Neutrinoless Double Beta Decay $0\nu\beta\beta$ – part 2

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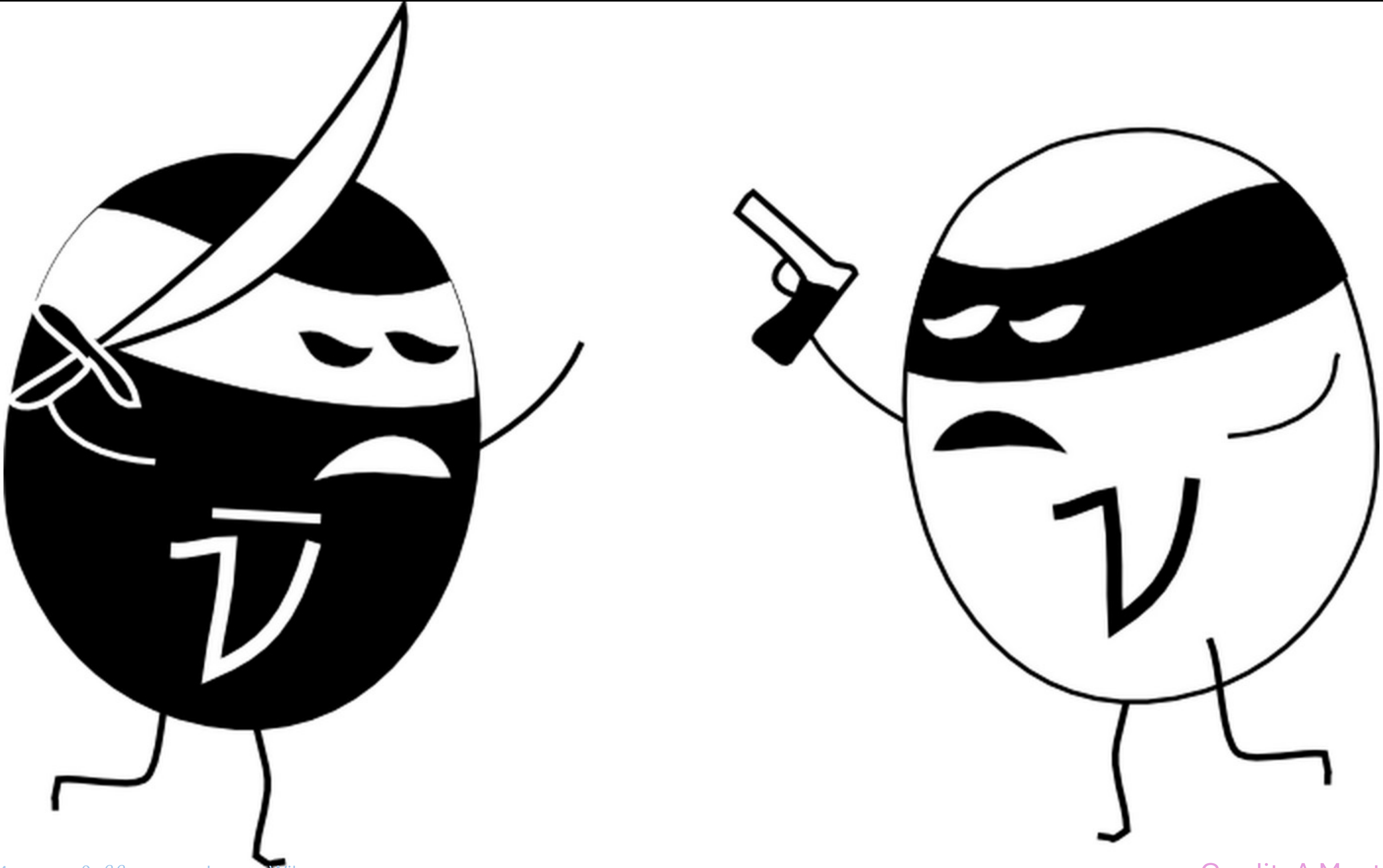
TRISEP 2024, Sudbury



Credit: A Mastbaum

Outline

Lecture 1
- What is double beta decay?
  - SEMF splitting
  - Known isotopes
- 2 neutrino double beta decay
- Neutrinoless double beta decay
  - Theory
  - Dirac and Majorana neutrinos
  - See-saw mechanism

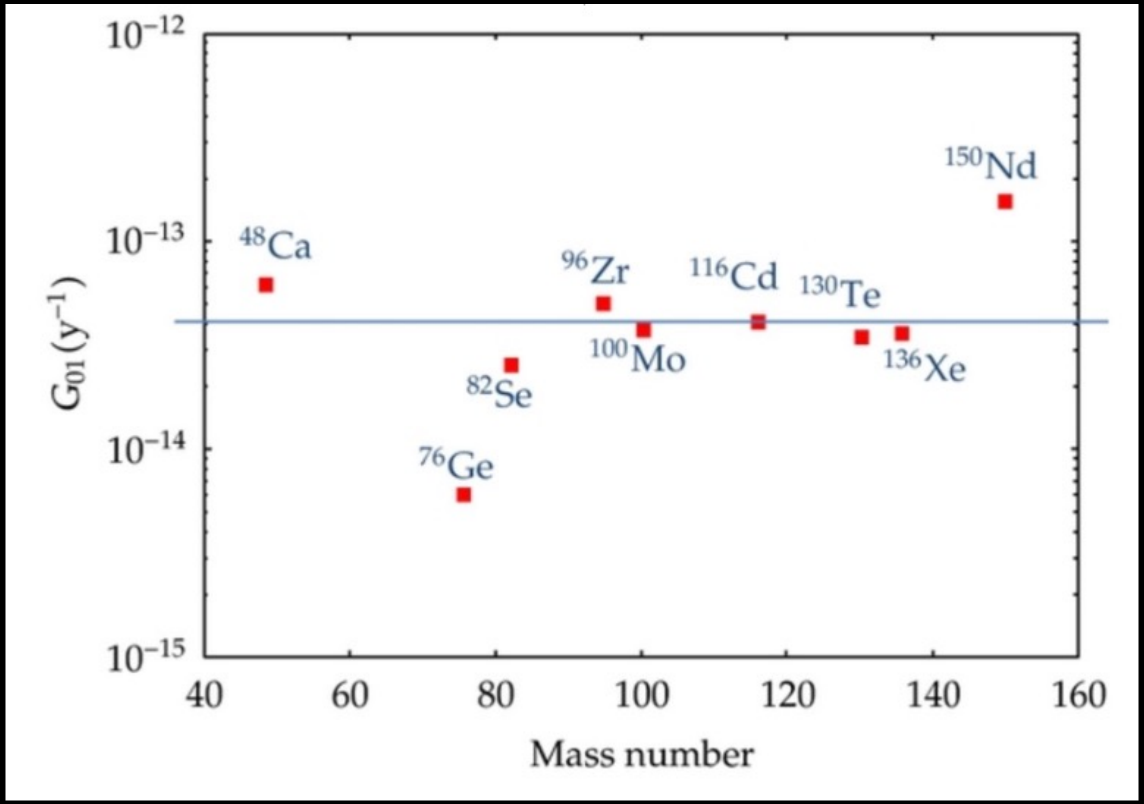
Lecture 2
- Half-life / rate
  - Phase space
  - Matrix elements
- Experimental considerations
  - Challenges
  - Backgrounds
- Experiment examples

Lecture 3
- Neutrino mass
- Lobster plots
- Limits vs Discovery
- Alternative mechanisms and probing new physics
- $\beta^+\beta^+$ decays
- Future prospects

$0\nu\beta\beta$ Rate

$$\left(t_{0\nu}^{1/2}\right)^{-1} = G^{0\nu} g_A^4 \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

- $G^{0\nu}$ phase space factor
  - Dependent on nucleus (Z and Q-value)
  - Directly calculable
- g_A^4 = axial coupling constant
  - Free nucleon value $g_A = 1.27$
  - Quenching due to multinucleon effects

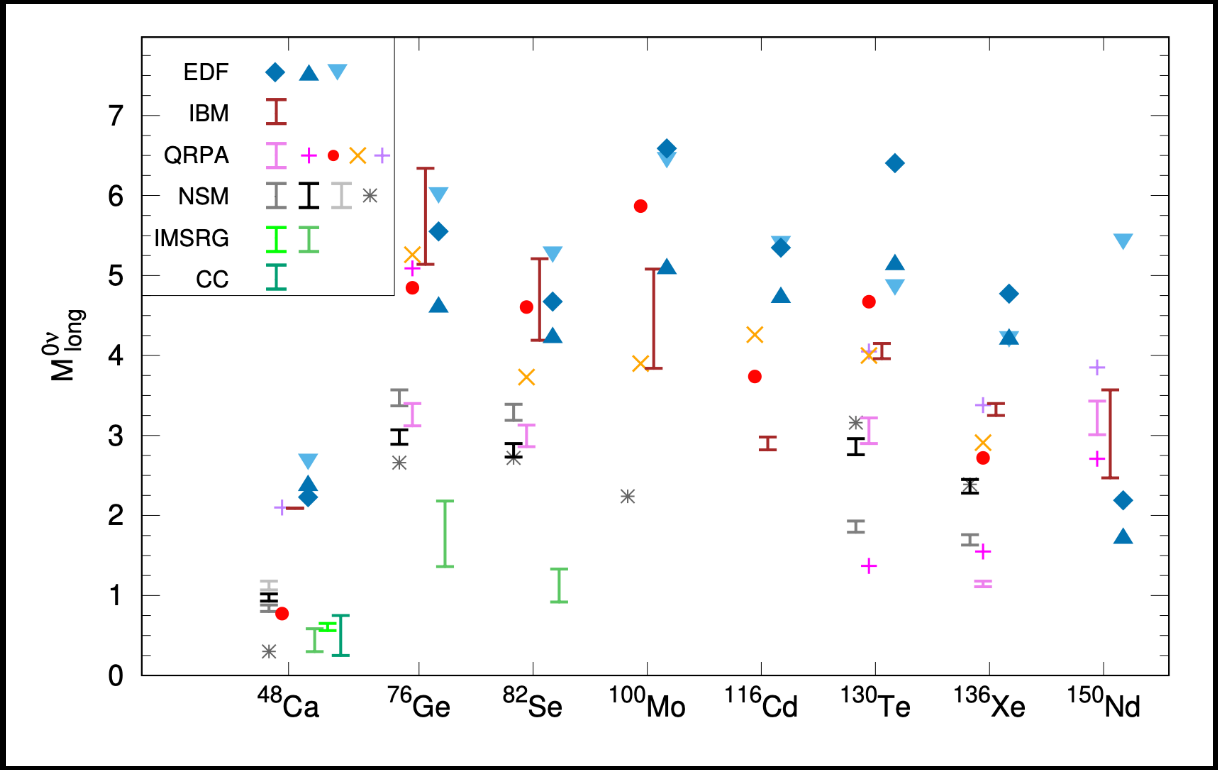


typical values $G^{0\nu} \sim 10^{-14}\ y^{-1}$

$0\nu\beta\beta$ Rate

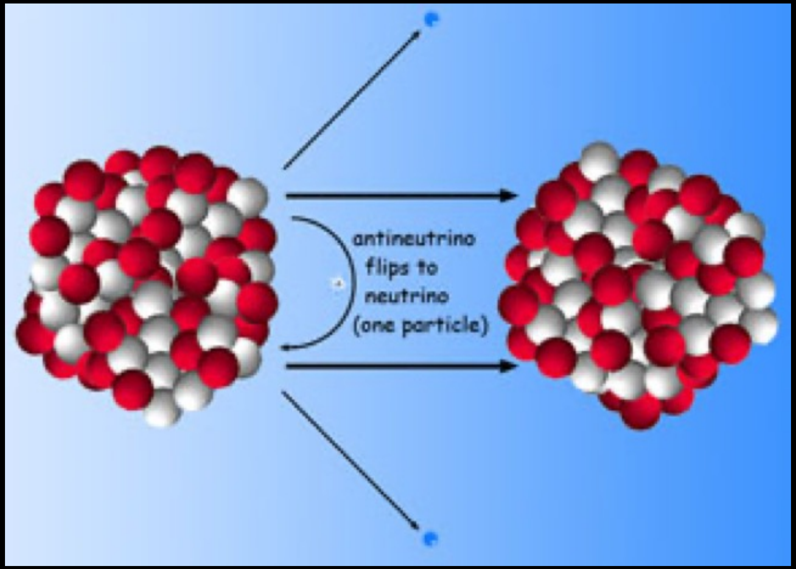
$$\left(t_{0\nu}^{1/2}\right)^{-1} = G^{0\nu} g_A^4 \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

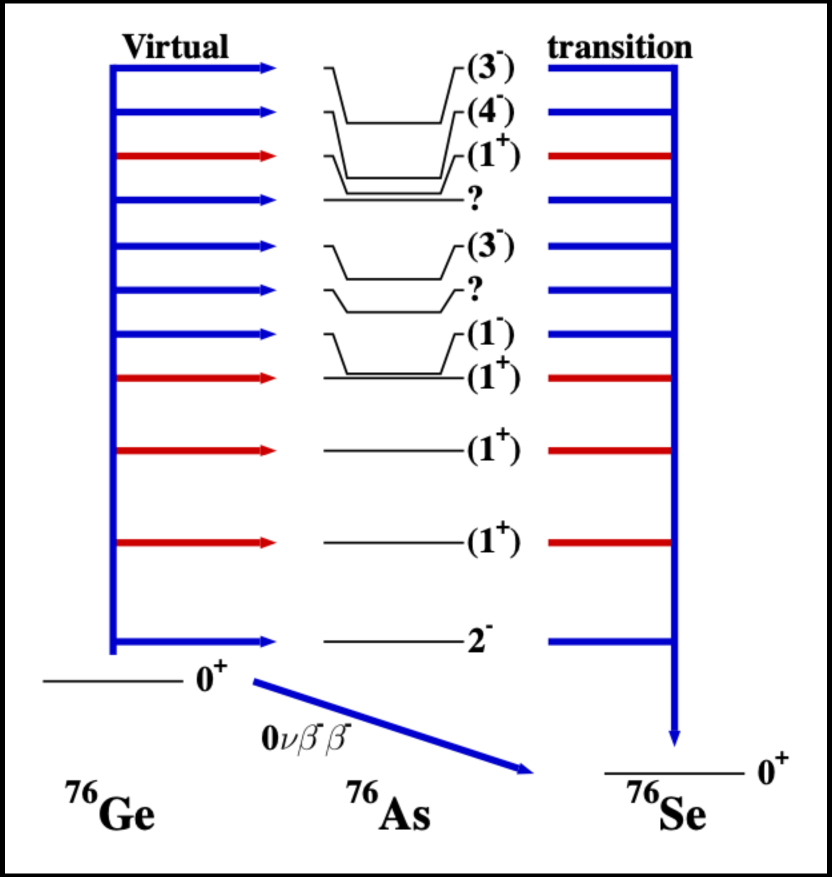
- $|M^{0\nu}|^2$ = nuclear matrix element
  - Depends on nuclear structure of parent, daughter and intermediate nuclei
  - Very computationally intensive to calculate – requires model approximations
  - Factor 4 variation between models → 2 order mag variation in predicted half-life for given $\langle m_{\beta\beta}\rangle^2$



Agostini et al, Rev Mod Phys 95 025002 (2023)
https://arxiv.org/abs/2202.01787

Nuclear Matrix Element Calculations





- Initial state consists of $\mathcal{O}(100)$nuclei
- Final state consists of $\mathcal{O}(100)$nuclei + electrons
- Via large number of potential intermediate states
- Short range correlations? Quenching?

- Computationally infeasible without model assumptions
- Some aspects of models can be tested with $2\nu\beta\beta$ measurements (but not all)

$0\nu\beta\beta$ Rate

$$\left(t_{0\nu}^{1/2}\right)^{-1} = G^{0\nu} g_A^4 \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

Square of the effective Majorana mass

See lecture 3

$0\nu\beta\beta$ Rate

- Looking at half-lives $T_{1/2} > 10^{25}$years and longer
- Very rare decays:
  - Need a lot of candidate isotopes
  - Need to measure for a long time

$$N_{iso} = \mathrm{m} \times a \times N_A$$

Mass of element (m)

Isotopic abundance (a)

Avogadros Number (N_A) $\sim 6 \times 10^{23}$

- Measure number of $'0\nu\beta\beta'$ decays, $N_{\beta\beta}$ in a given time t

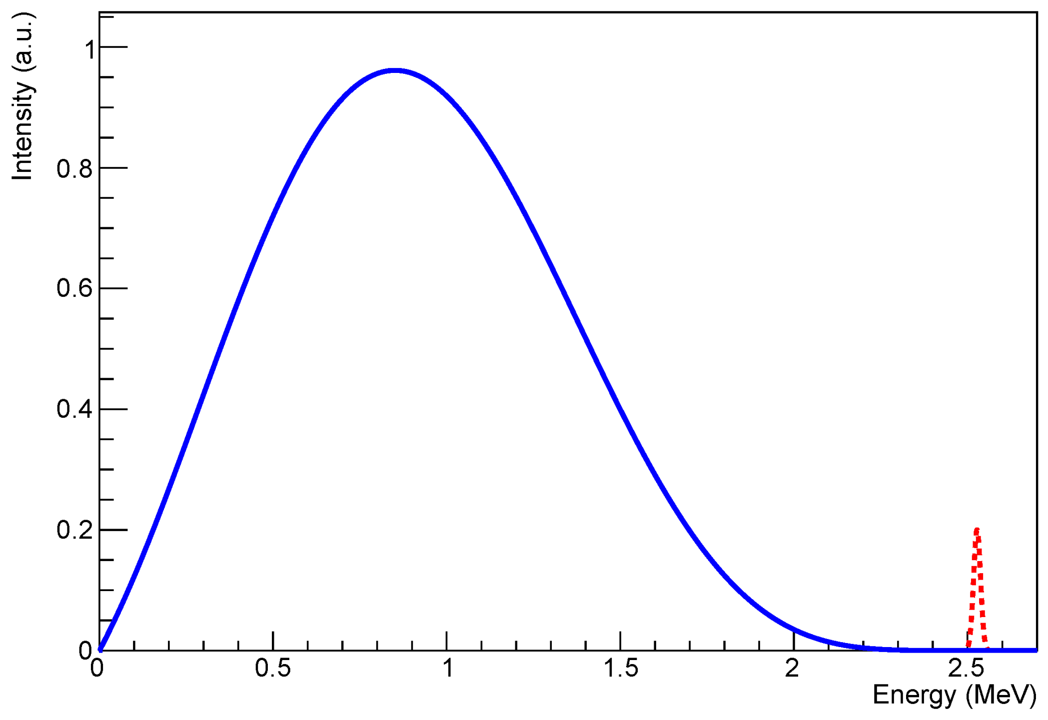
- $N_t = N_{iso} - N_{\beta\beta} = N_0 e^{-({t}/{\tau})}$

$$\rightarrow T_{1/2}^{\beta\beta}$$

N_t= number of isotopes after time t
N_o= initial number of isotopes
N_d= number of decays
t = measuring time
τ= time it takes to reduce to ${}^{1}/{}_{e}$

Experimental Considerations

- Signature of $0\nu\beta\beta$ is a peak at the endpoint of the $2e^-$ spectrum
  - Need to detect the electrons efficiently and measure their energy very accurately
  - Need to minimize the chance of any other events mimicking your signal



