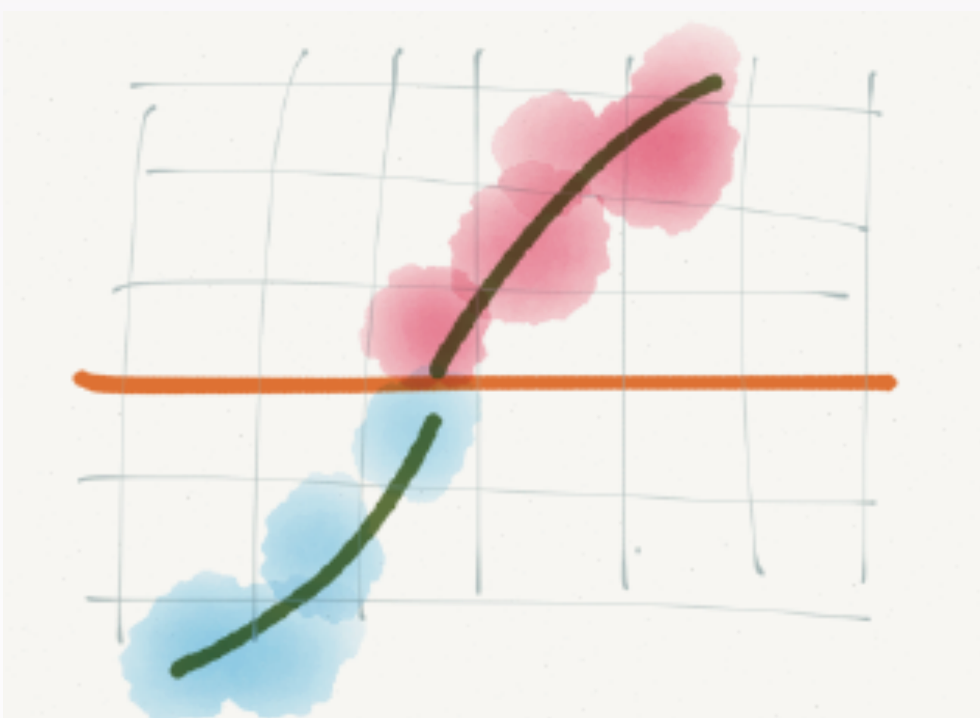
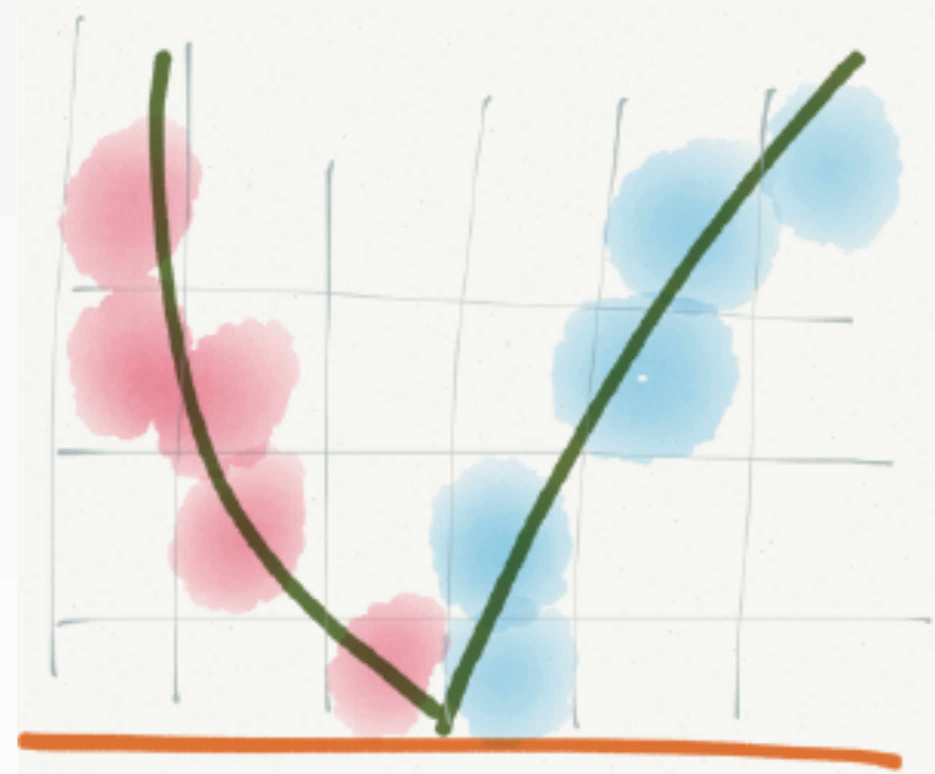
Topological detection of ββ-decay with NEMO-3 and SuperNEMO





Ruben Saakyan

University College London

NDM-2015 Jyvaskyla, Finland

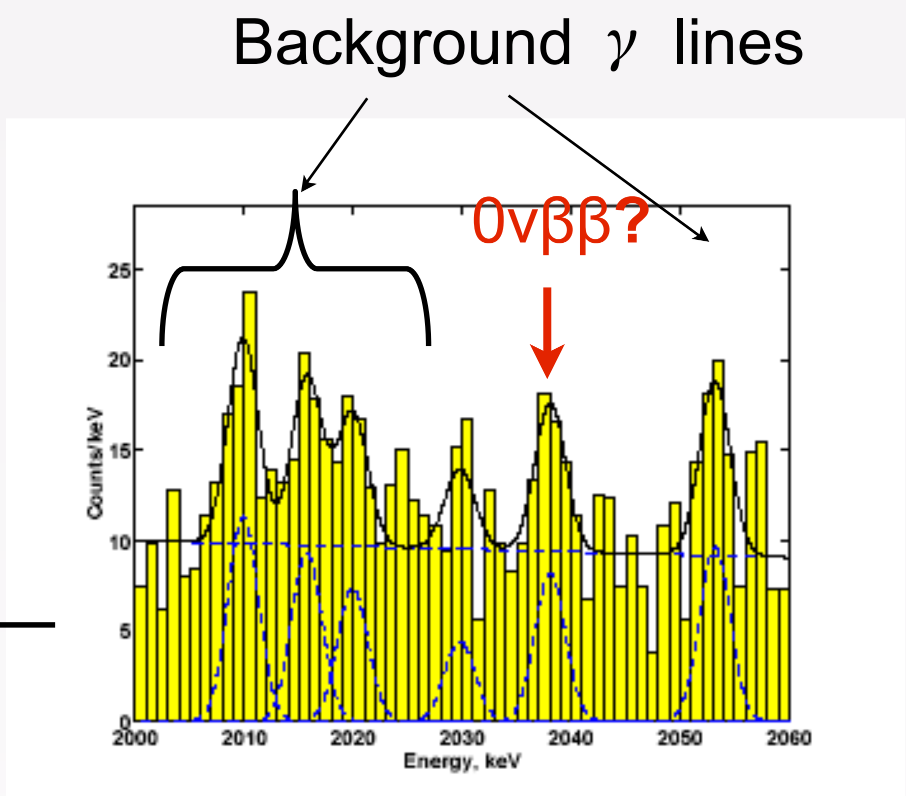
4 June 2015

Location, Location…

Two ways of searching for ββ

$E_{e1} + E_{e2} = Q_{\beta\beta}$ (for 0ν)

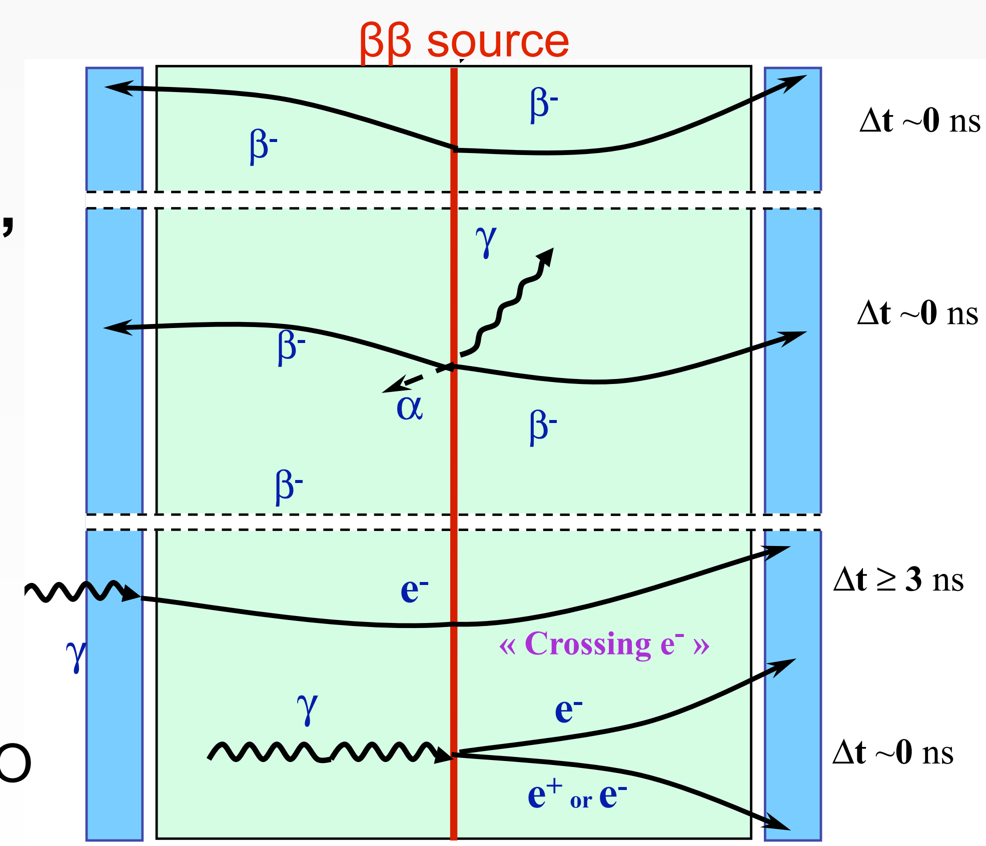
"Calorimeter"



HPGe spectrum (KK claim)

- **Several** observables
- Two **electrons**
- **Coincident**
- From the **same vertex**
- **Angular** distributions between two electrons

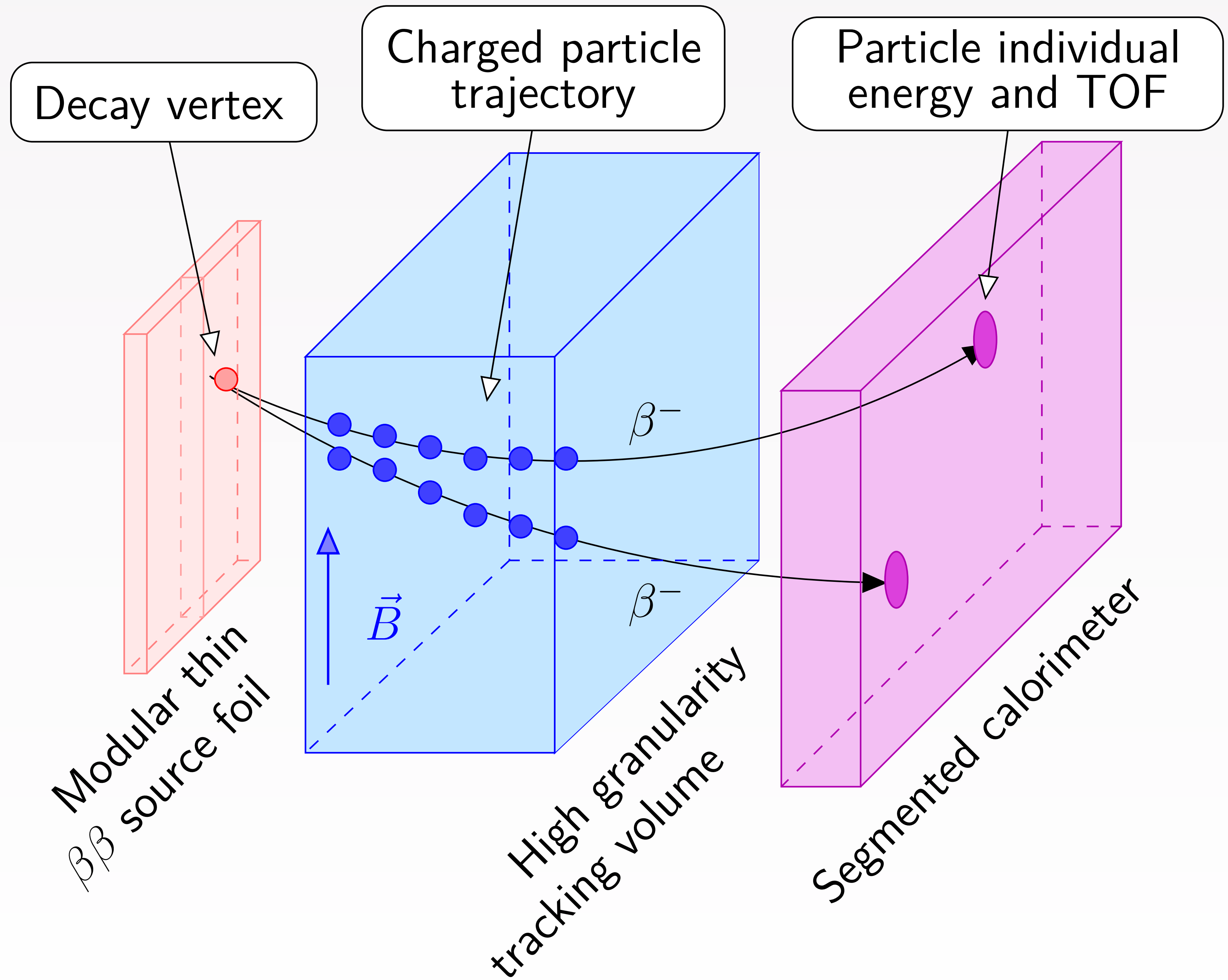
"Topological"



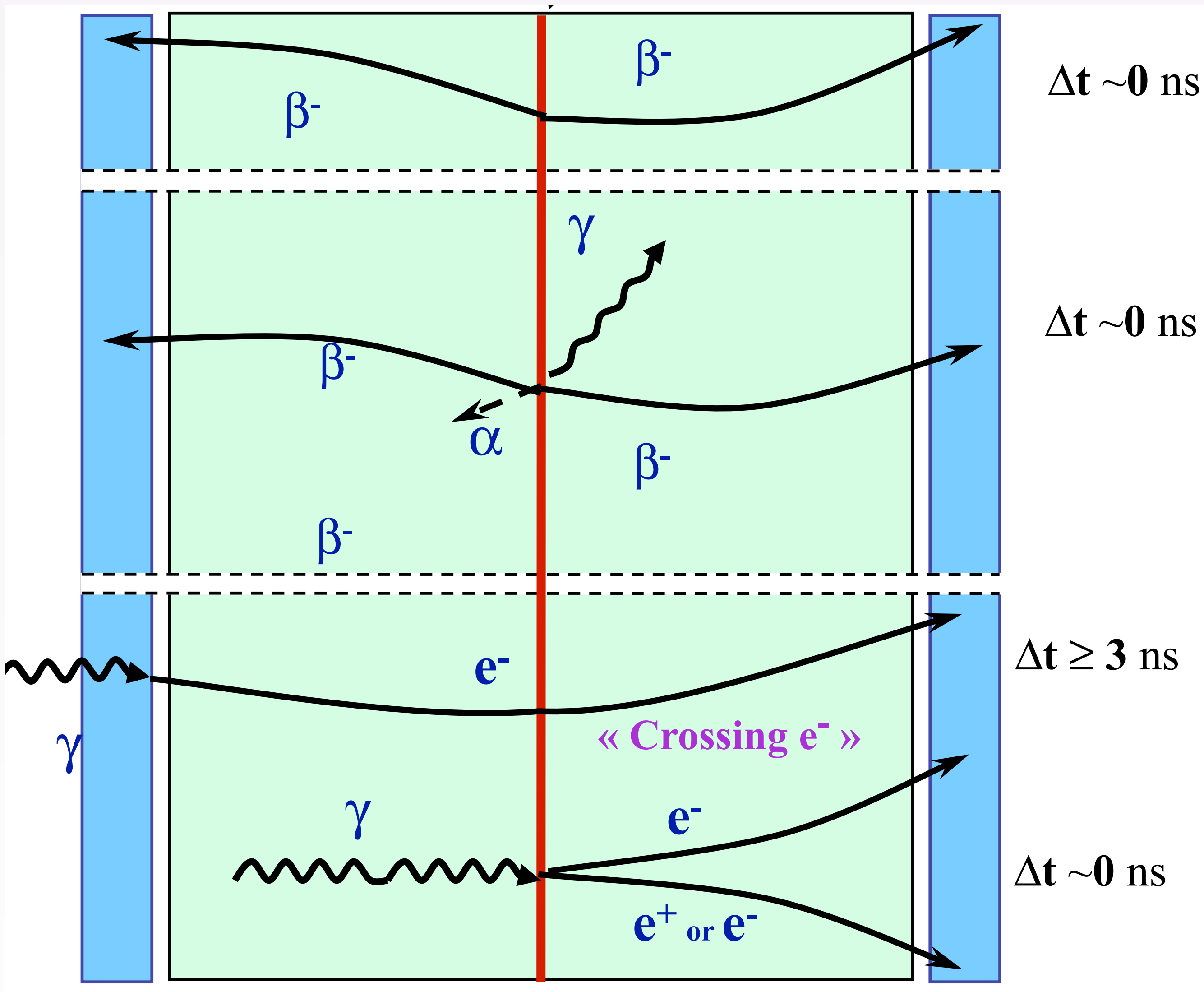
Tracko-Calo, e.g. NEMO3/SuperNEMO

NEMO-3/SuperNEMO Design

Unique Detection principle: reconstruct topological signature



Background Suppression



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

Lowest background index

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^{-2} cnts kg^{-1} keV^{-1} yr^{-1}

(ultimately down to 10^{-3})

But much more modest energy resolution

see next slide

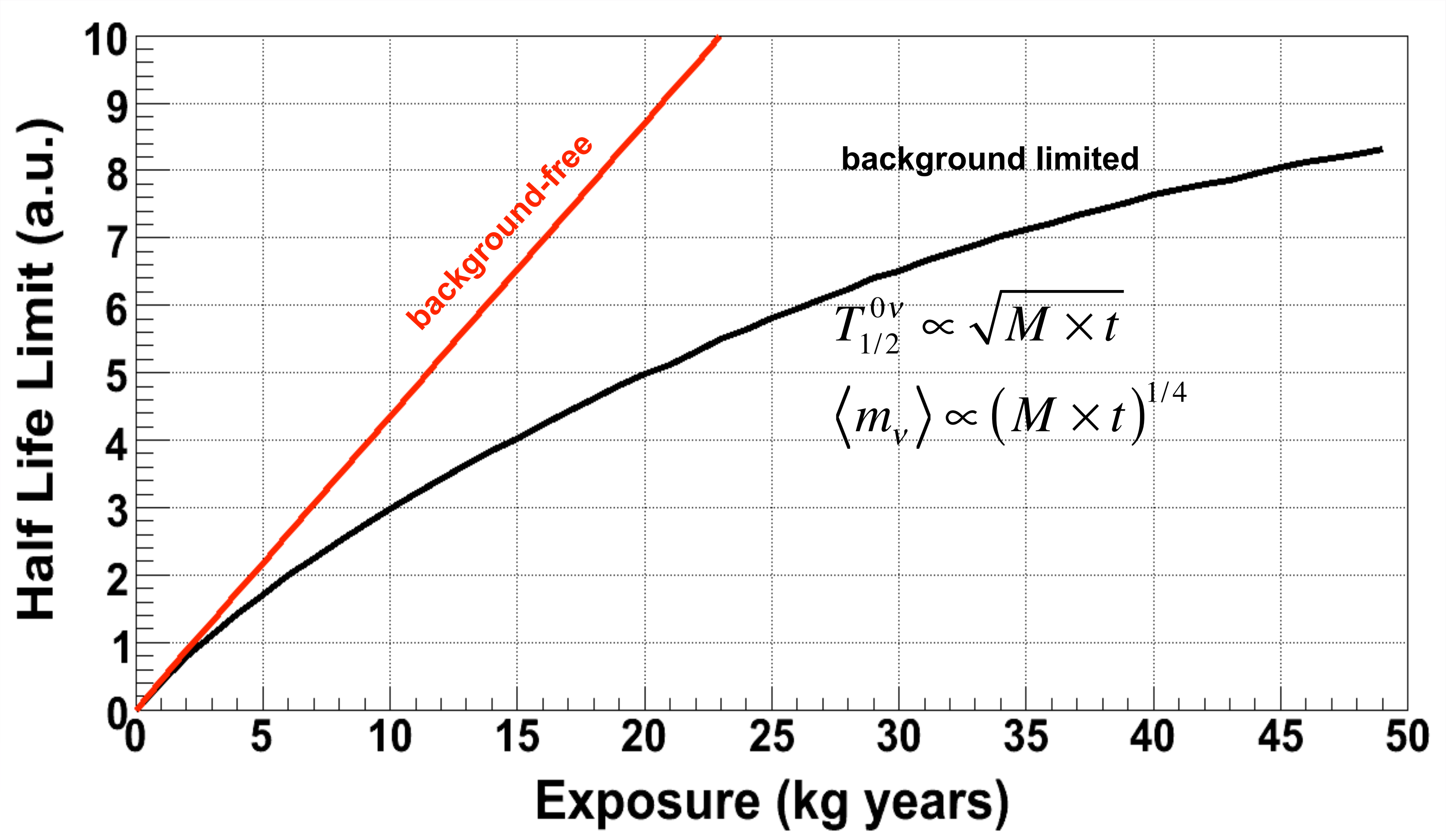
Experimental Sensitivity

maximise efficiency & isotope abundance

maximise exposure = mass × time

$$T_{1/2}^{0\nu}(90\%\ \text{C.L.}) = 2.54\times10^{26}\,\text{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

minimise background **&** energy resolution



b×ΔE (in RoI) is what's important (not just FWHM)

E.g.:

Gerda/CUORE, FWHM=0.2%

b×ΔE = 0.01 x **4keV** = **0.04**

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

b×ΔE = **5×10^{-5}** x 120keV = **0.006**

"Ultimate Calo", FWHM=0.2%

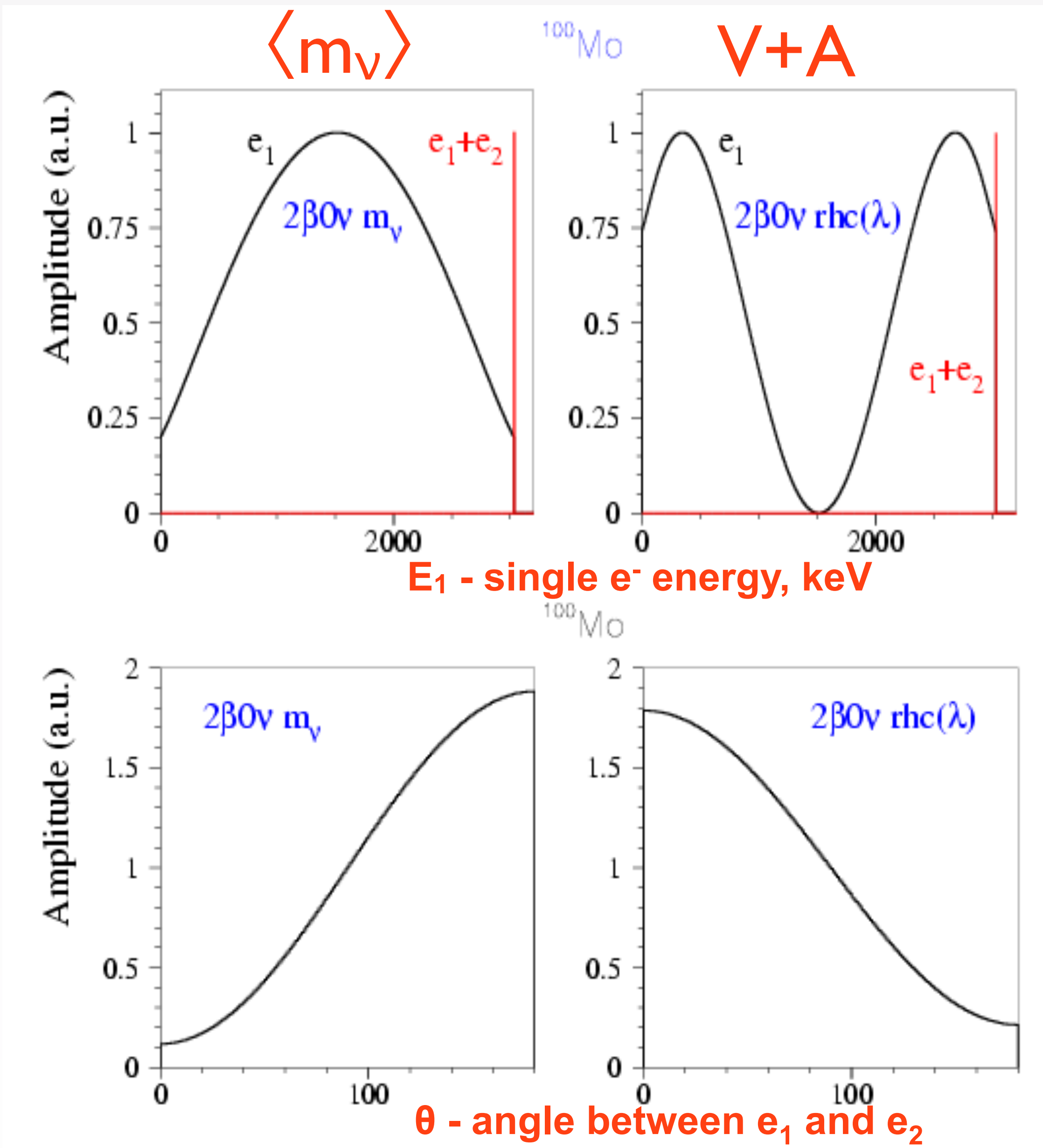
b×ΔE = 0.001 x **4keV** = **0.004**

NEMO-3/SuperNEMO Design Implications

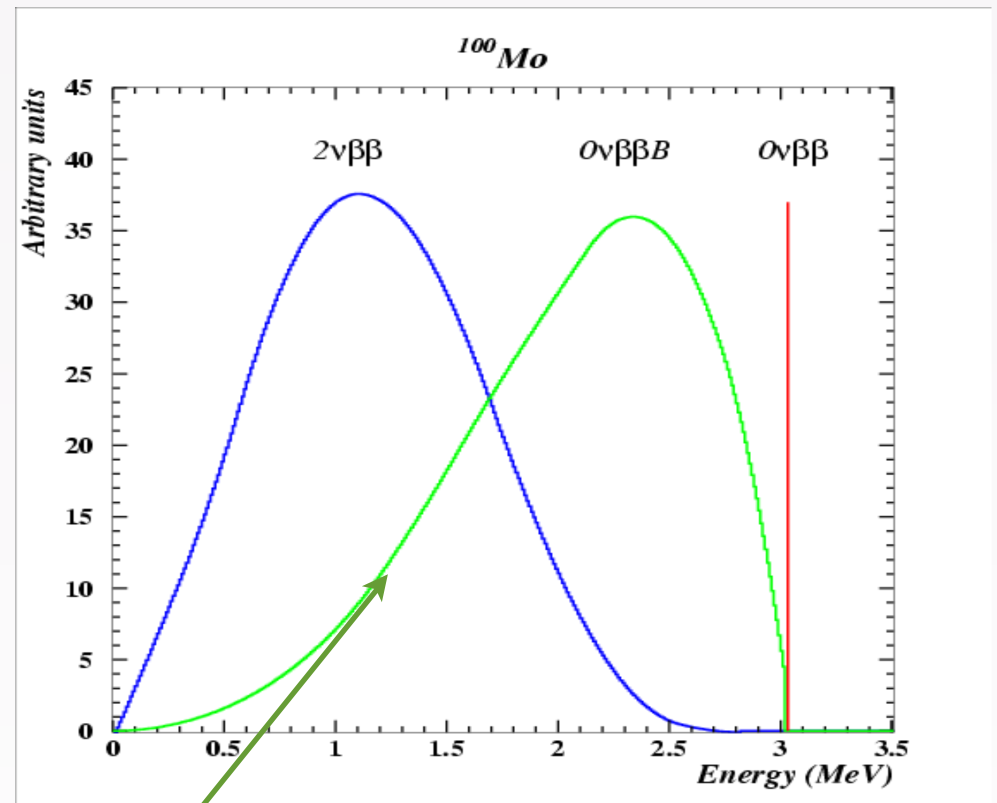
Topology Reconstruction — open-minded search for any 0νββ mechanism

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

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



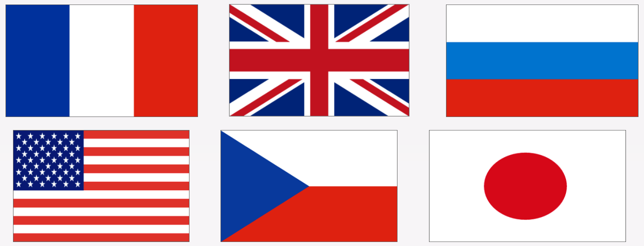
Topology can be used to disentangle underlying physics mechanism



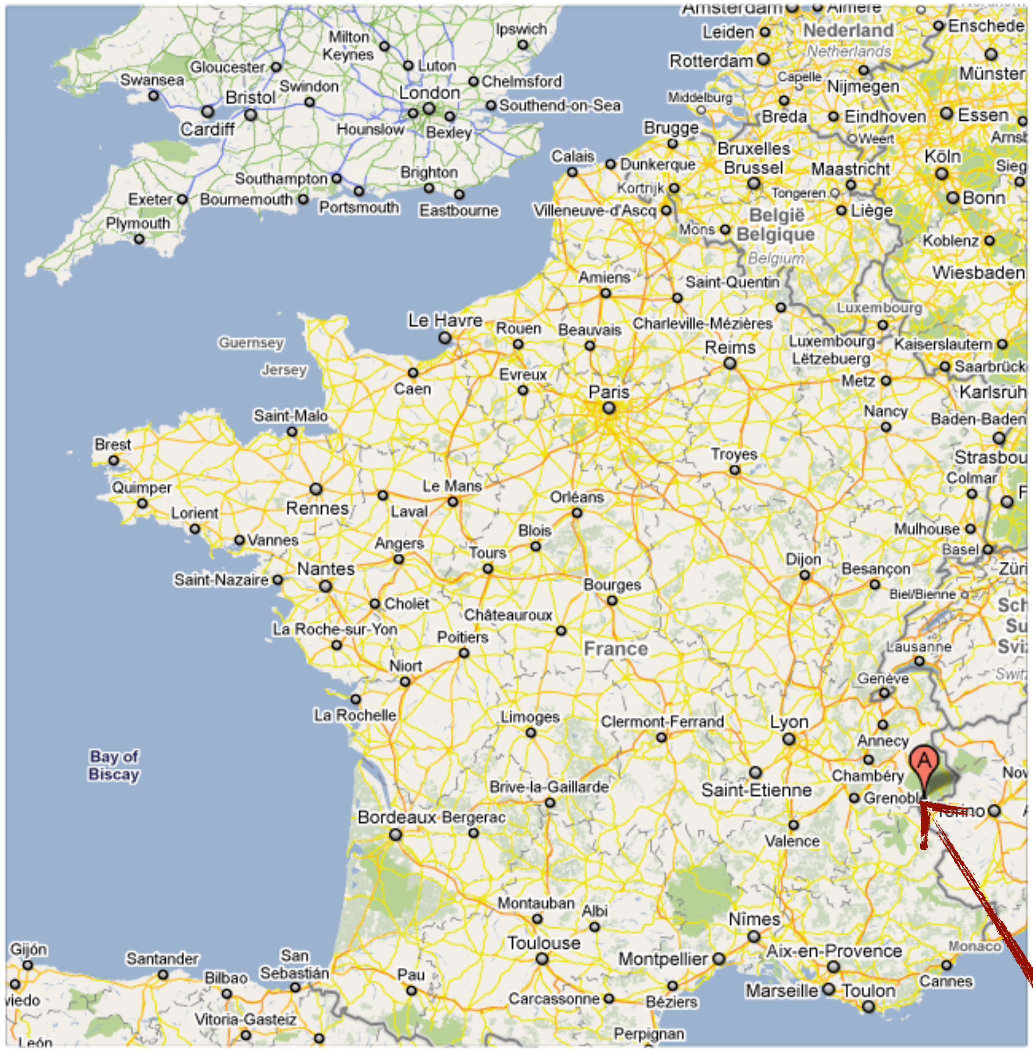
Majoron

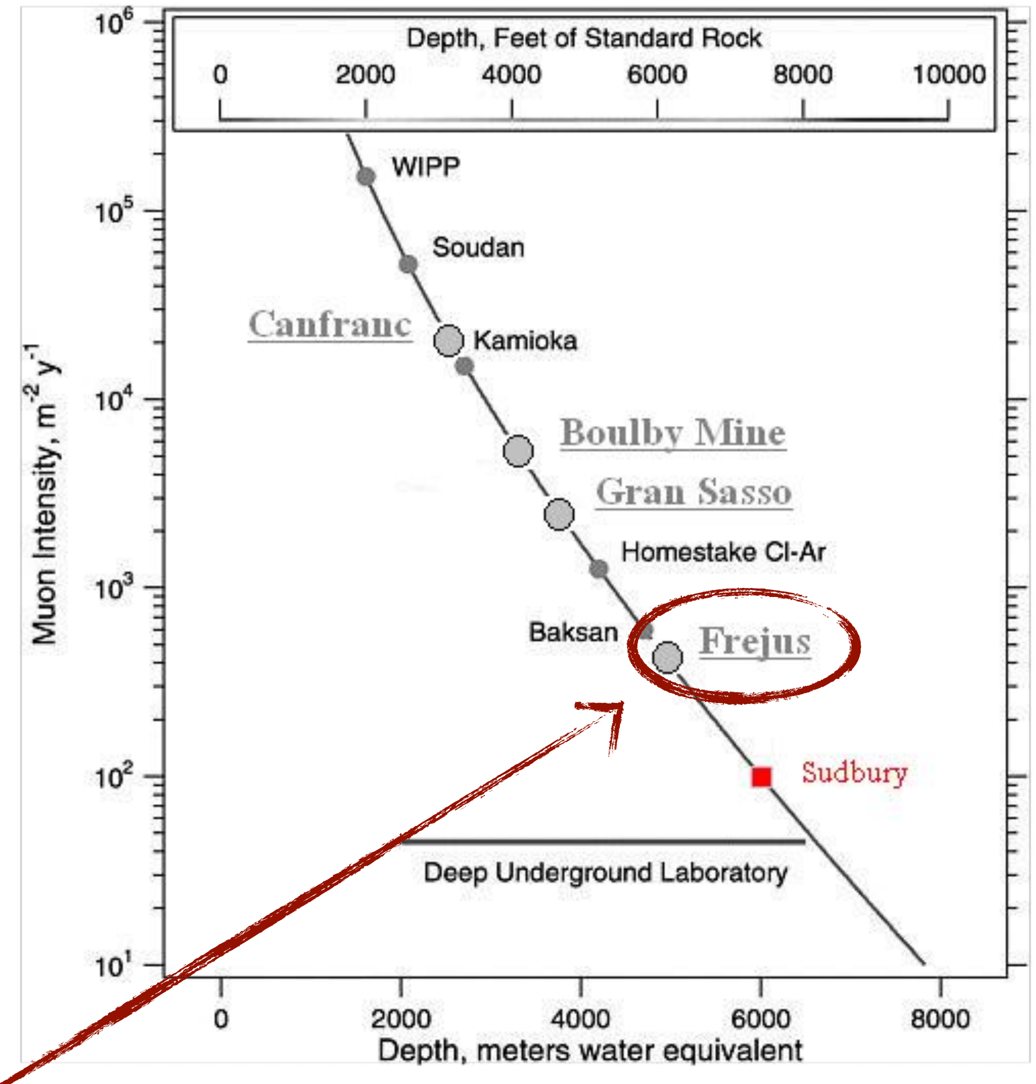
Topology detection is a more sensitive method for phenomena with continuous spectra, e.g. 2νββ, 0νββB (Majoron)

Neutrino Ettore Majorana Observatory 3



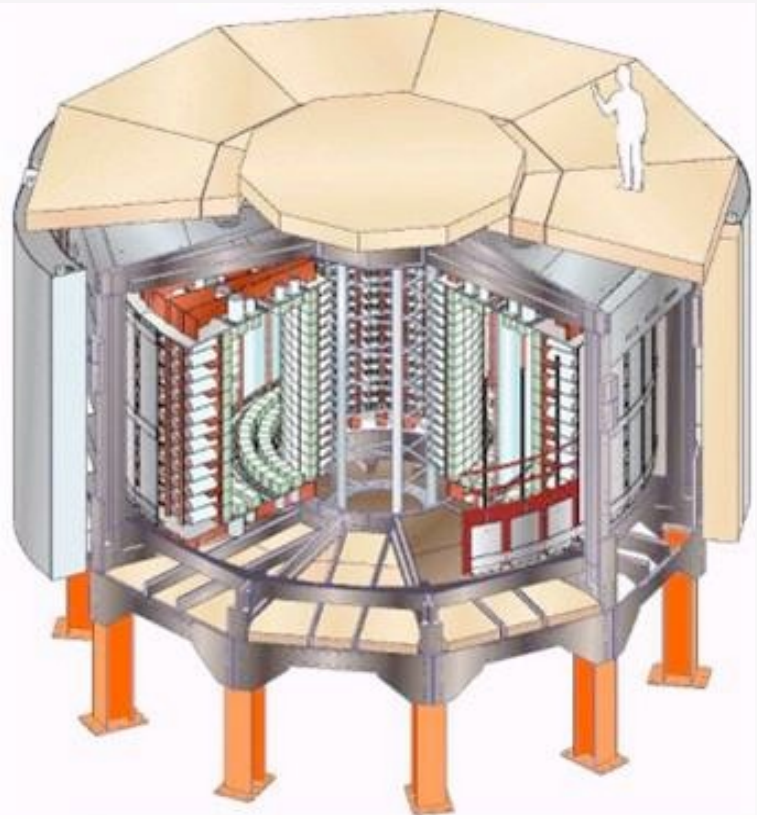
Data taking: Feb’03 - Jan’11





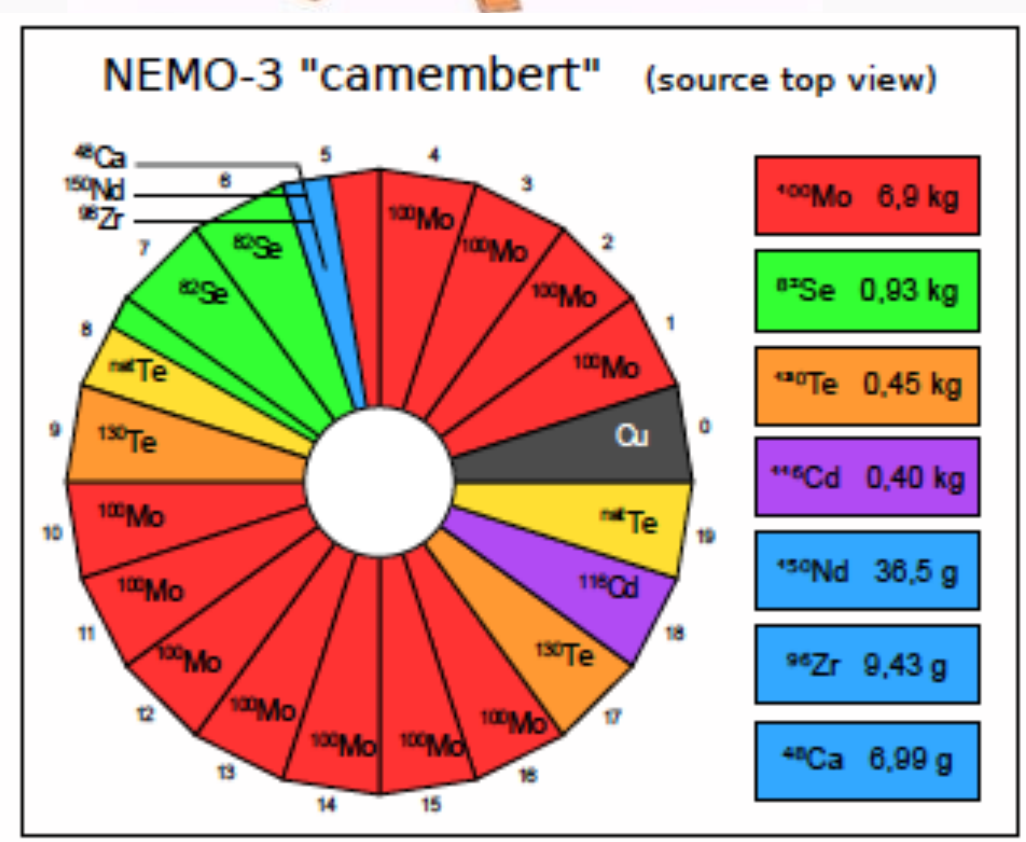
Laboratoire Souterrain de Modane (**LSM**)
Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

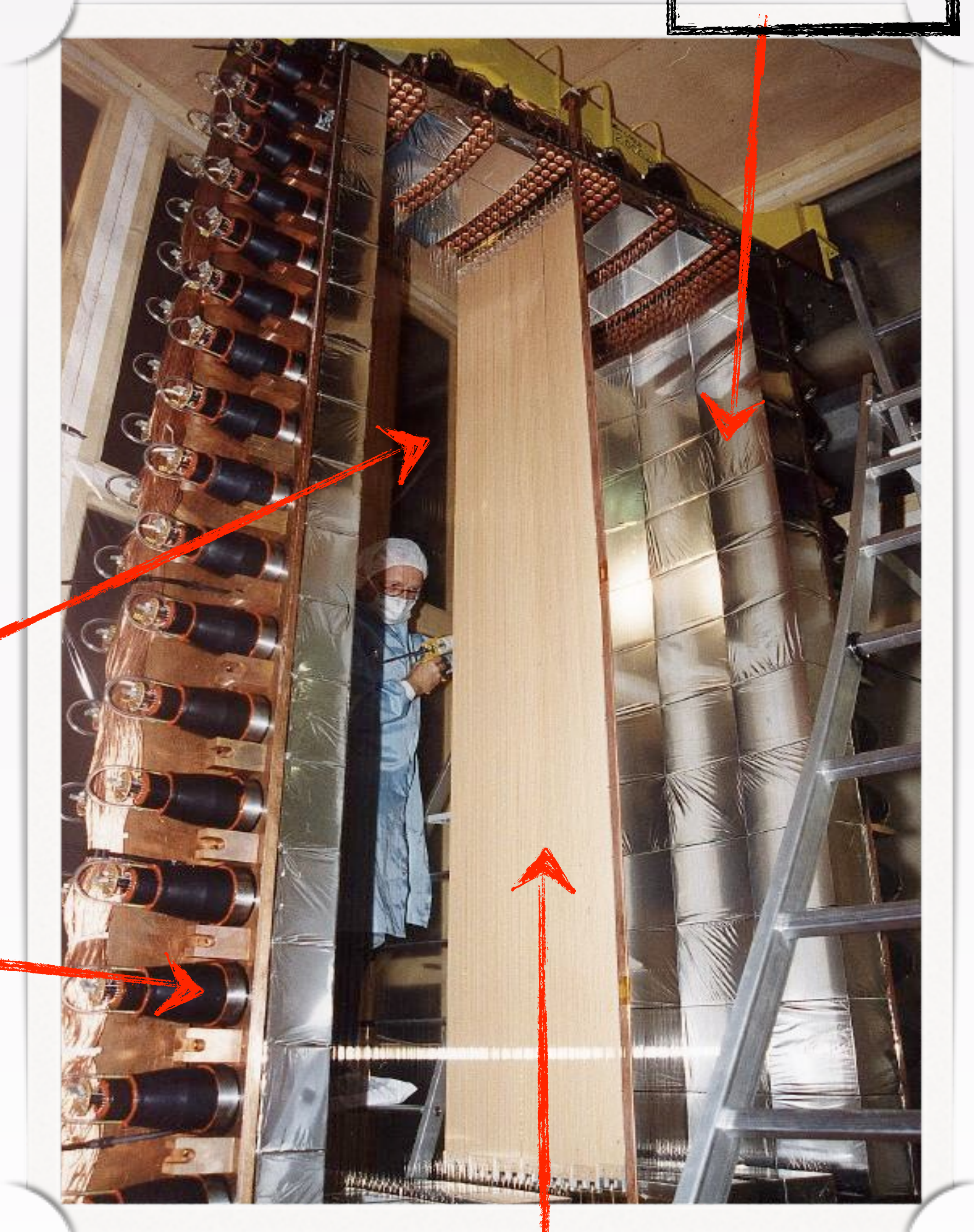
NEMO-3 - 20 sectors with ~10 kg of isotopes



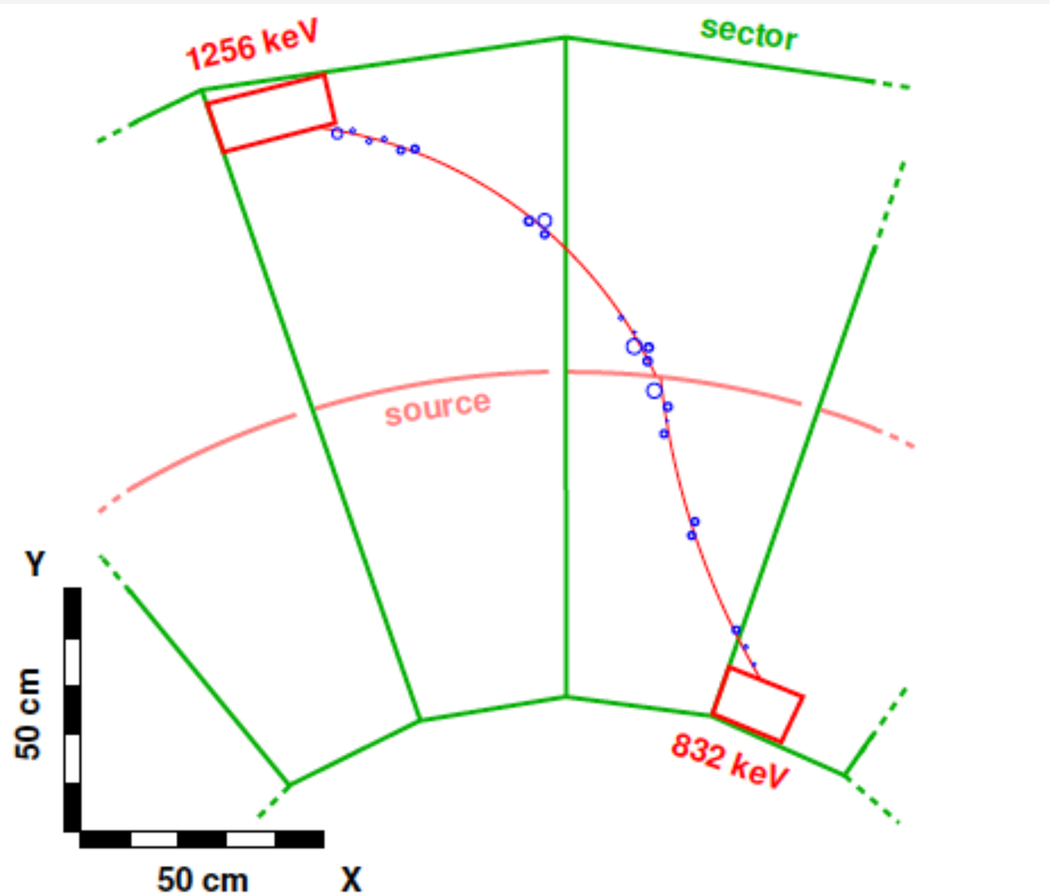
25G B-field

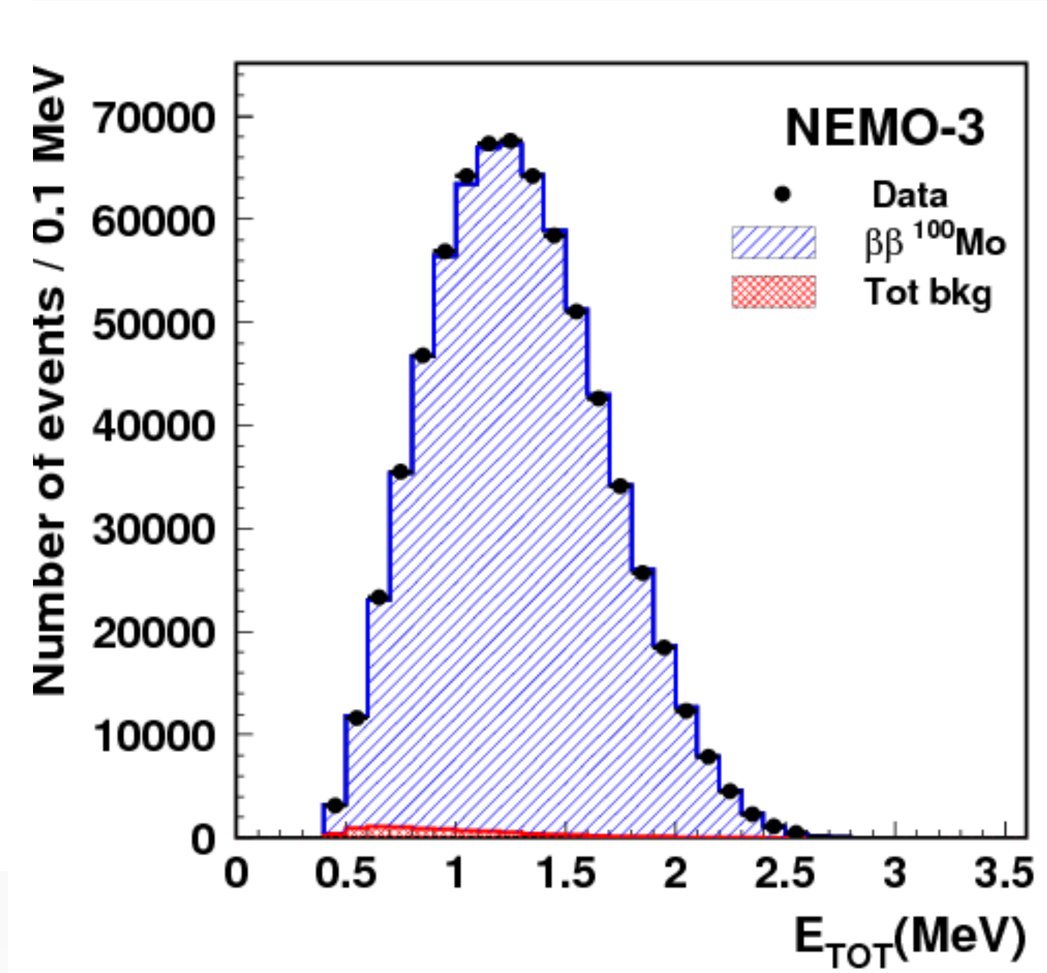
Passive shielding
+ anti-radon shielding

