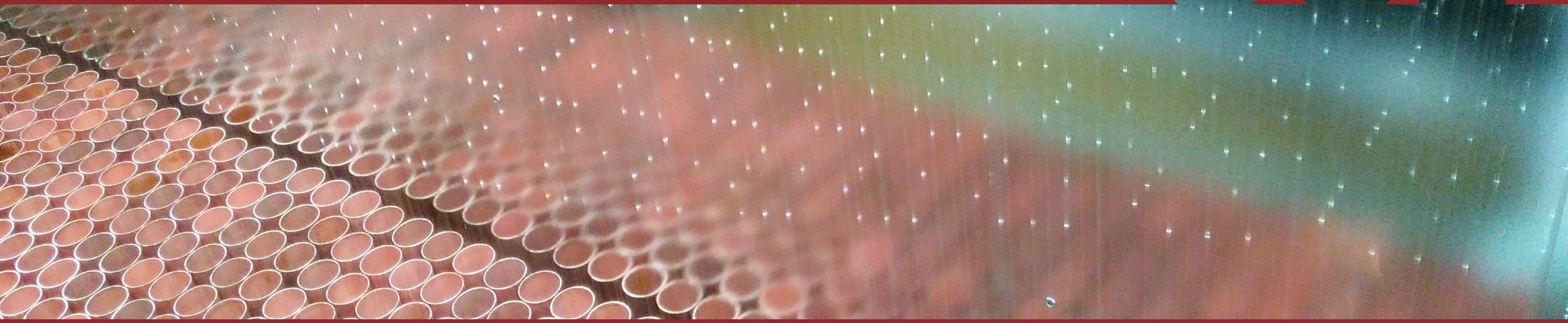


SuperNEMO and the mystery of matter

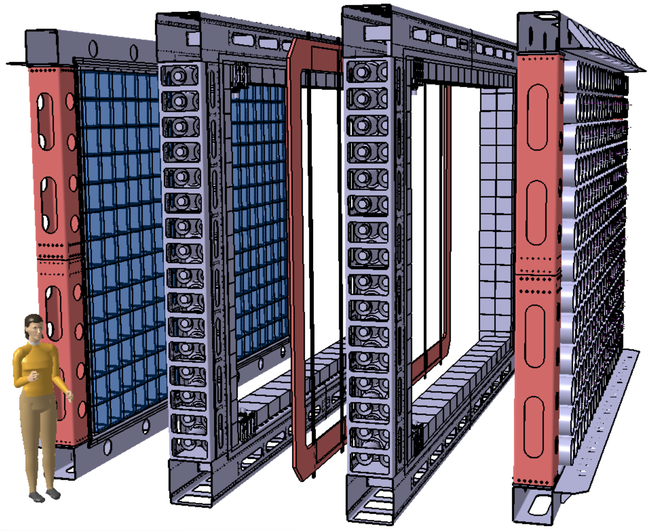
Cheryl Patrick, University College London

Fermilab neutrino seminar, April 24, 2018

supernemo collaboration

SuperNEMO in one slide

The SuperNEMO demonstrator…



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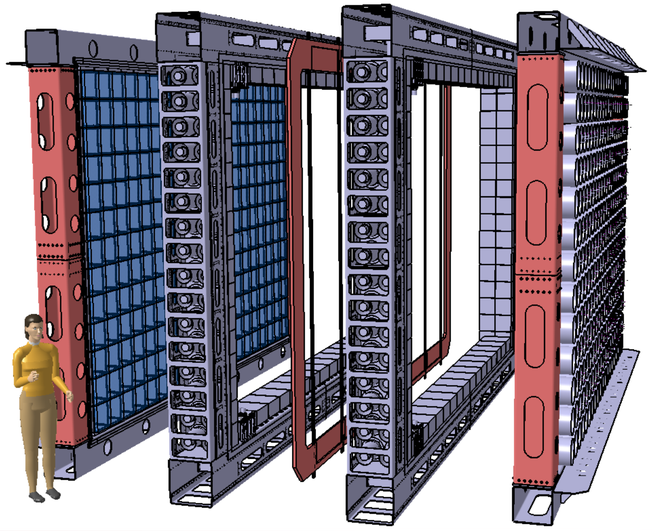

…at the LSM underground lab in France…

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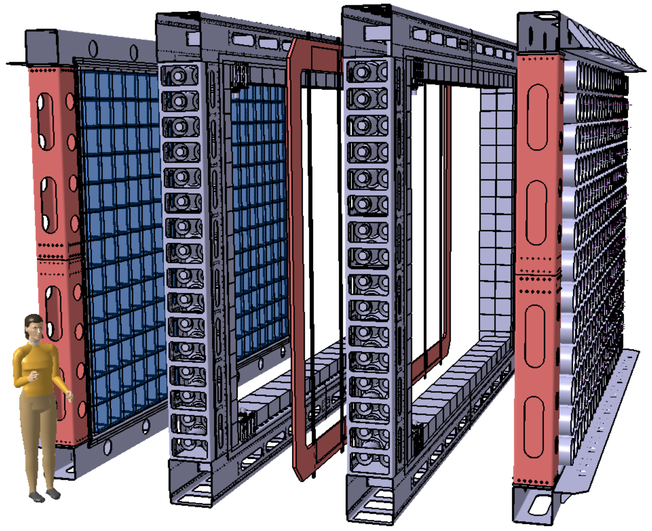

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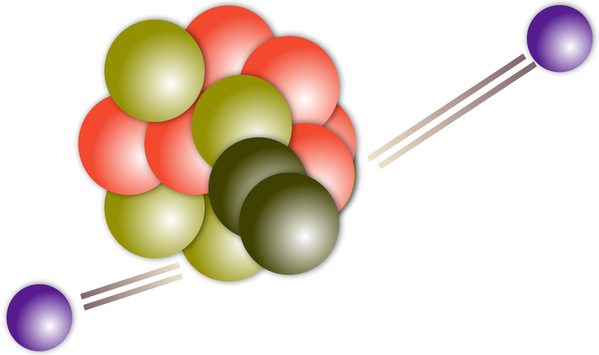

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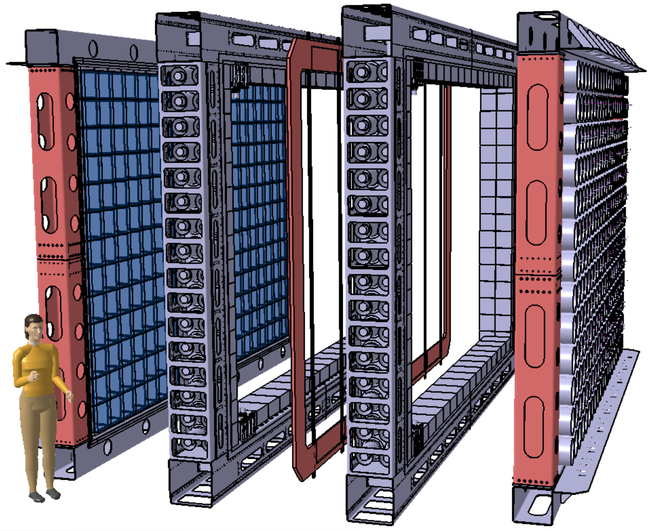

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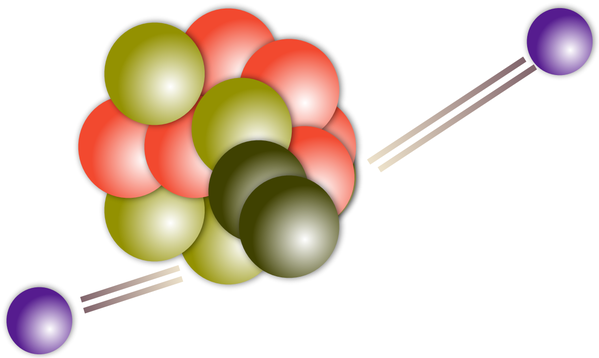
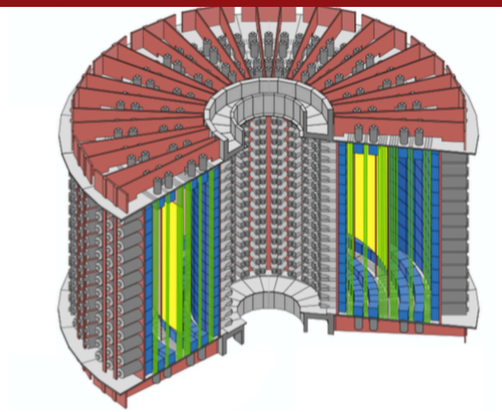


Building on the success of NEMO-3…



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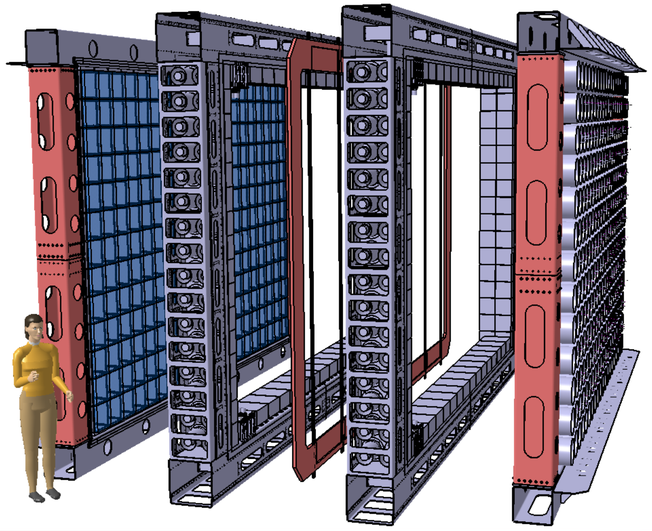

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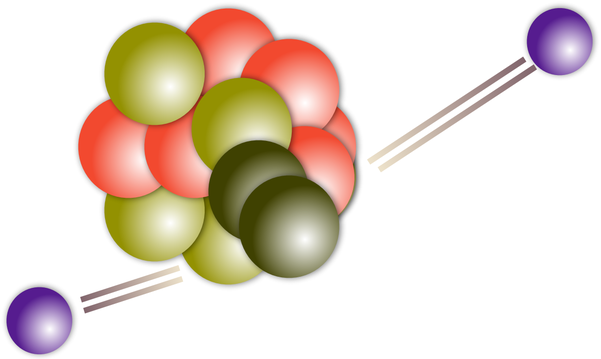

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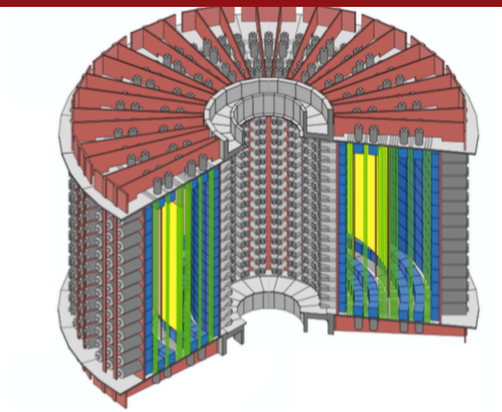

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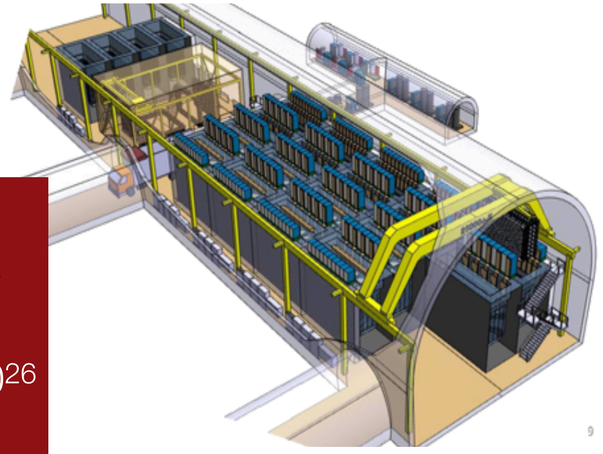

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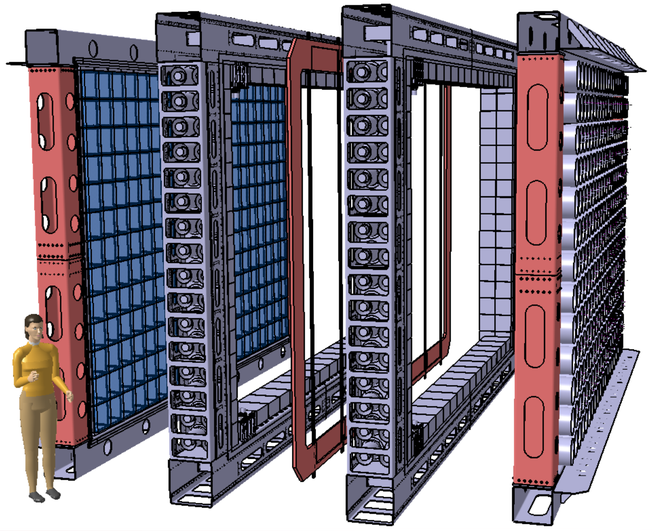

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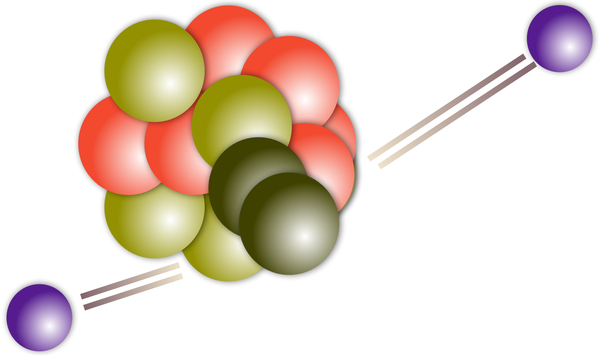

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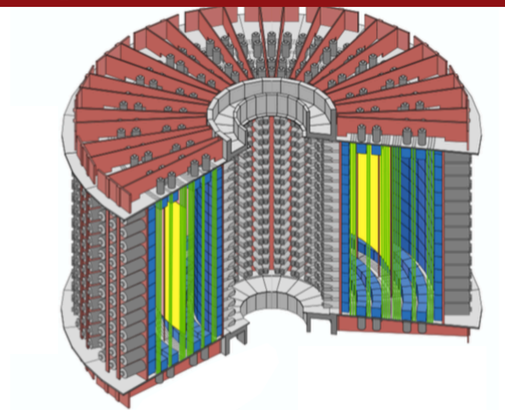

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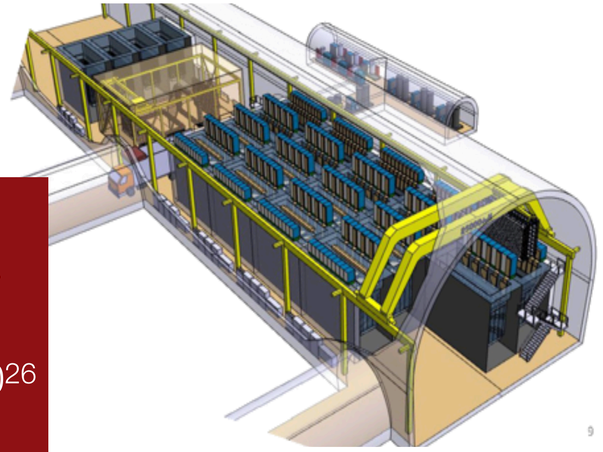


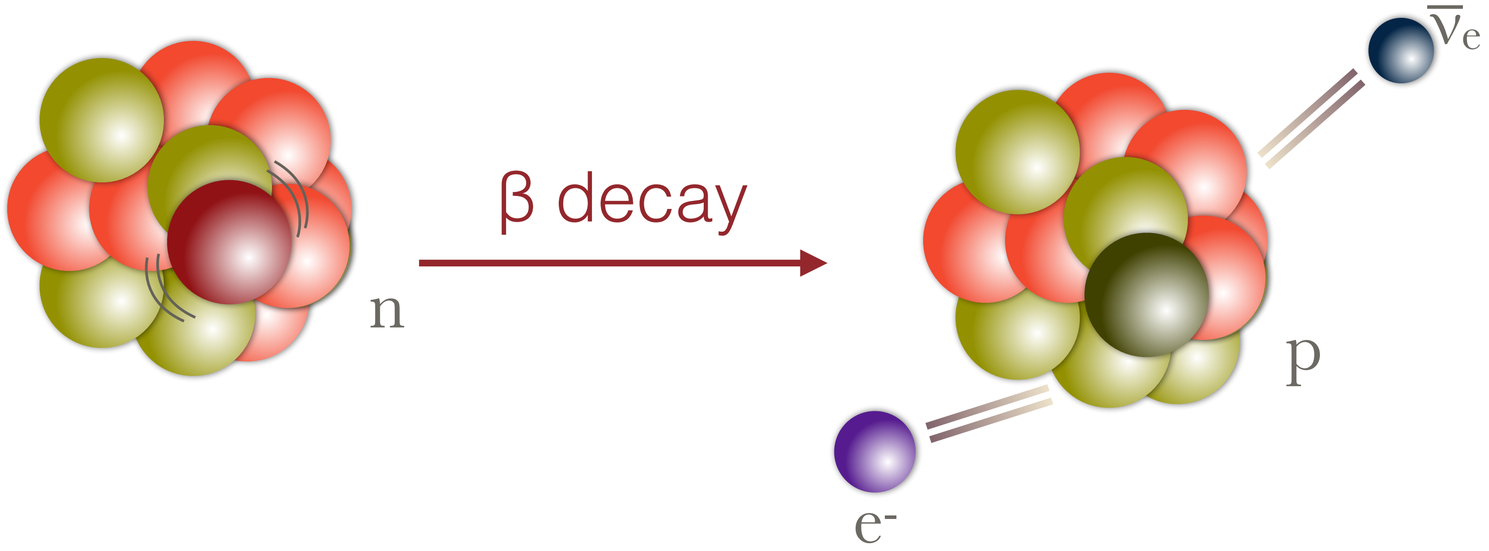
…and expects first data this year

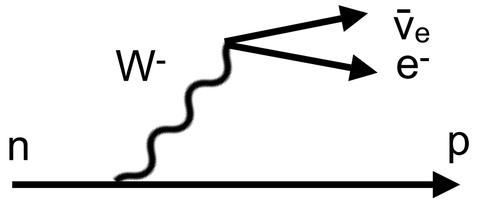
Our collaboration

Collaboration meeting last week, in Paris

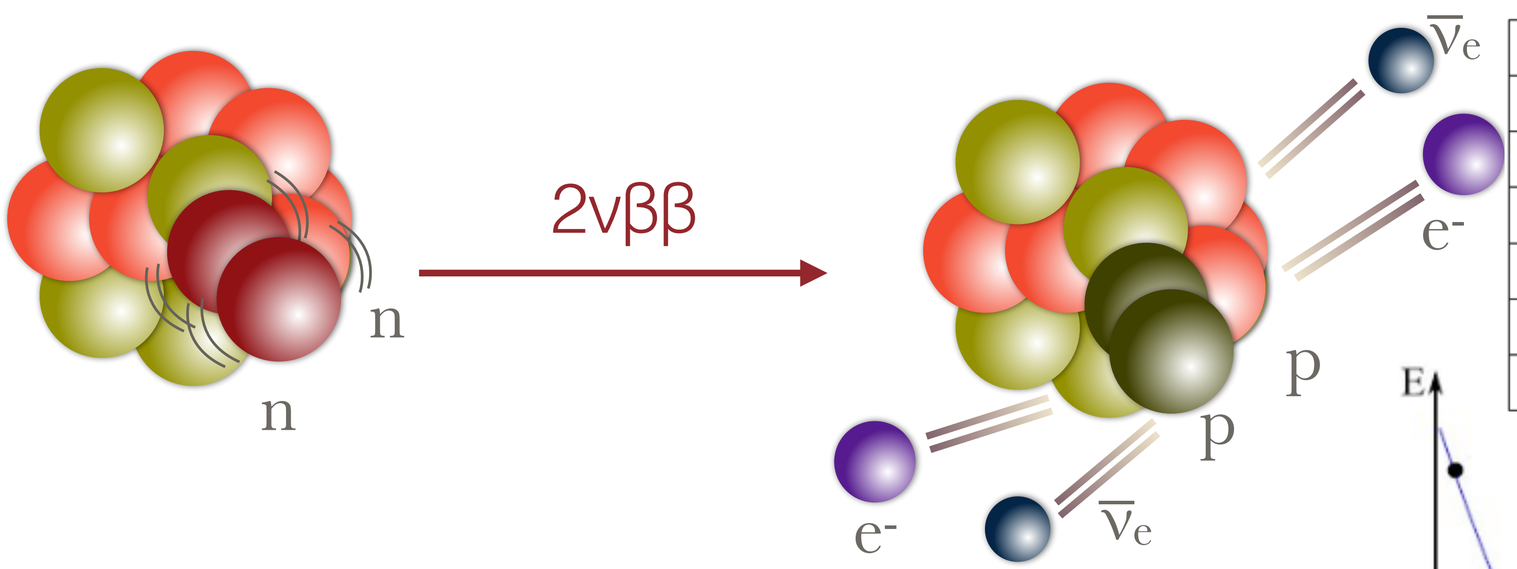
http://supernemo.org

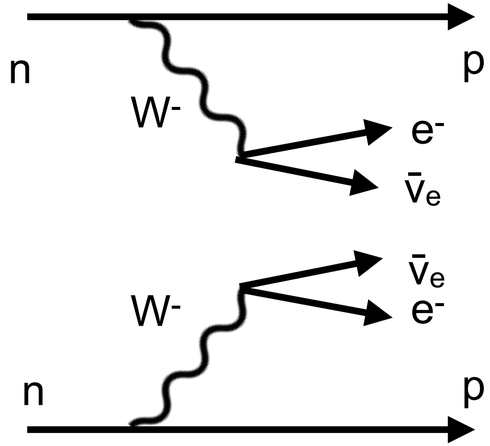
beta decay





double-beta decay

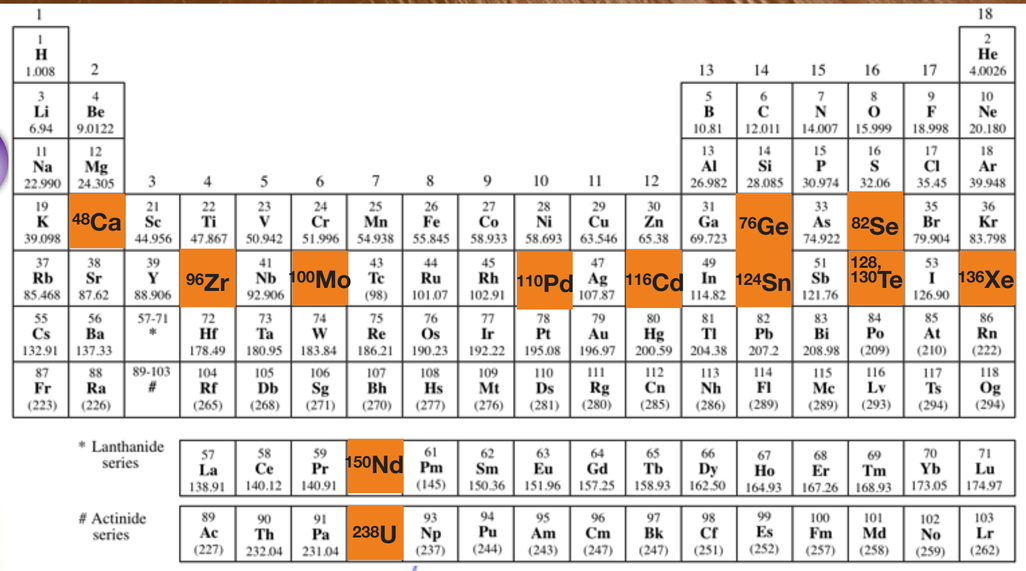




Lepton number conserved

$\Delta L = 0$

$T_{1/2} \sim 10^{20}$ years



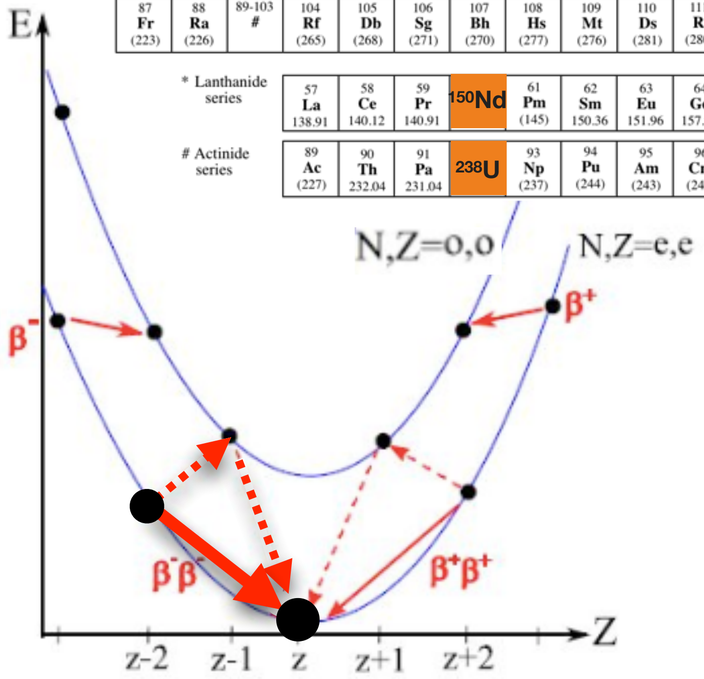
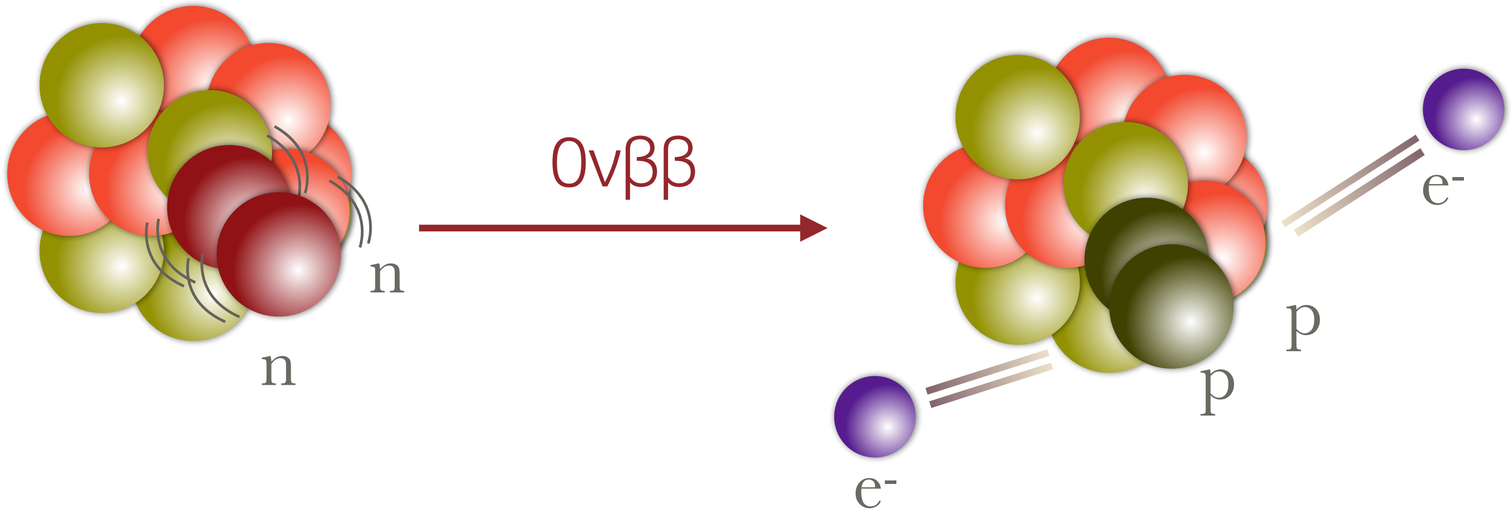
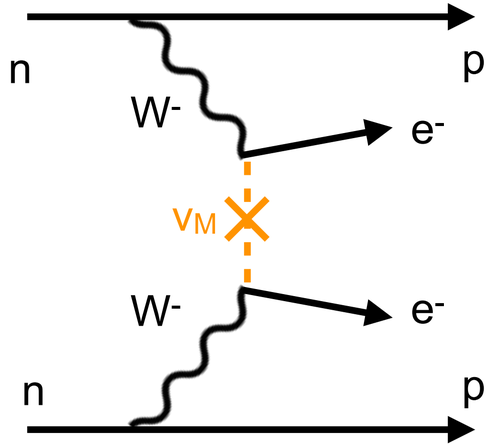


Diagram - E. Falk

Neutrinoless double-beta decay





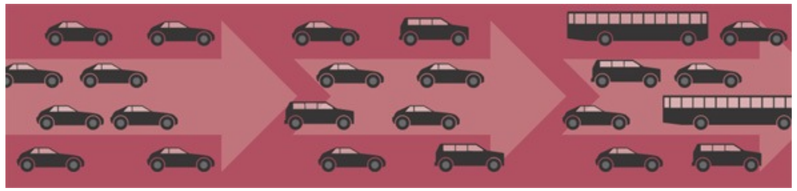
Lepton number violated

$\Delta L = 2$

$T_{1/2} > 10^{26}$ years

Neutrino must be Majorana ($\nu=\bar{\nu}$)

Why do we think this might happen?



Neutrinos **oscillate** between flavour states as they travel

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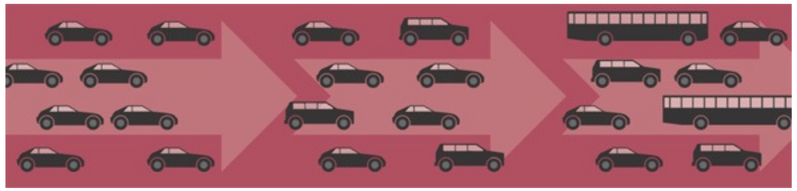

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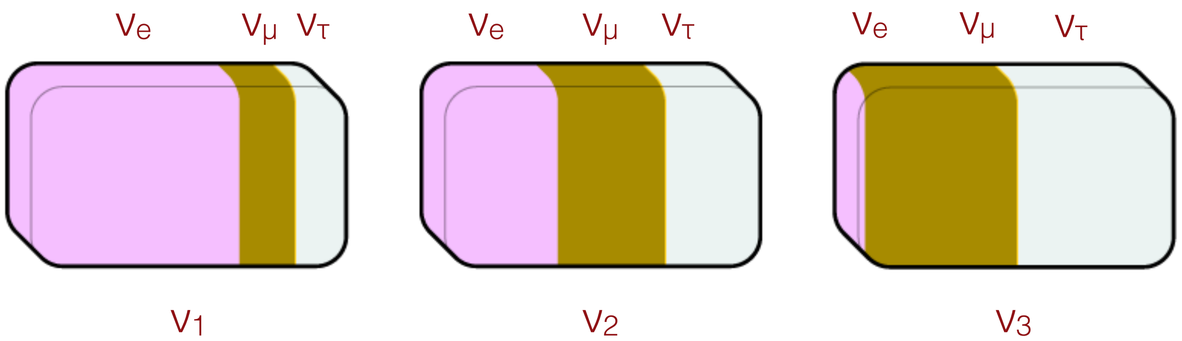
Quantum diaries



The flavour states are a superposition of **mass** states with different wavelengths

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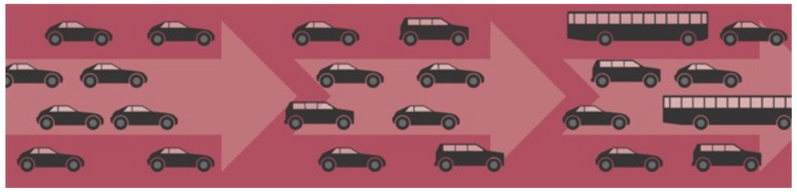

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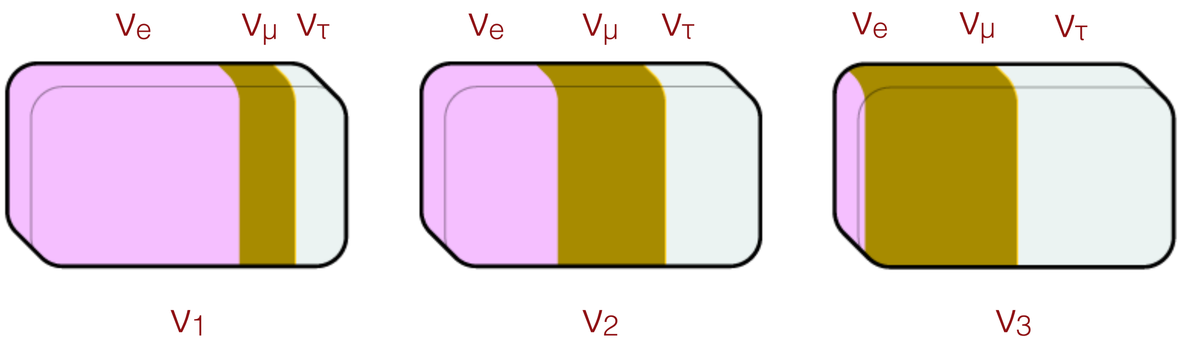
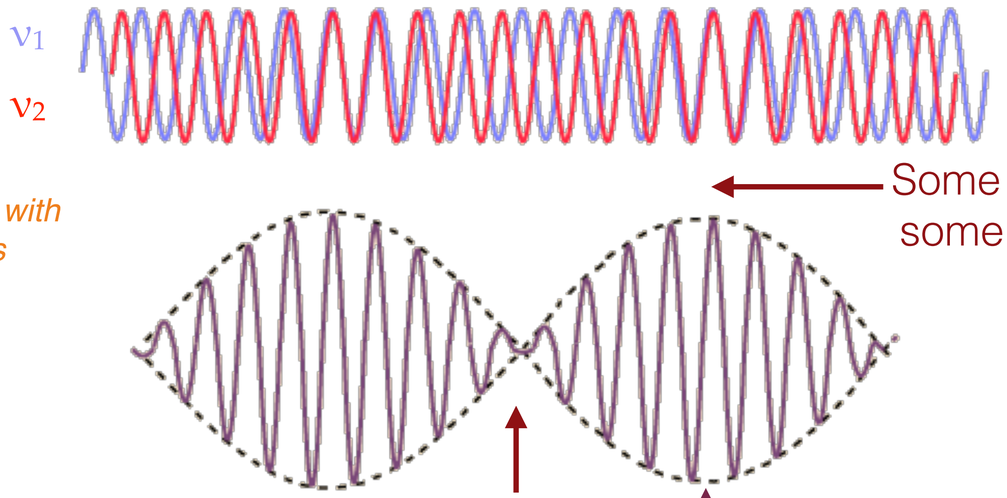




Simplified version with just 2 flavours

$$|\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle$$

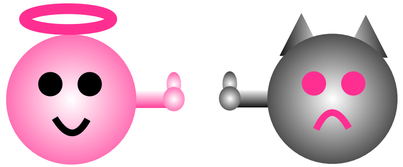
The flavour states are a superposition of **mass** states with different wavelengths

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

PMNS matrix

How do neutrinos get their mass?

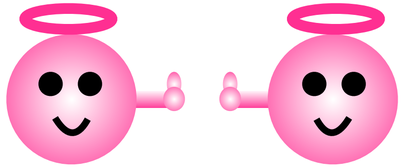
Dirac



$\nu \neq \bar{\nu}$

$$\mathcal{L}_D = -m_D \overline{\nu_R^0} \nu_L^0 + \text{ h. c.}$$

Majorana



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$$\mathcal{L}_{m_L} = -\frac{m_L}{2} \overline{(\nu_L^0)^c} \nu_L^0 + \text{ h. c.}$$

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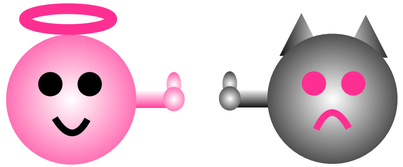

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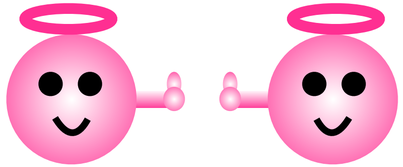
- Requires implausibly weak coupling to give plausible neutrino mass
- Requires a right-handed neutrino
- … but if that existed, Majorana coupling would no longer be outside standard model…
- … so they could BOTH exist…
- … but if they did, neutrinos would be Majorana particles!

Majorana



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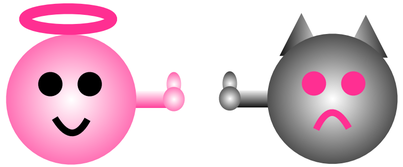

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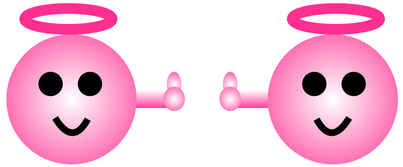

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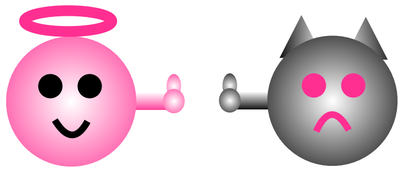
- Neutrino and antineutrino differ only in helicity
- But that is enough to explain how they appear different
- Gives elegant explanation for light neutrinos via see-saw mechanism
- Allows lepton number violation!

How do neutrinos get their mass?

Dirac



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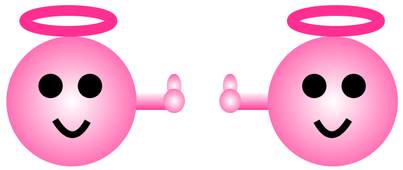
Majorana



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Theorists' choice!

0νββ and neutrino mass

$$0\nu\beta\beta \text{ rate} = \frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{{m_e}^2}$$

Effective neutrino mass

Phase space factor

Nuclear matrix element

0νββ and neutrino mass

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Effective neutrino mass

Phase space factor

Nuclear matrix element

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

PMNS neutrino-mixing matrix

$$\begin{aligned} U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix} \\ &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix} \end{aligned}$$

0νββ and neutrino mass

$$0\nu\beta\beta \text{ rate} = \frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{{m_e}^2}$$

Effective neutrino mass

Phase space factor

Nuclear matrix element

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

Individual neutrino masses

PMNS neutrino-mixing matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

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Effective neutrino mass

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sines and cosines of neutrino mixing angles

PMNS neutrino-mixing matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

0νββ and neutrino mass

$$0\nu\beta\beta \text{ rate} = \frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{{m_e}^2}$$

Effective neutrino mass

Phase space factor

Nuclear matrix element

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

Majorana phases

PMNS neutrino-mixing matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

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$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

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$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

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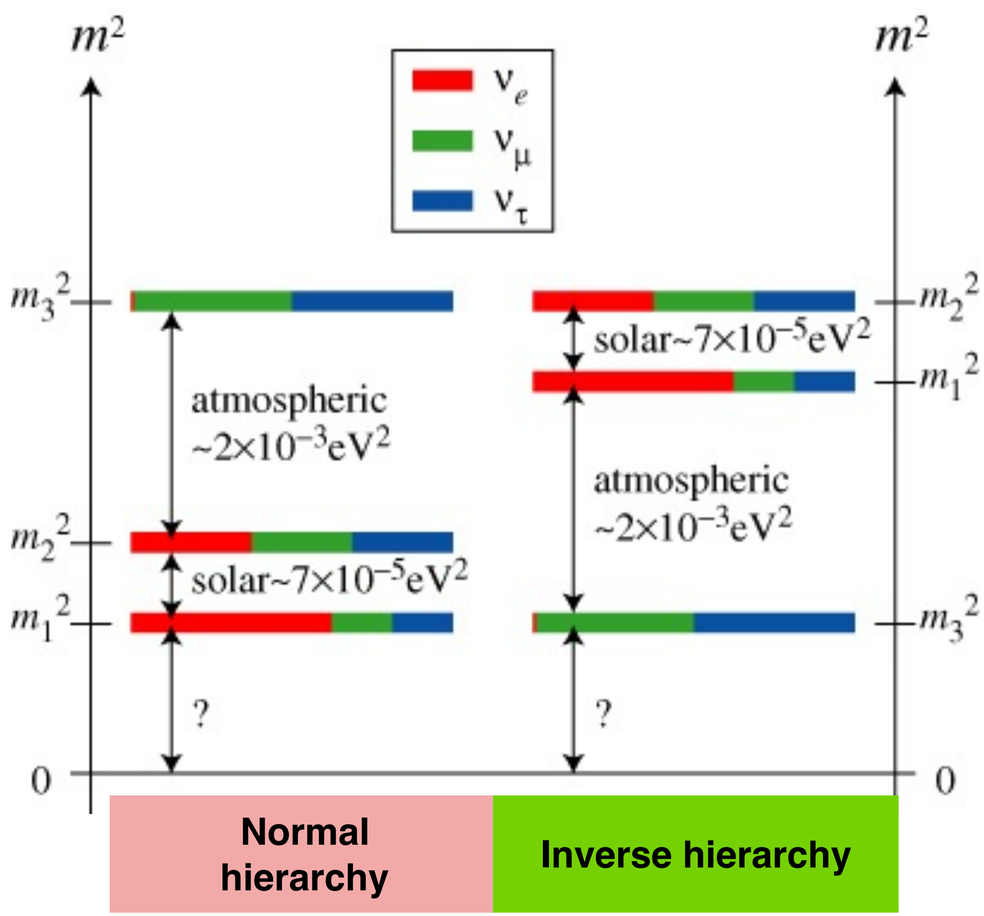
$$|m_{\beta\beta}| = m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\phi_{12}}{2}\right)}$$

If masses >> mass splittings (degenerate regime)

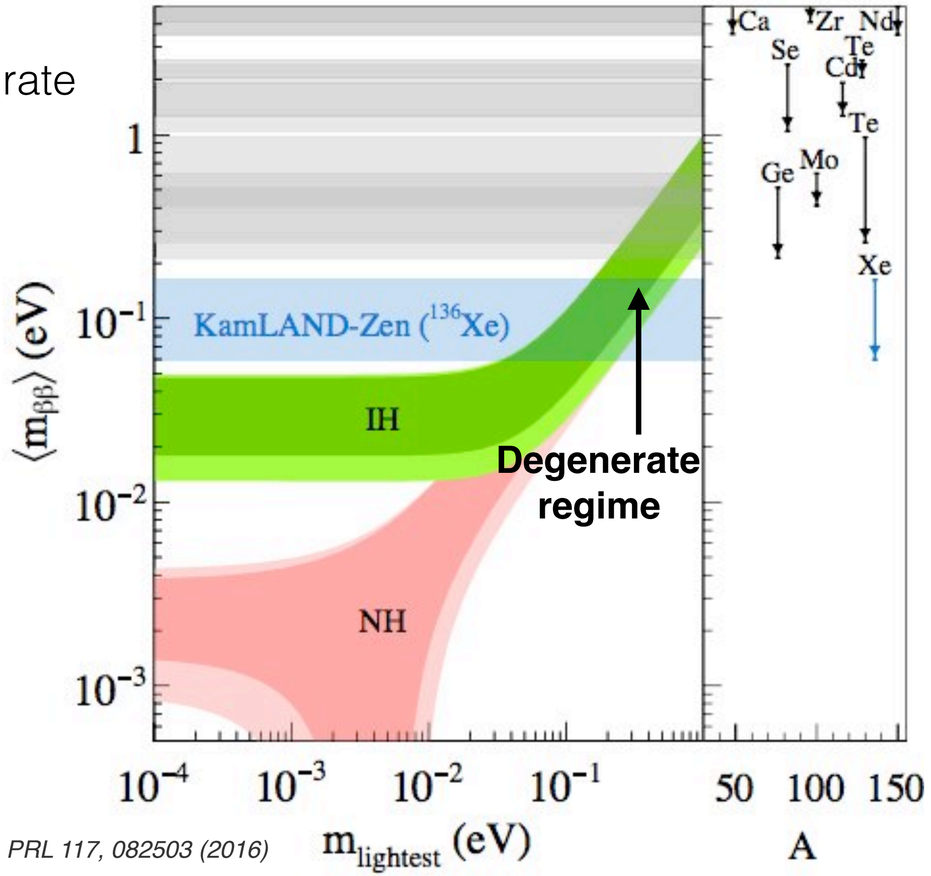
0νββ and mass hierarchy

Oscillation experiments (at first order) tell us the **mass-squared** splitting

$$P(\nu_{l_a} \to \nu_{l_b}, x) = \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta M^2 (eV^2) x(\mathrm{km})}{p_\nu(\mathrm{GeV})}\right)$$

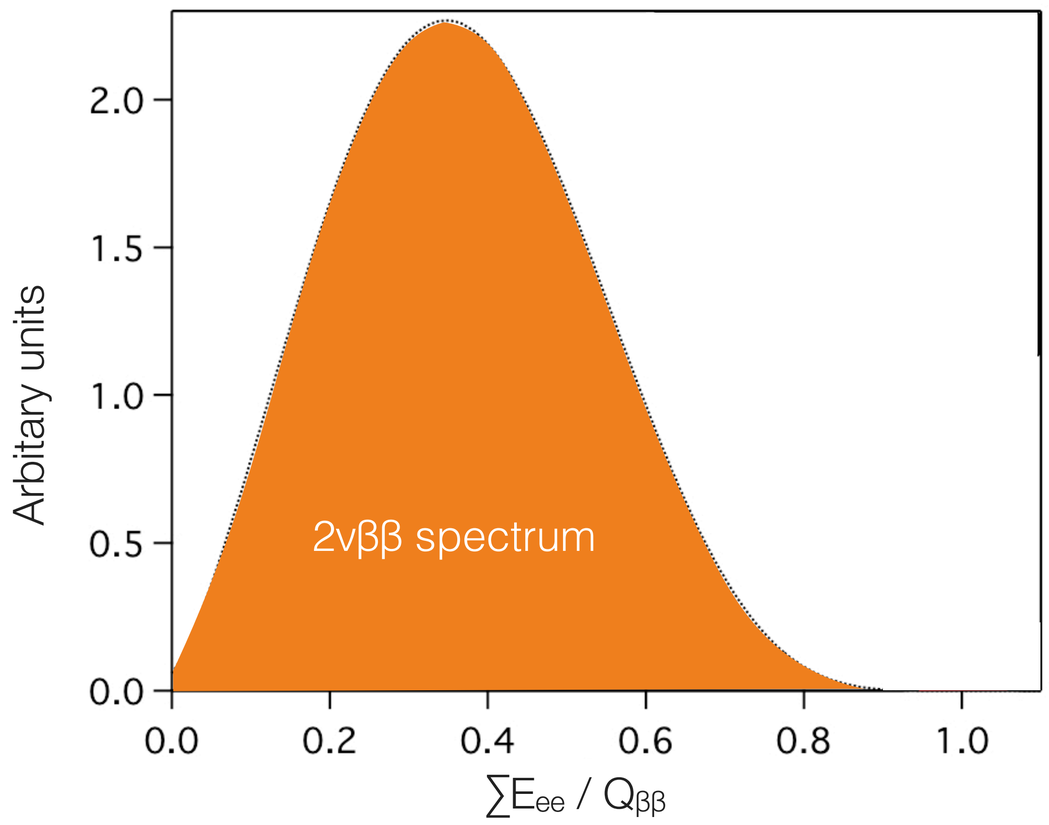


The sign of the splitting, or **hierarchy**, affects 0νββ rate



PRL 117, 082503 (2016)

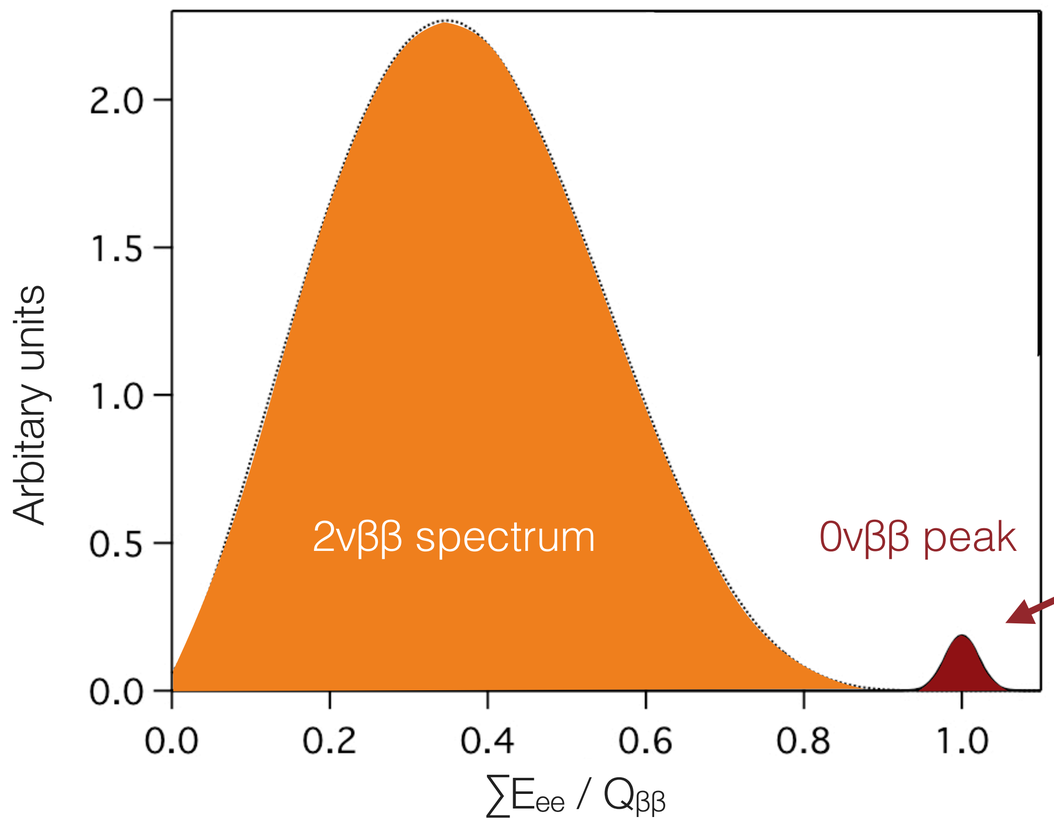
So how does this look?



Summed 2-electron energy as fraction of ββ decay energy

Some fraction of energy goes to neutrinos

So how does this look?



No neutrinos means all energy goes to electrons (smeared in reconstruction)

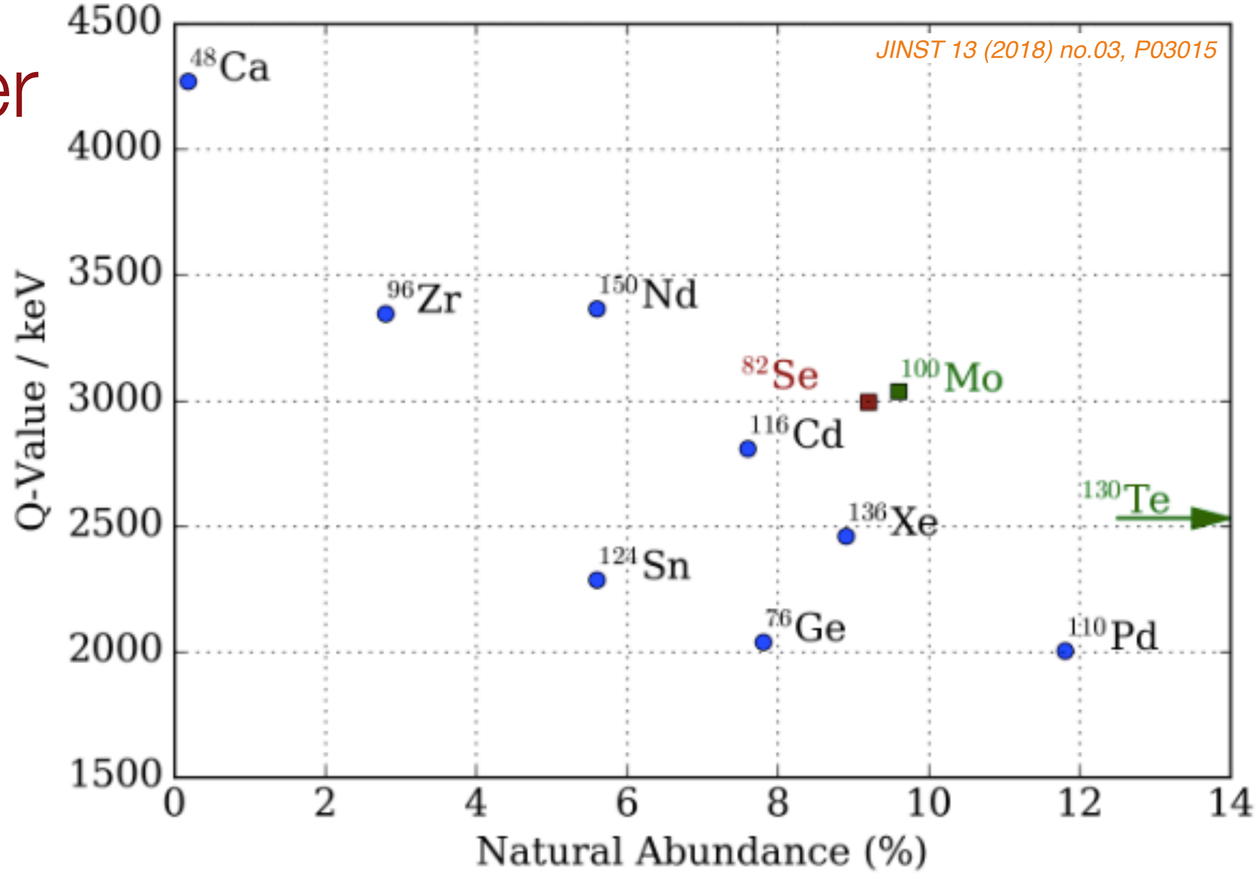
Summed 2-electron energy as fraction of ββ decay energy

Choosing an isotope

- **“Short” half-life**

Better

$T_{1/2}^{0\nu} \propto Q^{-5}$



Choosing an isotope

- "Short" half-life
- **Lots of isotope**

ββ isotopic abundance

mass of source material

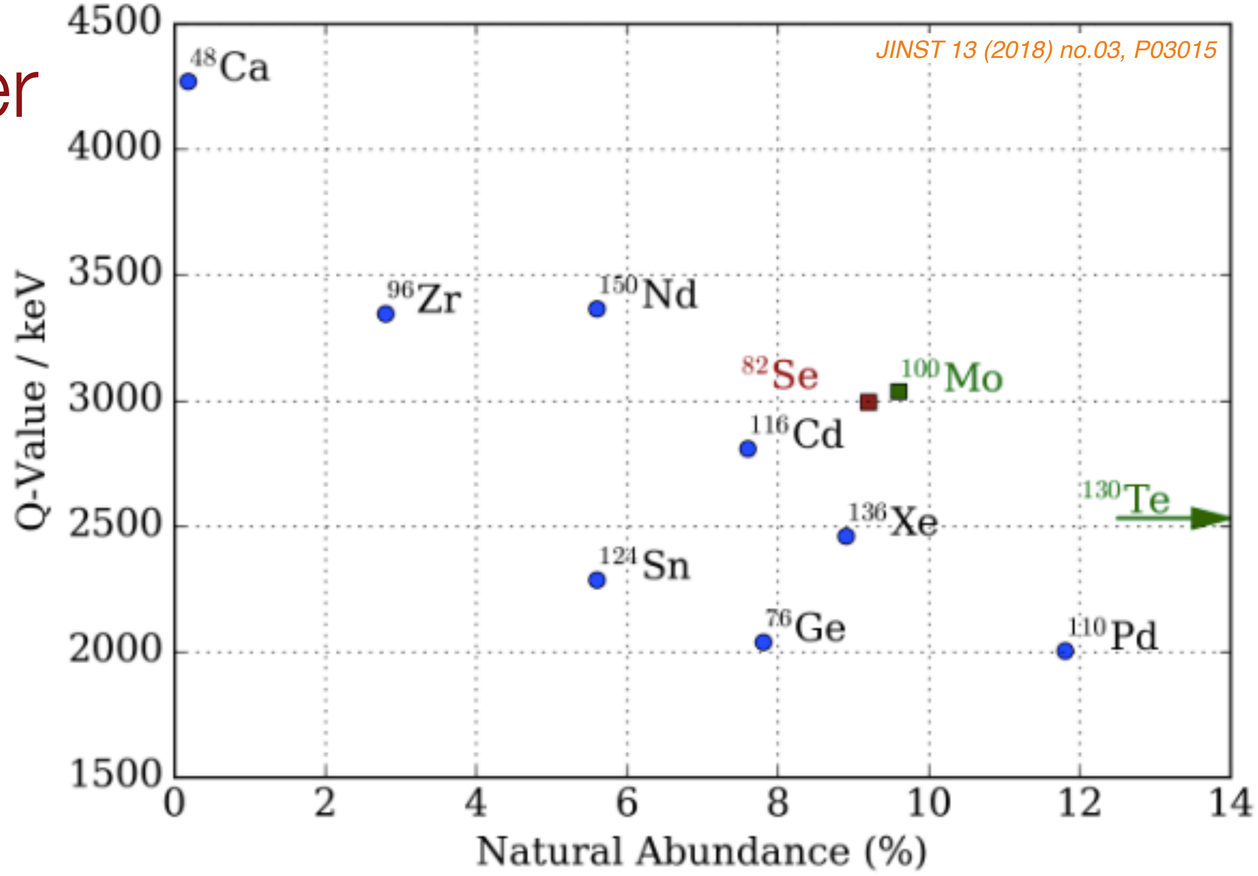
$T_{1/2}^{0\nu}$ limit ∝ amεt

run time

efficiency

(if no backgrounds)

Better



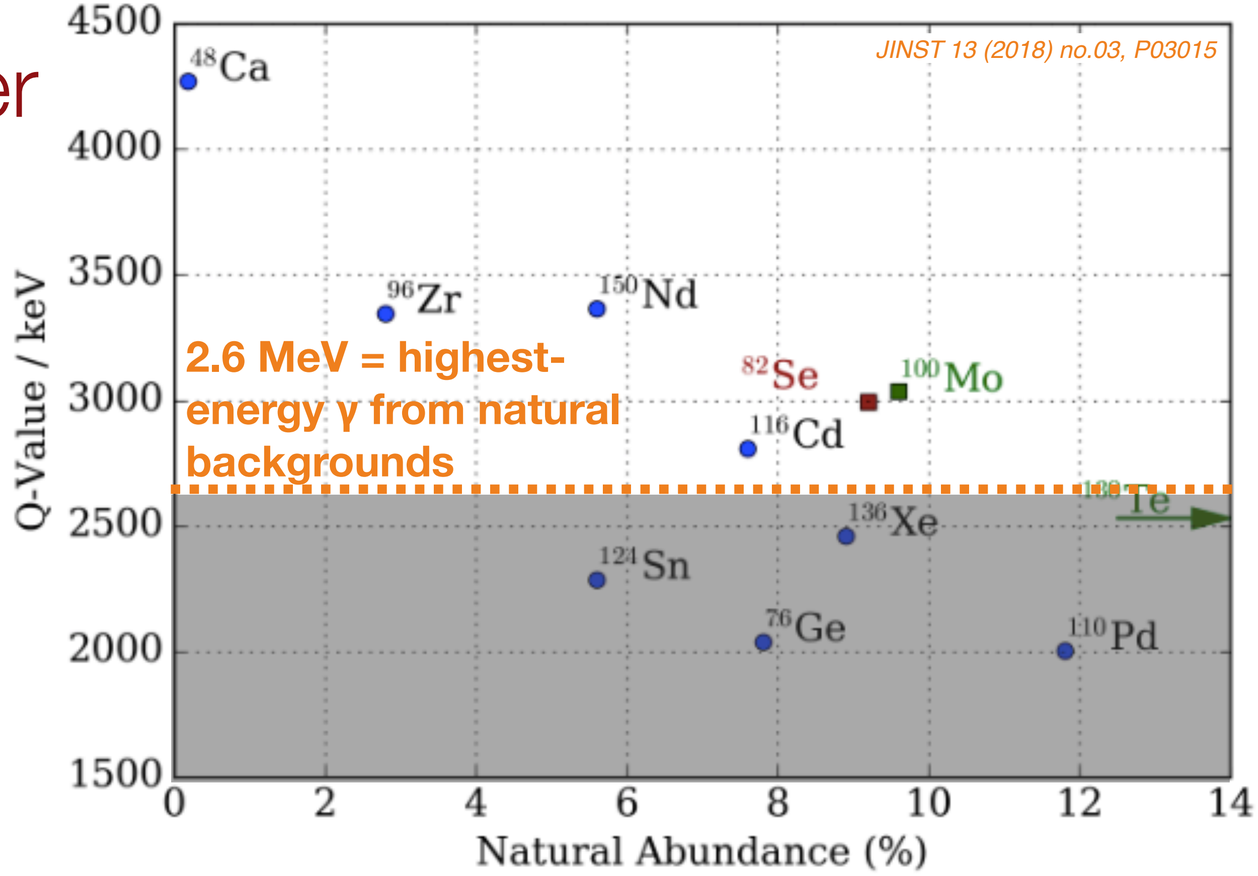
Better

Choosing an isotope

- "Short" half-life
- Lots of isotope
- **Low backgrounds**

$$T_{1/2}^{0\nu} \text{ limit} \propto a\epsilon\sqrt{\frac{mt}{b\Delta E}}$$

Better



Better

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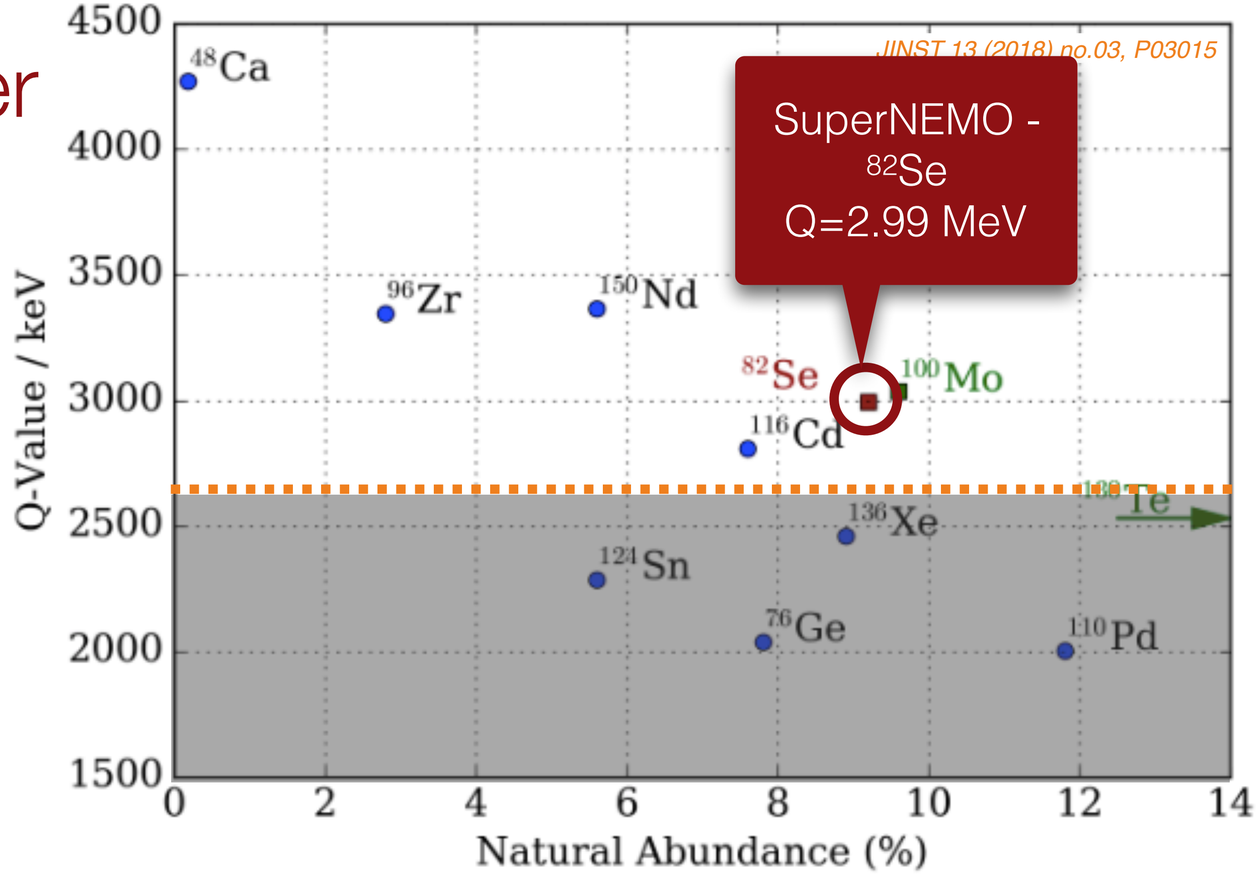

Better

Choosing an isotope

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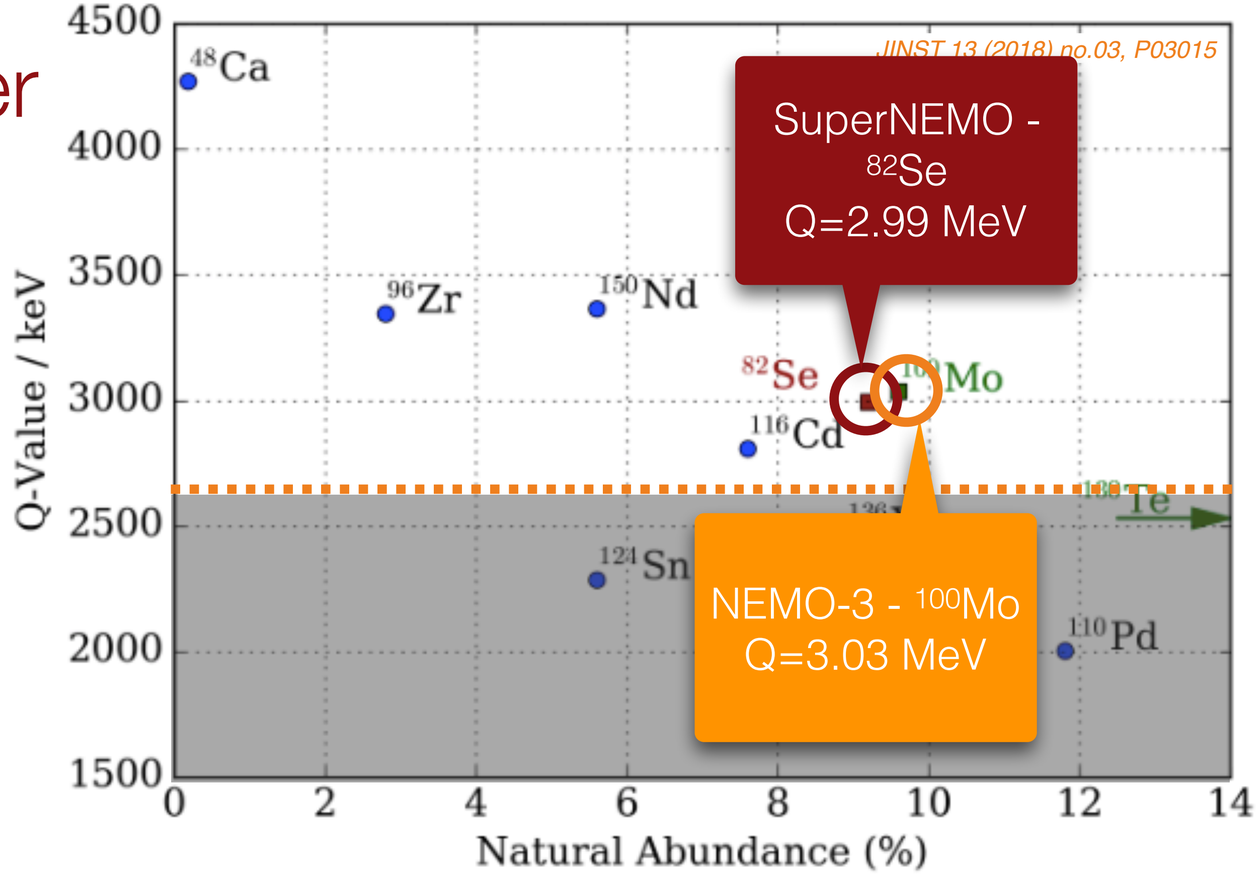
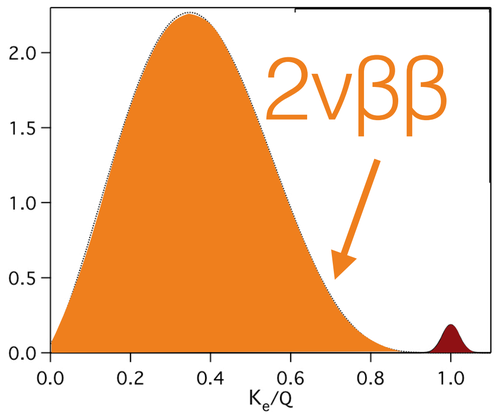


