Neutrinoless ββ decay: physics that matters

(…but doesn’t antimatter)

Cheryl Patrick, UCL

Joint IoP APP/HEPP Conference 2019

In the beginning was…

In the beginning was…

In the beginning was…

In the beginning was...

2 matter particles

No antimatter particles

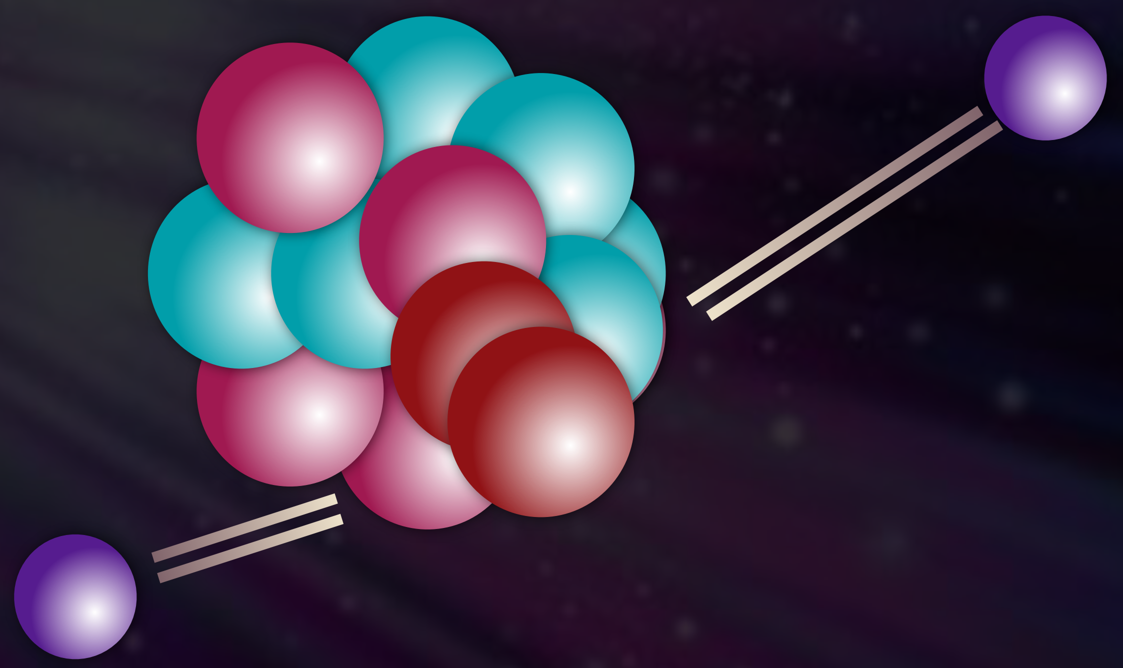
- **How did we get this imbalance?**

In the beginning was…

2 matter particles

No antimatter particles

- How did we get this imbalance?
- Neutrinoless double-beta decay would CREATE matter…



In the beginning was…

2 matter particles

No antimatter particles

- How did we get this imbalance?
- Neutrinoless double-beta decay would CREATE matter…
- … tells us about the nature of the neutrino (that isn't there)…

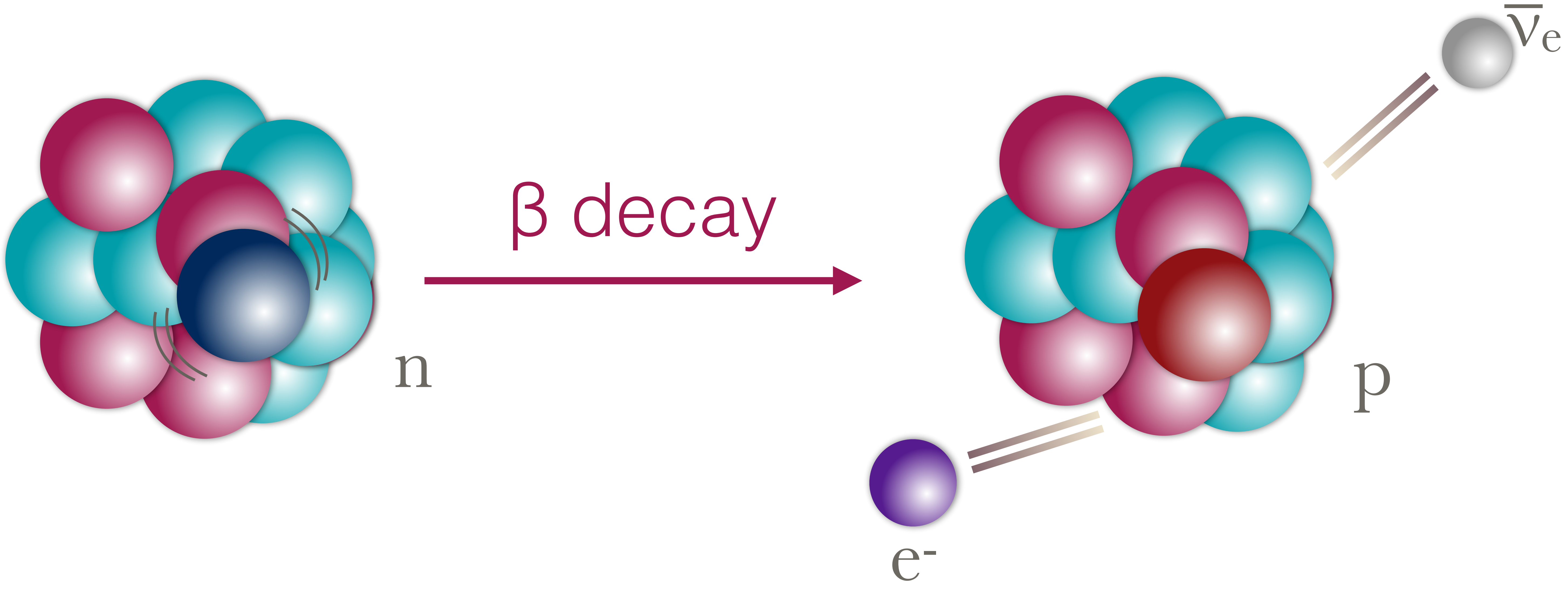
In the beginning was…

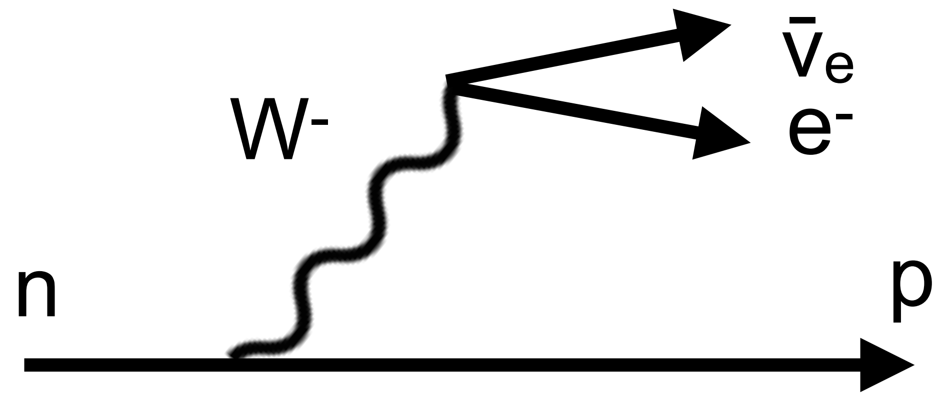
2 matter particles

No antimatter particles

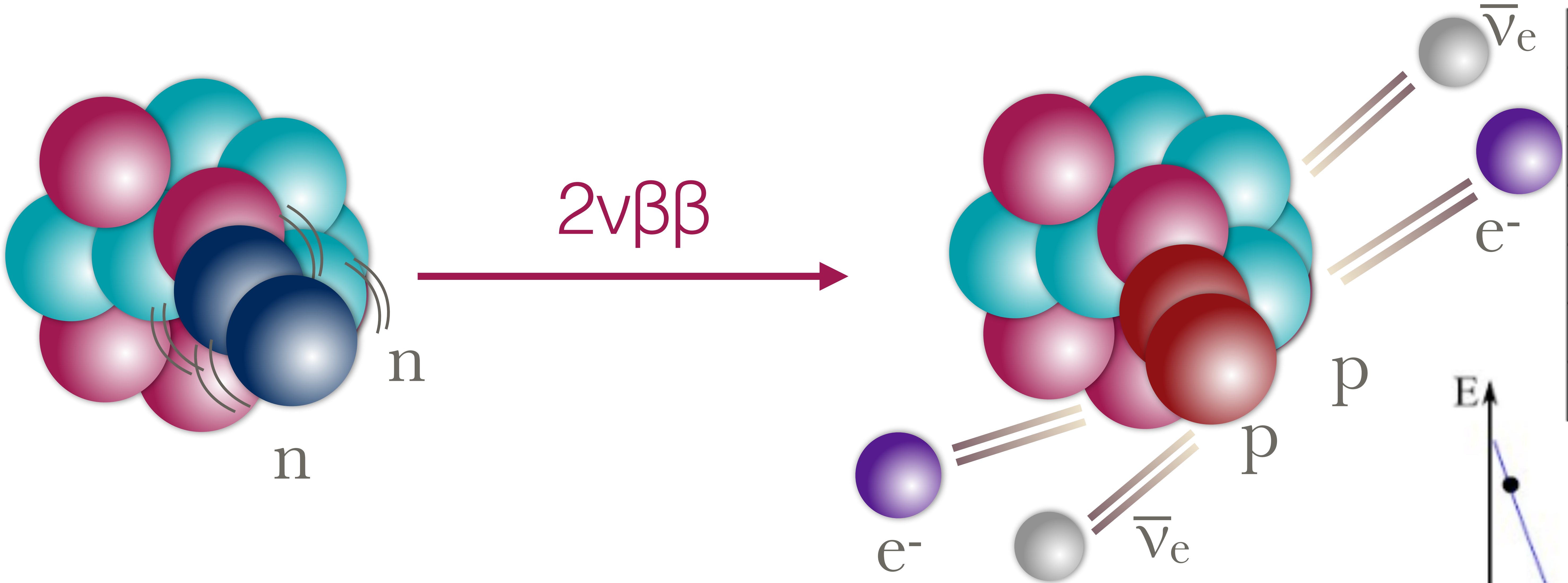
- How did we get this imbalance?
- Neutrinoless double-beta decay would CREATE matter…
- … tells us about the nature of the neutrino (that isn't there)…
- … and could help us measure its mass

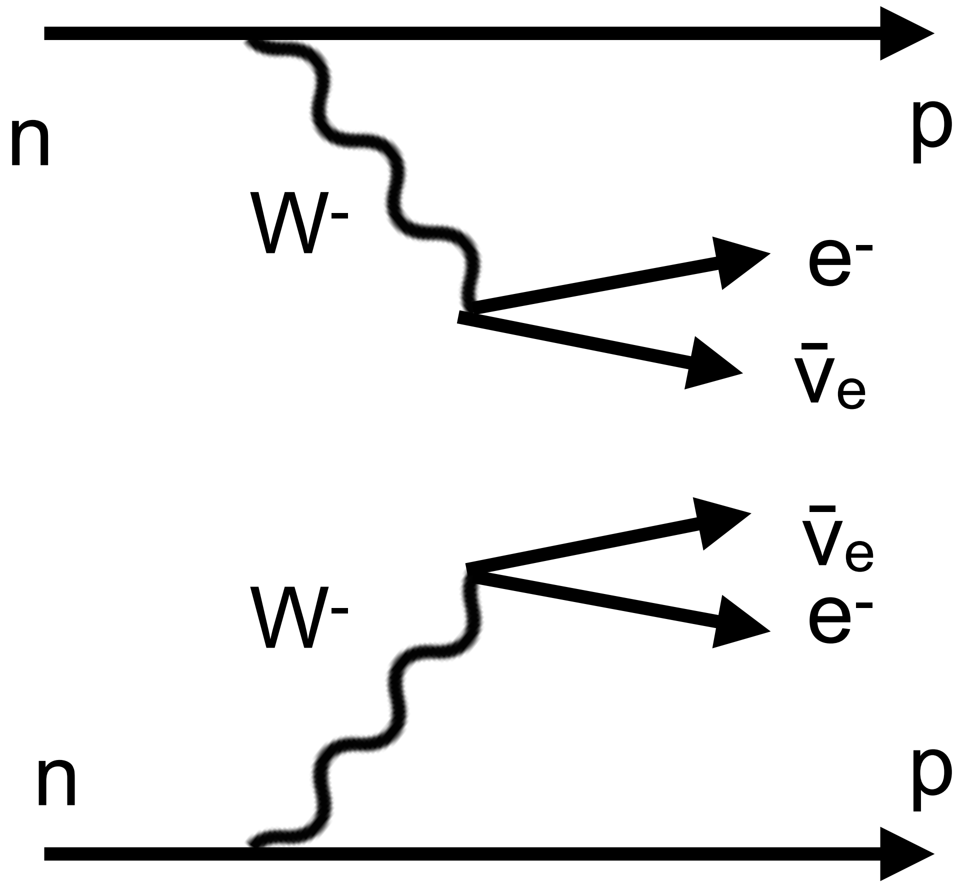
beta decay





double-beta decay

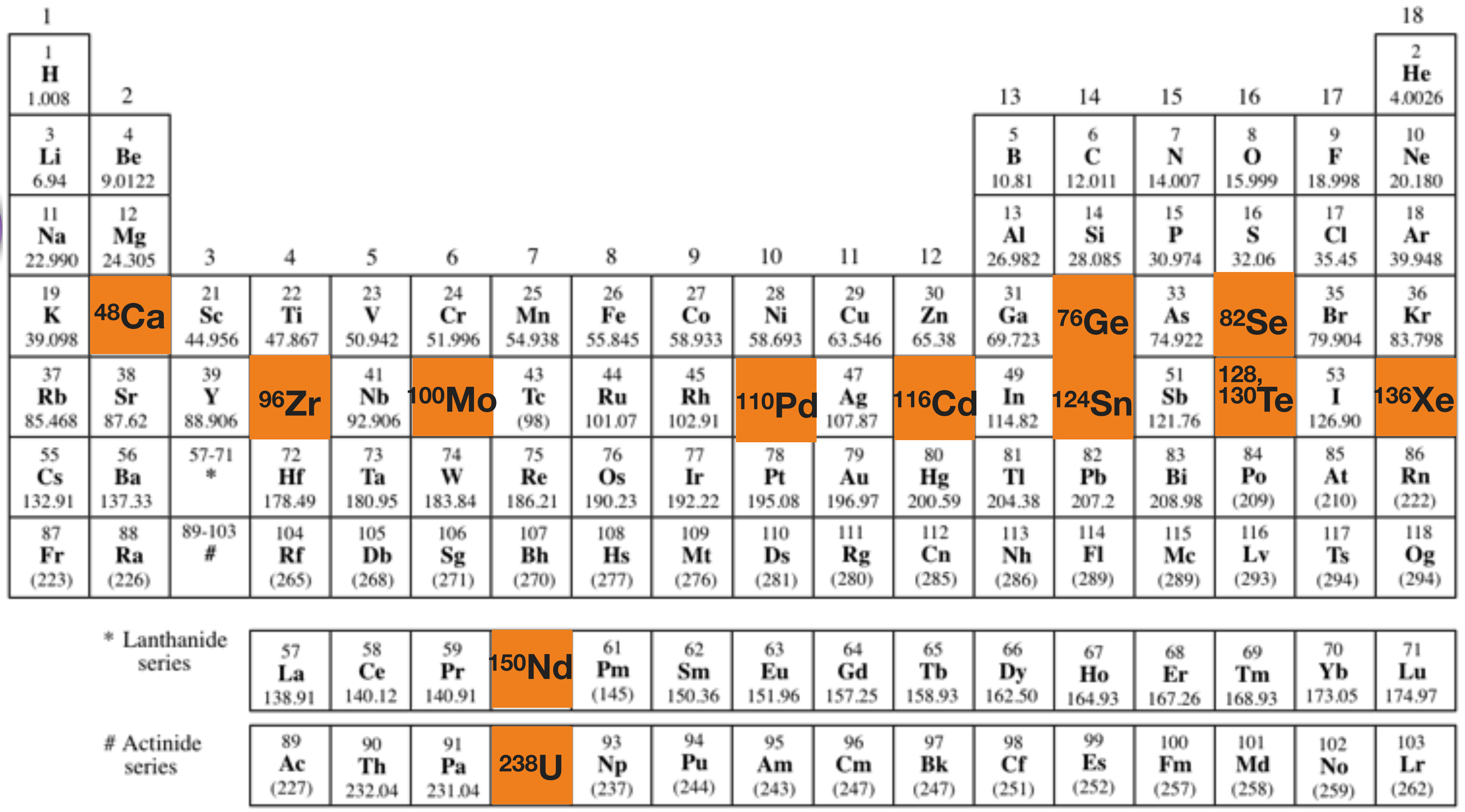




Lepton number conserved

$\Delta L = 0$

$T_{1/2} \sim 10^{20}$ years



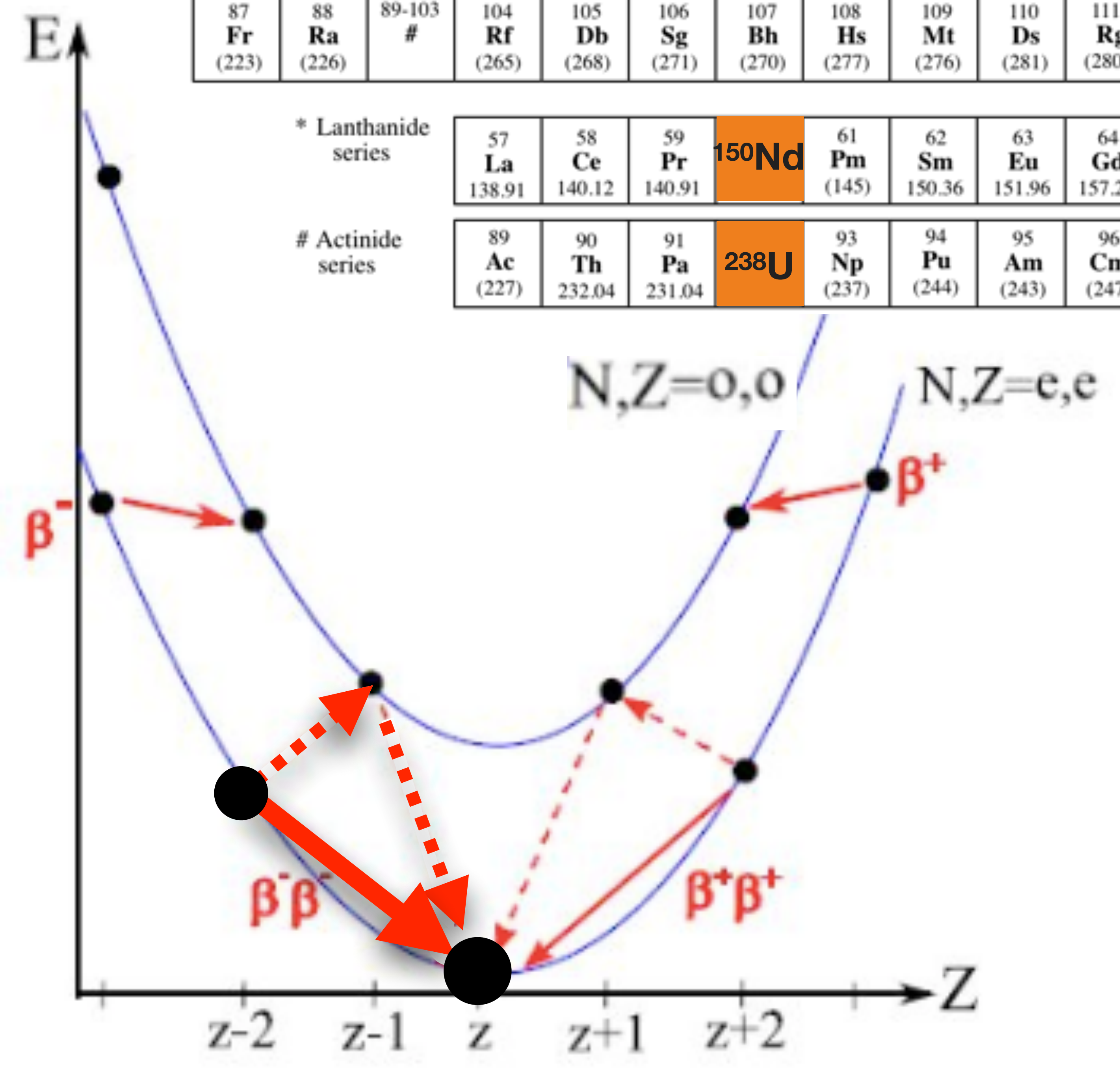
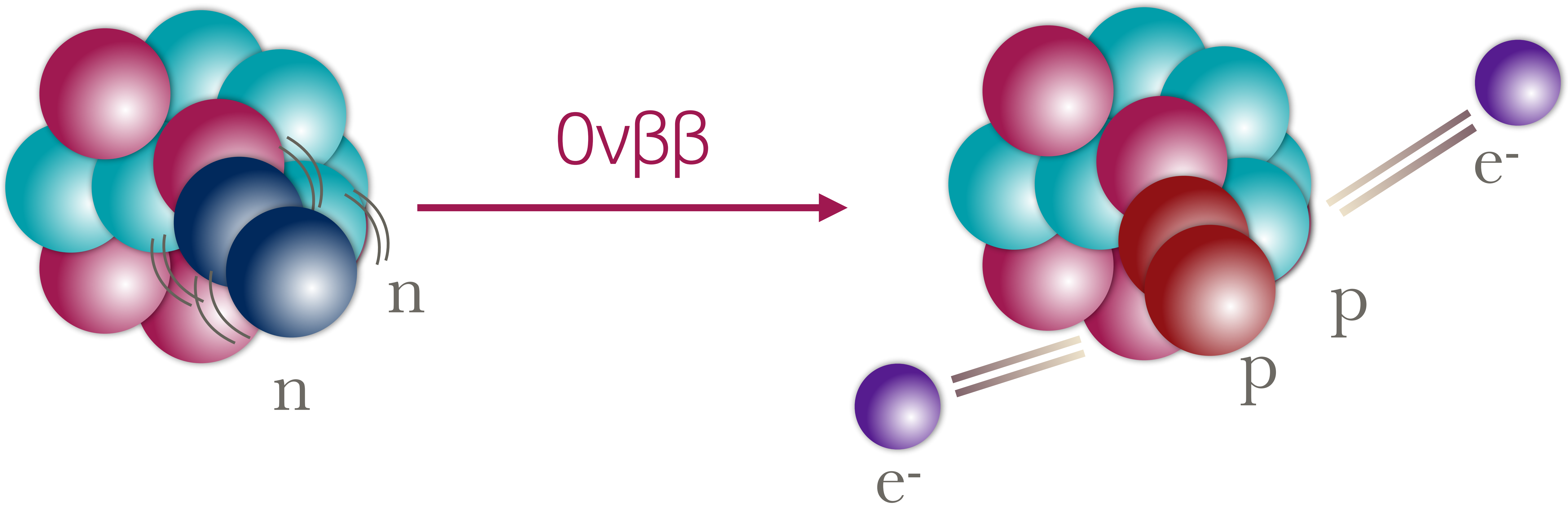
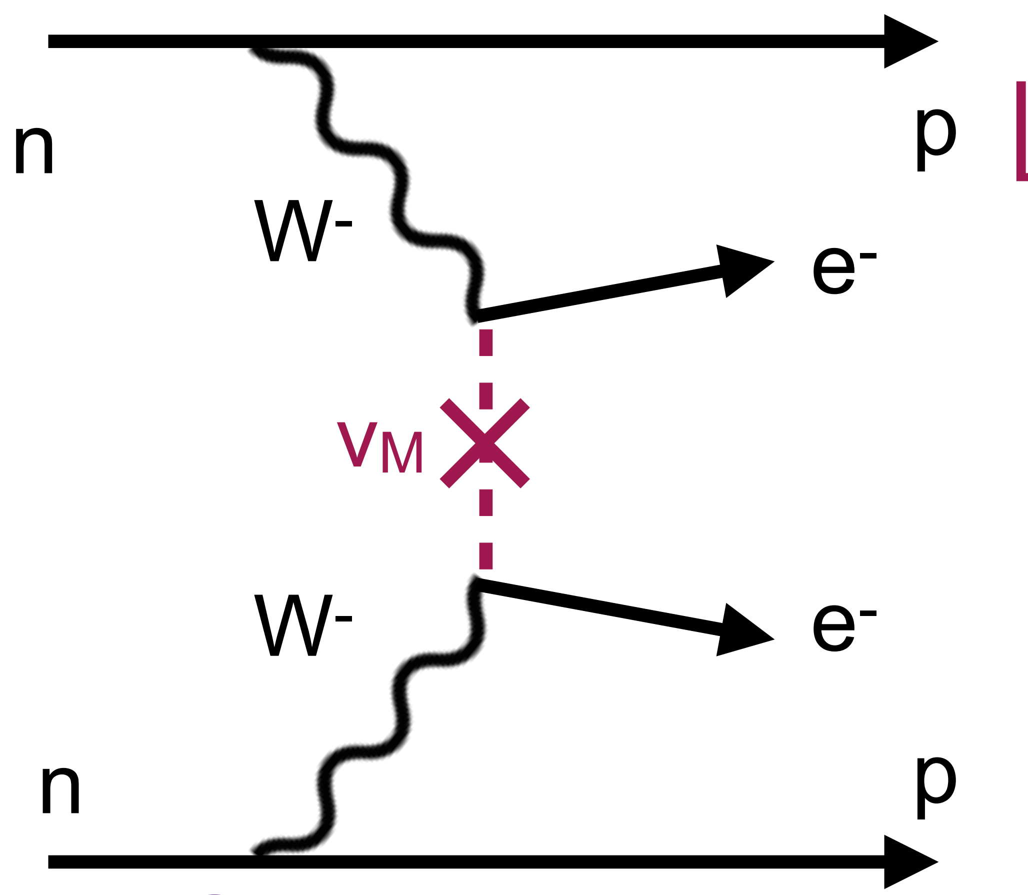


Diagram - E. Falk

Neutrinoless double-beta decay : the smoking gun for Majorana



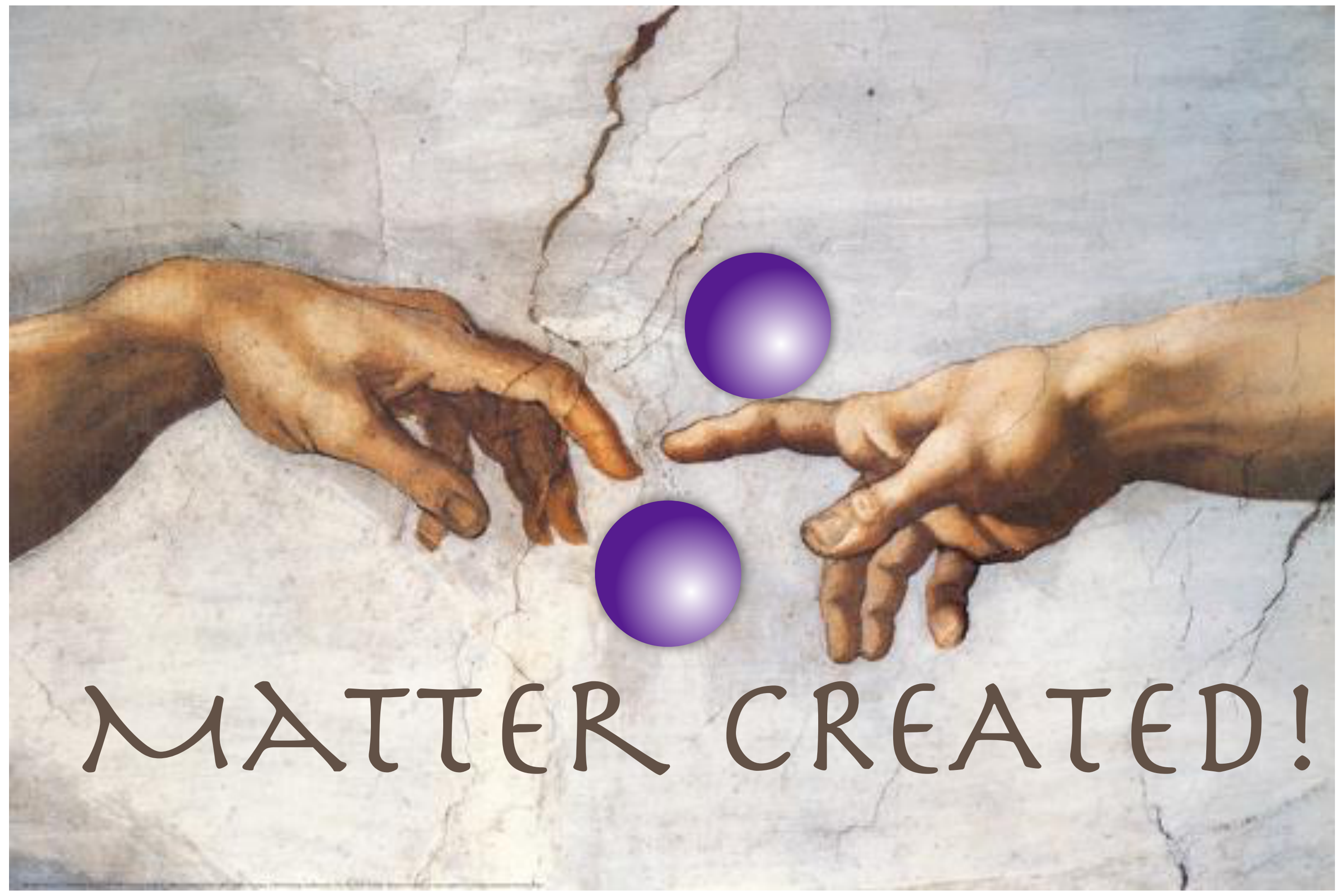


Lepton number violated

$\Delta L = 2$

$T_{1/2} > 10^{24} - 10^{26}$ years

Only if $\nu = \bar{\nu}$: **Majorana** neutrino



0νββ could tell us about neutrino mass

$$0\nu\beta\beta \text{ rate} = \frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{{m_e}^2}$$

Phase space factor

Nuclear matrix element
(hard to calculate)

Effective neutrino mass

0vββ could tell us about neutrino mass

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$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

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PMNS mixing angles/phases

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Individual neutrino masses

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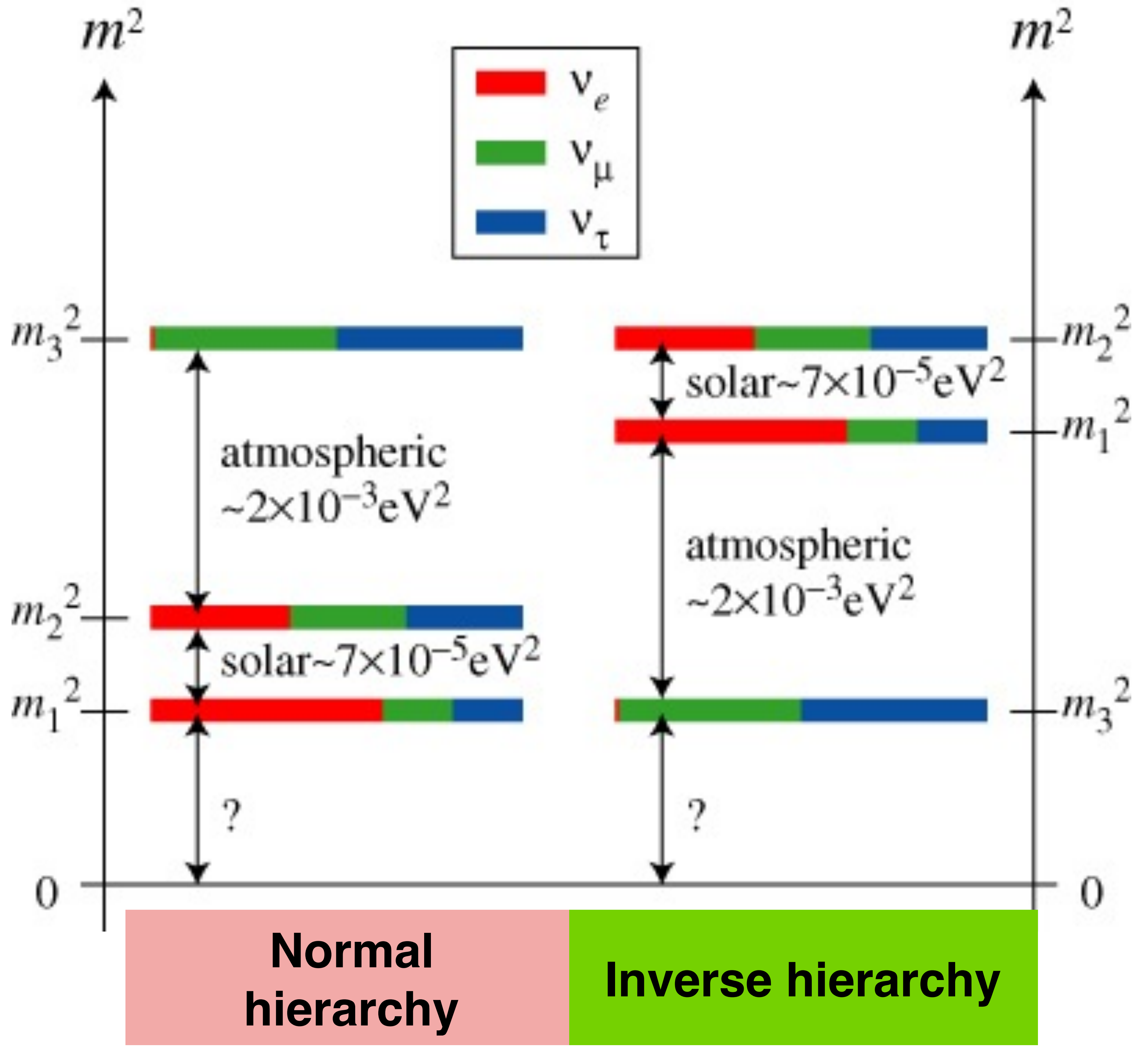
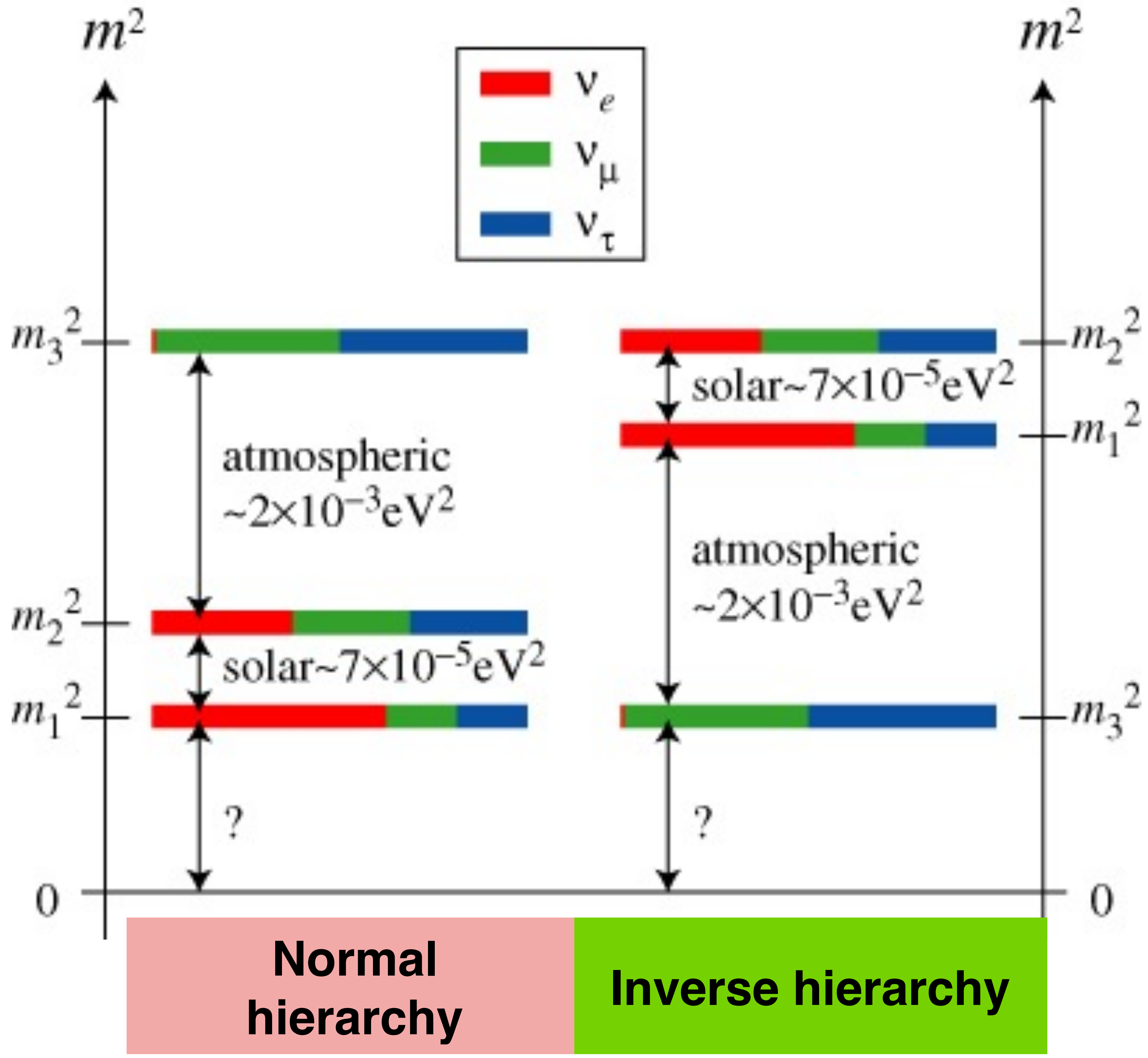
Individual neutrino masses

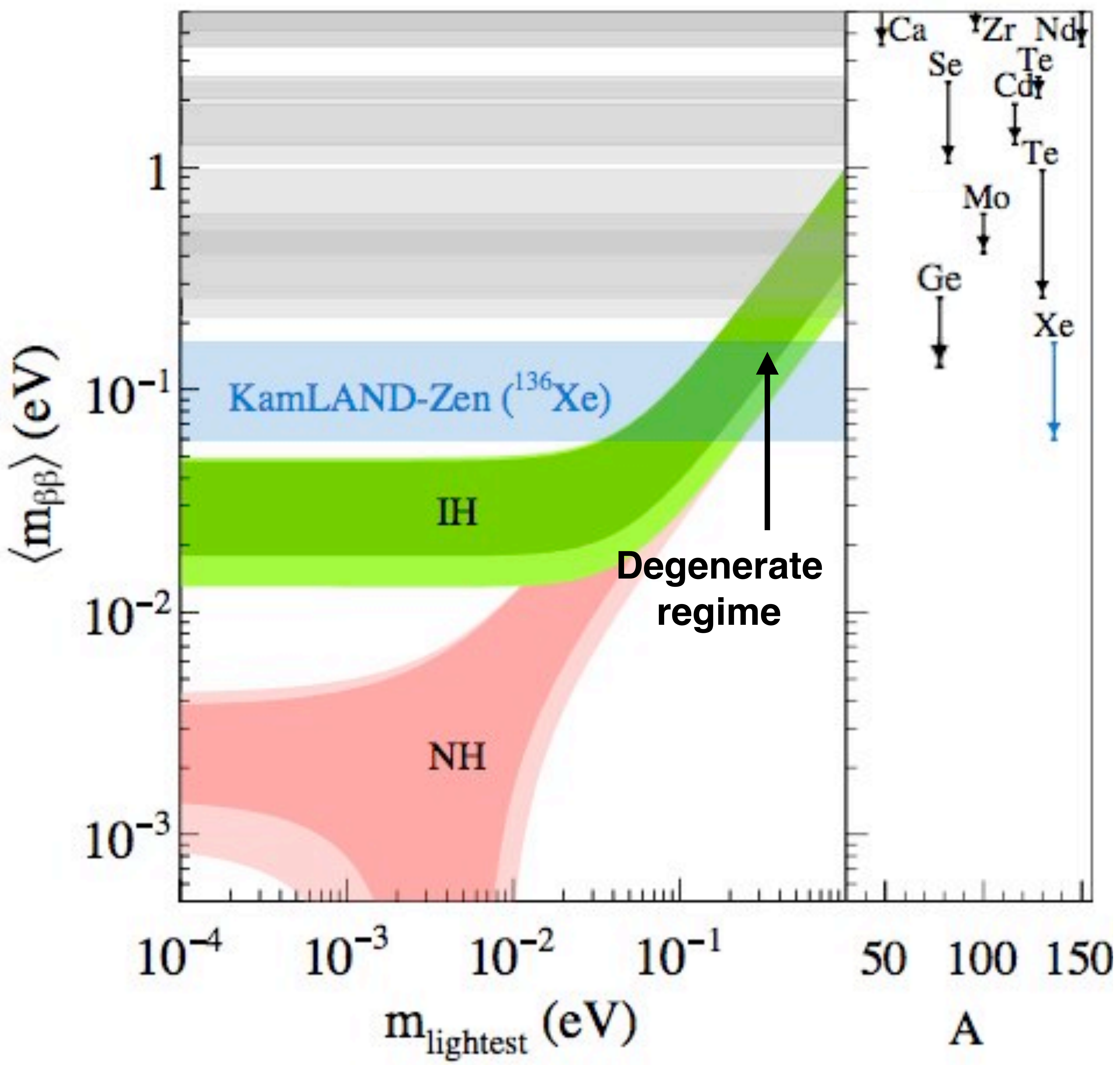


0νββ could tell us about neutrino mass

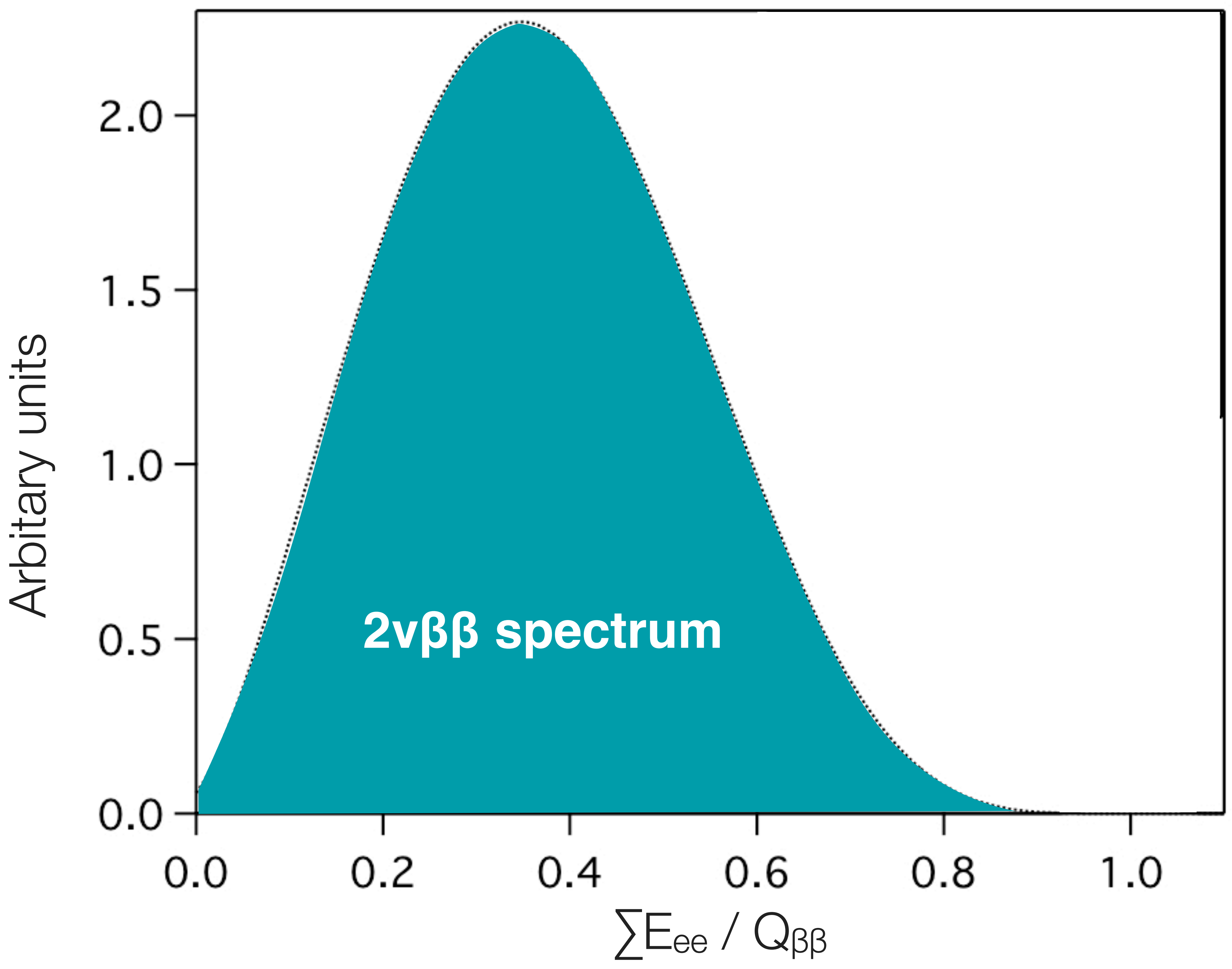
$$0\nu\beta\beta \text{ rate} = \frac{1}{T^{0\nu\beta\beta}_{1/2}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e{}^2}$$

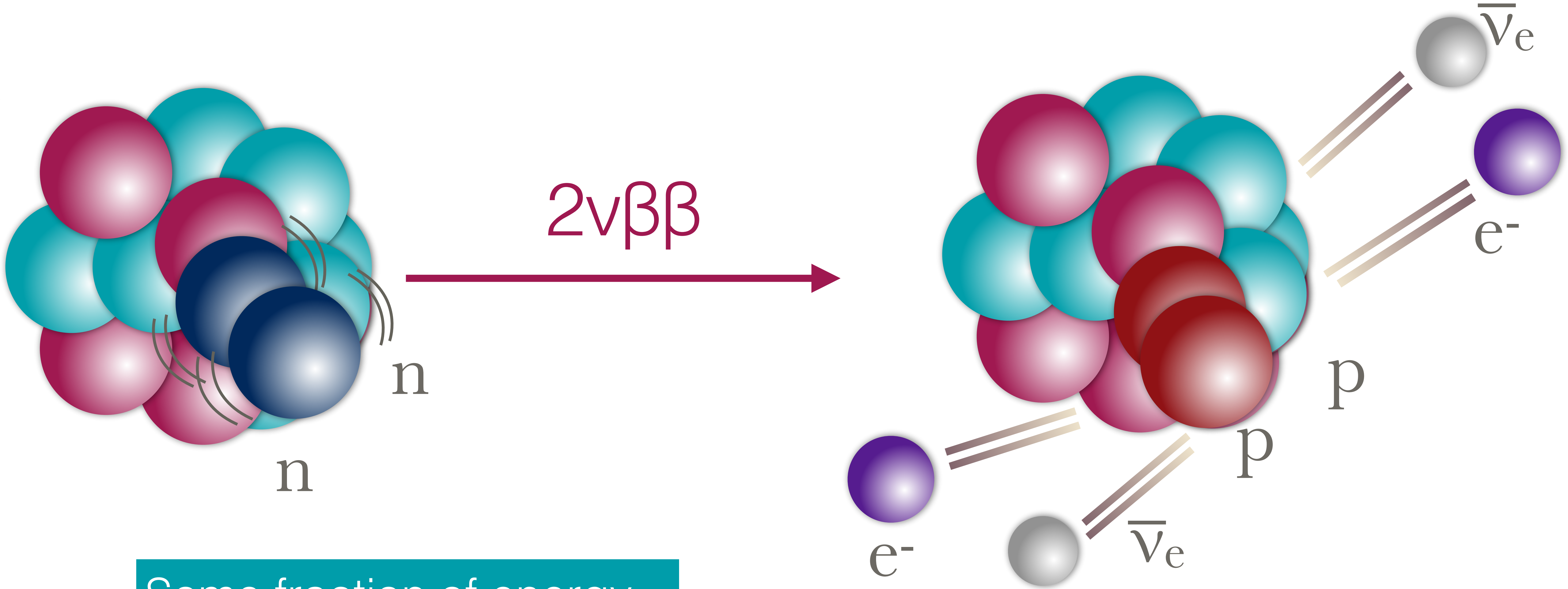


Adapted from PRL 117, 082503 (2016)



Looking for 0νββ

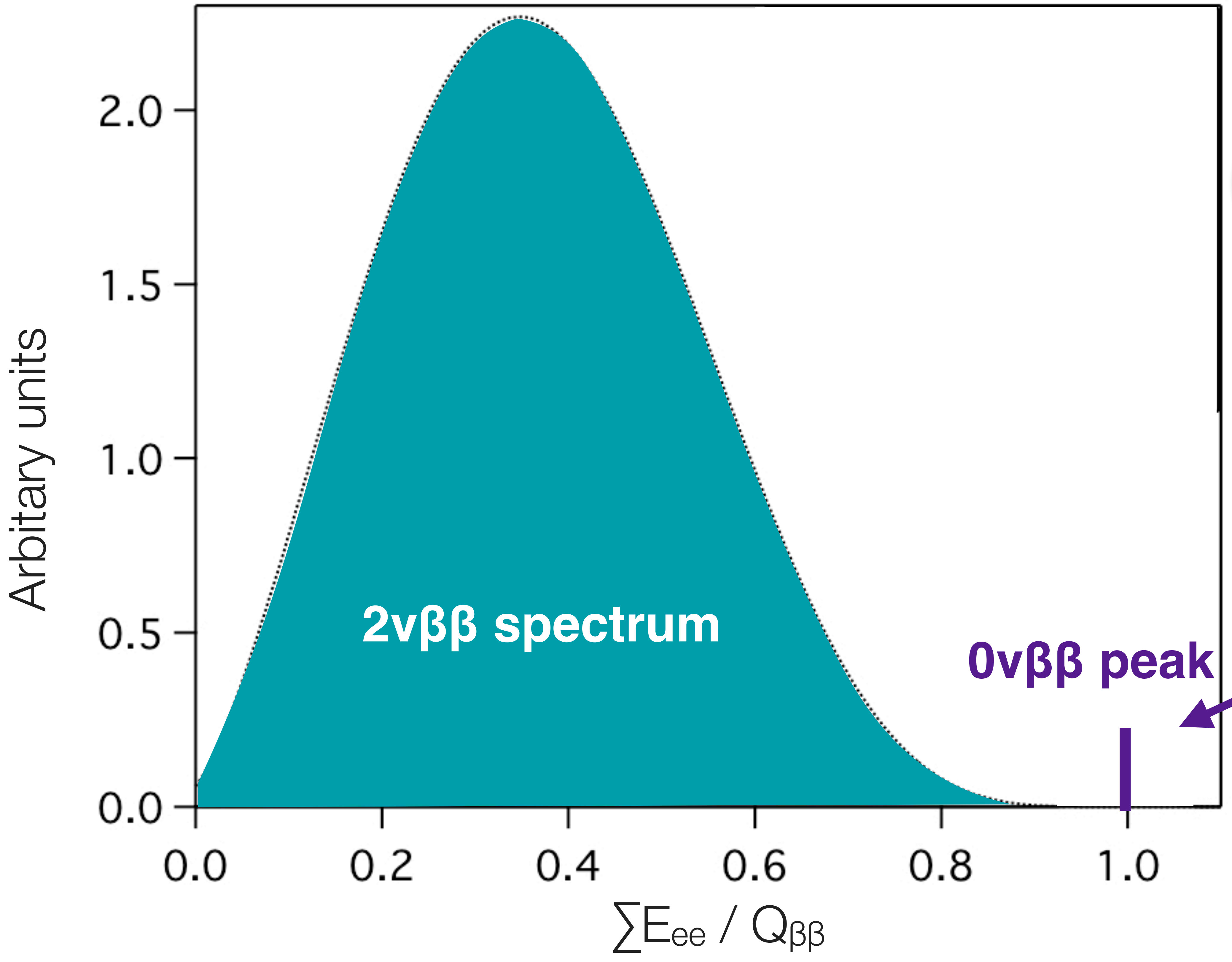


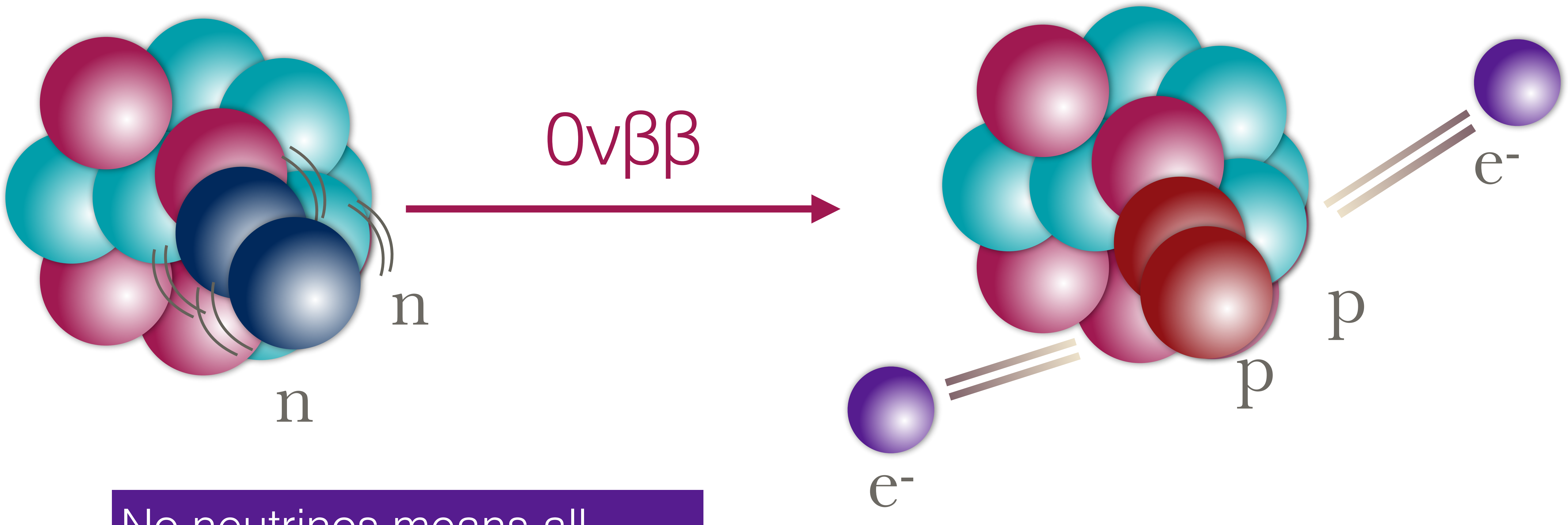


Some fraction of energy goes to neutrinos

Sum of the **2 electron energies**, as fraction of ββ decay energy

Looking for 0νββ

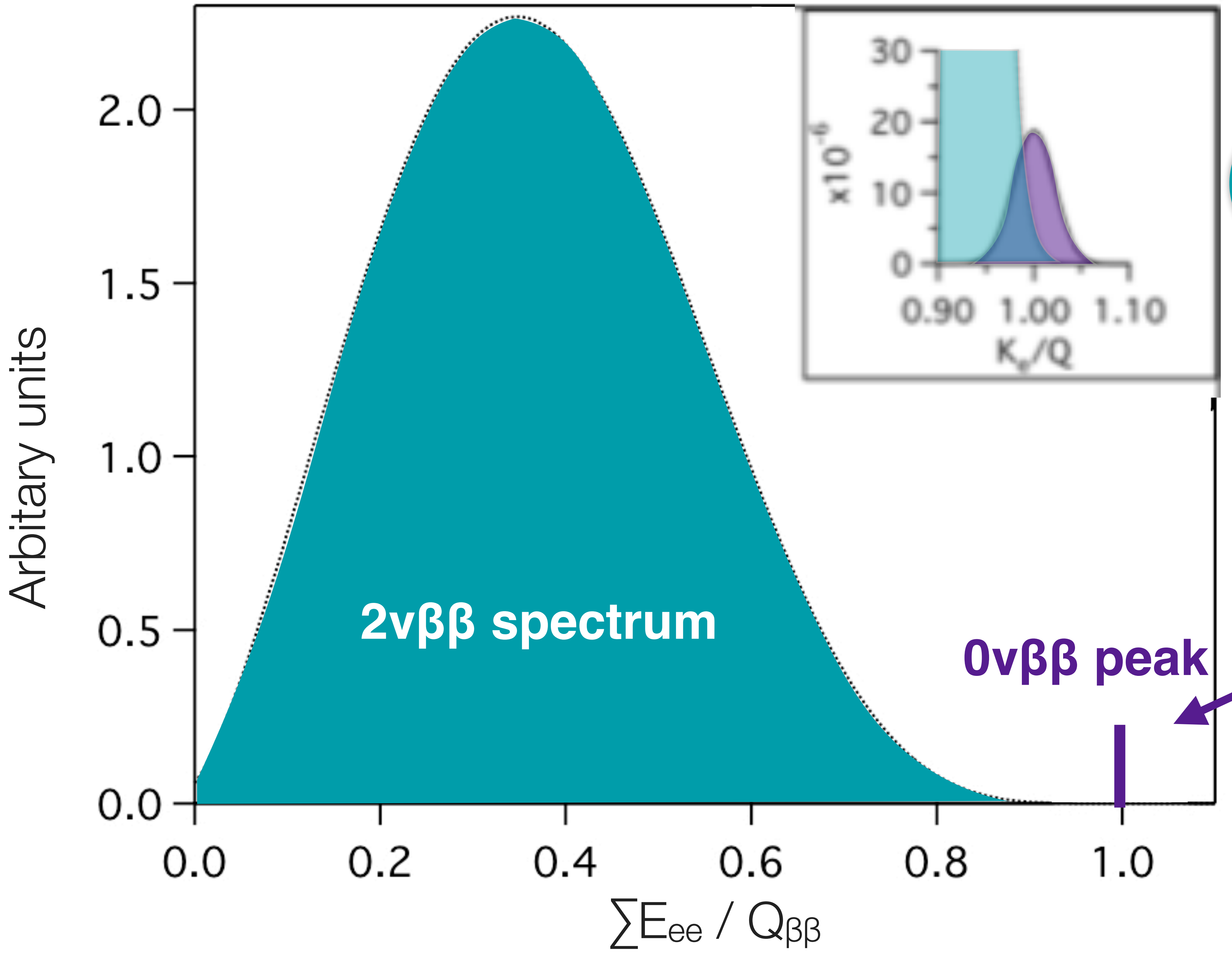


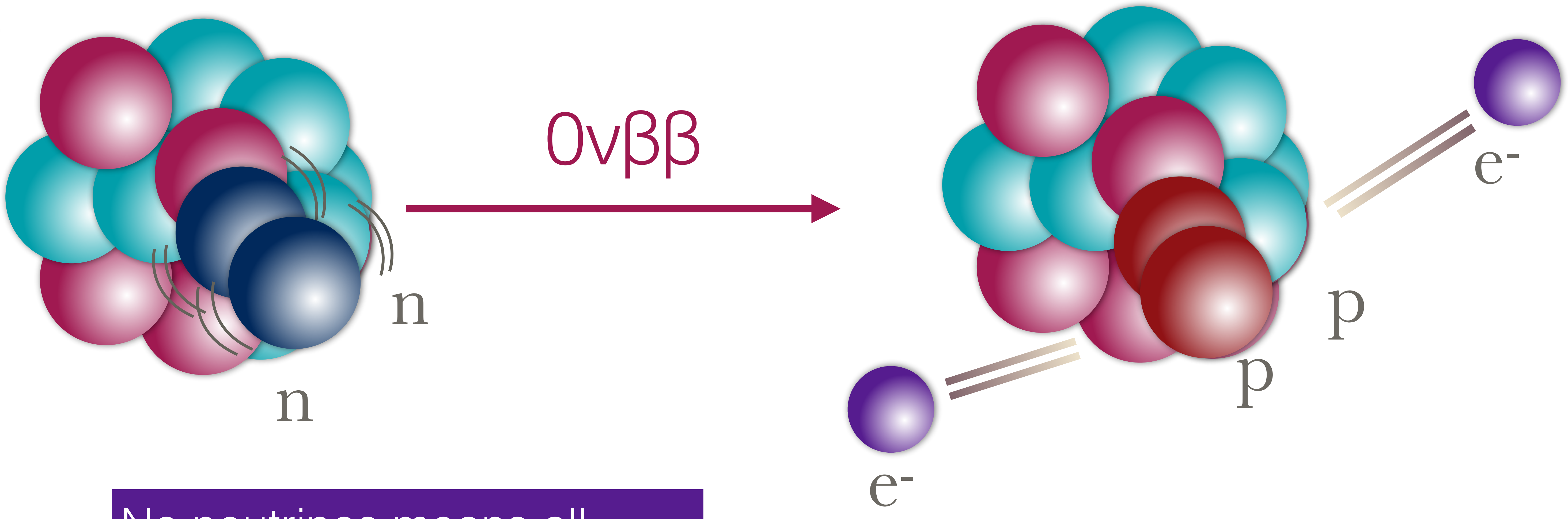


No neutrinos means all energy goes to electrons

Sum of the **2 electron energies**, as fraction of ββ decay energy

Looking for 0νββ





No neutrinos means all energy goes to electrons

Sum of the **2 electron energies**, as fraction of ββ decay energy

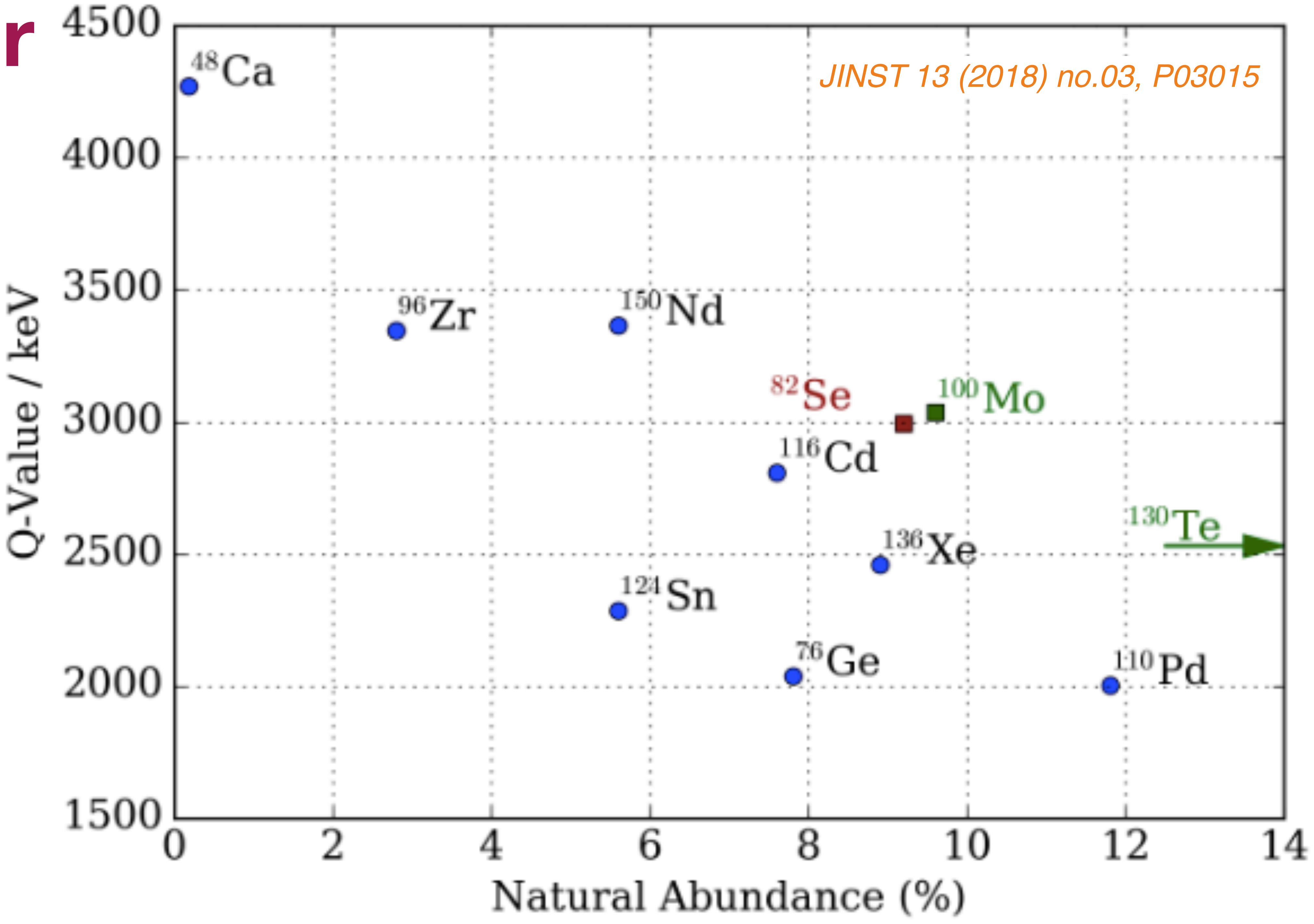
Choosing an isotope

- **"Short" half-life**

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e{}^2}$$

Better

$T_{1/2}^{0\nu} \propto Q^{-5}$



Choosing an isotope

- **“Short” half-life**
- **Lots of isotope**

ββ isotopic abundance

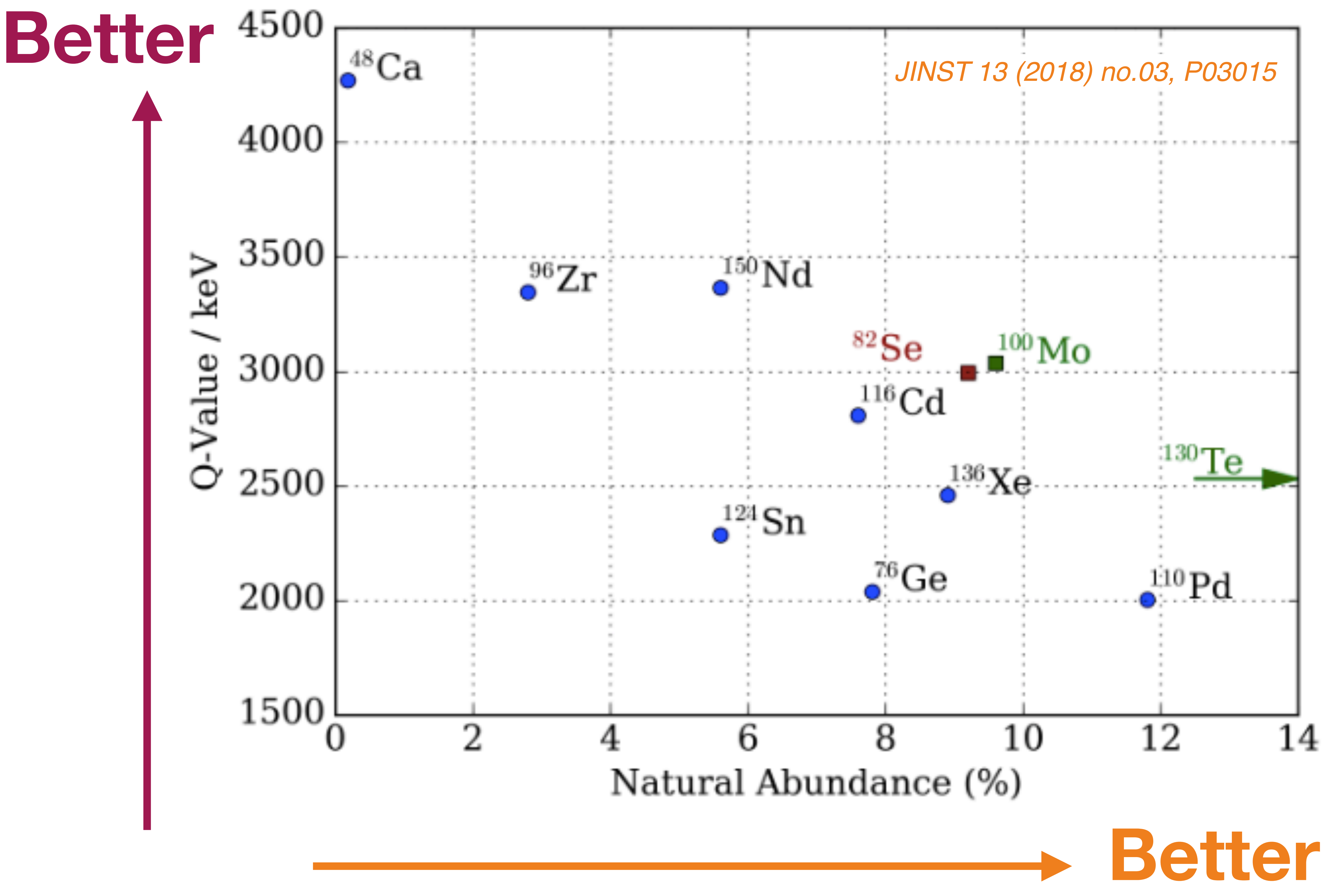
mass of source material

$$T_{1/2}^{0\nu\beta\beta}\,\text{limit} \propto a\epsilon m t$$

efficiency

run time

(if no backgrounds)