Sum energy of 2 betas

Background Free

Detection efficiency

Isotope mass

Measurement time

$$T_{1/2}^{0\nu} \propto M\epsilon t$$

Experimental Considerations

ROI = Region Of Interest

Detection efficiency

Isotope mass

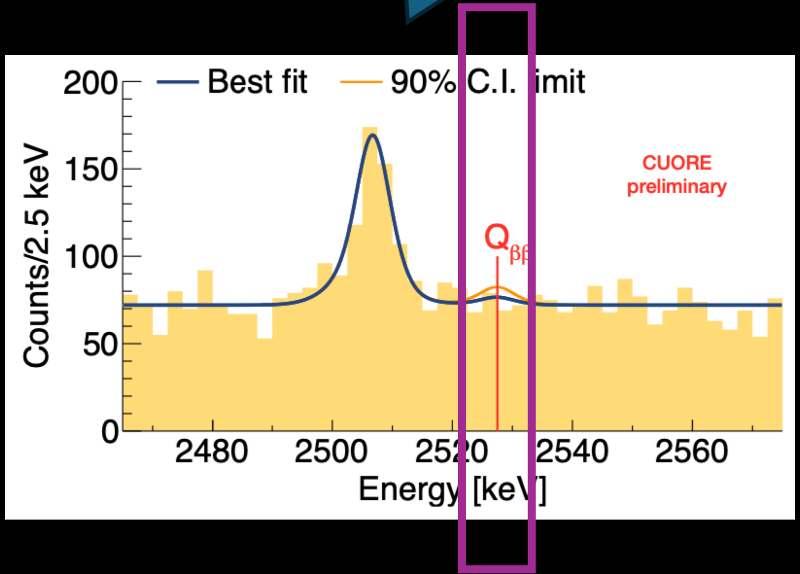
Measurement time

$$T_{1/2} \propto \frac{M.\epsilon.\sqrt{t}}{\sqrt{(b.M + c)\Delta E}}$$

In ROI

Backgrounds that scale with amount of isotope

Constant Backgrounds



EXAMPLE:

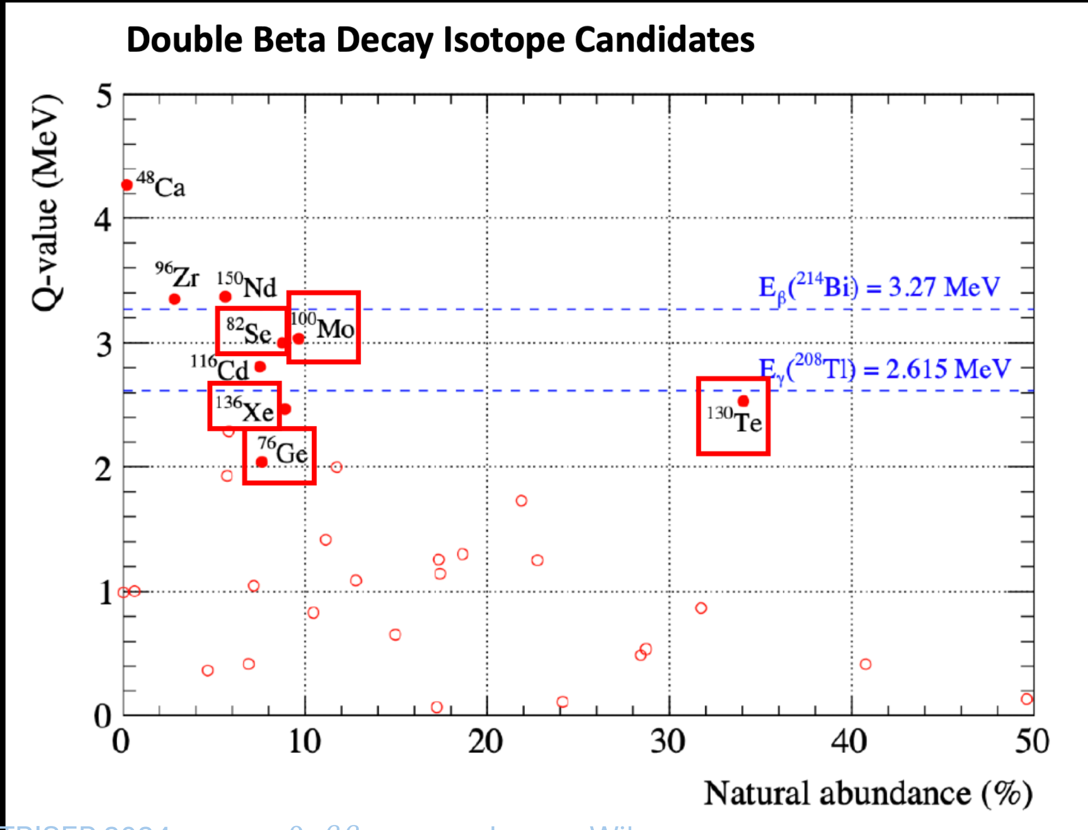
Backgrounds = 70 $counts$ / $2.5keV$
ROI = $10keV$ wide
Background count = 280 counts
Poisson uncertainty = $\sqrt{280} = 16.7$

Choose your Isotope

High Q value:

- Generally better phase space
- Above many low energy backgrounds

$\beta\beta$ Decay Reaction	Isotopic Abundance [atomic %]	Q-value [keV]
$^{48}Ca \to ^{48}Ti$	0.2	4274
$^{76}Ge \to ^{76}Se$	7.6	2039
$^{82}Se \to ^{82}Kr$	8.7	2996
$^{96}Zr \to ^{96}Mo$	2.8	3348
$^{100}Mo \to ^{100}Ru$	9.6	3034
$^{116}Cd \to ^{116}Sn$	7.5	2814
$^{124}Sn \to ^{124}Te$	5.8	2288
$^{128}Te \to ^{128}Xe$	31.8	866
$^{130}Te \to ^{130}Xe$	34.2	2528
$^{136}Xe \to ^{136}Ba$	8.9	2458
$^{150}Nd \to ^{150}Sm$	5.6	3368

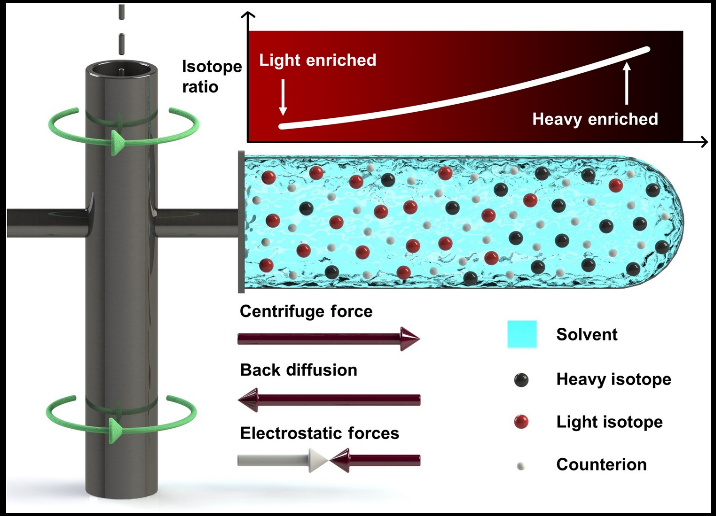


High Isotopic Abundance:

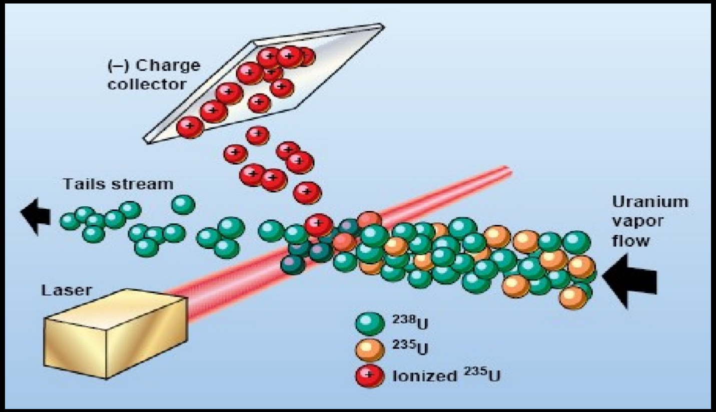
- More isotope per $$£
- Isotopic enrichment is challenging (money time and politics!)

Isotope Enrichment

- If abundance is low, enrich in your desired isotope.
- Method depends on element.
  - Can you make it gaseous? Soluble in liquid?

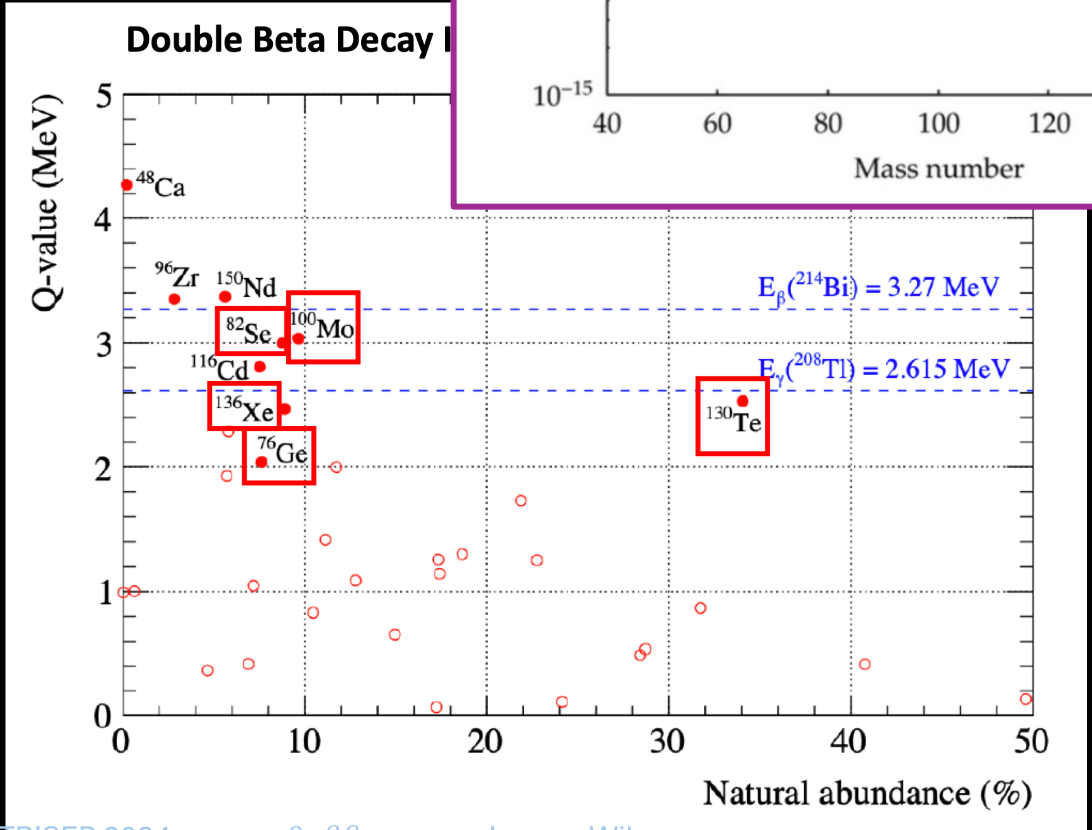


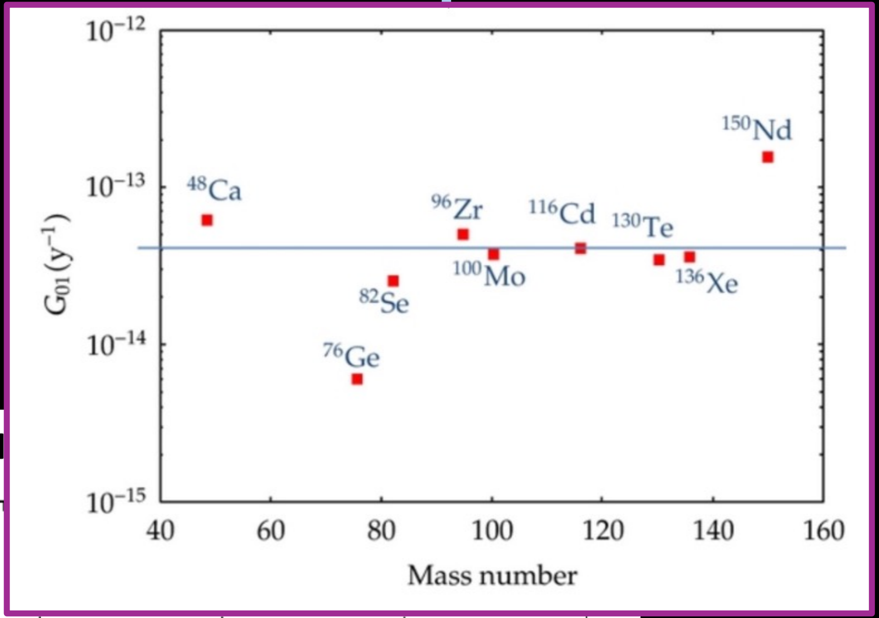
- Centrifugal force:
  - gas centrifuge – Xenon, GeF_4 or GeH_4, SeF_6, MoF_6
  - Liquid solution centrifuge



- Atomic vapor laser isotope separation (AVLIS):
  - Inject laser energy at the precise frequency to ionize only the specific isotope
  - Separate ions from atoms with EM field

Choose your Isotope





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Correlation between Q-value and Phase Space Factor (not exact – other factors at play)

Choose your Isotope

Source = Detector

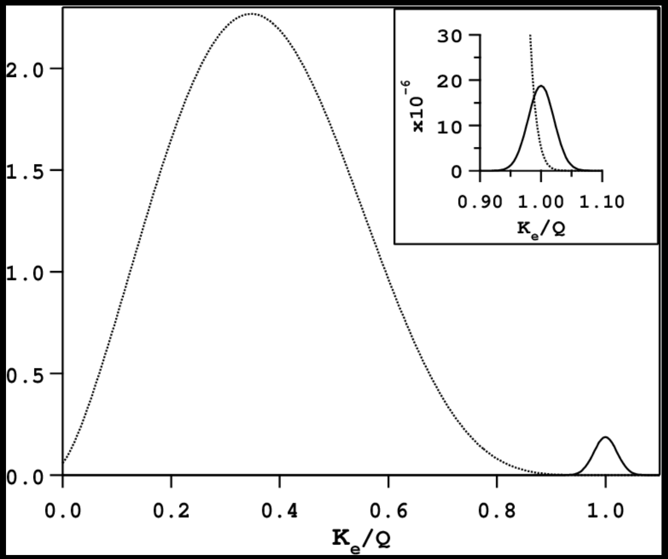
- $\sim MeV\ \beta$s don't travel far so restricted to thin films if detectors separate from source
- Need to 'see' the $\beta\beta$ and accurately record their energy
  - Detection Efficiency
  - Energy Resolution
- Even better
  - Can you be sure it was a $\beta\beta$ event ? → Tracking would be nice
  - Can you be sure it was a decay of your isotope? → Tagging of the decay product would be very nice

Backgrounds

- $2\nu\beta\beta$ decays $\Delta E, b$

$$T_{1/2} \propto \frac{M.\epsilon.\sqrt{t}}{\sqrt{(b.M + c)\Delta E}}$$

- Internal radiological backgrounds b
- Surface backgrounds $\sim b$
- External radiological backgrounds c



- Cosmogenic b, c
- Neutrinos and Neutrino-genic b, c

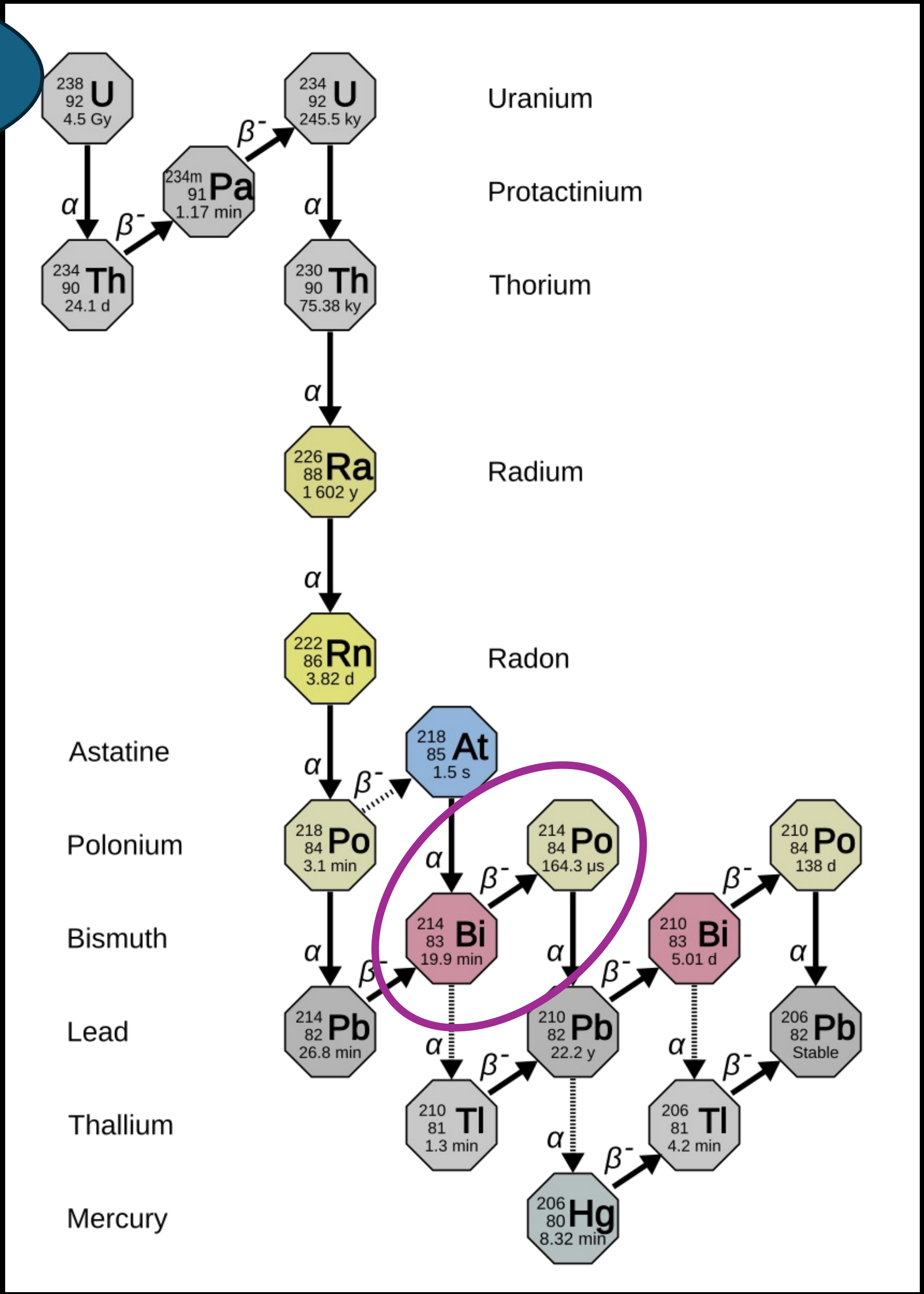
^{238}U chain

Remember ^{238}U is a $\beta\beta$ decay candidate

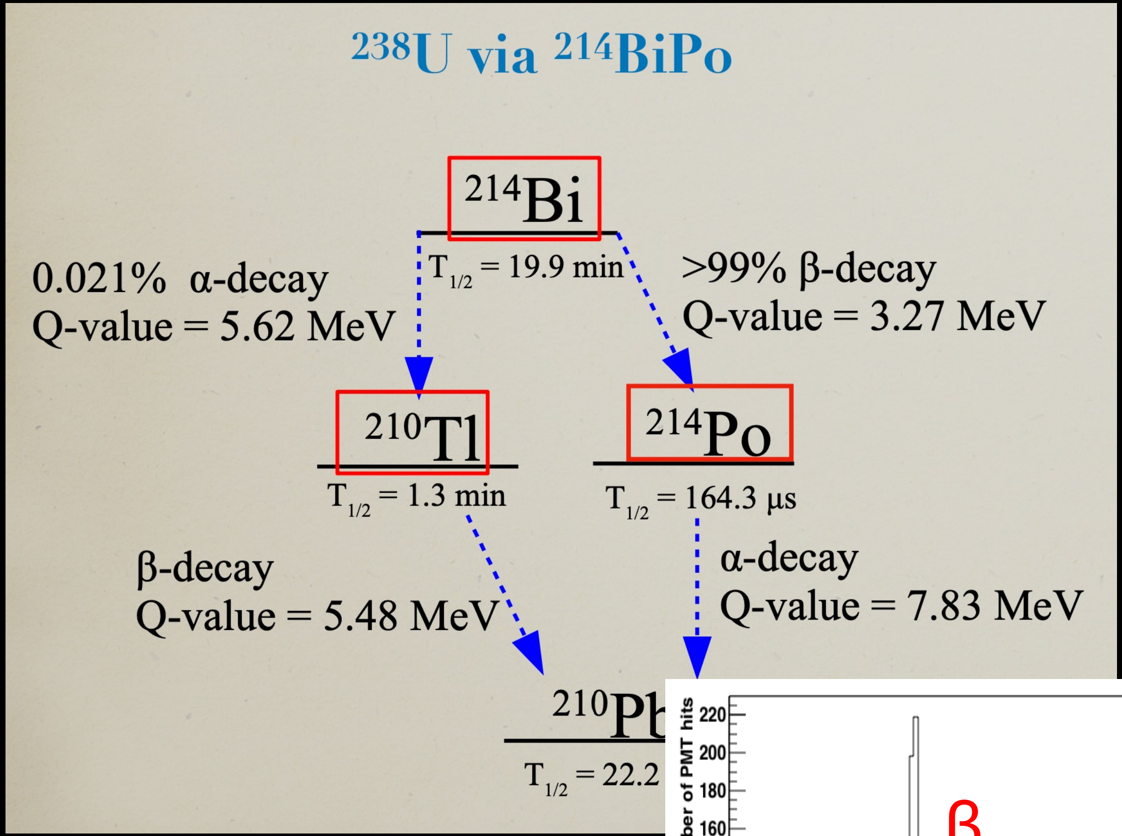
Naturally occurring (few ppm in rock, soil, water), long lived $T_{1/2} = 4.5{\times}10^{6}$years