Better

Backgrounds to 0νββ

2νββ

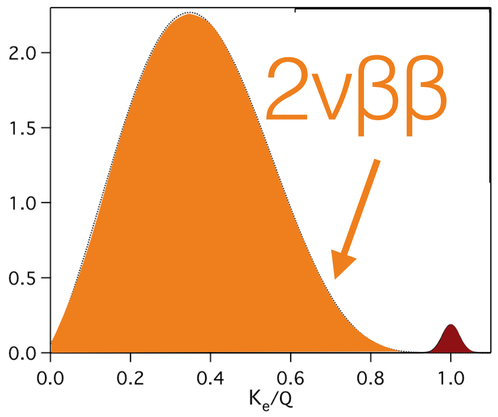


Irreducible background

Need good energy resolution

Backgrounds to 0νββ

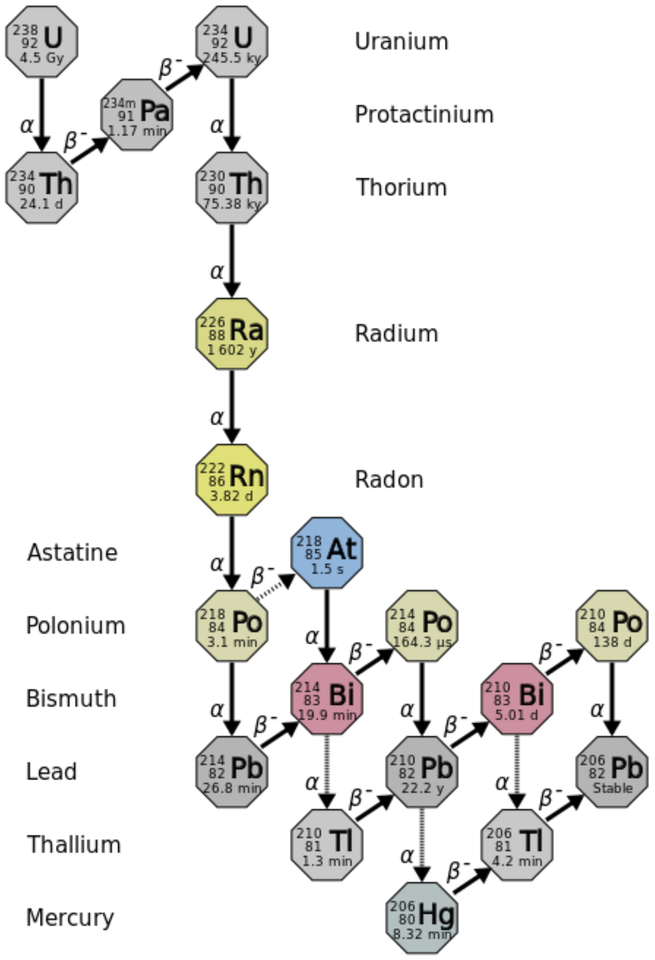
2νββ

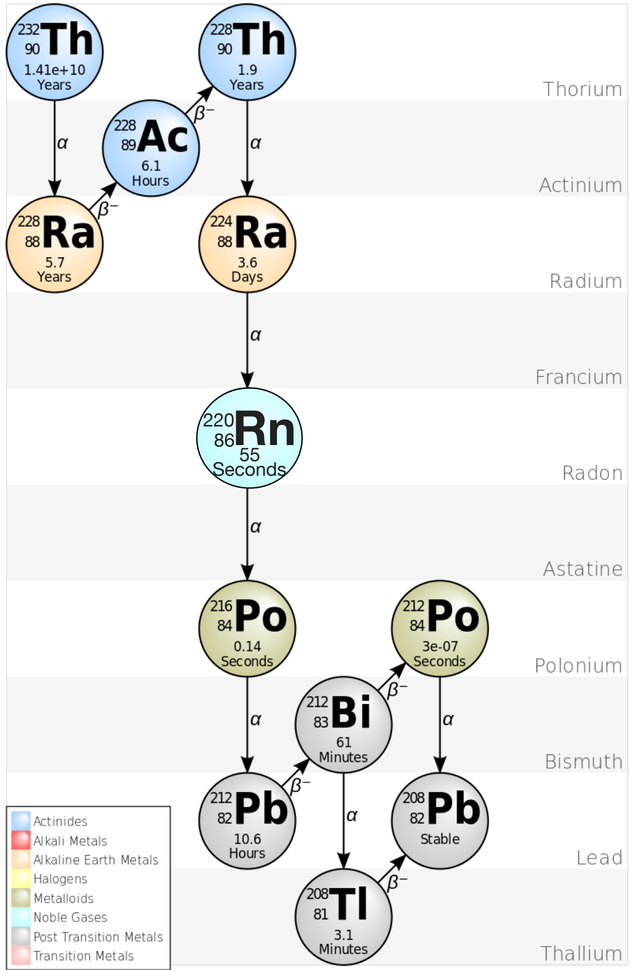


Irreducible background

Need good energy resolution

Natural radiation

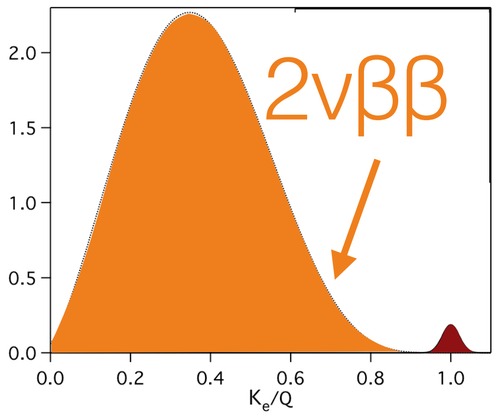




Thorium: By http://commons.wikimedia.org/wiki/User:BatesIsBack - http://commons.wikimedia.org/wiki/File:Decay_Chain_of_Thorium.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16983885
Uranium: Licensed under the Creative Commons Attribution 3.0 Unported license, by wikipedia user Tosaka https://commons.wikimedia.org/wiki/File:Decay_chain(4n%2B2,_Uranium_series).PNG

Backgrounds to 0νββ

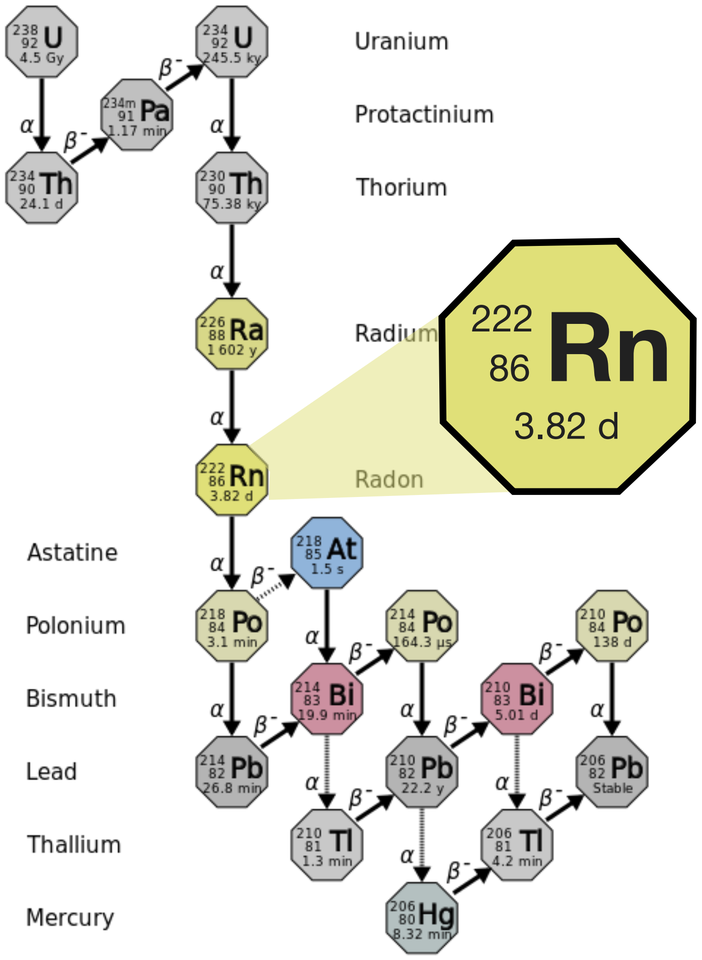
2νββ

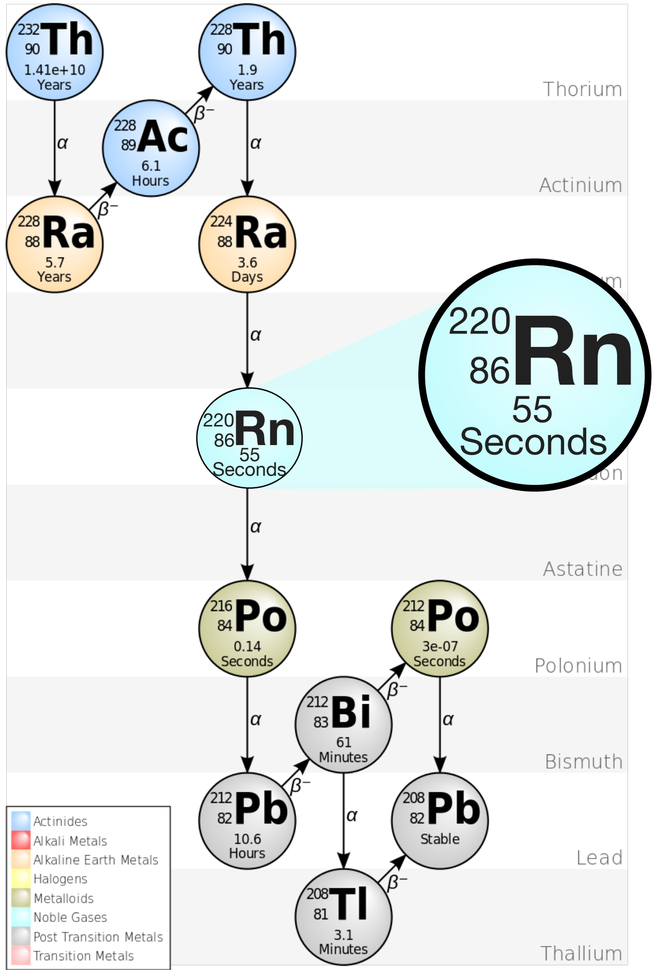


Irreducible background

Need good energy resolution

Natural radiation





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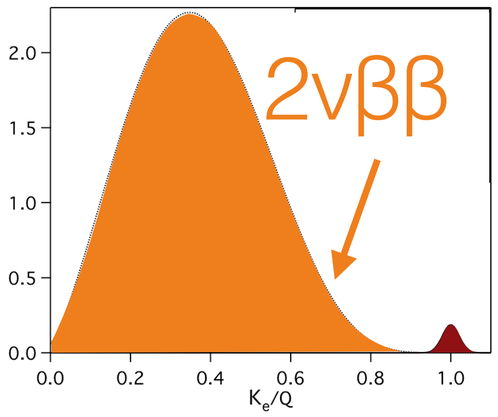
Uranium: Licensed under the Creative Commons Attribution 3.0 Unported license, by wikipedia user Tosaka https://commons.wikimedia.org/wiki/File:Decay_chain(4n%2B2,_Uranium_series).PNG

Backgrounds to 0νββ

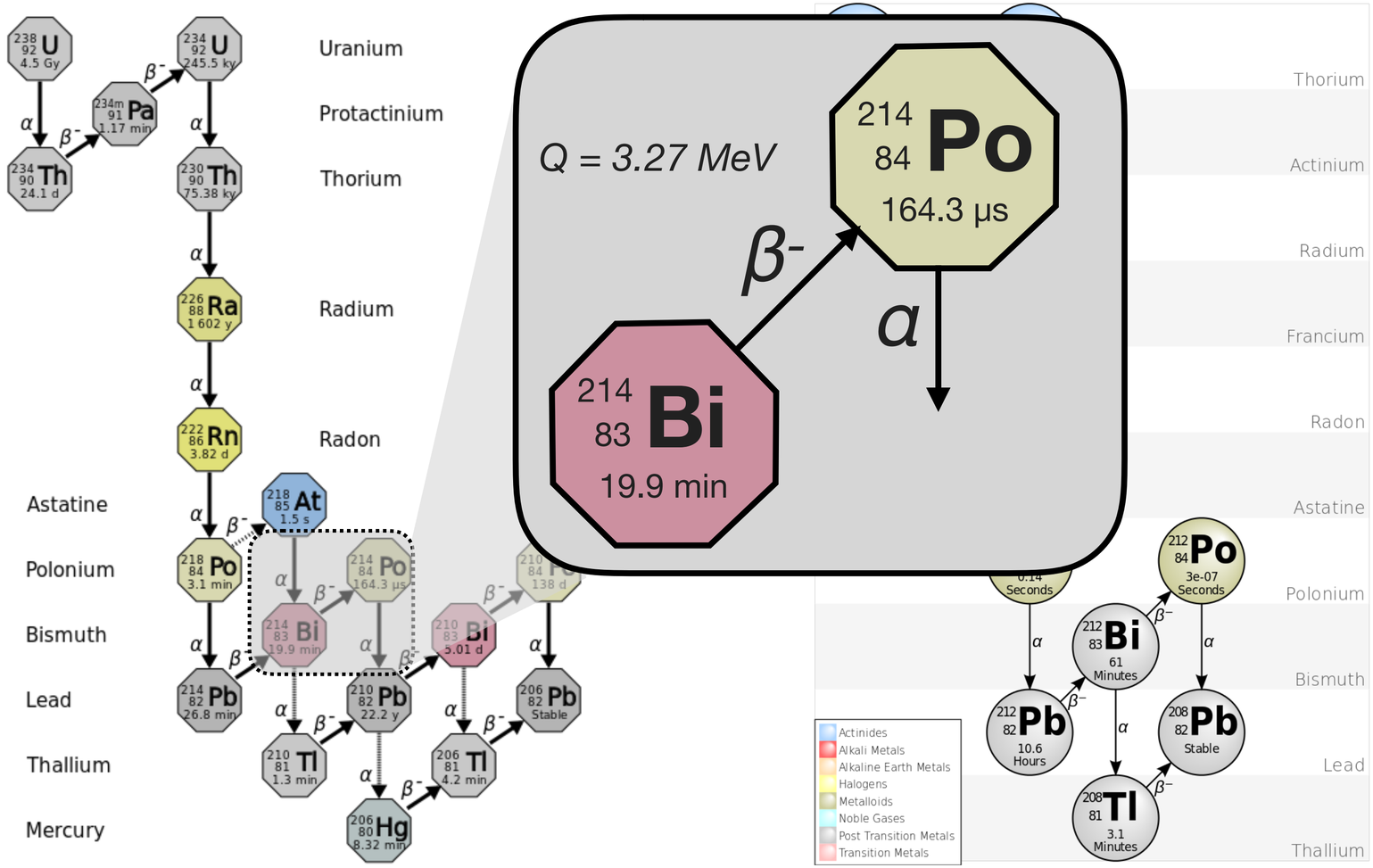
2νββ



Irreducible background

Need good energy resolution

Natural radiation



Thorium: By http://commons.wikimedia.org/wiki/User:BatesIsBack - http://commons.wikimedia.org/wiki/File:Decay_Chain_of_Thorium.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16983885
Uranium: Licensed under the Creative Commons Attribution 3.0 Unported license, by wikipedia user Tosaka https://commons.wikimedia.org/wiki/File:Decay_chain(4n%2B2,_Uranium_series).PNG

Backgrounds to 0νββ

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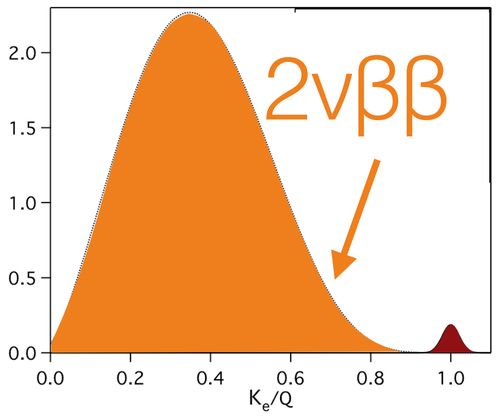

Irreducible background

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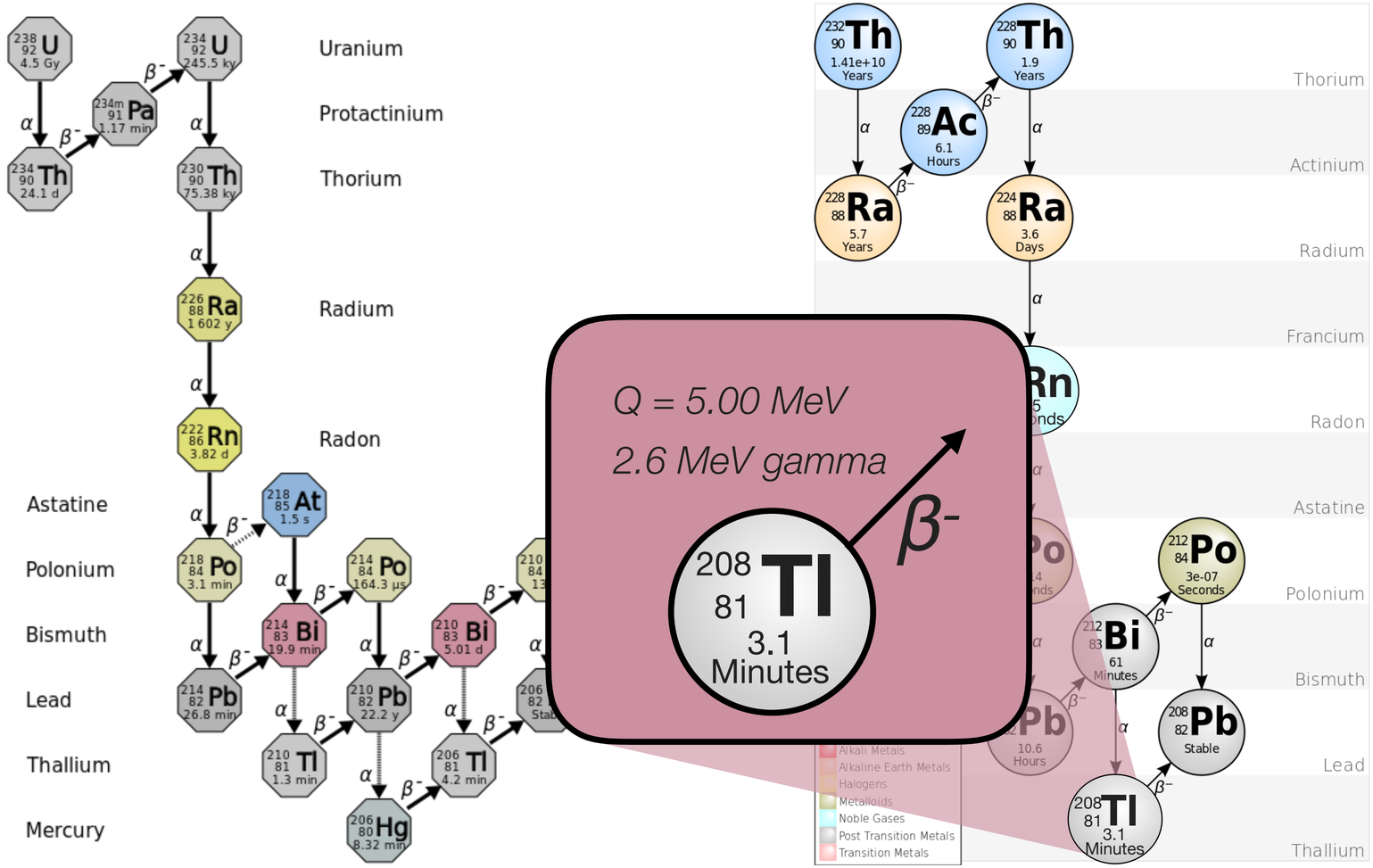

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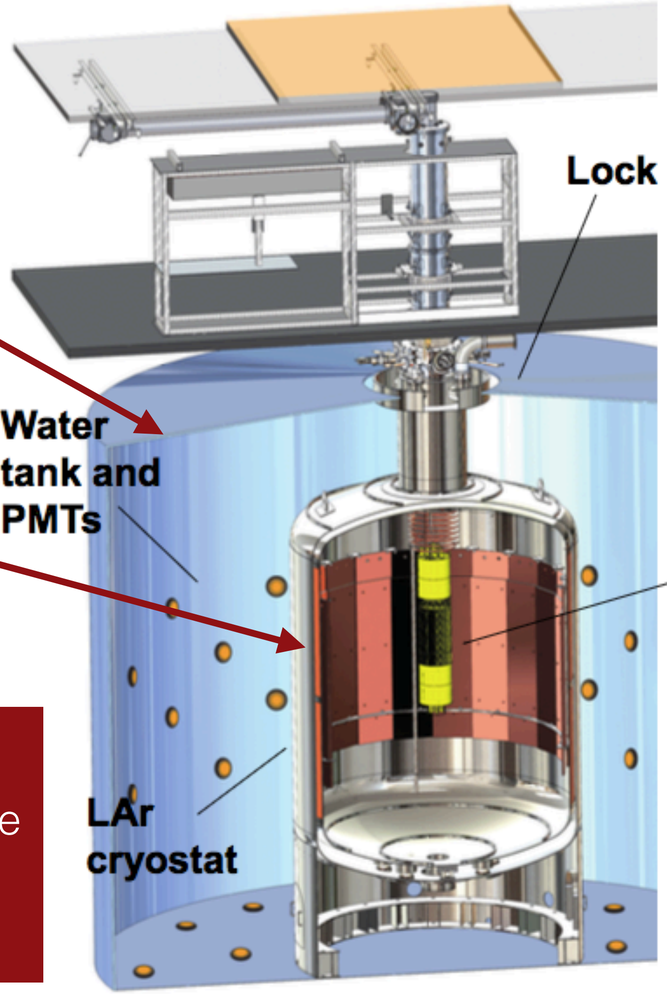
Uranium: Licensed under the Creative Commons Attribution 3.0 Unported license, by wikipedia user Tosaka https://commons.wikimedia.org/wiki/File:Decay_chain(4n%2B2,_Uranium_series).PNG

GERDA: HPGe detector at Gran Sasso, Italy

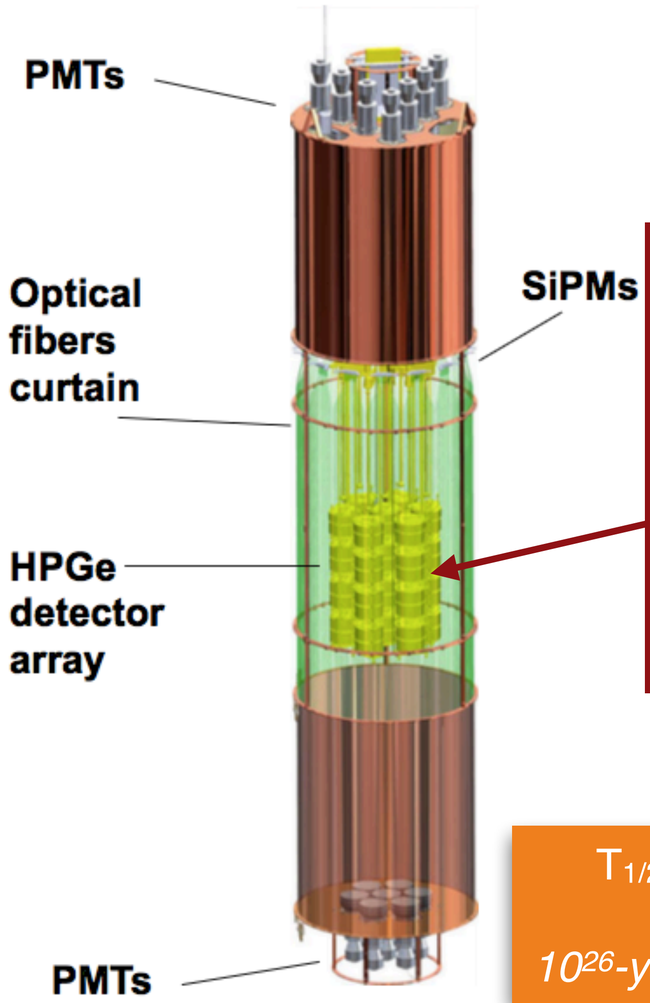
Water+PMTs add Cherenkov veto

Detectors in LAr cryostat: LAr scintillation as veto

Other background suppression: pulse-shape discrimination, detector anti-coincidence



arXiv: 1710.07776 [nucl-ex]

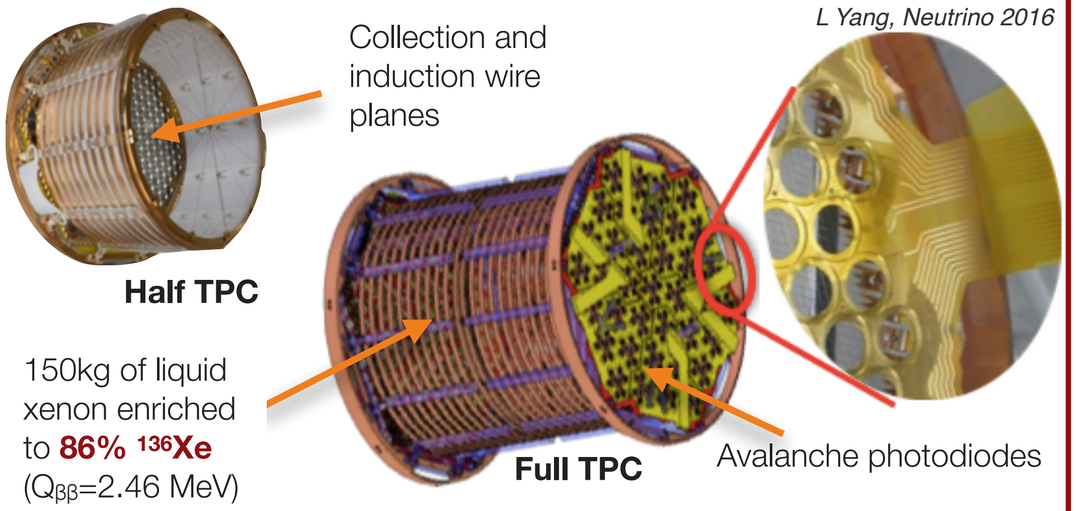


M Agostini, Neutrino 2016

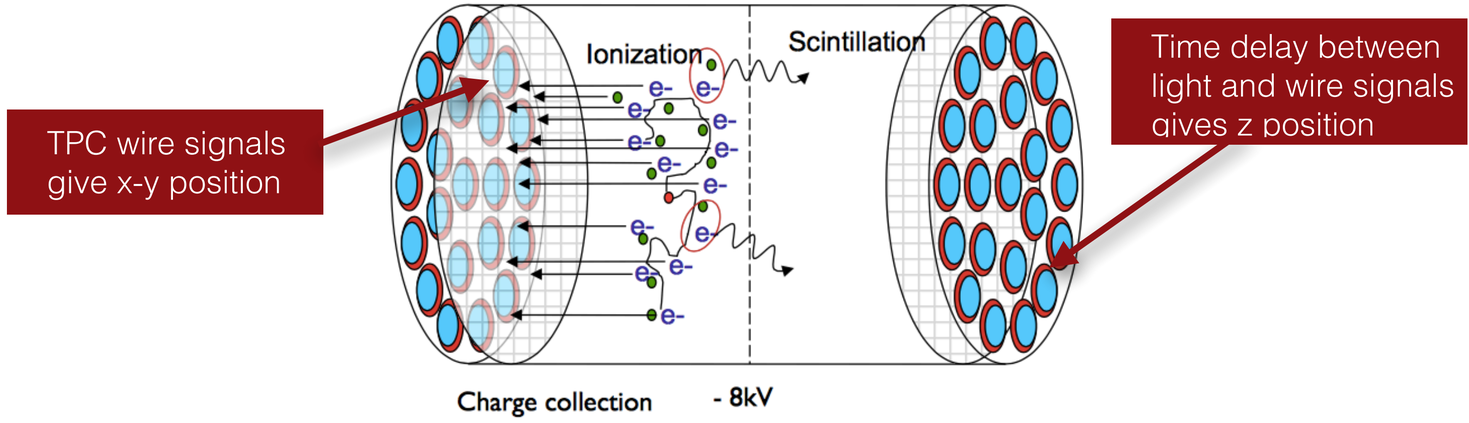
- **87% ^{76}Ge** ($Q_{\beta\beta}$ = 2.04 MeV) serves as both source and detector: high **efficiency**
- Electron range in Ge = 1mm: ββ contained in **one detector**
- High **resolution** ($\sigma_E/E \approx 0.2\%$): **zero background** in ROI (3-4 keV)

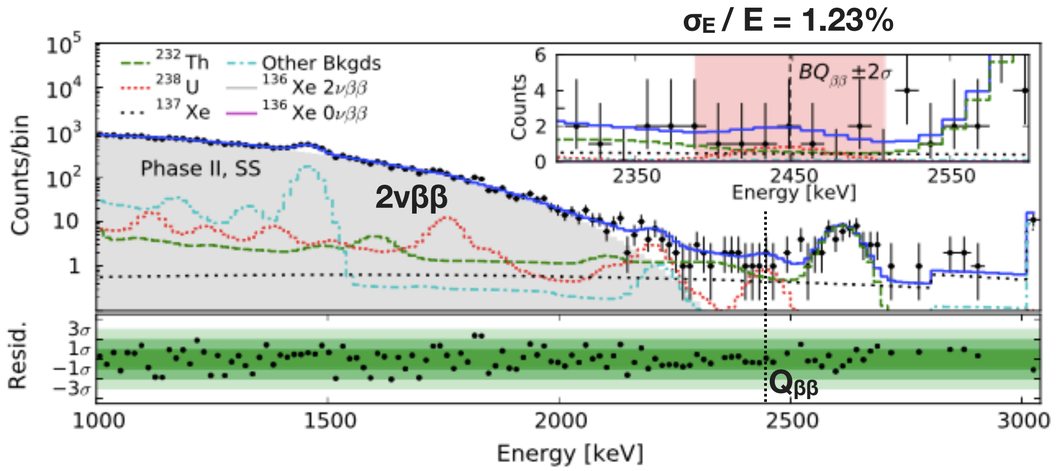
$T_{1/2} > 8.0 \times 10^{25}$ years (90% C.L)
47.7 kg.years;
10^{26}-year sensitivity expected this year

EXO-200: Liquid xenon TPC at WIPP, New Mexico

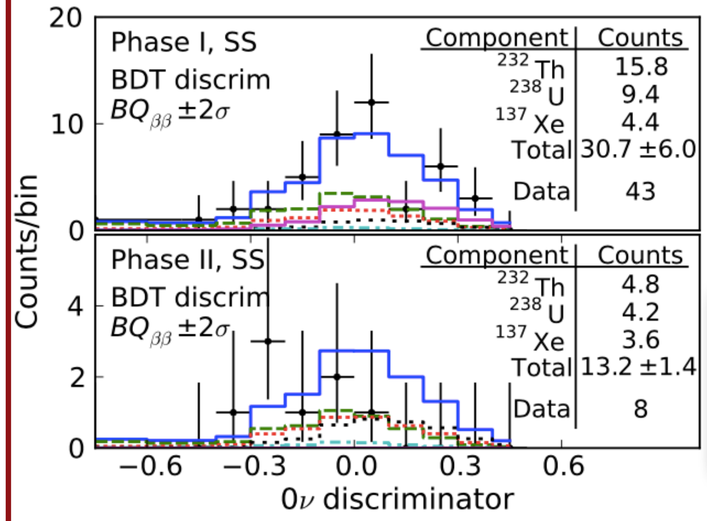


3-D reconstruction distinguishes between single-site (ββ) and multi-site (γ background) events





Main backgrounds: γ from ^{232}Th, ^{238}U; cosmogenically produced ^{137}Xe



BDT used to distinguish signal from background. Discriminators:

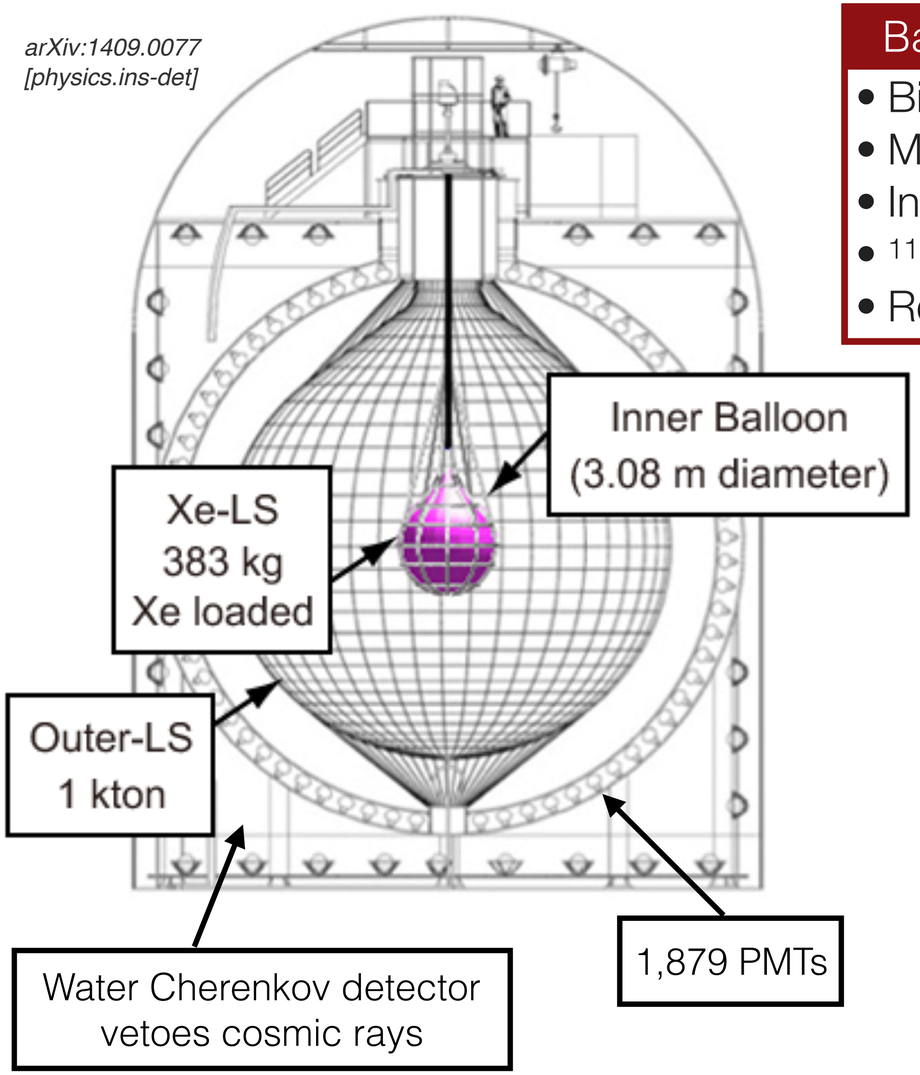
- number of channels hit
- pulse rise time
- distance from cluster to TPC surface

$T_{1/2} > 1.8 \times 10^{25}$ years (90% C.L)
177.6 kg.years
Target 5.7 x 10^{25} years

Phys Rev Lett 120, 072701 (2018)

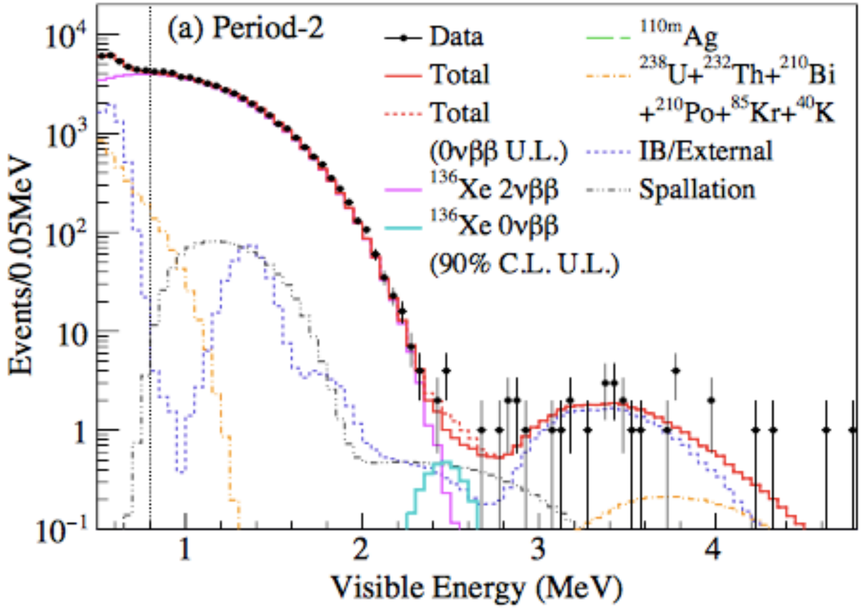
KamLAND-Zen: ^{136}Xe in scintillator in Kamioka, Japan

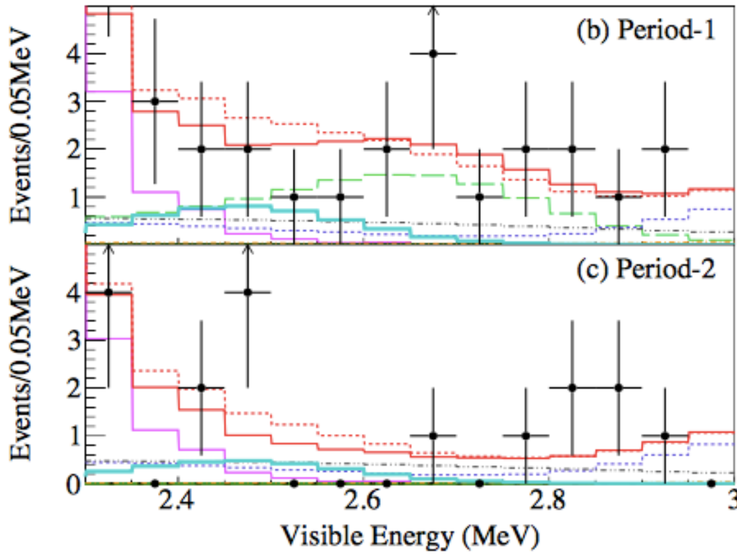
arXiv:1409.0077 [physics.ins-det]



Backgrounds

- BiPo in Xe-LS: identified by double pulse
- Muon-induced spallation
- Inner balloon contamination (Fukushima fallout)
- ^{110m}Ag in XeLS - cleaned for Phase II
- Reactor $\bar{\nu}_e$'s

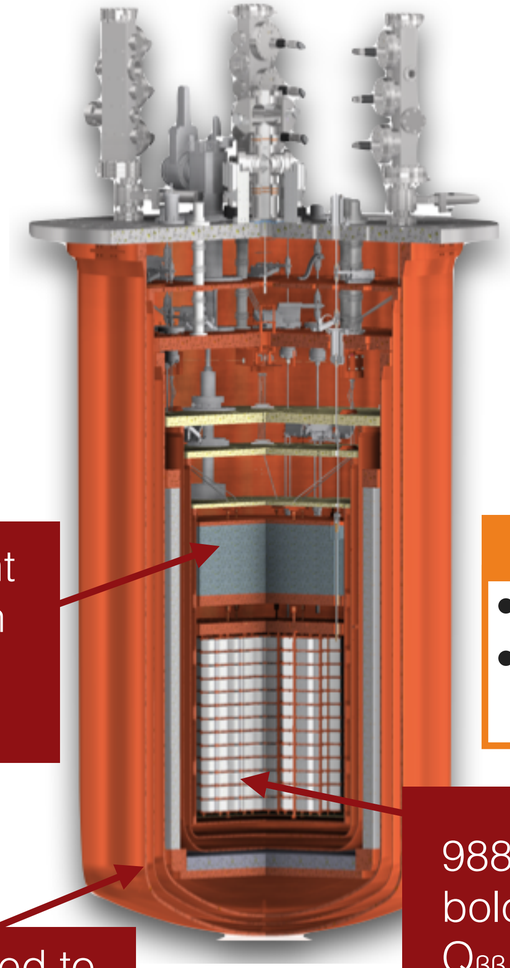




$T_{1/2} > 1.07 \times 10^{26}$ years
($\langle m_{\beta\beta} \rangle < 61$-165 meV)
504 kg.years
800kg version planned

Phys Rev Lett 117, 082503 (2016)

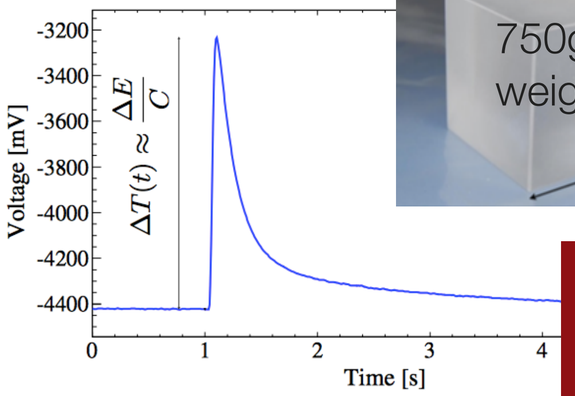
CUORE: TeO_2 bolometers at LNGS, Italy

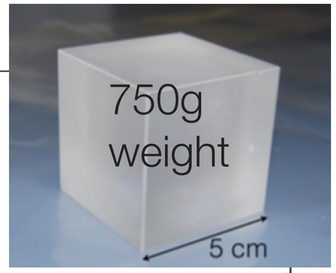


Ancient Roman lead shield

Cooled to 10mK

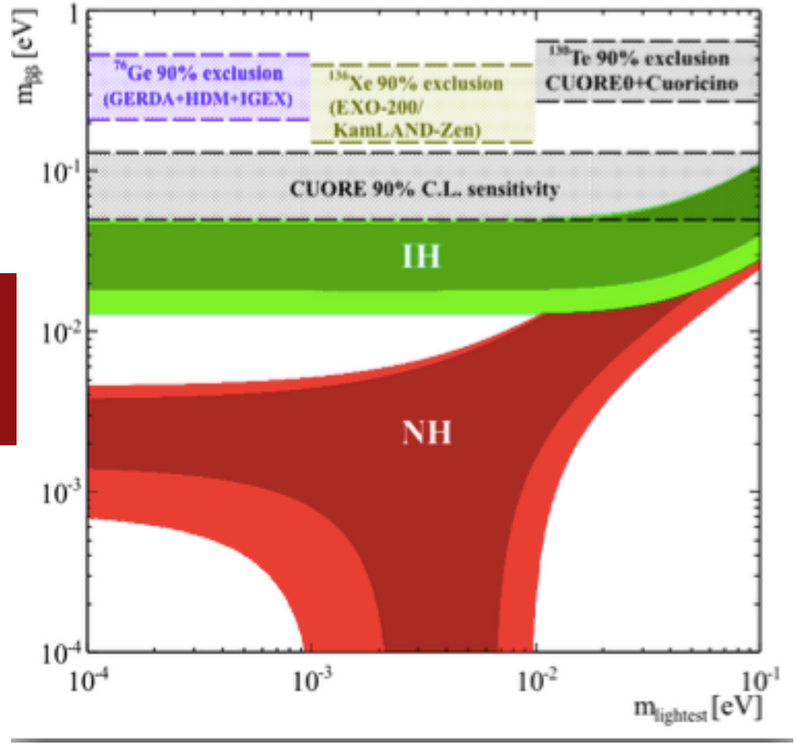
988 Natural TeO_2 bolometers (34% ^{130}Te, $Q_{\beta\beta}$ = 2.53 MeV)





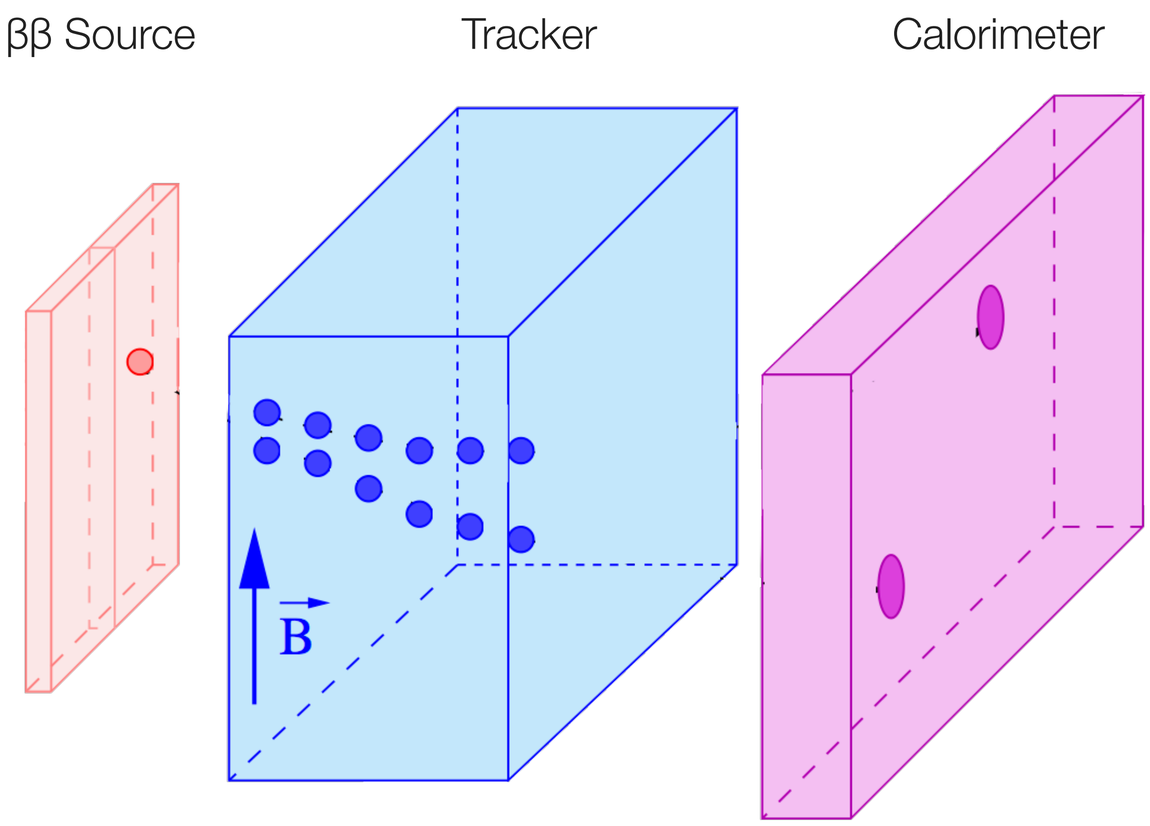
Decay increases temperature in TeO_2 crystal

Pros	Cons
• 0.2% energy resolution • high natural abundance of ^{130}Te	• No particle ID • Slow • Difficult conditions

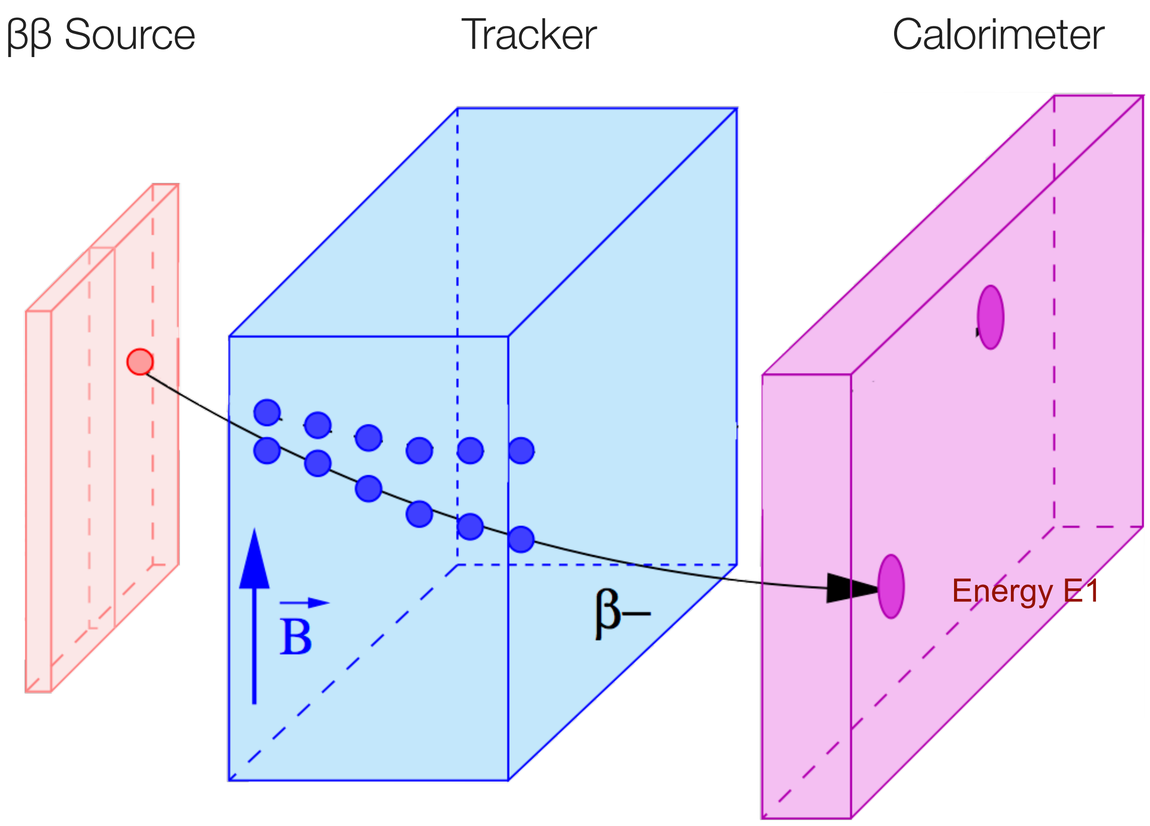


$T_{1/2} > 1.5 \times 10^{25}$ years
($\langle m_{\beta\beta} \rangle < 110\text{-}520$ meV)
86.3 kg.years
5 years: 9.5×10^{25} years

The NEMO principle



The NEMO principle



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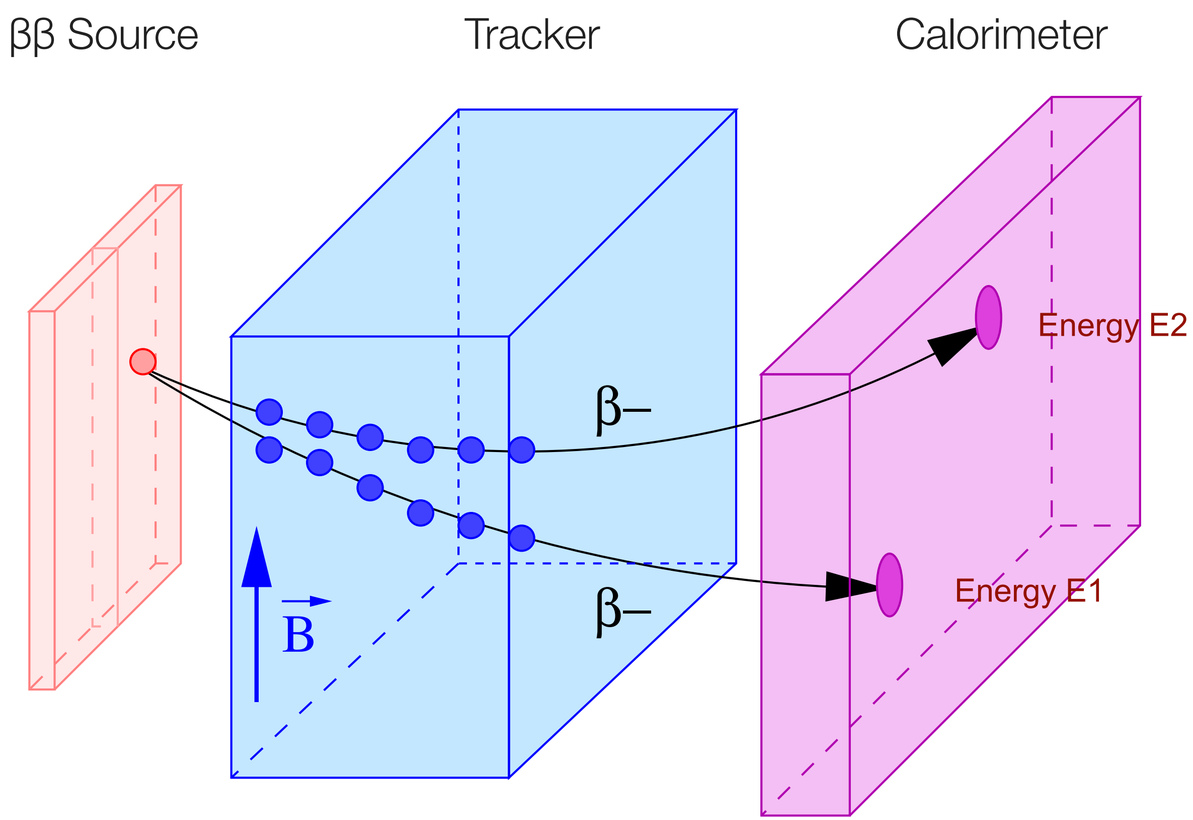
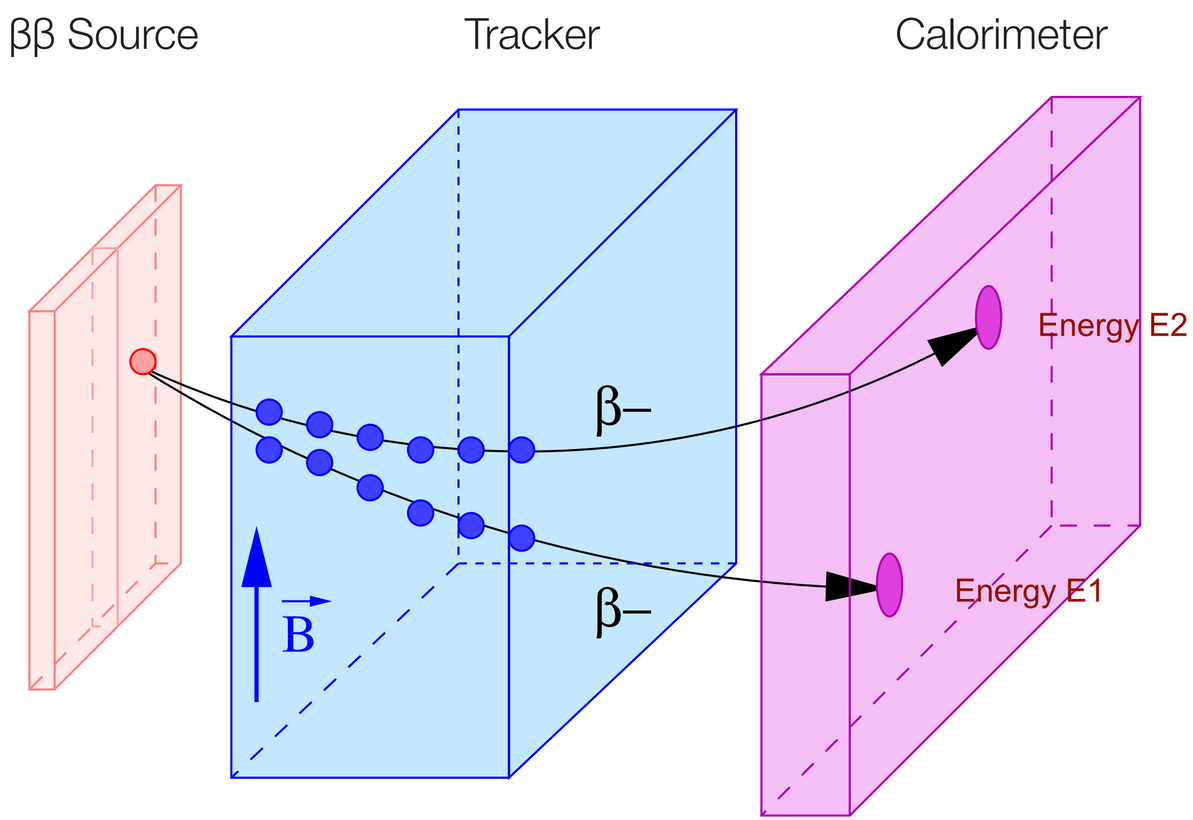
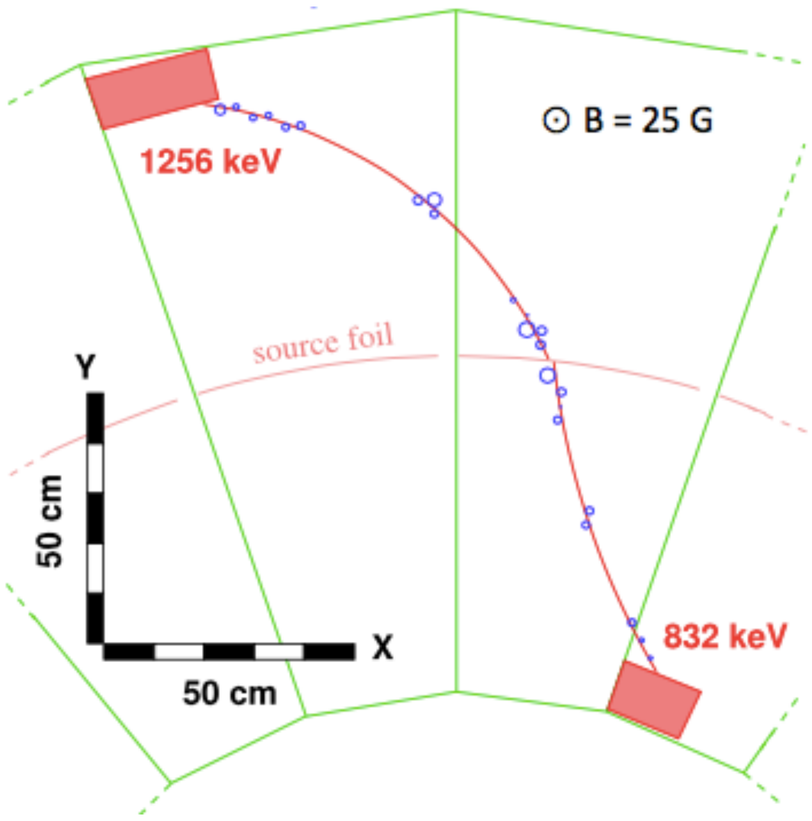


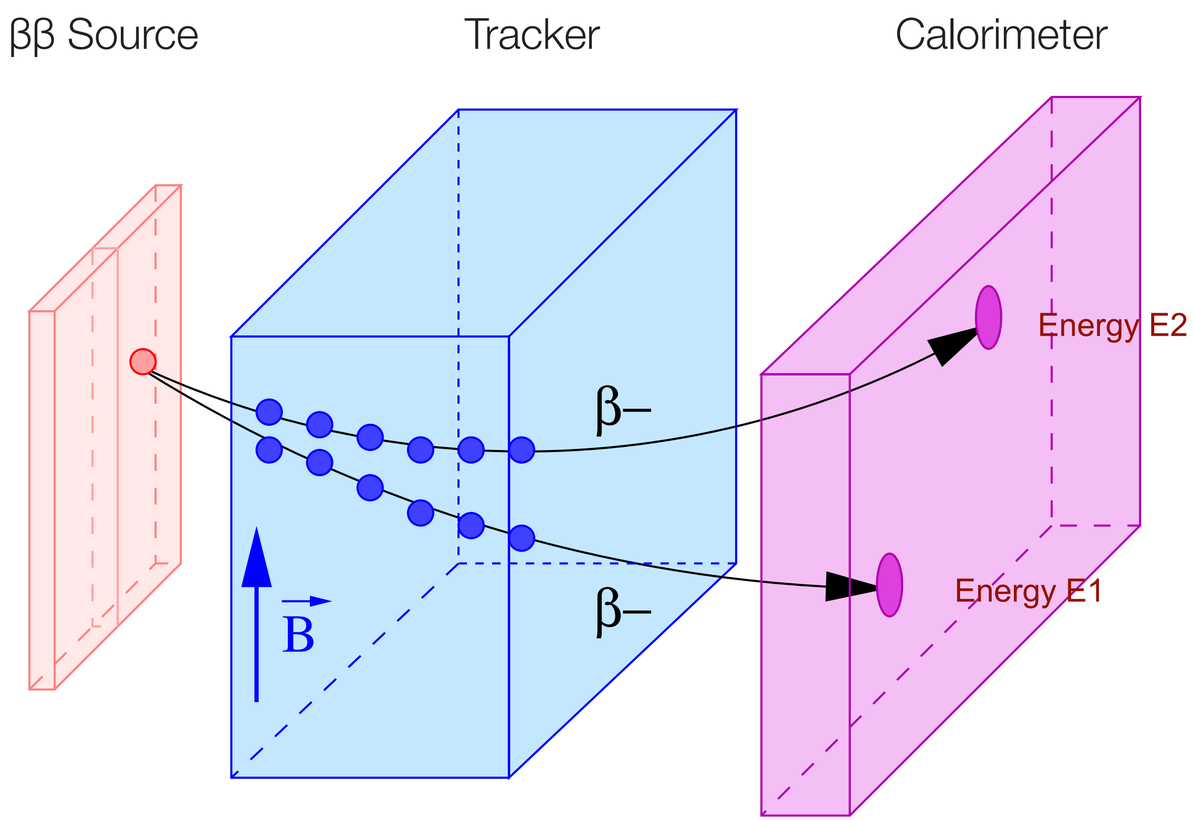
The NEMO principle





ββ candidate from NEMO-3 (Data)

The NEMO principle



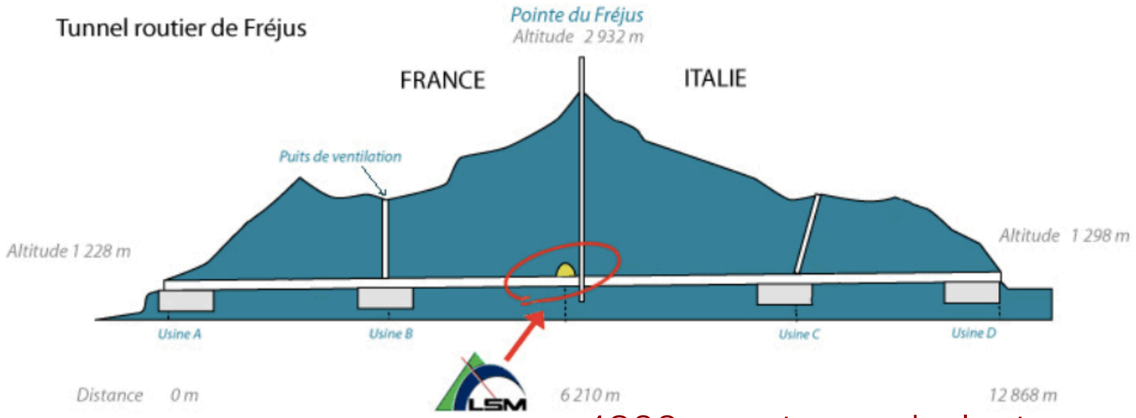
Strengths

- Tracker gives **particle identification**
- Combine with timings to identify topologies for ultra-high **background rejection**
- Tracking info (angle between tracks etc) can distinguish between **0νββ mechanisms**
- Modular design - **swap the source** isotope

Weaknesses

- **Energy resolution** poorer than some other technologies (eg bolometers, HPGe)

