

SuperNEMO Demonstrator

A double-beta-decay experiment

Status & Objectives

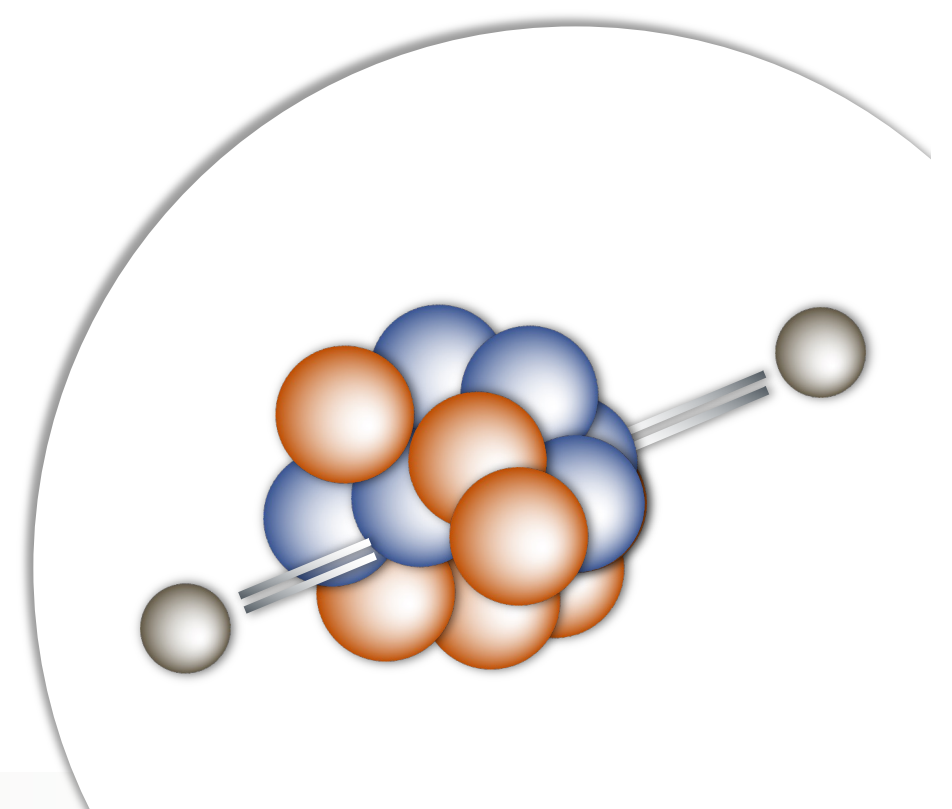
IN2P3 Scientific Council – 6 October 2025

Christine Marquet, for the SuperNEMO collaboration



Why Double beta?

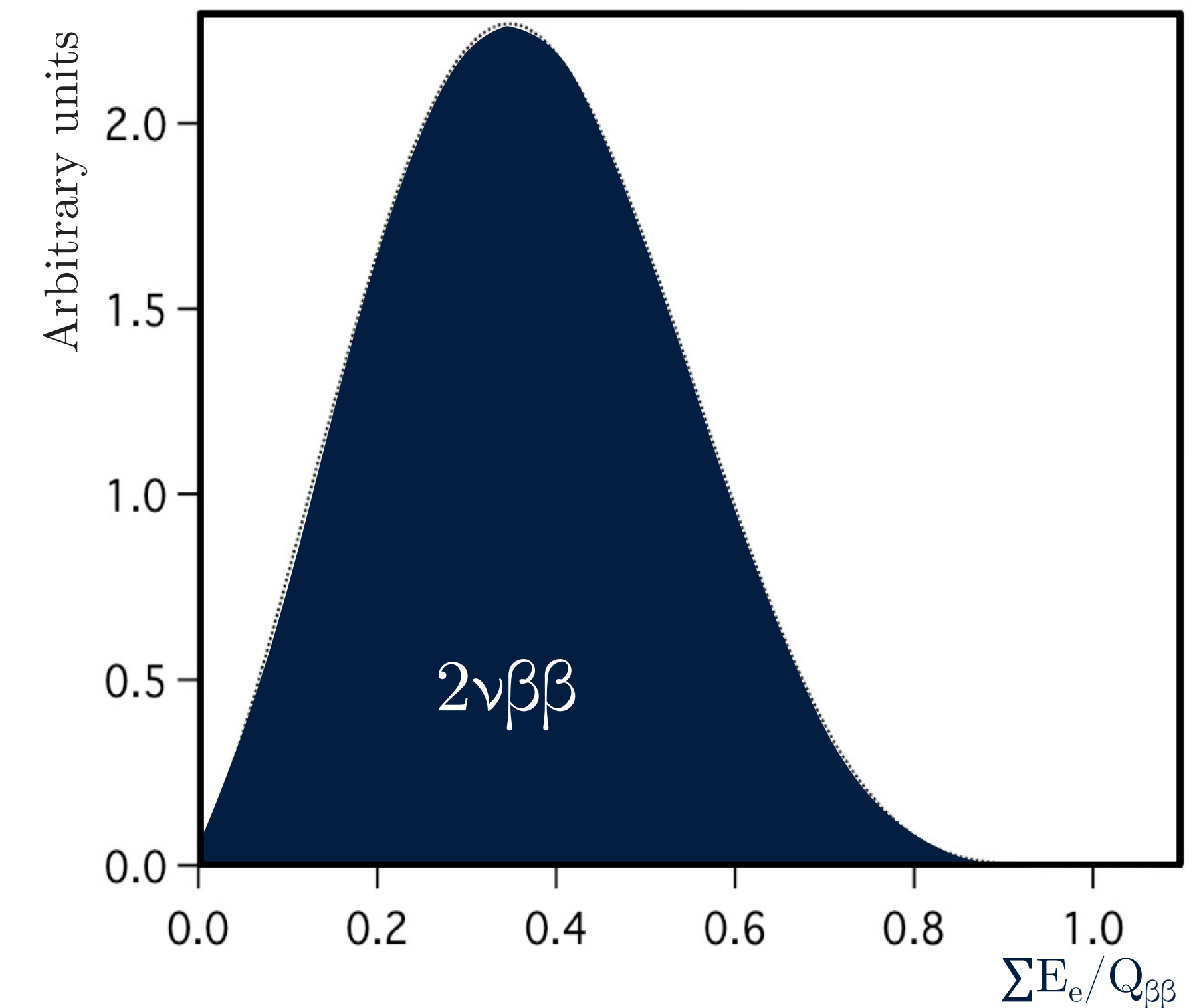
... and why SuperNEMO?



Standard-Model double-beta decay ($2\nu\beta\beta$)



- Observed in several isotopes
- $T_{1/2} \sim 10^{18} - 10^{24}$ years – longest measured (doubly weak)
- Standard Model process
- Lepton number conserved



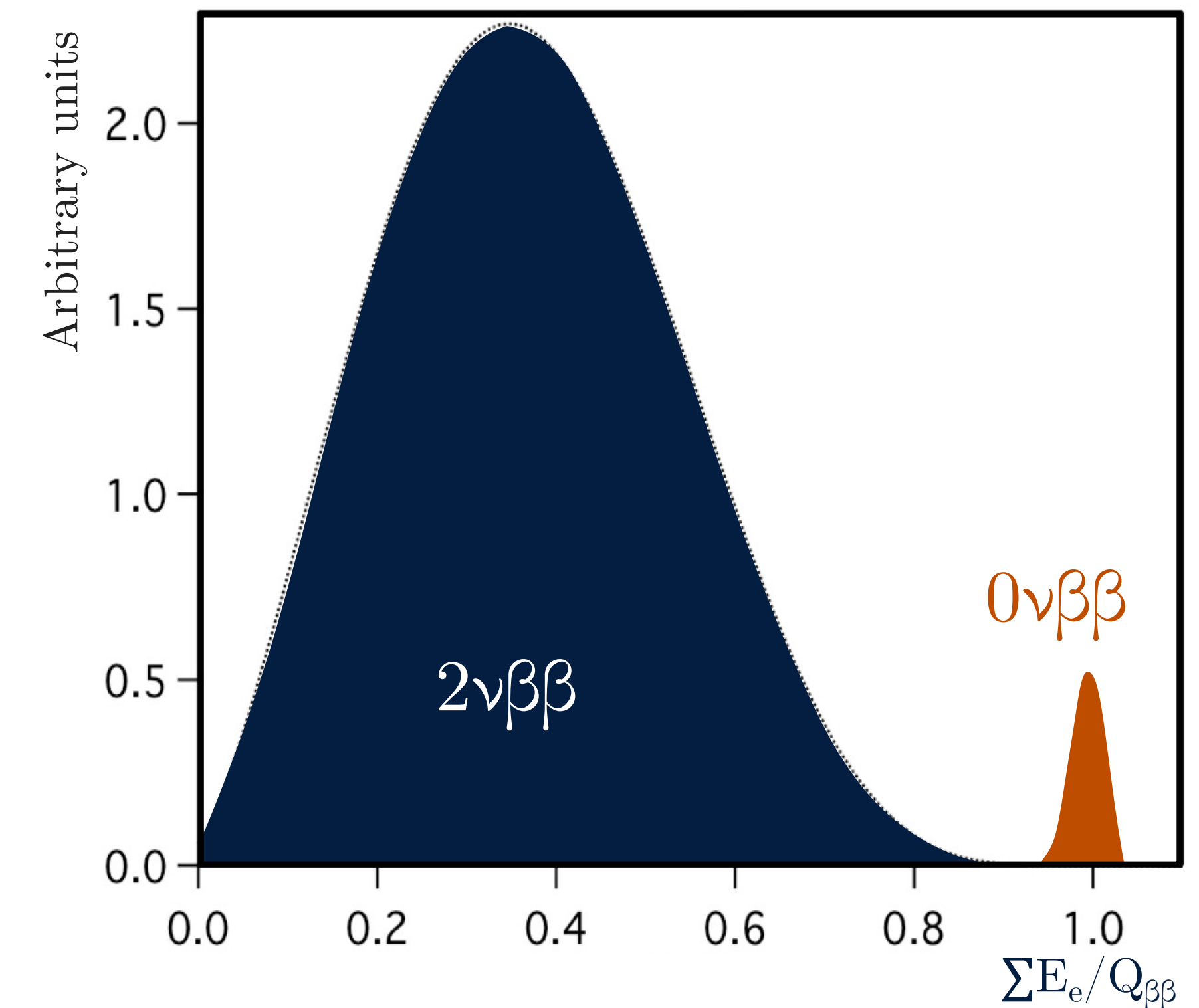
Neutrinoless double-beta decay ($0\nu\beta\beta$)



- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed - $T_{1/2} > 10^{24} - 10^{26}$ years

$0\nu\beta\beta$ observation means:

- Neutrinos are Majorana particles
- Lepton number $\Delta L=2$ + B-L (global) symmetry violation



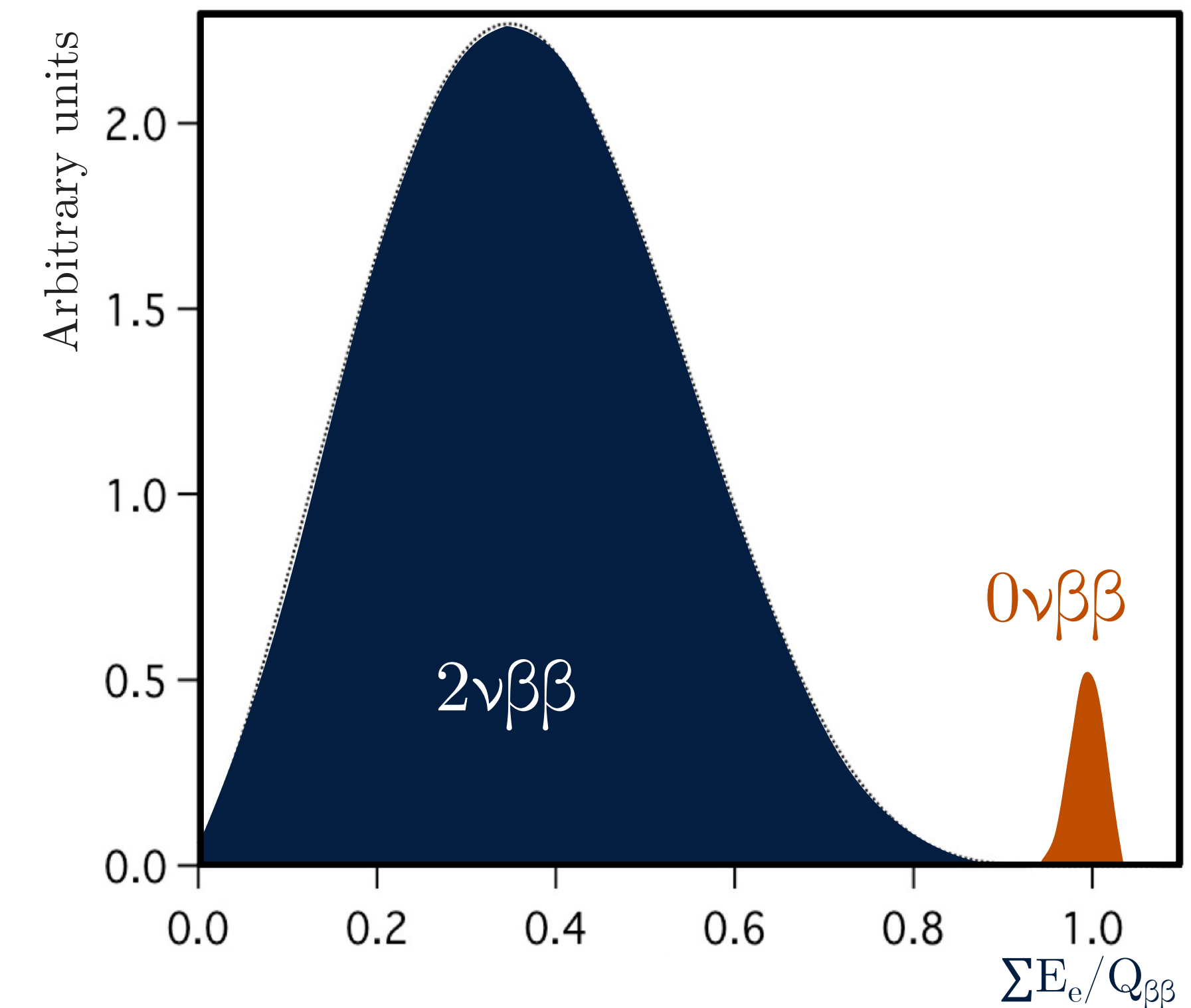
Neutrinoless double-beta decay ($0\nu\beta\beta$)



- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed - $T_{1/2} > 10^{24} - 10^{26}$ years

$0\nu\beta\beta$ observation means:

- Neutrinos are Majorana particles
- Lepton number $\Delta L=2$ + B-L (global) symmetry violation



- Neutrino Physics: Nature & Inputs for tiny ν mass models
- Cosmology: Matter-antimatter asymmetry via leptogenesis (LNV+Majorana ν required)
- Nuclear physics: Nuclear structure insights
- Particle physics: Possible new interactions (V+A?), new bosons (Majorons?)

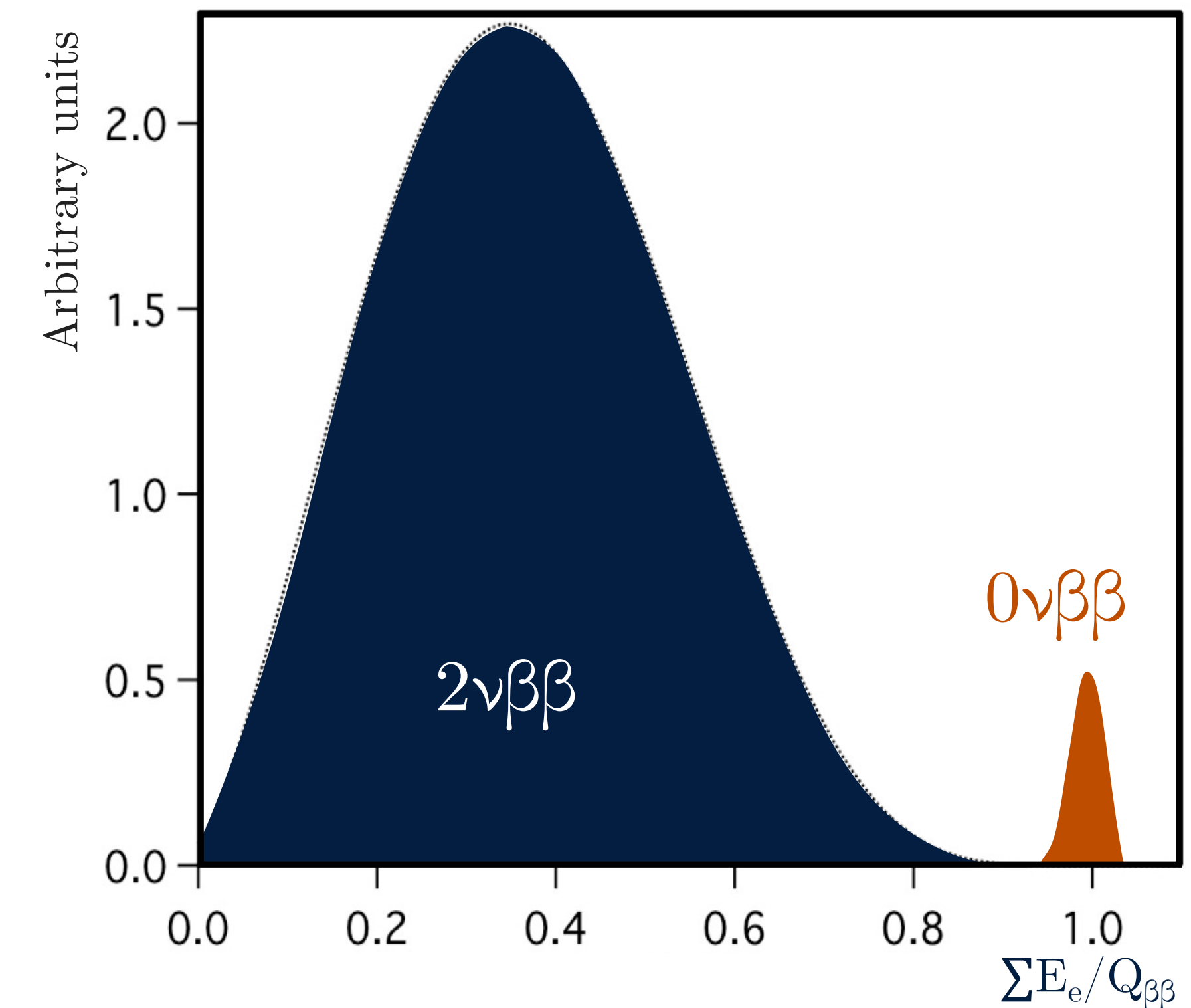
Neutrinoless double-beta decay ($0\nu\beta\beta$)



- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed - $T_{1/2} > 10^{24} - 10^{26}$ years

$0\nu\beta\beta$ observation means:

- Neutrinos are Majorana particles
- Lepton number $\Delta L=2$ + B-L (global) symmetry violation



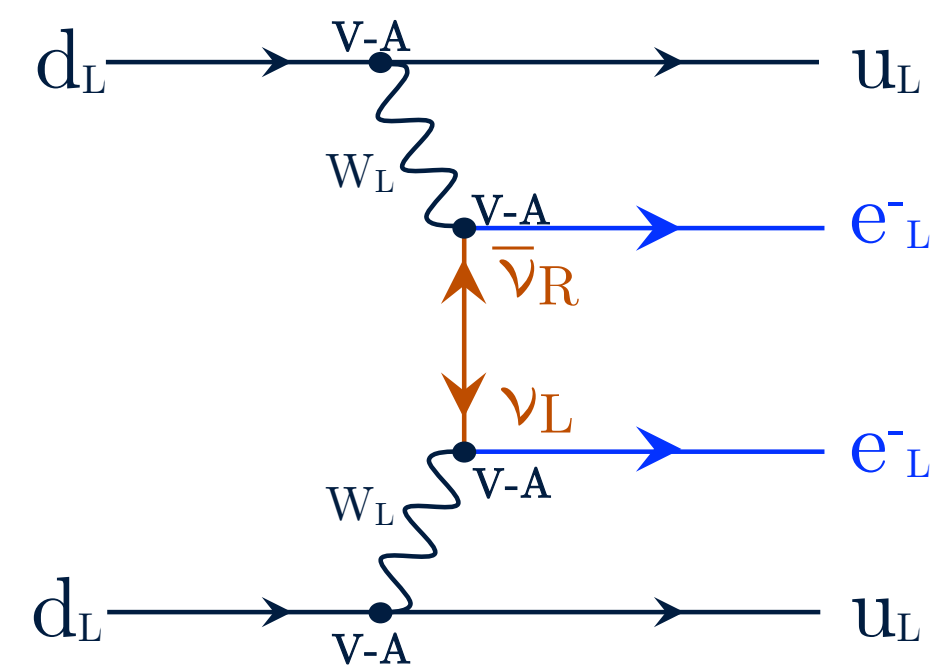
- **Neutrino Physics:** Nature & Inputs for tiny ν mass models
- **Cosmology:** Matter-antimatter asymmetry via leptogenesis (LNV+Majorana ν required)
- **Nuclear physics:** Nuclear structure insights
- **Particle physics:** Possible new interactions (V+A?), new bosons (Majorons?)

BSM physics investigation
complementary to reactor- and
accelerator-based experiments

Neutrinoless double-beta decay ($0\nu\beta\beta$)



Still-unknown underlying mechanisms ...



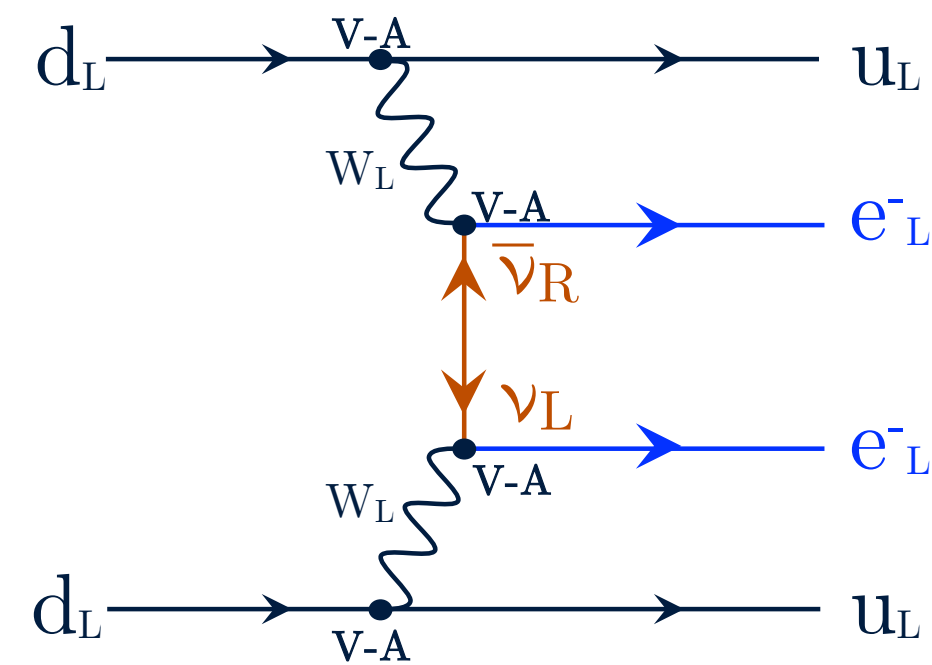
Light neutrino Exchange
(V-A)

Commonly considered
by all experiments
 $\rightarrow m_{\beta\beta}$

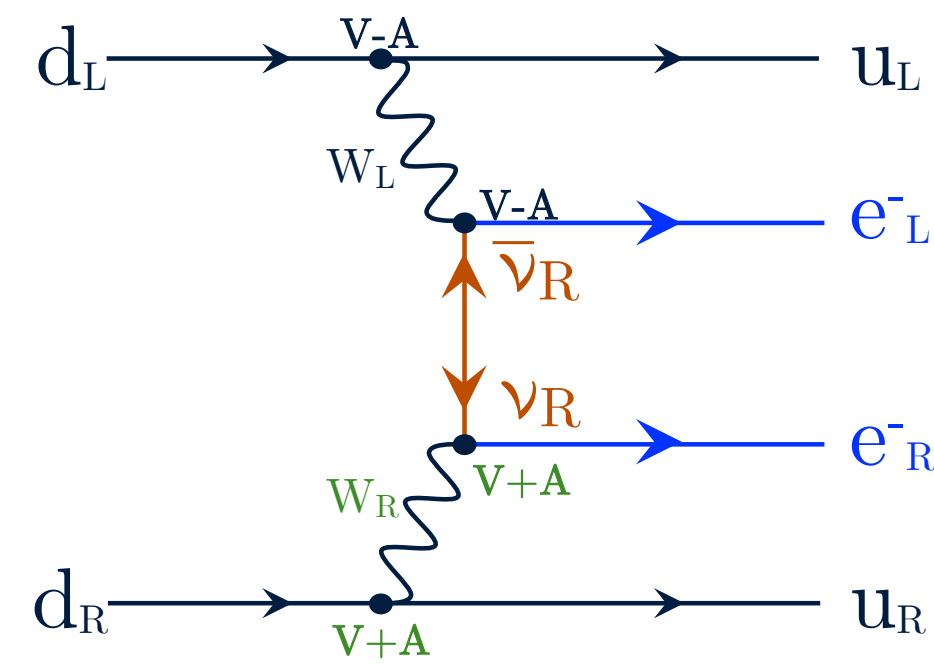
Neutrinoless double-beta decay ($0\nu\beta\beta$)



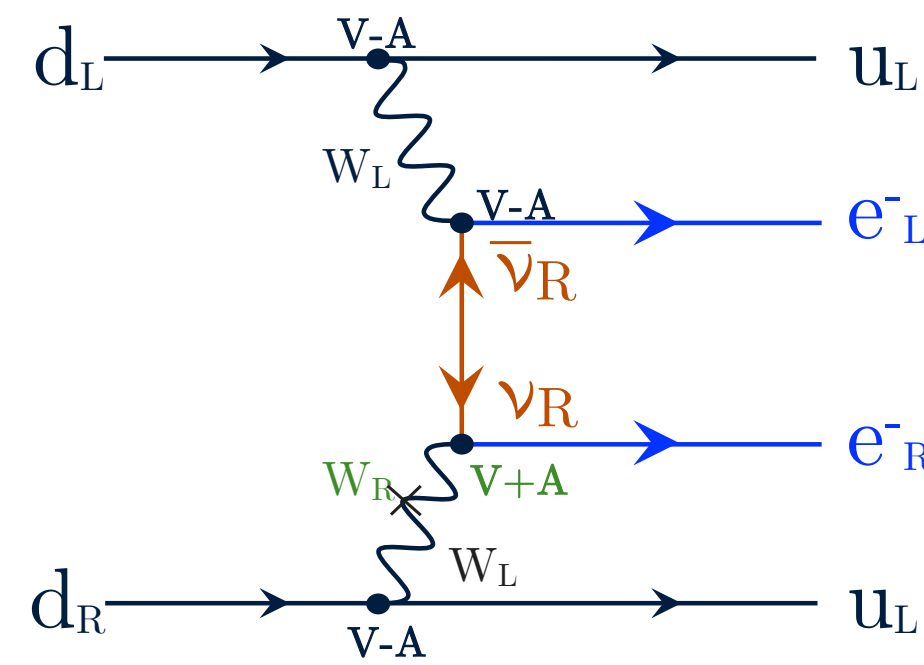
Still-unknown underlying mechanisms ...



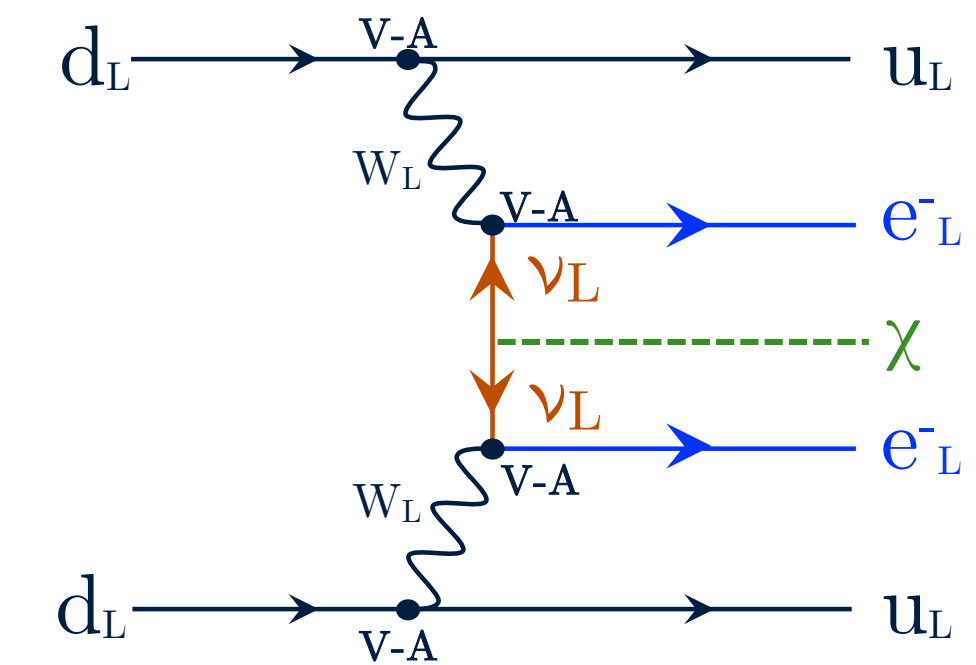
Light neutrino Exchange
(V-A)



Left-Right Symmetry (λ)
(V+A)_l + (V+A)_h



Left-Right Symmetry (η)
(V+A)_l



Majoron emission

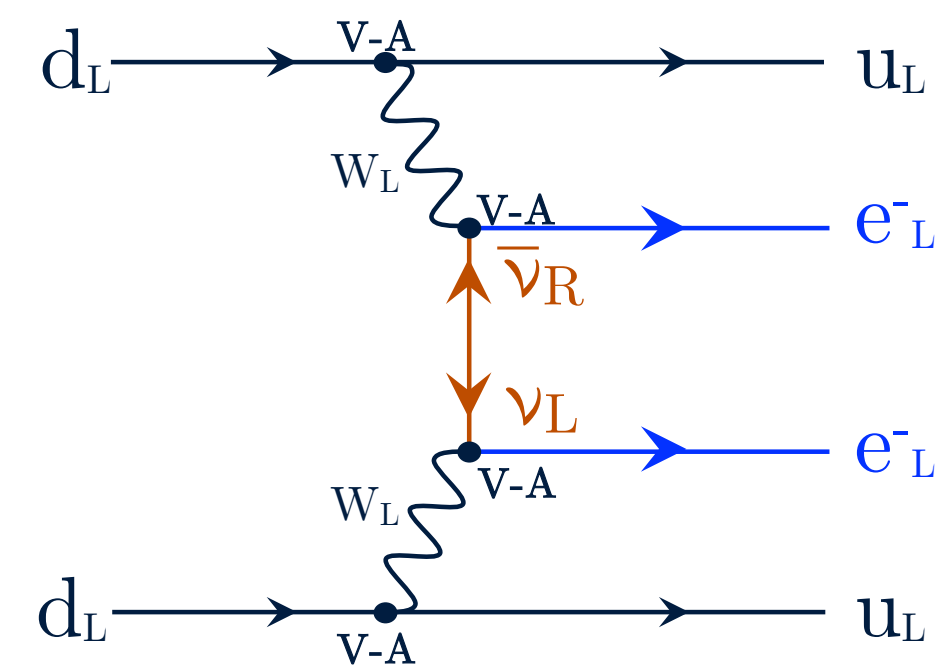
etc...

Commonly considered
by all experiments
 $\rightarrow m_{\beta\beta}$

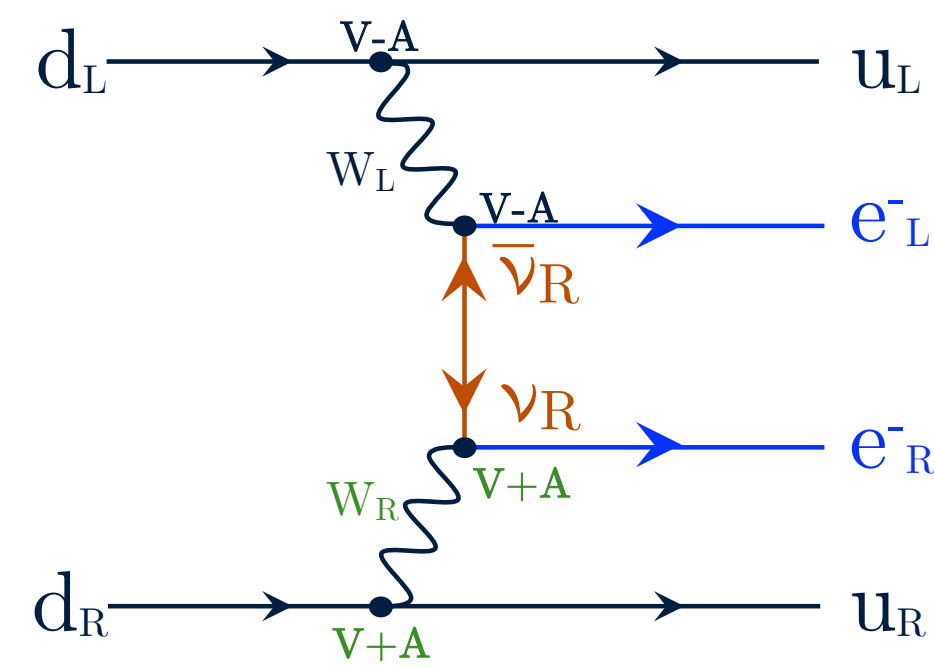
Neutrinoless double-beta decay ($0\nu\beta\beta$)

$$(A, Z) \longrightarrow (A, Z+2) + 2e^- + \cancel{2\bar{\nu}_e}$$

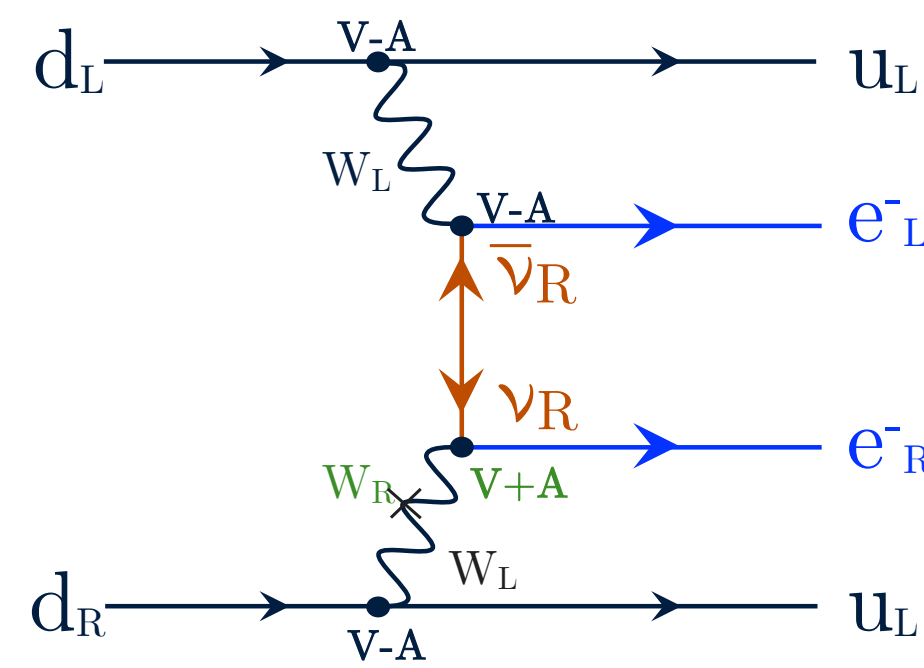
Still-unknown underlying mechanisms ...



