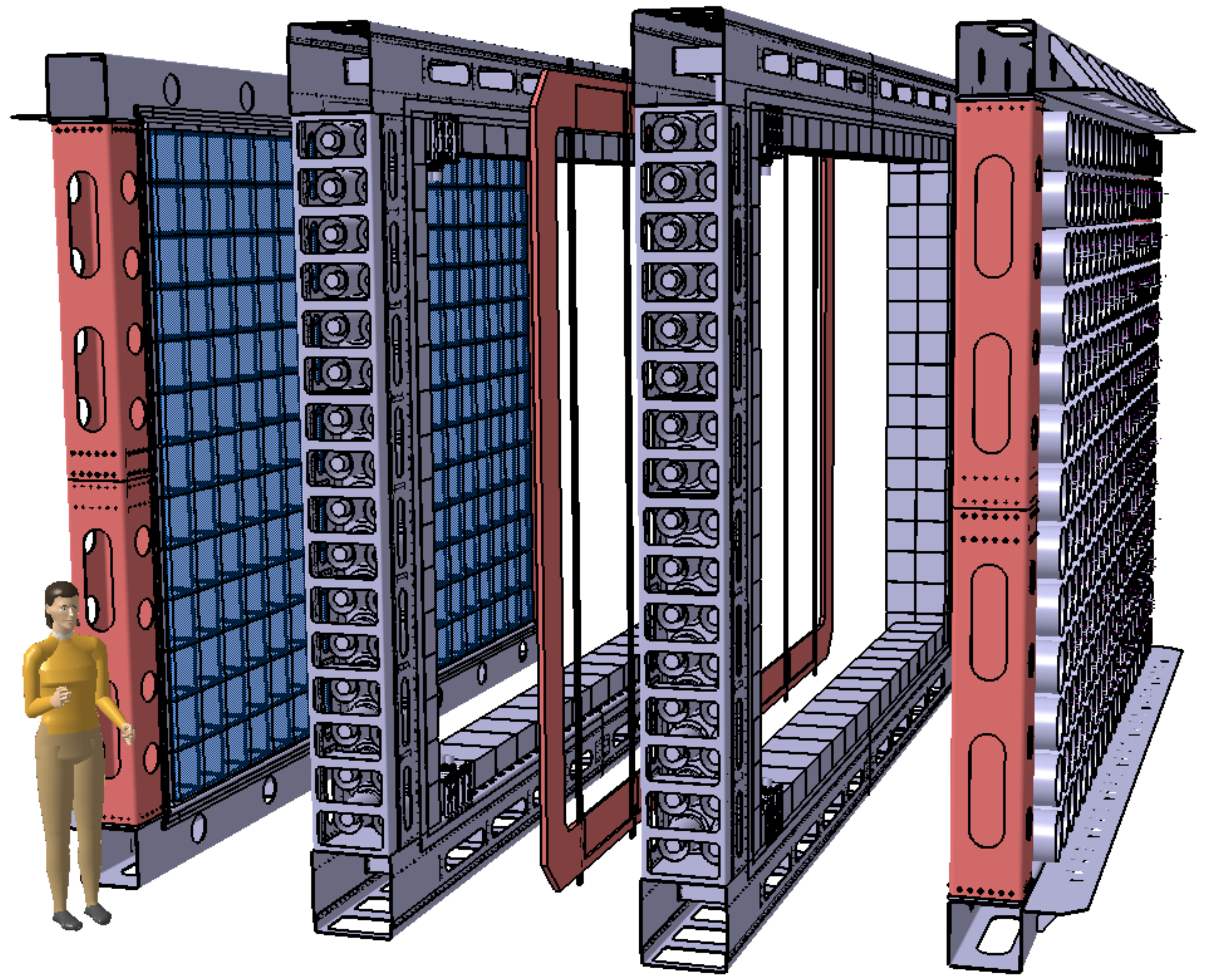
The SuperNEMO project, and final results from NEMO-3

DBD-18, Hawai’i, October 21-23, 2018

Cheryl Patrick, University College London, for the SuperNEMO collaboration

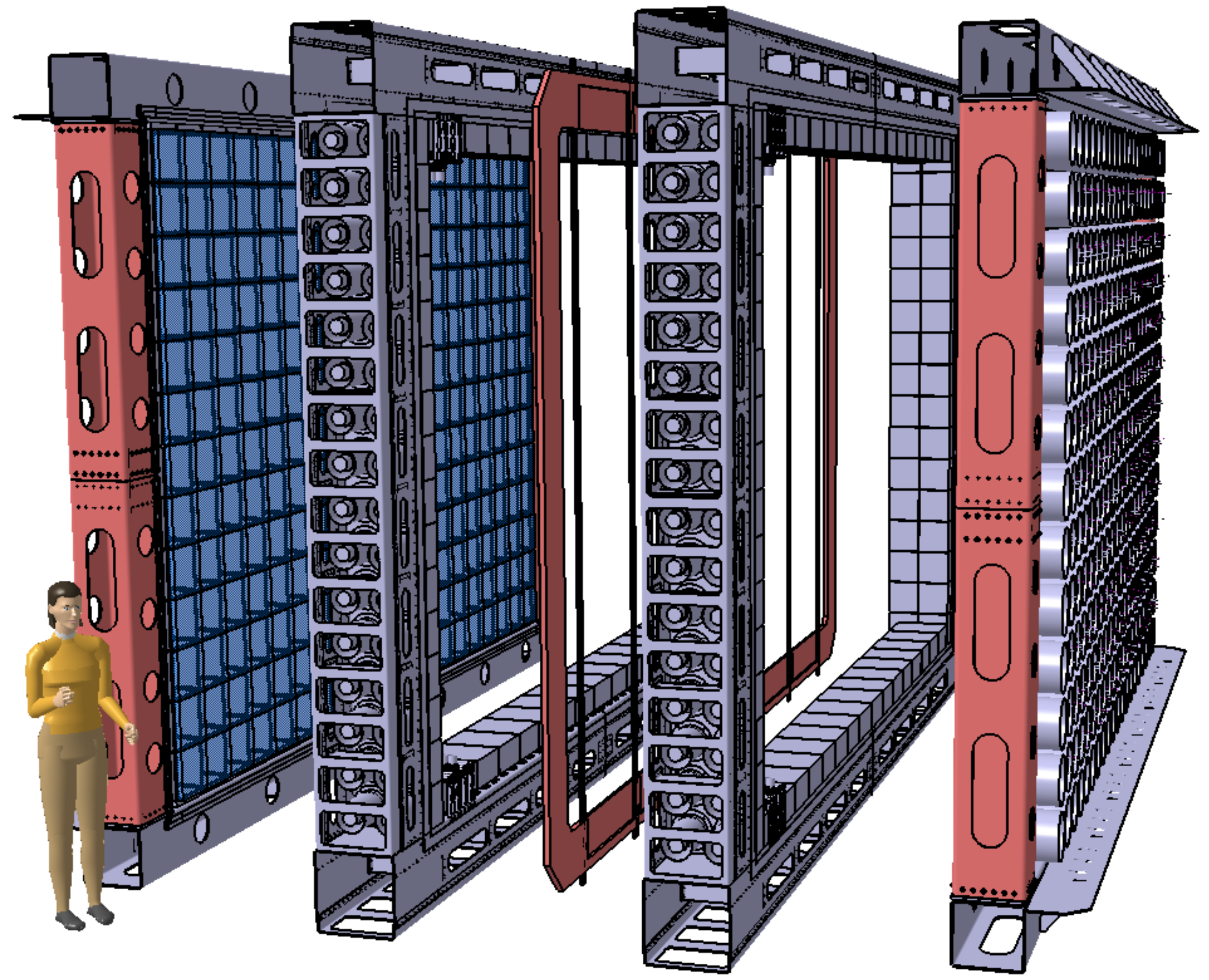
http://supernemo.org

The SuperNEMO demonstrator…



SuperNEMO in one slide

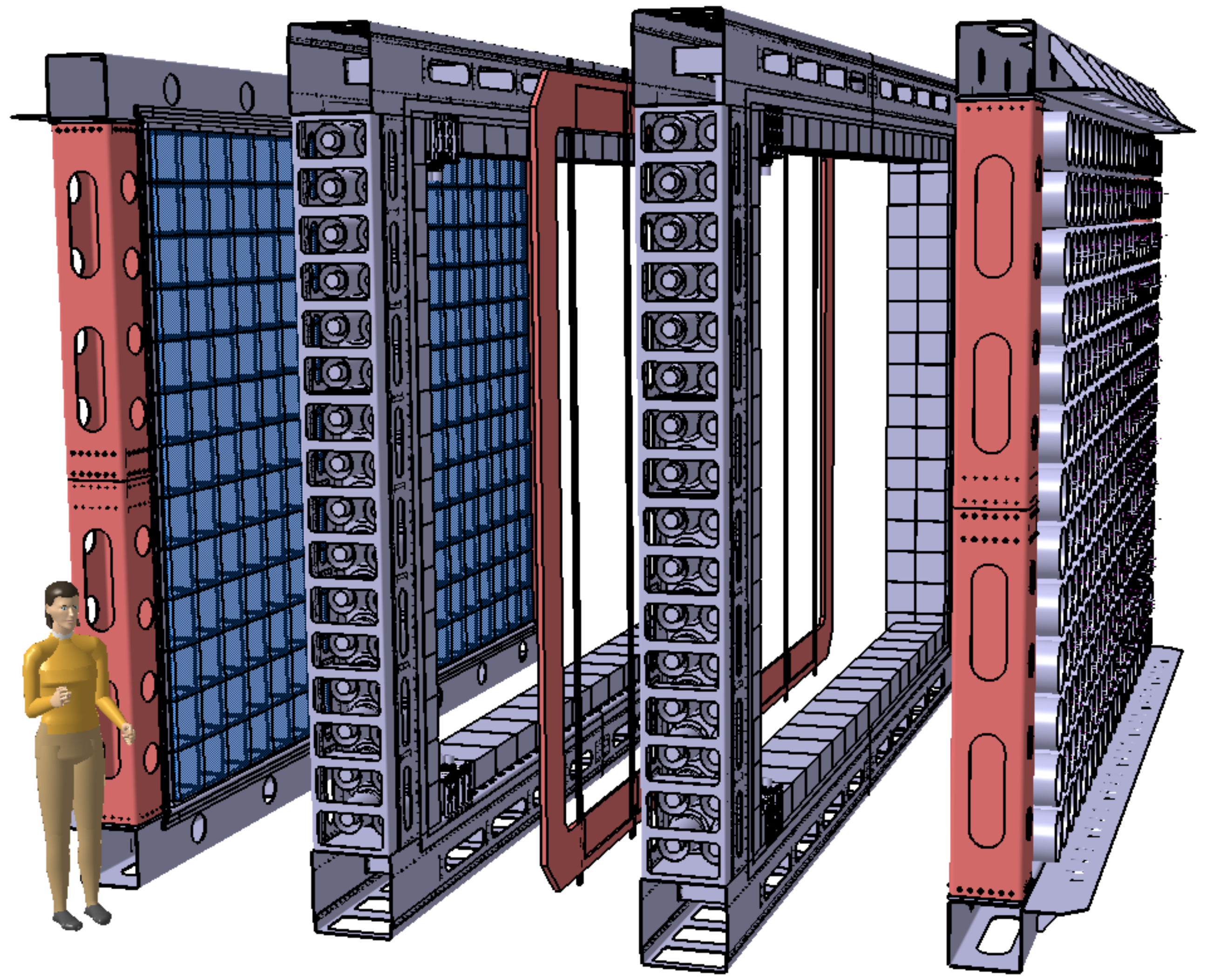
The SuperNEMO demonstrator…



…at the LSM underground lab in France…

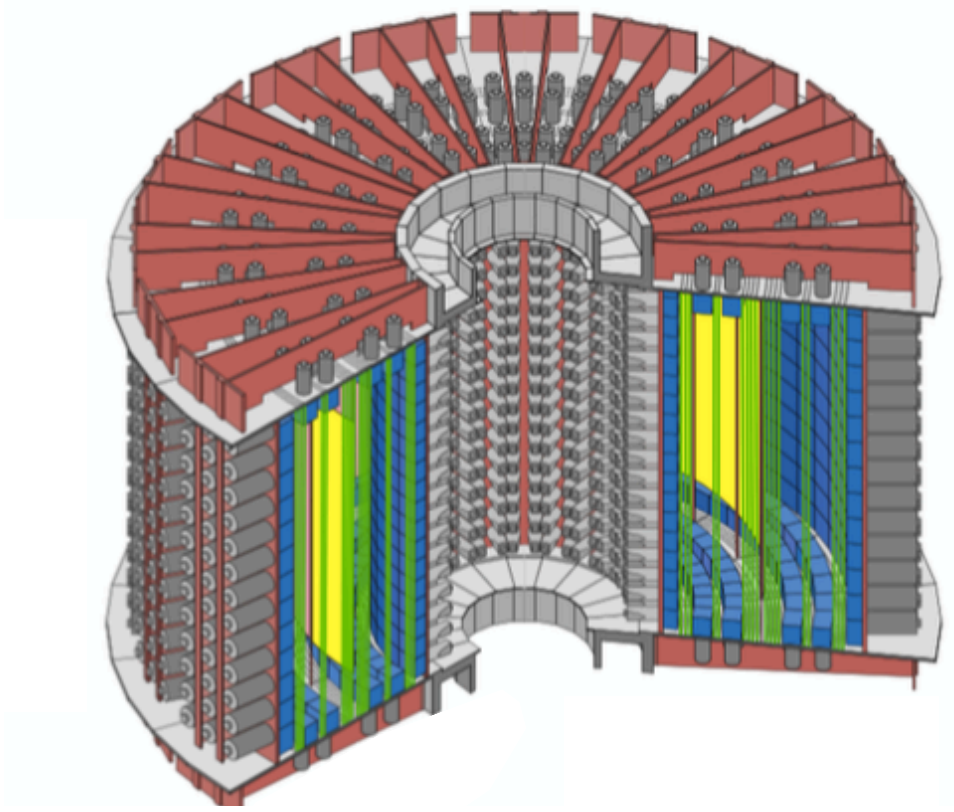
SuperNEMO in one slide

The SuperNEMO demonstrator…



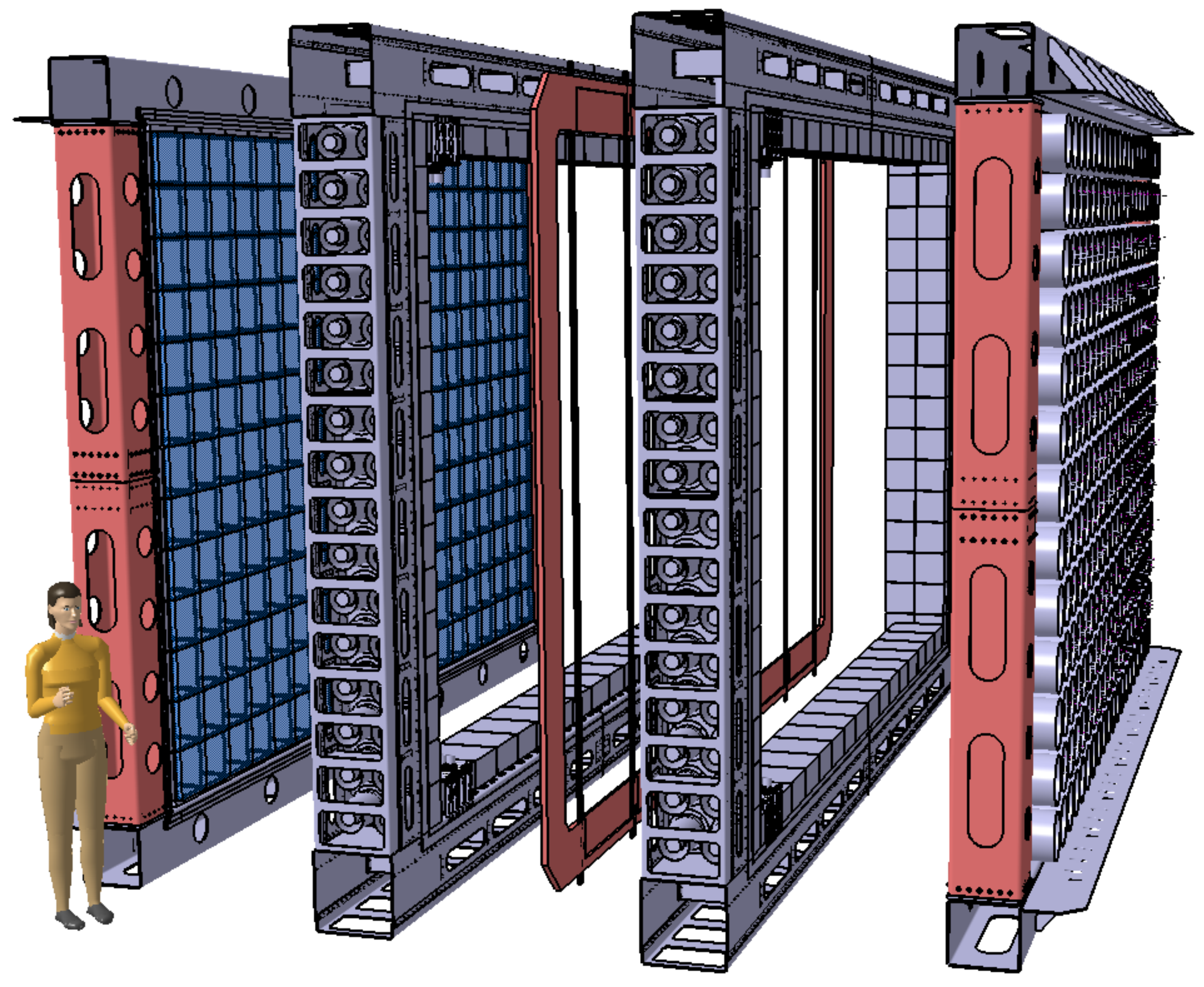
…at the LSM underground lab in France…

…builds on the successful NEMO-3 tracker-calorimeter architecture…



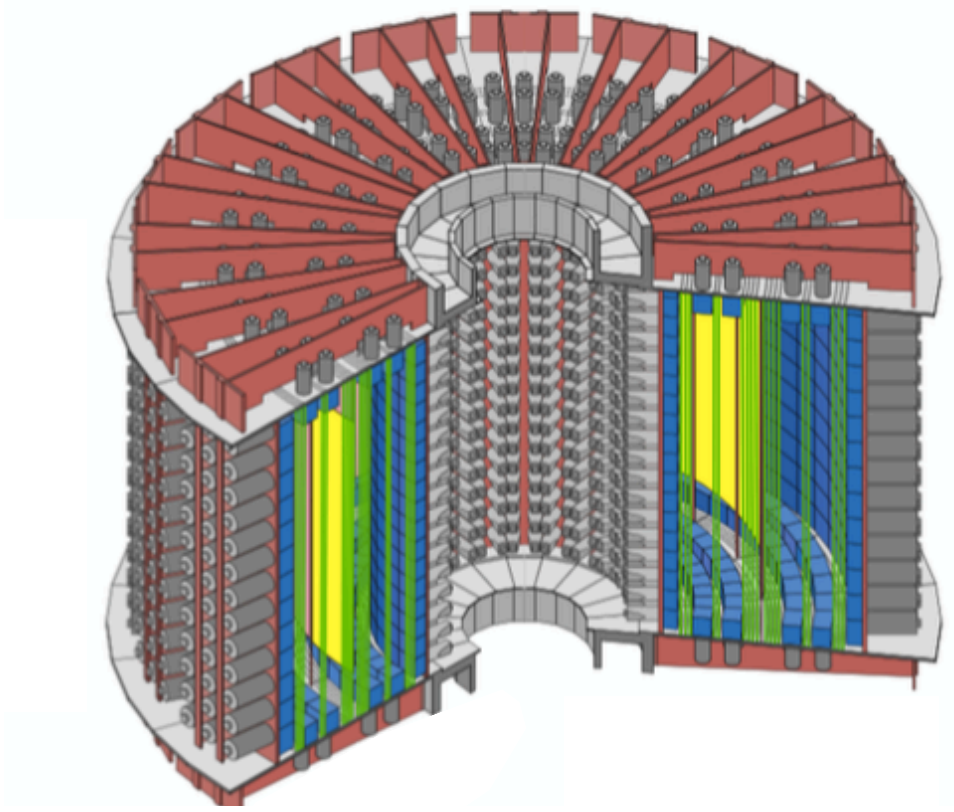
SuperNEMO in one slide

The SuperNEMO demonstrator…

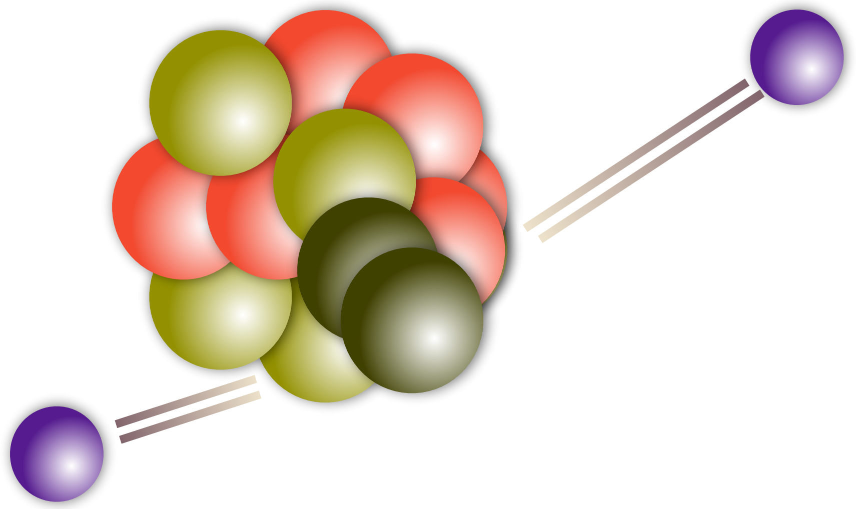


…at the LSM underground lab in France…

…builds on the successful NEMO-3 tracker-calorimeter architecture…

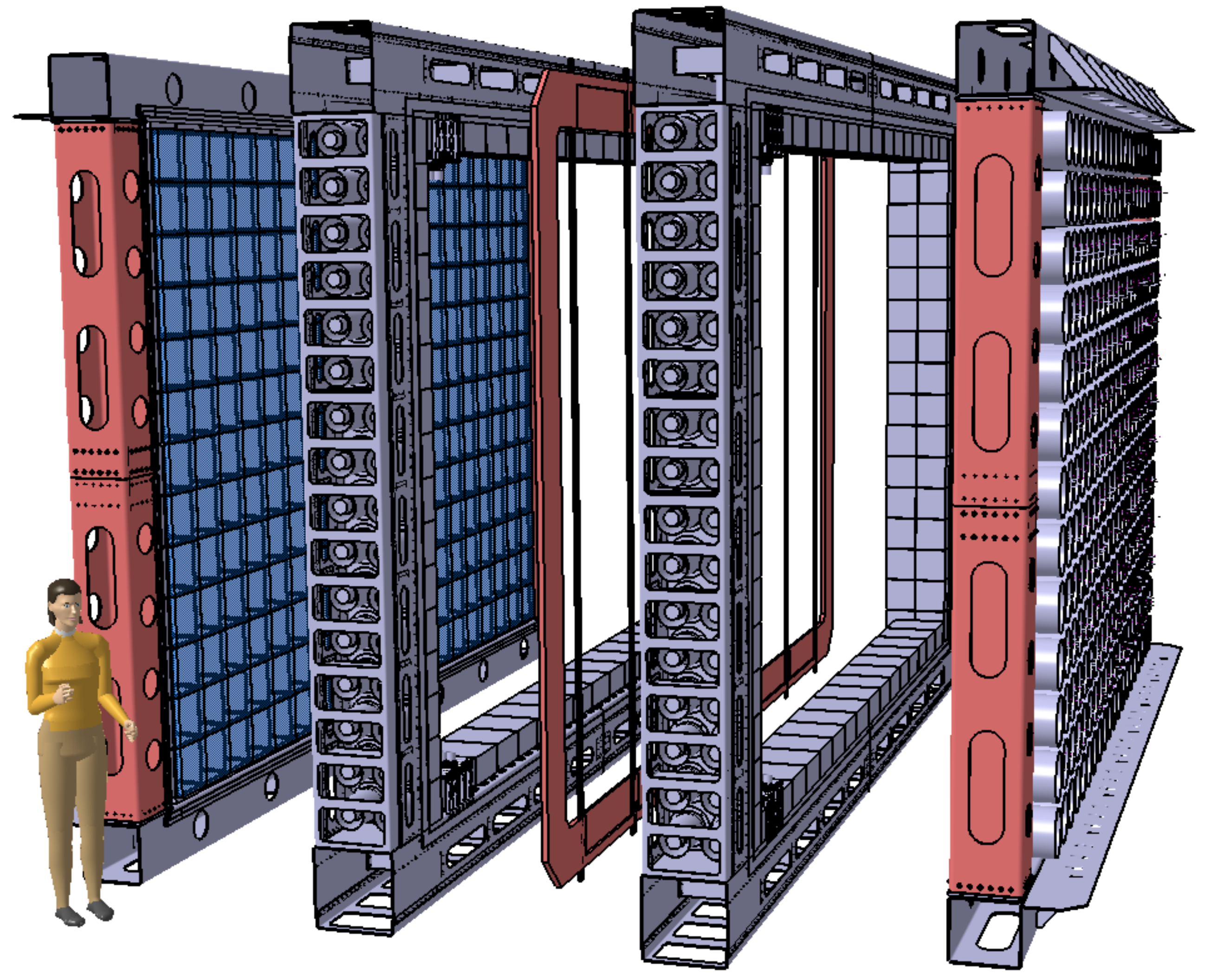


… to probe the underlying mechanisms of ββ decay.



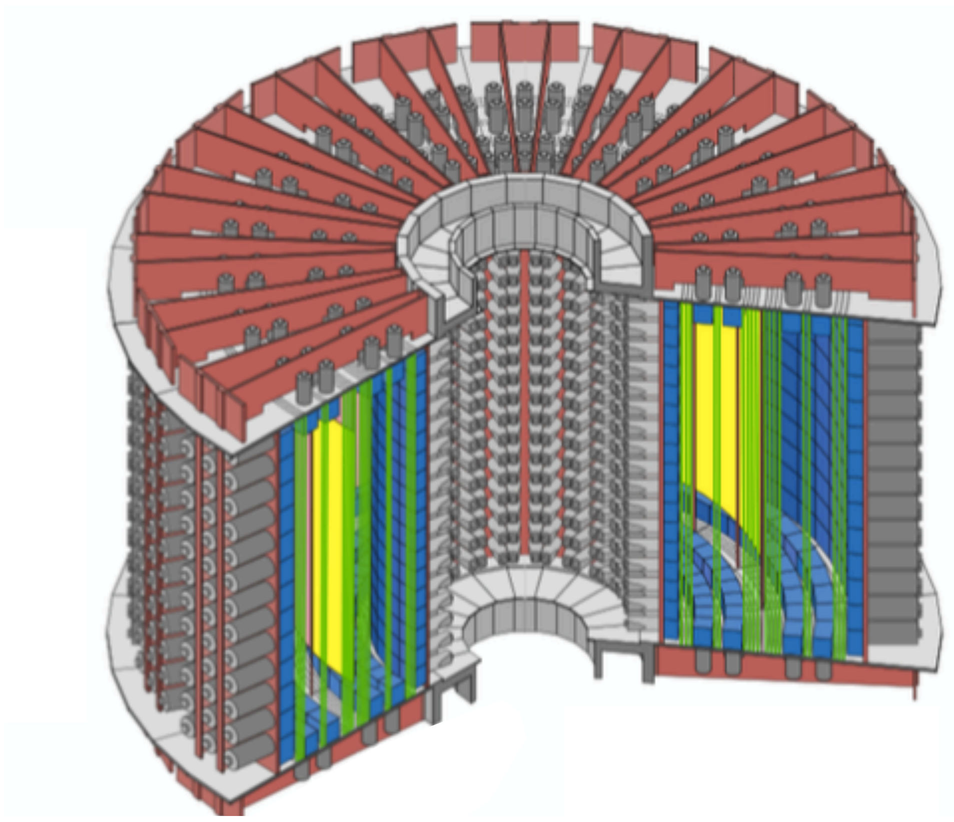
SuperNEMO in one slide

The SuperNEMO demonstrator…

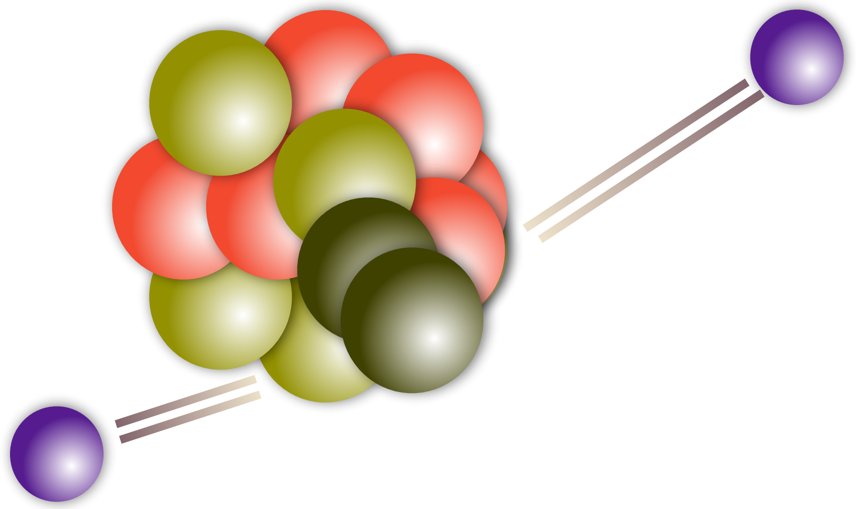


…at the LSM underground lab in France…

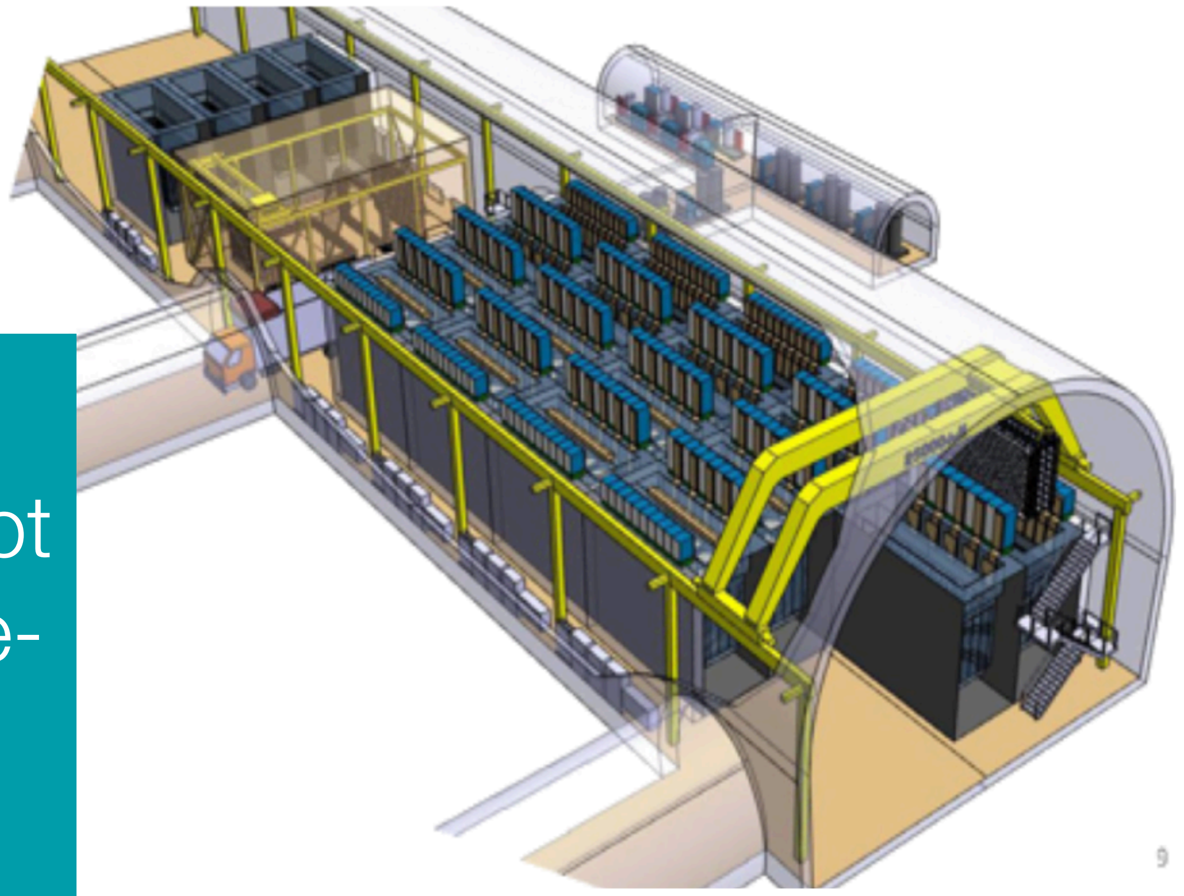
…builds on the successful NEMO-3 tracker-calorimeter architecture…



… to probe the underlying mechanisms of ββ decay.

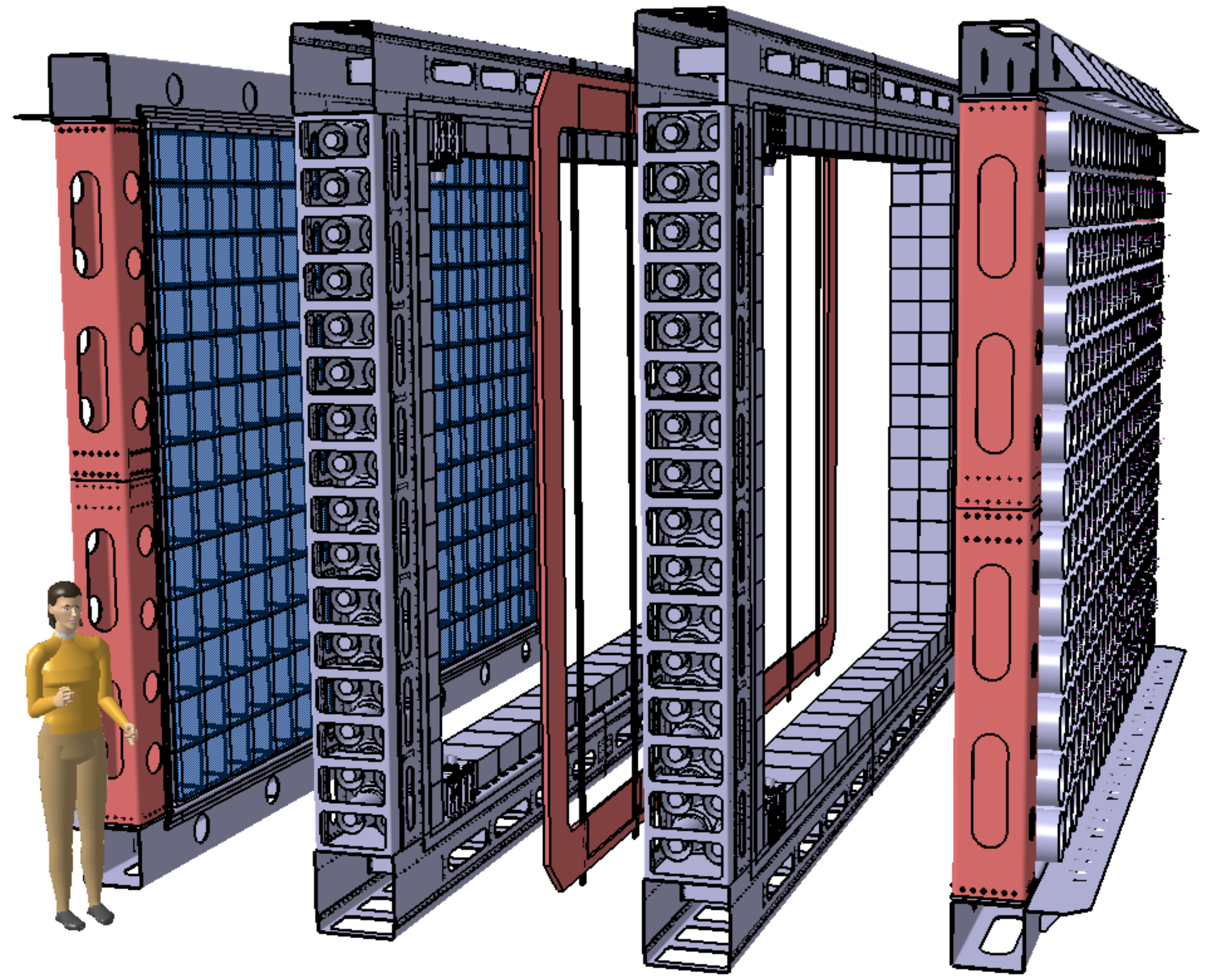


It serves as a proof of concept for future world-class isotope-agnostic detectors



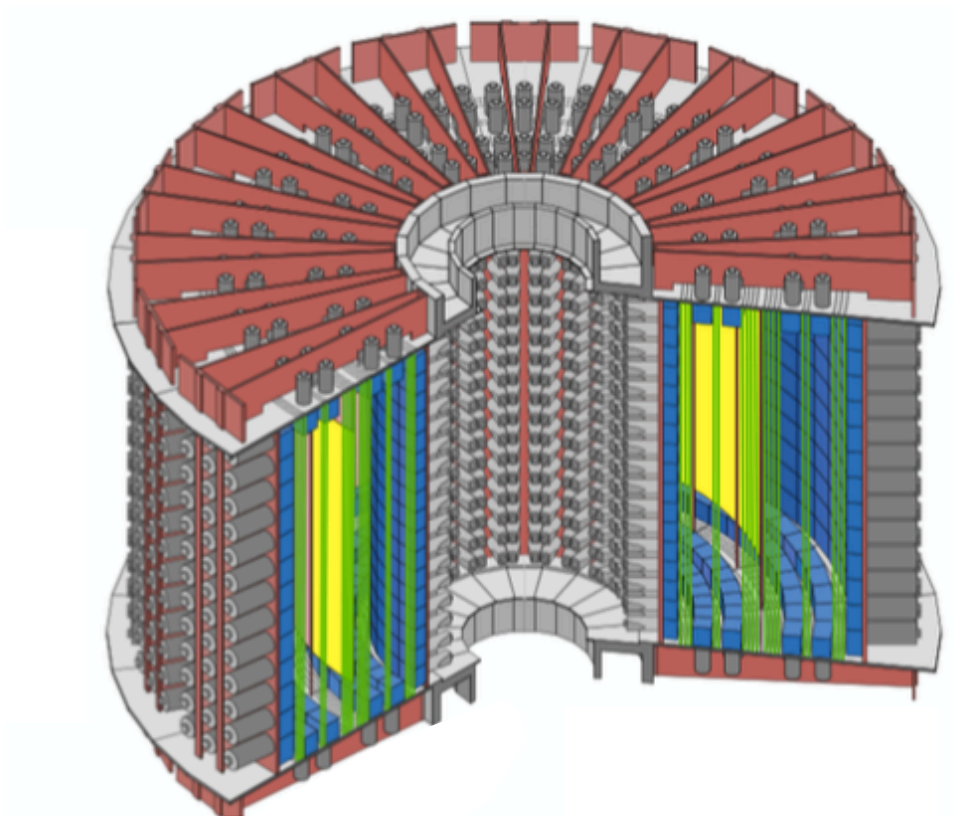
SuperNEMO in one slide

The SuperNEMO demonstrator…

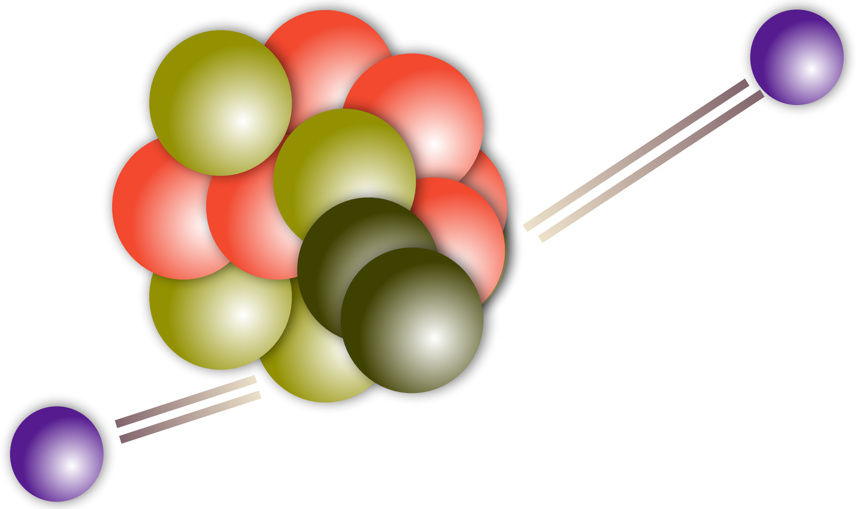


…at the LSM underground lab in France…

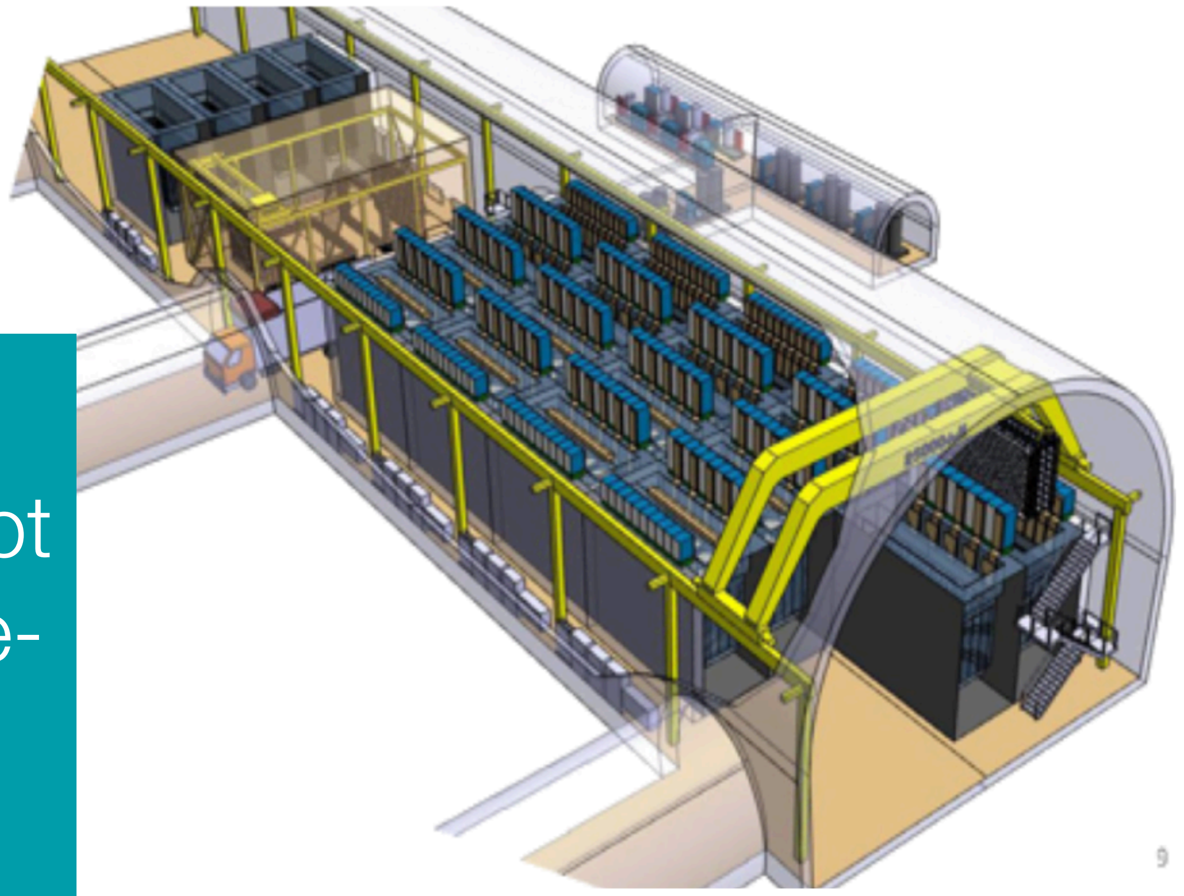
…builds on the successful NEMO-3 tracker-calorimeter architecture…



… to probe the underlying mechanisms of ββ decay.



It serves as a proof of concept for future world-class isotope-agnostic detectors

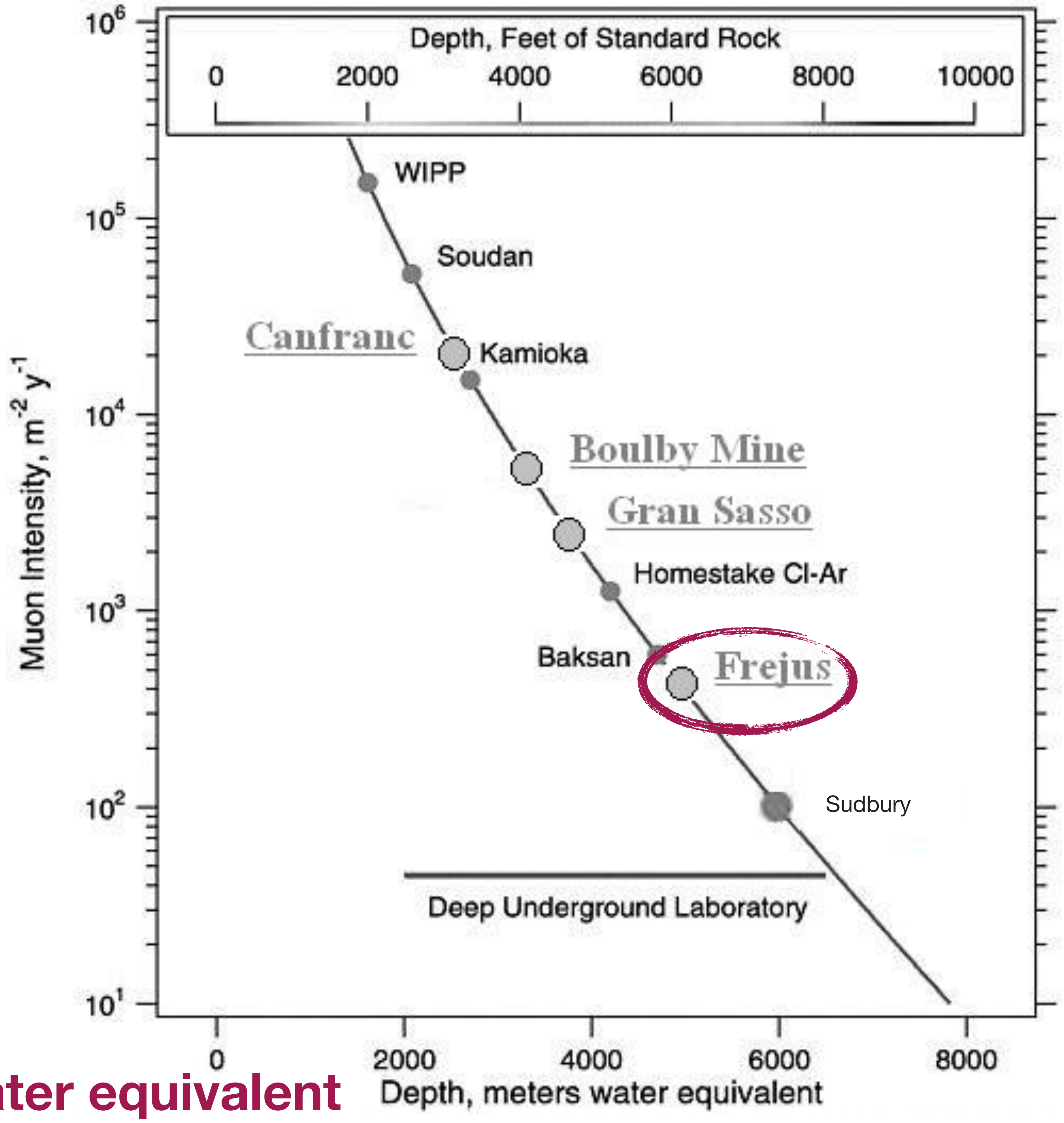


…and expects first data in the next few months!

LSM - the home of SuperNEMO

Laboratoire Souterrain de Modane

in the Fréjus tunnel connecting France and Italy

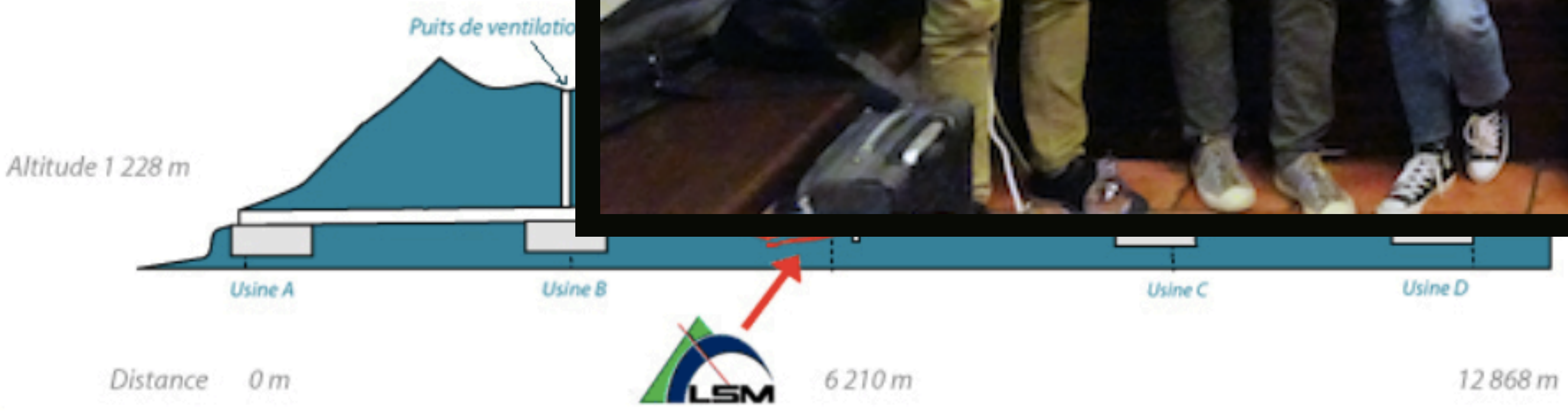


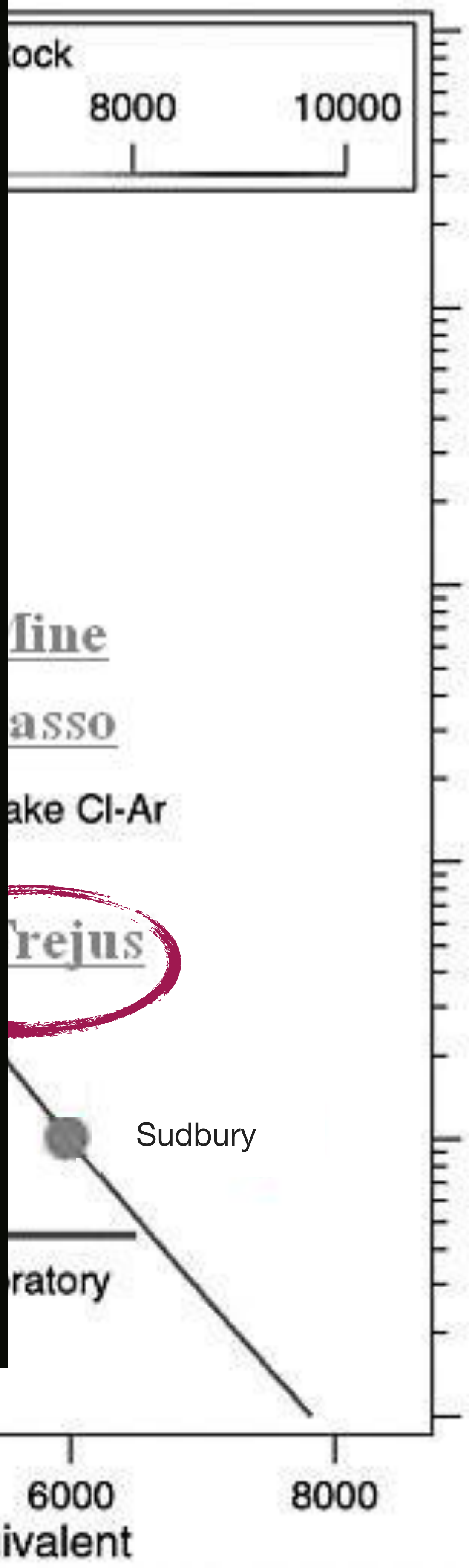
4800m water equivalent

LSM - the home of SuperNEMO

lodane
d Italy

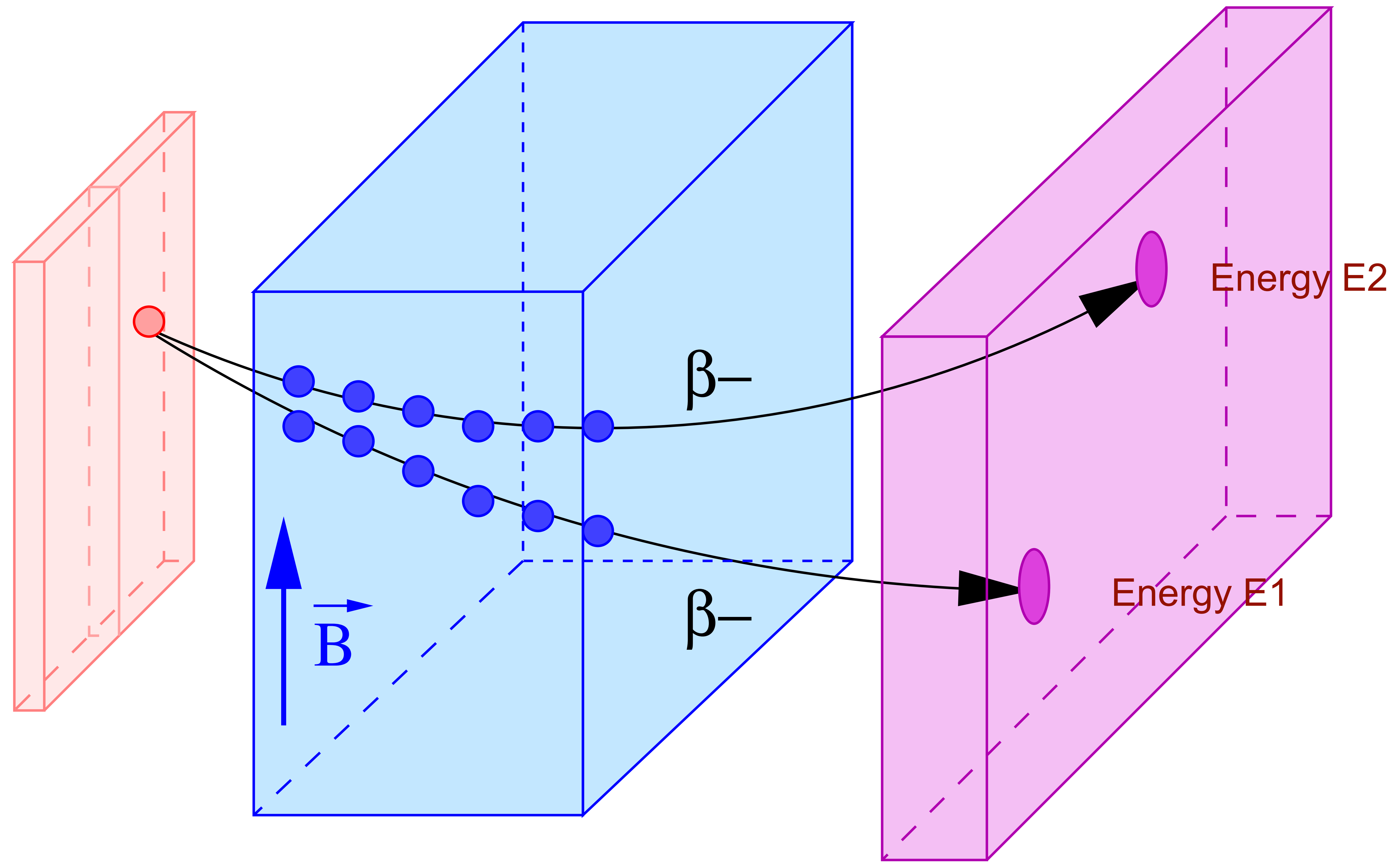
Tunnel routier de Fréjus





4800m water equivalent

The NEMO principle



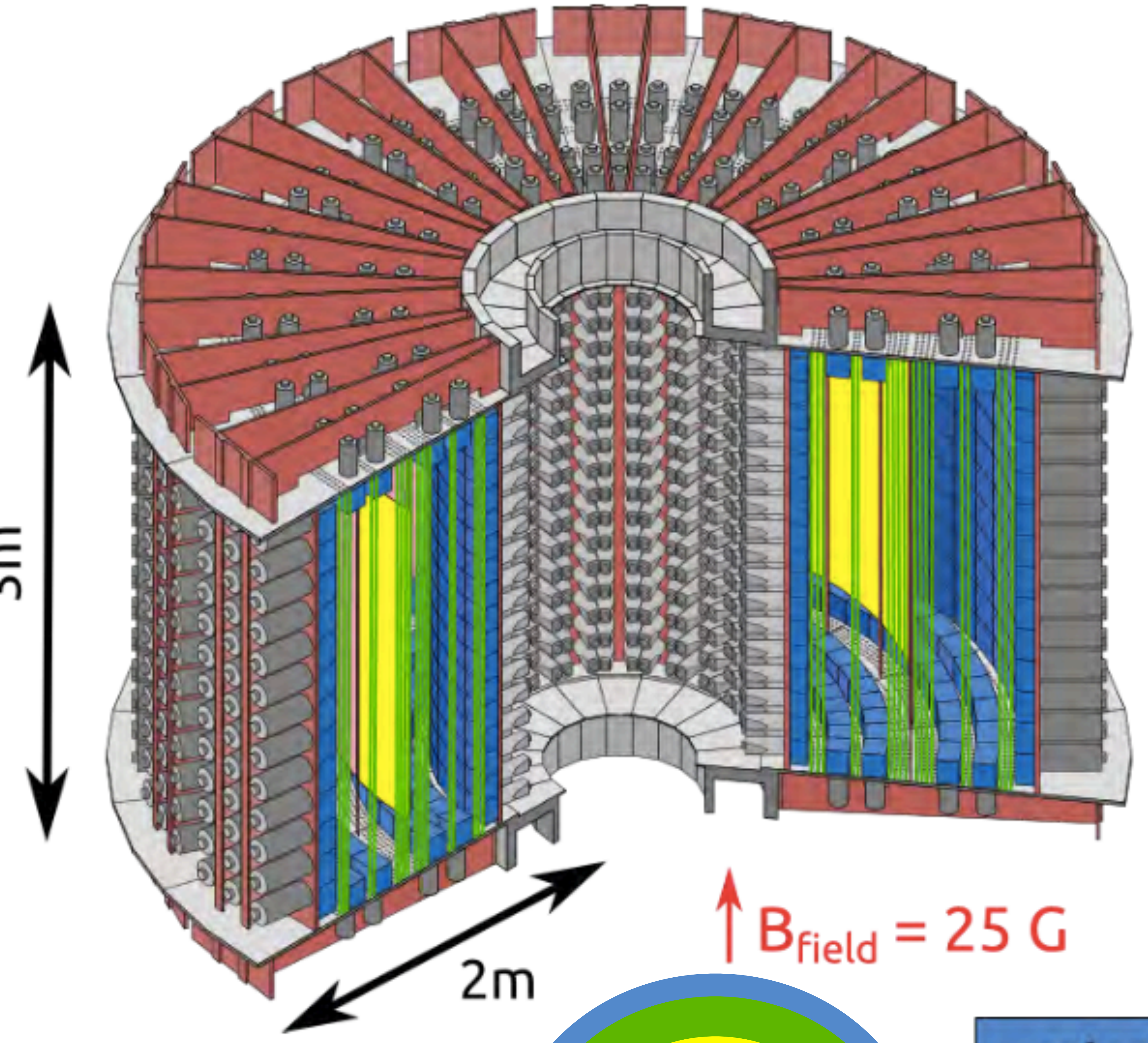
Strengths

- Source decoupled from detector - use **any solid ββ source** isotope
- Track reconstruction gives **particle identification**
- Combine with timings to identify topologies for ultra-high **background rejection**
- Tracking info (angle between tracks) & individual energy distributions can distinguish between **ββ mechanisms**
- **Scalable** with multiple modules

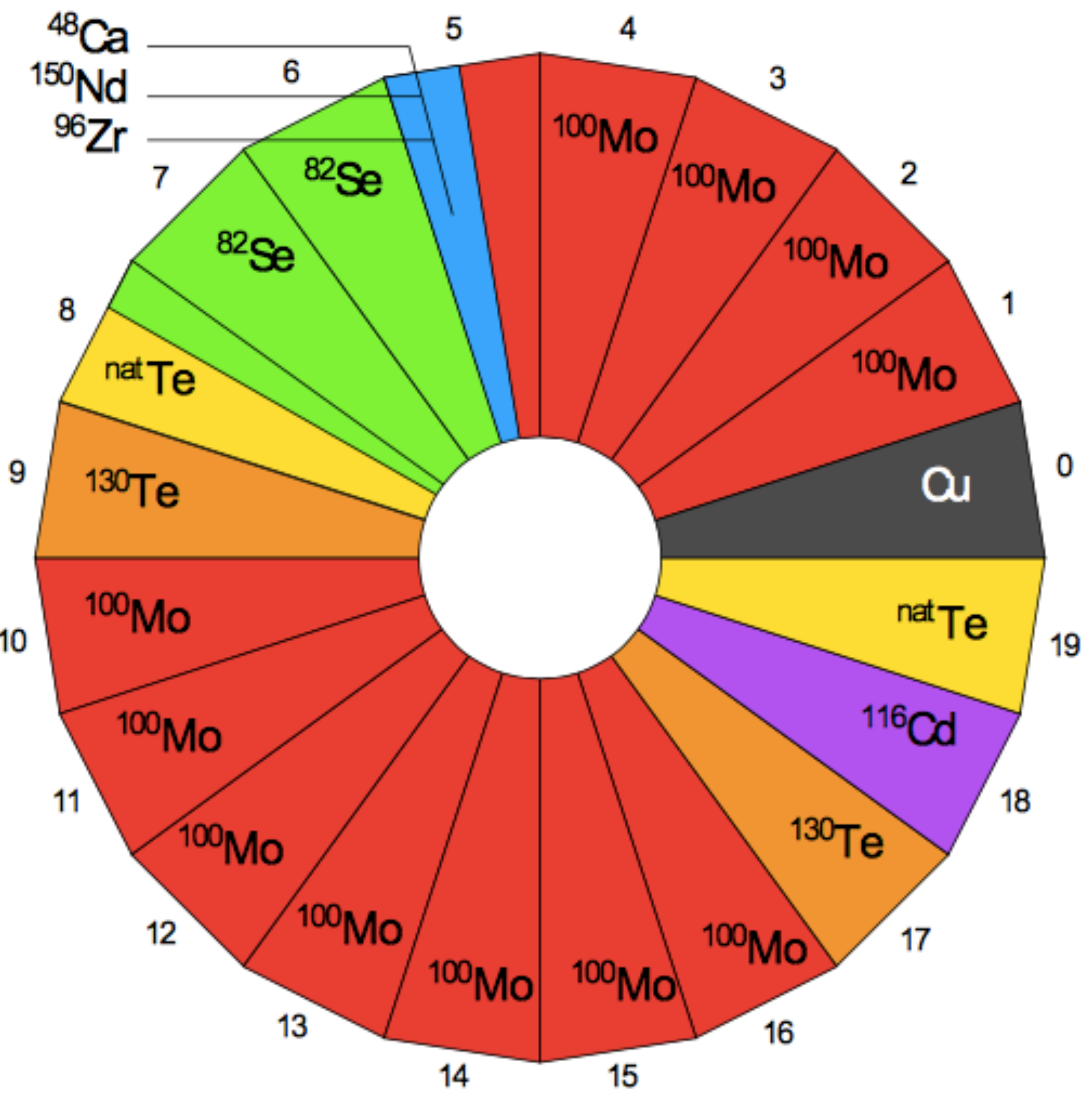
Weaknesses

- **Energy resolution** poorer than for most homogenous detectors
- Harder to achieve world-leading **0νββ half-life sensitivity** than with some other designs

NEMO-3 (2003-2011)



NEMO-3 "camembert" (source top view)



^{100}Mo 6,9 kg

^{82}Se 0,93 kg

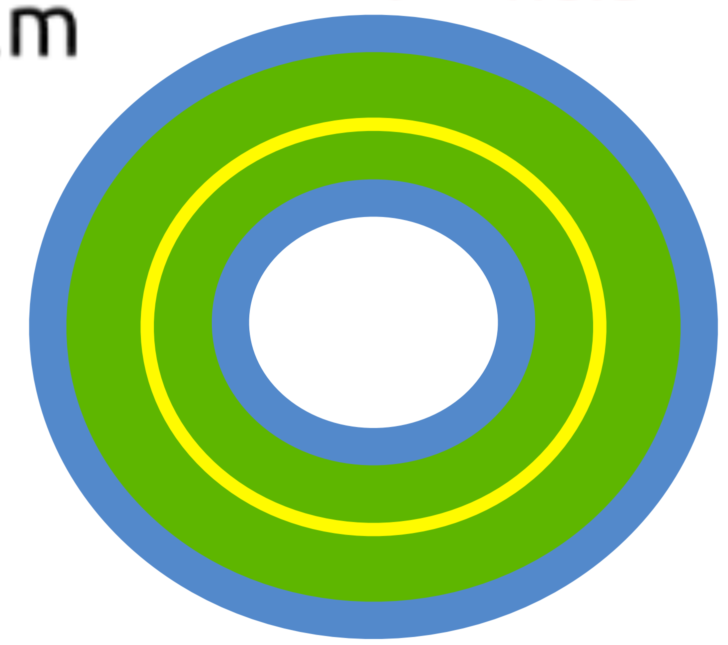
^{130}Te 0,45 kg

^{116}Cd 0,40 kg

^{150}Nd 36,5 g

^{96}Zr 9,43 g

^{48}Ca 6,99 g



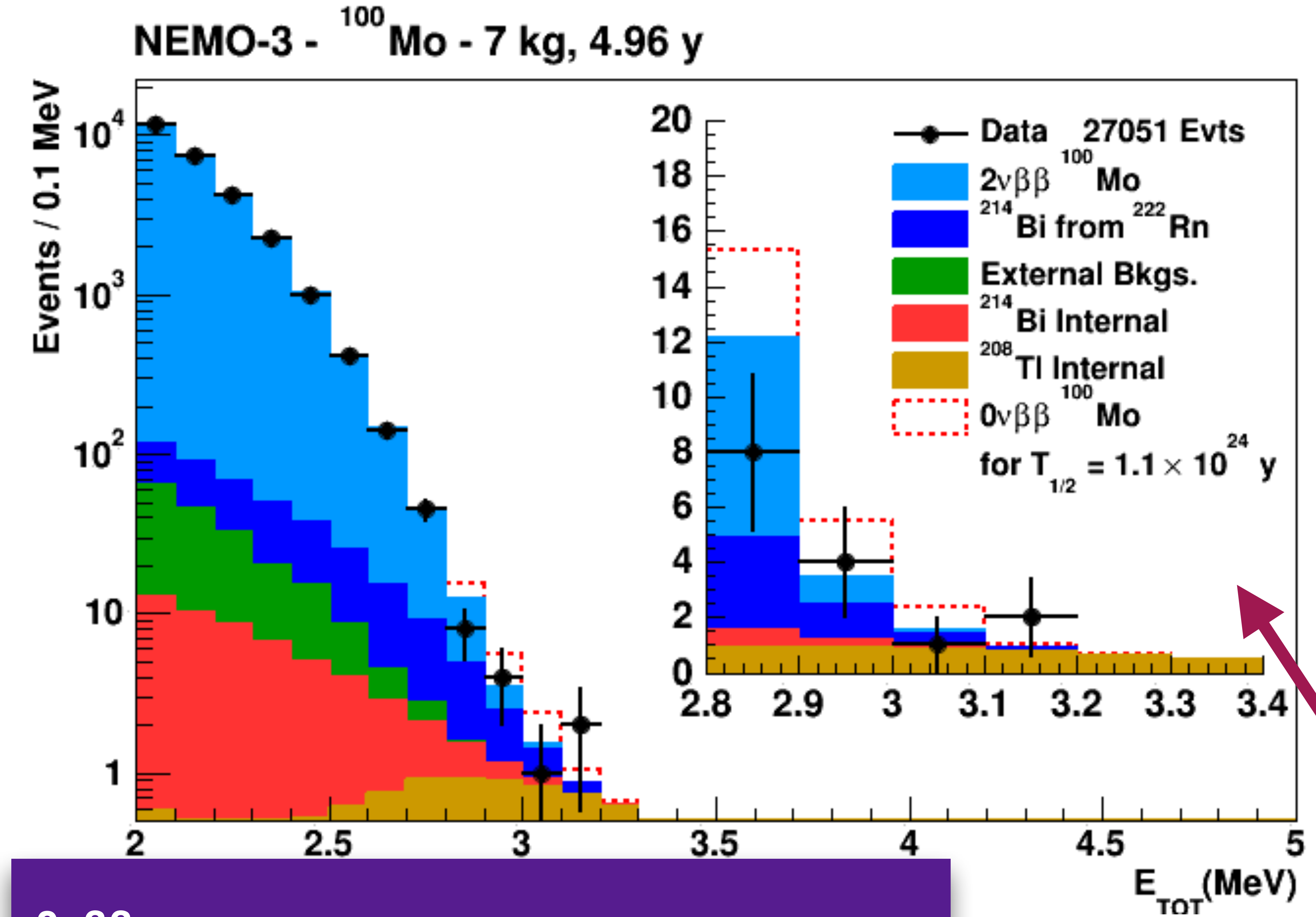
calorimeter
1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
$FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
$\sigma_t \sim 250$ ps

tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

sources
60 mg/cm² foils
10 kg of ββ isotopes

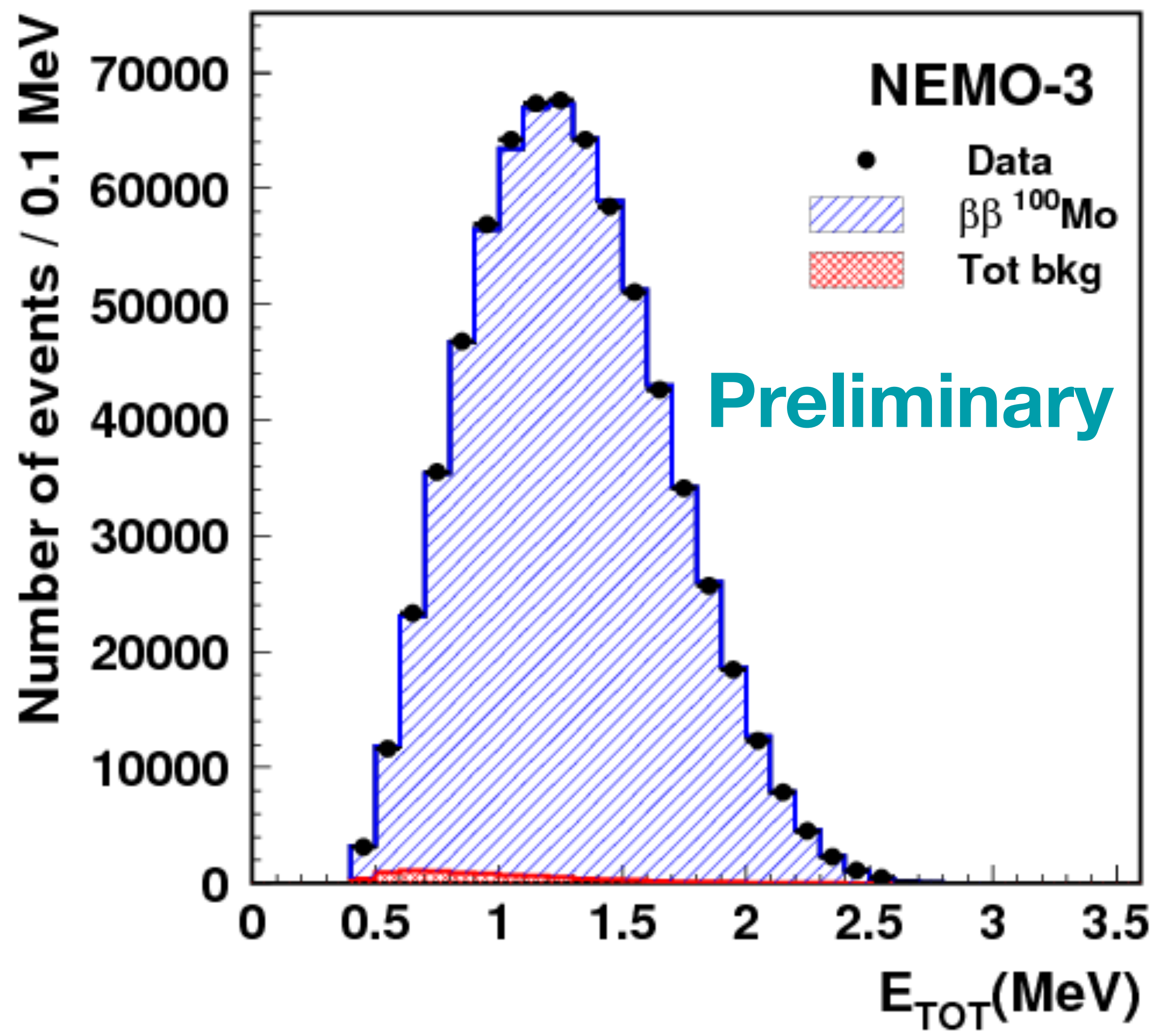
NEMO-3 flagship analysis: ^{100}Mo ββ decay