The home of NEMO - LSM



4800m water equivalent

Laboratoire Souterraine de Modane

in the Fréjus tunnel connecting France and Italy

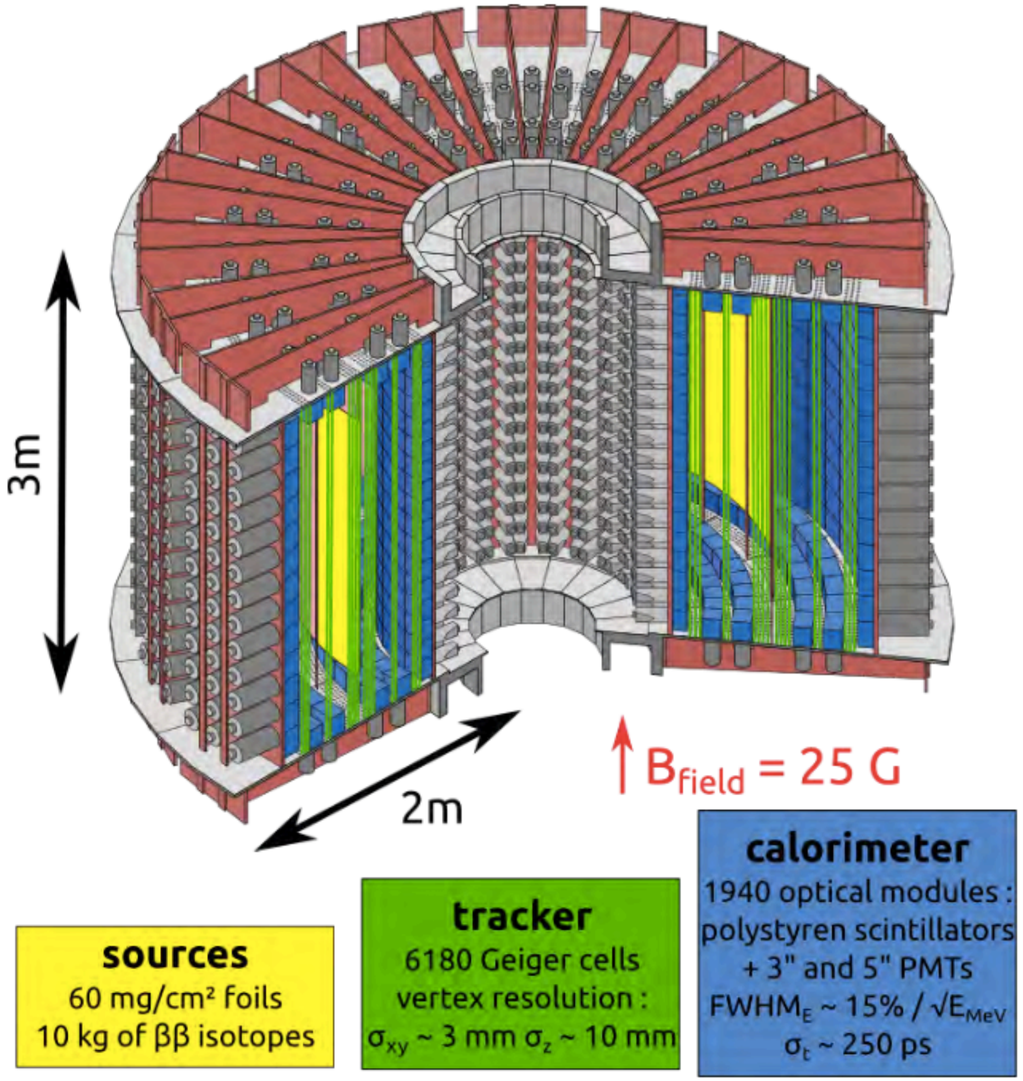
The home of NEMO - LSM

water equivalent

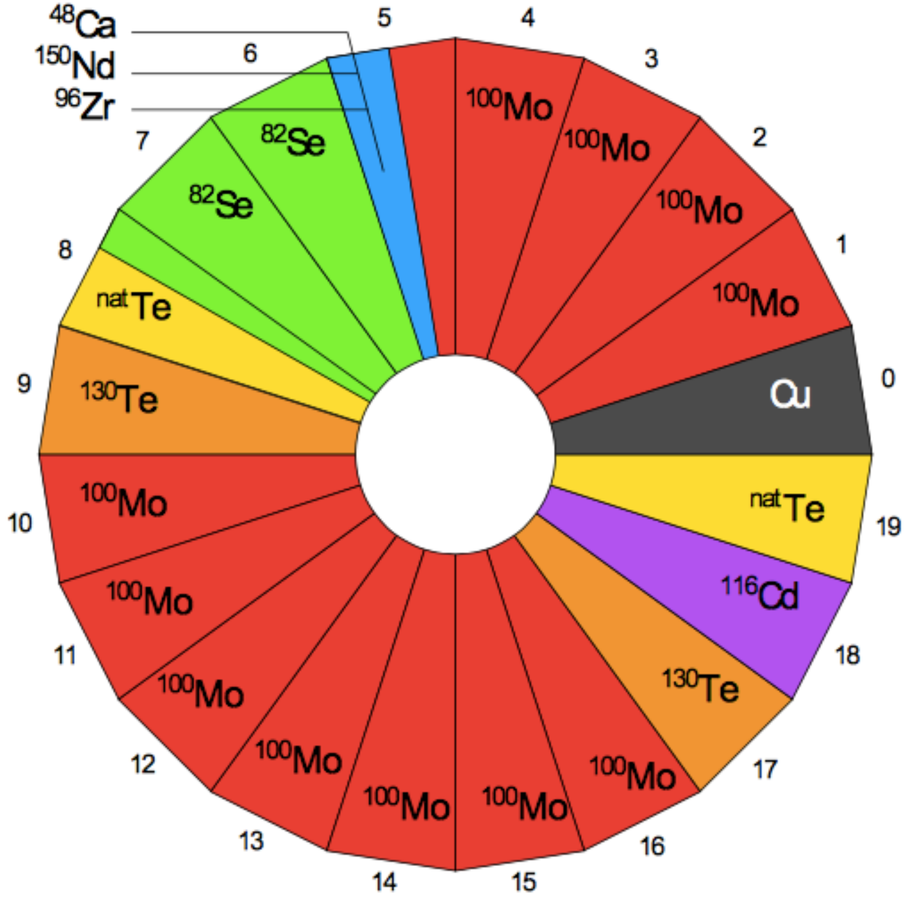
Laboratoire Sc

in the Fréjus tunnel c

NEMO-3 detector: 2003-2011



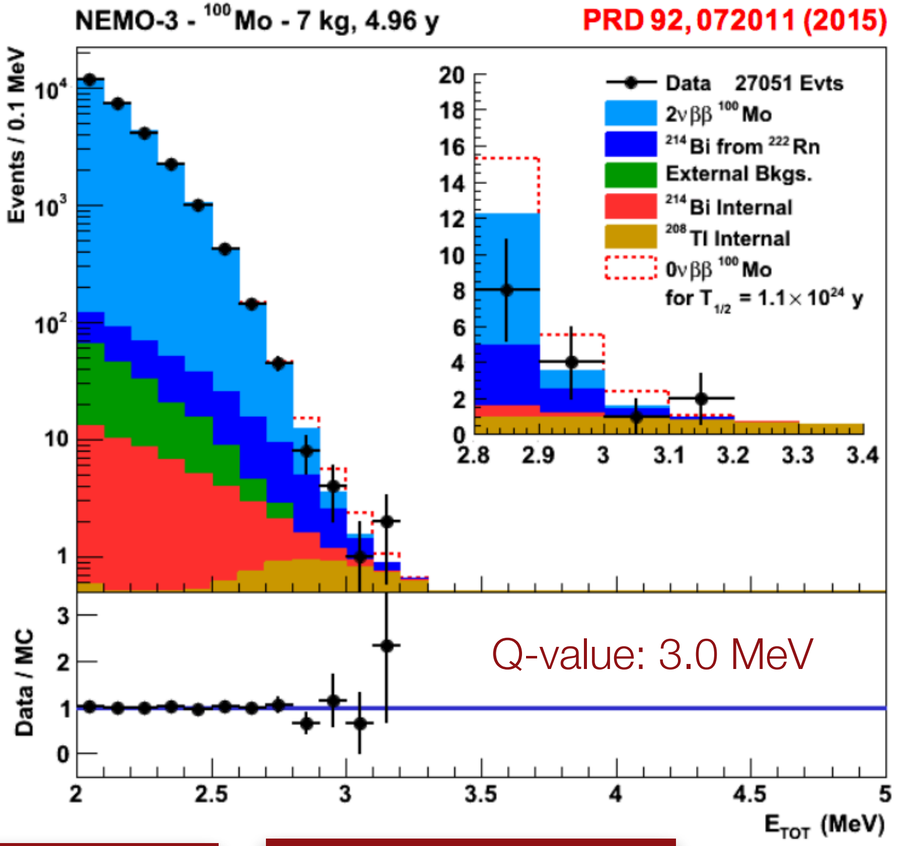
NEMO-3 "camembert" (source top view)



^{100}Mo	6,9 kg
^{82}Se	0,93 kg
^{130}Te	0,45 kg
^{116}Cd	0,40 kg
^{150}Nd	36,5 g
^{96}Zr	9,43 g
^{48}Ca	6,99 g

NEMO-3 flagship analysis: ^{100}Mo ββ decay

- 2νββ measurements and 0νββ limits for several isotopes
  - **^{100}Mo** (Phys. Rev. Let. 95, 182302)



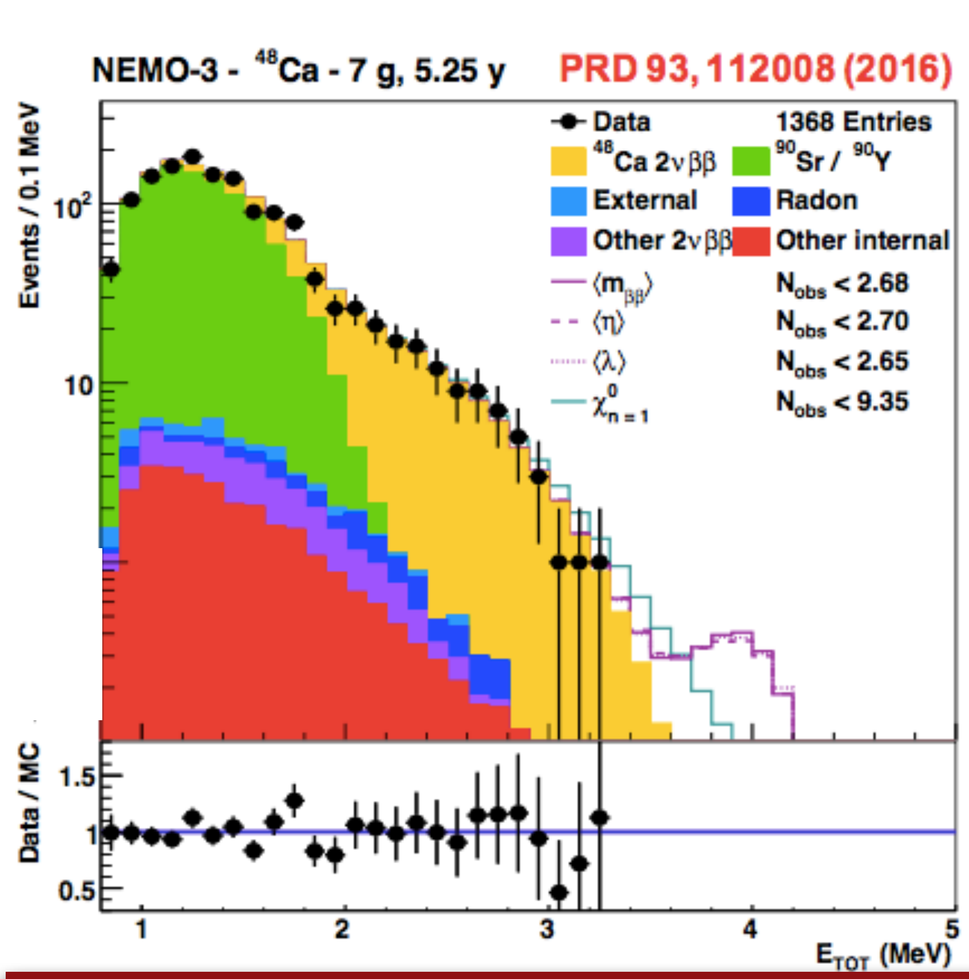
2νββ:
$T_{1/2}$ = 7.1 ± 0.02 (stat) ± 0.54 (sys) x 10^{18} yr

0νββ:
$T_{1/2}$ > 1.1 x 10^{24} years
⟨m_ν⟩ < 0.33 - 0.62 eV
Close to world's best limit

Plus competitive limits on alternative ββ mechanisms

NEMO-3 analyses

- 2νββ measurements and 0νββ limits for several isotopes
  - **^{100}Mo** (Phys. Rev. Let. 95, 182302)
  - **^{48}Ca** (Phys. Rev. D 93, 112008)



7g of ^{48}Ca (9 CaF_2 disks)

2νββ: $T_{1/2}$ = 6.4 + 0.7 / -0.6 (stat) + 1.2 / - 0.9 (sys) **x 10^{19}**

NEMO-3 analyses

- 2νββ measurements and 0νββ limits for several isotopes
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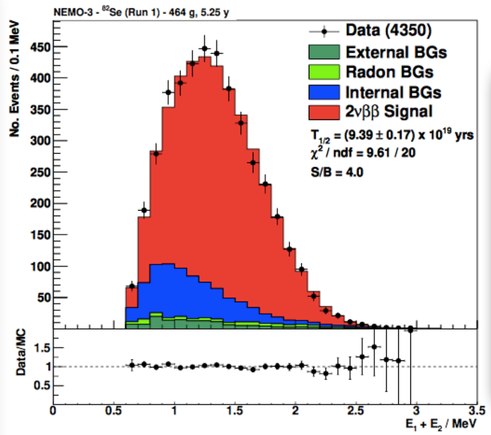
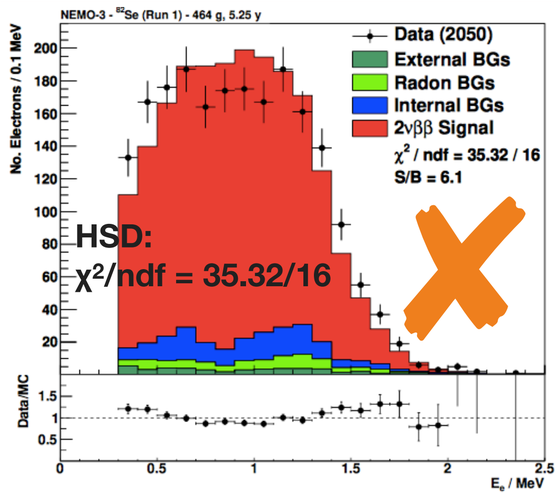
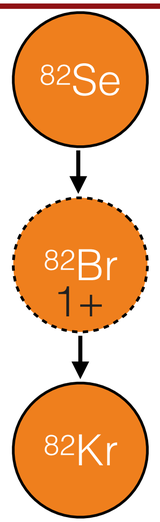


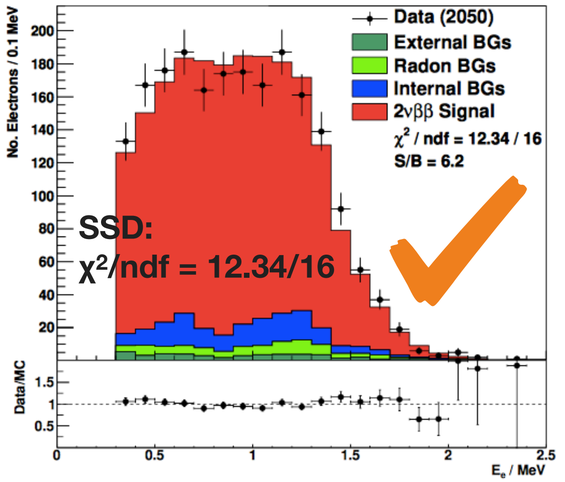
Summed 2-electron spectrum

2νββ:
$T_{1/2}$ = **9.39** ± 0.17 (stat) ± 0.58 (sys) **x 10^{19} years**
(SSD hypothesis)

0νββ:
$T_{1/2}$ = **2.5 x 10^{23} years** (90% C.L.)







Higher state dominated - many excited states

Single state dominated - mostly one intermediate state

Individual electron spectrum tells us about intermediate 1+ states

NEMO-3 analyses

- 2νββ measurements and 0νββ limits for several isotopes
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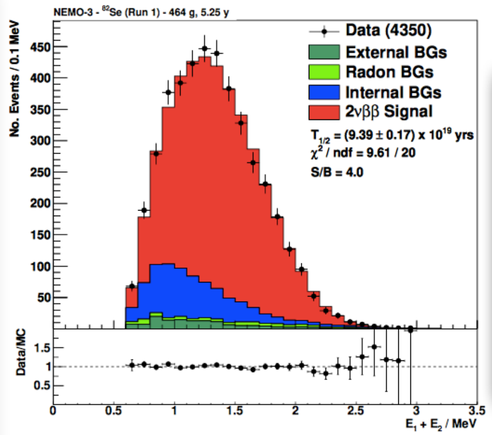
  - **^{150}Nd** (Phys. Rev. D 94, 072003)
  - **^{116}Cd** (Phys. Rev. D 95, 012007)
  - **^{130}Te** (Phys. Rev. Lett. 107, 062504)
  - **^{96}Zr** (Nucl.Phys.A847:168-179)



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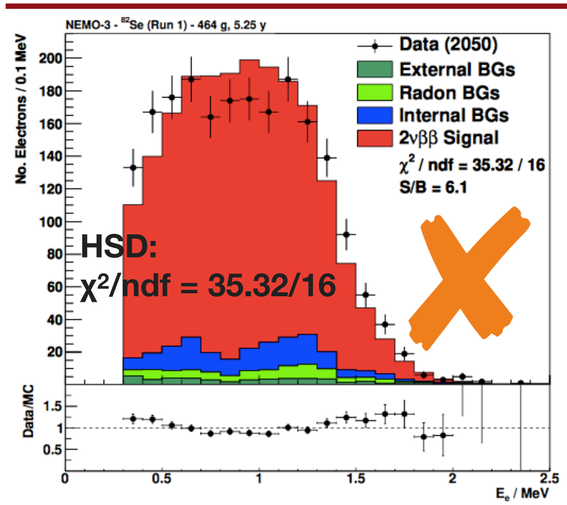

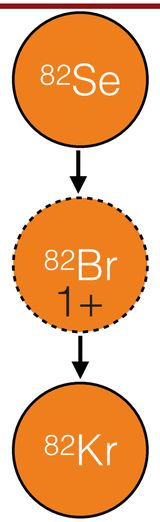

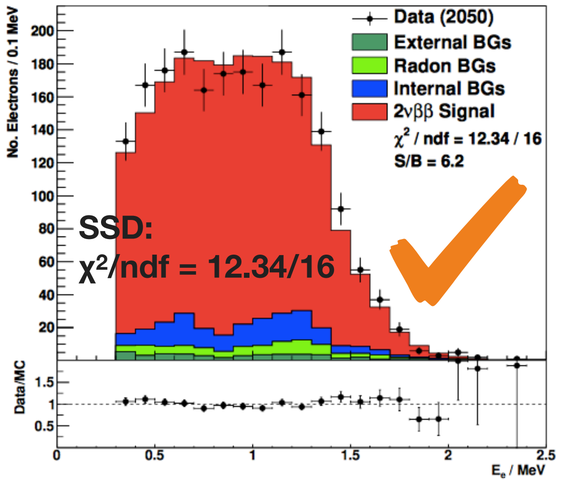

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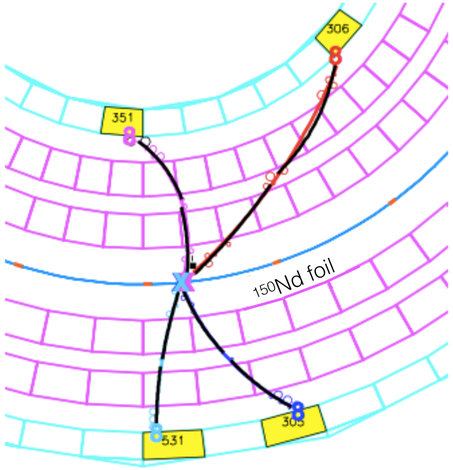
- **Quadruple β decay** (Phys. Rev. Lett. 119, 041801)

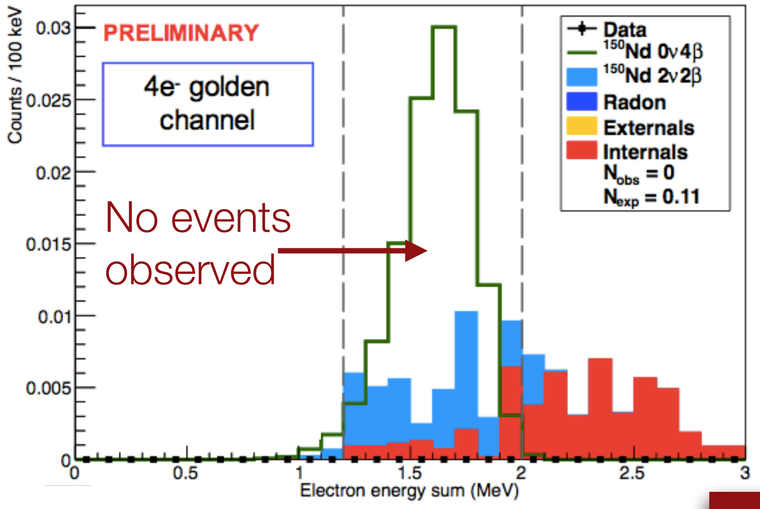


0v4β decays would violate lepton number, but could occur even if neutrinos are Dirac fermions

Heeck and Rodejohann 2013

Allowed for 3 isotopes, including

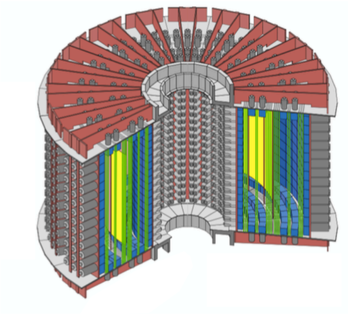
$$^{150}\mathrm{Nd} \xrightarrow{2.079\ \mathrm{MeV}} {}^{150}\mathrm{Gd} + 4e^-$$

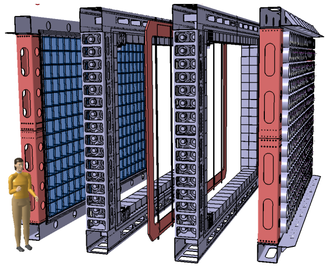


NEMO architecture helps us identify these topologies

$T_{1/2}$ > 2.6 x 10^{21} yr

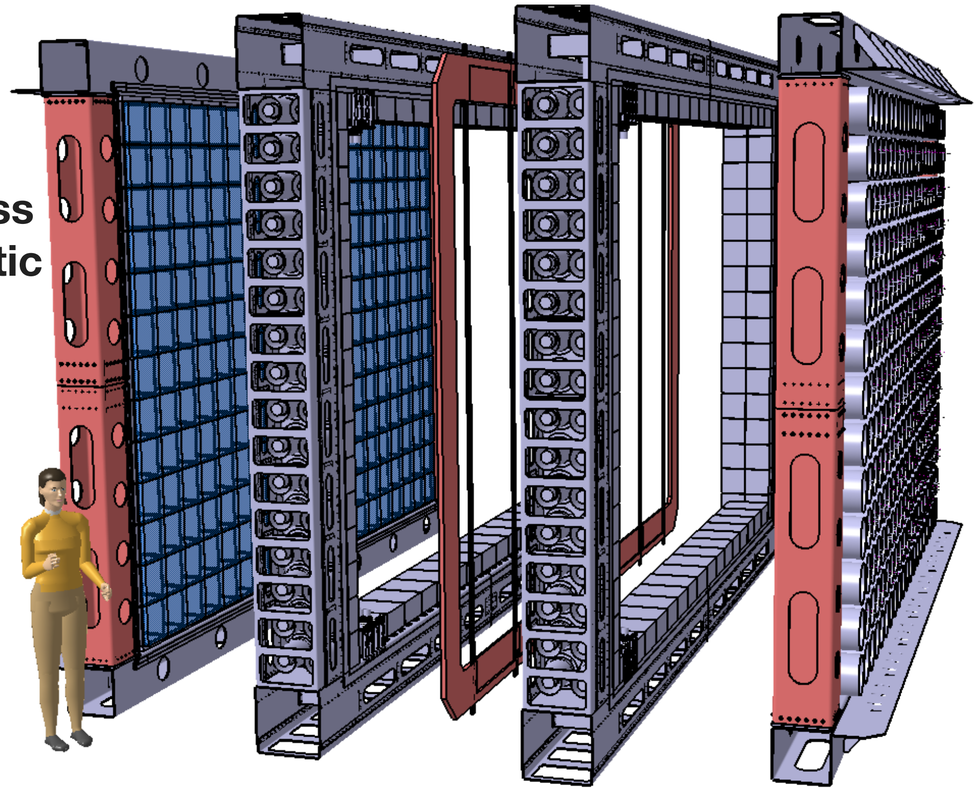
NEMO-3 vs. SuperNEMO



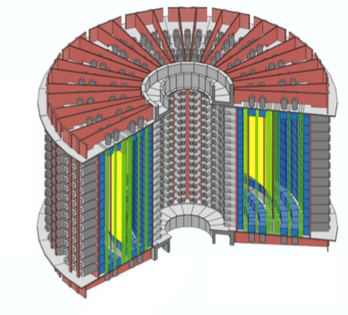


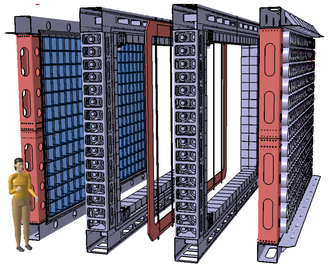
	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	7.2×10^{18}	9.9×10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
A(^{214}Bi)	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg
Level of radon A(^{222}Rn)	~ 5.0 mBq/m^3	< 0.15 mBq/m^3
Sensitivity after 5 (2.5) y data taking	$T^{0\nu}_{1/2} > 10^{24}$ y	$T^{0\nu}_{1/2} > 6 \times 10^{24}$ y

25 gauss magnetic field



NEMO-3 vs. SuperNEMO





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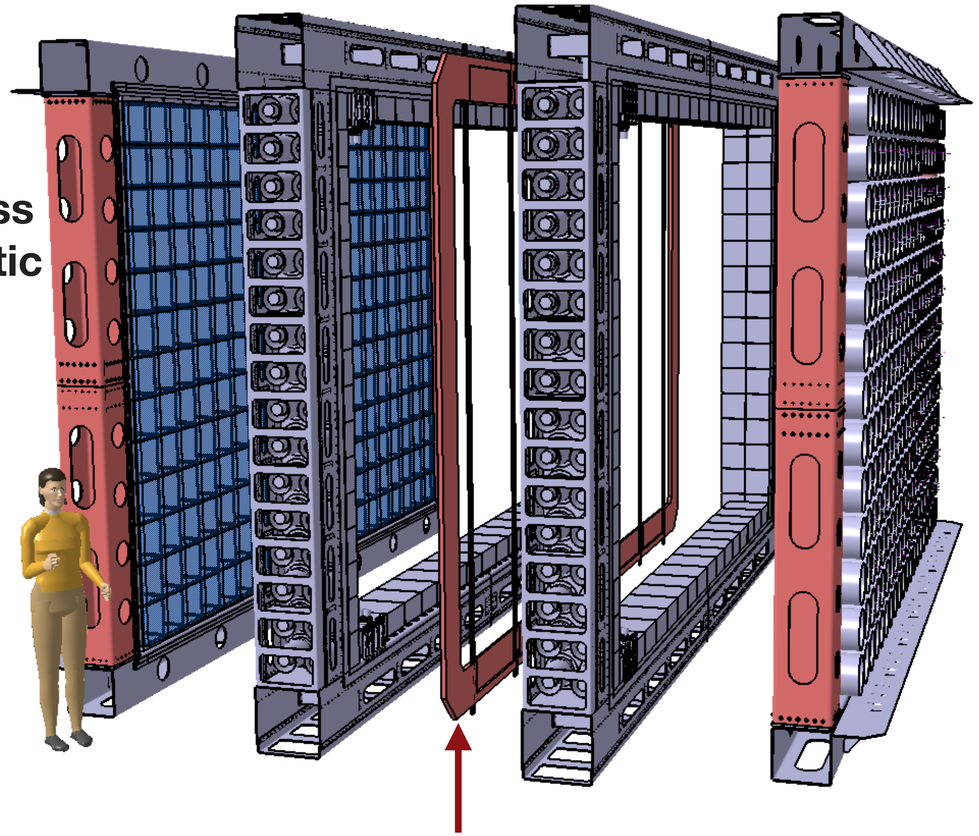
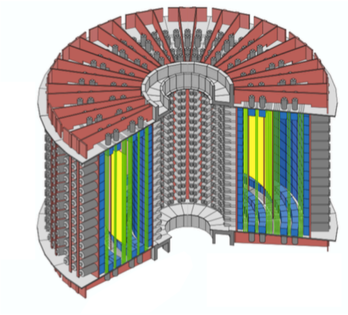
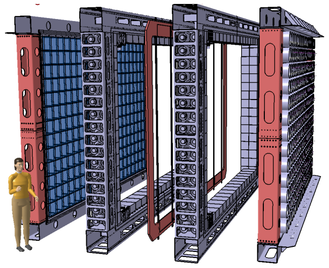


Source frame holding 7kg of ββ emitter (^{82}Se)

NEMO-3 vs. SuperNEMO





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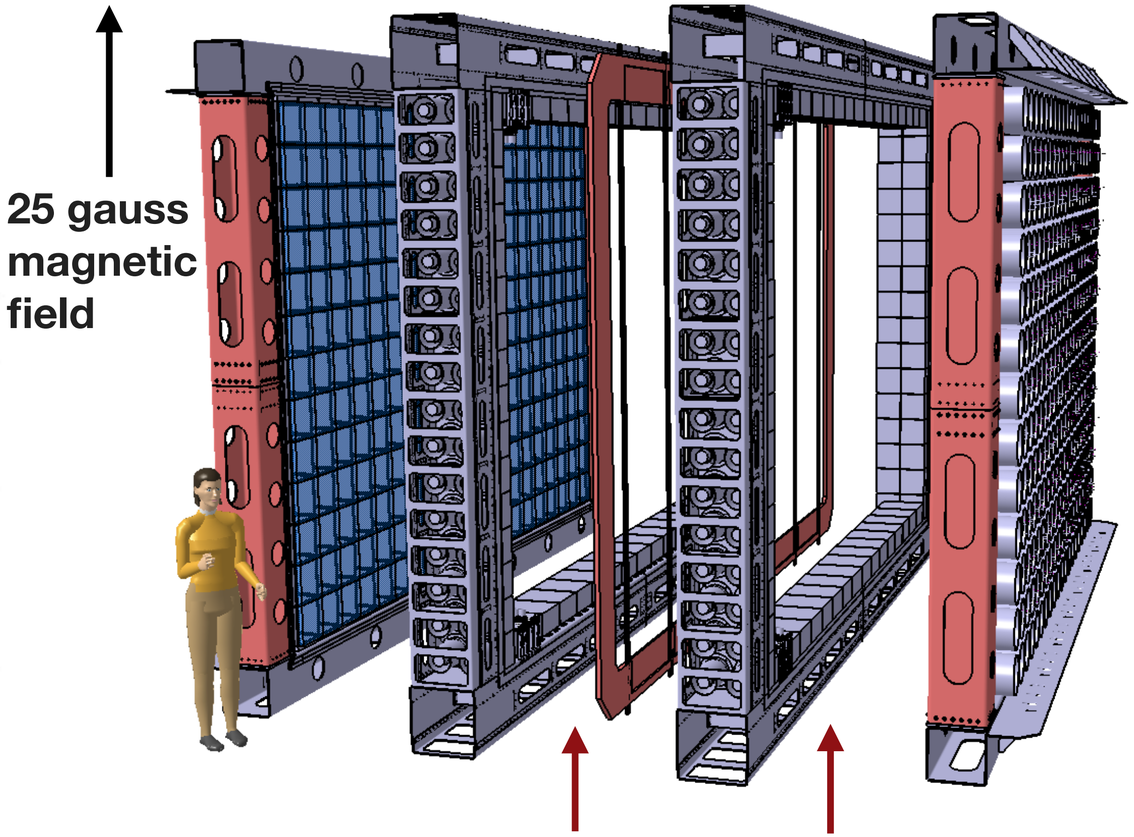

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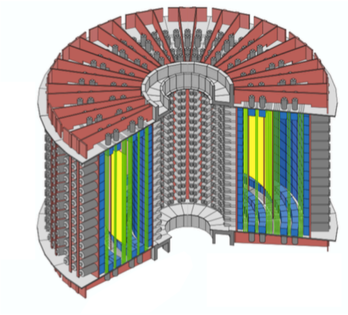

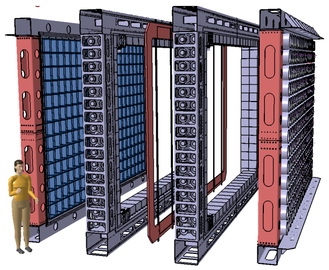

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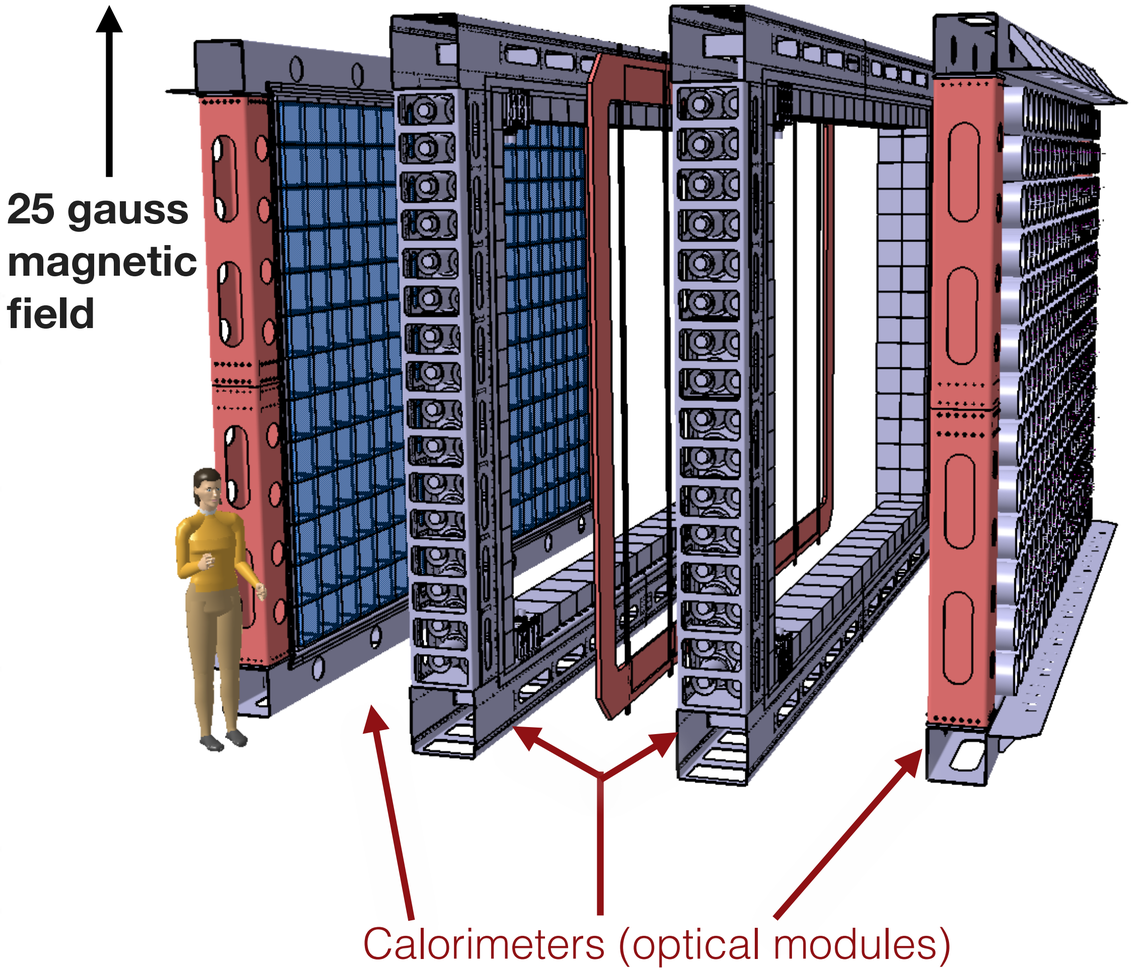
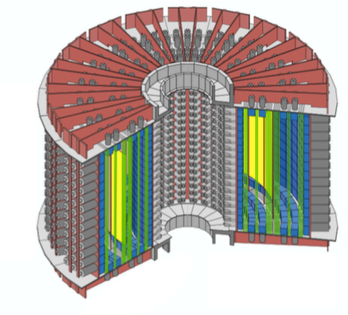
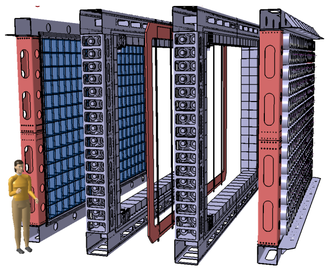


NEMO-3 vs. SuperNEMO





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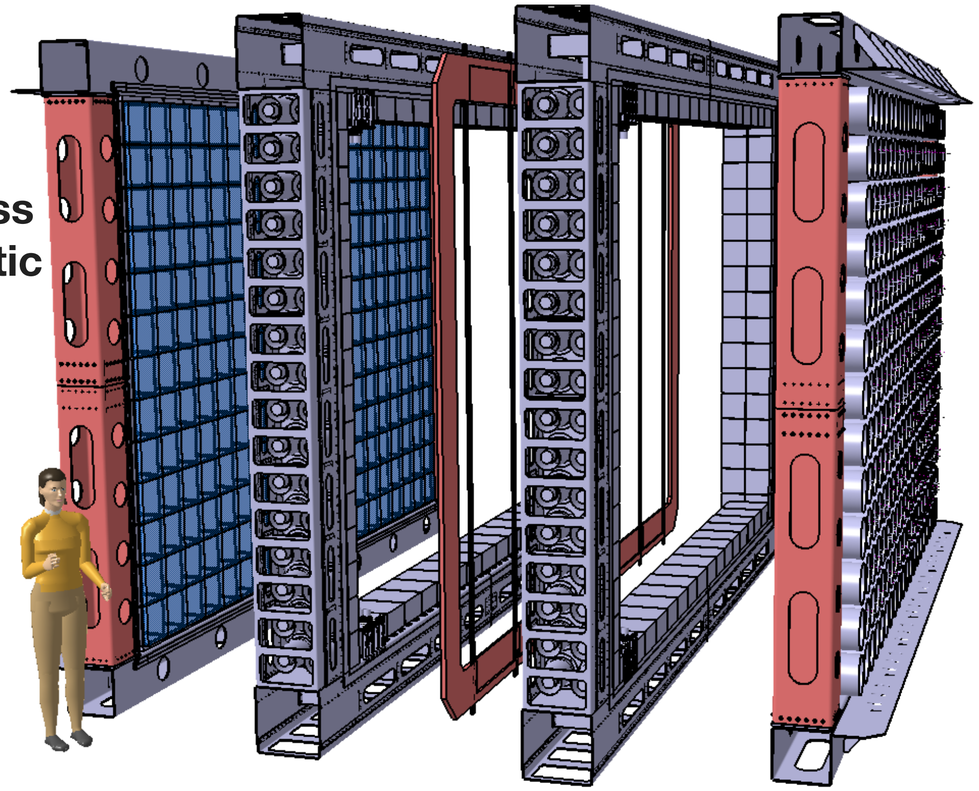
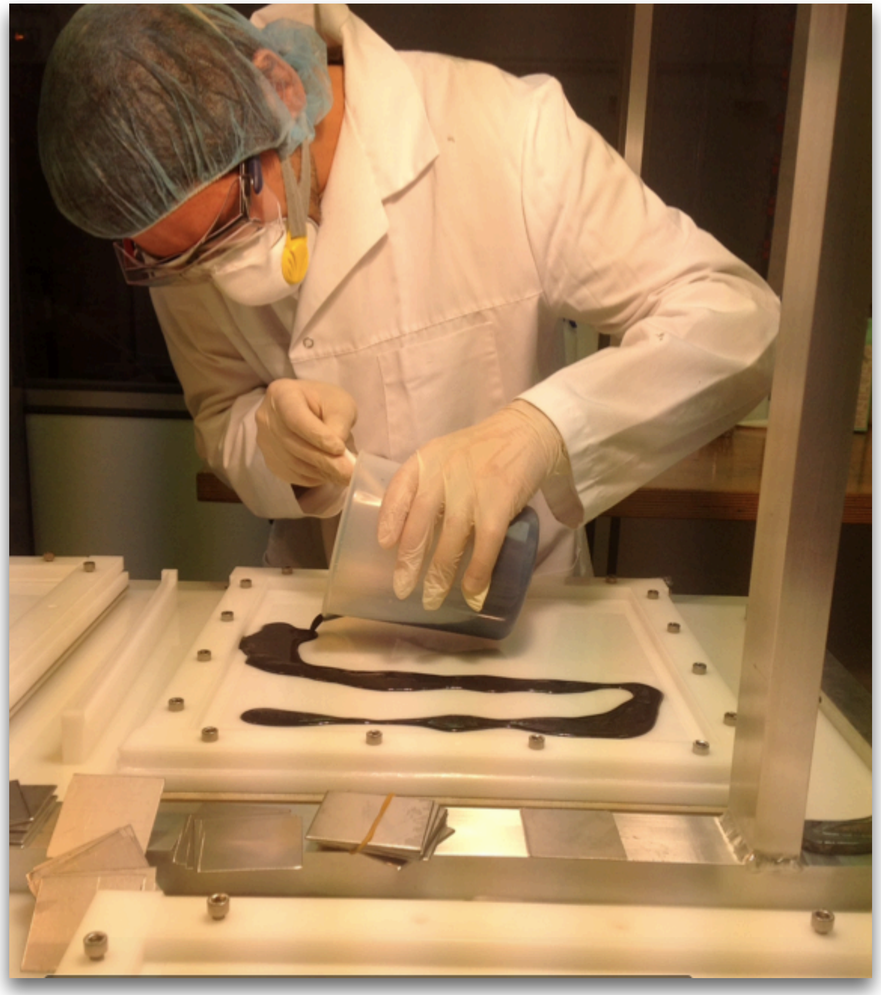
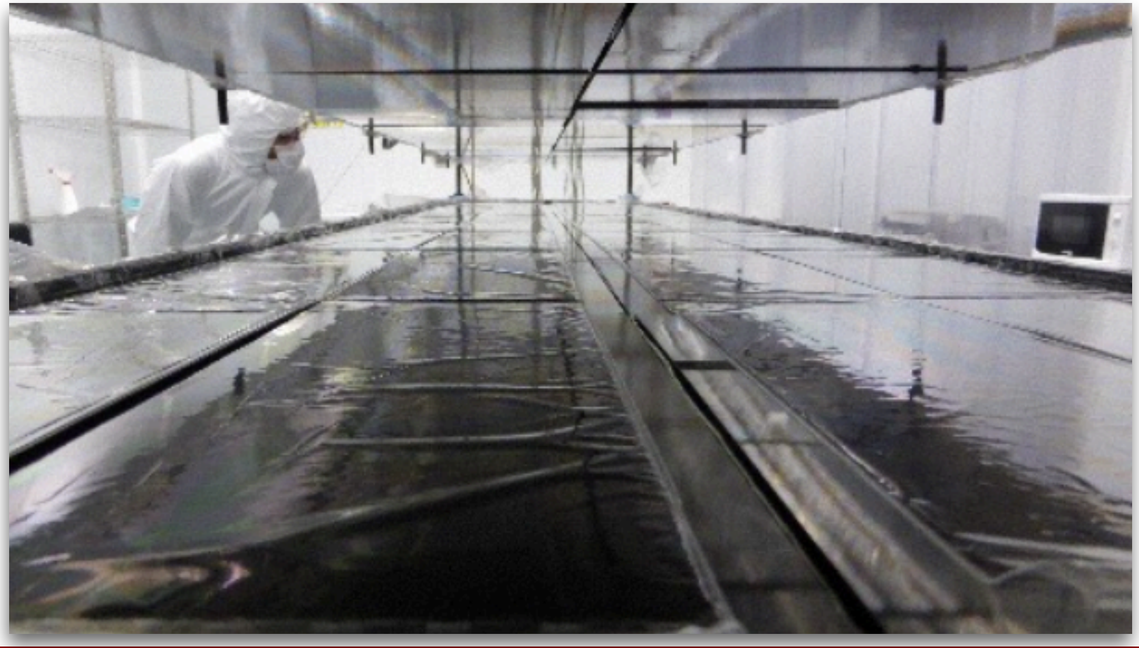


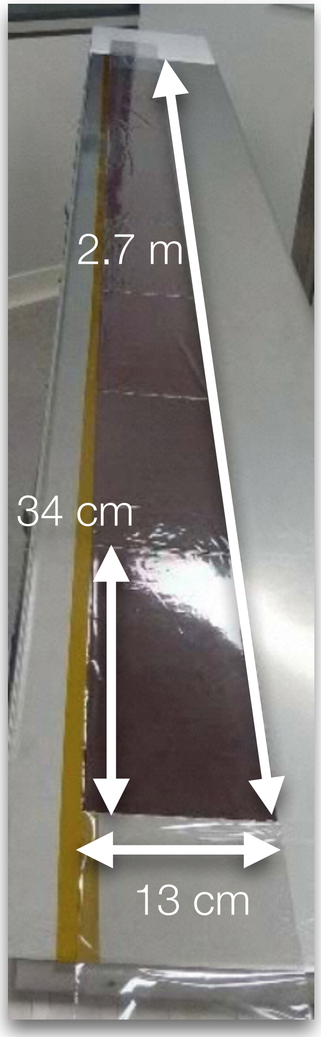
$T_{1/2}^{0\nu} > 6 \times 10^{24}$ years

ββ Sources



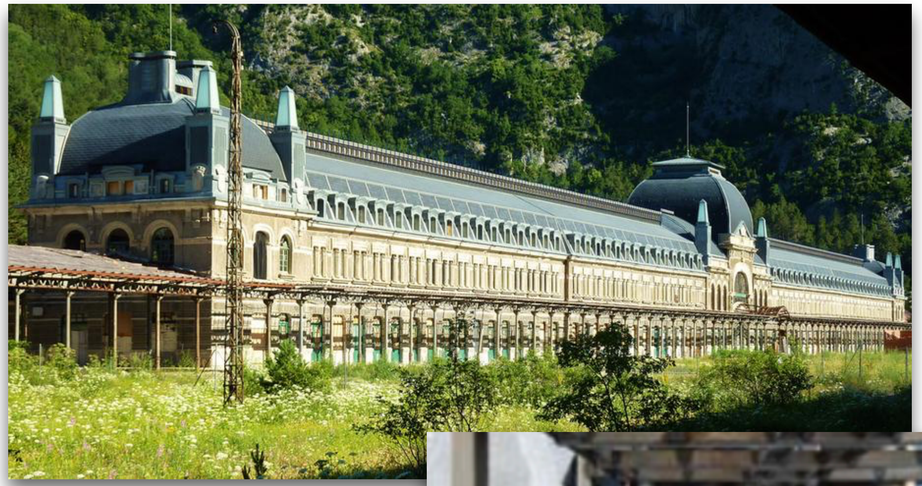
- 7kg of ββ emitter (^{82}Se)
- 34 Se foils plus 2 Cu
- Enriched selenium mixed with PVA in Mylar wrapper
- Purified with distillation / chromatography / chemical precipitation
- Ready to hang at LSM
- BiPo detector measures ^{208}Tl and ^{214}Bi contamination

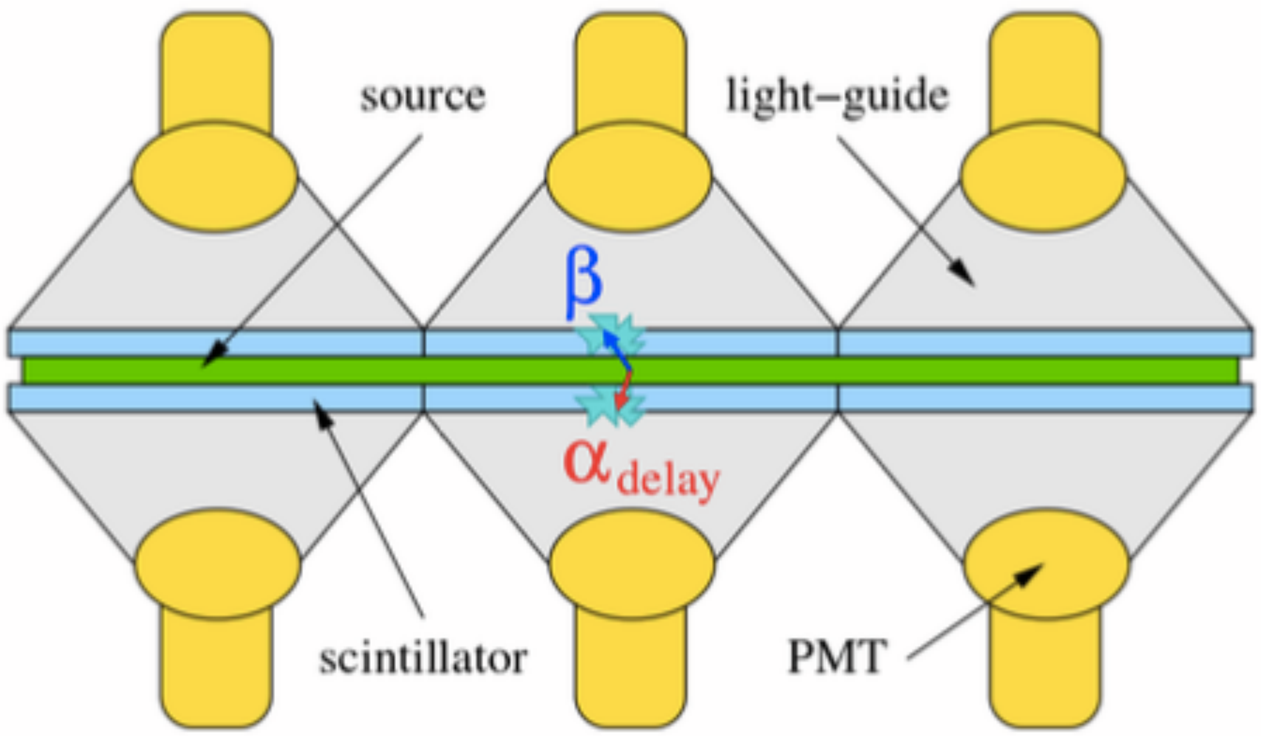




~400 μm thick

BiPo-3 detector

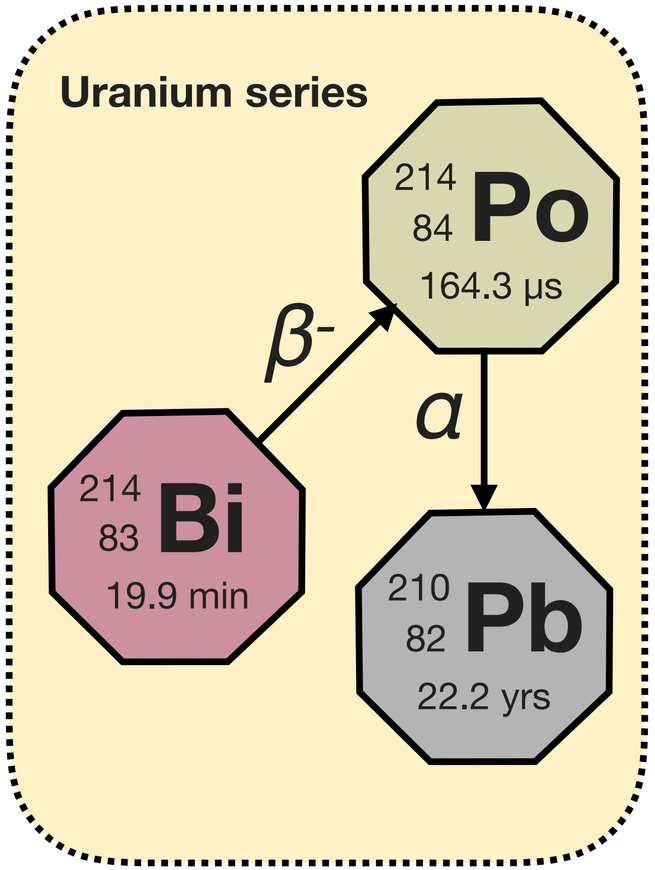


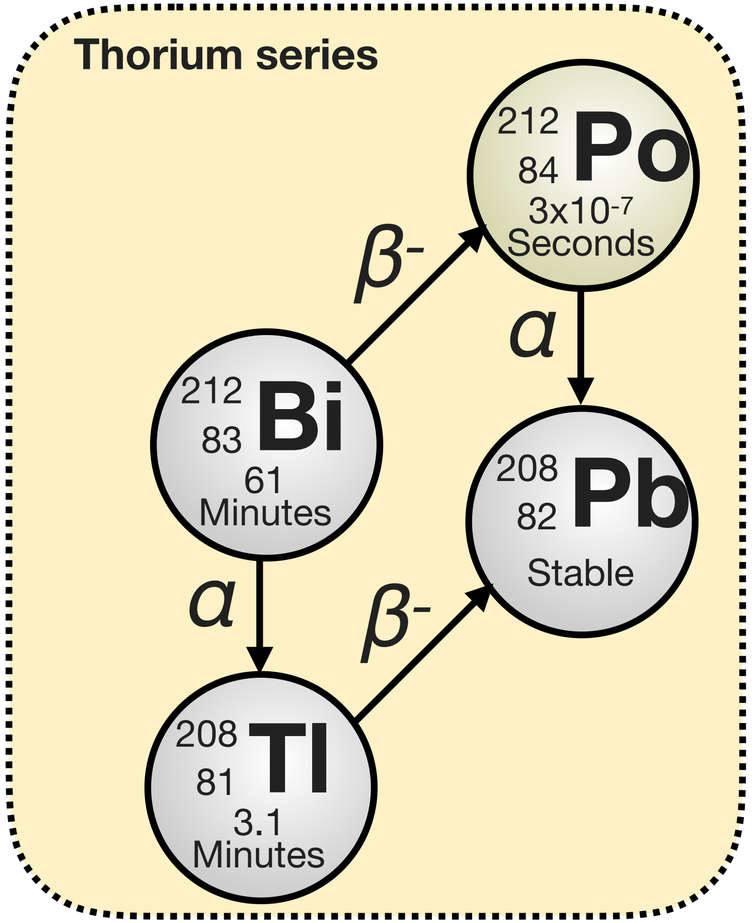


- Dedicated detector at Canfranc Underground Laboratory, Spain (formerly Europe's largest railway station)
- Designed to measure very low activities
- Looks for characteristic signature of Bi β decay followed by α decay of Po daughter

JINST 12 (2017) P06002

BiPo-3 detector





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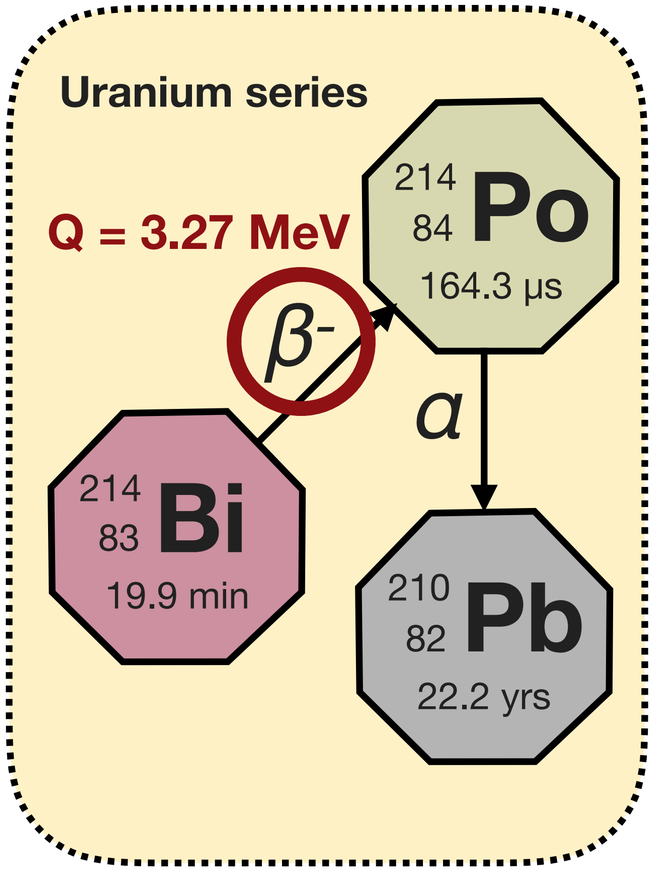
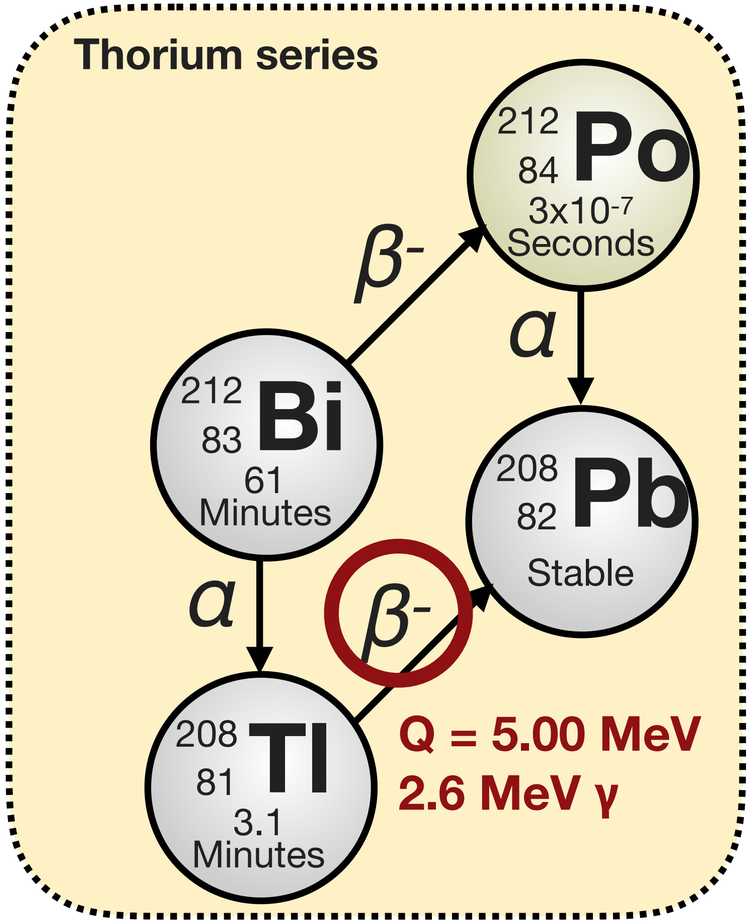
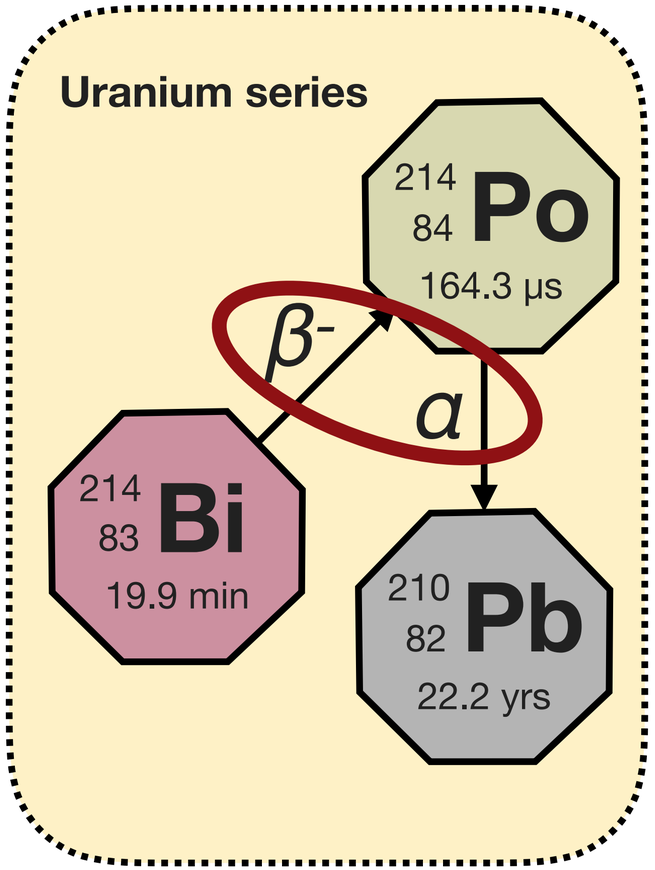
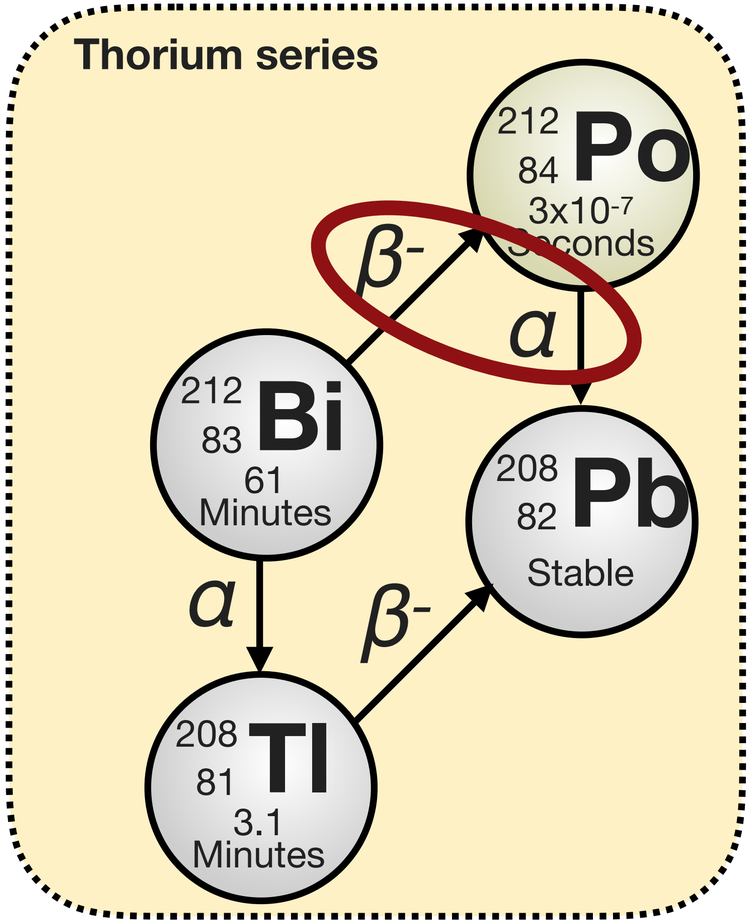




- We care about ^{214}Bi and ^{208}Tl

BiPo-3 detector





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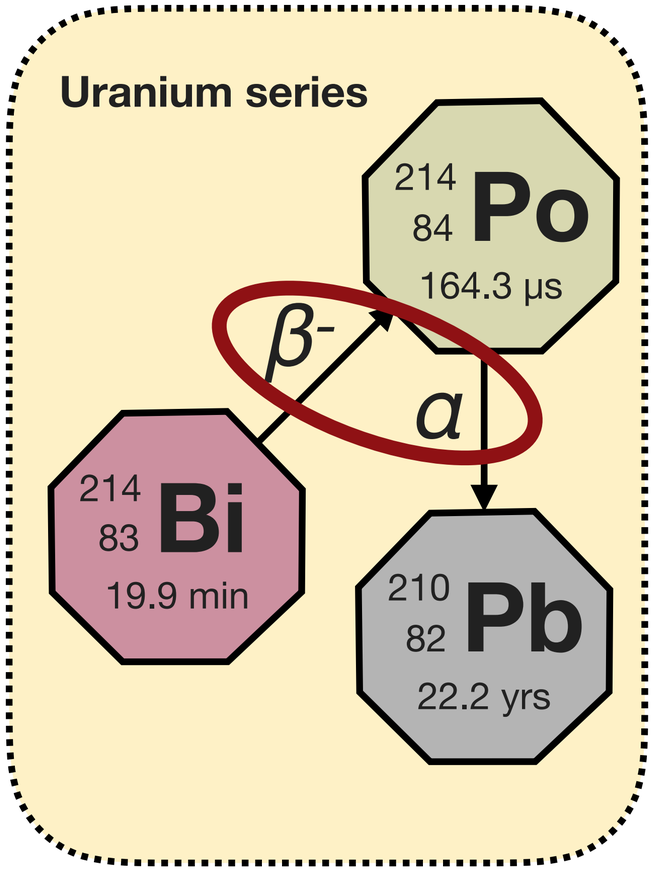

