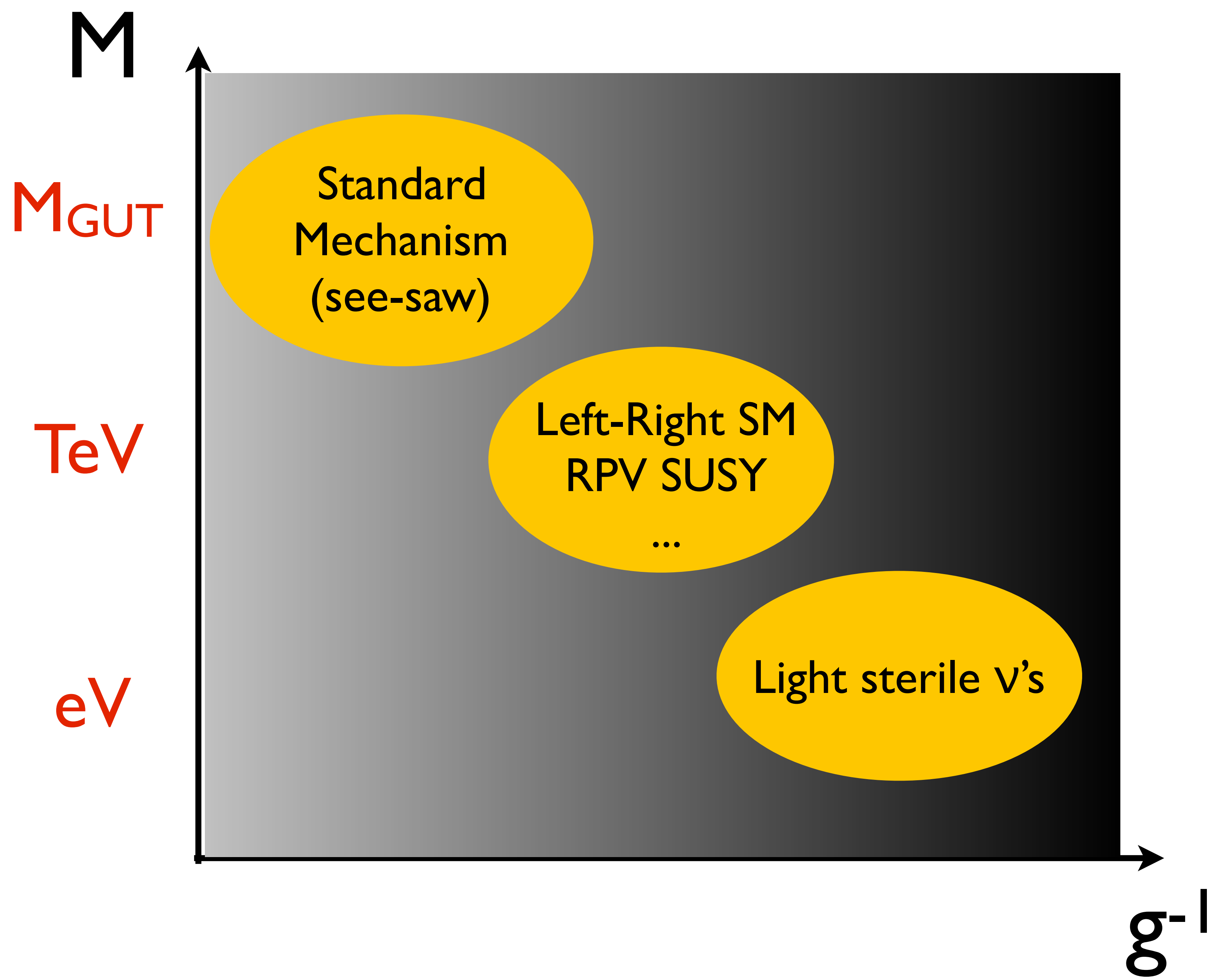
$$-\frac{1}{2}M_R\,\overline{\nu_R^c}\nu_R\;+\;Y_\nu\,\bar{\ell}\nu_R\,H$$

Affects NLDBD in significant ways, depending on mass scale M_R: eV → 100 GeV

Various Possibilities for the Black Box

V. Cirigliano

- In summary: ton-scale $0\nu\beta\beta$ probes LNV from variety mechanisms, involving different scales (M) and coupling strengths (g)



Choosing a Nuclide

Typical $2\nu\beta\beta$ half-life is very long: second-order weak process

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

$$\frac{1}{G^{2\nu}} \simeq 10^{20} \text{ years}$$

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even A nuclei occupy 2 parabolas,
even-even below odd-odd

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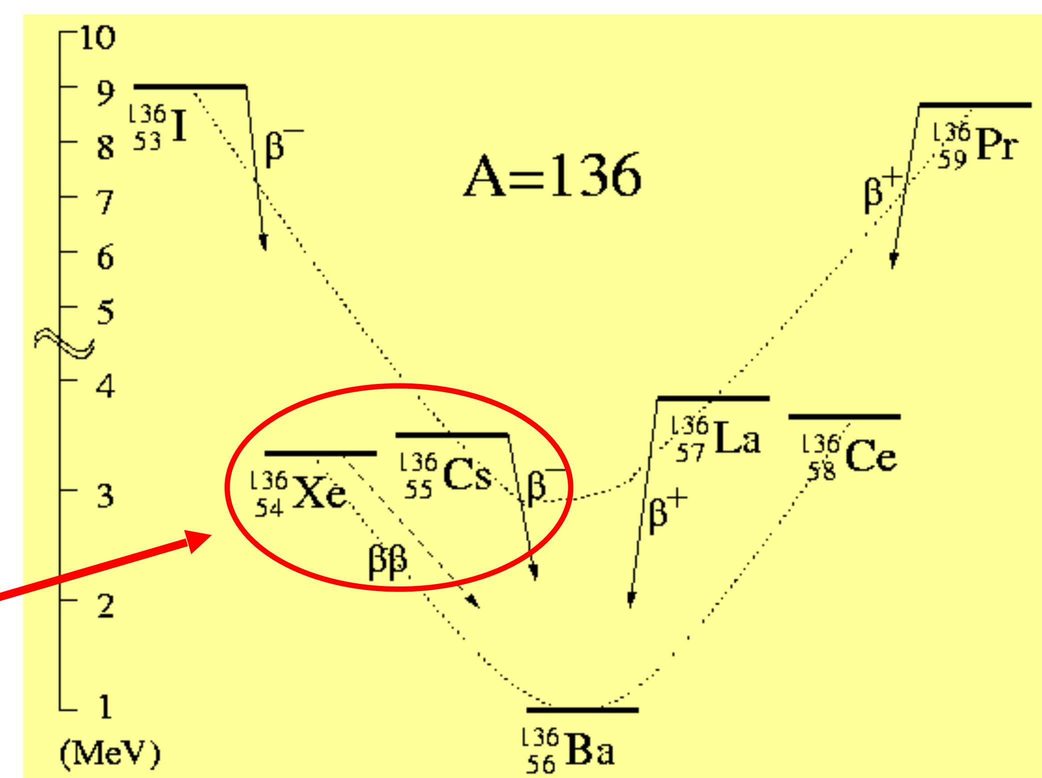
Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



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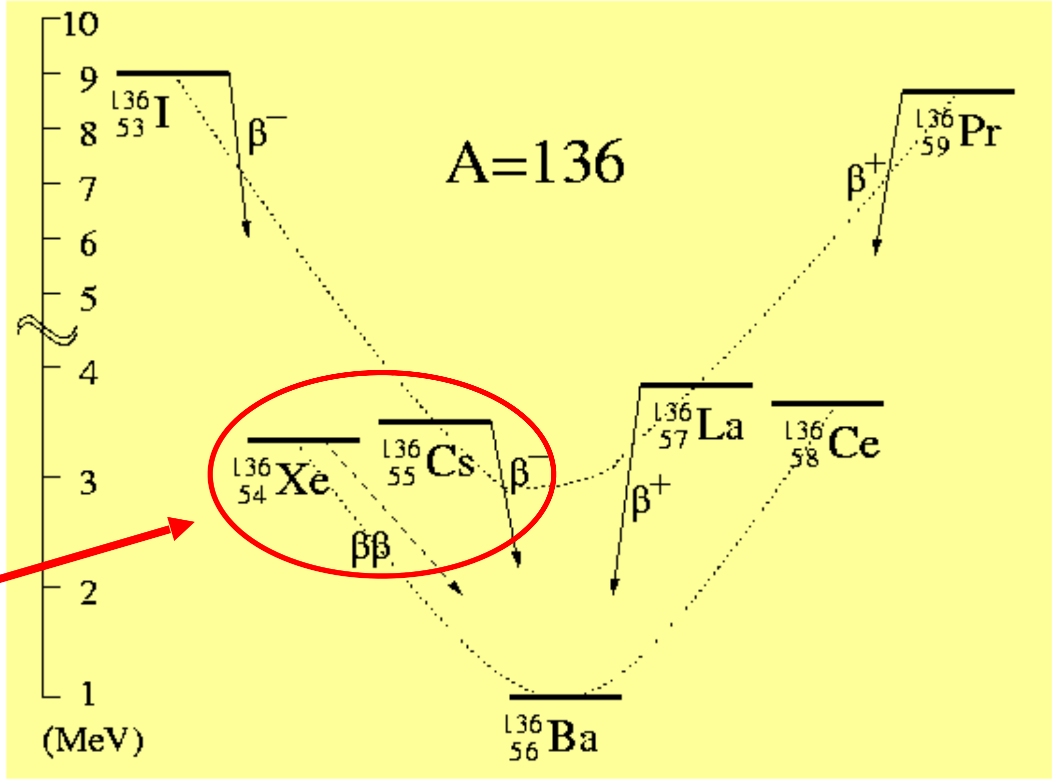


Choosing a Nuclide

Typical 2$\nu\beta\beta$ half-life is very long: second-order weak process

$$\frac{1}{T^{0\nu}_{\frac{1}{2}}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

Atomic mass affected by nuclear pairing term: even A nuclei occupy 2 parabolas, even-even below odd-odd

$$\frac{1}{G^{2\nu}} \simeq 10^{20} \text{ years}$$

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

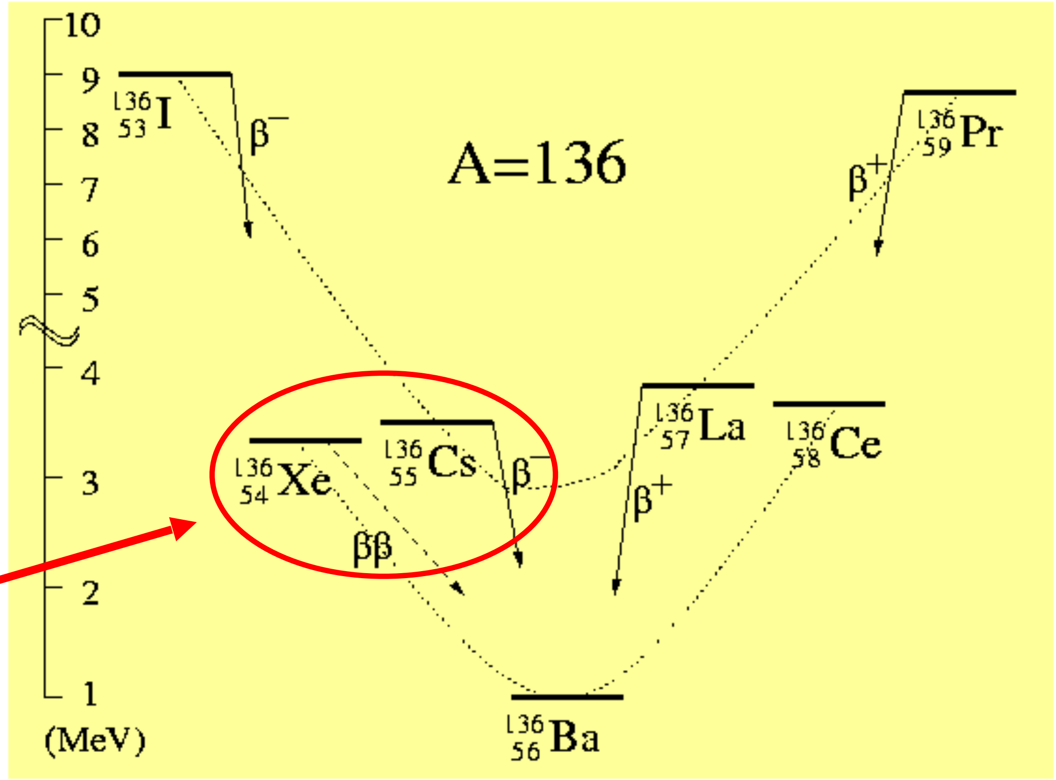
Choose nuclei where single beta decay forbidden

but double-beta decay is possible

Candidate nuclei with Q>2 MeV

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Decay Rate for 0νββ

$$\Gamma^{0\nu} = G(Q,Z)\left|M(A,Z)\eta\right|^2$$

Transition Probability $\alpha \frac{m}{Q^2}$ $(Q \sim m_e)$

Phase Space Factor $G \sim G_F^4 g_A^4 m_e^5$

$M(A,Z)$ Nuclear Matrix Element

η Particle Physics of the Black Box

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For light neutrino exchange

PMNS Matrix

All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta} \rangle = \sum_i U_{ie}^2 m_i$

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$m_{\beta\beta} \sim 1$ eV $\Longrightarrow T_{1/2} \sim 10^{24}$ years

$m_{\beta\beta} \sim 0.1$ eV $\Longrightarrow T_{1/2} \sim 10^{26}$ years

$m_{\beta\beta} \sim 0.01$ eV $\Longrightarrow T_{1/2} \sim 10^{28}$ years

The PMNS Matrix

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

$(W \rightarrow e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau)$

are superpositions of the mass eigenstates:

$$|\nu_\alpha> = \sum_i U^*_{\alpha i}\, |\nu_i> \;.$$

Neutrino of flavor $\alpha = e, \mu$, or τ

Neutrino of definite mass m_i

Unitary Leptonic Mixing Matrix

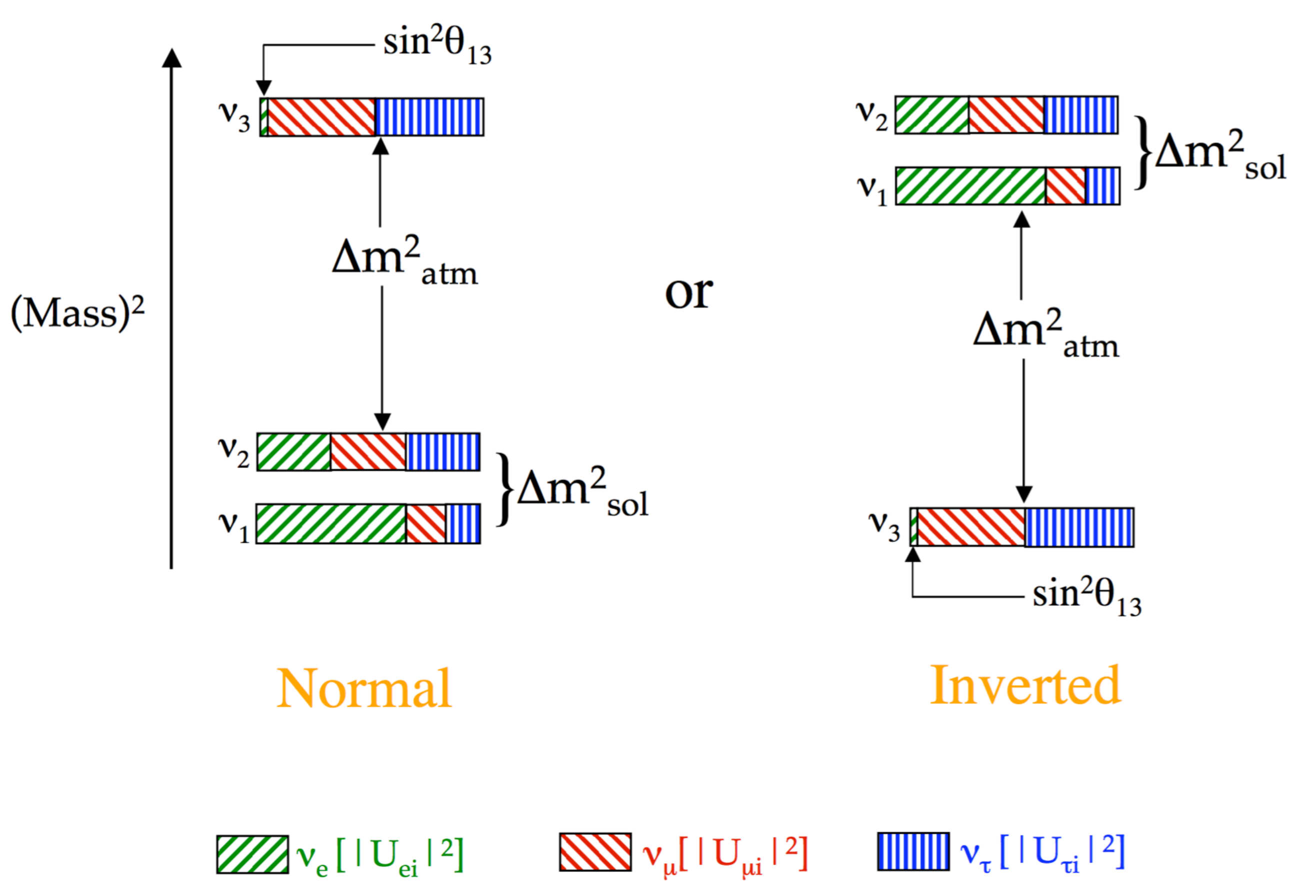
$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana ~~CP~~ phases

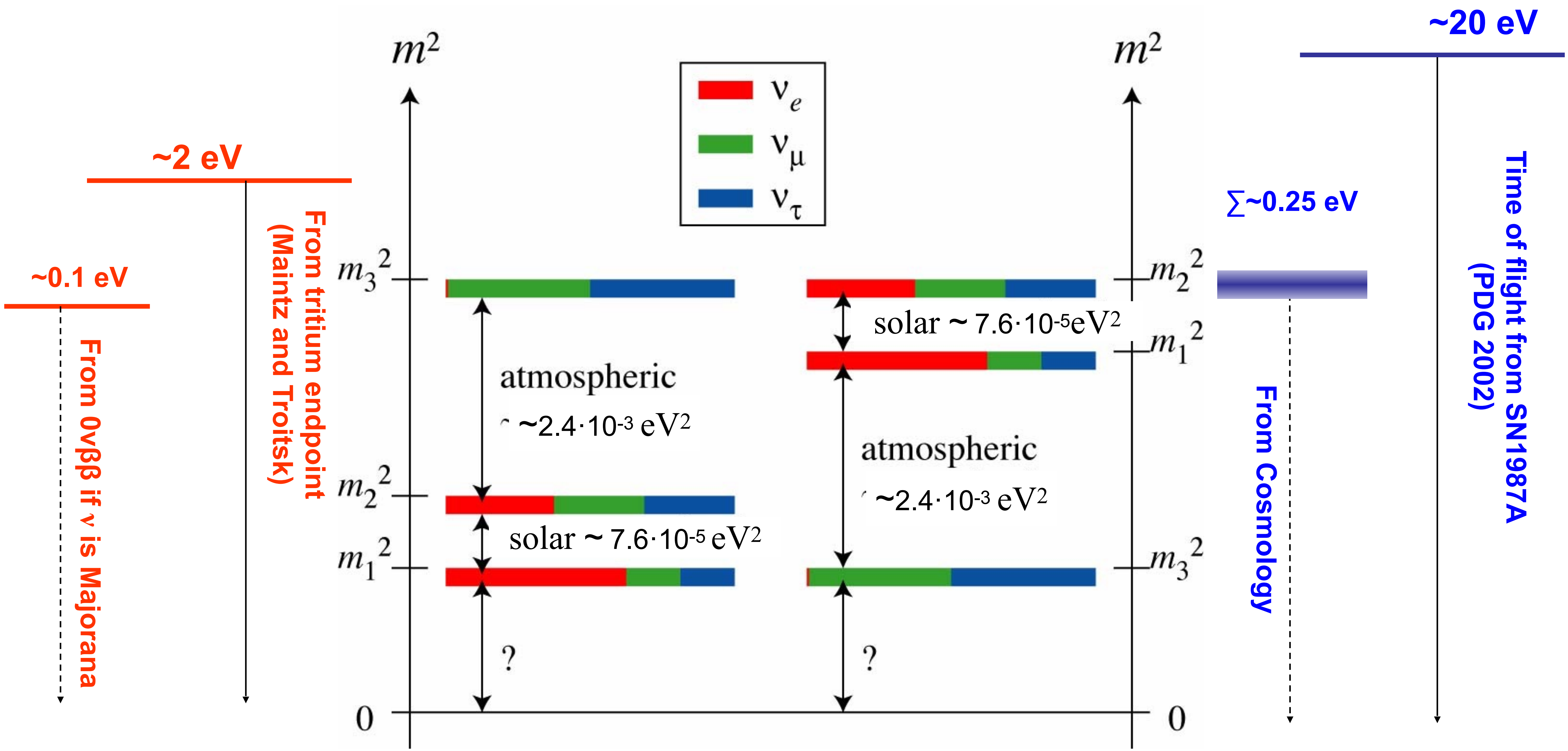
$\theta_{12} \approx \theta_{sol} \approx 34°,\ \theta_{23} \approx \theta_{atm} \approx 37\text{-}53°,\ \theta_{13} \lesssim 10°$



For double-beta decay, the electron flavor content of all 3 mass eigenstates is what is relevant

U_{ie}

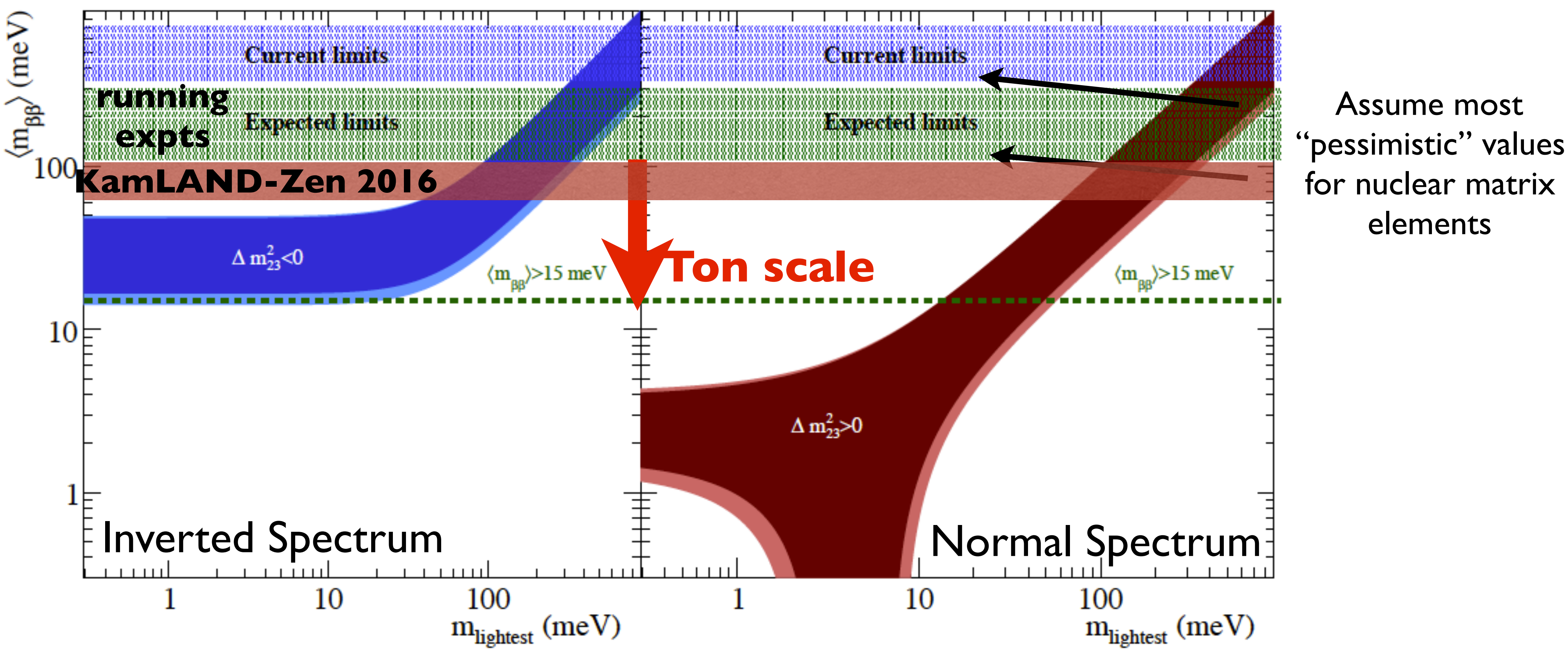
Absolute Neutrino Mass Scale



The Experiments and their Challenges

Discovery Reach

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



Dark bands: unknown phases

Light bands: uncertainty from oscillation parameters(90% CL)

- Discovery *possible* for inverted spectrum OR $m_{lightest}$ > 50 meV

Signal and Background

An experimental challenge of rare events

Most measured half-lives of $2\nu\beta\beta$ are $O(10^{21})$ years
- Compare to lifetime of Universe: 10^{10} years
- Compare to Avogadro's number 6×10^{23}
- Mole of isotope will produce ~ 1 decay/day

If it exists, half-lives of $0\nu\beta\beta$ would be longer (^{136}Xe limits is > 10^{25} years)

Half life (years)	Signal (cts/tonne-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1

Natural radioactivity: a nanogram produces more than 1 decay/day!
Cosmogenically induced radioactivity exacerbates technical challenge

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

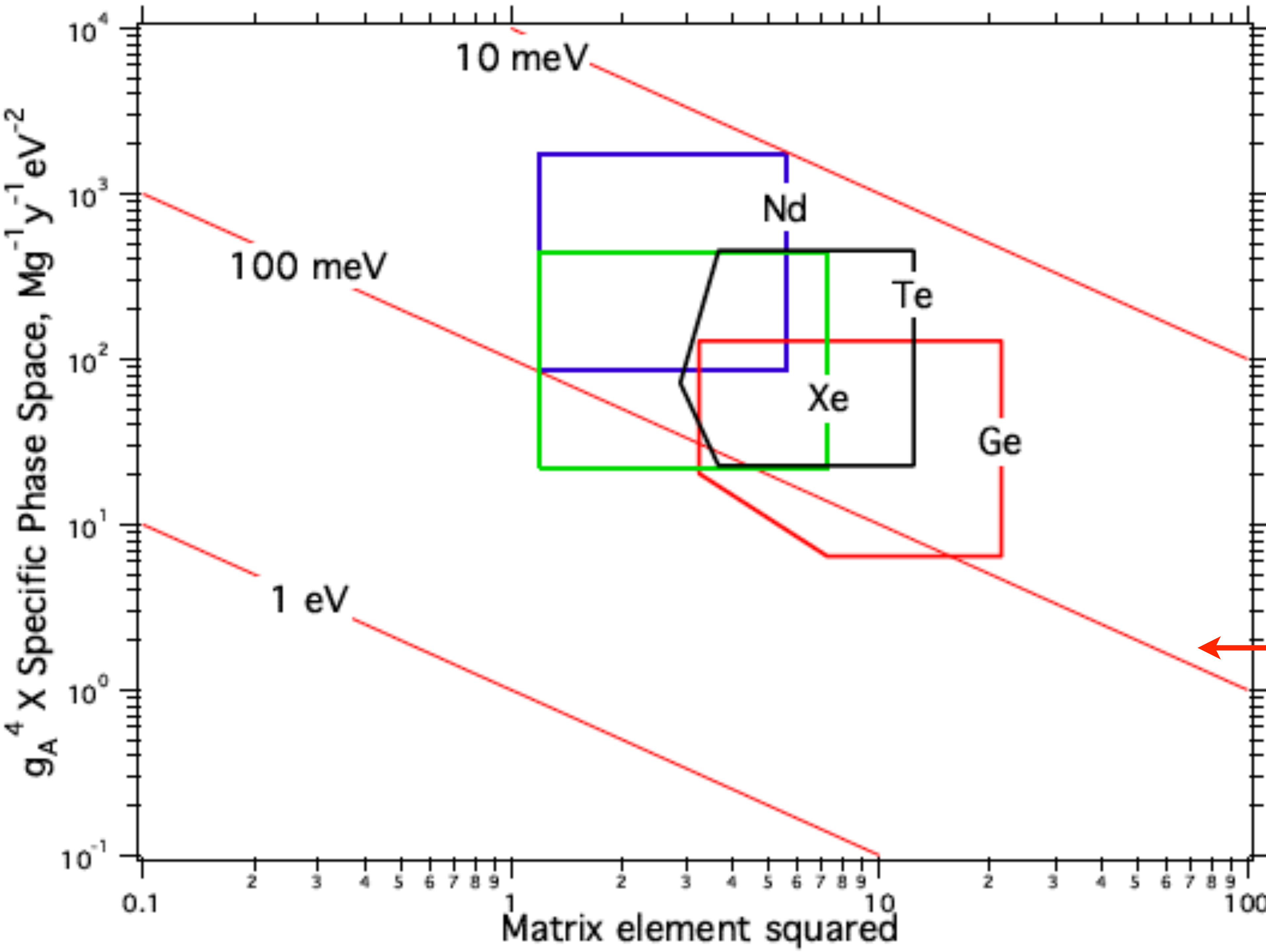
backgrounds do not always scale with detector mass

Favorite Isotope?

For Ge, Te, Xe, Nd

uncertainty on NME^2

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



uncertainty on value of $g_A{}^4$

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

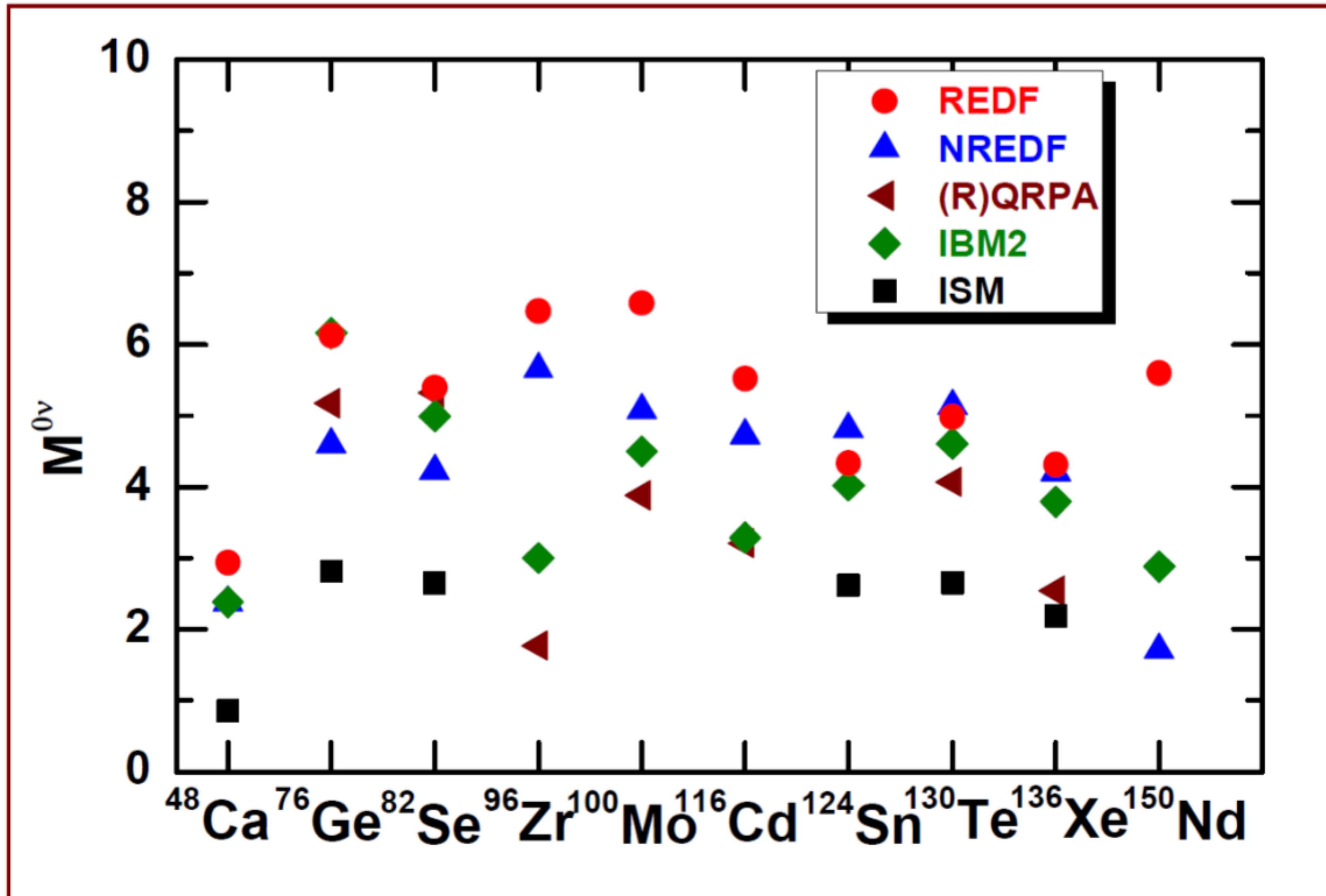
J. Engel

NME Current Status

For light neutrino exchange

Significant spread. And all the models could be missing important physics.

Uncertainty hard to quantify.



