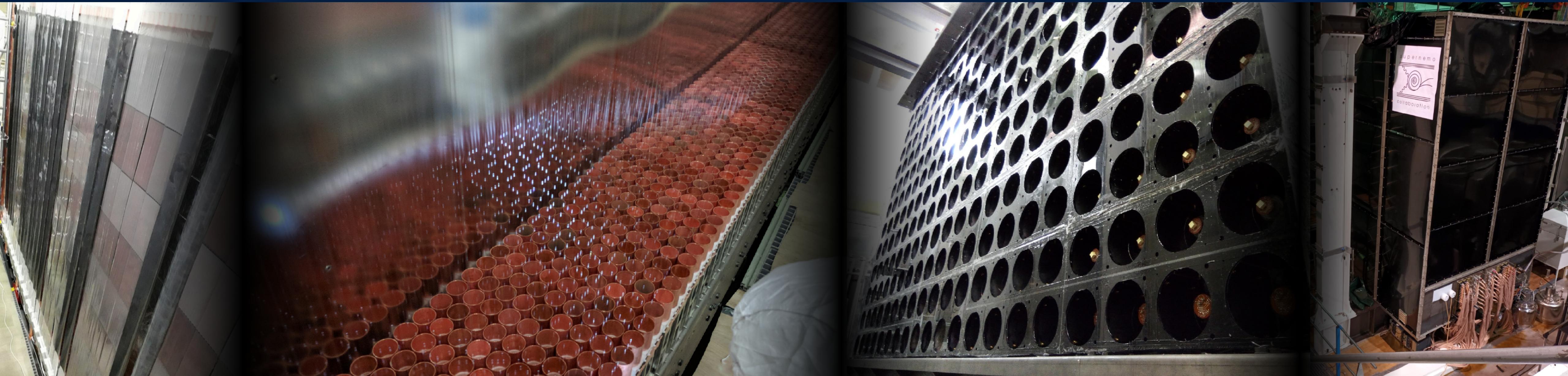
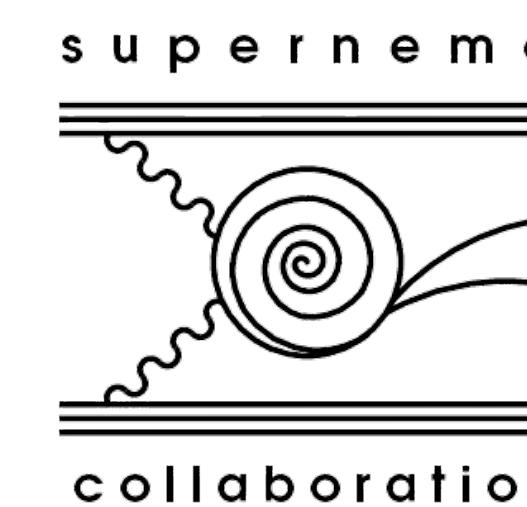


# Status of SuperNEMO, and analysis of our first data



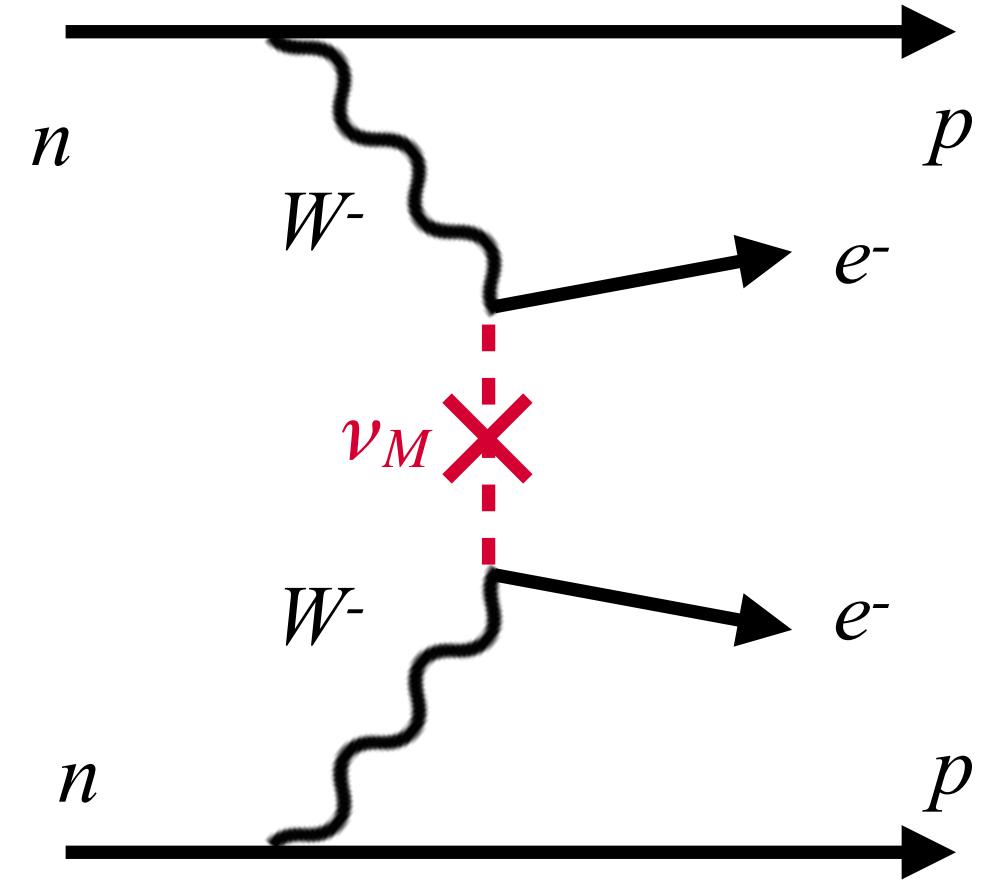
Cheryl Patrick University of Edinburgh, on behalf of the SuperNEMO collaboration



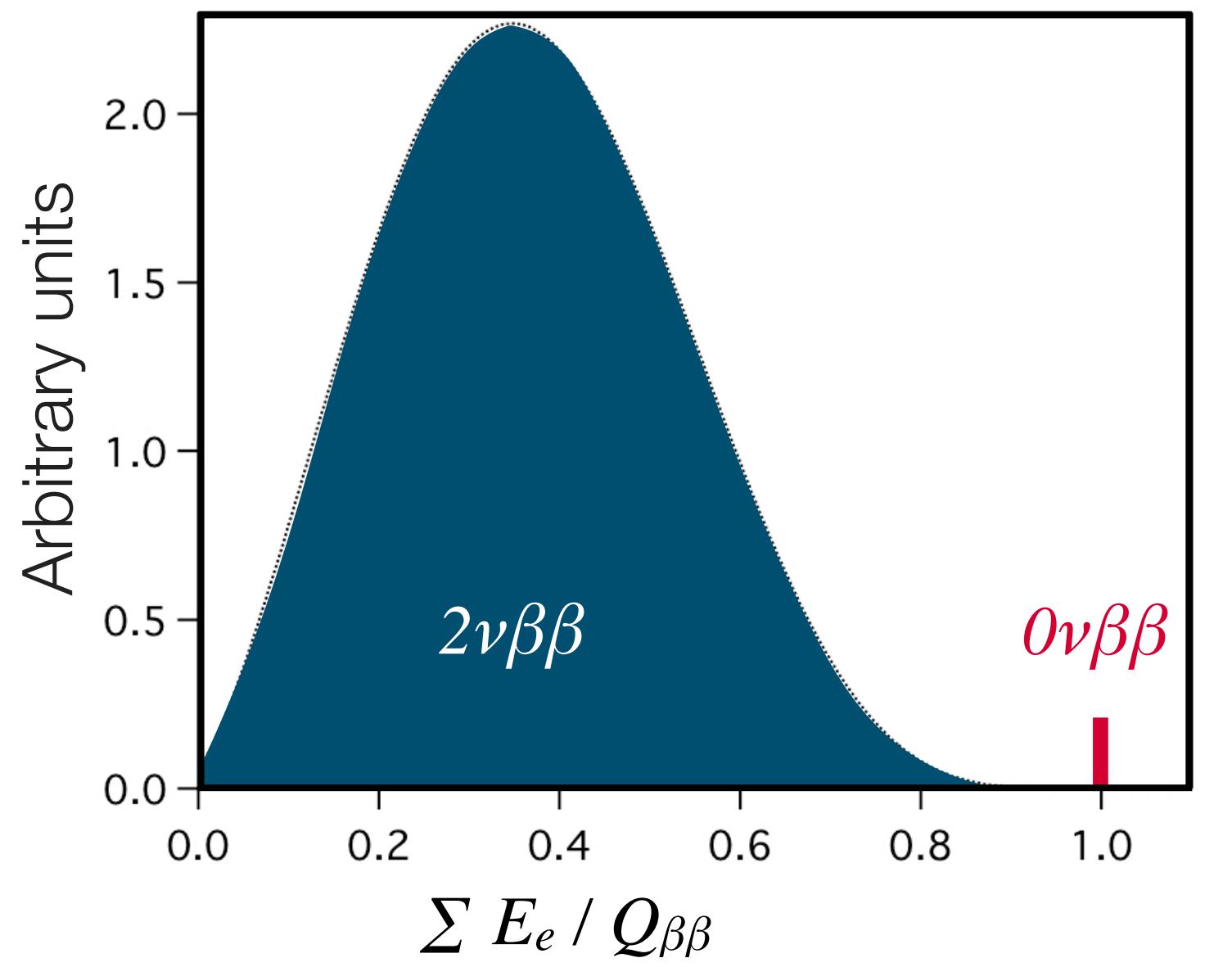
THE UNIVERSITY  
of EDINBURGH

# What makes NEMO super?

Neutrinoless  
double-beta-  
decay searches...

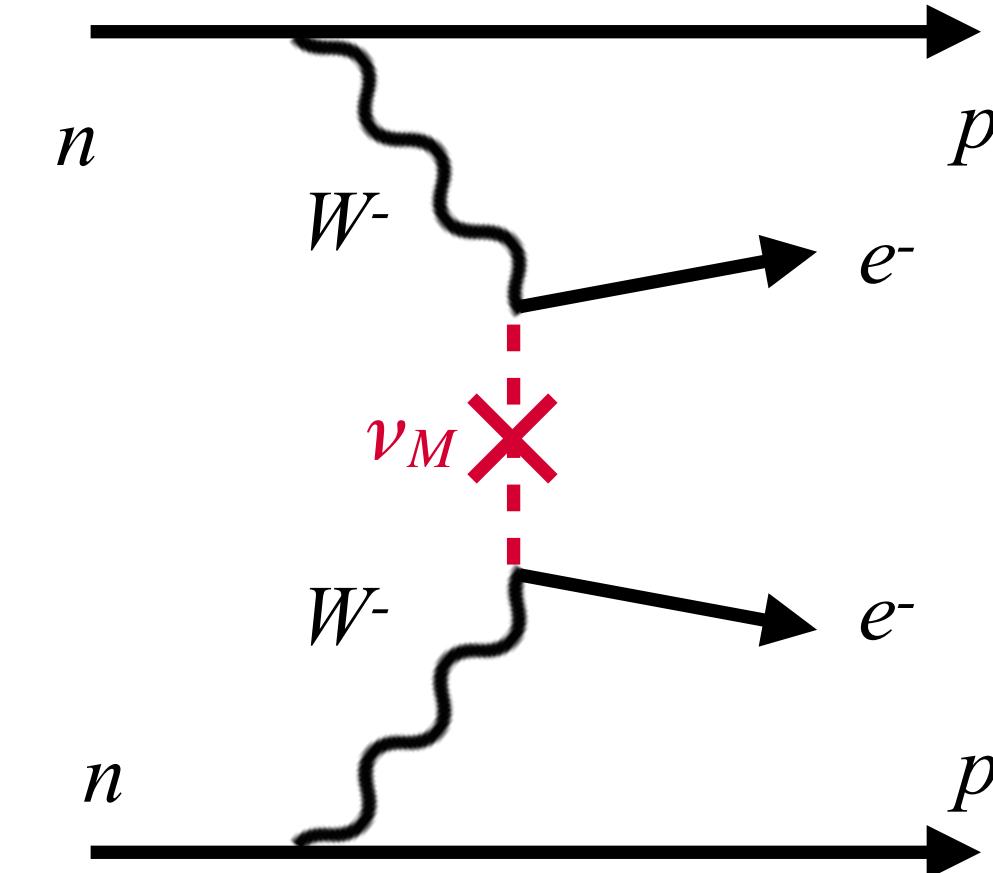


...study the total  
decay energy

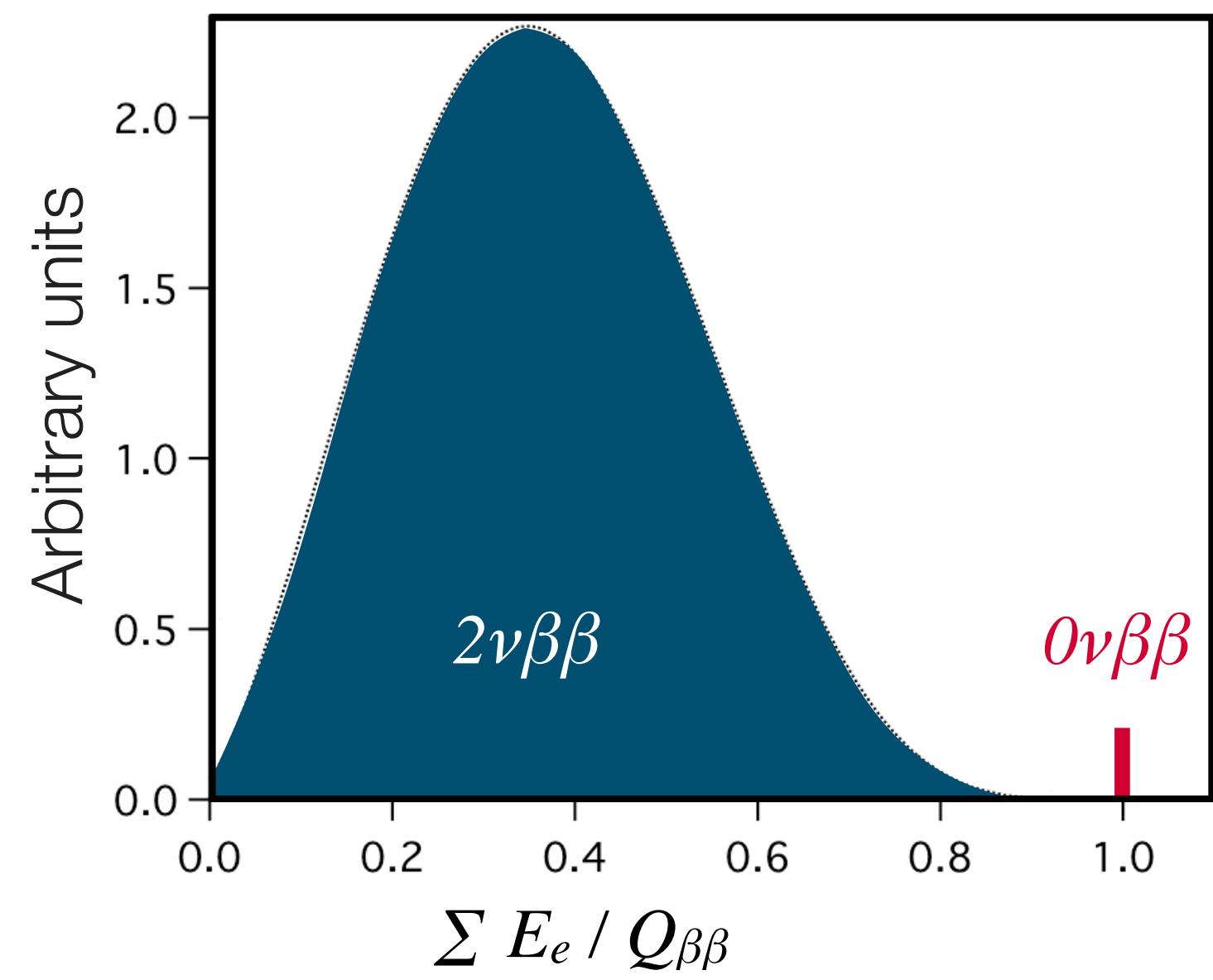


# What makes NEMO super?

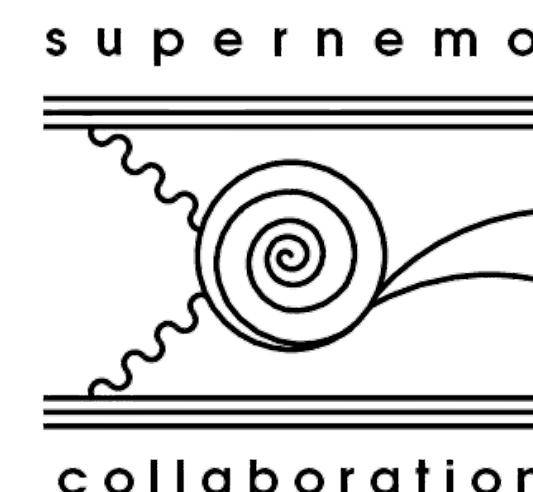
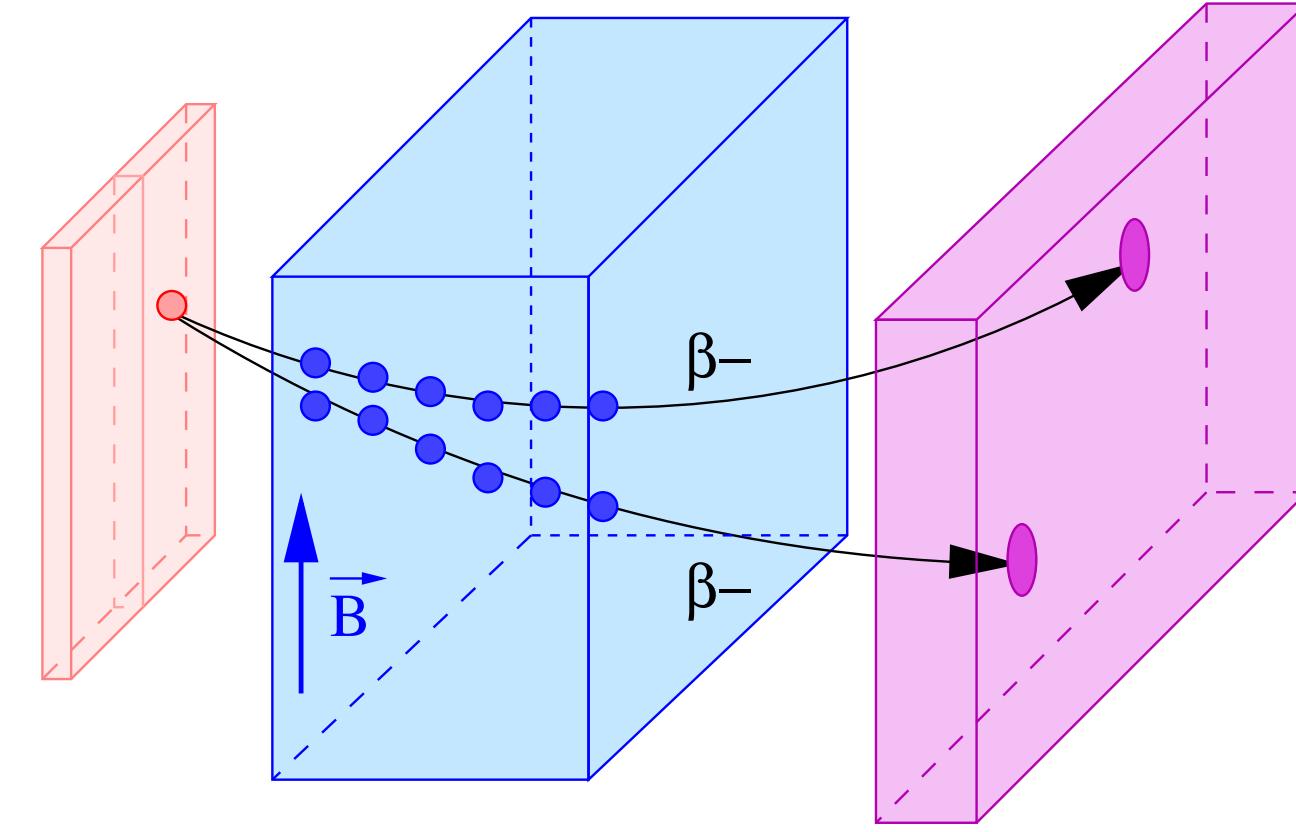
Neutrinoless double-beta-decay searches...



...study the total decay energy



SuperNEMO tracks the individual particles

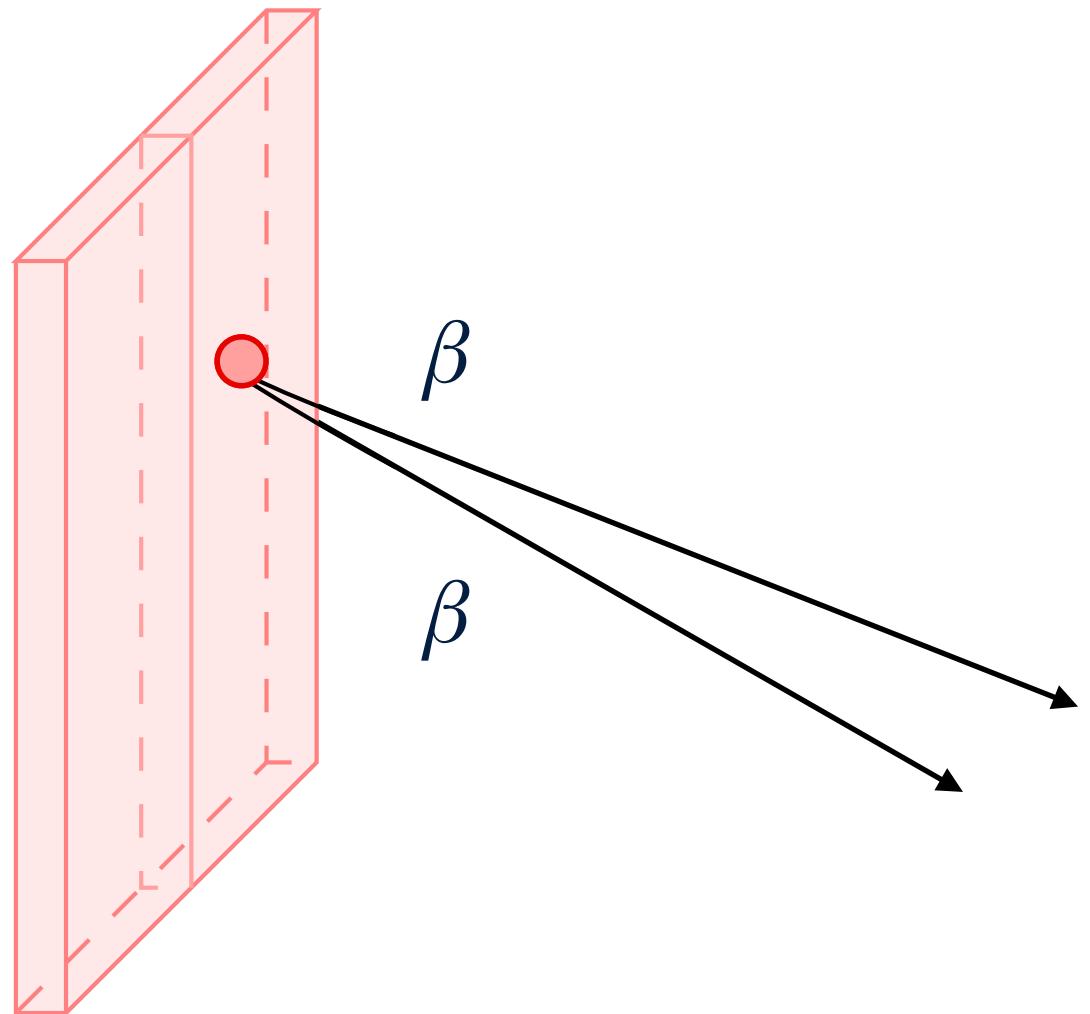


- (Almost) isotope agnostic
- Excellent background rejection
- Nuclear structure effects
- Decays to excited states
- Exotic decay searches

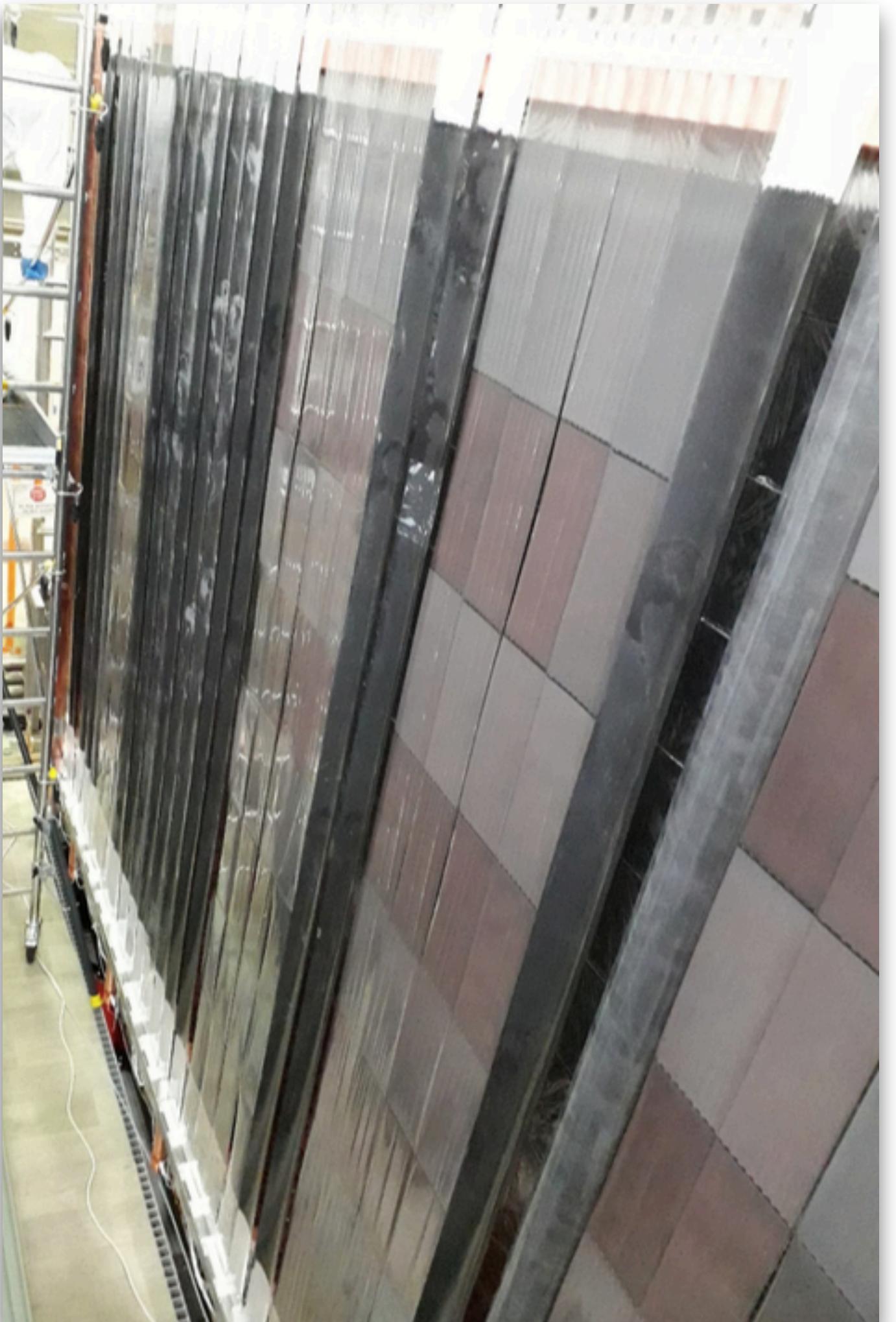
Key to understanding  $0\nu\beta\beta$  mechanism if it's discovered