- α- decays
- β-decays
- Accompanying γs

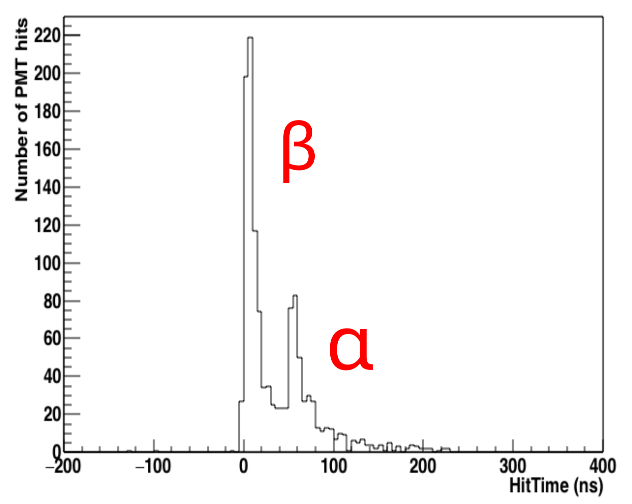
- Very short decay steps can be used for 'tagging': ^{214}Po $T_{1/2} = 164\mu s$



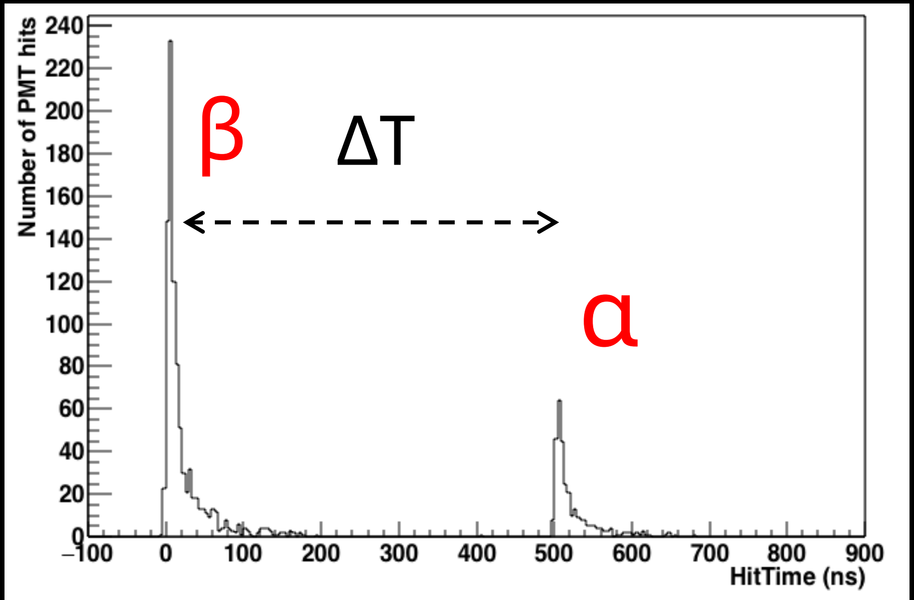
BiPos



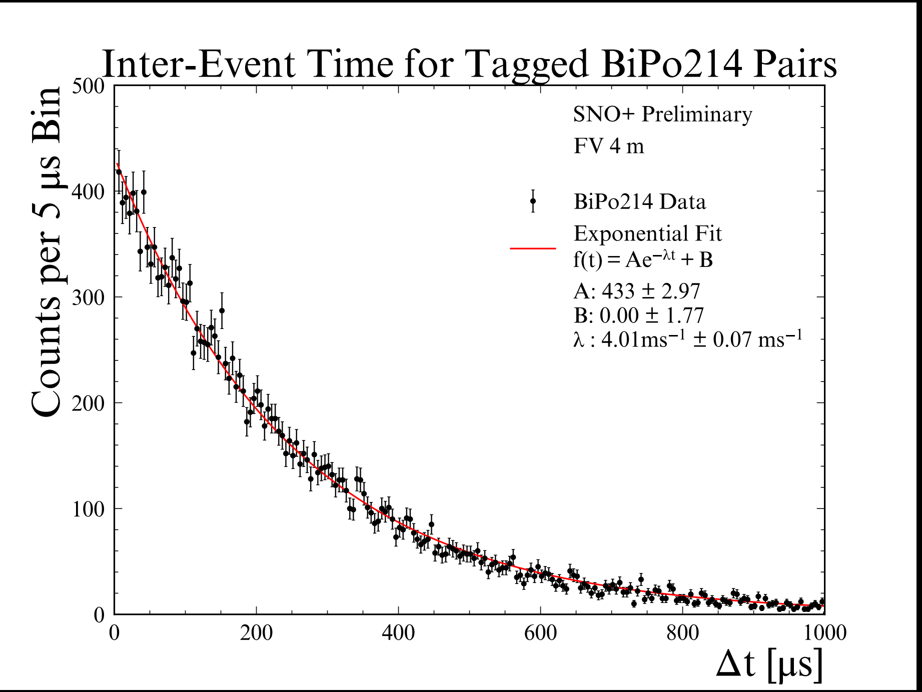
^{238}U via ^{214}BiPo
^{214}Bi
$T_{1/2}$ = 19.9 min
0.021% α-decay
Q-value = 5.62 MeV
>99% β-decay
Q-value = 3.27 MeV
^{210}Tl
$T_{1/2}$ = 1.3 min
^{214}Po
$T_{1/2}$ = 164.3 μs
β-decay
Q-value = 5.48 MeV
α-decay
Q-value = 7.83 MeV
^{210}Pb
$T_{1/2}$ = 22.2



Number of PMT hits
β
α
HitTime (ns)



Number of PMT hits
β
ΔT
α
HitTime (ns)



Inter-Event Time for Tagged BiPo214 Pairs
SNO+ Preliminary
FV 4 m
BiPo214 Data
Exponential Fit
$f(t) = Ae^{-\lambda t} + B$
A: 433 ± 2.97
B: 0.00 ± 1.77
λ : 4.01ms^{-1} ± 0.07 ms^{-1}
Counts per 5 μs Bin
Δt [μs]

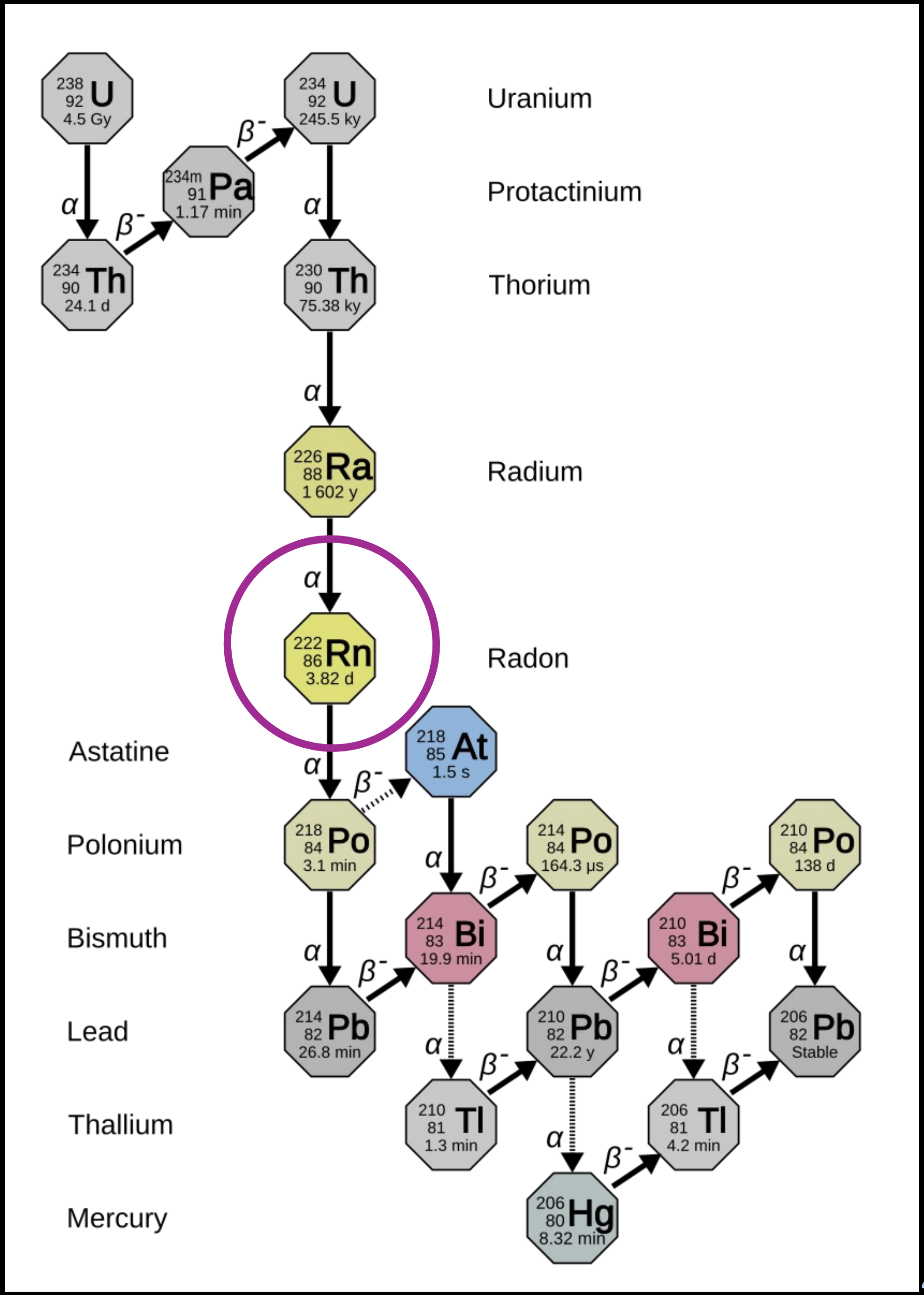
^{238}U chain

Naturally occurring (few ppm in rock, soil, water), long lived $T_{1/2} = 4.5 \times 10^{6}$years

- α- decays
- β-decays
- Accompanying γs

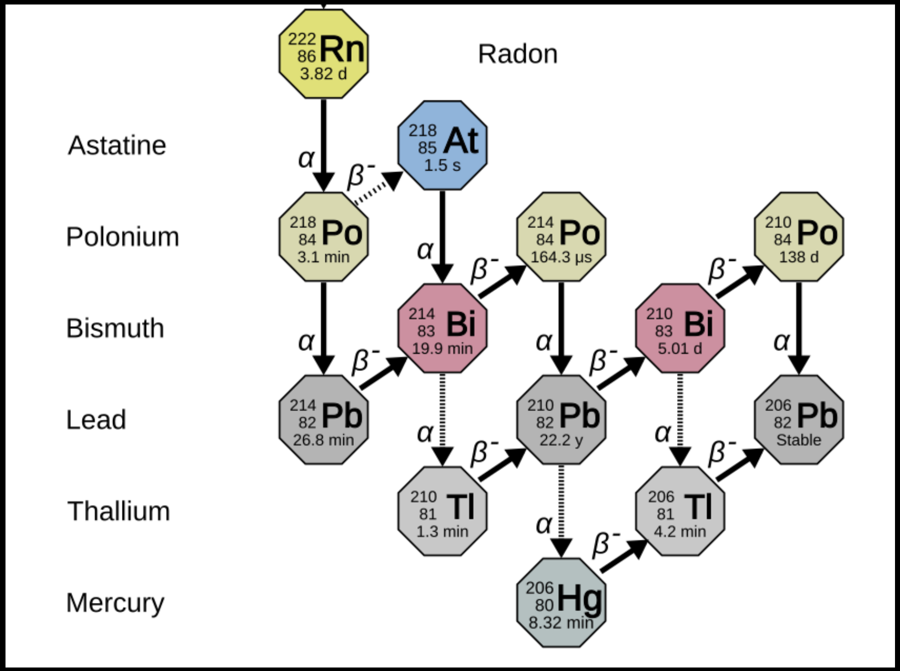
- Very short decay steps can be used for ‘tagging’

- Radon gaseous and short lived ^{222}Rn $T_{1/2} = 3.82$ days



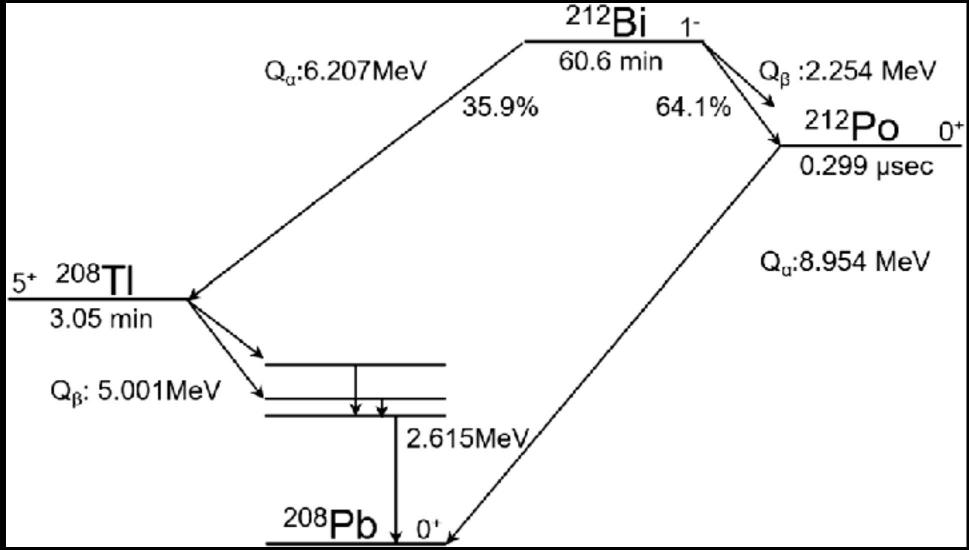
Radon

- ^{222}Rn $T_{1/2} = 3.82$ days
- Produced in the ^{238}U decay chain, can then emanate out of solid detector components into a liquid or gaseous region
- Or radon in air can dissolve into a liquid
- Both can break ‘equilibrium’
  - Different activity in the top and bottom part of the chain
- Radon decays in air, can implant daughters into solid materials
  - Those radioactive daughters can later leach out into liquids

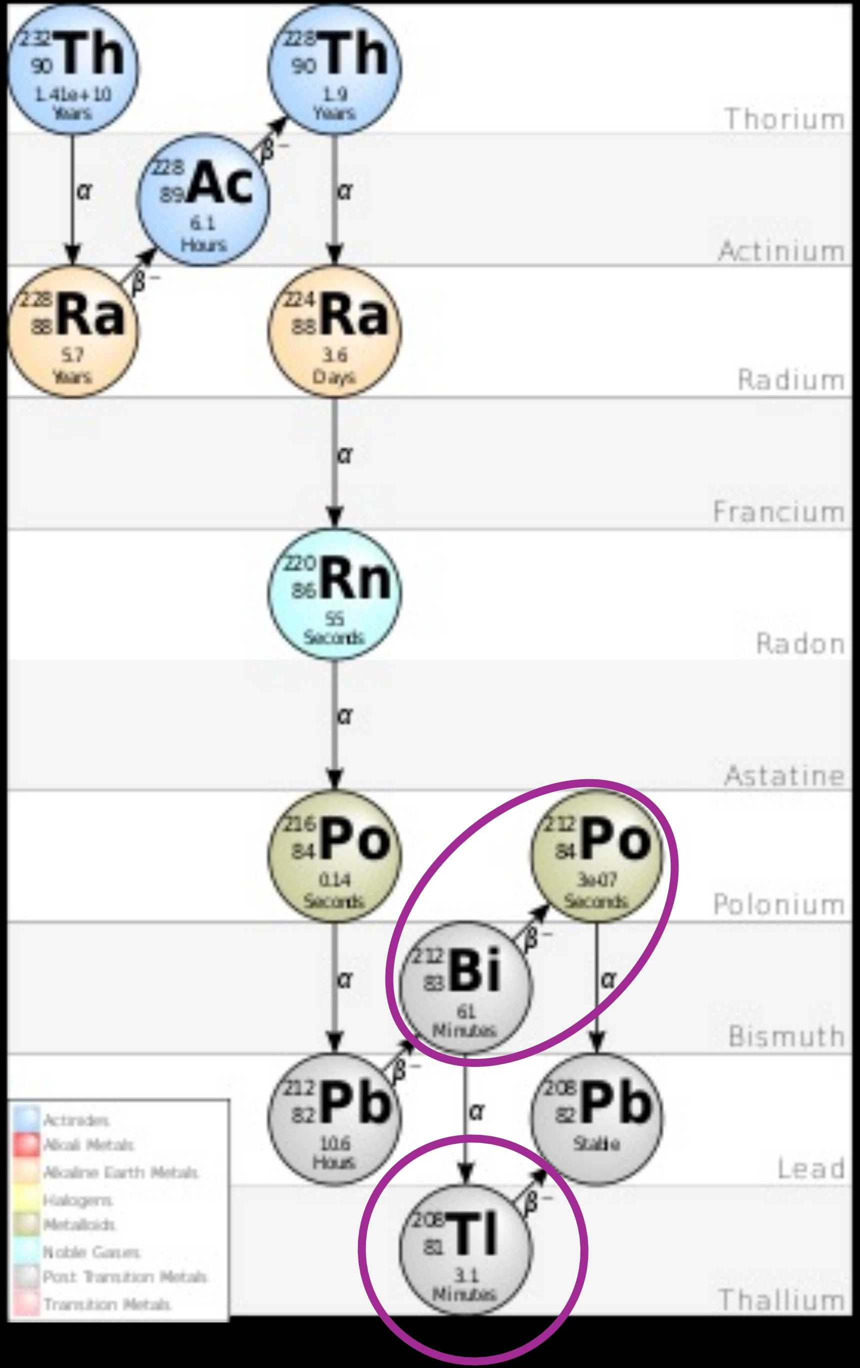


^{232}Th chain

- Also naturally occurring
- Highest 'naturally occurring' gamma
  - ^{208}Tl E = 2.615MeV



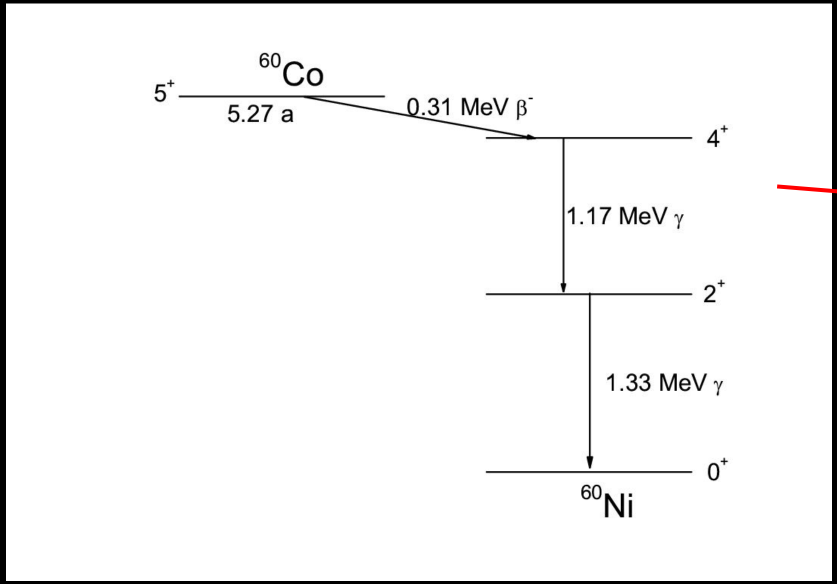
- ^{212}Po $T_{1/2} = 0.3\mu s$
  - Can also be BiPo 'tagged' but more challenging as shorter half-life that ^{214}BiPos