One must do different calculations if other mechanisms are in play

The Experimental Challenge

0νββ source with

- high isotopic abundance

Detector with

- high detection efficiency
- good energy resolution
- low-background

Experiment

- long exposure time
- large total mass of isotope

$$T^{0\nu}_{1/2} \text{ sensitivity} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

a = source isotopic abundance

ϵ = detection efficiency

M = total mass

t = exposure time

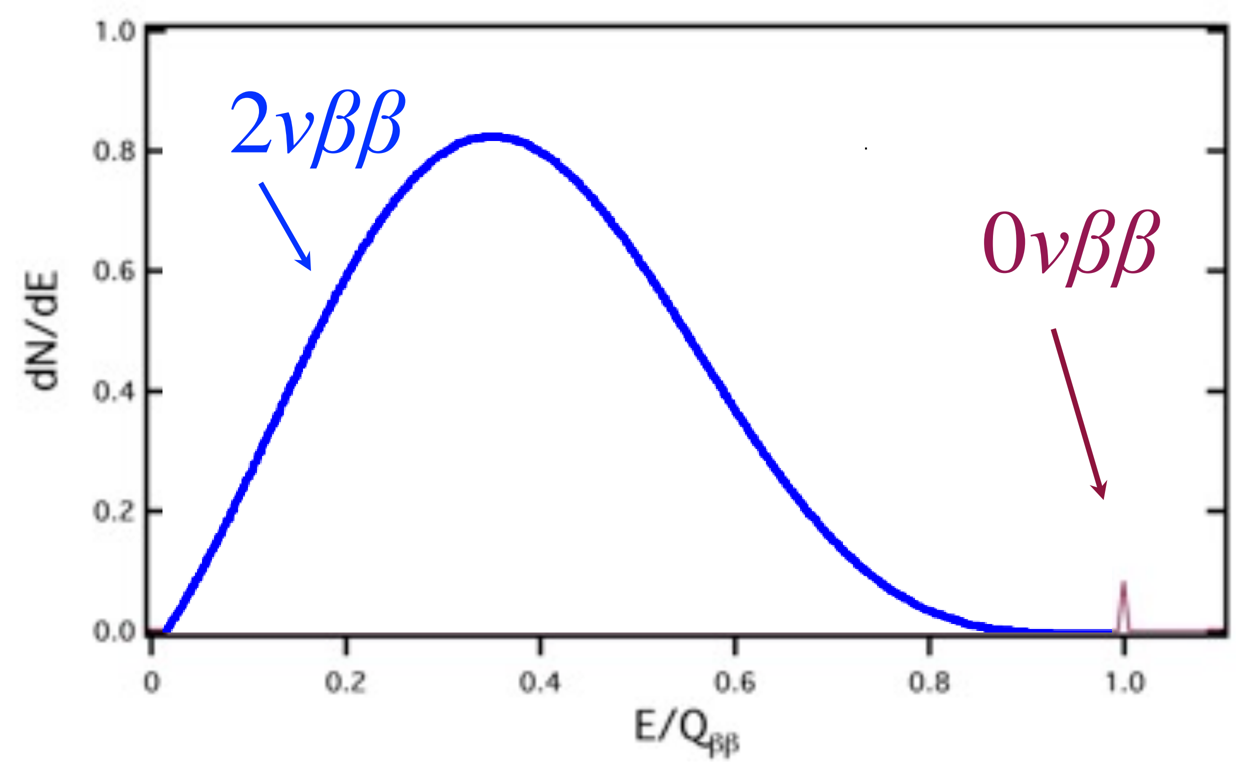
b = background rate at $0\nu\beta\beta$ energy

δE = energy resolution

To reach 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)



Background Strategies

Potential Backgrounds

- Primordial, **natural radioactivity** in detector components: U, Th, K
- Backgrounds from **cosmogenic activation** while material is above ground ($\beta\beta$-isotope or shield specific, ^{60}Co, ^{3}H...)
- 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), $\beta\beta$-decay specific(n,n),(n,γ), direct μ
- **2 neutrino double beta decay** (irreducible, E resolution dependent)
- neutrino backgrounds (negligible)

Reduce Backgrounds

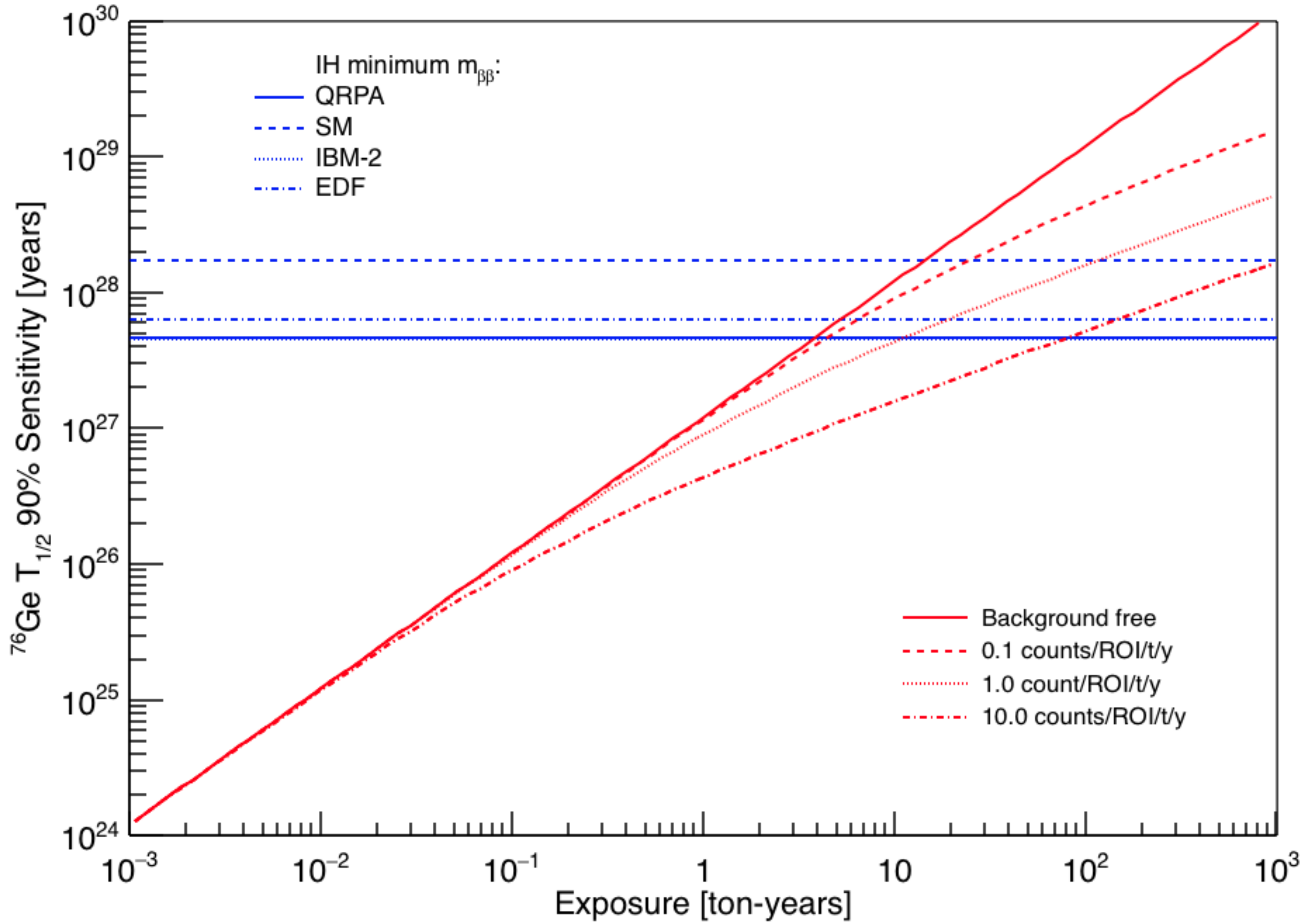
- ultra-pure materials
- shielding
- deep underground
- …

Discriminate Backgrounds

- energy resolution
- tracking (even topology)
- fiducial fits
- pulse shape discrimination (PSD)
- particle ID
-…

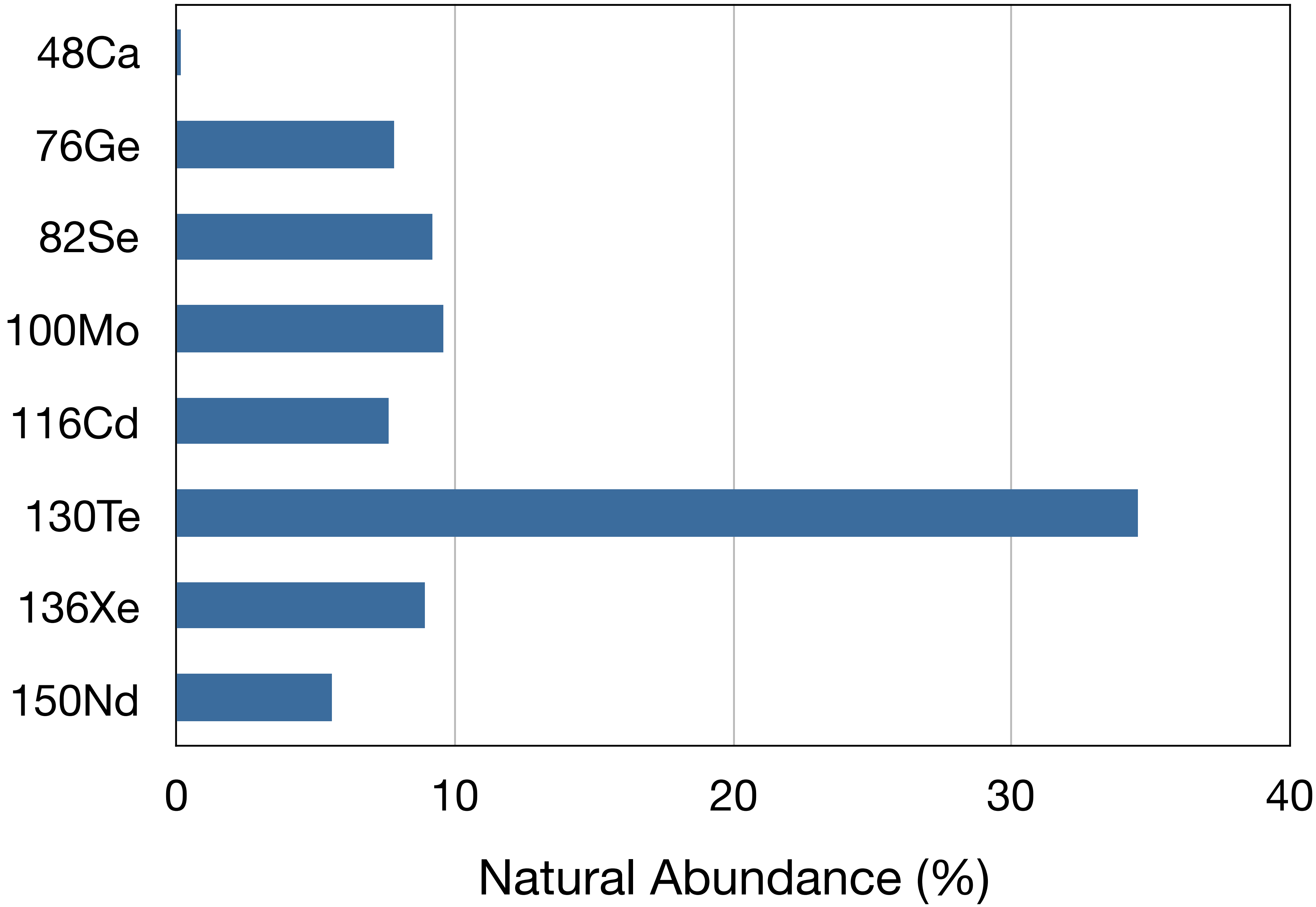
Sensitivity vs Exposure

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



J. Detwiler

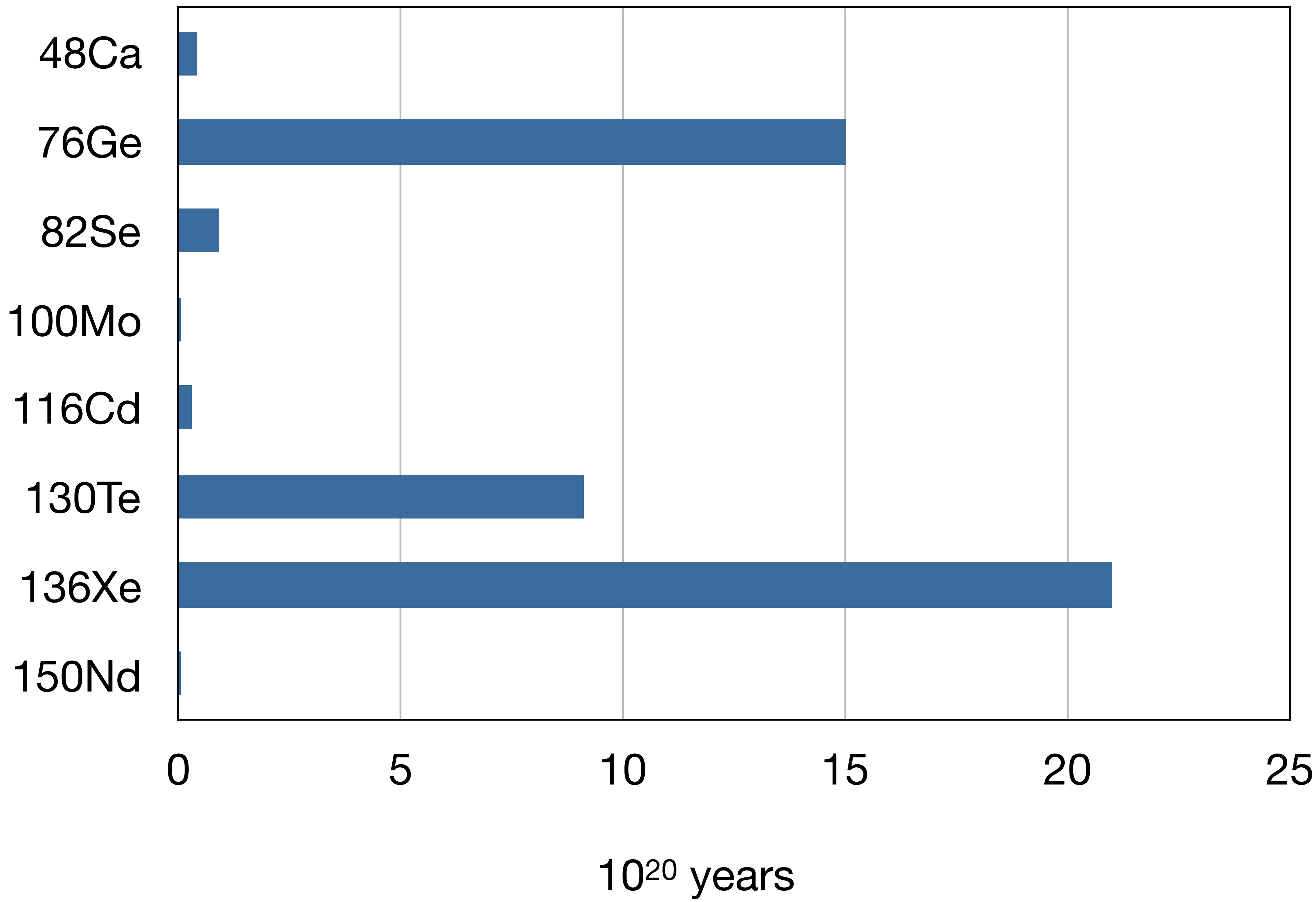
Natural Abundances



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

2nu Half-Life

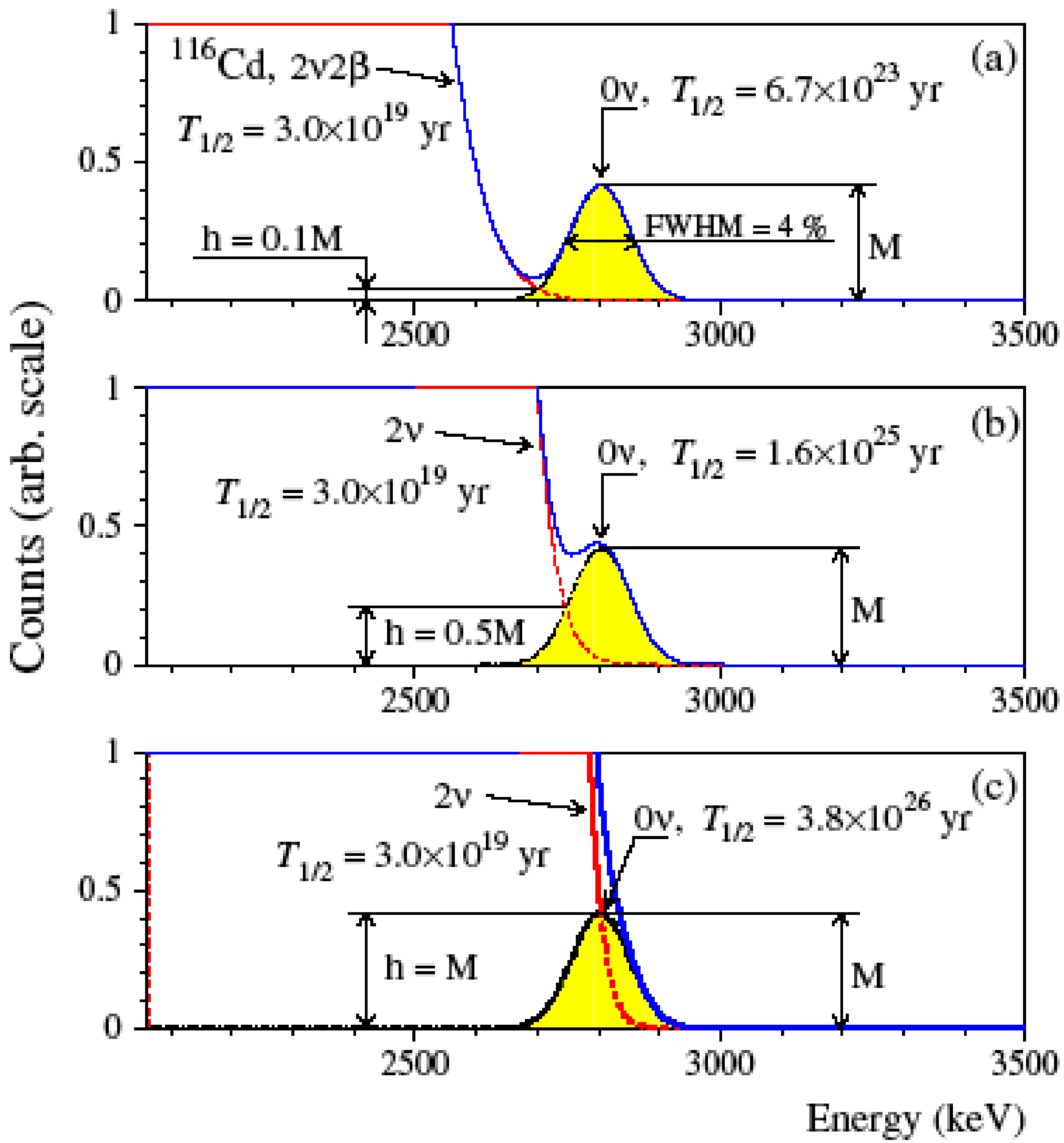


ββ Isotope	2νββ $T_{1/2}$ 10^{20} years
^{48}Ca	0.44
^{76}Ge	15
^{82}Se	0.92
^{100}Mo	0.07
^{116}Cd	0.29
^{130}Te	9.1
^{136}Xe	21
^{150}Nd	0.08

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

Irreducible background ⇒ minimize with good resolution

Effect of Resolution

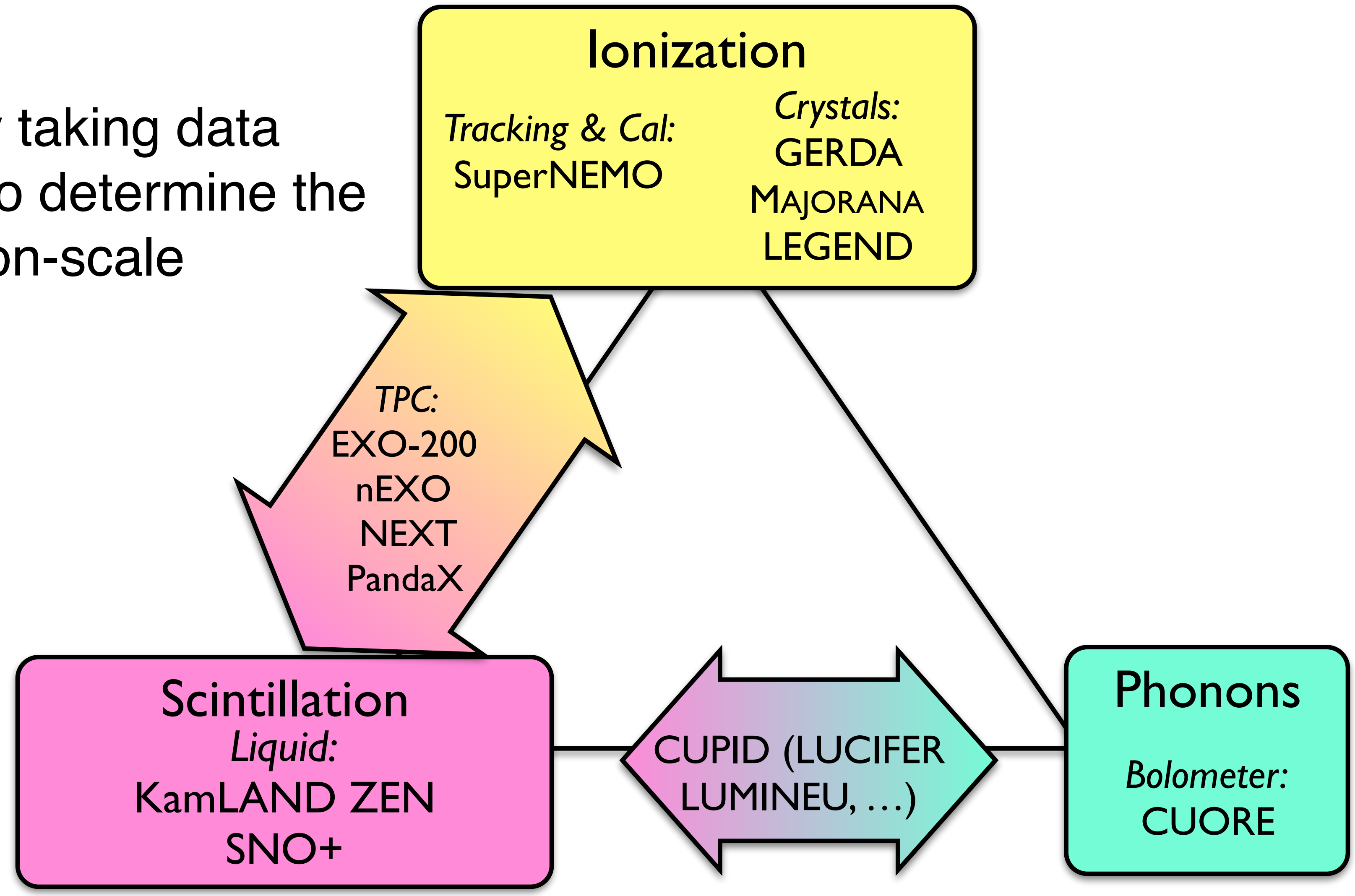


From Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

Multi-Prong Detection Strategy

- 100 kg class experiments currently taking data
- In parallel, major R&D under way to determine the optimum path to discovery at the ton-scale

Best:
source = detector!
^{76}Ge, ^{130}Te, ^{136}Xe



- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms
- If light Majorana neutrinos are responsible for $0\nu\beta\beta$, then absolute neutrino mass scale determination within reach of ton-scale experiments

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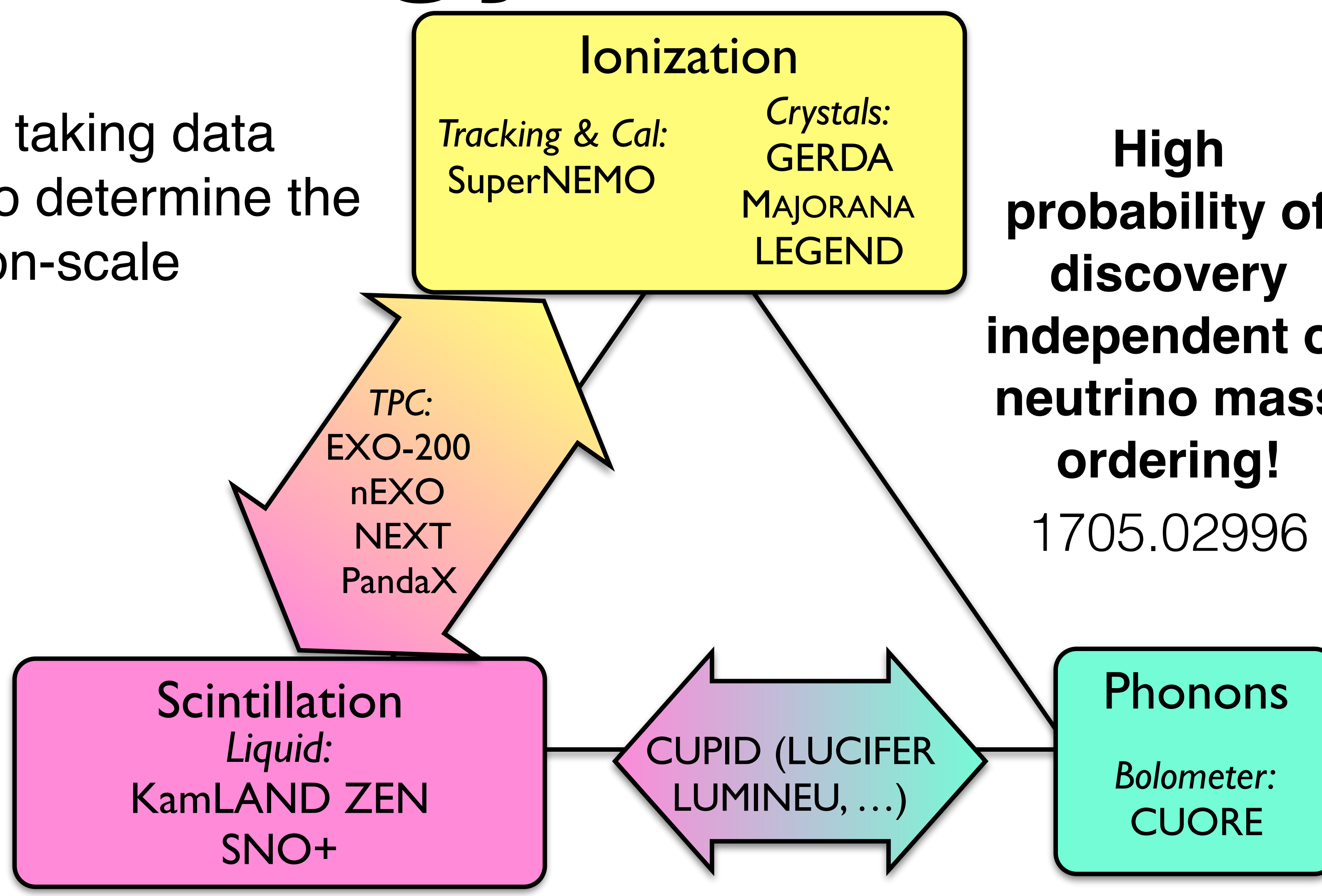

High probability of discovery independent of neutrino mass ordering!
1705.02996

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J. Wilkerson

International Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

1980 - 2007

2007 - 2018

2016 - 2025

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If $0\nu\beta\beta$
Observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

200-500 kg scale

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Inverted hierarchy
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(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

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If $0\nu\beta\beta$ Observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

~ tonne scale

1980 - 2007 | 2007 - 2018 | 2016 - 2025

J. Wilkerson

International Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}\text{-}10^{26}$ y
(~100 meV)
30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}\text{-}10^{28}$ y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

Normal hierarchy
~5 meV
≥10's ton scale

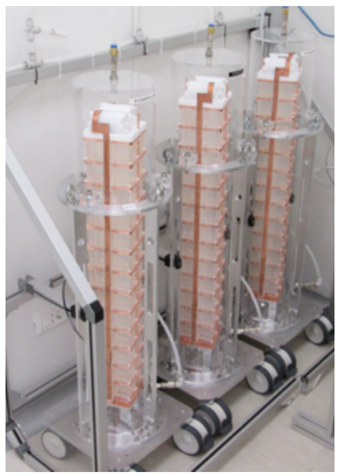
1980 - 2007

2007 - 2018

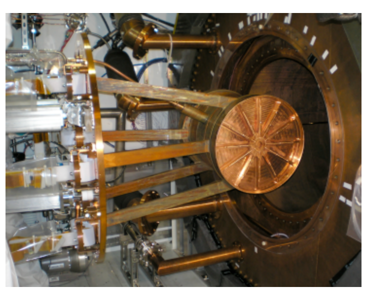
2016 - 2025

World Program

CUORE



EXO200

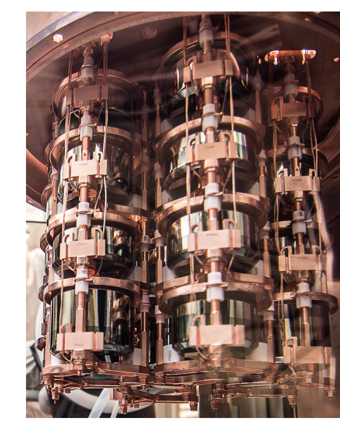


KamLAND Zen

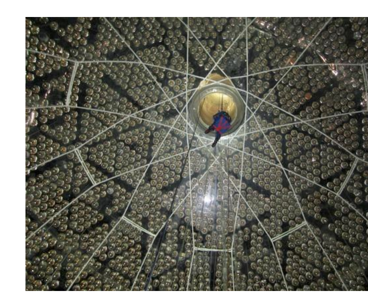
Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	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+



Ton Scale Experiments

- Active international collaborations building on current efforts.
  - **^{76}Ge :** LEGEND, HPGE crystals, ~ton (builds on GERDA & MAJORANA)
  - ^{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
    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
    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

EXO-200

Advantages of Xenon

Isotopic enrichment easier & known: ***Xe is a gas and ^{136}Xe is the heaviest isotope.***

Xenon is "reusable": ***can be re-purified (noble gas: relatively easy) during measurement and easily recycled into a different detector (no crystal growth)***

.... replace ^{136}Xe with $^{nat'l}$Xe if signal observed

Monolithic detector: ***LXe is self shielding, surface contamination minimized.***

Minimal cosmogenic activation: ***no long lived radioactive isotopes of Xe.***

Energy resolution in LXe improved: ***scintillation light + ionization anti-correlation.***

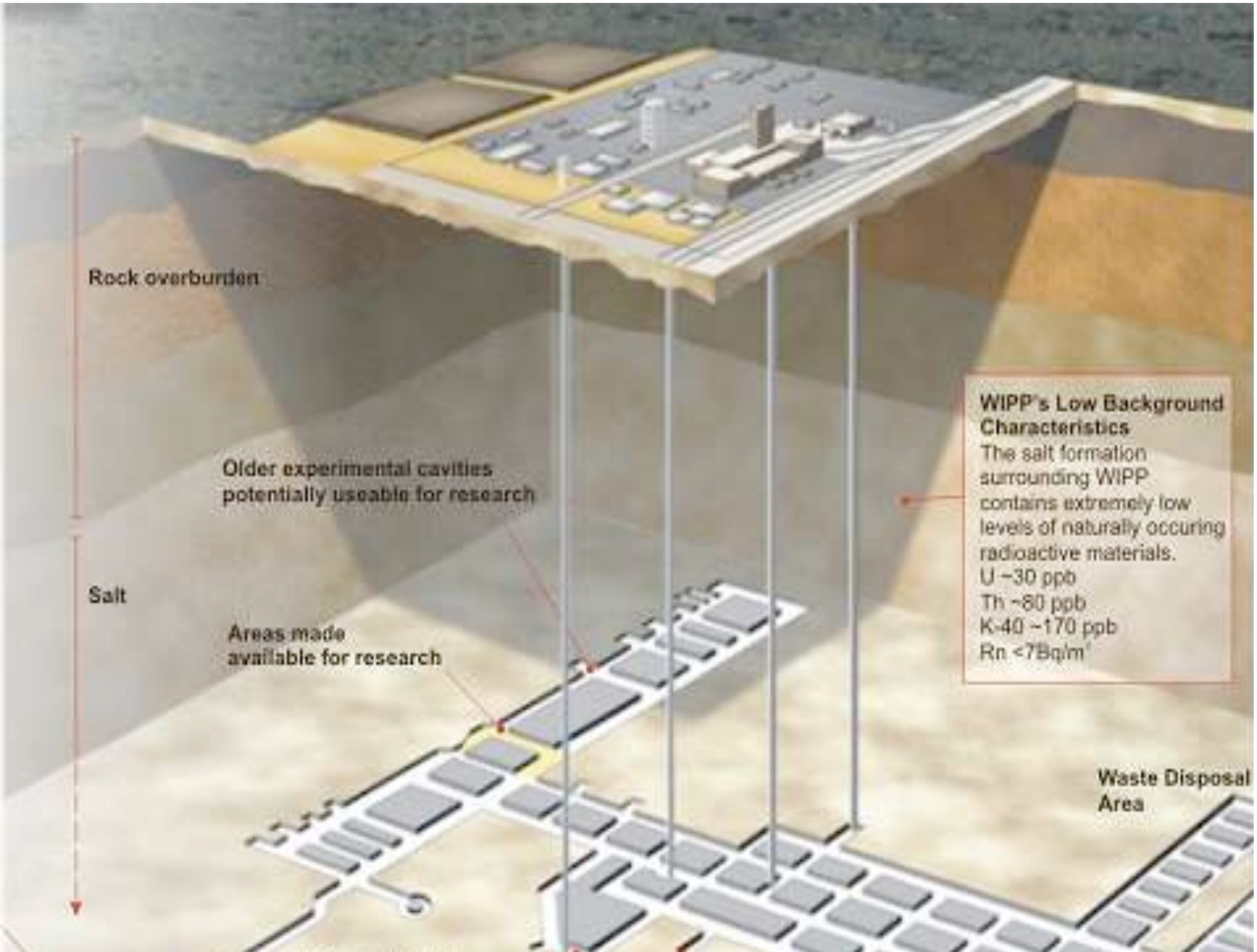
Standard $2\nu\beta\beta$ is slow! (see later): ***get away with modest energy resolution***

… admits a novel coincidence technique: ***background reduction by Ba tagging***

.... potentially access normal hierarchy

Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP



Waste Isolation Pilot Plant, Carlsbad, NM

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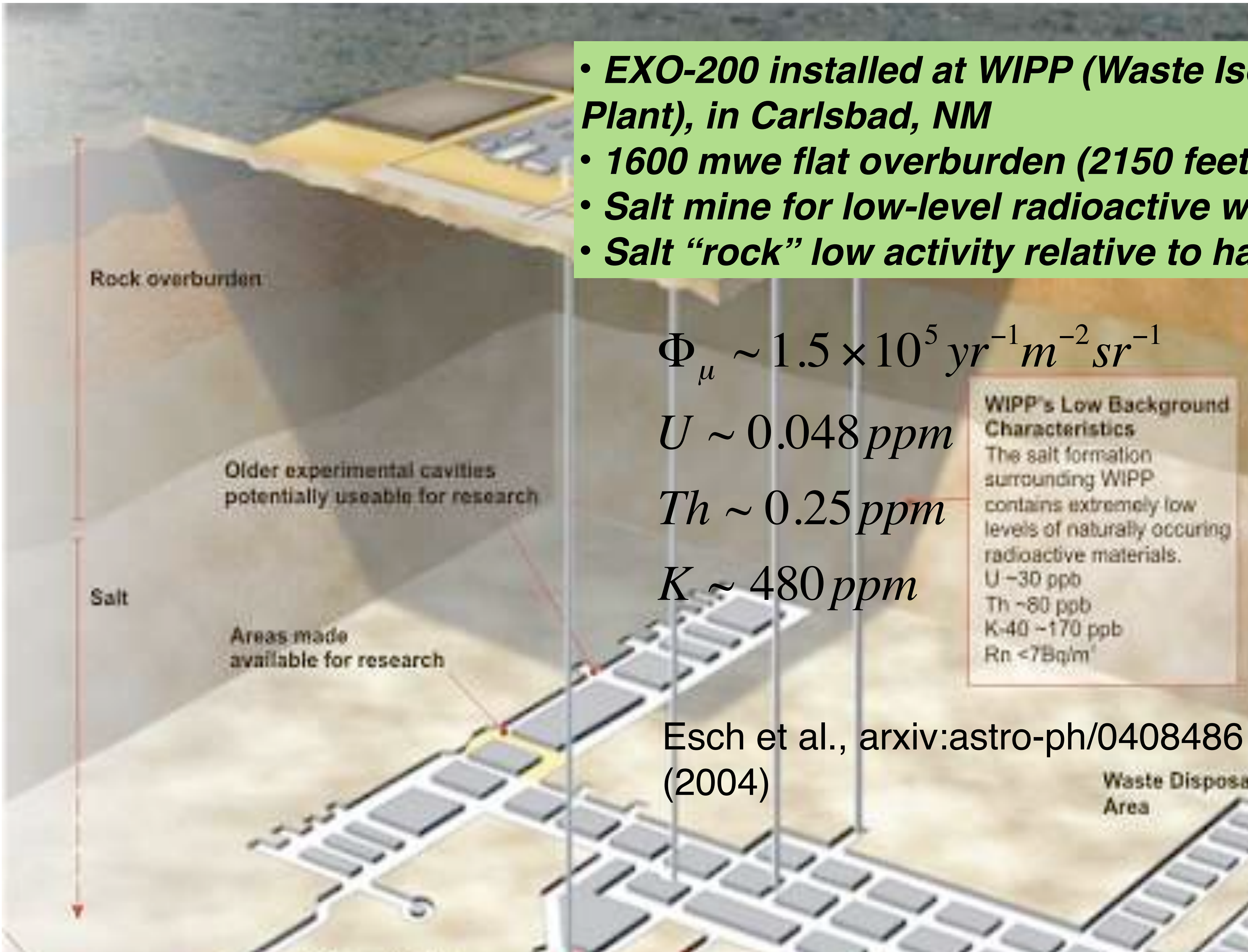