# The NEMO principle

$\beta\beta$  source

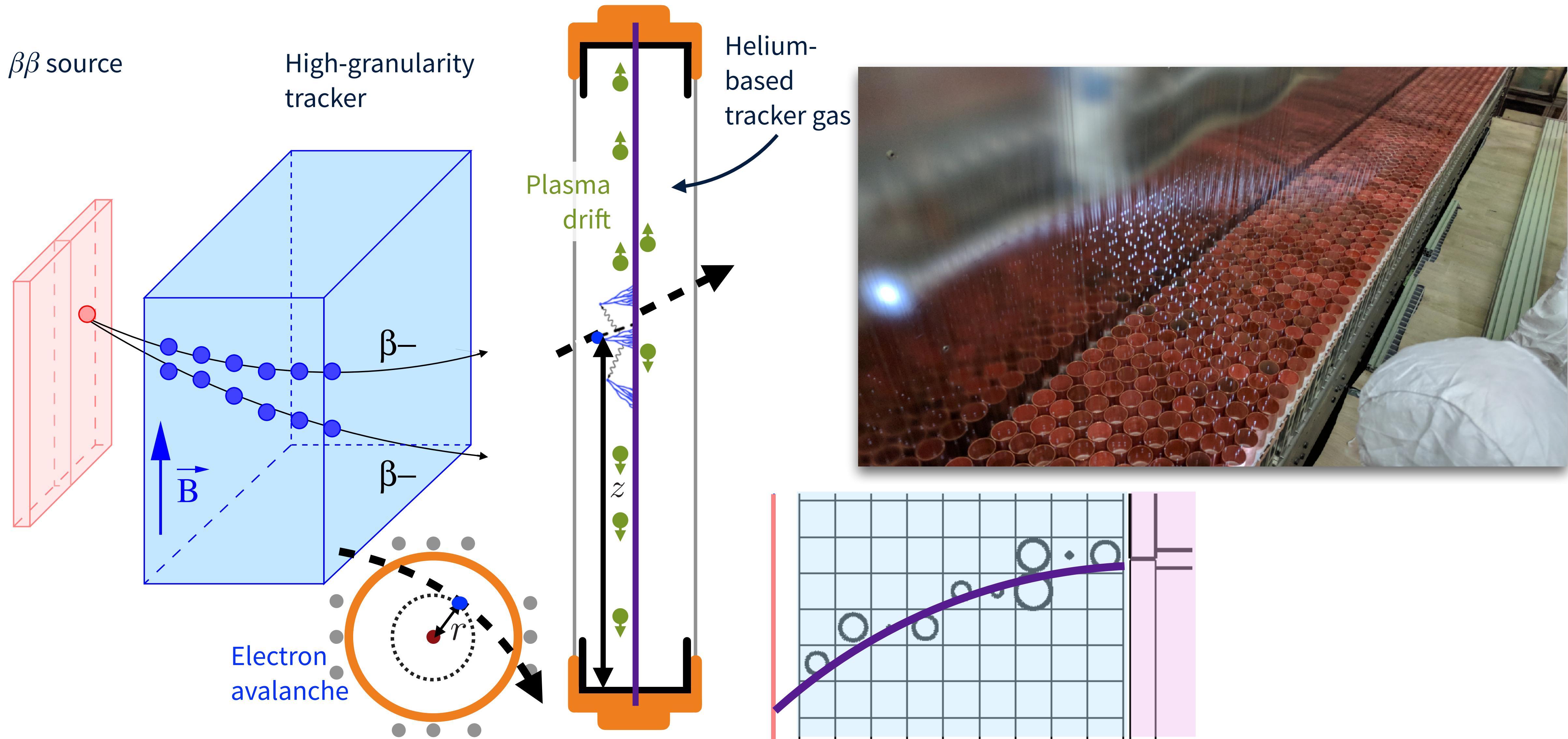


Any solid  $\beta\beta$  isotope

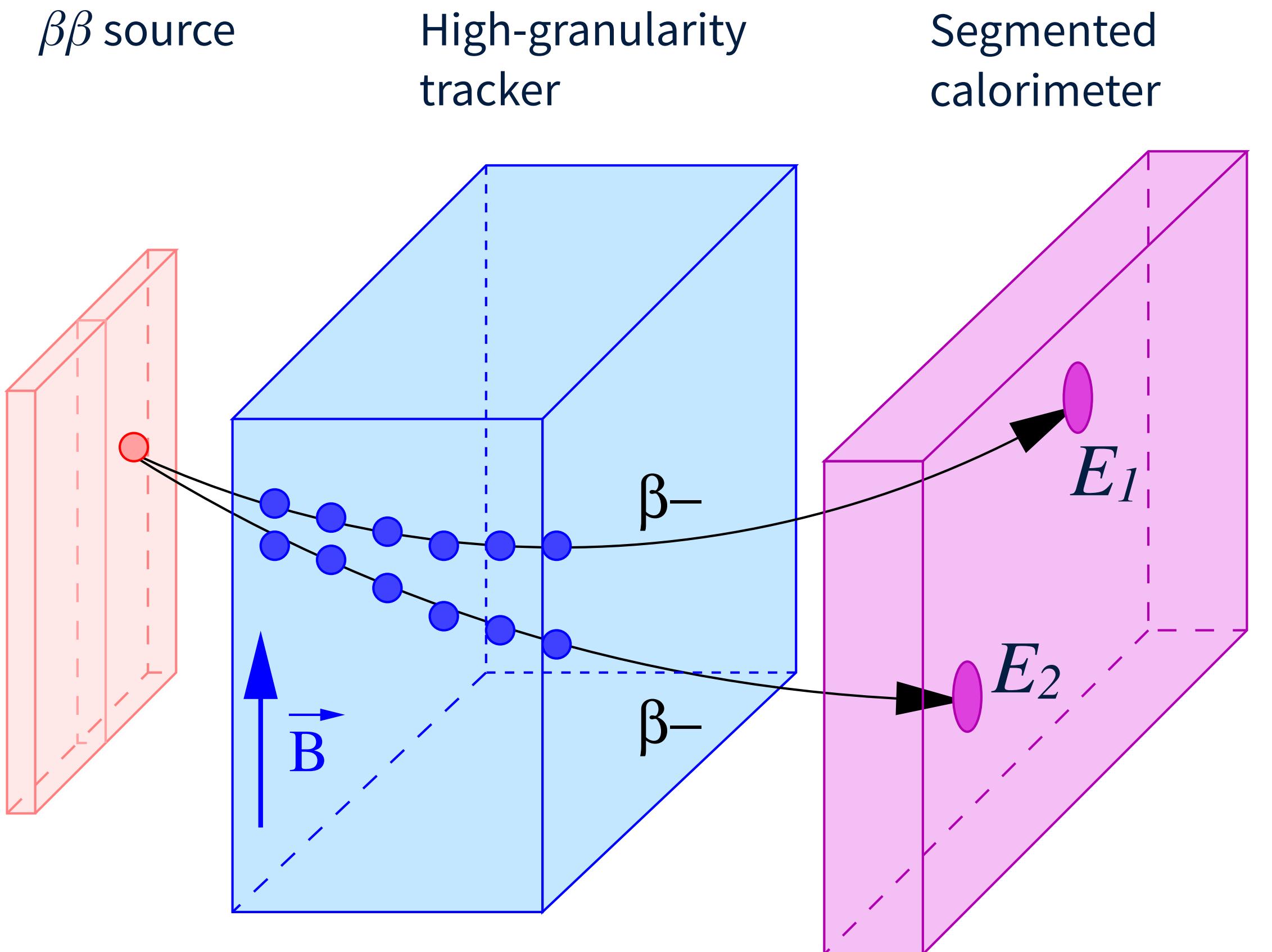


*Radiochimica Acta, 108 (2020) 11*

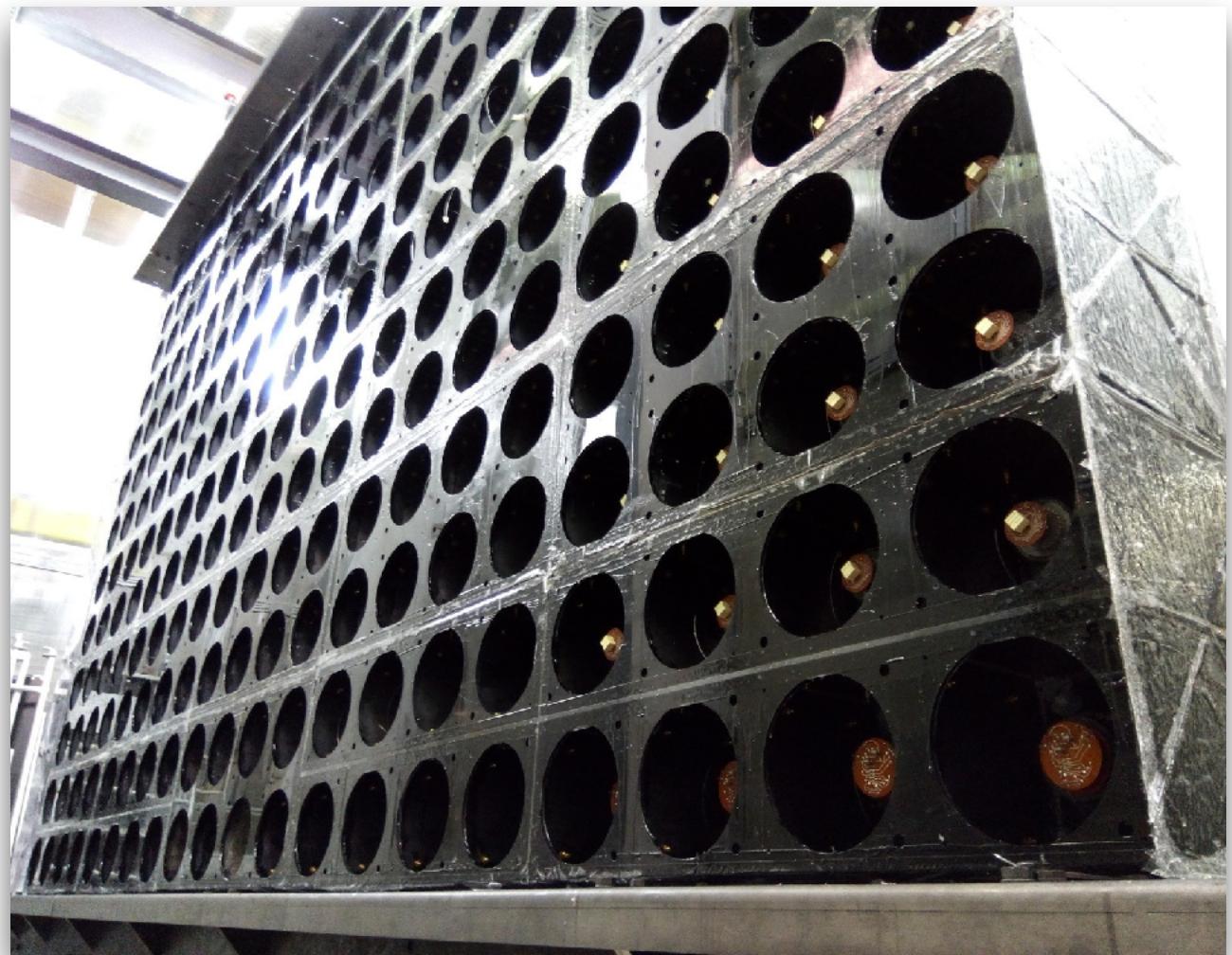
# The NEMO principle



# The NEMO principle



Individual energies  
& times

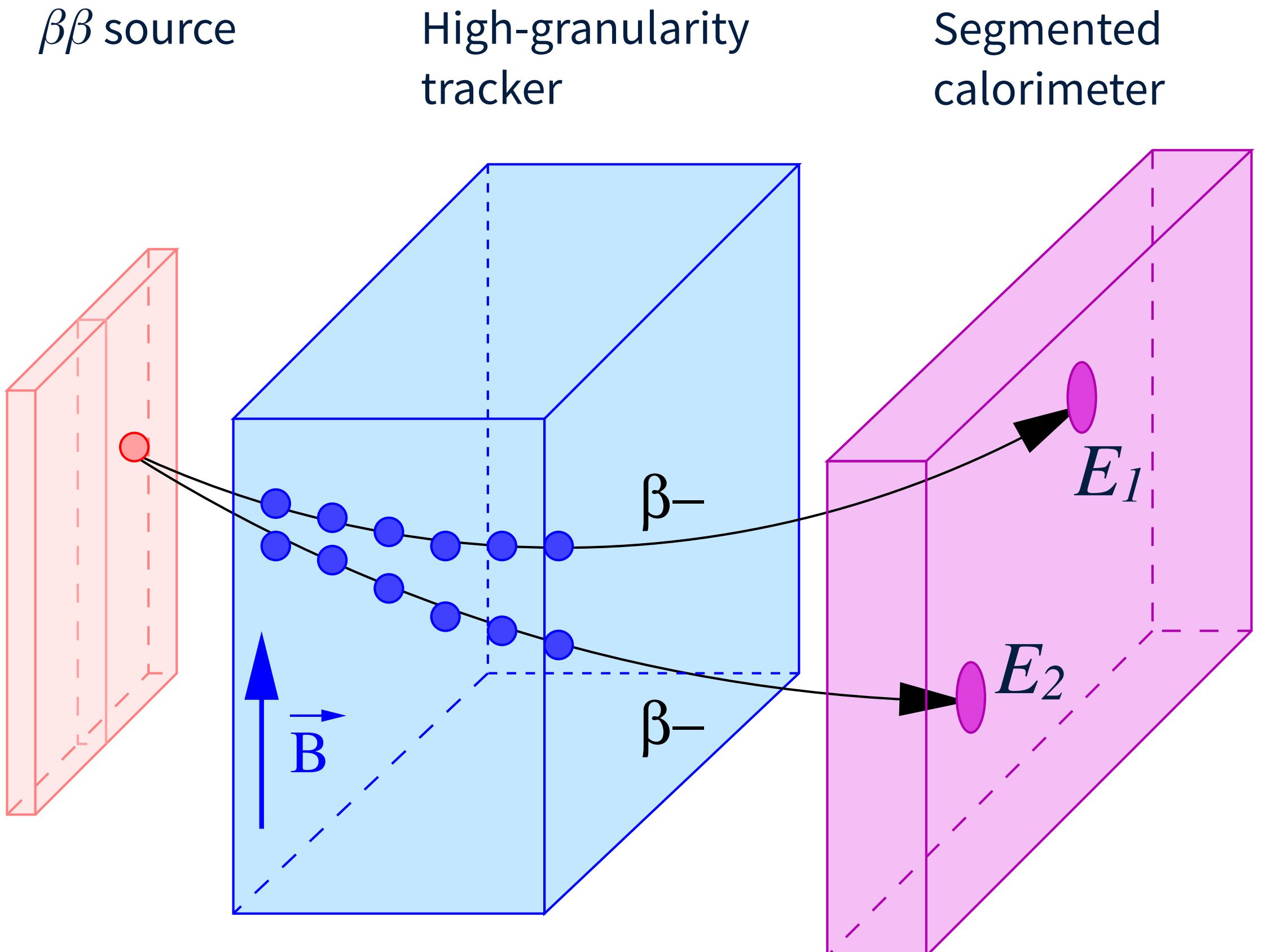


PMT-plus-scintillator  
optical modules



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

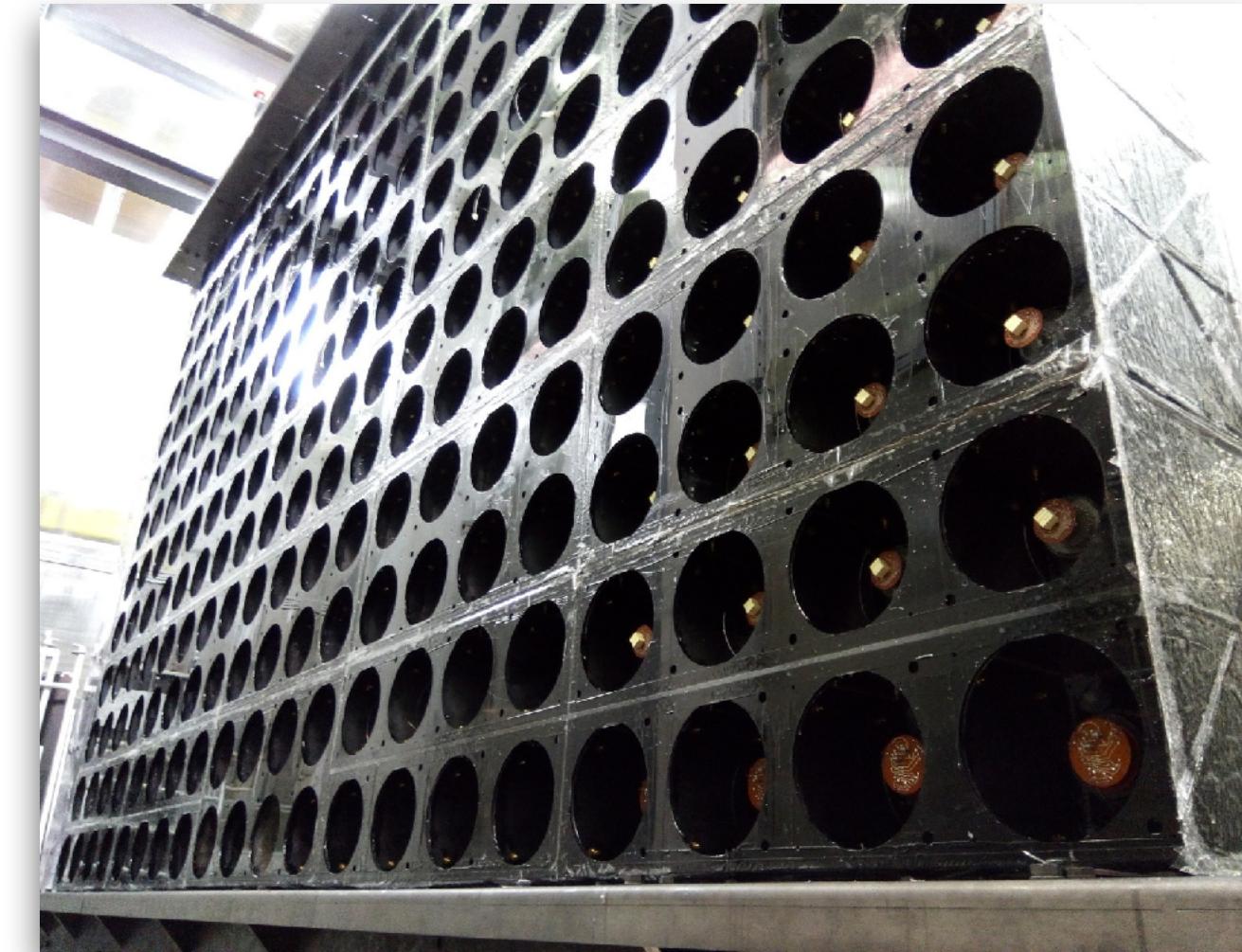
# The NEMO principle



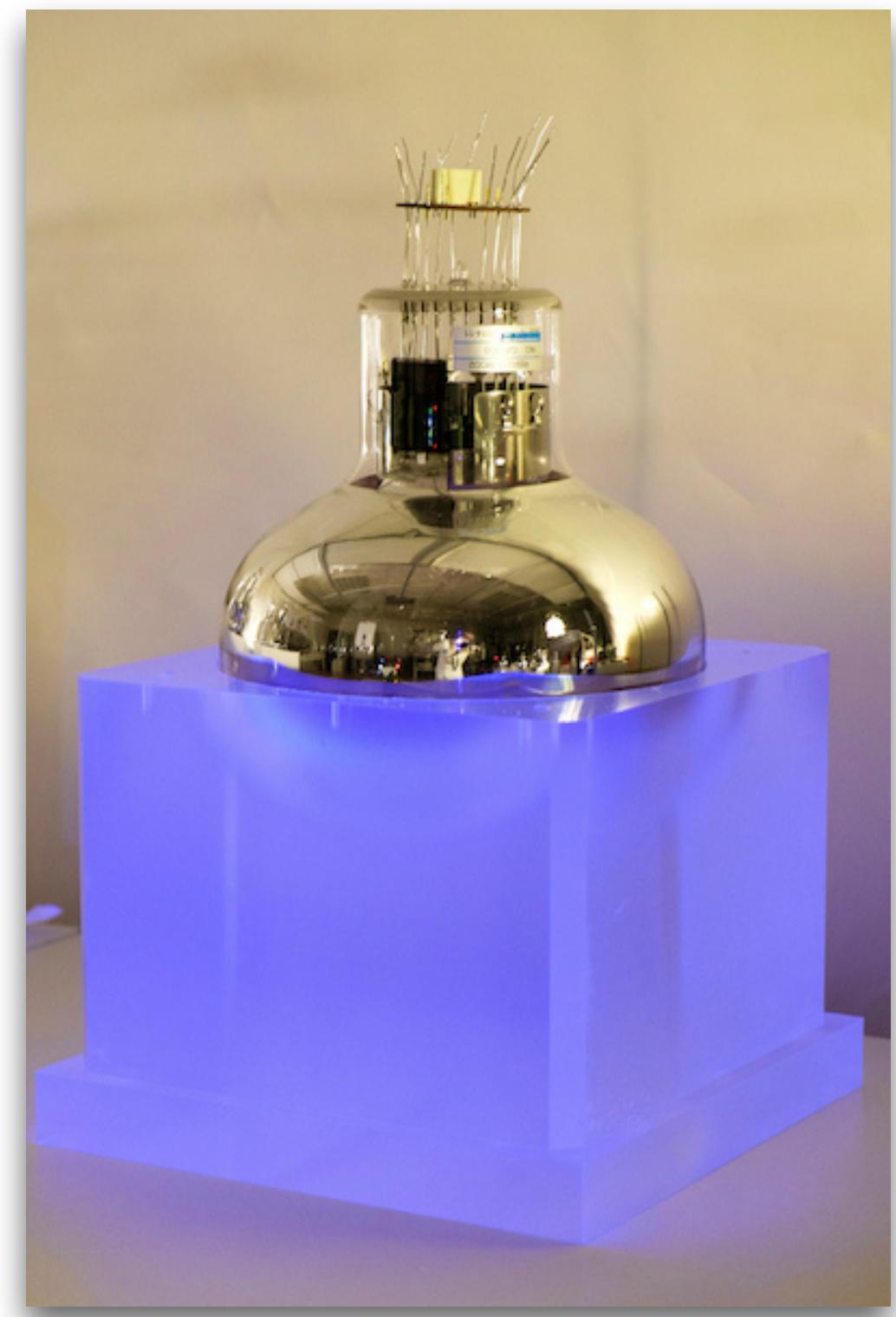
Angle between tracks  
+ particle / charge ID

+ Individual energies  
& times

= discrimination between  $\beta\beta$   
mechanisms and nuclear effects;  
background rejection



PMT-plus-scintillator  
optical modules

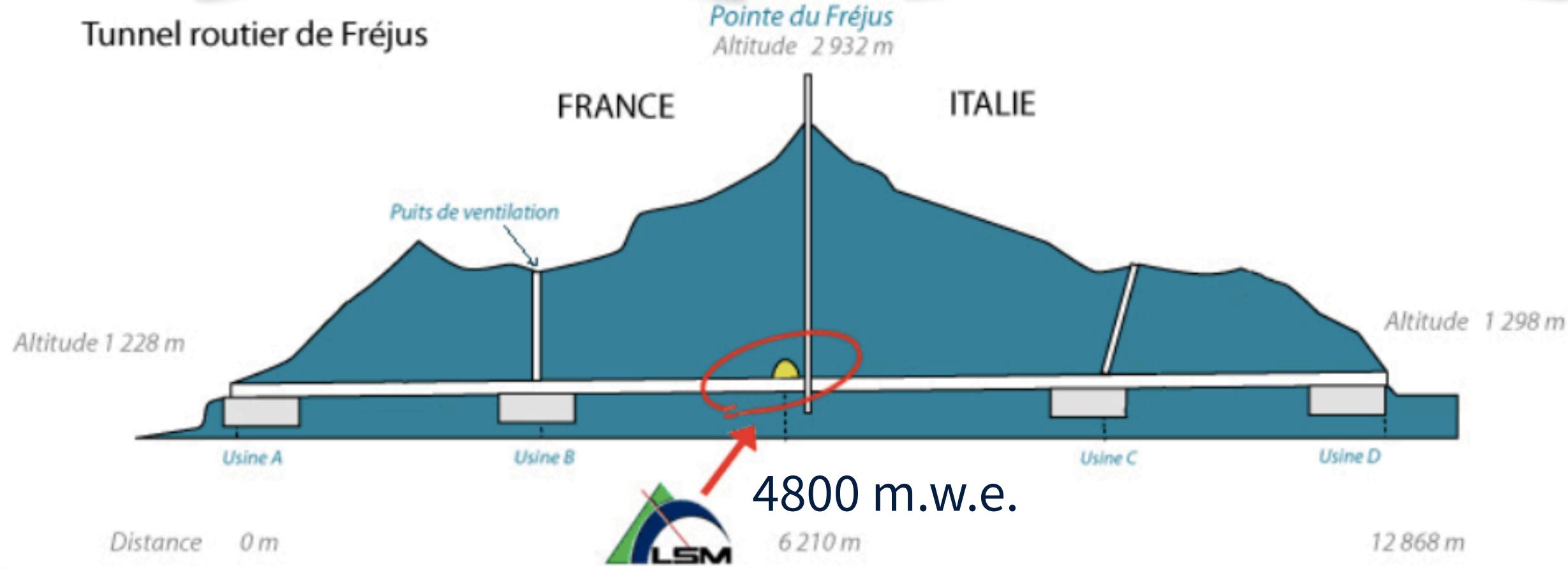


*Nucl.Inst.Meth. A 868 98-108 (2017)*

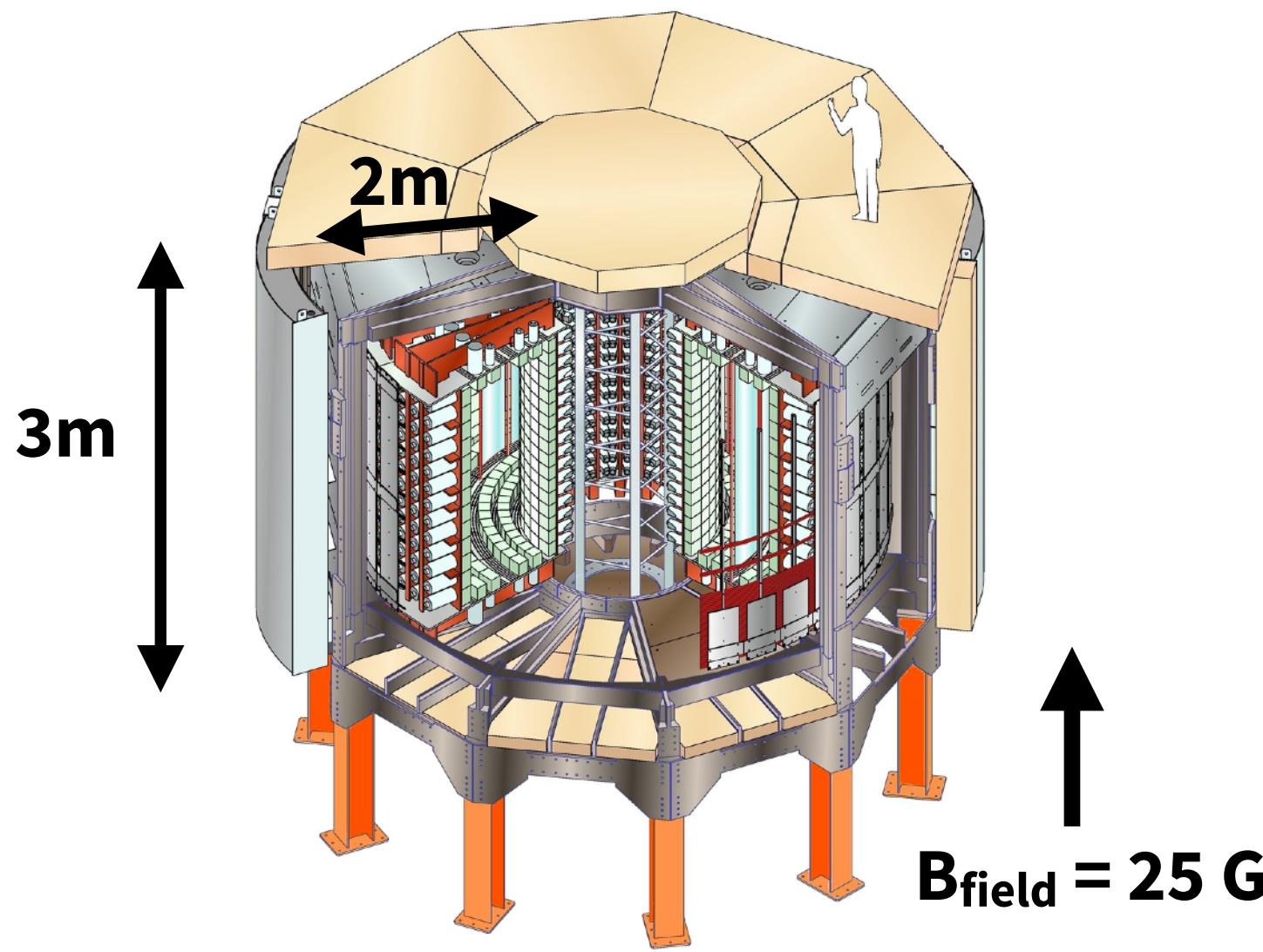
# SuperNEMO and NEMO-3 at LSM, Modane, France

~100 collaborators from 9 countries

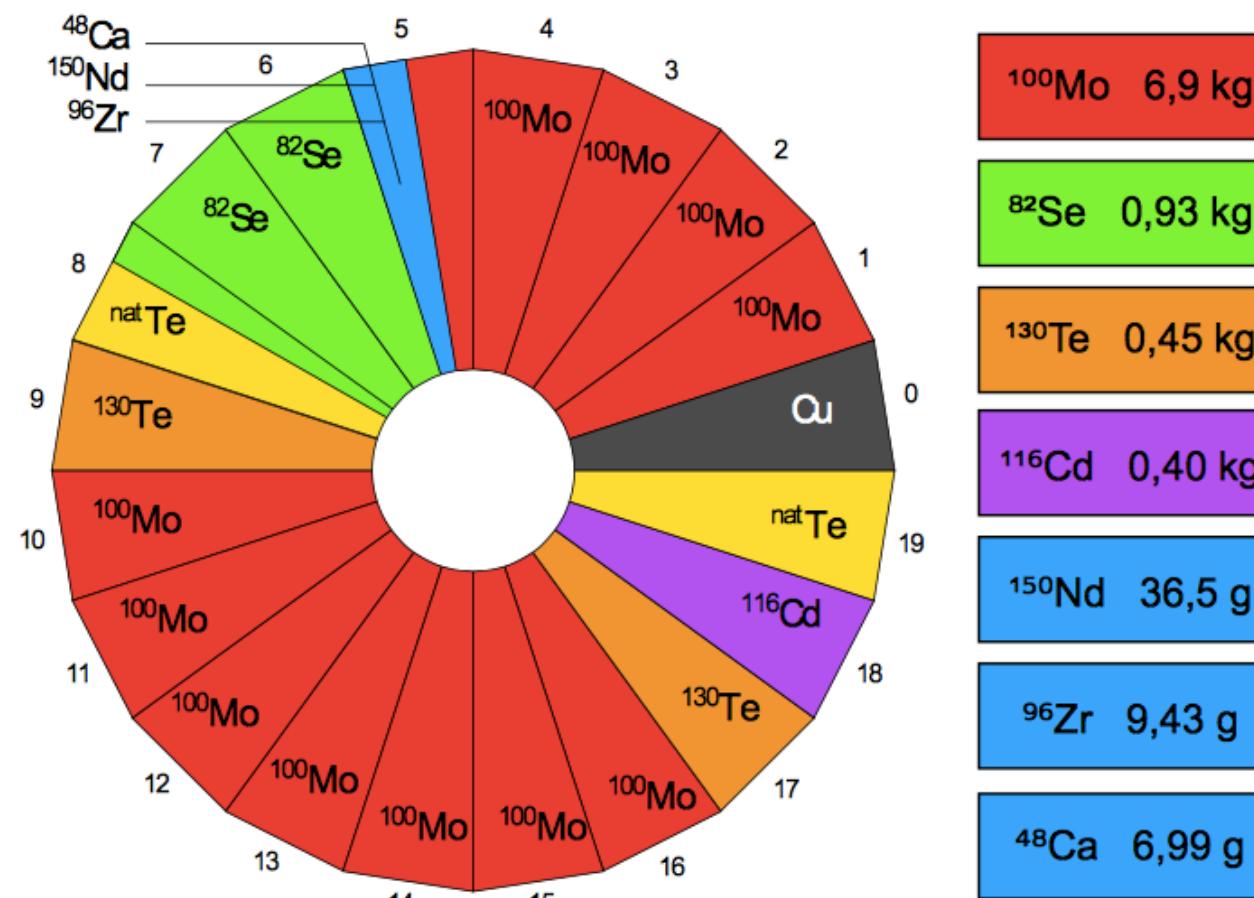
<https://supernemo.org>



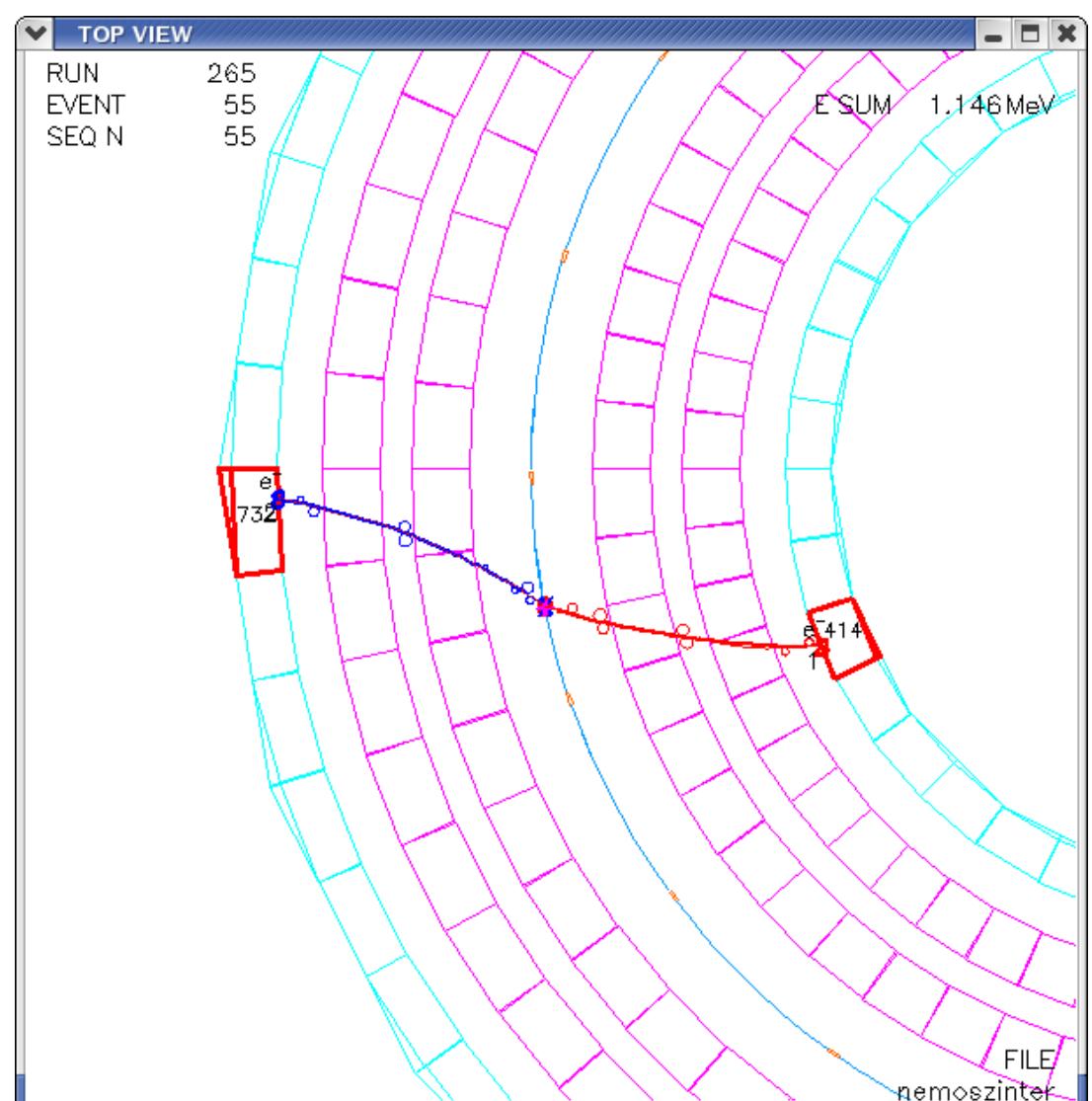
# Our predecessor: NEMO-3 (running 2003-2011)



