Lecture 2

Neutrinoless Double Beta Decay

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Resources and Acknowledgements

- The Physics of Massive Neutrinos: Boehm and Vogel, Cambridge University Press, 2nd Edition, 1992
- The Dynamics of the Standard Model: Donoghue, Golowich and Holstein, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Second Edition, 2014
- 2016 NNPSS Lectures of Vincenzo Cirigliano at MIT
- Writeup of Lectures by Petr Vogel, Massive Neutrinos, 1997 Mexican Summer School on Astrophysics and Cosmology
- Slides from the opening workshop of the INT Program on Neutrinoless Double-Beta Decay, June 2017: http://www.int.washington.edu/talks/WorkShops/int_17_2a/

The EXO-200 and nEXO collaborations and many other colleagues: J. Detwiler, J. Engel, K. Heeger, Y. Kolomensky, R. Maruyama, M. Ramsey-Musolf, W. Rodejohann, J. Wilkerson…

Plan for Lectures

- **Lecture 1**

  necessary general knowledge for experimentalists

  - Nomenclature, Theoretical Overview, Physics Motivation, Goal for Experiments

- **Lecture 2**

  necessary general knowledge for theorists

  - Overview of Experimental Techniques, Overview of Experimental Program Worldwide, Details of 2 Initiatives aiming for the Ton-Scale, Detailed Description of EXO-200 and nEXO (the 3rd ton-scale initiative)

Recap

Postulate the Right-Handed Neutrino

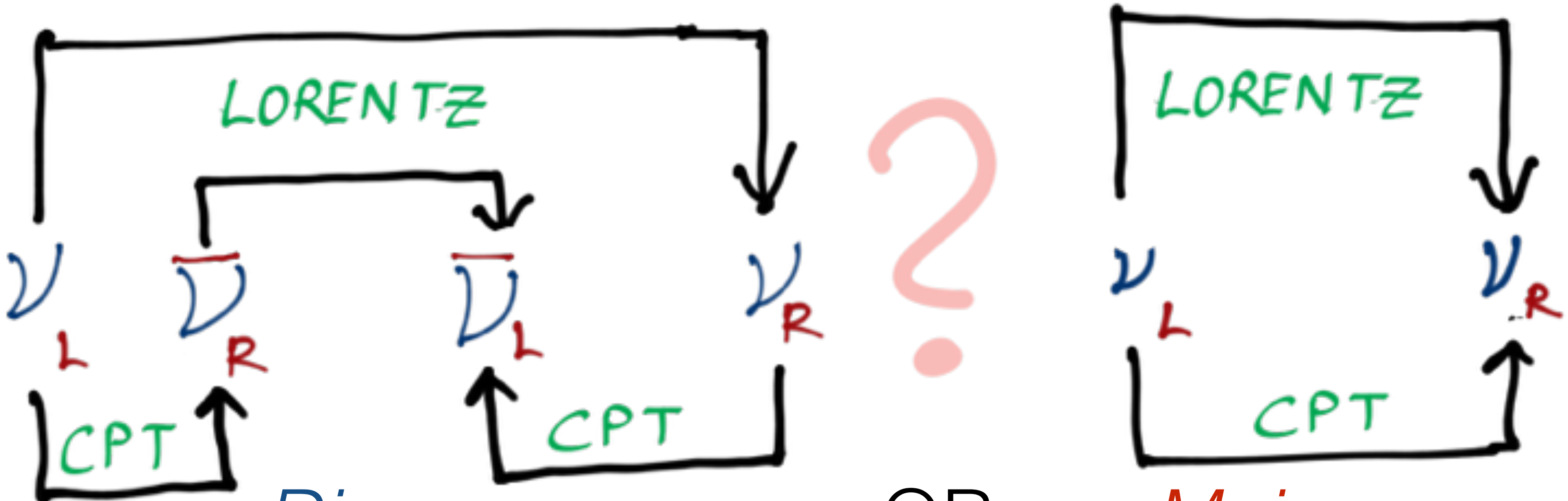
$$\nu_L \xrightarrow[\text{boost}]{\text{Lorentz}} \nu_R \qquad\qquad u_L \xrightarrow[\text{propagation}]{\text{free}} u_R$$

helicity: conserved but
not Lorentz invariant

chirality: not conserved
but Lorentz invariant

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

A profound question:



Dirac OR *Majorana*

What is the Discovery Measurement?

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

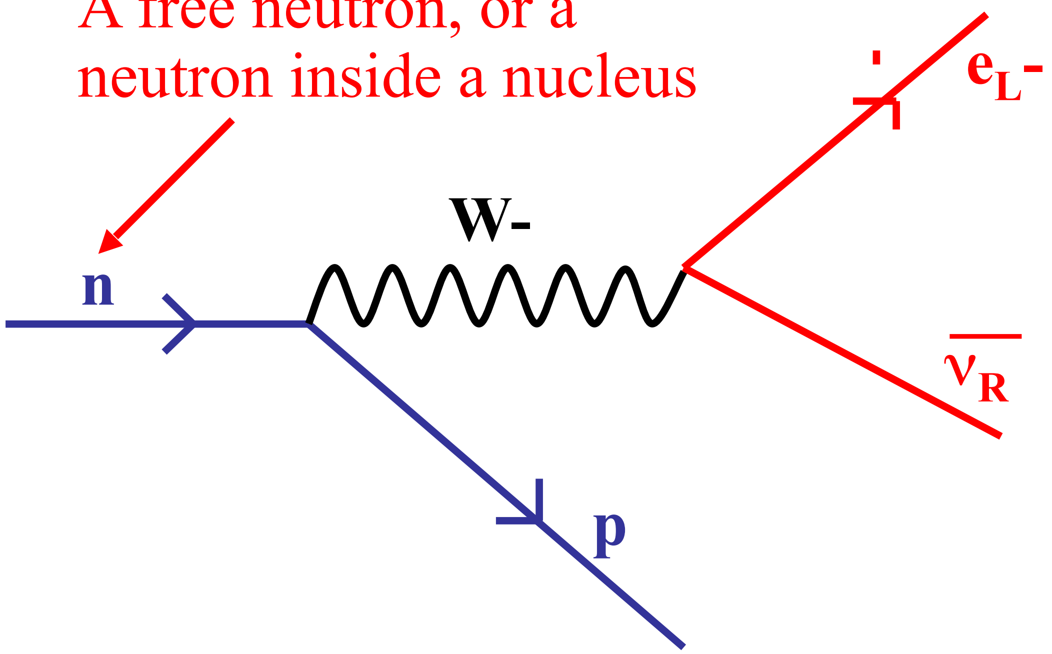
Practically: discover **Neutrinoless Double-Beta Decay**

($0\nu\beta\beta$)

Lepton Number Conserving Standard Model Process

2ν Double Beta Decay

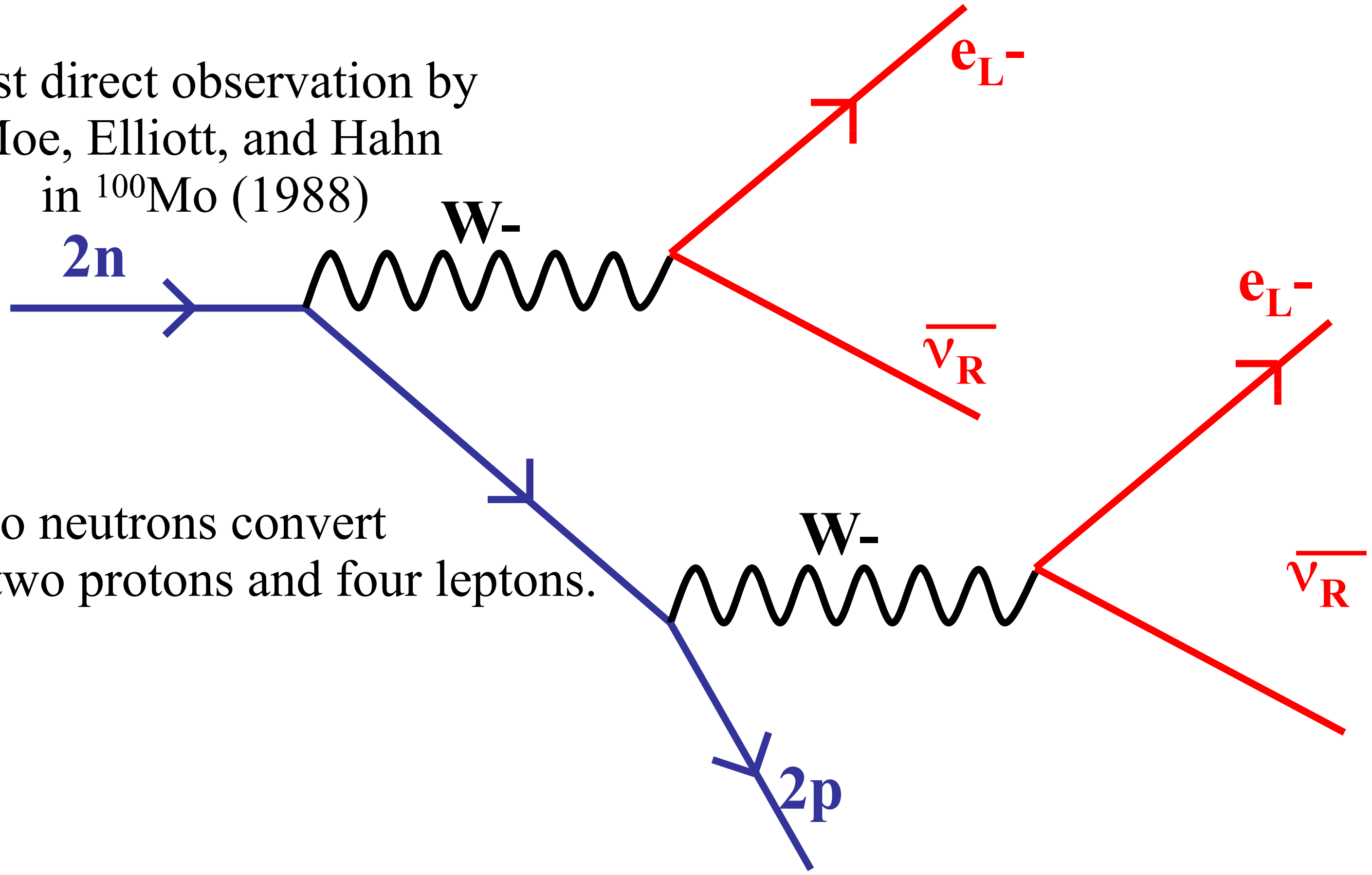
A free neutron, or a neutron inside a nucleus



Nuclear Beta Decay

Nuclear Double-Beta Decay with the emission of two neutrinos

First direct observation by Moe, Elliott, and Hahn in ^{100}Mo (1988)

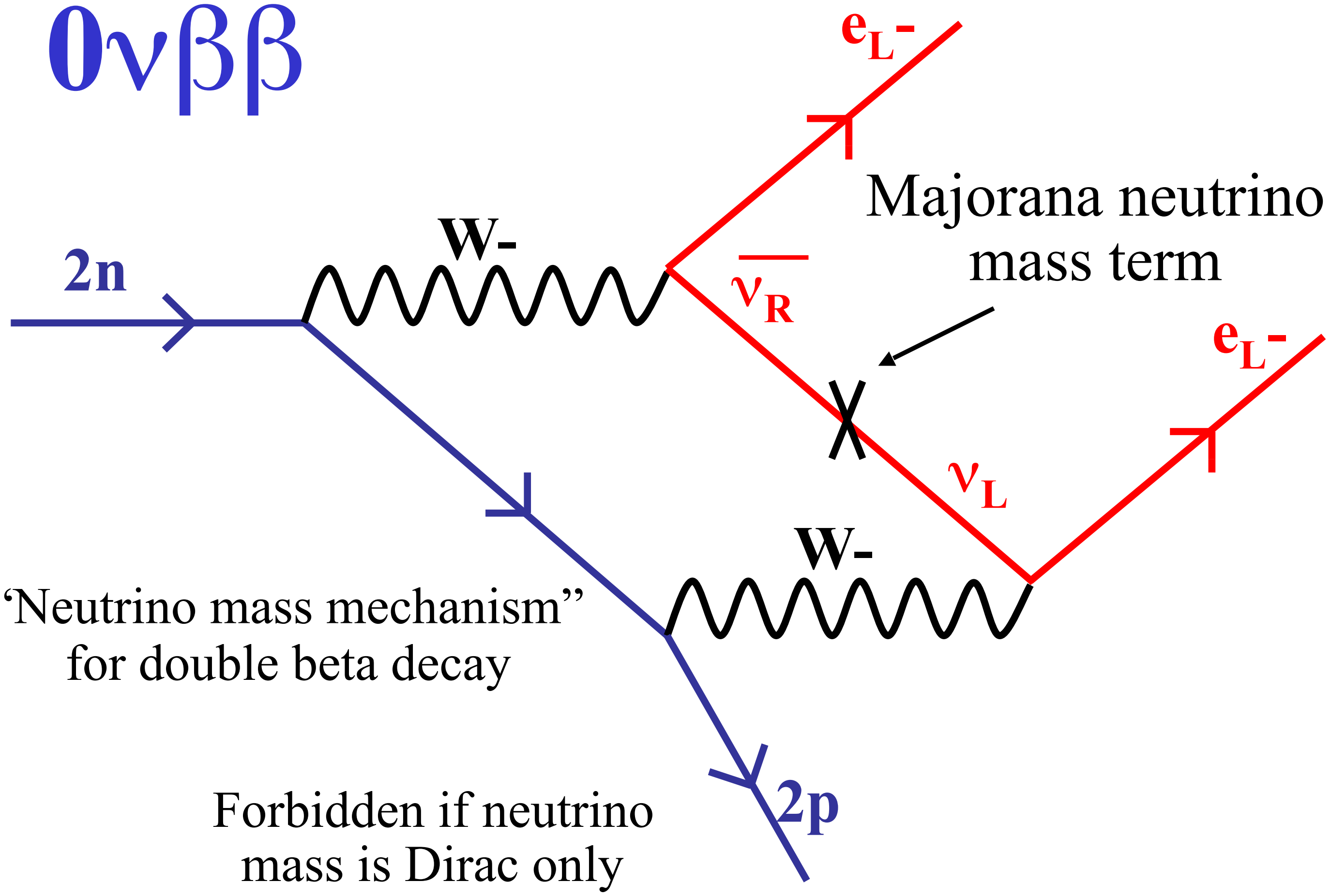


Two neutrons convert to two protons and four leptons.

0ν Double Beta Decay

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

0νββ



Majorana neutrino mass term

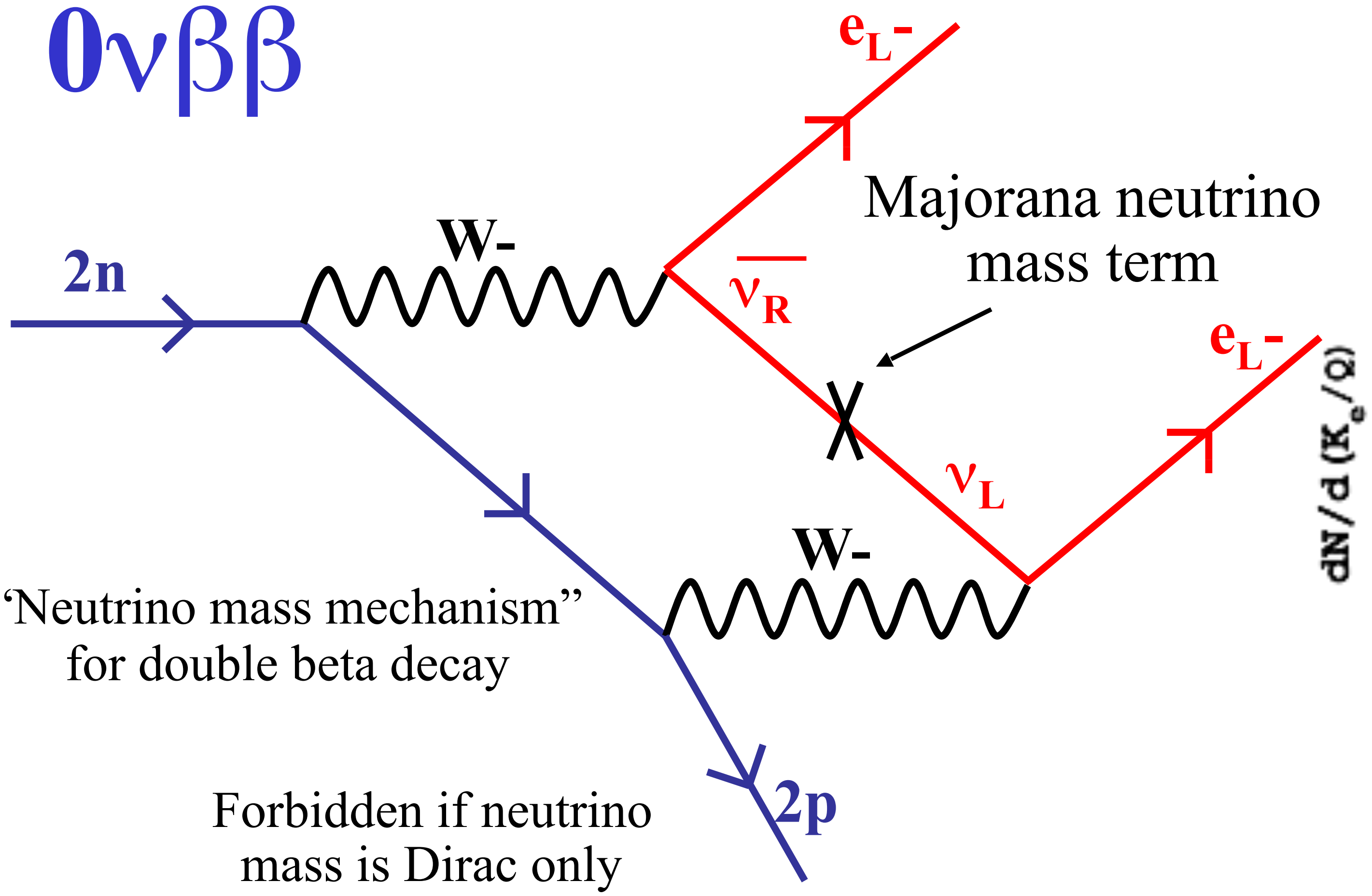
“Neutrino mass mechanism” for double beta decay

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

0ν Double Beta Decay

Experimental Signature

0νββ



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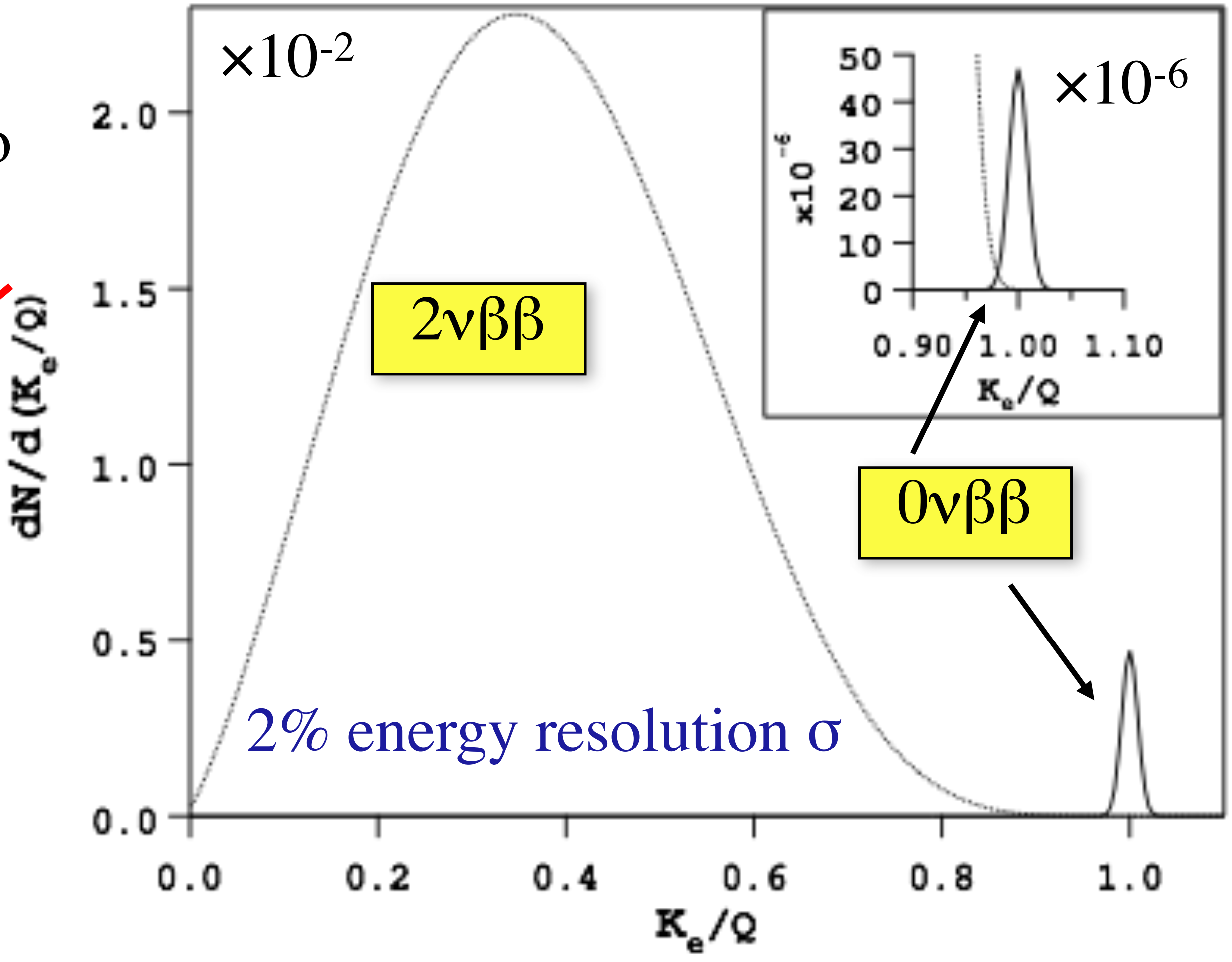
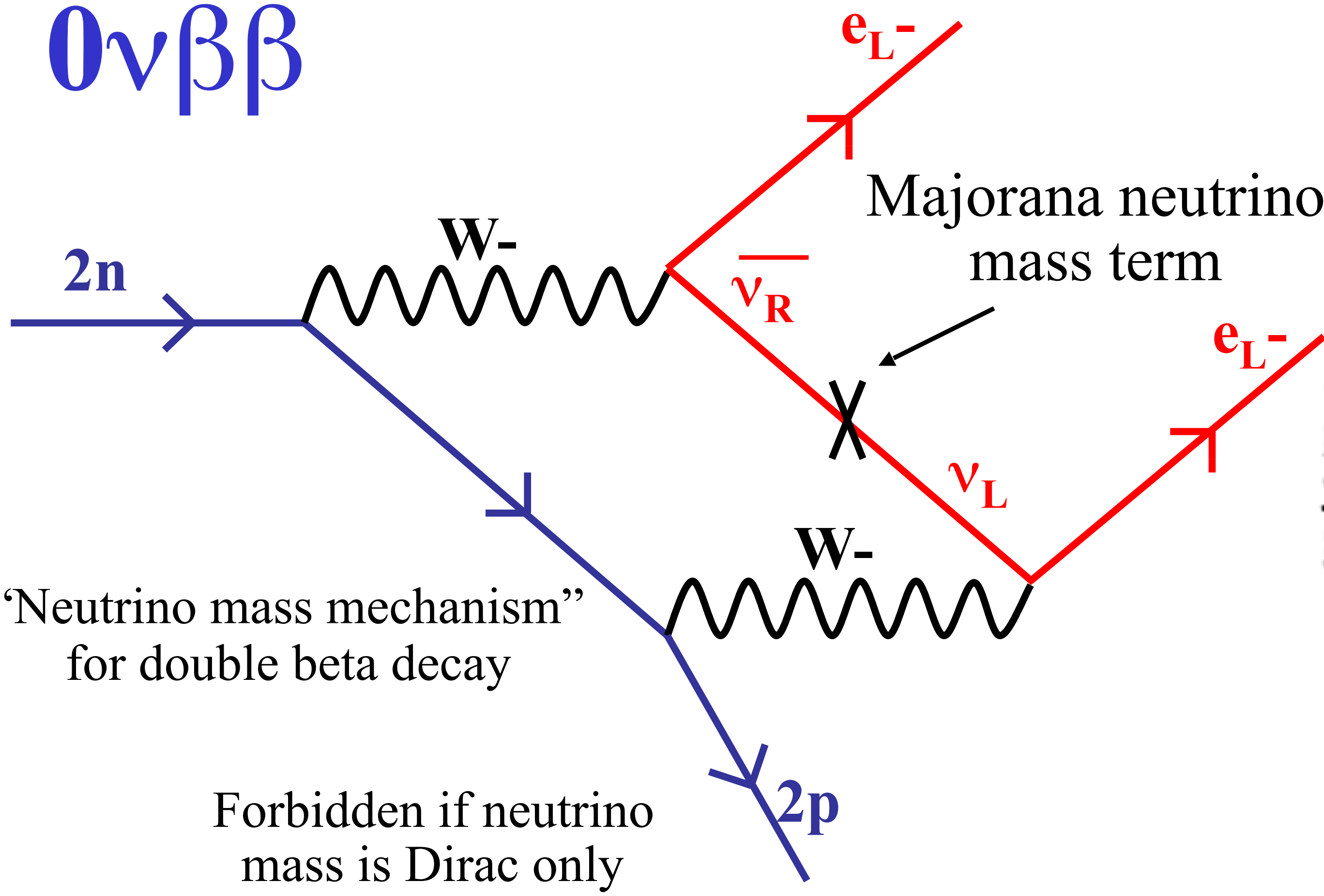


2% energy resolution σ

0ν Double Beta Decay

Experimental Signature

$0\nu\beta\beta$



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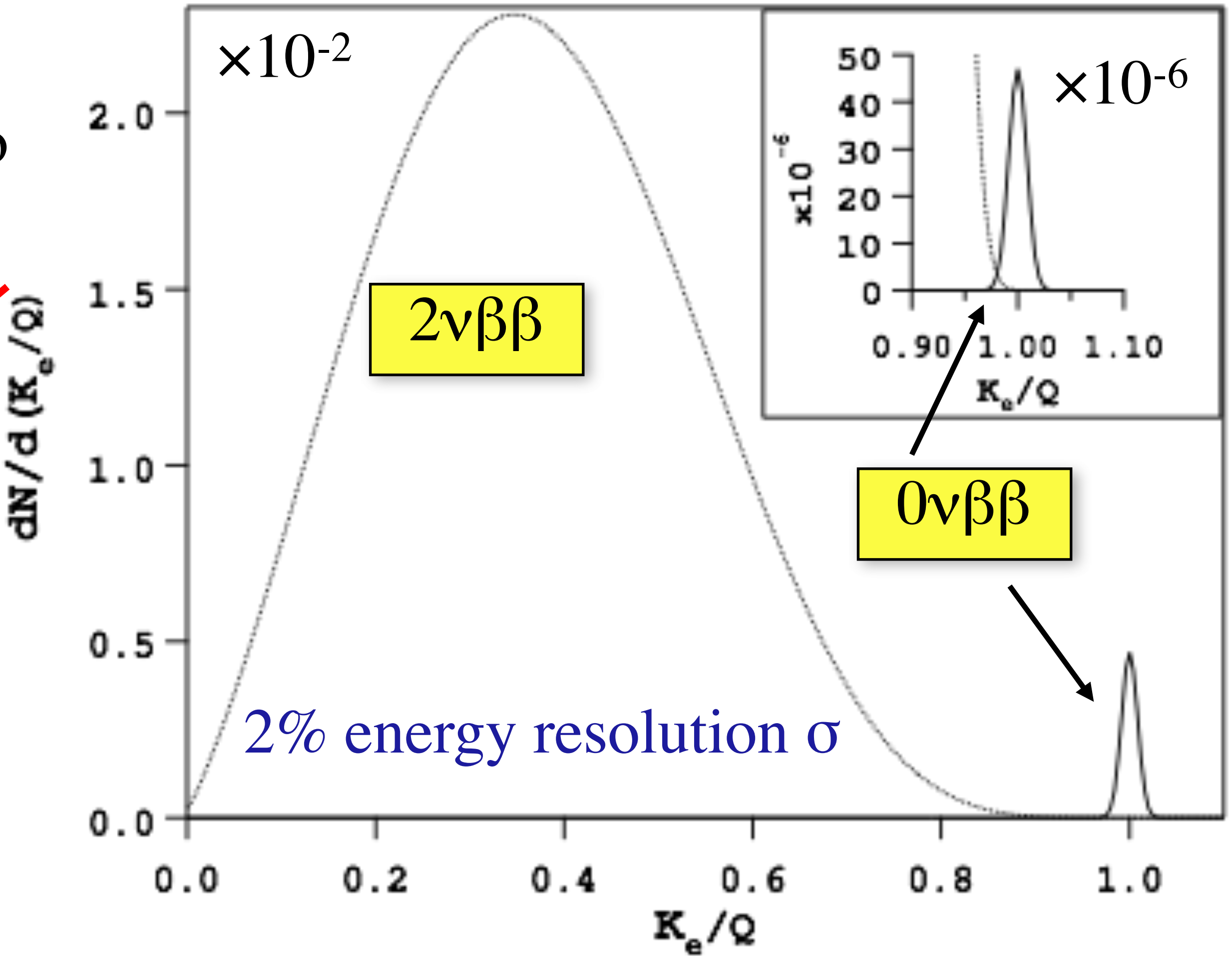


2% energy resolution σ

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

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→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn→^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.479	8.9
^{150}Nd→^{150}Sm	3.367	5.6

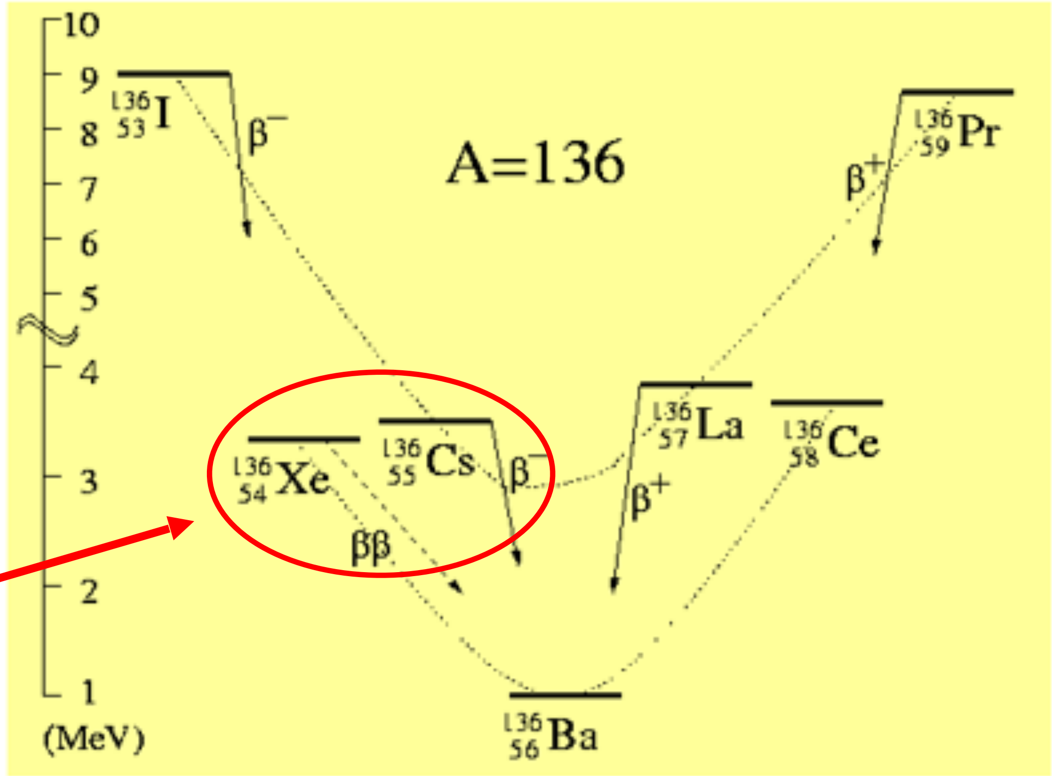
Choose nuclei where single beta decay forbidden

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

Decay Rate for 0νββ

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

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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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For light neutrino exchange

PMNS Matrix

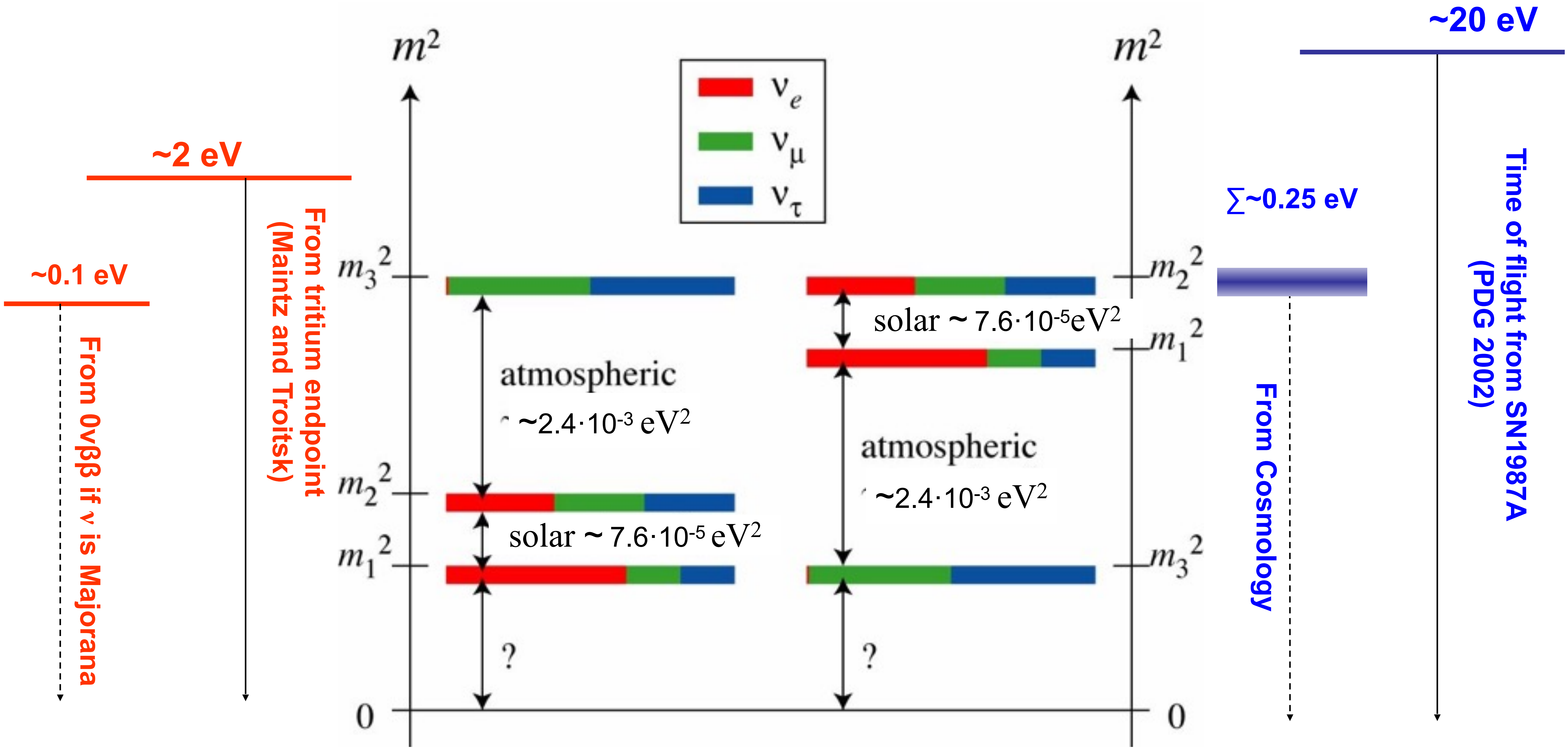
All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta} \rangle = \sum_i U_{ie}^2 m_i$

$m_{\beta\beta} \sim 1$ 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

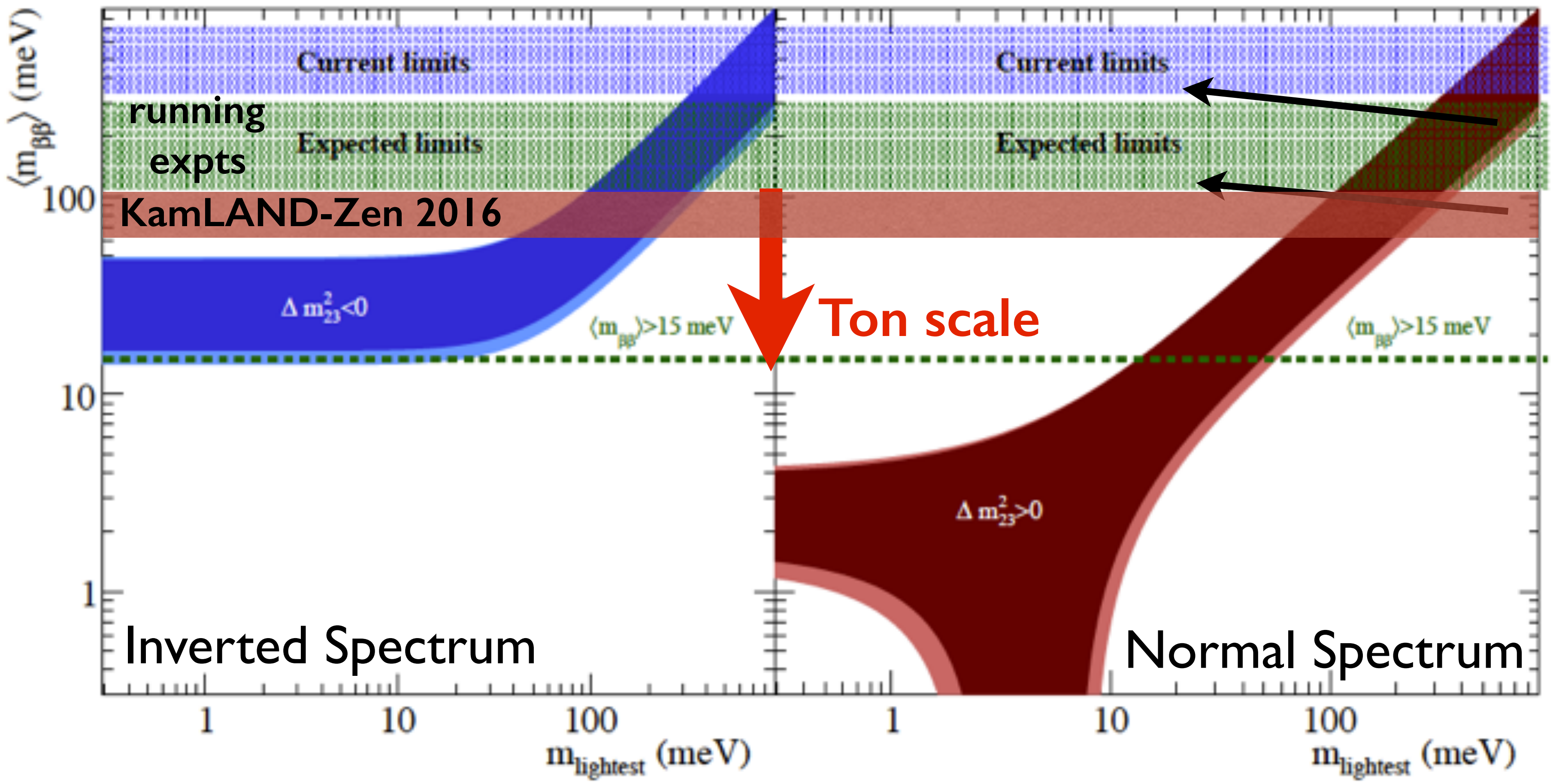
Absolute Neutrino Mass Scale



Discovery Reach

- Strong correlation of 0νββ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

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



Assume most "pessimistic" values for nuclear matrix elements

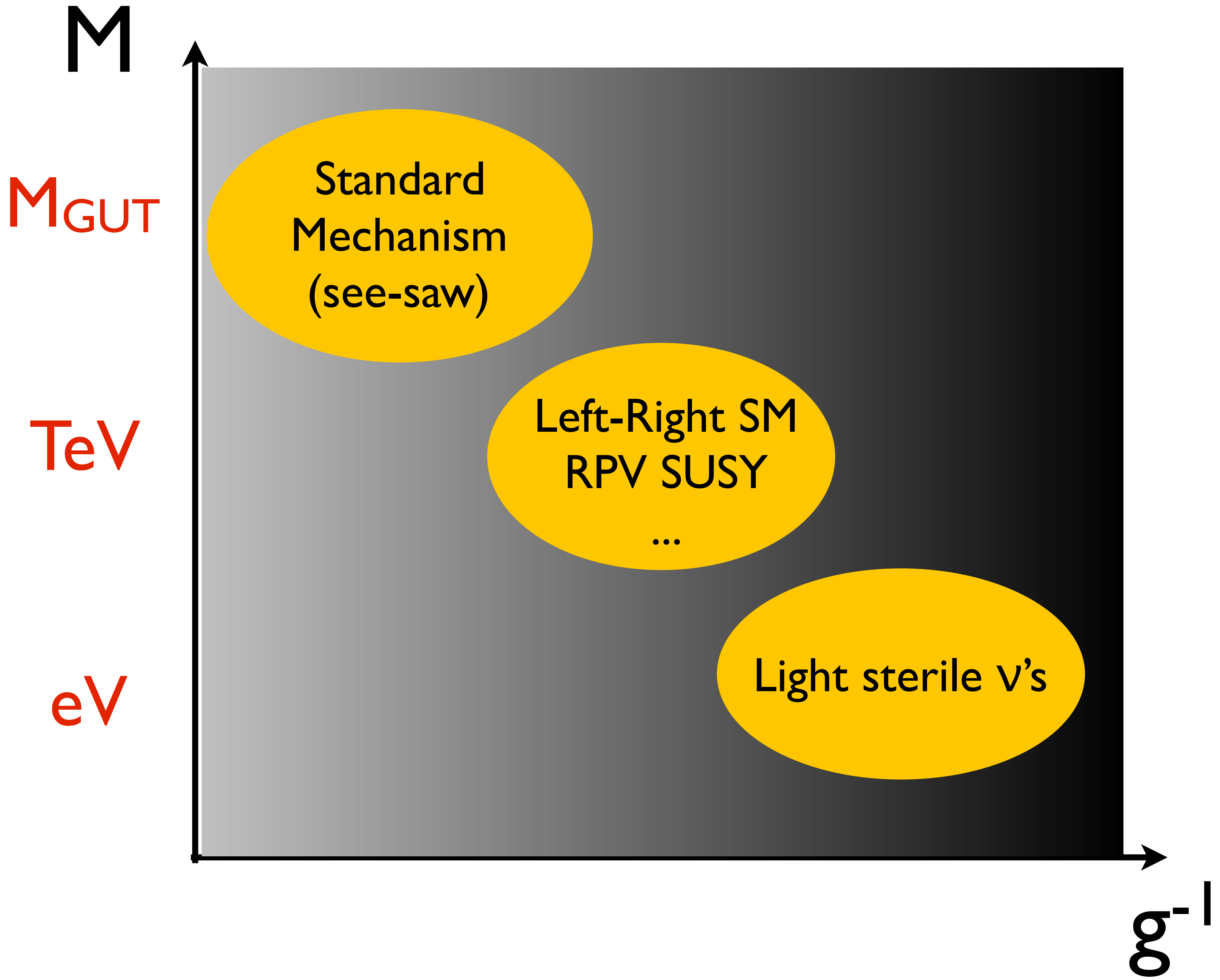
Dark bands: unknown phases

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

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

Other Possibilities for the Black Box

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



M

M_{GUT}

TeV

eV

Standard Mechanism (see-saw)

Left-Right SM
RPV SUSY
...