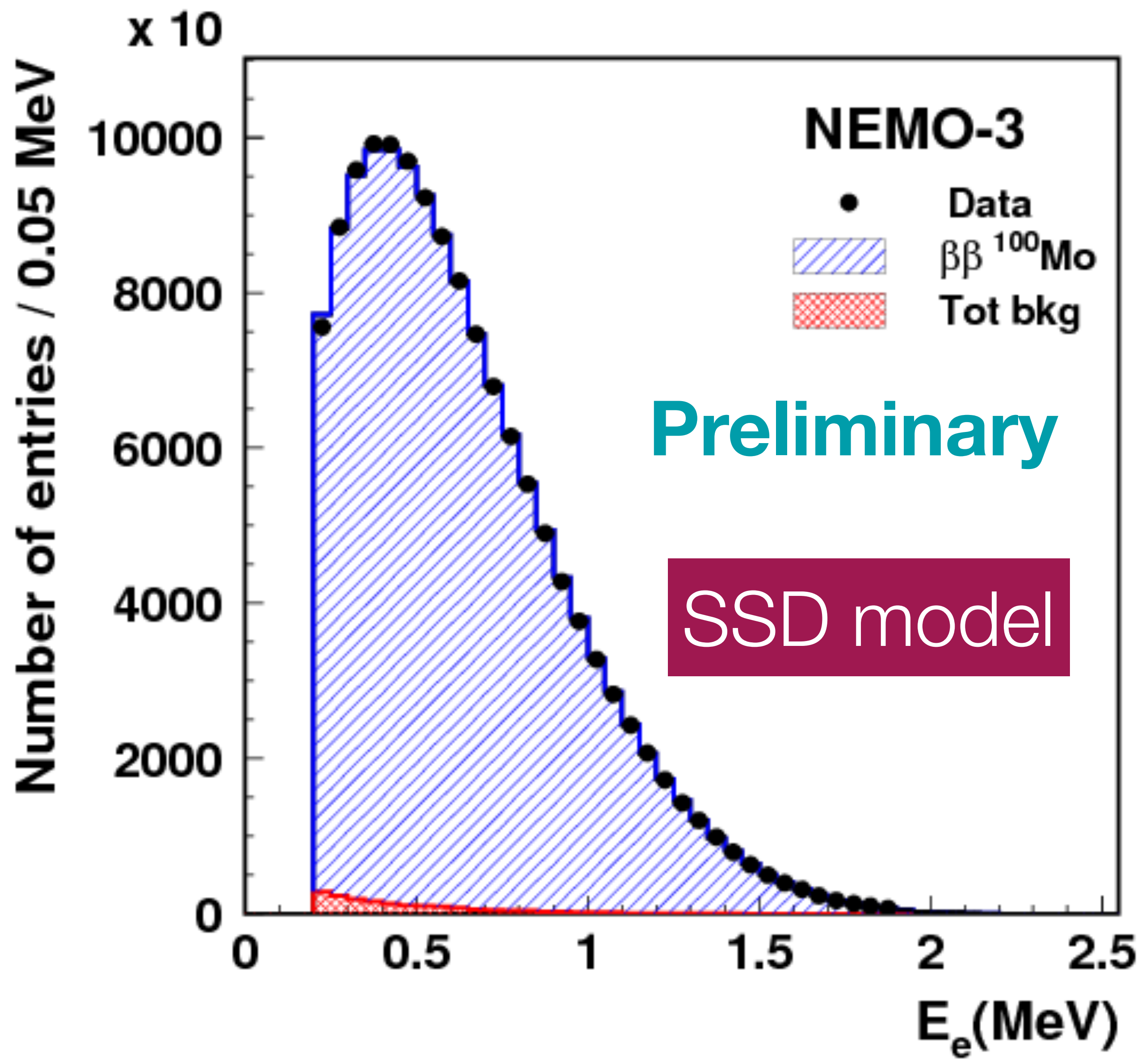
- 2νββ measurements and 0νββ limits for several isotopes
  - **^{100}Mo** (Phys. Rev. Let. 95, 182302)
    (Phys. Rev. D 89, 111101)
    (Nucl. Phys. A 925 (2014) 25)
    (Nucl.Phys.A781 (2007) 209-226,)



0νββ:
$T_{1/2} > 1.1 \times 10^{24}$ years; ⟨m_ν⟩ < 0.33 - 0.62 eV (90% CL) Close to world's best limit

5 years of running - no backgrounds over 3.2MeV

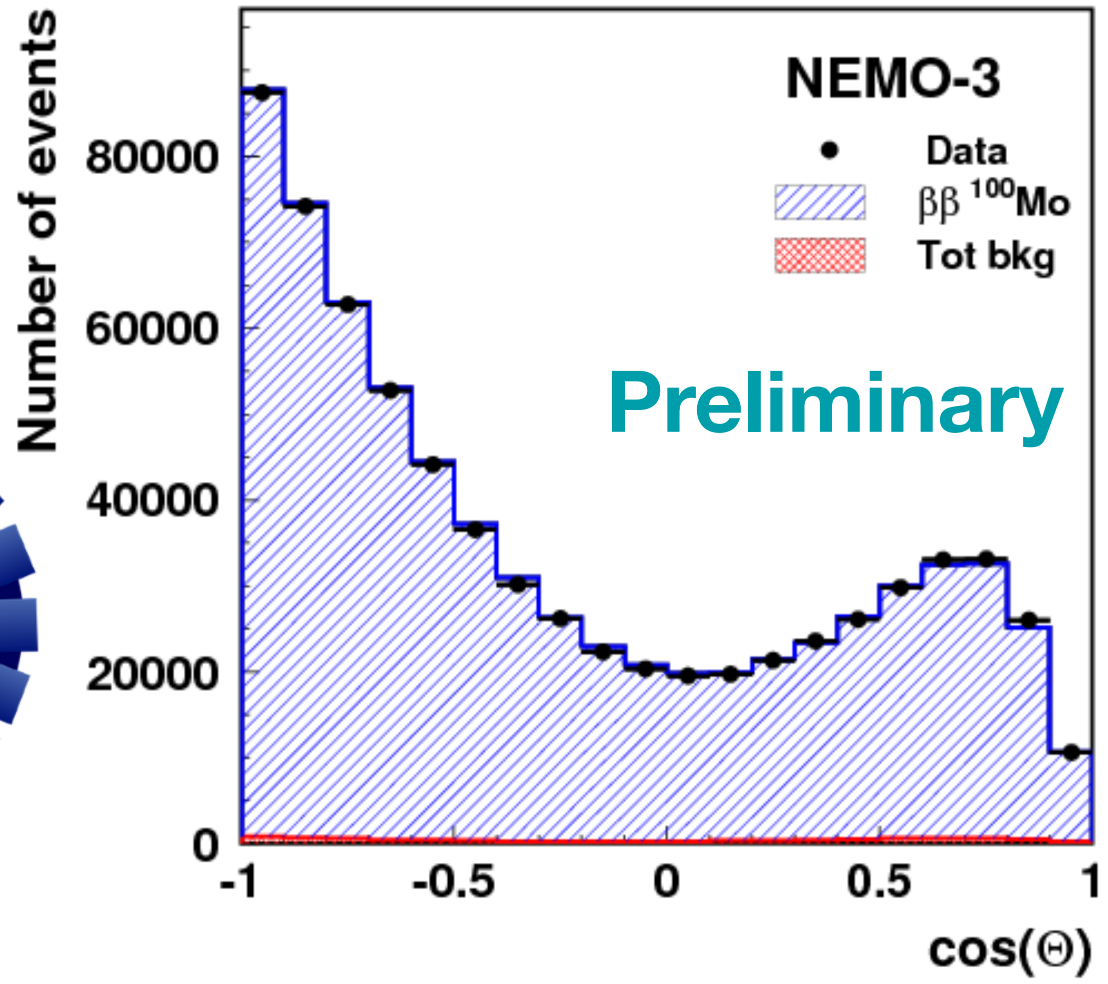




Preliminary

2νββ:
$T_{1/2}$ = 6.81 ± 0.01 (stat) ± 0.46 (sys) x 10^{18} years

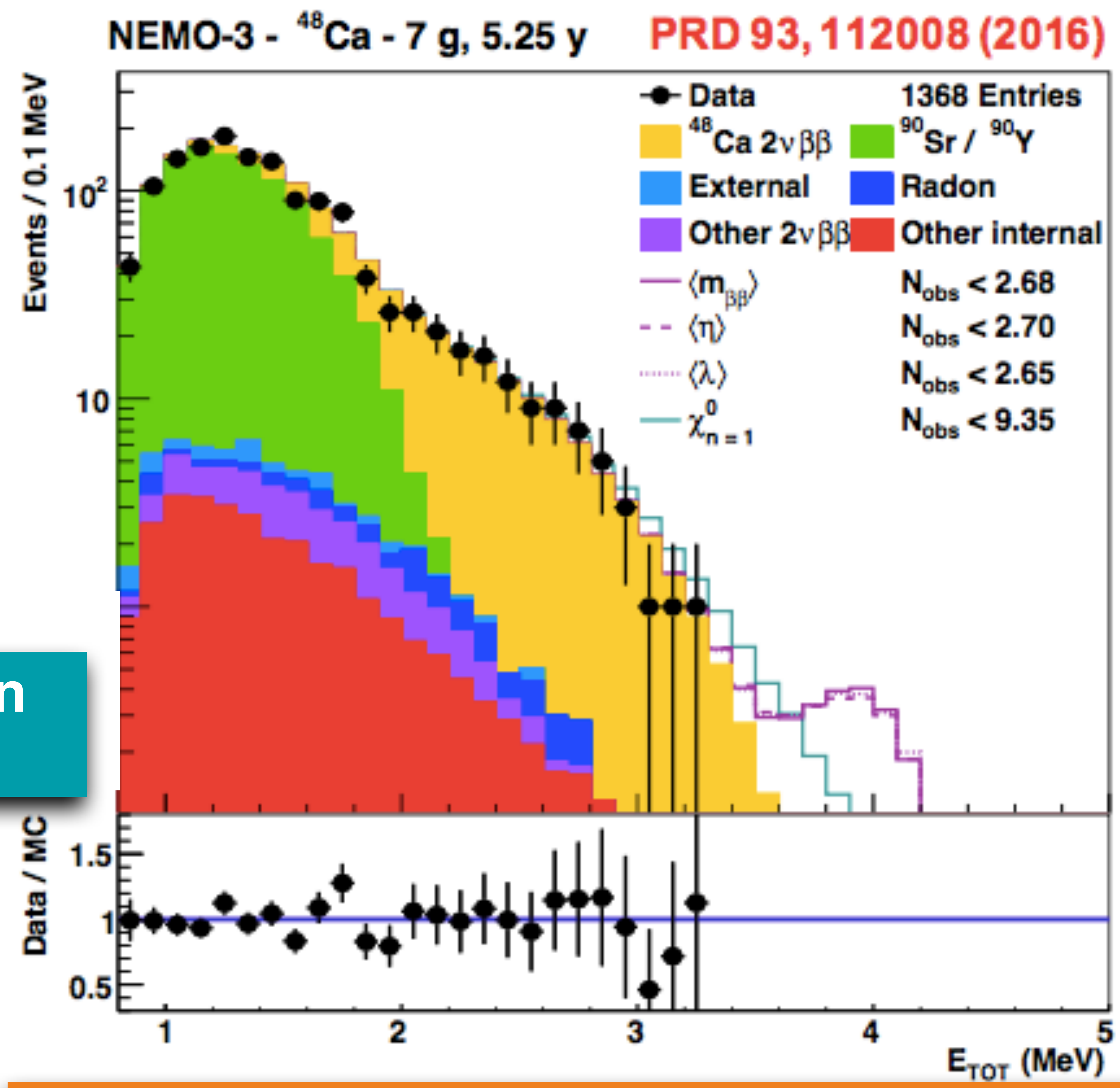
- **O(10^6) events** with S/B ≈ 80
- Distributions other than ∑E help us understand ββ mechanism
- **S**ingle-**S**tate **D**ominance favoured



NEMO-3 analyses

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

Background-free in $0\nu\beta\beta$ region for high-$Q_{\beta\beta}$ isotopes

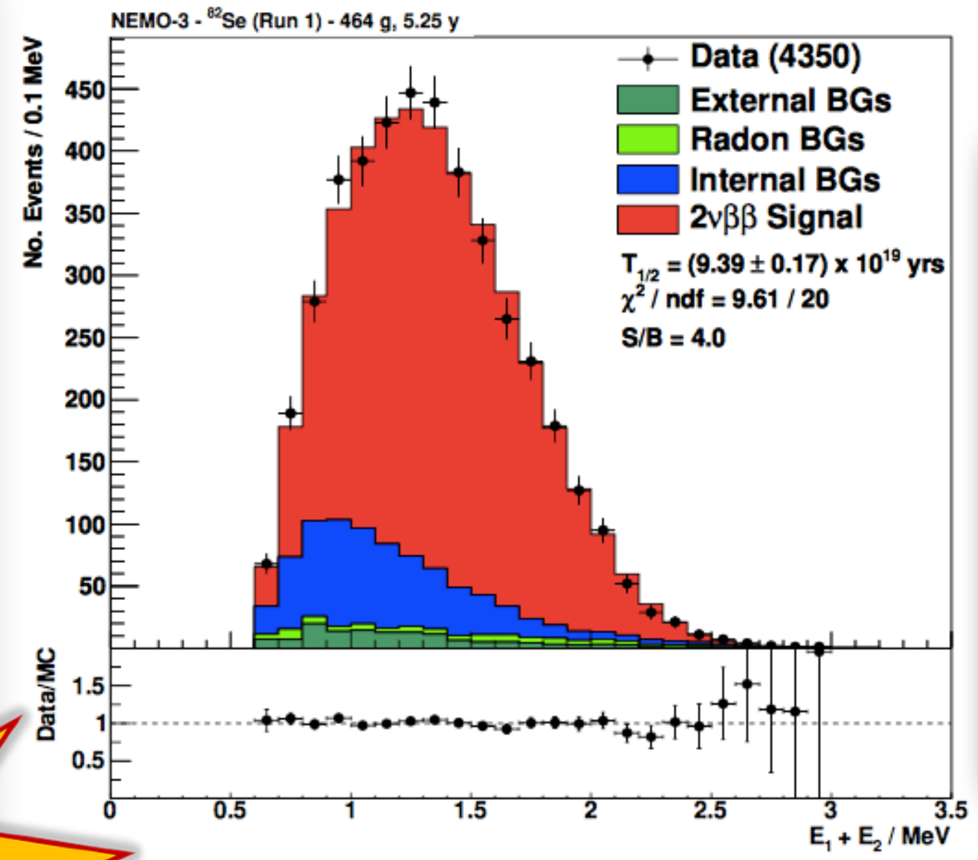


7g of ^{48}Ca ($9\ CaF_2$ disks)

$2\nu\beta\beta$: $T_{1/2} = 6.4\ ^{+0.7}_{-0.6}\,(stat)\ ^{+1.2}_{-0.9}\,(sys) \times 10^{19}$ yr

NEMO-3 analyses: ^{82}Se

- $2\nu\beta\beta$ measurements and $0\nu\beta\beta$ limits for several isotopes
  - **^{100}Mo** (Phys. Rev. Let. 95, 182302)
  - **^{48}Ca** (Phys. Rev. D 93, 112008)
  - **^{82}Se** (Eur. Phys. J. C (2018) 78: 821)



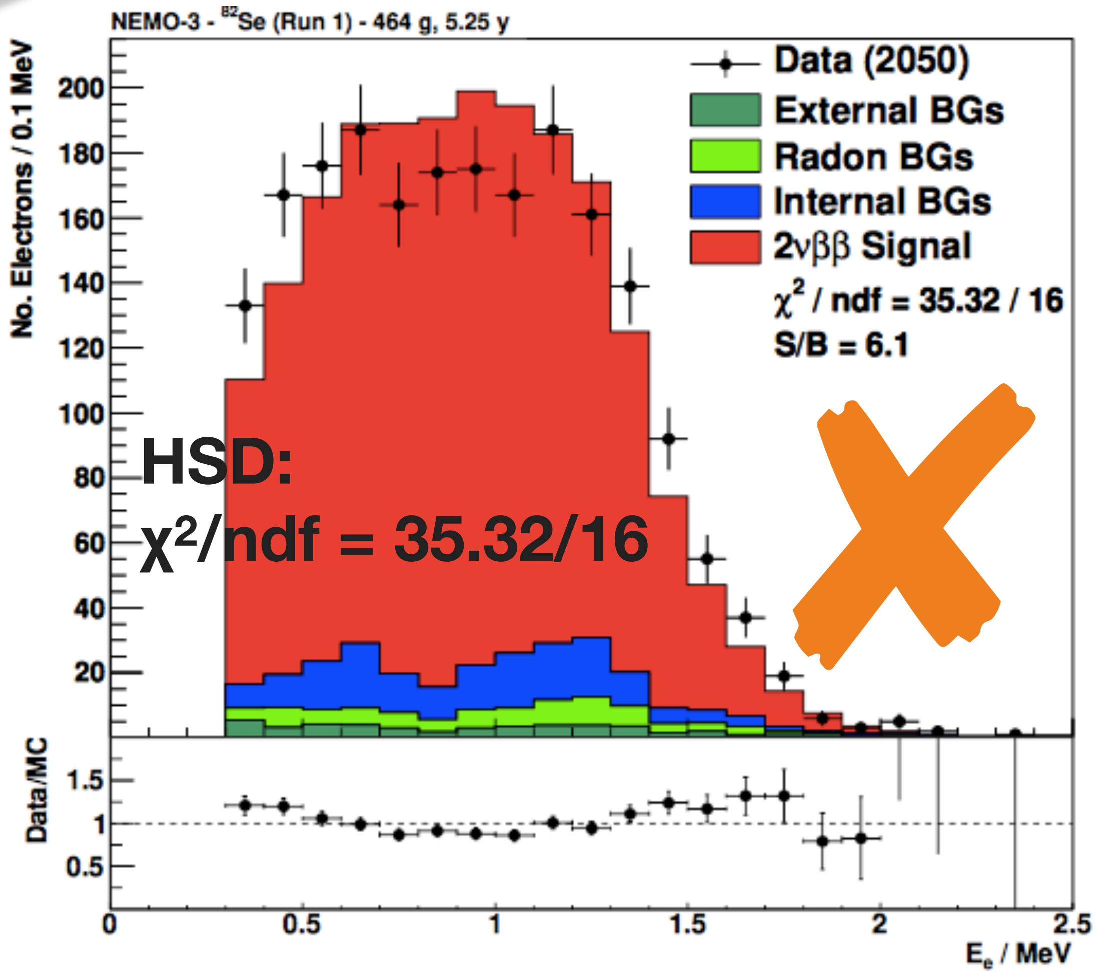
Summed 2-electron spectrum

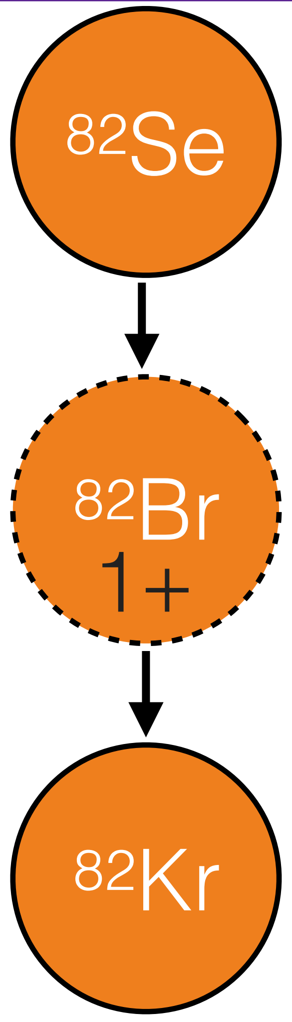
$2\nu\beta\beta$:

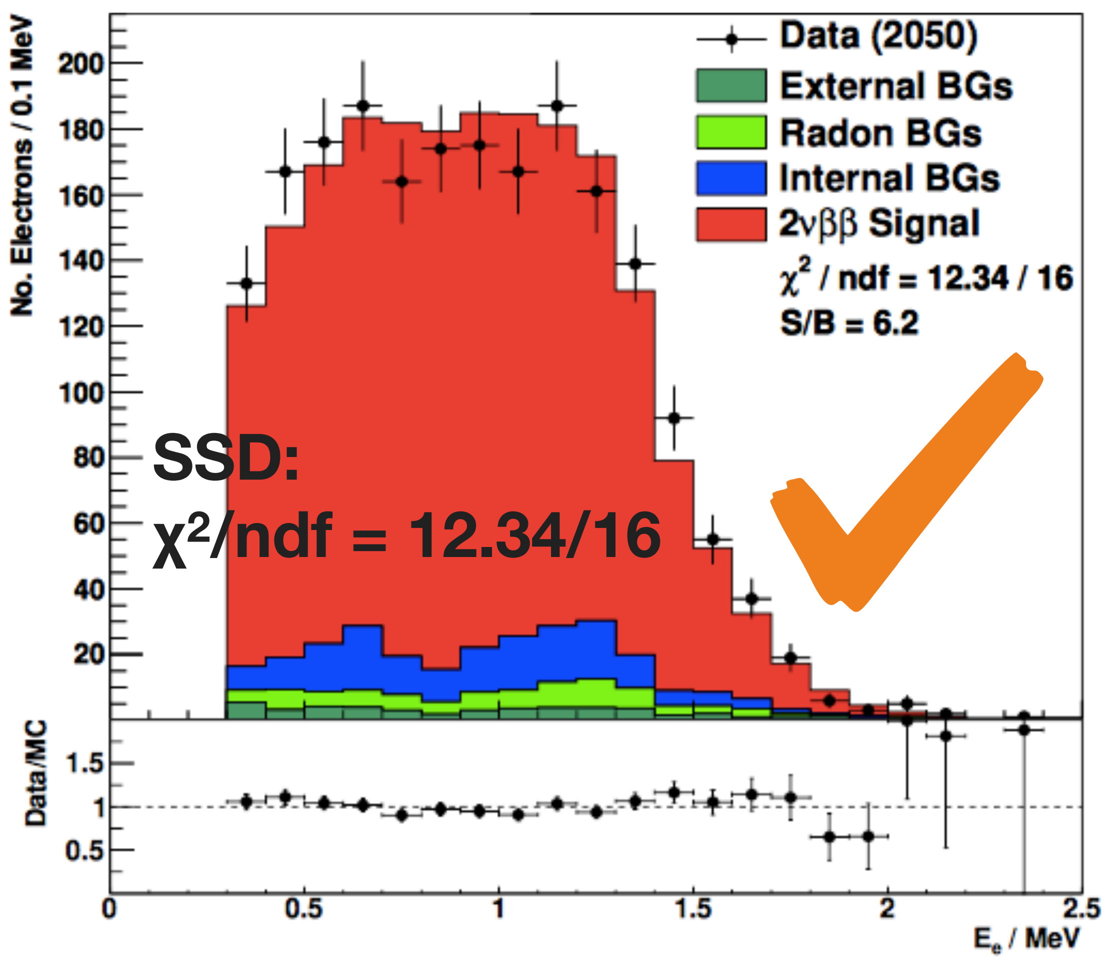
$T_{1/2}$ = **9.39** ± 0.17 (stat) ± 0.58 (sys) **x 10^{19} years** (SSD hypothesis)

$0\nu\beta\beta$:

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







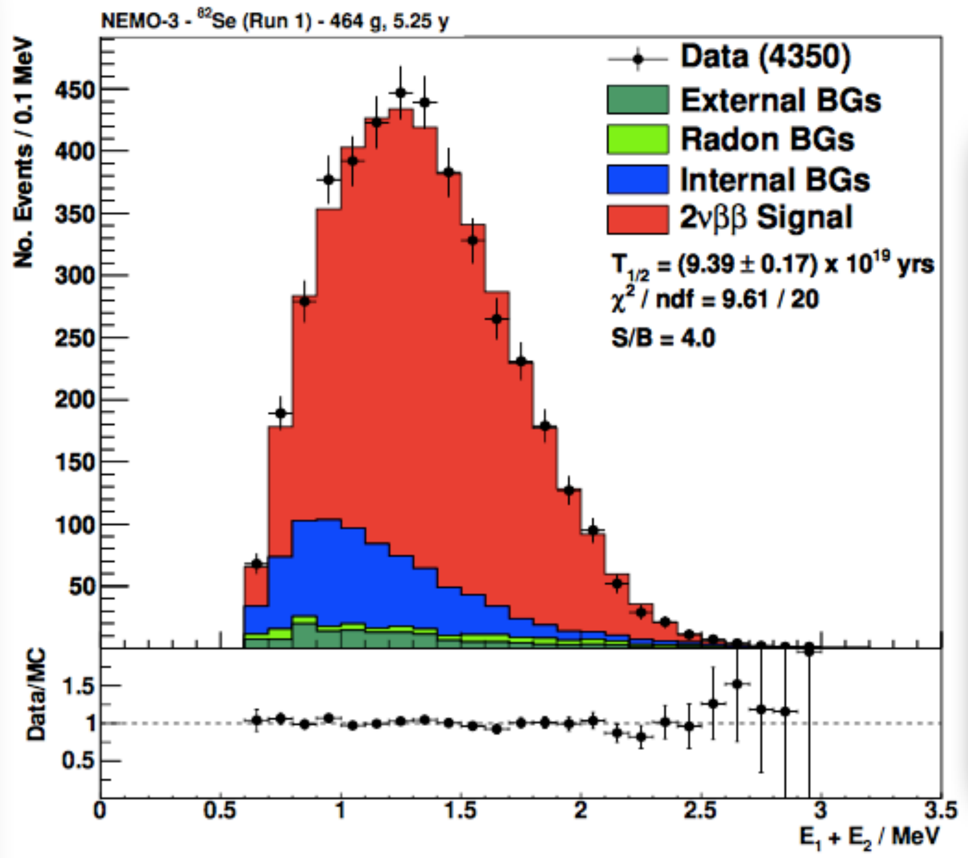
Higher state dominated - many excited states

Single state dominated - mostly one intermediate state

Individual electron spectrum helps identify intermediate states in ββ transition

NEMO-3 analyses: ^{82}Se

- 2νββ measurements and 0νββ limits for several isotopes
  - ^{100}**Mo** (Phys. Rev. Let. 95, 182302)
  - ^{48}**Ca** (Phys. Rev. D 93, 112008)
  - ^{82}**Se** (Eur. Phys. J. C (2018) 78: 821)
  - ^{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)



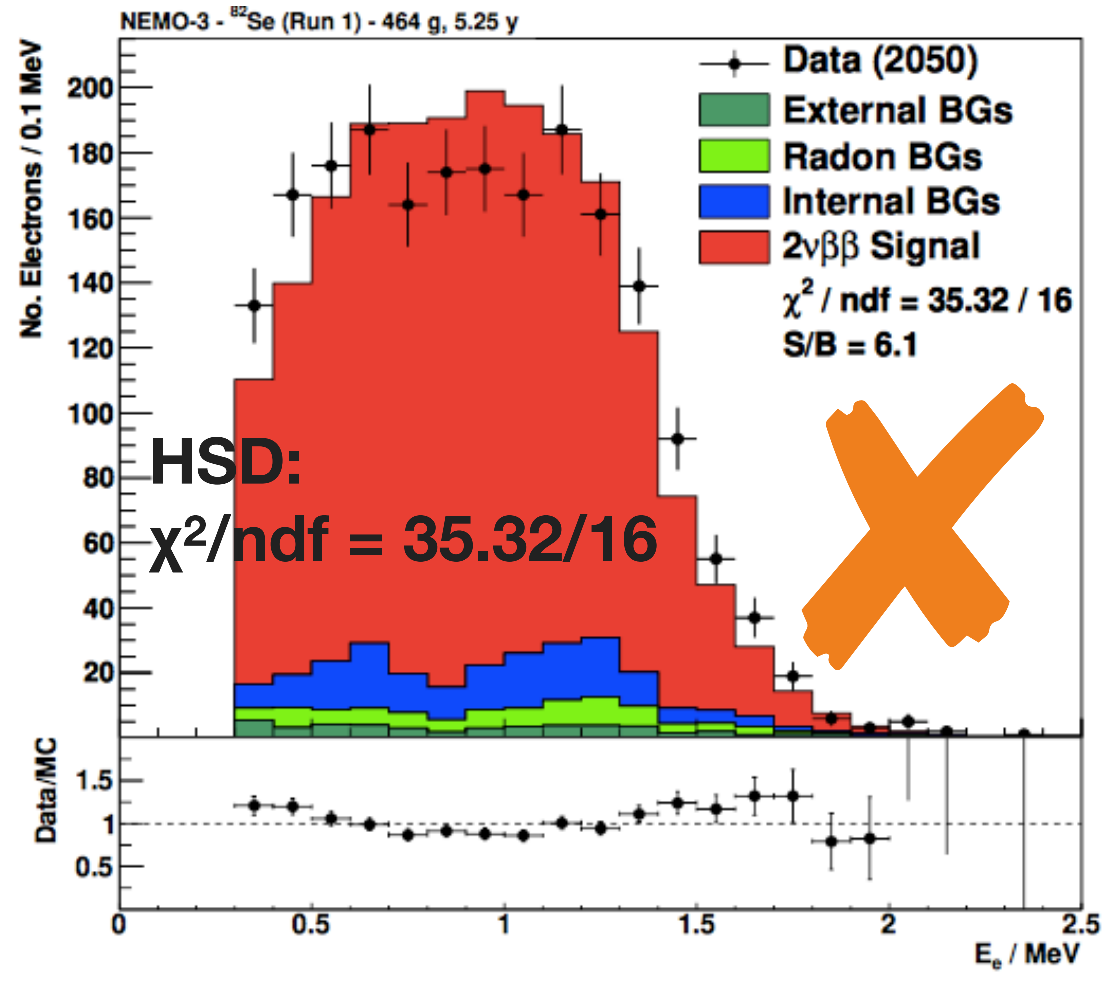
Summed 2-electron spectrum

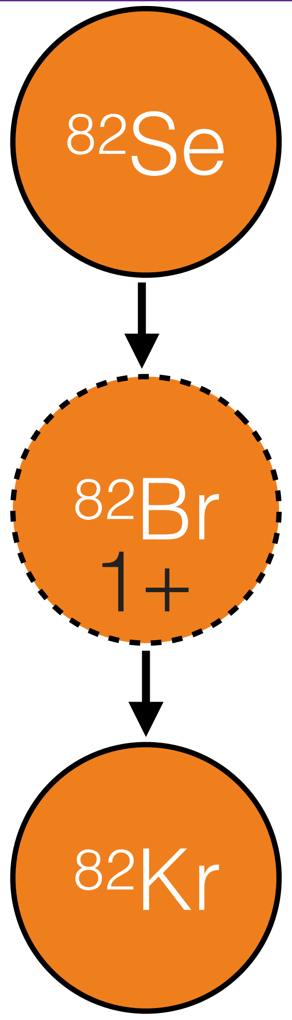
2νββ:

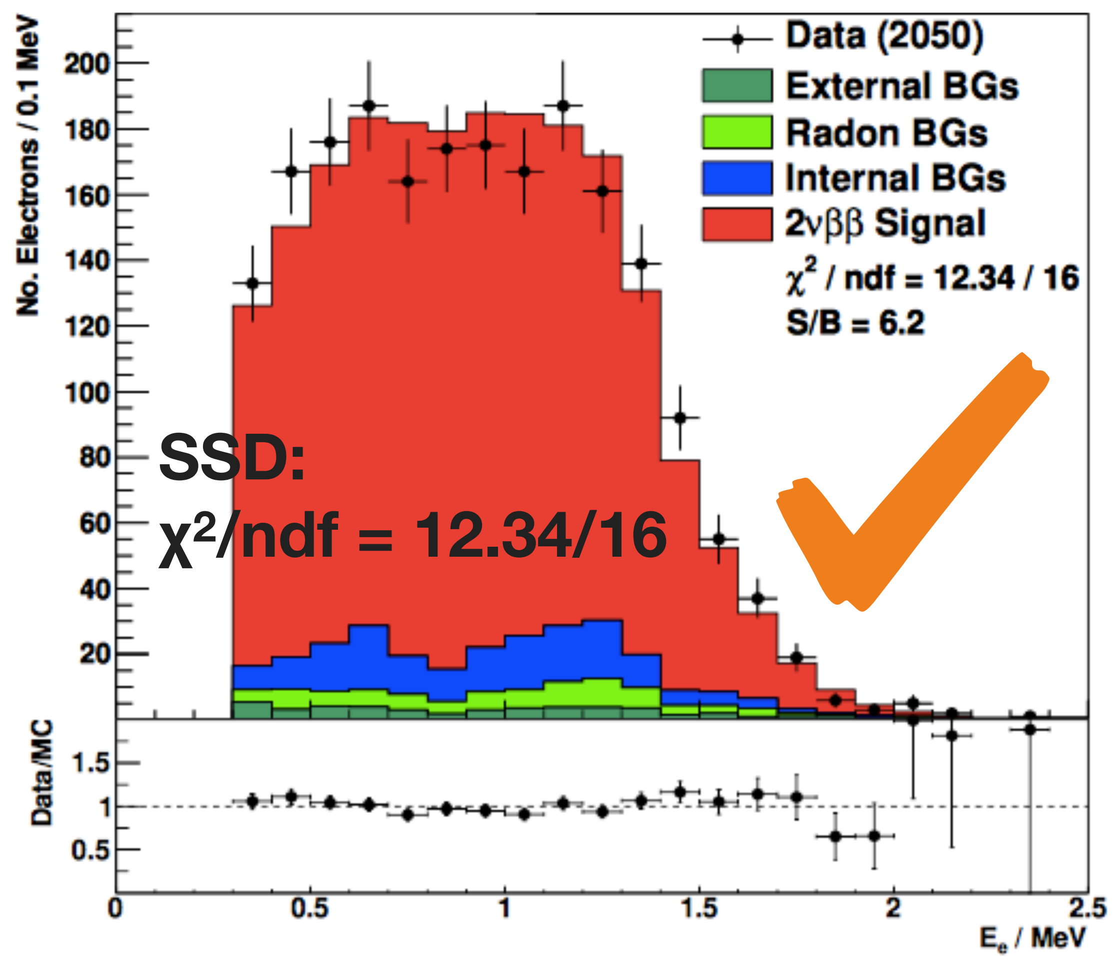
$T_{1/2}$ = **9.39** ± 0.17 (stat) ± 0.58 (sys) **x 10^{19} years** (SSD hypothesis)

0νββ:

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







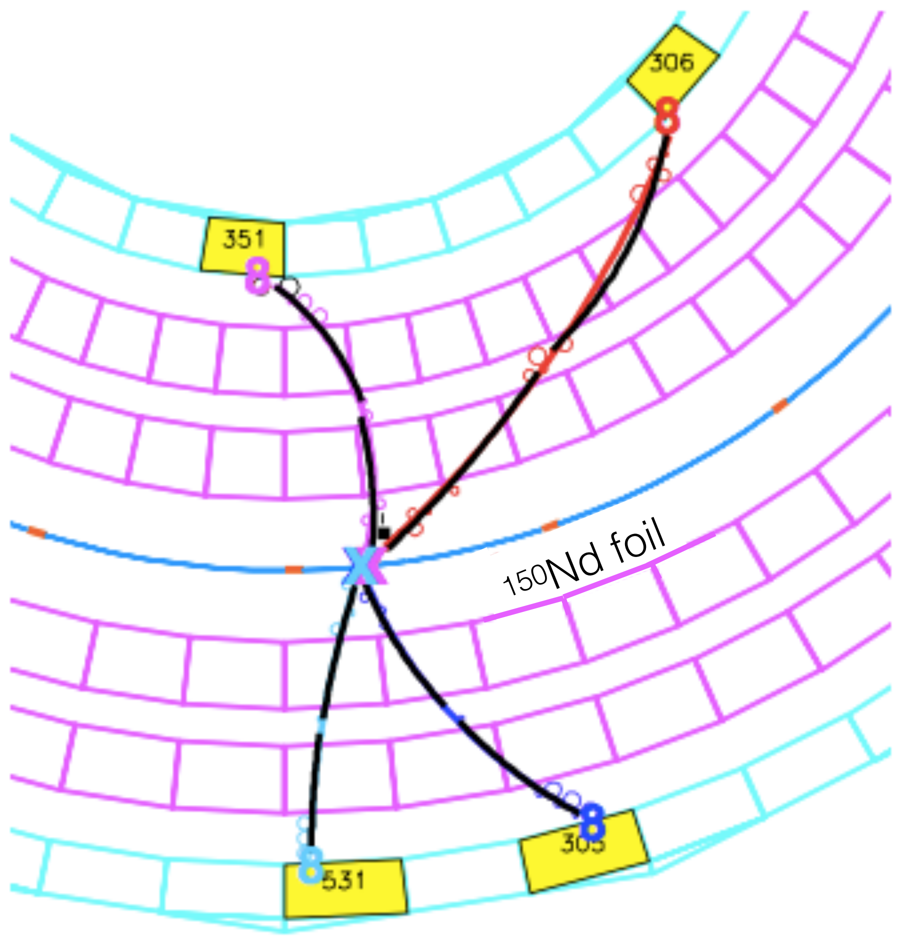
Higher state dominated - many excited states

Single state dominated - mostly one intermediate state

Individual electron spectrum helps identify intermediate states in ββ transition

NEMO-3 - quadruple beta decay

- 2νββ measurements and 0νββ limits for several isotopes
  - ^{100}**Mo** (Phys. Rev. Let. 95, 182302)
  - ^{48}**Ca** (Phys. Rev. D 93, 112008)
  - ^{82}**Se** (Eur. Phys. J. C (2018) 78: 821)
  - ^{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)
- **Quadruple β decay** (Phys. Rev. Lett. 119, 041801)

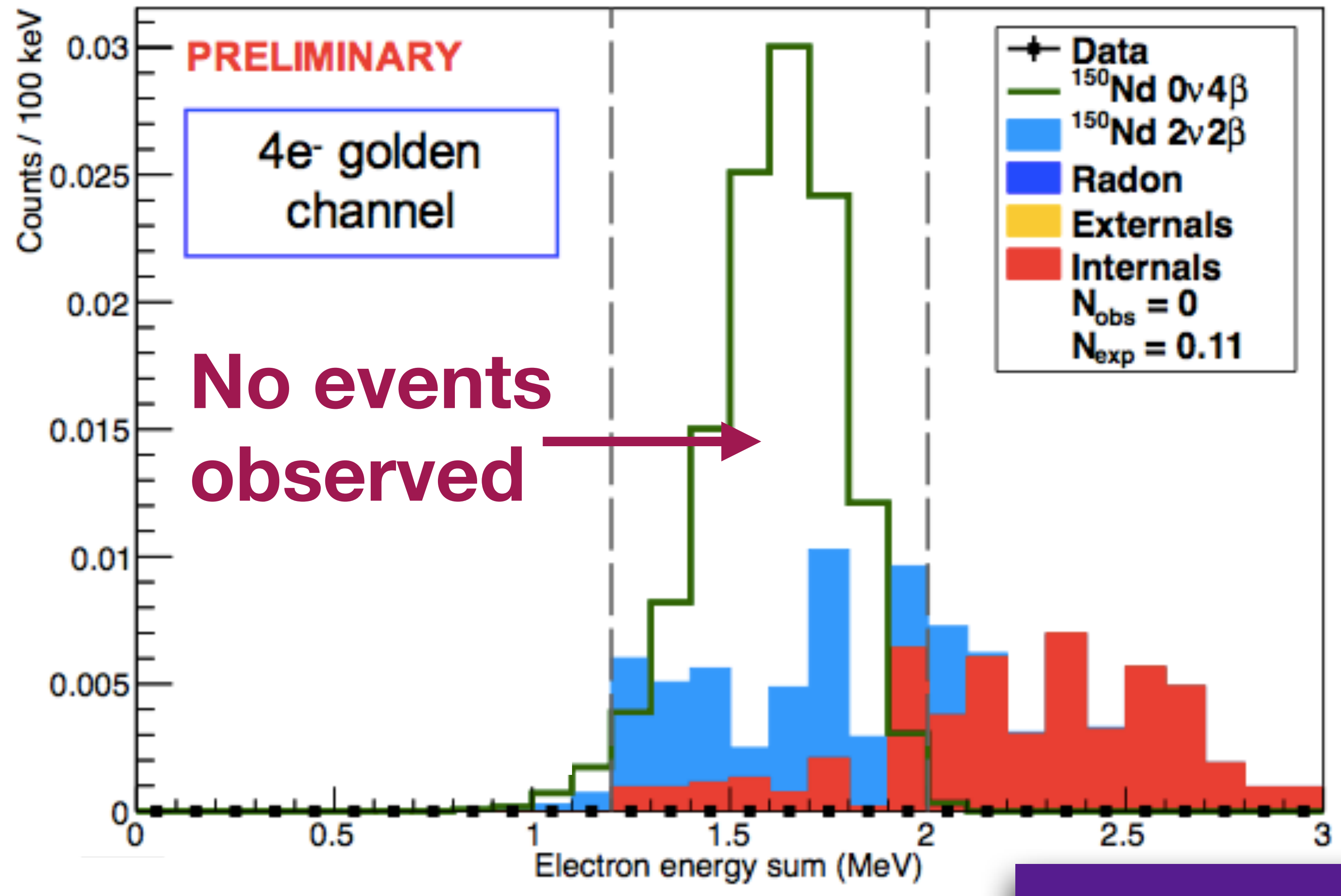


0ν4β decays would violate lepton number, but could occur even if neutrinos are **Dirac** fermions

Heeck and Rodejohann 2013

Allowed for 3 isotopes, including

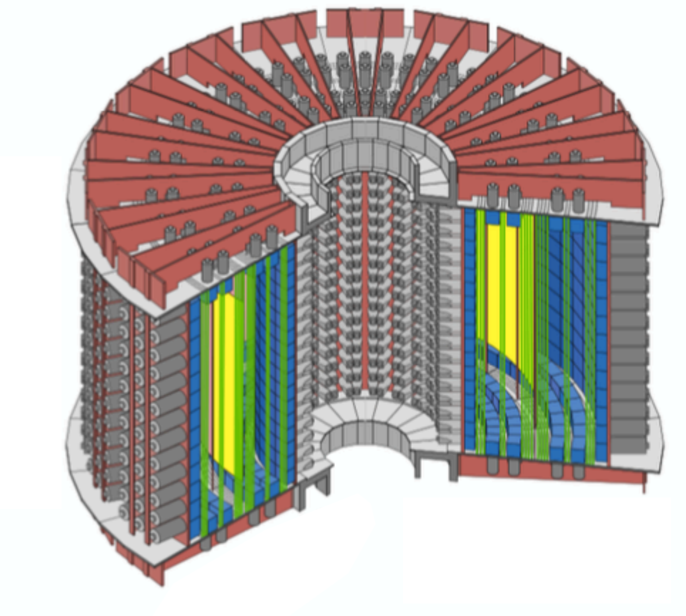
$$^{150}\mathrm{Nd} \xrightarrow{2.079\ \mathrm{MeV}} {}^{150}\mathrm{Gd} + 4e^-$$

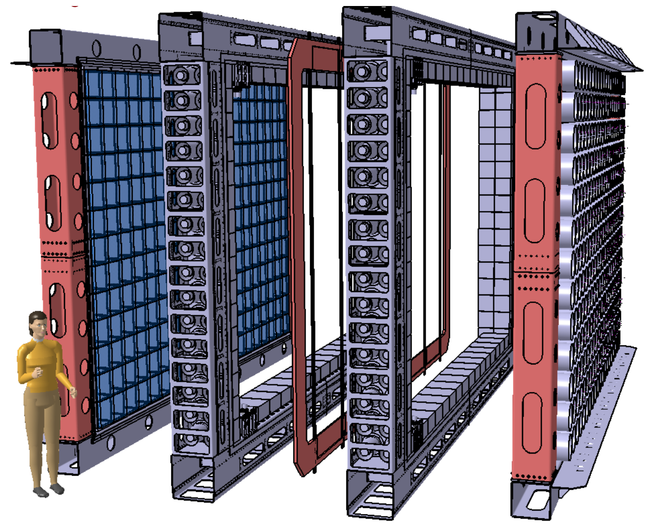


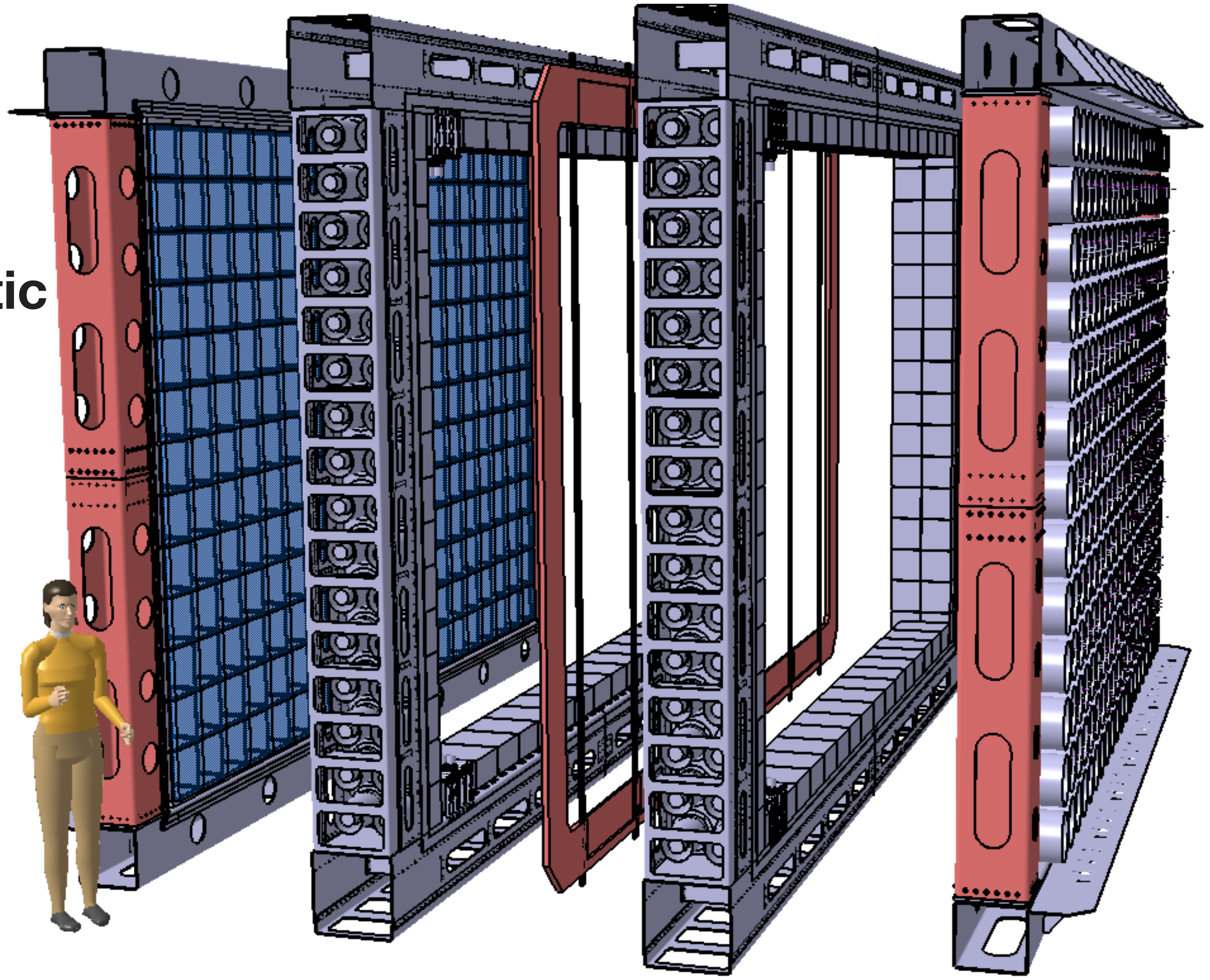
NEMO architecture helps us identify these topologies

$T_{1/2}$ > 2.6 x 10^{21} yr (90%CL)

Next stop: SuperNEMO demonstrator

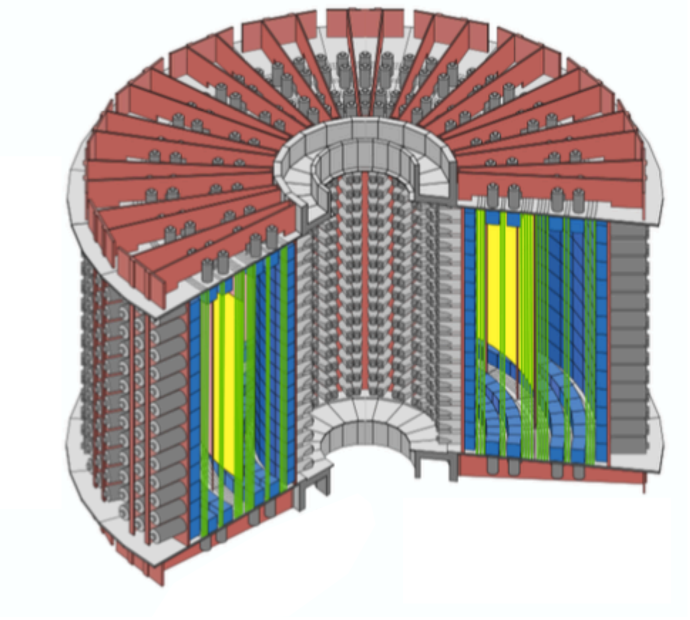


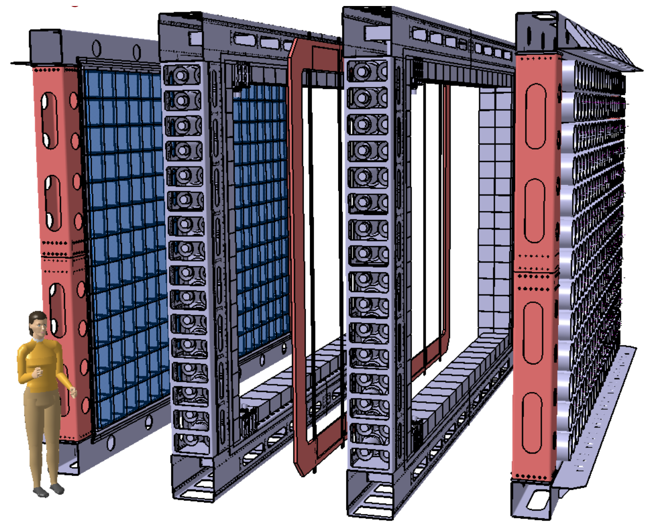




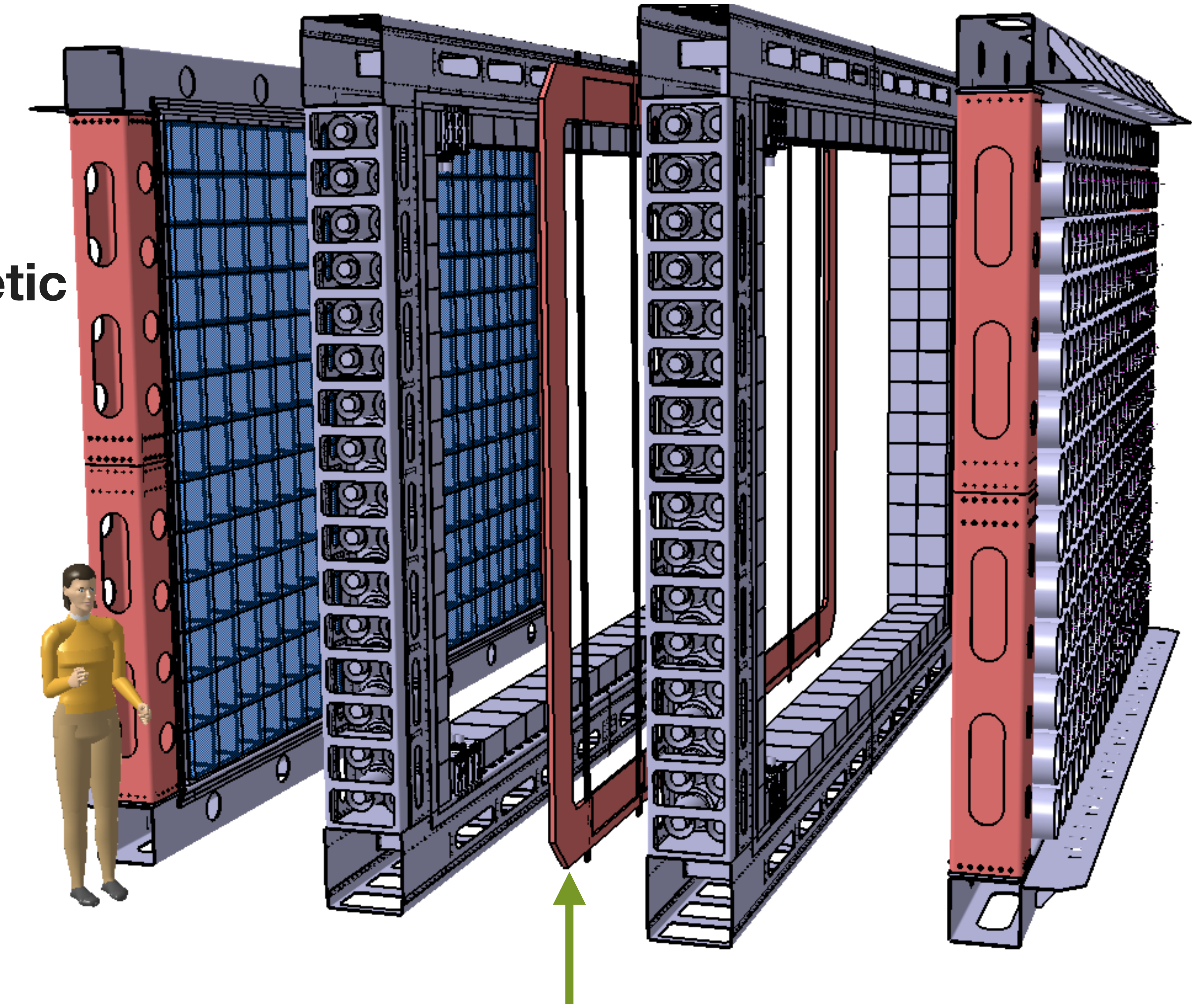
	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	6.8 x 10^{18}	9.4 x 10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
A(^{214}Bi)	$< 300\ \mu$Bq/kg	$< 10\ \mu$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

Next stop: SuperNEMO demonstrator





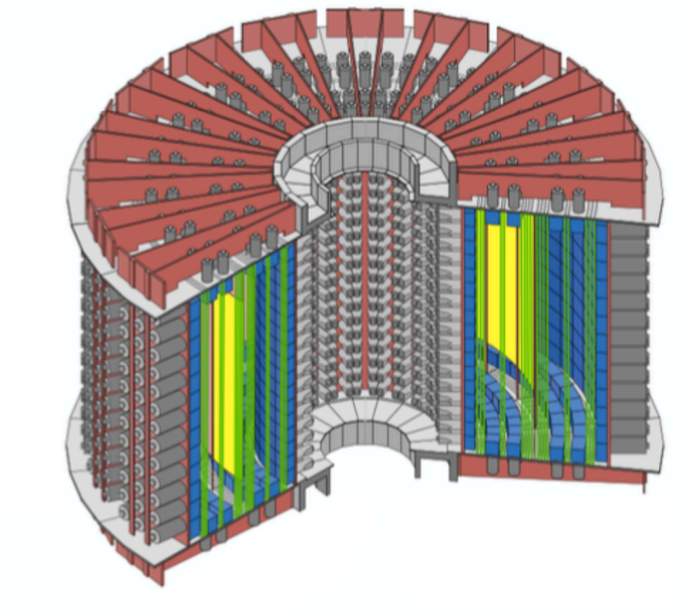
Magnetic field

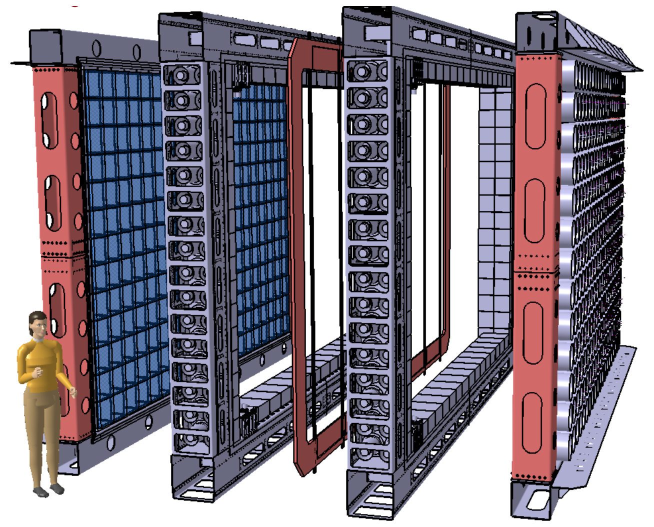


Source frame holding 7kg of ββ emitter (^{82}Se)

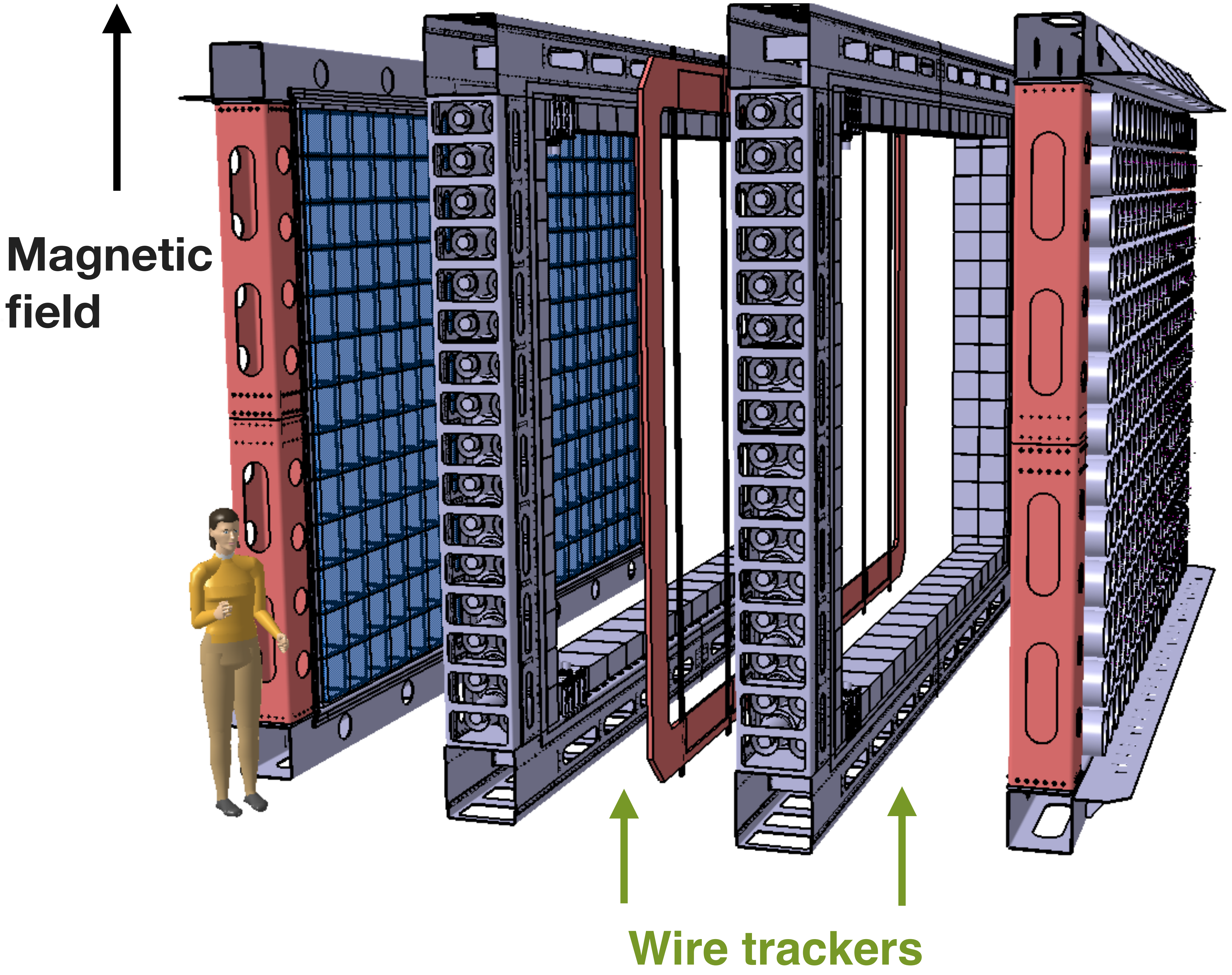
	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	6.8×10^{18}	9.4×10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
$A(^{208}Tl)$	$\sim 100\ \mu Bq/kg$	$< 2\ \mu Bq/kg$
$A(^{214}Bi)$	$< 300\ \mu Bq/kg$	$< 10\ \mu Bq/kg$
Level of radon $A(^{222}Rn)$	$\sim 5.0\ mBq/m^3$	$< 0.15\ mBq/m^3$
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

Next stop: SuperNEMO demonstrator

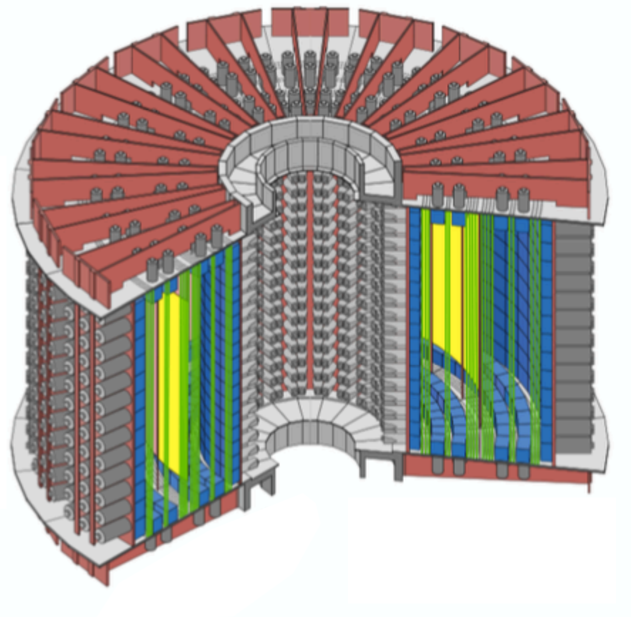


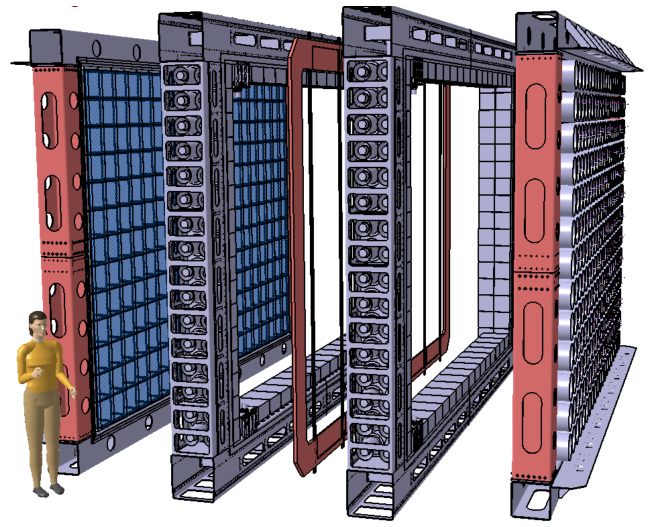


	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	6.8 x 10^{18}	9.4 x 10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim$ 100 μBq/kg	< 2 μBq/kg
A(^{214}Bi)	< 300 μBq/kg	< 10 μBq/kg
Level of radon A(^{222}Rn)	$\sim$ 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

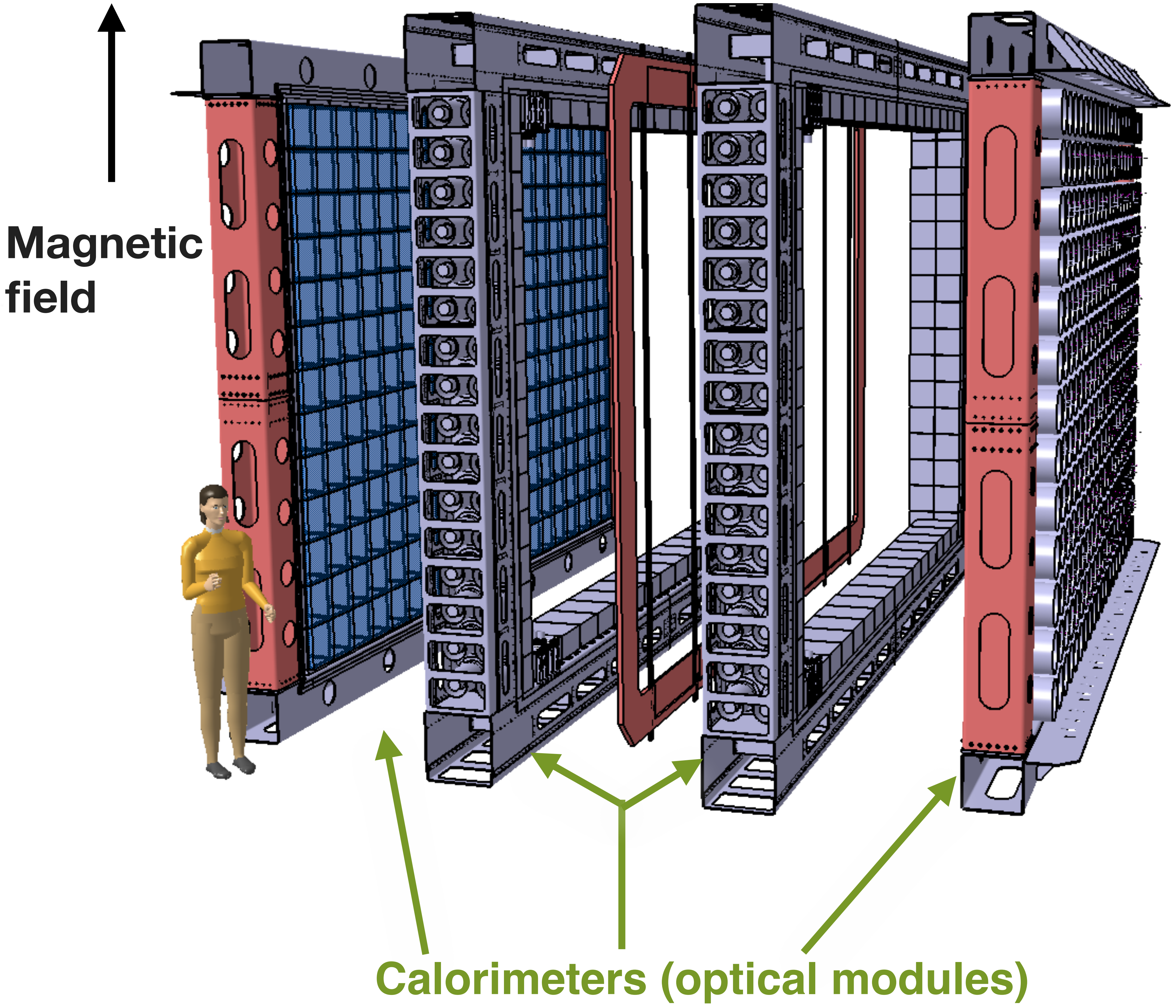


Next stop: SuperNEMO demonstrator

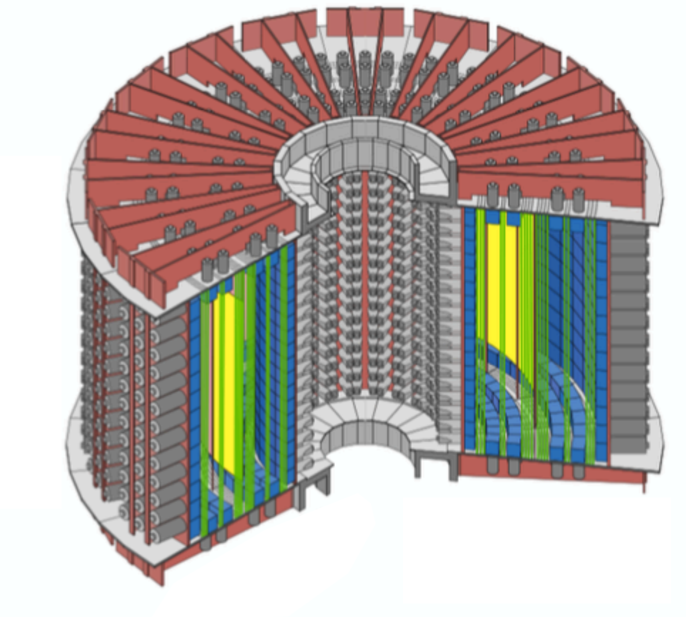


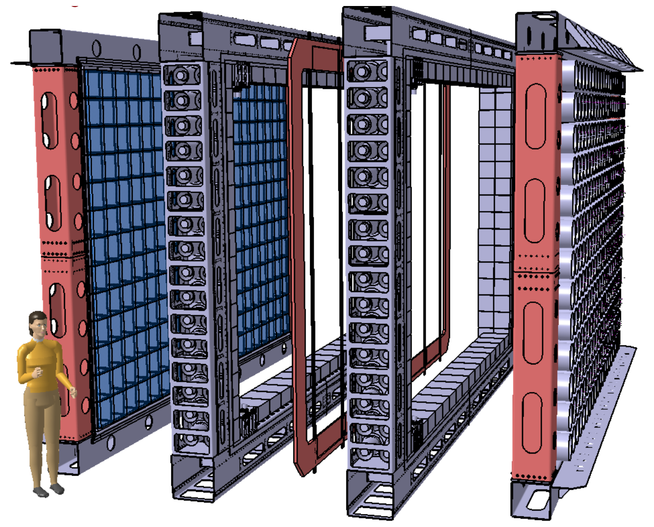


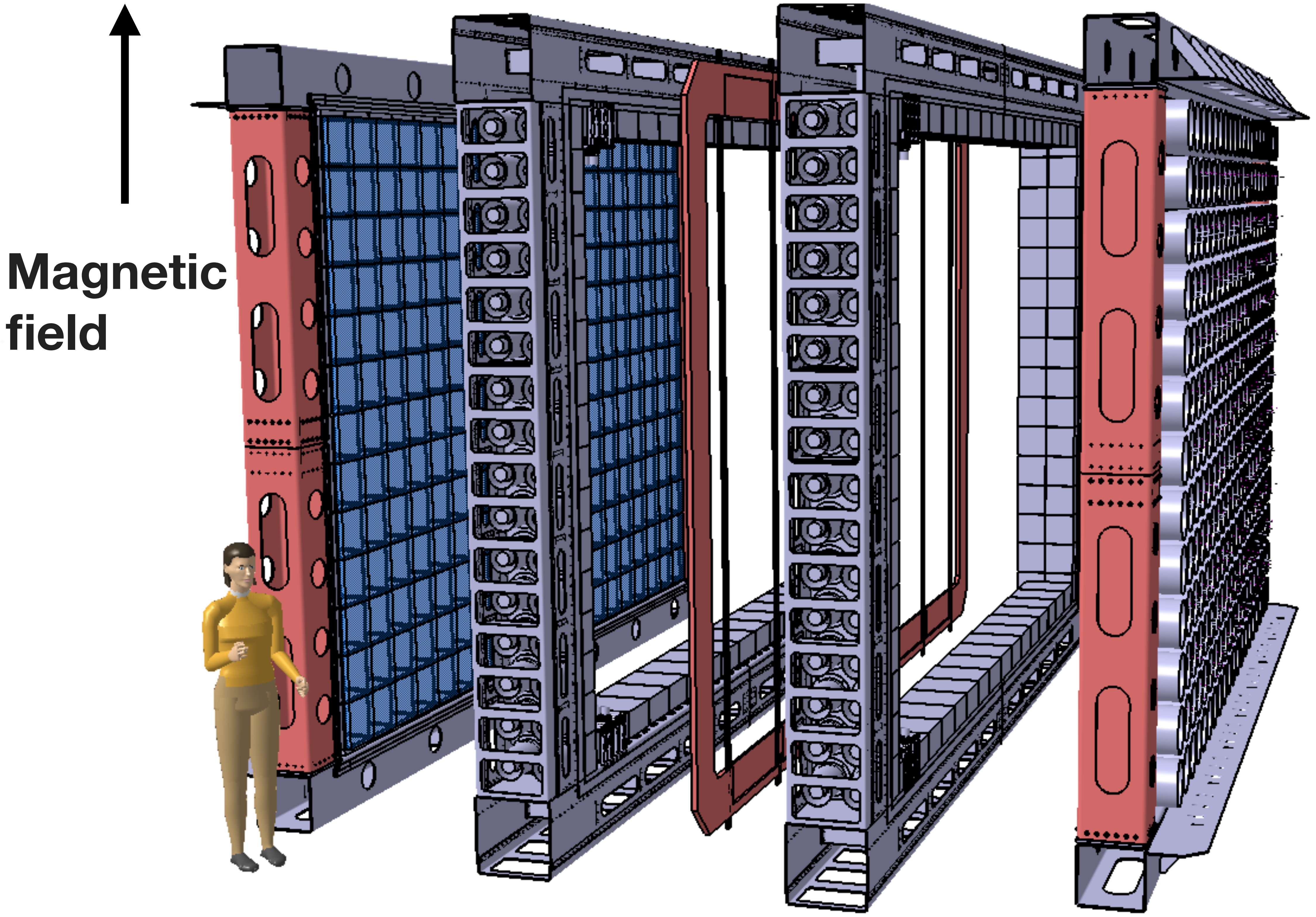
	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	6.8 x 10^{18}	9.4 x 10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
A(^{214}Bi)	$< 300\ \mu$Bq/kg	$< 10\ \mu$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