Choosing an isotope

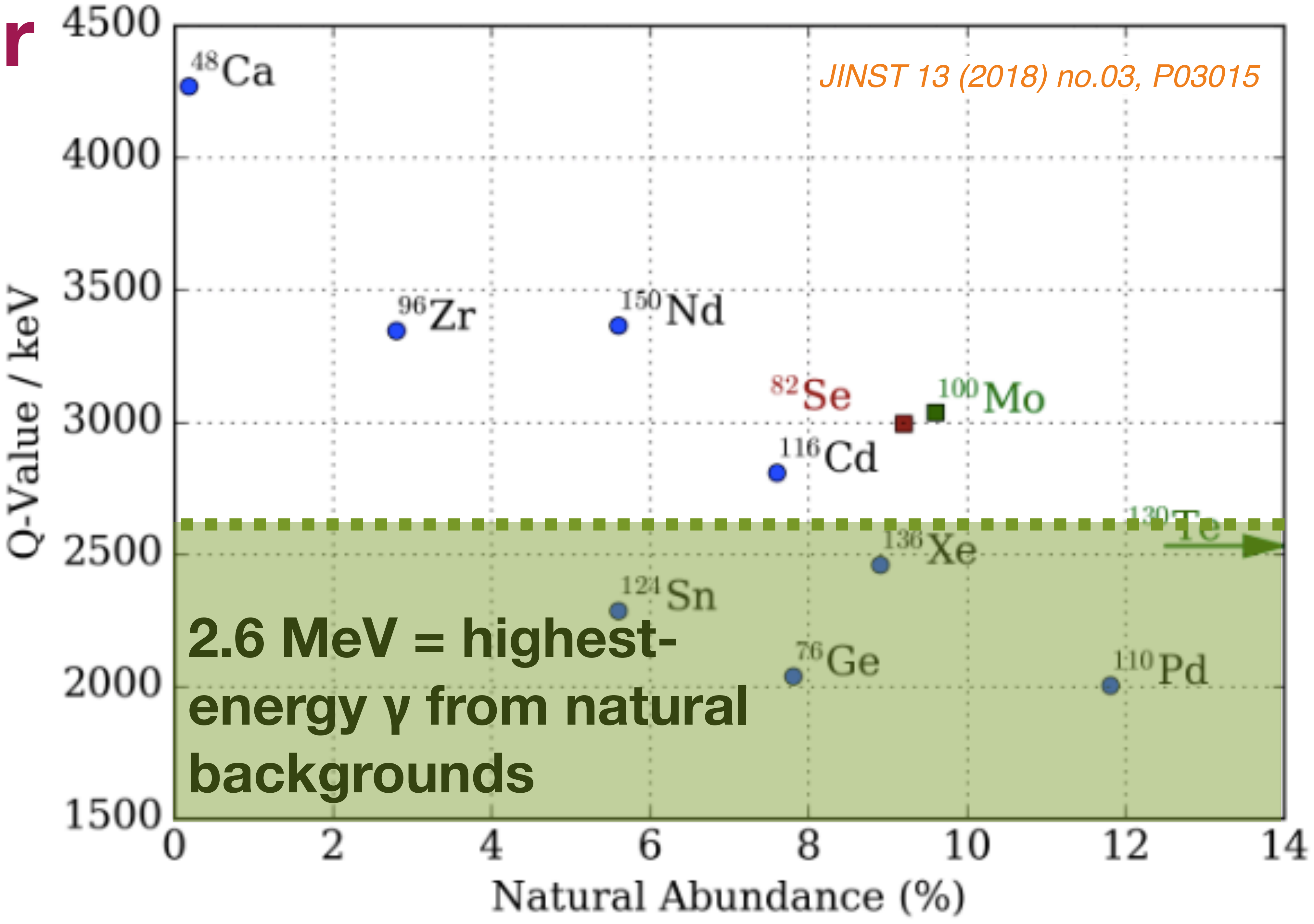
- **“Short” half-life**
- **Lots of isotope**
- **(Ultra-) Low backgrounds**

$$T_{1/2}^{0\nu}\ \text{limit} \propto a\epsilon\sqrt{\frac{mt}{b\Delta E}}$$

background events

energy resolution

Better

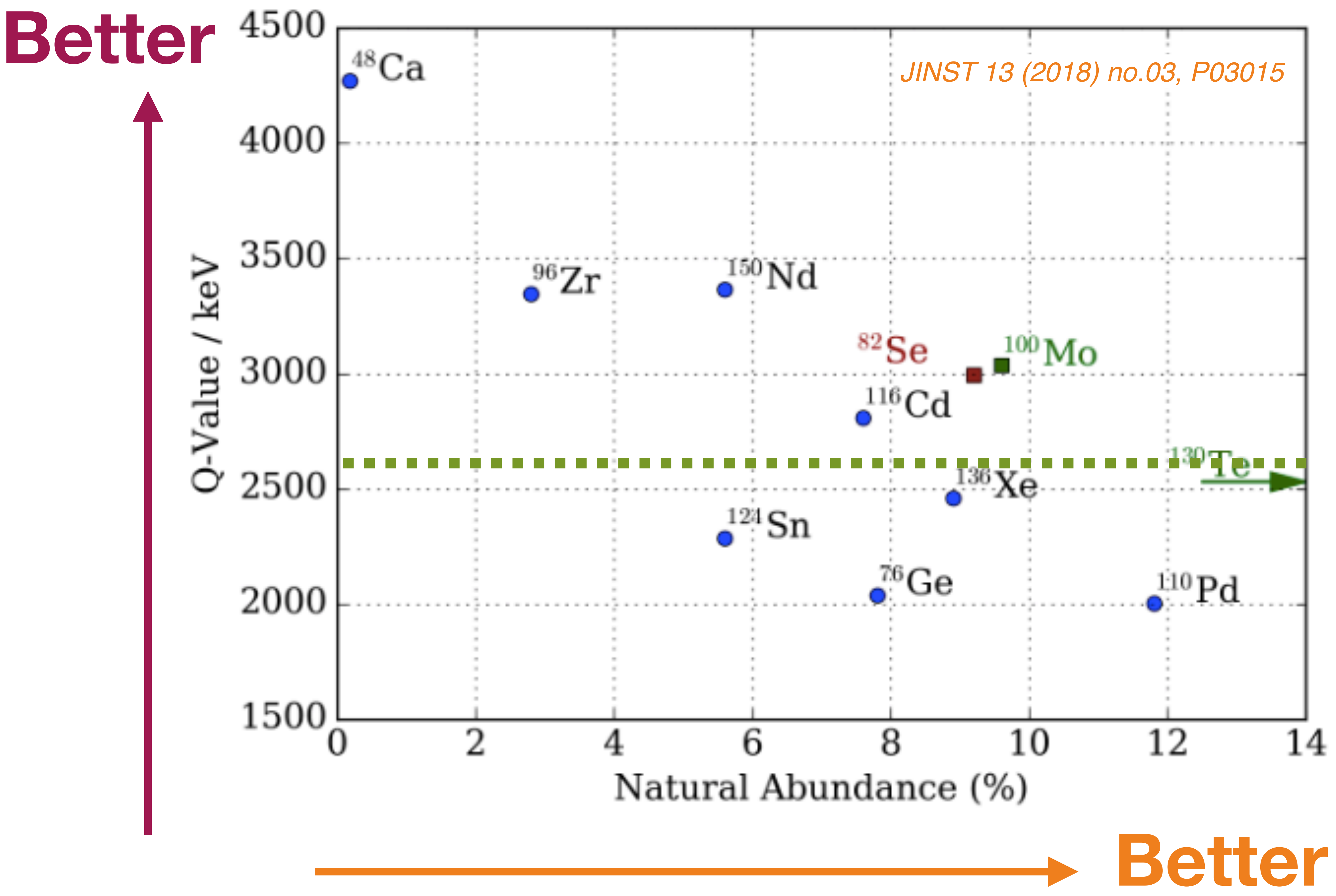


Better

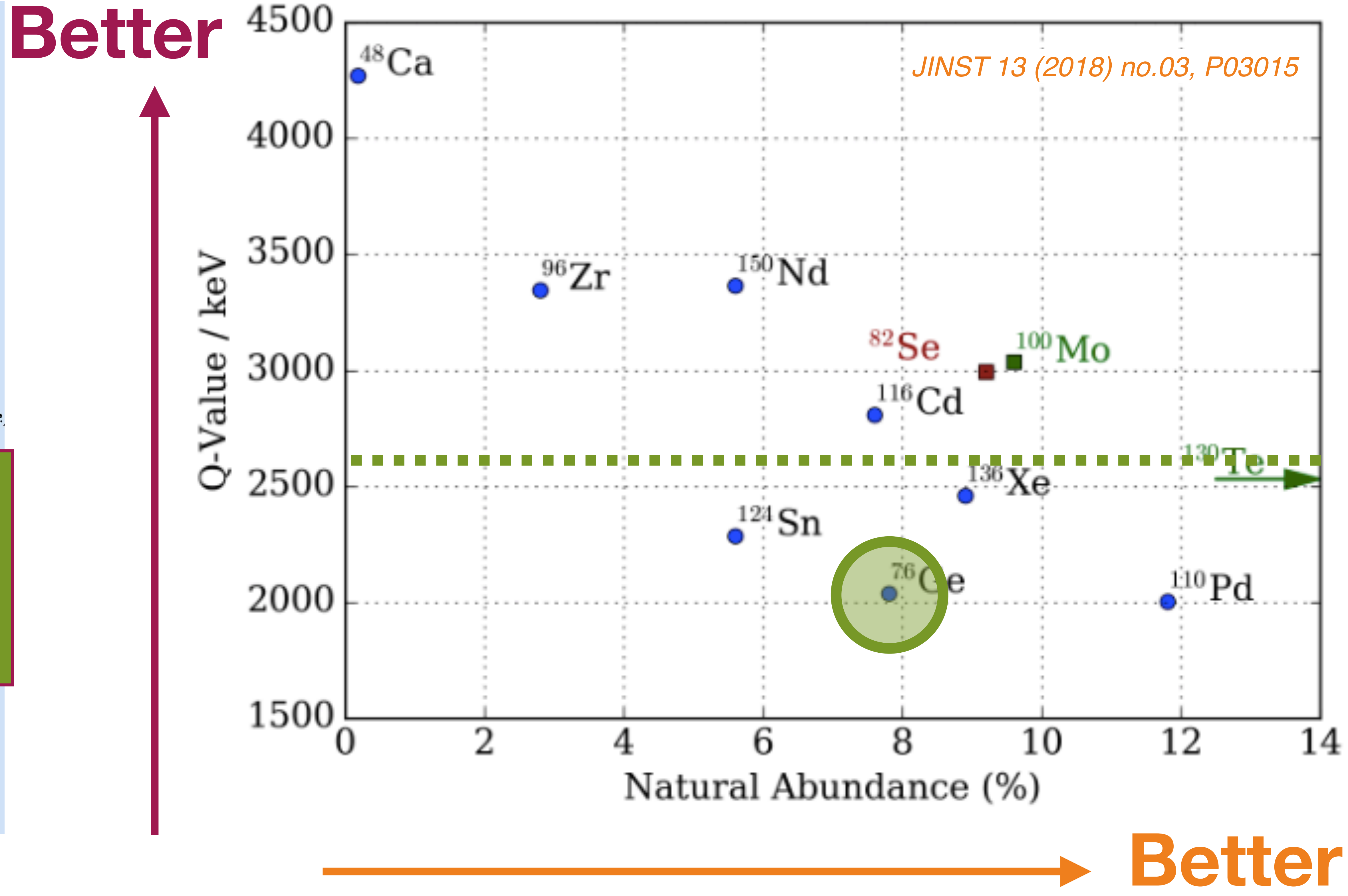
Backgrounds include

- ^{214}**Bi** and ^{208}**Tl** - β-emitting daughters of U & Th
- Particular danger from **radon**
- Irreducible **2νββ** background

Choosing an isotope

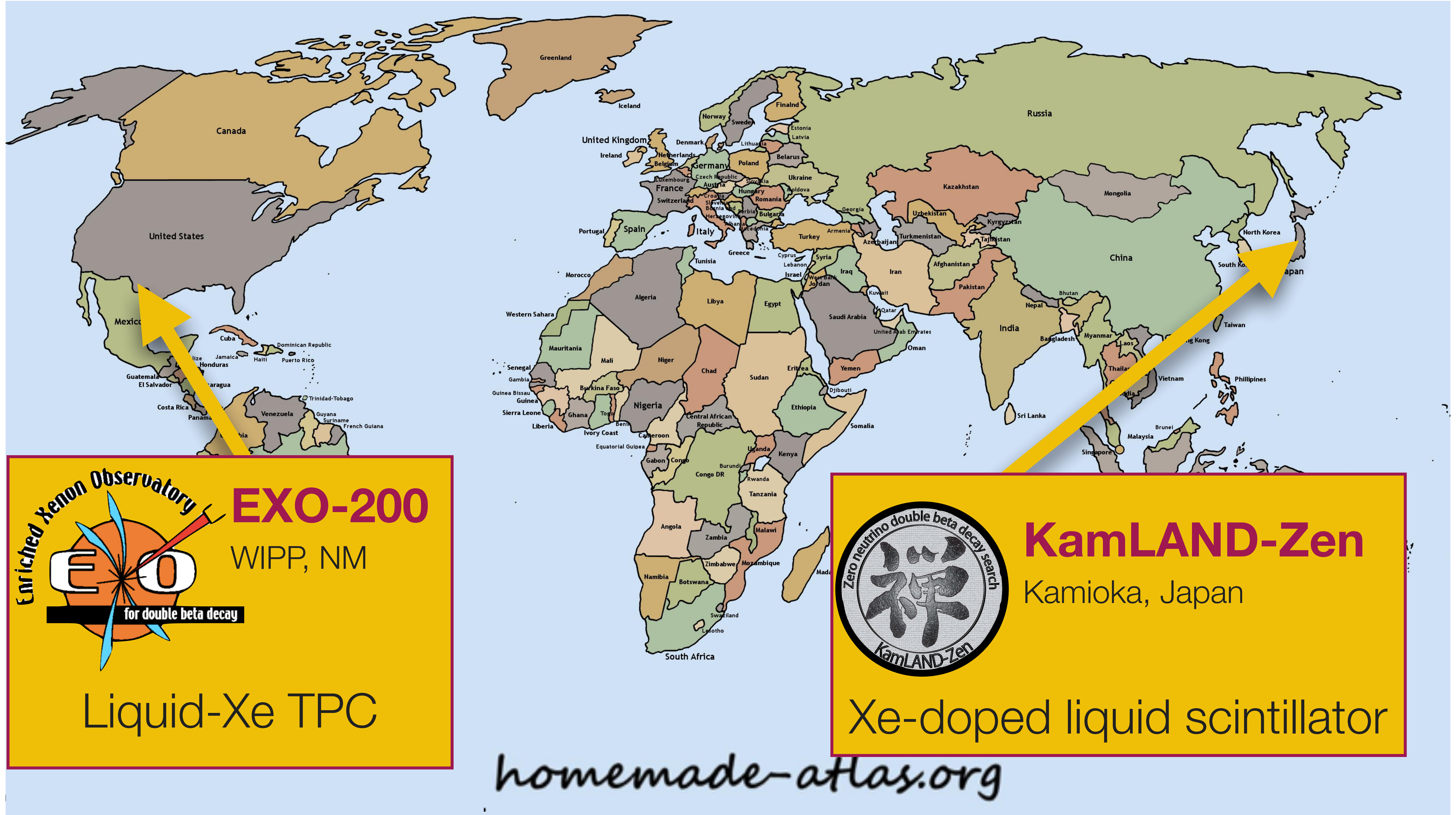


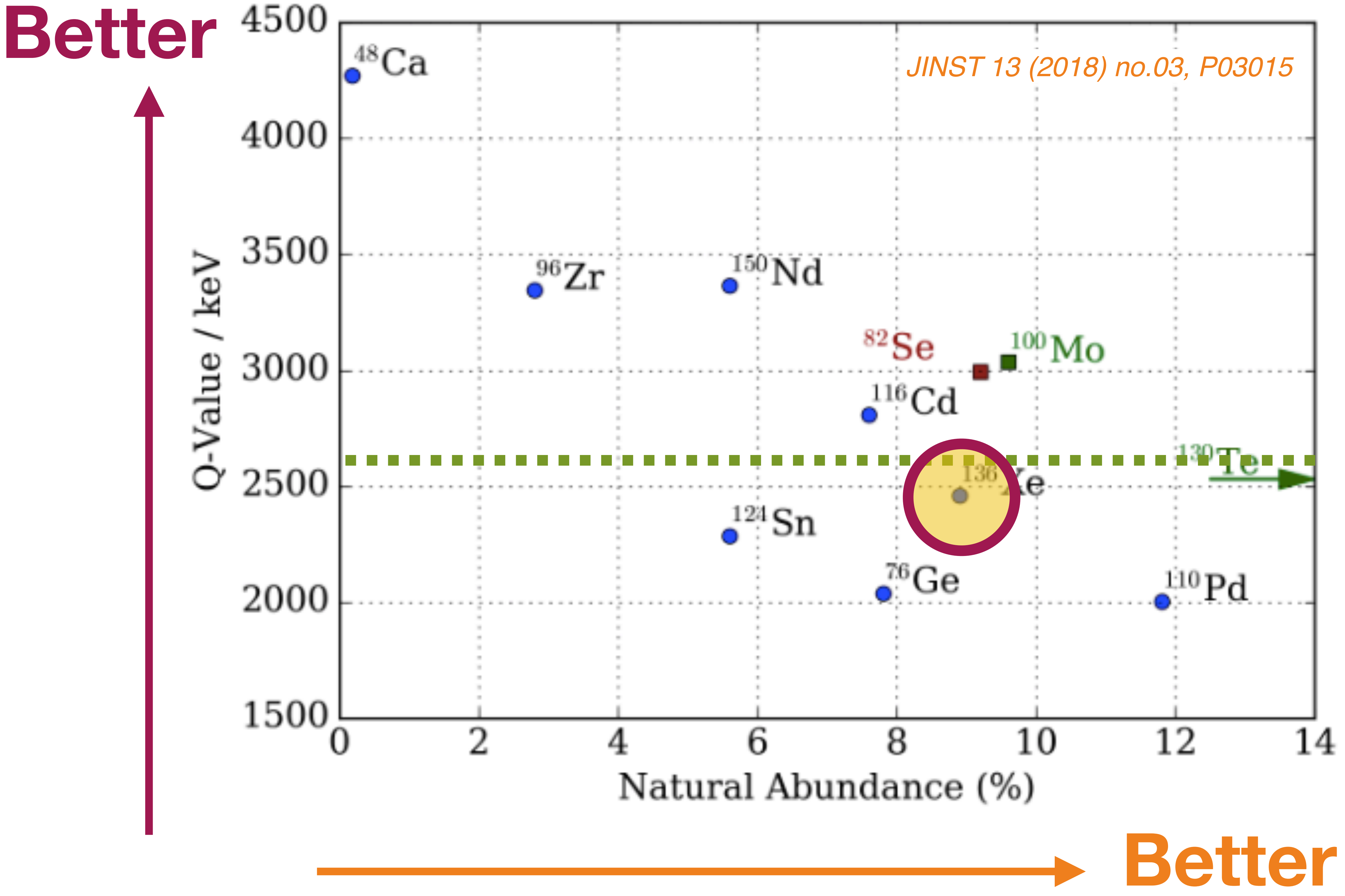
Choosing an isotope



- High-purity germanium **detector** array is **also ββ source** (^{76}Ge)
- Excellent **efficiency** and **resolution**: zero background in 0νββ region of interest
- Future detector: LEGEND

Choosing an isotope

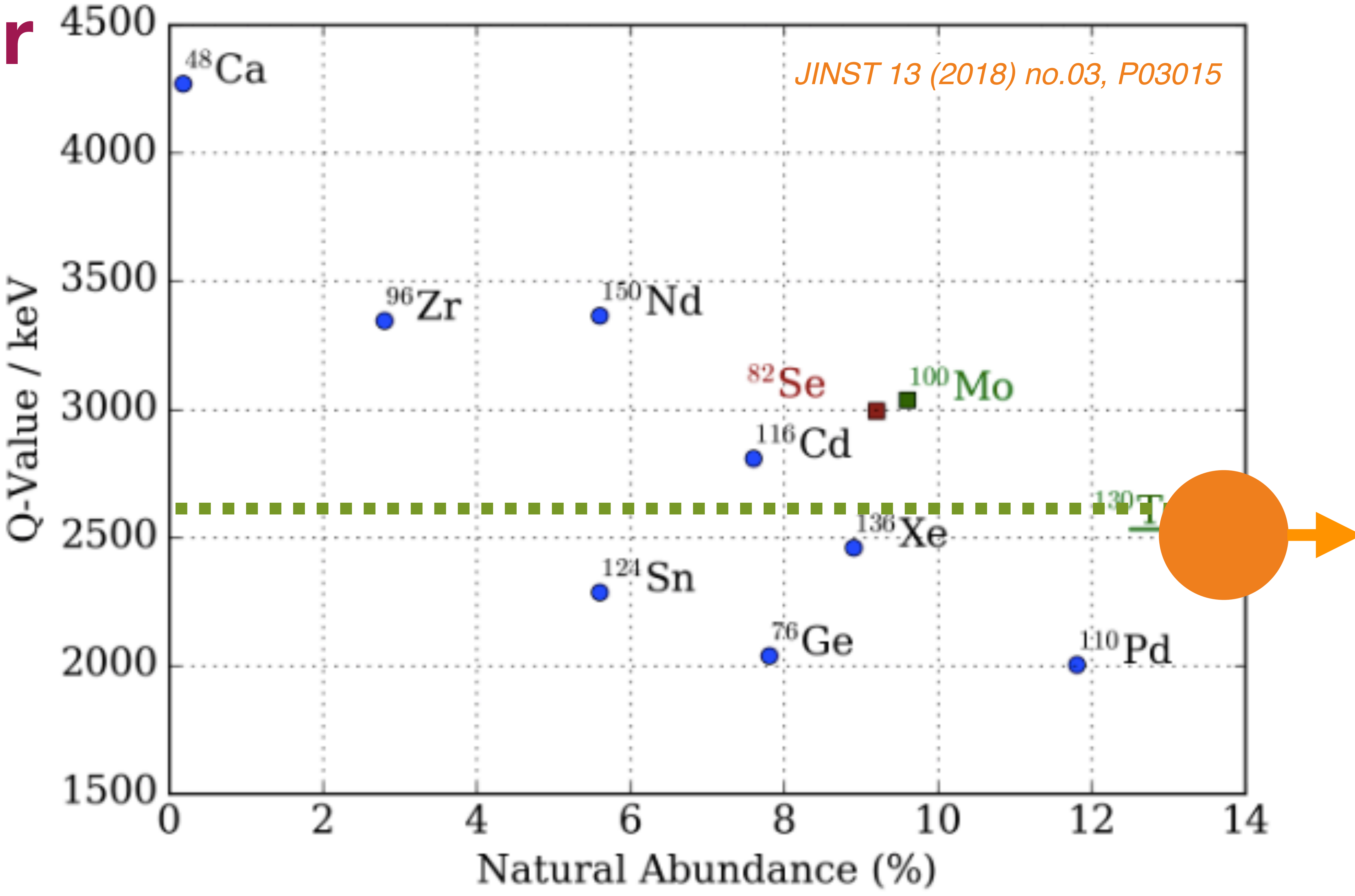




- Large detectors with **hundreds of kg** of isotope (^{136}Xe)
- KamLAND-Zen has current best 0νββ half-life /$m_{\beta\beta}$ mass limit
- $T_{1/2} > 1.07 \times 10^{26}$ years (**$\langle m_{\beta\beta} \rangle$ < 61-165 meV**)
- Future detectors - nEXO, KamLAND2 Zen

Choosing an isotope

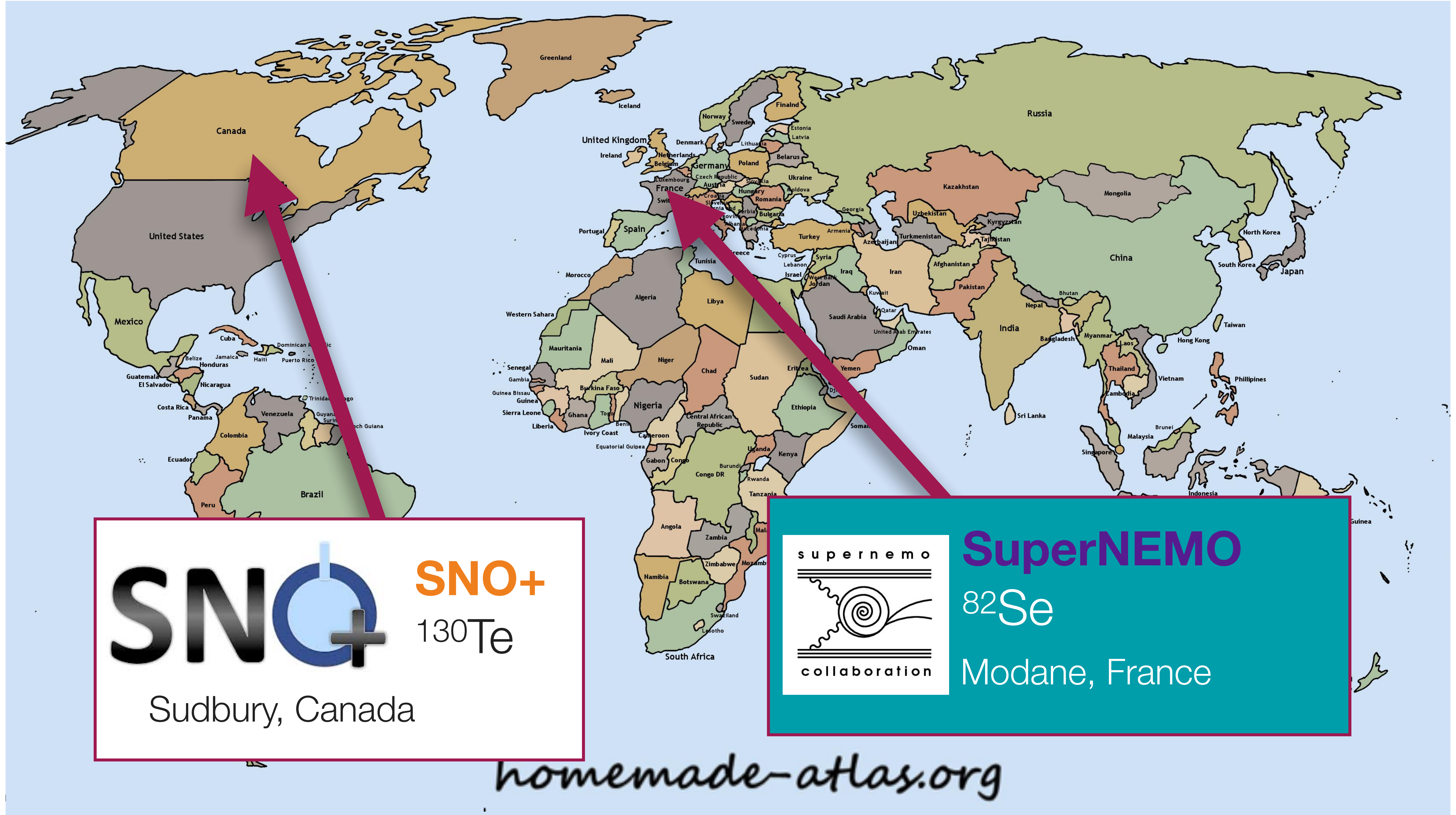
Better



Better

- ^{130}Te has 34% natural **abundance**
- TeO_2 crystals at 10mK heat up when decay occurs
- 0.2% energy **resolution**
- **CUPID** adds particle ID

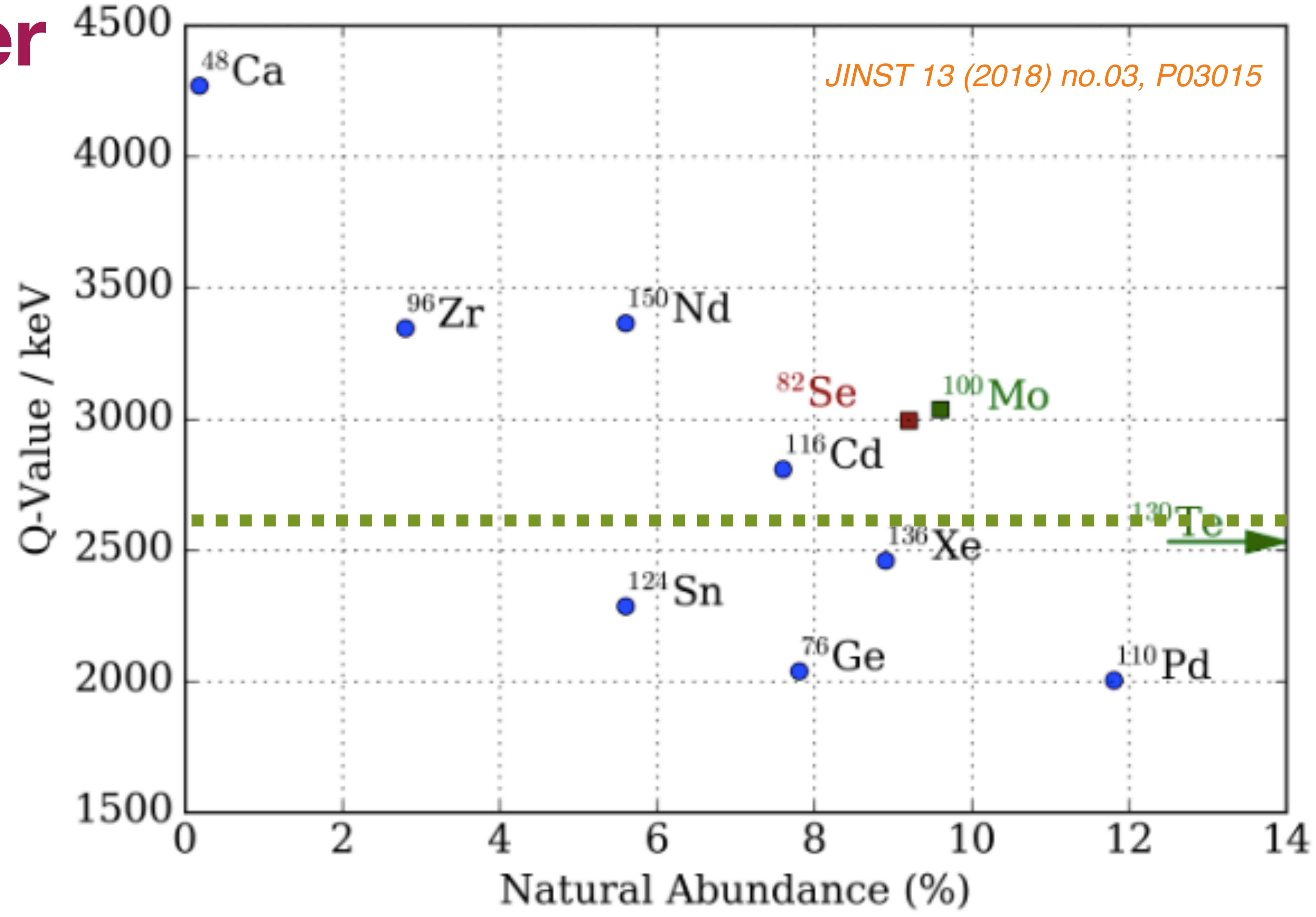
Choosing an isotope



SNO+
^{130}Te
Sudbury, Canada

SuperNEMO
^{82}Se
Modane, France

Better



Better

Significant UK involvement

SNO+ at Sudbury, Canada

Thanks to Steve Biller & Esther Turner for slide content

SNO+

Lancaster University

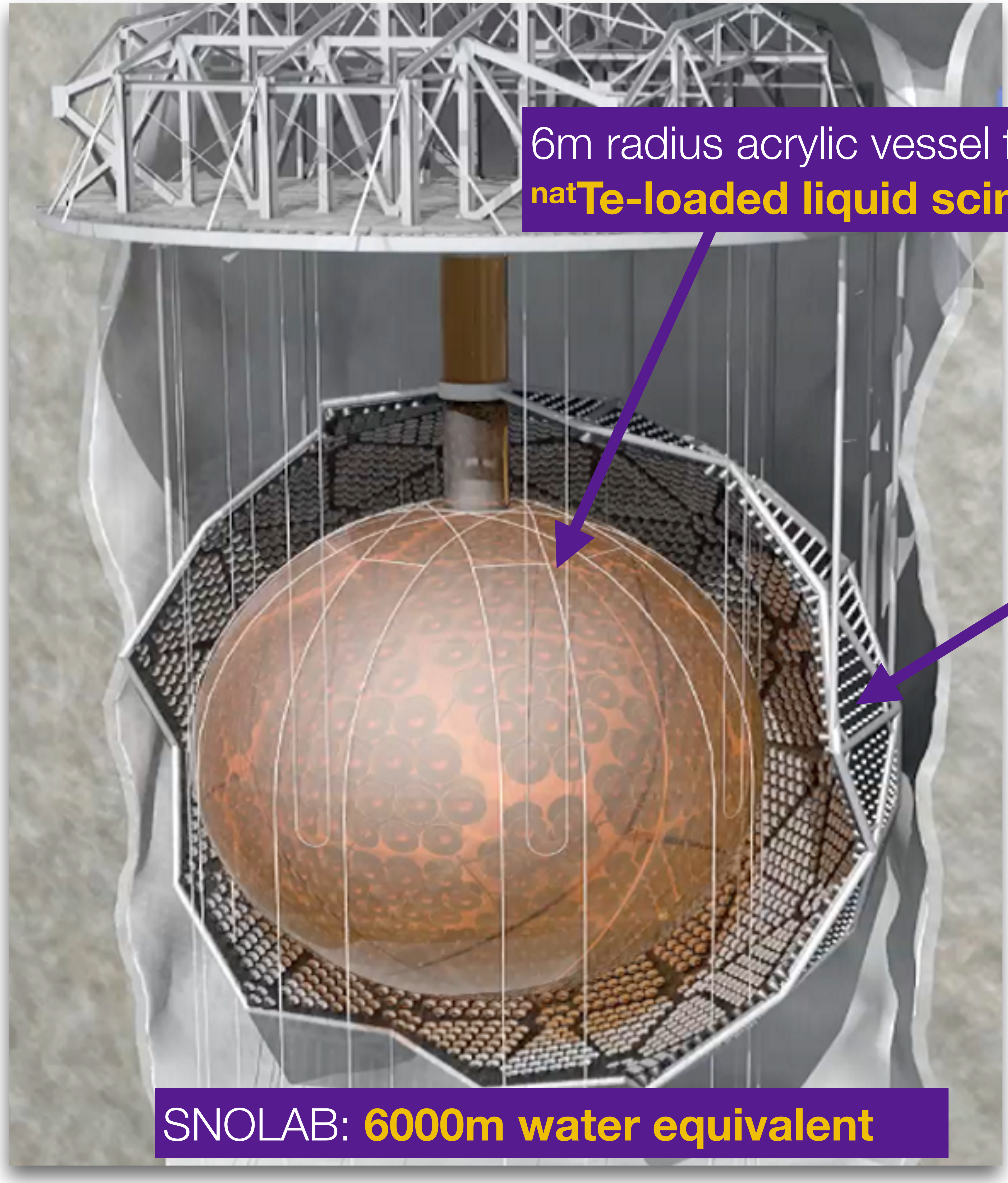
University of Liverpool

University of Oxford

Queen Mary University of London

University of Sussex

SNO+ - a new approach for $0\nu\beta\beta$

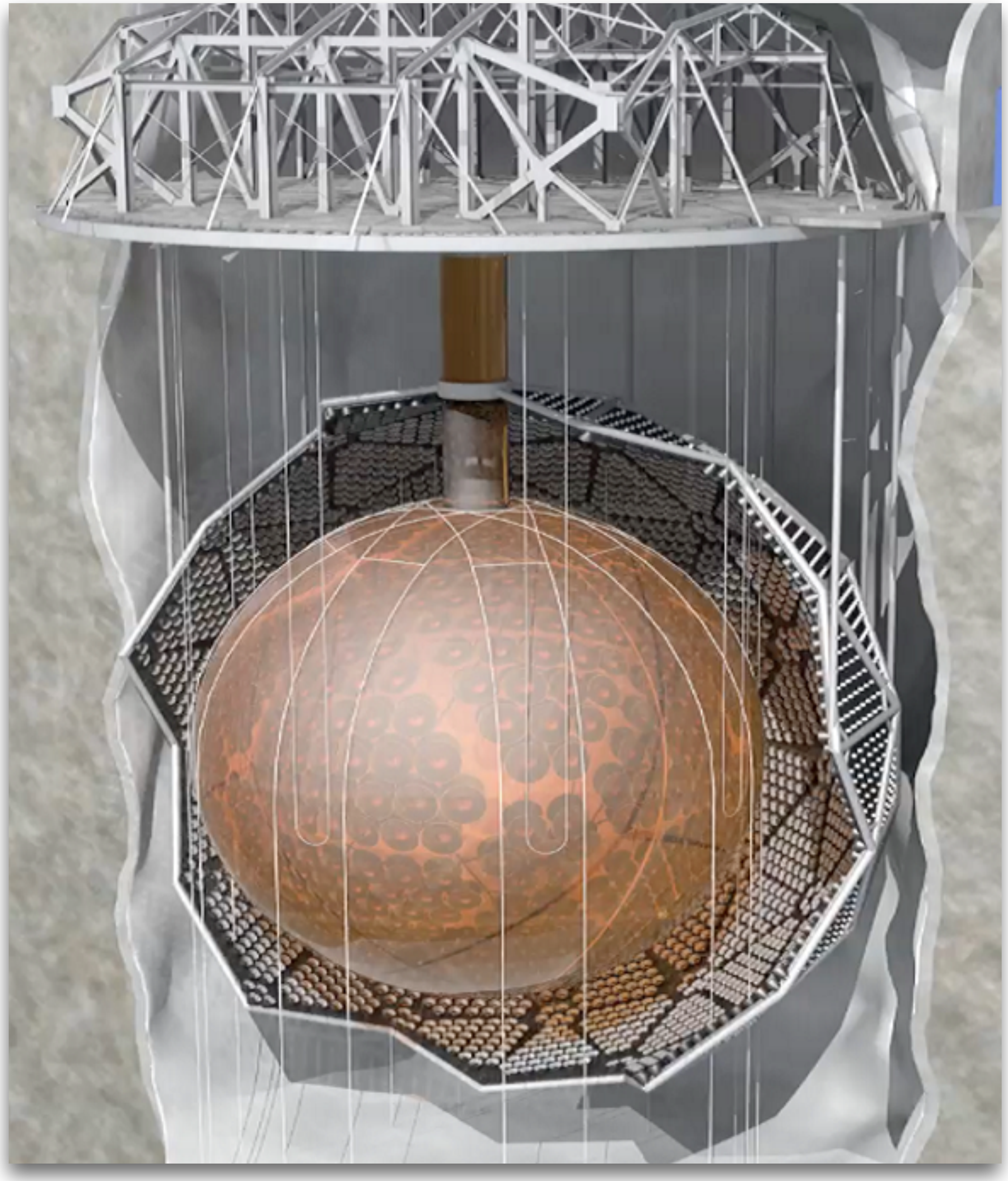


6m radius acrylic vessel filled with **^{nat}Te-loaded liquid scintillator**

Surrounded by ~**9300 PMTs** in a water-filled cavity

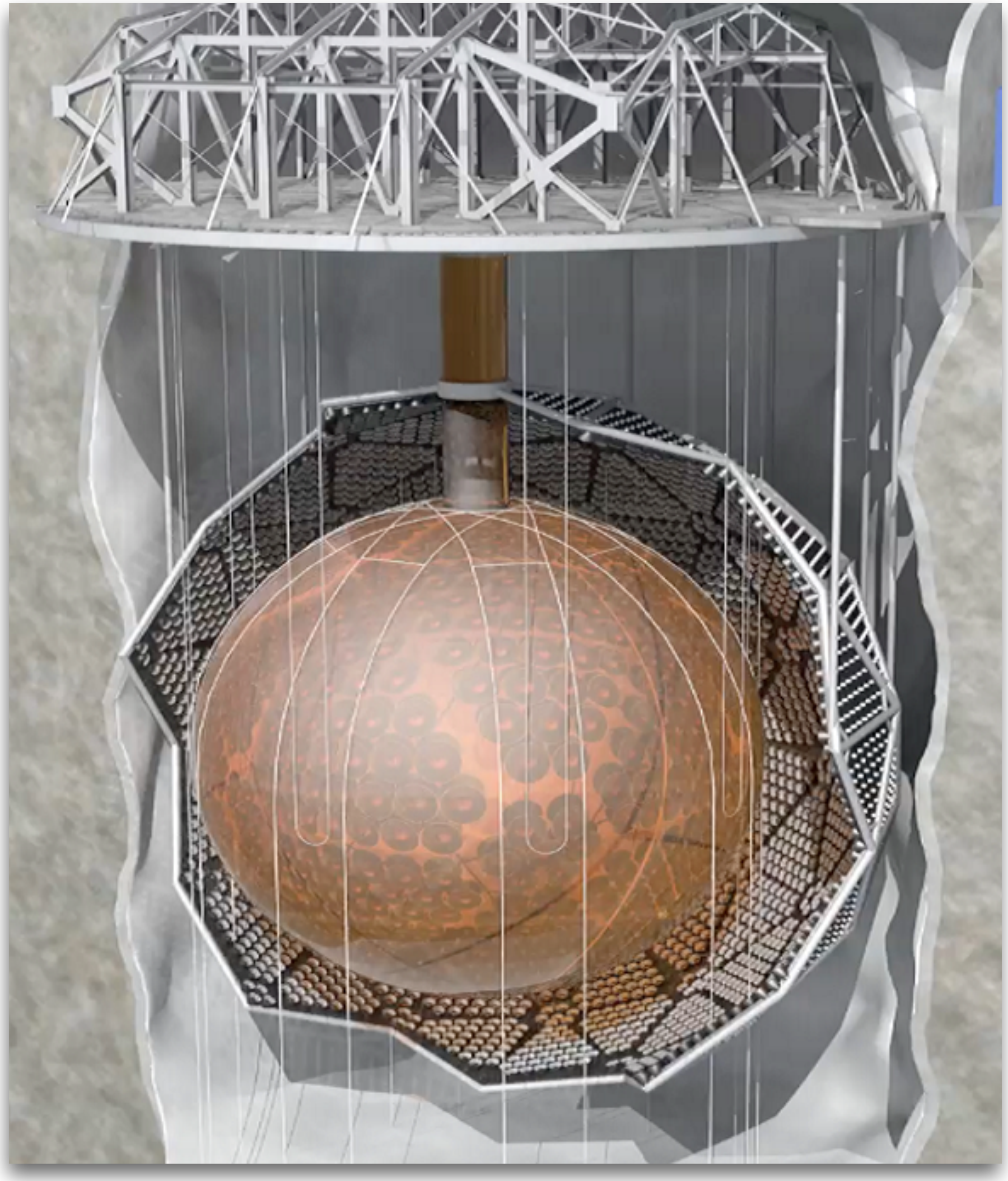
SNOLAB: **6000m water equivalent**

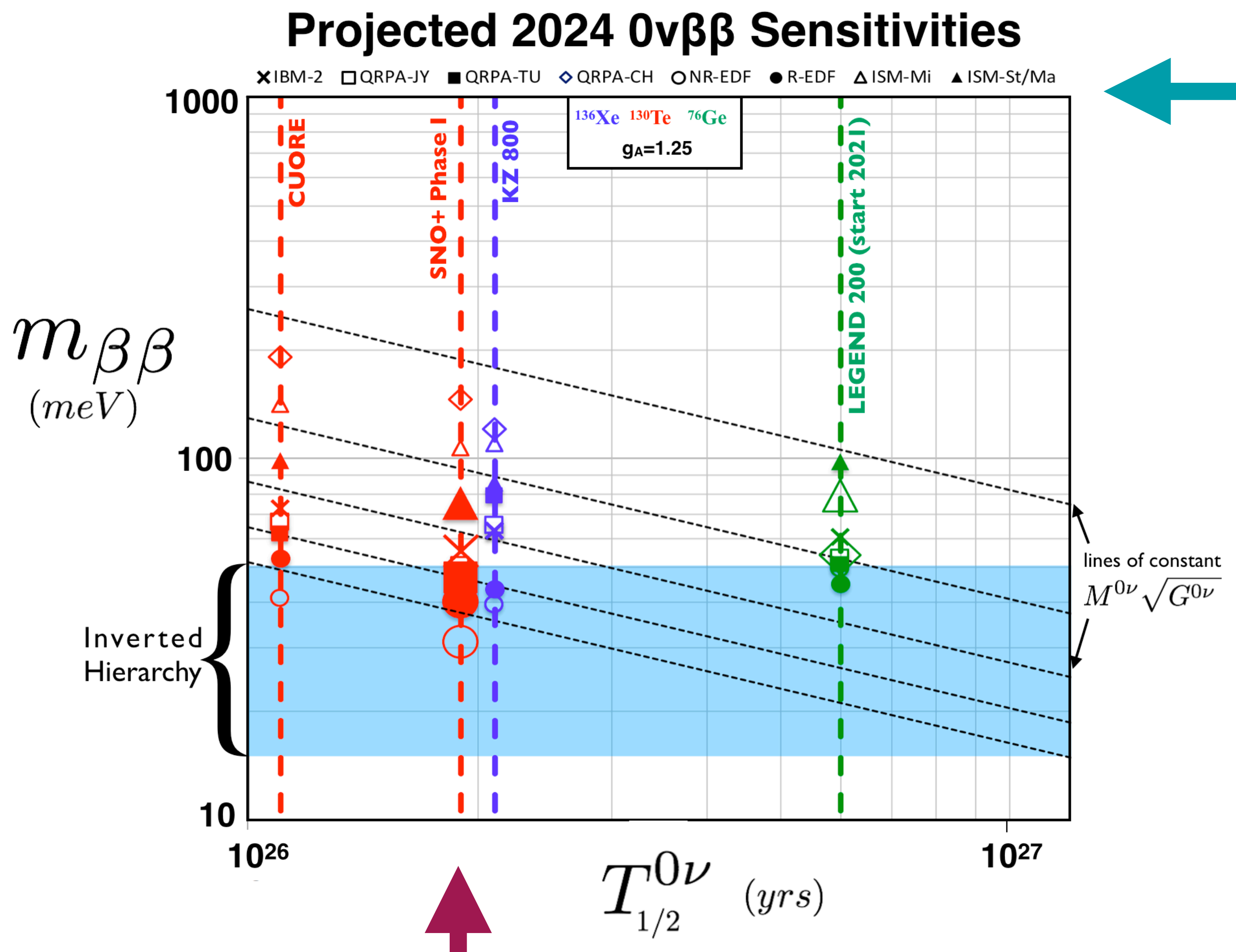
SNO+ - a new approach for $0\nu\beta\beta$



- Highly **economical**
  - ^{130}Te is the most economically scalable **isotope** (high natural abundance);
  - Liquid scintillator also very economically scalable **detector technology**!
- Potential for dramatic **scale-up**

SNO+ - a new approach for 0νββ





Different matrix element calculations give different masses for the same half-life

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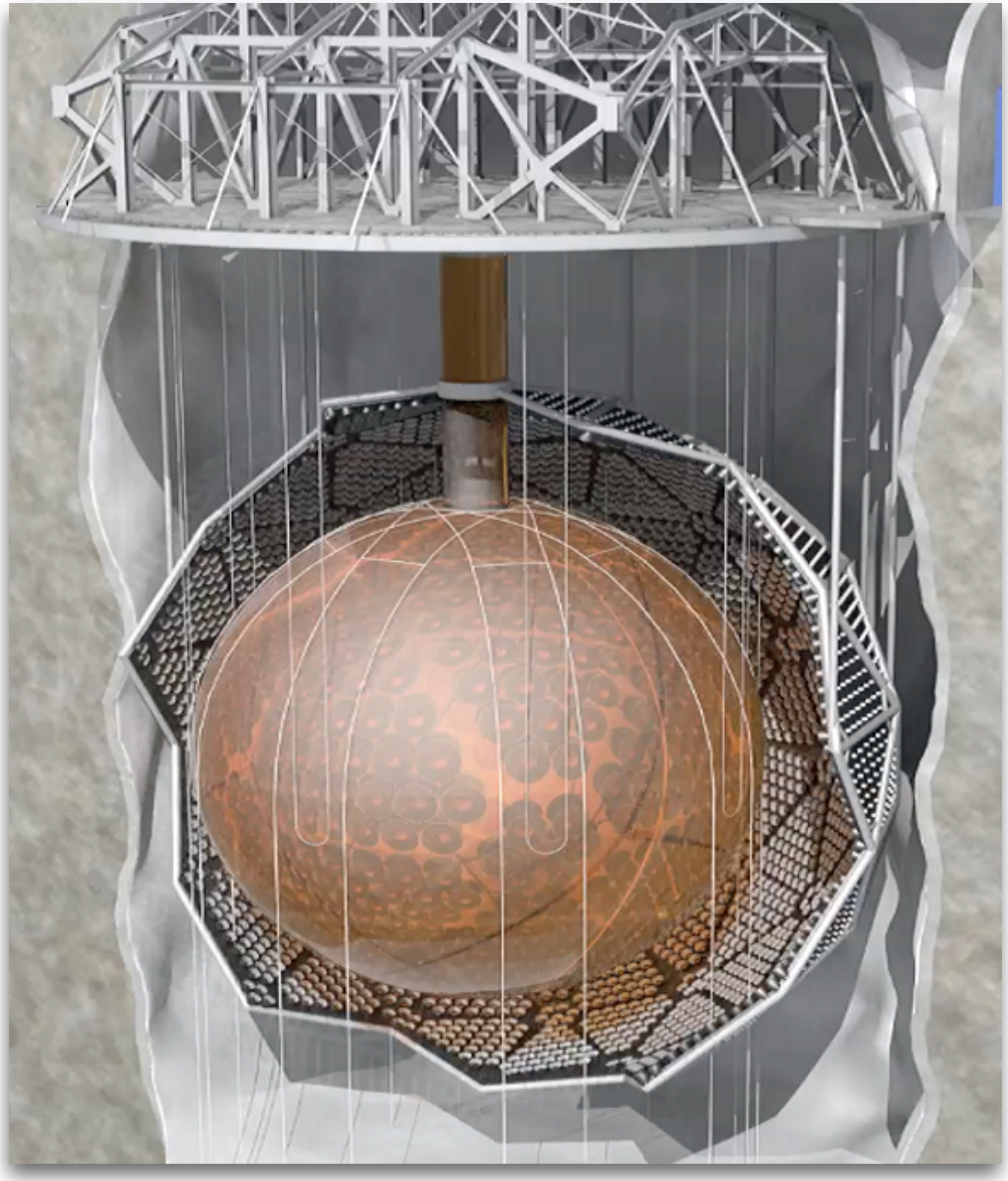
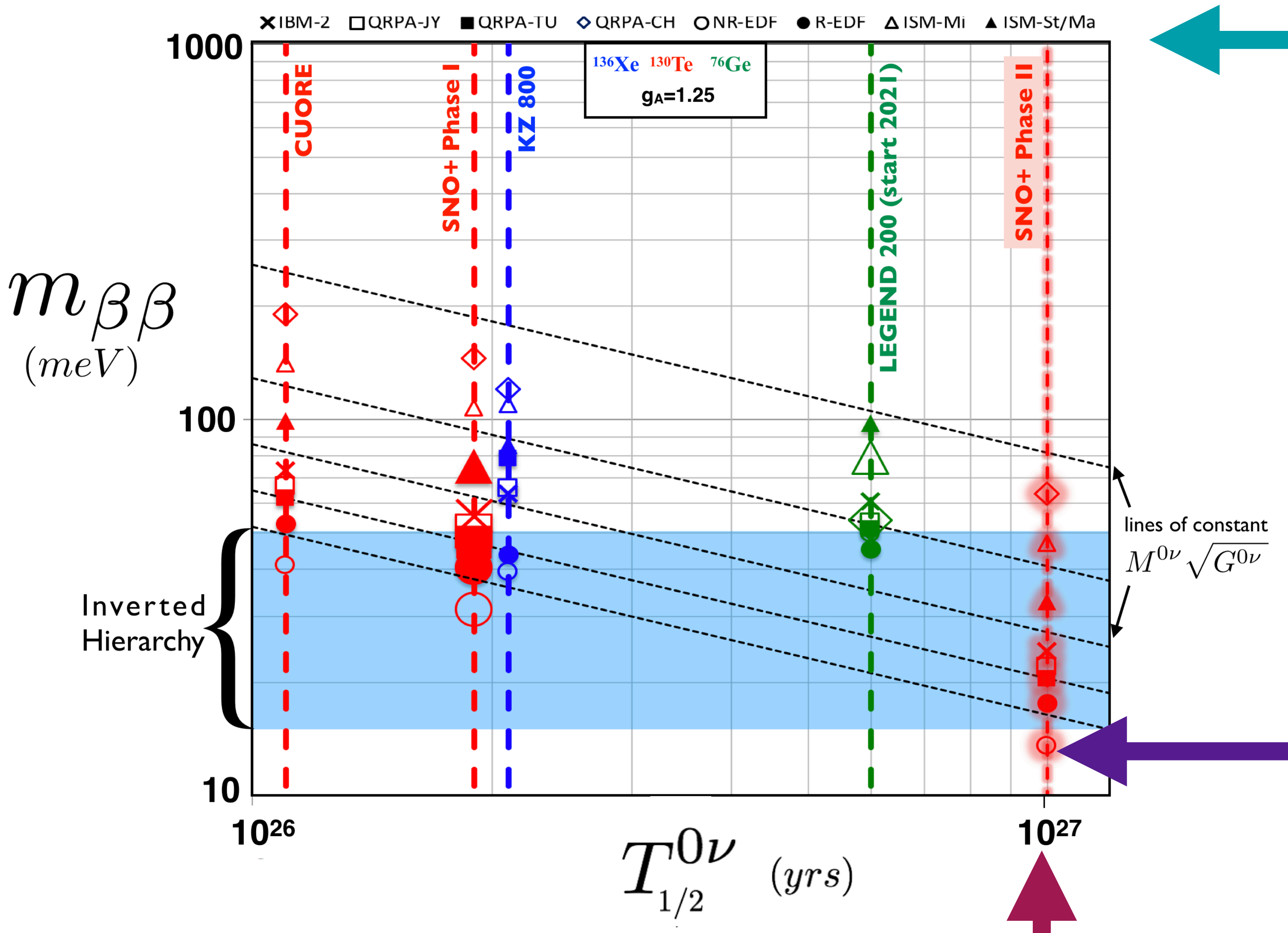
- Potential for dramatic **scale-up**
- Allows **sensitivity** above current leading measurement:
  - $T^{1/2}_{0\nu\beta\beta} > 2.1e^{26}$ years (**$m_{\beta\beta}$ < 37- 89 meV**) after 5 years of running

SNO+ - a new approach for 0νββ





Different matrix element calculations give different masses for the same half-life

New chemistry developments may make it possible to simply increase the loading in the current instrument to achieve this

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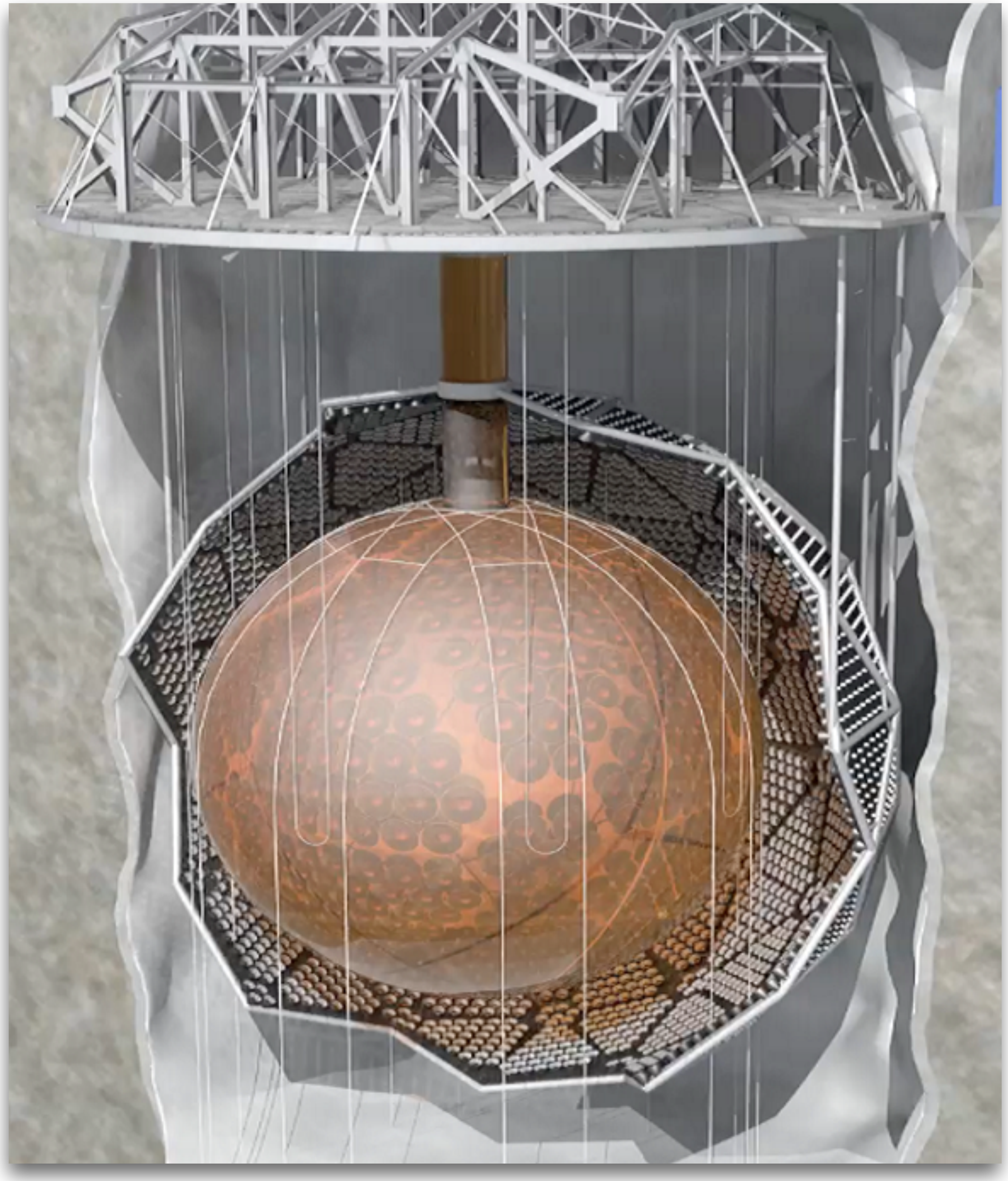
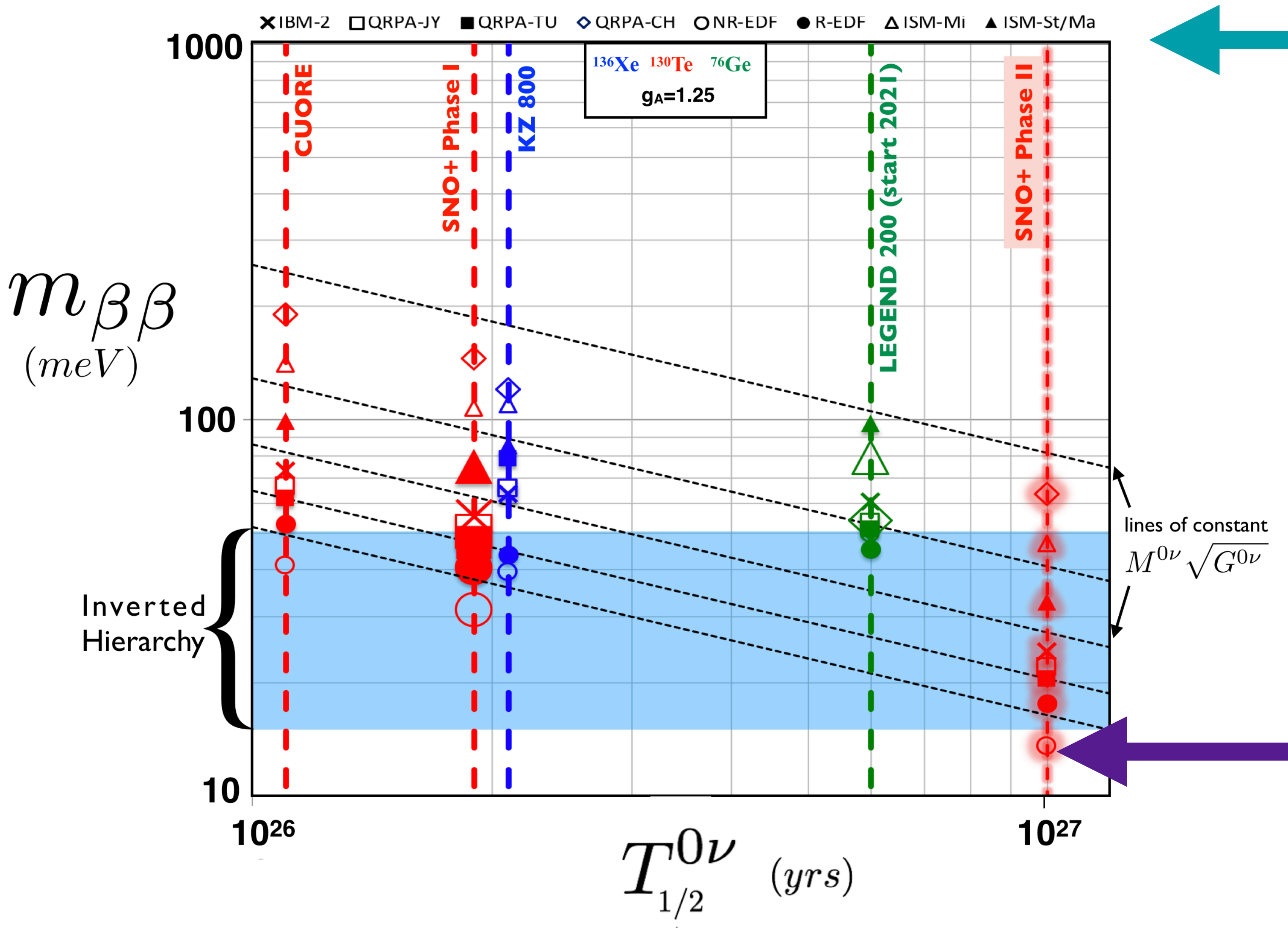
- **Phase II** could reach **10^{27}** years with the same detector but **higher loading**

SNO+ - a new approach for 0νββ





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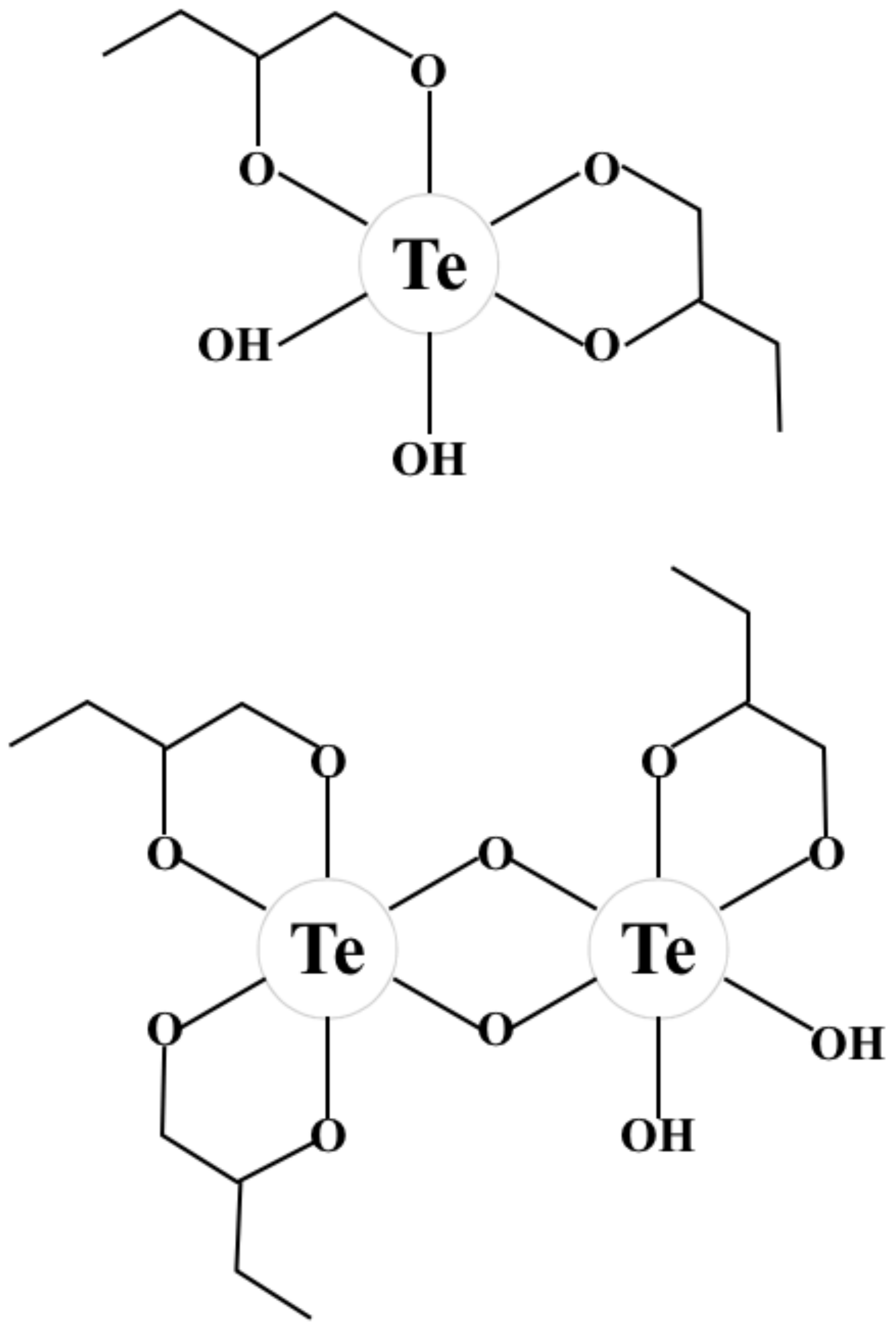
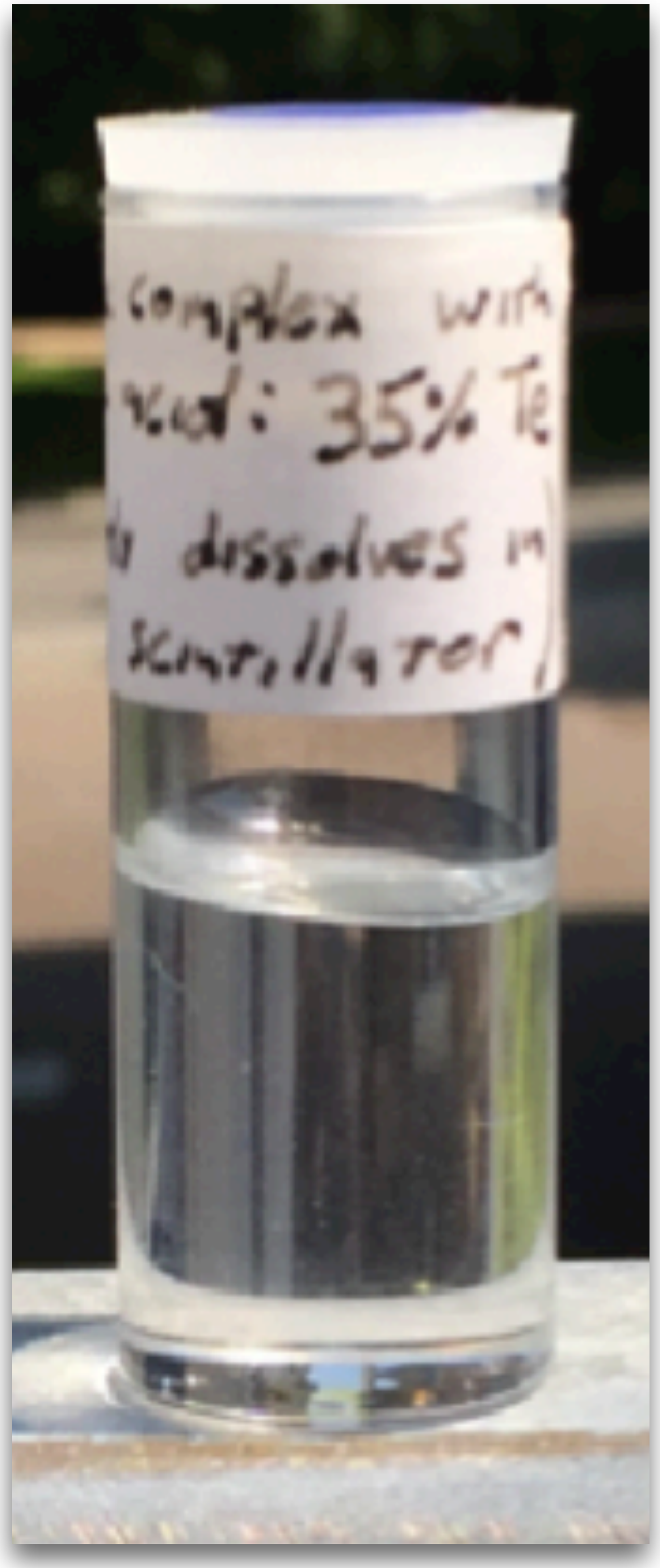
- **Phase II** could reach **10^{27}** years with the same detector but **higher loading**
- Concept originated in **UK** (Biller & Chen, 2012)

New loading method: Te-butanediol complex dissolves in liquid scintillator

- Simple **synthesis**
- Single **safe**, distillable chemical
- Low **radioactivity** levels
- Minimal optical **absorption**
- High **light levels** at 0.5% ^{nat}Te loading
- Developed in UK! 



Natural tellurium is 34% ^{130}Te



See Tereza Kroupova's slides!

Detector progress

- Operating with **water** from 2017

- **Invisible nucleon decay**
- **Solar neutrinos**
- **Supernova neutrinos**

PHYSICAL REVIEW D **99,** 012012 (2019)

Measurement of the ^8B solar neutrino flux in SNO+ with very low backgrounds

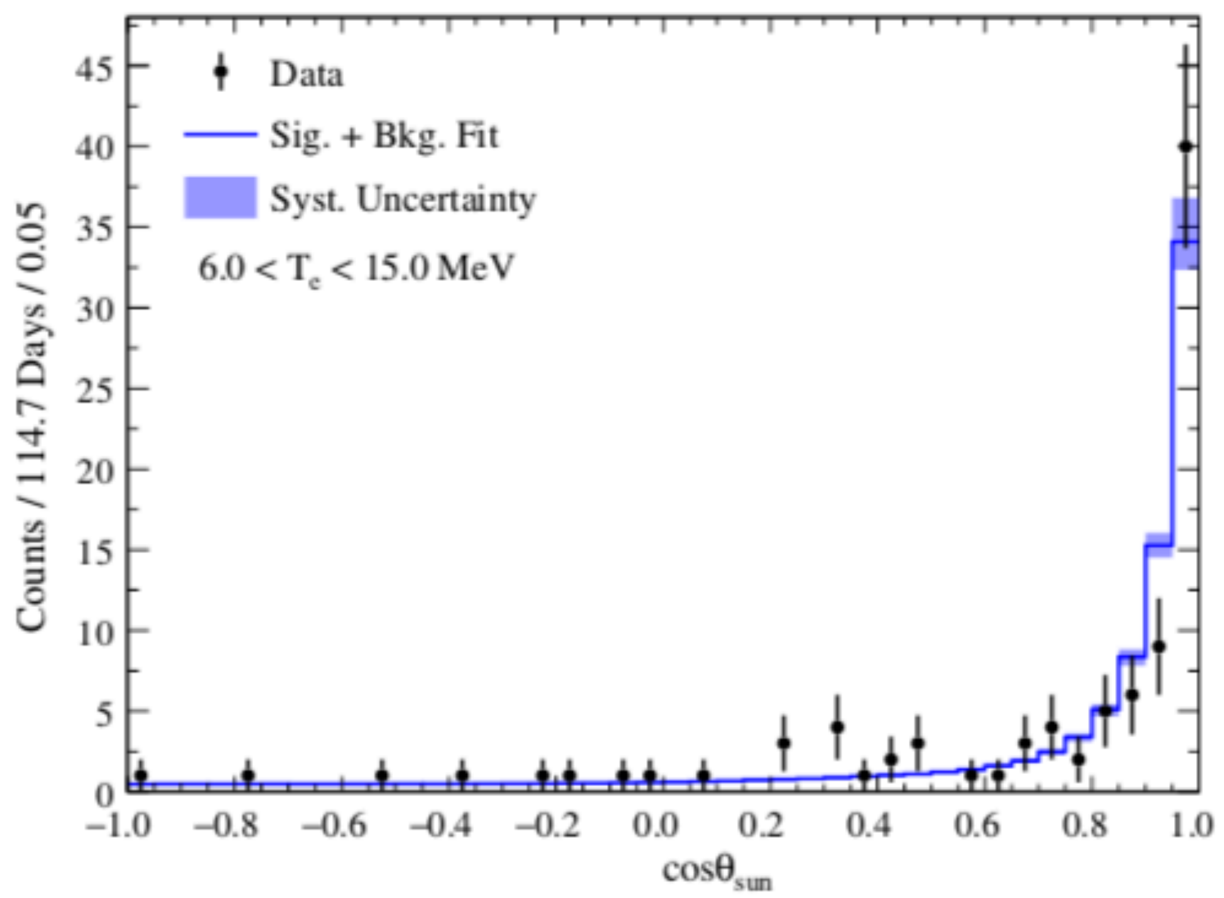


FIG. 4. Distribution of event directions with respect to solar direction for events with energy in the range 6.0–15.0 MeV.

Largest background to 0νββ

PHYSICAL REVIEW D **99,** 032008 (2019)

Search for invisible modes of nucleon decay in water with the SNO+ detector

TABLE VI. Lifetime limits at 90% C.I. for the spectral and counting analysis, including statistical and systematic uncertainties alongside the existing limits.

	Spectral analysis	Counting analysis	Existing limits
n	2.5×10^{29} y	2.6×10^{29} y	5.8×10^{29} y [9]
p	3.6×10^{29} y	3.4×10^{29} y	2.1×10^{29} y [10]
pp	4.7×10^{28} y	4.1×10^{28} y	5.0×10^{25} y [11]
pn	2.6×10^{28} y	2.3×10^{28} y	2.1×10^{25} y [13]
nn	1.3×10^{28} y	0.6×10^{28} y	1.4×10^{30} y [9]

See Martti Nirkko's slides!

Plus other analyses underway

Detector progress

- Operating with **water** from 2017
- Transition to **scintillator** happening now

- Invisible nucleon decay
- Solar neutrinos
- Supernova neutrinos
- **Reactor neutrinos (Δm^2_{12})**
- **Geo-neutrinos**

- Scintillator purification plant commissioned
- **LAB** successfully distilled underground
- **PPO** prep underway
- N_2/steam stripping tested

Detector progress

- Operating with **water** from 2017
- Transition to **scintillator** happening now
- **Tellurium** loading for ββ due in 2019-20 (1330 kg ^{130}Te)

- Invisible nucleon decay
- Solar neutrinos
- Supernova neutrinos
- Reactor neutrinos (Δm^2_{12})
- Geo-neutrinos
- **Neutrinoless double-beta decay**

Te needed for Phase I **all underground**

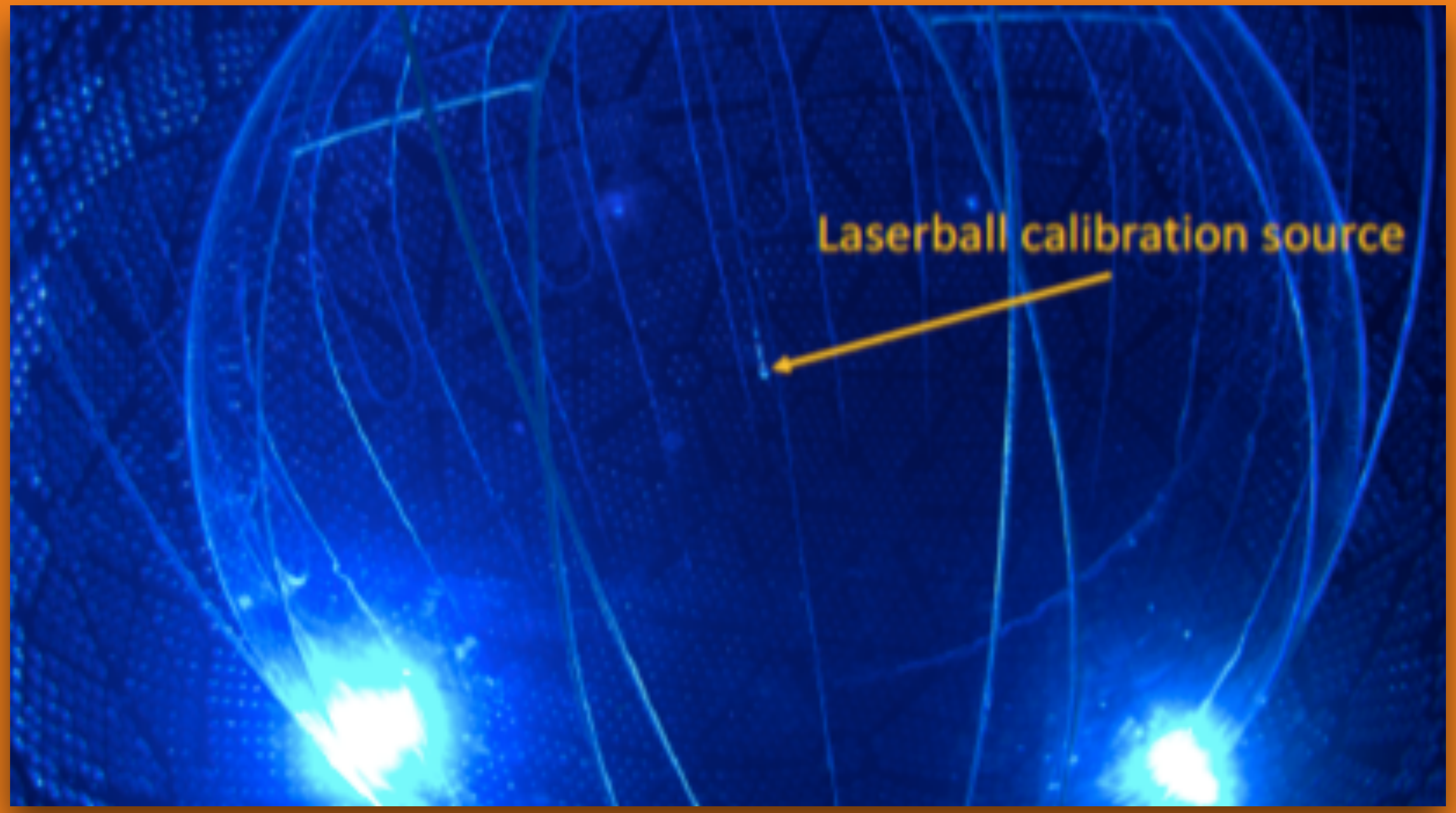
Te **purification system** almost complete

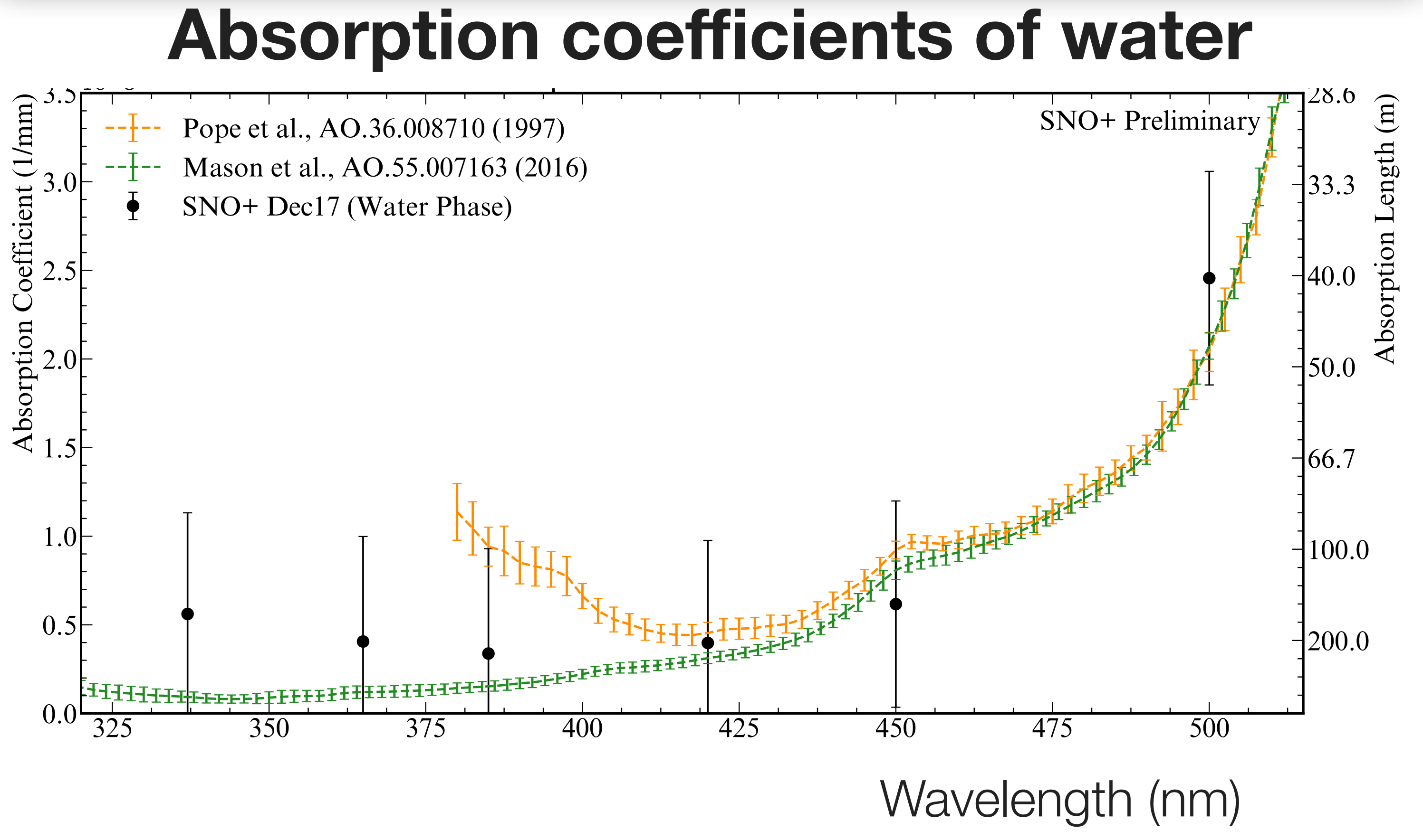
Te-diol synthesis plant construction is well advanced (synthesised from telluric acid)

Detector calibrations

See Martti Nirkko's slides!