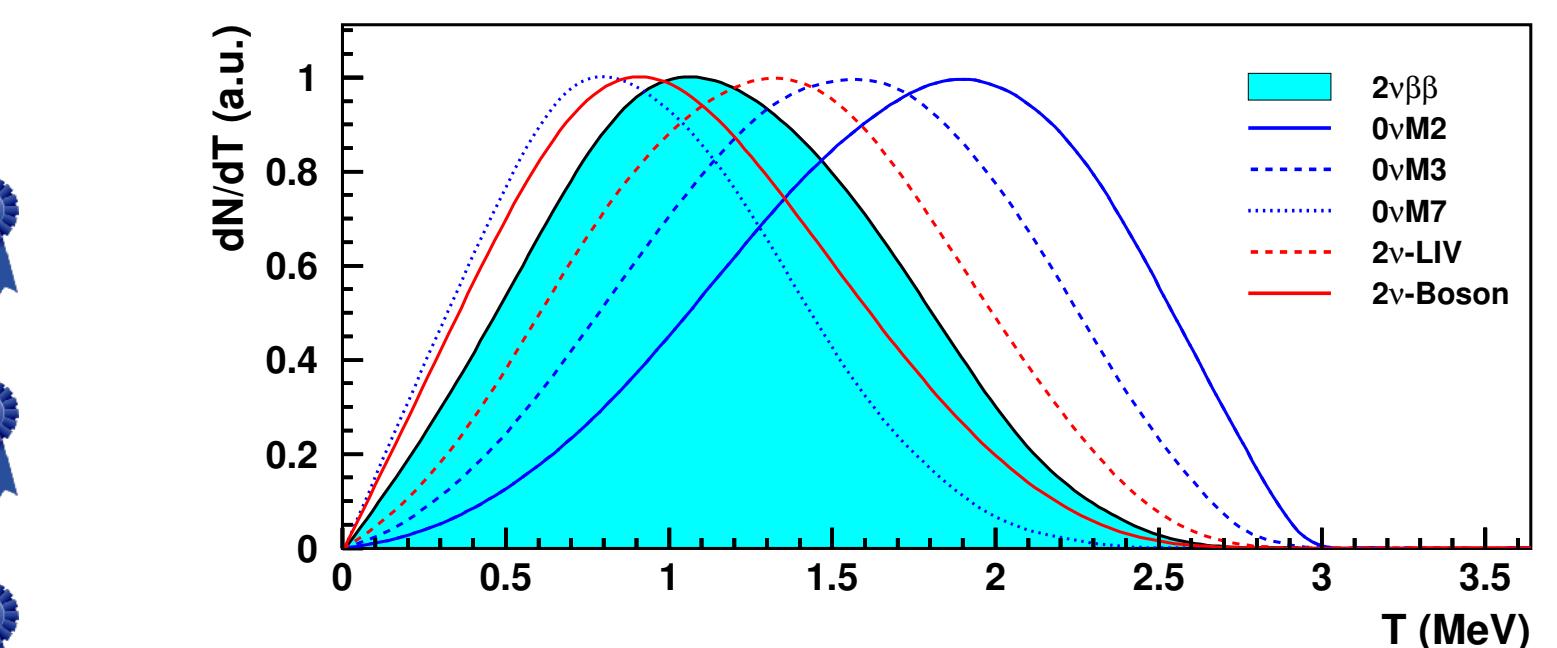
NEMO-3 "camembert" (source top view)



## 2 $\nu\beta\beta$ measurements and 0 $\nu\beta\beta$ limit



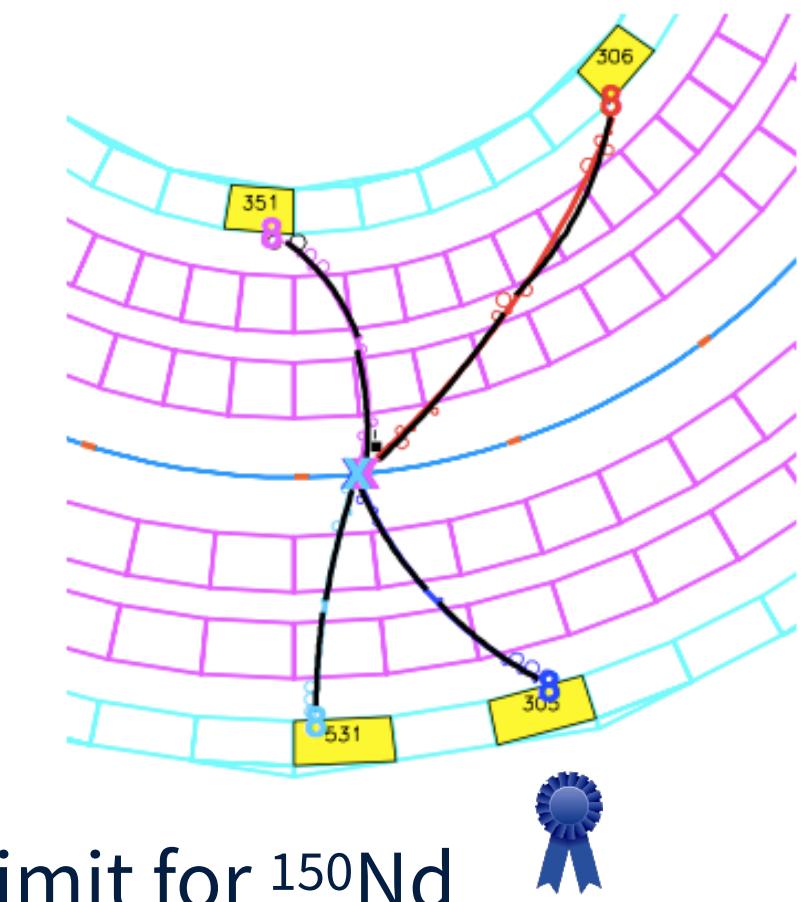
- **100Mo** (Eur. Phys. J. C (2019) 79: 440)
- **82Se** (Eur. Phys. J. C (2018) 78: 821)
- **48Ca** (Phys. Rev. D 93 (2016), 112008)
- **150Nd** (Phys. Rev. D 94 (2016), 072003)
- **116Cd** (Phys. Rev. D 95 (2017), 012007)
- **130Te** (Phys. Rev. Lett. 107 (2011), 062504)
- **96Zr** (Nucl.Phys.A847 (2010):168-179)



- 0 $\nu$ 4 $\beta$  limit for  $^{150}\text{Nd}$

*Phys. Rev. Lett. 119, 041801*

## New-physics searches



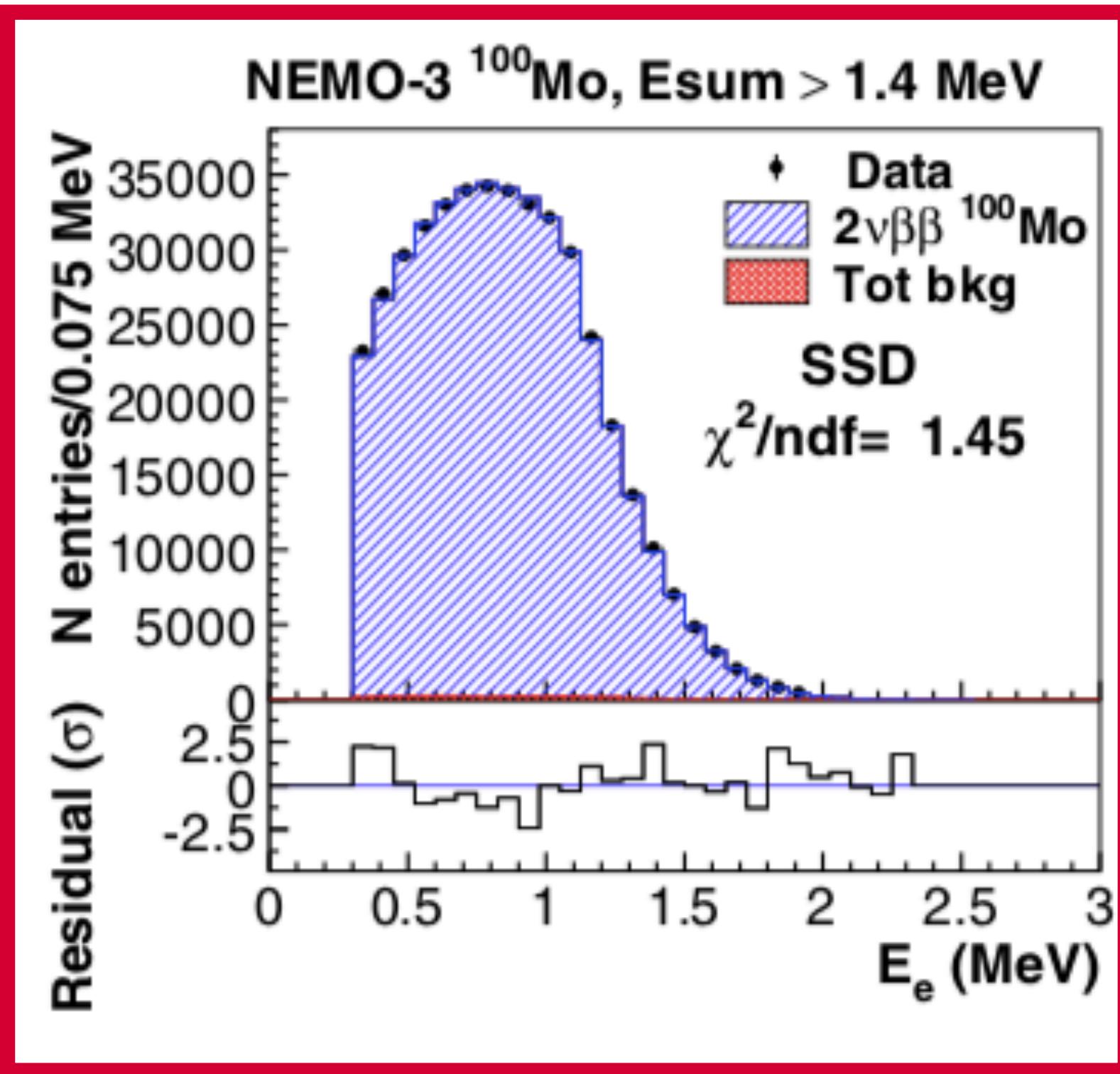
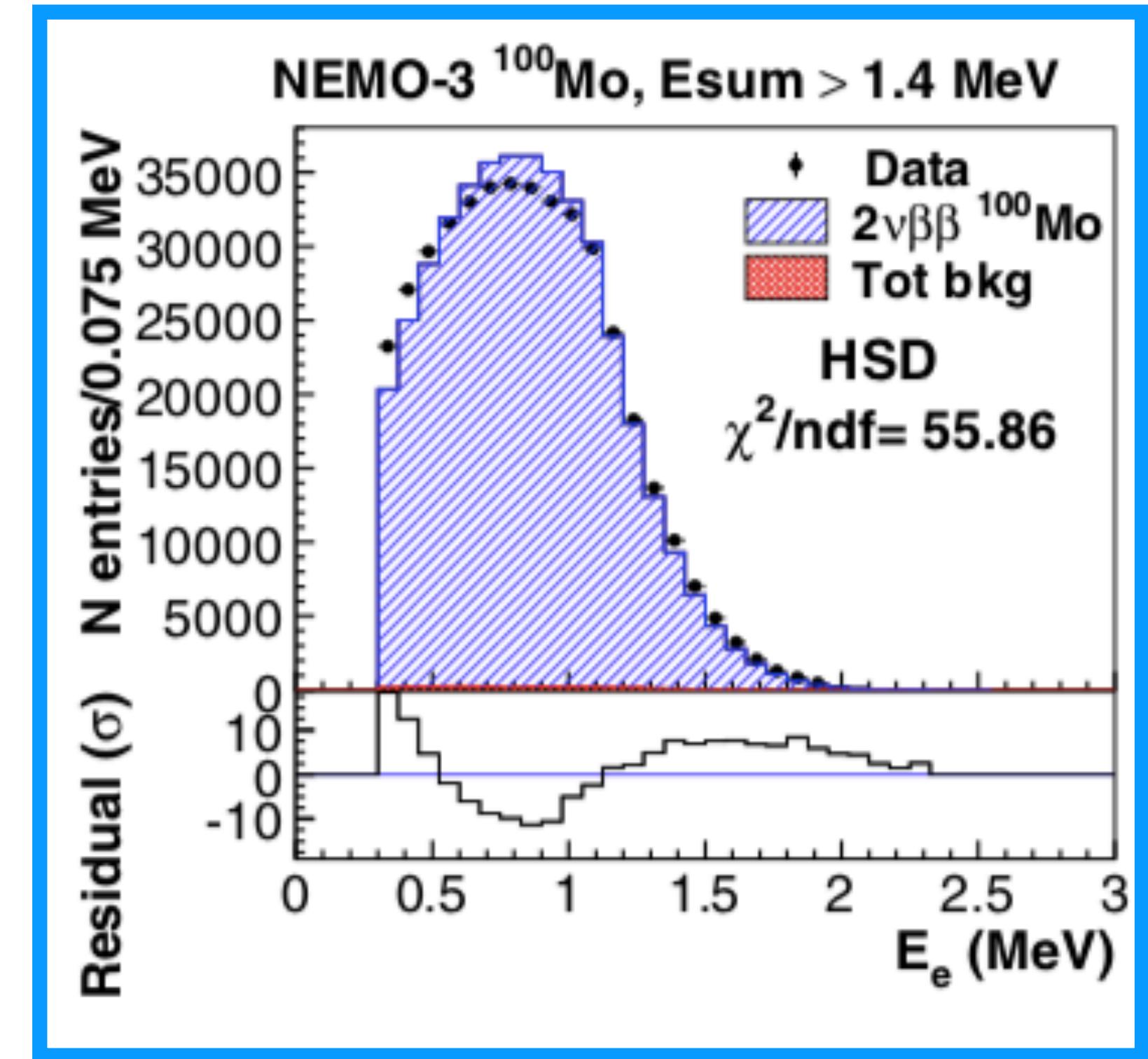
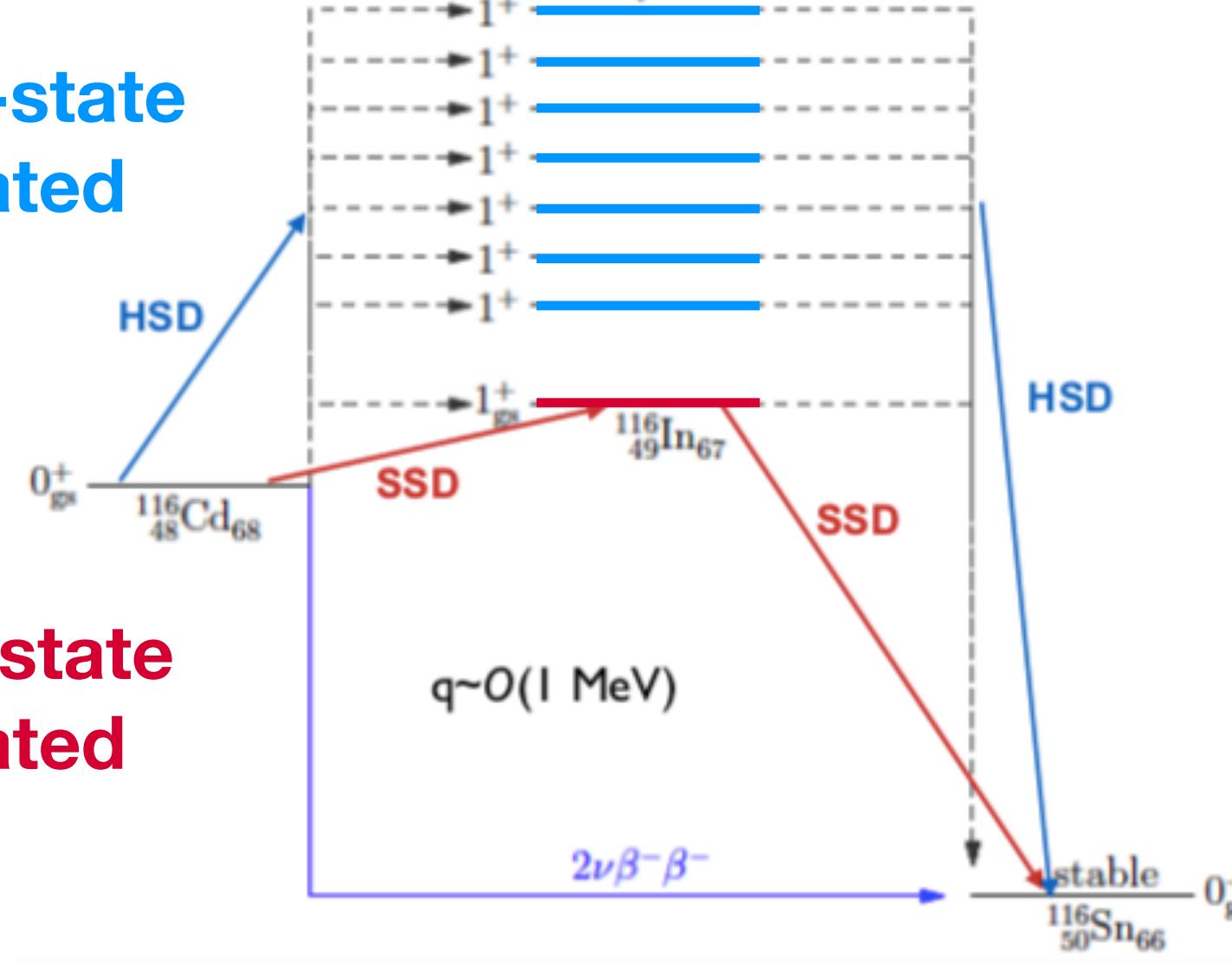
- Lorentz-invariance violation
- Exotic decay modes *Eur. Phys. J. C (2019) 79: 440*
- Time invariance with 2 $\nu\beta\beta$

*Phys. Rev. C 104, L061601 (2021)*

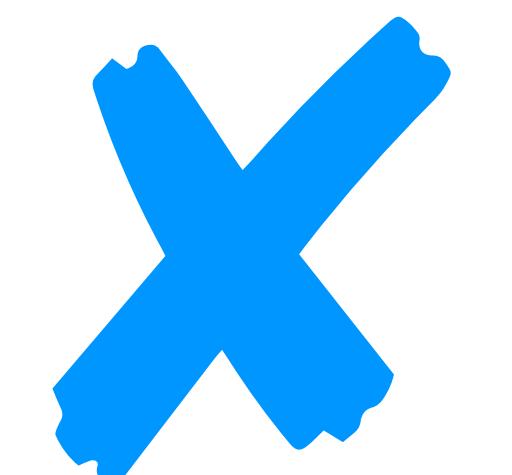
# The power of topological reconstruction with $2\nu\beta\beta$ at NEMO-3

Higher-state dominated

Single-state dominated



- $^{100}\text{Mo}$  flagship measurement
- $5 \times 10^5$  events; signal / bkgd  $\sim 80$
- **SSD preferred with  $5\sigma$  significance**

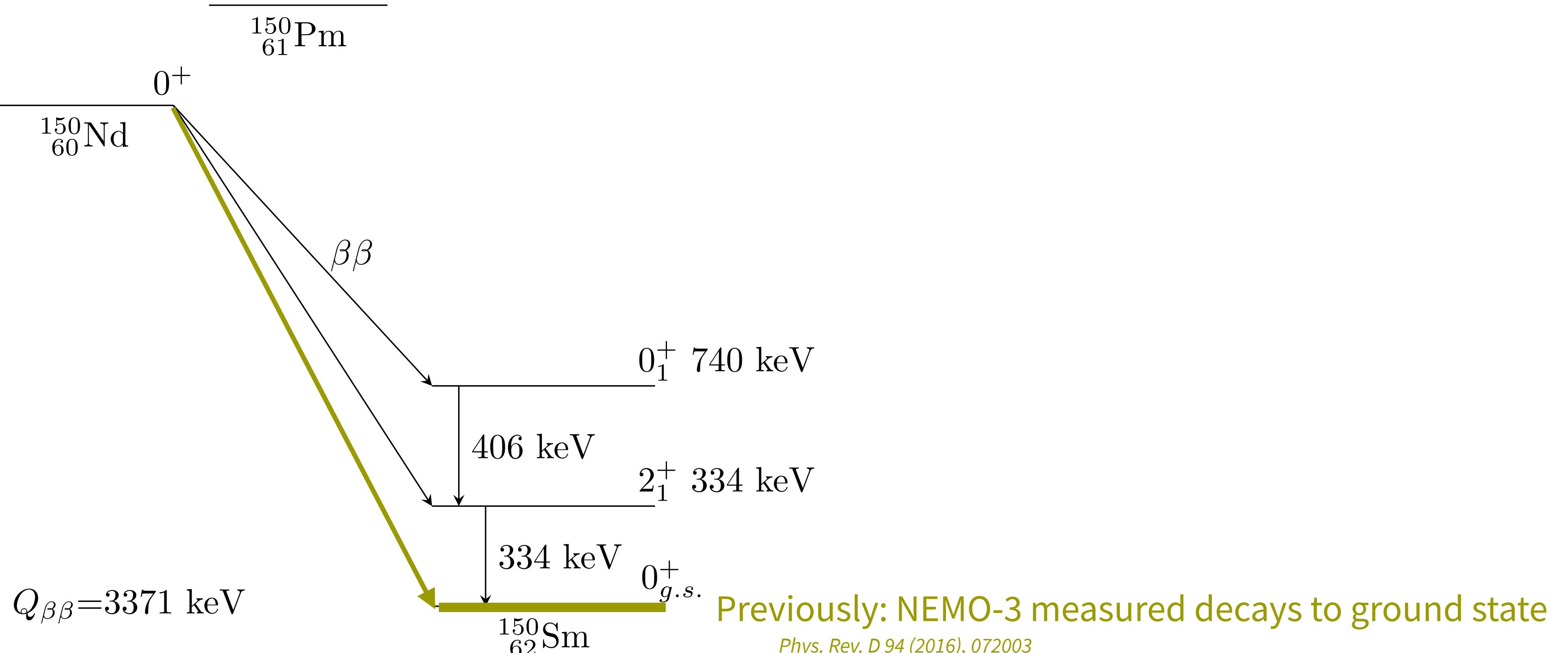


(Eur. Phys. J. C (2019) 79: 440)

# $^{150}\text{Nd}$ decays to excited states at NEMO-3

[arXiv:2203.03356 \[nucl-ex\]](https://arxiv.org/abs/2203.03356) - to be submitted to Eur Phys J C

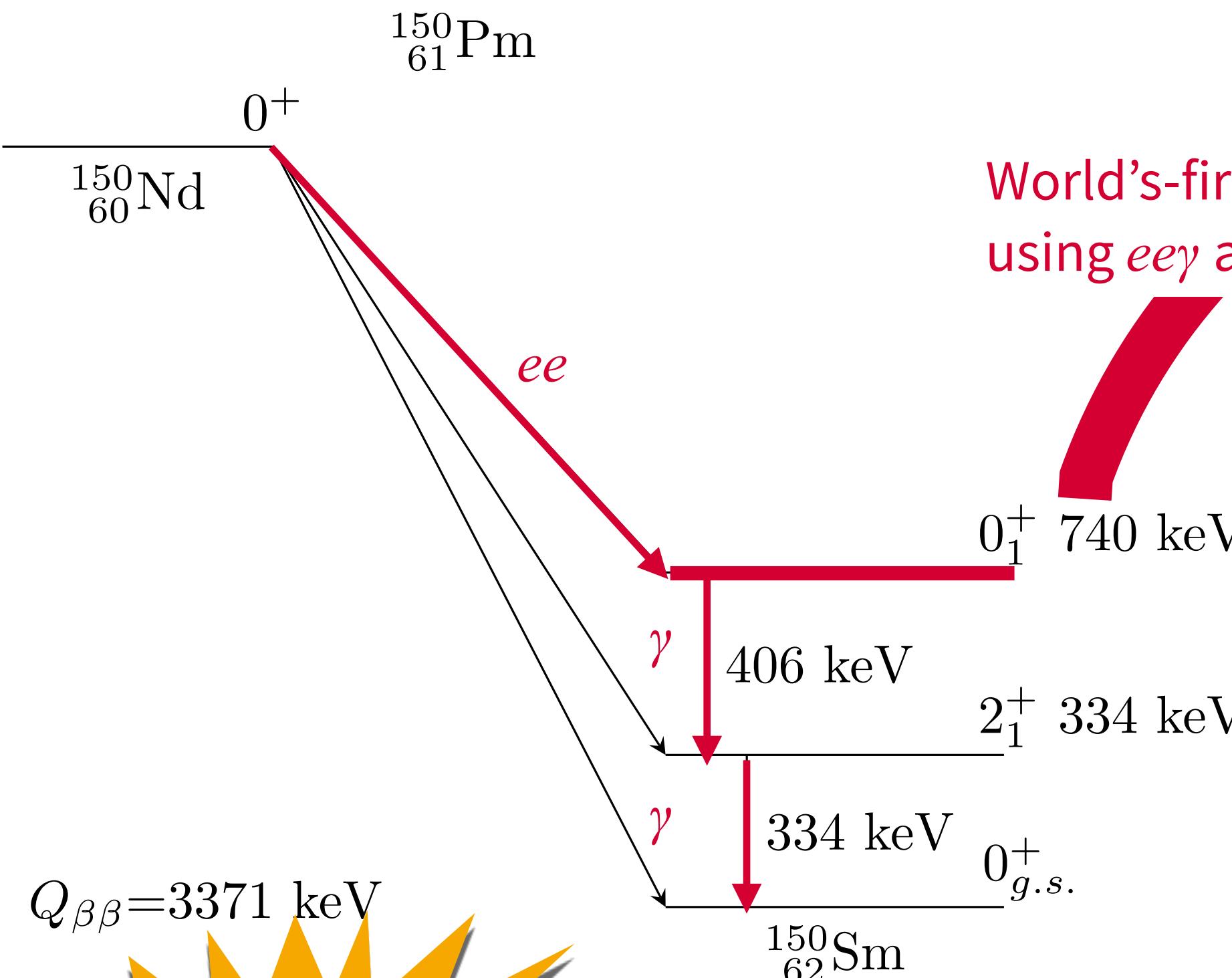
36.6g  $^{150}\text{Nd}$ , 5.25-year run time



# $^{150}\text{Nd}$ decays to excited states at NEMO-3

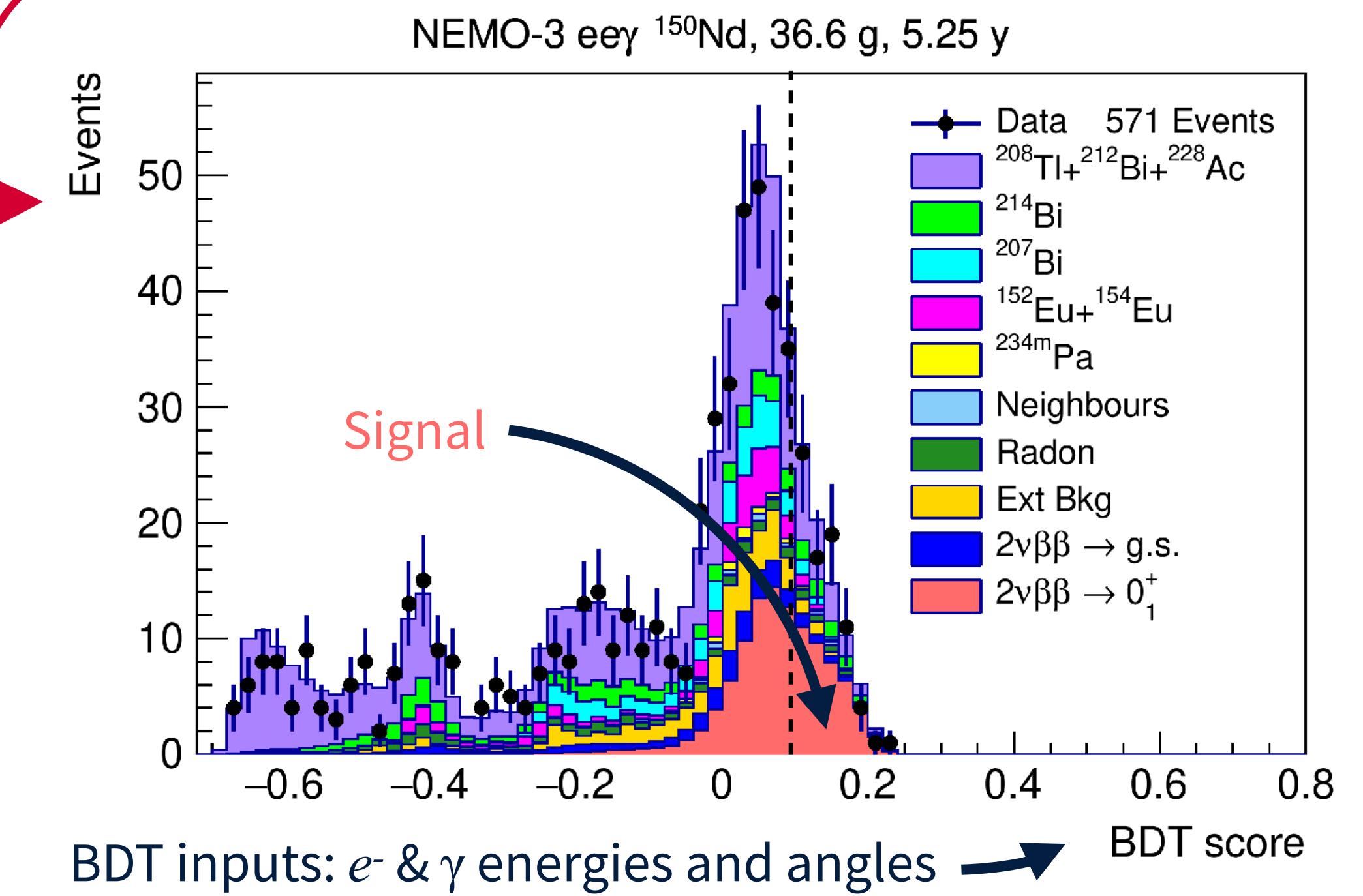
arXiv:2203.03356 [nucl-ex] - to be submitted to Eur Phys J C

36.6g  $^{150}\text{Nd}$ , 5.25-year run time



World's-first observation,  
using  $eey$  and  $ee\gamma\gamma$  data

**NEW!**

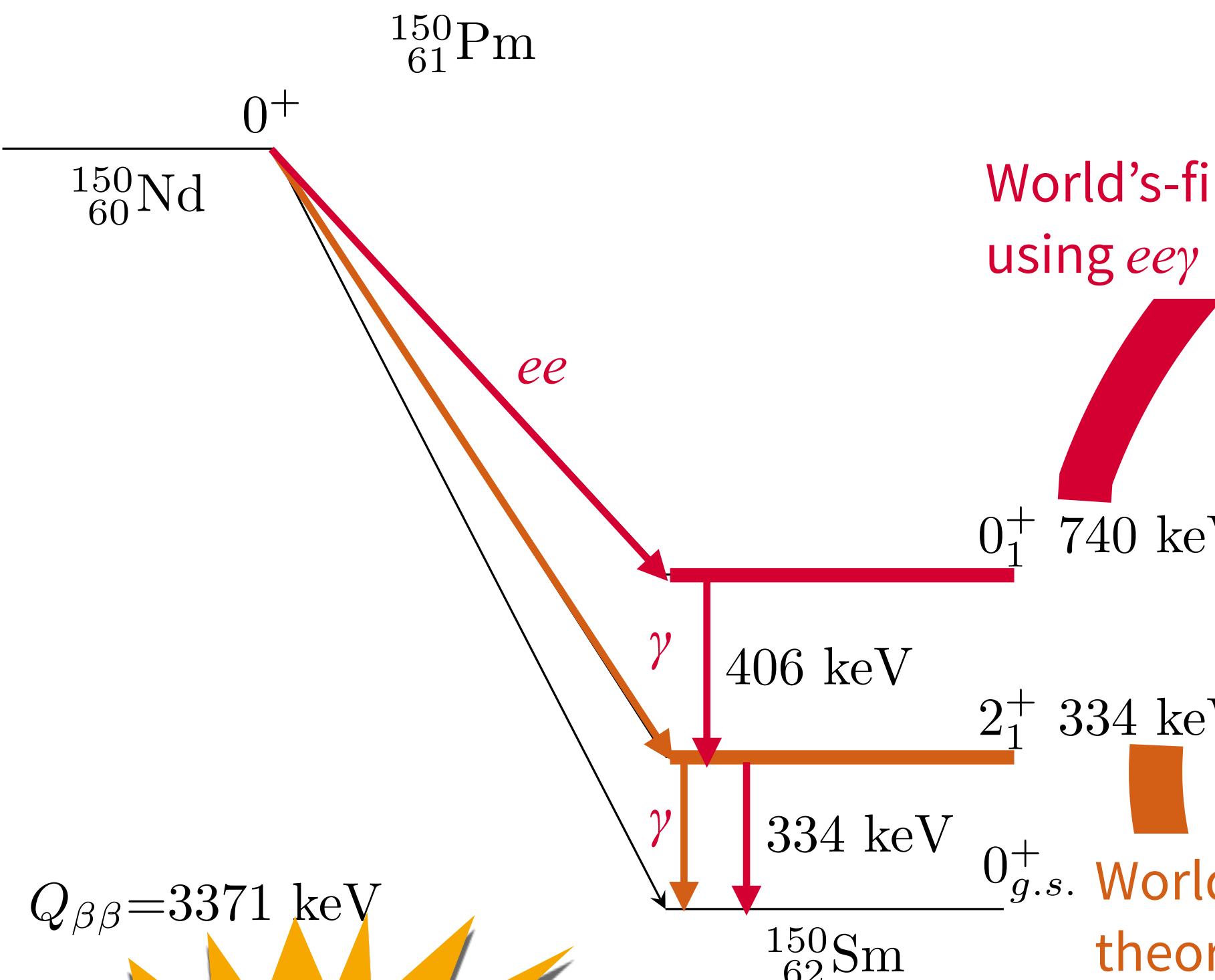


$$T_{1/2}^{2\nu\beta\beta}(0_1^+) = [1.11^{+0.19}_{-0.14} \text{ (stat)}^{+0.17}_{-0.15} \text{ (syst)}] \times 10^{20} \text{ yr}$$

