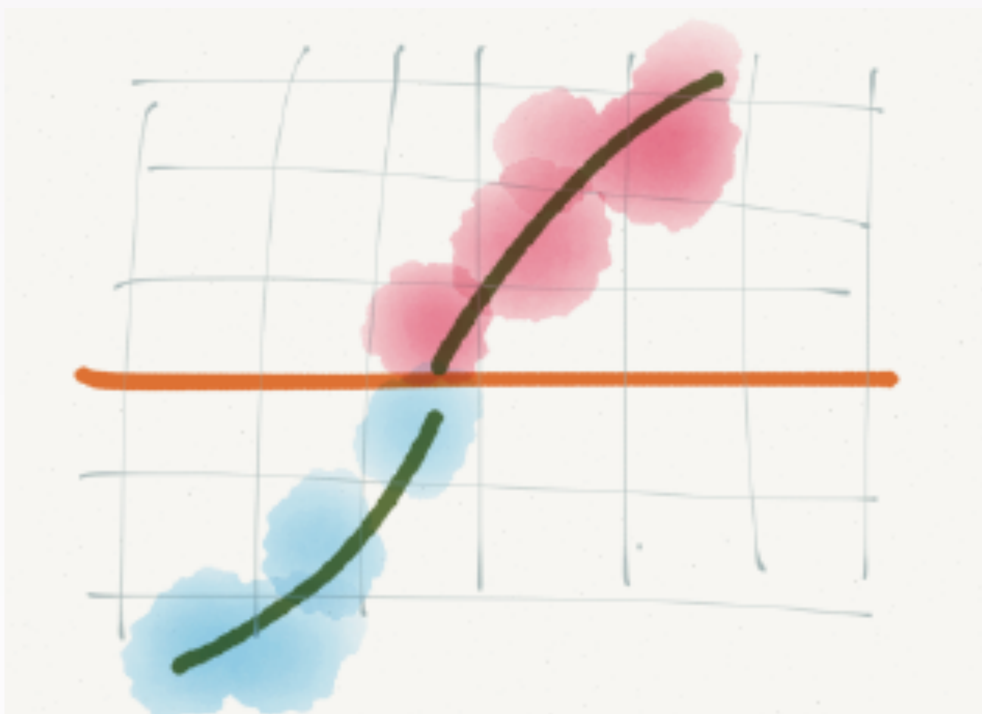
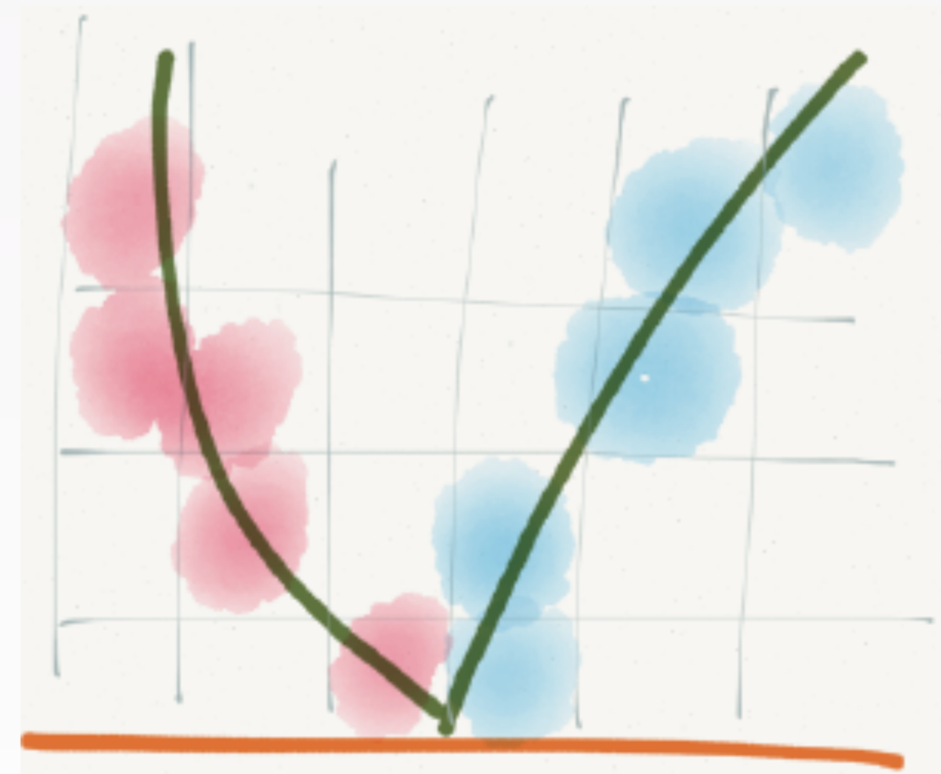
# Topological search for Matter Creation©
# with NEMO-3 and SuperNEMO



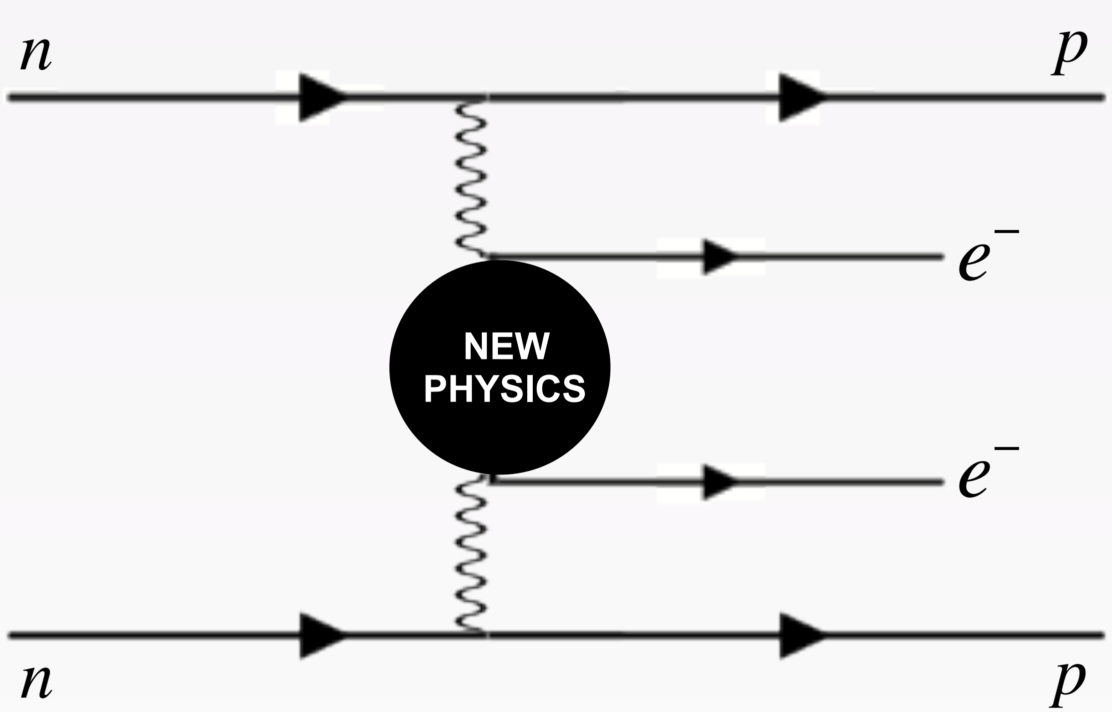



**Ruben Saakyan**
**University College London**

**CNNP-2017, Catania, Italy**
**18 October 2017**

© Francesco Vissani, CMMP-2017

# Experimentalist’s view on 0vbb




**$\Delta$L = 2!**

**(now also known as Matter Creation)**

**Lepton number violating parameter**

phase space

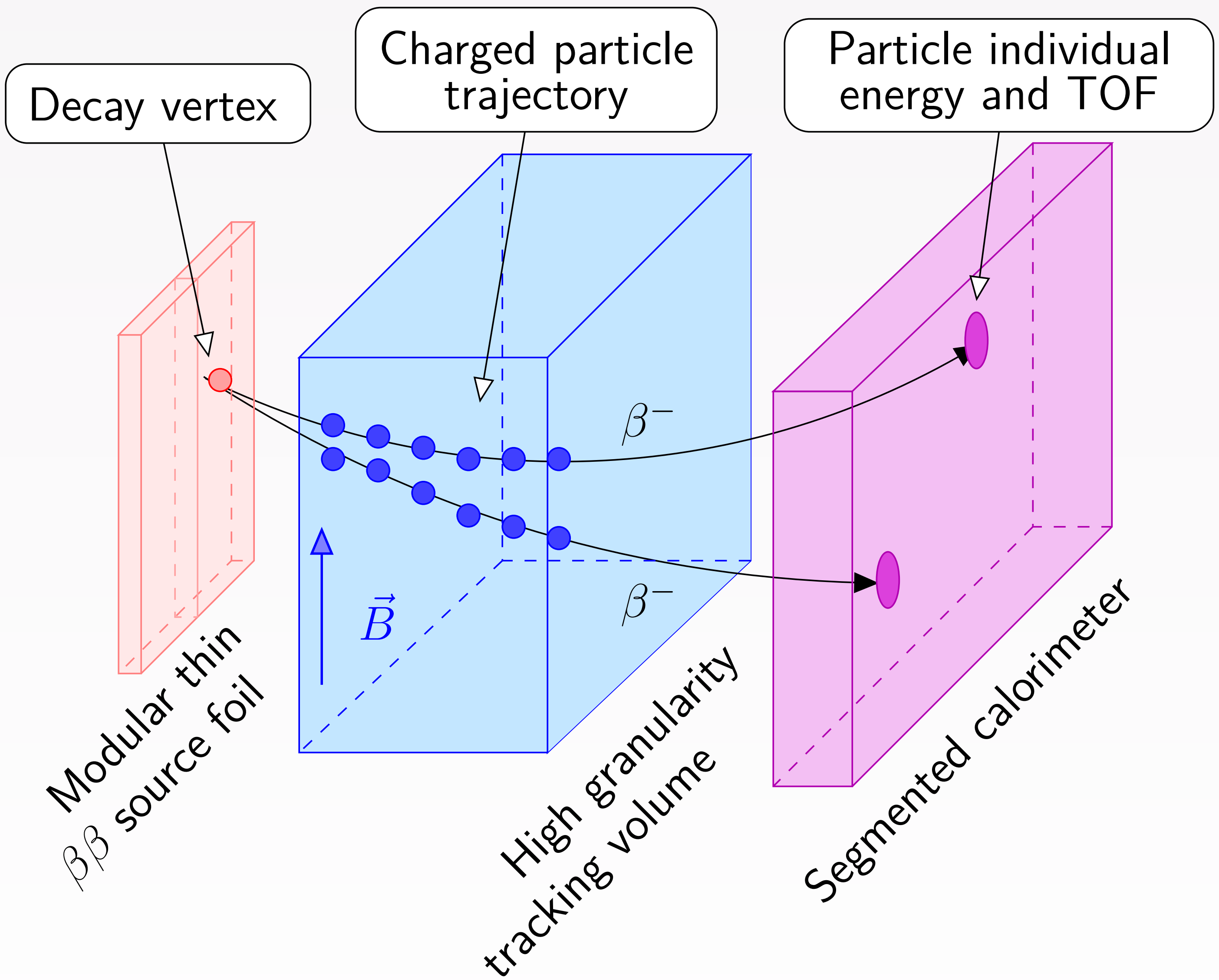
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q_{\beta\beta},Z)\left|M^{0\nu}\right|^2 \eta^2$$

NME: ~~Nasty~~ Nuclear Matrix Element

$\eta$ can be due to $\langle m_\nu \rangle$ ,V+A Majoron, SUSY, $H^{--}$, leptoquarks, *or a combination of them*

# NEMO-3/SuperNEMO Design

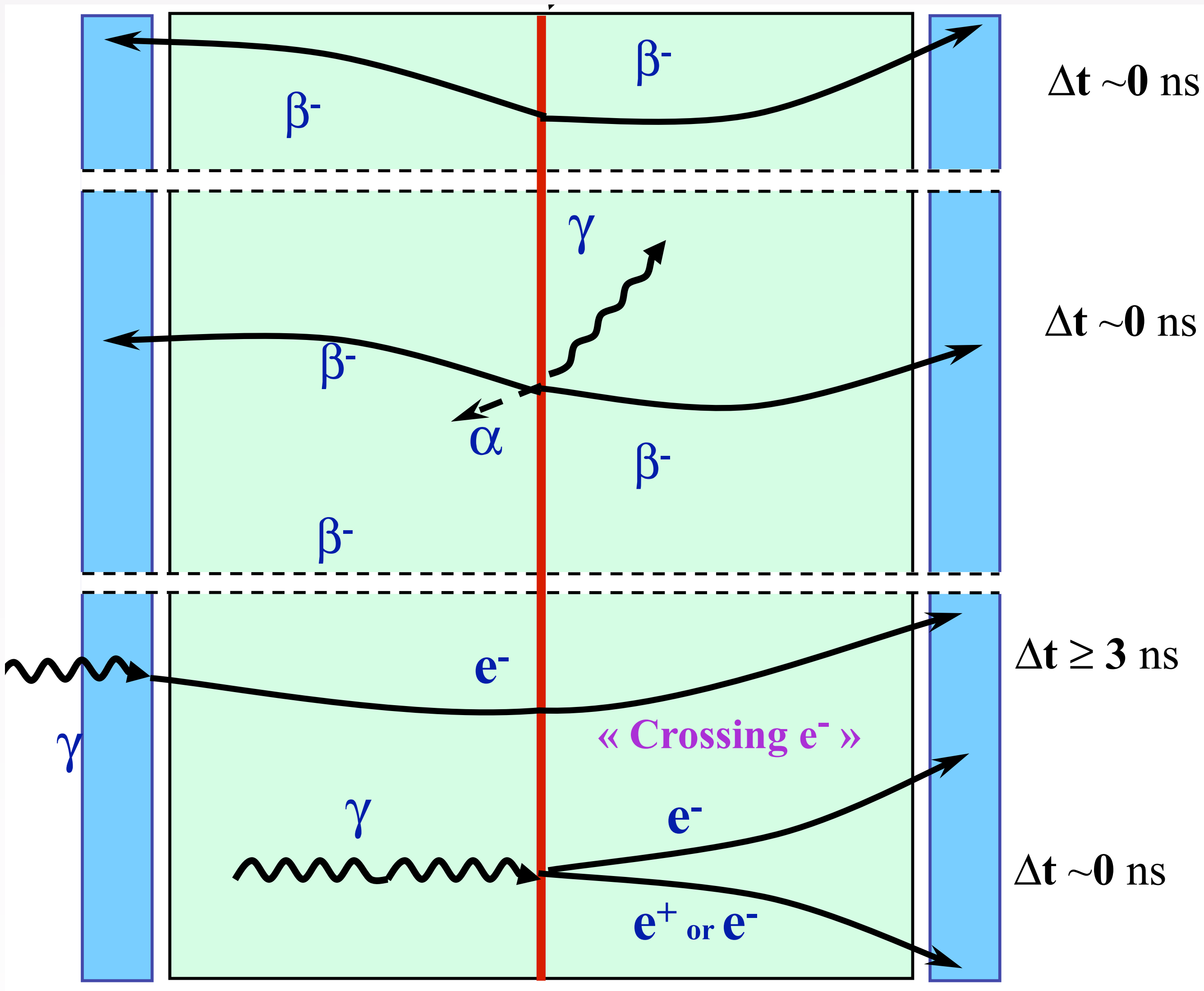
## **Unique** Detection principle: reconstruct topological signature




- **Source separated from detector: (almost) any solid isotope can be hosted.**
- **Generally poorer energy resolution than "homogeneous" detectors such as HPGe and bolometers.**
- **Full topological event reconstruction including $e^{\pm}$, $\gamma$-ray and $\alpha$-particle identification.**

- **Strong background suppression by particle identification, event characterisation & timing.**
- **Ability to disentangle different mechanisms for $0\nu\beta\beta$, by looking at variables other than $\Sigma E$.**

## Background Suppression




Powerful **background rejection** and **characterisation** through topology, timing, particle ID (e+, e-, α, γ)

One of the **lowest** background indices

**NEMO-3**

b = $10^{-3}$ cnts $kg^{-1}$ $keV^{-1}$ $yr^{-1}$ — **data!**

**SuperNEMO**

b = $(0.5\text{-}1)\times10^{-4}$ cnts $kg^{-1}$ $keV^{-1}$ $yr^{-1}$

**Calorimeter expts (GERDA, CUORE)**

b = $10^{-3}$ cnts $kg^{-1}$ $keV^{-1}$ $yr^{-1}$

(fantastic achievement by GERDA)

But much more modest energy resolution:

**SuperNEMO($^{82}$Se)**, FWHM=4%

$b\times\Delta E$ = **$5\times10^{-5}$** x 120keV = **0.006**

**HPGe**, FWHM=0.2%

$b\times\Delta E$ = 0.001 x **4keV** = **0.004**

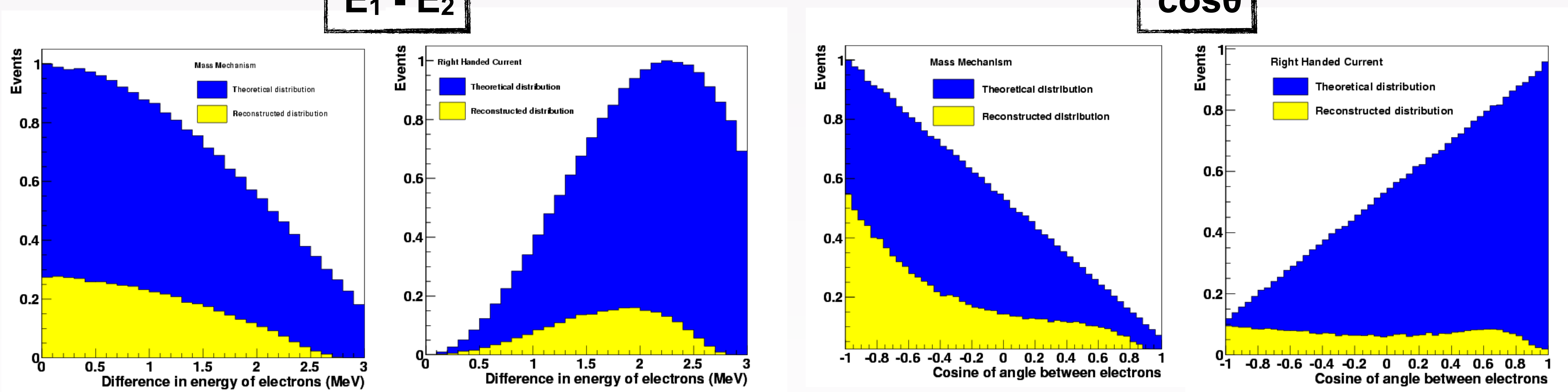
# NEMO-3/SuperNEMO Design Implications

## Topology Reconstruction — open-minded search for Lepton Number Violation

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta},Z)\left|M^{0\nu}\right|^2 \eta^2$$

$\eta$ can be due to $\langle m_\nu \rangle$, V+A, Majoron, SUSY, $H^-$ or a combination of them

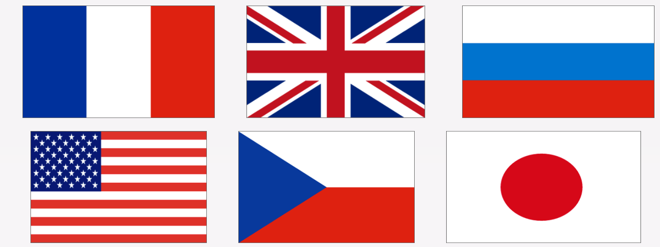
$\langle m_\nu \rangle$ | E1 - E2 | V+A | $\langle m_\nu \rangle$ | cosθ | V+A



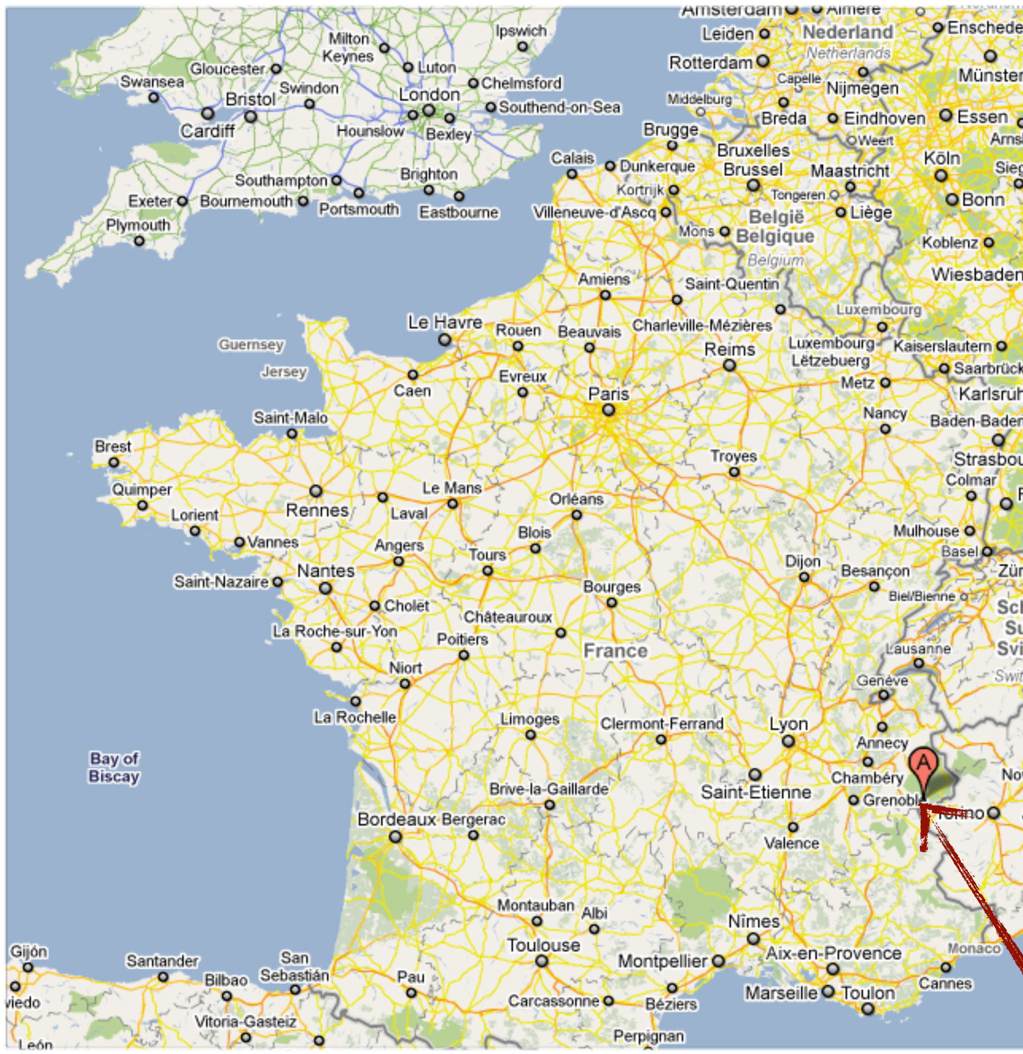

*"Probing new physics models of 0νββ with SuperNEMO"*, EPJ C (2010) 70, pp. 972-943.

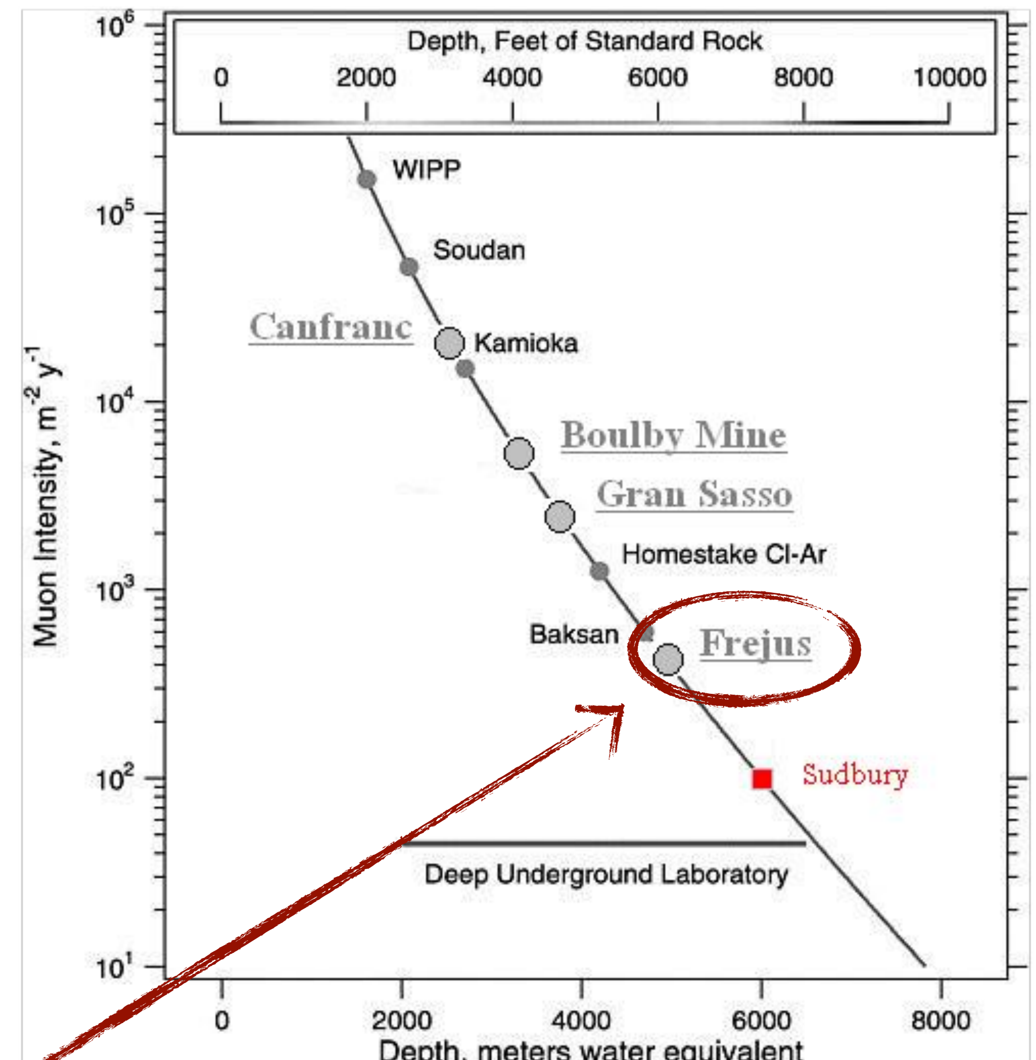
**Topology** can be used to **disentangle** underlying physics **mechanism**

# NEMO-3 — Neutrino Ettore Majorana Observatory



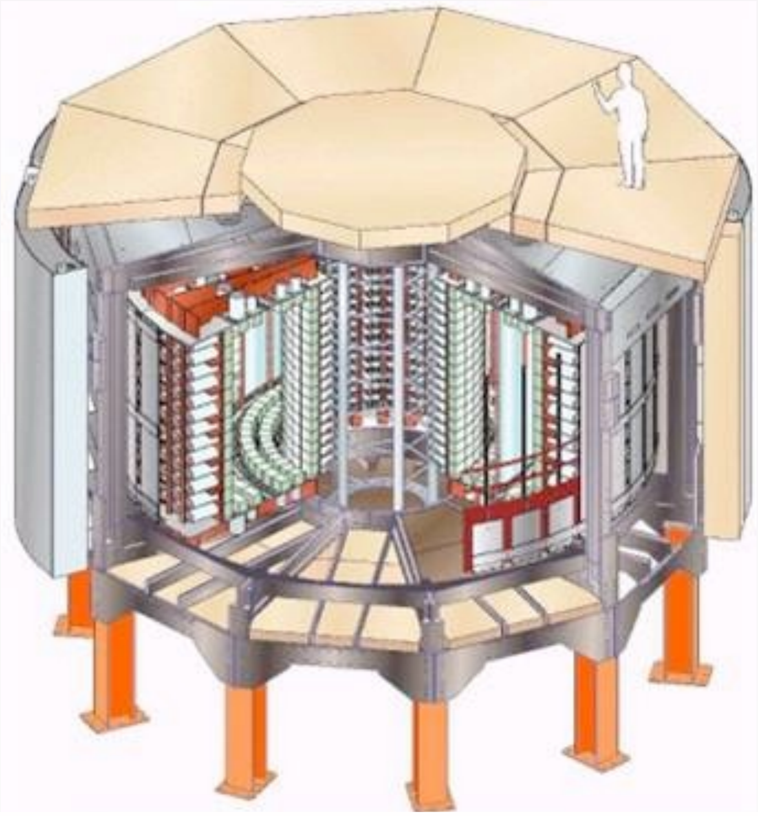
Data taking: Feb'03 - Jan'11



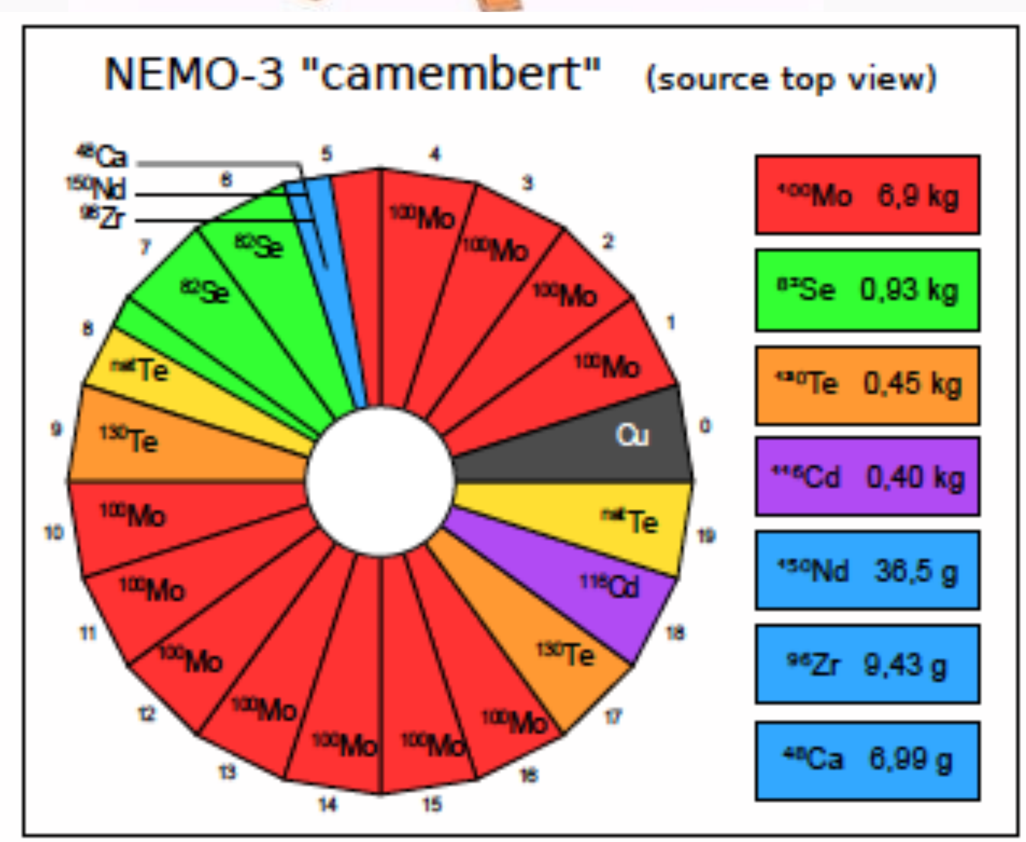

Laboratoire Souterrain de Modane (**LSM**)
Modane, France
(Tunnel Frejus, depth of ~4,800 mwe )

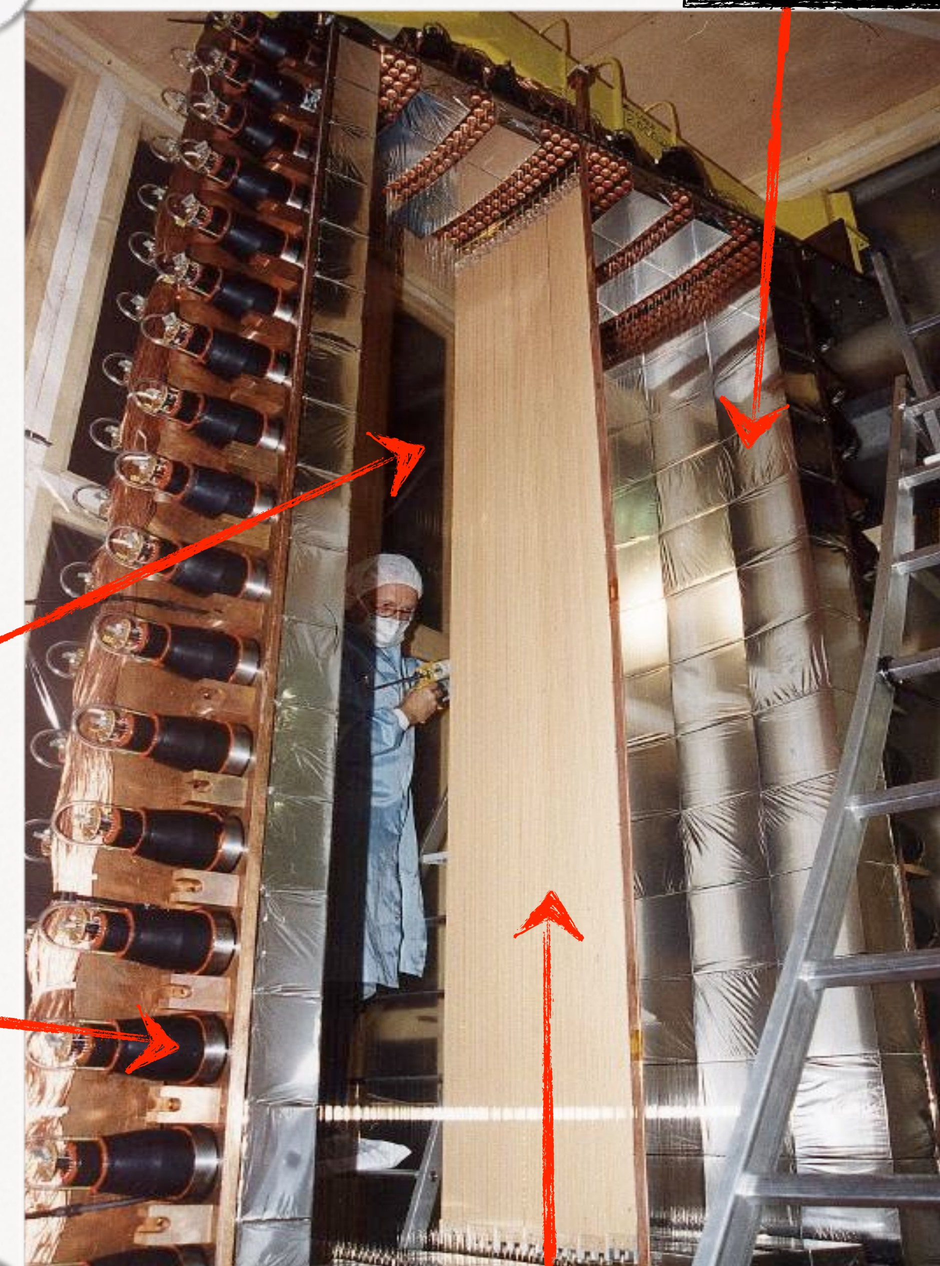
# NEMO-3 - 20 sectors with ~10 kg of isotopes