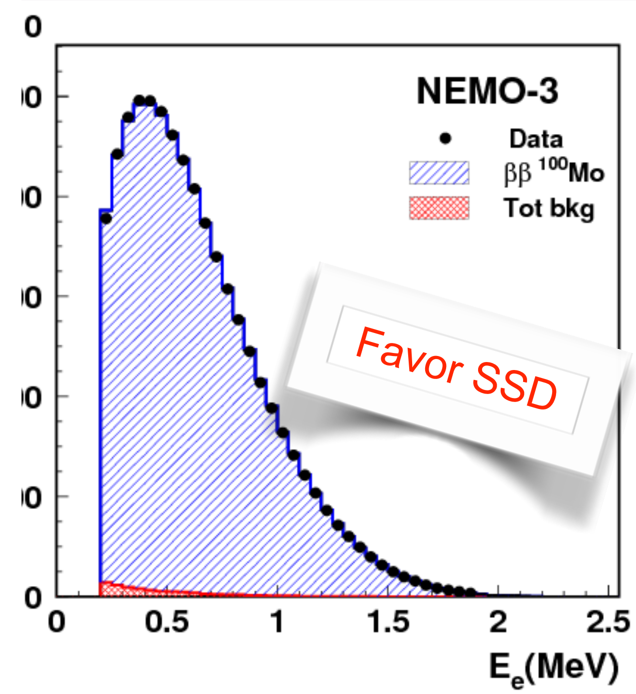


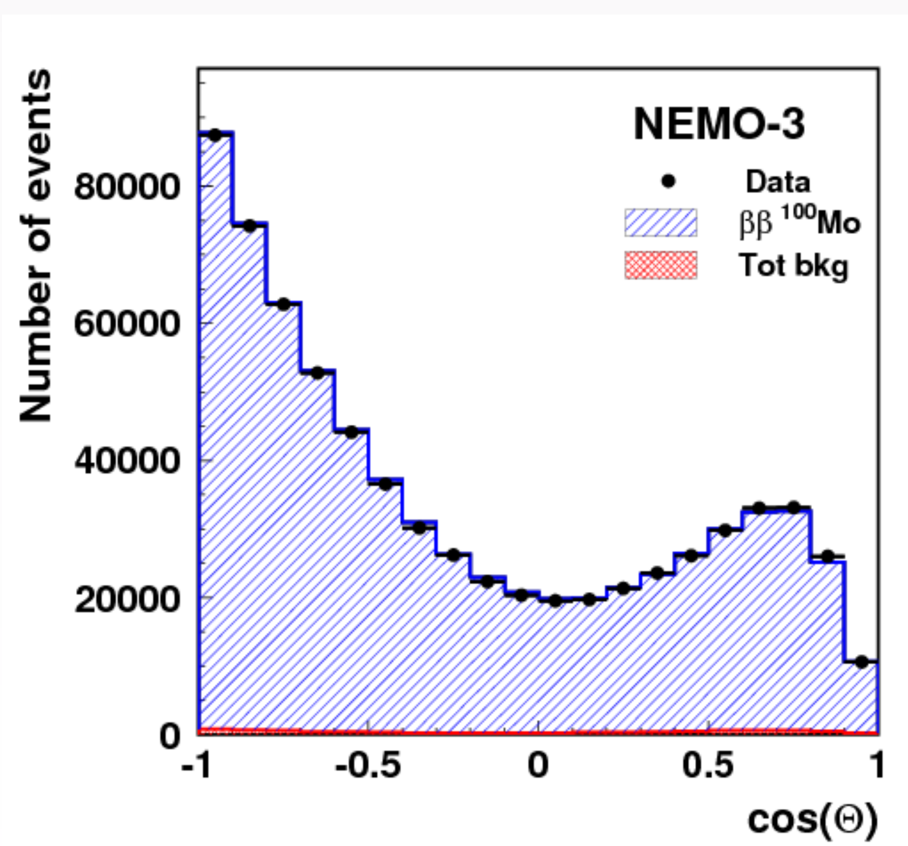


The "Anatomy" of ββ decay with NEMO









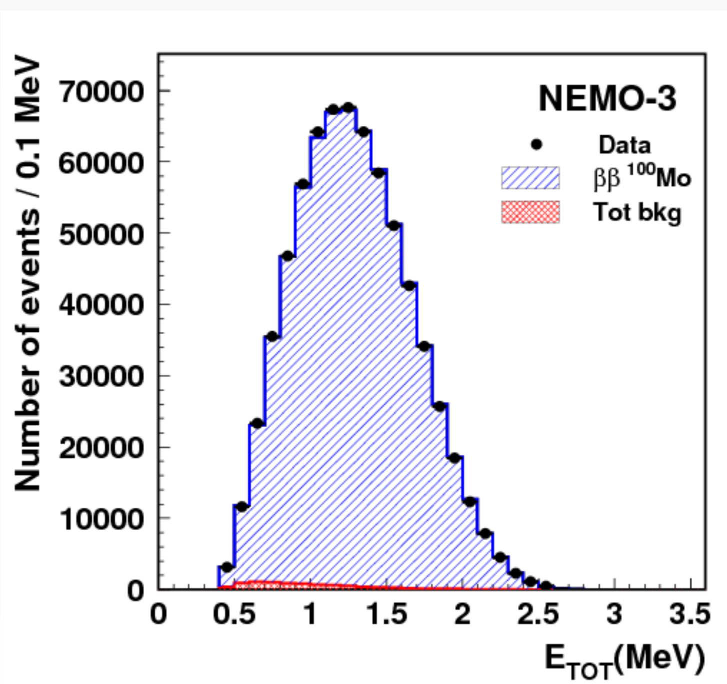
NEMO-3 **2νββ** result for ^{100}Mo to ground state

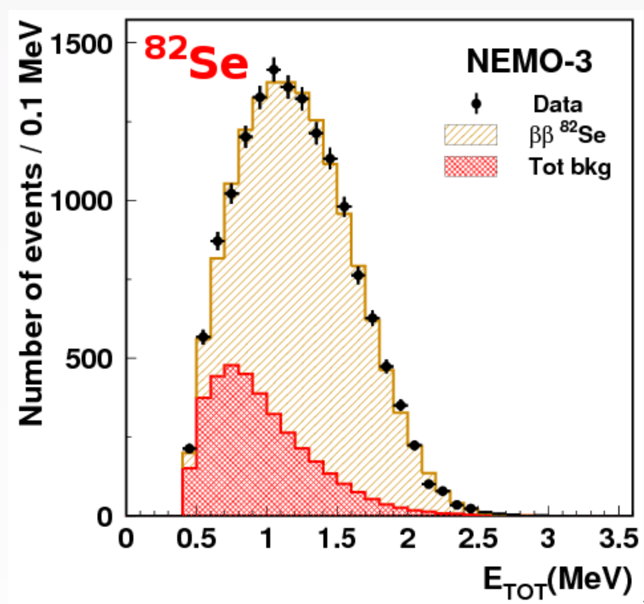
Unprecedented statistics — O(**10^6**) events with **S/B ≈ 80**

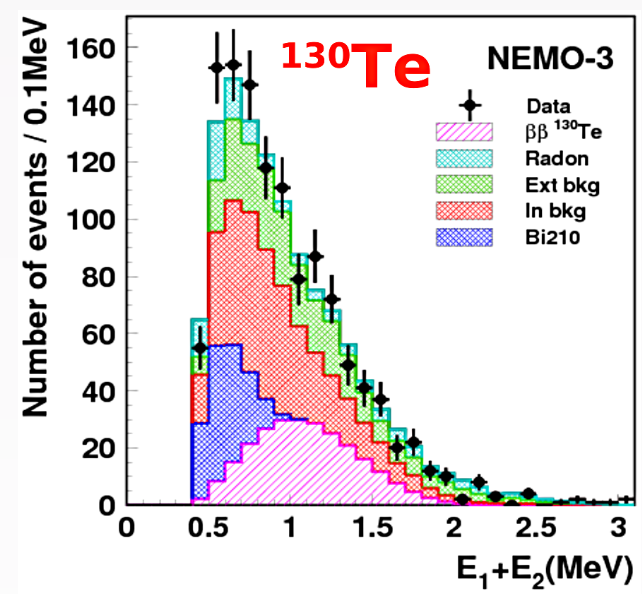
$$T_{1/2}^{2\nu} = \left[7.16 \pm 0.01(\text{stat}) \pm 0.54(\text{syst})\right] \times 10^{18}\ \text{yr}$$

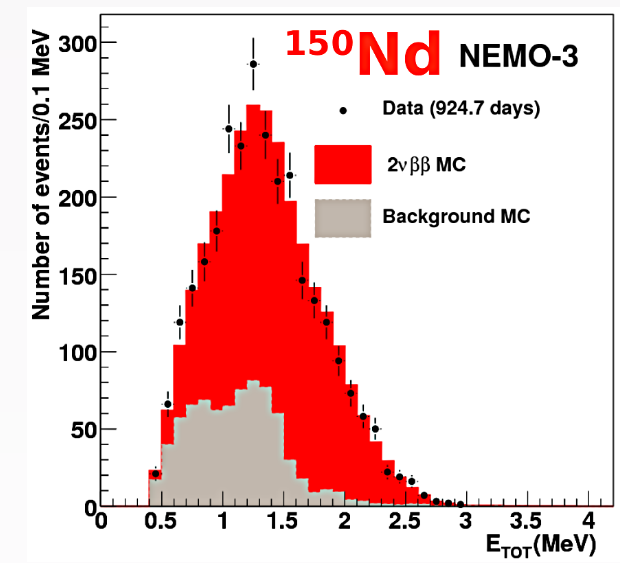
Summary of 2νββ Results

Isotope	Mass (g)	Qββ(keV)	T(2v) (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	2.8 ± 0.3	10	World's best	*Preliminary*
Nd150	37	3367	0.9 ± 0.07	2.7	World's best	Phys. Rev. C 80, 032501 (2009)
Zr96	9.4	3350	2.35 ± 0.21	1	World's best	Nucl.Phys.A 847(2010) 168
Ca48	7	4271	4.4 ± 0.6	6.8 (h.e.)	World's best	*Preliminary*
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)

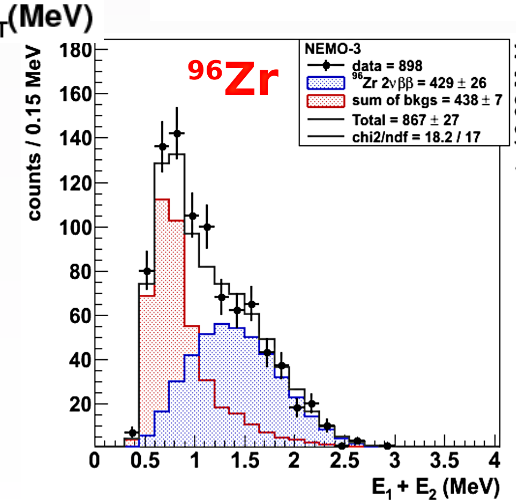


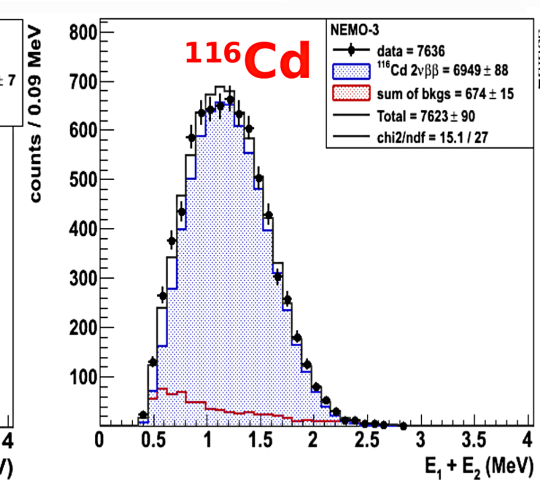


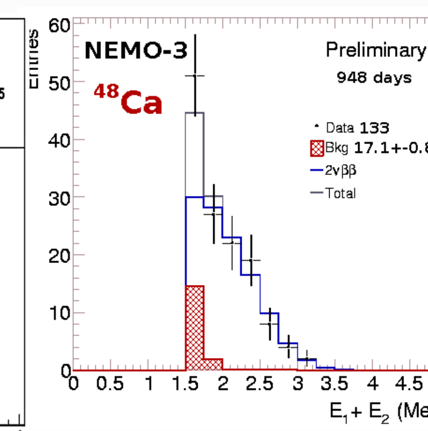




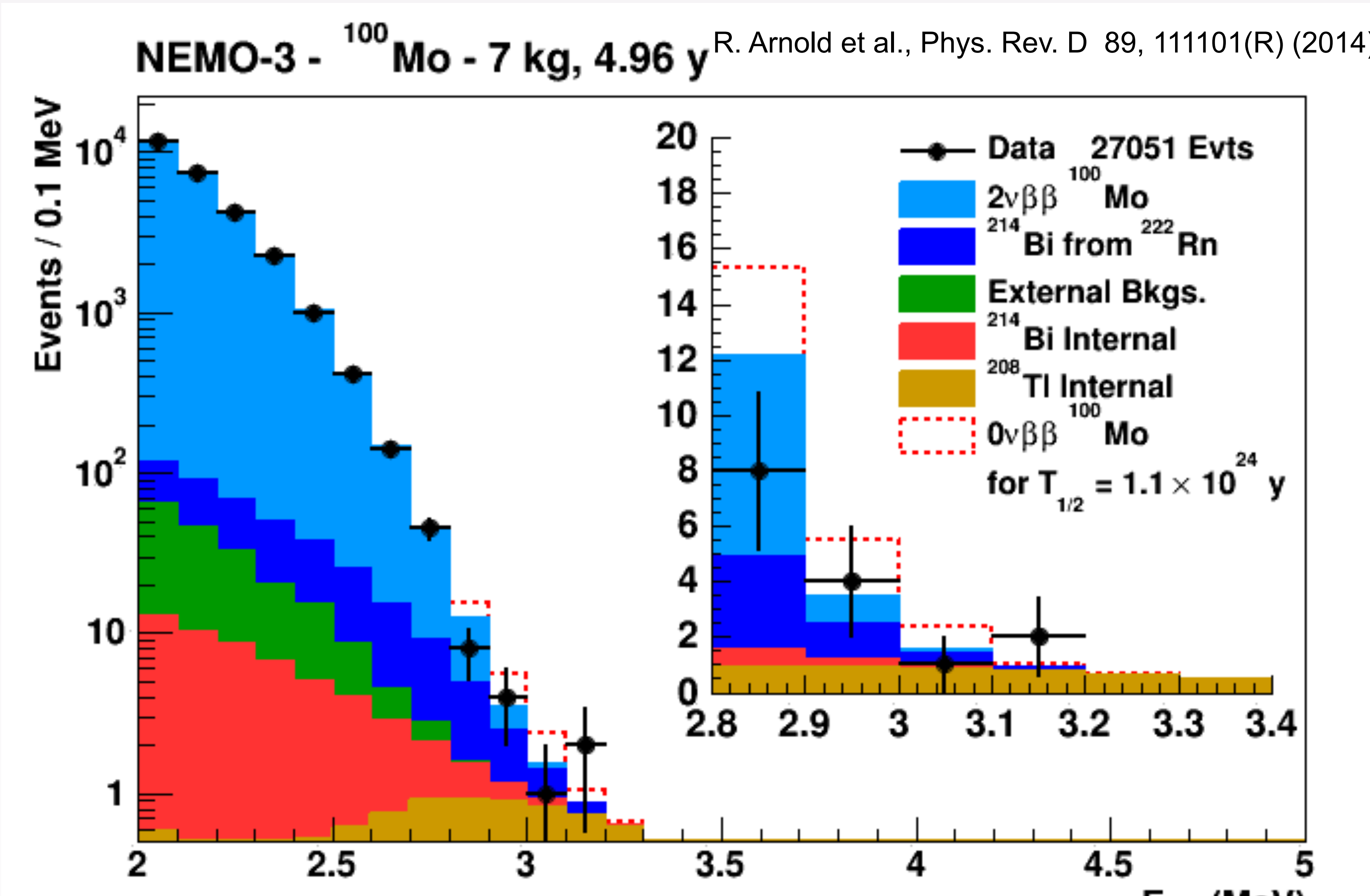
Crucial experimental input for
1) NME calculations
2) Ultimate background characterisation for 0ν







Search for 0νββ



$$T_{1/2}(0\nu\beta\beta) > 1.1\times10^{24}\ \text{yr at 90\%CL}$$

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

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

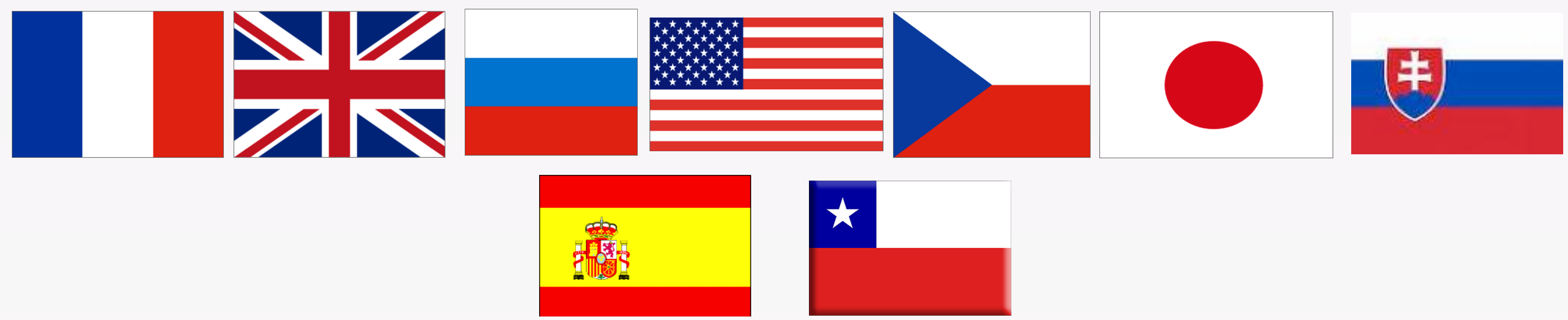
^{48}Ca(4.27 MeV), ^{150}Nd(3.37 MeV) ^{96}Zr(3.35 MeV)

More results in pipeline

multivariate analysis (stronger limits), excited states

Other 0νββ results

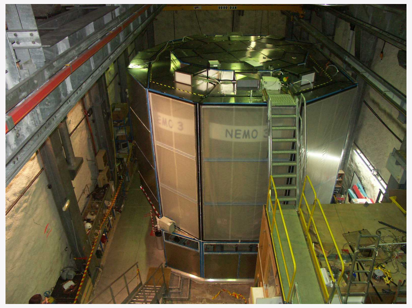
Isotope	T(1E25) yr (<)	⟨λ⟩ (1E-6)	⟨η⟩ (1E-8)	λ'111/f (1E-2)	⟨gee⟩ (1E-5)
Mo100 (NEMO3)	**0.11**	**0.9-1.3**	**0.5-0.8**	**4.4-6.0**	**1.6-3.0**
Te130(CUORICINO)	0.28	1.6-2.4	0.9-5.3		17-33
Xe136 (K-Z)	1.9				0.8-1.6
Ge76 (GERDA)	2.1				3.4-8.7
Ge76 (HdM)	1.9	1.1	0.64		8.1

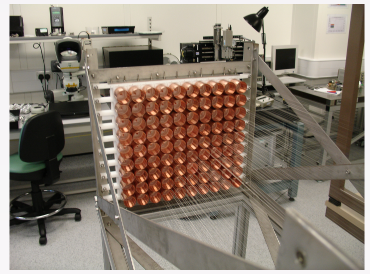


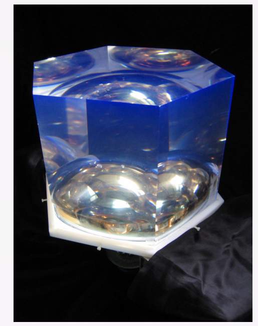
The goals of SuperNEMO :

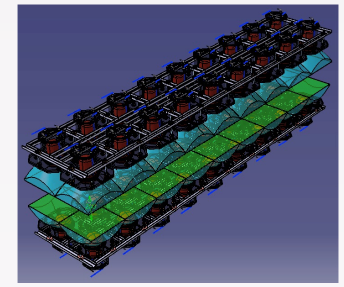
1. Build on the experience of the extremely successful **NEMO-3** experiment.
2. Use the power of the **tracking-calorimeter** approach to identify and suppress backgrounds. This will yield a **zero-background** experiment in the first (**Demonstrator Module**) phase.
3. Prove that a 100 kg scale experiment can probe the **inverted mass hierarchy** (~50 meV) domain.
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







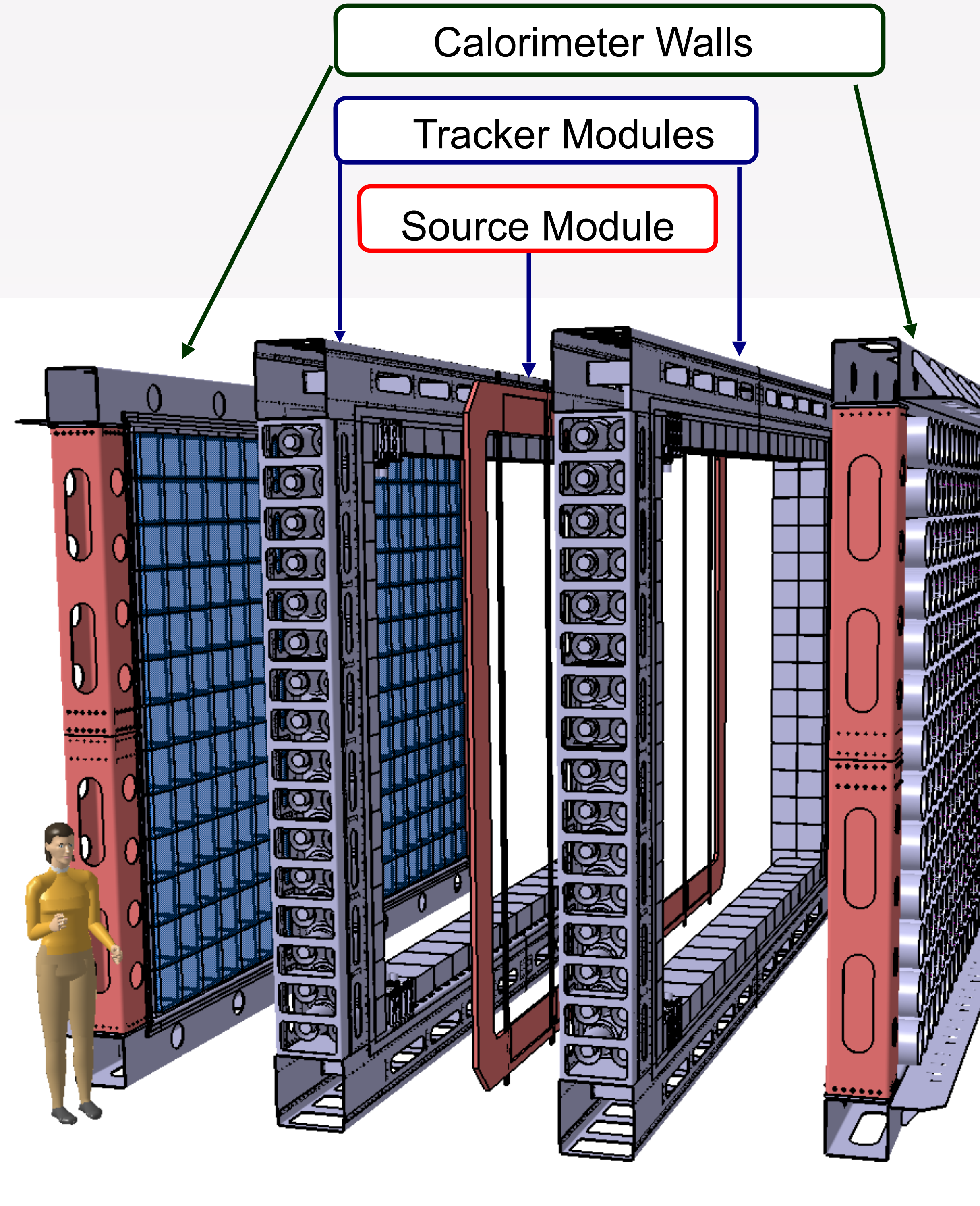


R&D since 2006 →

NEMO-3		SuperNEMO
^{100}Mo	Isotope	^{82}Se (or ^{150}Nd or ^{48}Ca)
7 kg	Isotope mass M	100+ kg
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: < 300 μBq/kg	Contaminations in the ββ foil	^{208}Tl ≤ 2 μBq/kg ^{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)	4% @ 3 MeV
$T_{1/2}(\beta\beta0\nu) > 1.1 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 0.6$ eV	Sensitivity	$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y $\langle m_\nu \rangle < 0.04 - 0.1$ 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_50H + 1%Ar) ~2000 cells in Geiger mode
- **Calorimeter**
  - 550 PMTs + scintillators + endcap + veto
- **25G B-field**
- **Passive shielding**: iron + water
- **Anti-Rn system**