- ***EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM***
- ***1600 mwe flat overburden (2150 feet, 650 m)***
- ***Salt mine for low-level radioactive waste storage***
- ***Salt "rock" low activity relative to hard-rock mine***

$$\Phi_{\mu} \sim 1.5 \times 10^{5}\, yr^{-1} m^{-2} sr^{-1}$$

$$U \sim 0.048\, ppm$$

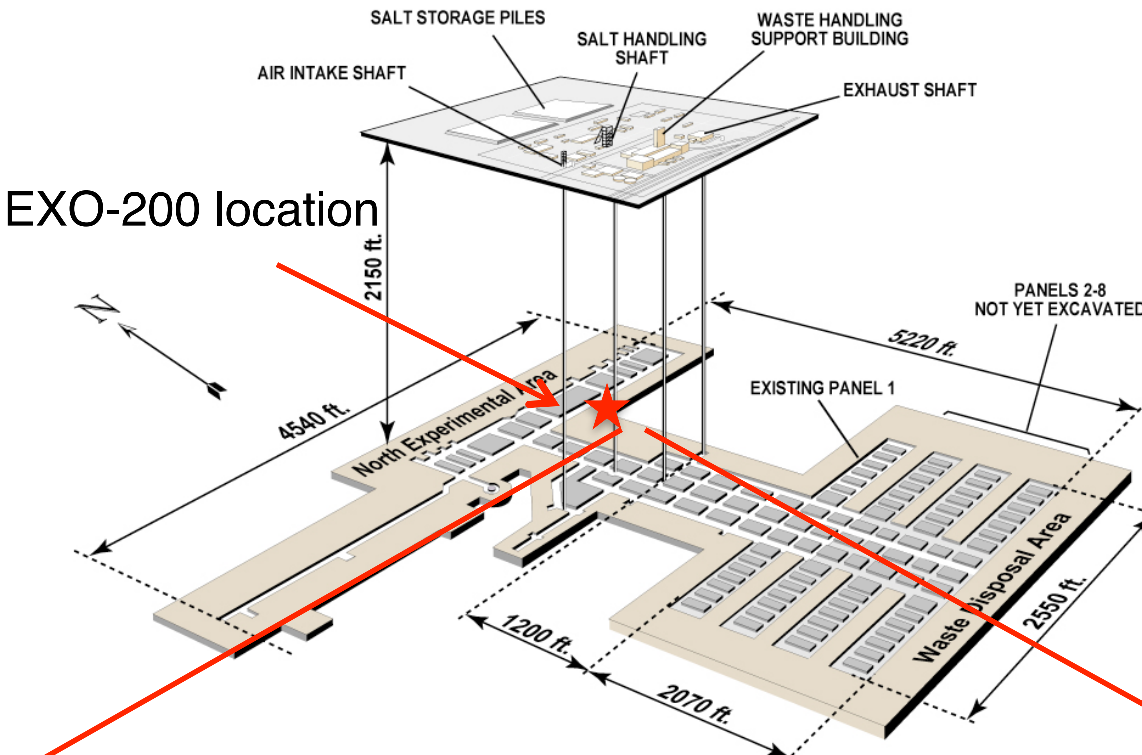
$$Th \sim 0.25\, ppm$$

$$K \sim 480\, ppm$$

Esch et al., arxiv:astro-ph/0408486 (2004)

Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP



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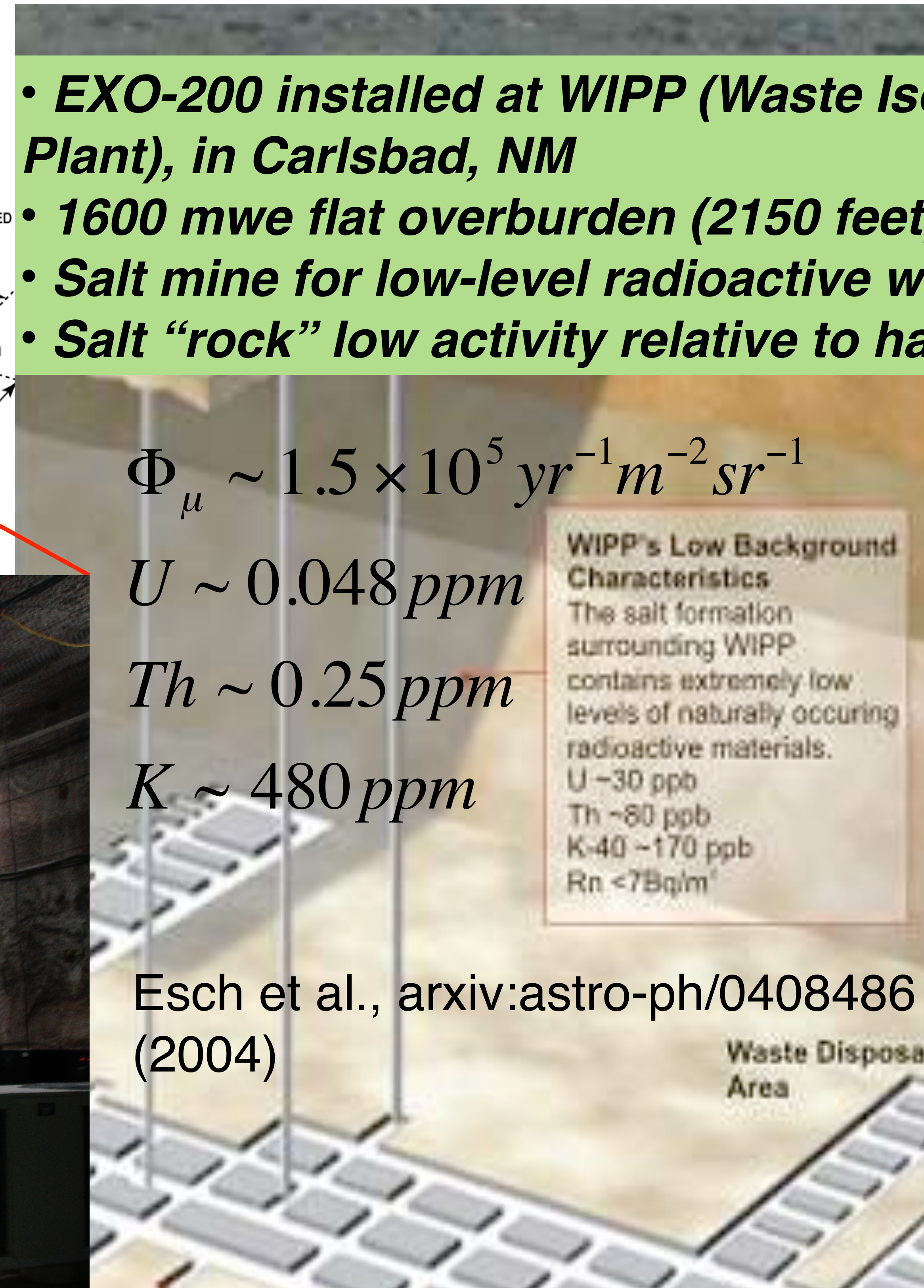

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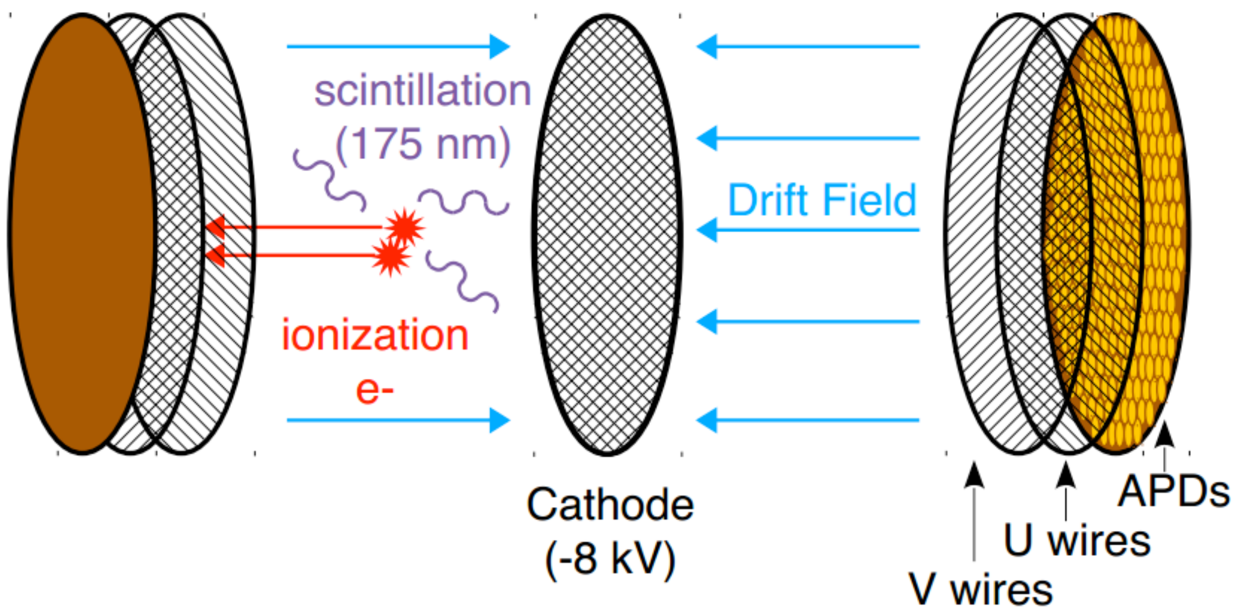
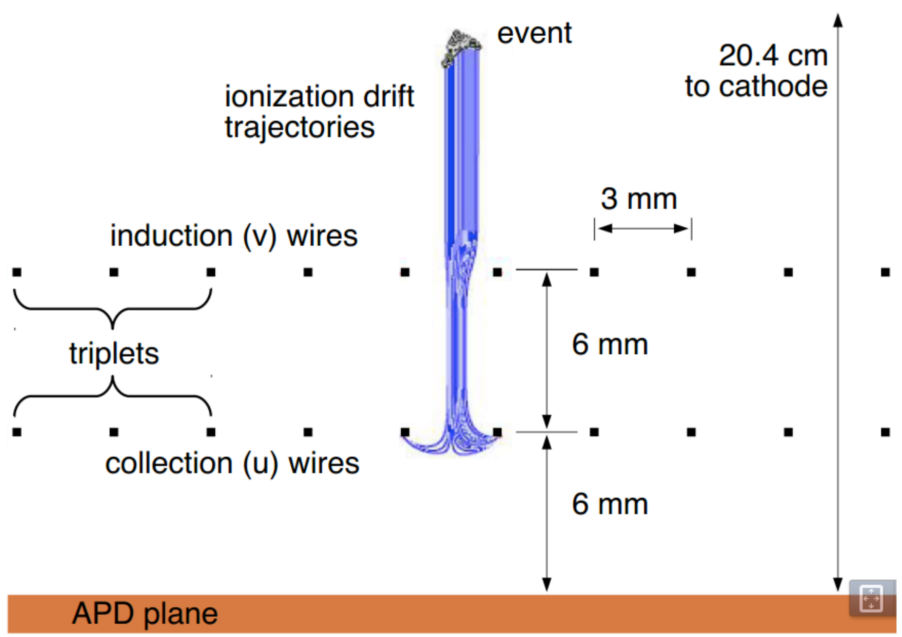
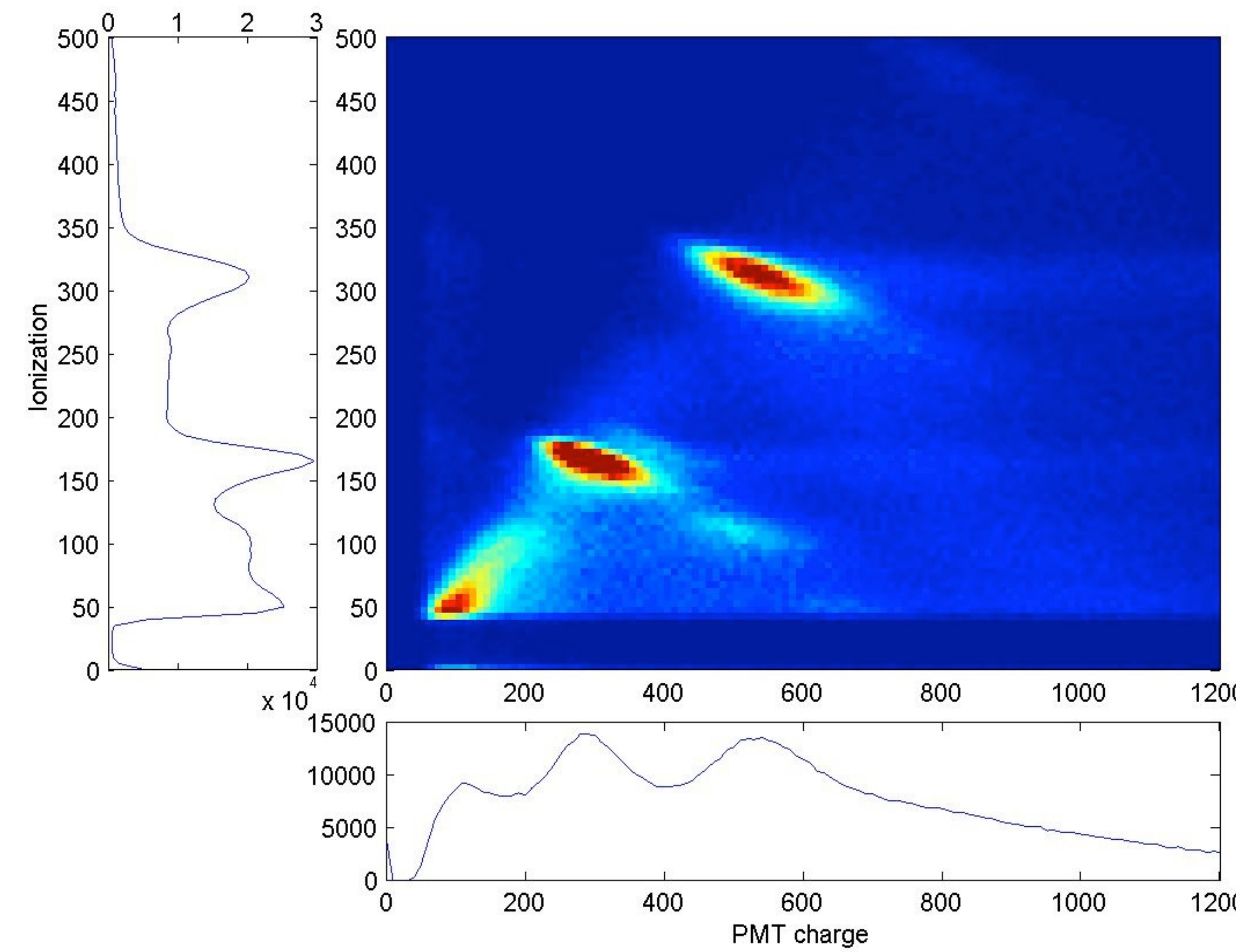
EXO-200 Concept



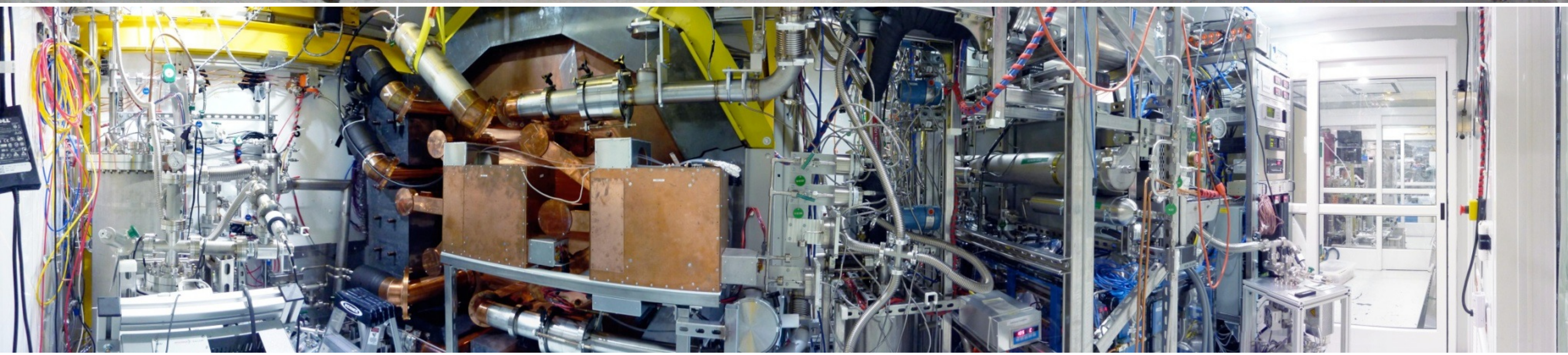
EXO R&D showed the way to improved energy resolution in LXe: Use (anti)correlations between ionization and scintillation signals



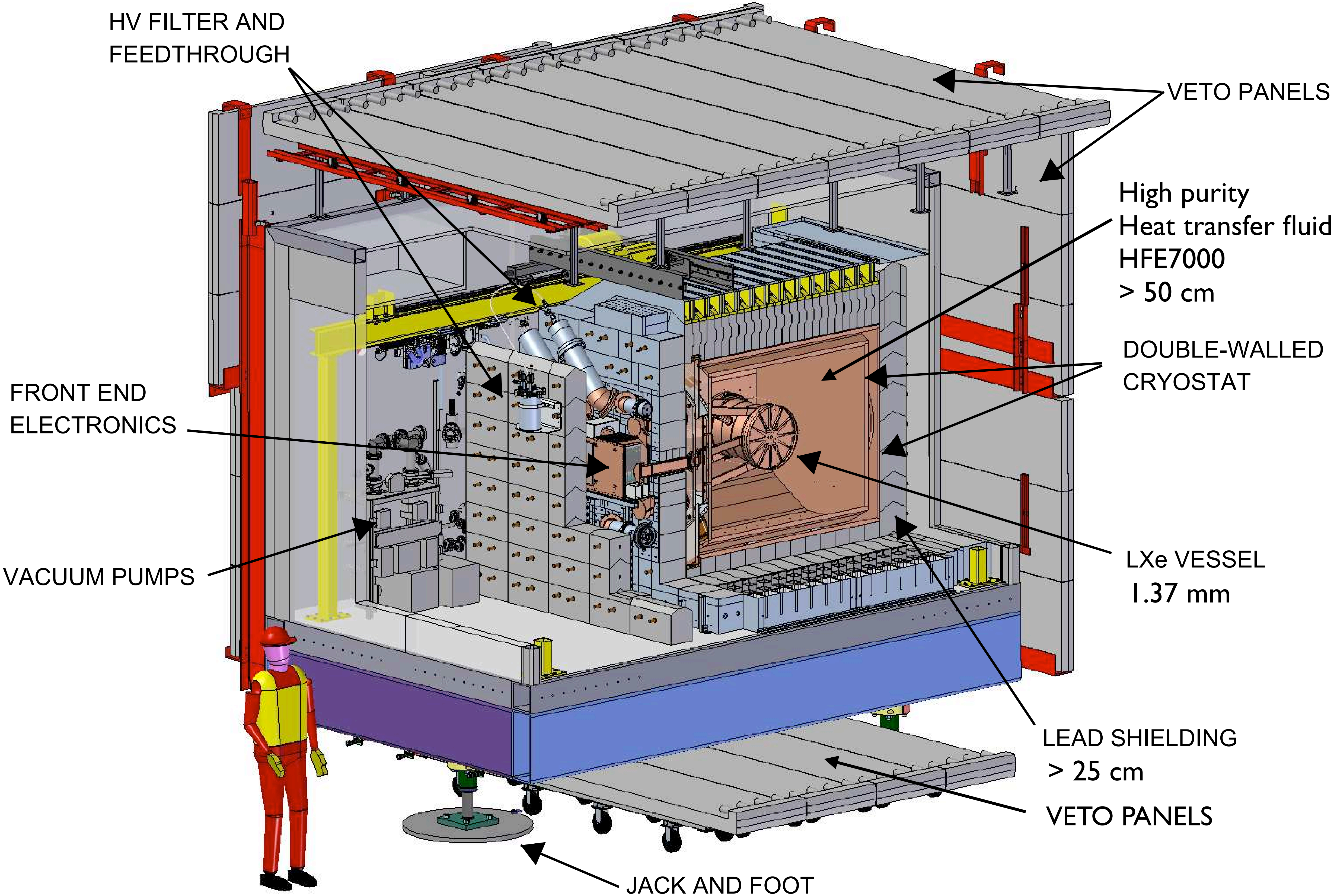


- **Two TPCs with common cathode in middle**
- **APD planes observe prompt scintillation for drift time measurement.**
- **V-position given by induction signal on shielding grid.**
- **U-position and energy given by charge collection grid.**

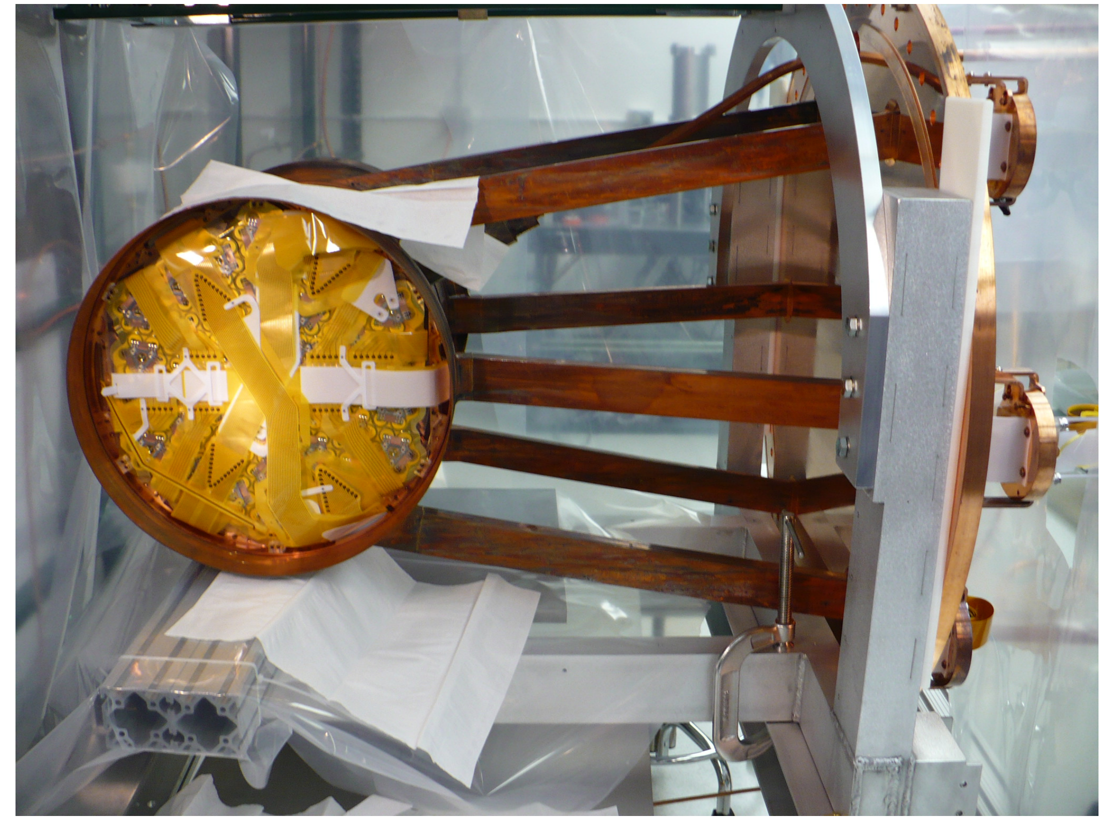
EXO-200 at WIPP



Module 1

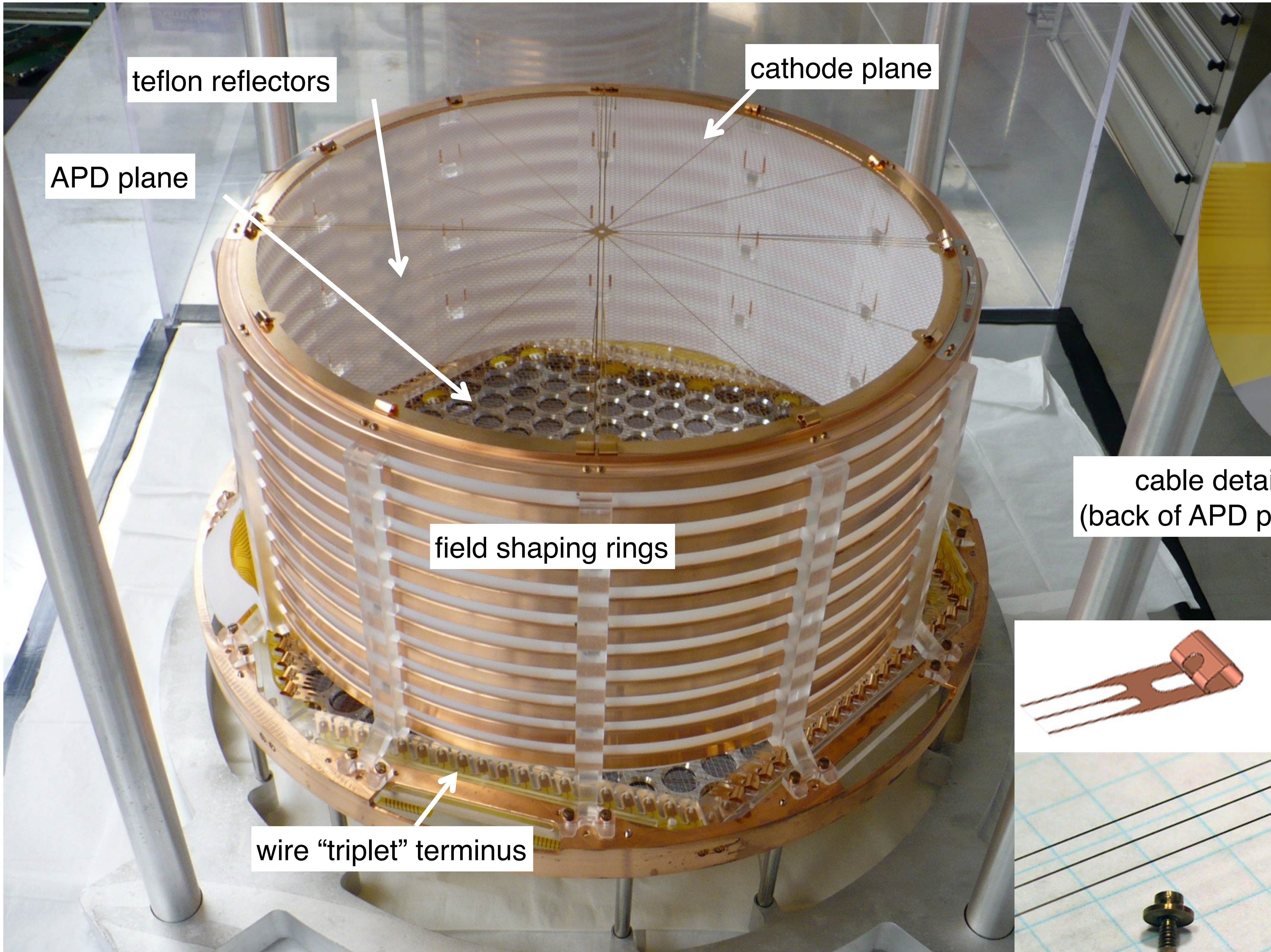

HV FILTER AND
FEEDTHROUGH
VETO PANELS
High purity
Heat transfer fluid
HFE7000
> 50 cm
DOUBLE-WALLED
CRYOSTAT
FRONT END
ELECTRONICS
VACUUM PUMPS
LXe VESSEL
1.37 mm
LEAD SHIELDING
> 25 cm
VETO PANELS
JACK AND FOOT

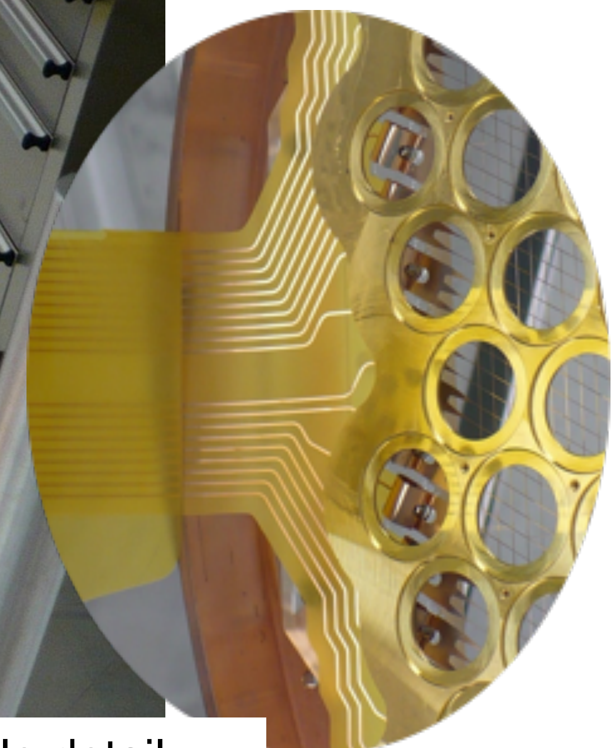
Low Activity Copper

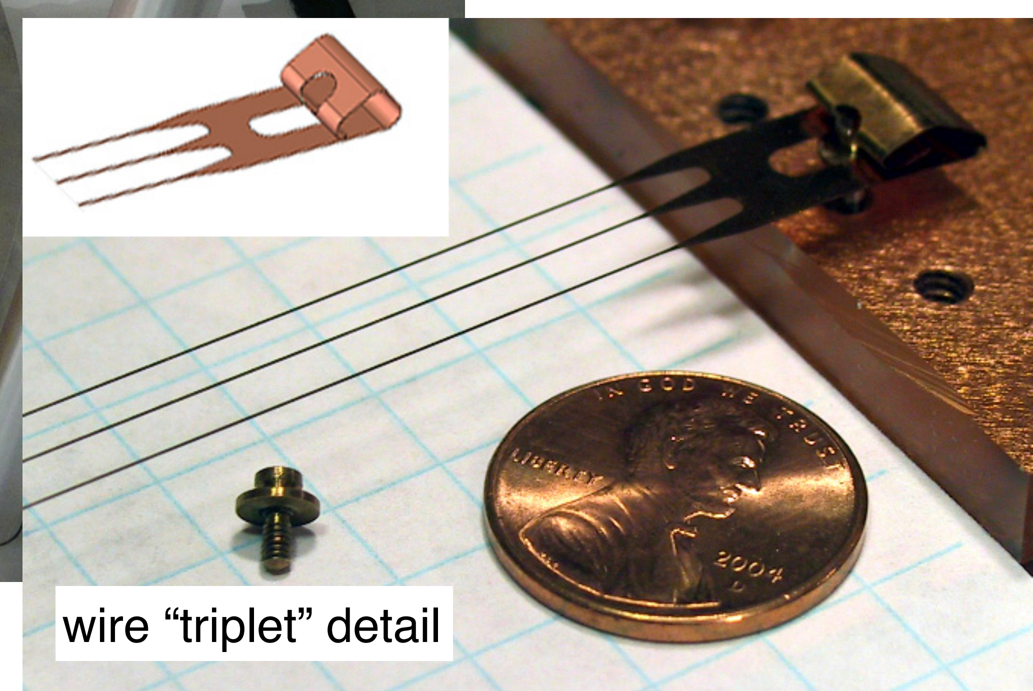


- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done in cosmic-ray shielded building)

TPC: The Innards



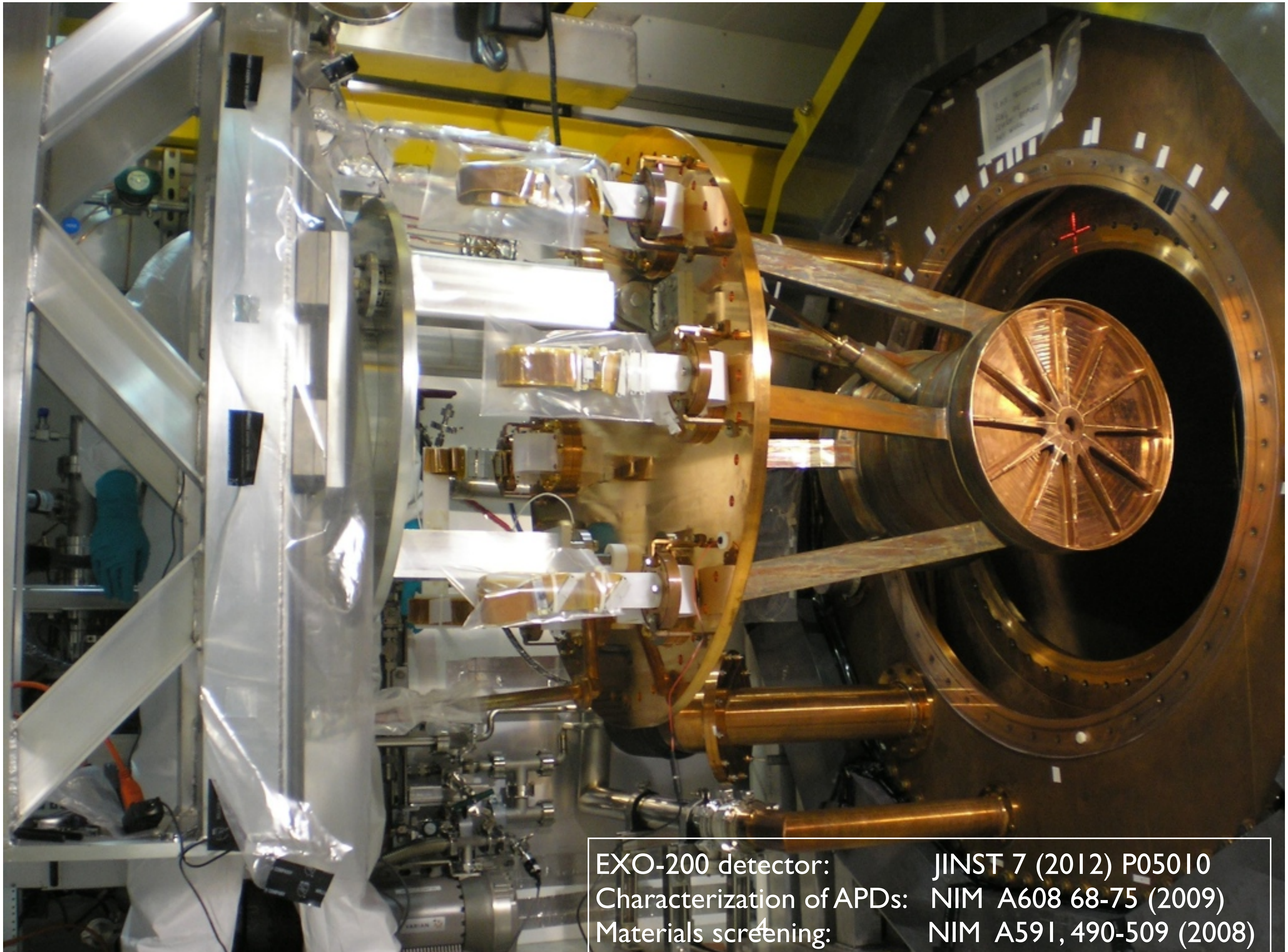




TPC Construction (1 full drift region)