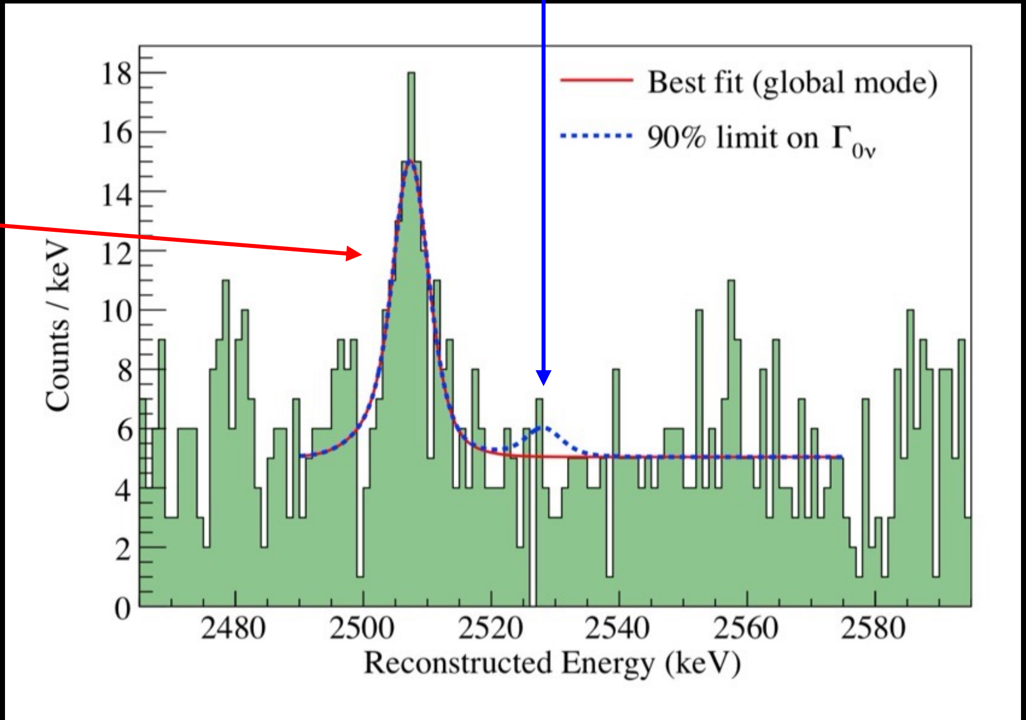
Radioactive Isotopes

- Most ‘dangerous’ depends on detector and Q-value

e.g. ^{60}Co →2.5MeV visible gammas



Signal region



CUORE spectrum

^{130}Te Q-value = 2.528MeV

Backgrounds

$$T_{1/2} \propto \frac{M.\epsilon.\sqrt{t}}{\sqrt{(b.M + c)\Delta E}}$$

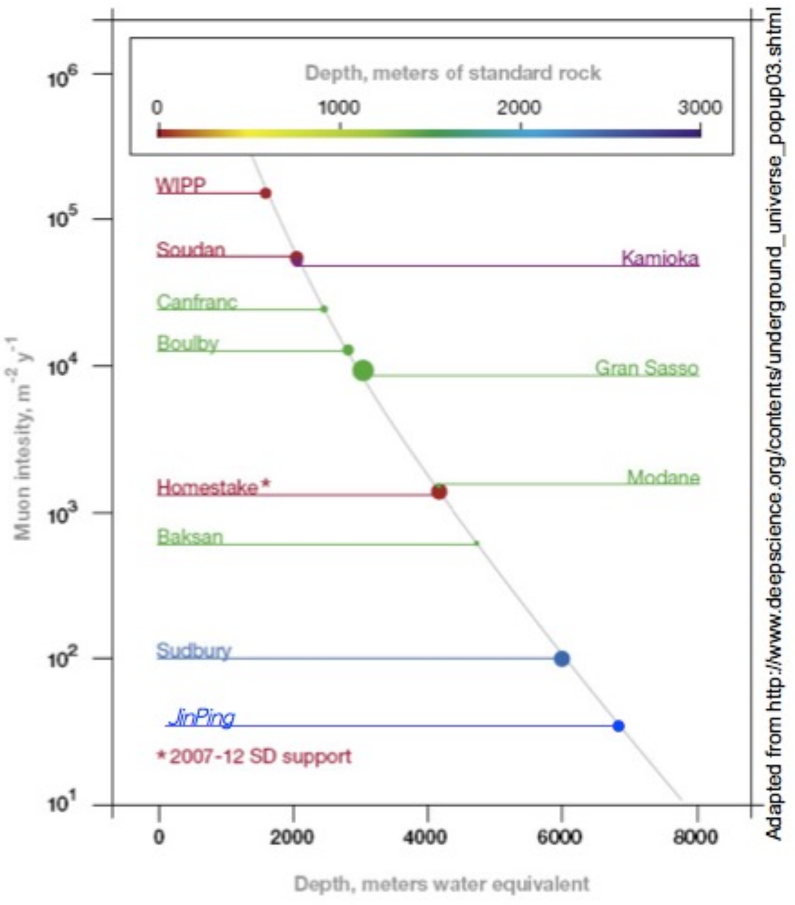
- $2\nu\beta\beta$ decays ΔE

- Internal radiological backgrounds b
- External radiological backgrounds c

- Cosmogenic b, c
- Neutrinos and Neutrino-genic b, c

Cosmic Muons

- Muons produced in the atmosphere from cosmic ray interactions
- Deeper underground, lower muon flux
- Muons are generally easily vetoed
  - Characteristic high energy deposits
  - Veto detectors
- However…



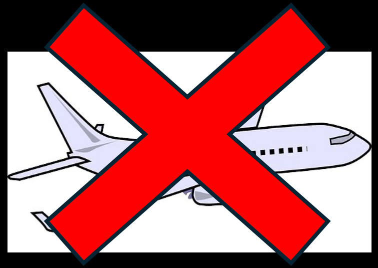
SNOLAB

Muon flux = 70 muons/day

Class-2000 clean room lab

Cosmogenic Backgrounds

- Muons can interact with material in the detector producing n,p, radioactive isotopes
- Materials above ground experience higher activation rates
  - Source material
  - During construction
  - In transit



  Isotopes produced with short (<1year) half-lives can be mitigated by allowing materials to ‘cool’ underground

- In-situ cosmogenic production
  - Can veto short-lived isotopes with time-cut after muon

Experiment Examples

- Not a complete list
- Use these examples to illustrate the different backgrounds and challenges

Liquid scintillator
^{136}Xe, ^{130}Te
KamLAND-Zen
SNO+

TPC
^{136}Xe
nEXO, NEXT

Cryogenic Bolometer
^{130}Te, ^{82}Se
CUORE, CUPID

Semi-conductors
^{76}Ge
LEGEND

Tracking calorimeters
^{82}Se
SuperNEMO

Experiment Examples

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Liquid scintillator
^{136}Xe, ^{130}Te
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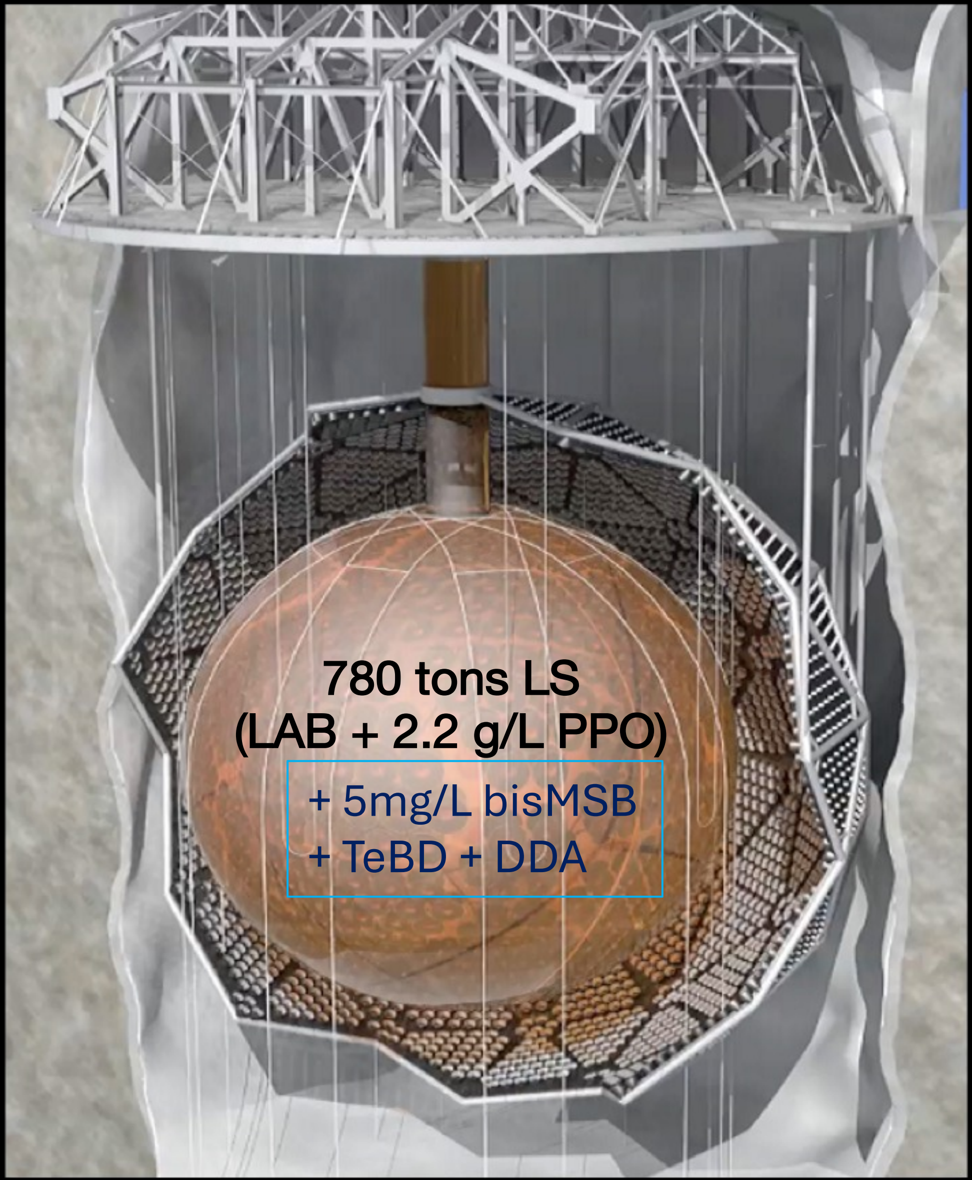
LEGEND

Tracking calorimeters
^{82}Se
SuperNEMO

SNO+

- 2km underground (~6000 mwe)
- Observe events through scintillation light with ~9300 PMTs
  - $e^{\pm}, \gamma, \alpha, \mu$
- ^{130}Te – 34% nat abundance
- Highly scalable, cost effective (no enrichment required)
- Load natural Te into the scintillator (chemistry!)
  - 'Source out' measurements first
  - Initially add 0.5% by mass (3.9tonnes)
  - $\rightarrow$ 1%, 1.5%, 2.5% …

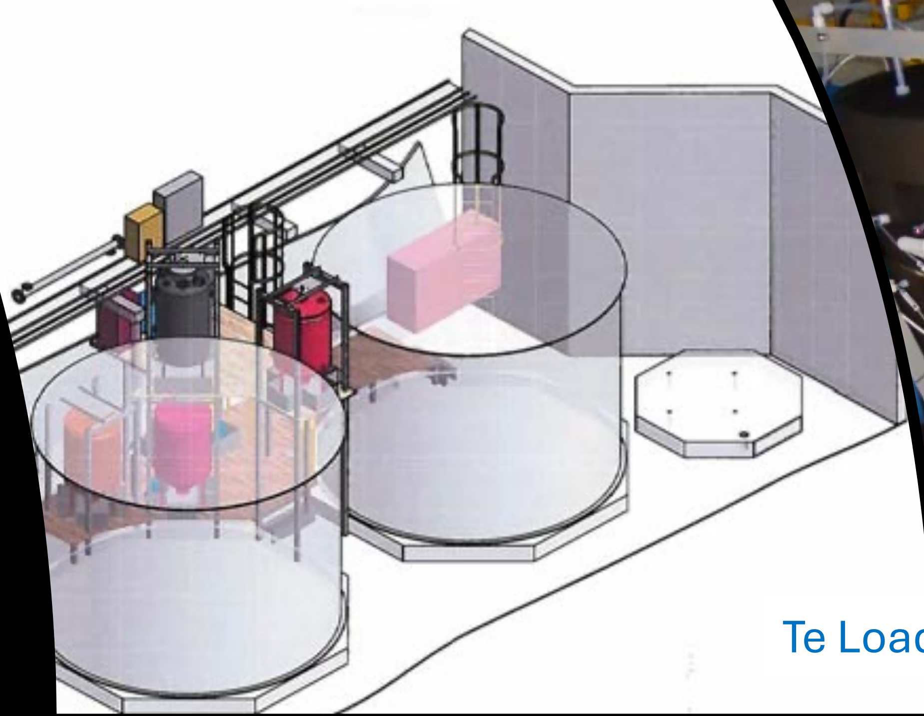


Te loading

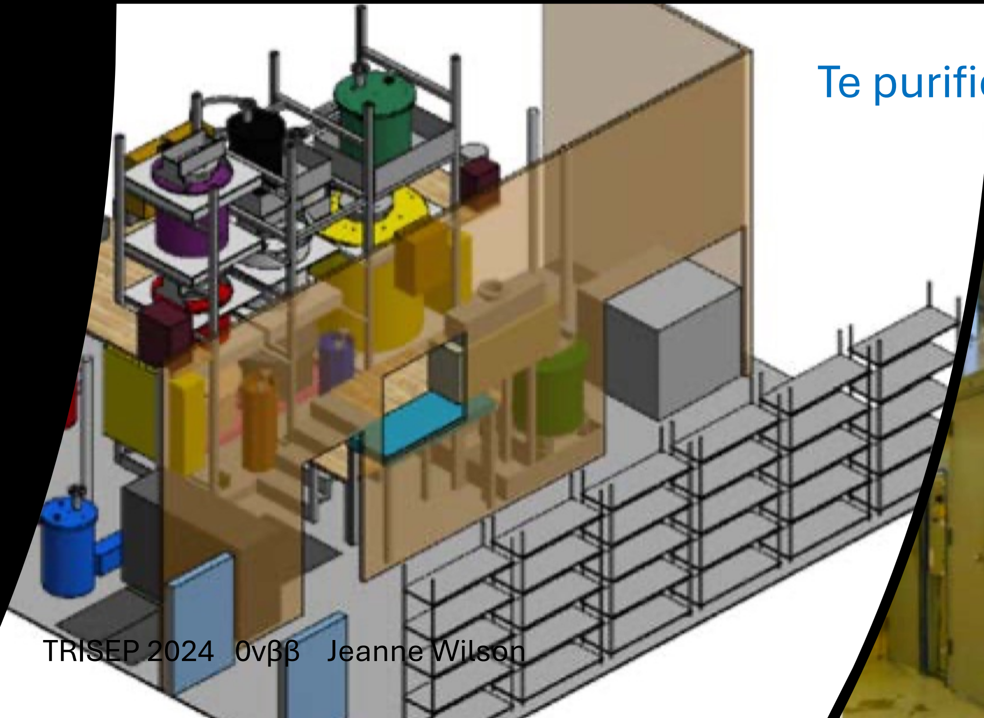
- ~8 tons of telluric acid (TeA) “cooling” underground
- Target purification for Te cocktail:

  ~ 10^{-15} g/g U

  ~ 10^{-16} g/g Th



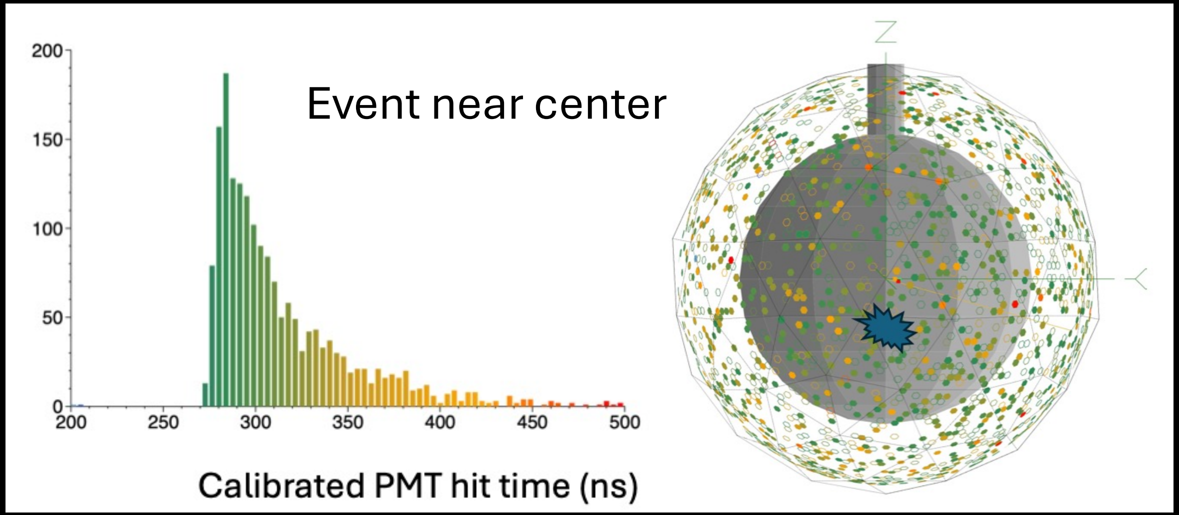
Te Loading plant

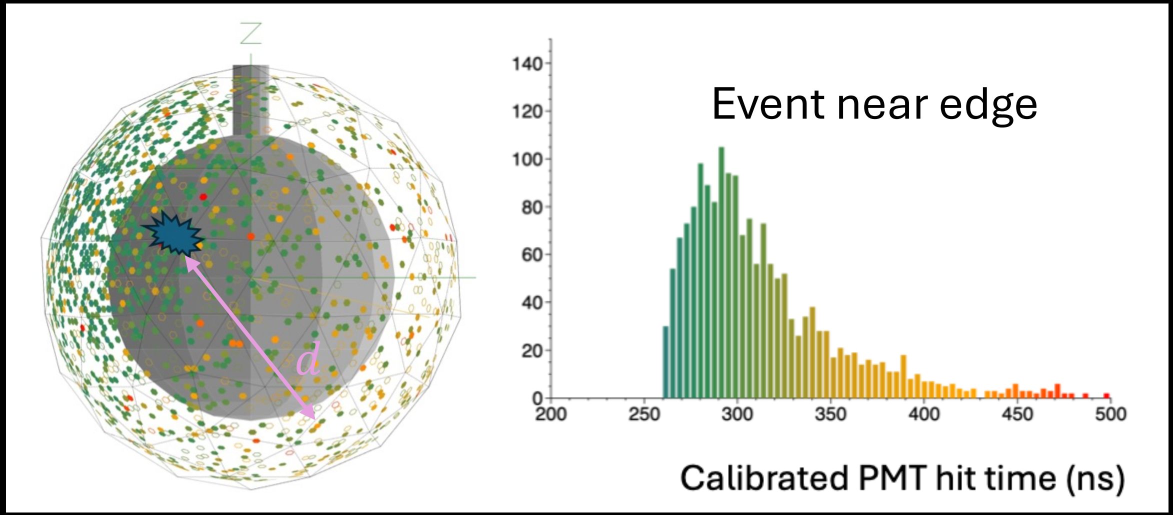


Te purification plant

Event Reconstruction

- ‘Events’ → scintillation light → photons → PMT hits
- $> 10{,}0000\ \gamma/\text{MeV} \rightarrow \sim 300\ \text{hits}/\text{MeV}$