# $^{150}\text{Nd}$ decays to excited states at NEMO-3

arXiv:2203.03356 [nucl-ex] - to be submitted to Eur Phys J C

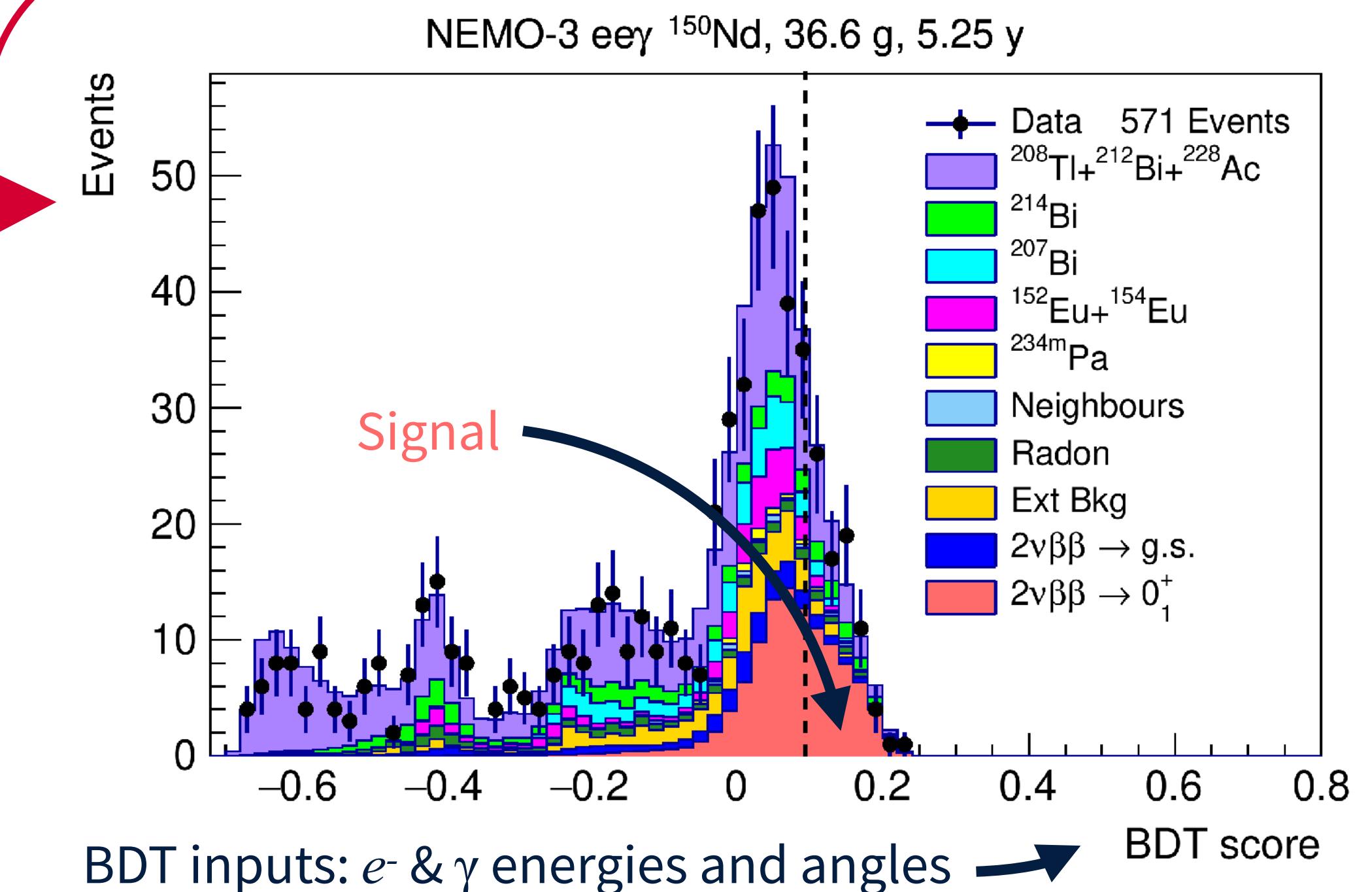
36.6g  $^{150}\text{Nd}$ , 5.25-year run time



**NEW!**

World's-first observation,  
using  $ee\gamma$  and  $ee\gamma\gamma$  data

World's-best limit set (below  
theoretical prediction)



$$T_{1/2}^{2\nu\beta\beta}(0^+_1) = [1.11^{+0.19}_{-0.14} \text{ (stat)}^{+0.17}_{-0.15} \text{ (syst)}] \times 10^{20} \text{ yr}$$

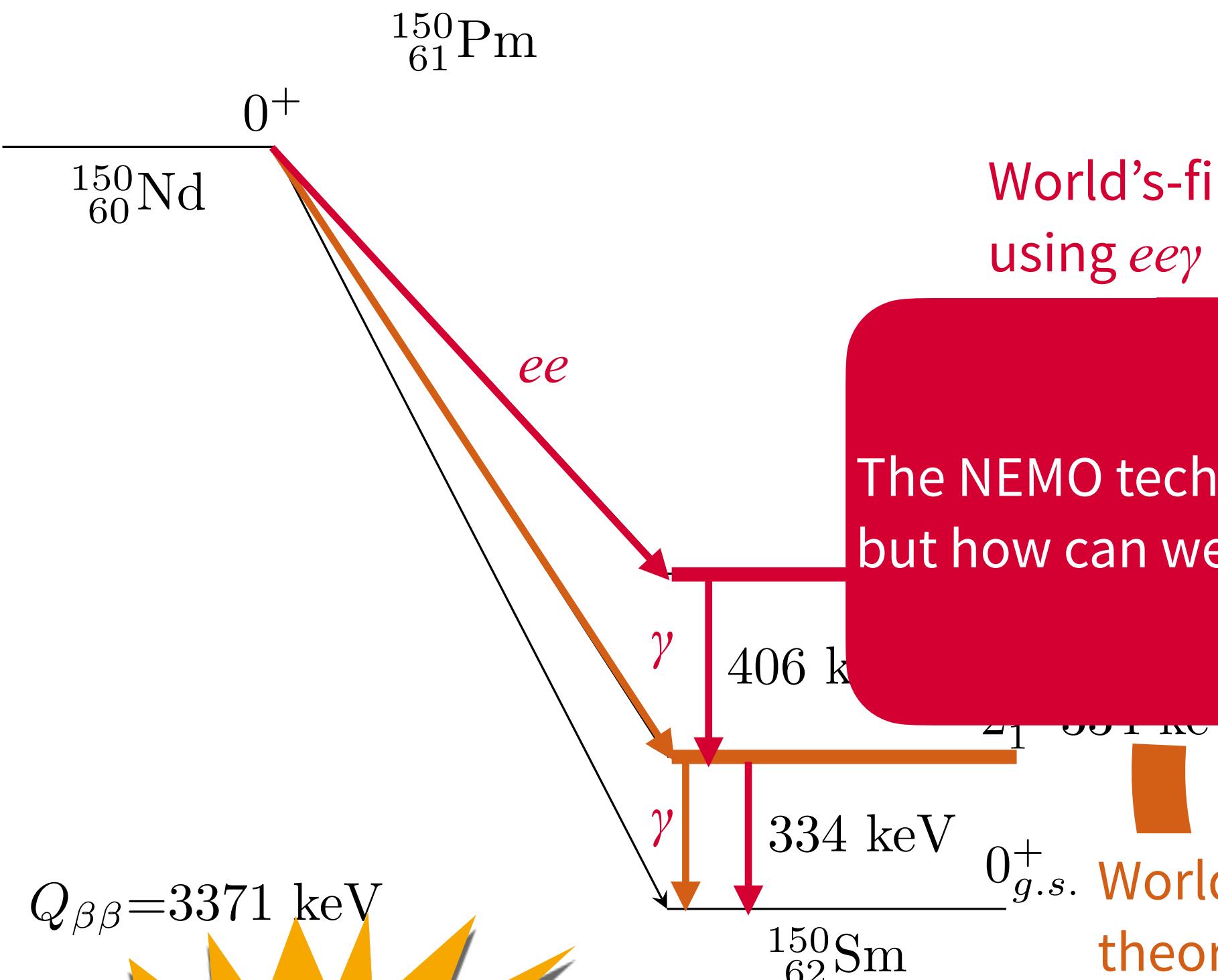
$$T_{1/2}^{2\nu\beta\beta}(2^+_1) > 2.42 \times 10^{20} \text{ yr (90% C.L.)}$$

Plus new limits on  $0\nu\beta\beta$  to excited states

# $^{150}\text{Nd}$ decays to excited states at NEMO-3

arXiv:2203.03356 [nucl-ex] - to be submitted to Eur Phys J C

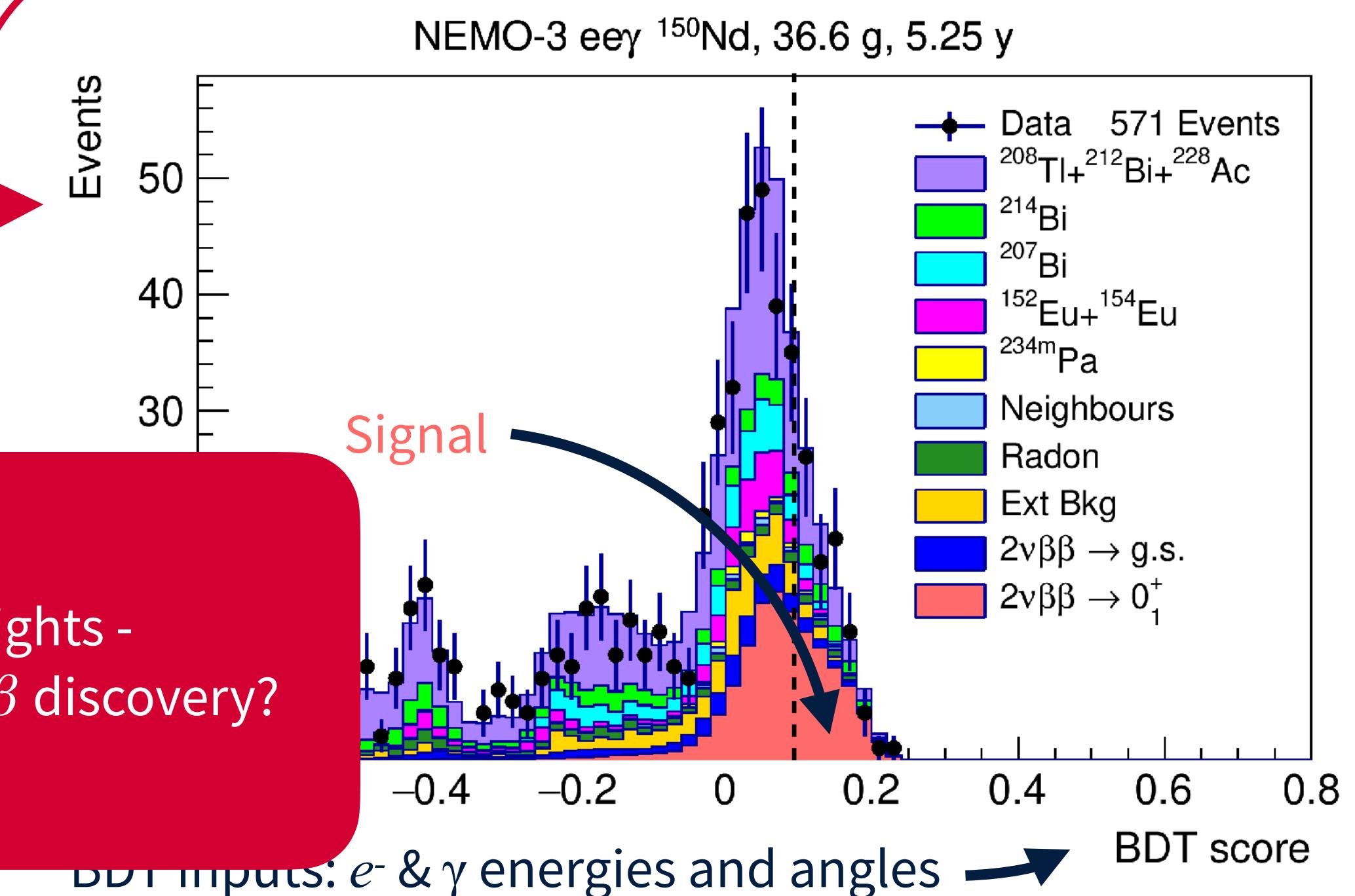
36.6g  $^{150}\text{Nd}$ , 5.25-year run time



World's-first observation,  
using  $e\gamma\gamma$  and  $e\gamma\gamma\gamma$  data

The NEMO technique can give unique insights -  
but how can we scale to be ready for  $0\nu\beta\beta$  discovery?

World's-best limit set (below  
theoretical prediction)

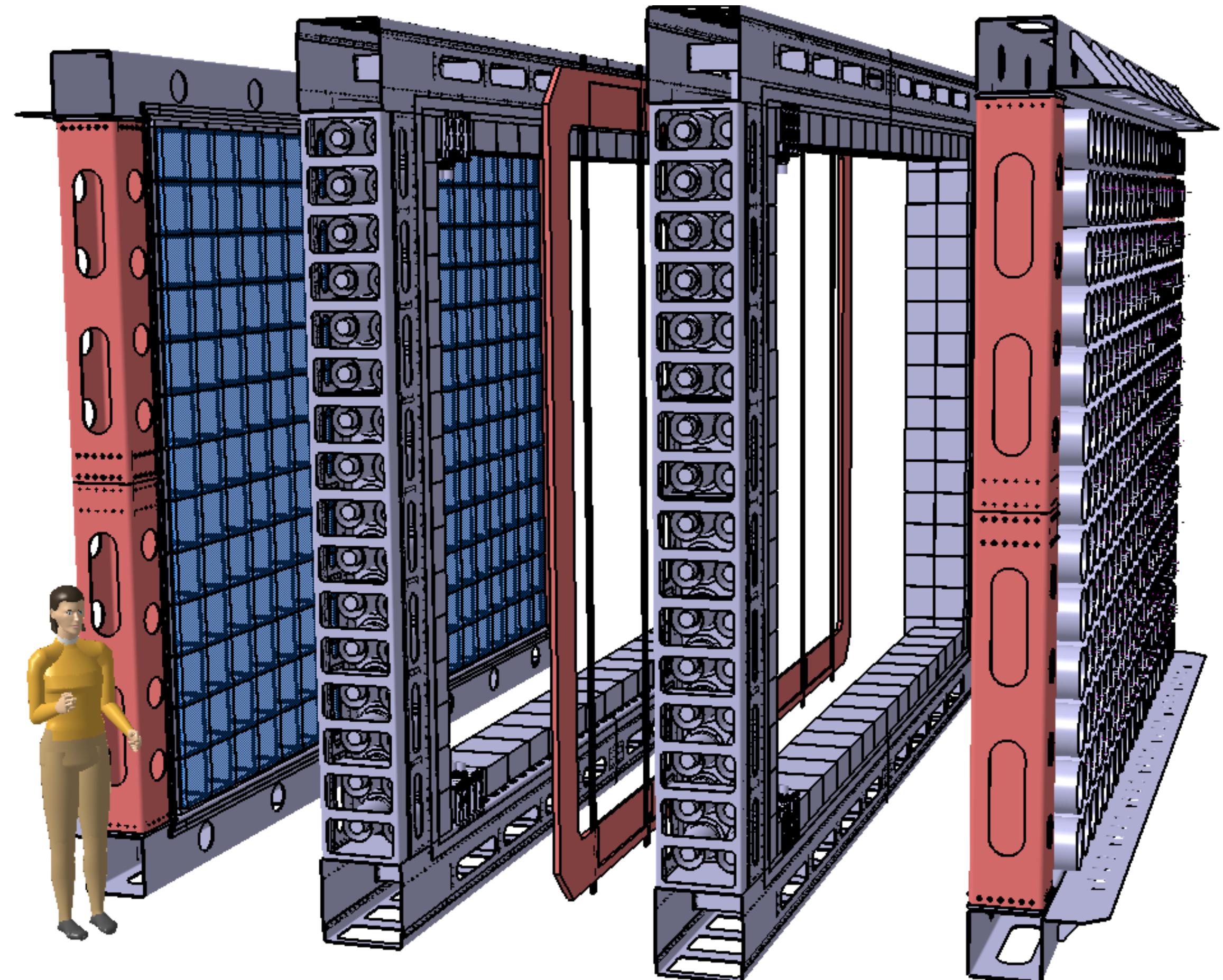


$$T_{1/2}^{2\nu\beta\beta}(0_1^+) = [1.11^{+0.19}_{-0.14} \text{ (stat)}^{+0.17}_{-0.15} \text{ (syst)}] \times 10^{20} \text{ yr}$$

$$T_{1/2}^{2\nu\beta\beta}(2_1^+) > 2.42 \times 10^{20} \text{ yr (90\% C.L.)}$$

Plus new limits on  $0\nu\beta\beta$  to excited states

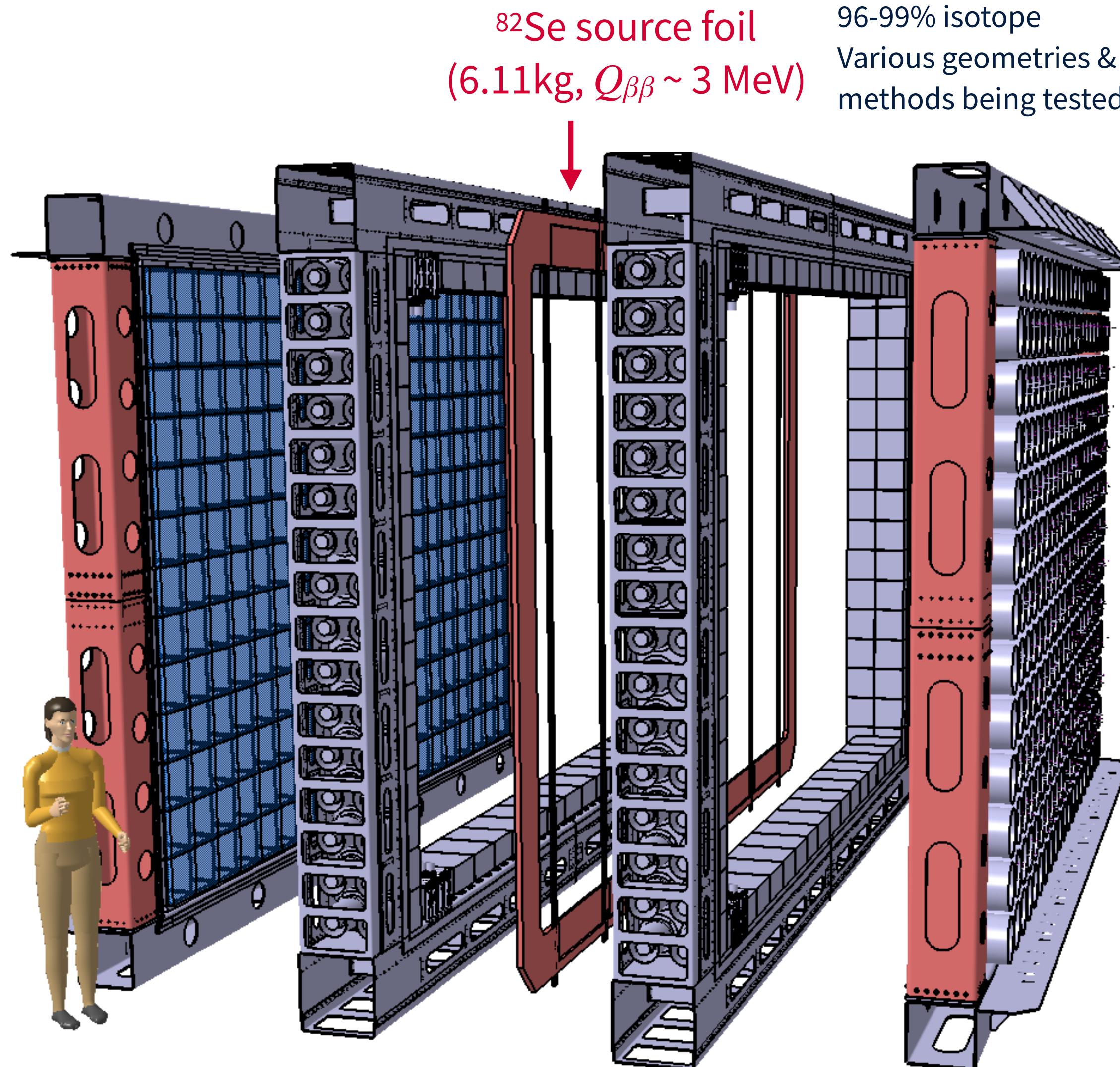
# SuperNEMO Demonstrator (now at LSM)



Modular design to test scalability



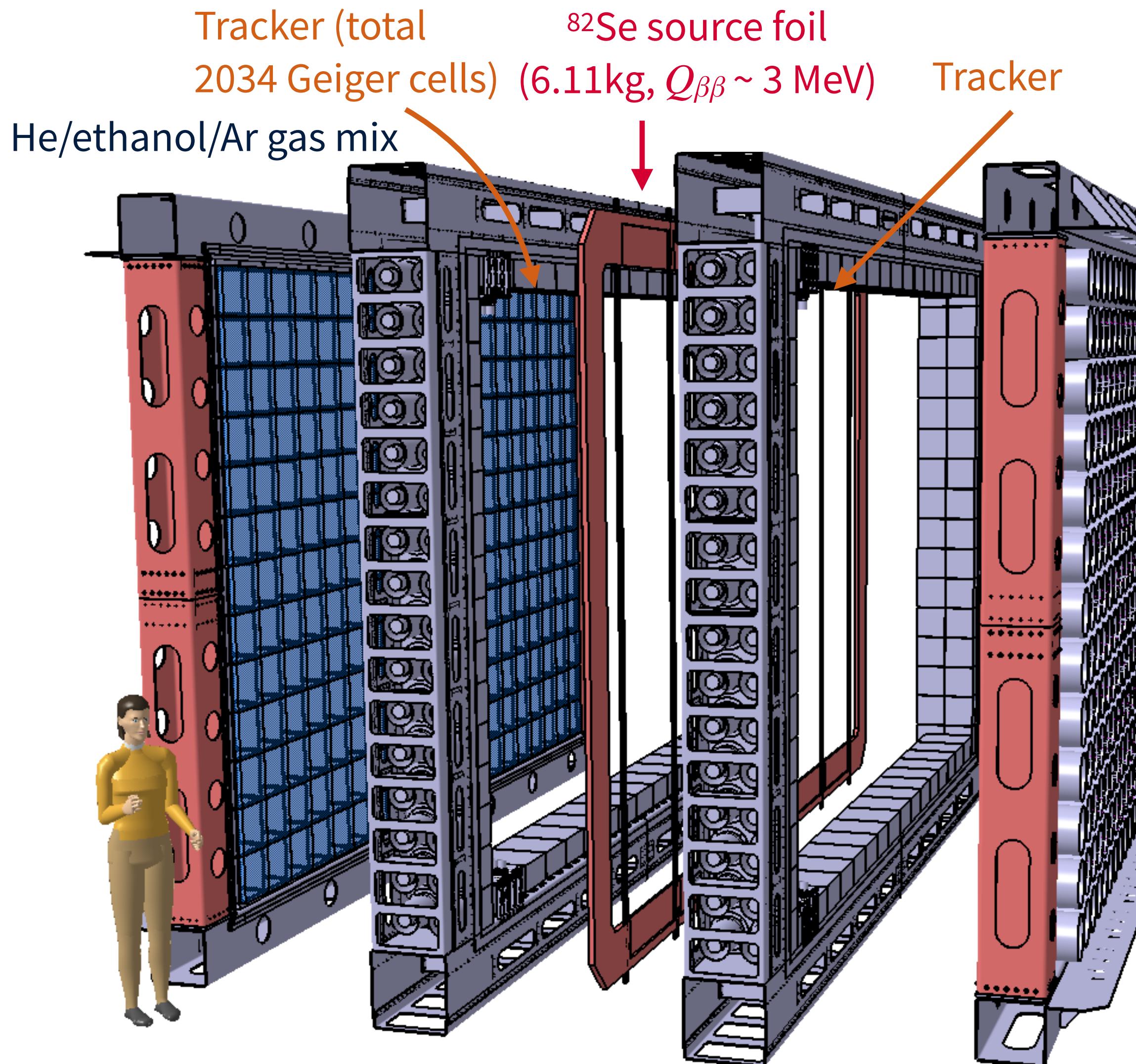
# SuperNEMO Demonstrator (now at LSM)



Modular design to test scalability



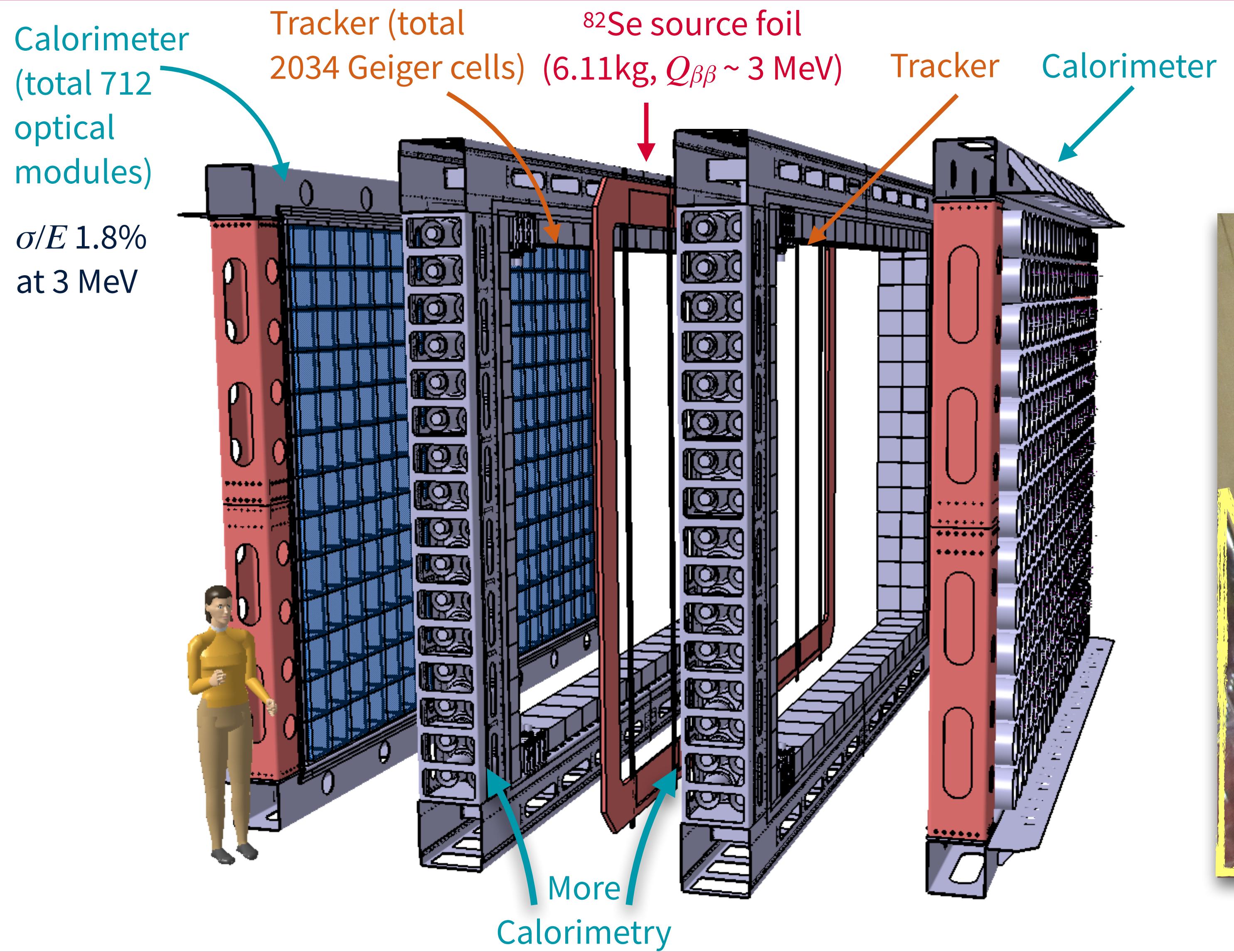
# SuperNEMO Demonstrator (now at LSM)



Modular design to test scalability



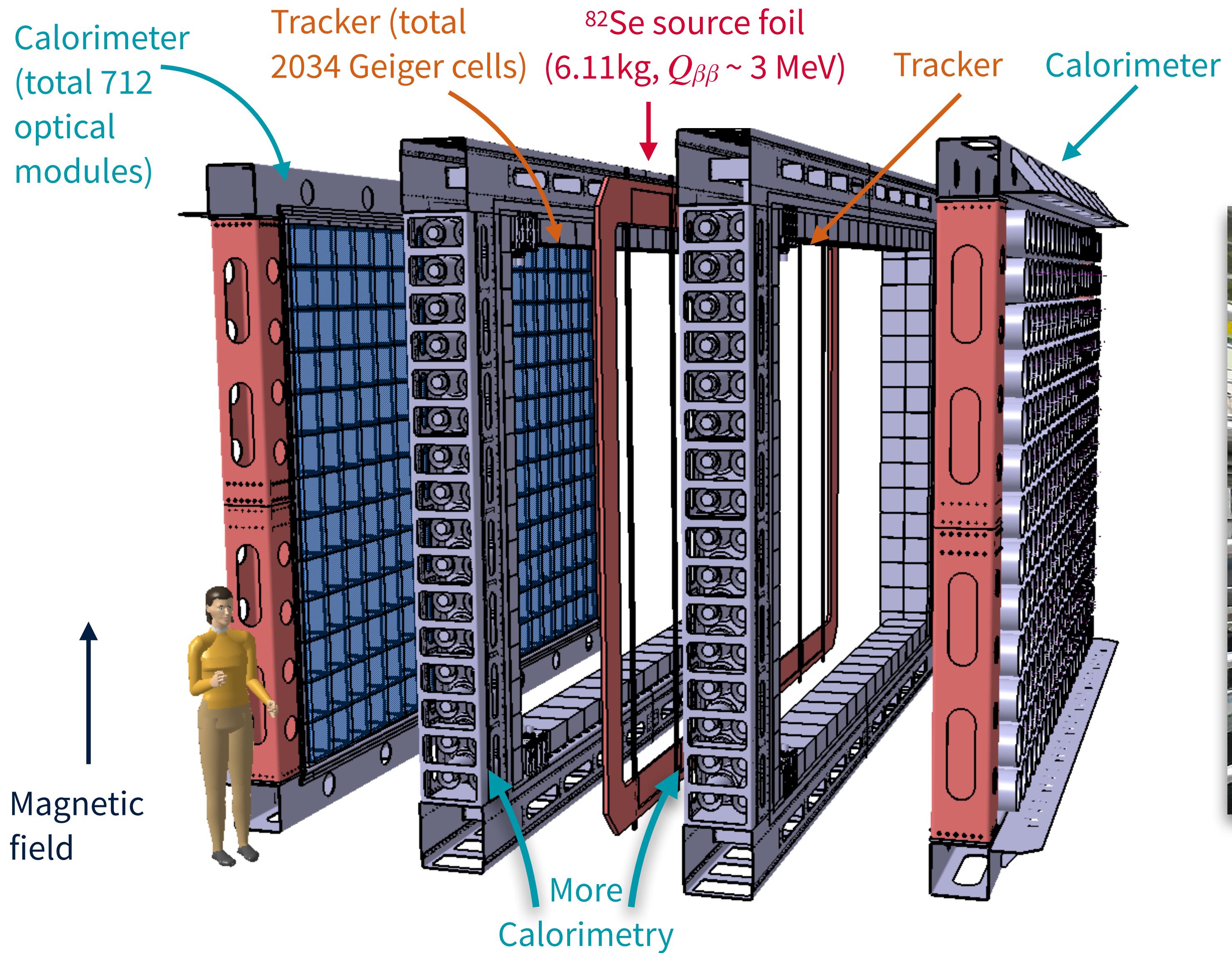
# SuperNEMO Demonstrator (now at LSM)