Water phase: measure **absorption** coefficient with light-diffusing "**laserball**" and underwater camera

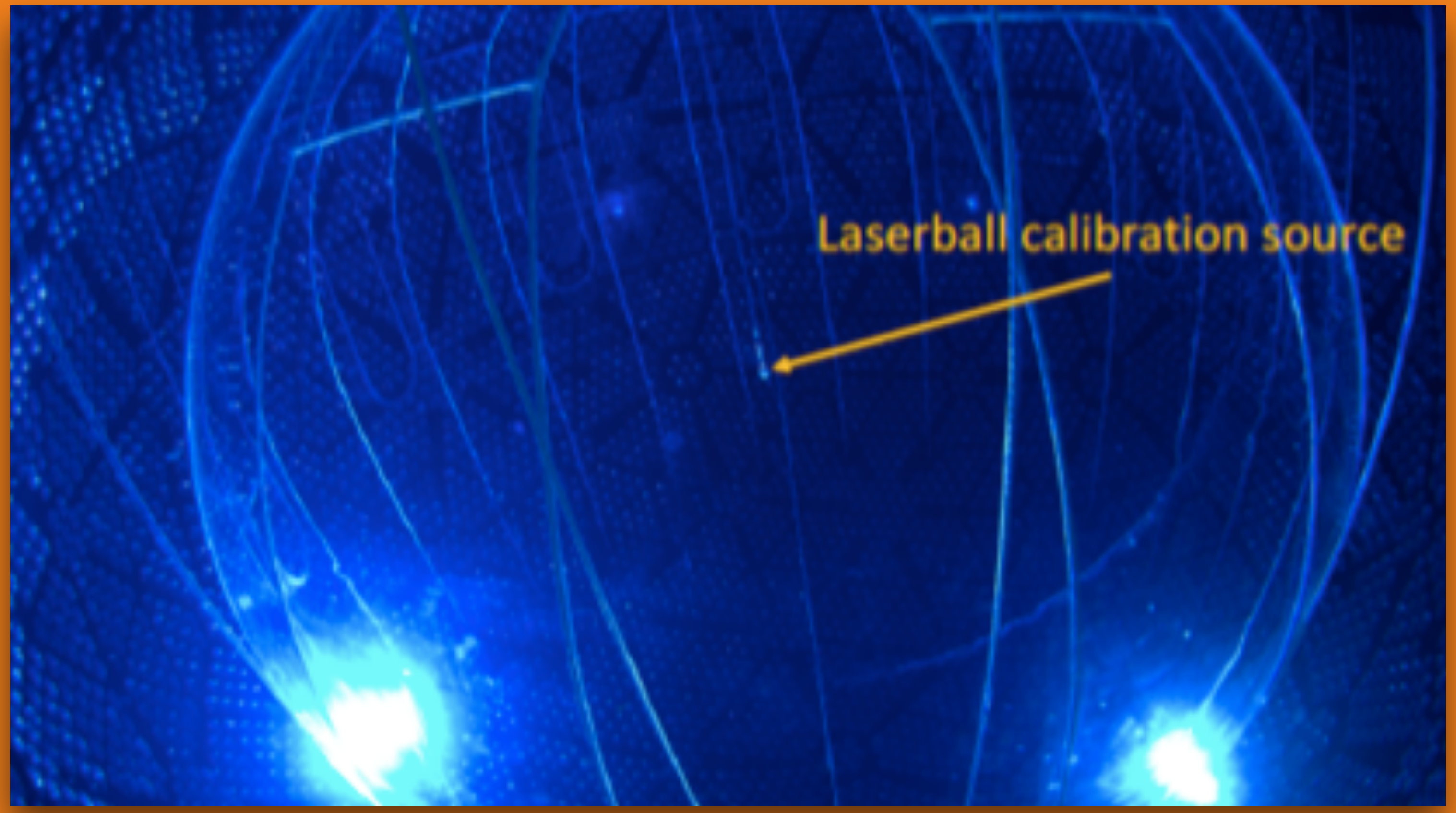


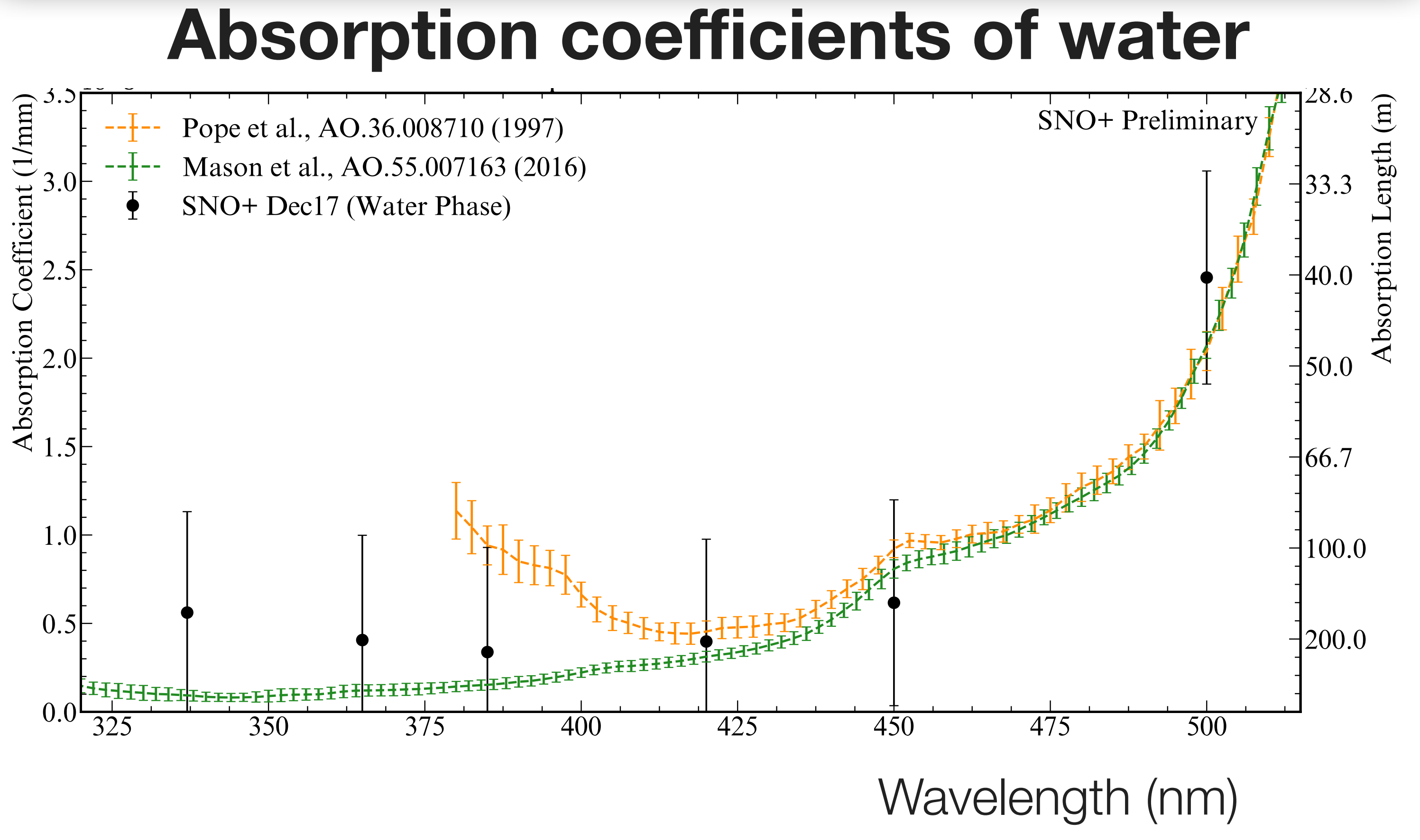


Detector calibrations

See Martti Nirkko's slides!

Water phase: measure **absorption** coefficient with light-diffusing "**laserball**" and underwater camera





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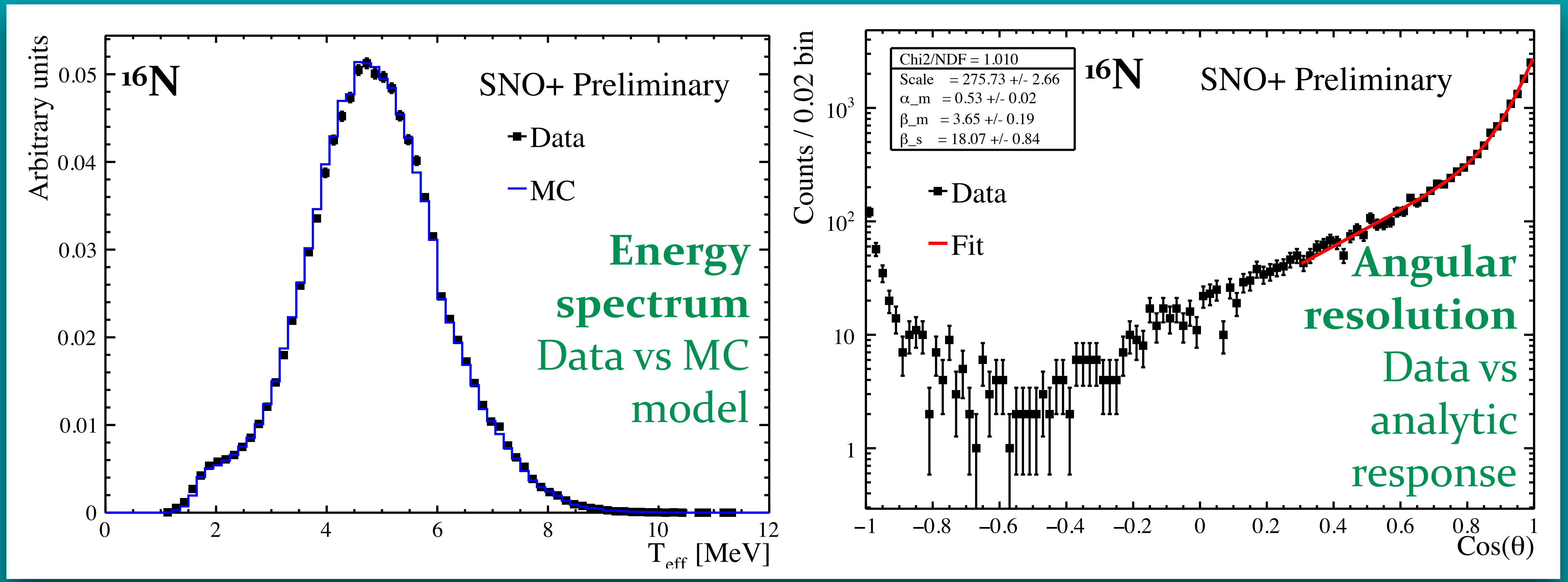

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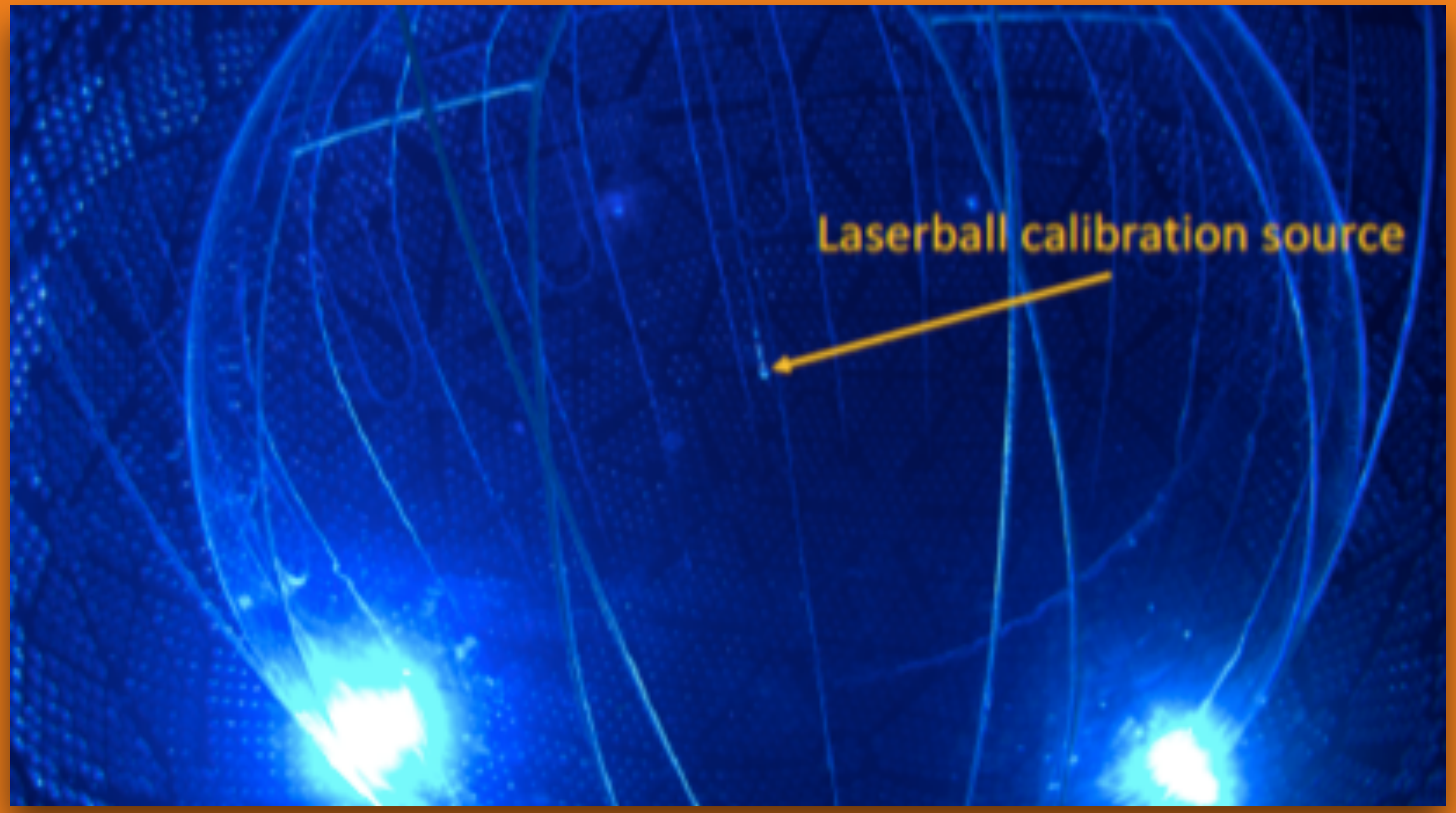

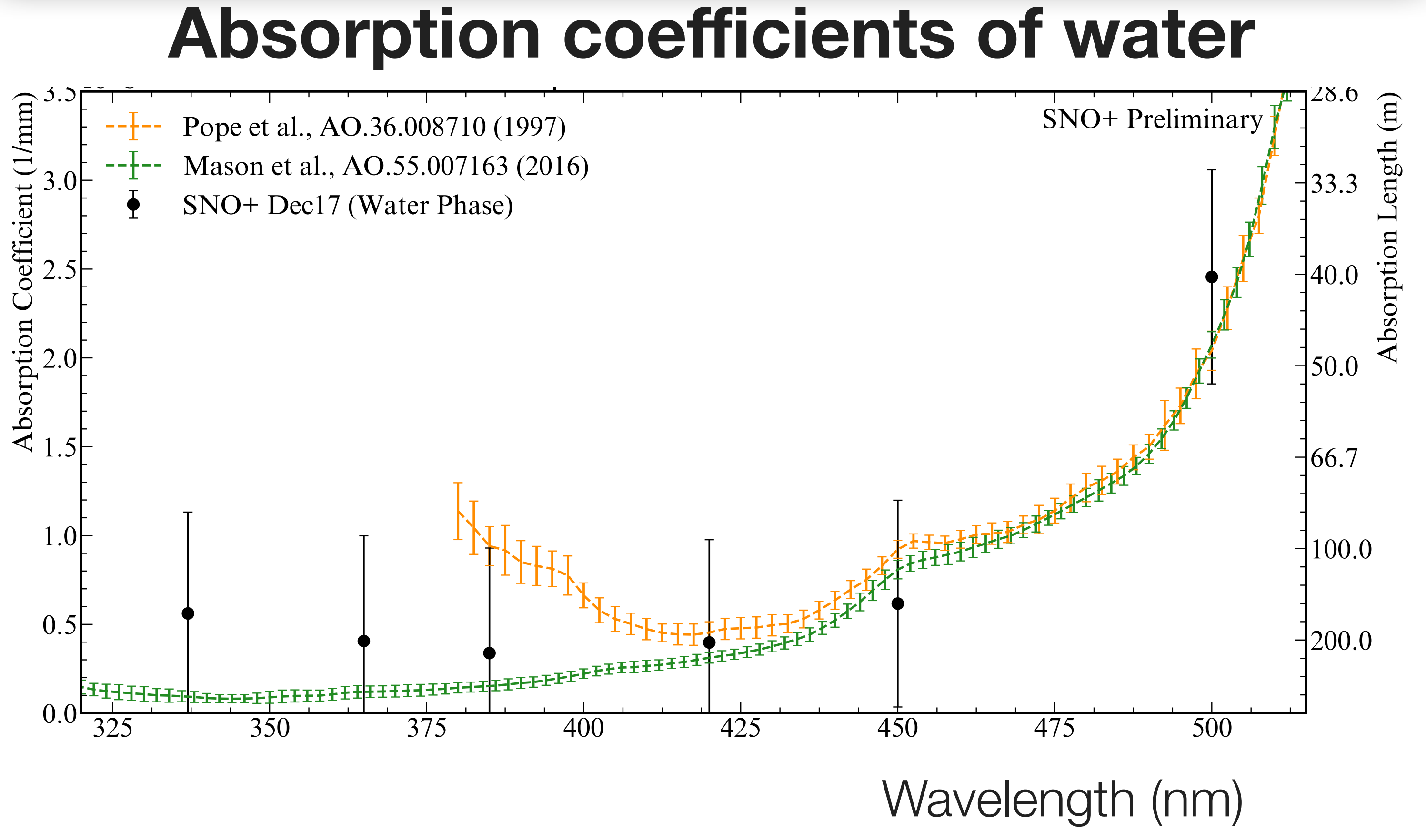

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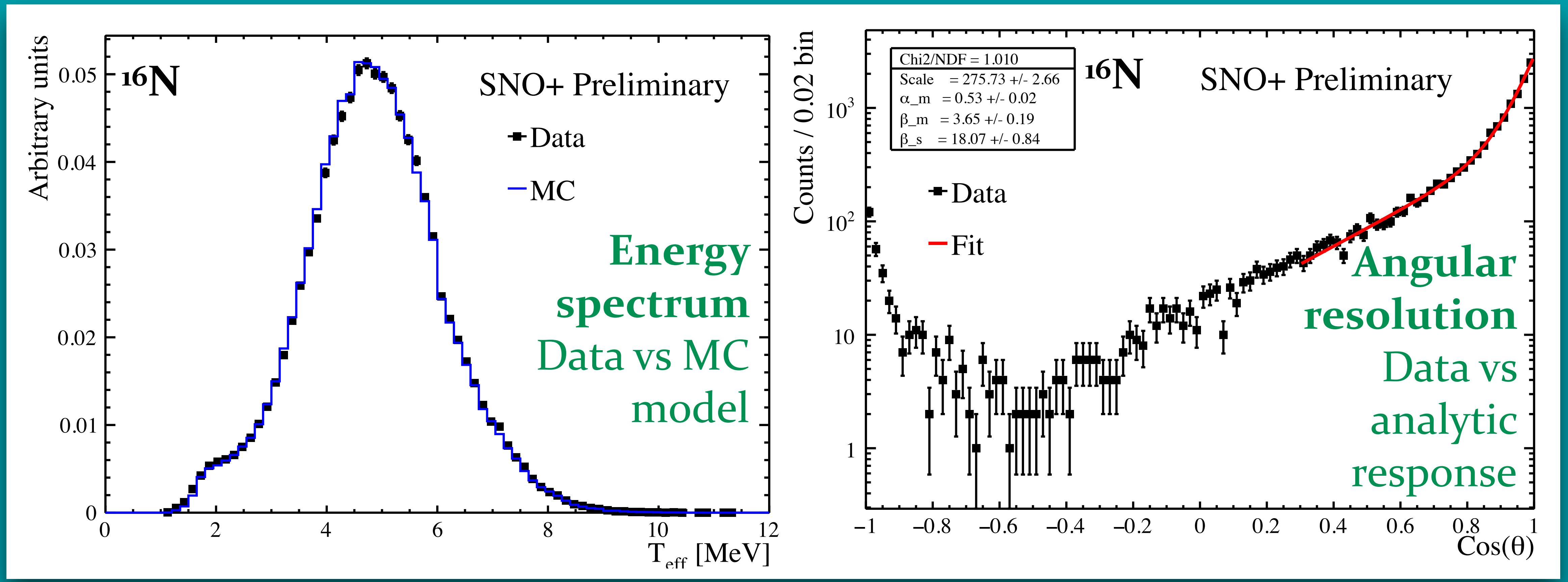

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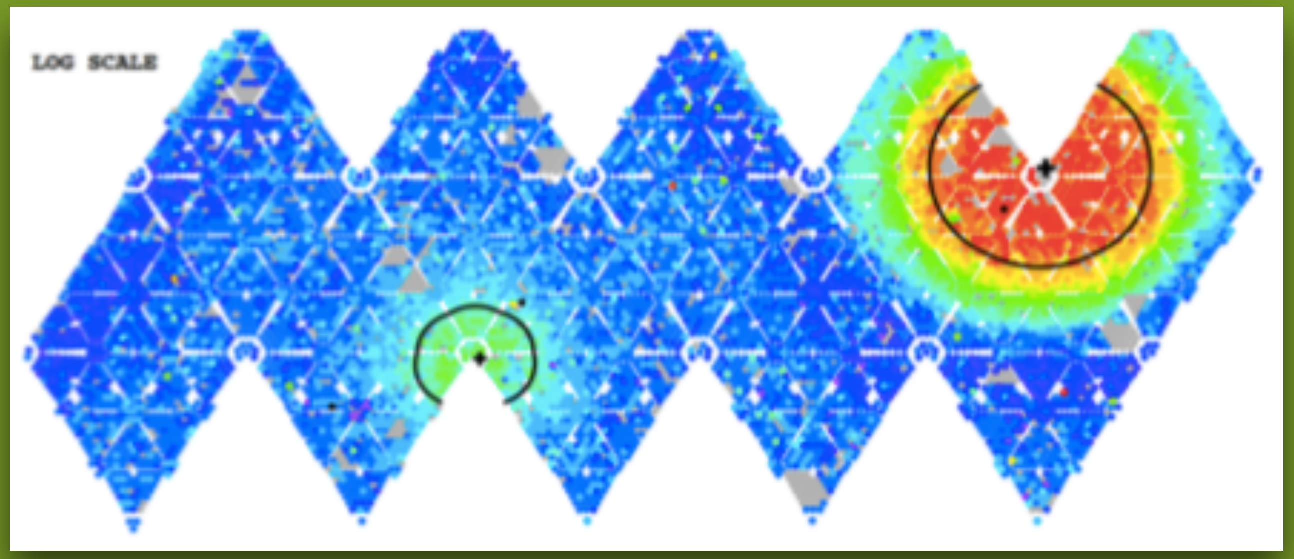

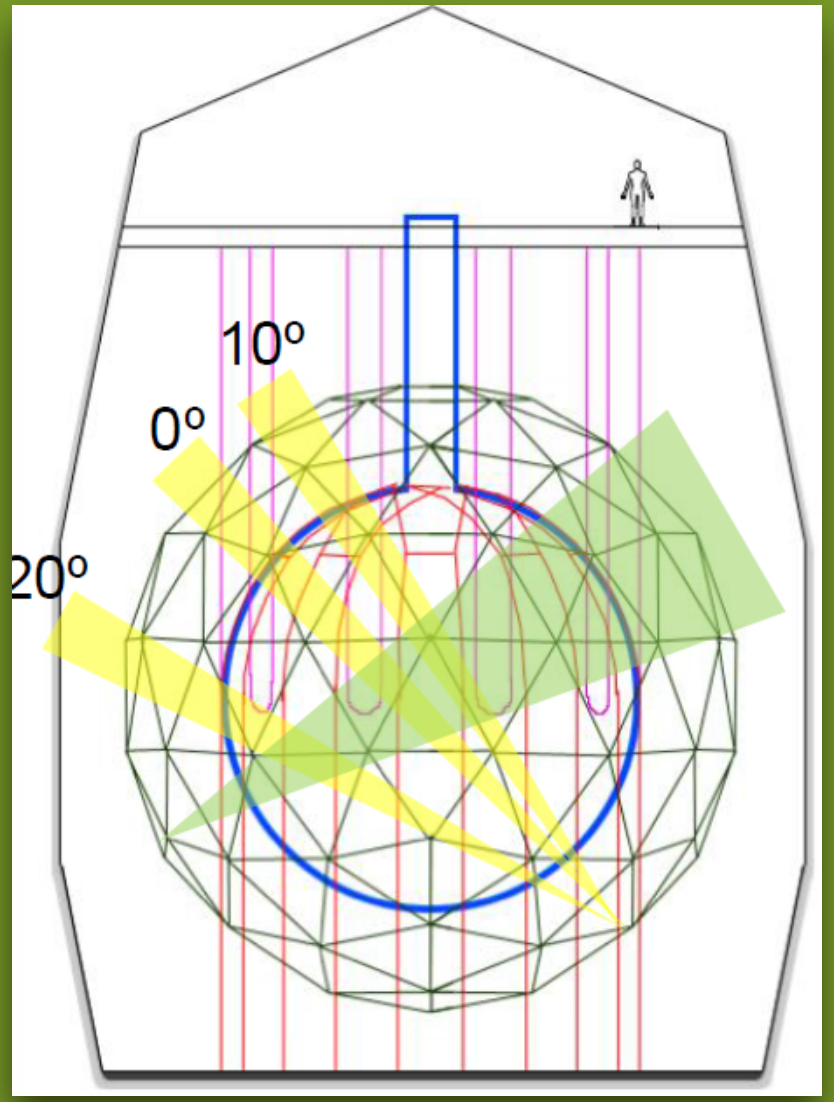

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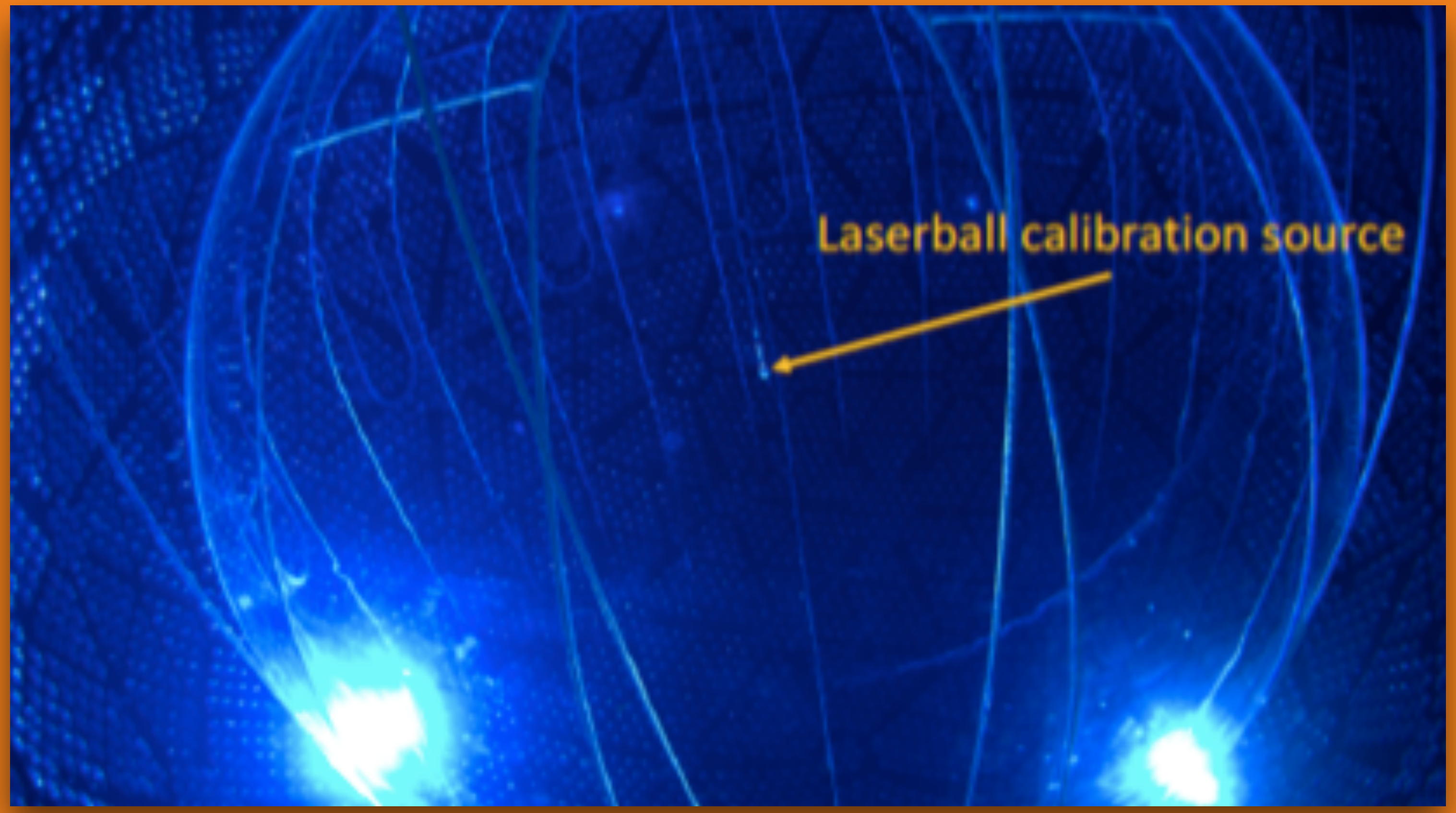

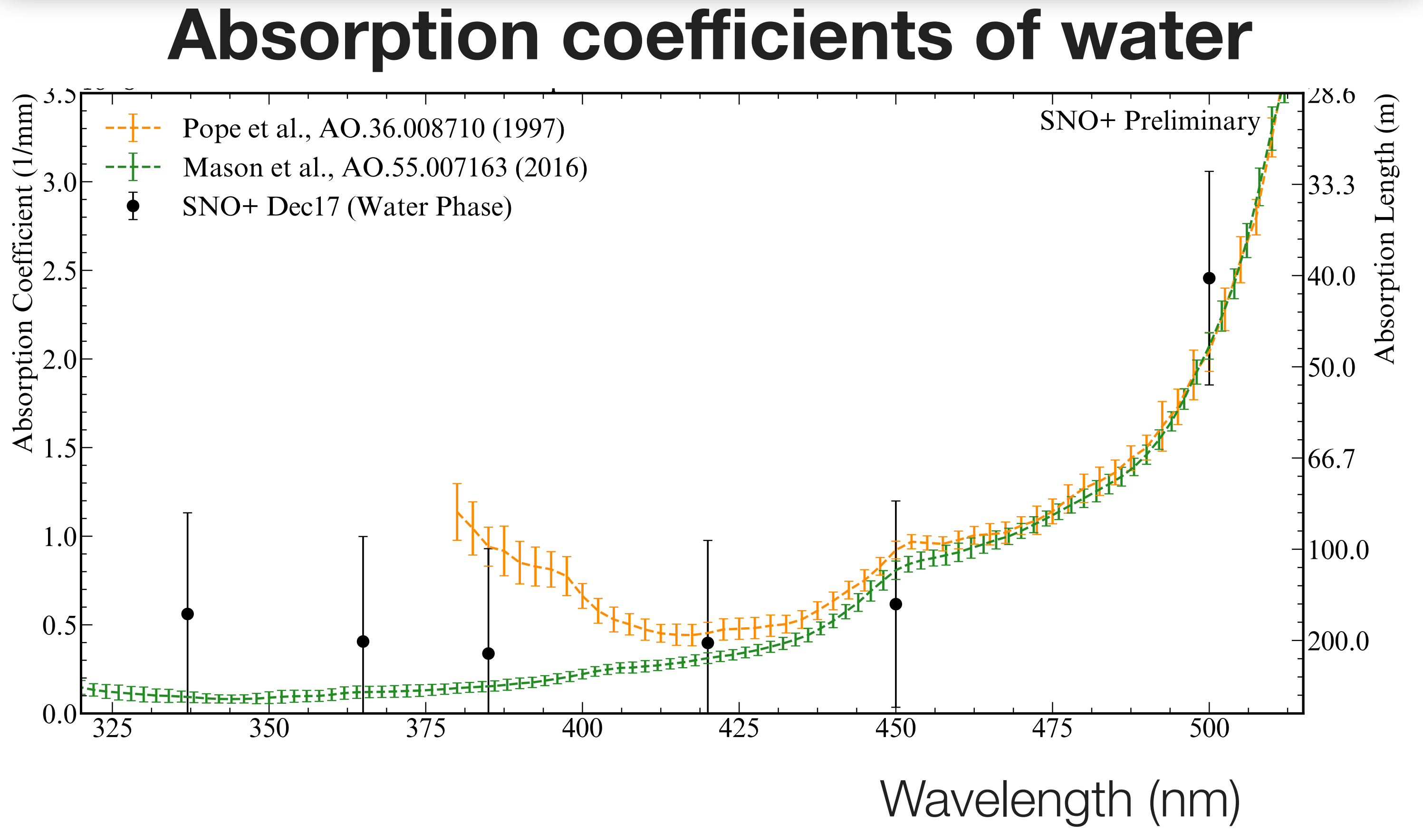

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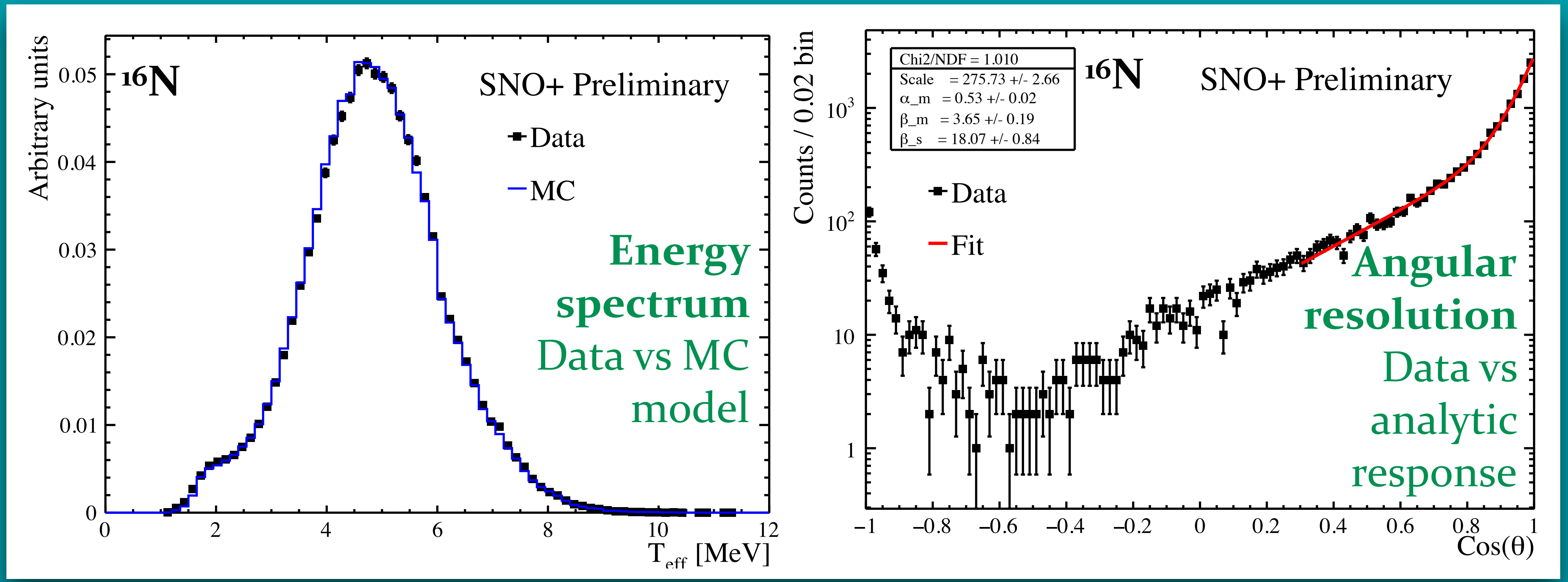

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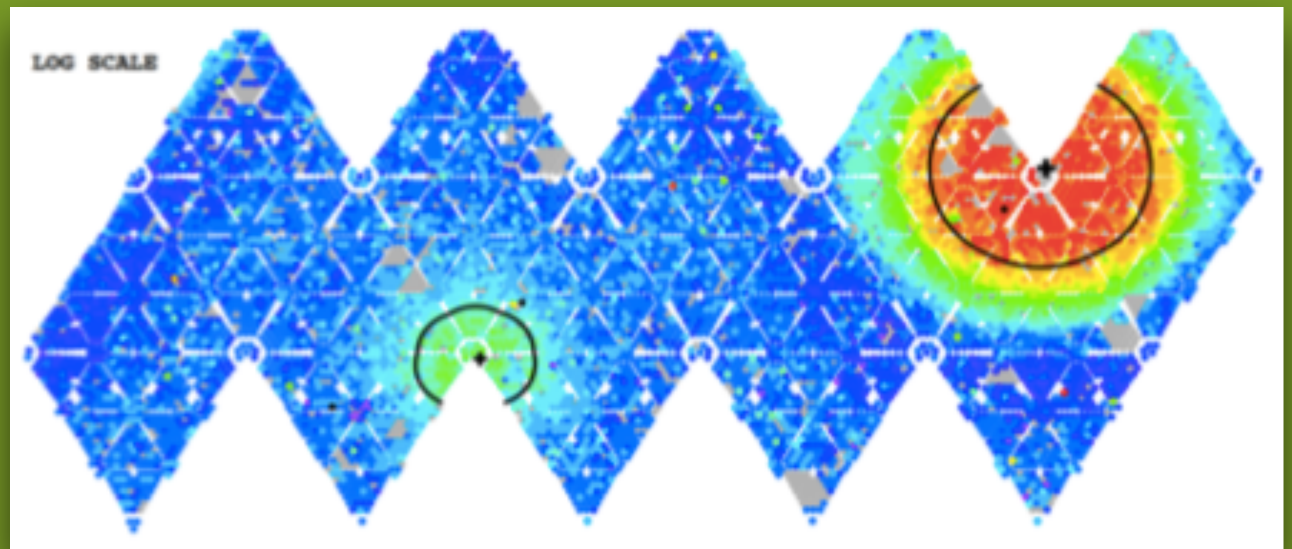

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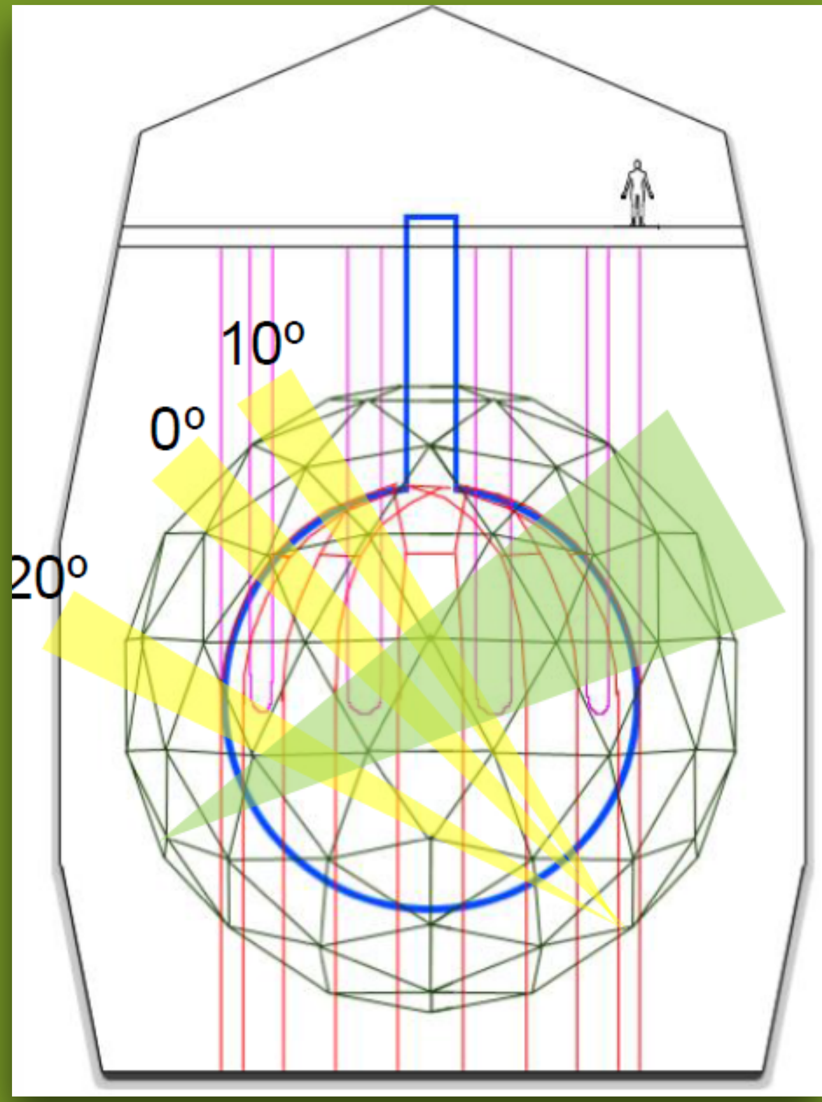

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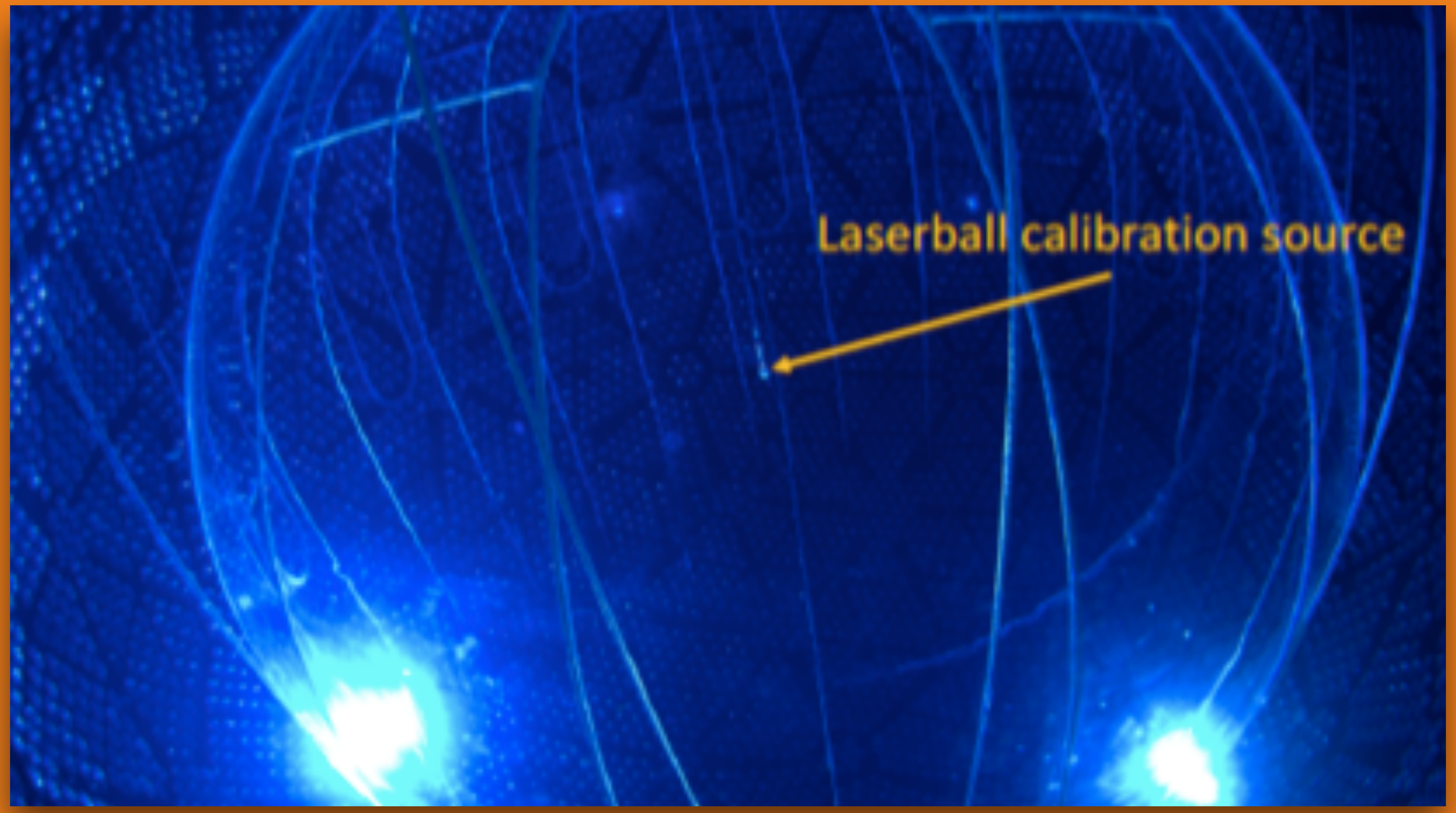

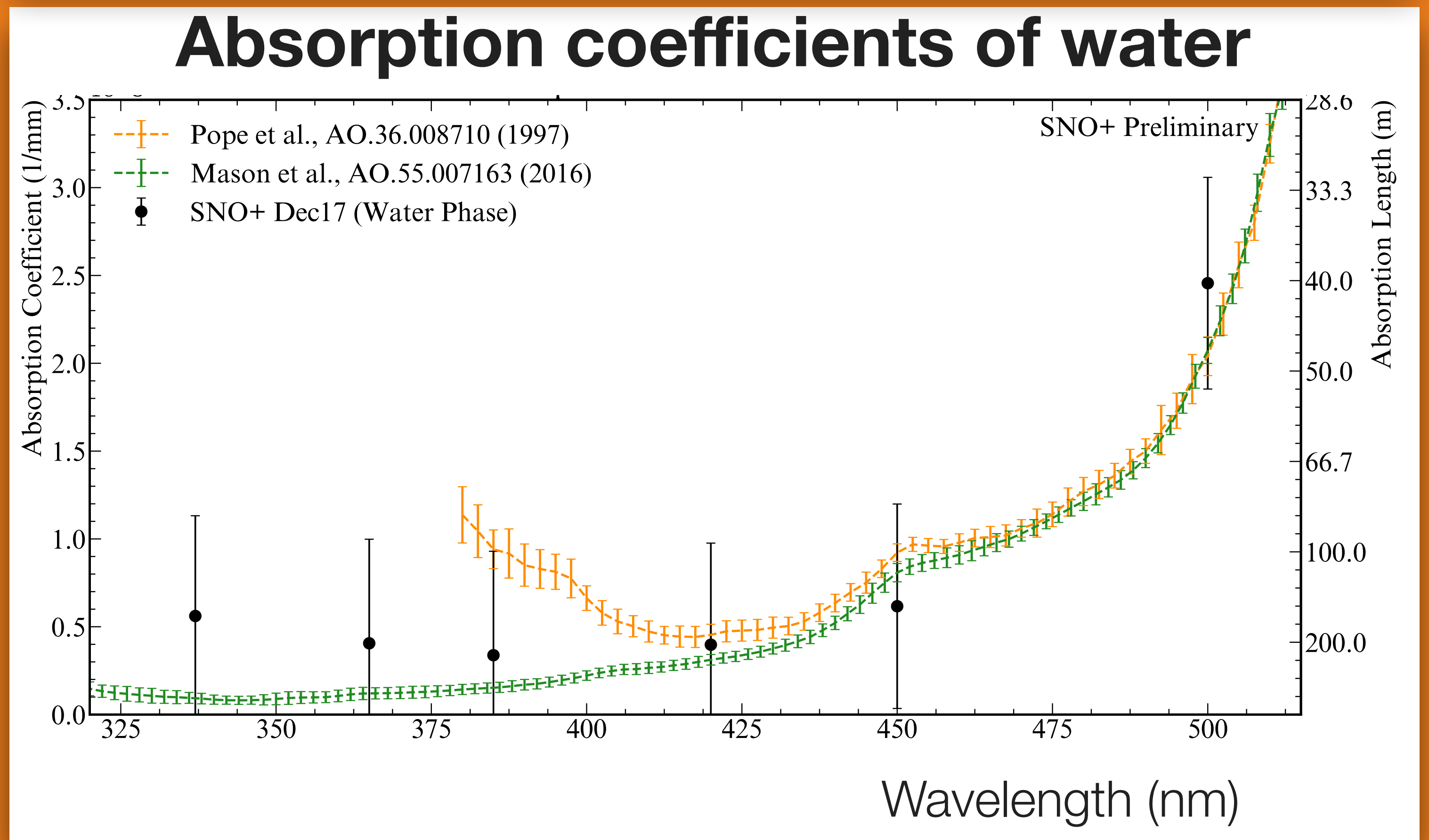

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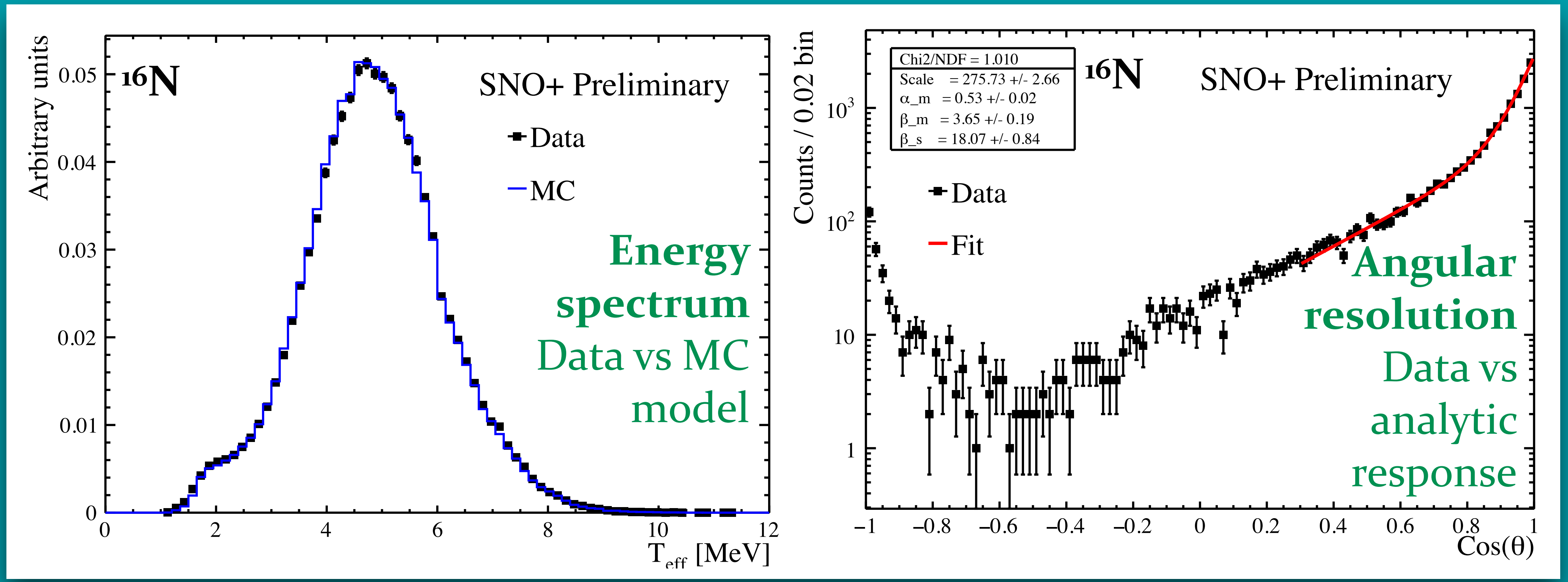

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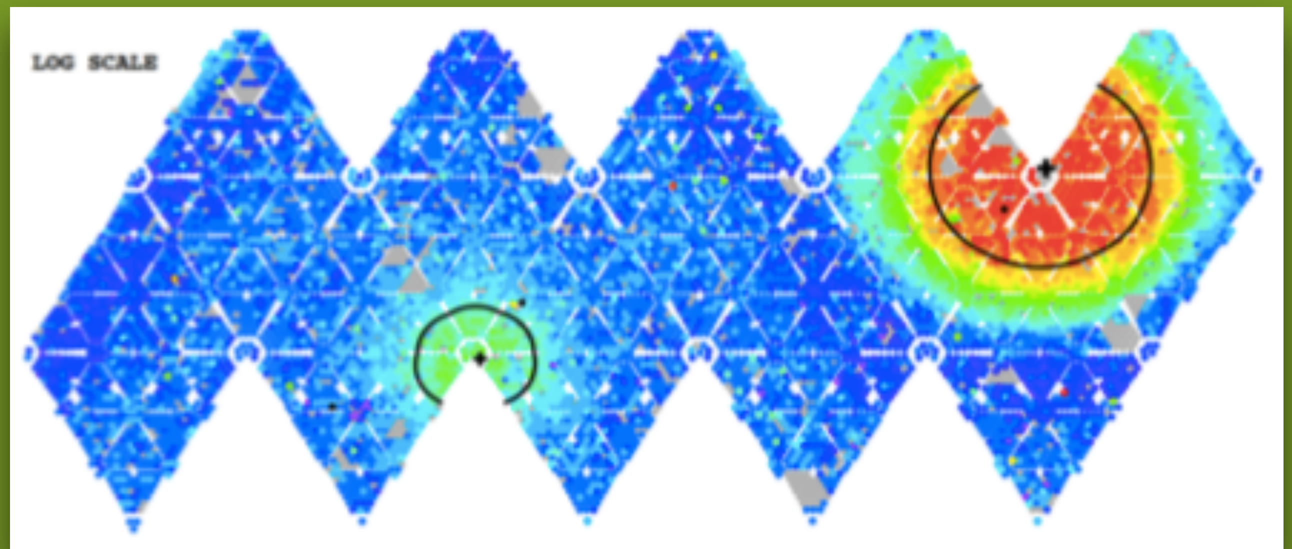

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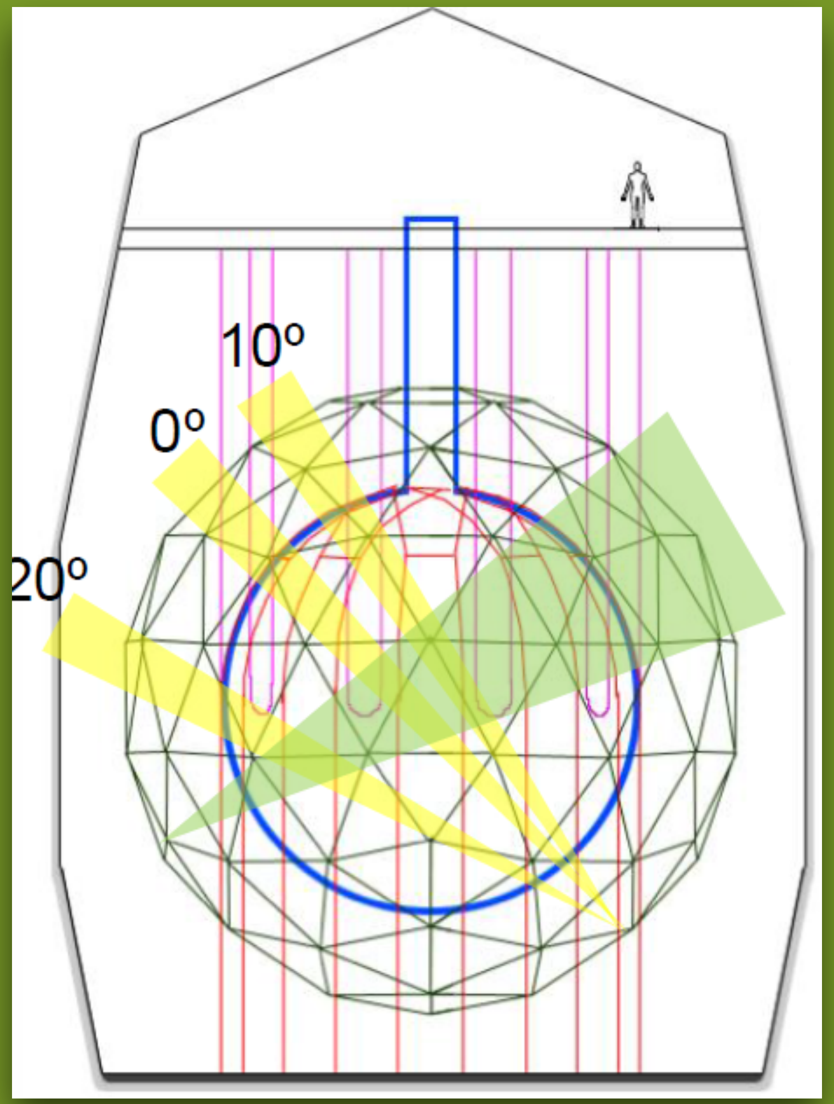

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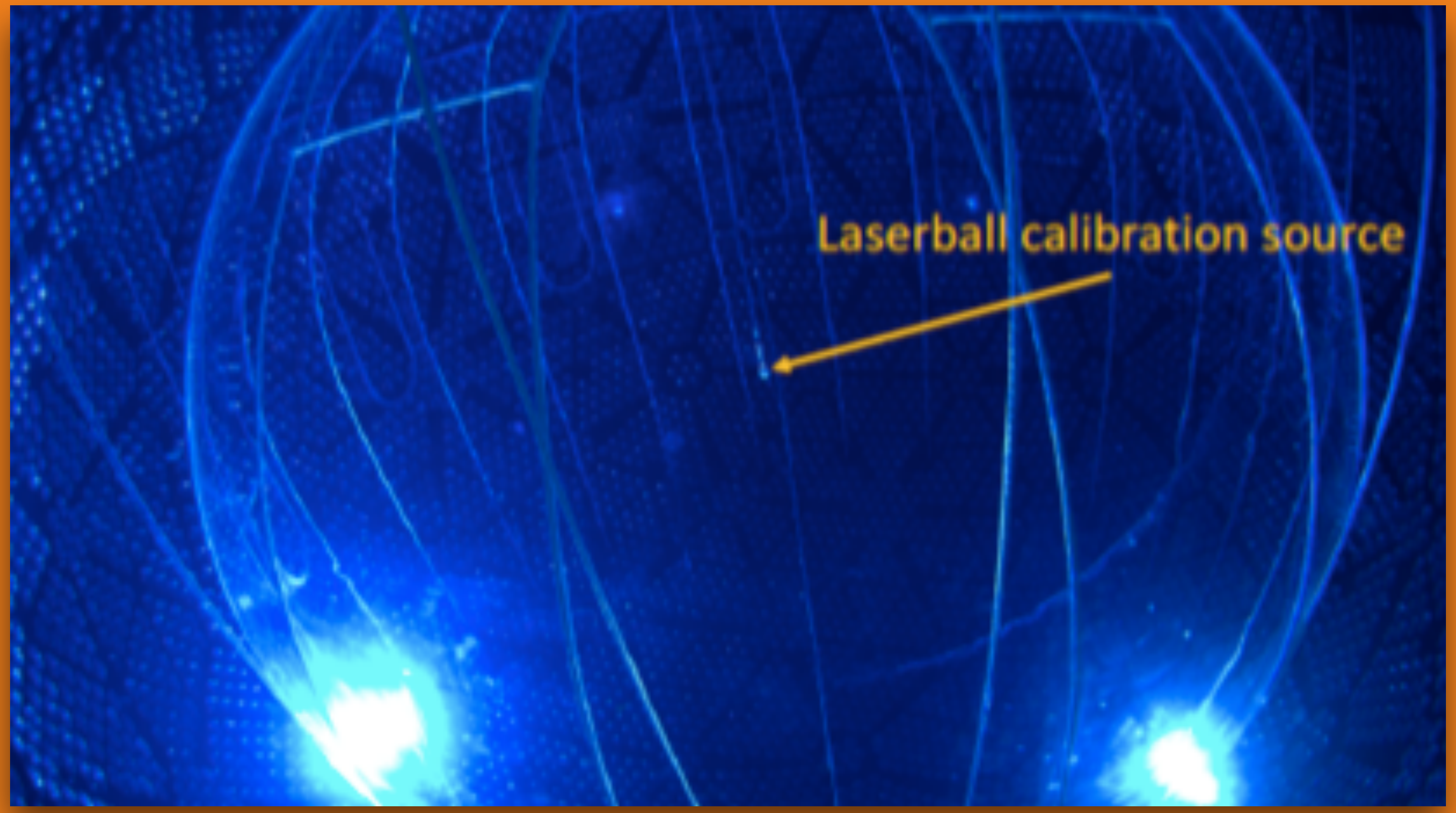

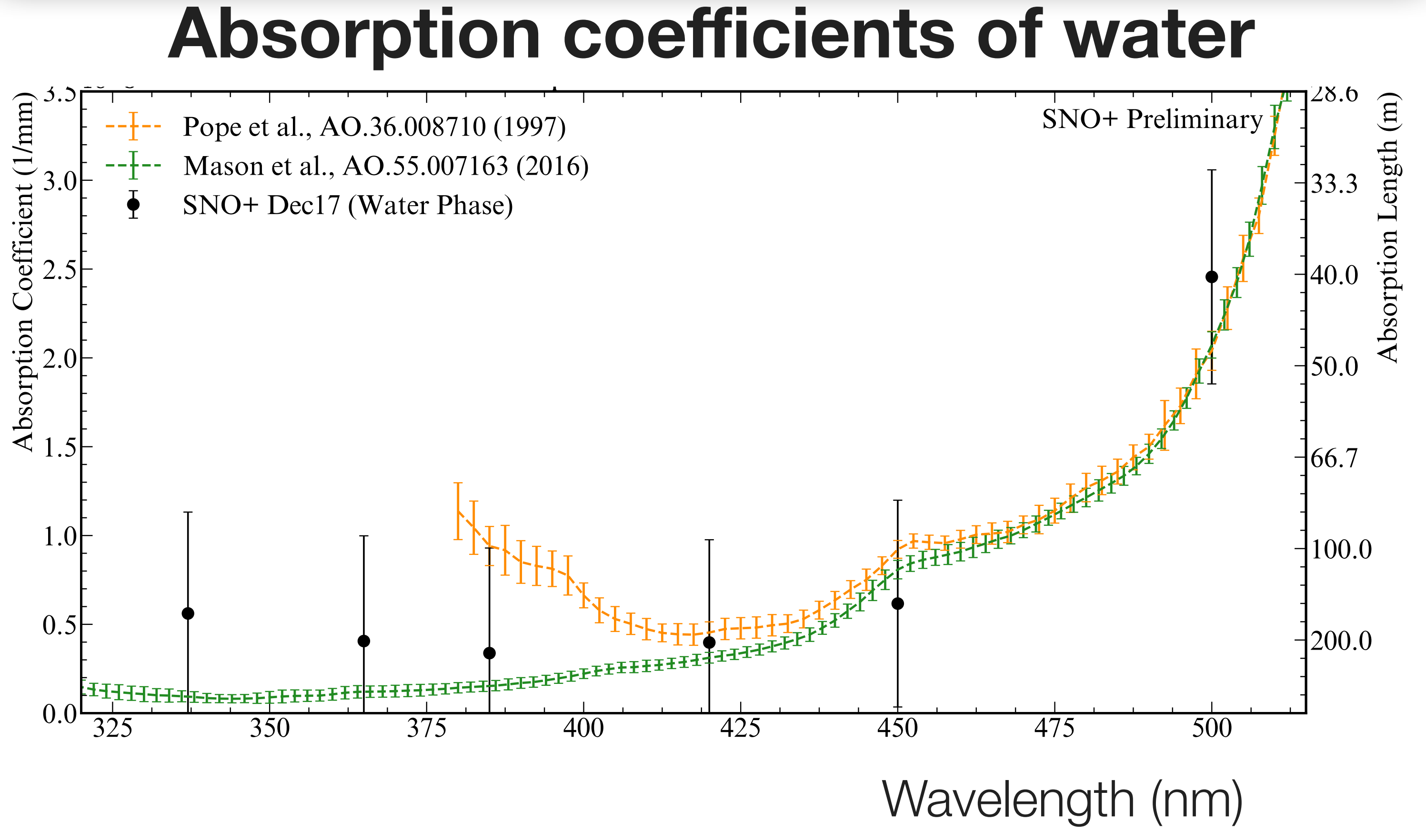

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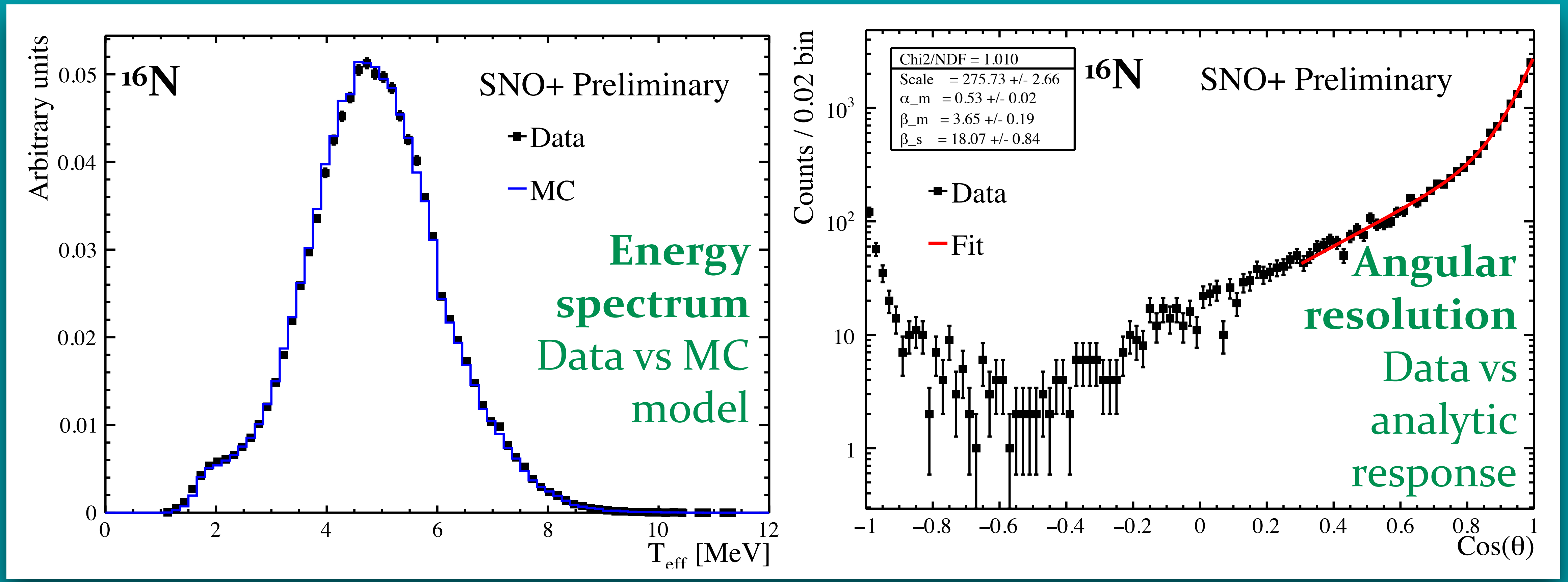

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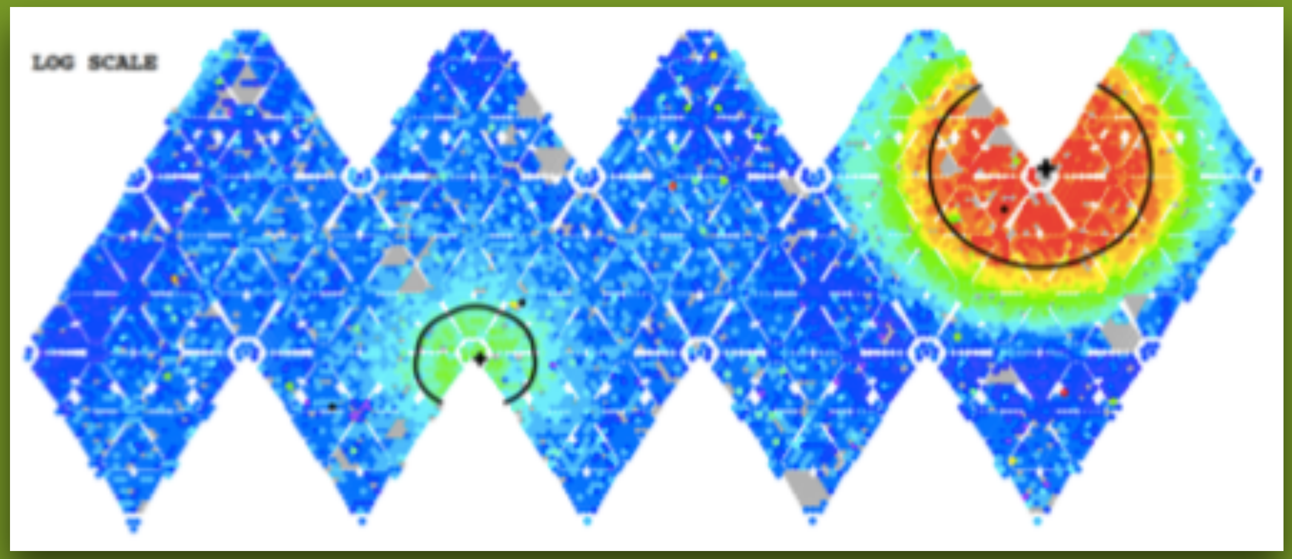
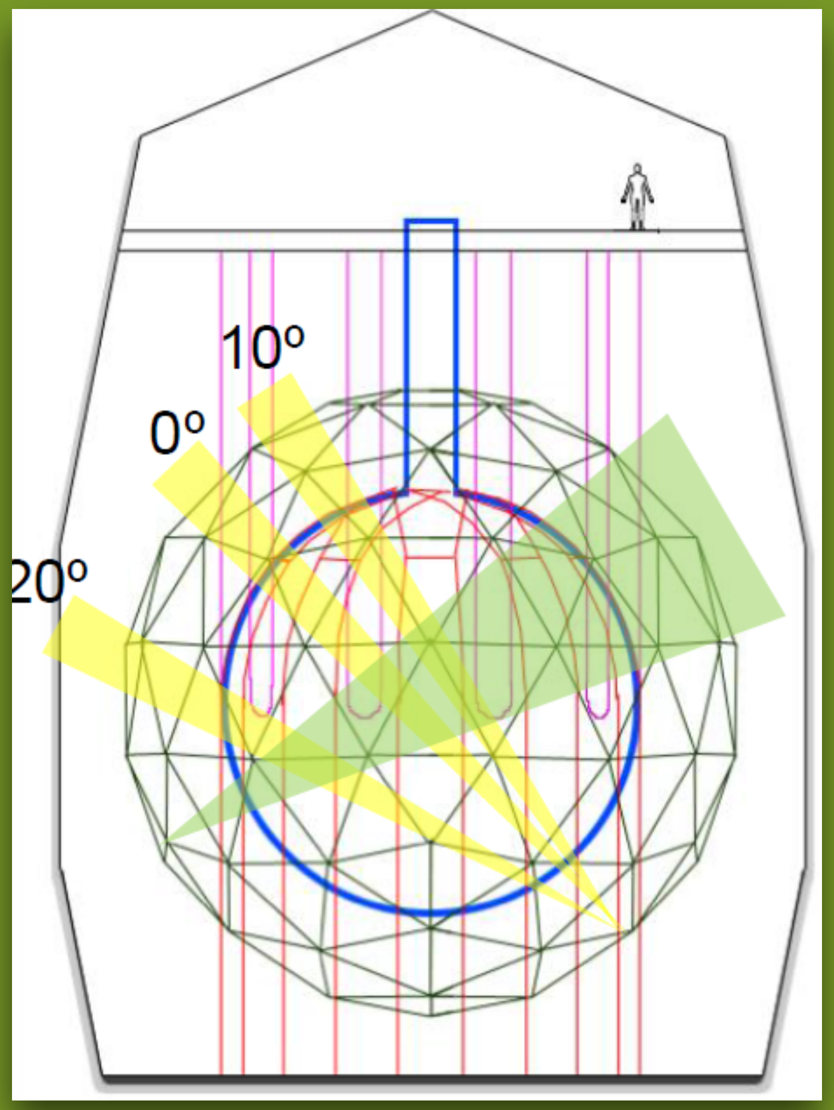