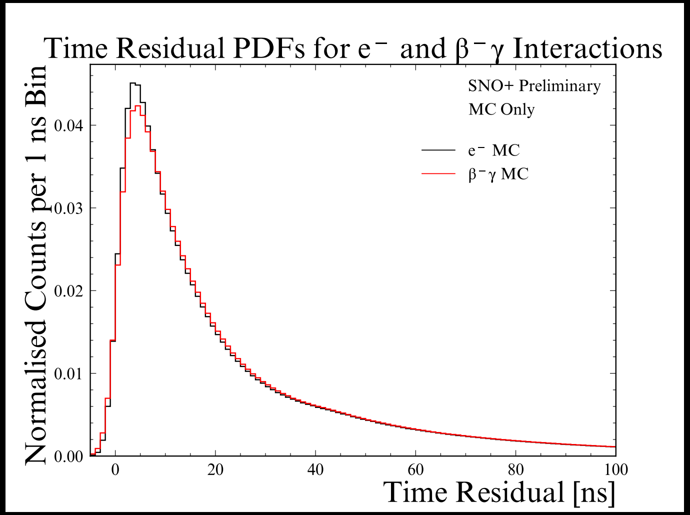




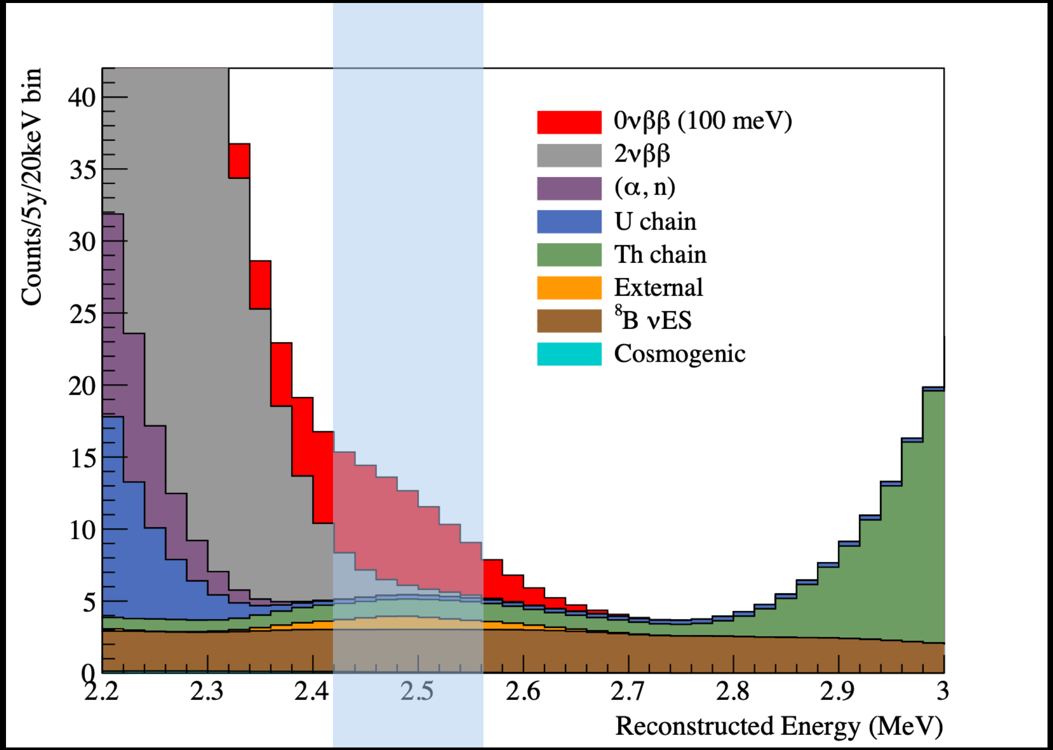
- Reconstruct position and energy of event from time and number of PMT hits

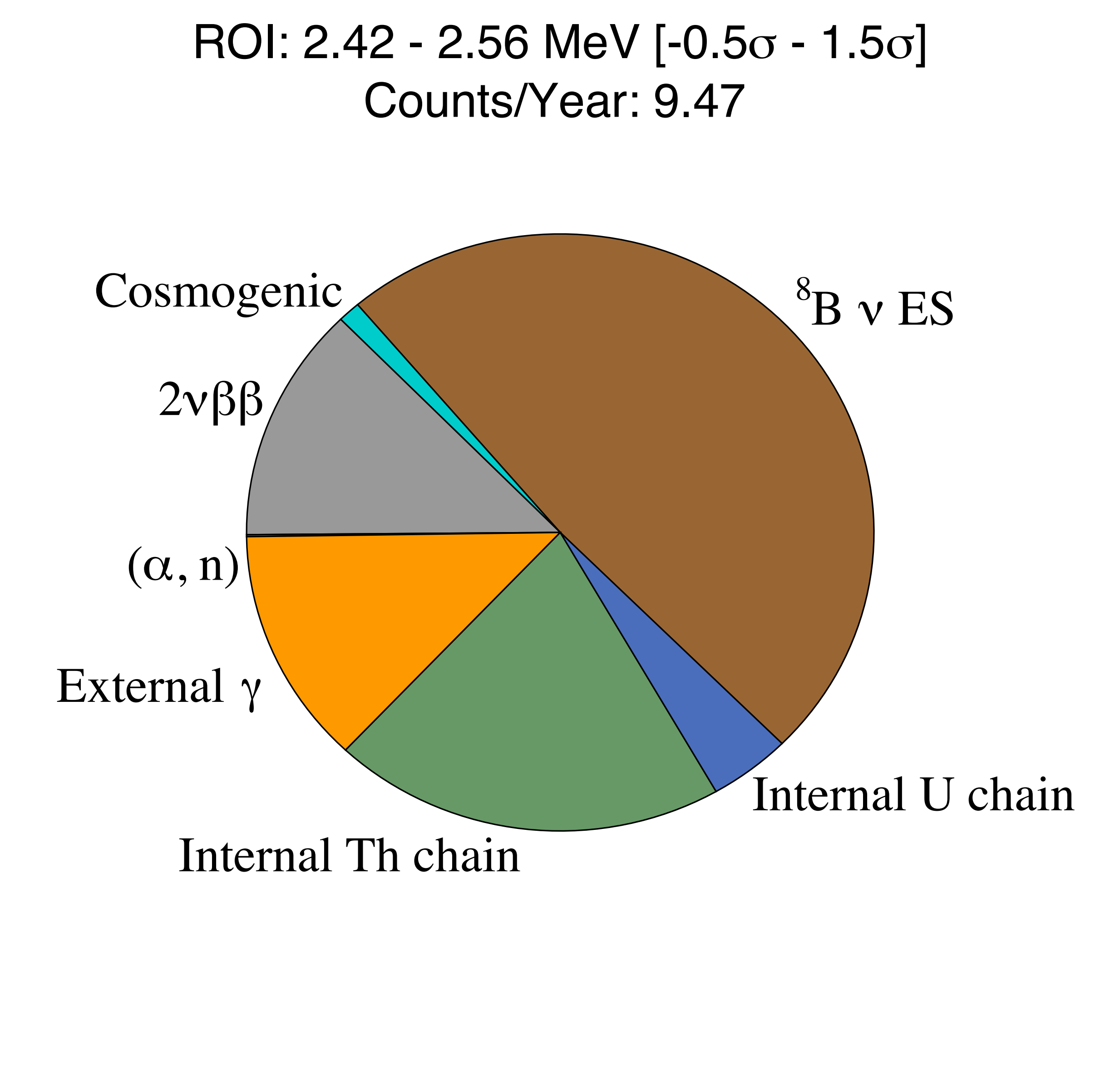
$$t_{res} = t_{hit} - t_{event} - d/c$$

- Some sensitivity to event type through timing distribution



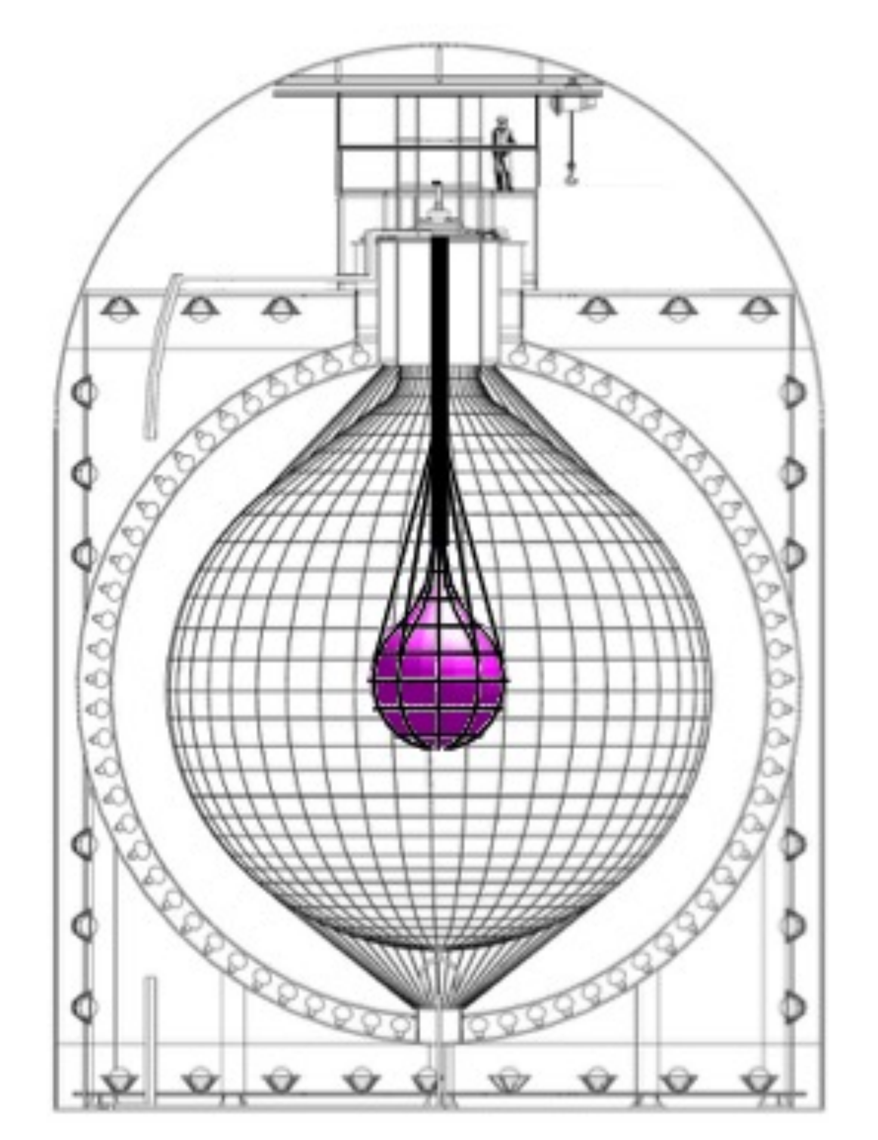
SNO+ 0.5% loading





KamLAND-Zen

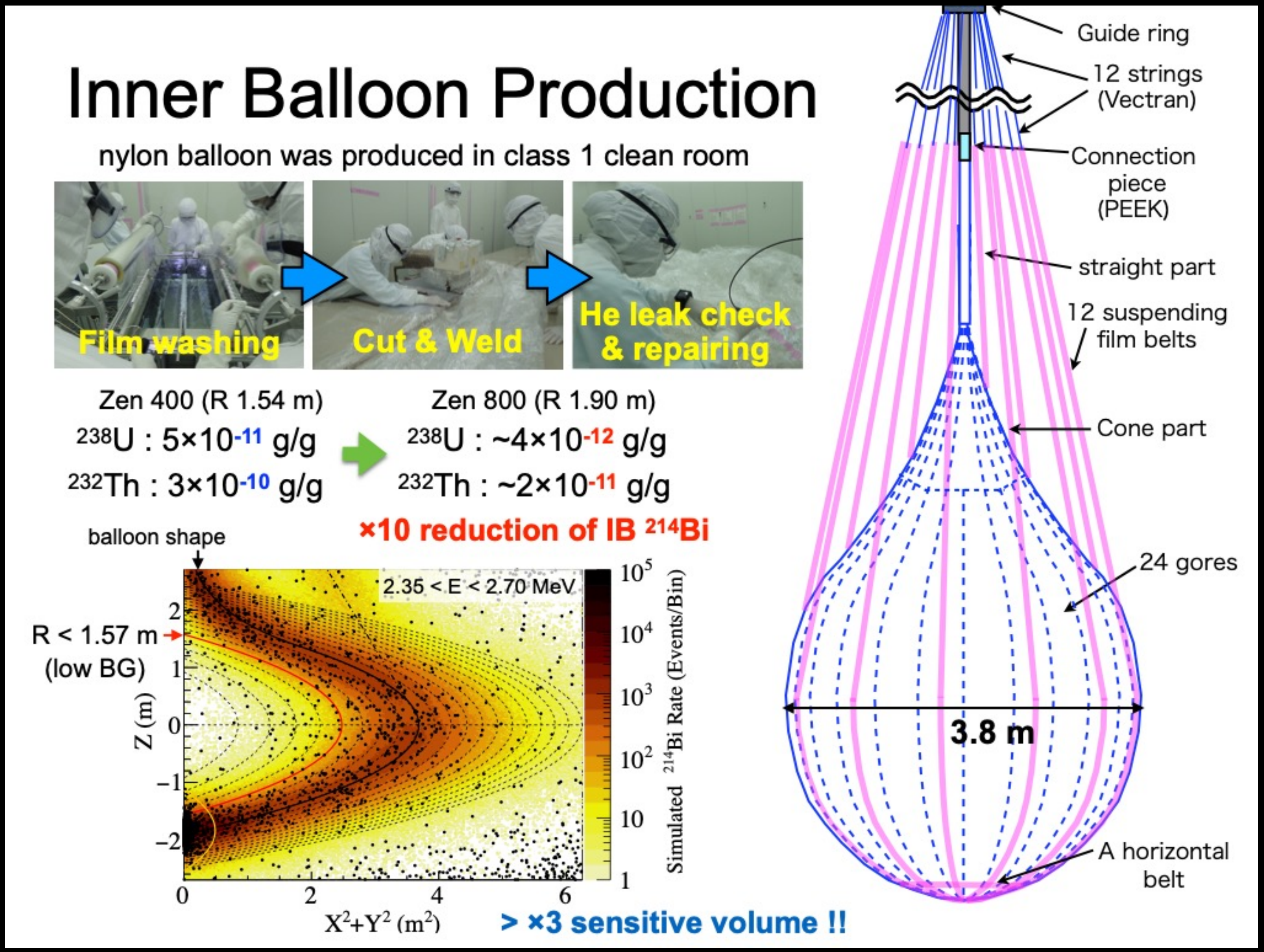
- 1000-ton pure liquid scintillator
  $U, Th < 10^{-17} g/g$
- ~745kg of ^{136}Xe (91% enrichment) loaded into inner balloon
- ~8000 photons/MeV from Liquid scintillator