Modular design to test scalability



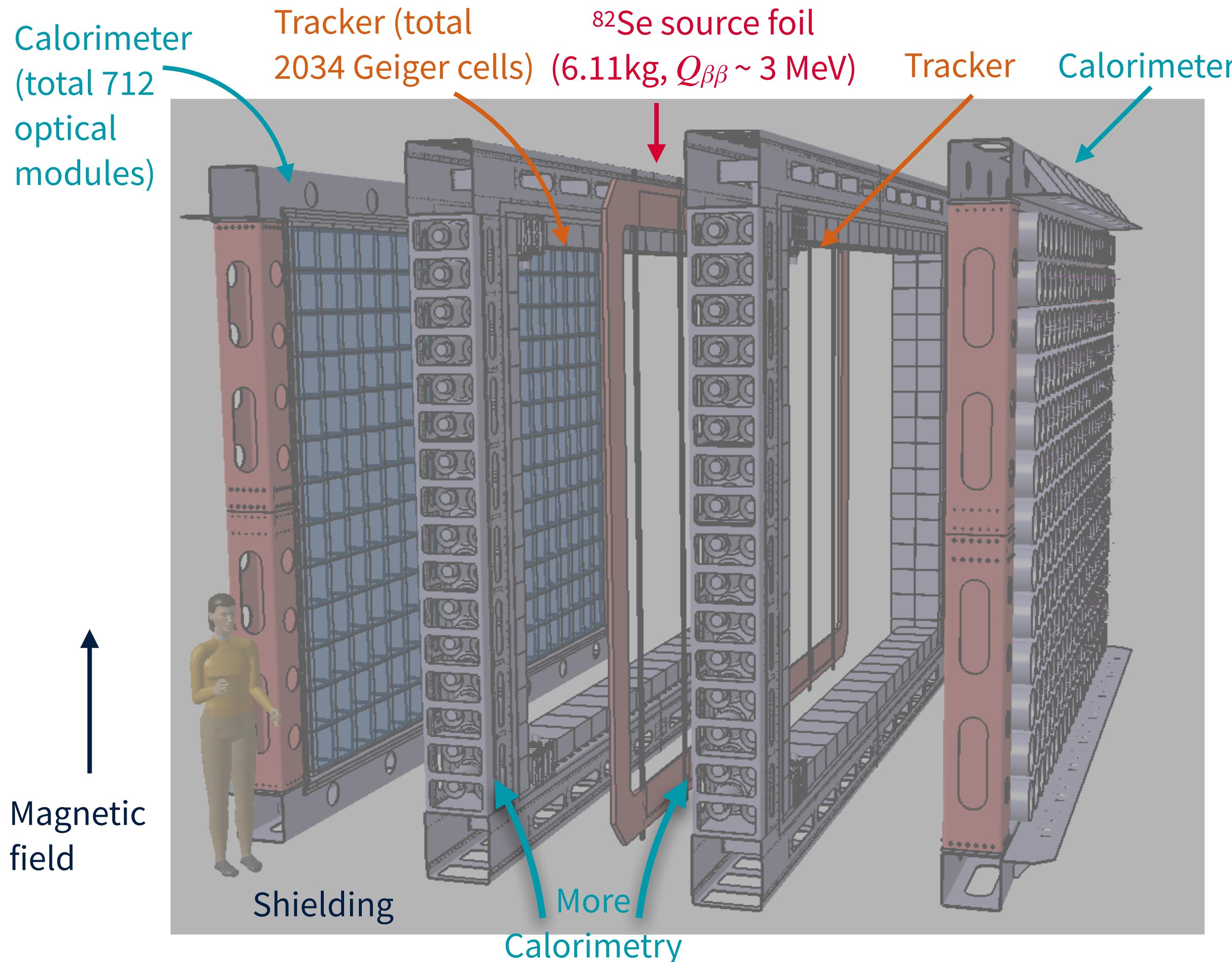
# SuperNEMO Demonstrator (now at LSM)



Modular design to test scalability



# SuperNEMO Demonstrator (now at LSM)



Modular design to test scalability

Projected background events  
 $< 10^{-4}$  per keV.kg.yr

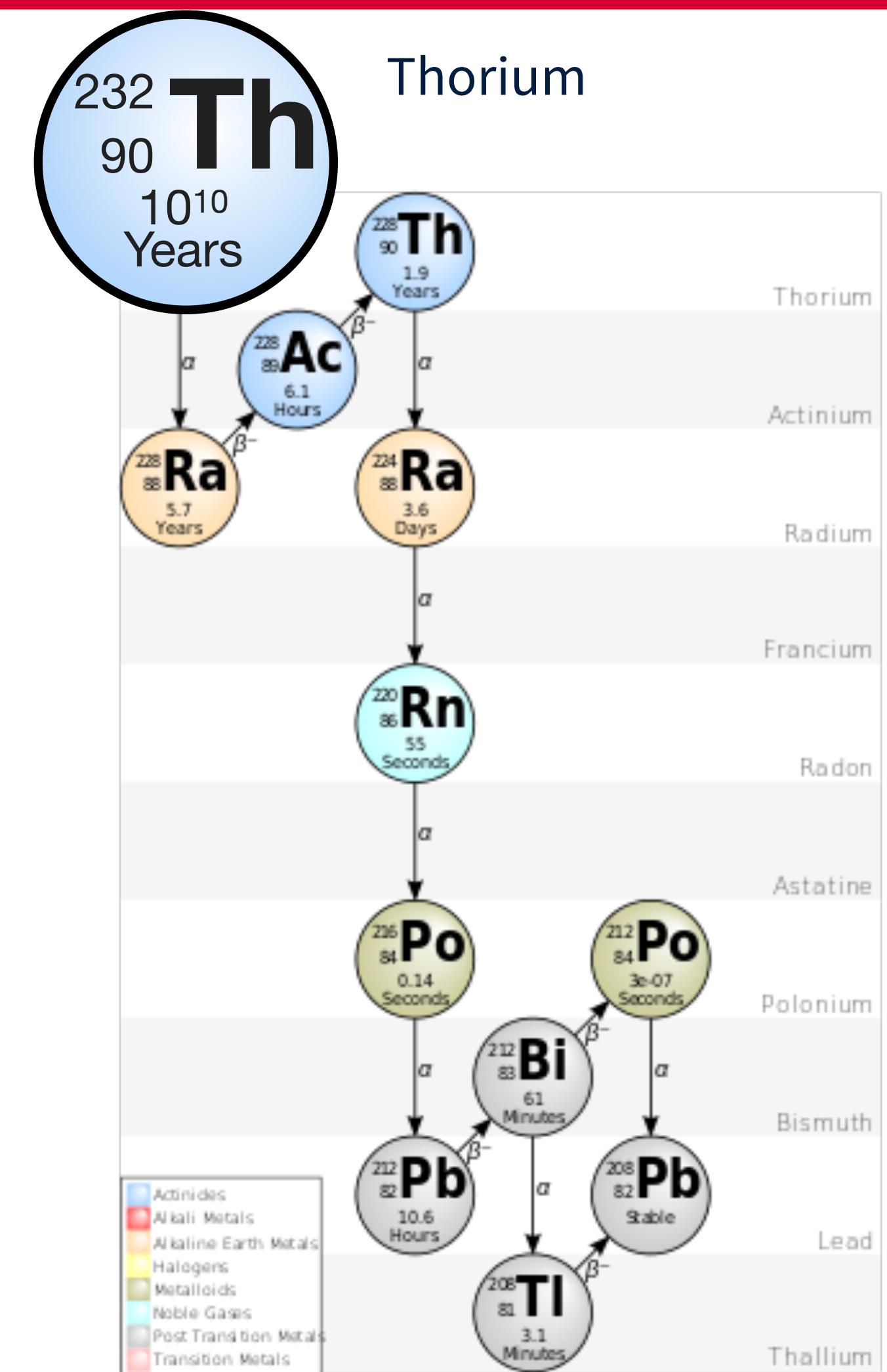
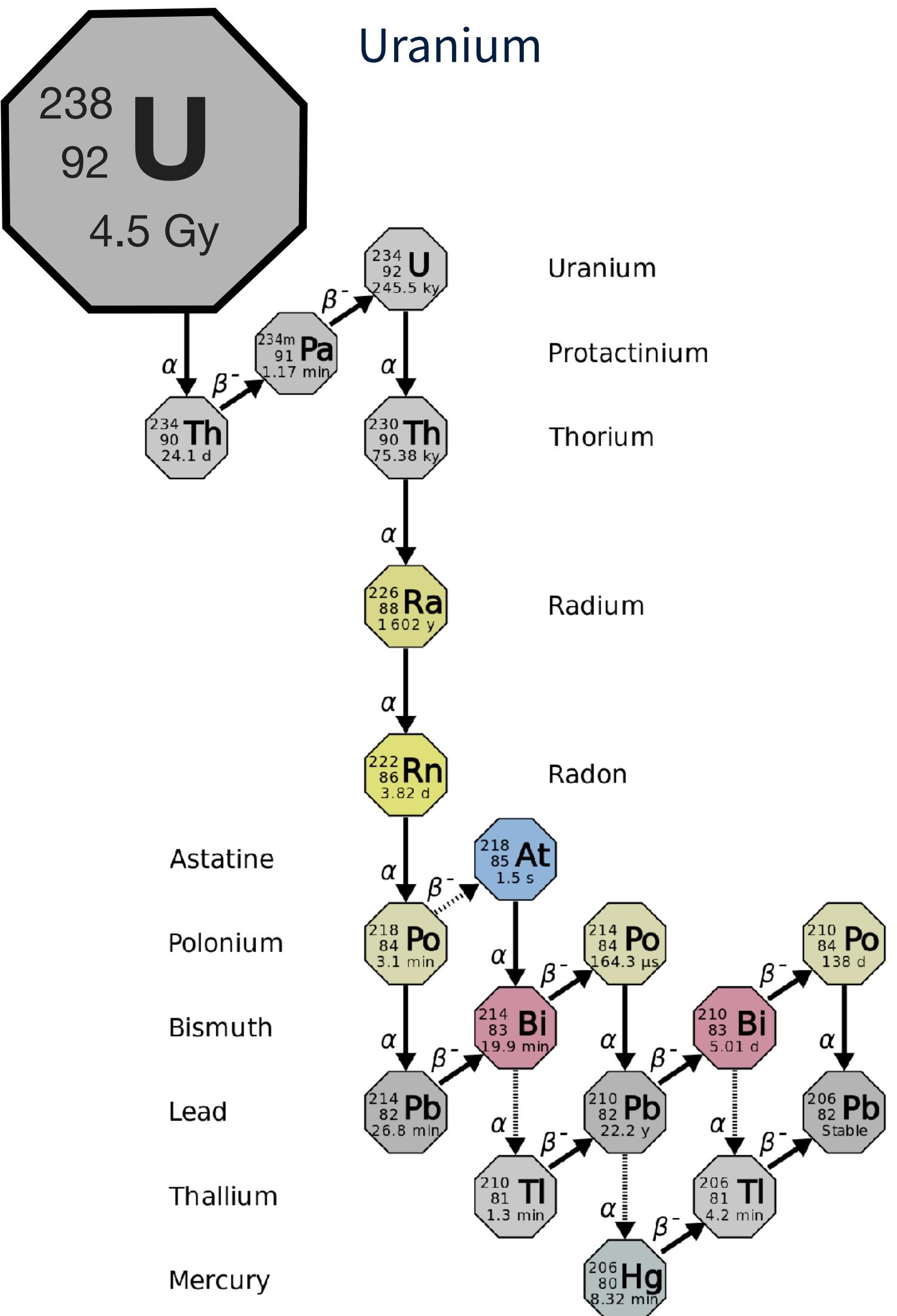
Sensitive to  $0\nu\beta\beta T_{1/2} > 4 \times 10^{24}$  years  
 $\langle m_{\beta\beta} \rangle < 260\text{-}500$  meV (in 2.5 years)

Sensitive to  $g_A$  quenching, Lorentz violation,  
exotic  $\beta\beta$  mechanisms... via  $2\nu\beta\beta$

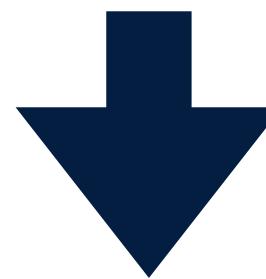
# Ultra-low backgrounds with SuperNEMO



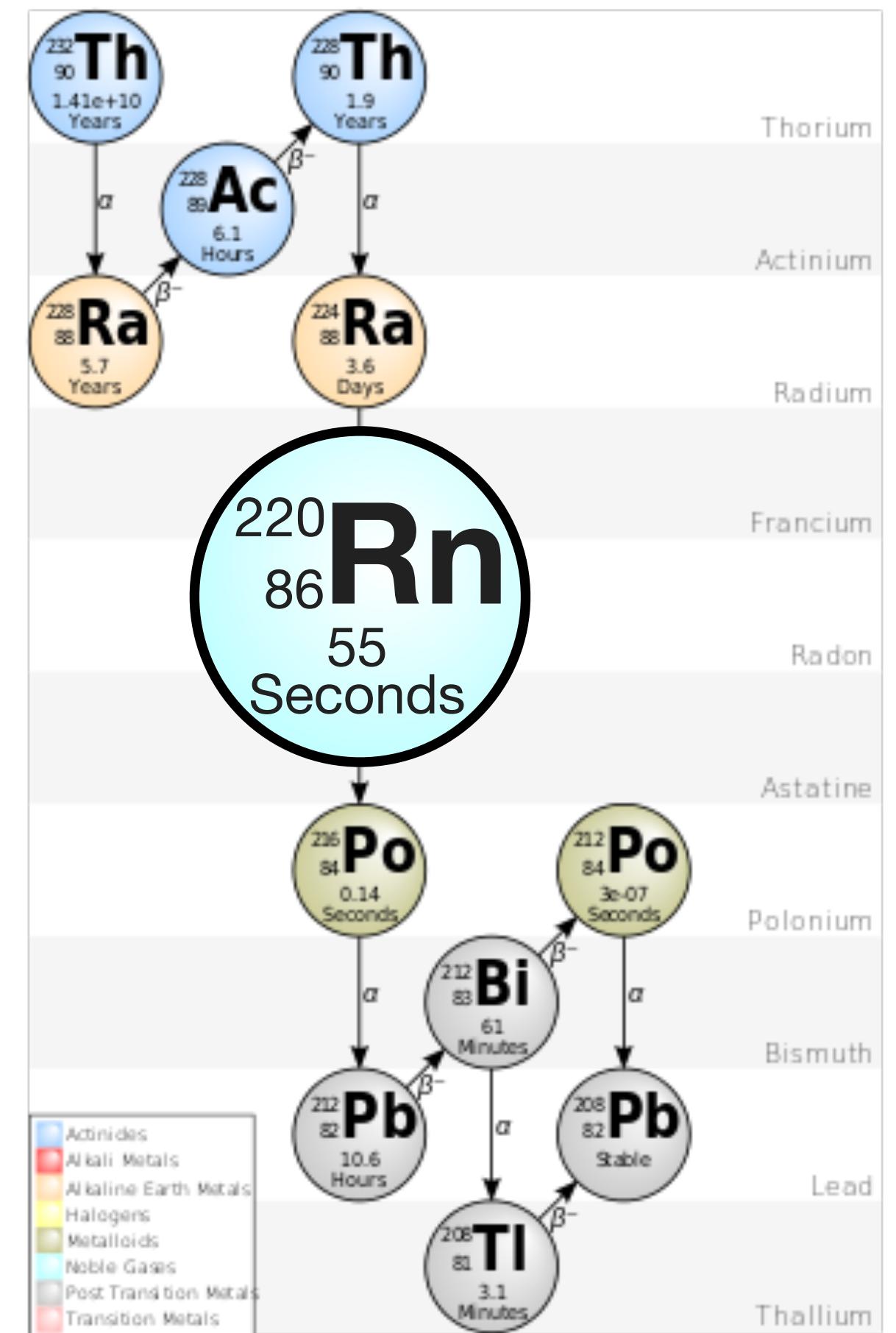
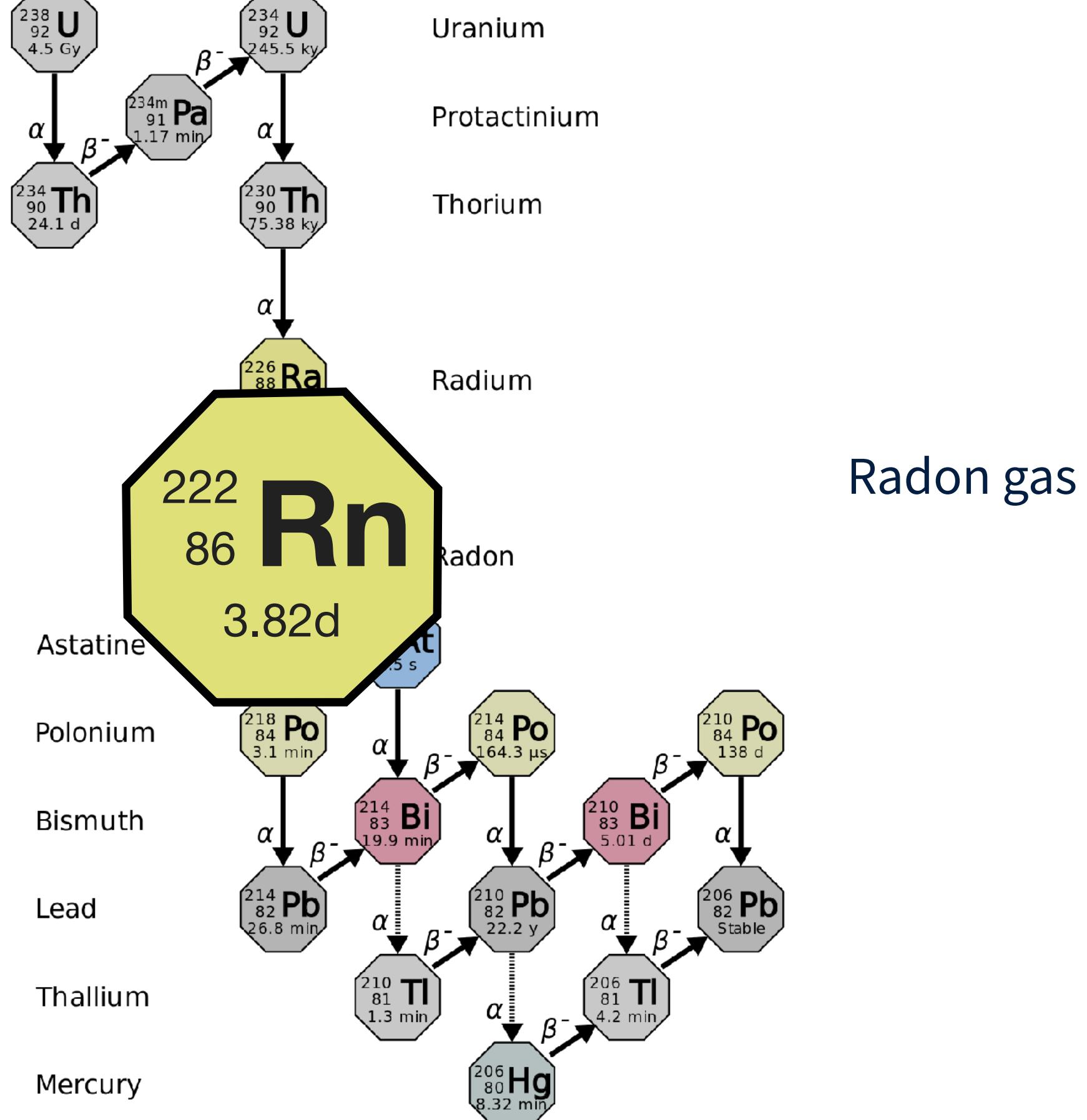
Rocks!



# Ultra-low backgrounds with SuperNEMO



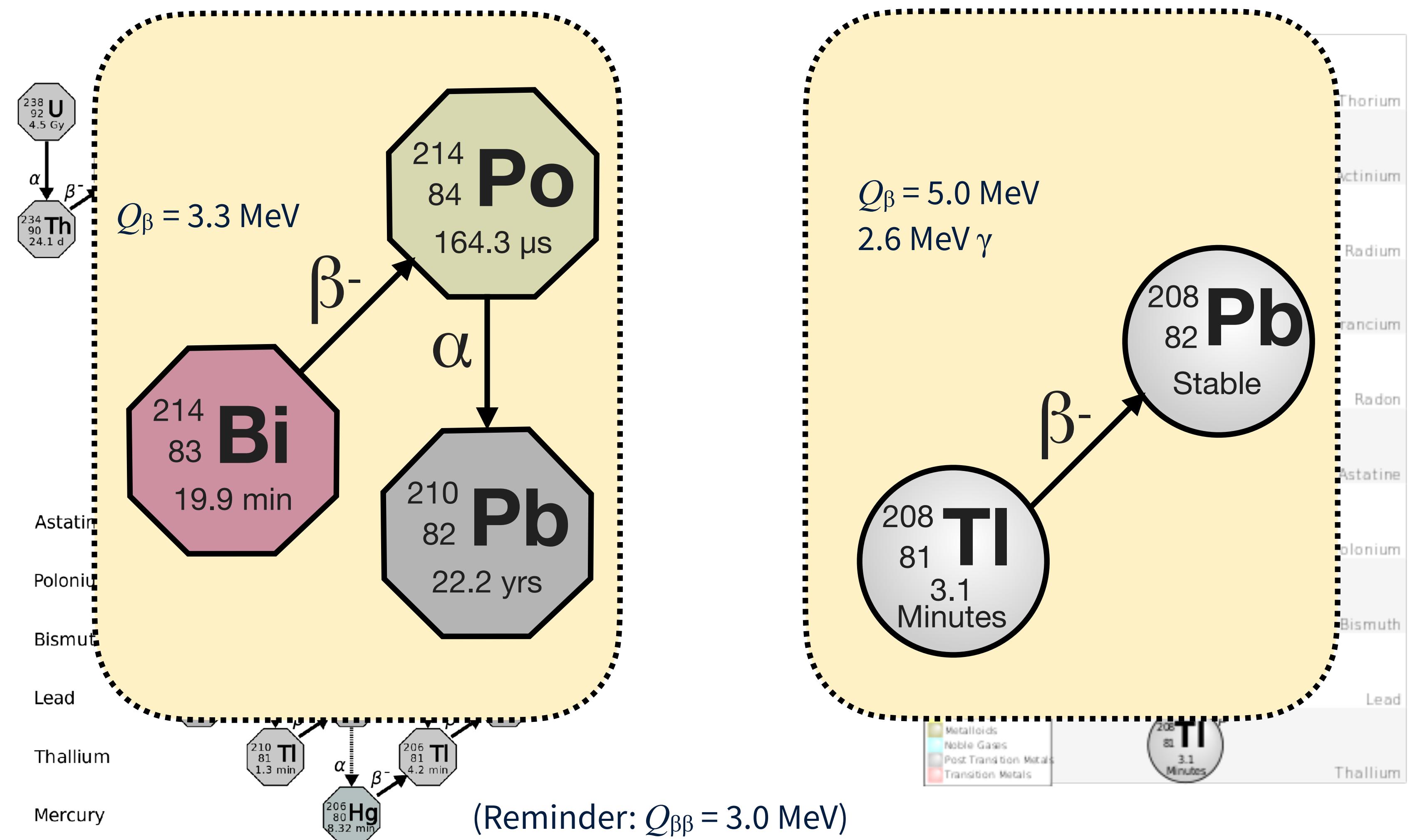
Rocks!



# Ultra-low backgrounds with SuperNEMO



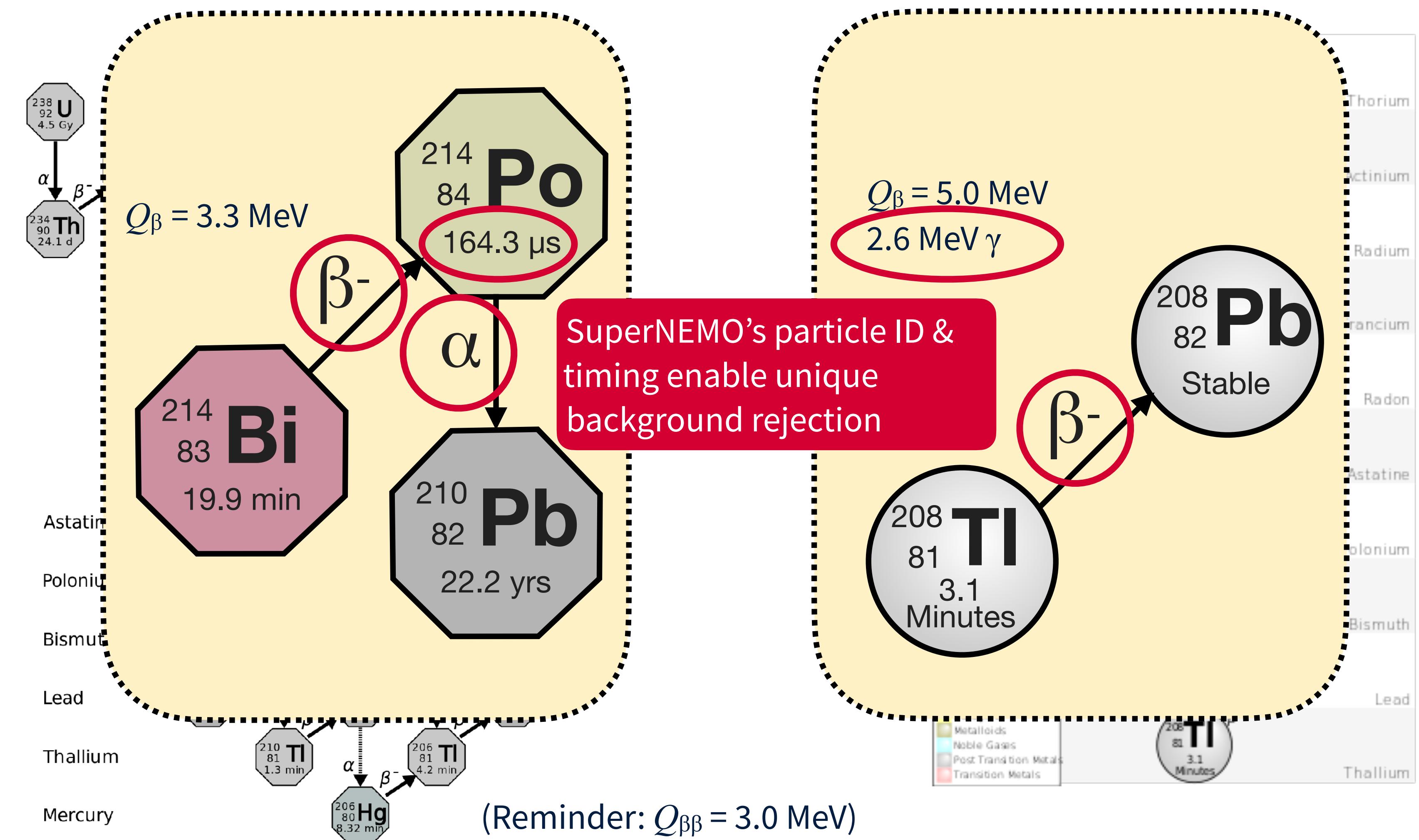
Rocks!



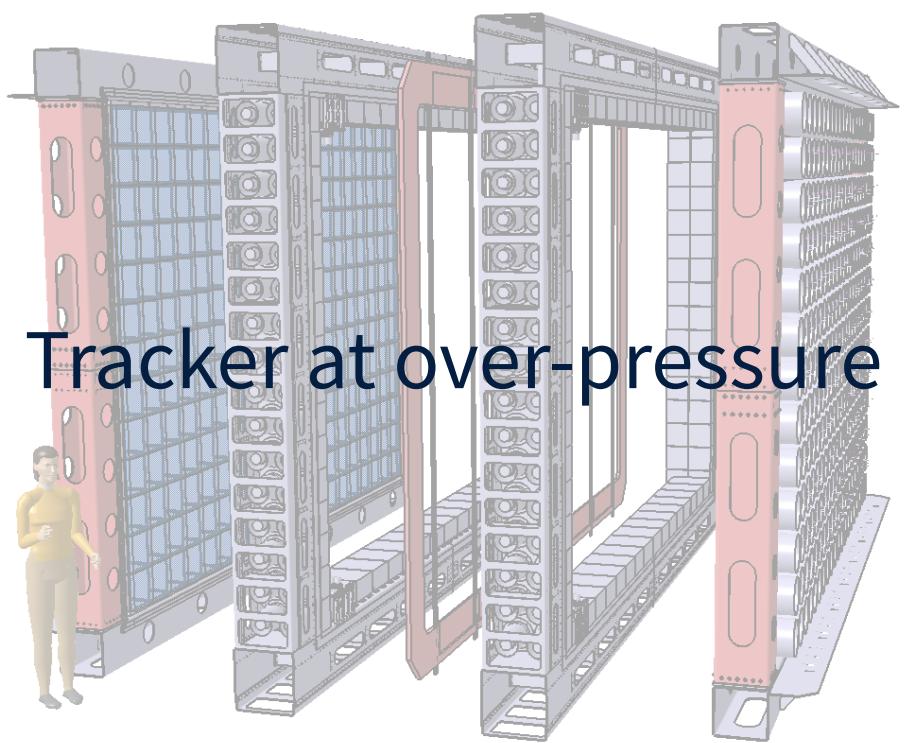
# Ultra-low backgrounds with SuperNEMO



Rocks!