Timing and Monitoring: **TELLIE**
Attenuation Module:



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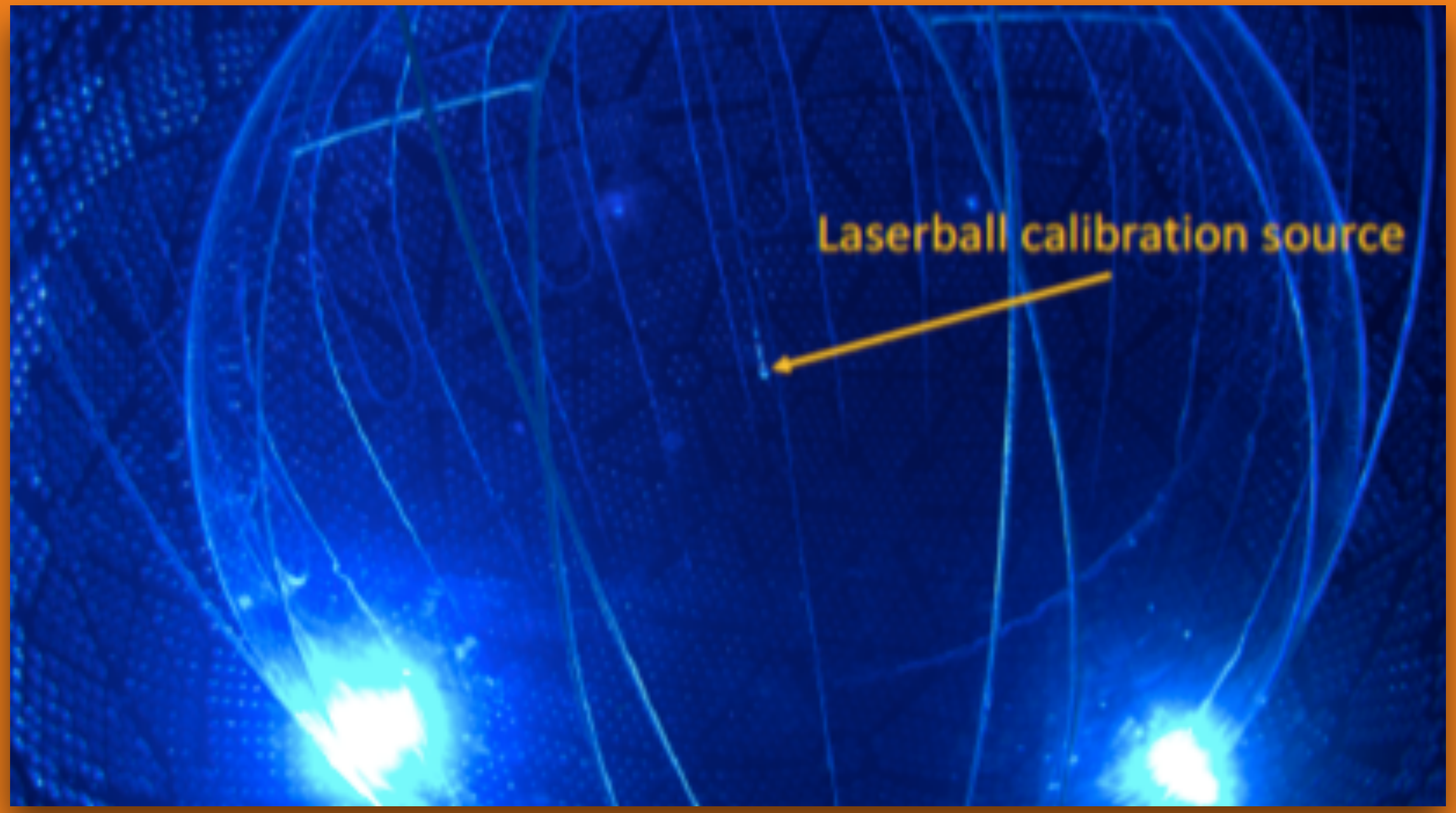

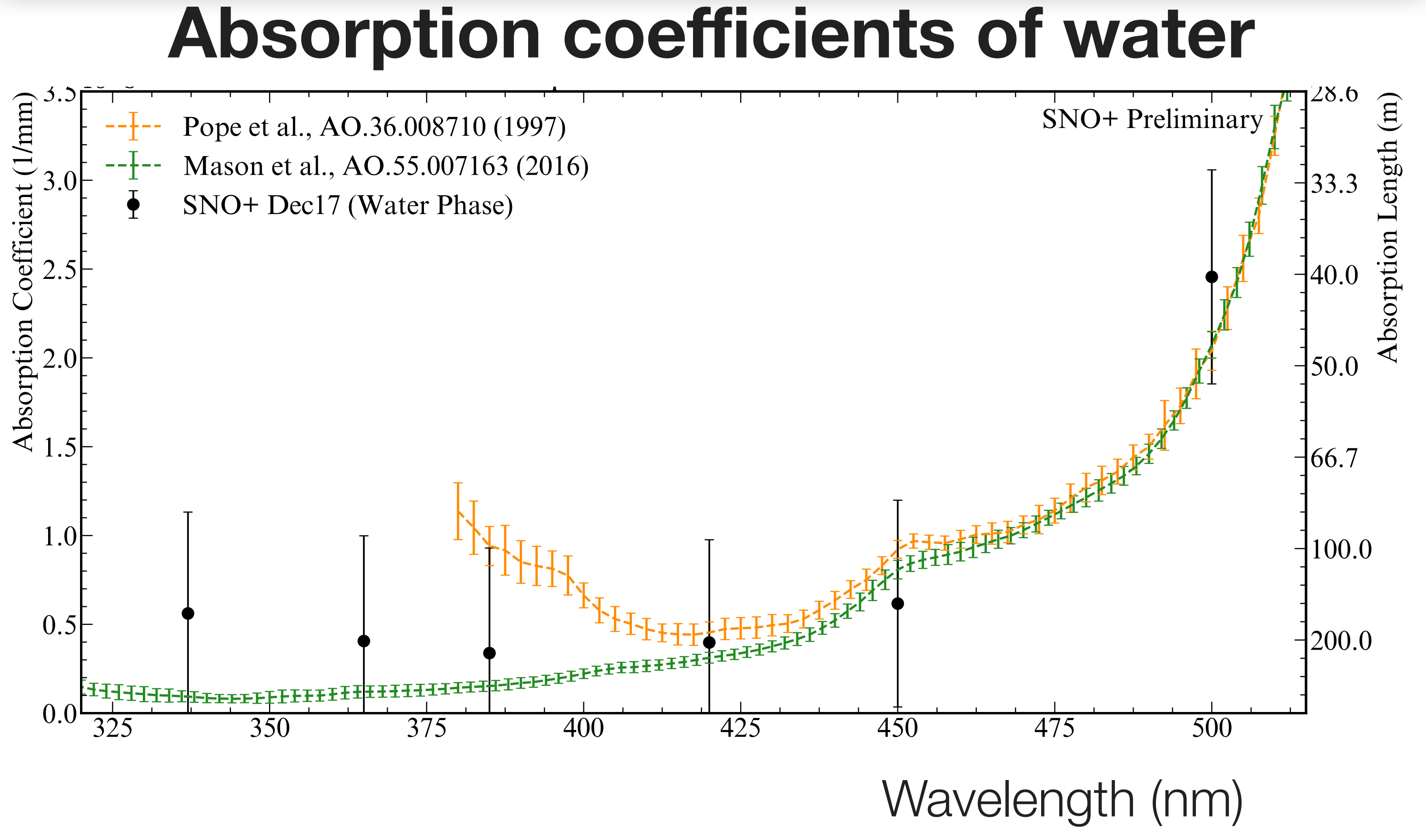

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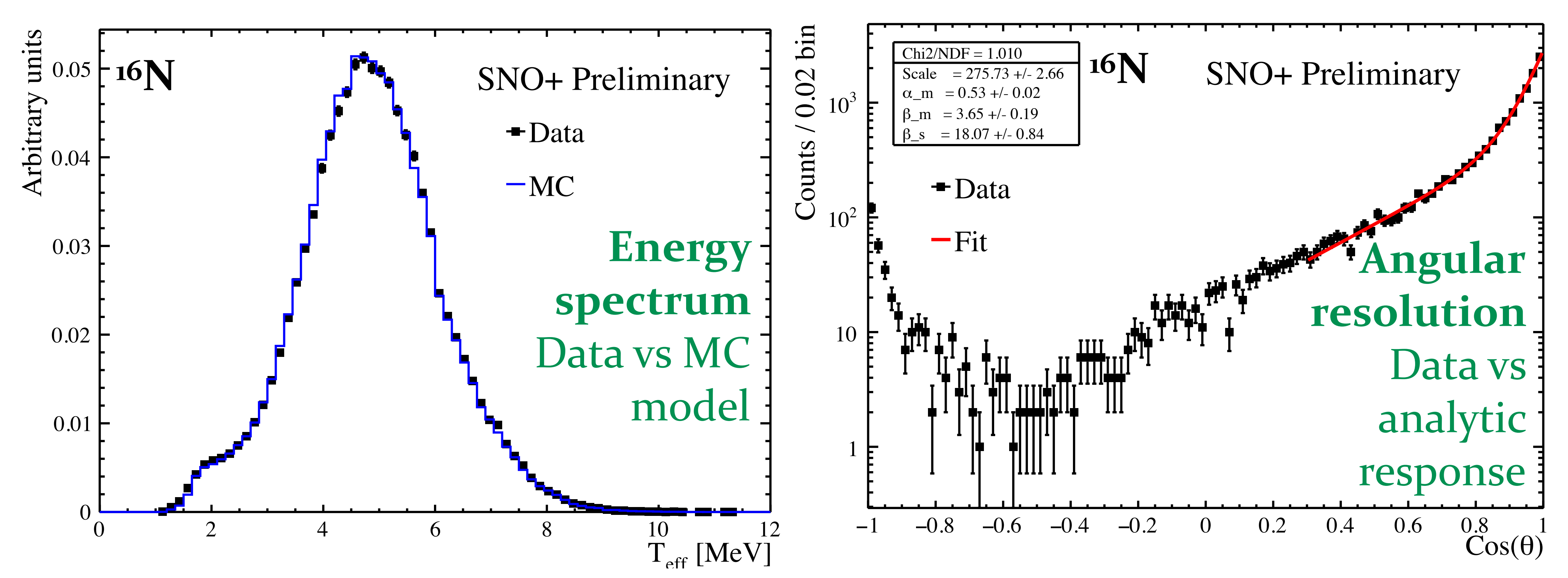

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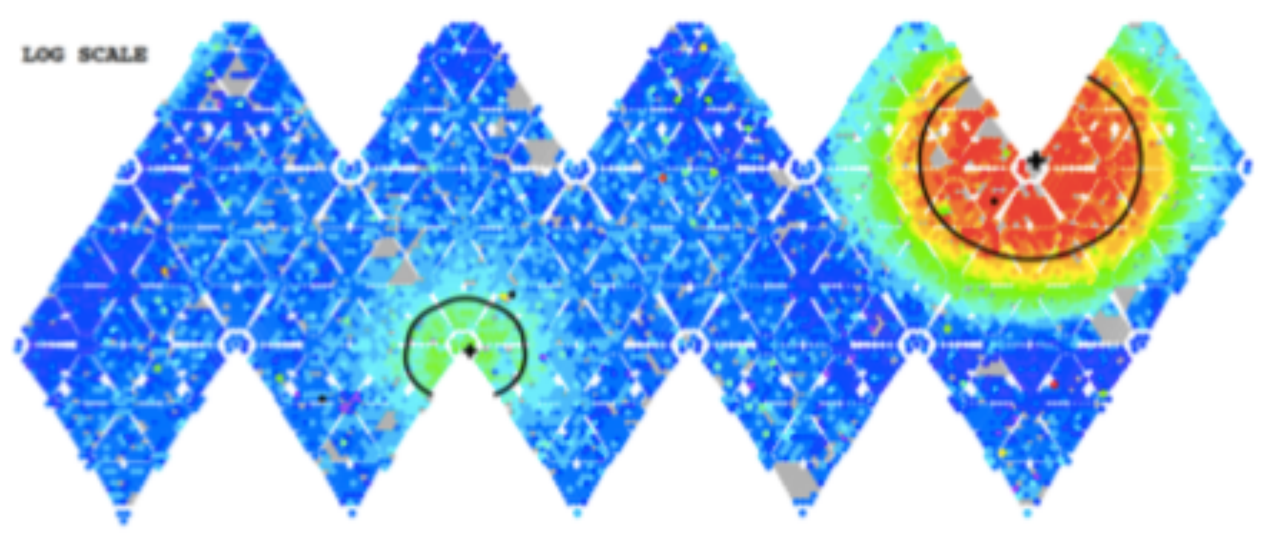
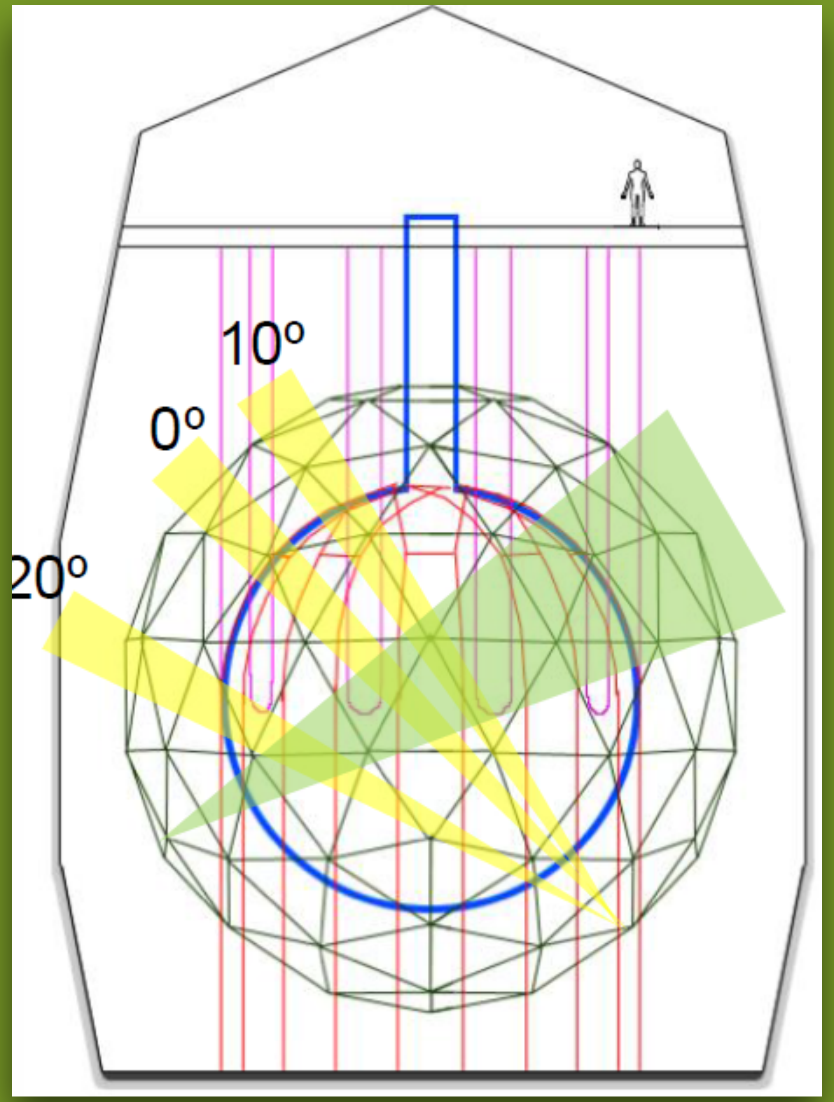


Timing and Monitoring: **TELLIE**
Attenuation Module: **AMELLIE**



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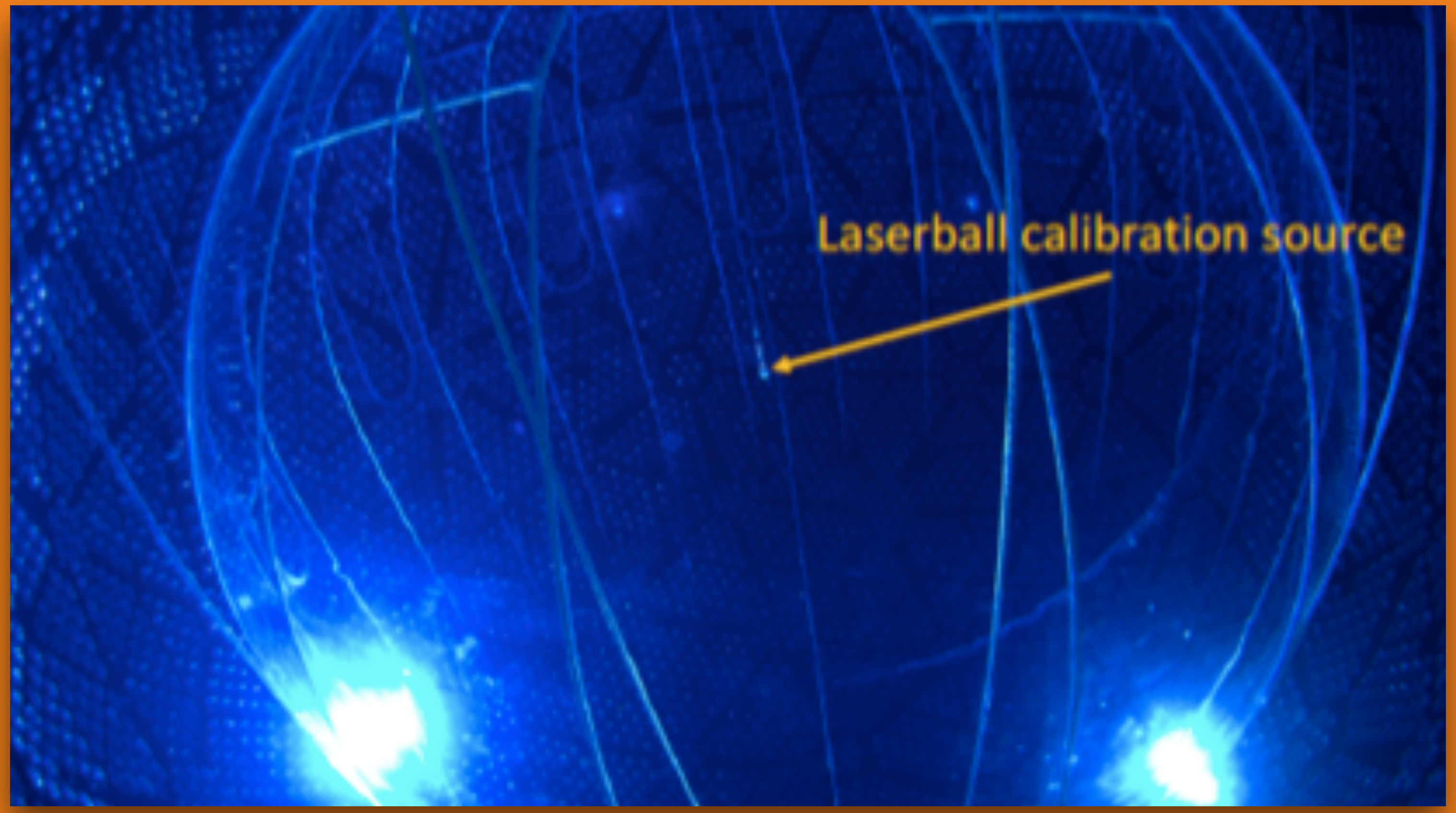

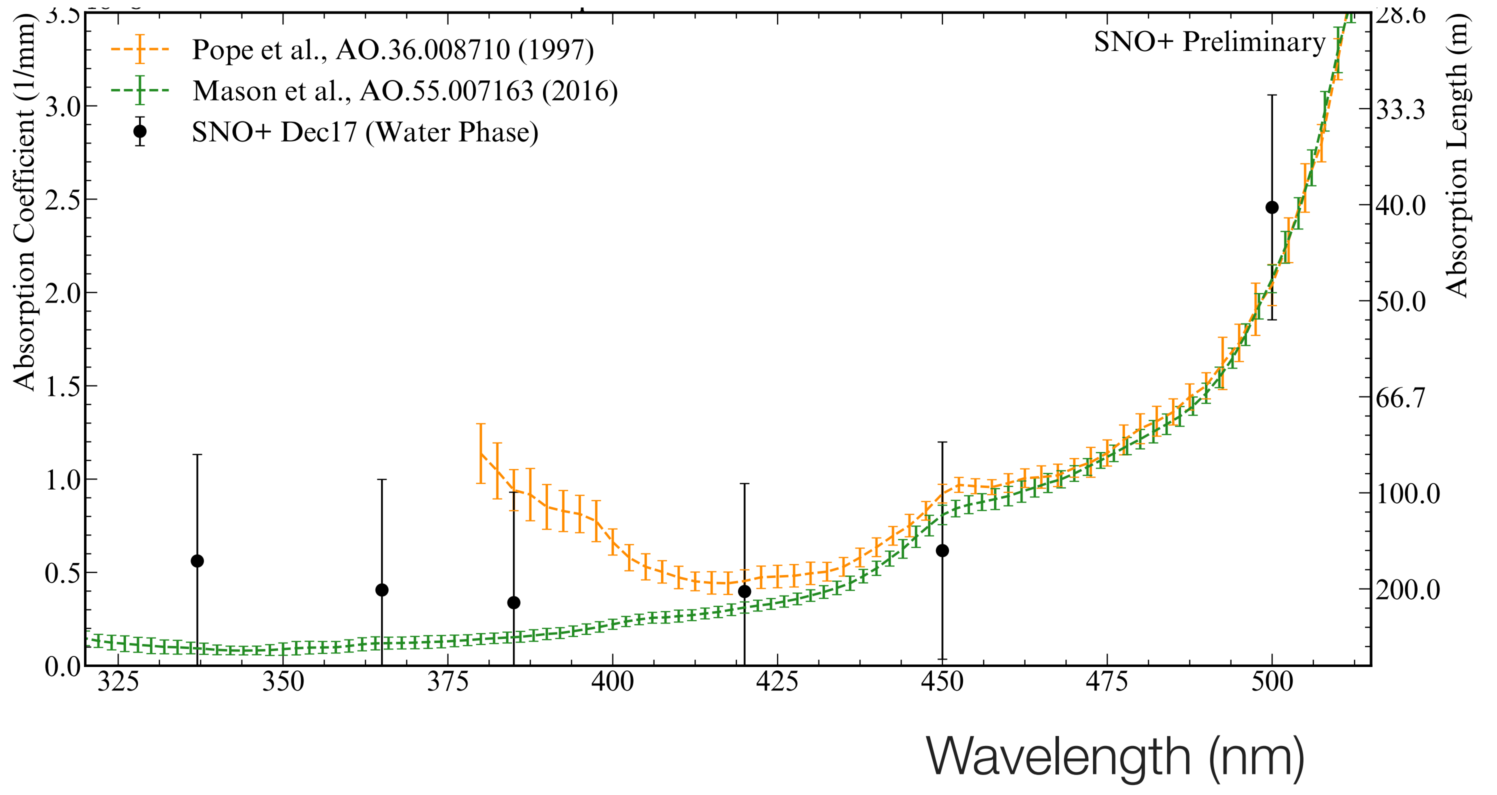

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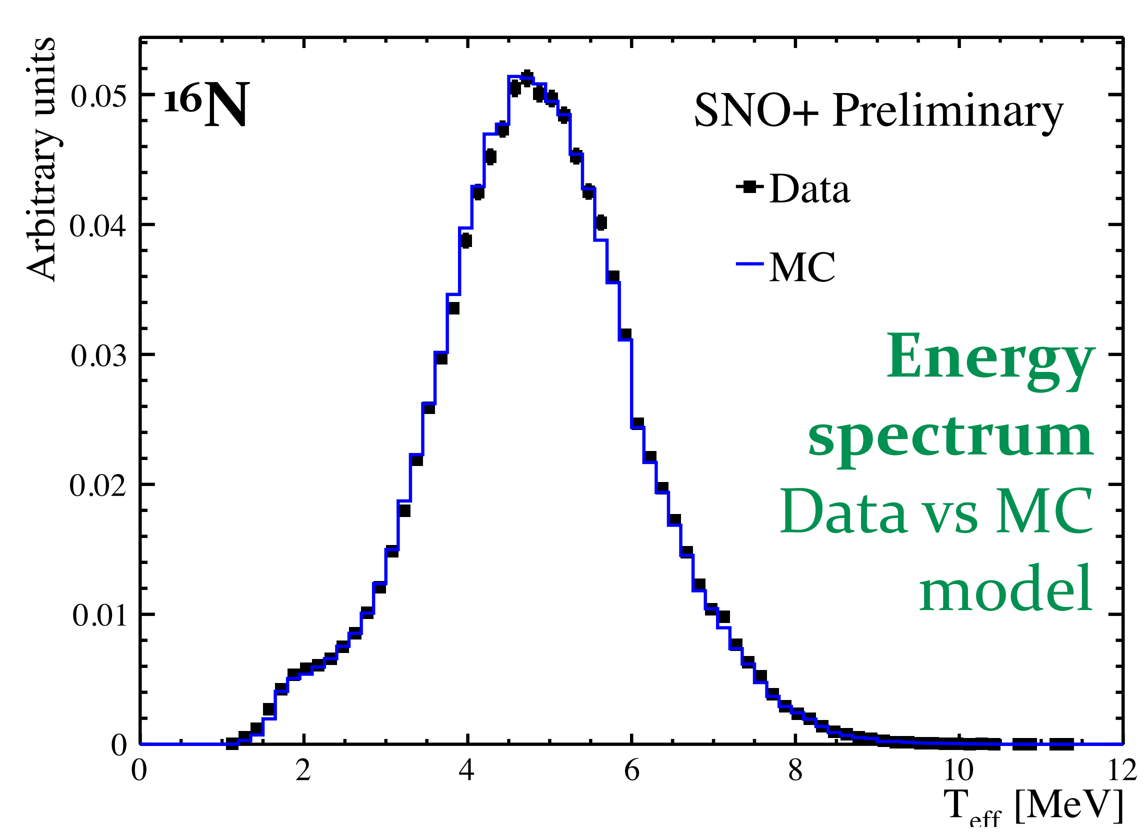

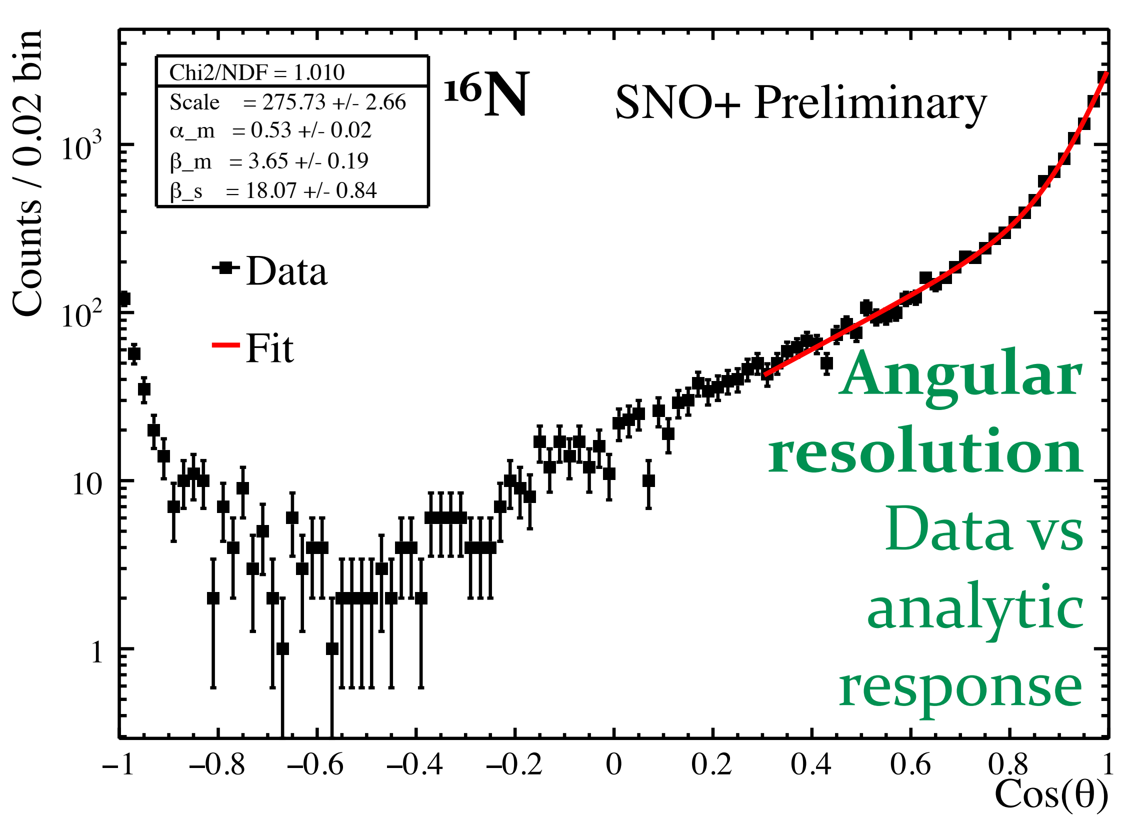

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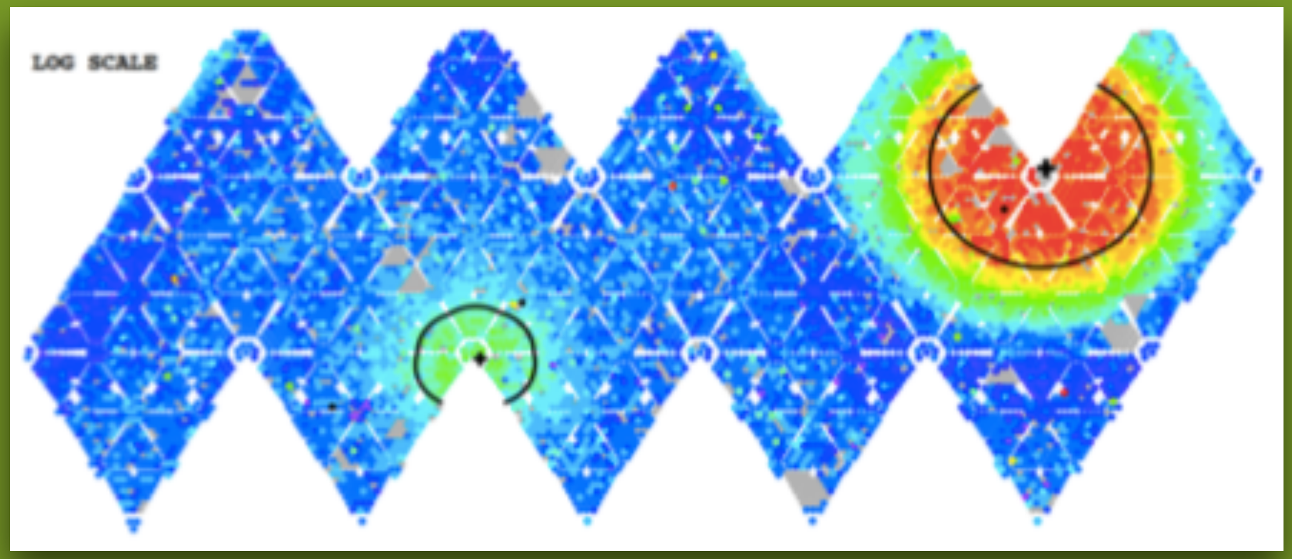
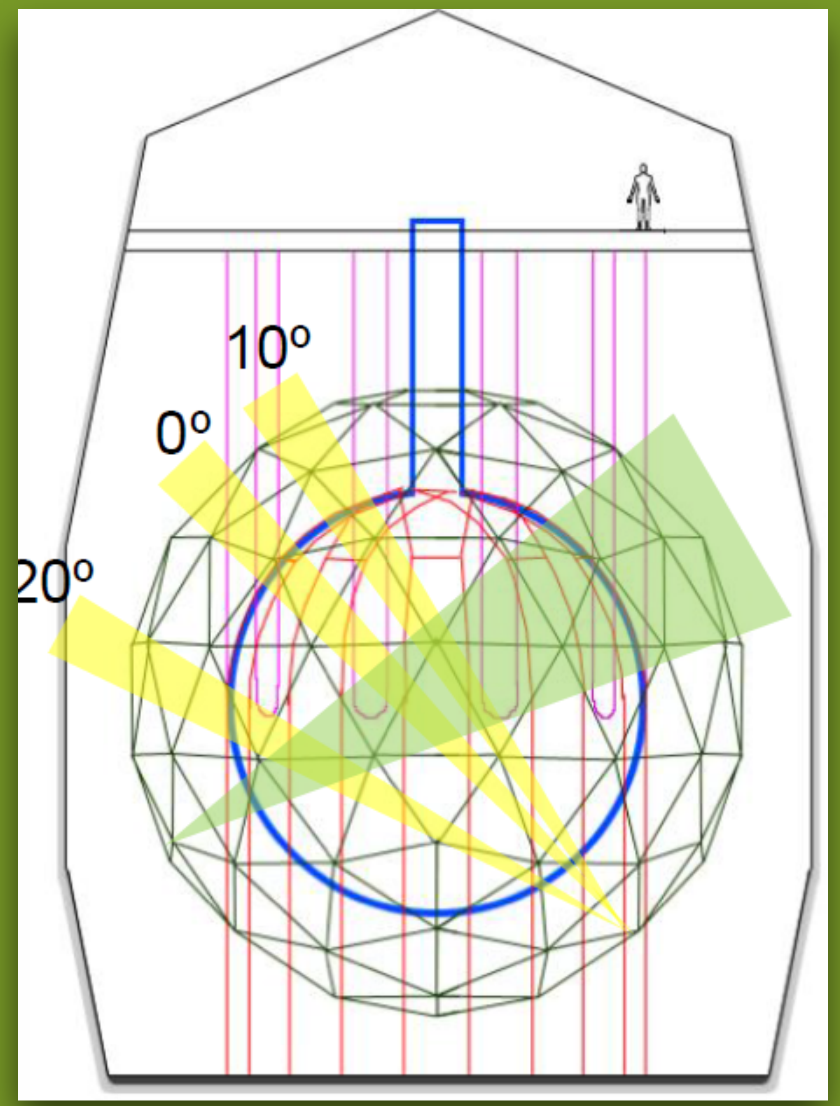


Timing and Monitoring: **TELLIE**
Attenuation Module: **AMELLIE**
Scattering Module:



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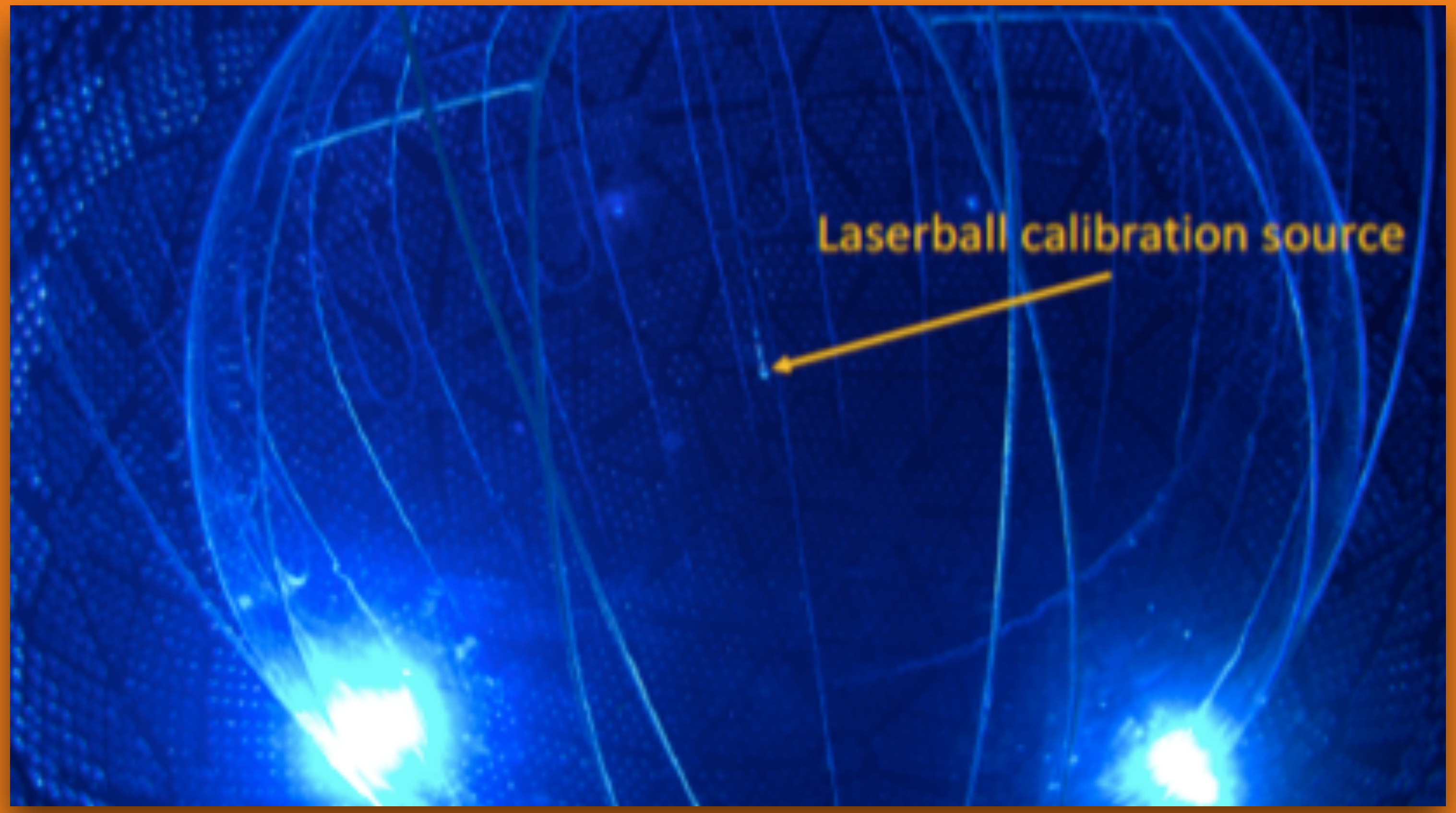

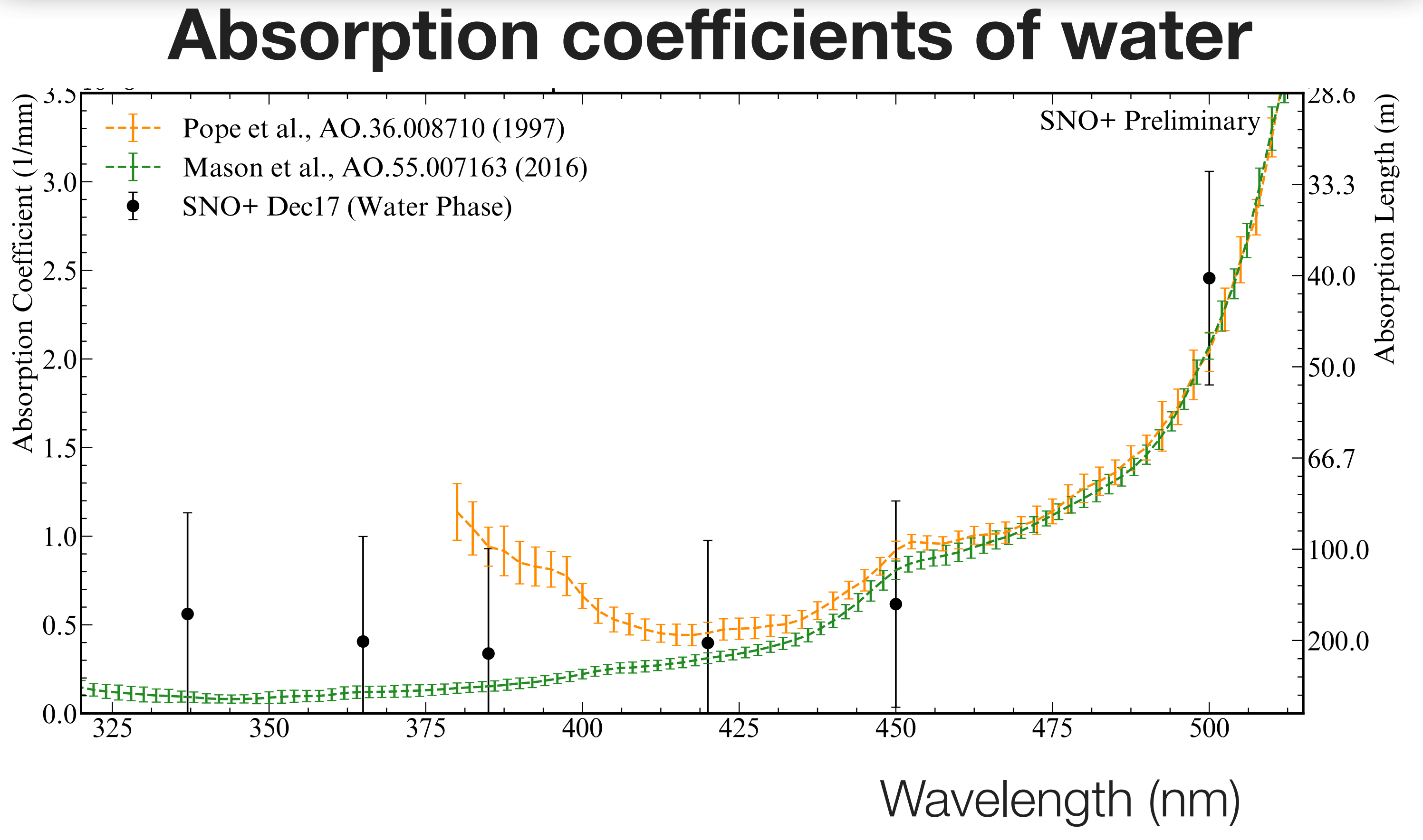

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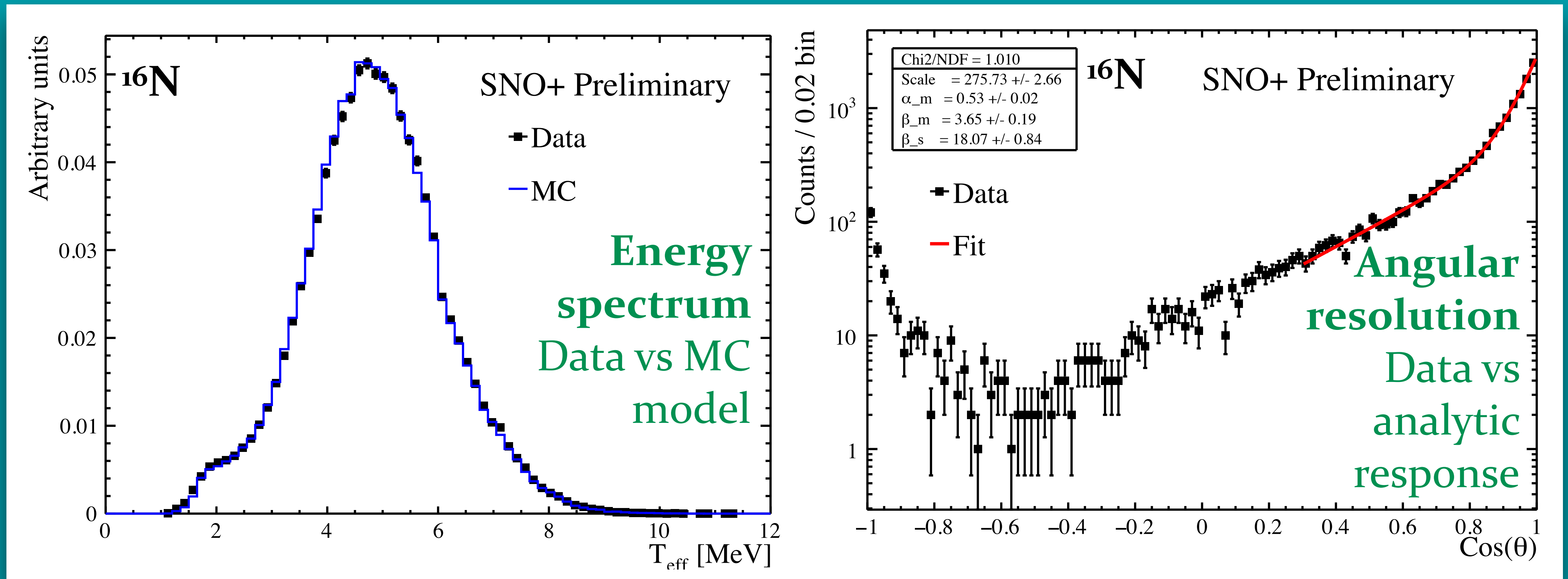

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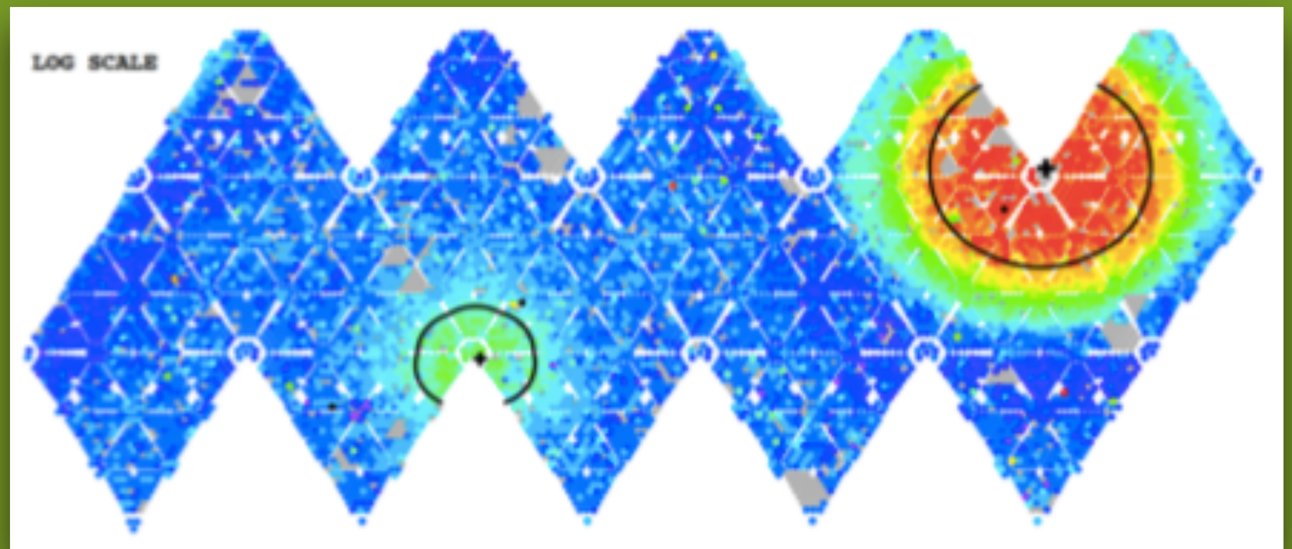
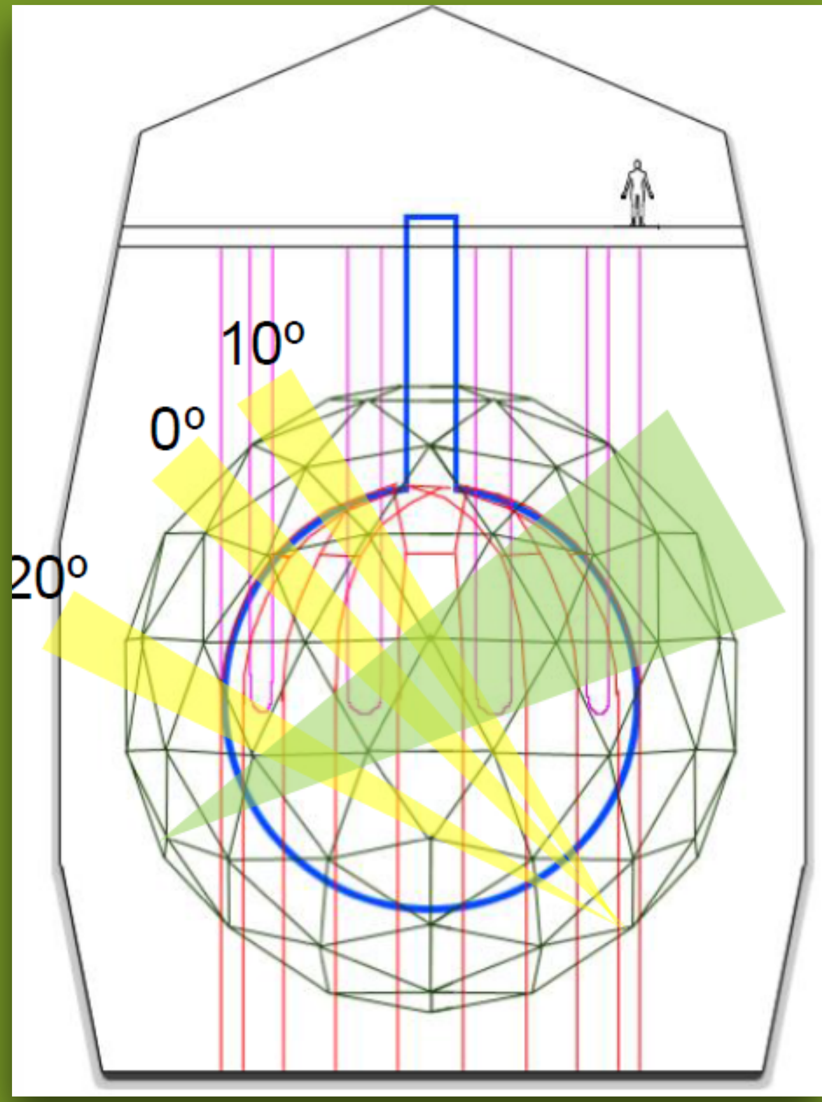
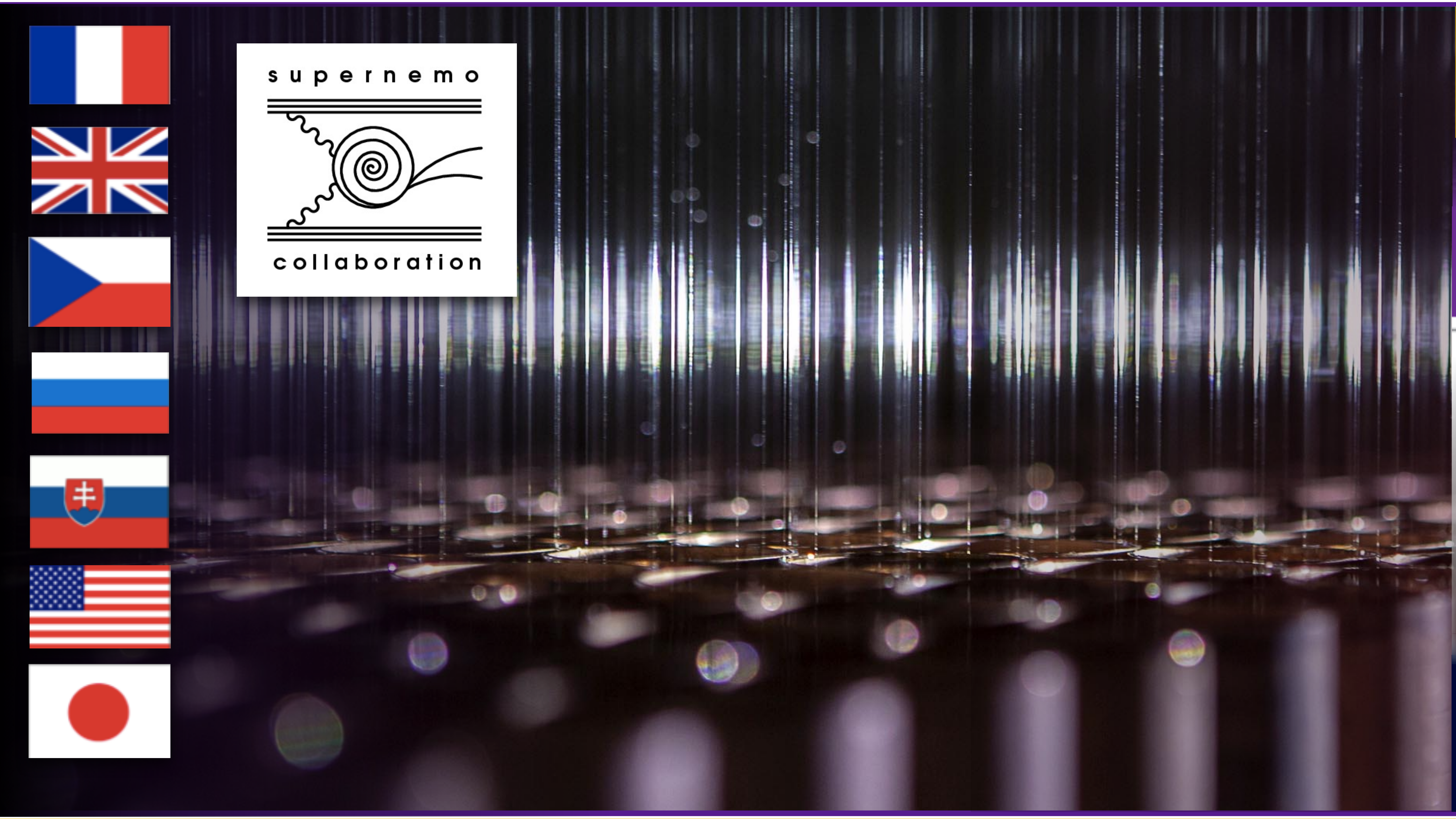


Timing and Monitoring: **TELLIE**
Attenuation Module: **AMELLIE**
Scattering Module: **SMELLIE**



SuperNEMO and NEMO-3, at LSM, France



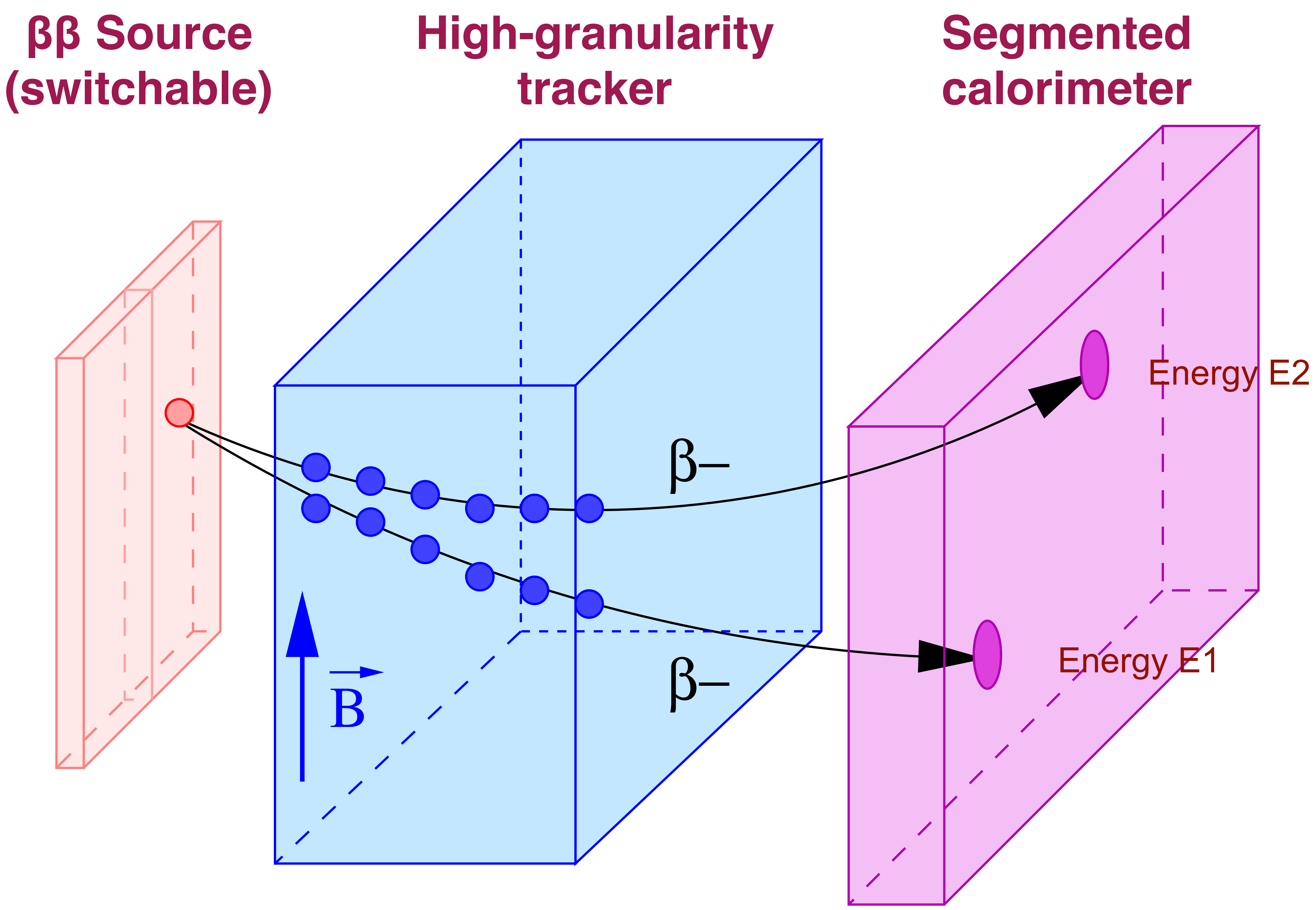
UCL

MANCHESTER 1824
The University of Manchester

WARWICK
THE UNIVERSITY OF WARWICK

Imperial College London

The NEMO principle



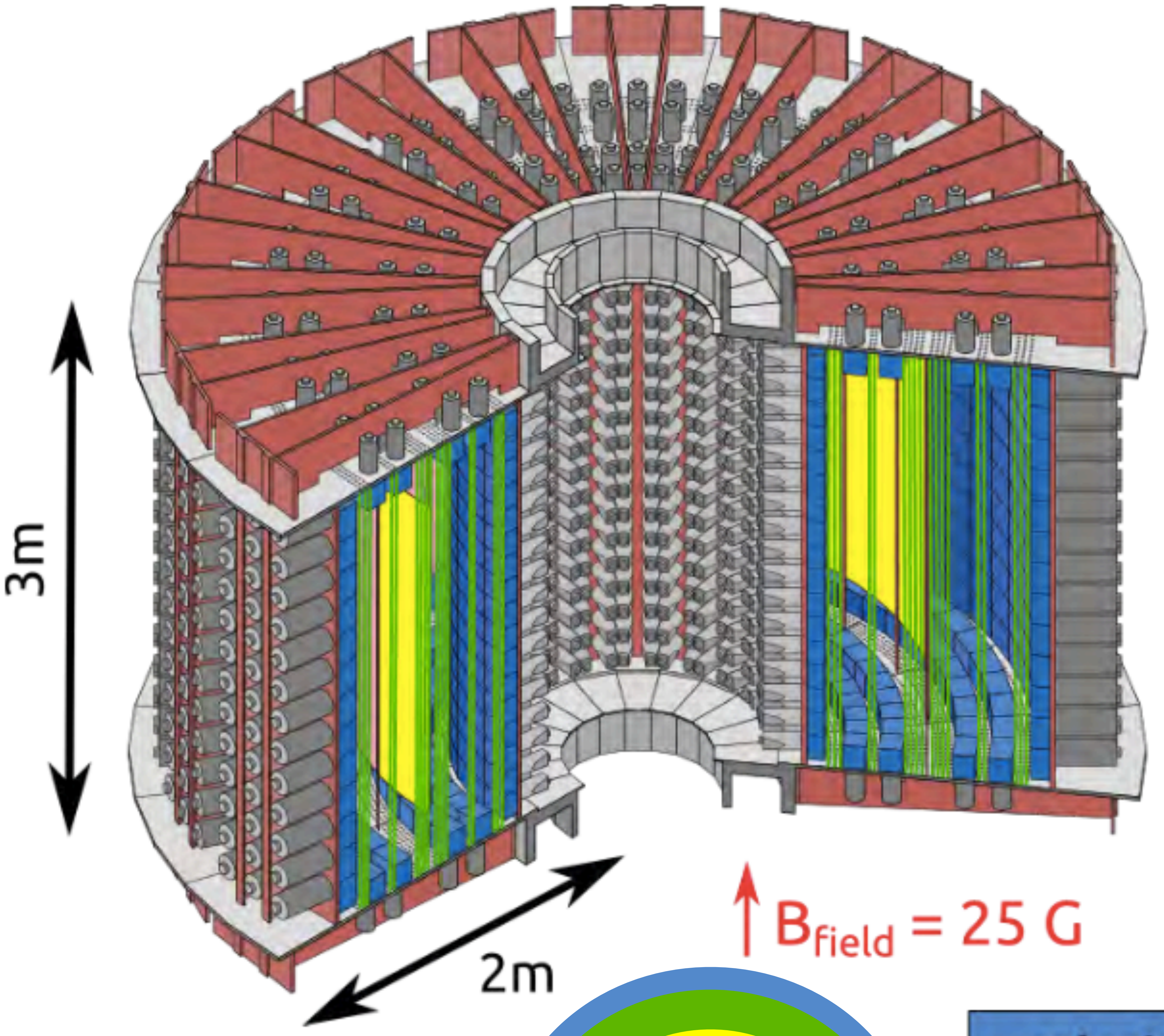
Strengths

- 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**

Weaknesses

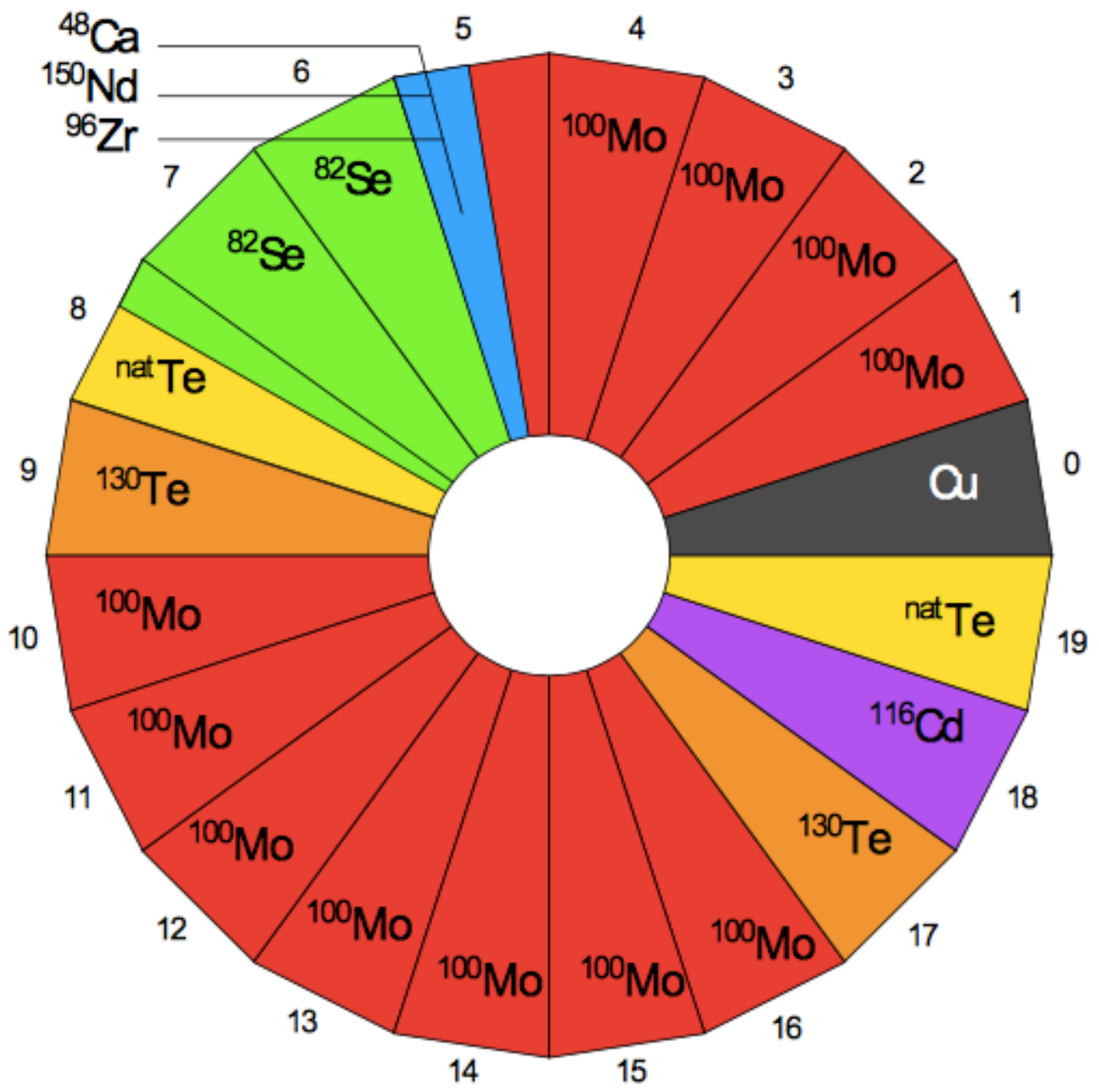
- **Energy resolution** poorer than for most homogenous detectors
- Doesn’t scale as well as some other designs

NEMO-3 (2003-2011)

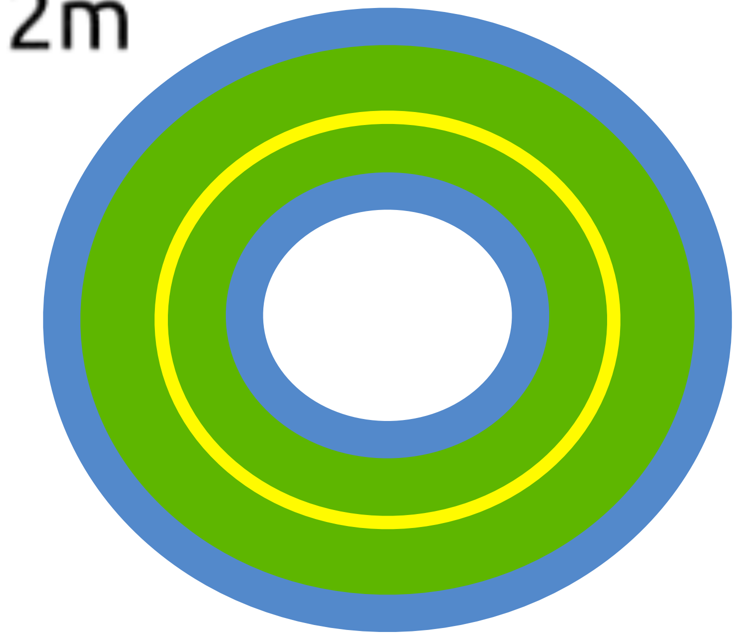


B_{field} = 25 G

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

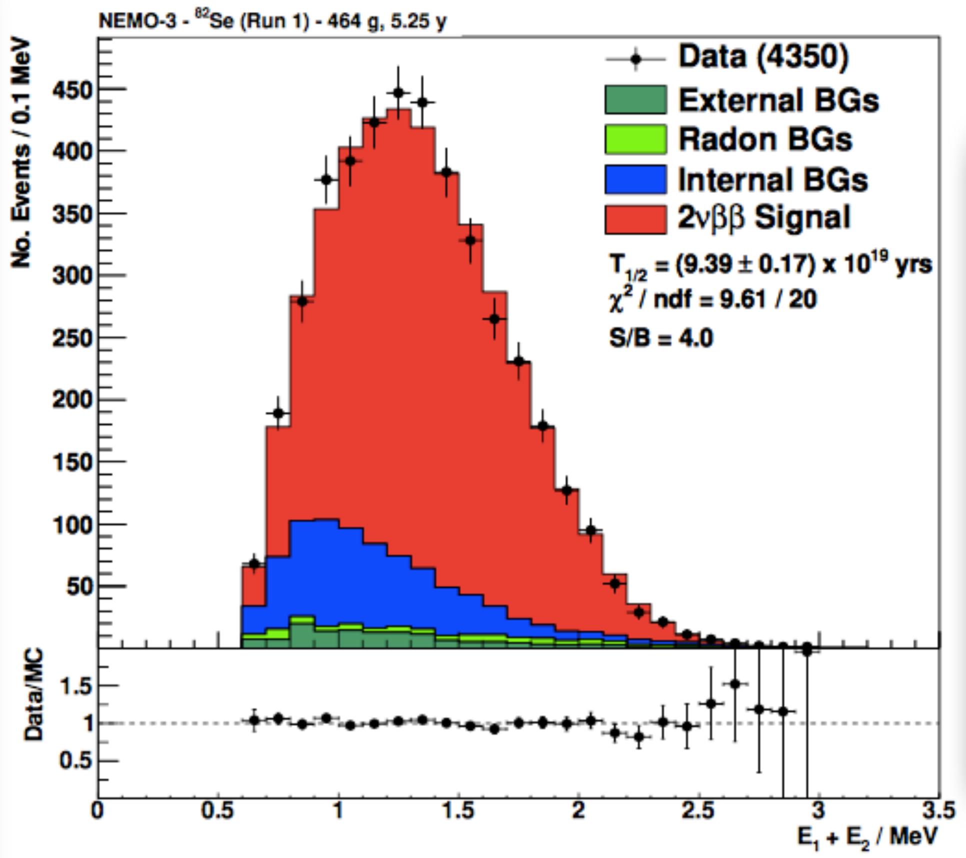
tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

sources
60 mg/cm² foils
10 kg of ββ isotopes

results from NEMO-3

2vββ measurements and 0vββ limit

- ^{82}**Se** (Eur. Phys. J. C (2018) 78: 821)



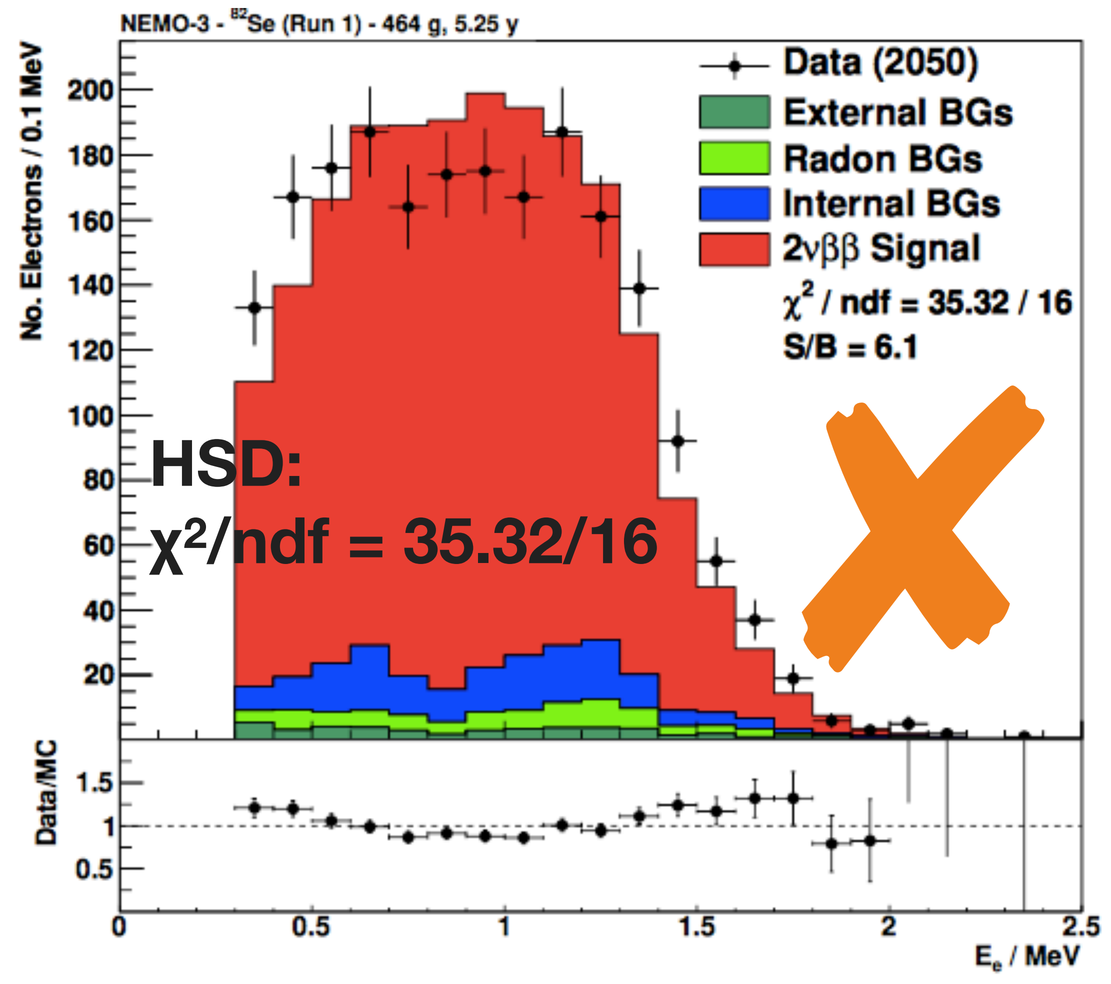
Summed 2-electron spectrum

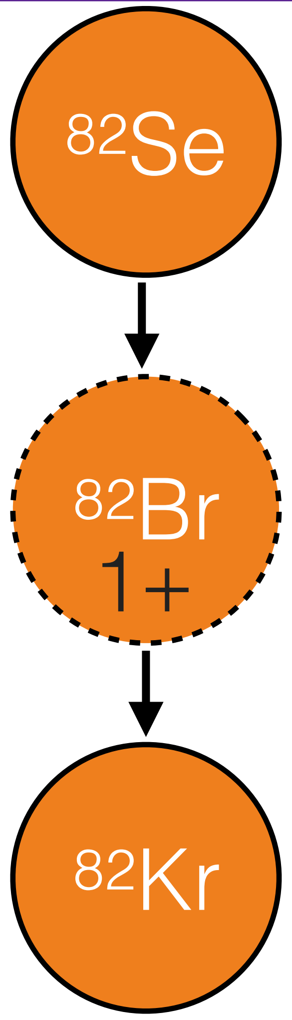
2vββ:

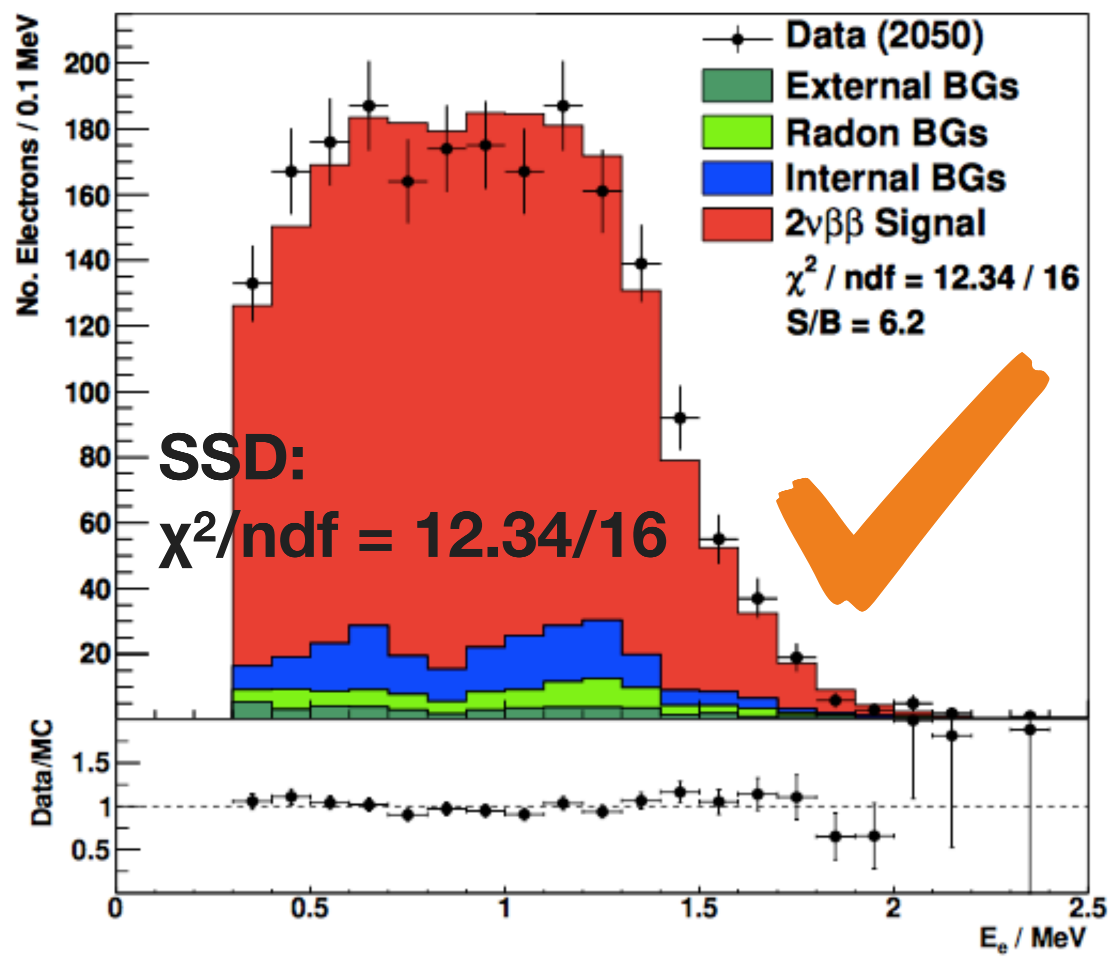
$T_{1/2}$ = **9.39** ± 0.17 (stat) ± 0.58 (sys) **x 10^{19} years** (SSD hypothesis)

0vββ:

$T_{1/2}$ > **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 tells us about intermediate 1+ states

NEW results from NEMO-3

2νββ measurements and 0νββ limit

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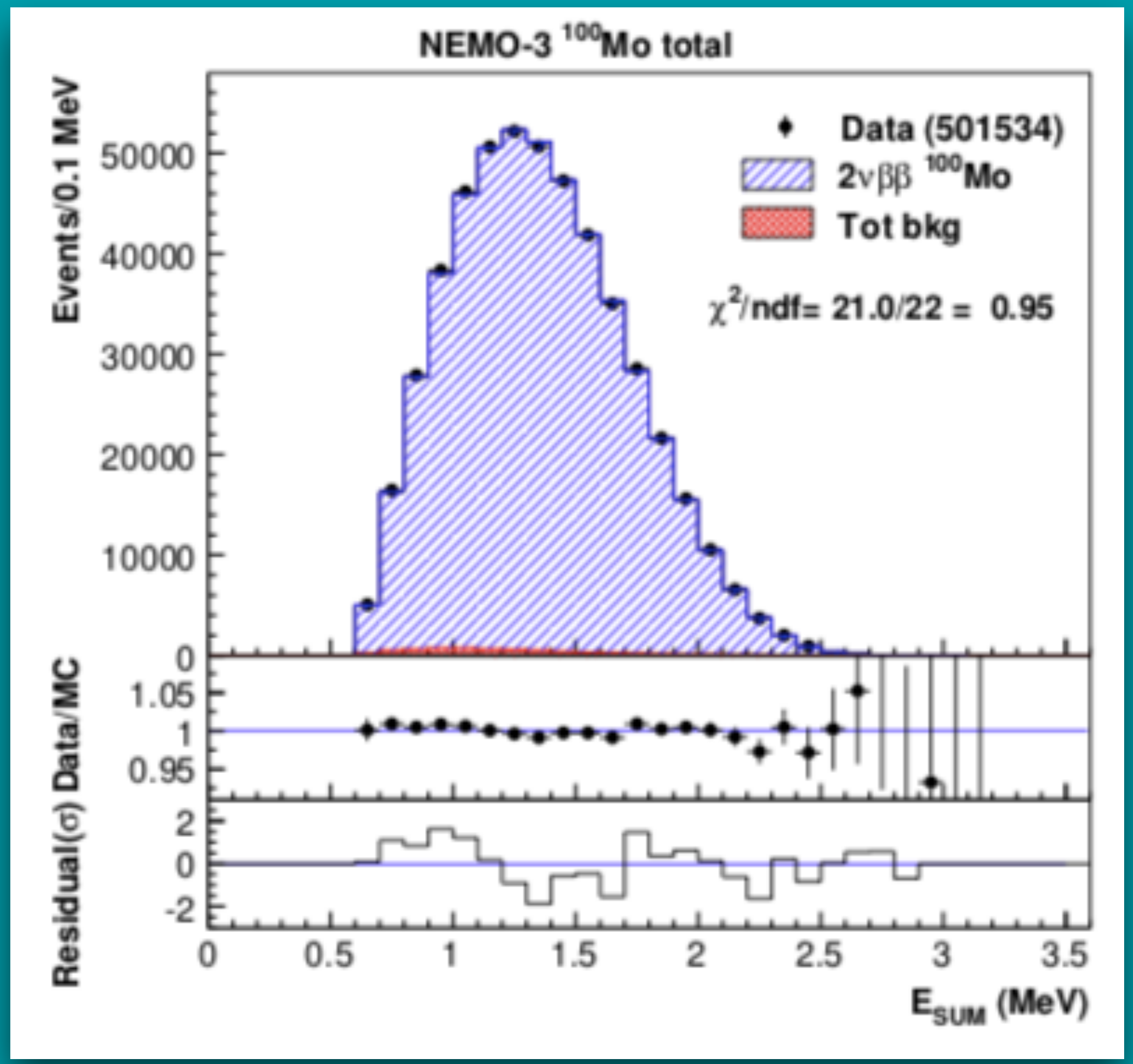
- ^{100}**Mo** arXiv 903.08084 [nucl-ex]



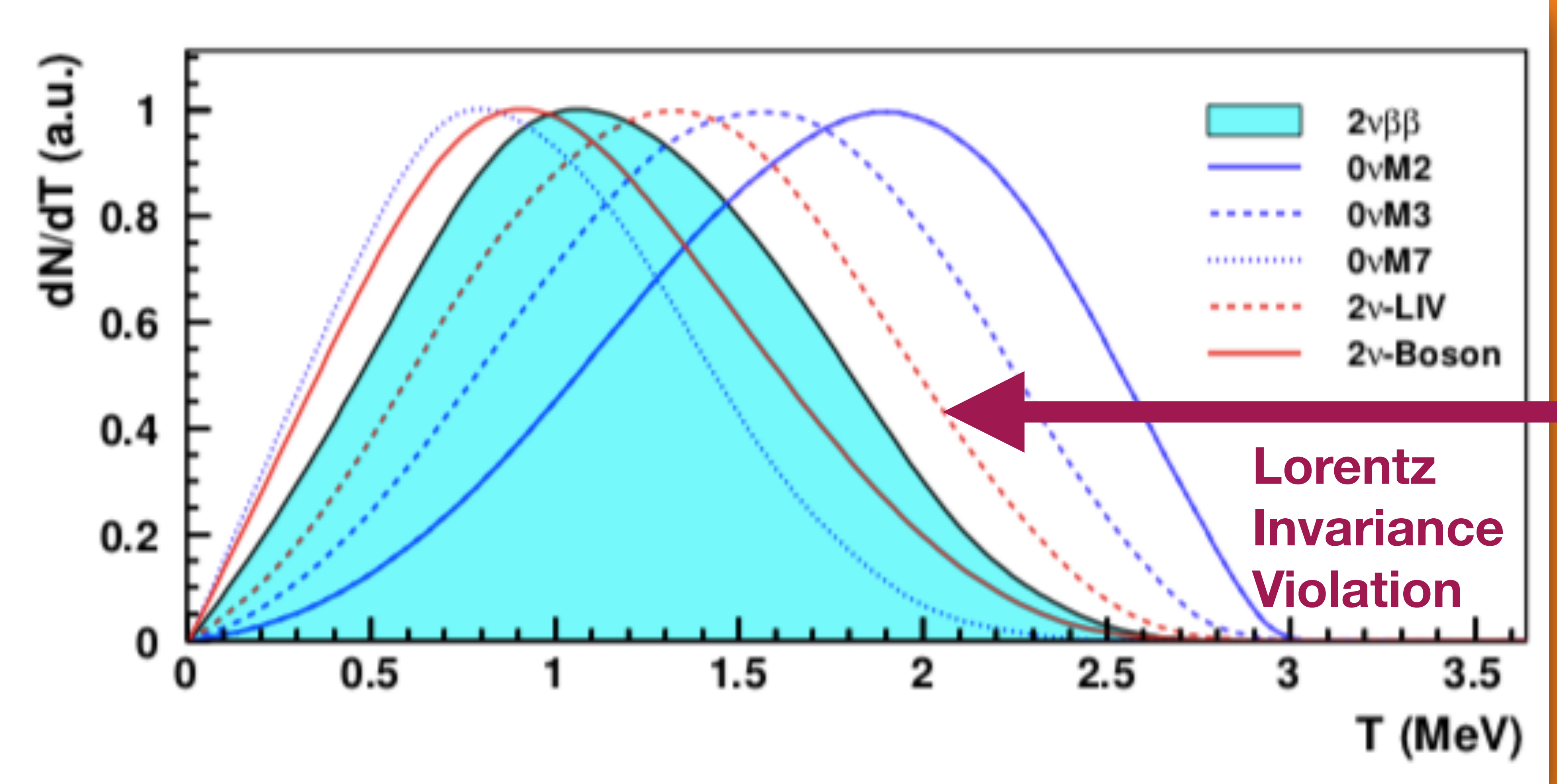
2νββ

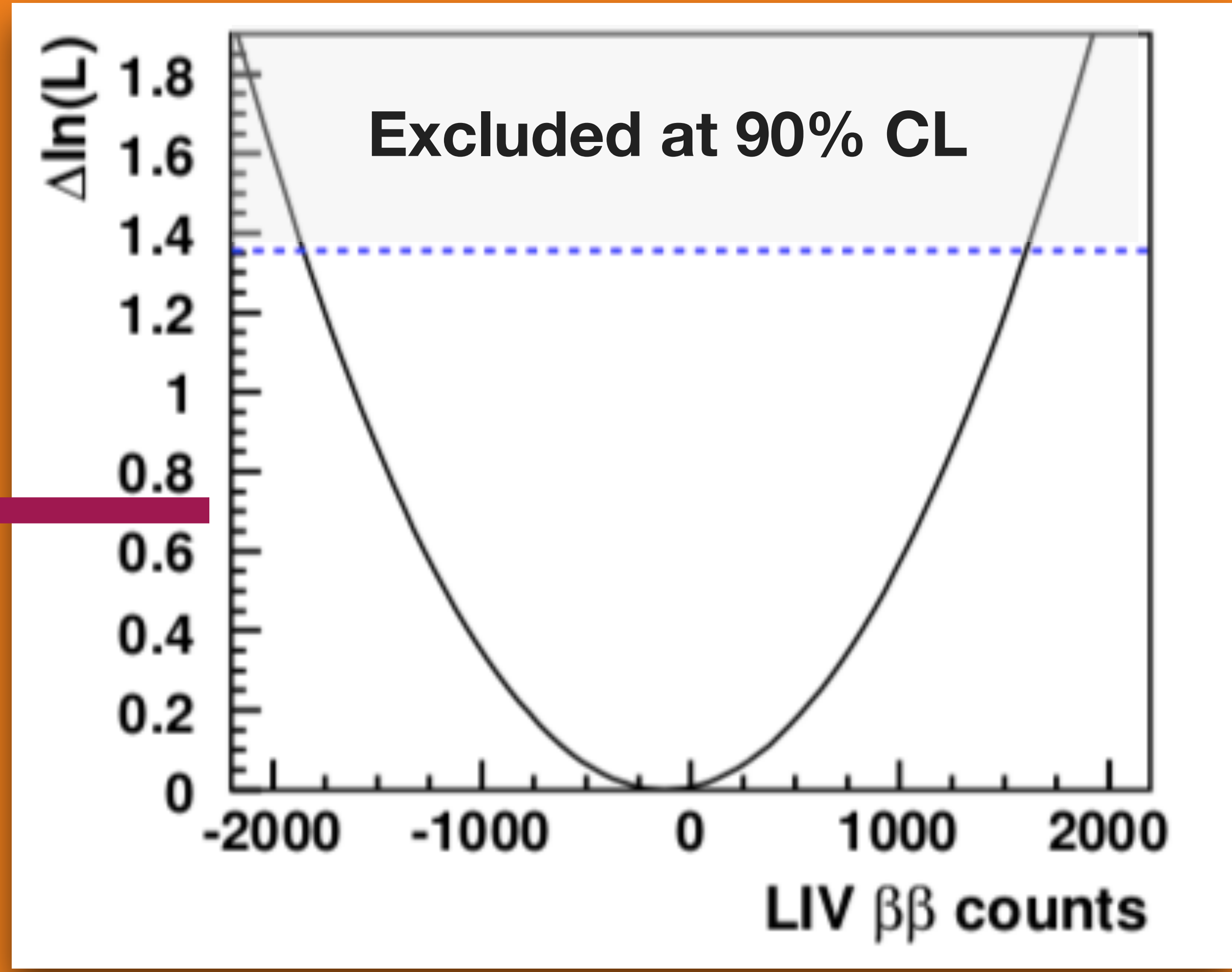
$T_{1/2}$ = 6.81 ± 0.01 (stat) ± 0.46 (sys) x 10^{18} years (SSD model)

- Over **5 x 10⁵ events** with S/B ≈ 80
- **Lorentz Invariance Violation** and exotic 0νββ **mechanisms** would modify energy spectrum
- Limit set on contribution from Lorentz-Invariance violating events

$$-4.2 \times 10^{-7}\ \mathrm{GeV} < \mathring{a}^{(3)}_{of} < 3.5 \times 10^{-7}\ \mathrm{GeV}\ (90\%\ \mathrm{C.L.}).$$

Best published result!





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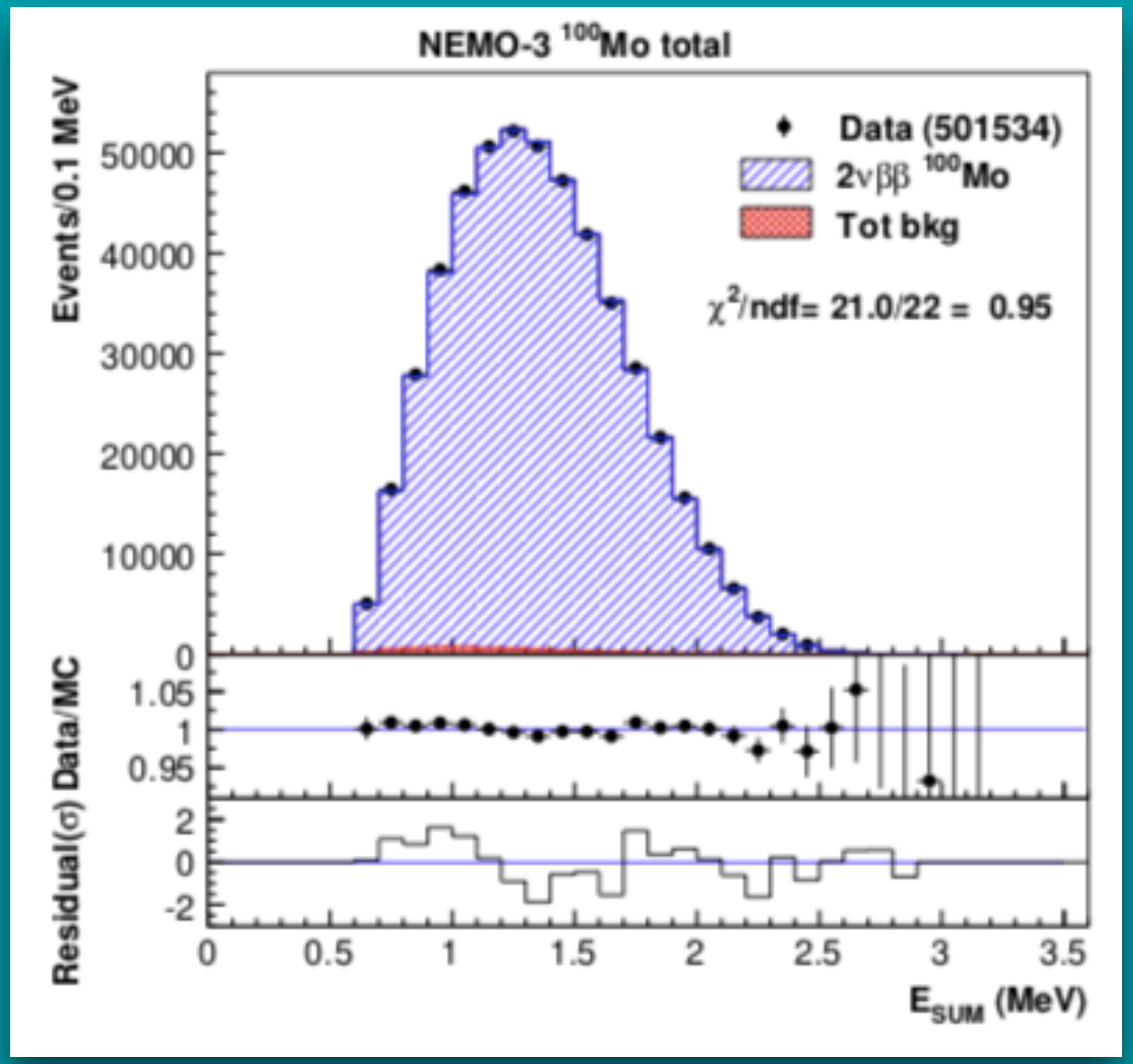
- ^{130}**Te** (Phys. Rev. Lett. 107, 062504)
- ^{96}**Zr** (Nucl.Phys.A847:168-179)



2νββ

World's best

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

- Over **5 x 10^5 events** with S/B ≈ 80
- **Lorentz Invariance Violation** and exotic 0νββ **mechanisms** would modify energy spectrum
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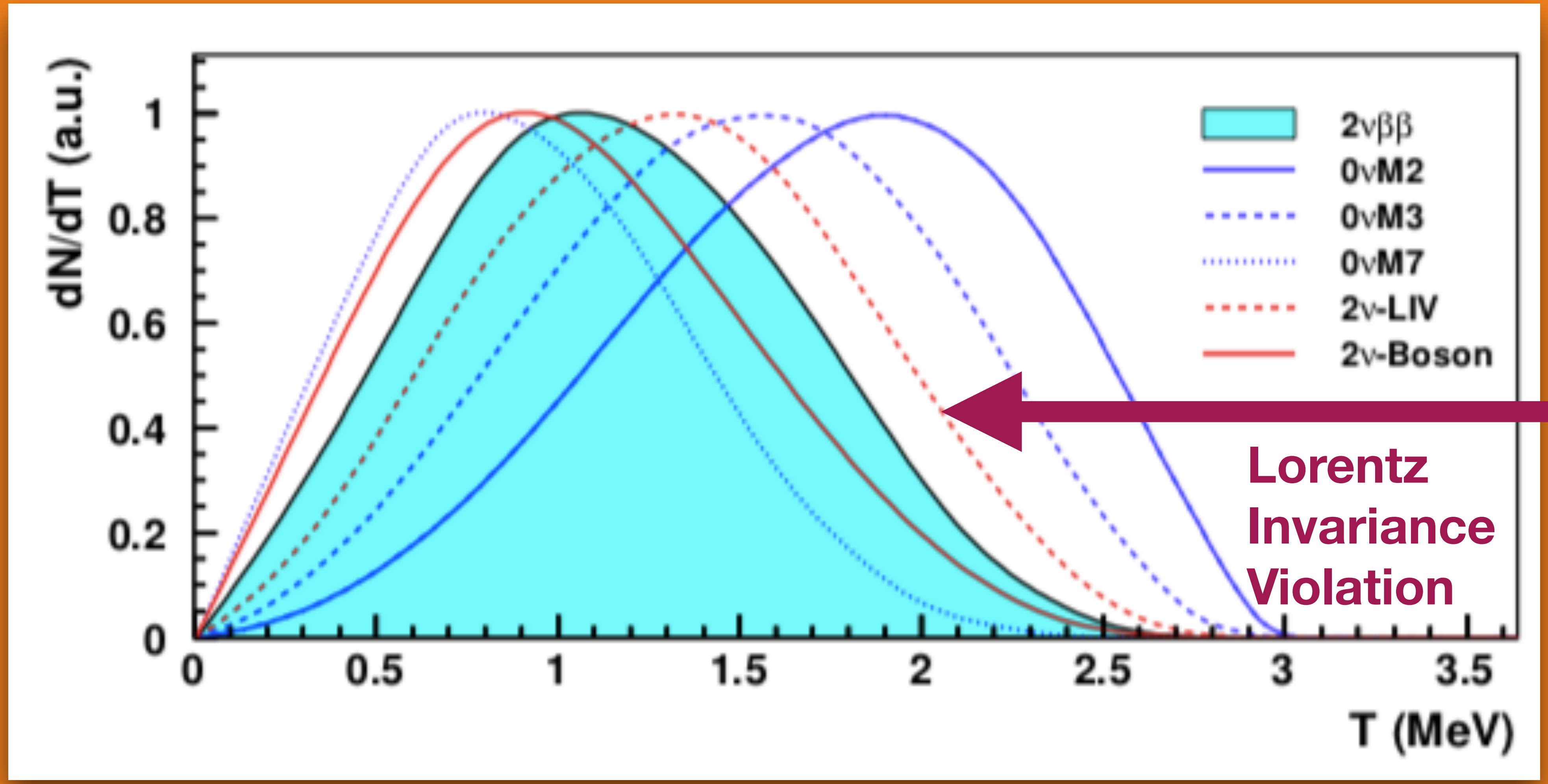
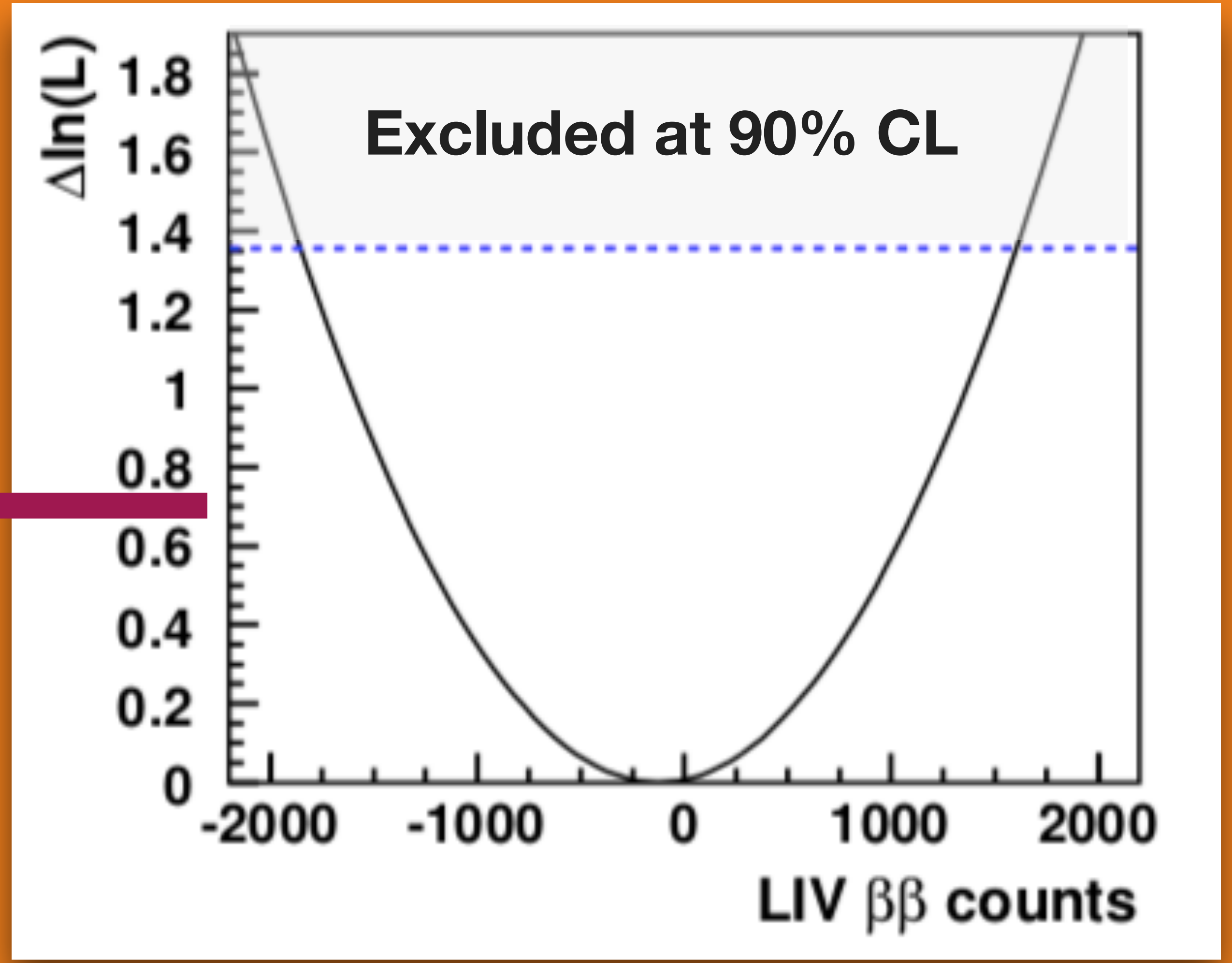
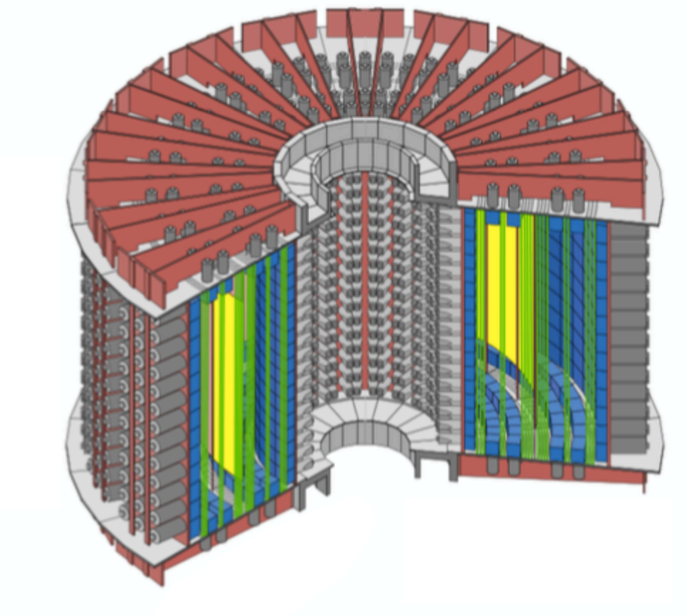
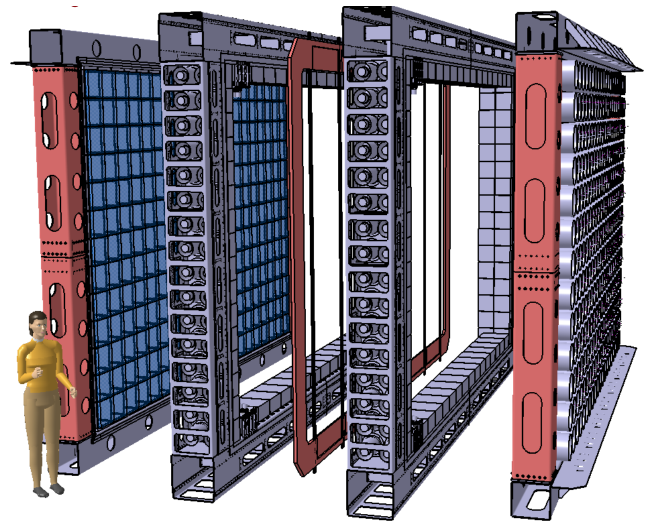
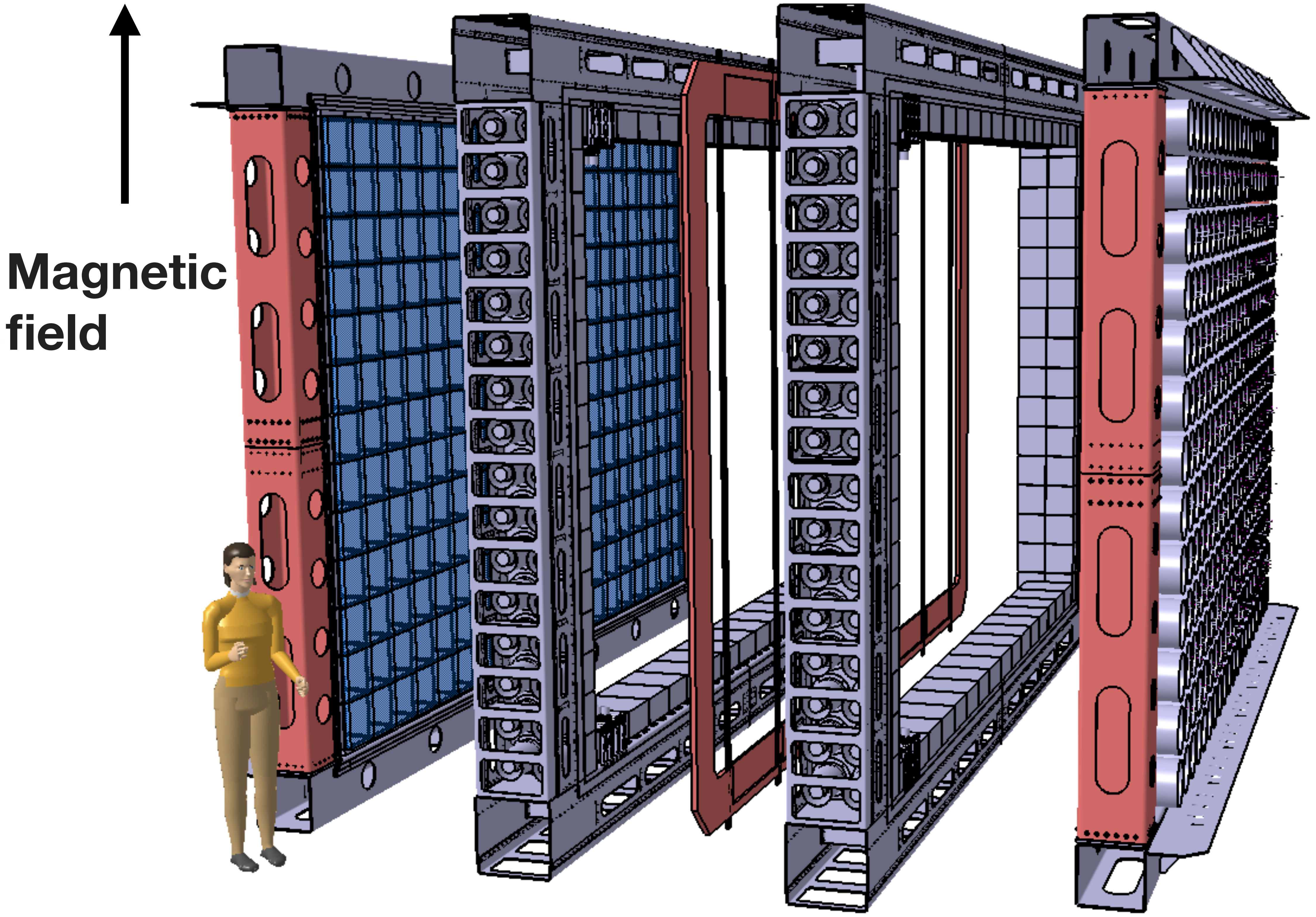




Currently at LSM: SuperNEMO Demonstrator







	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	6.3 (^{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 %
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A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
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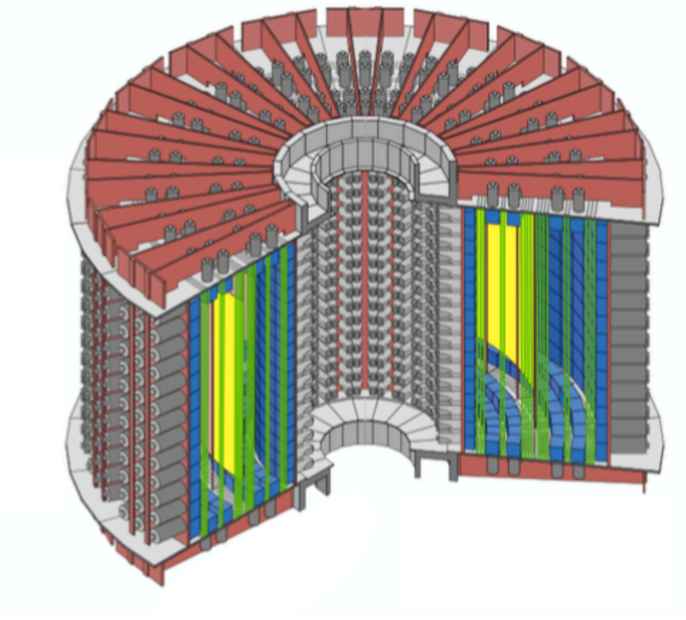

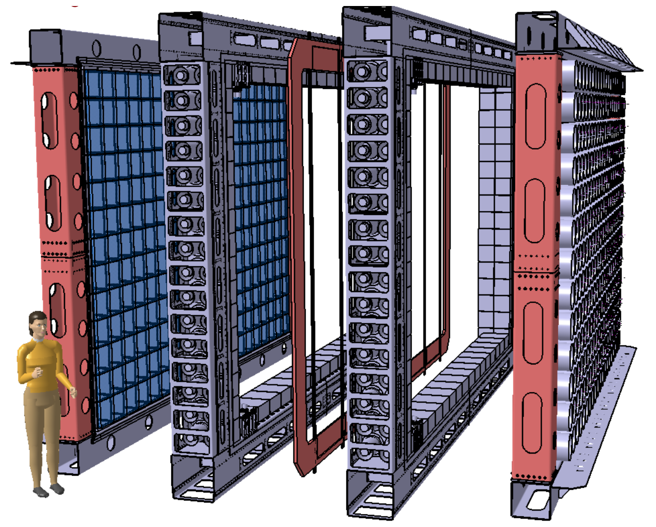

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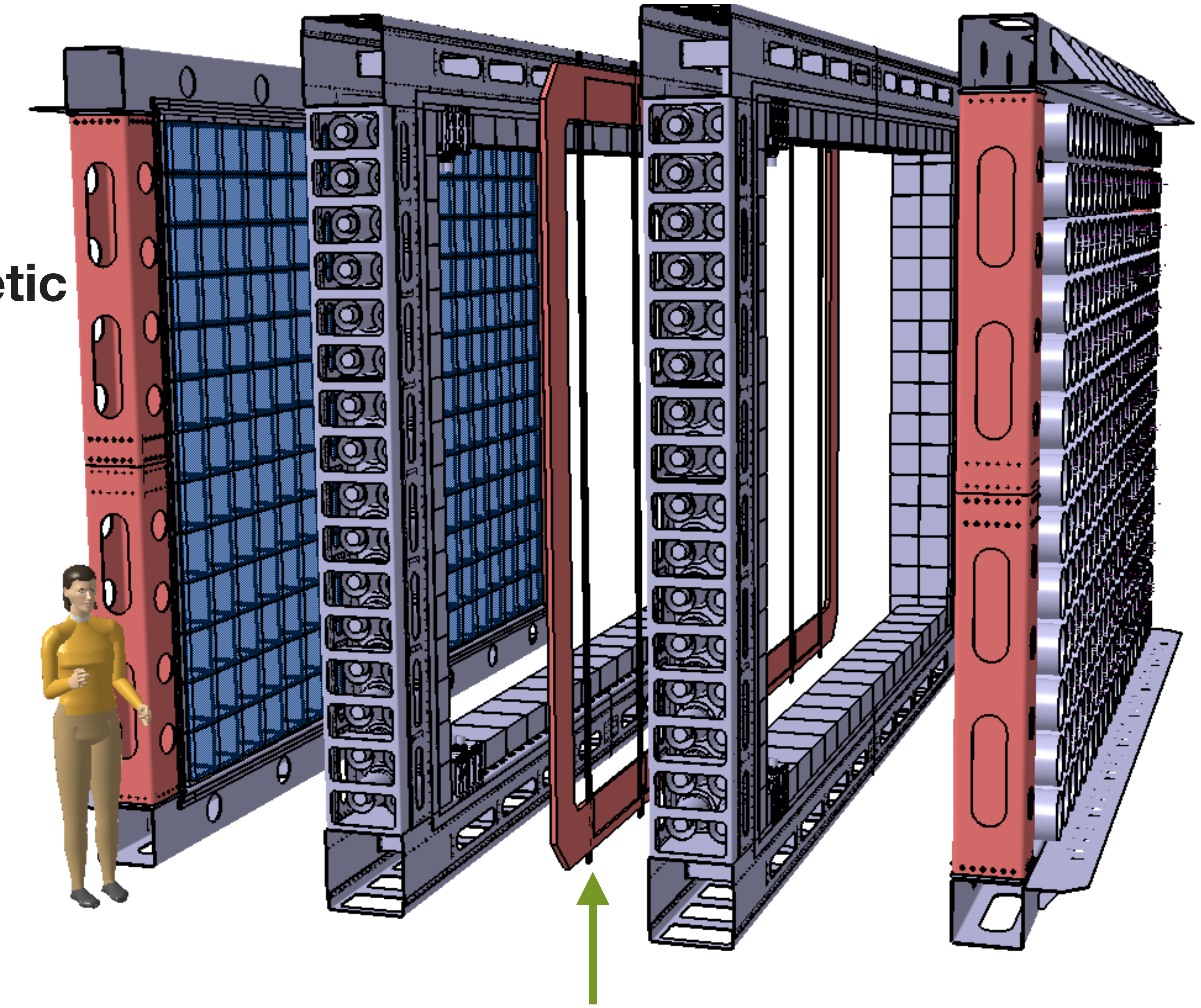
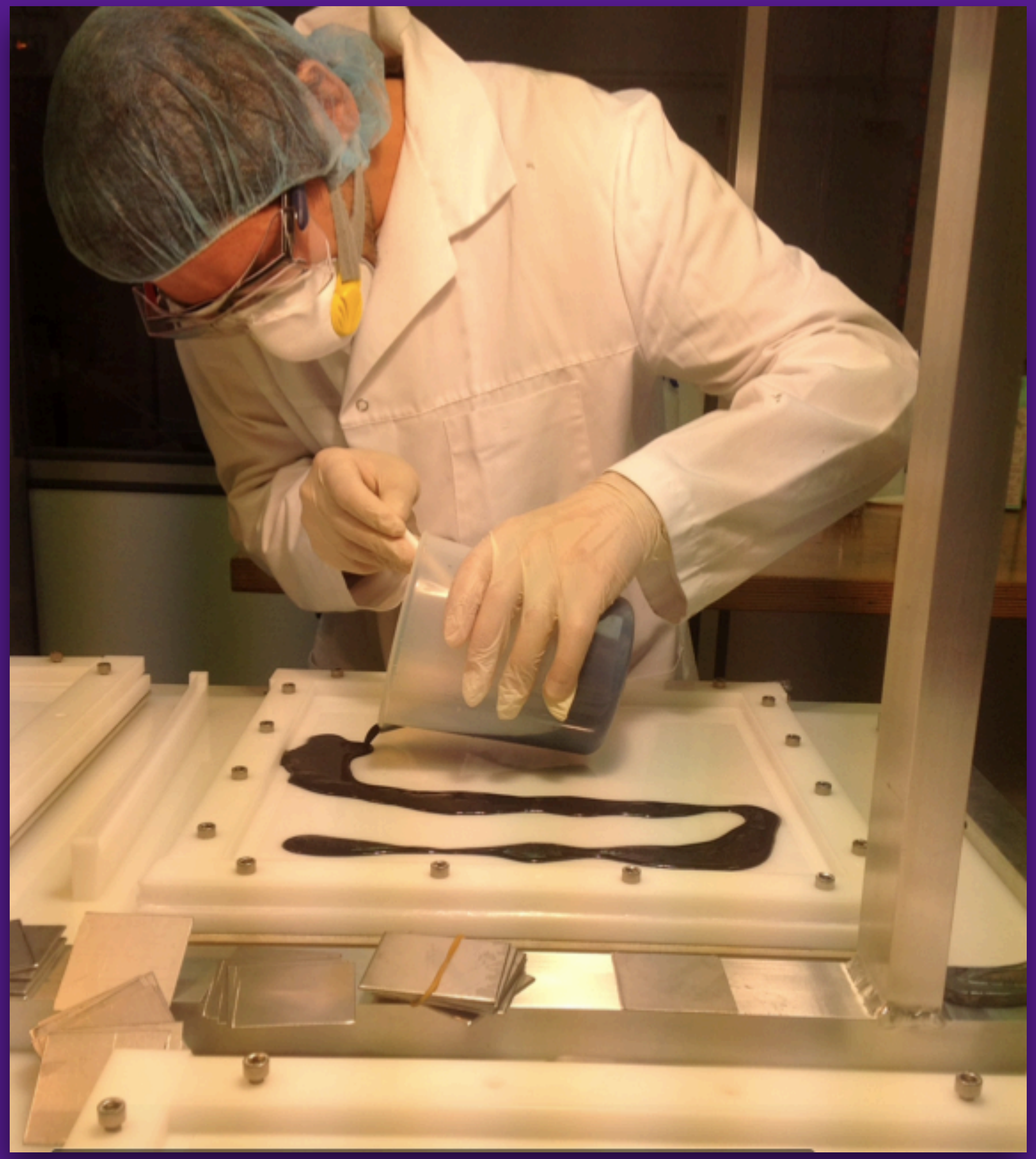
Magnetic field



Source frame holding 6.3kg of ββ emitter (^{82}Se)

Currently at LSM: SuperNEMO Demonstrator



- 34 foils
- Enriched Se powder mixed with PVA
- Increased radio purity through distillation / chromatography / chemical precipitation

Se

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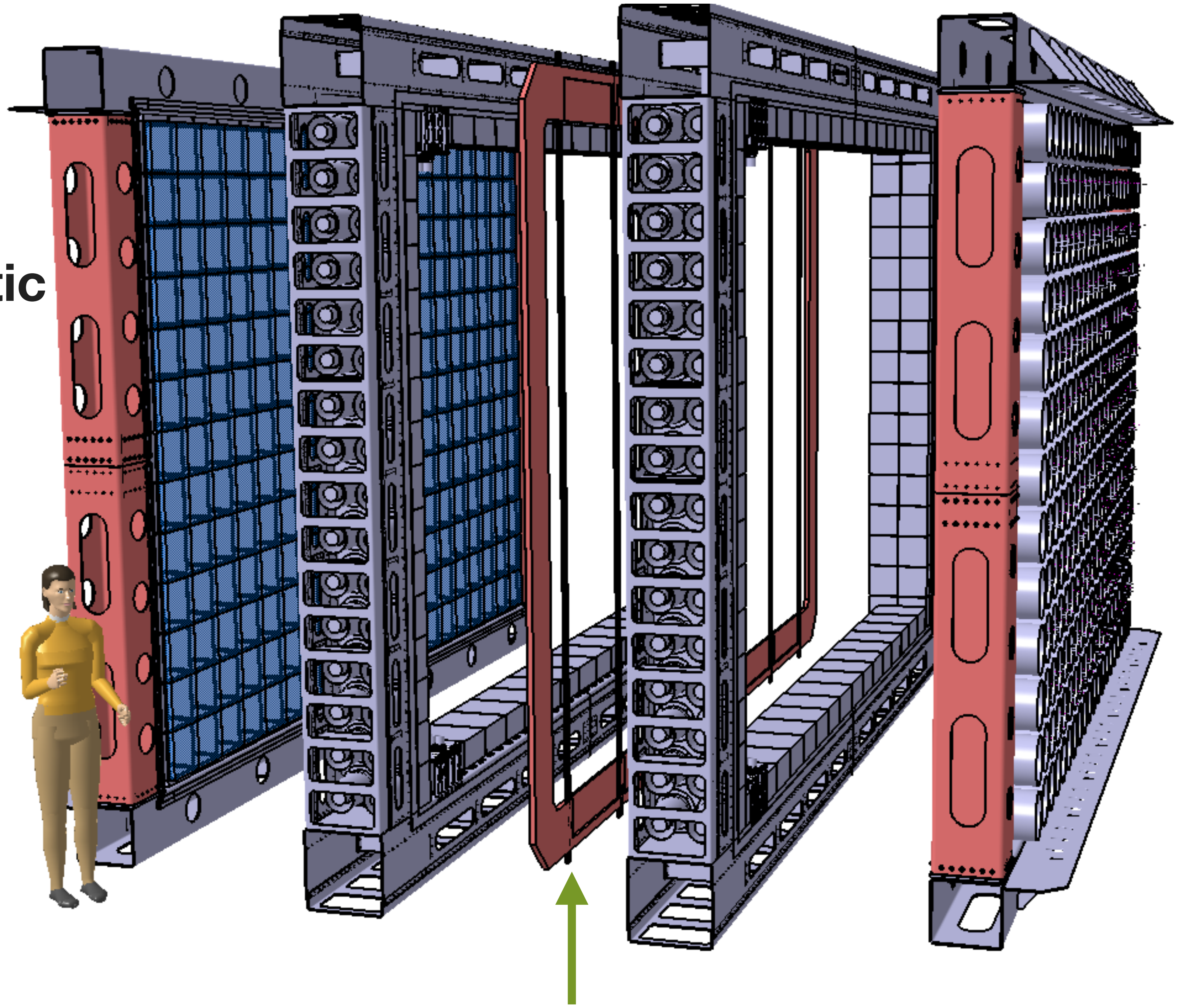

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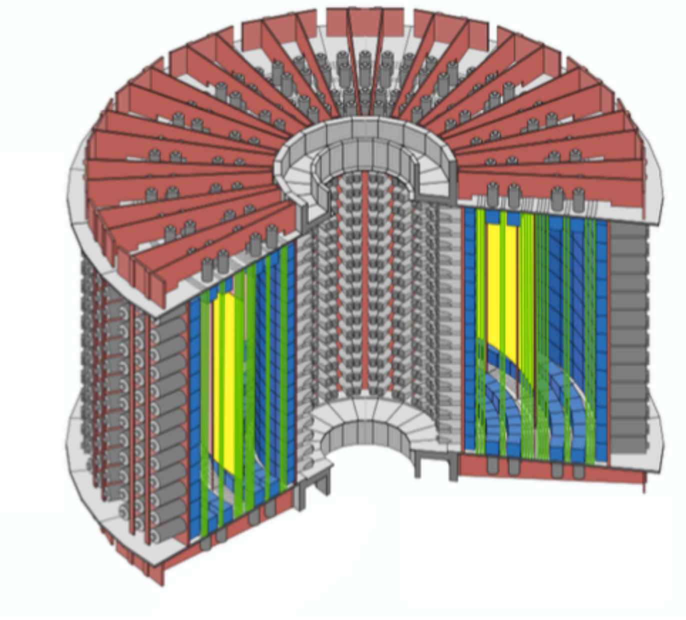

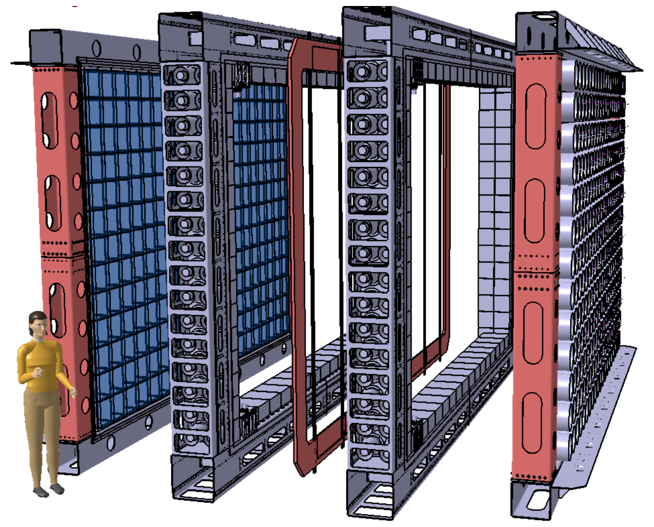

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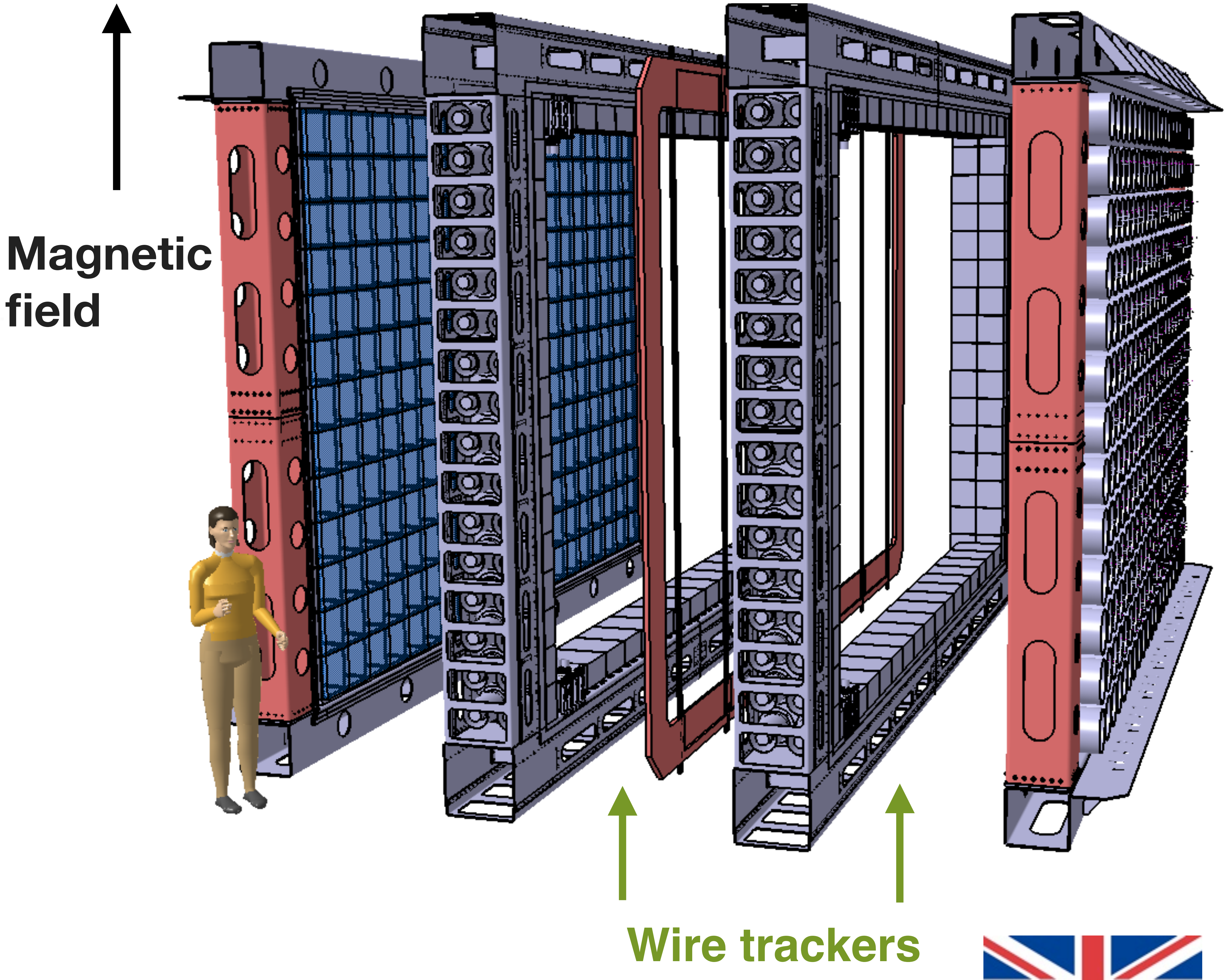

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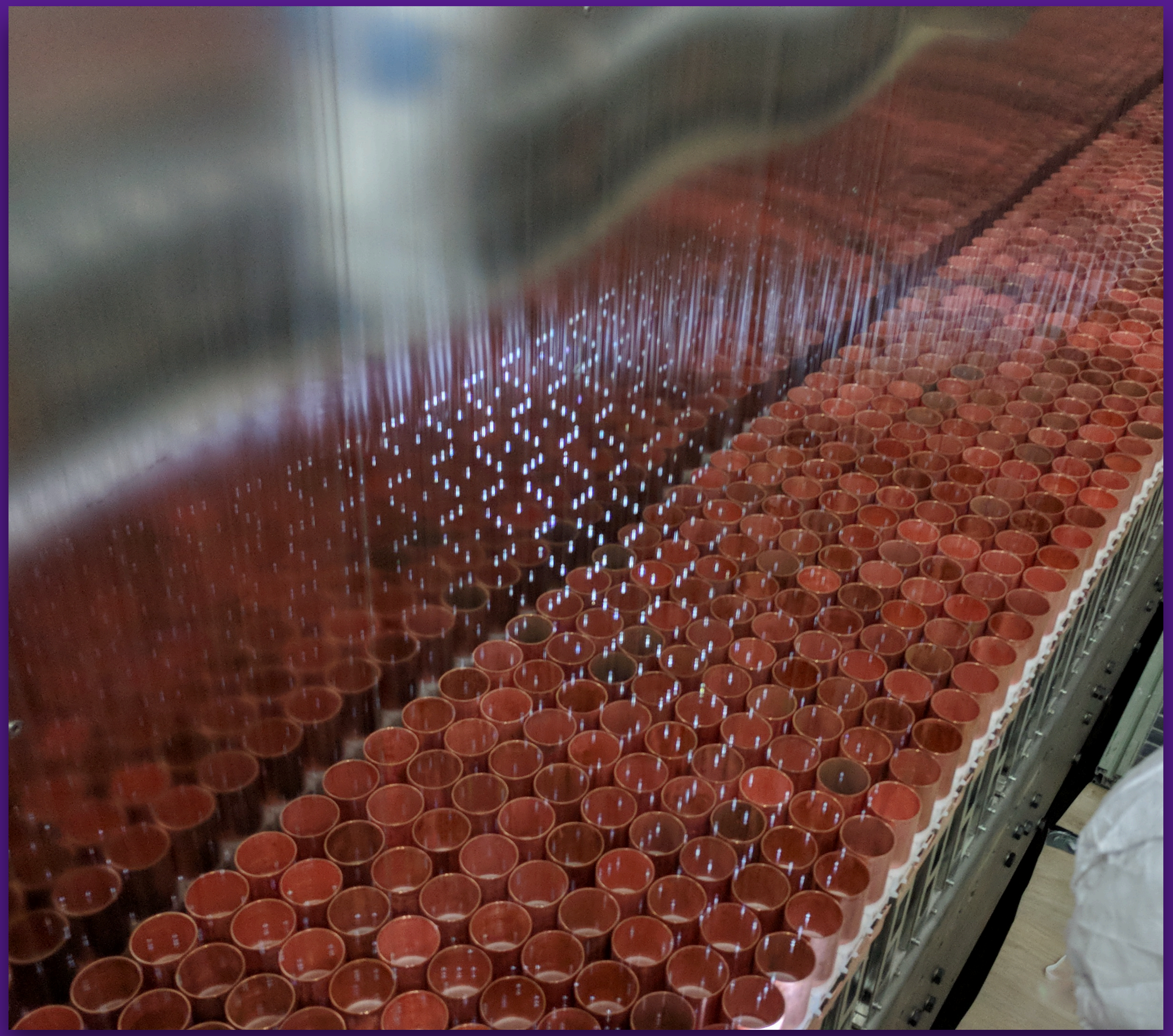

- 2034 drift cells (13,000 wires!)
- Built and installed by UK team
- UK radon reduction / measurement programme also used by dark matter experiments

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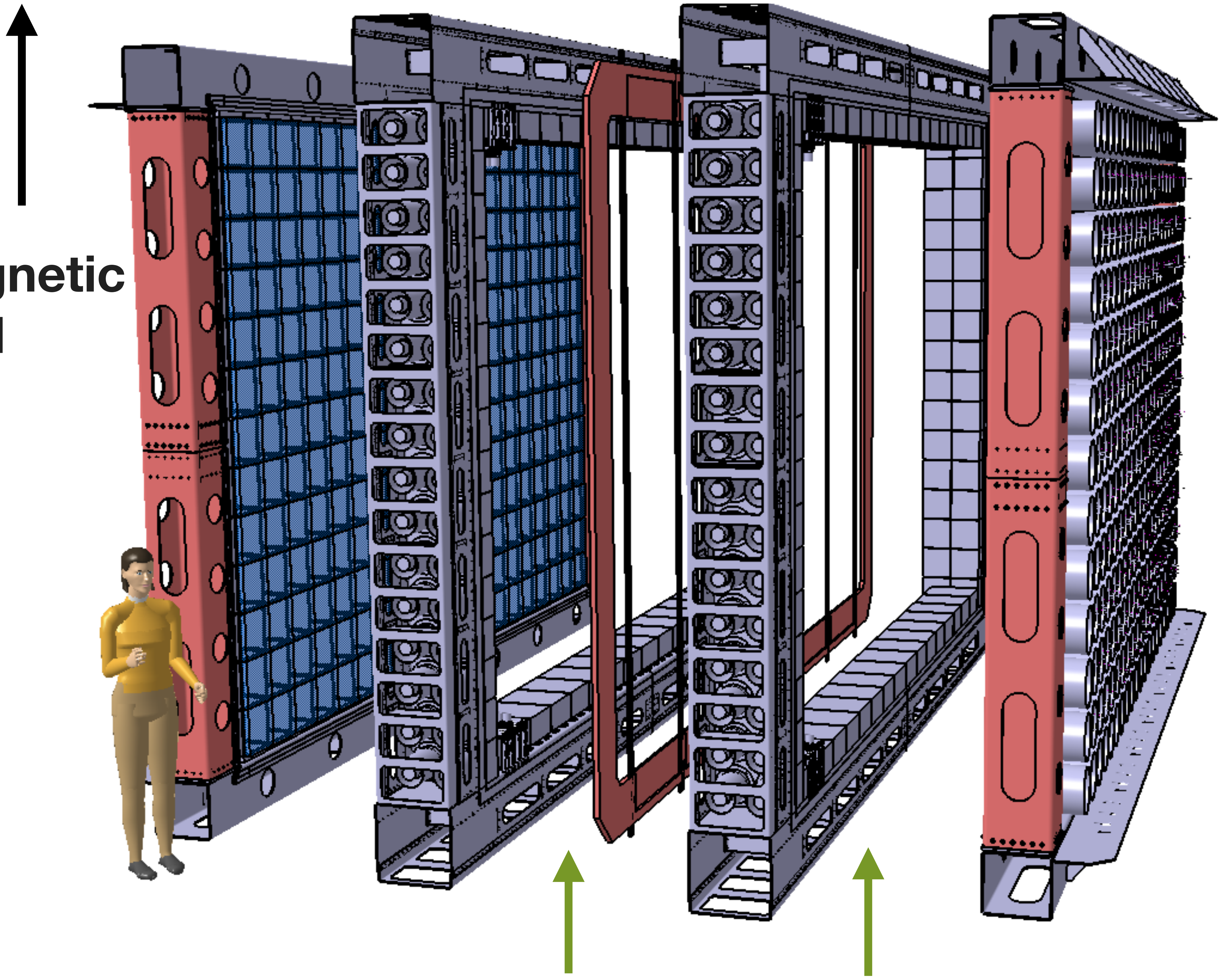
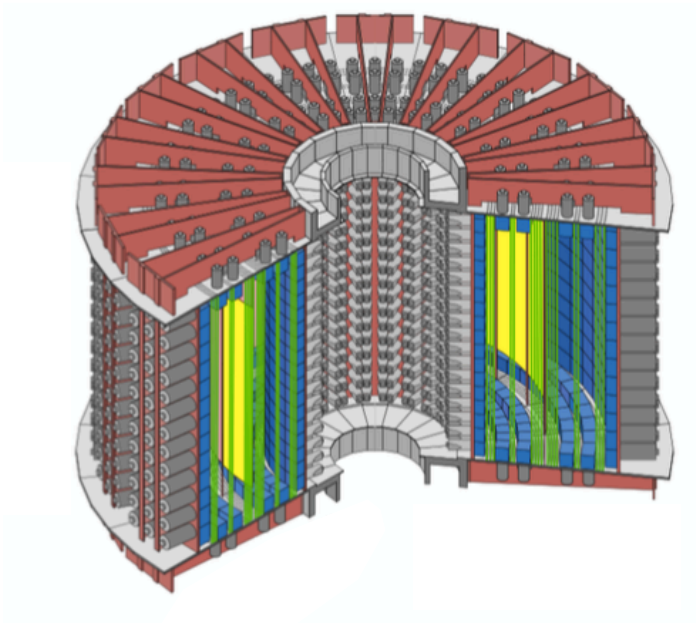
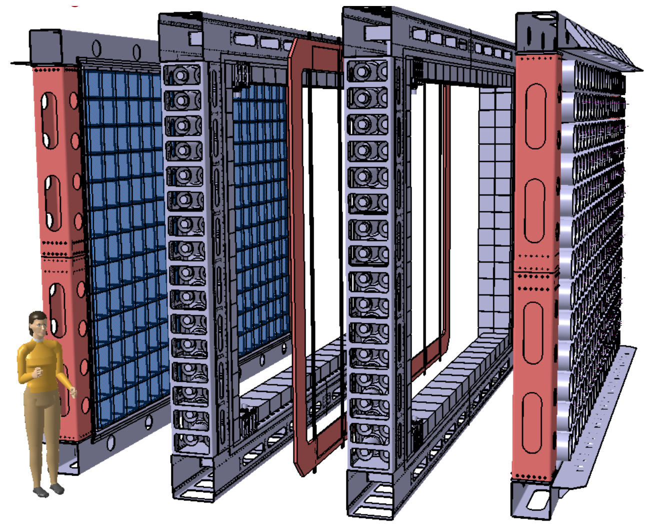


Se

Currently at LSM: SuperNEMO Demonstrator





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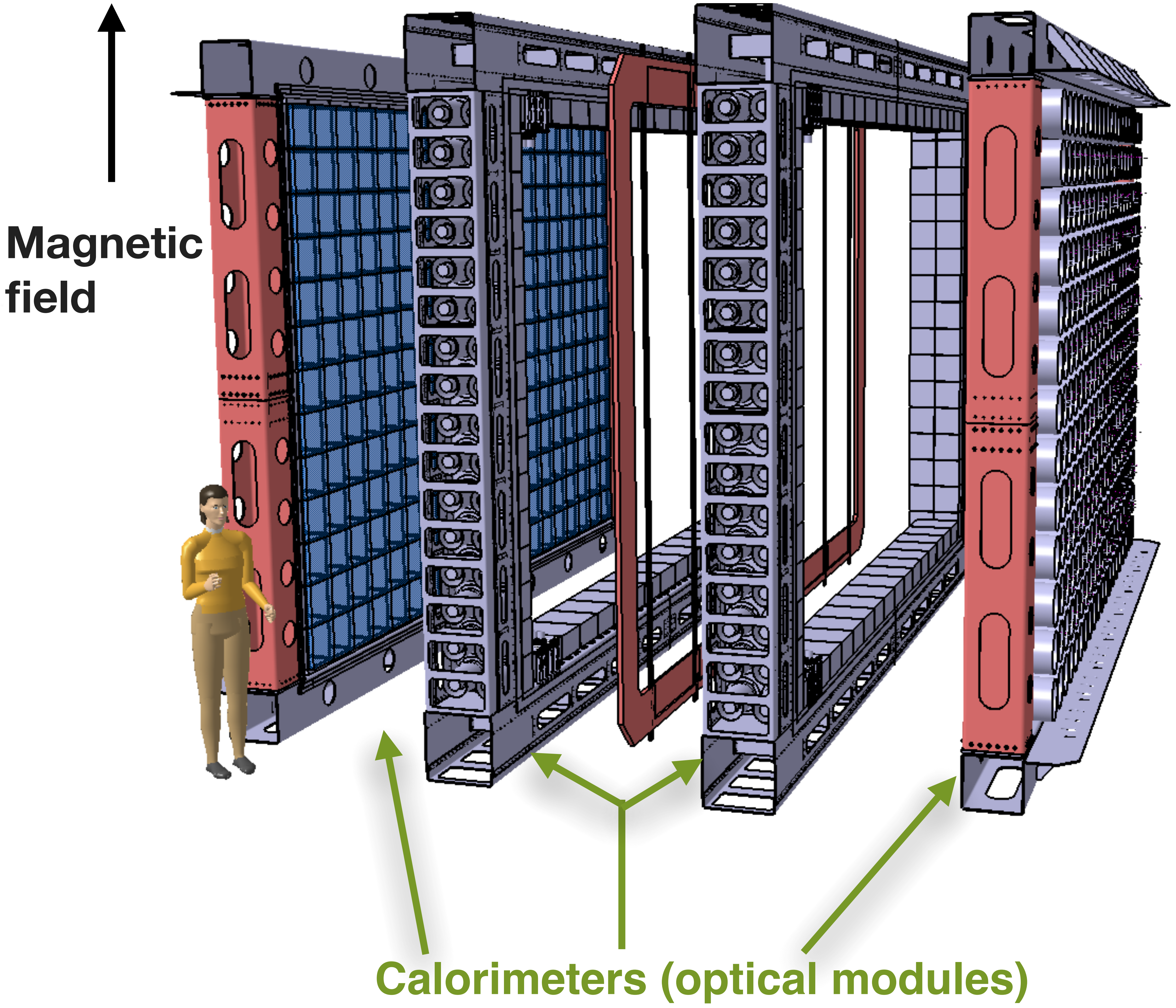

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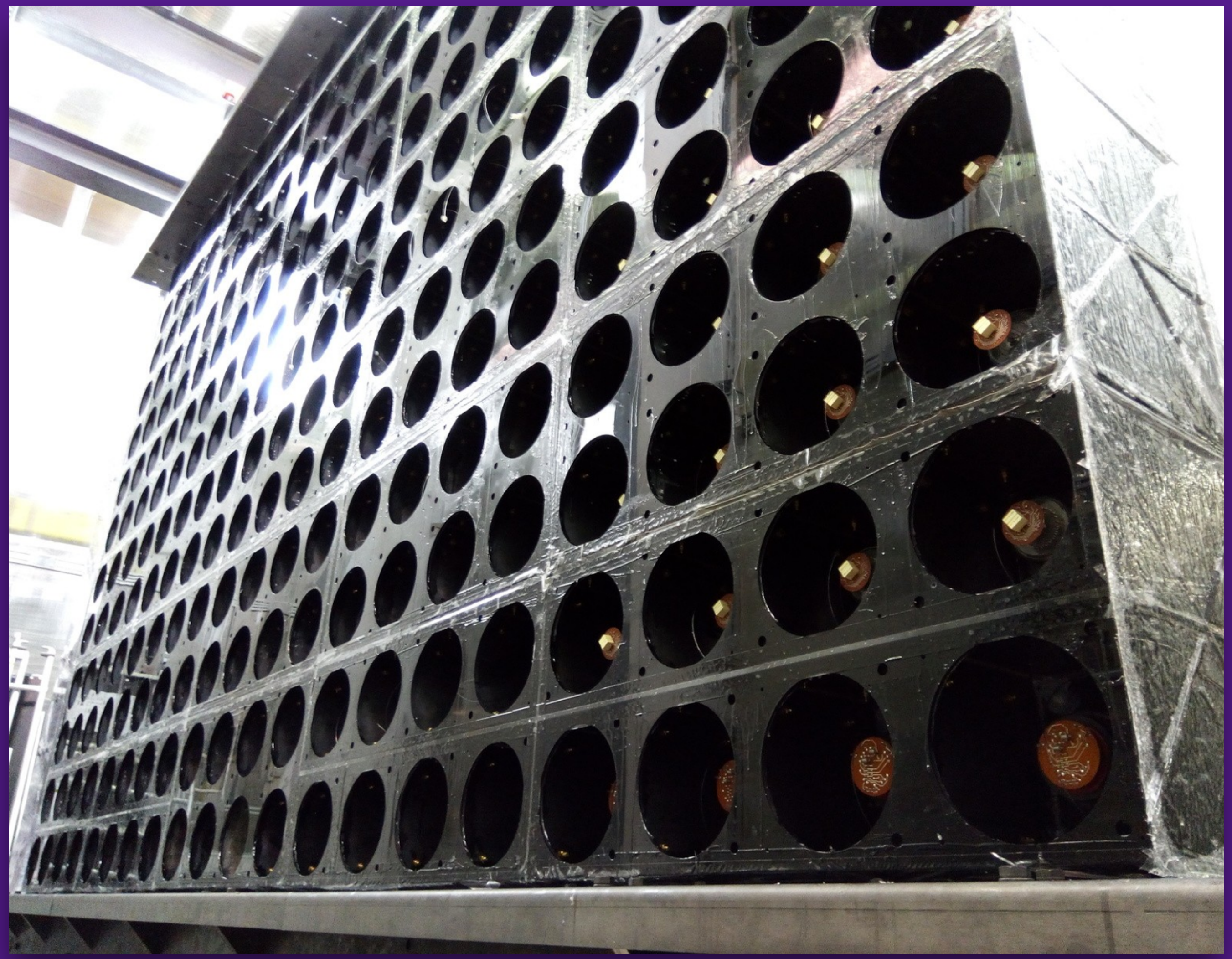
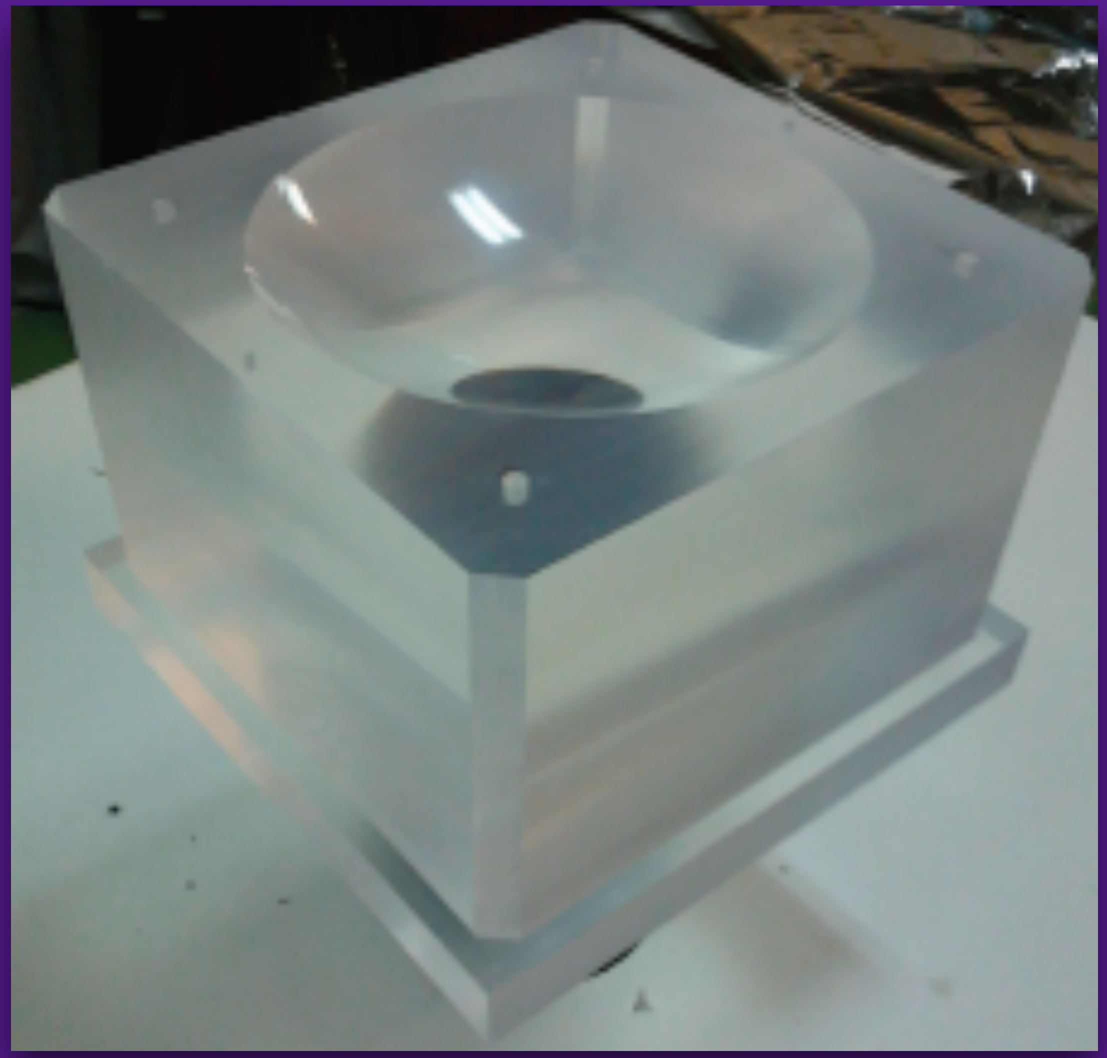
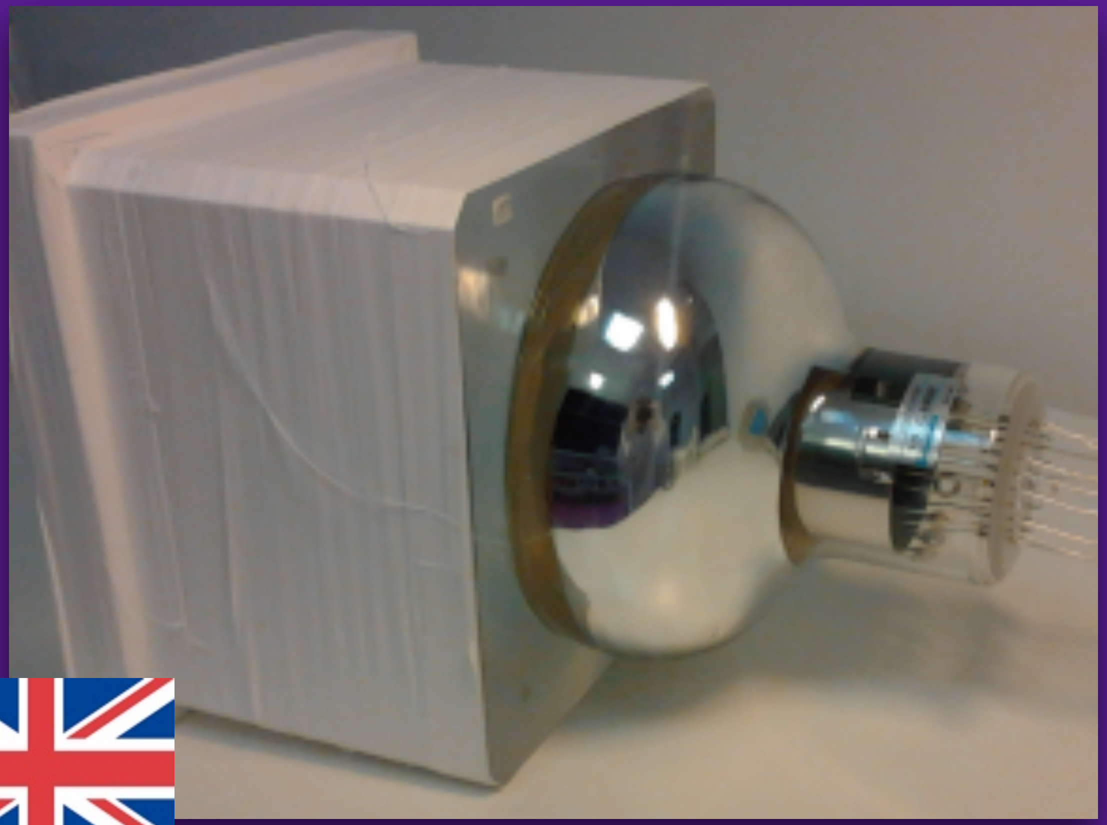