25G B-field

Passive shielding
+ anti-radon shielding



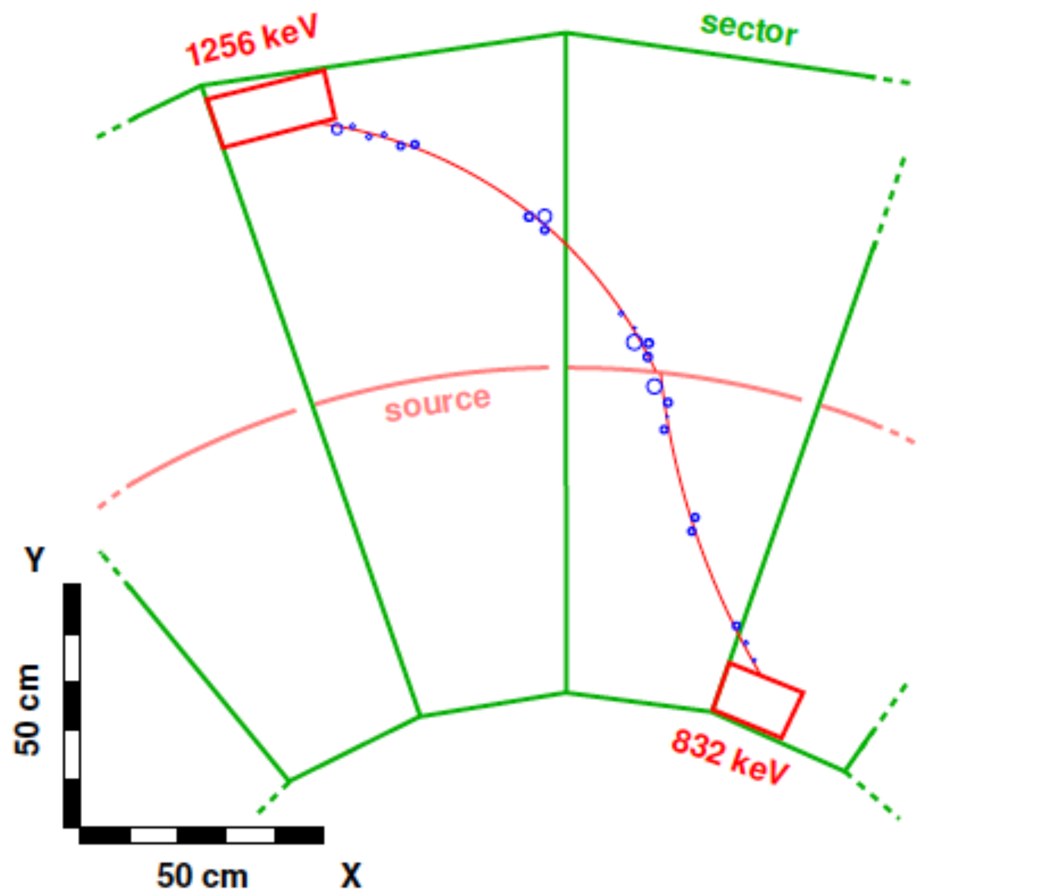
Plastic scintillator

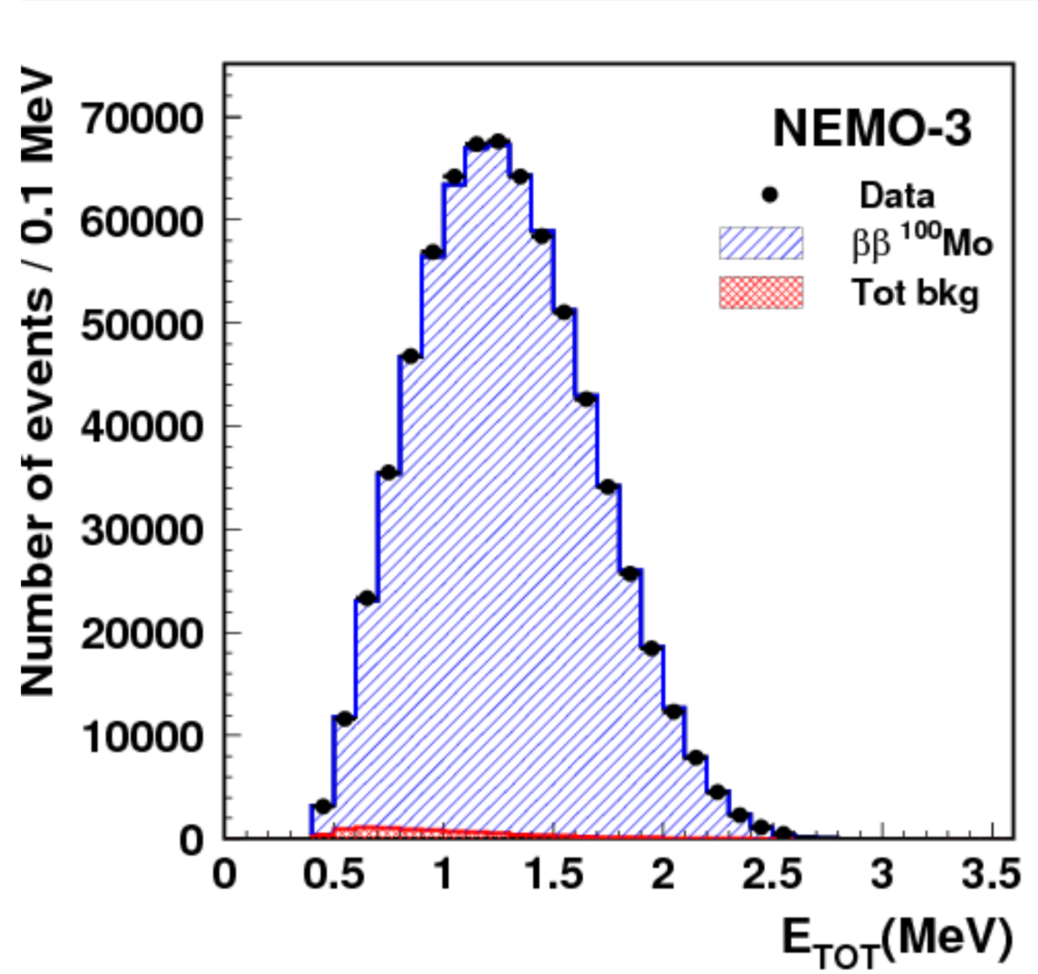
Wire Chamber

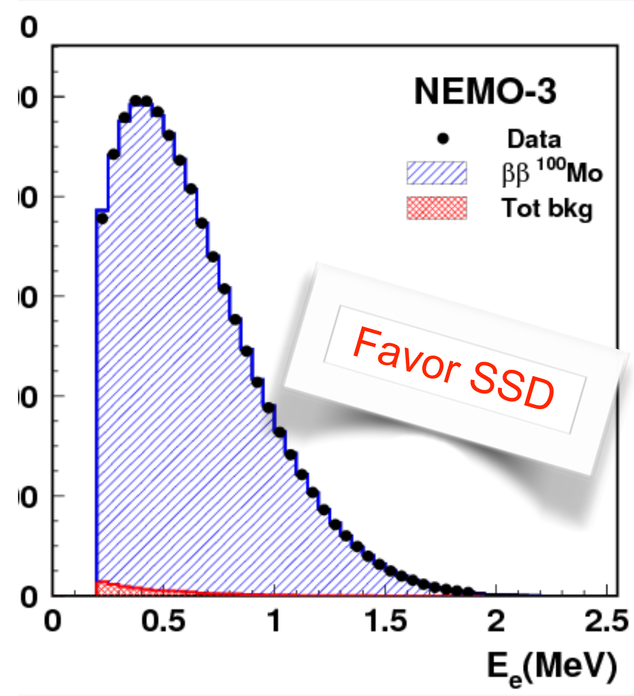
PMTs

ββ isotope foils

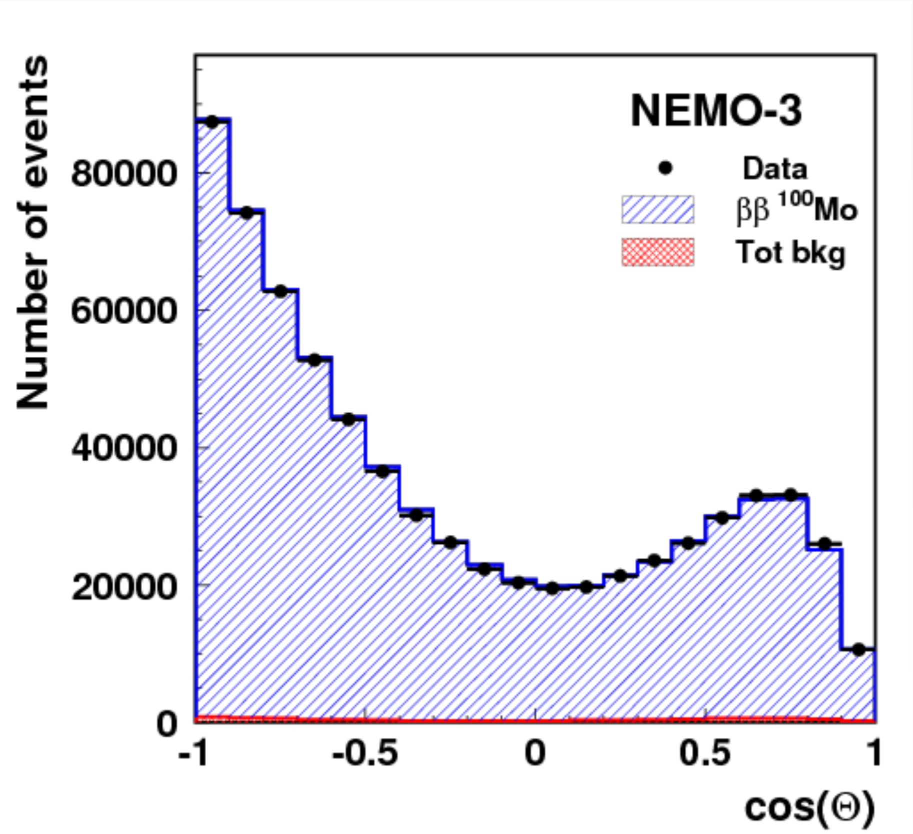
# The “Anatomy” of ββ decay with NEMO



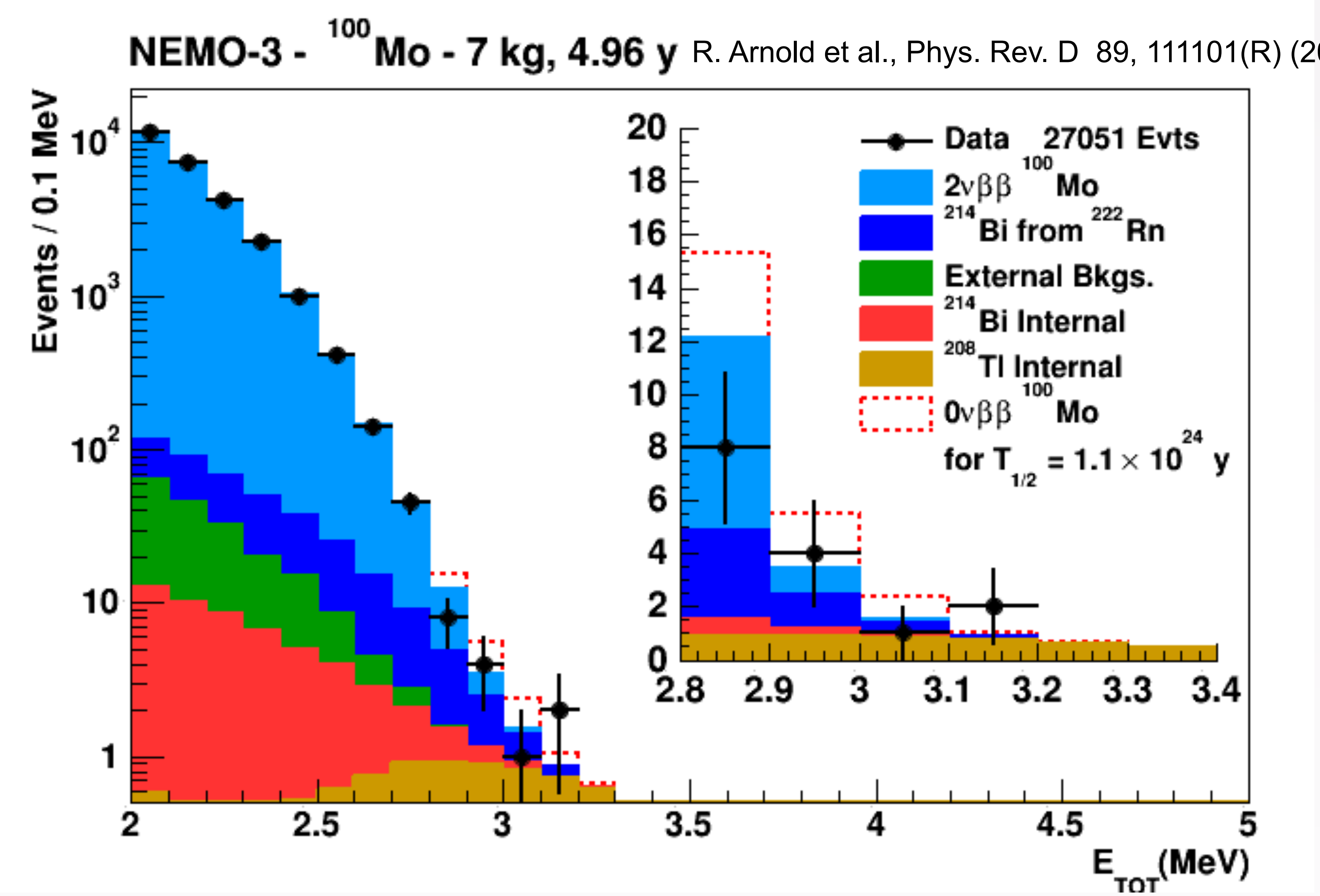

*Ability to disentangle*
***nuclear models***
*Single State Dominance*




NEMO-3 **2νββ** result for **$^{100}$Mo** to ground state

Unprecedented statistics — O(**$10^6$**) events with **S/B ≈ 80**

$$T^{2\nu}_{1/2} = [7.16 \pm 0.01(\text{stat}) \pm 0.54(\text{syst})] \times 10^{18}\ \text{yr}$$




$$T_{1/2}(0\nu\beta\beta) > 1.1 \times 10^{24} \text{ yr at } 90\%\text{CL}$$

$$\langle m_\nu \rangle < 0.33 - 0.62 \text{ eV}$$

*(with **only 7kg** of isotope!)*

**No events > 3.2 MeV after 5 yr of running! (34.3 kg x yr of $^{100}$Mo)**

**Background free technique for high $Q_{\beta\beta}$ isotopes**

$^{48}$Ca(4.27 MeV), $^{150}$Nd(3.37 MeV) $^{96}$Zr(3.35 MeV)

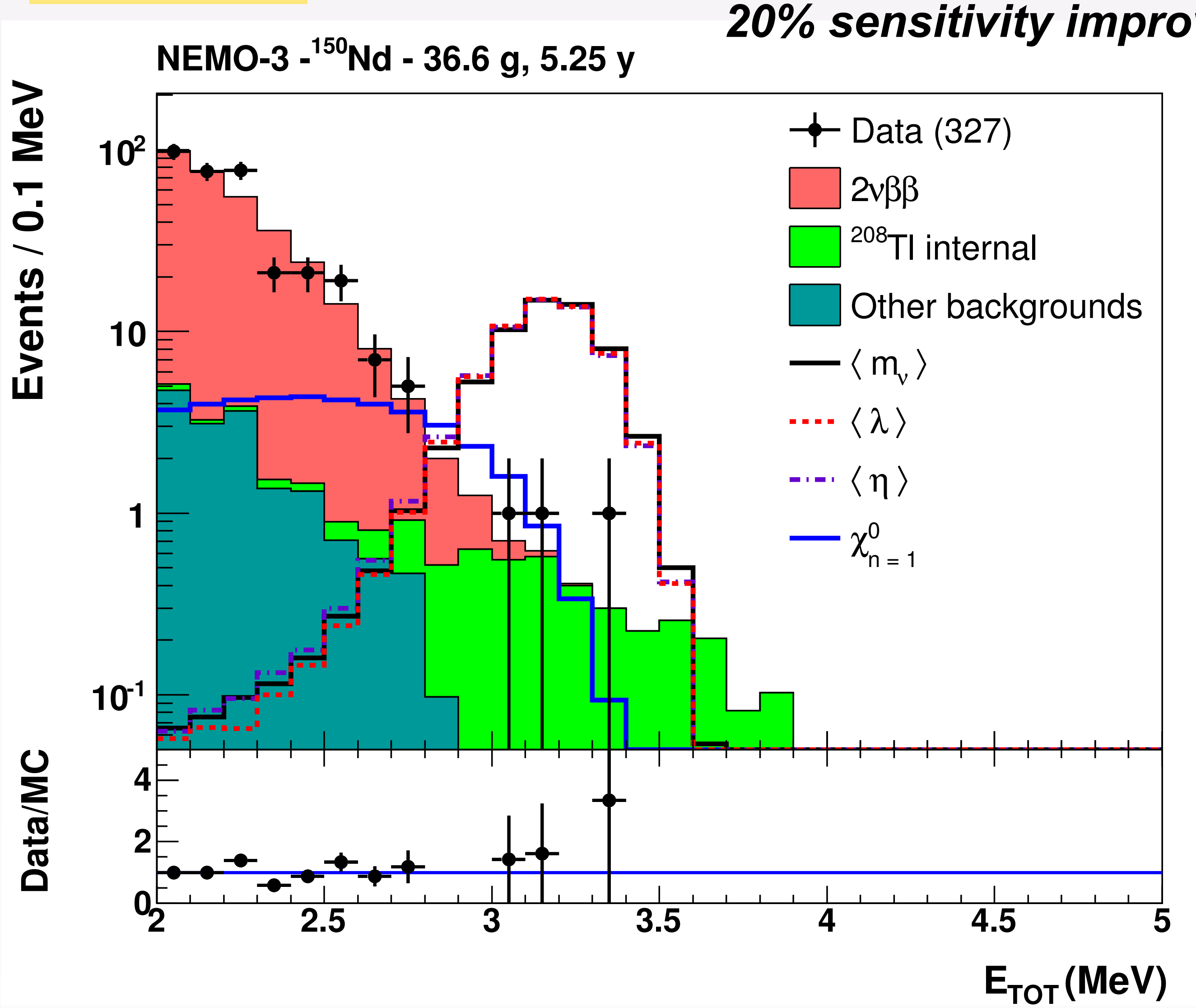
## Other 0νββ results

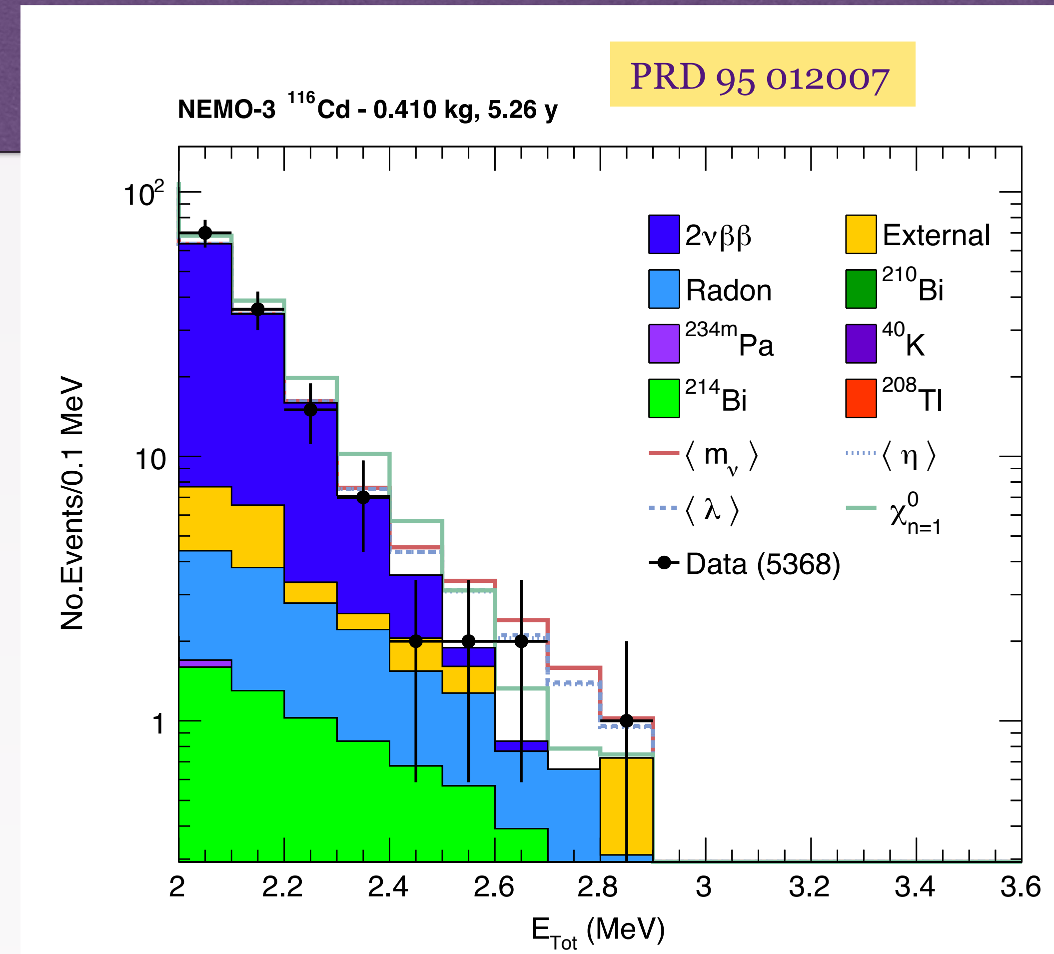
V+A — SUSY — Majoron

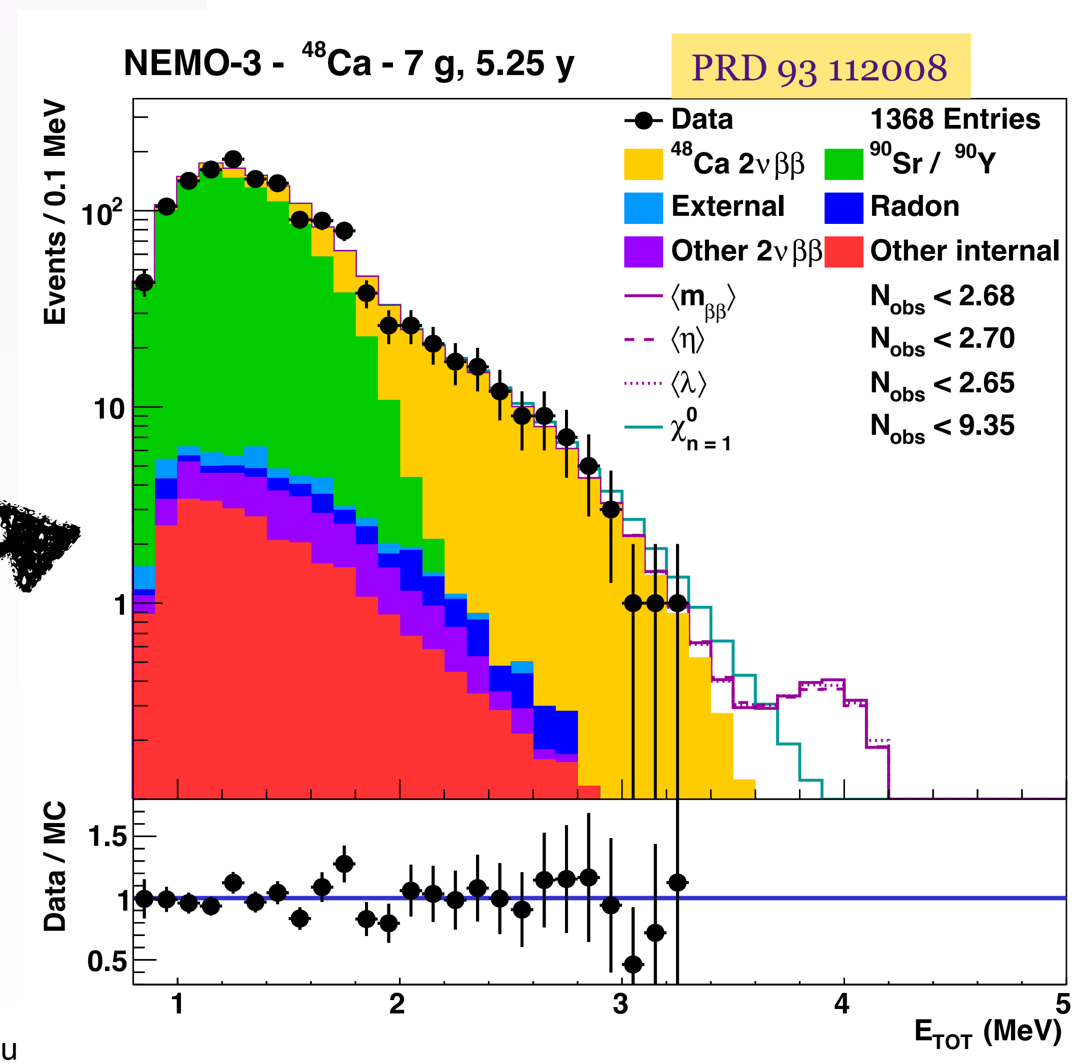
| Isotope | ⟨λ⟩ (1E-6) | ⟨η⟩ (1E-8) | λ'111/f (1E-2) | ⟨gee⟩ (1E-5) |
|---|---|---|---|---|
| **Mo100 (NEMO3)** | **0.9-1.3** | **0.5-0.8** | **4.4-6.0** | **1.6-3.0** |
| Te130(CUORICINO) | 1.6-2.4 | 0.9-5.3 | | 17-33 |
| Xe136 (K-Z) | | | | 0.8-1.6 |
| Ge76 (GERDA) | | | | 3.4-8.7 |
| Ge76 (HdM) | 1.1 | 0.64 | | 8.1 |

# Updated 2vbb Results

PRD 94 072003 (Editor's suggestion) **Multivariate techniques**
***20% sensitivity improvement***




$^{48}$Ca

$$T_{1/2}^{2\nu} = \left[6.4^{+0.7}_{-0.6}(stat)^{+1.2}_{-0.9}(syst)\right] \times 10^{19}\ \text{yr}$$

some tension with Shell Model
Nuclear Matrix Elements Calculations

# Summary of 2νββ Results

| Isotope | Mass (g) | Qββ(keV) | T(2ν) (1E19yrs) | S/B | Comment | Reference |
|---|---|---|---|---|---|---|
| Se82 | 932 | 2996 | 9.6 ± 1.0 | 4 | World's best | Phys.Rev.Lett. 95(2005) 483 |
| Cd116 | 405 | 2809 | 2.74 ± 0.18 | 10 | World's best* | Phys. Rev. D 95 (**2017**) 012007 |
| Nd150 | 37 | 3367 | 0.93 ± 0.06 | 2.7 | World's best | Phys. Rev. D 94 (**2016**) 072003 |
| Zr96 | 9.4 | 3350 | 2.35 ± 0.21 | 1 | World's best | Nucl.Phys.A 847(2010) 168 |
| Ca48 | 7 | 4271 | 6.4 ± 1.2 | 6.8 (h.e.) | World's best | Phys. Rev. D 93 (**2016**) 112008 |
| Mo100 | 6914 | 3034 | 0.71 ± 0.05 | 80 | World's best | Phys.Rev.Lett. 95(2005) 483 |
| Te130 | 454 | 2533 | 70 ± 14 | 0.5 | First direct detection | Phys. Rev. Lett. 107, 062504 (2011) |

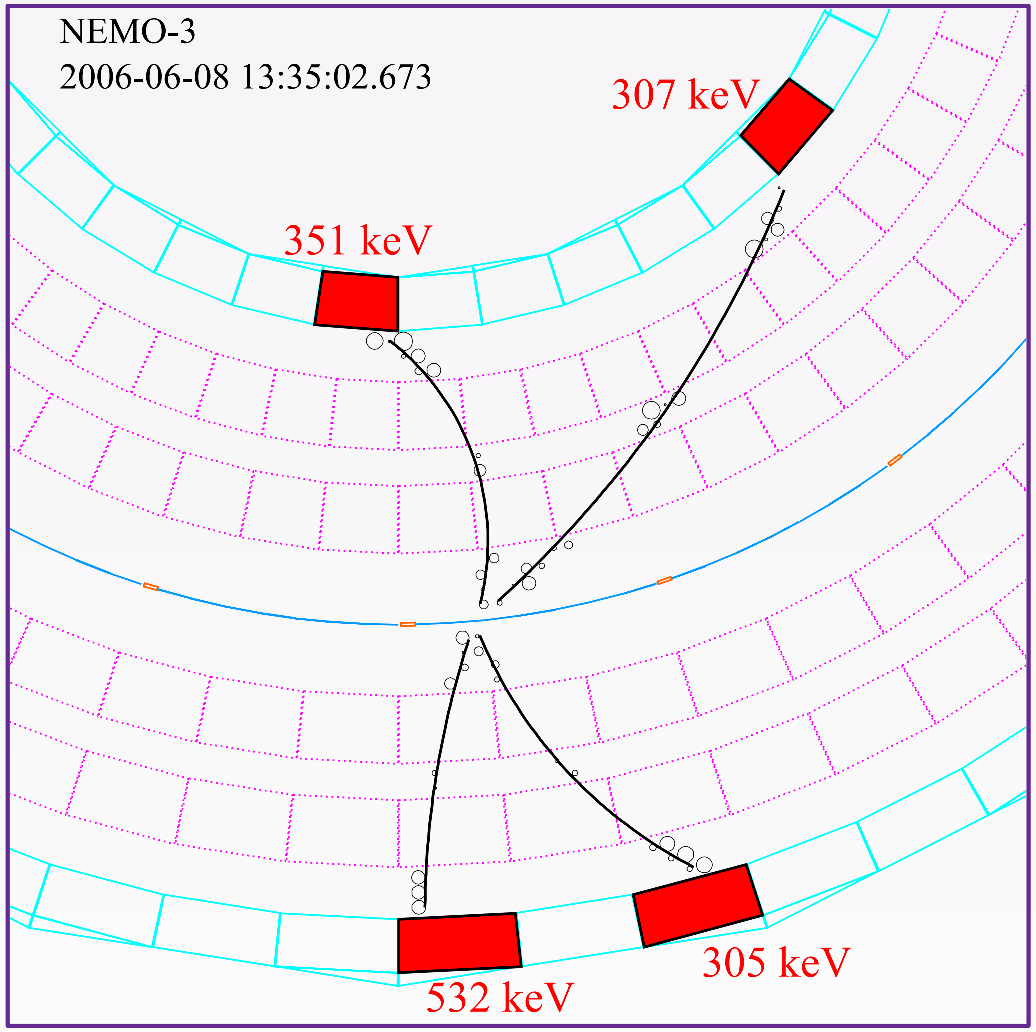
* Together with Aurora

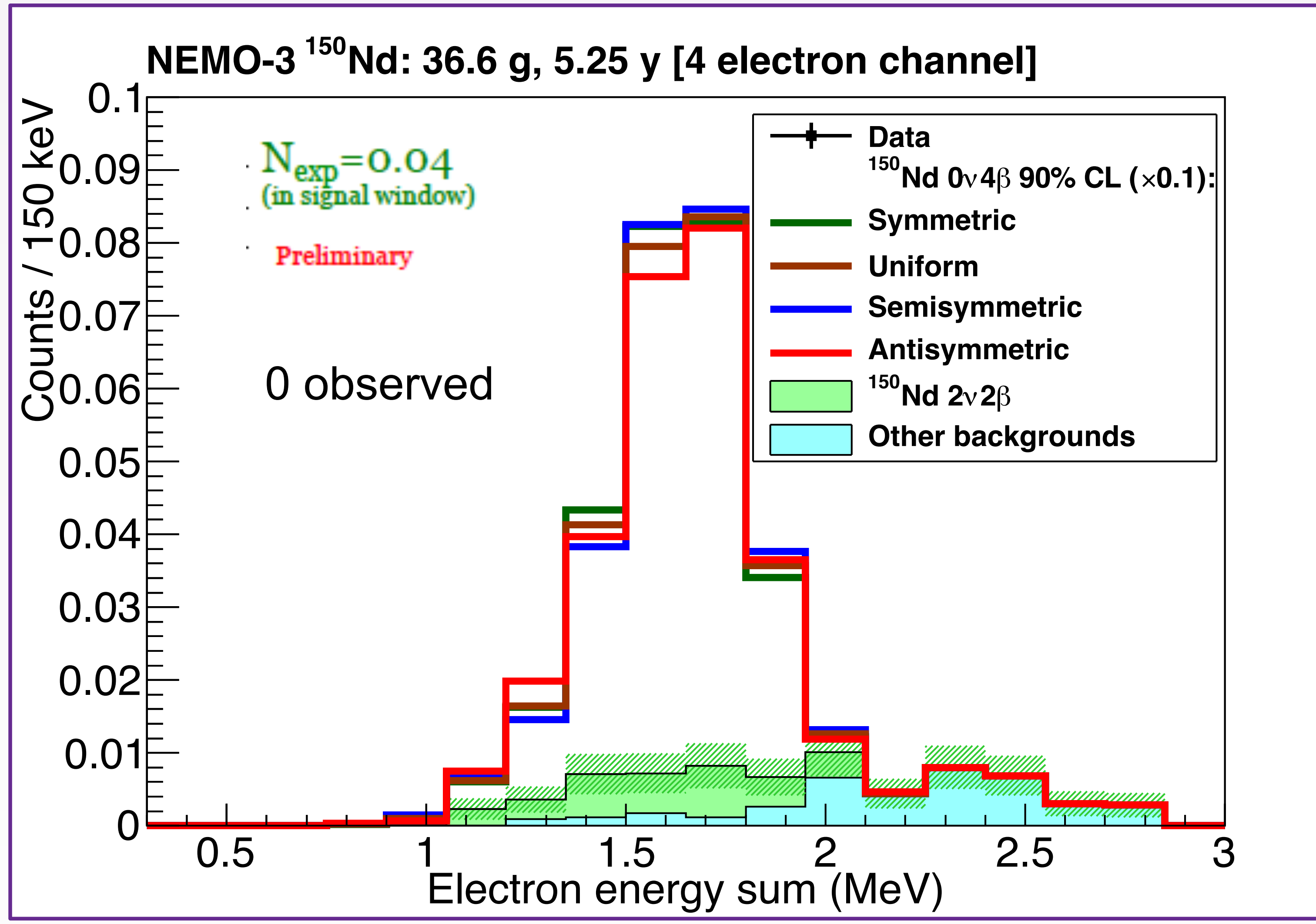
**Crucial experimental input for**
**1) NME calculations**
**2) Ultimate background characterisation for 0ν**
**3) Sensitive to exotic BSM physics (e.g. Lorentz violation, $G_f$ time dependence, bosonic neutrinos etc)**

# Quadruple (!) beta decay — 0v4b

**ΔL = 4** BSM physics with Dirac neutrinos

J. Heeck, W. Rodejohann, Europhys. Lett. 103, 32001 (2013).
M.-C. Chen, M. Ratz, C. Staudt, P. K. S. Vaudrevange,Nucl. Phys. B 866, 157 (2013).
J. Heeck, Phys. Rev. D 88, 076004 (2013).



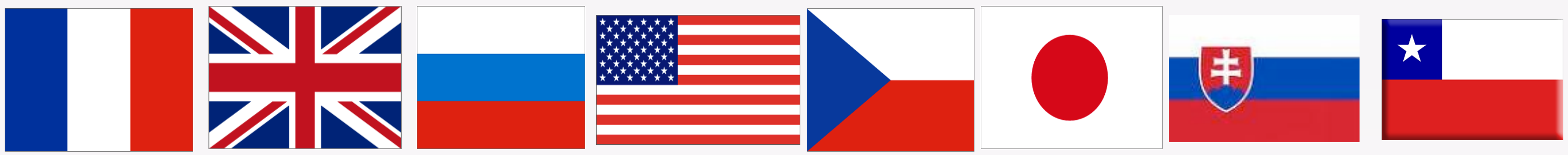




Only possible with full topological reconstruction of all electrons

| 90%CL limit | Symmetric | Uniform | Semi-symmetric | Anti-symmetric |
|---|---|---|---|---|
| Observed | $3.2 \times 10^{21}$y | $2.6 \times 10^{21}$y | $1.7 \times 10^{21}$y | $1.1 \times 10^{21}$y |
| Sensitivity | $3.7 \times 10^{21}$y | $3.0 \times 10^{21}$y | $2.0 \times 10^{21}$y | $1.3 \times 10^{21}$y |

(combined limits for 3 topologies) Preliminary

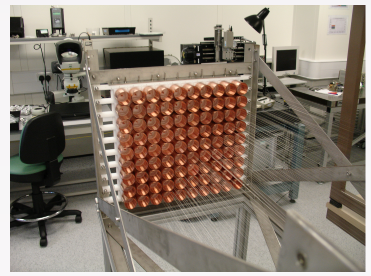
**First experimental limit**
on this process
***Phys. Rev. Lett. 119 031801 (jul-2017)***
*Editor's suggestion*

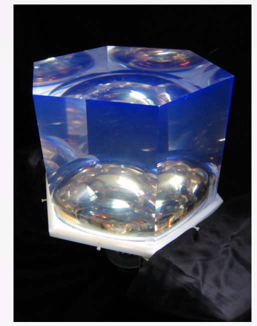


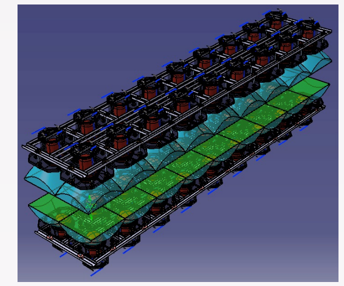
**The goals of SuperNEMO :**

1. Build on the experience of the extremely successful **NEMO-3** experiment.
2. Use the power of the **tracking-calorimeter** approach to identify and suppress backgrounds aiming at a **zero-background** experiment in the first (**Demonstrator Module**) phase.
3. Prove that a 100 kg scale experiment can reach **50 meV neutrino mass scale**. Explore feasibility of **scaling up topological technique** beyond 100kg and probe **inverse mass ordering**.
4. In the event of a **discovery** by any of the next-generation experiments, use the tracking-calorimeter approach to provide **“smoking gun”** evidence, measure **multiple isotopes** and attempt to **characterise** the **mechanism** of $0\nu\beta\beta$ decay.

# From NEMO-3 to SuperNEMO

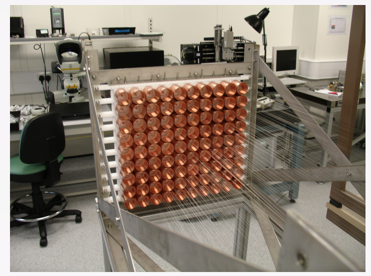


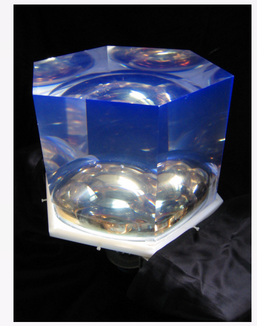


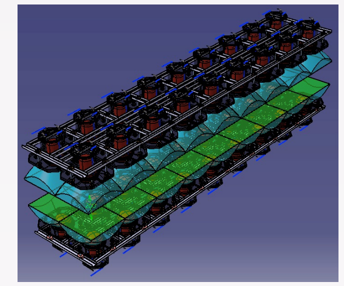
R&D since 2006 →

| | NEMO-3 | SuperNEMO |
|---|---|---|
| Isotope | $^{100}Mo$ | $^{82}Se$ (or $^{150}Nd$ or $^{48}Ca$) |
| Isotope mass M | 7 kg | 100+ kg |
| Contaminations in the ββ foil | $^{208}Tl$: ~ 100 μBq/kg<br>$^{214}Bi$: < 300 μBq/kg | $^{208}Tl$ ≤ 2 μBq/kg<br>$^{214}Bi$ ≤ 10 μBq/kg |
| Rn in the tracker | Rn: 5 mBq/m$^3$ | Rn ≤ 0.15 mBq/m$^3$ |
| Calorimeter energy resolution (FWHM) | ~8% @ 3MeV | ~4% @ 3 MeV |
| Sensitivity | $T_{1/2}(\beta\beta0\nu) > 1.1 \times 10^{24}$ y<br>$<m_\nu> < 0.3 – 0.6$ eV | $T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y<br>$<m_\nu> < 0.04 - 0.1$ eV |

# From NEMO-3 to SuperNEMO



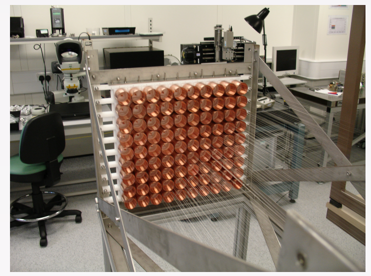


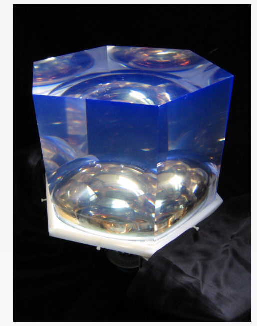


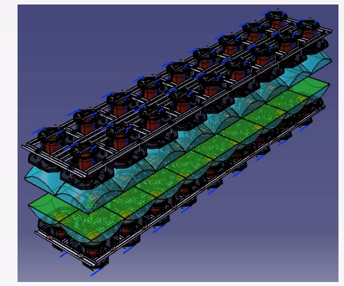
R&D since 2006 →

| NEMO-3 | | SuperNEMO |
|---|---|---|
| $^{100}Mo$ | Isotope | $^{82}Se$ (or $^{150}Nd$ or $^{48}Ca$) |
| 7 kg | Isotope mass M | 100+ kg |
| $^{208}Tl$: ~ 100 μBq/kg<br>$^{214}Bi$: < 300 μBq/kg | Contaminations in the ββ foil | $^{208}Tl$ ≤ 2 μBq/kg<br>$^{214}Bi$ ≤ 10 μBq/kg |
| Rn: 5 mBq/m$^3$ | Rn in the tracker | Rn ≤ 0.15 mBq/m$^3$ |
| ~8% @ 3MeV | Calorimeter energy resolution (FWHM)<br>**demonstrated** | ~4% @ 3 MeV |
| $T_{1/2}(\beta\beta0\nu) > 1.1 \times 10^{24}$ y<br>$<m_\nu> < 0.3 – 0.6$ eV | Sensitivity | $T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y<br>$<m_\nu> < 0.04 - 0.1$ eV |