A zero background experiment

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	
$2\nu\beta\beta$	7.16 ± 0.05	0.20	Mo100 to Se82 8% to 4% resolution
Total expected	13.1 ± 0.3	0.39	
Data	12	N/A (yet)	

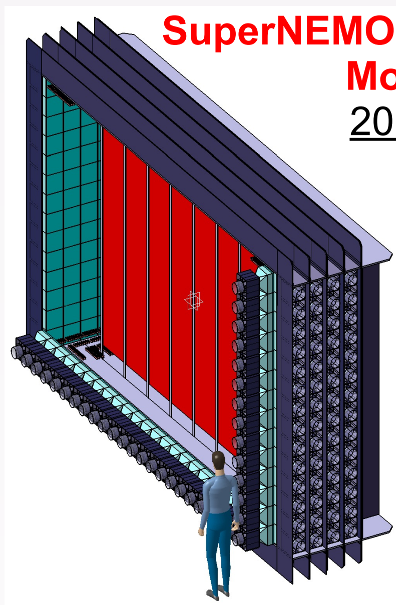
NEMO-3 sensitivity in **4.5 months !**

- **Demonstrator** 18 kg.yr (~2.5 yr of running)
  - $T_{1/2} > 6.6 \times 10^{24}$ 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)

SuperNEMO Demonstrator Module
20 tons



=

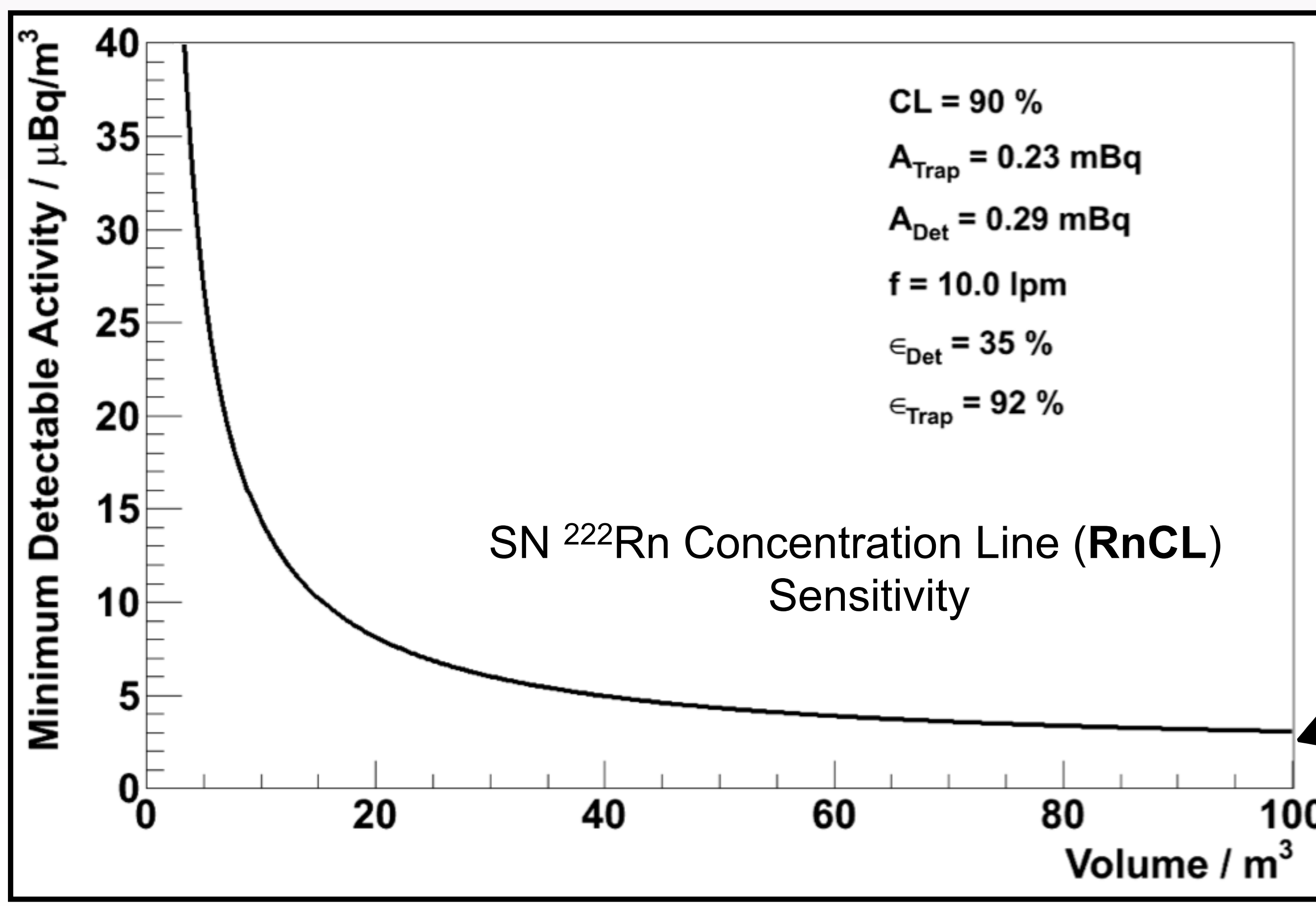
1kg of bananas

= 100 Bq

Pushing low background technology boundaries

Rn removal from gas with cold charcoal trap:

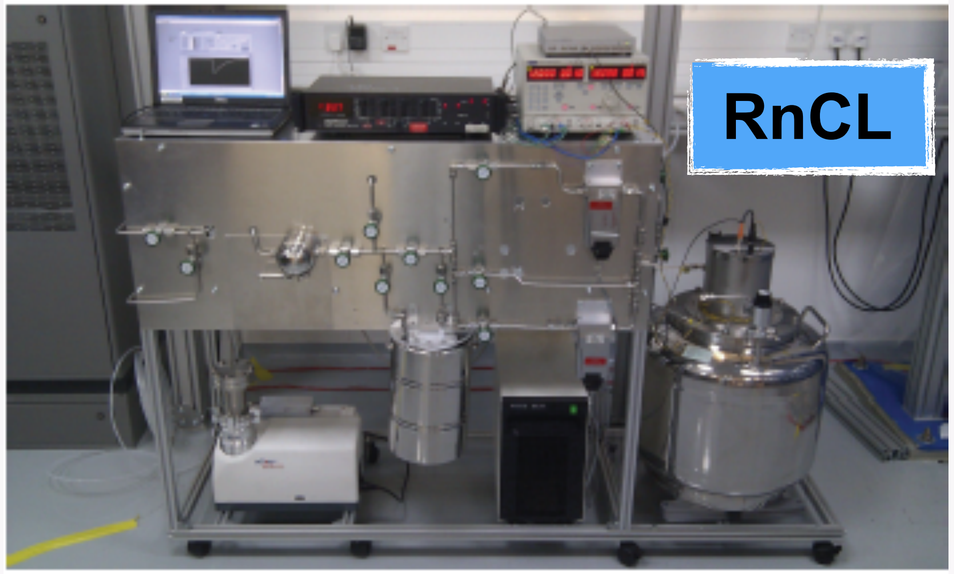
- **He**: 10^{10}(!) suppression, complete removal
- **N_2**: ~x20 suppression purification down to **20μB/m^3 (measured!)**



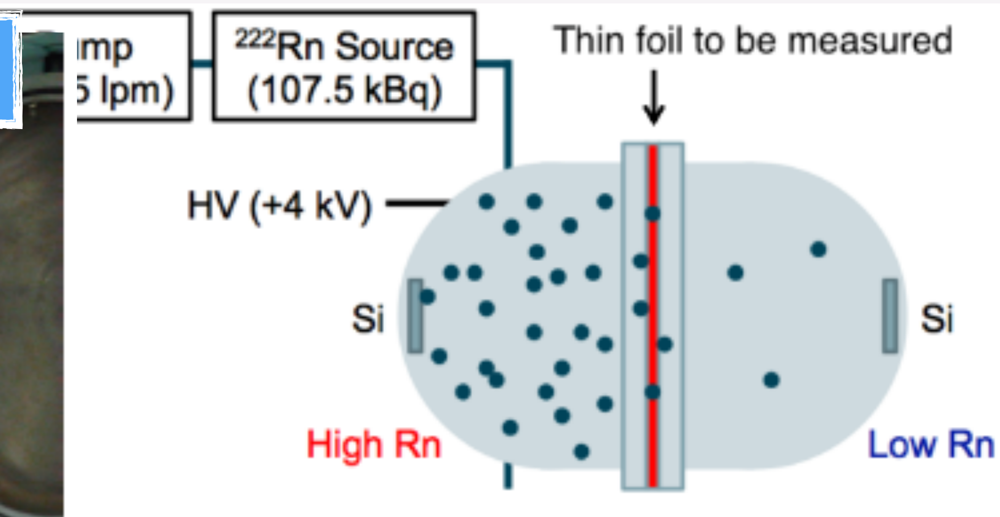
2.4 ^{222}Rn atoms/m^3 of N_2/He/Ar/etc.
or
1 part in 10^{25} !!!

SuperNEMO Low Background Program

RnCL

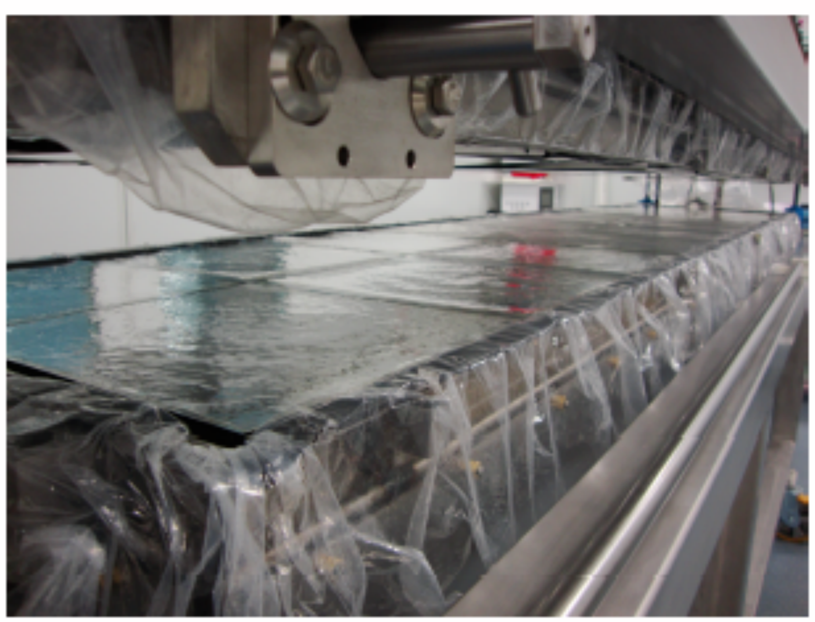


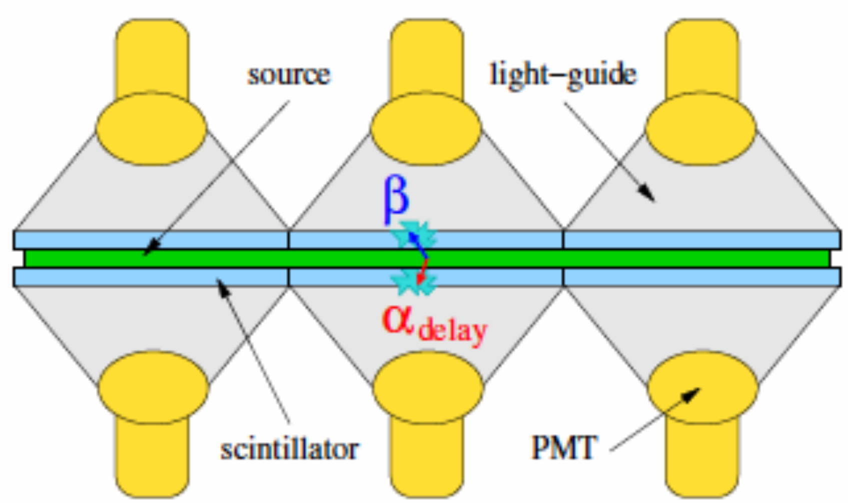
Rn Emanation setup

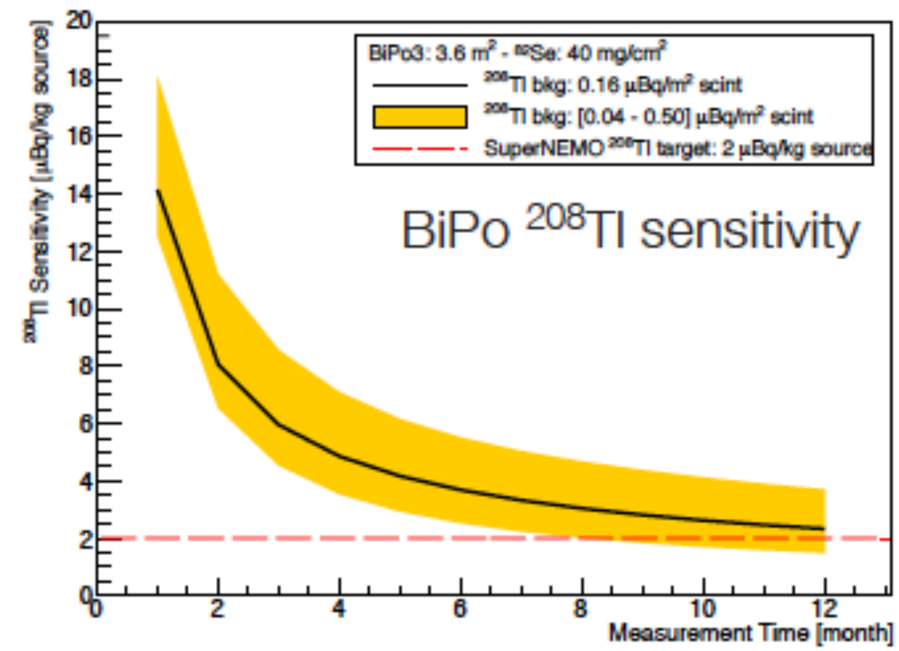


Rn Permeability setup

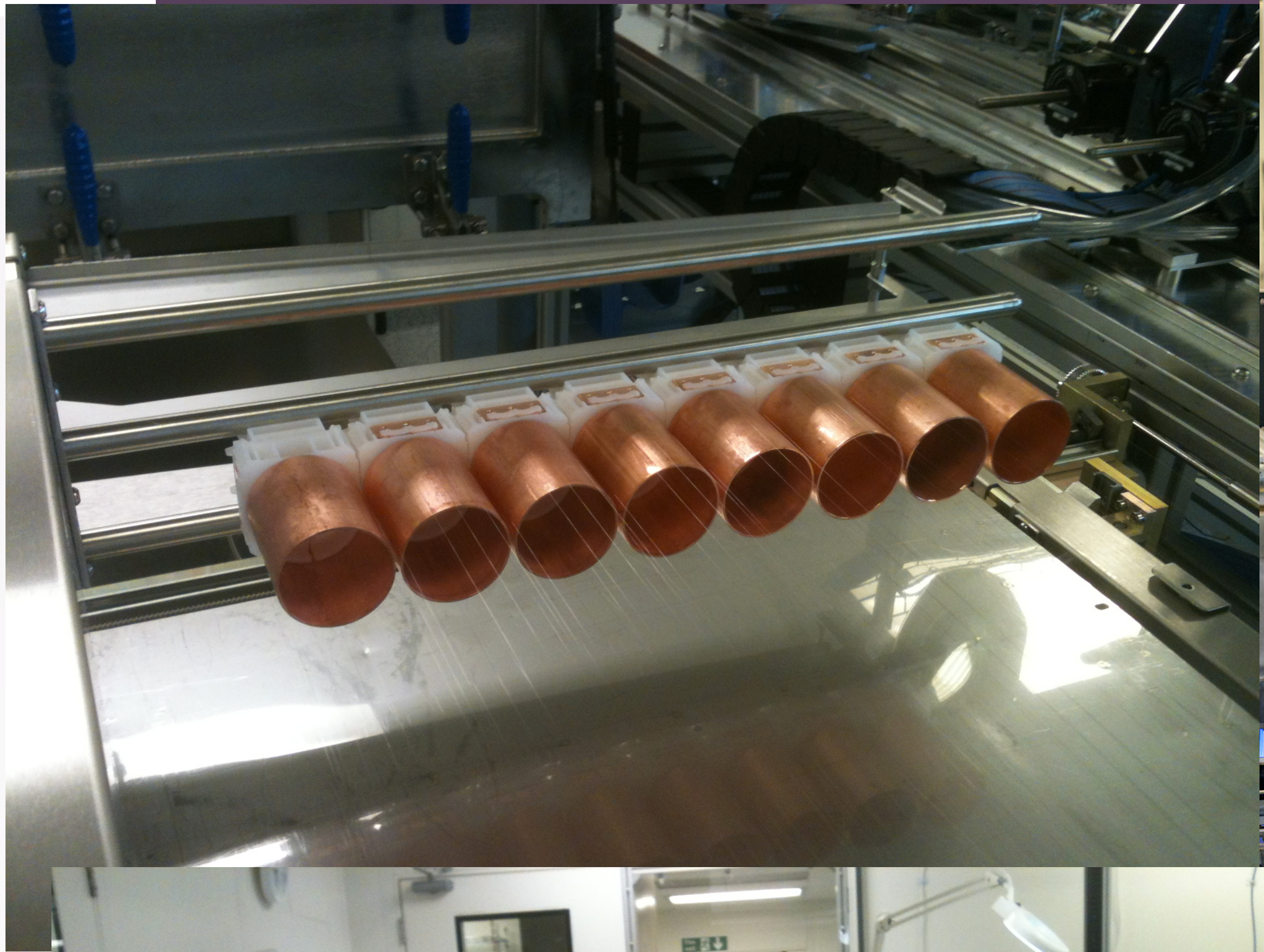
Dedicated BiPo detector to measure ββ source foil contamination, 10μBq/kg for ^{214}Bi, 2 μBq/kg for ^{208}Tl — operating since Feb'13 @LSC (Canfranc)







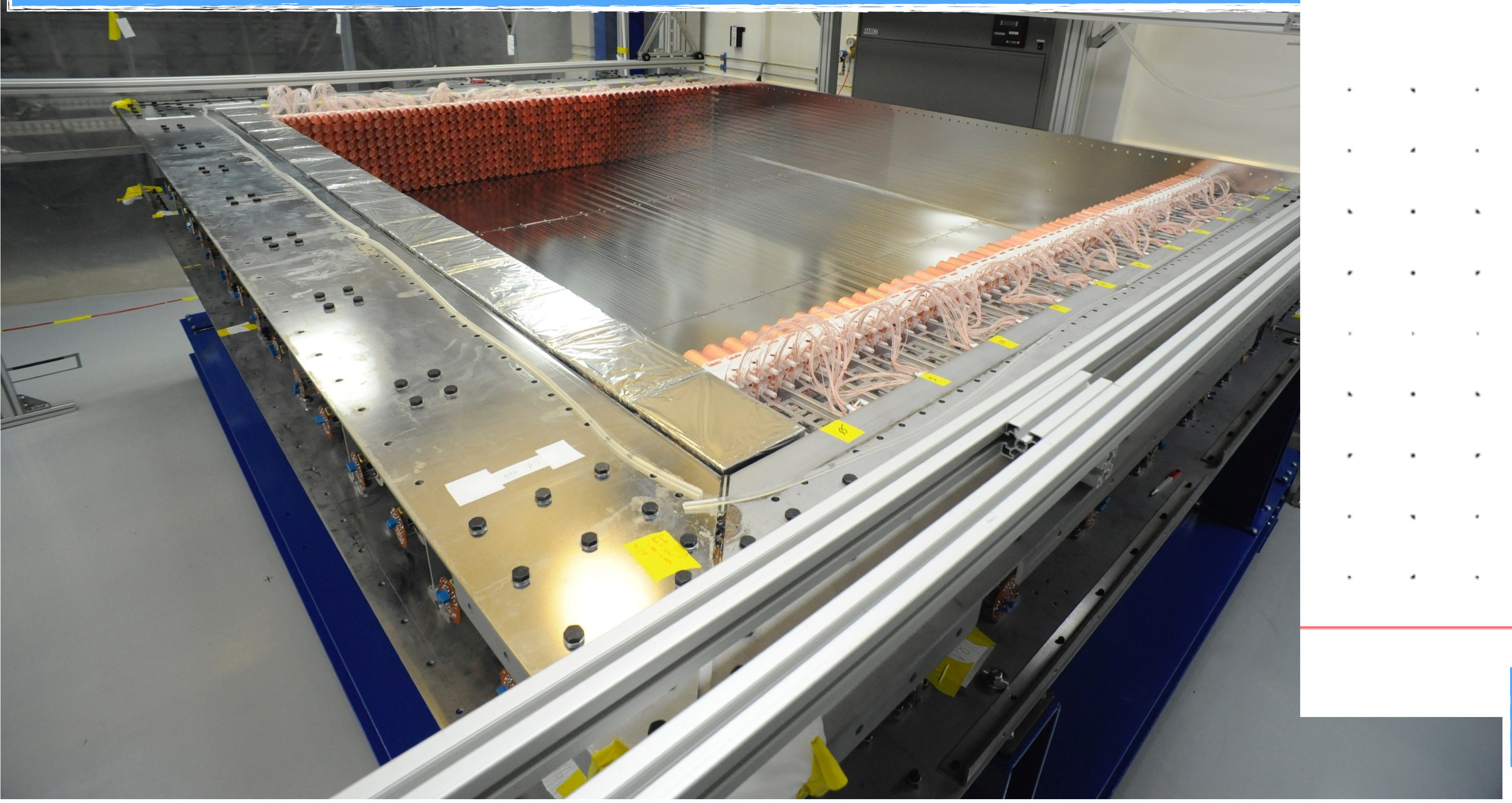
Tracker Cell Production

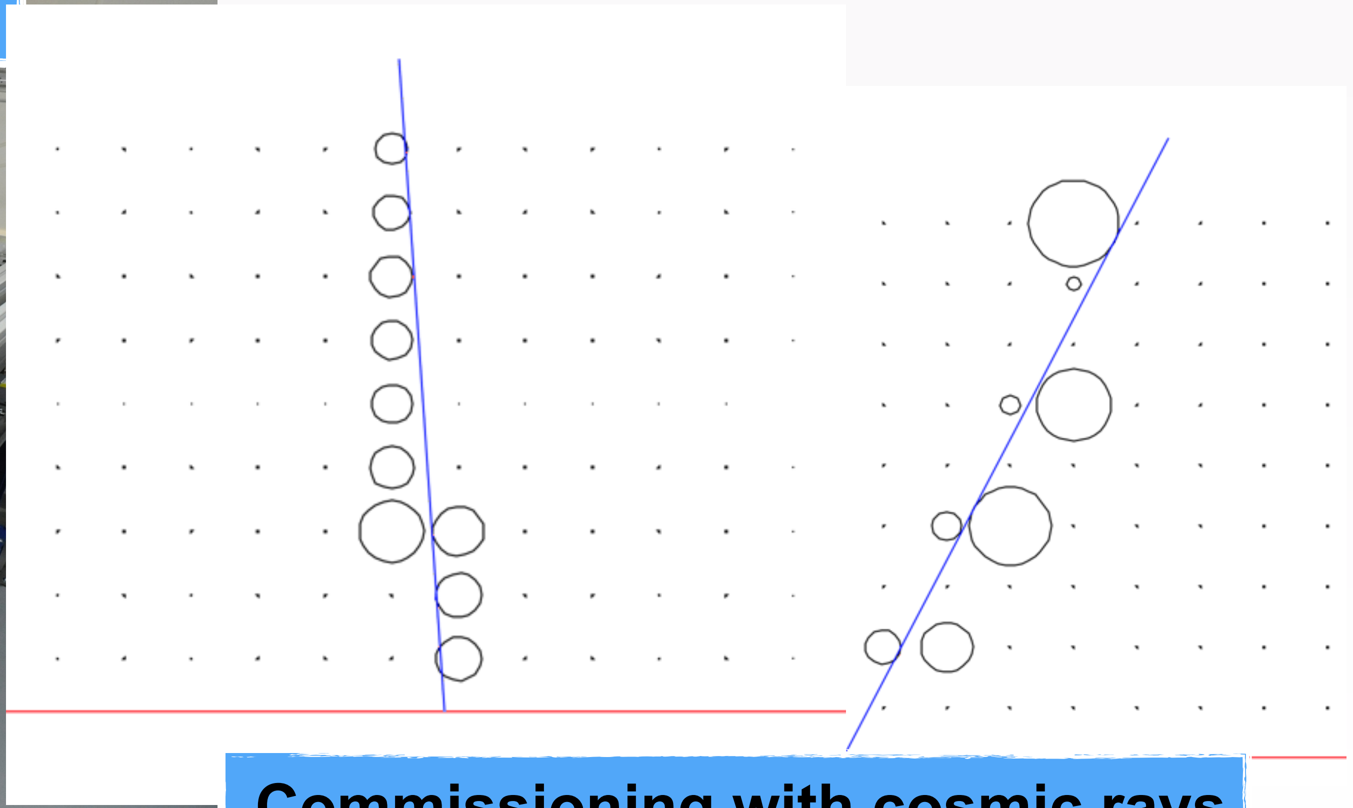


Tracker Assembly and Commissioning

2nd quarter-tracker (“C1”) by mid-Jun — half of tracker ready.
C0 to be shipped to LSM in July

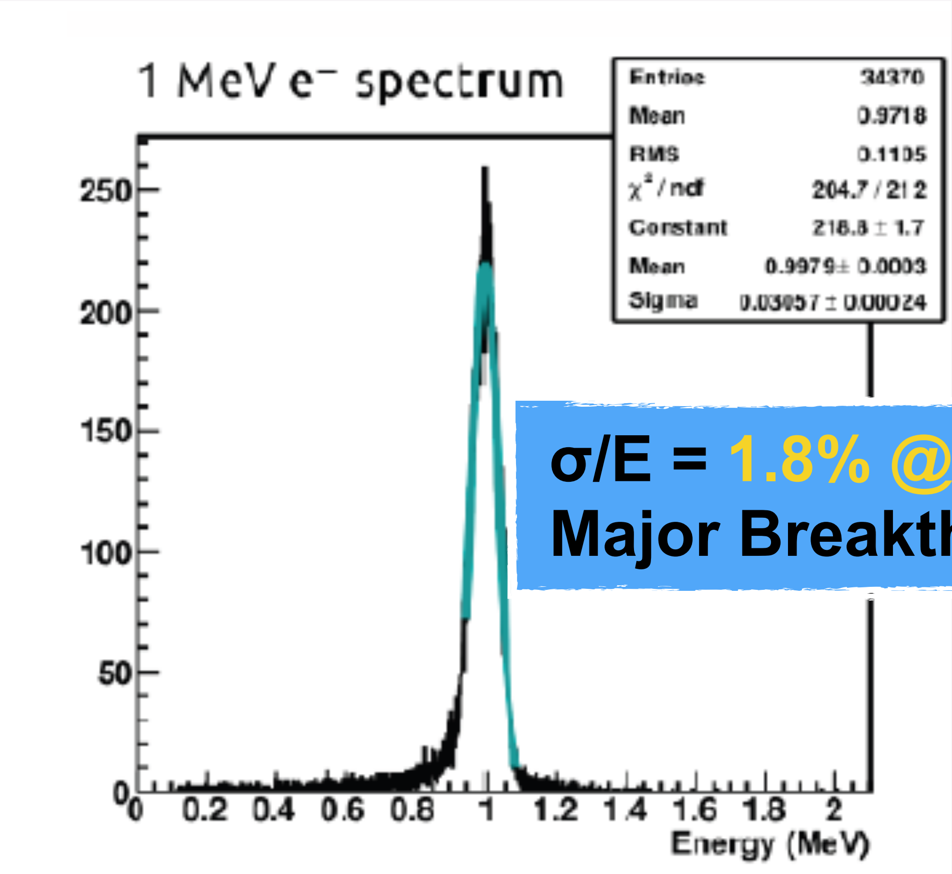
1st quarter-tracker (“C0”)
Rn emanation from fully assembled detector
Target (150 μBq/m^3) within reach!