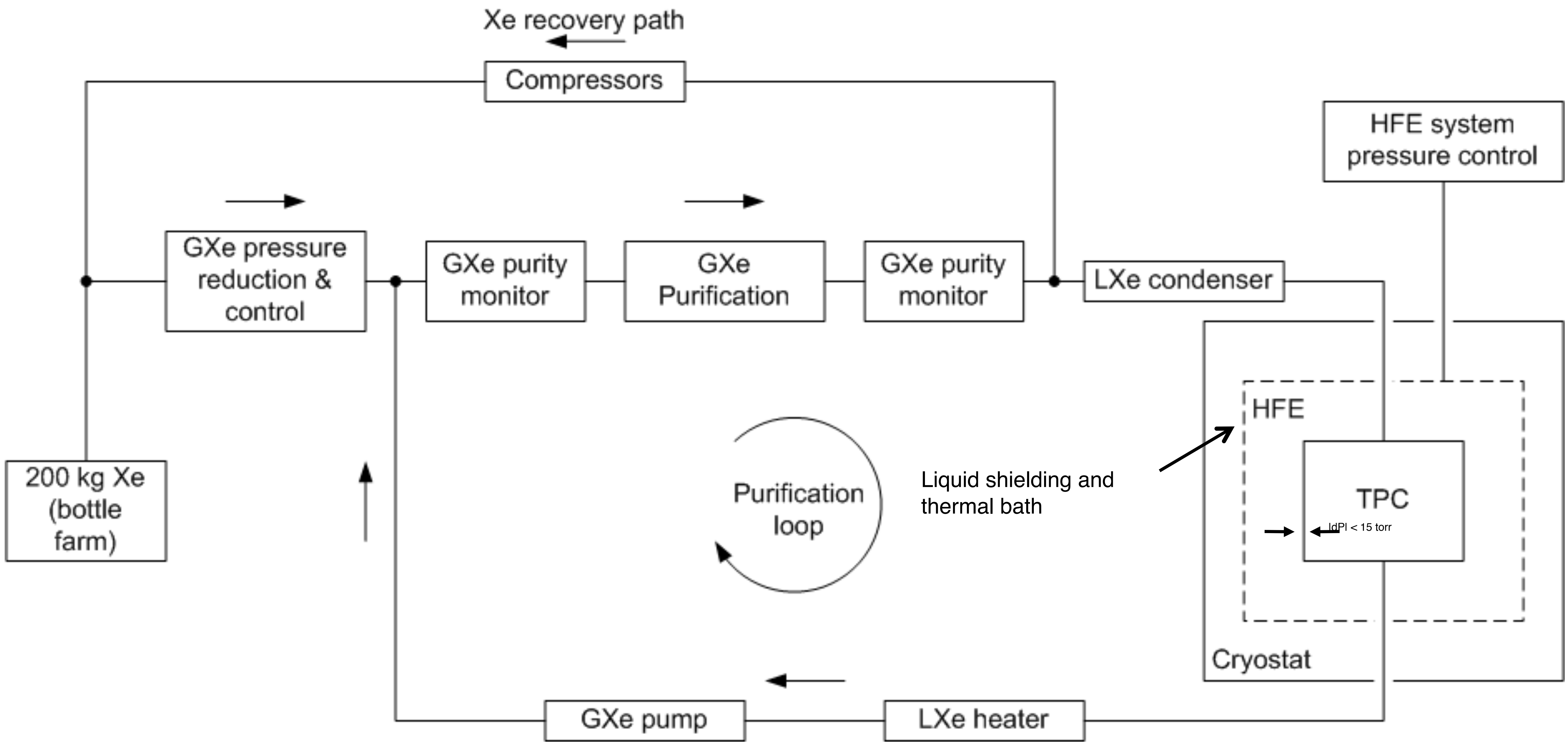
TPC Entering the Cryostat

TPC Entering the Cryostat

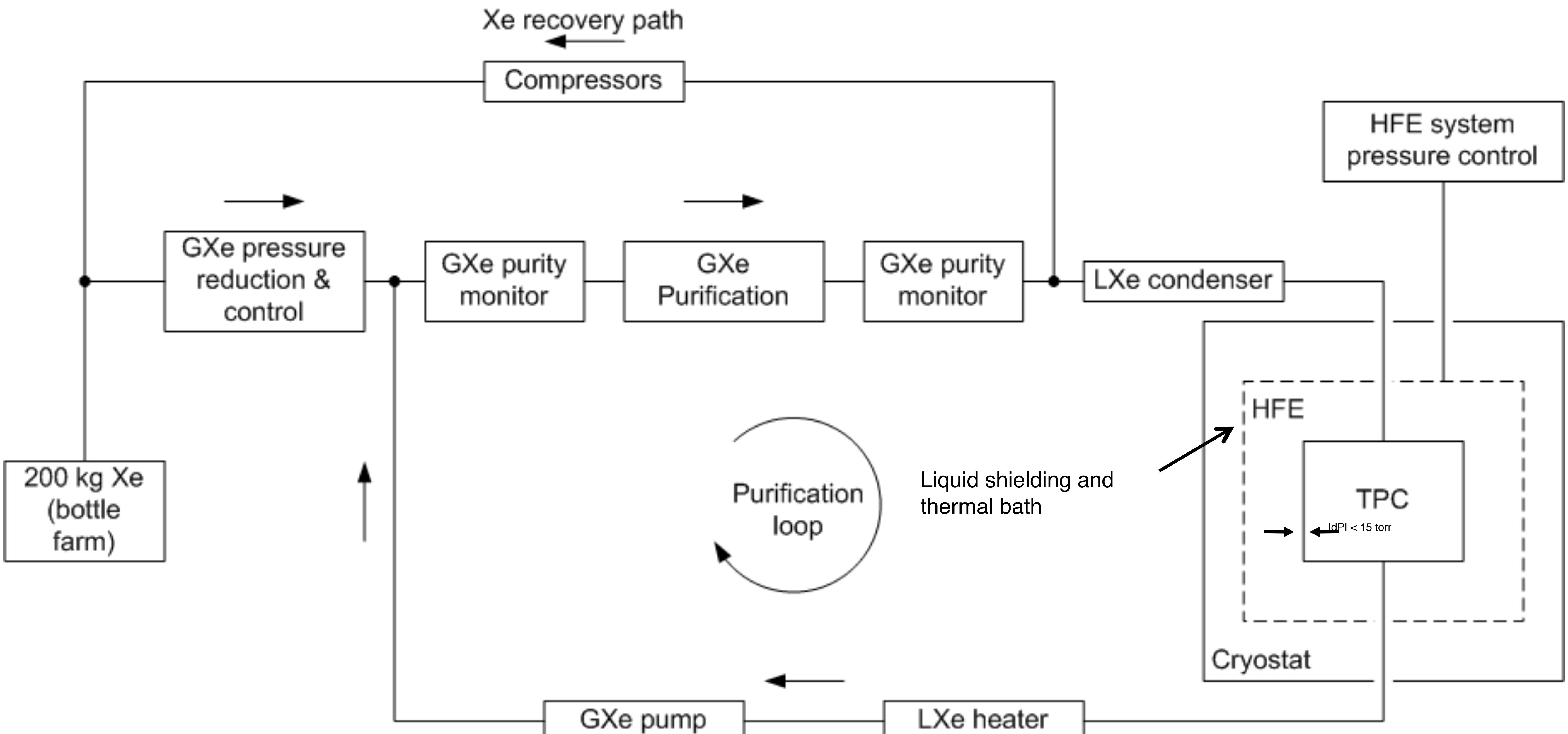


EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

Xenon Recirculation



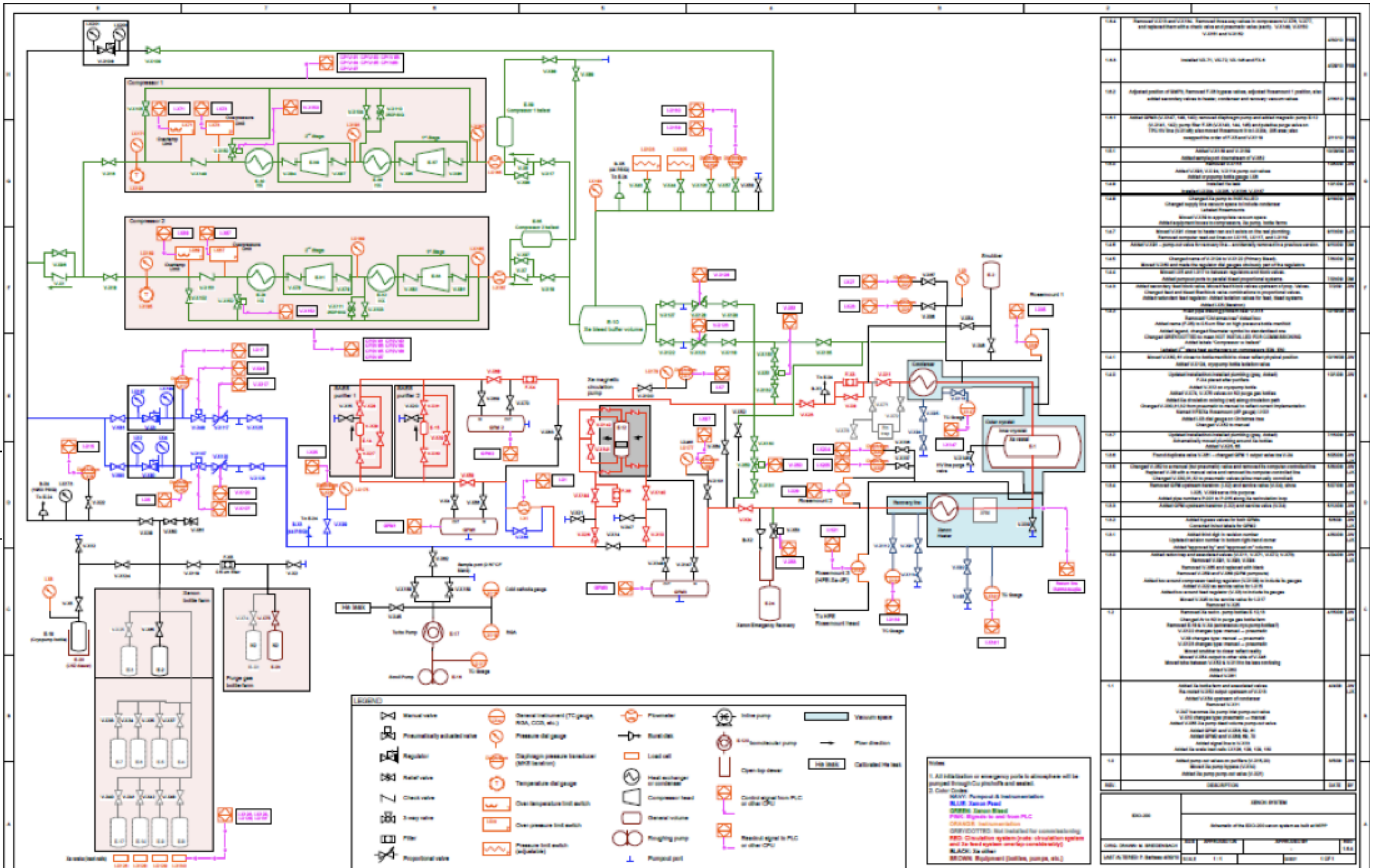
Xenon Recirculation



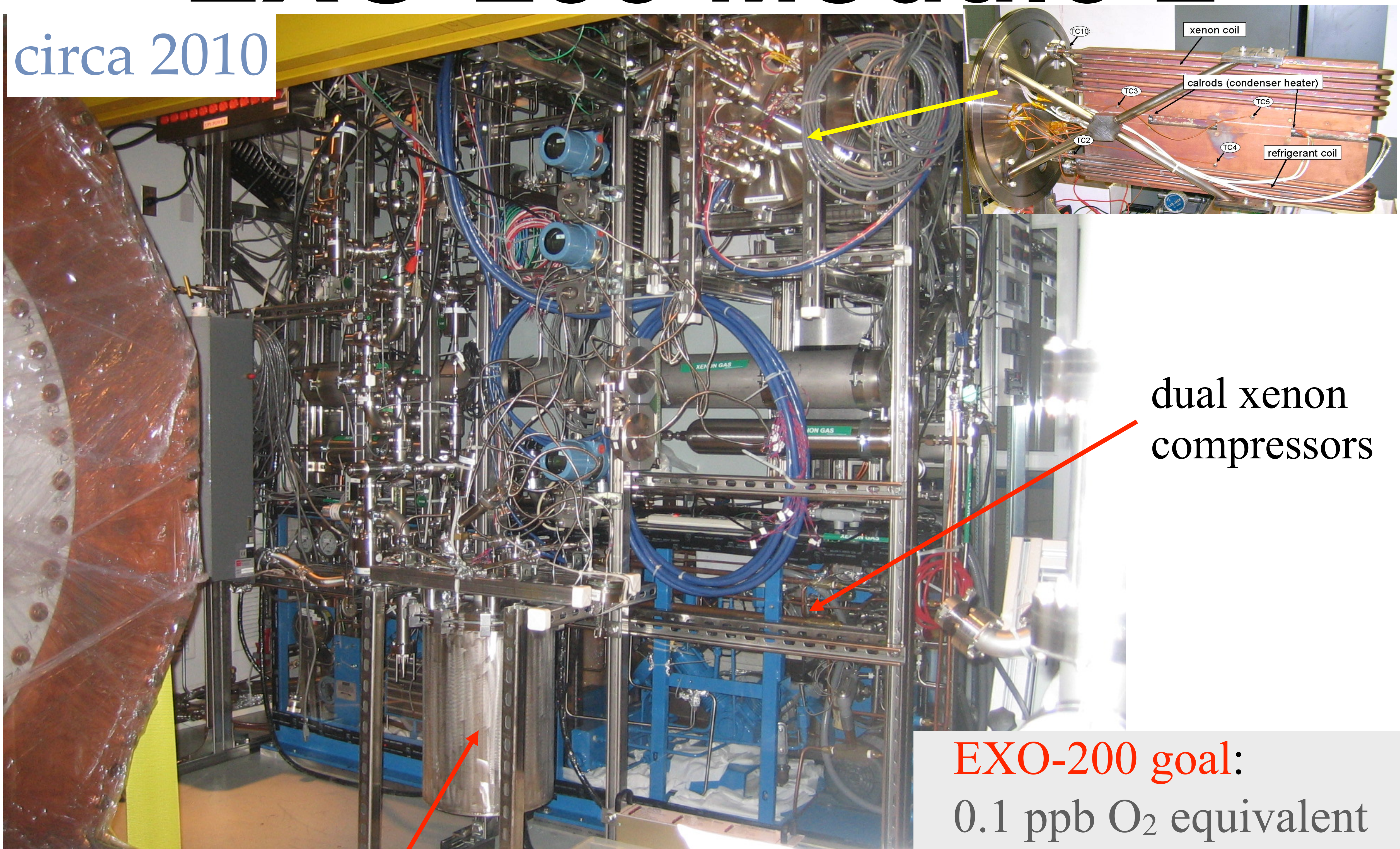
complicating factors:

ultra-radiopurity, emergency recovery, electronic noise environment, thermal stability

Xenon Recirculation



EXO-200 Module 2

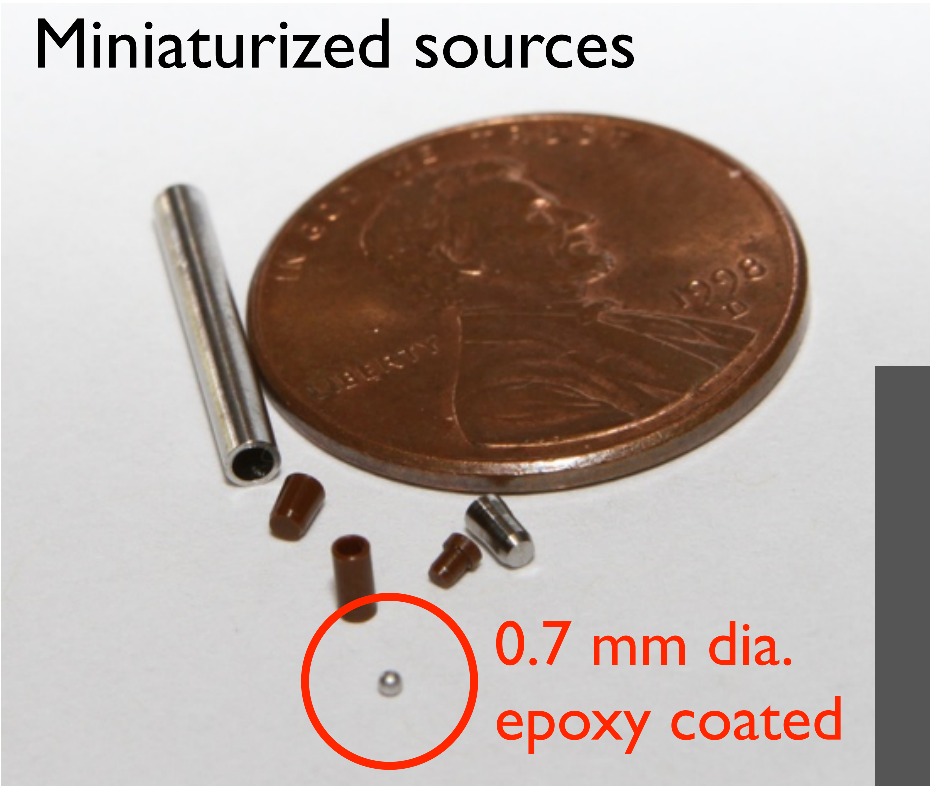


dual xenon compressors

LXe boil-off heater

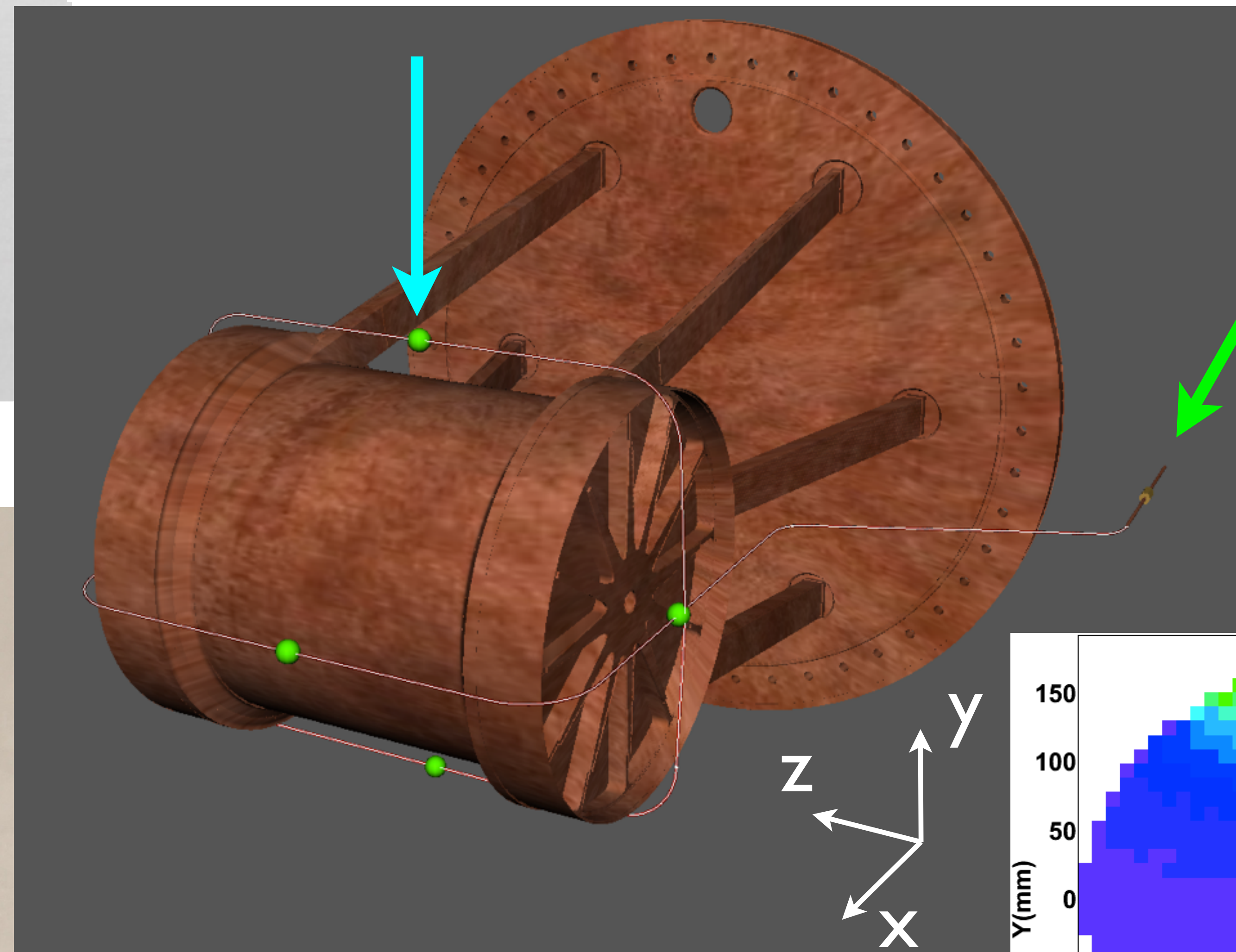
EXO-200 goal:
0.1 ppb O_2 equivalent
(~ 4 ms electron lifetime)

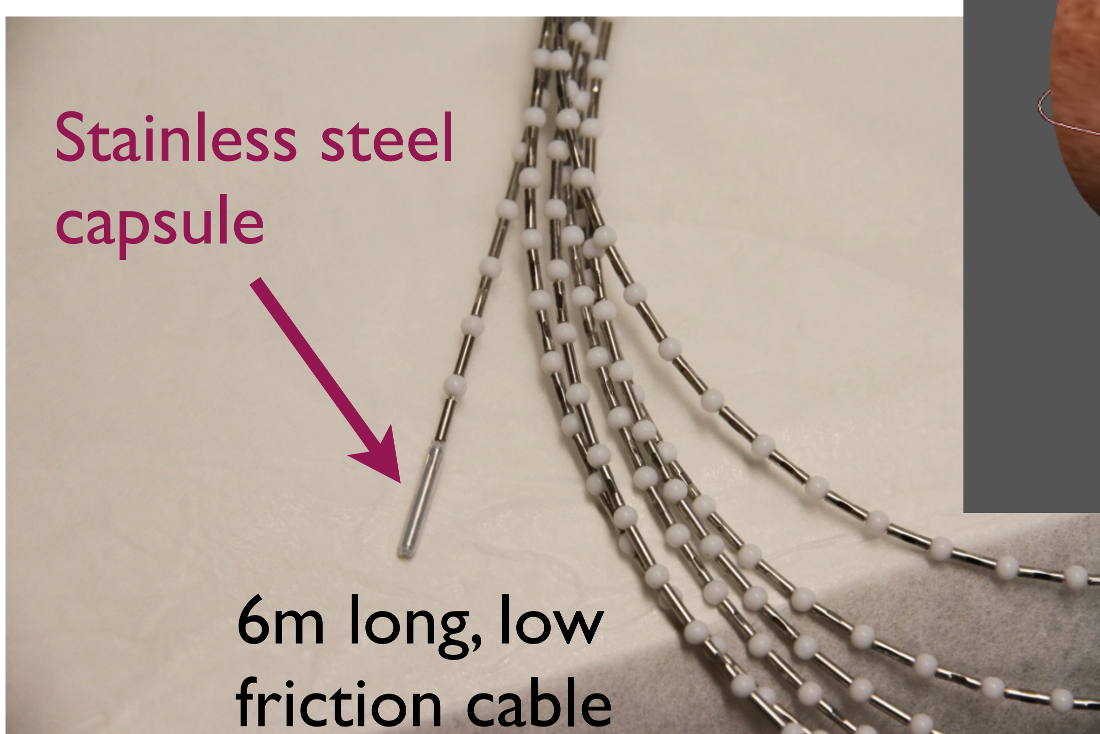
Calibration System



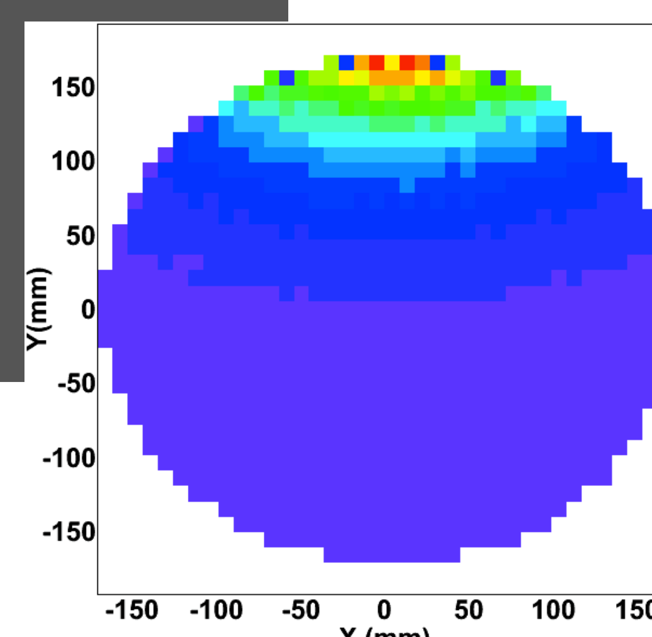
Source	Weak (kBq)	Strong (kBq)
60-Co	3.0	15.0
137-Cs	0.5	7.2
228-Th	1.5	38.0

new ^{226}Ra source also added



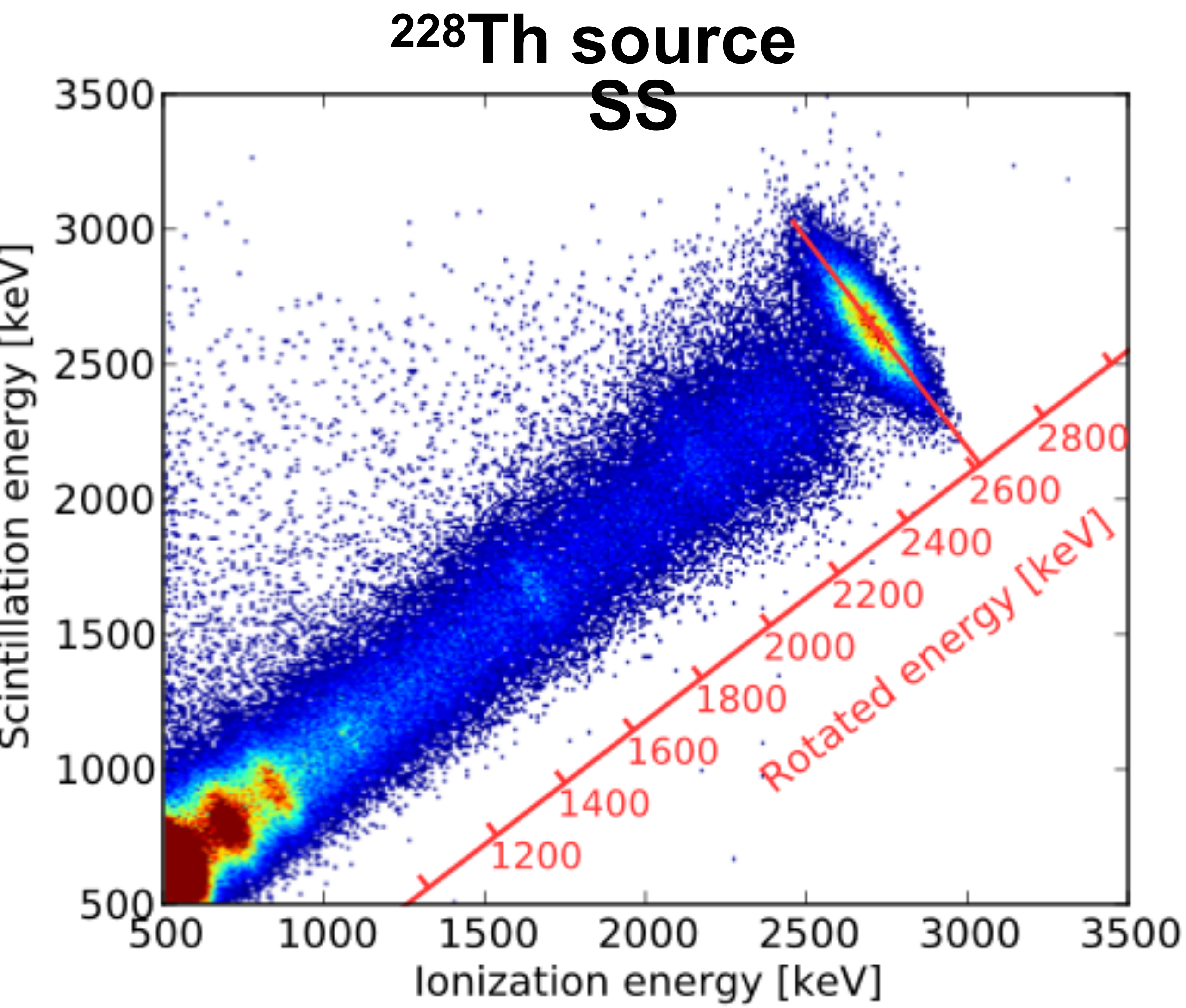


weak ^{228}Th



Provide 4 full energy deposition peaks in the energy range
662 keV – 2615 keV

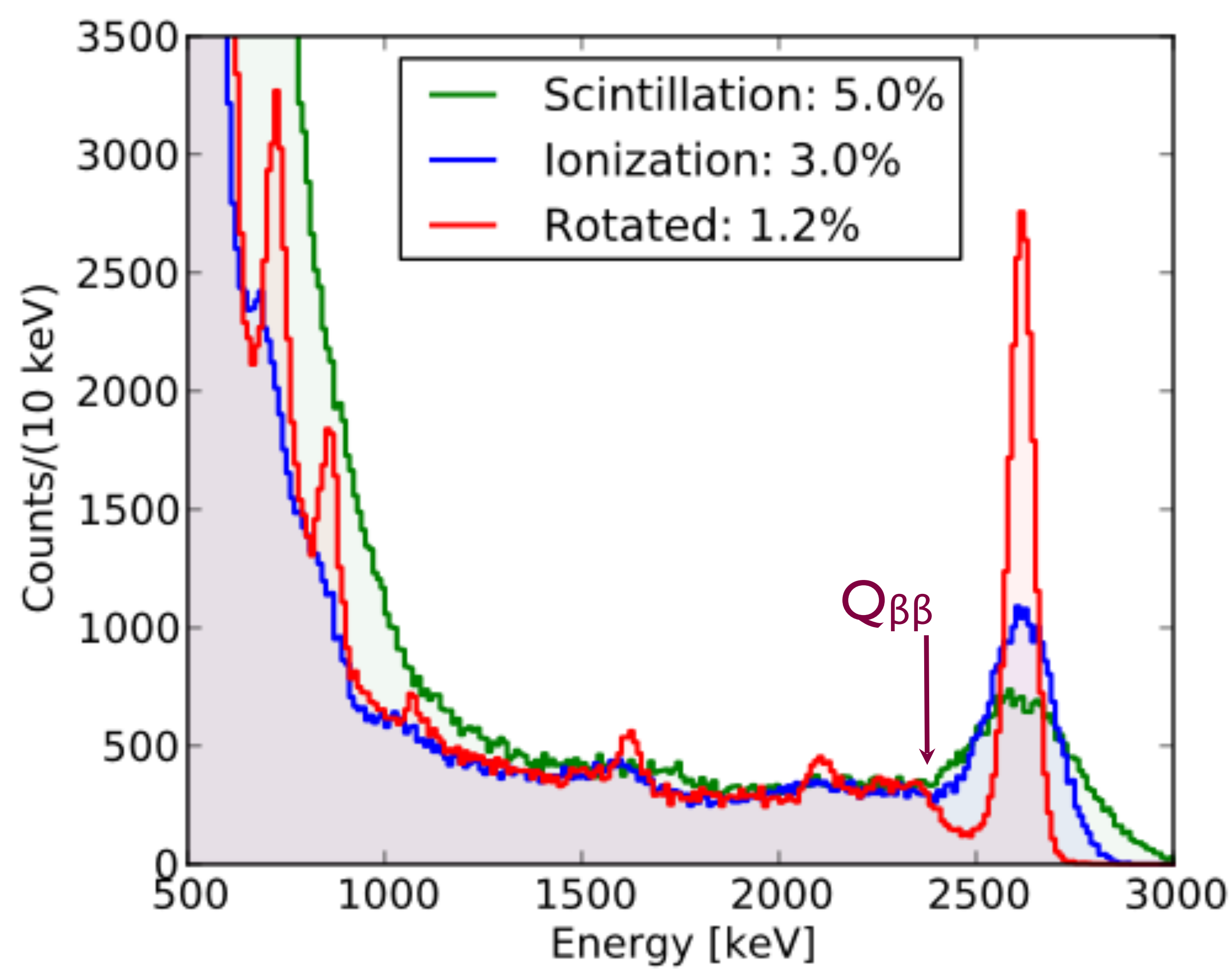
Energy Resolution



Combining Ionization and Scintillation energy to enhance energy resolution

Anti-correlation between scintillation and ionization in LXe known since early EXO R&D

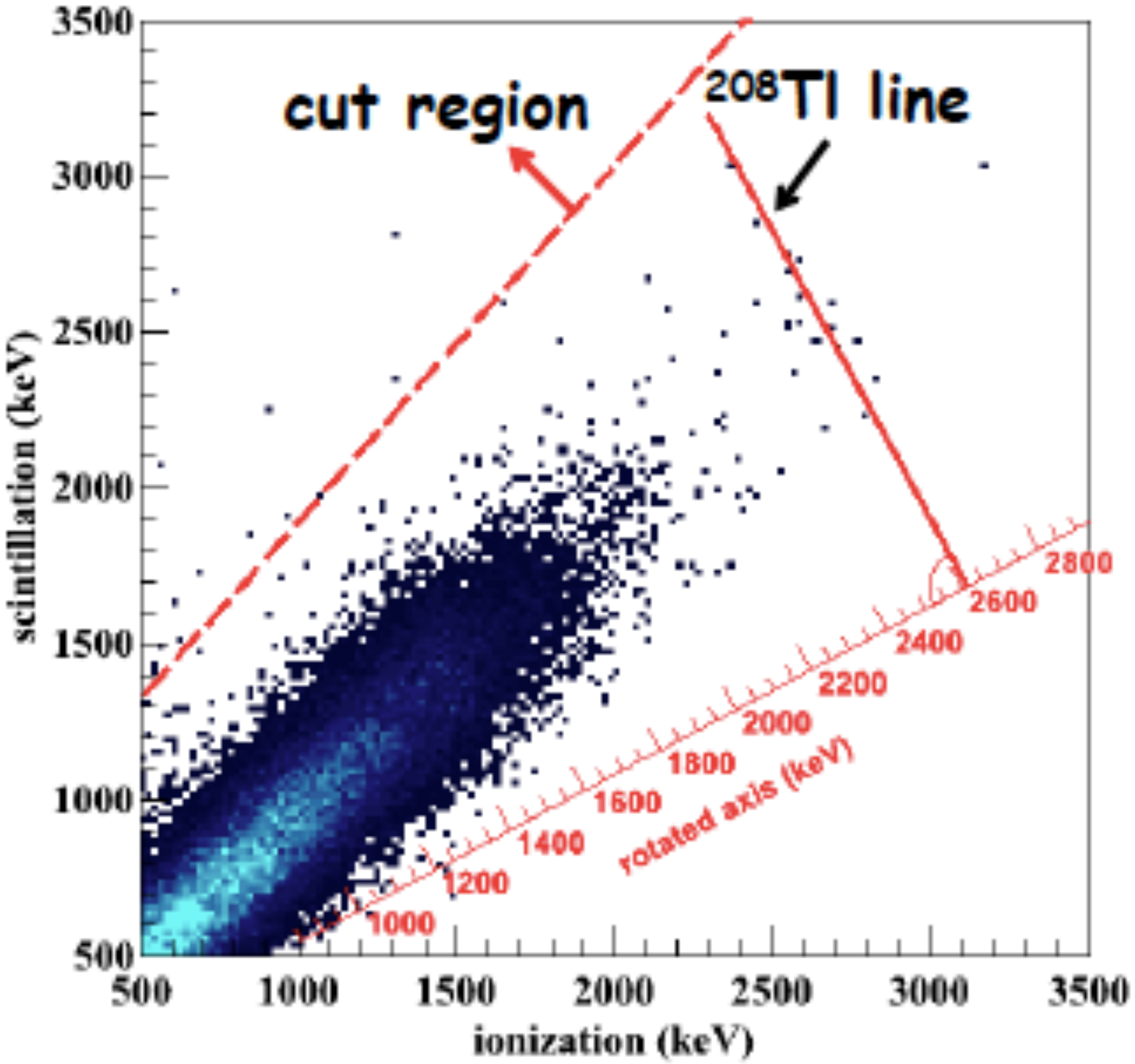
(E.Conti et al. Phys Rev B 68 (2003) 054201)

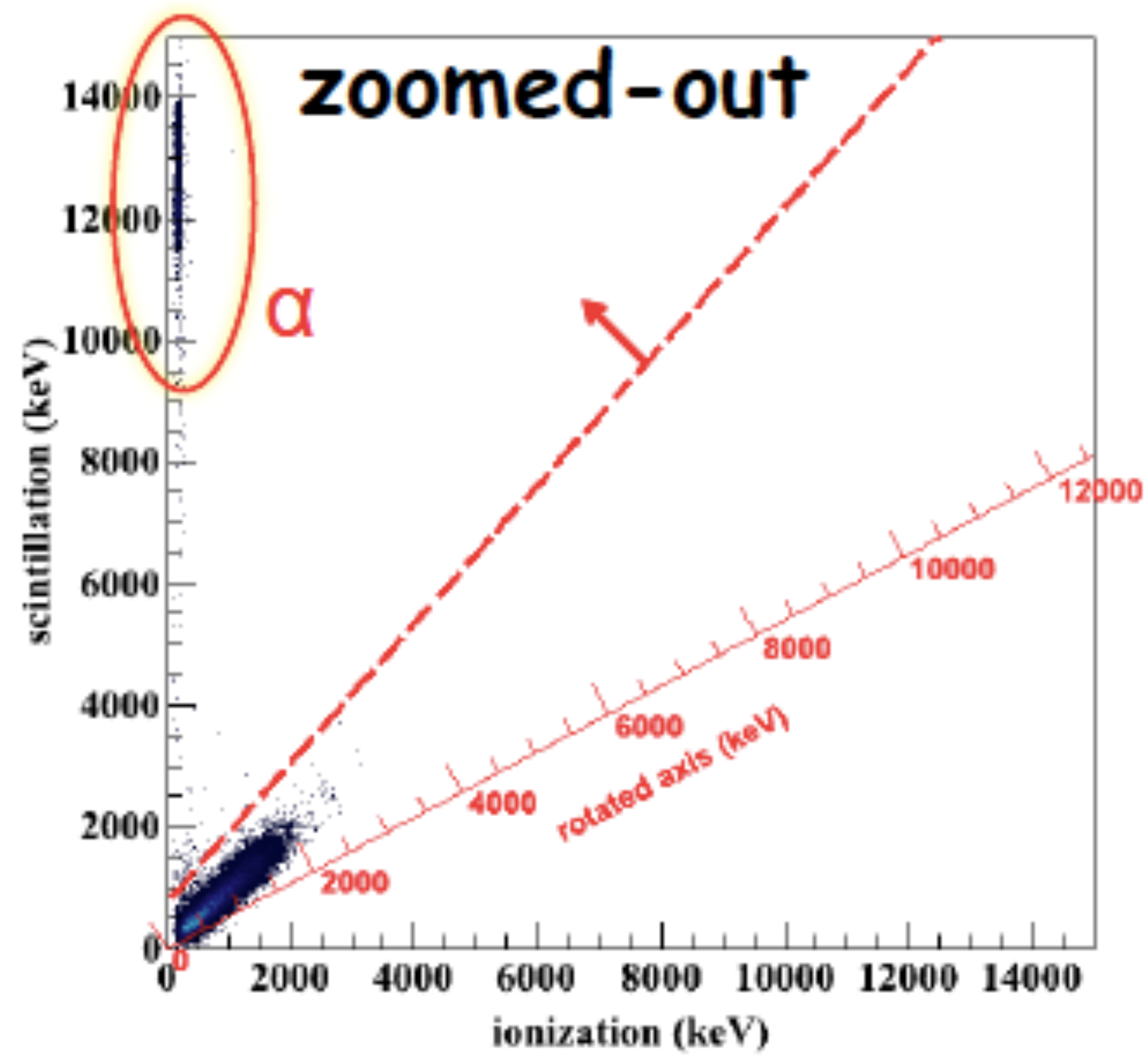


EXO-200 has achieved ~ 1.25% energy resolution at the Q value.

nEXO will reach resolution < 1%, sufficient to suppress background from $2\nu\beta\beta$.