# From NEMO-3 to SuperNEMO





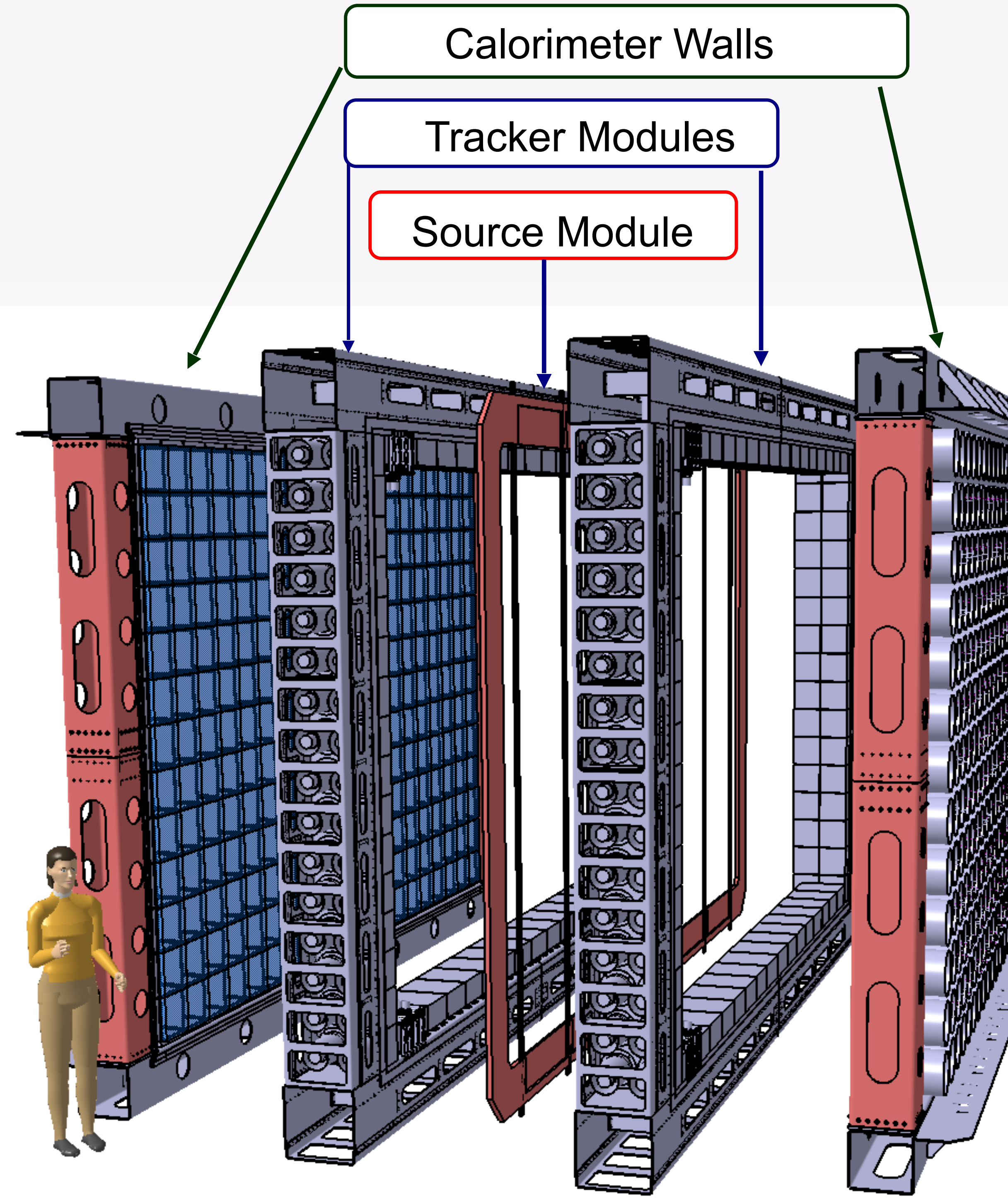


R&D since 2006 →

| NEMO-3 | | SuperNEMO |
|---|---|---|
| $^{100}Mo$ | Isotope | $^{82}Se$ (or $^{150}Nd$ or $^{48}Ca$) |
| 7 kg | Isotope mass M | 100+ kg |
| $^{208}Tl$: ~ 100 μBq/kg<br>$^{214}Bi$: < 300 μBq/kg | Contaminations in the ββ foil | $^{208}Tl$ ≤ 2 μBq/kg<br>$^{214}Bi$ ≤ 10 μBq/kg |
| Rn: 5 mBq/m$^3$ | Rn in the tracker<br>**partly demonstrated** | Rn ≤ 0.15 mBq/m$^3$ |
| ~8% @ 3MeV | Calorimeter energy resolution (FWHM)<br>**demonstrated** | ~4% @ 3 MeV |
| $T_{1/2}(\beta\beta0\nu) > 1.1 \times 10^{24}$ y<br>$<m_\nu> < 0.3 – 0.6$ eV | Sensitivity | $T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y<br>$<m_\nu> < 0.04 - 0.1$ eV |

# SuperNEMO Demonstrator

- Location: **LSM**
- **ββ Source** (40-50mg/cm$^2$ foil)
  - Baseline: **$^{82}$Se** (high $Q_{\beta\beta}$, long $T_{1/2}(2\nu)$)
  - Possibility to add $^{150}$Nd, $^{48}$Ca almost **any isotope** possible
- **Tracker**
  - drift chamber (95% He + 4%$C_2H_5OH$ + 1%Ar) ~2000 cells in Geiger mode
- **Calorimeter**
  - 550 PMTs + scintillators + endcap + veto
- **25G B-field**
- **Passive shielding**: iron + water
- **Anti-Rn system**




**Full baseline SuperNEMO:**

**15-20 Demonstrator-like modules with 5-7kg of isotope = 100kg** →

**Straightforward extrapolation due to modular design!**

# SuperNEMO Demonstrator Goals

## Aiming at zero background

| Events in window $E_{SUM} \in [2.8, 3.2]$ MeV | NEMO-3 Phase 2 (29 kg.yr) | Demonstrator Module (29 kg.yr) | Comments |
|---|---|---|---|
| External Bkgnd | <0.16 | <0.16 | (conservative) |
| Bi214 from Rn222 | 2.5 ± 0.2 | 0.07 | radon reduction |
| Bi214 internal | 0.80 ± 0.08 | 0.07 | internal contamination reduction |
| Tl208 internal | 2.7 ± 0.2 | 0.05 | |
| 2νββ | 7.16 ± 0.05 | 0.20 | Mo100 to Se82<br>8% to 4% resolution |
| Total expected | 13.1 ± 0.3 | 0.39 | |
| Data | 12 | N/A (yet) | |

NEMO-3 sensitivity in **4.5 months !**

- **Demonstrator** 17.5 kg.yr (~2.5 yr of running)
  - $T_{1/2} > 6.5 \times 10^{24}$ yr , $\langle m_\nu \rangle < 0.16$ — 0.40 eV (90%CL)
- **Straightforward extrapolation** to full SuperNEMO (**20 modules**)
- Full SuperNEMO
  - $T_{1/2} > 1 \times 10^{26}$ yr , $\langle m_\nu \rangle < 0.04$ — 0.10 eV (90%CL)

# SuperNEMO Low Background Program

SuperNEMO **Strategy**: Background **Reduction** (U, Th, Rn assays) and **Rejection** (topology, timing etc)

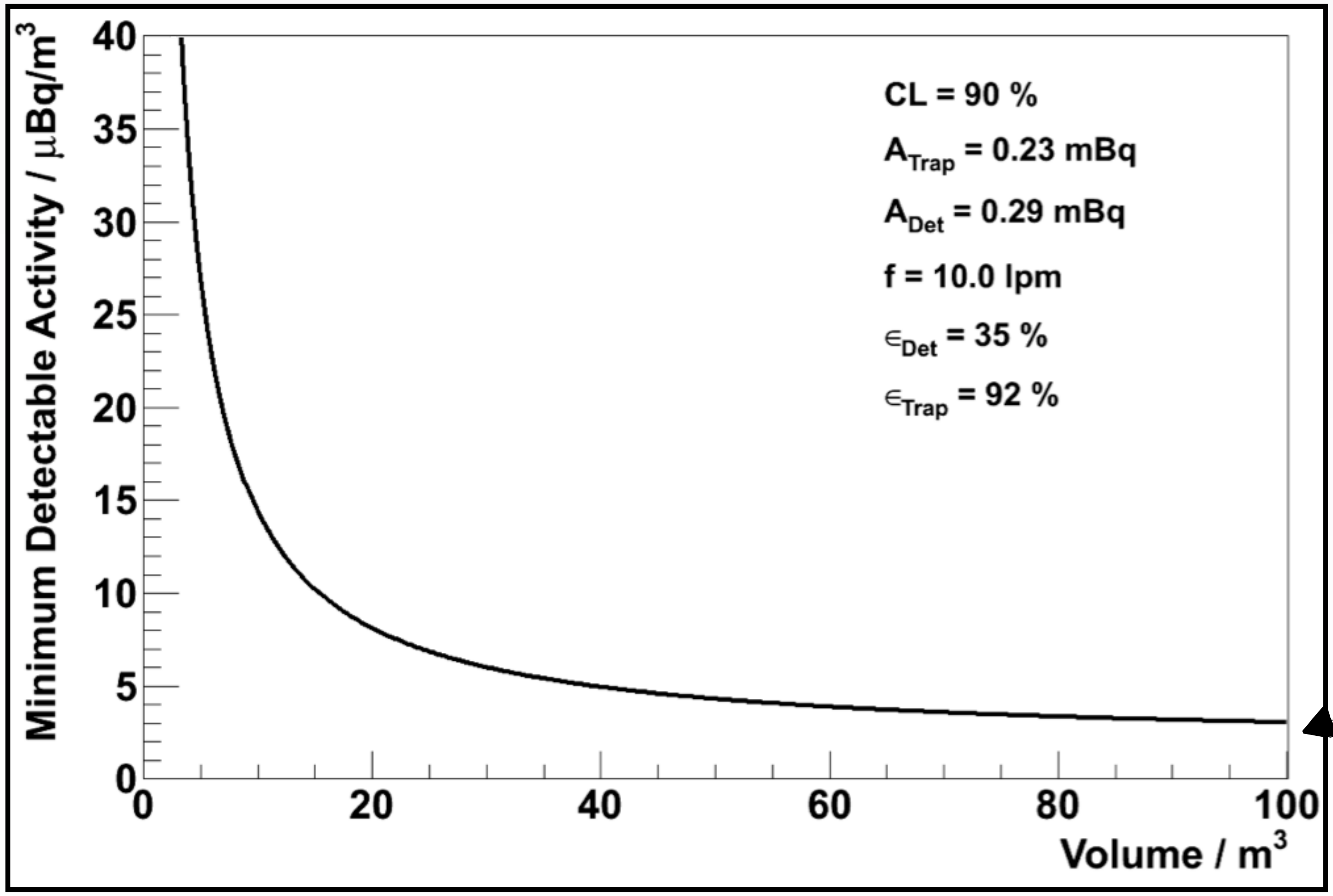
**$^{222}$Rn is one of the key problems**

Dedicated facilities developed, built and commissioned

**Rn removal** from gas with cold charcoal trap:

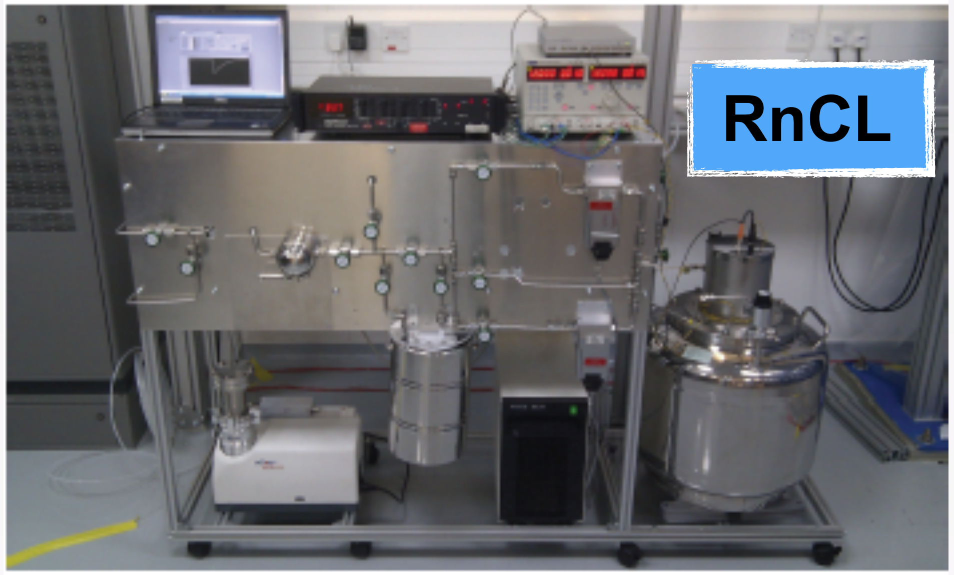
- **He**: $10^{10}$(!) suppression, complete removal
- **$N_2$**: ~x20 suppression purification down to **20µB/m$^3$ (measured!)**

SN **$^{222}$Rn Concentration Line** (**RnCL**) Sensitivity

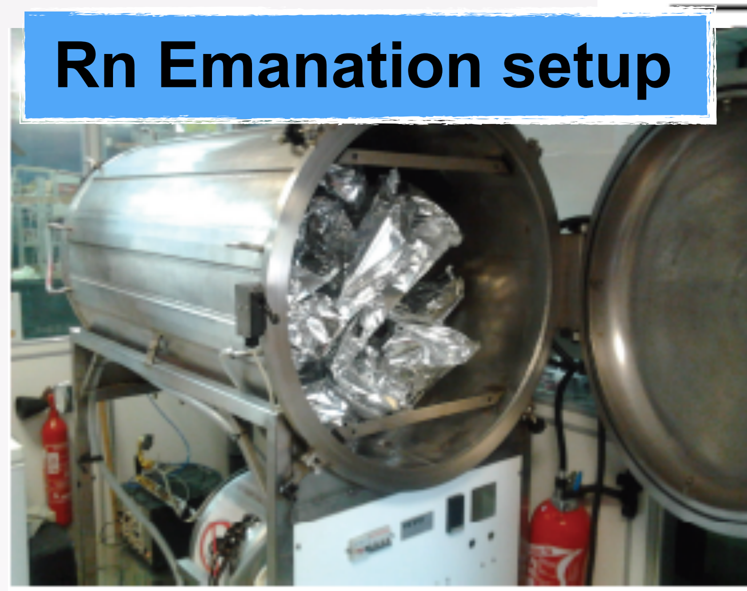



2.4 $^{222}$Rn atoms/m$^3$ of $N_2$/He/Ar/etc.
or
1 part in $10^{25}$ !!!

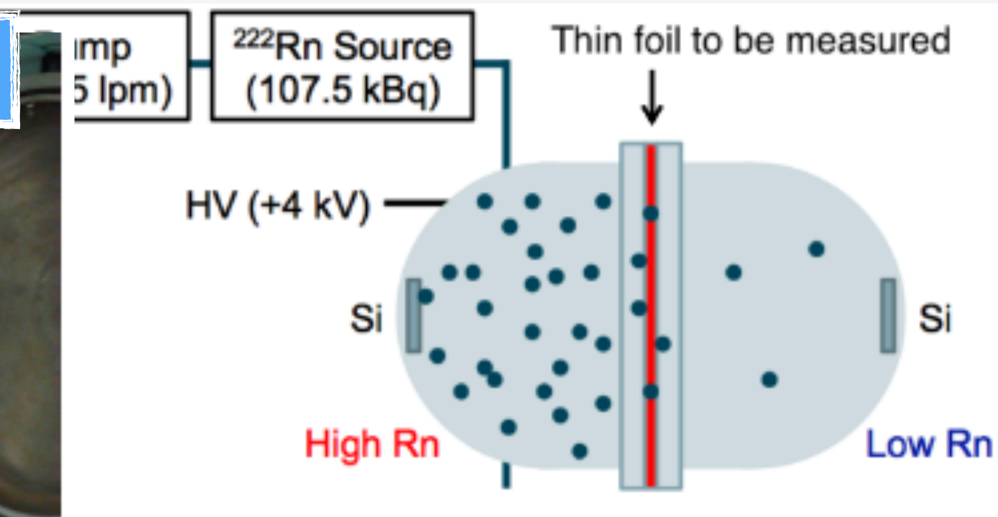
# SuperNEMO Low Background Program



RnCL

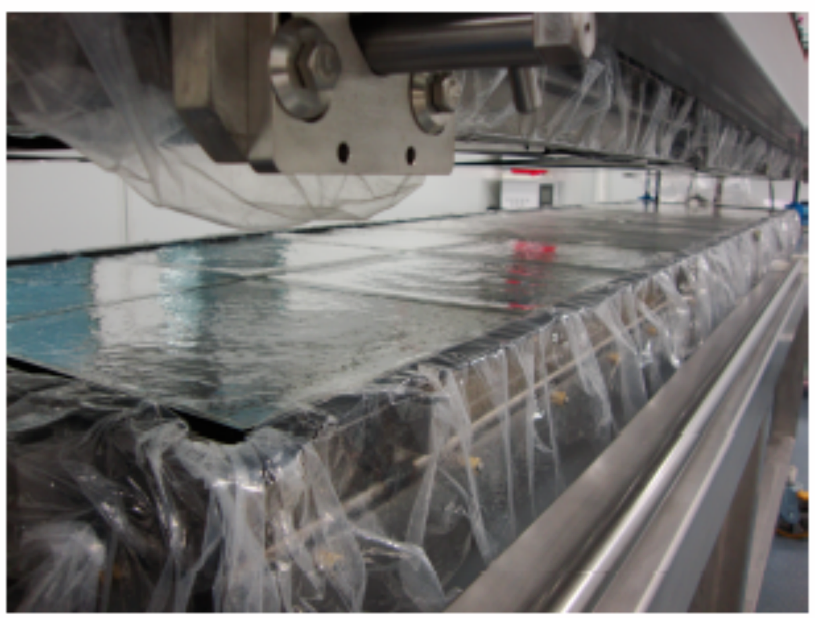


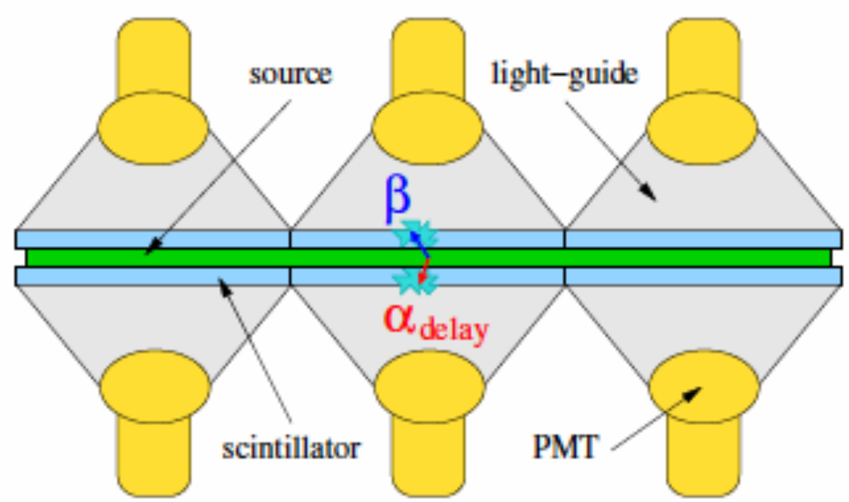
Rn Emanation setup

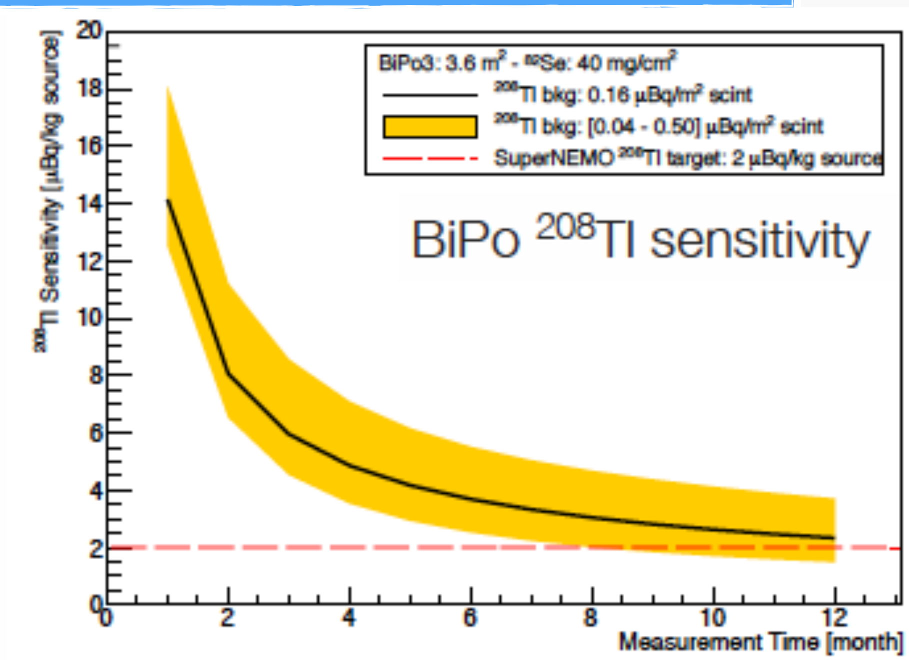



Rn Permeability setup

**Dedicated BiPo detector to measure ββ source foil contamination, 10μBq/kg for $^{214}$Bi, 2 μBq/kg for $^{208}$Tl — operating since Feb'13 @LSC (Canfranc)**

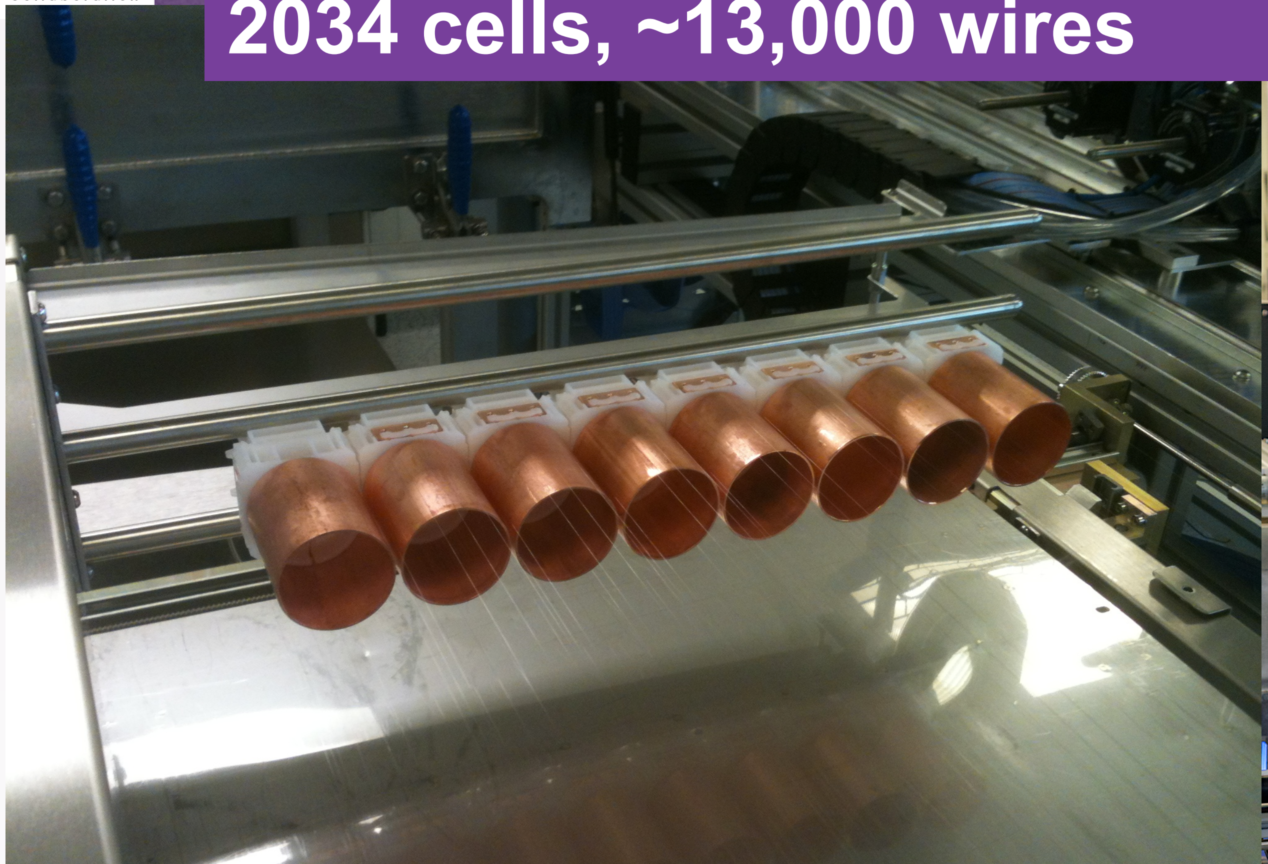
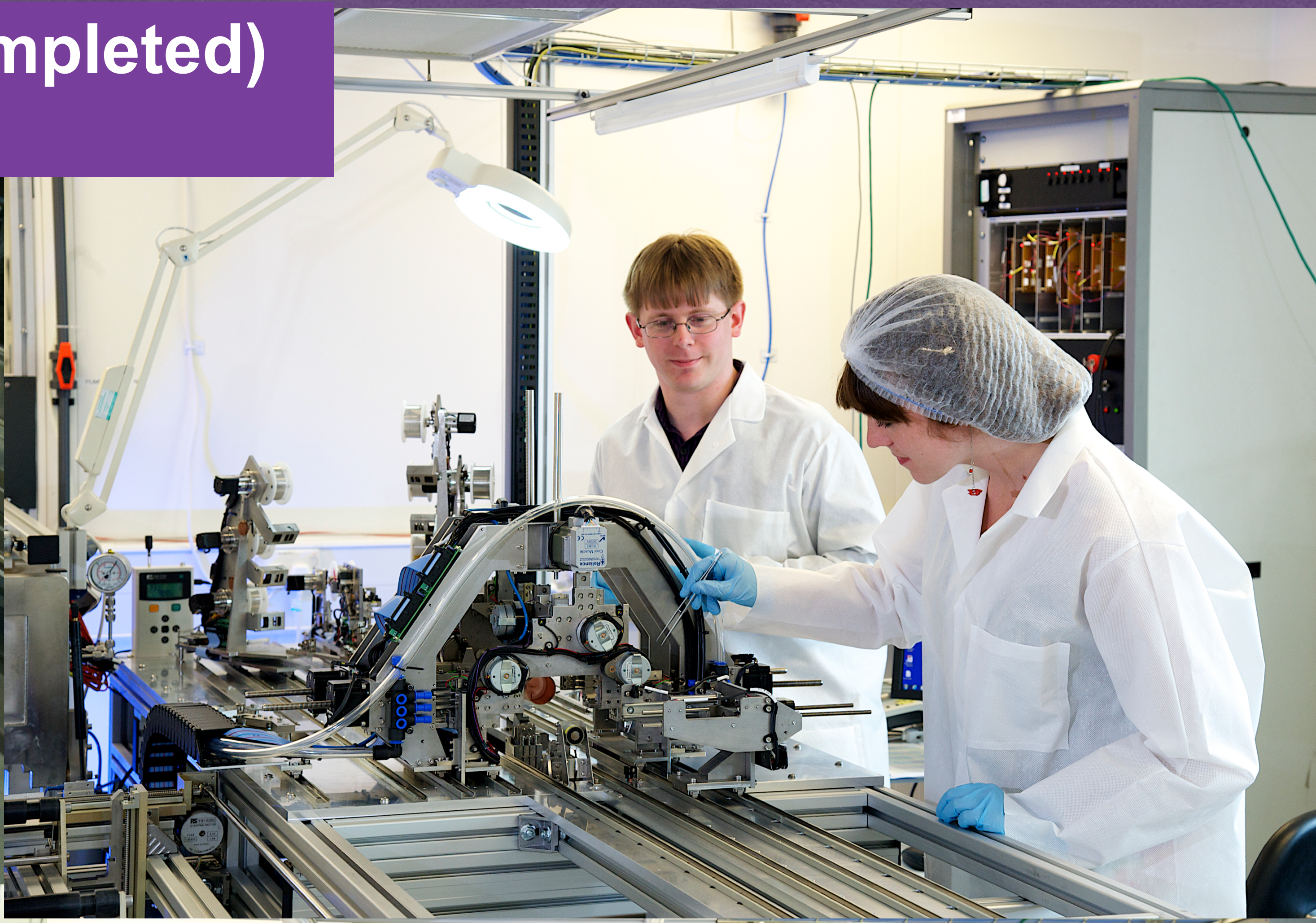


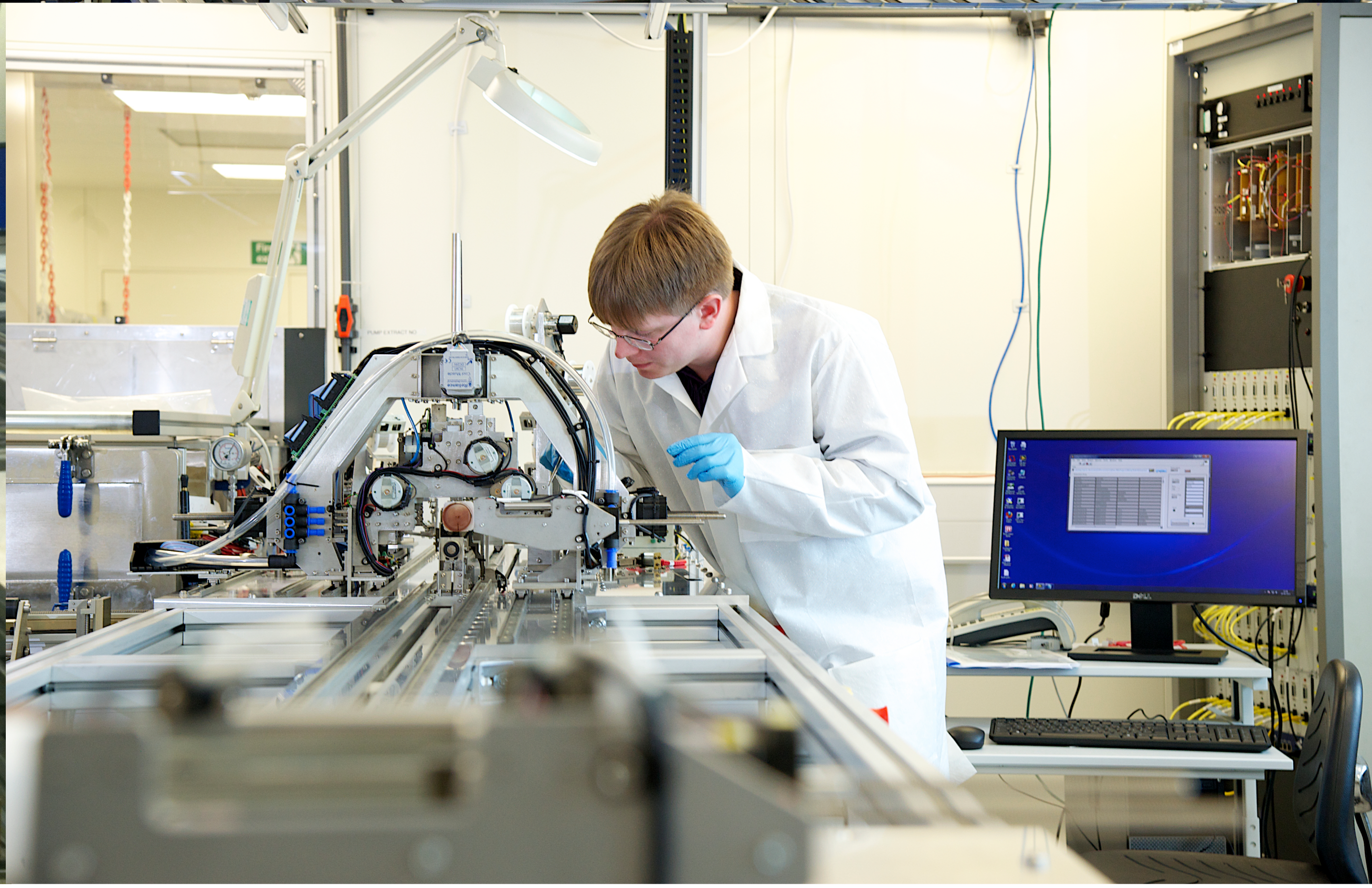



**+ low background HPGe facilities at LSM, Bordeaux and Boulby, ICPMS at UCL**

# Tracker Cell Production (completed)
# 2034 cells, ~13,000 wires



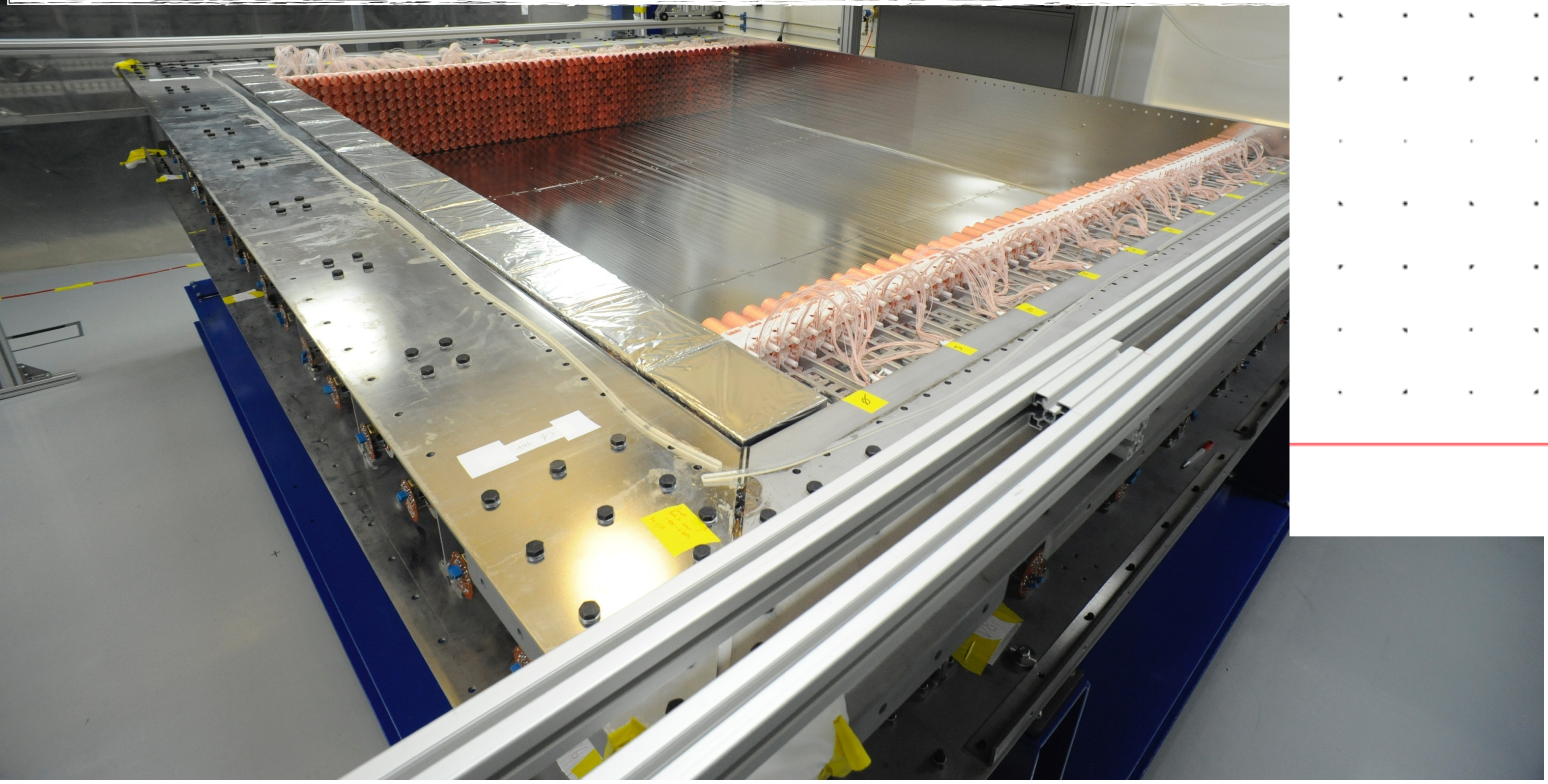
# Quarter-tracker zoomed view

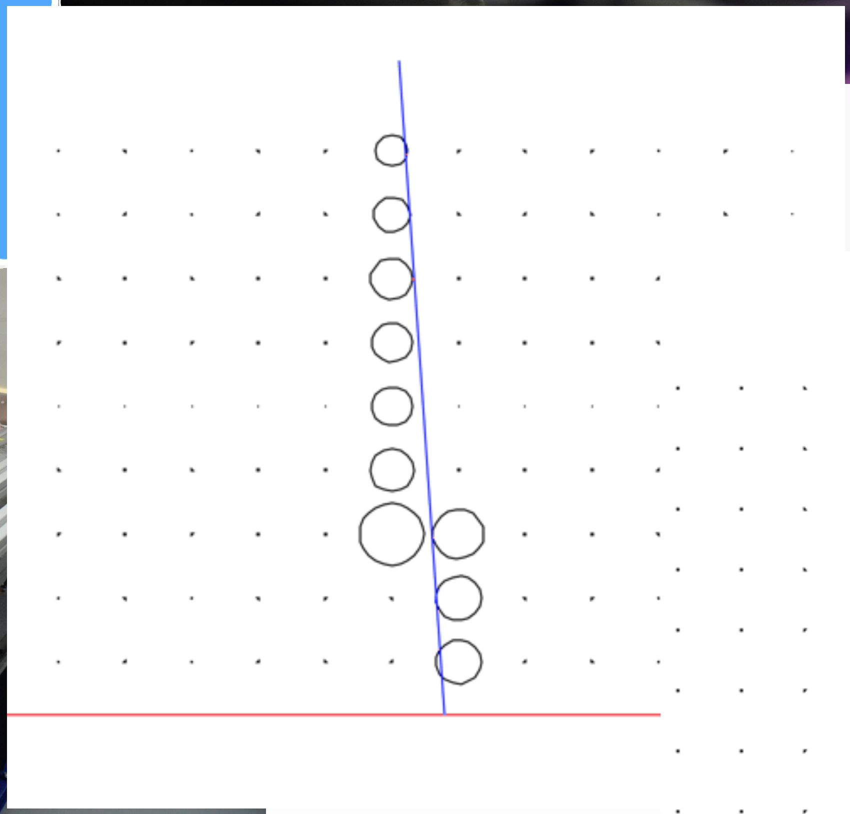
# Tracker Assembly and Commissioning (completed)

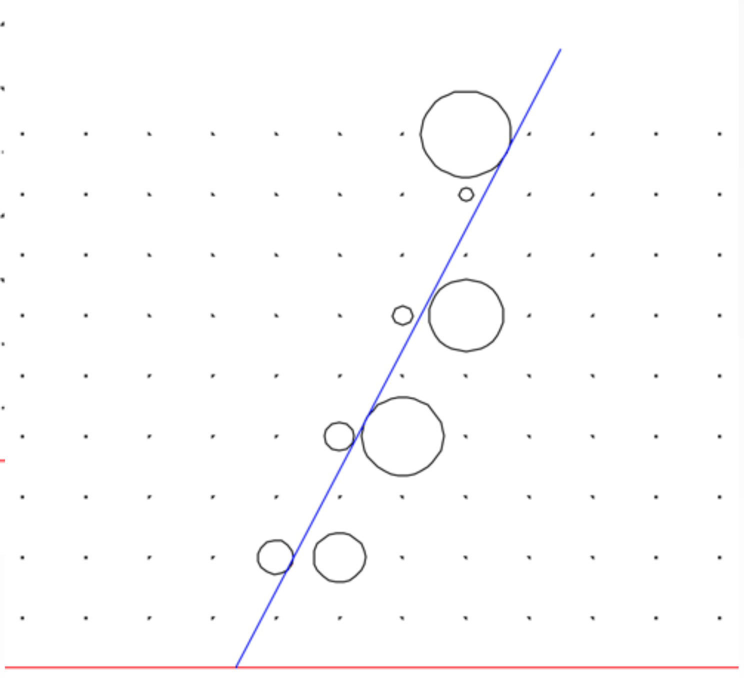
**4 C-shaped tracker modules**

**Rn emanation from fully assembled tracker**

**Target (150 μBq/m$^3$) <u>reached with fully instrumented tracker!</u>**







**Commissioning with cosmic rays**


**All 4 quarter-tracker modules delivered to LSM**

supernemo collaboration



theguardian



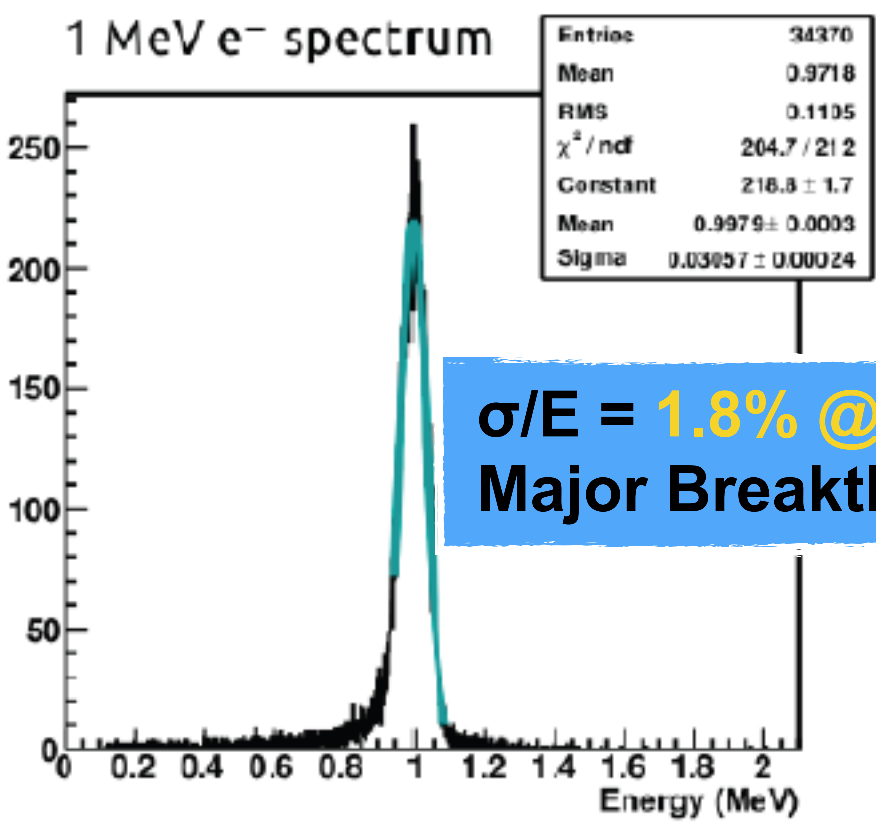
**Science** Life and Physics

# How the particle that led Bohr to think energy might not be conserved could lead the next revolution in physics

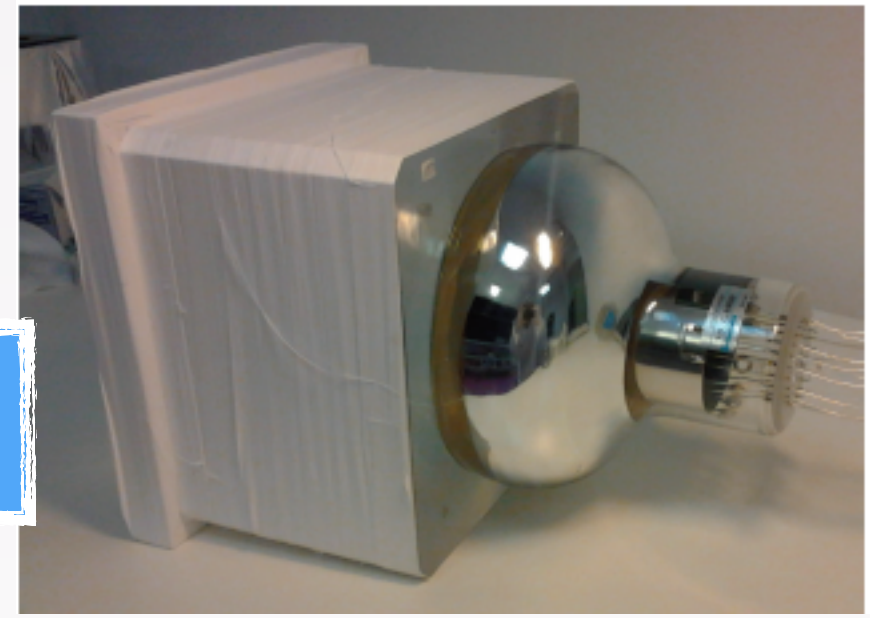
Neutrinos are ubiquitous, but mysterious. A Nobel prize was awarded this year for the discovery that they have mass, and undergo quantum oscillations as they travel - discoveries that fundamentally changed our understanding of physics and cosmology. A rare nuclear decay, being searched for now, might lead to a similar revolution