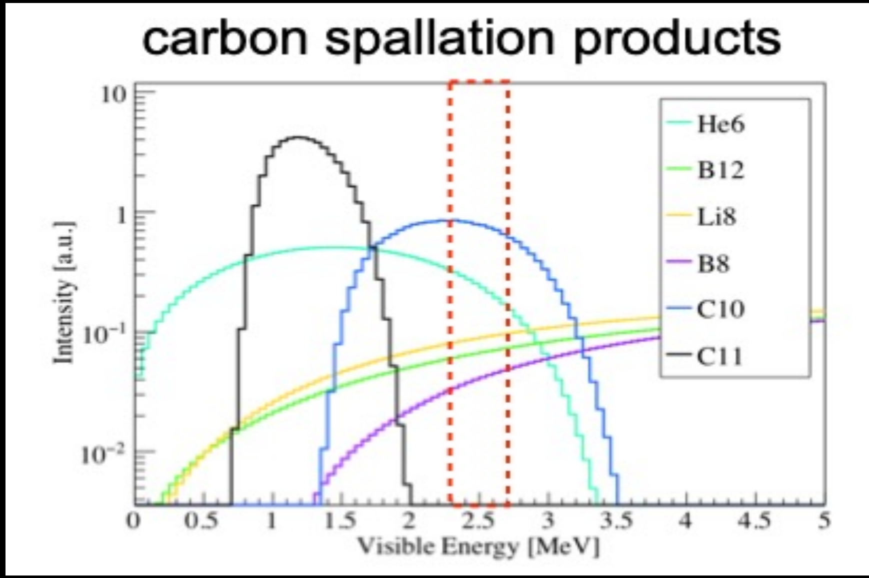
KamLAND-Zen backgrounds 1

Slide from I Shimizu, Neutrino 2024

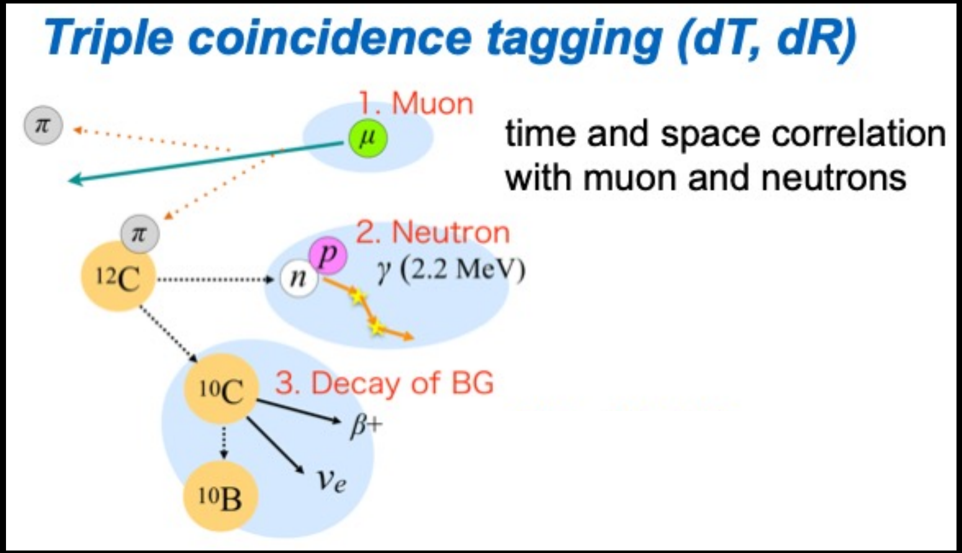
Mitigating backgrounds from the balloon

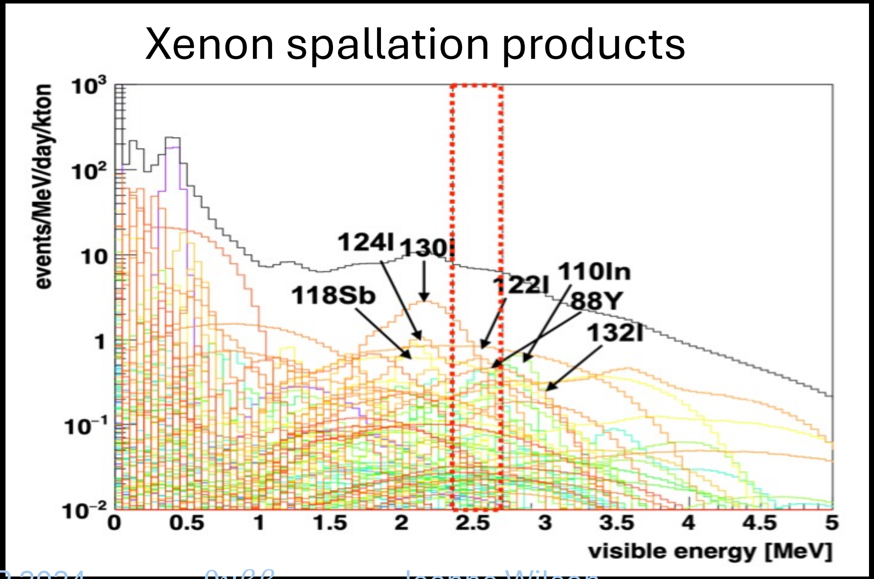


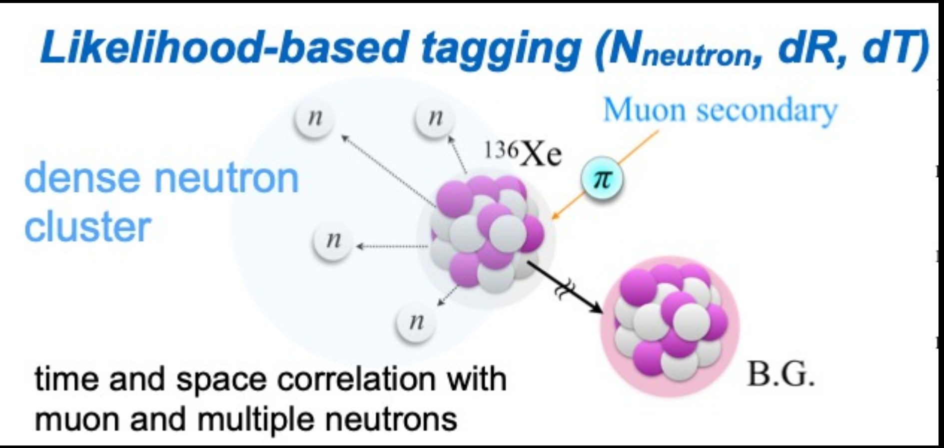
KamLAND-Zen backgrounds 2



2700 m.w.e. over-burden





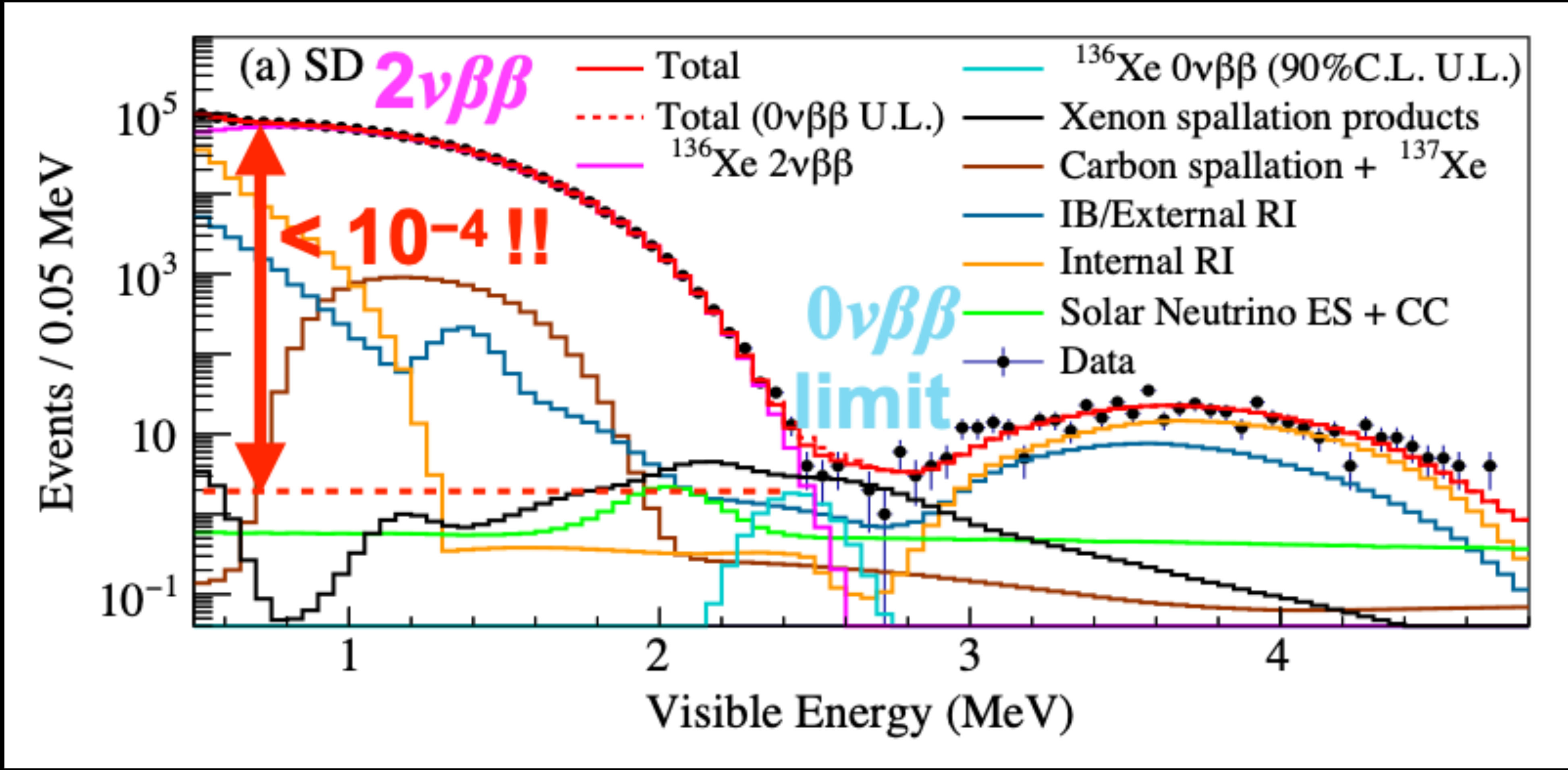


KamLand-Zen latest results

1131 days of data

Best fit = 0 events , 90% CL < 10 events

$$T^{0\nu}_{1/2} > 3.8\times10^{26} years$$



Experiment Examples

- Not a complete list
- Use these examples to illustrate the different backgrounds and challenges

Liquid scintillator
^{136}Xe, ^{130}Te
KamLAND-Zen
SNO+

TPC
^{136}Xe
nEXO, NEXT

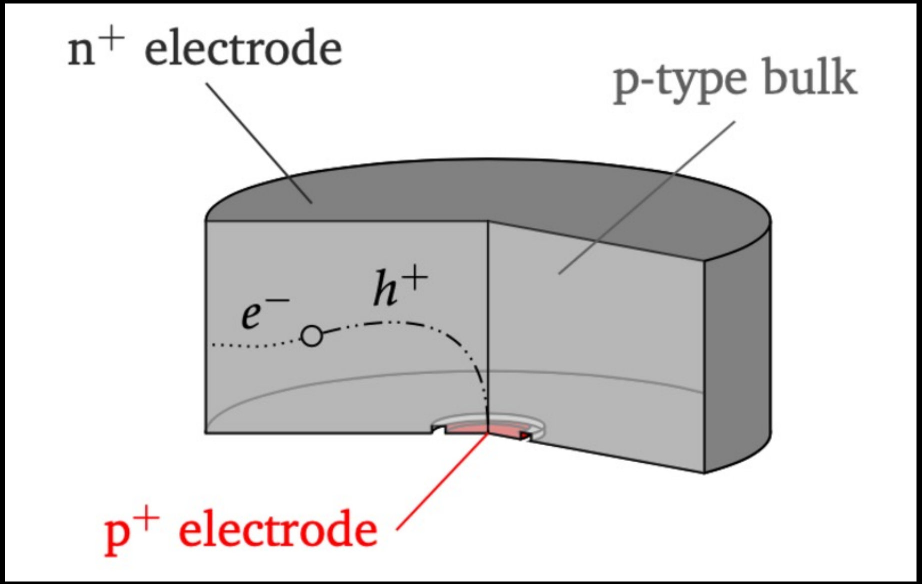
Cryogenic Bolometer
^{130}Te, ^{82}Se
CUORE, CUPID

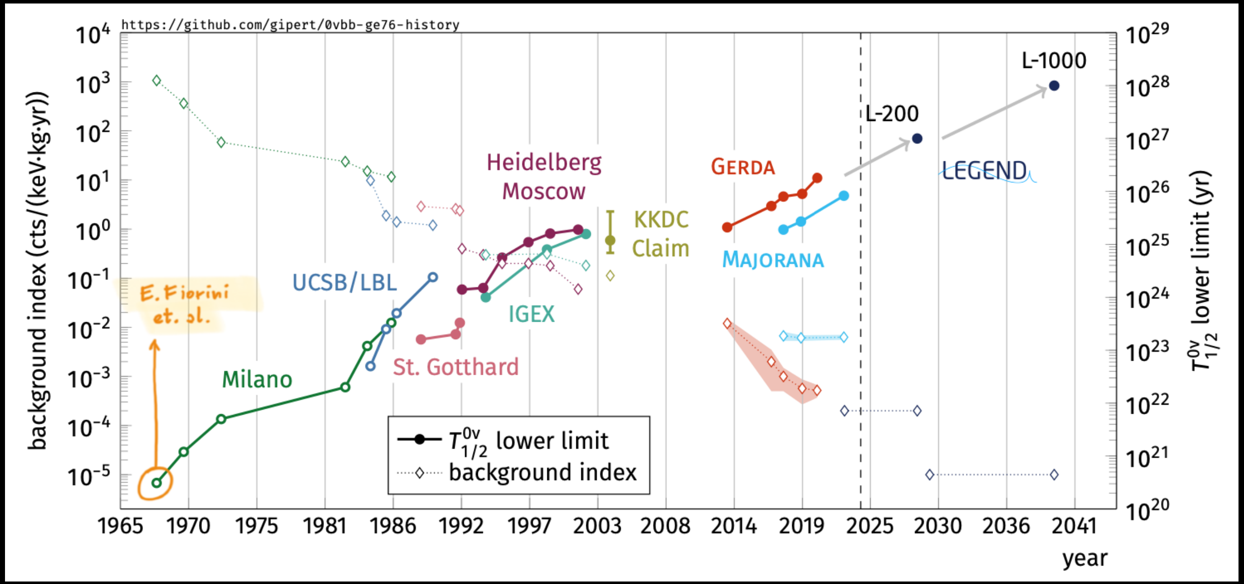
Semi-conductors
^{76}Ge
LEGEND

Tracking calorimeters
^{82}Se
SuperNEMO

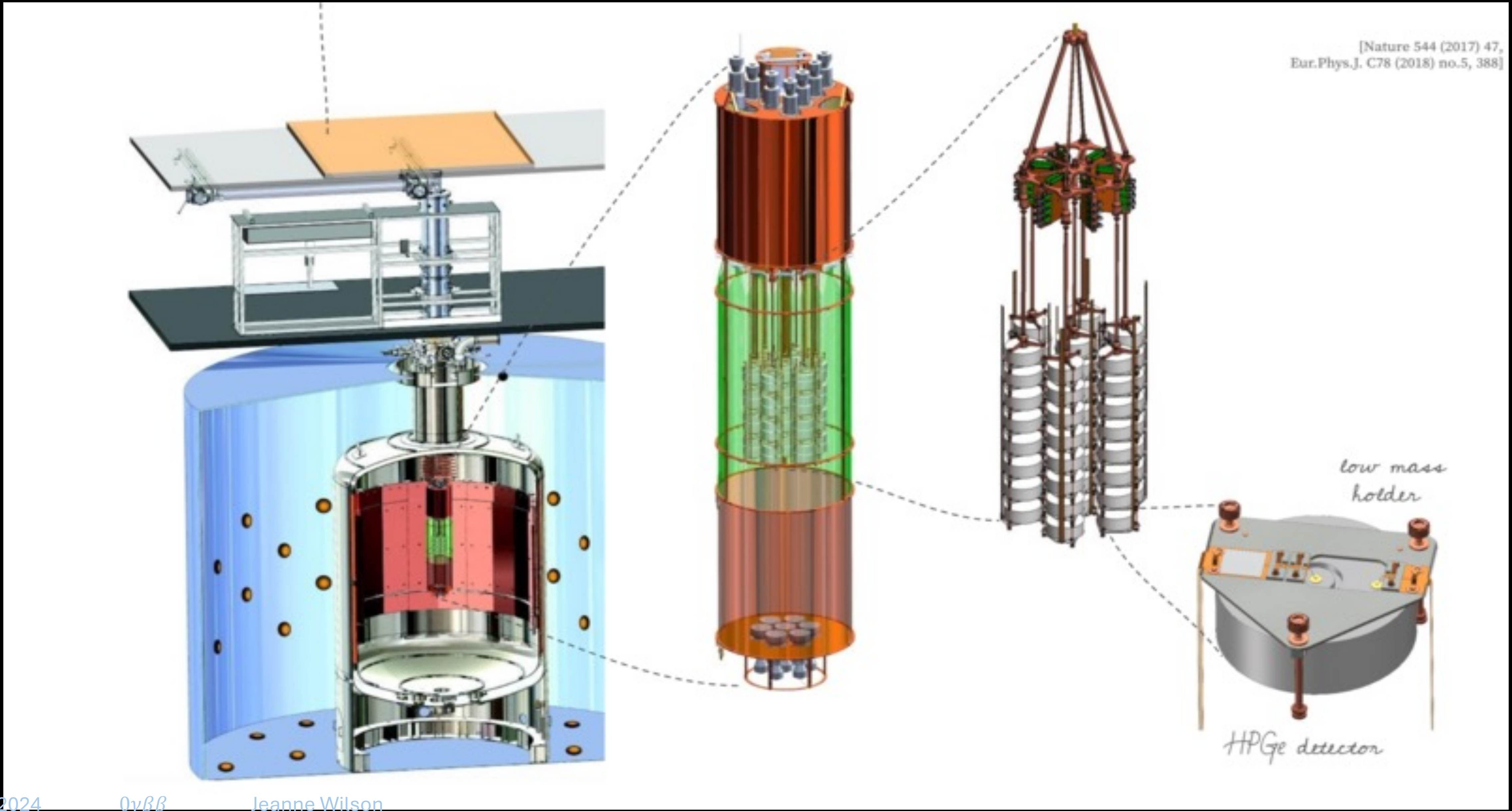
LEGEND

- High Purity Germanium detectors enriched in ^{76}Ge
- Solid state semi-conductors with outstanding energy resolution
- Very pure – low backgrounds
- HPGe commonly used for very low background screening
- Long-standing history for $0\nu\beta\beta$ searches

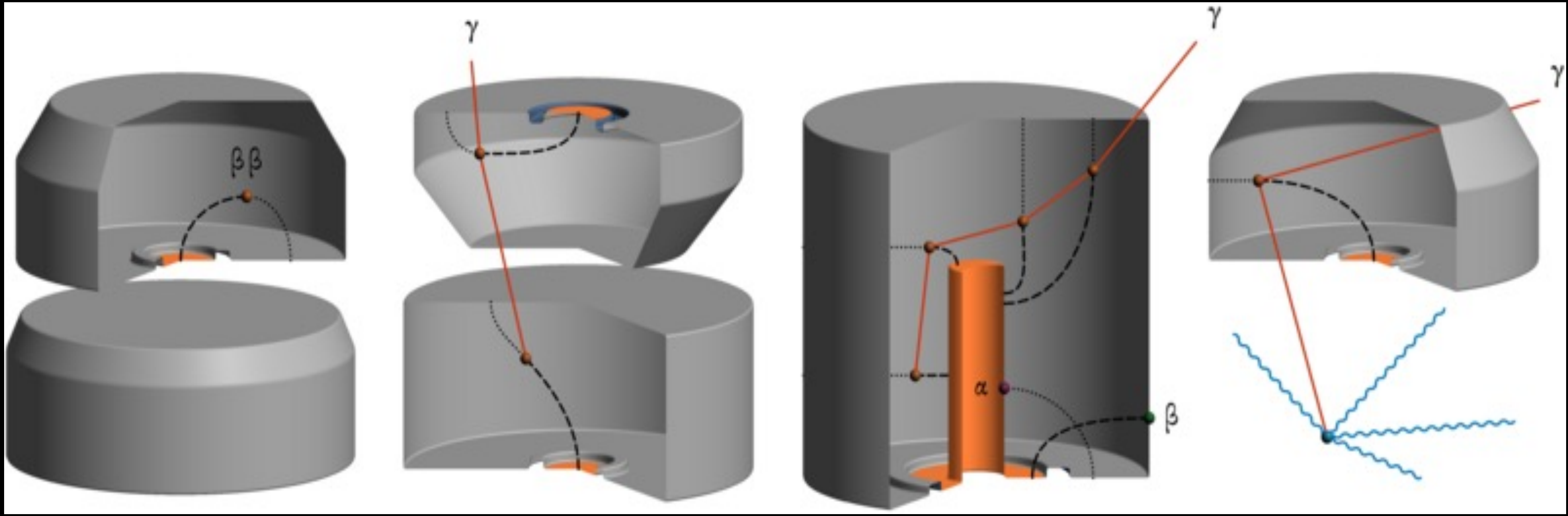




LEGEND


[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]
low mass
holder
HPGe detector