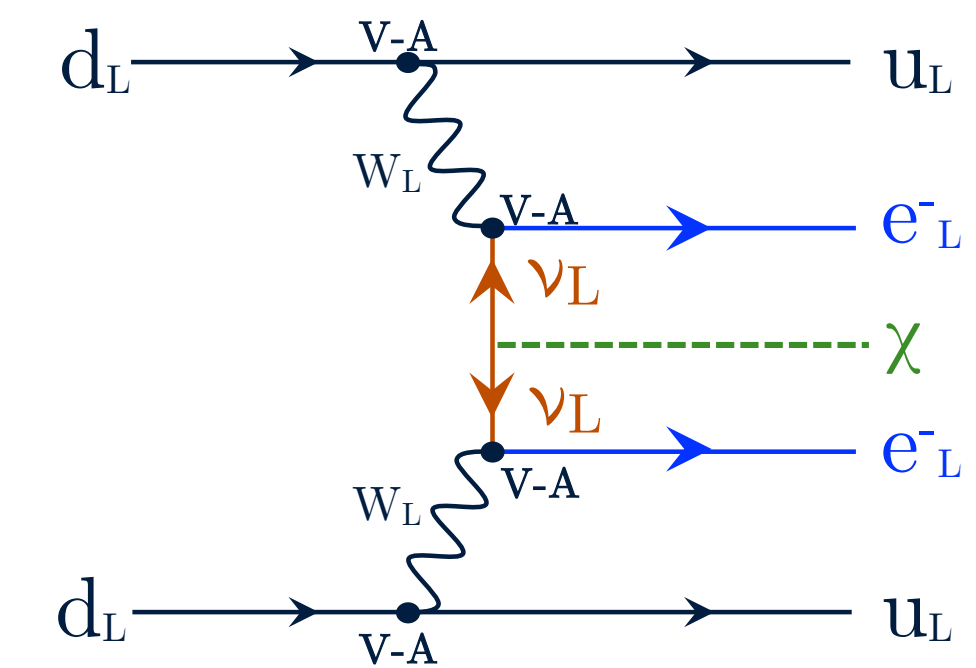
Light neutrino Exchange
(V-A)



Left-Right Symmetry (λ)
 $(V+A)_l + (V+A)_h$



Left-Right Symmetry (η)
 $(V+A)_l$



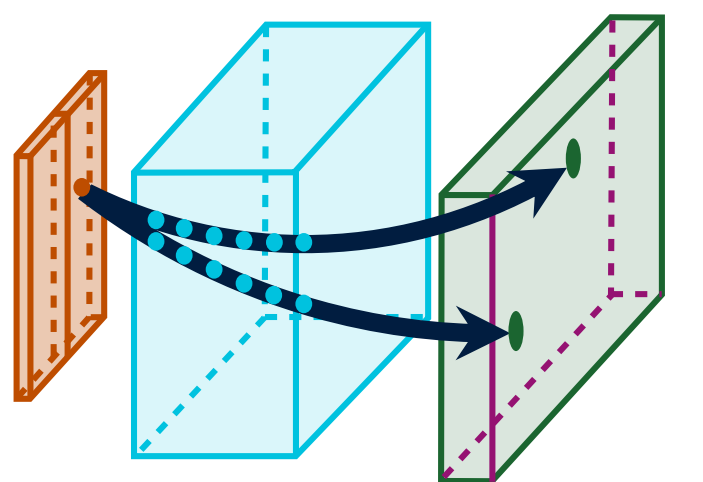
Majoron emission

etc...

- $0\nu\beta\beta$ can probe B-L BSM physics and potentially *explore* it!
- Need a maximum number of observables (individual e^- energy, angular correlations,...)
- Unique opportunity with SuperNEMO technology

[Eur. Phys. J. C 70 (2010) 927-943]

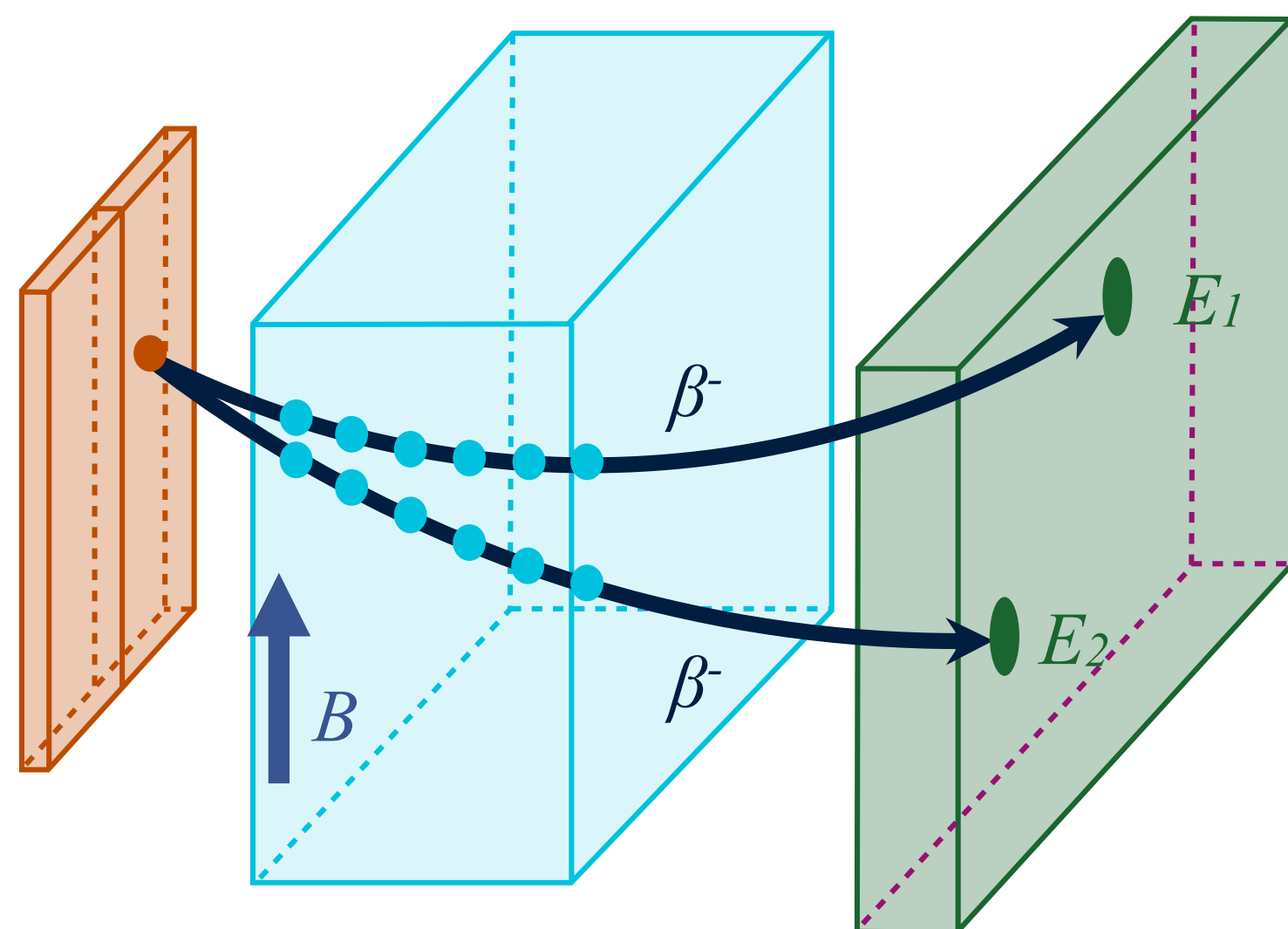
SuperNEMO approach highlights



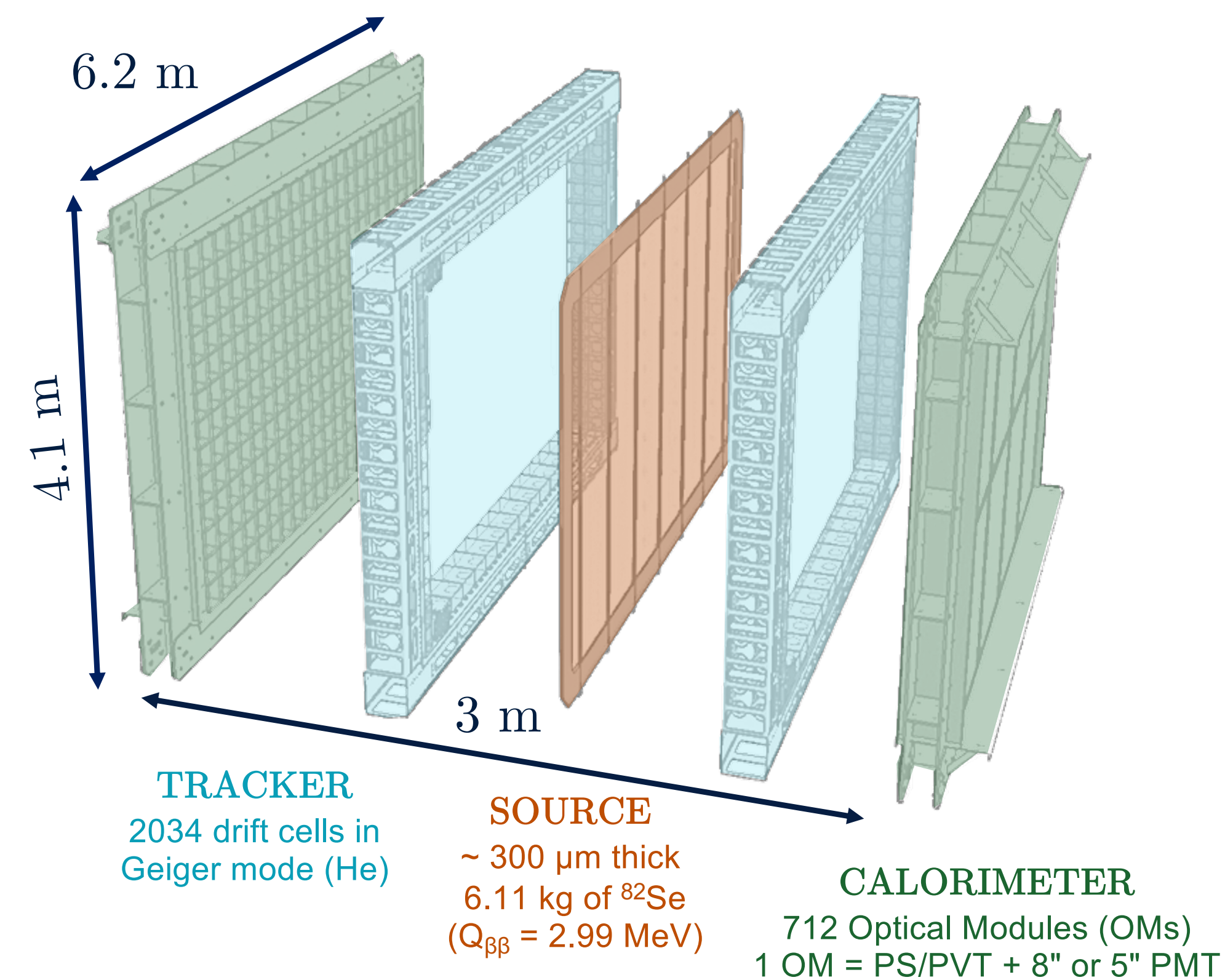
What makes SuperNEMO unique?

Tracker-calorimeter approach

$\beta\beta$ source foil Gaseous tracker Segmented calorimeter



Demonstrator @ LSM underground lab

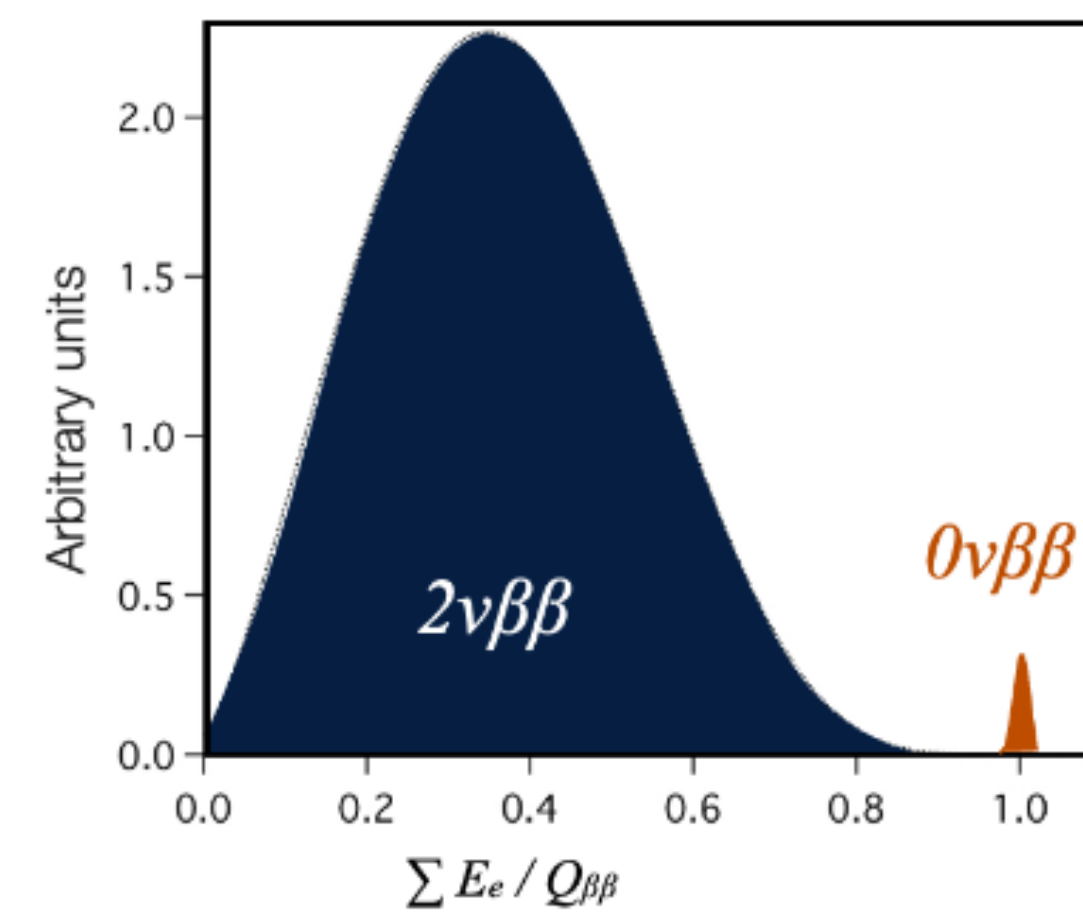


SuperNEMO combines 3 **separate** sub-systems: thin source + tracker + calorimeter

What makes SuperNEMO unique?

ALL $\beta\beta$ experiments

Total energy

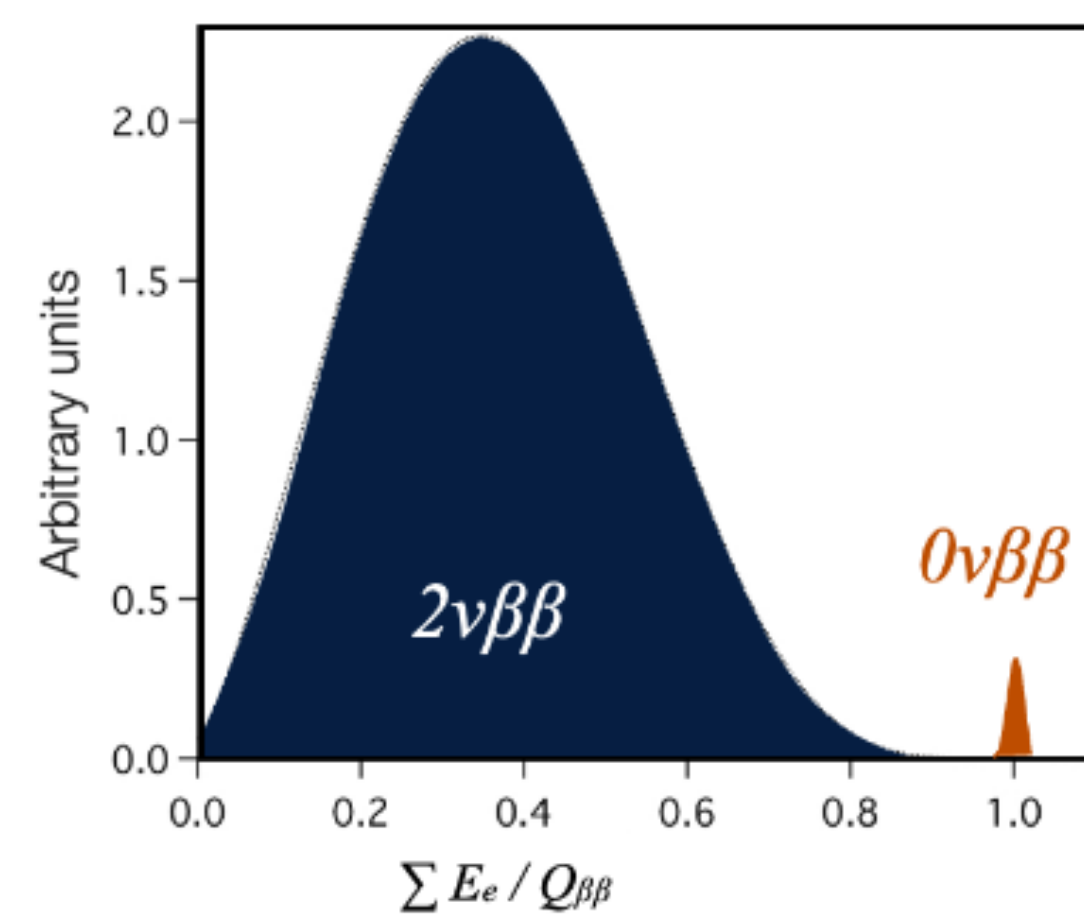


Modest E resolution & efficiency

What makes SuperNEMO unique?

ALL $\beta\beta$ experiments

Total energy



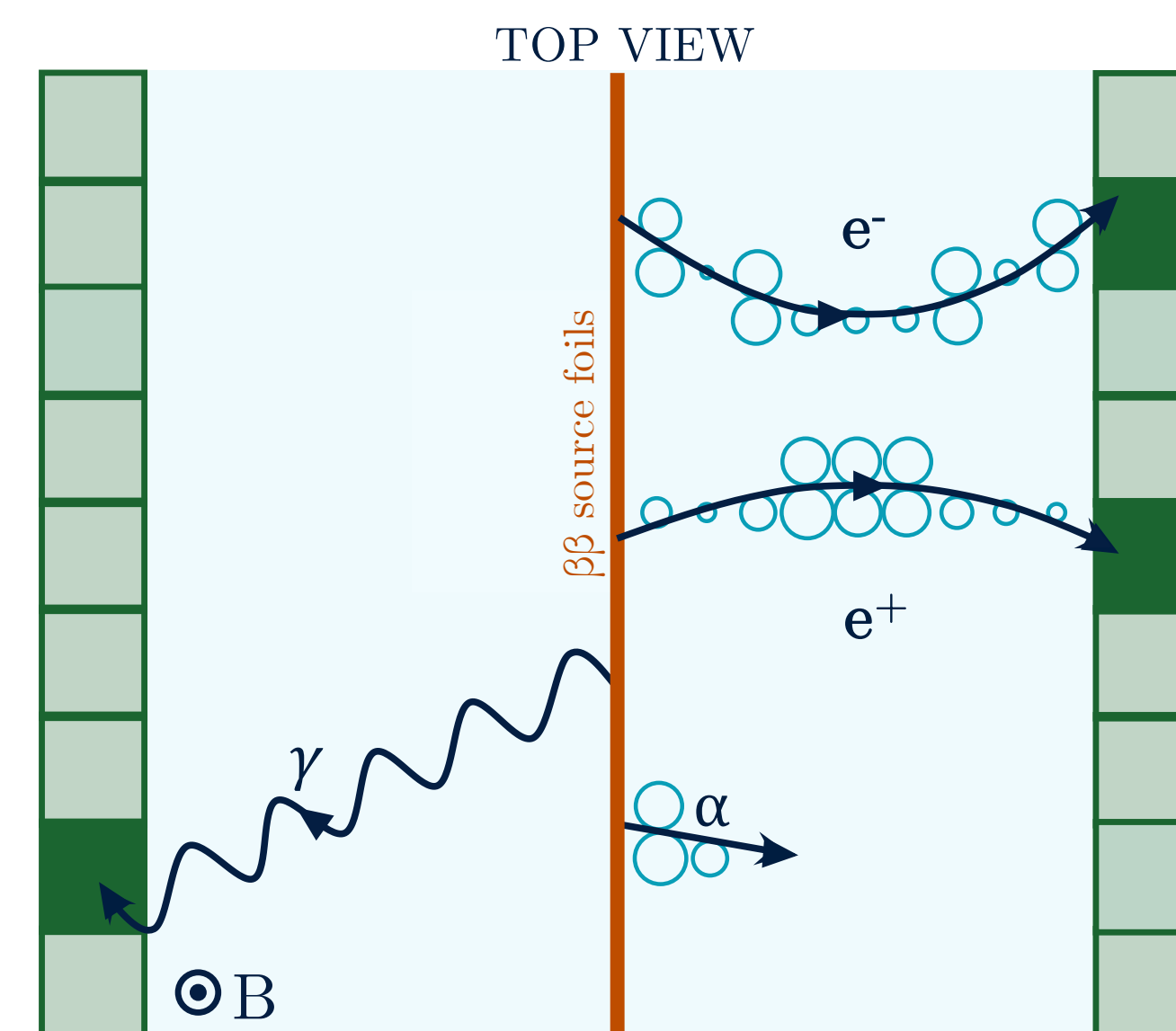
Modest E resolution & efficiency



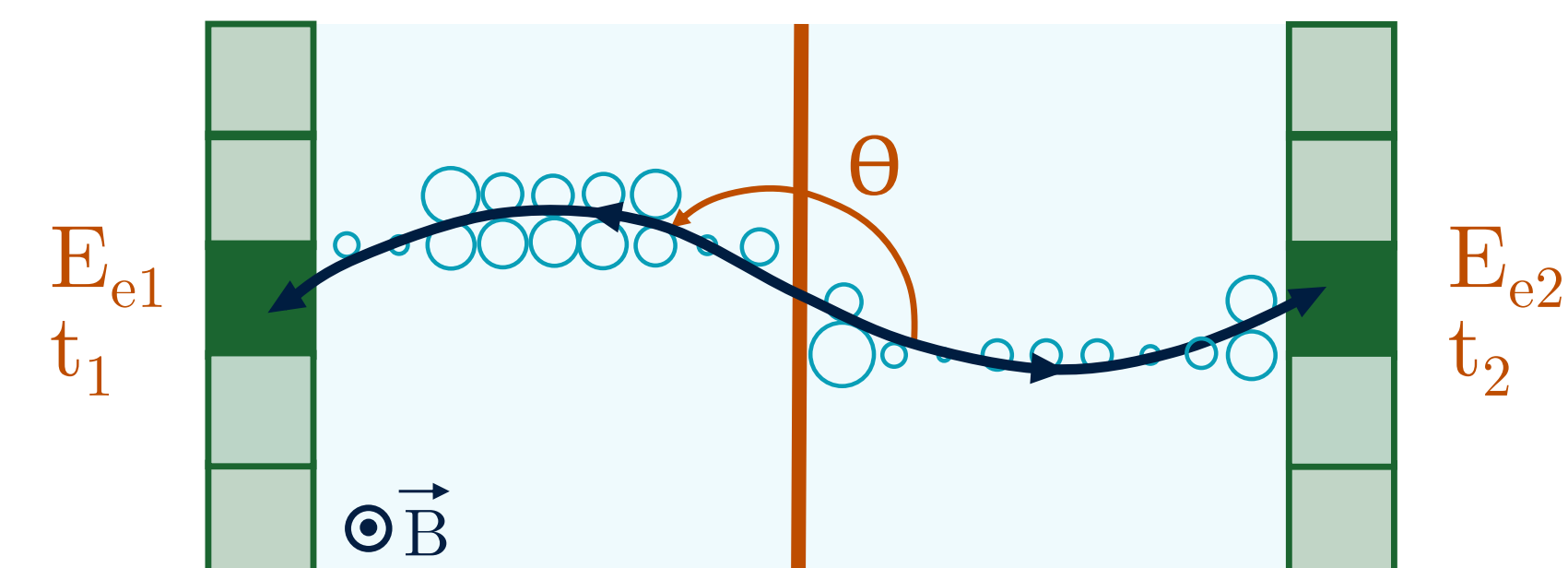
ONLY SuperNEMO

Particle signature

Full kinematic of $\beta\beta$ events



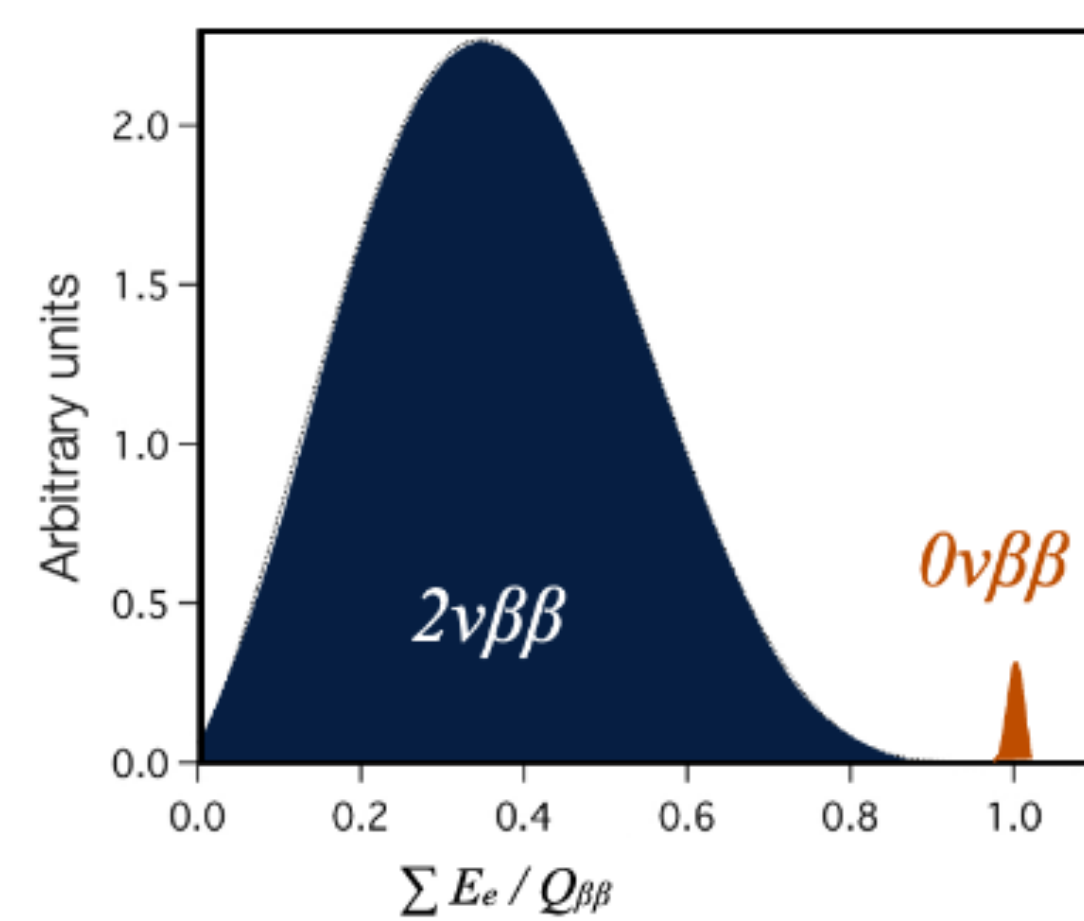
Individual electron energy
Time of flight
Angular correlation



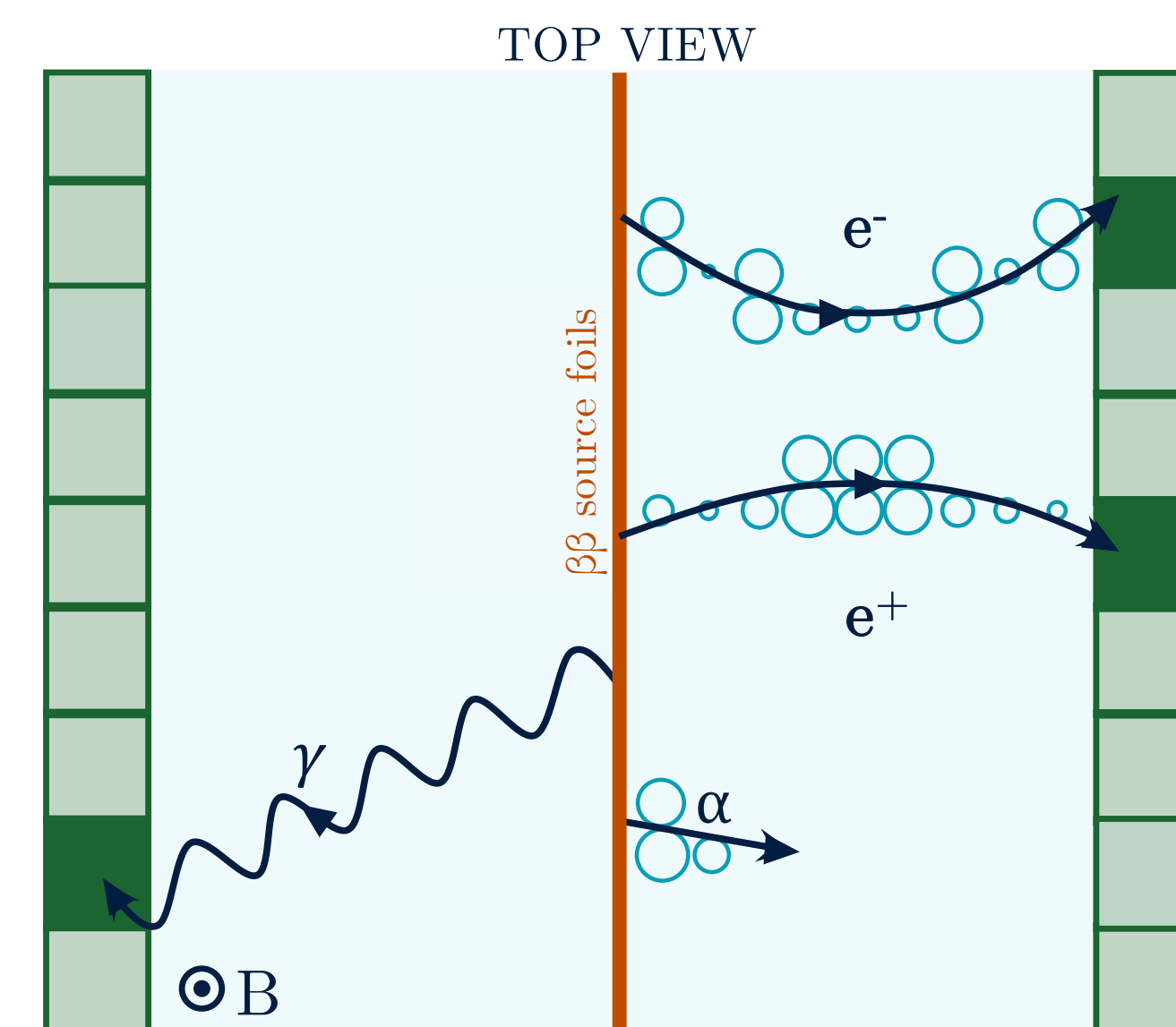
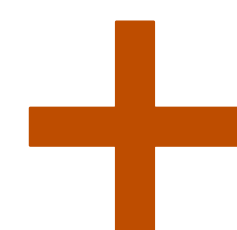
What makes SuperNEMO unique?

ALL $\beta\beta$ experiments

Total energy



Modest E resolution & efficiency

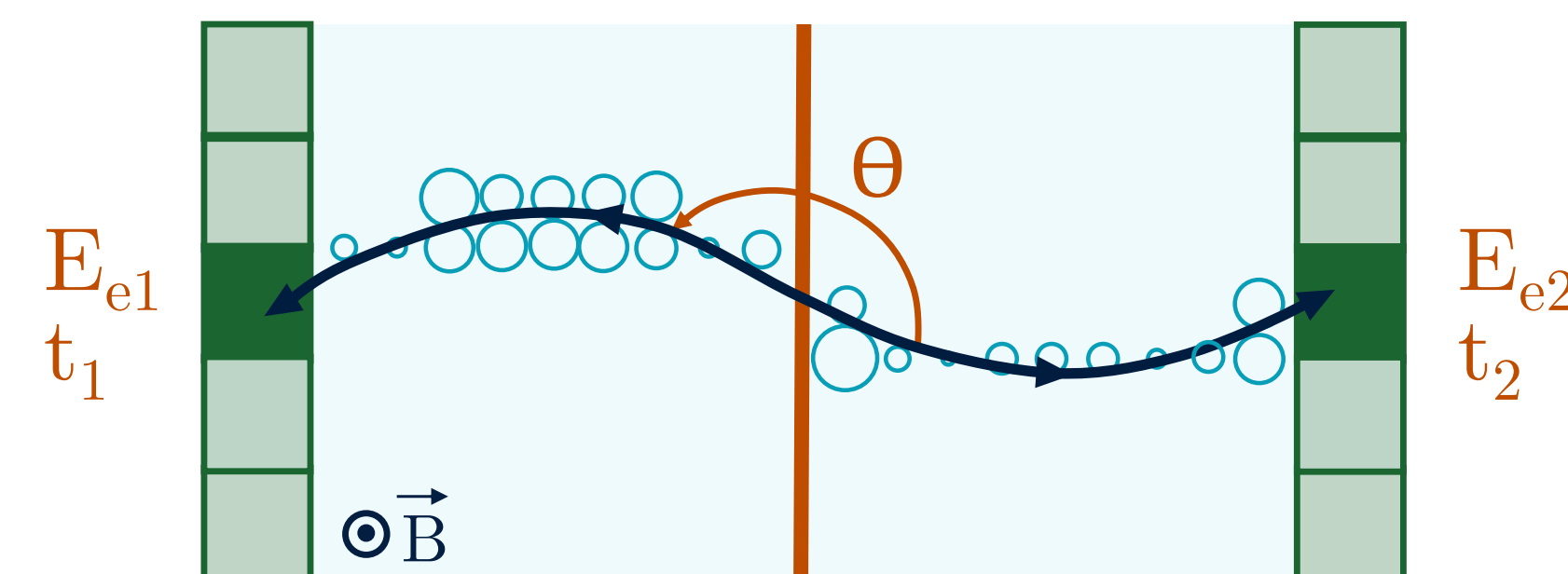


ONLY SuperNEMO

Particle signature

Full kinematic of $\beta\beta$ events

Individual electron energy
Time of flight
Angular correlation



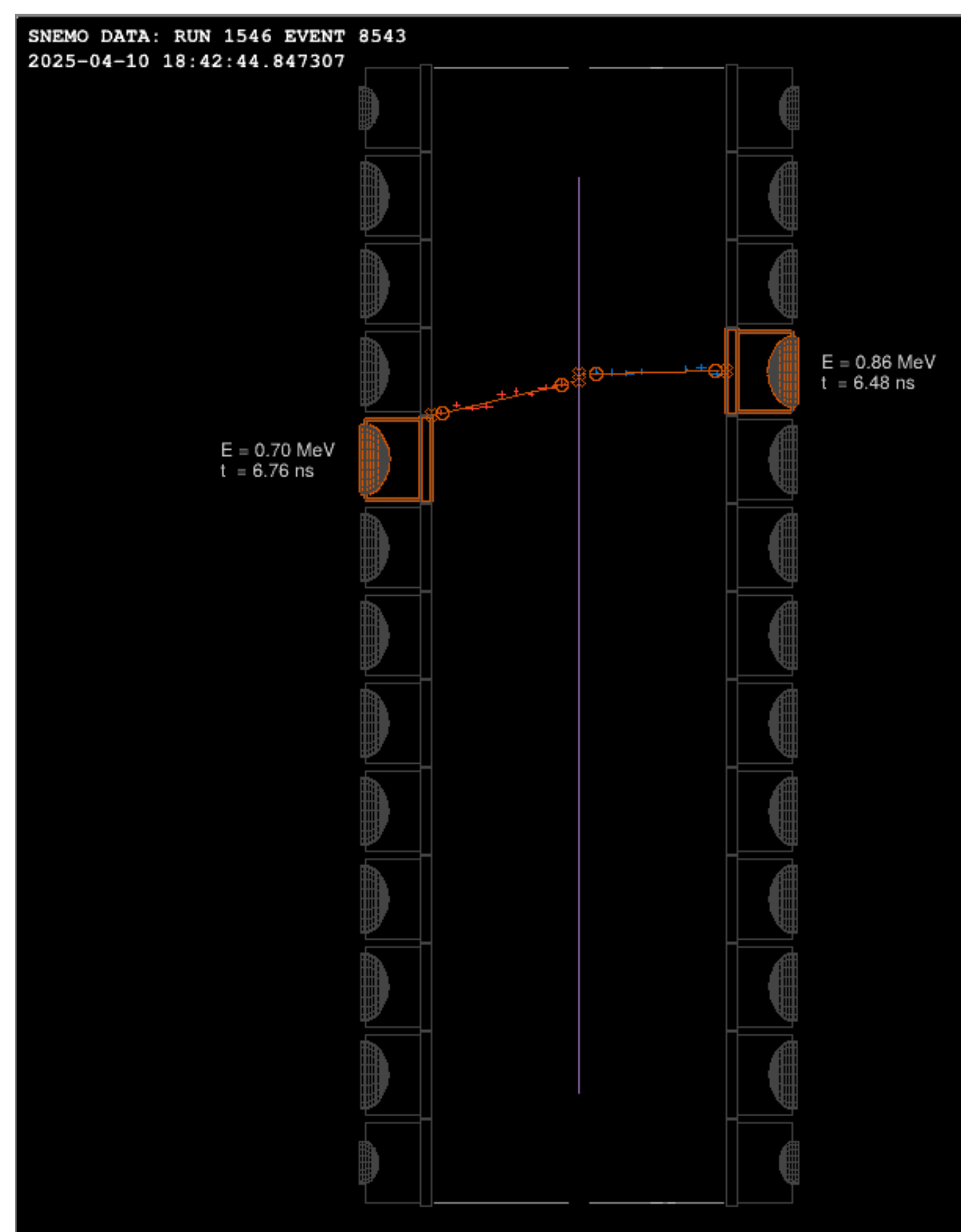
- Many observables for physics investigation
- $\beta\beta$ Golden-event signature
- Bkg rejection and measurement (dedicated channels)
- (Almost) isotope agnostic