- 440 8” radiopure PMTs (plus 5” NEMO-3 PMTs)
- Improved photocathode quantum efficiency
- Directly coupled to polystyrene scintillator (no light guide)
- UK involved in upgraded design *(Nucl.Inst.Meth. A 868 98-108)*



Se

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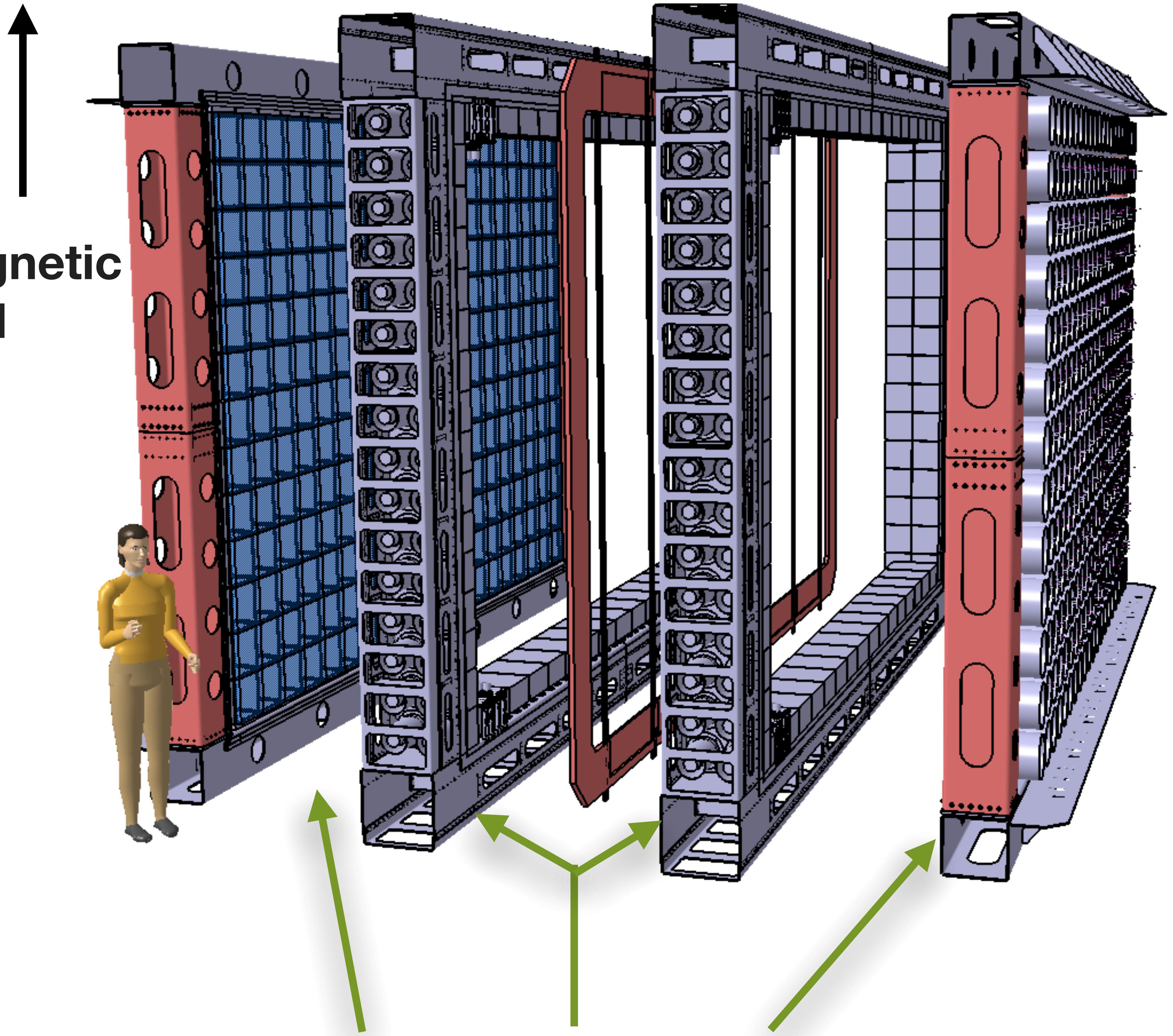

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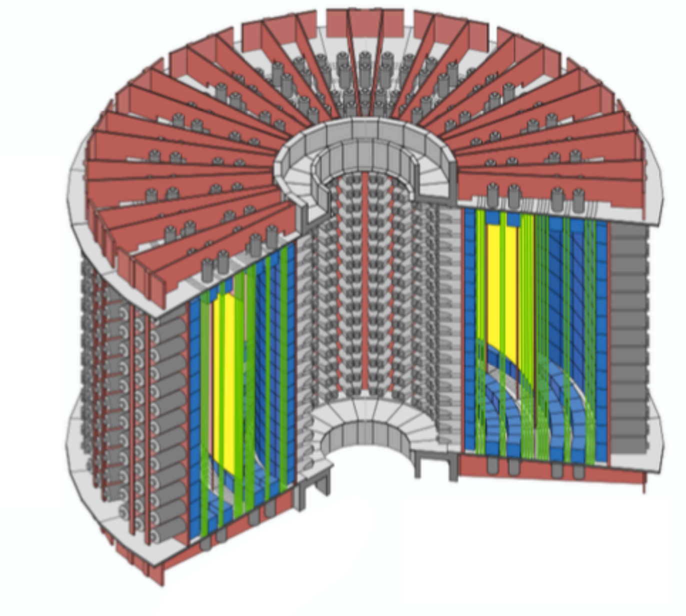

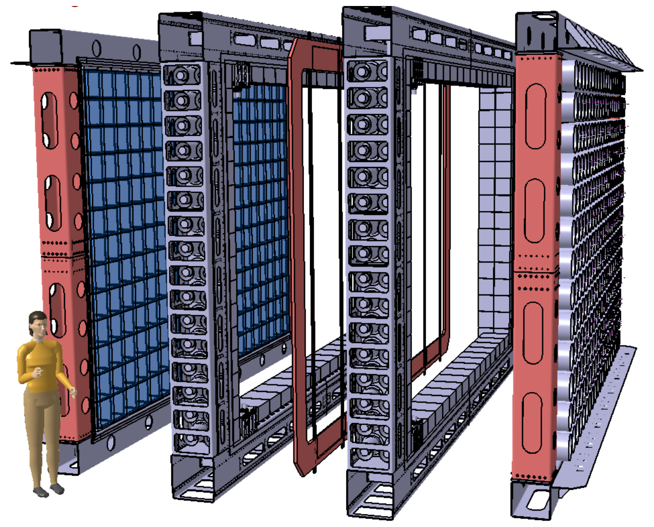

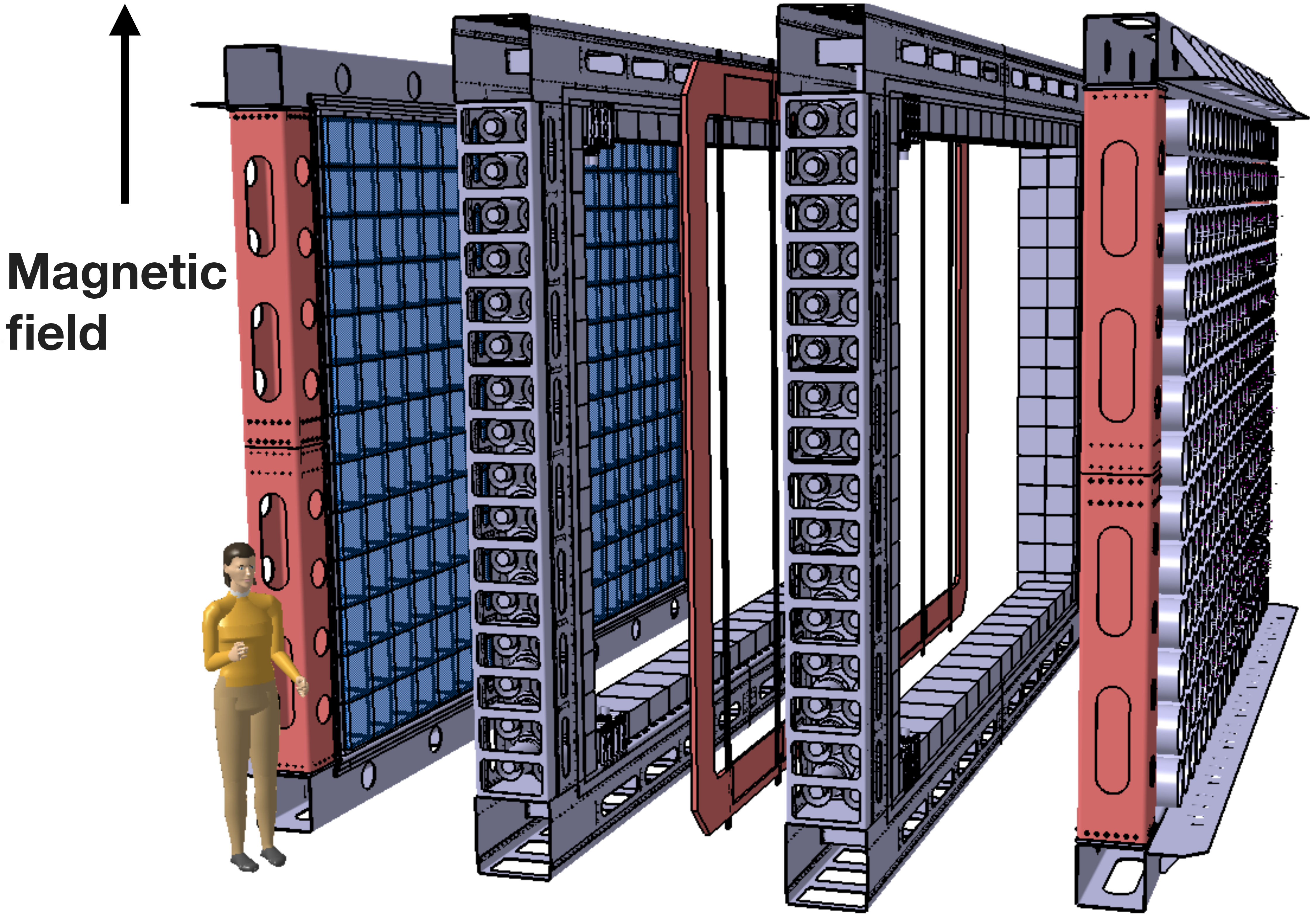

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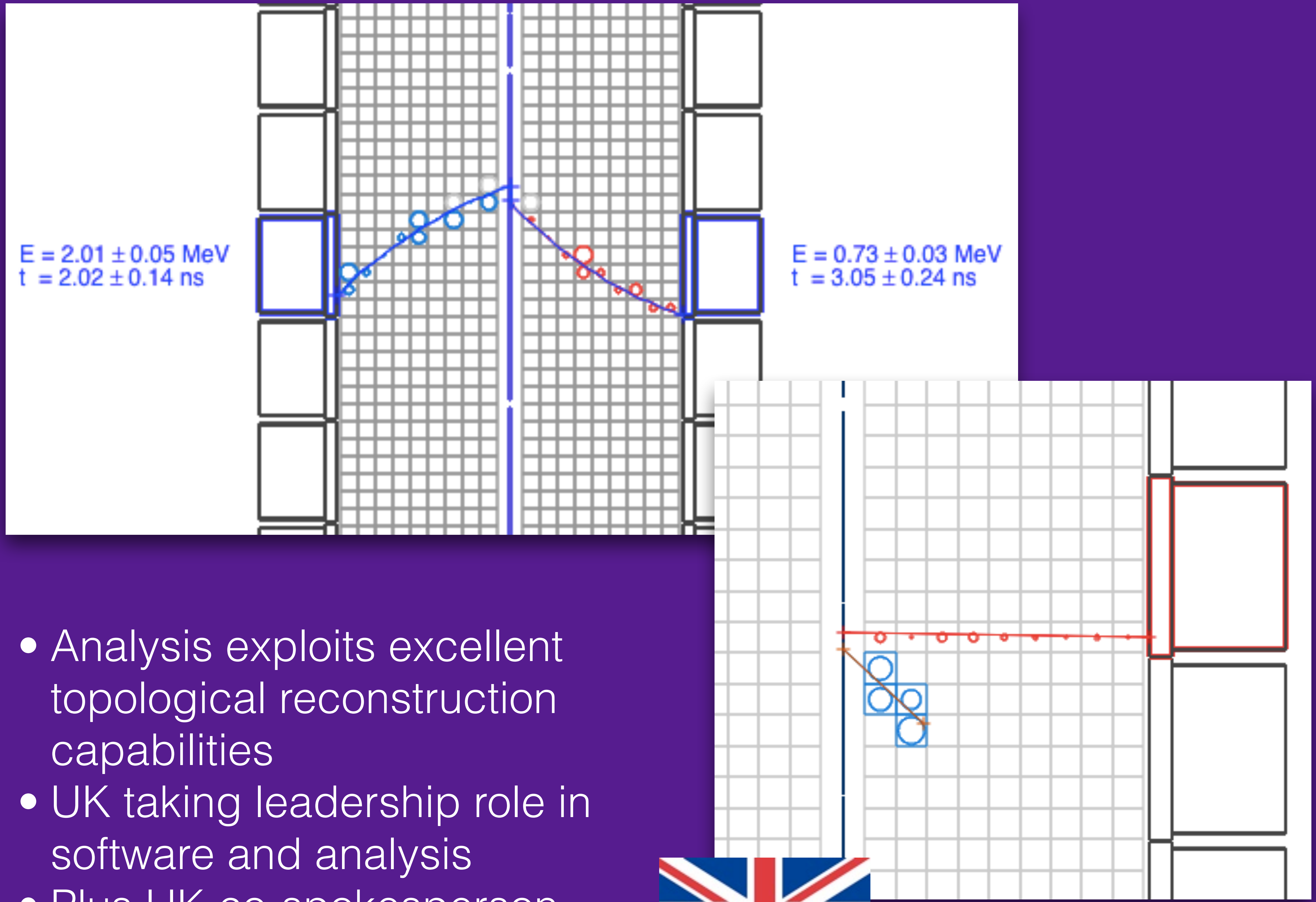
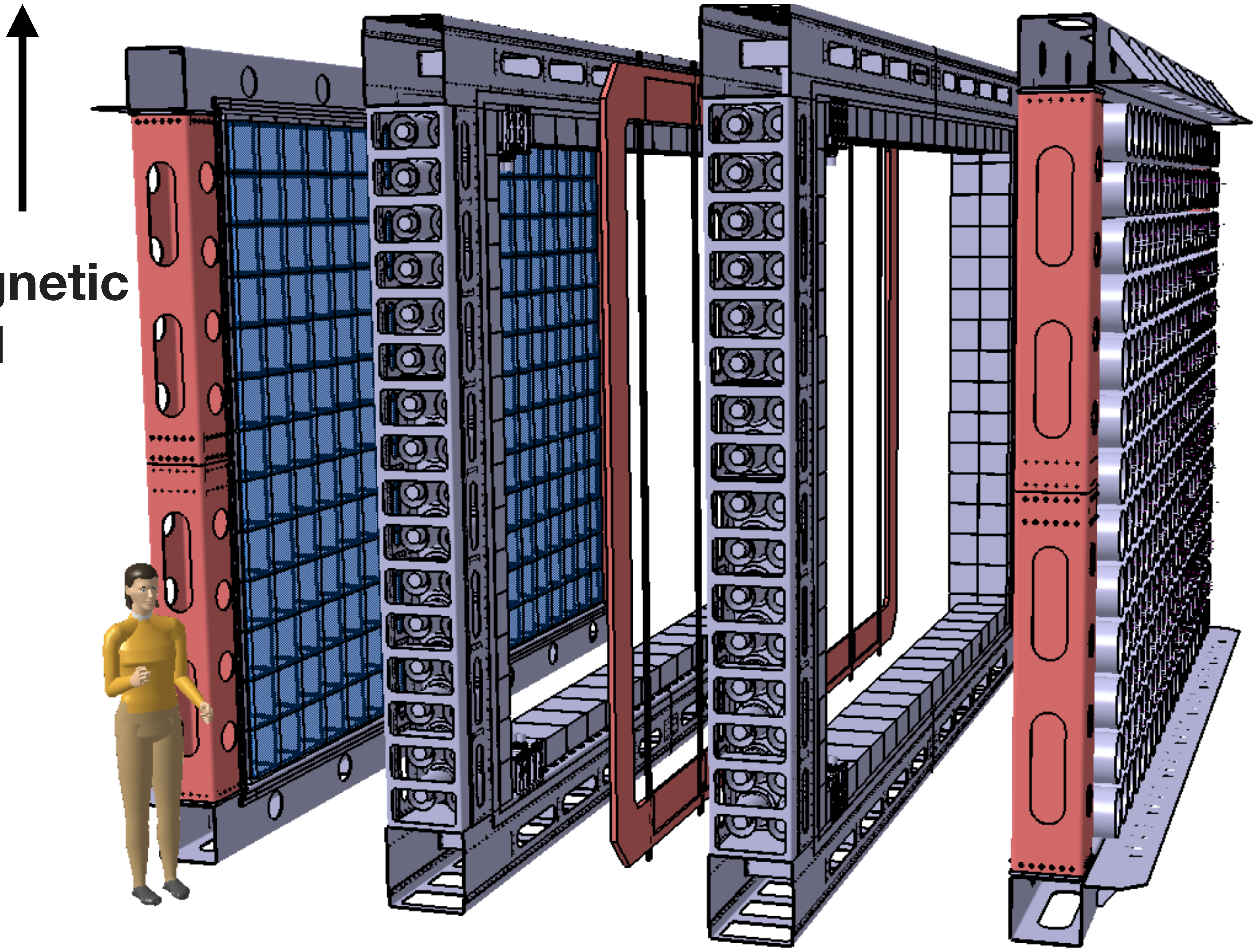
$T_{1/2}^{0\nu} > 6 \times 10^{24}$ years

Currently at LSM: SuperNEMO Demonstrator

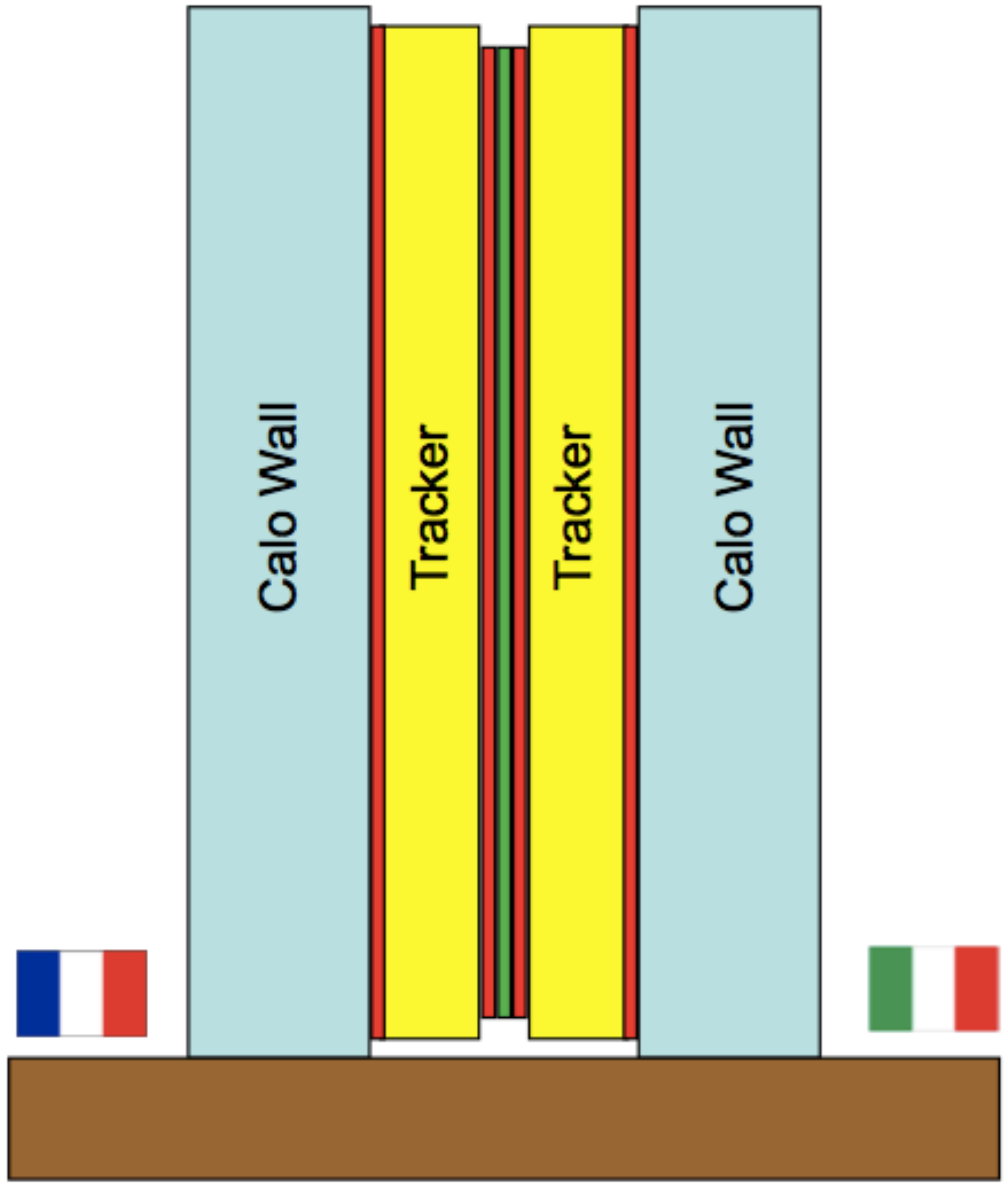


- Analysis exploits excellent topological reconstruction capabilities
- UK taking leadership role in software and analysis
- Plus UK co-spokesperson



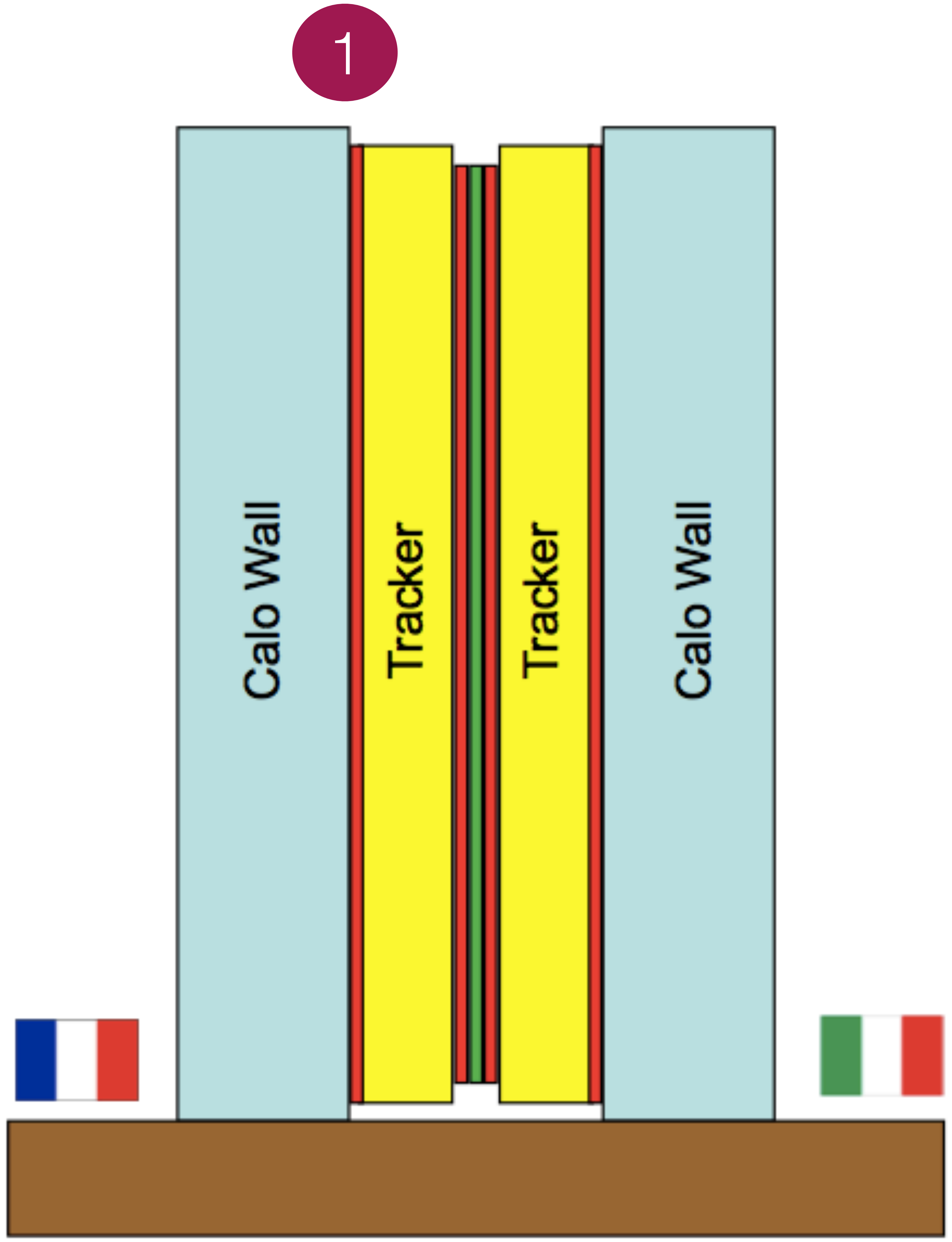
$T_{1/2}^{0\nu} > 6 \times 10^{24}$ years

Installation progress since last year



Installation progress since last year

1. Trackers joined to calorimeter wall



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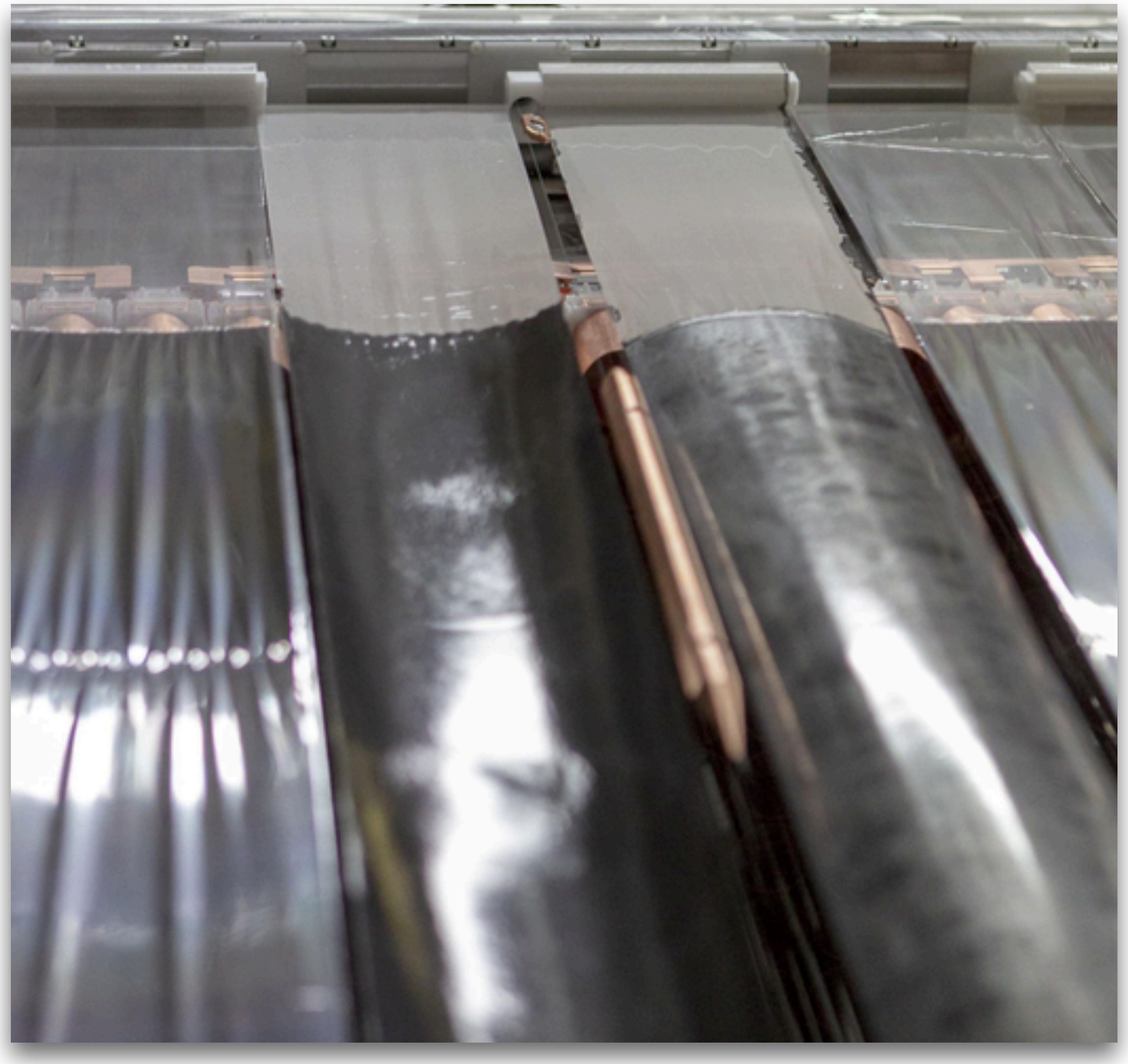
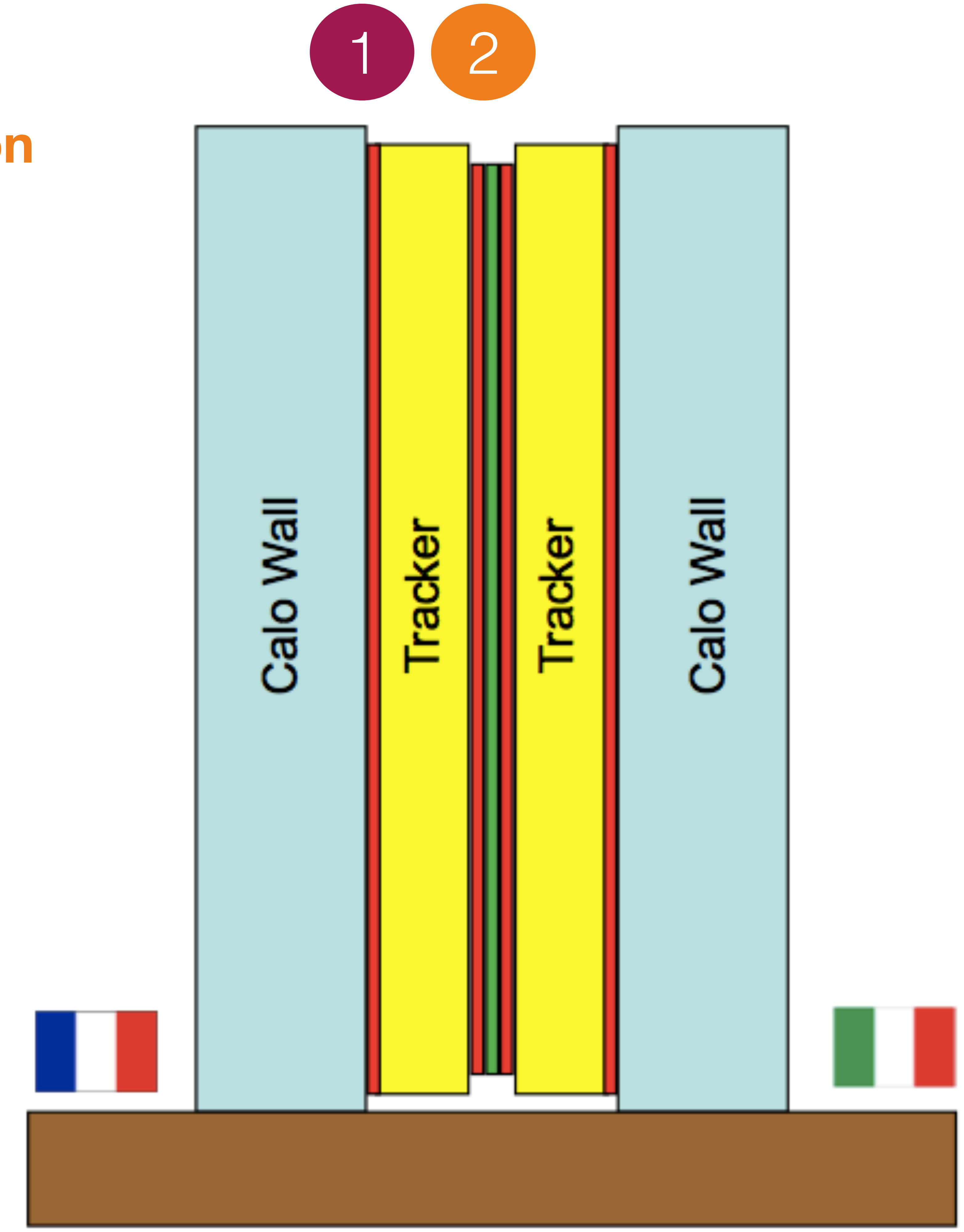


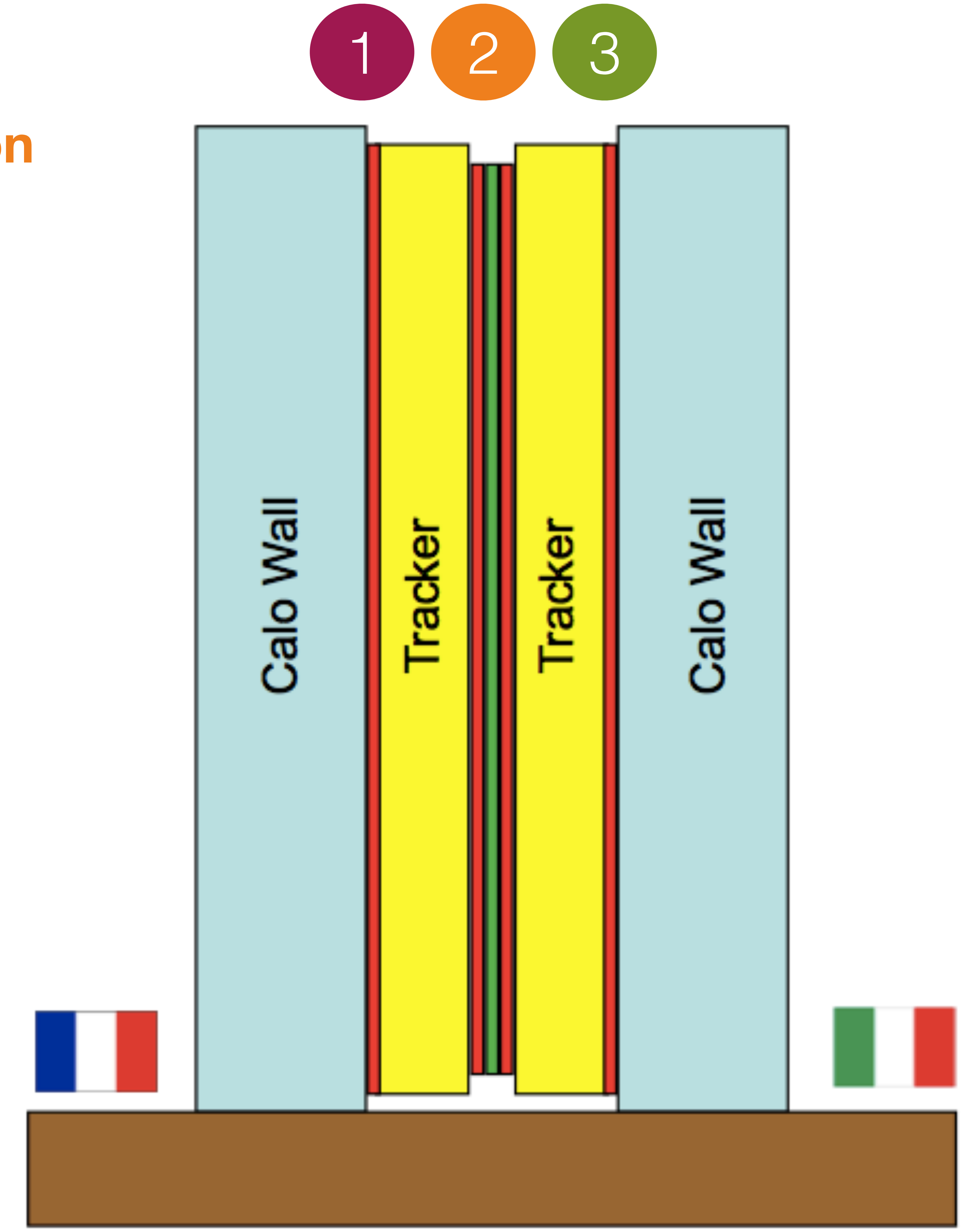
1. Trackers joined to calorimeter wall

2. Source foils and ^{207}Bi calibration system installed



Installation progress since last year

1. Trackers joined to calorimeter wall
2. Source foils and ^{207}Bi calibration system installed
3. Detector closed



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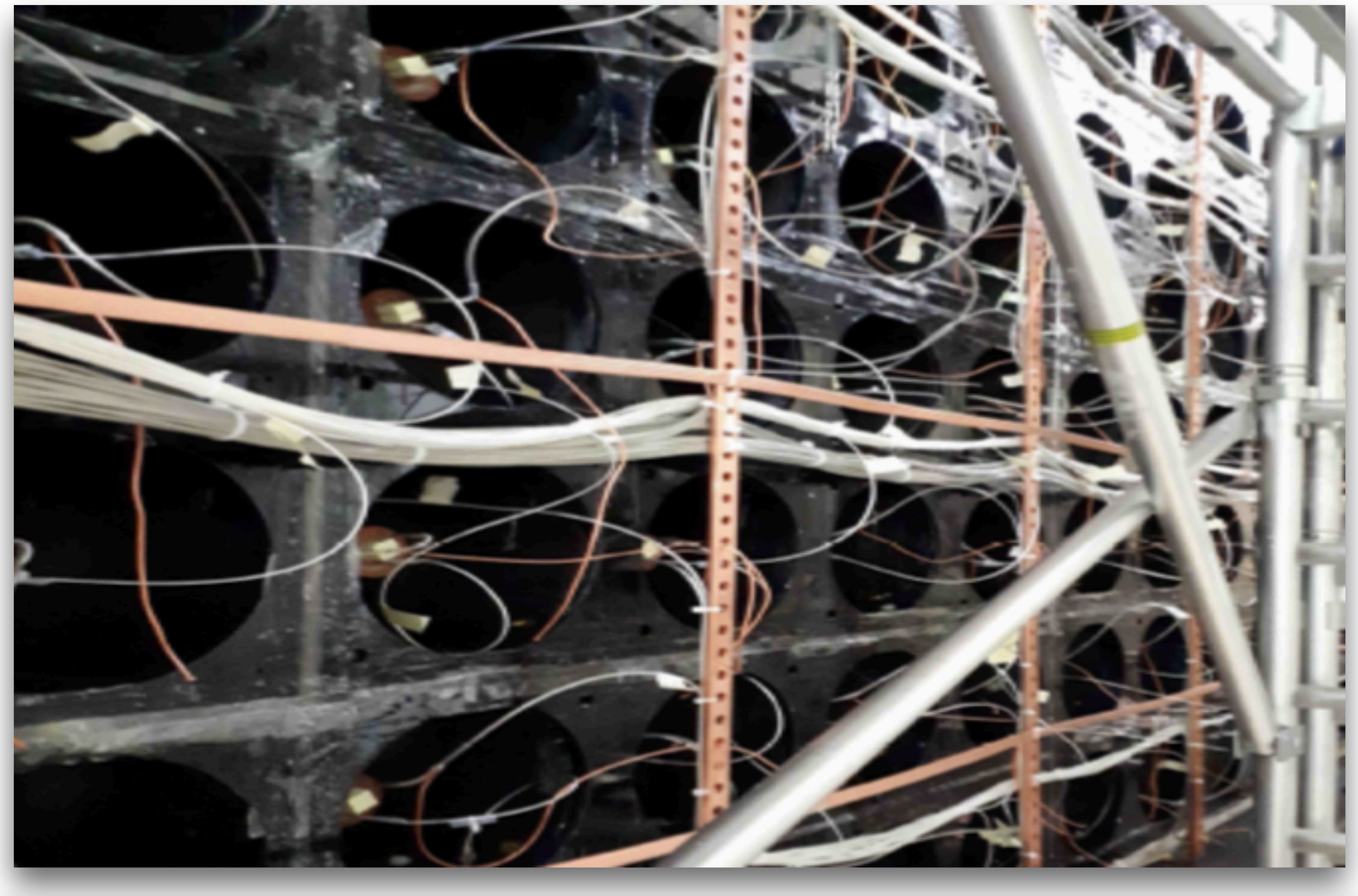
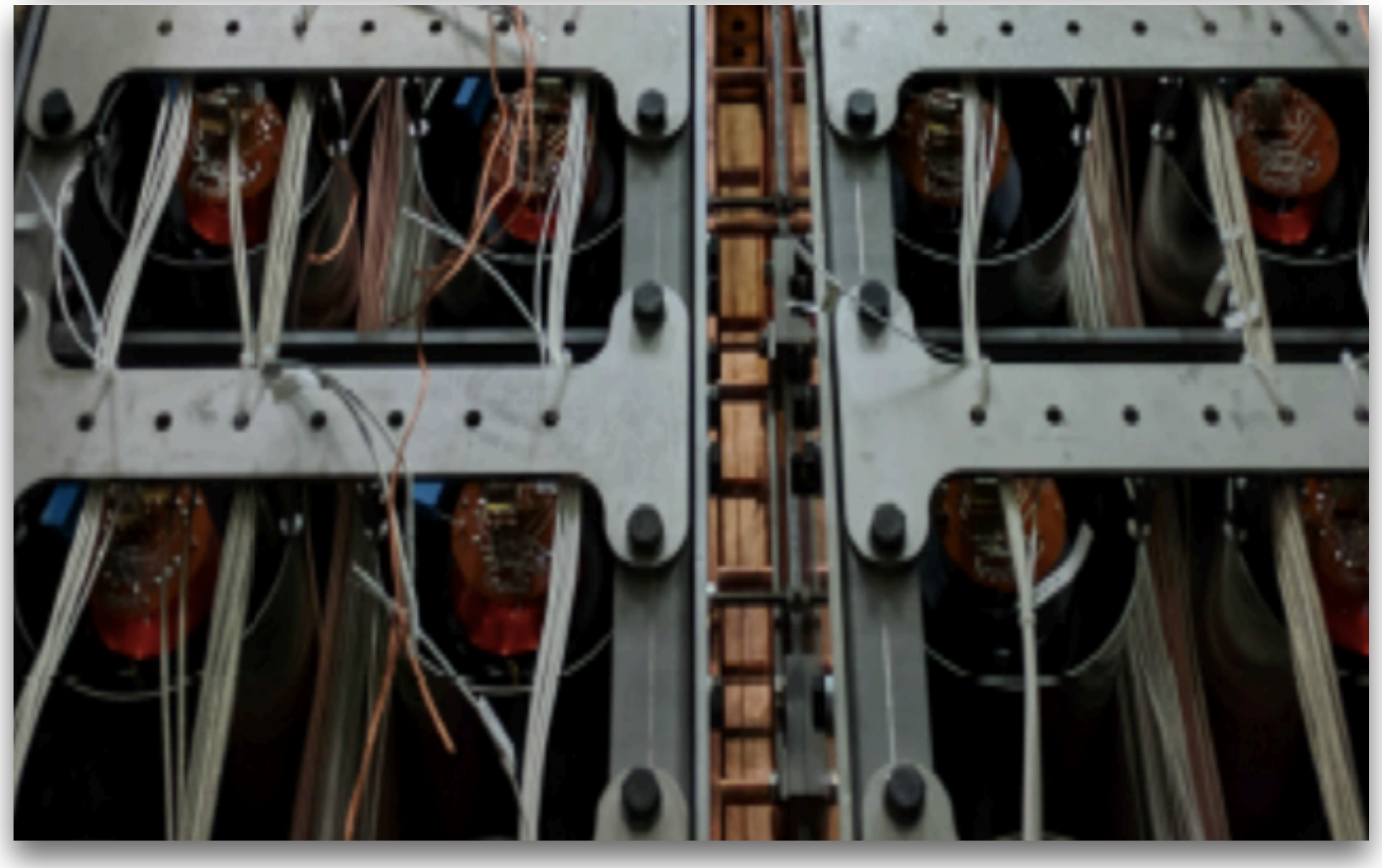
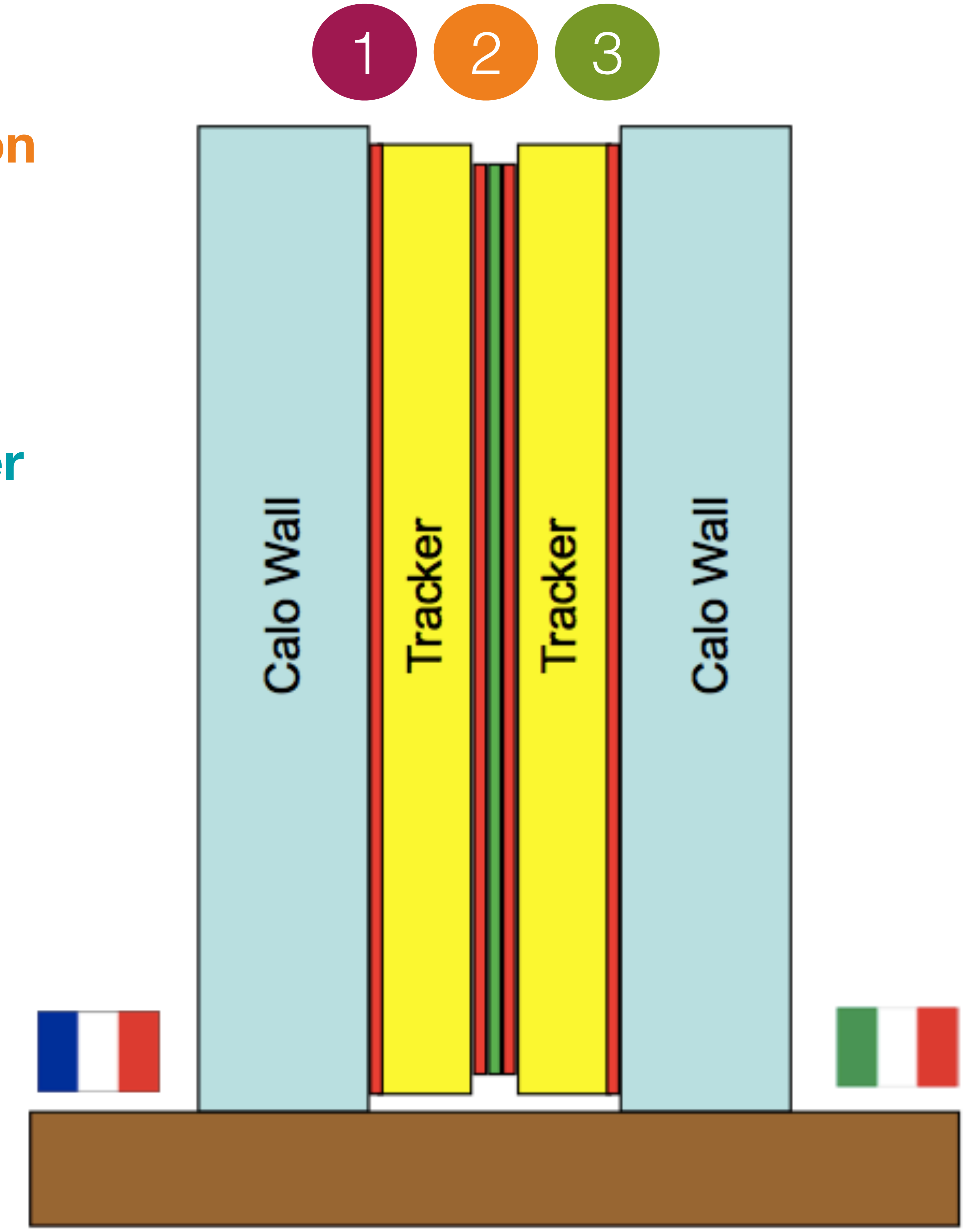
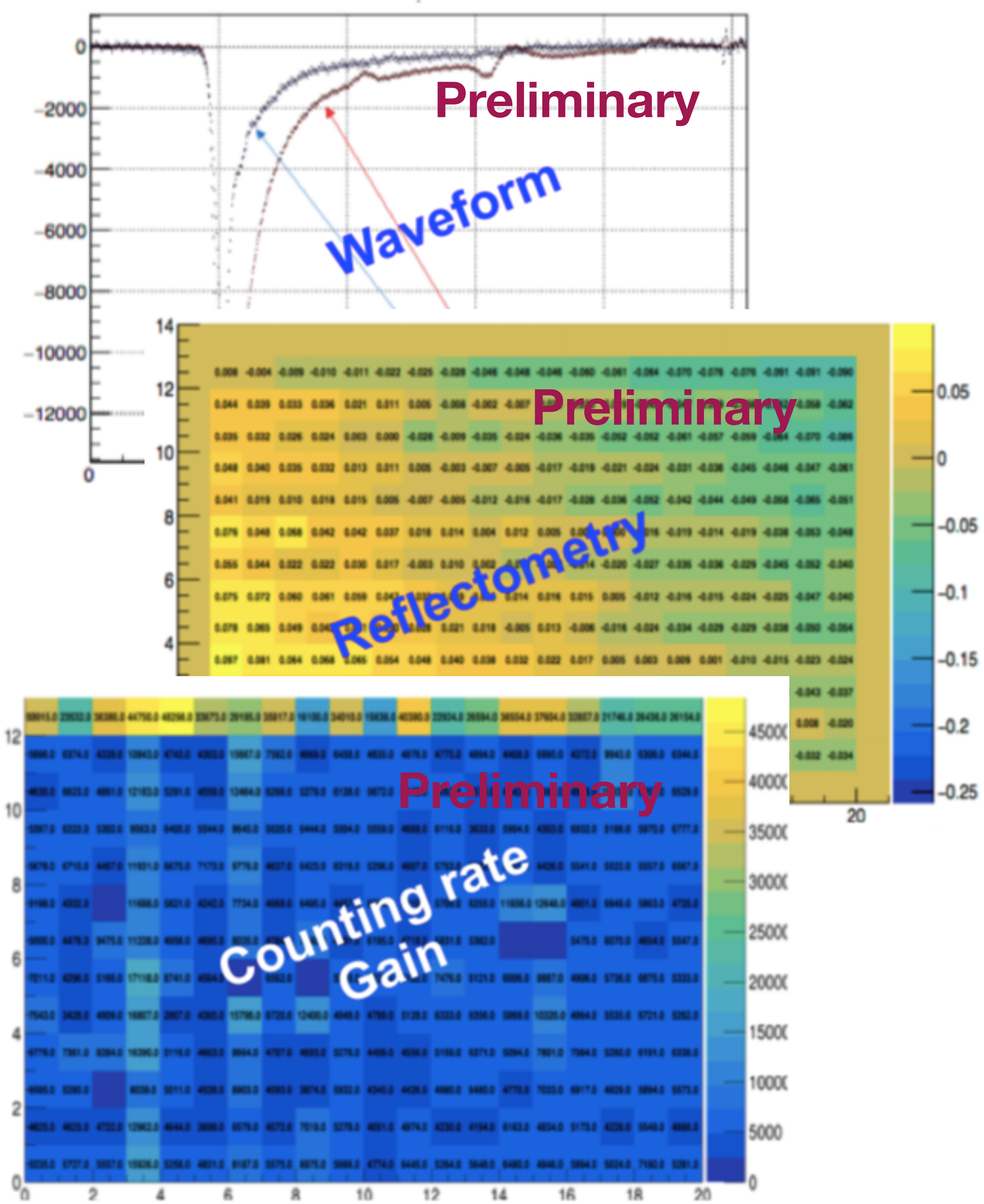




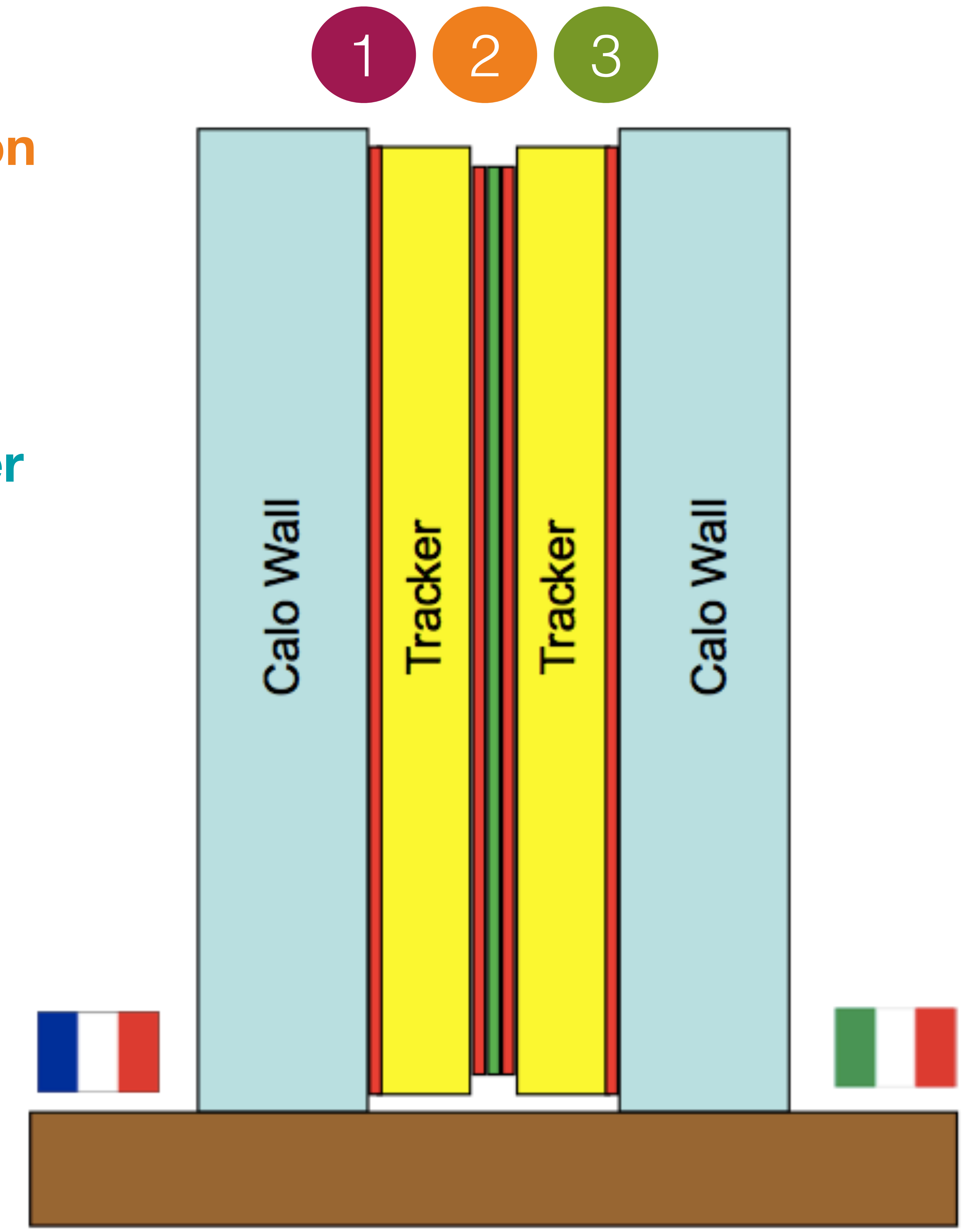
1. Trackers joined to calorimeter wall
2. Source foils and ^{207}Bi calibration system installed
3. Detector closed
4. Cabling calorimeter and tracker



Installation progress since last year



1. Trackers joined to calorimeter wall
2. Source foils and ^{207}Bi calibration system installed
3. Detector closed
4. Cabling calorimeter and tracker
5. First commissioning data!



Physics goals

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

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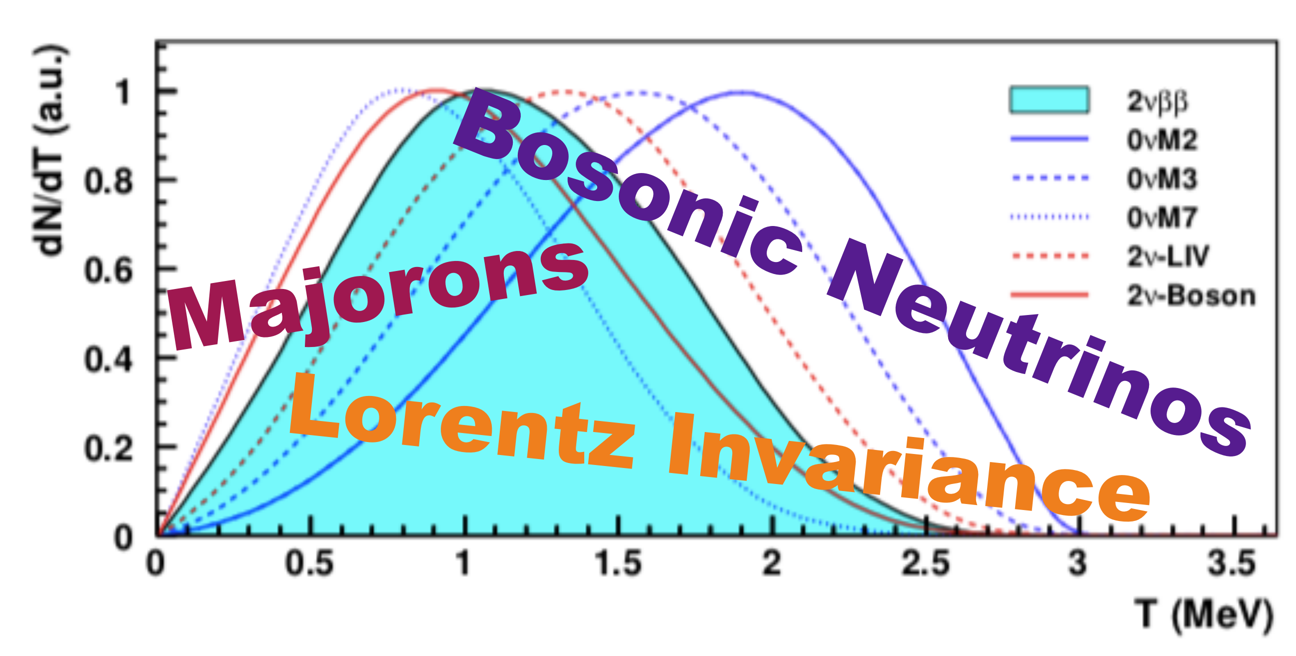
Exotic $0\nu\beta\beta$ mechanisms

Lorentz invariance violation test



Extend NEMO-3's measurements

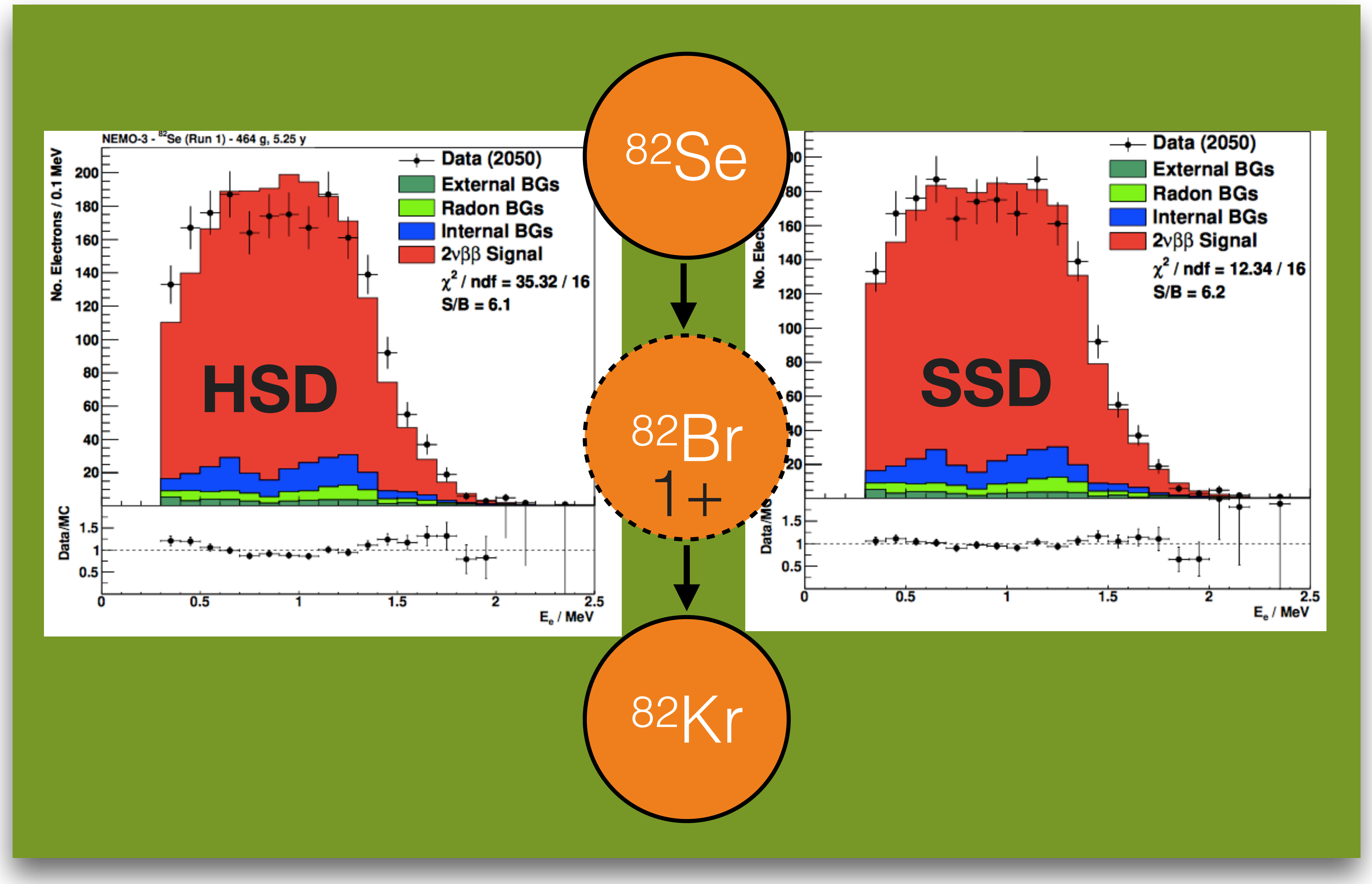
Physics goals

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

Exotic $0\nu\beta\beta$ mechanisms

Lorentz invariance violation test

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



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Lorentz invariance violation test

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

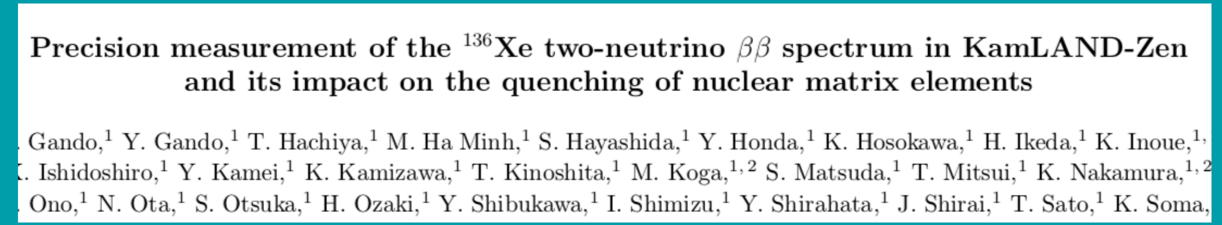
Probe nuclear physics by investigating g_A

- Axial-vector coupling constant g_A is **quenched** in heavy nuclei

- **$2\nu\beta\beta$ rate** proportional to g_A^4

$$\left(T^{2\nu}_{1/2}\right)^{-1} = \left(g_A^{\mathrm{eff}}\right)^4 \left|M^{2\nu}_{GT}\right|^2 G^{2\nu}$$

- New KamLAND-Zen paper investigates this quenching https://arxiv.org/pdf/1901.03871.pdf


Precision measurement of the ^{136}Xe two-neutrino $\beta\beta$ spectrum in KamLAND-Zen and its impact on the quenching of nuclear matrix elements

Gando,[1] Y. Gando,[1] T. Hachiya,[1] M. Ha Minh,[1] S. Hayashida,[1] Y. Honda,[1] K. Hosokawa,[1] H. Ikeda,[1] K. Inoue,[1,] . Ishidoshiro,[1] Y. Kamei,[1] K. Kamizawa,[1] T. Kinoshita,[1] M. Koga,[1,2] S. Matsuda,[1] T. Mitsui,[1] K. Nakamura,[1,2] Ono,[1] N. Ota,[1] S. Otsuka,[1] H. Ozaki,[1] Y. Shibukawa,[1] I. Shimizu,[1] Y. Shirahata,[1] J. Shirai,[1] T. Sato,[1] K. Soma,

- NEMO's topological capabilities mean it could do even **better**!