Light sterile ν's

g^{-1}

Towards Discovery Experiments

Nuclear Matrix Elements

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

with

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

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

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

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

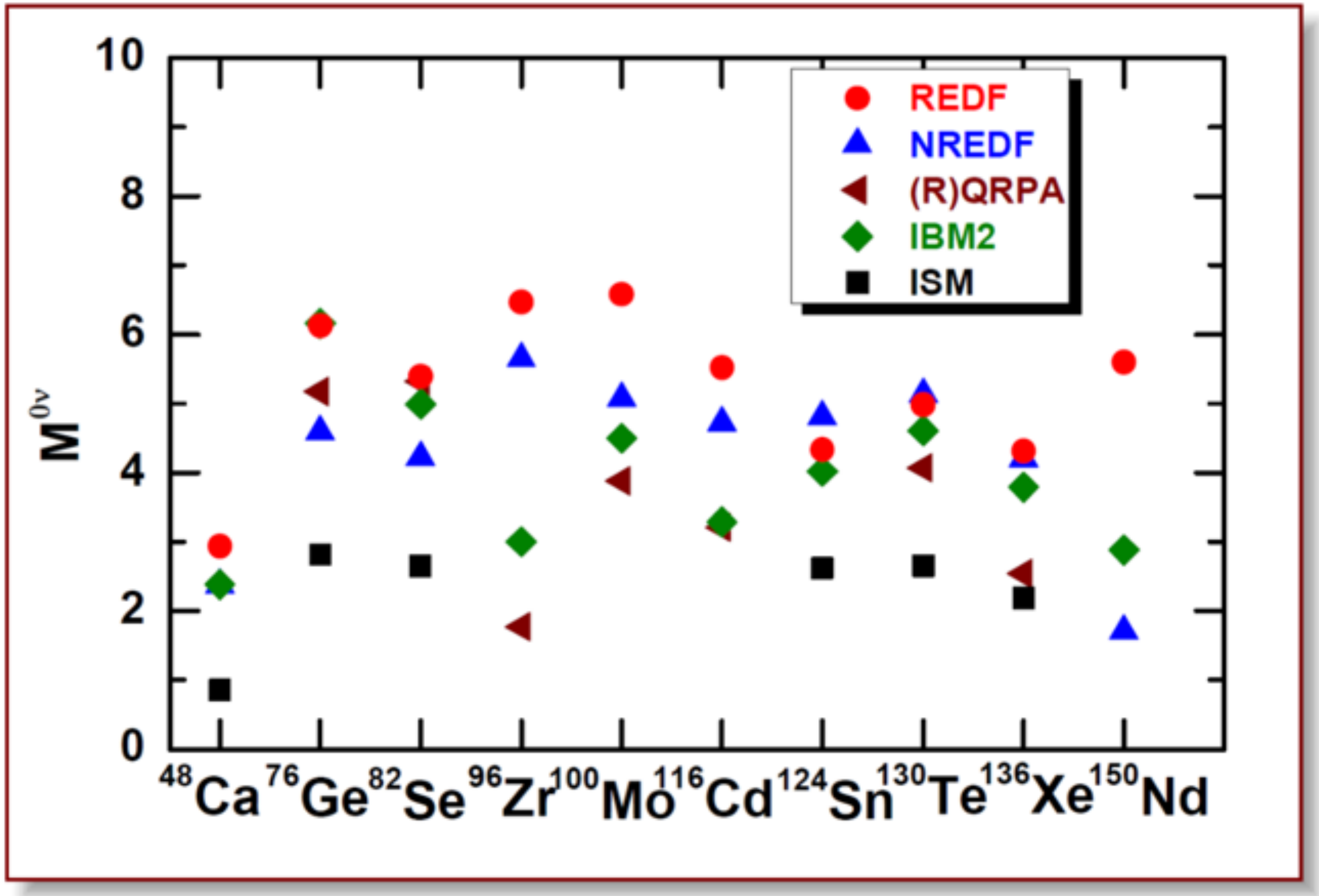
Corrections are from "forbidden" terms, weak nucleon form factors, many-body currents …

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

Signal and Background

An experimental challenge of rare events

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

If it exists, half-lives of 0νββ would be longer (Current limits > few x 10^{25} years)

Half life (years)	Signal (cts/tonne-year)
10^{25}	500
5x10^{26}	10
5x10^{27}	1
5 x10^{28}	0.1

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

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

background free

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

background limited

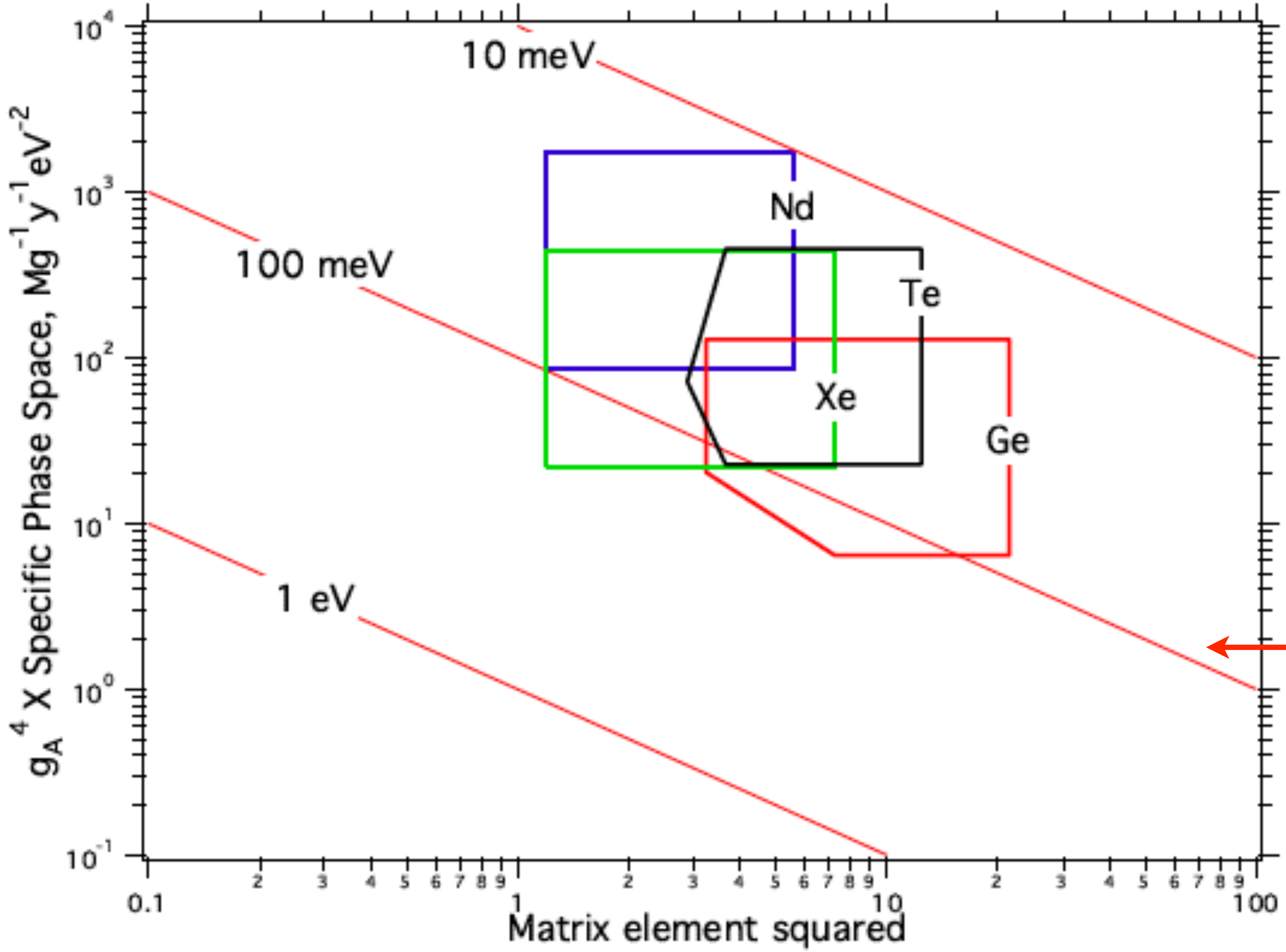
backgrounds do not always scale with detector mass

Favorite Isotope?

For Ge, Te, Xe, Nd

← uncertainty on NME^2 →

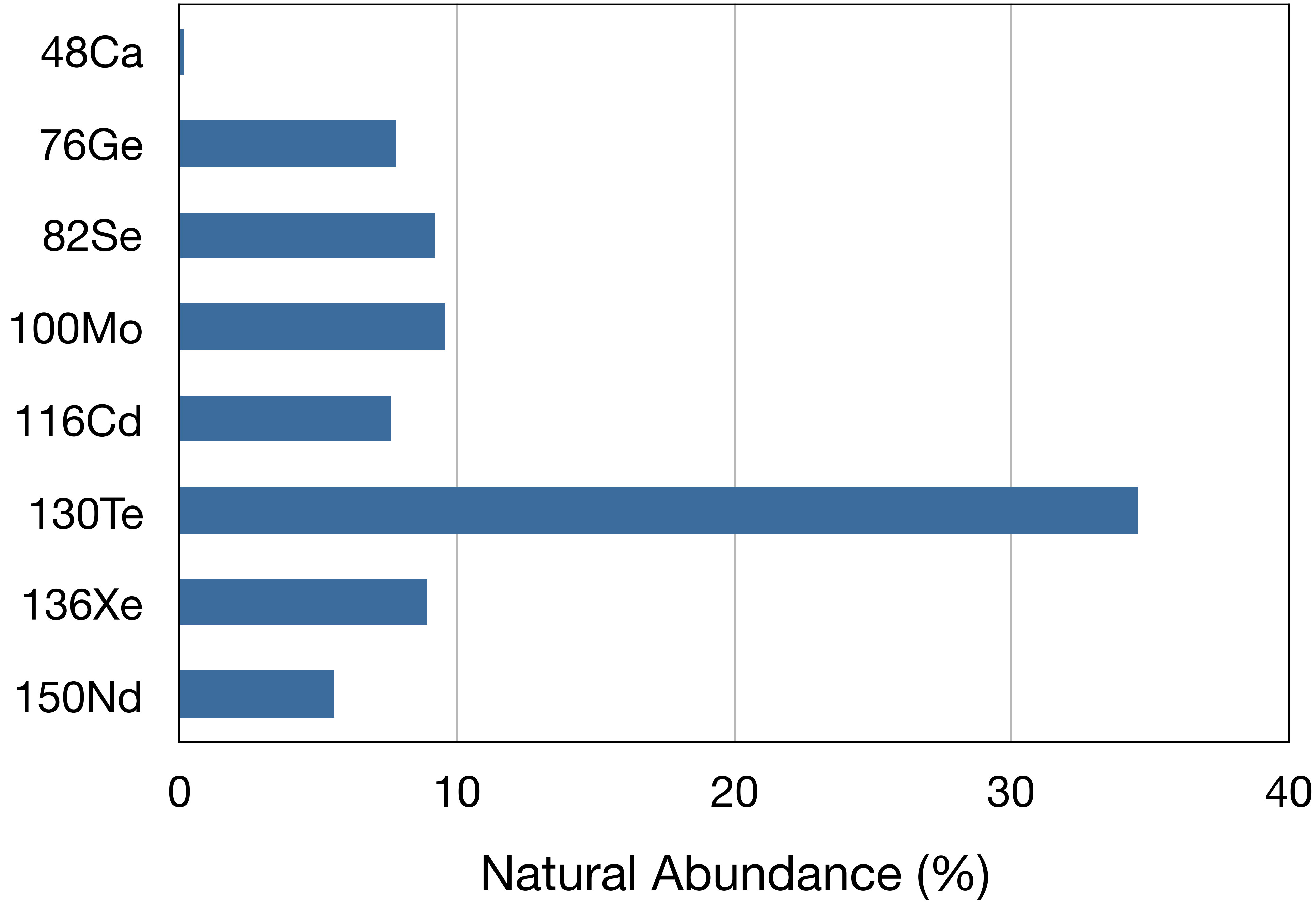
R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)



↑ uncertainty on value of g_A^4 ↓

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

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

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**

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)

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

a = source isotopic abundance

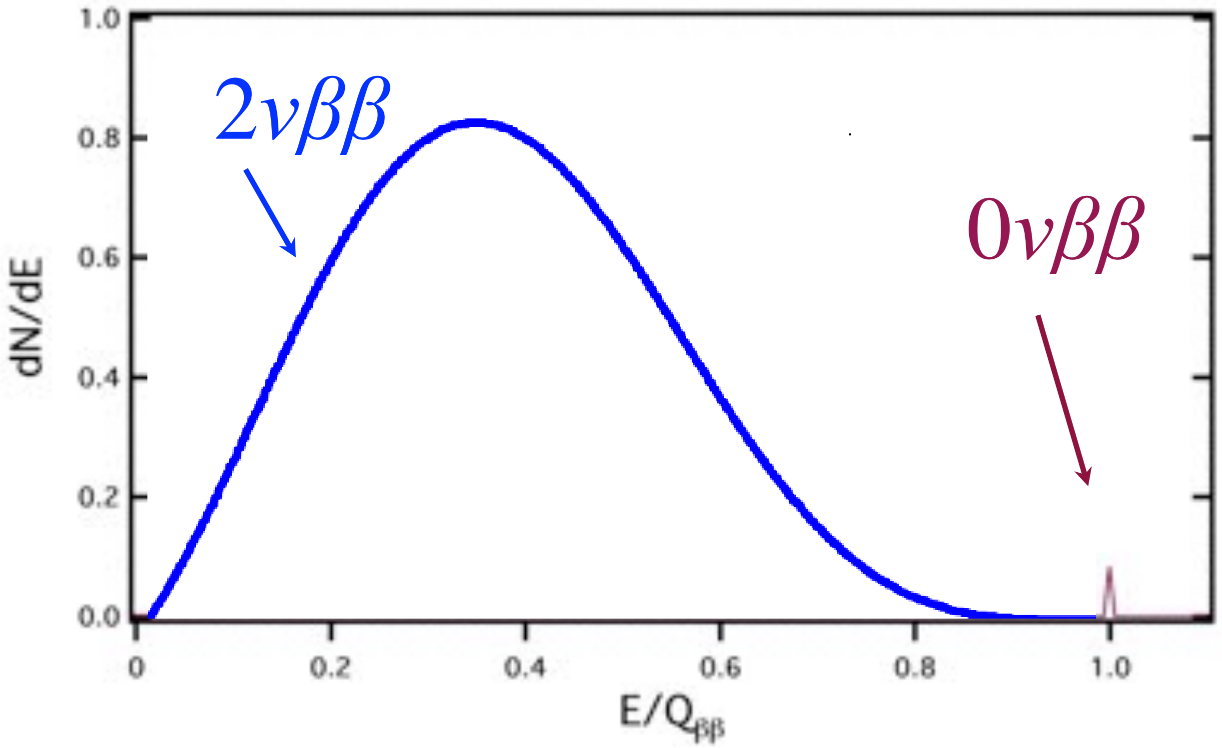
ϵ = detection efficiency

M = total mass

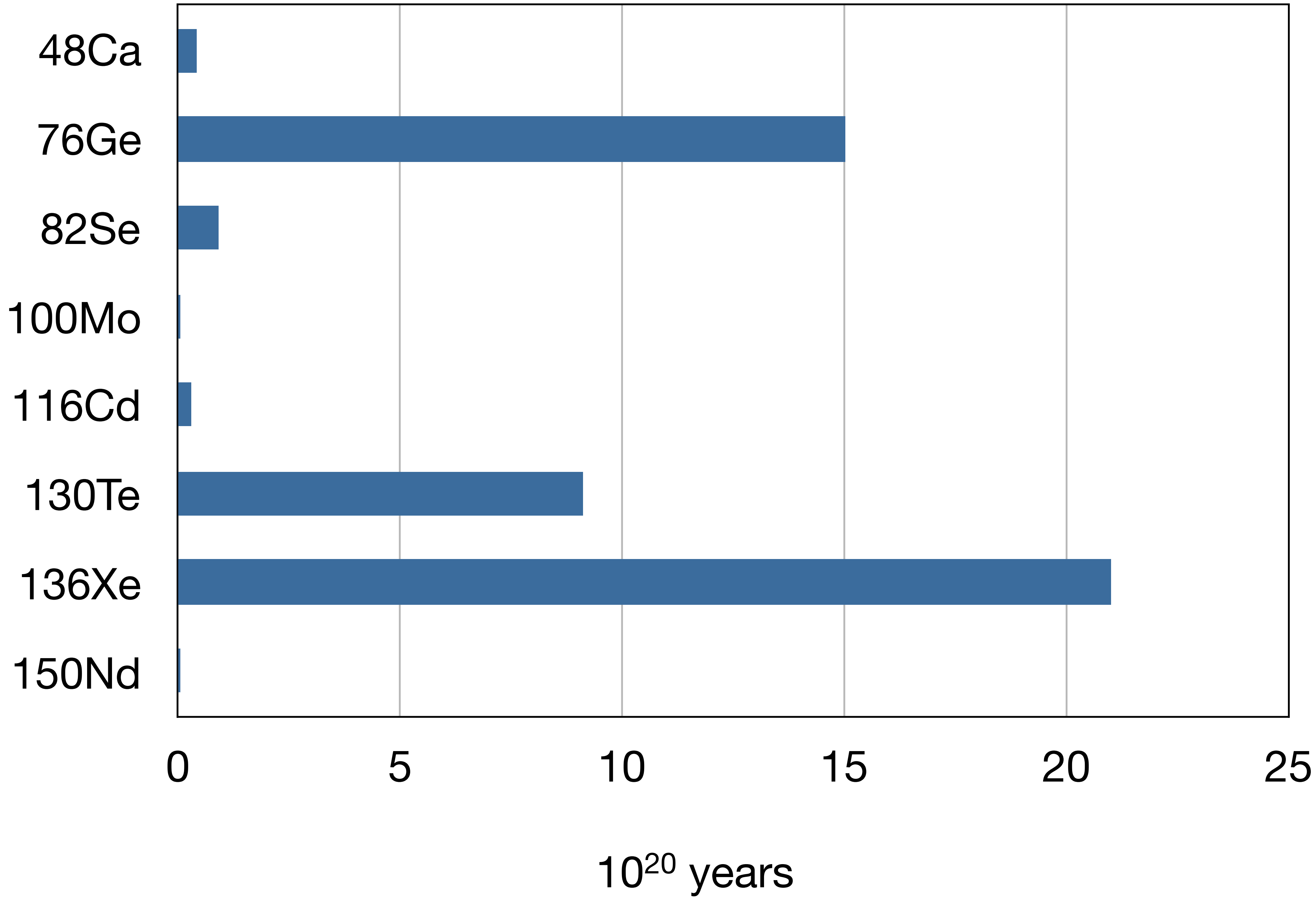
t = exposure time

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

δE = energy resolution



2nu Half-Life

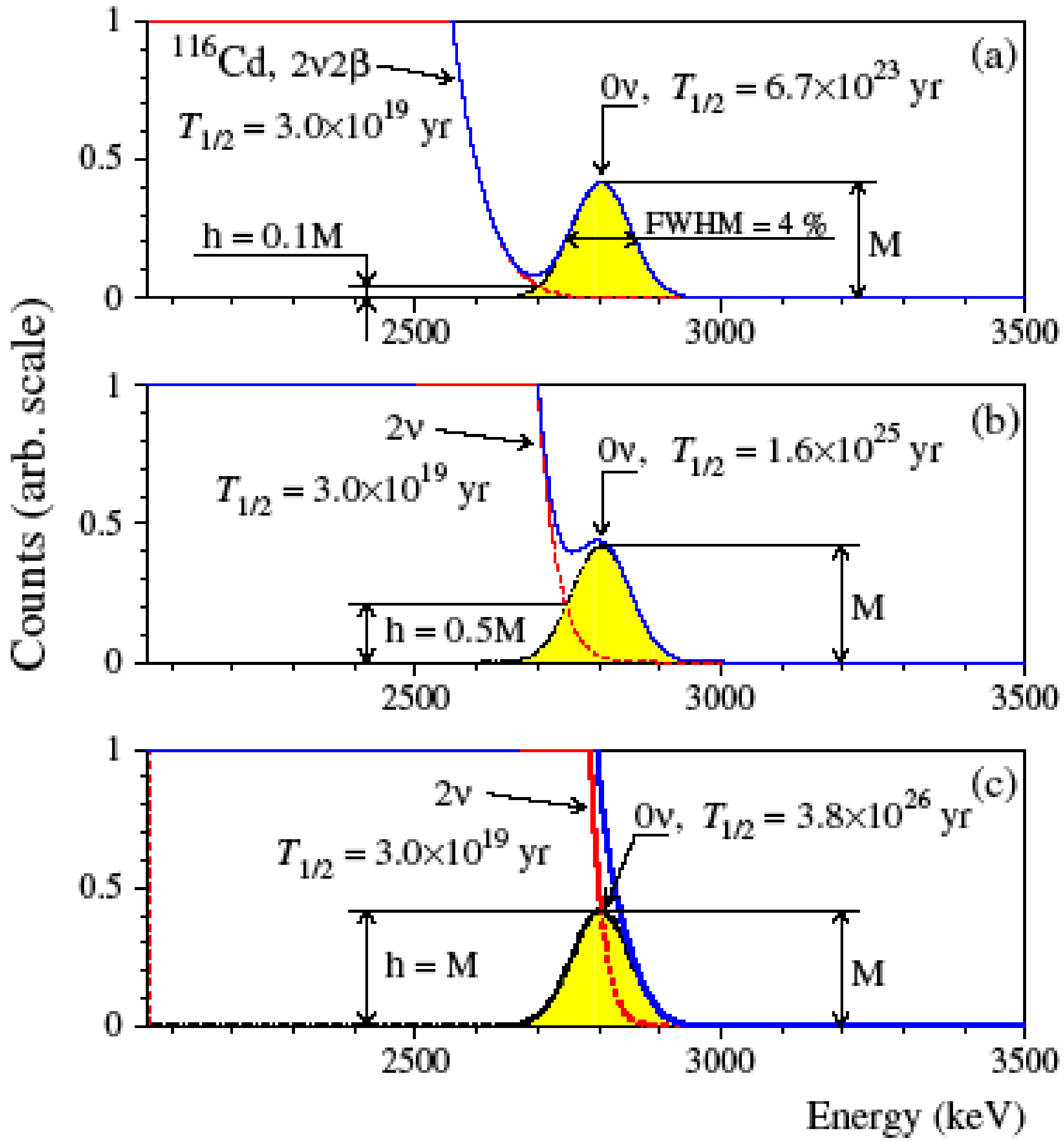


ββ Isotope	2νββ $T_{1/2}$ 10^{20} years
^{48}Ca	0.44
^{76}Ge	15
^{82}Se	0.92
^{100}Mo	0.07
^{116}Cd	0.29
^{130}Te	9.1
^{136}Xe	21
^{150}Nd	0.08

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

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)

Attacking Backgrounds

- 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

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

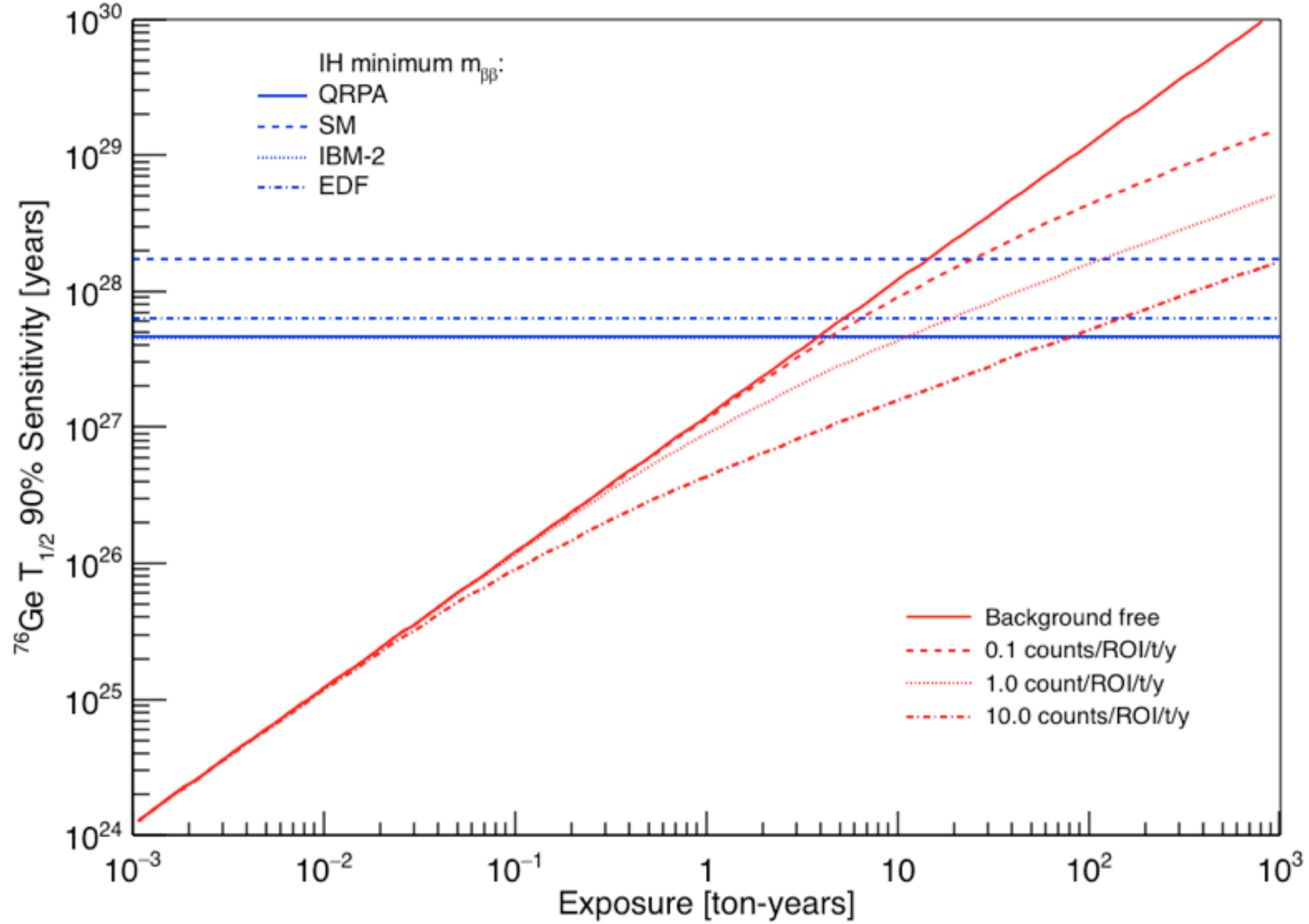
- Utilize background measurement & discrimination techniques

0νββ is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions

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

Sensitivity vs Exposure

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



J. Detwiler

International Program

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

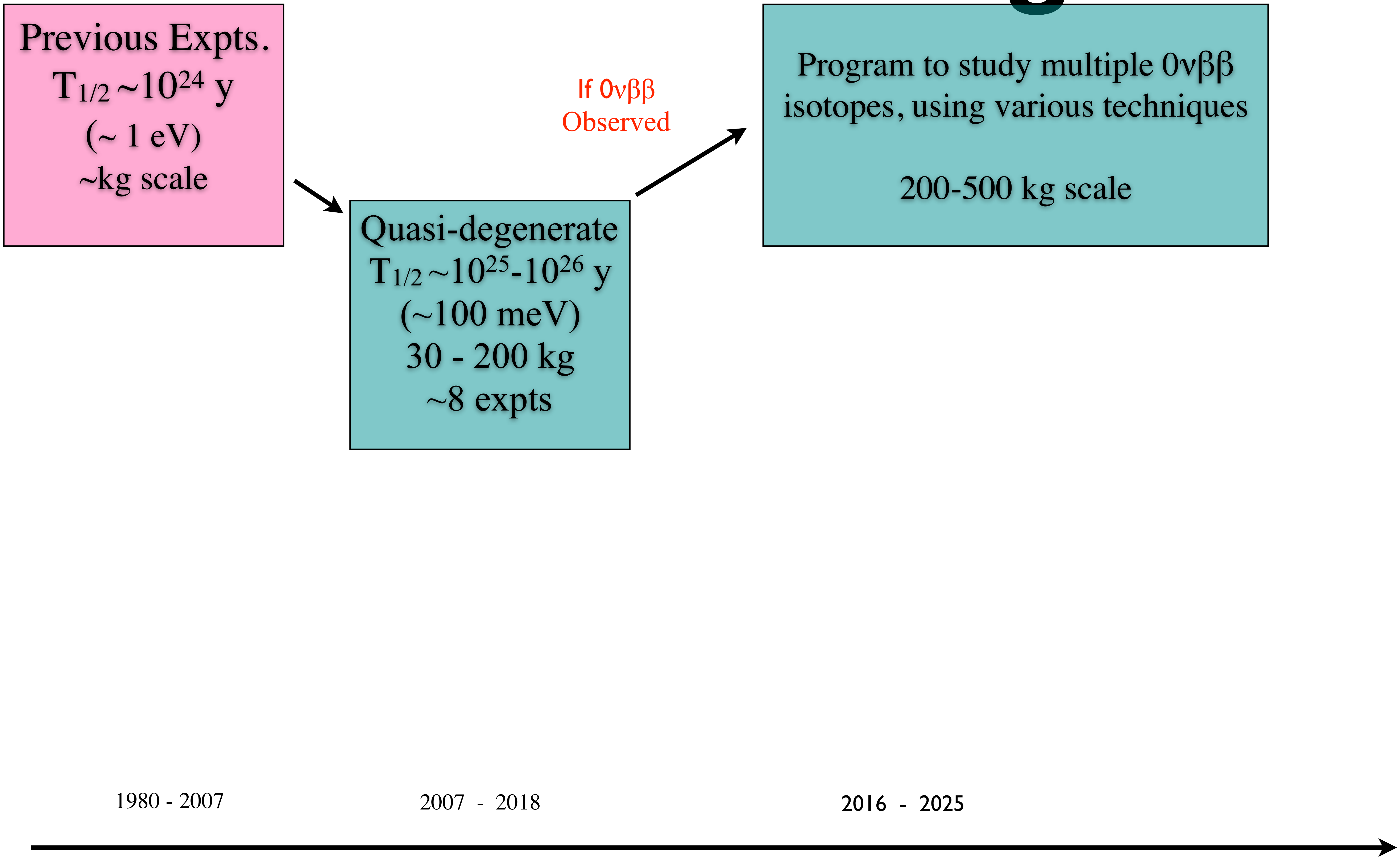
Quasi-degenerate
$T_{1/2} \sim 10^{25}\text{-}10^{26}$ y
(~100 meV)
30 - 200 kg
~8 expts

1980 - 2007

2007 - 2018

2016 - 2025

International Program



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30 - 200 kg
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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

1980 - 2007

2007 - 2018

2016 - 2025

International Program

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Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~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

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~ tonne scale

1980 - 2007

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Inverted hierarchy
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tonne (phased)
~3 experiments
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Normal
hierarchy
~5 meV
≥10's ton
scale

1980 - 2007

2007 - 2018

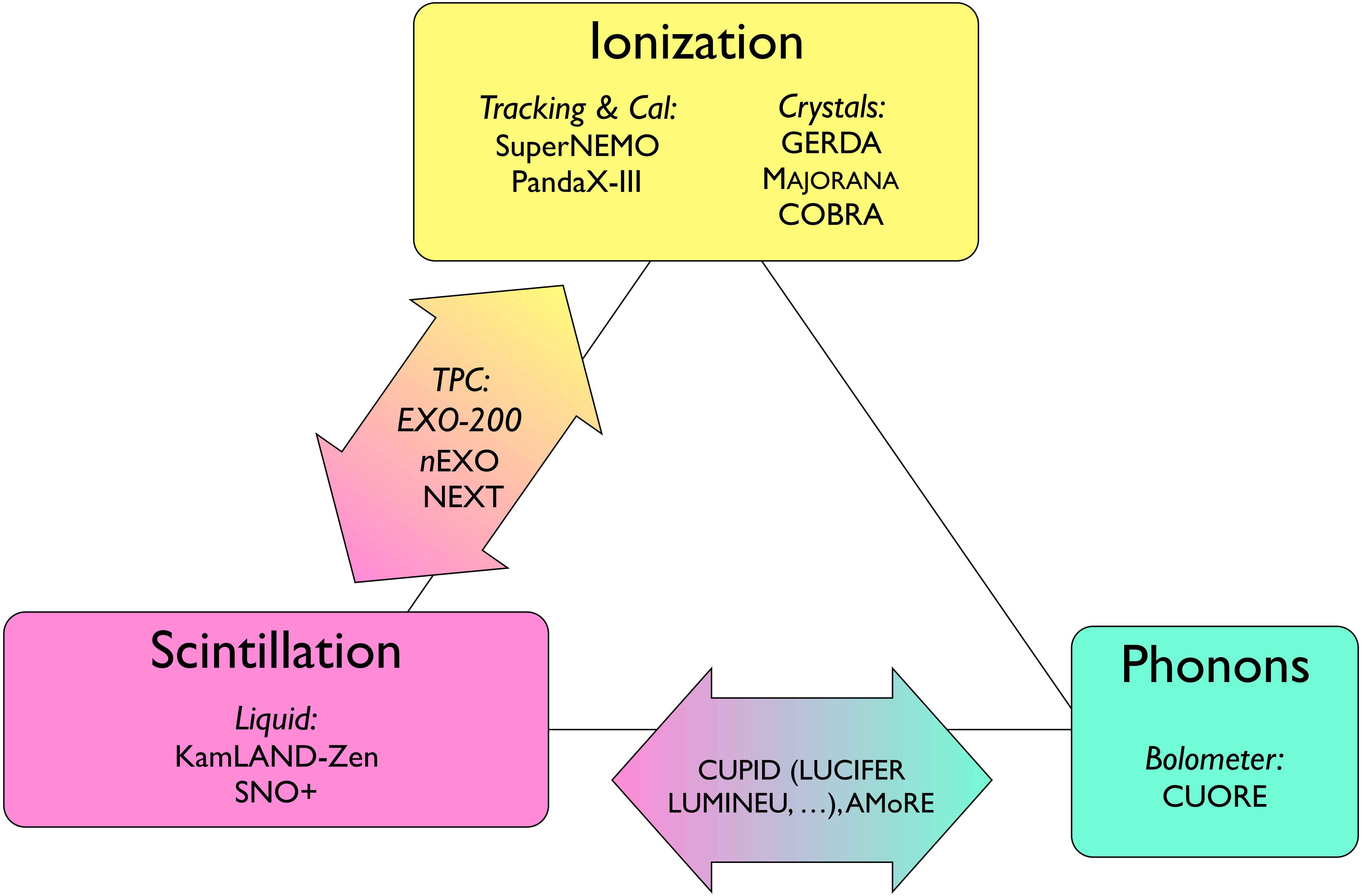
2016 - 2025

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

Overview of Techniques

Multi-Prong Detection Strategy



Ionization

Tracking & Cal:
SuperNEMO
PandaX-III

Crystals:
GERDA
MAJORANA
COBRA

TPC:
EXO-200
*n*EXO
NEXT

Scintillation

Liquid:
KamLAND-Zen
SNO+

CUPID (LUCIFER
LUMINEU, …), AMoRE

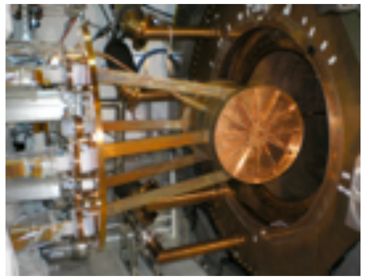
Phonons

Bolometer:
CUORE

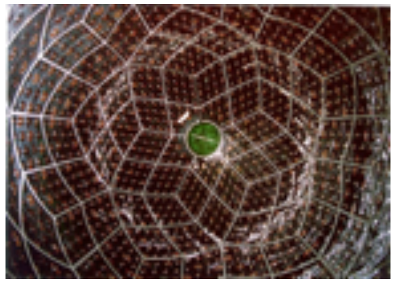
World Program

CUORE

EXO200



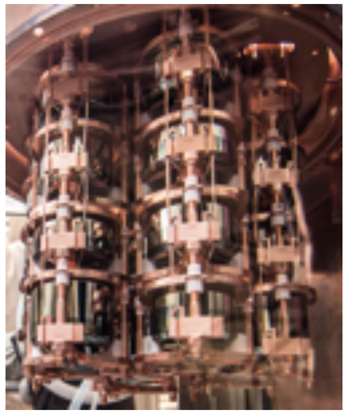
KamLAND Zen



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$_2$MoO$_4$ 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% $^{\text{nat}}$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