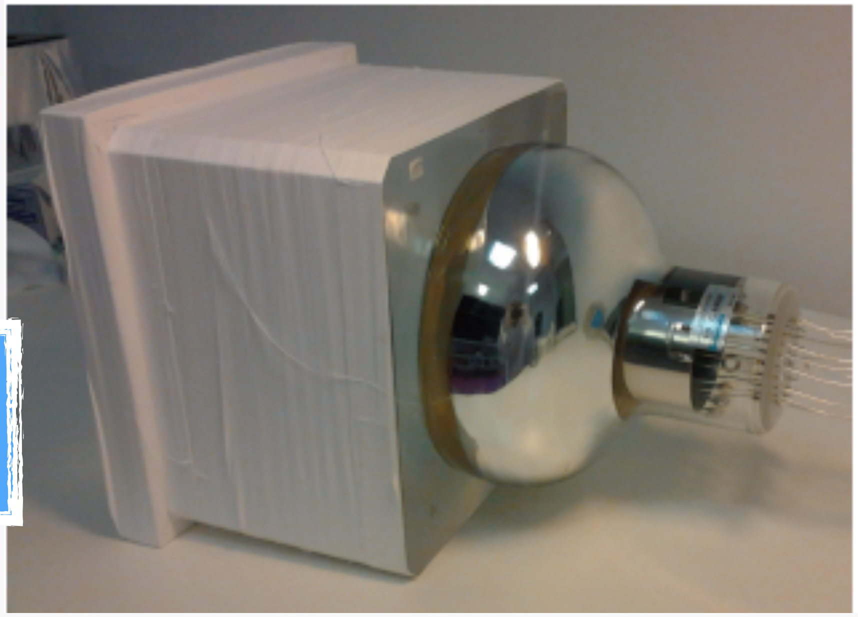


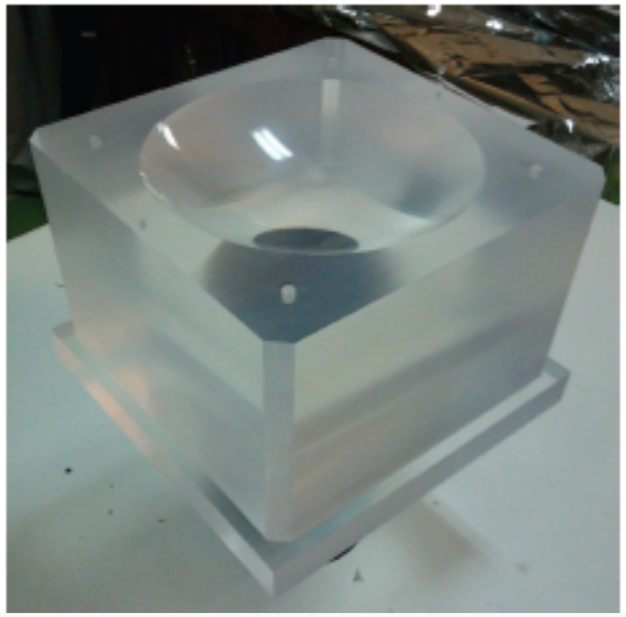
Commissioning with cosmic rays

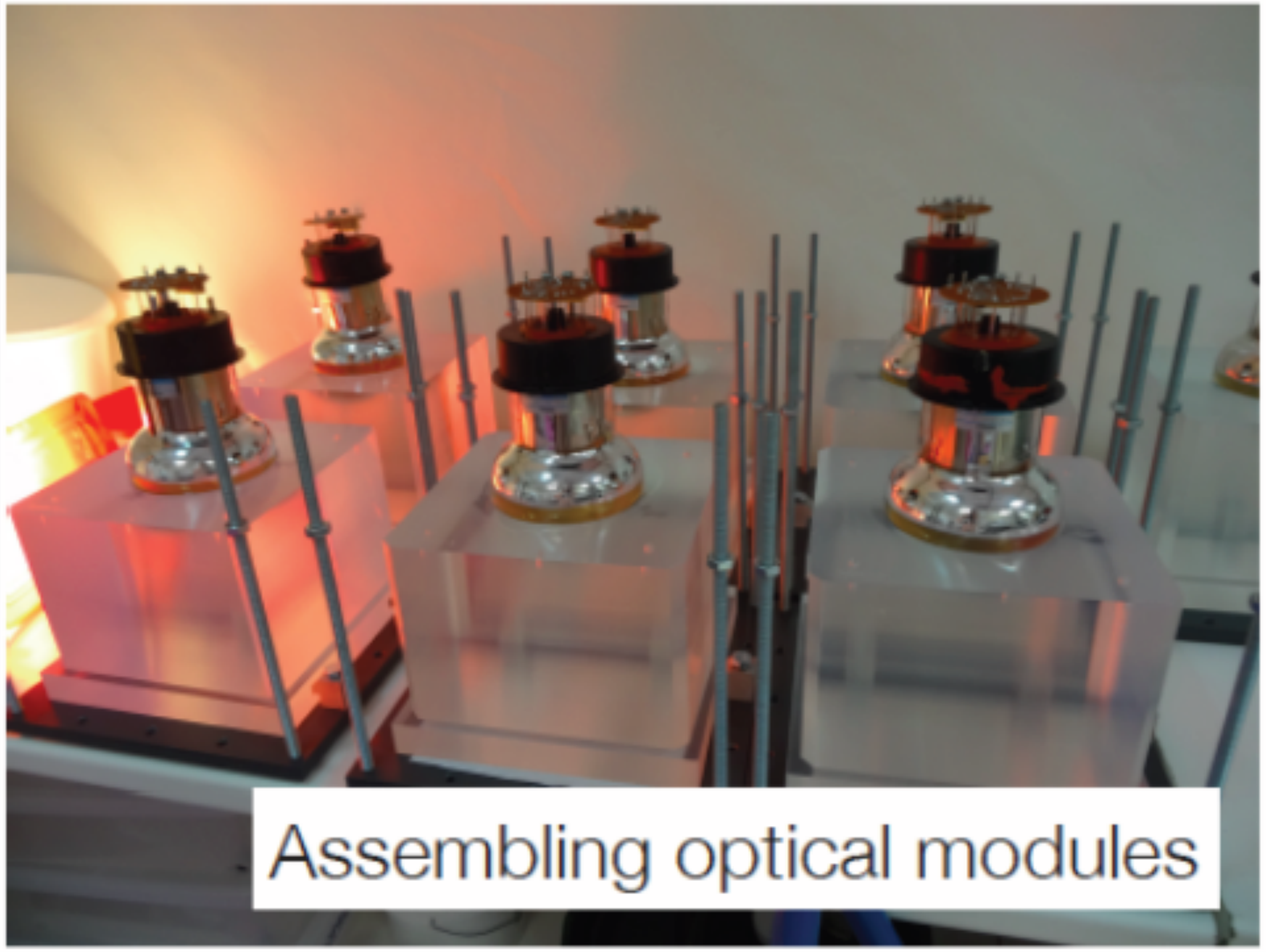
Calorimeter Production



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



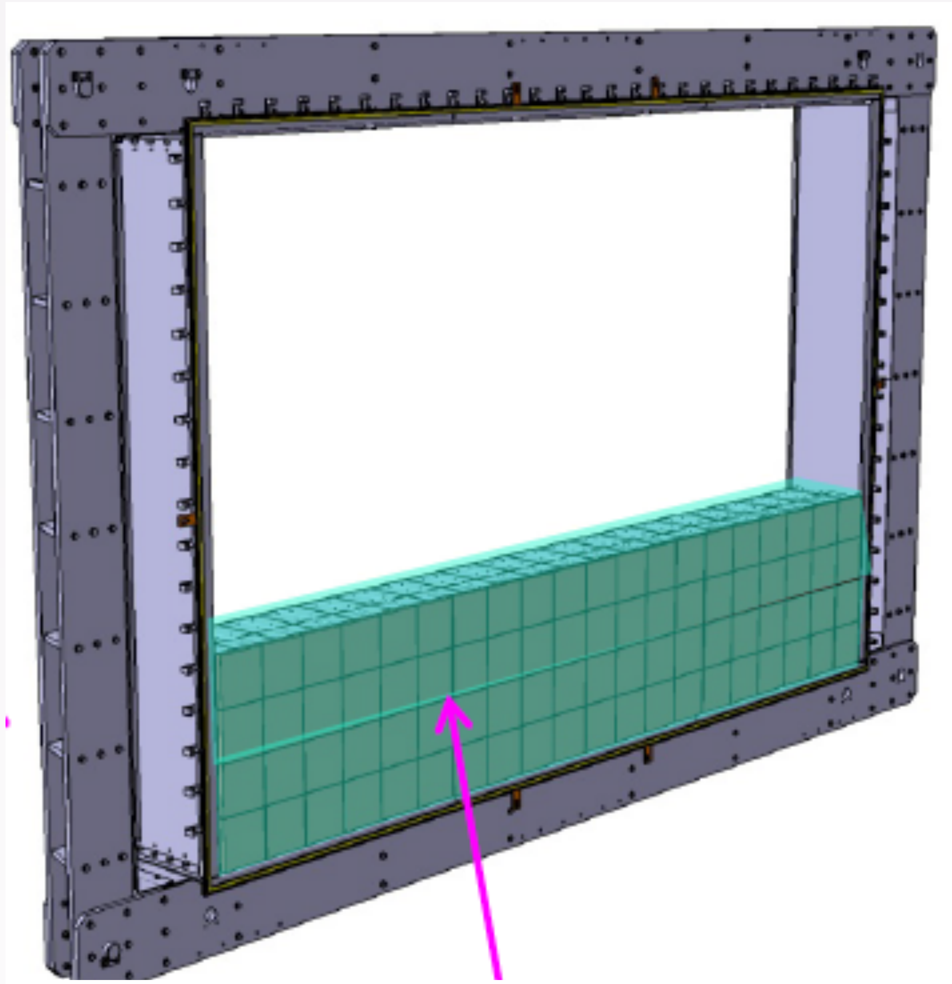


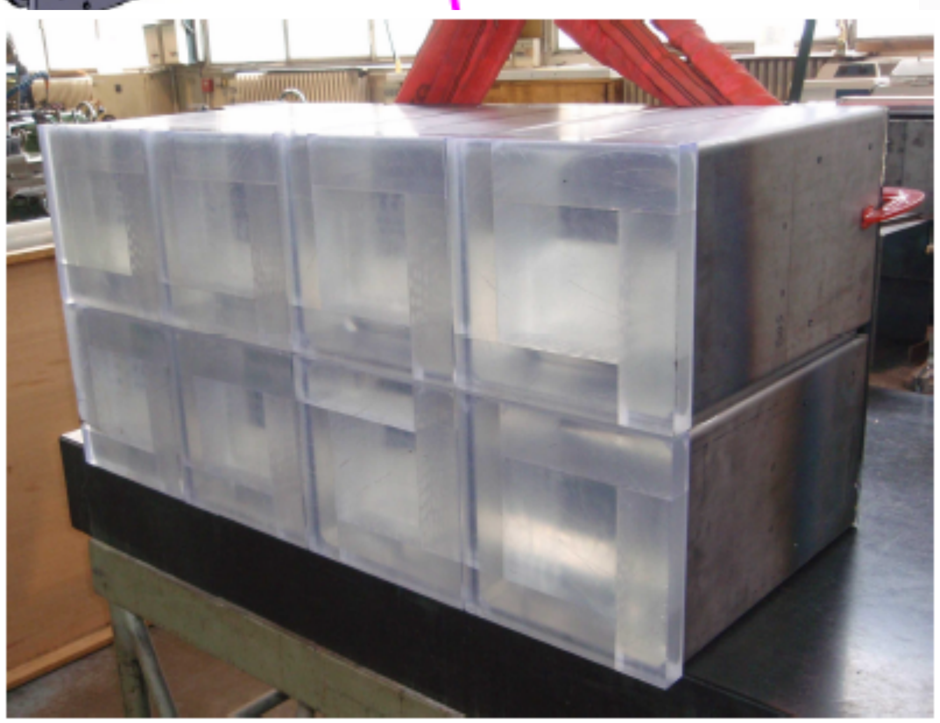


Assembling optical modules

- 8” PMTs with large blocks (440 modules)
- 5” PMTs in outer rows/columns, endcaps and veto
- Production in full swing

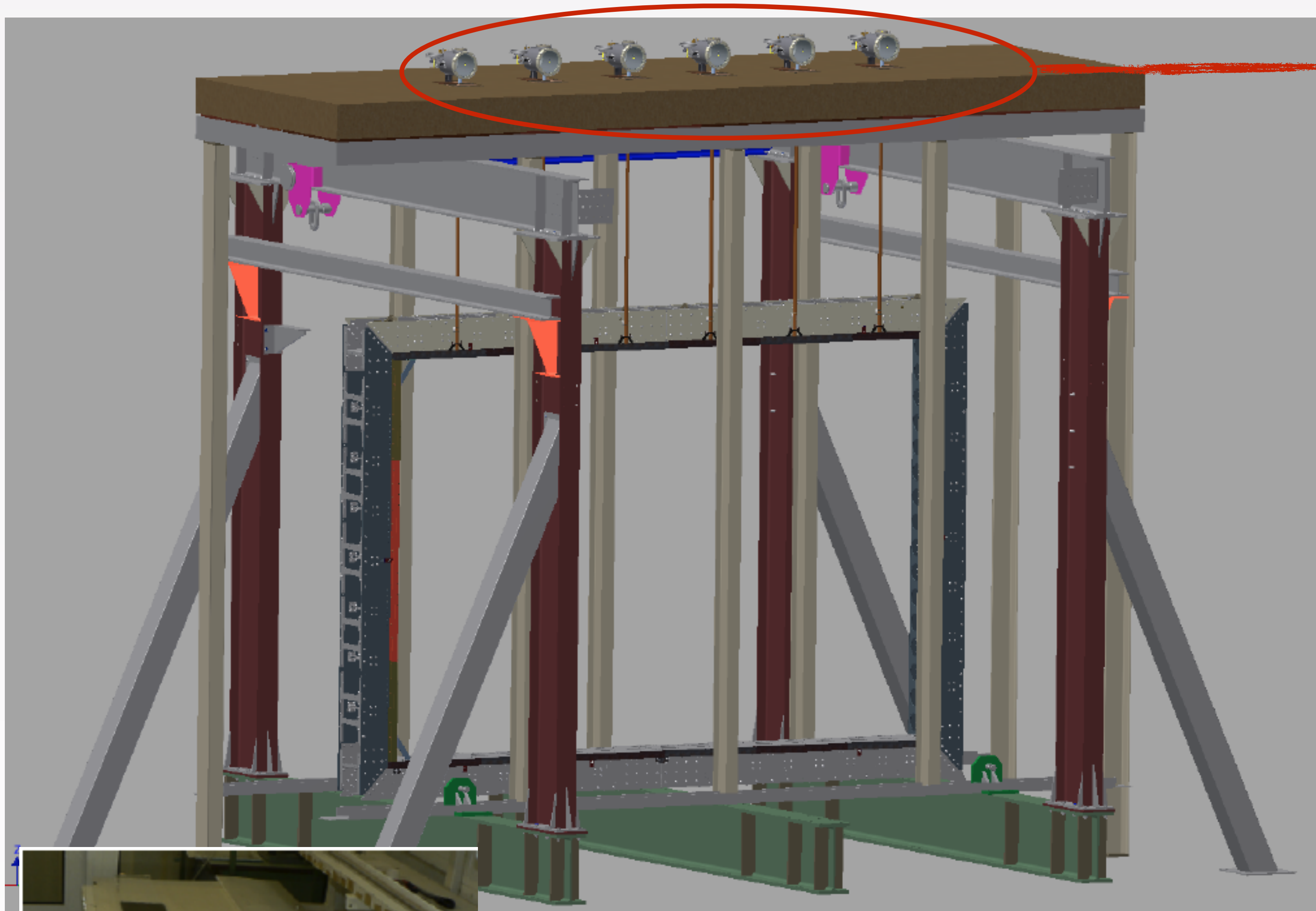
Calorimeter Integration

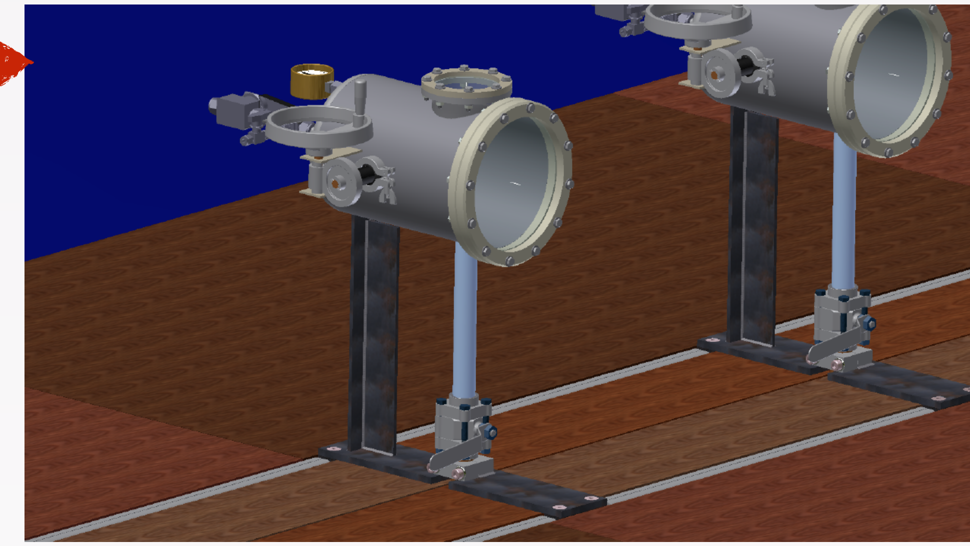




- 1st Calorimeter wall assembled at **LSM** in **autumn 2015,** 2nd — **spring 2016**
- Light Injection calibration system to monitor gain drift within 1%

ββ Source Module and Calibration Sources Deployment System





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

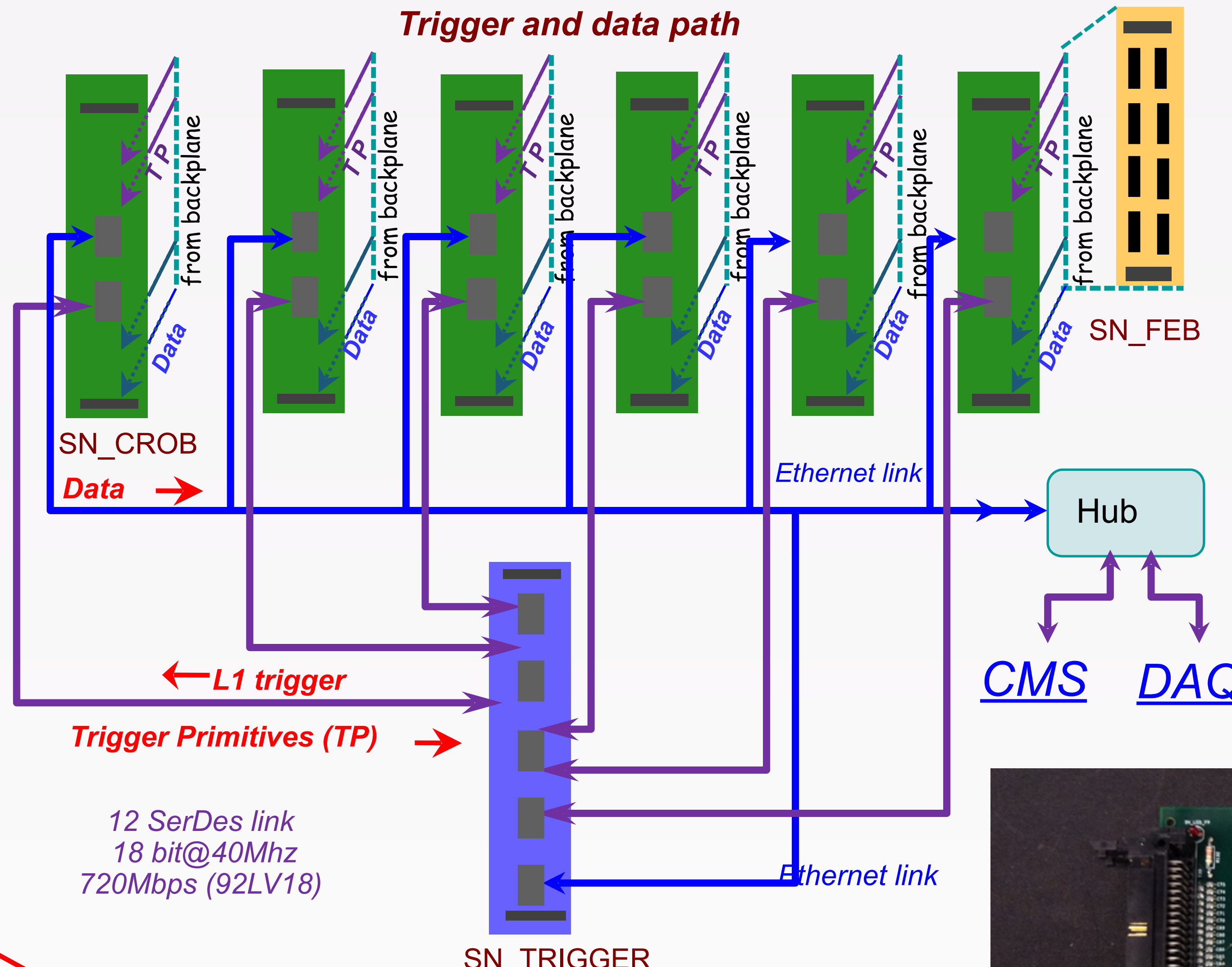
- 7kg ^{82}Se produced, 4.5kg purified
- R&D on ^{150}Nd and ^{48}Ca