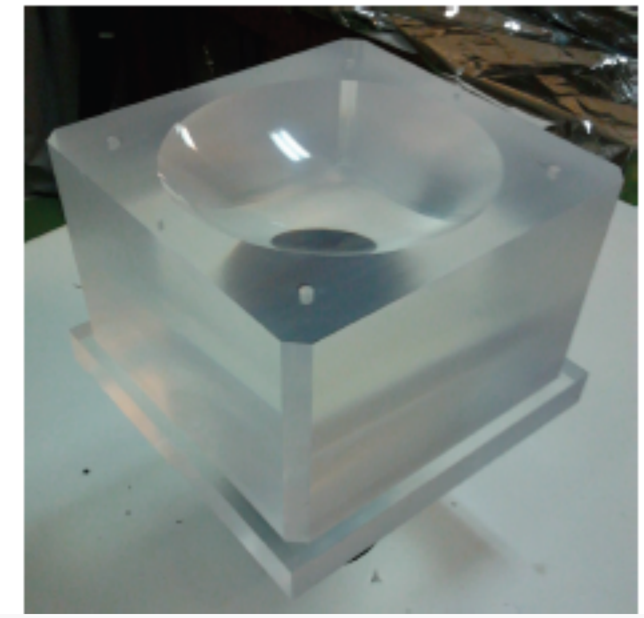
The tunnel where, in Oct 2015, the first module of the SuperNEMO neutrinoless-double-beta-decay detector arrived after making the trip from the Surrey Hills to the Cottian Alps (from UCL's Mullard Space Science Laboratory to the Laboratoire Souterrain de Modane). Photograph: David Waters

# Calorimeter Production

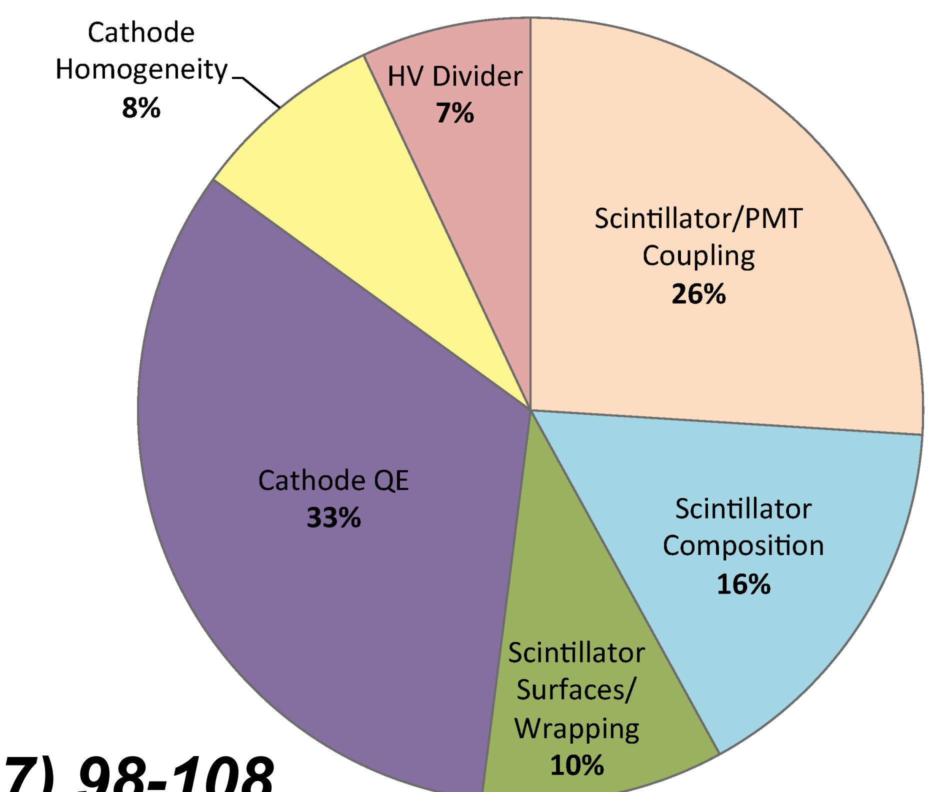



**σ/E = 1.8% @ 3 MeV**
**Major Breakthrough!**



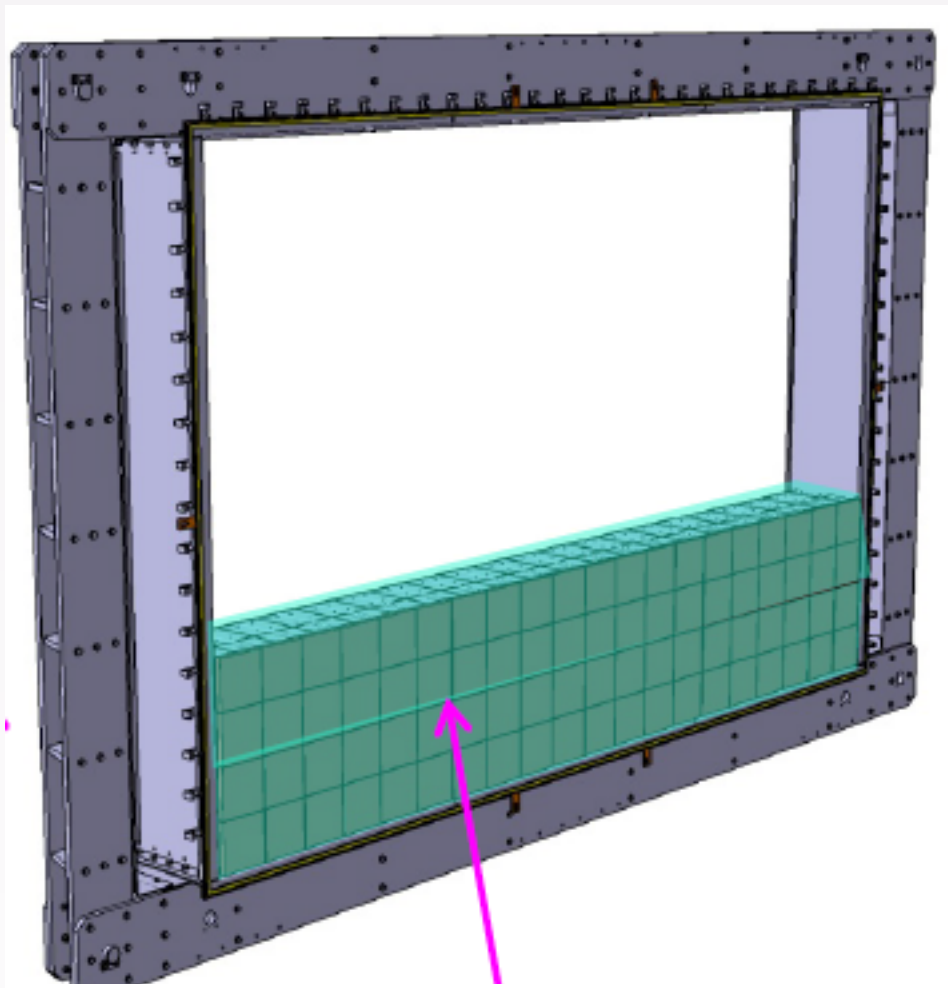


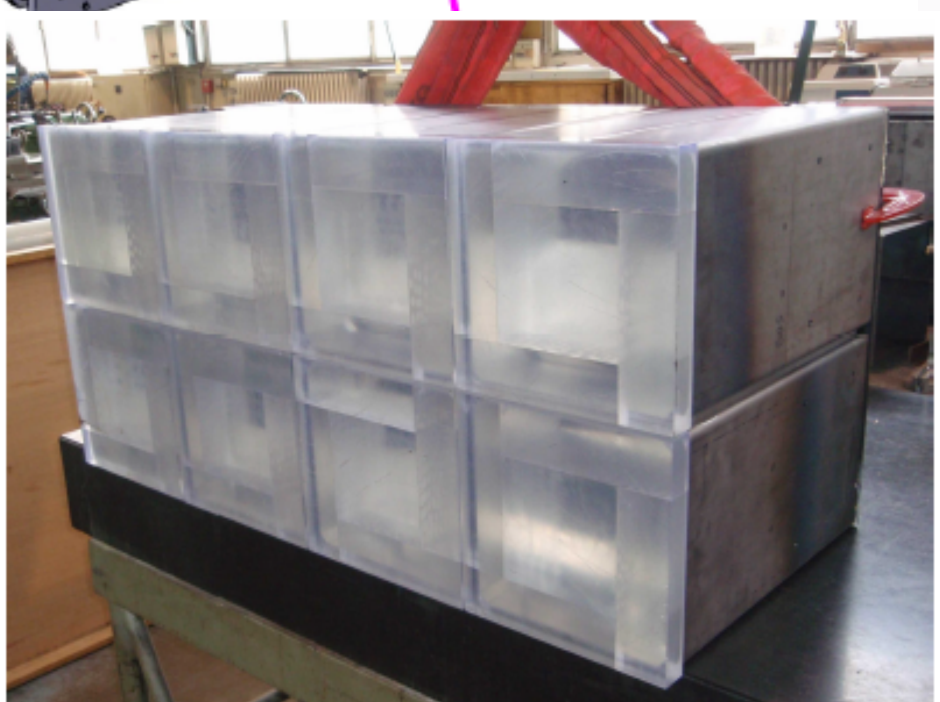
- 8” PMTs with large blocks (440 modules)
- 5” PMTs in outer rows/columns, endcaps and veto
- Every block characterised
- **Target performance achieved with full production**

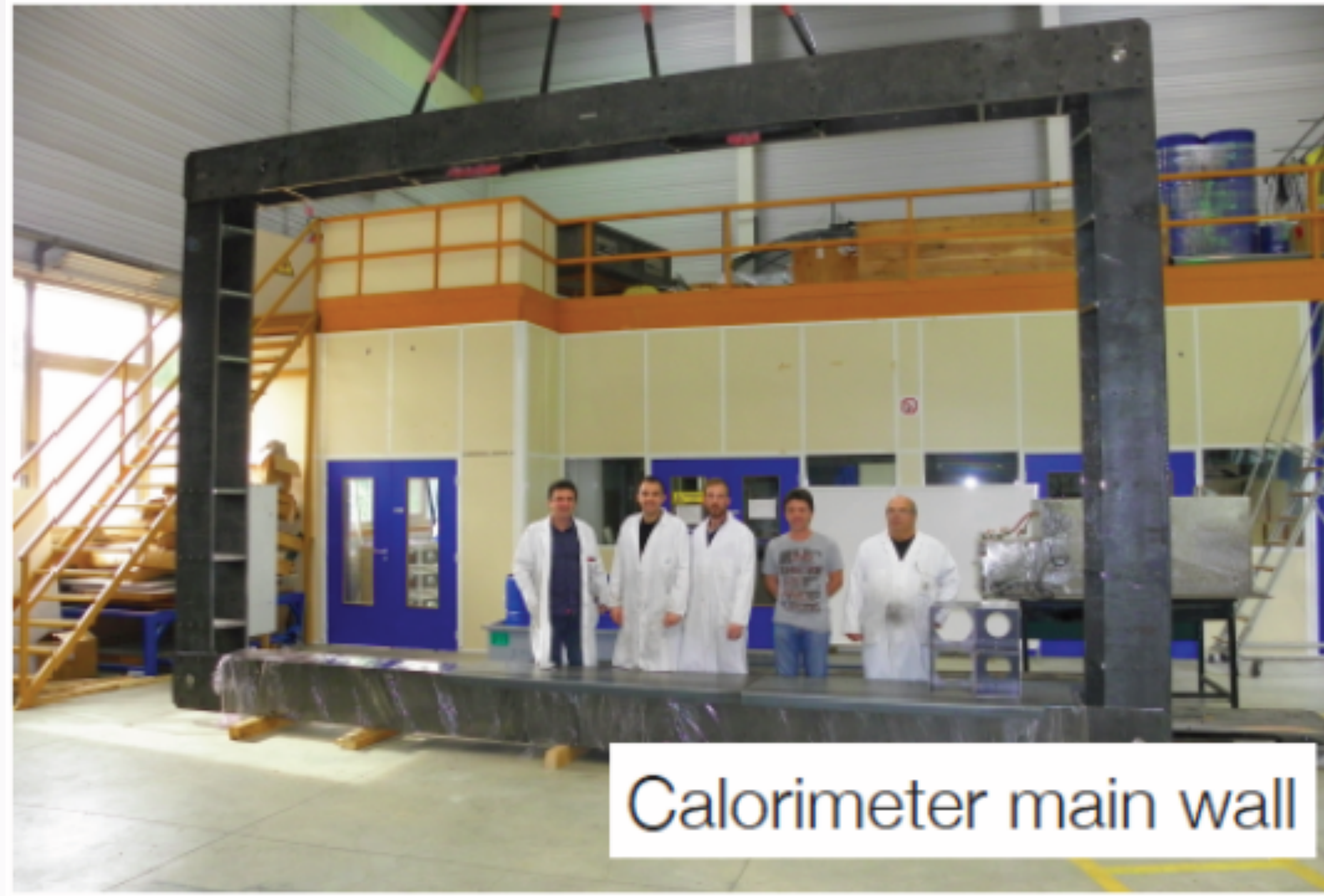



***Nucl. Instr. Meth. A 868 (2017) 98-108.***

# Calorimeter Construction



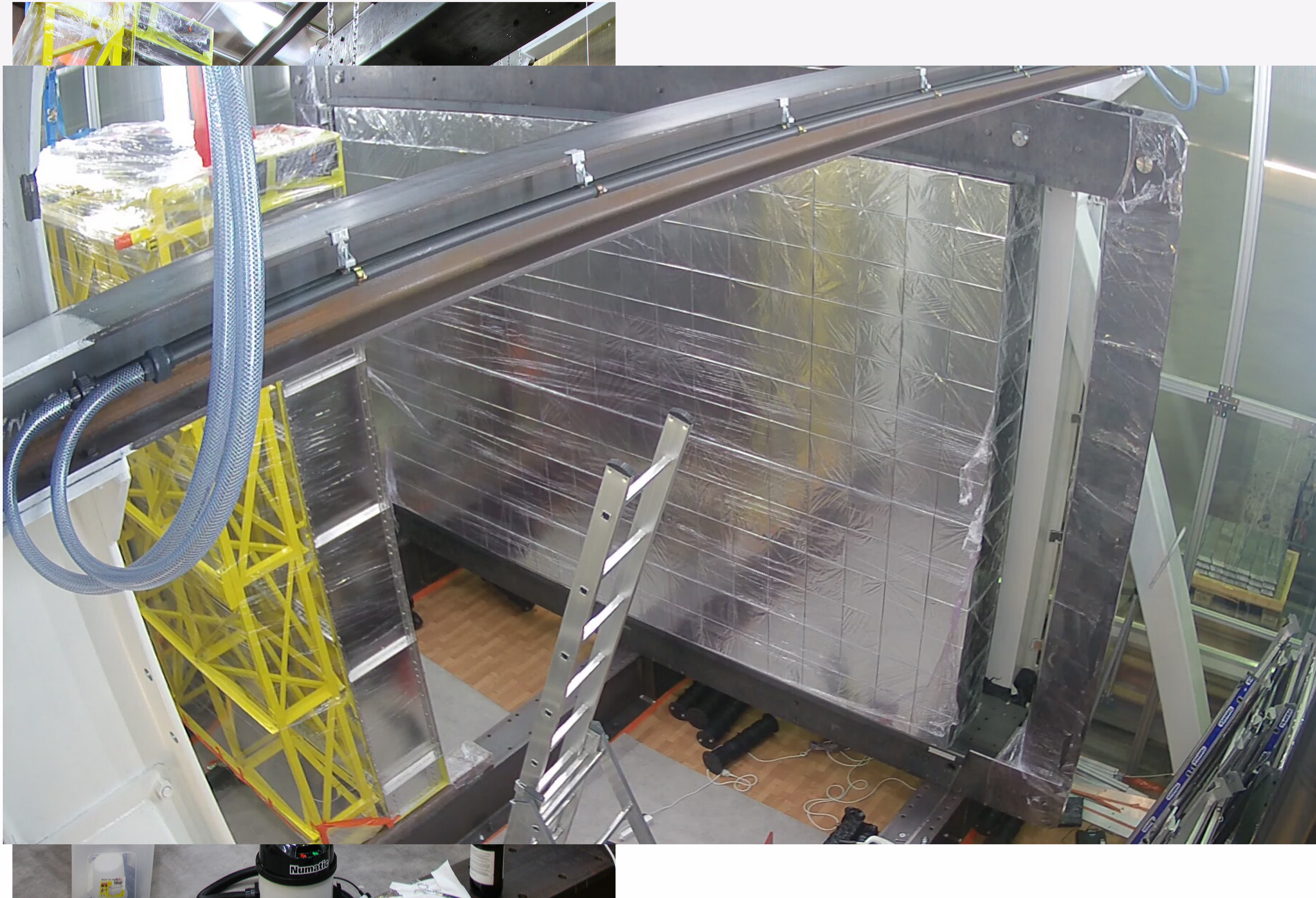




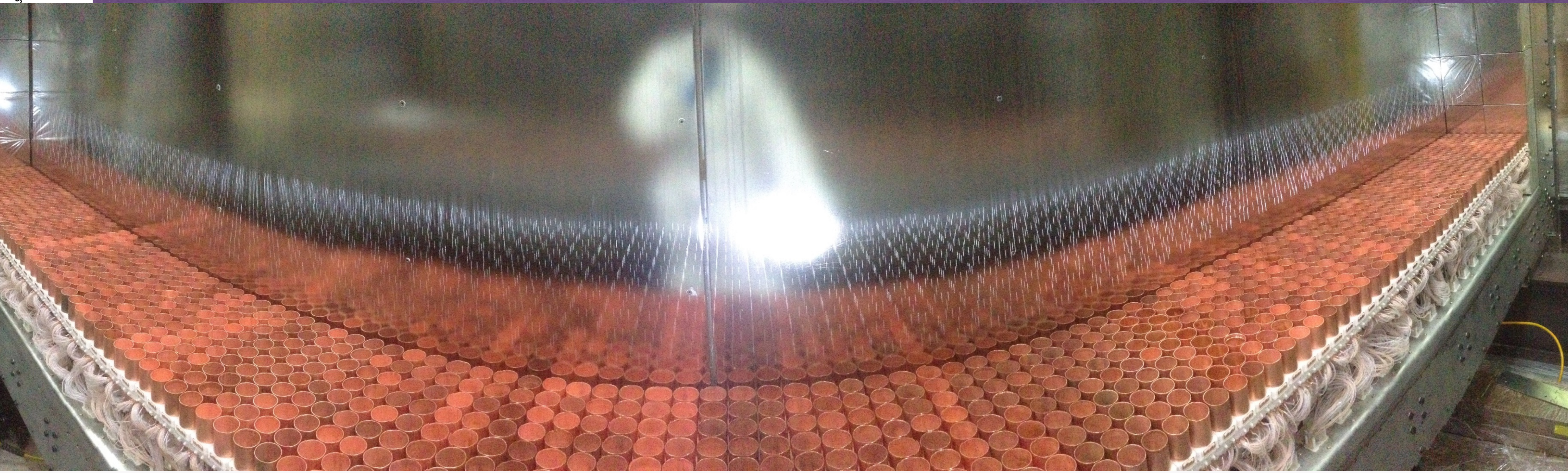

- Both **calorimeter** walls are **assembled** and **installed** at **LSM**
- Light Injection calibration system to monitor gain drift within 1%

# Calorimeter Integration at LSM

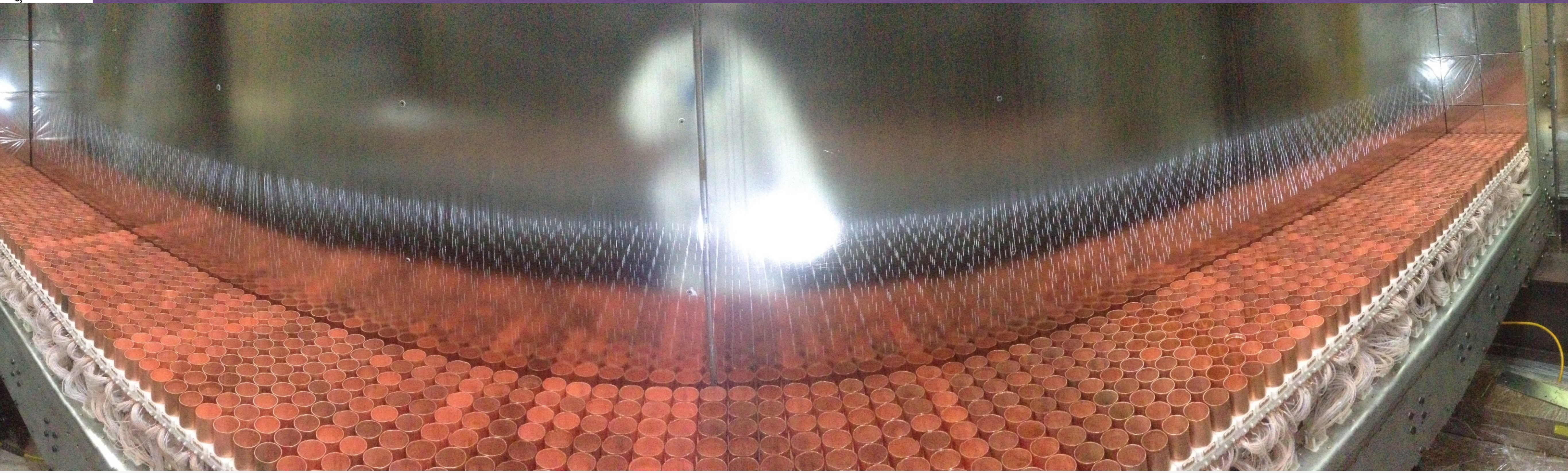
# Calorimeter Integration at LSM



All detector modules delivered underground (LSM)
Half of detector (calorimeter + tracker) fully integrated

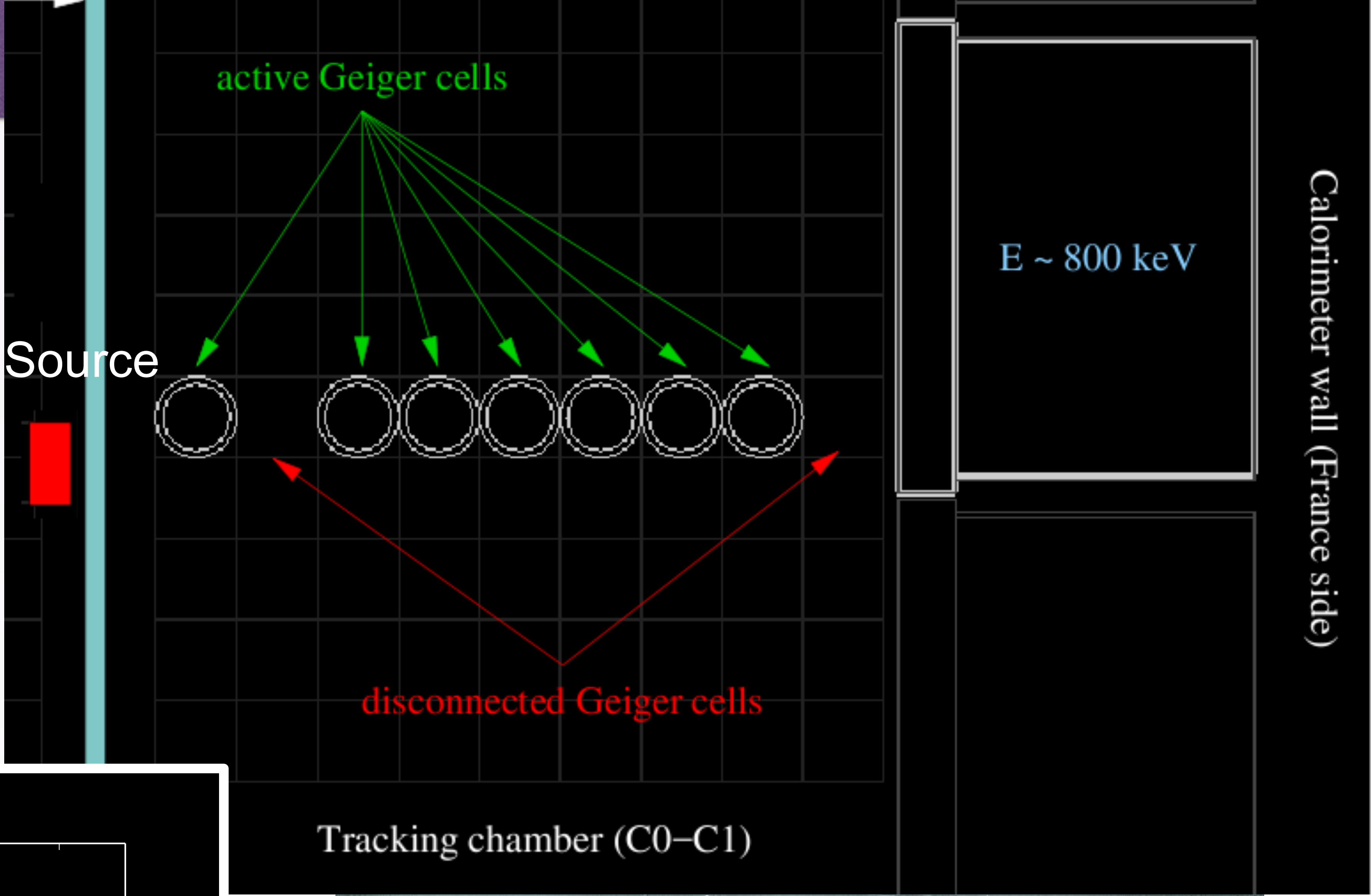


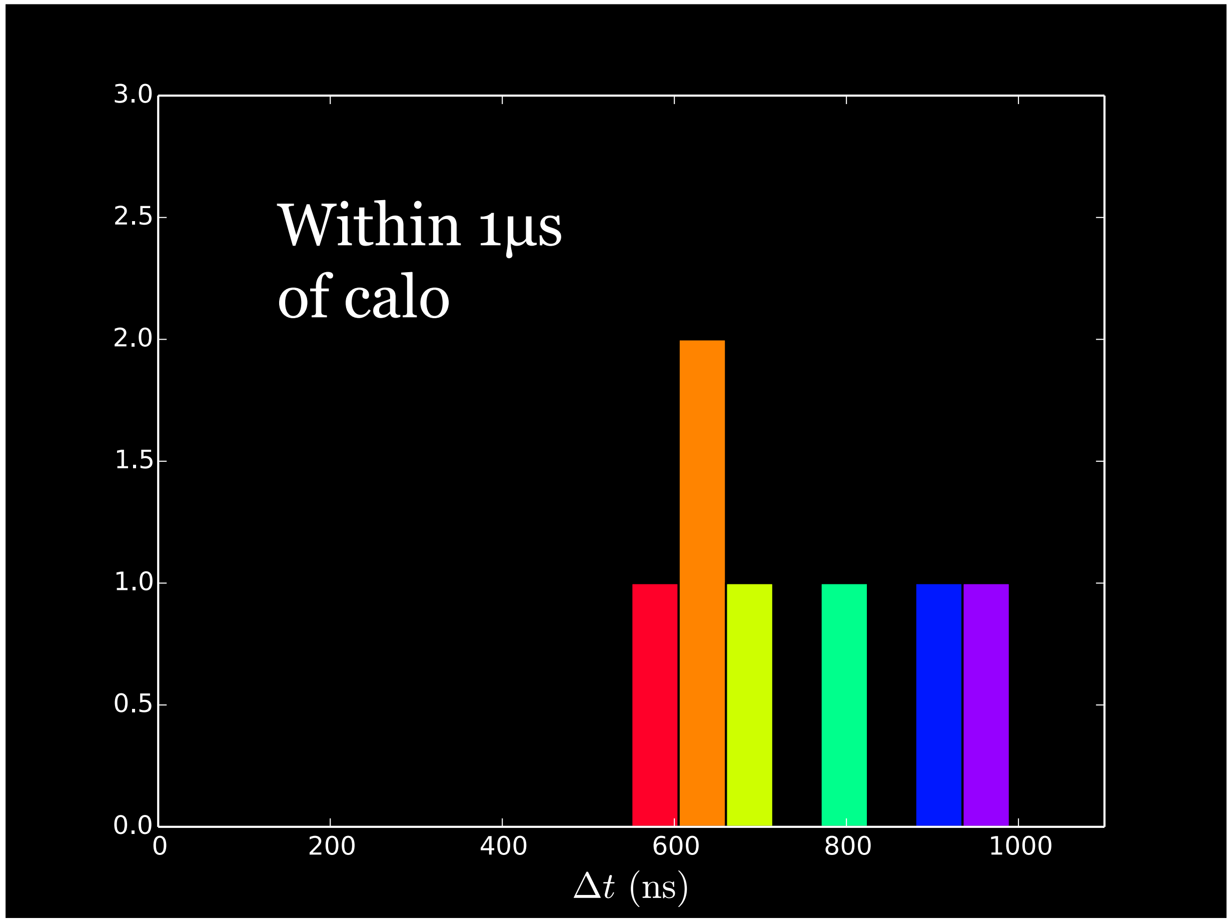
All detector modules delivered underground (LSM)
Half of detector (calorimeter + tracker) fully integrated

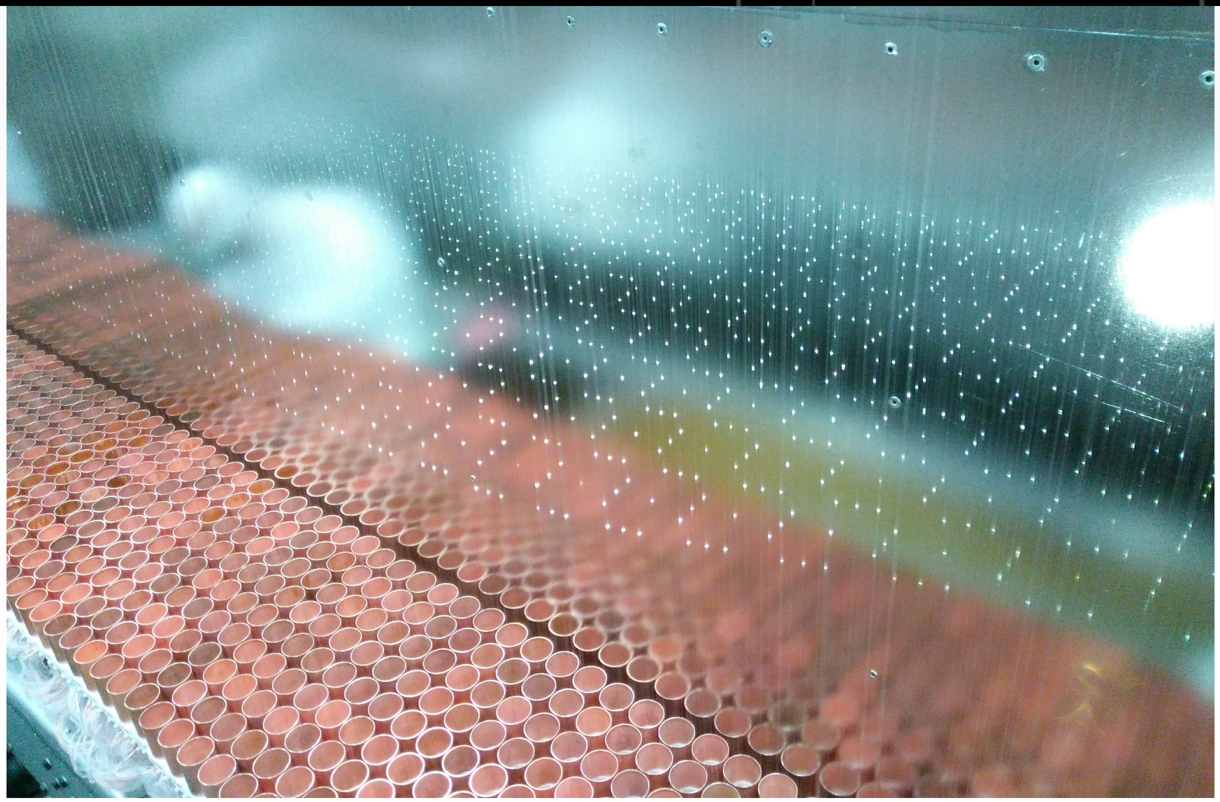


All detector modules delivered underground (LSM)
Half of detector (calorimeter + tracker) fully integrated

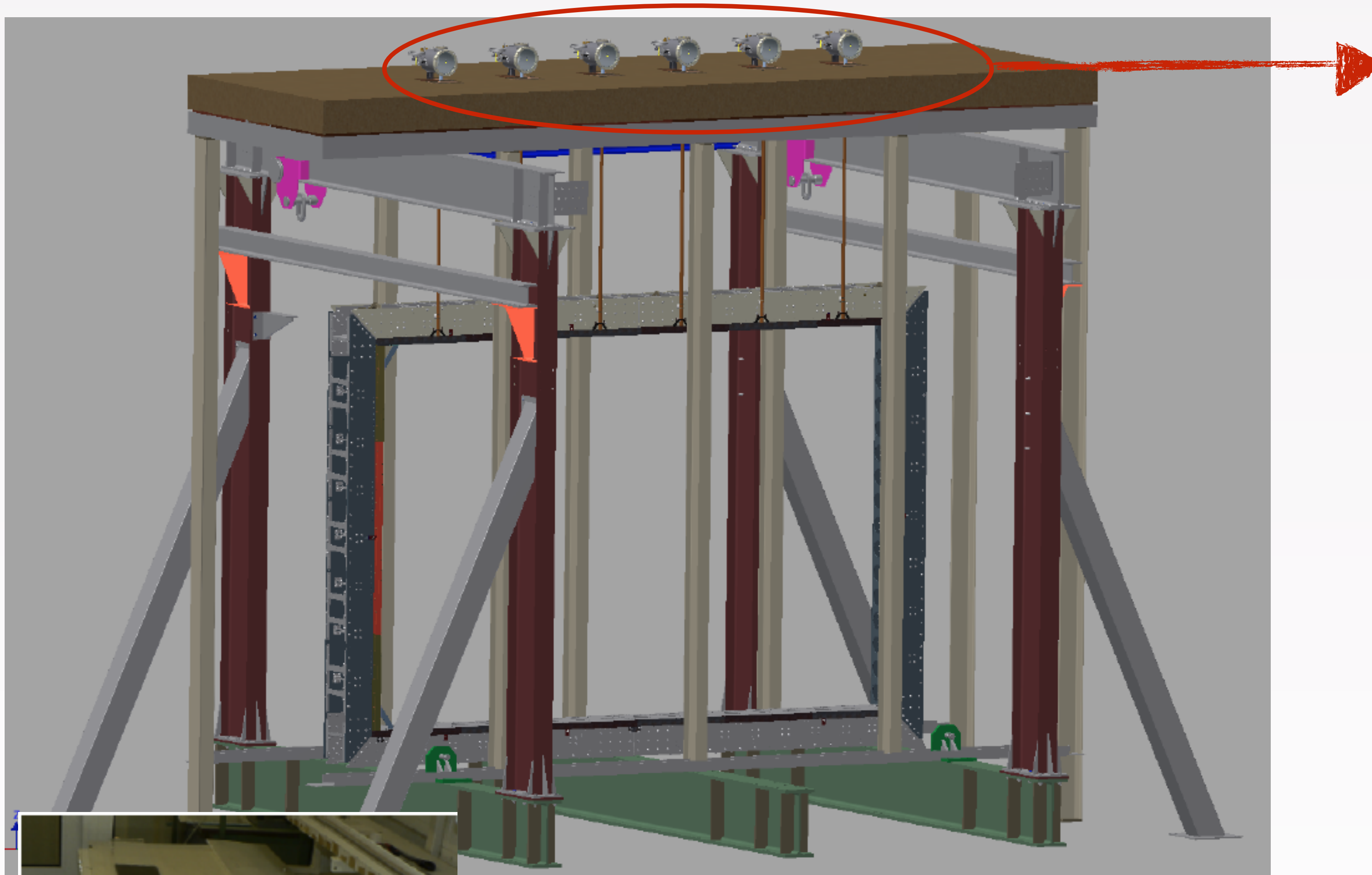
# First events from half-detector commissioning Mar’17