Next stop: SuperNEMO demonstrator



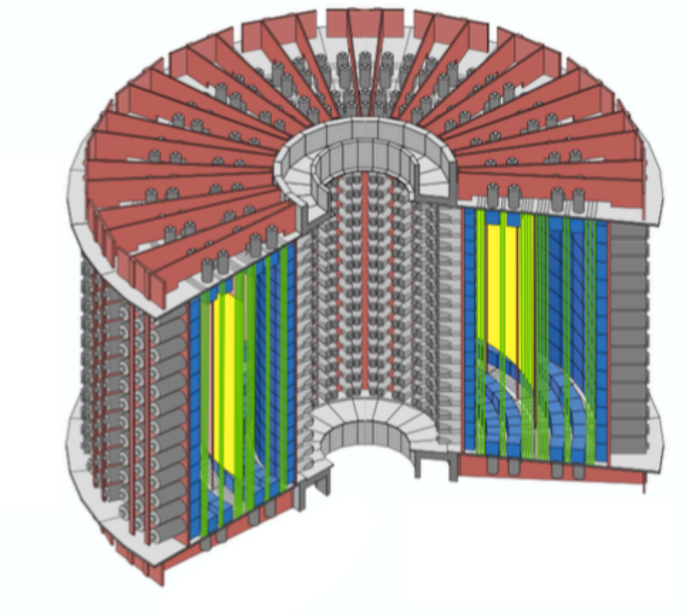


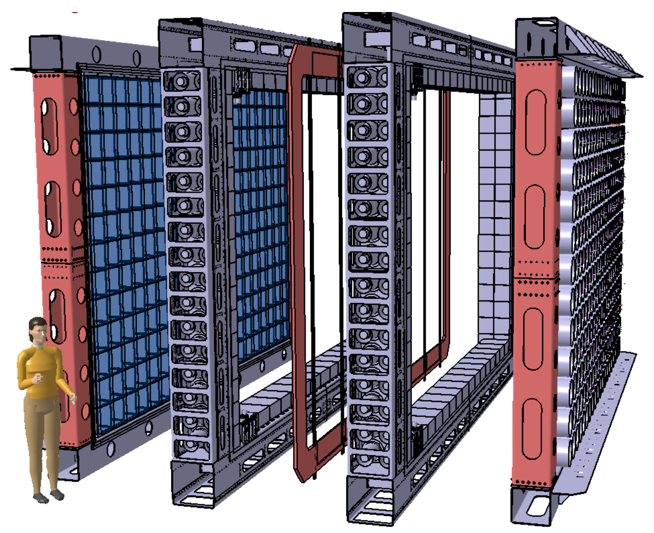


	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	6.8 x 10^{18}	9.4 x 10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
A(^{214}Bi)	$< 300\ \mu$Bq/kg	$< 10\ \mu$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

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

Full SuperNEMO (15-20 demonstrator modules)

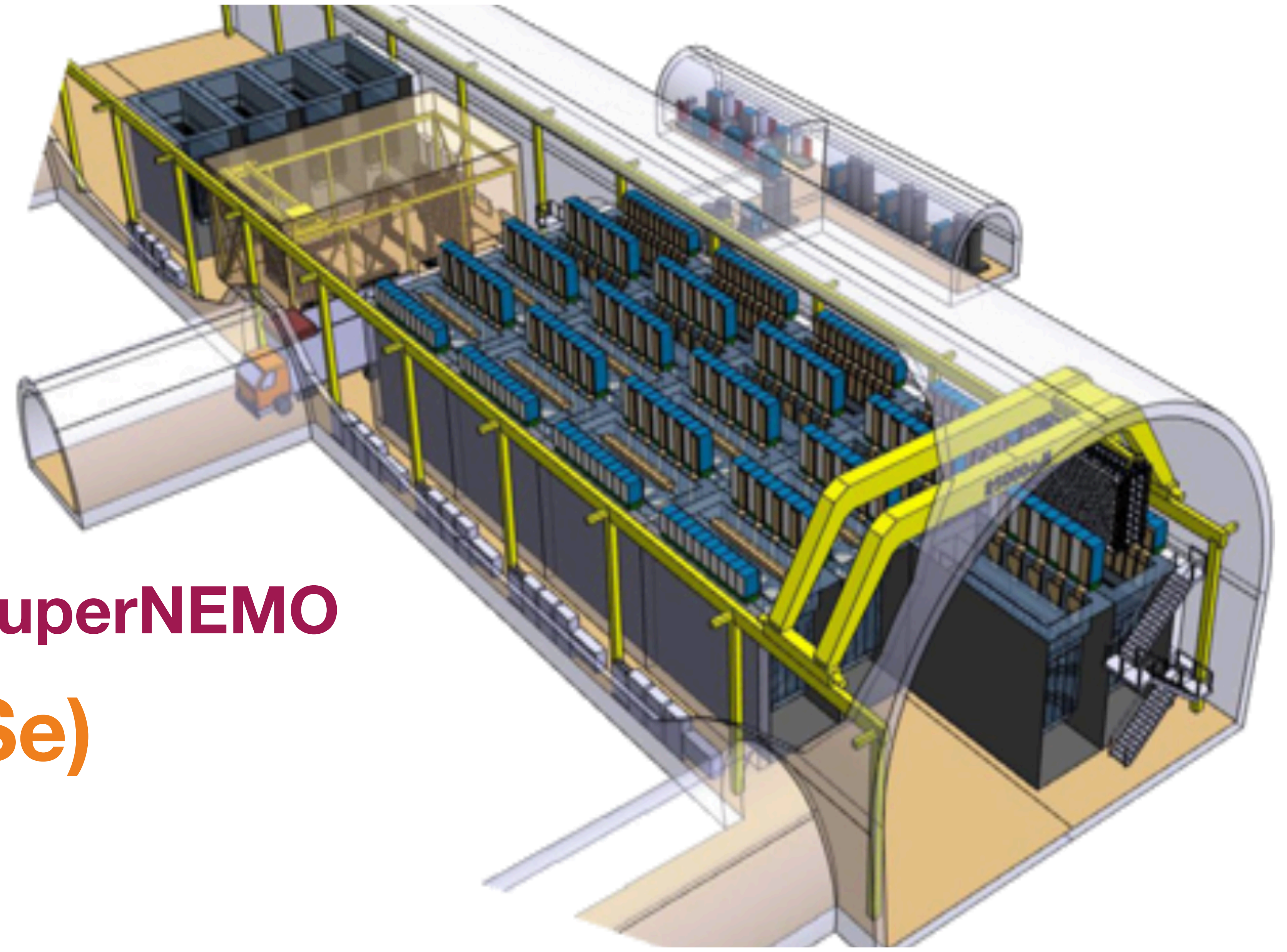




	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	6.8×10^{18}	9.4×10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
A(^{214}Bi)	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg
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

Proposed full SuperNEMO

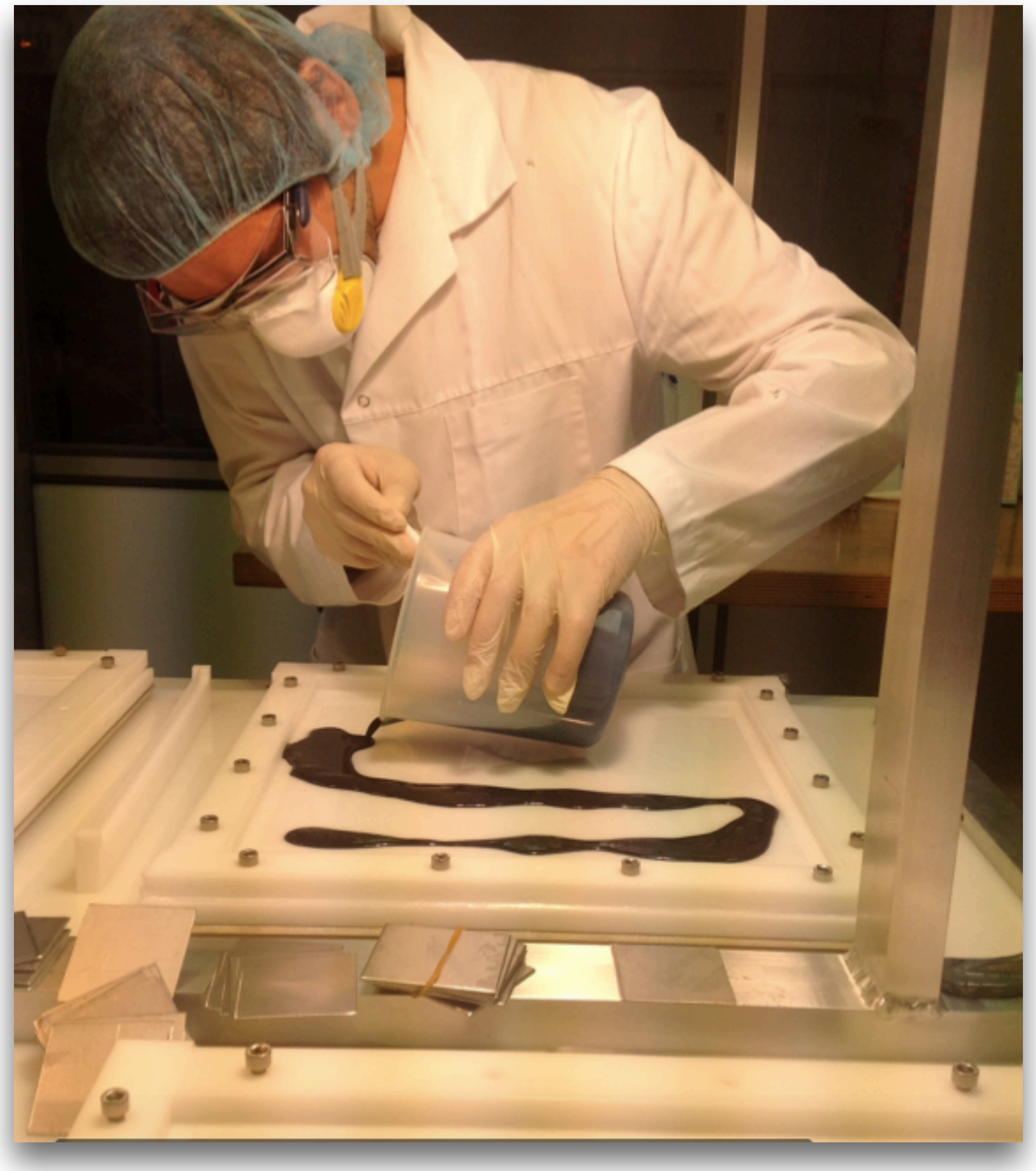
100 kg (^{82}Se)

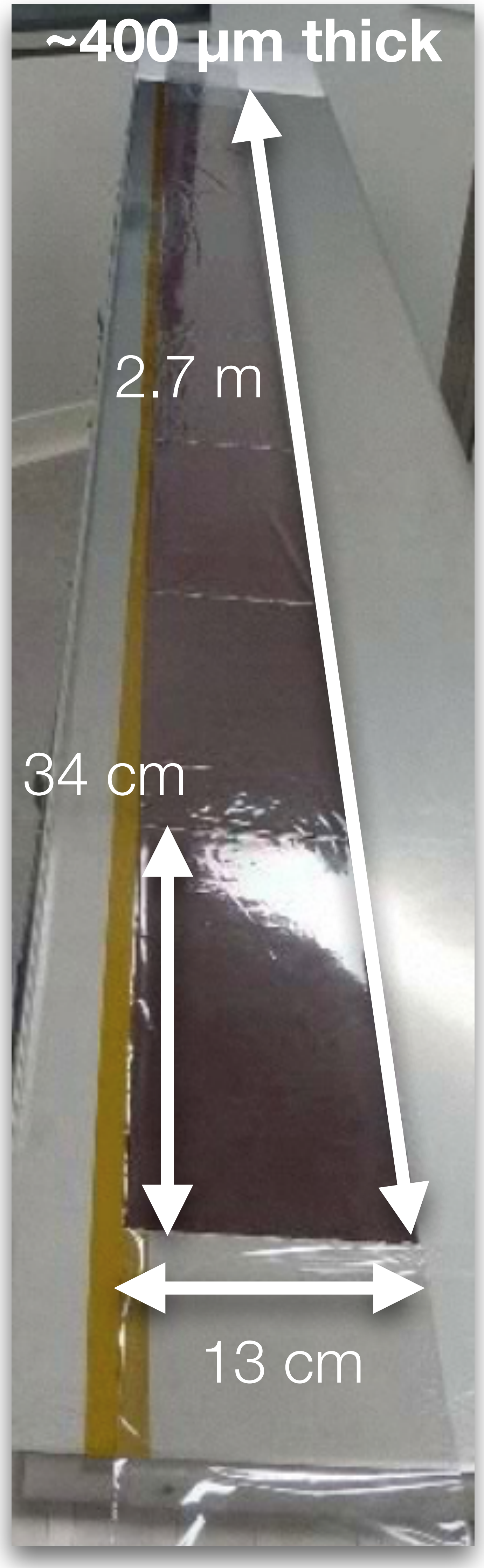


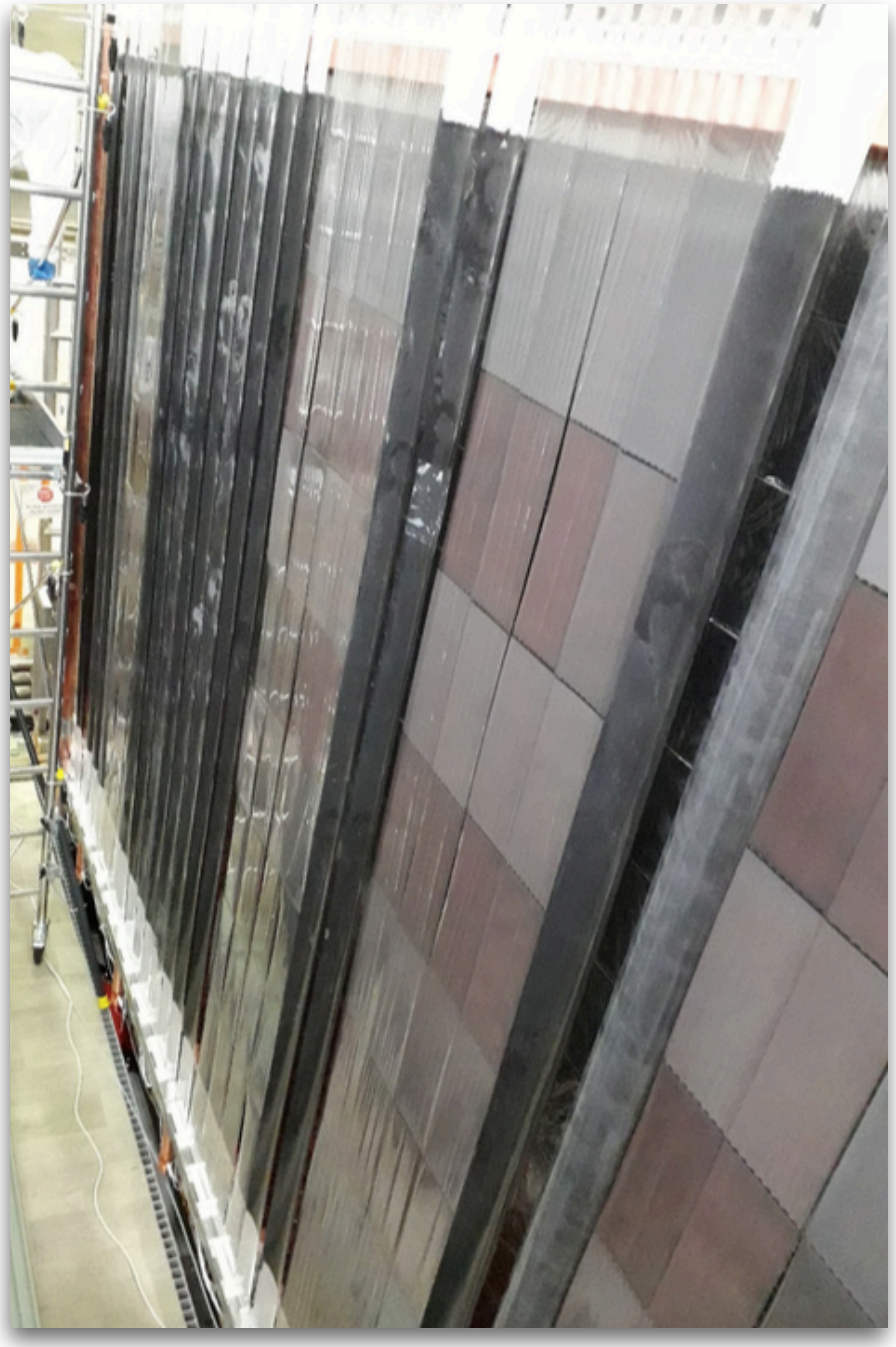
$T_{1/2} > 10^{26}$ years; $\langle m_\nu \rangle <$ 40-100 meV

(5 years of data taking)

^{82}Se source foils

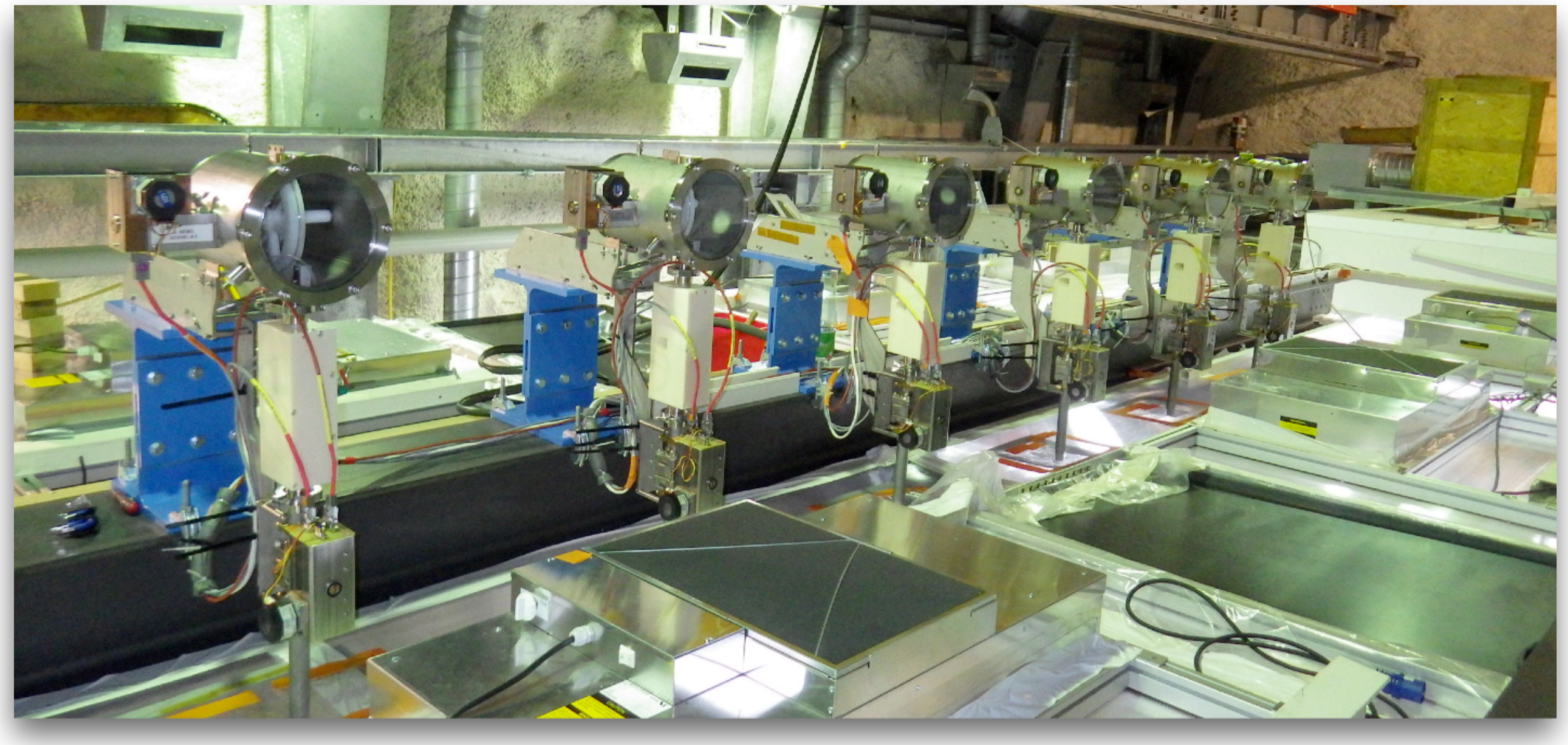




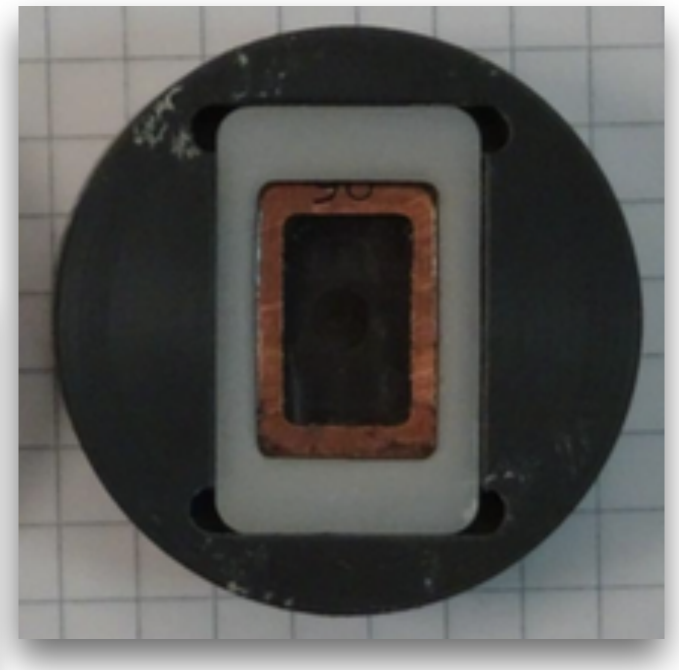


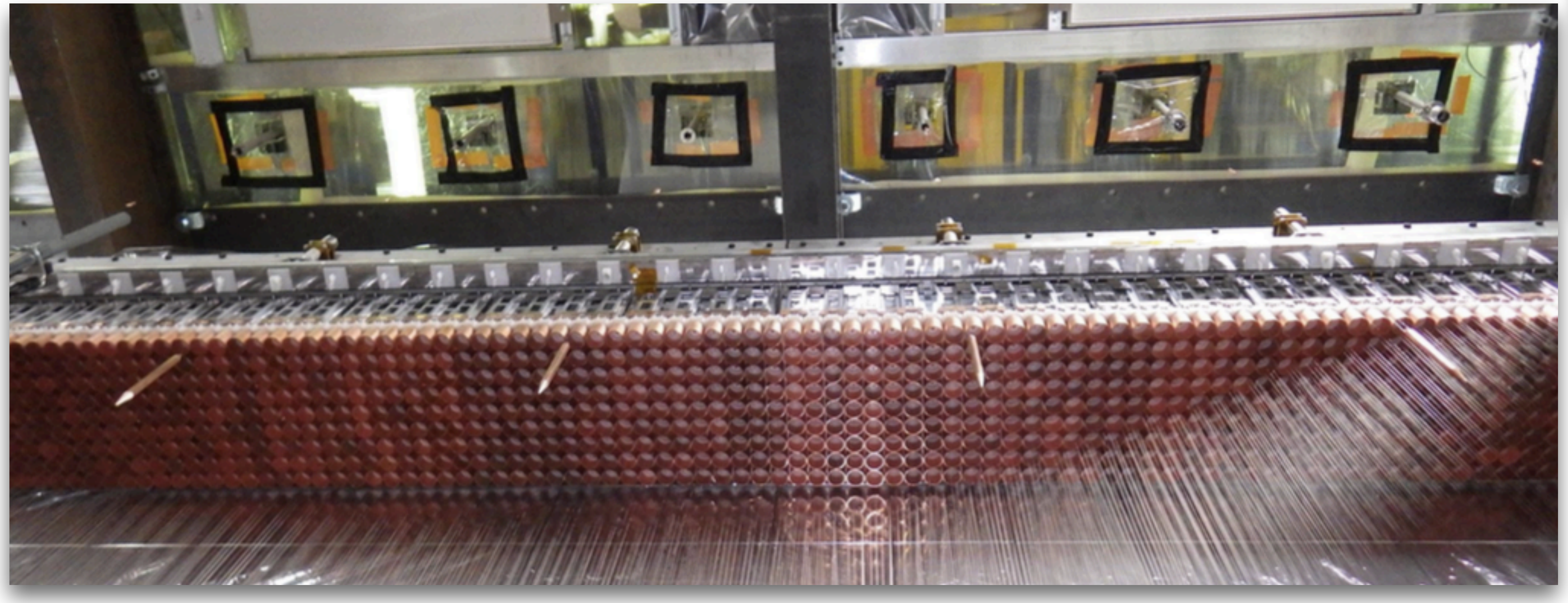
- **6.3 kg** of ββ emitter (**^{82}Se**) in 34 foils (plus 2 Cu foils)
- Enriched selenium powder mixed with PVA in Mylar wrapper
- Purified with distillation / chromatography / chemical precipitation
- **Now installed** at LSM
- **BiPo detector** measured ^{208}Tl and ^{214}Bi contamination:
  - targets 10μBq/kg ^{214}Bi, 2μBq/kg ^{208}Tl too low to confirm with current BiPo measurement
  - measure activities *in situ*

Source frame and calibration source deployment system

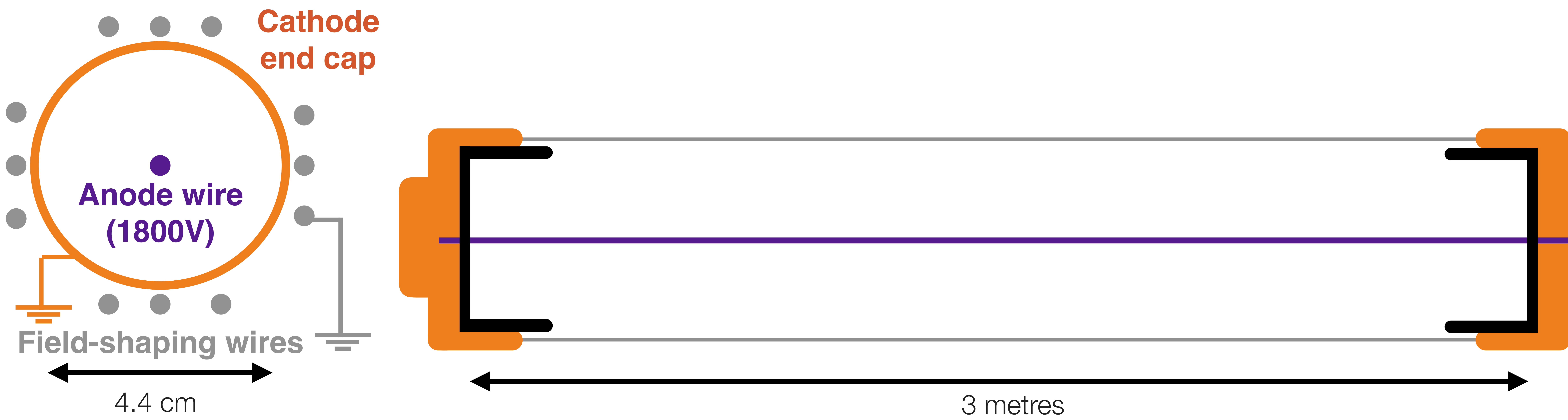


- 42 ^{207}**Bi** sources with known spectrum
- **Automatically deployed** ~ once a week for ~15 hours
- **Lowered** from top of detector (**between foils**) via copper wire with plumb bob
- Position controlled with lasers

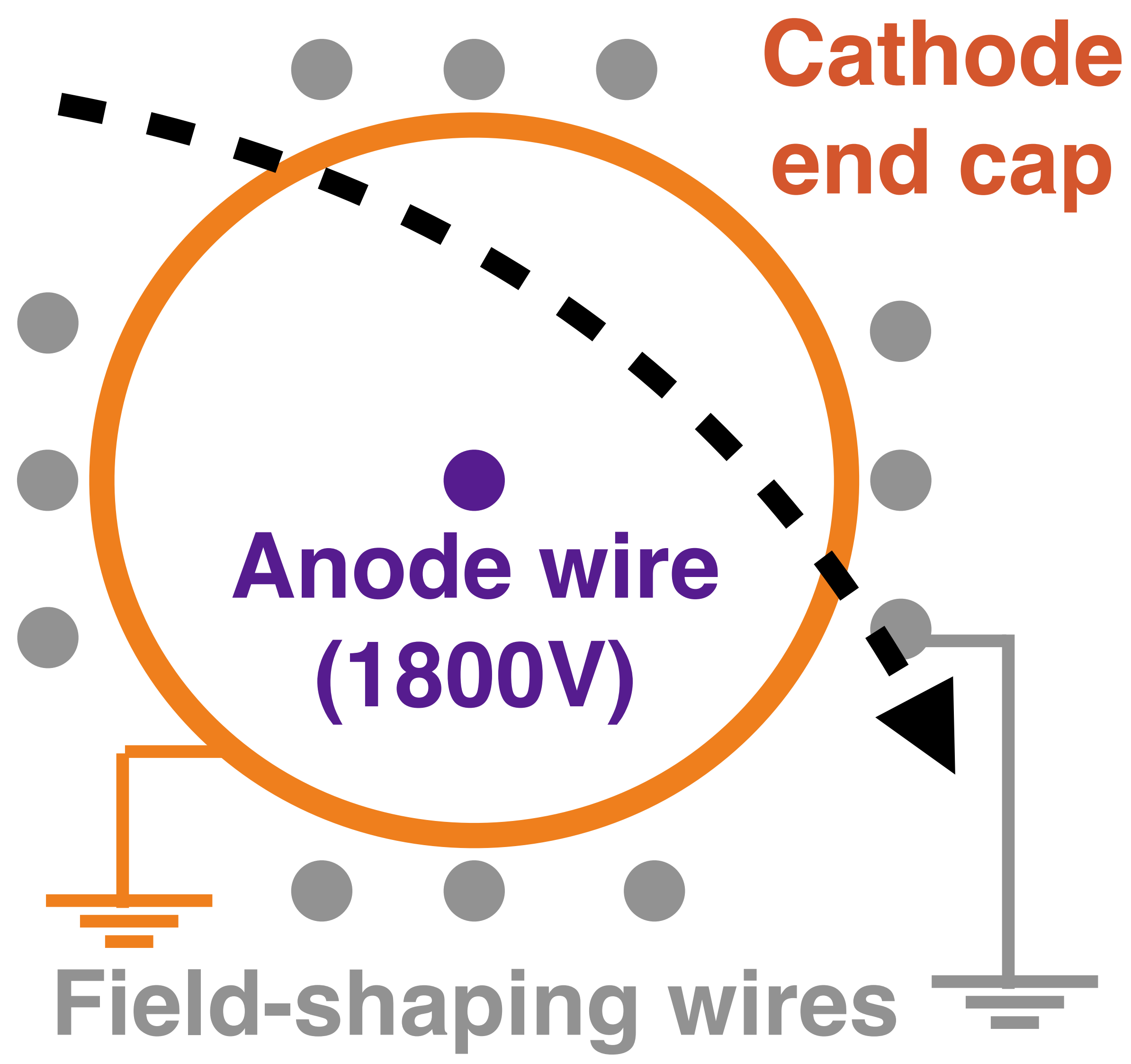


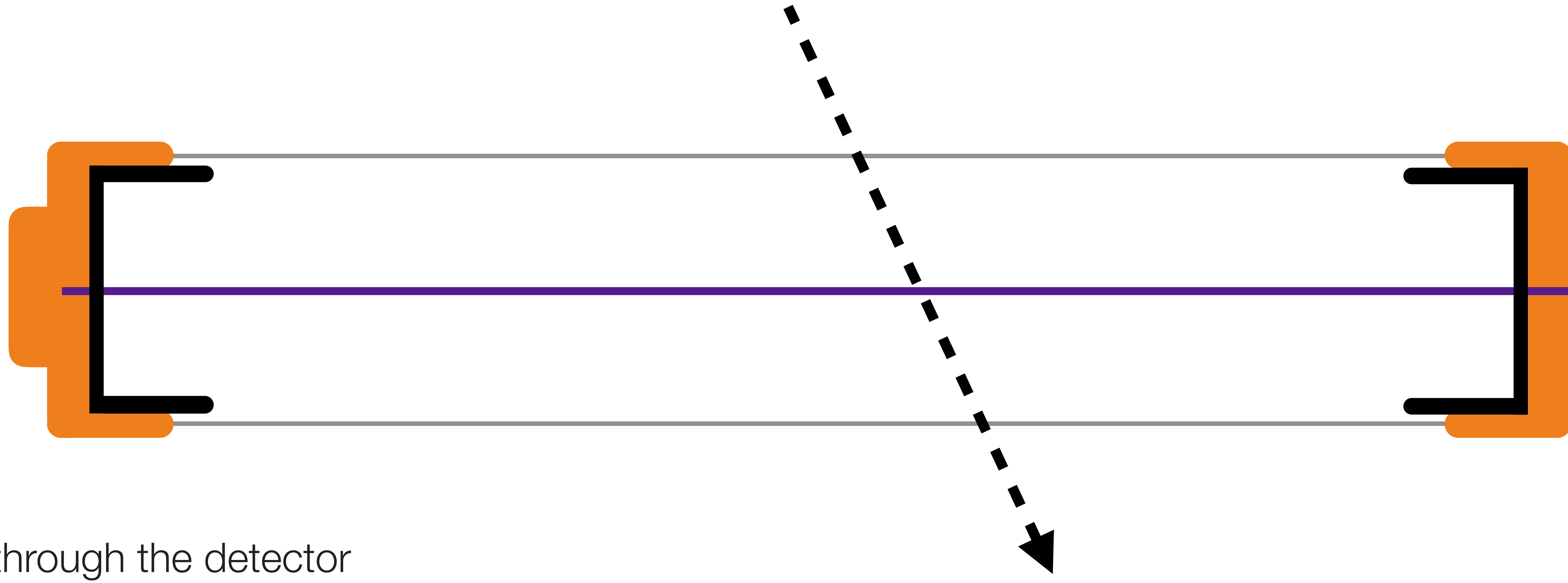


Wire trackers



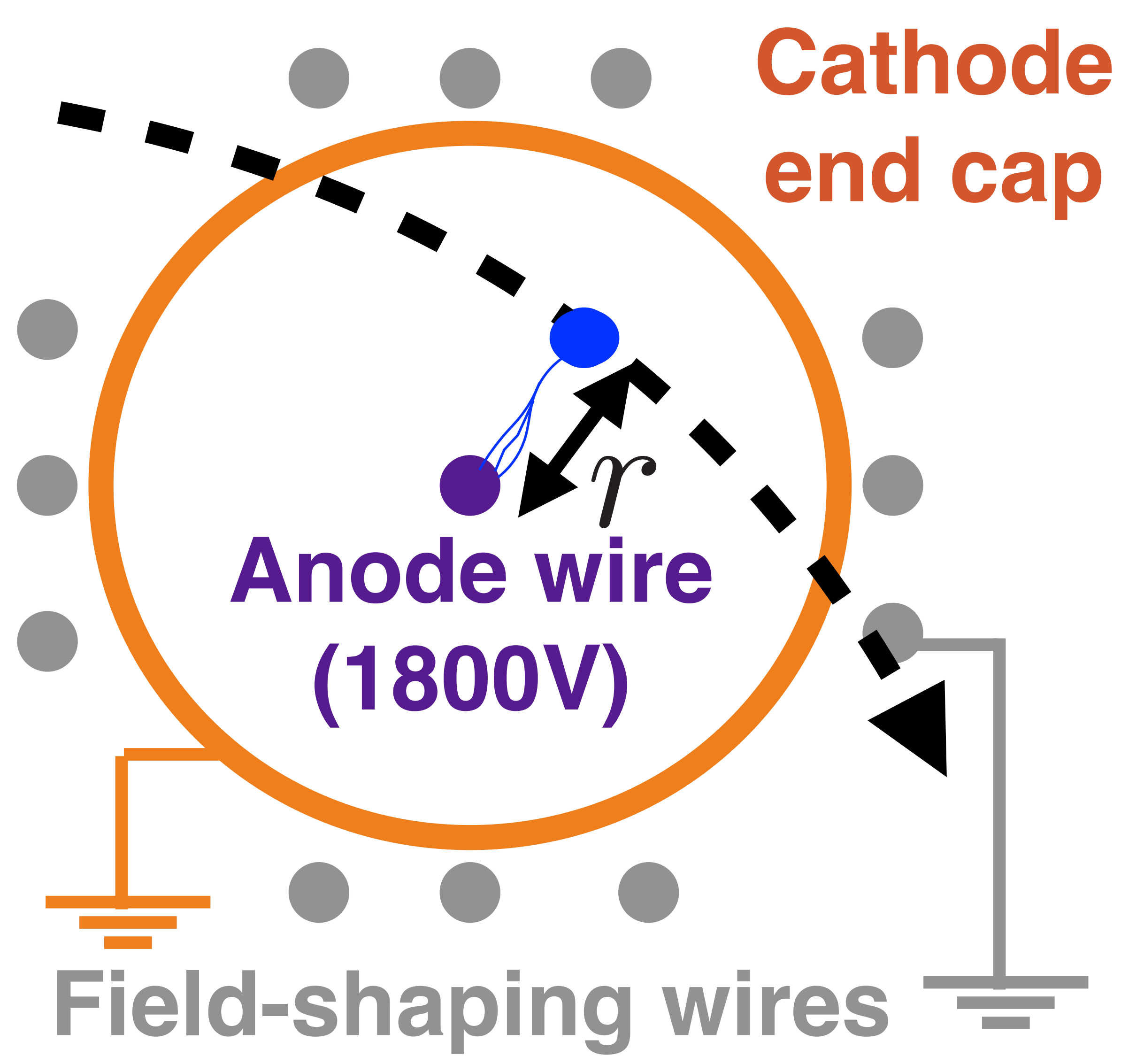
Wire trackers

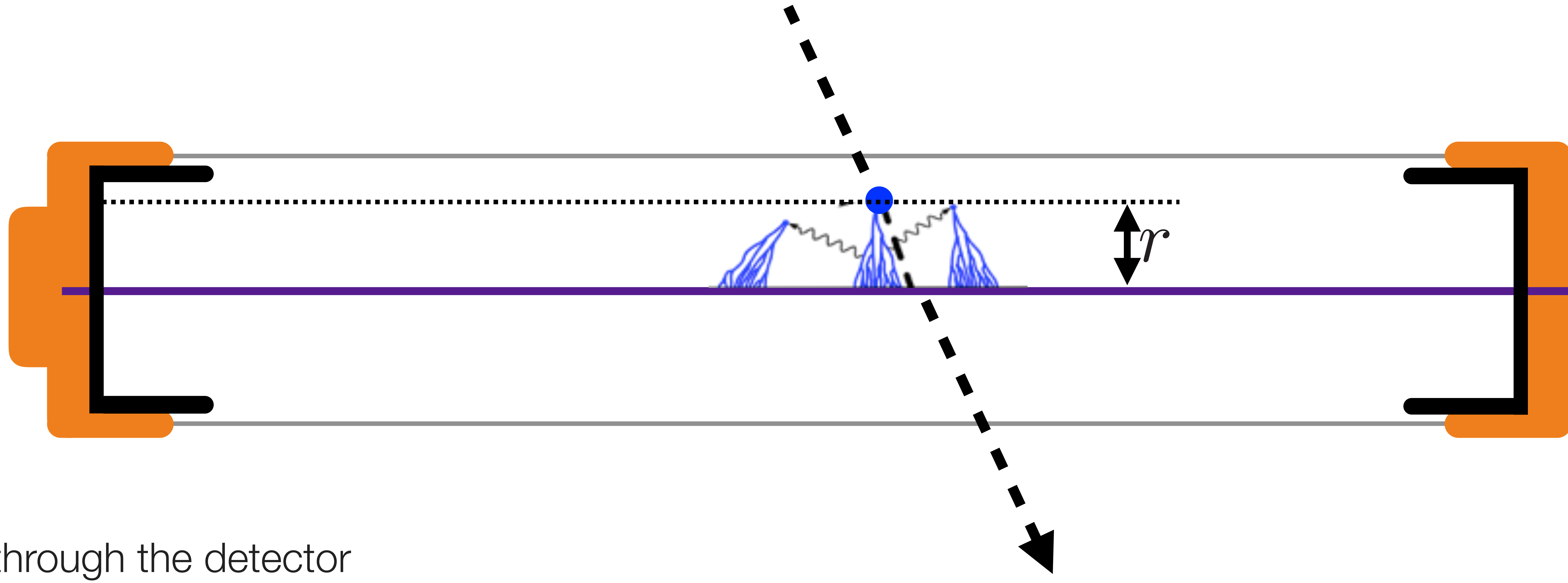




- Charged particle passes through the detector

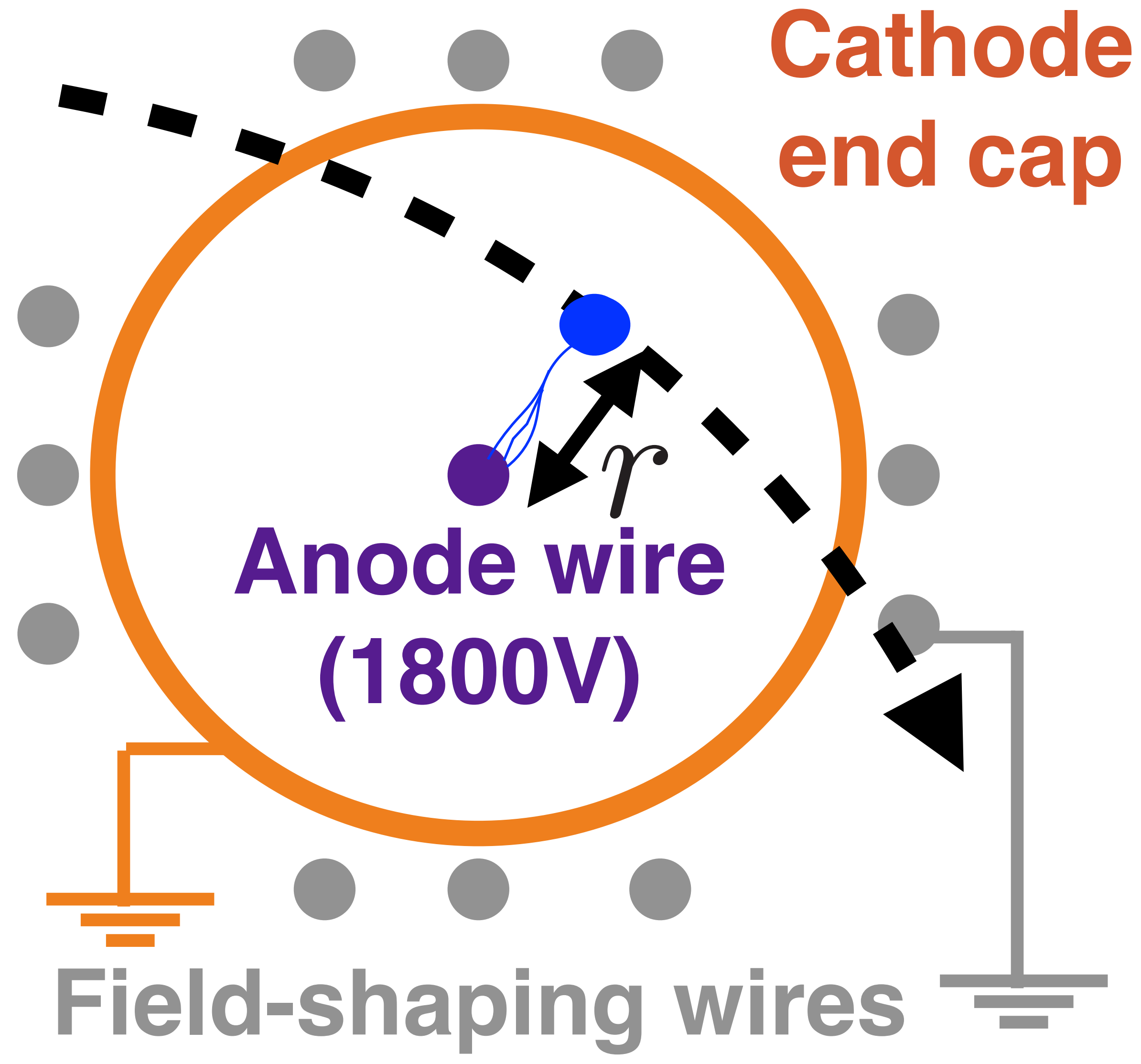
Wire trackers

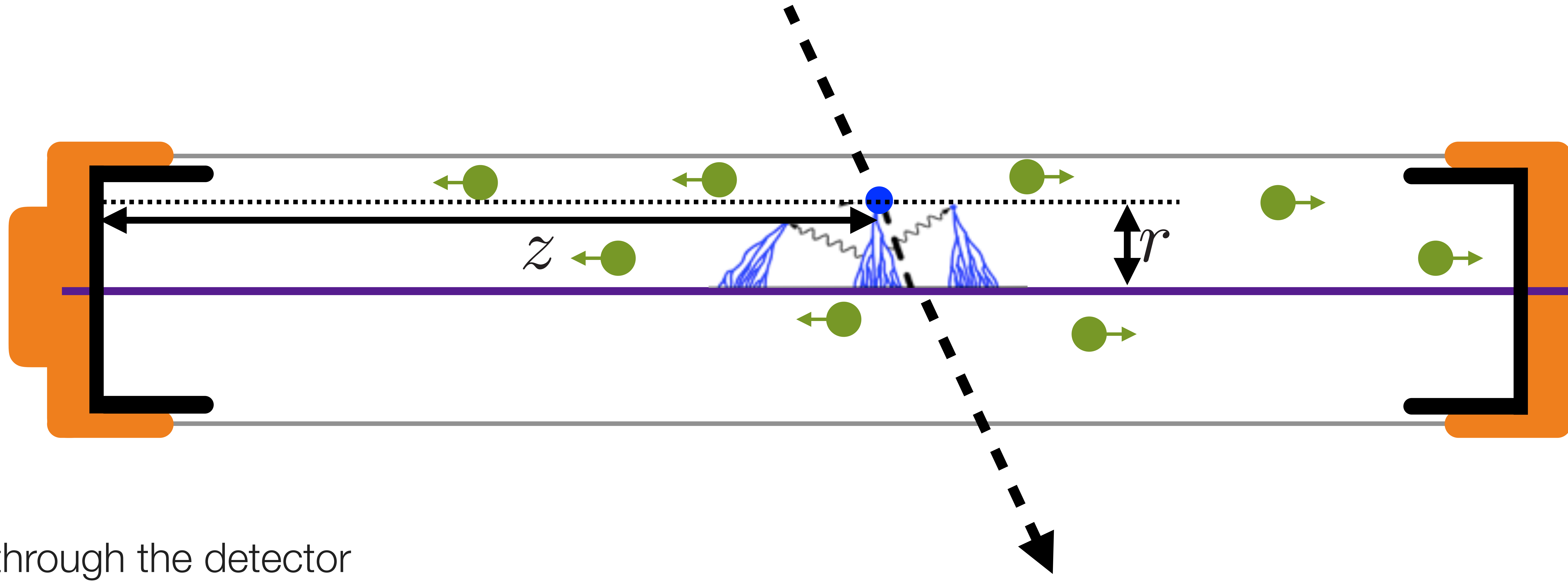




- Charged particle passes through the detector
- Electron avalanche drifts to anode (Geiger mode)
  - Drift time gives radius of closest approach r

Wire trackers

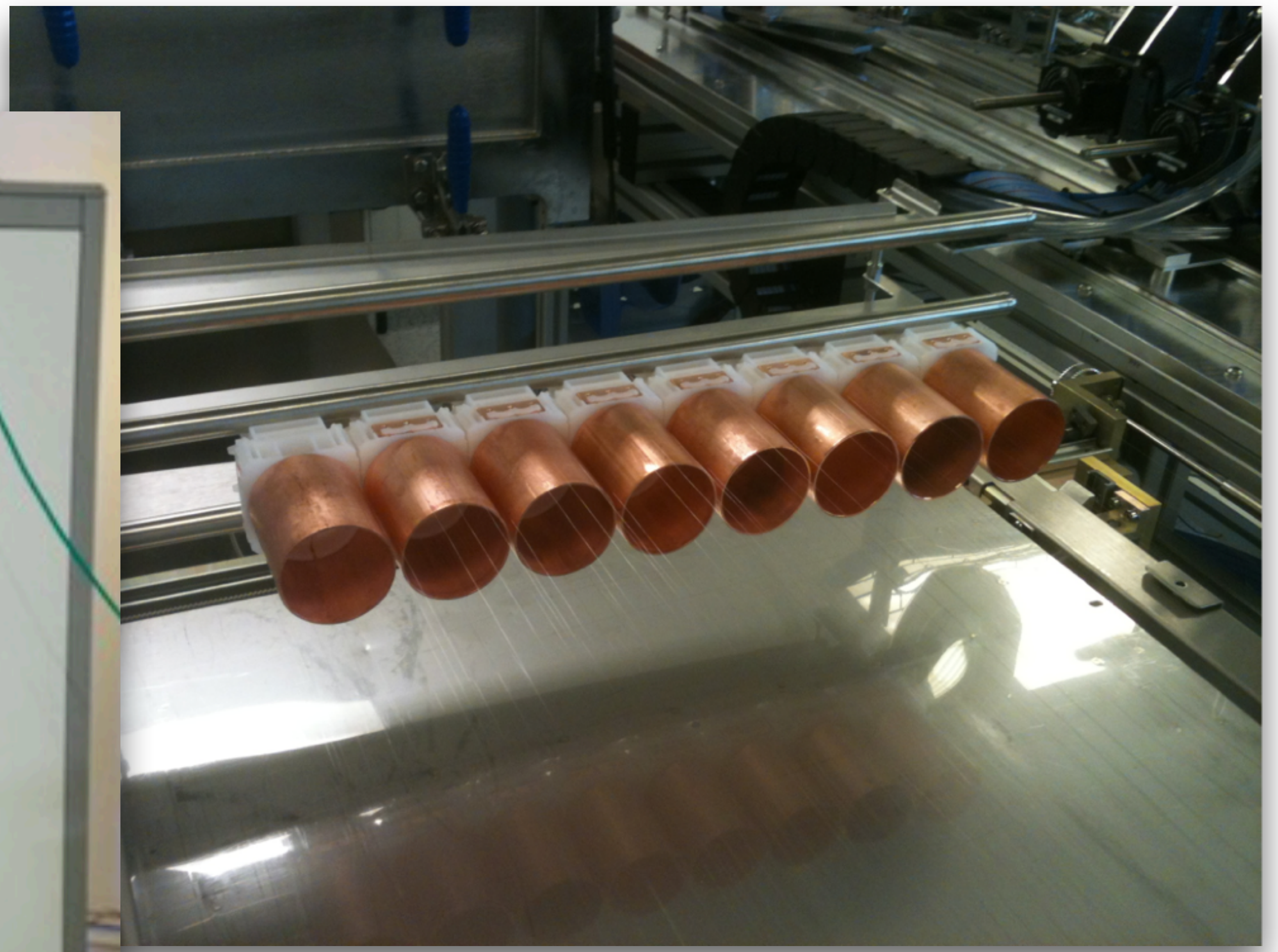




- Charged particle passes through the detector
- Electron avalanche drifts to anode (Geiger mode)
  - Drift time gives radius of closest approach r
- Plasma propagates towards the two cathode end caps
  - Difference in drift times gives distance along wire z

Allows 3-d track reconstruction

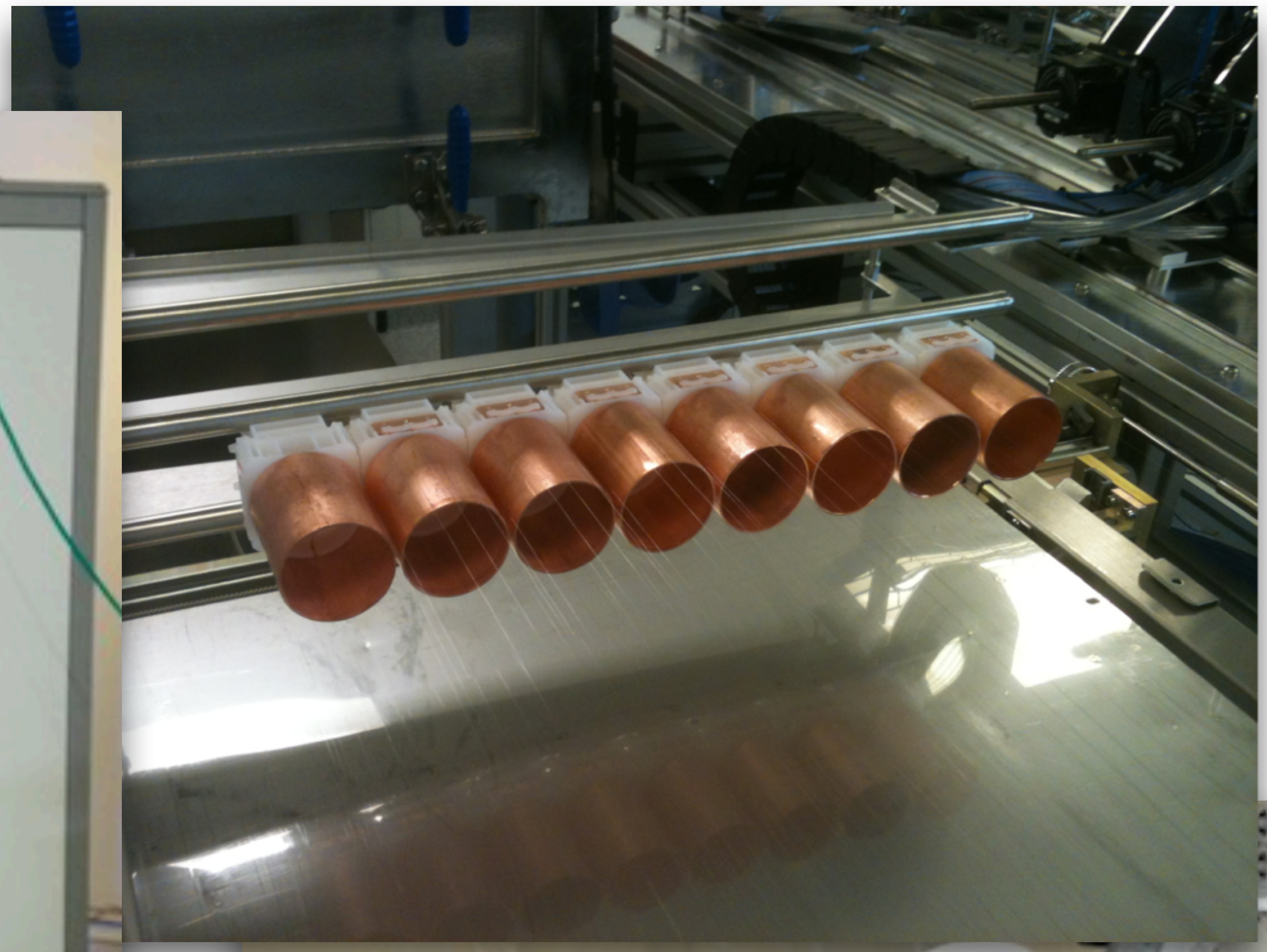
Building the tracker



2034 drift cells (13,000 wires!)

Arranged in 113 rows of 9 cells (from source to calorimeter wall) on each side of ββ source

Building the tracker



2034 drift cells (13,000 wires!)

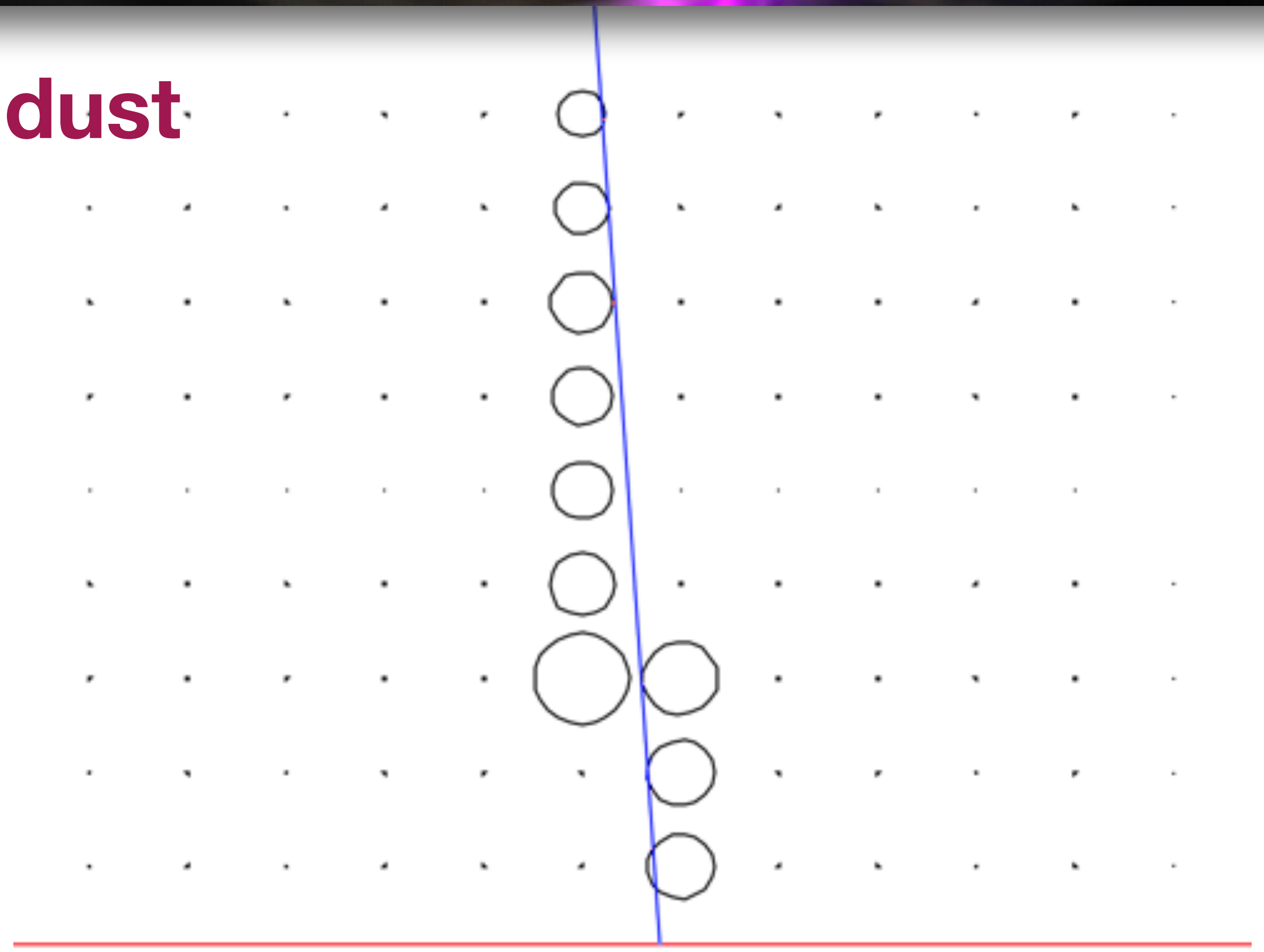
Arranged in 113 rows of 9 cells (from source to calorimeter wall) on each side of ββ source

Installed into 4 C-shaped tracker sections

Tracker assembly and commissioning

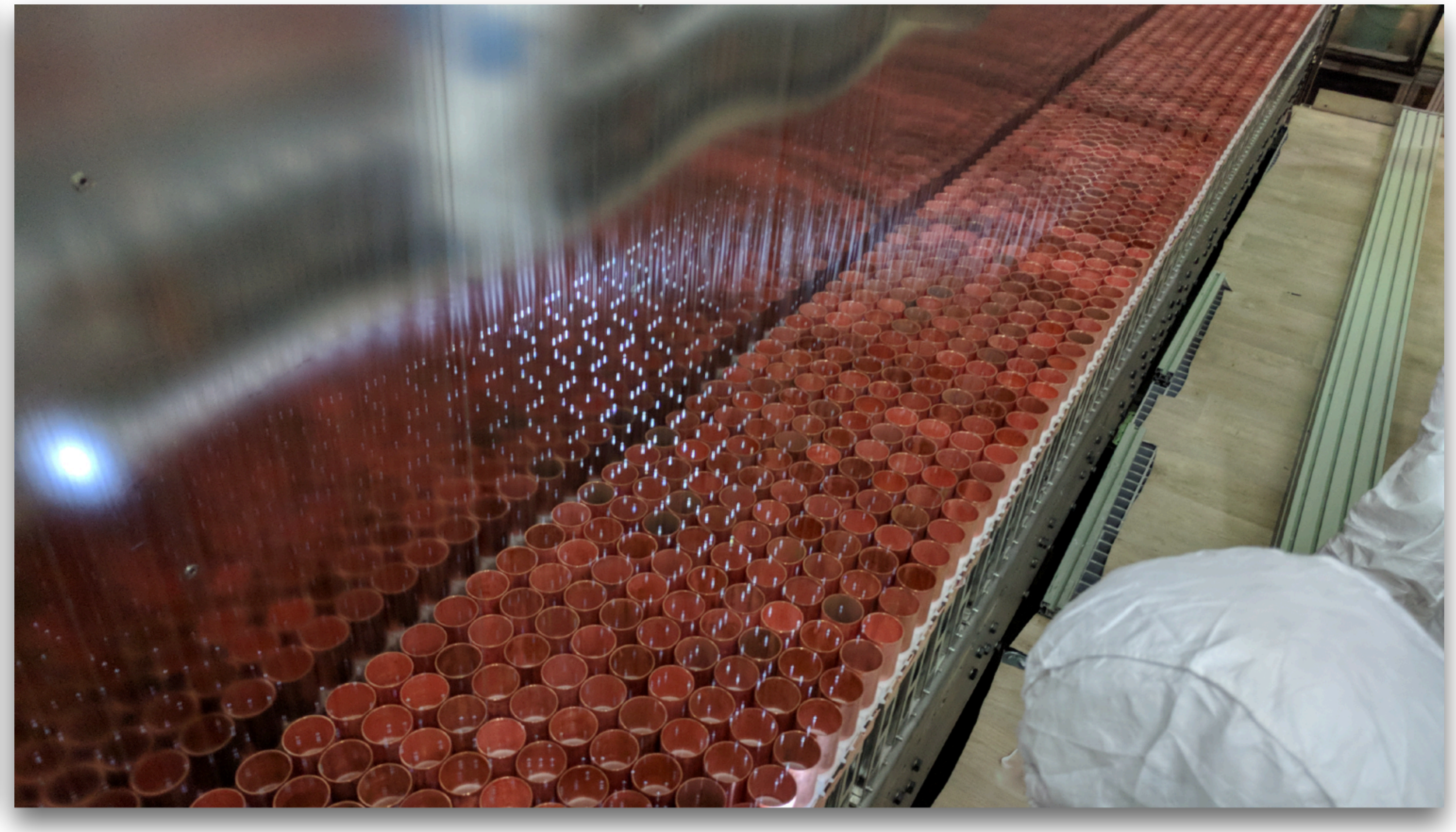
Completed C-section

Checking for dust



Commissioning with cosmic rays

The tracker at LSM



Low background strategy: reduce, remove, reject

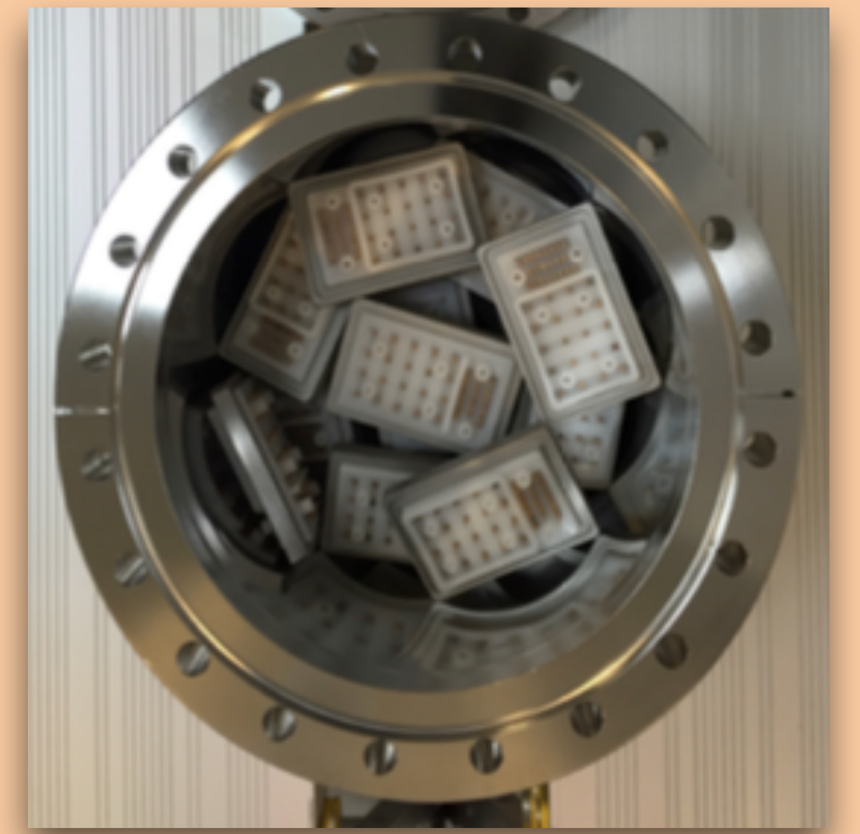
Radon 222 (from U decay chain): target activity 150 µBq / m³

~ 30 times lower than NEMO-3

Low background strategy: reduce, remove, reject

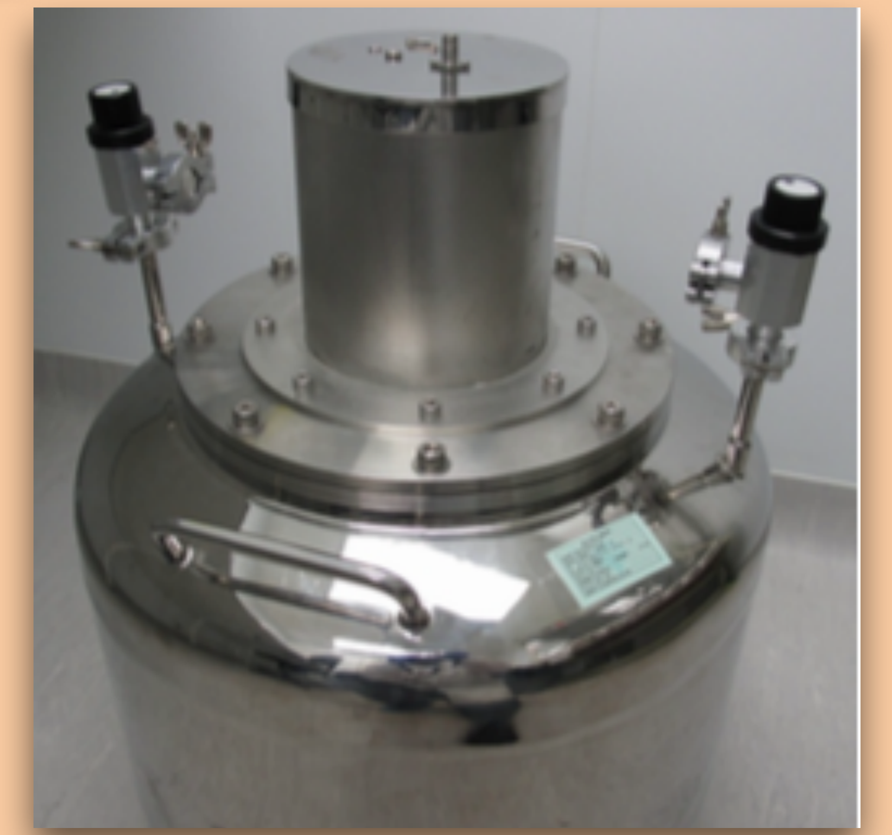
Radon 222 (from U decay chain): target activity 150 µBq / m^3

Reduce radon contamination with radio-pure components



Emanation chamber lets us measure activity of **tracker components** and materials: select only the most **radio-pure**

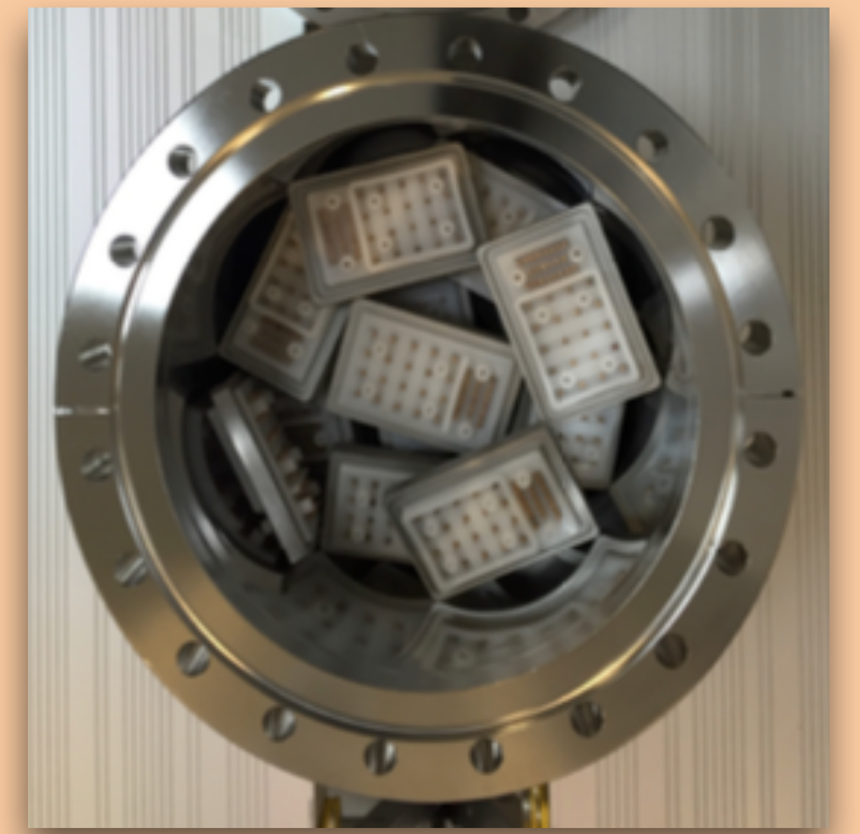
70 litre **electrostatic detector** sensitive down to 0.09mBq



Low background strategy: reduce, remove, reject

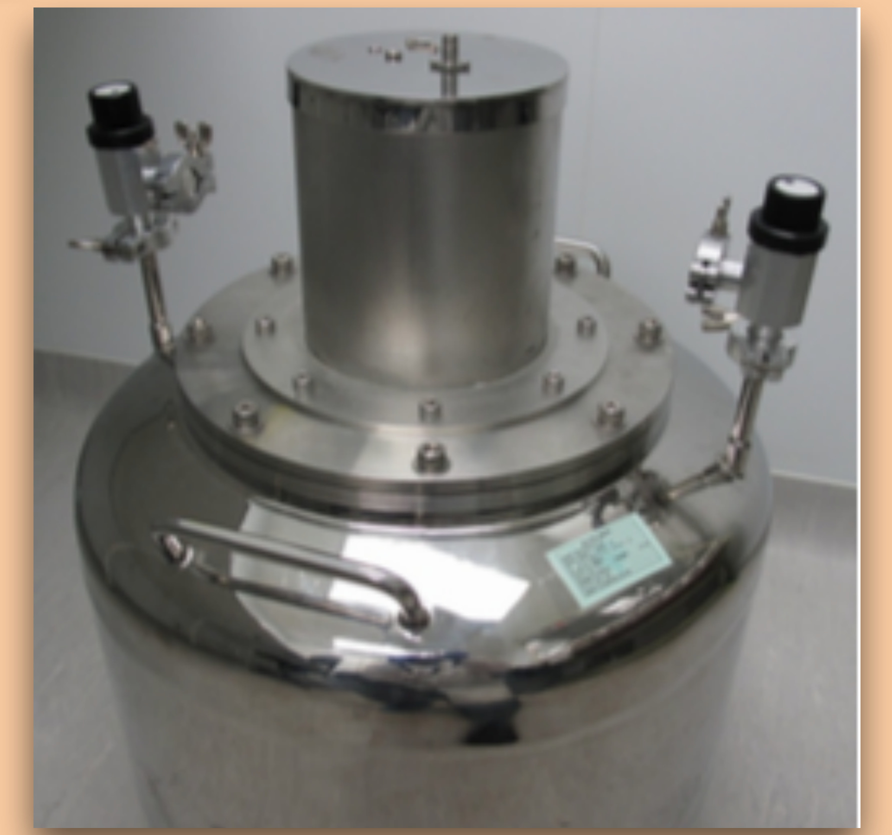
Radon 222 (from U decay chain): target activity 150 µBq / m^3

Reduce radon contamination with radio-pure components



Emanation chamber lets us measure activity of **tracker components** and materials: select only the most **radio-pure**

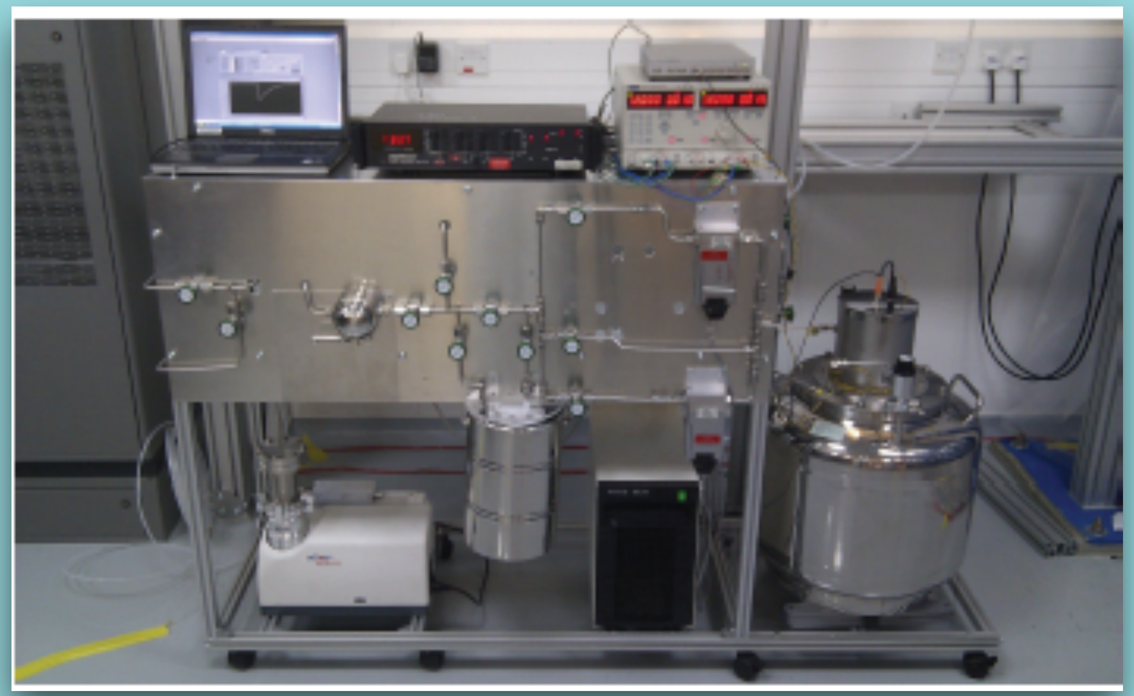
70 litre **electrostatic detector** sensitive down to 0.09mBq



Remove radon from tracker gas (95% helium, 1% argon, 4% ethanol)

Remove Rn with **cold carbon trap**

- **He:** 10^{10} x suppression - completely **clean**
- **N_2:** 20x purification - 20 µBq/m^3