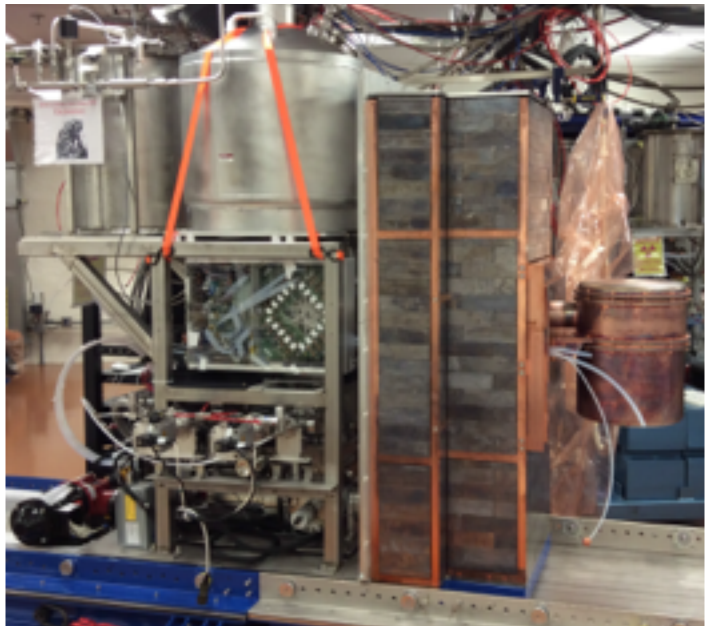
Germanium-76

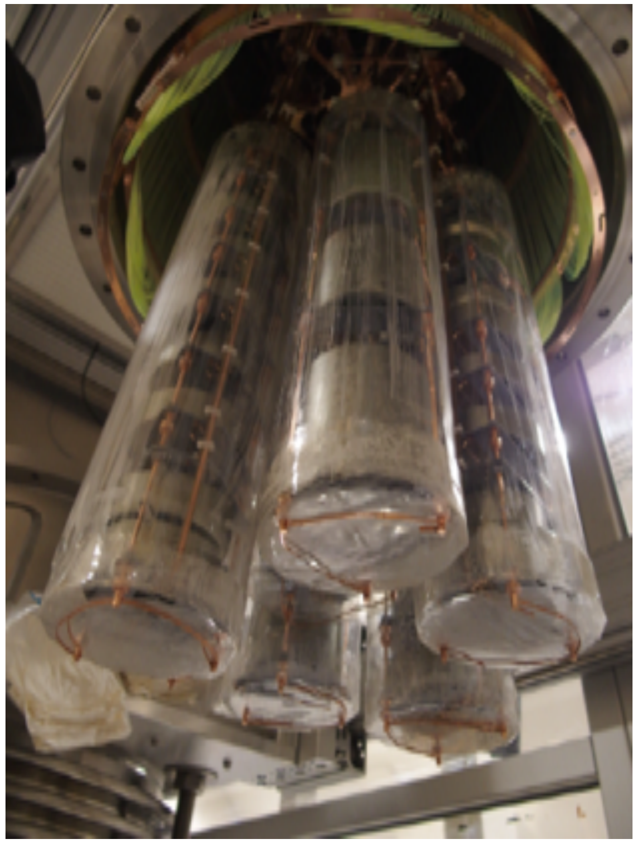
Advantages of Germanium

- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: approaching 0.1% at 2039 keV (~2.4 keV ROI)
- Demonstrated ability to enrich from 7.44% to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape discrimination

Majorana and GERDA

MAJORANA
“Traditional” configuration:
Vacuum cryostats in a
passive graded shield
with ultraclean materials





GERDA
“Novel” configuration:
Direct immersion
in active LAr shield

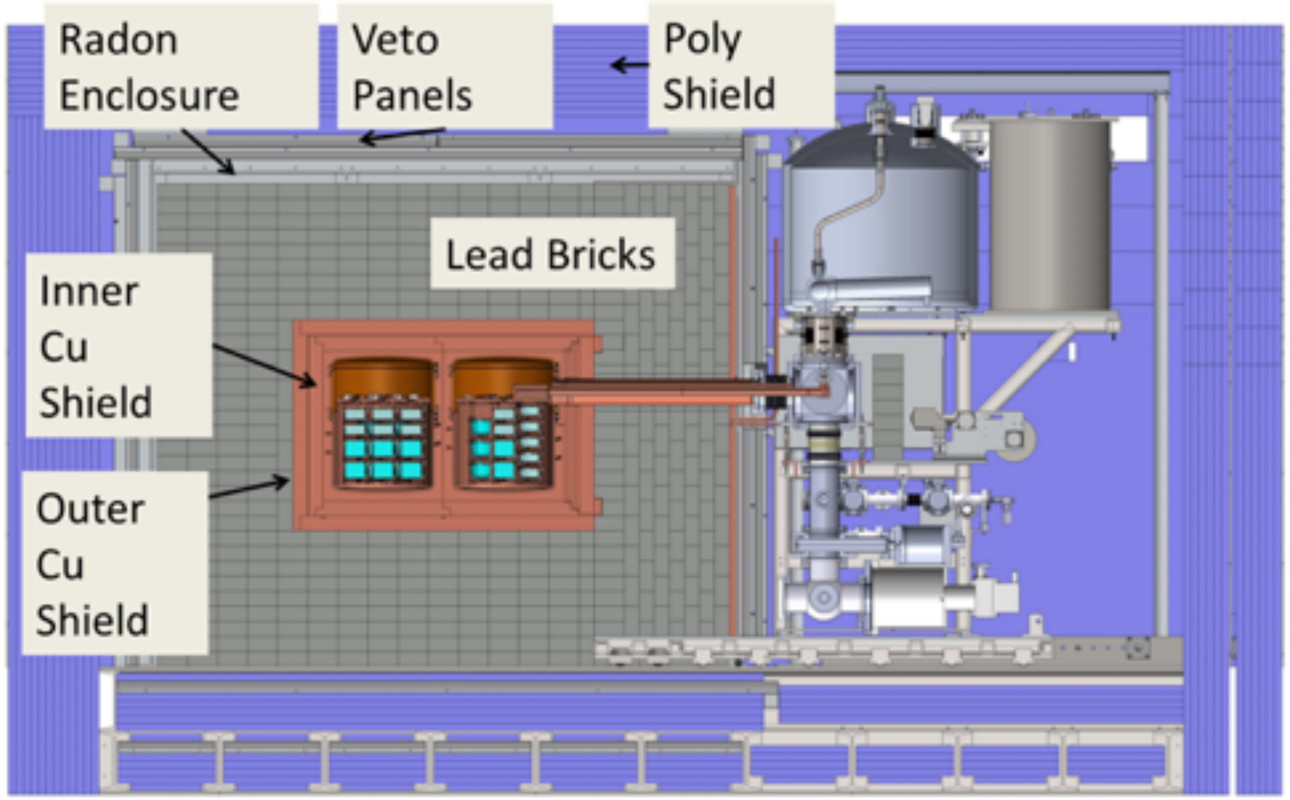
Majorana Demonstrator

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics
with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

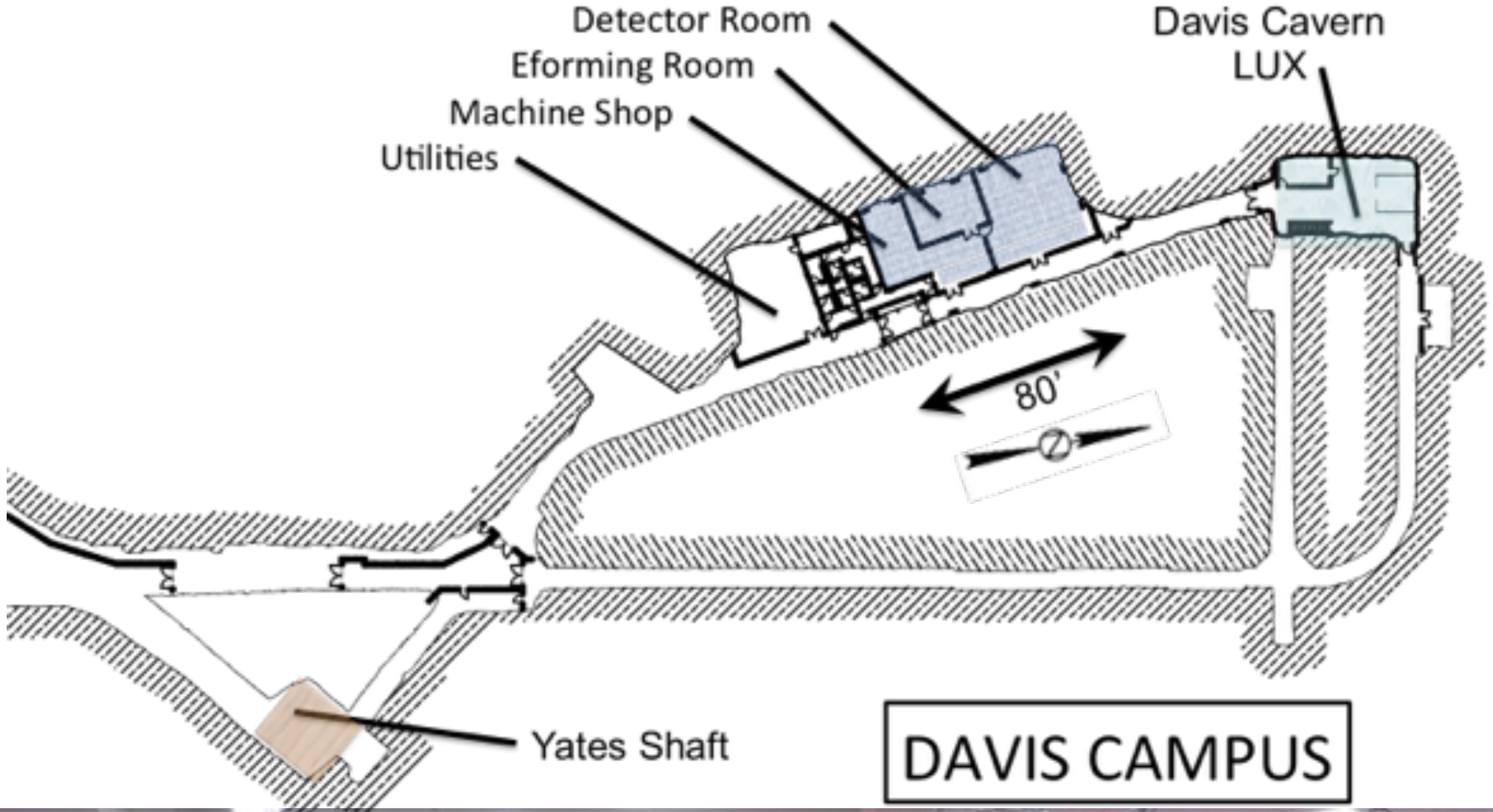
- Located underground at 4850’ Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5

- 44.1-kg of Ge detectors
  - 29.7 kg of 87% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto

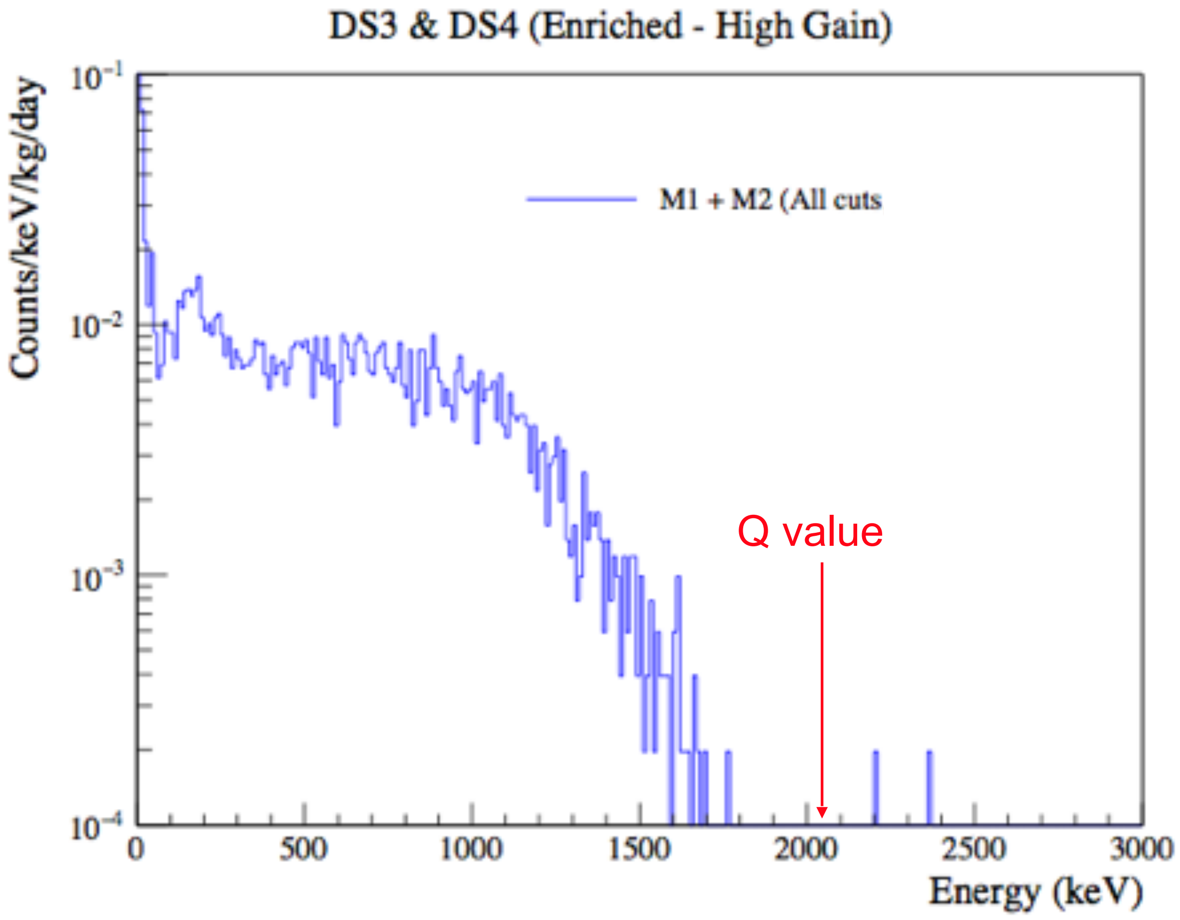


Majorana Underground Laboratory

4850’ level, SURF, Lead SD
Clean room conditions
Muon flux: 5 x 10^{-9} μ/cm^2 s
(arXiv:1602.07742)



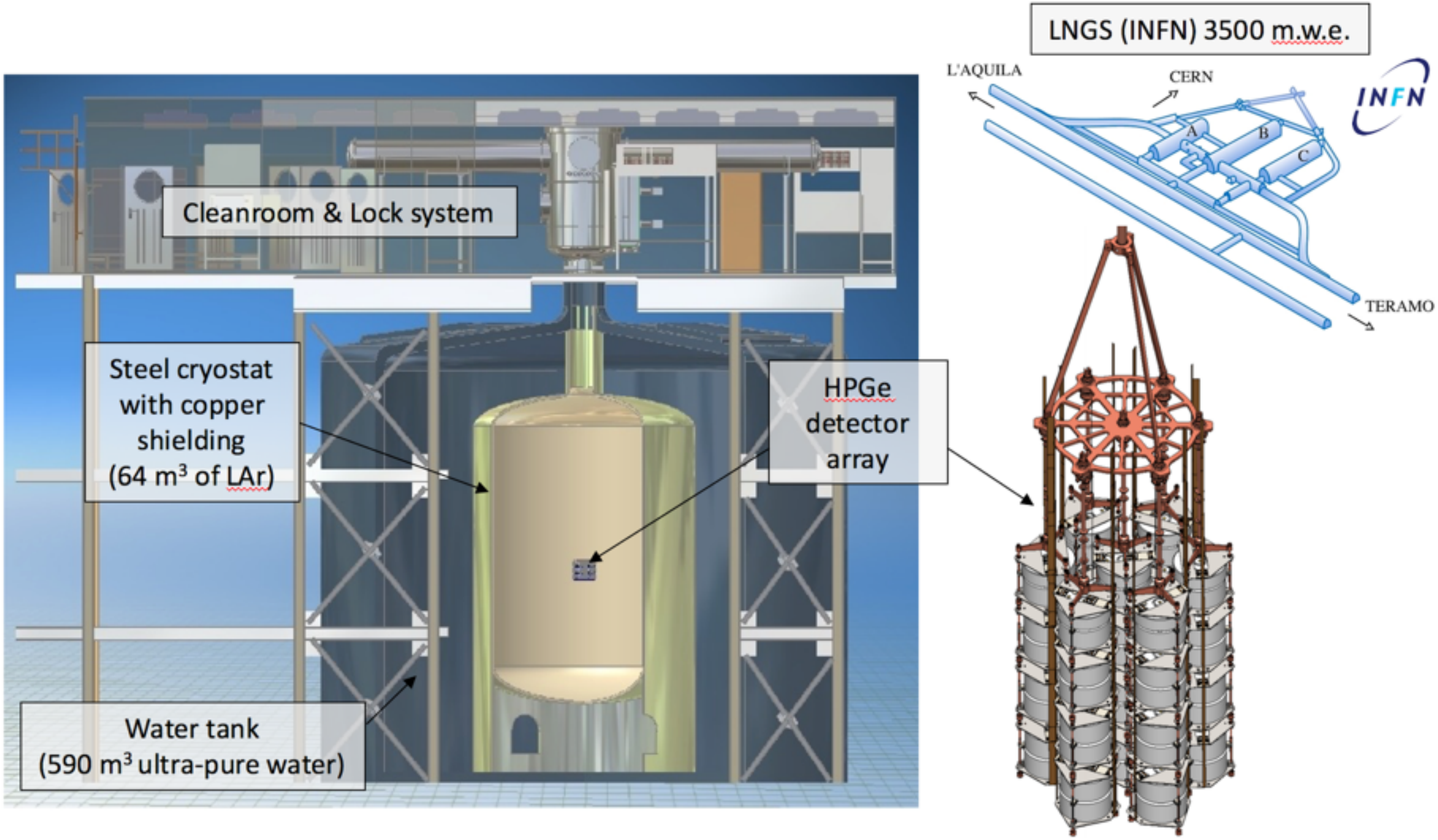
Initial Results



First results from Modules 1 and 2 in-shield

- Exposure: 1.39 kg y
- After cuts, 1 count in 400 keV window centered at 2039 keV ($0\nu\beta\beta$ peak)
- Projected background rate is $5.1^{+8.9}_{-3.2}$ c /(ROI t y) for a 2.9 keV (Modue 1- DS3) and 2.6 keV (Module 2 - DS4) ROI, (68% CL).
- Background index of 1.8×10^{-3} c/(keV kg y)
- Analysis cuts are still being optimized.
- Through mid-May, have 10x more exposure in hand. Analysis is in progress.

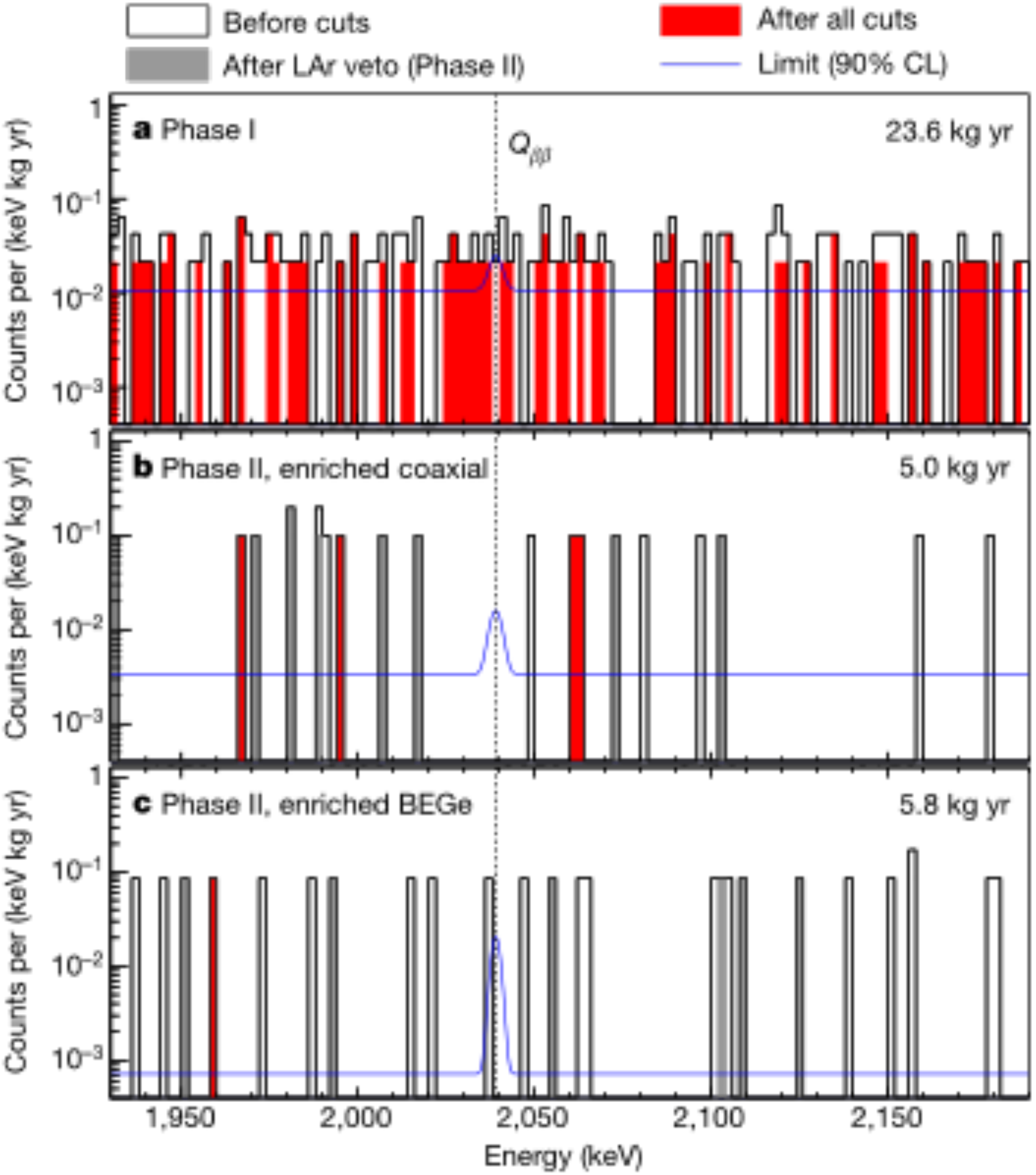
GERDA Configuration



30 BEGe (20 kg) and
7 Coax (15.6 kg) (Phase II)

GERDA Results

- Phase I and II Exposure: 34.4 kg y
- Projected background from 1930 to 2190 keV window excludes 2104 ± 5 keV and 2119 ± 5 keV. Window of ±20 keV around $Q_{\beta\beta}$ blinded.
- For Phase II BEGes, have achieved "background free" measurement with background index of
  1.8 c/(FWHM-t-y) or
  $(0.6\,^{+0.6}_{-0.4}) \times 10^{-3}$ c/kky)
- $T_{1/2}$ $(0\nu\beta\beta) \geq 5.3 \times 10^{25}$ years (90%CL)



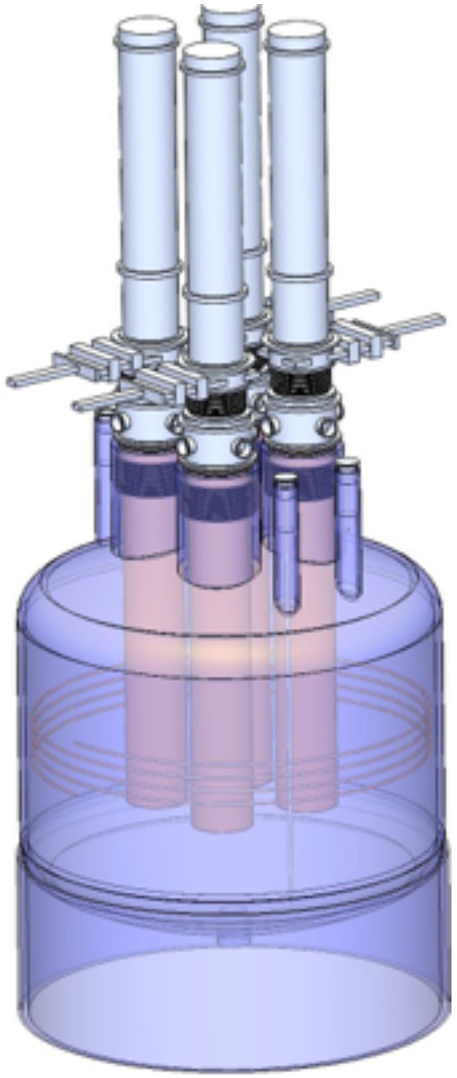
LEGEND

Mission: The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results.

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First Phase:
- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c /(FWMH t y)
- start by 2021

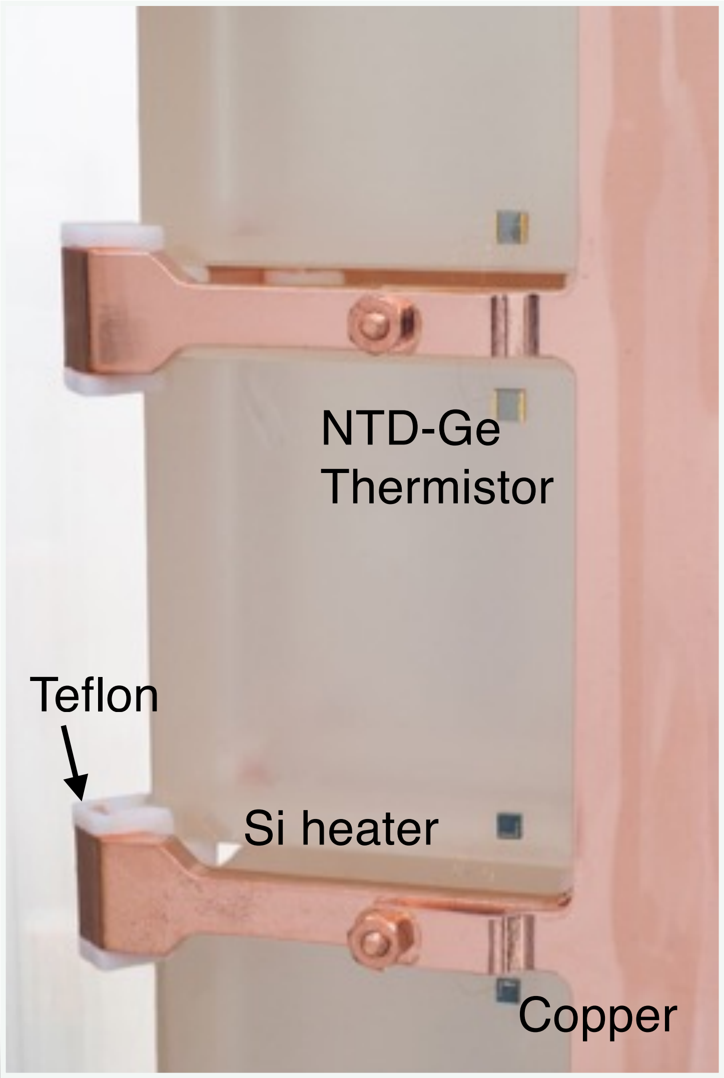
Subsequent Stages:
- 1000 kg (staged)
- timeline connected to U.S. DOE down selec process
- BG: goal (x30 lower) 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (^{77m}Ge) under investigation

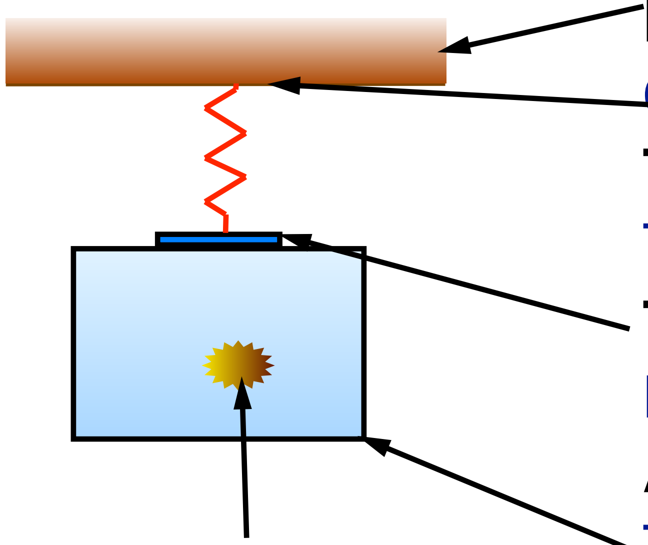


Tellurium-130

CUORE Bolometer

TeO_2 Bolometer: Source = Detector

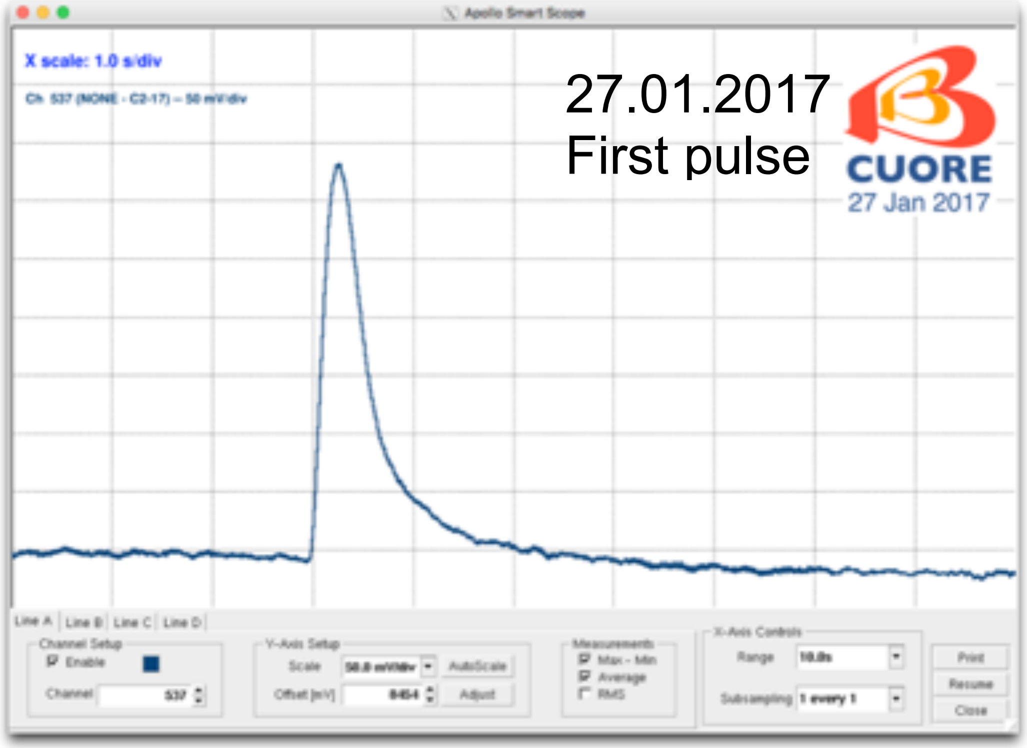




deposited energy

Heat sink:
Cu structure (10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor (100 kΩ/µK)
Absorber:
TeO_2 crystal
(C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

main candidate isotope: ^{130}Te
Q-value: 2526.515 ± 0.013 keV
Isotopic abundance: 34%



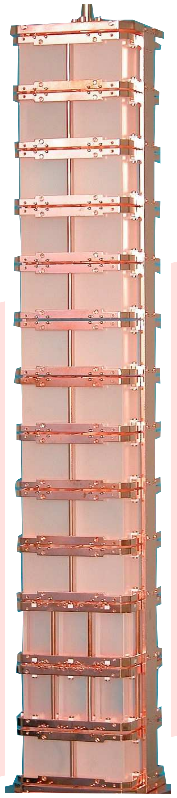
27.01.2017
First pulse

For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK
Signal size: 1 mV

Time constant: $\tau = C/G = 0.5$ s
Energy resolution: ~ 5-10 keV at 2.5 MeV

CUORE Overview

Cuoricino
(2003 – 2008)



Astropart. Phys. 34
(2011) 822–831

$T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24}$ y (90% C.L.)

CUORE-0
(2013 – 2015)

EPJC 74, 2956 (2014)
arXiv:1504.0245

$T_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24}$ y (90% C.L.)

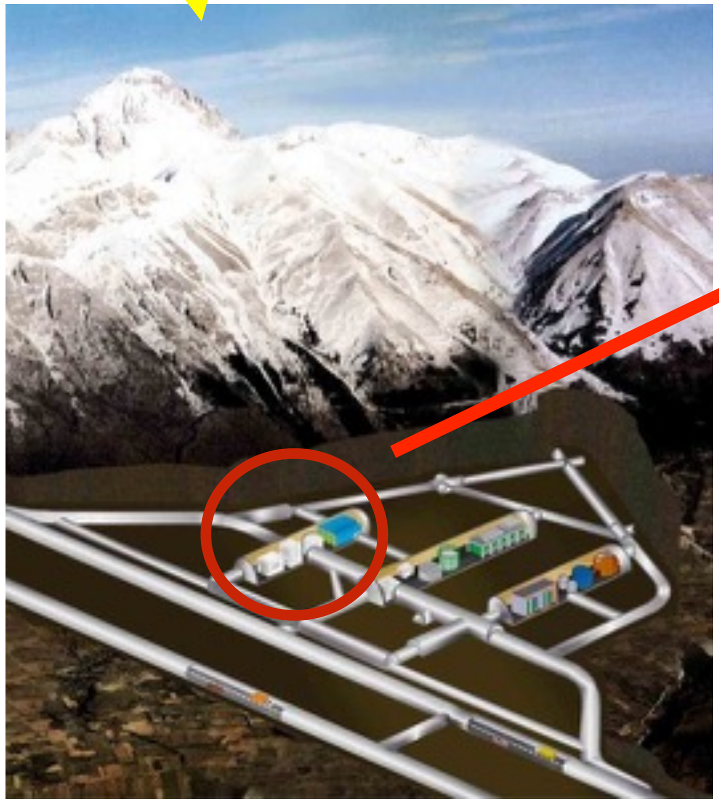
CUORE
(2017 –)

arXiv:1109.0494
arXiv:1705.10816

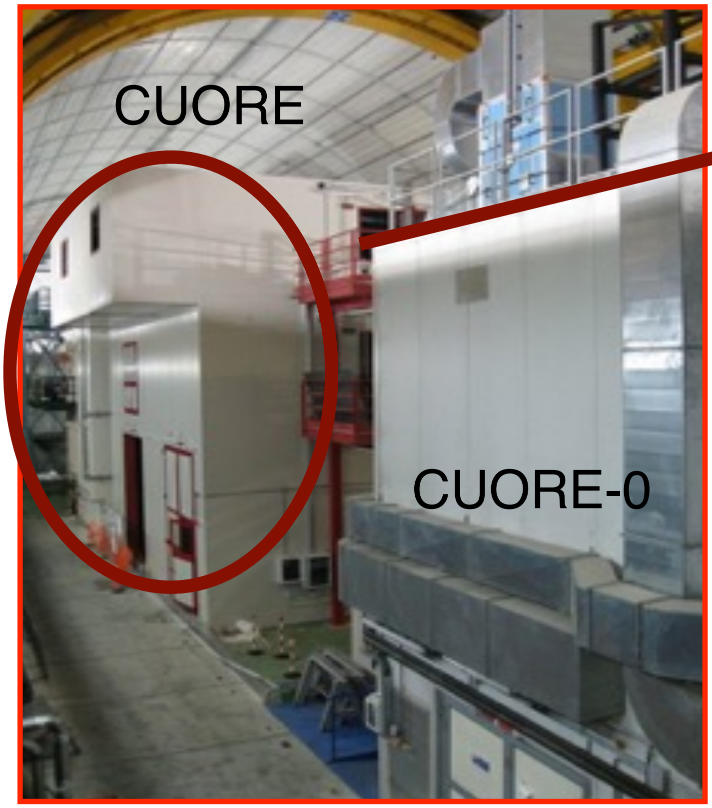
Projected
$T_{1/2}^{0\nu\beta\beta} \sim 9 \times 10^{25}$ yr (90% C.L.)