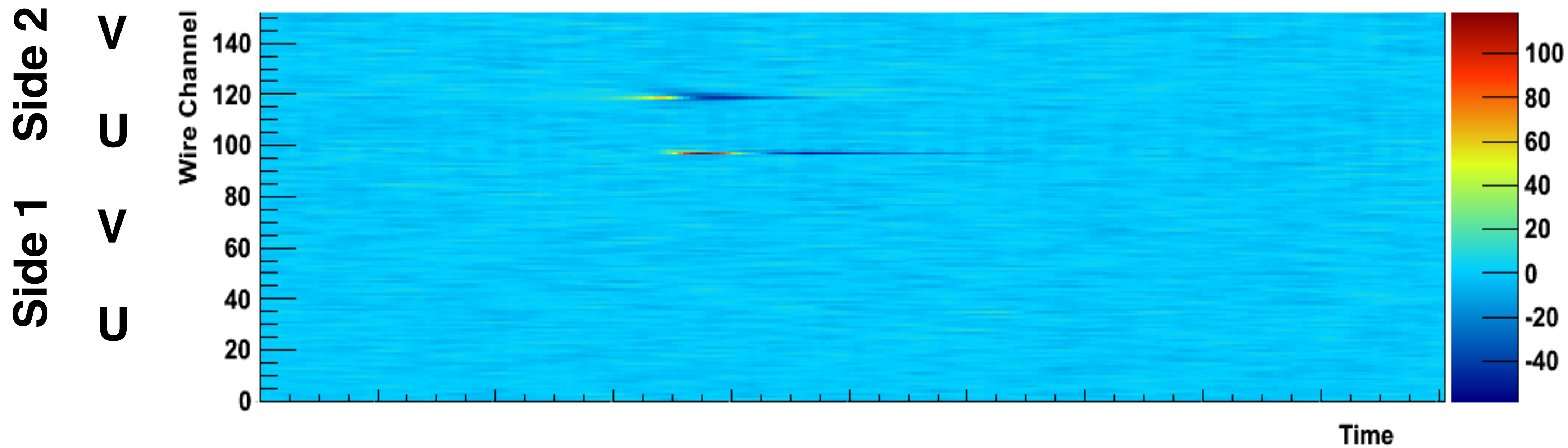
Alpha Identification

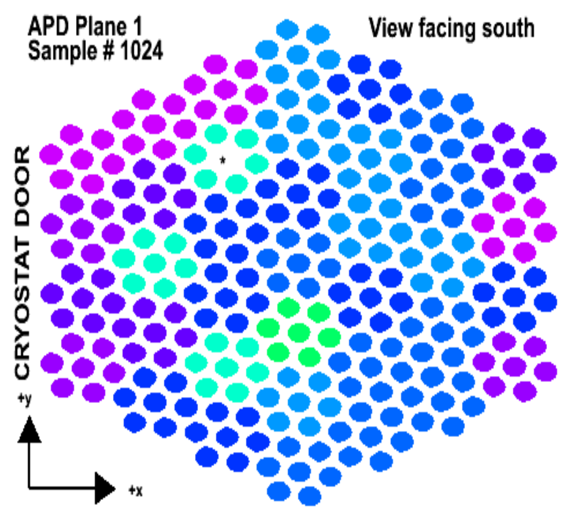


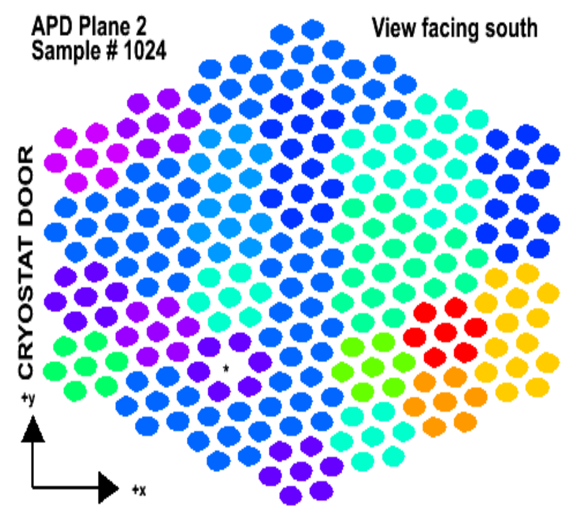


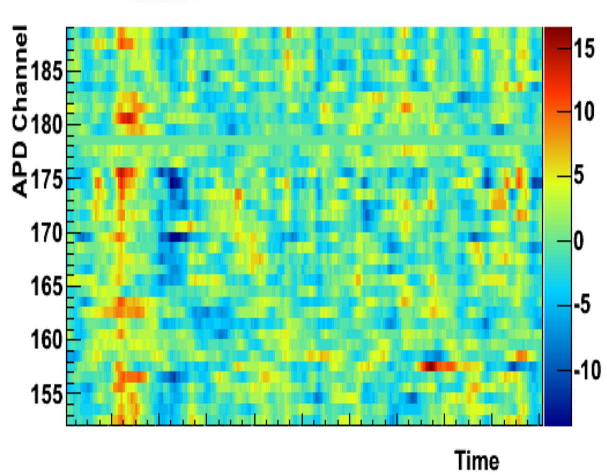
a diagonal cut (large scintillation, low charge) eliminates:
1) alphas
2) edge events (partial charge collection)

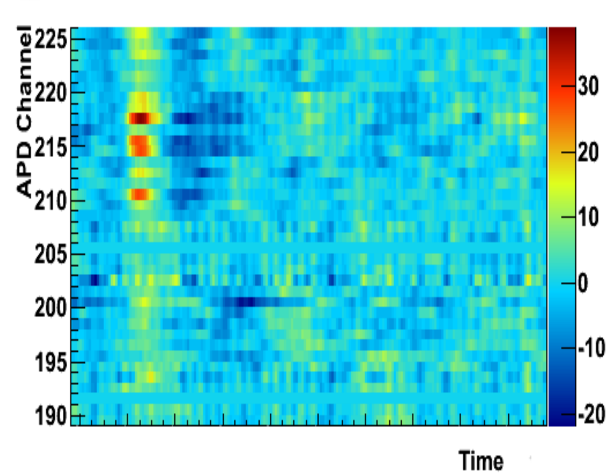
Single Site Event











Top display is charge readout (V are induction wires and U are collection wires).

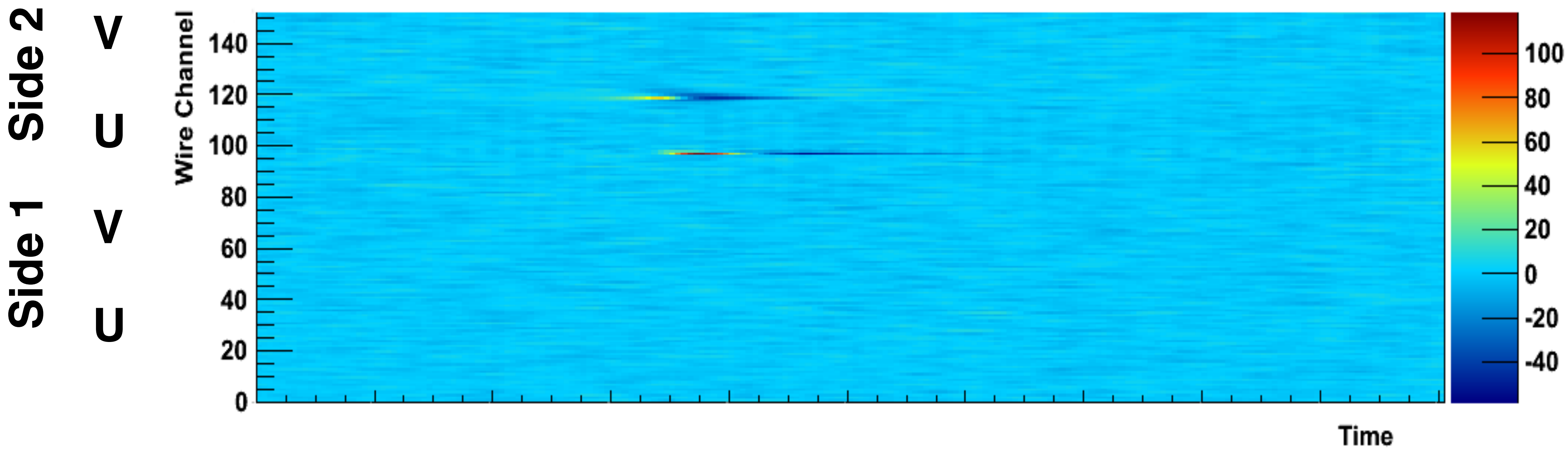
Left display is light readout. APD map refers to the sample with max signal.

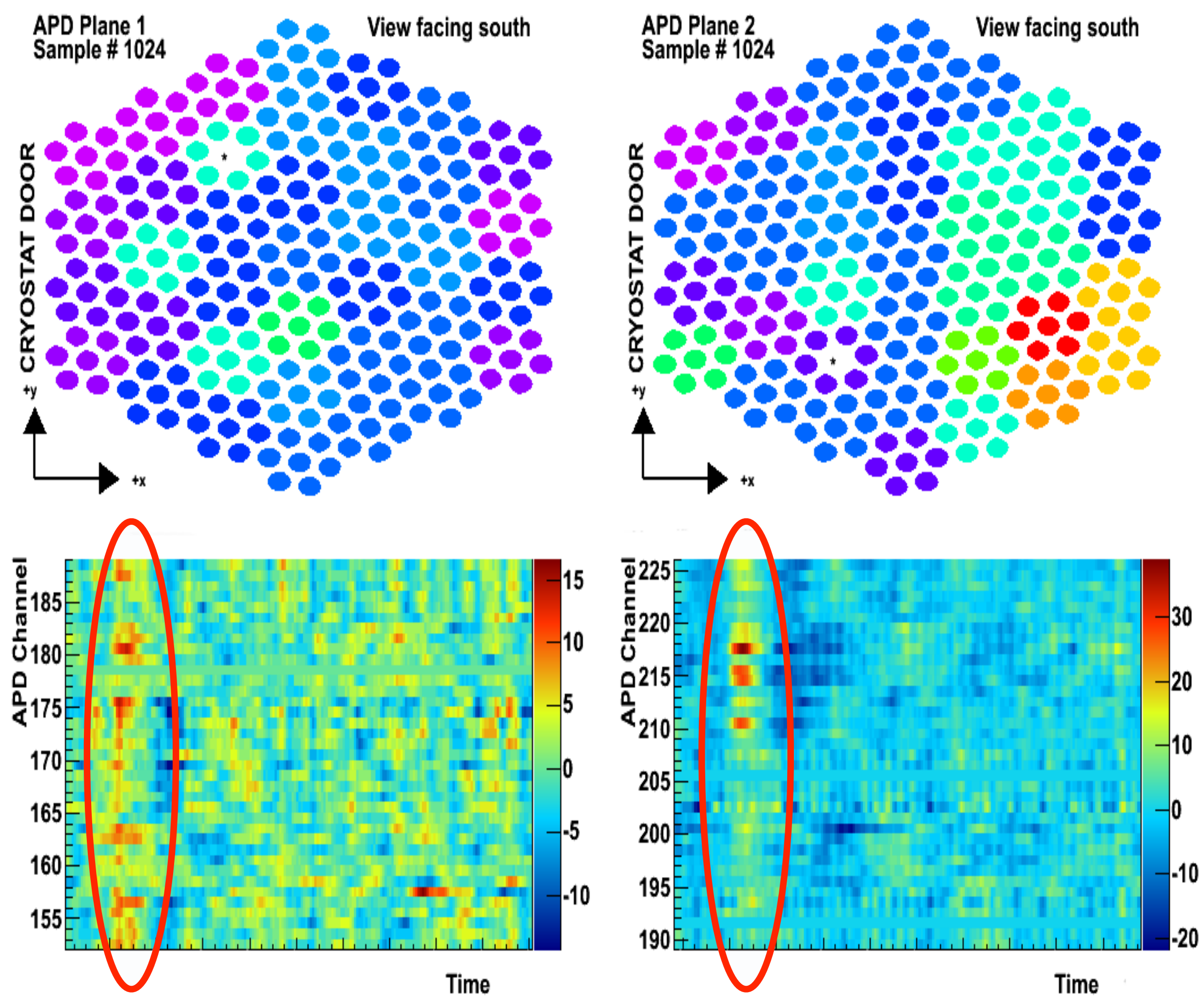
Scintillation light is seen from both sides, although more intense and localized on side 2, where the event occurred.

Small depositions produce induction signals on more than one V wires but are collected by a single U wire. V signal always comes before U.

Light signals precede in time the charge ones

Single Site Event





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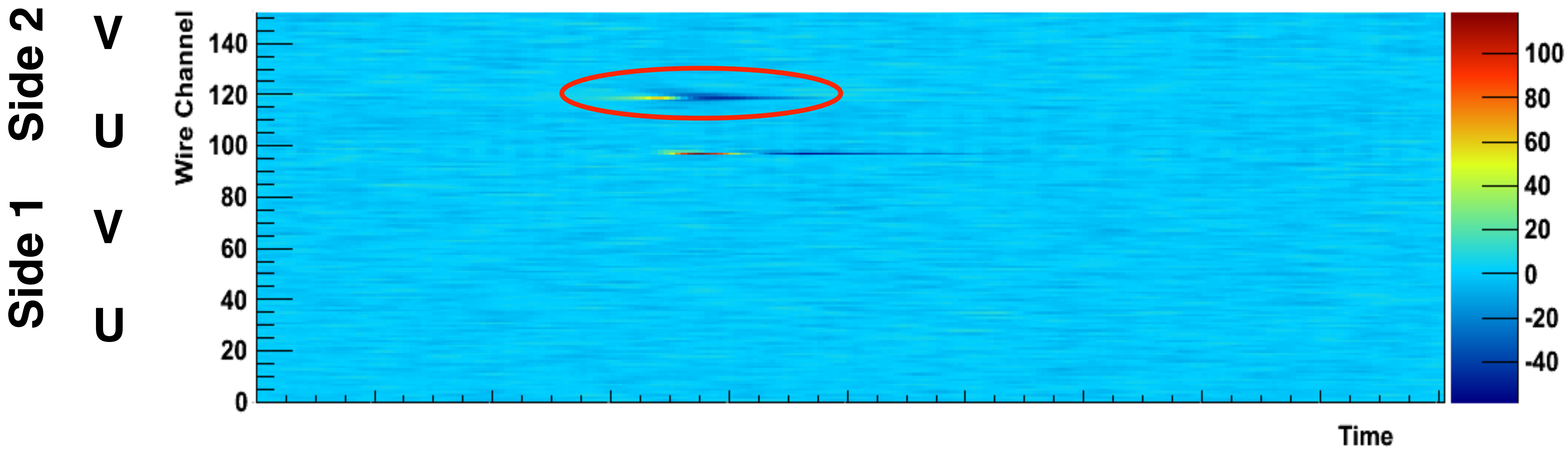

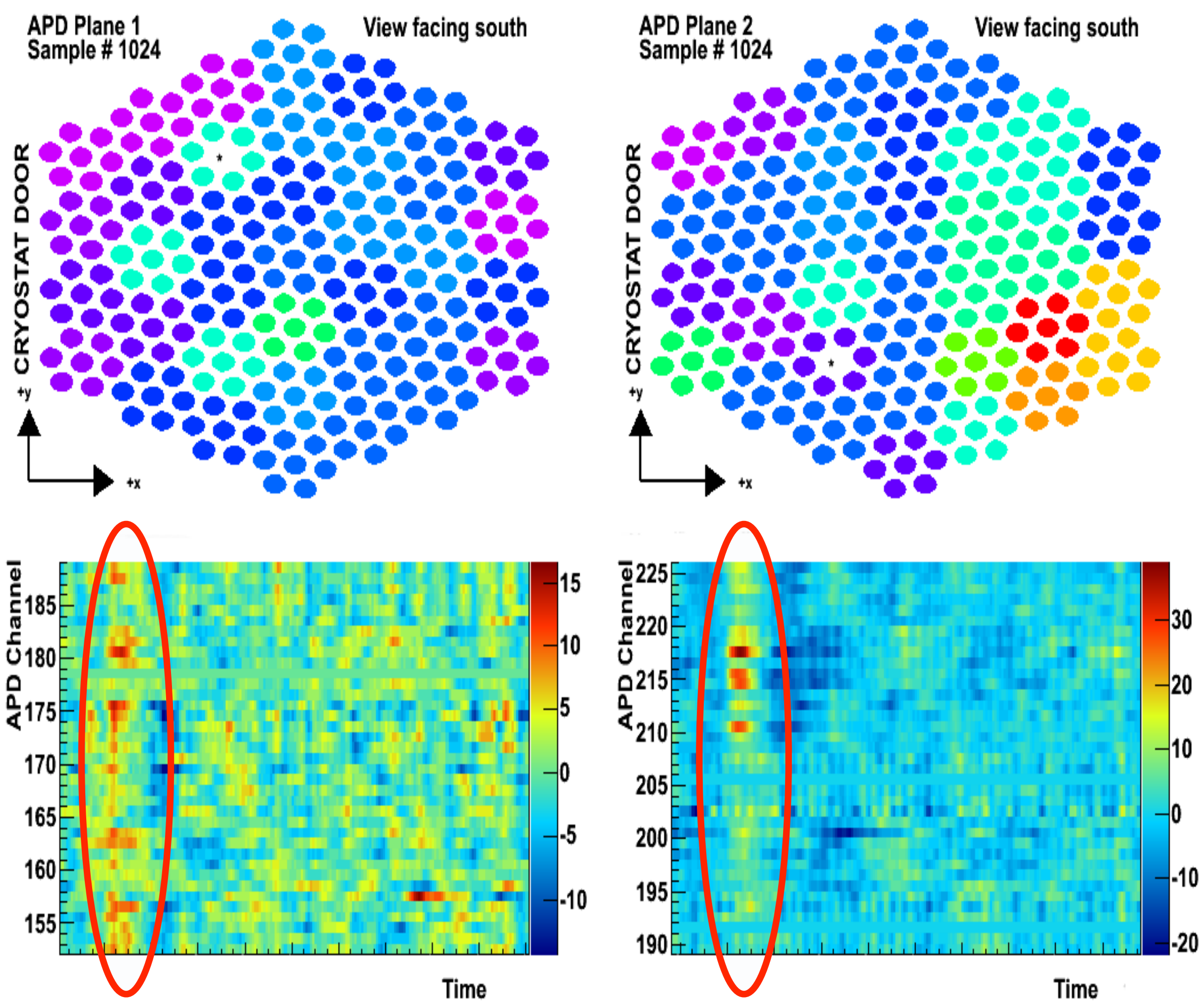

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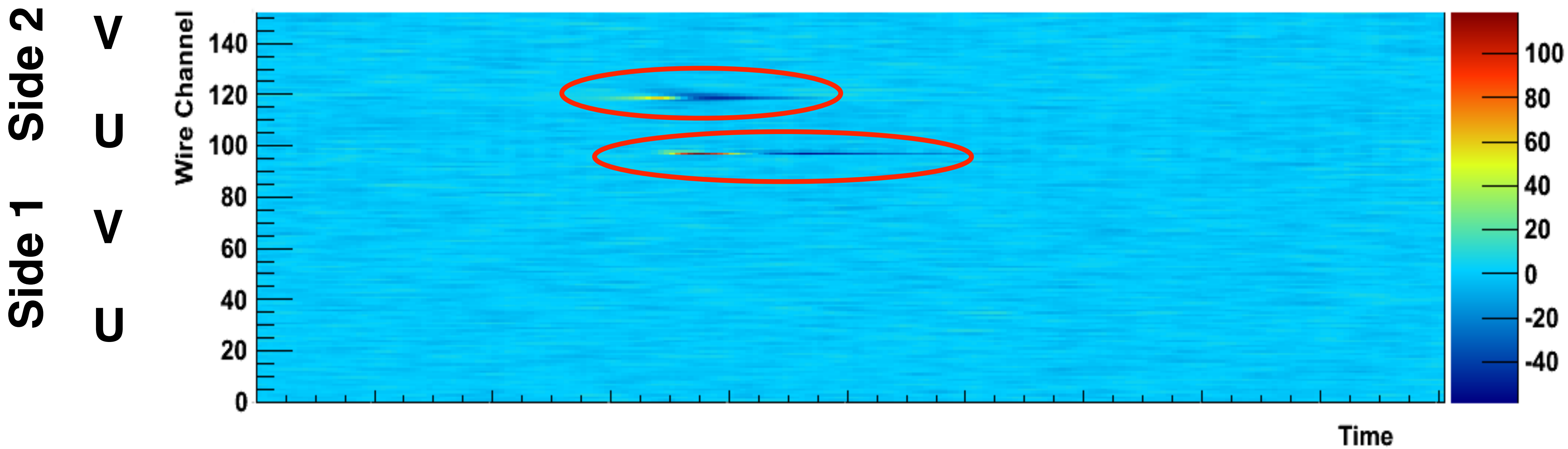

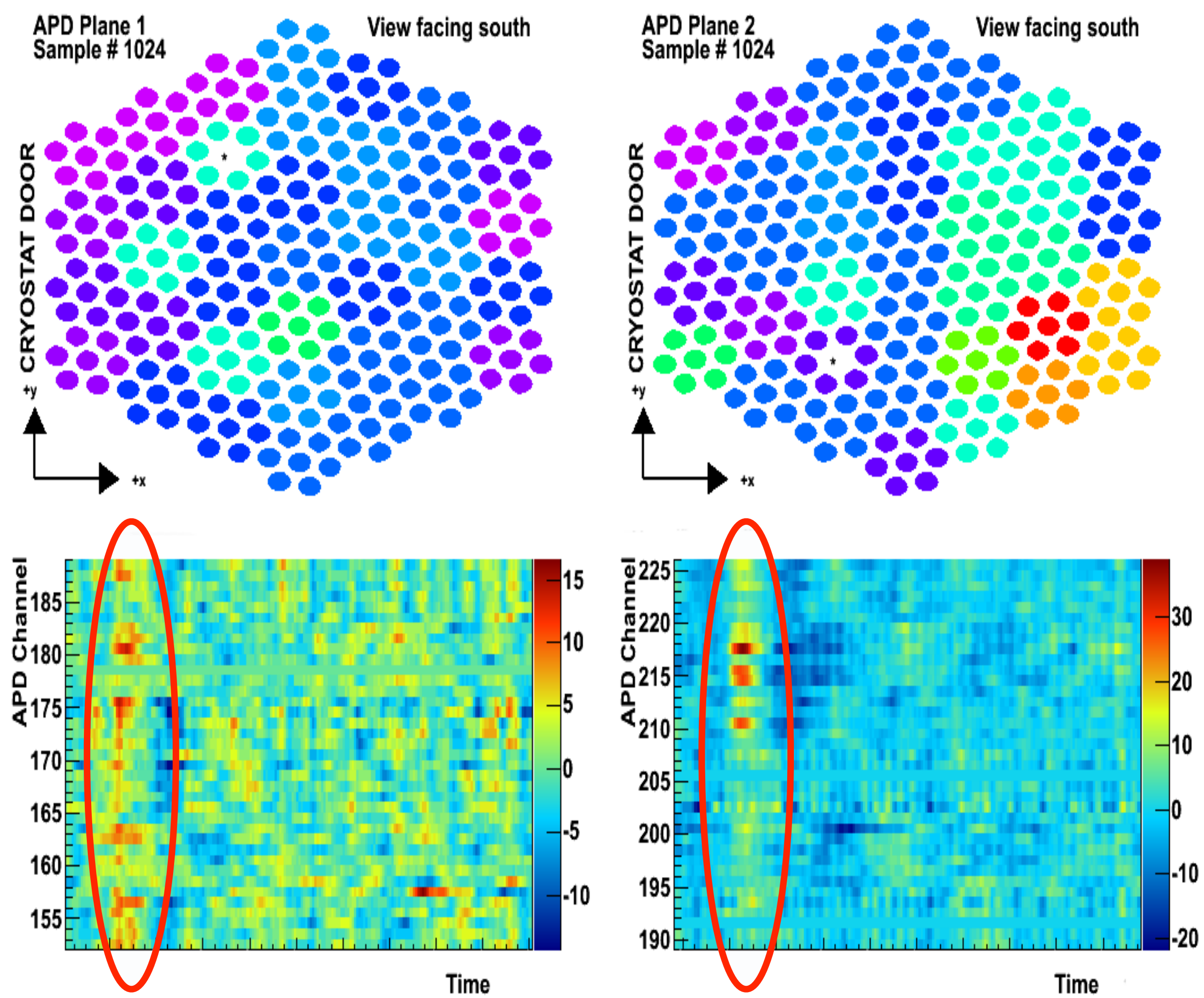

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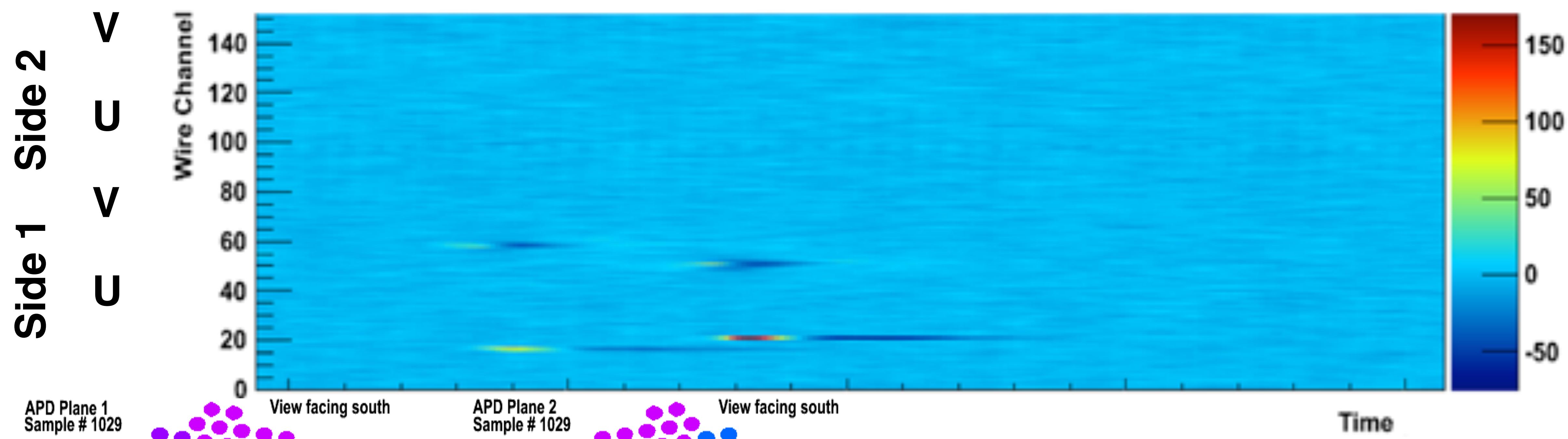
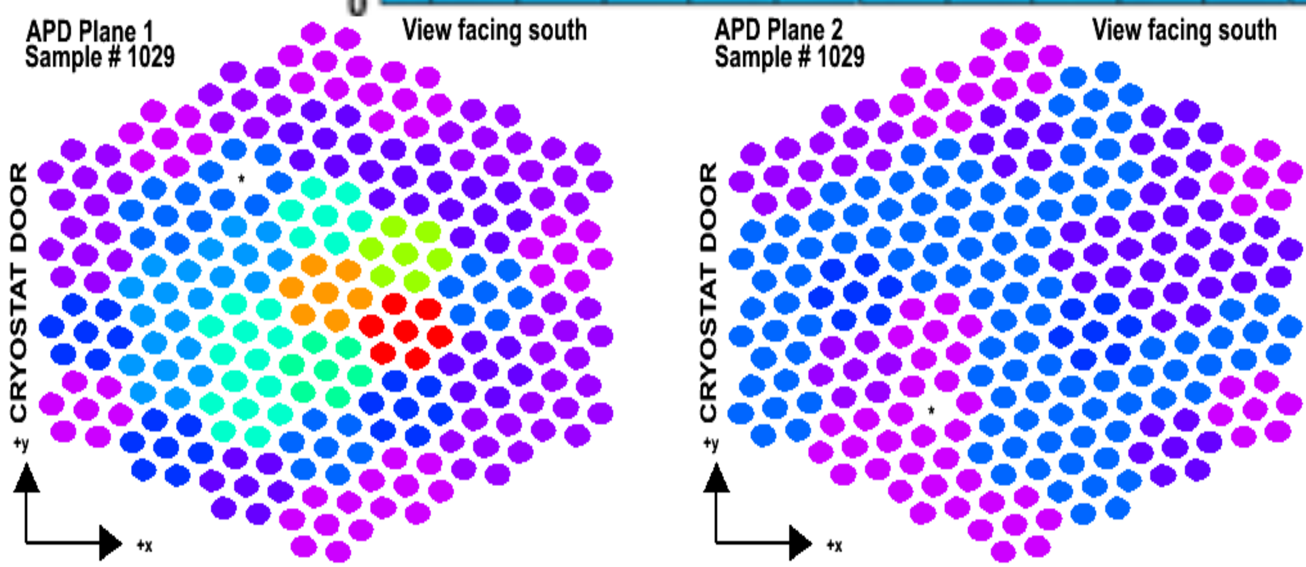
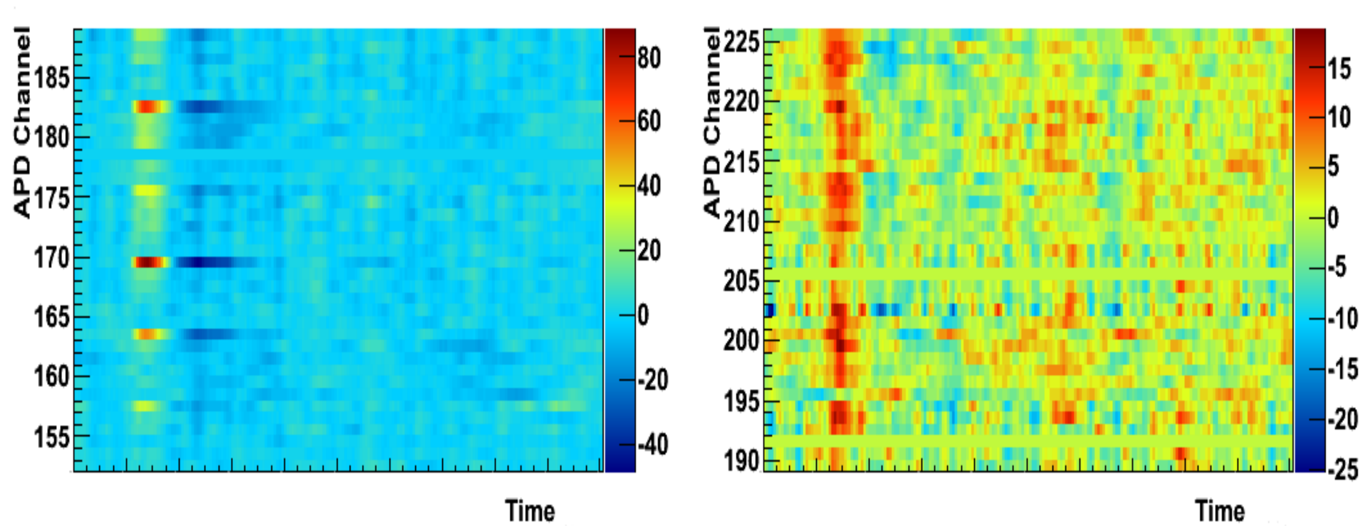
Two-Site Compton Event



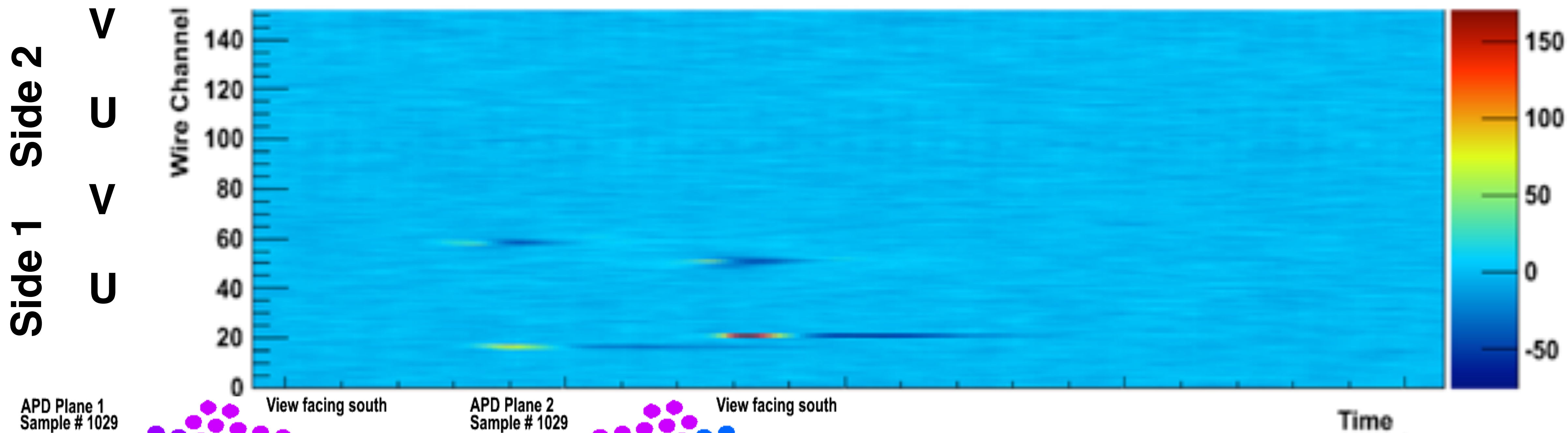


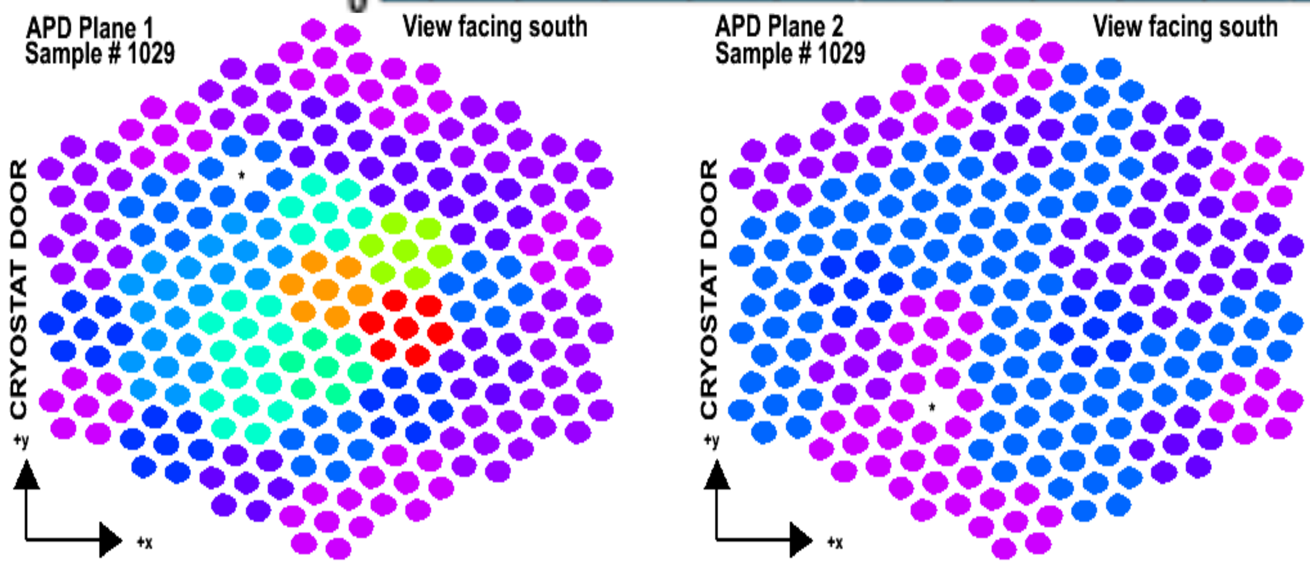
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