Radon concentration line lets us measure the low activities in the tracker

Measured activity: 2.7 ± 0.3 mBq / m^3

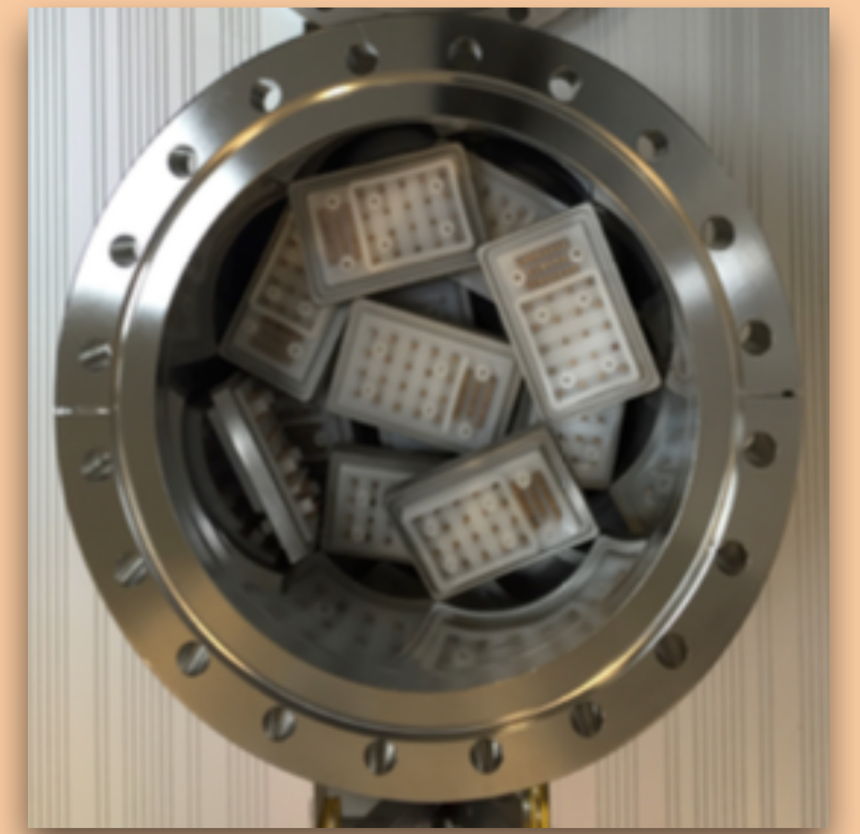
Flush with He: 2 m^3 / hour

Resulting activity: 0.15 mBq / m^3

Low background strategy: reduce, remove, reject

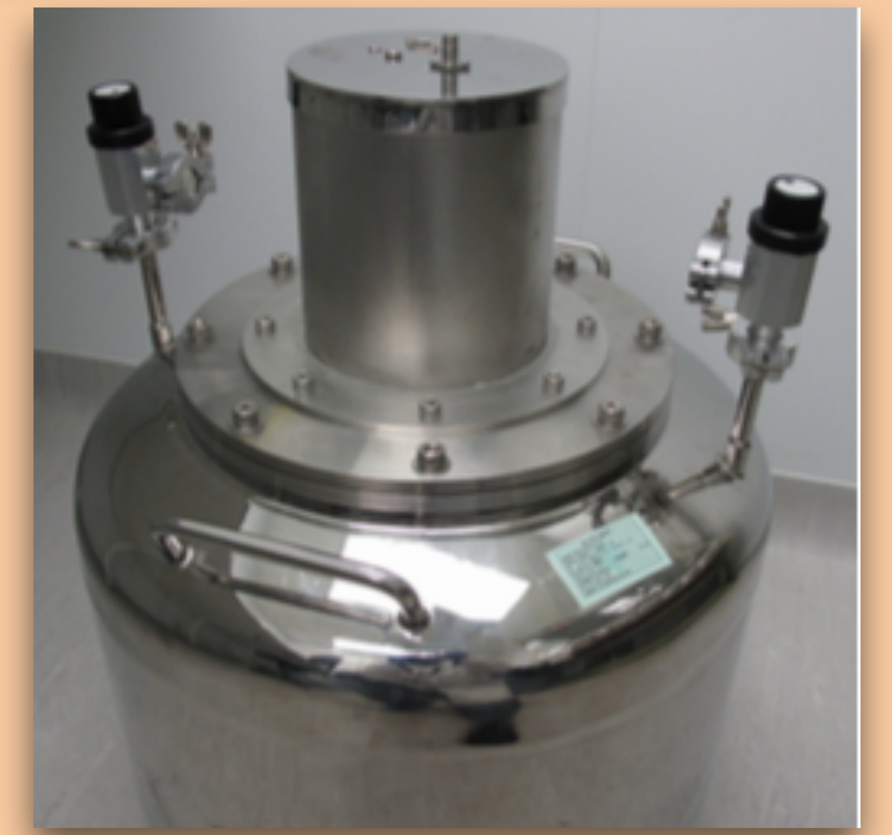
Radon 222 (from U decay chain): target activity 150 µBq / m^3

Reduce radon contamination with radio-pure components



Emanation chamber lets us measure activity of **tracker components** and materials: select only the most **radio-pure**

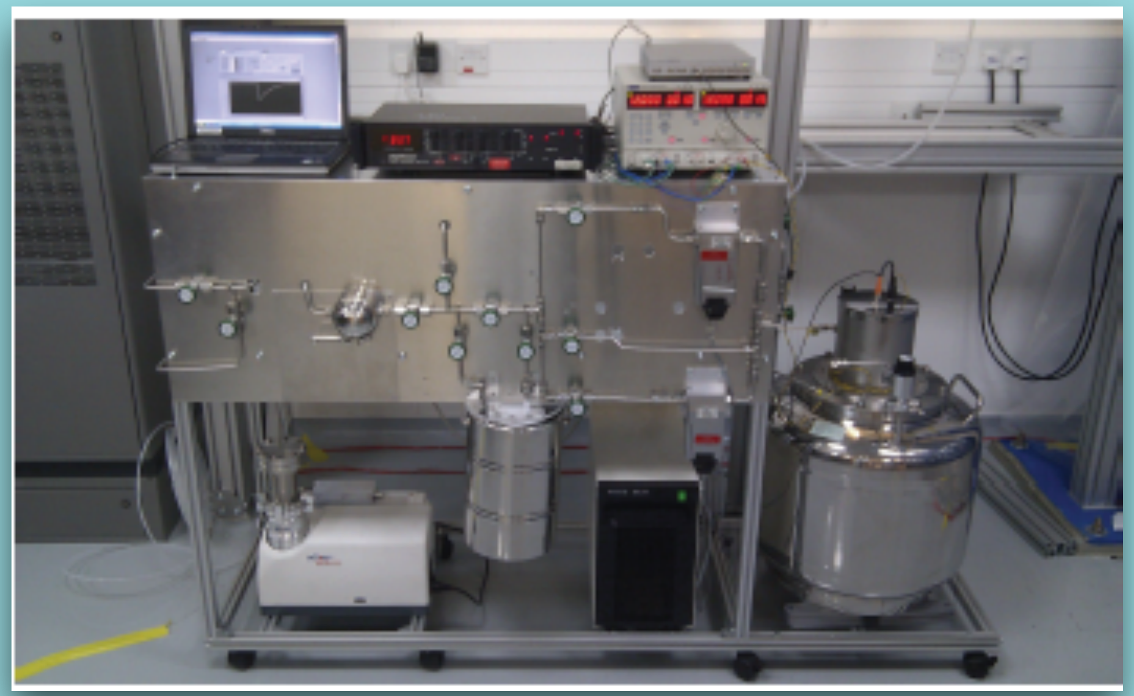
70 litre **electrostatic detector** sensitive down to 0.09mBq



Remove radon from tracker gas (95% helium, 1% argon, 4% ethanol)

Remove Rn with **cold carbon trap**

- **He:** 10^{10} x suppression - completely **clean**
- **N_2:** 20x purification - 20 µBq/m^3



Radon concentration line lets us measure the low activities in the tracker

Measured activity: 2.7 ± 0.3 mBq / m^3

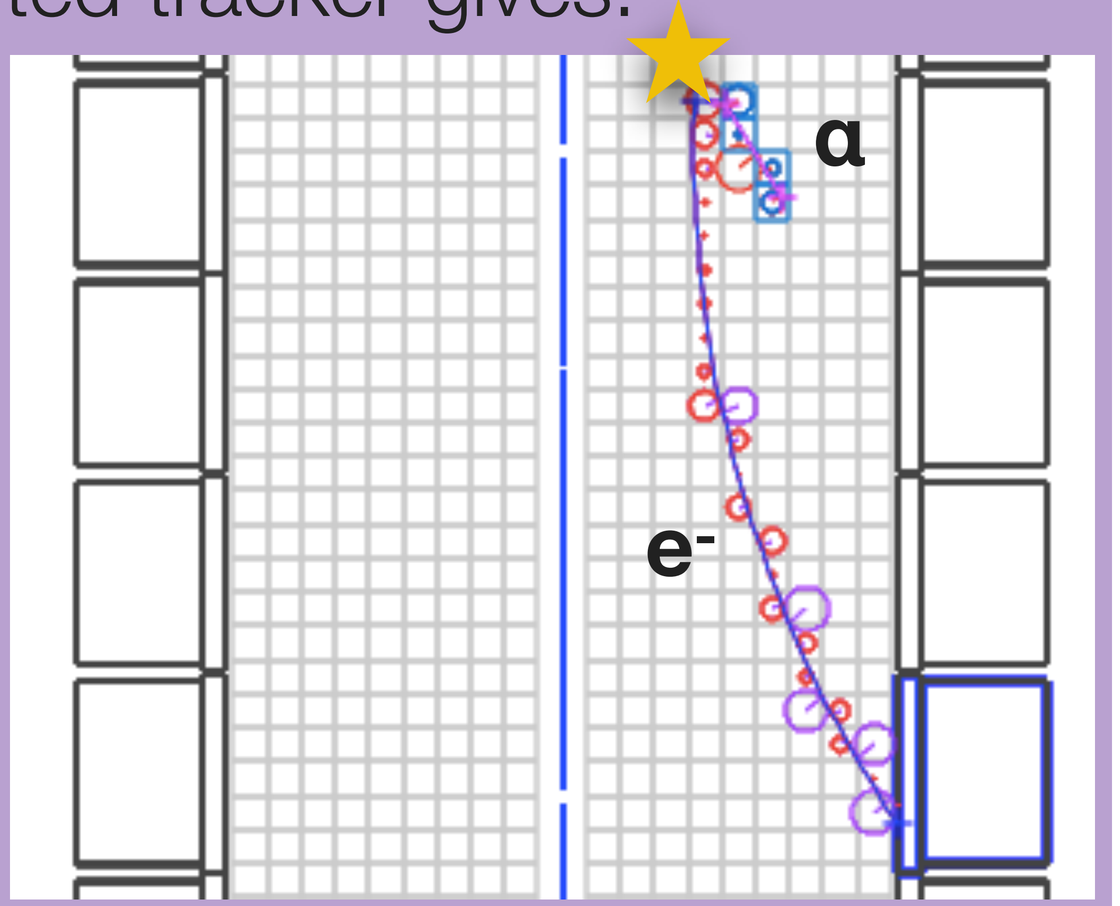
Flush with He: 2 m^3 / hour

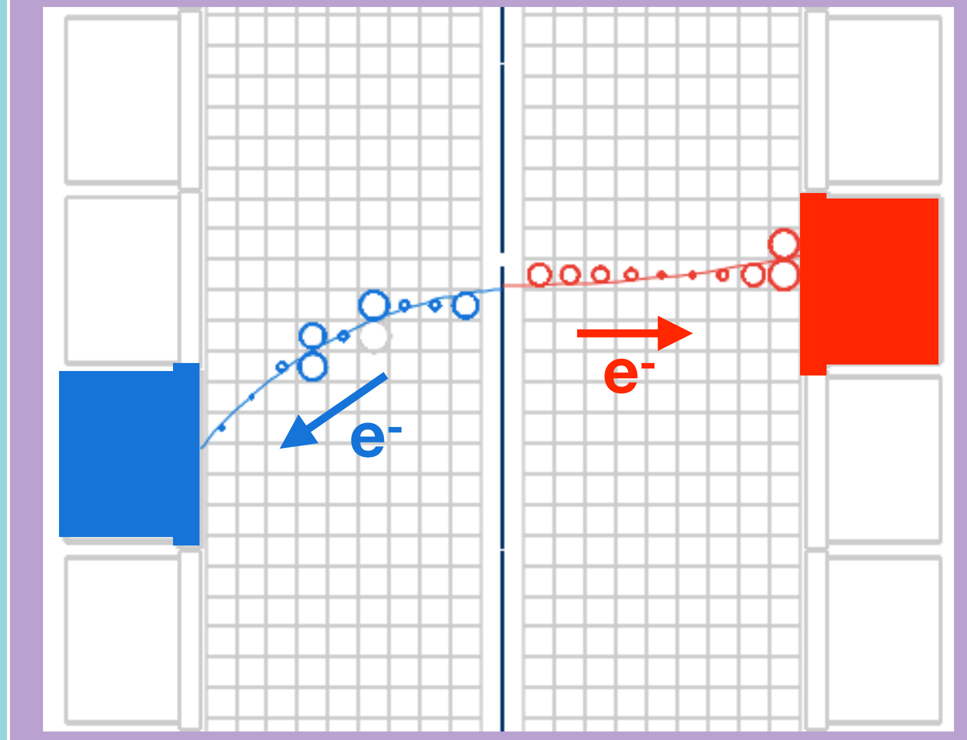
Resulting activity: 0.15 mBq / m^3

Reject background events with topological and timing cuts

Fully-instrumented tracker gives:

- Event vertex
- Particle ID
- Timings → direction of travel



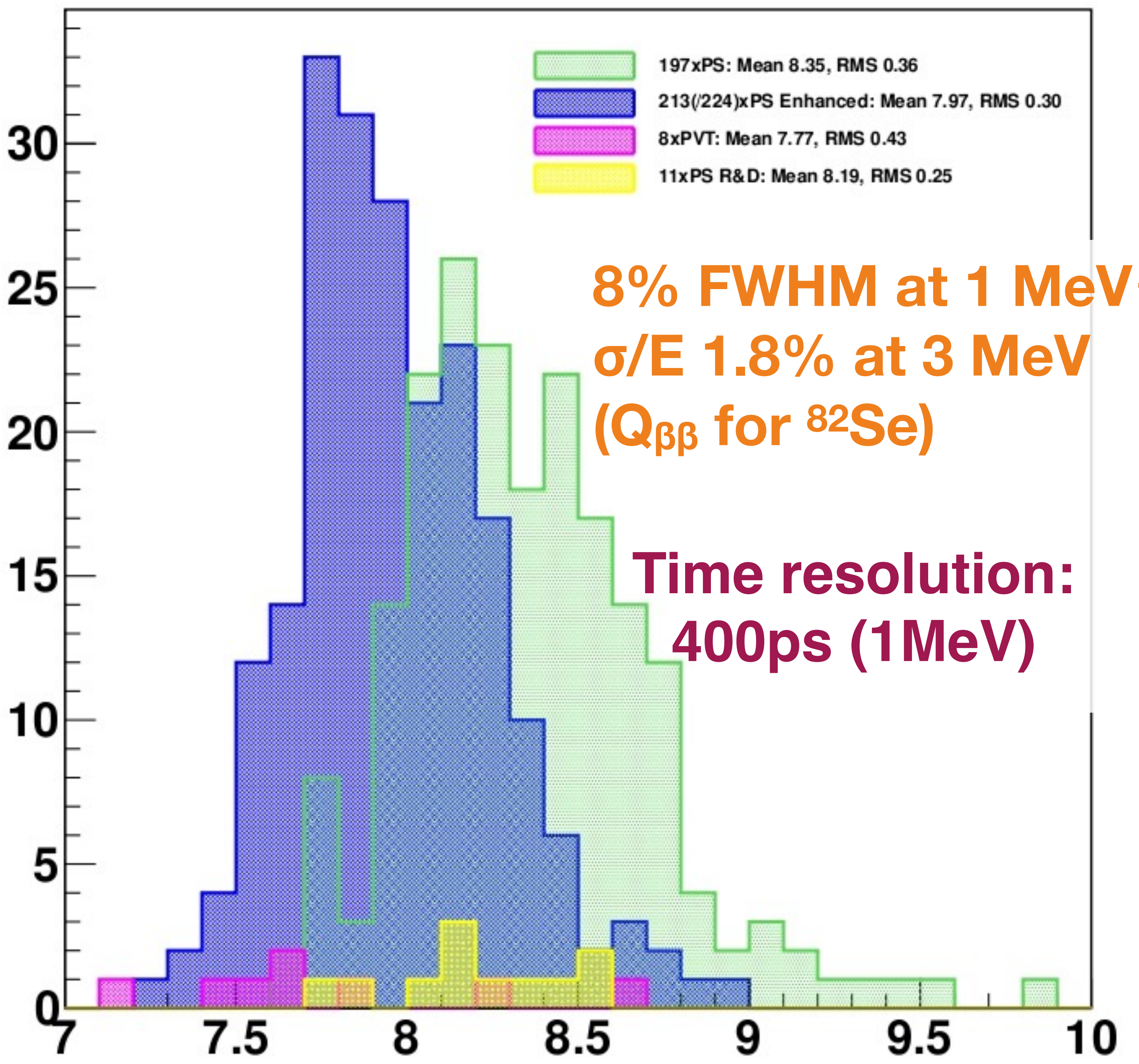


Reject non-ββ topologies at analysis time

Calorimeter development

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

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



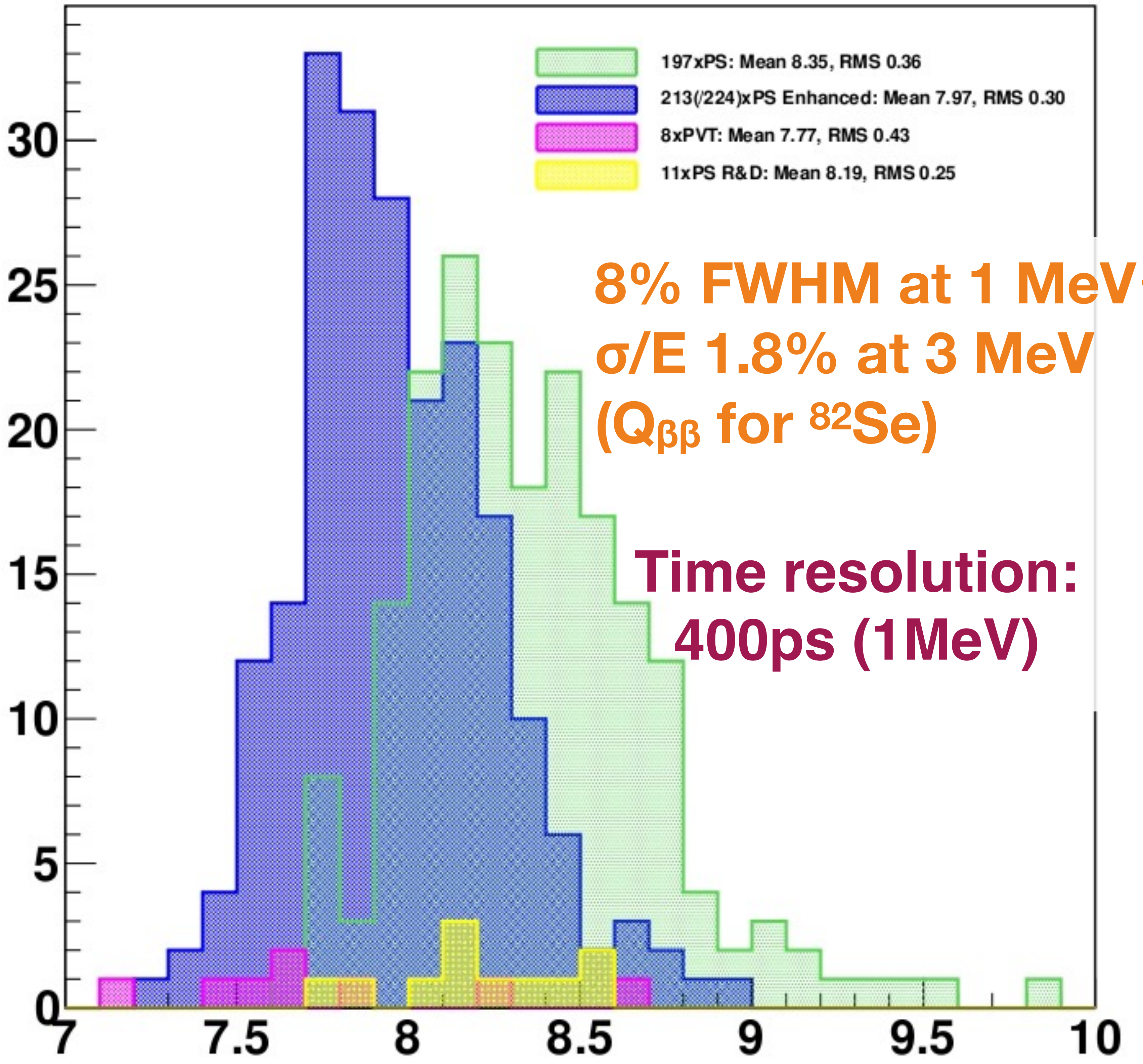
8% FWHM at 1 MeV→ σ/E 1.8% at 3 MeV ($Q_{\beta\beta}$ for ^{82}Se)

Time resolution: 400ps (1MeV)

Calorimeter development

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

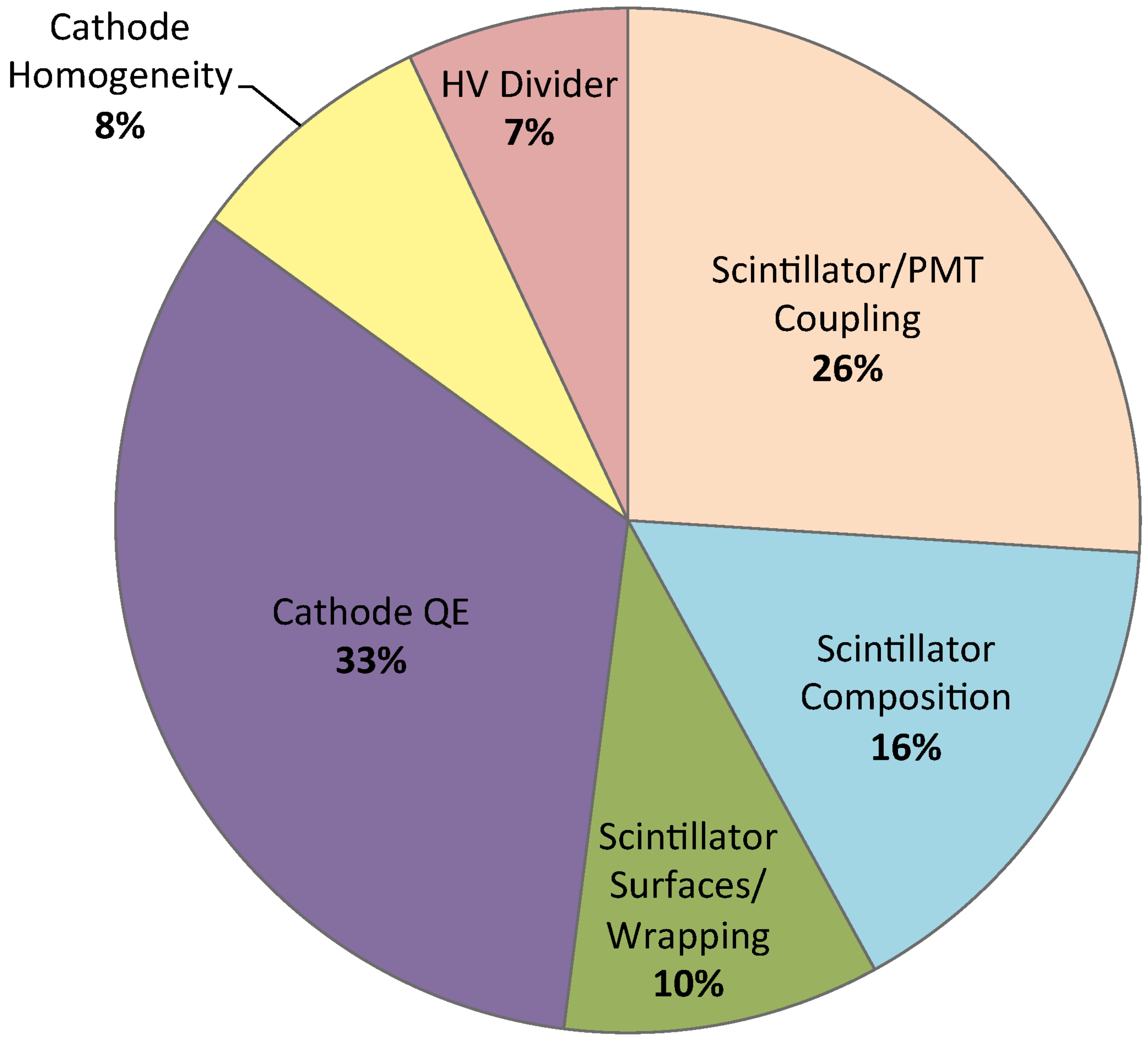
Nucl. Inst. Meth. A 868, 98-108 (2017)



8% FWHM at 1 MeV→ σ/E 1.8% at 3 MeV ($Q_{\beta\beta}$ for ^{82}Se)

Time resolution: 400ps (1MeV)

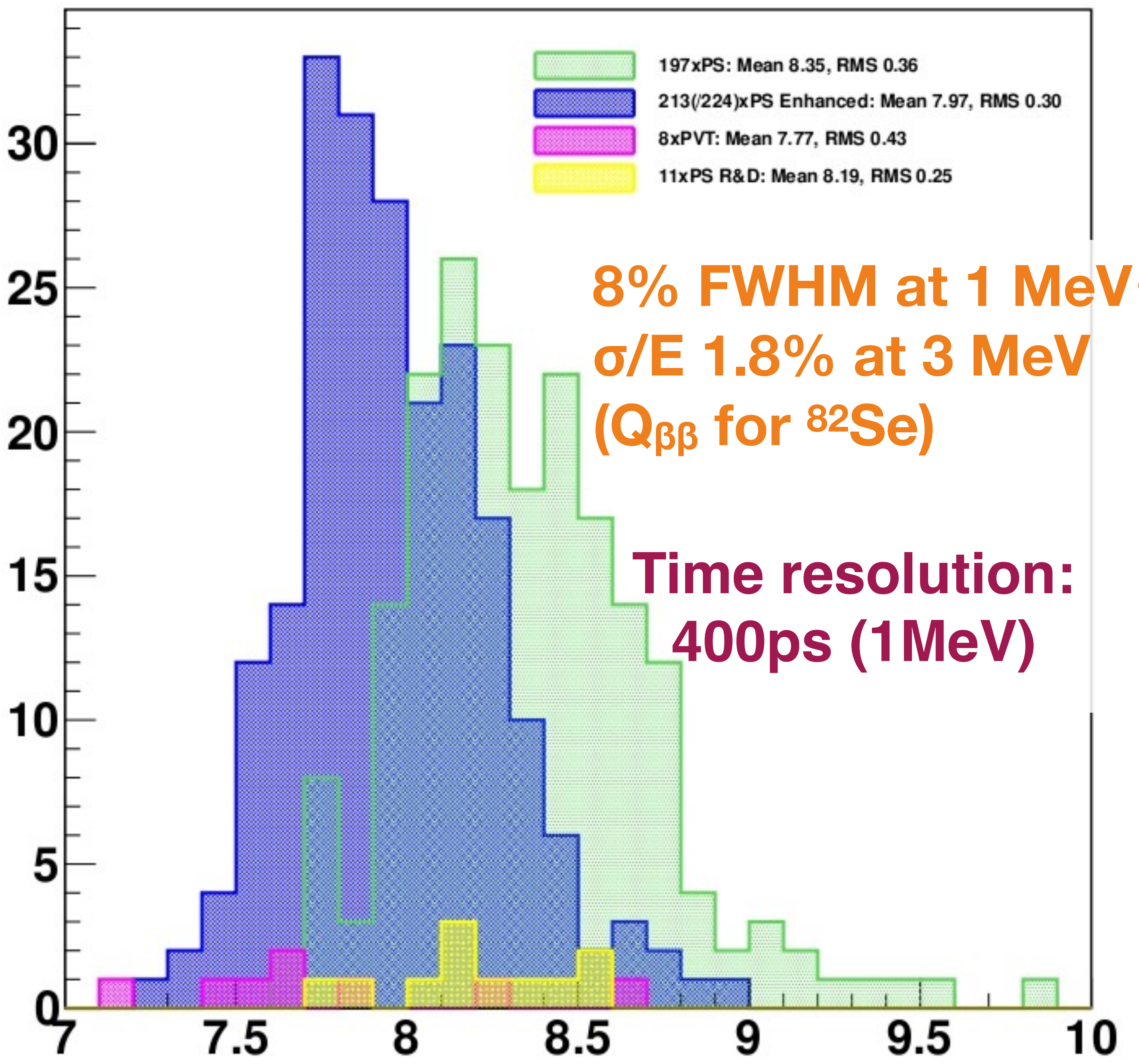
Contributions to improved resolution



Calorimeter development

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

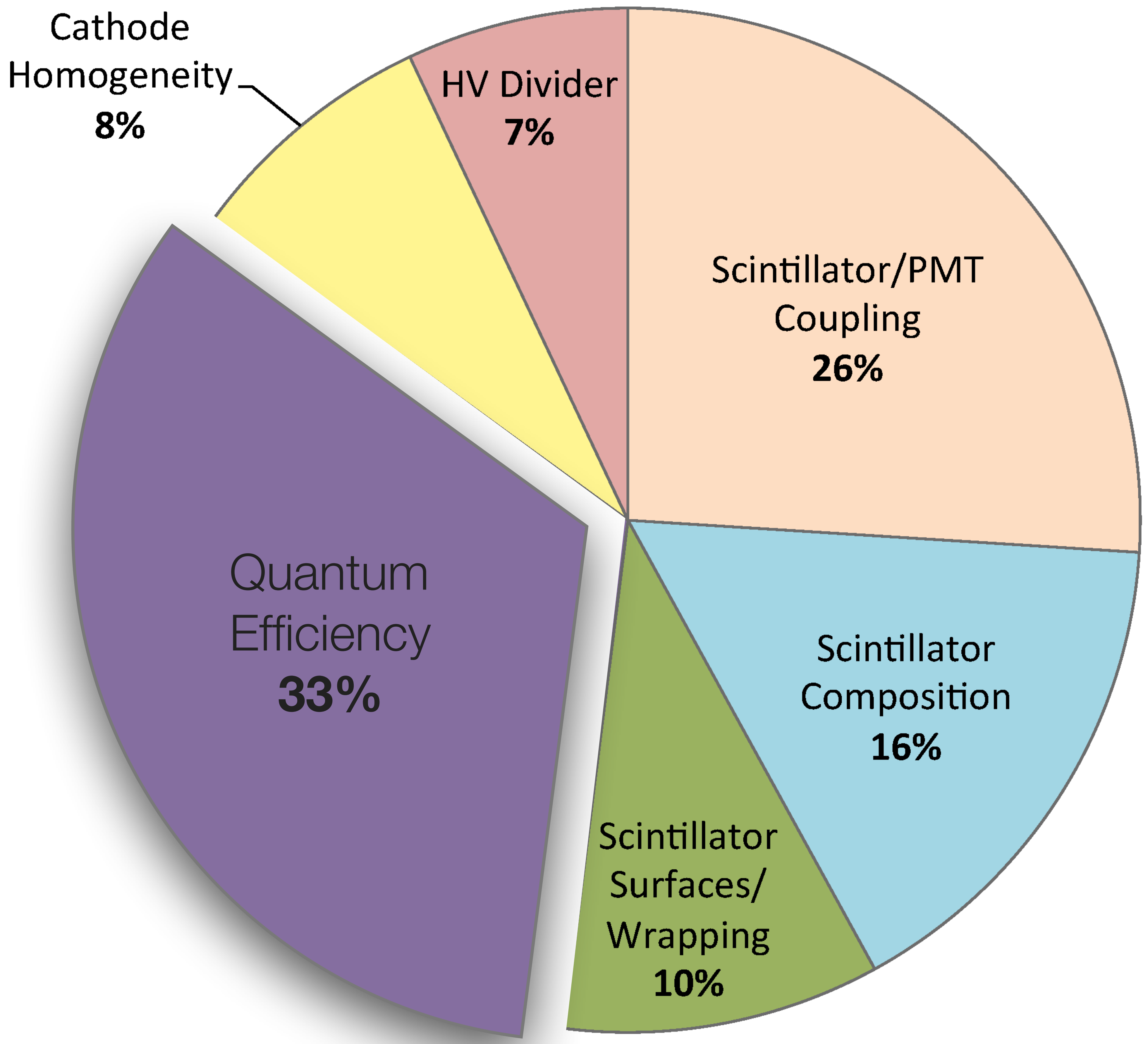
Nucl. Inst. Meth. A 868, 98-108 (2017)



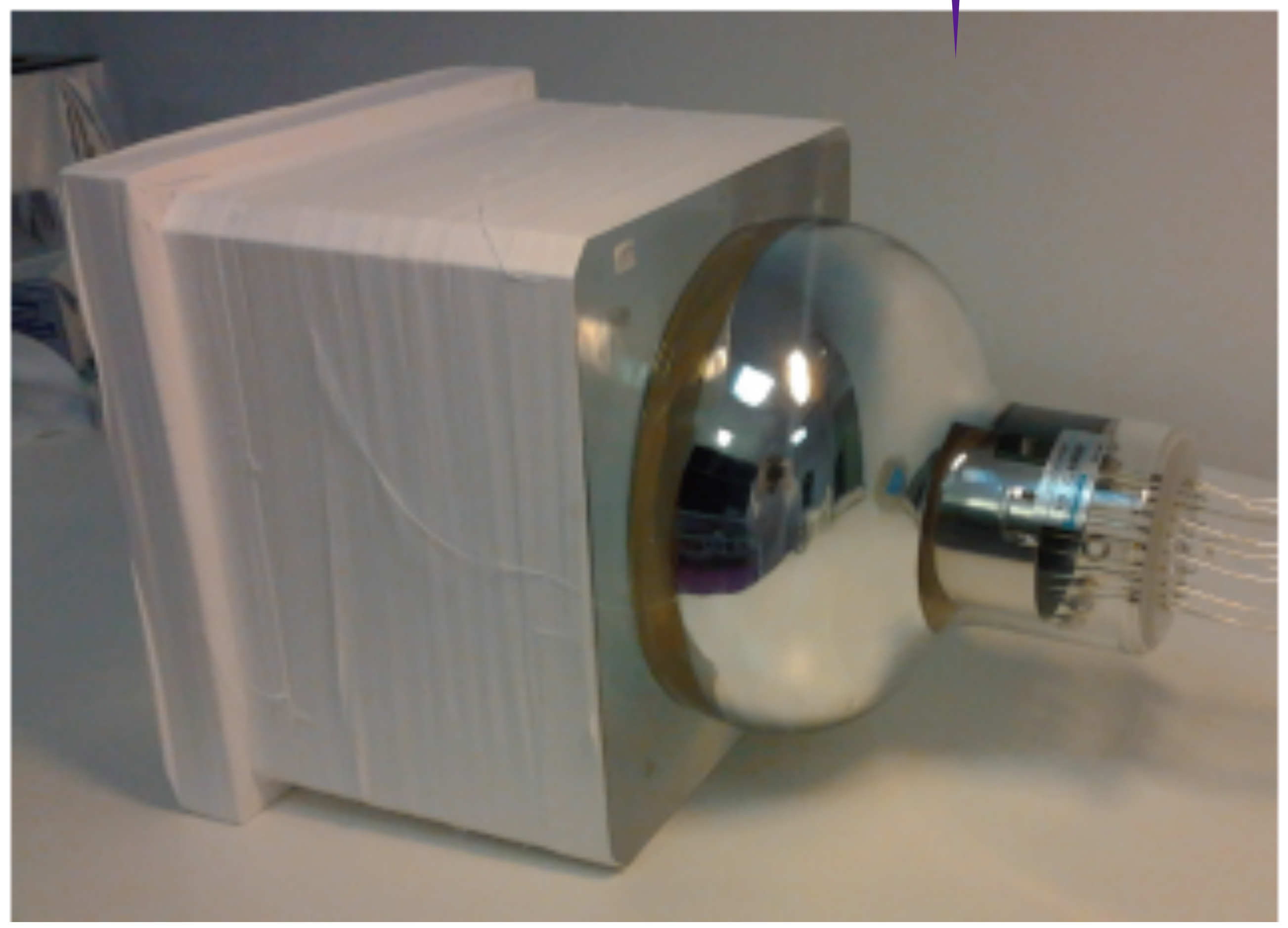
8% FWHM at 1 MeV→
σ/E 1.8% at 3 MeV
($Q_{\beta\beta}$ for ^{82}Se)

Time resolution: 400ps (1MeV)

Contributions to improved resolution



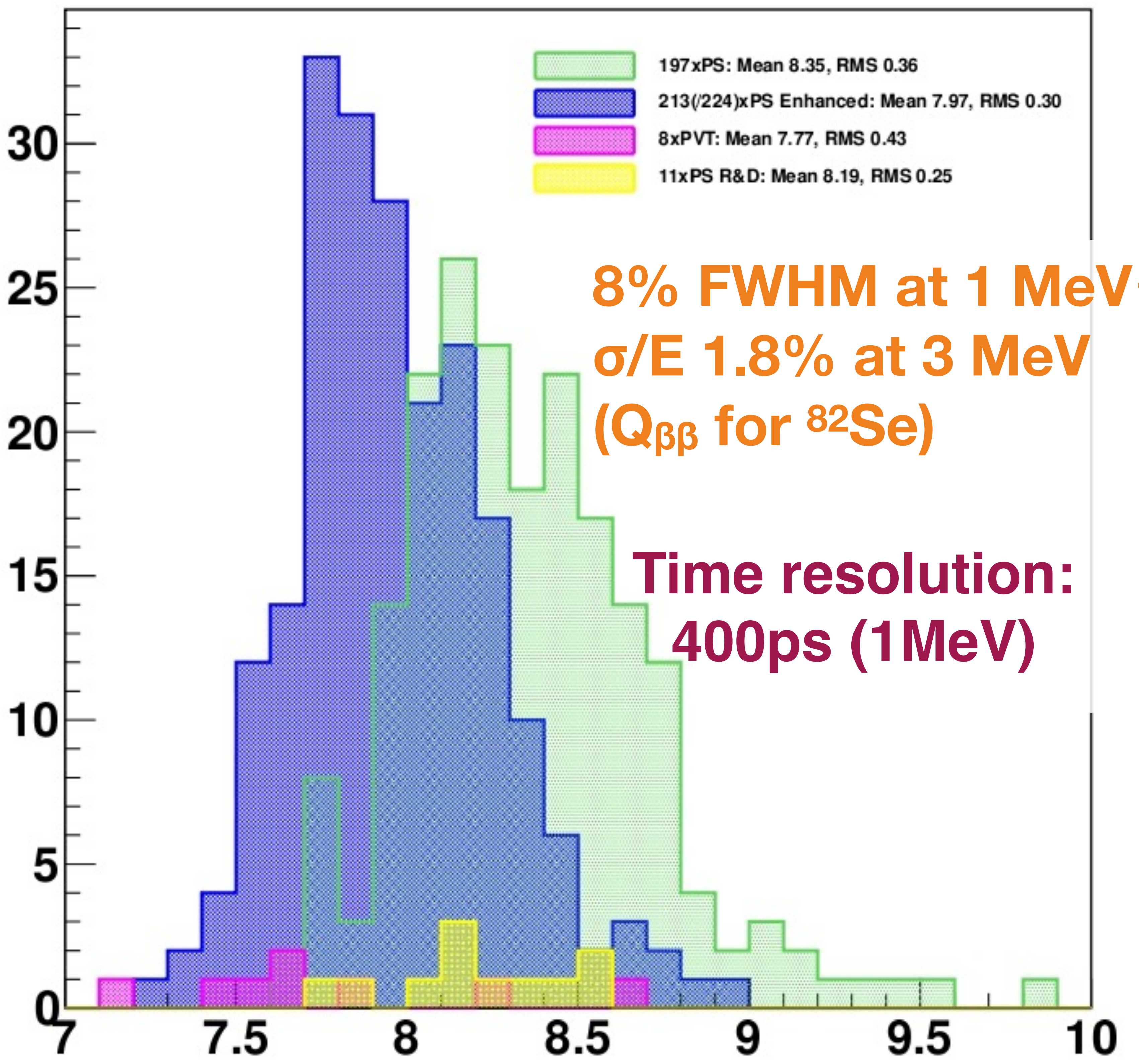
440 **8" radiopure PMTs**
with improved photocathode quantum efficiency
(5" PMTs for outer rows and columns. side, top and bottom)



Calorimeter development

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

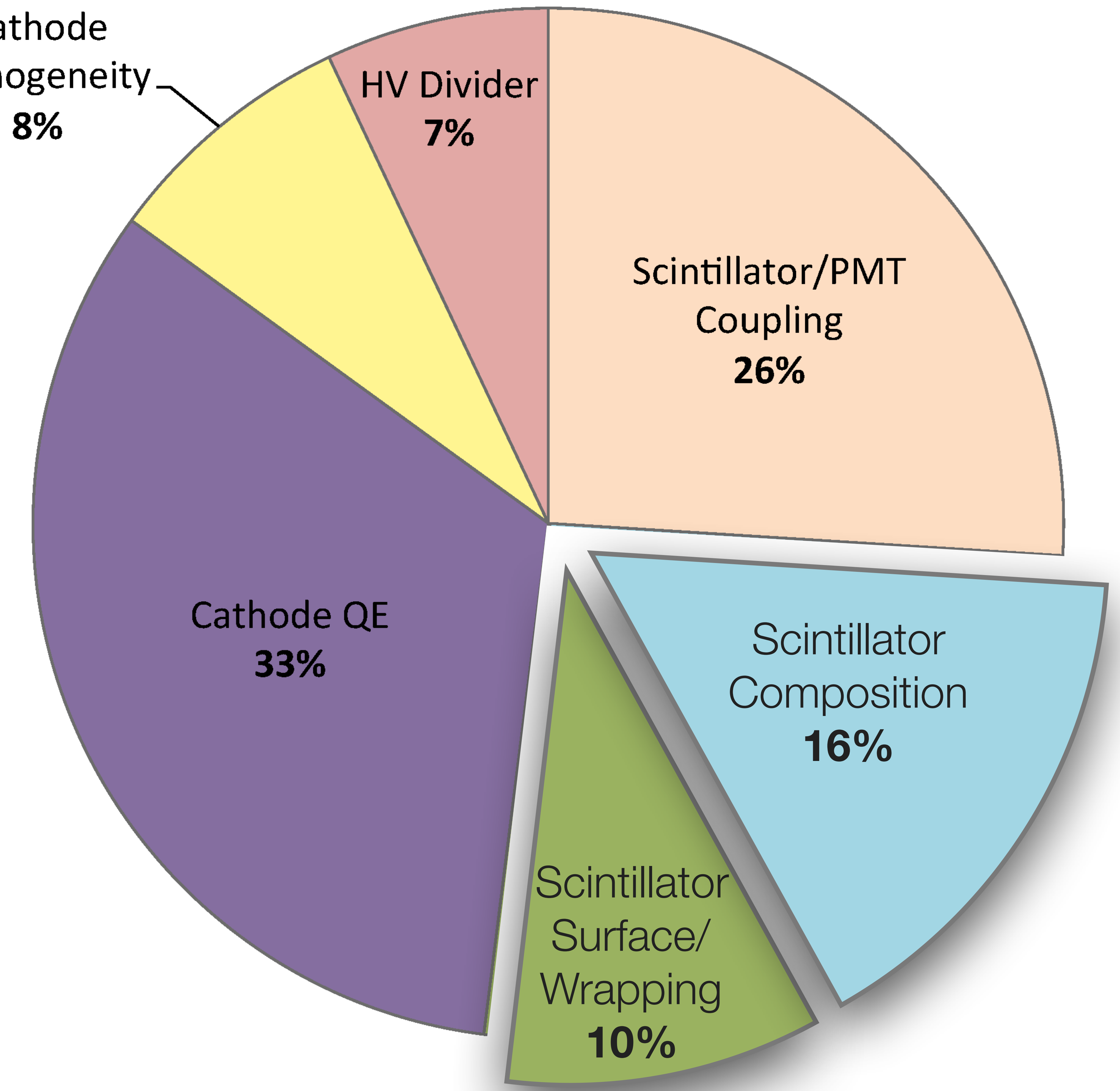
Nucl. Inst. Meth. A 868, 98-108 (2017)



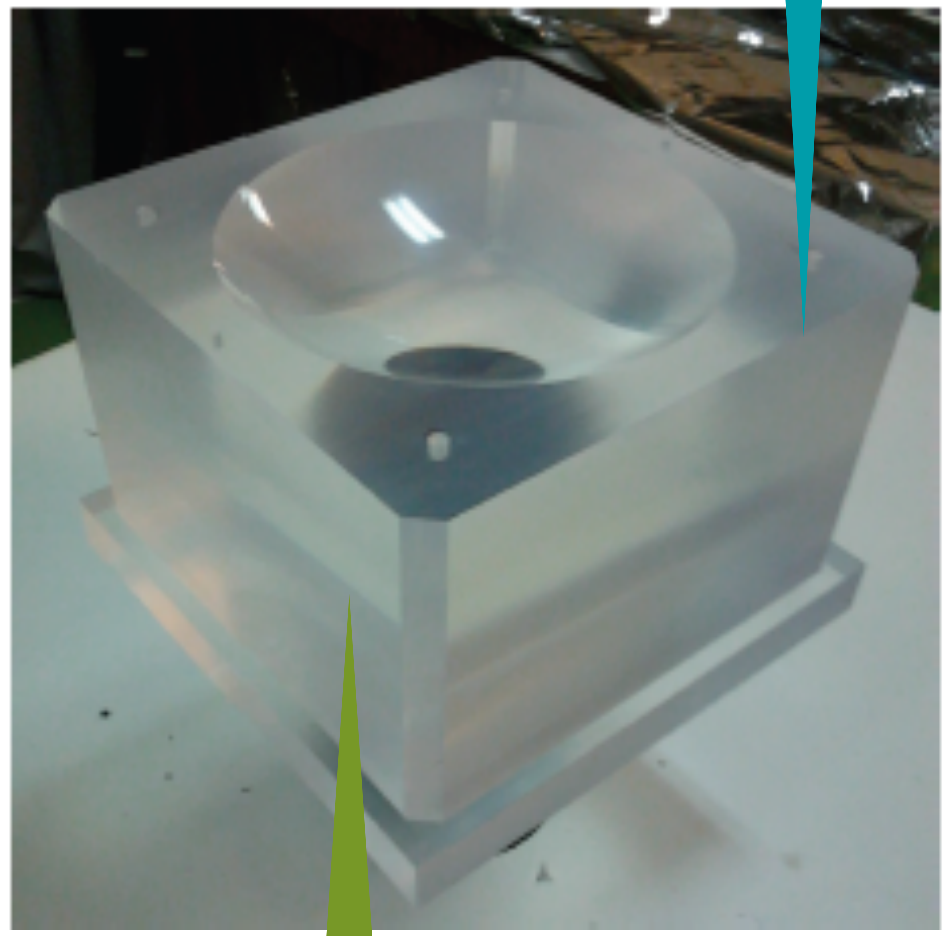
8% FWHM at 1 MeV→
σ/E 1.8% at 3 MeV
($Q_{\beta\beta}$ for ^{82}Se)

Time resolution: 400ps (1MeV)

Contributions to improved resolution



256 x 256 x 194 mm
Polysytrene scintillator block

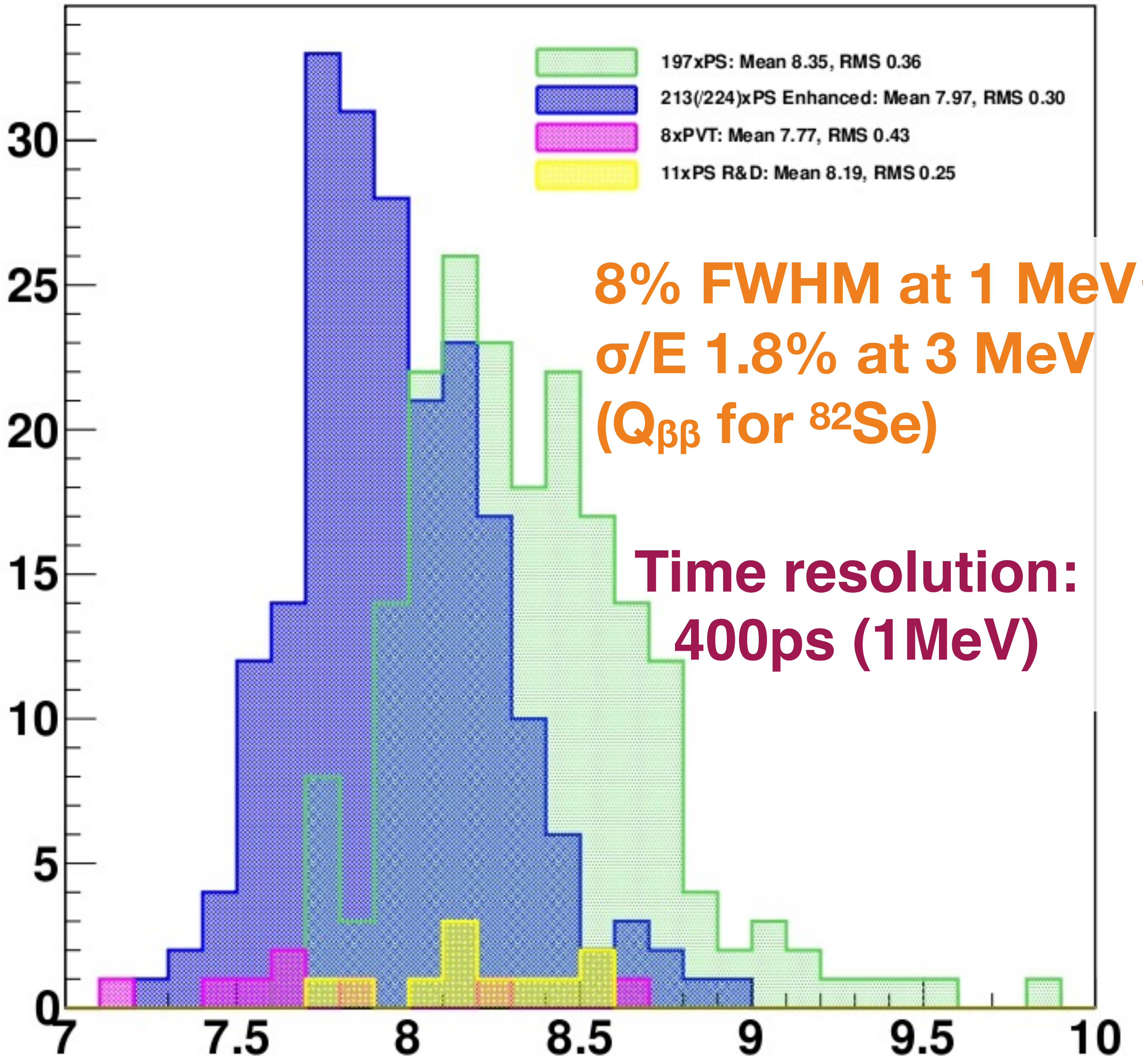


Optimised surface finish

Calorimeter development

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

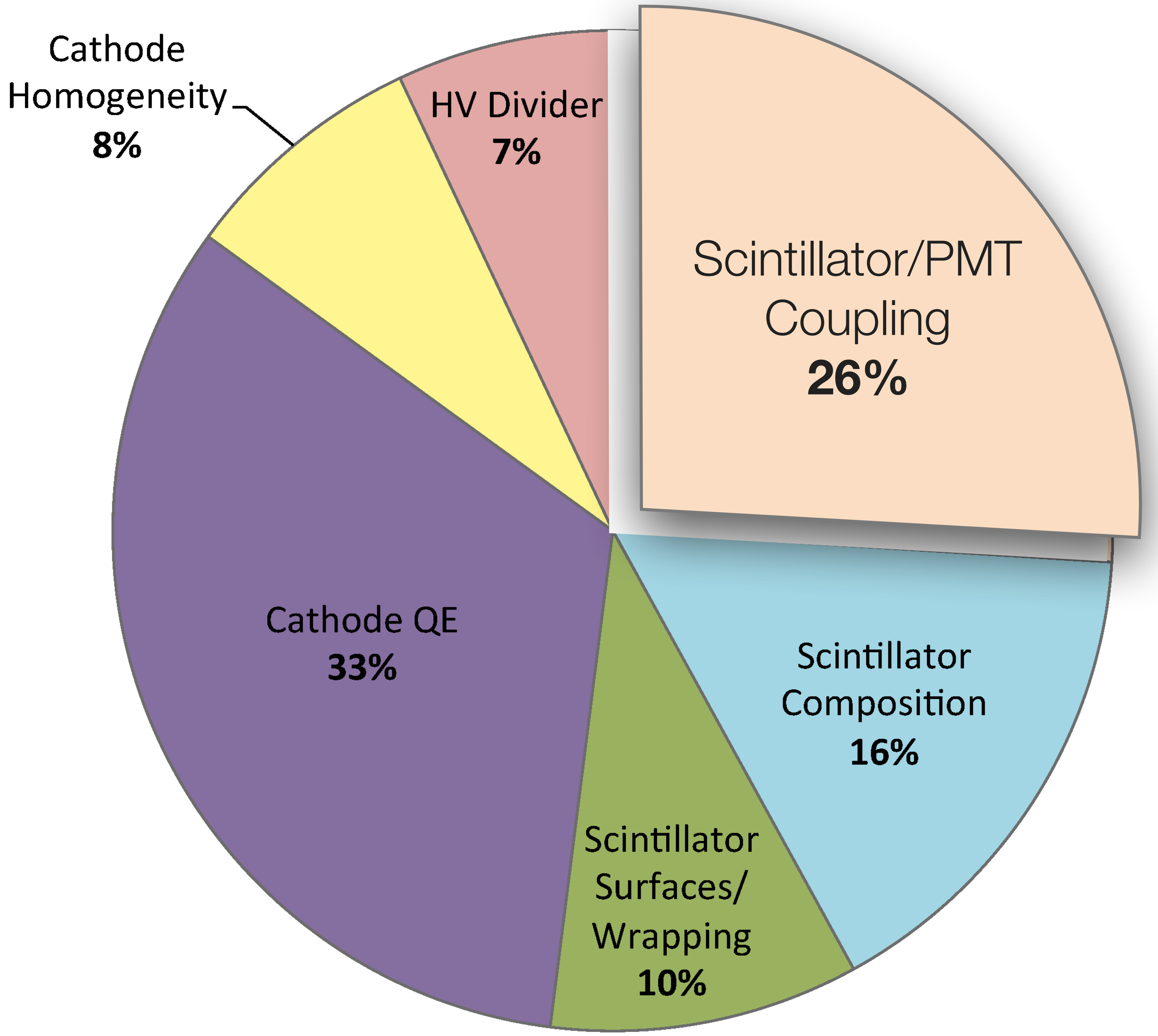
Nucl. Inst. Meth. A 868, 98-108 (2017)



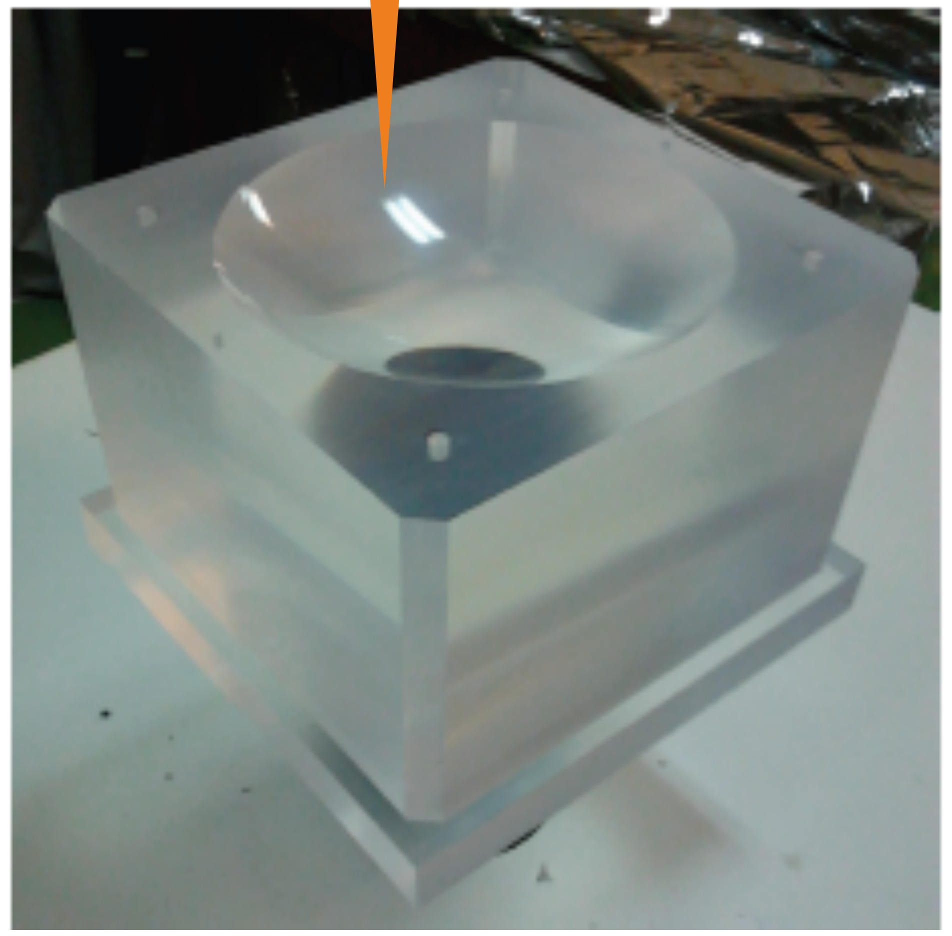
8% FWHM at 1 MeV→
σ/E 1.8% at 3 MeV
($Q_{\beta\beta}$ for ^{82}Se)

Time resolution:
400ps (1MeV)

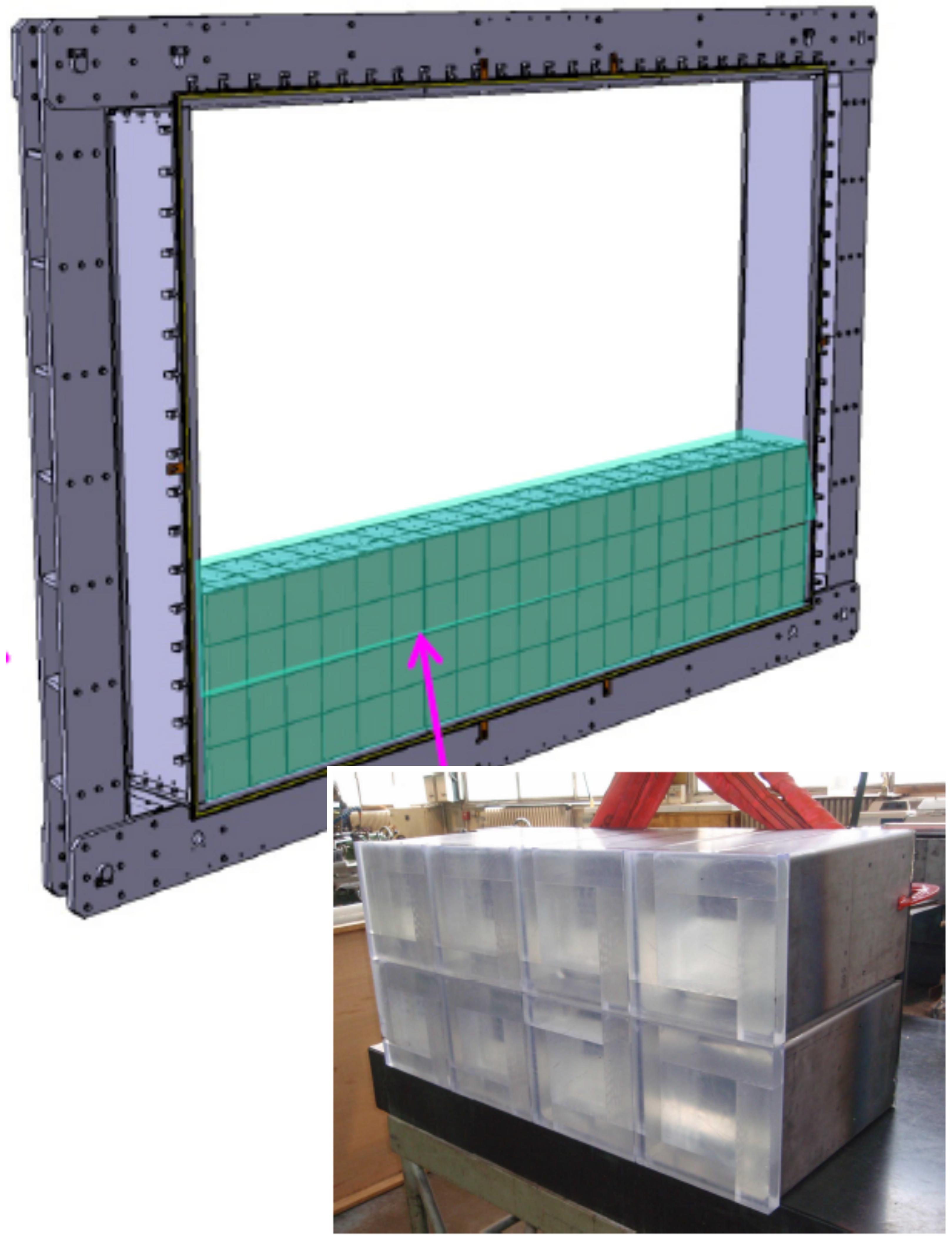
Contributions to improved resolution

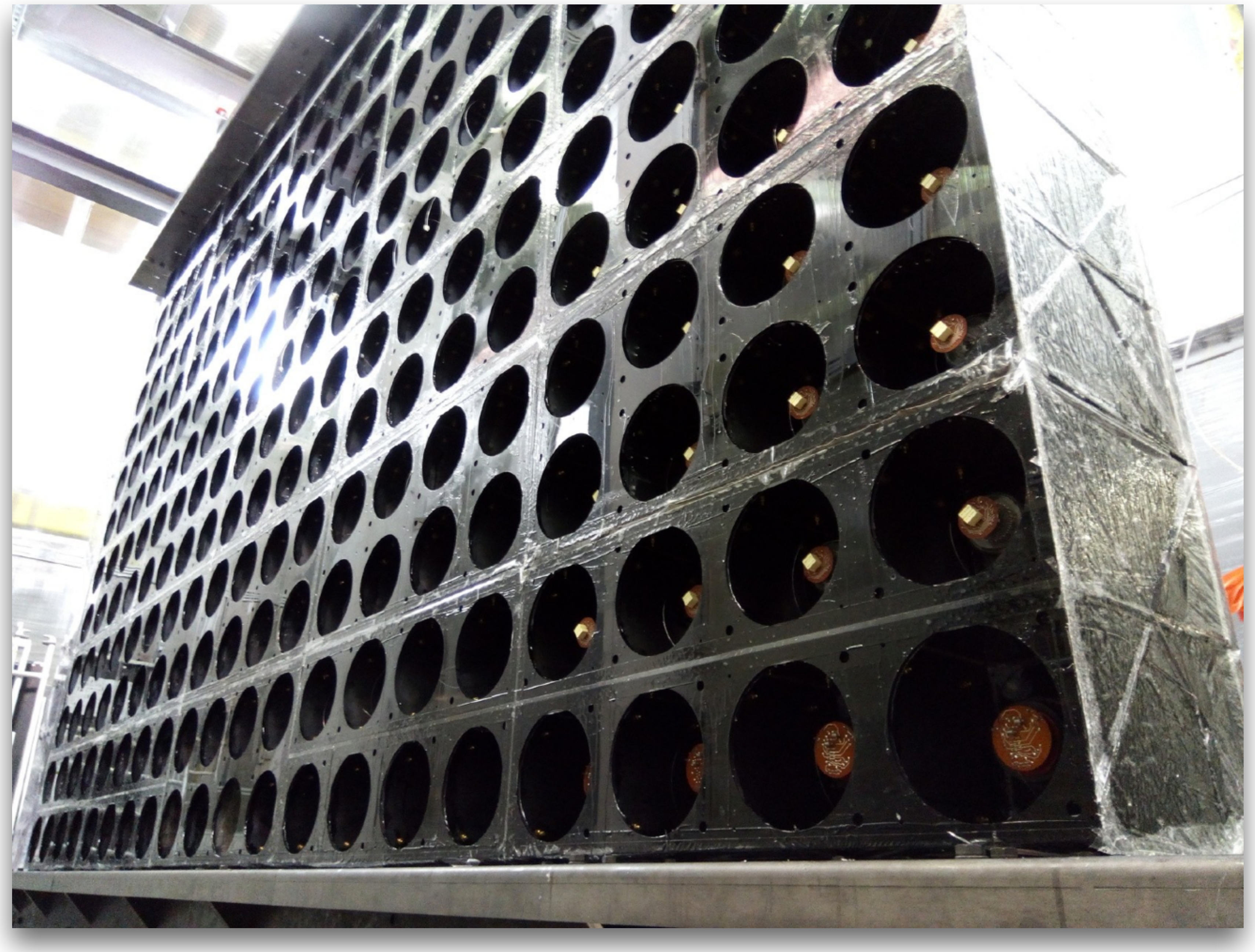


Directly coupled - no light-guide



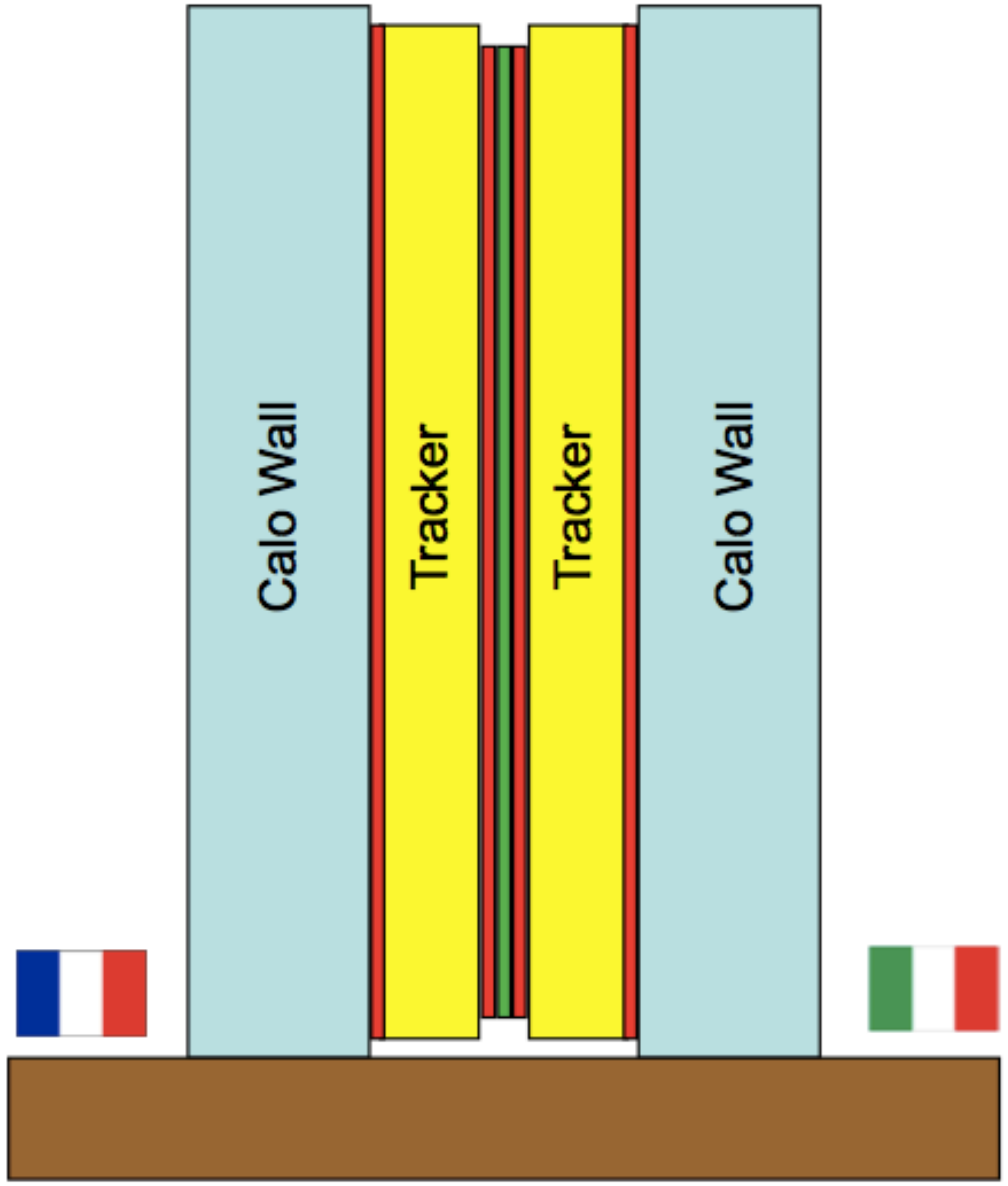
Calorimeters in place at LSM





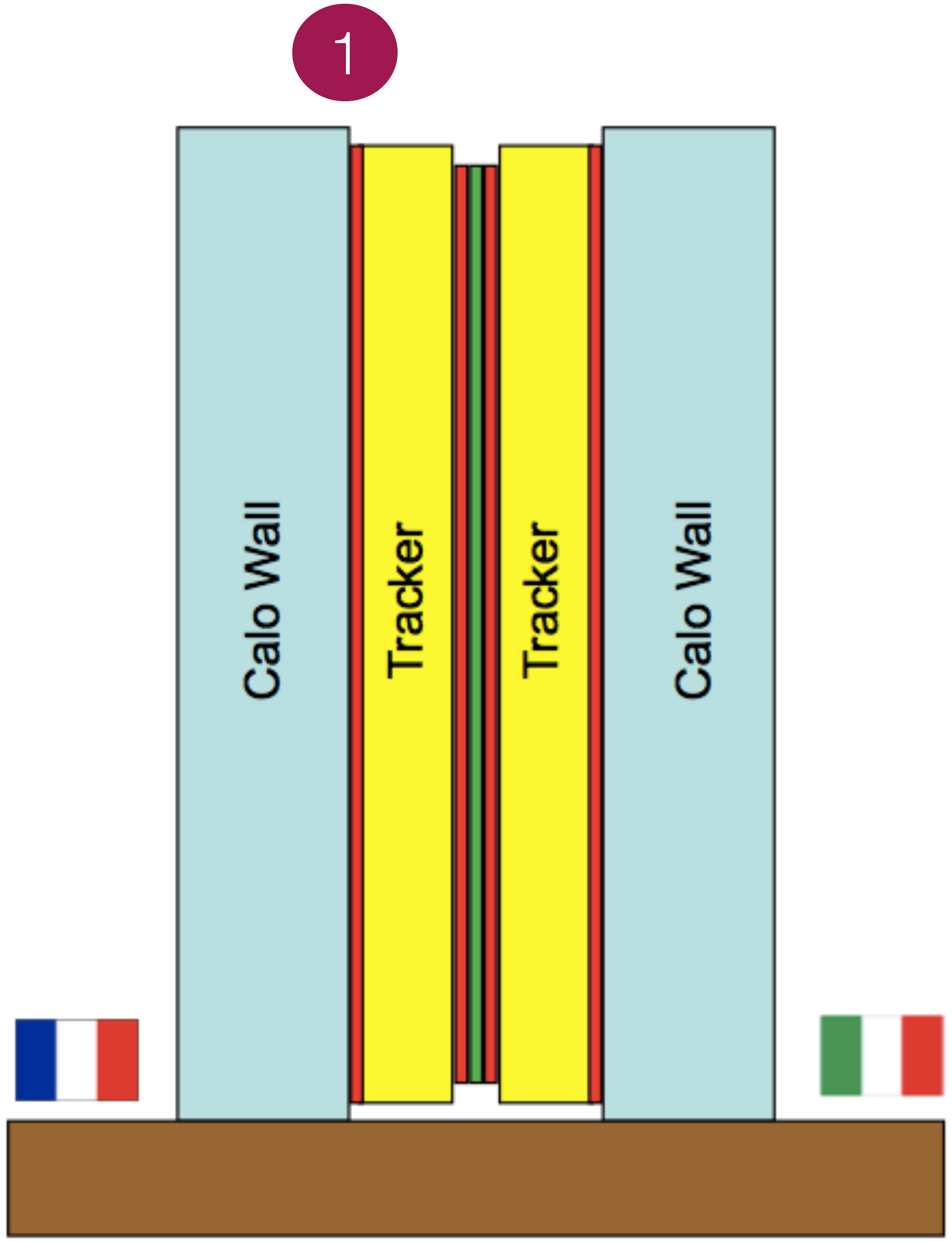
- Both calorimeter walls in place at LSM
- Light Injection calibration system to monitor gain drift within 1%