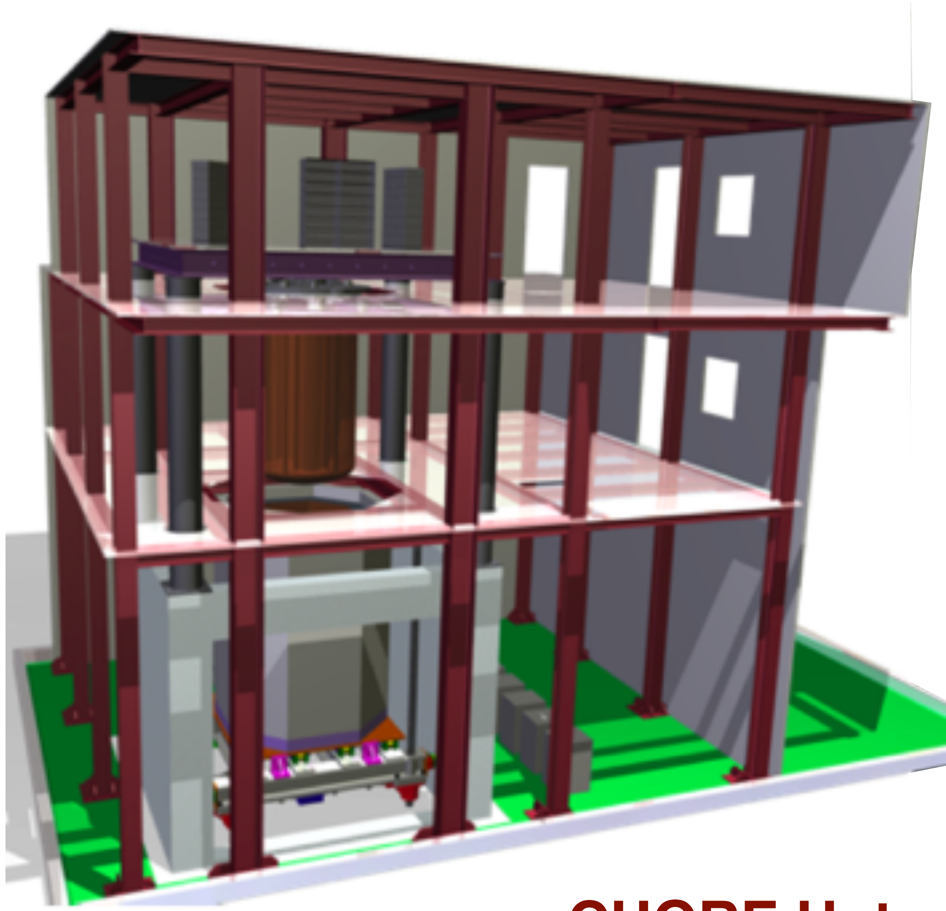
CUORE at LNGS

Gran Sasso National Laboratory



Hall A



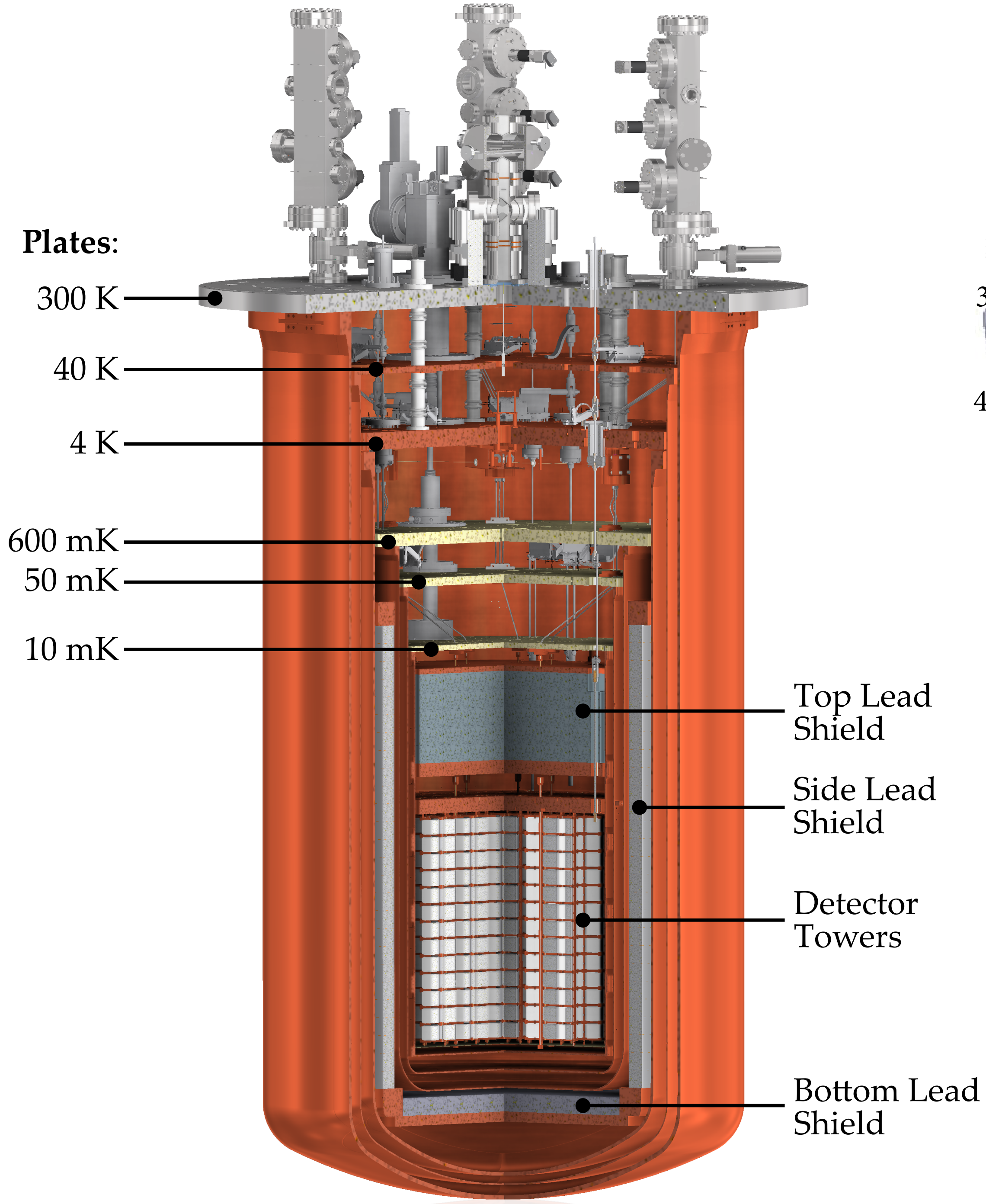


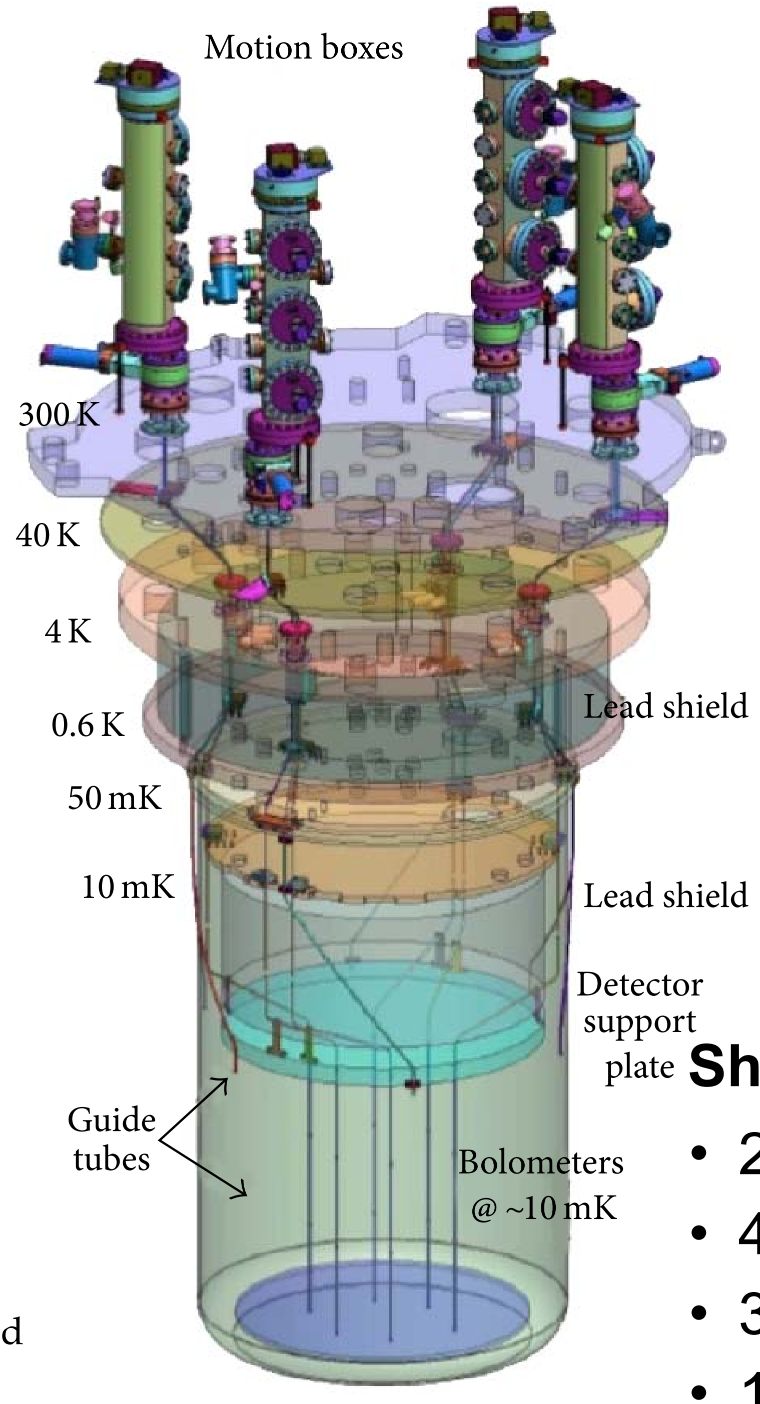
CUORE Hut

Average depth ~ 3600 m.w.e.

- **μ: 3×10^{-8} μ/s/cm^2**
- **n < 10 MeV: 4×10^{-6} n/s/cm^2**
- **γ < 3 MeV: 0.73 γ/s/cm^2**

CUORE Cryostat



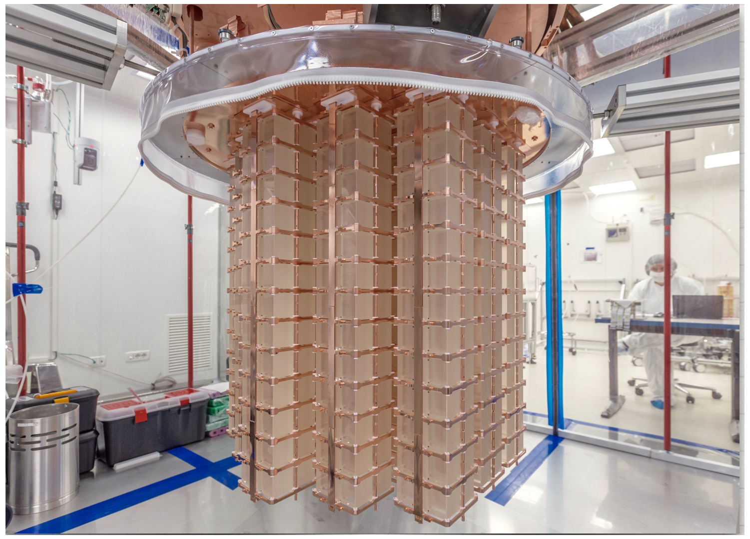


Shielding

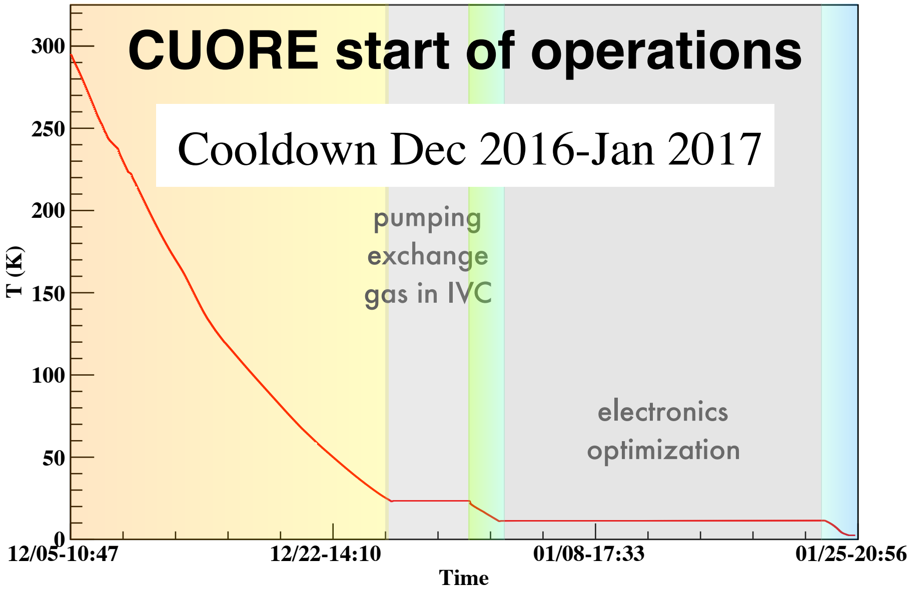
- 2.1t modern lead @ 50 mK
- 4.6 t roman lead @ 4 K
- 35 cm external lead
- 18 cm PET + 2 cm H_3BO_3

CUORE/CUPID

CUORE detectors installed



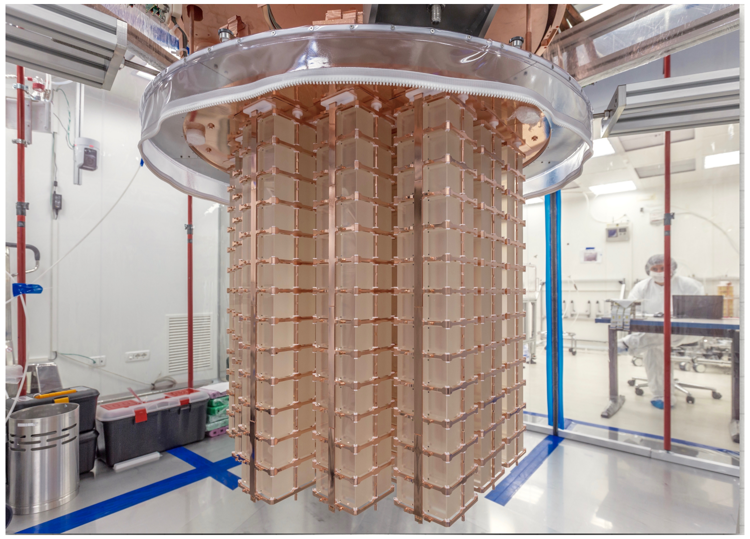
Diode thermometer at 10mK plate

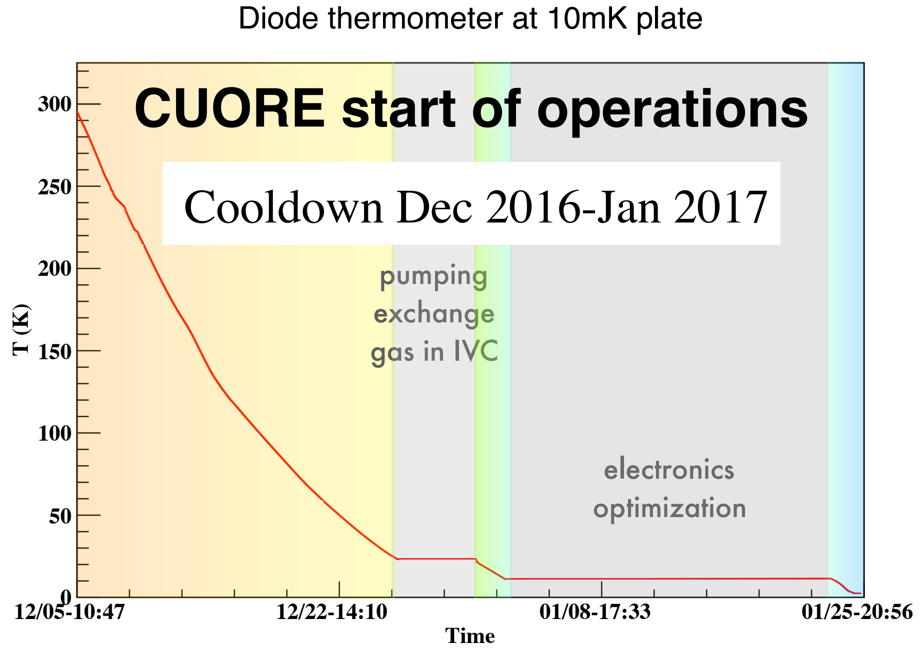


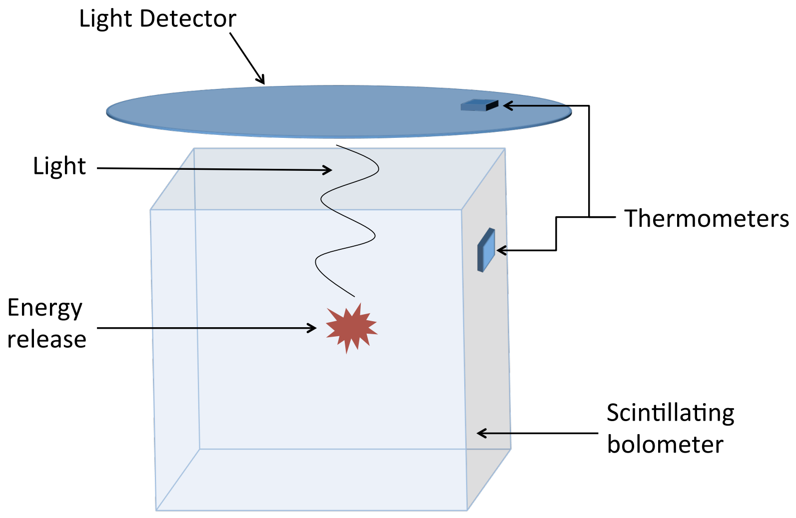
- CUORE Milestones:
  - Tower installation: Jul-Aug 2016
  - Cryostat closeout: Nov 2016
  - Cooldown: Dec-Jan 2016
  - Commissioning and initial performance optimization: Jan-May 2017
  - First science run: May 2017
- Cryostat performs very well: base T < 7 mK
- >95% of detectors operational
- First data to be reported in Summer 2017

CUORE/CUPID

CUORE detectors installed







Next-generation bolometric tonne-scale experiment based on the CUORE design, proven CUORE cryogenics

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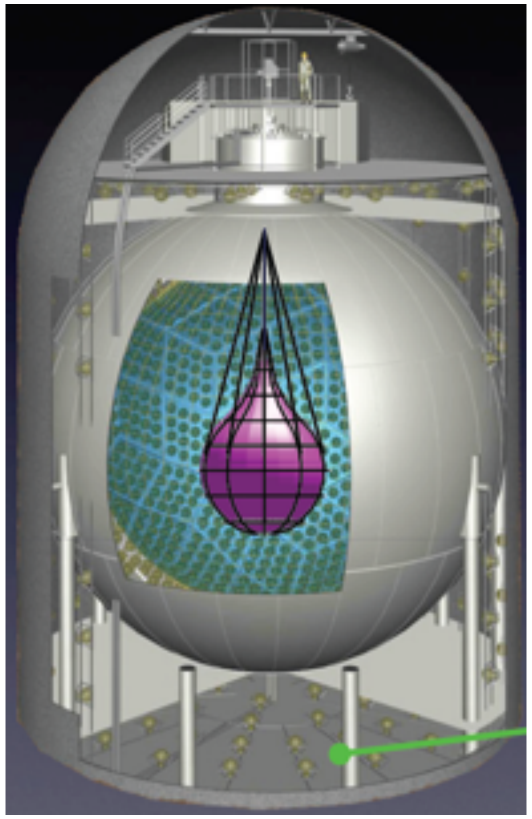
- Intense CUPID R&D effort in the next 2-3 years
  - ☞ US focus: $^{130}TeO_2$ enrichment and purification, high-resolution sensors for Cherenkov light
  - ☞ Complementary European efforts
  - ☞Background goal is 0.1 cts/ROI-t-yr; achieve sensitivity to the full Inverted Hierarchy
  - ☞ Other important R&D: detailed background analysis, cosmogenic backgrounds @ LNGS — to be addressed before downselect
  - ☞ Worldwide efforts: 8 countries, 32 institutions
  - ☞ Data from CUORE and pilot detectors will drive technology and isotope choice

Xenon-136

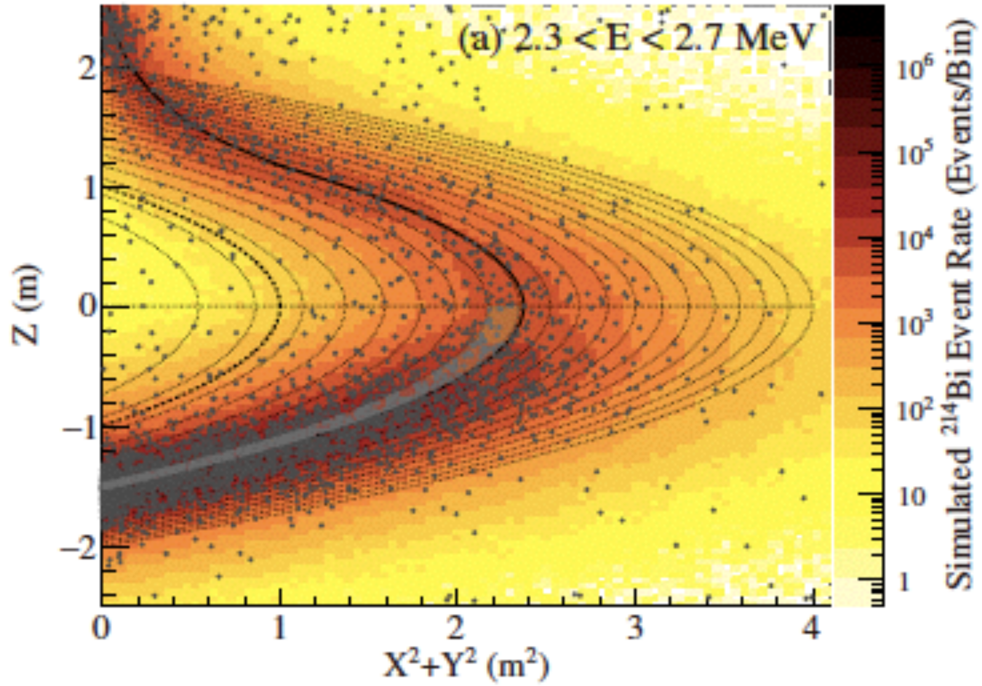
Kamland-ZEN



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

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

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

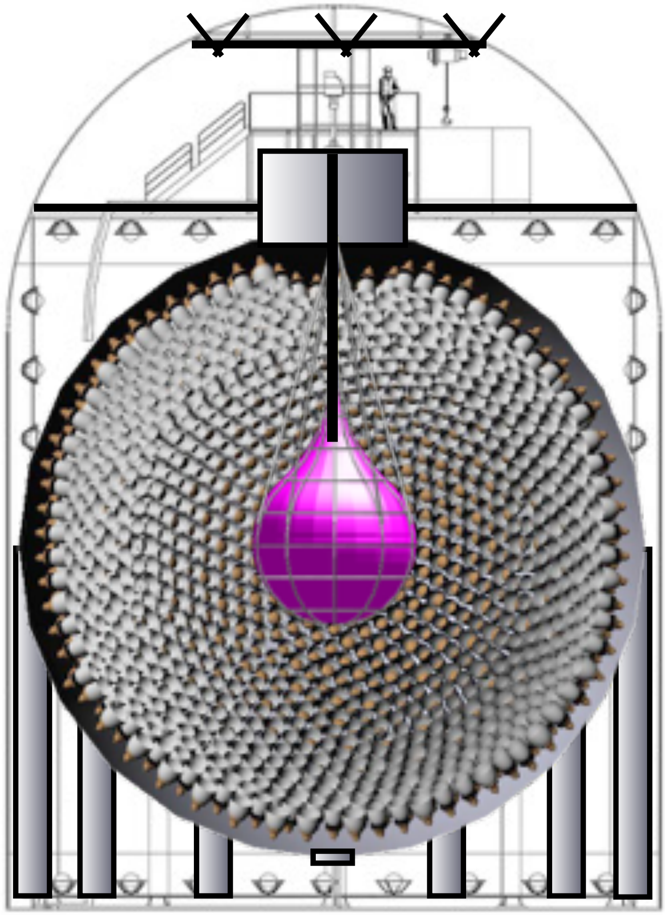


Unsuccessful new larger mini balloon deployment - 2016

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

Kamland-ZEN Future

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



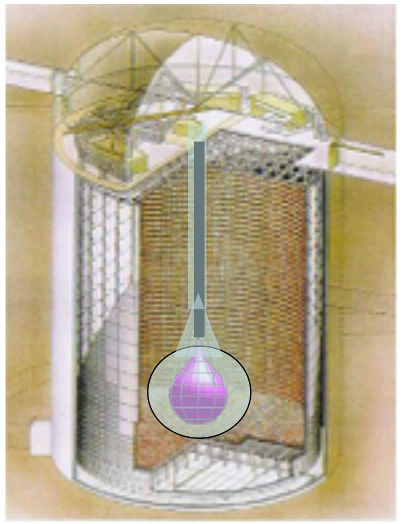
1000+ kg xenon

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

expected σ(2.6MeV)= 4% → ~2%

target sensitivity: 20 meV

Far future:



Super-KamLAND-Zen

in connection with Hyper-Kamiokande

target sensitivity 8 meV

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.***

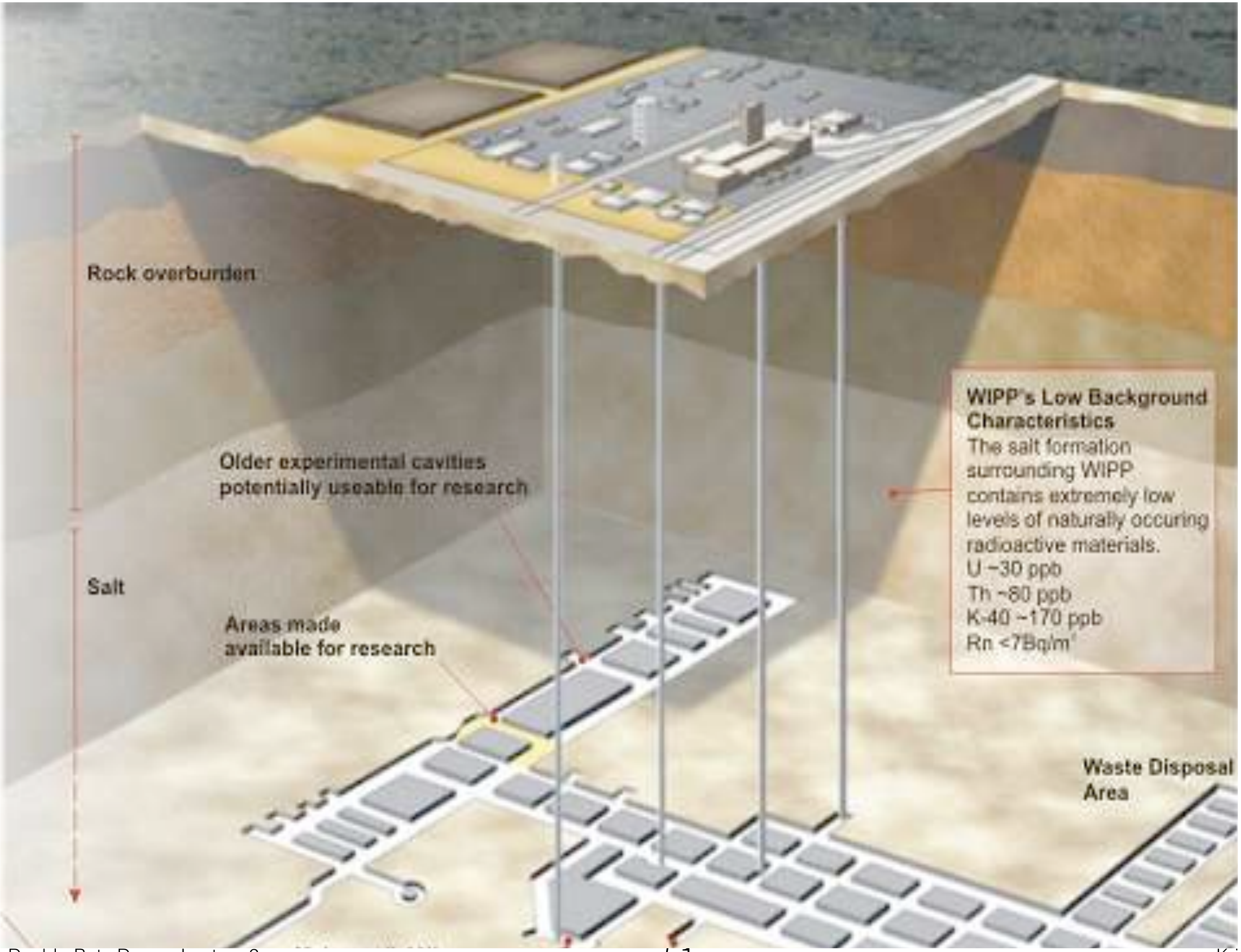
Standard 2νββ is slow! (see later): ***get away with modest energy resolution***

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

.... potentially access normal hierarchy

Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP

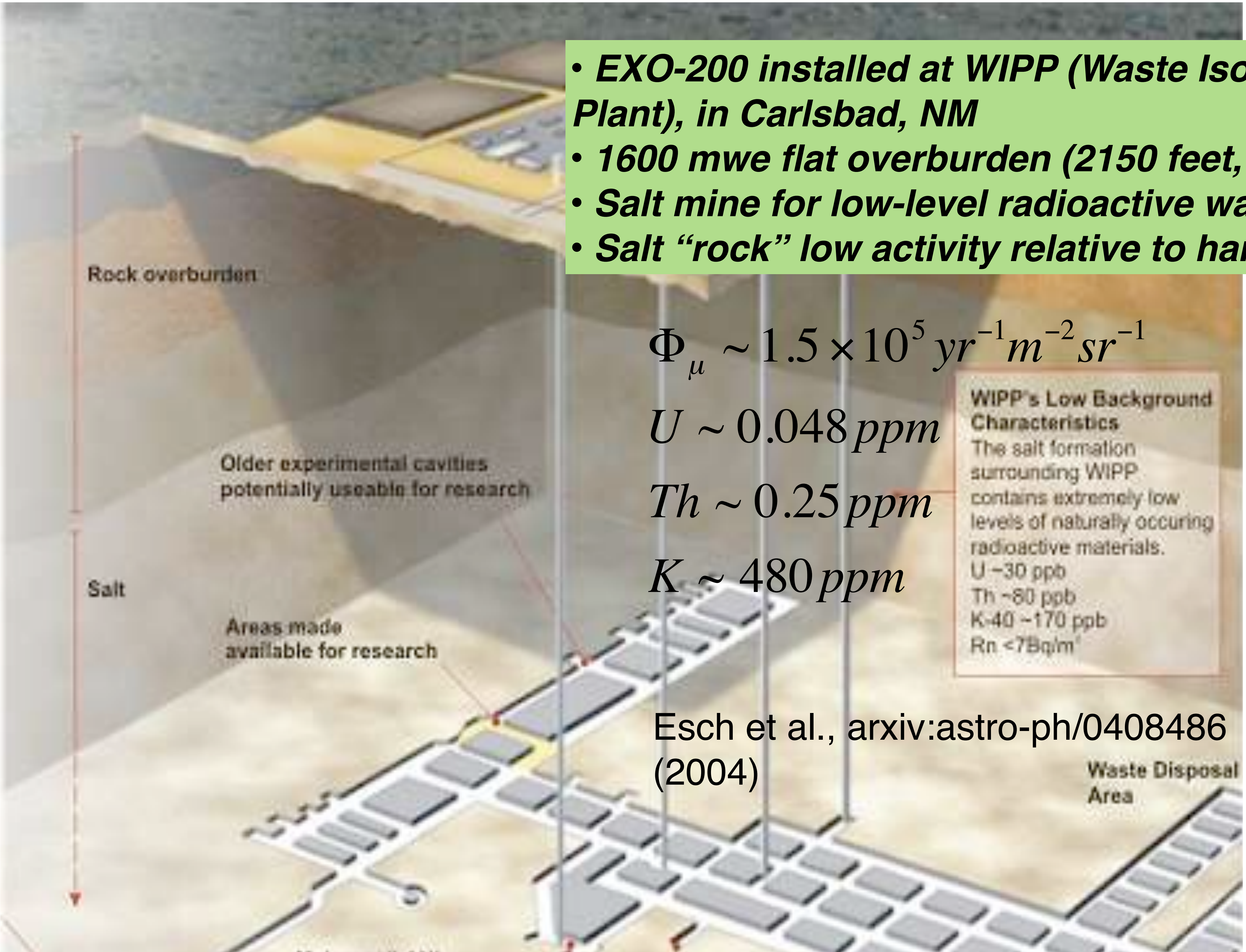


WIPP's Low Background Characteristics
The salt formation surrounding WIPP contains extremely low levels of naturally occuring radioactive materials.
U ~30 ppb
Th ~80 ppb
K-40 ~170 ppb
Rn <7Bq/m^3

Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP

- ***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***



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

$$U \sim 0.048\, ppm$$

$$Th \sim 0.25\, ppm$$

$$K \sim 480\, ppm$$

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

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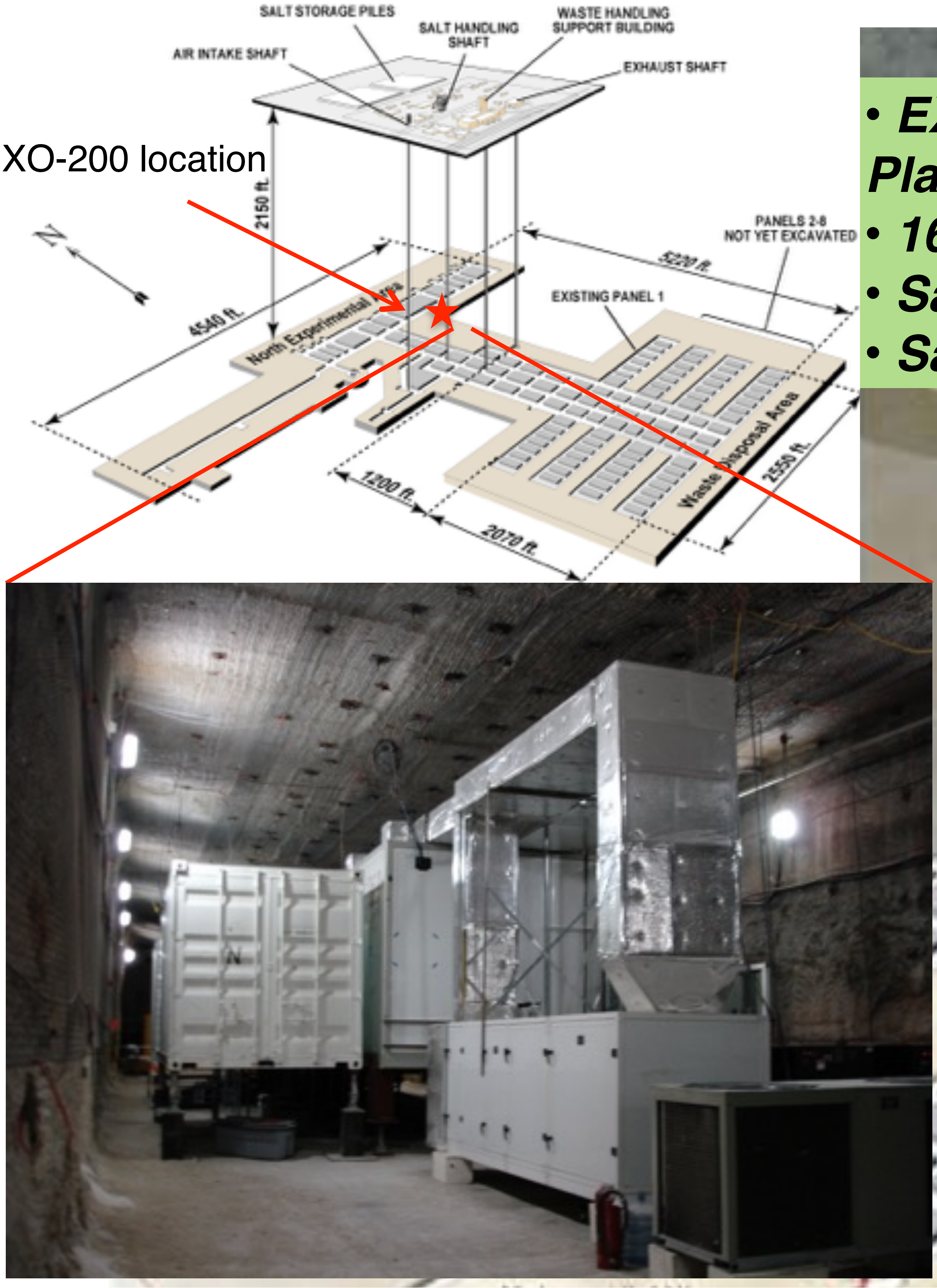
EXO-200 location