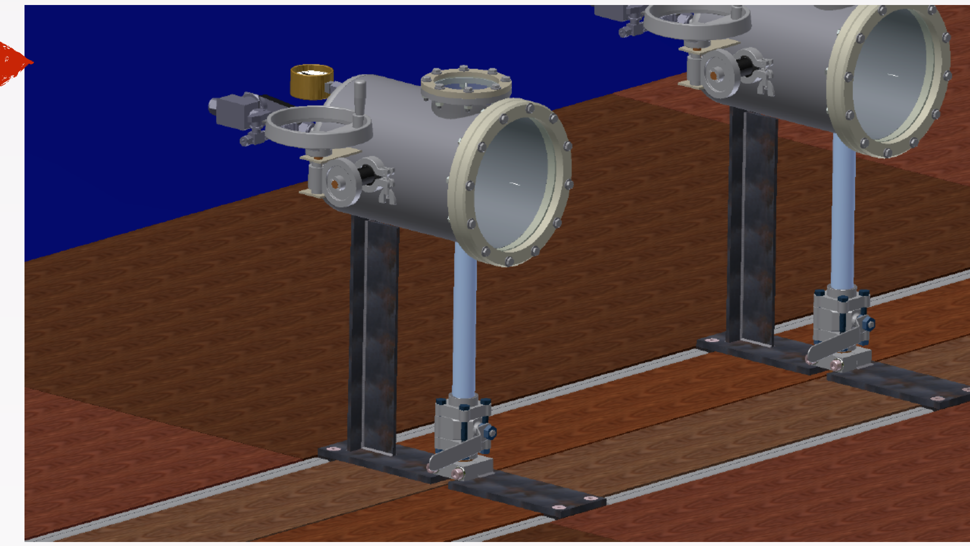


# ββ Source Module and Calibration Sources Deployment System

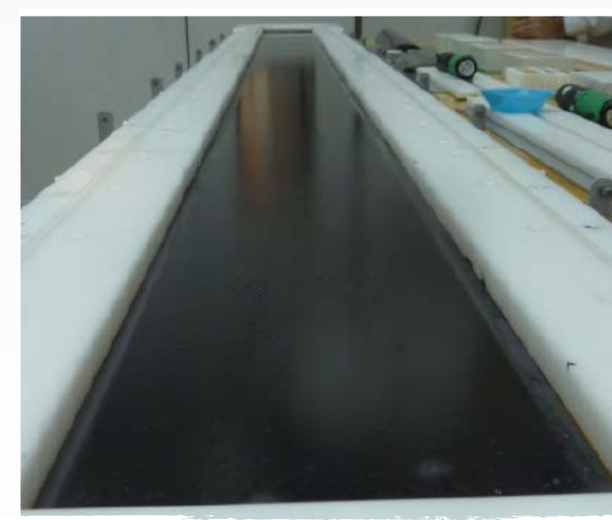




- Calibration sources: $^{207}$Bi + $^{60}$Co + others
- "Rn-free" deployment system

$^{82}$Se foil production at ITEP

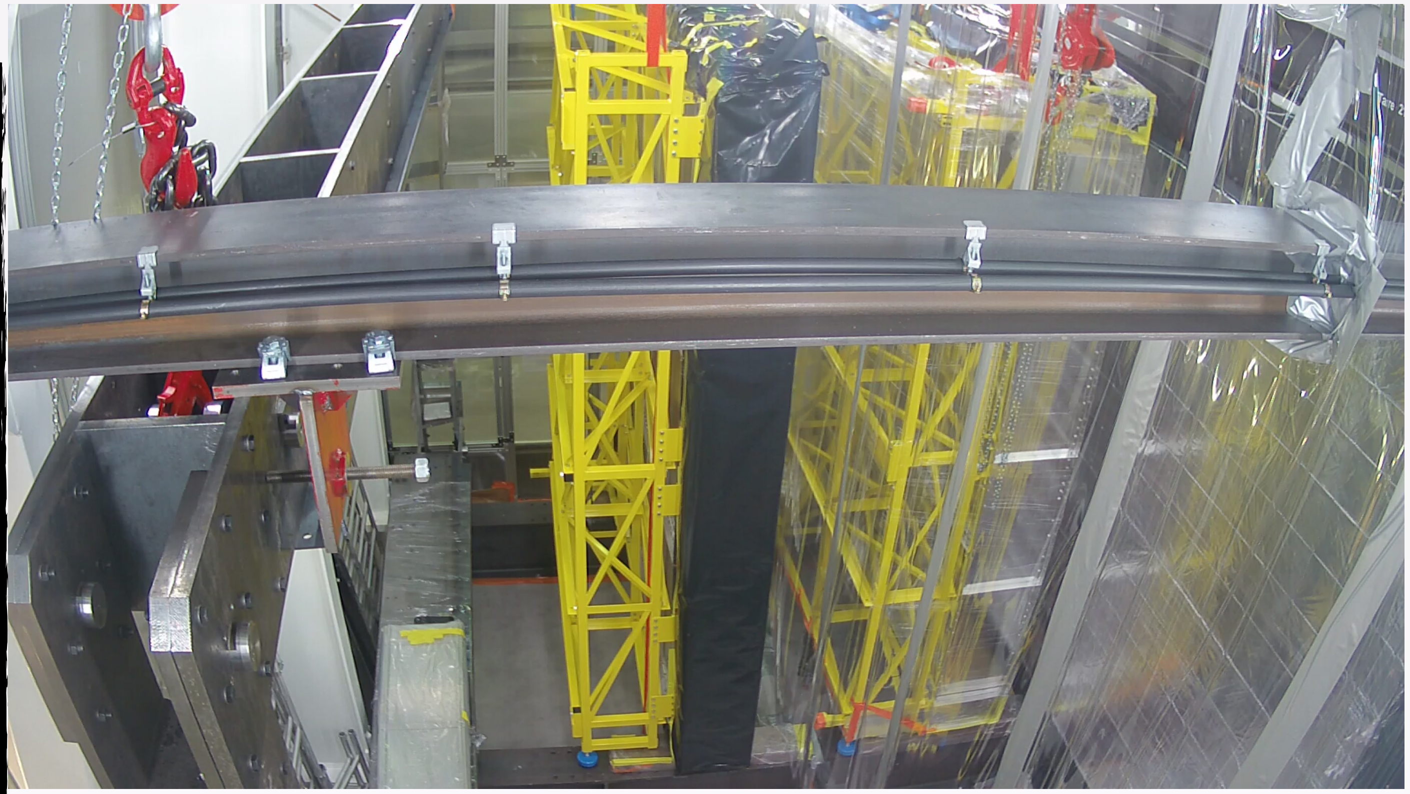
- $^{82}$Se (6.3kg) source foil production **completed**
- R&D on $^{150}$Nd and $^{48}$Ca
- Source foil installation on a month's time scale



$^{82}$Se foil production at LAPP

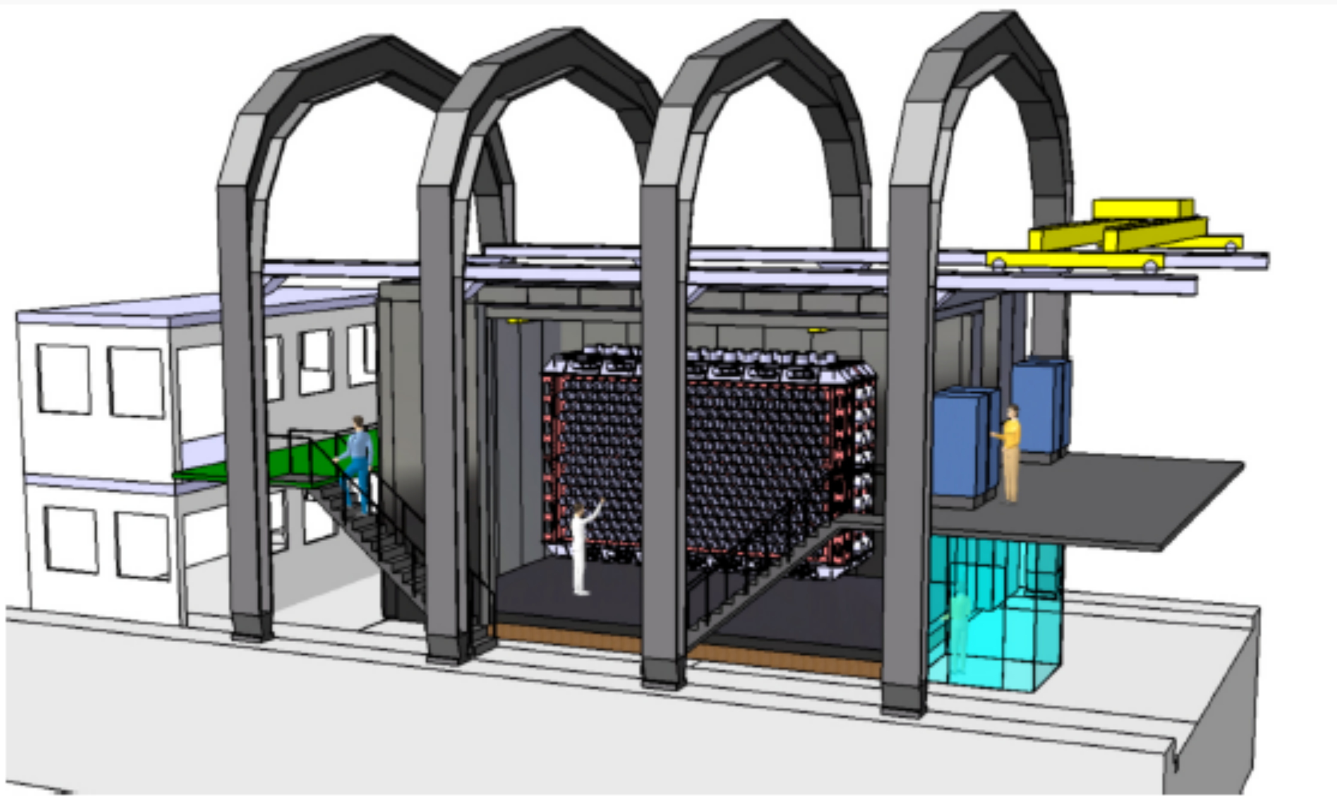
# SuperNEMO Demonstrator Schedule

- Detector integration complete by Jan'18
- Start running for physics early 2018
- Measure target levels of $^{214}Bi$ in foil and $^{222}Rn$ within couple of months
- $^{208}Tl$ ~ 1 year
- Target sensitivity ($6.5 \times 10^{24}$ yr) in 2.5 yr
- ***Critical input to future tracko-calo and other ββ experiments — unique ability to constrain and characterise backgrounds***



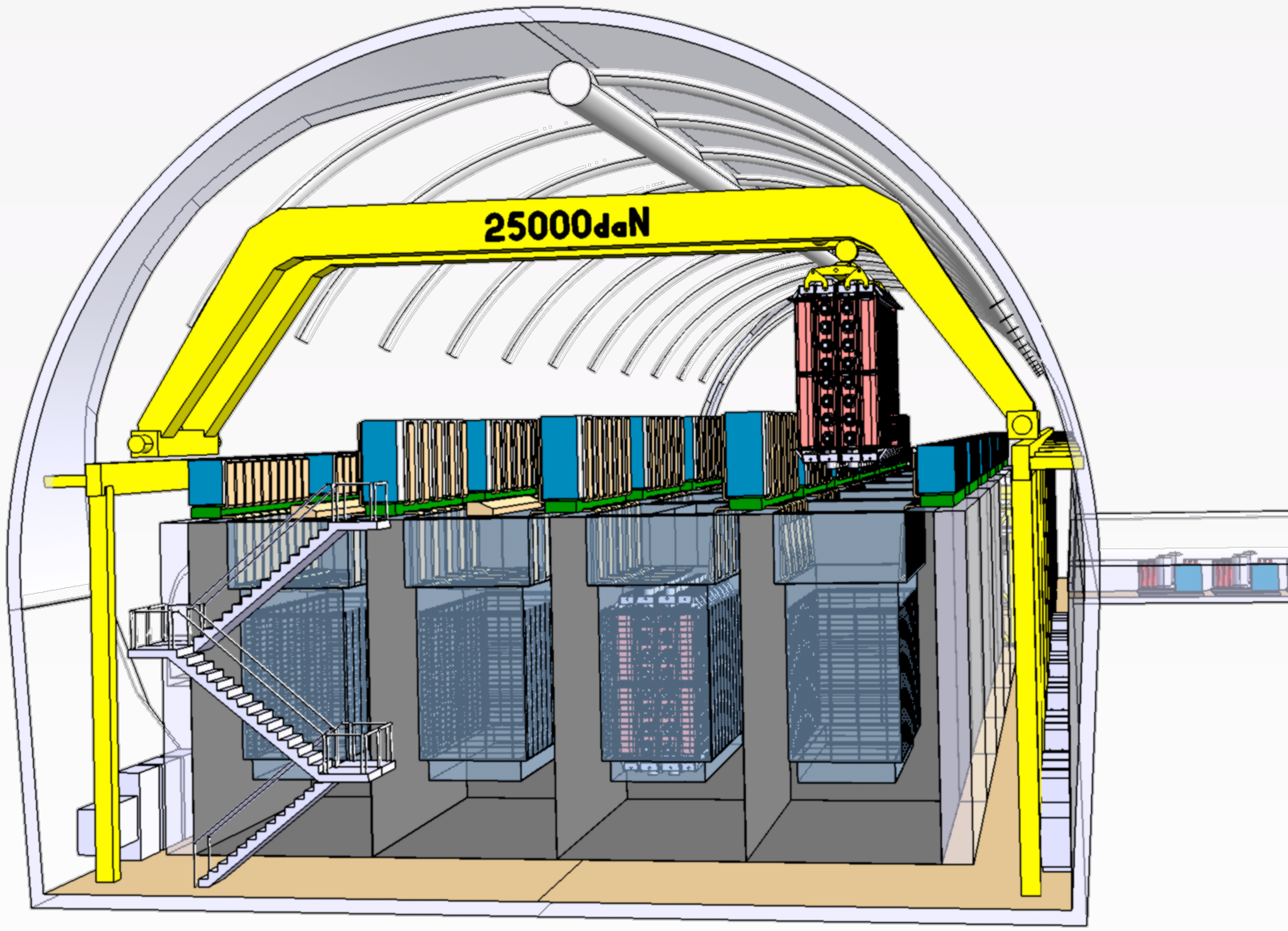
**SuperNEMO Inauguration**

**9-Nov-2017**



# Full SuperNEMO — 15-20 modules, 100kg of isotope(s)

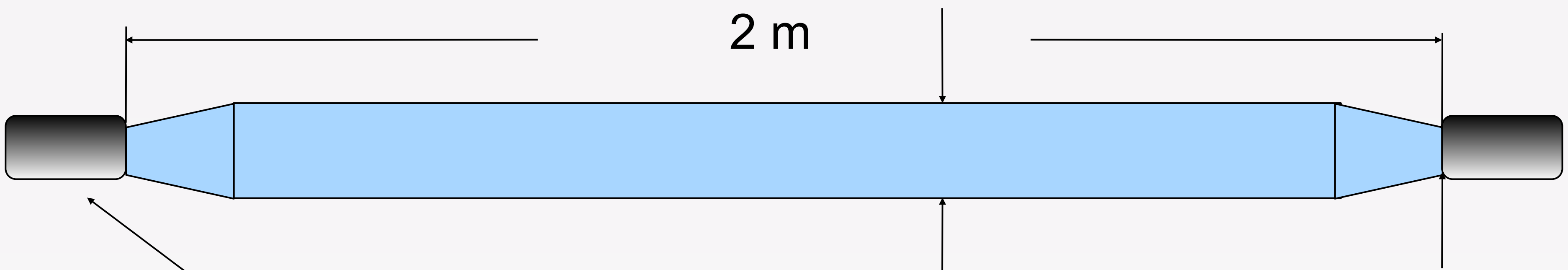
- Distributed location in different underground labs possible/ beneficial
- Construction can proceed in parallel with data taking
- Can provide superior sensitivity with high $Q_{\beta\beta}$ isotopes ($^{150}Nd$, $^{48}Ca$, $^{96}Zr$)
- Cost range: €2.5M/module
- Expensive to extrapolate >100kg




**Is it possible to reduce footprint and cost?**

**In particular, is it possible to achieve detector cost ≤ isotope cost?**

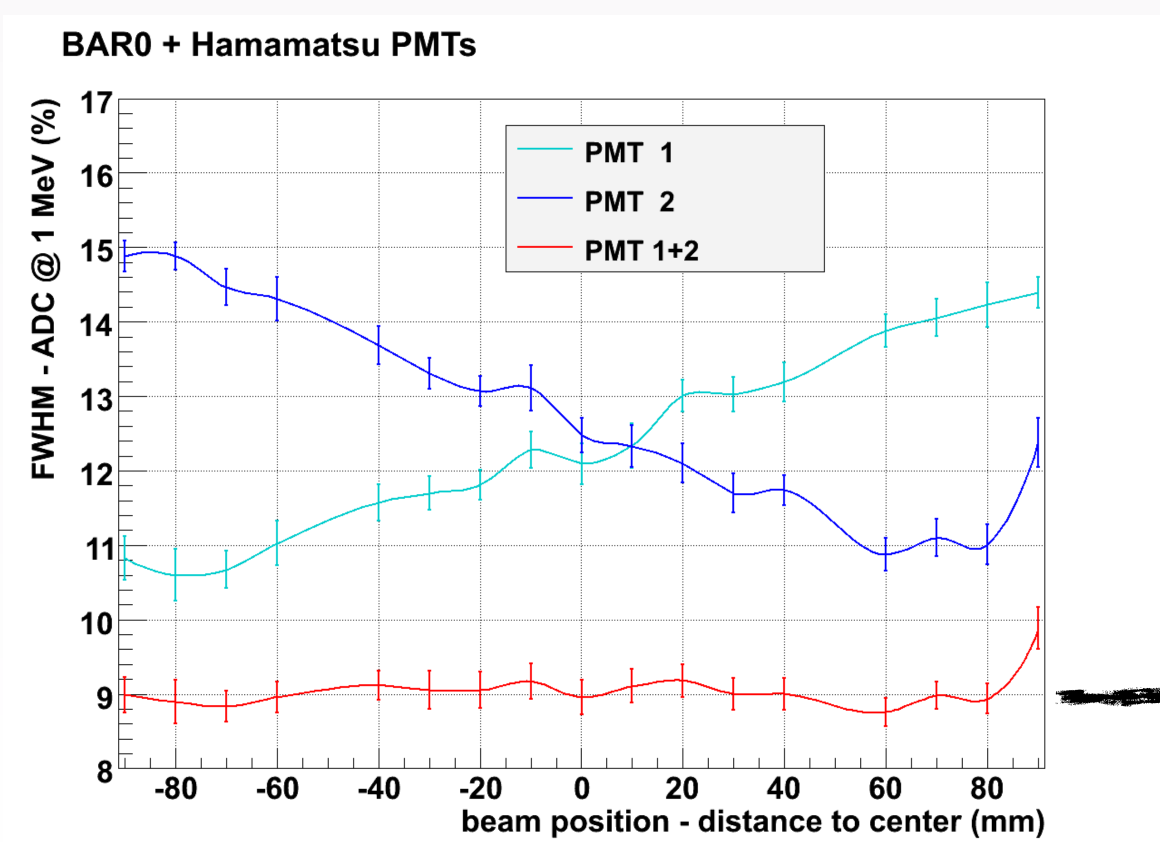
# SuperNEMO Design with scintillator bars

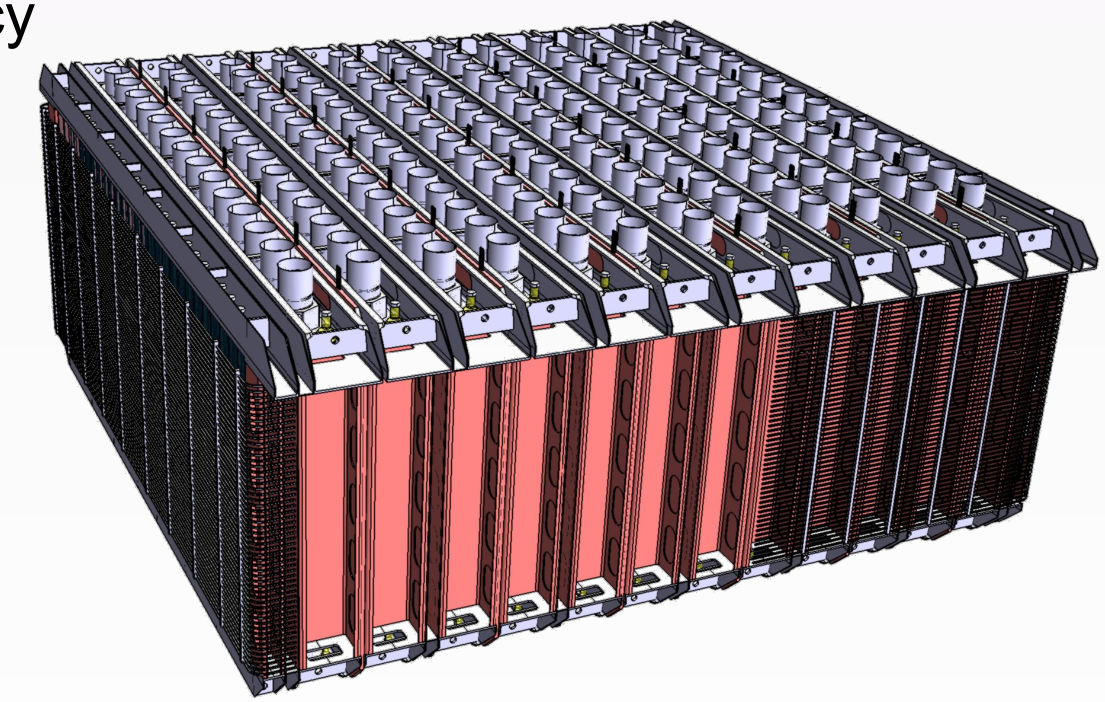



*Disclaimer:*
*One of ideas being discussed within collaboration rather than agreed direction of travel.*

**Main goals:**
- Significant cost reduction
- Eliminate all BKG apart from 2ν

- Fewer much cheaper PMTs (with less radioactivity)
- Compact design (at expense of modularity)
- Very high (close to ~100%) efficiency of γ tagging
- No B-field. Tagging e+ with 511 keV γ's ⇒ better efficiency



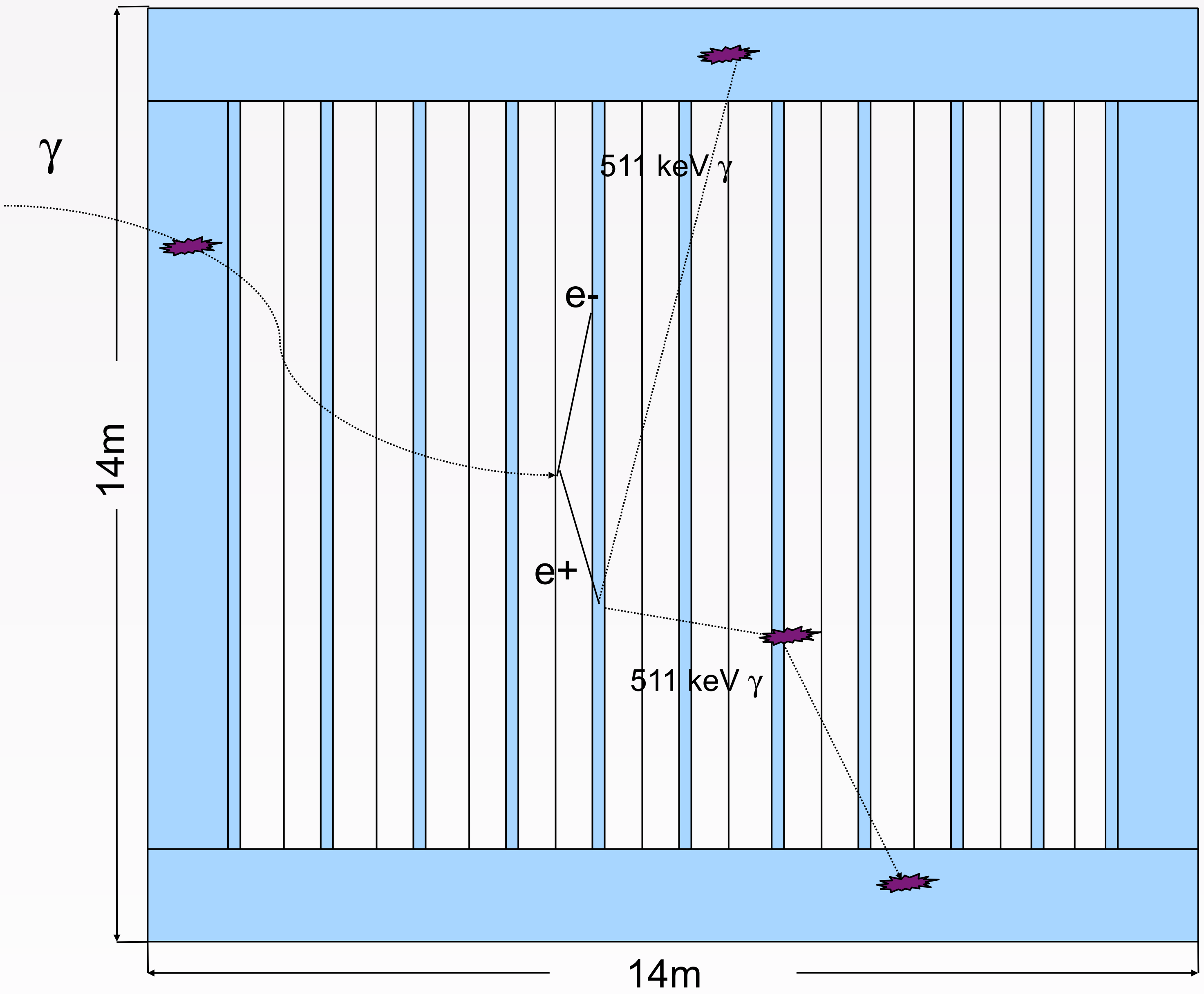



$$\frac{\sigma_E}{E}(3\ \mathrm{MeV}) = 2.3\%$$

(c.f. 1.8% for baseline design)

# SuperNEMO Design with scintillator bars

Background suppression with bars. Top View.




***Input from Demonstrator (background, resolutions and their interplay) crucial!***

- 14mx14mx2.5m sufficient to accommodate 100kg of isotope*
- Detector cost estimate: ~€50k per kg of isotope (c.f. >€250k/kg for baseline design),
- i.e. **detector cost ~ isotope cost**

**scalability**

- Further optimisation possible/ needed
  - Fewer tracker cells, perhaps 3-4 hits enough?
  - Shorter distance between foil and calorimeter — more compact, higher efficiency
  - Readout
  - ….

* Can fit in new hall at Boulby lab

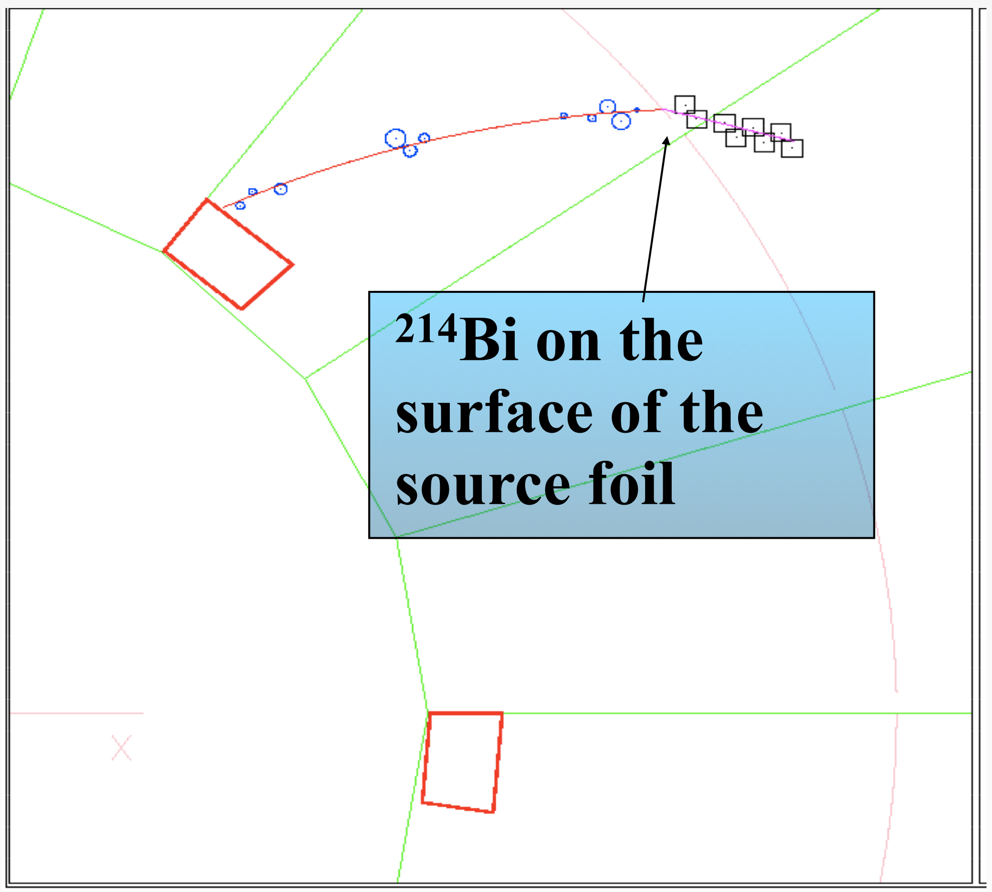
# Concluding Remarks

- Topological approach to bb detection is **unique**
  - **Smoking gun** signature and comprehensive **background characterisation**
  - Isotope **flexibility**
  - Sensitive to **different 0νββ mechanisms**
  - Rich **physics potential outside 0νββ**, both BSM (Lorentz violation, 0ν4β, bosonic neutrino, etc) and nuclear models (e.g. Single State Dominance vs Higher State Dominance) as demonstrated by **NEMO-3**
- **Topological reconstruction** approach can *in principle* eliminate all backgrounds apart from 2νββ. Will learn a lot more once **Demonstrator** starts running next year.
- If radioactive backgrounds and cost (detector~isotope) are brought under control — **topological technique** can be in principle scalable to **tonnes**.
  - Even better if enrichment of high $Q_{\beta\beta}$ isotopes becomes feasible
- In case of discovery — best way for **full characterisation** of **0νββ**

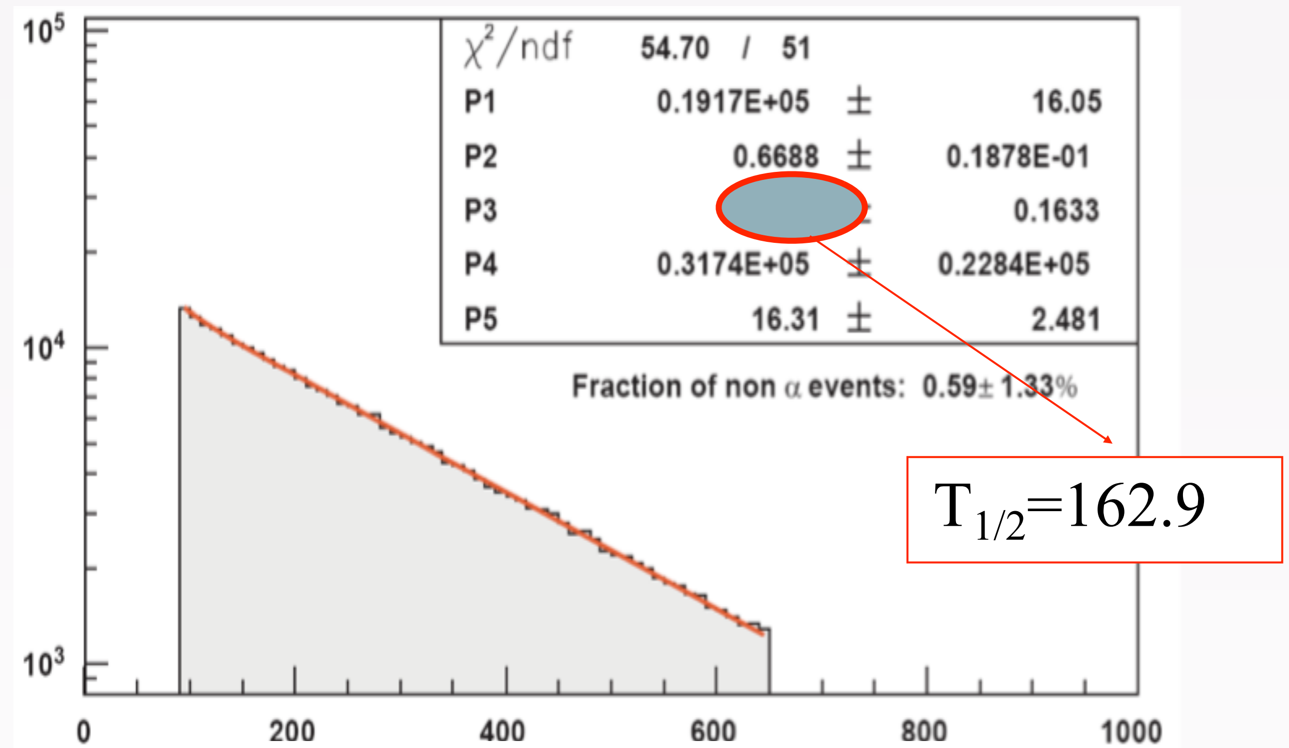
# Thank You

# BACKUP

Full topology reconstruction = unprecedented understanding of backgrounds




**Pure sample of $^{214}$Bi – $^{214}$Po**

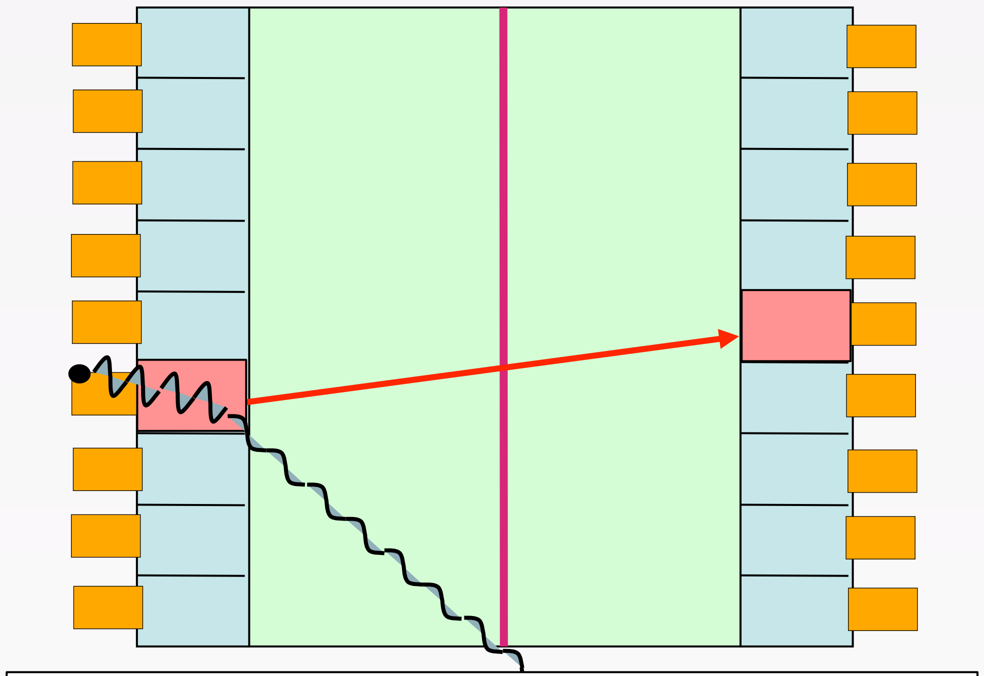


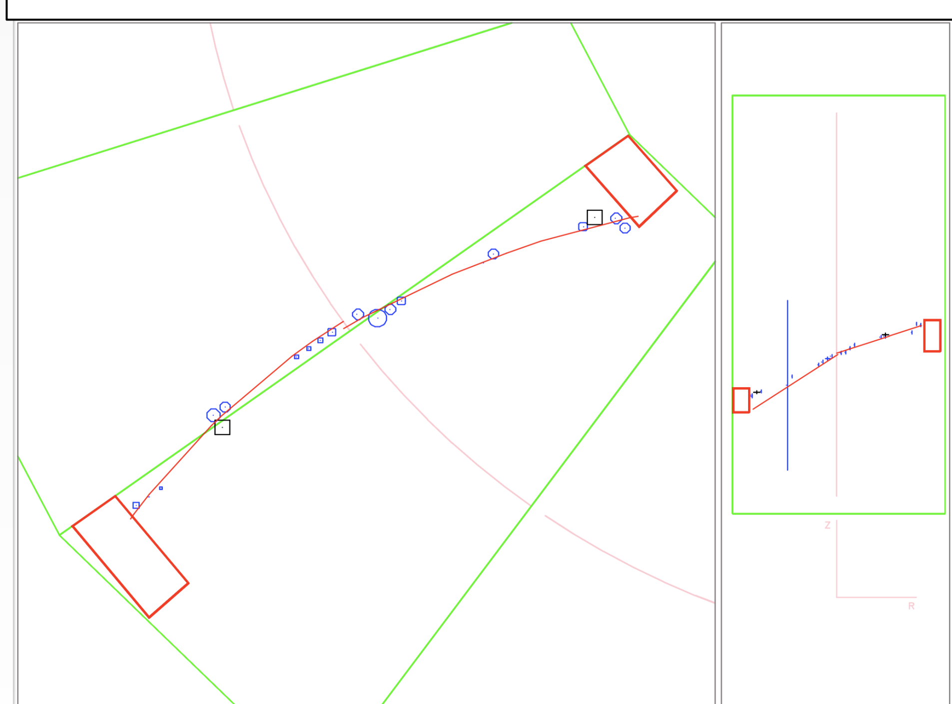

Delay time of the α track

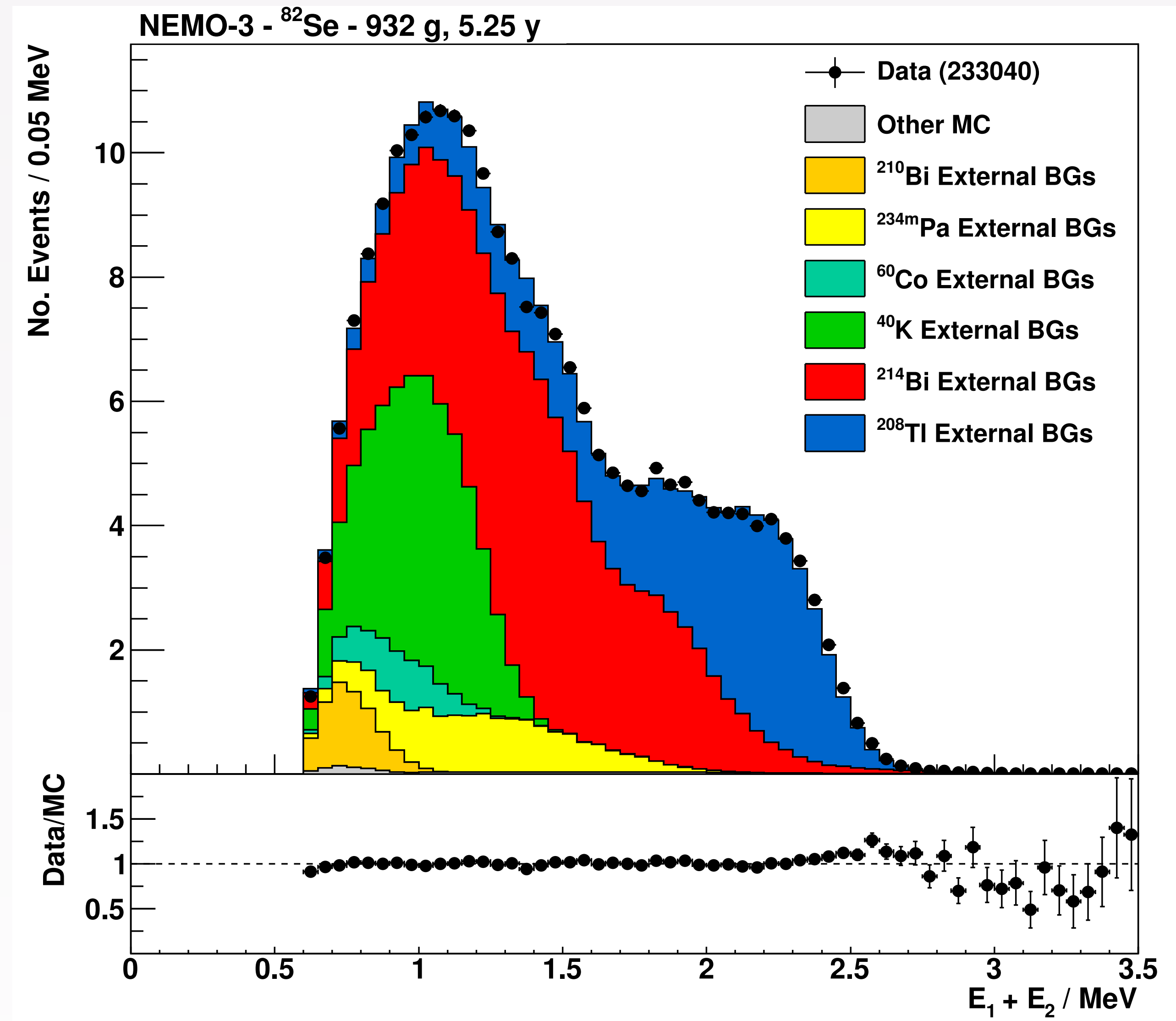
Measuring $^{222}$Rn in NEMO-3. 5mBq/m$^3$ in Phase-II

Full topology reconstruction = unprecedented understanding of backgrounds

E.g.: External background

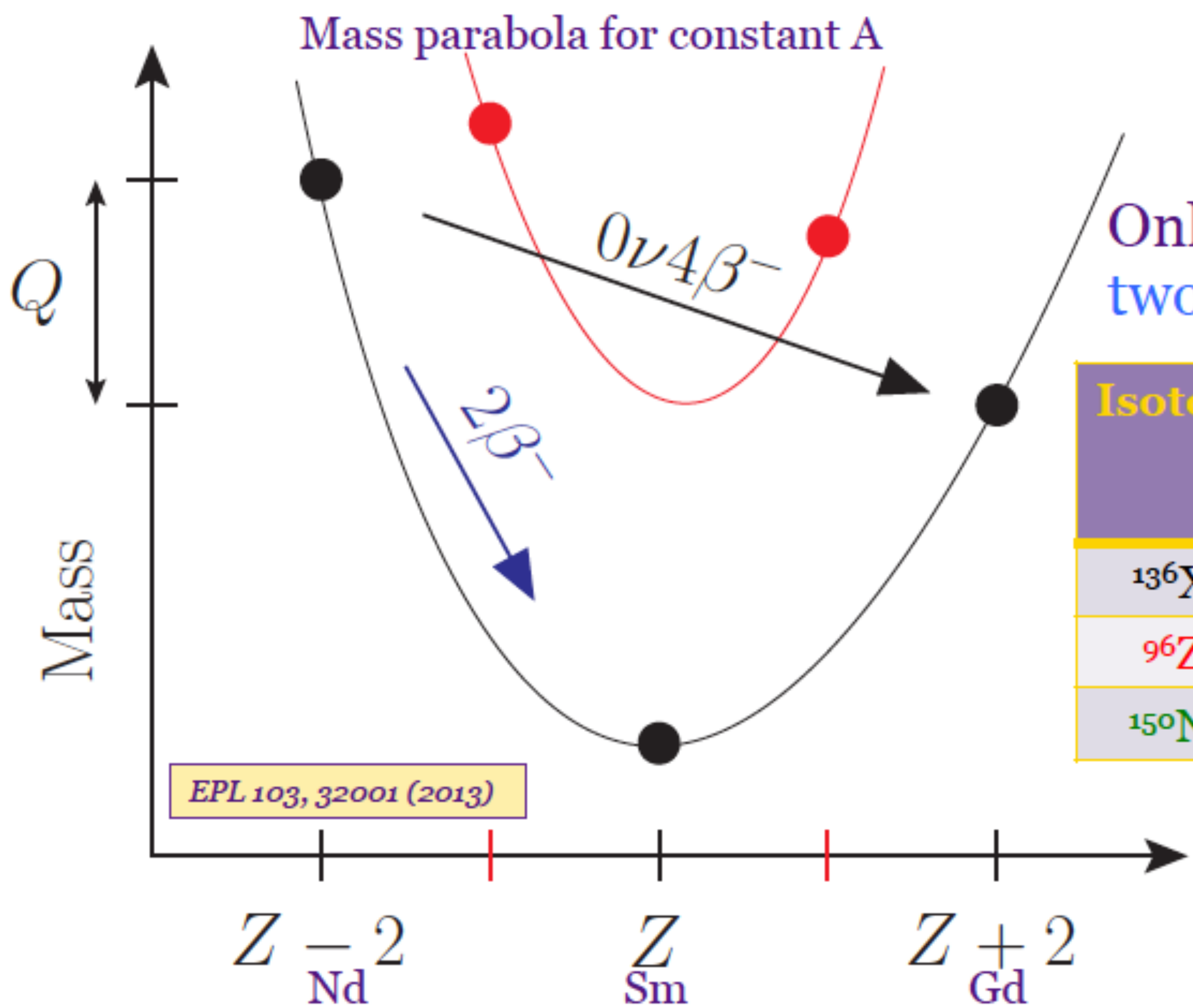







"Handbook" on backgrounds for ββ experiments:
Background measurement in NEMO3:
NIM A 606 (2009) pp. 449-465.