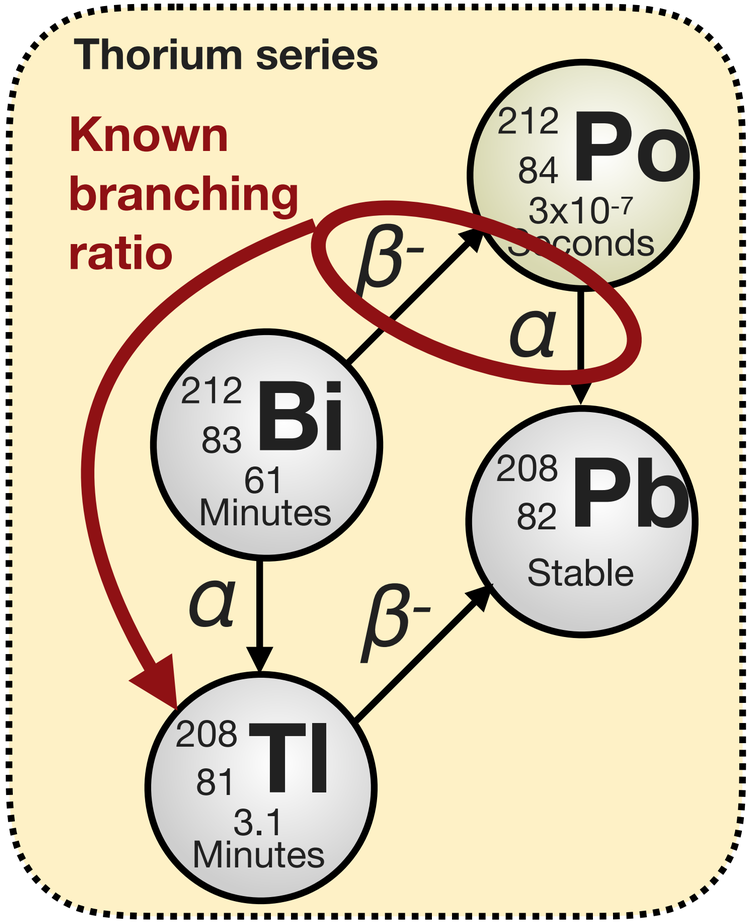

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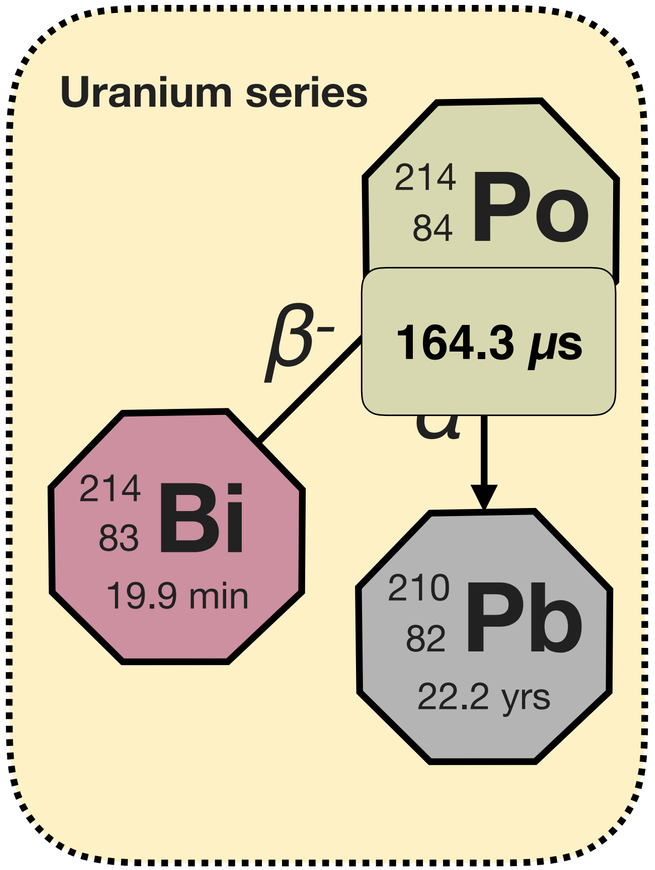
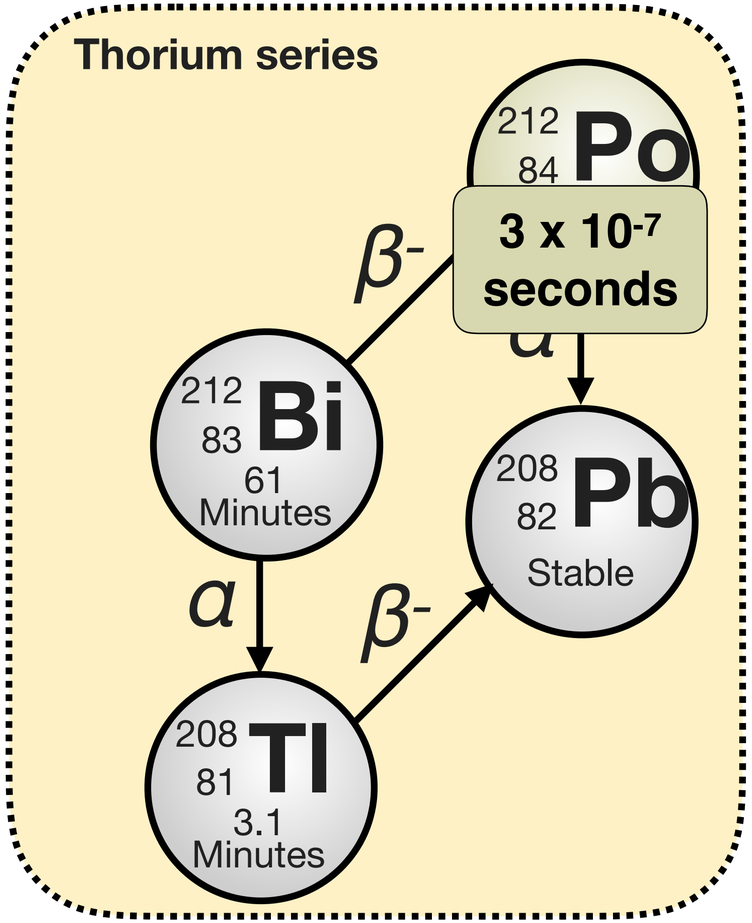
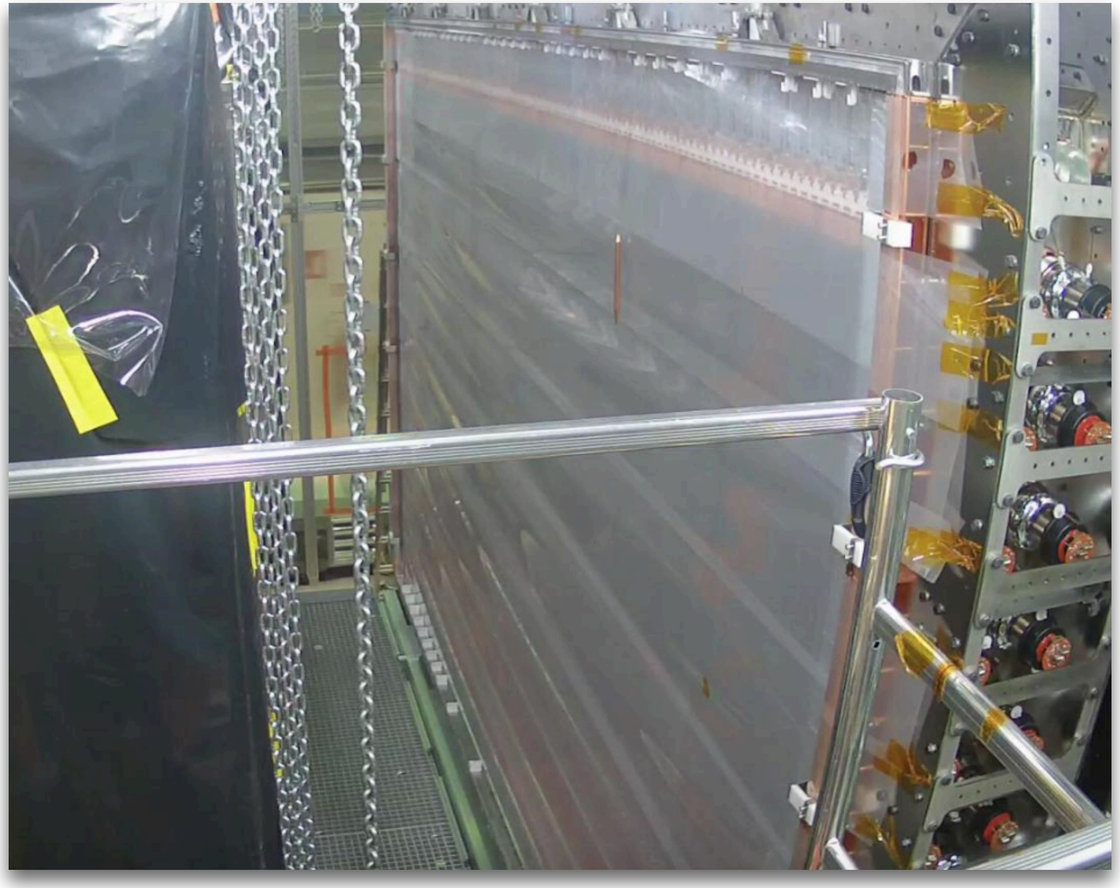




- We care about ^{214}Bi and ^{208}Tl
- BiPo looks for β$^-$ followed by α
- Shorter α delay makes the thorium-series decay easier to measure:
  - ^{208}Tl Sensitivity: 2 μBq/kg
  - ^{214}Bi Sensitivity: 140 μBq/kg
    (90% CL, 6 months measurement)
- Foil testing and analysis ongoing
- Absolute worst-case scenario:
  - ^{208}Tl activity: 370 μBq
  - ^{214}Bi activity: 2200 μBq

Source frame installation

Source frame clamped to half detector



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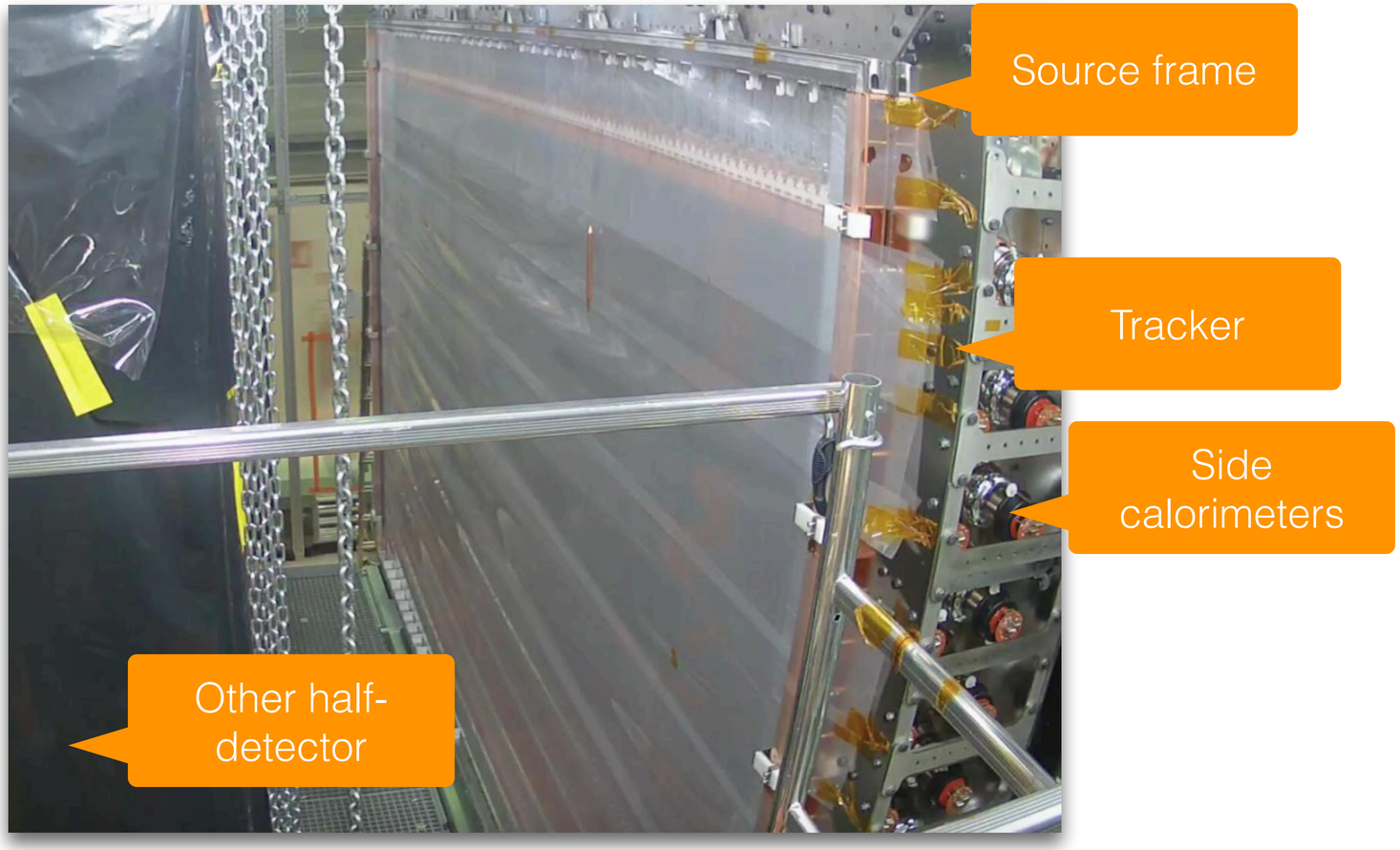

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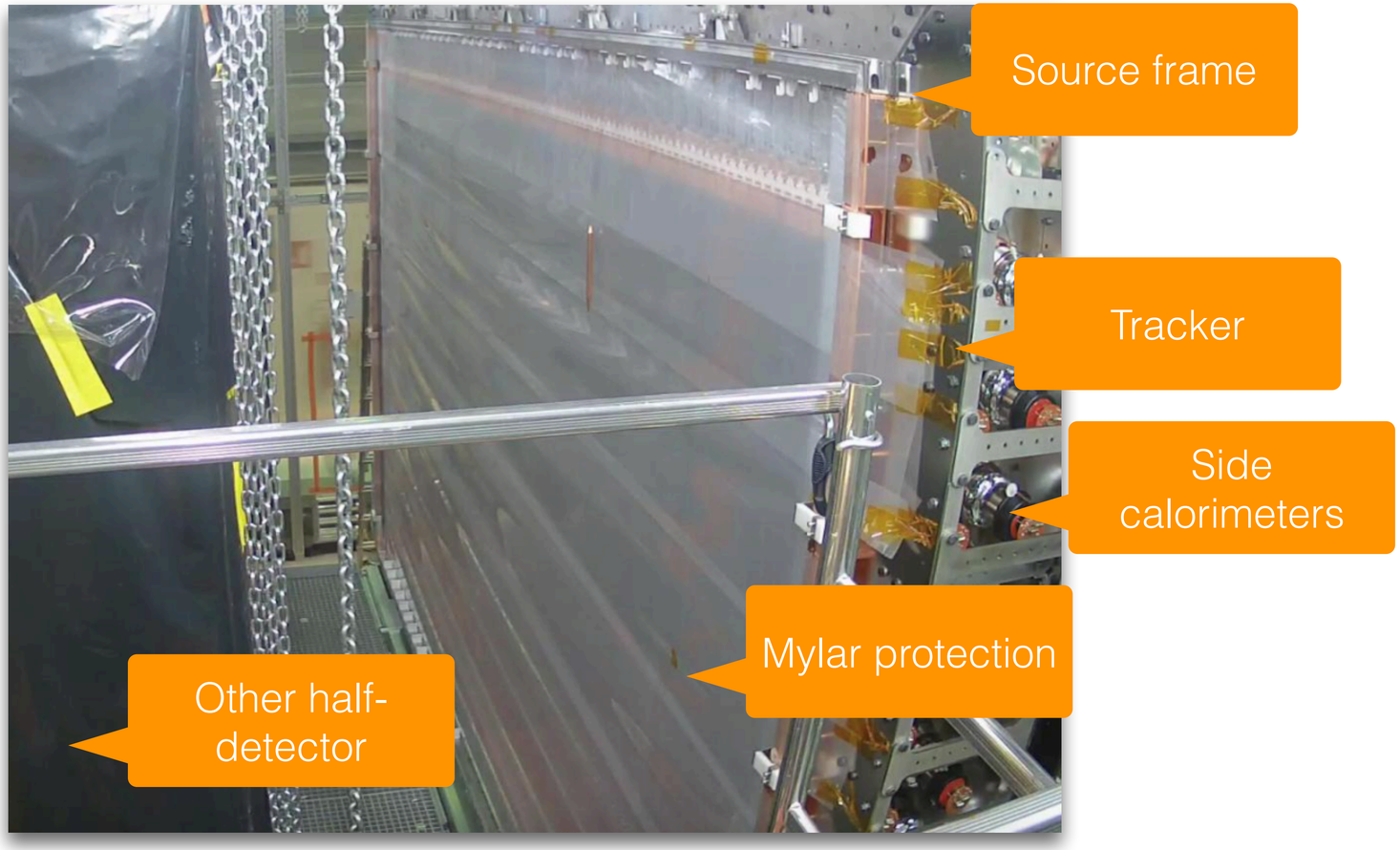

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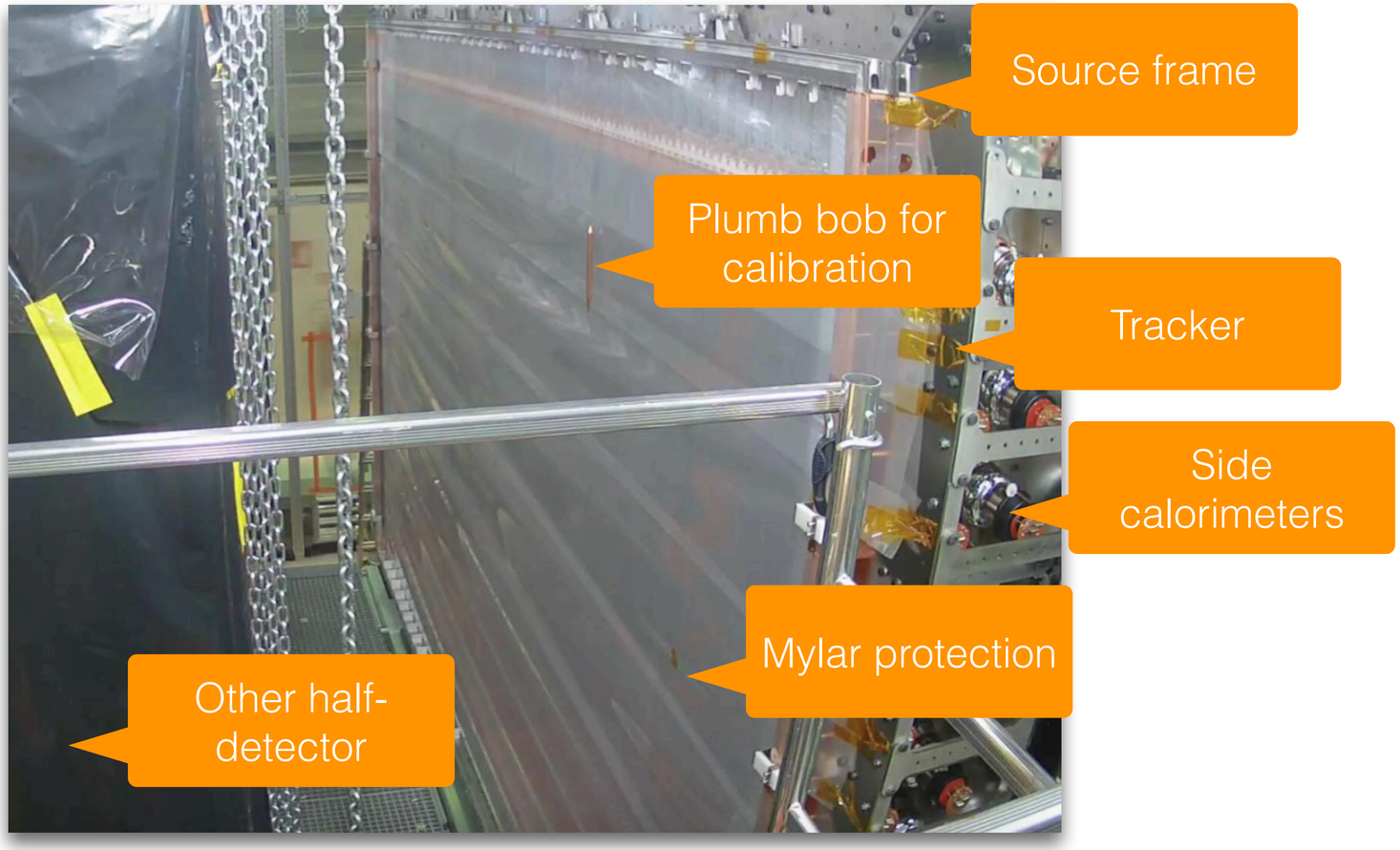

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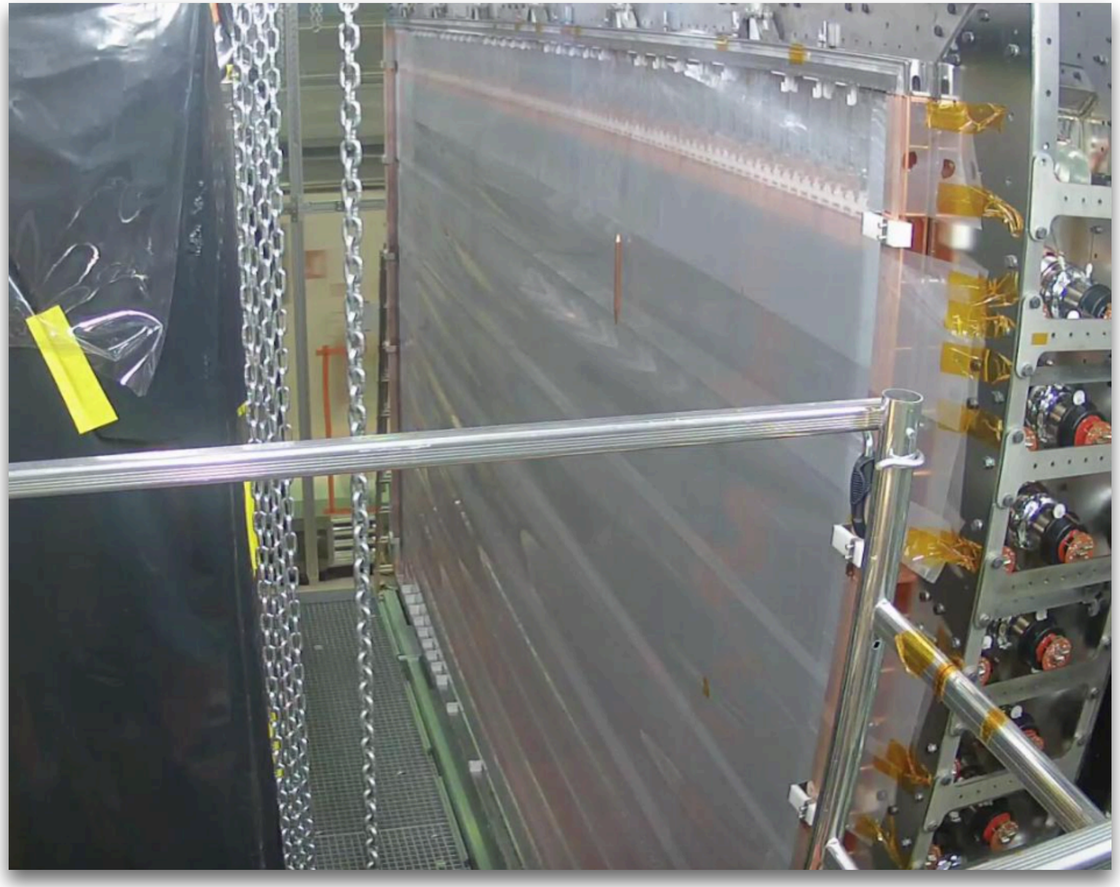
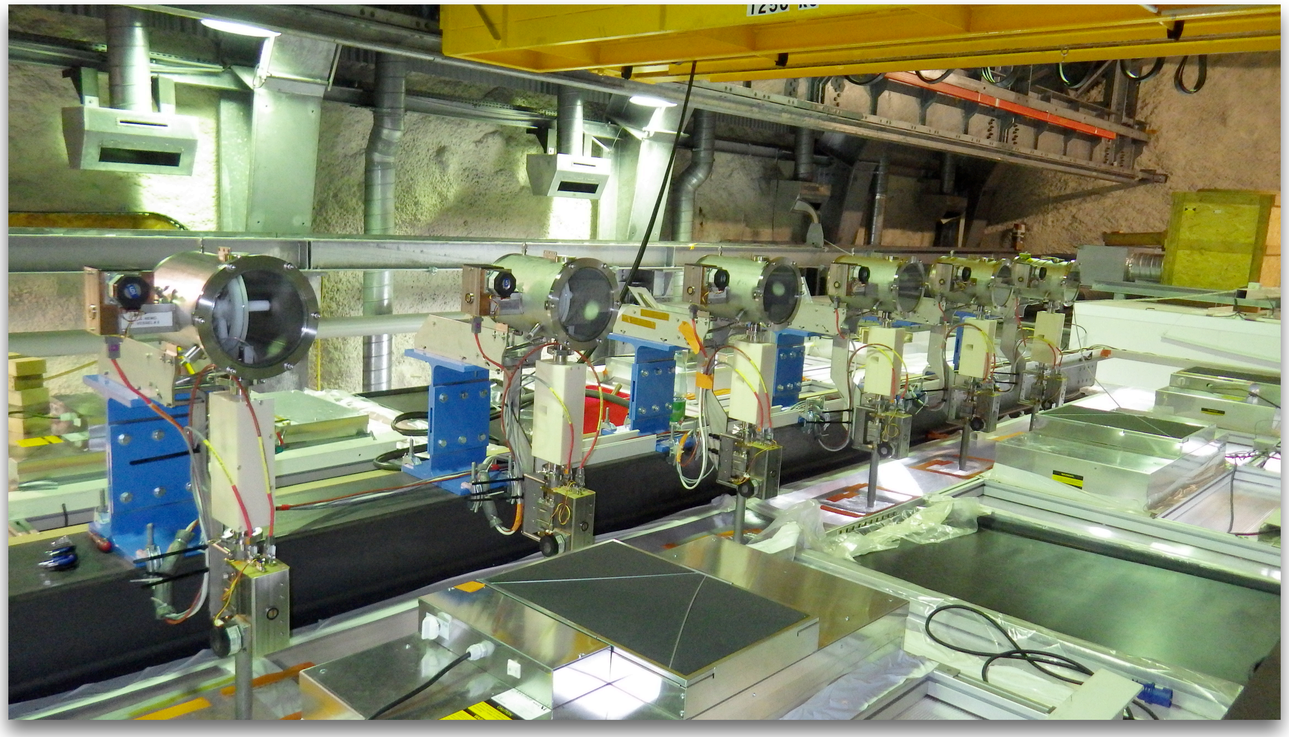
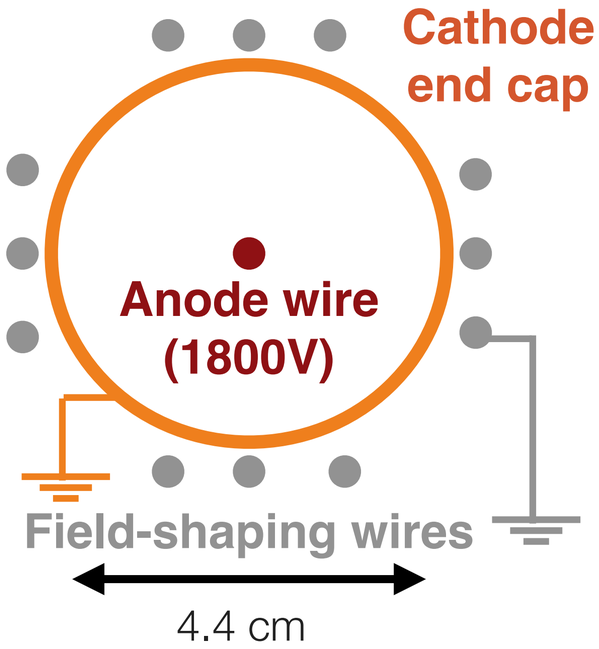
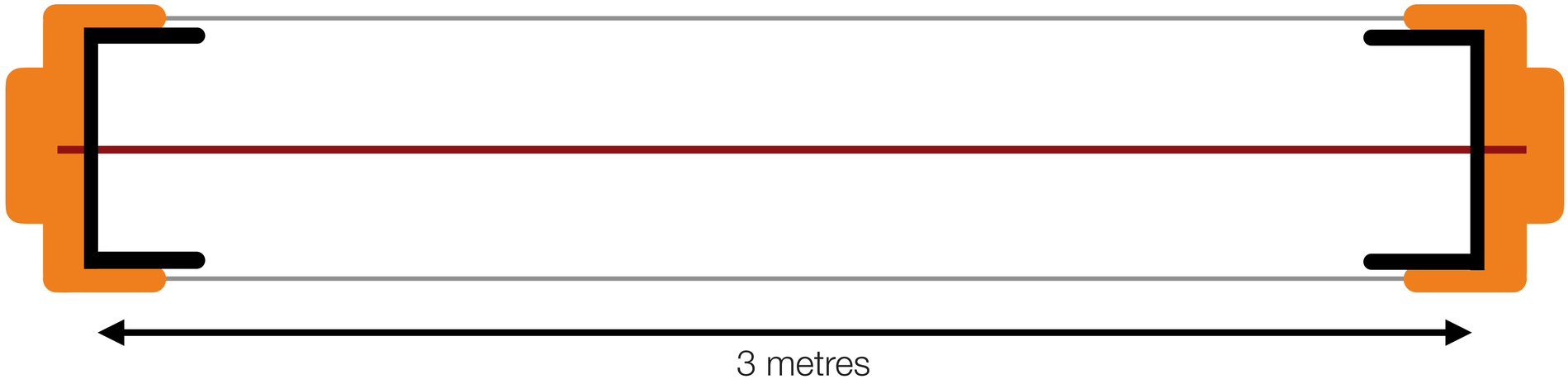


Calibration source (^{207}Bi) deployment system installed



A tracker drift cell





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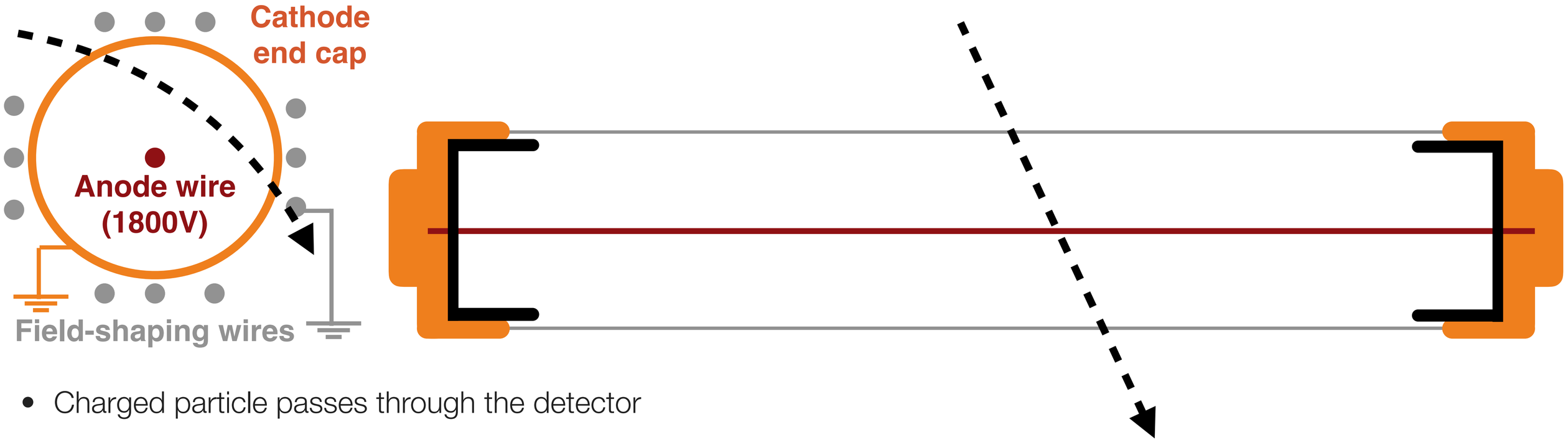
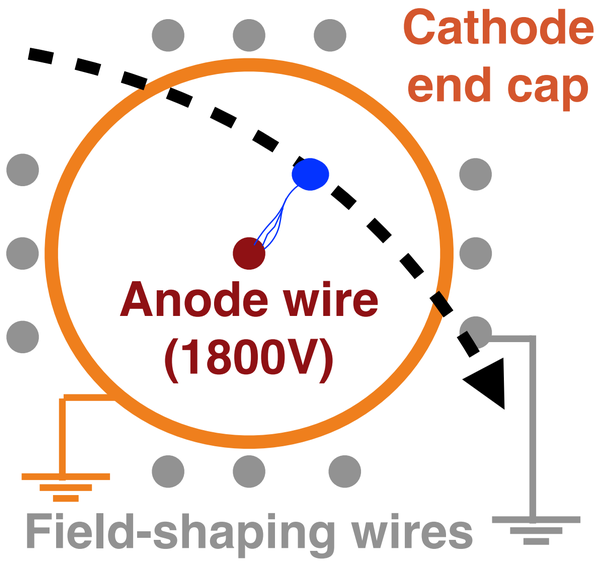
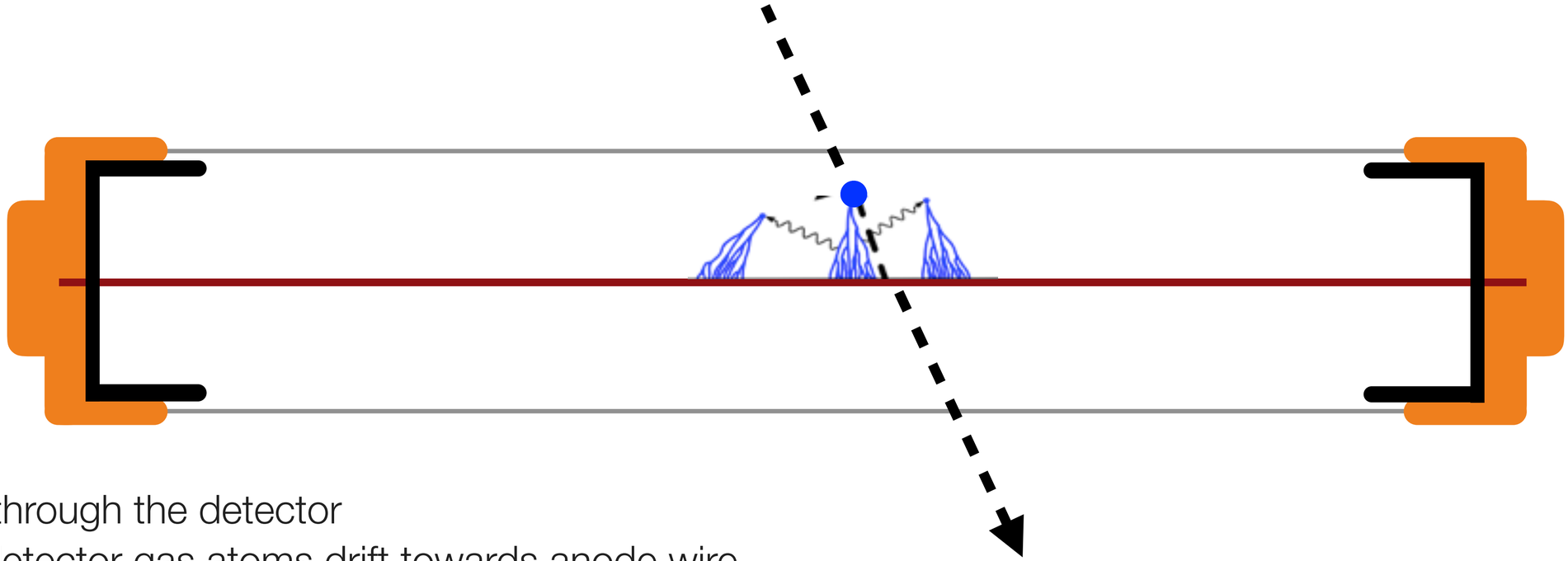


- Charged particle passes through the detector

A tracker drift cell





- Charged particle passes through the detector
- Electrons knocked from detector gas atoms drift towards anode wire
  - Electrons ionise more atoms, causing an avalanche
  - Geiger mode: shower saturates (electric field of anode shielded by ion pairs)
  - Drift time gives radius of closest approach r

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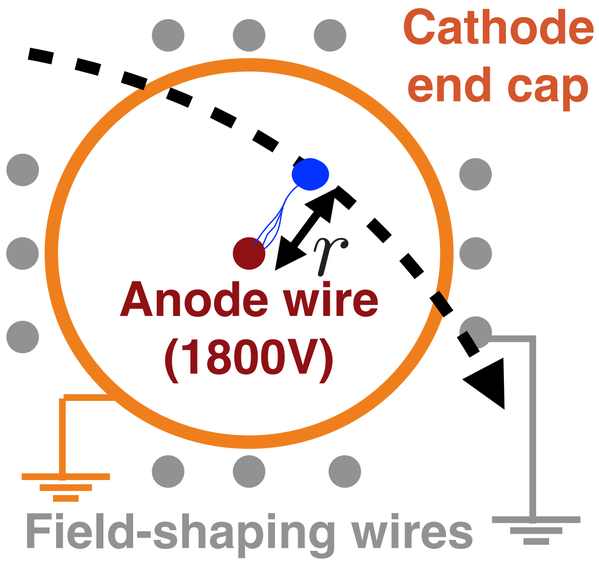

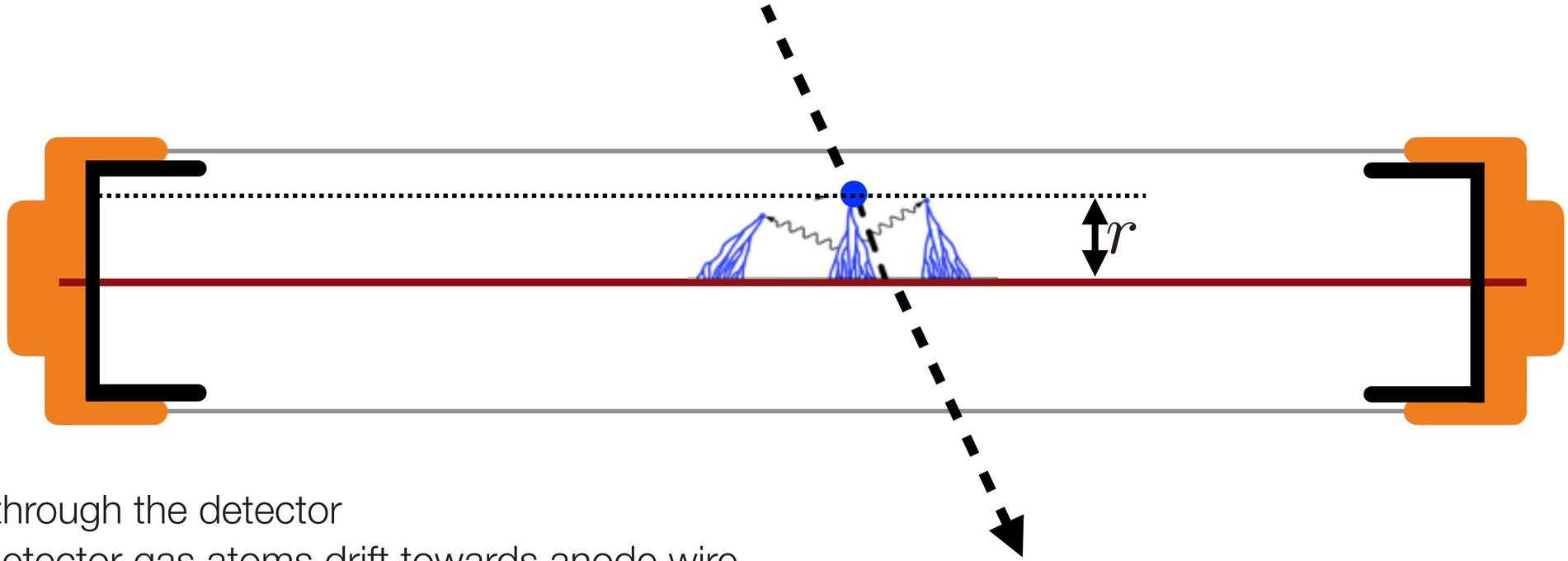

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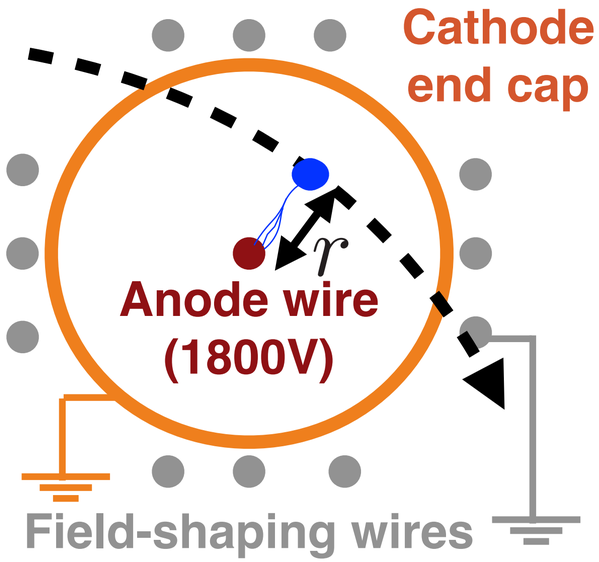

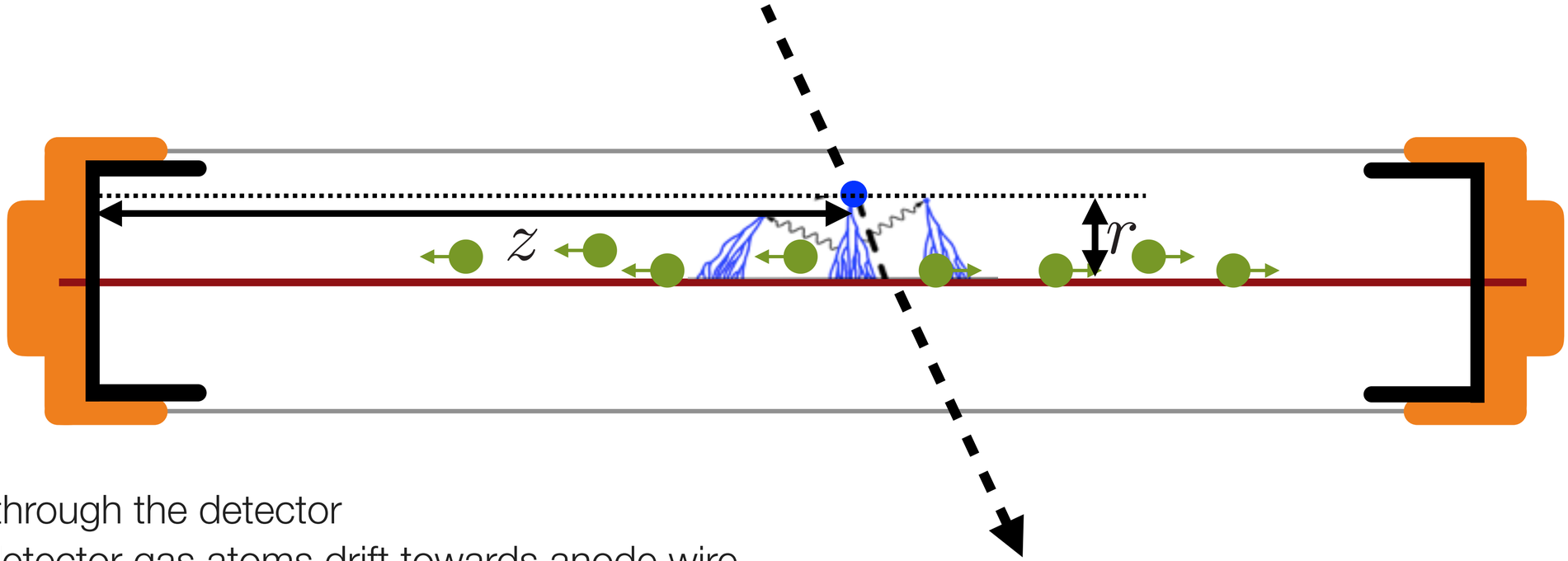

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  - Electrons ionise more atoms, causing an avalanche
  - Geiger mode: shower saturates (electric field of anode shielded by ion pairs)
  - Drift time gives radius of closest approach r
- Geiger plasma propagates along the wire towards the two end caps
  - Difference in arrival times at the two end caps gives distance along wire z

Tracker gas mixture

95% Helium

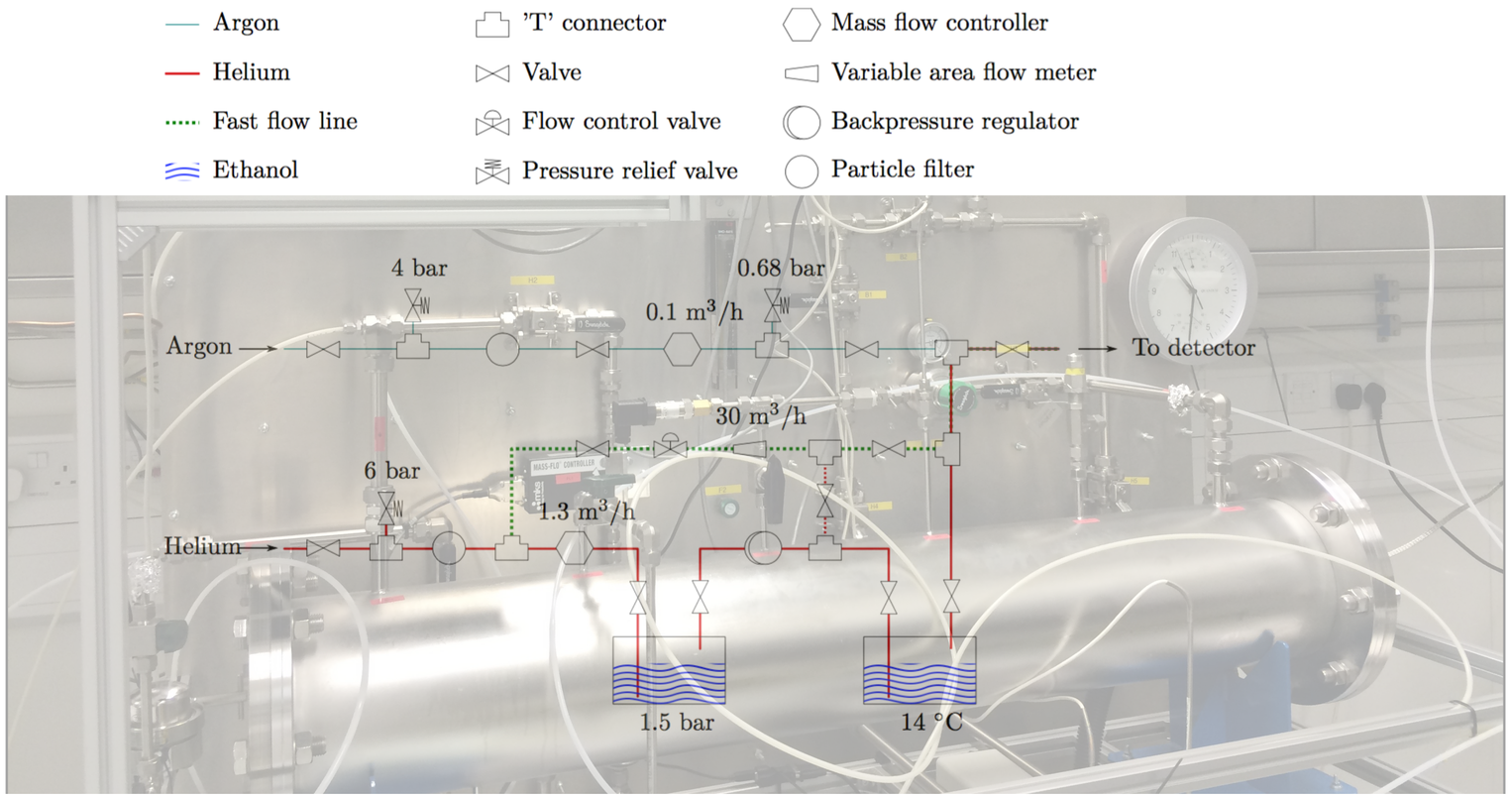
Low atomic mass; prevents multiple scattering and energy loss

1% Argon

Low ionisation energy; helps avalanche propagate

4% Ethanol

Quenches avalanche; prevents re-firing



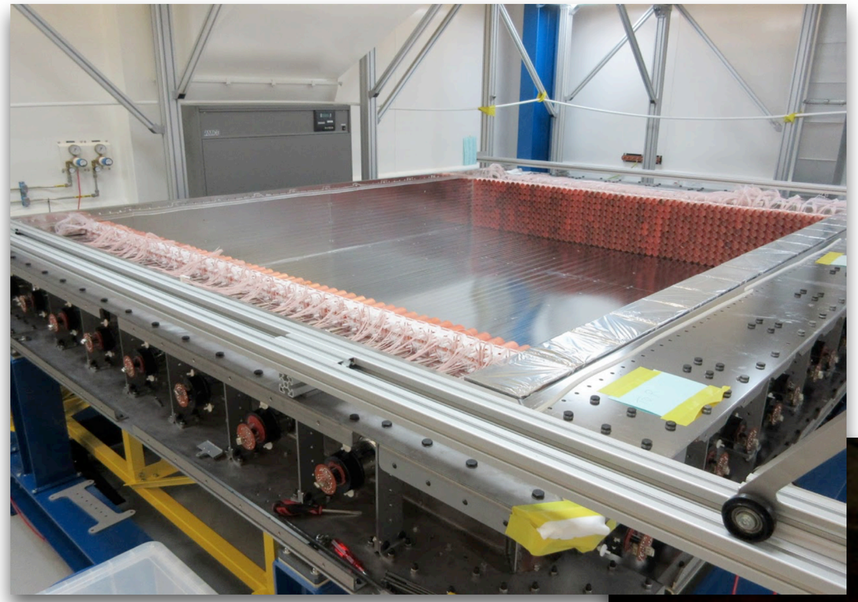
Gas system controlled by Raspberry Pi to monitor and control temperature, pressure, flow rate
2°C temperature change → 0.5% change in ethanol fraction → tracker efficiency

Building the tracker

2034 drift cells wired in Manchester
Arranged in rows of 9 cells (from source end to calorimeter end).

Installed into 4 C-shaped tracker sections at MSSL (UCL);
C-sections commissioned and tested for radon

Wire trackers



Completed C-section ready for shipping

In the Fréjus tunnel, approaching LSM

Pairs of C-sections joined and attached to a calorimeter wall

Radon in the tracker

Target activity: 0.15 mBq / m^3

Two things to consider: tracker components and gas mixture

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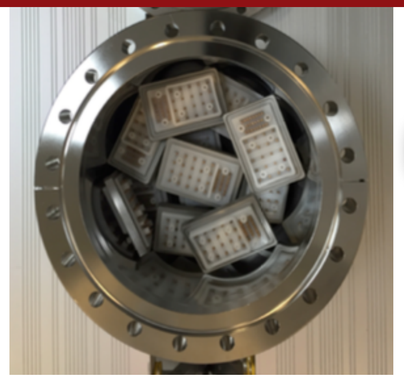
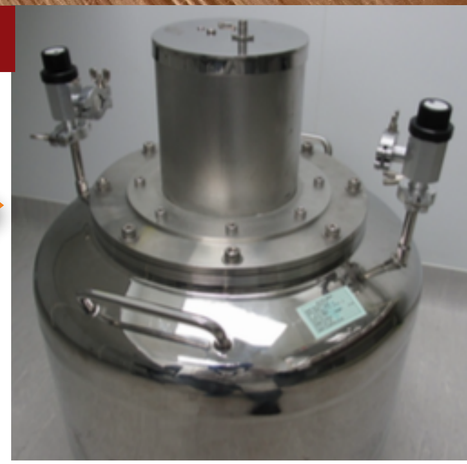


Flush with helium



Potential component emanates radon in chamber (10 days+)

70-litre electrostatic detector can measure activities down to **0.09 mBq**

Radon in the tracker

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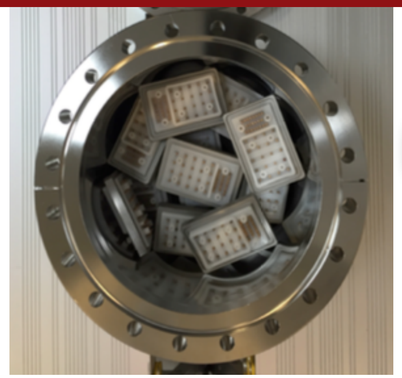
Tracker gas

0.15 mBq / m^3 → **0.01 mBq in 70 litres**

Tracker components



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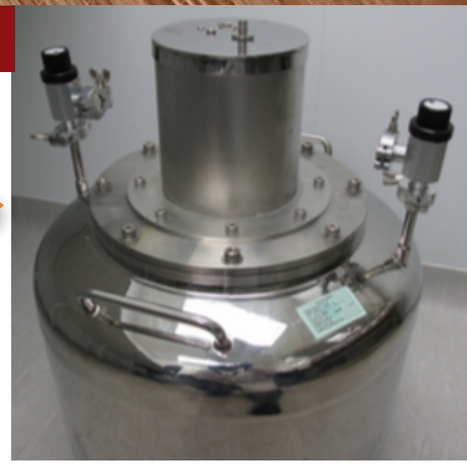

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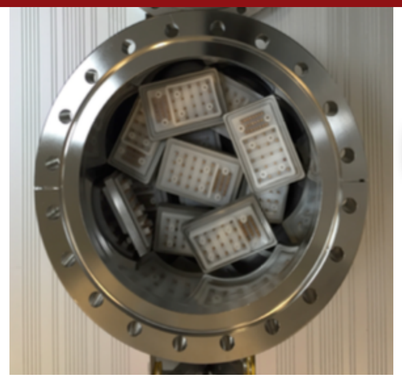

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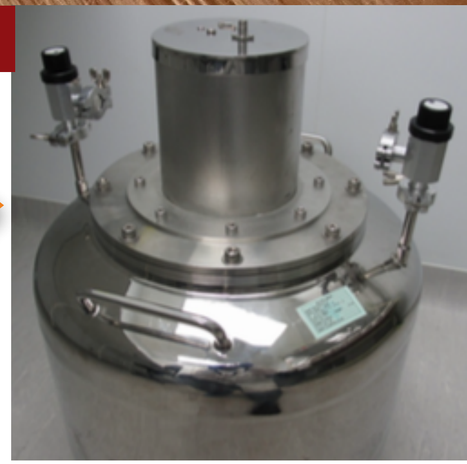

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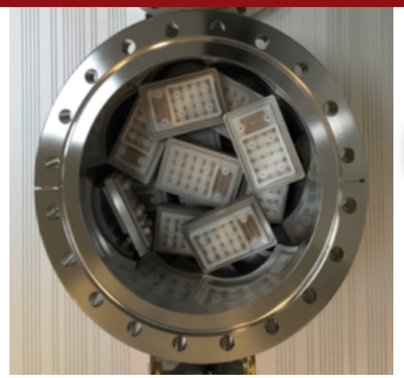
UCL developed the **radon concentration line (RnCL)**

Tracker components



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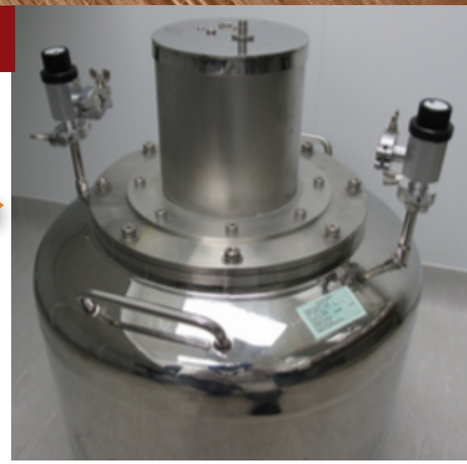

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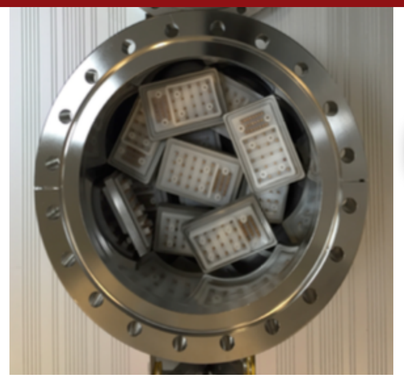

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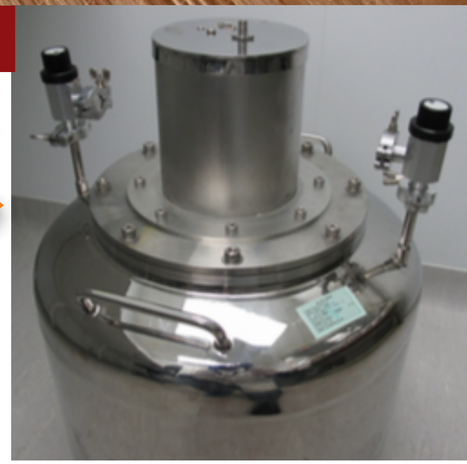
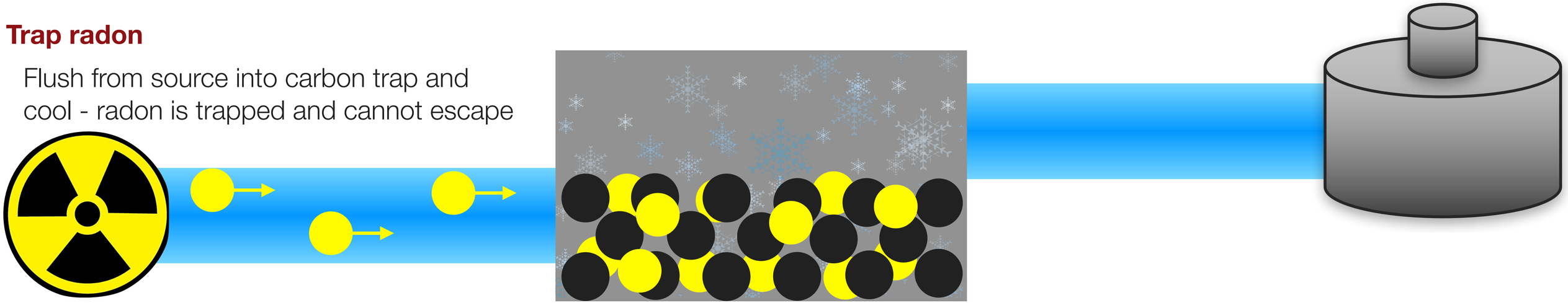


70-litre electrostatic detector can measure activities down to **0.09 mBq**

Trap radon

Flush from source into carbon trap and cool - radon is trapped and cannot escape



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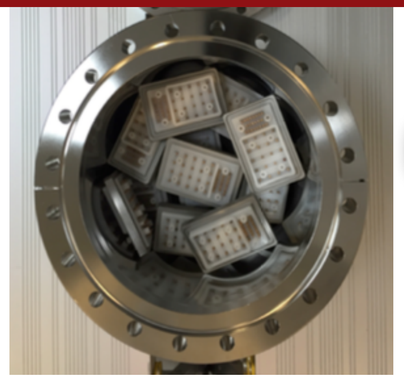

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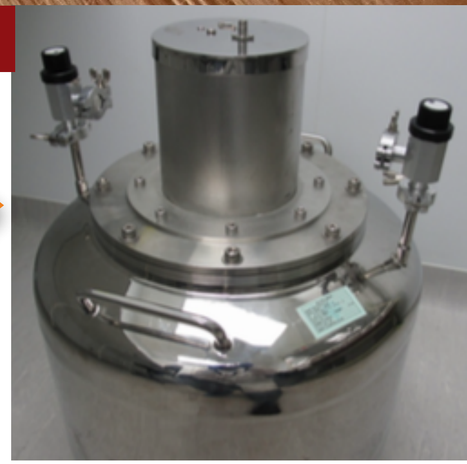
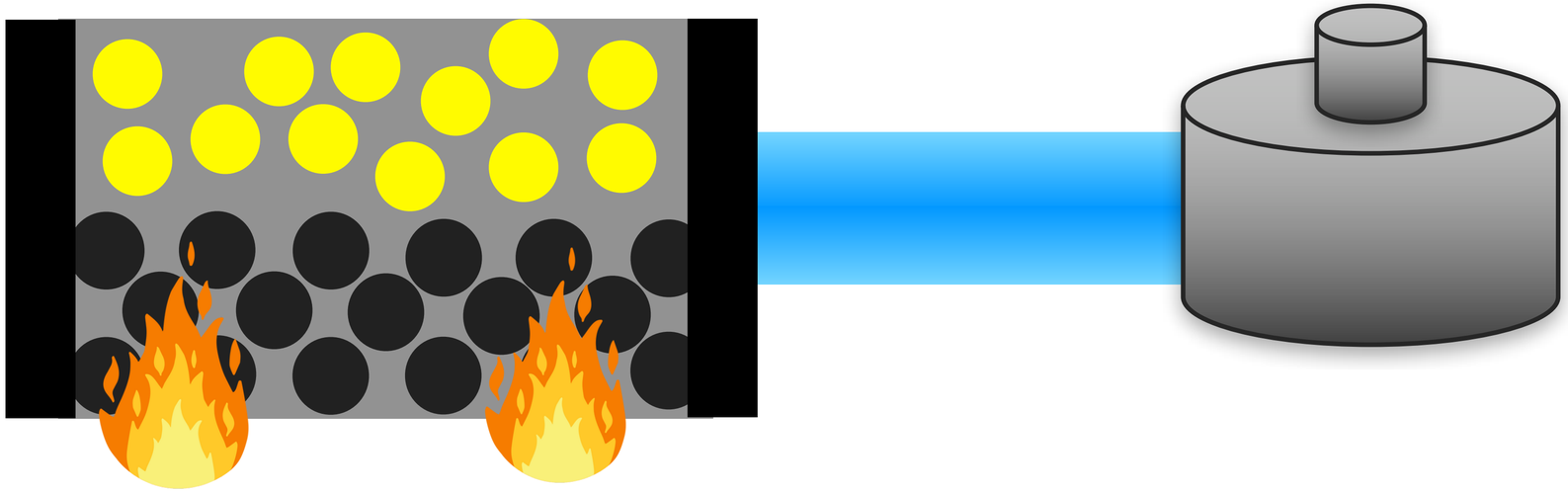


70-litre electrostatic detector can measure activities down to **0.09 mBq**

Release the radon

Seal and heat trap to release the trapped radon



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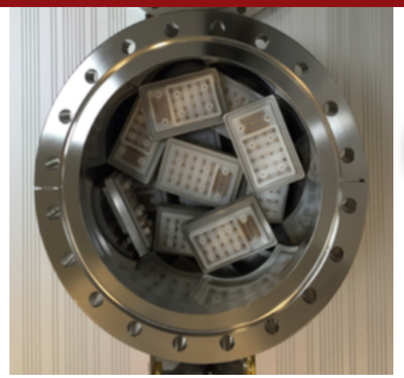

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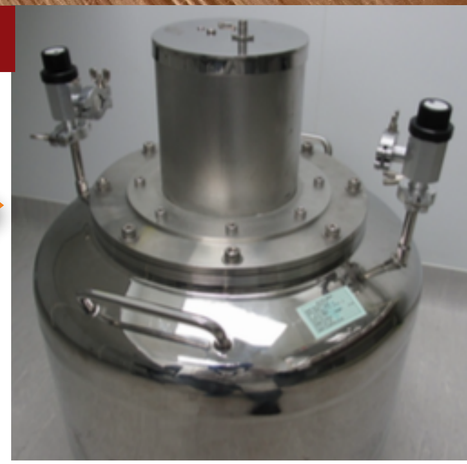
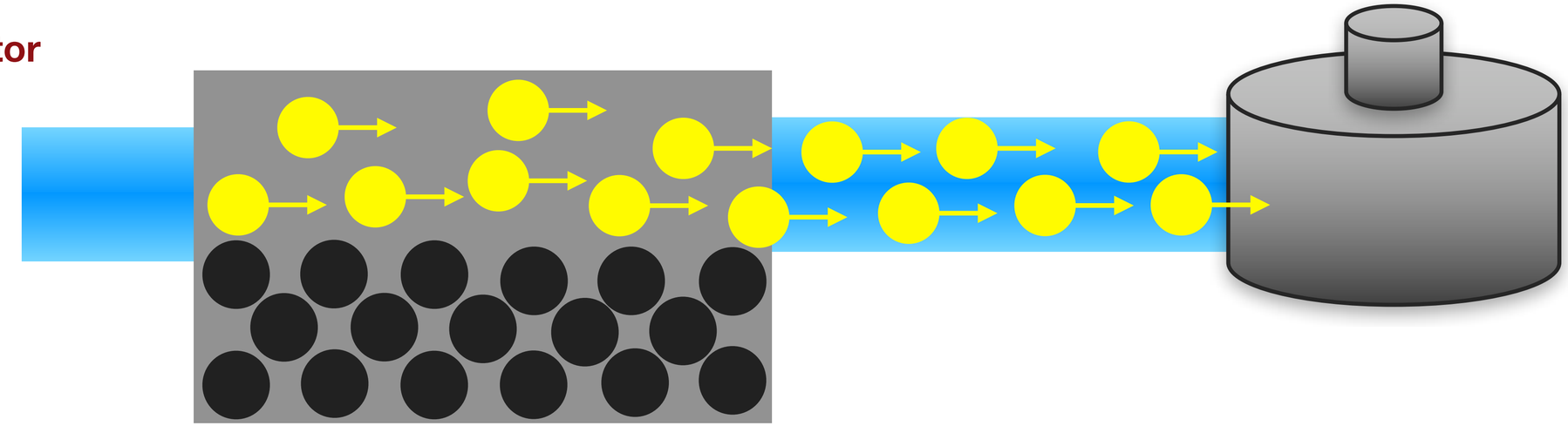


70-litre electrostatic detector can measure activities down to **0.09 mBq**

Flush helium through trap to detector

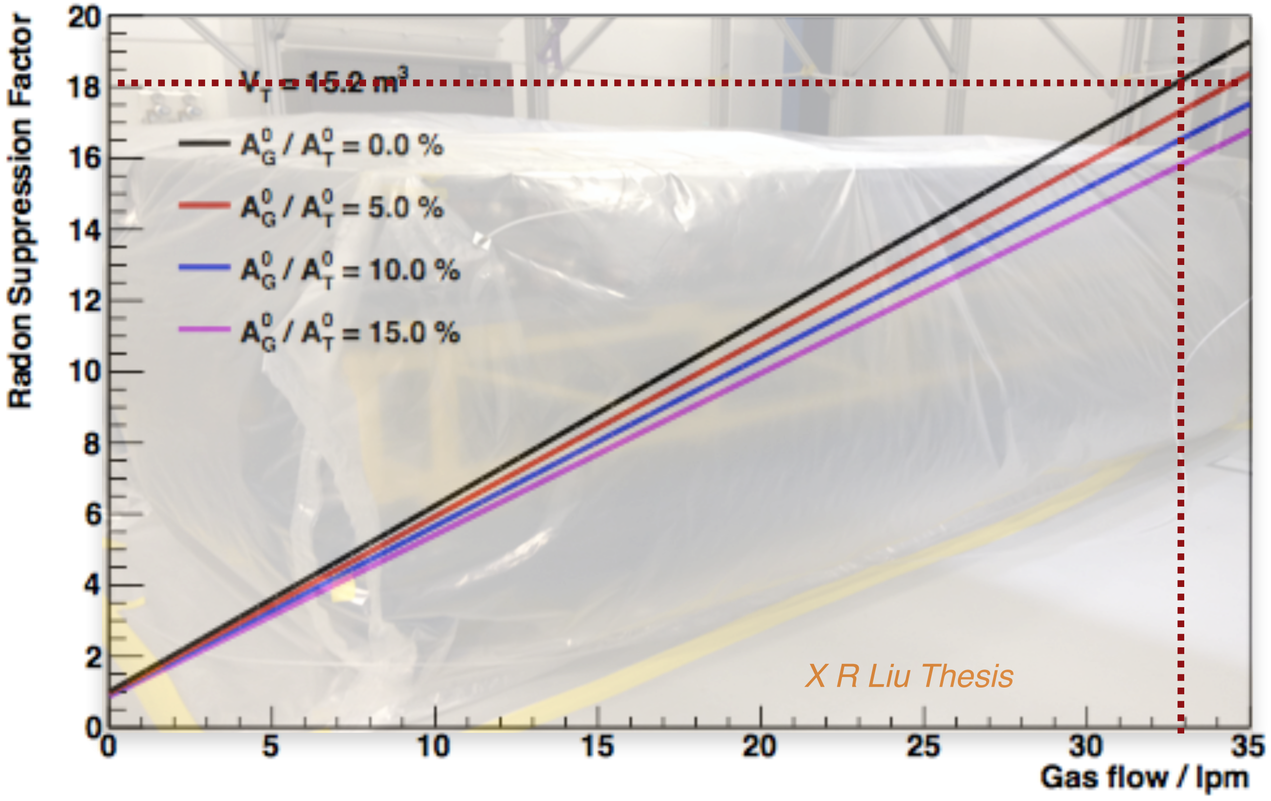
Radon is now concentrated enough that the we can detect it.

Use trapping and detection efficiencies to get from measured activity to original activity.