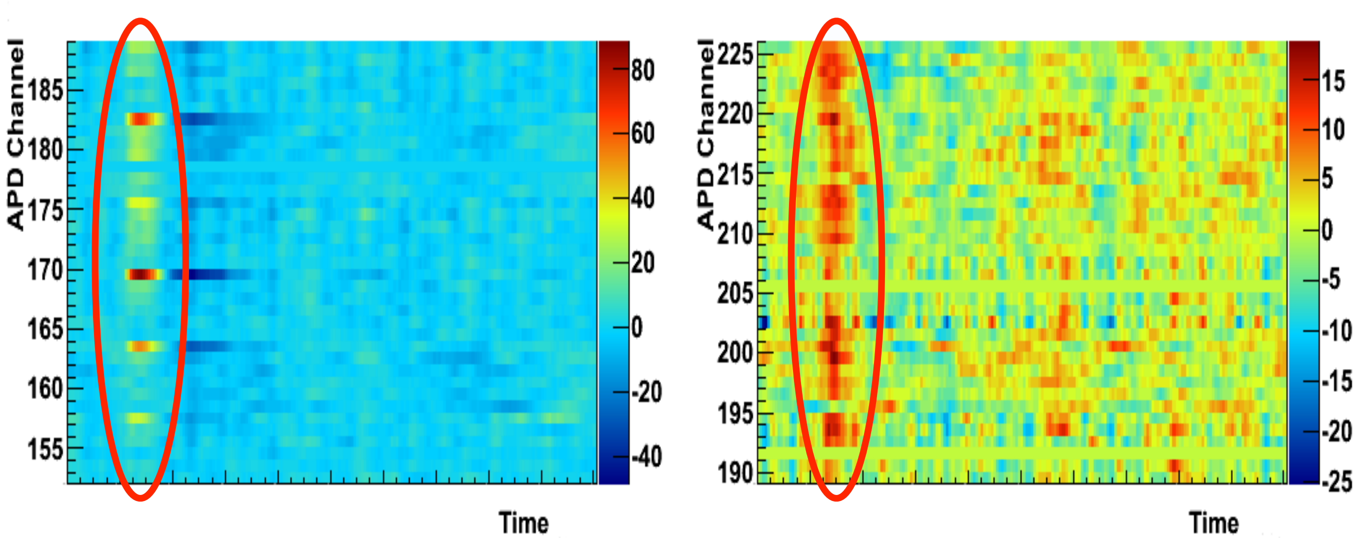


The scintillation light is brighter and more localized on Side 1 where the scattering occurs

Two-Site Compton Event







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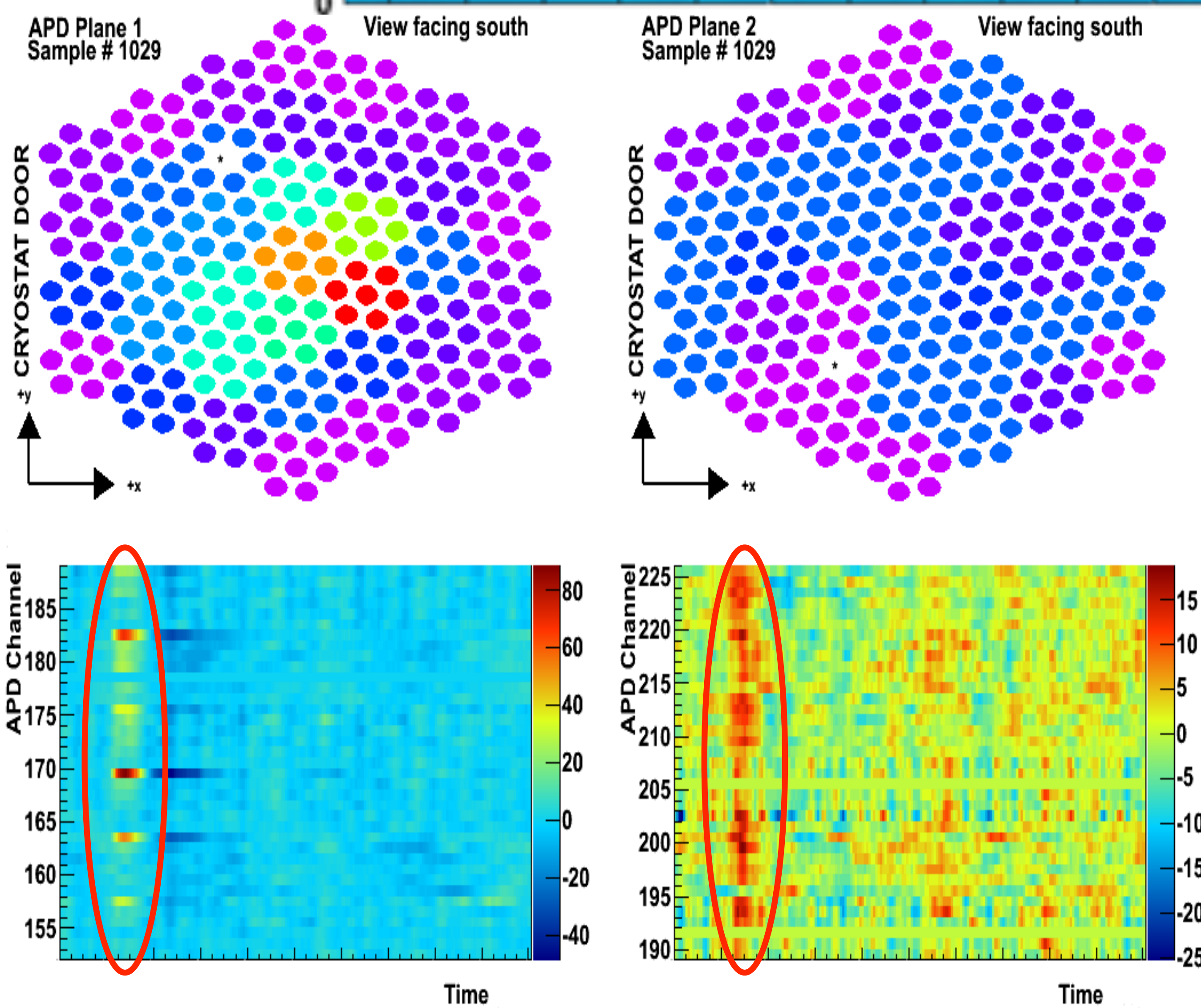

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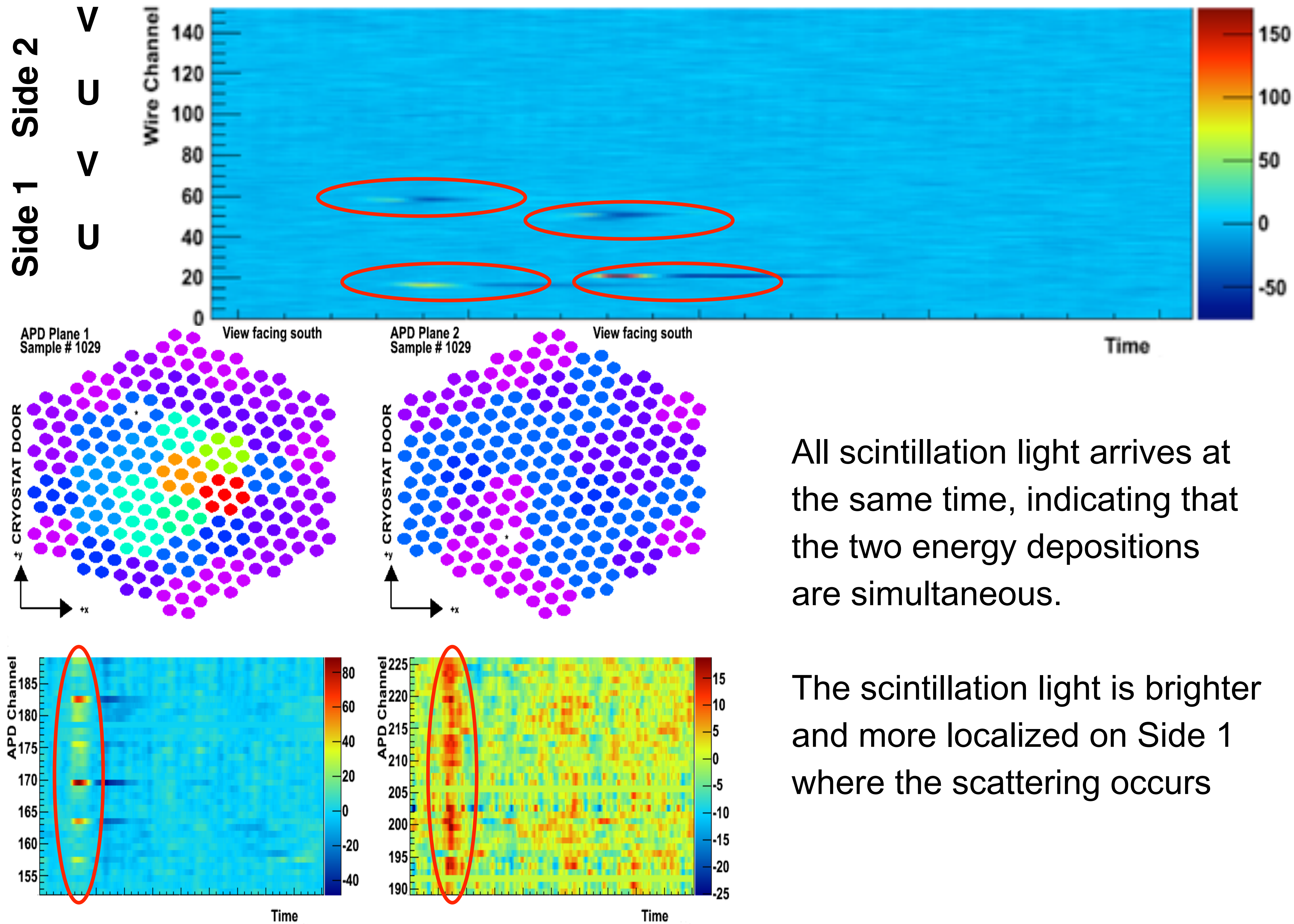

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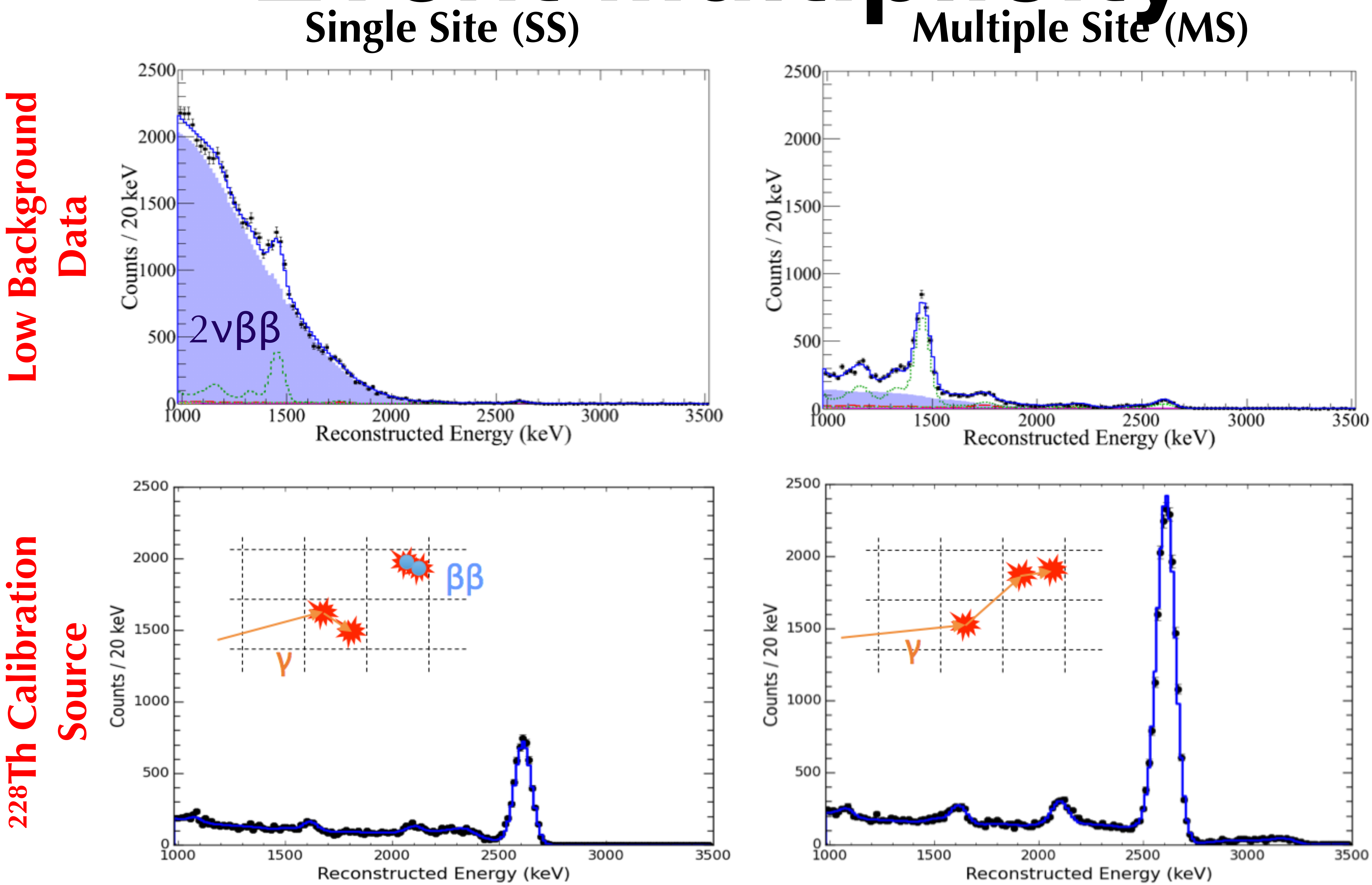
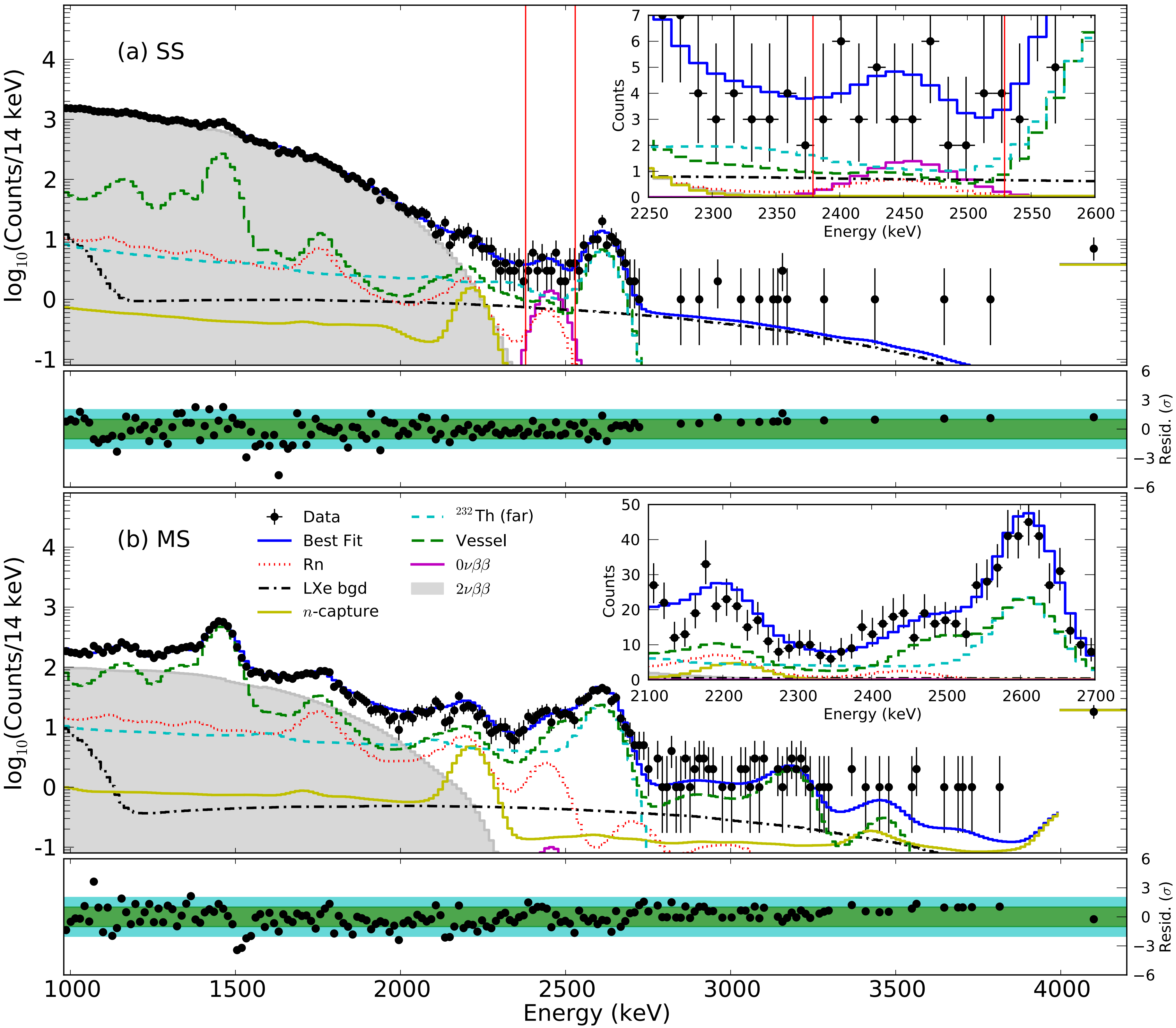
Event Multiplicity



EXO-200 2014 Result



$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$yr (90%CL)

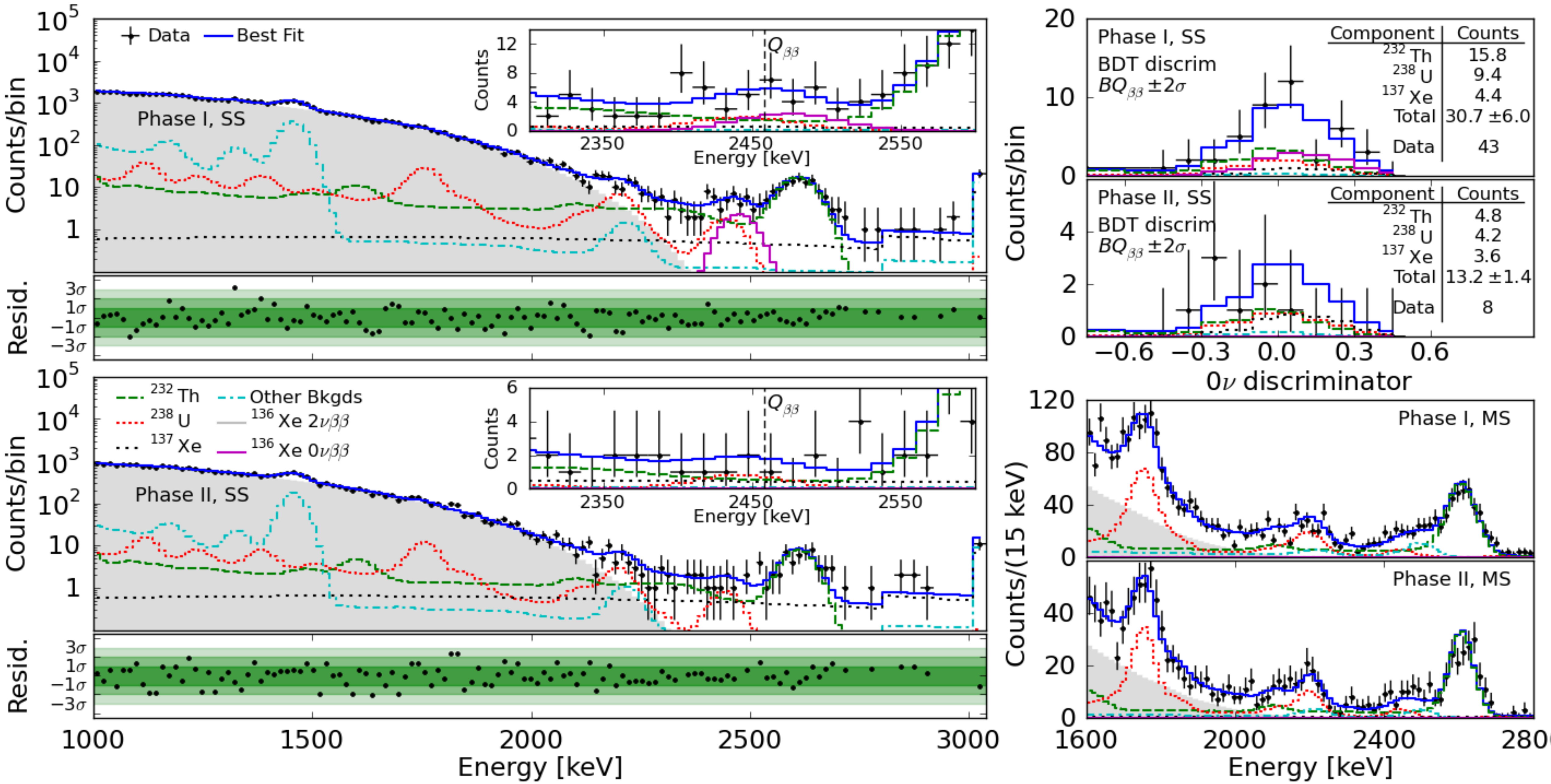
$\langle m_\nu \rangle < 190 - 450$ meV

$T_{1/2}^{0\nu\beta\beta}$ sensitivity:

$1.9 \cdot 10^{25}$ yr

J.B.Albert et al. (EXO-200)
Nature 510 (2014) 229

Phase-II 2018 Result



- background model + data —> maximum likelihood fit
- combine Phase-I and Phase-II profiles
- no statistically significant effect (combined p-value ~1.5σ)

Main Result Summary

median sensitivity (90% C.L.)
3.7×10^{25} yr
(Phase 1 & 2 combined)

90% C.L. limits

$T^{0\nu\beta\beta}_{1/2} > 1.8 \times 10^{25}$ yr

$m_{\beta\beta} < 147\text{-}398$ meV

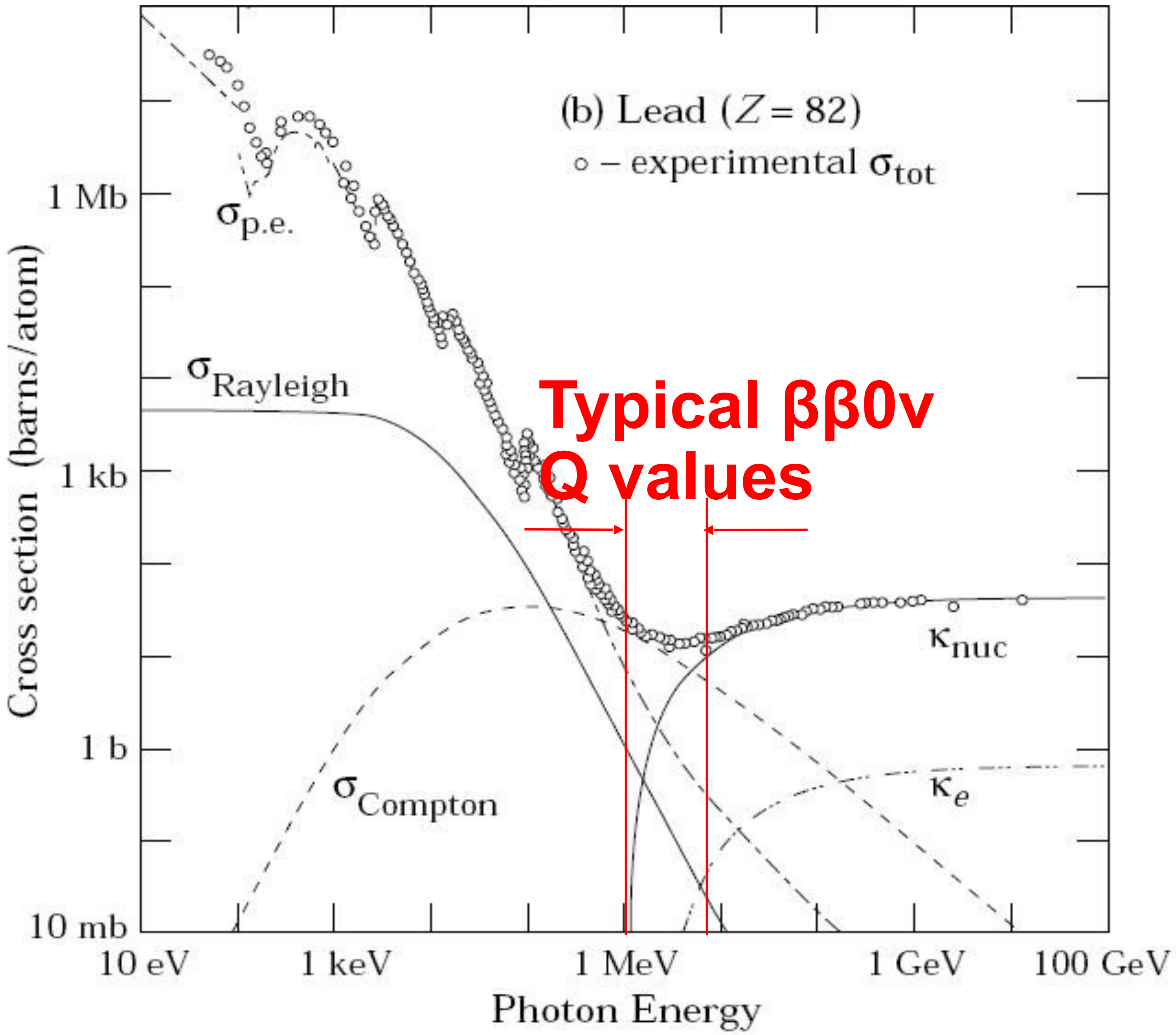
	Phase-I	*Phase-II*
exposure	122 kg-yr 898 mol-yr 596.7 d	55.6 kg-yr 409 mol-yr 271.8 d
BQ ± 2σ	*cts*	*cts*
^{232}Th	15.8	4.8
^{238}U	9.4	4.2
^{137}Xe	4.4	3.6
Total	30.7 ± 6.0	13.2 ± 1.4
Data	43	8
sensitivity	2.9×10^{25} yr	1.7×10^{25} yr
$0\nu\beta\beta$ lifetime limit	1.0×10^{25} yr	4.4×10^{25} yr
1D bg index	1.5 /tonne/yr/keV	1.6 /tonne/yr/keV

The Future: nEXO

Shielding a detector from gammas is difficult!

Gamma Shielding

Gamma interaction cross section



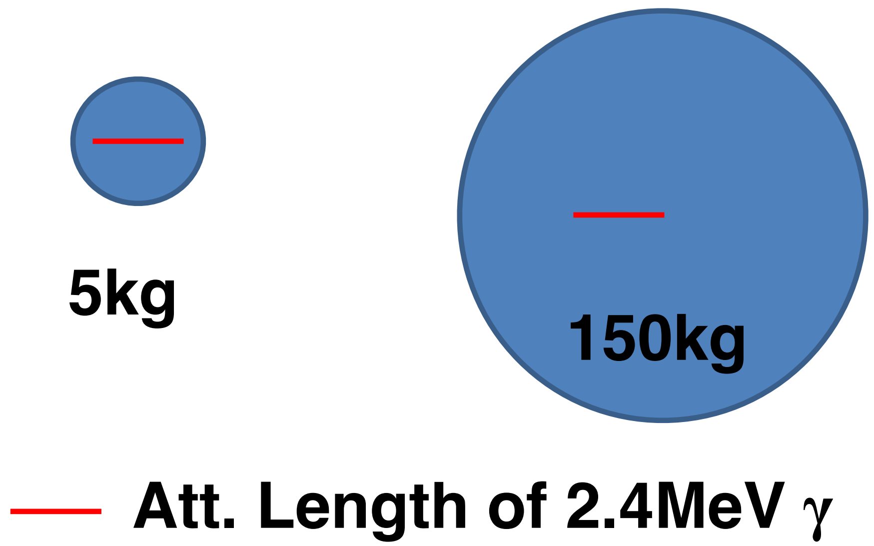
Example:

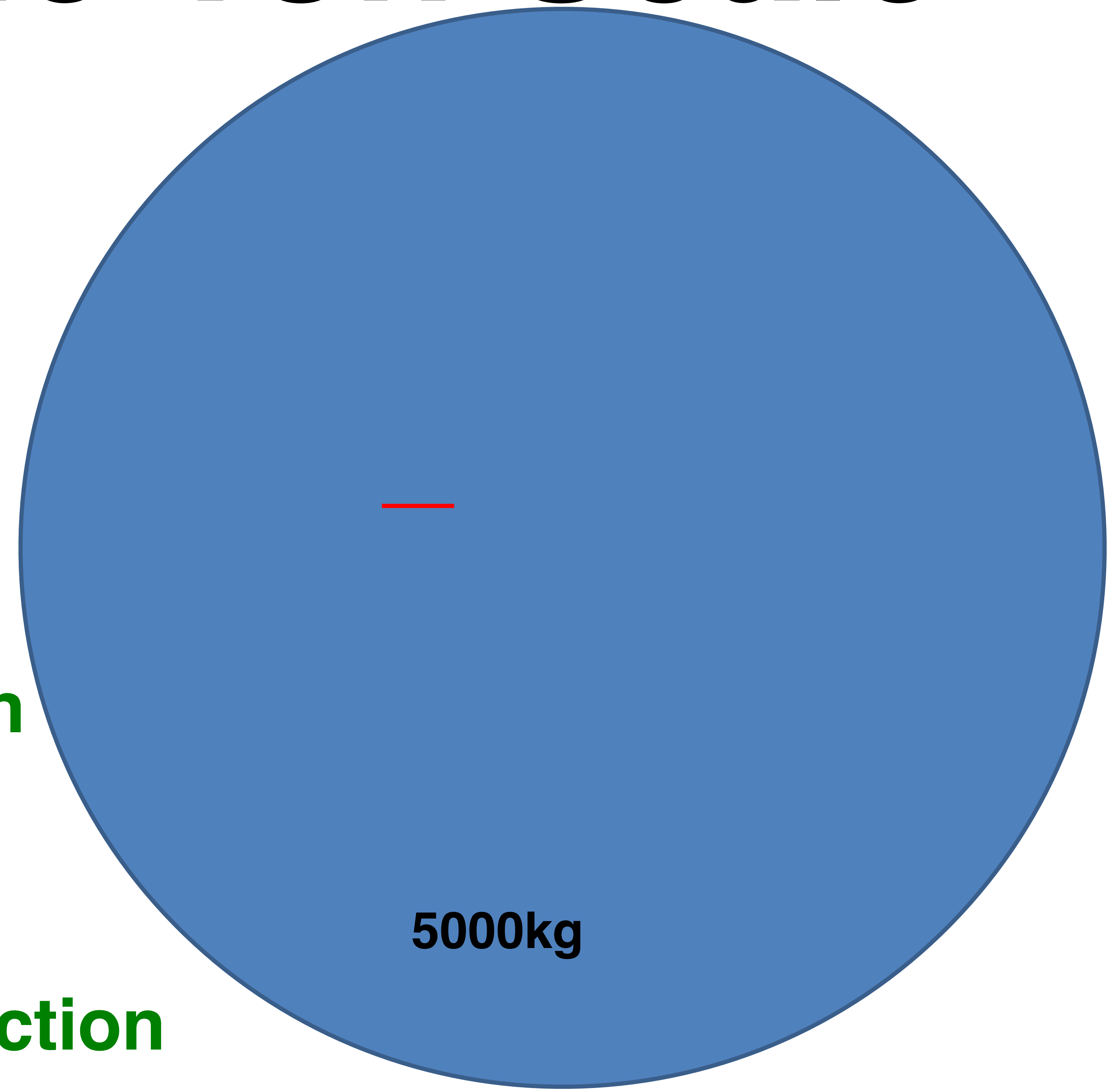
γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding ββ decay detectors is much harder than shielding Dark Matter ones

We are entering the "golden era" of ββ decay experiments as detector sizes exceed int lengths

Towards the Ton Scale





Because one can take full advantage of:

1) Compton tag and rejection

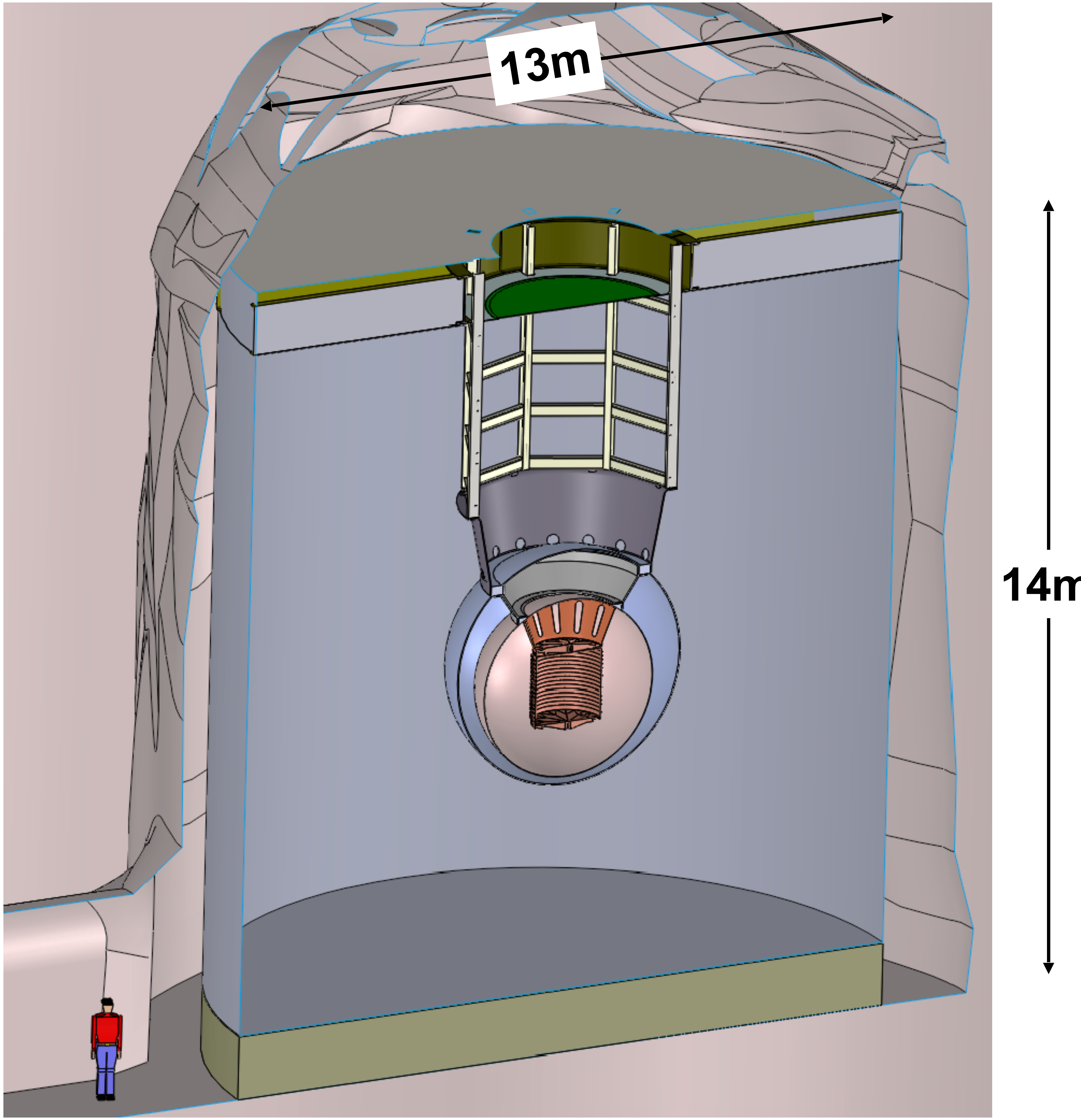
(if detector has double-hit recognition ability)

2) External background identification and rejection

The larger the detector the more useful this is.