Physics goals

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

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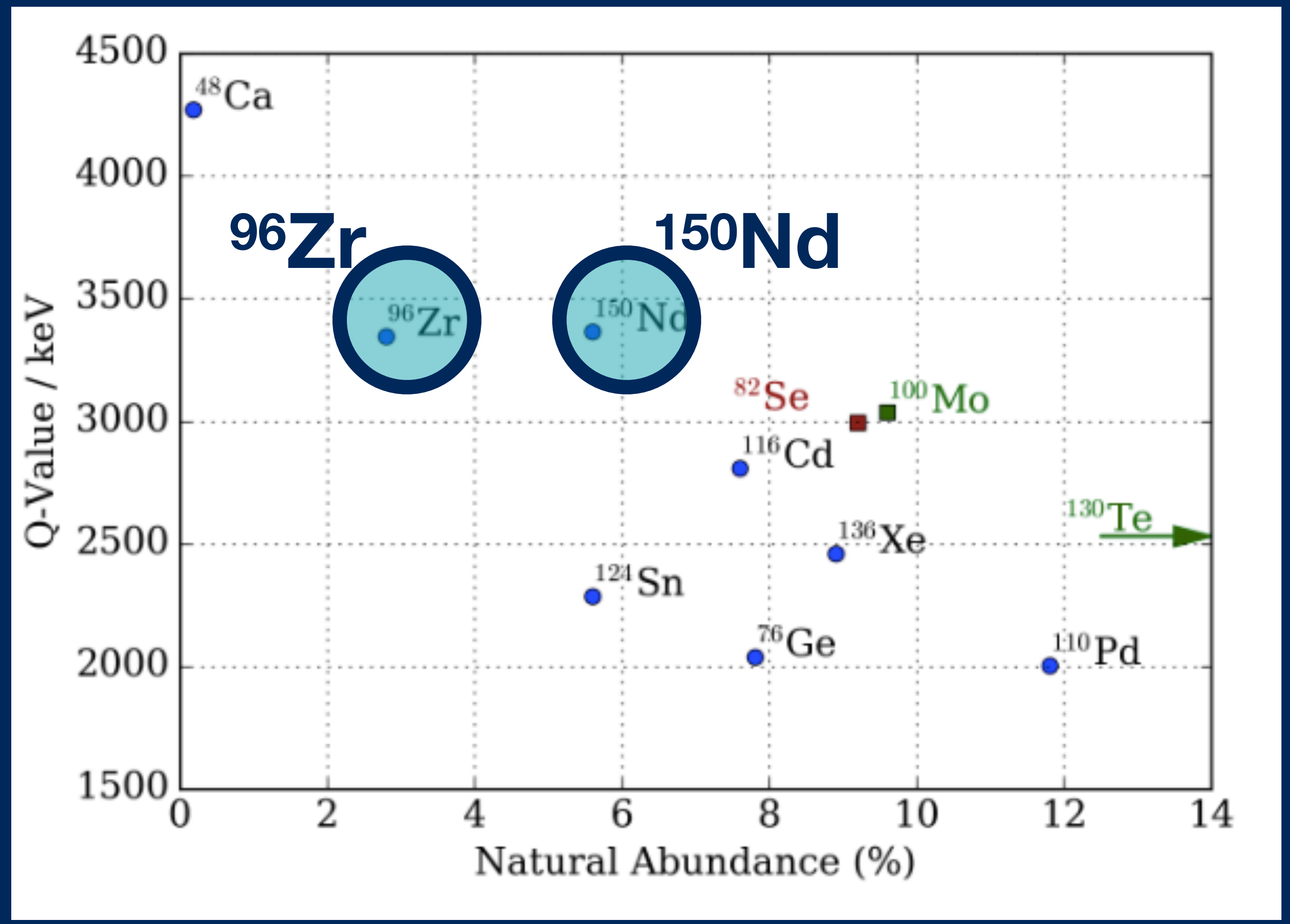
Probe nuclear physics by investigating g_A

Alternative isotopes: ^{150}Nd and ^{96}Zr



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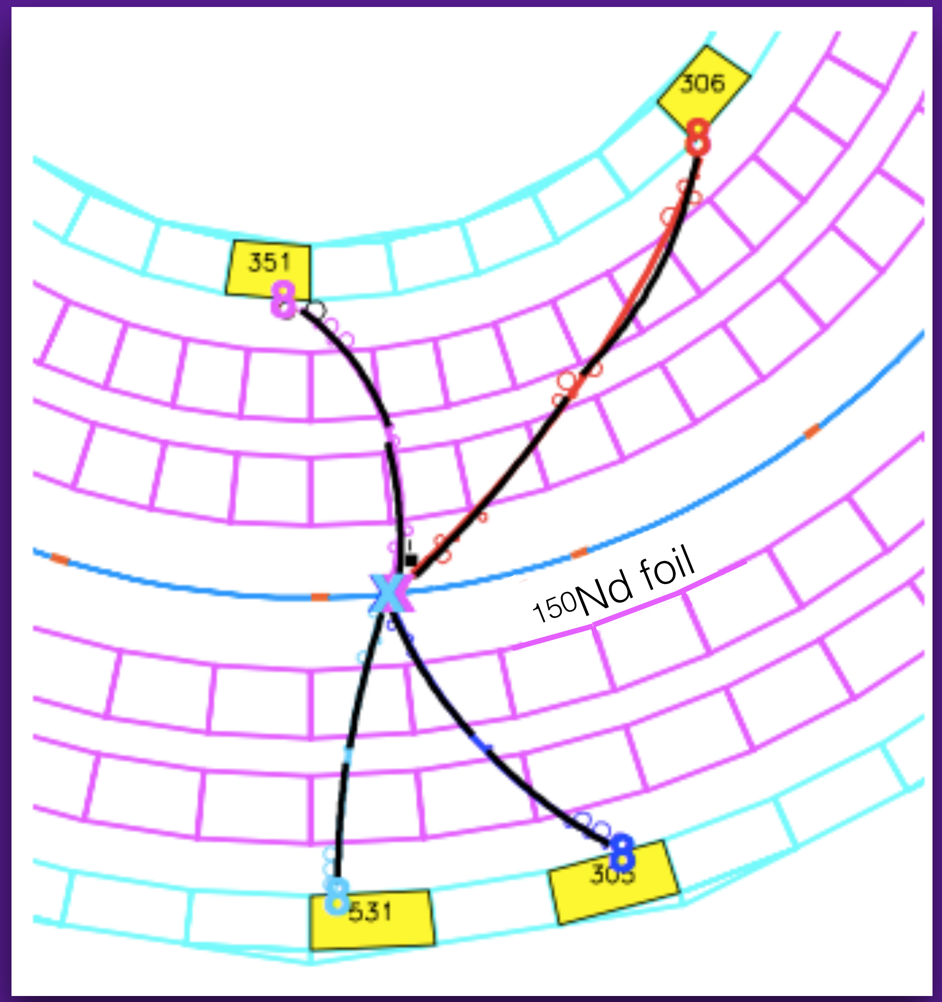
$0\nu4\beta$: for ^{150}Nd



NEMO-3 placed limit on lepton number-violating process, which could affect even Dirac neutrinos

Phys. Rev. Lett. 119, 041801

Physics goals

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

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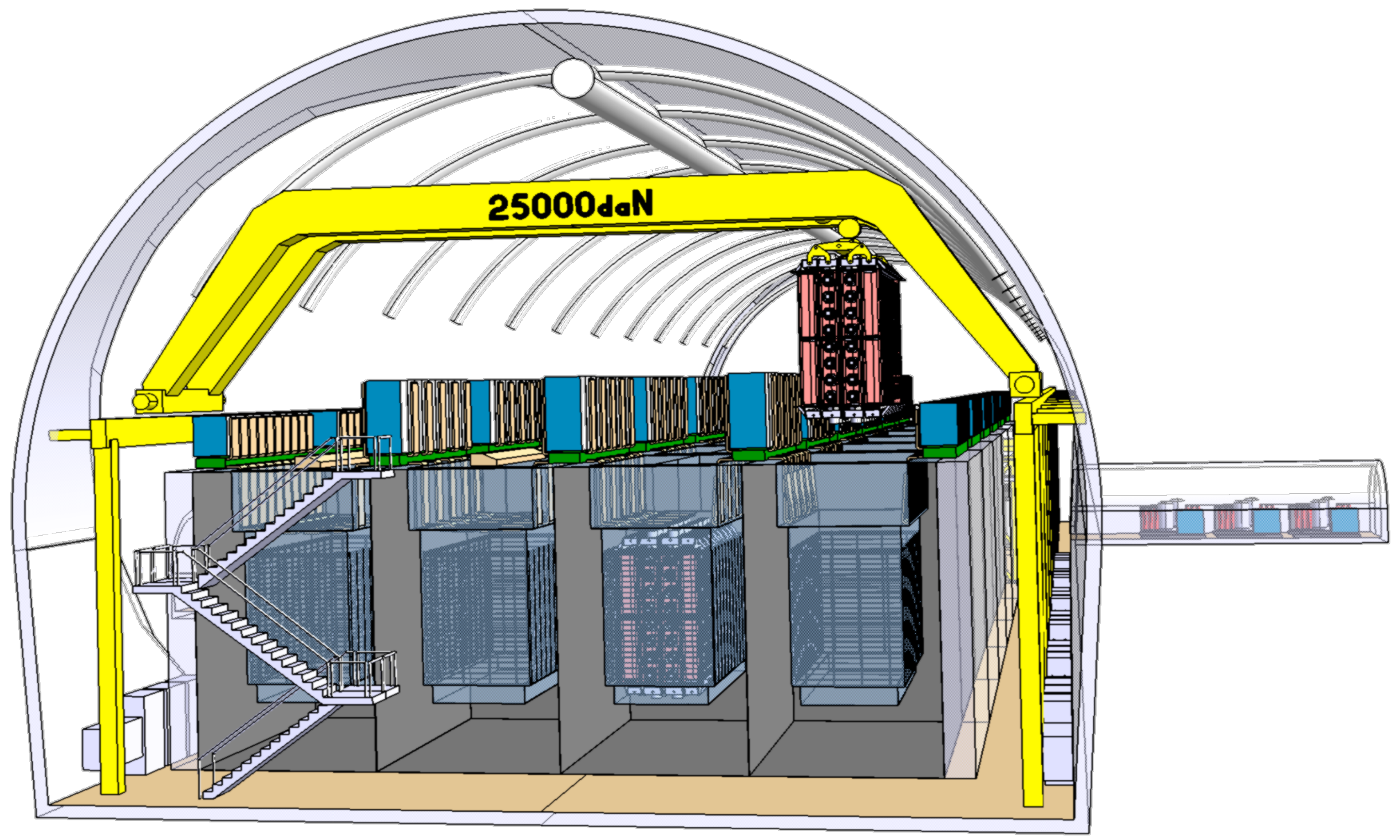
$0\nu4\beta$: for ^{150}Nd

plus proof of concept for…



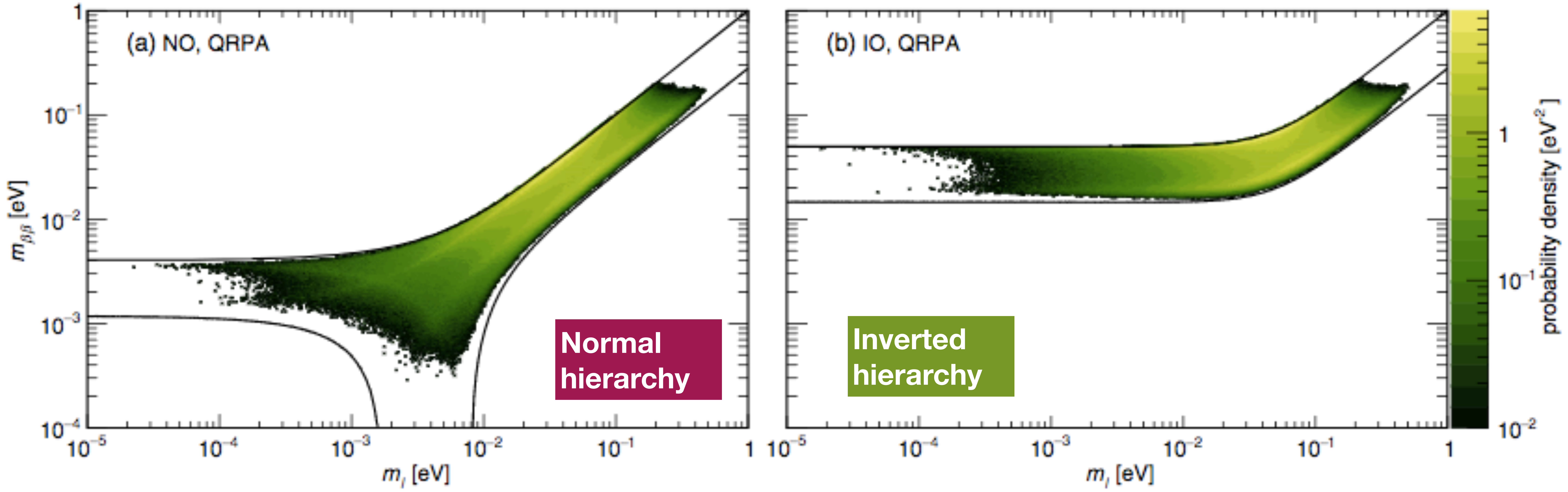
Full SuperNEMO

- **Modular** design allows easy scaling up
- 20 modules x 5 years (500 kg year) gives sensitivity comparable or better than current **leading experiments**
- Best technique to understand more about **$0\nu\beta\beta$ mechanism** in the event of discovery

Look to the future…

Next-generation 0νββ searches

Bayesian probability density fit by D'Agostini, Benato & Detwiler: Phys. Rev. D 96, 053001 (2017)



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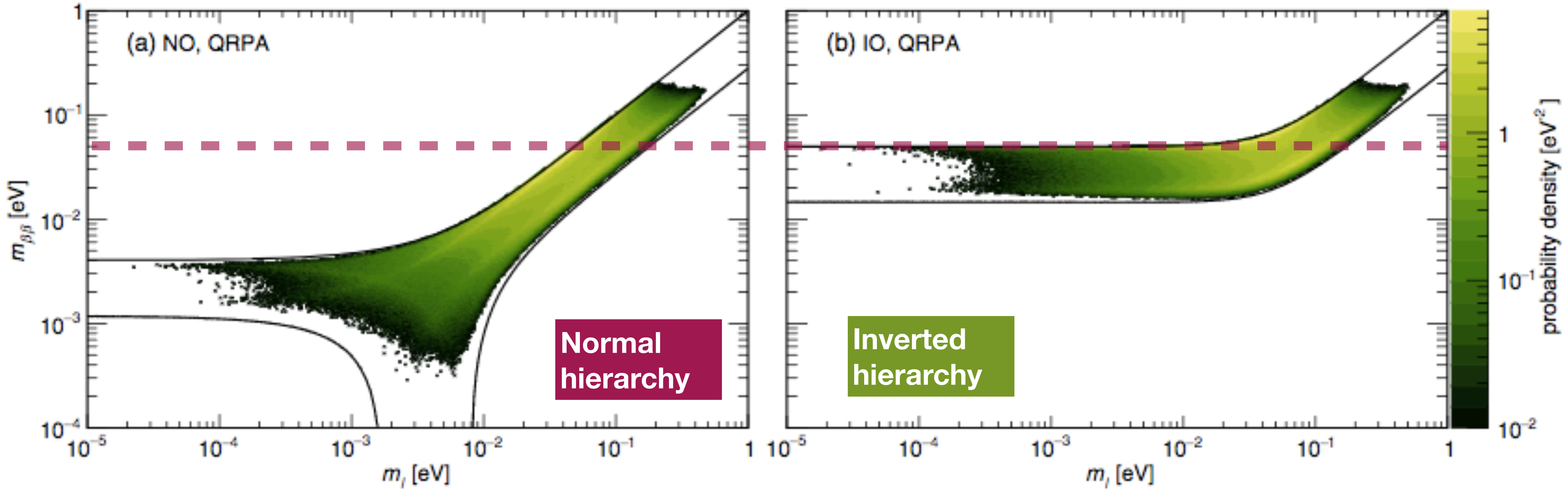

- Current experiments probe the **degenerate** regime

Next-generation 0νββ searches

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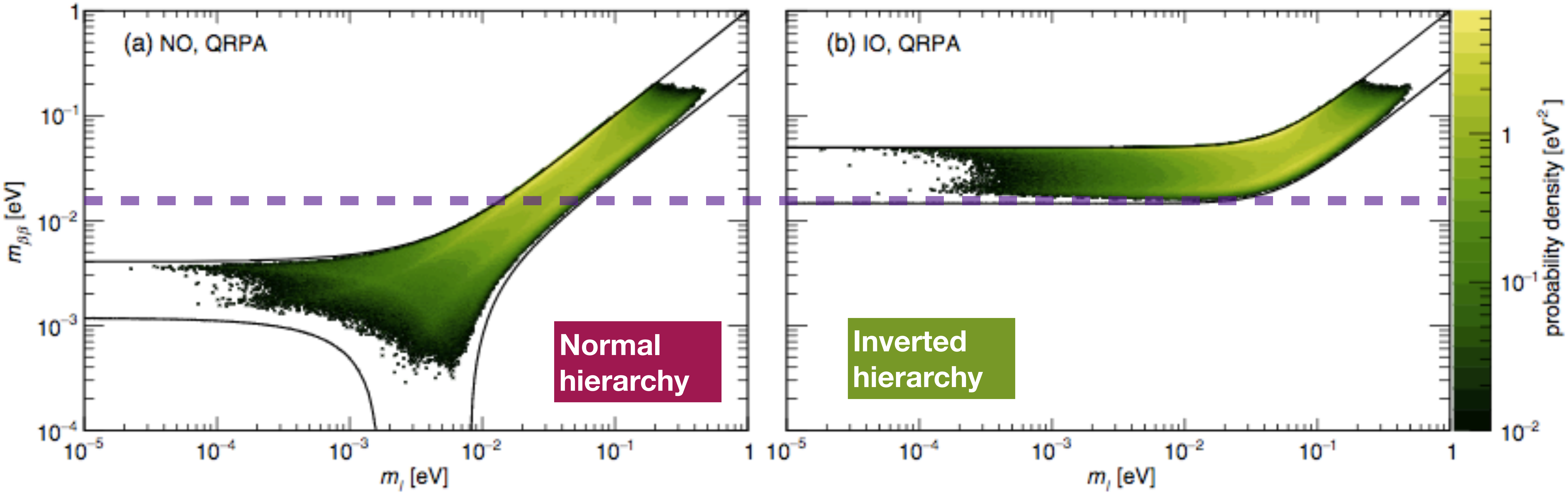
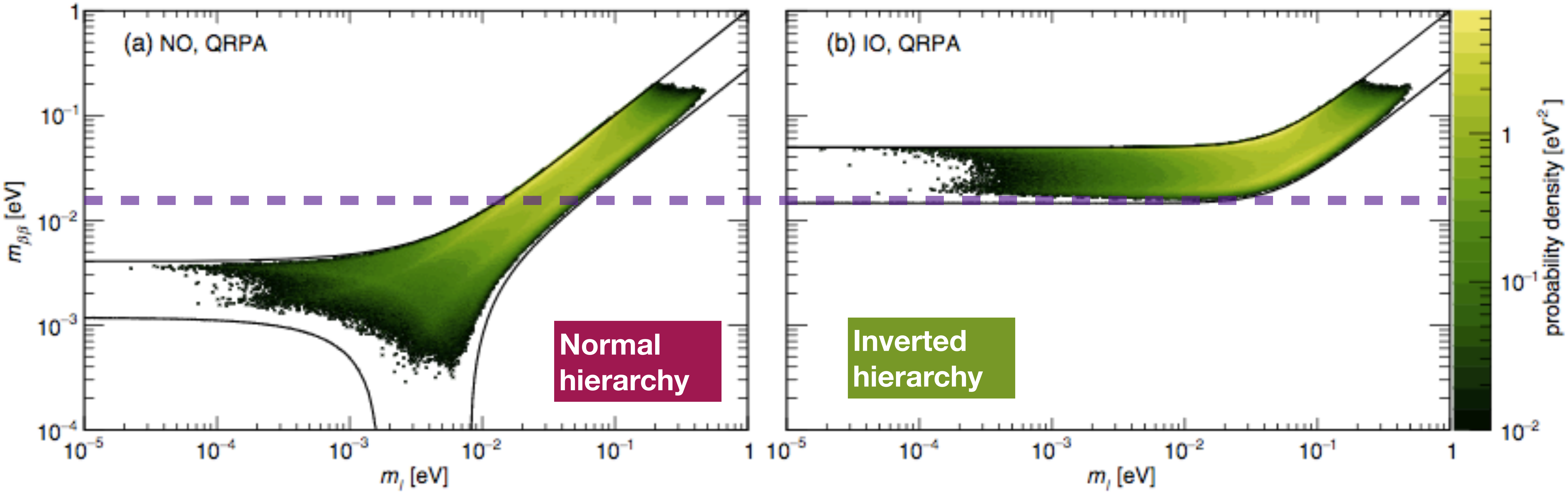


- Current experiments probe the **degenerate** regime
- Next-generation will cover **full inverted hierarchy** region

Next-generation 0νββ searches

Bayesian probability density fit by D'Agostini, Benato & Detwiler: Phys. Rev. D 96, 053001 (2017)

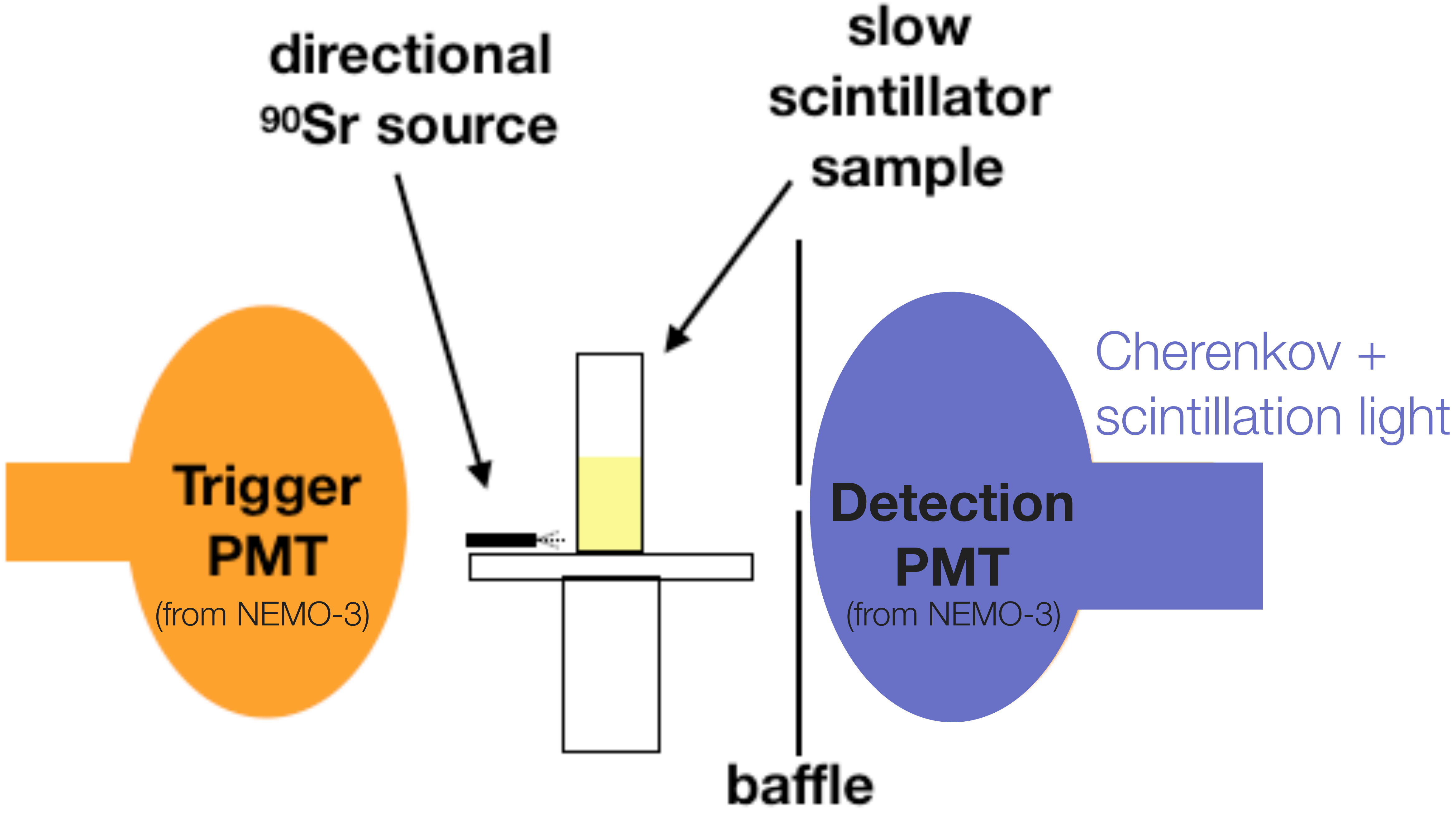


- Current experiments probe the **degenerate** regime
- Next-generation will cover **full inverted hierarchy** region
- When likelihood density is considered, this mass range also covers more than **50% of normal hierarchy** probability

UK R&D: slow liquid scintillator

Several slow liquid scintillator mixtures developed at Oxford provide:

- excellent **time separation** of Cherenkov light to help reconstruct event **topology**
- high **scintillation light** yield for high **energy resolution**



Thanks to Steve Biller for slide content

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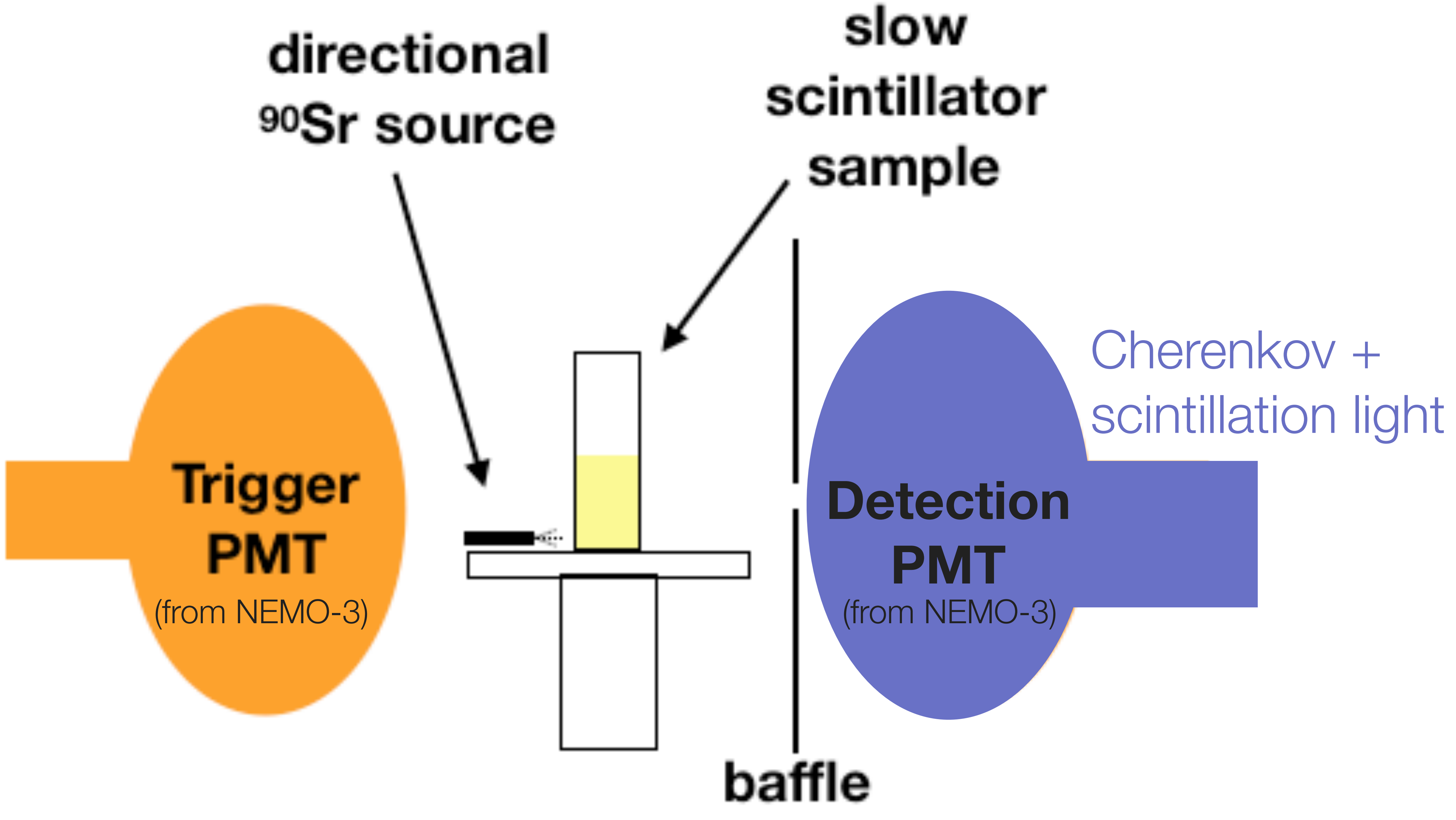

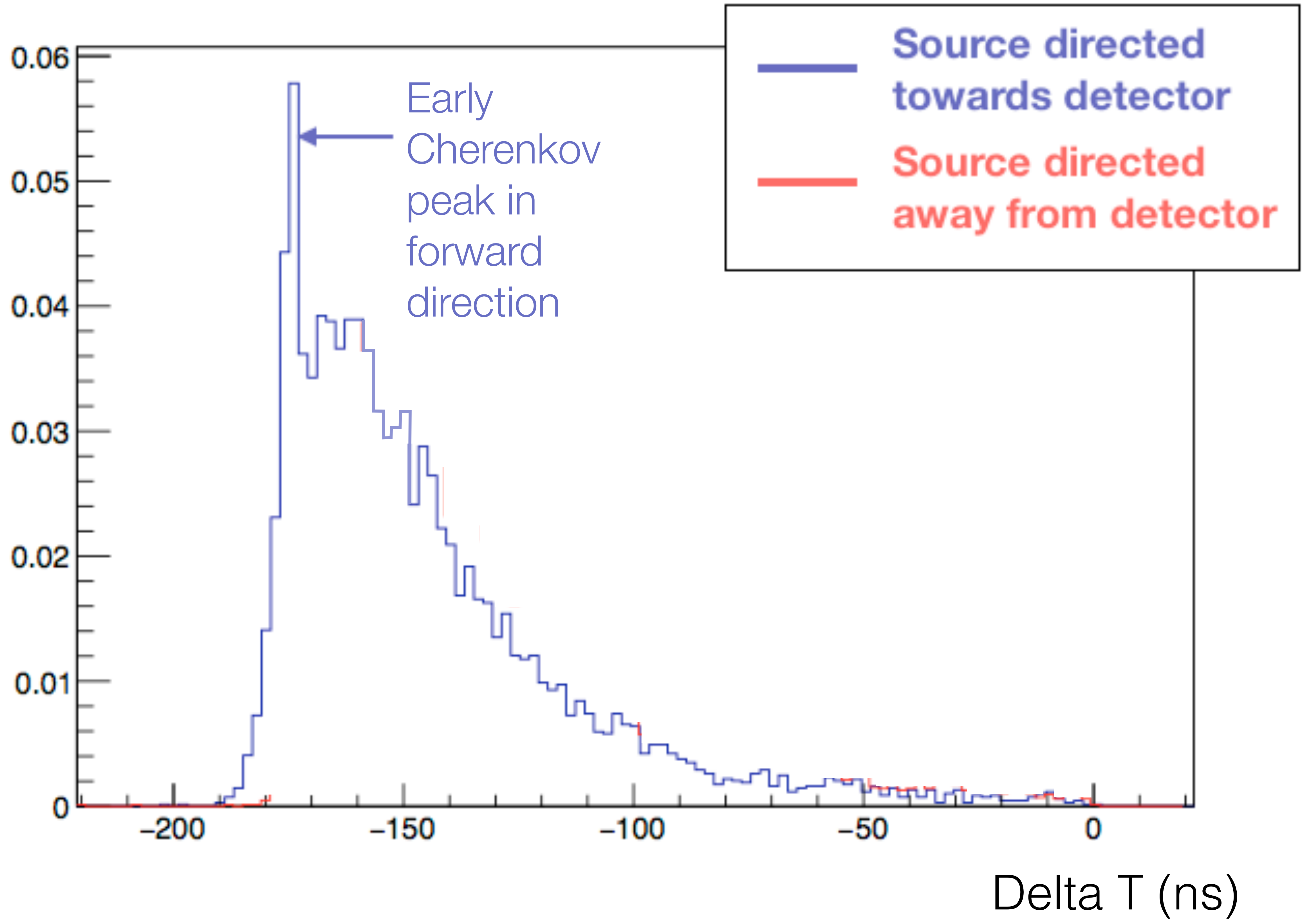

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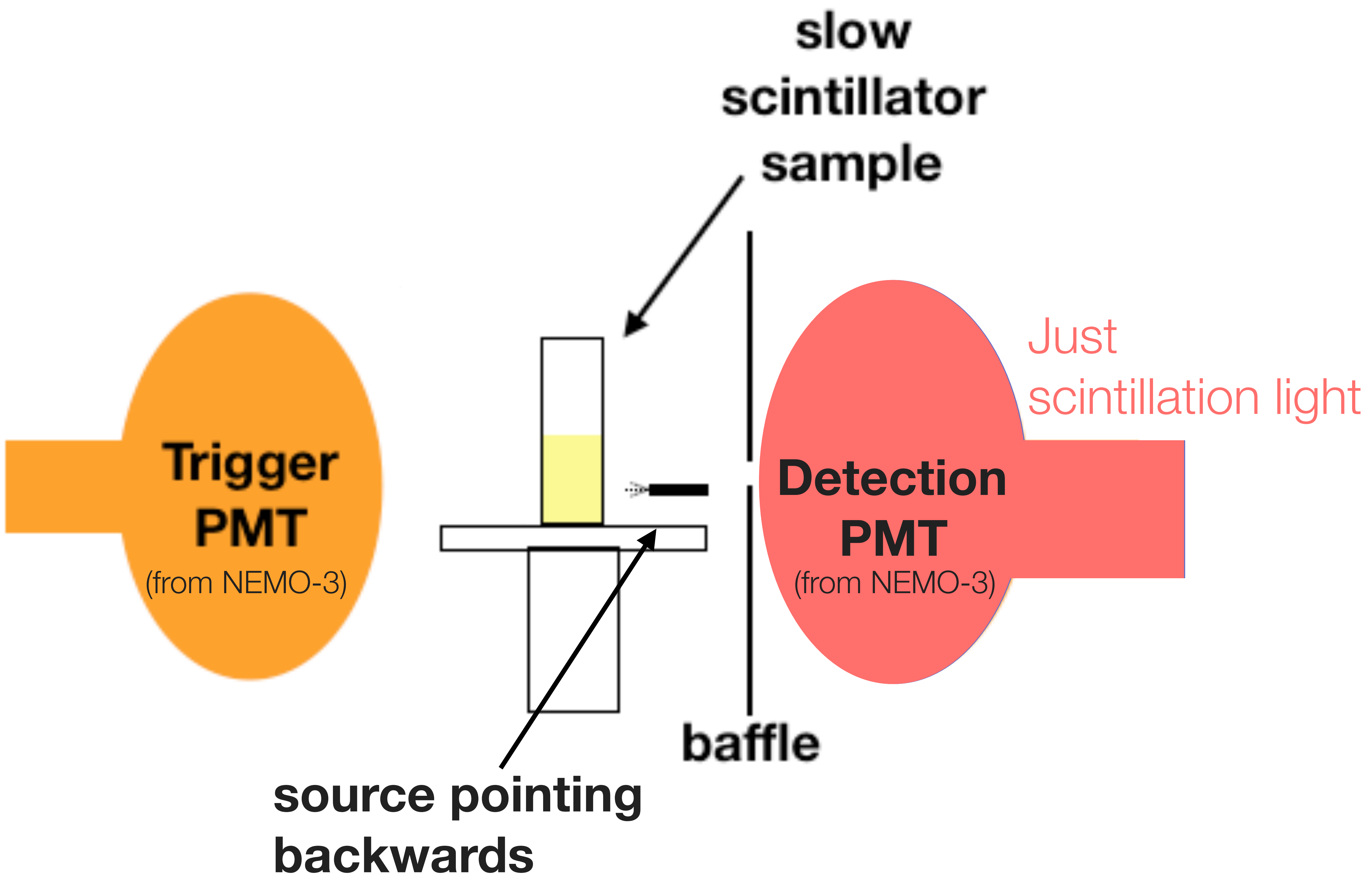

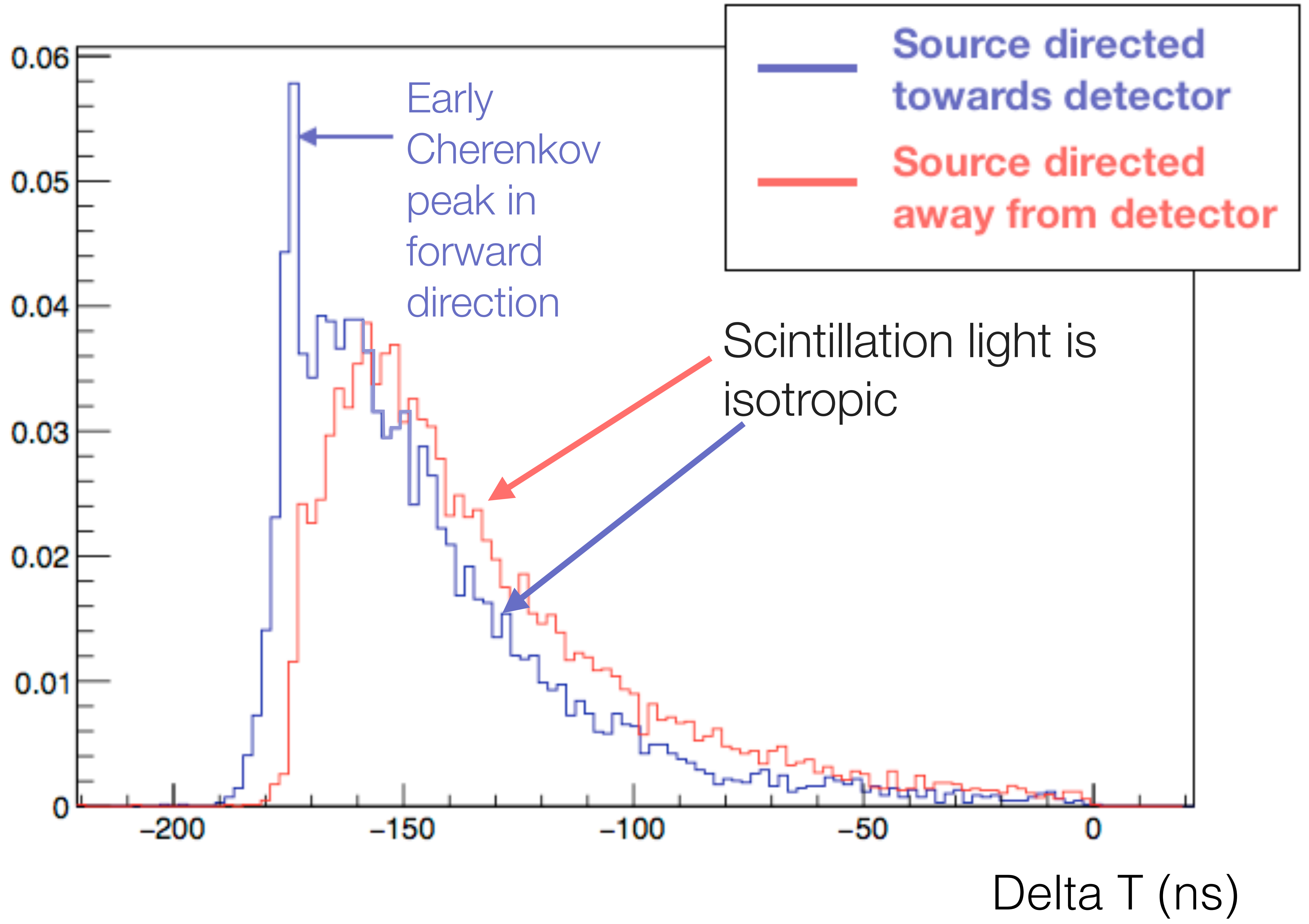

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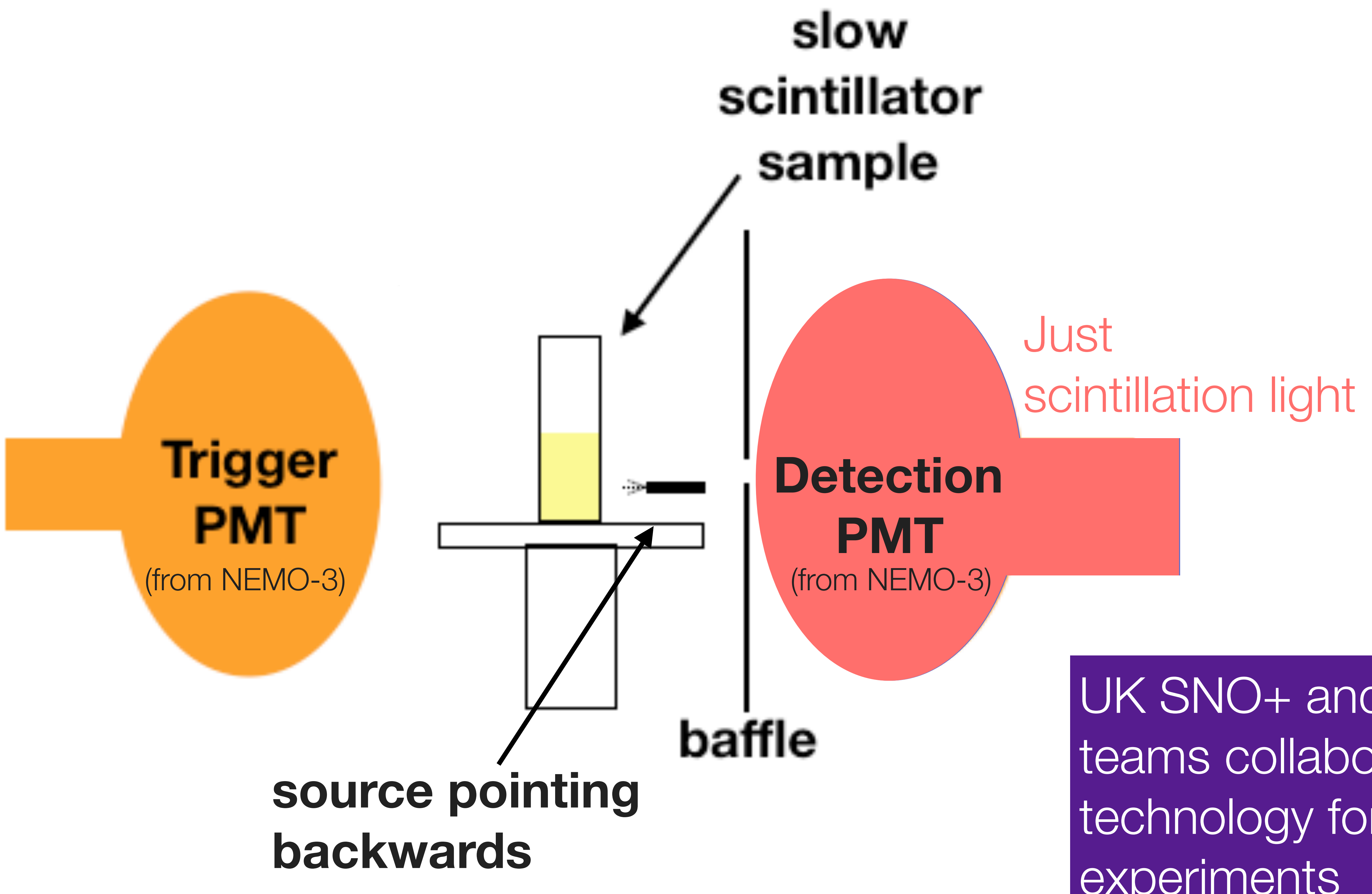
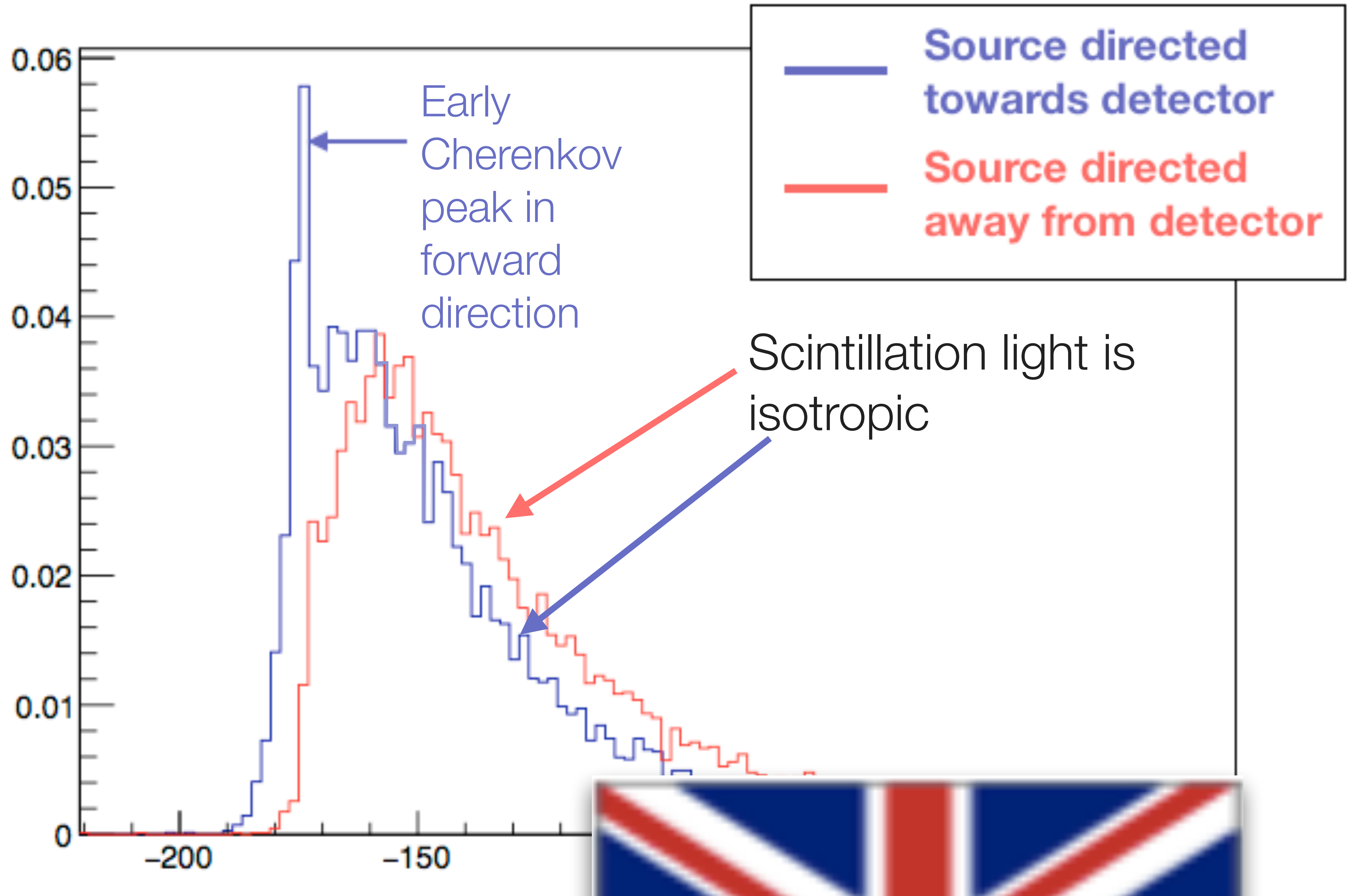
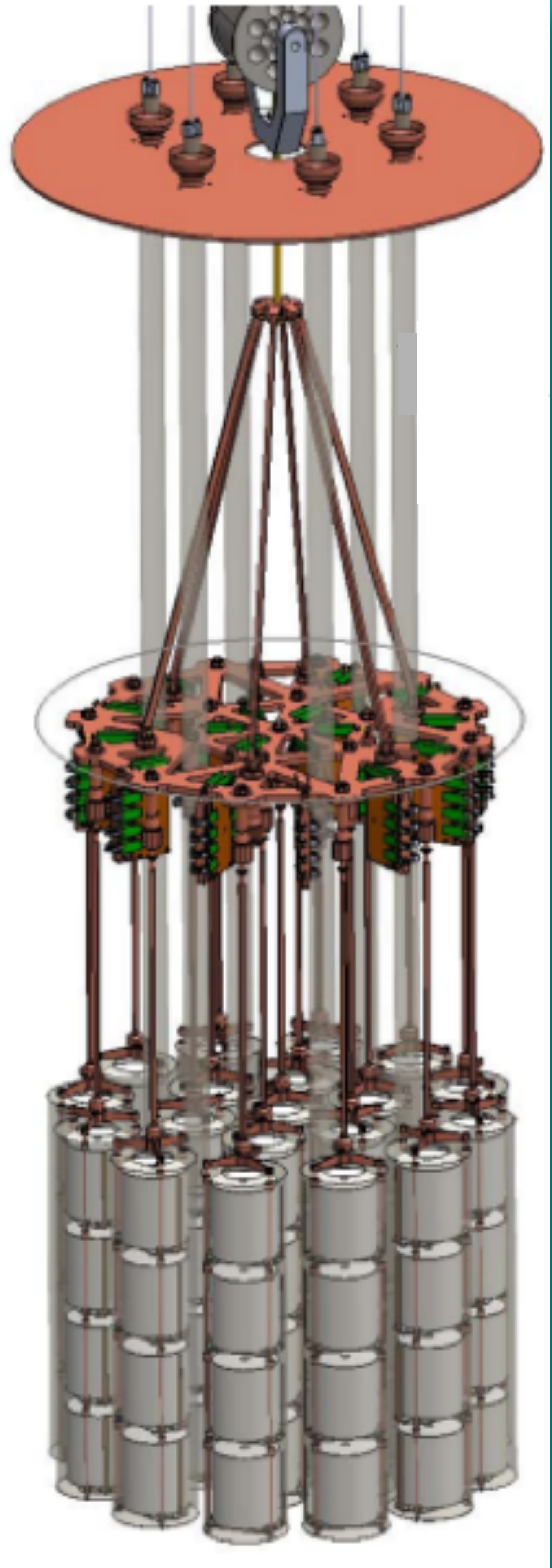




UK SNO+ and SuperNEMO teams collaborating to research technology for future $0\nu\beta\beta$ experiments

Thanks to Steve Biller for slide content

UK future involvement - LEGEND HP^{76}Ge detector



LEGEND-200kg @ LNGS

- **10^{27} yrs** : 1 order of magnitude more sensitive than current leading experiments. Neutrino mass discovery reach **50 meV**.
- Start running **2021**, run for 5-7 years.

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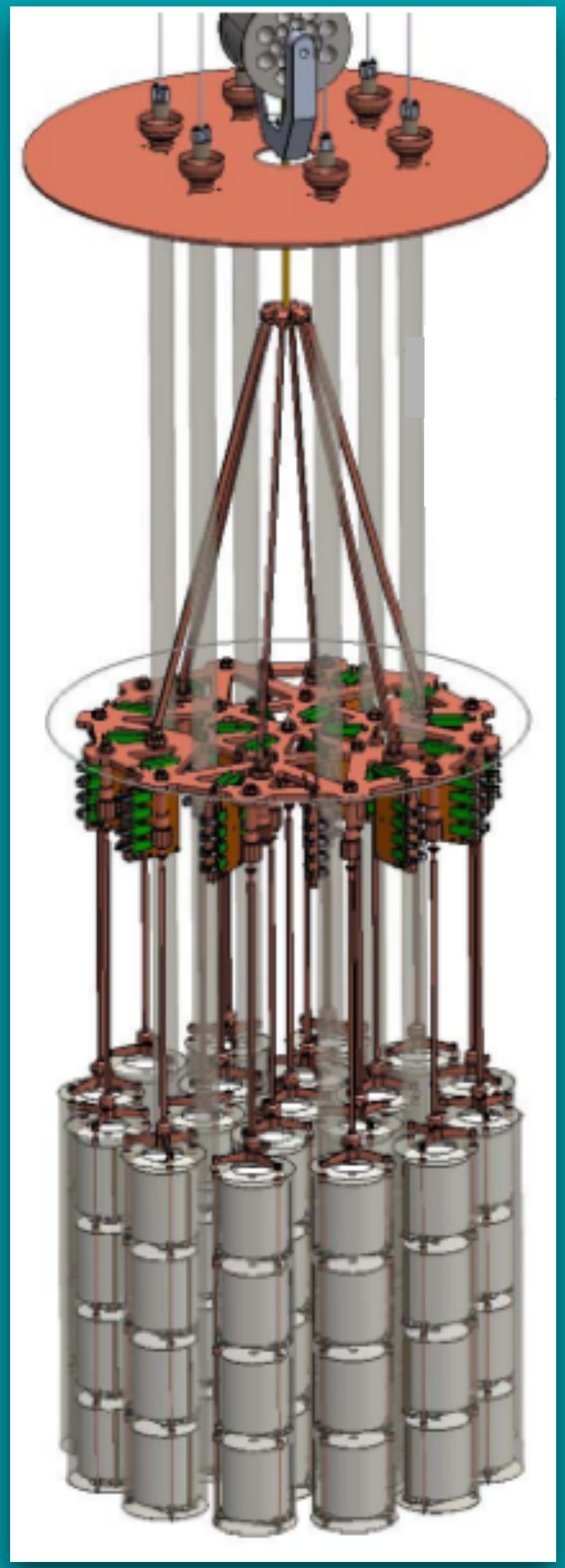

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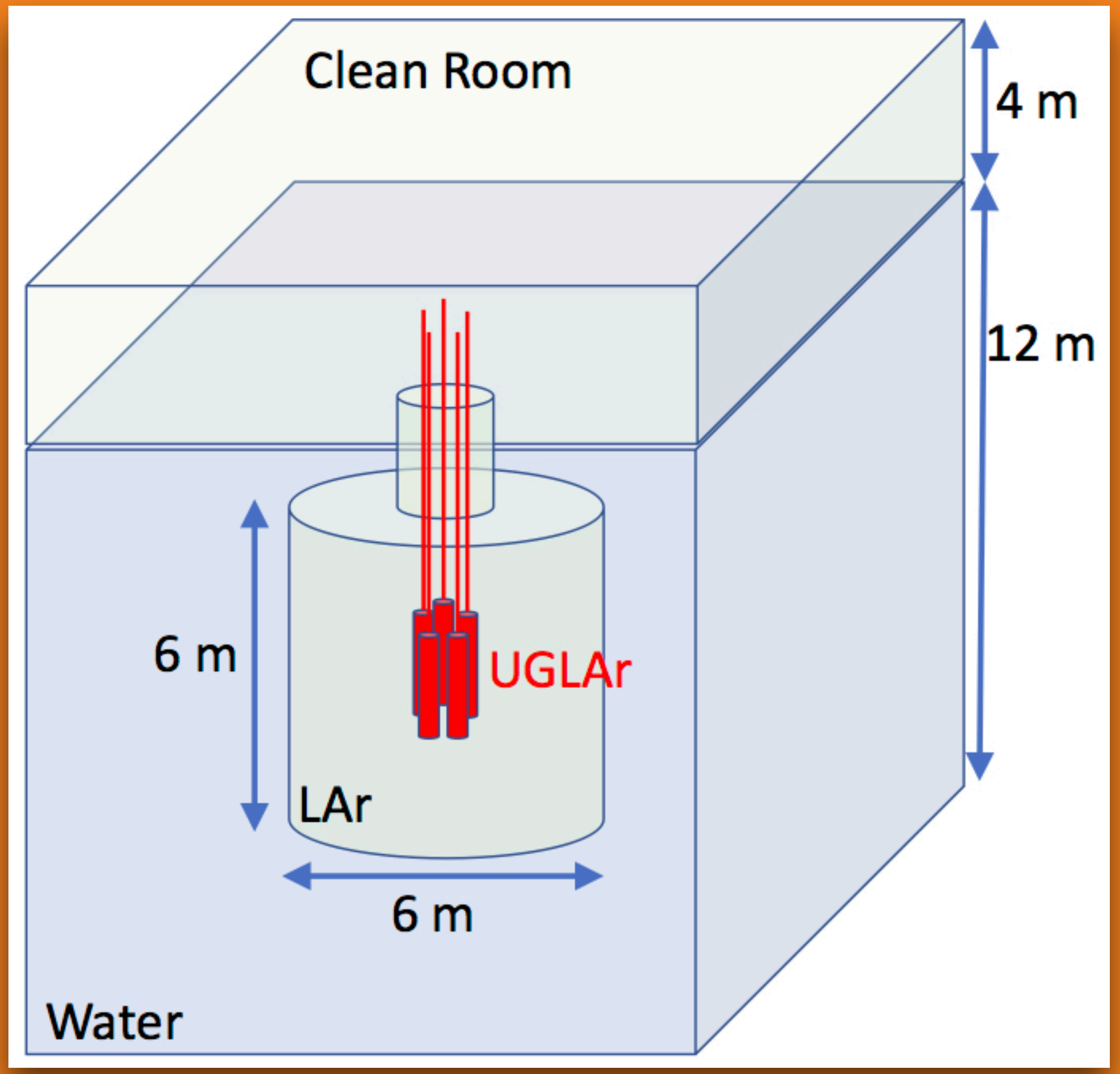
LEGEND-1T

- **10^{28} yrs** : Neutrino mass discovery reach **18 meV** even for pessimistic NMEs.
- Turn on in **2025** with 1-tonne of isotope.



Thanks to Dave Waters for slide content

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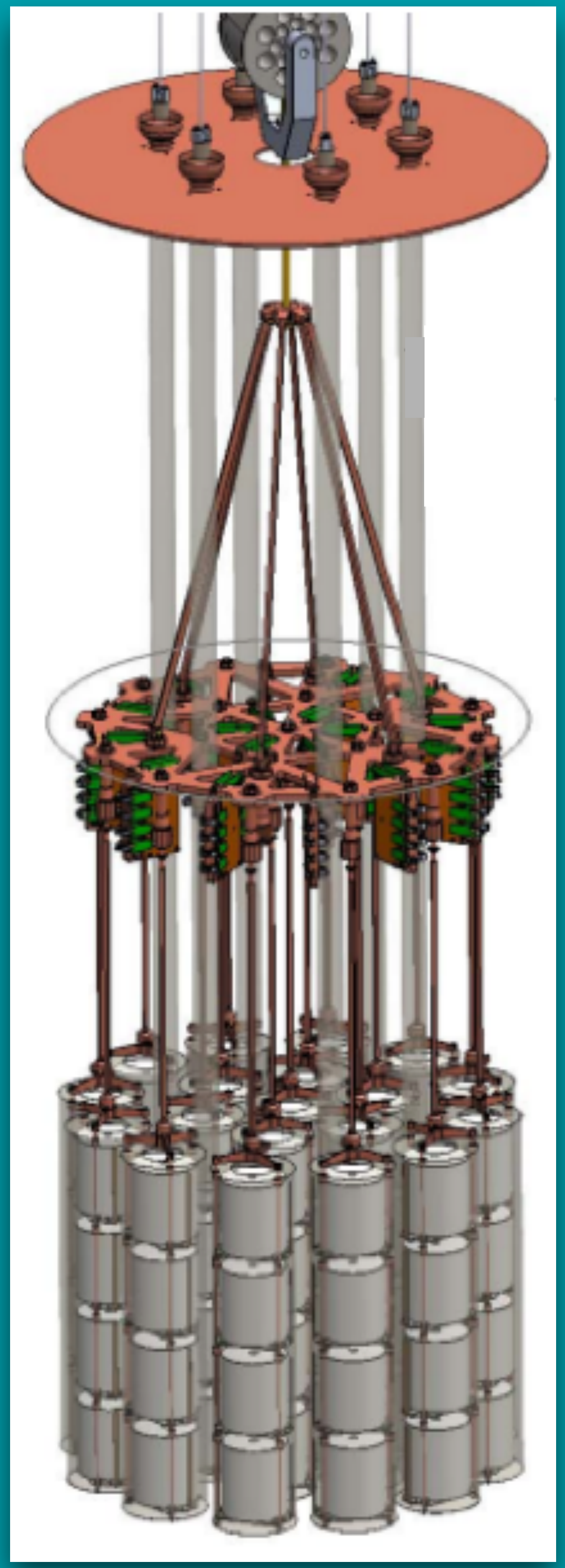

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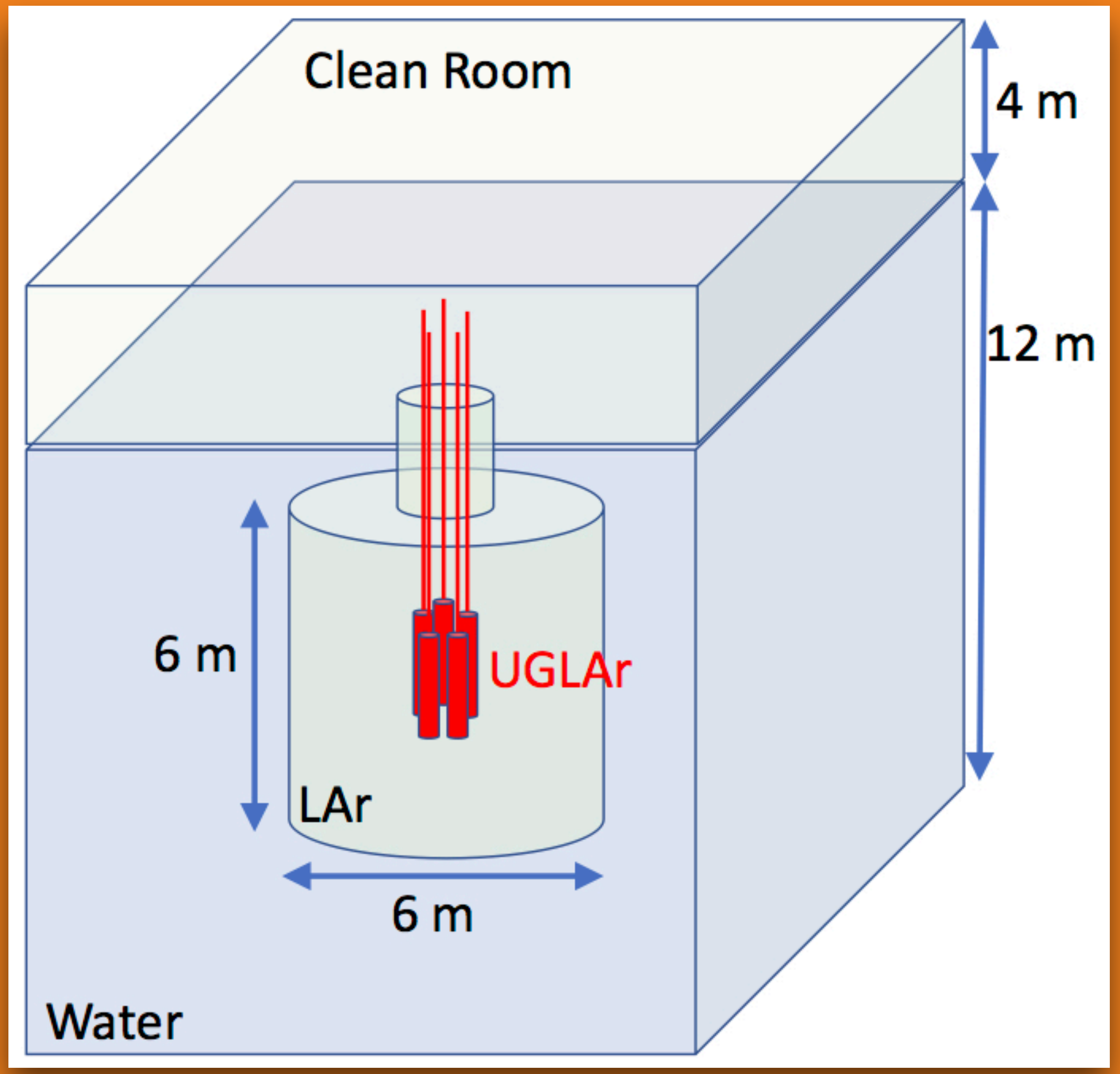
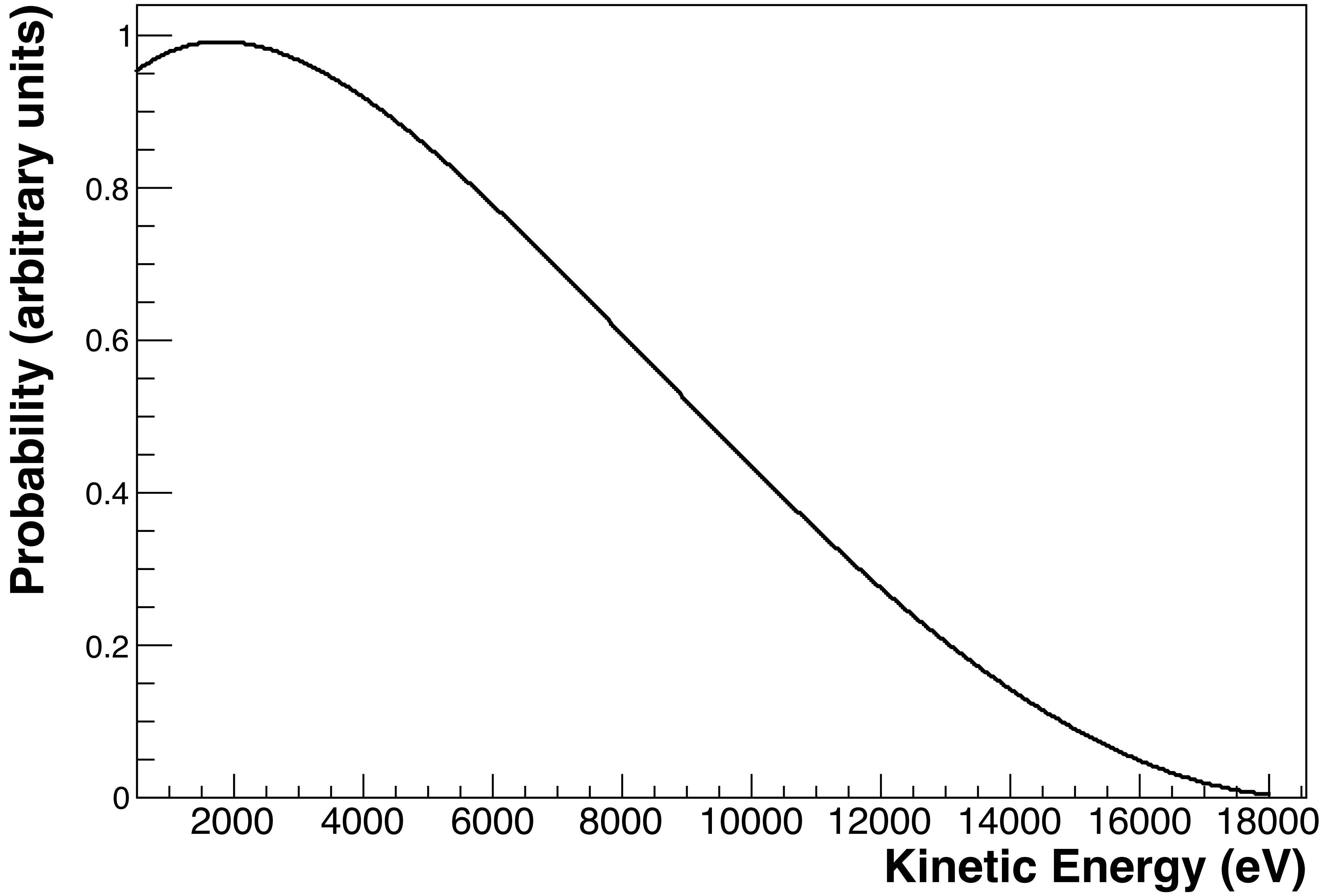


Thanks to Dave Waters for slide content

UK Initial Participation :

- Combination of **Particle** Physics and **Nuclear** Physics groups.
- Builds on world-renowned expertise in **HPGe** detector development, **low-background** techniques and **software/analysis** expertise.

Direct mass measurement: single β-decay endpoint



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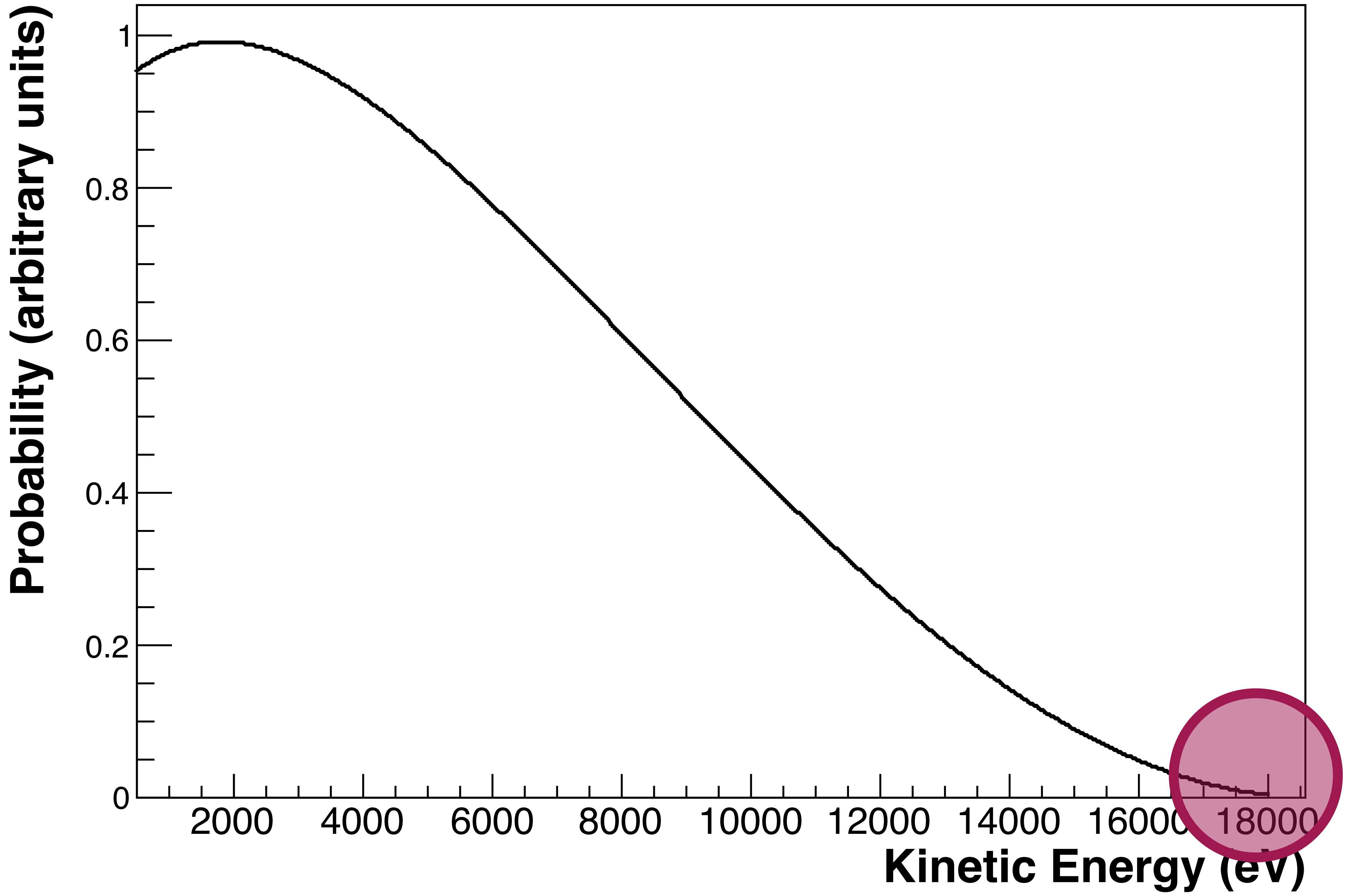

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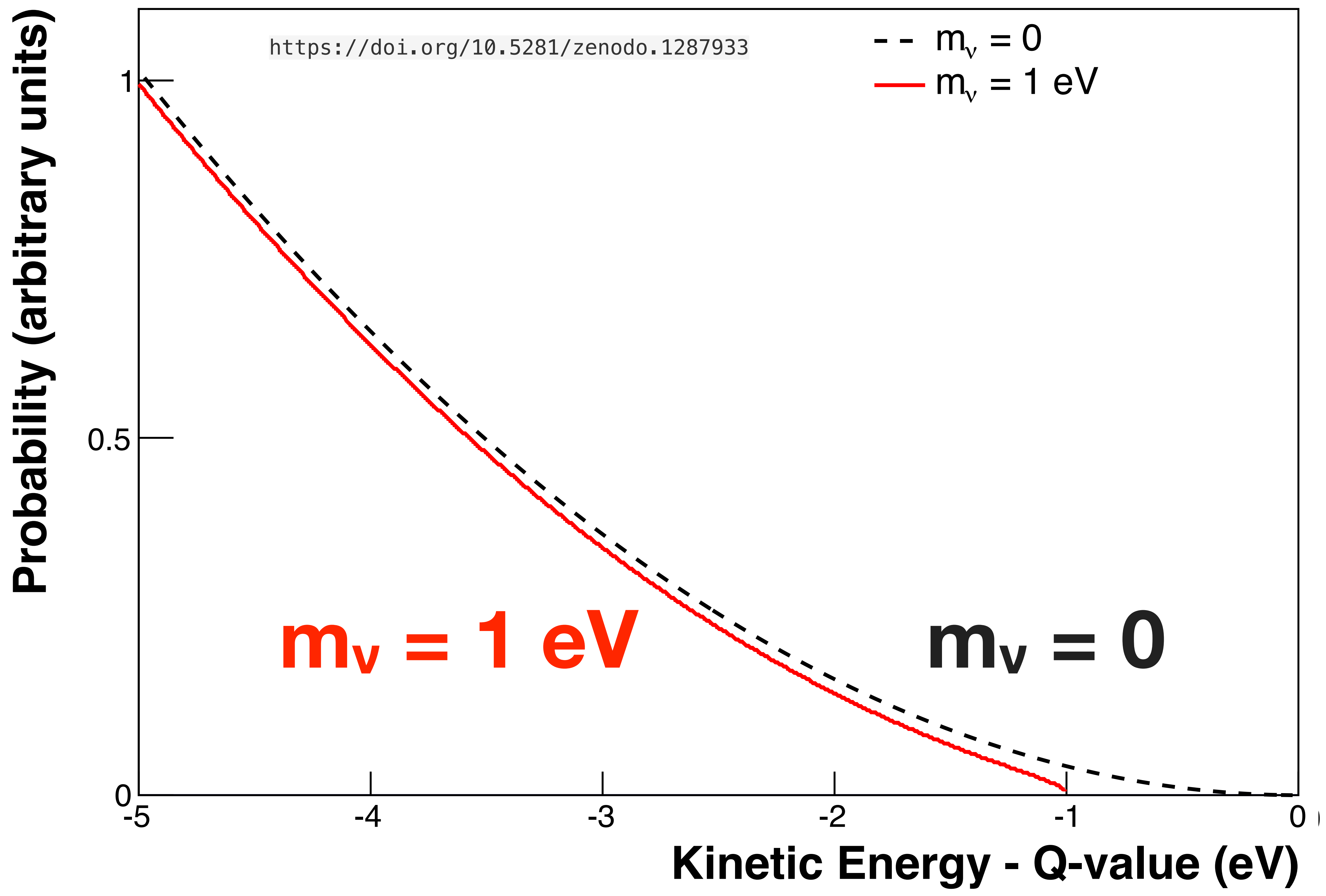

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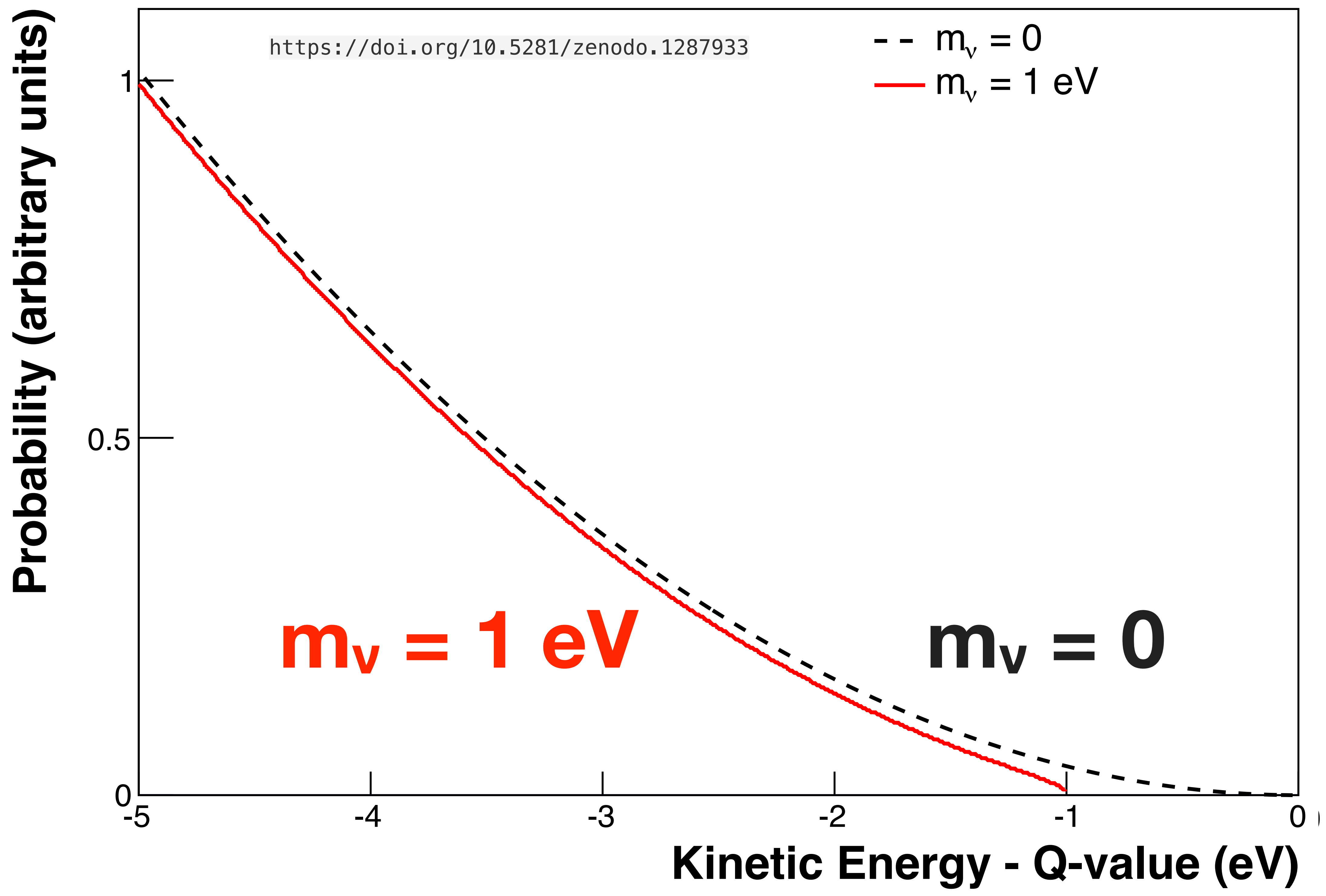
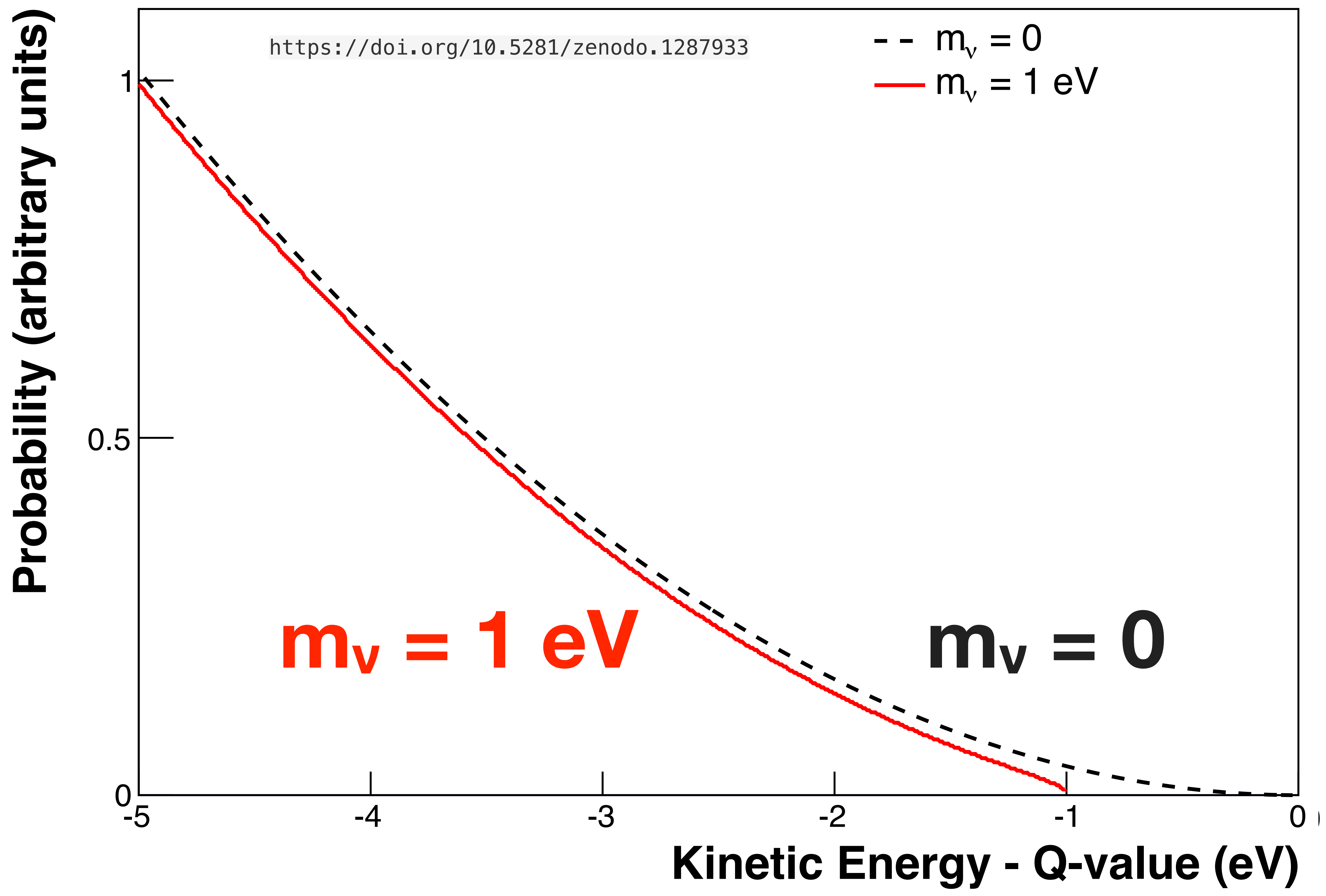


KATRIN (Karlsruhe, Germany)

- Launched **June 2018**
- β decay of **tritium molecules**
- Spectrometer uses collimator/filter to measure highest energy electrons
- Sensitivity **m_ν < 240 meV** is the best achievable with this technique

Photo: KATRIN

Direct mass measurement: single β-decay endpoint



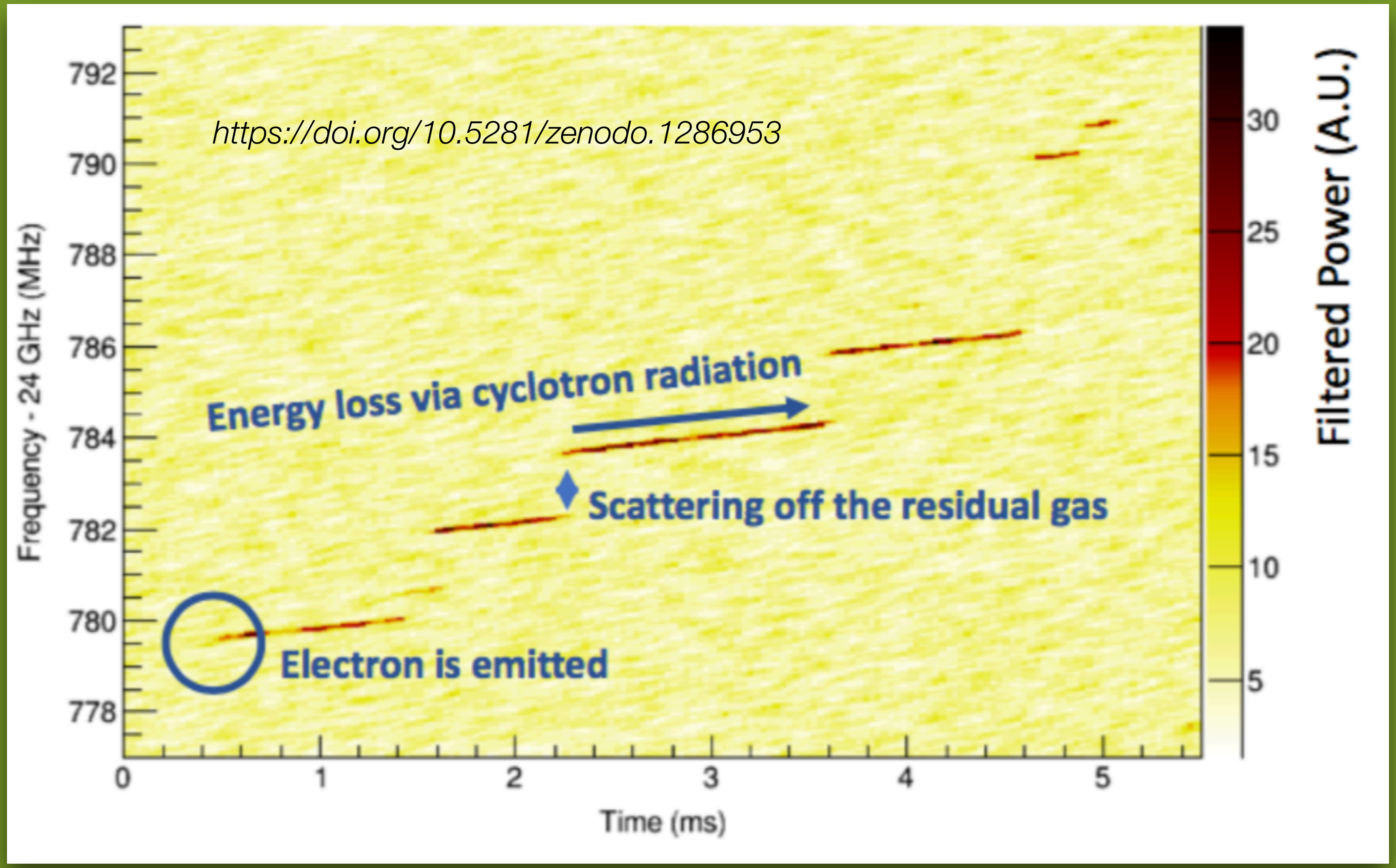
Quantum Sensors for Fundamental Physics

QS FP

See Jon Coleman's slides!