Installation status

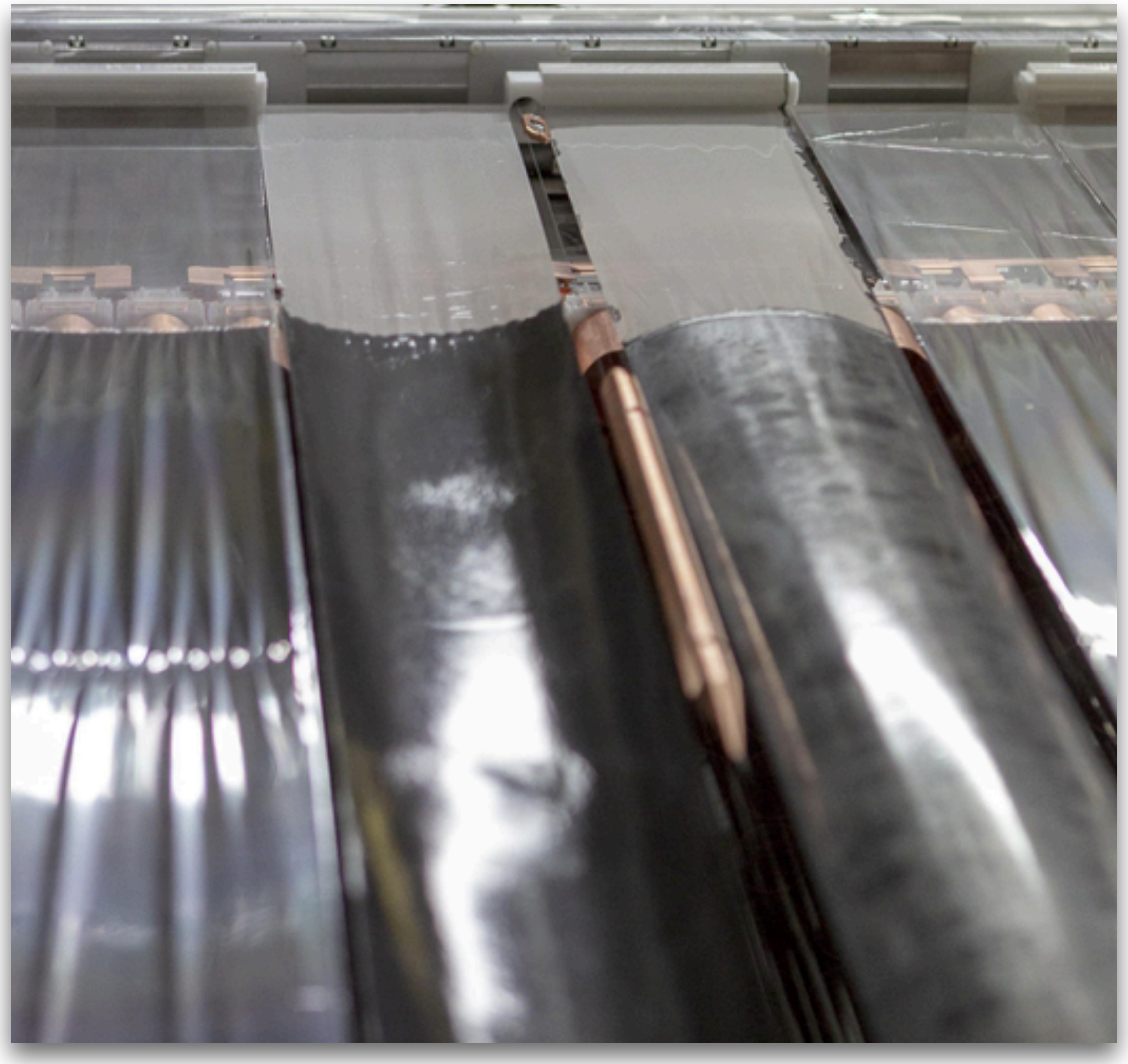


Installation status

1. French-side tracker joined to calorimeter wall

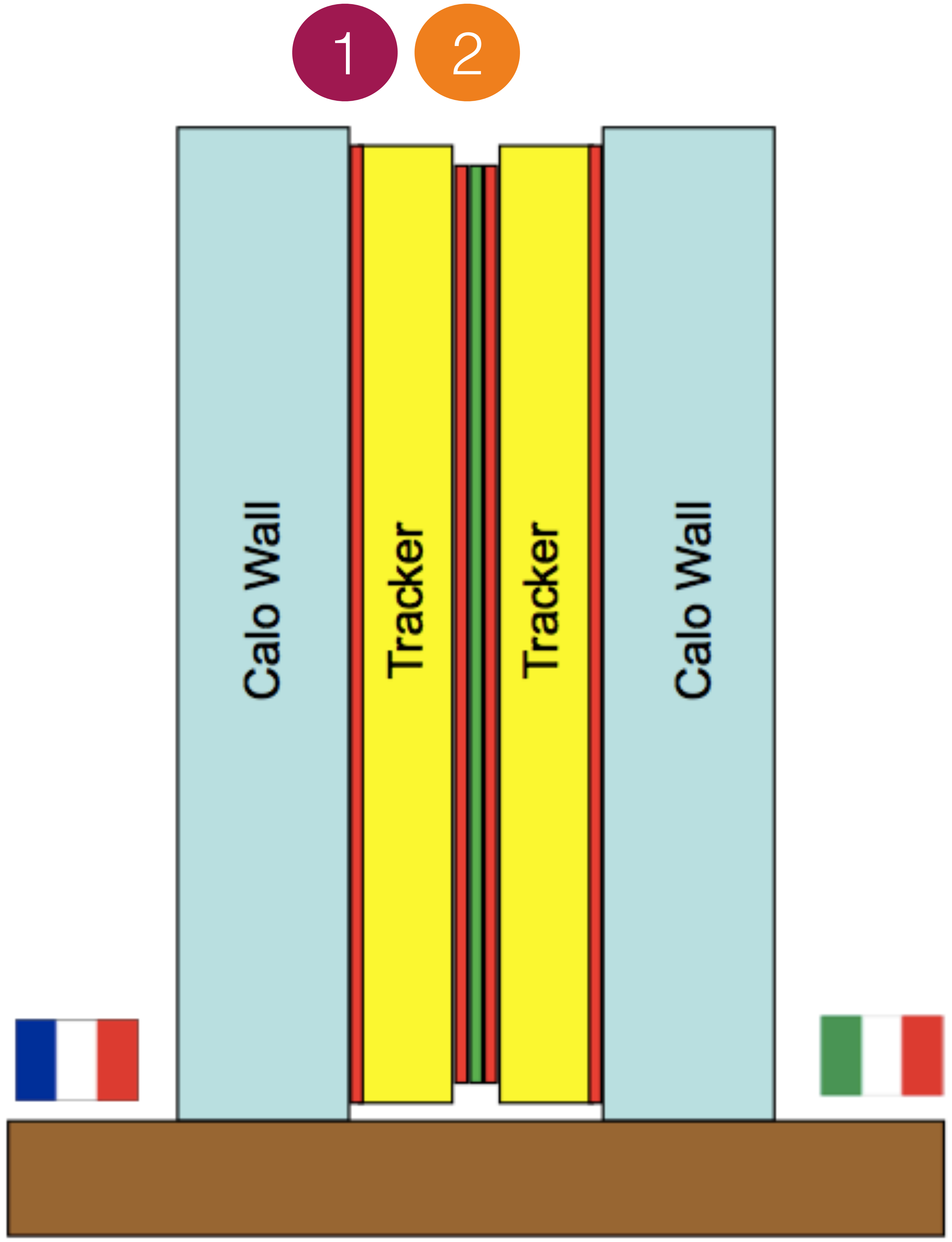


Installation status

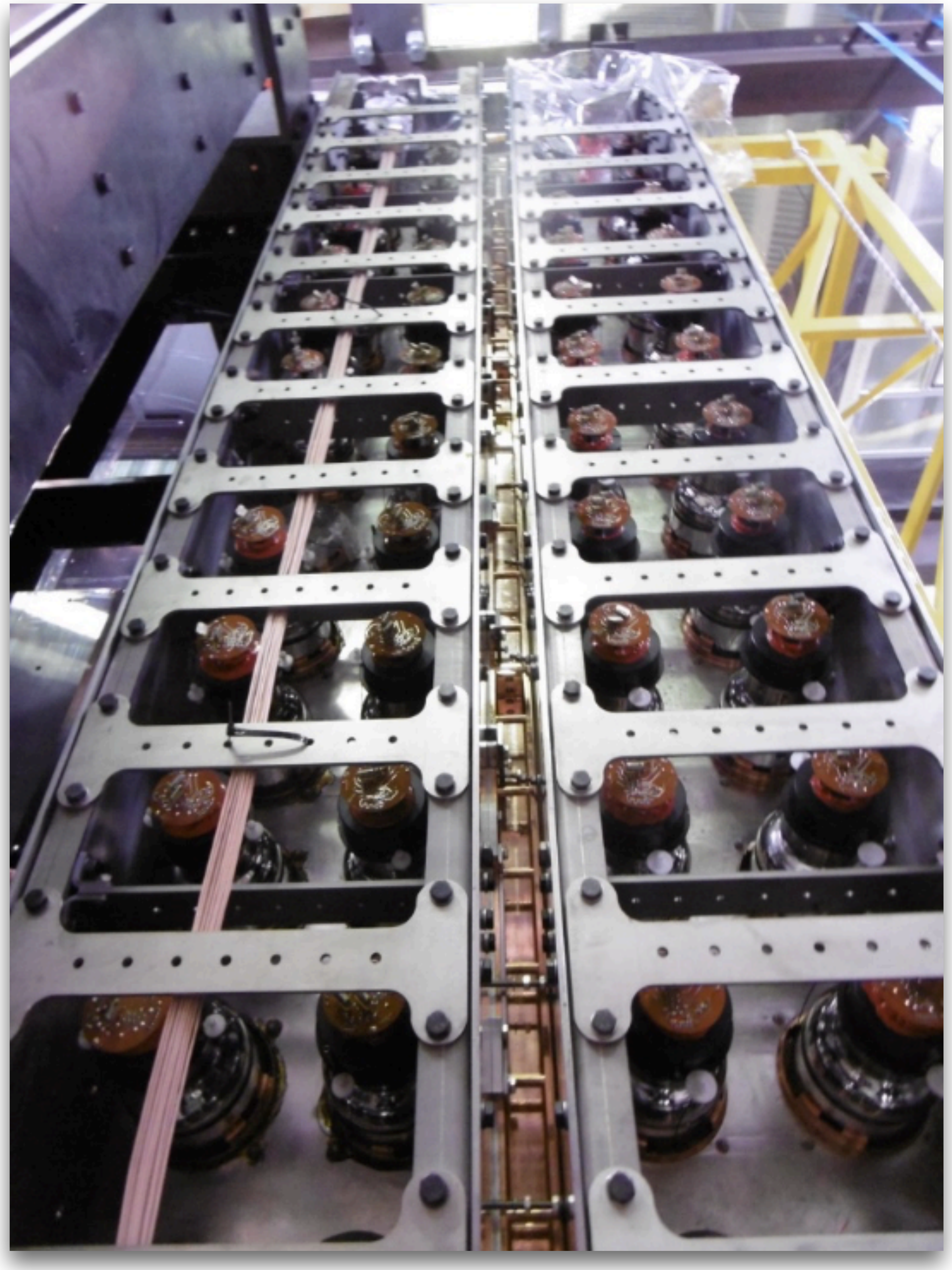


1. French-side tracker joined to calorimeter wall

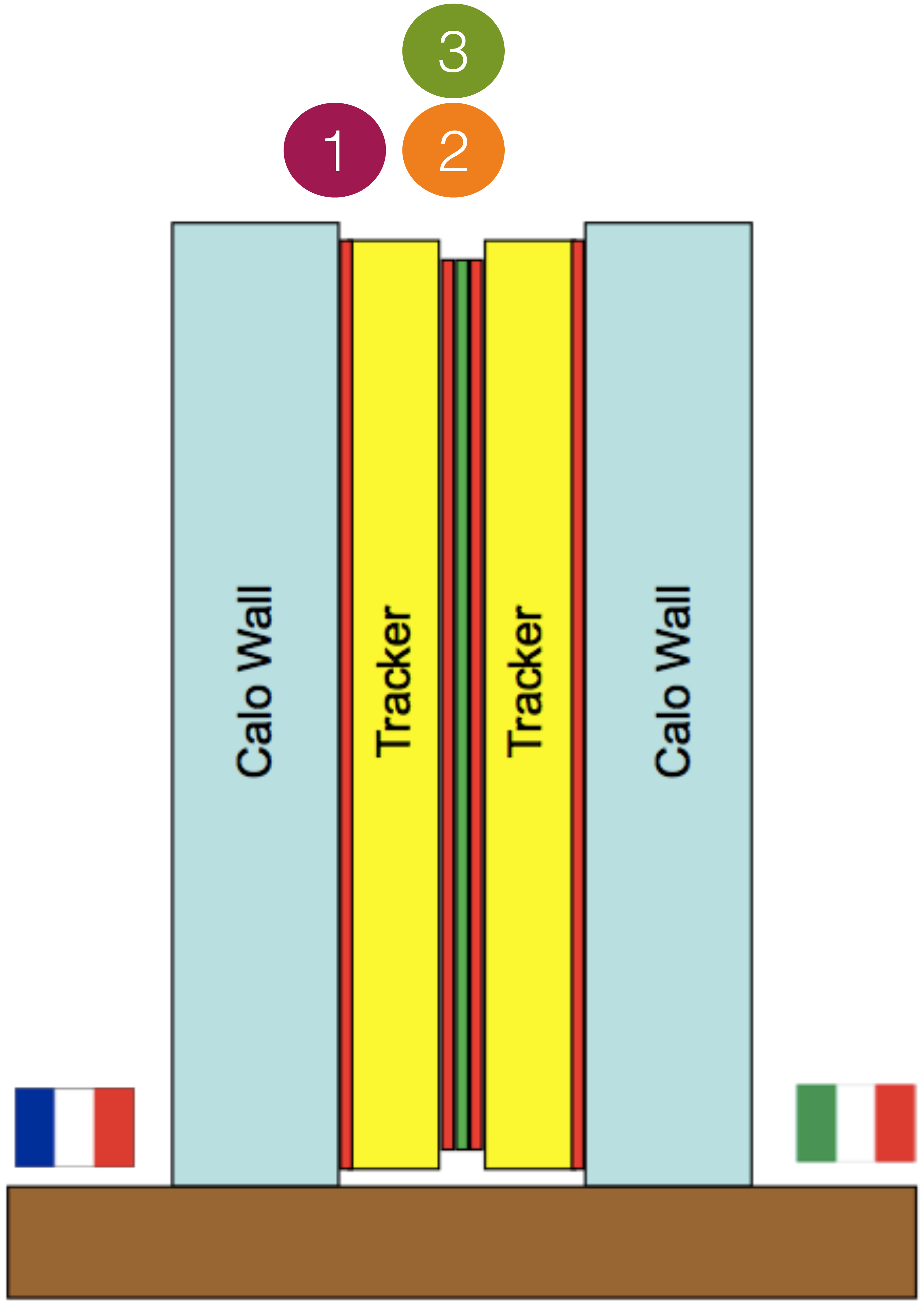
2. Source foils and calibration system installed



Installation status

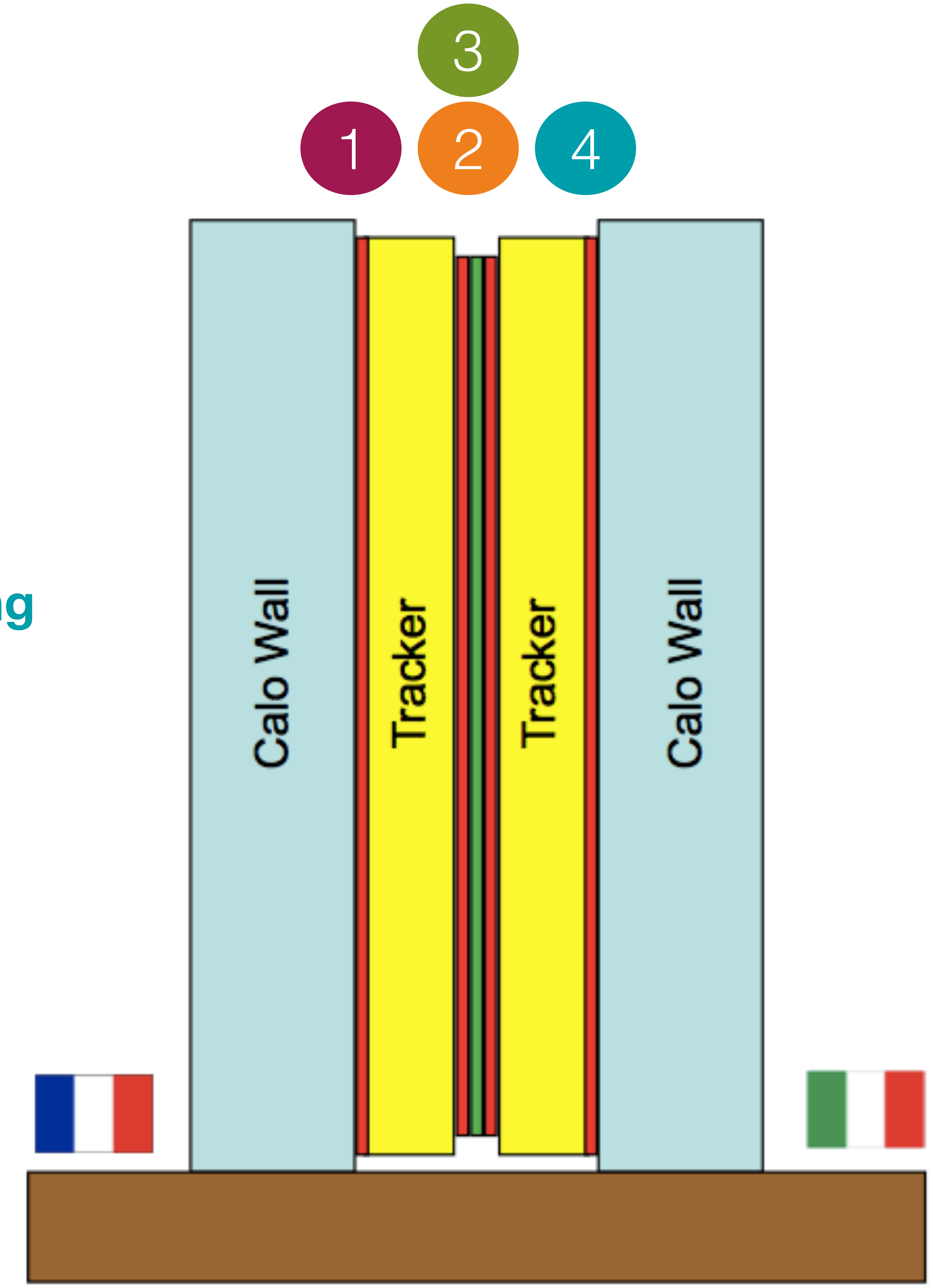


1. French-side tracker joined to calorimeter wall
2. Source foils and calibration system installed
3. Tracker closed

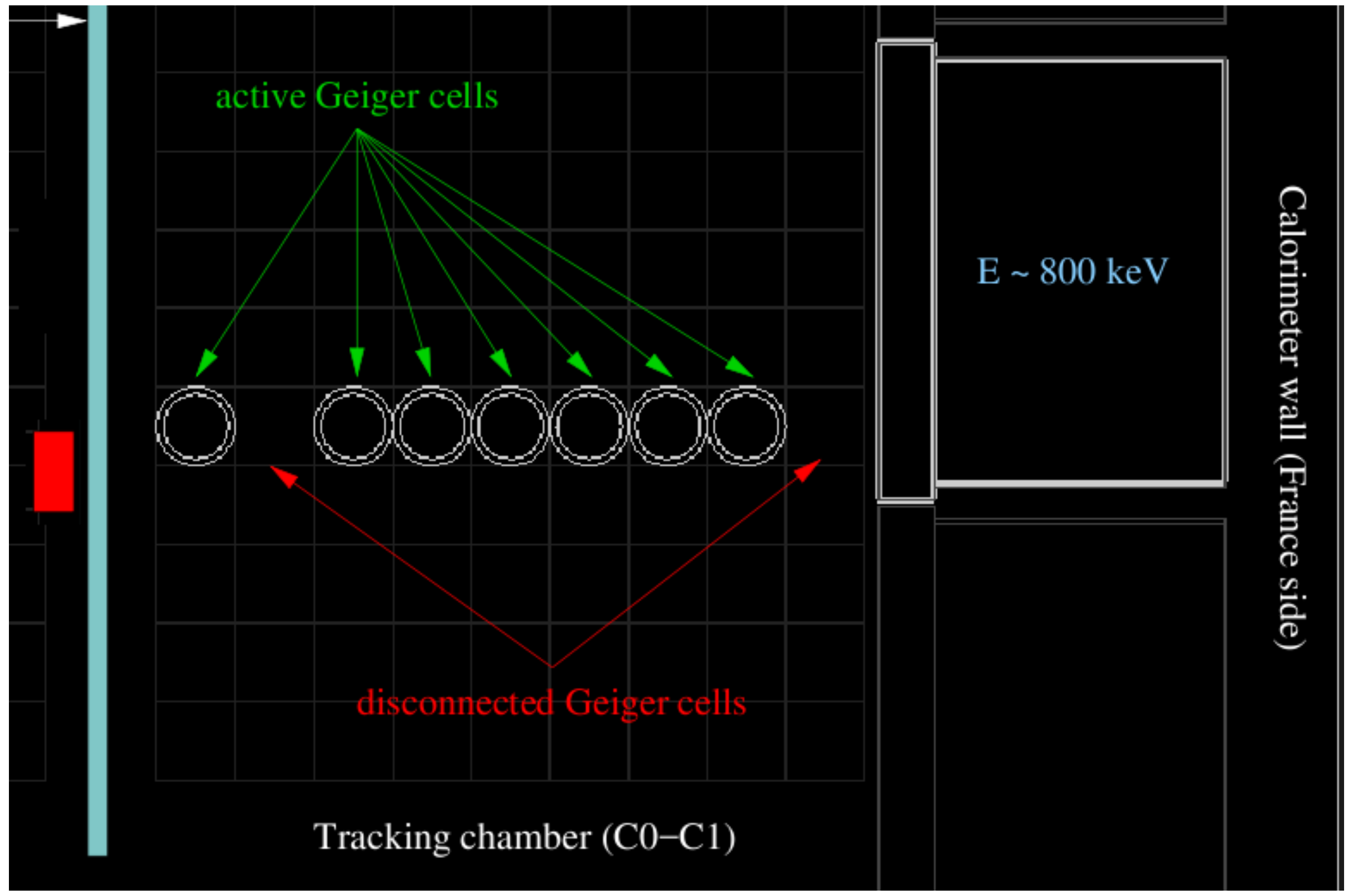


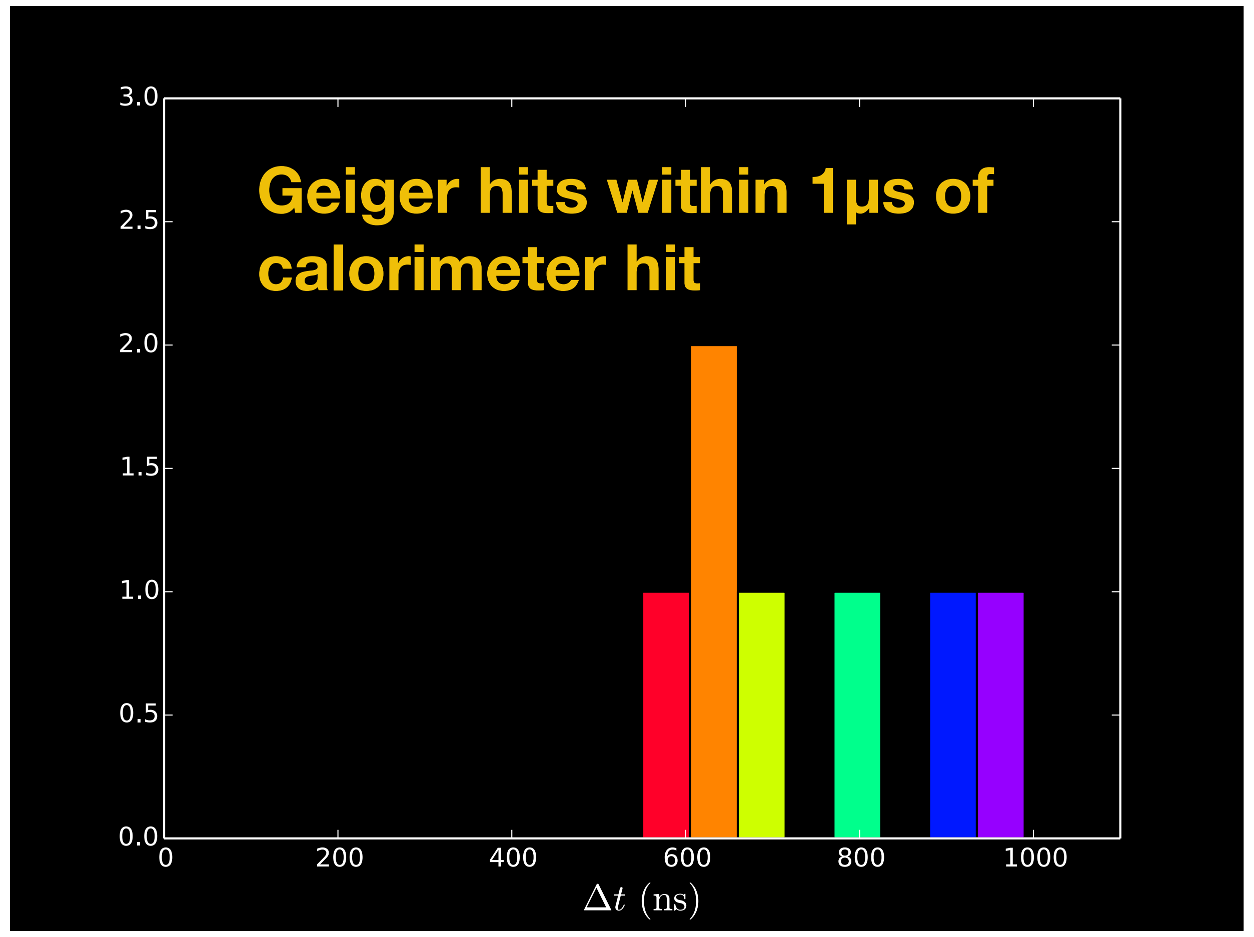
Installation status

1. French-side tracker joined to calorimeter wall
2. Source foils and calibration system installed
3. Tracker closed
4. Italian-side tracker transport frame removed ready for attaching calorimeter wall



Installation status



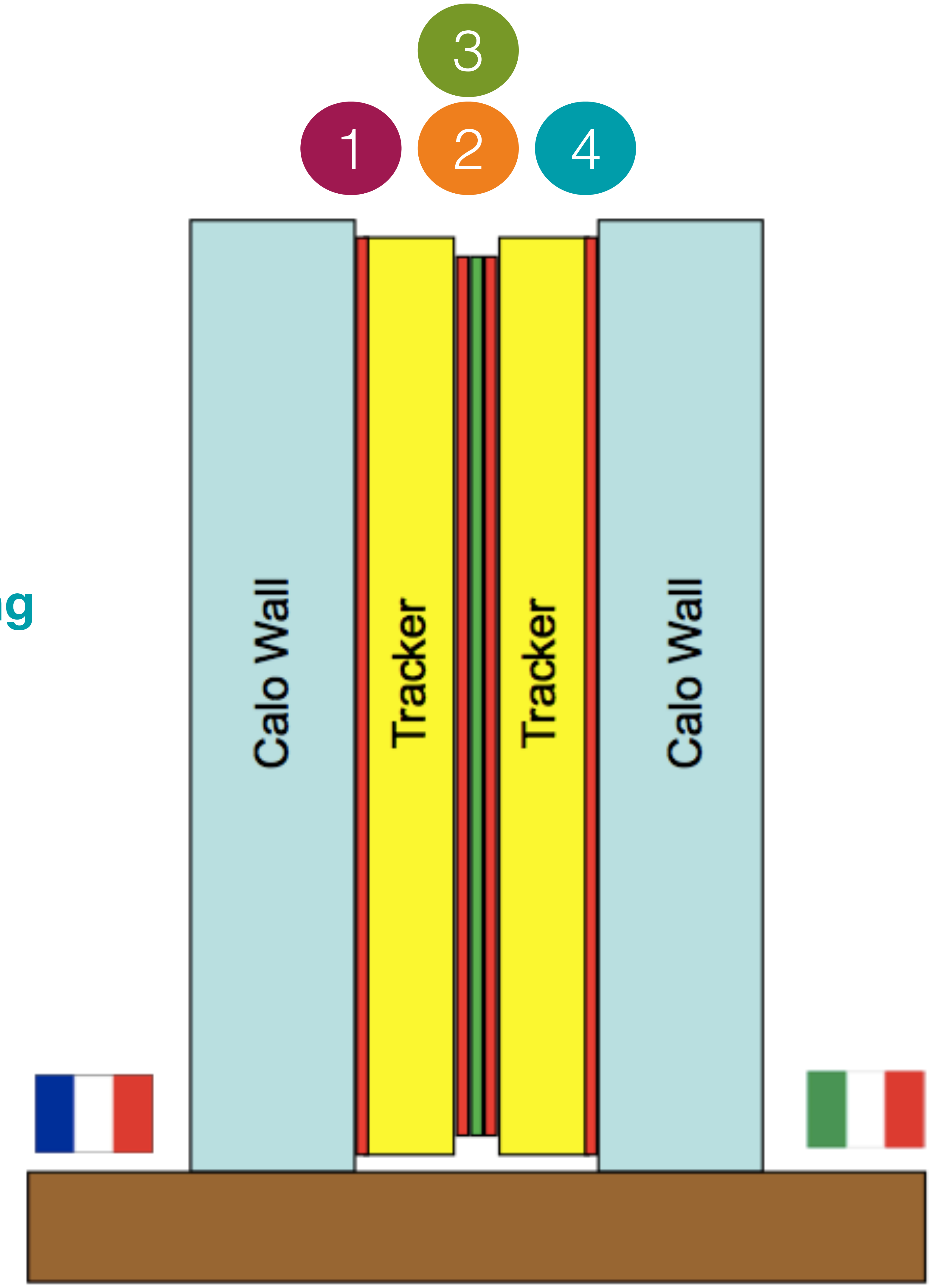


Half-detector commissioning results

1. French-side tracker joined to calorimeter wall
2. Source foils and calibration system installed
3. Tracker closed
4. Italian-side tracker transport frame removed ready for attaching calorimeter wall

To do:

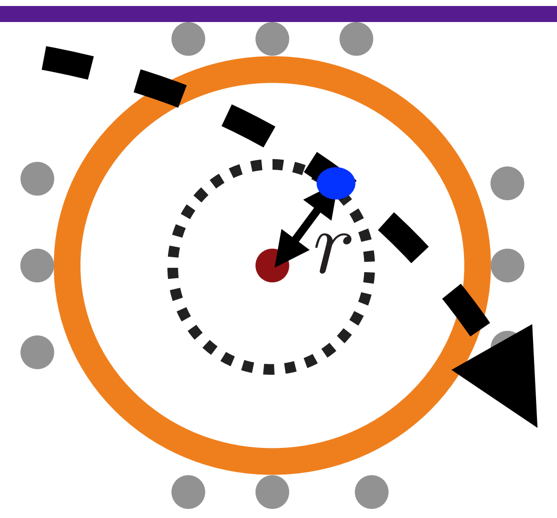
- Attach final calorimeter wall
- Install cabling and electronics
- Commissioning
- First data!



Particles in SuperNEMO

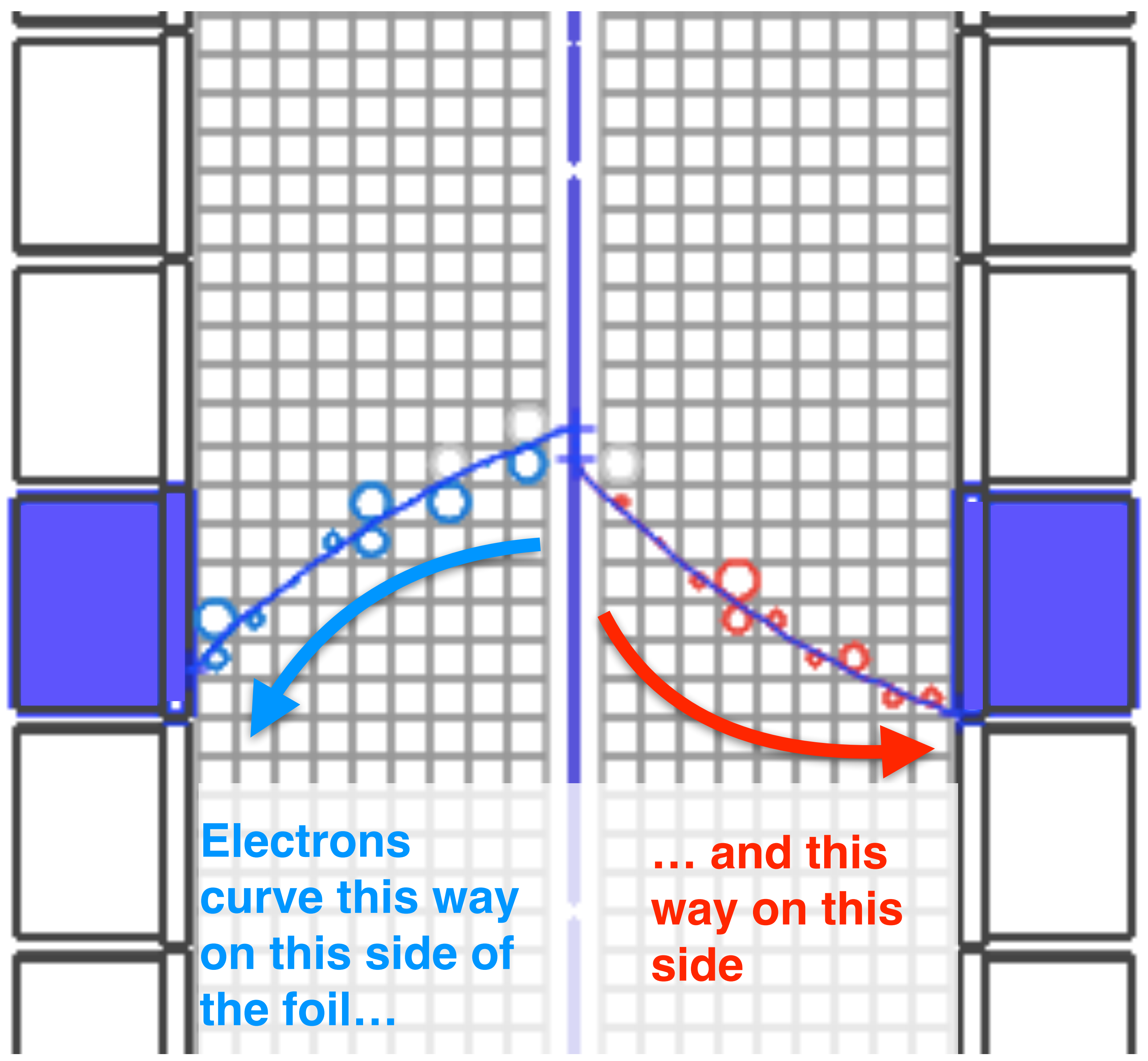
e^-

Tracker hits appear as circles (radius depends on drift time)



Individual electron energy and time

= 2.01 ± 0.05 MeV
= 2.02 ± 0.14 ns

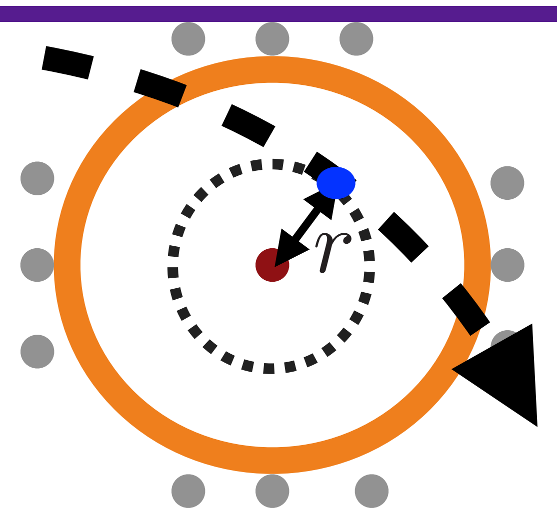


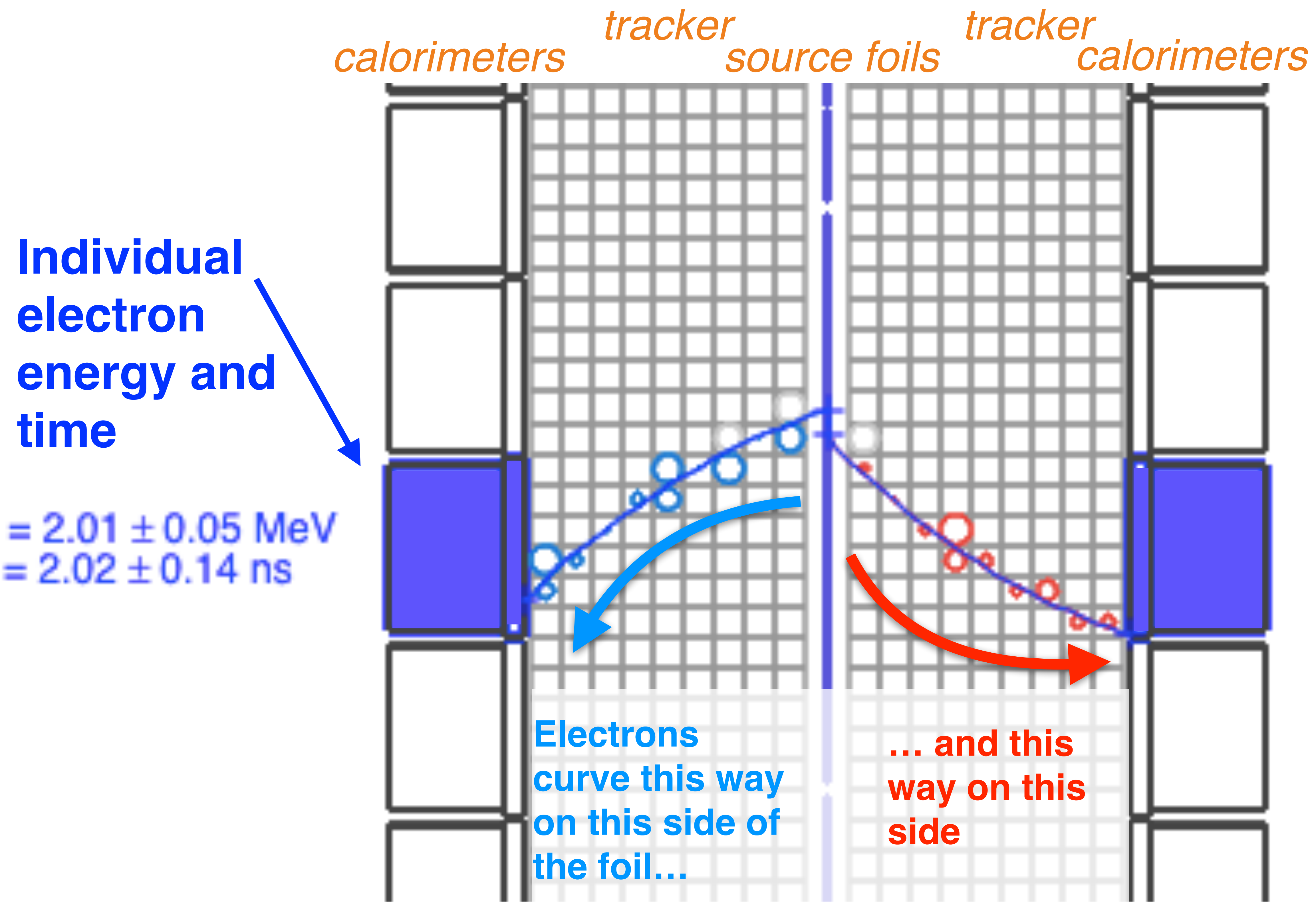
Plan view (partial)

Particles in SuperNEMO

e⁻

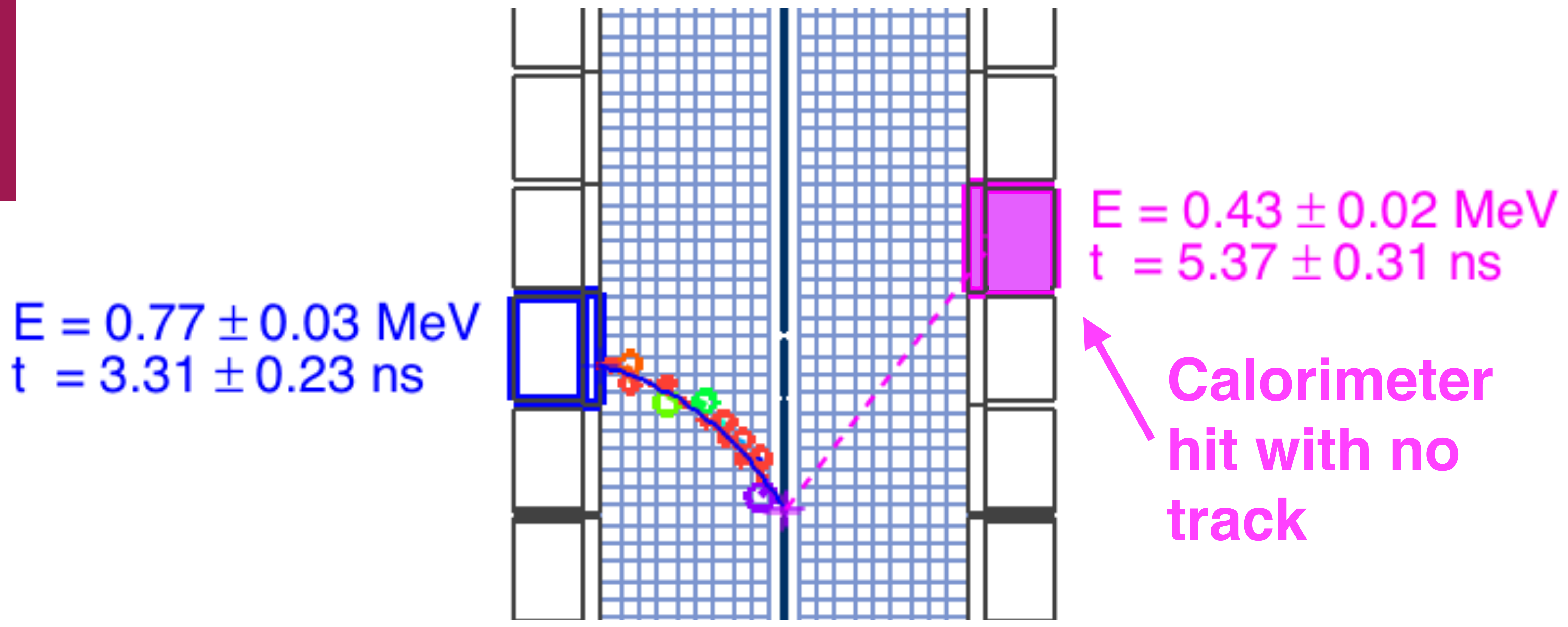
Tracker hits appear as circles (radius depends on drift time)





Plan view (partial)

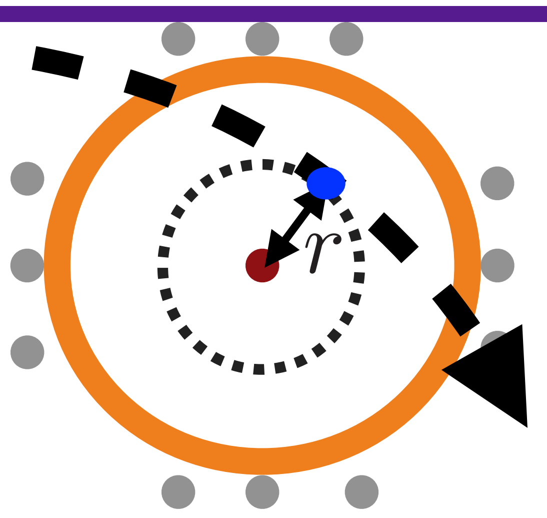
γ



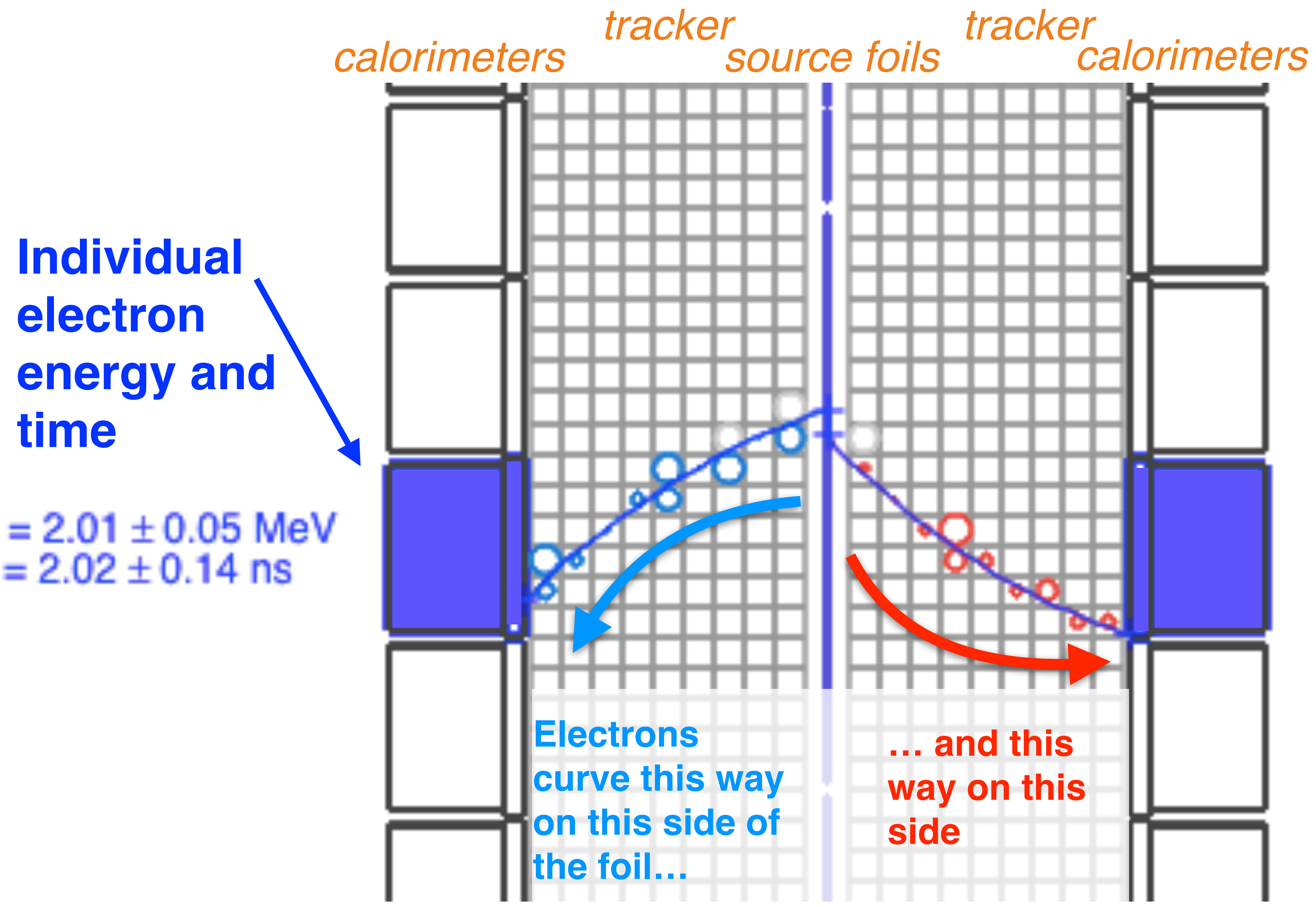
Particles in SuperNEMO

e⁻

Tracker hits appear as circles (radius depends on drift time)

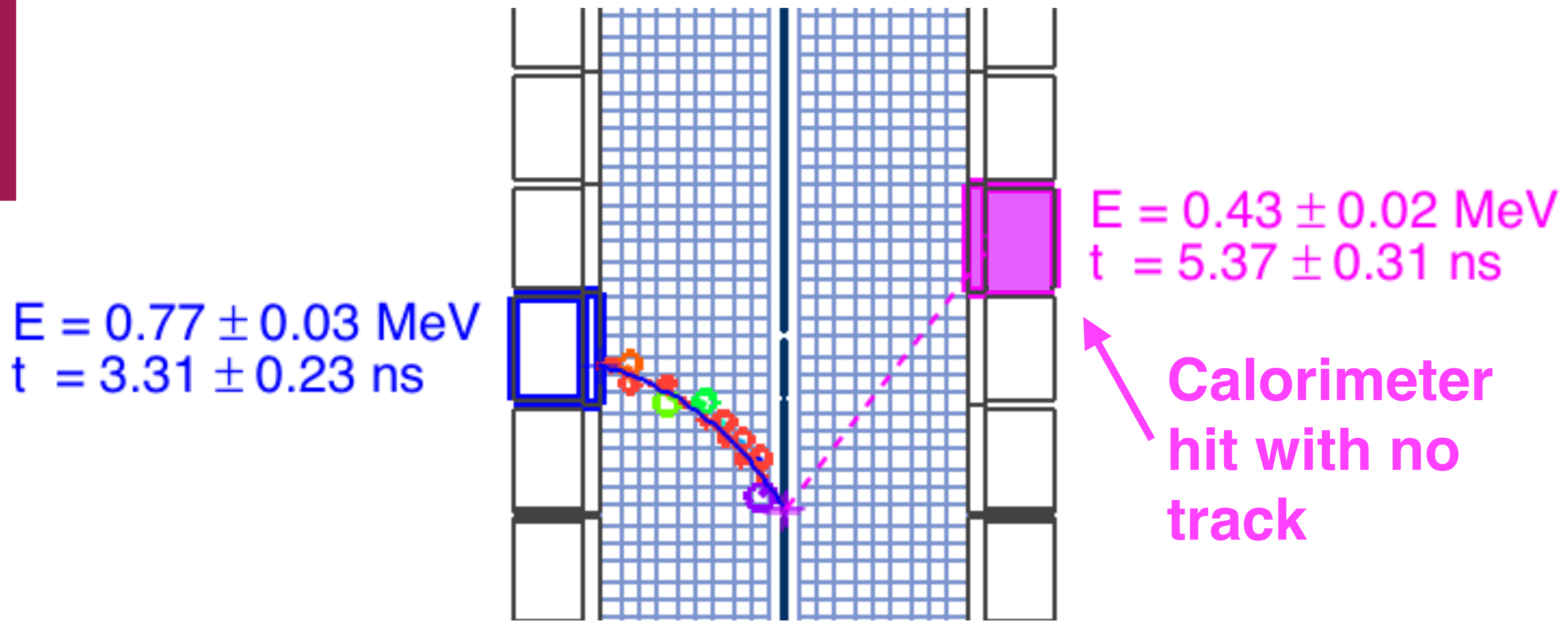


Individual electron energy and time

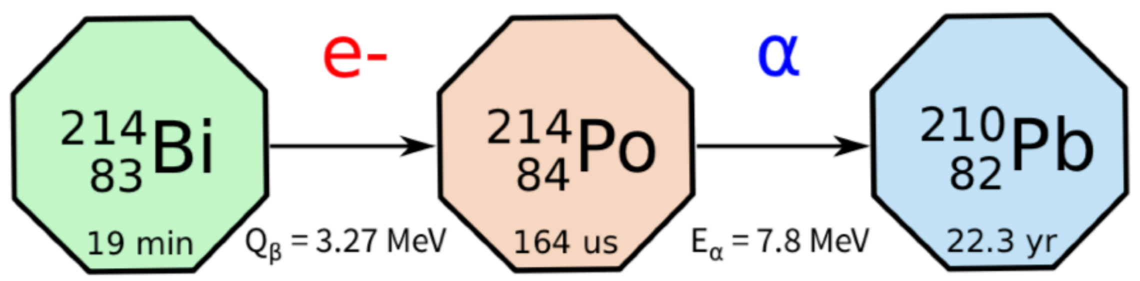


Plan view (partial)

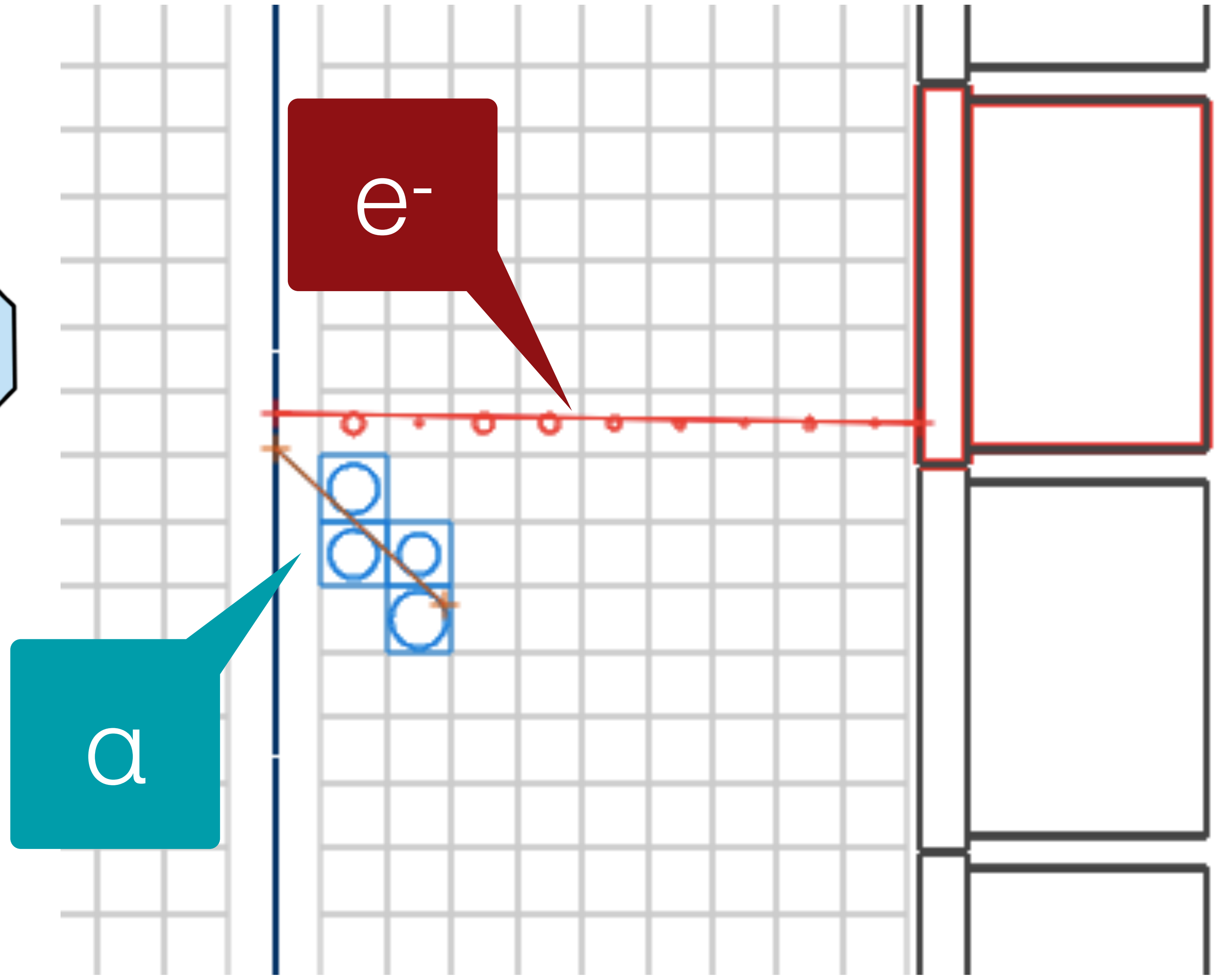
γ



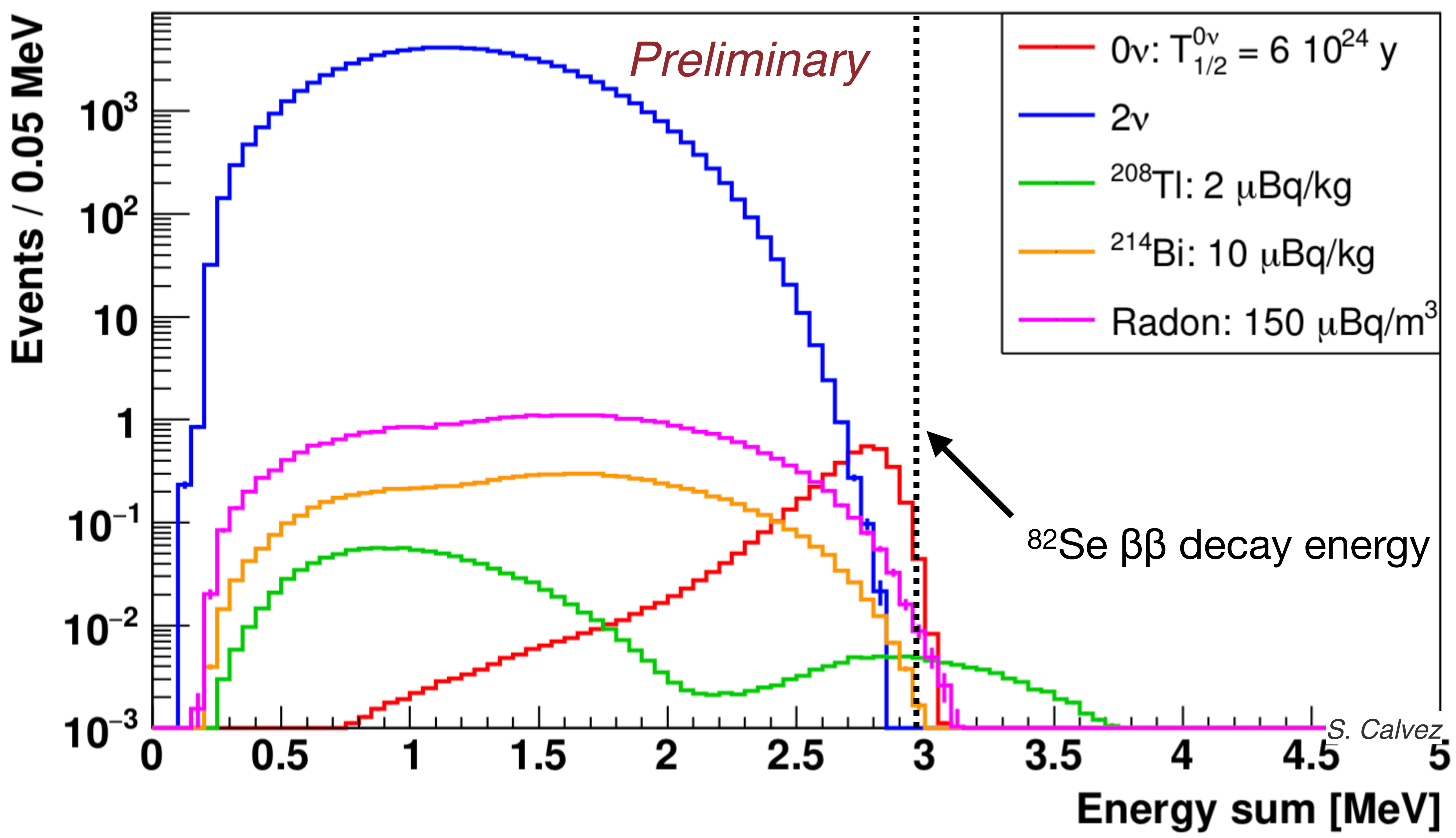
α



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

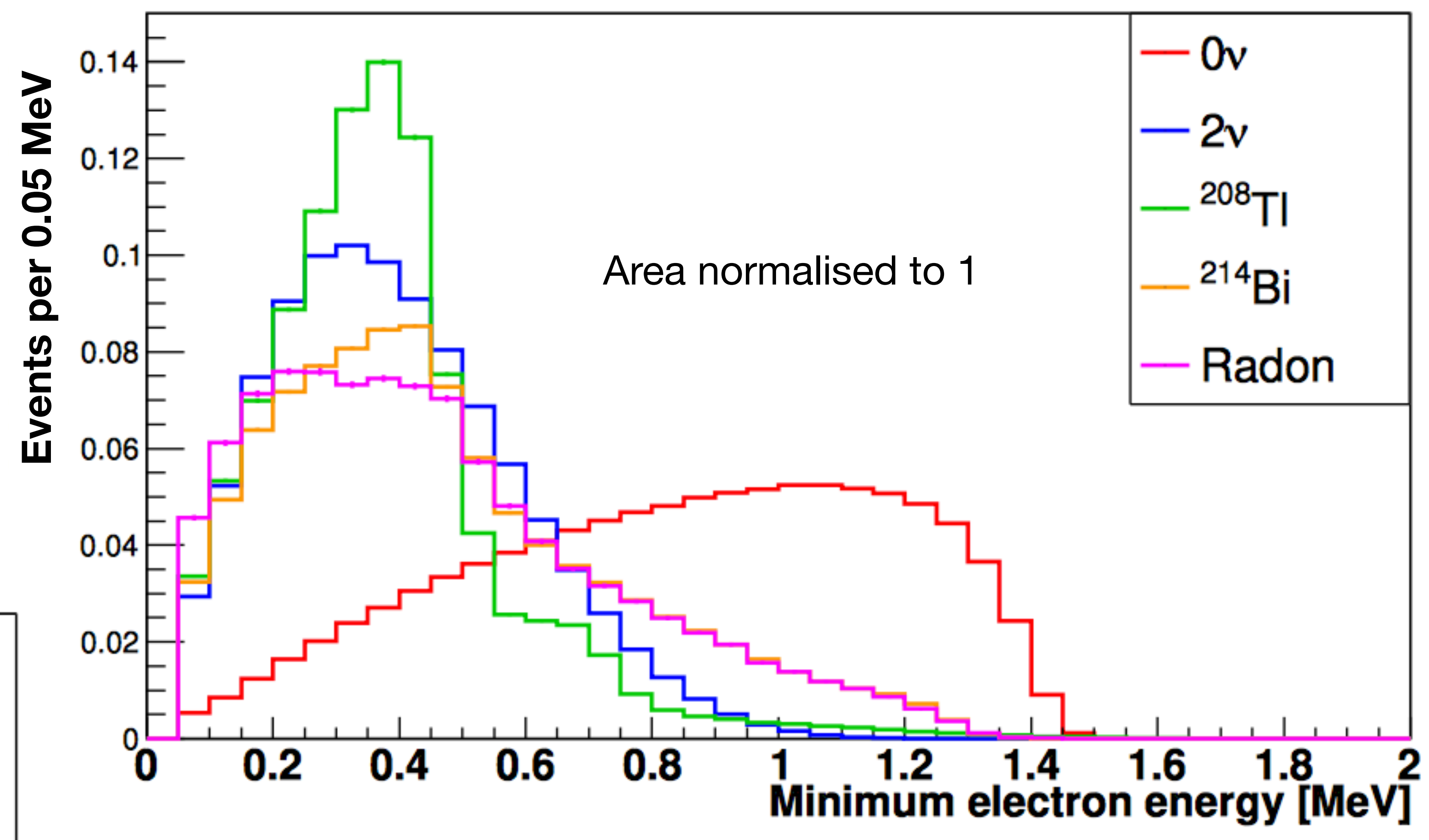


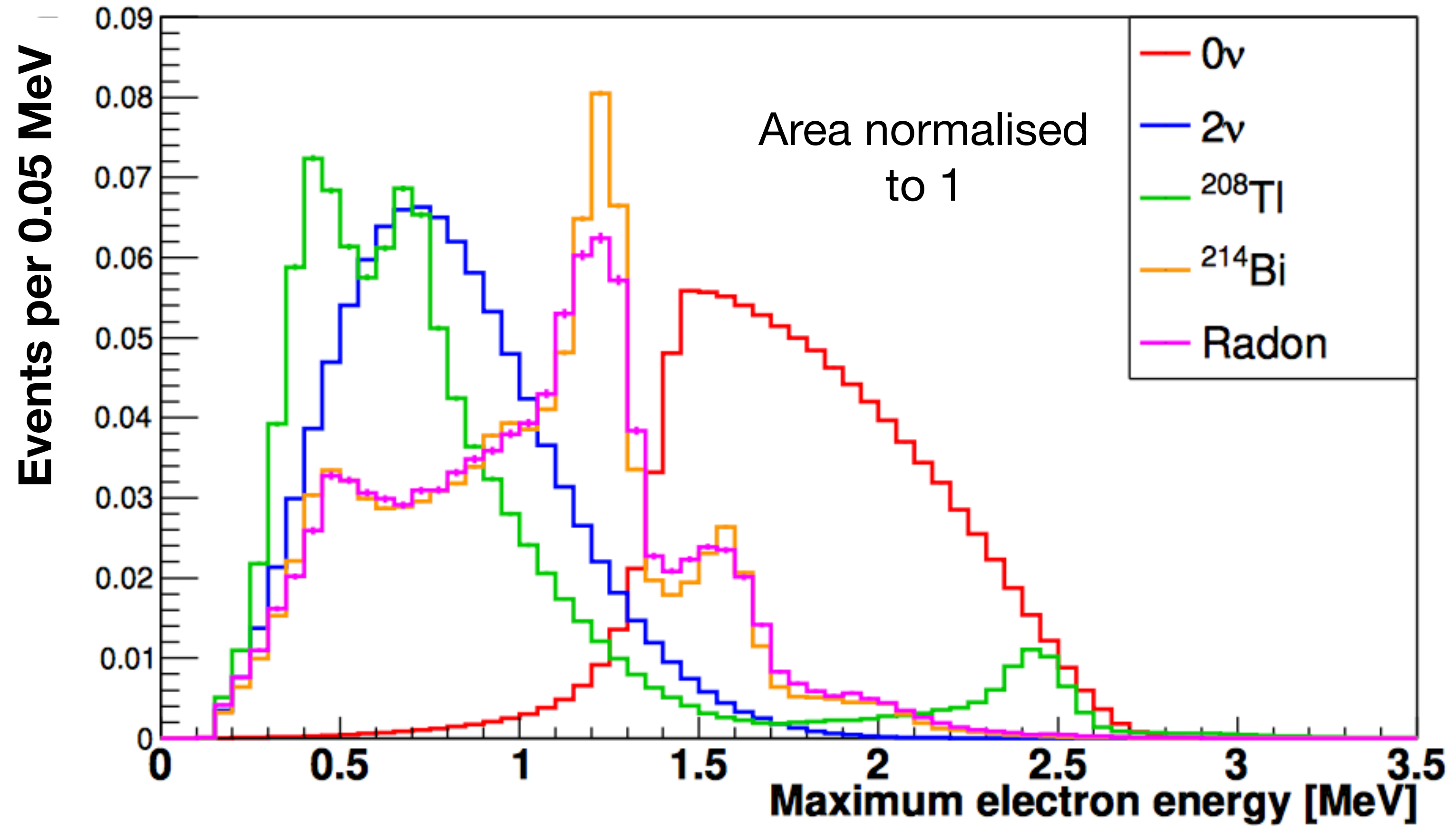
Sensitivity to 0νββ



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

Sensitivity to 0νββ

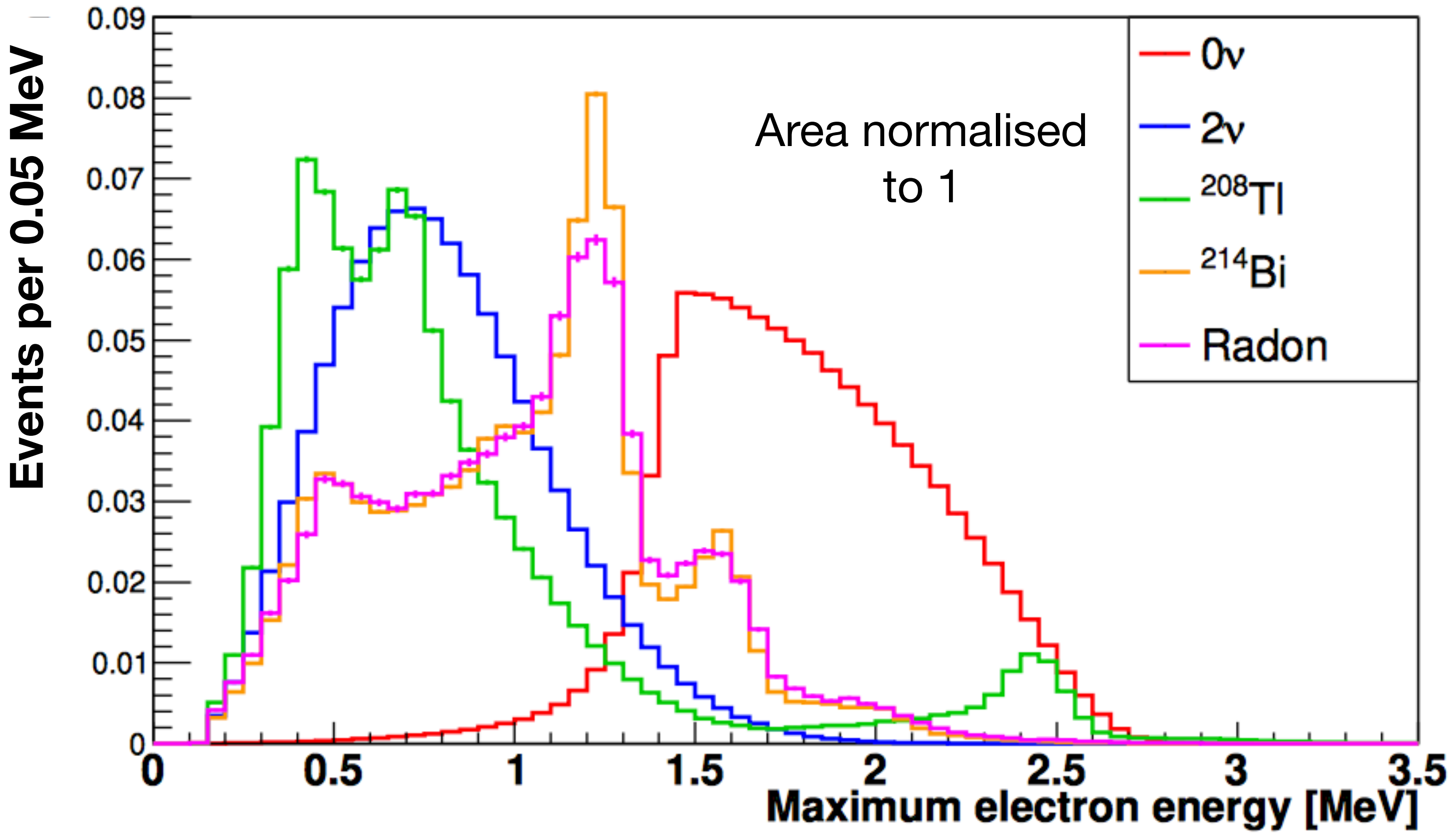


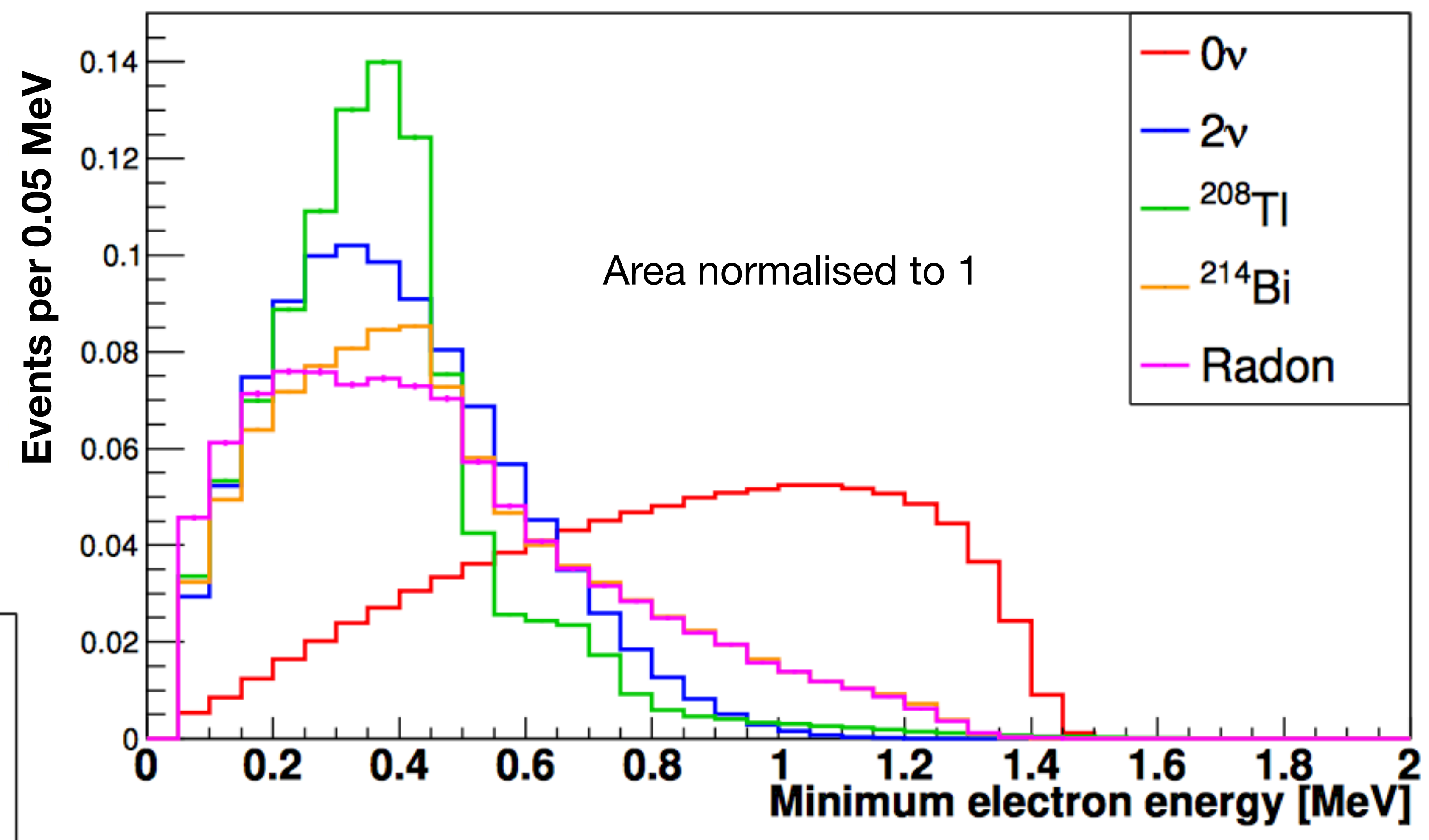


Summed 2-electron energy is best distribution to separate signal from background

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)*

Sensitivity to 0νββ





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

Demonstrator physics goals

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle <$ 160-400 meV

Demonstrator physics goals

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle <$ 160-400 meV

Exotic $0\nu\beta\beta$ mechanisms

Demonstrator physics goals

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle <$ 160-400 meV

Exotic $0\nu\beta\beta$ mechanisms

$2\nu\beta\beta$: SSD/HSD discrimination at 5σ level

Demonstrator physics goals

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle <$ 160-400 meV

Exotic $0\nu\beta\beta$ mechanisms

$2\nu\beta\beta$: SSD/HSD discrimination at 5σ level

Probe nuclear physics by measuring g_A

Demonstrator physics goals

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle < 160\text{-}400$ meV

Exotic $0\nu\beta\beta$ mechanisms

$2\nu\beta\beta$: SSD/HSD discrimination at 5σ level

Probe nuclear physics by measuring g_A

Lorentz invariance violation test

Demonstrator physics goals

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle < 160\text{-}400$ meV

Exotic $0\nu\beta\beta$ mechanisms

$2\nu\beta\beta$: SSD/HSD discrimination at 5σ level

Probe nuclear physics by measuring g_A

Lorentz invariance violation test

Alternative isotopes: ^{150}Nd and ^{48}Ca, with high $Q_{\beta\beta}$

Demonstrator physics goals

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle <$ 160-400 meV

Exotic $0\nu\beta\beta$ mechanisms

$2\nu\beta\beta$: SSD/HSD discrimination at 5σ level

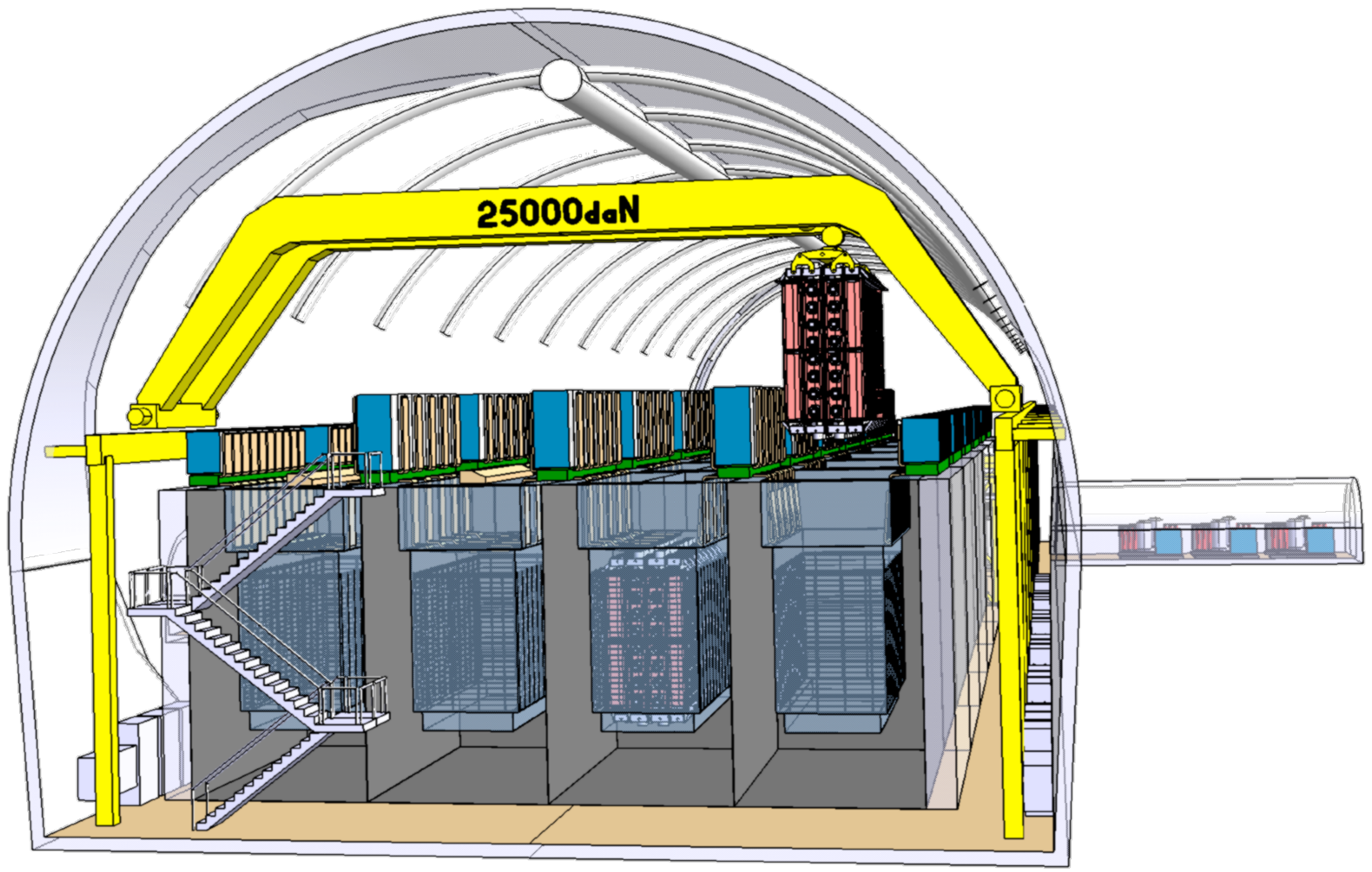
Probe nuclear physics by measuring g_A

Lorentz invariance violation test

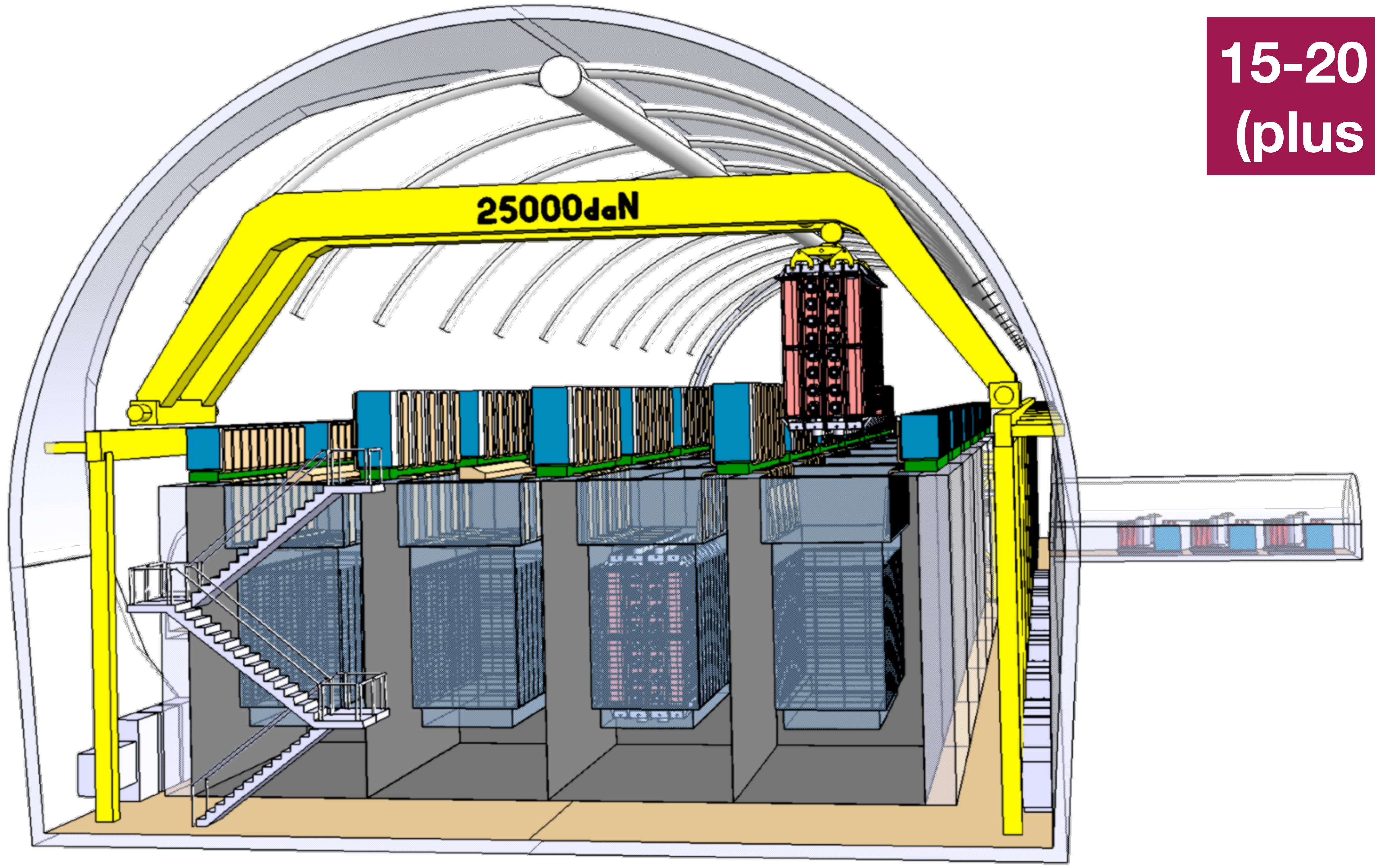
Alternative isotopes: ^{150}Nd and ^{48}Ca, with high $Q_{\beta\beta}$