→ Ton scale is where these features become dominant.

nEXO Concept



Preliminary artist view of nEXO in the SNOlab Cryopit

nEXO Collaboration

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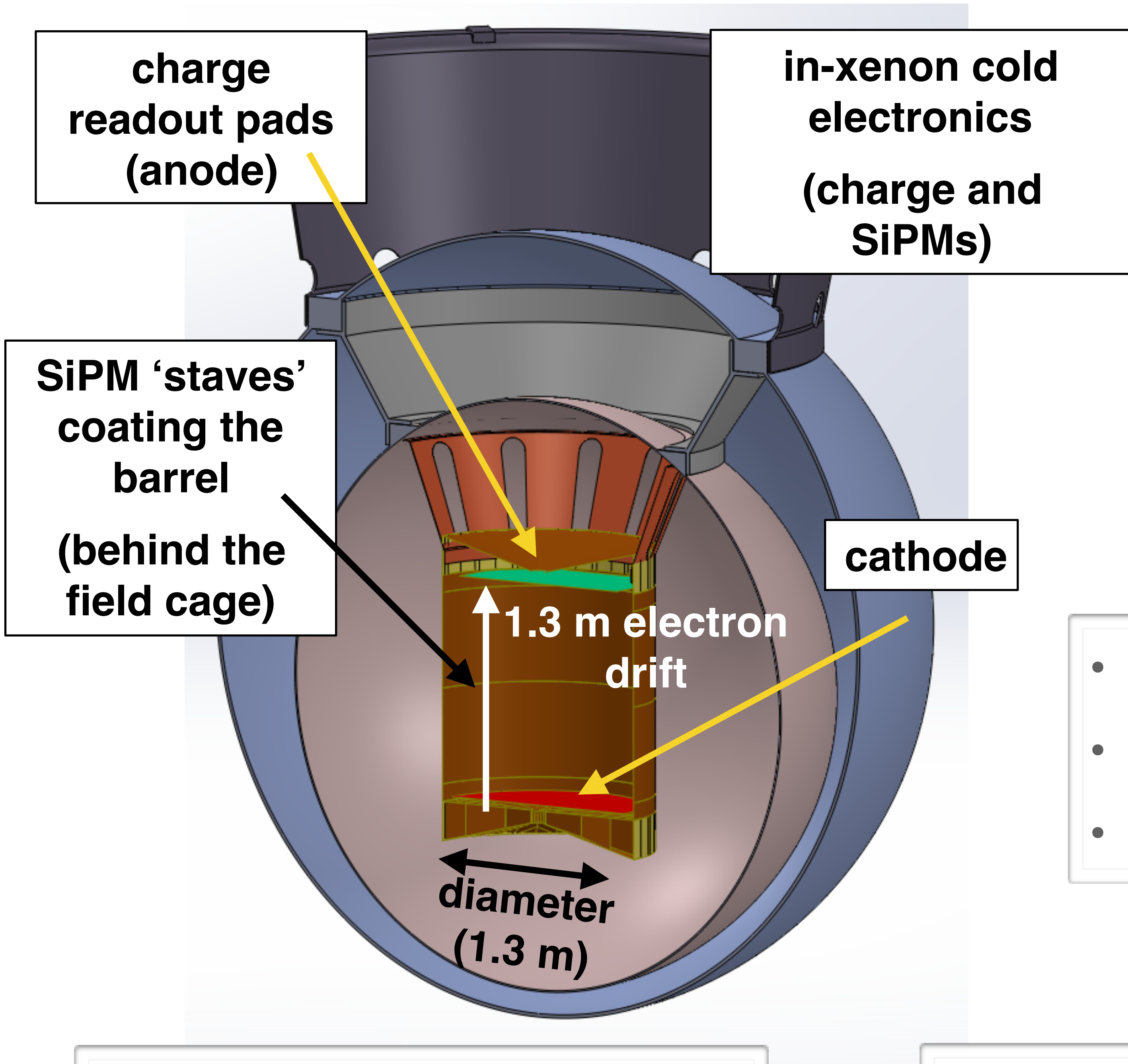
Yale University, New Haven CT, USA — A Jamil, Z Li, D Moore, Q Xia

The nEXO TPC



- < 1% energy resolution
- no central cathode
- ≳ 10 ms electron lifetime
- ~500 Rn atoms

- no plastics, in-Xe cold electronics
- VUV-sensitive SiPMs behind field cage
- charge readout strips

- 25x EXO-200
- enhanced self-shielding
- x100 better $T_{1/2}$ sensitivity

- **sensitivity (10 years): 9 x 10^{27} yr**
- **energy, topology, standoff & particle ID**

One essential point:

nEXO IS NOT A PURE CALORIMETER

To think about nEXO exclusively in terms of energy resolution is misleading

nEXO uses optimally *more* than just the energy measurement.

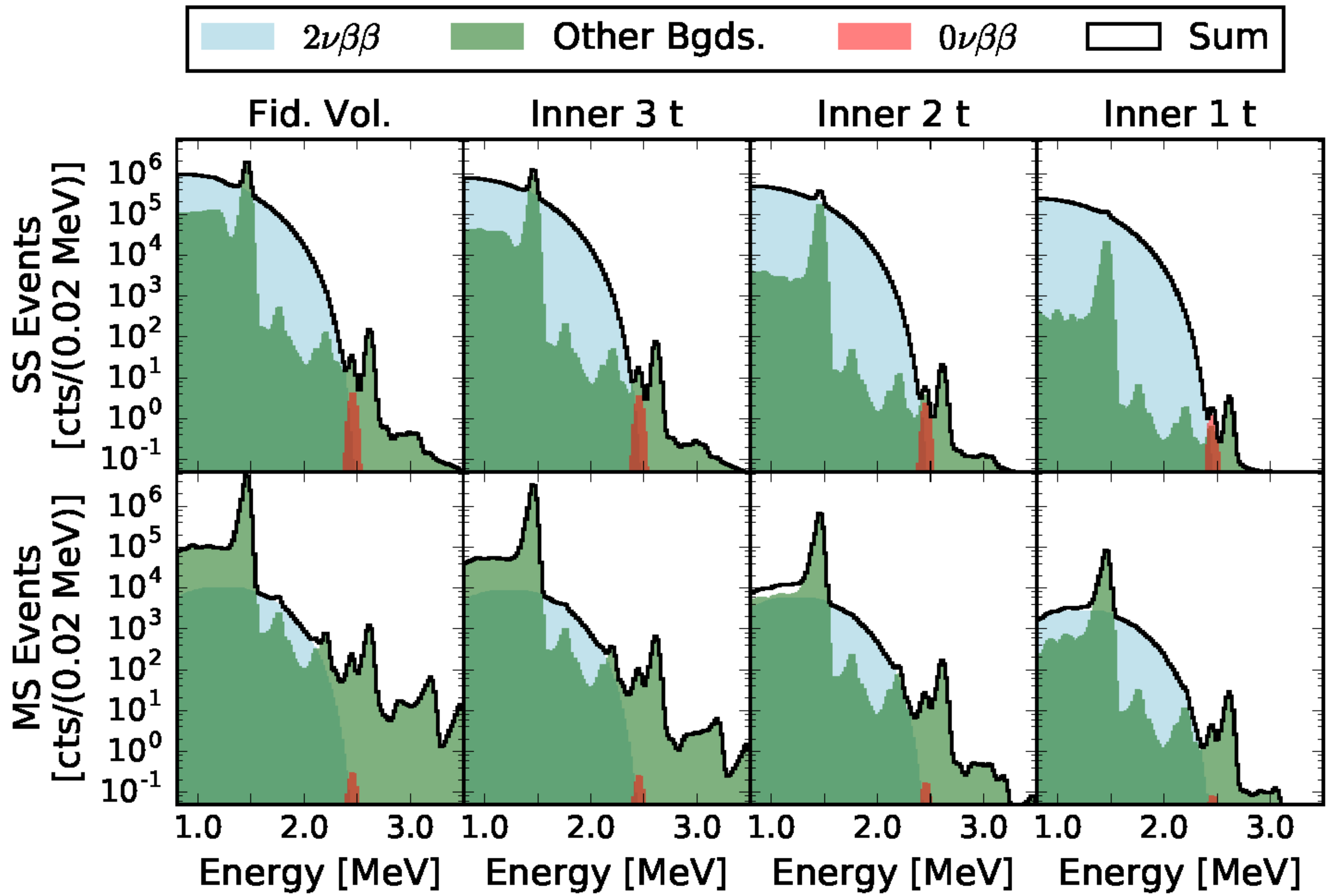
The signal/background discrimination is based on four parameters:

1. **Energy measurement**
2. **Event multiplicity (SS/MS in EXO-200)**
3. **Distance from the TPC surface**
4. **Particle ID (α-electron)**

There is no rational reason to prefer the use of an "Energy ROI" over a "topology ROI" or a "topology ⊗ energy ROI". In fact, more independent axes provide a more powerful constraint on the signal.

nEXO Sensitivity

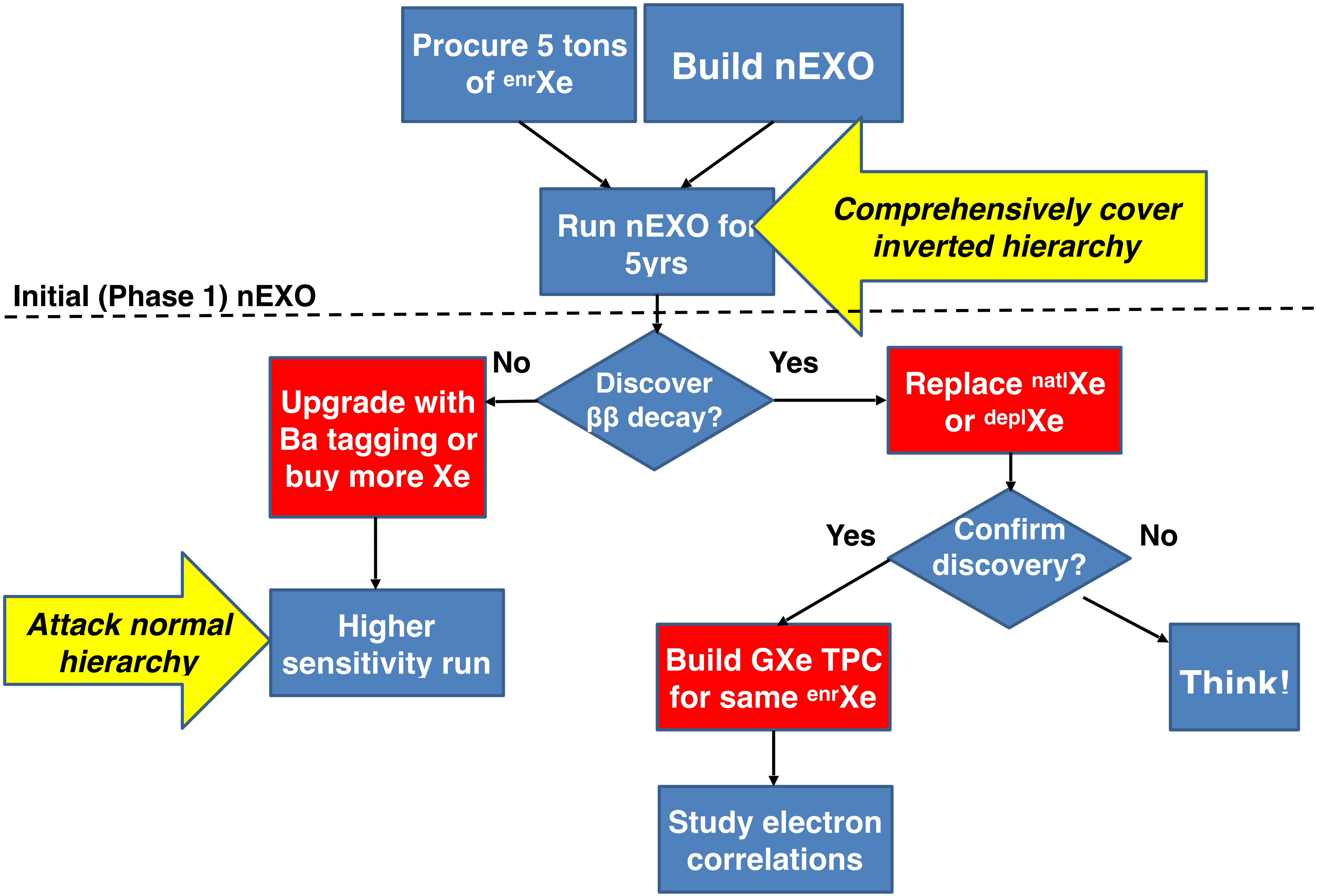
Fit using event energy, multiplicity, and position



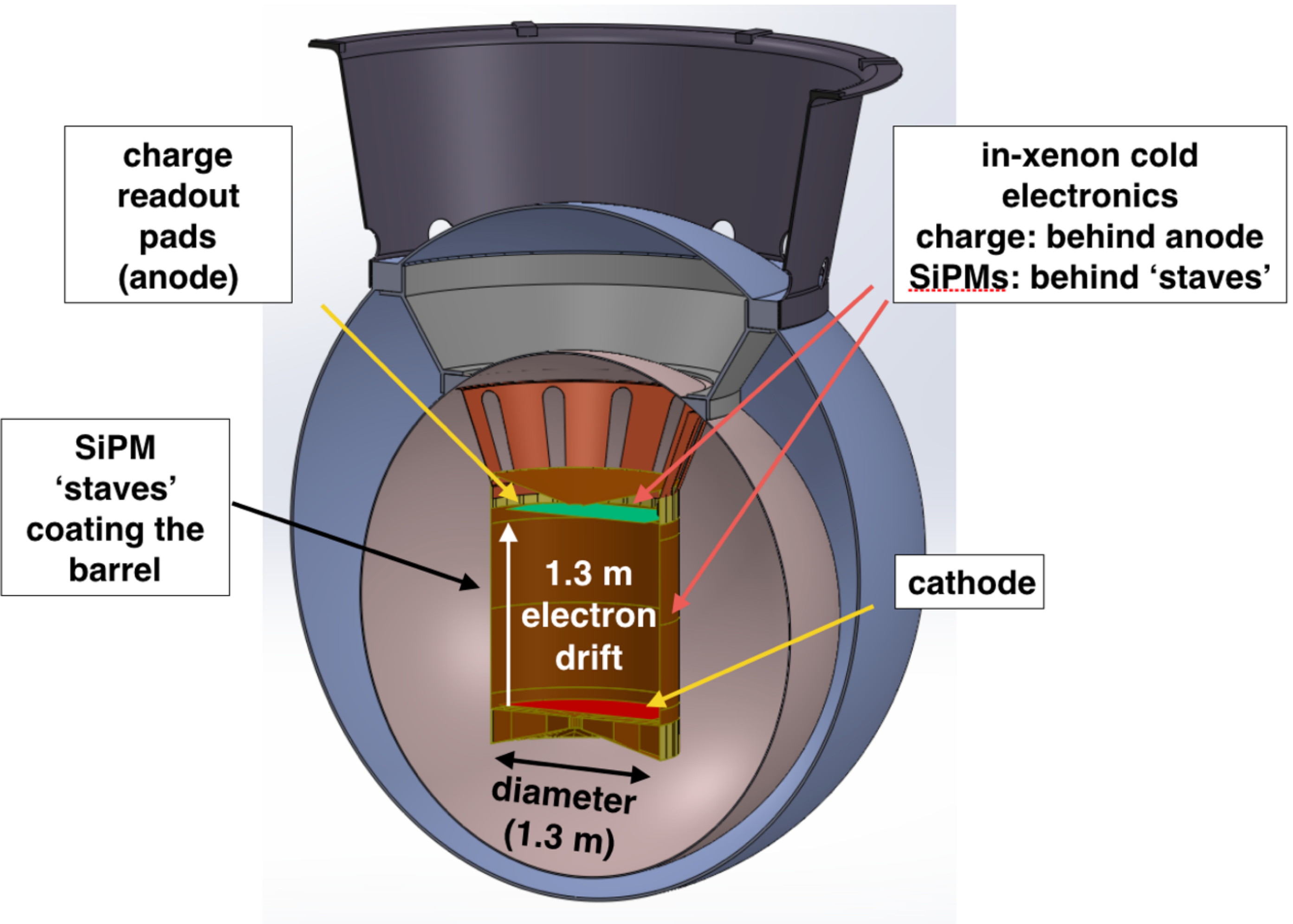
for: $T_{1/2} = 5.7 \times 10^{27}$ yr

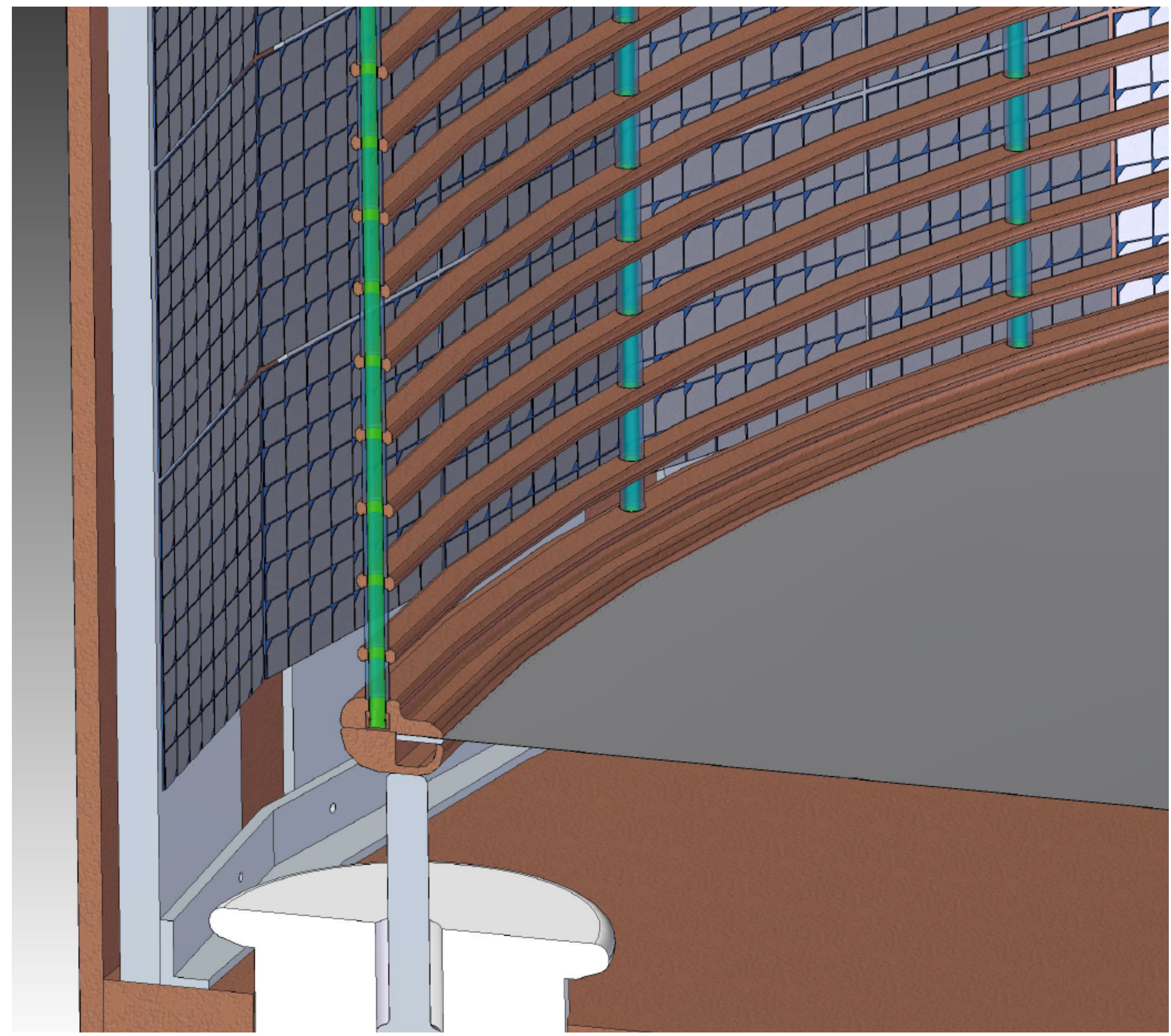
nEXO Strategy

Flexible program based on the initial nEXO investment



nEXO R&D



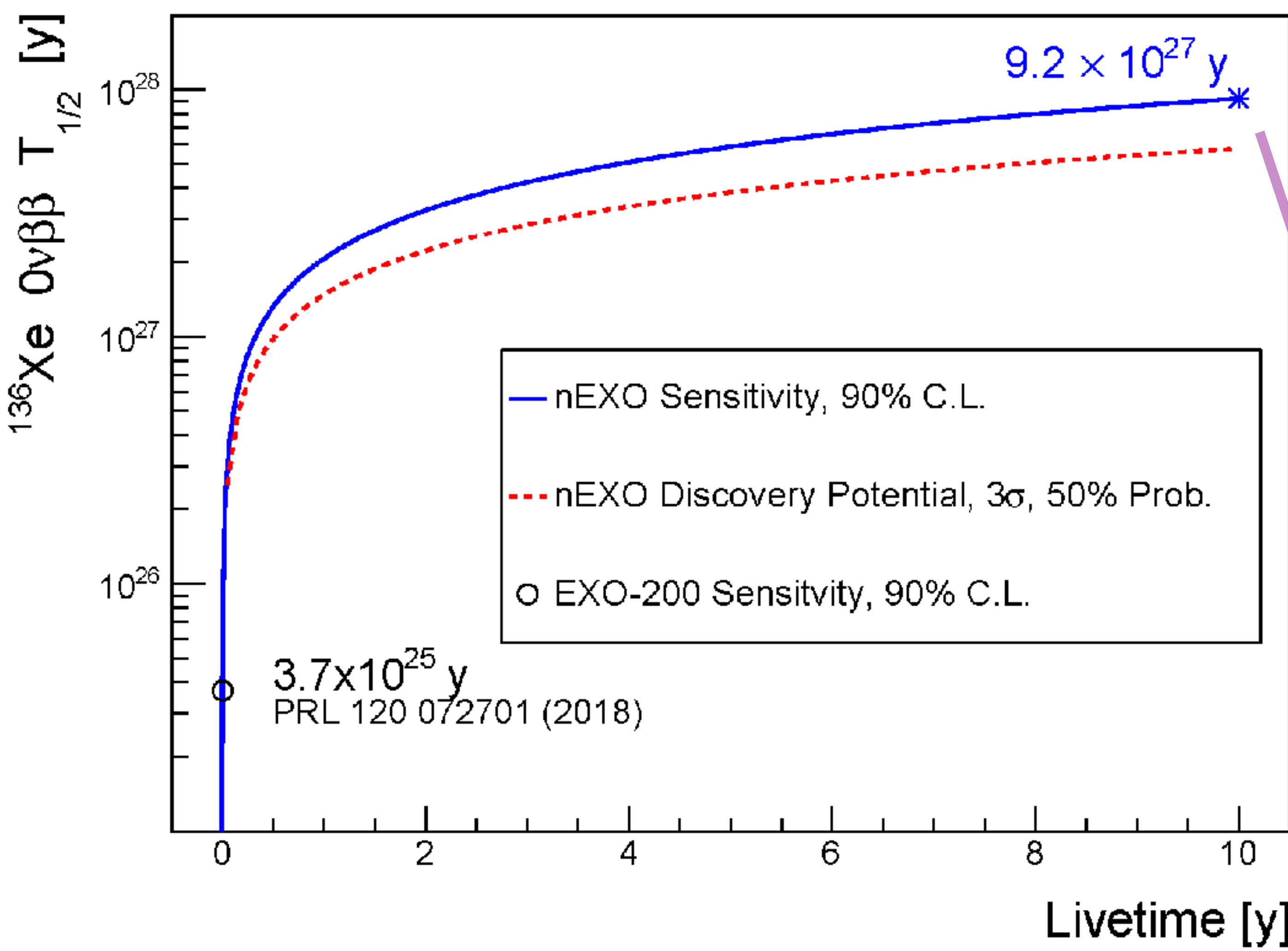


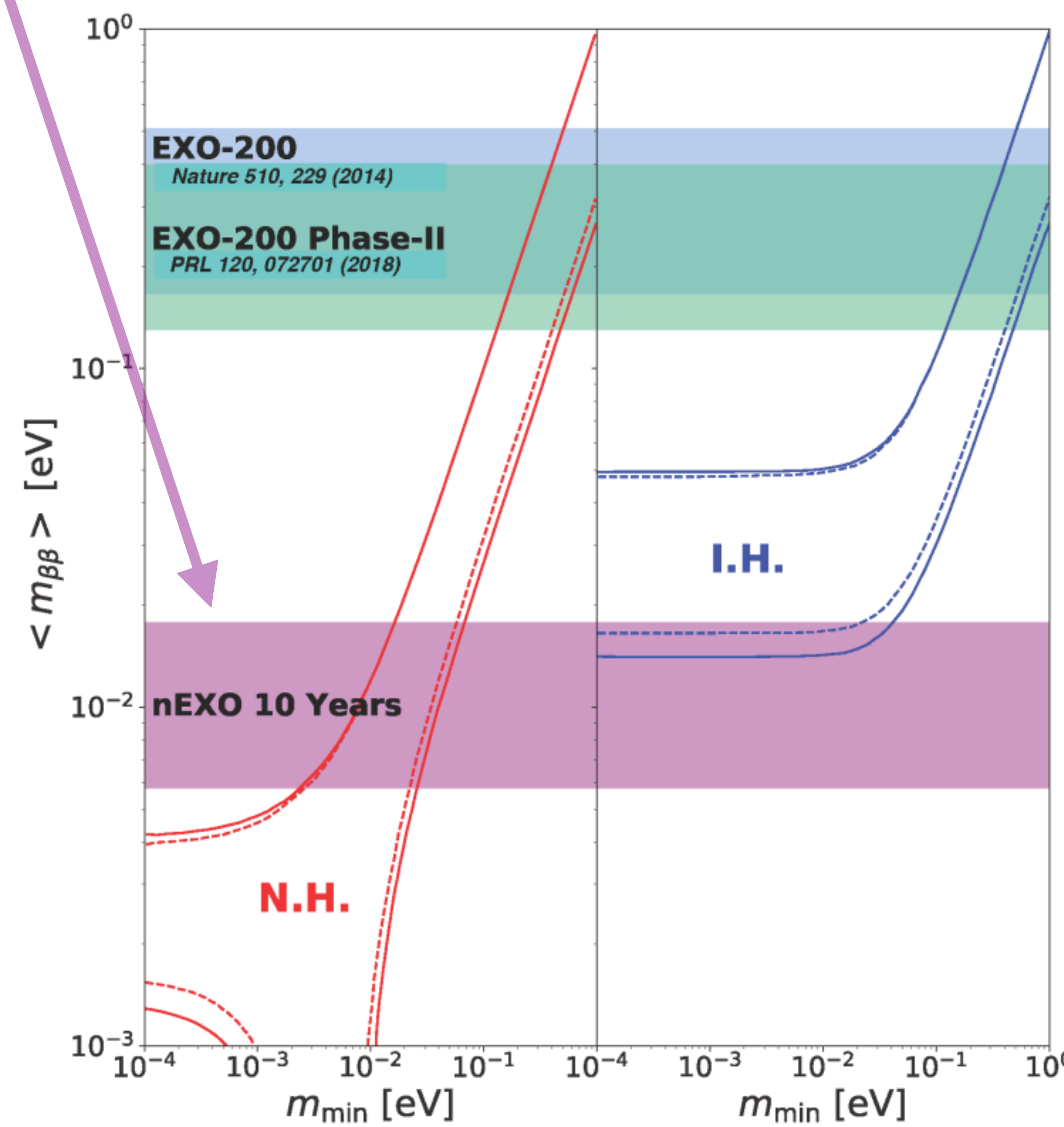
- High Voltage
- SiPMs: QE, radiopurity…
- Internal Electronics
- TPC Internals
- Calibration Concepts

My R&D (BNL/SBU, UMass)

- Coordination of all nEXO R&D
- laser-driven in-situ electron lifetime monitoring using a gold photocathode

nEXO Sensitivity Timeline



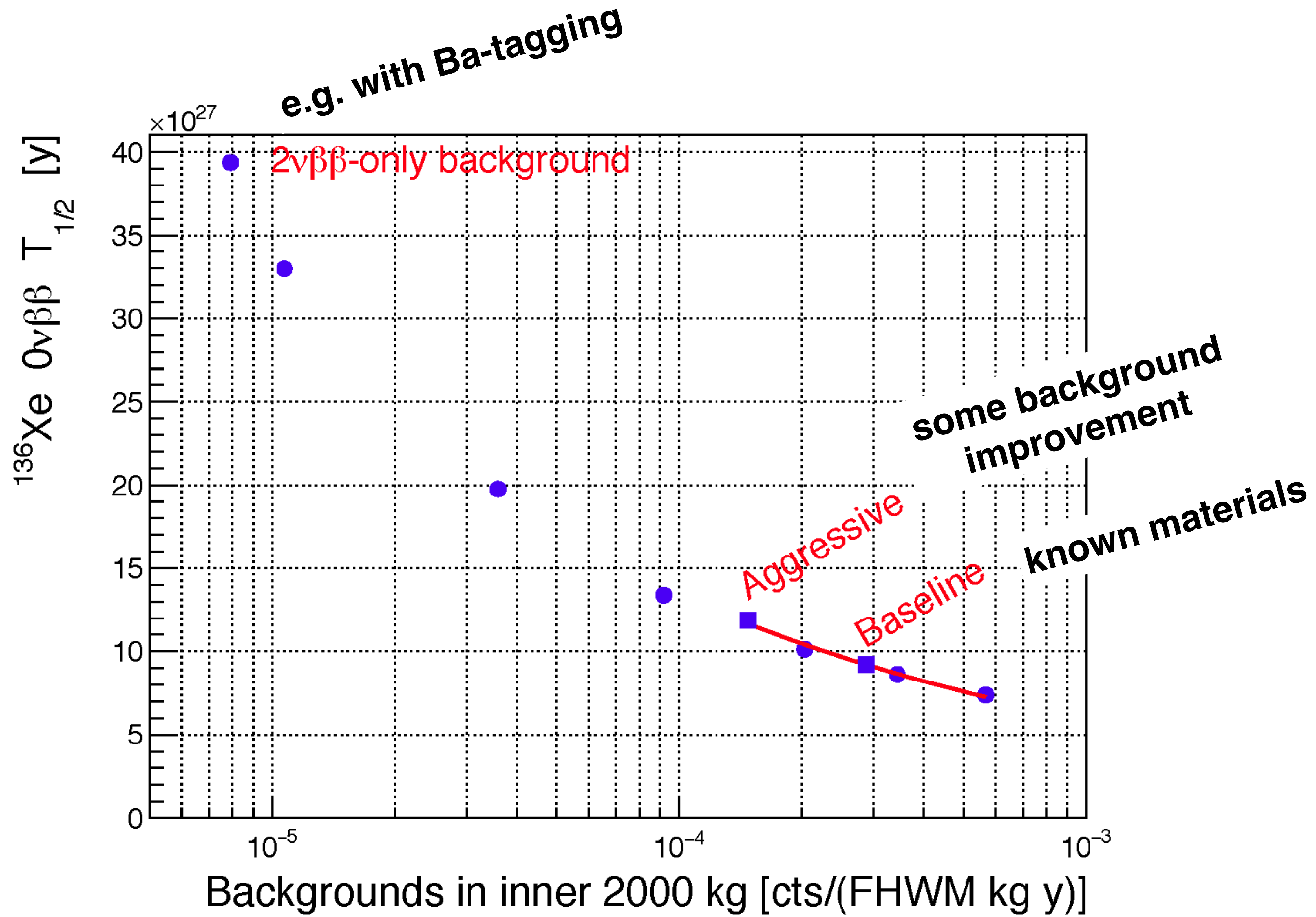


-gA= gAfree=-1.2723

-Band is the envelope of NME:

EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., NuclPhysA 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovicet al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonenand J. Engel PRC 87 064302 (2013)