Key to **probing** and **understanding** $0\nu\beta\beta$ mechanism if it's discovered!
+ Detailed studies on $2\nu\beta\beta$ & other exotic processes

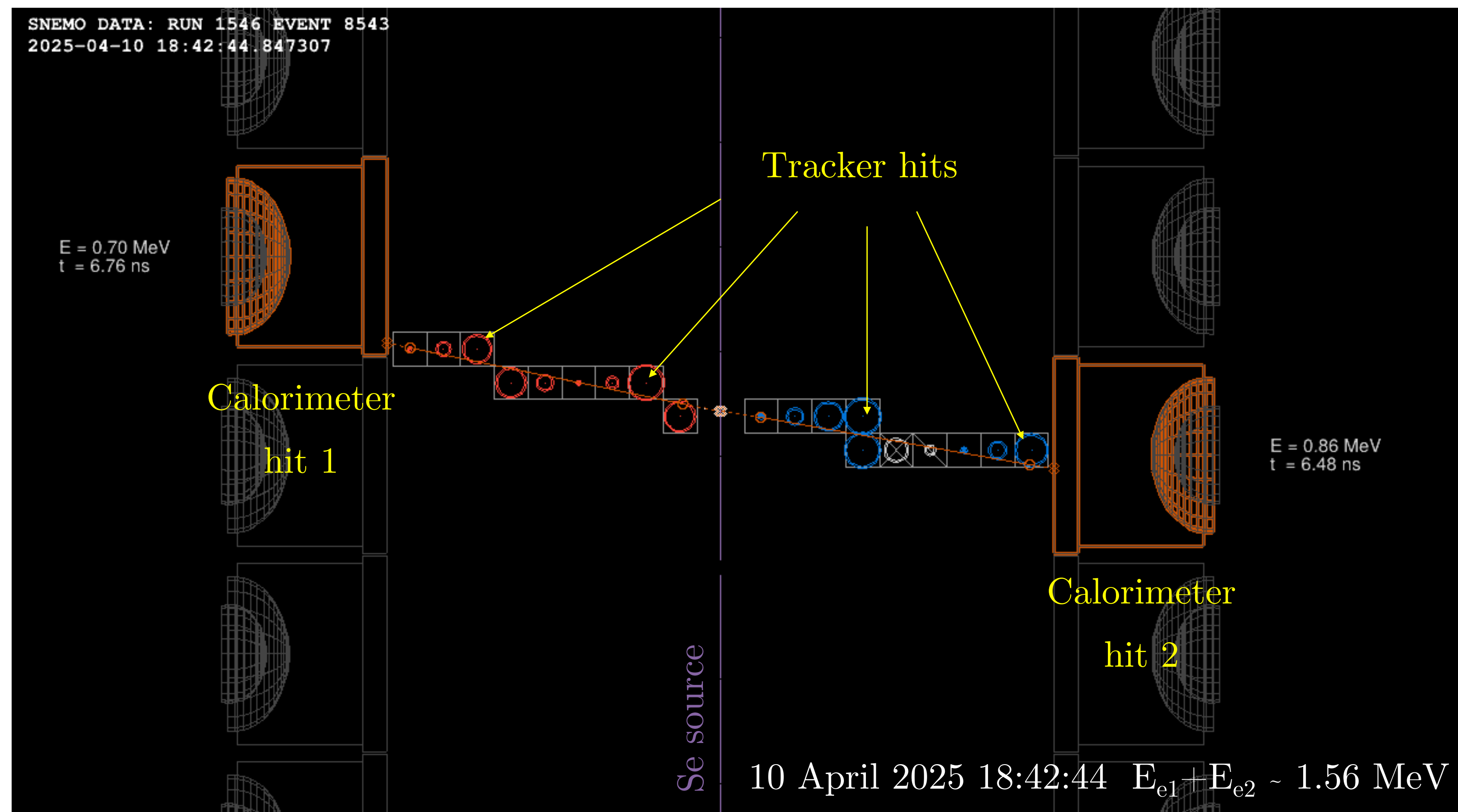
Double-beta events in SuperNEMO

$\beta\beta$ -like event

Side view



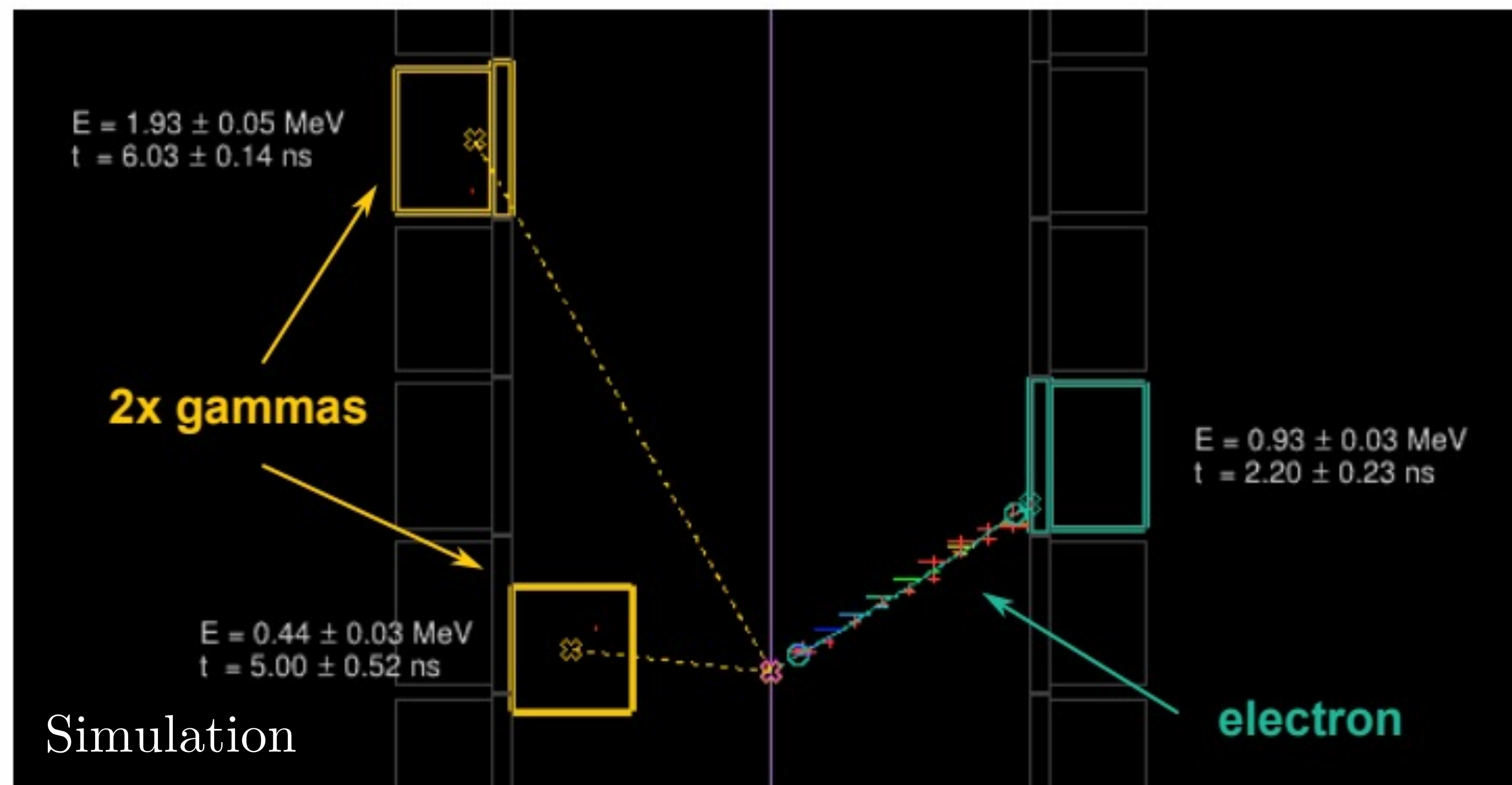
Top view



Background events in SuperNEMO (dedicated channels)

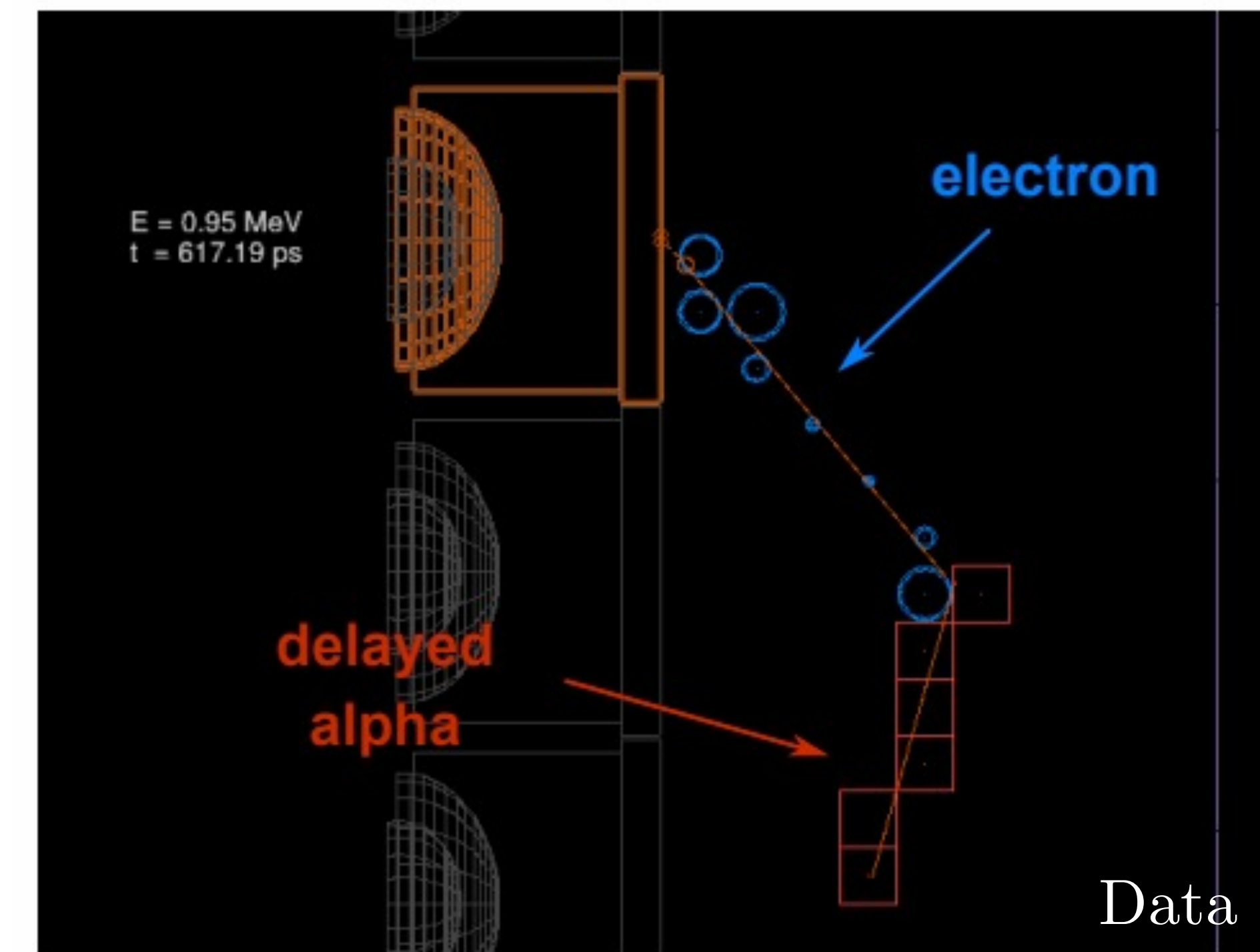
(1e, 2 γ) channel

^{208}Tl event



(1e, 1 α delayed) channel

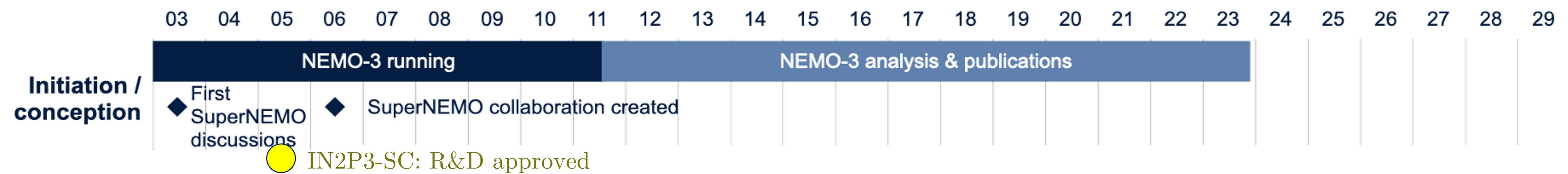
Rn event (= BiPo effect)



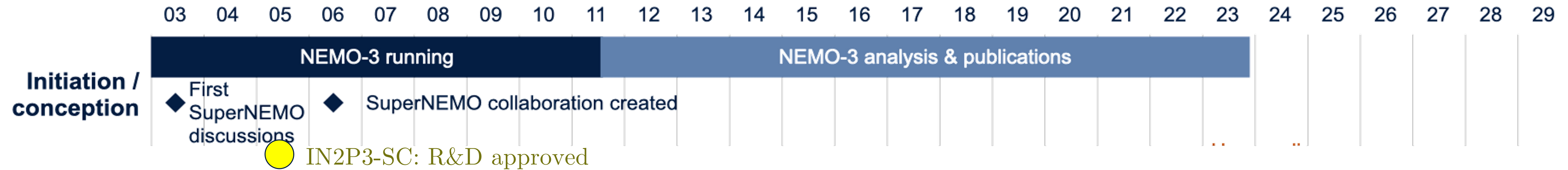
SuperNEMO timeline & current status



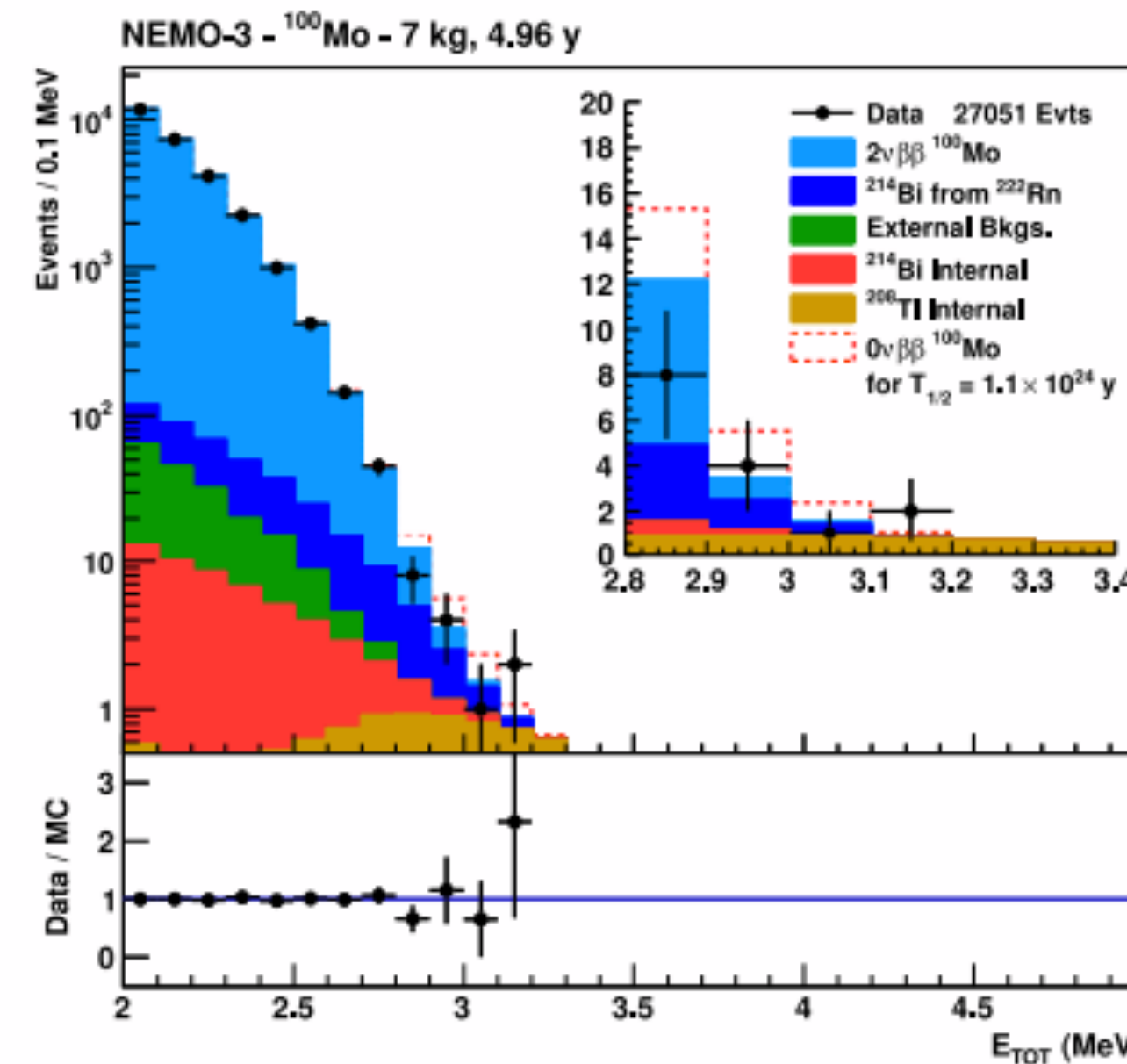
Initiation: 2003-2006



Initiation: 2003-2006



NEMO-3: 2003-2011 at LSM



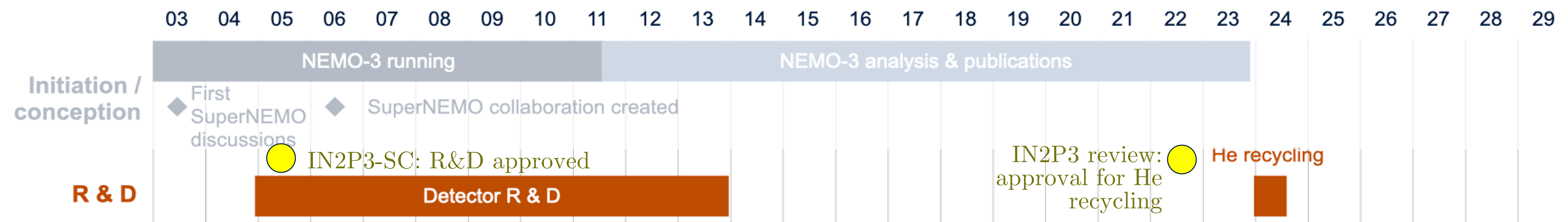
Phys. Rev. D89, 111101 (2014)

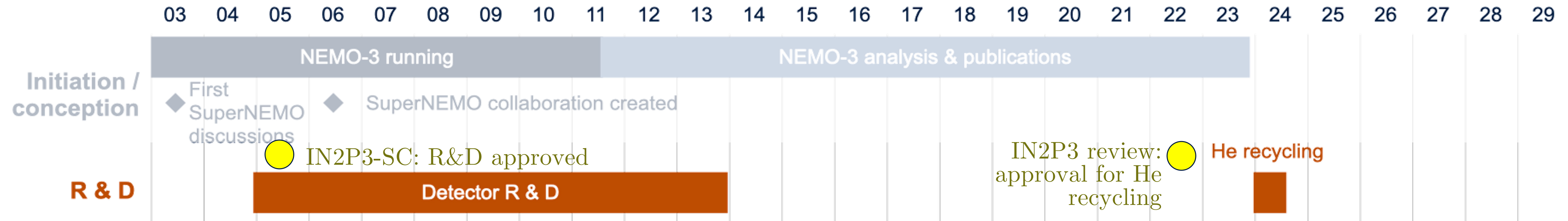
Successor of NEMO-3

- $T_{1/2}^{0\nu} > 1.1 \cdot 10^{24}$ y 90% CL (7kg ^{100}Mo x 5y)
- 0 background events above $0\nu\beta\beta$ region
- NEMO-3 had 20 world's-best $0\nu\beta\beta$ and $2\nu\beta\beta$ results (PDG 2018)
- + 23 articles in peer-reviewed journals

- SuperNEMO improves NEMO-3 design for next-generation sensitivities
- Initial goal of SuperNEMO: $T_{1/2}^{0\nu} > 10^{26}$ y 90% CL (100 kg ^{82}Se)

R&D





^{82}Se foils

- Prospects for isotope enrichment
- New fabrication & purification
- Radiopurity ($\mu\text{Bq/kg}$):

	NEMO-3	Target	R&D BiPo
^{214}Bi	220	10	<300
^{208}Tl	113	2	24 ± 20

[JINST 12, P06002 (2017)]

Tracker

- Radon screening strategies
- Radiopurity ^{222}Rn (mBq/m^3):

NEMO-3	Target	R&D $\frac{1}{4}$ tracker
6.46 ± 0.05	0.15	0.16 ± 0.05

Calorimeter

- Radiopurity (PMT glass)
- FWHM @ 1 MeV (%)

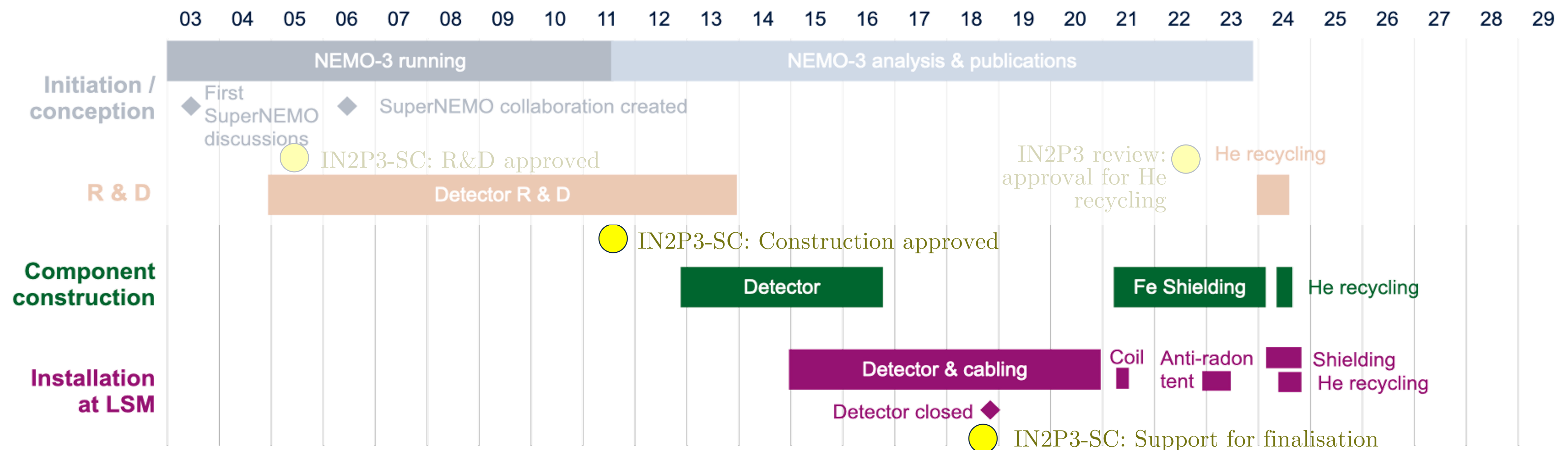
NEMO-3	Target	Production
14-17	<8	$8.2 [7.2-9.1]$

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

+ calibrations, electronics, acquisition, software, mechanics...

[JINST 16 (2021) T07012], [<https://github.com/SuperNEMO-DBD>], [Nucl.Inst.Meth. A 629-1 (2011), 123-132]

Installation



Construction & installation

Calorimeter

260/712 optical modules [arXiv 2412.18021], [Nucl.Inst.Meth.A (2017) 868 98-108]



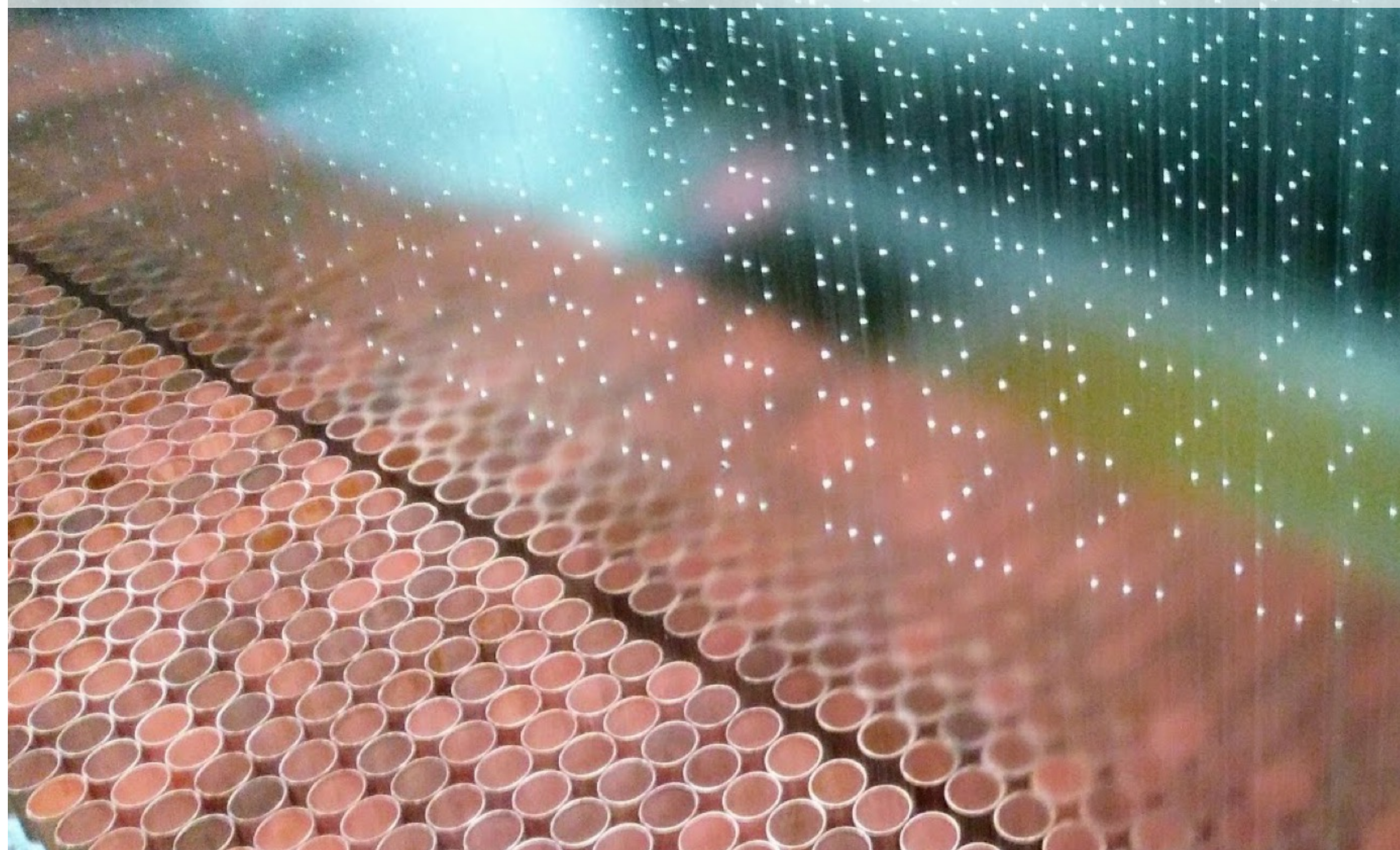
Production @ LP2i



Construction & installation

Tracker

Tracker: 13 m³ 2034 cells (15.000 wires) [Nucl.Inst.Meth. A (2016) 824 507-509]



Gas system

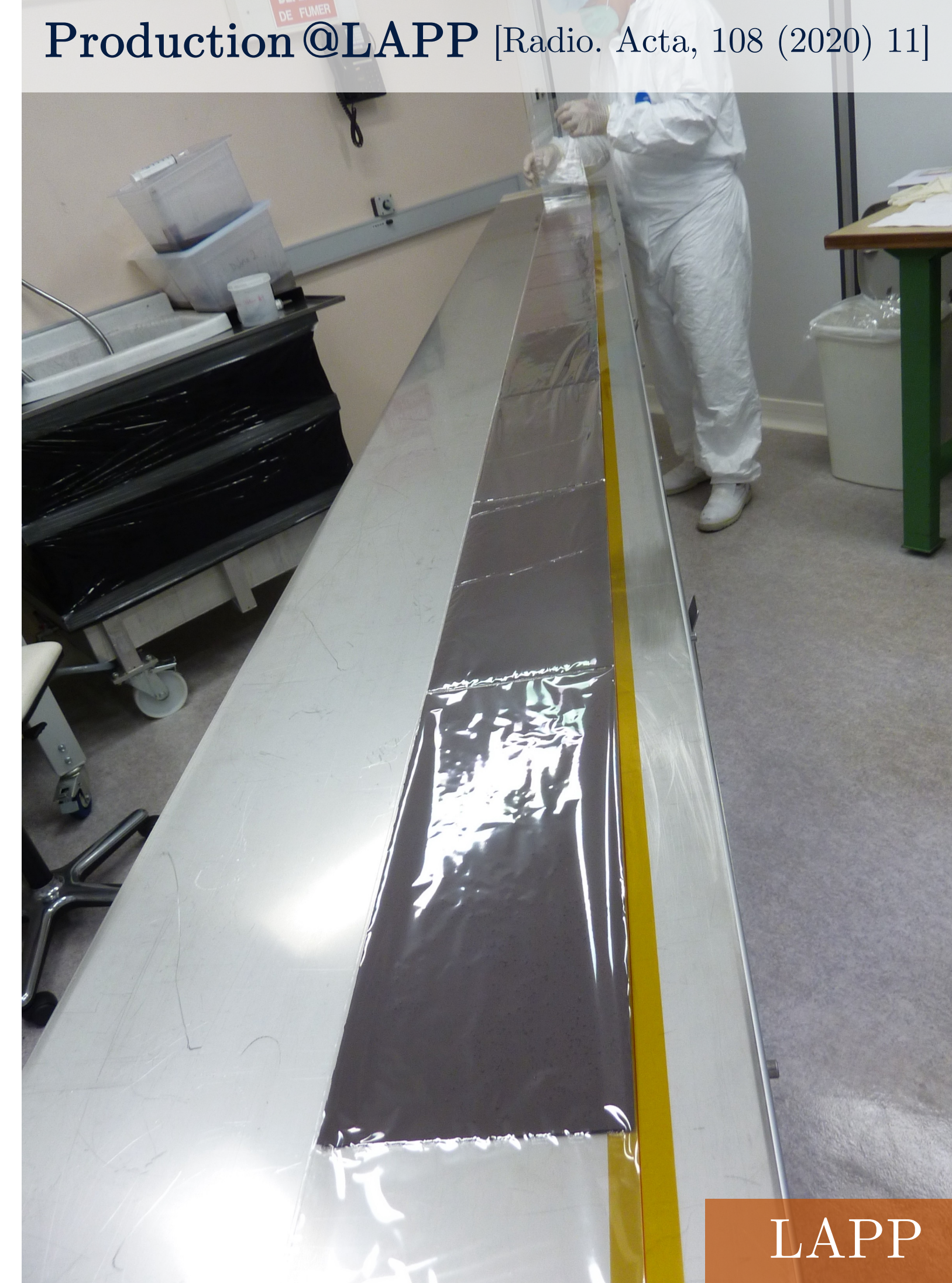
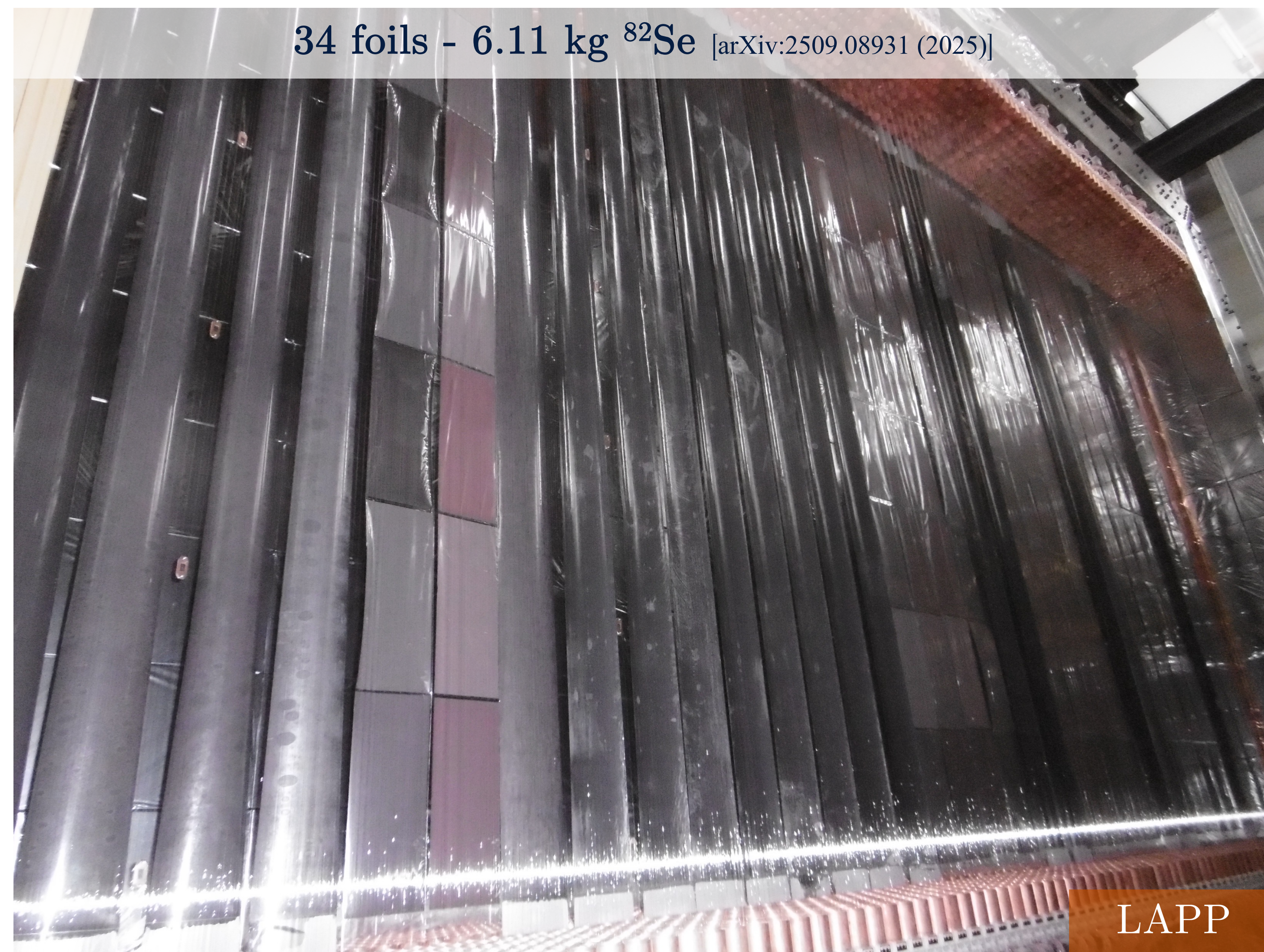