# Quadruple beta decay




Only three candidates, two used in NEMO-3

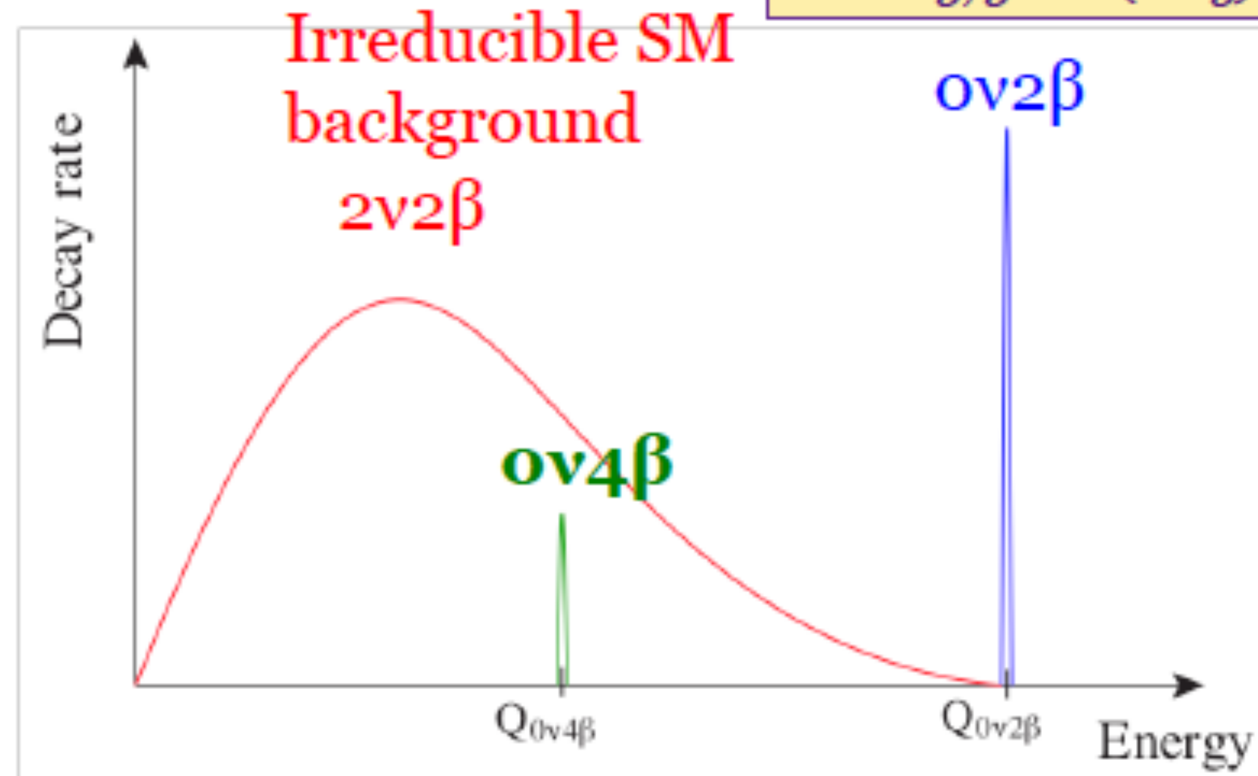
| Isotope | Q-value 4β (MeV) | Q-value 2β (MeV) |
|---|---|---|
| $^{136}Xe$ | 0.044 | 2.462 |
| $^{96}Zr$ | 0.629 | 3.348 |
| $^{150}Nd$ | 2.079 | 3.367 |

Focus of this analysis

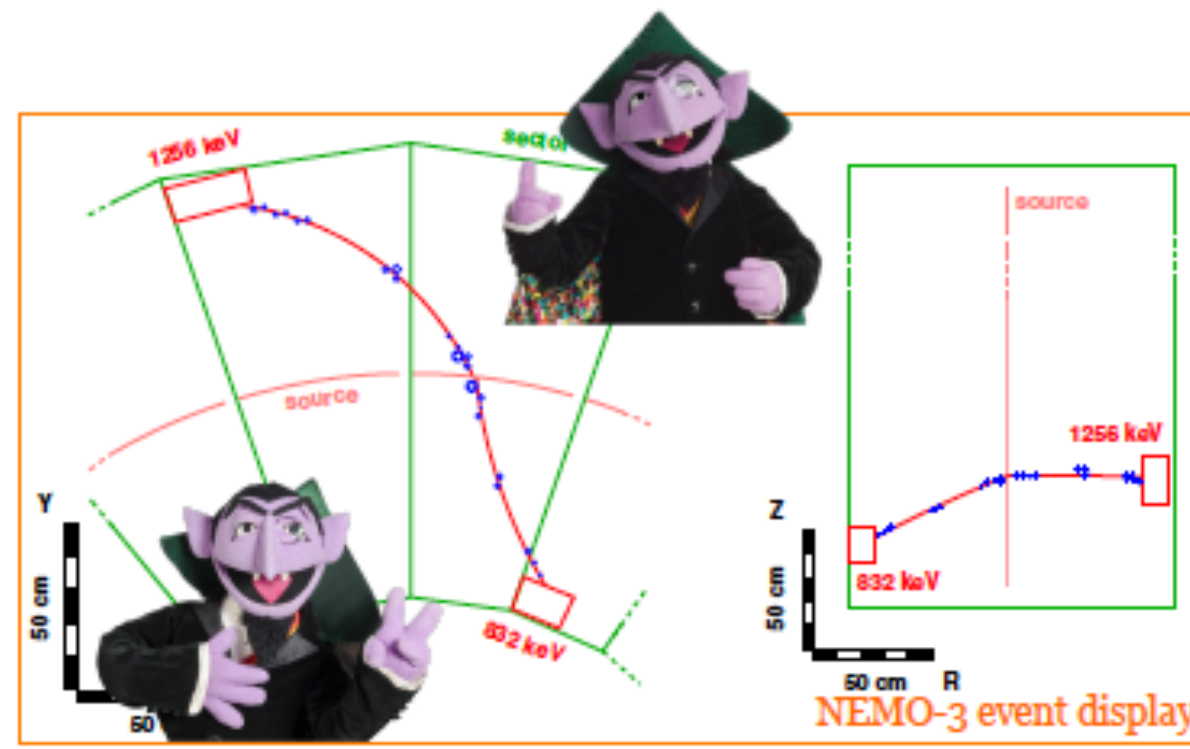
# Experimental signature

- 4 electrons in the decay
- No neutrinos – no invisible energy
- Q(4β) < Q(2β)
  - Peak lies in middle of 2ν background spectrum

*EPL 103, 32001 (2013)*

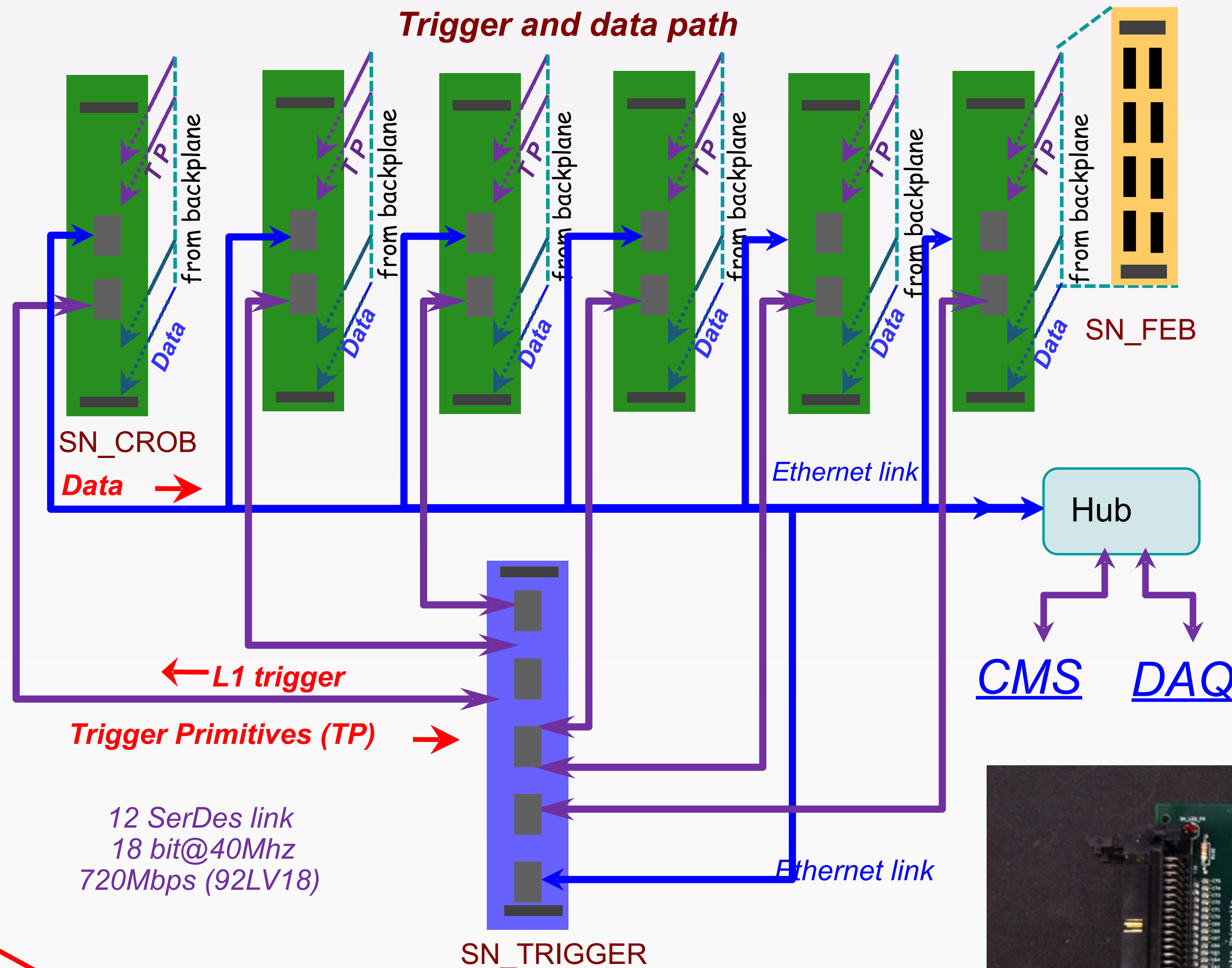


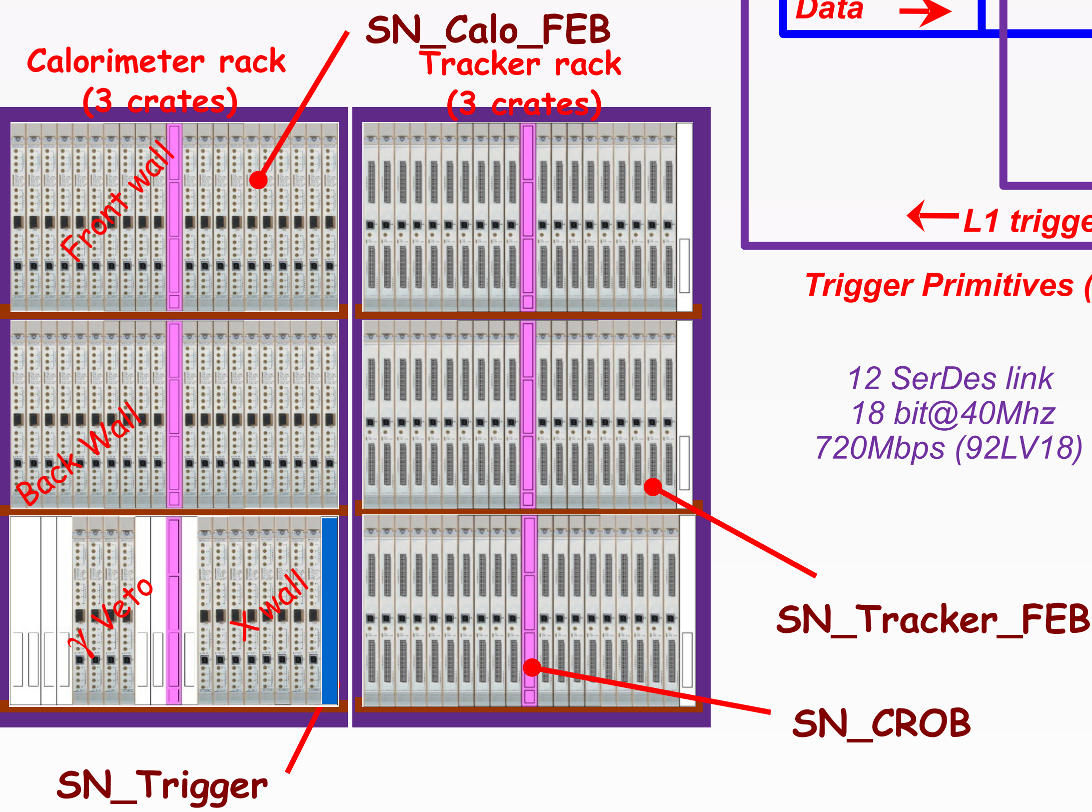

- You will need to count electrons and reject two-electron events
  - Only NEMO technique can do this

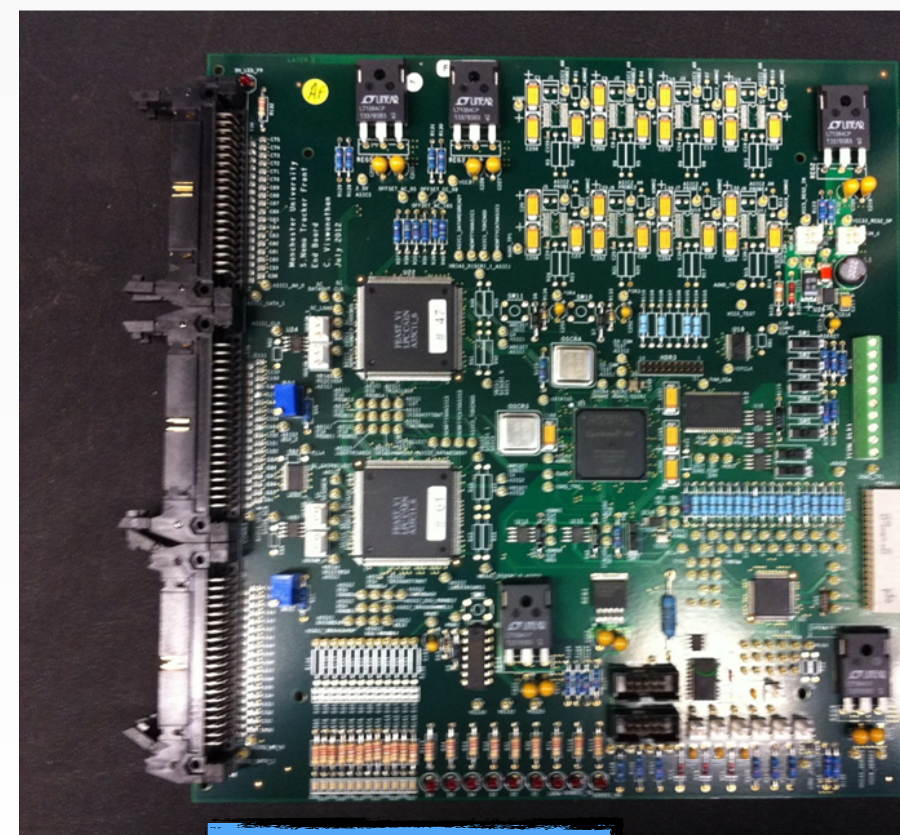


# Electronics, Slow Control and DAQ

- **Electronic architecture (demonstrator):**
  - **52 Calorimeter FEB (712 Channels).**
  - **57 Tracker FEB (6102 channels).**
  - **6 Control and Readout Board.**
  - **1 Trigger board.**



Tracker FEB

# New Underground Lab at Boulby

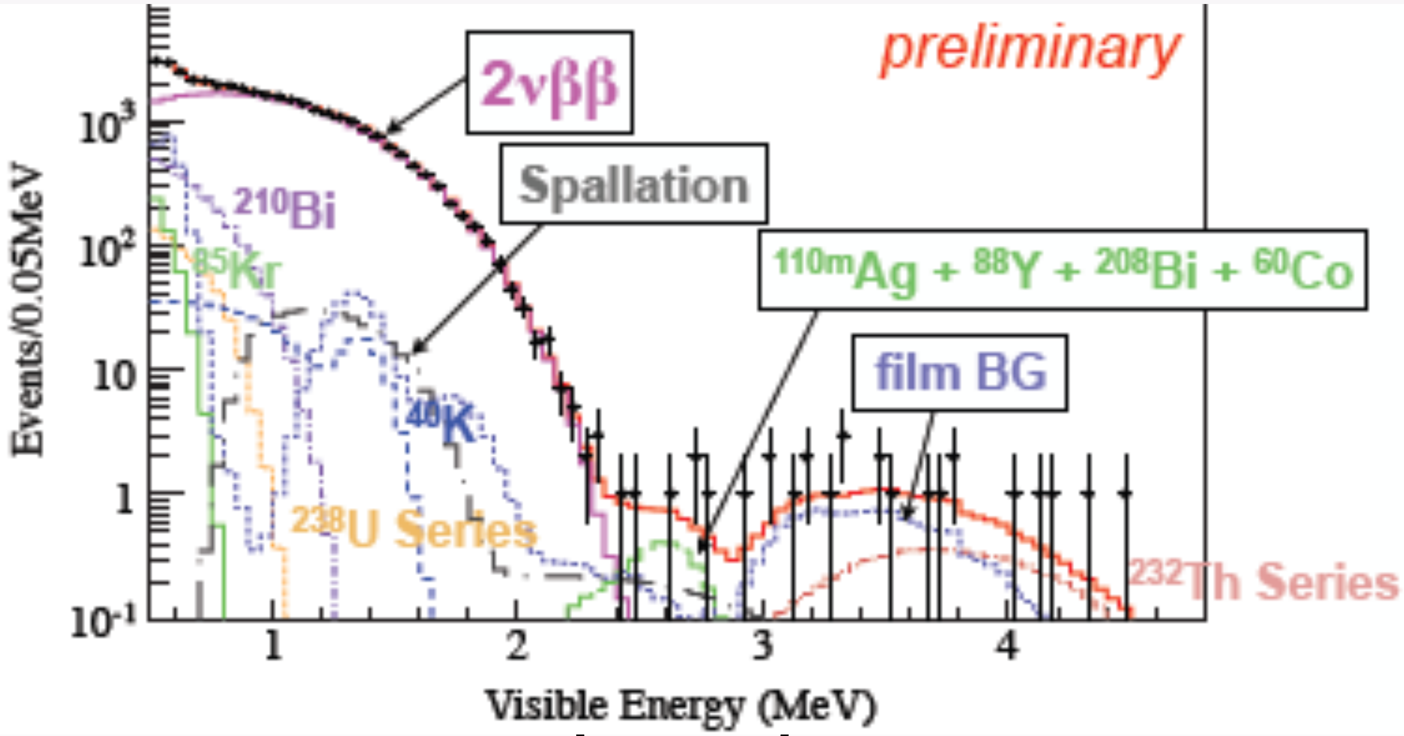
UCL

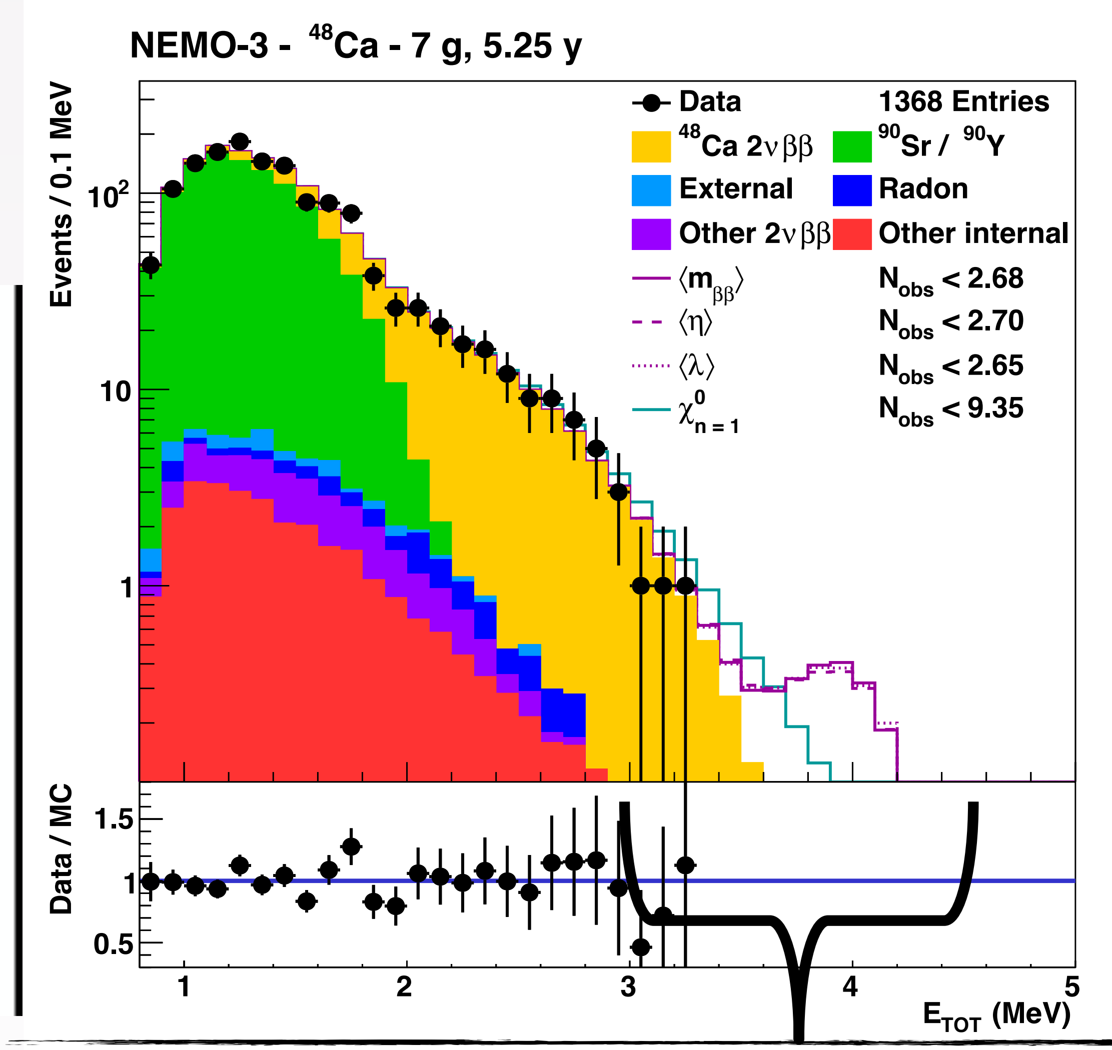

- Large Experimental Hall: 45m(L) x 7m(W) x 6.5m(H). Class < 10,000 cleanroom throughout.
- Low background screening laboratory: < 1,000 cleanroom
- 10T lifting capacity
- Transportation capacity: 2m x 2.1m x 2.1m in manshaft cage. Up to 8m long items with a week notice. Larger than in SNO and Homestake
- Uninterrupted Power Supply, 100-1000 Mbps internet
- Low natural Rn, 2.5 Bq/m$^3$
- **Essentially ready for beneficial occupancy**

# Scalability of topological technique

All ~tonne detectors will be background limited

KamLAND-Zen

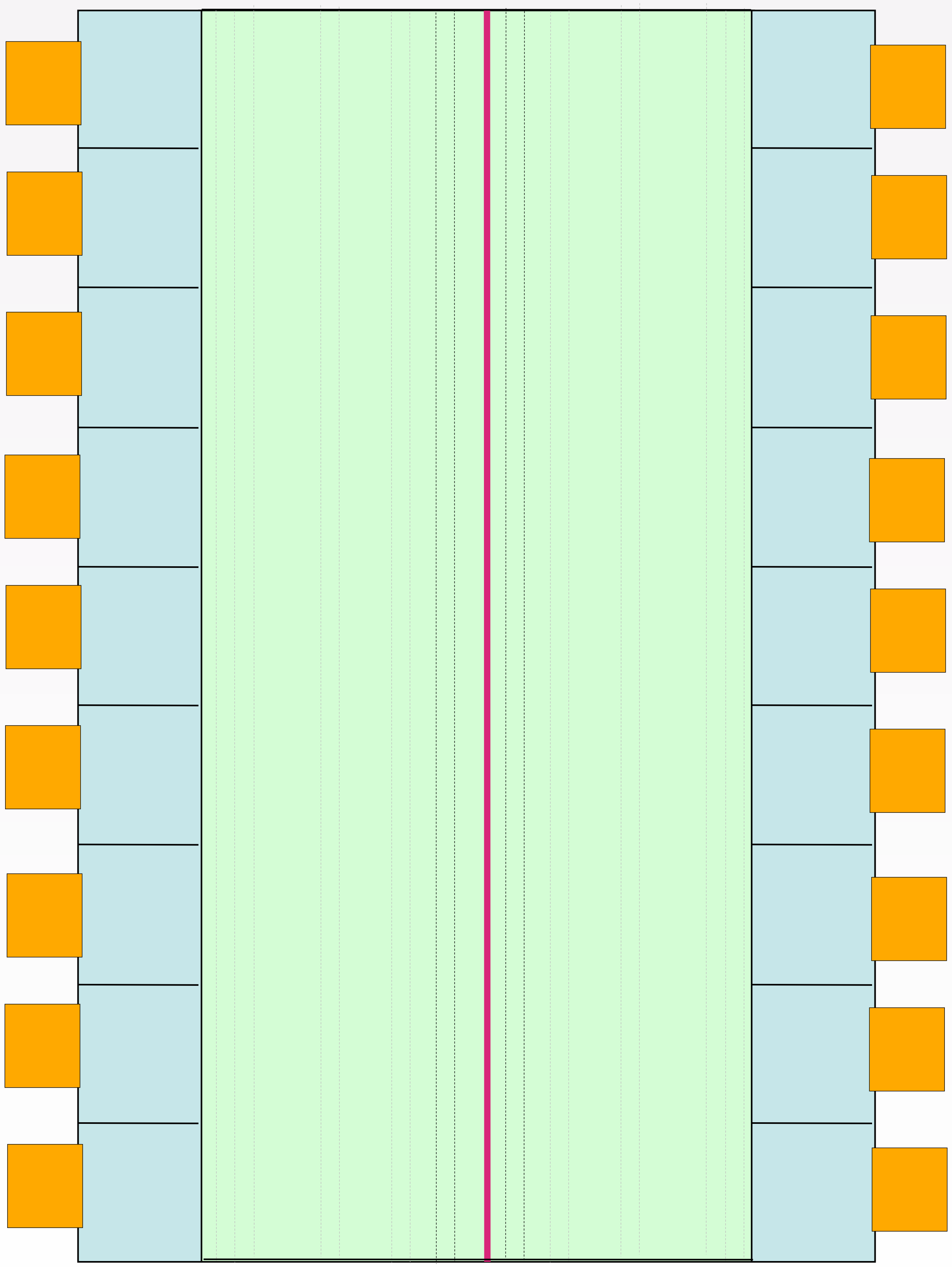



- Hard to model
- many unknown backgrounds
- systematic becomes dominant factor

- Can achieve 2νββ only background *in principle*.
- Can be constrained with minimum systematics (>$10^7$ events) !

# Background: The Enemy and how to fight it

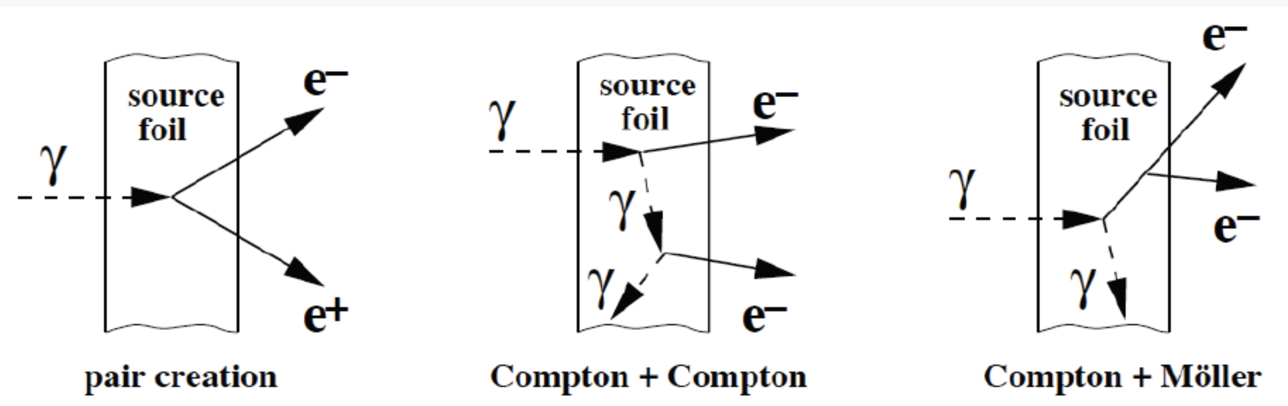


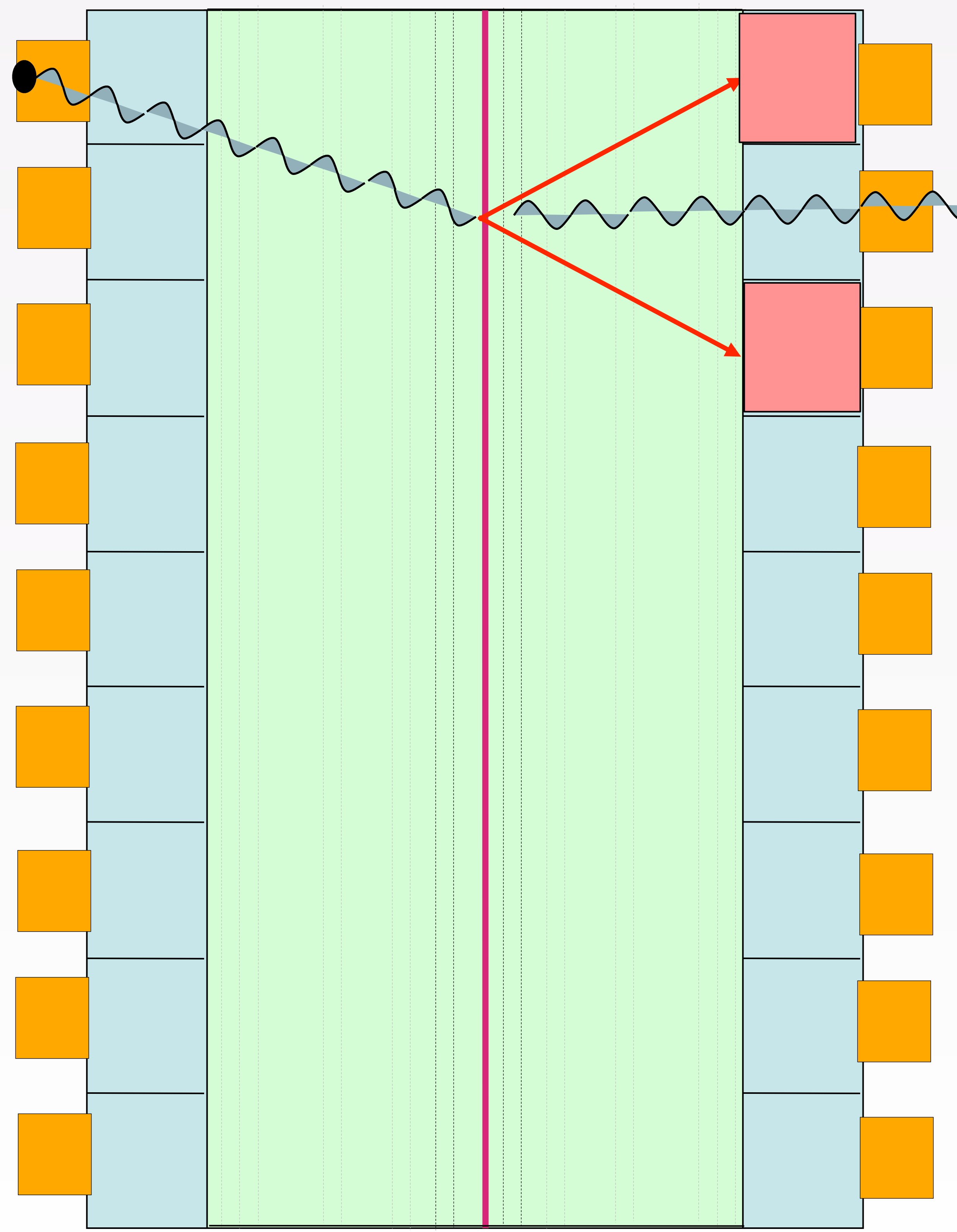
- **External** γ (if the γ is not detected in the scintillators)