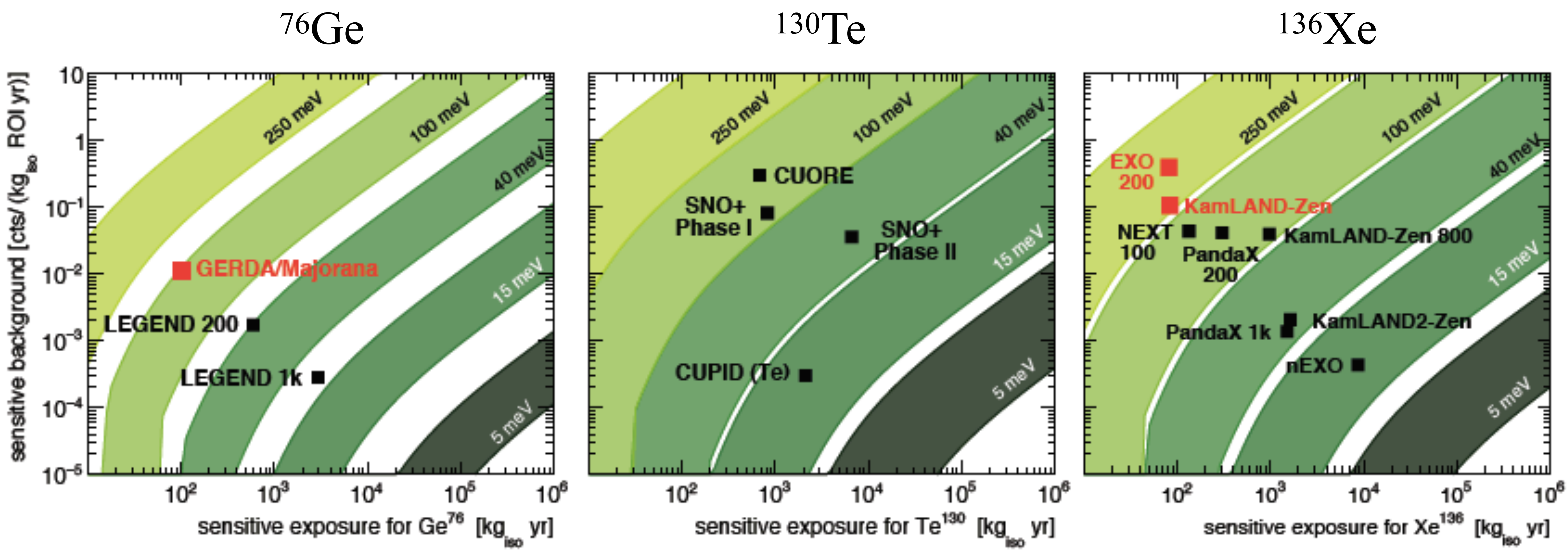
Sensitivity vs Background



Outlook for the Field

Discovery Sensitivity Comparison

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

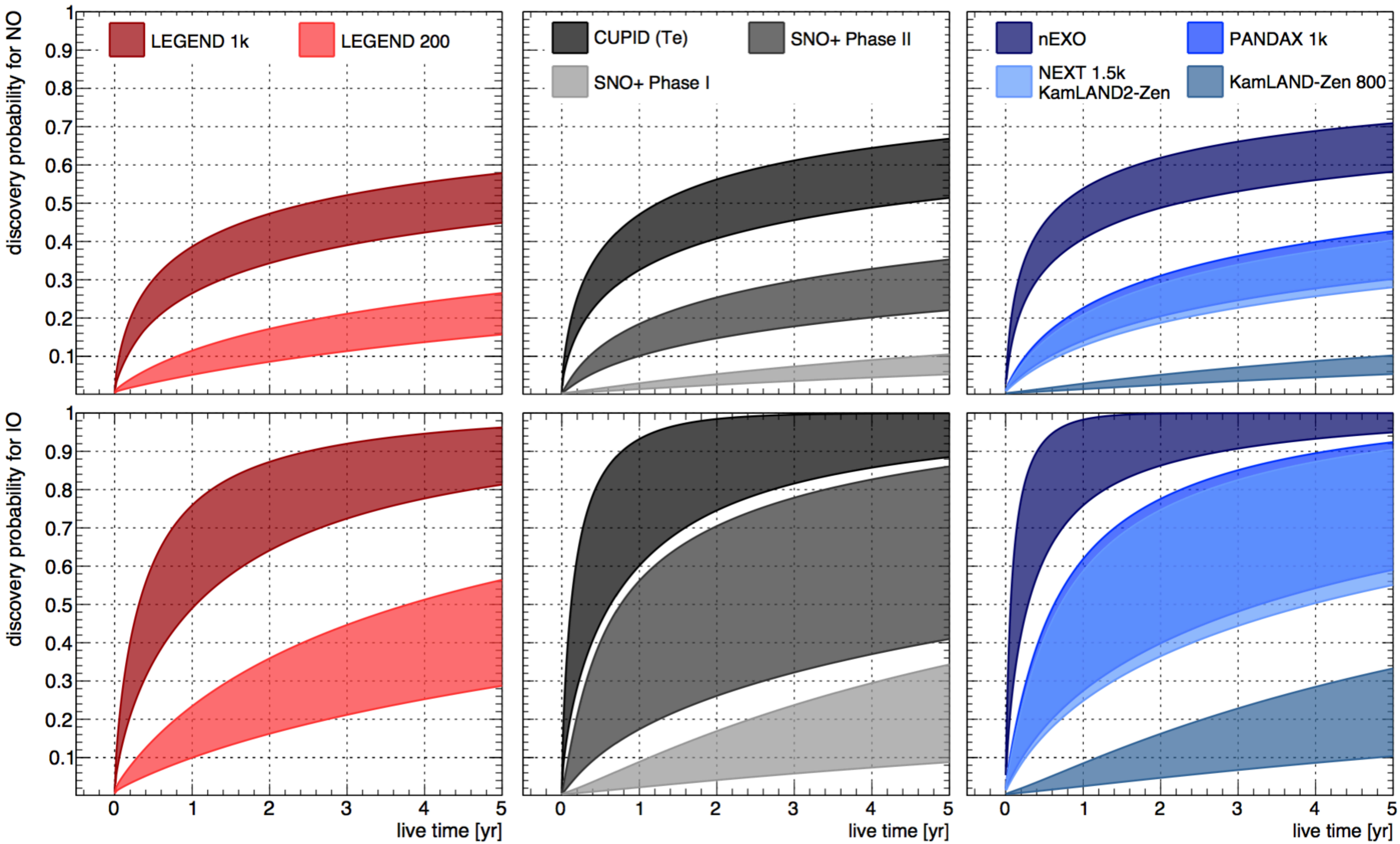


Red : Achieved Backgrounds; Black : Projected Backgrounds

Width of bands based on range of NME values

arXiv:1705.02996v1

Discovery Probability



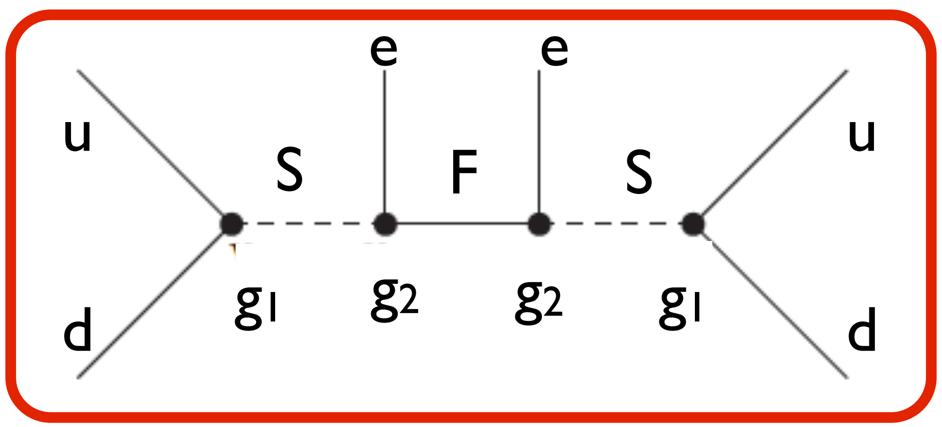
Summary

- There is a worldwide effort to search for neutrinoless double-beta decay in a variety of nuclei
  - Ongoing experiments are working with ~10s to ~100s of kg of isotope
  - Half-life sensitivities are of the order of 10^{26} years
  - Mass sensitivities are beginning to approach the inverted hierarchy
  - EXO-200 terminated in December 2018: sensitivity ~100 meV
- US Nuclear Physics has designated a ton-scale next generation experiment as the highest priority
  - half-life sensitivities approaching 10^{28} years
  - CD-0 was announced for "ton-scale double beta decay"!
  - A "down-select" process will be completed by 2020
  - Liquid Xenon TPC (nEXO) is a leading contender
- The next decade will be exciting
  - Cover the inverted hierarchy (if $0\nu\beta\beta$ dominated by light neutrino exchange)
  - Cross-check a discovery in at least two isotopes
  - Identify the technology to approach the normal hierarchy

TeV-Scale Complementarity

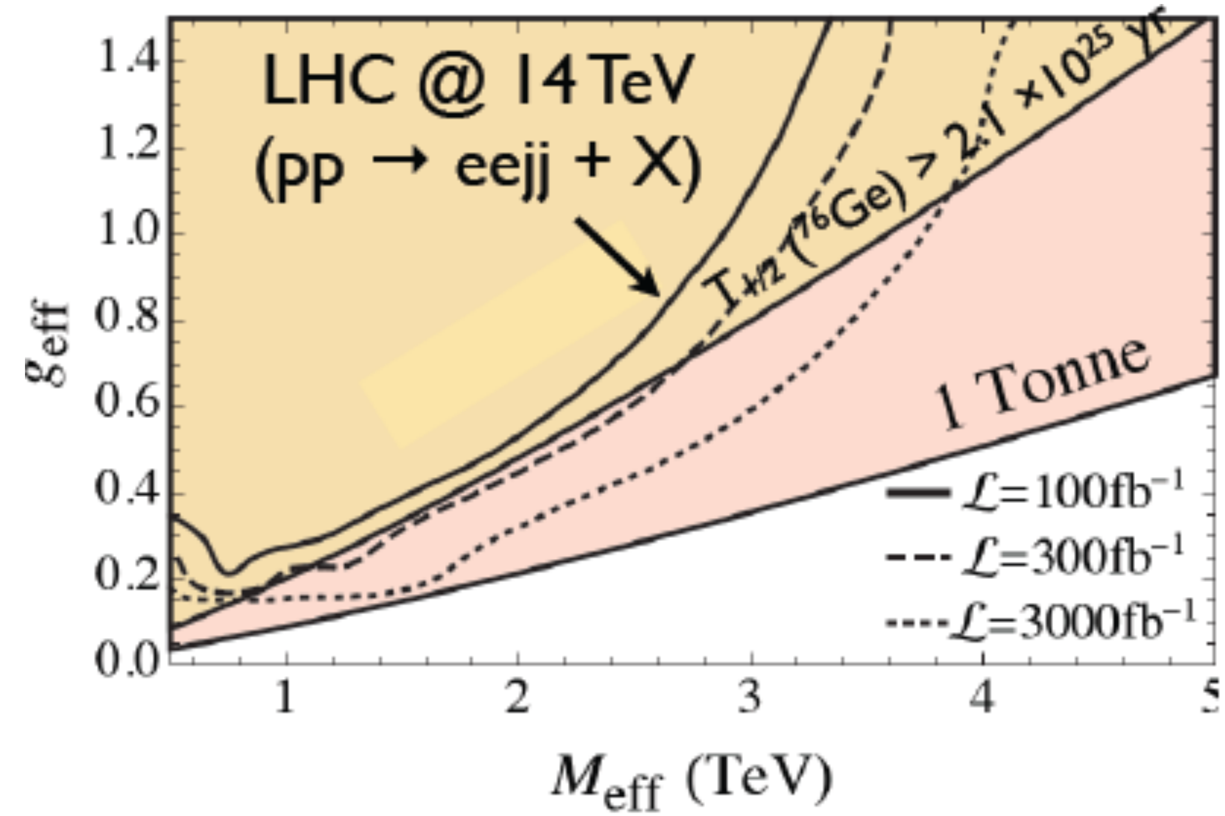
Simplified model ~ RPV-SUSY

$M_S = M_F = M_{eff}$ $(g_{eff})^4 = g_1^2 g_2^2$



$A_{0\nu\beta\beta} \sim (g_{eff})^4 / (M_{eff})^5$

Peng, Ramsey-Musolf, Winslow, 2015

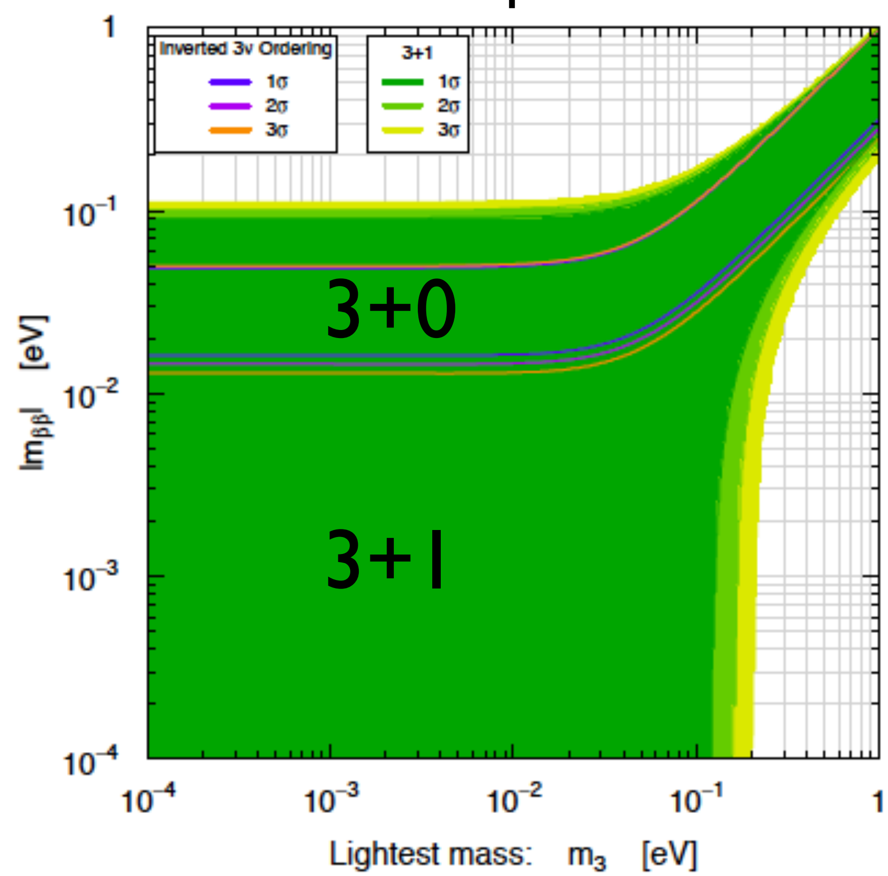


Ton-scale NLDBD significantly extends mass reach (multi TeV) and covers LHC-inaccessible regions

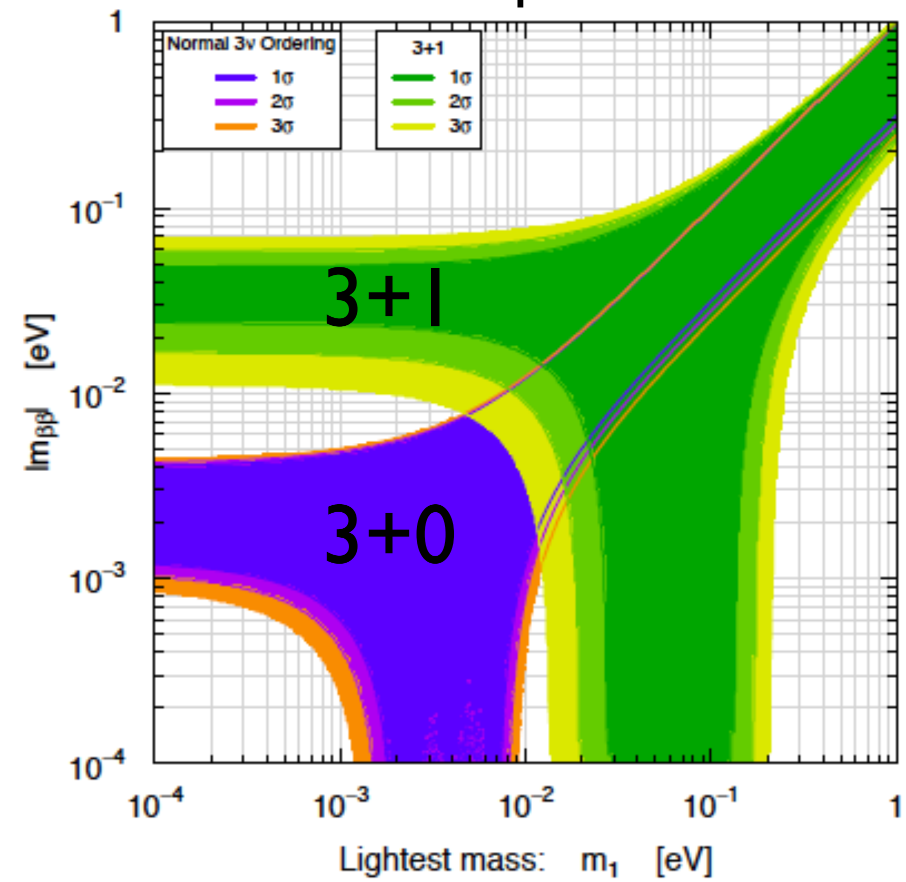
Light Scale BSM

$$m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2\, e^{2i\Phi}\, m_4$$

Inverted Spectrum



Normal Spectrum



Giunti-Zavanin 2015

Usual phenomenology turned around!!

Theory Motivation Summary

- The discovery of neutrino oscillations has made the issue of the existence of Majorana neutrinos particularly pressing
- This is intimately connected to the issue of whether Lepton Number is a conserved quantity in Standard Model processes
- Neutrinoless Double-Beta Decay is the only plausible terrestrial experiment that can shed light on the aforementioned critical questions
- The discovery of this process and its subsequent study could shed light on some of the most profound questions in nuclear physics, particle physics, astrophysics and cosmology

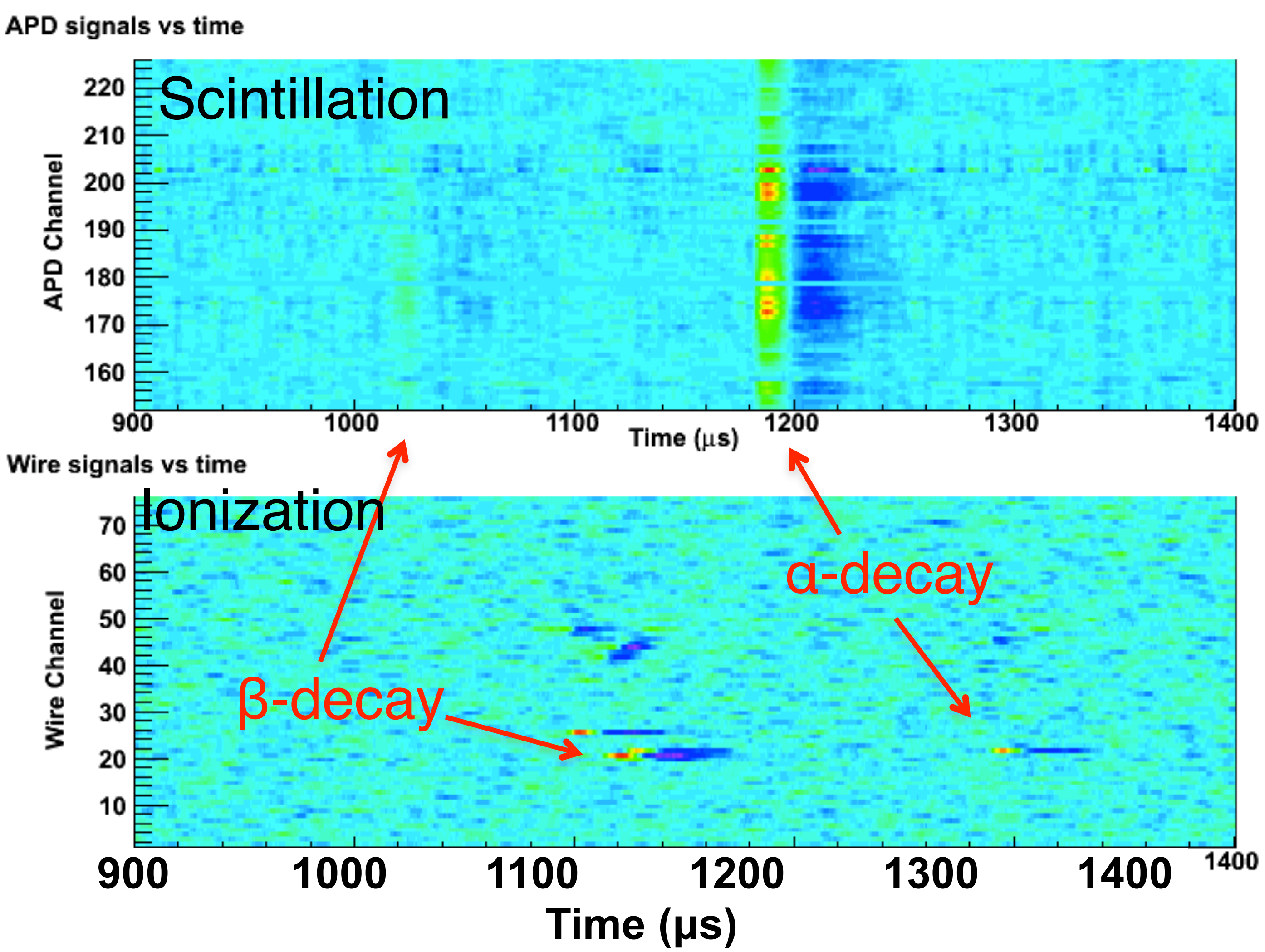
Backgrounds

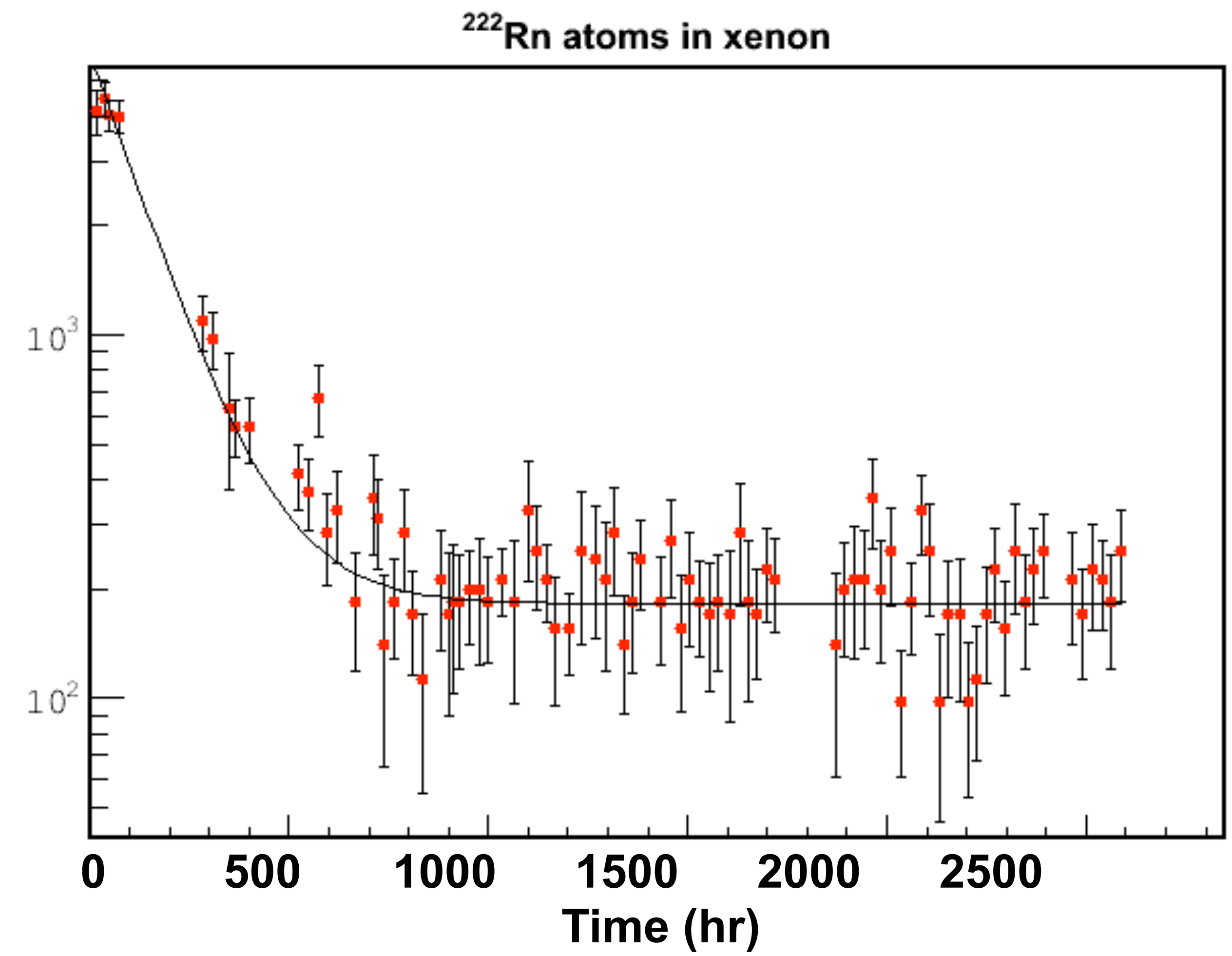
- Primordial, natural radioactivity in the detector and array components: U, Th, K
- Backgrounds from cosmogenic activation while material is above ground (ββ-isotope or shield specific, ^{60}Co, ^{3}H, ^{39}Ar, ^{42}Ar, …)
- Backgrounds from the surrounding environment:
  external γ, (α,n), (n,α), Rn 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 ton-scale, impact depends on resolution)
- neutrino backgrounds (for ton-scale, can be a contribution)

Discovery Strategy

- 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

Rn Content in Liquid Xenon



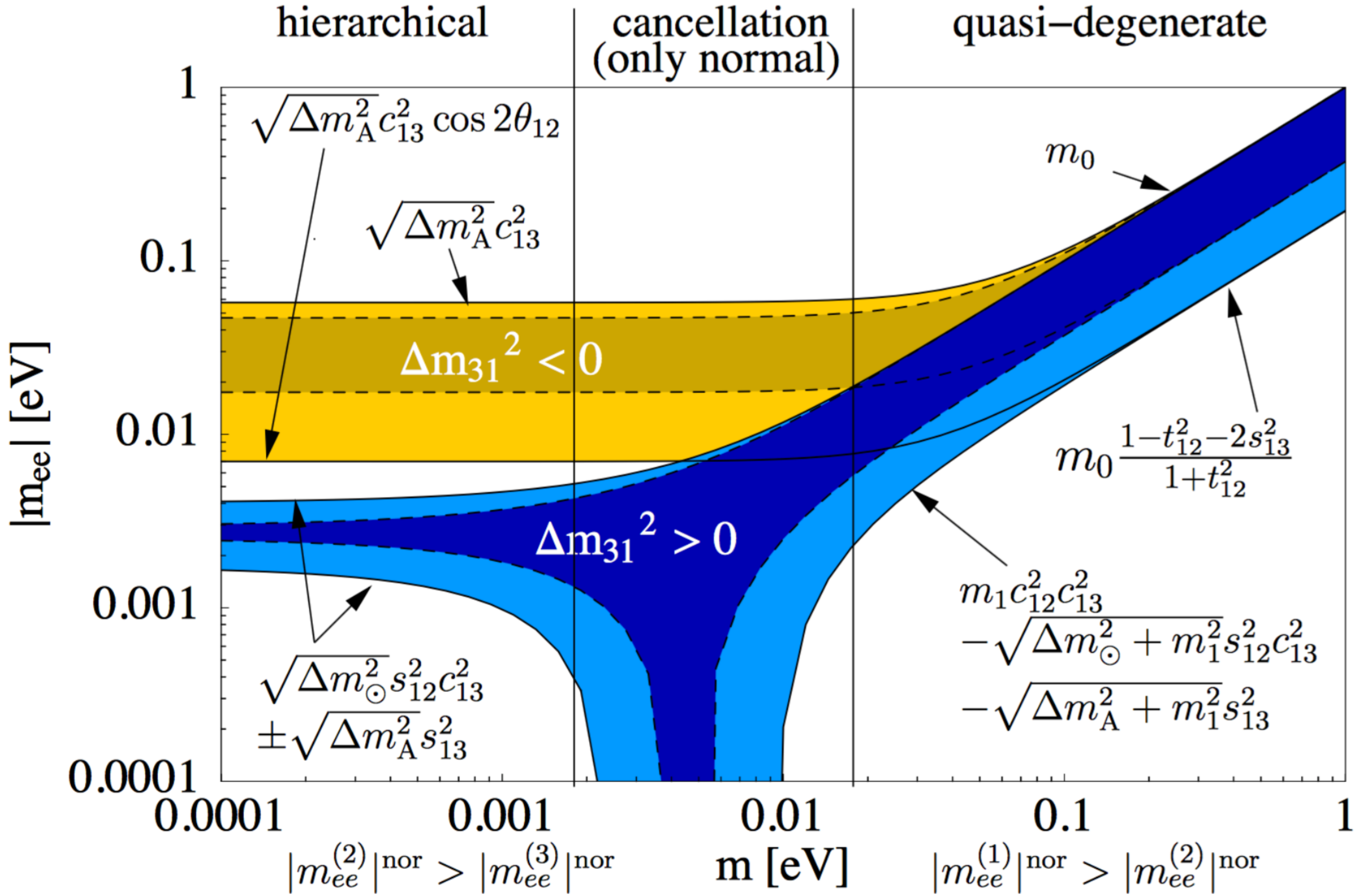


^{214}Bi – ^{214}Po correlation in the EXO-200 detector

Total ^{222}Rn in LXe after initial fill

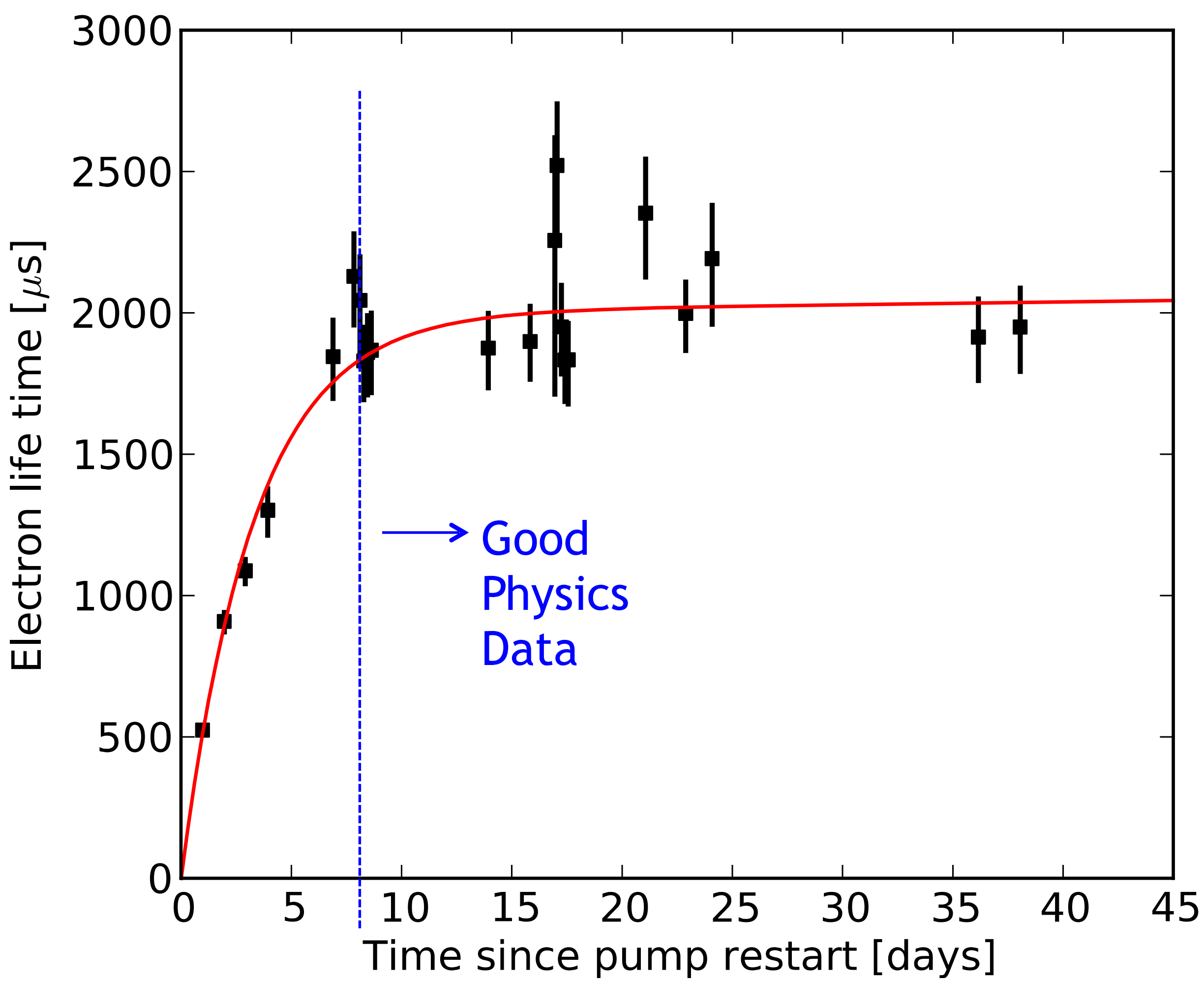
Long-term study shows a constant source of ^{222}Rn dissolving in ^{enr}LXe: 360 ± 65 μBq (Fid. vol.)

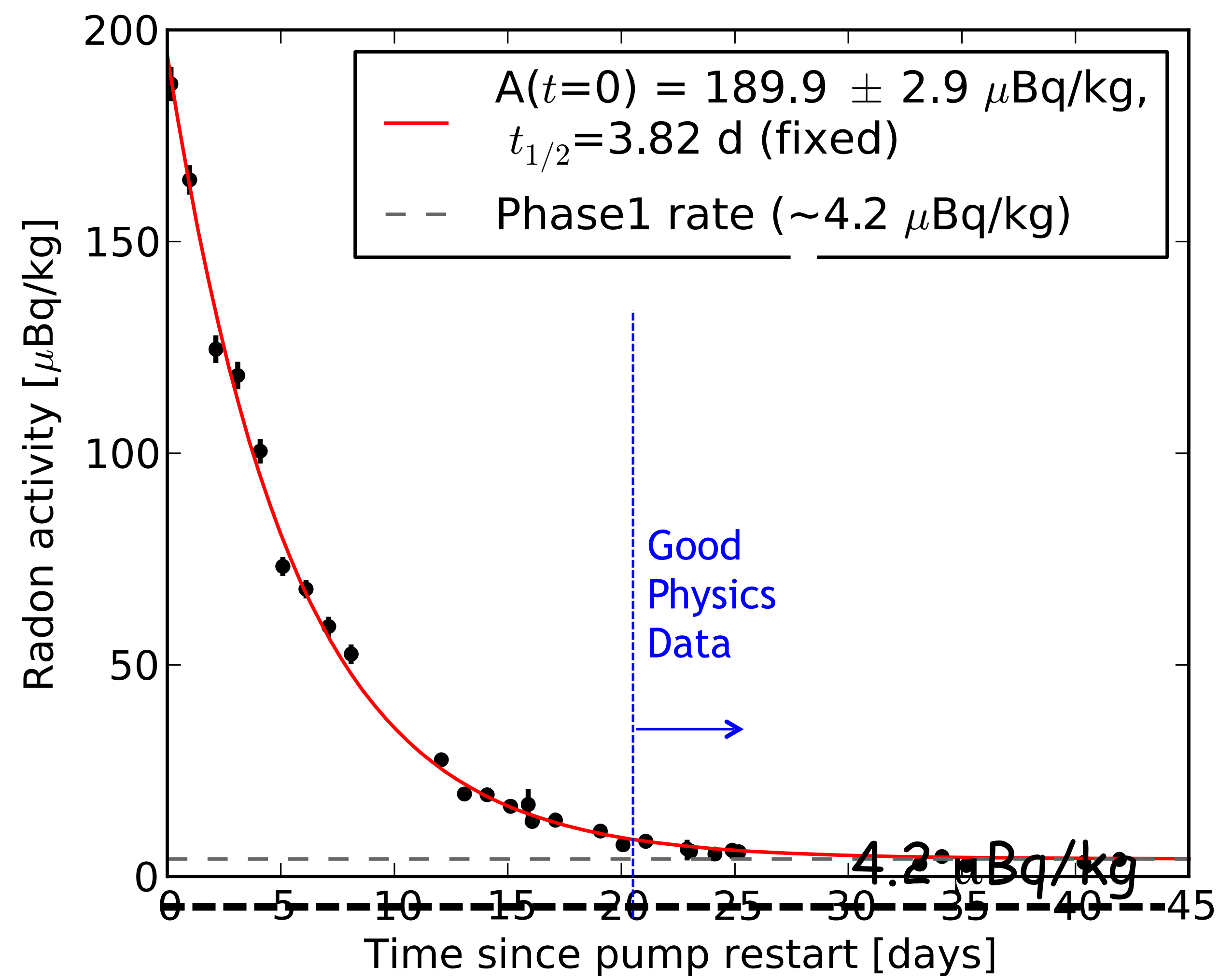
Mass Reach Plot



Phase-II Running

- **EXO-200 Phase-II operation begins on 31 Jan 2016, after enriched liquid xenon fill.**
- **Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.**





New results to be released next week!

J. Engel

Nuclear Matrix Elements

$$M_{0\nu} = M_{0\nu}^{GT} - \frac{g_V^2}{g_A^2} M_{0\nu}^{F} + \ldots$$

with

$$M_{0\nu}^{GT} = \langle F | \, | \sum_{i,j} H(r_{ij}) \, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \; \tau_i^+ \tau_j^+ \; | I \rangle + \ldots$$

$$M_{0\nu}^{F} = \langle F | \sum_{i,j} H(r_{ij}) \; \tau_i^+ \tau_j^+ \; | I \rangle + \ldots$$

$$H(r) \approx \frac{2R}{\pi r} \int_0^\infty dq \frac{\sin qr}{q + \bar{E} - (E_i + E_f)/2} \quad \text{roughly} \propto 1/r$$

Contribution to integral peaks at $q \approx 100$ MeV inside nucleus.

Corrections are from "forbidden" terms, weak nucleon form factors, many-body currents …

Barium Tagging in Solid Xenon