# Protecting against backgrounds



In progress - helium recycling system



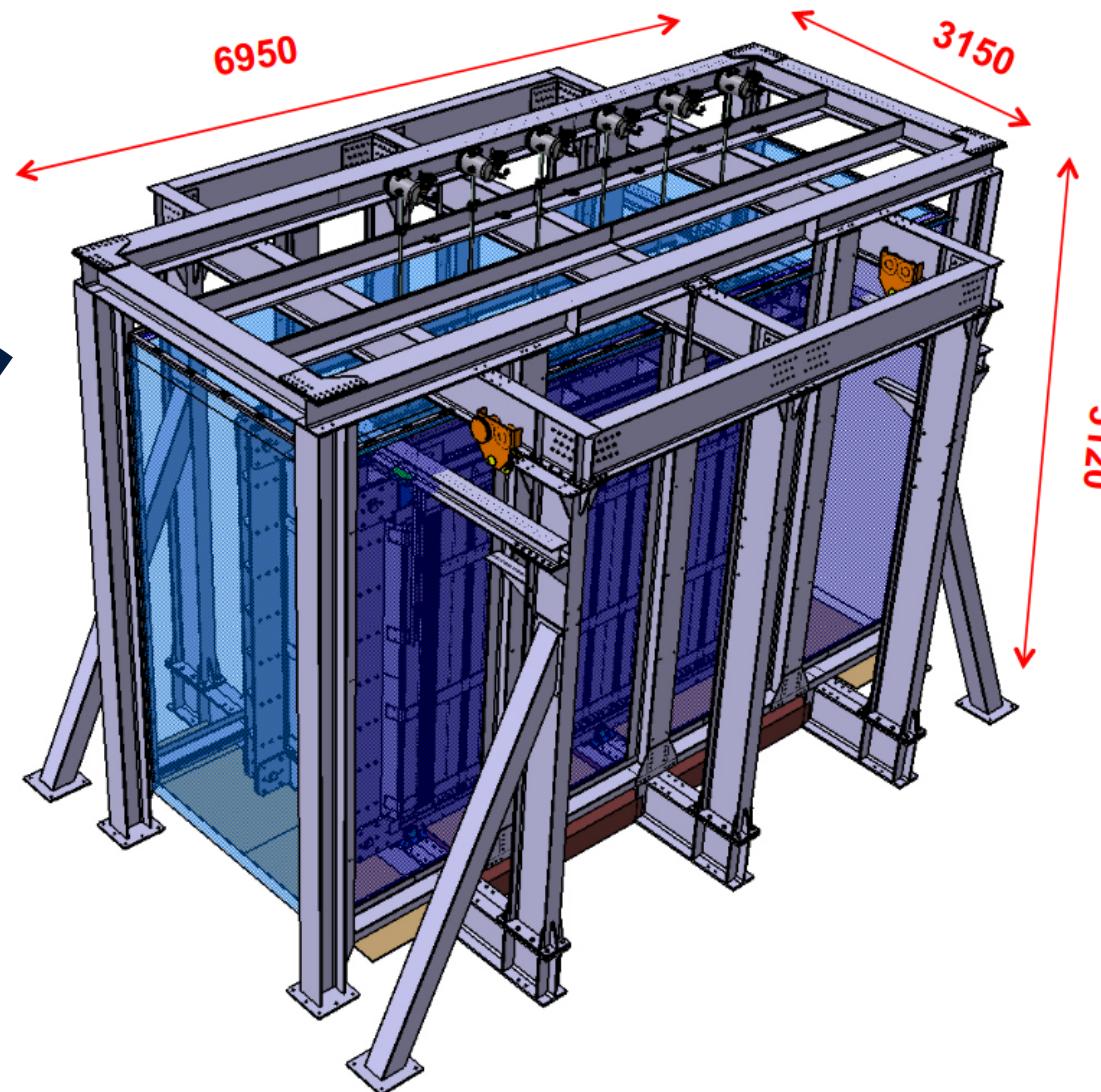
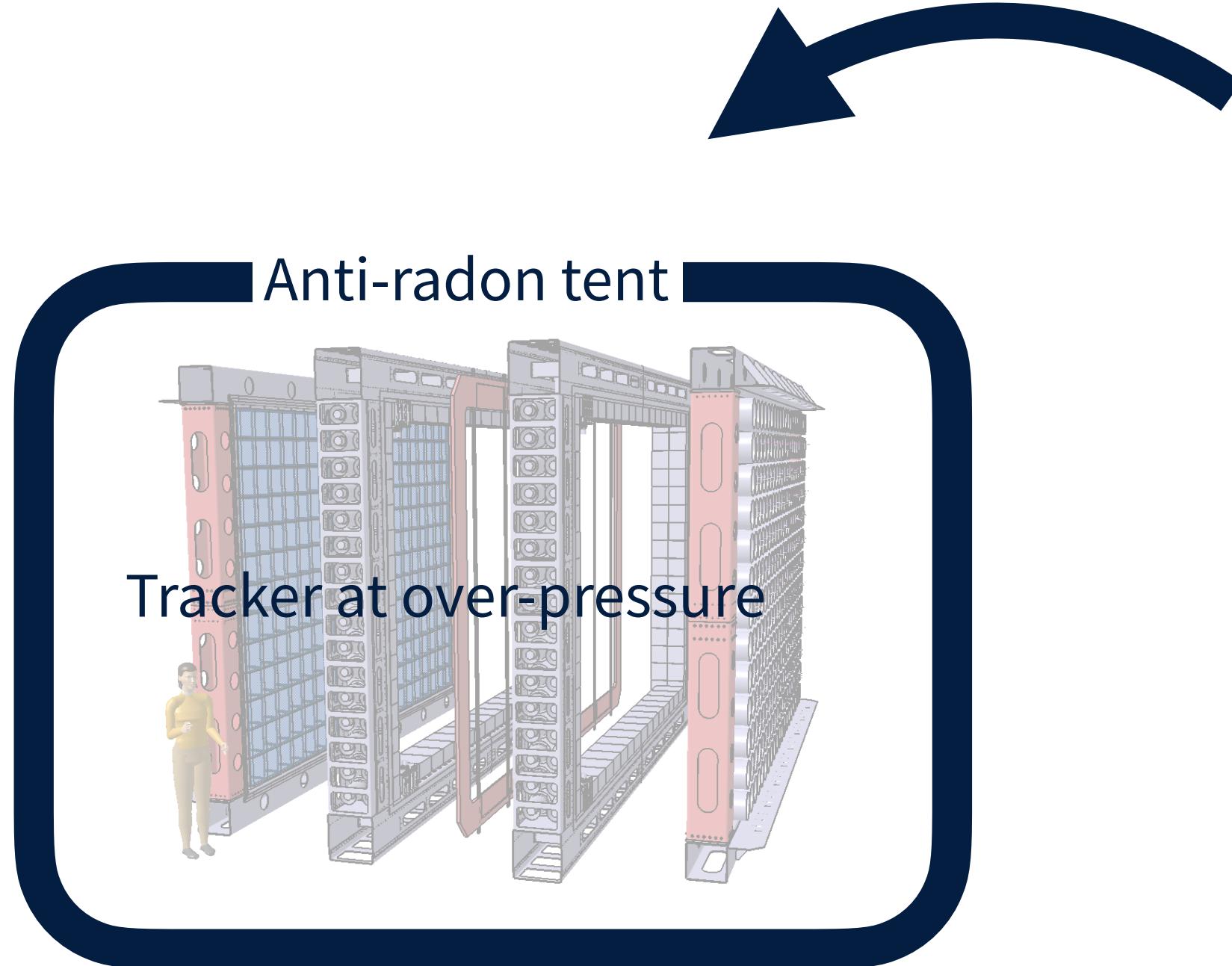
SuperNEMO gas system controls tracker gas mixture:

- 95% helium - low density
- 4% ethanol - quencher
- 1% argon - low ionisation potential



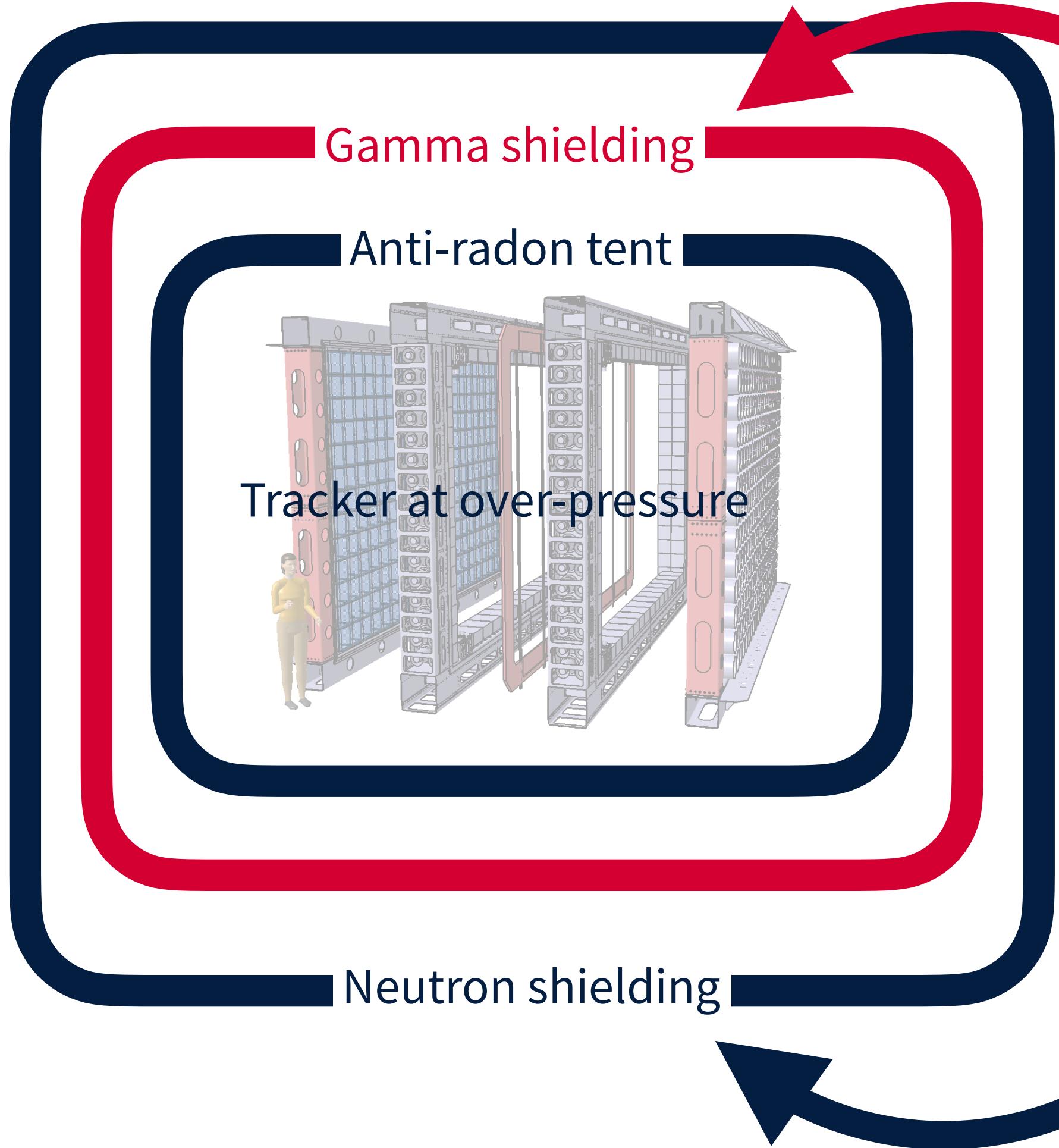
*Radon trap cleans the gas*

# Protecting against backgrounds

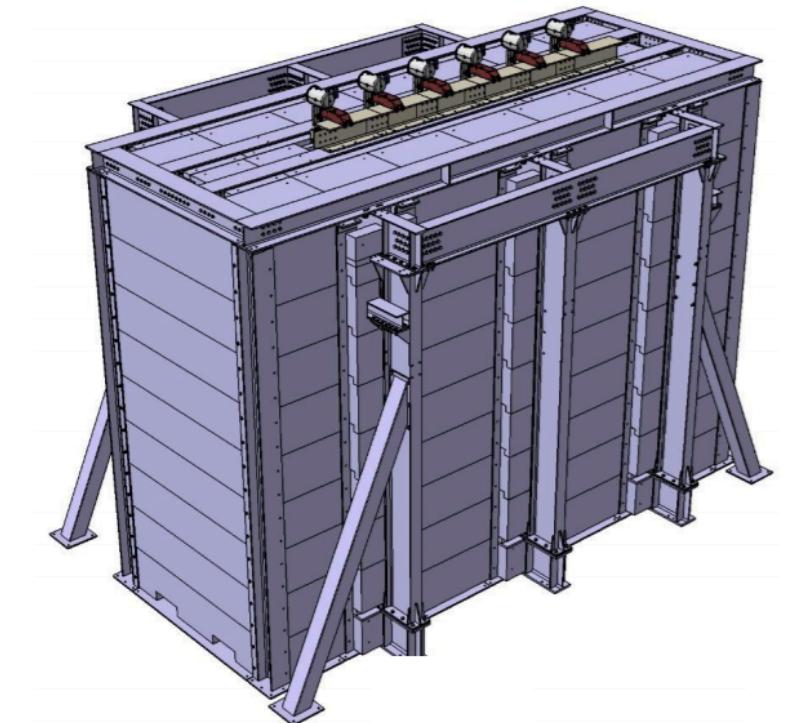


- Plastic panels on metal frame
- Patch panel for cables (>7000 channels!)
- To be filled with radon-reduced air

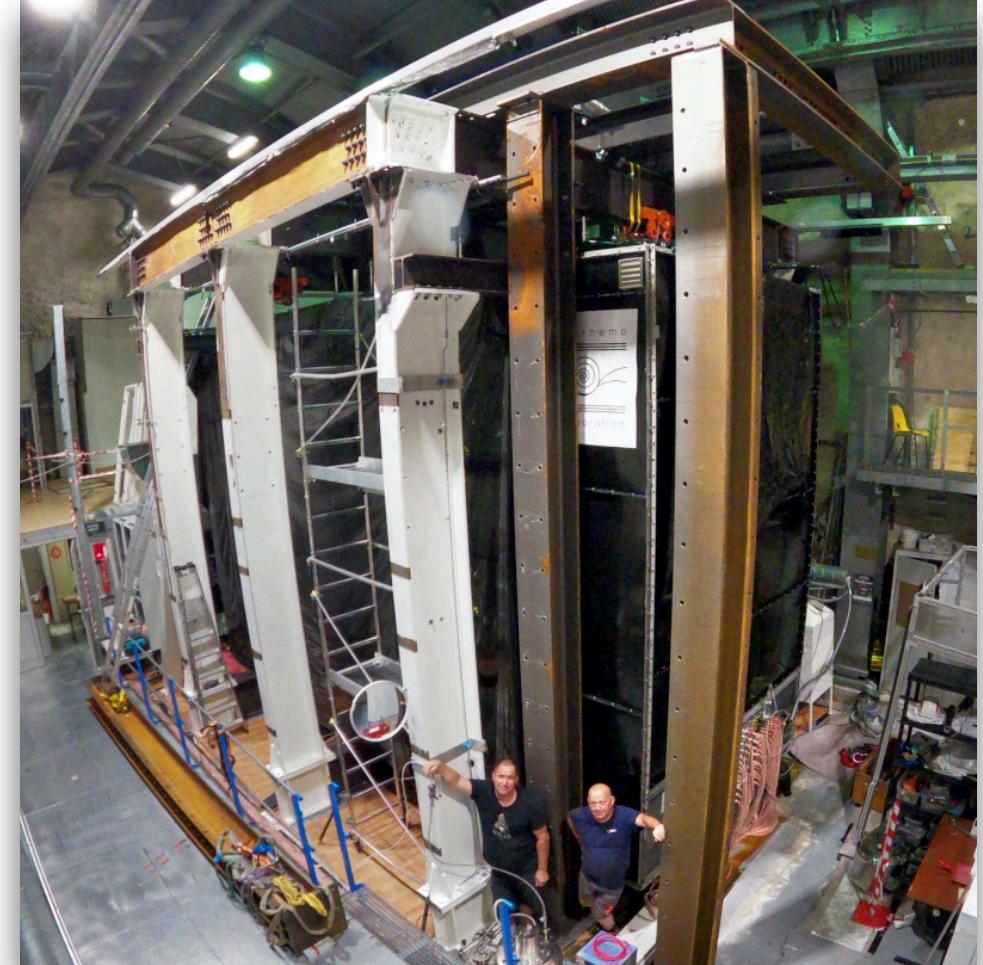
# Protecting against backgrounds



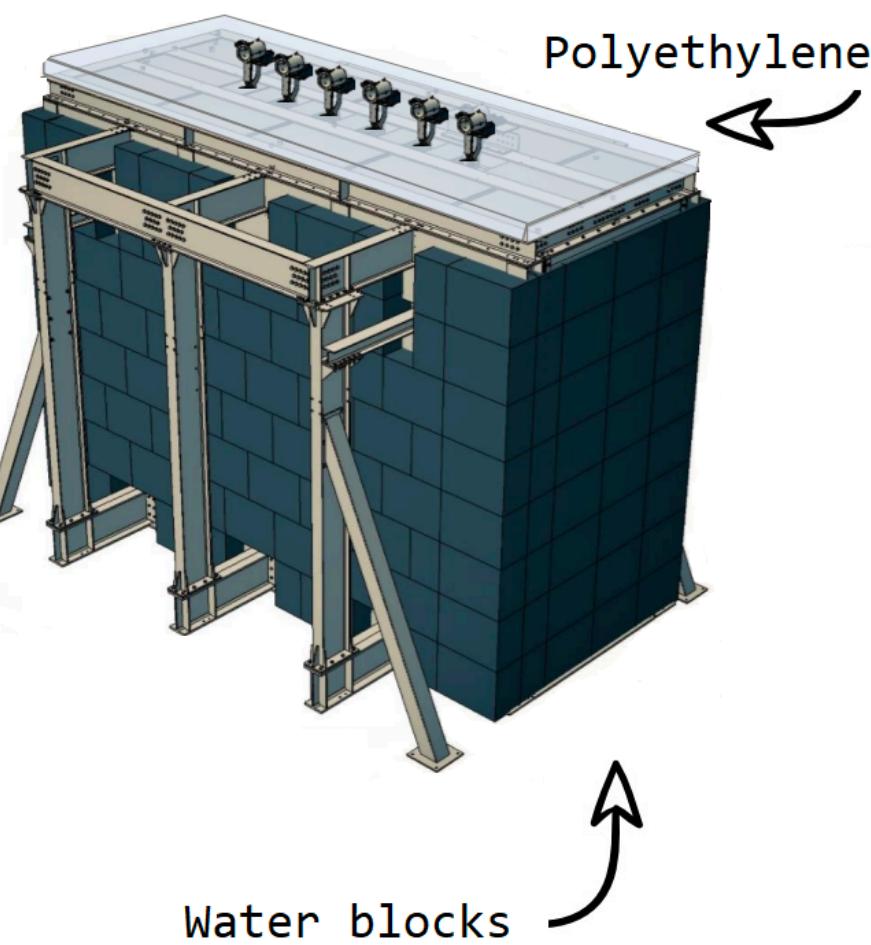
- 18cm-thick iron plates currently being machined
- Support structure being installed now



$3.0 \text{ (no shield)} \rightarrow 0.016 \text{ (Fe shield)}$   $\gamma$  events/yr in  $0\nu\beta\beta$  ROI

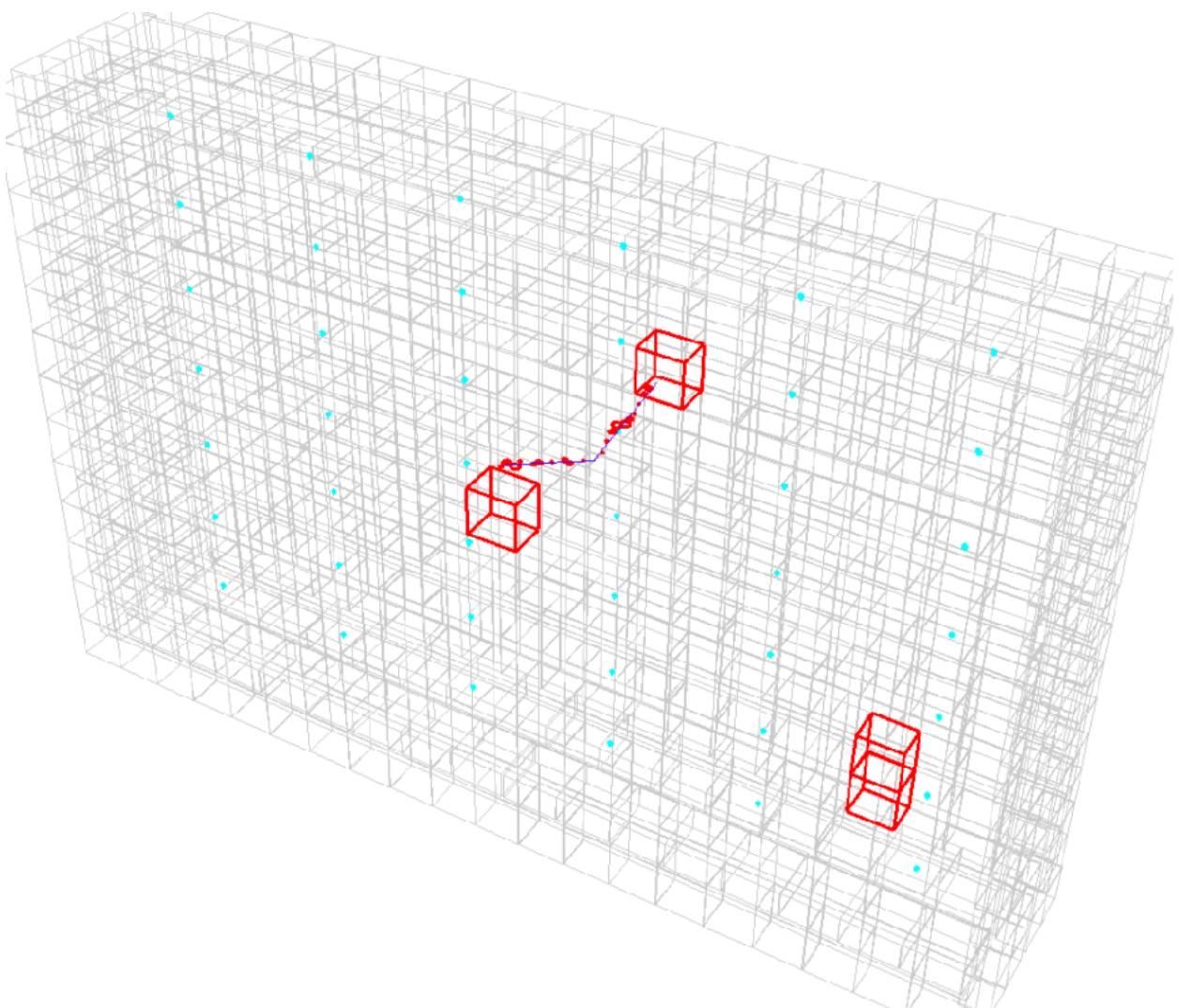
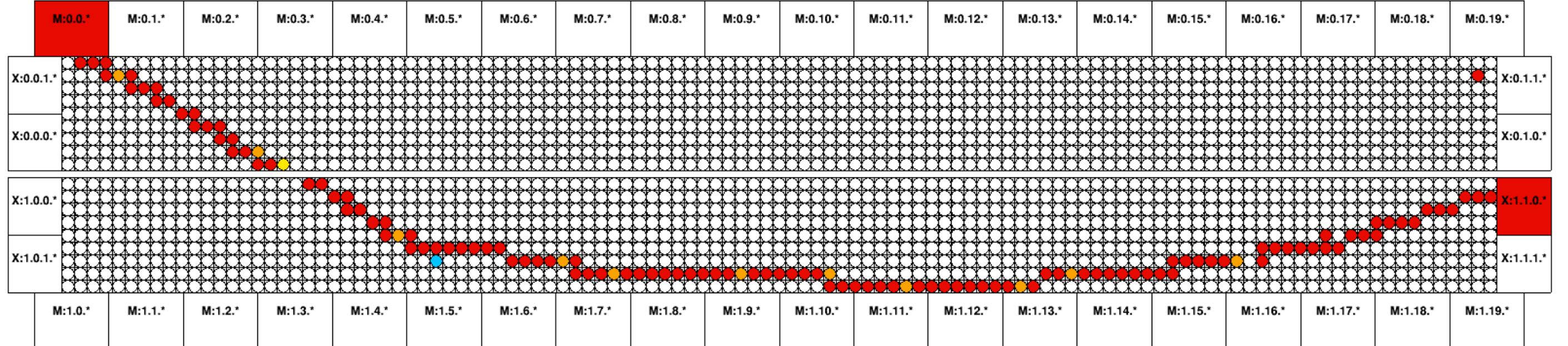


- 243 50cm-thick water-filled polyethylene tanks
- 20cm PE plates (top, bottom and end)
- All now at LSM

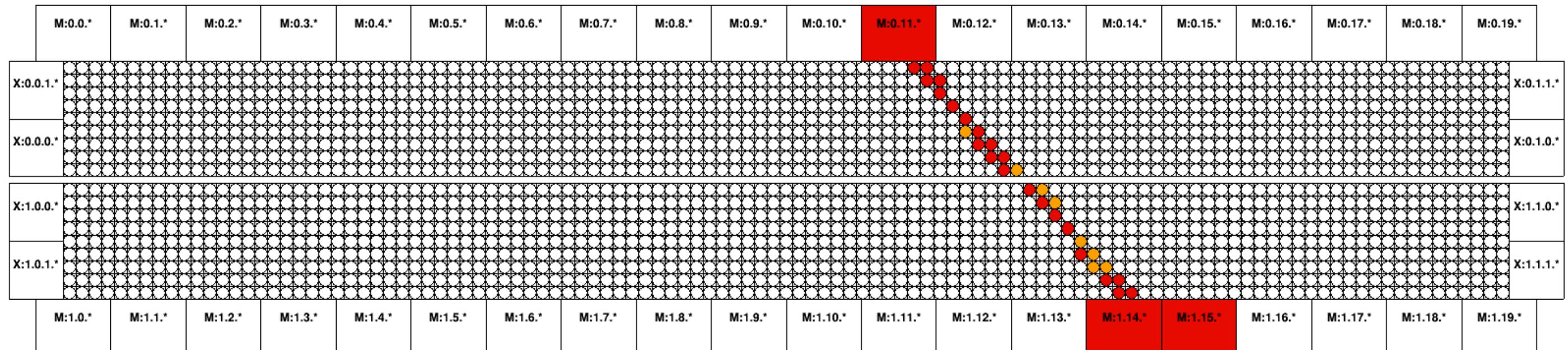


# Full detector operational and taking background & calibration data!

RUN 1051 // TRIGGER 1187719+1187720+1187721

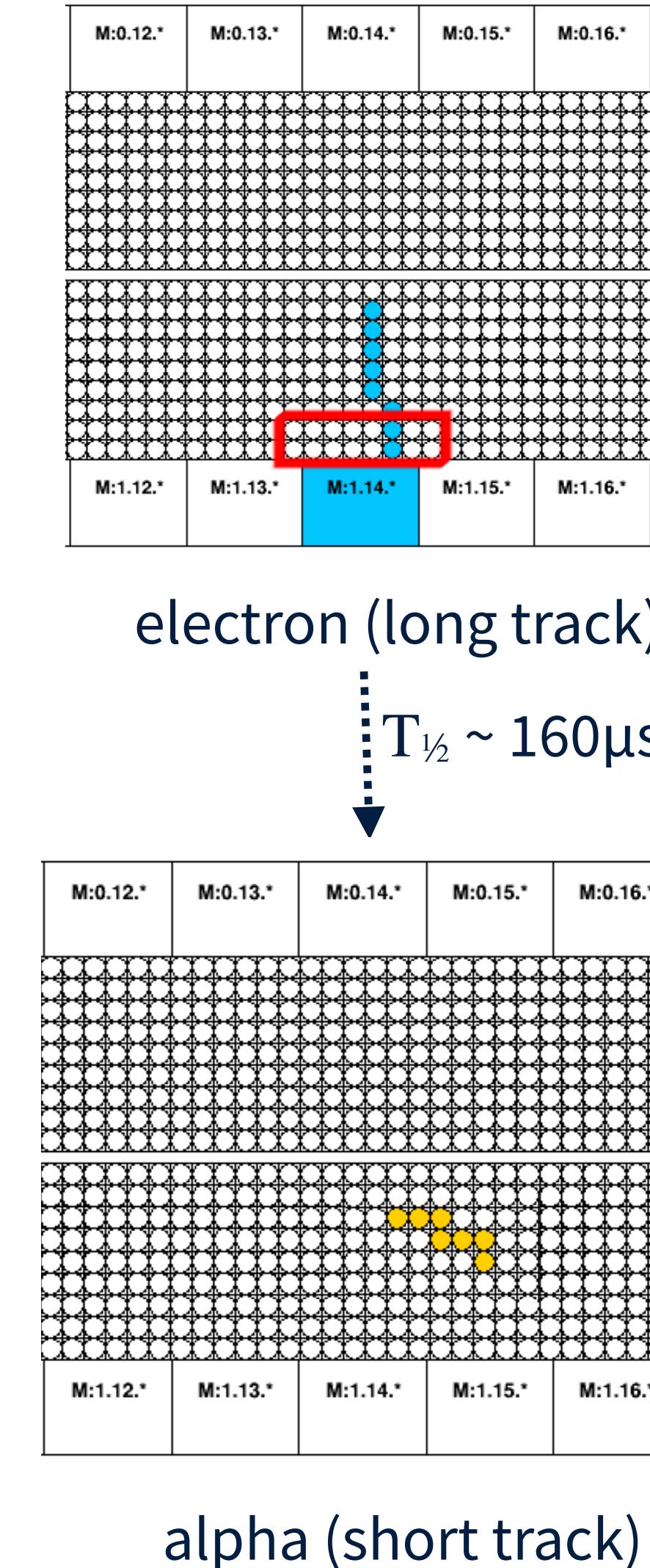
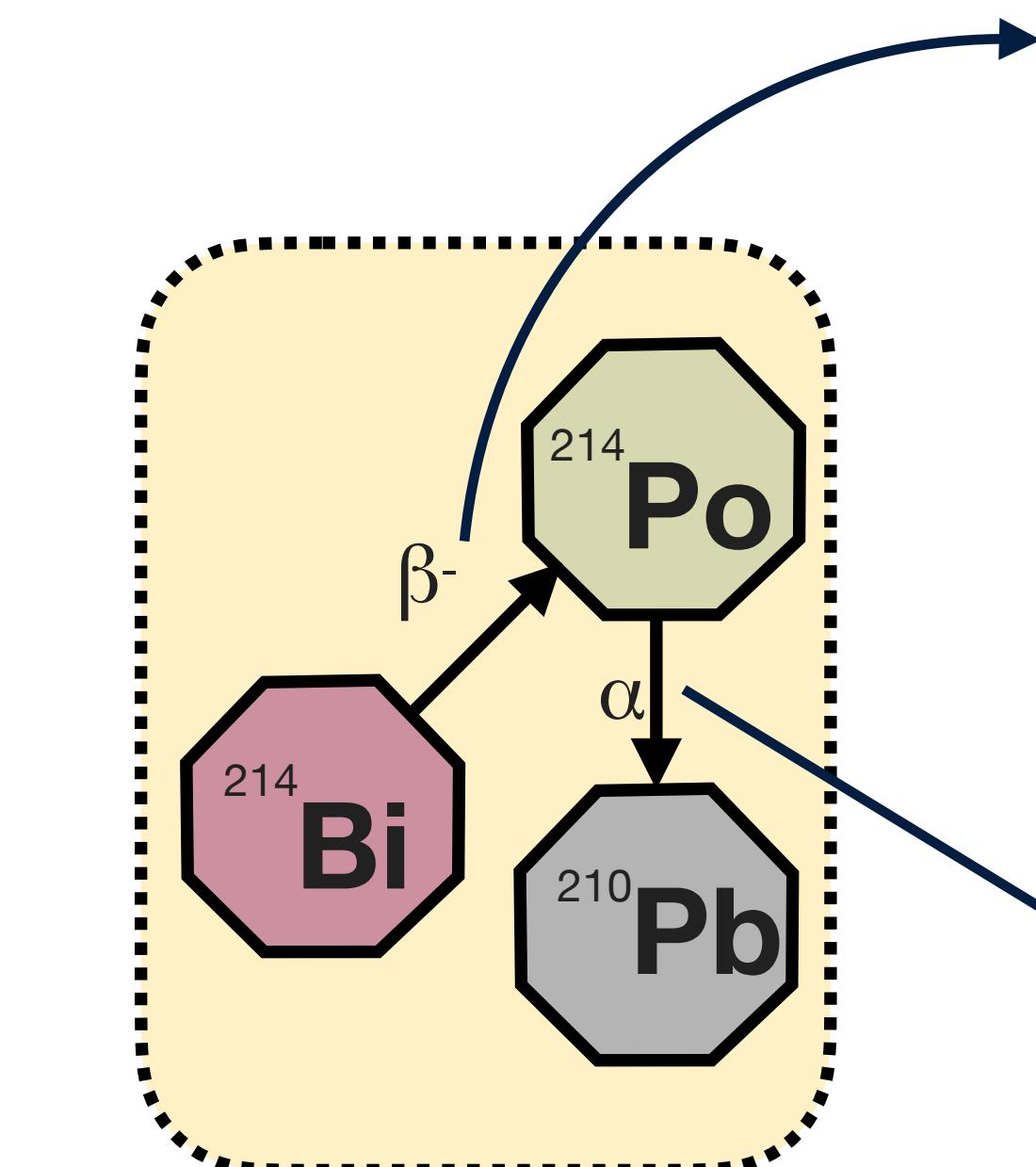