Production @ UK



Construction & installation

$\beta\beta$ sources

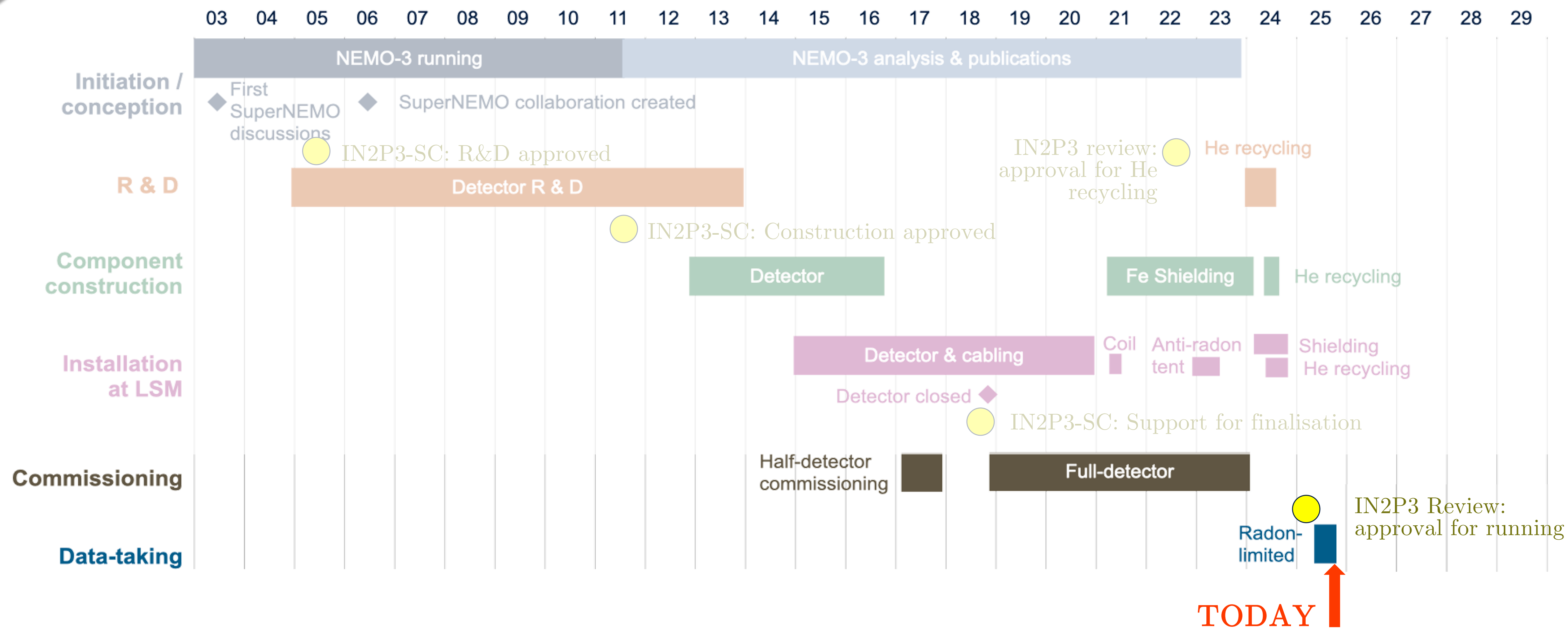


Construction & installation

Surroundings



Data-taking

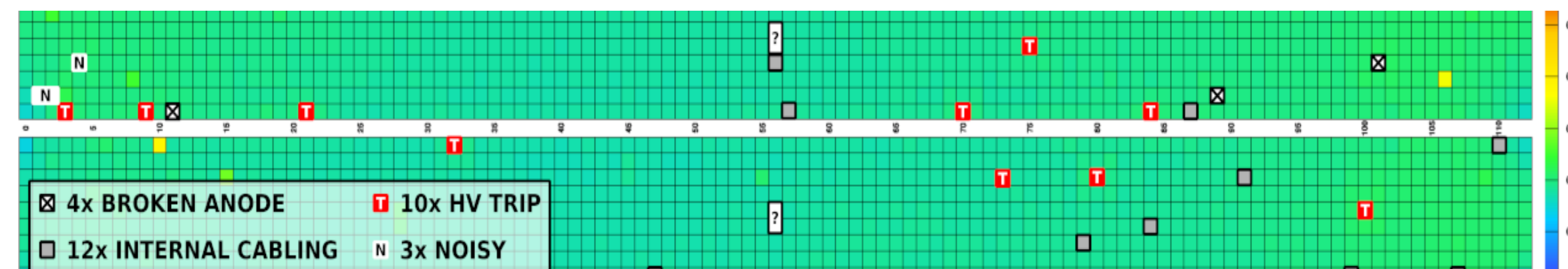


- Start of data acquisition with the complete detector on April 10, 2025

Demonstrator running

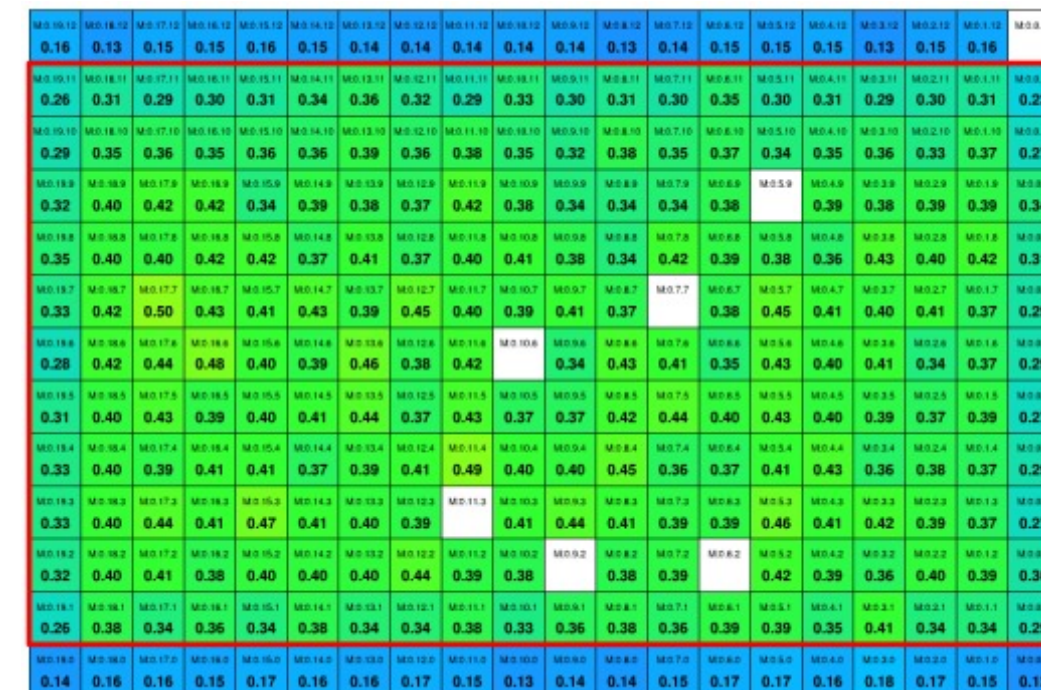
Now in full data-taking mode (radon-limited)

Tracker status: 98.6% of cells operational

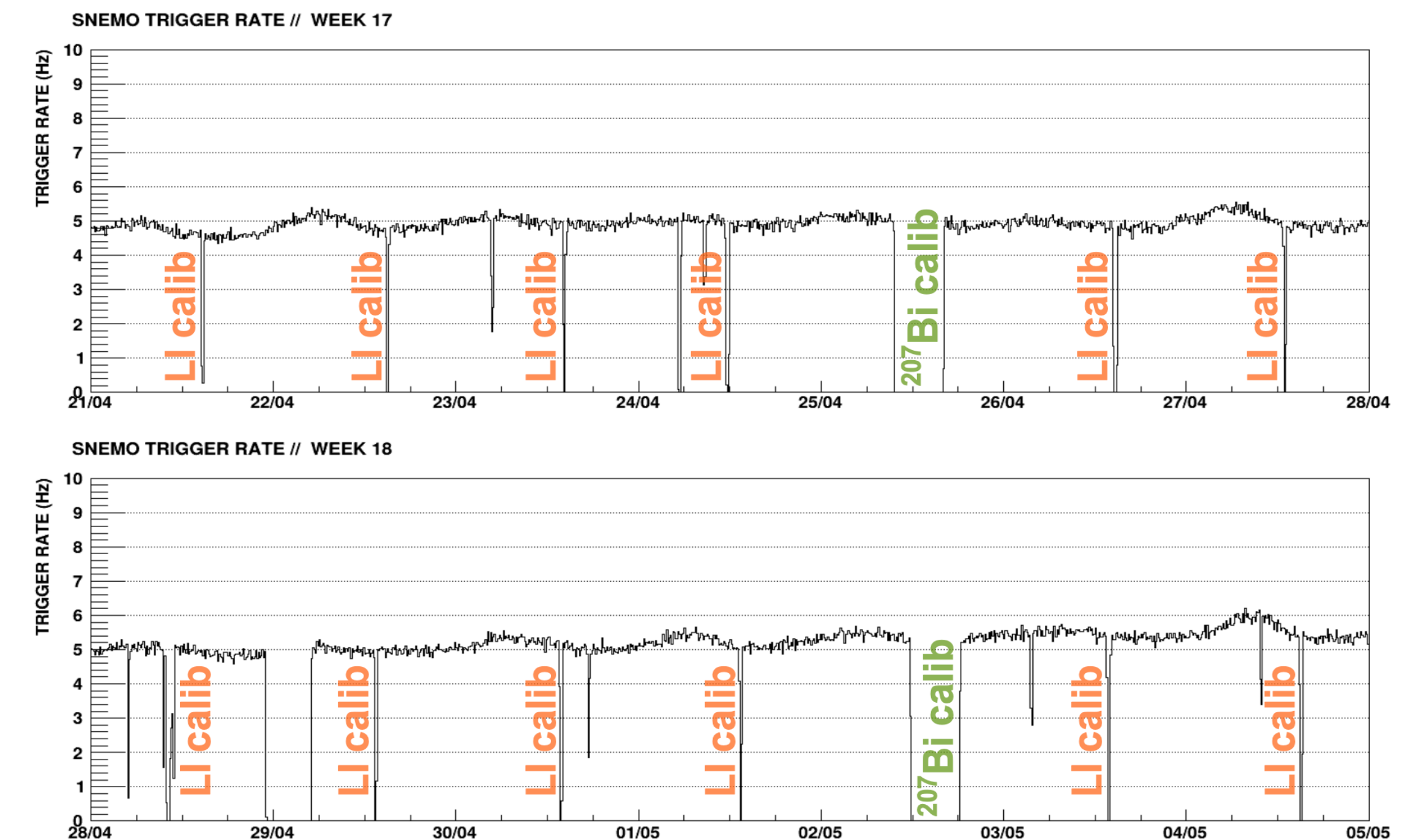


Calorimeter status:

97.4% of calorimeter channels operational

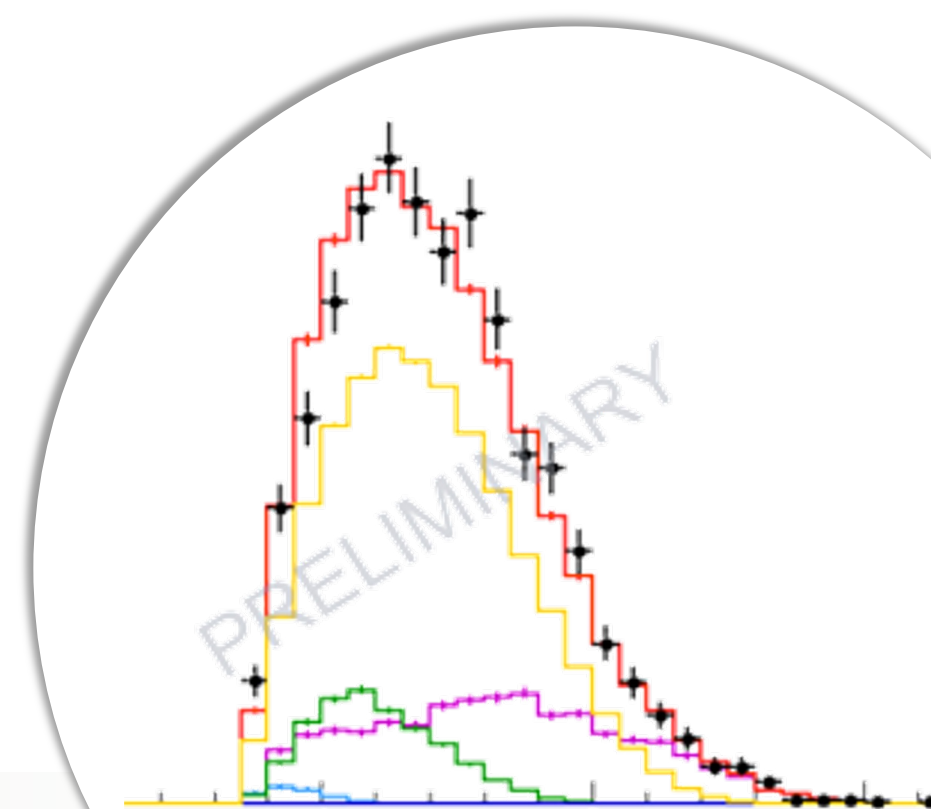


Example Duty Cycle



- Average $\beta\beta$ duty cycle of 92% (+ 5% weekly ^{207}Bi calibration & 1% daily light injection system calibration)
- Currently accumulated: 142 days of data = 2.38 kg.y exposure

SuperNEMO objectives & preliminary results



Demonstrator main purposes



Technological validation

« Scaled-up version of SuperNEMO Demonstrator is the only way to determine $0\nu\beta\beta$ mechanism in the event of discovery » (APPEC 2019)

Physics results with 6.11 kg of ^{82}Se

- $0\nu\beta\beta$ search in multiple modes
- $2\nu\beta\beta$ spectrum study:
 - Nuclear physics (g_A , excited states, NME)
 - Exotic $2\nu\beta\beta$ decays (V+A, bosonic neutrinos..)

Demonstrator main purposes

Technological validation

- **Background control**
 - Radiopurity of $\beta\beta$ foils
 - Radon mitigation strategies
 - Energy & time resolutions and calibration accuracy
 - Magnetic field utility
- **Scalability feasibility**
 - Ability to **construct** large-scale components
 - **Cost** management (funding and personpower)
 - **Size** optimization

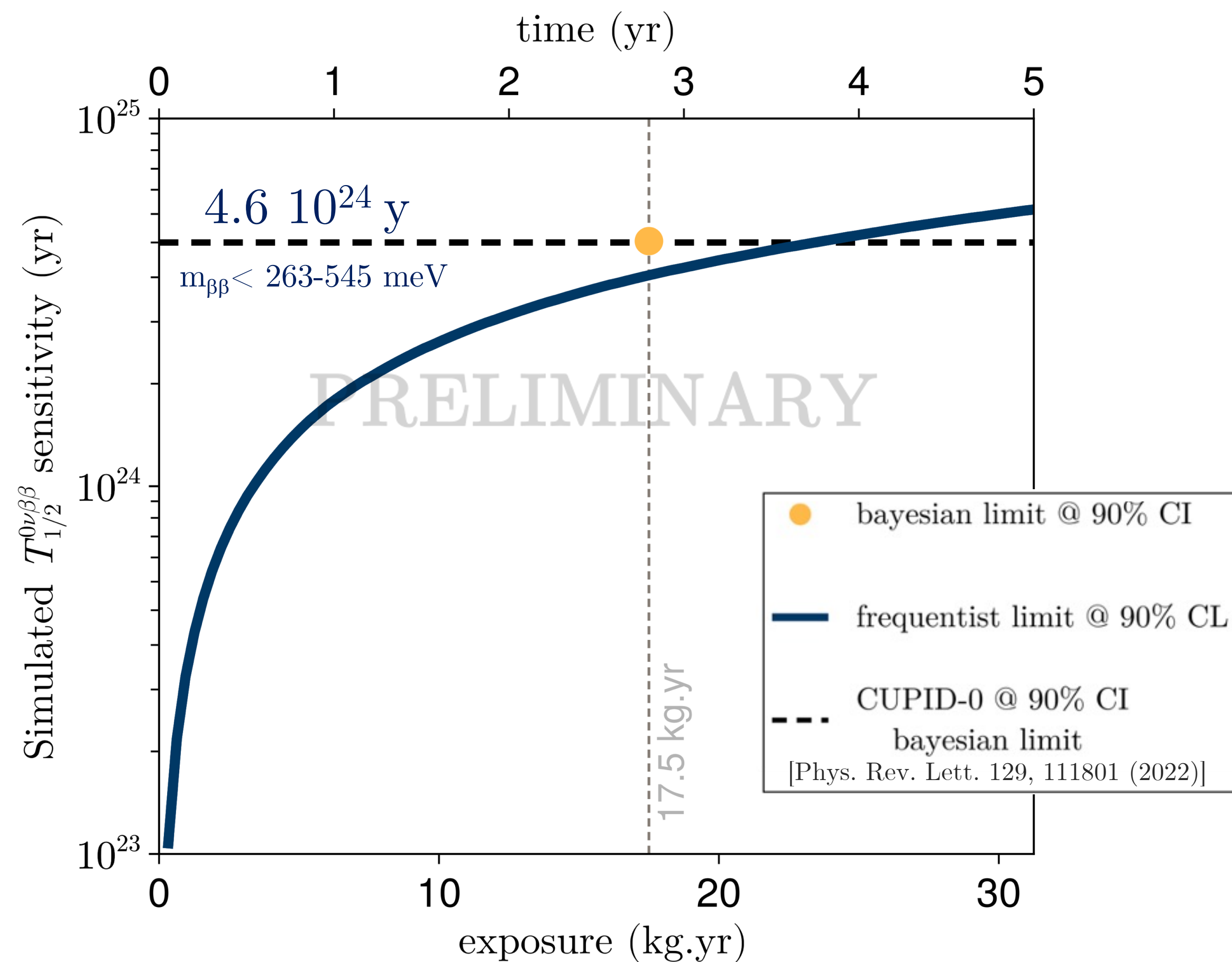
- Deliverable: Insights **report** for a larger-scale experiment, considering construction experience and upcoming analysis results
- **Technical outcomes:** software, electronics, gas purification, low-background developments, radon mitigation...

Demonstrator physics sensitivities

$0\nu\beta\beta$ with light neutrino exchange & V-A current (mass mechanism)

Demonstrator physics sensitivities

$0\nu\beta\beta$ with light neutrino exchange & V-A current (mass mechanism)



Background	Events for 17.5 kg.yr in [2700-3100] keV *
$2\nu\beta\beta$	0.98 ± 0.13
^{208}Tl	0.04 ± 0.01
^{214}Bi	0.09 ± 0.01
Radon	0.23 ± 0.04
Neutrons	0.60 ± 0.30
Total	1.9 ± 0.4

$0\nu\beta\beta$ efficiency	16.5 %
-----------------------------	--------

(*) considering FWHM=12%@1MeV, 4-faces neutron shield, target radiopurity (^{208}Tl , ^{214}Bi , Rn)

Background index in ROI: $2.7 \cdot 10^{-4} \text{ event keV}^{-1}\text{kg}^{-1} \text{ y}^{-1}$
(NEMO-3 ^{100}Mo : $10^{-3} \text{ event keV}^{-1}\text{kg}^{-1} \text{ y}^{-1}$)

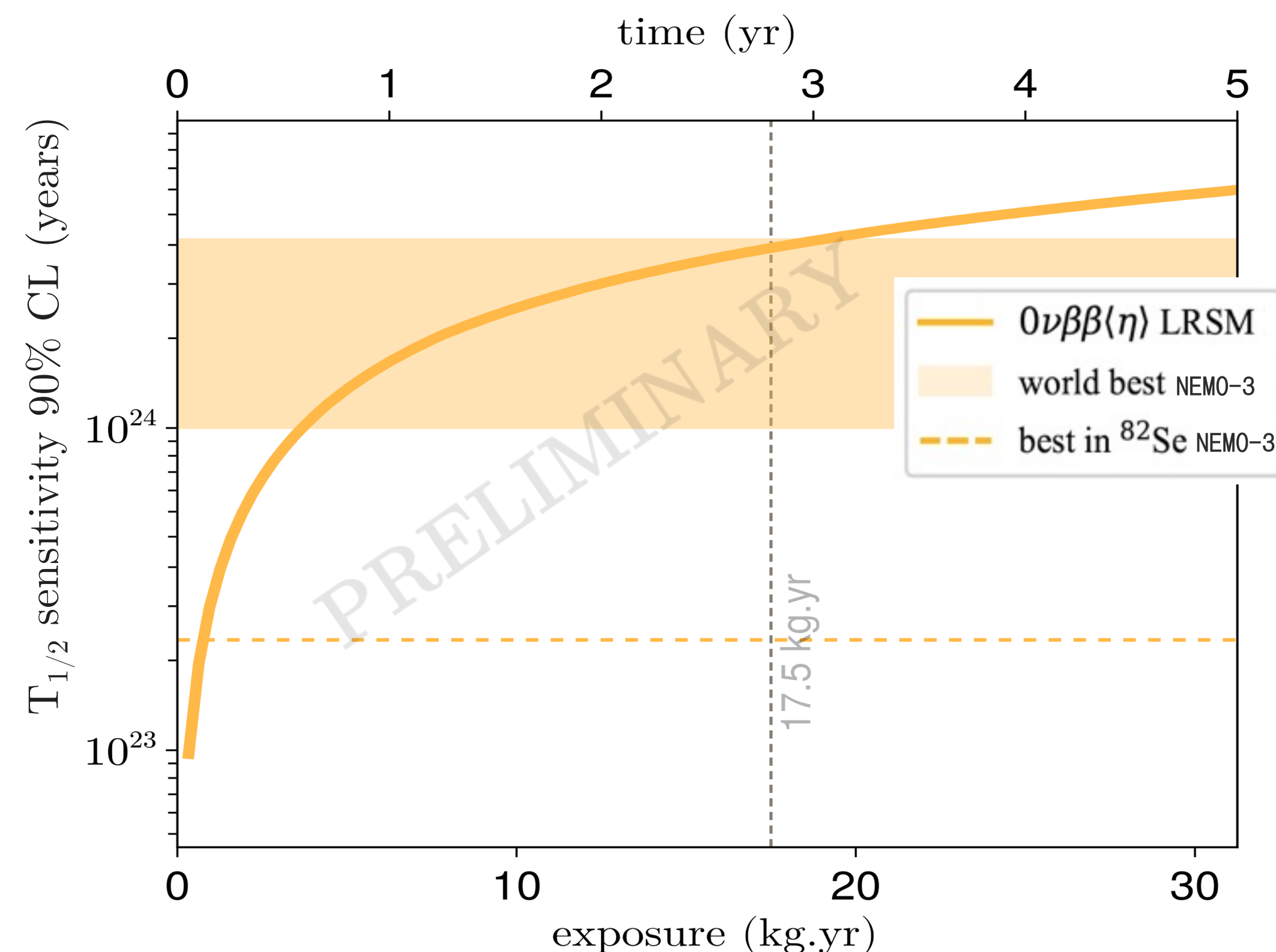
- Bayesian and multi-variable analysis in progress
- Demonstrator can surpass world-best ^{82}Se $0\nu\beta\beta$ (V-A) limit with 17.5 kg.y (originally requested)

Demonstrator physics sensitivities

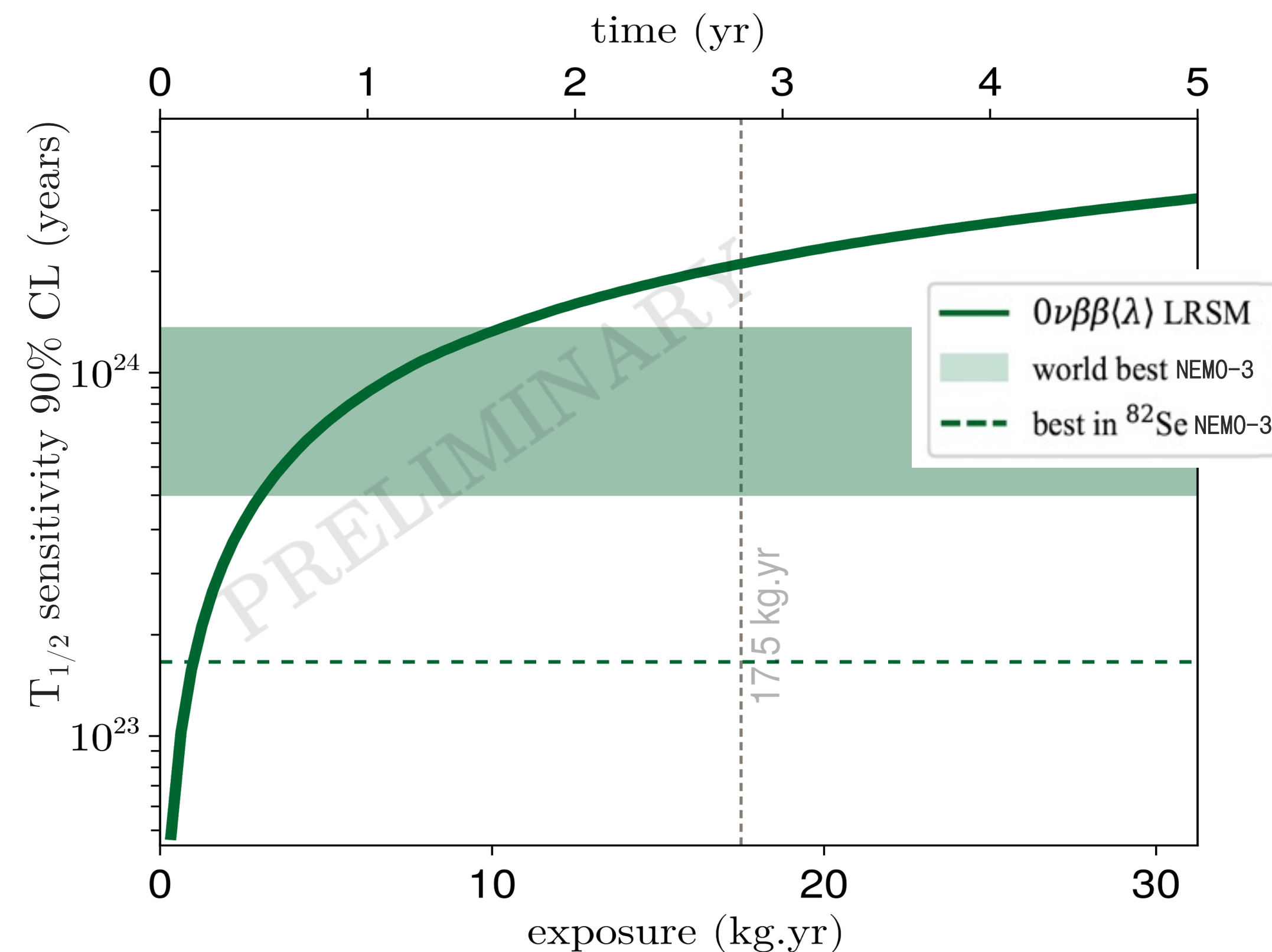
$0\nu\beta\beta$ & $V+A$ current

Preliminary sensitivity (Frequentist + Based only on total energy)

LR Symmetry (η) ($V+A$) leptonic



LR Symmetry (λ) ($V+A$) leptonic + hadronic

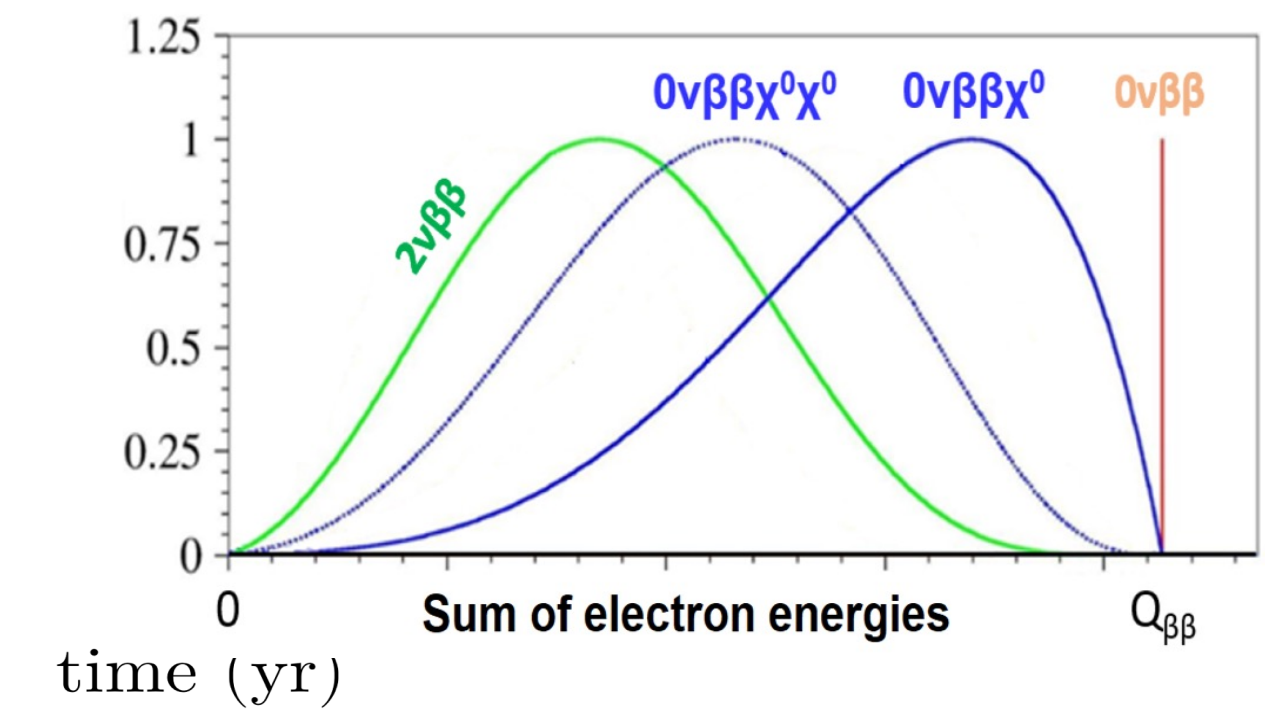
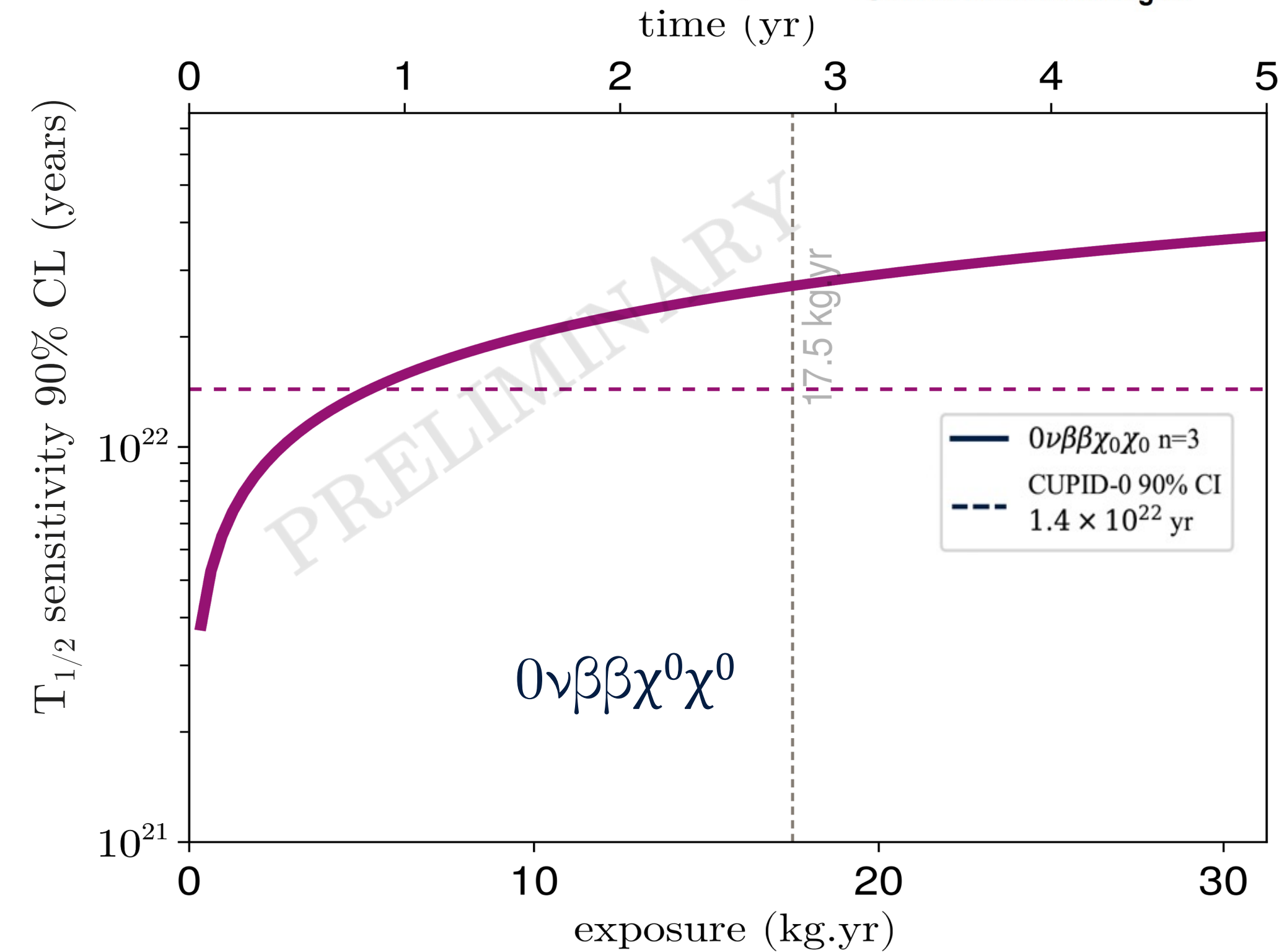
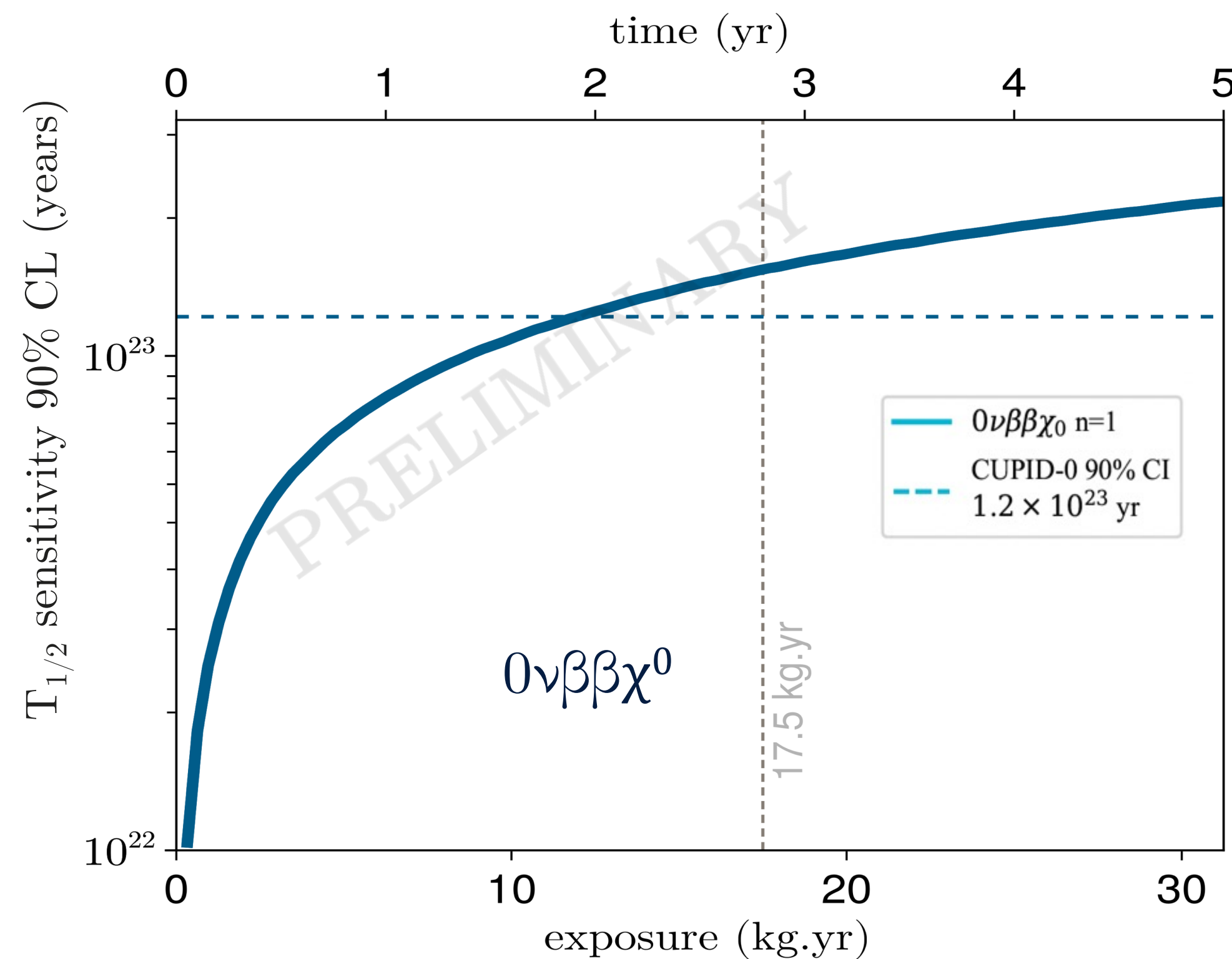


- Multi-variable analysis in progress (favors small angle between electrons & energy asymmetry)
- Demonstrator can surpass **world's best limits** in < 1 year (^{82}Se) or 2-3 years (all isotopes)