$0\nu4\beta$: for ^{150}Nd

Full SuperNEMO prospects



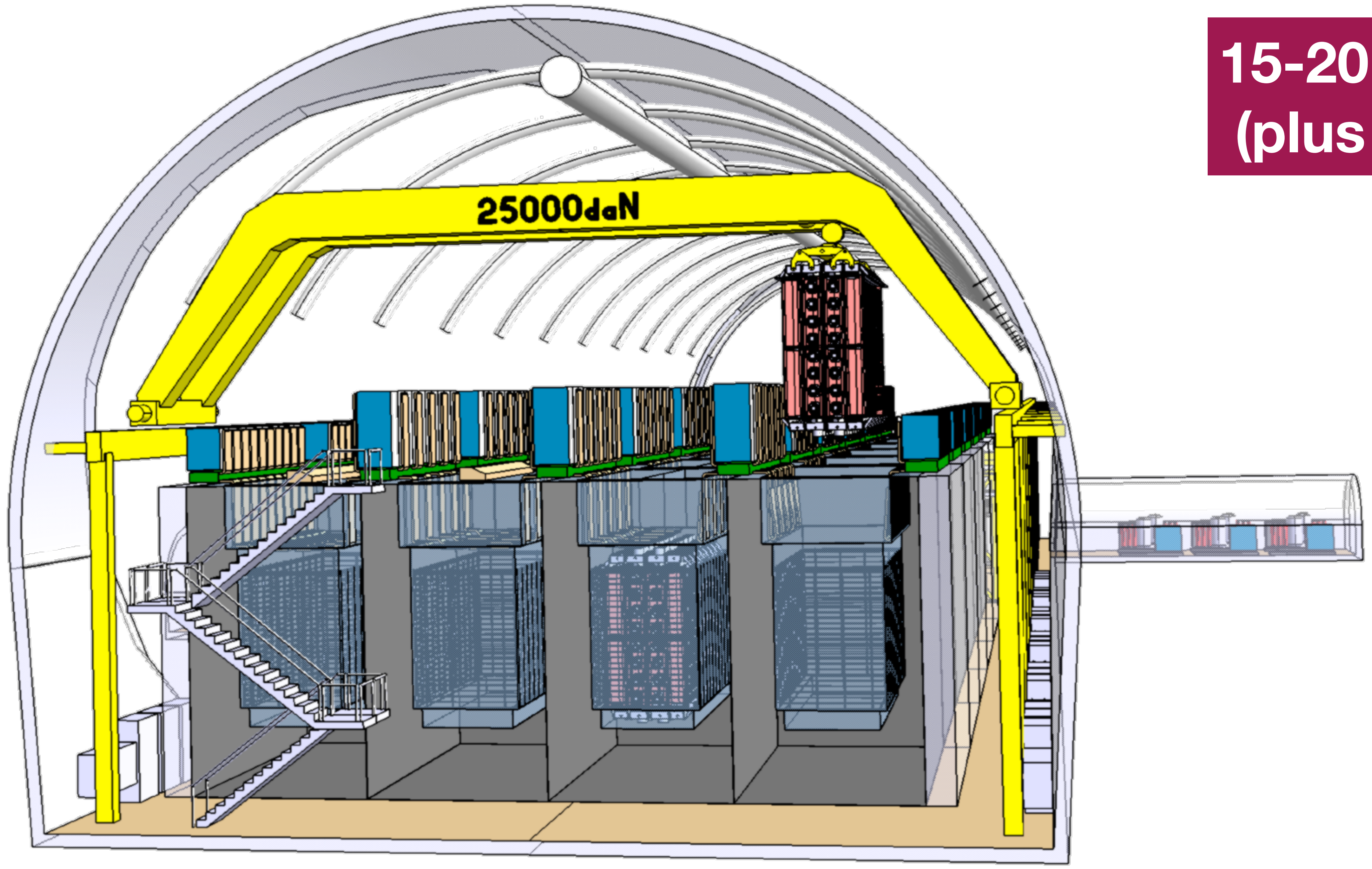
Full SuperNEMO prospects



15-20 modules @ ~ €2.5M each (plus labour…)

→ 100kg isotope - $T_{1/2} \sim 10^{26}$ years
$\langle m_\nu \rangle <$ 40-100 meV

Full SuperNEMO prospects



15-20 modules @ ~ €2.5M each (plus labour…)

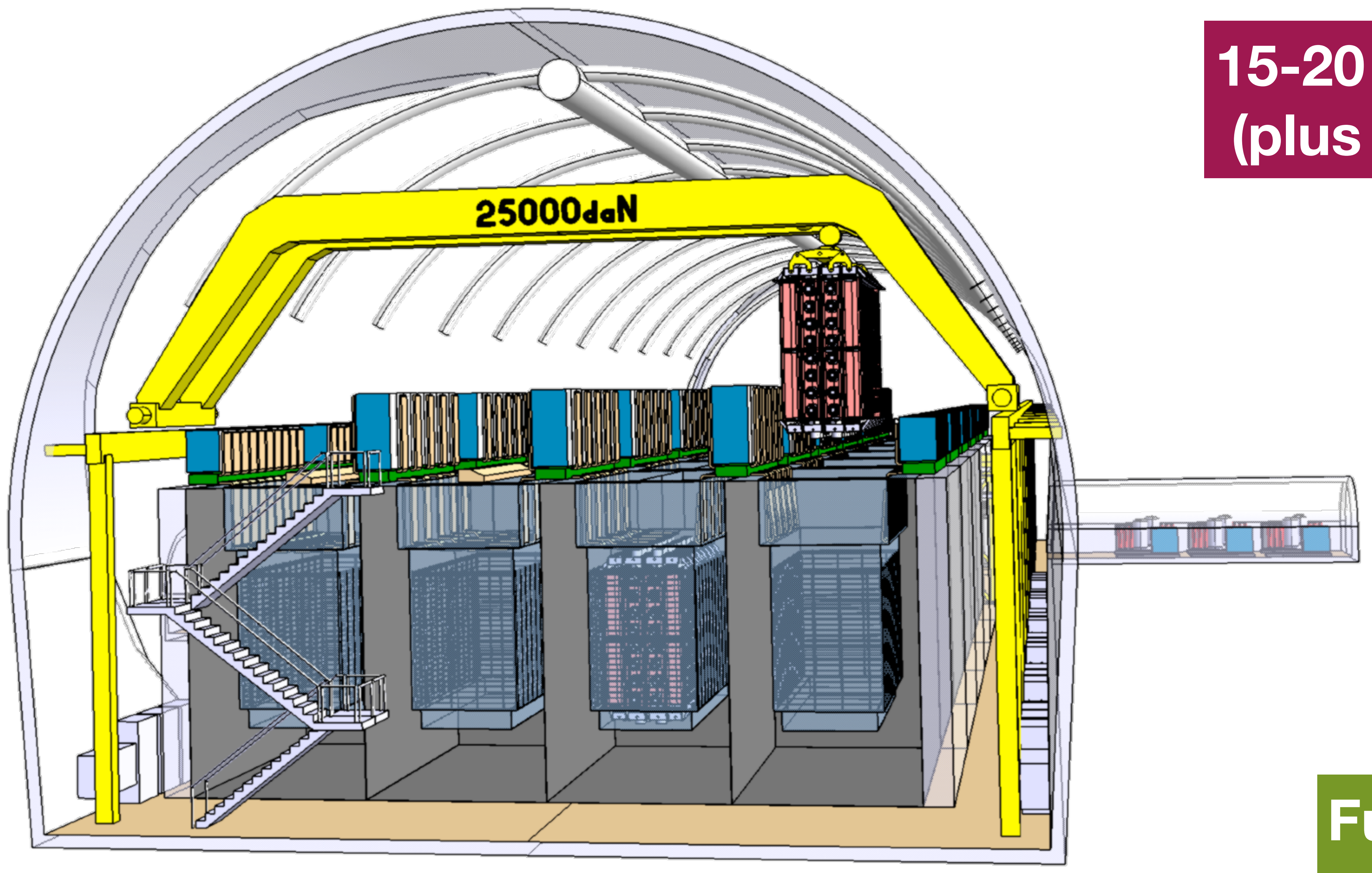
100kg isotope - $T_{1/2} \sim 10^{26}$ years
$\langle m_\nu \rangle < 40\text{-}100$ meV

Modular design allows other isotopes

High $Q_{\beta\beta}$ isotopes give better sensitivity

Distribute modules among multiple labs?

Full SuperNEMO prospects



15-20 modules @ ~ €2.5M each (plus labour…)

100kg isotope - $T_{1/2}$ ~ 10^{26} years
$\langle m_\nu \rangle$ < 40-100 meV

Modular design allows other isotopes

High $Q_{\beta\beta}$ isotopes give better sensitivity

Distribute modules among multiple labs?

Full topological reconstruction at the inverted hierarchy regime

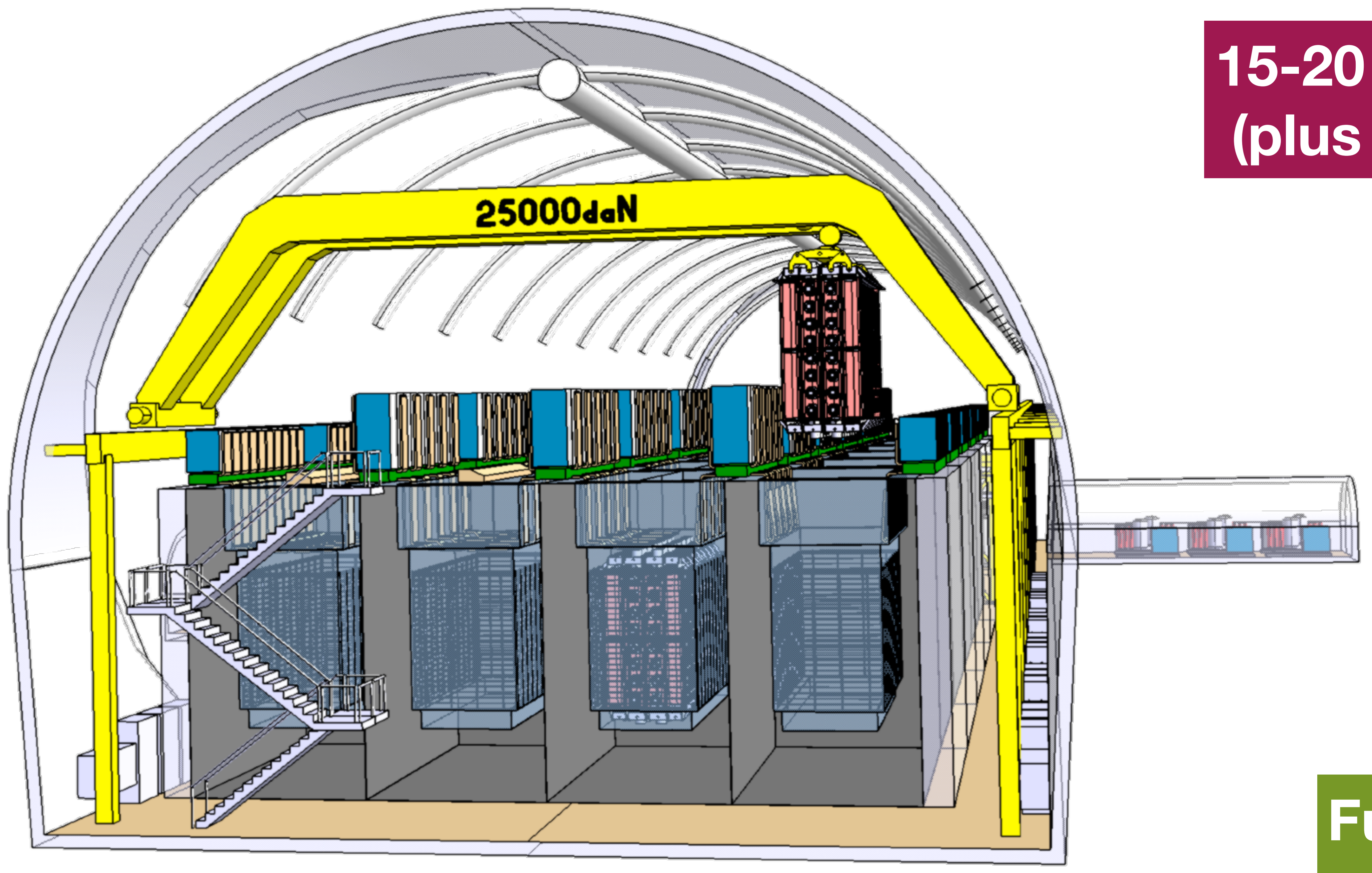
Distinguish 0νββ mechanism ($\langle m_\nu \rangle$, V+A, Majoron…?)

Use topology to eliminate (non-2νββ) backgrounds

2νββ mechanism (excited states)

Investigate other new physics (nuclear models, 0ν4β, Lorentz violation…)

Full SuperNEMO prospects



15-20 modules @ ~ €2.5M each (plus labour…)

100kg isotope - $T_{1/2}$ ~ 10^{26} years
〈m_ν〉 < 40-100 meV

Modular design allows other isotopes

High $Q_{\beta\beta}$ isotopes give better sensitivity

Distribute modules among multiple labs?

Full topological reconstruction at the inverted hierarchy regime

Distinguish 0νββ mechanism (〈m_ν〉, V+A, Majoron…?)

Use topology to eliminate (non-2νββ) backgrounds

2νββ mechanism (excited states)

Investigate other new physics (nuclear models, 0ν4β, Lorentz violation…)

Can we reduce cost (detector cheaper than isotope) without harming performance?

Tracker-calorimeter detectors for the next generation

Choosing an isotope

- **^{150}Nd, ^{48}Ca** have shorter $2\nu\beta\beta$ half-lives
- Currently too **expensive to enrich** large amounts… but research is ongoing
- Current investigation - **how much** would we need to probe inverted hierarchy? (O(10^3) kg.year)

Tracker-calorimeter detectors for the next generation

Choosing an isotope

- ^{150}**Nd**, ^{48}**Ca** have shorter $2\nu\beta\beta$ half-lives
- Currently too **expensive to enrich** large amounts… but research is ongoing
- Current investigation - **how much** would we need to probe inverted hierarchy? ($O(10^3)$ kg.year)

Efficiency

- Could a different **geometry** improve our detector acceptance (eg scintillator bar design)?
- What about other **tracker** or **calorimeter** technologies?
- Can we improve **reconstruction** algorithms' efficiency?

Tracker-calorimeter detectors for the next generation

Choosing an isotope

- ^{150}**Nd**, ^{48}**Ca** have shorter 2νββ half-lives
- Currently too **expensive to enrich** large amounts… but research is ongoing
- Current investigation - **how much** would we need to probe inverted hierarchy? (O(10^3) kg.year)

Efficiency

- Could a different **geometry** improve our detector acceptance (eg scintillator bar design)?
- What about other **tracker** or **calorimeter** technologies?
- Can we improve **reconstruction** algorithms' efficiency?

Background suppression

- **Demonstrator** will tell us how well we are suppressing backgrounds
- Irreducible **2νββ background** depends on isotope

Tracker-calorimeter detectors for the next generation

Choosing an isotope

- **^{150}Nd, ^{48}Ca** have shorter $2\nu\beta\beta$ half-lives
- Currently too **expensive to enrich** large amounts… but research is ongoing
- Current investigation - **how much** would we need to probe inverted hierarchy? (O(10^3) kg.year)

Efficiency

- Could a different **geometry** improve our detector acceptance (eg scintillator bar design)?
- What about other **tracker** or **calorimeter** technologies?
- Can we improve **reconstruction** algorithms' efficiency?

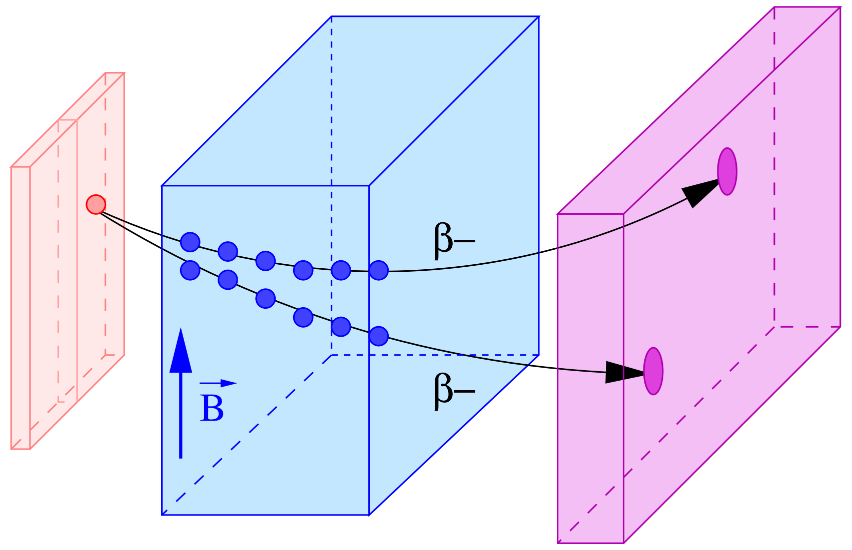
Background suppression

- **Demonstrator** will tell us how well we are suppressing backgrounds
- Irreducible **$2\nu\beta\beta$ background** depends on isotope

Construction

- Apply what we learned from Demonstrator to make further modules more quickly / cheaply
- Are there **cheaper components / designs**?
- Can we **contract out** the construction?

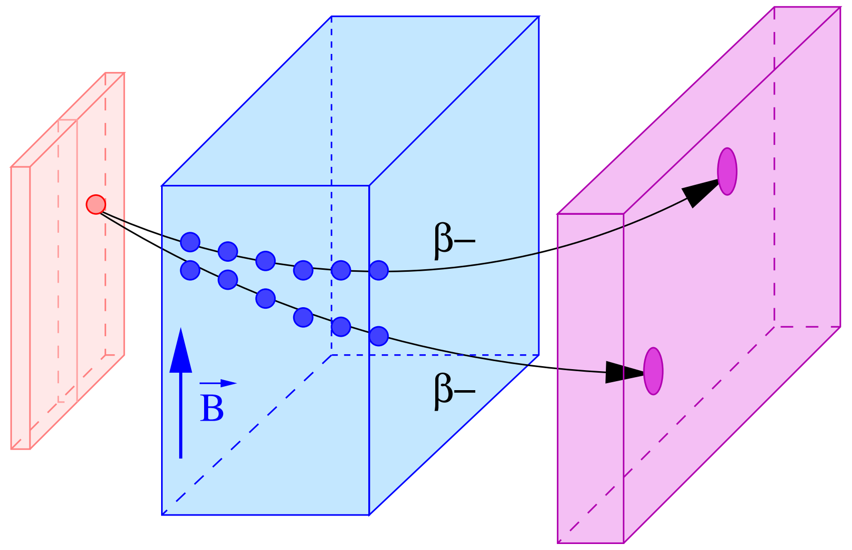
To summarise…



The NEMO tracker-calorimeter architecture

- **Topological information** lets us probe the **underlying physics** of double-beta decay
- **Particle ID** to reject backgrounds
- Can use any solid ββ isotope

To summarise…

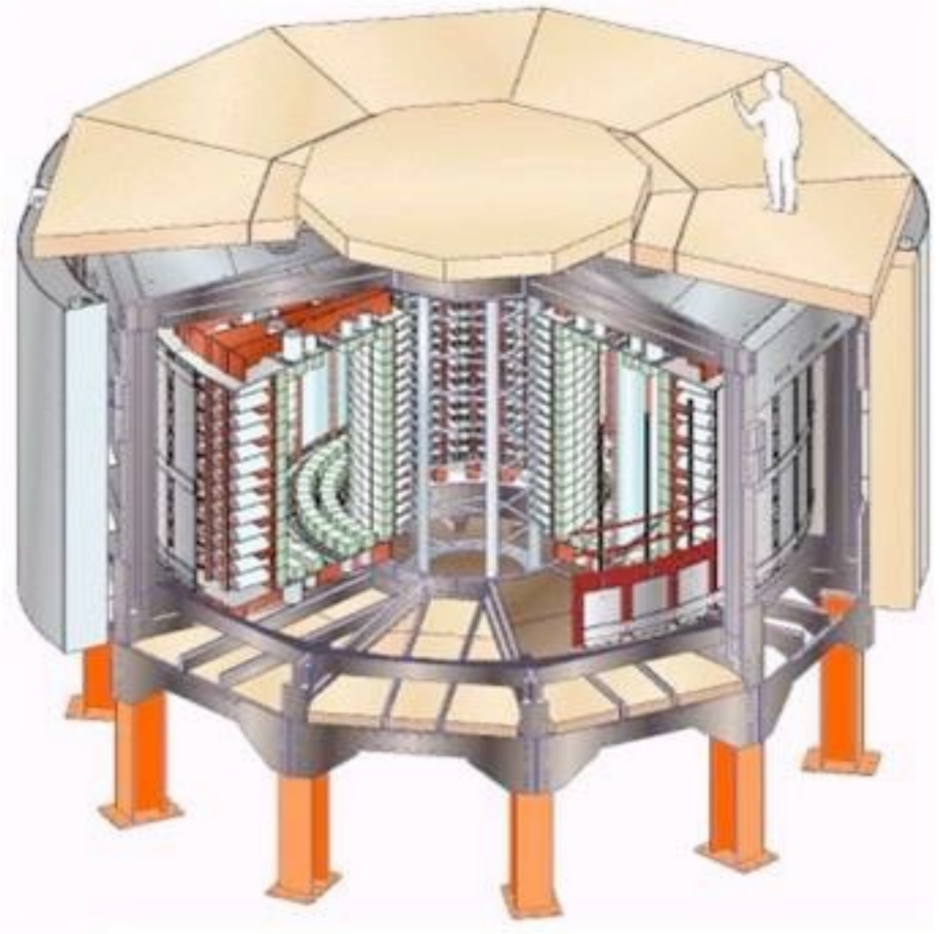


The NEMO tracker-calorimeter architecture

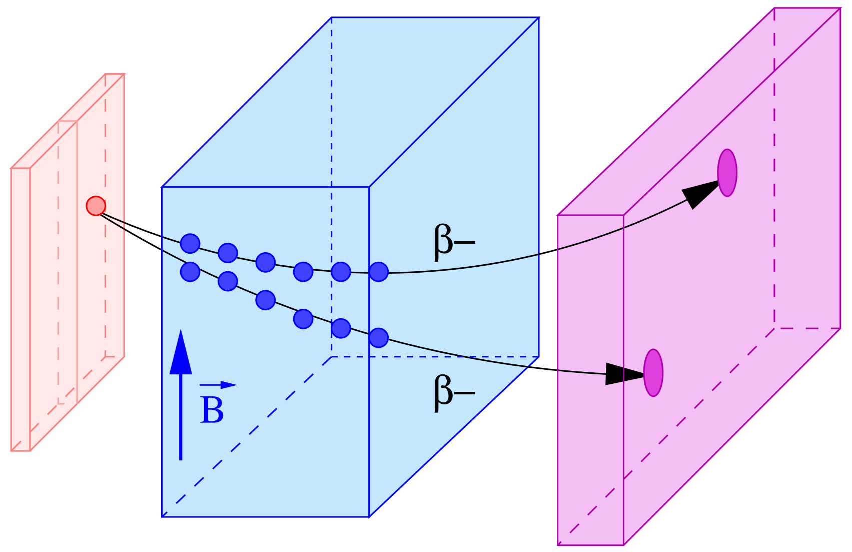
- **Topological information** lets us probe the **underlying physics** of double-beta decay
- **Particle ID** to reject backgrounds
- Can use any solid ββ isotope

NEMO-3

- Set limits on 0νββ and measured 2νββ half-lives for **7 isotopes**
- **World's best for 6** of these!
- ^{82}Se and ^{100}Mo favoured **SSD** decay mechanism

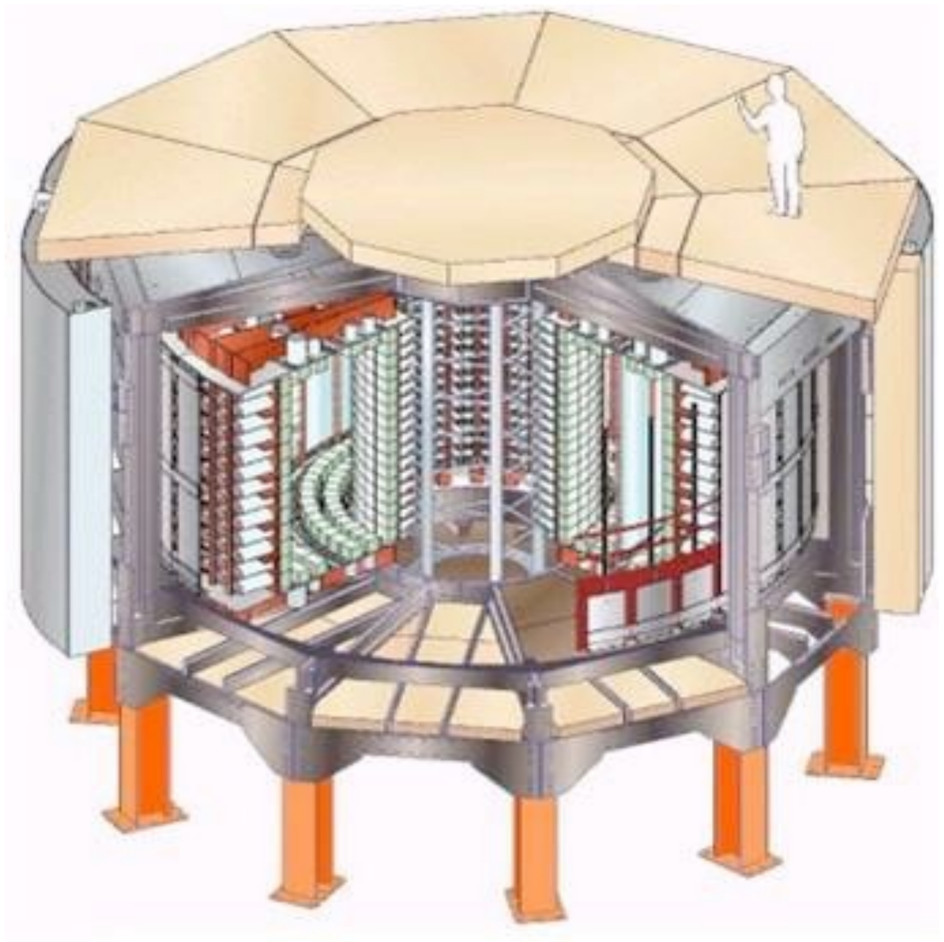


To summarise…



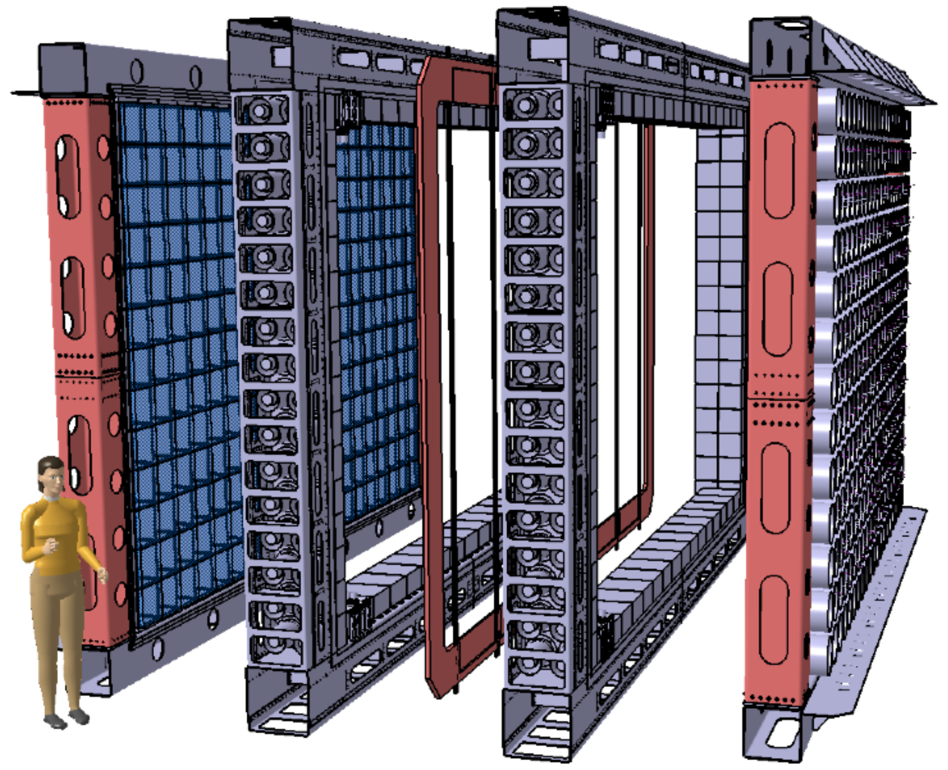
The NEMO tracker-calorimeter architecture

- **Topological information** lets us probe the **underlying physics** of double-beta decay
- **Particle ID** to reject backgrounds
- Can use any solid ββ isotope



NEMO-3

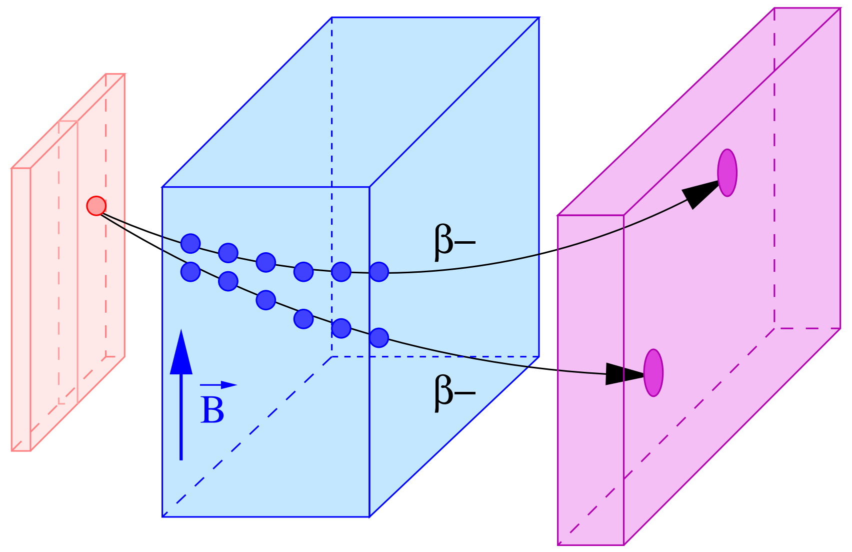
- Set limits on 0νββ and measured 2νββ half-lives for **7 isotopes**
- **World's best for 6** of these!
- ^{82}Se and ^{100}Mo favoured **SSD** decay mechanism



SuperNEMO Demonstrator

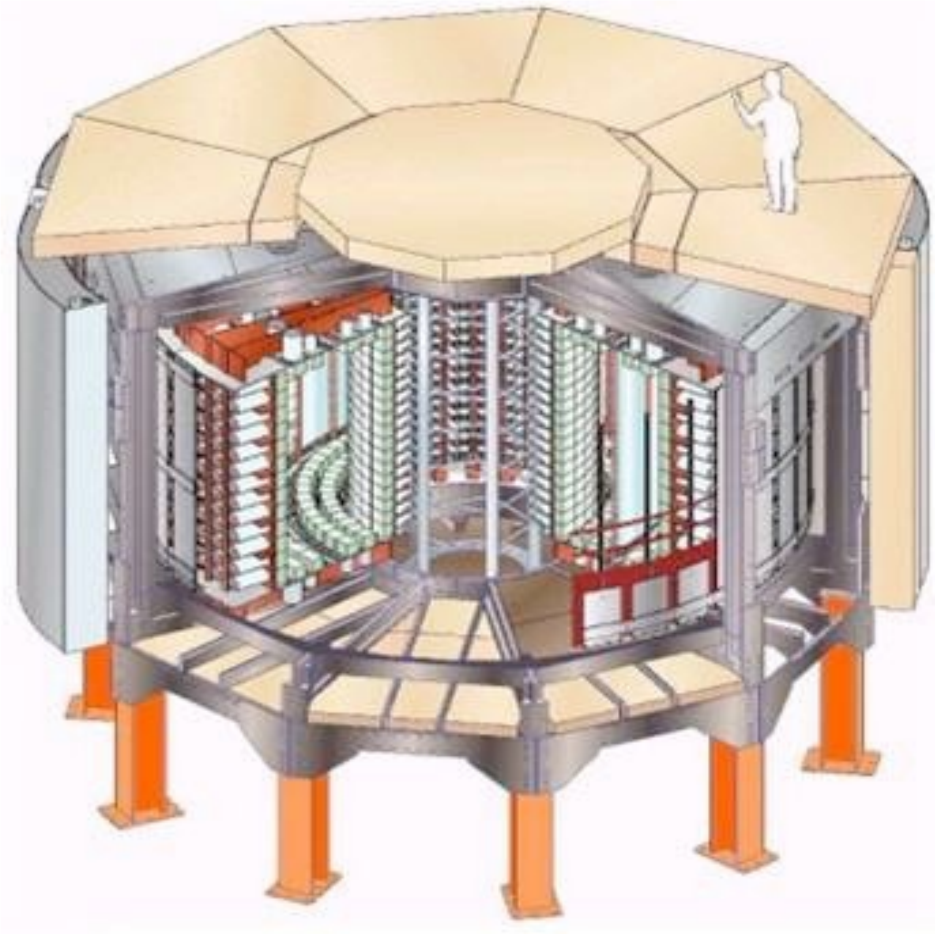
- Extensible, modular design starting with ~7kg of ^{82}Se
- **Improved** calorimeter resolution, radon removal, source radio-purity…
- NEMO-3 sensitivity in **4.5 months**
- **First data** coming soon

To summarise…



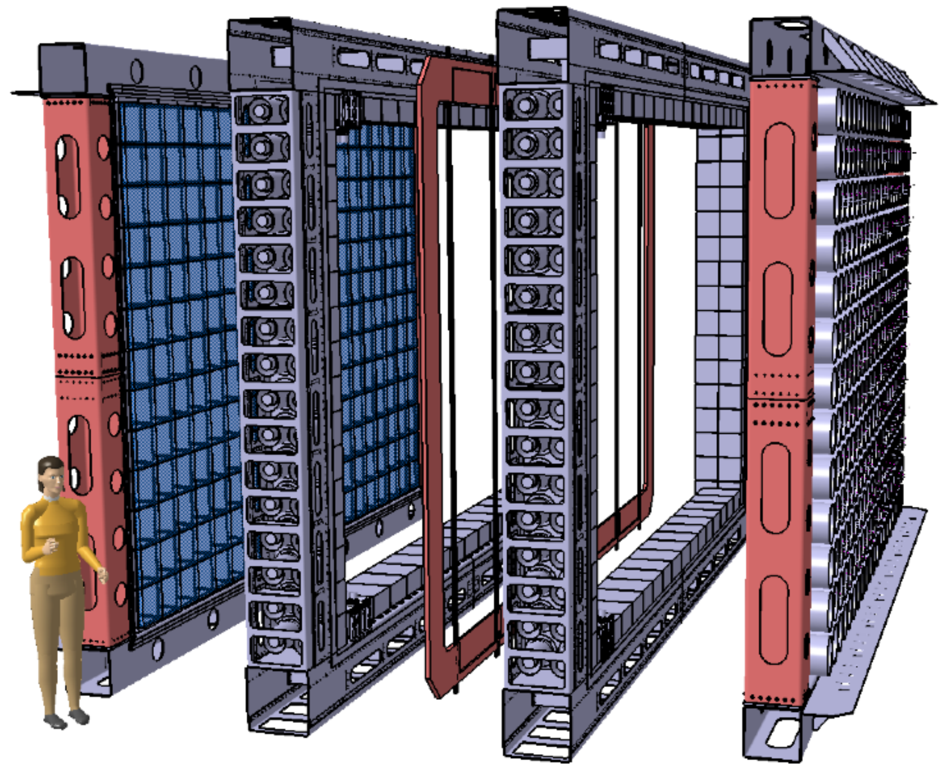
The NEMO tracker-calorimeter architecture

- **Topological information** lets us probe the **underlying physics** of double-beta decay
- **Particle ID** to reject backgrounds
- Can use any solid ββ isotope



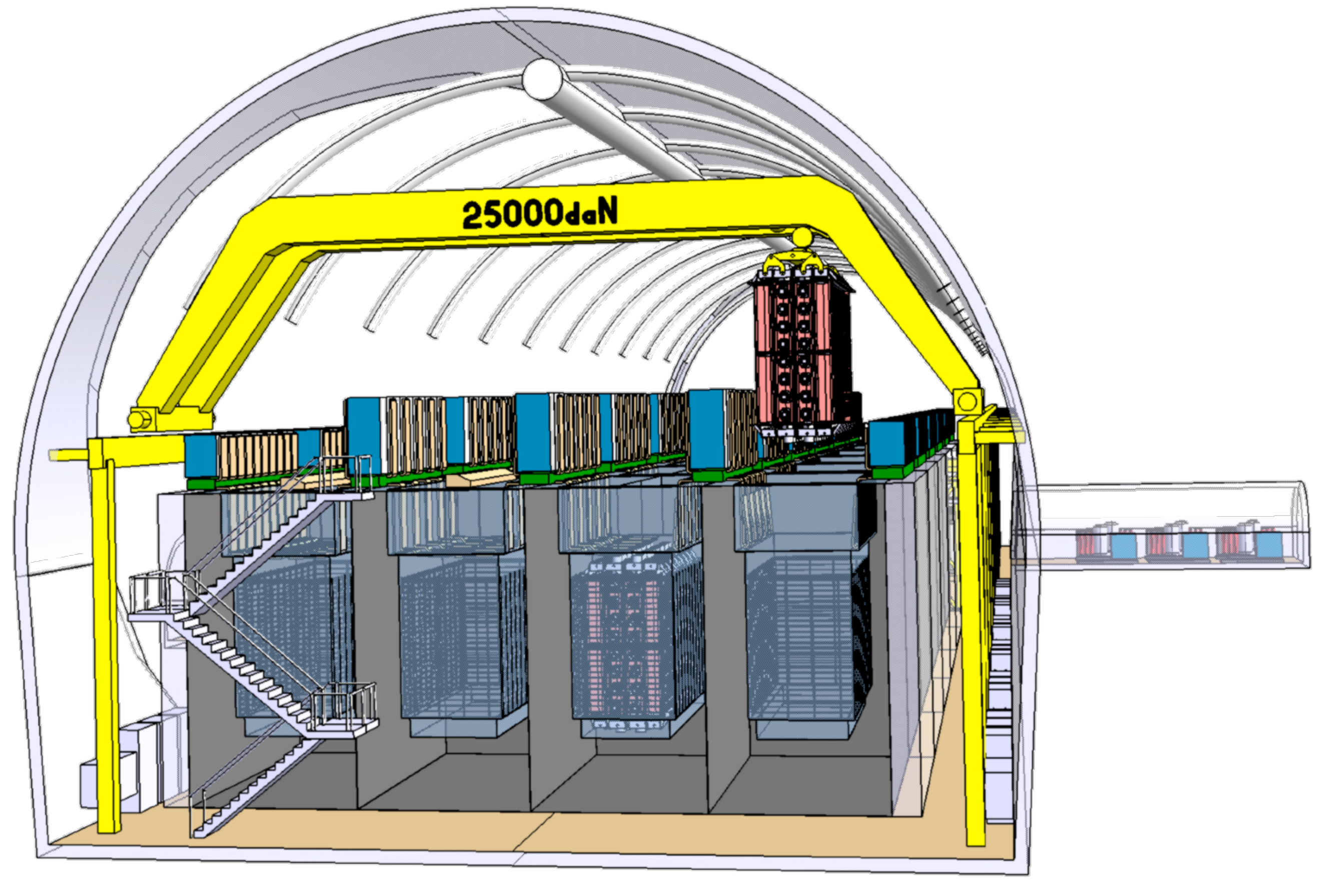
NEMO-3

- Set limits on 0νββ and measured 2νββ half-lives for **7 isotopes**
- **World's best for 6** of these!
- ^{82}Se and ^{100}Mo favoured **SSD** decay mechanism



SuperNEMO Demonstrator

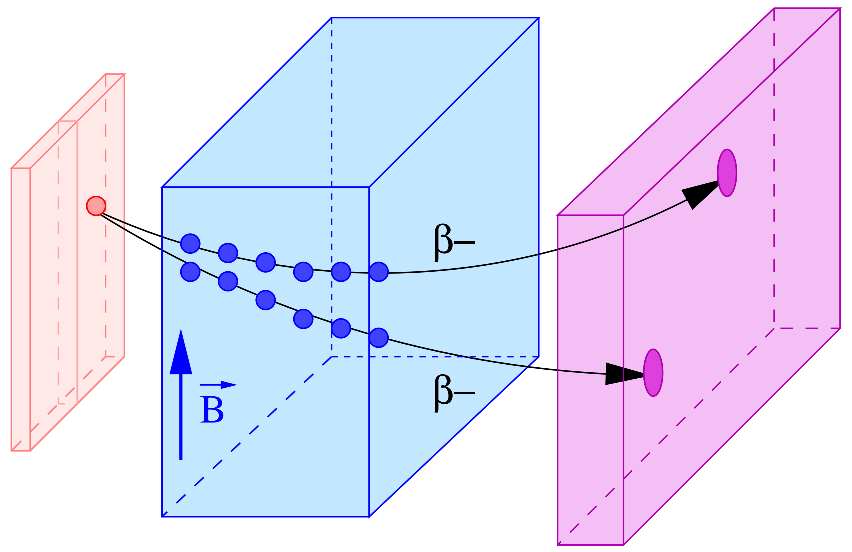
- Extensible, modular design starting with ~7kg of ^{82}Se
- **Improved** calorimeter resolution, radon removal, source radio-purity…
- NEMO-3 sensitivity in **4.5 months**
- **First data** coming soon



The future

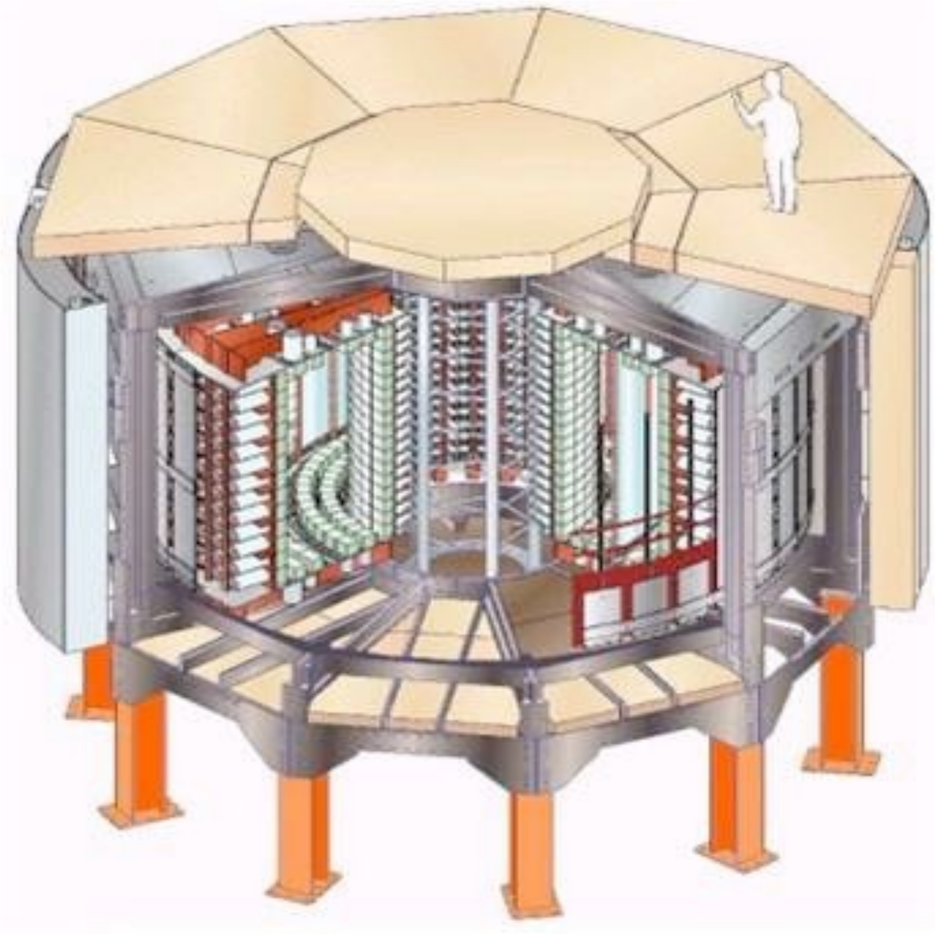
- R&D underway for next-generation tracker-calo experiments to cover full inverted hierarchy
- If there's a discovery - **best way to fully characterise 0νββ**

To summarise…



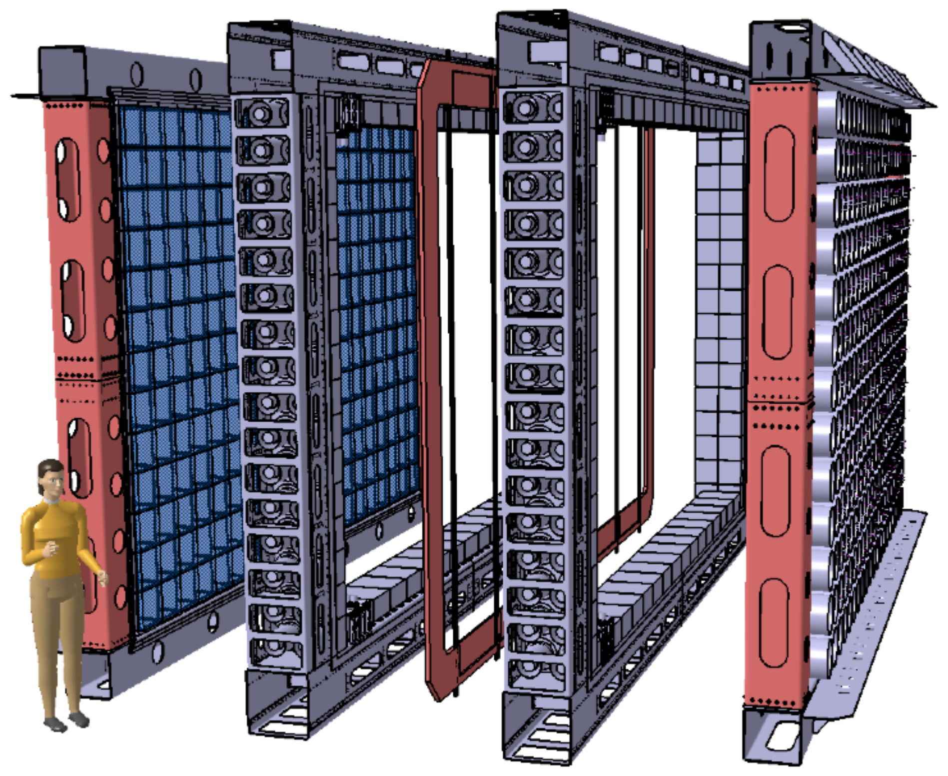
The NEMO tracker-calorimeter architecture

- **Topological information** lets us probe the **underlying physics** of double-beta decay
- **Particle ID** to reject backgrounds
- Can use any solid ββ isotope



NEMO-3

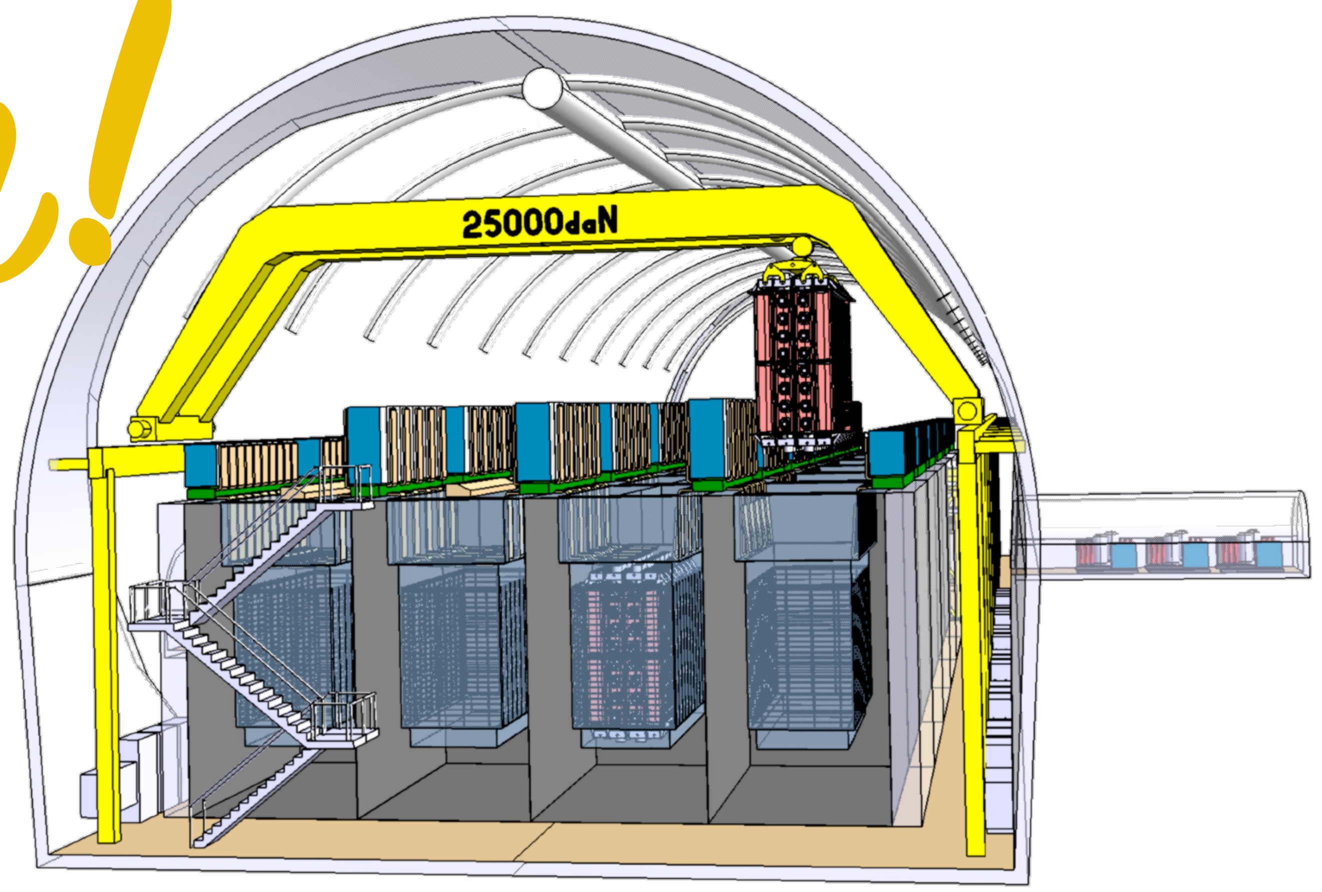
- Set limits on 0νββ and measured 2νββ half-lives for **7 isotopes**
- **World's best for 6** of these!
- ^{82}Se and ^{100}Mo favoured **SSD** decay mechanism



SuperNEMO Demonstrator

- Extensible, modular design starting with ~7kg of ^{82}Se
- **Improved** calorimeter resolution, radon removal, source radio-purity…
- NEMO-3 sensitivity in **4.5 months**
- **First data** coming soon

Thank you!

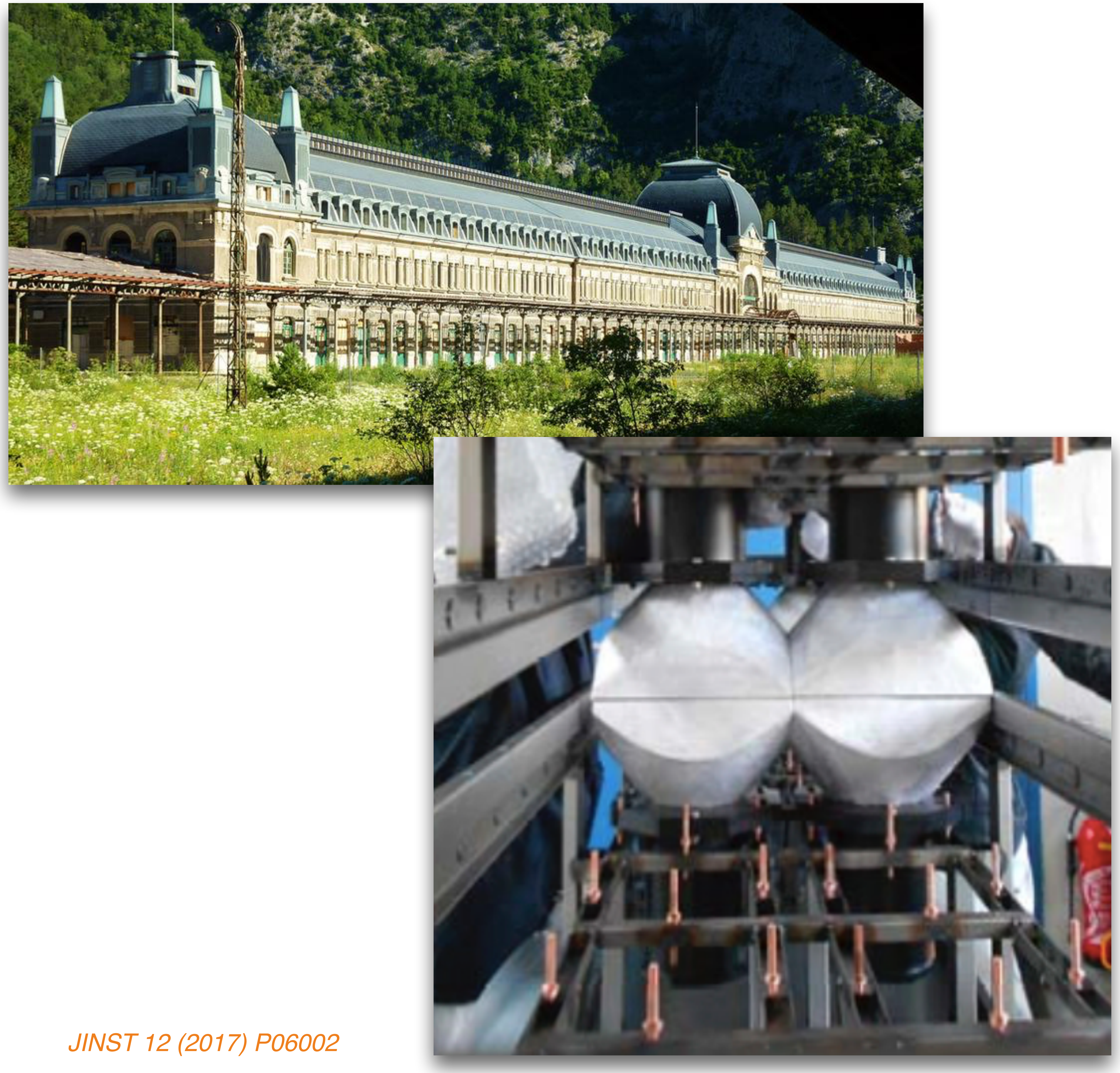


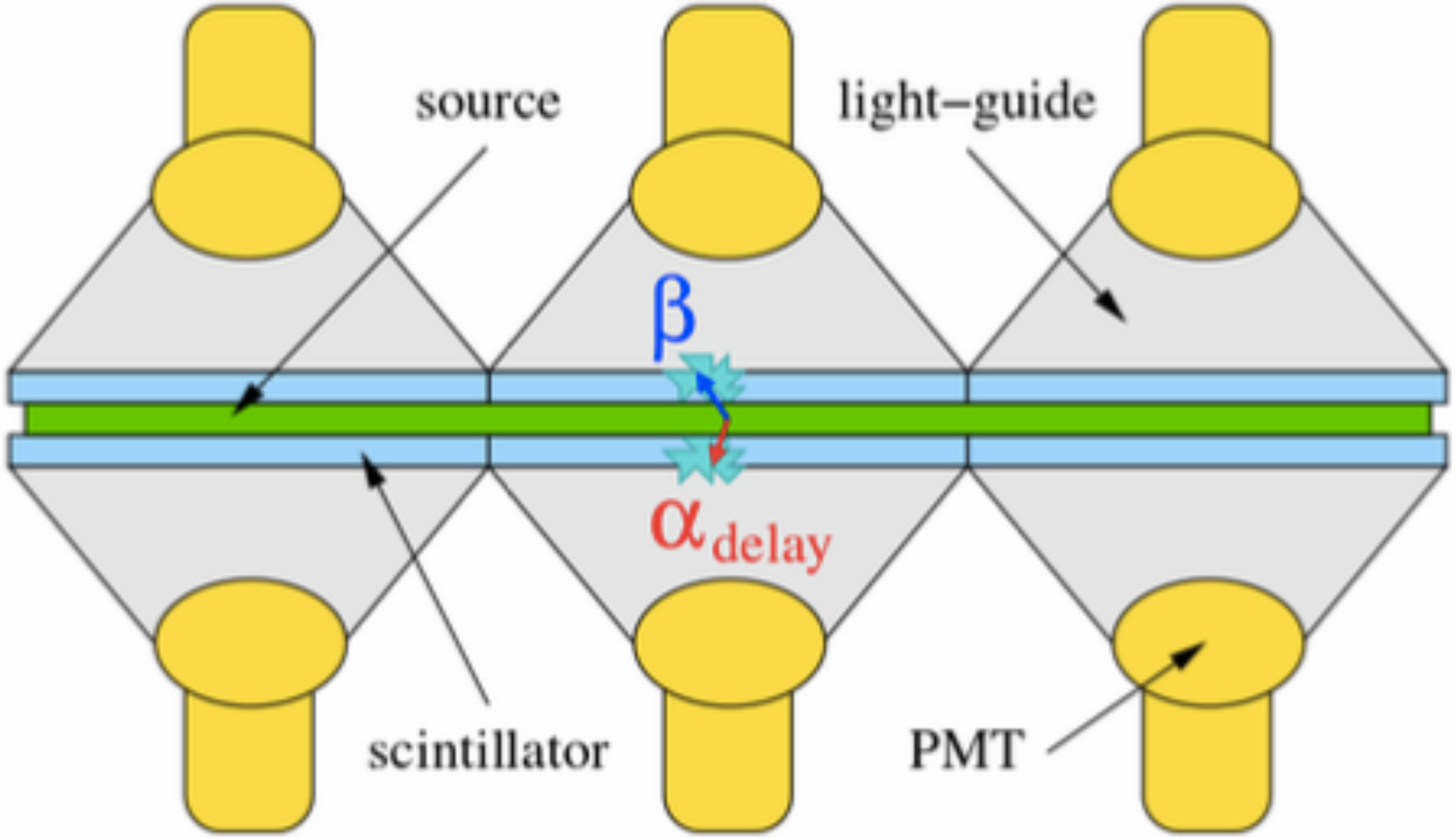
The future

- R&D underway for next-generation tracker-calo experiments to cover full inverted hierarchy
- If there's a discovery - **best way to fully characterise 0νββ**

Backup Slides

Source foil contamination measured at the BiPo-3 detector





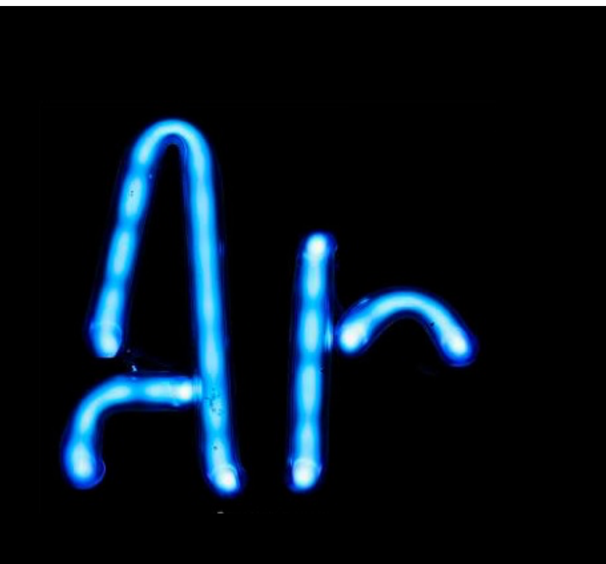
- Dedicated detector at Canfranc, Spain
- Designed to measure very **low activities**
- Looks for characteristic signature of Bi β decay followed by α decay of Po daughter (U and Th decay chains)
- Targets **10μBq /kg (^{214}Bi), 2μBq/kg (^{208}Tl)**
- Not very sensitive to ^{214}Bi - final measurements will be taken *in situ*

JINST 12 (2017) P06002

Tracker gas system

95% Helium

Low atomic mass; prevents multiple scattering and energy loss

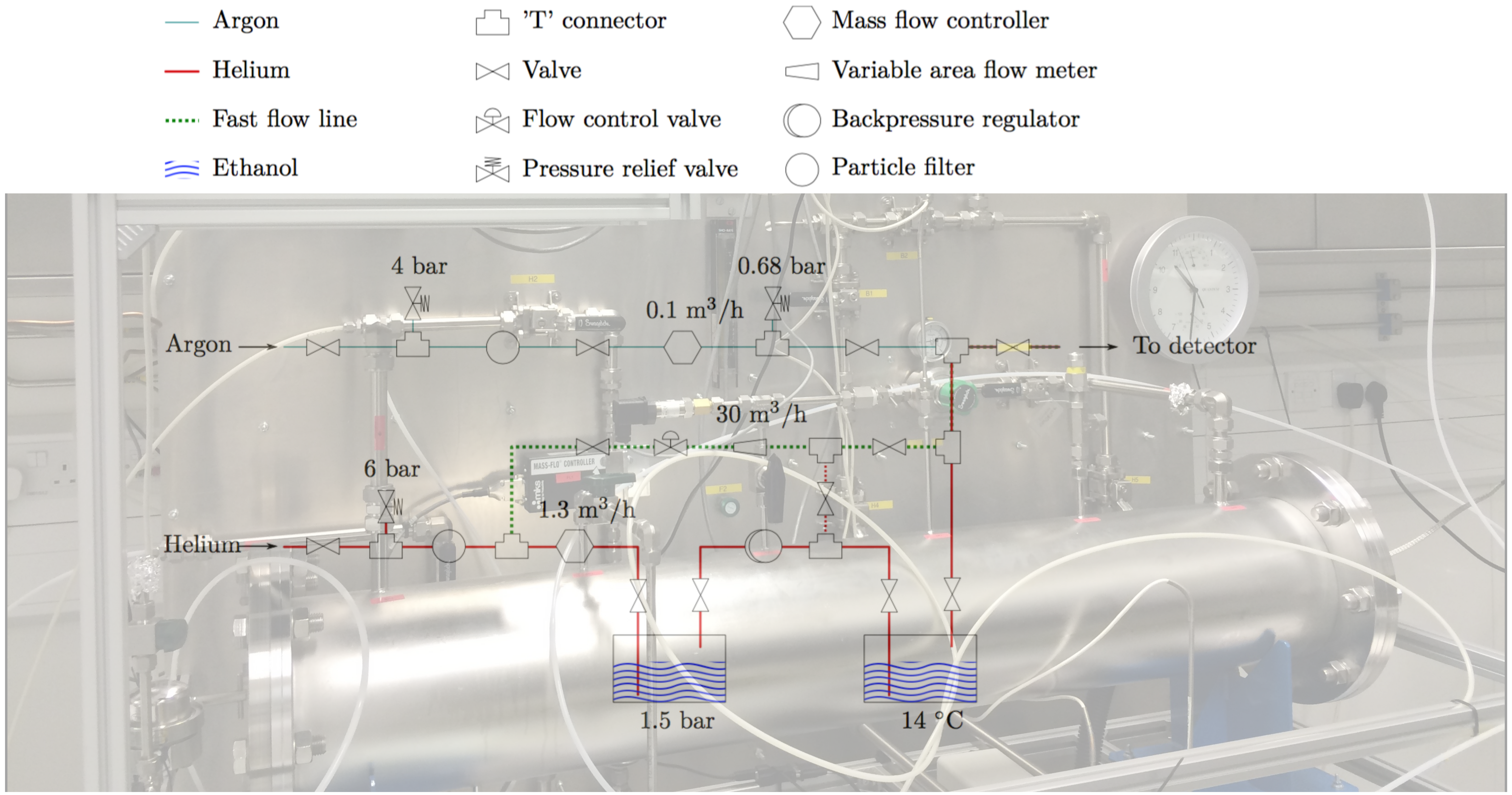


1% Argon

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

Radon in the tracker

Target activity: 0.15 mBq / m^3

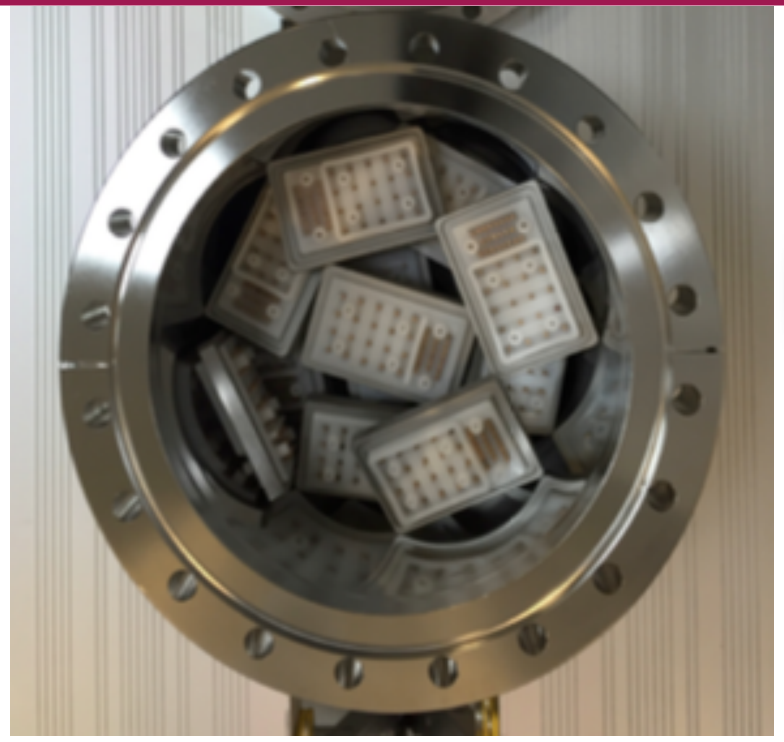
Two things to consider: tracker components and gas mixture