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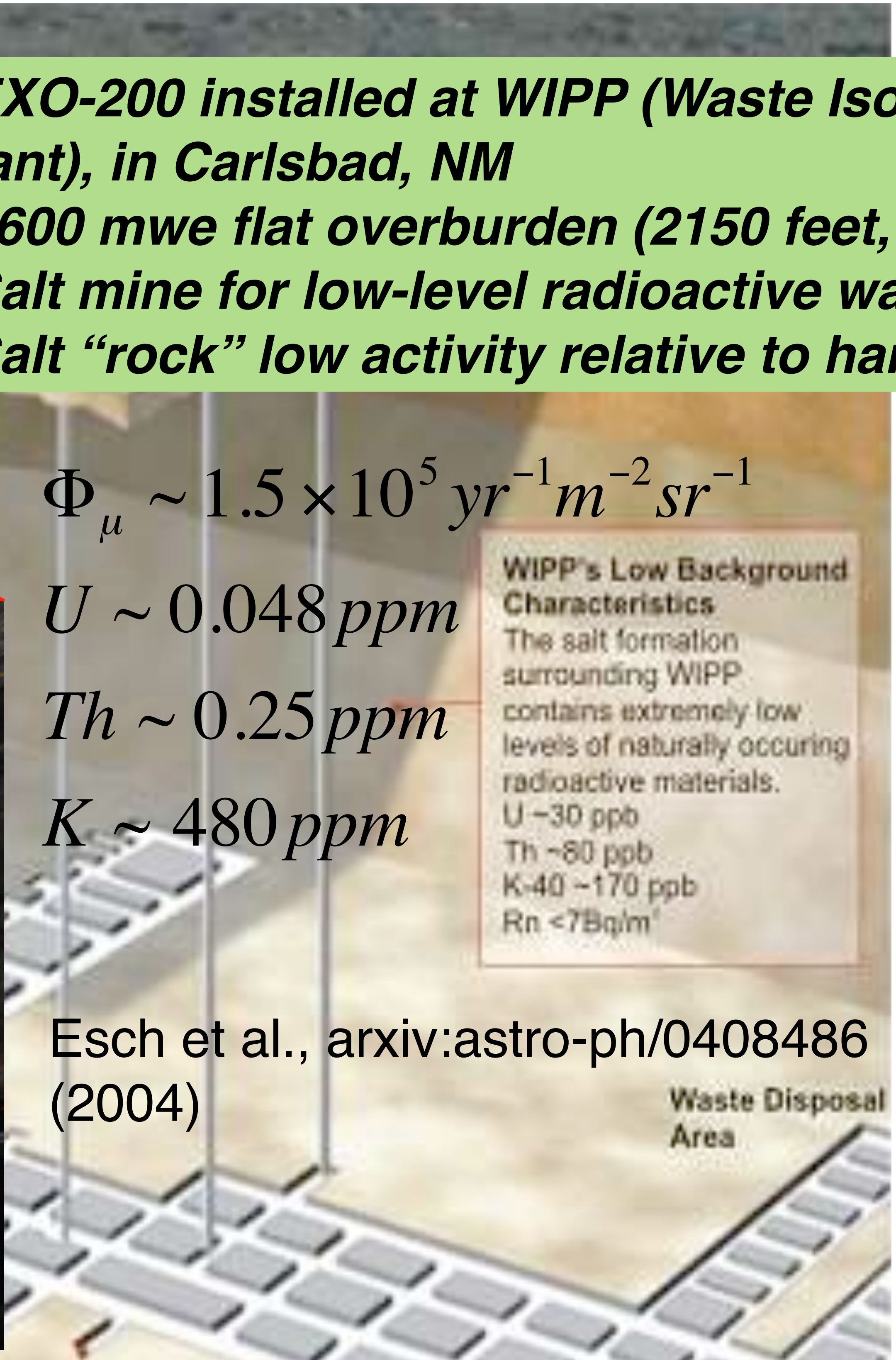
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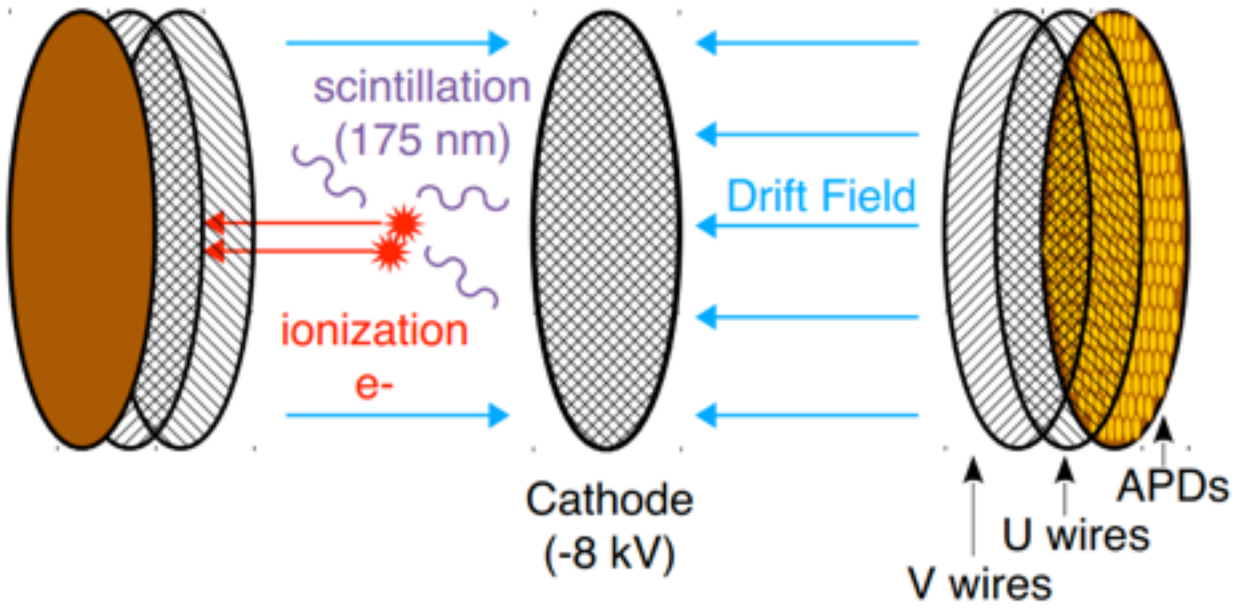
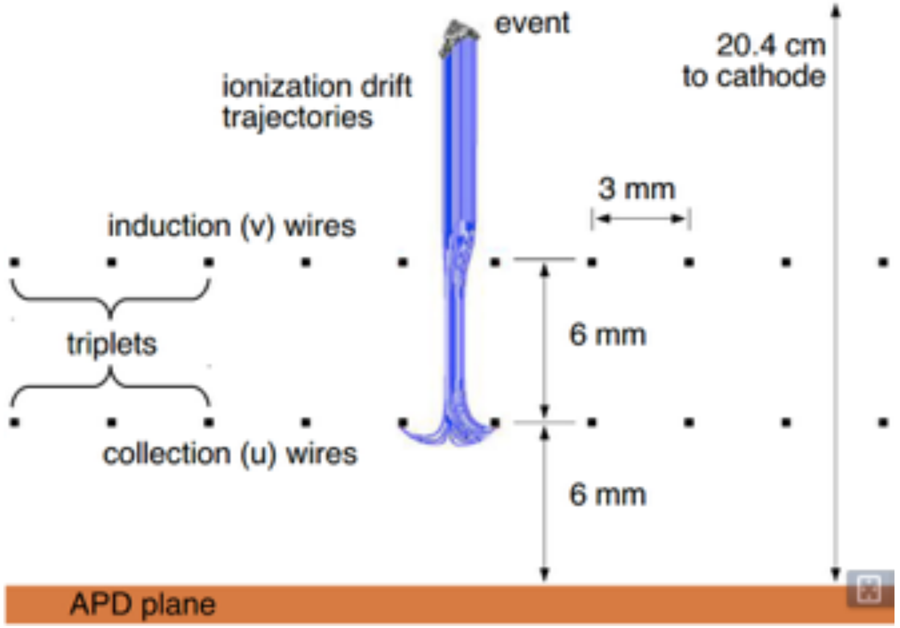
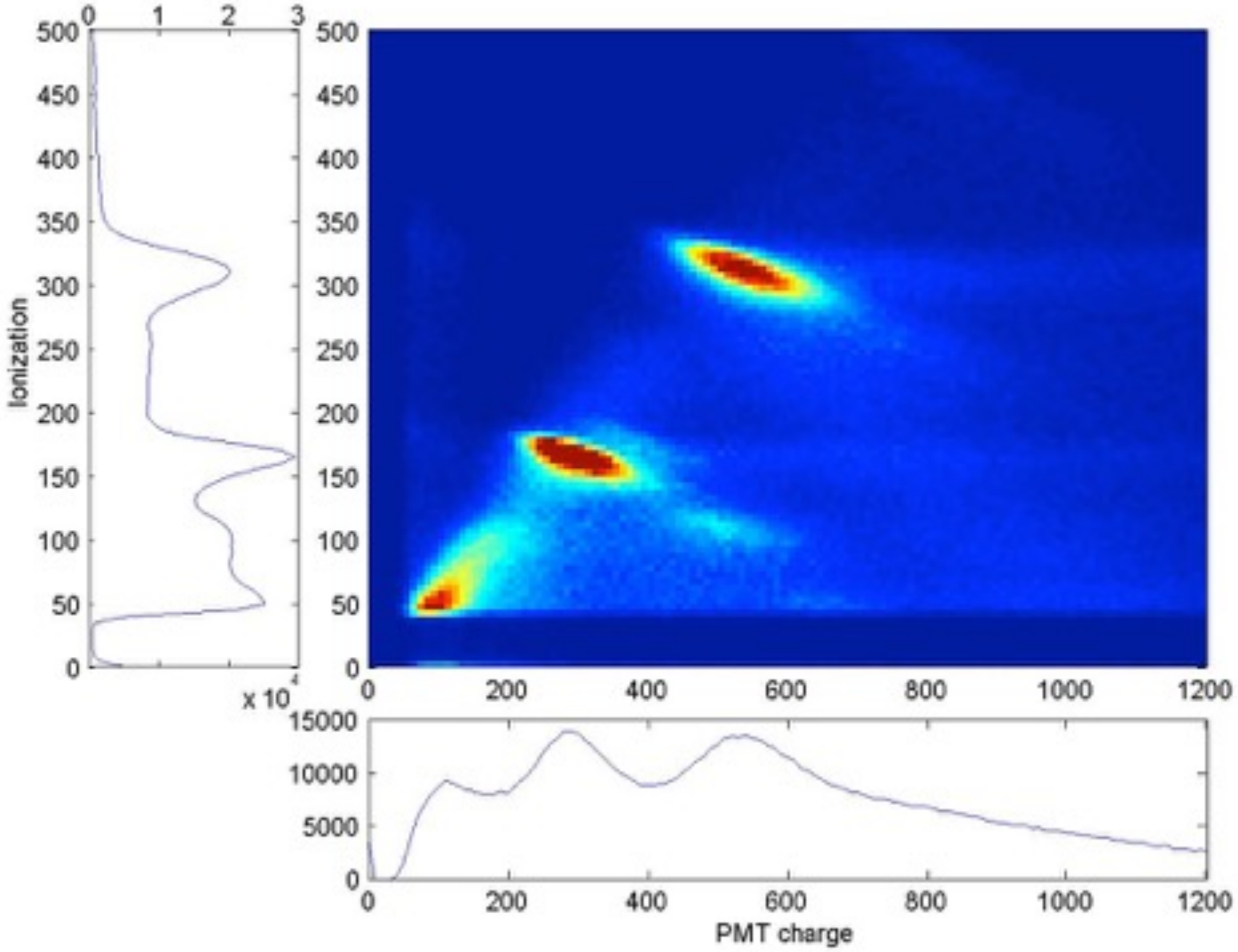
EXO-200 Concept





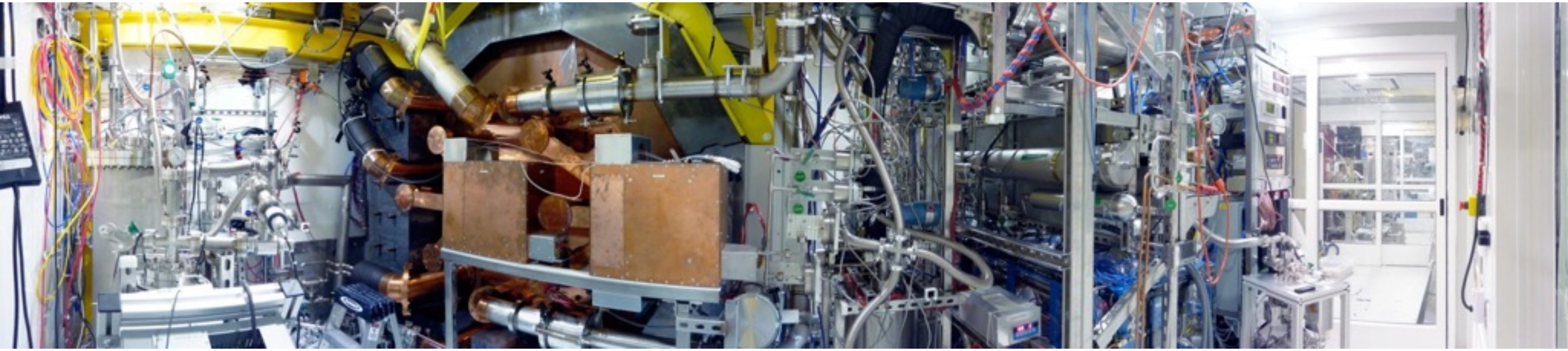
EXO R&D showed the way to improved energy resolution in LXe:

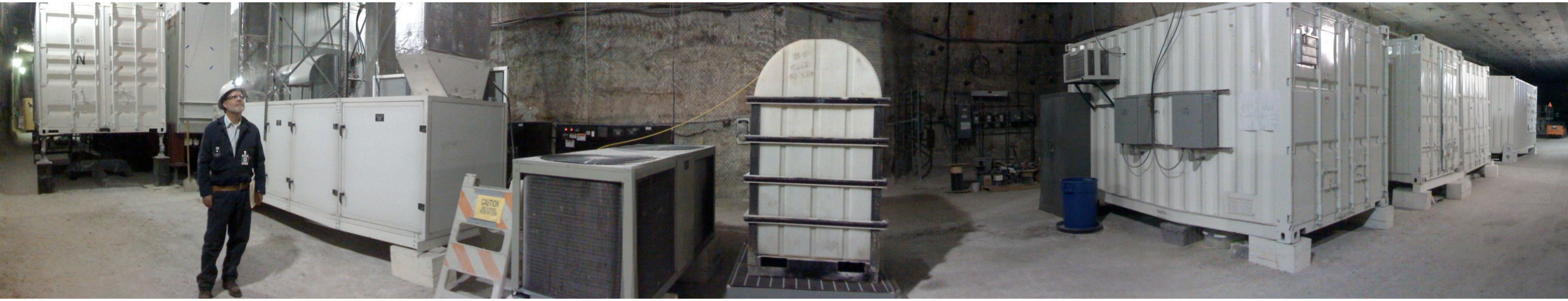
Use (anti)correlations between ionization and scintillation signals



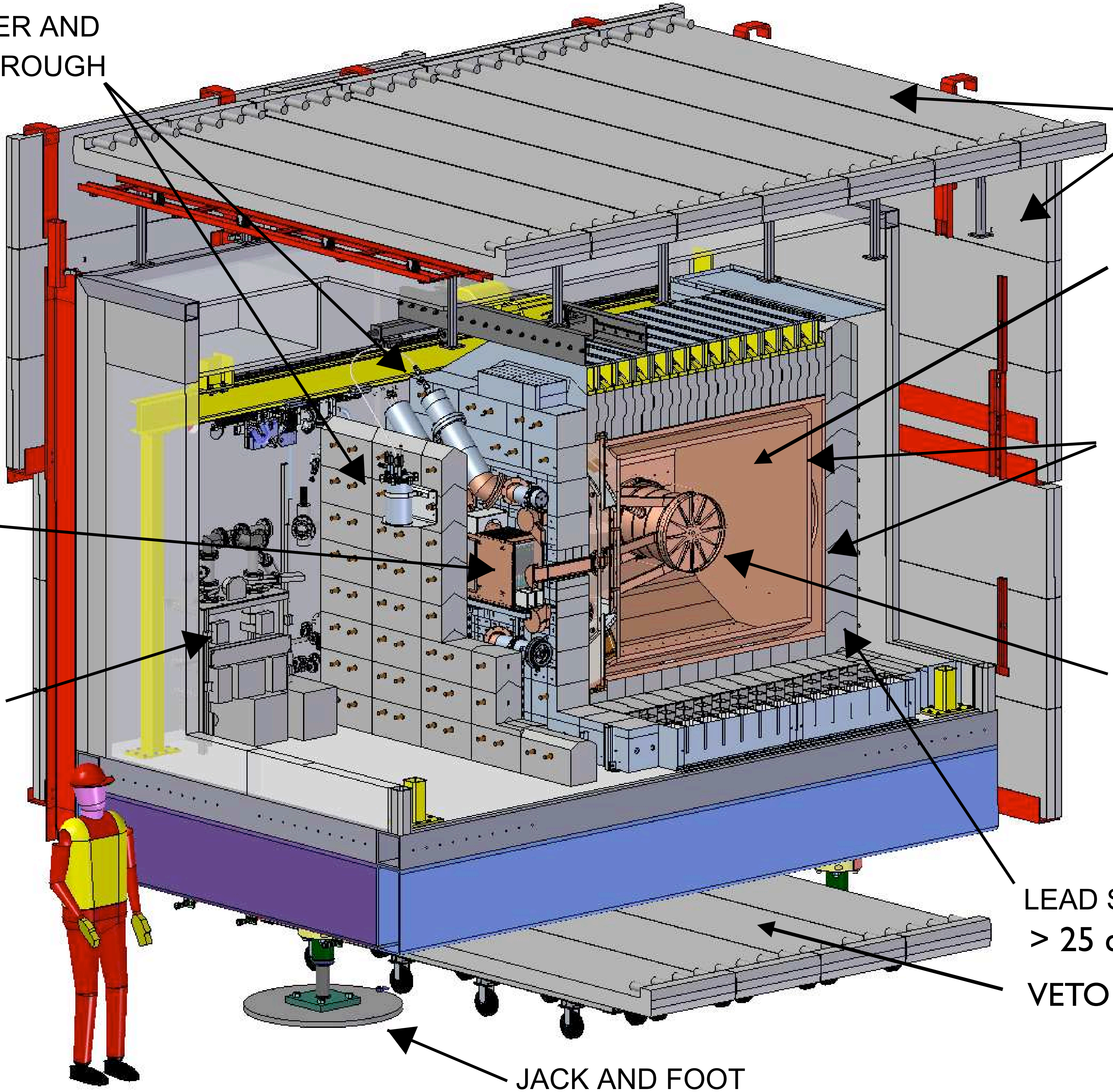
- **Two TPCs with common cathode in middle**
- **APD planes observe prompt scintillation for drift time measurement.**
- **V-position given by induction signal on shielding grid.**
- **U-position and energy given by charge collection grid.**

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

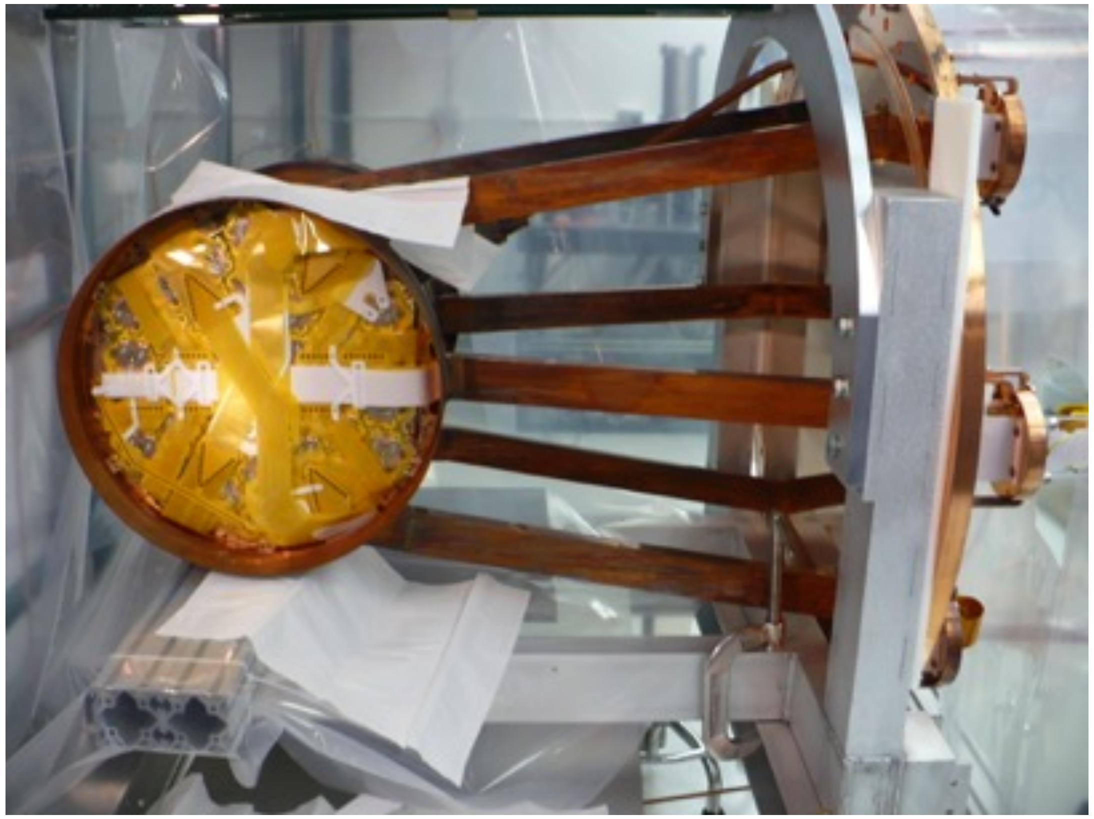
LEAD SHIELDING
> 25 cm

VETO PANELS

JACK AND FOOT

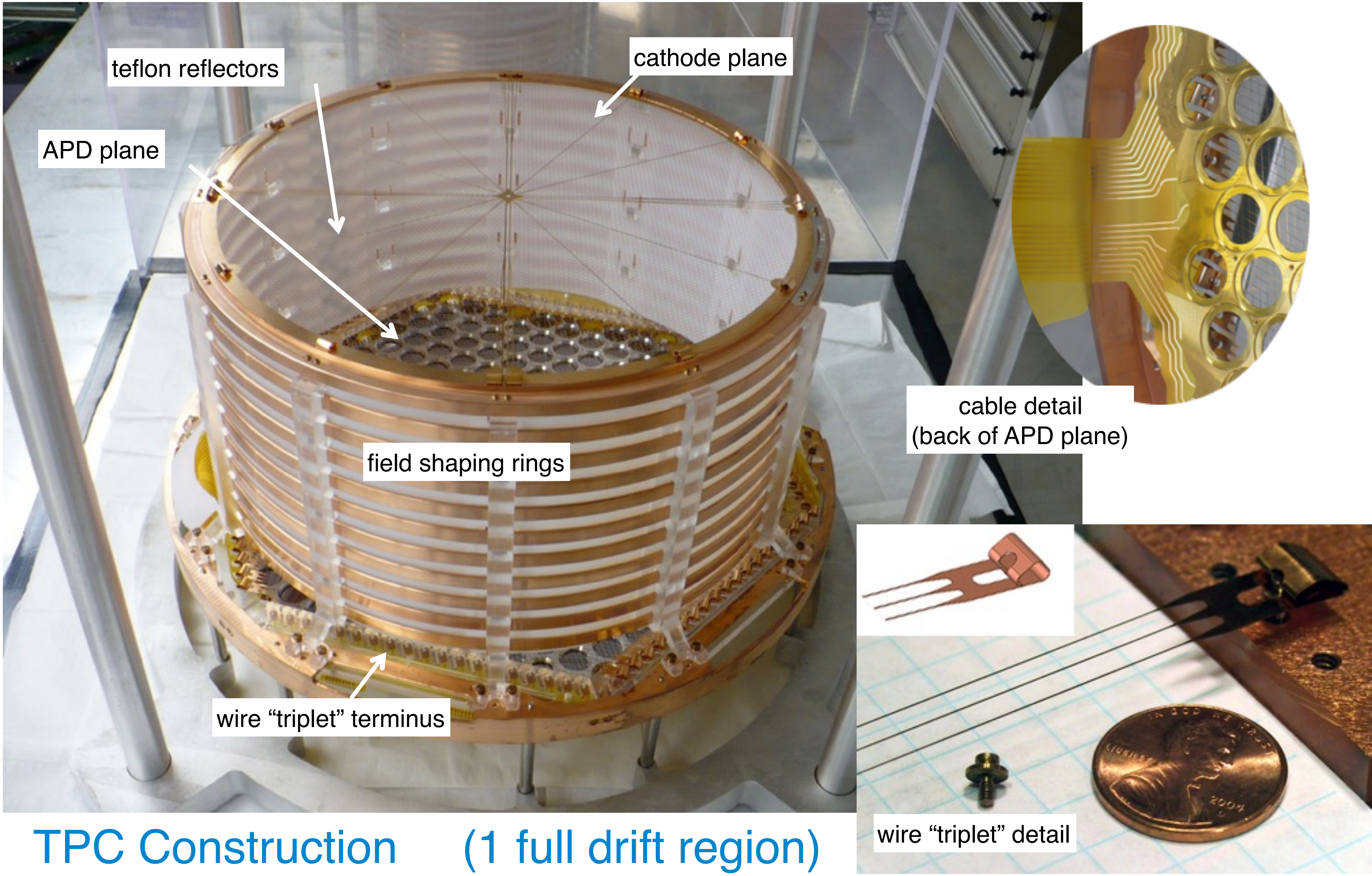
Low Activity Copper

- Very light (~1.5mm thin, ~15kg) to minimize materials



- 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)

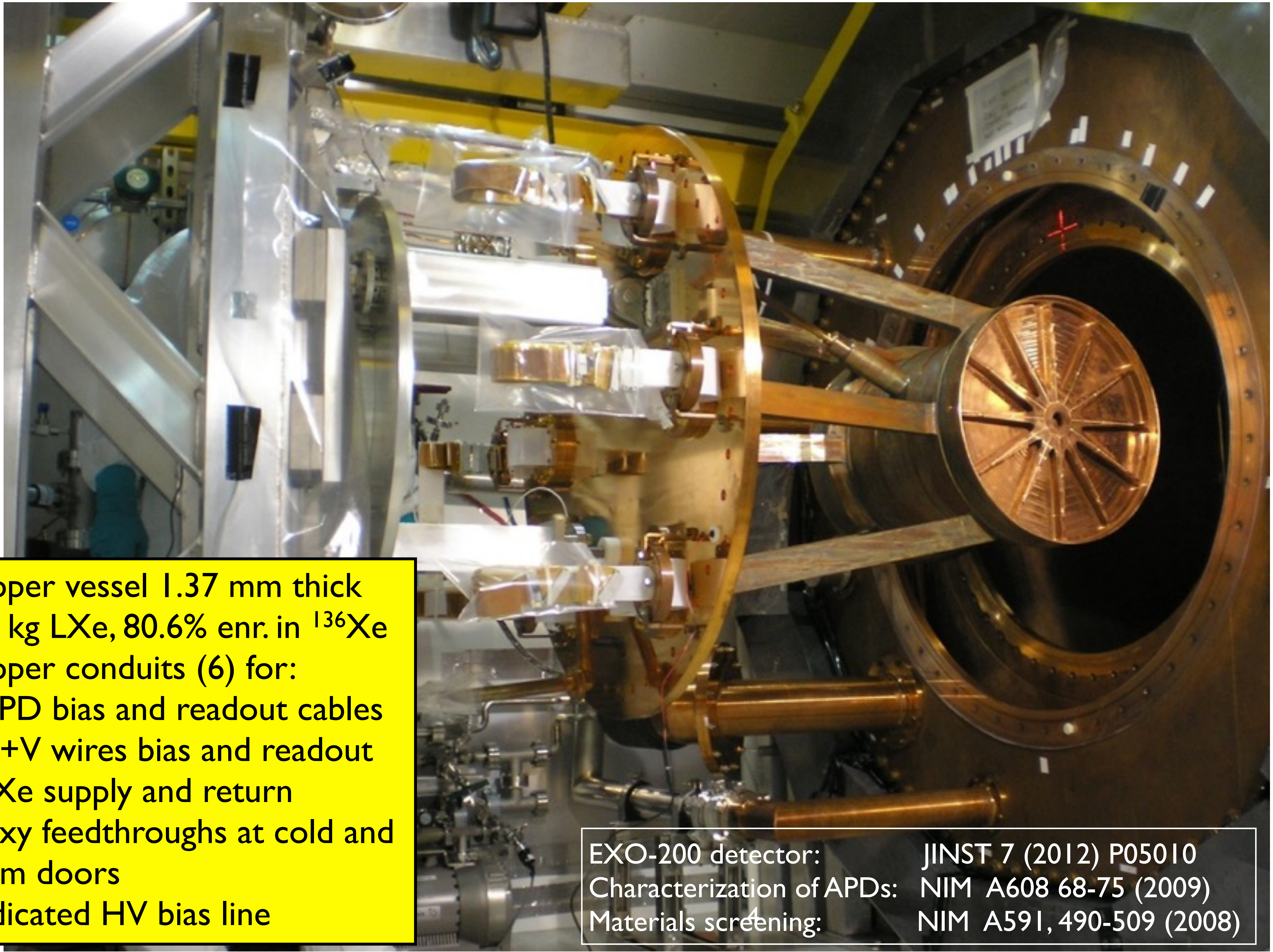
TPC: The Innards



TPC Construction (1 full drift region)

TPC Entering the Cryostat

TPC Entering the Cryostat



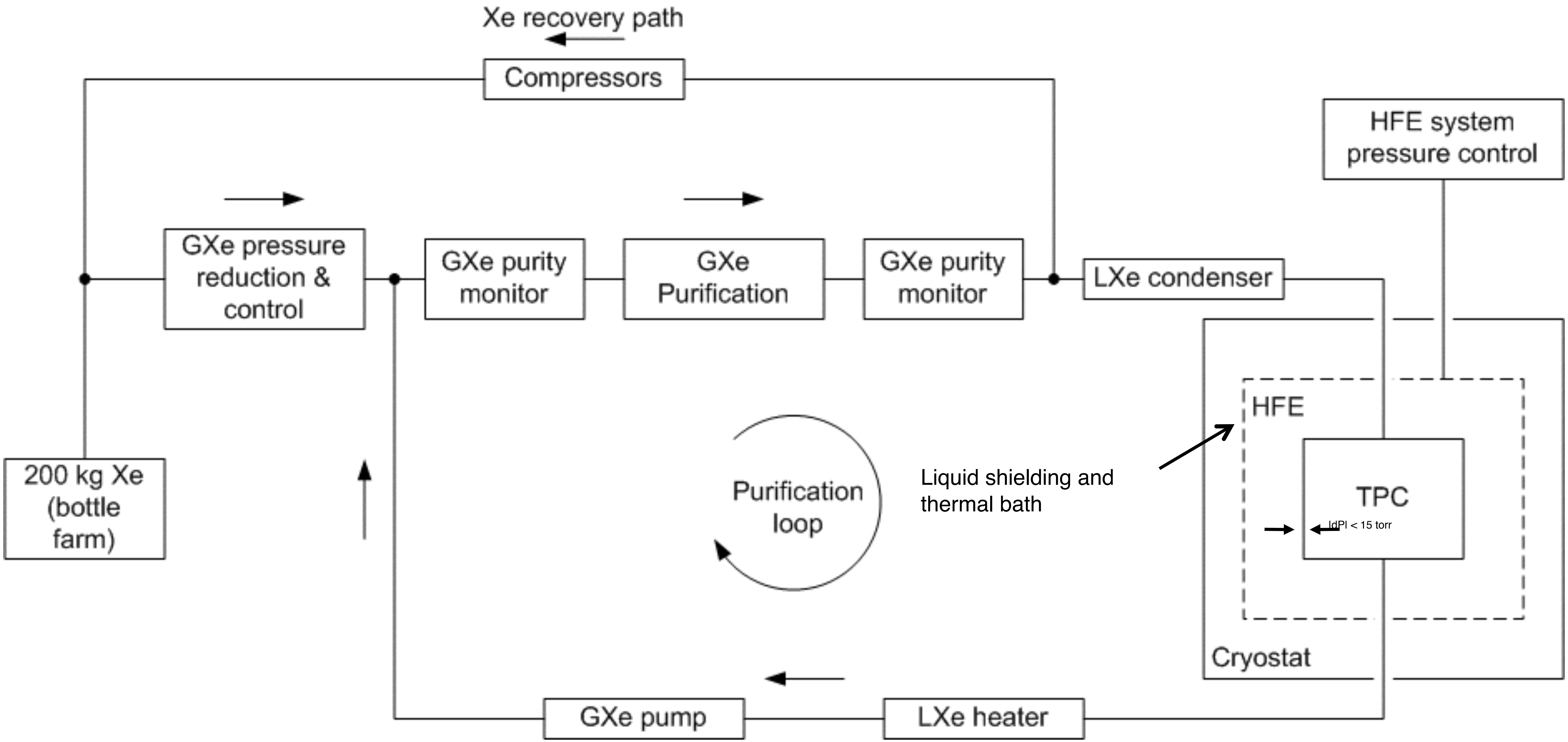
Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in ^{136}Xe
Copper conduits (6) for:

- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return

Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

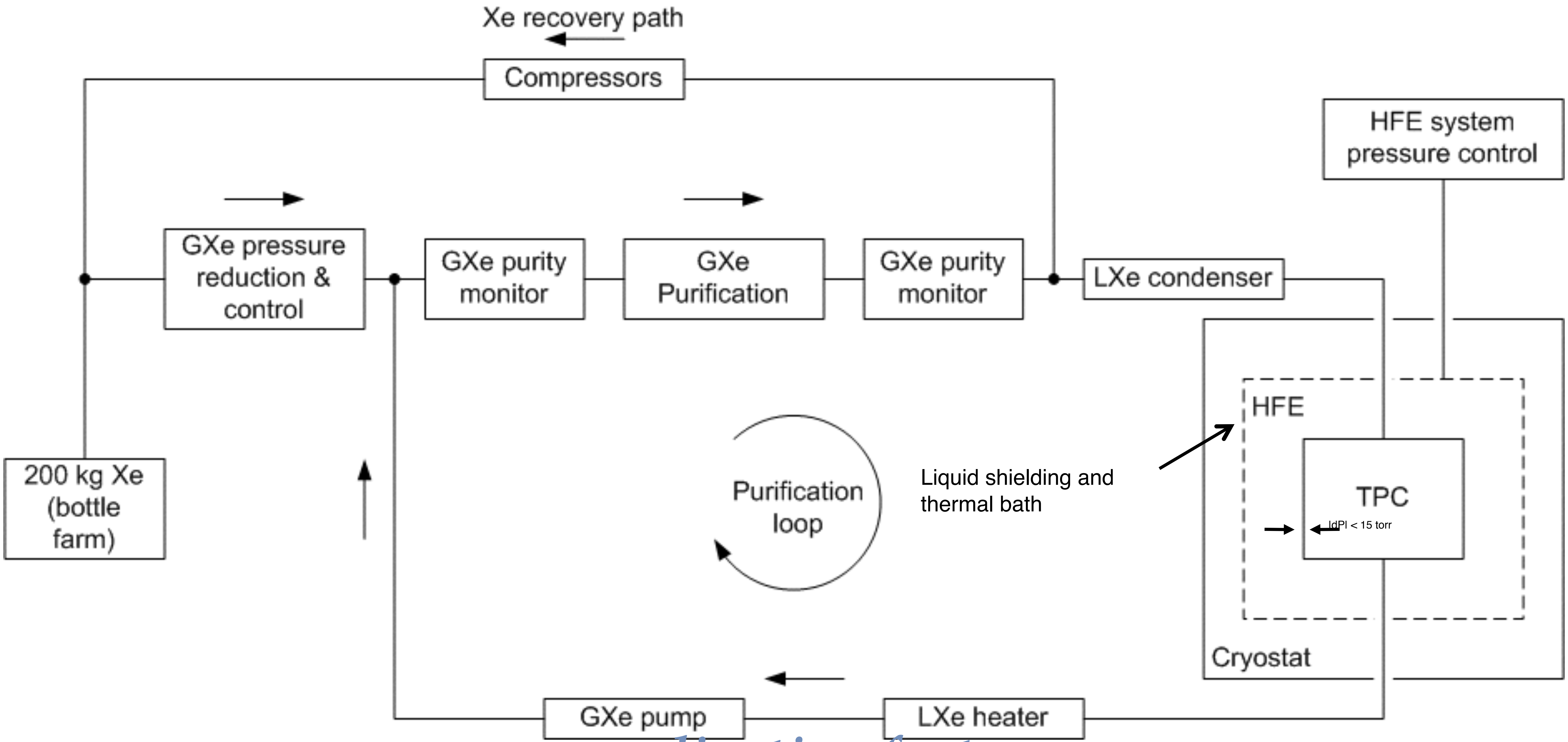
EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

Xenon Recirculation



Liquid shielding and thermal bath

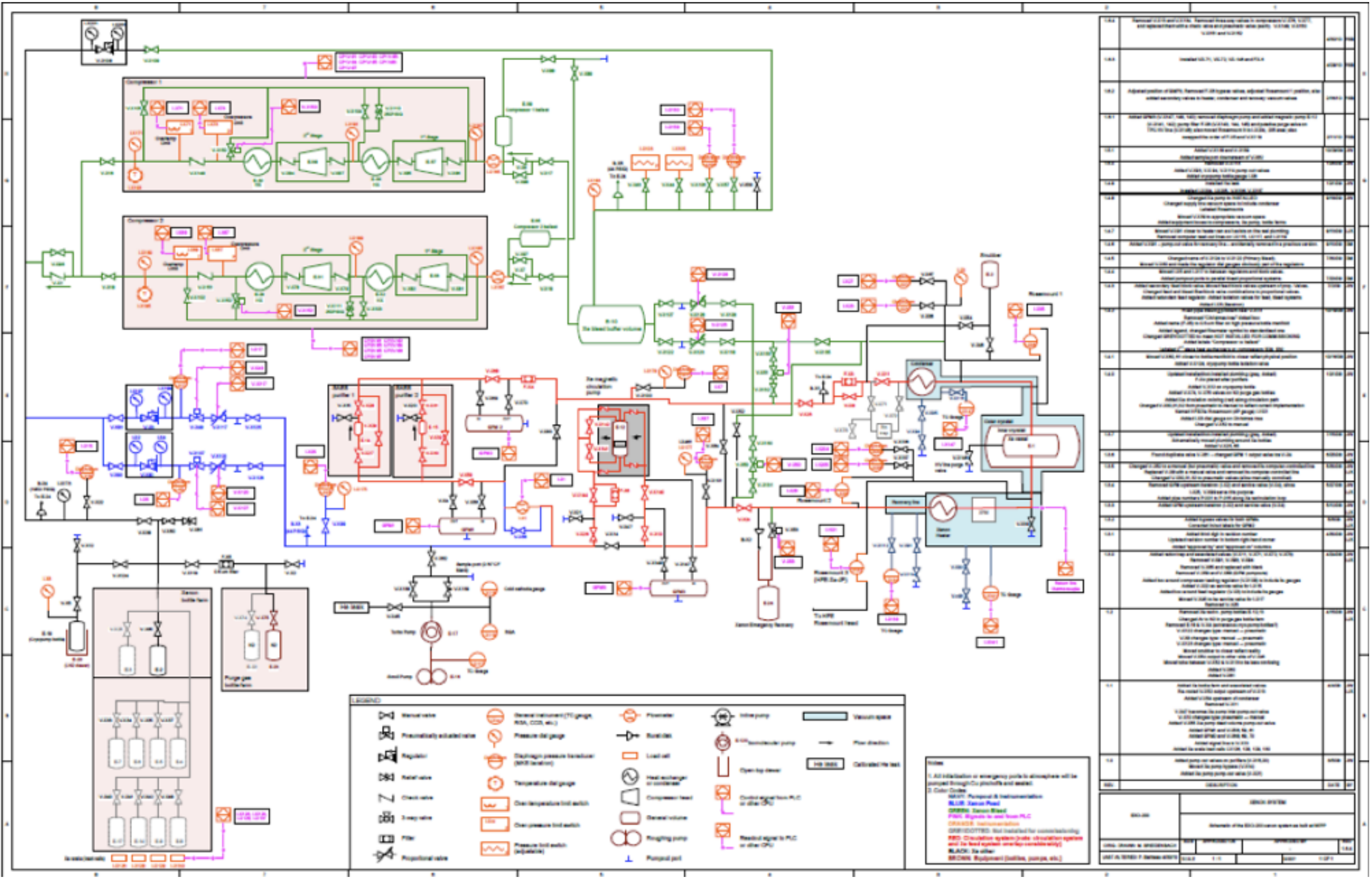
Xenon Recirculation



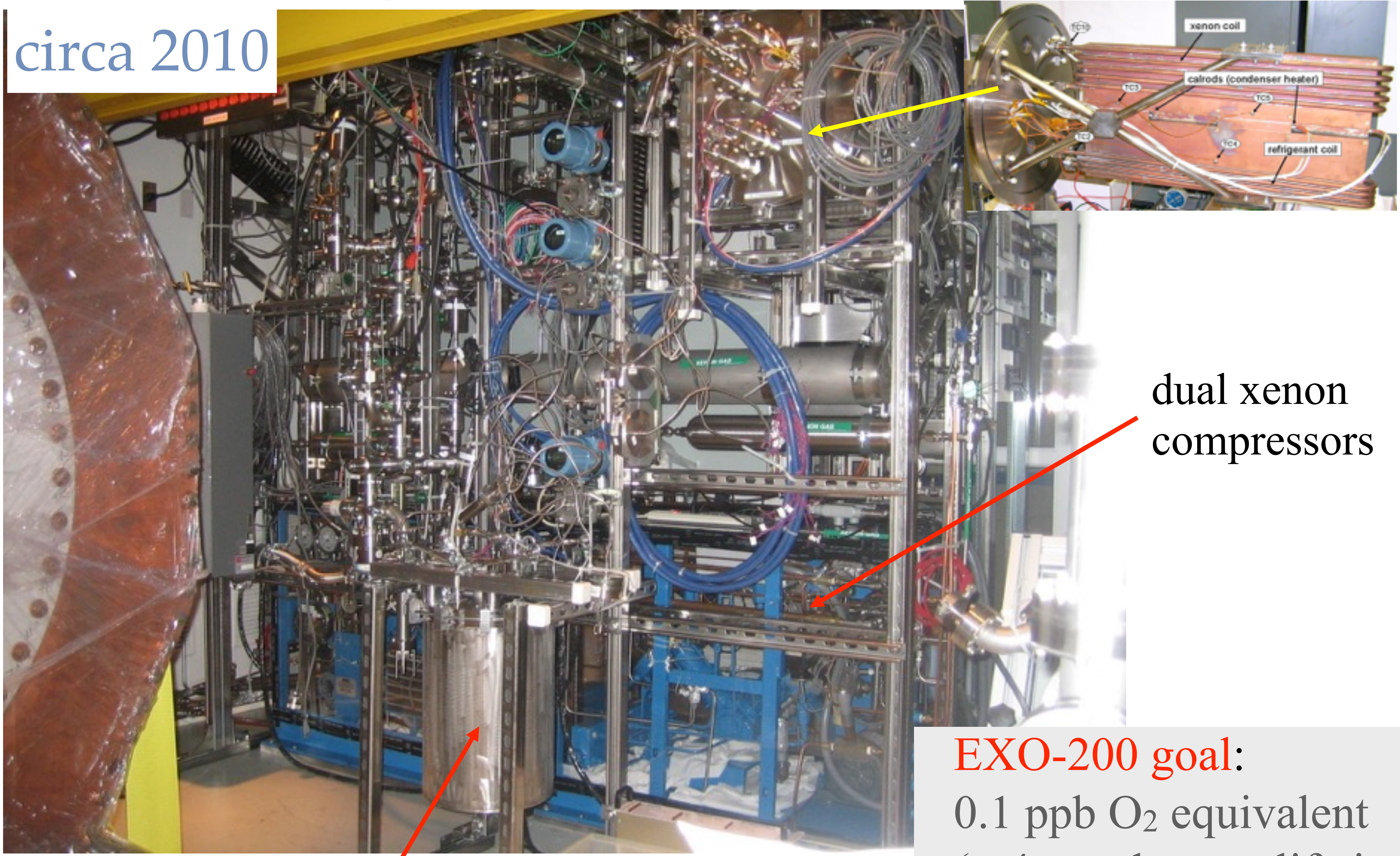
complicating factors:

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

Xenon Recirculation



EXO-200 Module 2



circa 2010

dual xenon compressors

LXe boil-off heater

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

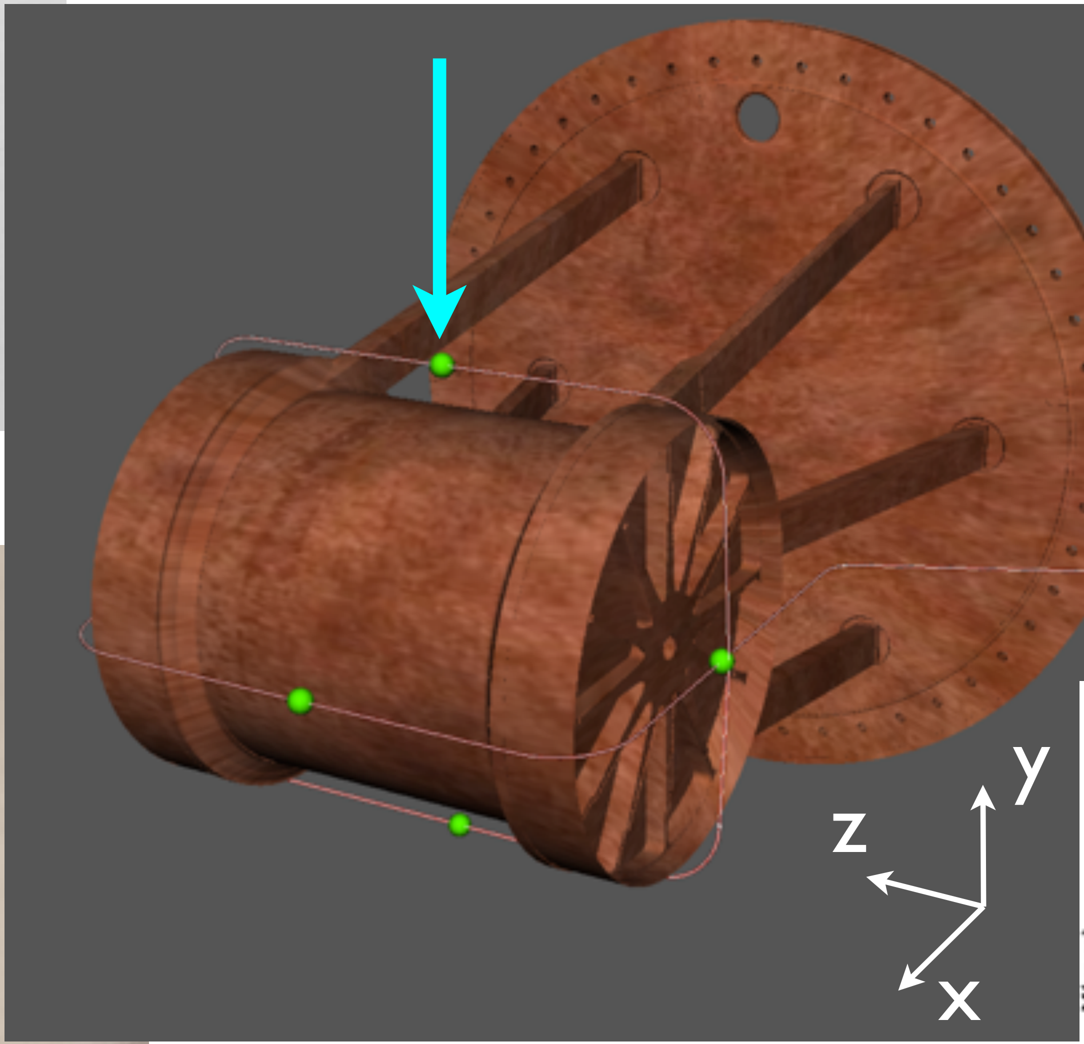
Calibration System

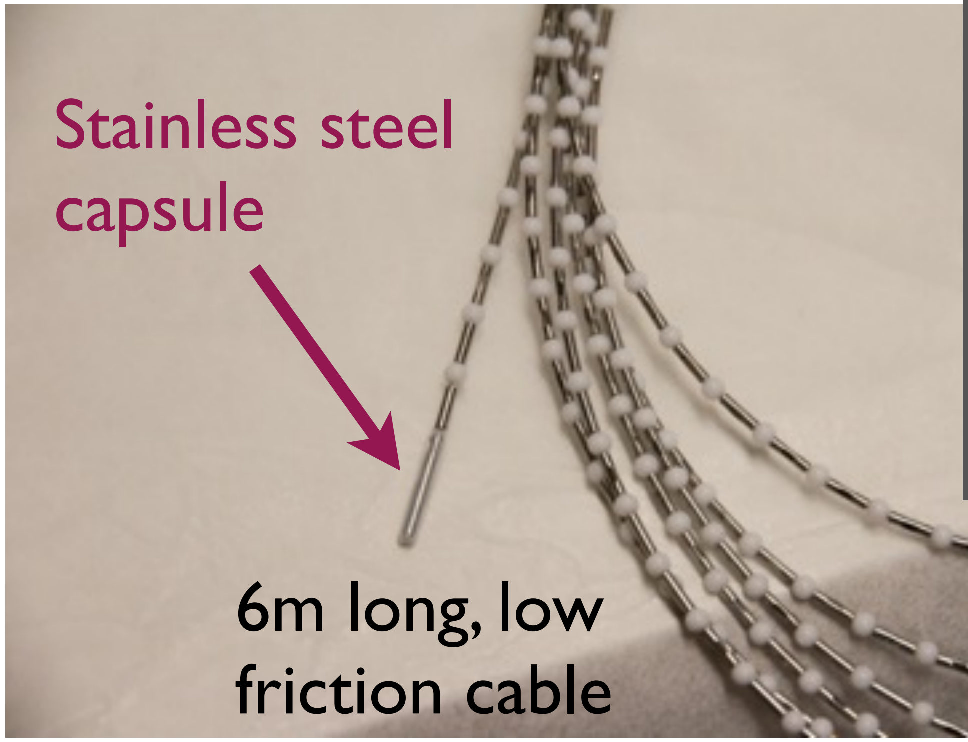
Miniaturized sources


0.7 mm dia. epoxy coated

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

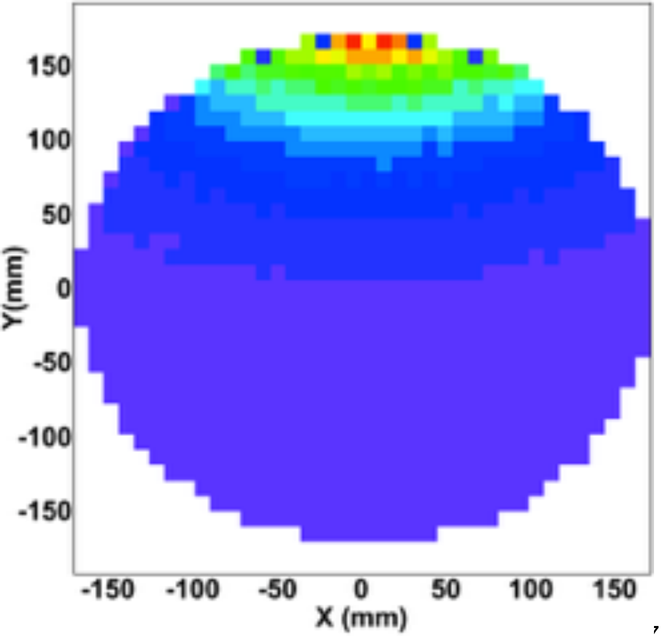
new ^{226}Ra source also added




Stainless steel capsule

6m long, low friction cable

weak ^{228}Th



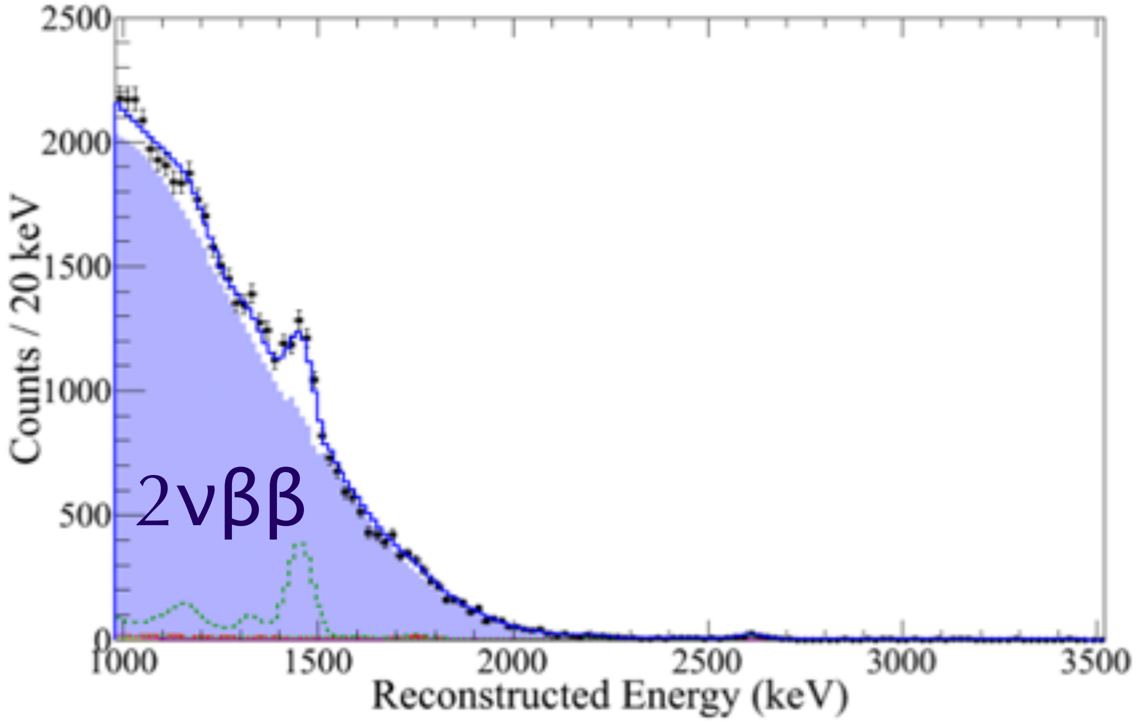
Provide 4 full energy deposition peaks in the energy range
662 keV – 2615 keV

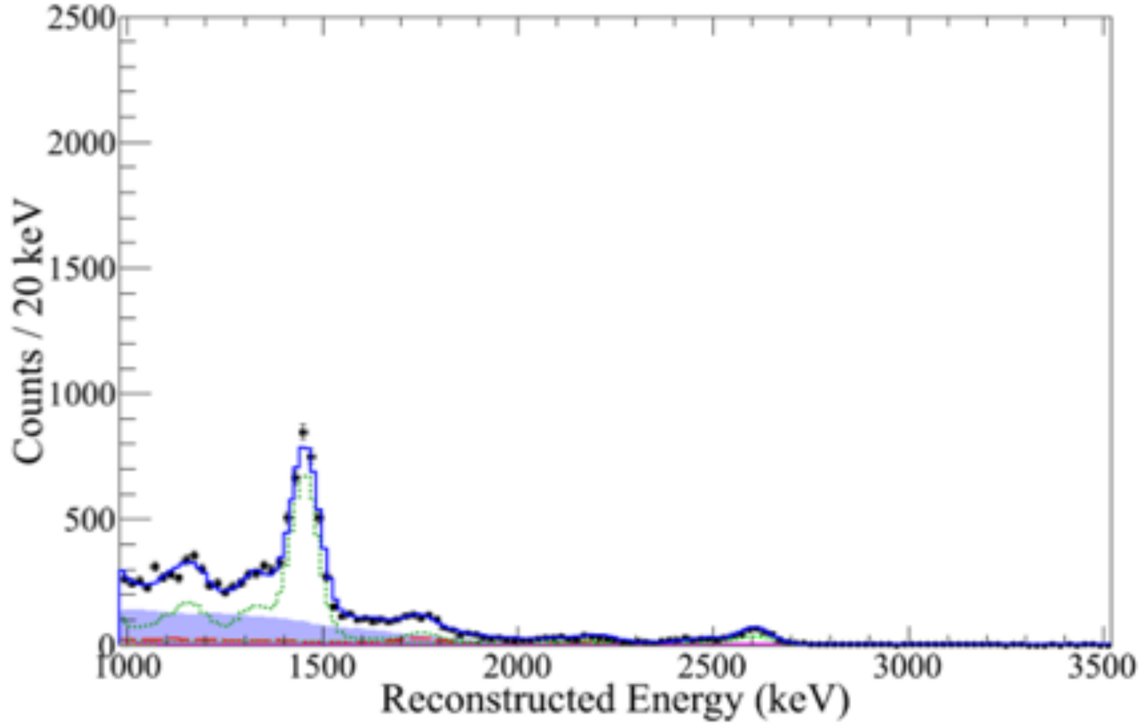
Event Multiplicity

Single Site (SS)

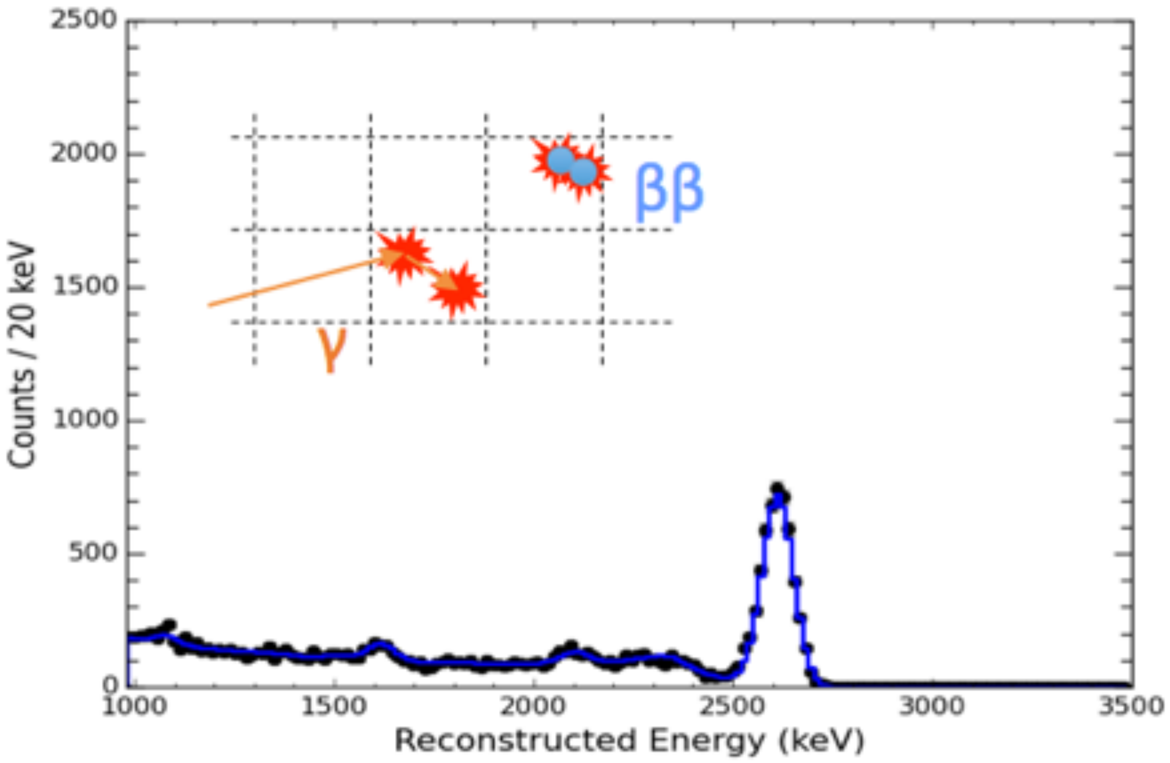
Multiple Site (MS)

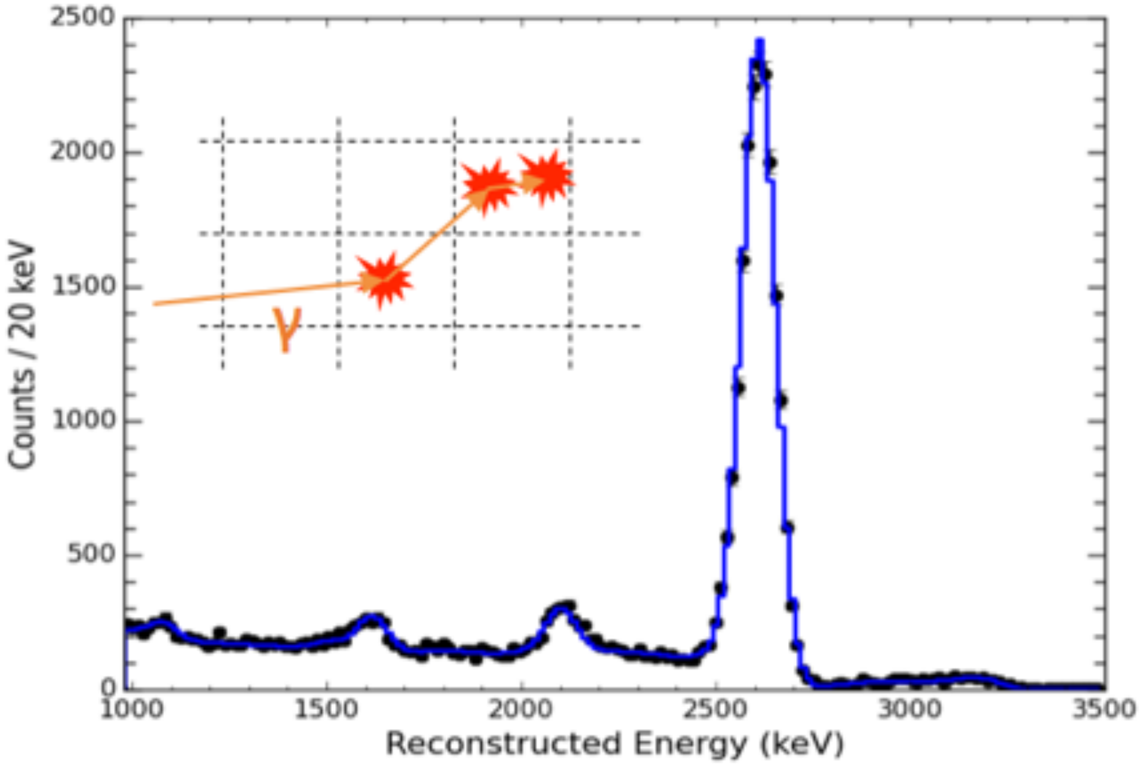
Low Background Data



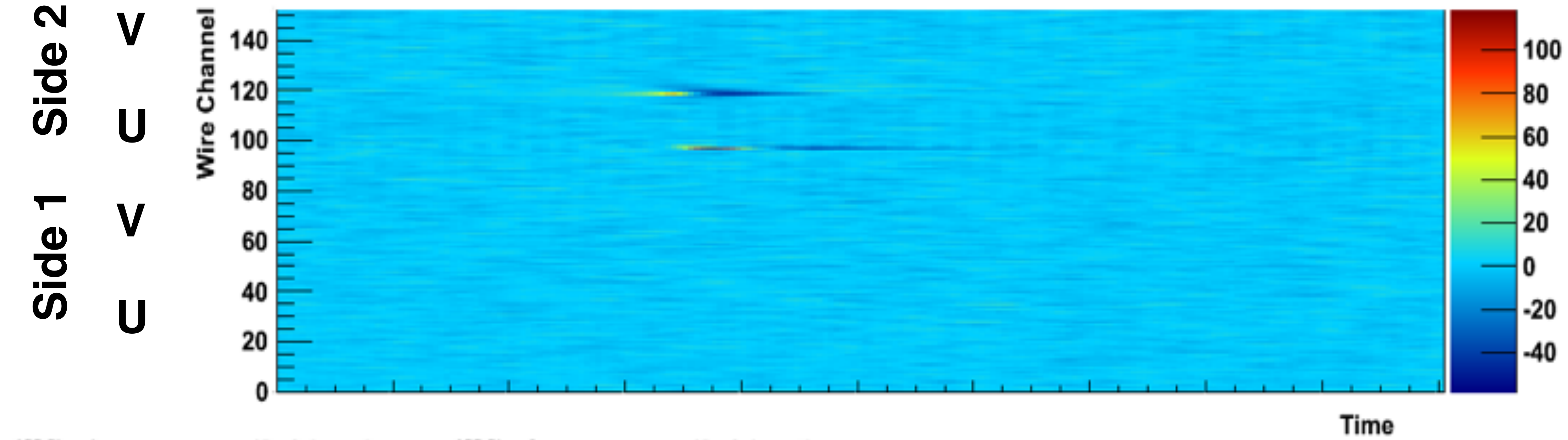


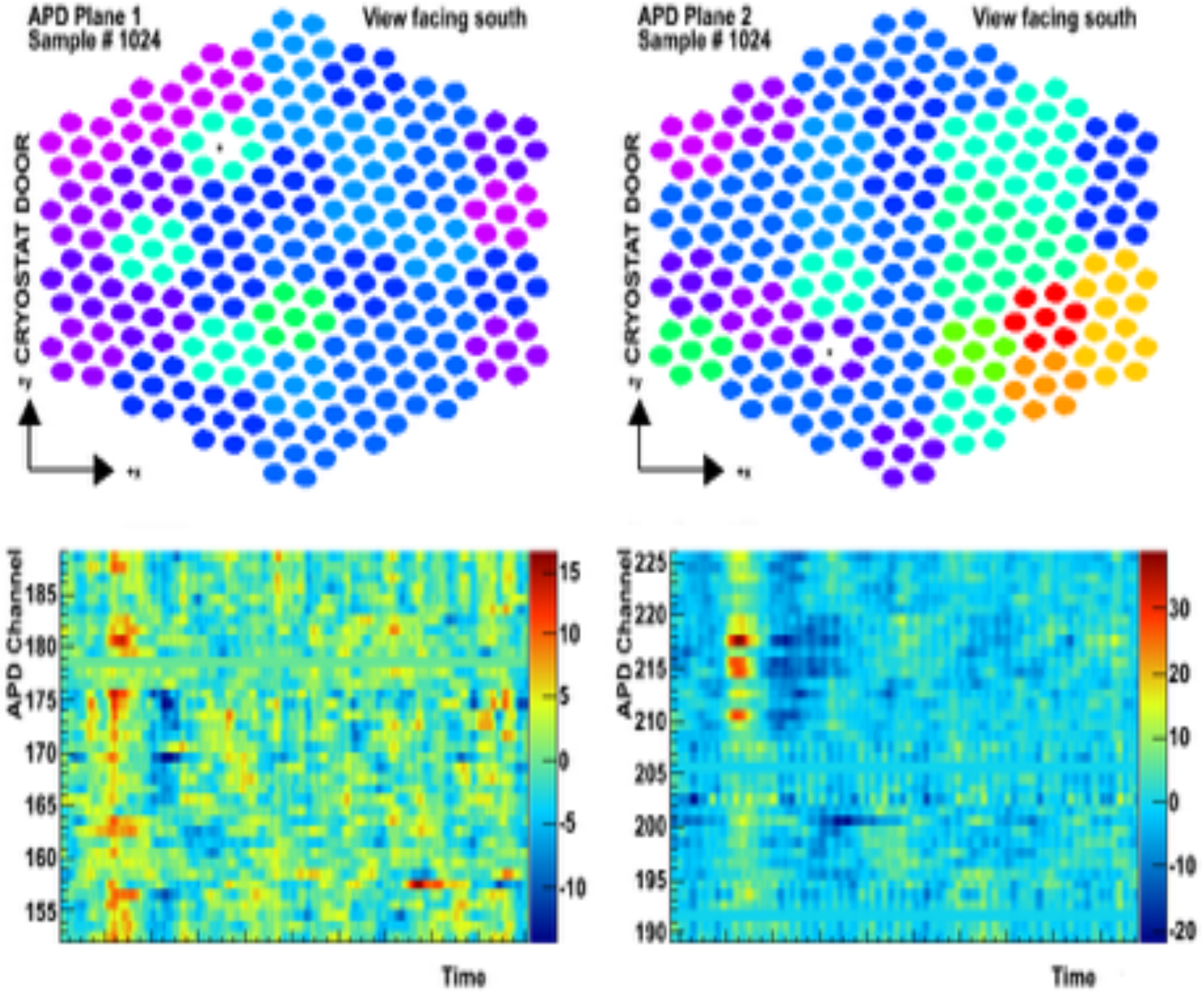
^{228}Th Calibration Source





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

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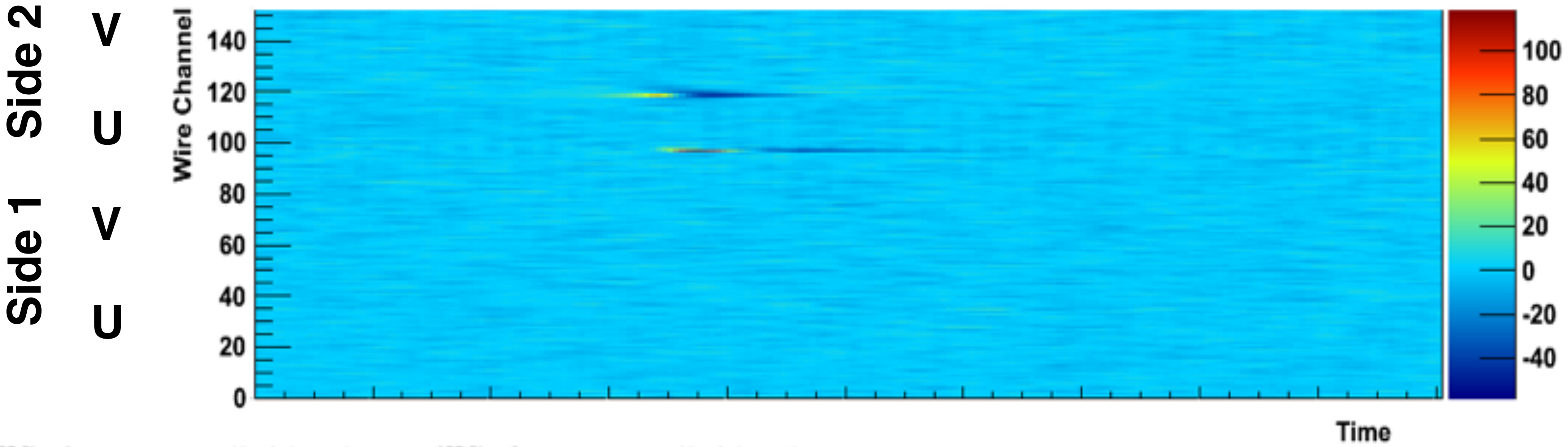

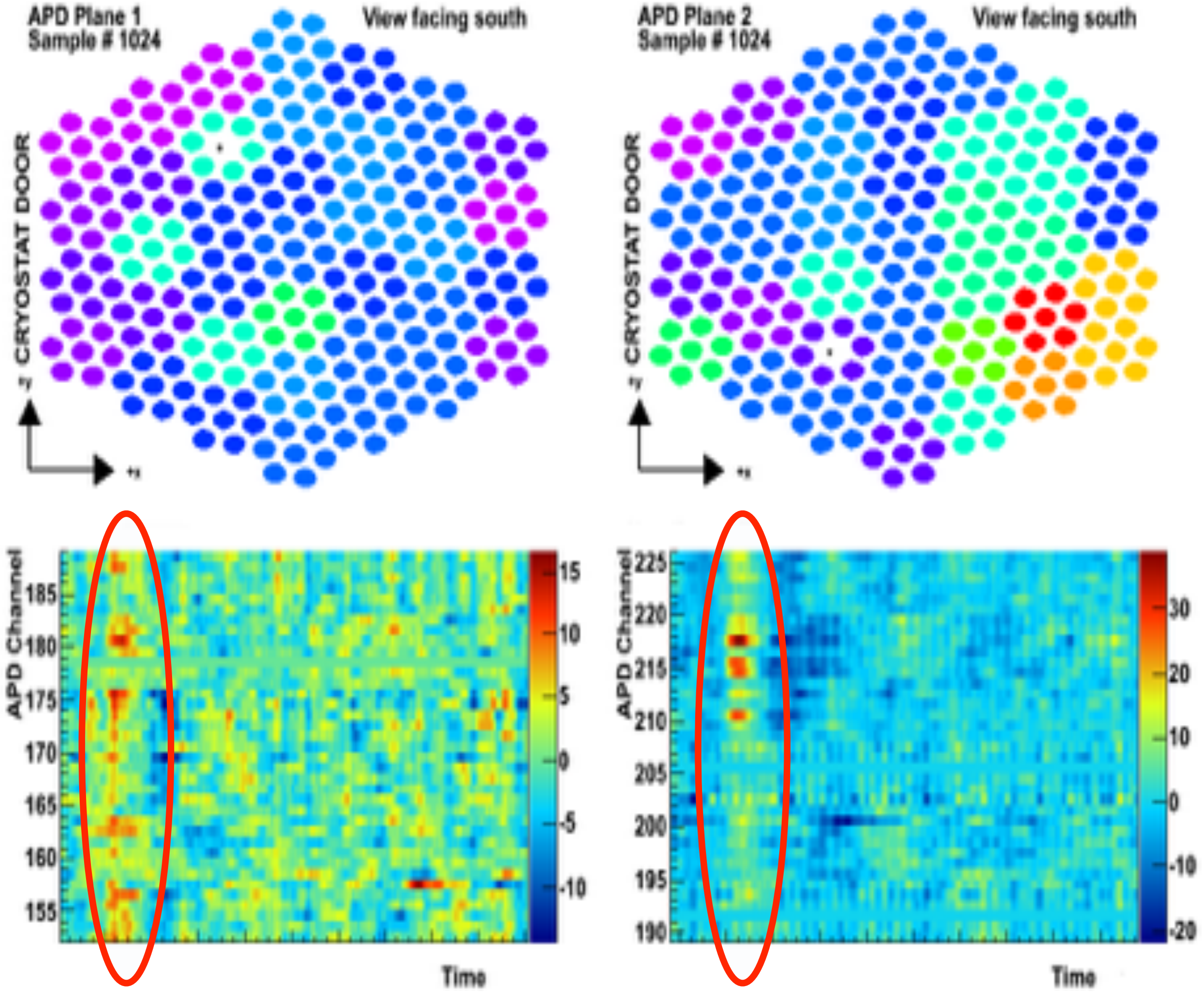

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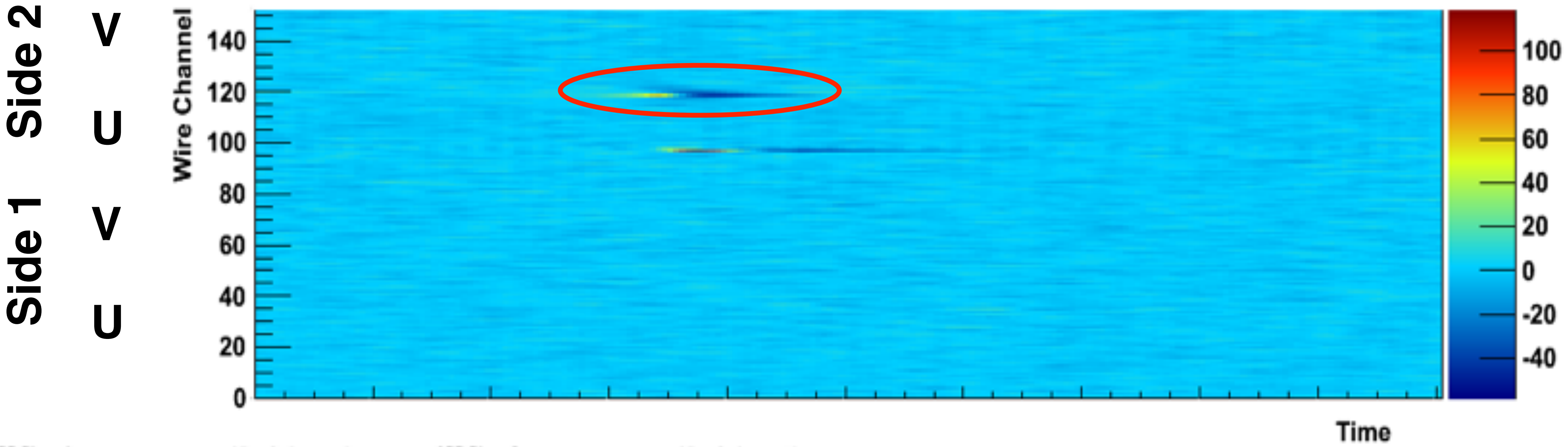

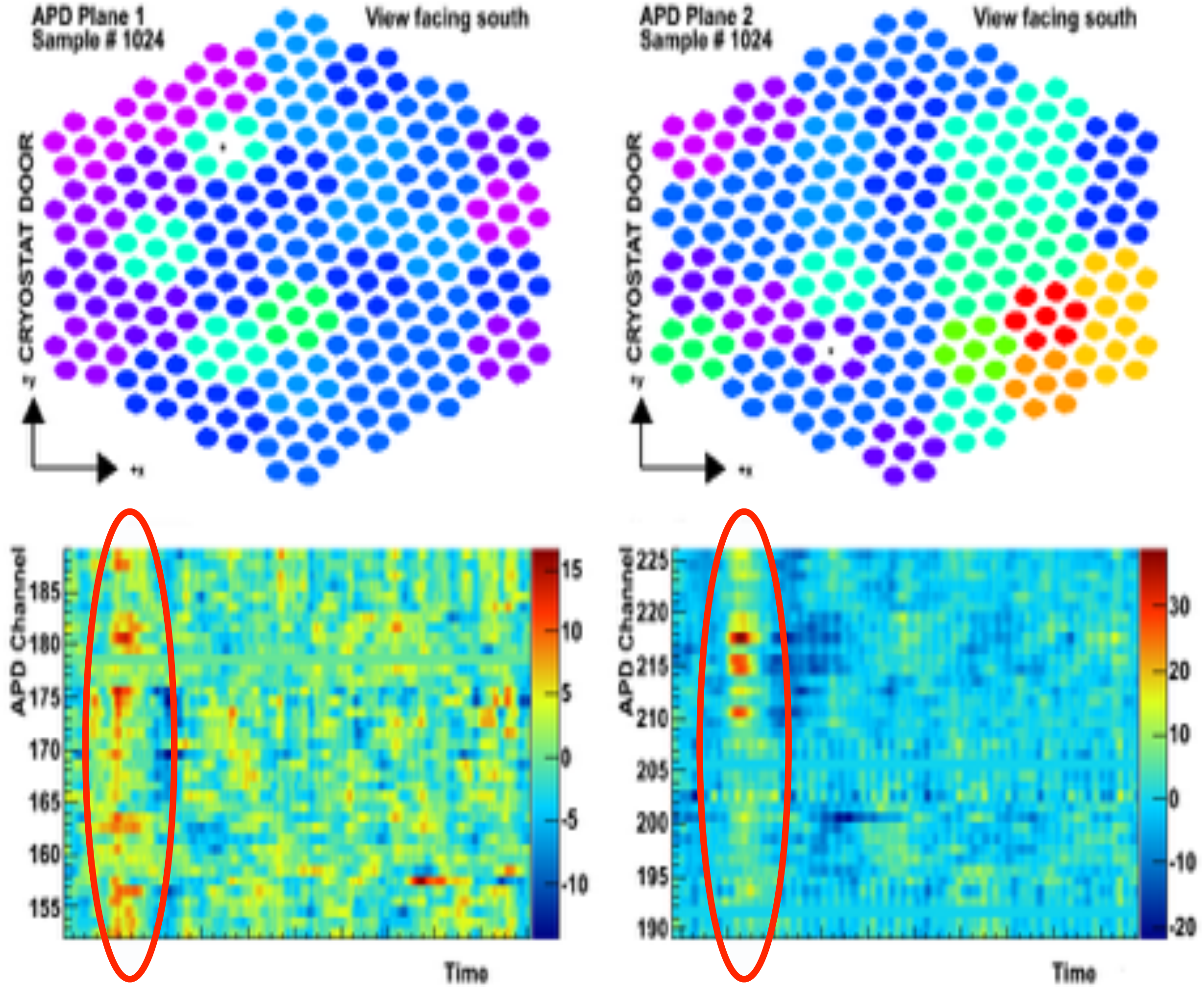

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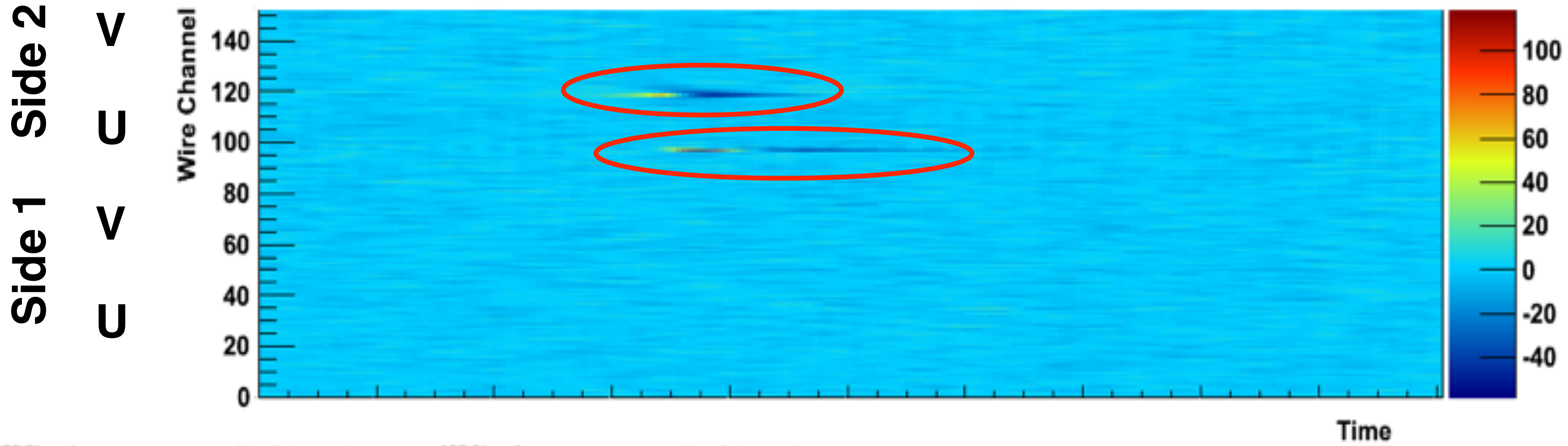