Demonstrator physics sensitivities

$0\nu\beta\beta$ with Majoron emission

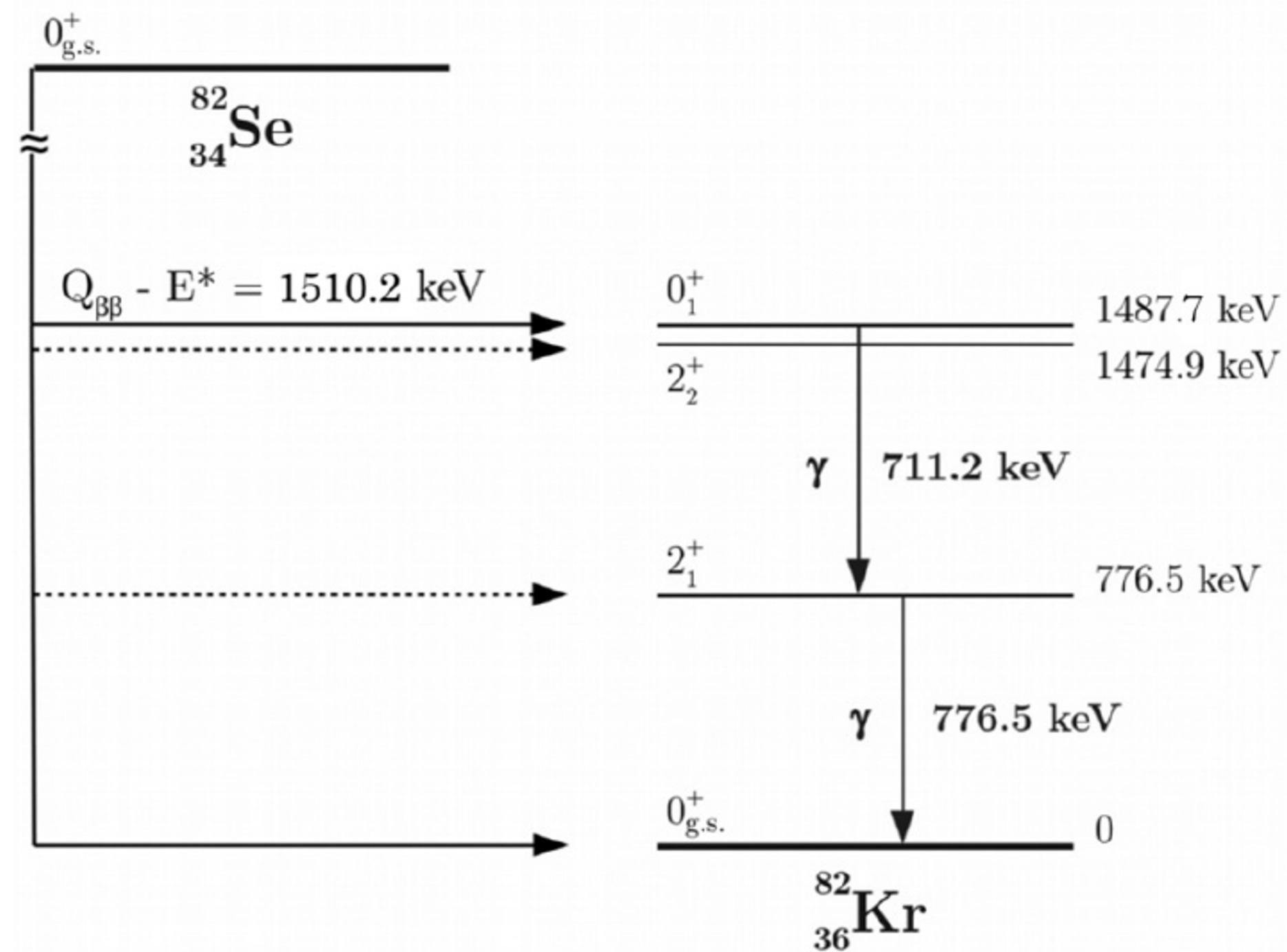
Preliminary sensitivity (Frequentist)



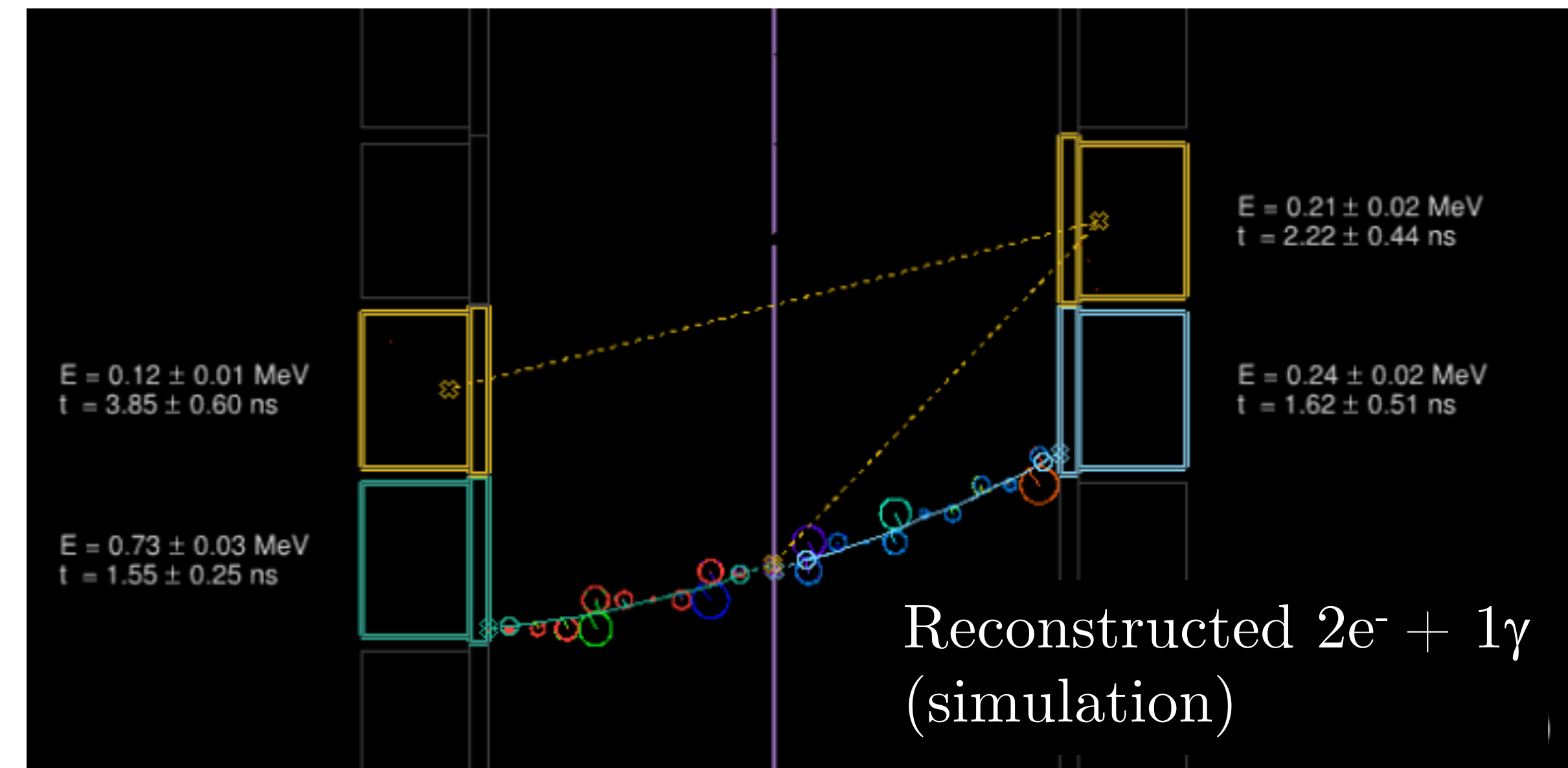
- Demonstrator expects to surpass ^{82}Se world's best limits in ≈ 2 years ($0\nu\beta\beta\chi^0$) and ≈ 1 year ($0\nu\beta\beta\chi^0\chi^0$)

Demonstrator physics sensitivities

$0\nu\beta\beta$ and $2\nu\beta\beta$ to excited states



Dedicated $2e^- + n\gamma$ channels with very low background



- Unique ability to see each individual electron and to perform gamma tracking
Example: from preliminary study SN can surpass world's best limit for $2\nu\beta\beta$ to 2_2^+ state
 $T_{1/2} > 1.9 \cdot 10^{22} \text{ y}$ 90% C.L. for 17.5 kg.y exposure (Best world: $1.3 \cdot 10^{22} \text{ y}$)

Demonstrator physics sensitivities

$2\nu\beta\beta$ axial coupling constant g_A

$$[T_{1/2}^{2\nu}]^{-1} \propto (g_A^{\text{eff}})^4 G^{2\nu} |M^{2\nu}|^2$$

Demonstrator physics sensitivities

$2\nu\beta\beta$ axial coupling constant g_A

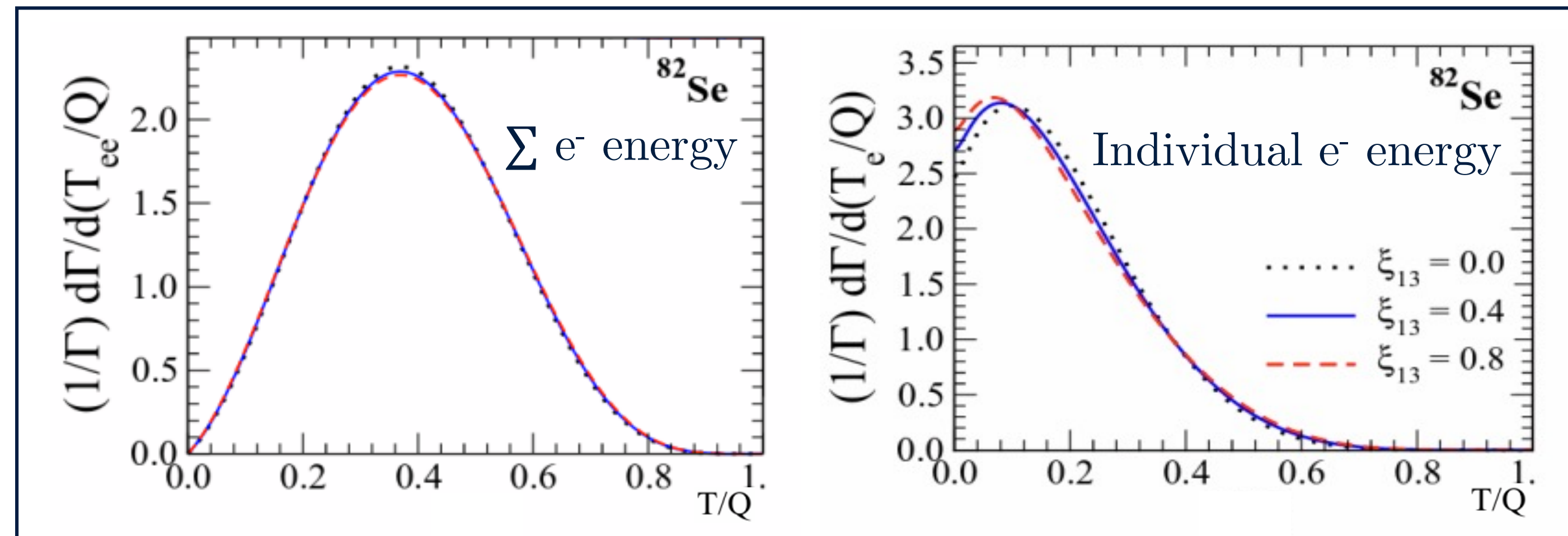
$$[T_{1/2}^{2\nu}]^{-1} \propto (g_A^{\text{eff}})^4 G^{2\nu} |M^{2\nu}|^2$$

[Phys. Rev. Lett. C 97, 034315 (2018)]

$$[T_{1/2}^{2\nu}]^{-1} \propto (g_A^{\text{eff}})^4 \left(M_{\text{GT}-3}^{2\nu} \right)^2 \frac{1}{|\xi_{31}^{2\nu}|^2}$$

Easy to calculate: including only the first states of the intermediate nucleus

Measurable



Demonstrator physics sensitivities

$2\nu\beta\beta$ axial coupling constant g_A

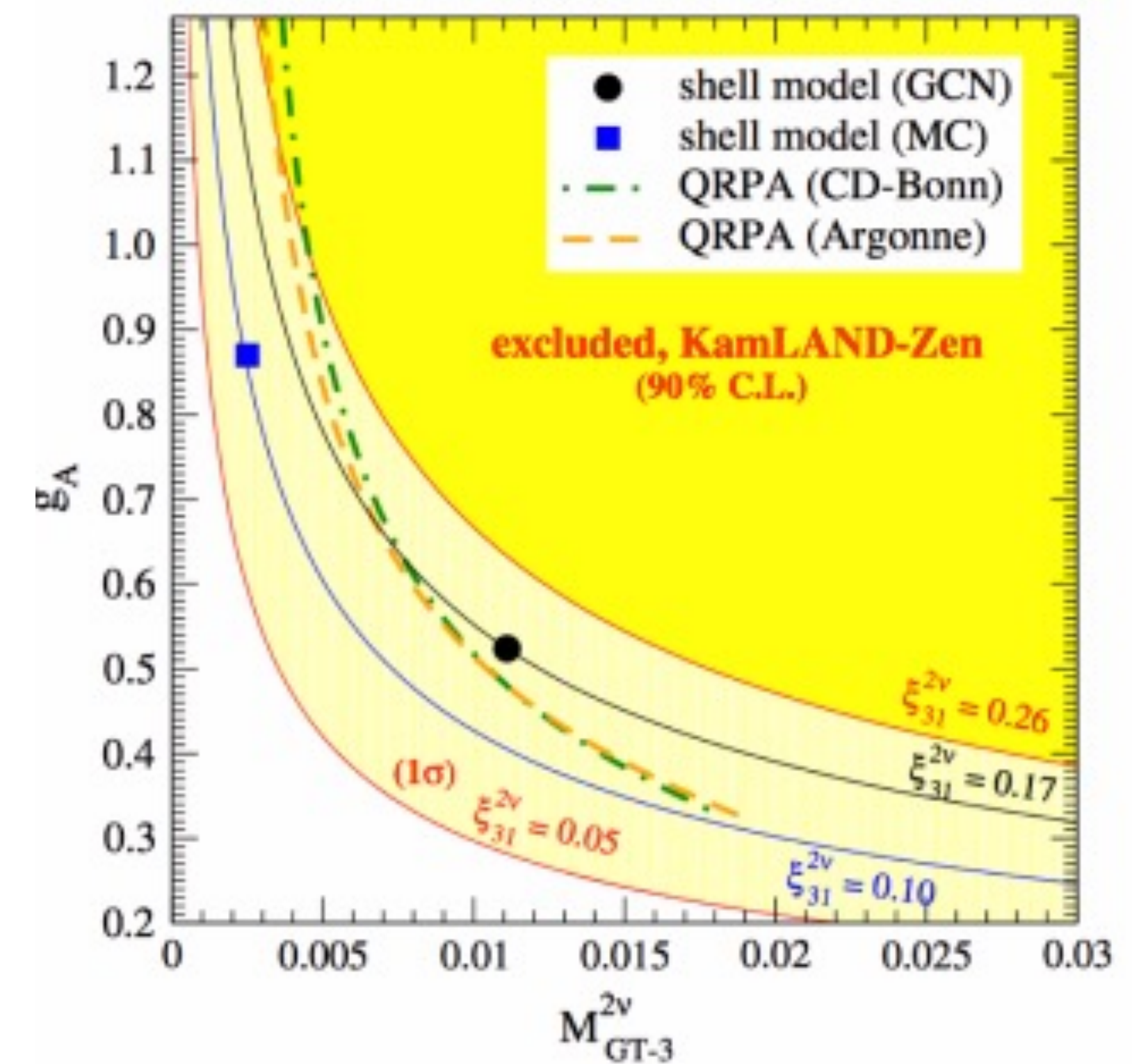
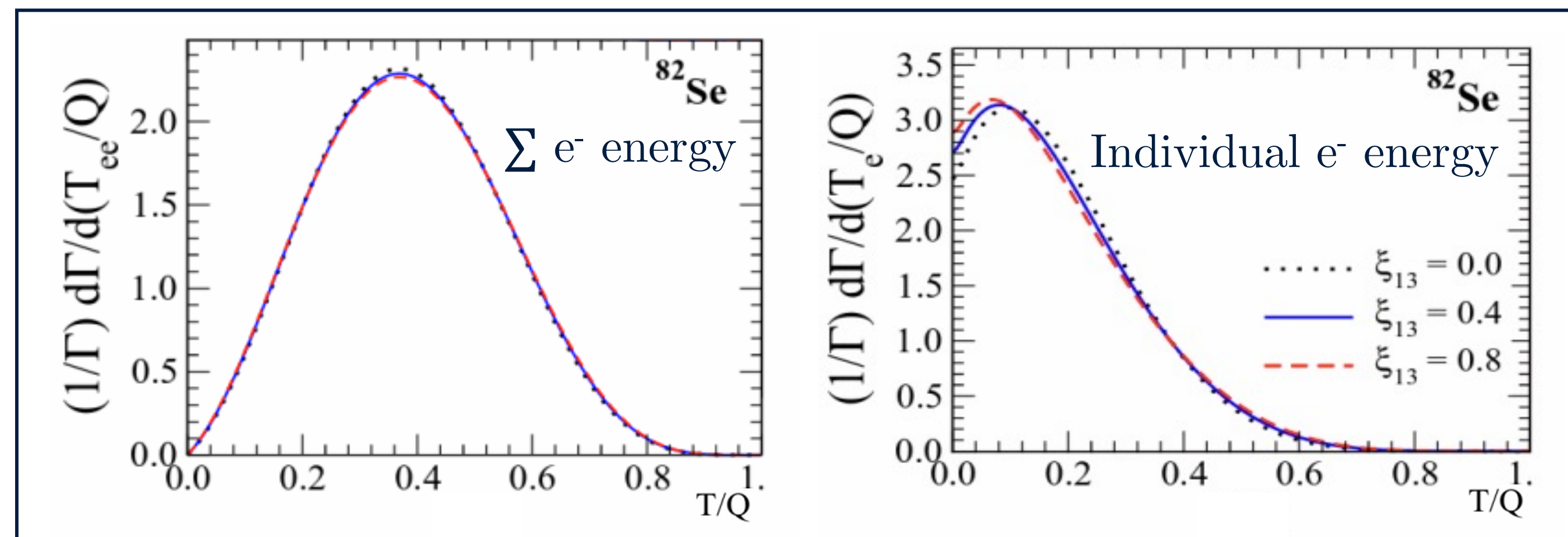
$$[T_{1/2}^{2\nu}]^{-1} \propto (g_A^{\text{eff}})^4 G^{2\nu} |M^{2\nu}|^2$$

[Phys. Rev. Lett. C 97, 034315 (2018)]

$$[T_{1/2}^{2\nu}]^{-1} \propto (g_A^{\text{eff}})^4 \left(M_{\text{GT}-3}^{2\nu} \right)^2 \frac{1}{|\xi_{31}^{2\nu}|^2}$$

Easy to calculate: including only the first states of the intermediate nucleus

Measurable



g_A constraint with ξ_{31} parameter
[Phys. Rev. Lett. 122, 192501 (2019)]

- Shape of $2\nu\beta\beta$ spectrum (35k $2\nu\beta\beta$ /year) can be used to constrain quenching of g_A
- Effect is stronger in **individual energy spectrum**, and only SuperNEMO can see this!

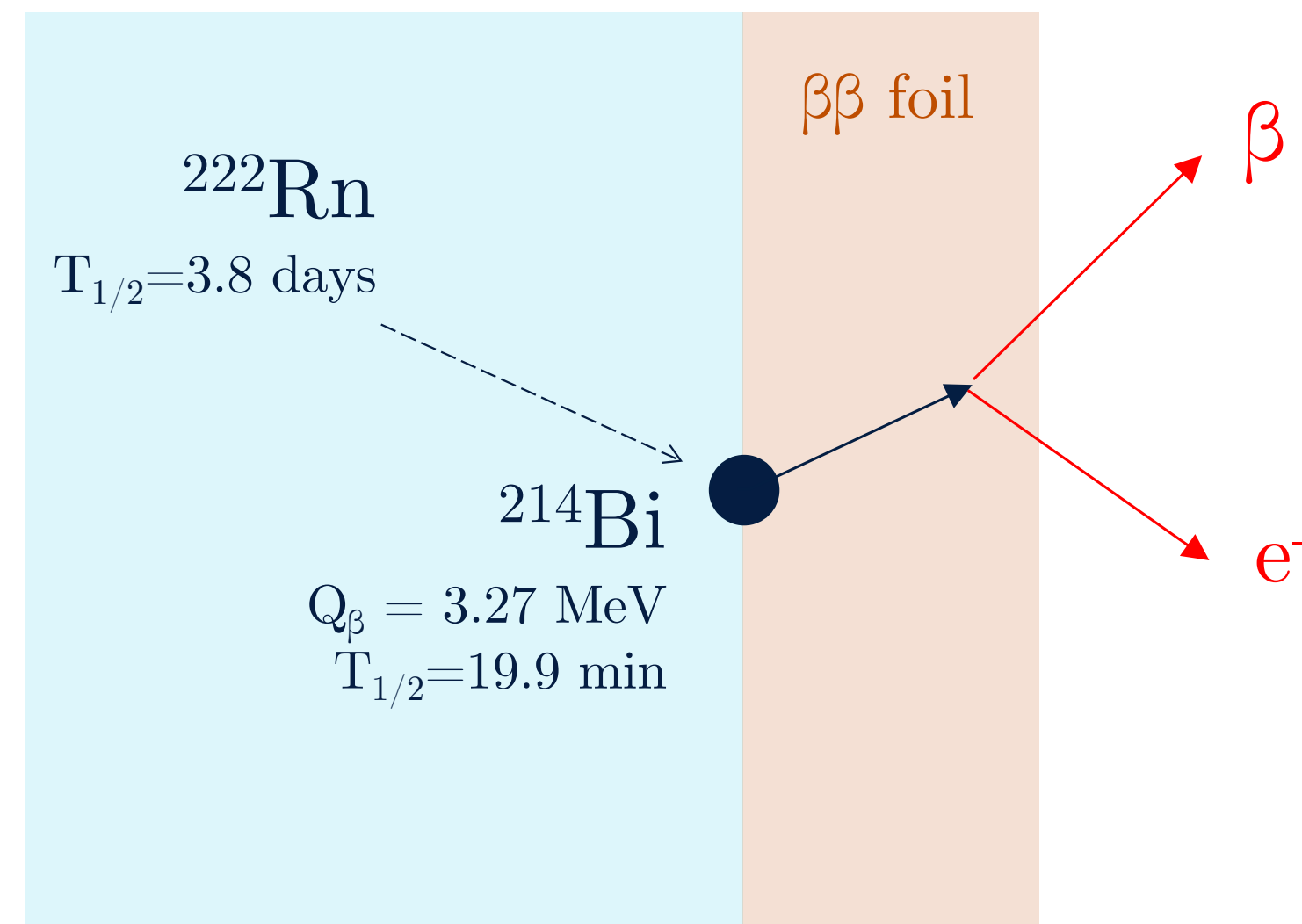
Preliminary physics results - 64.8 days of data (10 April – 20 June 2025)

Preliminary physics results - 64.8 days of data (10 April – 20 June 2025)

Radon activity inside the tracker

$\beta\beta$ background from Rn

- 2 electrons

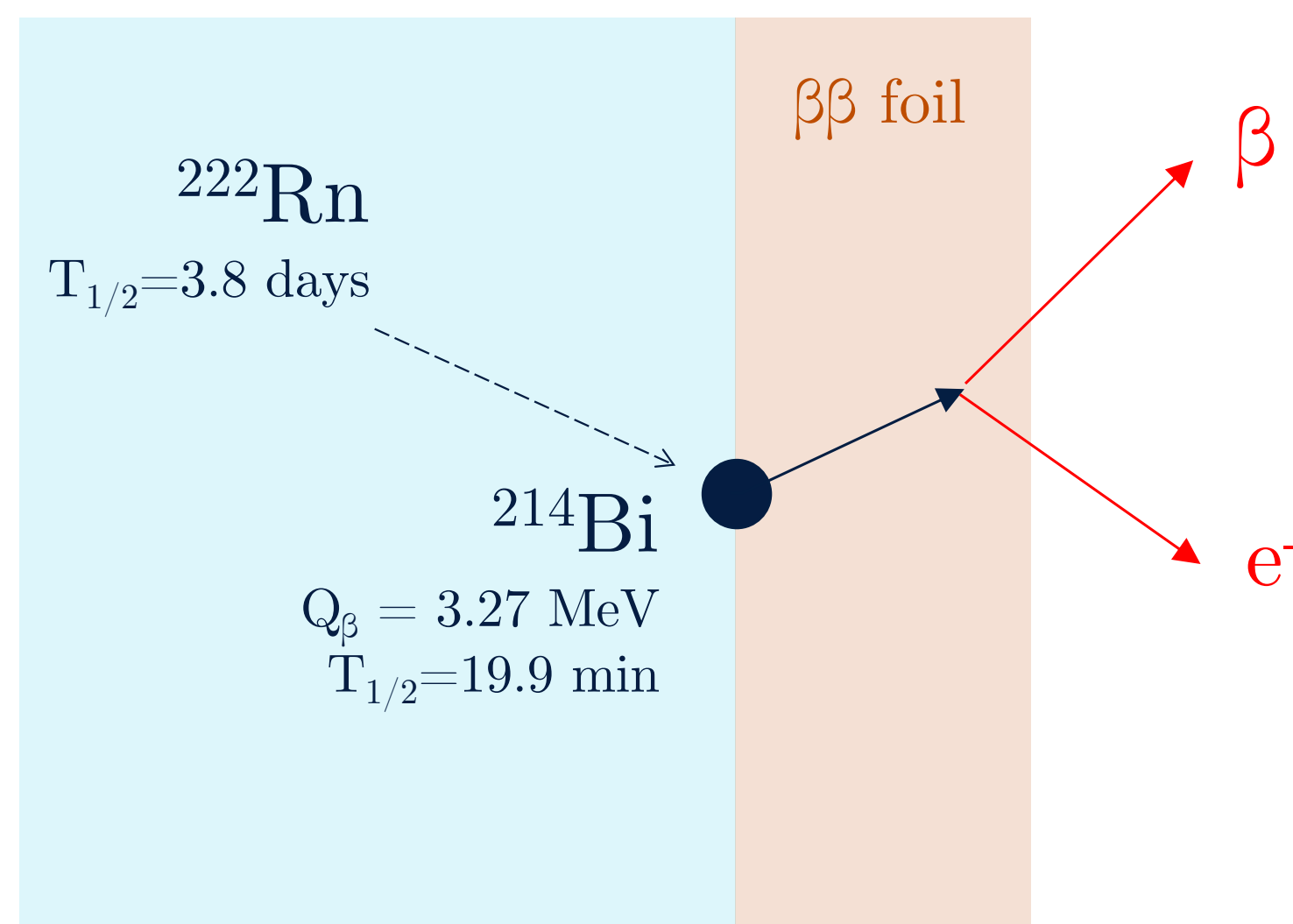


Preliminary physics results - 64.8 days of data (10 April – 20 June 2025)

Radon activity inside the tracker

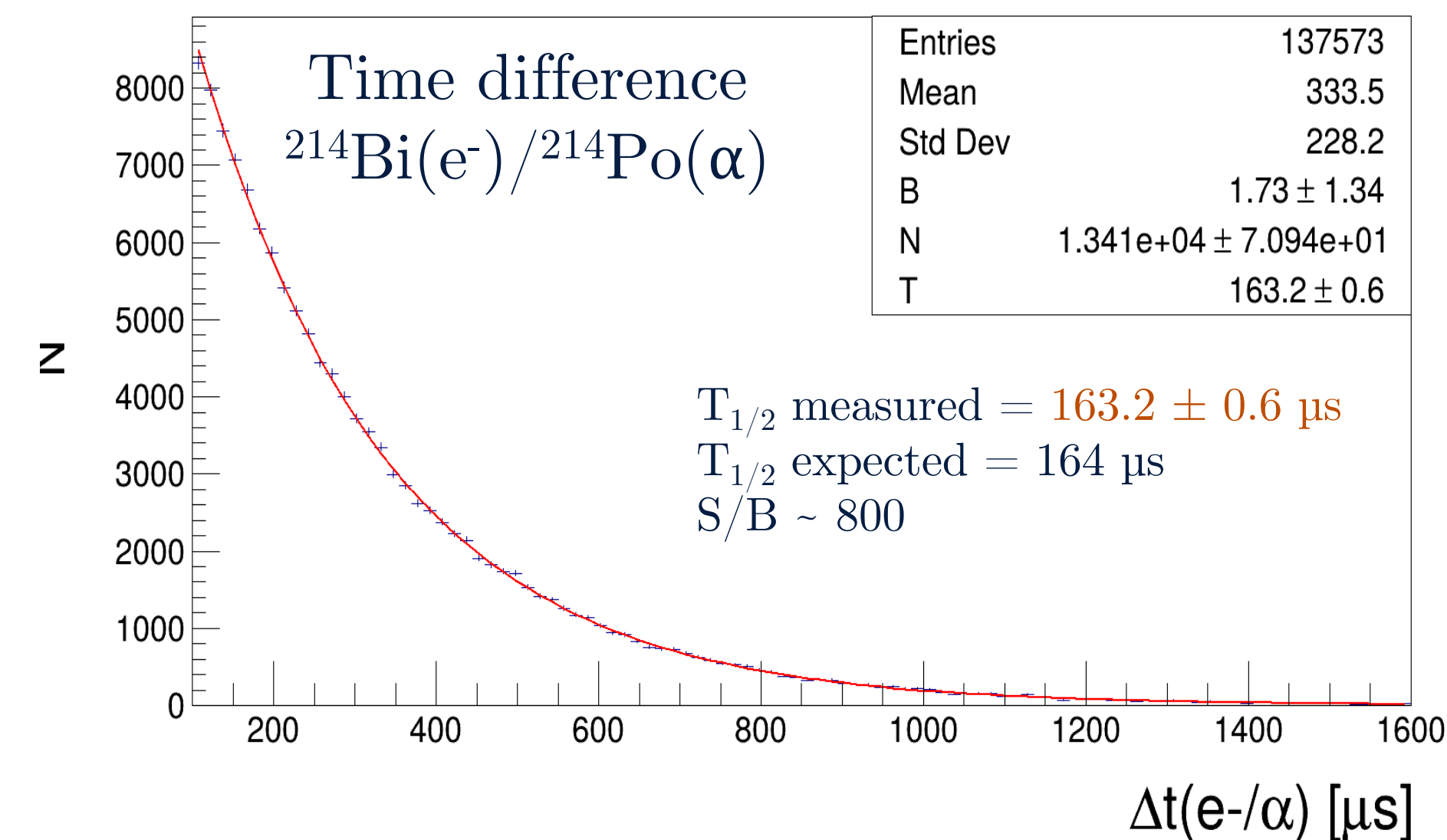
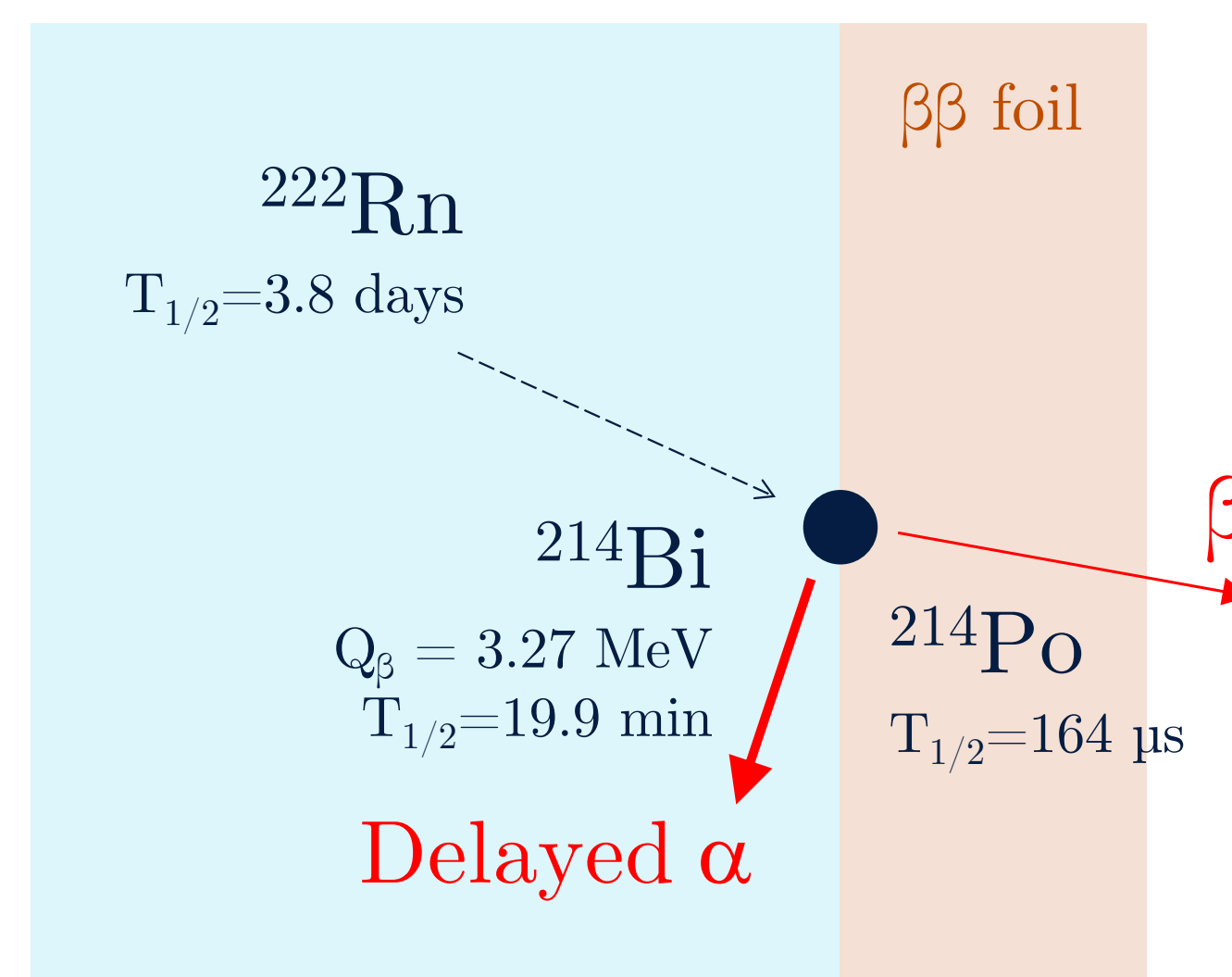
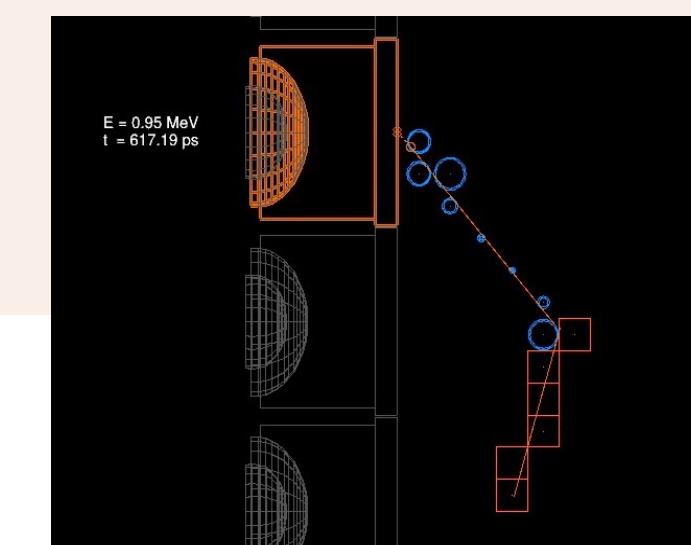
$\beta\beta$ background from Rn