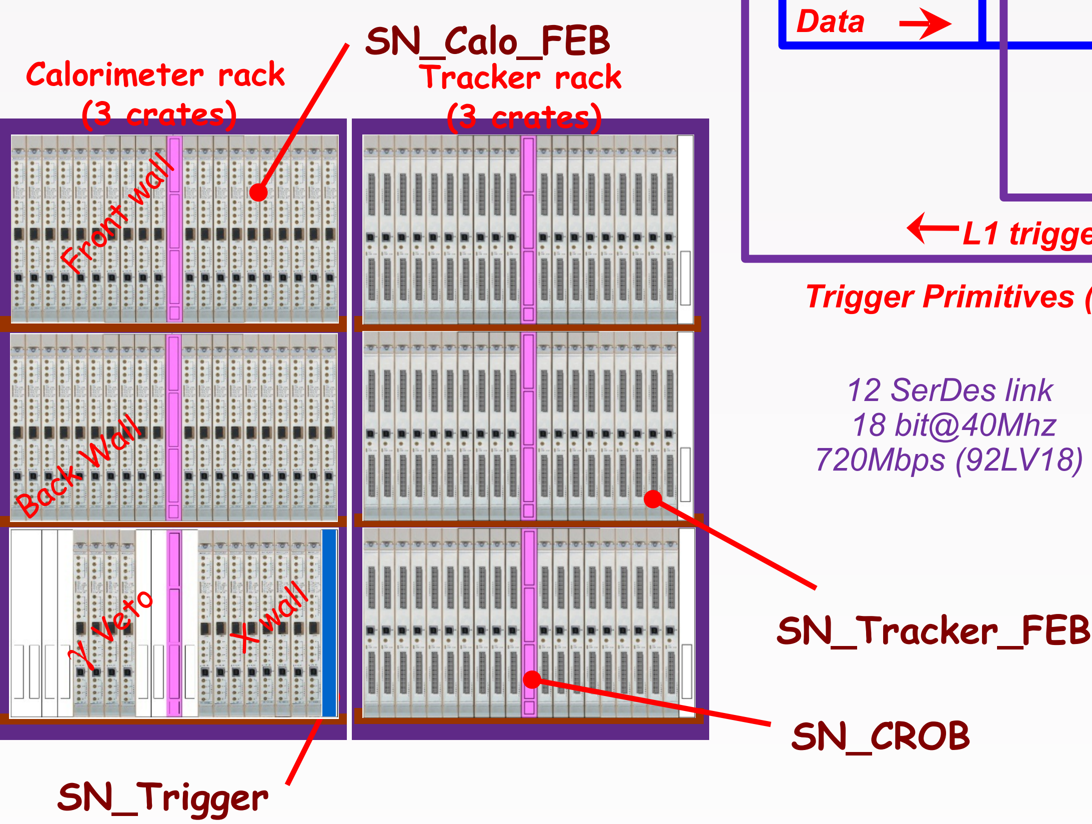
^{82}Se foil production at ITEP

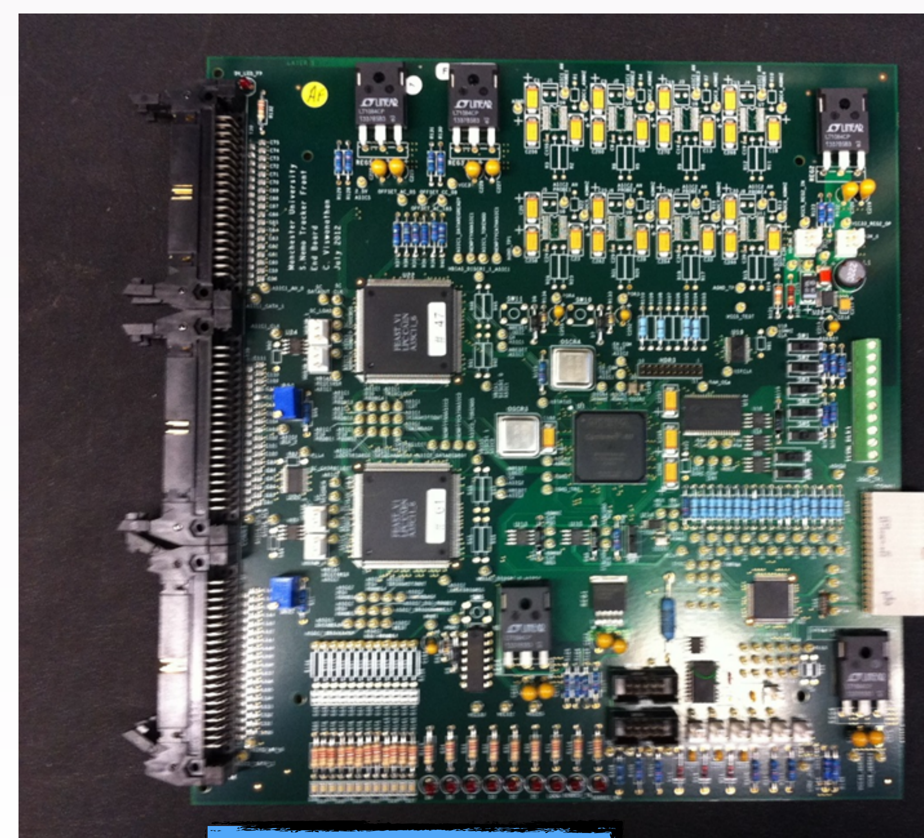
^{82}Se foil production at LAPP

Electronics, Slow Control and DAQ

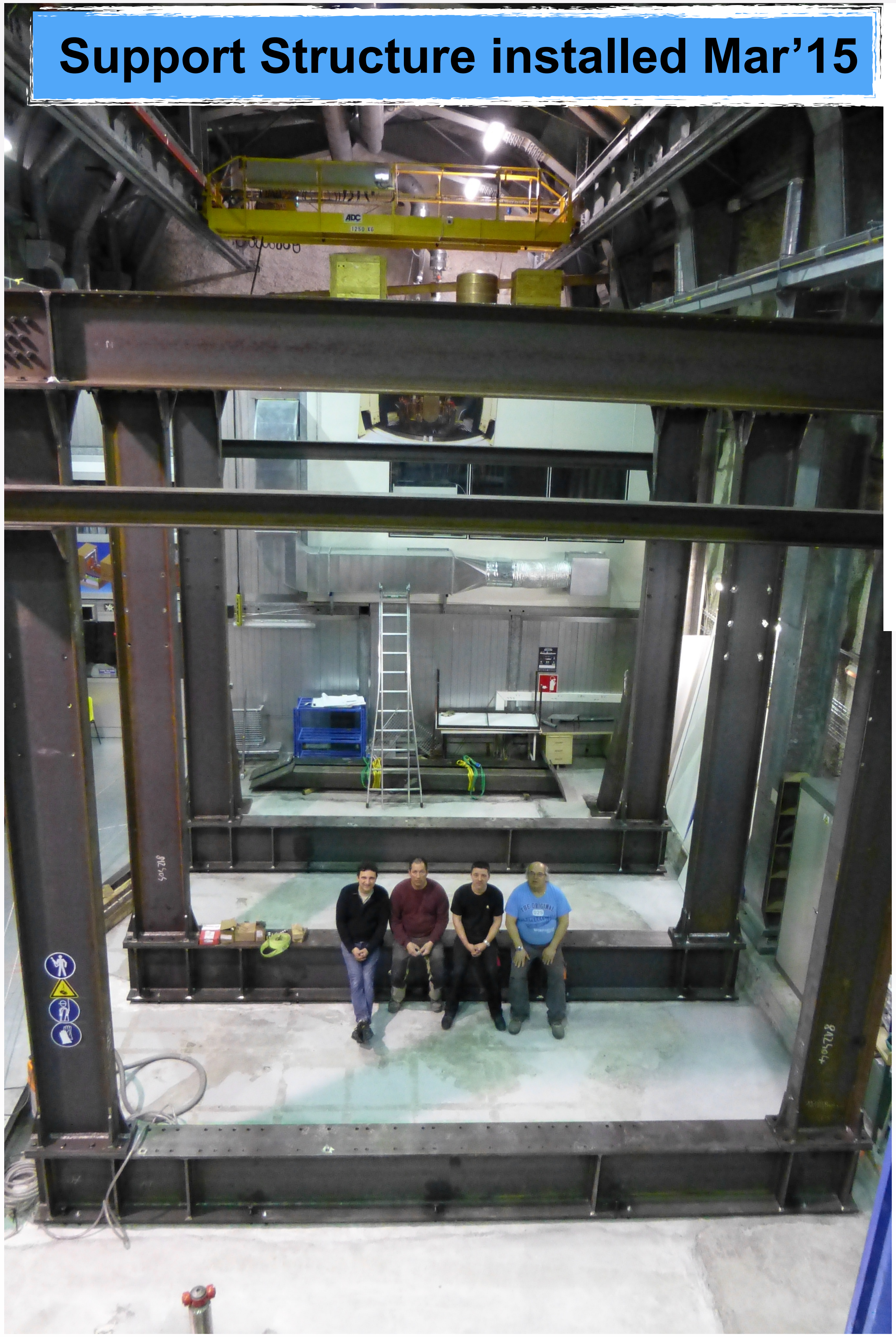
- **Electronic architecture (demonstrator):**
  - **52 Calorimeter FEB (712 Channels).**
  - **57 Tracker FEB (6102 channels).**
  - **6 Control and Readout Board.**
  - **1 Trigger board.**

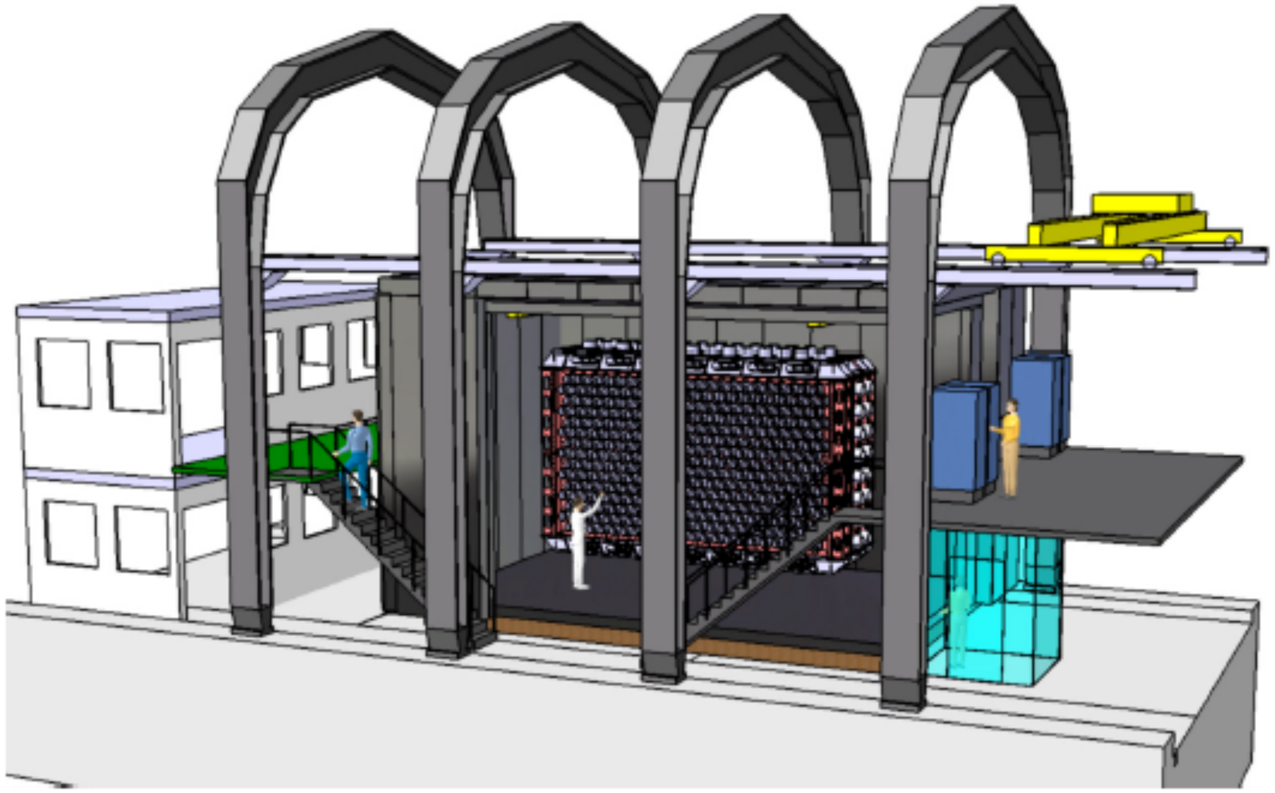






Tracker FEB

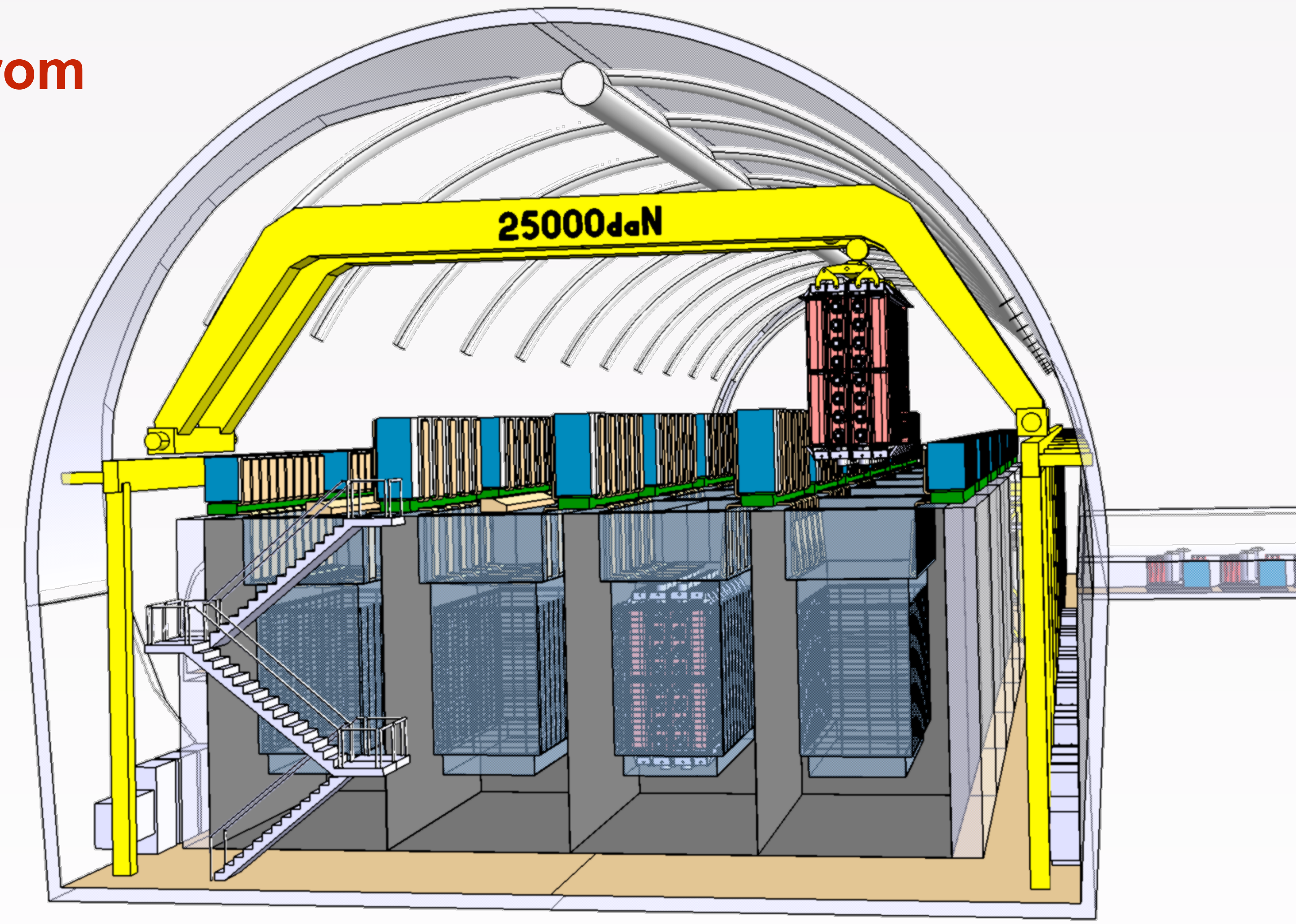




- **Installation at LSM in 2015-2016**
- **Commissioning of assembled detector 2016**
- **External BG run (passive shielding off end 2016**
- **ββ physics run starts 2017**

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

- **Straightforward extrapolation from Demonstrator**



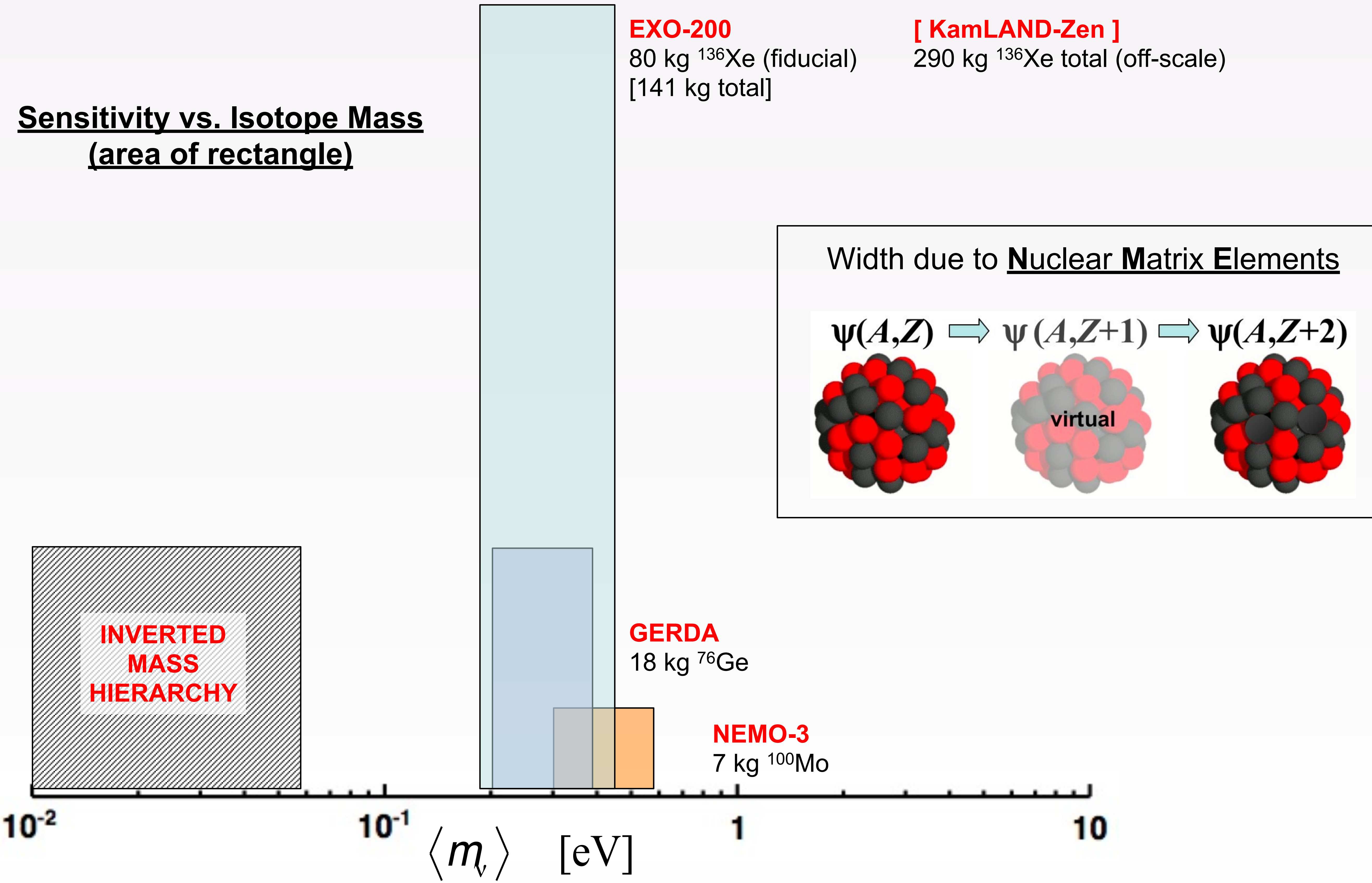
- Distributed location in different underground labs possible/ beneficial
- Construction in parallel with data taking (2017-2020)
- Cost range: €2M/module (capital)
- Ideas to reduce cost and footprint

Concluding Remarks

- NEMO-3/SuperNEMO approach is **unique**
  - **Event topology** fully reconstructed - **smoking gun** signature and comprehensive **background characterisation**
  - Isotope **flexibility**
  - **Modularity.** Possible distributed location in different underground labs.
- NEMO-3 results **demonstrated** the power of modest mass/ultra-low background approach
  - ^{100}Mo: $T_{1/2} > 1.1 \times 10^{24}$ yr, $\langle m_\nu \rangle < 0.33 - 0.62$ eV, 90%CL. Other lepton violating mechanisms probed.
  - Unprecedented **$2\nu\beta\beta$ measurements**: input for **NME** calculations, **$2\nu\beta\beta$** to excited states
- SuperNEMO **Demonstrator** to **start** taking data in **2016**
- **Full SuperNEMO** schedule depends on Demonstrator — **straightforward extrapolation** with ultimate sensitivity of **40 — 100 meV**
  - $2\nu\beta\beta$ results, excited states, non-$\beta\beta$ physics (e.g. Lorentz violation)
- In case of *O*(**0.1 eV**) discovery — best way for **full characterisation** of **$0\nu\beta\beta$** (isotope flexibility, physics mechanism through topology)

BACKUP

Sensitivity vs. Isotope Mass (area of rectangle)



Boulby Underground Laboratory (UK)

A NEW LABORATORY now being built at Boulby
To replace current facility and host planned & new projects for the next decade and more…

Fully-equipped 1000m^2 lab. Class 10K & 1K clean room throughout. 5-10T lifting capacity.