Concentration line and the tracker

Concentration line measures tracker activity **2.7 ± 0.3 mBq / m³**
Requirement is **0.15 mBq / m³**
Activity **18** times too high
What to do? **Flow clean gas** (radio-pure He measured by UCL)



Suppression factor = $\dfrac{1 + A_G/A_T}{1 + f/V_T\lambda}$

Gas and tracker activities

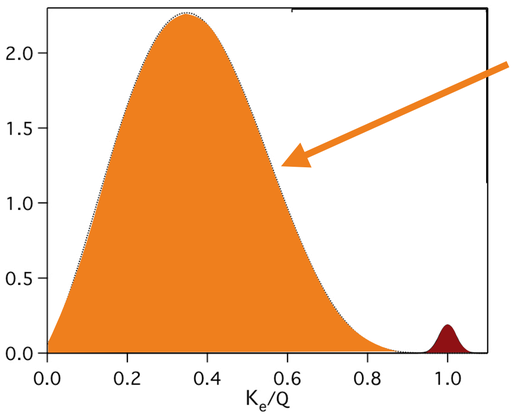
Radon half life

Flow rate

Tracker volume

For full tracker (15.2 m³)
Required flow rate is **33 litres per minute**
Equivalent to **2 m³ / hour**

Optical modules and calorimetry

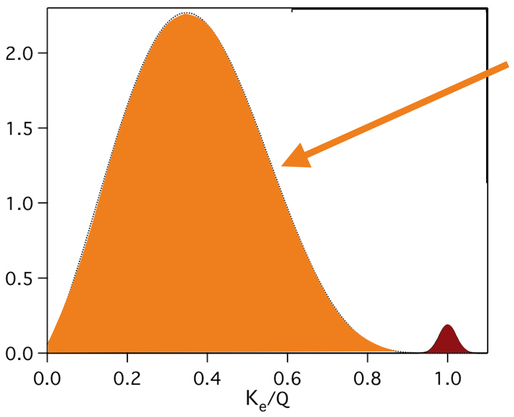


2νββ

Need good energy resolution

Nucl. Inst. Meth. A 868, 98-108 (2017)

Optical modules and calorimetry



2νββ

Need good energy resolution

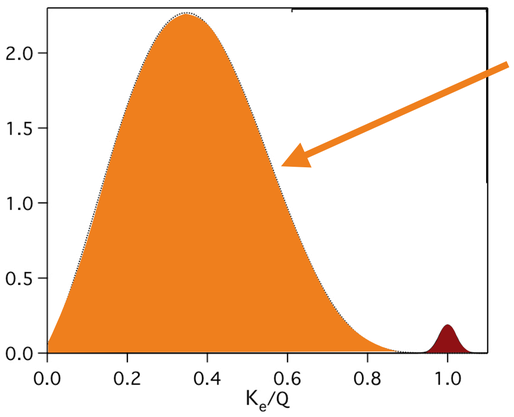
8” radiopure PMT with improved photocathode quantum efficiency

Directly coupled - no light-guide

256 x 256 x 194 mm Polysytrene scintillator block with optimised surface finish

Nucl. Inst. Meth. A 868, 98-108 (2017)

Optical modules and calorimetry



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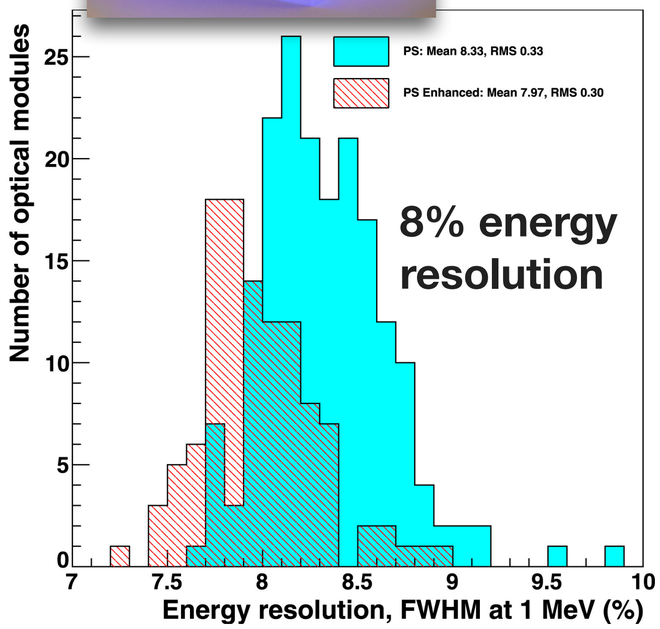
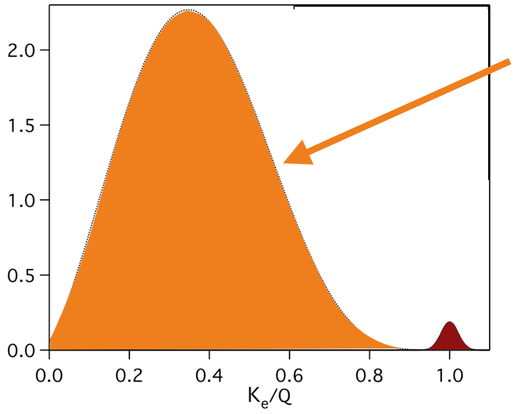


Time resolution: 400ps (1MeV)

Nucl. Inst. Meth. A 868, 98-108 (2017)

Optical modules and calorimetry



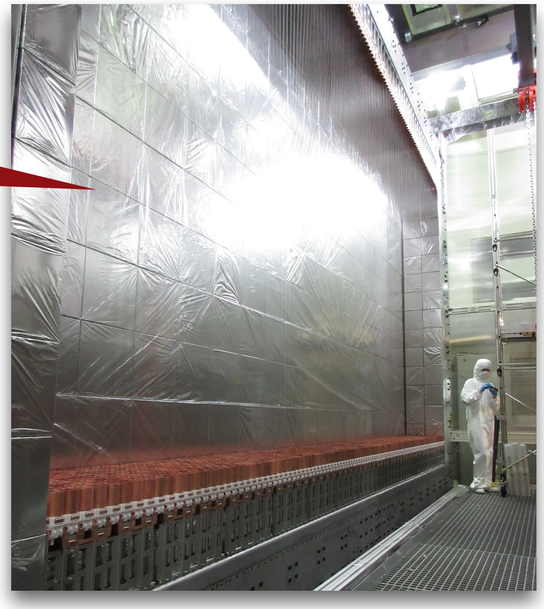
2νββ
Need good energy resolution

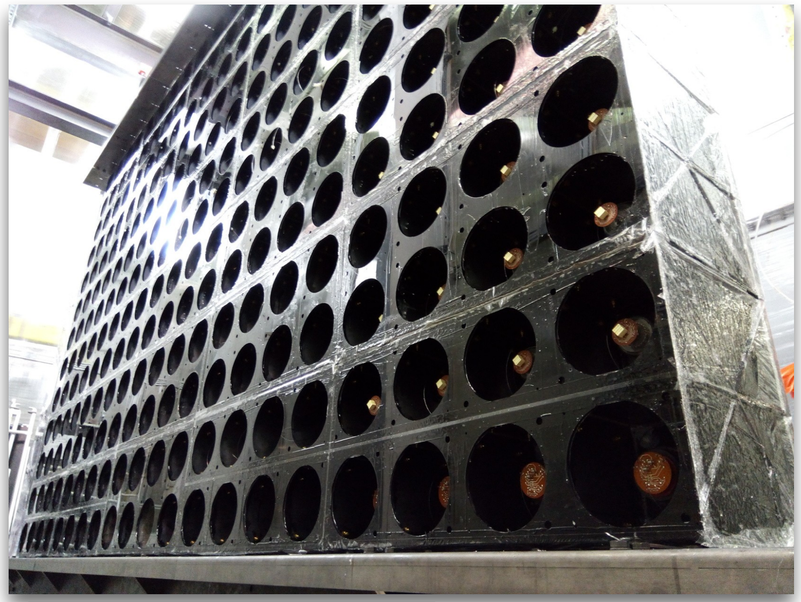
8” radiopure PMT with improved photocathode quantum efficiency

Directly coupled - no light-guide

256 x 256 x 194 mm Polysytrene scintillator block with optimised surface finish

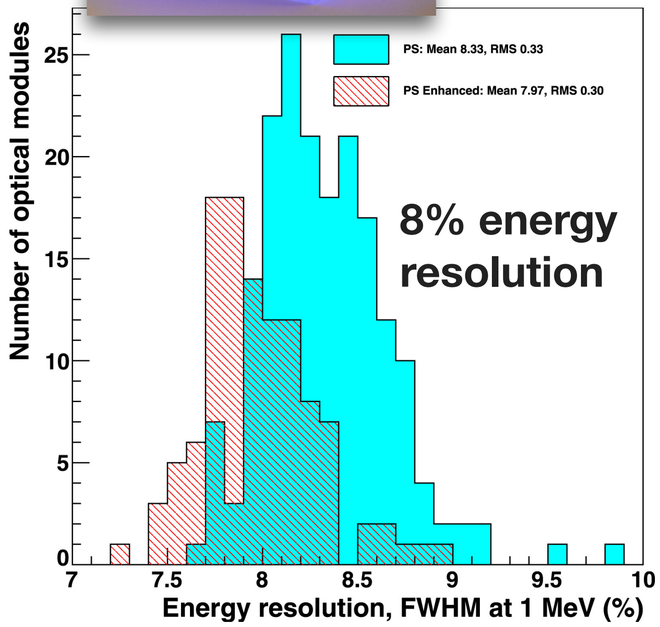
Wrapping also improved





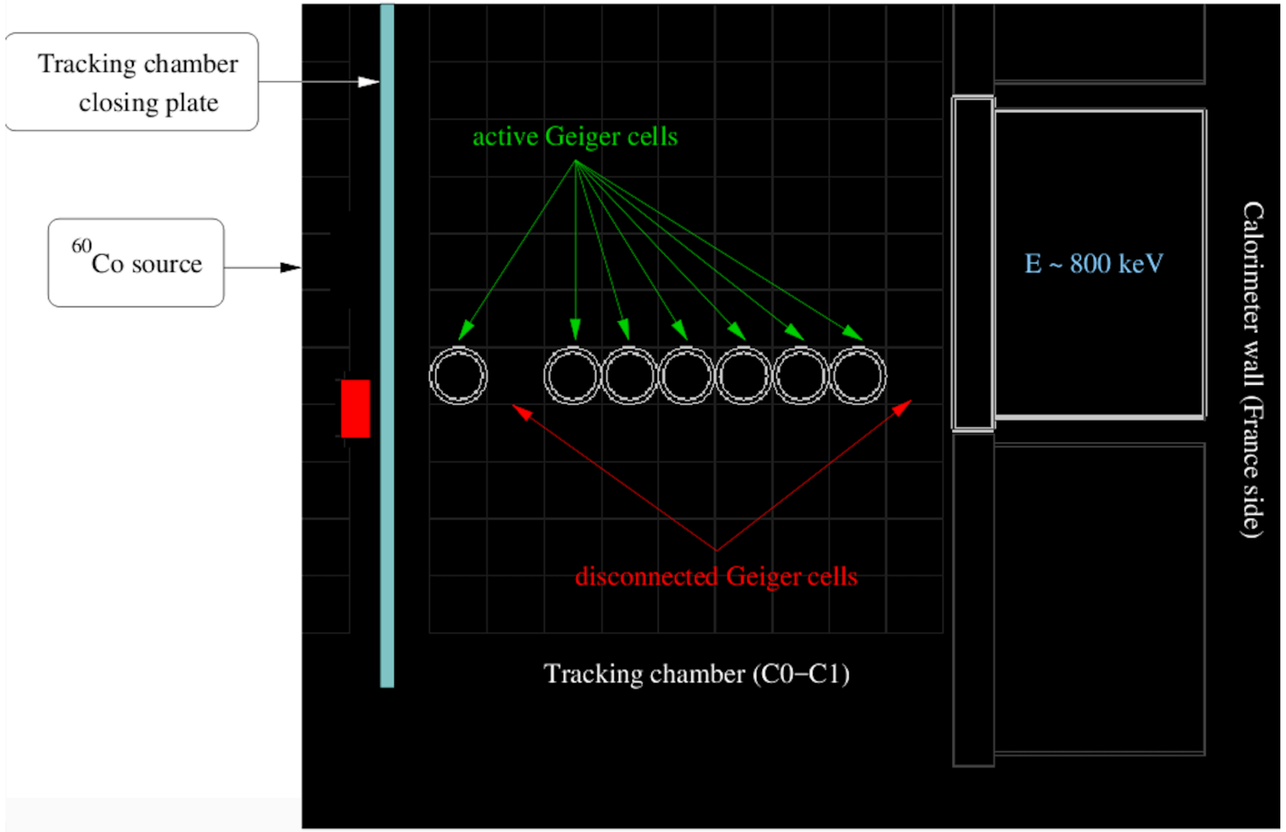
Nucl. Inst. Meth. A 868, 98-108 (2017)

Main calorimeter walls: 520 optical modules
With side, top and bottoms: 712 modules total



Time resolution: 400ps (1MeV)

Half-detector status

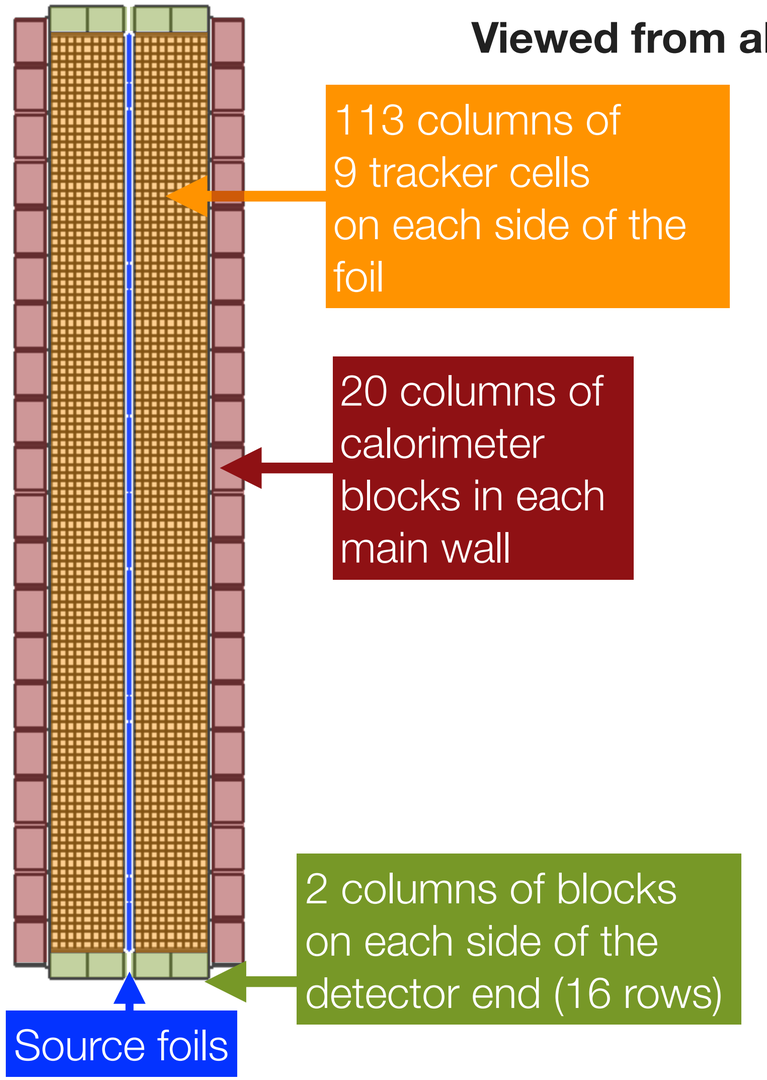


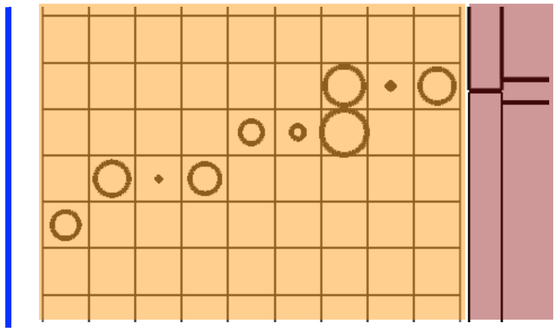
2017: half-detector commissioning with cobalt-60 source

Half-detector opened and awaiting source frame attachment

SuperNEMO in the event display

Viewed from above





Tracker hits appear as circles, whose radius is determined from drift time to the anode

SuperNEMO in the event display

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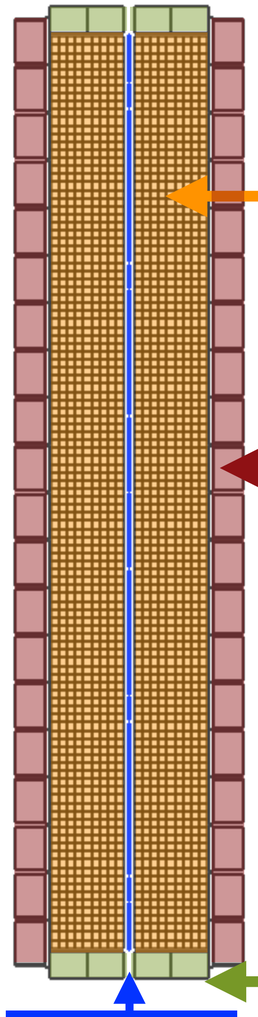
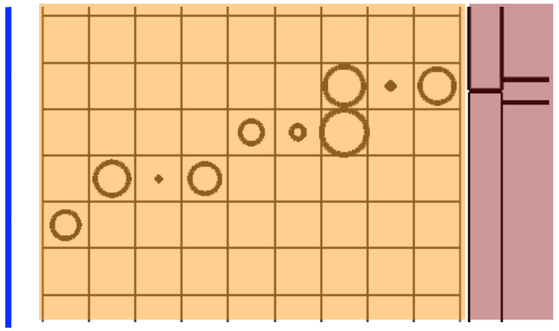


113 columns of 9 tracker cells on each side of the foil

20 columns of calorimeter blocks in each main wall

2 columns of blocks on each side of the detector end (16 rows)

Source foils



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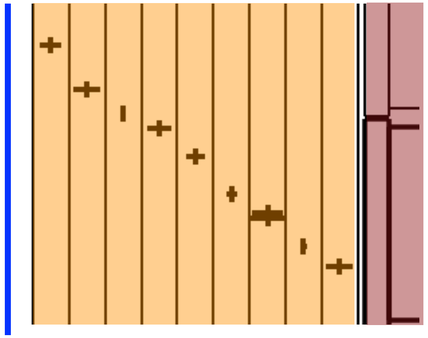
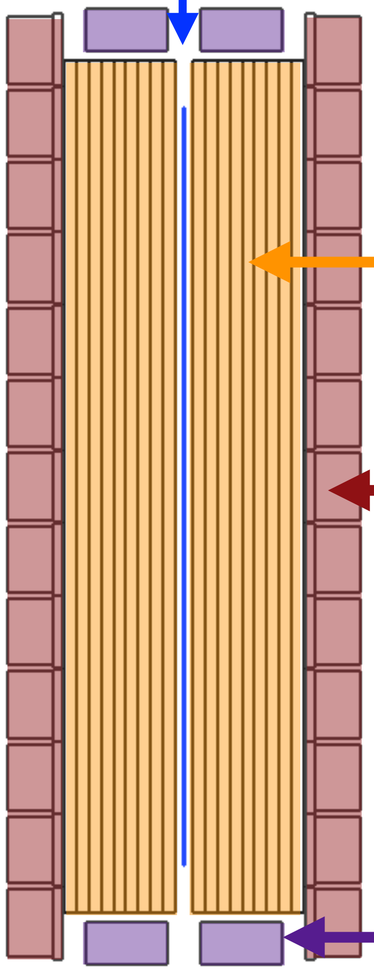


Position along the wire comes from plasma propagation times, and has a large uncertainty

Viewed from the side

Source foil

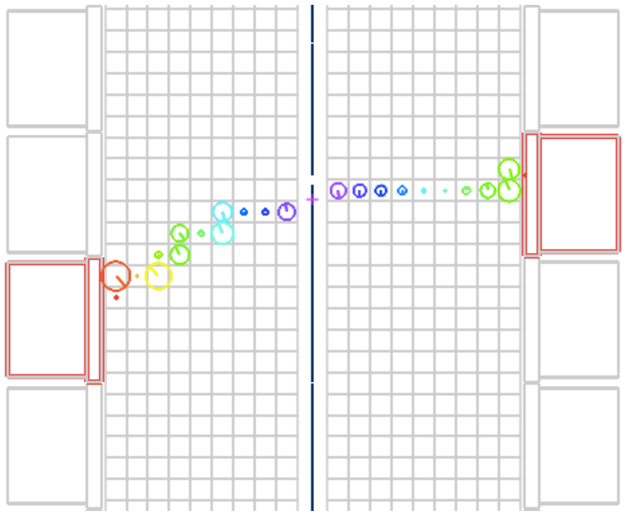


9 tracker cells (wires vertical)

13 rows of calorimeter blocks in each main wall

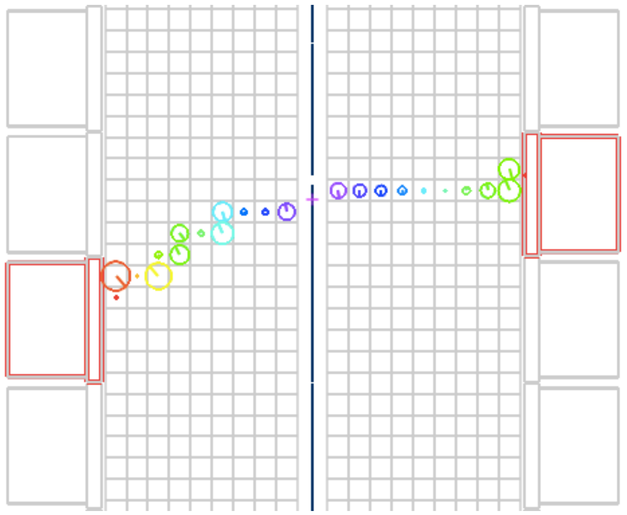
Single row of 16 blocks above and below each side, to veto gammas

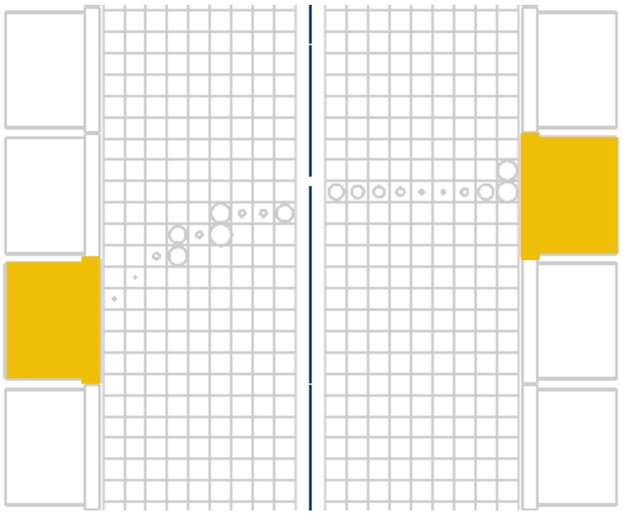
Reconstructing events



- What we are reconstructing: a simulated ββ event

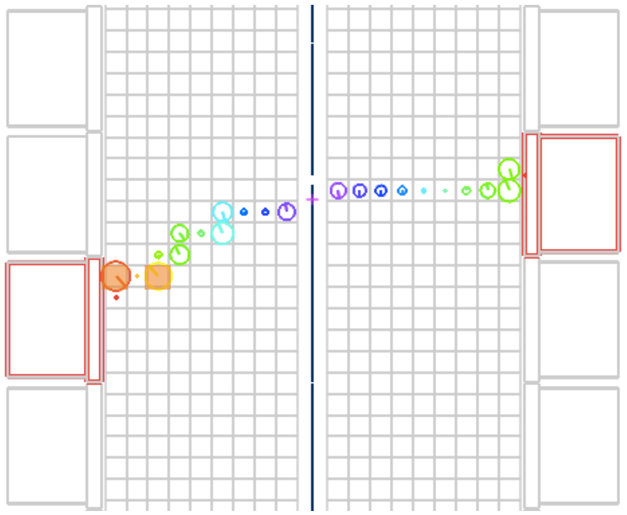
Reconstructing events

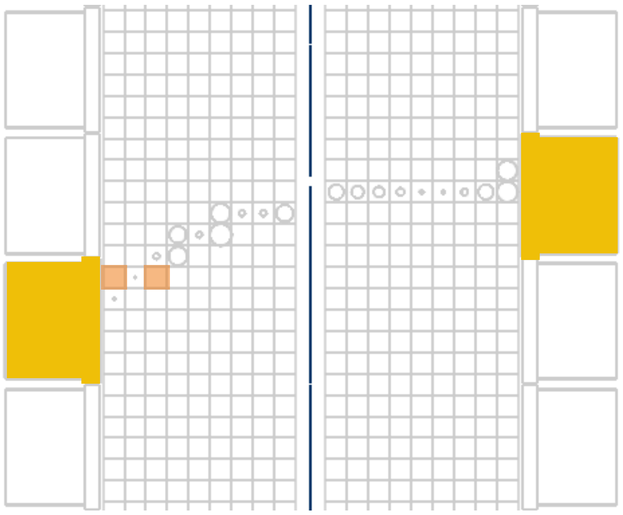




- What we are reconstructing: a simulated ββ event
- Detector gives us radius and longitudinal position of tracker hits, plus energy and time of calorimeter hits

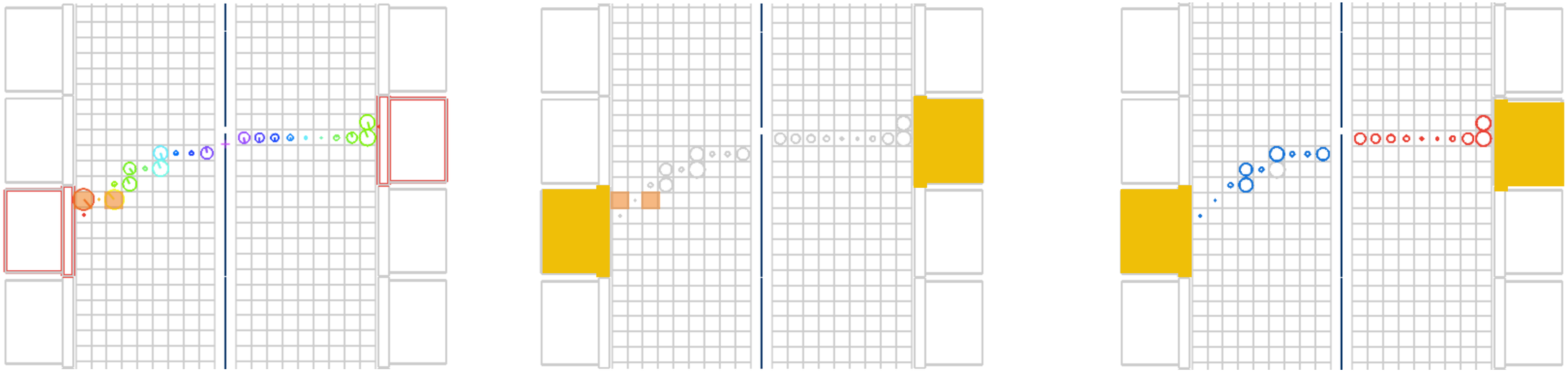
Reconstructing events





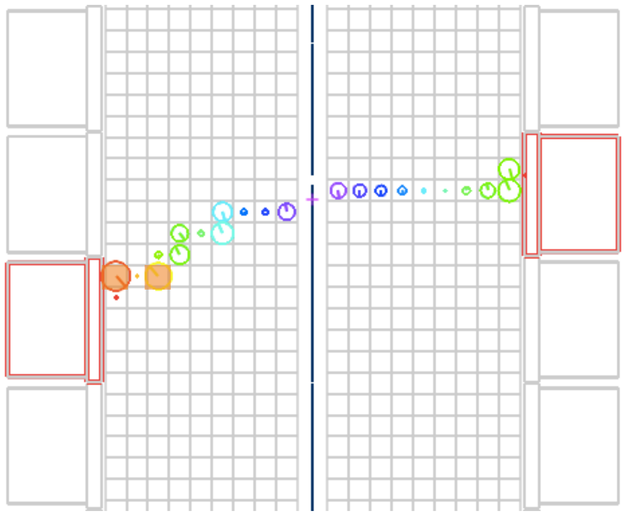
- What we are reconstructing: a simulated ββ event
- Detector gives us radius and longitudinal position of tracker hits, plus energy and time of calorimeter hits
    - Reconstruction efficiency decreases with hit radius

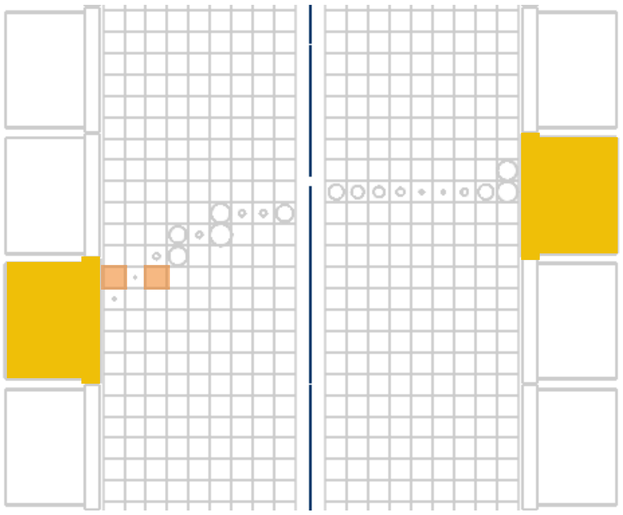
Reconstructing events

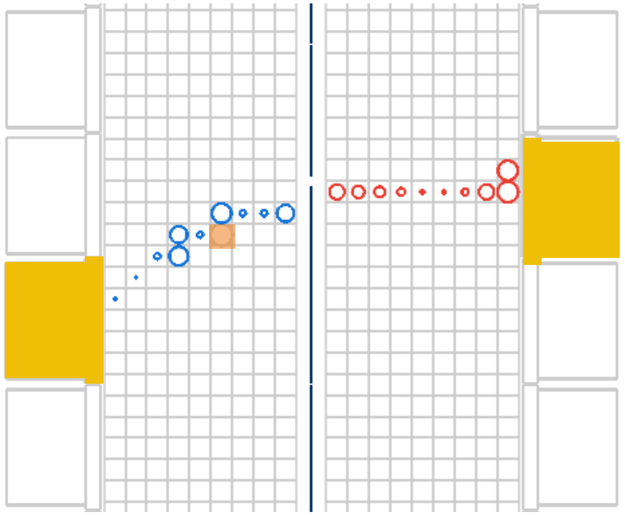


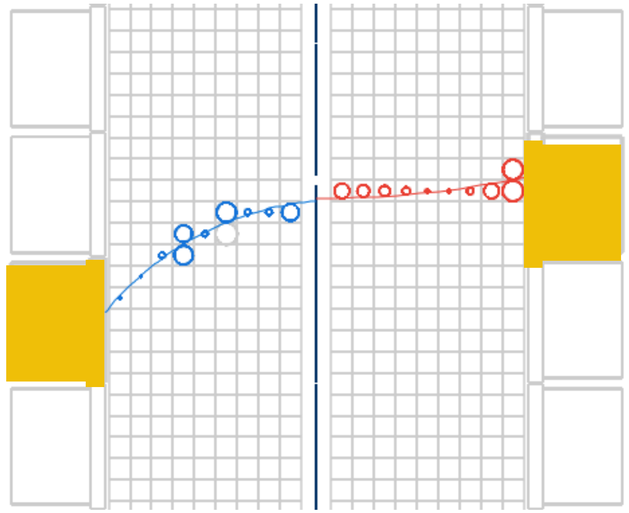
- What we are reconstructing: a simulated ββ event
- Detector gives us radius and longitudinal position of tracker hits, plus energy and time of calorimeter hits
- Cluster hits based on position and timing

Reconstructing events







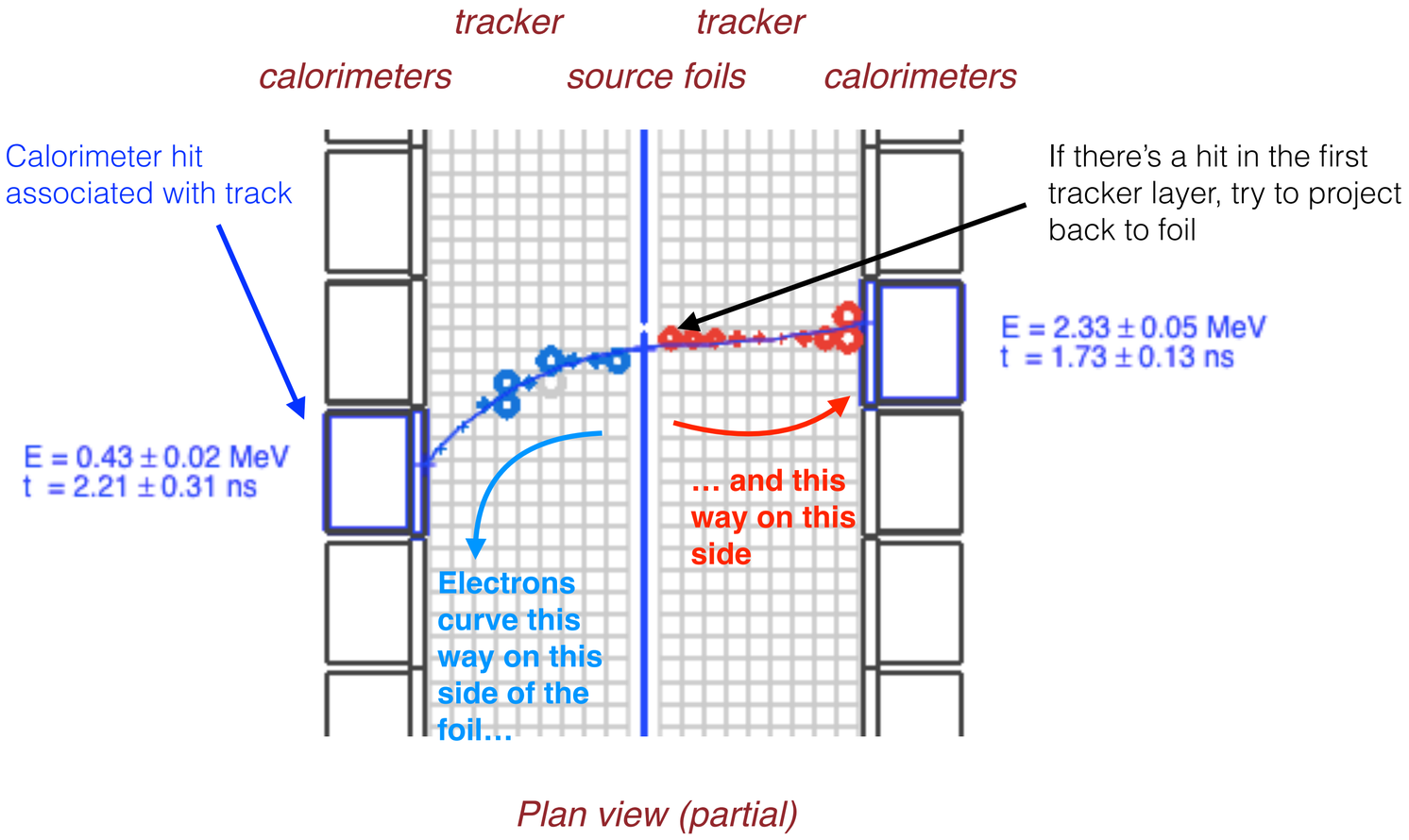


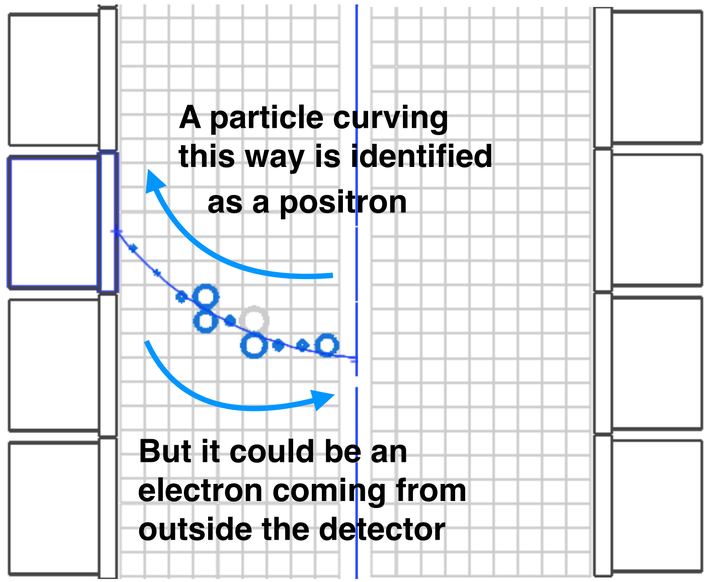
- What we are reconstructing: a simulated ββ event
- Detector gives us radius and longitudinal position of tracker hits, plus energy and time of calorimeter hits
- Cluster hits based on position and timing
- Try to fit helix and straight tracks; pick track with best χ^2

Reconstructing events

- What we are reconstructing: a simulated ββ event
- Detector gives us radius and longitudinal position of tracker hits, plus energy and time of calorimeter hits
- Cluster hits based on position and timing
- Try to fit helix and straight tracks; pick track with best χ^2
- Associate with calorimeter hits to reconstruct particles

Reconstruction: electrons and positrons

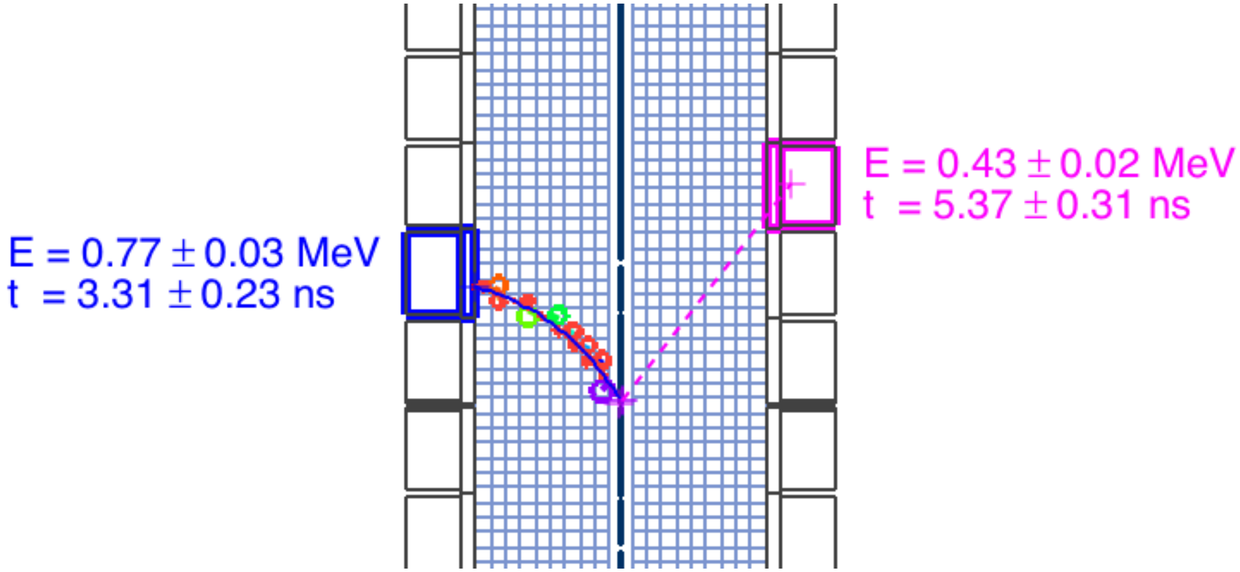




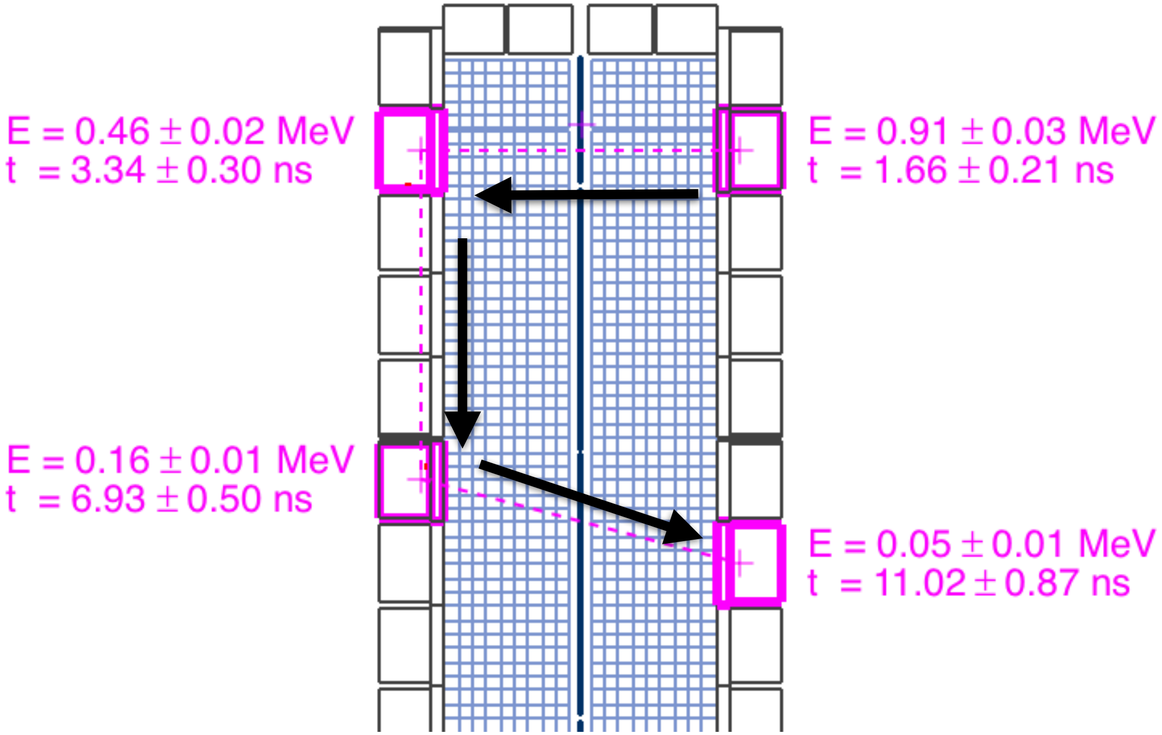
Electron tracks curve in the magnetic field. We get the electron's energy from an associated calorimeter hit.

Reconstruction: gammas

The signature of a gamma is an isolated calorimeter hit, with no associated charged particle track

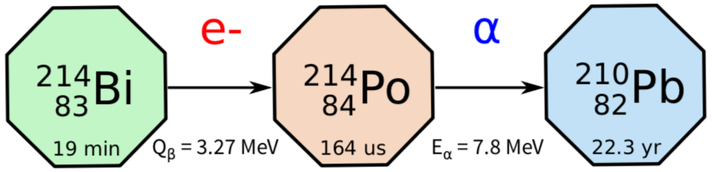


If there is an electron, we look at the difference in hit times and compare them to how far the electron and gamma would have traveled, to determine if they are likely to have come from the same interaction vertex.



Timing information can also group isolated calorimeter hits that could come from the same gamma

Reconstruction: alphas (from BiPo)



Short, straight tracks a few μs after an electron are characteristic of alpha particles from ^{214}Bi-^{214}Po decays

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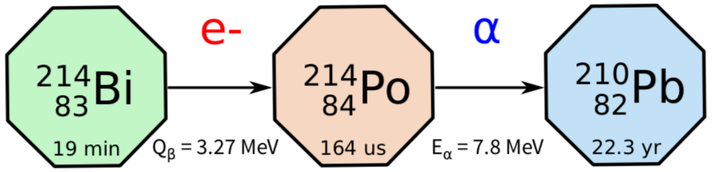

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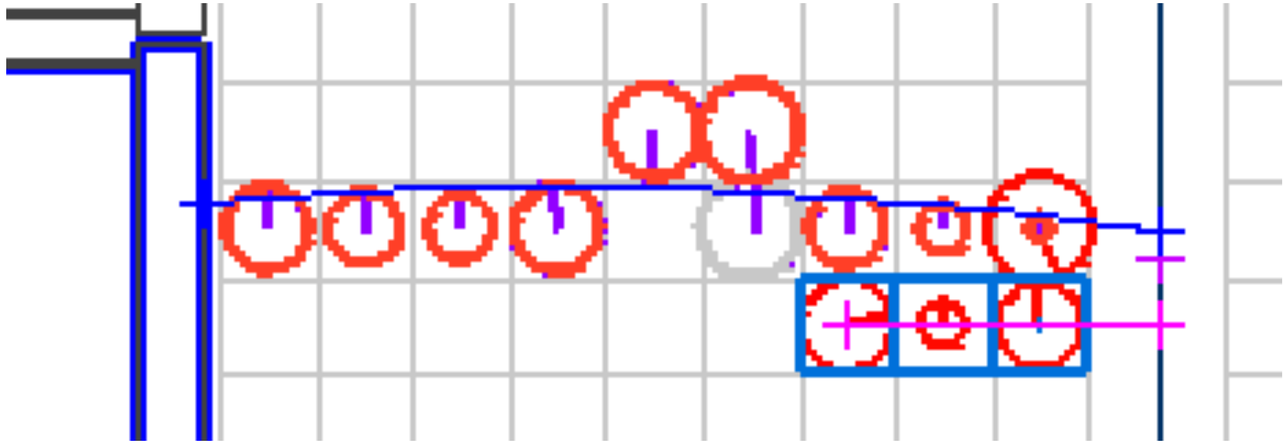

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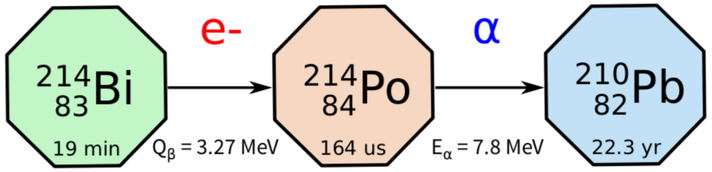

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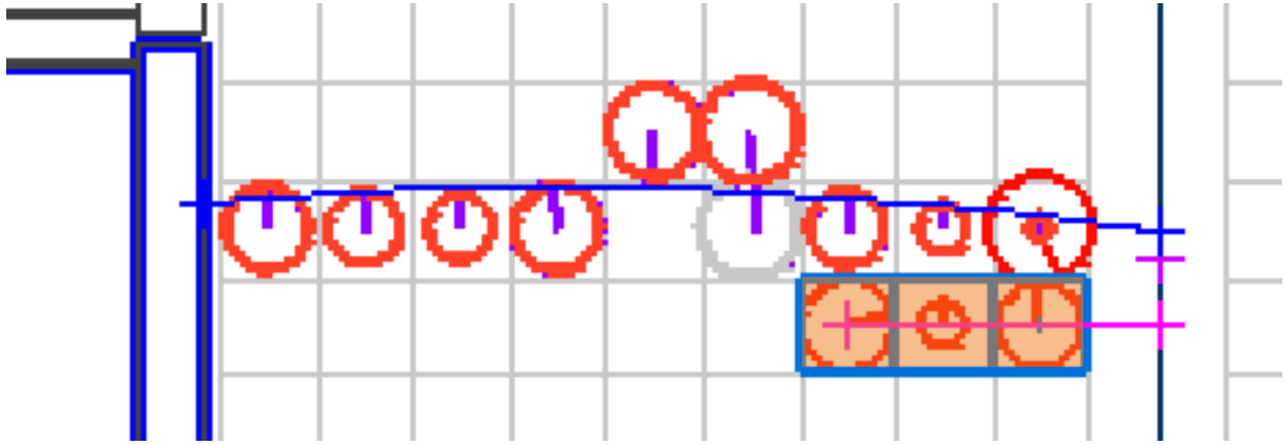

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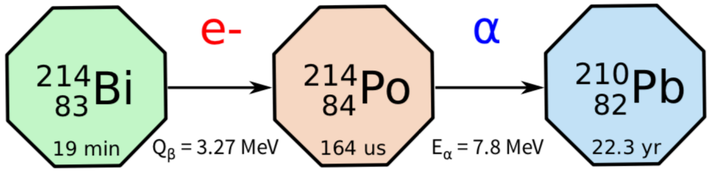

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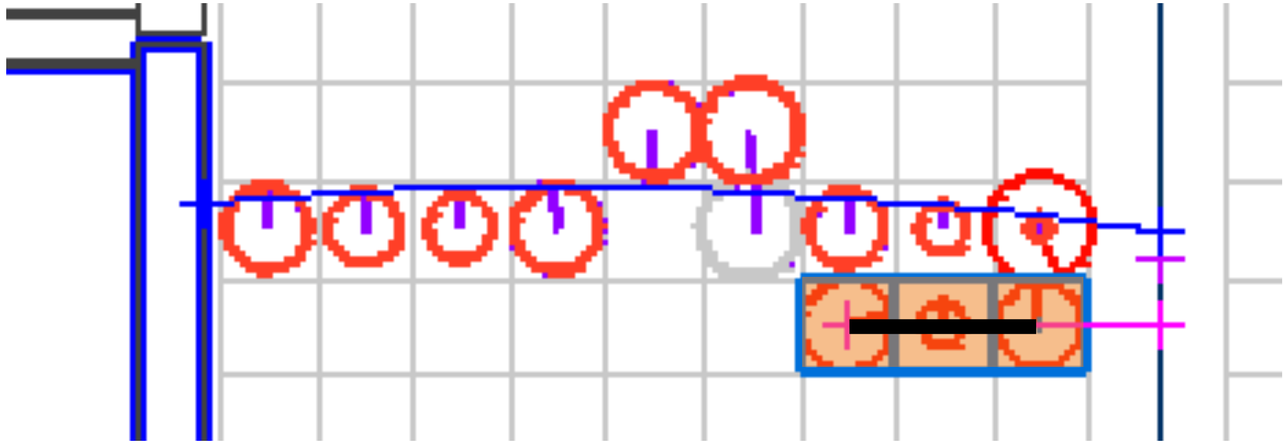
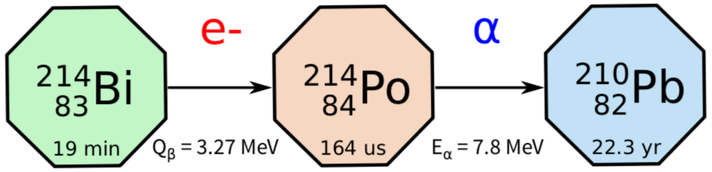


- Connect cells in delayed cluster with best-fit straight line (too heavy to curve)

Reconstruction: alphas (from BiPo)



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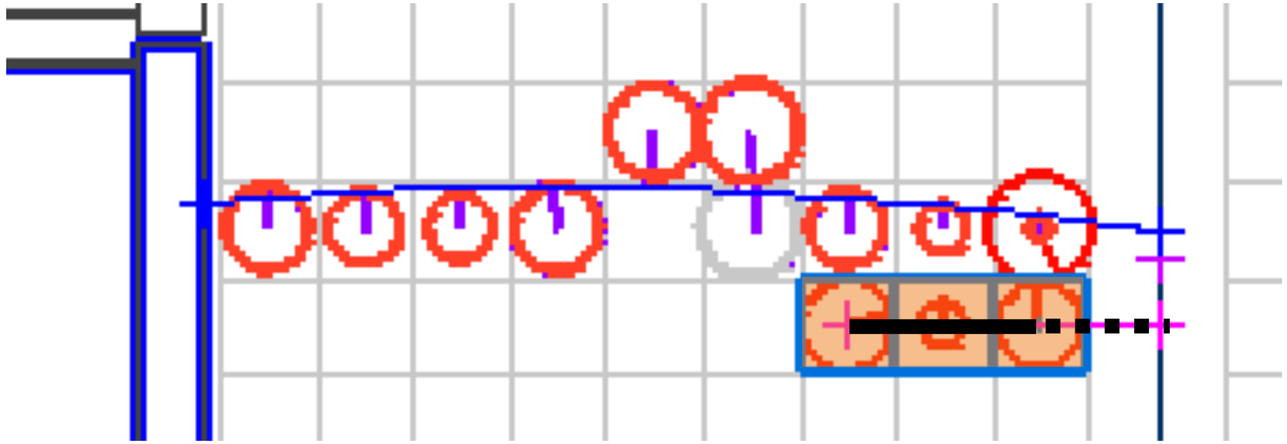

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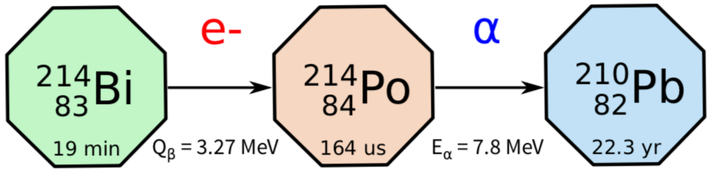
- If line projection would intercept foil, extend track to foil
- No input from electron track

Reconstruction: alphas (from BiPo)



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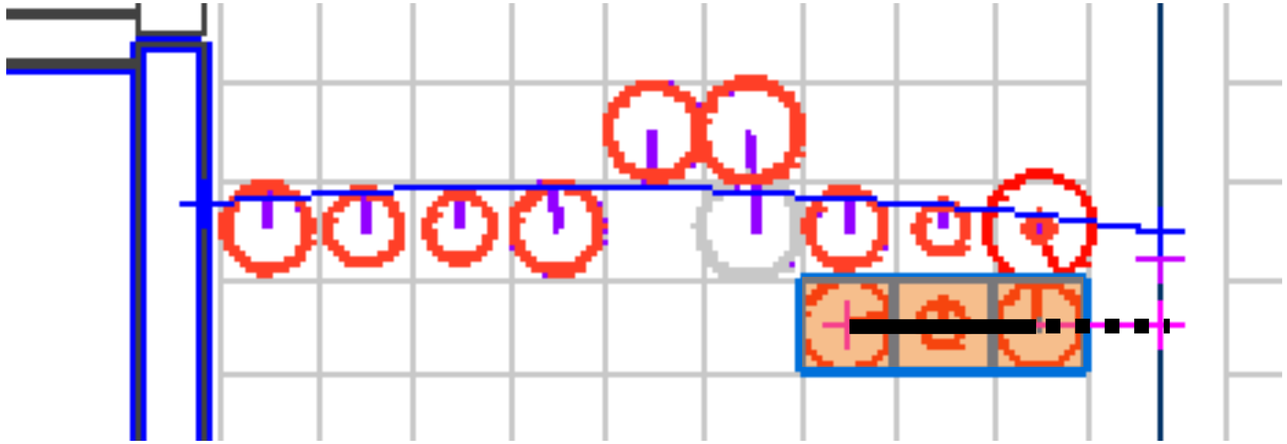

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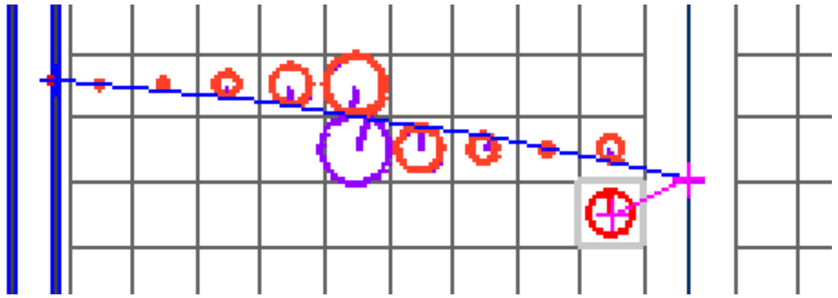
1 delayed hit



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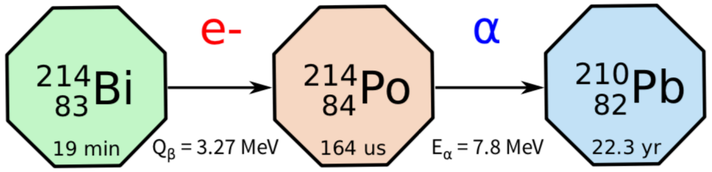

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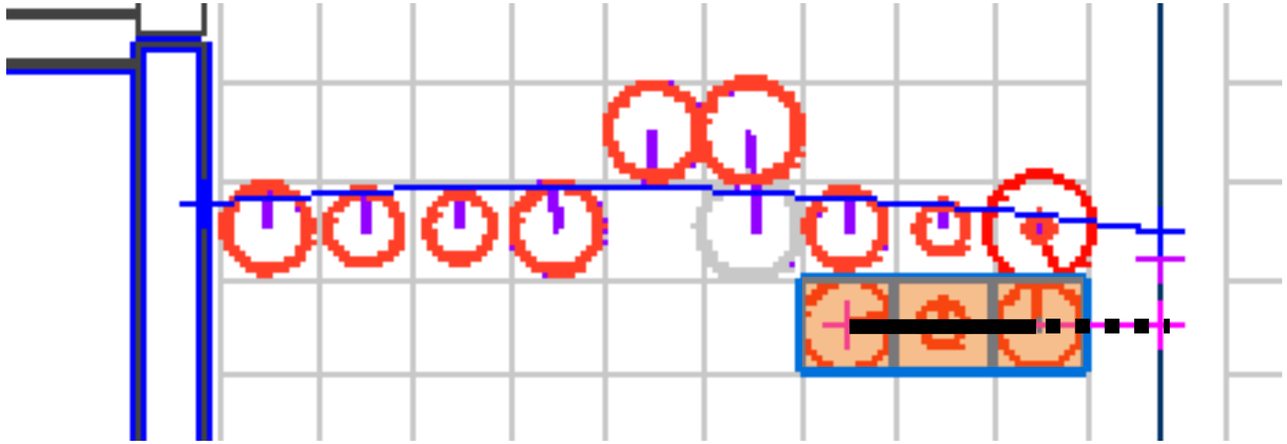

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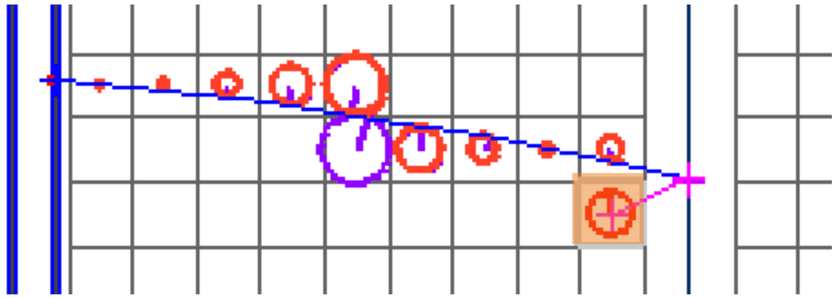

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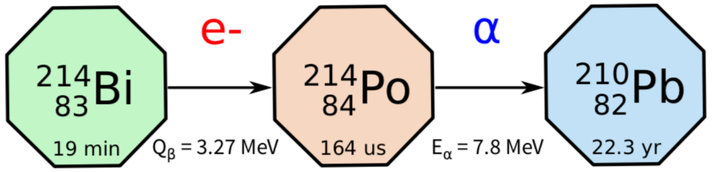

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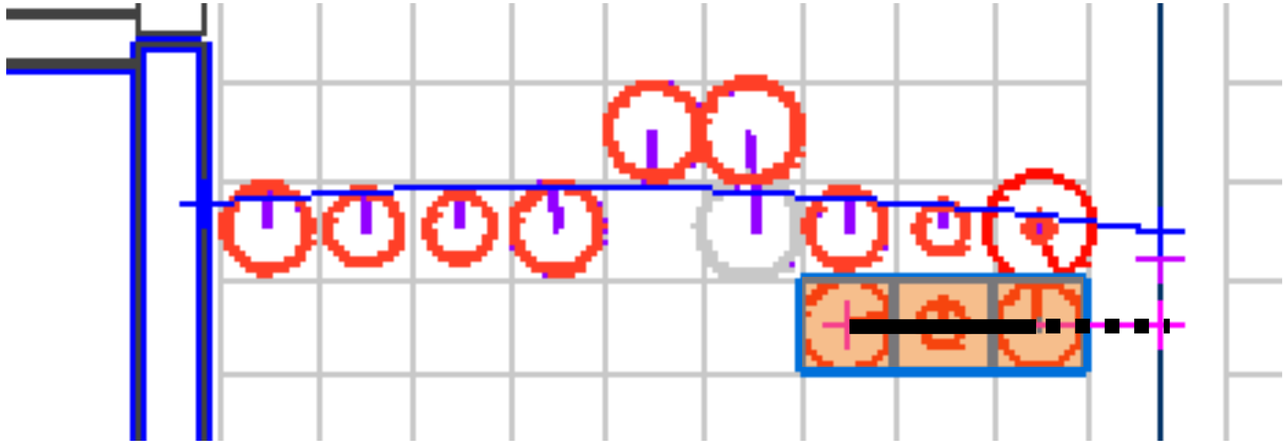

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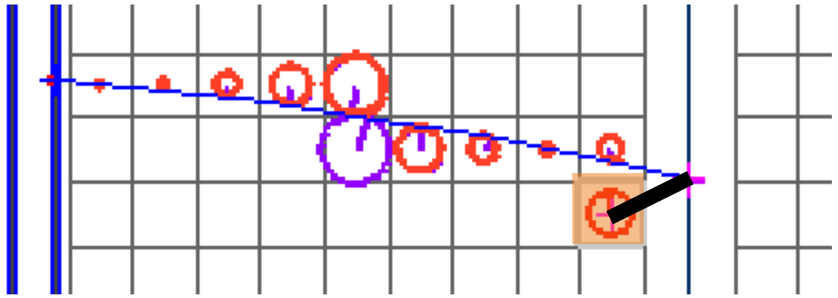
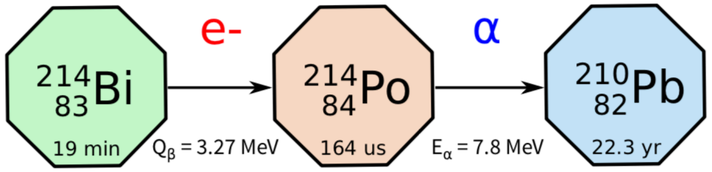
1 delayed hit



- Connect centre of cell with delayed hit to the closest end of a prompt (electron) track

Reconstruction: alphas (from BiPo)



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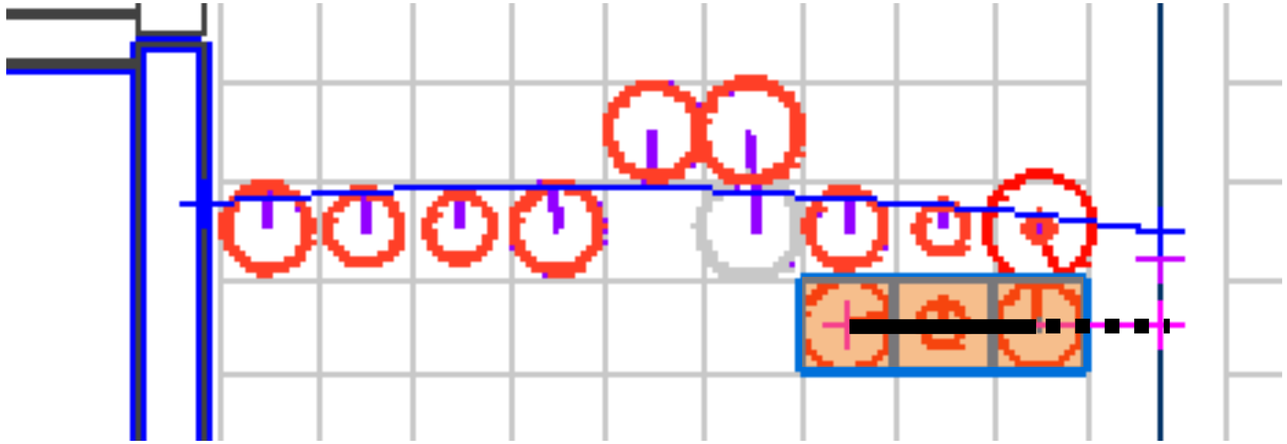

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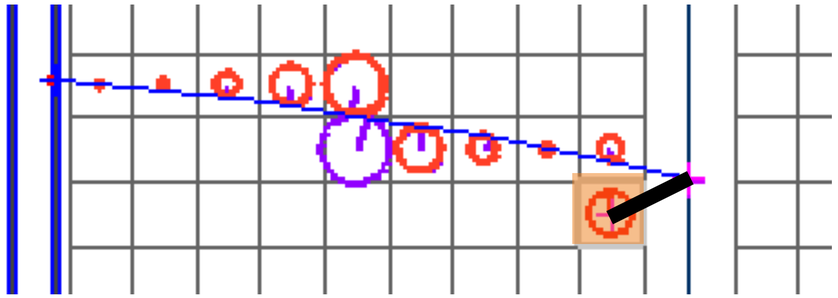
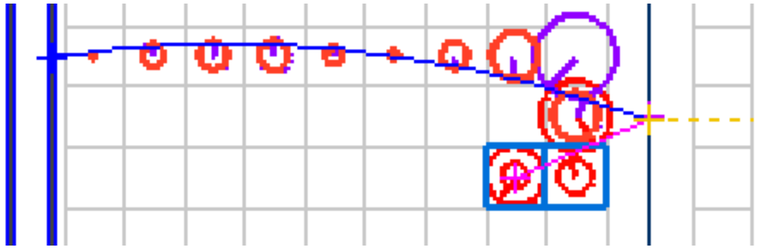
1 delayed hit

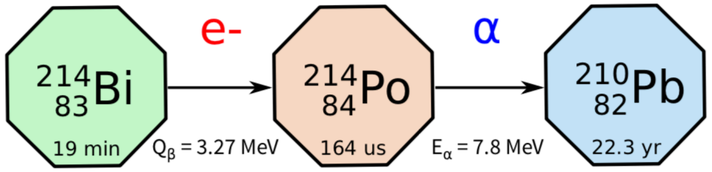


- Connect centre of cell with delayed hit to the closest end of a prompt (electron) track

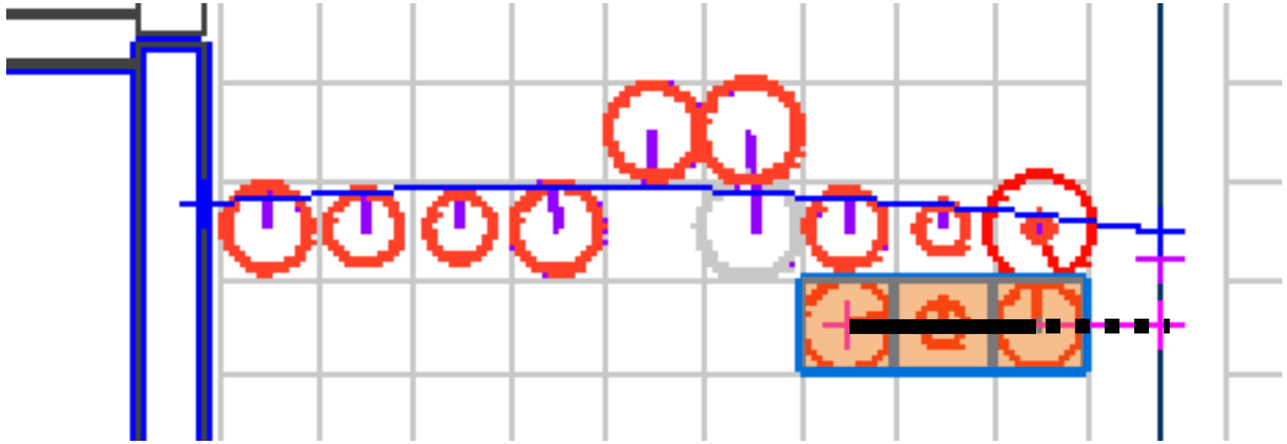
2 delayed hits



Reconstruction: alphas (from BiPo)

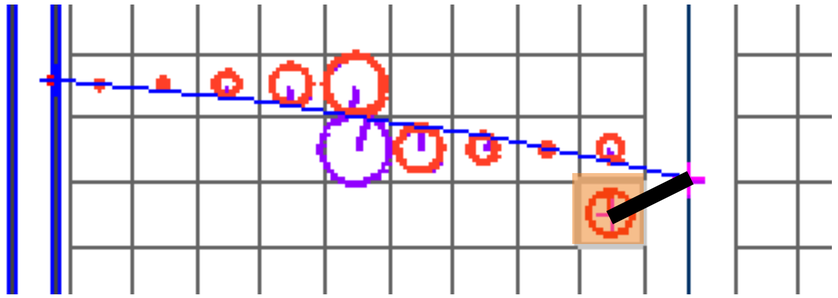


Short, straight tracks a few μs after an electron are characteristic of alpha particles from ^{214}Bi-^{214}Po decays



- Connect cells in delayed cluster with best-fit straight line (too heavy to curve)
- If line projection would intercept foil, extend track to foil
- No input from electron track

1 delayed hit



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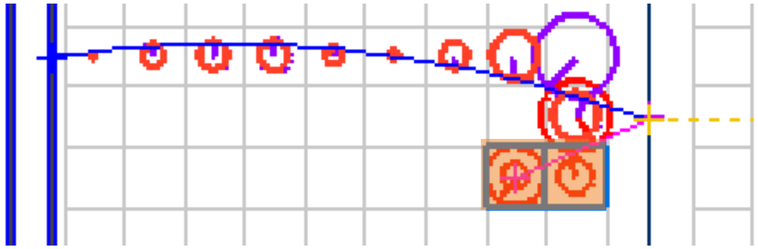

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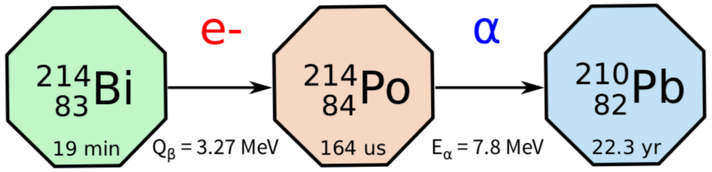

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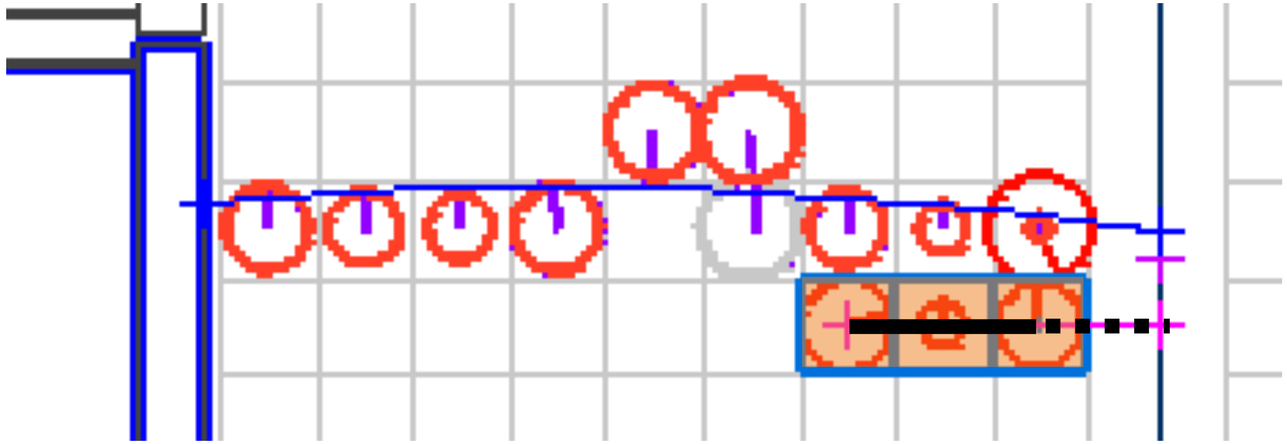

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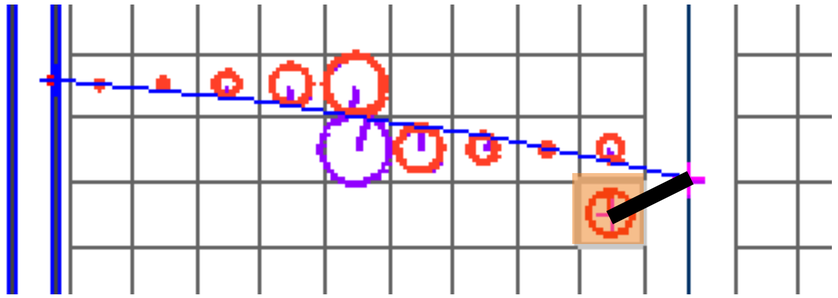

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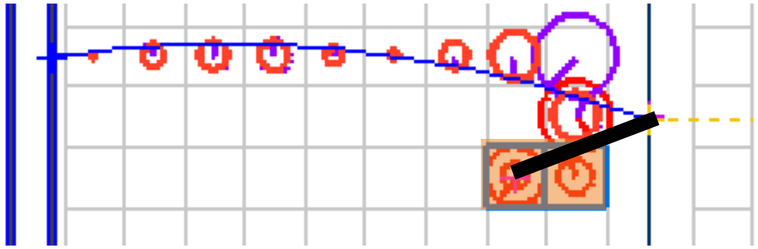

- Same tactic, but connect the centre of the furthest hit to the electron track vertex

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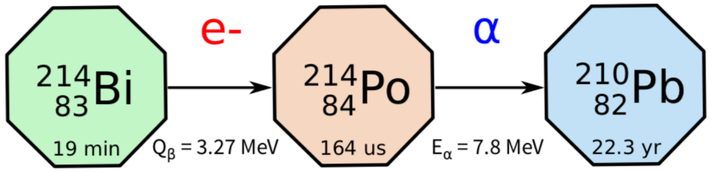

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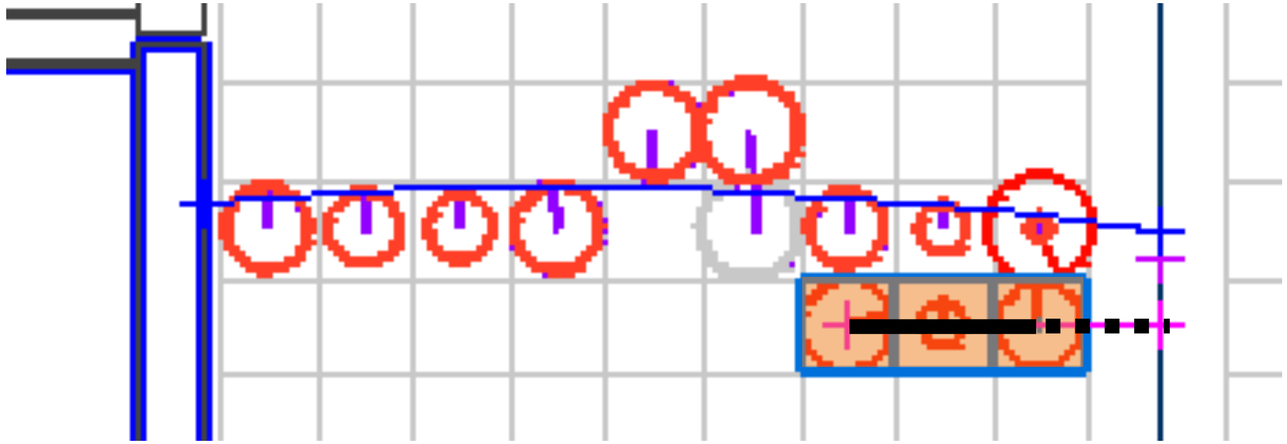

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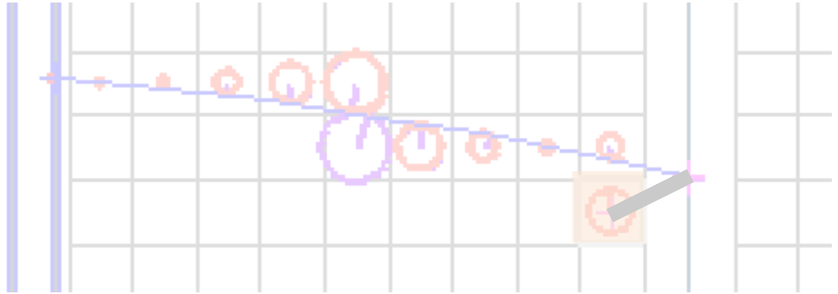

- Connect centre of cell with delayed hit to the closest end of a prompt (electron) track

Only if there is a prompt track!