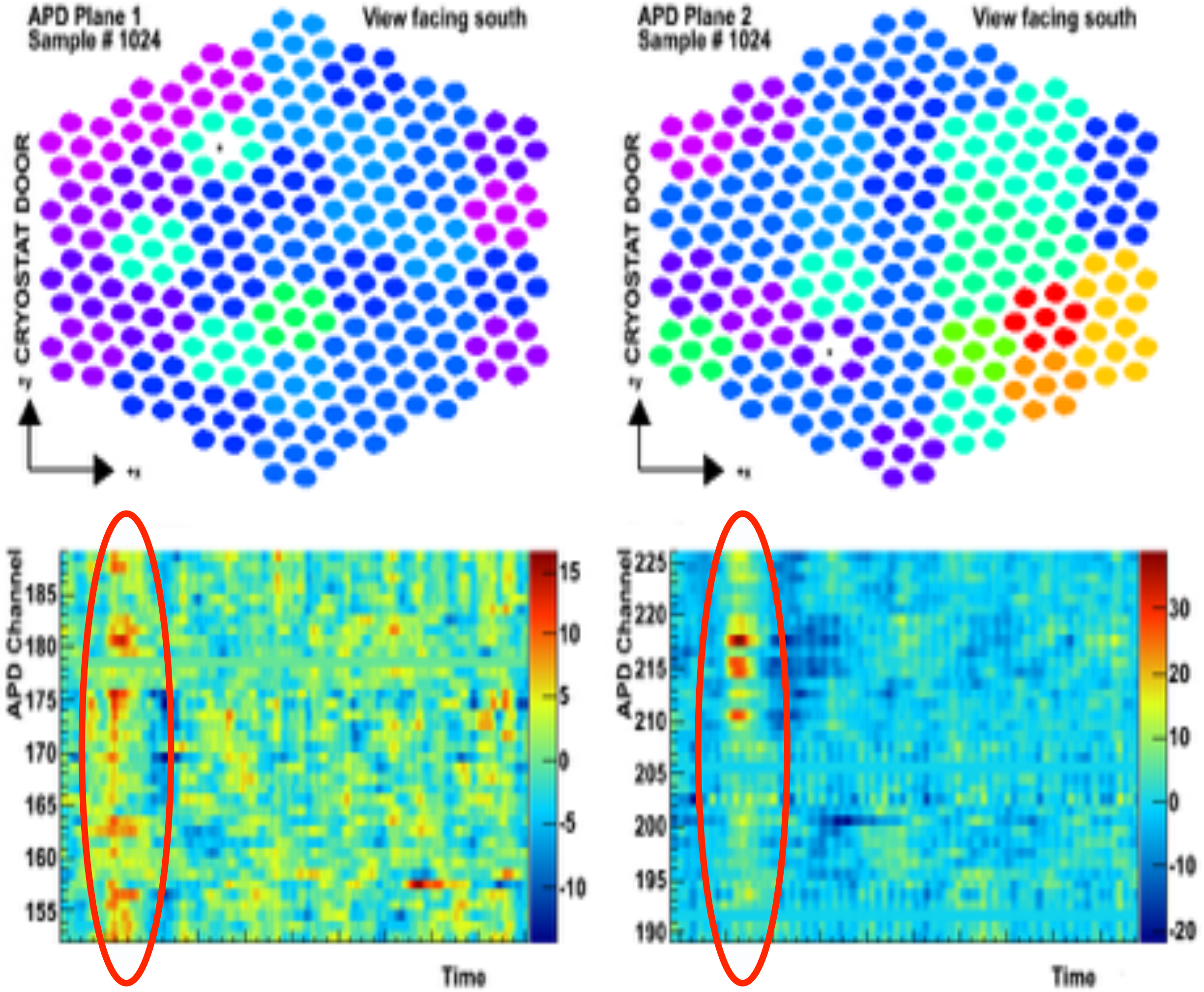

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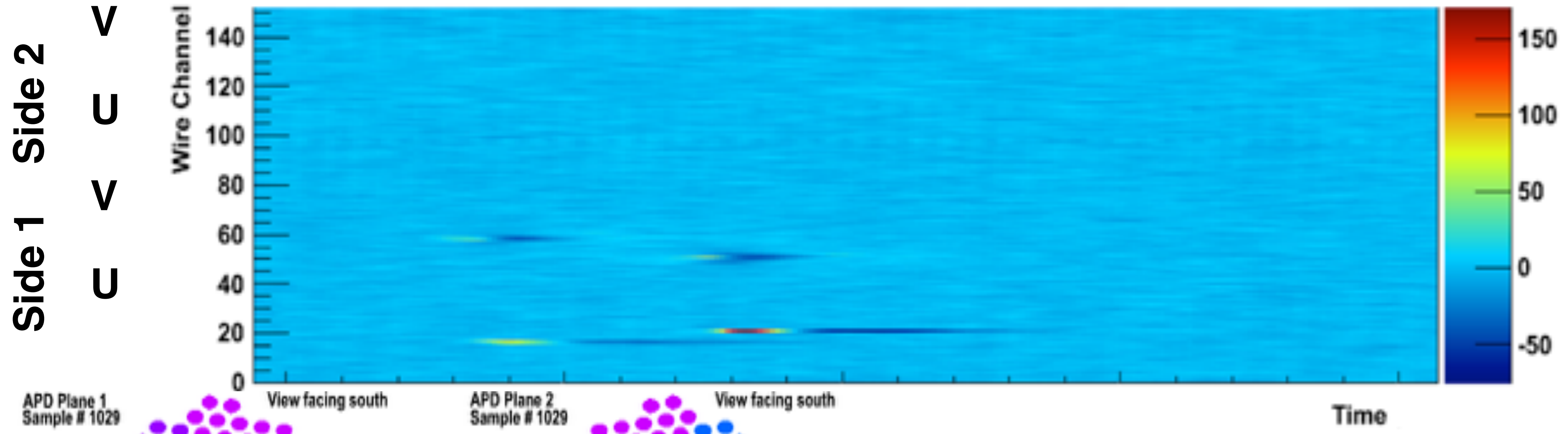
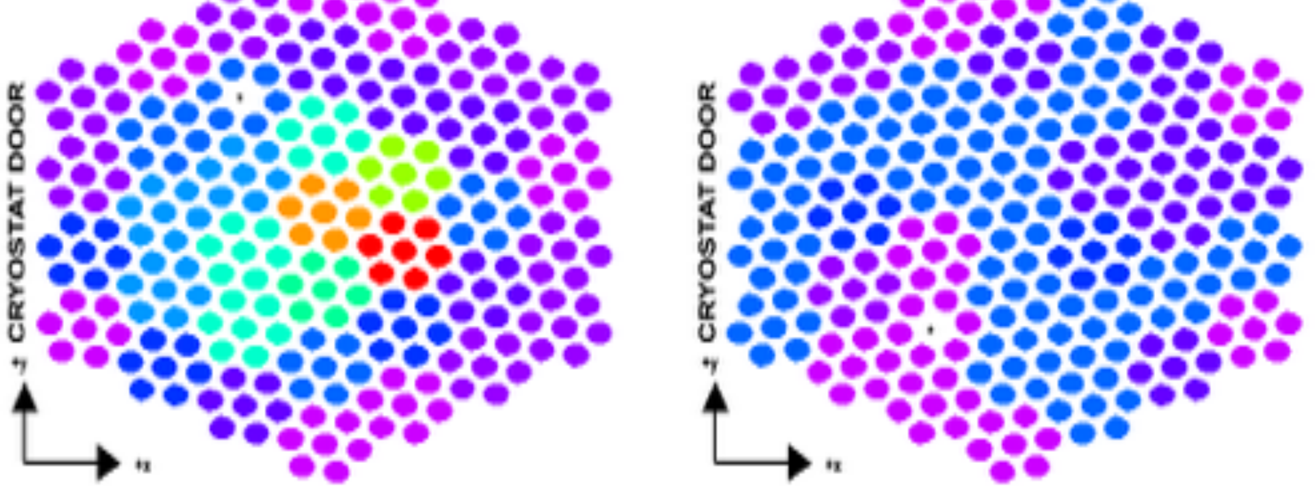
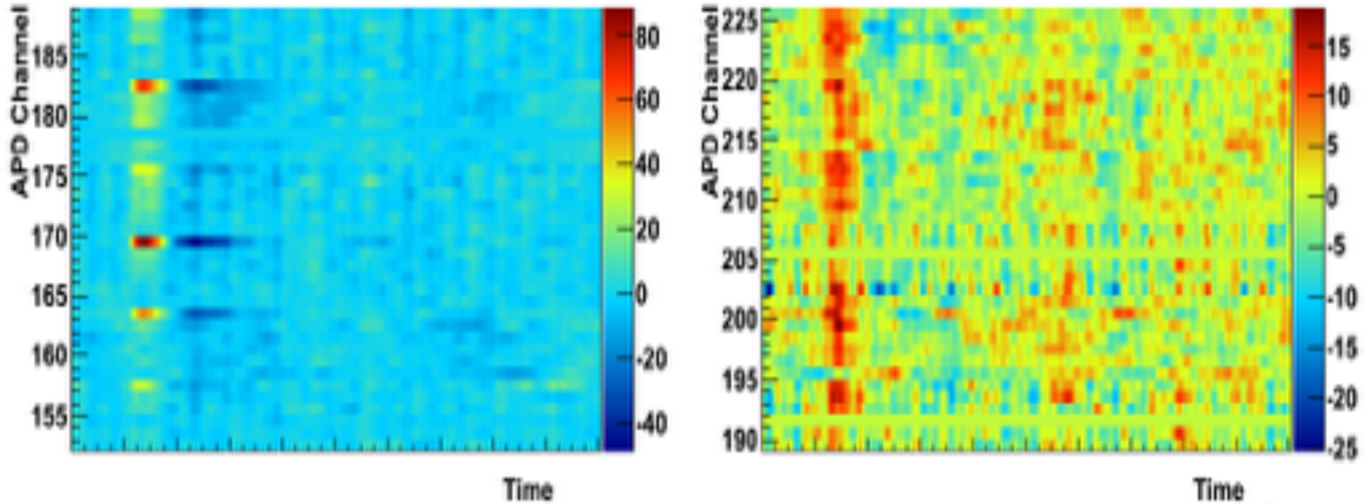
Two-Site Compton Event



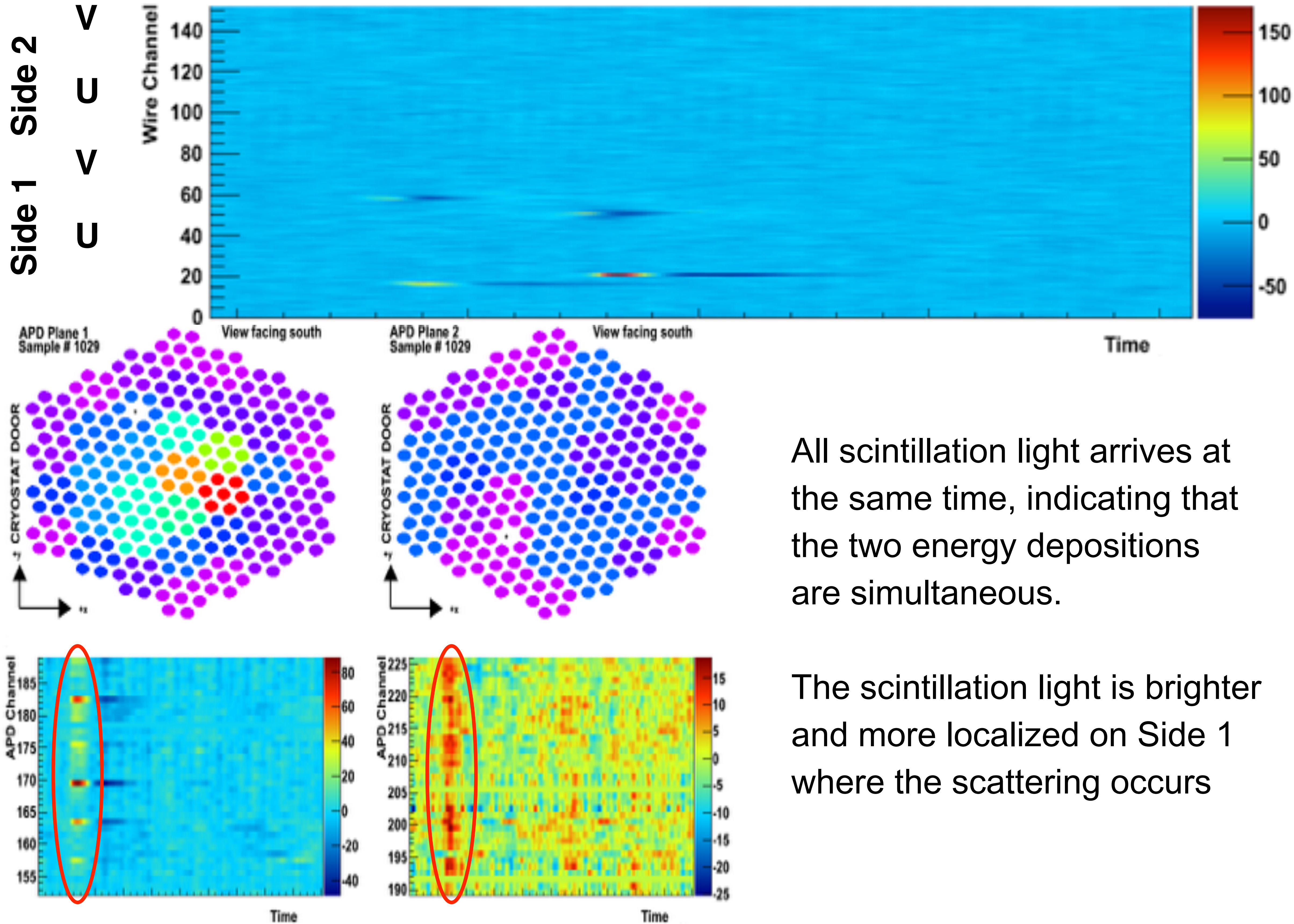




All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

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

Two-Site Compton Event



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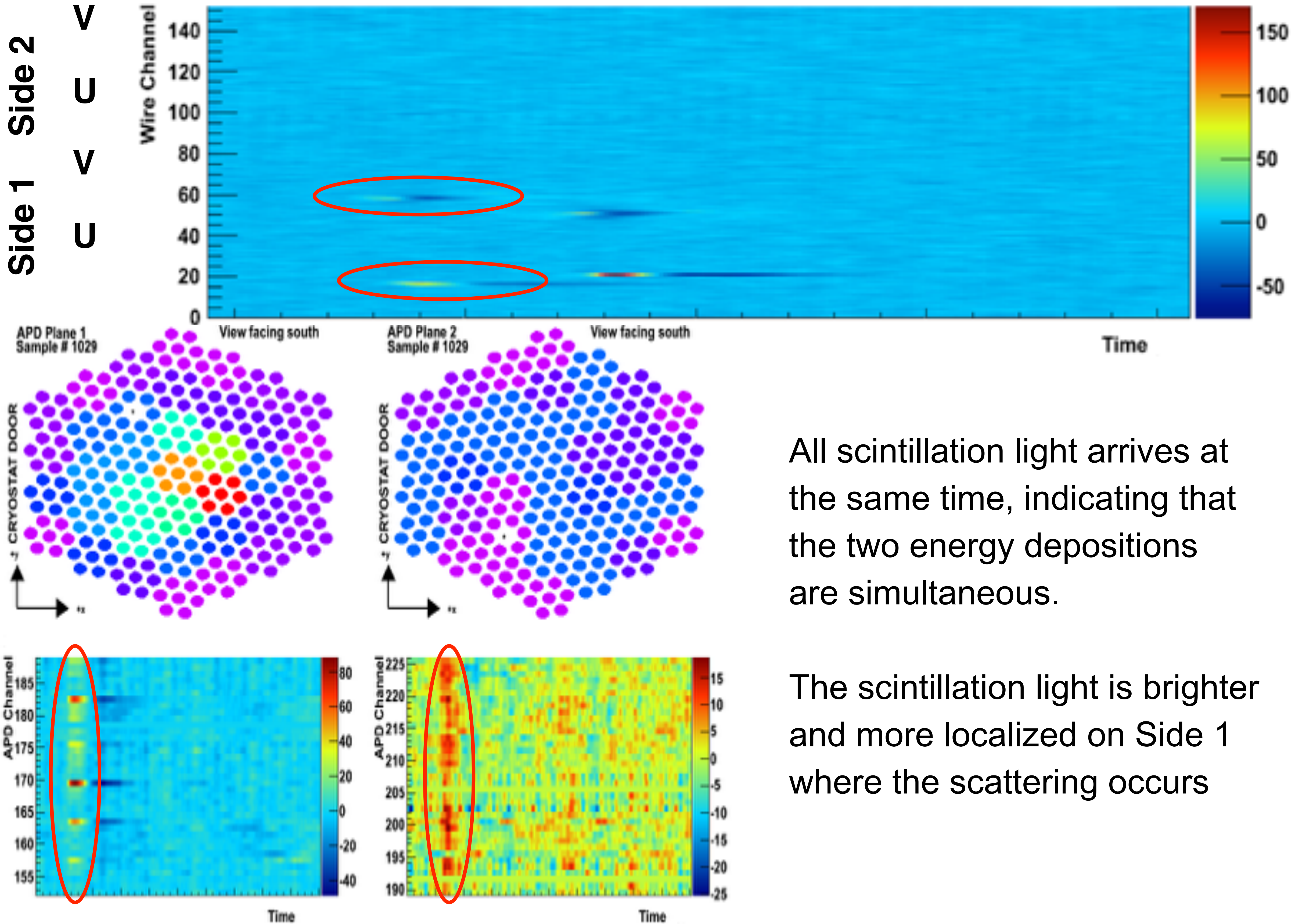

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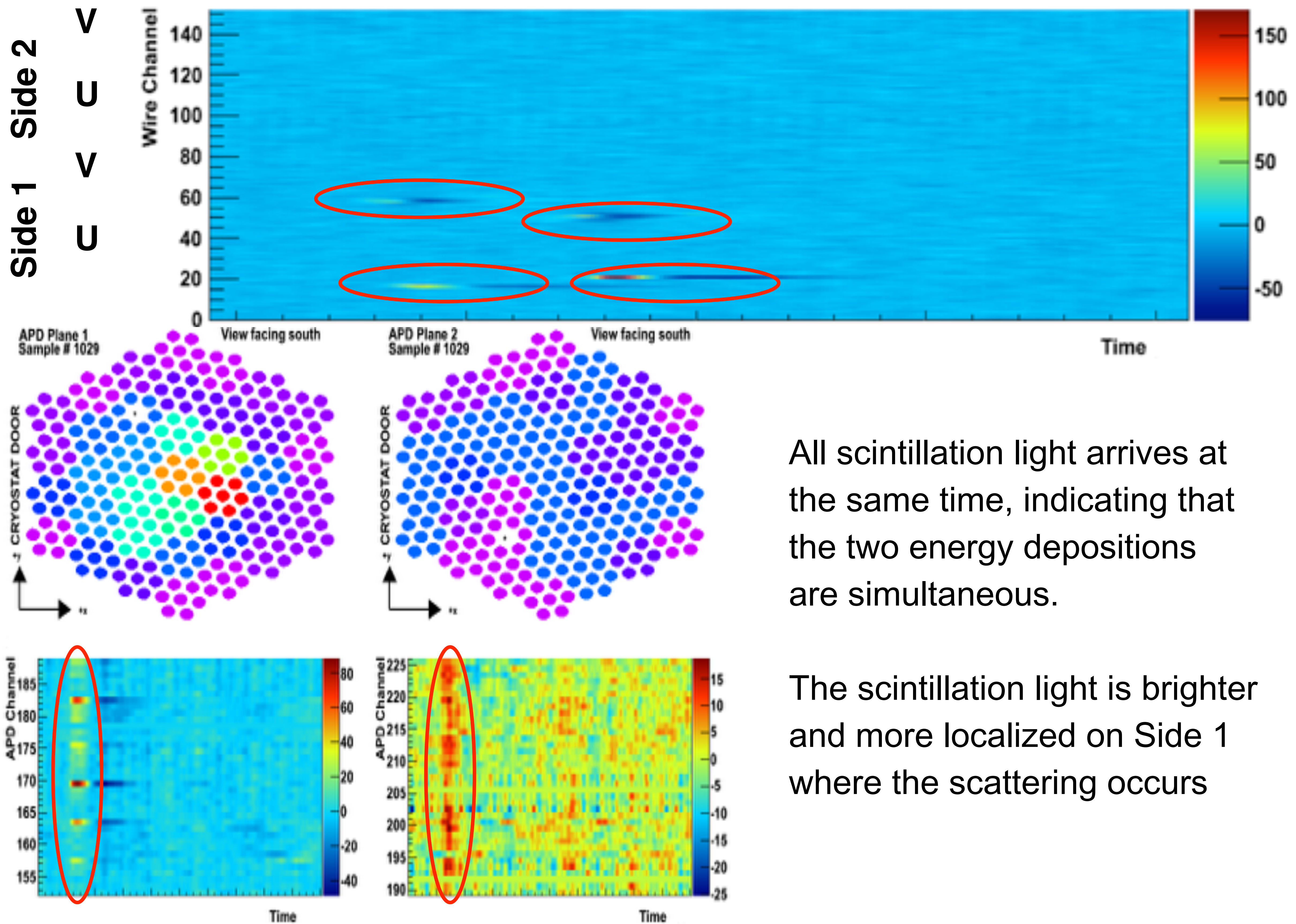

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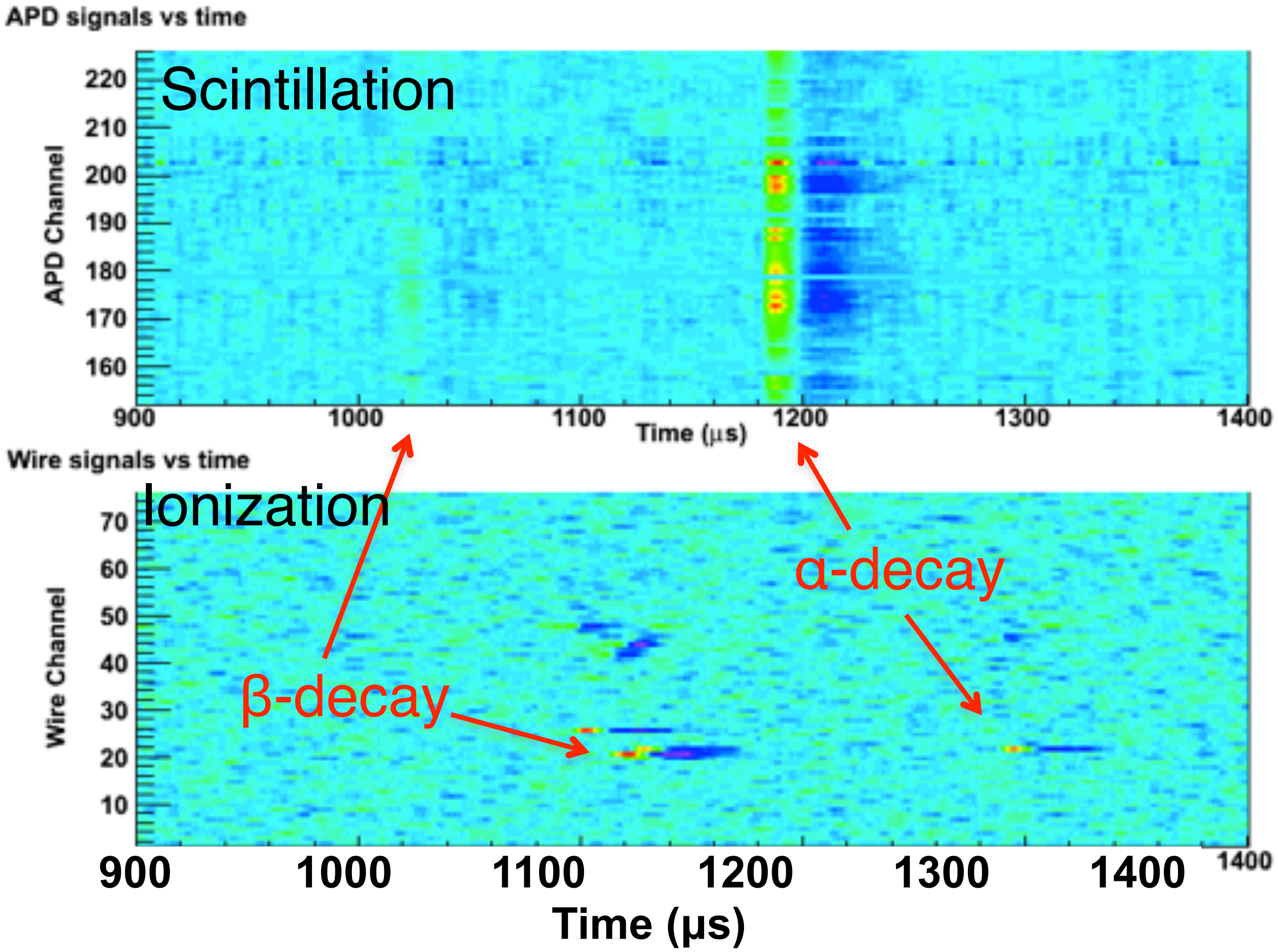
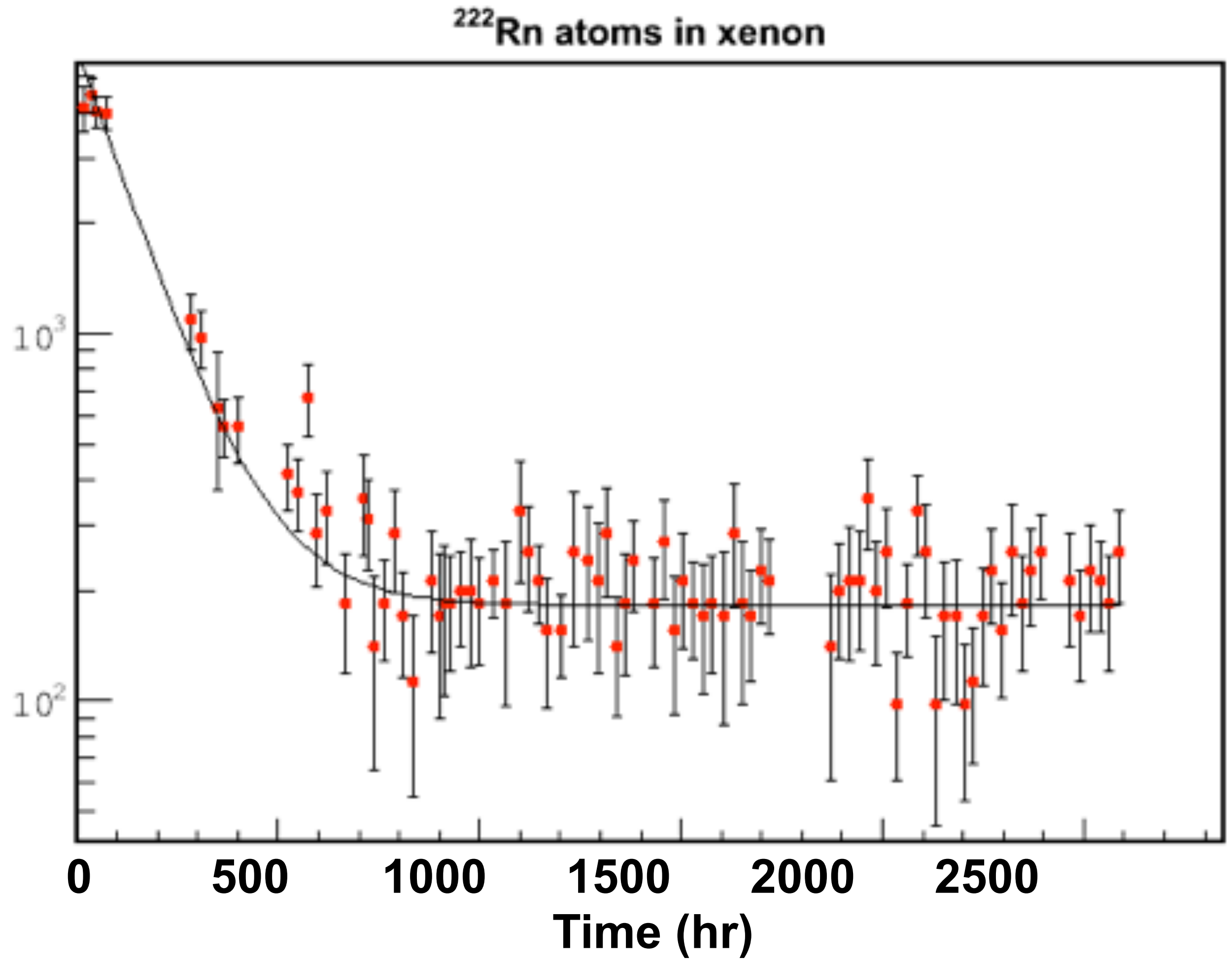
Rn Content in Liquid Xenon



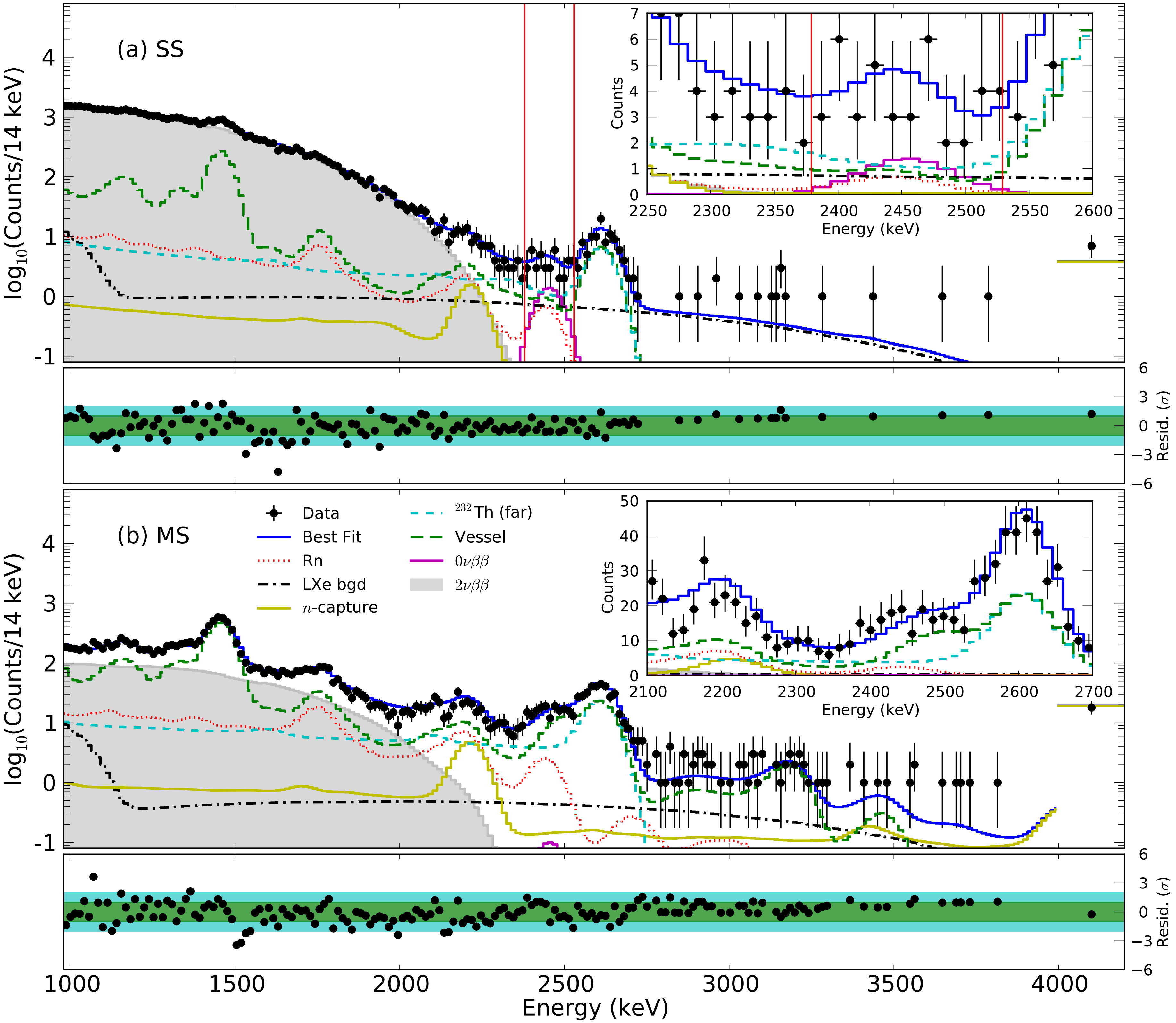
^{214}Bi – ^{214}Po correlation
in the EXO-200 detector



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.)

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

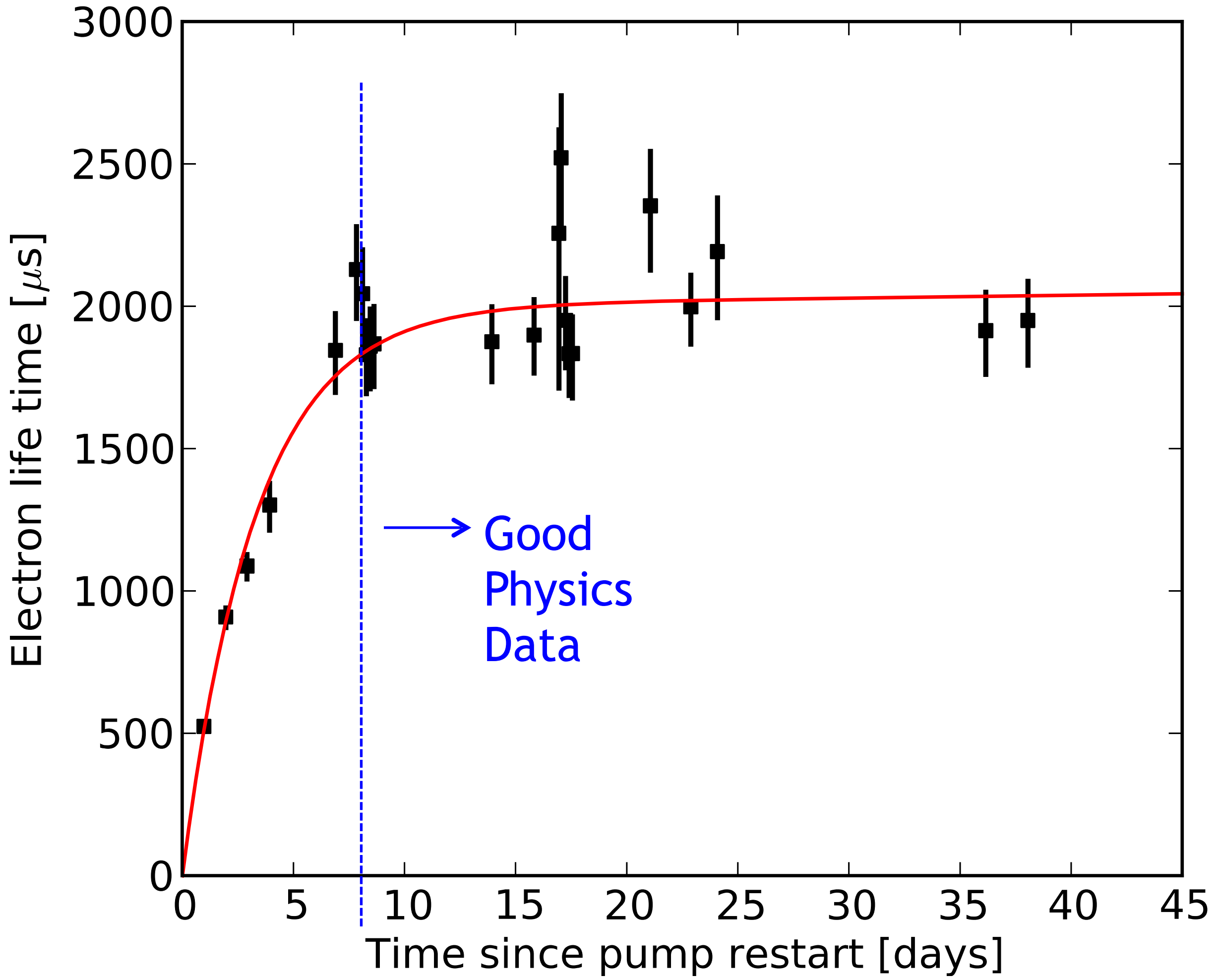
$T_{1/2}^{0\nu\beta\beta}$ sensitivity:

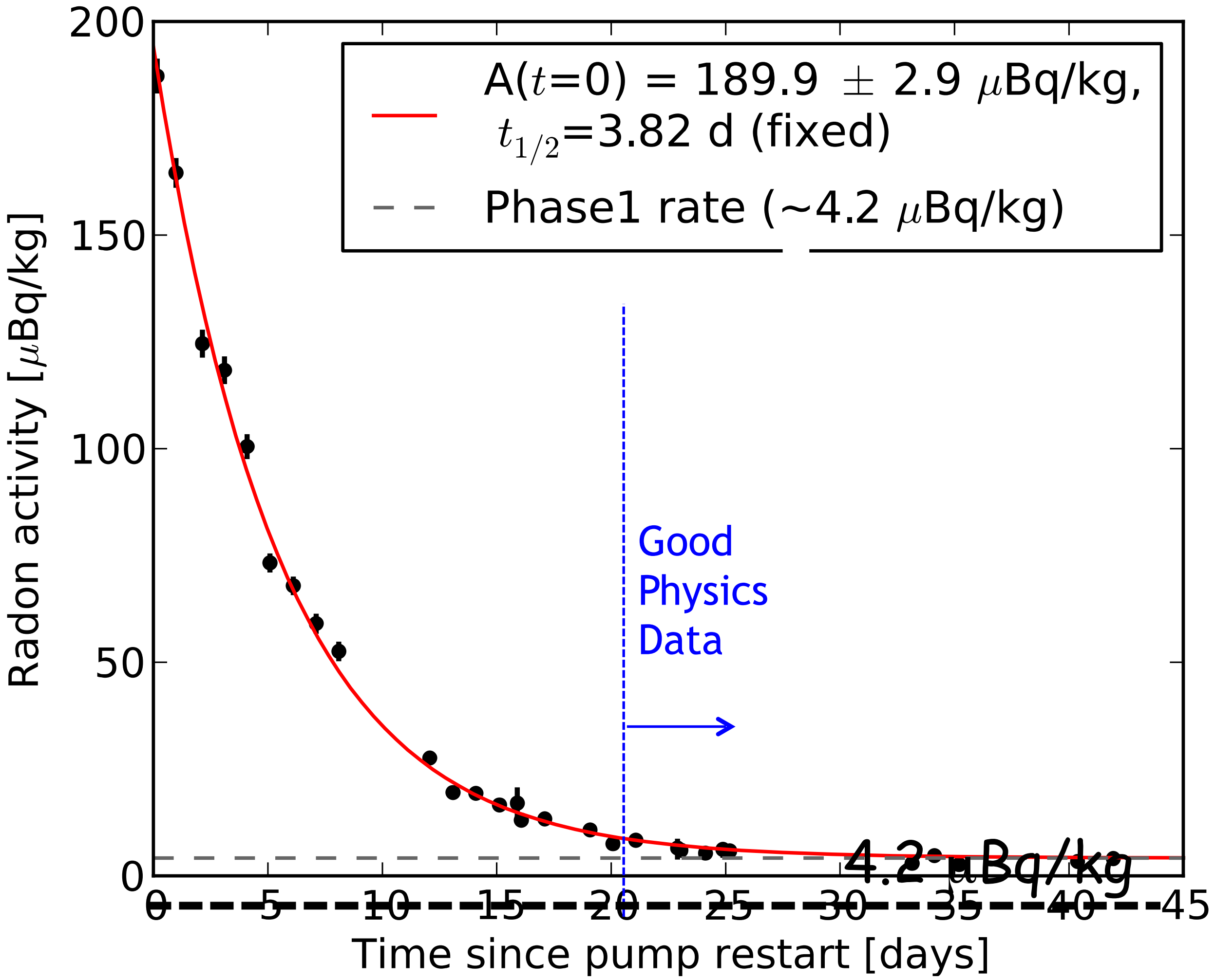
$1.9 \cdot 10^{25}$ yr

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

Phase-II Running

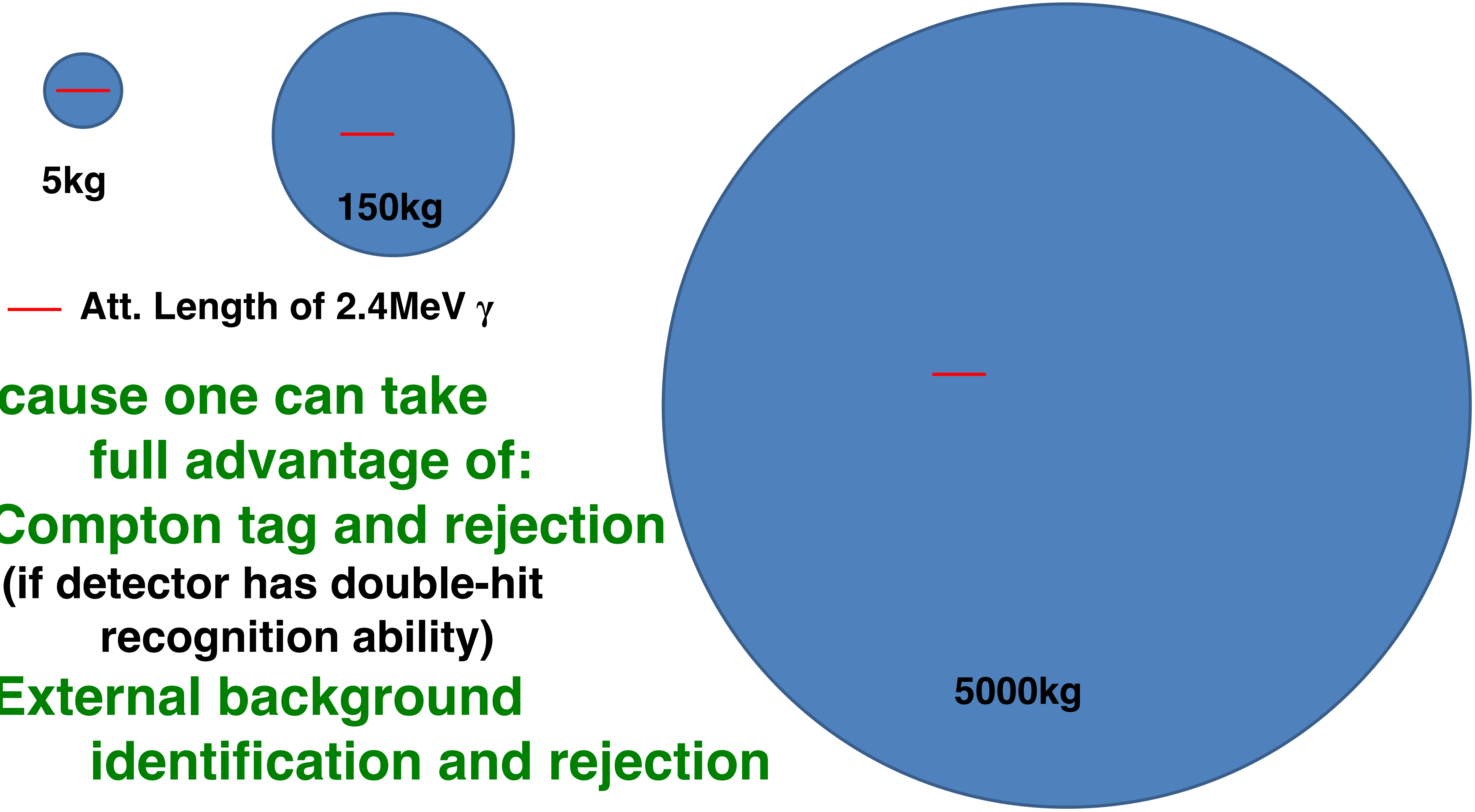
- **EXO-200 Phase-II operation begins on 31 Jan 2016, after enriched liquid xenon fill.**
- **Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.**





New results to be released next week!