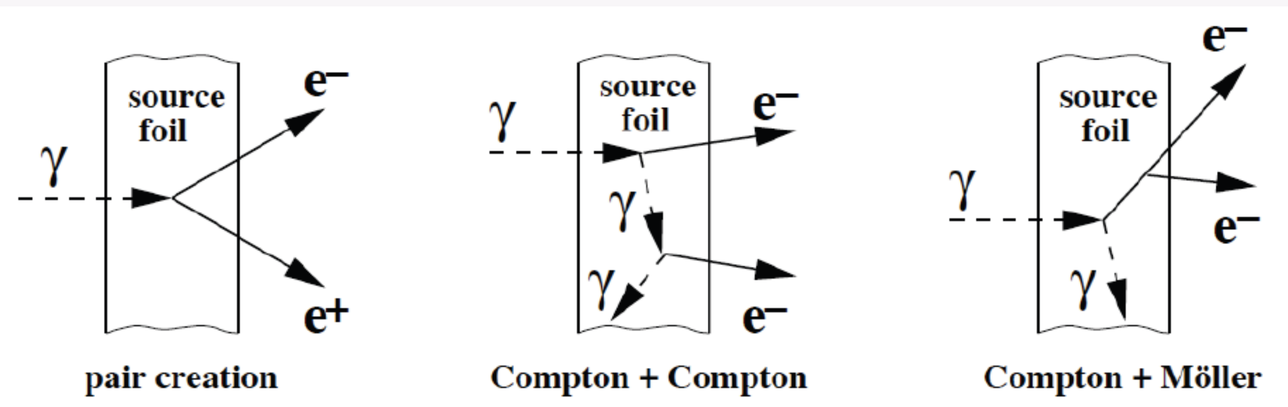
Project completion date: end 2015

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

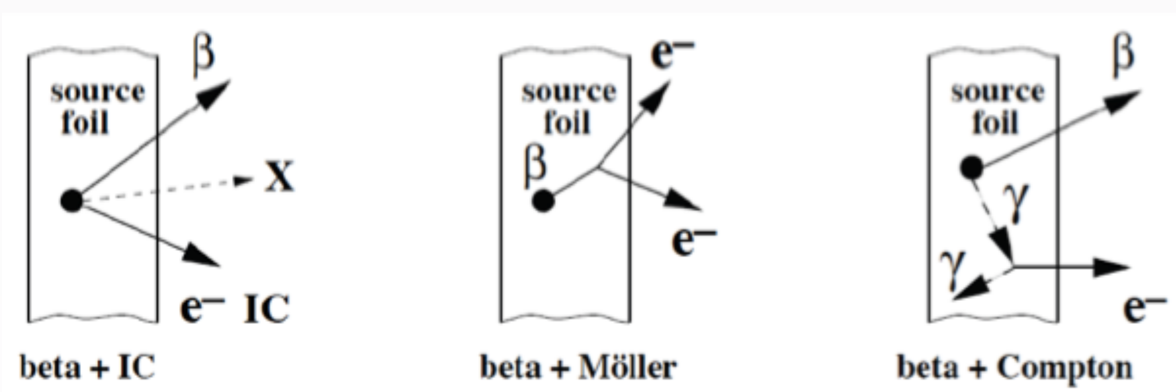
  Origin: natural radioactivity of the detector or neutrons

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

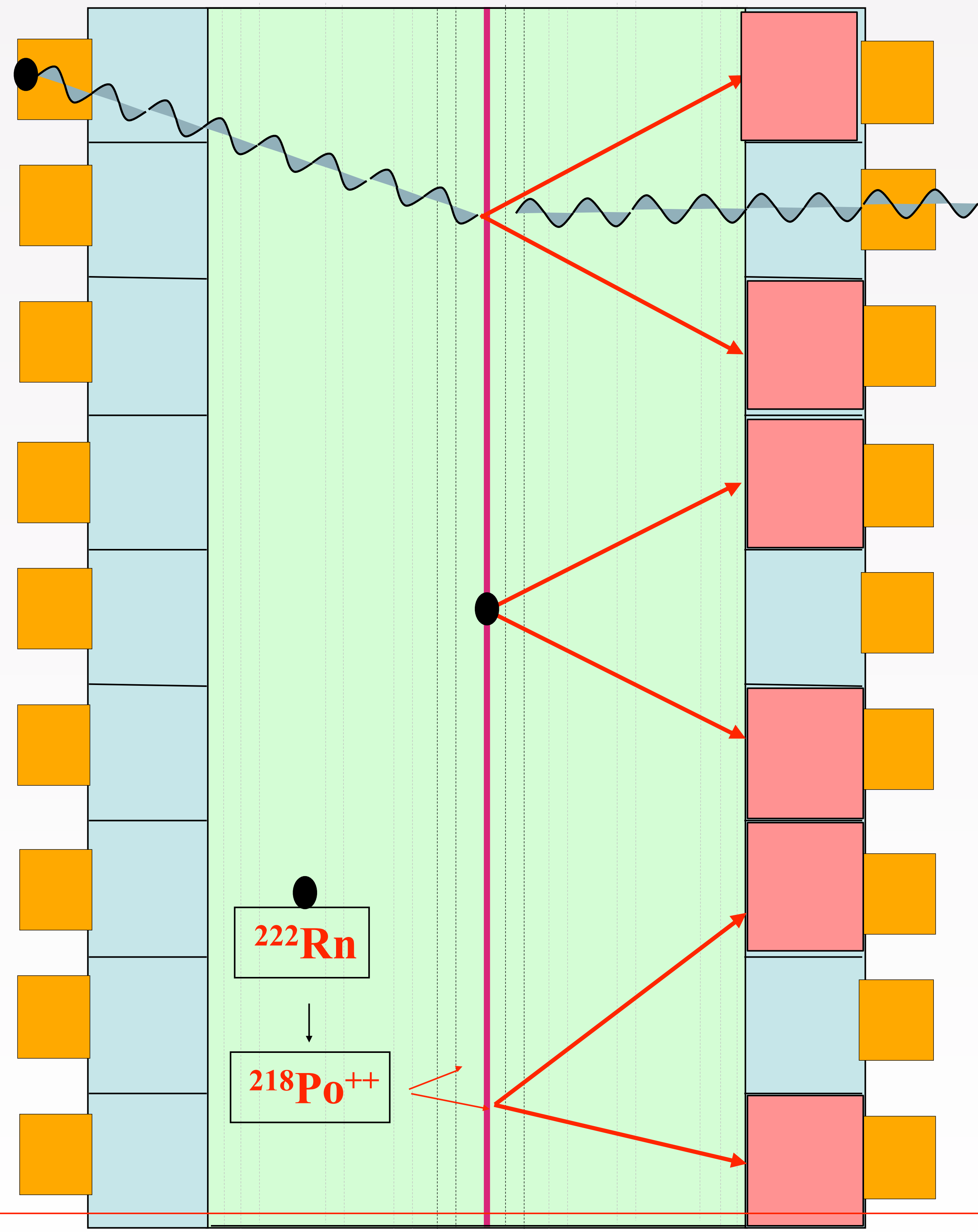
  (^{100}Mo and ^{82}Se $Q_{\beta\beta}\sim$ 3 MeV > $E\gamma(^{208}$Tl) ~ 2.6 MeV)



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

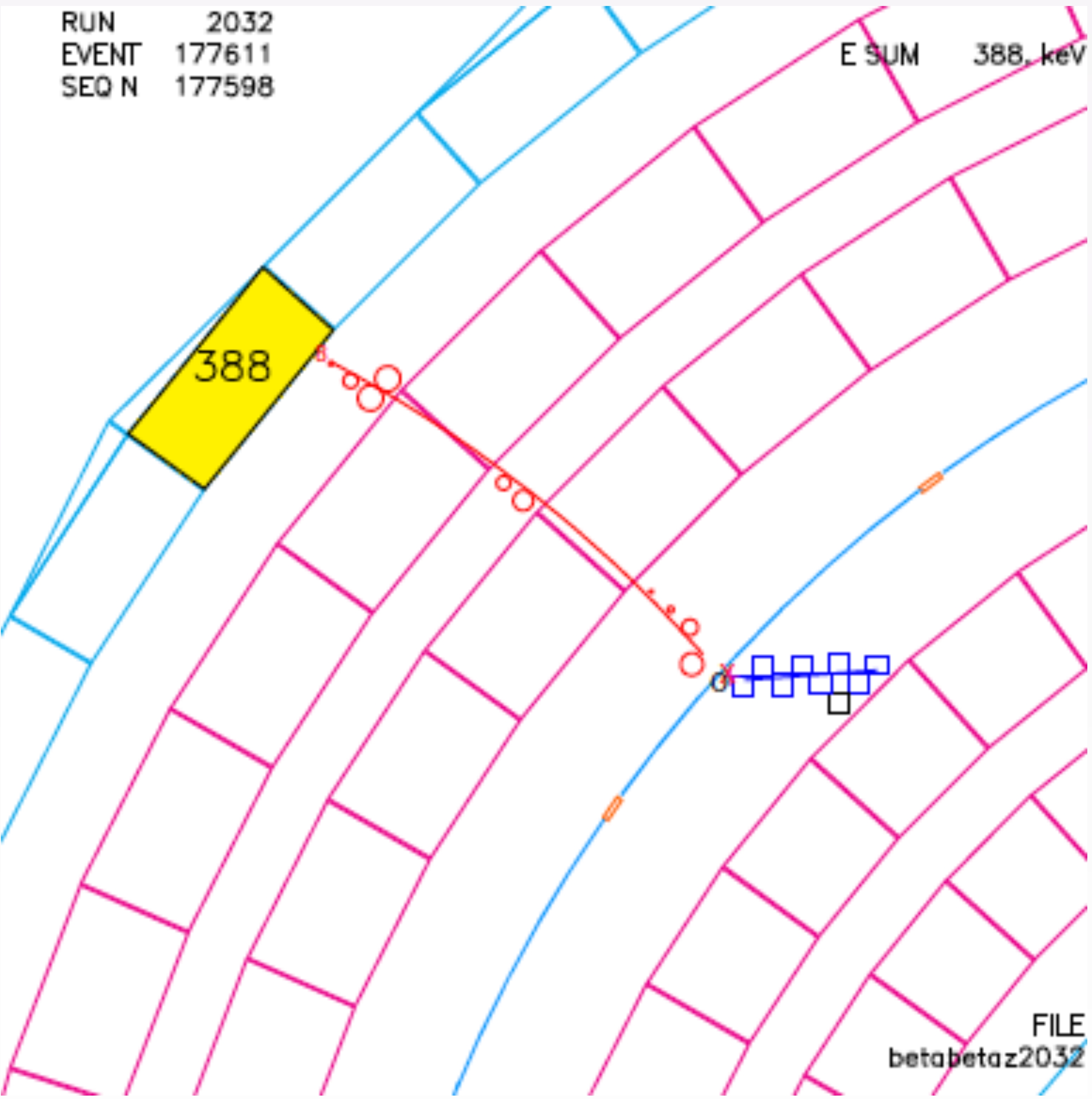


- **Radon (^{214}Bi) inside the tracking detector**
  - deposits on the wire near the $\beta\beta$ foil
  - deposits on the surface of the $\beta\beta$ foil

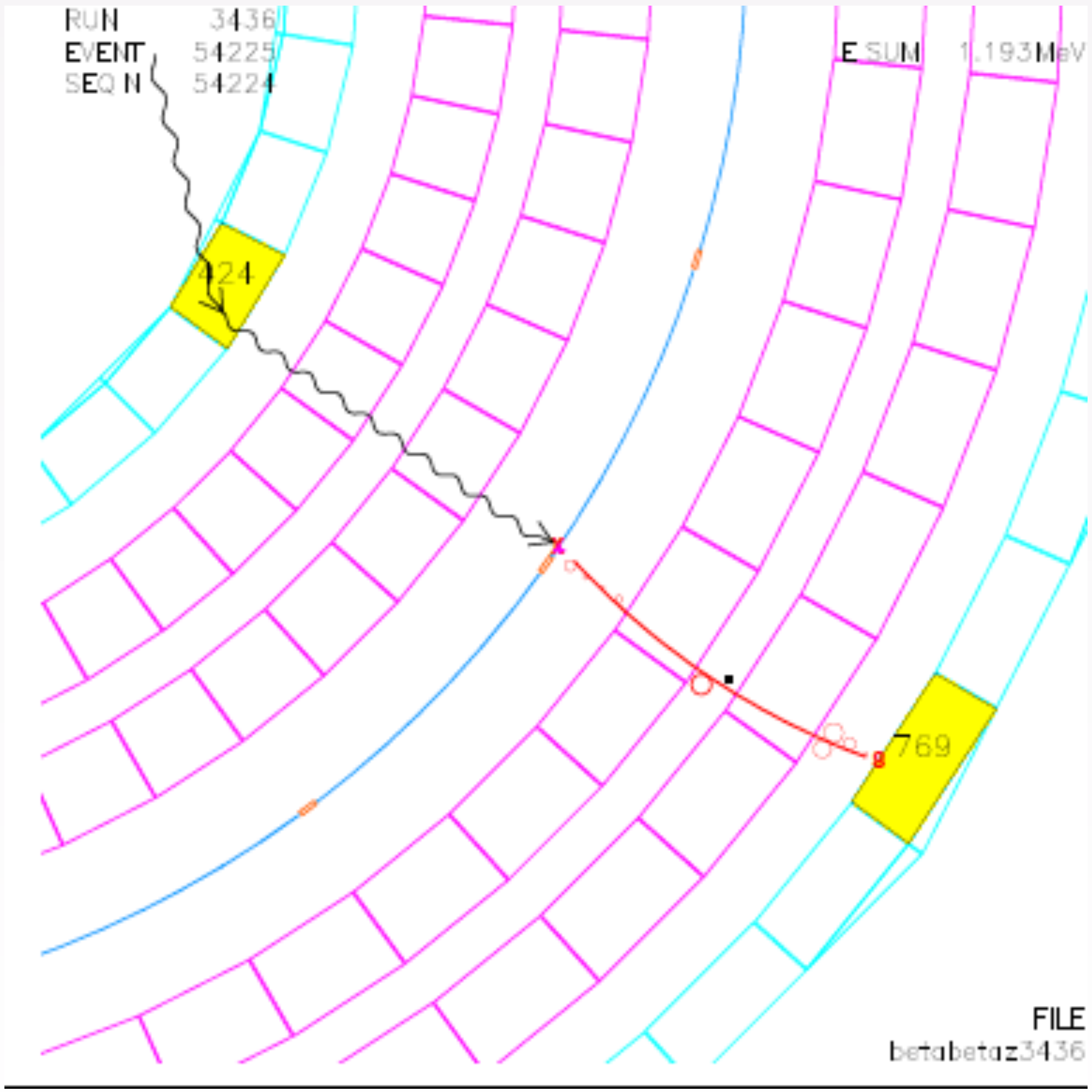


Each bkg is measured using the NEMO-3 data

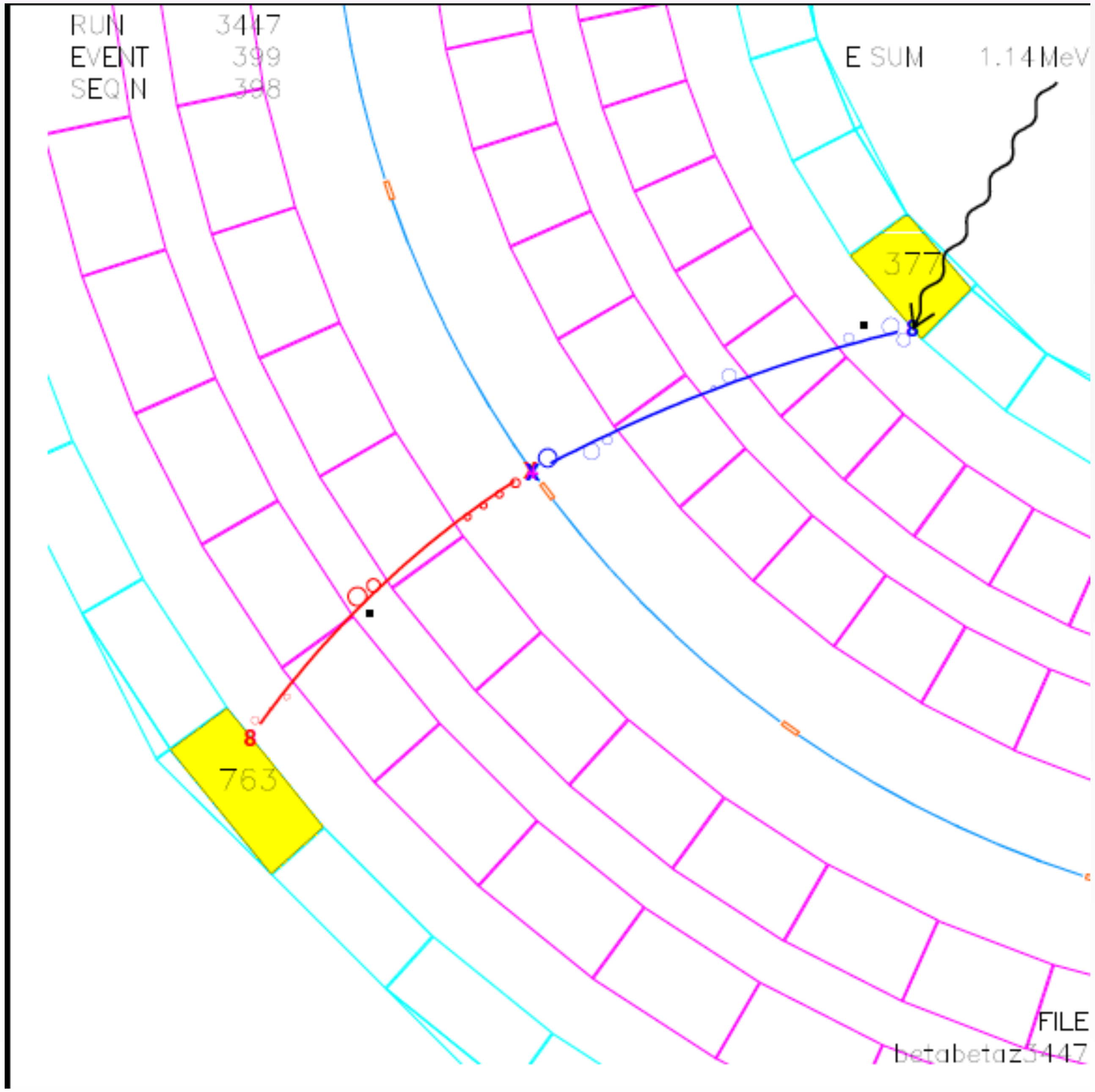
1e1α ($^{214}Bi \longrightarrow {}^{214}Po$)

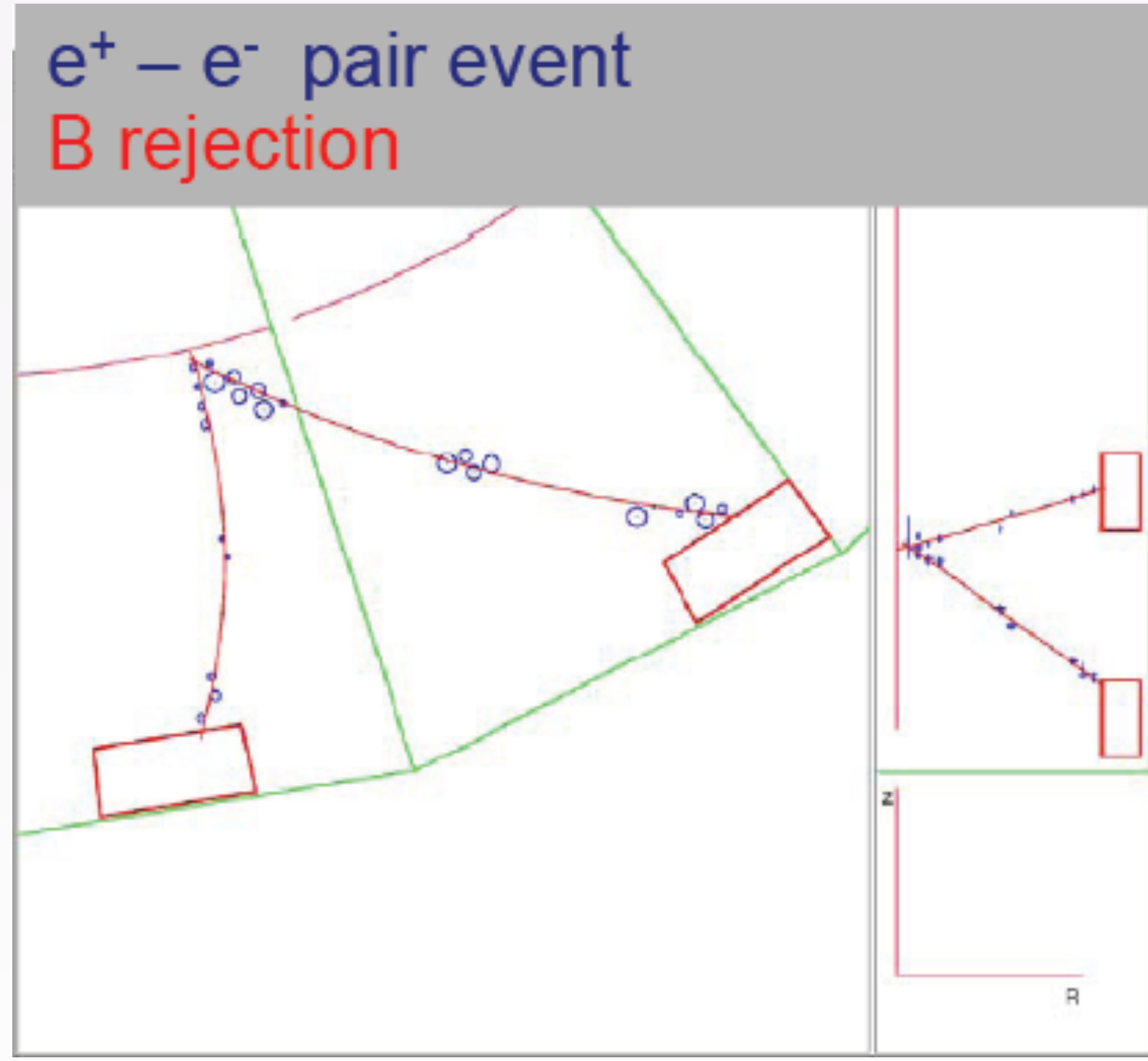


External γ



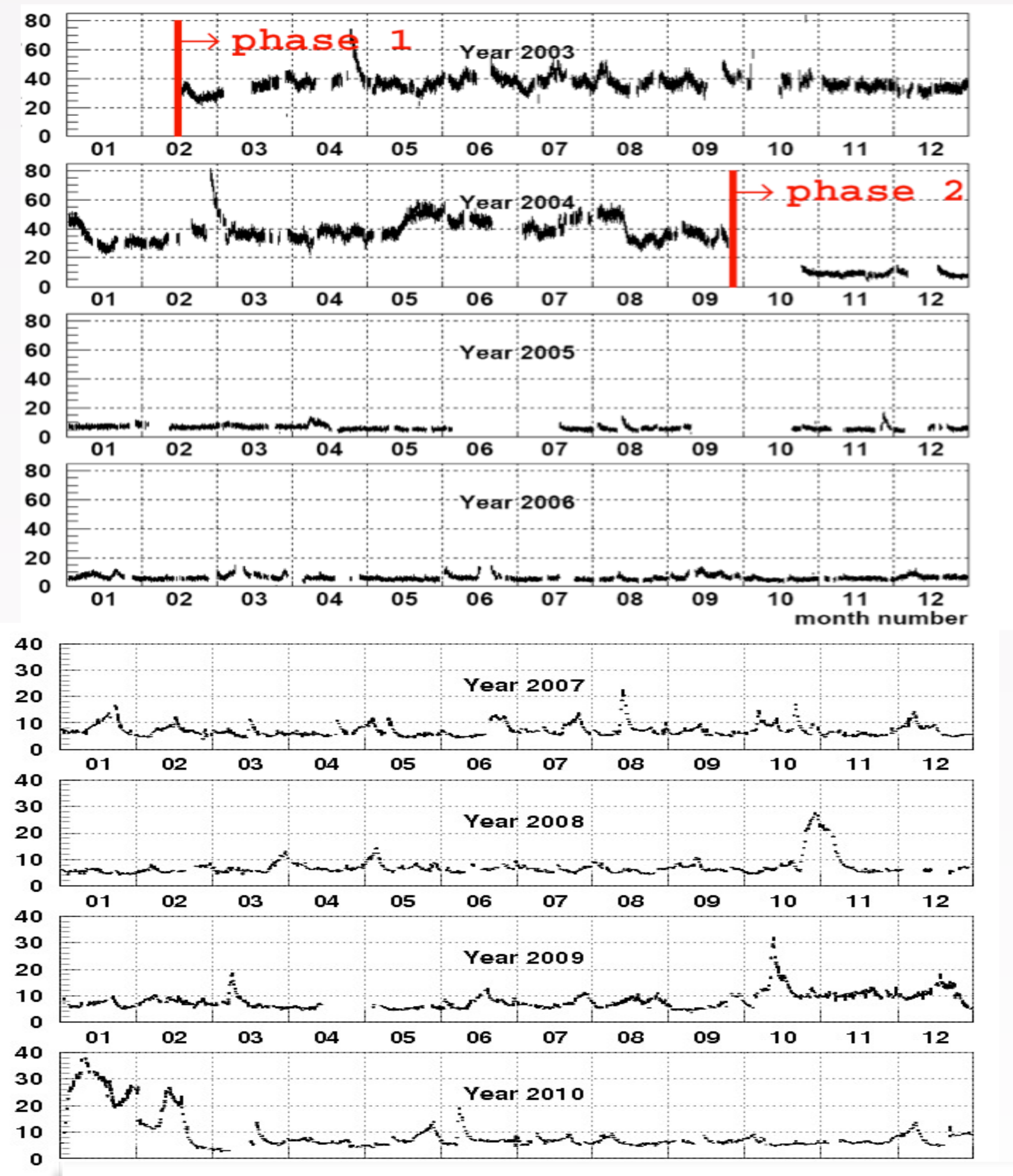
Crossing electron (external BG)





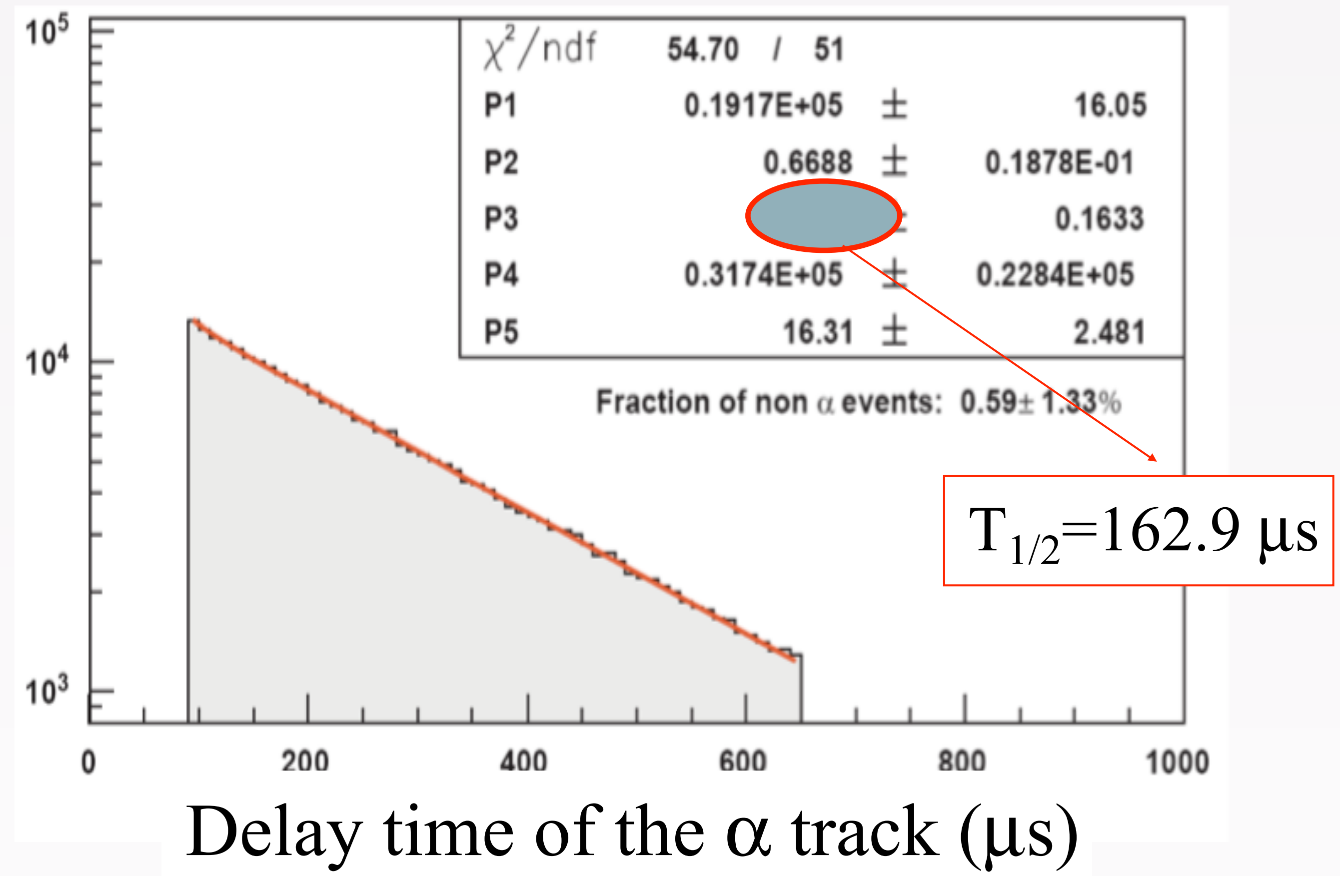
Anti-radon "factory" - trapping Rn in cooled charcoal. A must for a low-background lab.