RUN 1011 // TRIGGER 3210833



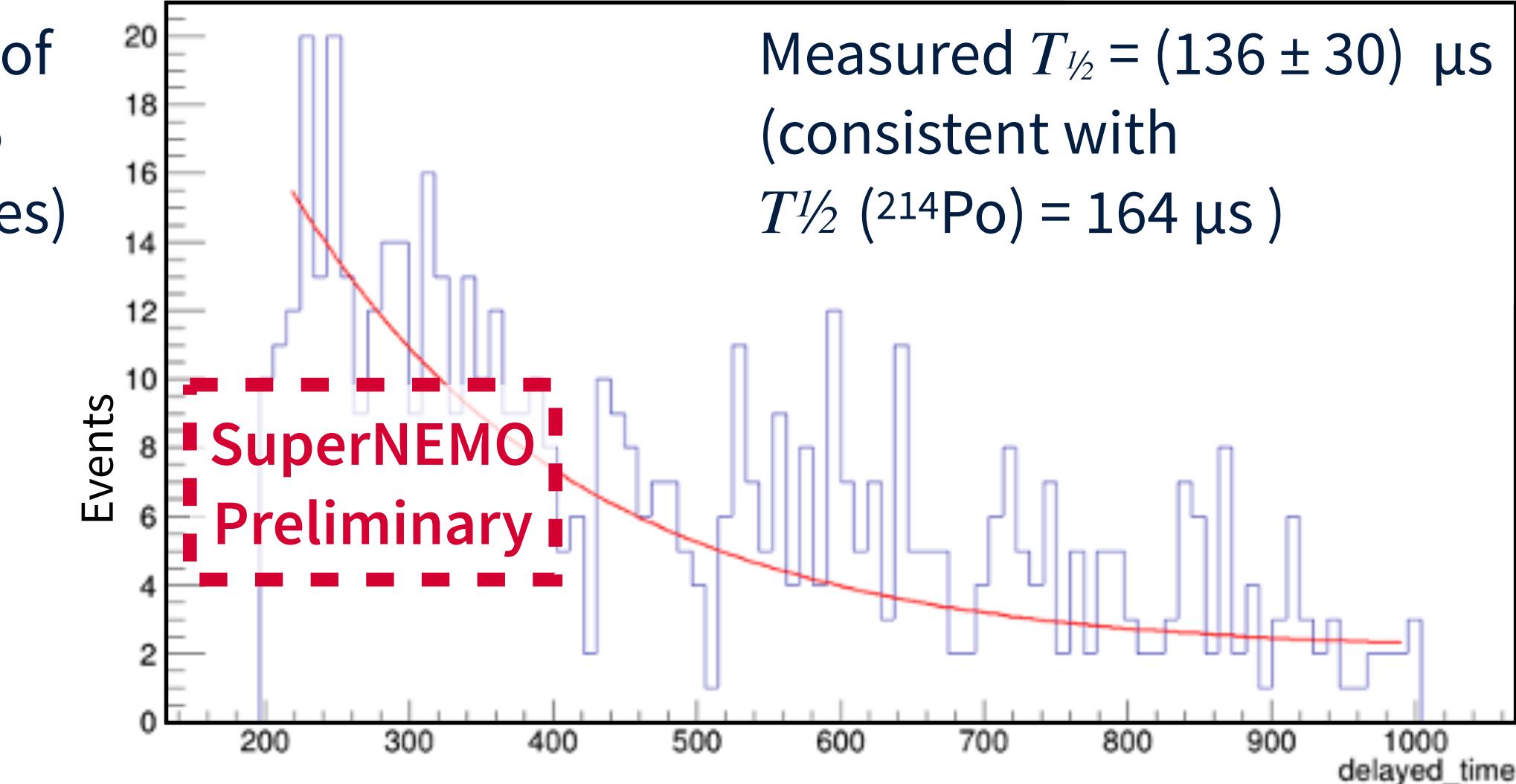
- 99% of tracker channels live!
- Track and event reconstruction

# Preliminary radon background measurement



47 hours of data (575 candidates)

Delay between  $e^-$  and  $\alpha$  ( $\mu\text{s}$ )

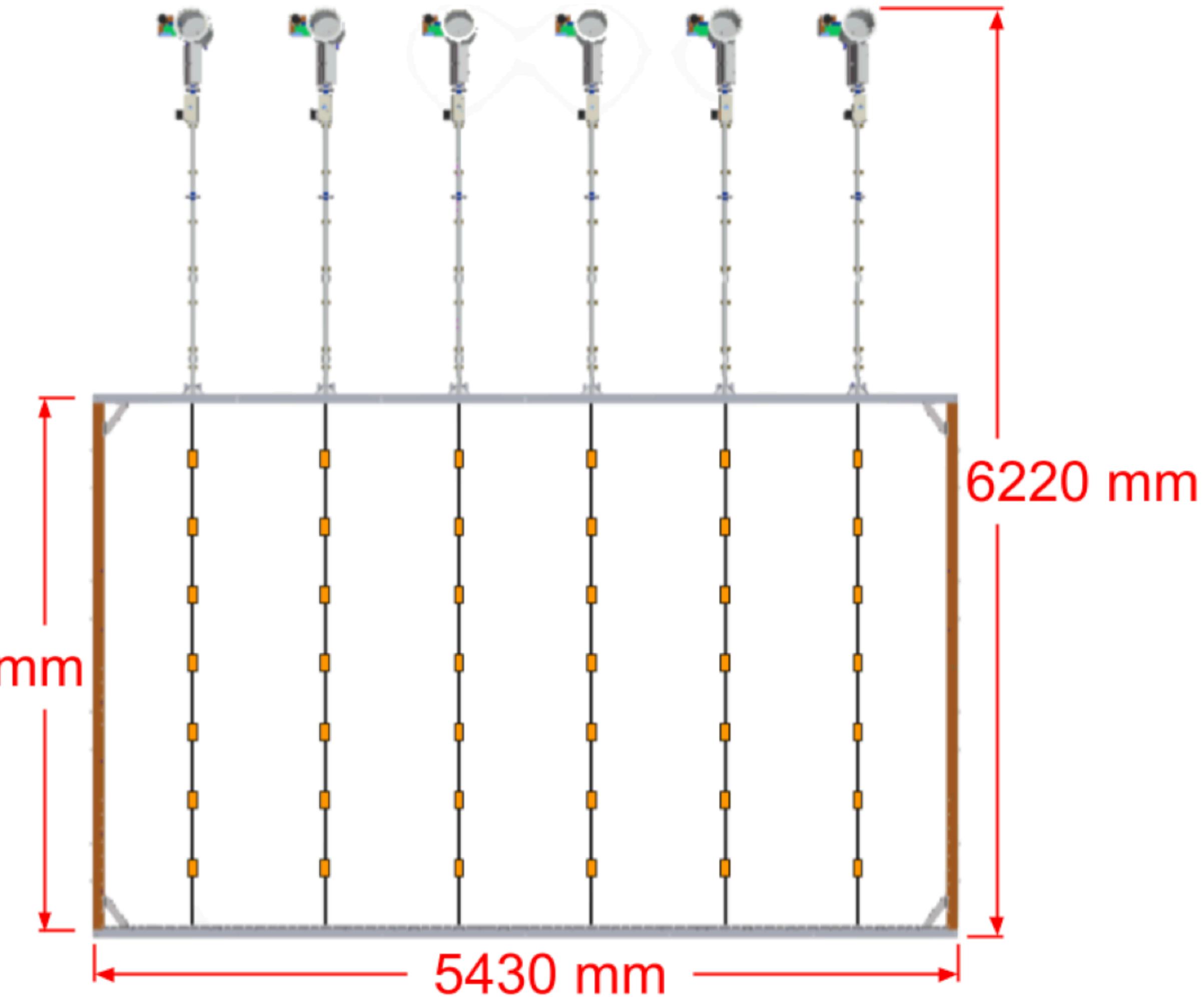
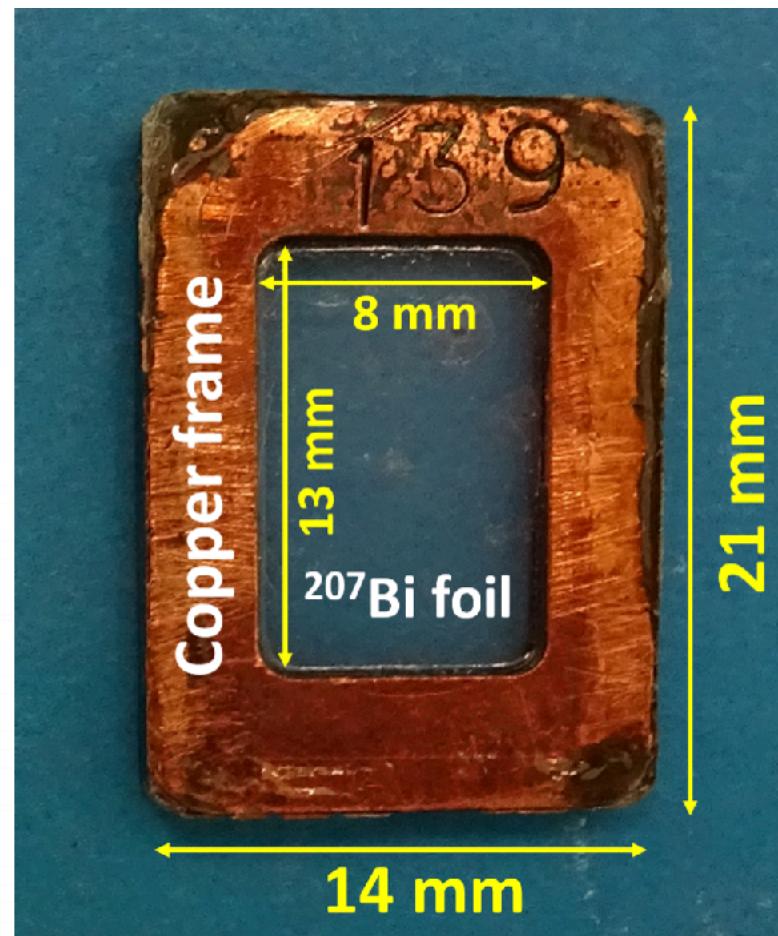
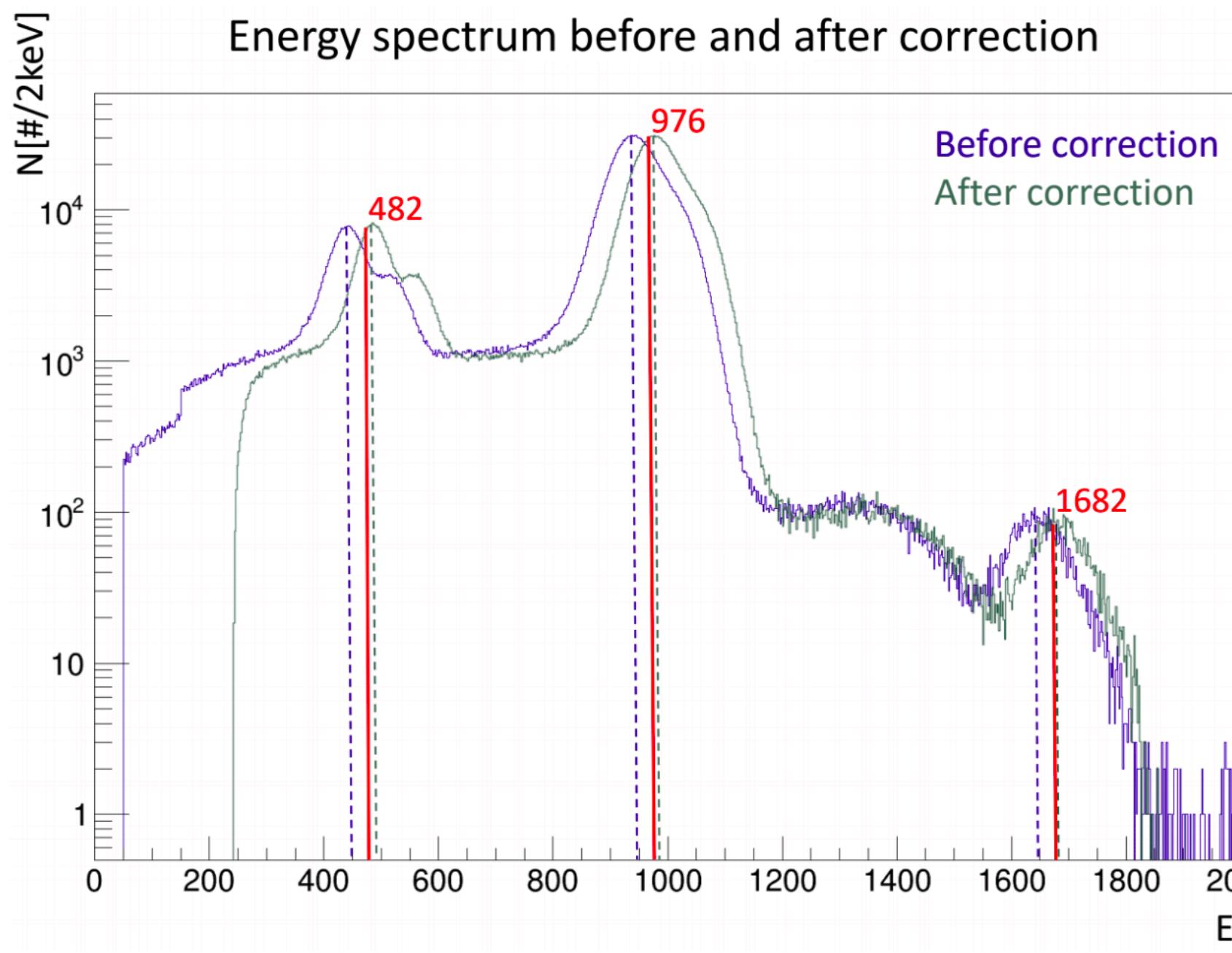


(Higher-statistics measurement underway with radon source)  
Preliminary tracker activity:  $6 \pm 2 \text{ mBq/m}^3$

- Lower than NEMO-3 phase 1; comparable to phase 2 NIMA 606, Issue 3 449-465
- Anti-radon tent/radon-free air will reduce greatly
- Gas flow rate lower than nominal
- Target:  $0.15 \text{ mBq/m}^3$

# Calibration and commissioning with $^{207}\text{Bi}$ sources

42  $^{207}\text{Bi}$  electron sources can be automatically deployed between the source foils for energy calibration

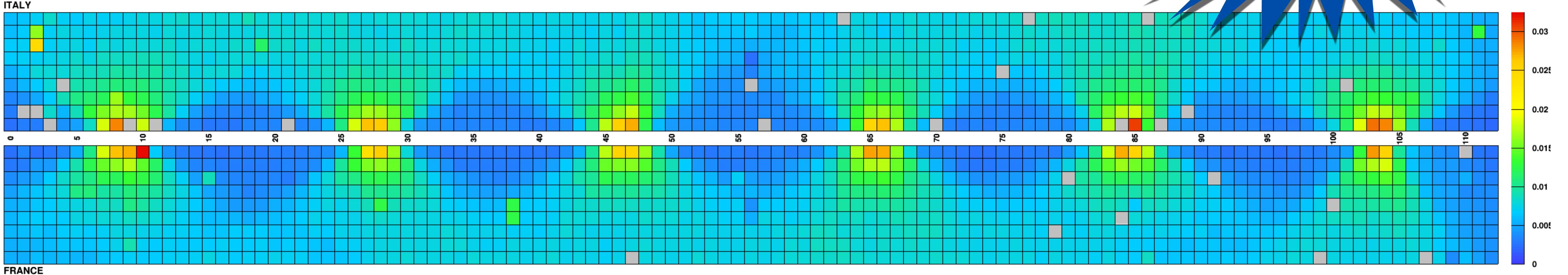


JINST 16 (2021) T07012

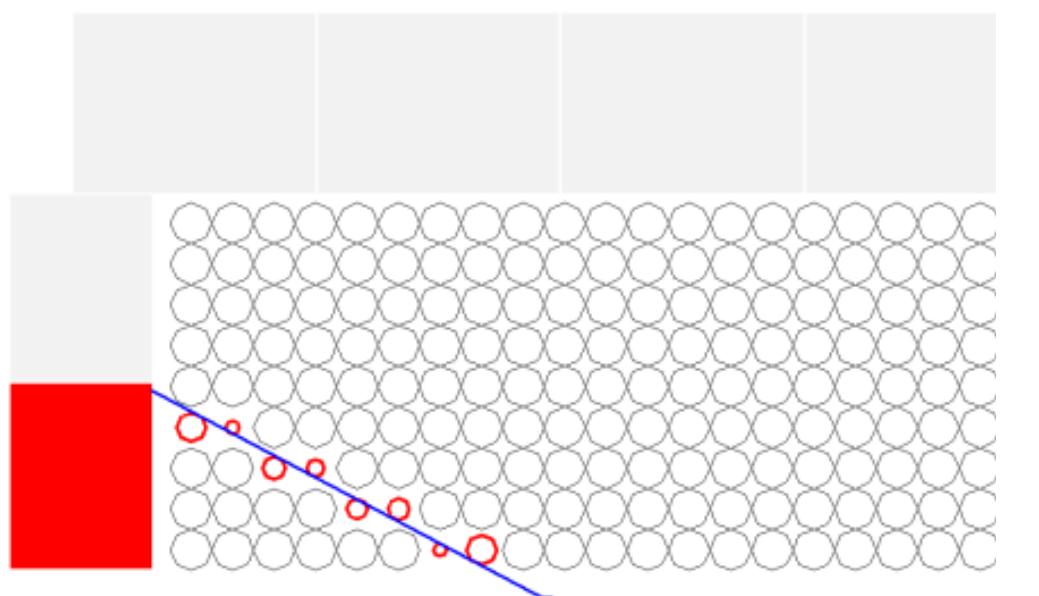
# Calibration and commissioning



Tracker occupancy with  $^{207}\text{Bi}$  sources deployed



## Run 728 | Event 1

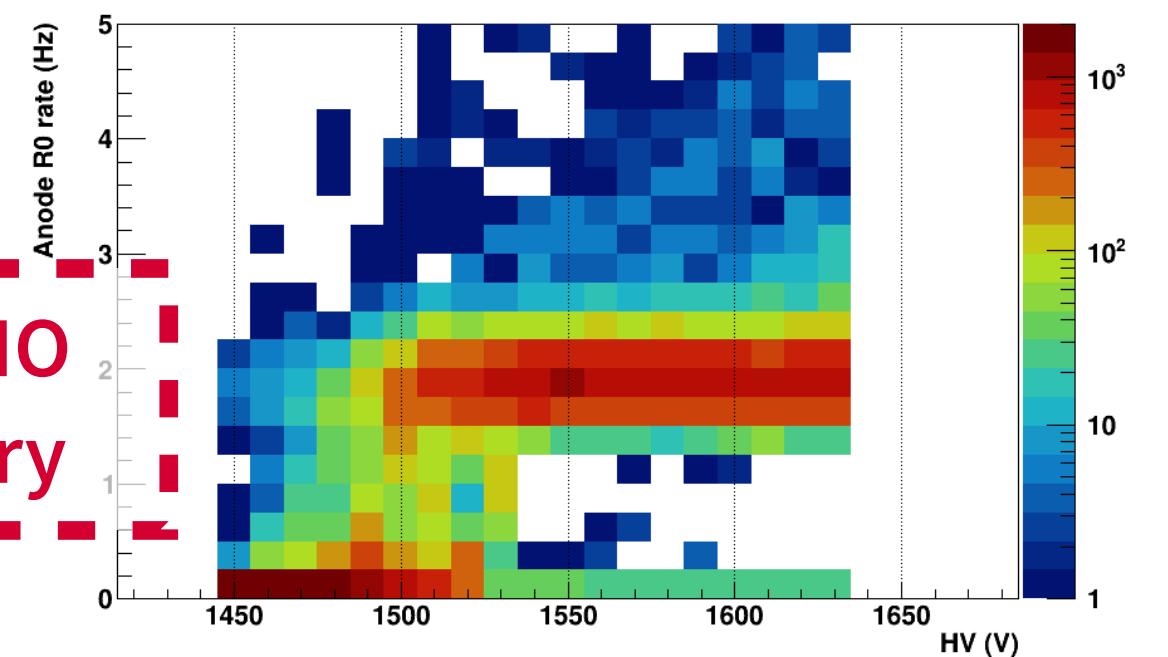


Tracking, time and energy calibration with  $^{207}\text{Bi}$  electrons

RUN 994 - Mean LI pulse start time (ns) \*\*\* BEFORE \*\*\* post trigger tuning

	ITALY	FRANCE
1540	148.3	112.4
1552	145.4	114.8
1563	143.9	116.8
1574	138.6	117.8
1585	135.7	122.8
1596	130.4	128.4
1607	129.8	129.2
1618	124.5	121.7
1629	118.2	118.2
1640	115.4	112.1
1651	112.1	112.1
1662	109.3	107.4
1673	106.5	105.2
1684	103.7	103.7
1695	100.9	101.9
1706	98.0	99.0
1717	95.1	101.6
1728	92.2	92.2
1739	89.3	90.3
1750	86.4	86.4
1761	83.5	83.5
1772	80.6	80.6
1783	77.7	77.7
1794	74.8	74.8
1805	71.9	71.9
1816	69.0	69.0
1827	66.1	66.1
1838	63.2	63.2
1849	60.3	60.3
1860	57.4	57.4
1871	54.5	54.5
1882	51.6	51.6
1893	48.7	48.7
1904	45.8	45.8
1915	42.9	42.9
1926	40.0	40.0
1937	37.1	37.1
1948	34.2	34.2
1959	31.3	31.3
1970	28.4	28.4
1981	25.5	25.5
1992	22.6	22.6
2003	19.7	19.7
2014	16.8	16.8
2025	13.9	13.9
2036	11.0	11.0
2047	8.1	8.1
2058	5.2	5.2
2069	2.3	2.3
2080	0.4	0.4

SuperNEMO  
Preliminary



## Anodic plateau

LI timing calibration corrects for cable lengths

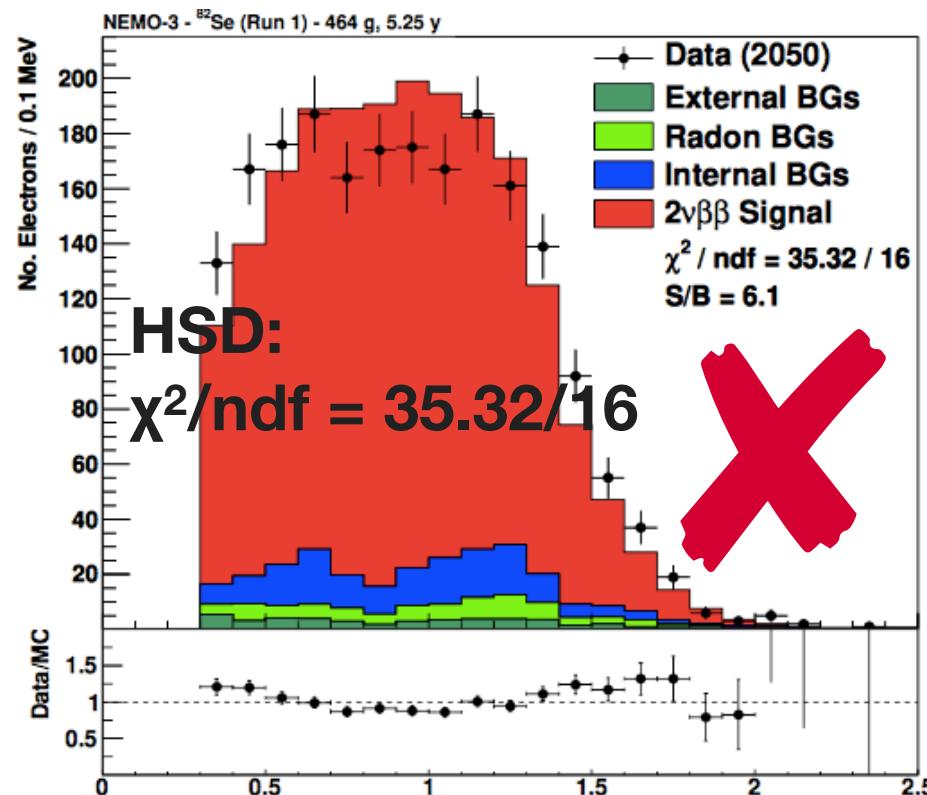
SuperNEMO is now in continuous data-taking mode!

Tuning voltages, thresholds and gas composition to optimise performance

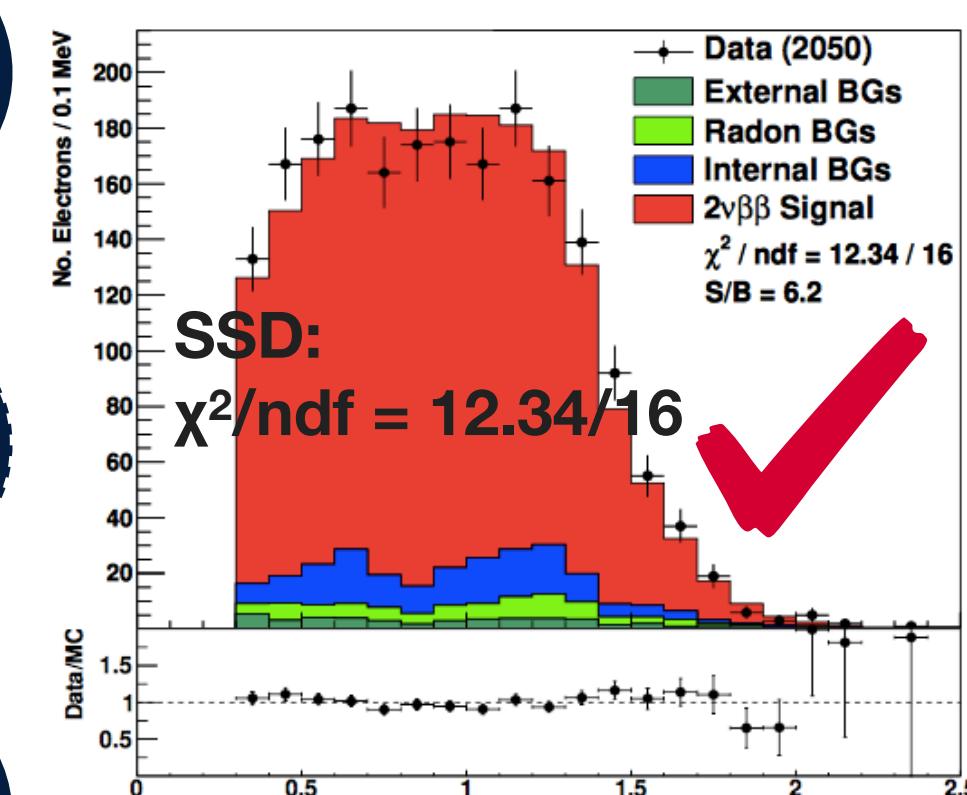
# SuperNEMO for nuclear effects with $2\nu\beta\beta$

## NEMO-3 : $3\sigma$ preference for SSD decays in $^{82}\text{Se}$

Eur. Phys. J. C (2018) 78: 821



Various excited states



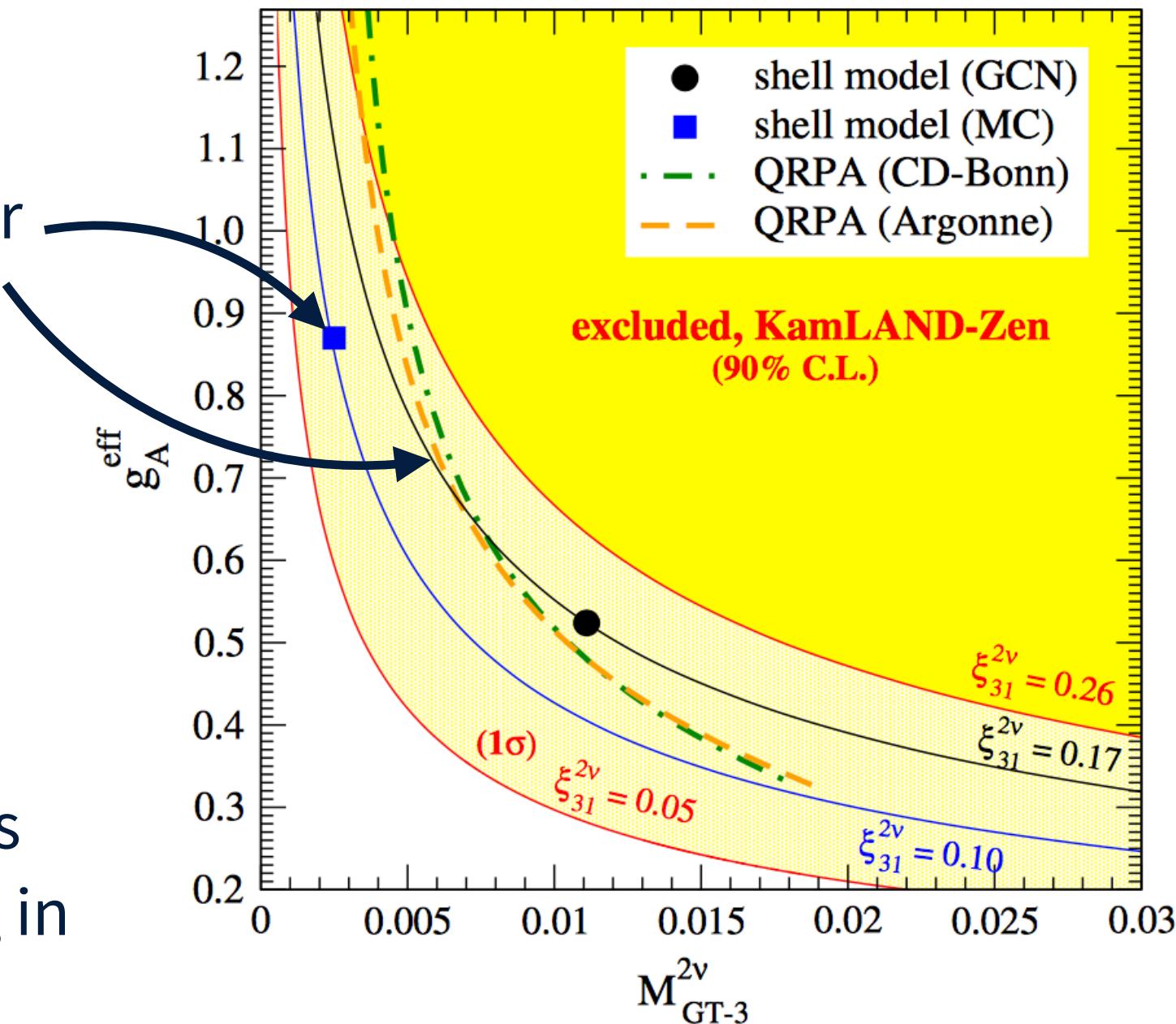
Mostly ground state

## Quenching of axial coupling $g_A$

Phys Rev Lett 122, 192501 (2019)

Nuclear models  $\rightarrow$  lines or points in plane

- Excluding areas can
- rule out nuclear models
  - constrain  $g_A$  quenching in heavy nuclei