2 delayed hits

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Estimating sensitivity: our strategy

Estimate activity from ^{214}Bi

- Identify characteristic ^{214}Bi topology
- Fit shapes from foil contamination and radon in tracker
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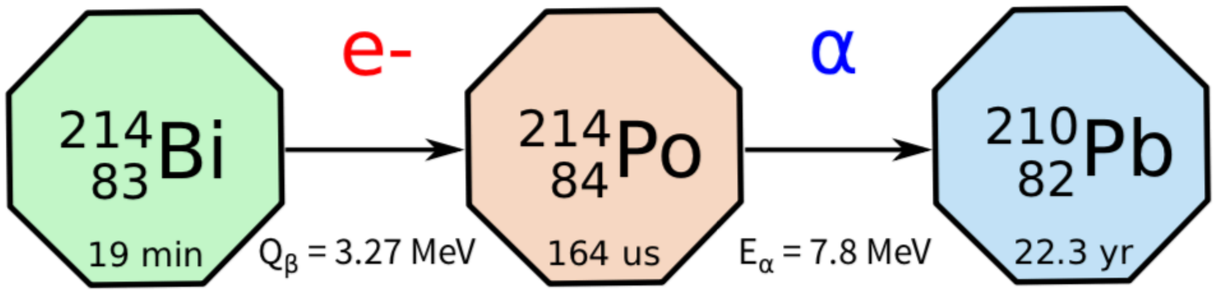
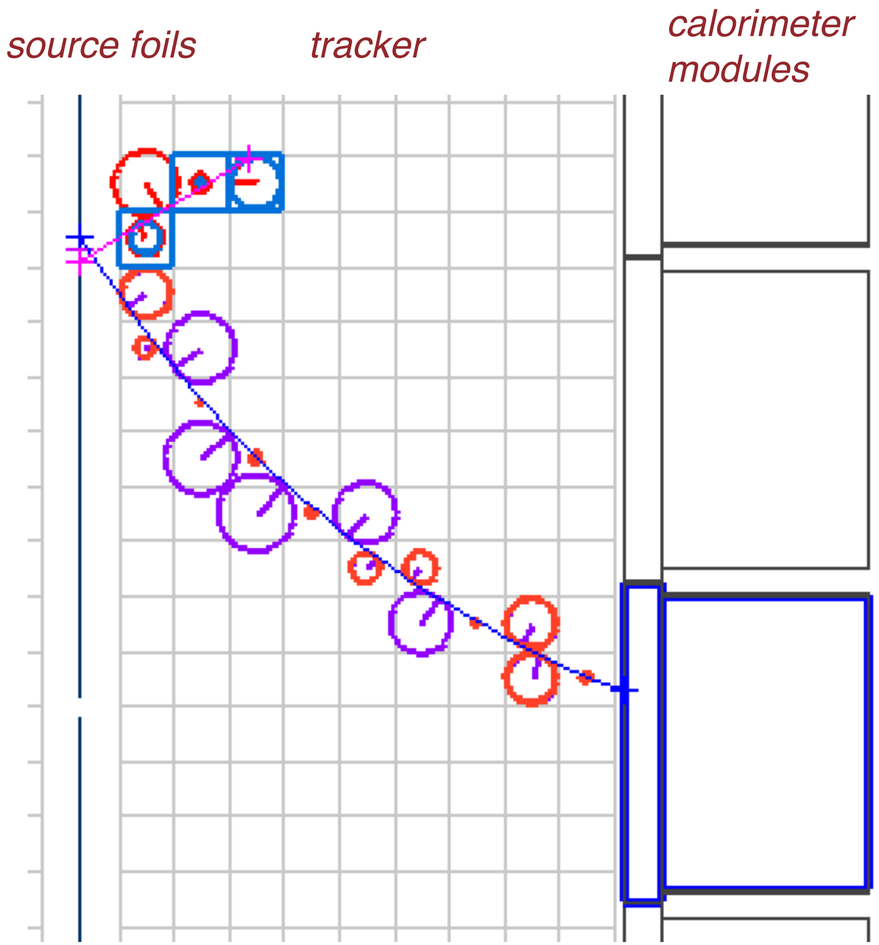
^{214}Bi foil contamination: 1e1α topology





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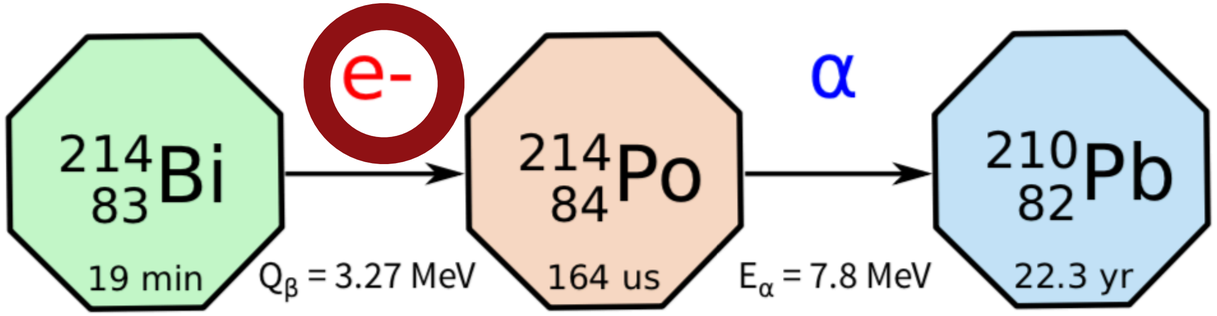

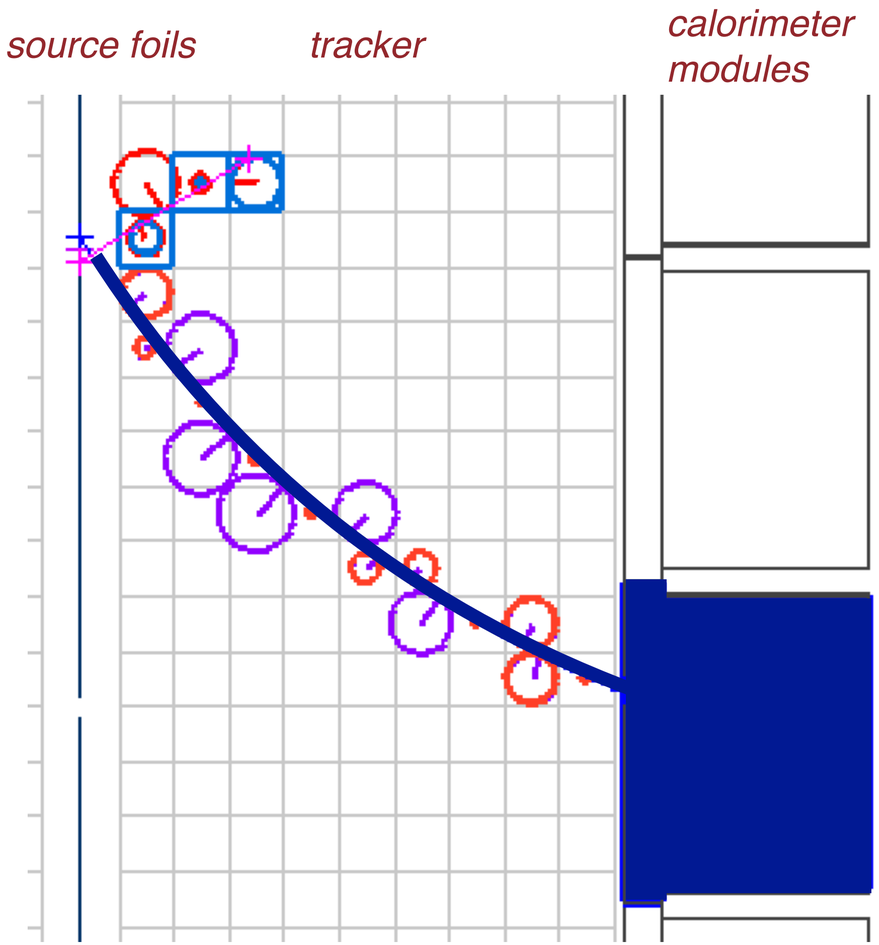

- Negative electron track with calorimeter hit

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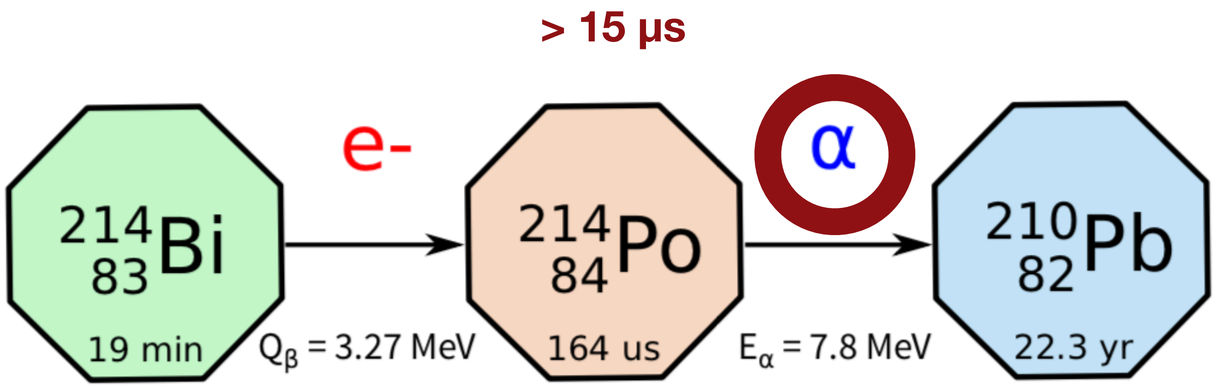

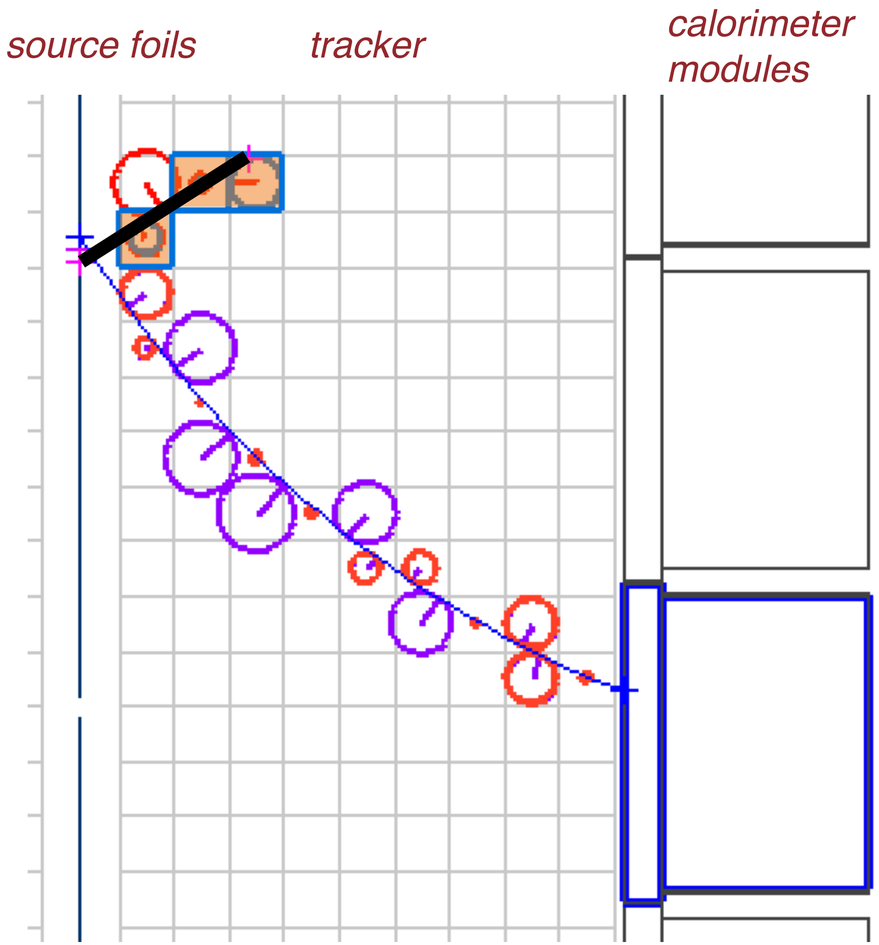

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- Delayed alpha track > 15μs after electron

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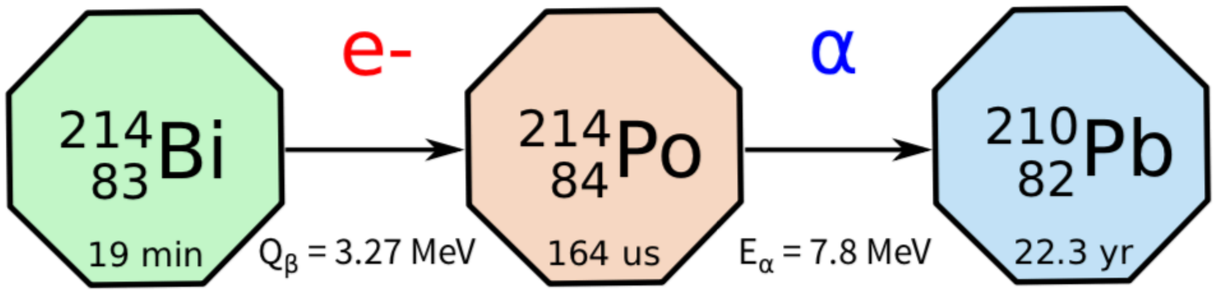
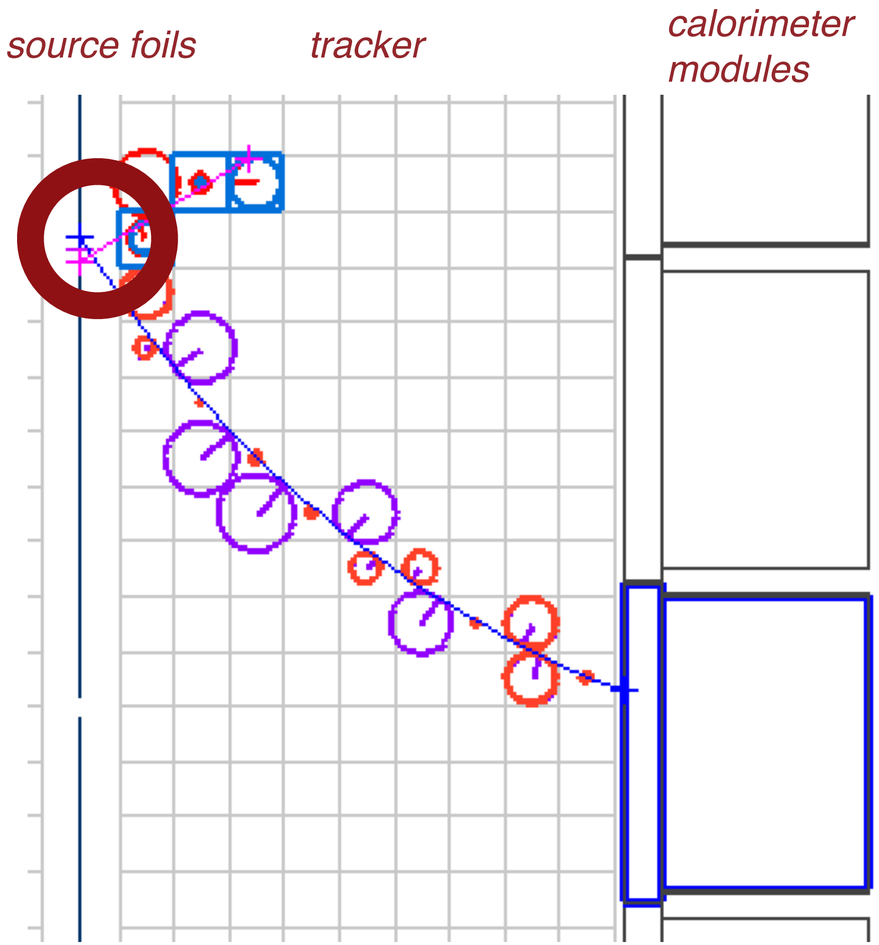
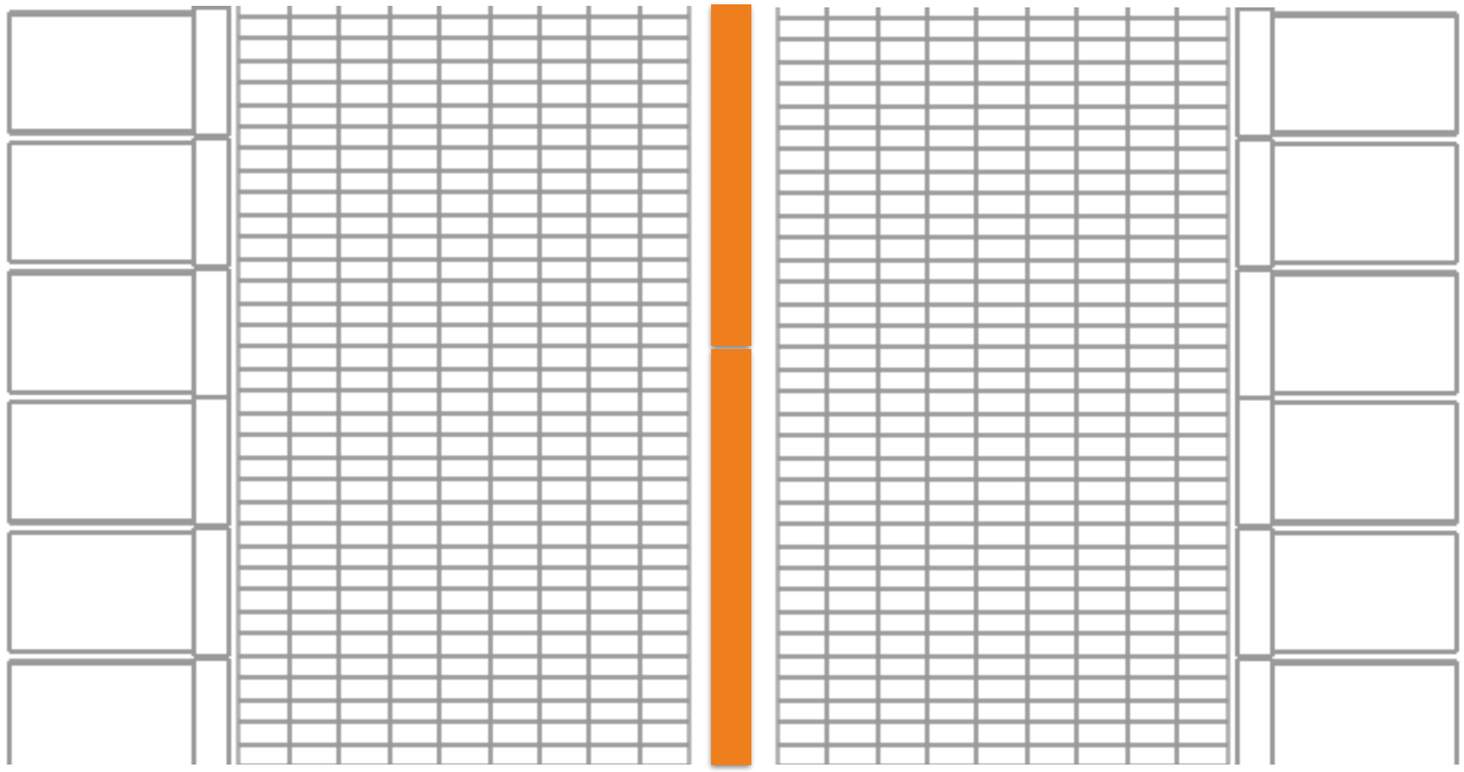




- Negative electron track with calorimeter hit
- Delayed alpha track > 15μs after electron
- Both tracks lead back to source foil

^{214}Bi decays: detector regions contributing to a foil cut

Assuming 7 kg isotope - Demonstrator



Source foil bulk:

- ^{214}Bi **contamination of foils** from natural ^{238}U decay chain

  estimated **15.4 mBq** (BiPo 'upper limit')

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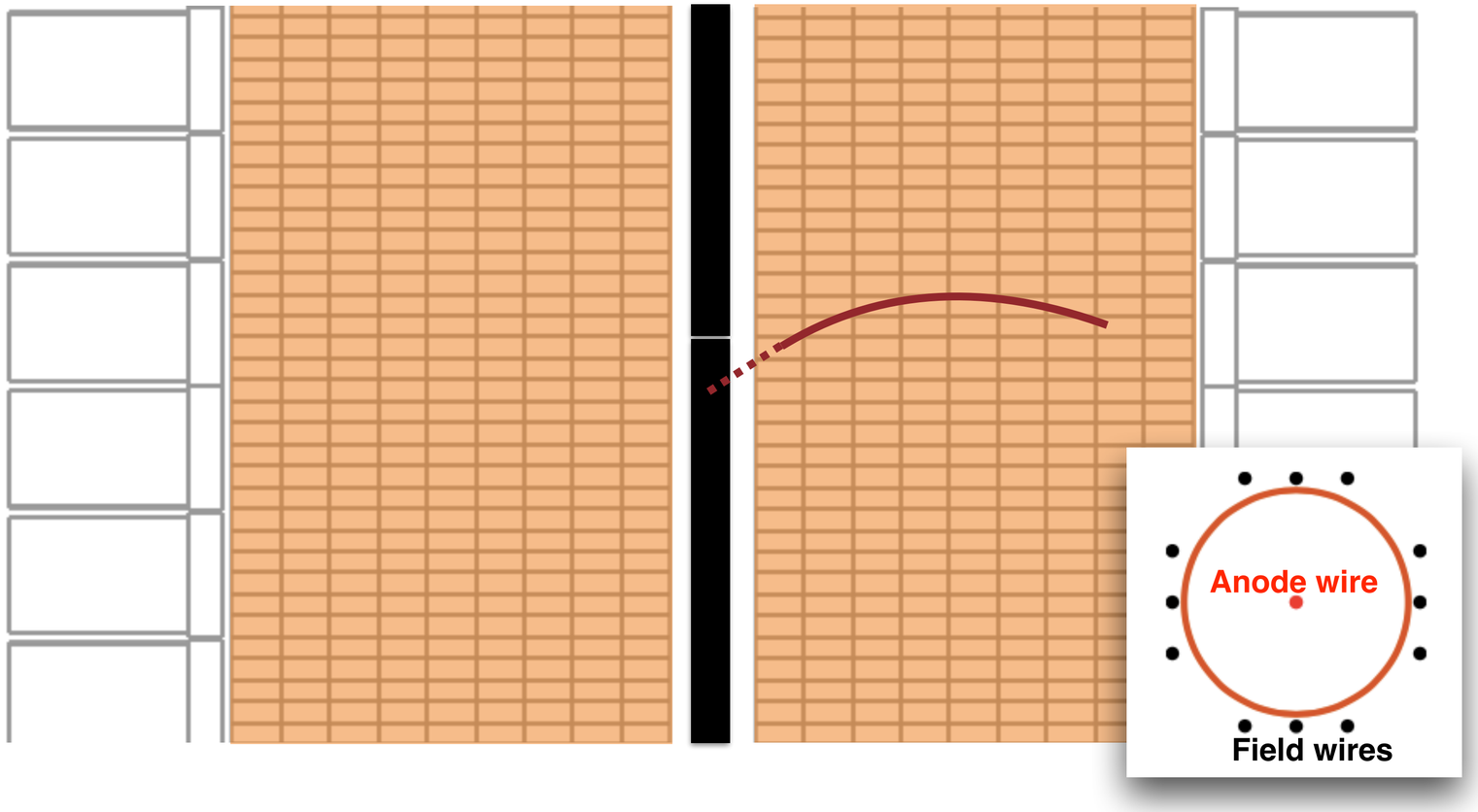

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Radon in tracker:

- Positive **^{214}Bi ions from Rn decay** are deposited on field shaping wires
- Impossible to distinguish activity in **first tracker layer** from activity in foil

  estimate **42.3 mBq** (in reality gas flow reduces this)

^{214}Bi decays: detector regions contributing to a foil cut

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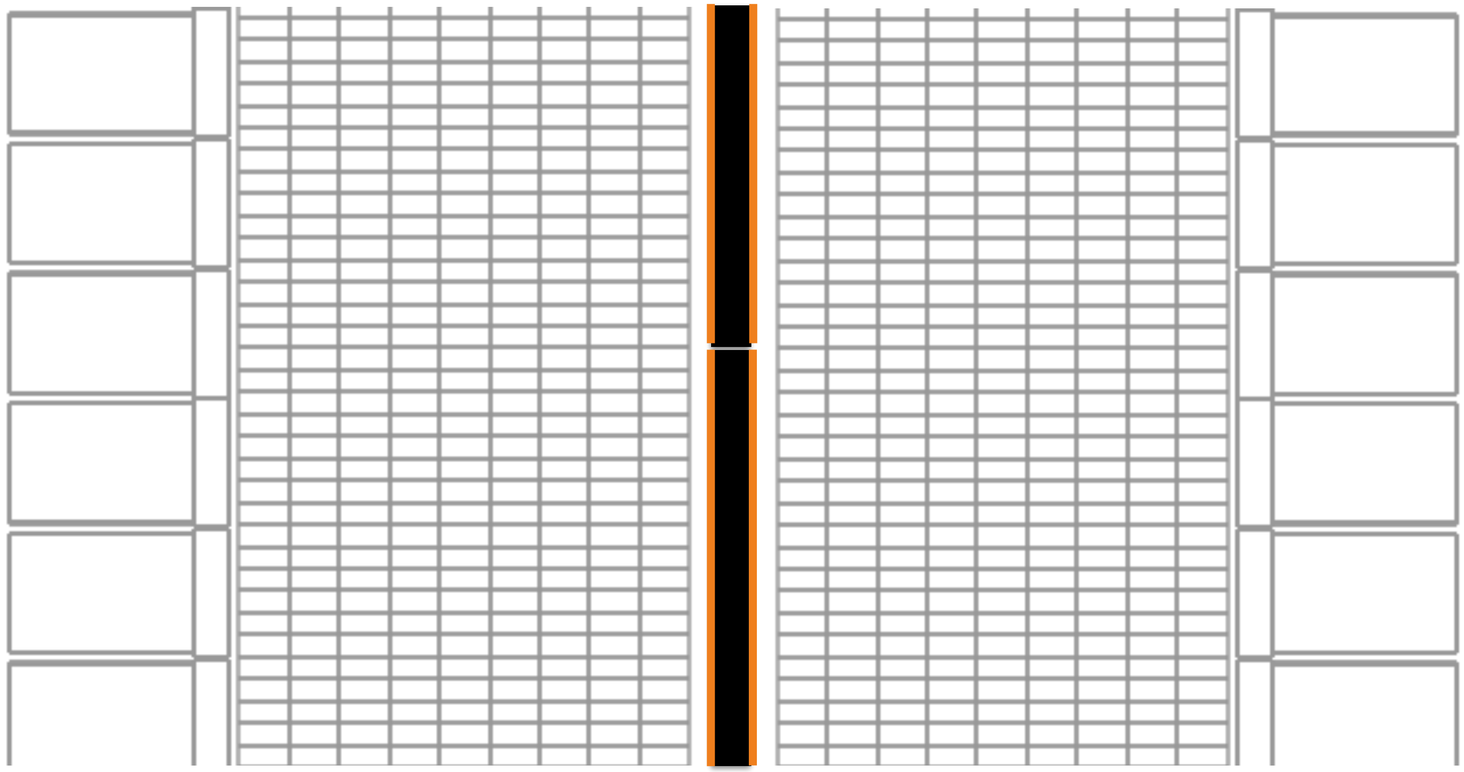

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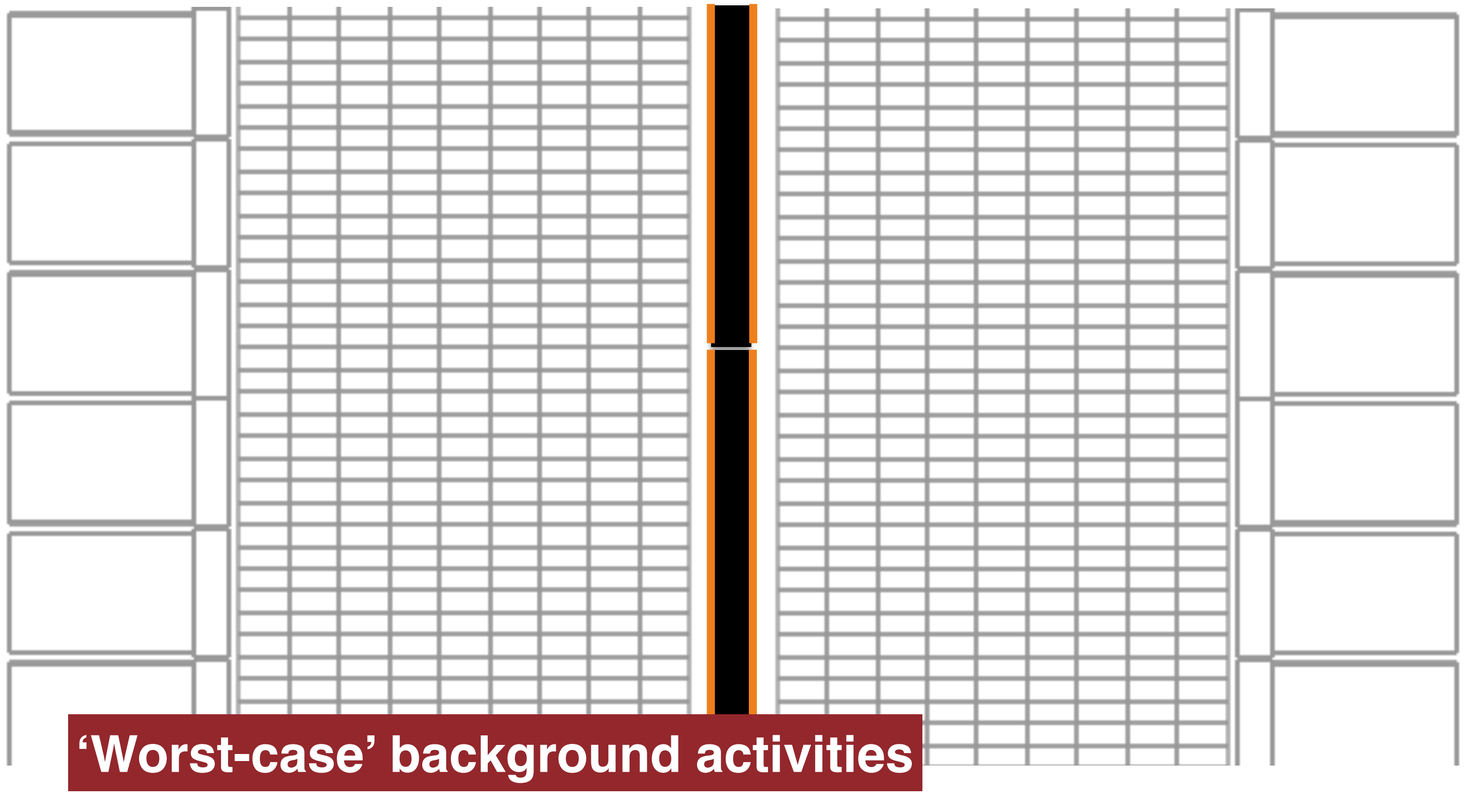
Source foil surface:

- ^{214}Bi **contamination of mylar** wrapper from natural ^{238}U and ^{232}Th decay chains
- ^{214}Bi deposited from **Rn in tracker**

  estimated **3.37 mBq** (in reality gas flow reduces this)

^{214}Bi decays: detector regions contributing to a foil cut

Assuming 7 kg isotope - Demonstrator



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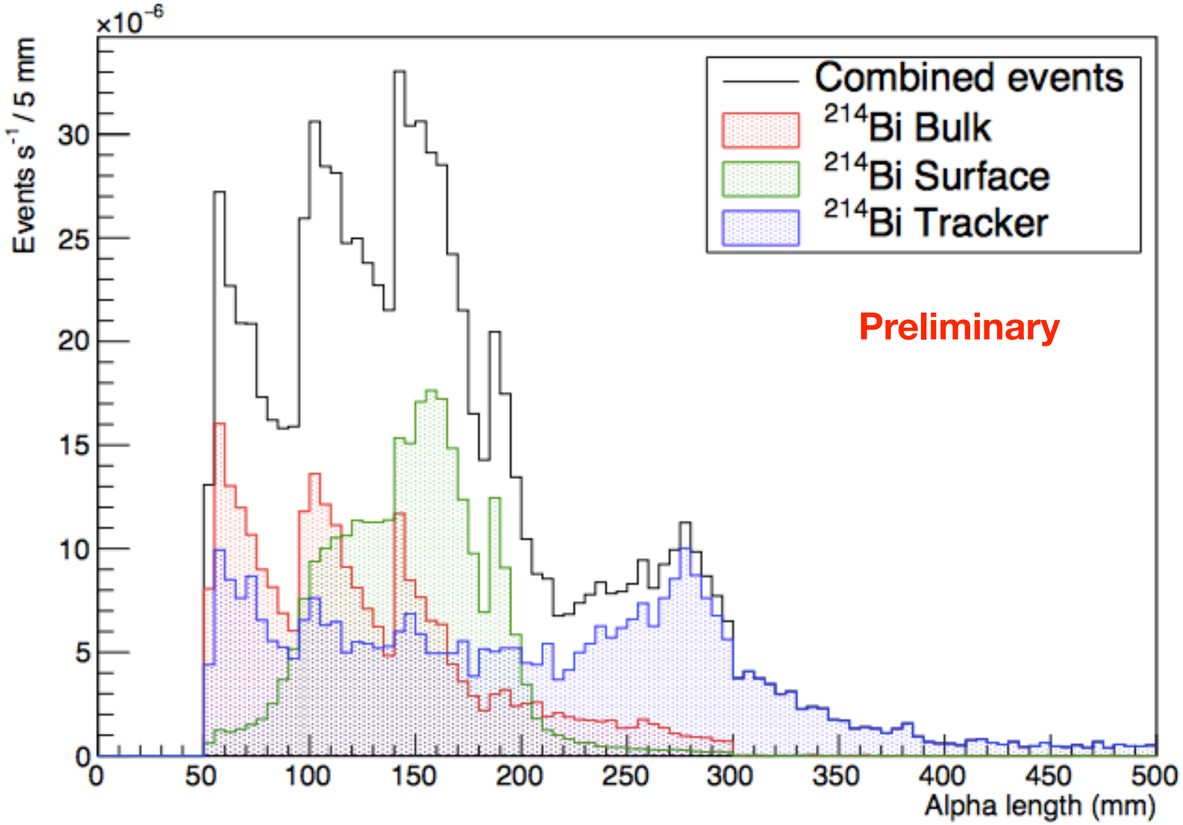
Extracting ^{214}Bi activity

Expected event rate from 1e1α topologies reconstructed on the source foil (worst-case activities assumed)



The samples' differing **shapes** vs **alpha track length** will allow us to fit for activities

Reconstruction efficiencies		
Foil bulk	Foil surface	Tracker
1.8%	8.4%	0.8%

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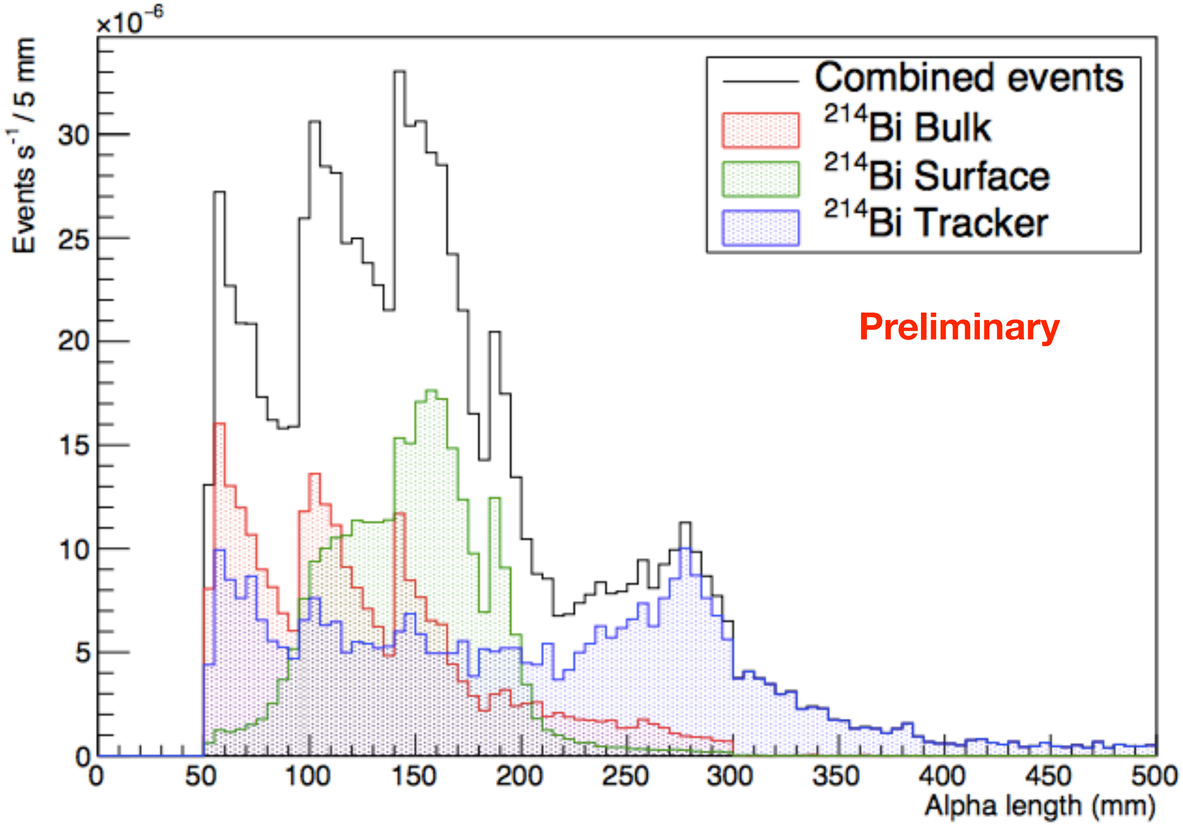

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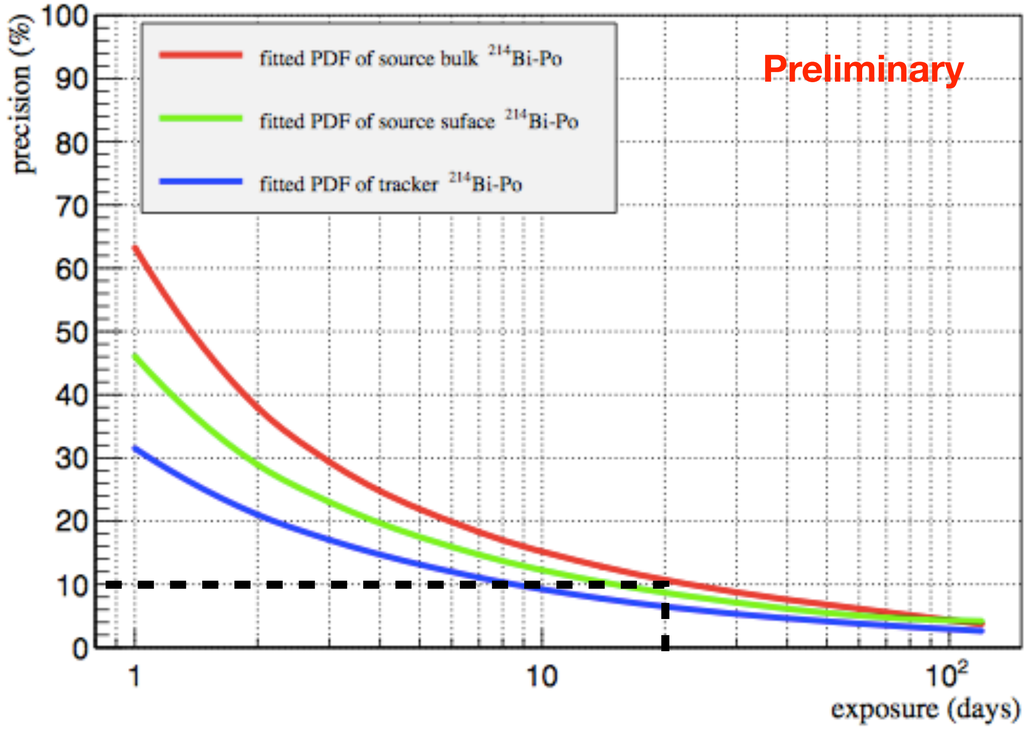
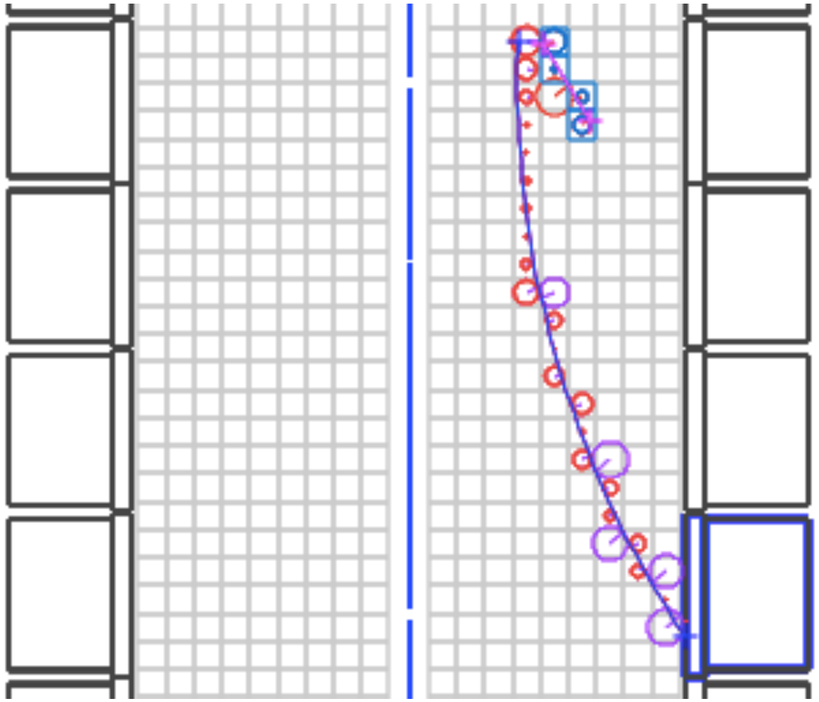


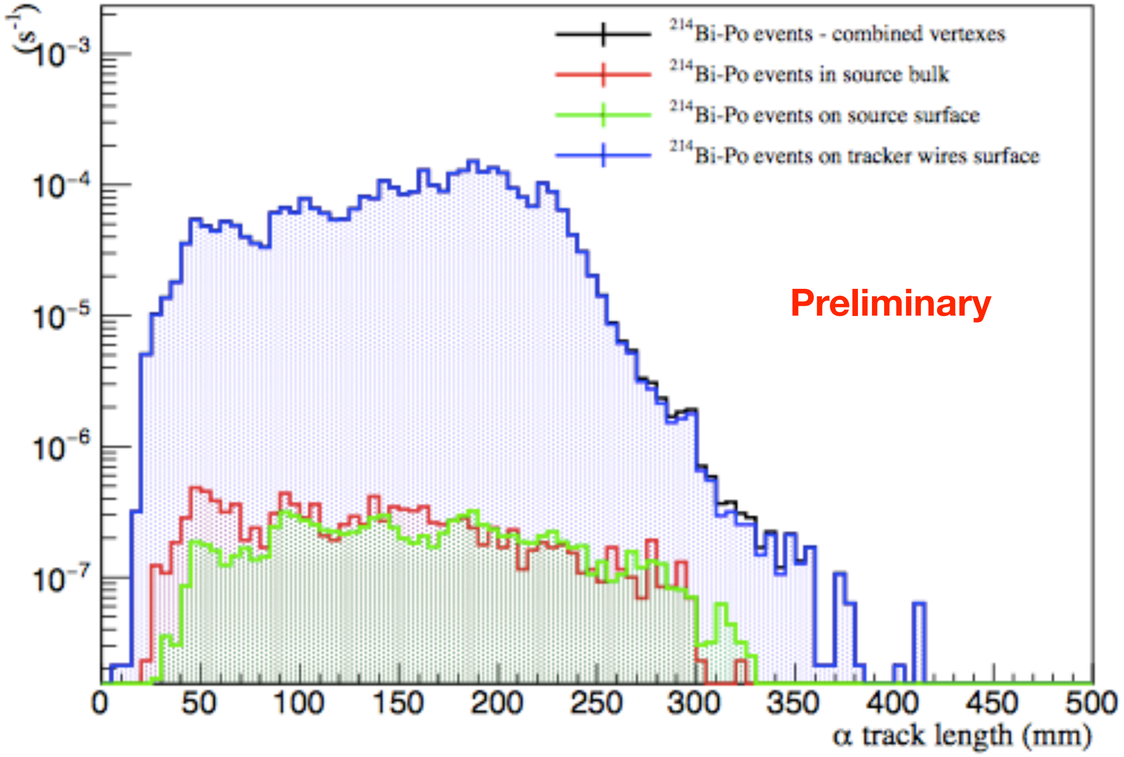
With the worst-case activity estimates, we would measure foil contamination to **10% uncertainty** in around **2 weeks**

Extract tracker contamination

For a faster measurement of tracker activity, change selection to require electron and alpha **vertex in the tracker**

Tracker reconstruction efficiency: **9%**





Contamination from the foil is minimal

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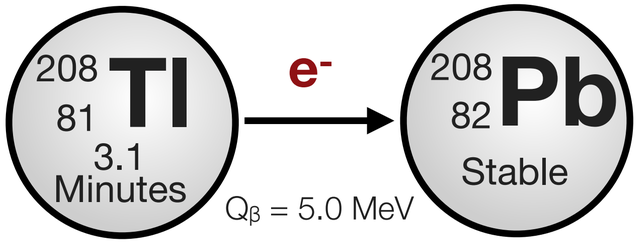
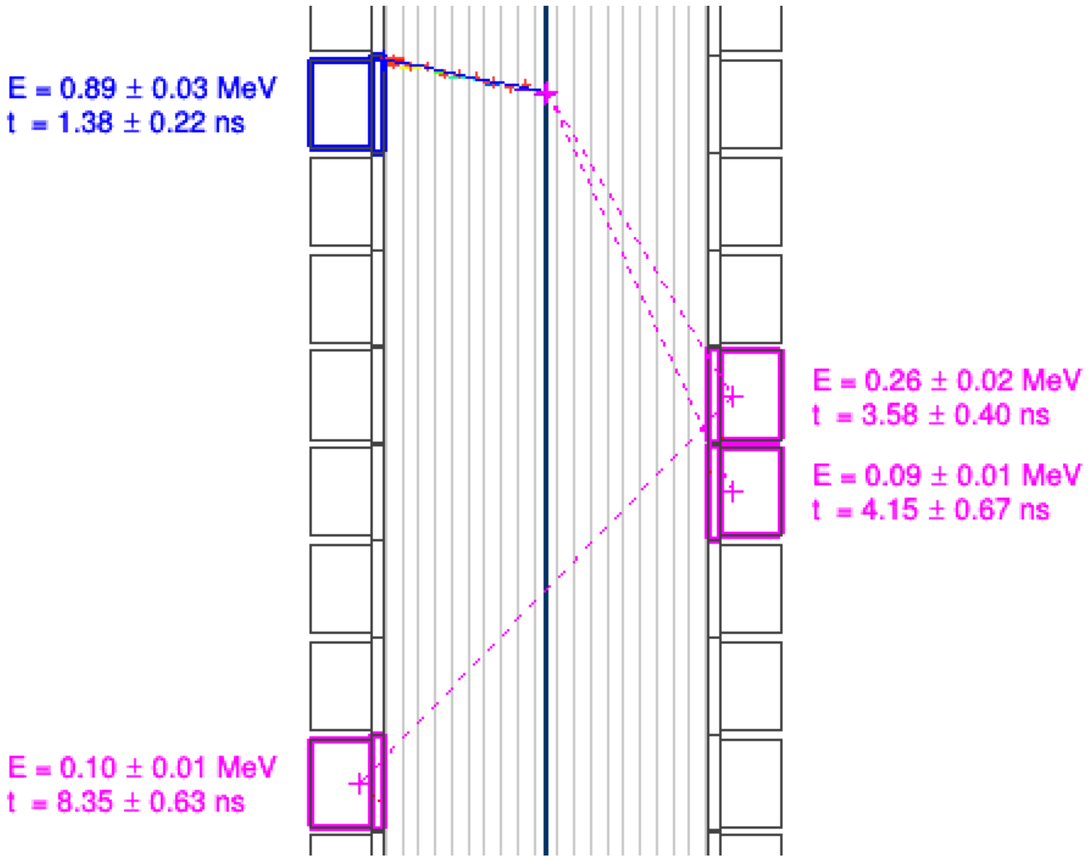
Topology for ^{208}Tl: 1eNγ



Simulated ^{208}Tl decay showing 1e2γ topology



Signature of ^{208}Tl decay is 1 electron plus 1 or more gammas

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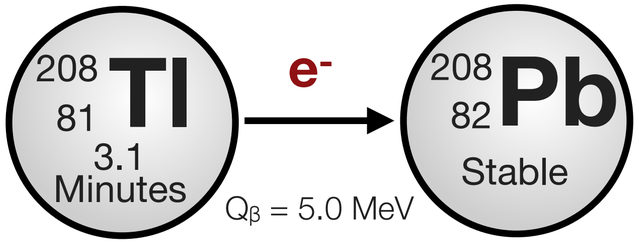

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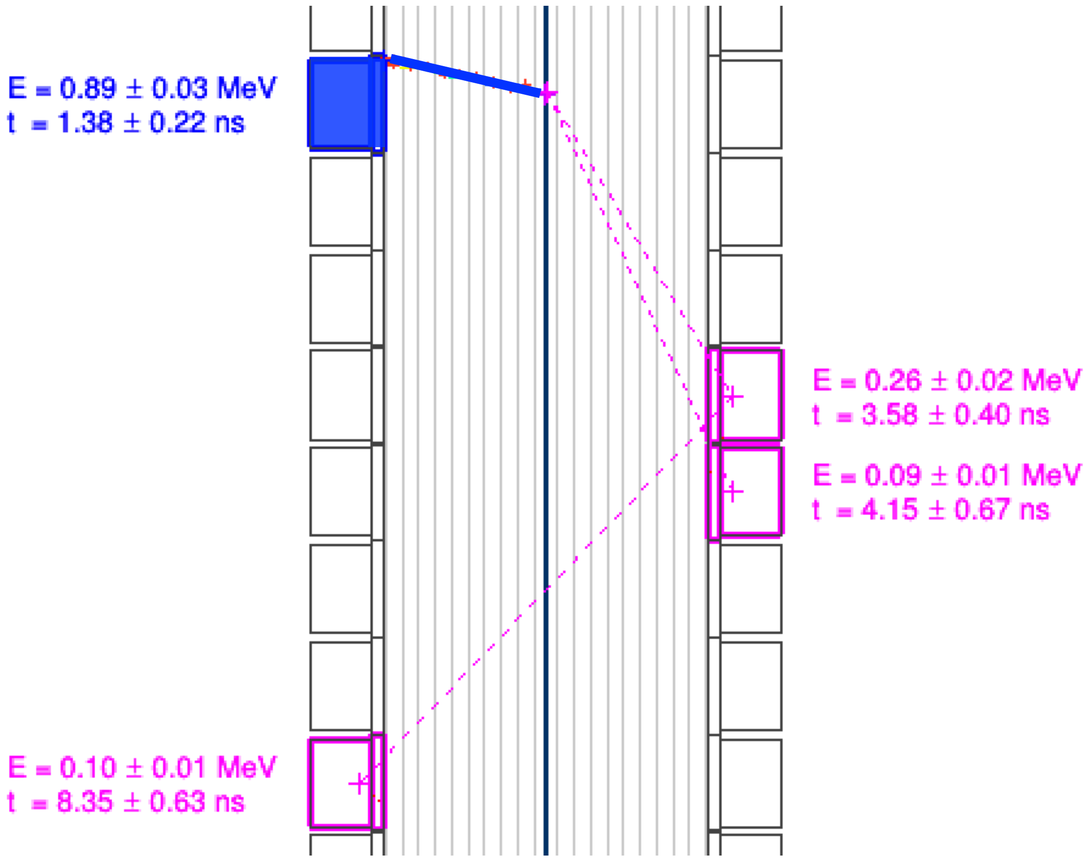

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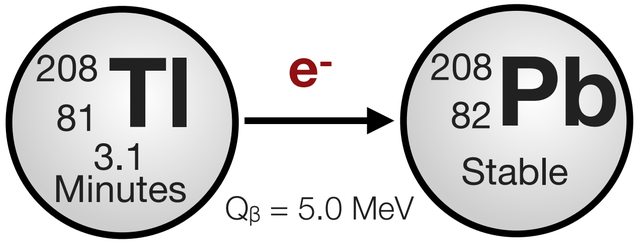

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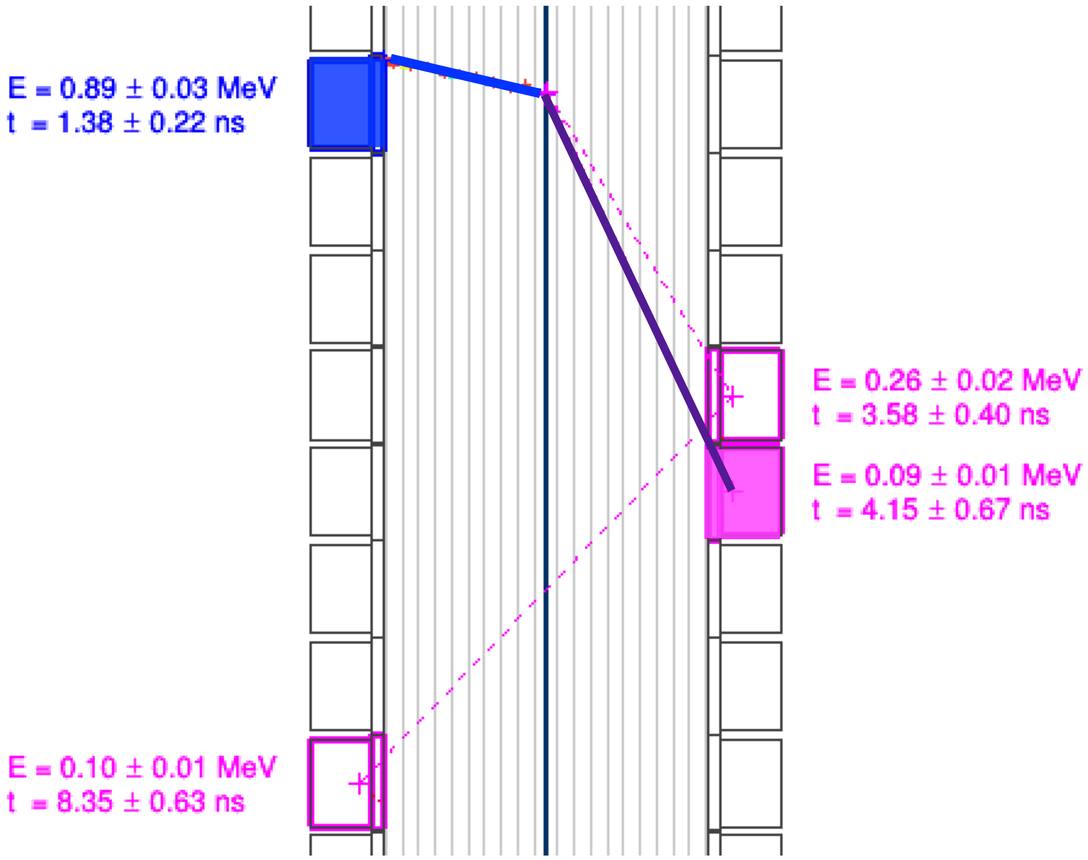

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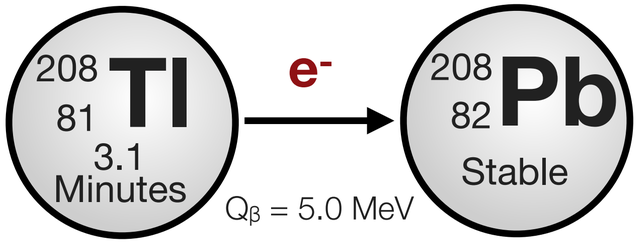

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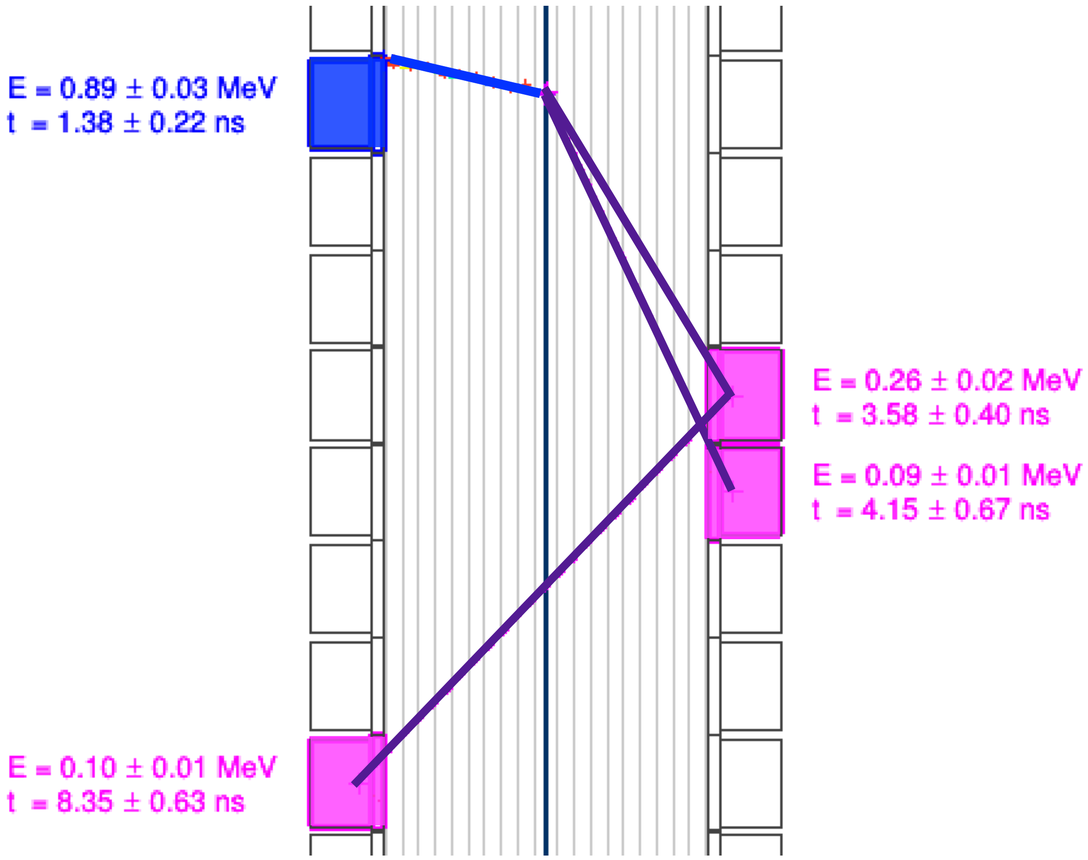