  Origin: natural radioactivity of the detector or neutrons

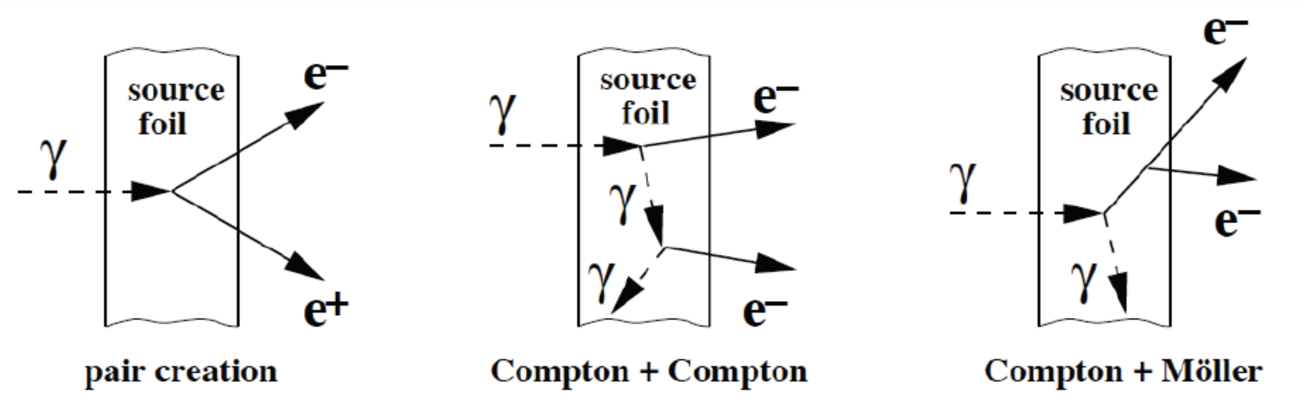
  Major bkg for 2νββ but small for 0νββ

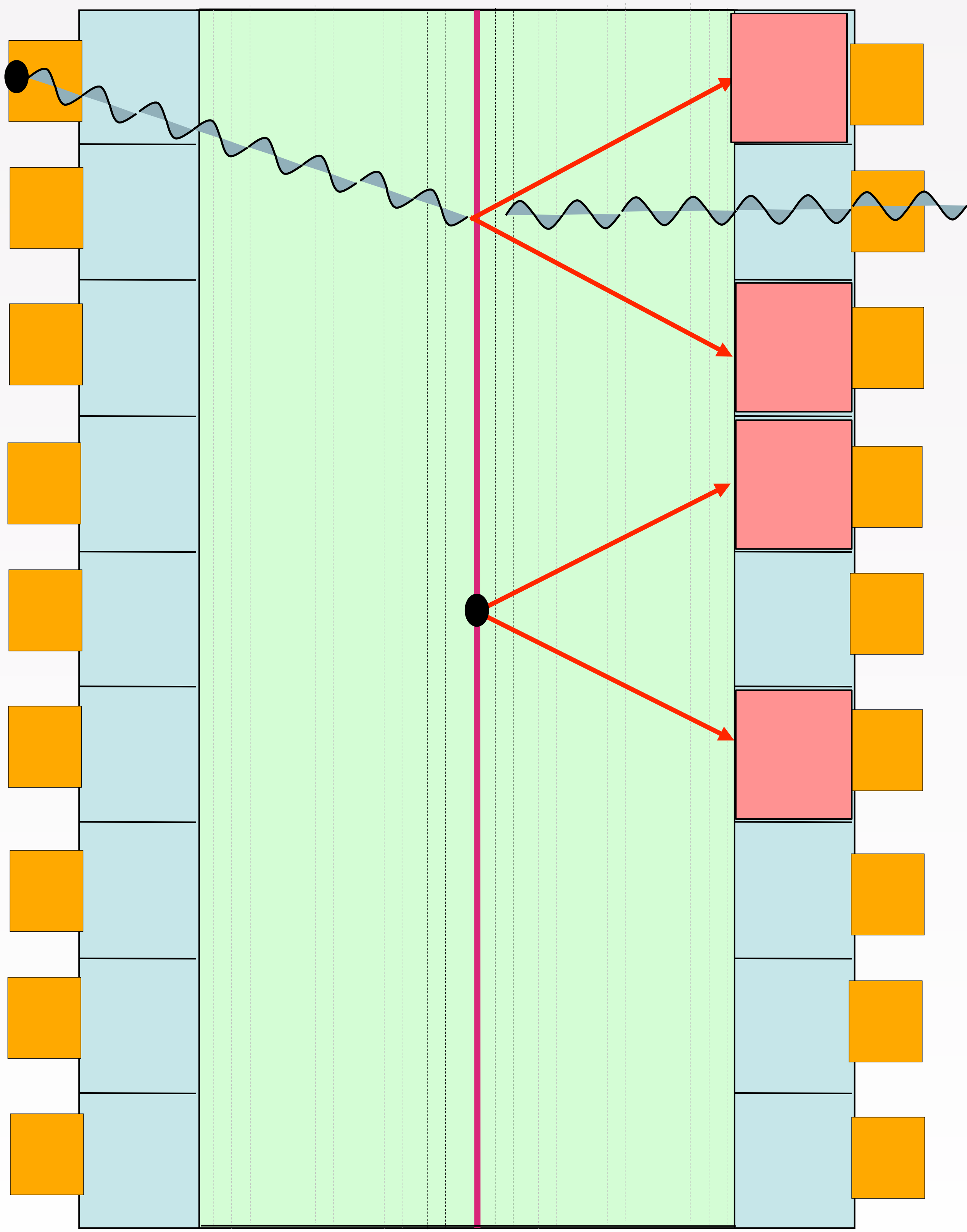
  ($^{100}$Mo and $^{82}$Se $Q_{\beta\beta}$~ 3 MeV > Eγ($^{208}$Tl) ~ 2.6 MeV )



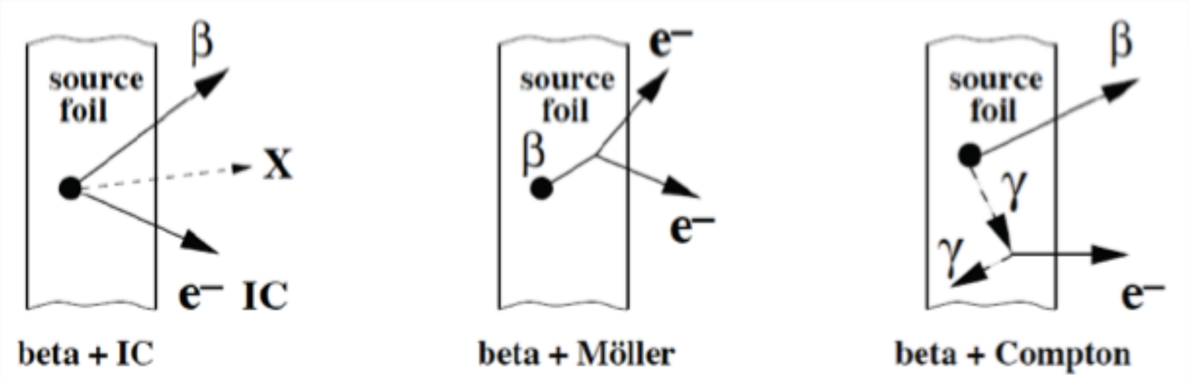



- **External** $\gamma$ (if the $\gamma$ is not detected in the scintillators)
  Origin: natural radioactivity of the detector or neutrons
  Major bkg for $2\nu\beta\beta$ but small for $0\nu\beta\beta$
  ($^{100}$Mo and $^{82}$Se $Q_{\beta\beta} \sim 3$ MeV > $E\gamma(^{208}$Tl) ~ 2.6 MeV )



- **$^{232}$Th ($^{208}$Tl) and $^{238}$U ($^{214}$Bi) contamination inside the $\beta\beta$ source foil**

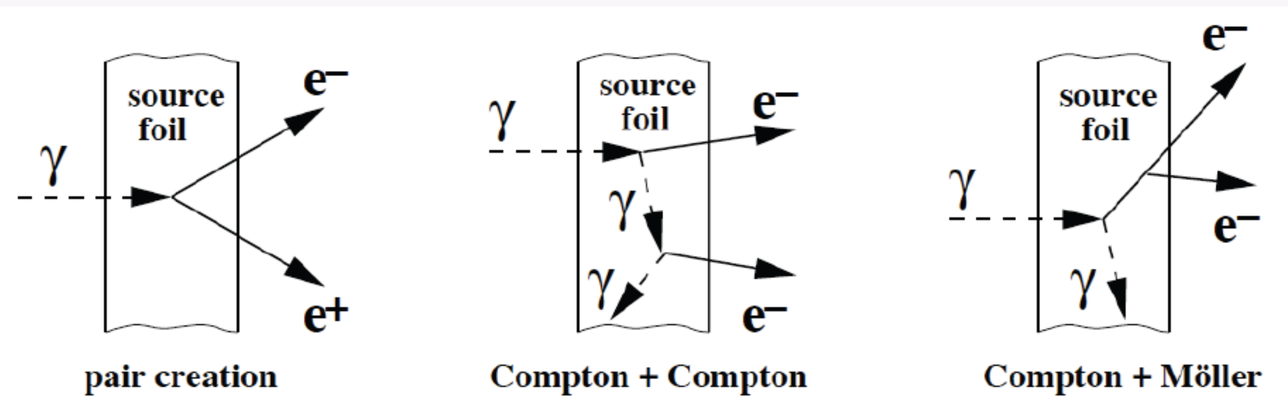


- **External γ** (if the γ is not detected in the scintillators)

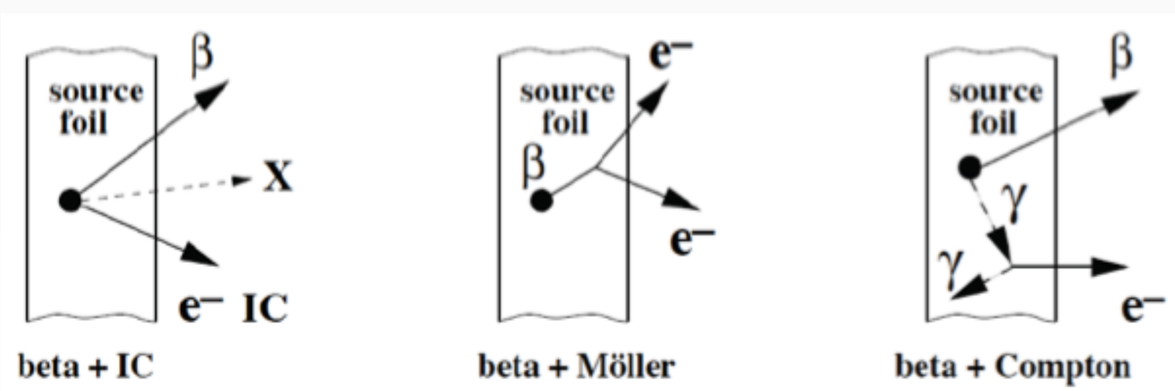
  Origin: natural radioactivity of the detector or neutrons

  Major bkg for $2\nu\beta\beta$ but small for $0\nu\beta\beta$

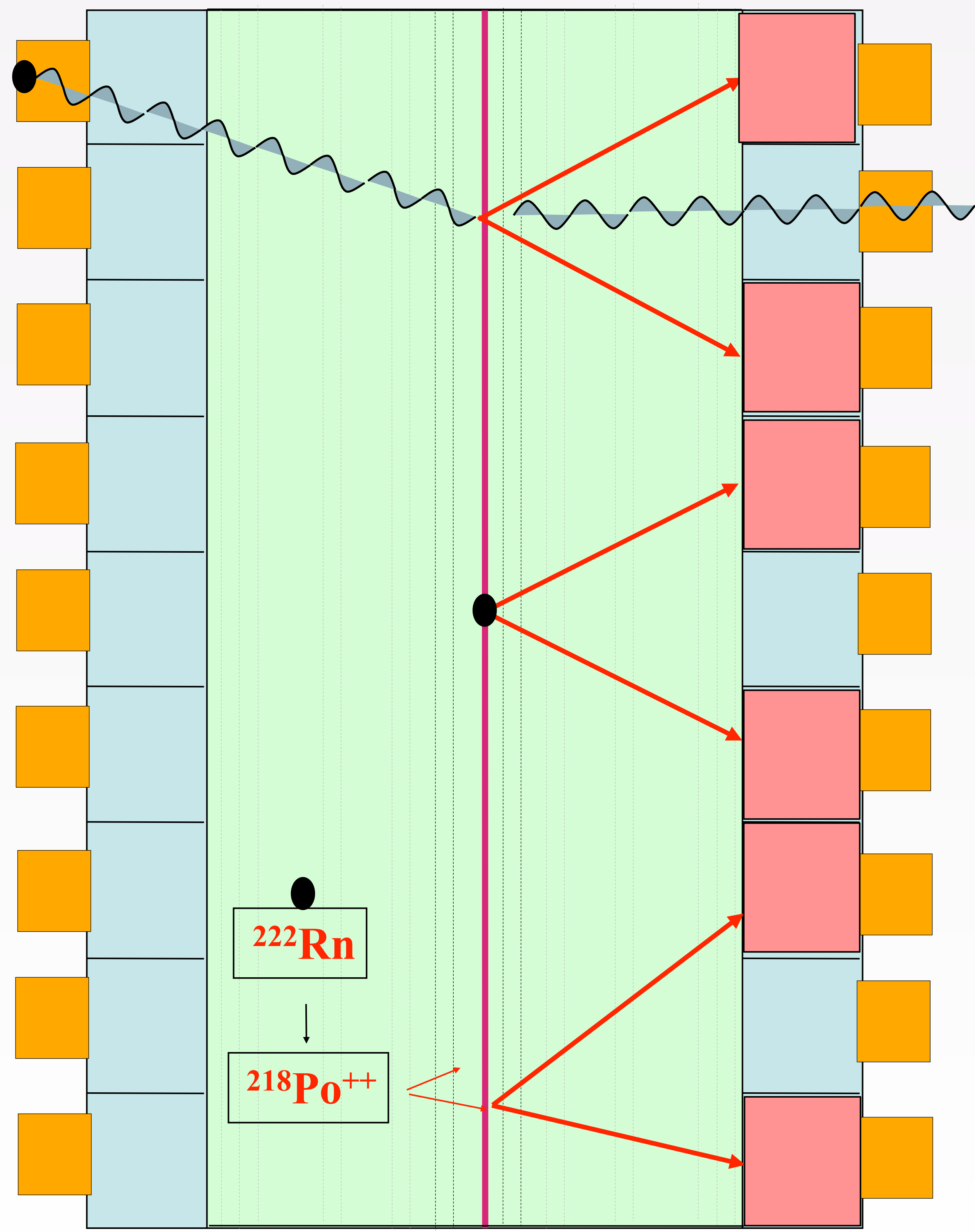
  ($^{100}$Mo and $^{82}$Se $Q_{\beta\beta} \sim 3$ MeV > $E\gamma(^{208}Tl) \sim 2.6$ MeV )




- **$^{232}$Th ($^{208}$Tl) and $^{238}$U ($^{214}$Bi) contamination inside the ββ source foil**




- **Radon ($^{214}$Bi) inside the tracking detector**
  - deposits on the wire near the ββ foil
  - deposits on the surface of the ββ foil



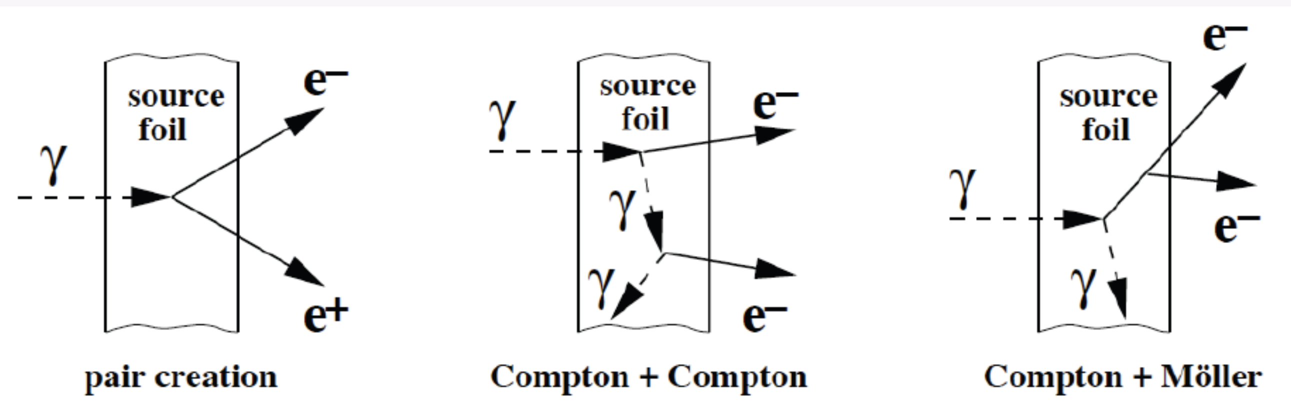
# Background: The Enemy and how to fight it

- **External** γ (if the γ is not detected in the scintillators)

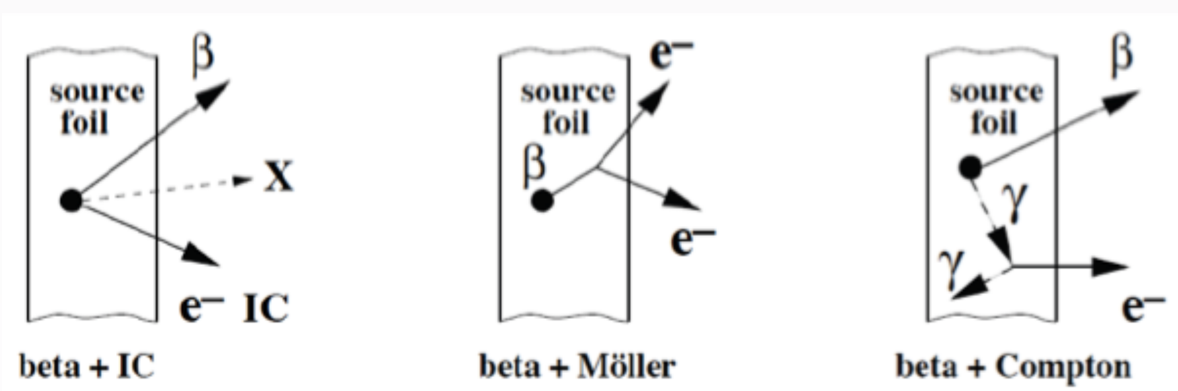
  Origin: natural radioactivity of the detector or neutrons

  Major bkg for 2νββ but small for 0νββ

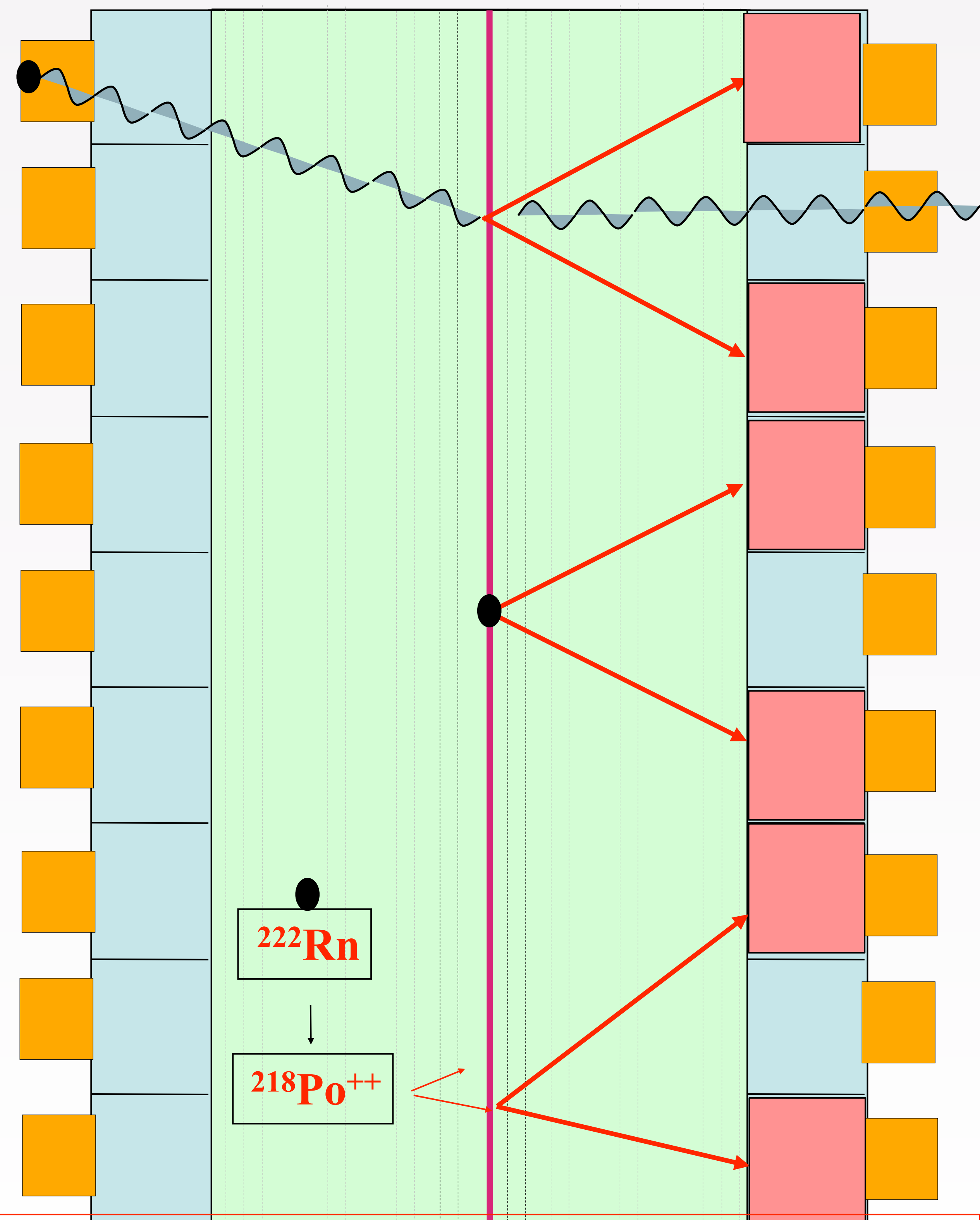
  ($^{100}$Mo and $^{82}$Se $Q_{\beta\beta}$~ 3 MeV > Eγ($^{208}$Tl) ~ 2.6 MeV )




- **$^{232}$Th ($^{208}$Tl) and $^{238}$U ($^{214}$Bi) contamination inside the ββ source foil**



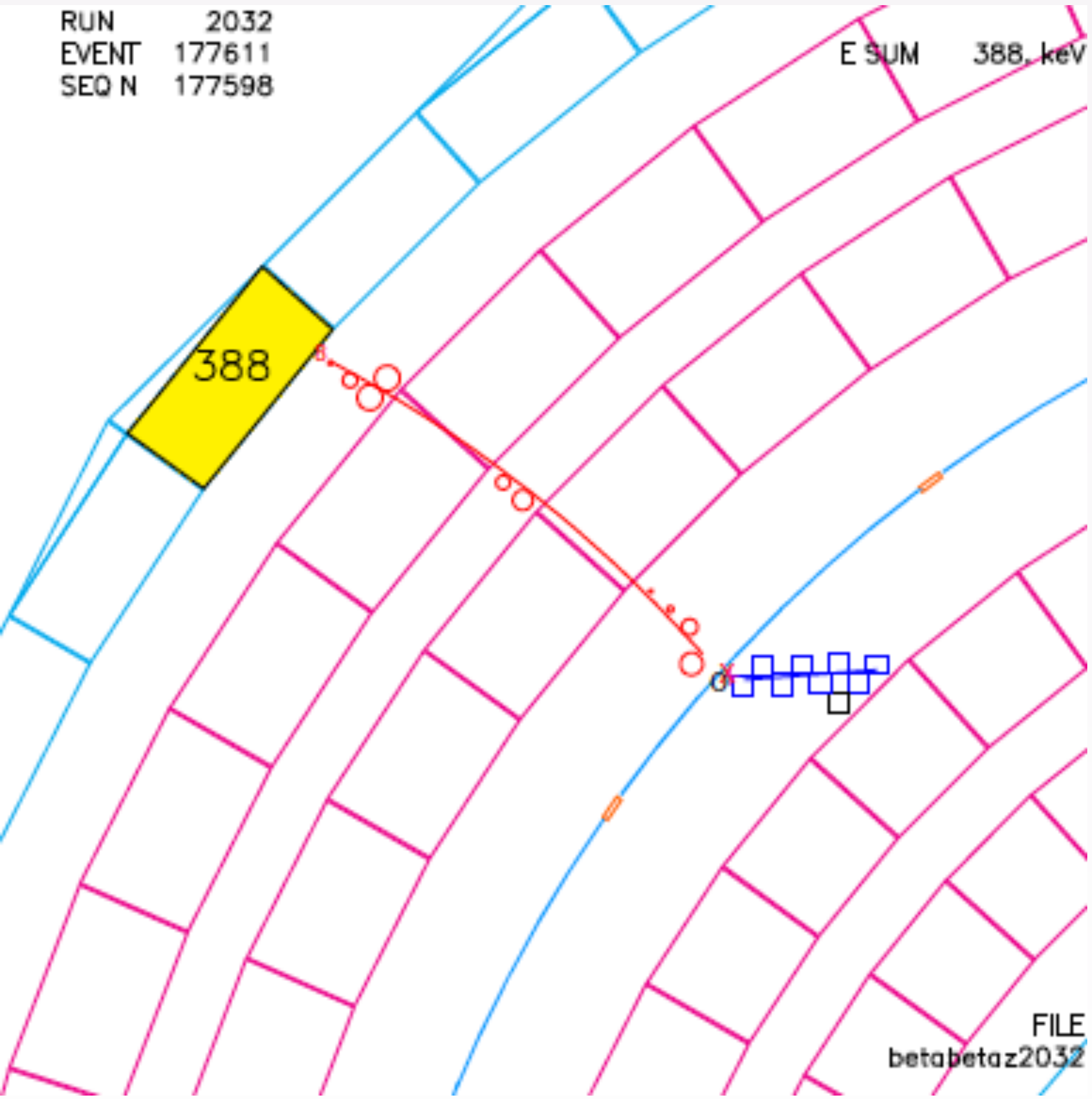

- **Radon ($^{214}$Bi) inside the tracking detector**
  - deposits on the wire near the ββ foil
  - deposits on the surface of the ββ foil



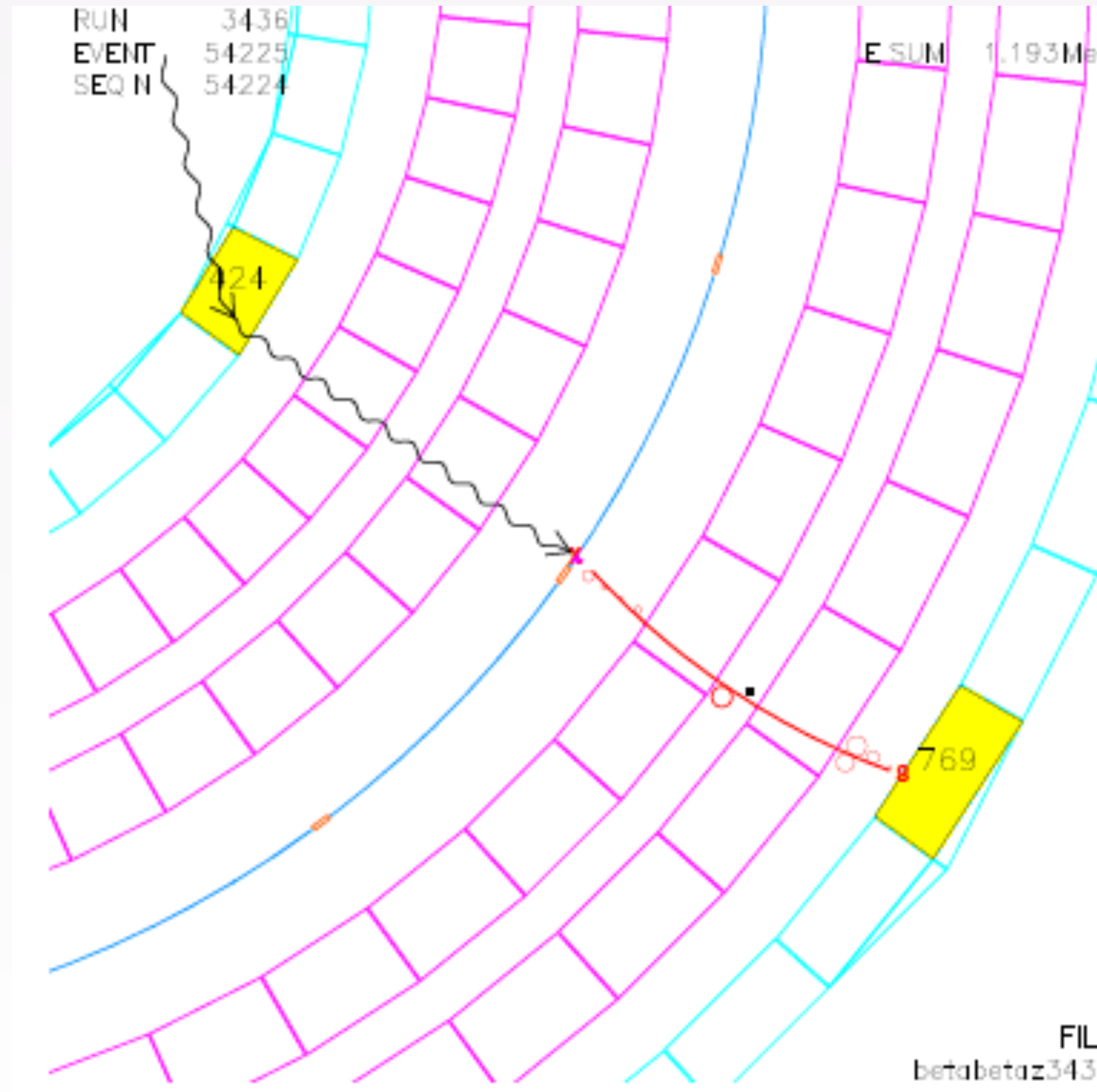

**Each bkg is measured using the NEMO-3 data**

# NEMO-3 Event Display

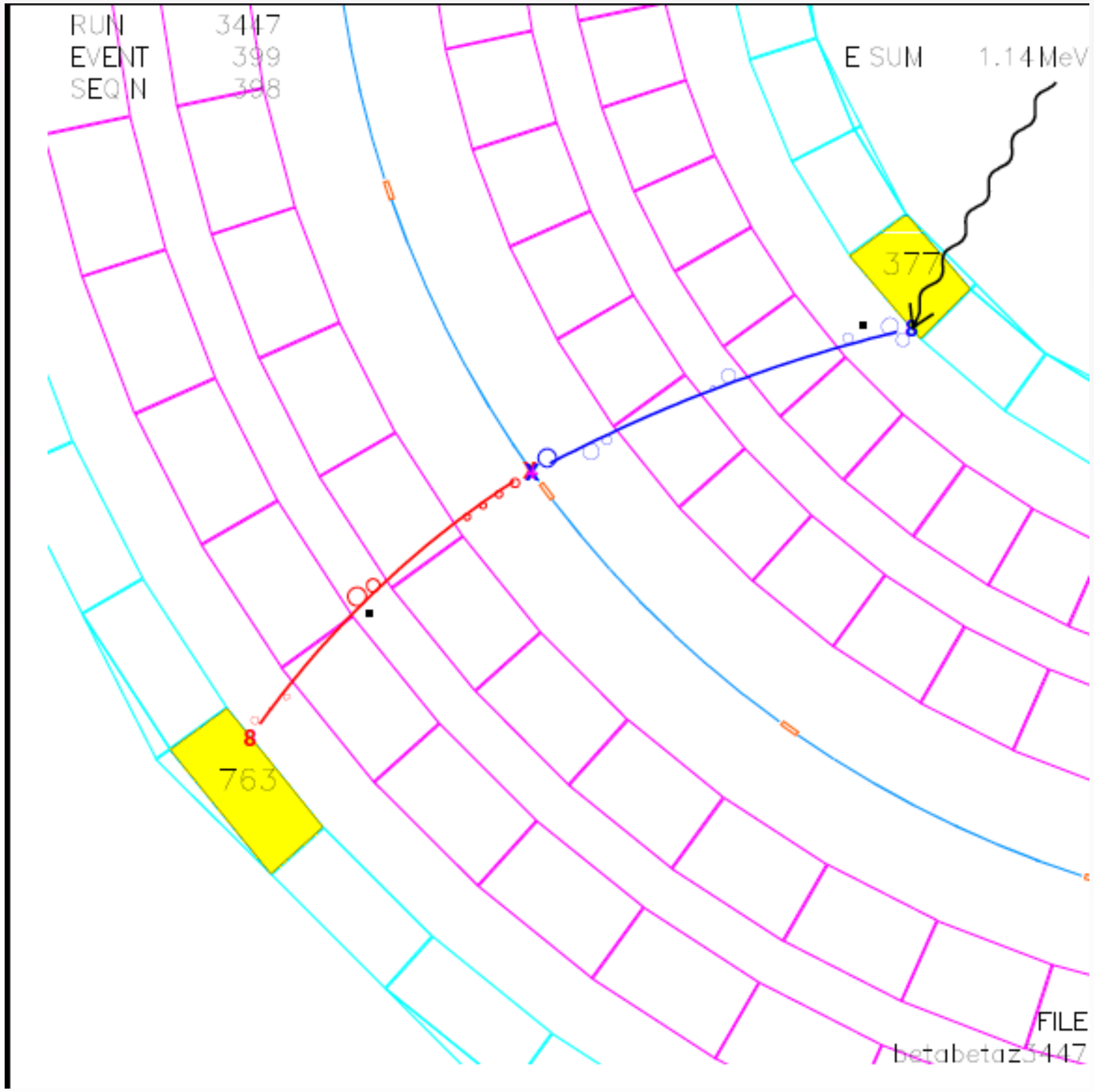
**1e1α ($^{214}Bi \rightarrow ^{214}Po$)**

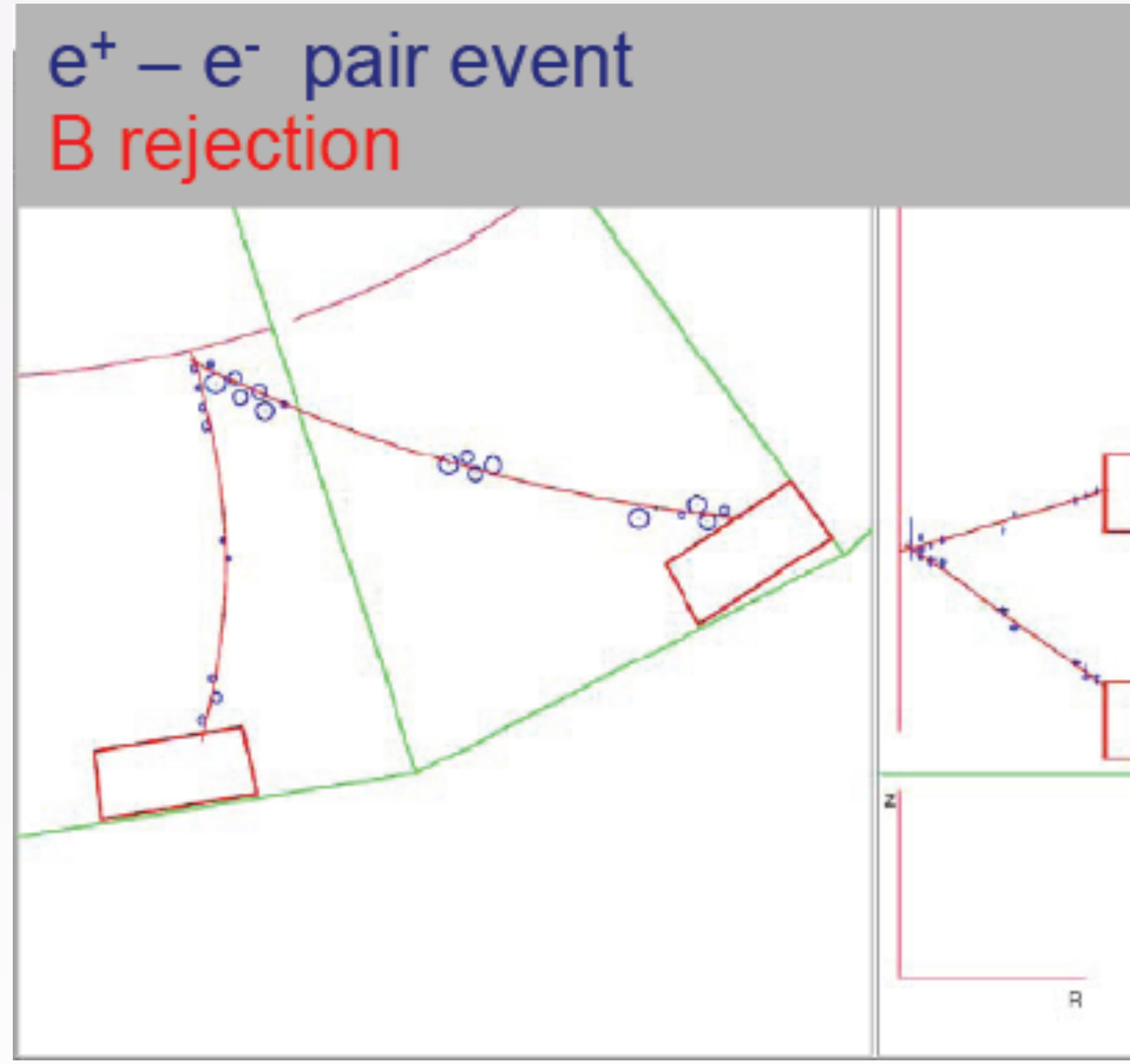


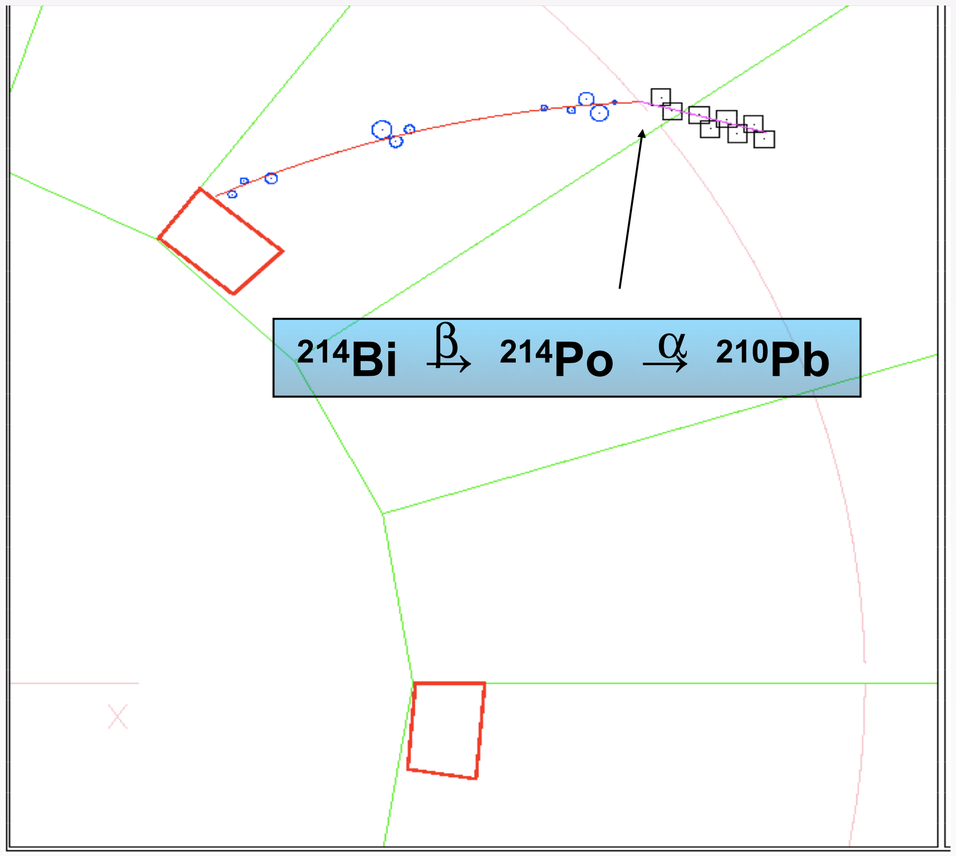

**External γ**



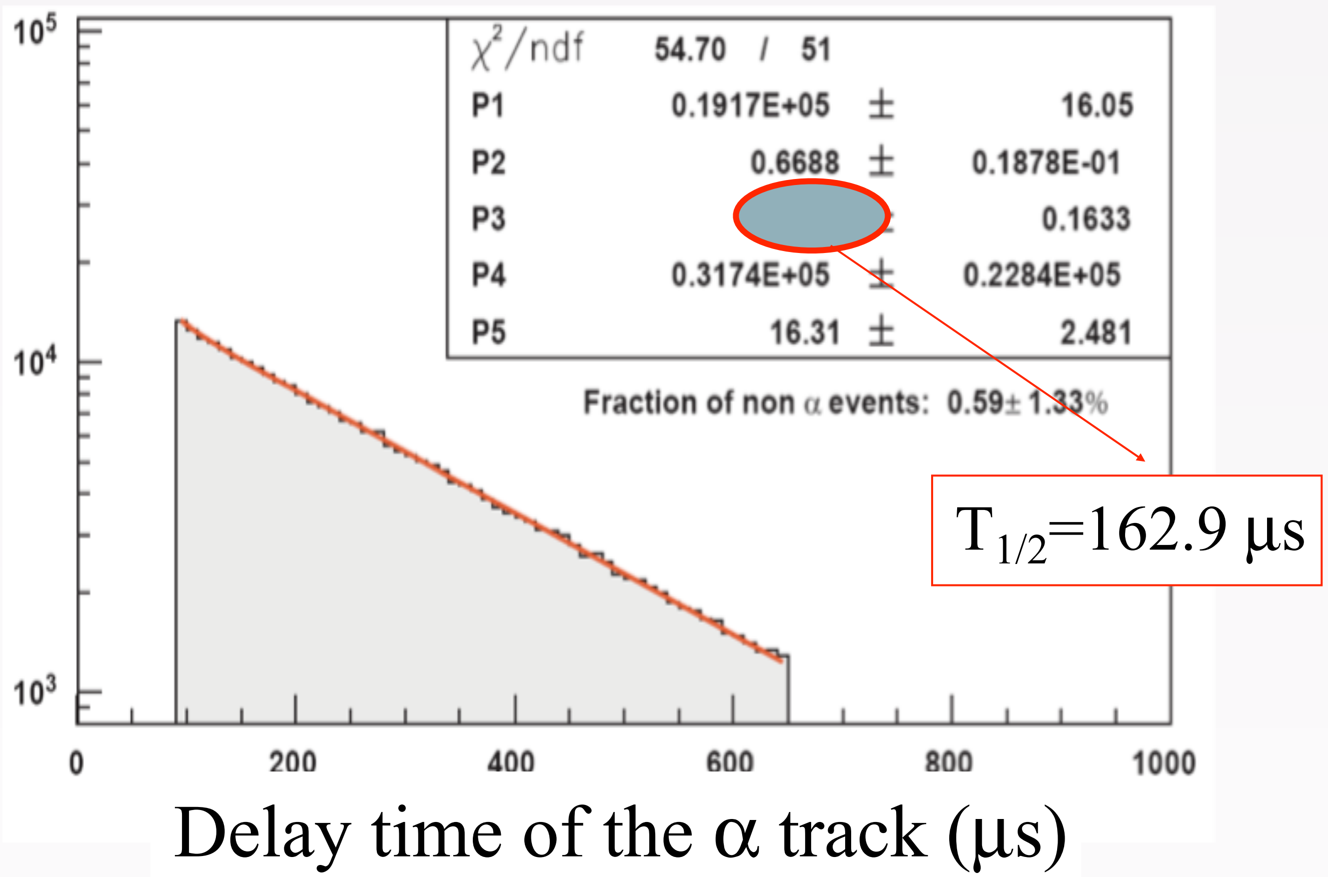
## Crossing electron (external BG)