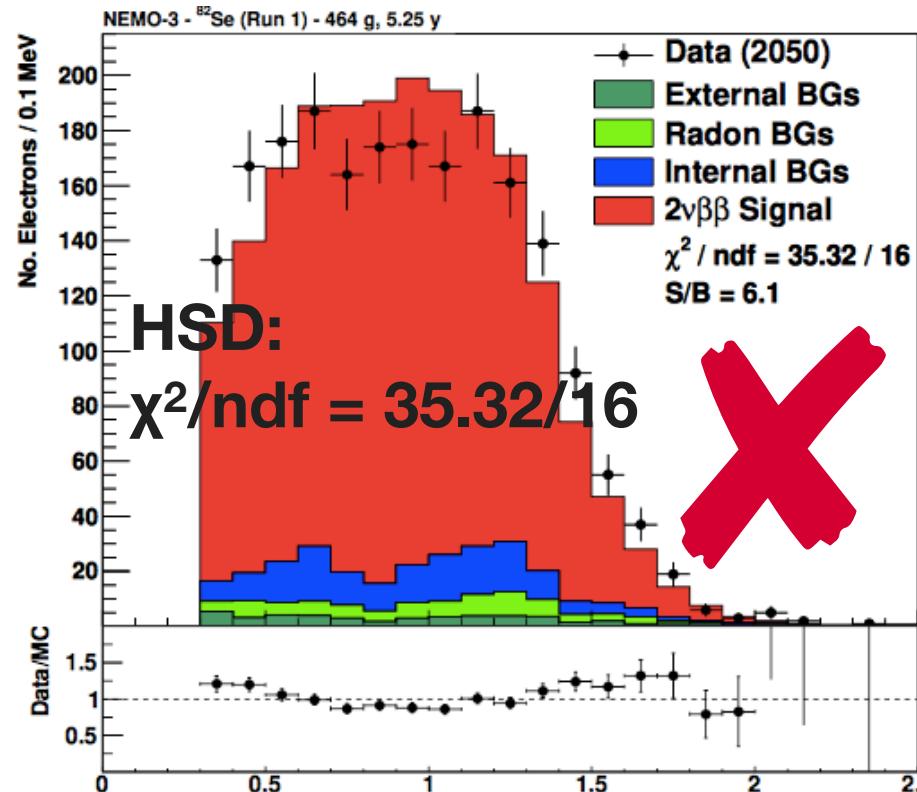


SuperNEMO :  $5\sigma$  SSD/HSD sensitivity in < 2.5 years

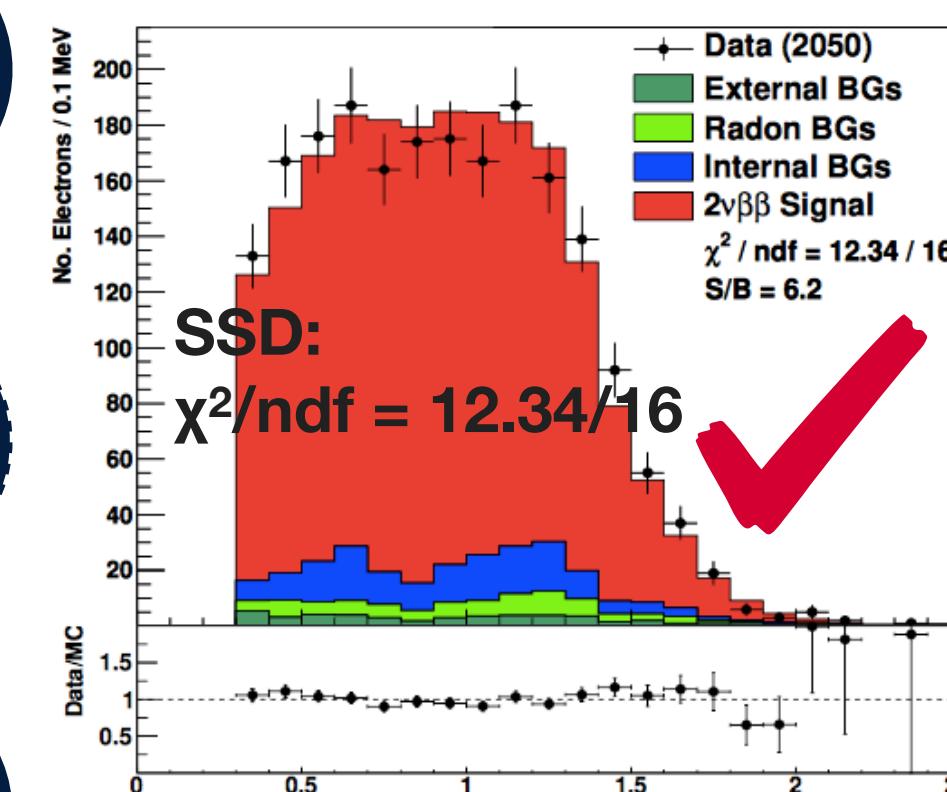
# SuperNEMO for nuclear effects with $2\nu\beta\beta$

## NEMO-3 : $3\sigma$ preference for SSD decays in $^{82}\text{Se}$

Eur. Phys. J. C (2018) 78: 821



Various excited states



Mostly ground state

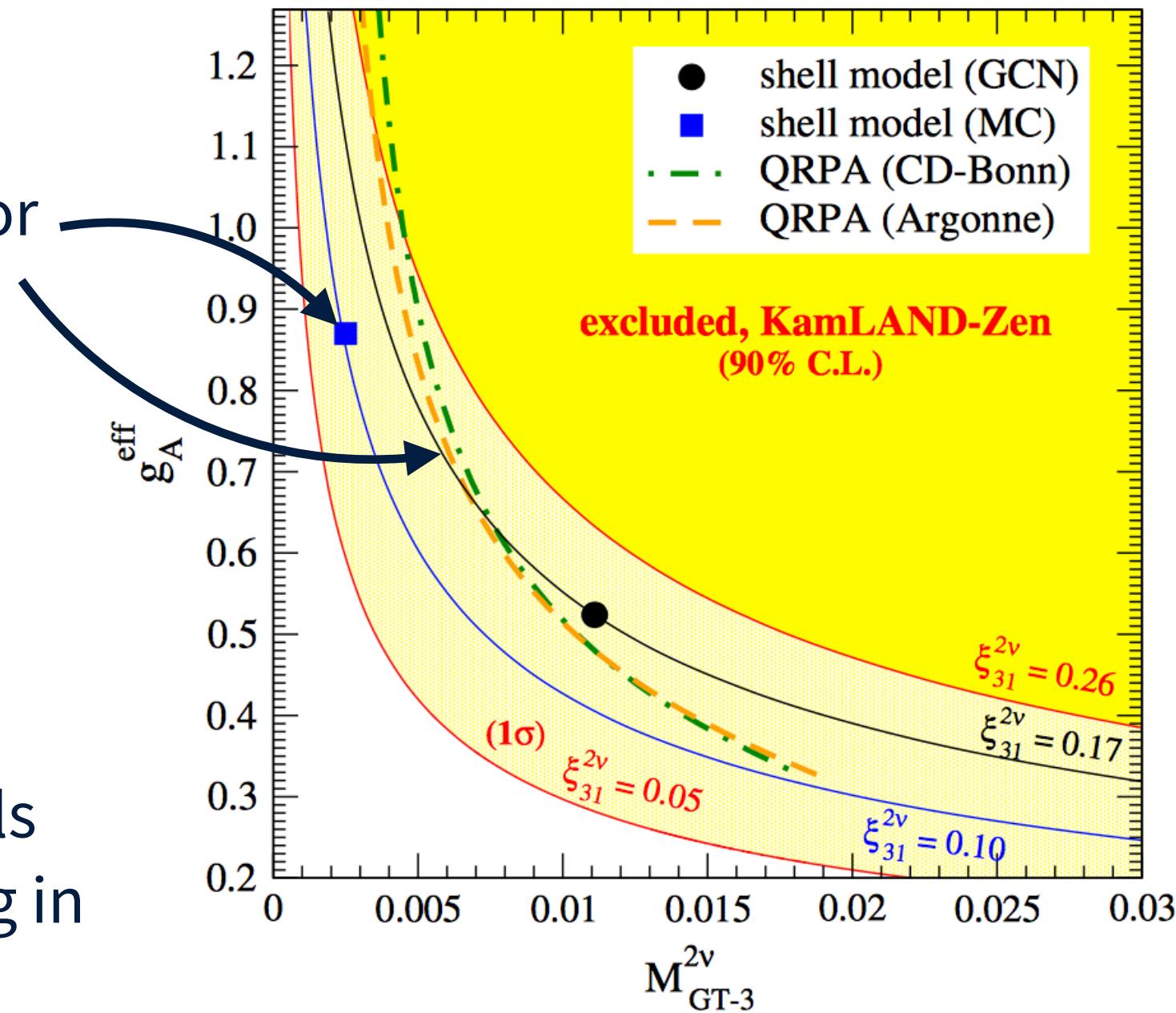
Topological reconstruction makes SuperNEMO the best technology for reducing nuclear uncertainties in  $\beta\beta$  decay

## Quenching of axial coupling $g_A$

Phys Rev Lett 122, 192501 (2019)

Nuclear models  $\rightarrow$  lines or points in plane

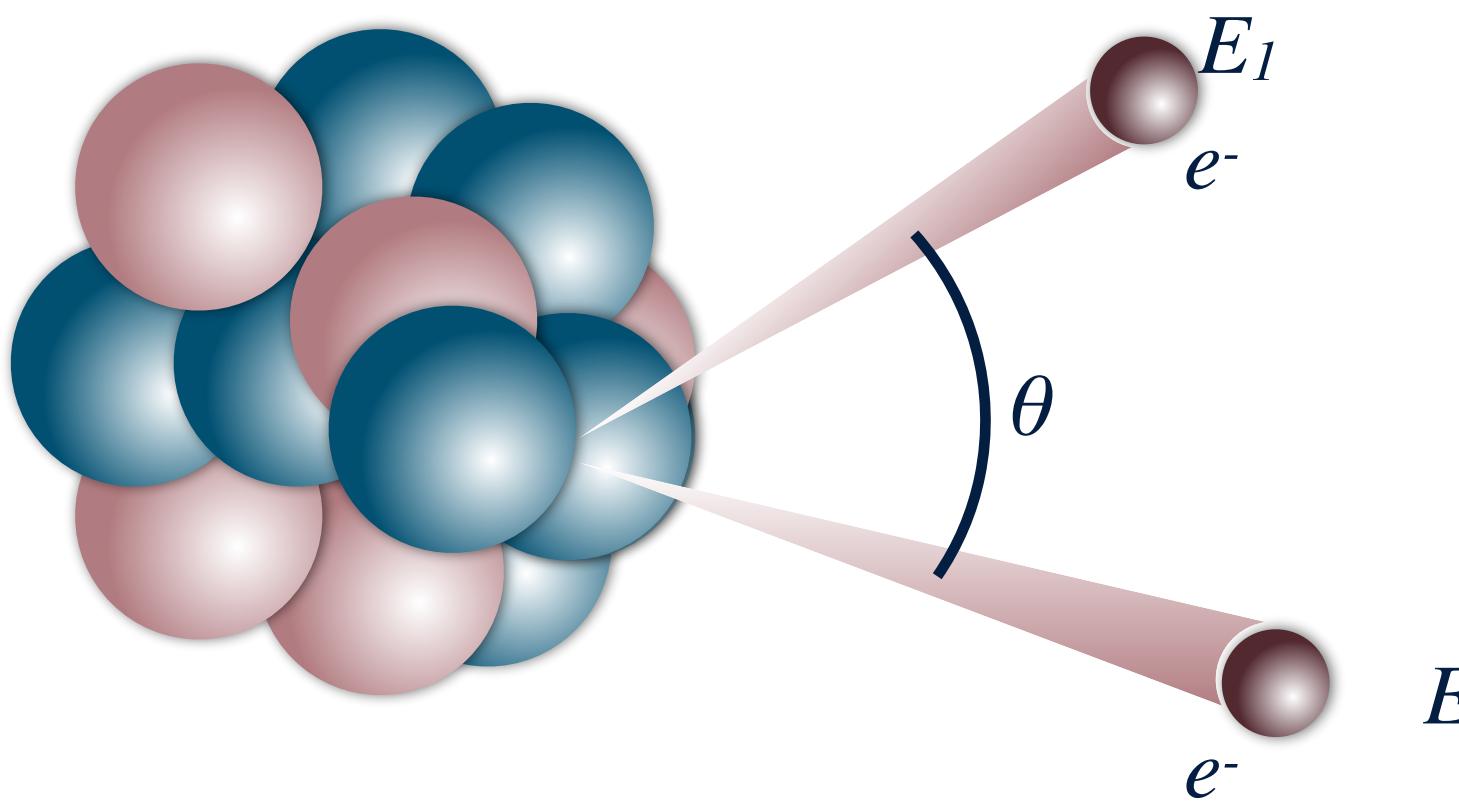
Excluding areas can  
• rule out nuclear models



SuperNEMO :  $5\sigma$  SSD/HSD sensitivity in < 2.5 years

SuperNEMO's individual  $e^-$  spectrum is more sensitive to  $g_A$

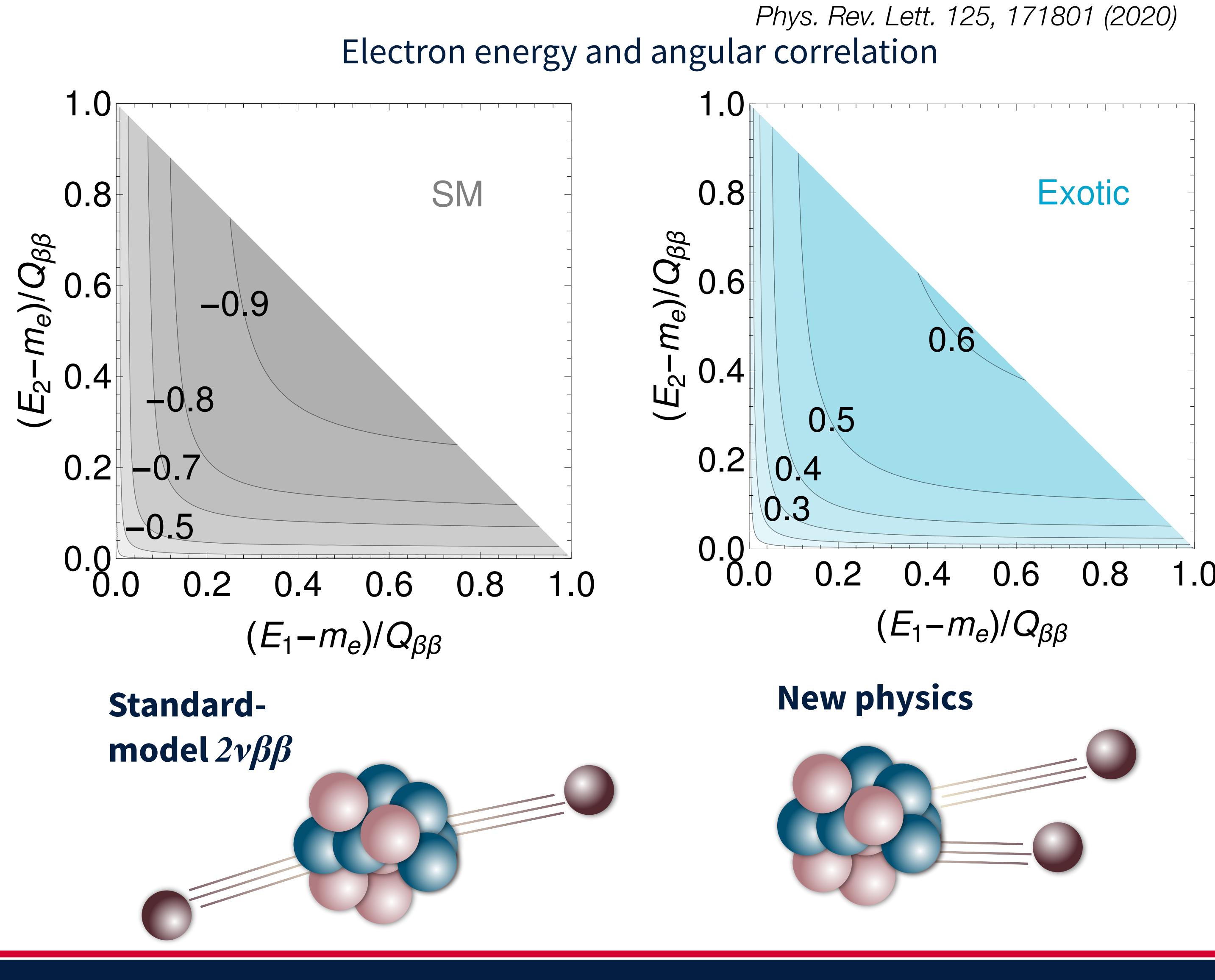
# SuperNEMO physics - looking for new physics with $2\nu\beta\beta$



Precision  $2\nu\beta\beta$  measurements can reveal BSM effects...

- Lorentz-invariance violation
- Exotic  $0\nu\beta\beta$  mechanisms
- Scalar currents
- Right-handed neutrinos (see right)

If  $0\nu\beta\beta$  is discovered, a SuperNEMO-style topological detector will be key to understanding the mechanism.

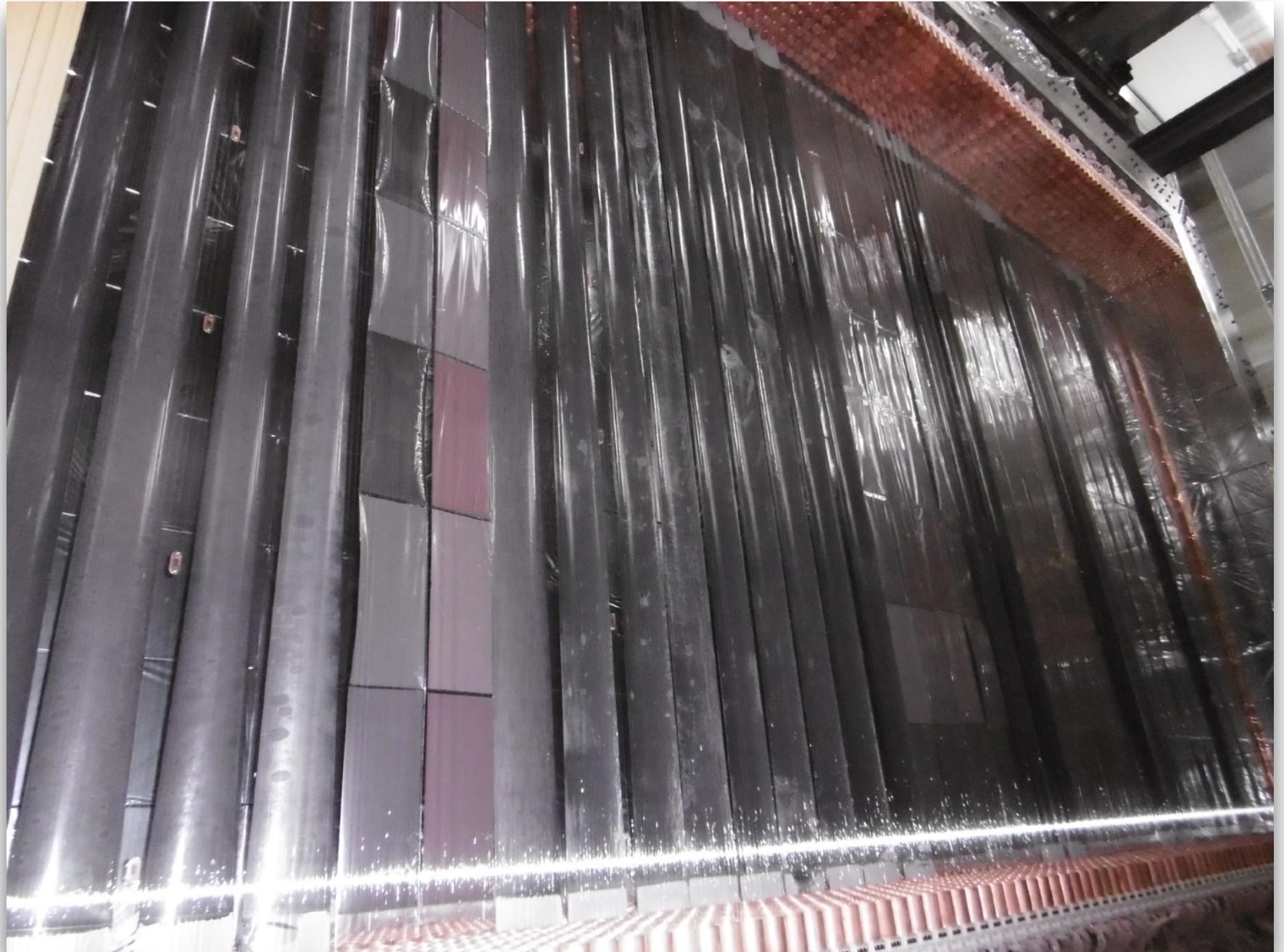


# The NEMO technique:



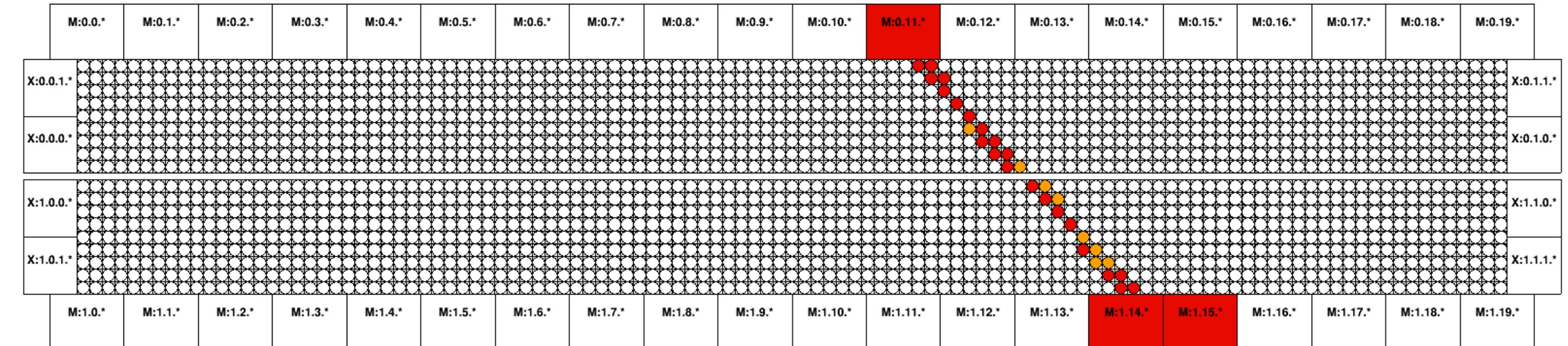
- Is (nearly) isotope-agnostic
- Gives full topological reconstruction and particle ID
- Can make unique  $2\nu\beta\beta$  measurements:
  - nuclear effects
  - exotic decays & new physics
- Could probe  $0\nu\beta\beta$  mechanism if discovered

# The NEMO technique:



# SuperNEMO Demonstrator is:

RUN 1011 // TRIGGER 3210833

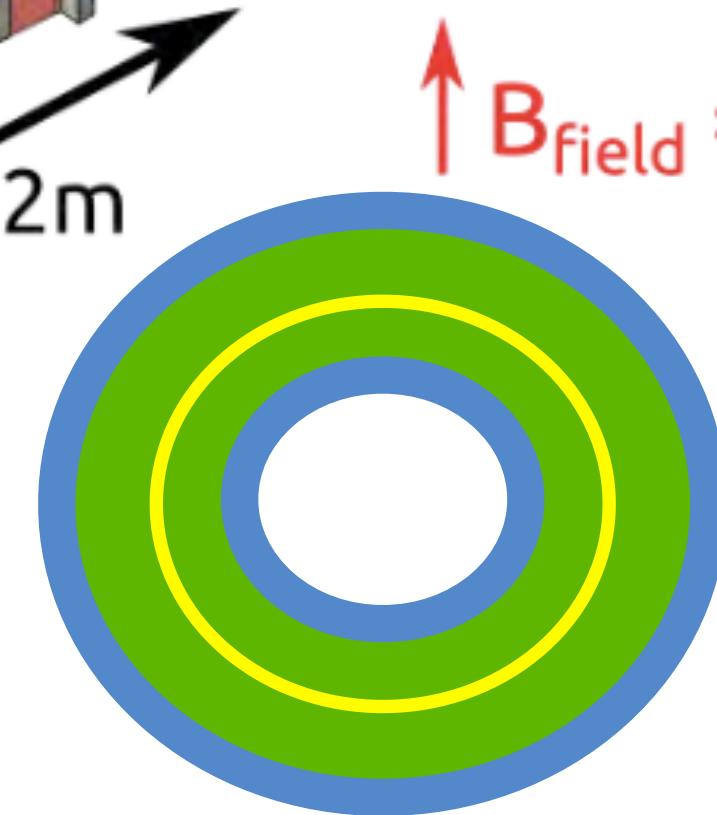
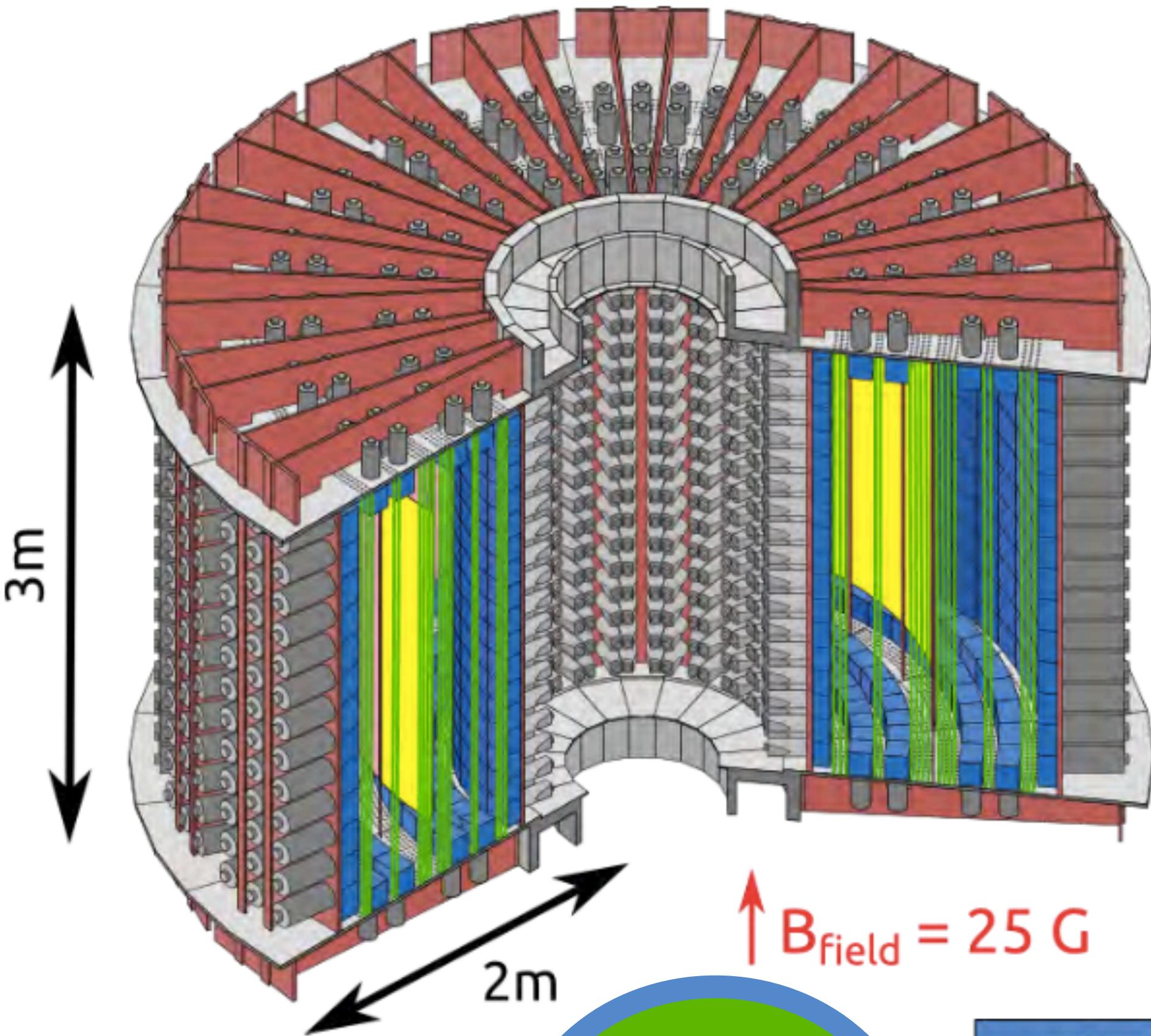


- Is (nearly) isotope-agnostic
- Gives full topological reconstruction and particle ID
- Can make unique  $2\nu\beta\beta$  measurements:
  - nuclear effects
  - exotic decays & new physics
- Could probe  $0\nu\beta\beta$  mechanism if discovered

- A proof of concept for future detectors
- In continuous data-taking mode
- Making first preliminary background measurements
- Undergoing shielding installation
- Excited for first  $\beta\beta$  data in the coming months, and world-leading measurements!

## Backup slides

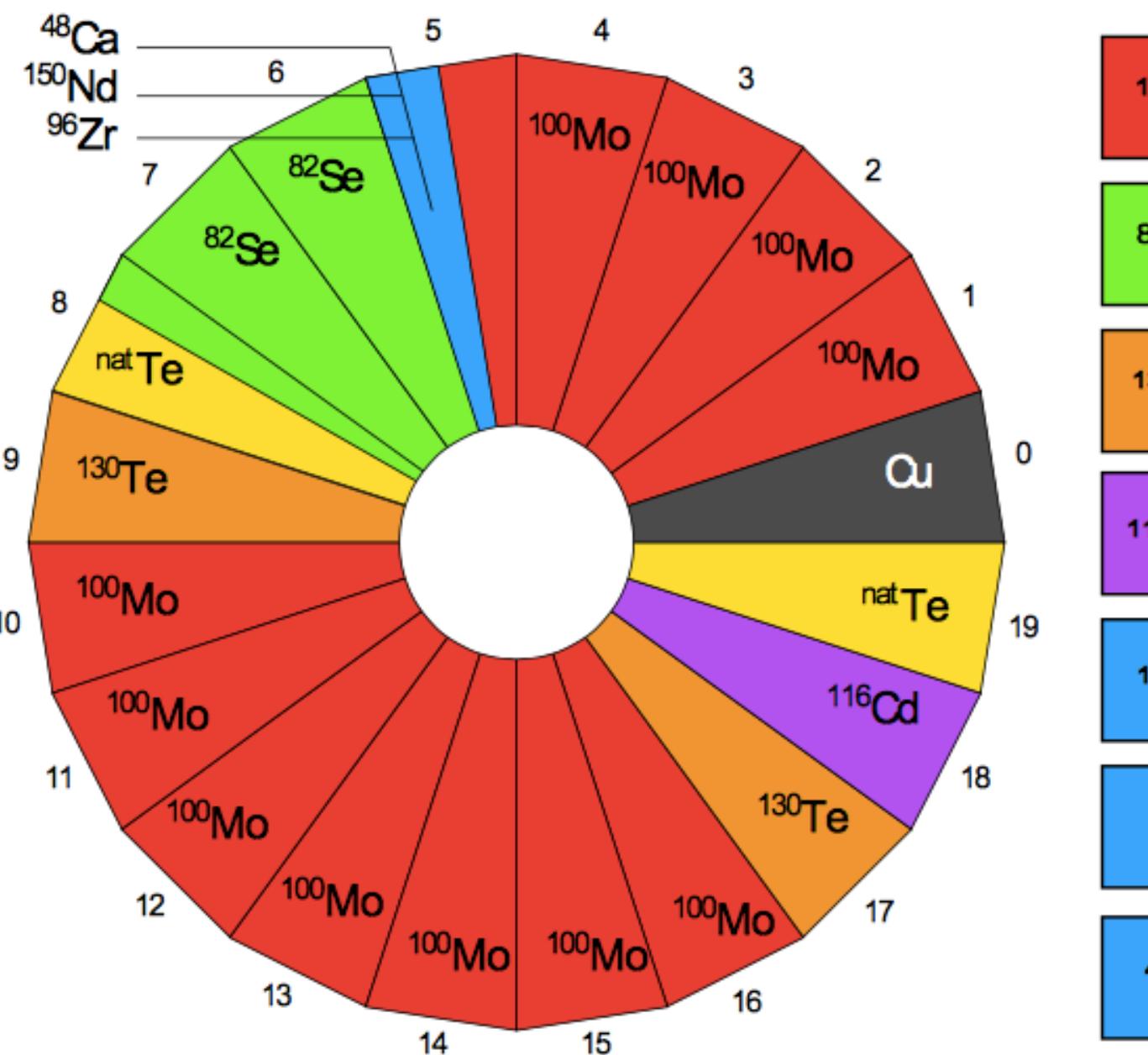
# NEMO-3 (running 2003-2011)



$B_{\text{field}} = 25 \text{ G}$

**calorimeter**  
 1940 optical modules :  
 polystyren scintillators  
 + 3" and 5" PMTs  
 $\text{FWHM}_E \sim 15\% / \sqrt{\text{E}_{\text{MeV}}}$   
 $\sigma_t \sim 250 \text{ ps}$

NEMO-3 "camembert" (source top view)



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

**sources**  
 60 mg/cm<sup>2</sup> Foils  
 10 kg of  $\beta\beta$  isotopes



# How the tracker works