- 2 electrons



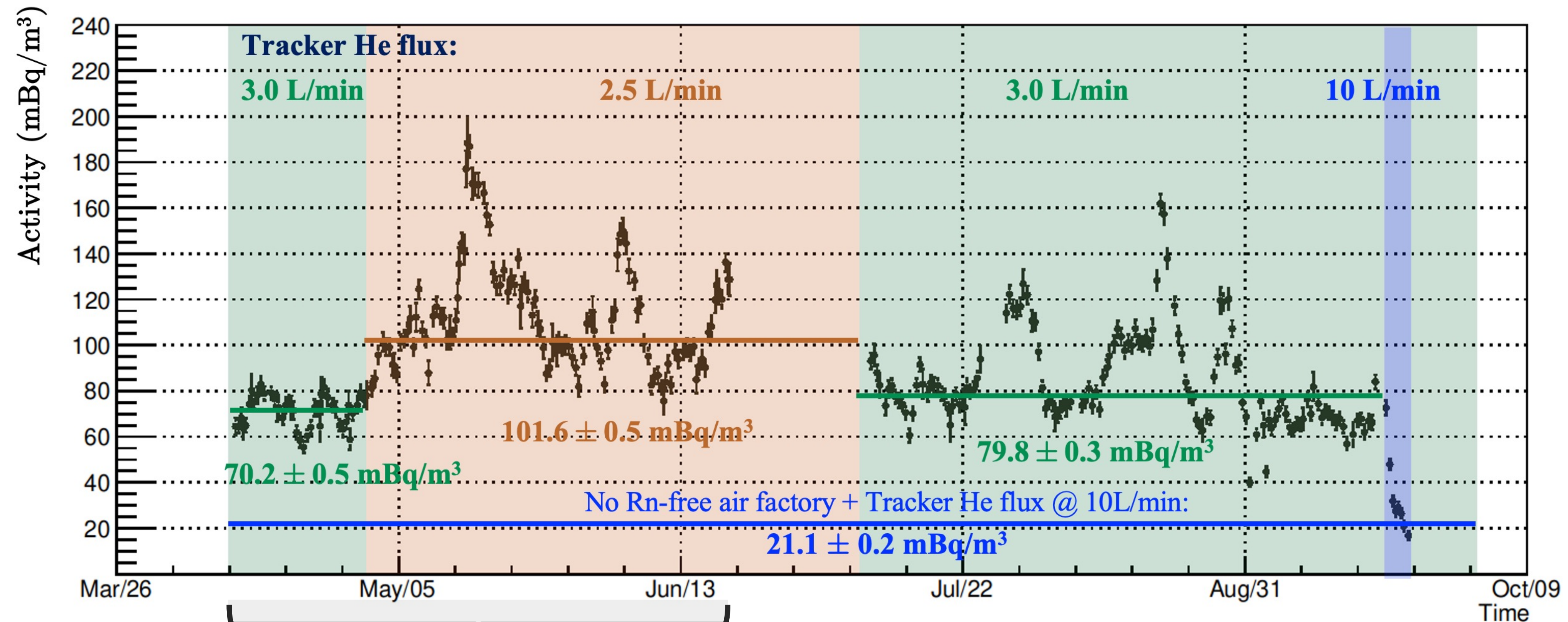
Dedicated channel for Rn study

- BiPo events: 1 electron + 1 delayed alpha



Preliminary physics results - 64.8 days of data (10 April – 20 June 2025)

Radon activity inside the tracker



Mean: $95.0 \pm 0.5^*$ mBq/m³ → ~ 20 mBq/m³ (10L/min He) **only statistical errors*

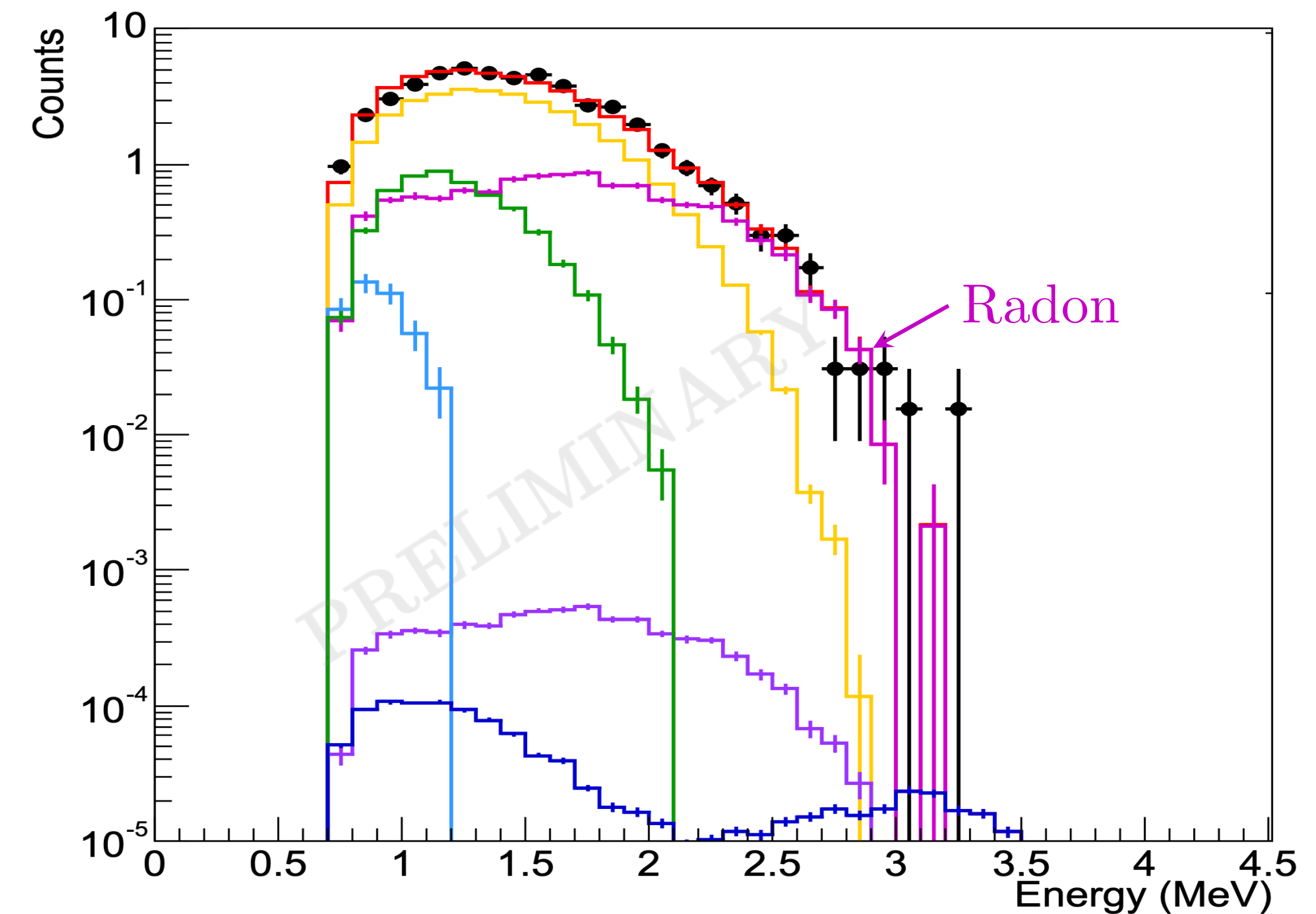
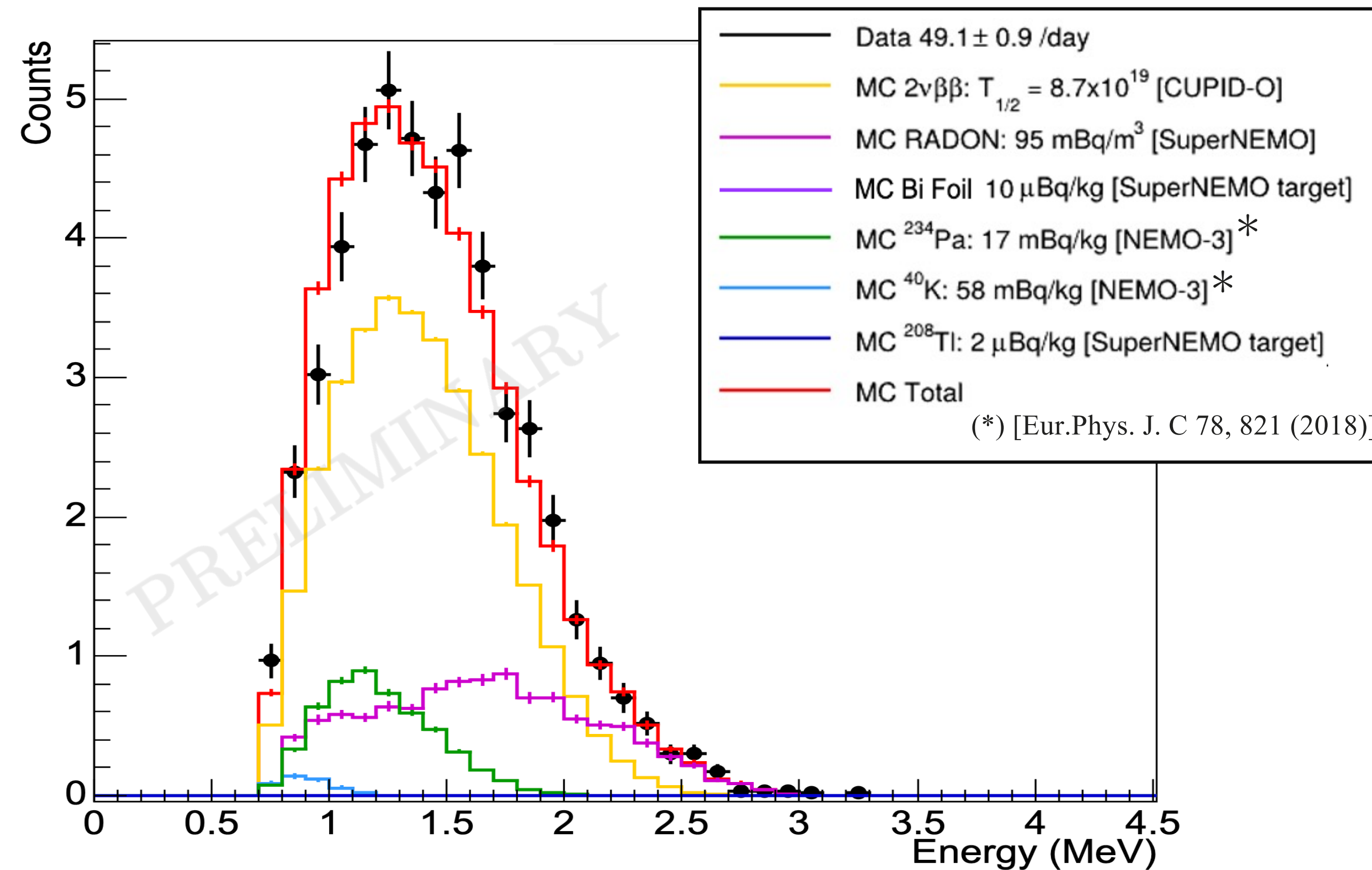
- Required: 0.15 mBq/m³ → factor ~150 improvement required
- Expected Rn reduction factor of ~10 000 at the output of the radon-free factory (~6 500* in NEMO-3 facility)
- LSM Rn-free air should be fully operational soon

* [J. Phys. G: Nucl. Part. Phys. 46 115105 (2019)]

Preliminary physics results - 64.8 days of data (10 April – 20 June 2025)

First $\beta\beta$ spectrum

Preliminary analysis (raw energy and time selections, preliminary radon level)

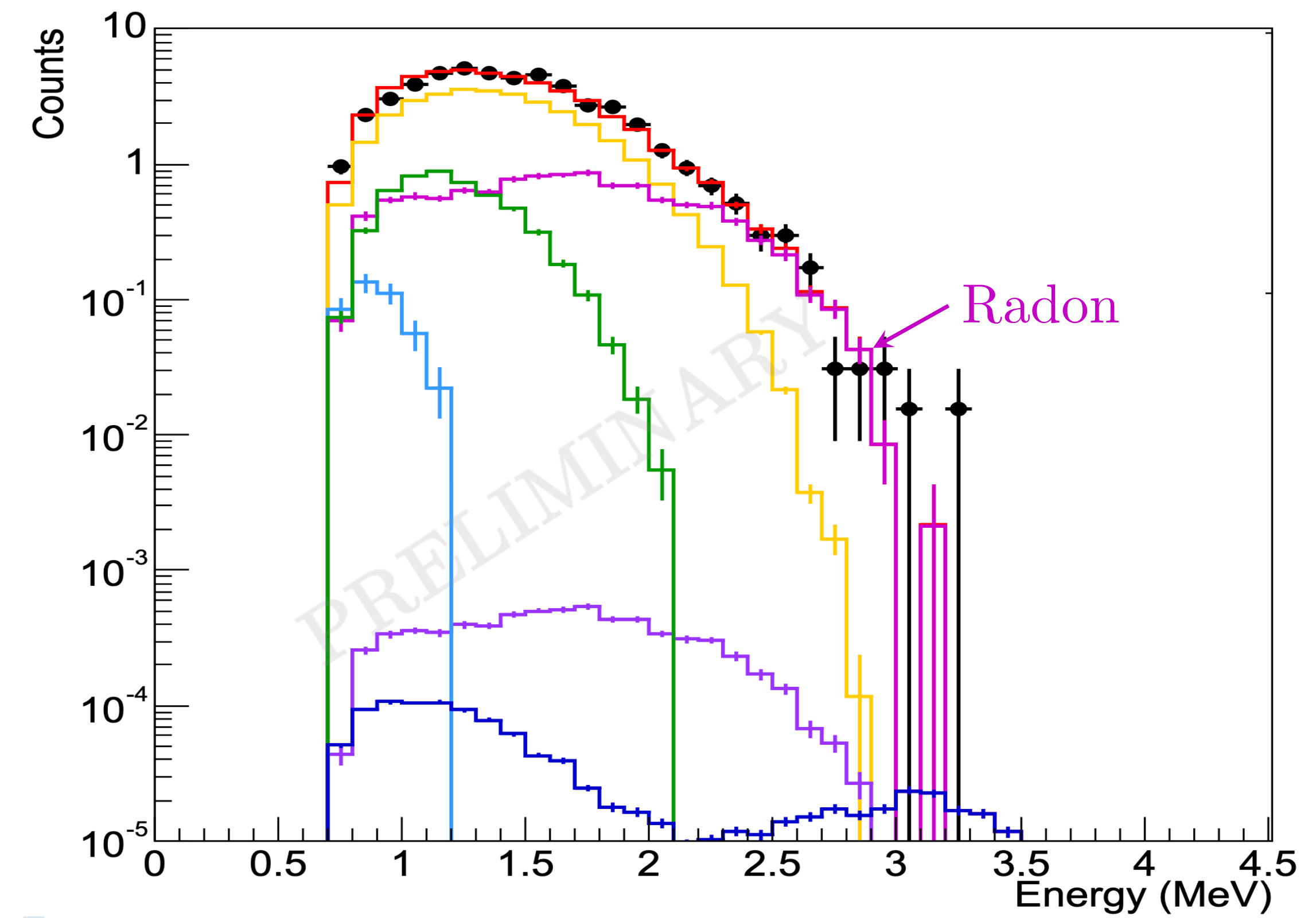
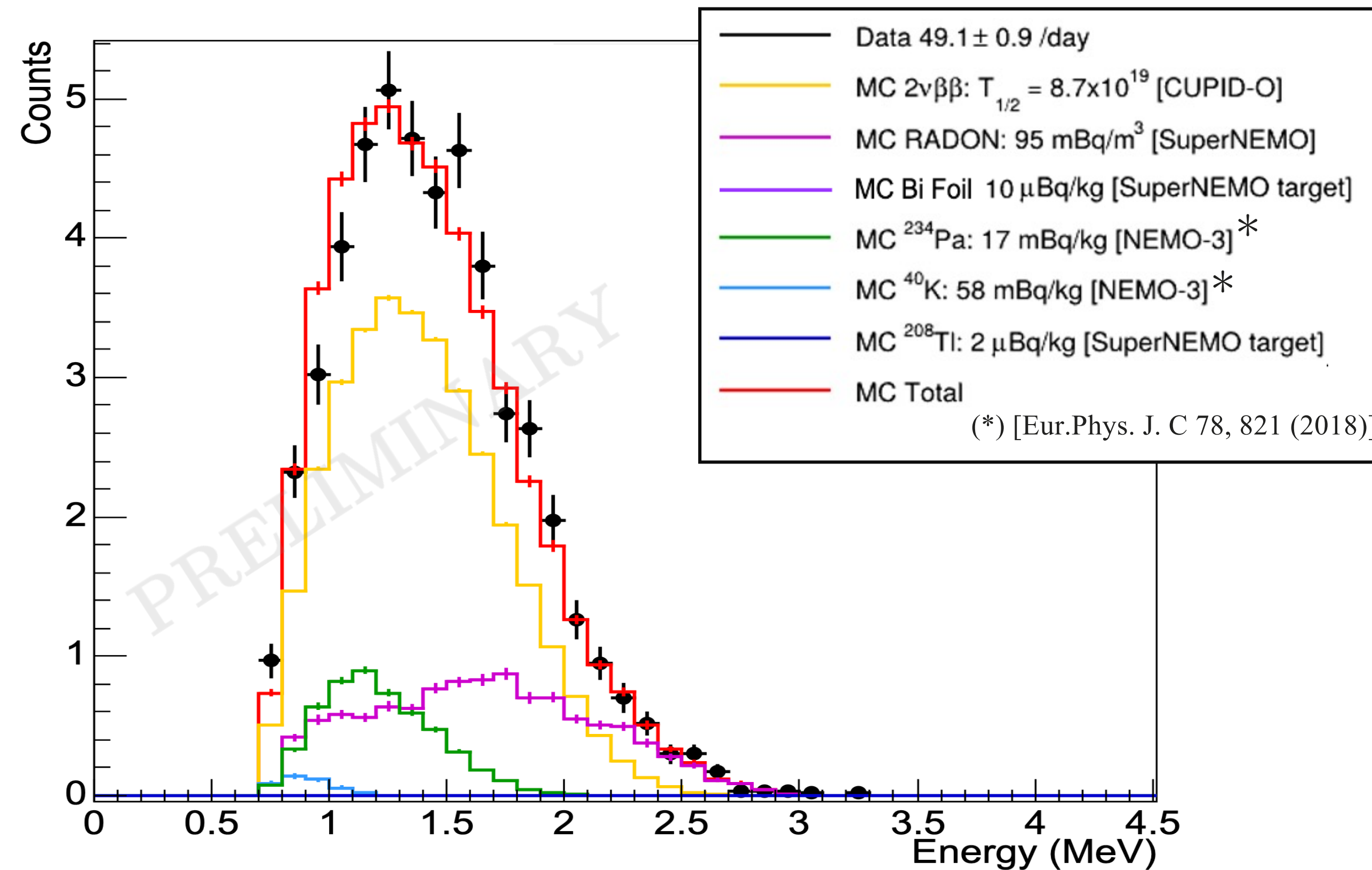


- Whole energy distribution dominated by the expected $2\nu\beta\beta$ decay shape with no events above 3.4 MeV
- Above 2 MeV: Radon dominates (as expected without LSM radon-free air facility)

Preliminary physics results - 64.8 days of data (10 April – 20 June 2025)

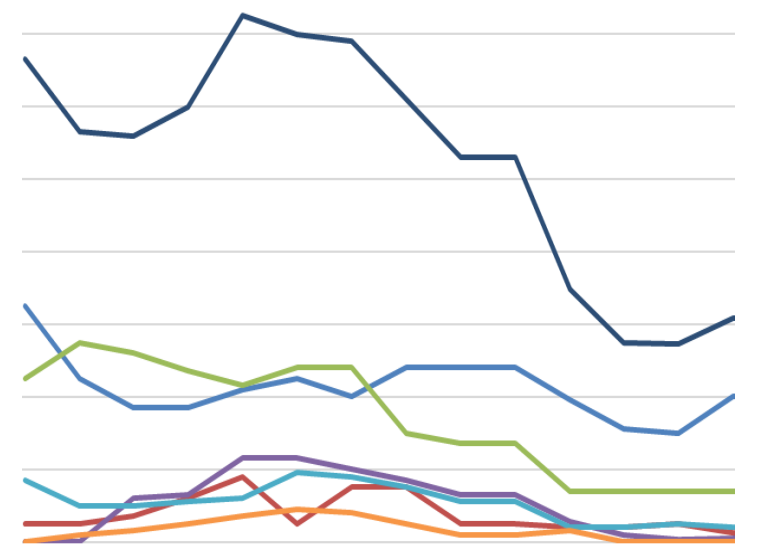
First $\beta\beta$ spectrum

Preliminary analysis (raw energy and time selections, preliminary radon level)



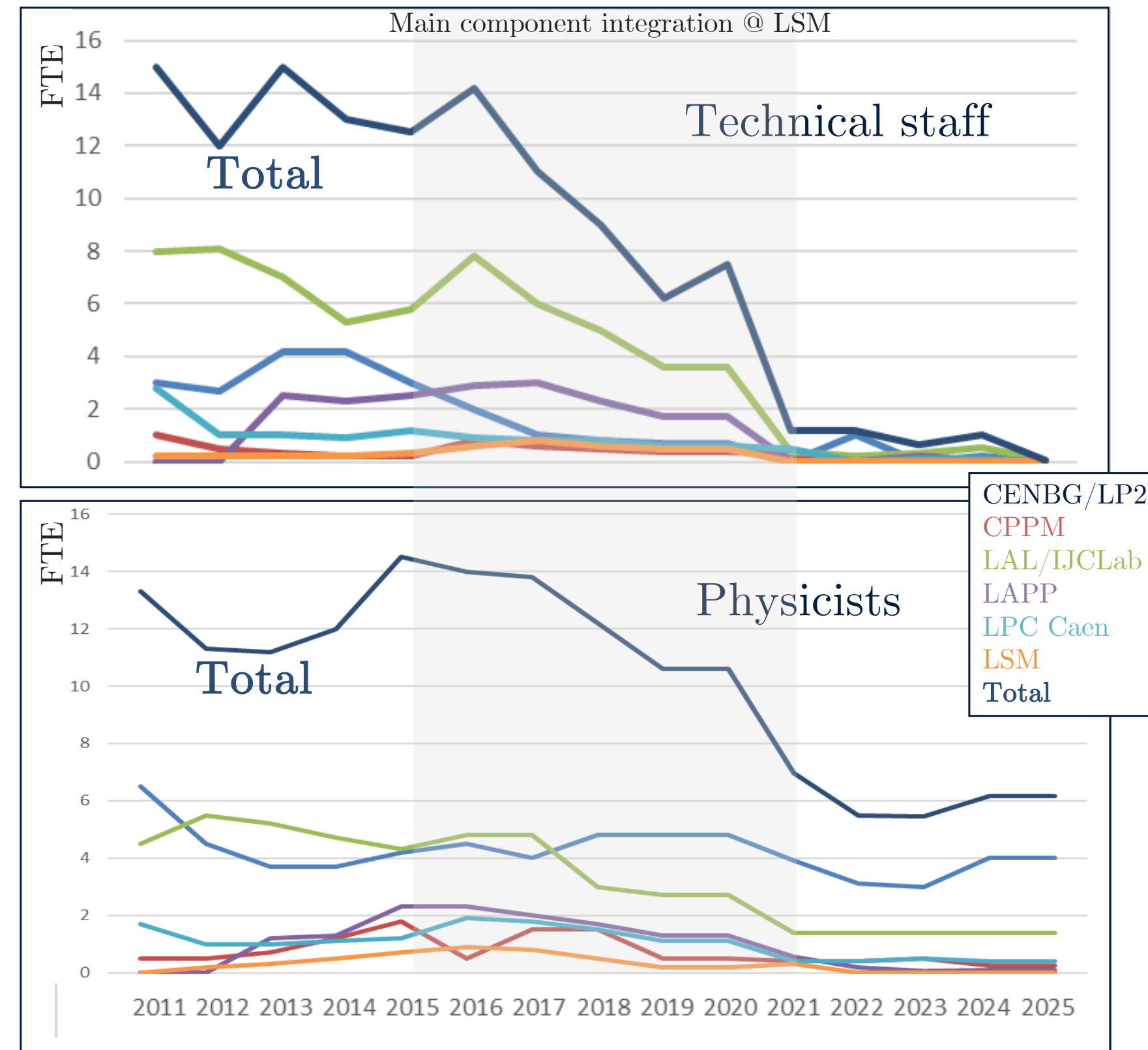
ROI [2700-3100] keV	Expected w/Rn-free air	Expected current	Measured
Events	0.12 ± 0.02	9.0 ± 1.5	7
Back. Index (events/keV.kg.y)	$2.7 \pm 0.5 \cdot 10^{-4}$	$208 \pm 35 \cdot 10^{-4}$	$161 \cdot 10^{-4}$

Resources



Human resources

IN2P3 FTE evolution



Number of personnel currently/ over the entire period

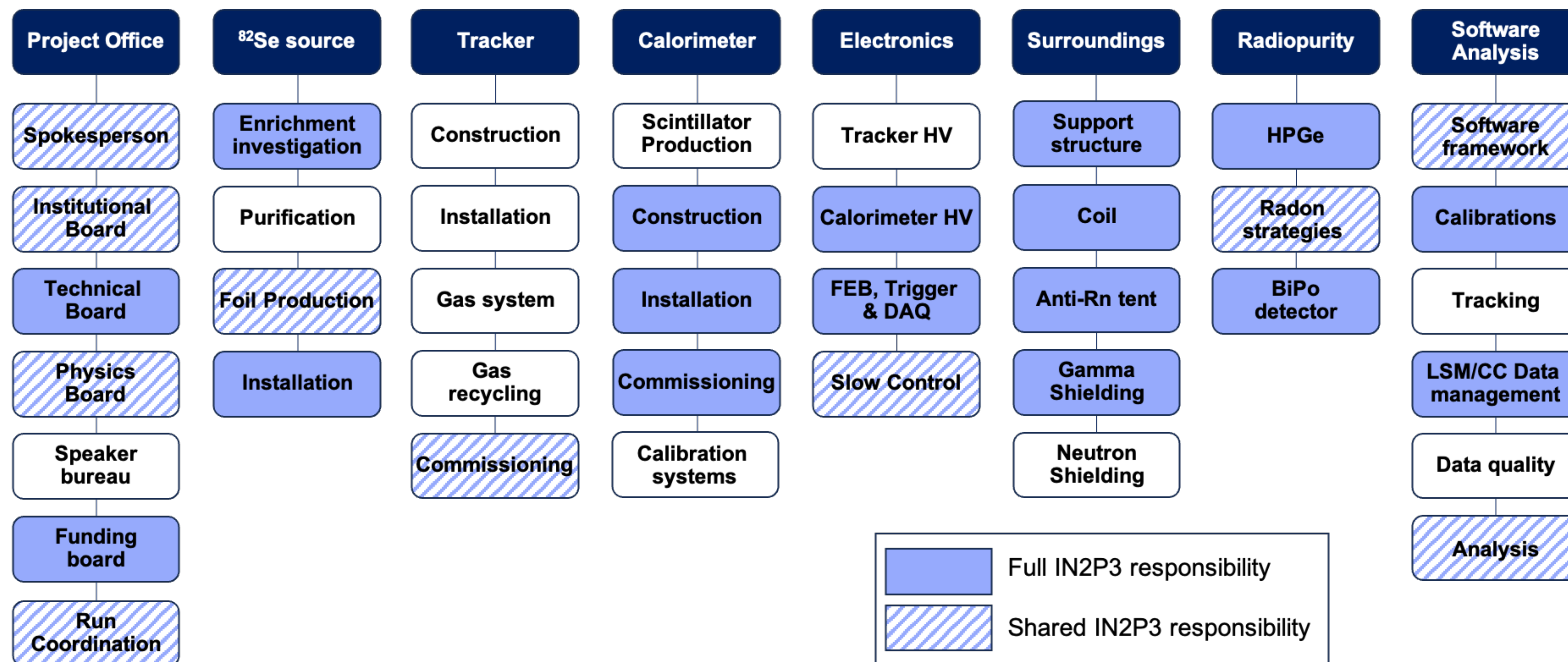
	LP2i	IJCLab	CPPM	LPC Caen	LAPP	TOTAL
Permanent physicists	4 / 7	2 / 6	1 / 1	2 / 3	1 / 1	10 / 18
Permanent technical staff	2 / 12	3 / 15	2 / 2	1 / 8	1 / 7	9 / 44
Postdocs	0 / 2	0 / 1	0 / 2	0 / 0	0 / 2	0 / 7
PhD students	2 / 12	1 / 8	0 / 1	0 / 2	0 / 1	3 / 24

TOTAL: 22 IN2P3 collaborators in 2025 / 93 (all period)

+ LSM staff (no longer collaboration members)

- **Permanent physicists** involved in the running and analysis at least for the 2-3 coming years
Parallel/upcoming projects → 2 DUNE, 2 JUNO, 2 CUPID, 1 LISA, 1 R2D2, 1 Retired + 1? (non-DBD)
- **Technical staff** required for dismantling
- **PhD** and/or **postdoctoral** researchers would enhance IN2P3's contributions to the analyses