Towards the Ton Scale



Because one can take full advantage of:

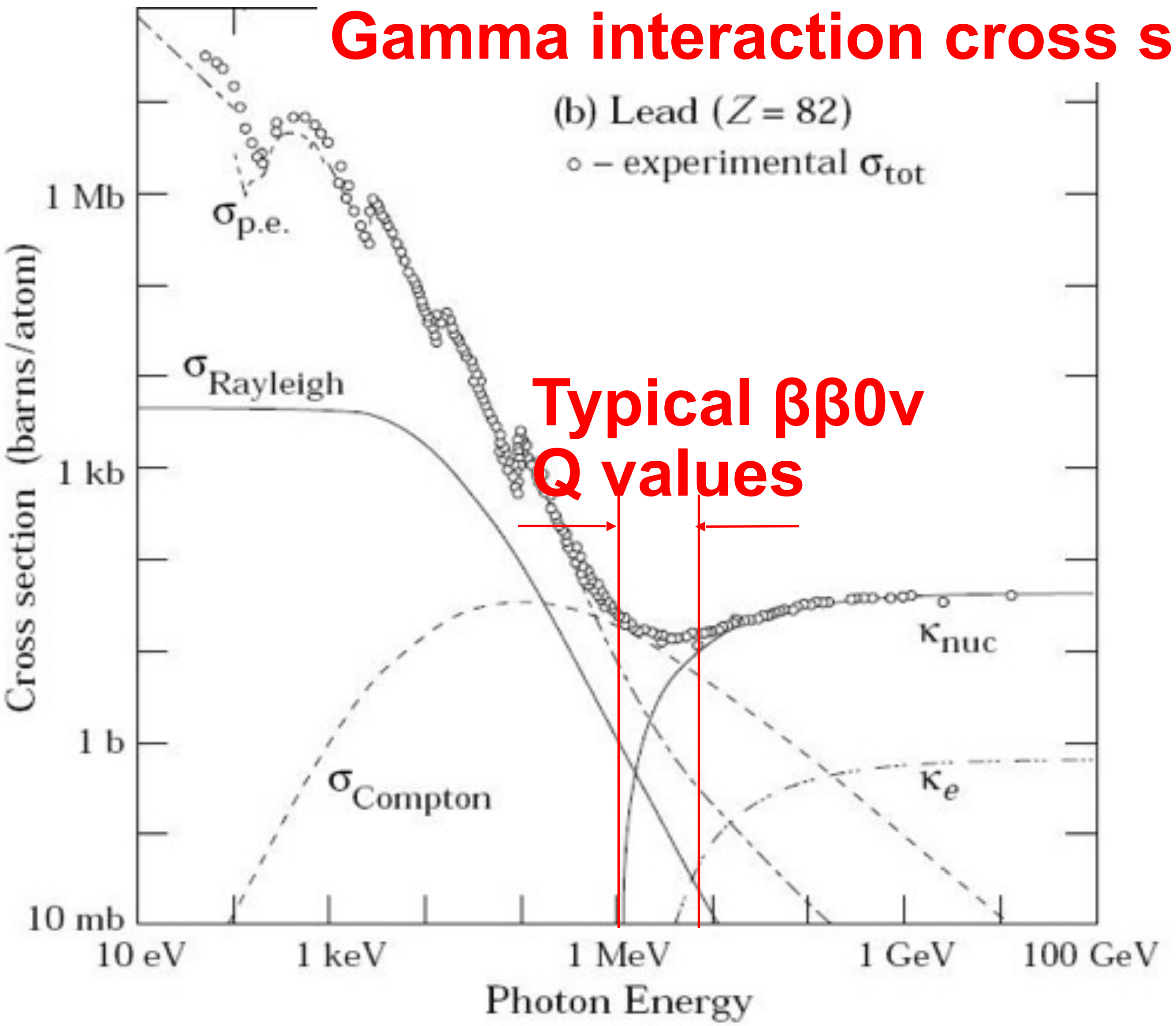
1) **Compton tag and rejection**
   (if detector has double-hit recognition ability)
2) **External background identification and rejection**

The larger the detector the more useful this is.

➔ Ton scale is where these features become dominant.

Shielding a detector from gammas is difficult!

Gamma Shielding



Example:

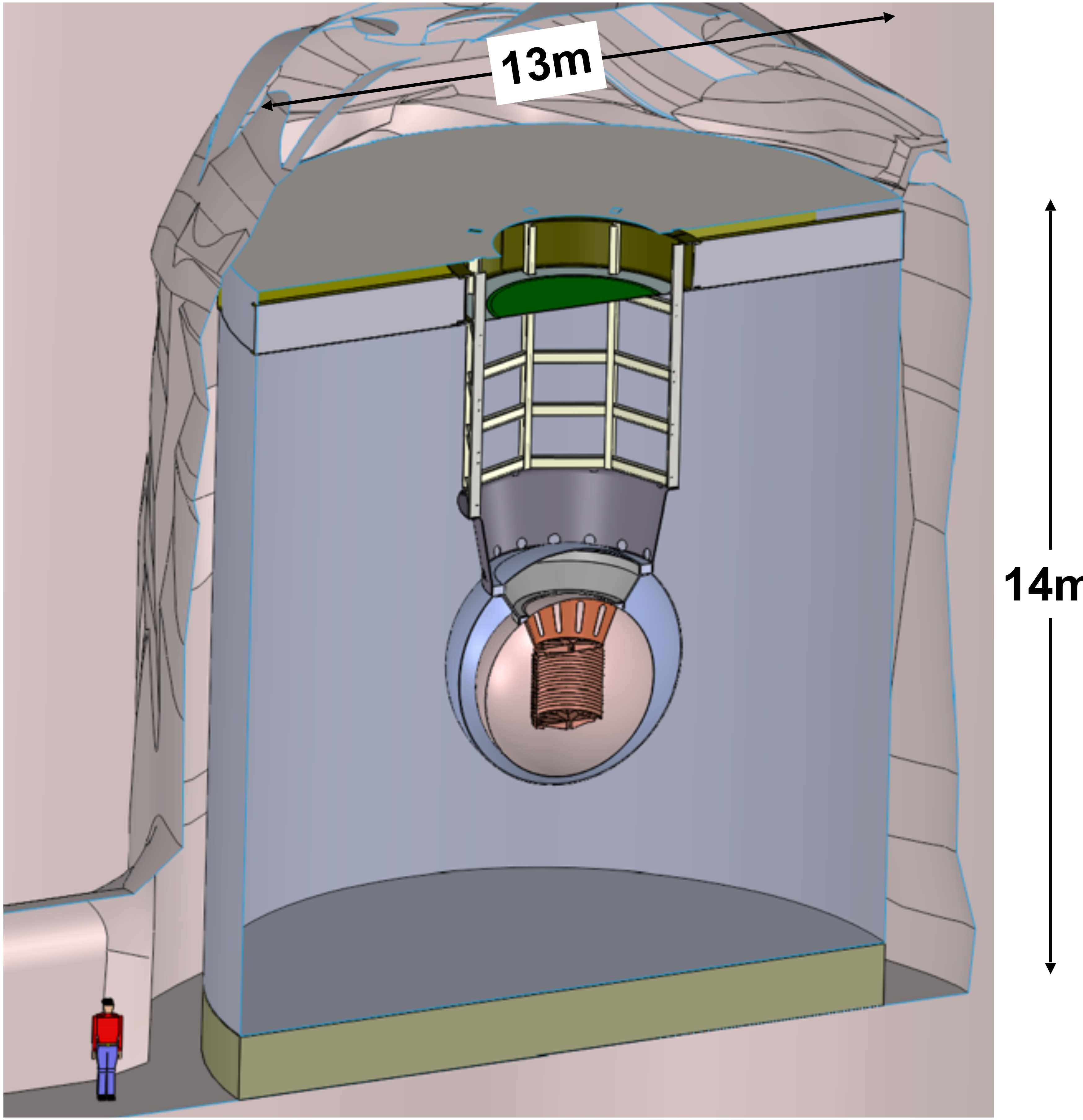
γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

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

nEXO Concept

Preliminary artist view of nEXO in the SNOlab Cryopit



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.

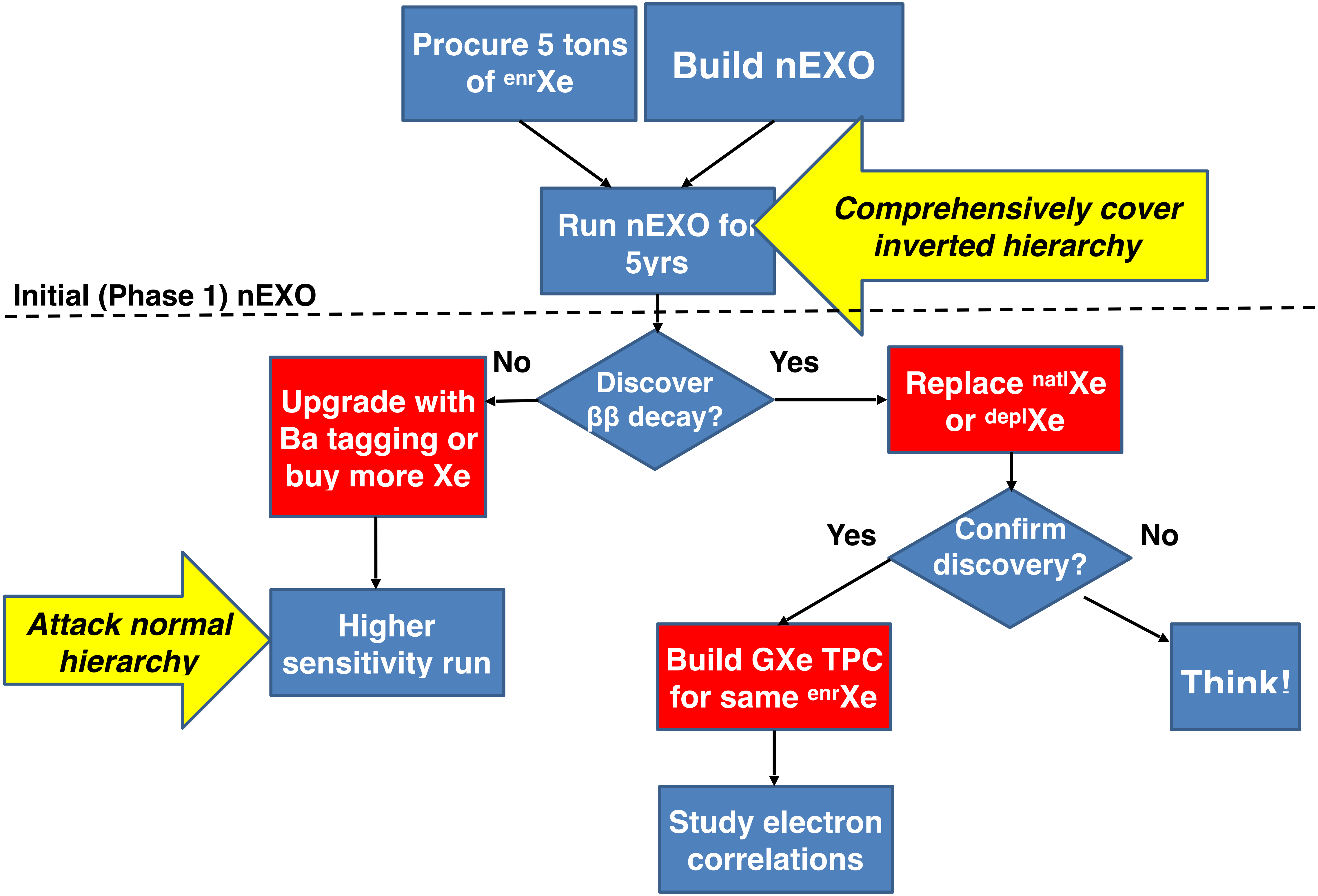
The signal/background discrimination is based on four parameters:

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 $\otimes$ energy ROI”. In fact, more independent axes provide a more powerful constraint on the signal.

nEXO Strategy

Flexible program based on the initial nEXO investment



Procure 5 tons of ^{enr}Xe

Build nEXO

Run nEXO for 5yrs

Comprehensively cover inverted hierarchy

Initial (Phase 1) nEXO

Discover ββ decay?

No

Upgrade with Ba tagging or buy more Xe

Higher sensitivity run

Attack normal hierarchy

Yes

Replace ^{natl}Xe or ^{depl}Xe

Confirm discovery?

Yes

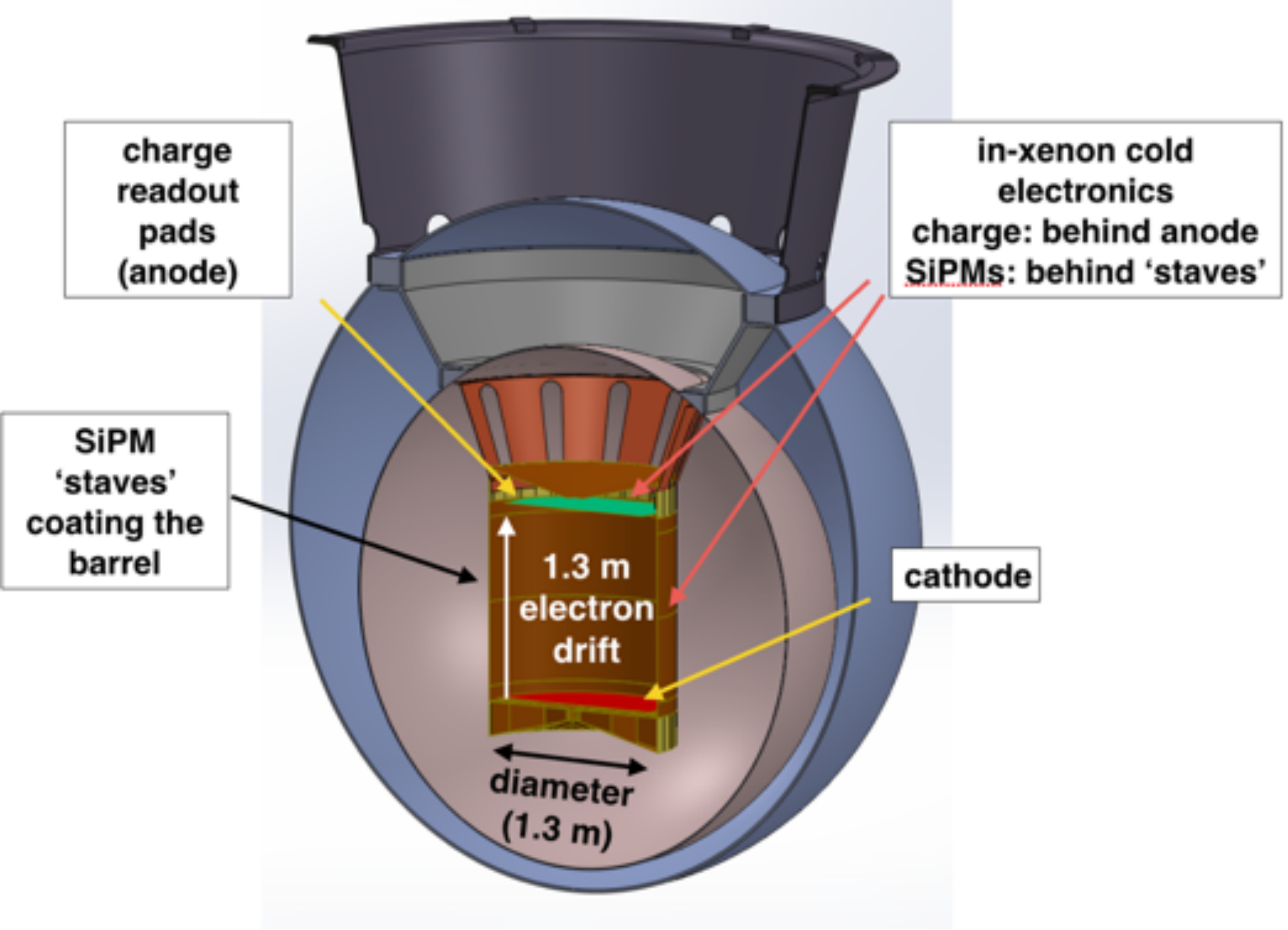
Build GXe TPC for same ^{enr}Xe

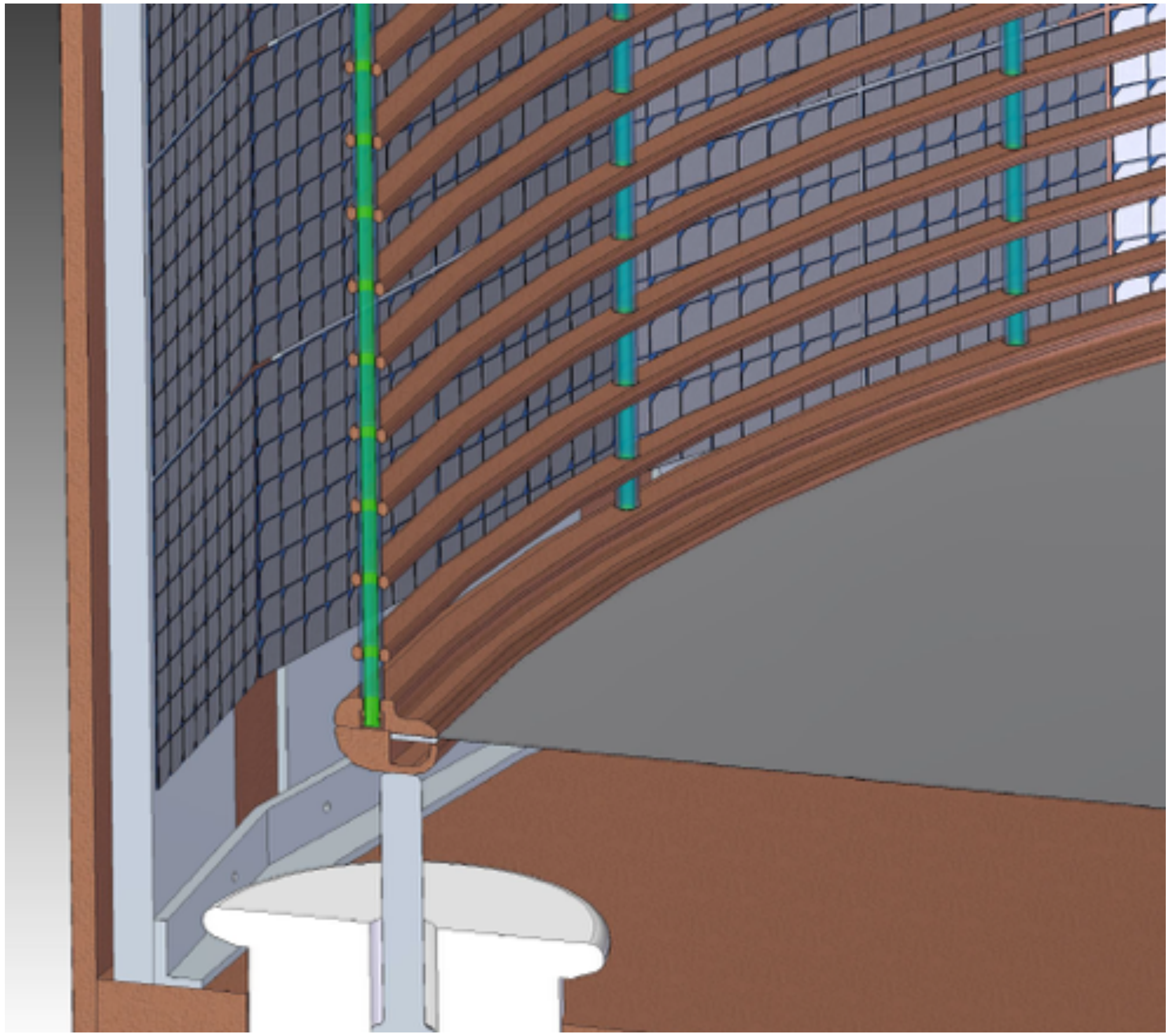
Study electron correlations

No

Think!

nEXO R&D





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

Local R&D

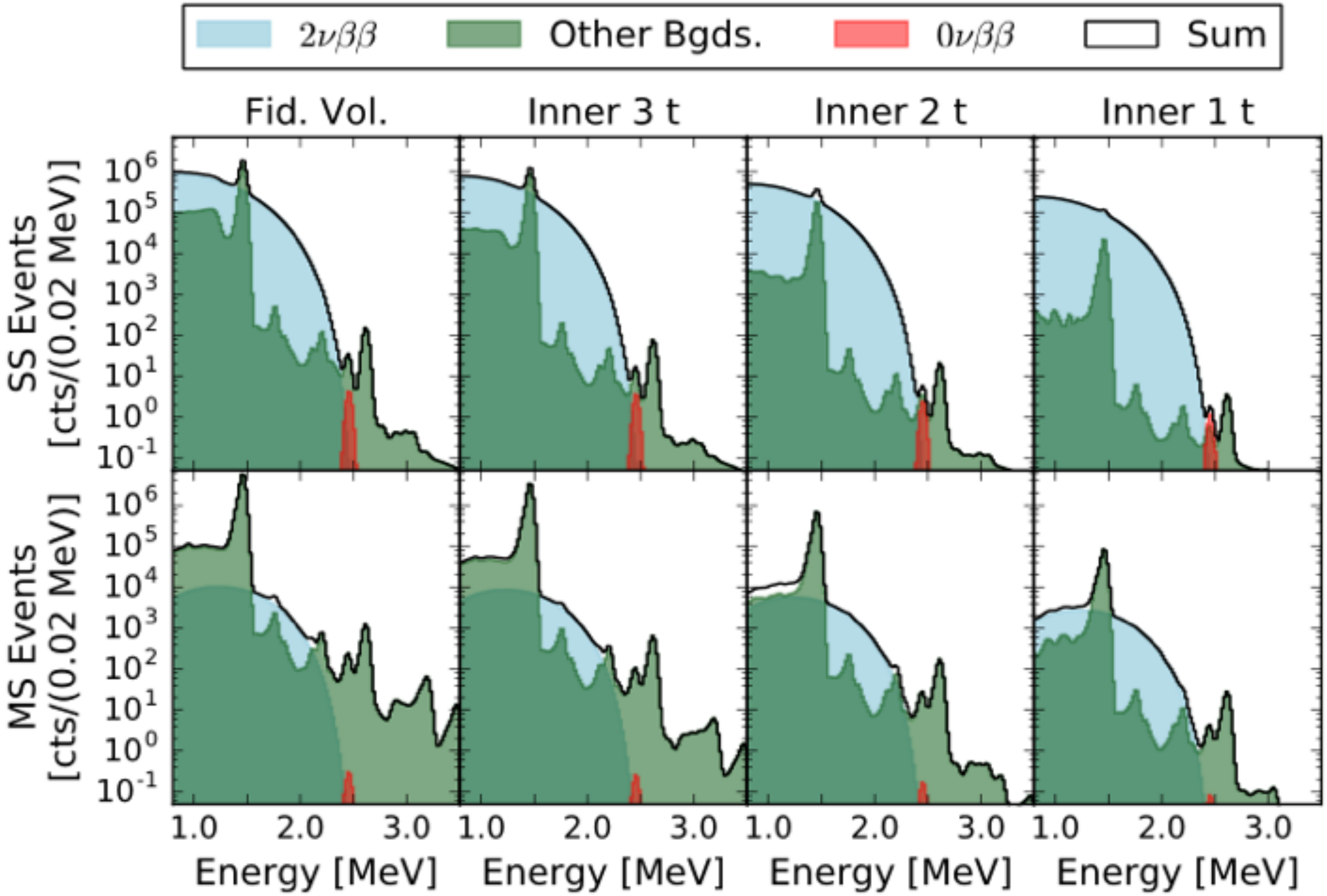
- **BNL Instrumentation Division: Internal Electronics**
- **SBU/BNL: Novel Calibration Concepts**

Particularly in the larger nEXO, background identification and rejection fully use a fit that considers simultaneously energy, multiplicity and event position.

→ ***The power of the homogeneous detector, this is not just a calorimetric measurement!***

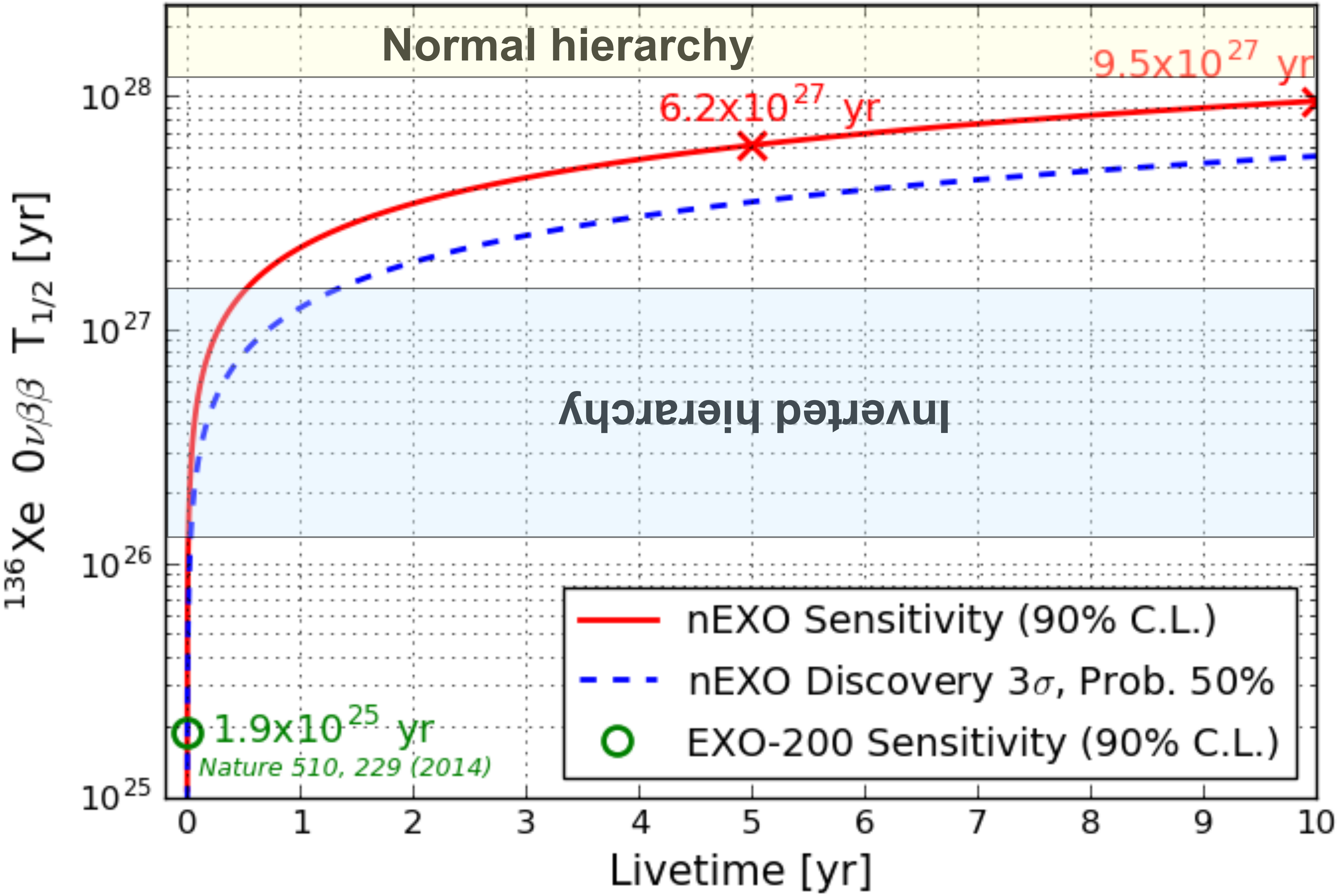
SS

MS



10 yr data, $0\nu\beta\beta$ corresponding to $T^{1/2}=5.5\times10^{27}$ yr

nEXO Sensitivity Reach

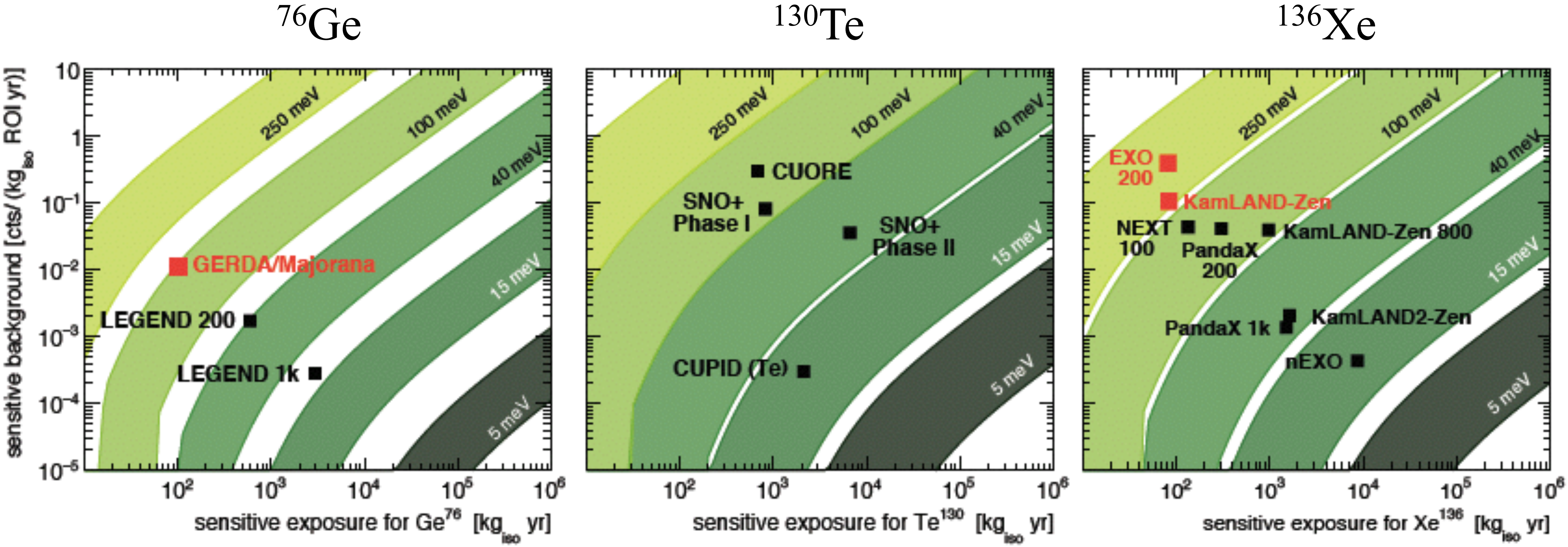


GCM: Rodriguez, Martinez-Pinedo,
Phys. Rev. Lett. 105 (2010) 252503

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

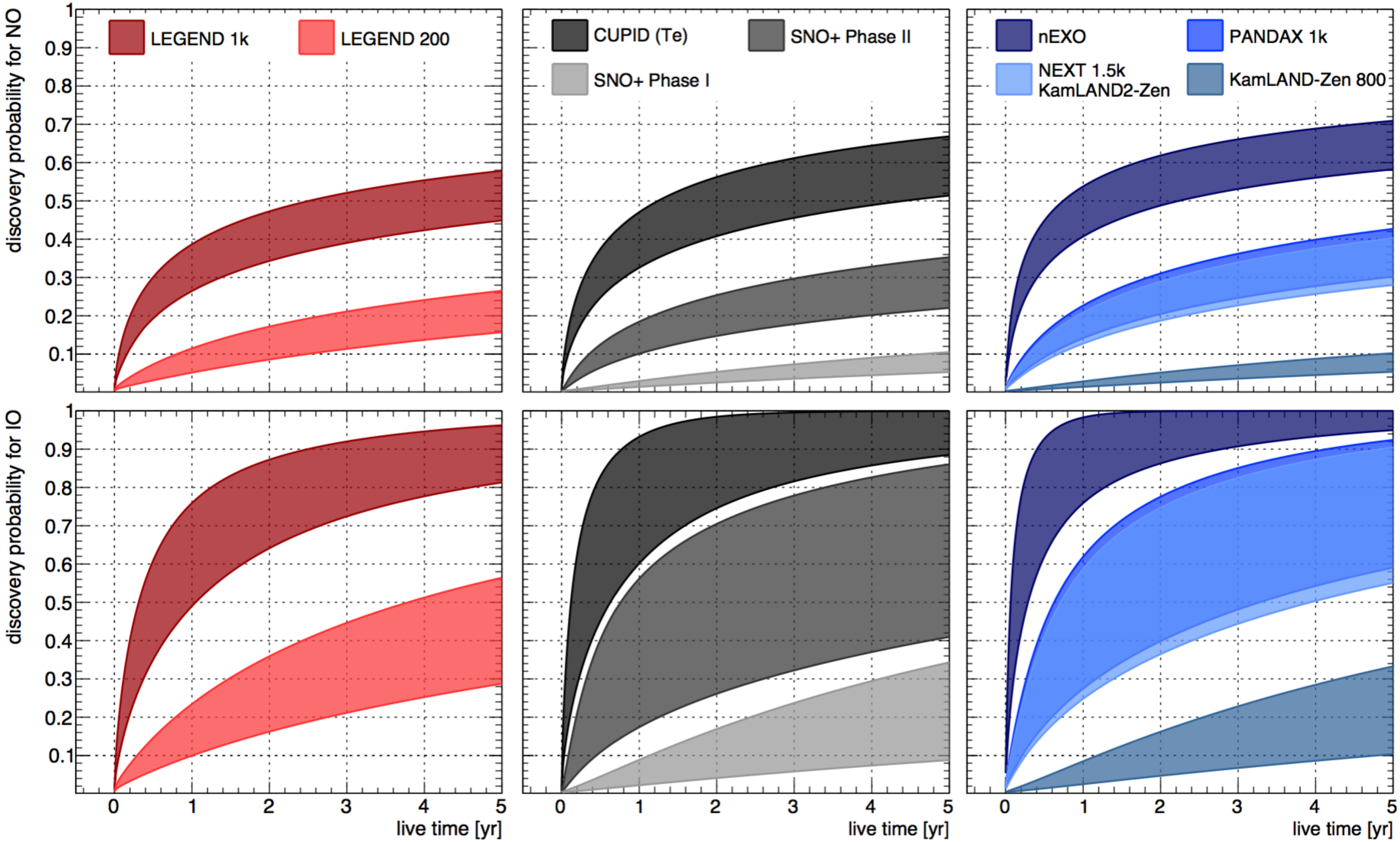


Red : Achieved Backgrounds; Black : Projected Backgrounds

Width of bands based on range of NME values

arXiv:1705.02996v1

Discovery Probability



Closing Thoughts

- Given the compelling theoretical motivation and discovery of neutrino mass, the search for neutrinoless double-beta decay has become one of the highest priorities for experimental nuclear physics research worldwide

- The field of experimental searches for neutrinoless double beta decay is now maturing and coalescing into a handful of ton-scale discovery experiments

In these lectures, I have tried to educate you on the above

- With a little bit of luck, we may learn whether neutrinos are their own antiparticles within a decade

- With a further bit of luck we might have a new paradigm for the origin of all matter in the universe

- In any case, this research will have tremendous impact well beyond nuclear physics, touching particle physics, astrophysics and cosmology