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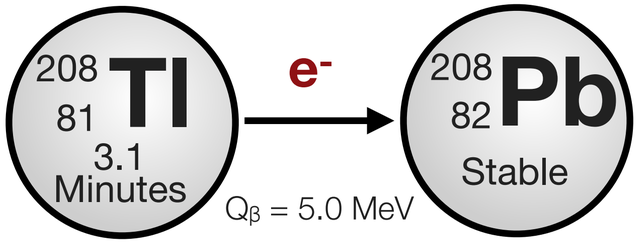
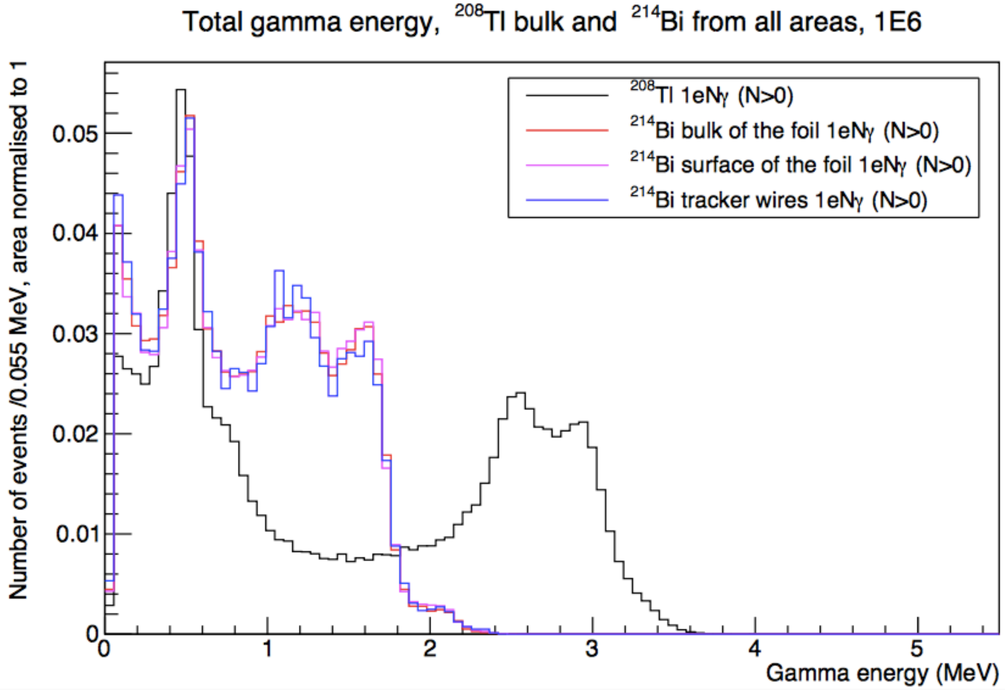
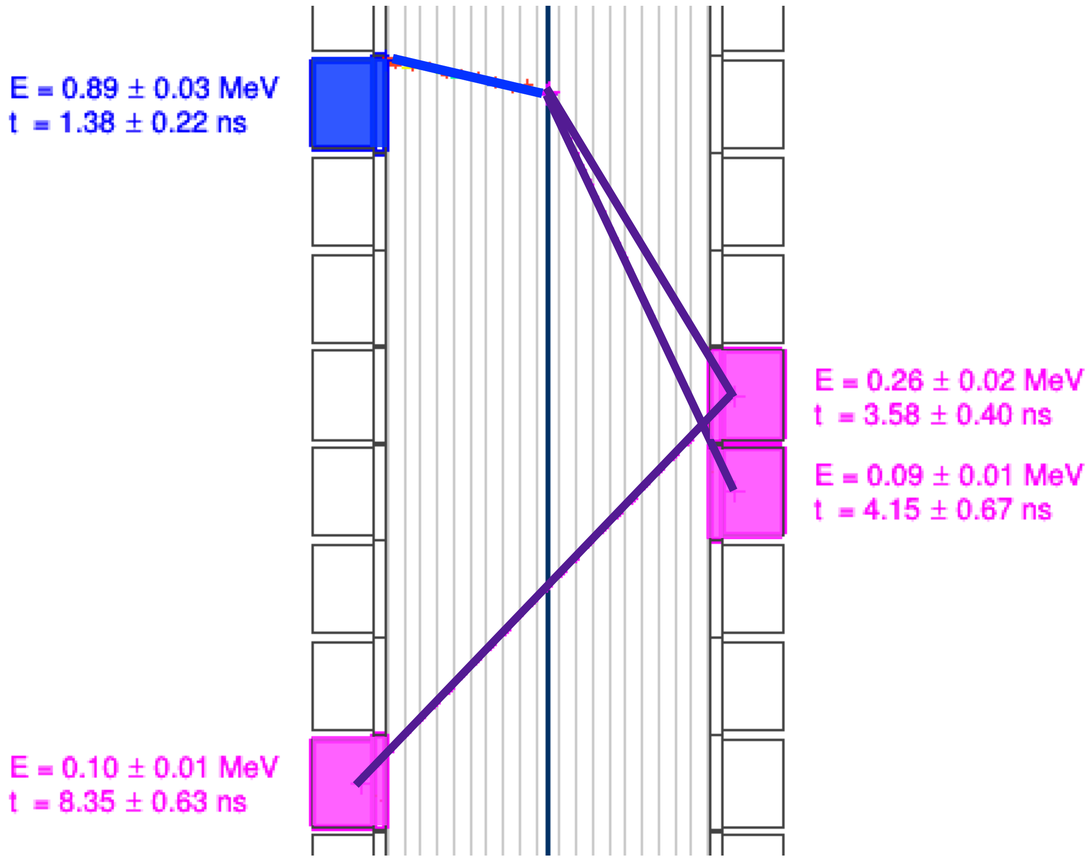




Summed gamma energy spectrum distinguishes ^{208}Tl from ^{214}Bi

Simulated ^{208}Tl decay showing 1e2γ topology



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Estimate sensitivity to $0\nu\beta\beta$

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- Measure efficiencies for ^{214}Bi, ^{208}Tl and $2\nu\beta\beta$
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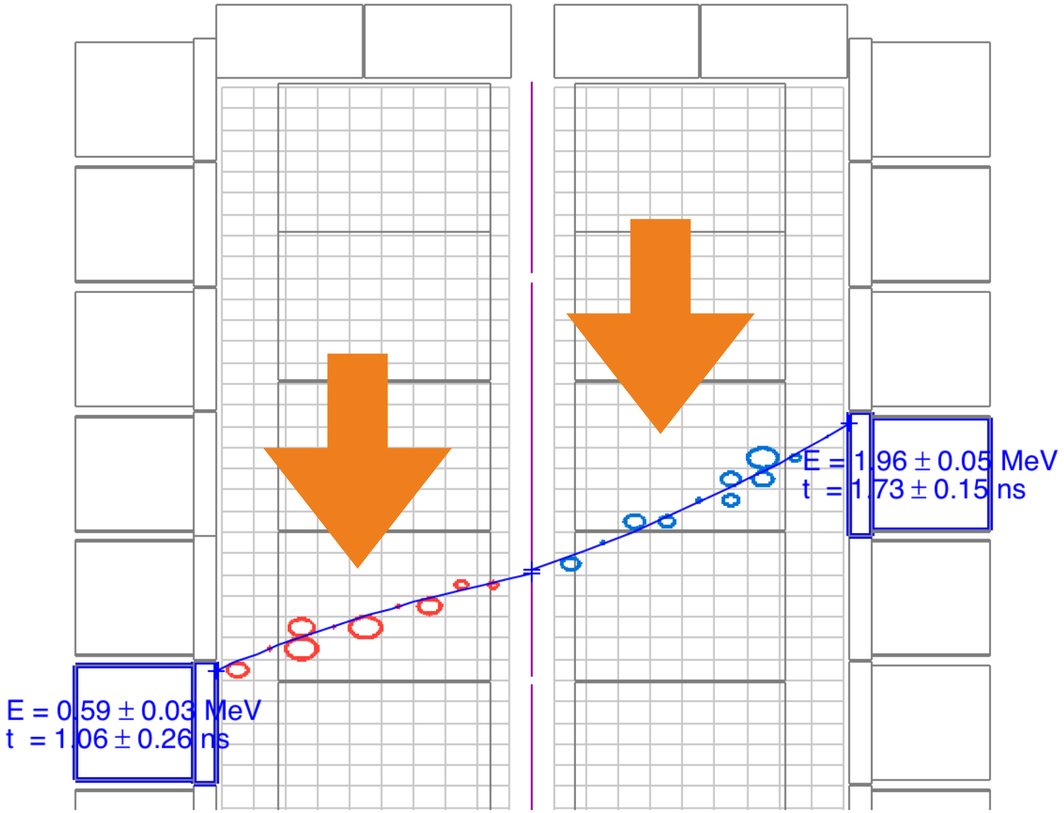
0νββ sensitivity

ββ events are characterised by

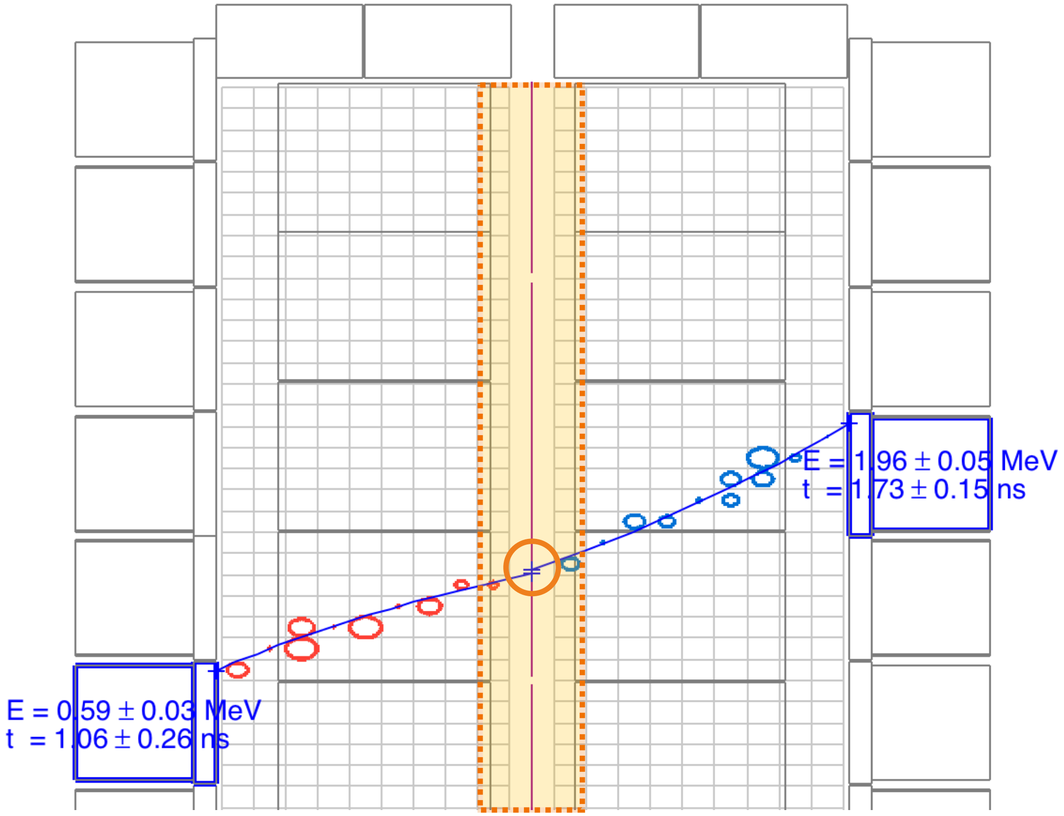
- Two electron-like tracks (negative curvature, associated calorimeter)



0νββ sensitivity

ββ events are characterised by

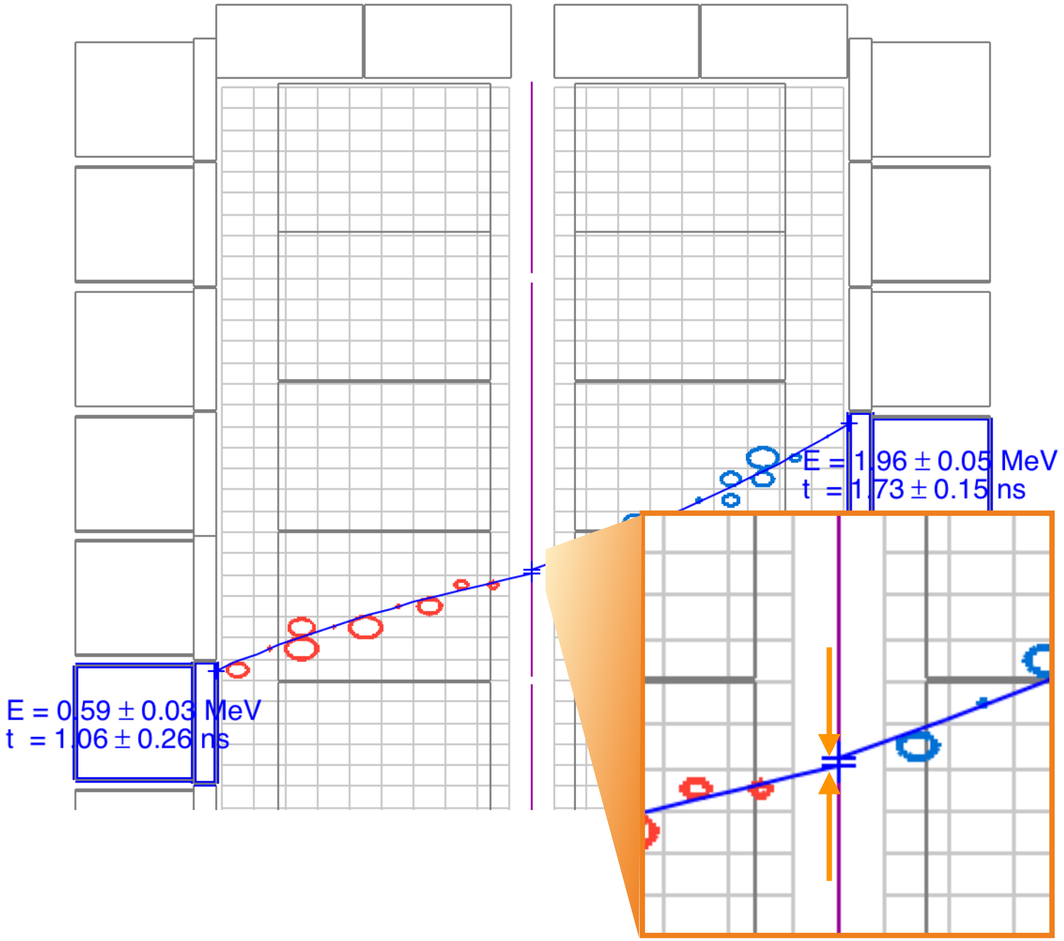
- Two electron-like tracks (negative curvature, associated calorimeter)
- A combined vertex on the source foil



0νββ sensitivity

ββ events are characterised by

- Two electron-like tracks (negative curvature, associated calorimeter)
- A combined vertex on the source foil
- Vertex separation < 7cm parallel and 6 cm perpendicular to wires



0νββ sensitivity

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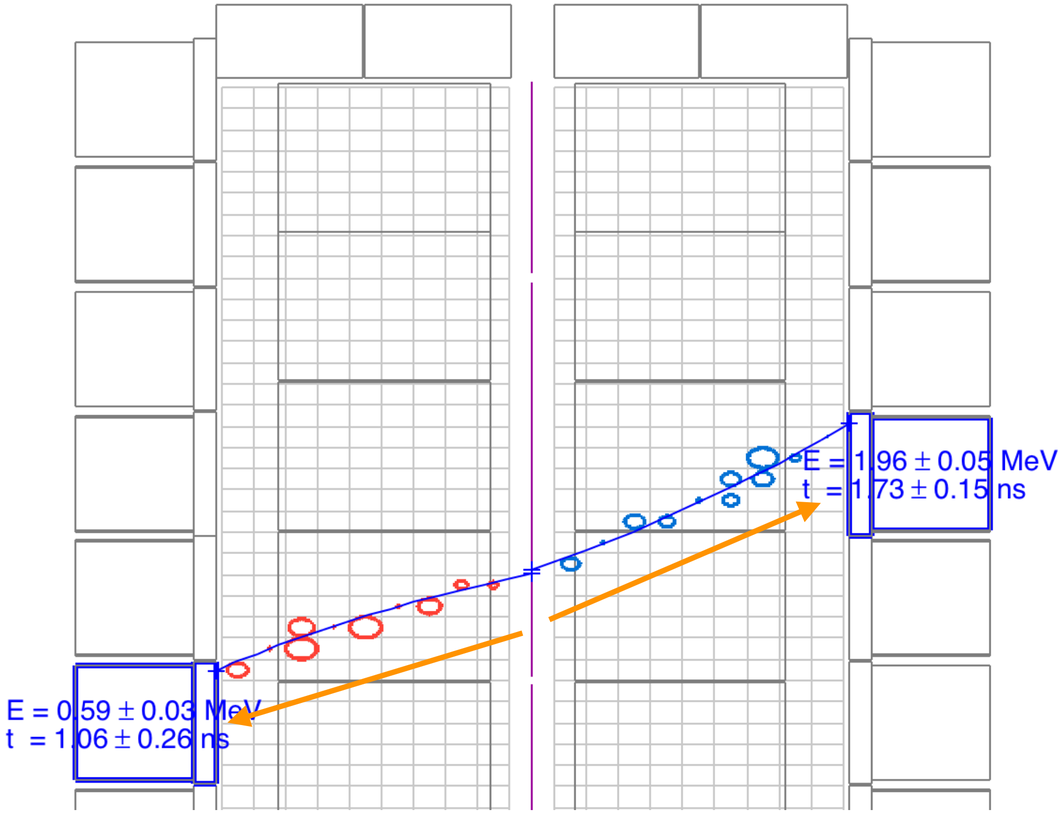
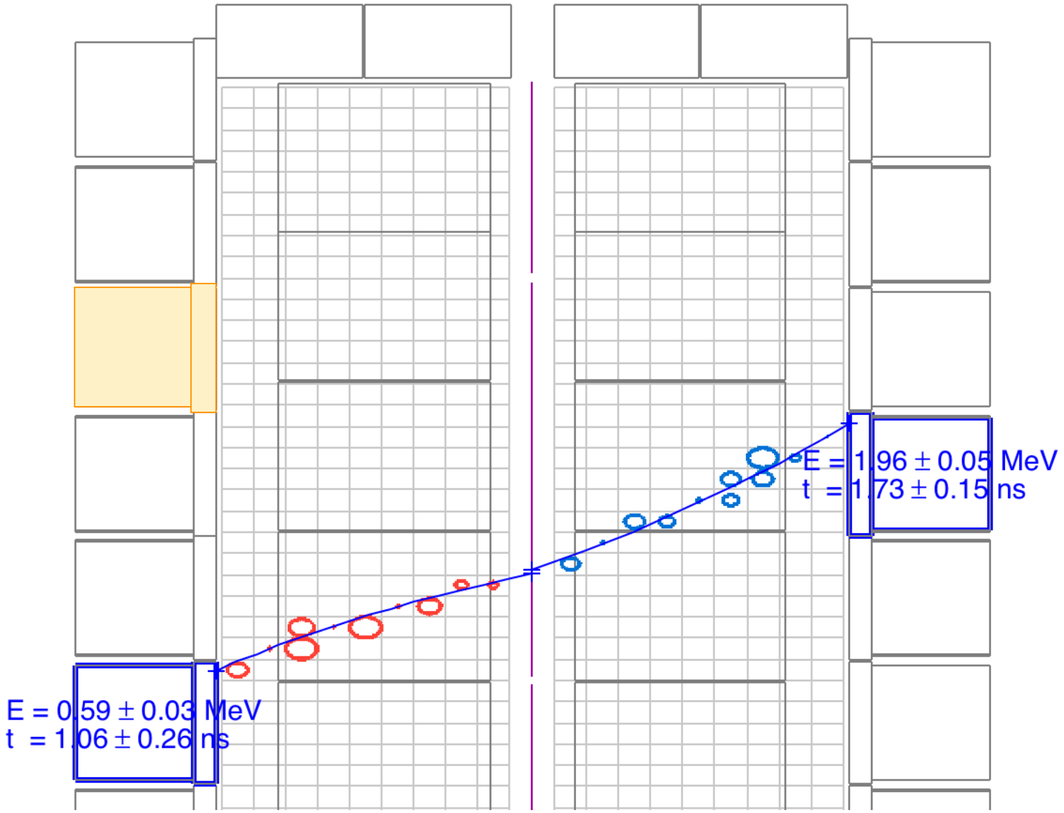
- Internal probability > 4%



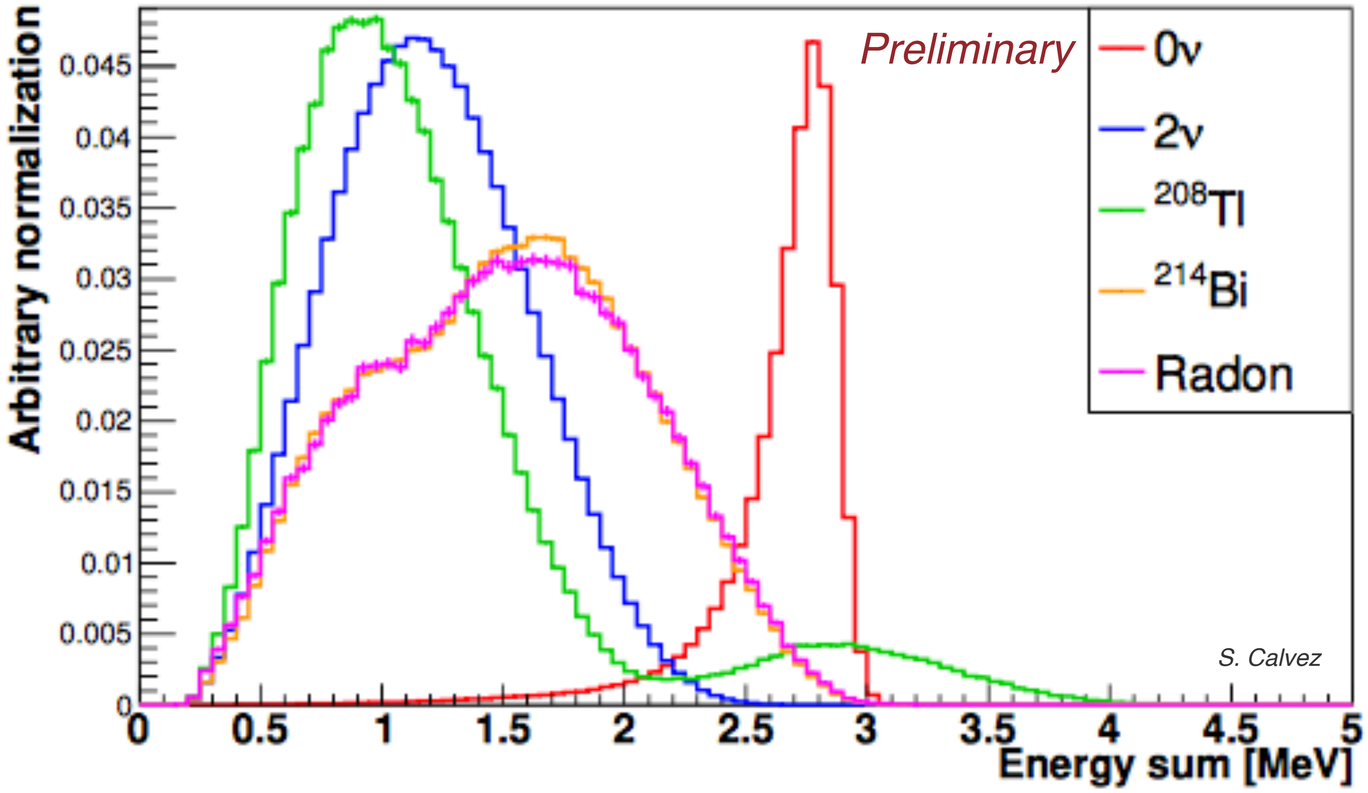
0νββ sensitivity

ββ events are characterised by

- Two electron-like tracks (negative curvature, associated calorimeter)
- A combined vertex on the source foil
- Vertex separation < 7cm parallel and 6 cm perpendicular to wires
- Internal probability > 4%
- No unassociated (gamma-like) hits



Demonstrator sensitivity



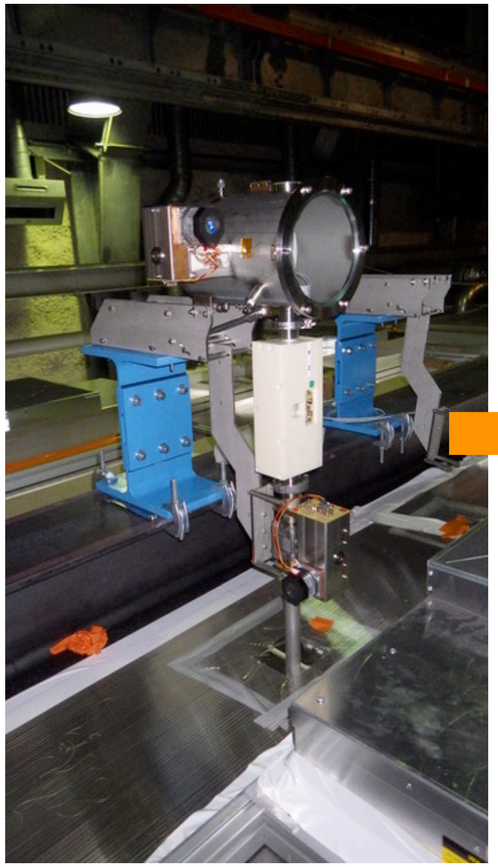
Summed 2-electron energy is best distribution to separate signal from background

Using a **boosted decision tree**, we can **improve sensitivity** by including **other variables** (angle between tracks, individual electron energies, internal/external probability, vertex separation…) *(approx 10% improvement)*

$T_{1/2} > 5.85 \times 10^{24}$ years (90% C.L)

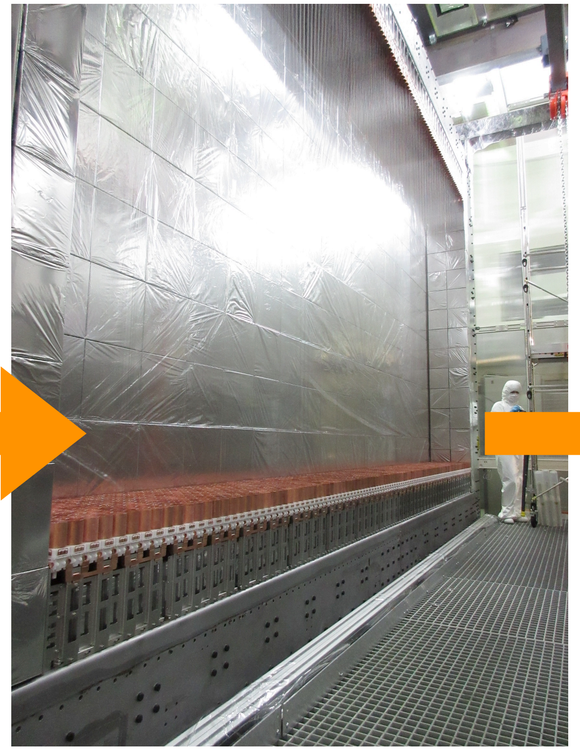
For 7kg of ^{82}Se (demonstrator) and 2.5 years' exposure

Next steps



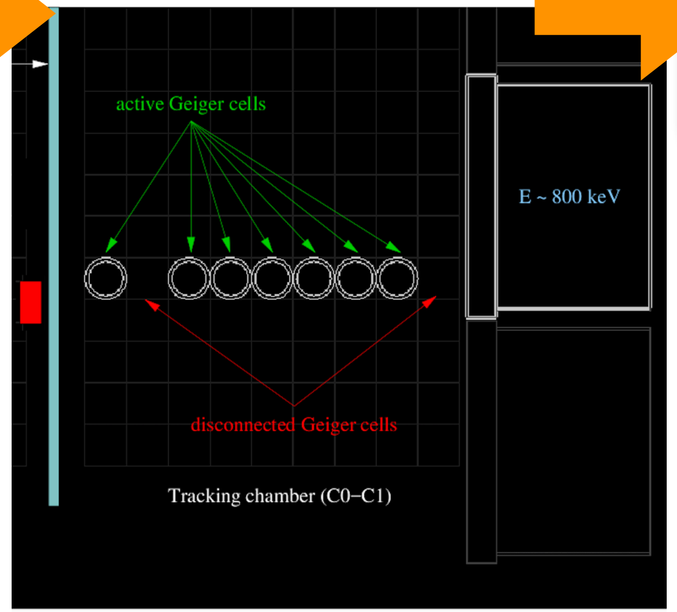
Validate calibration system

Install source foils



Close the detector

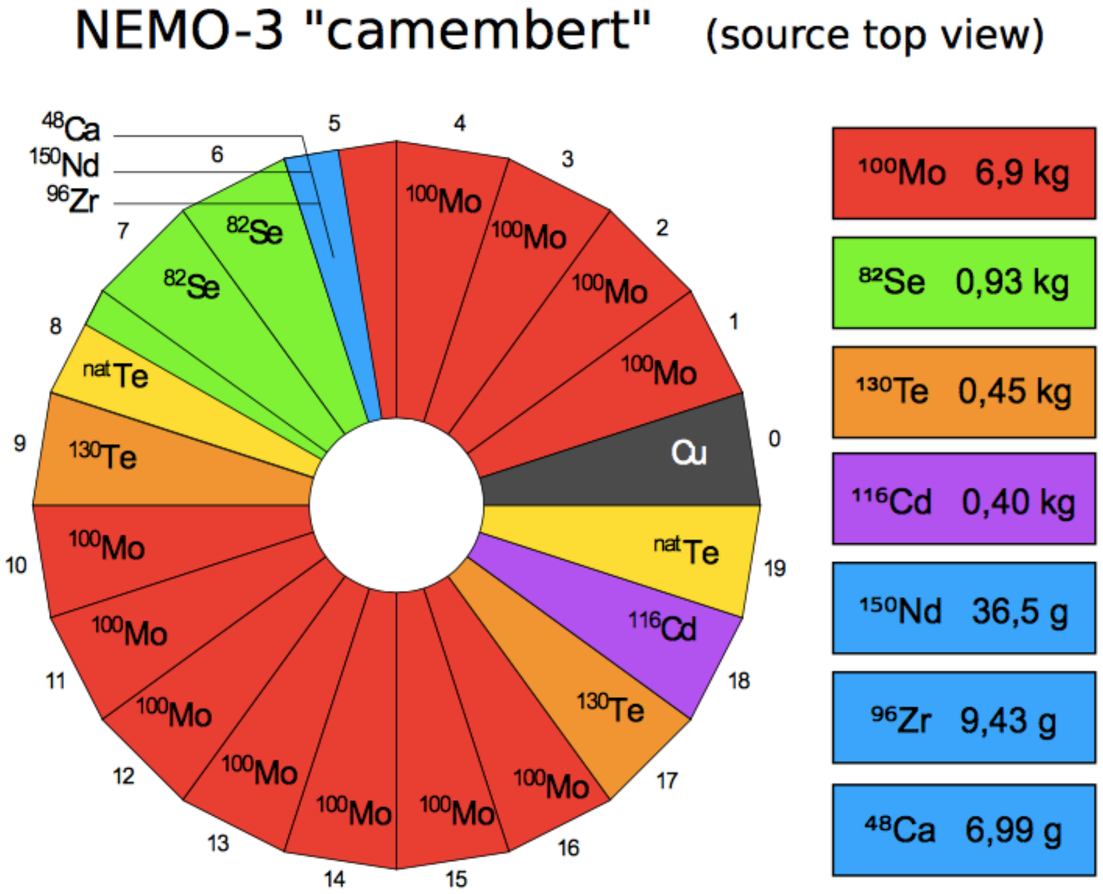
Commissioning
Calibration
Monte Carlo challenge



FIRST DATA!

Long-term plans

- Other isotopes

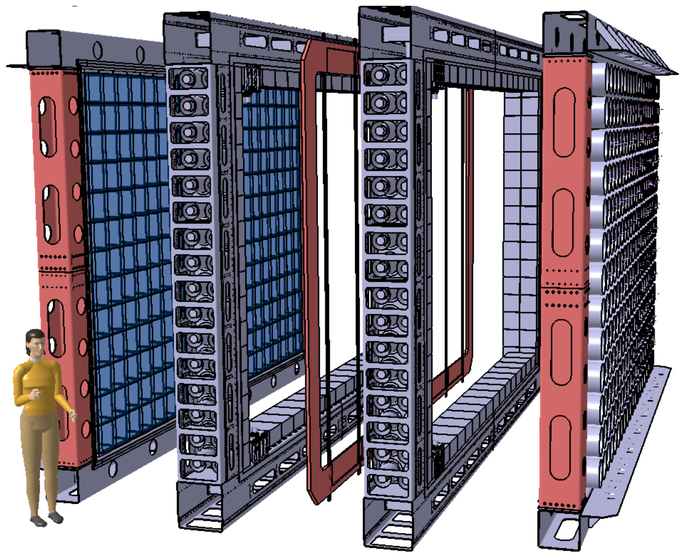


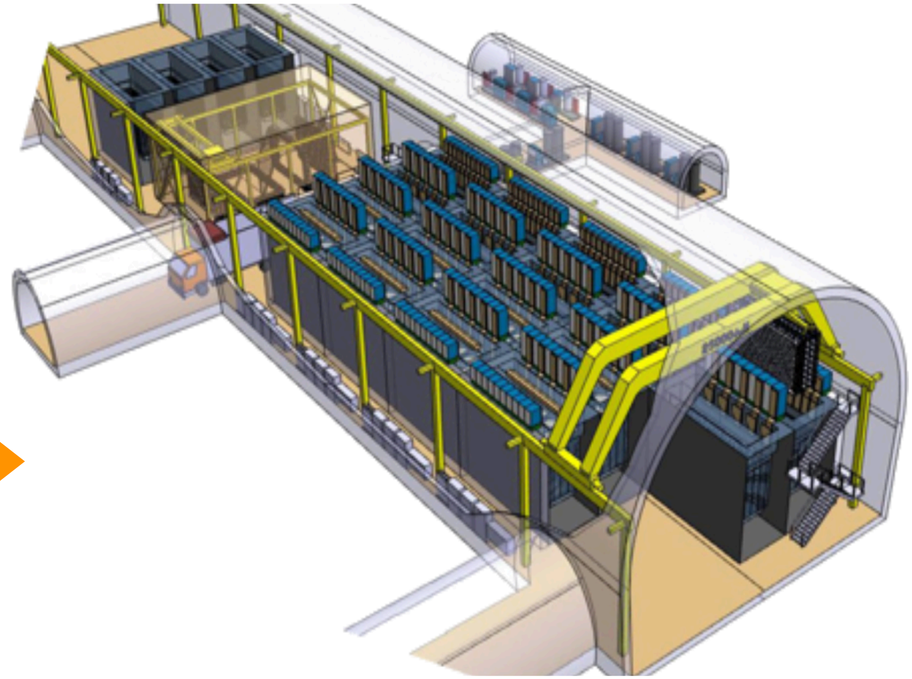
NEMO-3 studied 7 of the 13 observed ββ isotopes

SuperNEMO's design allows us to exchange the ^{82}Se source foils for foils of other materials

Long-term plans

- Other isotopes
- Full SuperNEMO





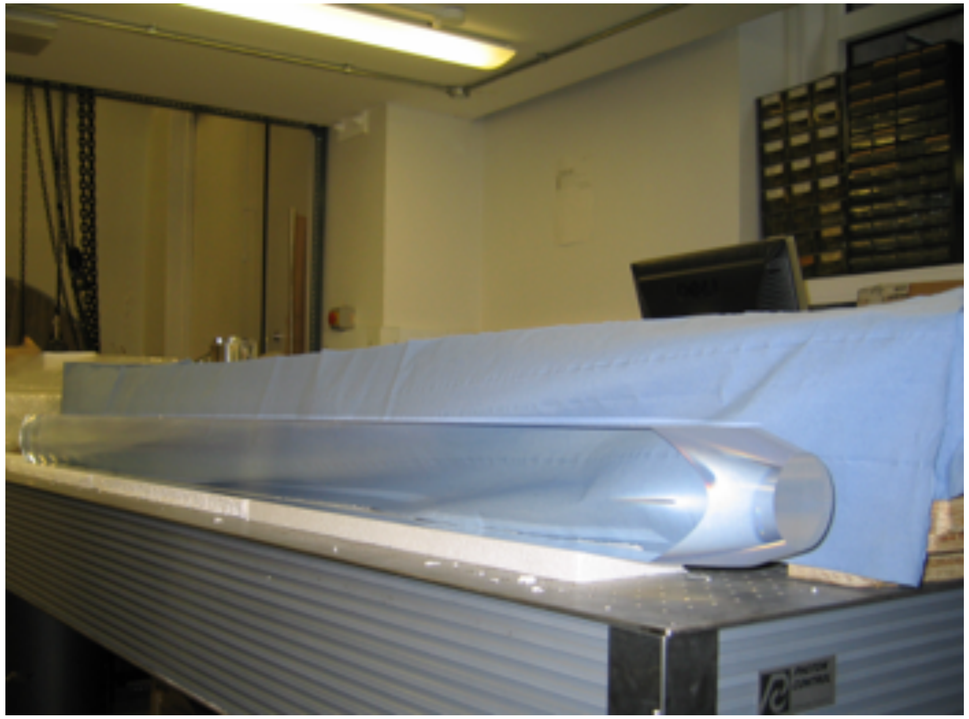
A proposed 20-module full SuperNEMO detector improves our sensitivity to

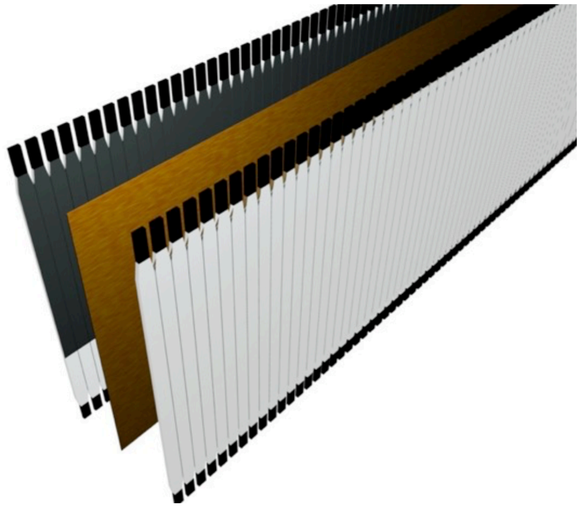
$T_{1/2} > 10^{26}$ years; $\langle m_\nu \rangle < 50\text{-}100$ meV

For 100kg of ^{82}Se and 5 years' exposure

Long-term plans

- Other isotopes
- Full SuperNEMO
- Detector R&D:
  - scintillator bars





Long-term plans

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- Full SuperNEMO
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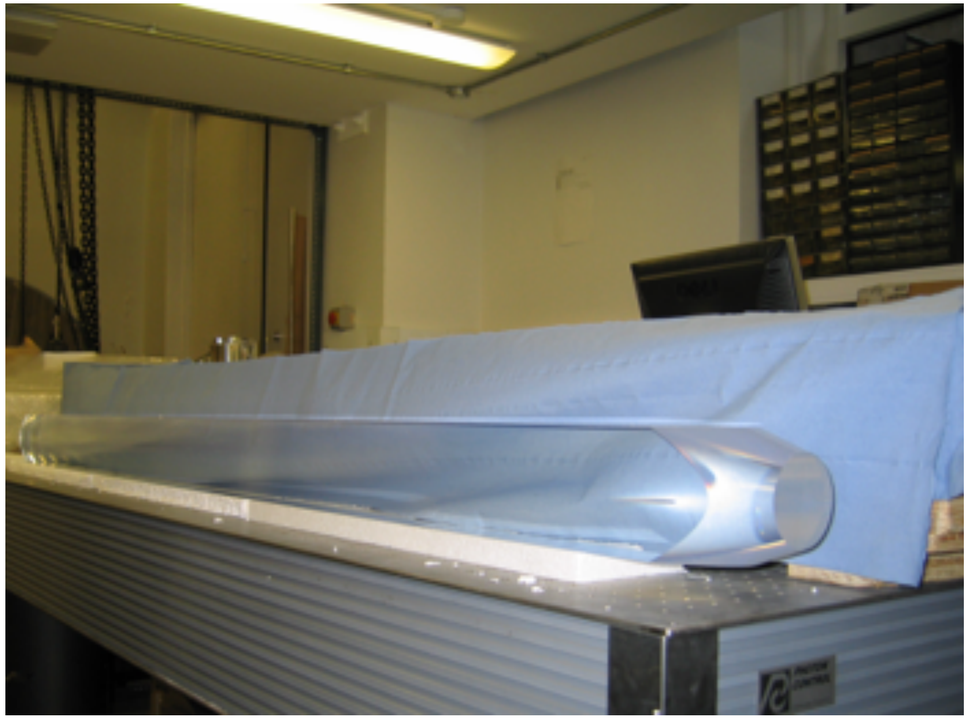
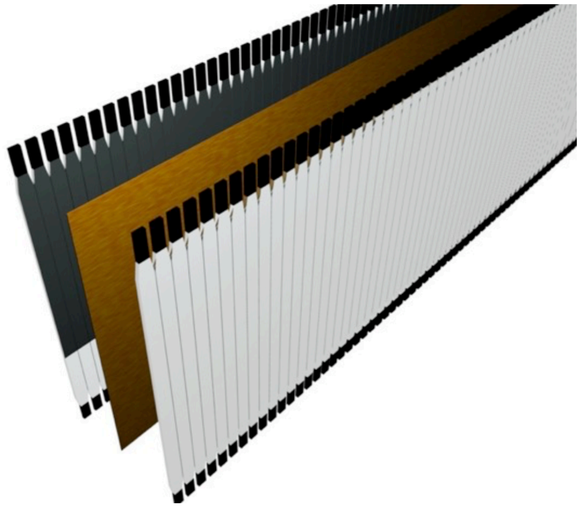
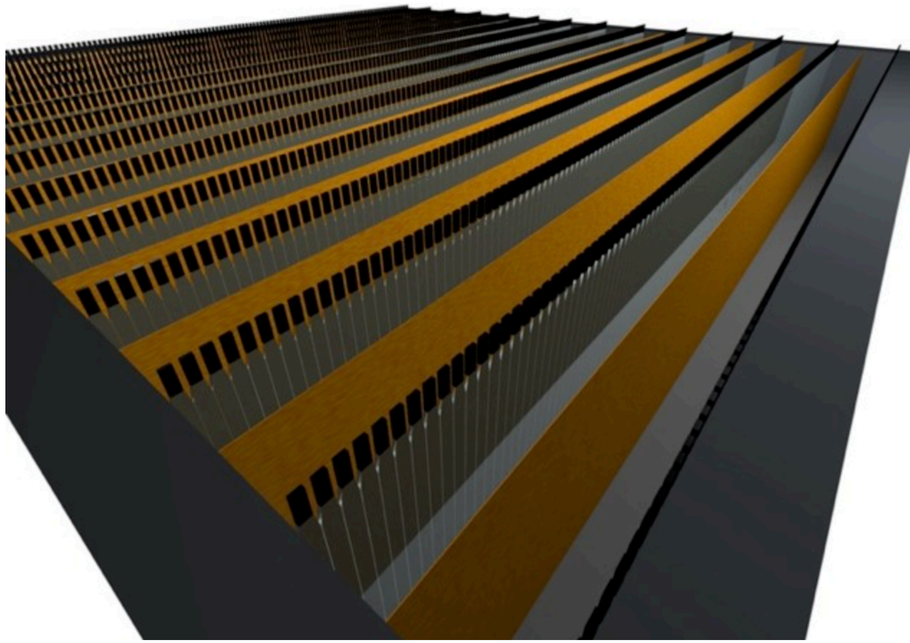


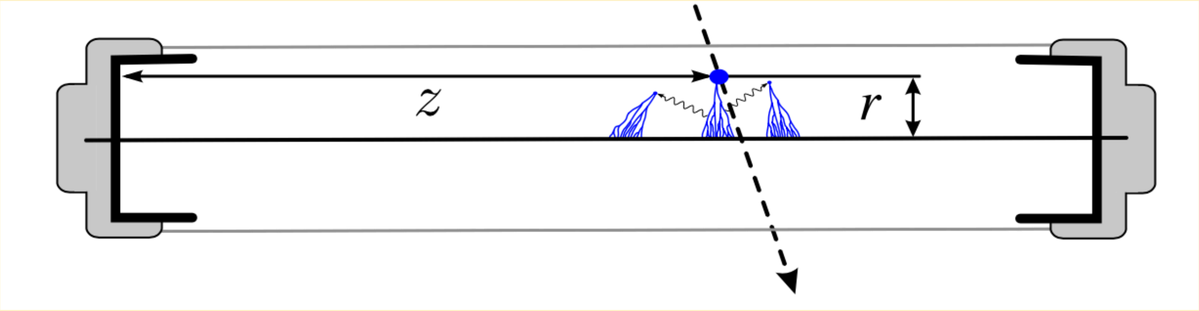




- *Walls of 2m scintillator bars sandwiched between tracker layers = good background rejection?*
- *Fewer PMTs - save $$ and radioactivity*
- *Easier to build*
- *But can we maintain our energy & time resolution?*

Long-term plans

- Other isotopes
- Full SuperNEMO
- Detector R&D:
  - scintillator bars
  - tracker improvements



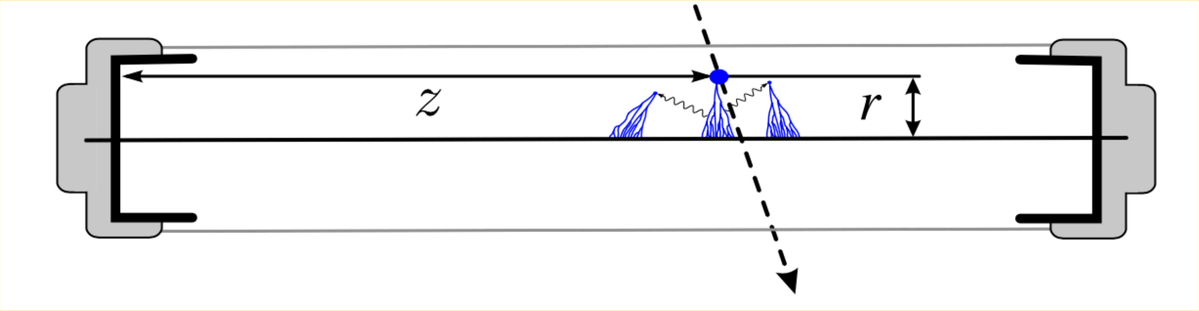
- SuperNEMO's tracker cells operate in the Geiger regime (electron avalanche saturated, independent of ionisation)
- Could we use proportional mode and measure the ionisation energy?

Long-term plans

- Other isotopes
- Full SuperNEMO
- Detector R&D:
  - scintillator bars
  - tracker improvements

Goal: an improved SuperNEMO that is

- extensible,
- compact and
- inexpensive,
- and retains the performance of the demonstrator



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- Could we use proportional mode and measure the ionisation energy?

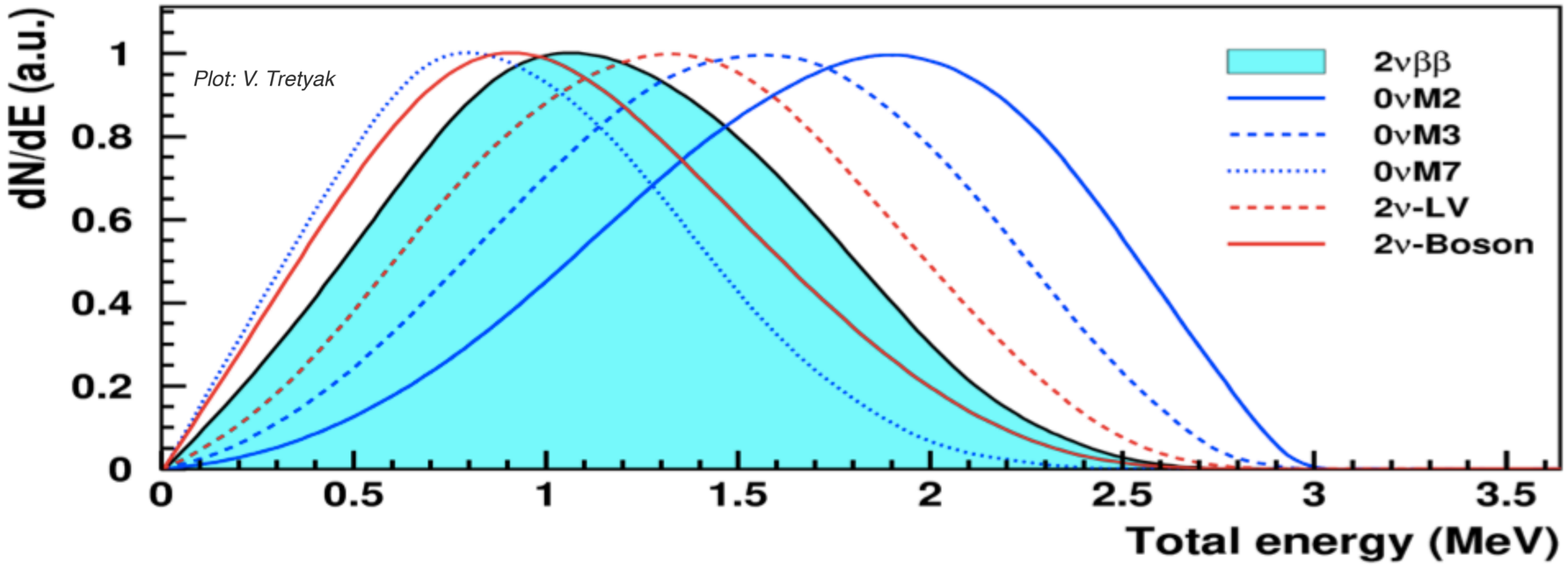
Sensitivity to new physics

Some theories predict additional **Majoron** bosons in 0νββ: $(A,Z) \rightarrow (A,Z+2) + 2\,e^- + \chi^0$ or $(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\chi^0$

If **Pauli principle** were violated, 2νββ neutrinos could have a **bosonic** component:

$A_{\beta\beta} = \cos^2\chi\, A_f + \sin^2\chi\, A_b$, where A_f -fermionic, A_b – bosonic

Both of these, as well as **Lorentz violation**, would affect the **summed 2e⁻** energy distribution (as well as separation angle etc)

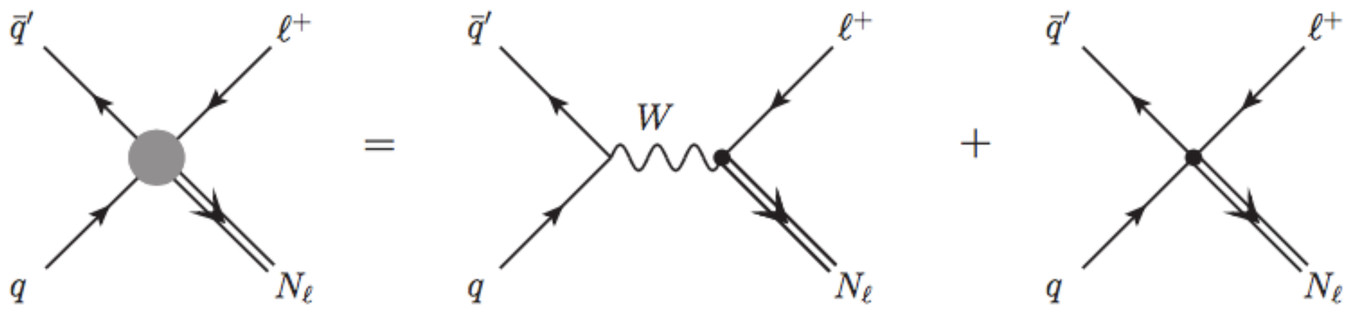


Sensitive to $T_{1/2} > 3\text{-}5 \times 10^{21}$ years for bosonic neutrinos (90% C.L)

4-6 times improvement for Majoron half-life limits

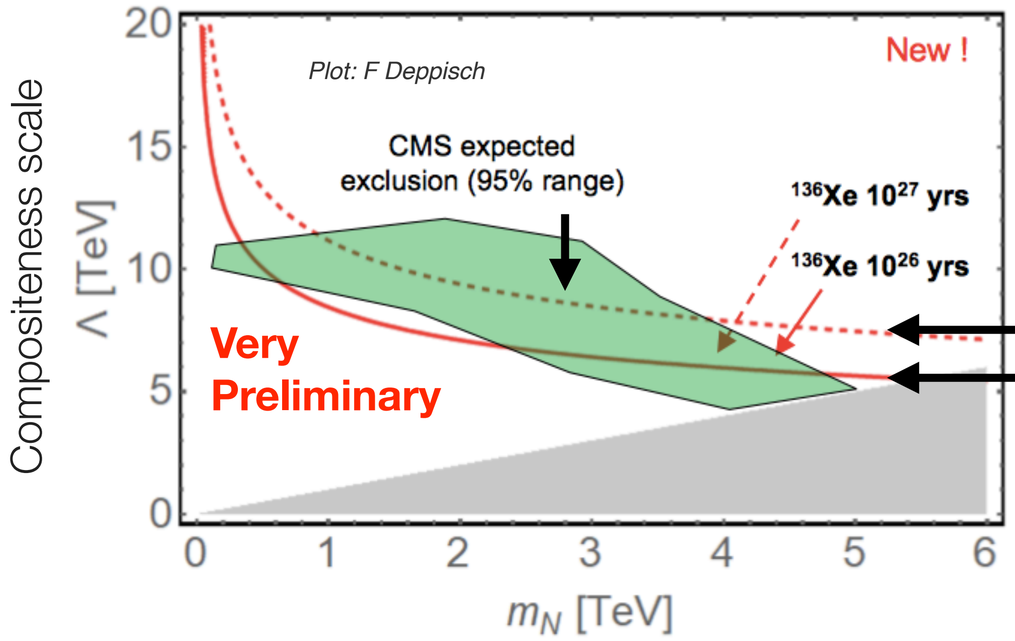
Astrophysical and exotic processes

Composite Majorana Neutrinos



CMS has set a limit

$N_\ell \to \ell q \bar{q}'$

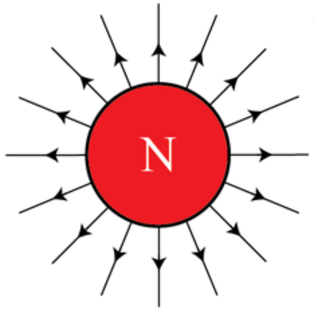


ββ half-life limit exclusions (examples)

Astrophysical and exotic processes

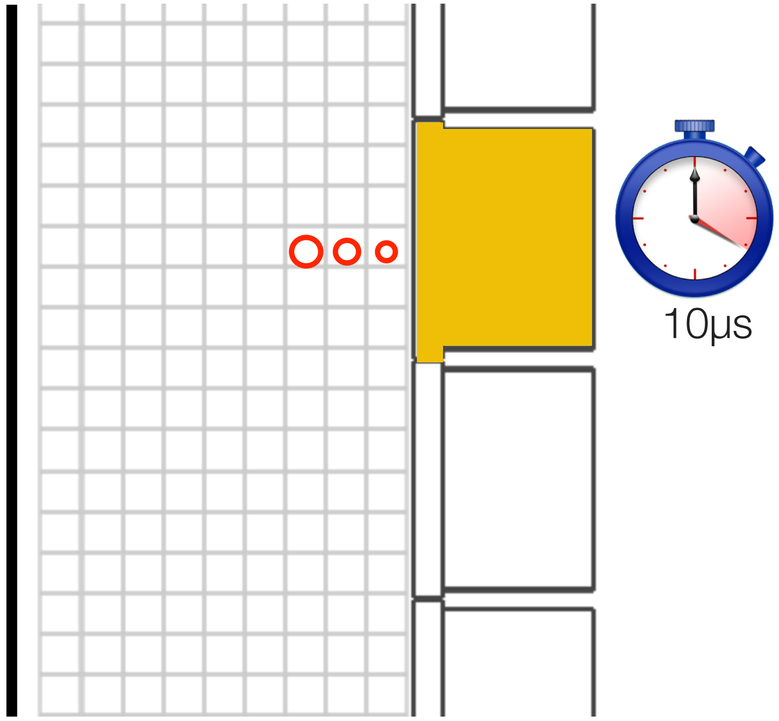
Composite Majorana Neutrinos

Magnetic monopoles



G T'Hooft, Nucl. Phys. B79 (1974) 276-284.

- Postulated by Dirac; needed for Grand Unified Theories
- Extremely **massive** (> 10^{17} GeV)
- Highly **ionising** due to large magnetic charge

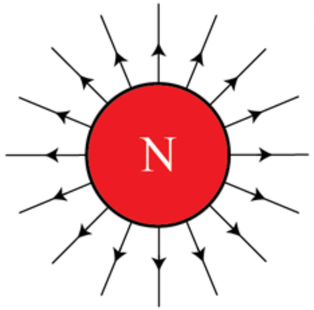


SuperNEMO signature - short track + calorimeter hit 10 μs

Astrophysical and exotic processes

Composite Majorana Neutrinos

Magnetic monopoles



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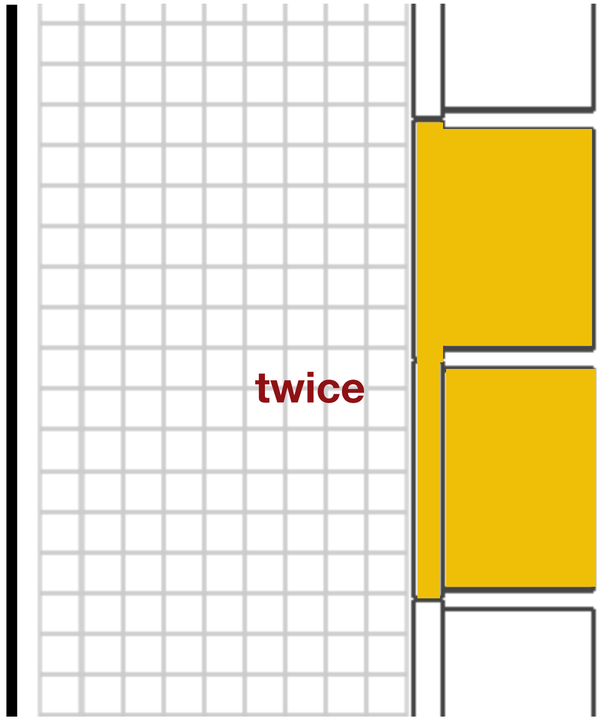


Or 2 saturated calorimeters registered in 2 different events

Astrophysical and exotic processes

Composite Majorana Neutrinos

Magnetic monopoles

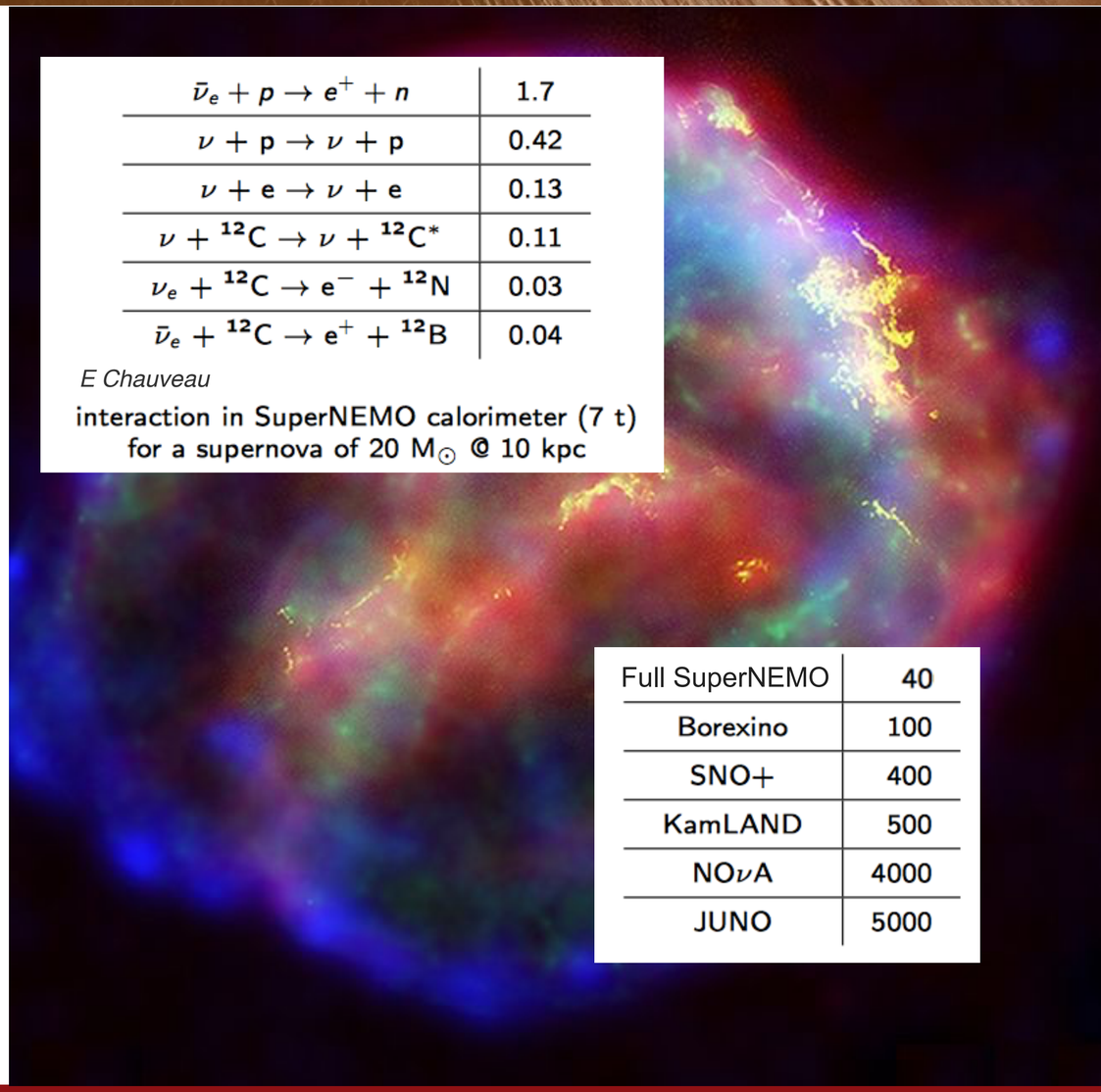
Supernova neutrino bursts

- Neutrinos of all flavours for **10 seconds**
- Mean energy 15 MeV
- Several interactions could show up
- **Full SuperNEMO** would have sensitivity comparable to Borexino, with unique detection capability

$\bar{\nu}_e + p \rightarrow e^+ + n$	1.7
$\nu + \mathrm{p} \rightarrow \nu + \mathrm{p}$	0.42
$\nu + \mathrm{e} \rightarrow \nu + \mathrm{e}$	0.13
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	0.11
$\nu_e + {}^{12}\mathrm{C} \rightarrow \mathrm{e}^- + {}^{12}\mathrm{N}$	0.03
$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow \mathrm{e}^+ + {}^{12}\mathrm{B}$	0.04

E Chauveau

interaction in SuperNEMO calorimeter (7 t) for a supernova of 20 $M_\odot$ @ 10 kpc

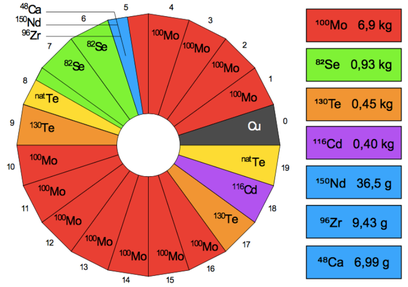


Full SuperNEMO	40
Borexino	100
SNO+	400
KamLAND	500
NOνA	4000
JUNO	5000

In summary, the SuperNEMO demonstrator is…

In summary, the SuperNEMO demonstrator is…

Adaptable



In summary, the SuperNEMO demonstrator is…

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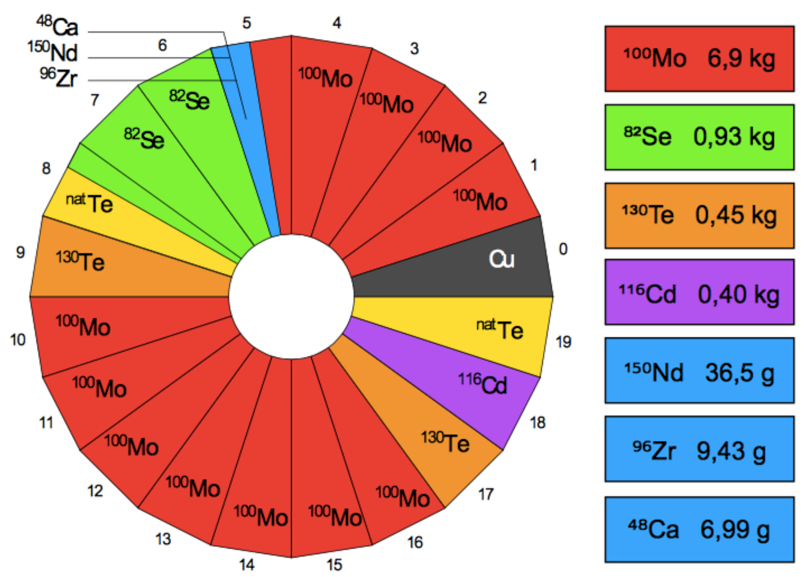
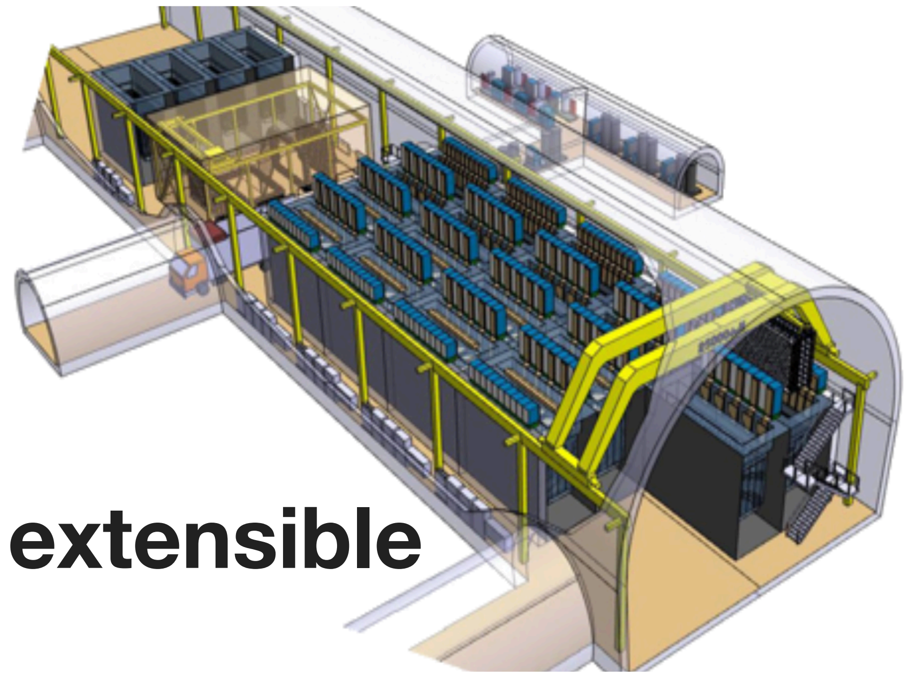
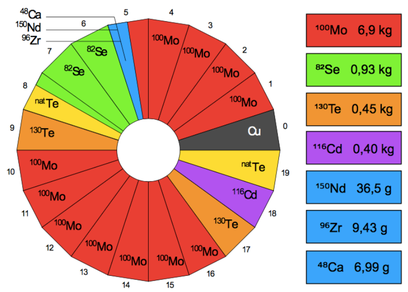