Radon in the tracker

Target activity: 0.15 mBq / m³

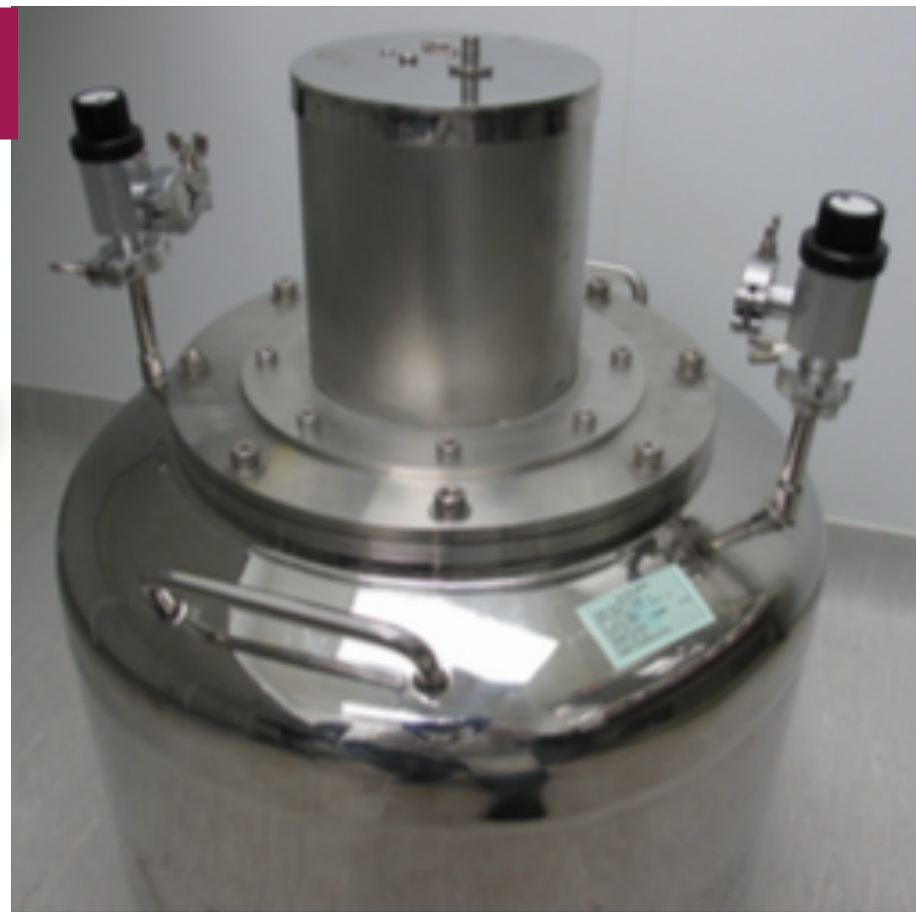
Two things to consider: tracker components and gas mixture

Tracker components



Potential component emanates radon in chamber (10 days+)

Flush with helium



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

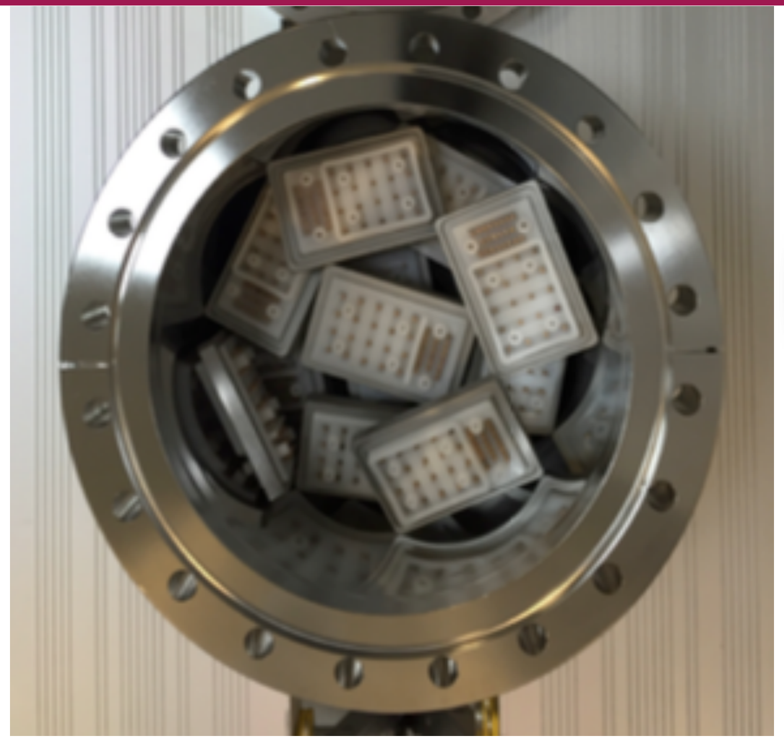
Radon in the tracker

Target activity: 0.15 mBq / m³
Two things to consider: tracker components and gas mixture

Tracker gas

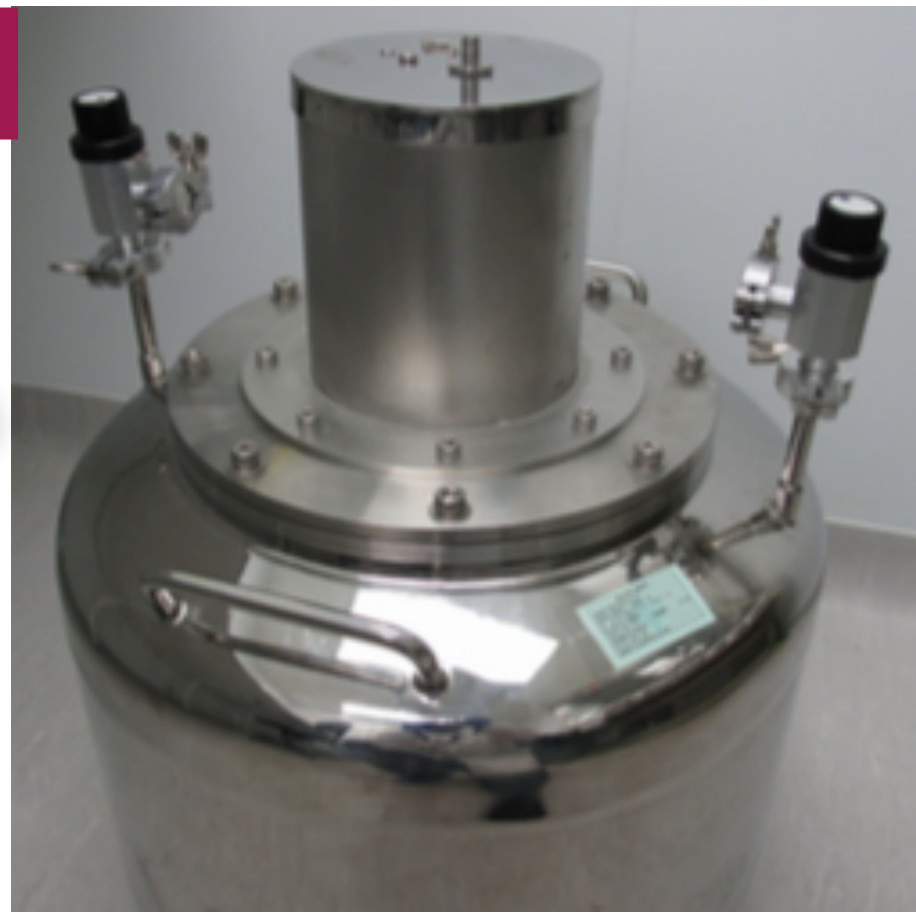
0.15 mBq / m^3 → **0.01 mBq in 70 litres**

Tracker components



Potential component emanates radon in chamber (10 days+)

Flush with helium



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

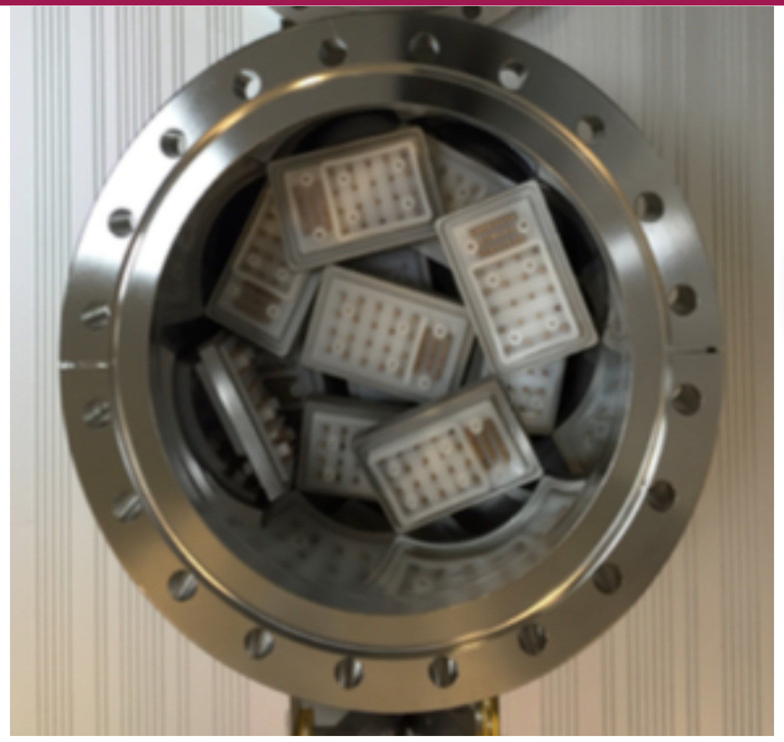
Radon in the tracker

Target activity: 0.15 mBq / m³
Two things to consider: tracker components and gas mixture

Tracker gas

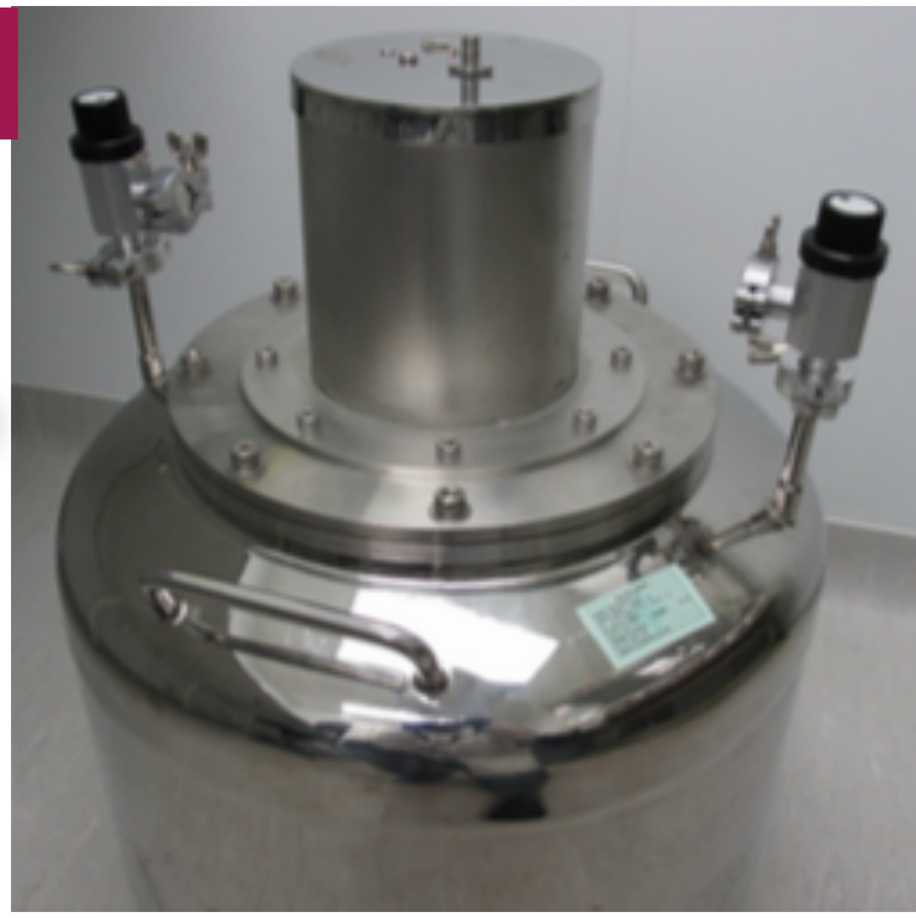
0.15 mBq / m³ → **0.01 mBq in 70 litres**

Tracker components



Potential component emanates radon in chamber (10 days+)

Flush with helium



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

Radon in the tracker

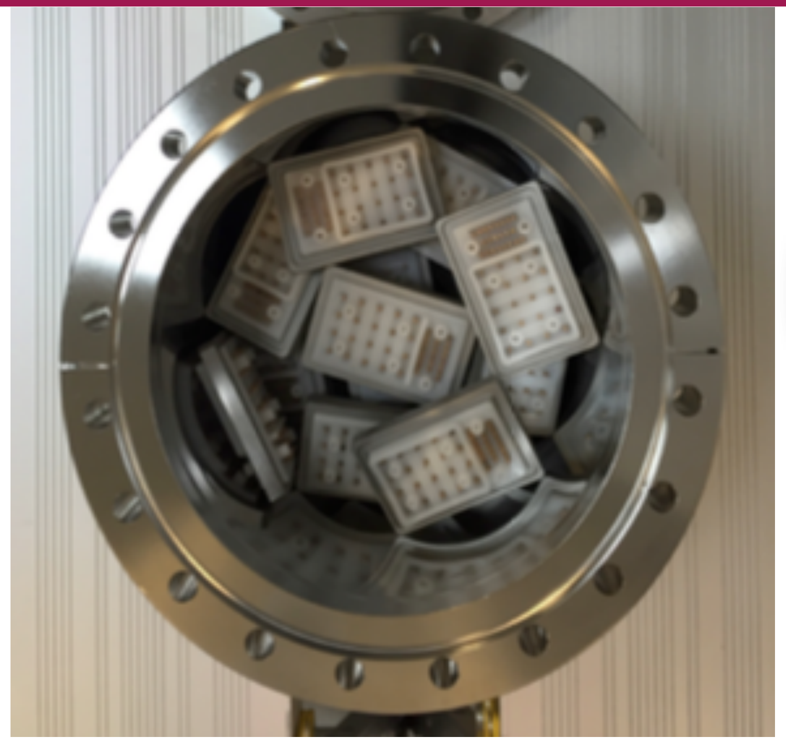
Target activity: 0.15 mBq / m³
Two things to consider: tracker components and gas mixture

Tracker gas

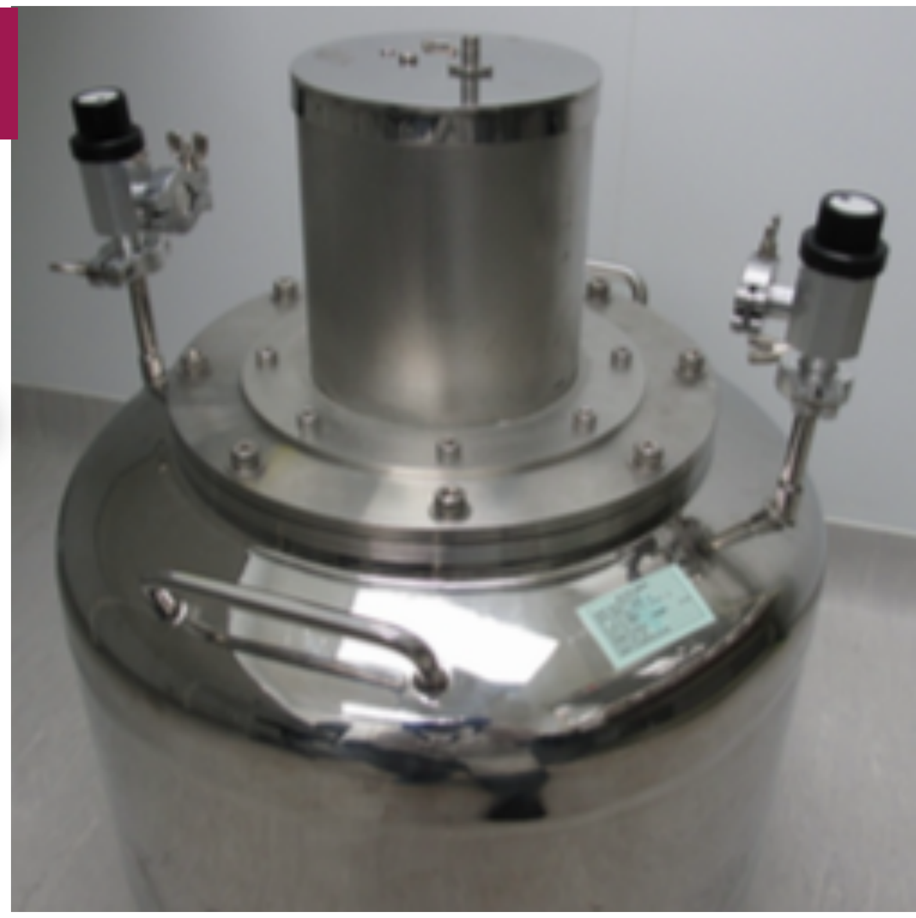
0.15 mBq / m³ → **0.01 mBq in 70 litres**

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

Tracker components



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

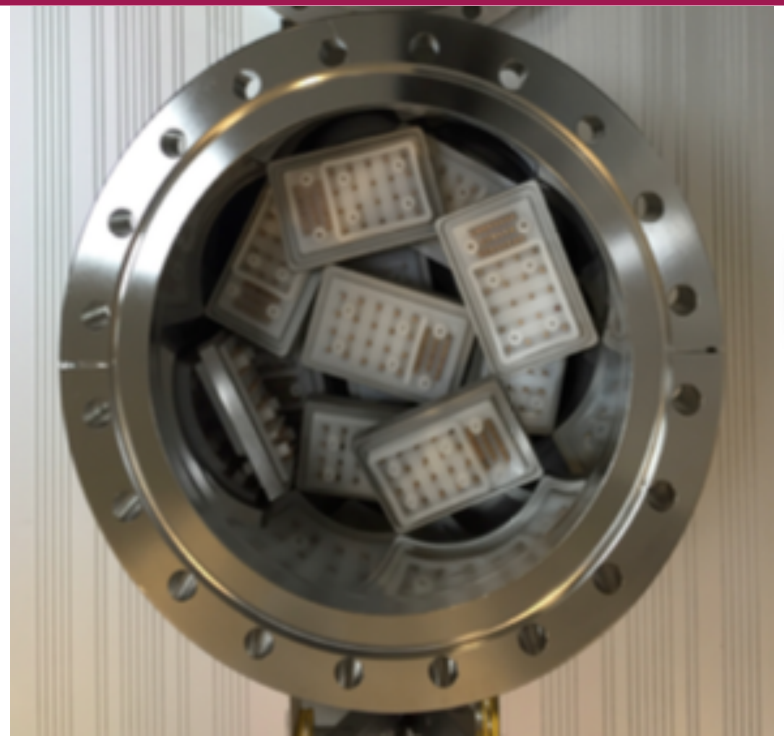
Target activity: 0.15 mBq / m³
Two things to consider: tracker components and gas mixture

Tracker gas

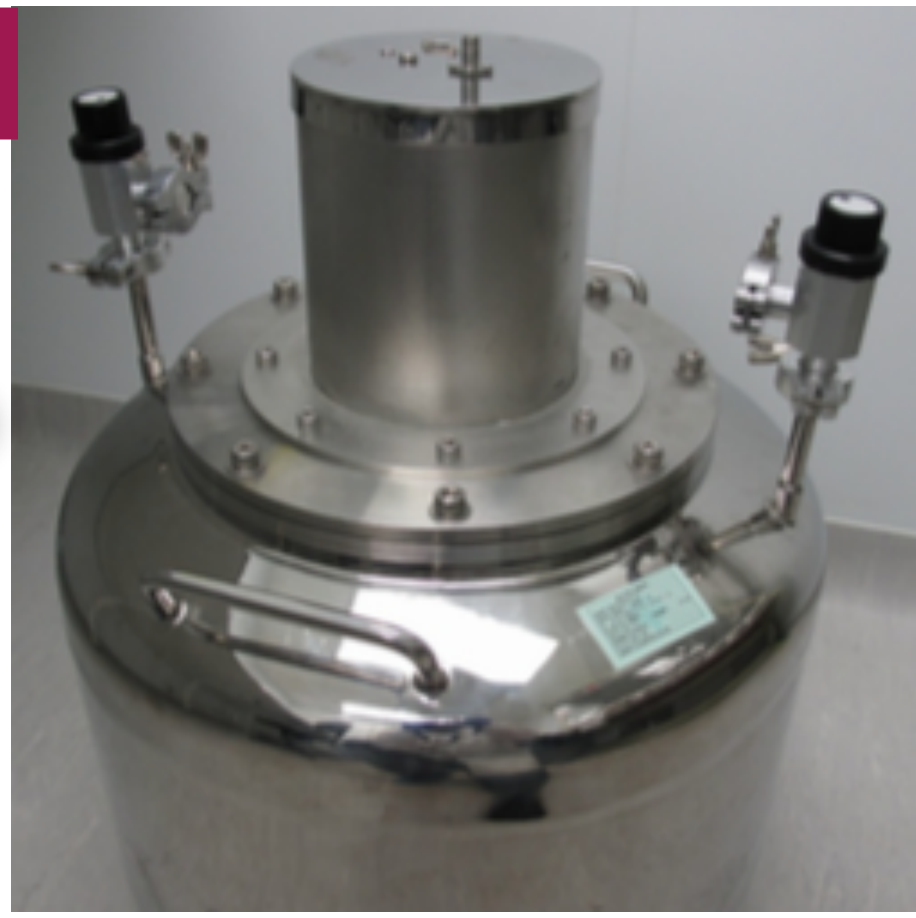
0.15 mBq / m³ → **0.01 mBq in 70 litres**

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

Tracker components



Flush with helium



Potential component emanates radon in chamber (10 days+)

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

Radon in the tracker

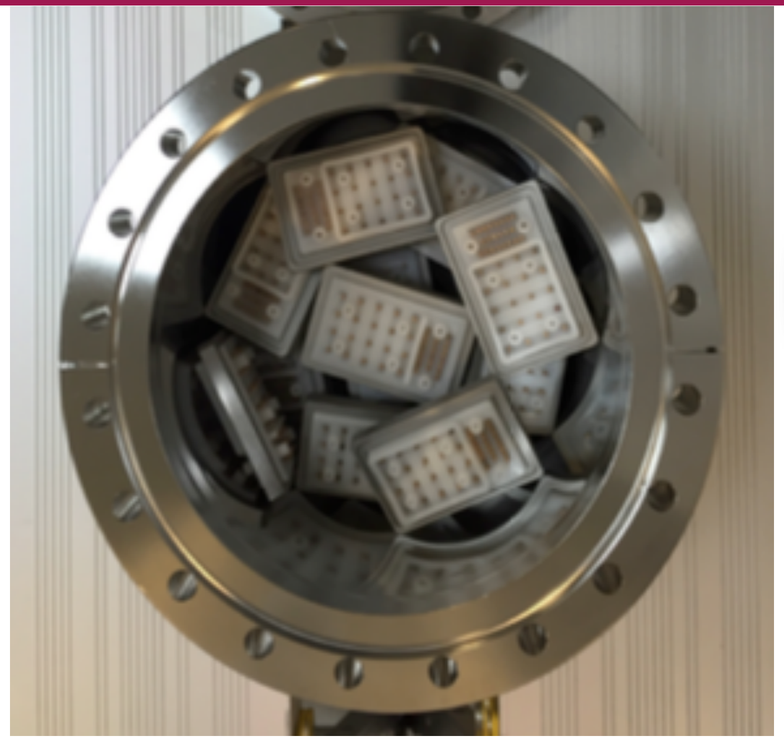
Target activity: 0.15 mBq / m³
Two things to consider: tracker components and gas mixture

Tracker gas

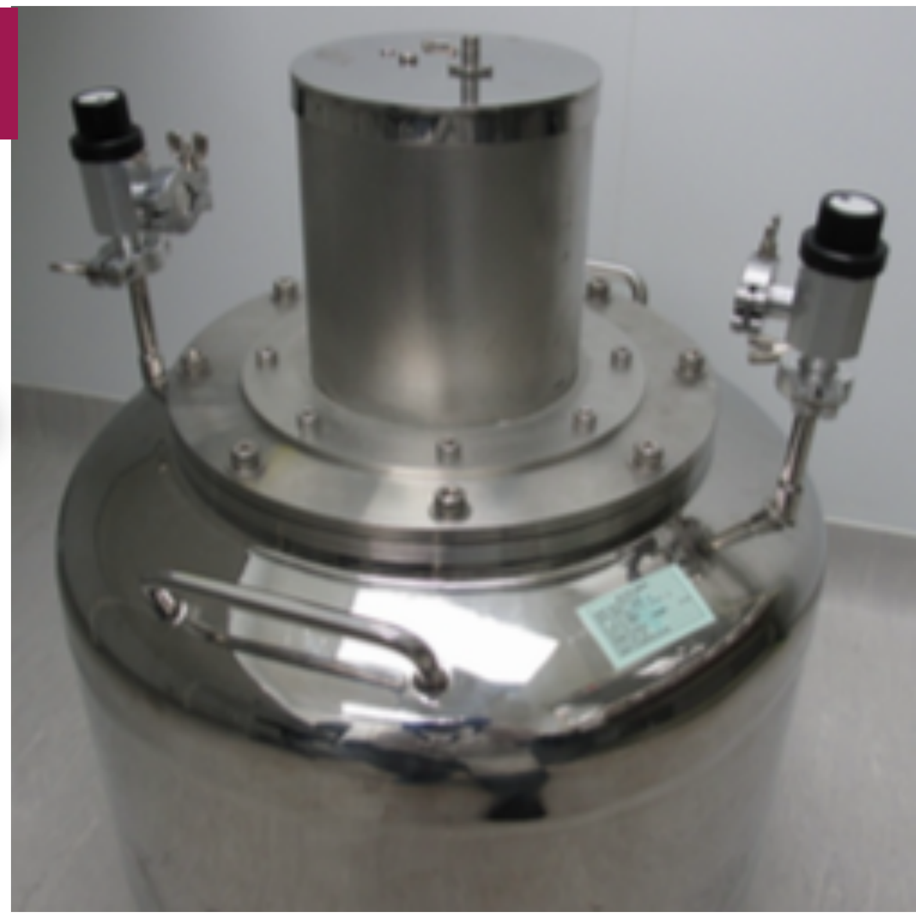
0.15 mBq / m³ → **0.01 mBq in 70 litres**

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

Tracker components



Flush with helium

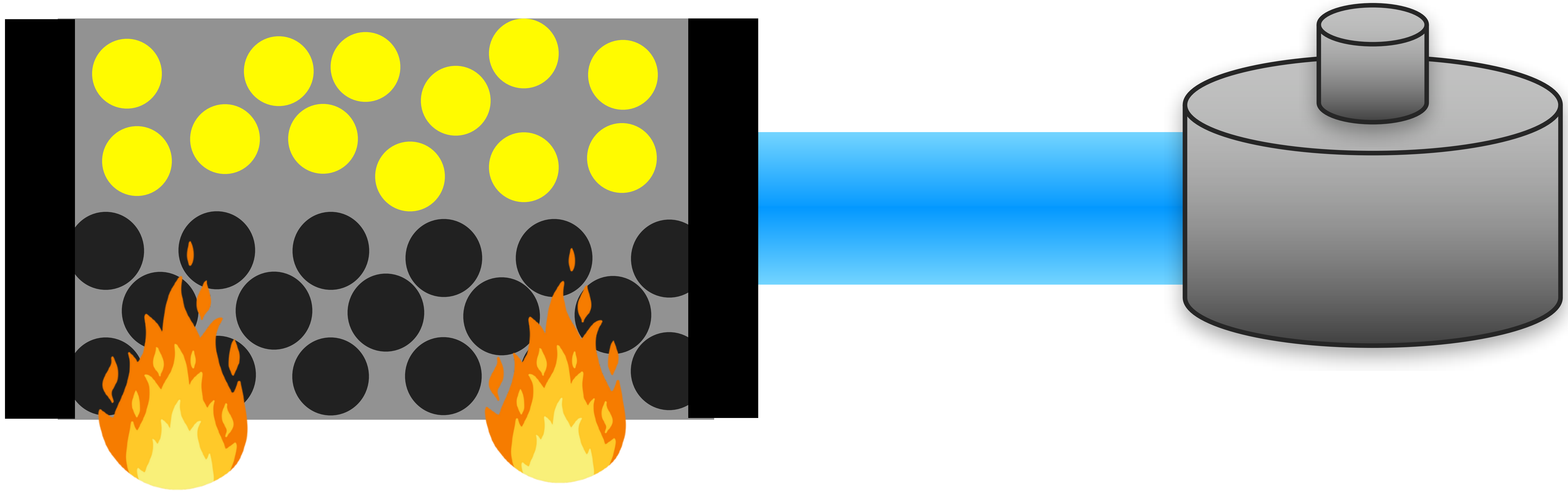


Potential component emanates radon in chamber (10 days+)

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

Release the radon

Seal and heat trap to release the trapped radon



Radon in the tracker

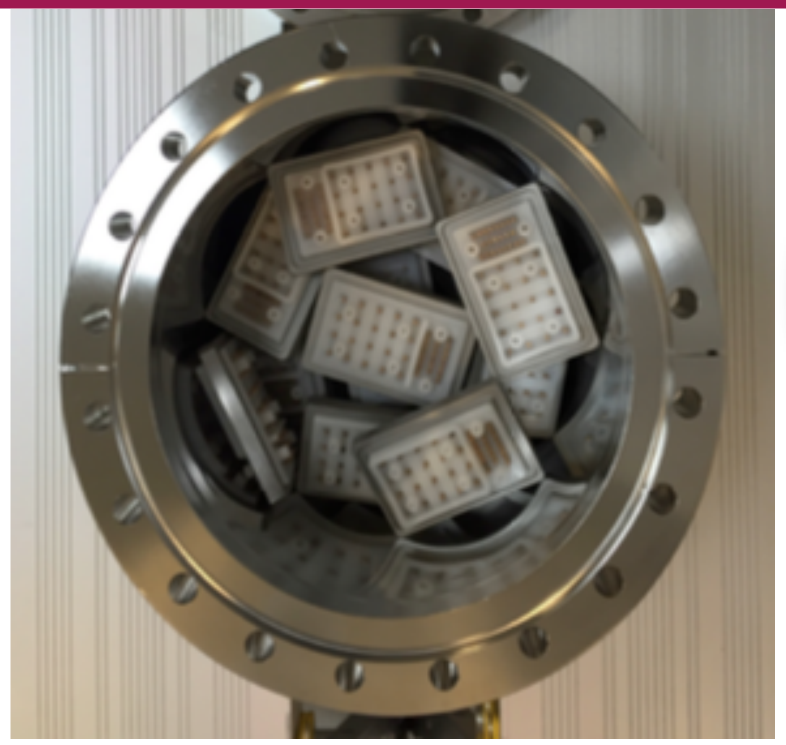
Target activity: 0.15 mBq / m^3
Two things to consider: tracker components and gas mixture

Tracker gas

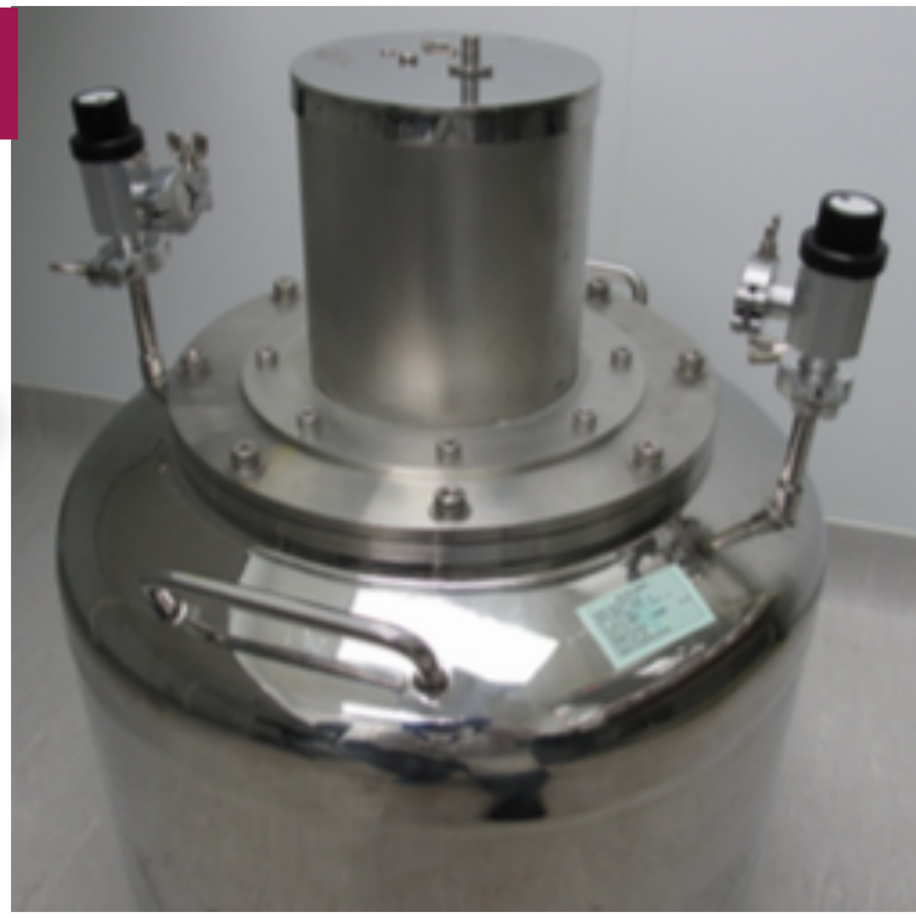
0.15 mBq / m^3 → **0.01 mBq in 70 litres**

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

Tracker components



Flush with helium



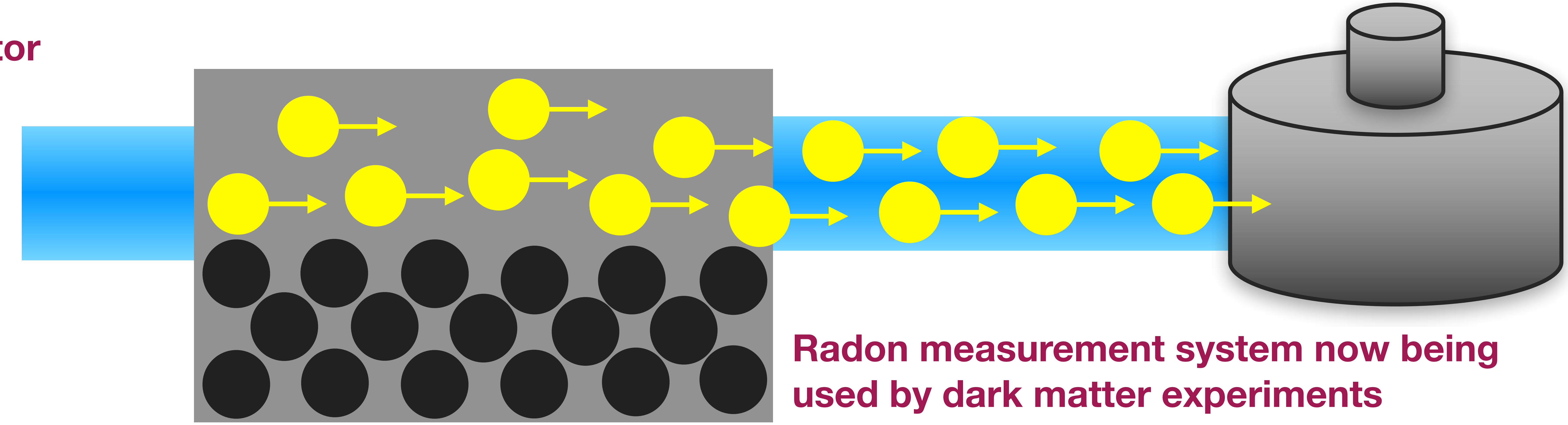
Potential component emanates radon in chamber (10 days+)

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.

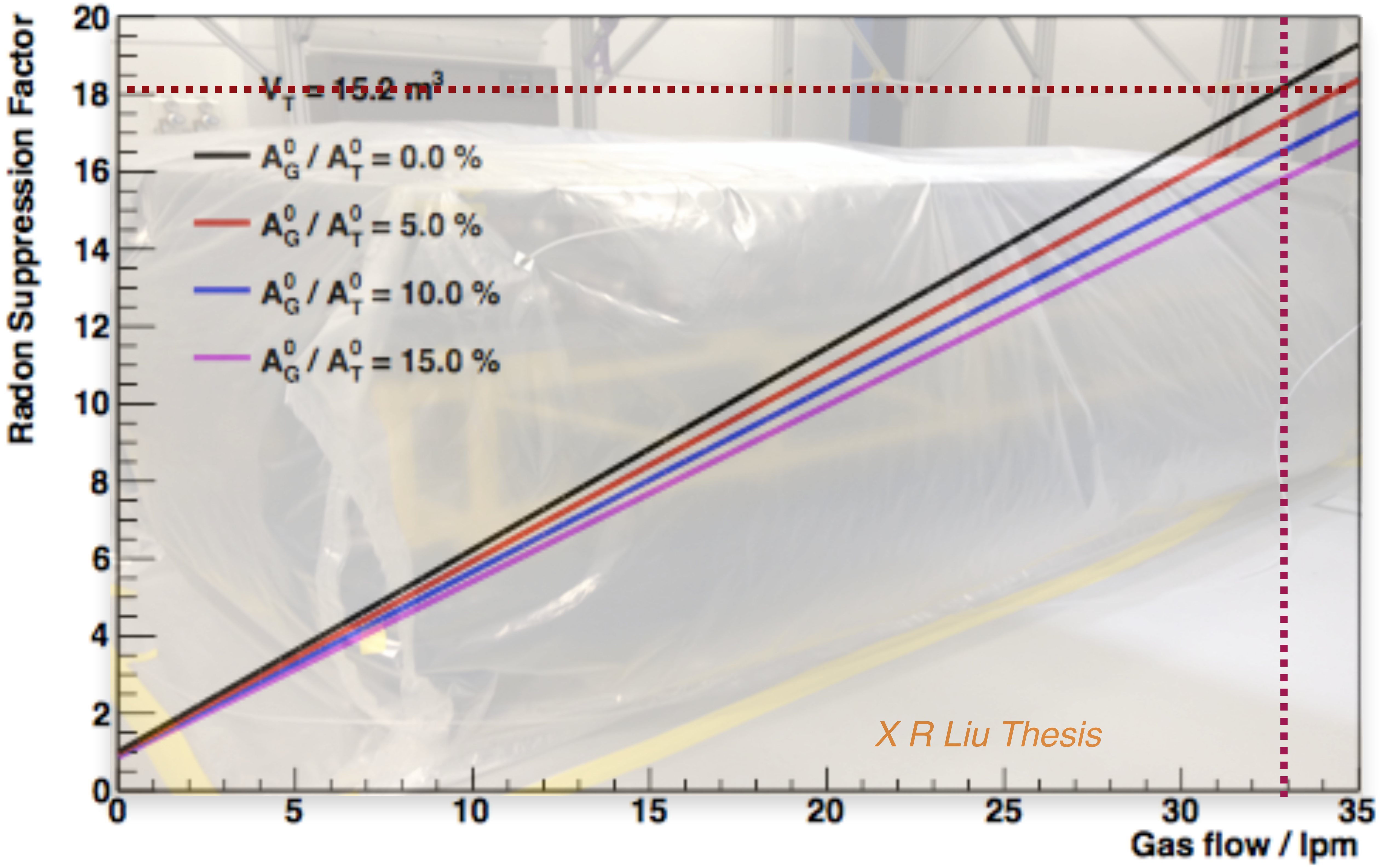
Use trapping and detection efficiencies to get from measured activity to original activity.



Radon measurement system now being used by dark matter experiments

Radon 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)



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

Gas and tracker activities
Radon half life
Flow rate
Tracker volume

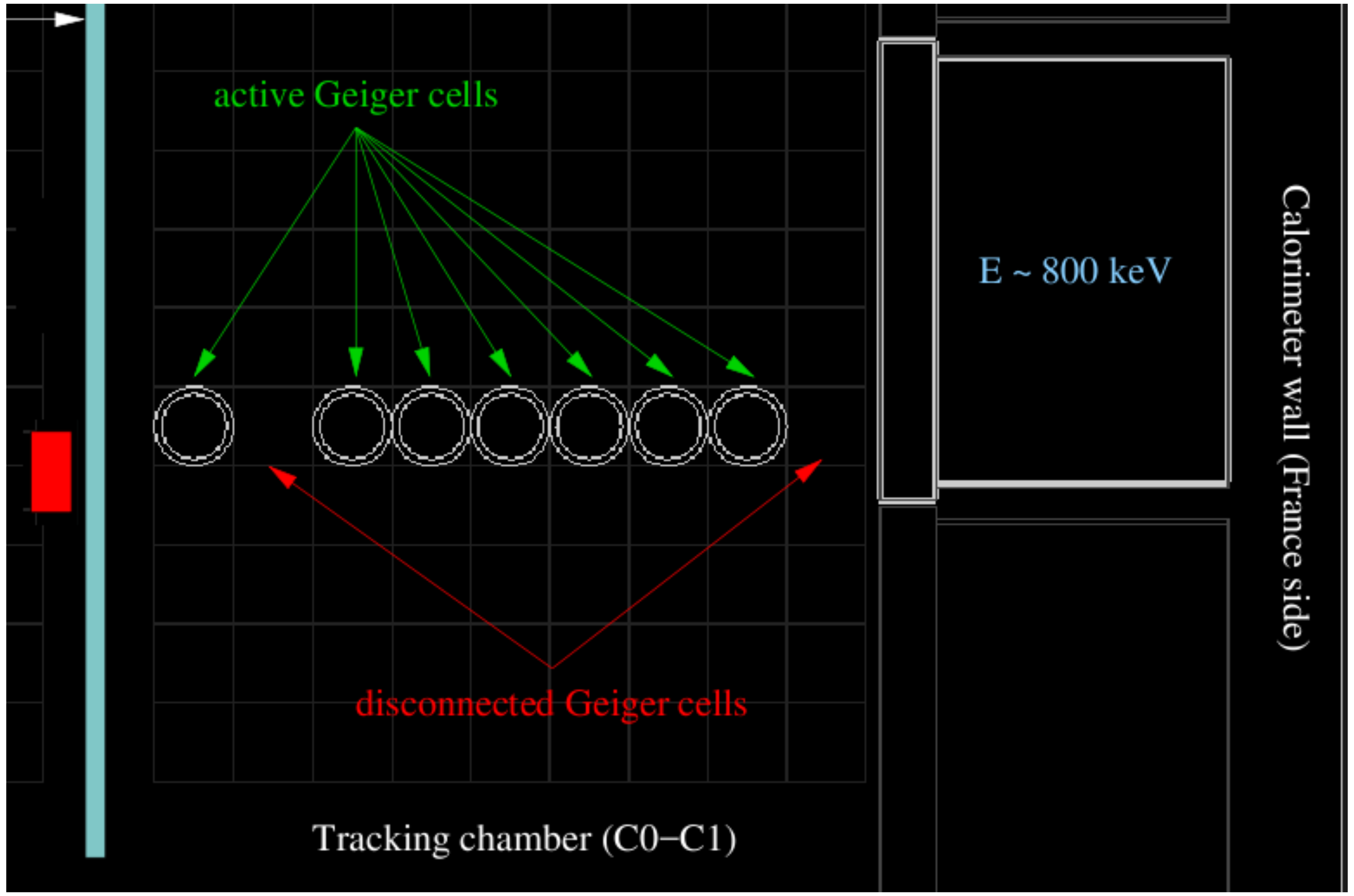
For full tracker (15.2 m³)
Required flow rate is **33 litres per minute** = **2 m³ / hour**

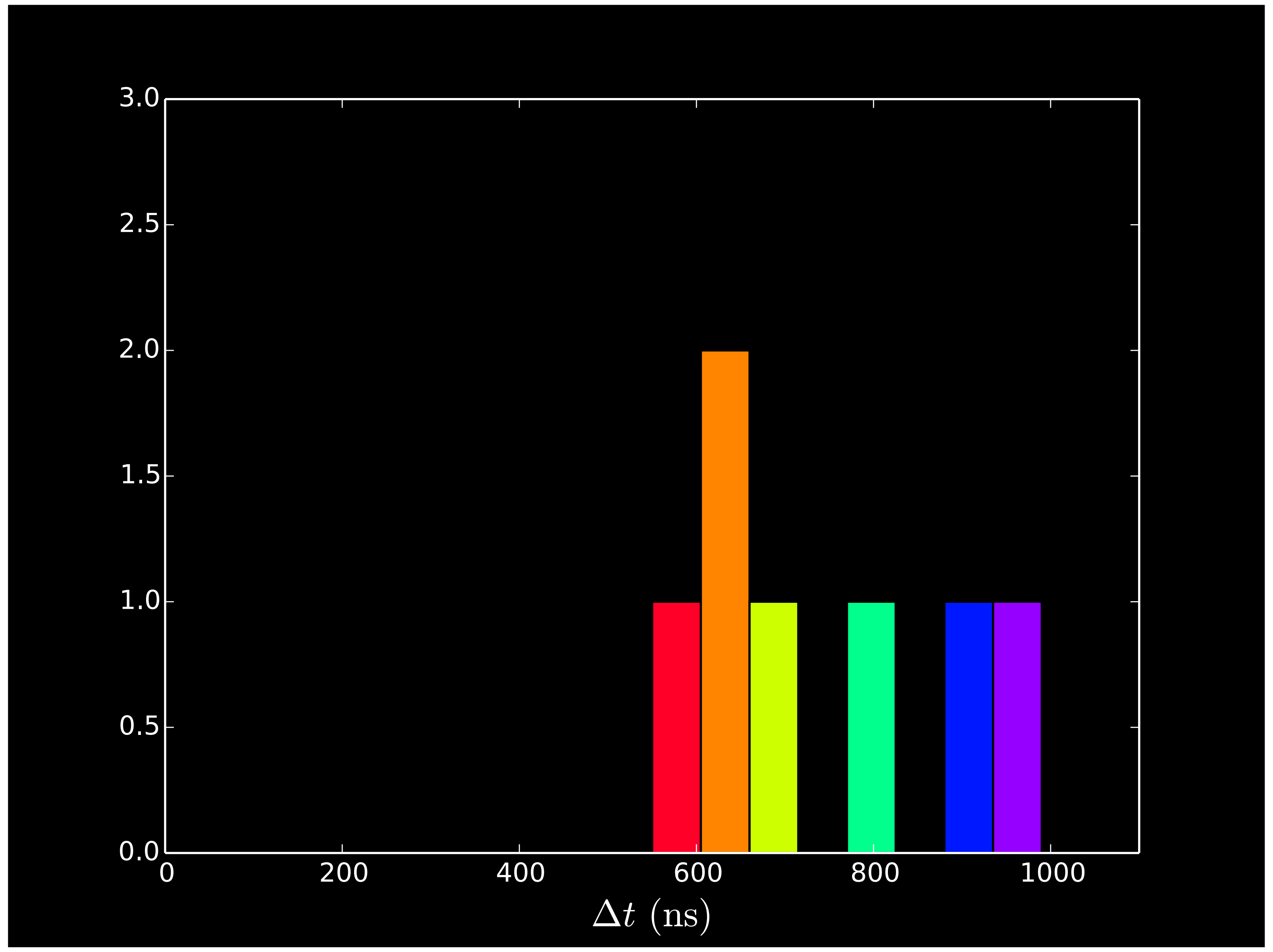
0.15 mBq / m³ achieved for fully-instrumented tracker!

At LSM now: half-detector commissioning

At LSM now: half-detector commissioning

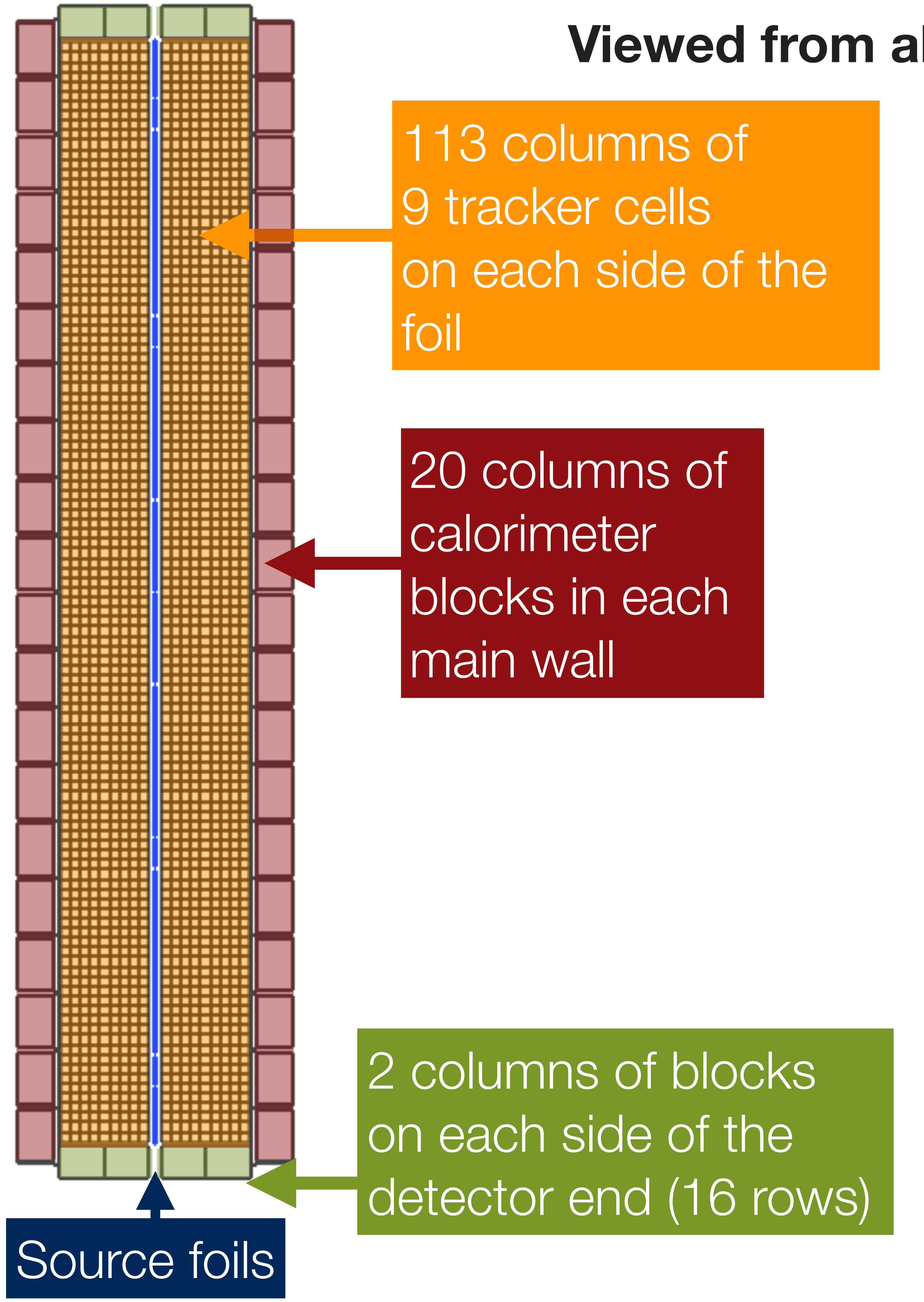
March 2017: **half-detector commissioning**



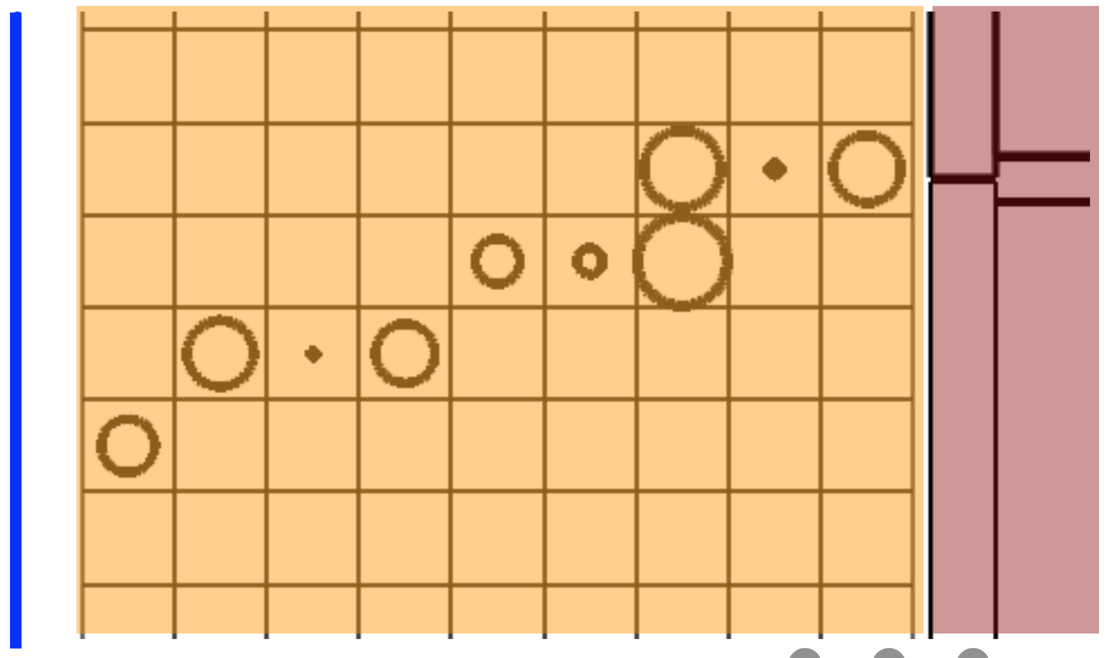


Geiger hits within 1μs of calorimeter hit

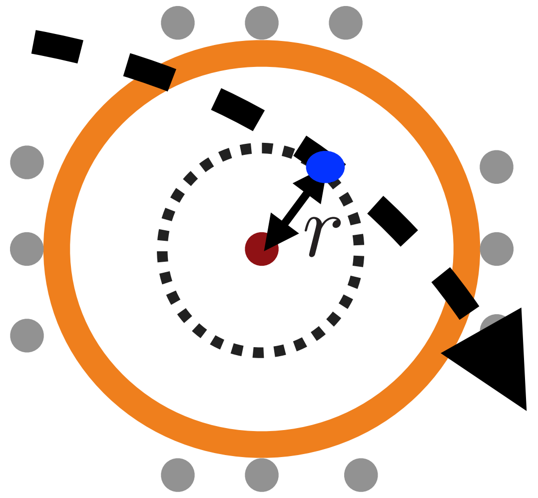
SuperNEMO event displays



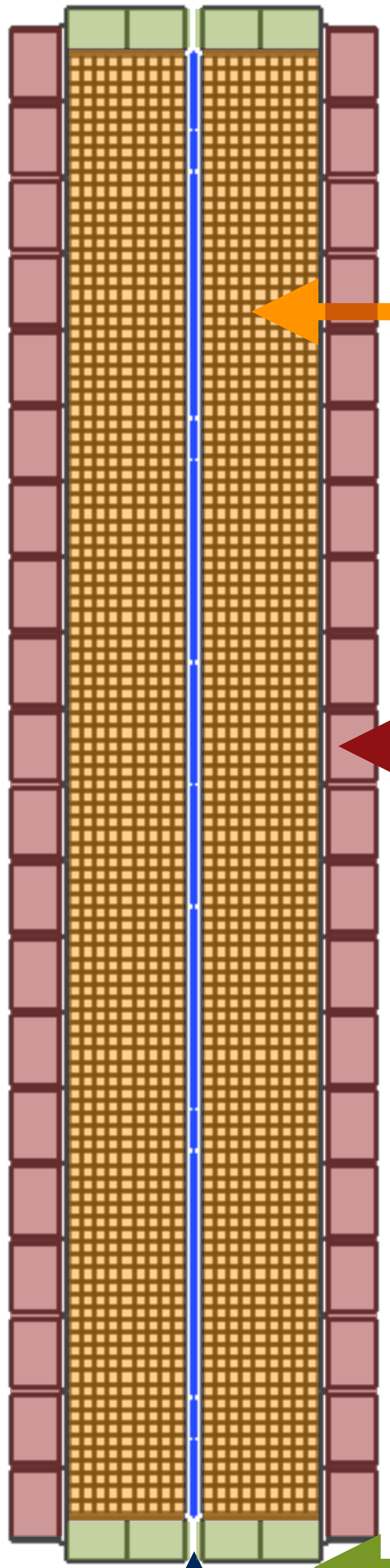
Viewed from above



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



SuperNEMO event displays



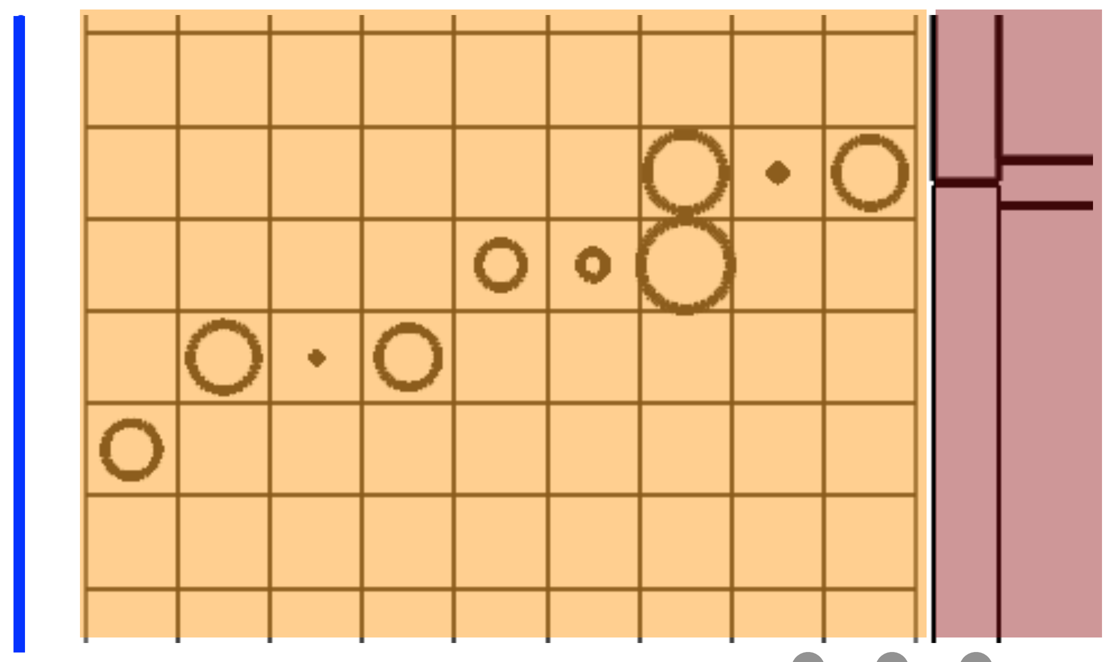
Viewed from above

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

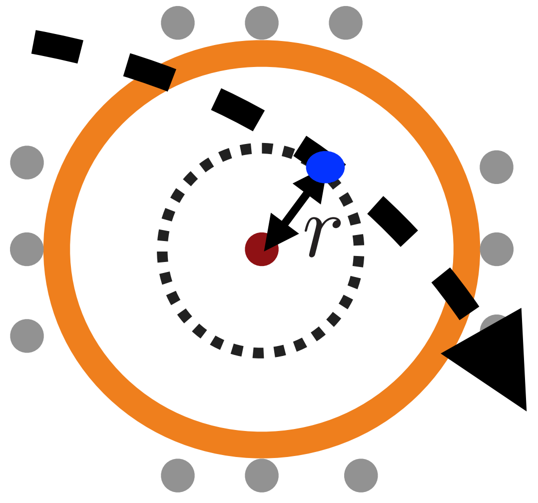
20 columns of calorimeter blocks in each main wall

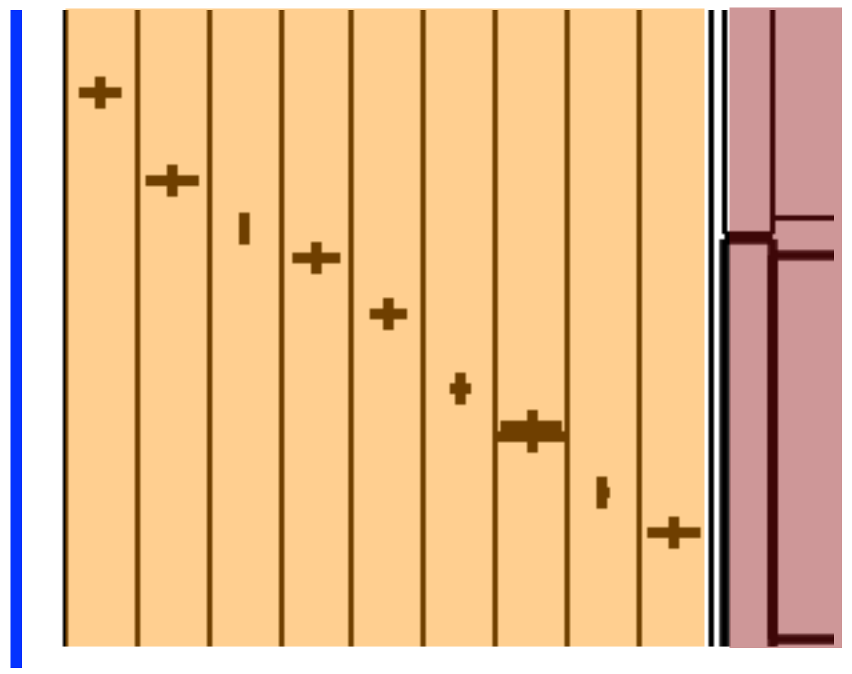
2 columns of blocks on each side of the detector end (16 rows)

Source foils



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

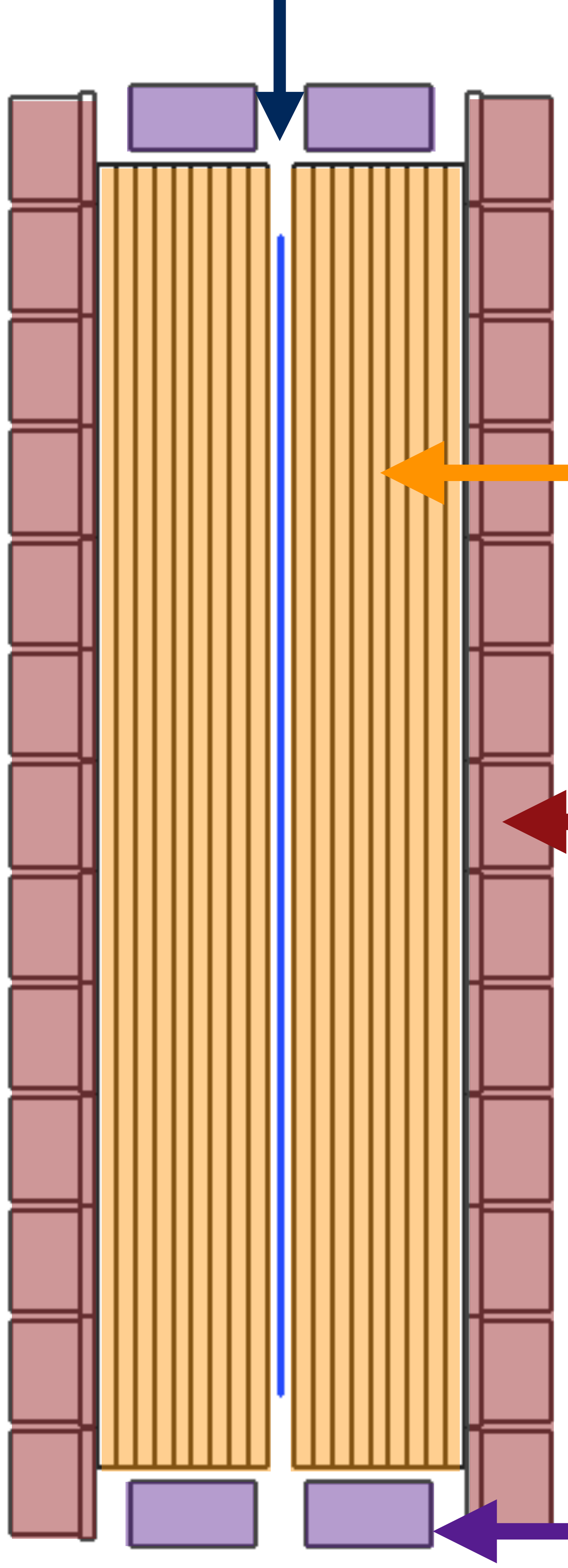




Position along the wire comes from plasma propagation times, and has a large uncertainty

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

Event count targets in SuperNEMO demonstrator

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	
Tl208 internal	2.7 ± 0.2	0.05	internal contamination reduction
2νββ	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 !**

NEMO-3 results summary

Isotope	Mass (g)	$Q_{\beta\beta}$(keV)	$T^{(2\nu)}$ ($\times 10^{19}$yrs)	S/B	Comment	Reference
Se82	932	2997.9	9.4 ± 0.6	4	World's best	**Eur. Phys. J. C (2018) 78: 821**
Cd116	405	2813.5	2.74 ± 0.18	10	World's best*	Phys. Rev. D 95 (**2017**) 012007
Nd150	37	3371.4	0.93 ± 0.06	2.7	World's best	Phys. Rev. D 94 (**2016**) 072003
Zr96	9.4	3355.8	2.35 ± 0.21	1	World's best	Nucl.Phys.A 847(2010) 168
Ca48	7	4268	6.4 ± 1.2	6.8 (h.e.)	World's best	Phys. Rev. D 93 (**2016**) 112008
Mo100	6914	3034	0.68 ± 0.05	80	World's best	**Neutrino 2018**
Te130	454	25227.5	70 ± 14	0.5	First direct detection	Phys. Rev. Lett. 107, 062504 (2011)

NEW!

UPDATED

* Together with Aurora

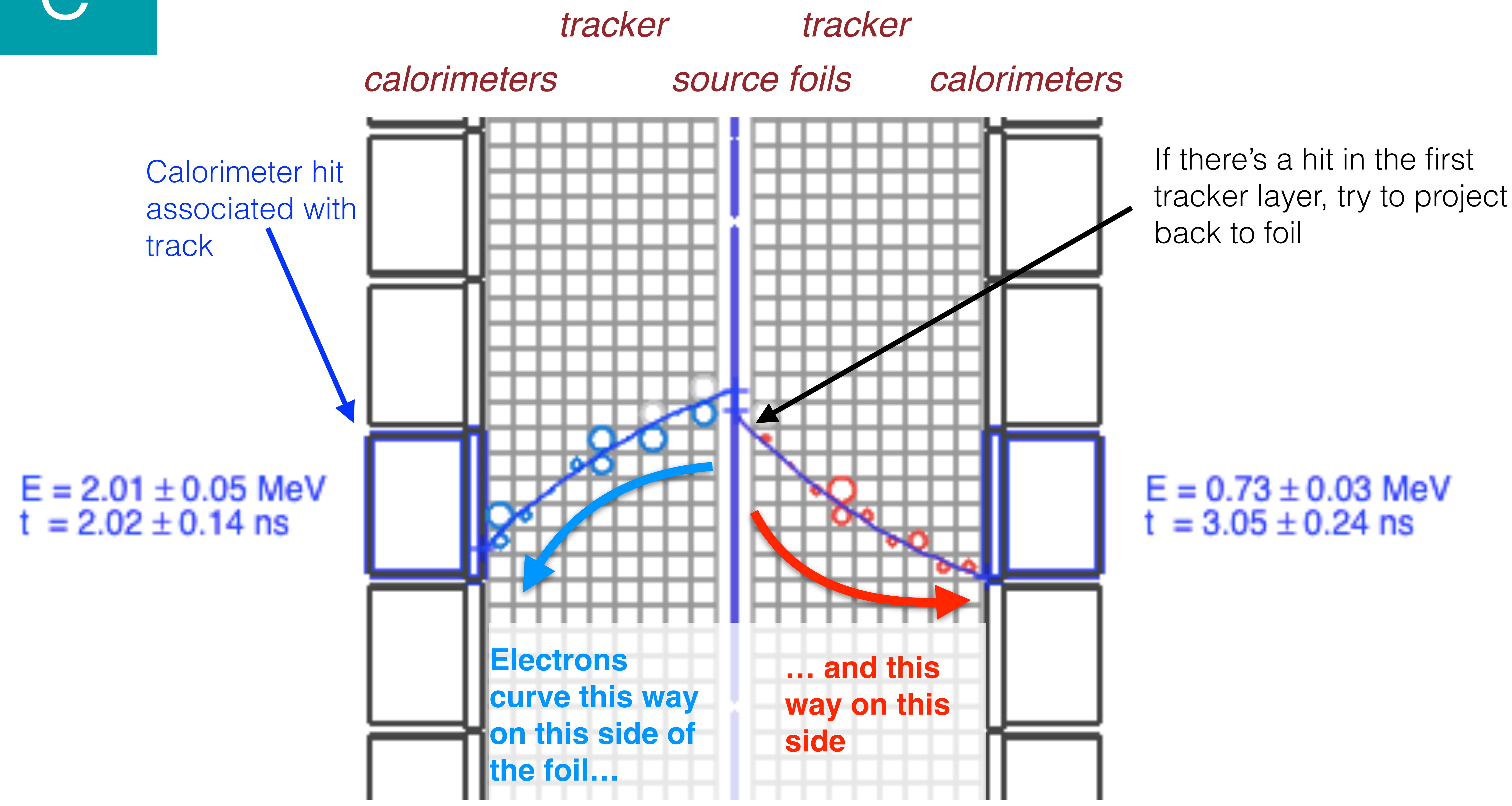
Crucial experimental input for
1) NME calculations
2) Ultimate background characterisation for 0ν
3) Sensitive to exotic BSM physics (e.g. Lorentz violation, G_f time dependence, bosonic neutrinos etc)

Taken from R Saakyan, NDM2018

38

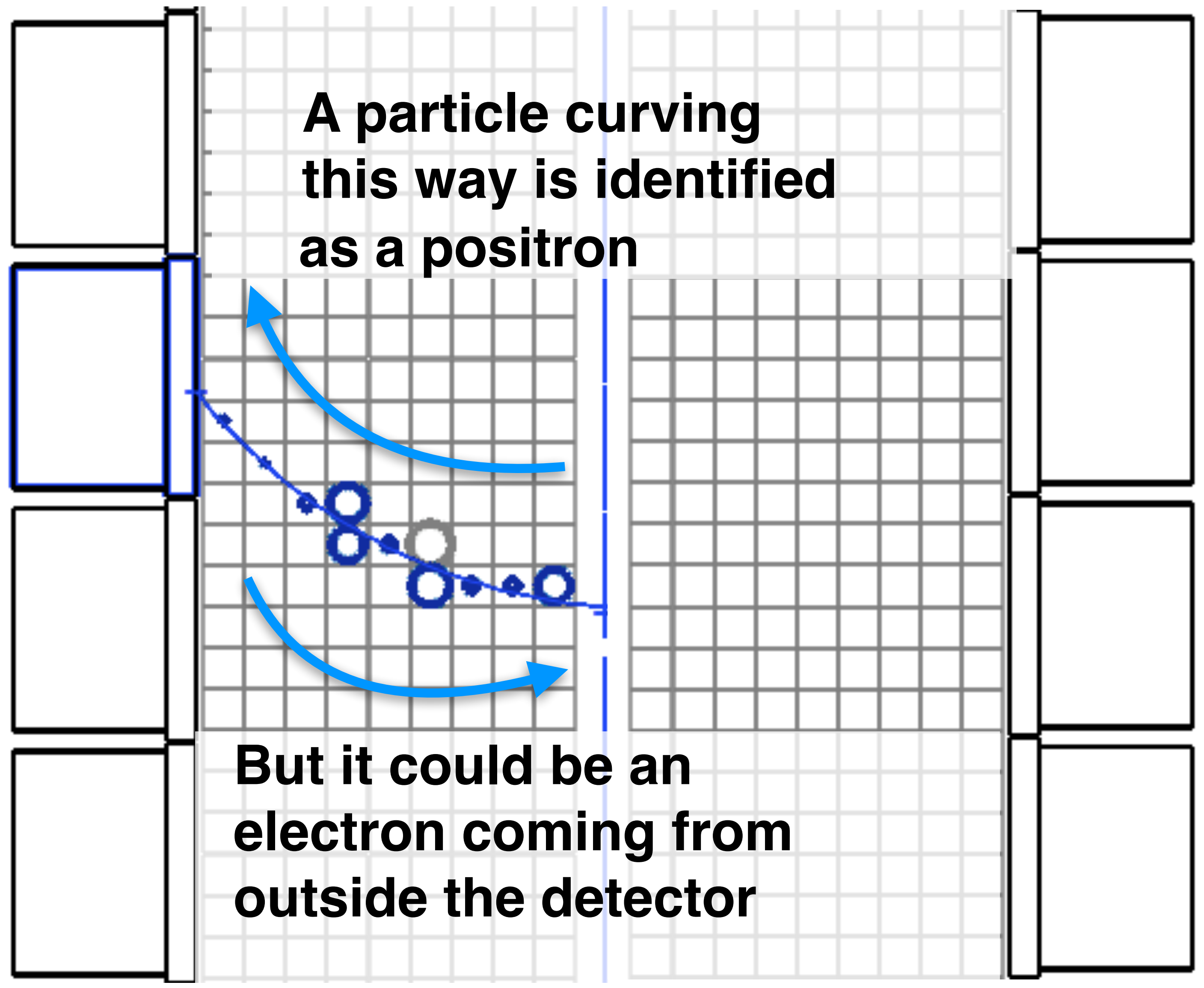
Electrons and positrons

e-



Plan view (partial)

e+

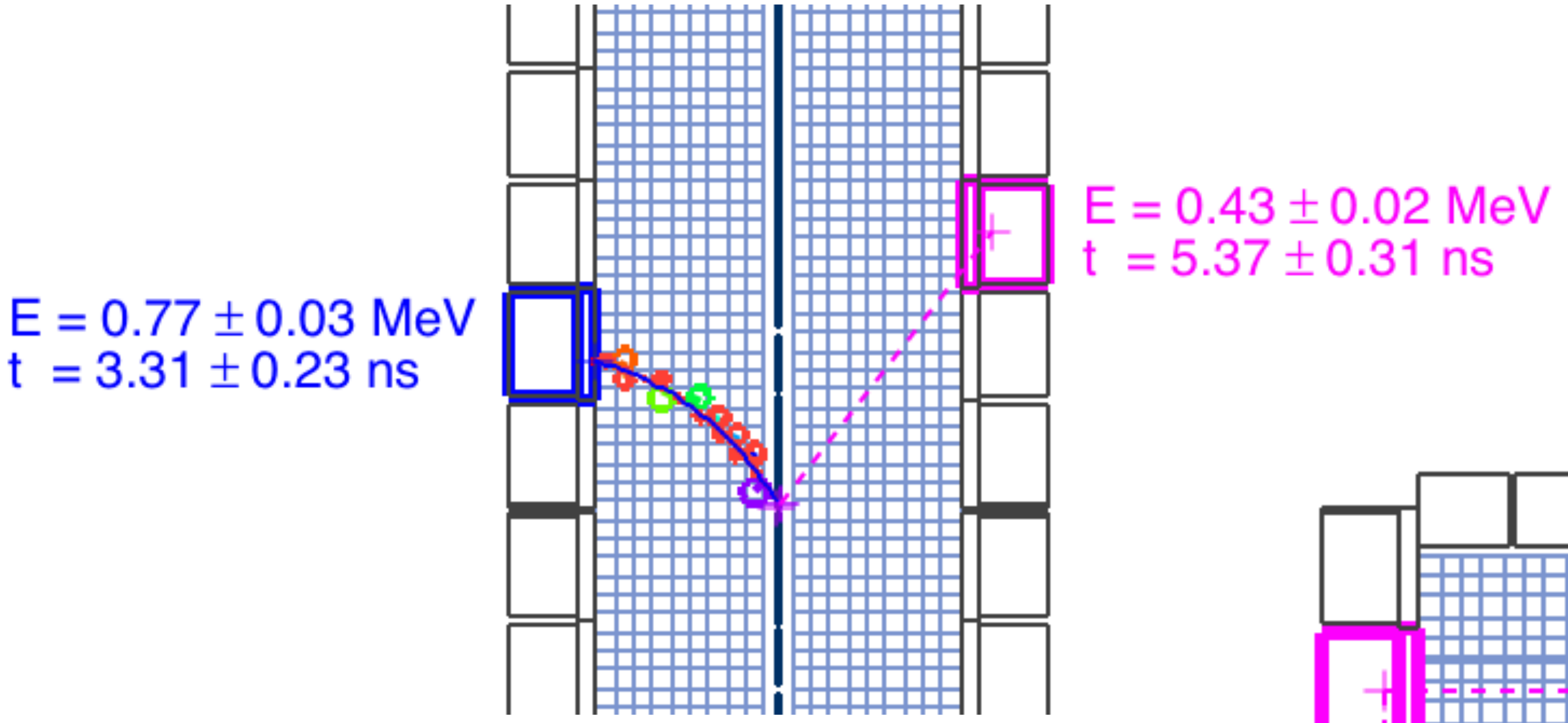


Electron tracks curve in the magnetic field. We get the electron's energy from an associated calorimeter hit.