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

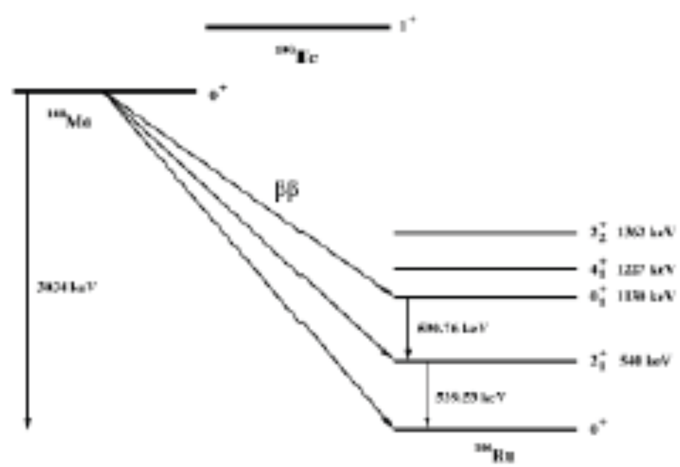


Anti-Rn factory: Input=15Bq/m^3 →Output 15mBq/m^3

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:

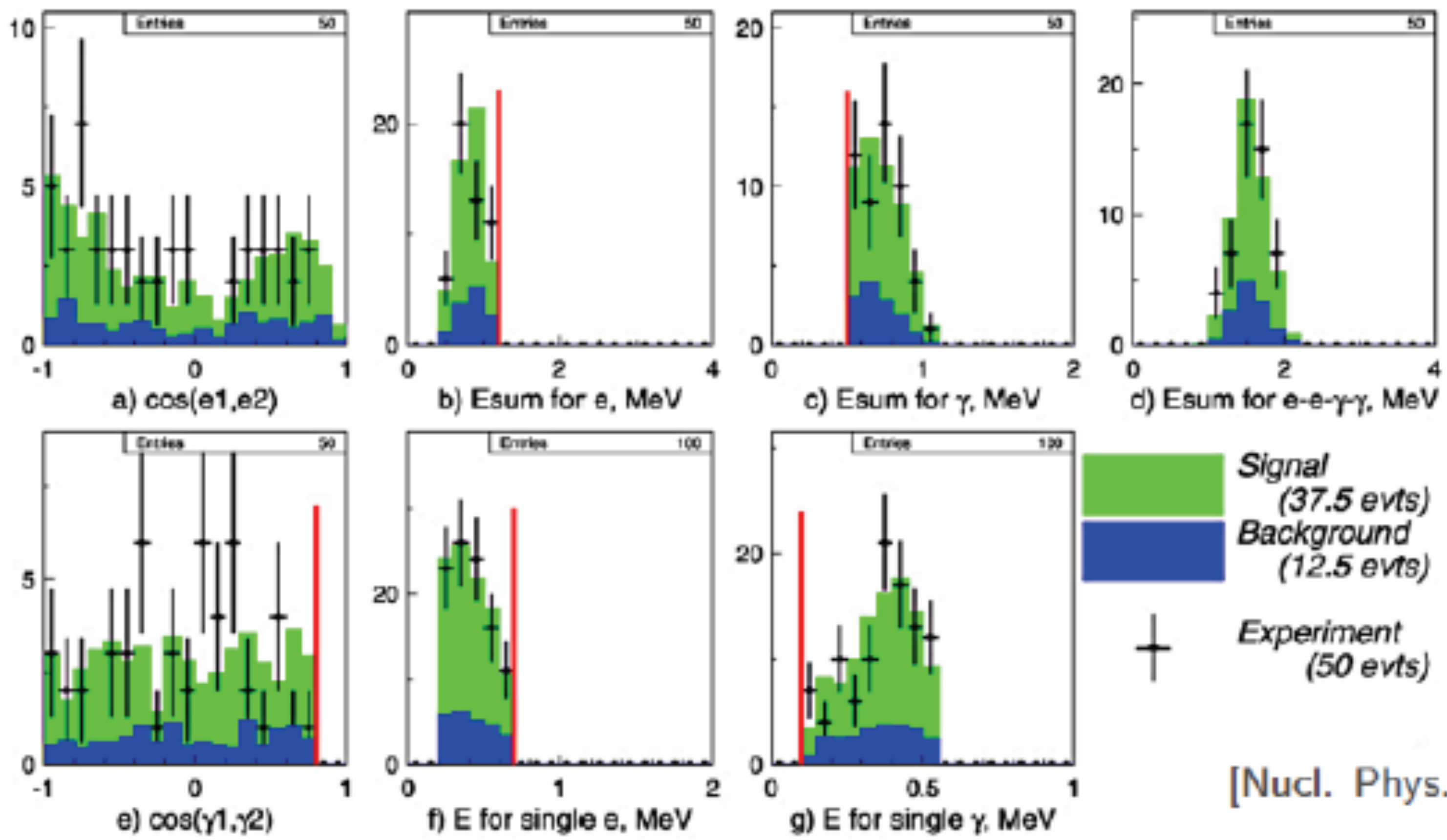
$\mathcal{T}^{2\nu}_{1/2}(0^+ \rightarrow 0^+_1) = 5.7\ ^{+1.3}_{-0.9}$ (stat) $\pm$ 0.8 (stat) 10^{20} y

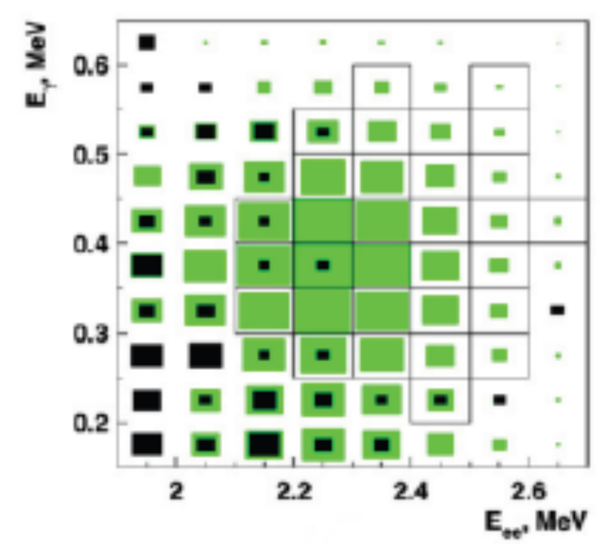
$\mathcal{T}^{2\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.1\ 10^{21}$ y @ 90 % CL

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

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

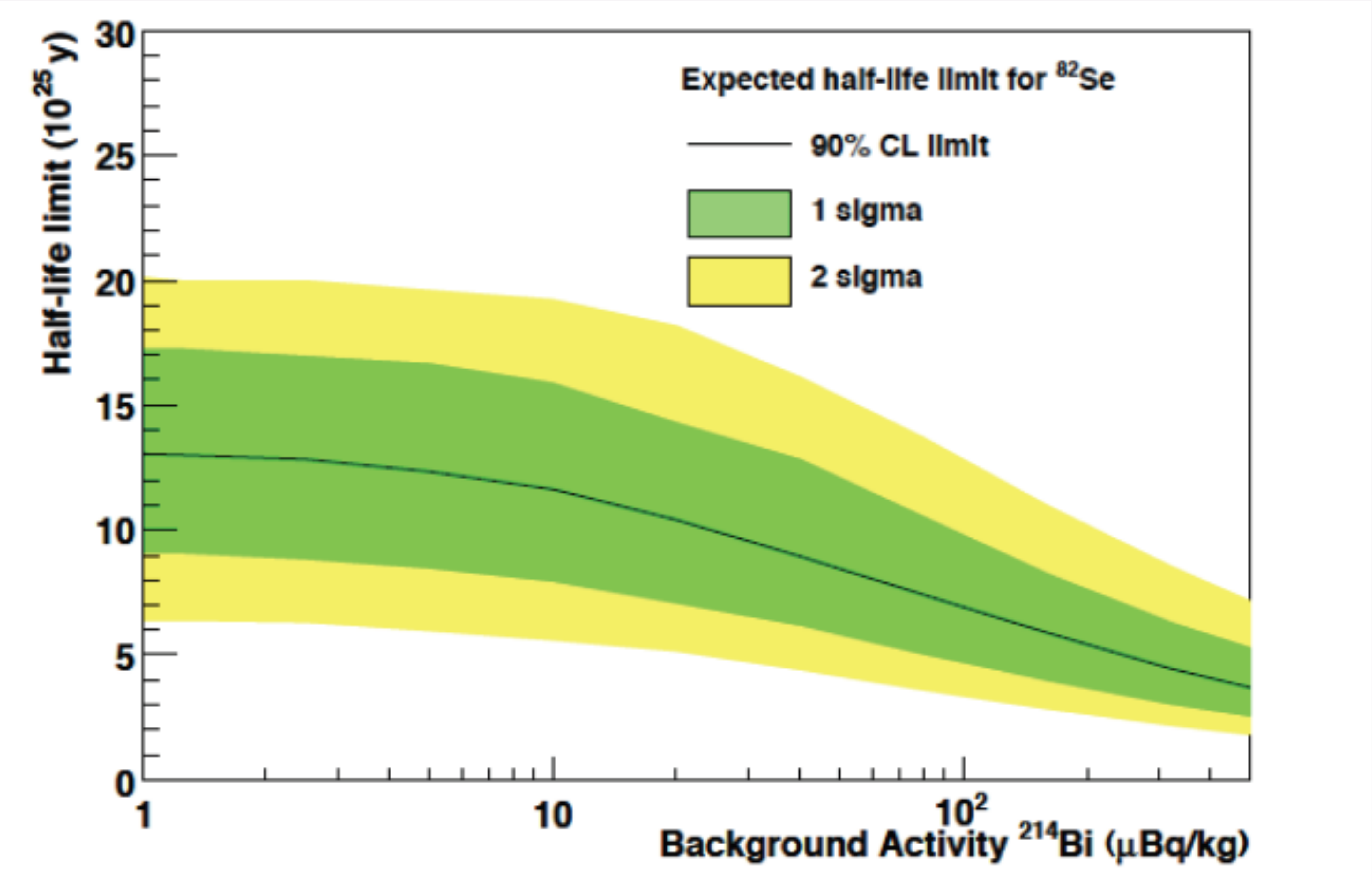
$\mathcal{T}^{0\nu}_{1/2}(0^+ \rightarrow 2^+_1) > 1.6\ 10^{23}$ y @ 90 % CL



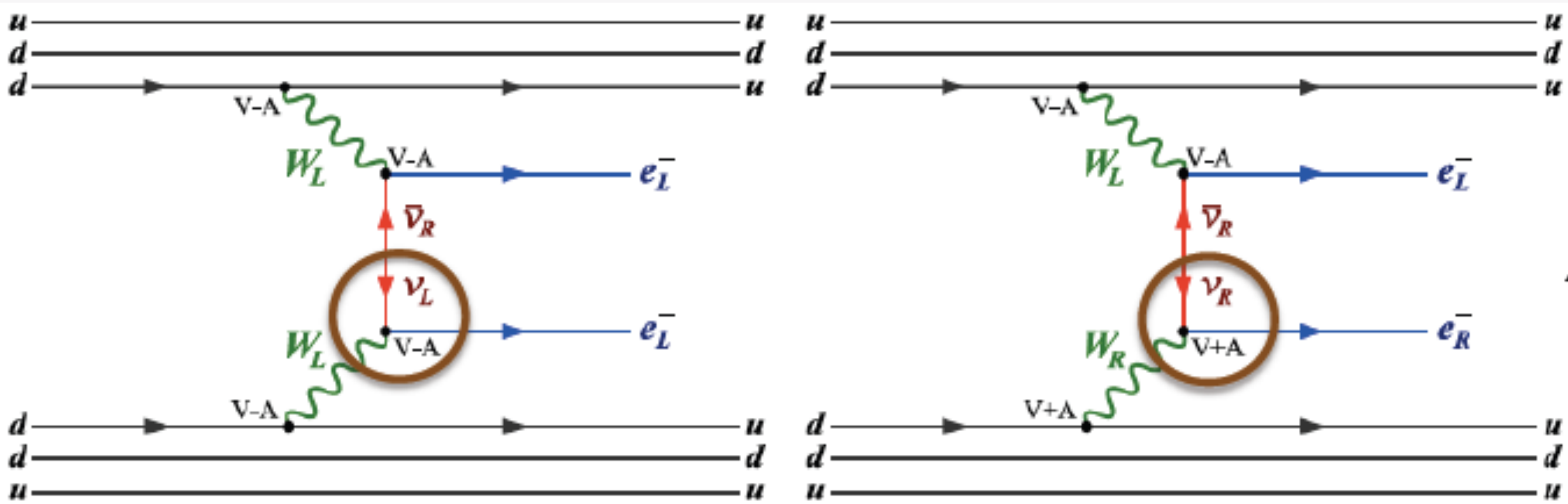


[Nucl. Phys. A 781 (2007) 209-226]

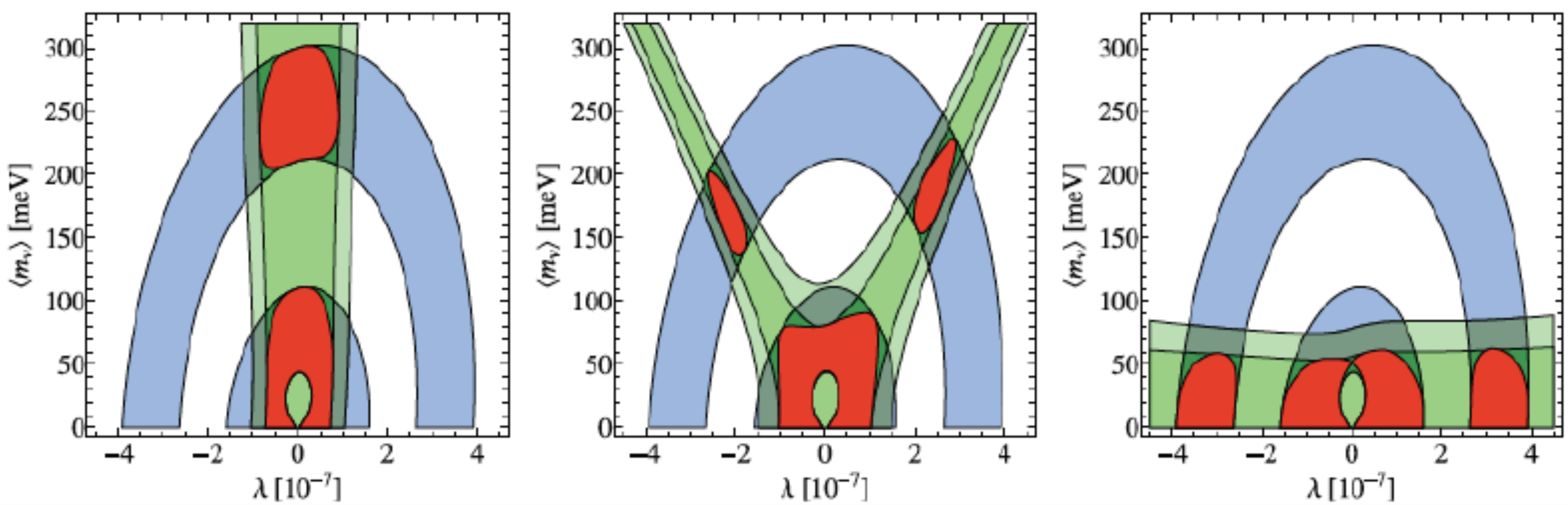
- Other results coming soon on ^{150}Nd and ^{96}Zr


Expected half-life limit for ^{82}Se
90% CL limit
1 sigma
2 sigma
Half-life limit (10^{25} y)
30
25
20
15
10
5
0
1
10
10^2
Background Activity ^{214}Bi (μBq/kg)

"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

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

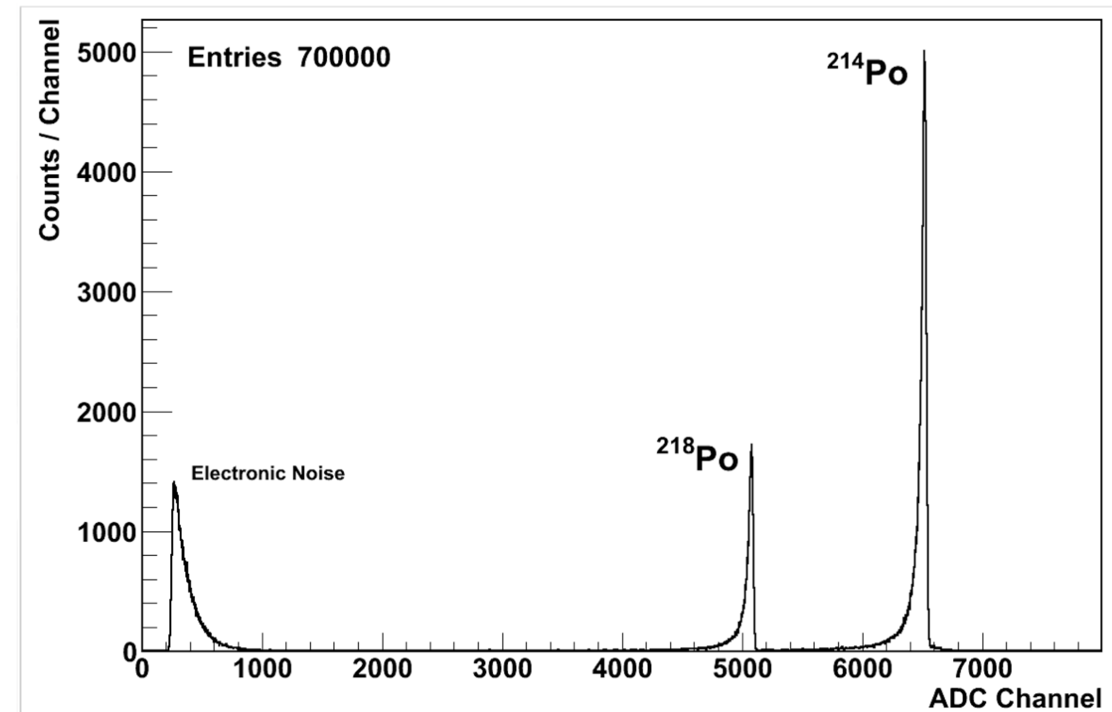
RnCL sensitivity (90%CL)
C-tracker < **50 μBq/m³**
Large gas volume < **5 μBq/m³**

Radon Concentration Line (**RnCL**)

Vacuum Pump

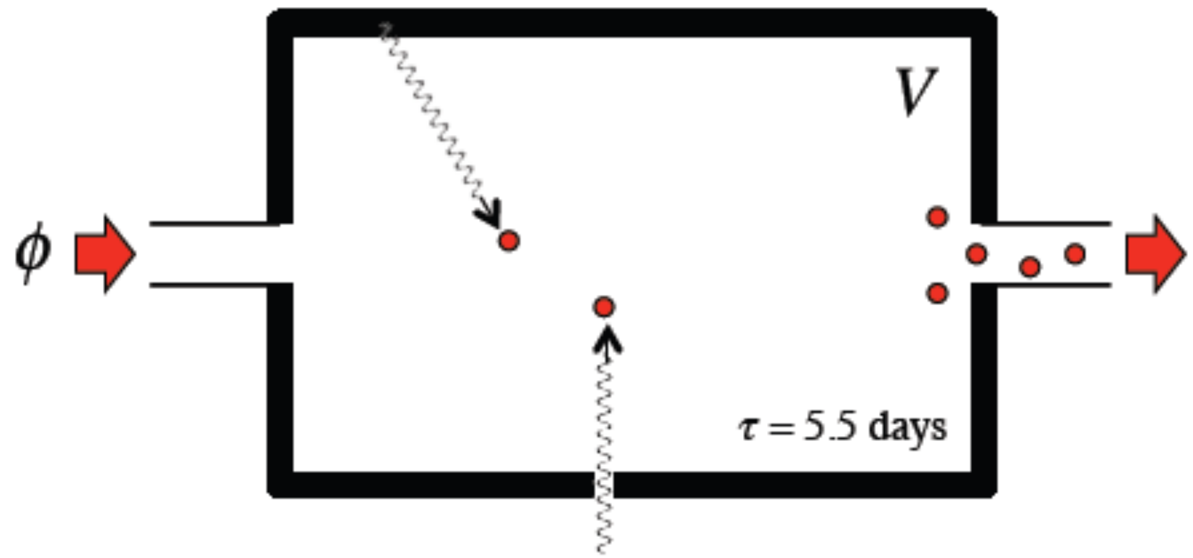
Carbon Trap

Radon Detector
(Electrostatic & Pin Diode)



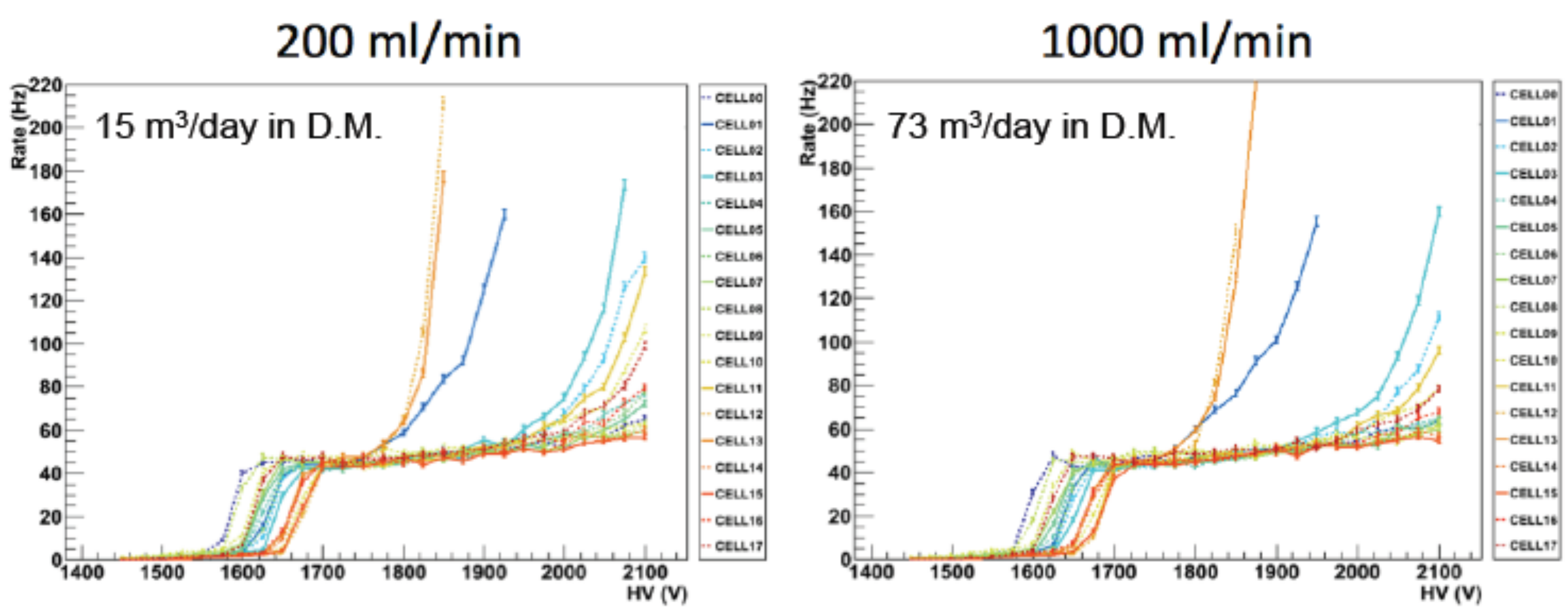
- Measurements of Rn emanation from materials
- Rn permeability measurements through membranes/seals

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.