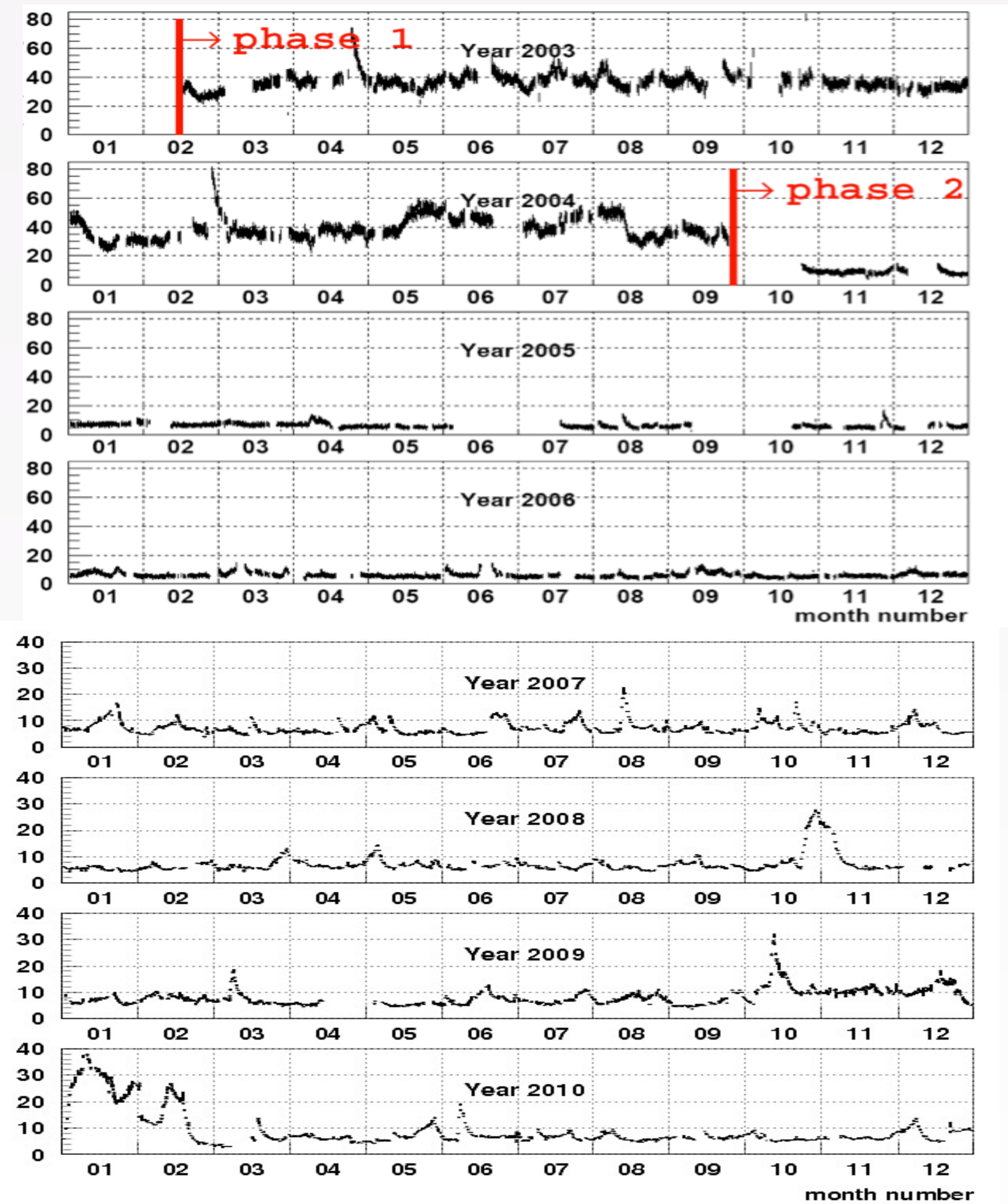



Pure sample of $^{214}$Bi – $^{214}$Po events

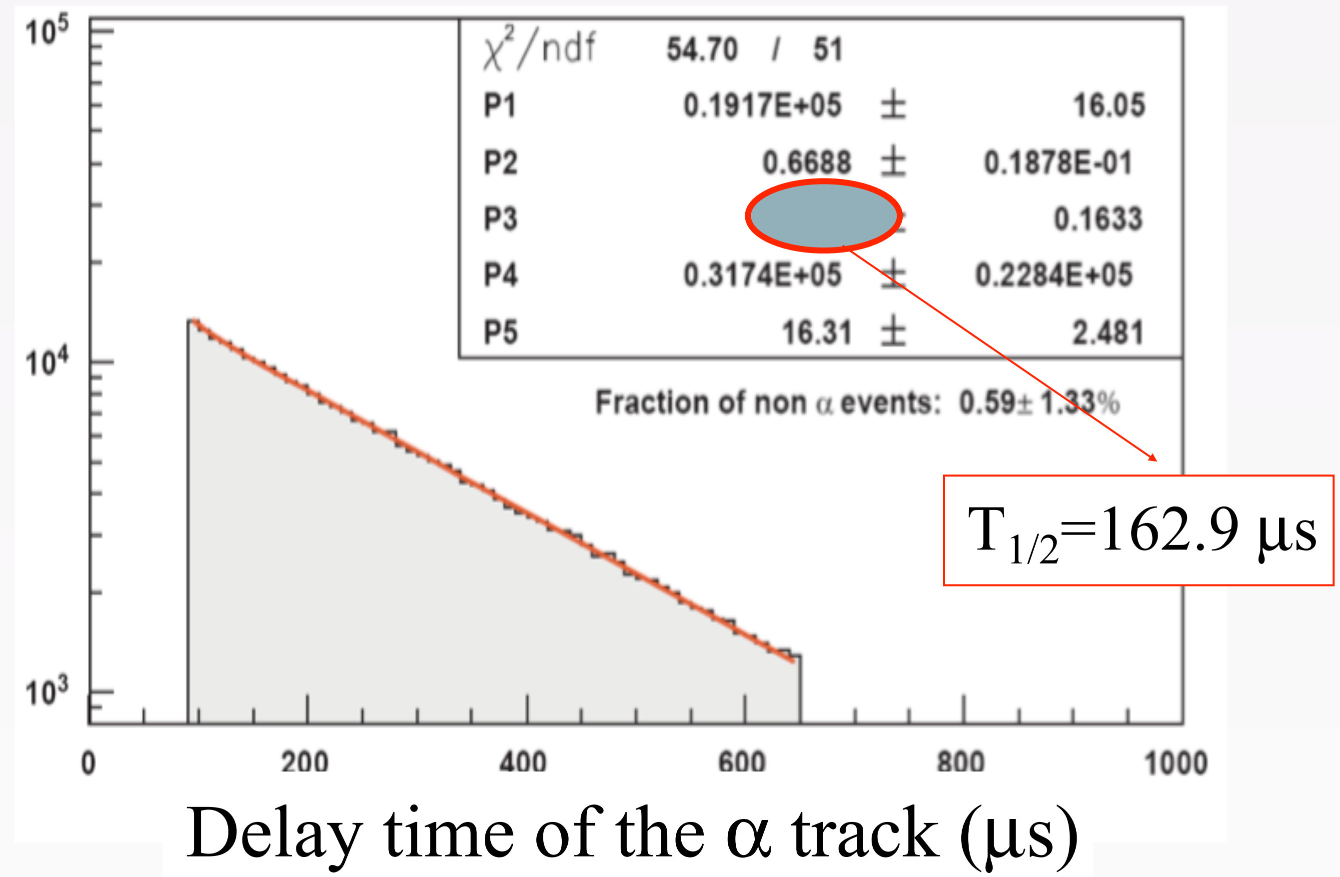


**Anti-radon "factory" - trapping Rn in cooled charcoal. A must for a low-background lab.**

Measurements of $^{222}Rn$ activity in the gas of tracker (mBq/m$^3$)




Pure sample of $^{214}Bi - ^{214}Po$ events




Anti-Rn factory: Input=15Bq/m$^3$ →Output 15mBq/m$^3$

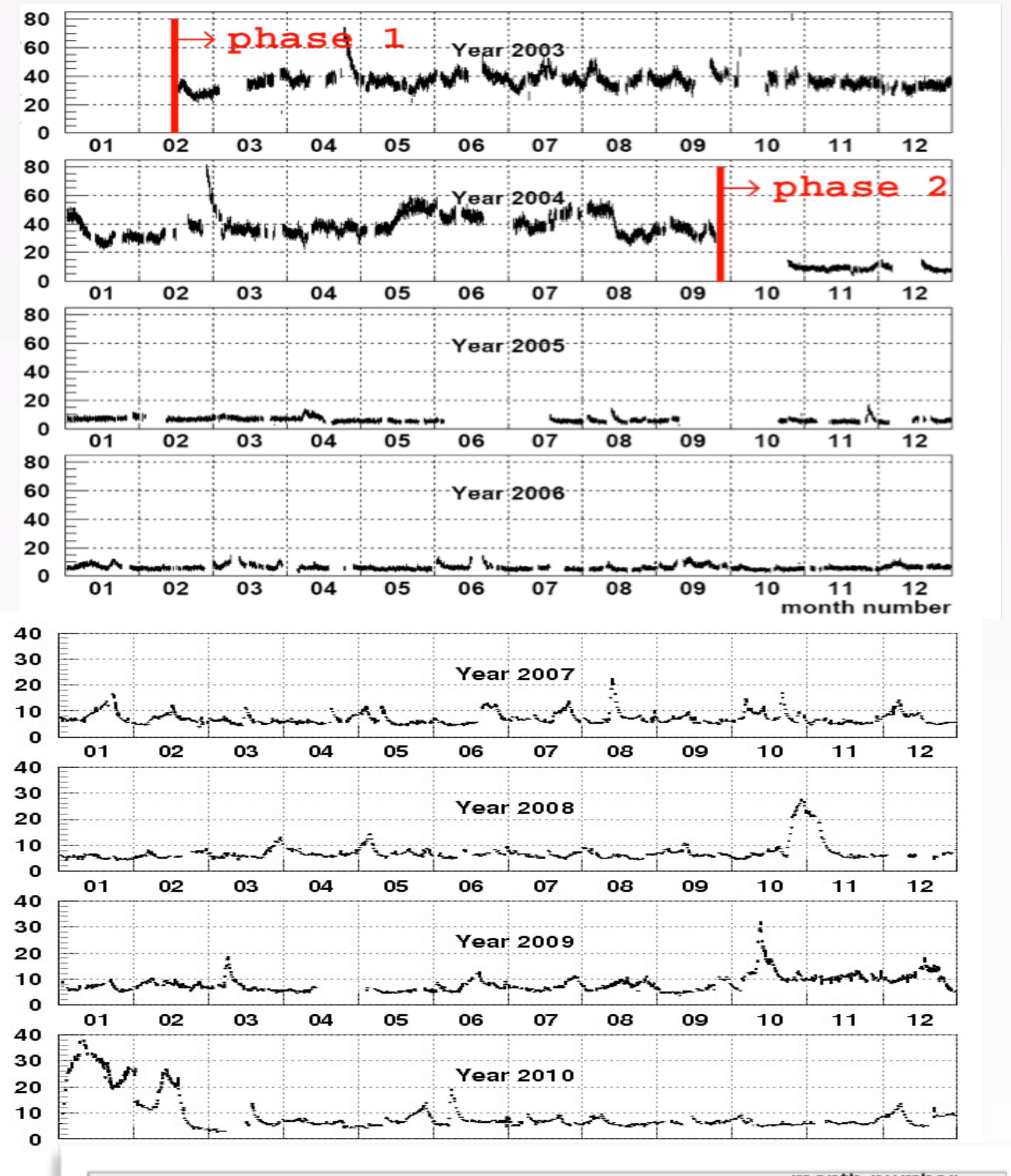
Inside the detector:

- Phase 1: Feb'03 → Sep'04
  A(Radon) ≈ 40 mBq/m$^3$
- Phase 2: Dec. 2004 → Jan'11
  **A (Radon) ≈ 5 mBq/m$^3$**

# Radon

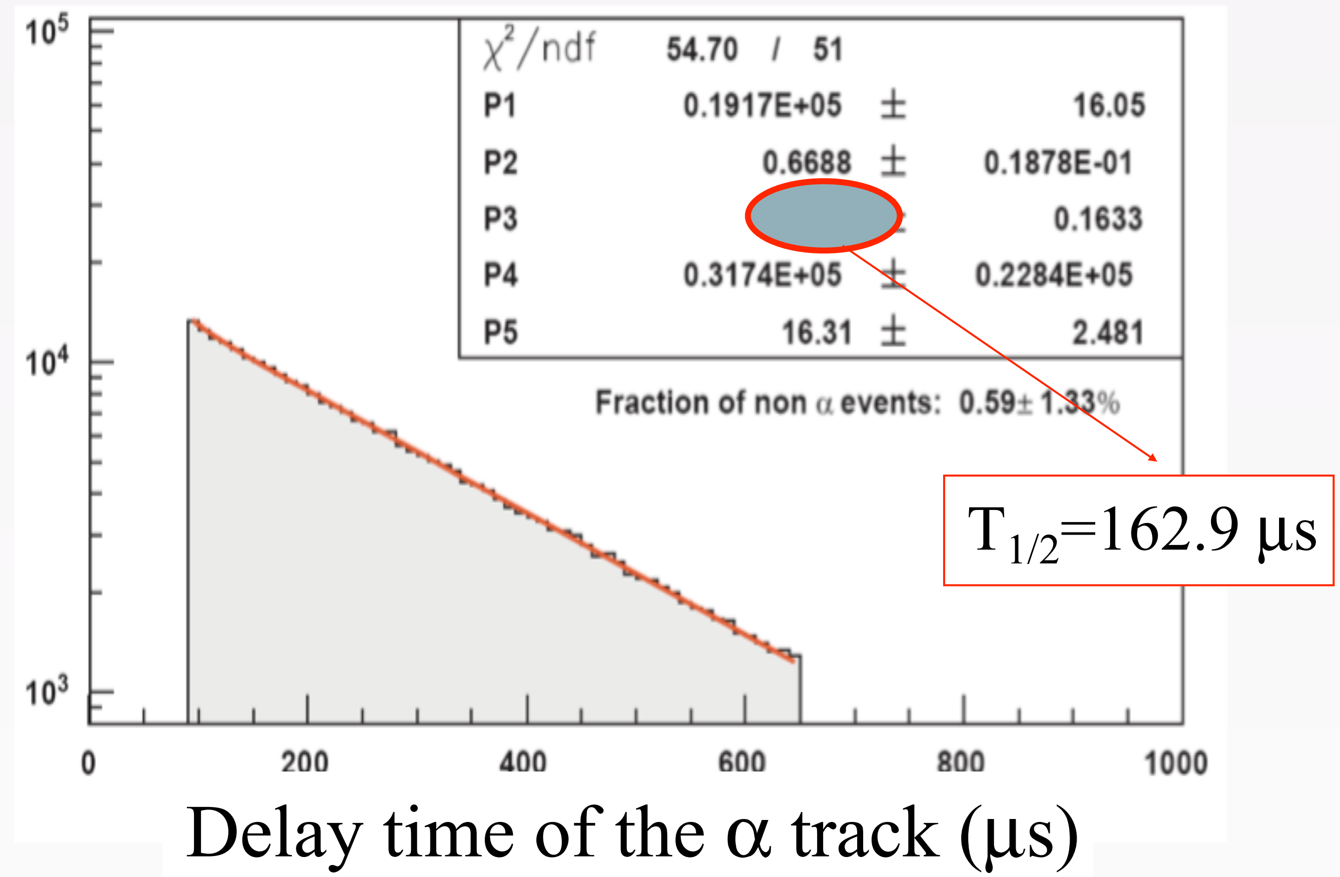
**Anti-radon "factory" - trapping Rn in cooled charcoal. A must for a low-background lab.**

Measurements of $^{222}Rn$ activity in the gas of tracker ($mBq/m^3$)




"Handbook" on backgrounds for ββ experiments:
Background measurement in NEMO3:
**NIM A 606 (2009) pp. 449-465.**

## Pure sample of $^{214}Bi - ^{214}Po$ events

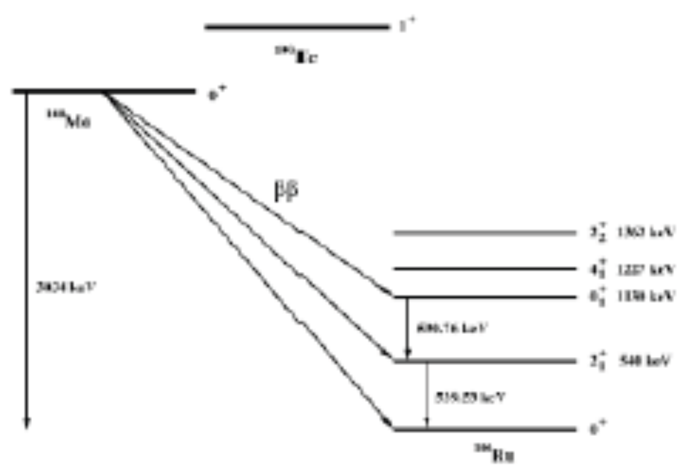



Anti-Rn factory: Input=15Bq/m$^3$ →Output 15mBq/m$^3$

Inside the detector:

- Phase 1: Feb'03 → Sep'04
  A(Radon) ≈ 40 mBq/m$^3$
- Phase 2: Dec. 2004 → Jan'11
  **A (Radon) ≈ 5 mBq/m$^3$**

# NEMO3 : 100Mo decay to excited states



$2\nu2\beta$ to excited states of $^{100}$Mo:

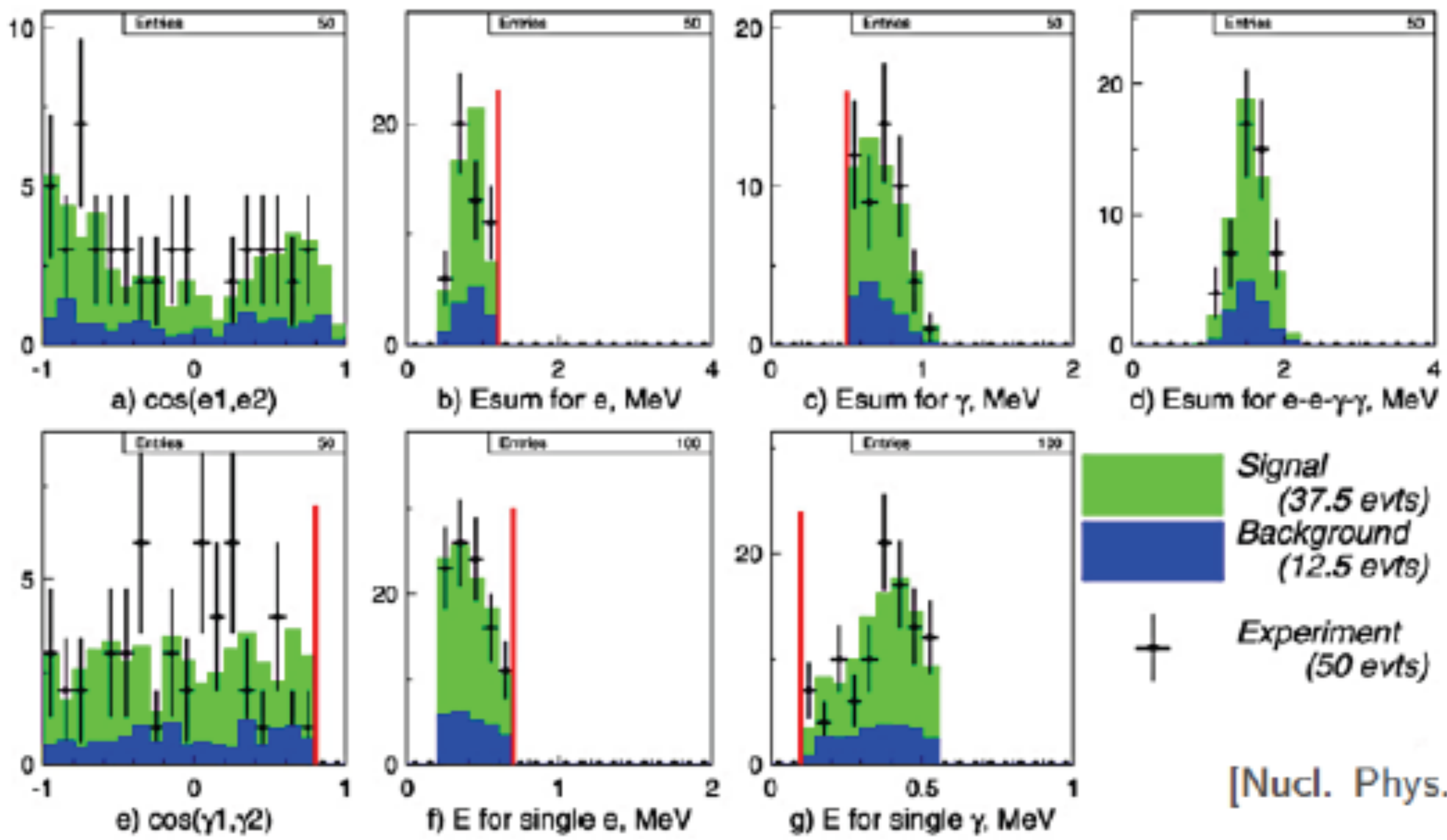
$\mathcal{T}^{2\nu}_{1/2}(0^+ \rightarrow 0^+_1) = 5.7\ ^{+1.3}_{-0.9}$ (stat) $\pm$ 0.8 (stat) $10^{20}$ y

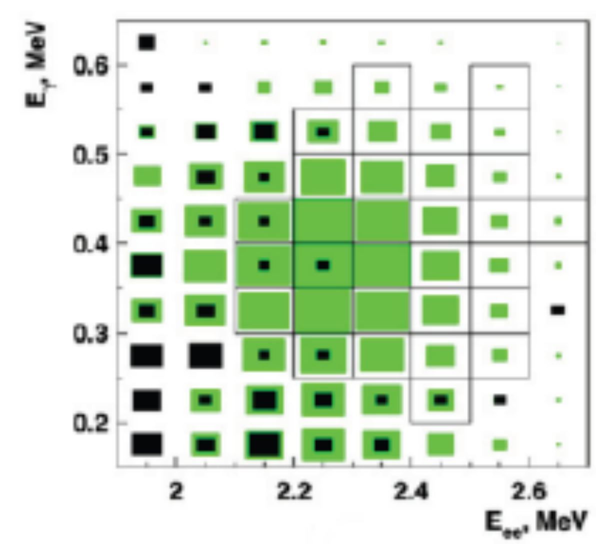
$\mathcal{T}^{2\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.1\ 10^{21}$ y @ 90 % CL

$0\nu2\beta$ to excited states of $^{100}$Mo:

$\mathcal{T}^{0\nu}_{1/2}(0^+ \rightarrow 0^+_1) > 8.9\ 10^{22}$ y @ 90 % CL

$\mathcal{T}^{0\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.6\ 10^{23}$ y @ 90 % CL

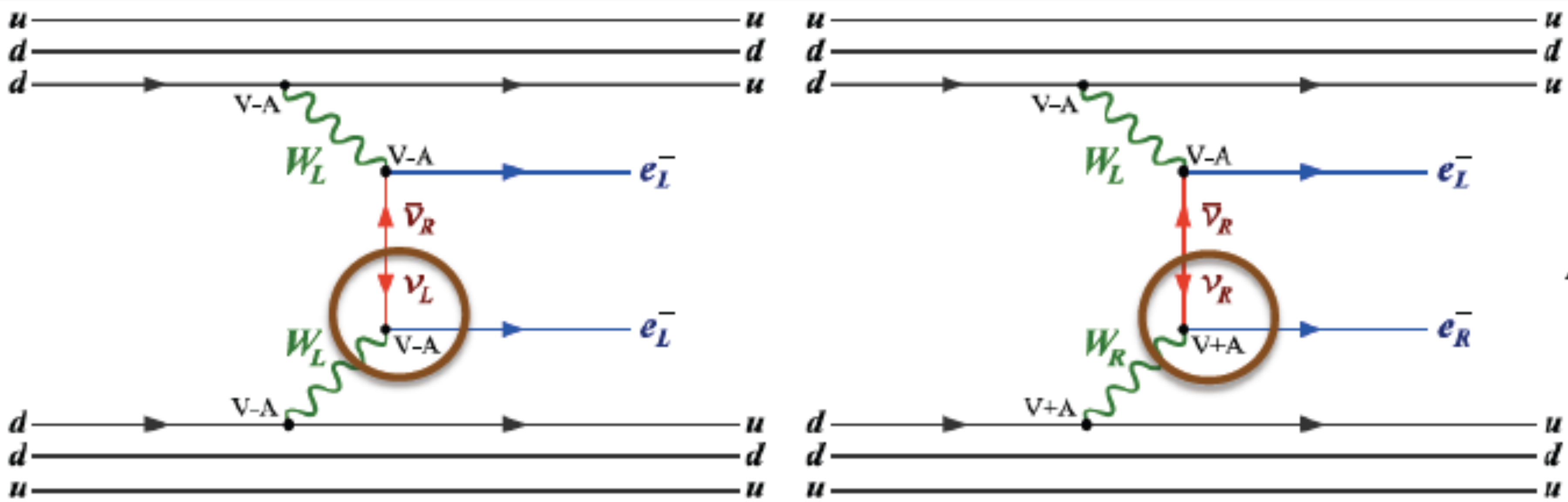


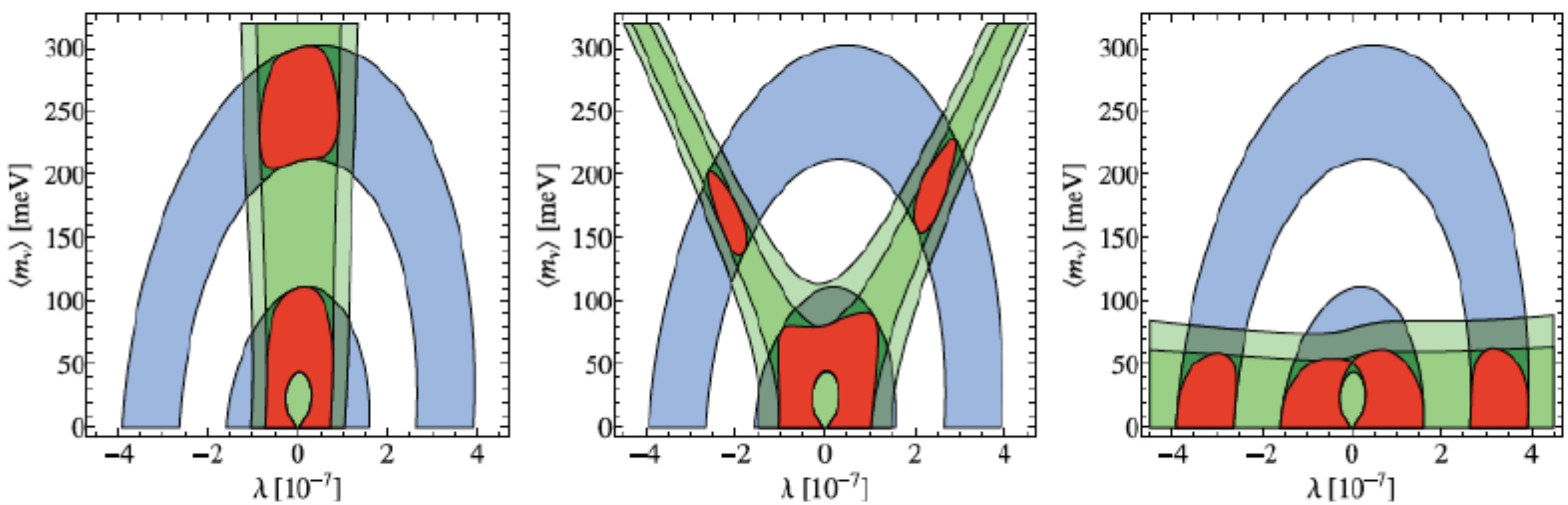

[Nucl. Phys. A 781 (2007) 209-226]

- Other results coming soon on $^{150}$Nd and $^{96}$Zr

*"Probing new physics models of neutrinoless double beta decay with SuperNEMO";*
*R. Arnold et al. , Eur. Phys. Jr. C* DOI 10.1140/epjc/s10052-010-1481-5




$$\lambda \approx \left( \frac{M_{W_L}}{M_{W_R}} \right)^2 \sqrt{\frac{m_\nu}{M_R}}$$



# Radon activity measurement

<u>Requirement</u>: Rn activity inside tracker < **150 μBq/m³**

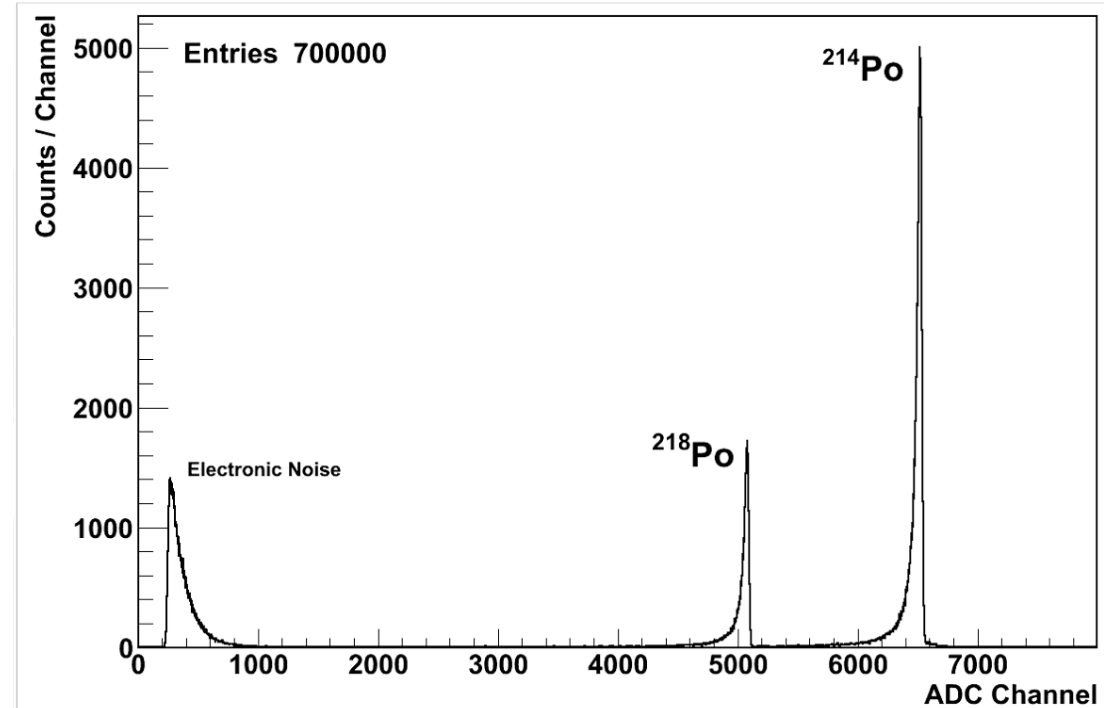
RnCL sensitivity (90%CL)
C-tracker < **50 μBq/m³**
Large gas volume < **5 μBq/m³**

Radon Concentration Line (**RnCL**)

Vacuum Pump

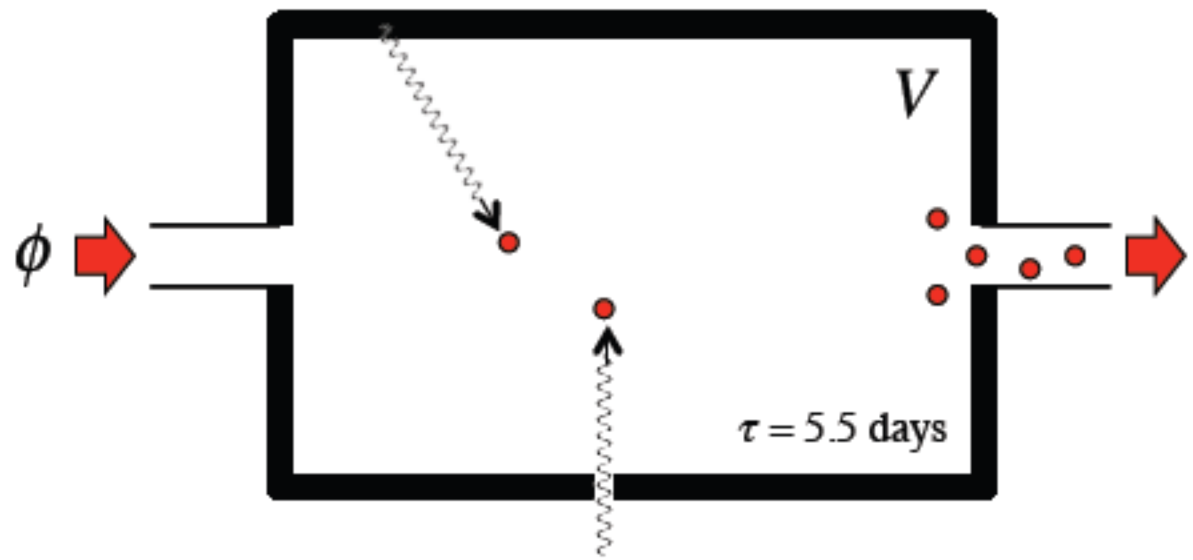
Carbon Trap

Radon Detector
(Electrostatic & Pin Diode)



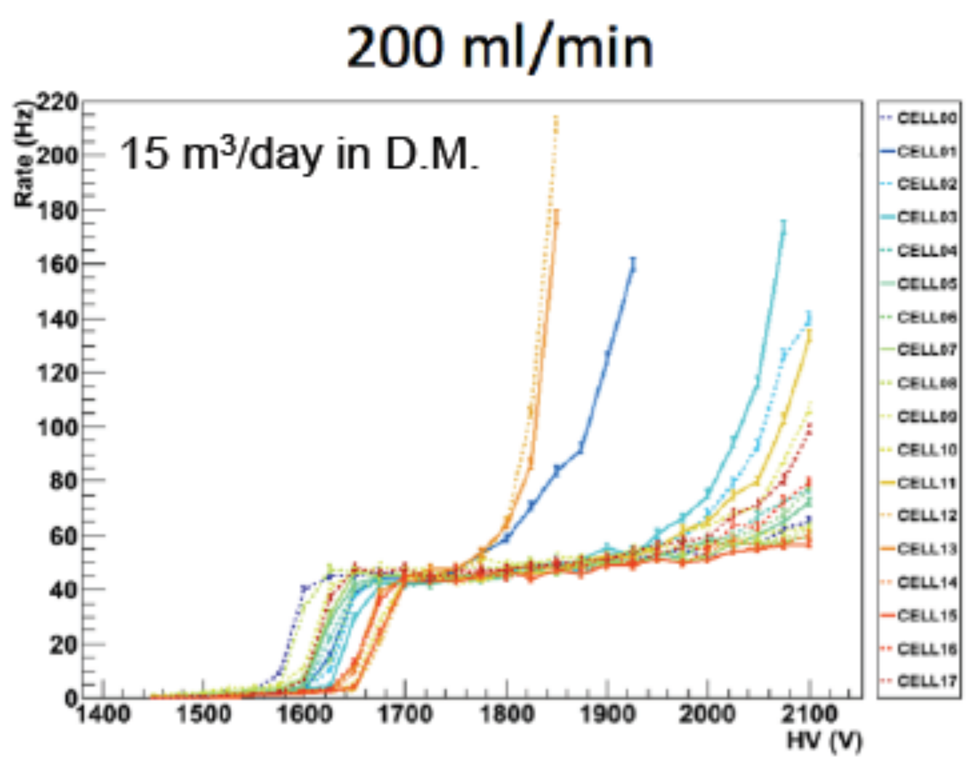

- Measurements of Rn emanation from materials
- Rn permeability measurements through membranes/seals

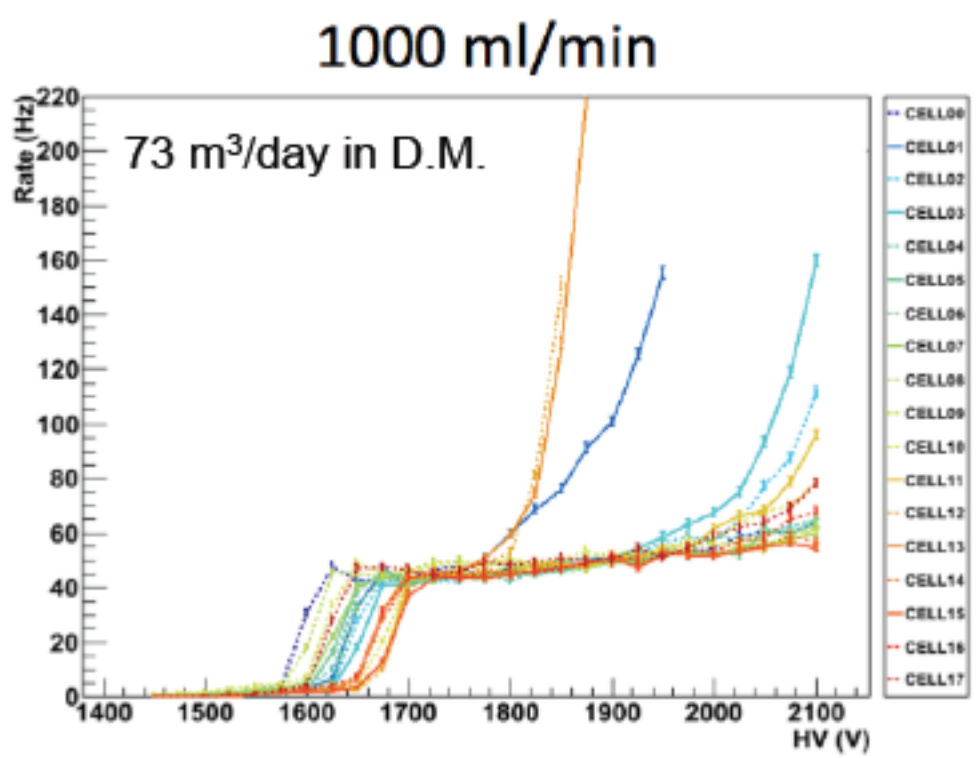
# Gas Flow Rate Study




Radon Suppression Factor :

$$S = \frac{1}{(\phi\tau/V)+1}$$




- The tracker works at high flow rates : a possible solution for suppressing radon.