Background topologies: gammas and alphas

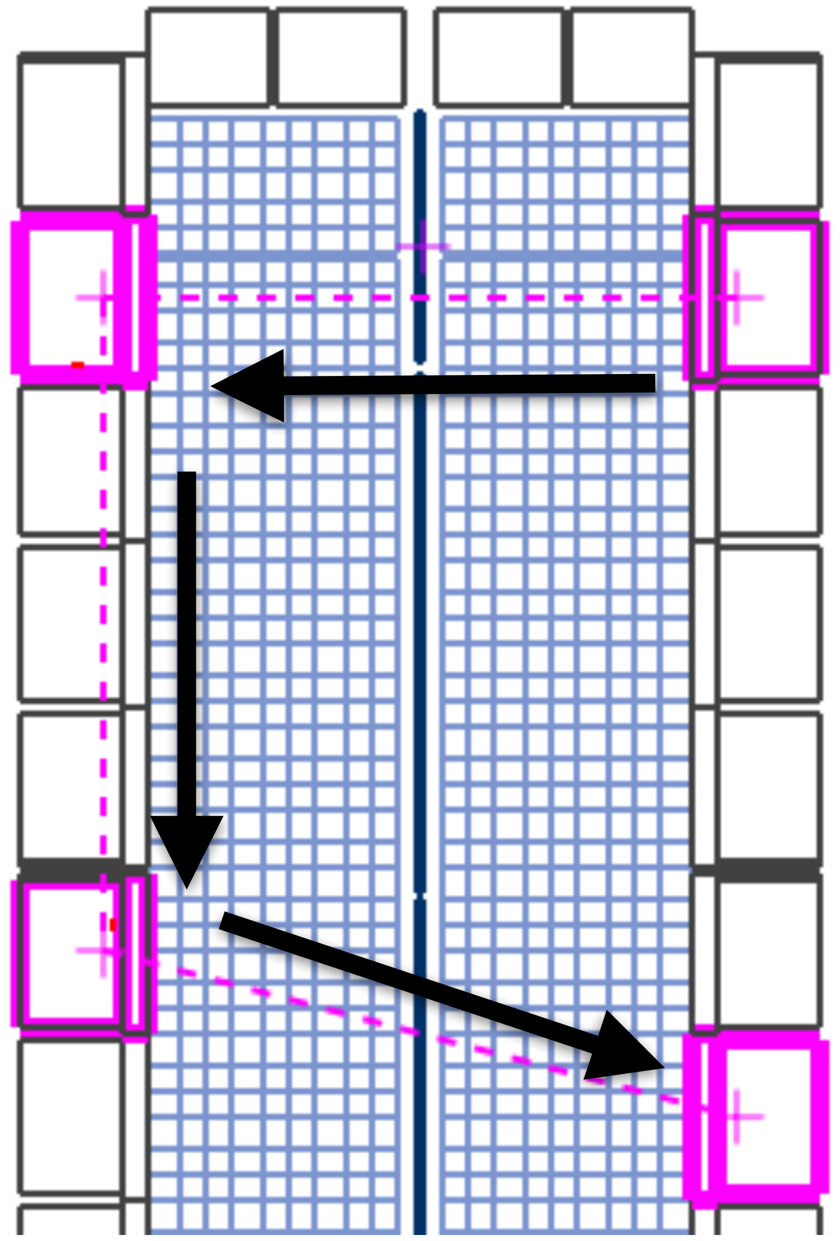
γ

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



Use timing and energies to assess probability that

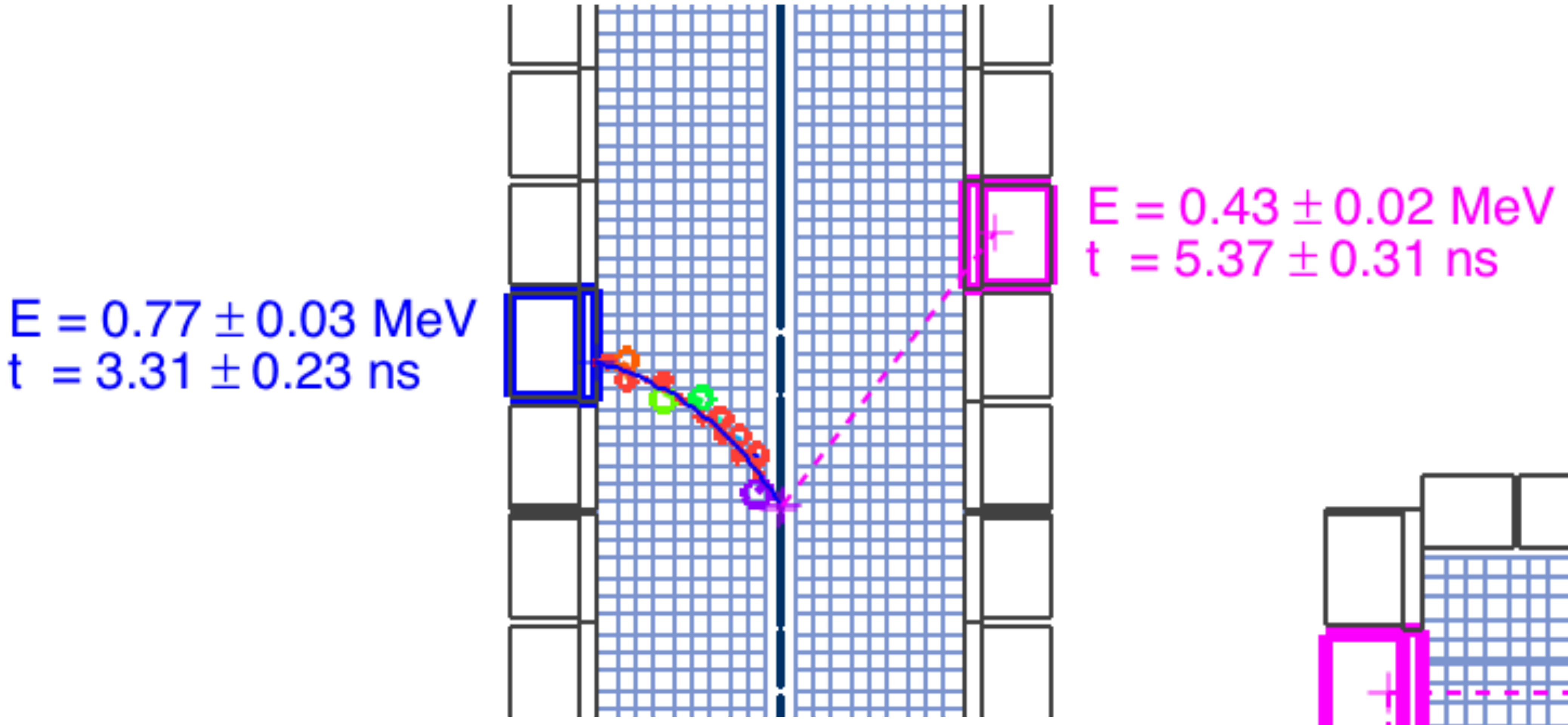
- a gamma originates from electron vertex
- multiple isolated hits originate from the same gamma

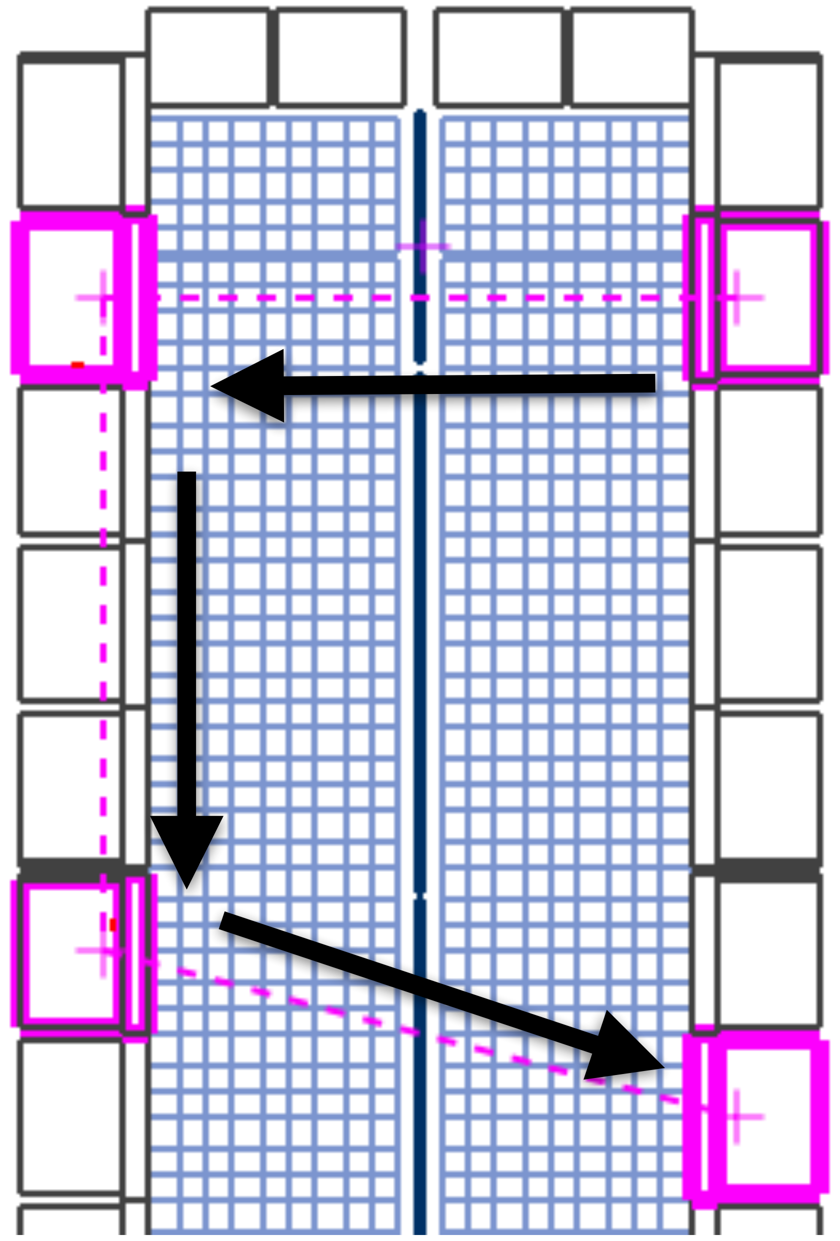


Background topologies: gammas and alphas

γ

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



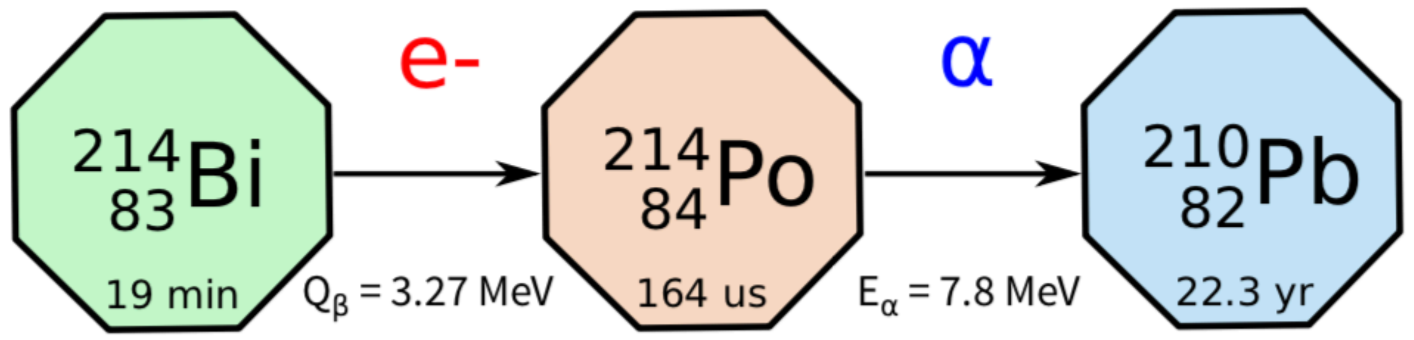


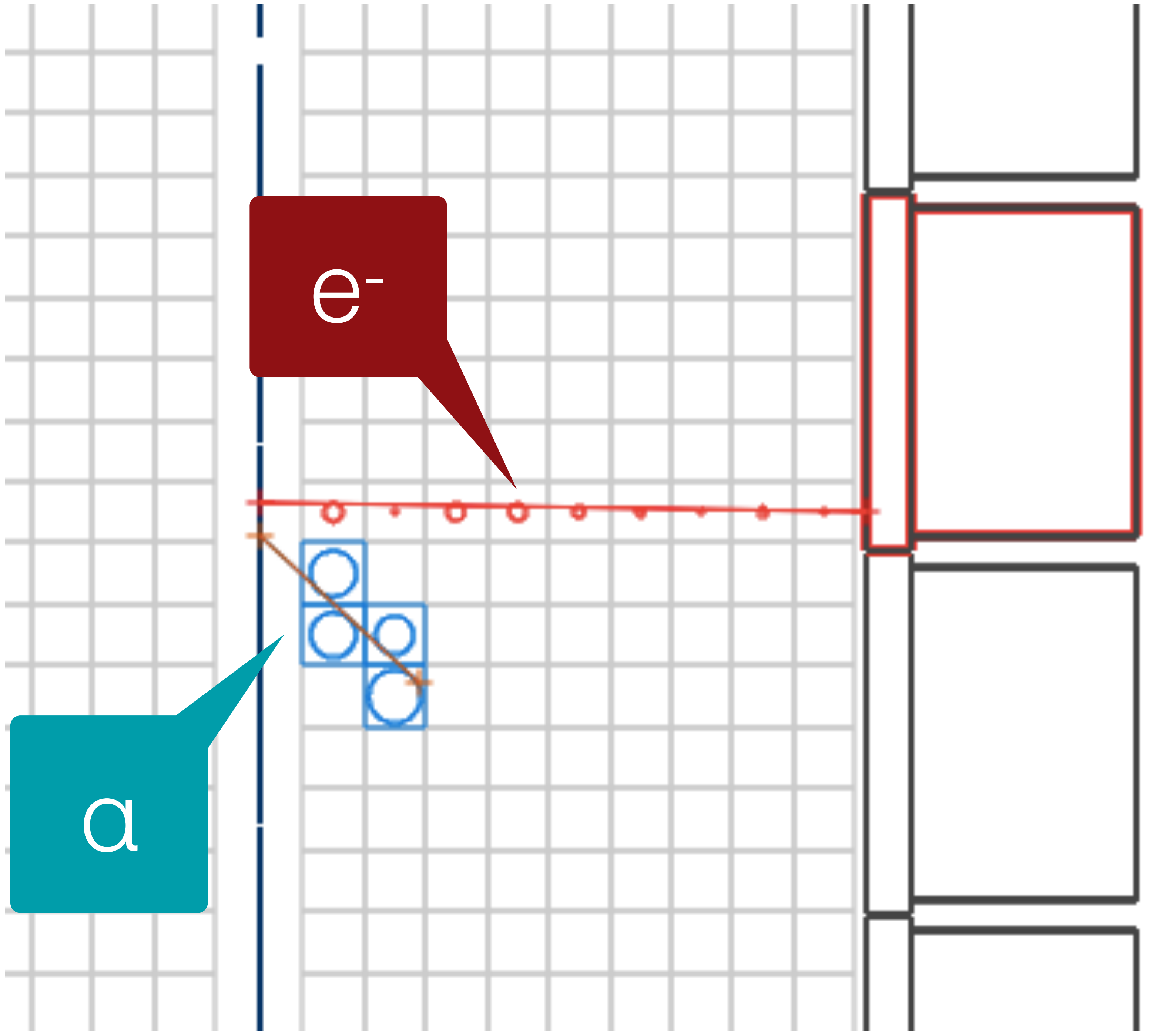
Use timing and energies to assess probability that

- a gamma originates from electron vertex
- multiple isolated hits originate from the same gamma

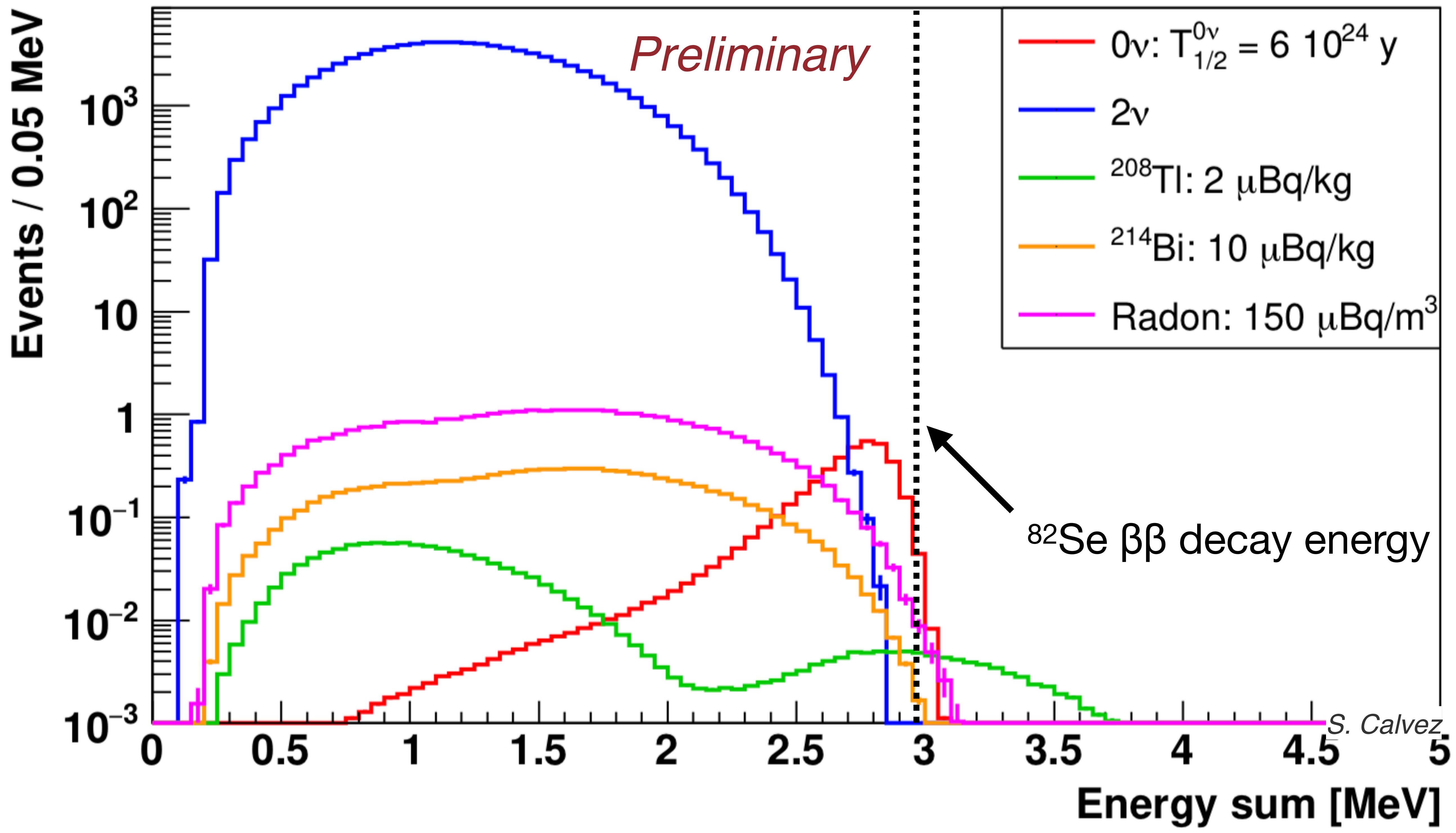
α

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



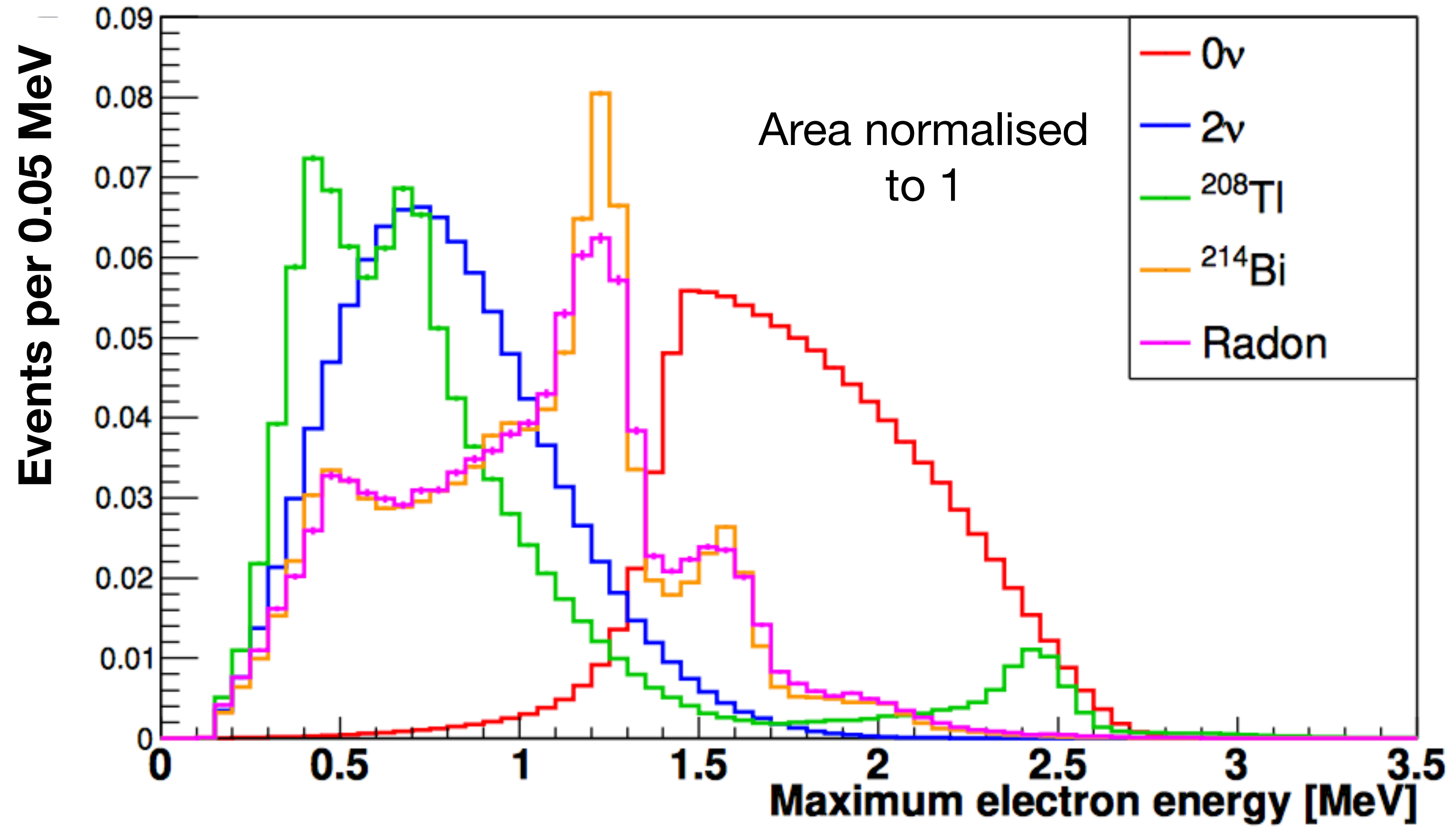


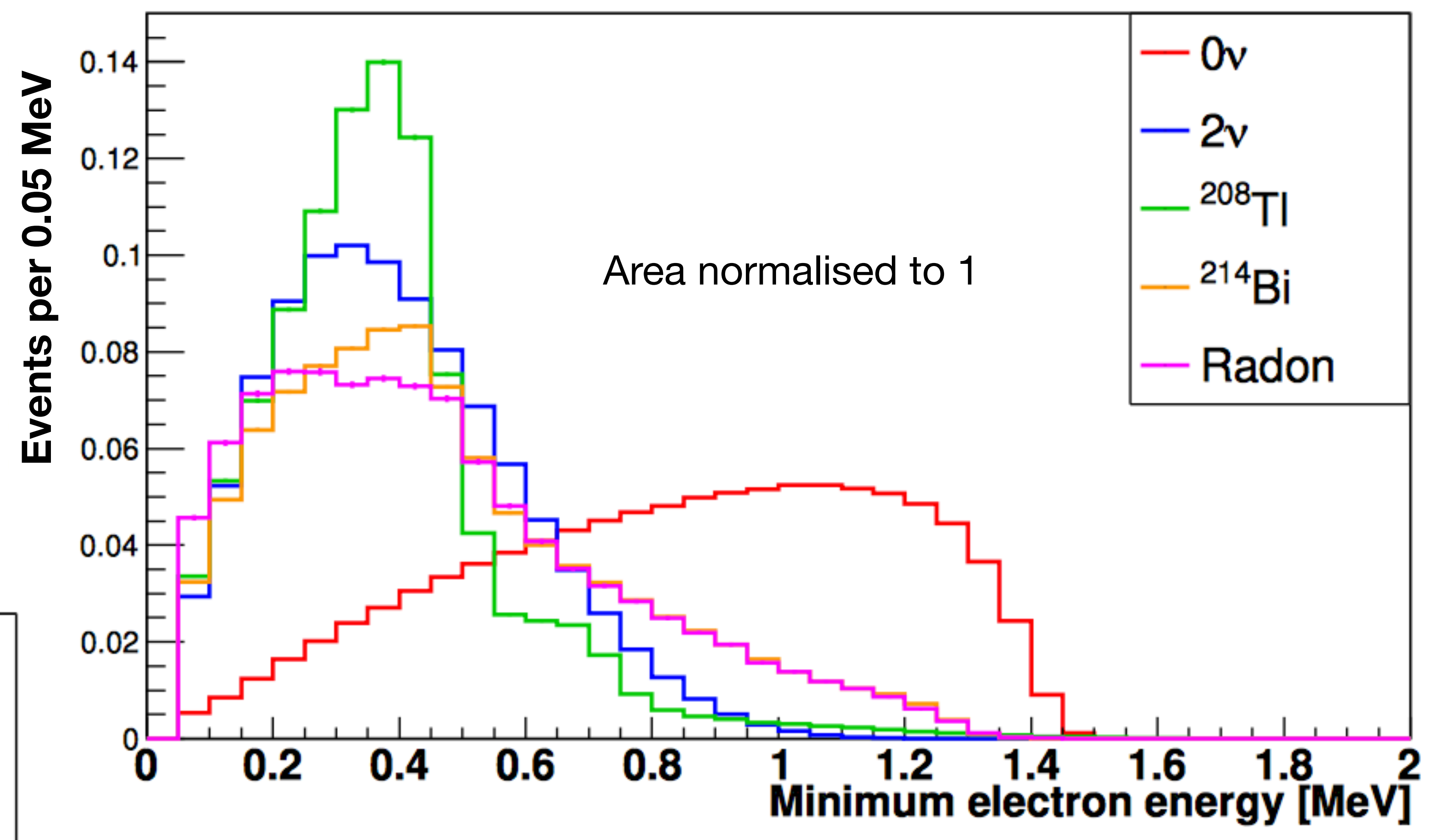
Sensitivity to 0νββ



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

Sensitivity to 0νββ

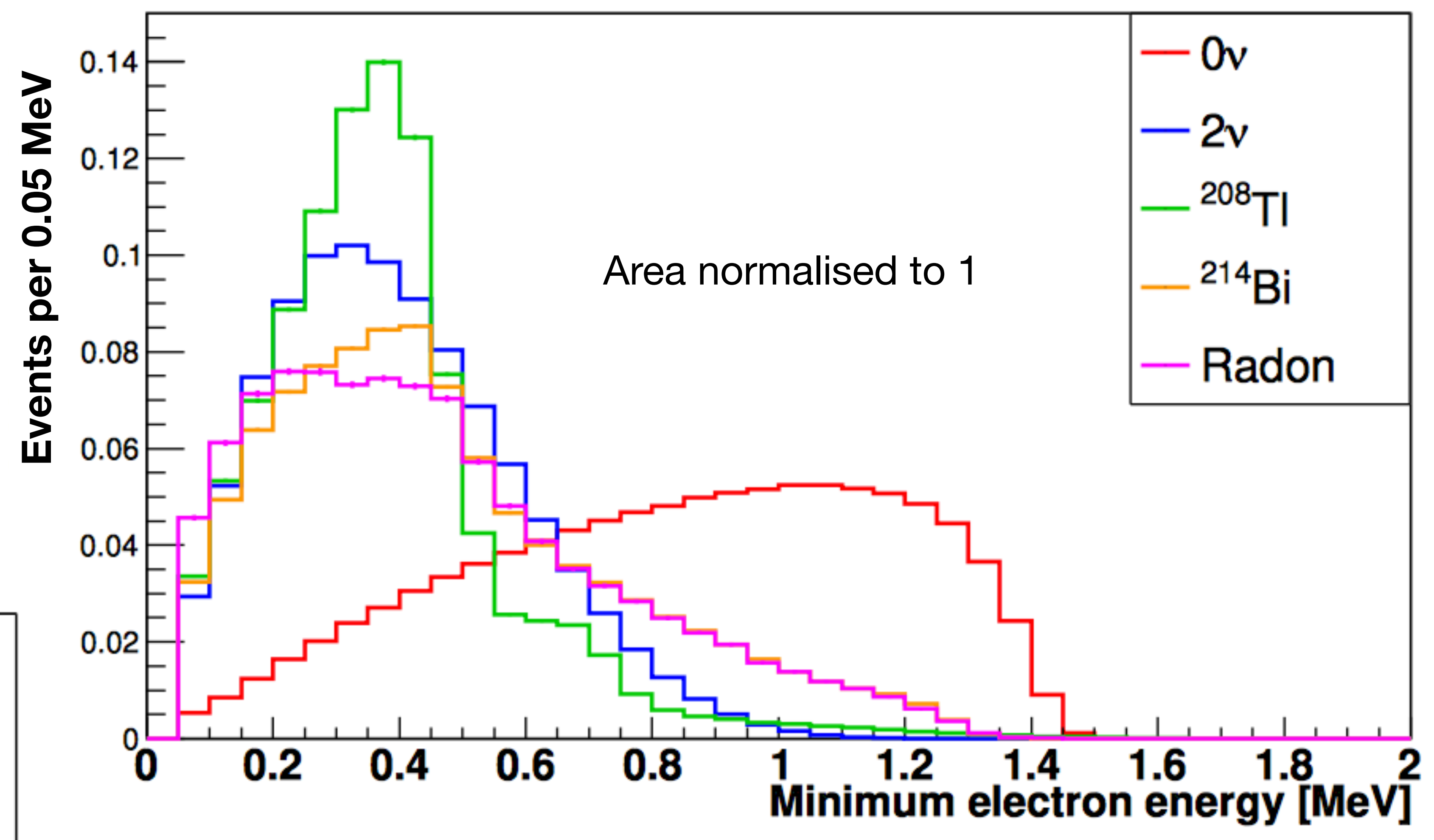


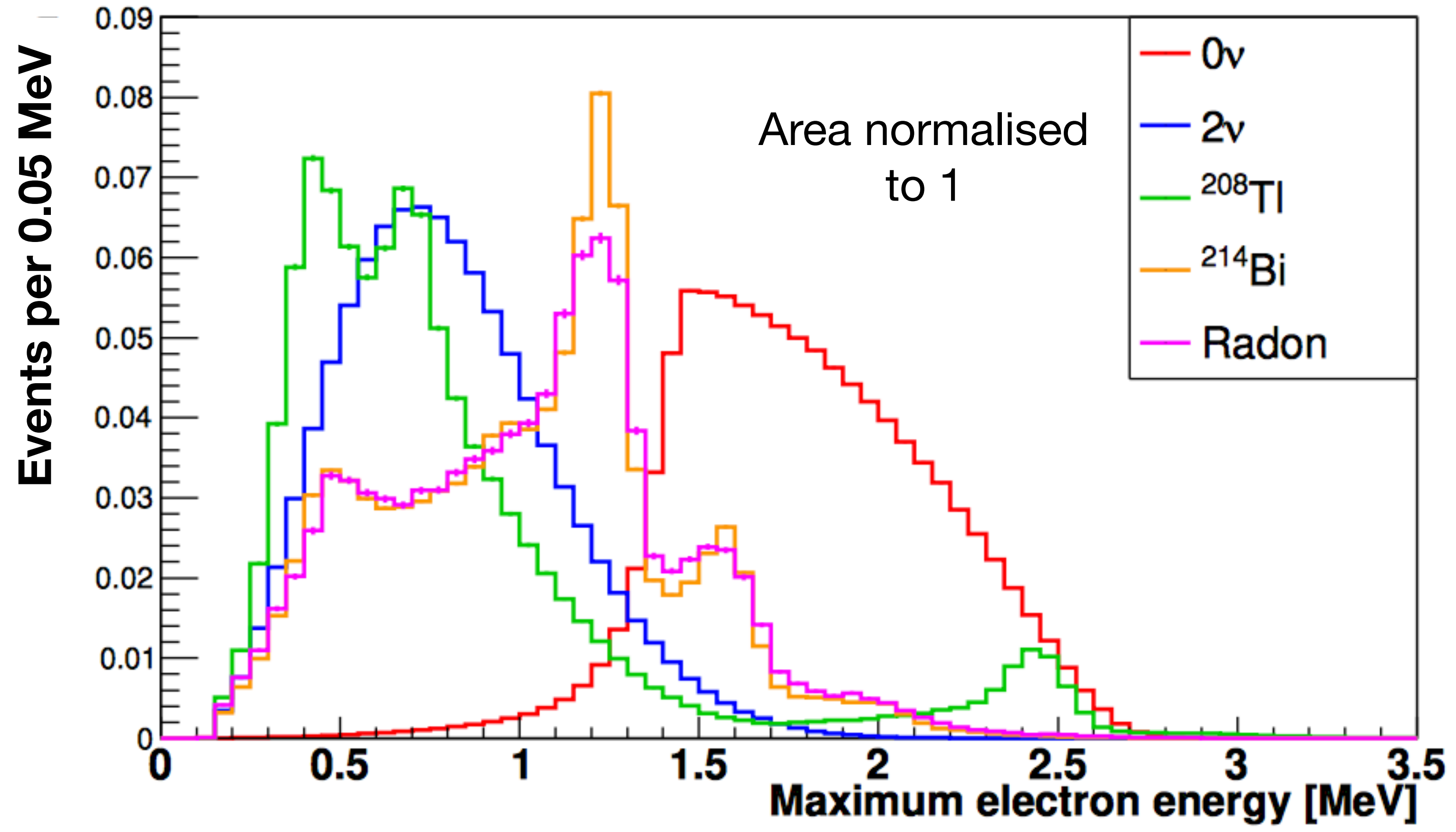


Summed 2-electron energy is best distribution to separate signal from background

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)*

Sensitivity to 0νββ





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)

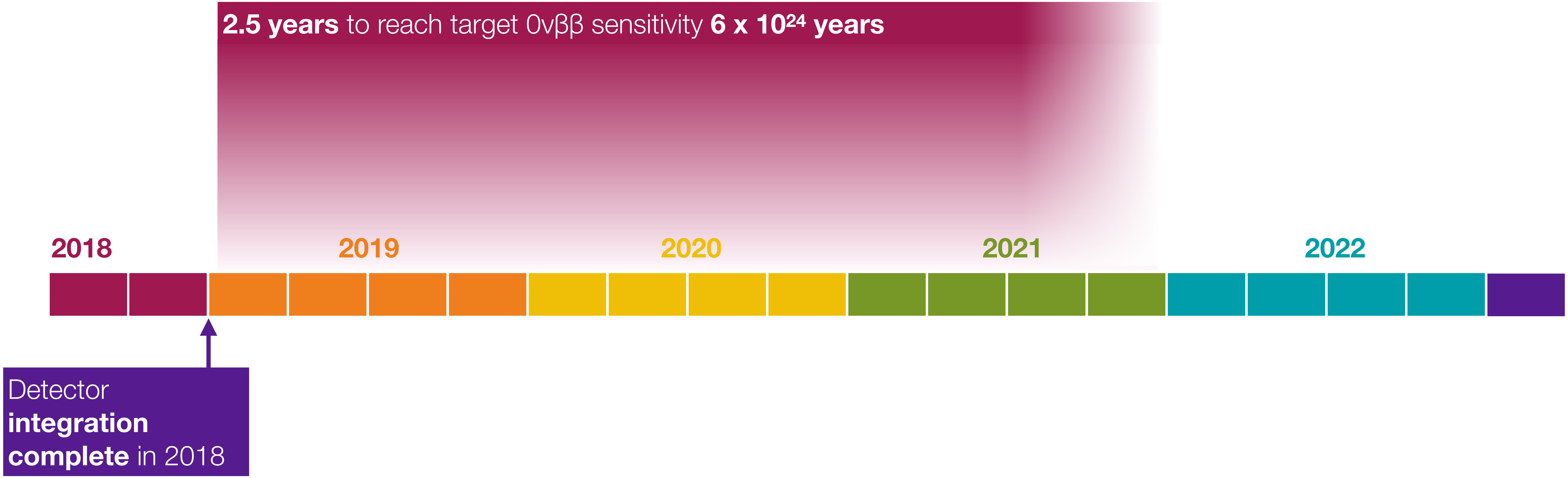
For 7kg of ^{82}Se (demonstrator) and 2.5 years' exposure

Schedule for the Demonstrator

Schedule for the Demonstrator

Detector **integration complete** in 2018

Schedule for the Demonstrator



Schedule for the Demonstrator

Schedule for the Demonstrator

2.5 years to reach target 0νββ sensitivity **6 x 10^{24} years**

Detector **integration complete** in 2018

Tracker ^{222}**Rn** and source foil ^{214}**Bi** contamination measured in ~ 2 months

Source foil ^{208}**Tl** contamination measured in ~ 1 year

Schedule for the Demonstrator

2.5 years to reach target $0\nu\beta\beta$ sensitivity **6×10^{24} years**

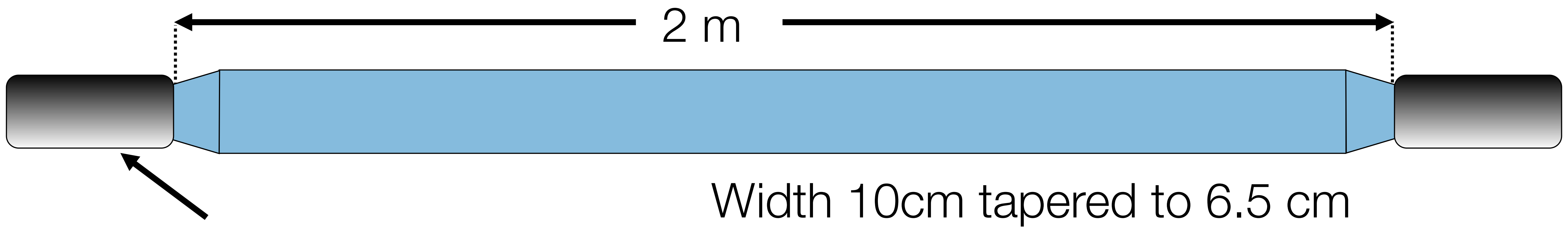
2018 | 2019 | 2020 | 2021 | 2022

R & D for full SuperNEMO can take place in parallel with data taking

Detector **integration complete** in 2018

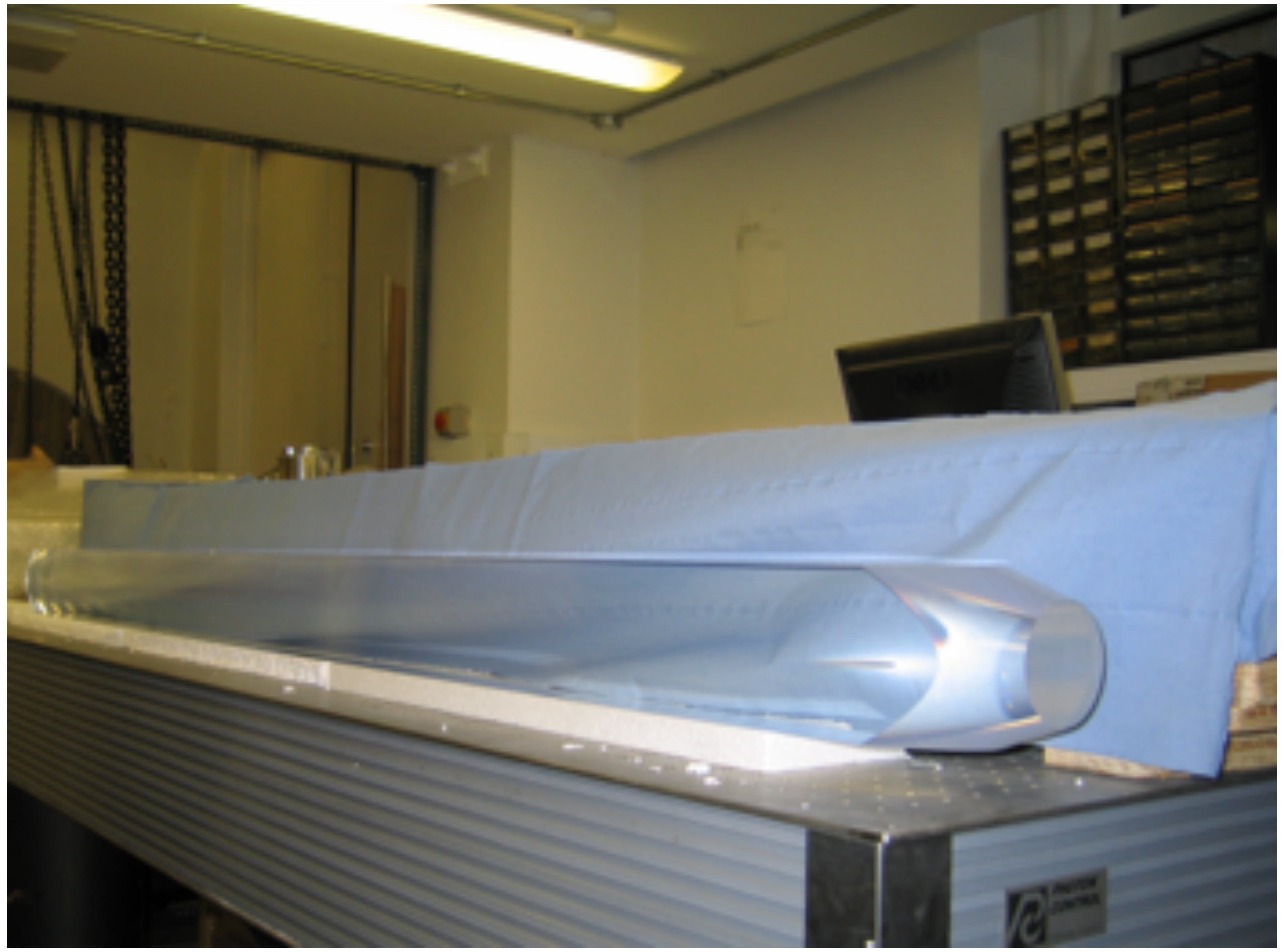
Tracker **^{222}Rn** and source foil **^{214}Bi** contamination measured in ~ 2 months

Source foil **^{208}Tl** contamination measured in ~ 1 year

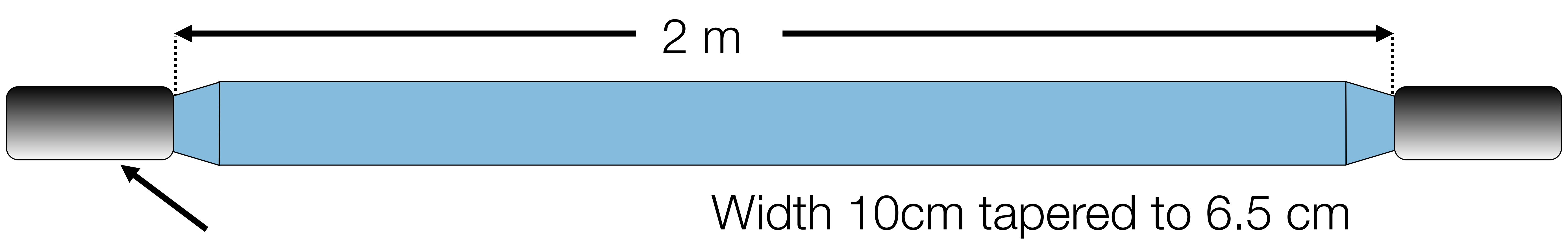


Hamamatsu high-QE 3”
PMT (QE~40%)

Width 10cm tapered to 6.5 cm
Thickness 2.5 cm

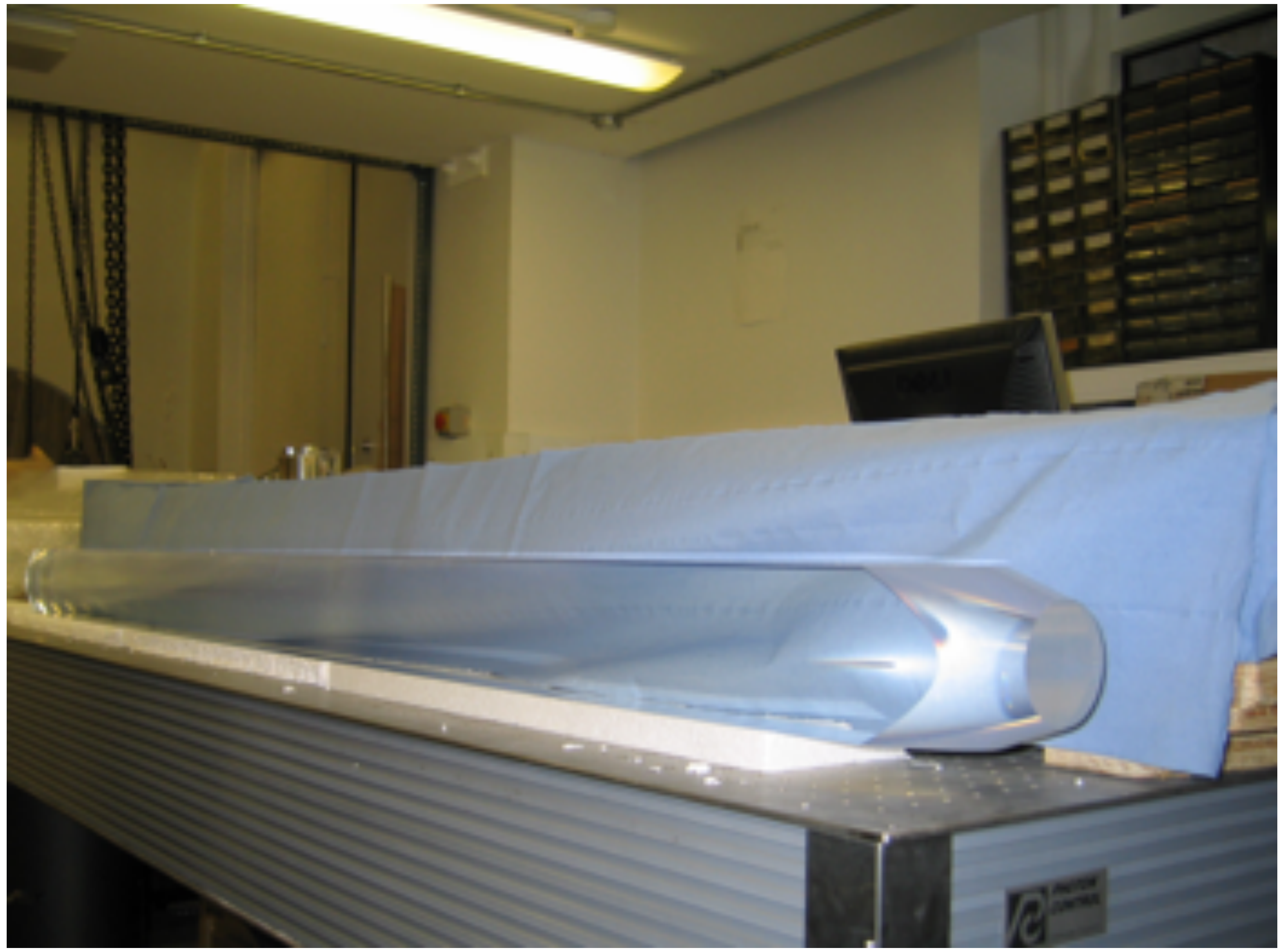


R & D for SuperNEMO: scintillator bar proposal (possible alternative)

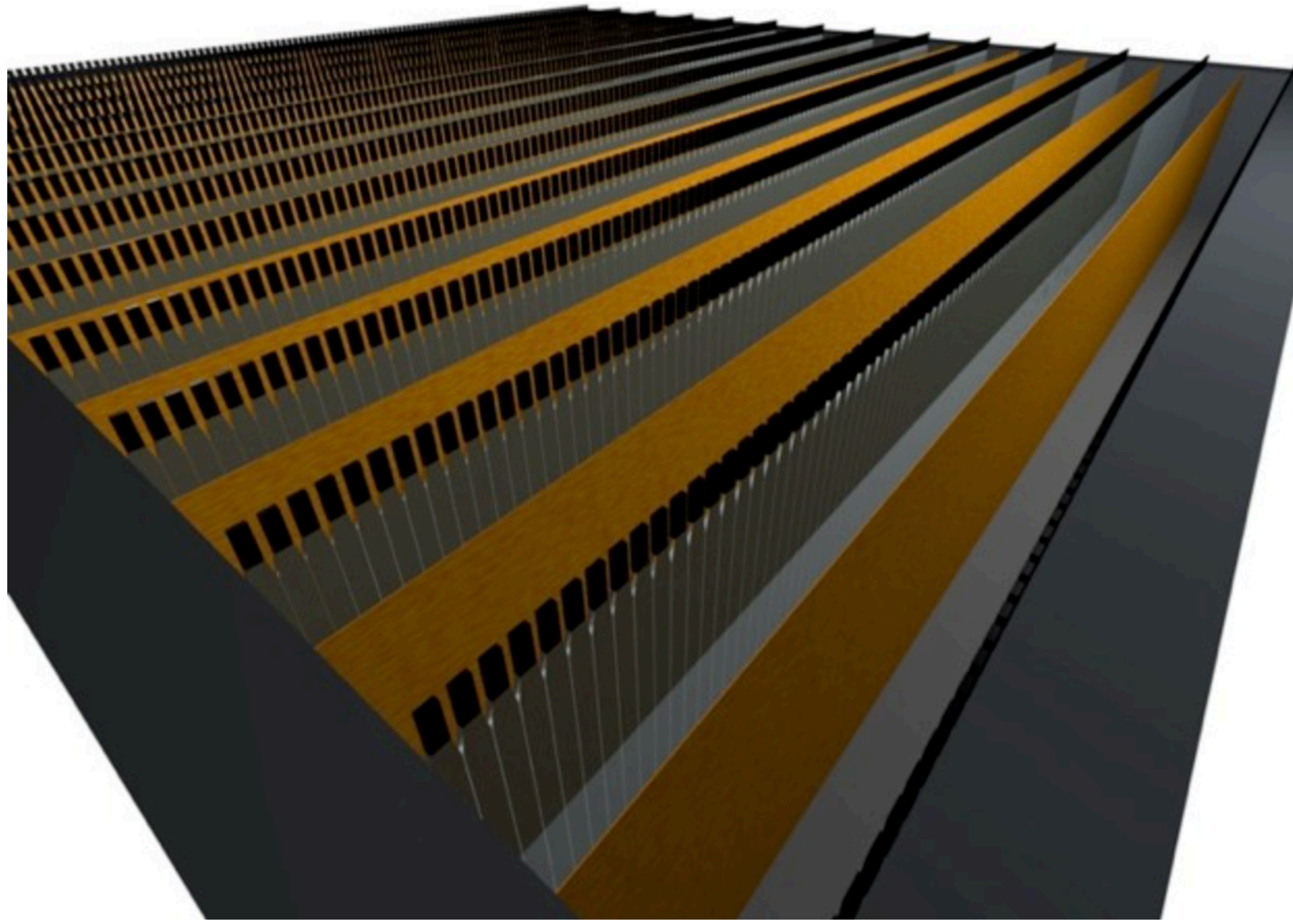


Hamamatsu high-QE 3”
PMT (QE~40%)

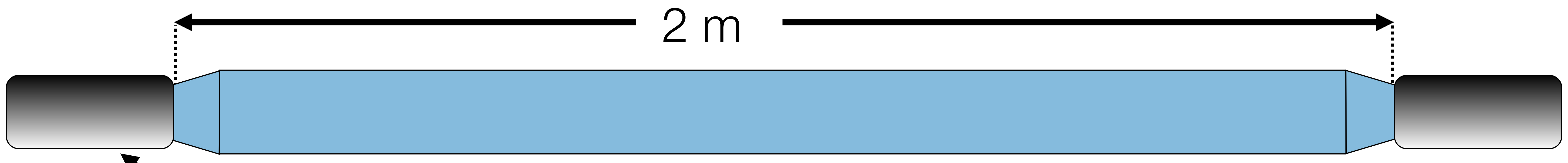
Width 10cm tapered to 6.5 cm
Thickness 2.5 cm



Alternating walls of bars and source foils sandwiched between trackers

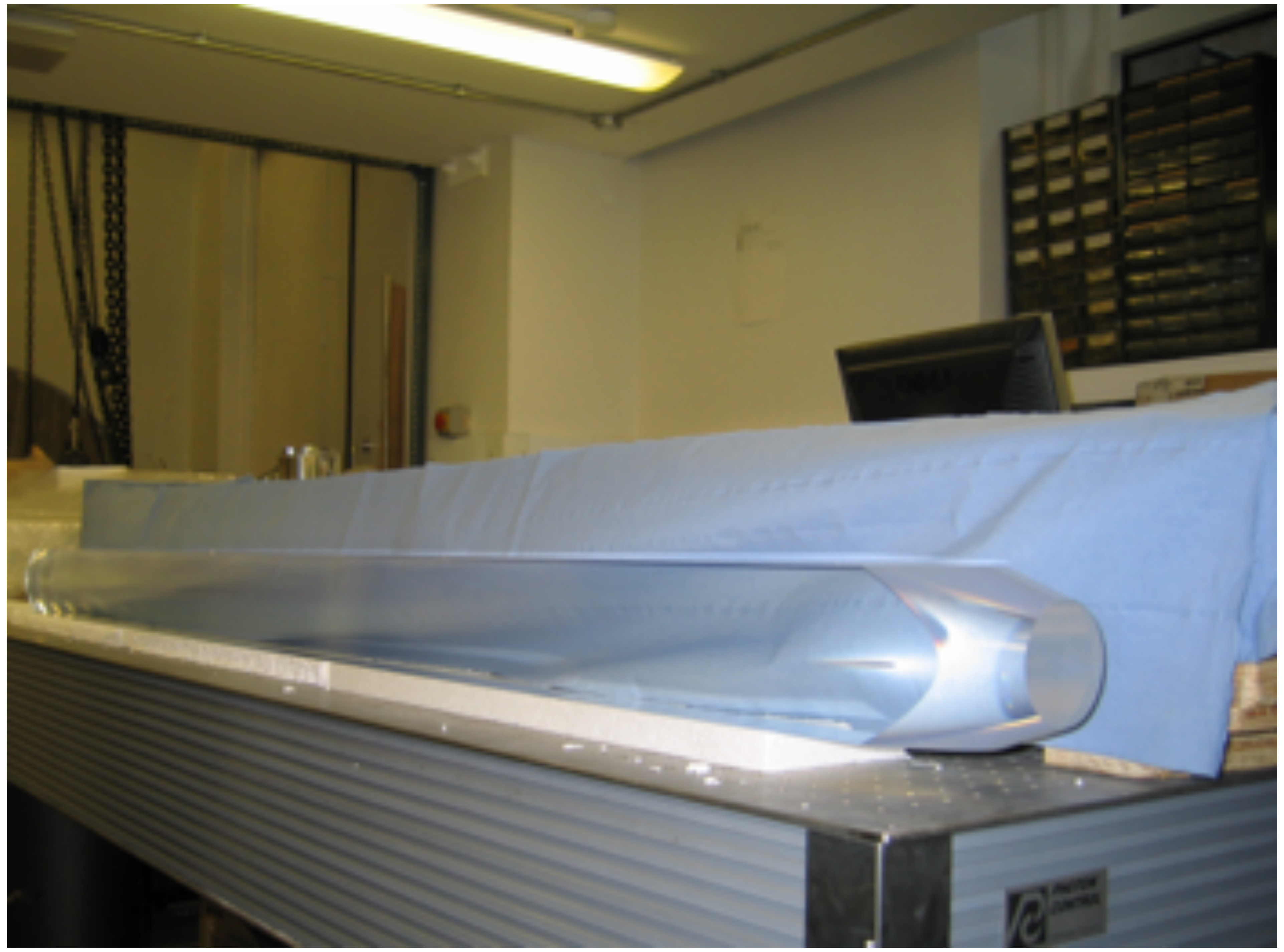


R & D for SuperNEMO: scintillator bar proposal (possible alternative)

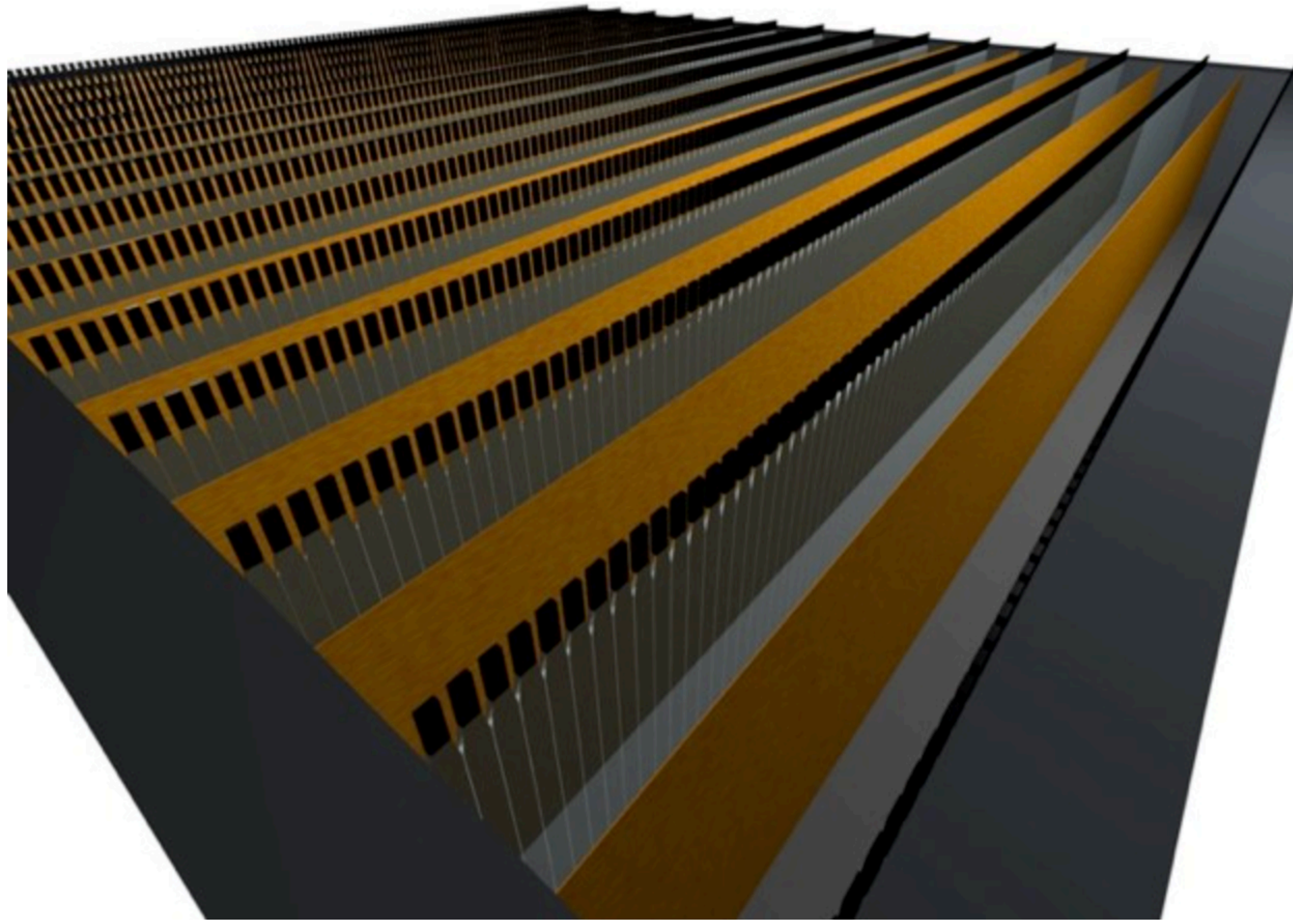


Hamamatsu high-QE 3” PMT (QE~40%)

Width 10cm tapered to 6.5 cm
Thickness 2.5 cm



Alternating walls of bars and source foils sandwiched between trackers

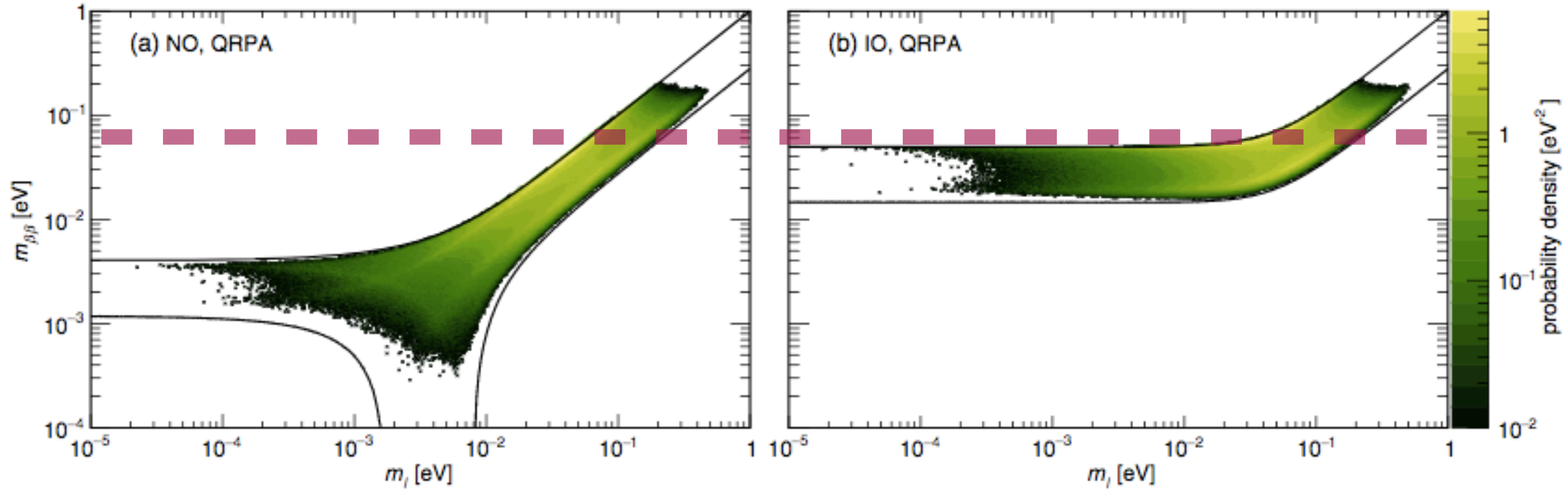


- Almost 100% γ rejection
- Fewer PMTs - save ££ and radioactivity
- Better efficiency
- Easier to build
- Smaller footprint
- No magnetic field needed

- Loses modular design
- Currently σ/E worse than for Demonstrator (2.3 vs 1.8% at 3MeV)

The future for SuperNEMO & tracker-calorimeter experiments

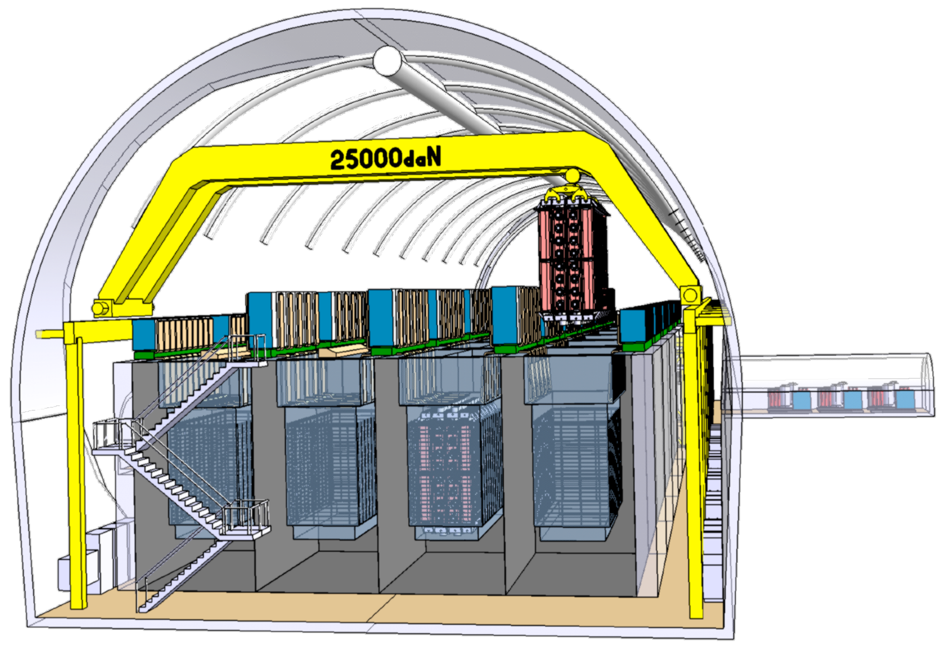
If current experiments (KamLAND-Zen, GERDA…) see 0νββ ($T_{1/2}$ ~10^{26} years)

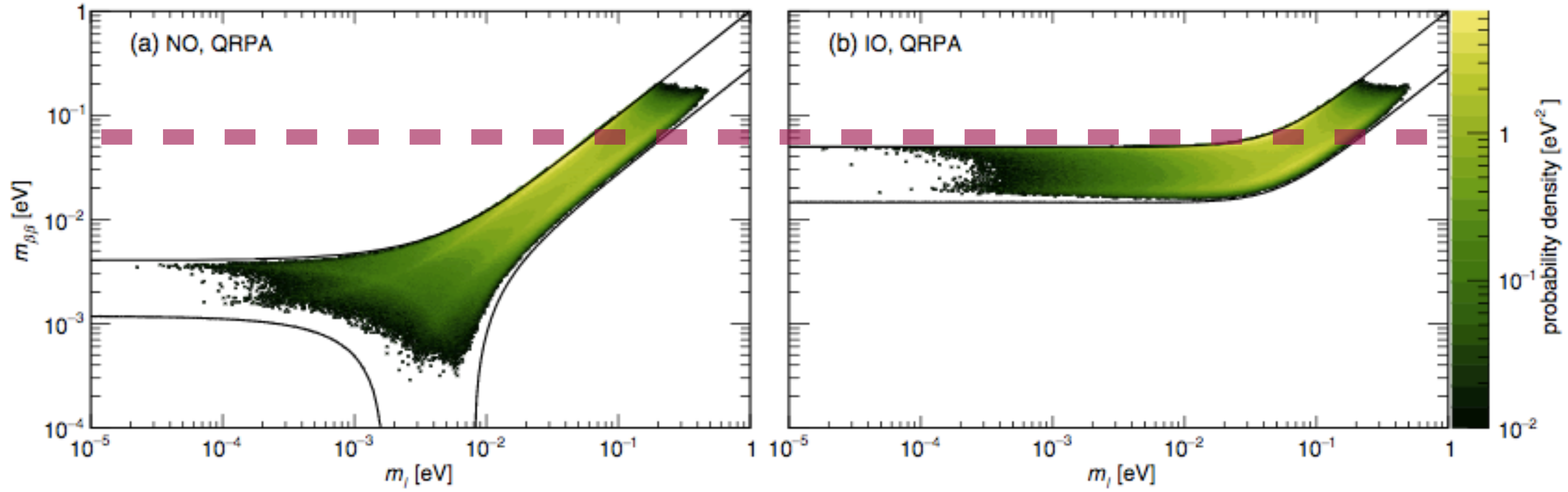


The future for SuperNEMO & tracker-calorimeter experiments

If current experiments (KamLAND-Zen, GERDA…) see $0\nu\beta\beta$ ($T_{1/2}$ ~10^{26} years)

- **SuperNEMO's** unique **tracker-calorimeter technology** is the best way to characterise the **$0\nu\beta\beta$ mechanism**
- **Full SuperNEMO** proposal has similar **half-life sensitivity** to current world-leading experiments
- **Mass sensitivity** could be even better by choosing high-$Q_{\beta\beta}$ isotopes with **shorter half-life**
- But scaling to even the current proposal is expensive…

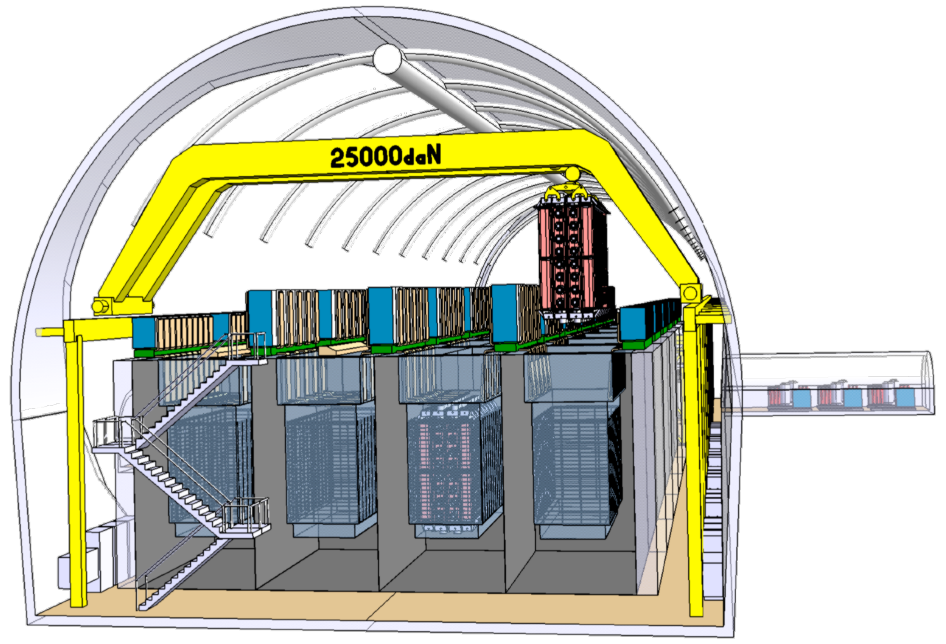




The future for SuperNEMO & tracker-calorimeter experiments

If current experiments (KamLAND-Zen, GERDA…) see 0νββ ($T_{1/2}$ ~10^{26} years)

- **SuperNEMO's** unique **tracker-calorimeter technology** is the best way to characterise the **0νββ mechanism**
- **Full SuperNEMO** proposal has similar **half-life sensitivity** to current world-leading experiments
- **Mass sensitivity** could be even better by choosing high-$Q_{\beta\beta}$ isotopes with **shorter half-life**
- But scaling to even the current proposal is expensive…



If next-generation experiments (NEXO, LEGEND…) see 0νββ ($T_{1/2}$ ~10^{28} years)

- Next-gen experiments will cover full **inverted hierarchy**
- Prohibitively **expensive** to increase to **tonne scale** (price scales linearly with size)
- Can we make an **affordable tracker-calorimeter detector** that can probe this mass range?