Responsibilities

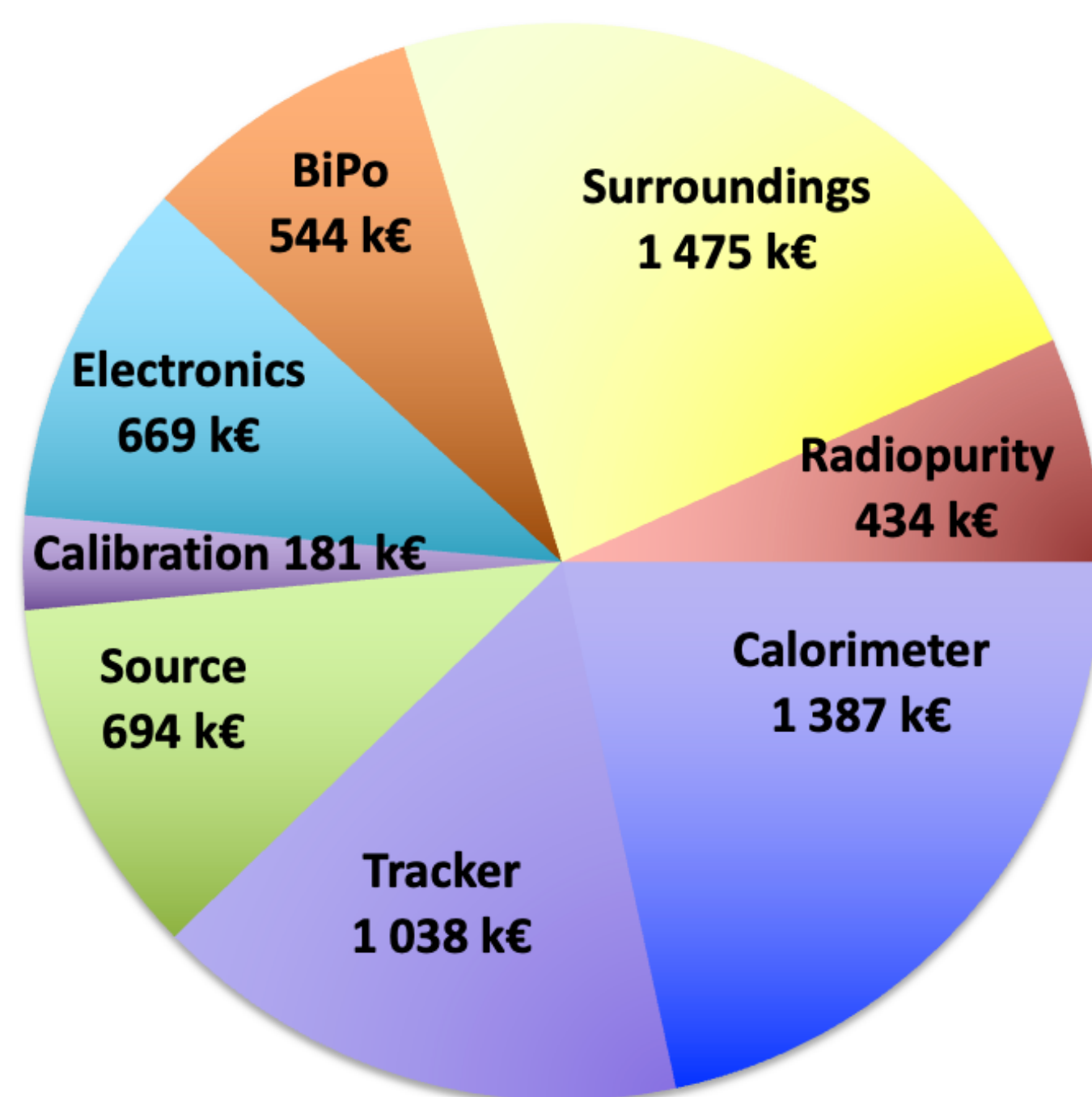


- IN2P3 collaborators involved in many responsibilities

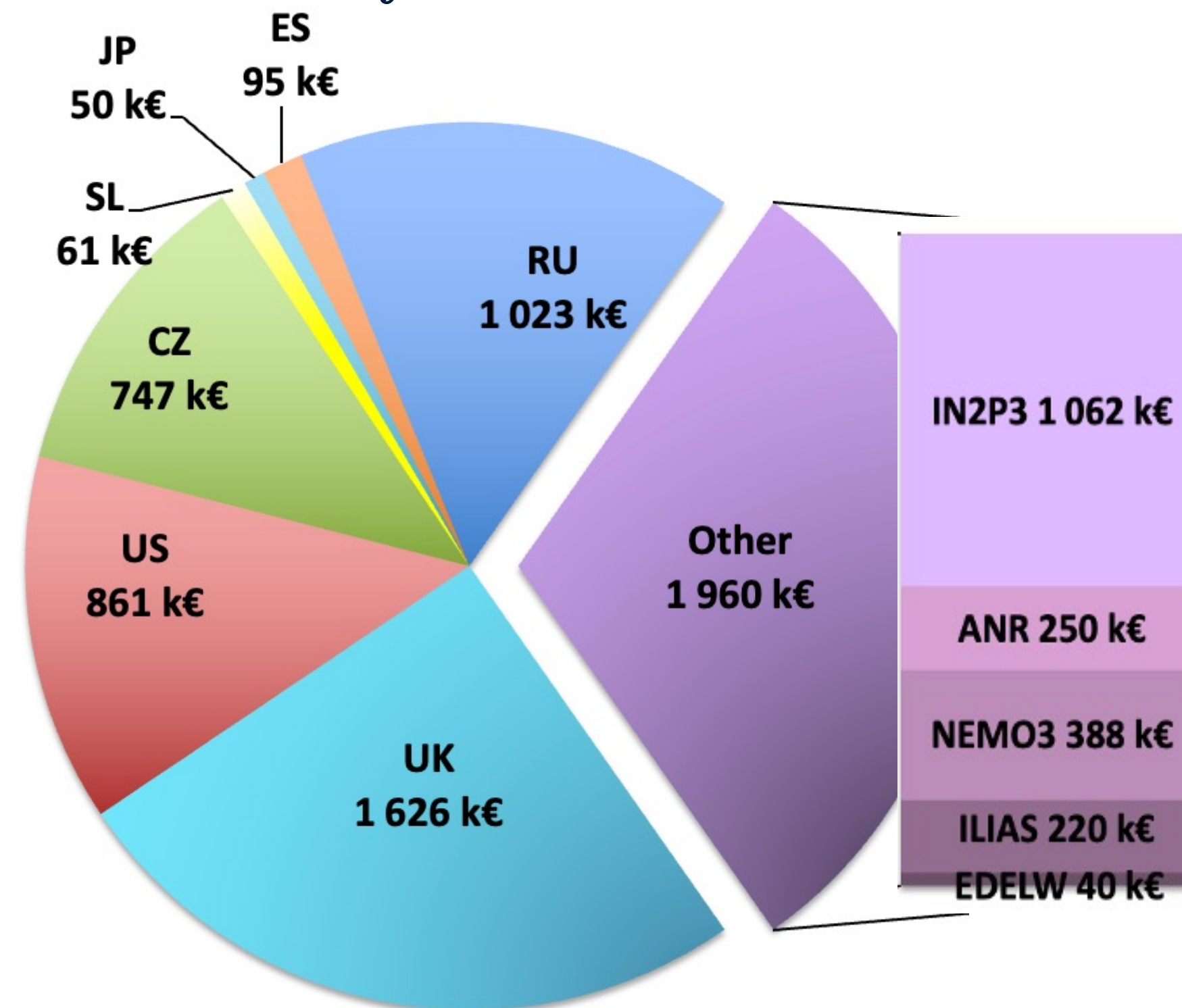
Fundings

Total cost (without travel and personnel): 6421.5 k€

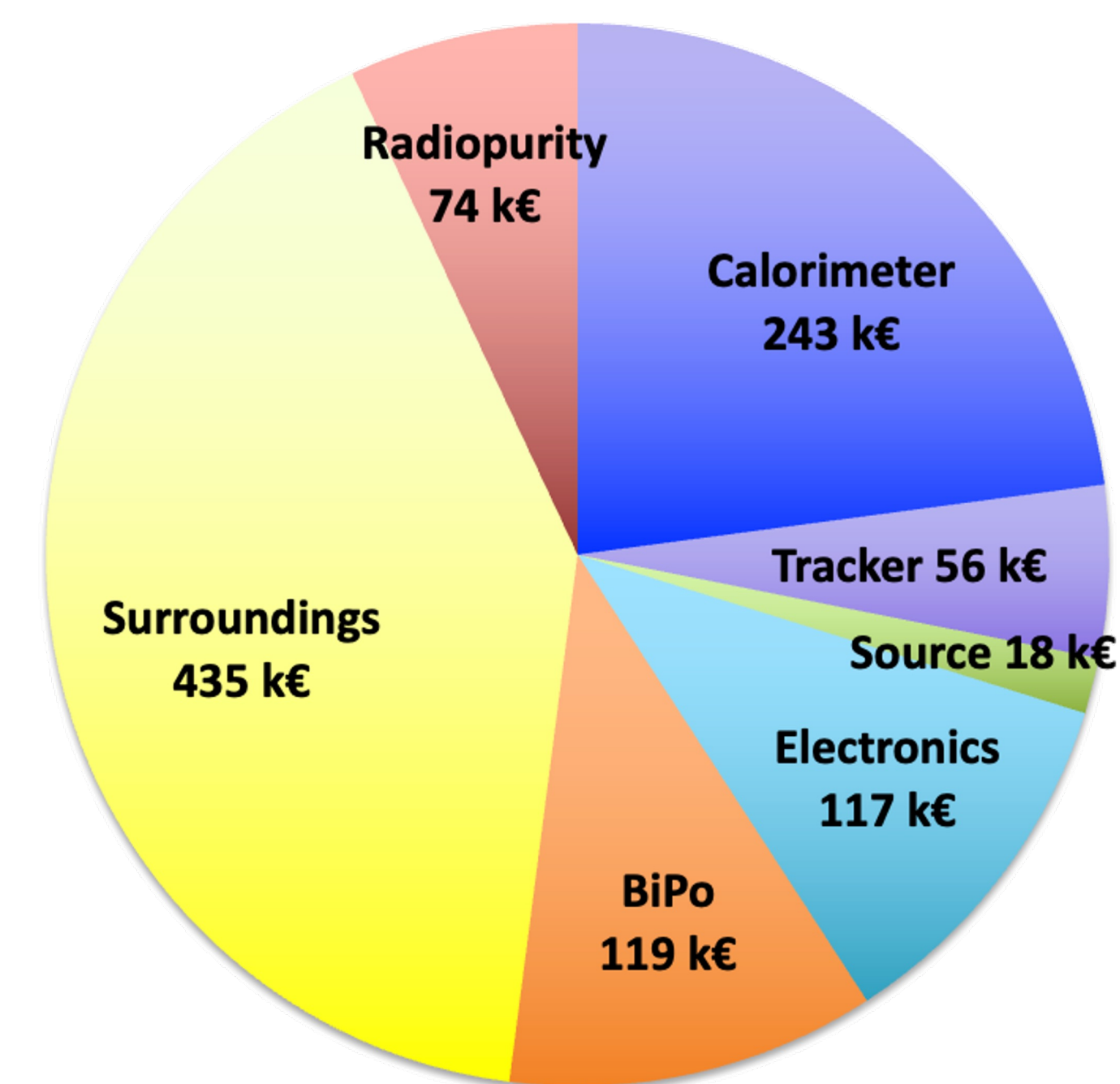
By sub-systems



By countries

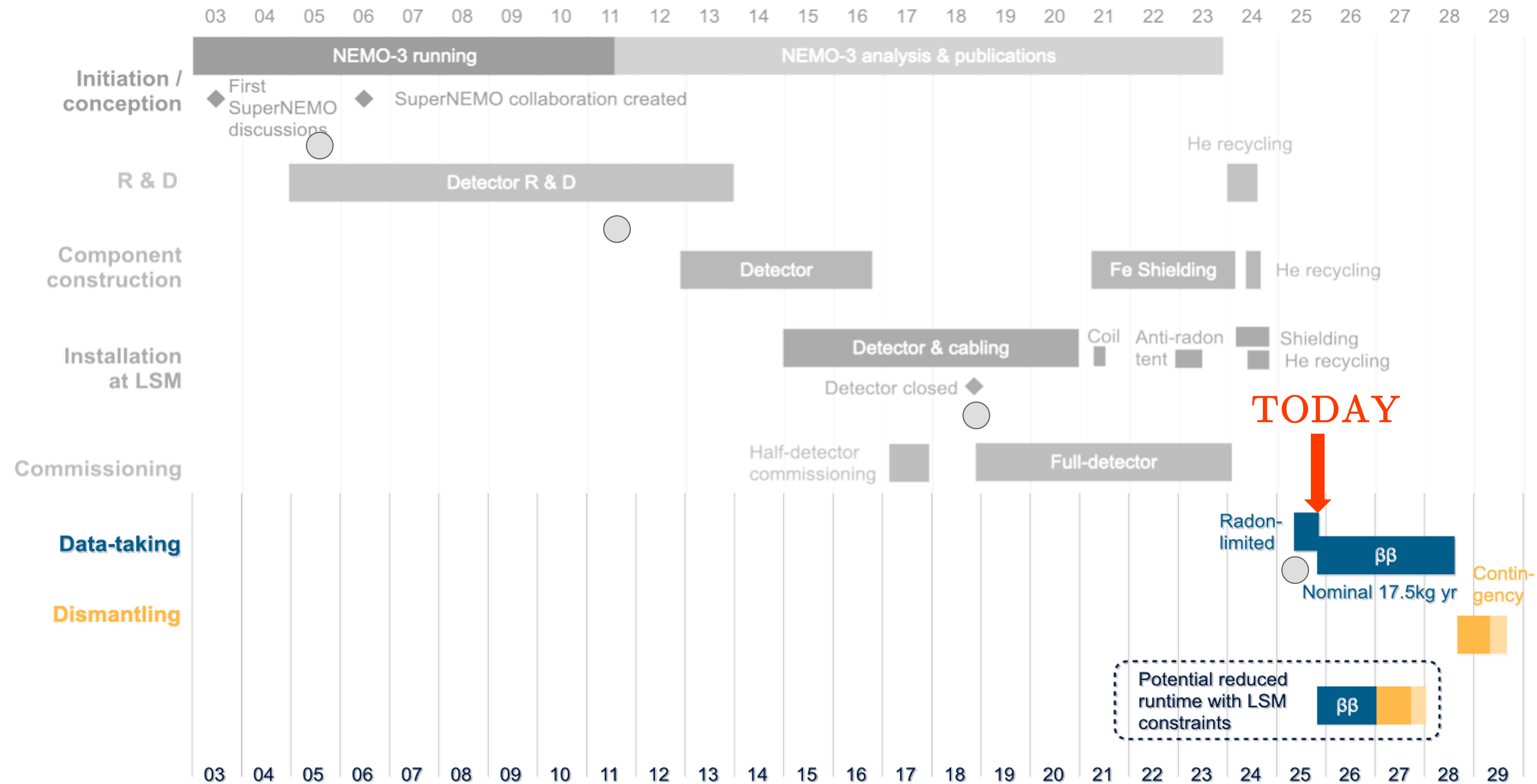


By sub-systems from IN2P3



- IN2P3 main contributions: γ shielding, calorimeter (electronics, mechanics and 8'' PMTs) and BiPo detector
 - Running costs (Gas mixture, maintenance): 128 000 euros/year
 - Dismantling (without travel): 80 000 euros
- 35% IN2P3, 35% UK, 19% Czechia, 11% Slovakia

Running time resources



- Running time allocated until end of 2026 (floor-occupation constraints at LSM)
- Equivalent to **6.9 kg.y exposure** for $\beta\beta$ studies (if Rn-free air facility operational October 2025)
- **17.5 kg.y exposure** required for Demonstrator's full potential...

Conclusions

SuperNEMO Demonstrator is now running: 2.37 kg.y exposure (radon-limited phase)

Demonstration

- Demonstrate its unique capability for *probing* $\beta\beta$ events and *investigating* BSM mechanisms
- Determine **optimisation drivers** for scaling up to the next-generation experiment

Unique opportunities for physics (depending on the allocated running time)

- **World-leading sensitivities** in ^{82}Se $0\nu\beta\beta$ processes (only possibility with ^{82}Se for years)
- **High-precision results** in $2\nu\beta\beta$ studies (+ exotic processes) and nuclear calculations (g_A , NME...)

Conclusions



The SuperNEMO collaboration
gratefully acknowledges
IN2P3 management, LSM staff
and CC-IN2P3
for their support

Backup

SWOT: SuperNEMO technology & Demonstrator

Strengths

- Full kinematic reconstruction and PID
- Ability to study a wide range of $\beta\beta$ isotopes
- Background rejection and measurement capabilities

SN-dem

- Proof of technological concept
- Wide range of physics studies

Weaknesses

- Complex construction and integration
- Large detector design
- Limited detection efficiency
- Limited energy resolution

SN-dem

- Limited isotope mass: 6.11 kg of ^{82}Se
- Possible unexpected background?

Opportunities

- Unique “golden event” $\beta\beta$ signature
- Unique capability to explore $\beta\beta$ decay process

SN-dem

- Possible best results for several BSM processes
- Unique inputs for nuclear calculations (g_A , NME)
- Many tools and expertise to benefit community

Threats

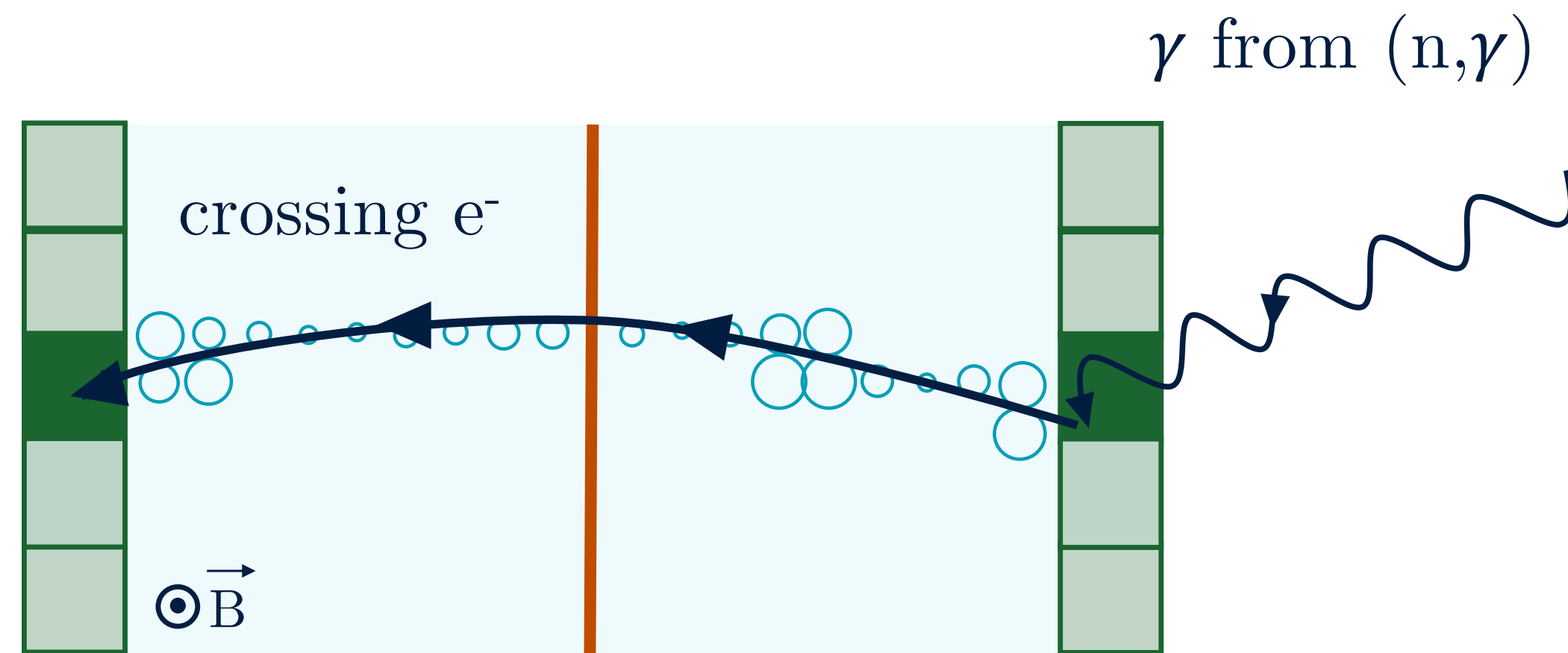
- High construction and operation costs
- Isotope production in the geo-political context
- Helium supply fluctuations
- Limited space availability in underground labs

SN-dem

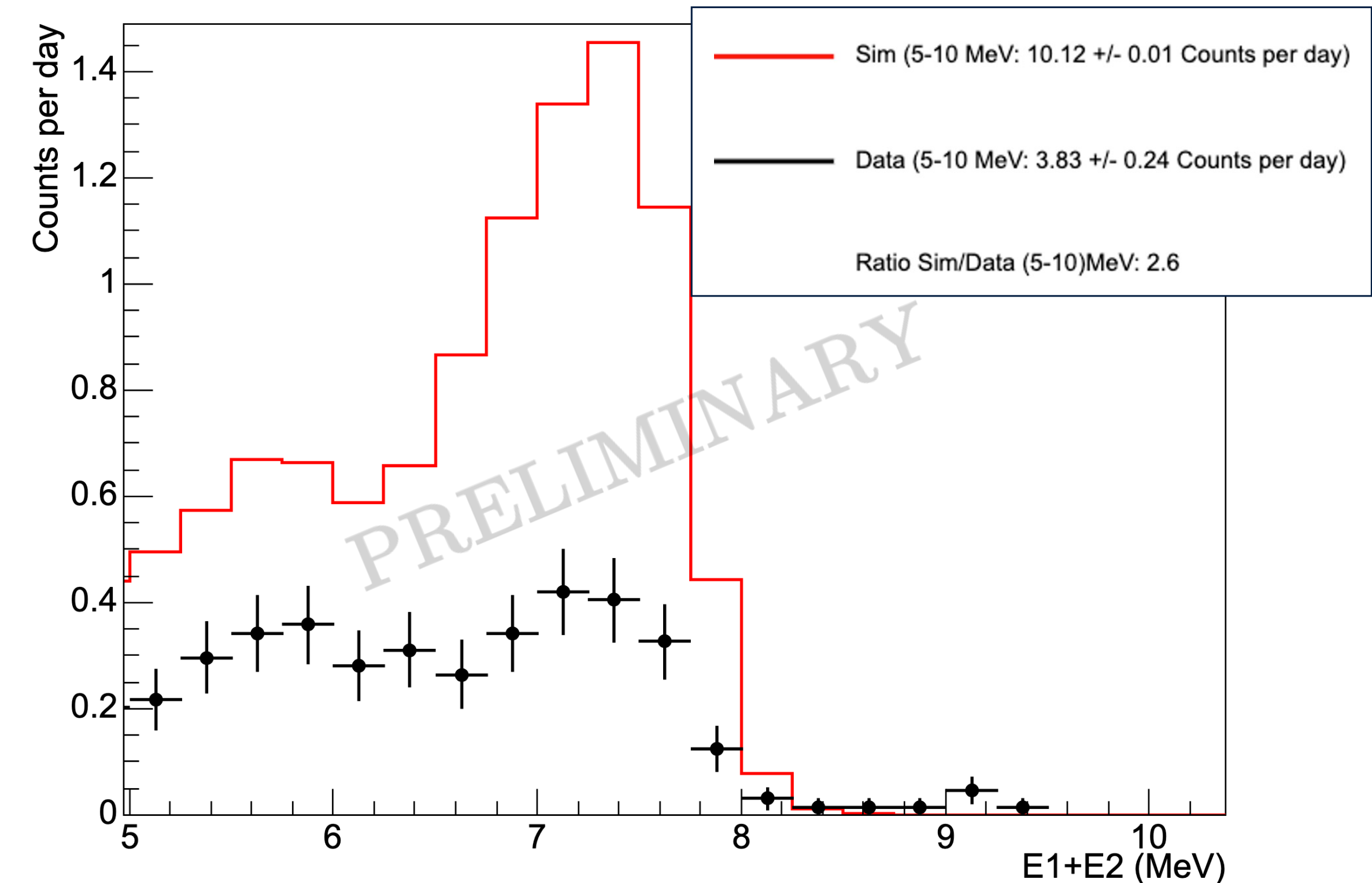
- Limited running period
- Limited radon-free phase
- Limited manpower (analysis & dismantling)

Neutron background - 64.8 days of data (10 April – 20 June 2025)

Dedicated channel: 1 crossing electron > 5 MeV (above ^{208}Tl)



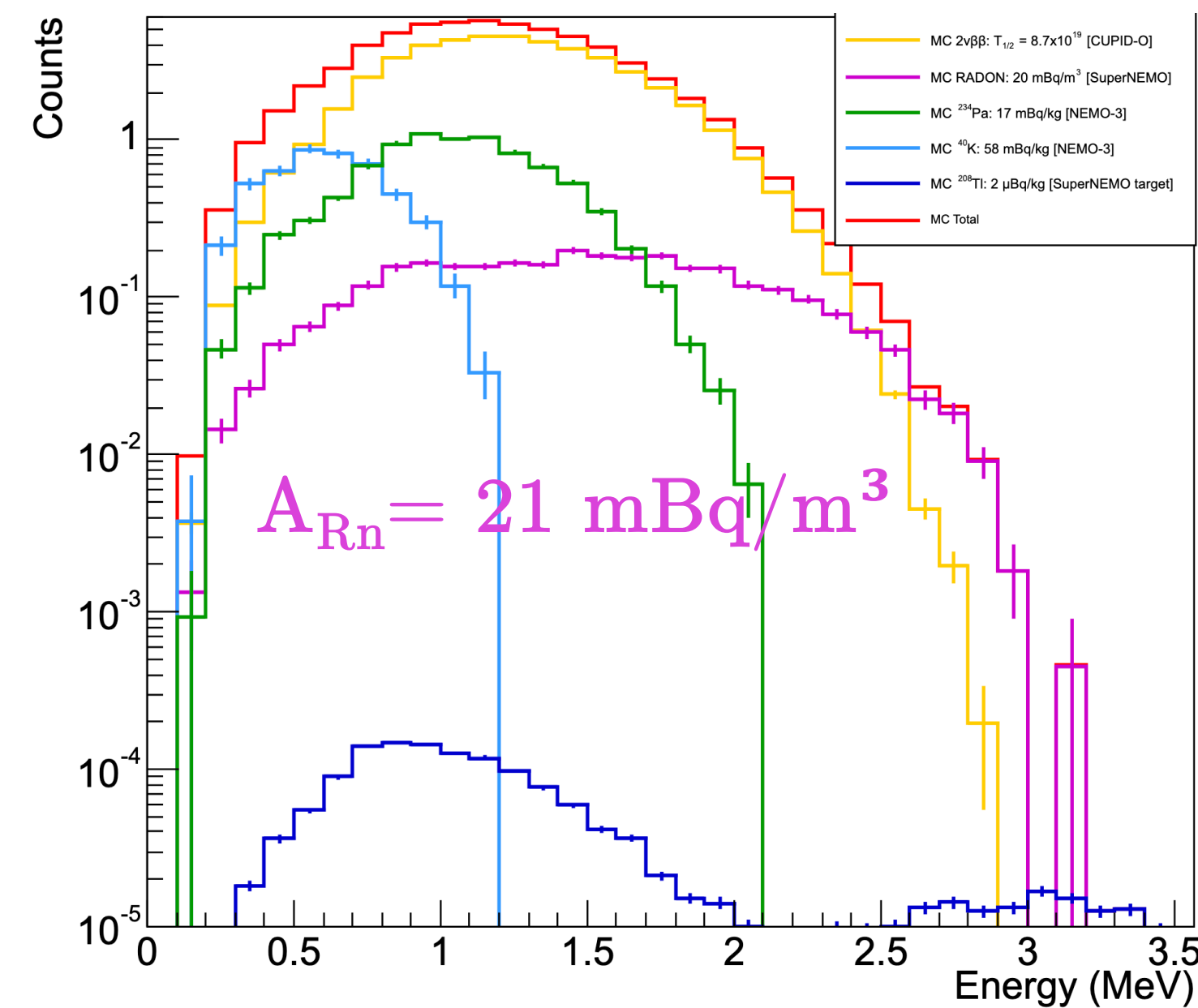
- n captures inside Fe, Cu give high energy γ
- Crossing electron created by Compton scattering



- Neutron background seems to be 2-3 times lower than expected (from old LSM n flux measurements)

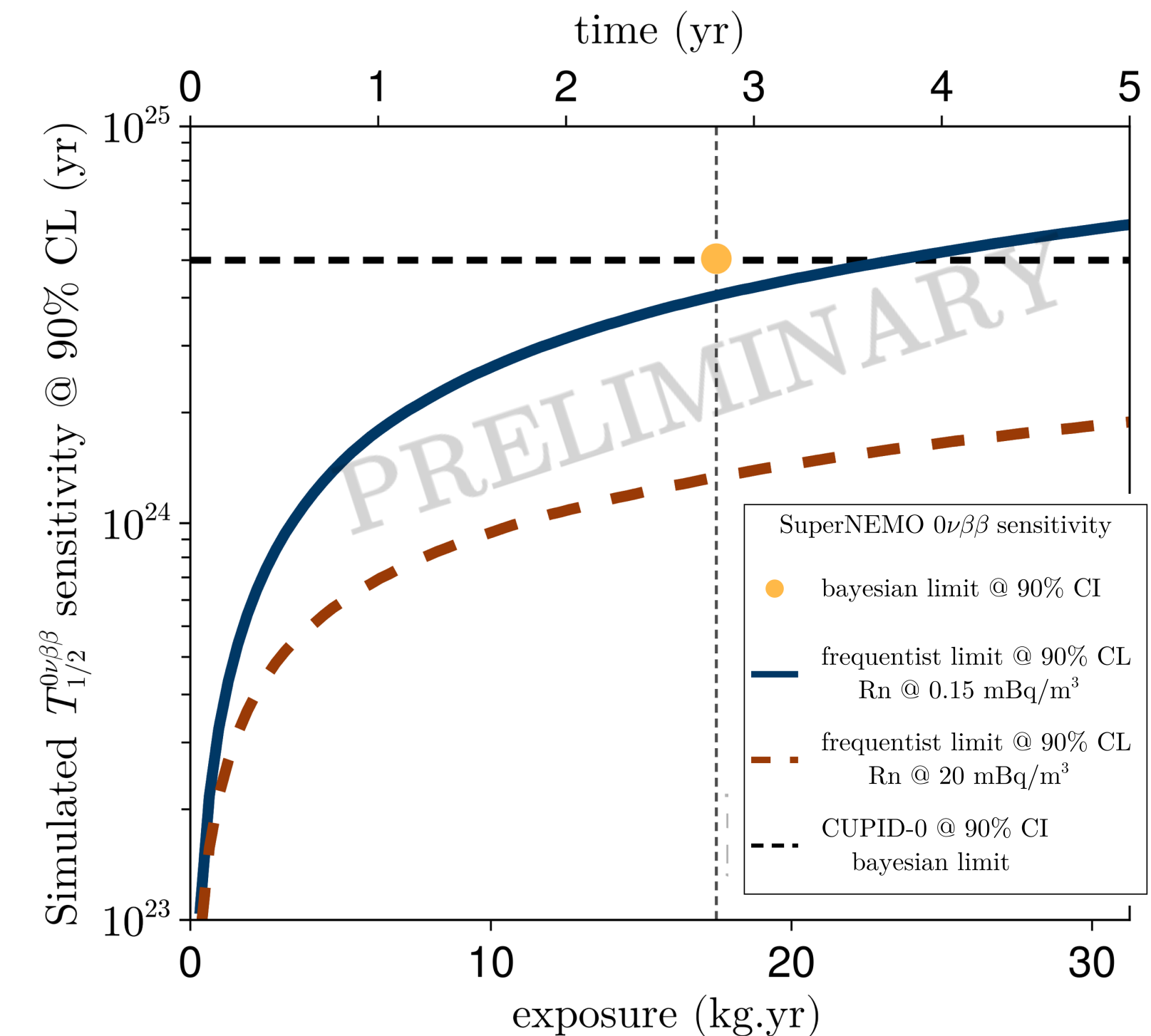
Radon impact on $0\nu\beta\beta$ V-A

$0\nu\beta\beta$ with light neutrino exchange & V-A current (mass mechanism)



Background	Events for 17.5 kg.yr [2.7-3.1] MeV
	$0.15 \rightarrow 21 \text{ mBq/m}^3 \text{ Rn}$
$2\nu\beta\beta$	0.98 ± 0.13
^{208}Tl	0.04 ± 0.01
^{214}Bi	0.09 ± 0.01
Radon	$0.23 \pm 0.04 \rightarrow 31 \pm 6$
Neutrons	0.60 ± 0.30
Total	$1.9 \pm 0.4 \rightarrow 33 \pm 6$

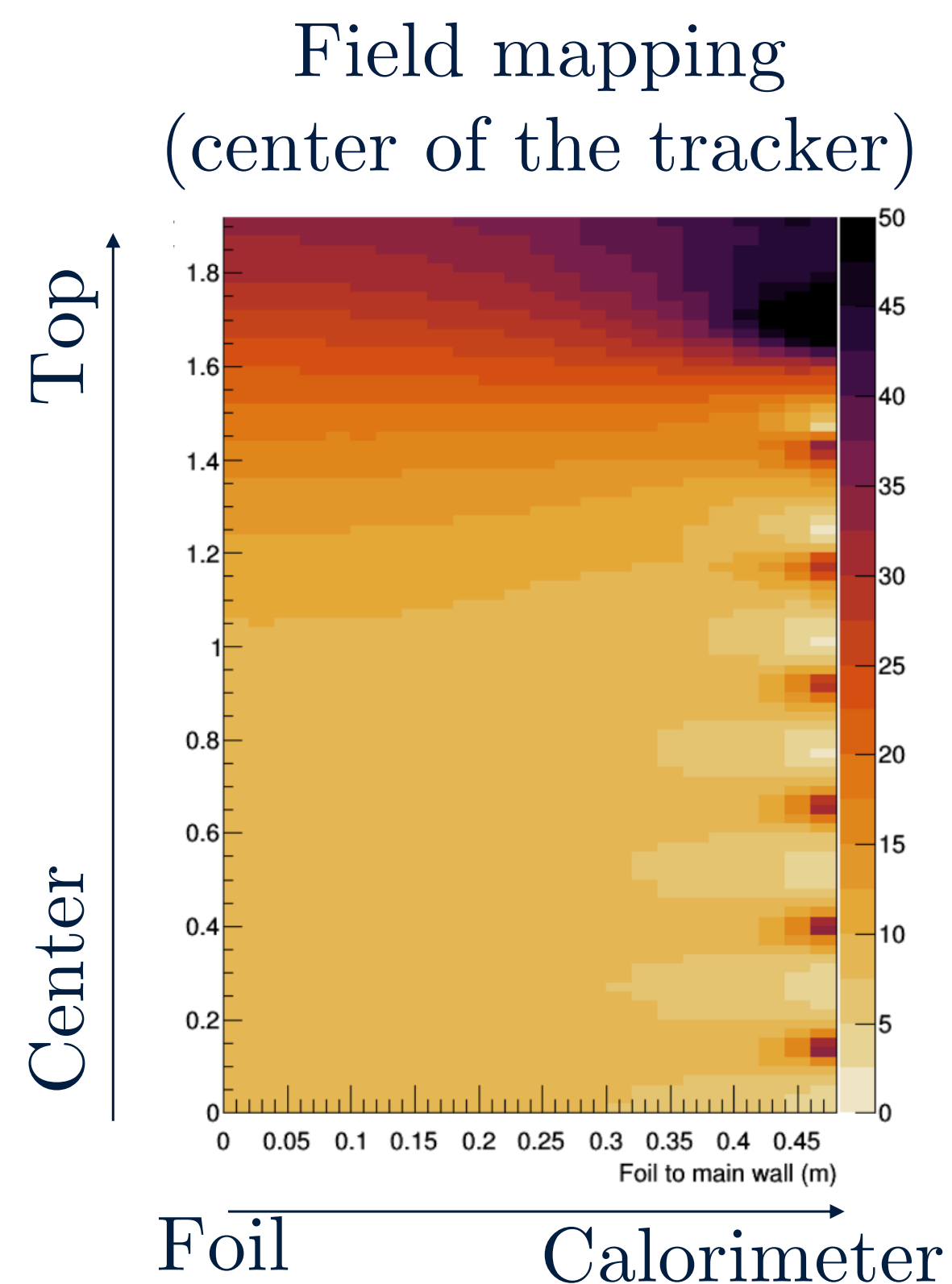
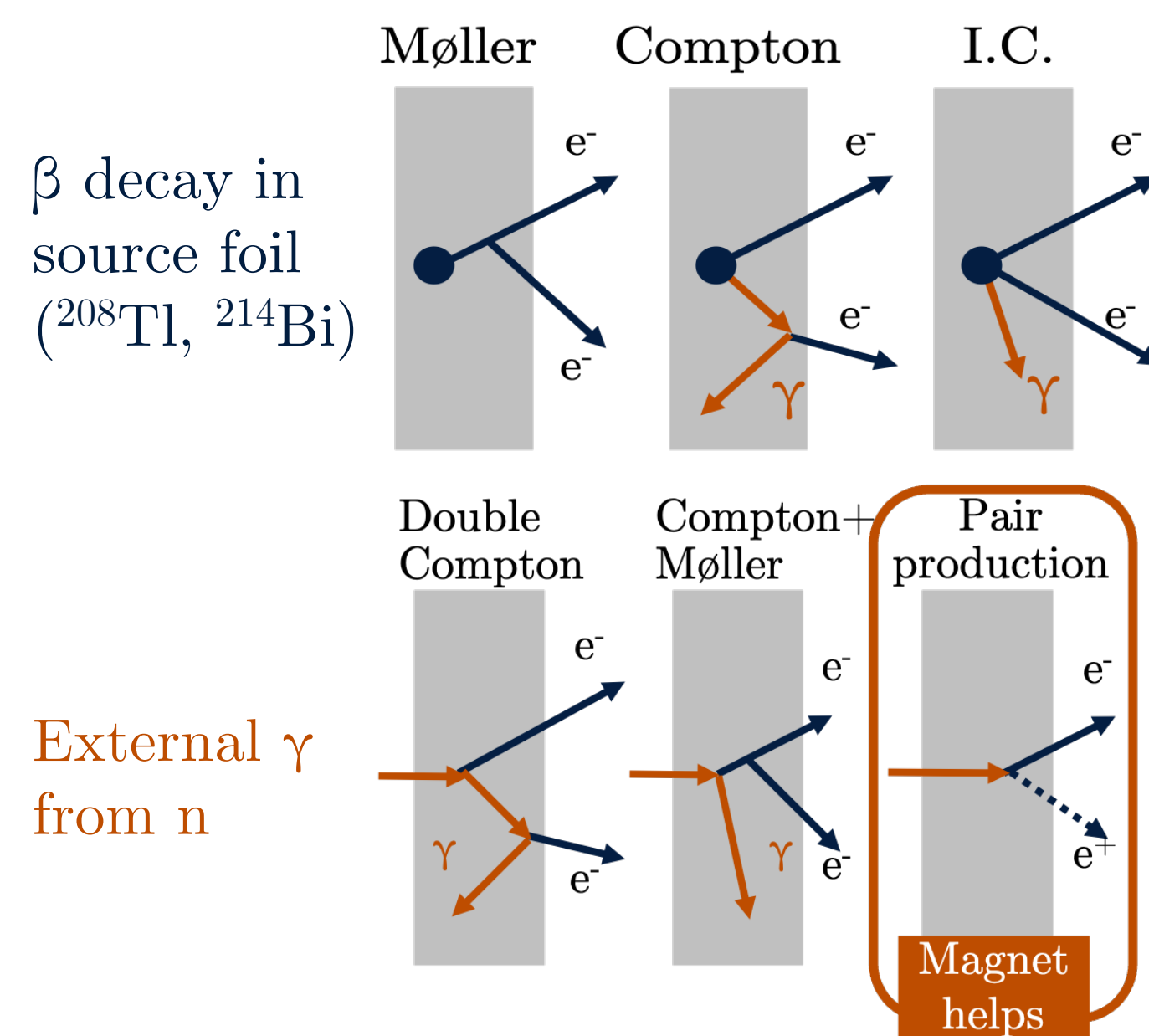
- Rn target: $\text{BI} = 2.7 \cdot 10^{-4} \text{ event keV}^{-1}\text{kg}^{-1} \text{ y}^{-1}$
- High Rn $\rightarrow \text{BI} = 4.6 \cdot 10^{-3} \text{ event keV}^{-1}\text{kg}^{-1} \text{ y}^{-1}$
(NEMO-3 ^{100}Mo : $10^{-3} \text{ event keV}^{-1}\text{kg}^{-1} \text{ y}^{-1}$)



- High radon level (without Rn-free air facility) would prevent any competitive results on physics
- High radon level would dominate all the backgrounds preventing precise background studies

Magnetic field: to $\vec{B}$ or not to $\vec{B}$?