Background suppression



Single site
$\beta\beta$ event

Multi-detector
γ event

segmentation

Multiple interactions
γ event and
α, β surface events

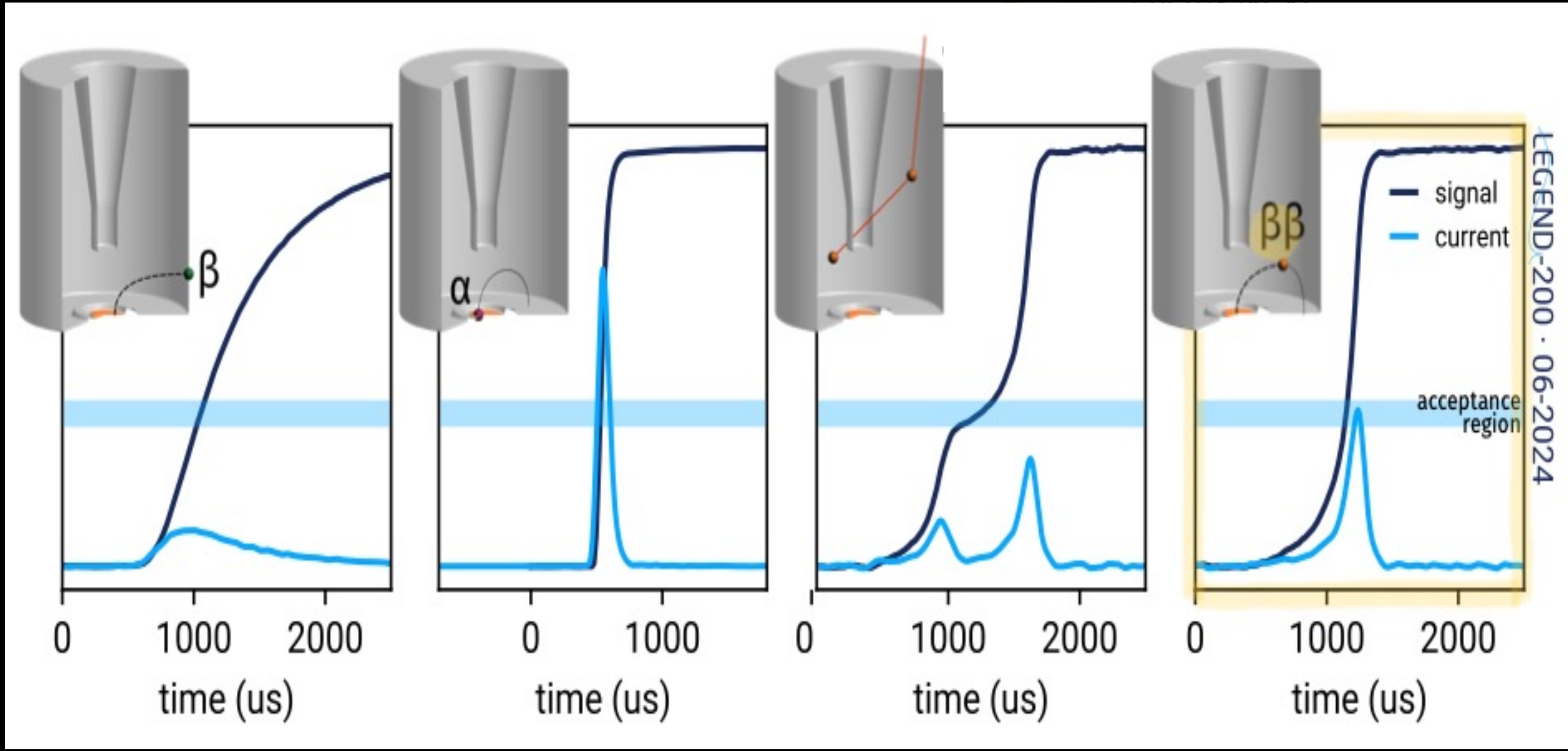
Pulse shape discrimination

γ event,
vetoed by activity in LAr

External veto

https://legend-exp.org/science/neutrinoless-bb-decay/legend-detectors

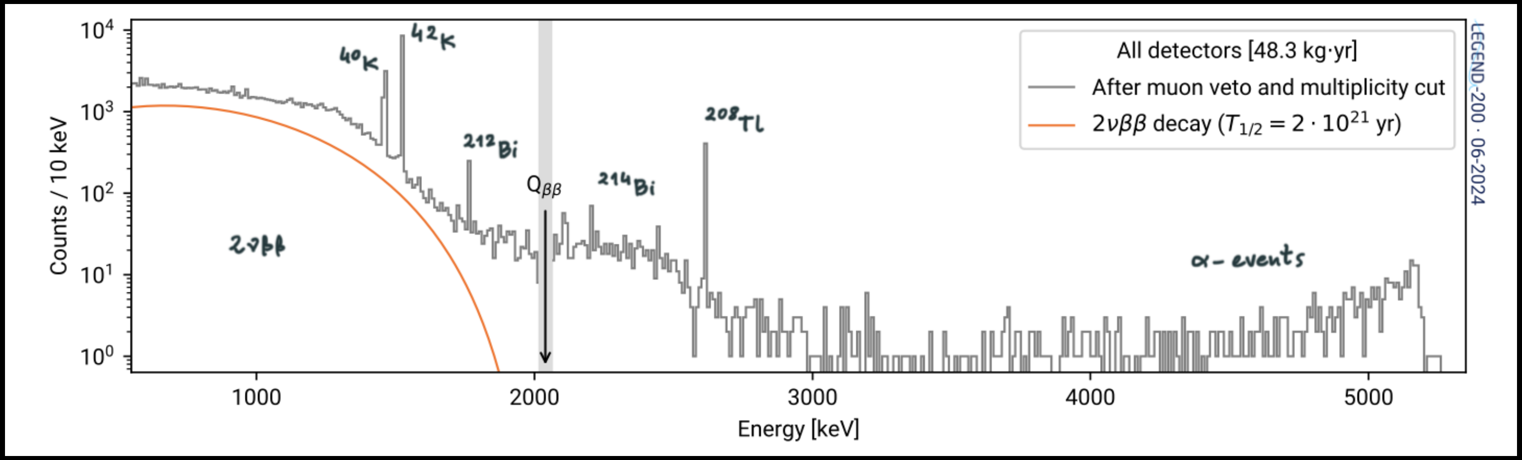
Background suppression



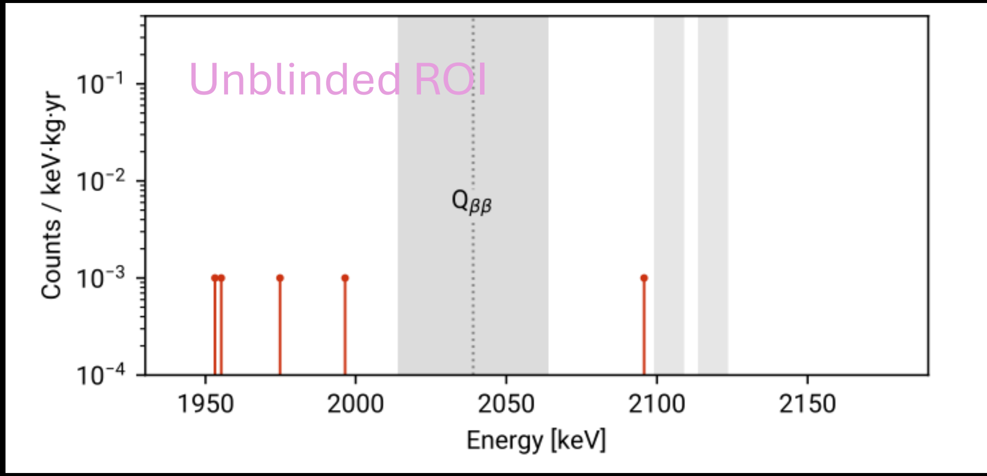
PSD – classify on $\frac{\max current}{Energy}$

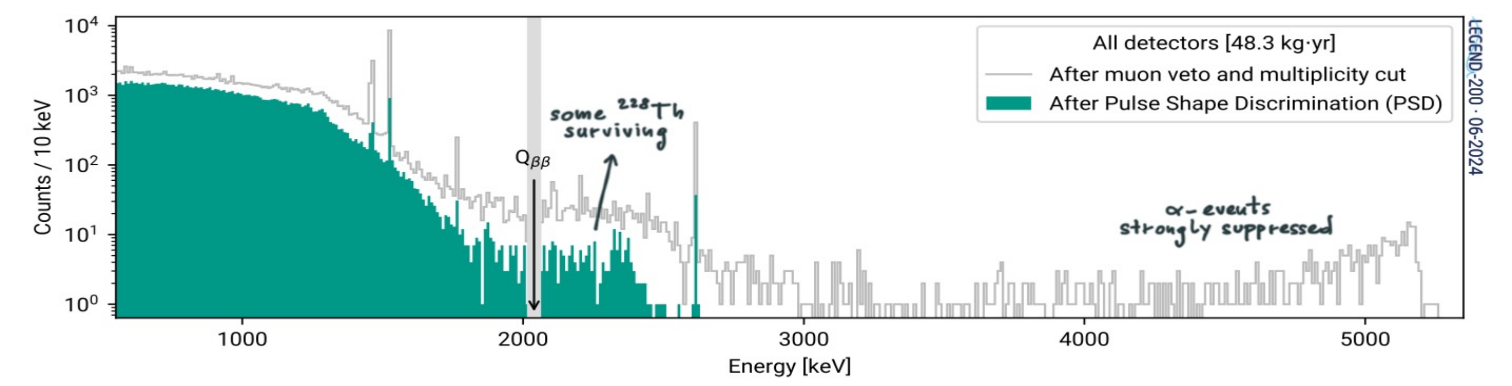
https://legend-exp.org/science/neutrinoless-bb-decay/legend-detectors

LEGEND-200 data

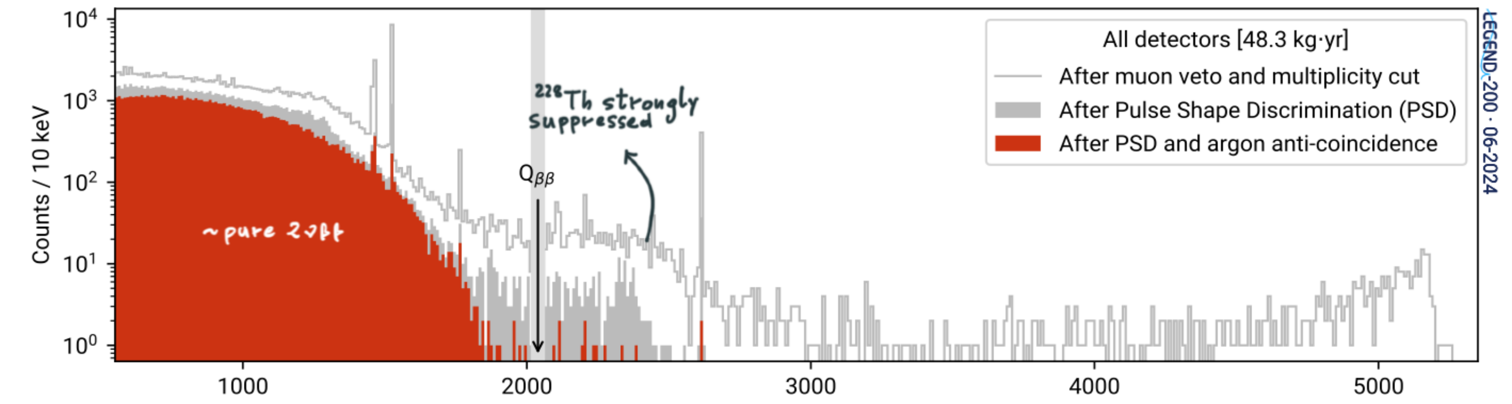


After muon veto and multiplicity cut





After Argon anti-coincidence



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LEGEND

Tracking calorimeters
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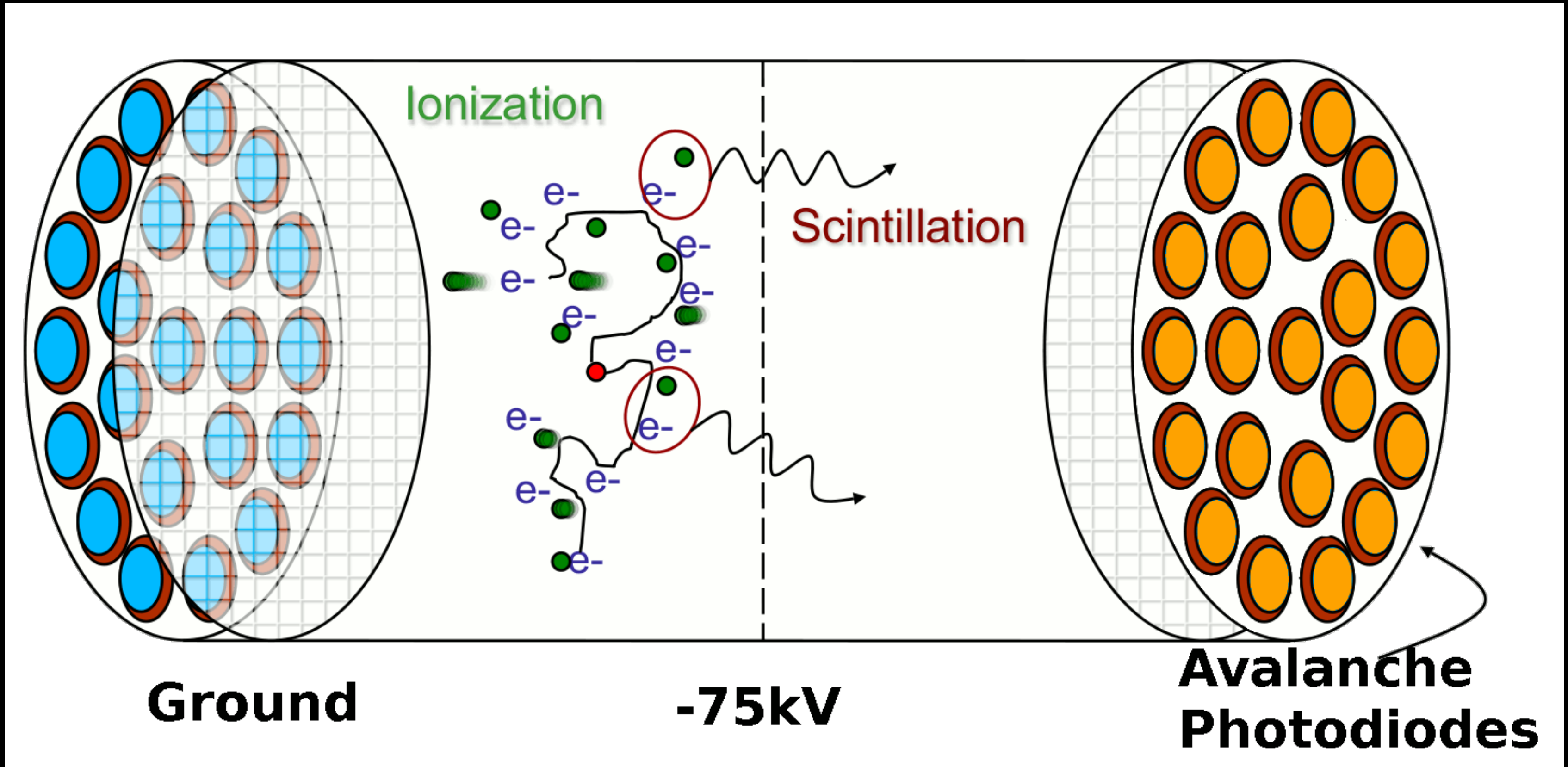
SuperNEMO

Xe TPCs



Charged particles produce light through scintillation and ionized track

Drift electrons to anodes – charge collection at wire grids

Simultaneous measurement of light and charge for better energy resolution and PID

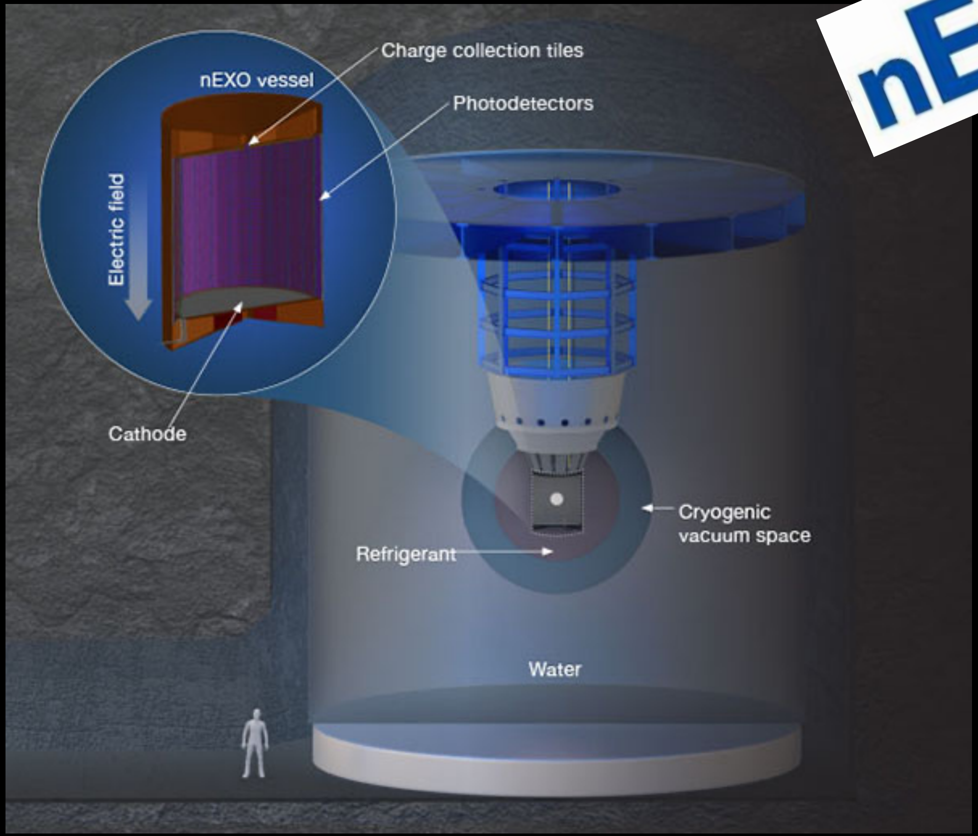
Xe Liquid or Gas

- high pressure better as more isotope
- Requires cryogenics → ~ -95°C
- Enrichment of ^{136}Xe

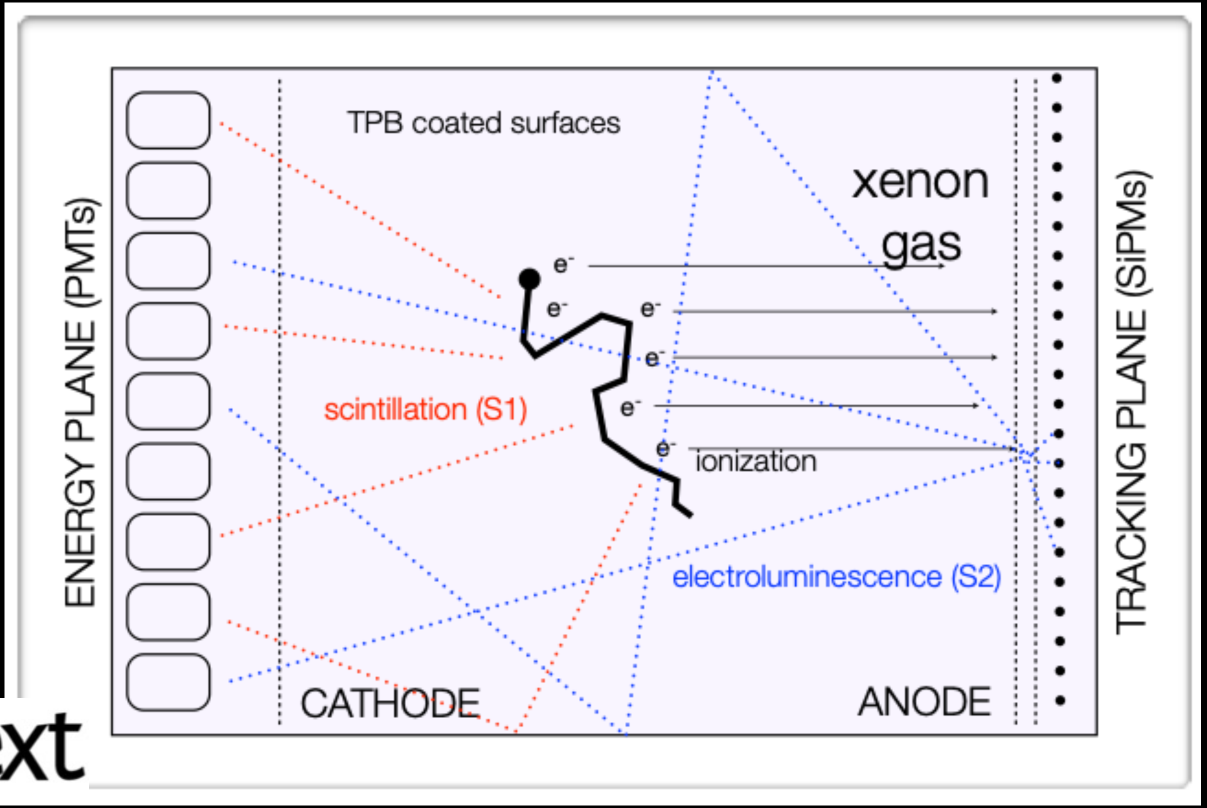
EXO-200

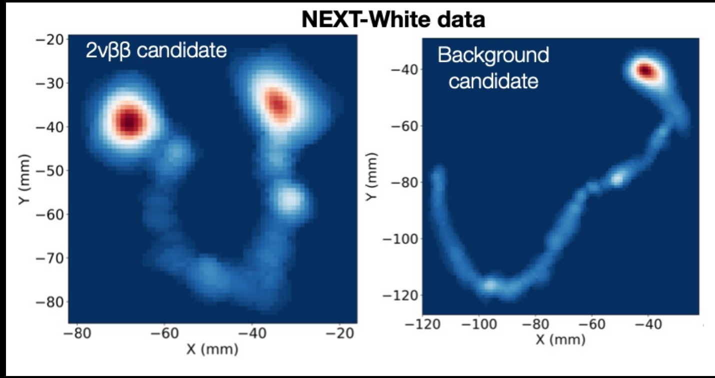
200kg Liquid Xe TPC (80% enrichment)
Central photo-cathode
Phys. Rev. Lett. 123, 161802
$T_{1/2} > 3.5\times10^{25}$ y (90% C.L.)