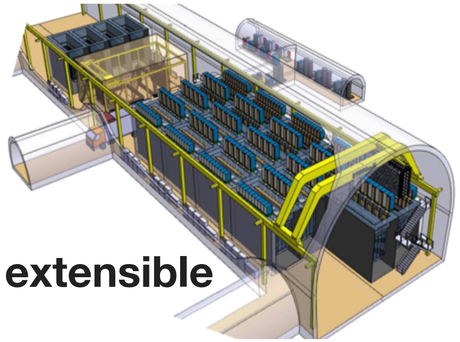


extensible

In summary, the SuperNEMO demonstrator is…

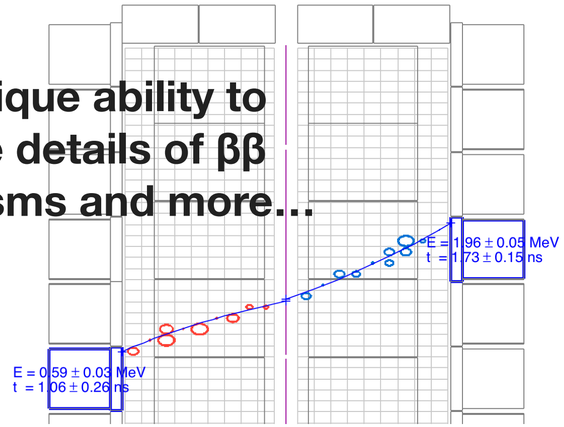
Adaptable





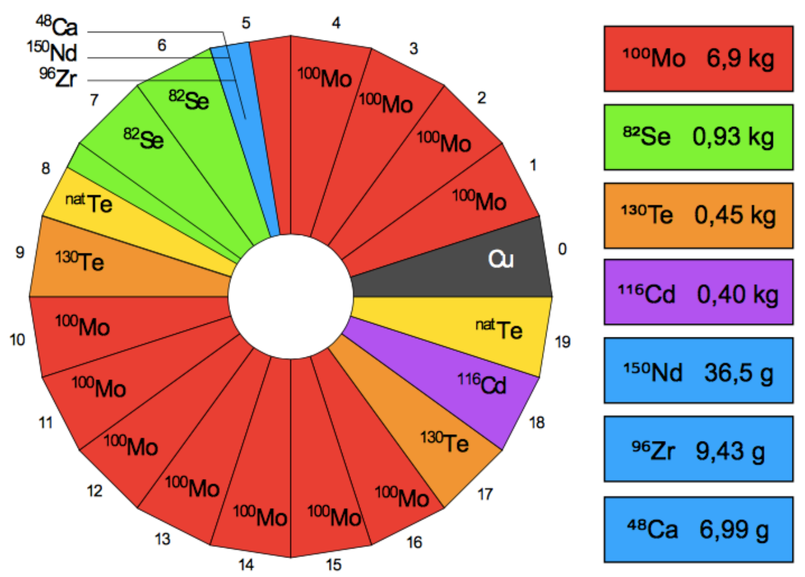
extensible

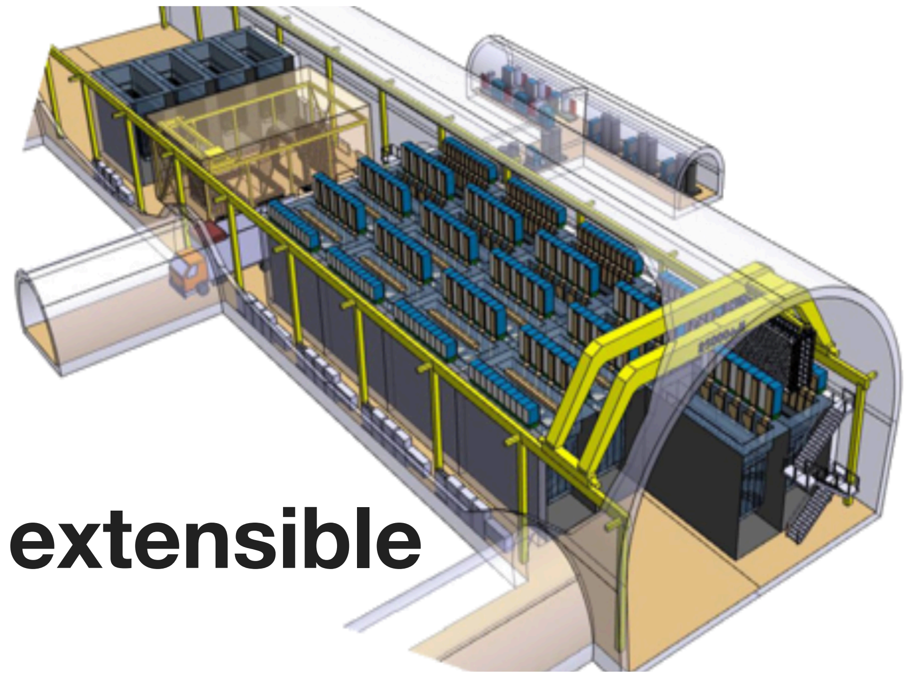
with a unique ability to probe the details of ββ mechanisms and more…



In summary, the SuperNEMO demonstrator is…

Adaptable





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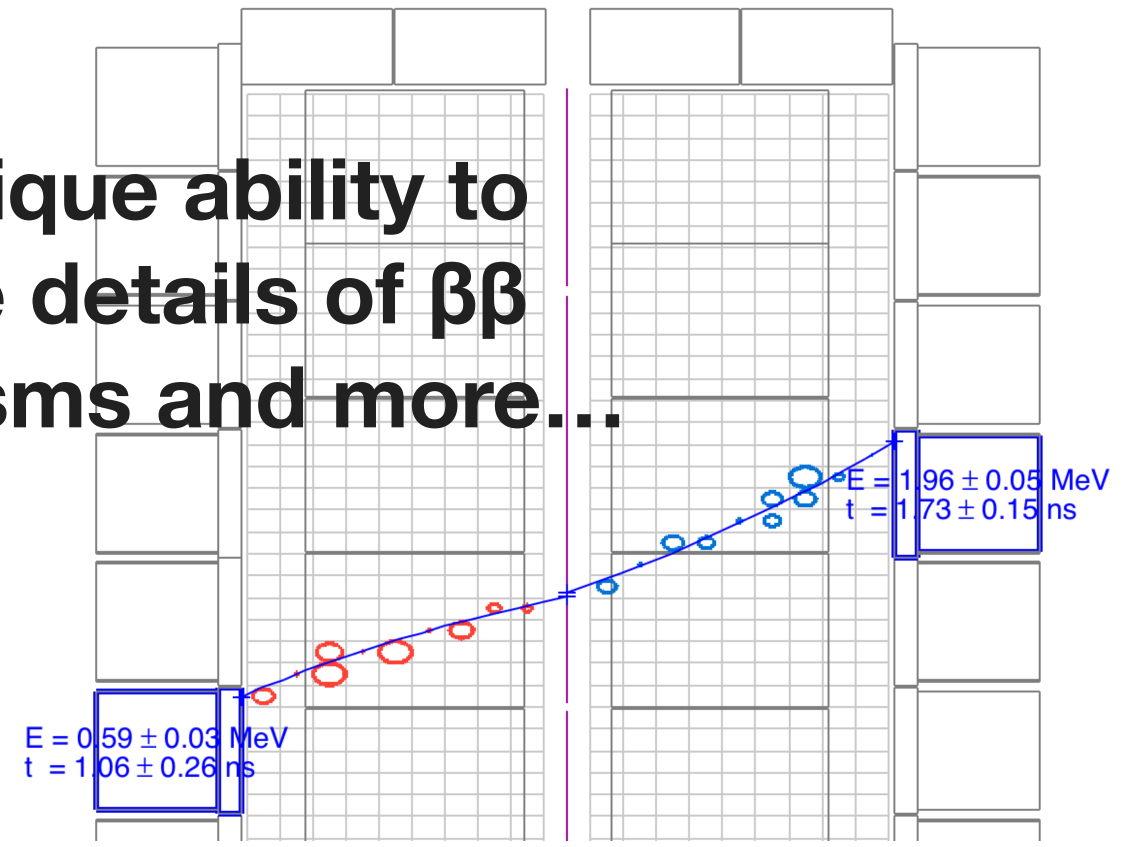
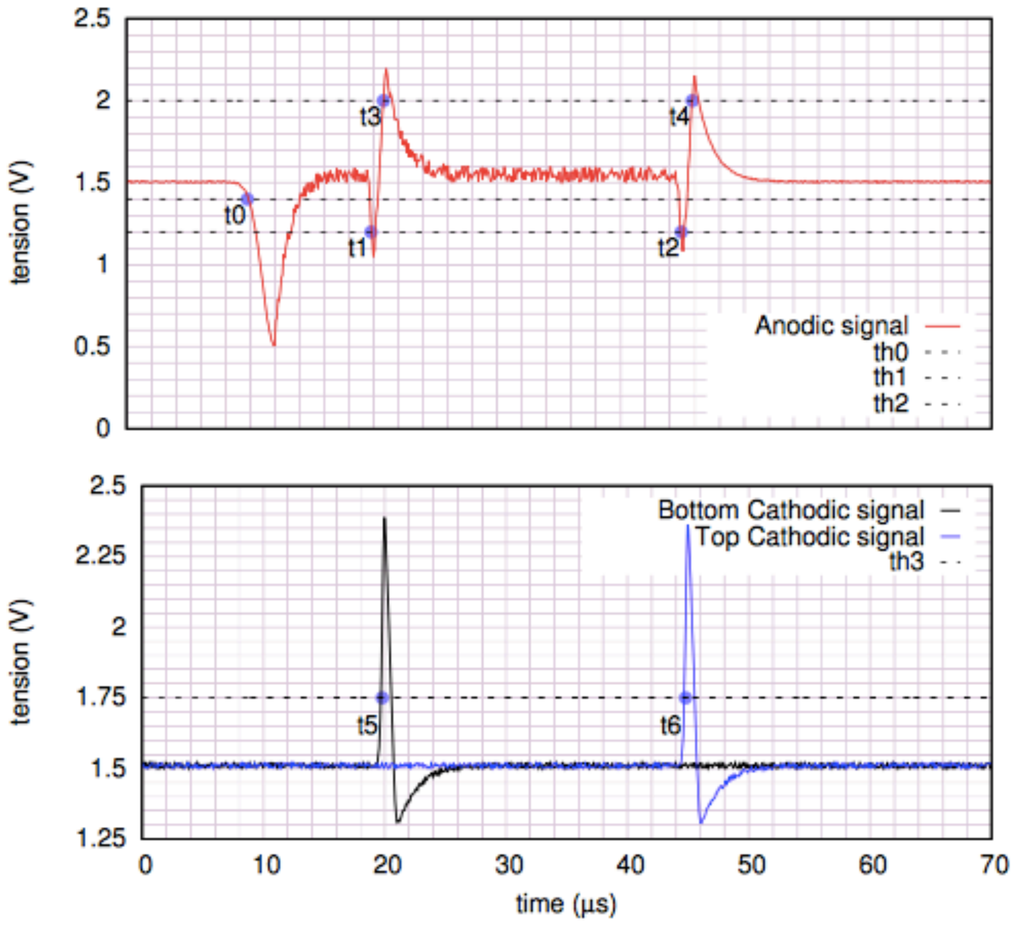


… and we can't wait to get started taking data later this year!

BACKUP SLIDES

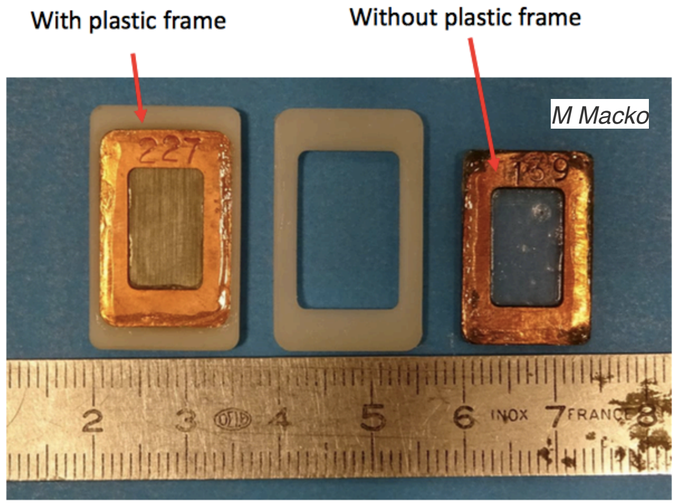
Pulse shapes for Geiger cell

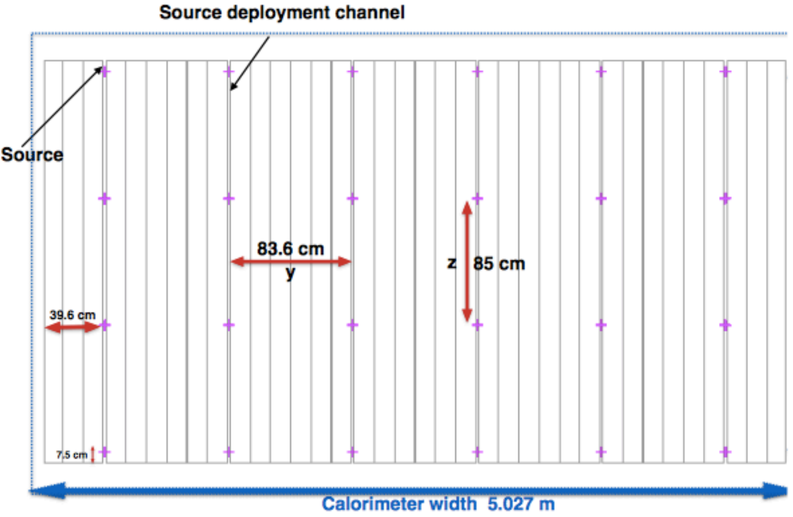


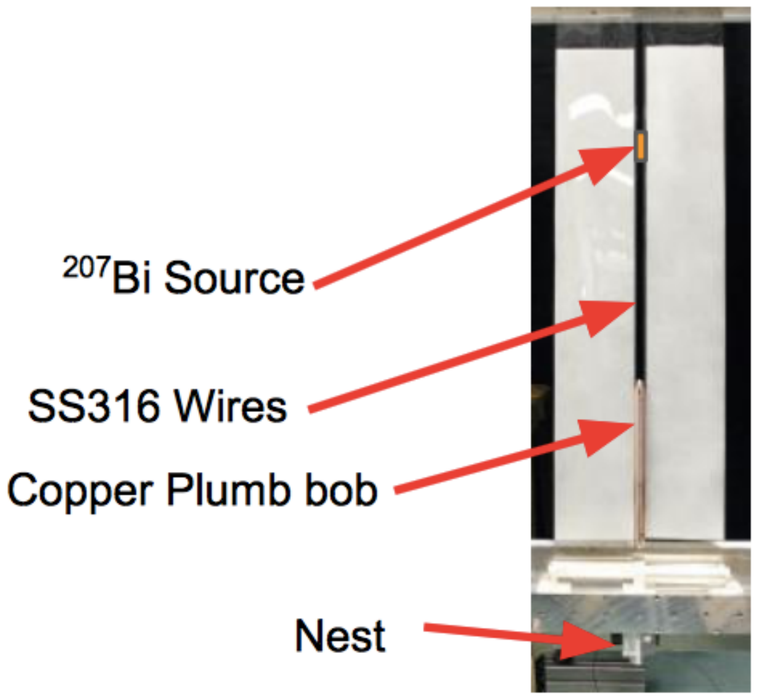
Anode

Two cathodes

Calibration with ^{207}Bi







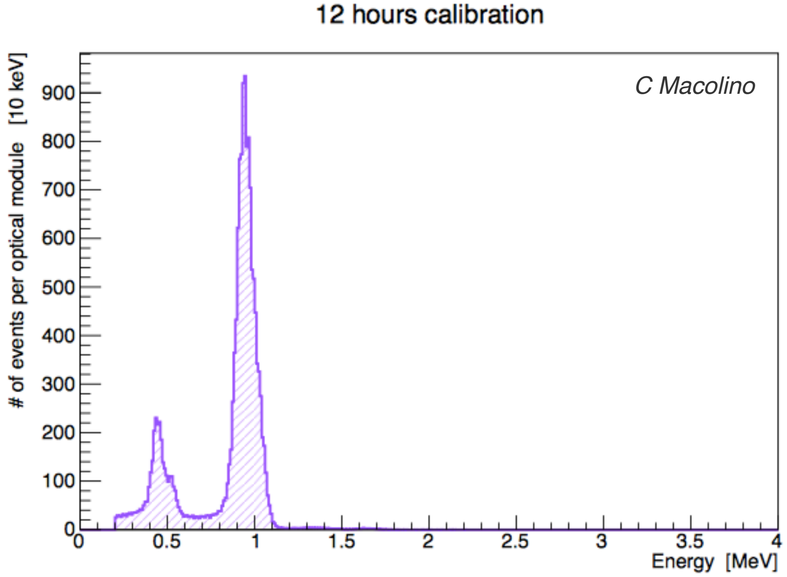
R Salazar

^{207}Bi source positions

^{207}Bi K-shell internal conversion electrons

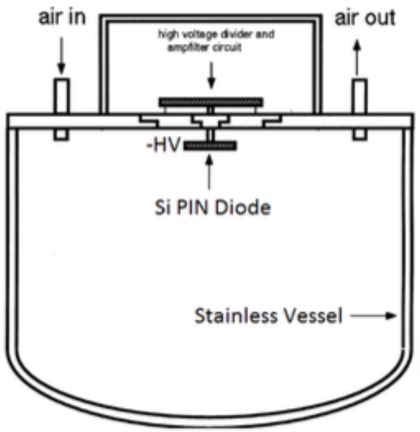
Energy [keV]	Intensity [%]
482	1.5
976	8
1682	0.02

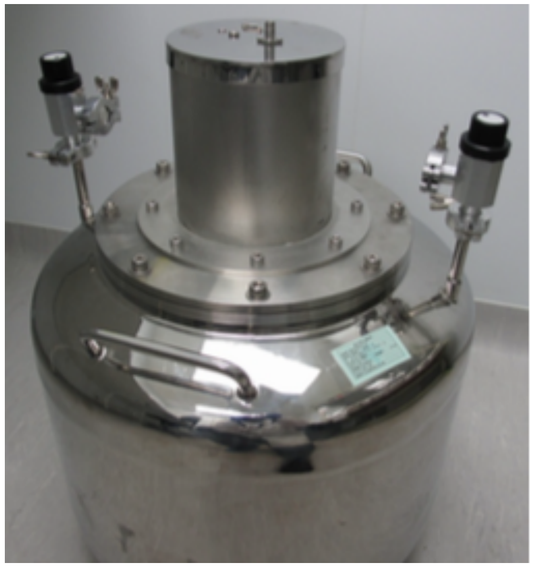
12 hours is enough to identify the first 2 peaks



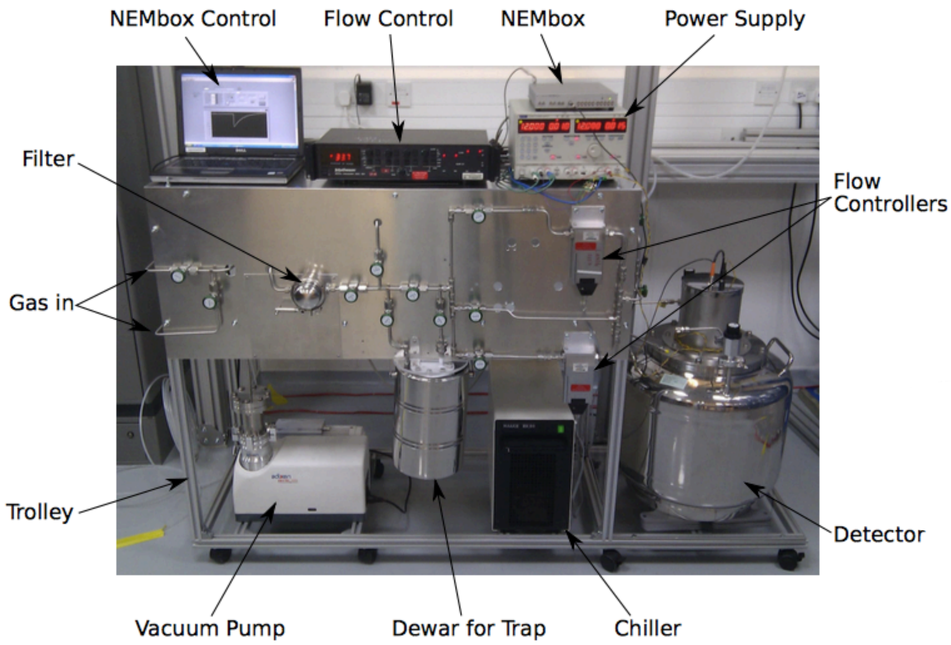
Radon in the tracker

Total tracker radon budget: 0.15 mBq / m³





UCL's 70-litre high-sensitivity electrostatic detectors can measure down to 0.09 mBq



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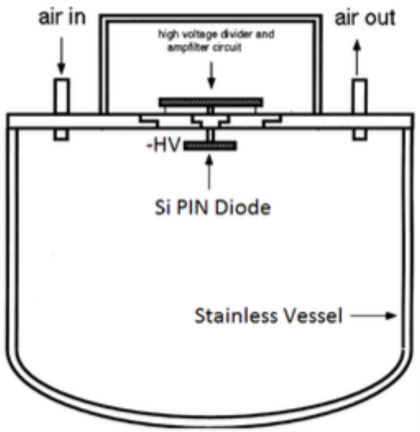

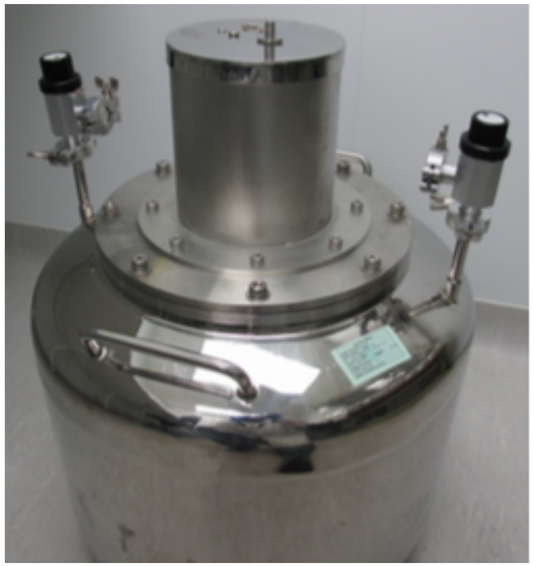

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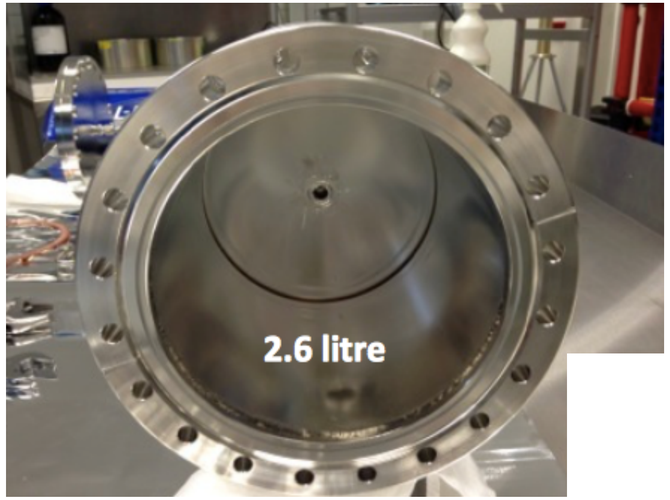
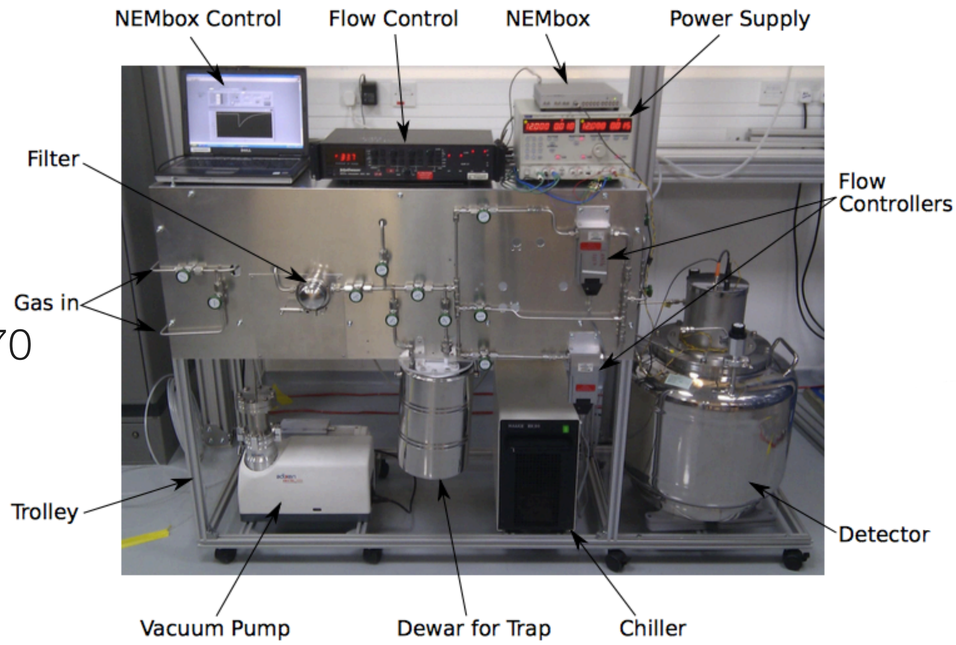


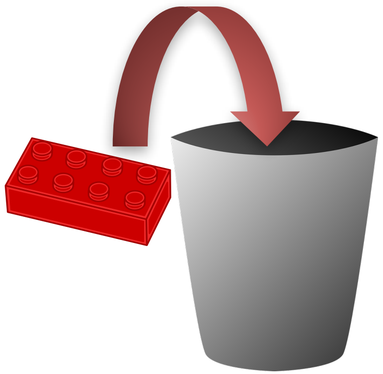
Radon emanation from potential tracker components is measured with an emanation chamber

0.15 mBq / m³ → 0.01mBq in 70 litre chamber

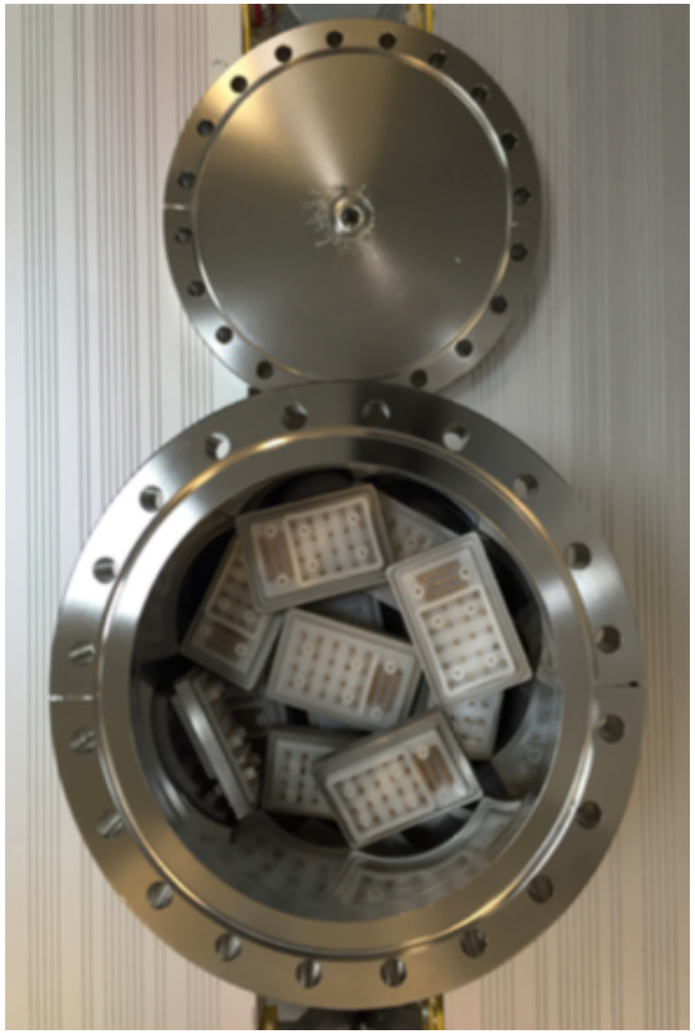
Below 0.09 mBq limit → concentrate radon before measuring



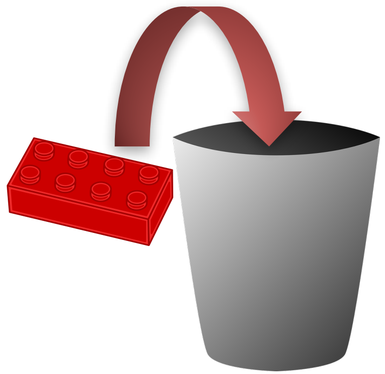
Emanation measurement



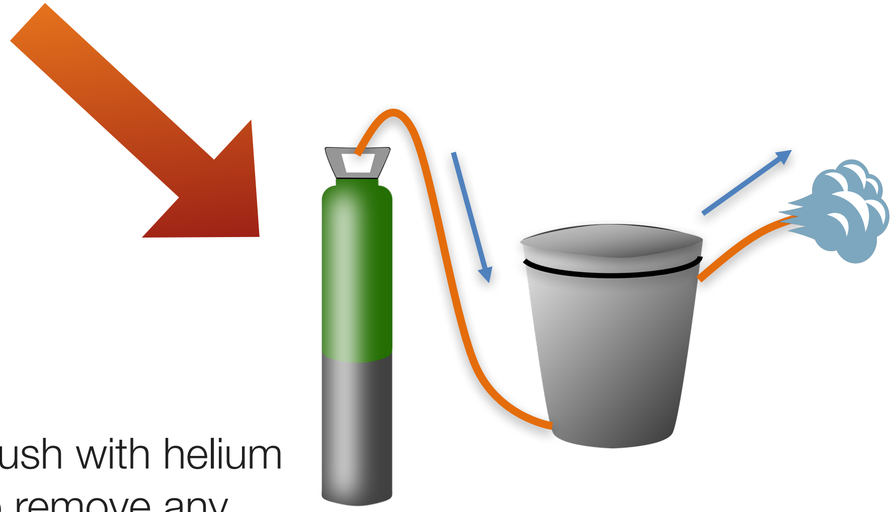
Put clean sample into emanation chamber and seal



Emanation measurement

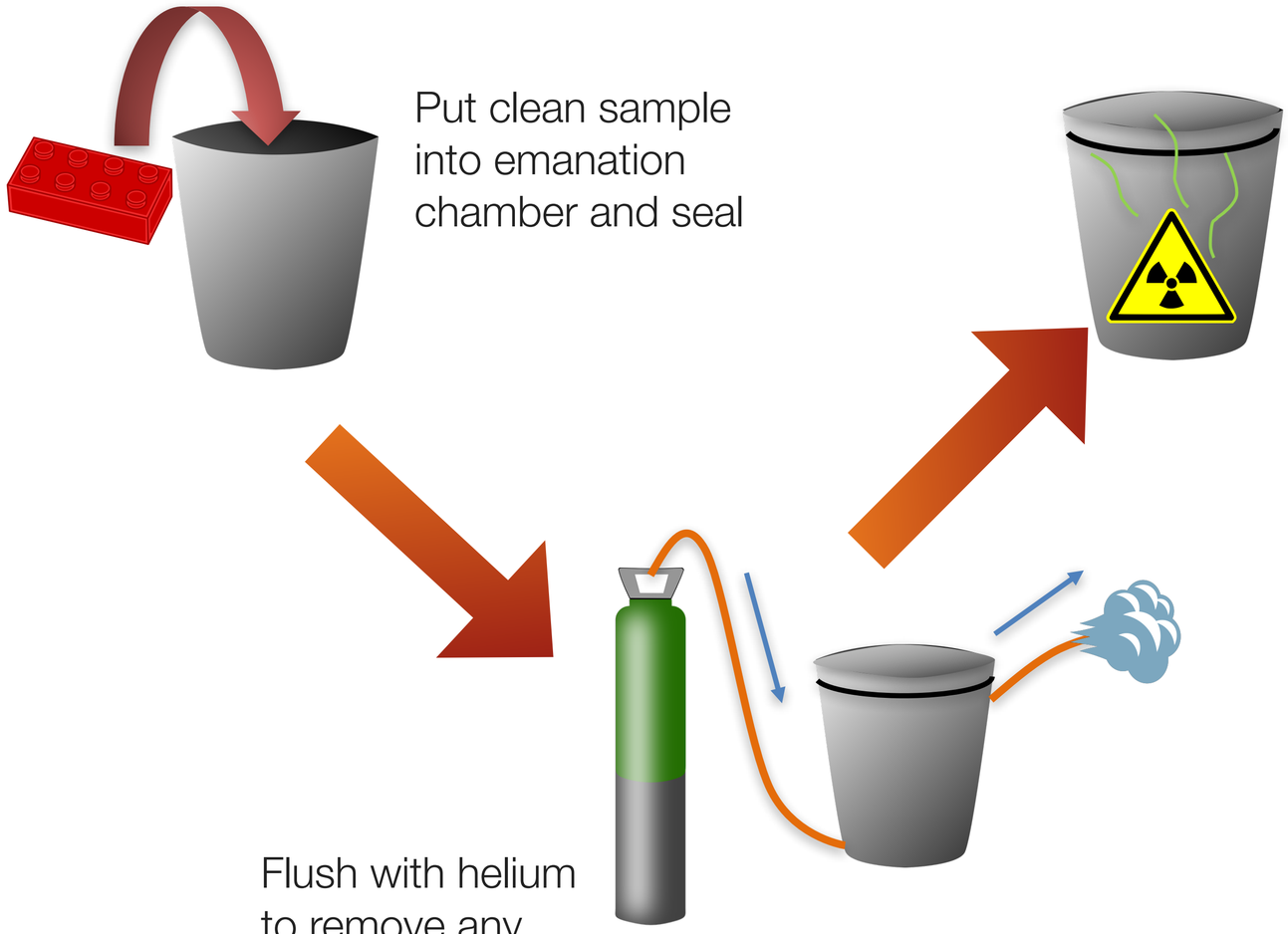


Put clean sample into emanation chamber and seal



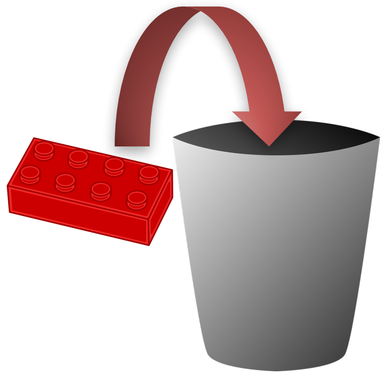
Flush with helium to remove any radon

Emanation measurement



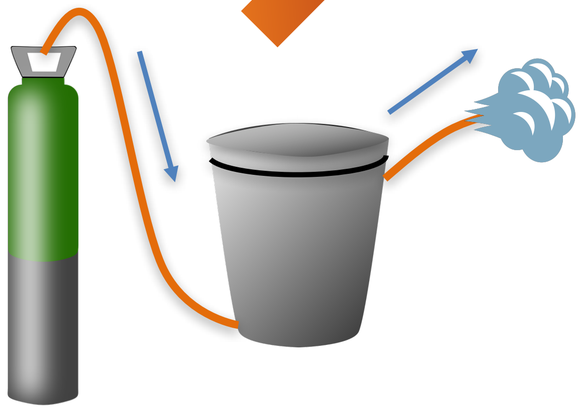
Sample emanates for 10+ days

Emanation measurement

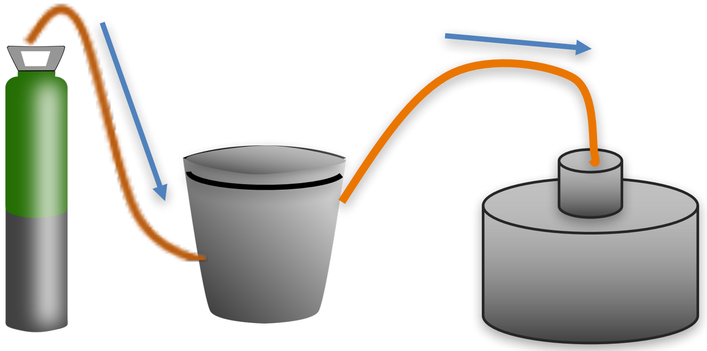


Put clean sample into emanation chamber and seal

Sample emanates for 10+ days

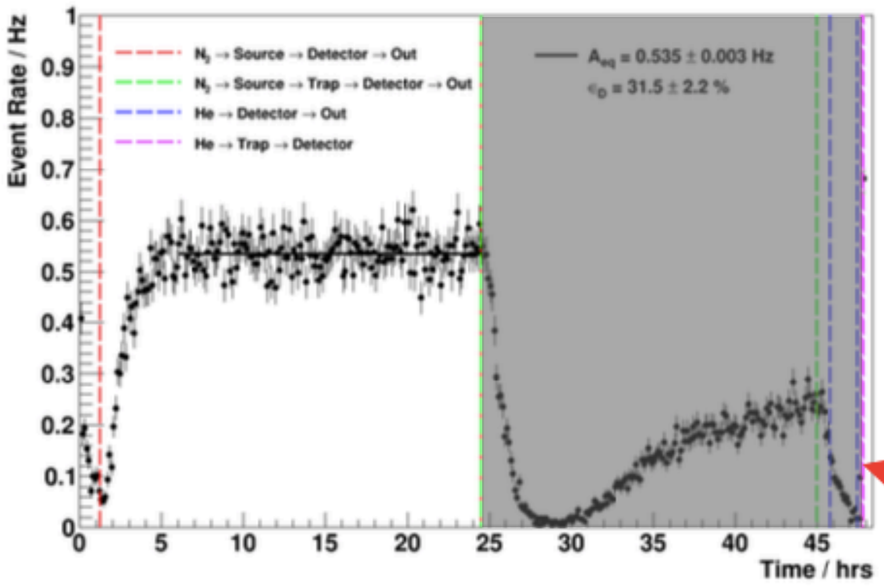


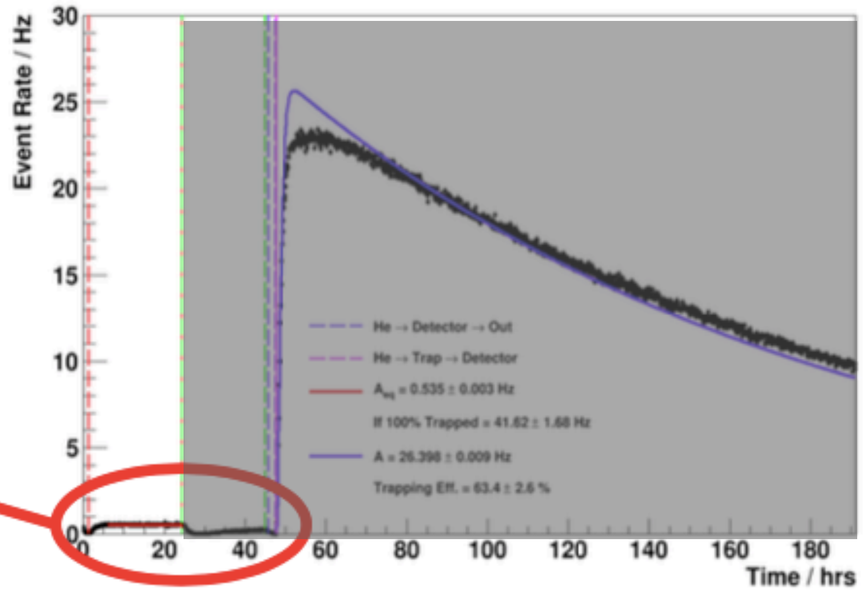
Flush with helium to remove any radon



Use helium to flush emanated radon into electrostatic detector

Calibrating the radon concentration line

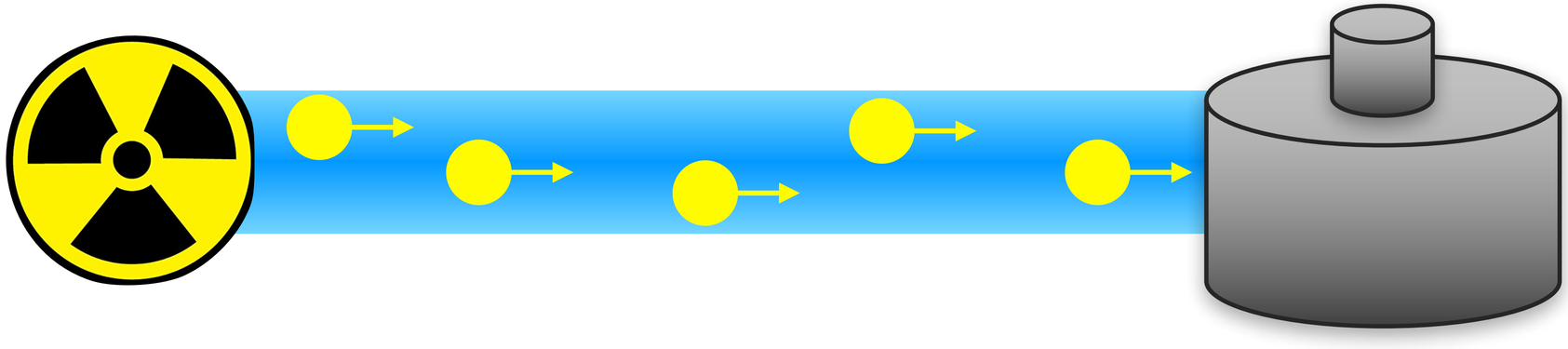




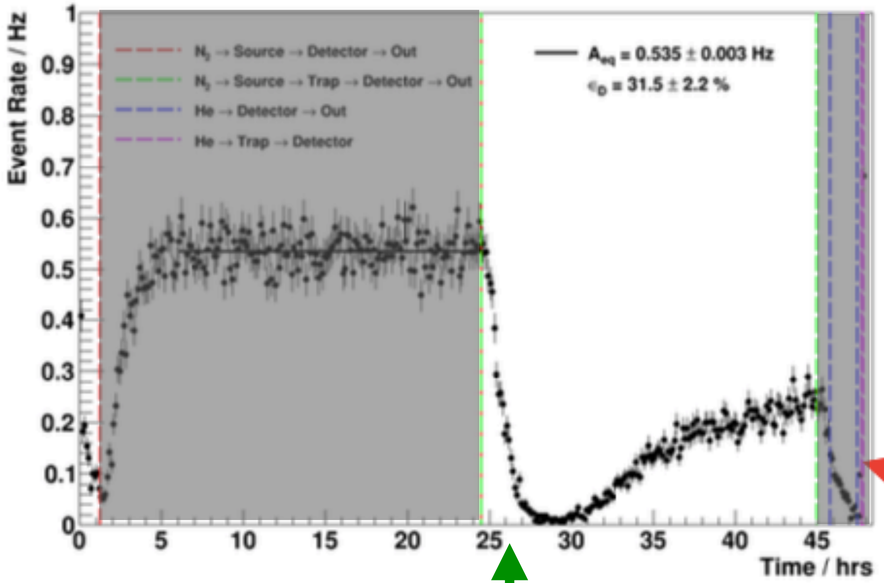
1) Measure detection efficiency

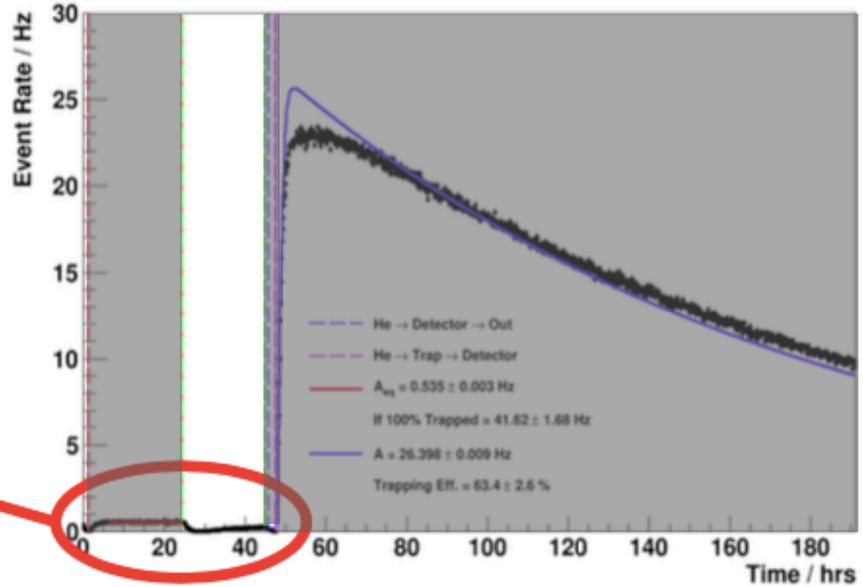
Flush nitrogen over source of known activity to detector (no concentration line)

Detection efficiency = measured activity / true activity



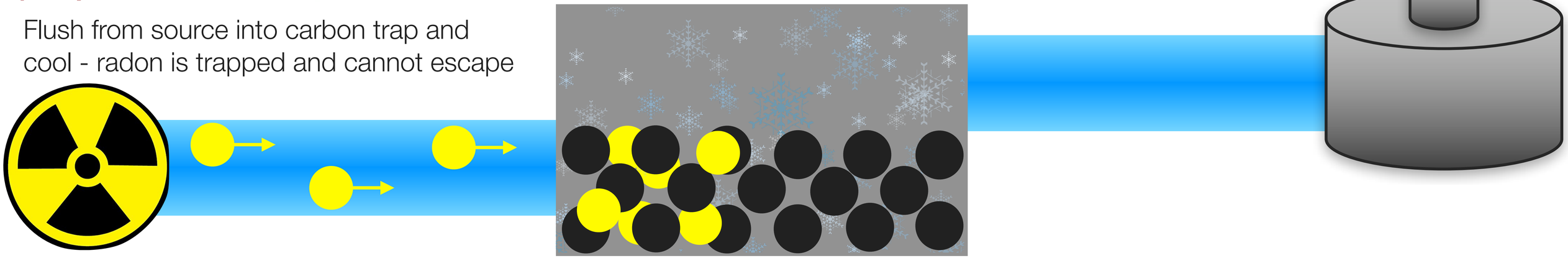
Calibrating the radon concentration line



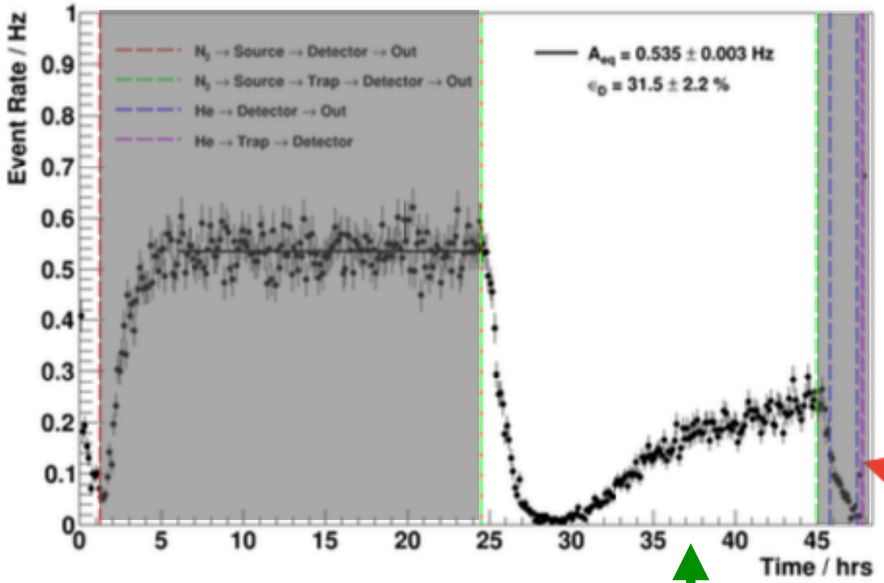


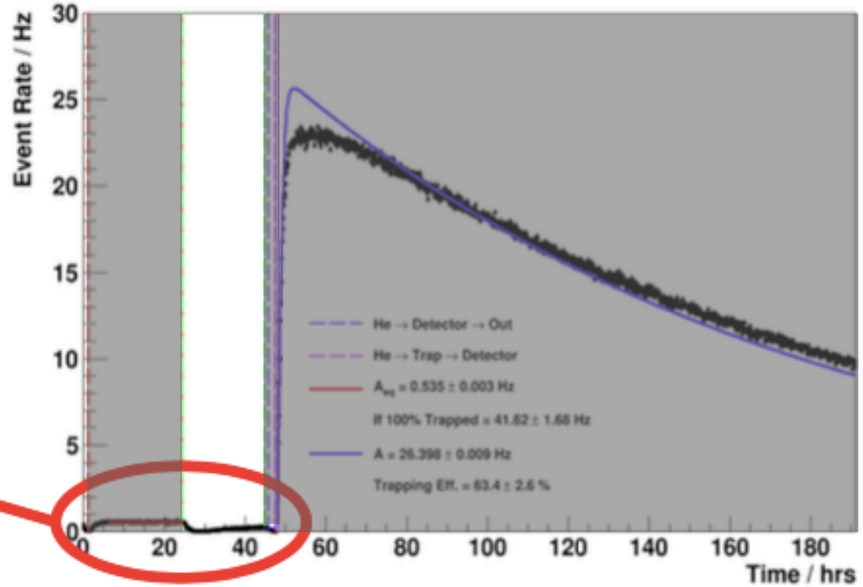
2) Trap radon

Flush from source into carbon trap and cool - radon is trapped and cannot escape



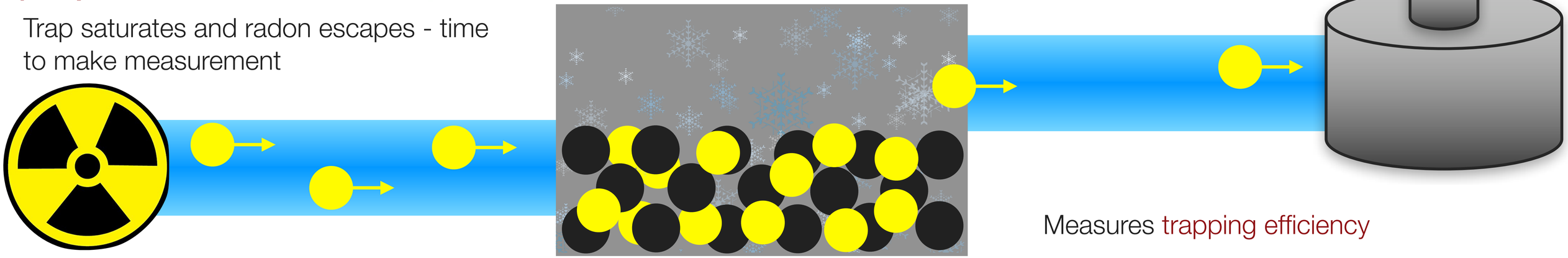
Calibrating the radon concentration line





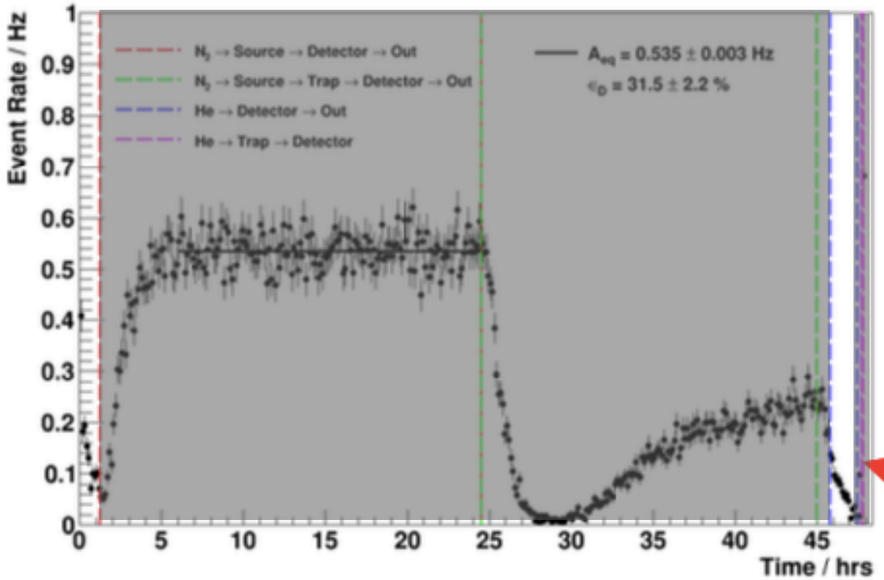
2) Trap radon

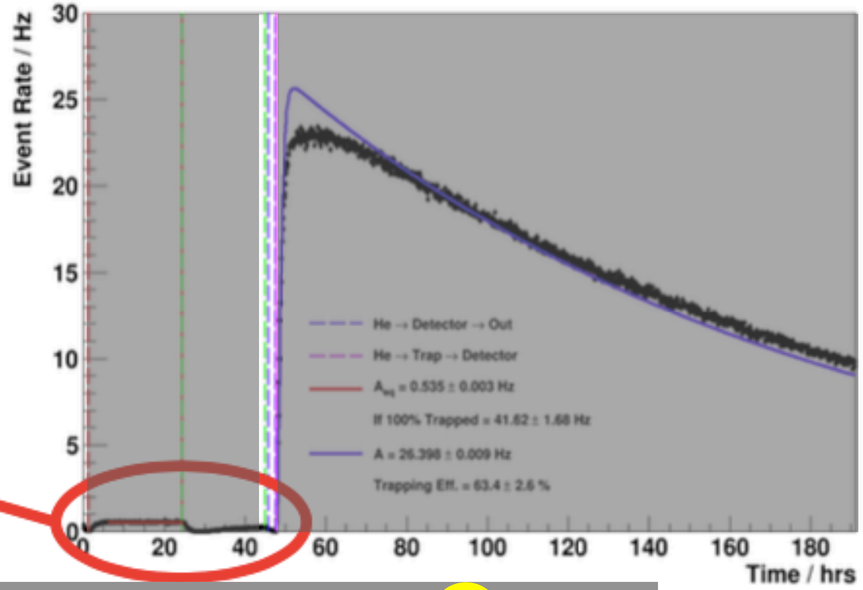
Trap saturates and radon escapes - time to make measurement



Measures trapping efficiency

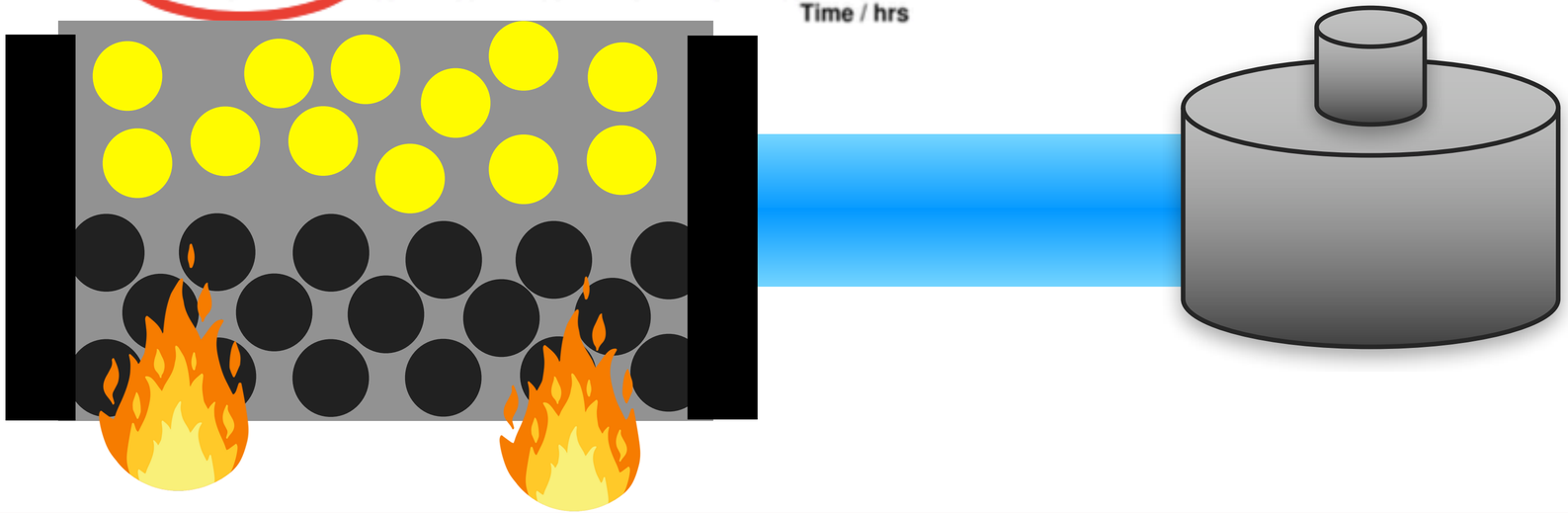
Calibrating the radon concentration line



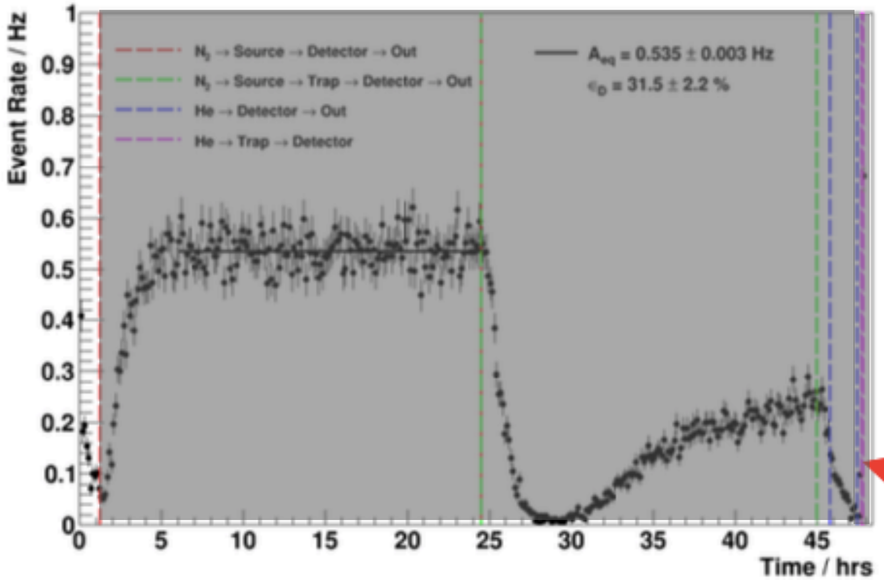


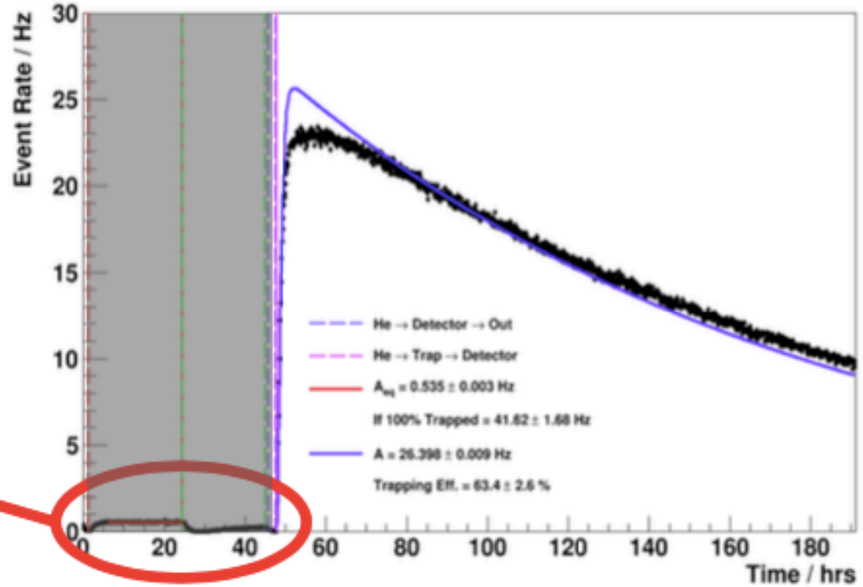
3) Release the radon

Seal and heat trap to release the trapped radon



Calibrating the radon concentration line

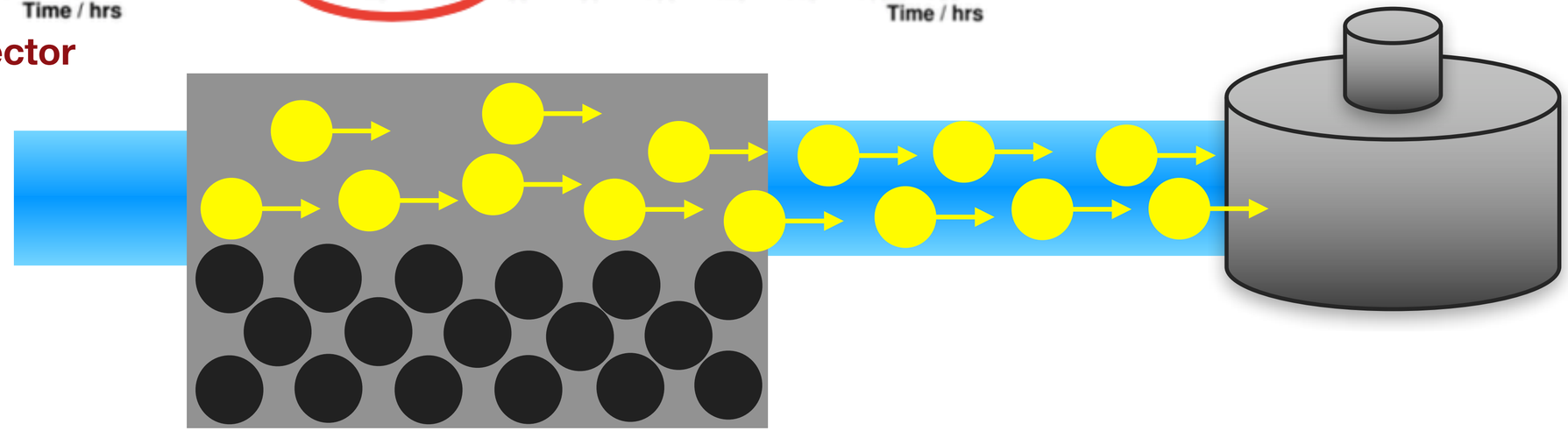




4) Flush helium through trap to detector

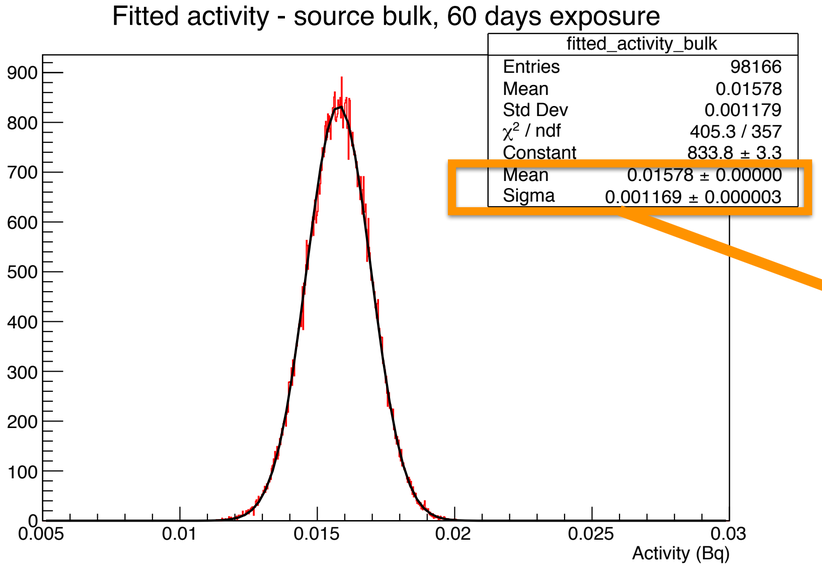
Radon is now concentrated enough that the we can detect it.

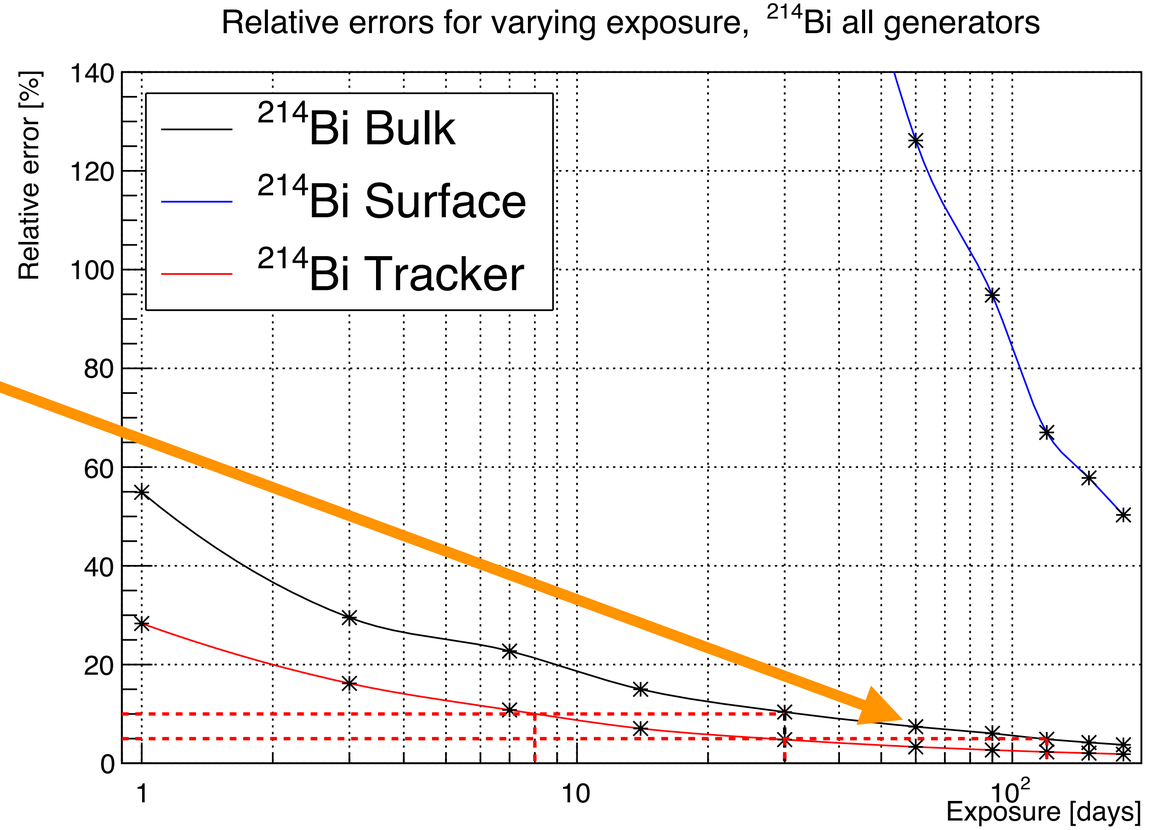
Measured activity/ expected activity gives trapping efficiency



Relative errors σ/μ

σ/μ from the distribution of the outputted activities.





- To test we can pick out the components:
  - Generate pseudo-data with various combinations of foil bulk, surface, and tracker events
  - Fractional fit: try to reproduce input fractions
  - Repeat the fit for various exposures
  - How long must we run for our activities to be correct to 10%?