Benefit - background rejection



	$T_{1/2}$ No B / $T_{1/2}$ with B
Homogenous 25 G field	~ 1.1
Actual field	~ 1.4

Points to consider:

- Efficiency is key especially with limited runtime
- Neutron flux appears lower than expected
- Track reconstruction is simpler without B field
- Strong impact on low energy electrons ($g_A \dots$)

- Current decision is to run **without B**
- Run for a few weeks at the end with field ON (irreversible process)

Dismantling

Cost

		Qty	Cost/U	Cost
Means	Slings	10	50,00 €	500,00 €
	Shackles	20	10,00 €	200,00 €
	Hydraulic Jacks	2		- €
	Calorimeter handling tools (hydraulic push /pull jack, calo axes...			- €
	Ladders and Scaffolding	2		- €
	Wood storage boxes	10	250,00 €	2 500,00 €
	Wooden pallet	22	21,49 €	472,78 €
	Wrenches	1	1 000,00 €	1 000,00 €
	Electromagnet	1	4 000,00 €	4 000,00 €
	Industrial vacuum cleaner	1	800,00 €	800,00 €
	Jackhammer	1	800,00 €	800,00 €
	Saber saw	1	200,00 €	200,00 €
	Rent Cherry picker	15	350,00 €	5 250,00 €
	Iron plate handling frame	2	7 500,00 €	15 000,00 €
	IMPACT wrench	1	1 200,00 €	1 200,00 €
	Truck socket box	1	900,00 €	900,00 €
	Safety equipment (Helmet, harnesses...)			- €
	Helmet	10	30,00 €	300,00 €
	Safety shoes	0		- €
	Harnesses	4	100,00 €	400,00 €
	Miscellaneous Gloves,... cloth,...	1	2 000,00 €	2 000,00 €
Transport to the surface :	Truck 25 t. Iron shielding + PE	11	1 300,00 €	14 300,00 €
	Truck 25 t. Detector	4	1 300,00 €	5 200,00 €
	LSM Truck			- €
Storage	Storage Freney	?		
Transport to SuperNEMO laboratories	Transport to IJCLab Mechanical structure, tools, ART, electronics	1	1 000,00 €	1 000,00 €
	Transport to LP2i Bordeaux PMTs	1	1 000,00 €	1 000,00 €
	Transport to CPPM J-Trap, radon detector	1	1 000,00 €	1 000,00 €
	Transport to UCL Tracker, Water tanks, PMTs, radon detector	1	8 000,00 €	8 000,00 €
	Transport to Prague University PE, compressor	1	4 000,00 €	4 000,00 €
	Transport to Edinburgh University Mass spectrometer	1	1 000,00 €	1 000,00 €
	Transport to USA PMT, LI system, calibration sources deployment system	1	6 000,00 €	6 000,00 €
	Transport to Russia? ?	1	4 000,00 €	4 000,00 €
Waste management	Destruction			To be estimated
	Buyback (iron, wires...)			To be estimated
			TOTAL	81 022,78 €

Preliminary schedule (approved by LSM)

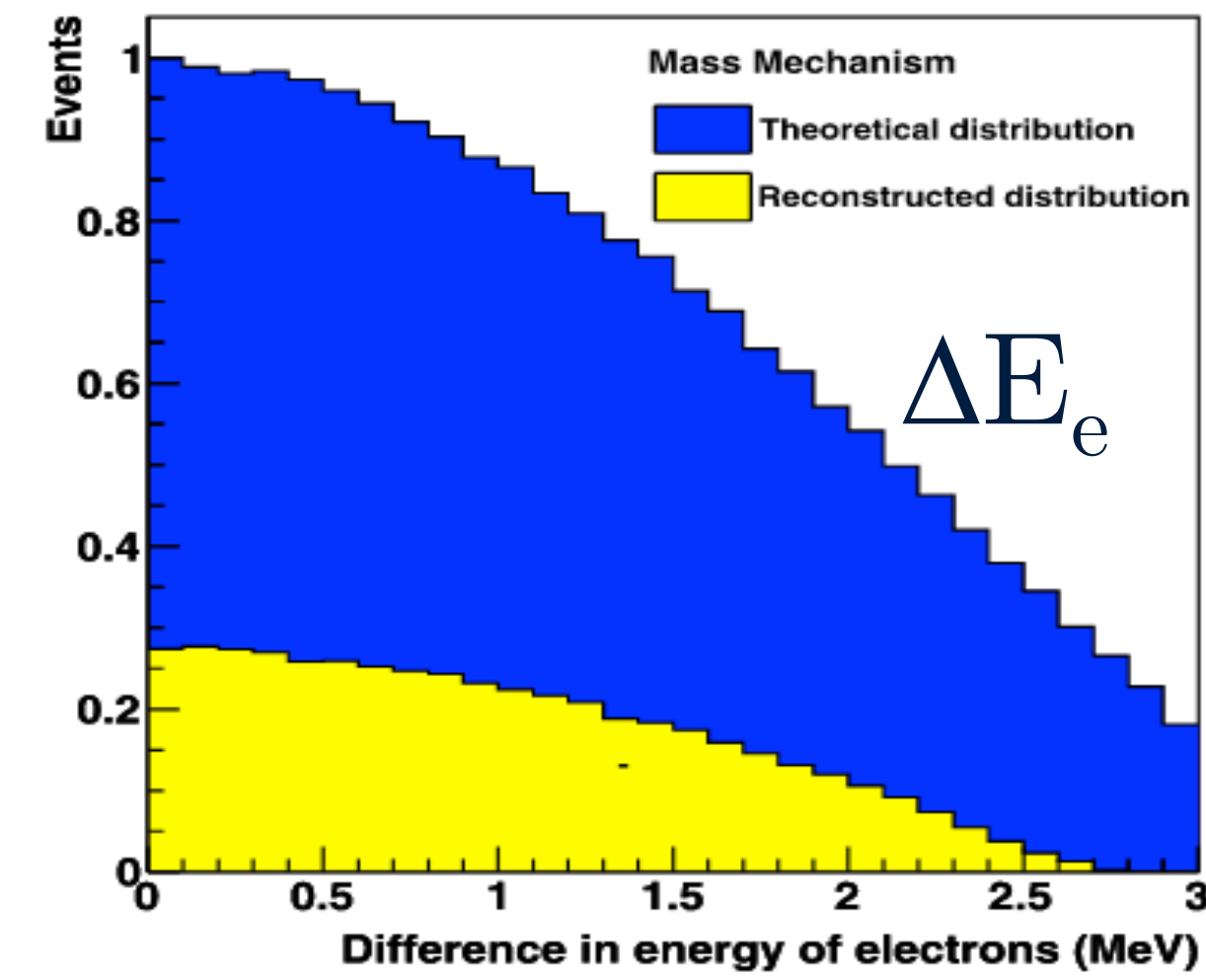
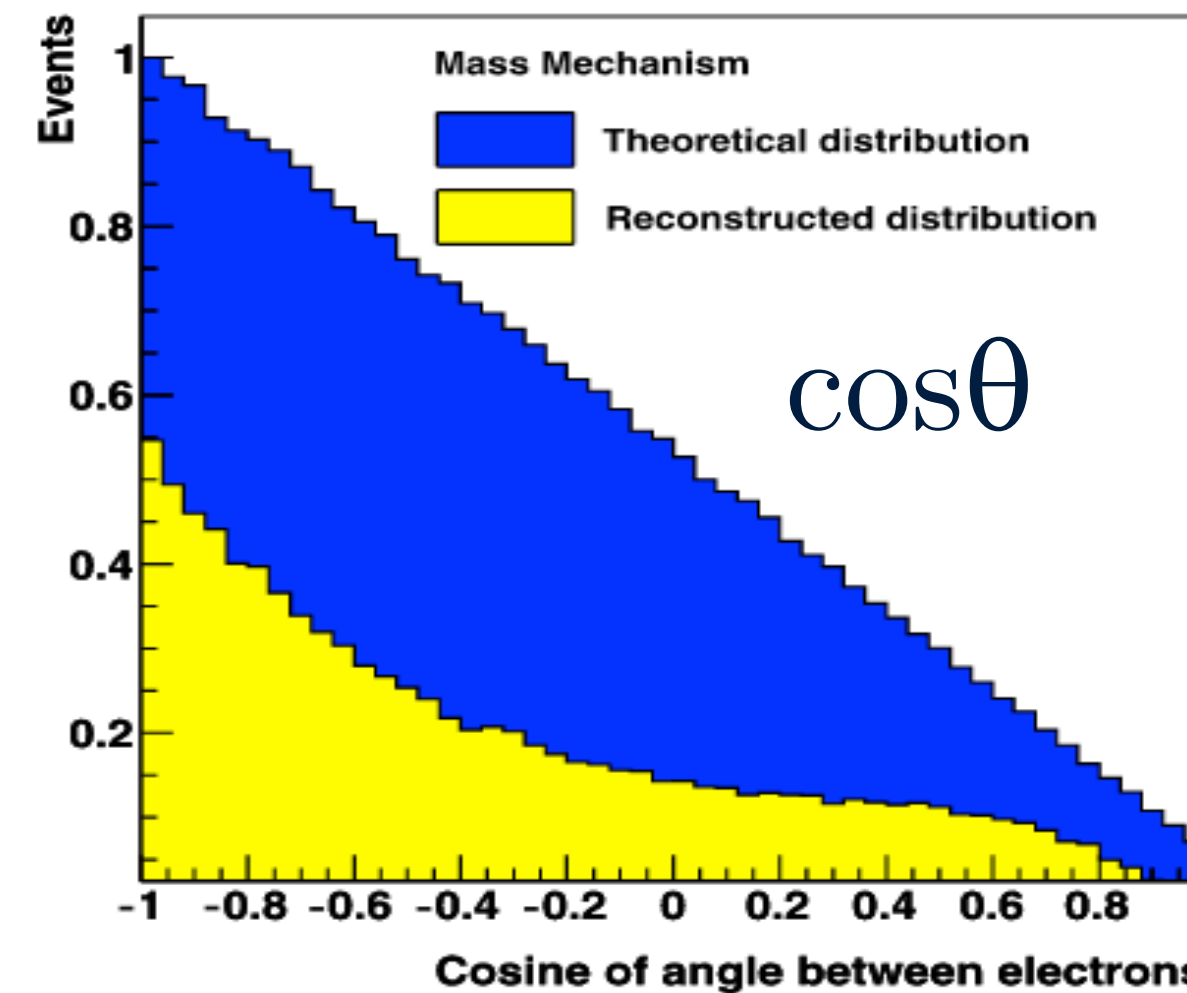
Nom de la tâche	Janvier D	Février D	Mars D	Avril D	Mai D	Juin D	Juillet D	Août D	Septembre D	Octobre D	Novembre D	Décembre D
Calibration sources + vessels												
Electronics racks (parallel)												
Water shielding if reinstalled												
PE shielding												
Iron shielding												
PE chips if installed (parallel)												
Iron structure of shielding												
Bottom shielding (PE + Fe)												
Anti-radon tent (parallel)												
Coil												
Tracker + Calorimeter + Se sources												
Detector structure												
Gas system (parallel)												
Floor												
Contingency												

- 1 year estimate including contingency
- Contingency includes holidays, tunnel closures...
- Possibility to decrease this period by extending the number of teams and the access hours into the LSM lab

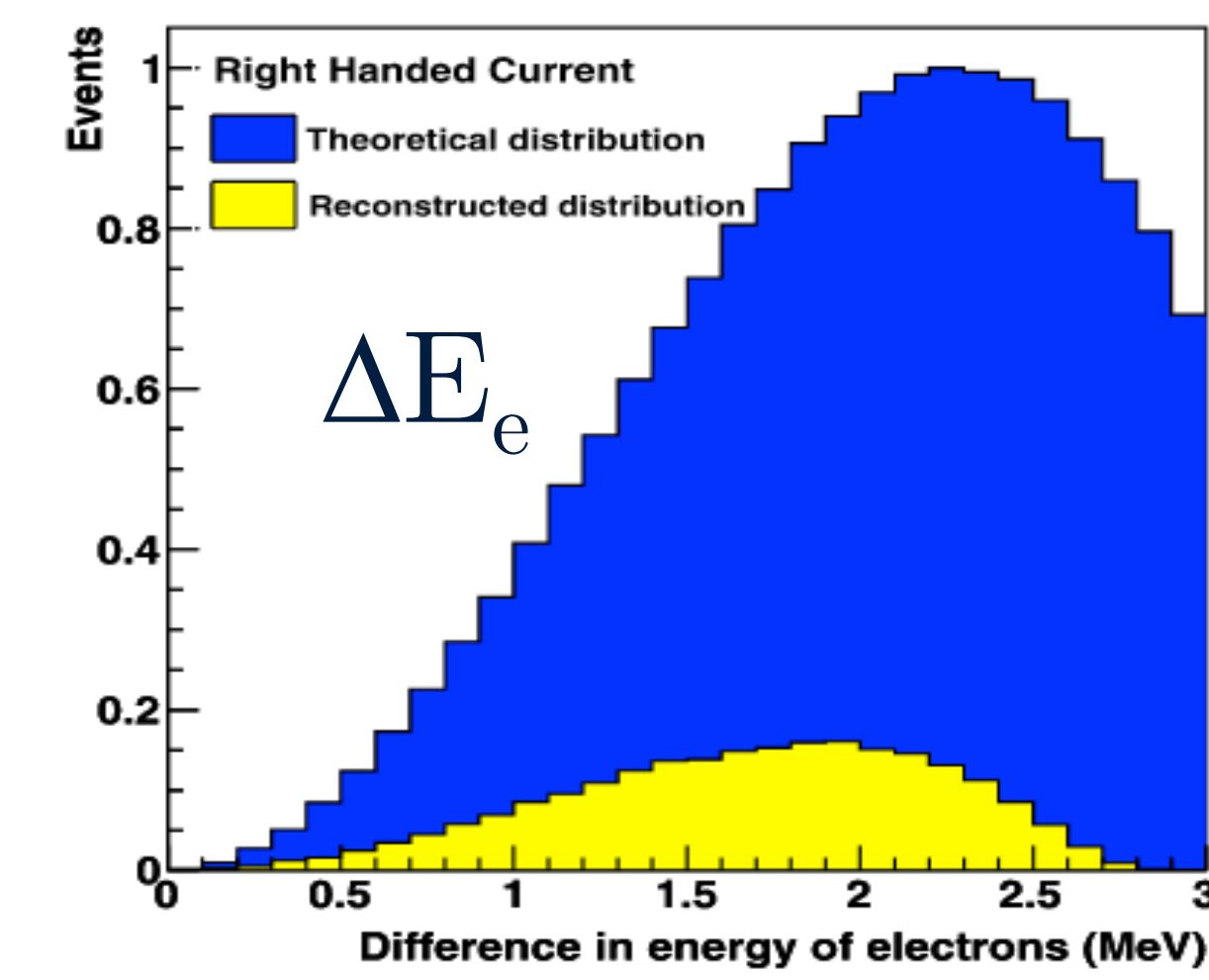
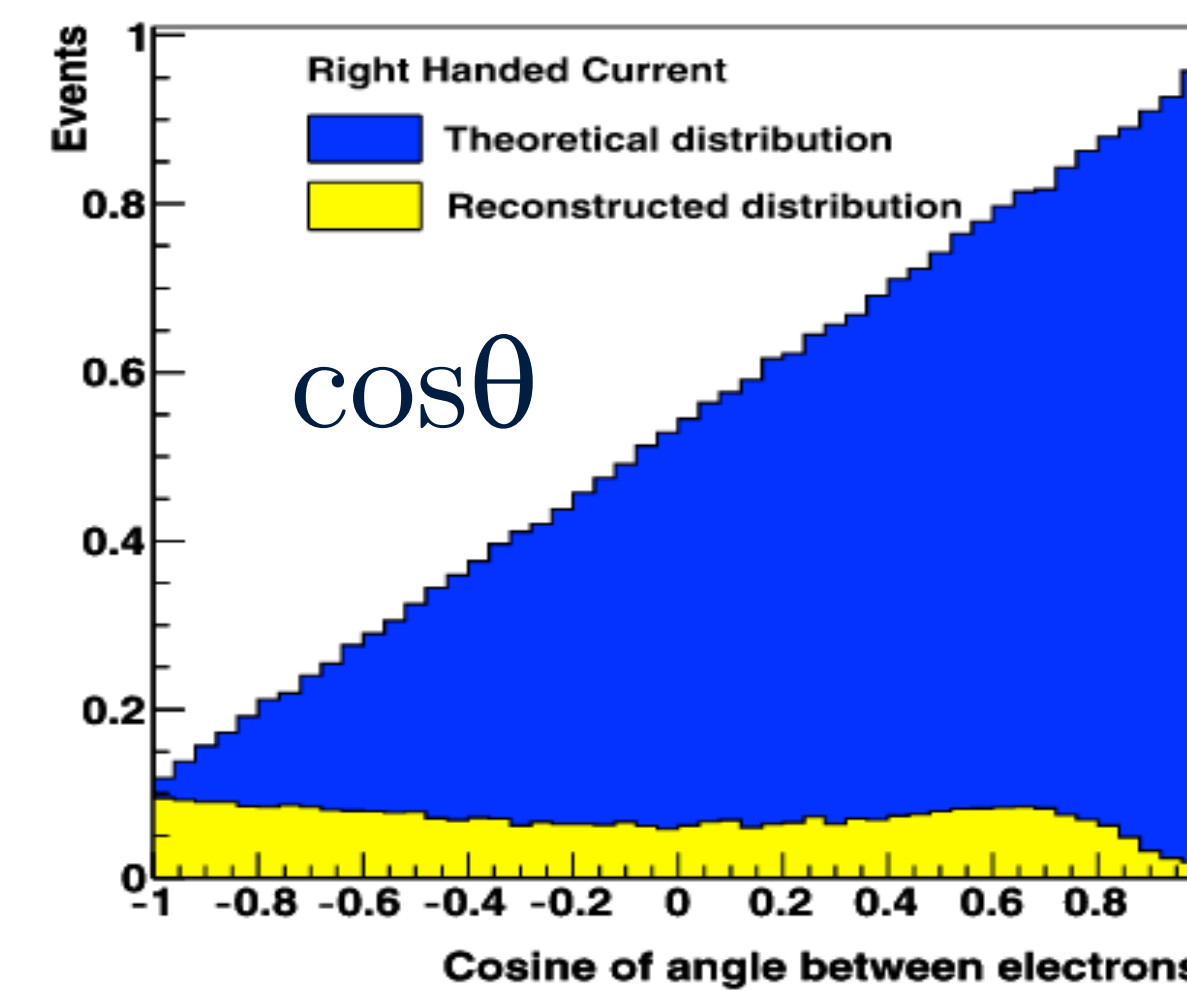
Individual observables & impact on physics

$0\nu\beta\beta$

Mass mechanism
V-A



LR Symmetry (λ)
(V+A) leptonic + hadronic



[Eur.Phys.J.C 70 (2010) 927-943]

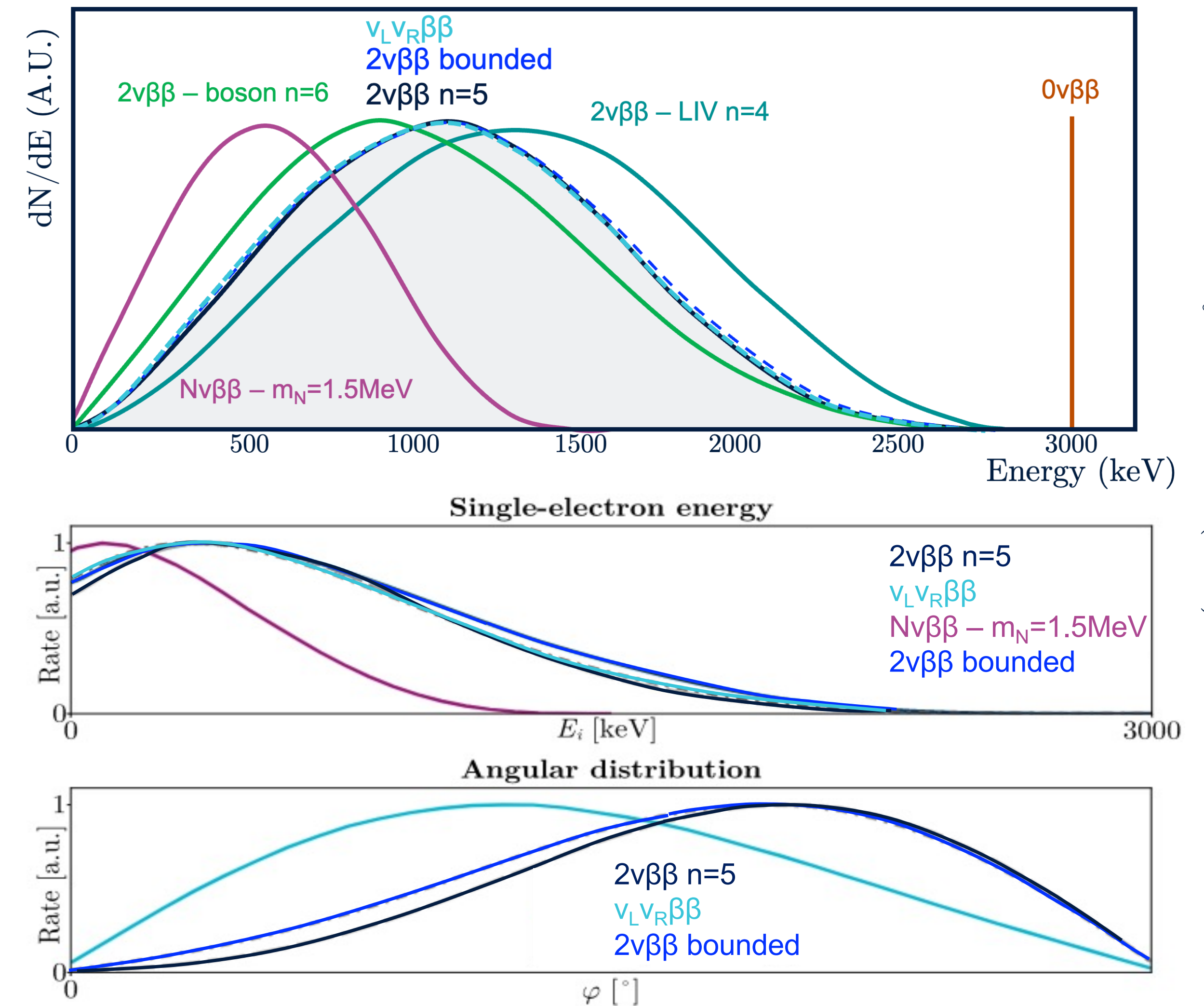
Exotic processes

~33 000 $2\nu\beta\beta$ events observed per year

Analysis of high-statistics data to search for tiny distortions in total energy, individual energy, and angular distributions.

Looking for:

- Light RH neutrinos
- Massive sterile neutrinos
- Bound electron
- Lorentz invariance violation
- Bosonic neutrinos
(Violation of Pauli exclusion principle)



Phys. Rev. C 98 (2018) 065501

SuperNEMO in case of discovery...

Discovery sensitivity of **LEGEND-200** (140 kg ^{76}Ge): $T_{1/2}=10^{27}$ yr corresponding to $m_{\beta\beta}=30\text{-}70$ meV

Experiment	Isotope	Q_{bb} (keV)	$T_{1/2}$ (10^{27} years) equivalent	Required Mass* (kg)
LEGEND-200	^{76}Ge	2039	1	140
SuperNEMO	^{82}Se	2995	~ 0.3	450
	^{150}Nd	3367	~ 0.08	90
	^{96}Zr	3350	~ 0.15	120
	^{100}Mo	3034	~ 0.1	70

*assuming $0\nu\beta\beta$ efficiency=25%, $\text{BI}=10^{-4}$

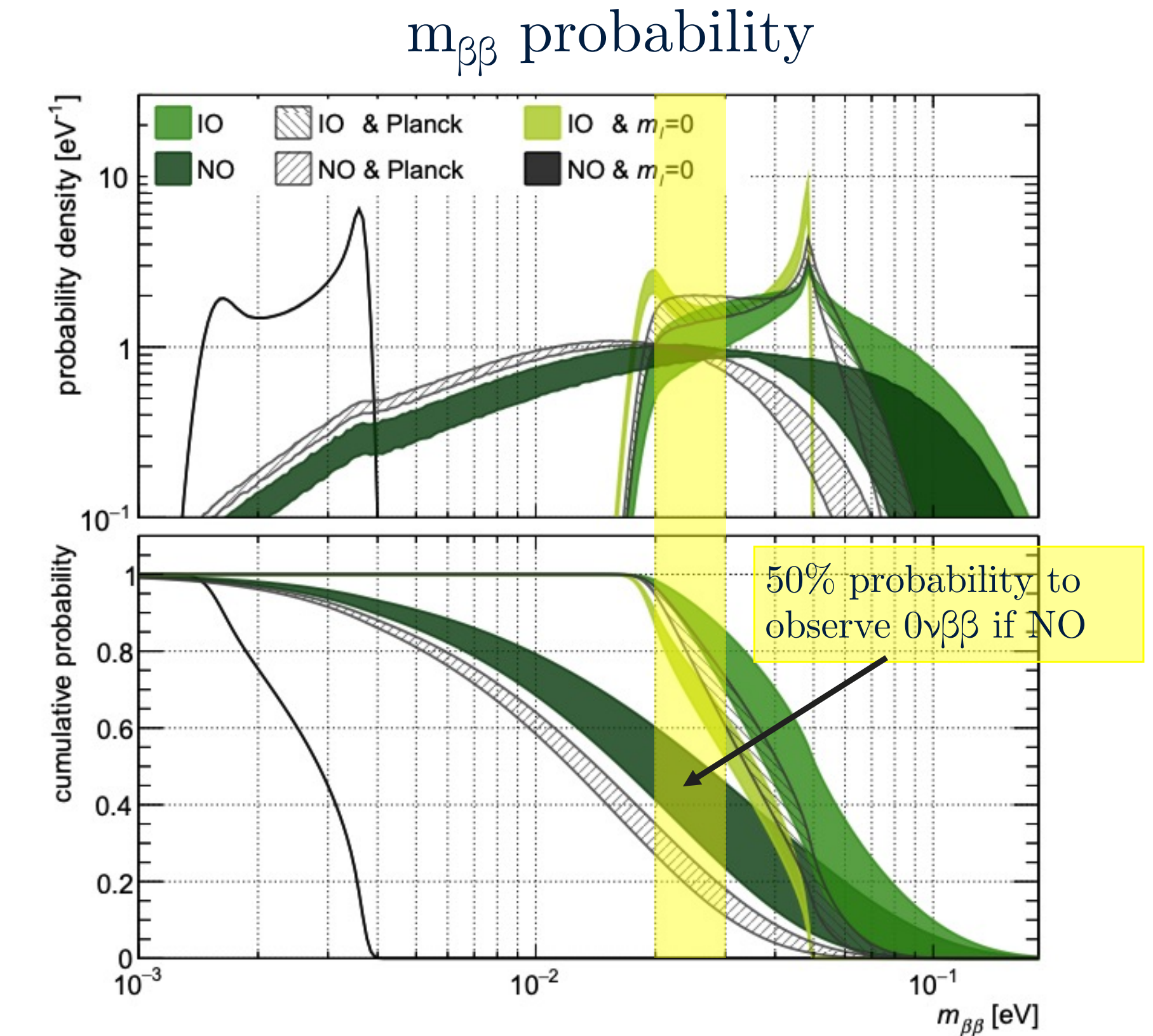
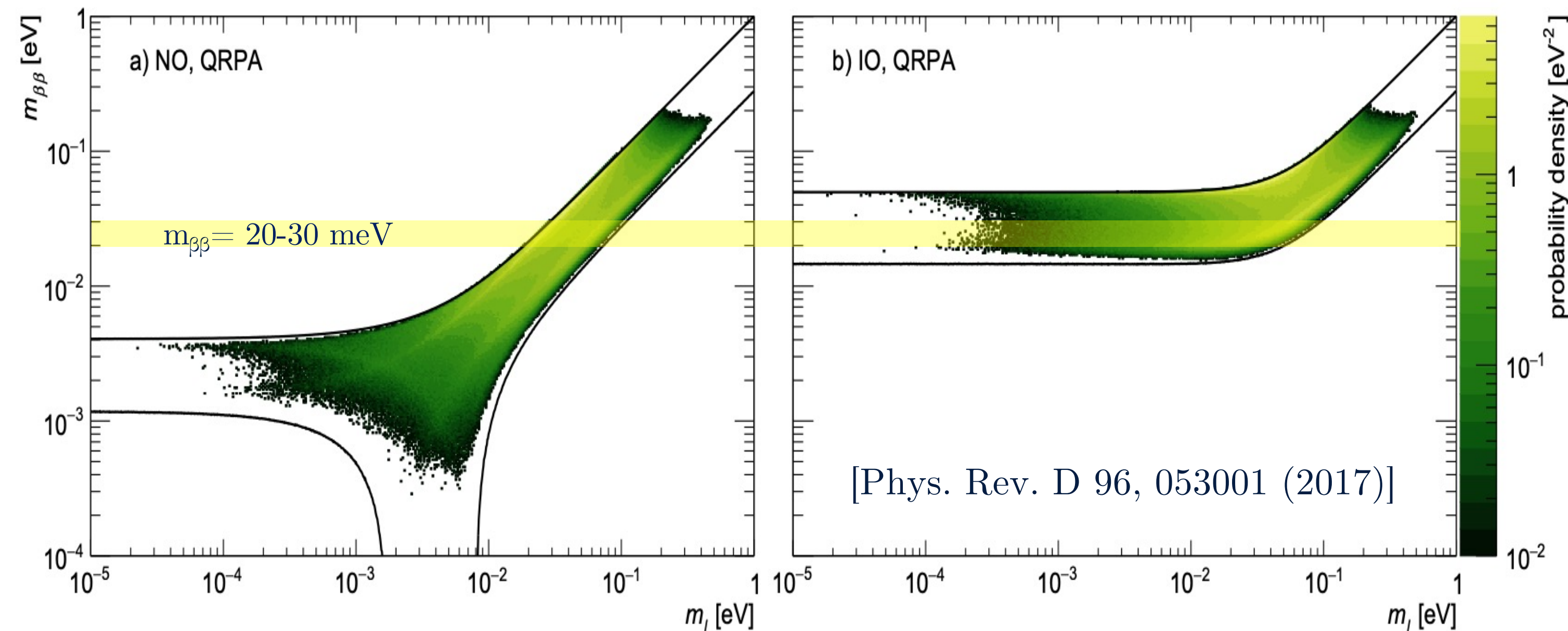
- Reaching 30-70 meV $m_{\beta\beta}$ (10^{27} y ^{76}Ge **LEGEND-200**) would need $O(100\text{kg})$ of isotopes in SuperNEMO
- Reaching 10-20 meV $m_{\beta\beta}$ (10^{28} y ^{76}Ge **LEGEND-1000**, 10^{27} y ^{100}Mo **CUPID**) will require significant design-scaling studies including improvements in BI, FWHM and size to accomodate $O(1\text{-}10\text{ tons})$ of isotopes
- SuperNEMO approach is currently the only one able to confirm $0\nu\beta\beta$ discovery but would need radical modifications to reach **next-to-next** generation sensitivity (based on Demonstrator experience)

Mass ordering and double-beta

For the mass mechanism

$$m_{\beta\beta} = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{2i\alpha_2} + m_3|U_{e3}|^2 e^{2i\alpha_3}|$$

$m_{\beta\beta}$ as function on the lightest mass (from oscillation, cosmo and DBD results)



+ Many other mechanism exists in the B-L context that are not affected by NO/IO scenario

- $0\nu\beta\beta$ may be observed in next generation experiments ... even under NO

READ

Isotope	$Q_{\beta\beta}$ (keV)	Experiment	Location	Mass (kg)	Exposure (kg.yr)	$T_{1/2}^{0\nu}$ (10^{24} yr)	$\langle m_{\beta\beta} \rangle$ (meV)
^{48}Ca	4628	CANDLES-III	Japan	0.27	0.045	0.062 [21]	3400-14900
^{76}Ge	2039	GERDA	Italy	44.2	127.2	180 [22]	79-180
^{82}Se	2998	CUPID-0	Italy	5.3	8.82	4.6 [23]	263-545
^{96}Zr	3355	NEMO-3	France	0.0094	0.031	0.0092 [24]	7200-19500
^{100}Mo	3034	CUPID-Mo	France	4.2	1.17	1.4 [25]	310-540
^{116}Cd	2813	AURORA	Italy	1.162	5.81	0.22 [26]	1000-1700
^{130}Te	2527	CUORE	Italy	206	288.8	22 [27]	90-135
^{136}Xe	2457	KamLAND-Zen	Japan	745	2097	380 [28]	28-122
^{150}Nd	3371	NEMO-3	France	0.037	0.19	0.02 [29]	1600-5300

$\beta\beta$ source

^{82}Se foils

Enrichment : ECP-Krasnoyarsk and Tomsk (Russia) @ 96.1-99.9 %
(For reminder, natural abundance of ^{82}Se is 8.7%)

Purification methods

- Barium precipitation (INL, USA)
- Double distillation (ECP, Russia)
- Reverse chromatography via ion exchange with a new resin (JINR, Russia)

Source foil production 34 foils

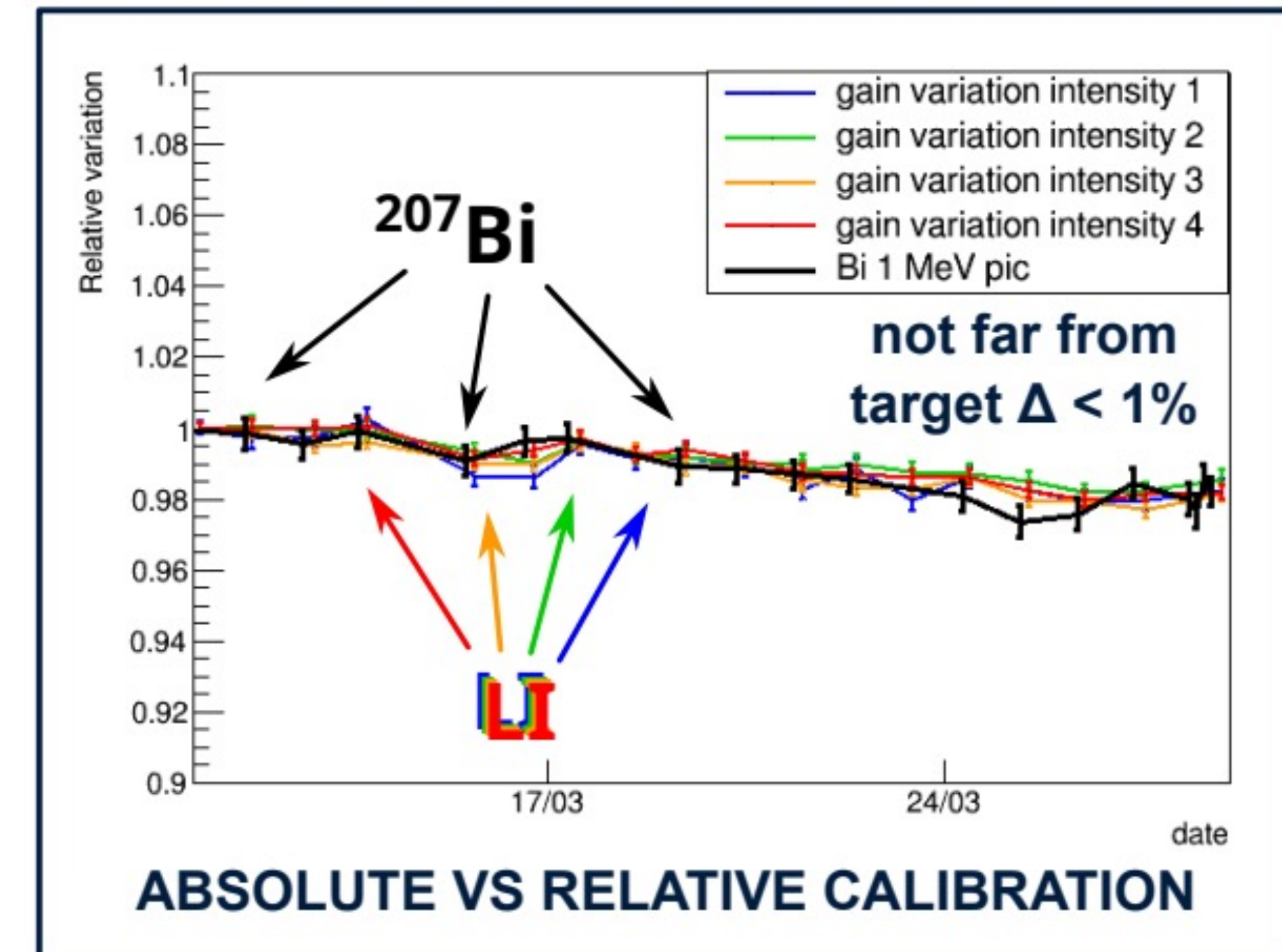
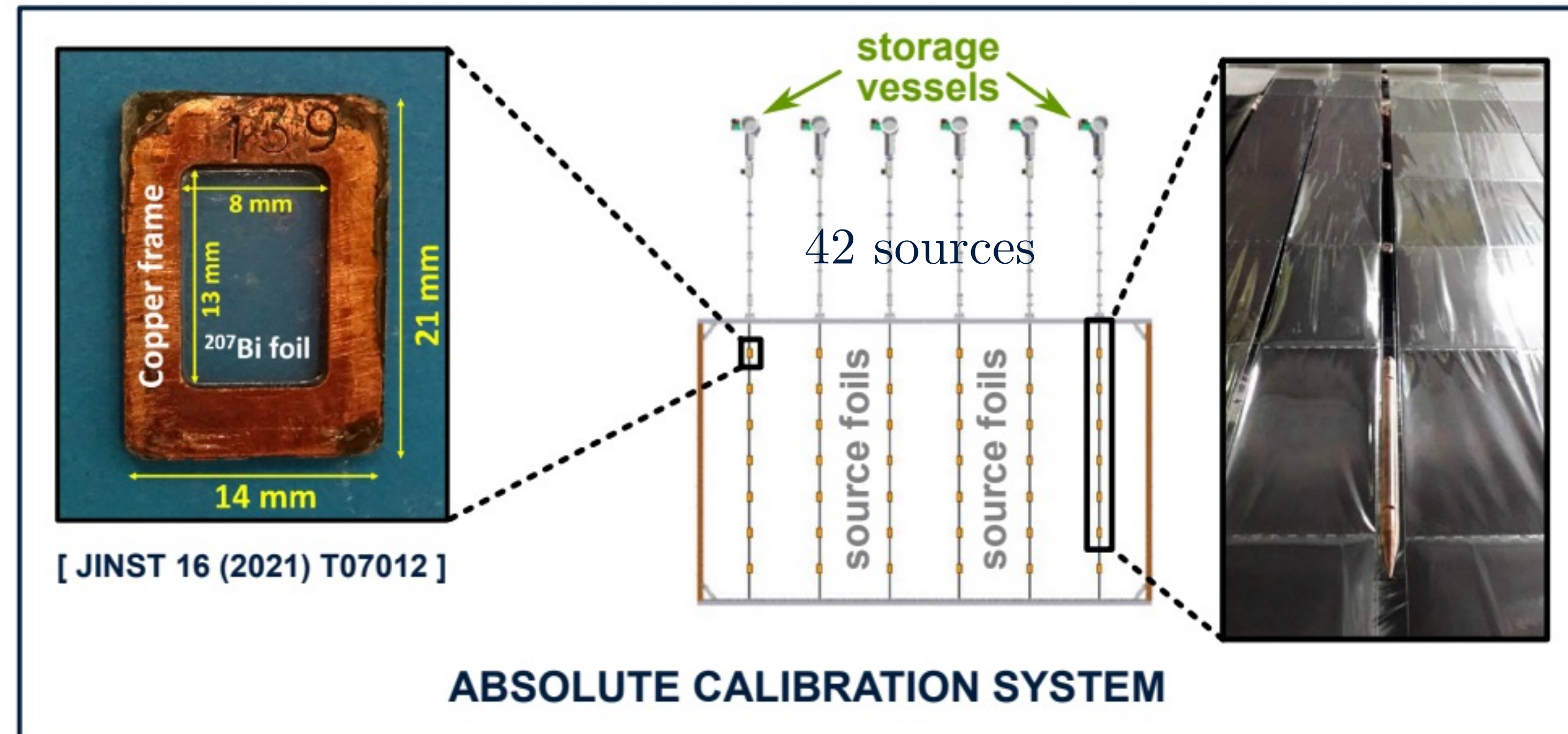
- (^{82}Se + PVA) Dried on irradiated mylar (ITEP, Russia)
- (^{82}Se + PVA) Molded and sandwiched into mylar (LAPP, France)

Prospects for other isotope enrichment

Isotope	$Q_{\beta\beta}$ (MeV)	Abundance (%)	R&D Status
$^{96}\text{Zr}^*$	3.35	2.8	New gaseous compounds for centrifugation @ECP (Russia)
$^{150}\text{Nd}^*$	3.37	5.6	First grams of ^{96}Zr produced for SuperNEMO
$^{48}\text{Ca}^*$	4.27	0.187	Laser enrichment studied @KAERI (Korea)

(*) in small quantities into NEMO-3, obtained by electromagnetic separation

Calibrations



- Absolute calibration ($\sim$ weekly): automated deployment system with 42x ^{207}Bi calibration sources
- Relative calibration ($\sim$ daily): Light Injection system (LI) = flashing LEDs + optical fibers

SuperNEMO @CC-IN2P3

63 NEMO accounts (40 active)

Disk usage

- 274 TB (hpss)
- 226/300 TB (sps)
- Around +30 %/year

CPU usage

- 40E6 HS06.h (130 % used)
- Request:under-estimated

MariaDB

- For calibrations (upcoming)