Xe TPCs



https://nexo.llnl.gov/nexo-overview

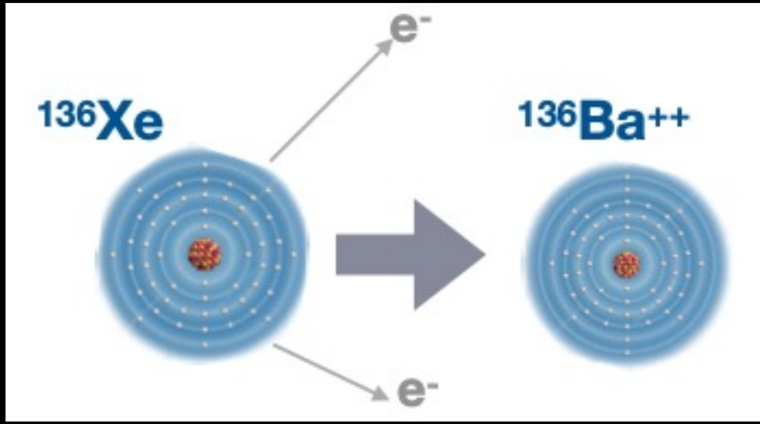




High pressure Xe gas TPC with electroluminescence

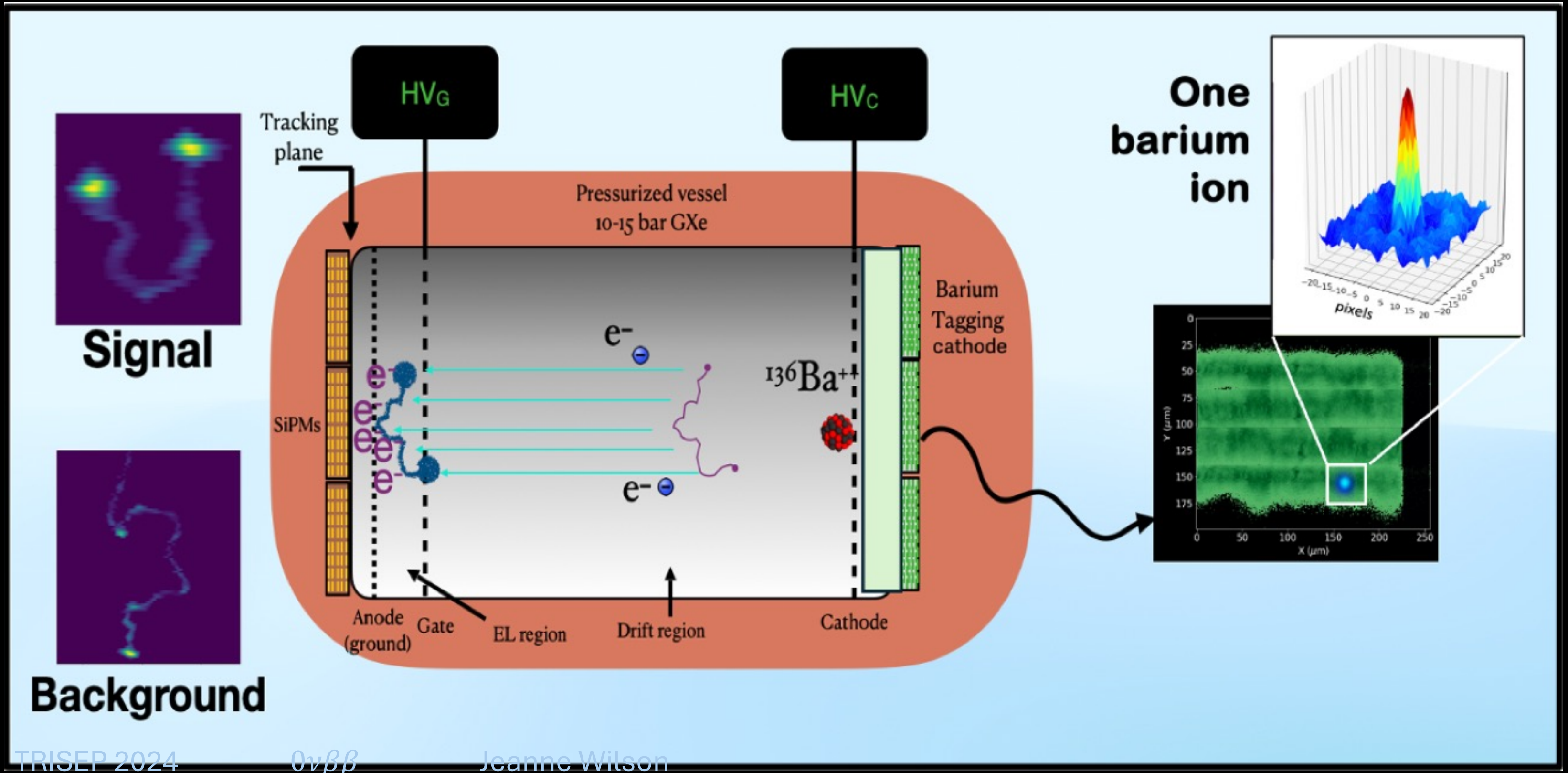
Topological signal/background separation

^{136}Xe daughter tagging



The Ba^{++} ion is only produced from $\beta\beta$ decay

If this can be tagged, distinguish $\beta\beta$ from all other radioactive events



Active R&D:

- Drift ++ ion to cathode
- Trap Ba – eg. cryogenic probe
- chemical sensors/ fluorescence

Eg https://www.nature.com/articles/s41586-019-1169-4

Experiment Examples

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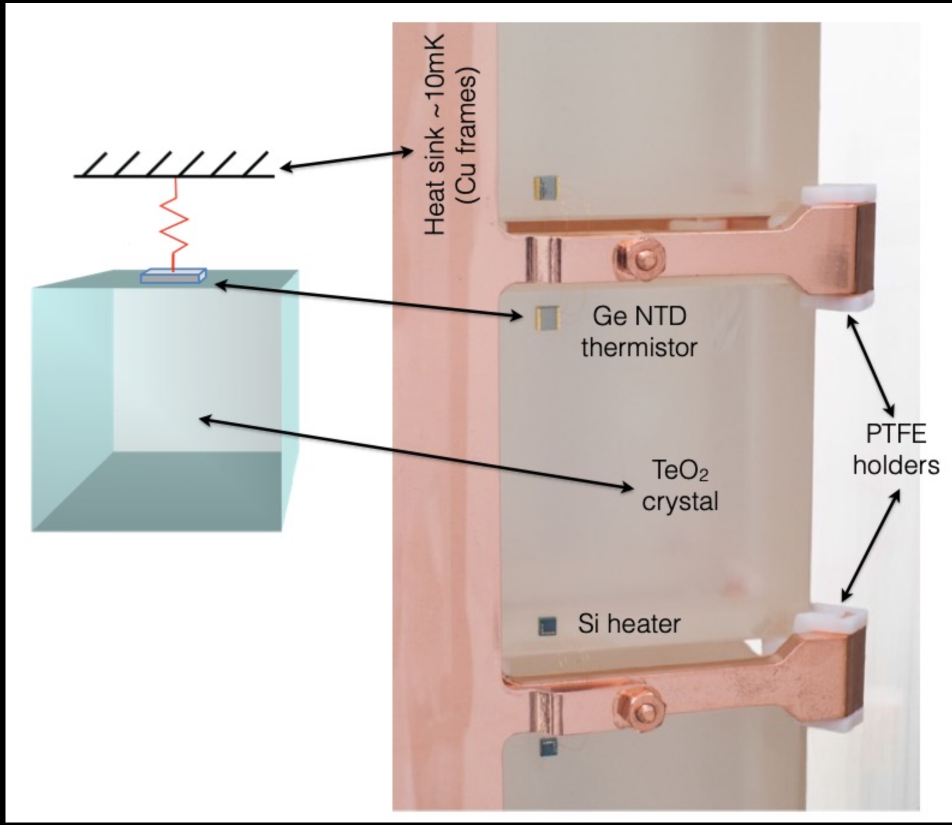
^{82}Se
SuperNEMO

CUORE

- Closely packed array of 988 TeO_2 crystals (750g each) working as cryogenic calorimeters
- Absorbed energy converted into temperature variation of crystal, measured by thermistor
  - Energy resolution $\sim 0.3\%\ FWHM$

Challenges:

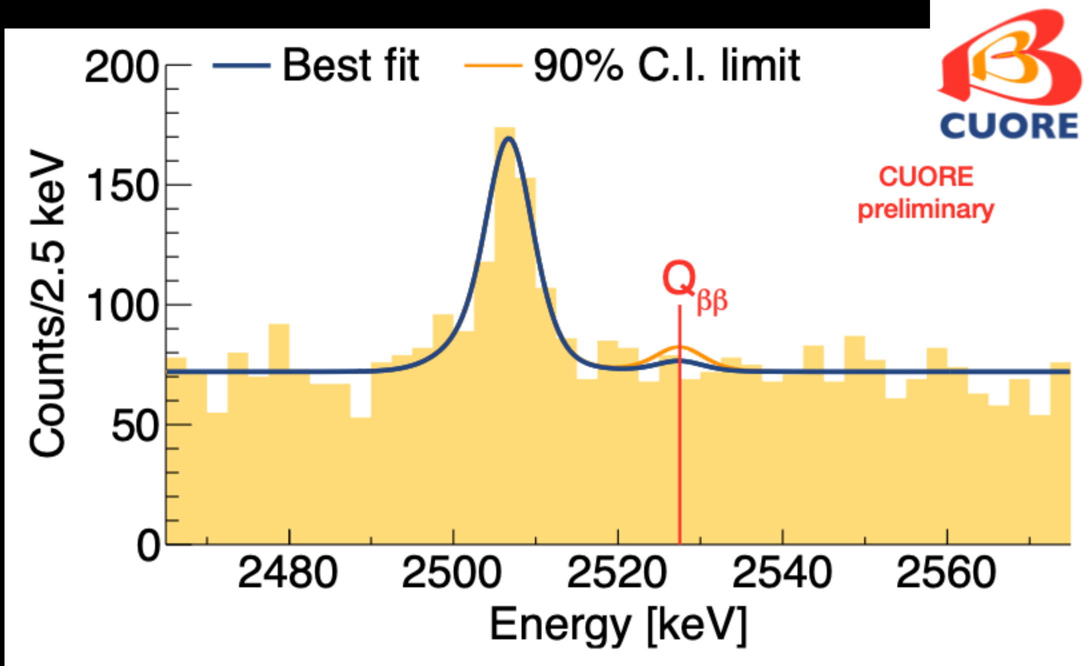
- operating temperature $\sim 10mK$!
- Surface backgrounds
- Sensitive to vibrations and seismic activity
  - Correlation between storms and low f noise
  - Sea waves!

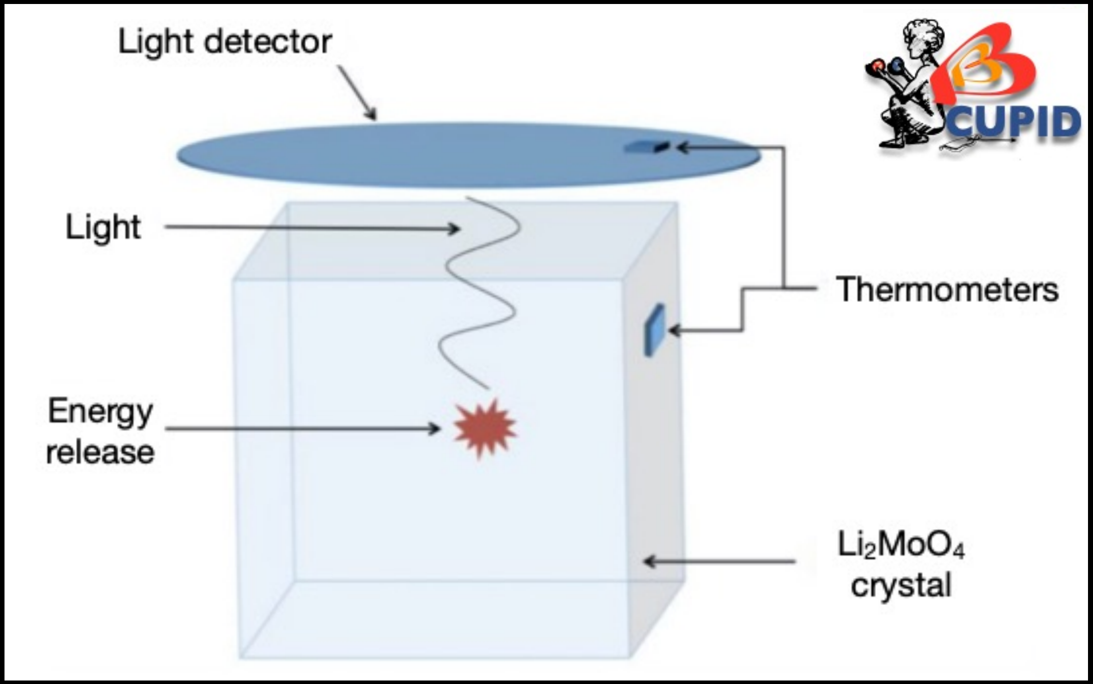


CUPID

CUORE Upgrade with Particle IDentification

- Li_2MoO_4 crystals enrich to 95% ^{100}Mo
- Higher $Q_{\beta\beta}$ for reduced γ/β backgrounds
- Both temperature and light detection for PID – rejection of surface αs





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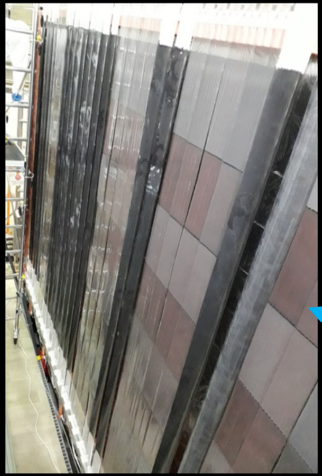
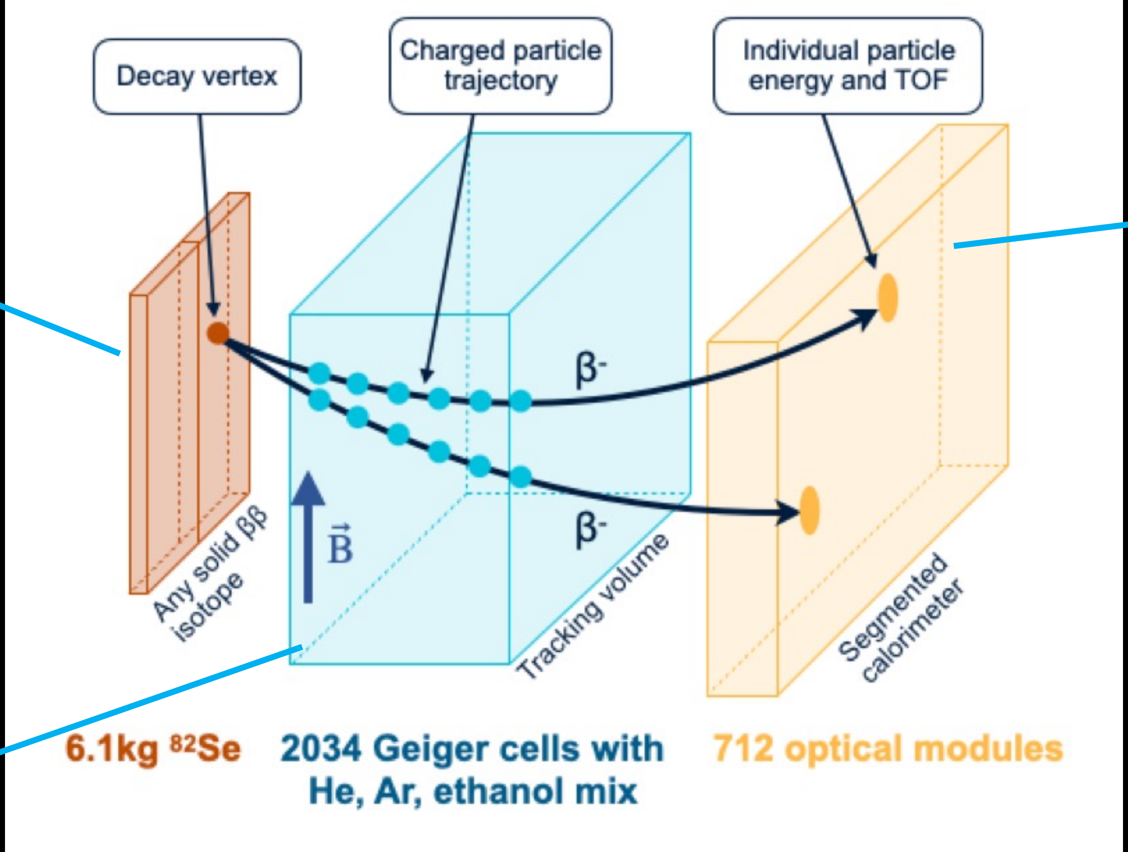
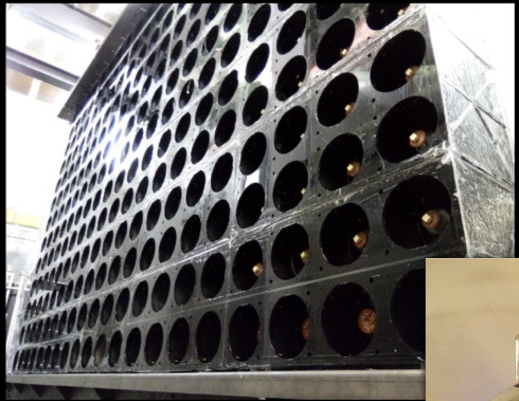
SuperNEMO

- An isotope agnostic technique to distinguish individual particles, and probe $0\nu\beta\beta$ mechanisms and nuclear effects



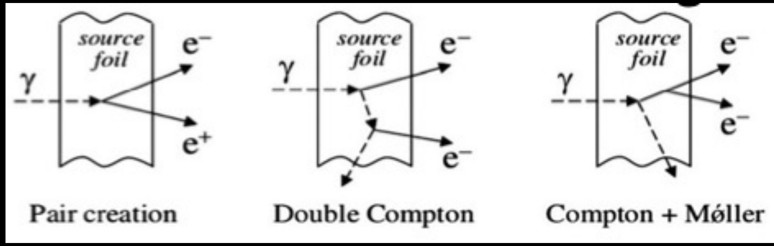


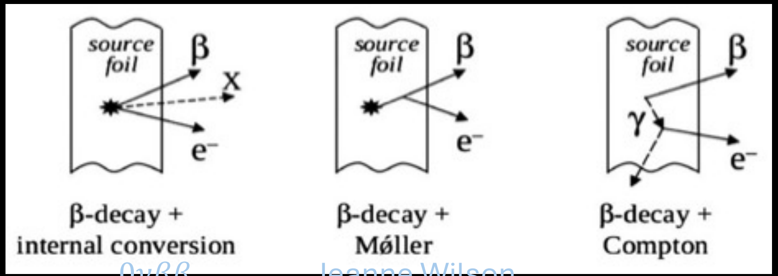


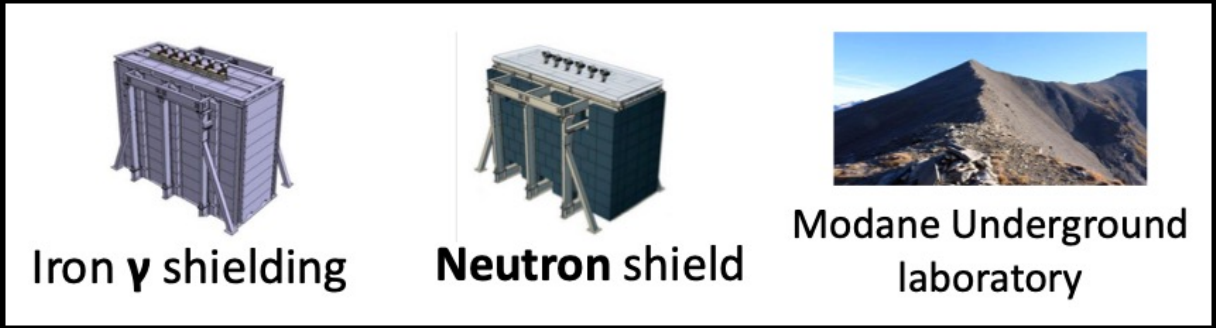
1.8% $\sigma/_E$ at 3MeV

SuperNEMO shielding

- Source ≠detector
- Great care with incoming backgrounds
  - U & Th in lab rock walls → shielding
  - Radon in lab air → anti-radon system







Experiments

- There are many experimental contenders
- Different strengths and weaknesses / challenges

- Require significant investment and international collaboration
- Complementarity important for discovery:
    - Different isotopes
    - Different techniques / locations

Top Trumps

- SNO+
- KamLAND-Zen
- LEGEND
- nEXO
- NEXT-HD
- NEXt-BOLD
- CUORE
- CUPID
- SuperNEMO
- AMORE
- PANDA-X
- Selena
- EXO-200
- Gerda
- Majorana demonstrator
- NEMO-3

https://tinyurl.com/BBTopTrumps

Name:
Isotope:
Method:
Main challenges:

Q-value / Phase Space:
Mass of Isotope:
Background Index:
Discovery Sensitivity:
Start of Data Taking:
Special Features:

https://tinyurl.com/BBTopTrumps

Summary – lecture 2

- How the rate of $0\nu\beta\beta$ relates to neutrino mass
  - Matrix element uncertainties
- How the rate of $0\nu\beta\beta$ relates to experiment design
  - Choice of isotope, mass
- Experimental challenges
  - Backgrounds! Backgrounds! Backgrounds !
- Experiment Examples
  - Liquid scintillator: isotope loading, reconstruction, background rejection
  - HPGe: PSD and energy resolution, readout
  - Xe TPCs: Track information, daughter tagging
  - Bolometers: cryogenics, surface backgrounds
  - Separate source, tracking + calorimetry: shielding and radon suppression