Project 8 (design phase)

- Electron energy measured using **cyclotron radiation:** frequency related to kinetic energy
- **Atomic tritium** improves sensitivity to **40meV**



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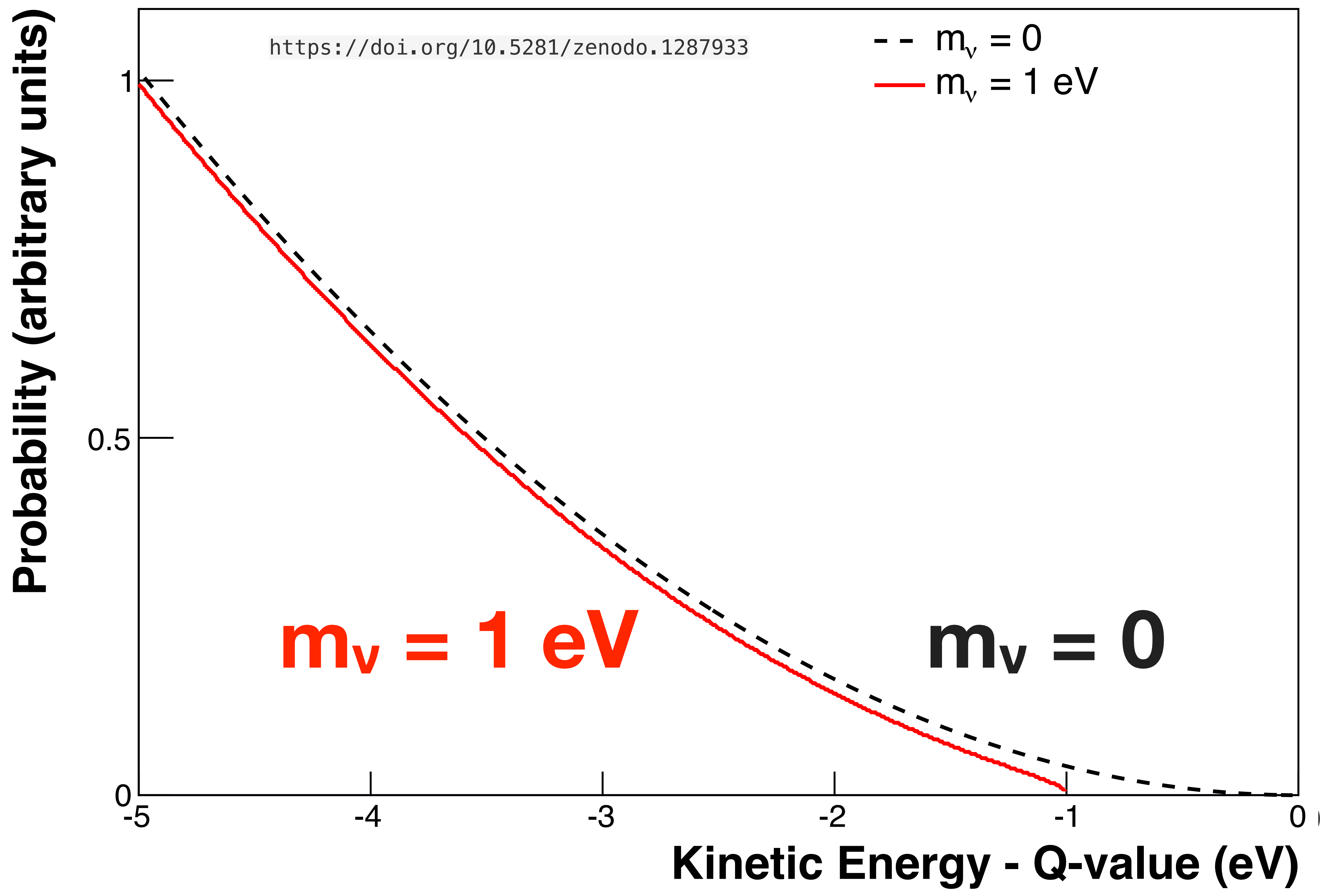

Quantum Sensors for Fundamental Physics

See Jon Coleman's slides!

Also for future ^{163}Ho electron-capture endpoint experiments

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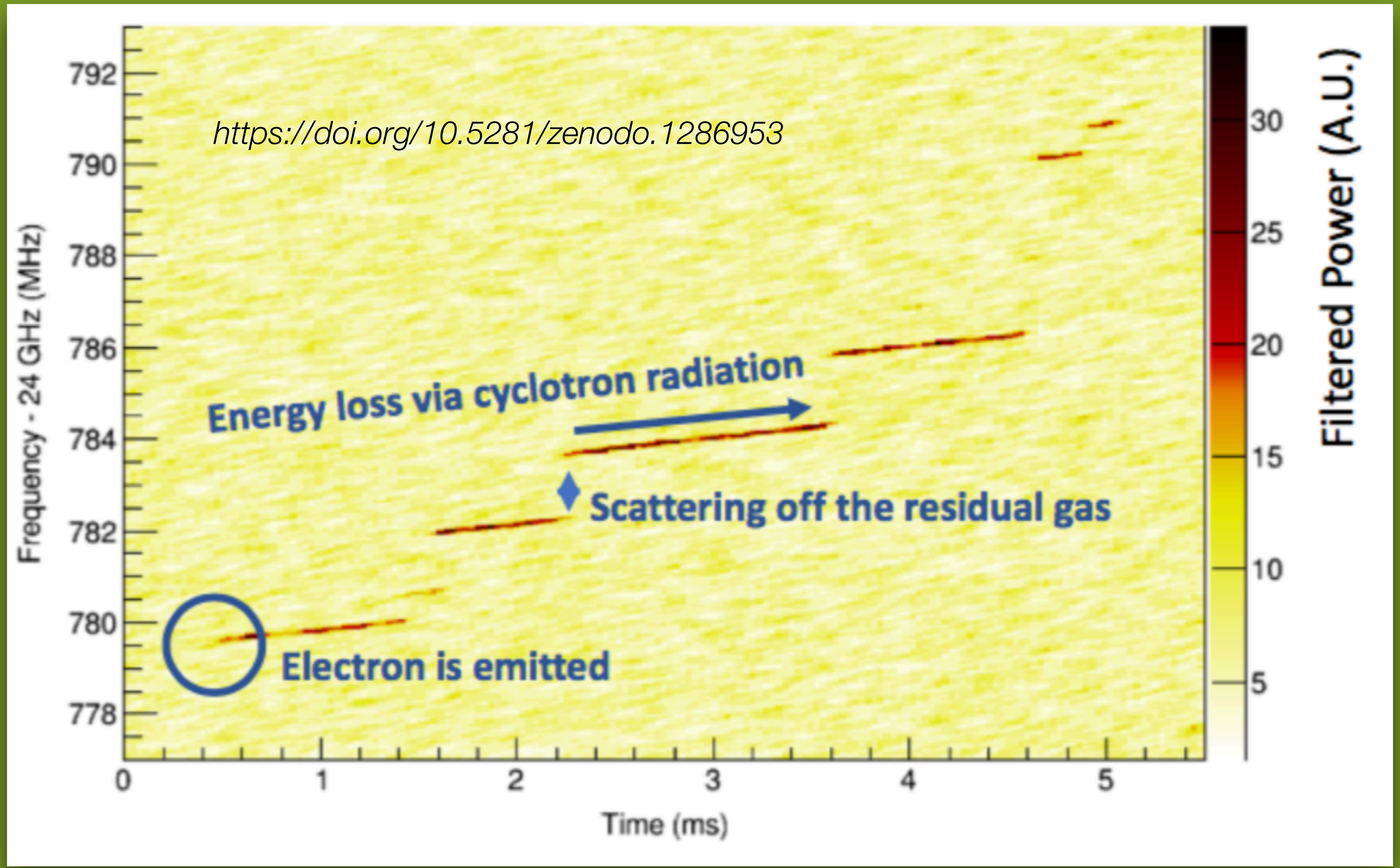

ββ decay in the UK

Entering exploitation phase: scintillator filling at SNO+, commissioning data at SuperNEMO

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- Slow scintillator
- LEGEND
- Low-background techniques
- Quantum sensors
- SNO+ phase II
- Full SuperNEMO

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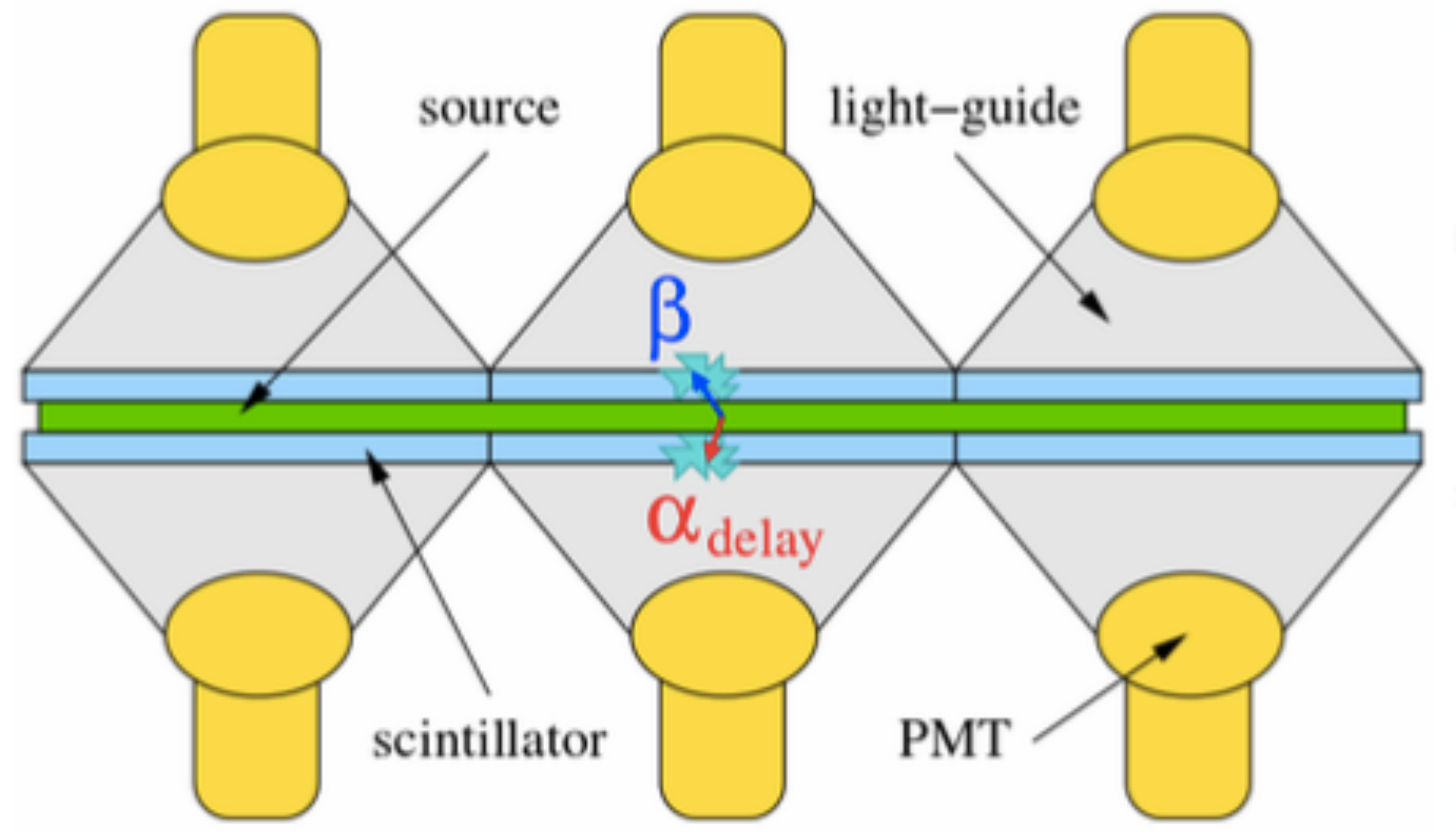
Backup Slides

Source foil contamination measured at the BiPo-3 detector

JINST 12 (2017) P06002



- 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*

Tracker gas system

95% Helium

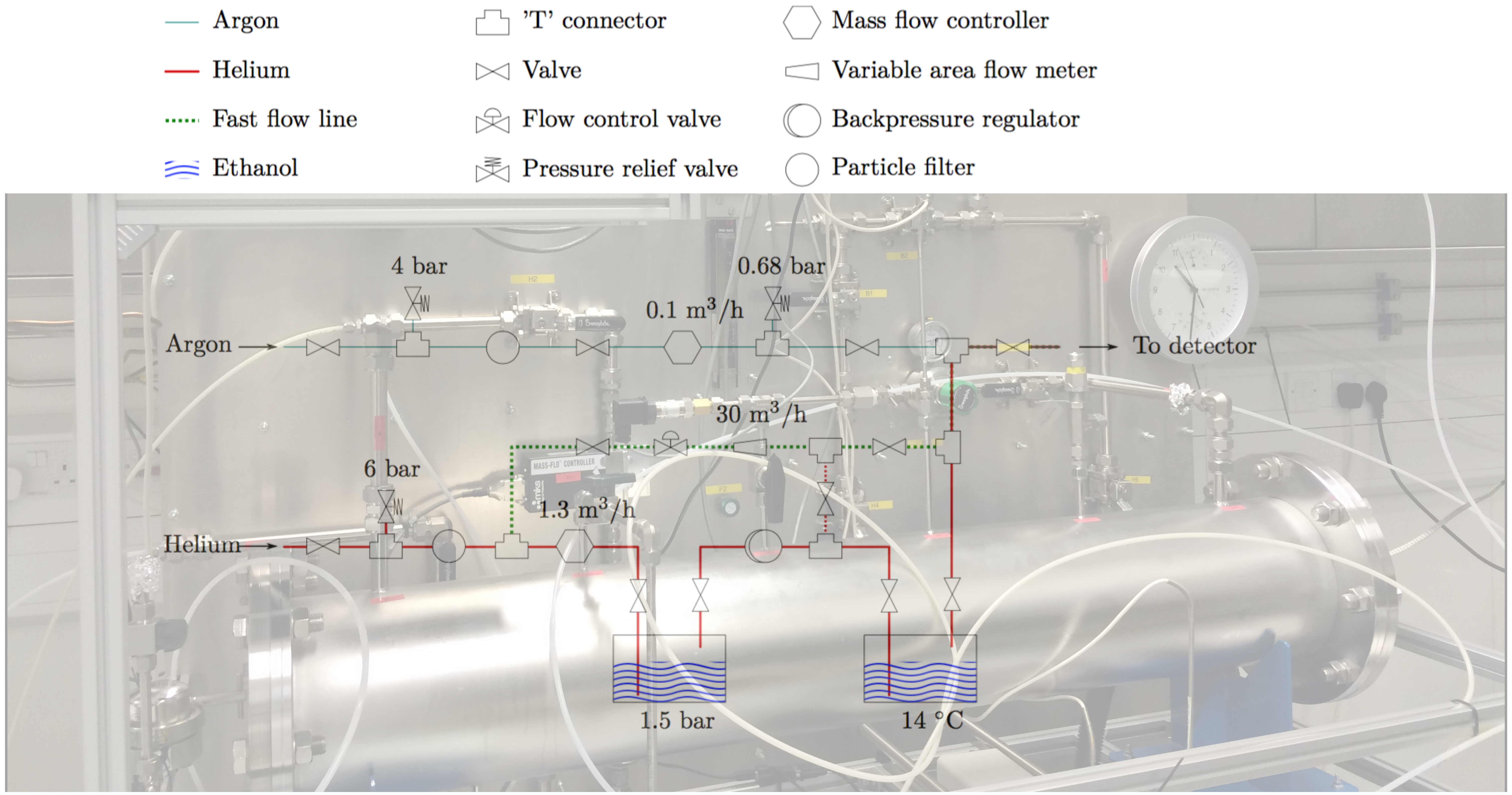
Low atomic mass; prevents multiple scattering and energy loss

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

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	internal contamination reduction
Tl208 internal	2.7 ± 0.2	0.05	
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)	$T^{(2\nu)}$ ($\times10^{19}$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)

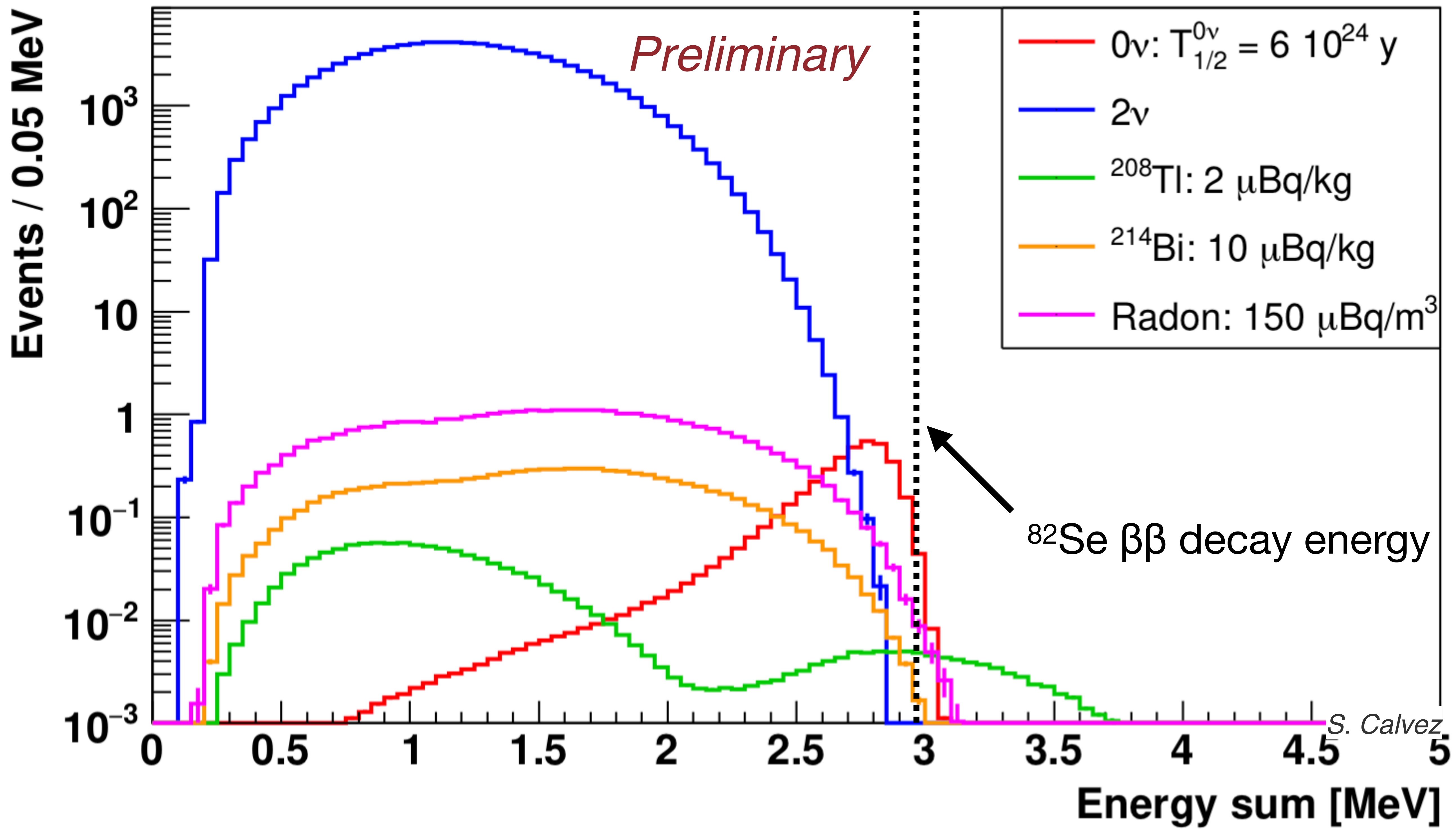
* Together with Aurora

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

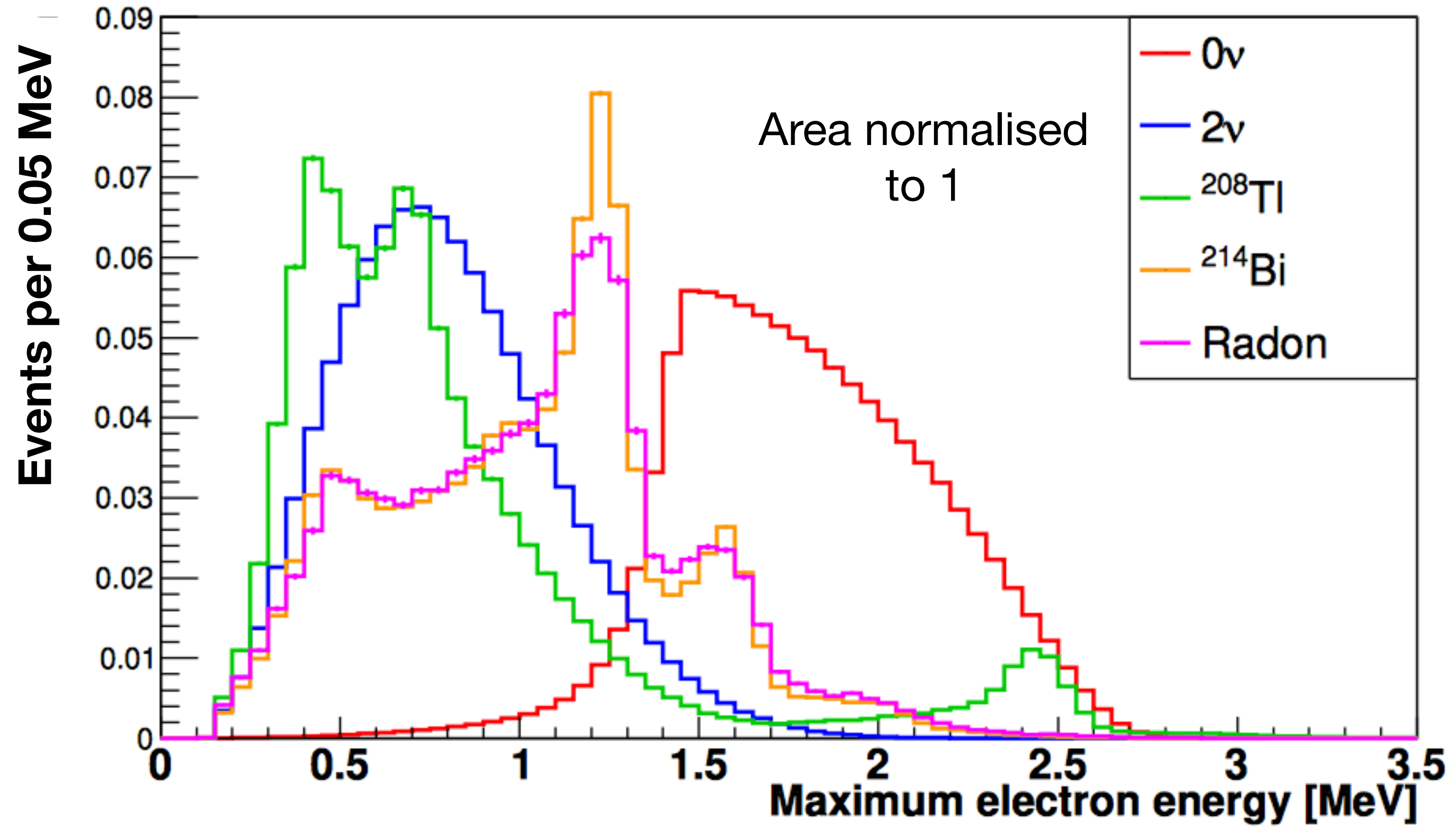
32

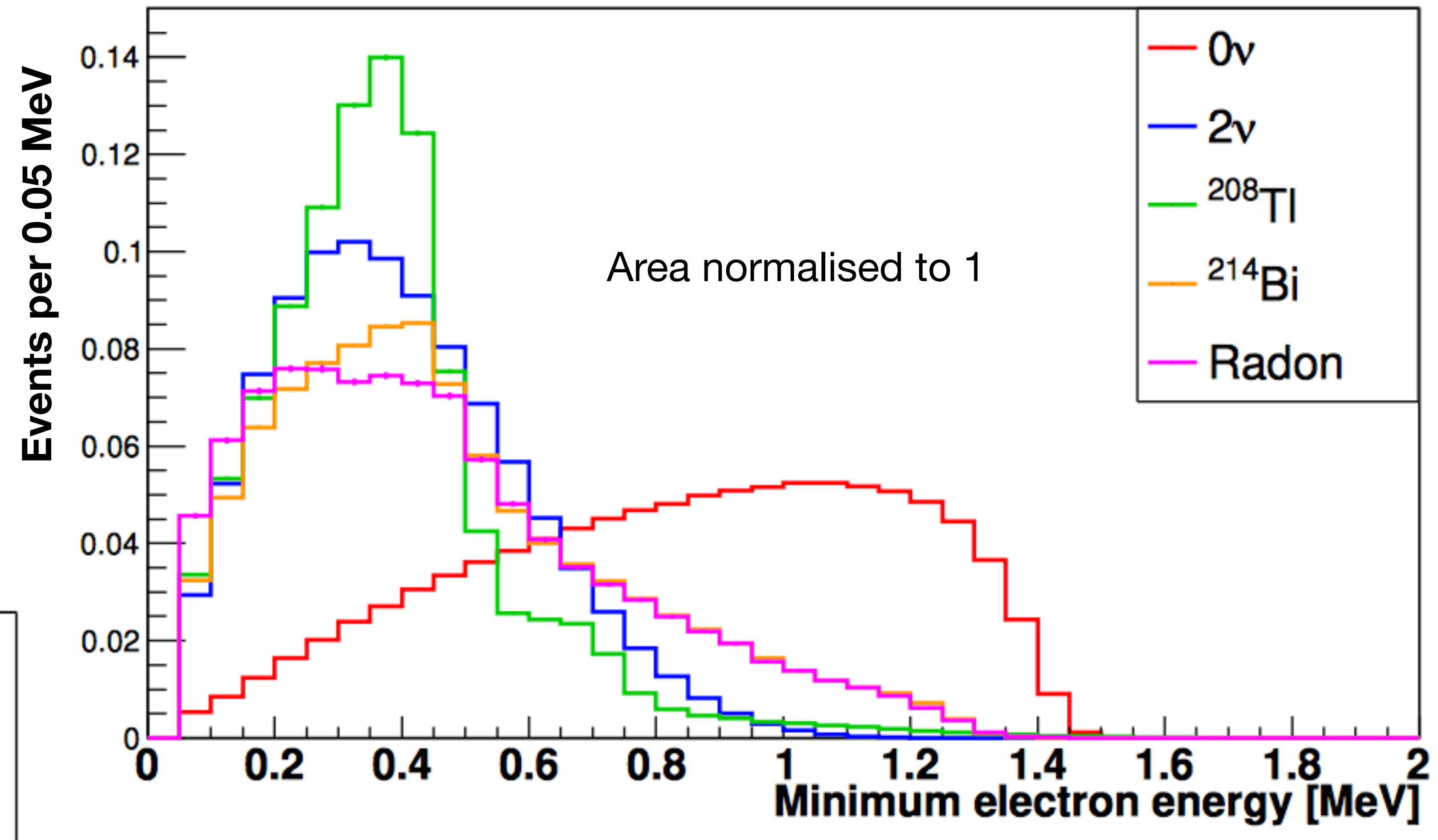
Sensitivity to 0νββ



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

Sensitivity to 0νββ

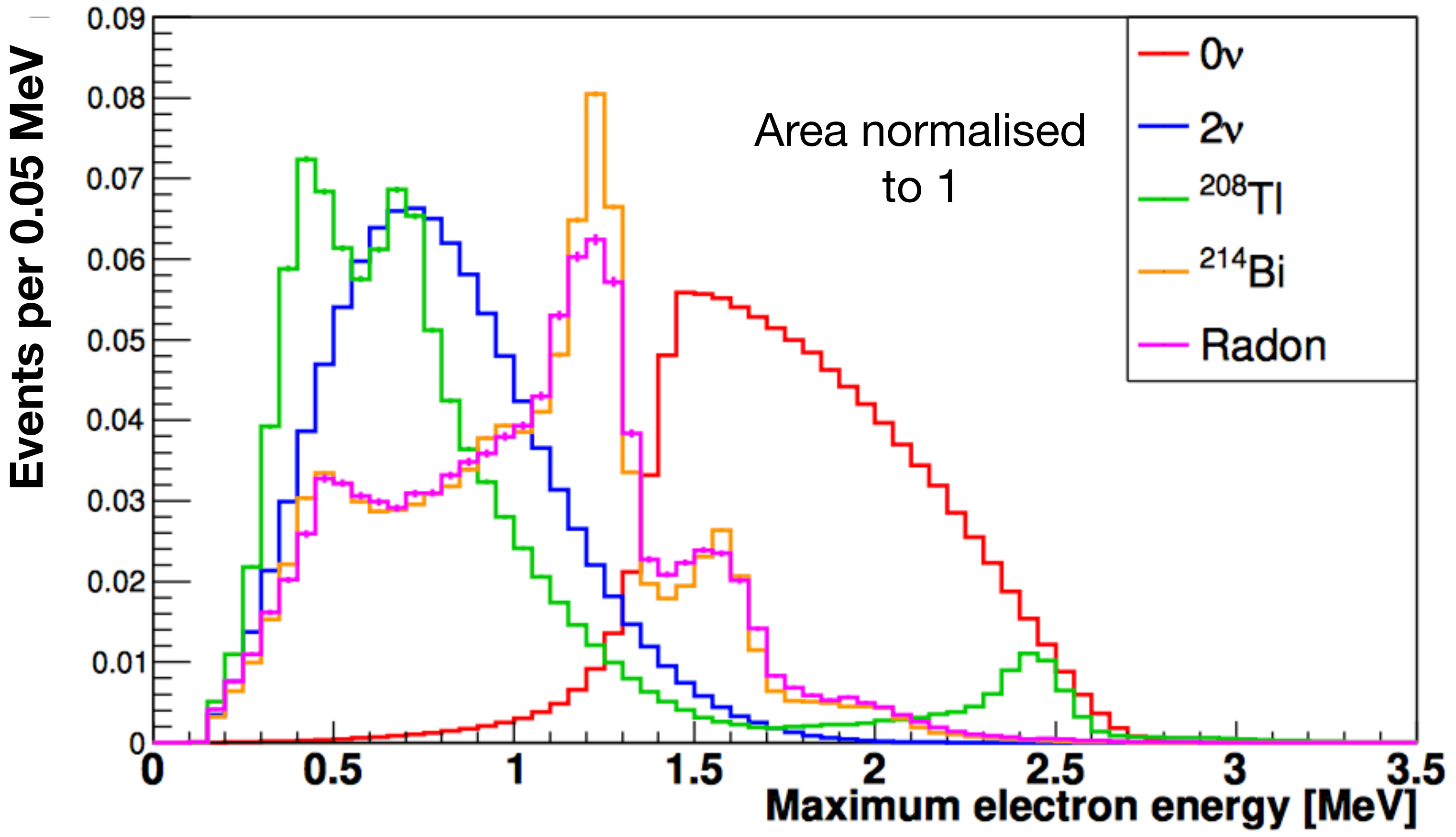


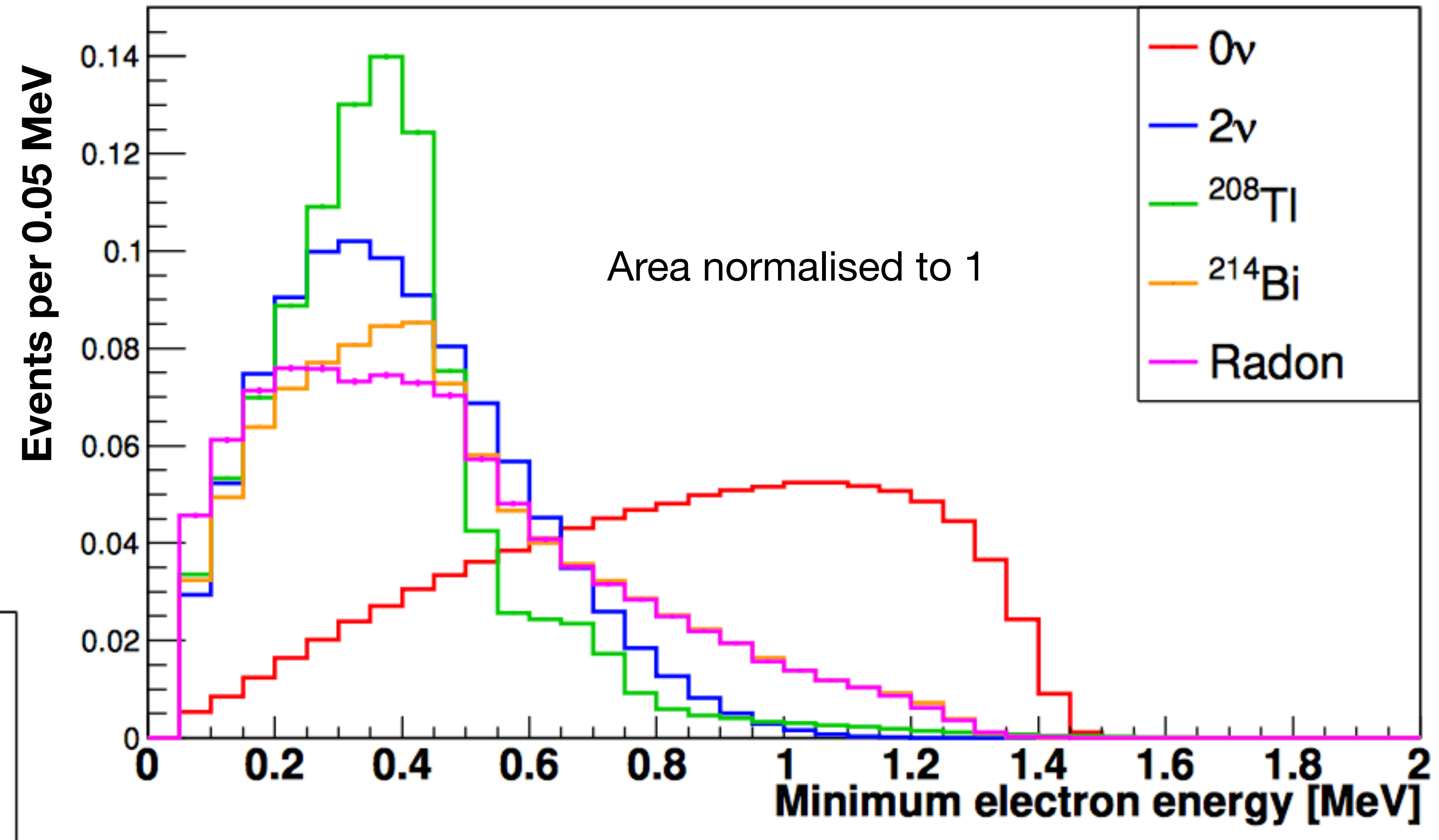


Summed 2-electron energy is best distribution to separate signal from background

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





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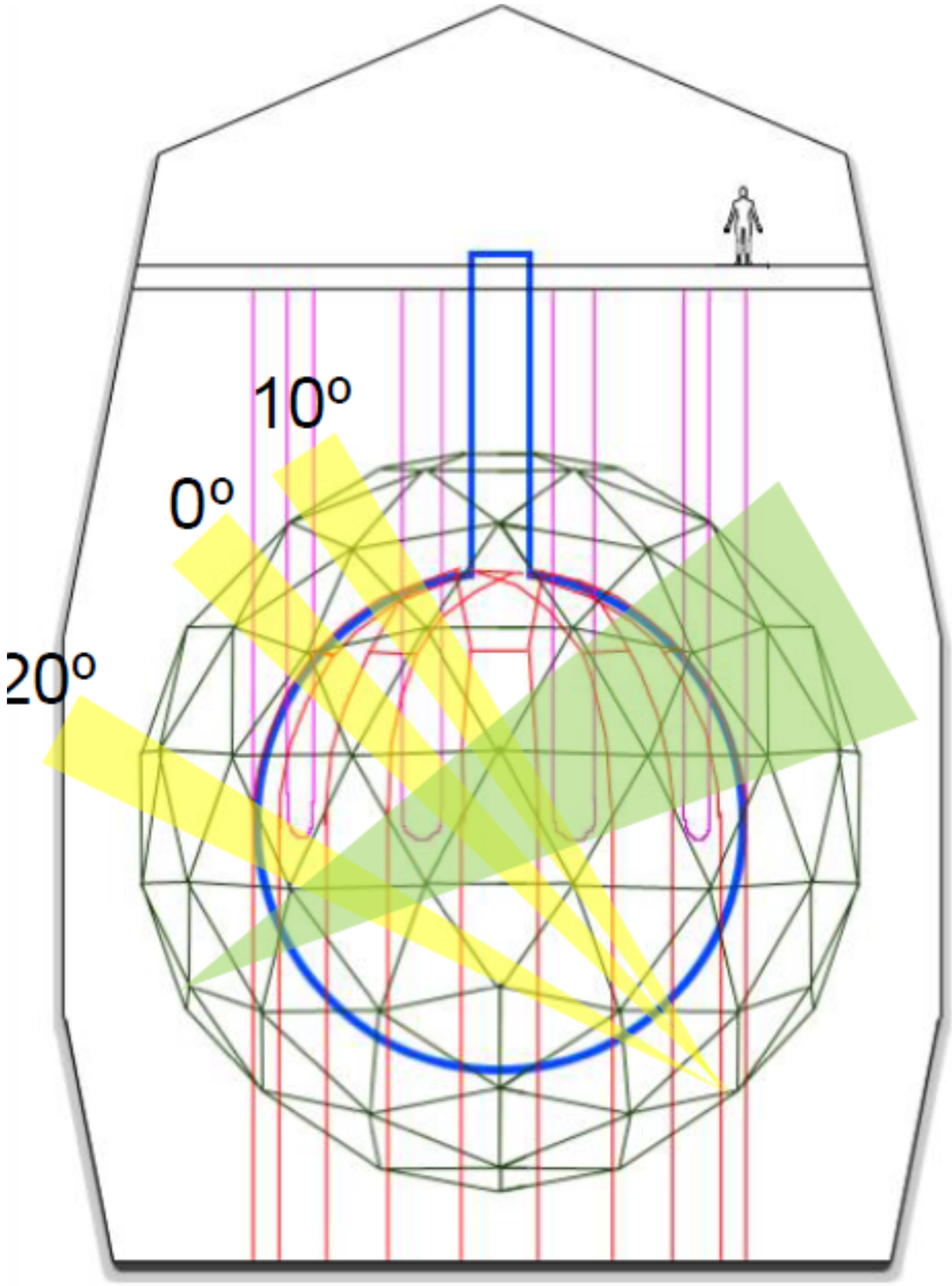
$T_{1/2} > 5.85 \times 10^{24}$ years (90% C.L)

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

ELLIE - Embedded Laser/LED Light-Injection Entity



- **UK**/Lisbon system providing a wealth of detector info
- Aim is to **minimise radon** ingress when source is deployed
- Now **deployed and operational**!

TELLIE: Timing and Monitoring

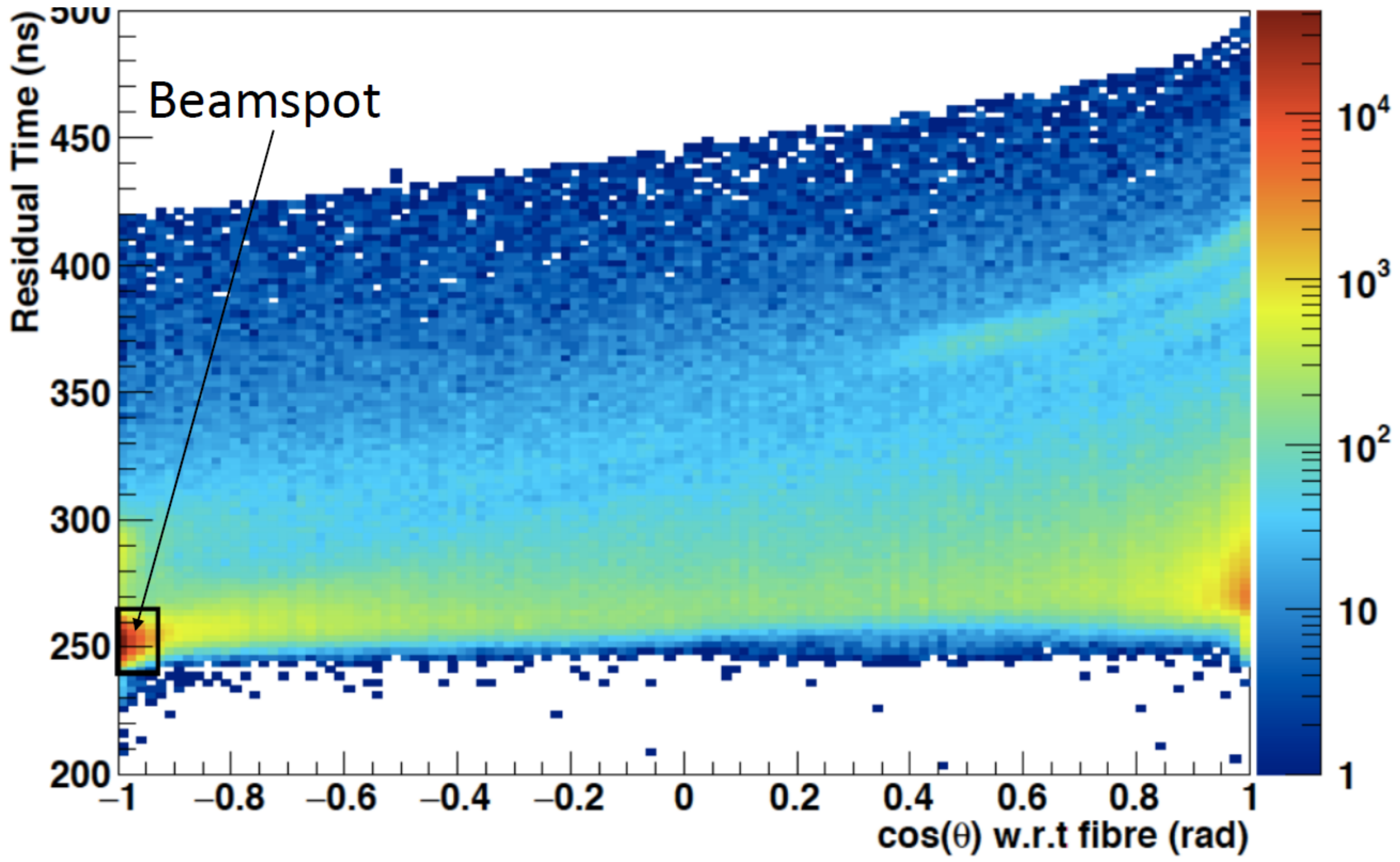
90 wide LED beams @520nm, aimed at the centre

SMELLIE: Scattering module

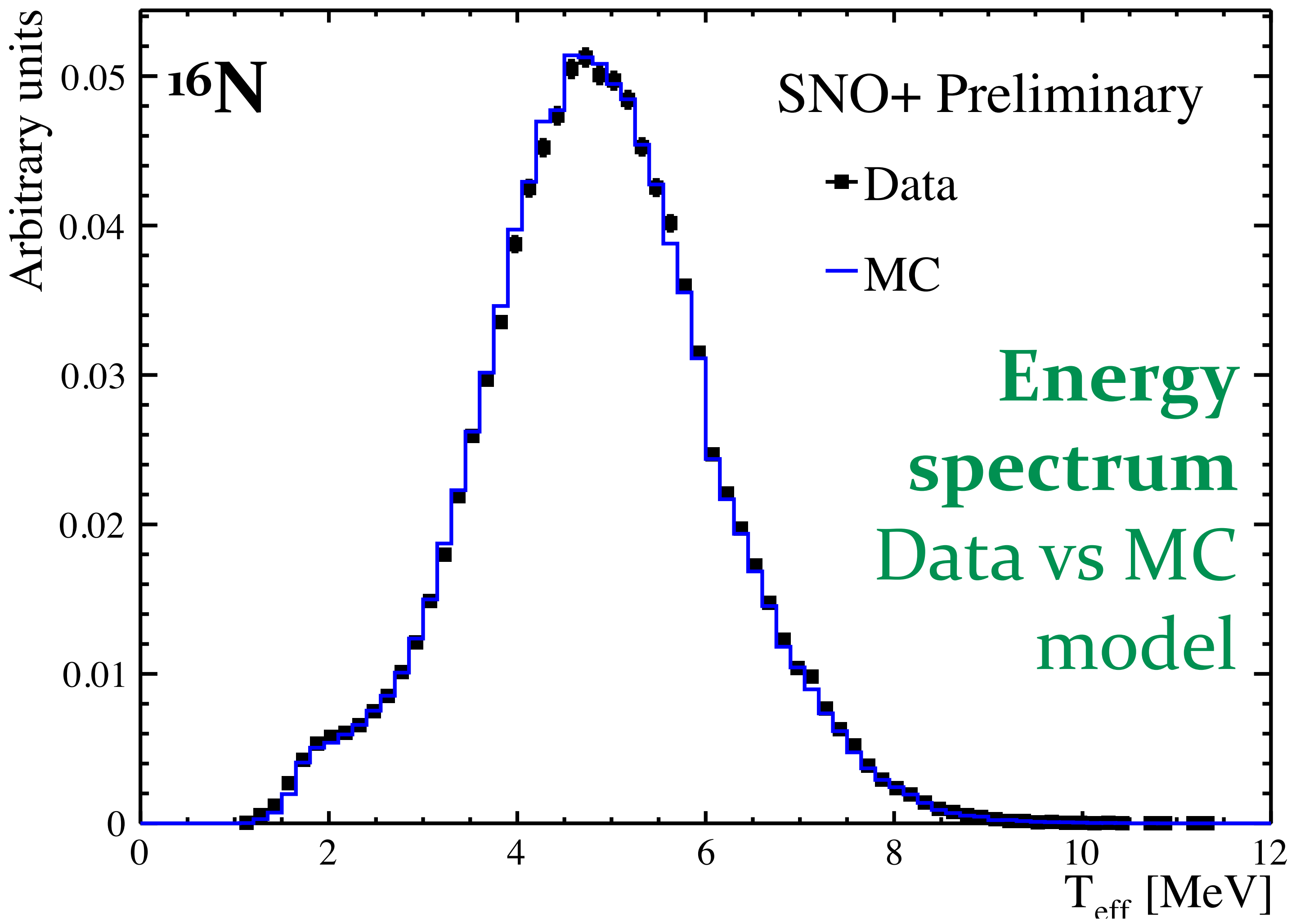
5 narrow laser beams injection points, 3 angles @ 375, 405, 495nm and 400-700nm

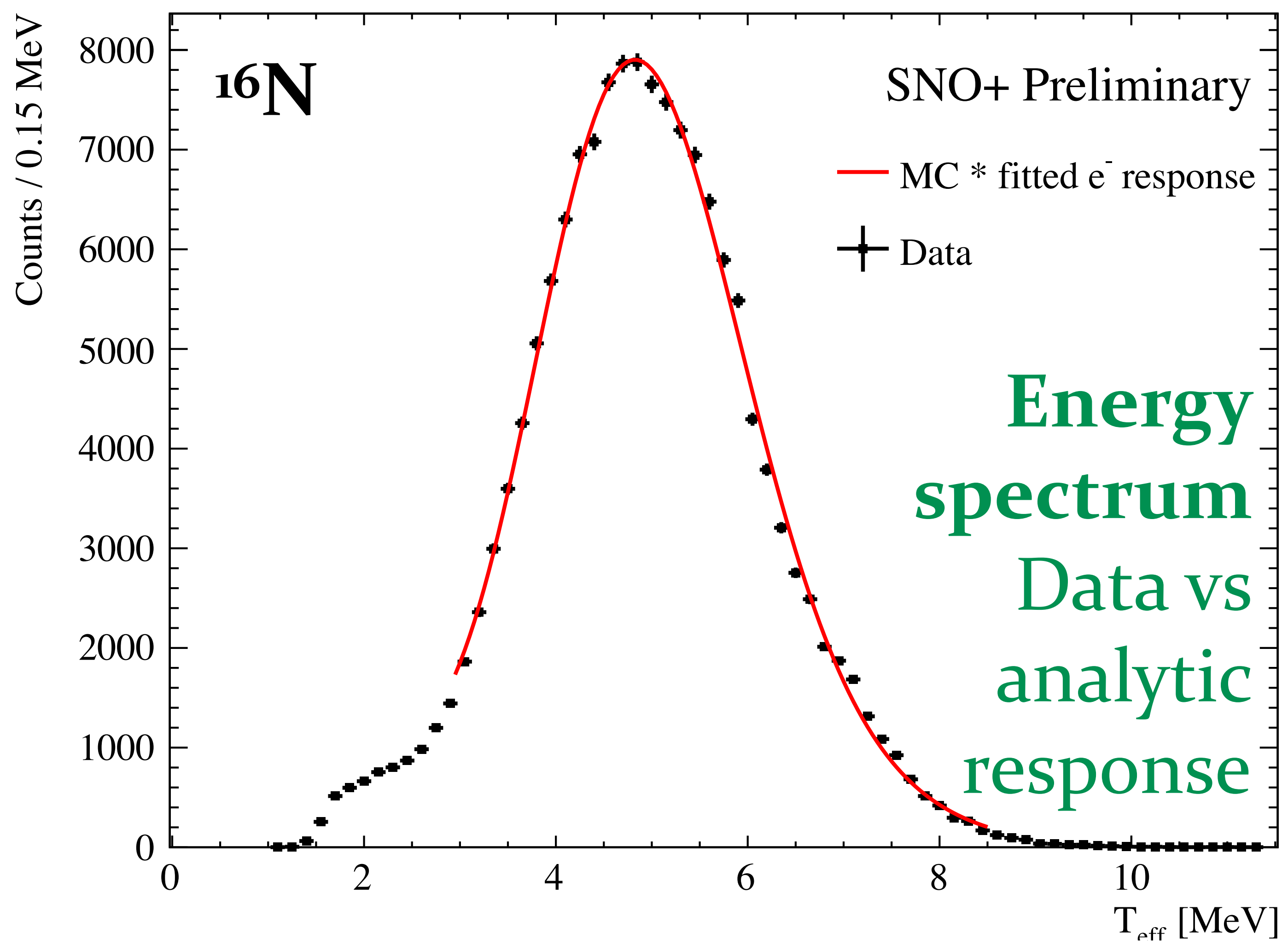
AMELLIE: Attenuation module

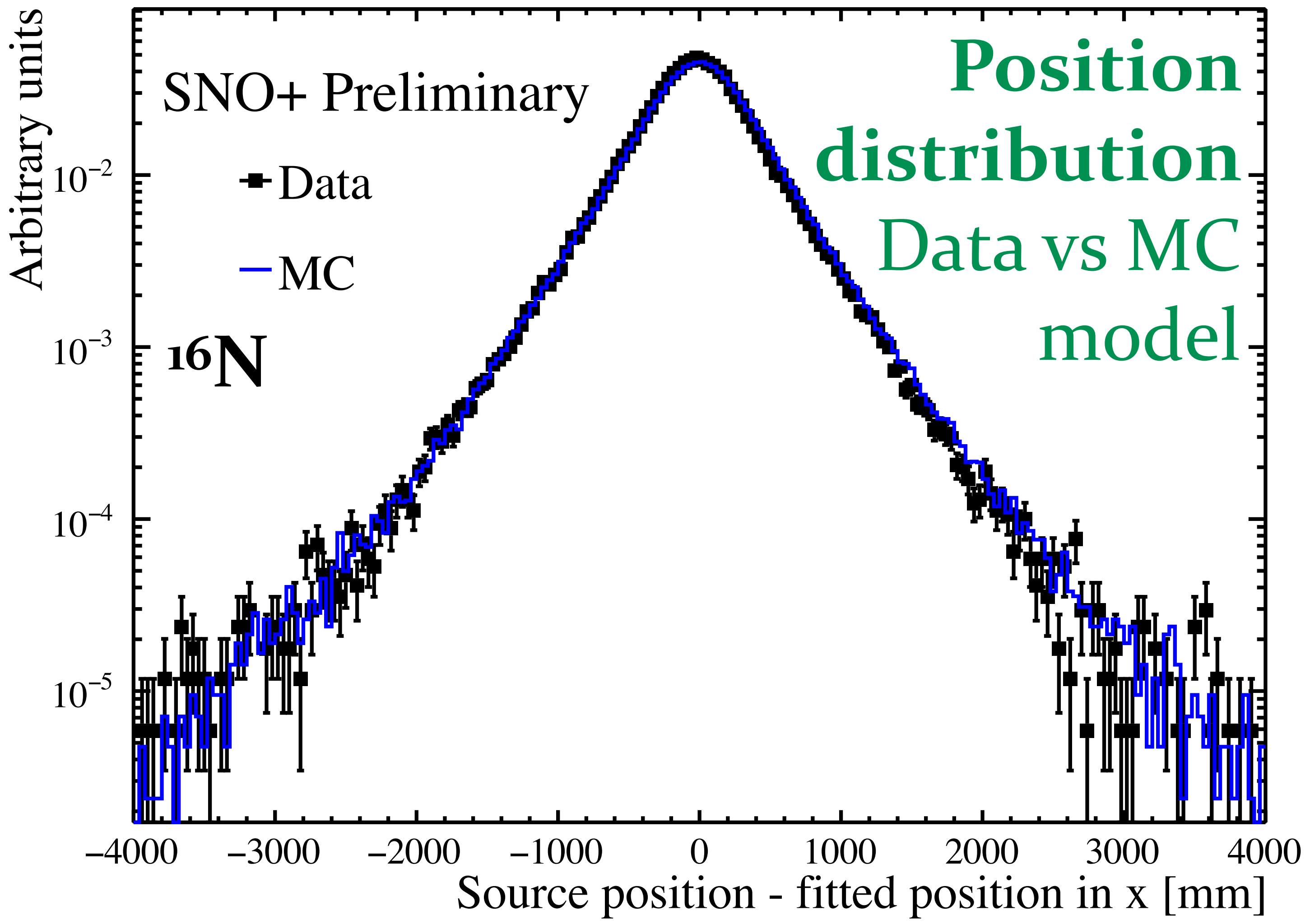
4 narrow LED beams at 0 and 20 degrees (wavelength TBD)

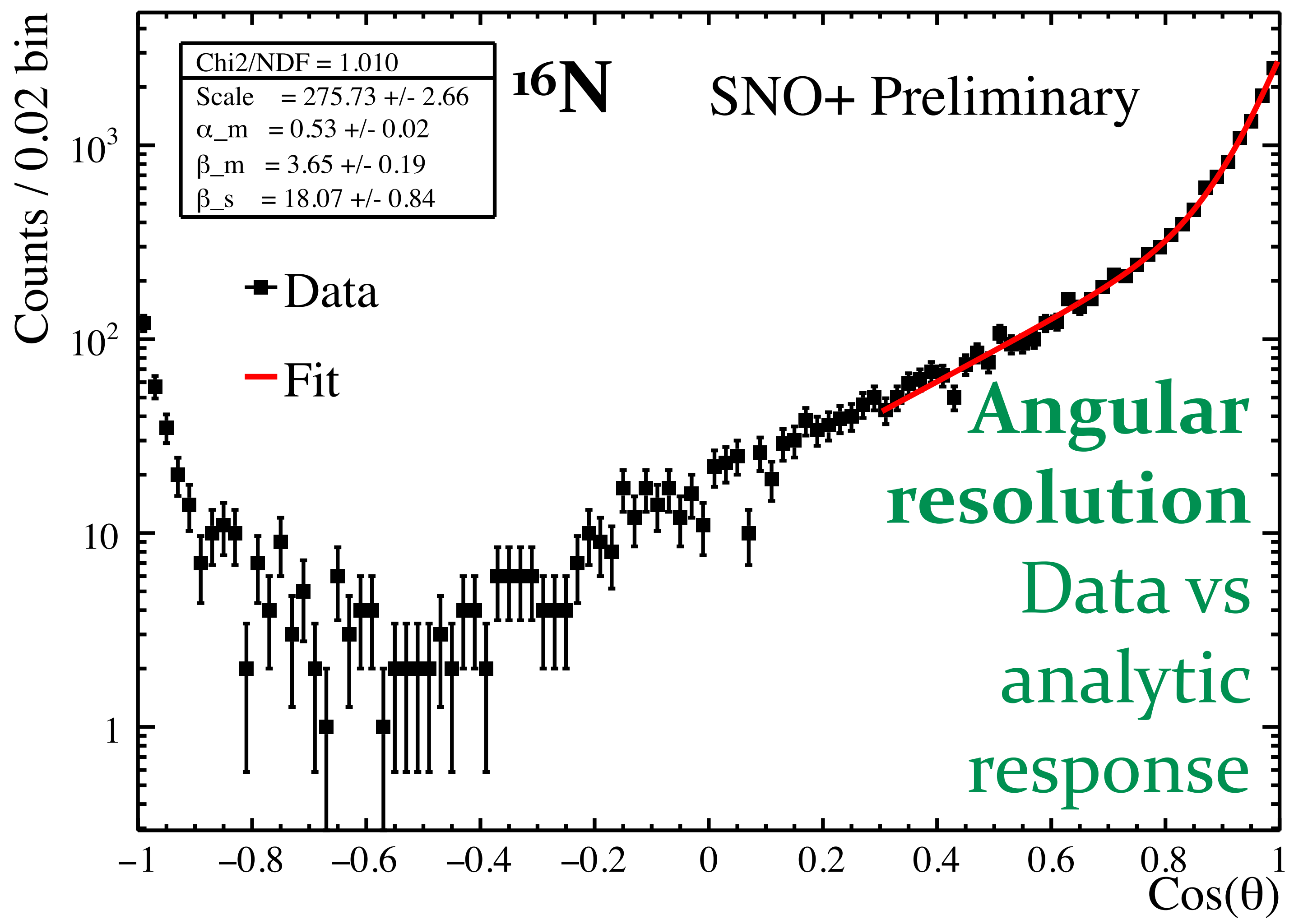


Detector response



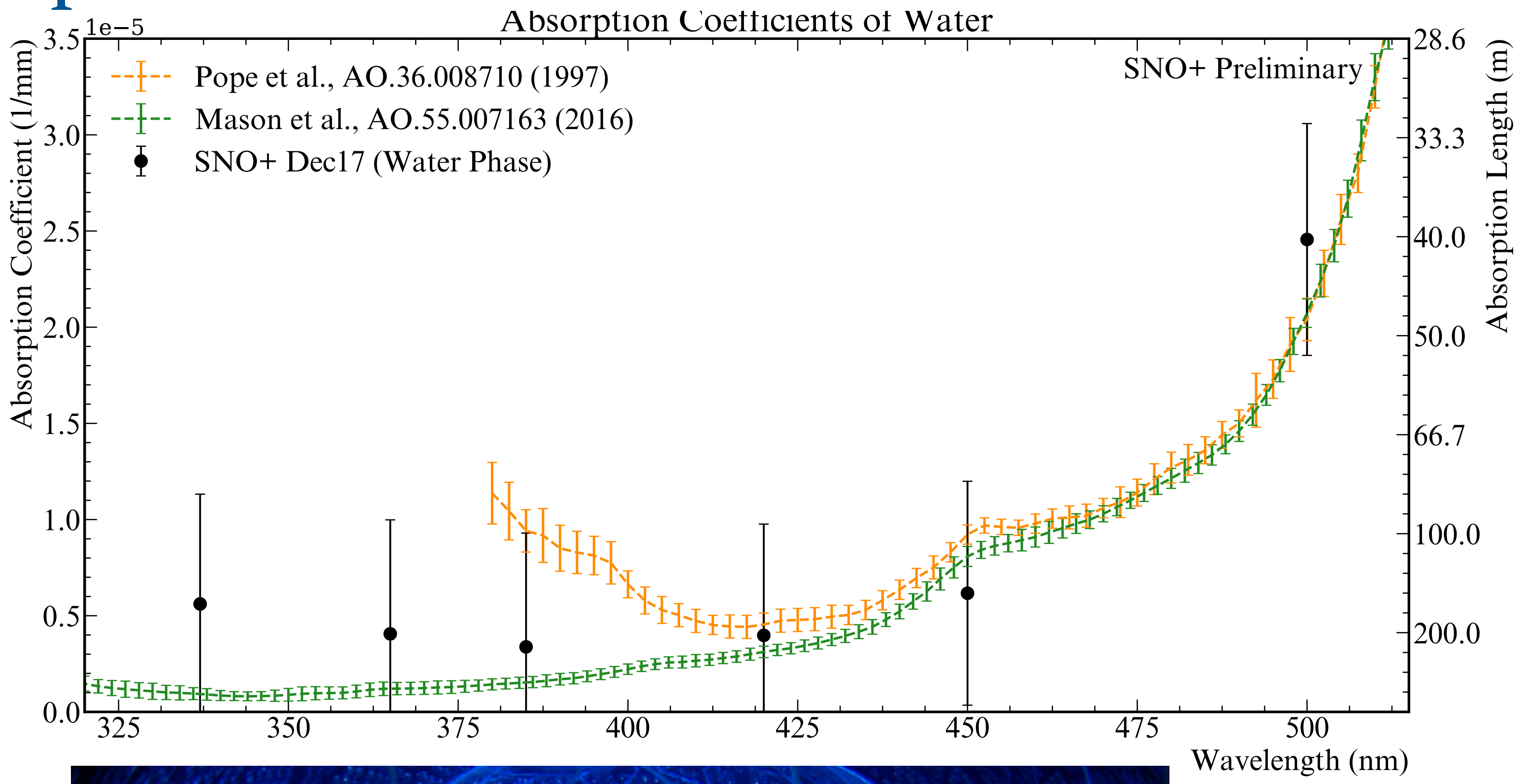




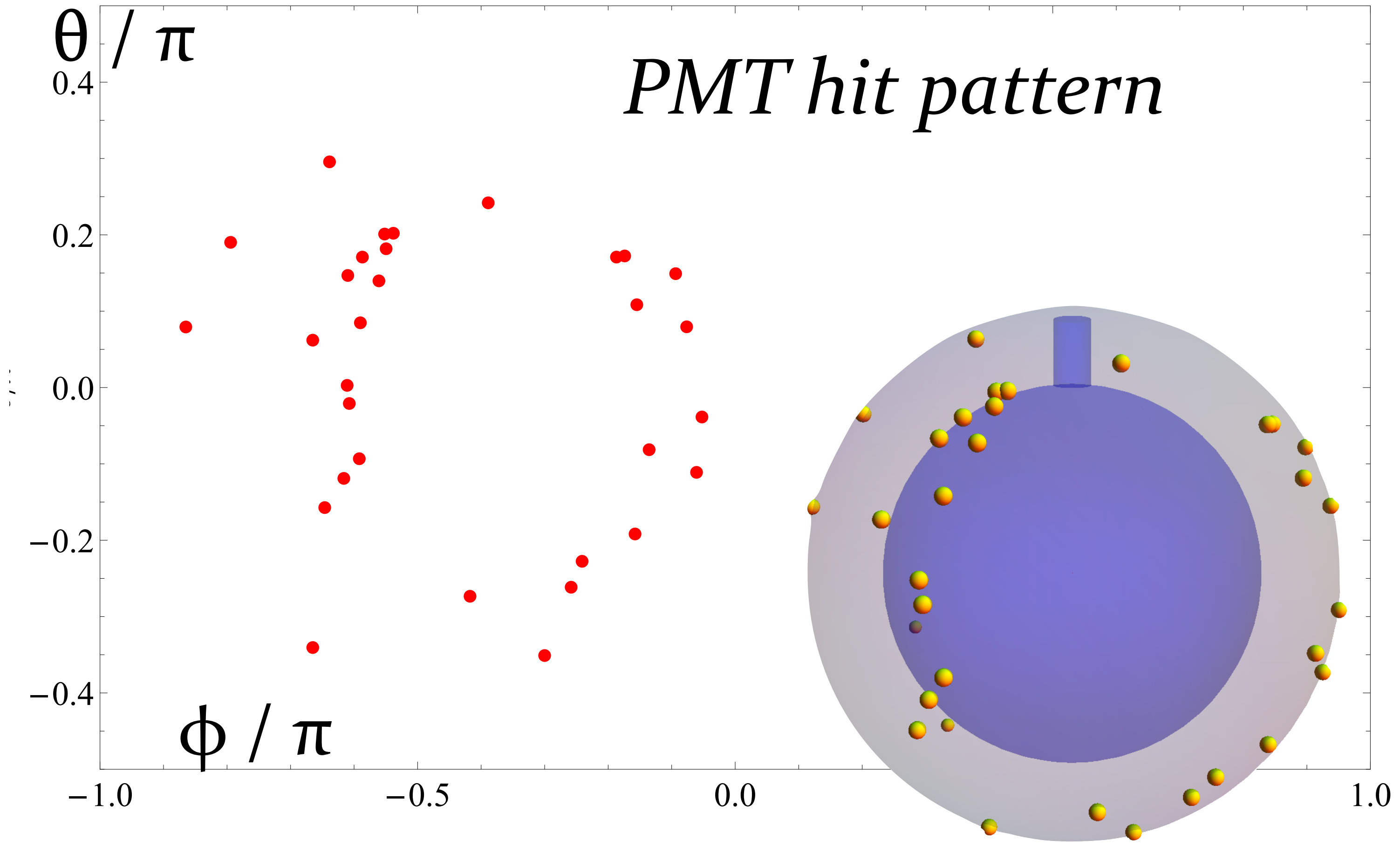


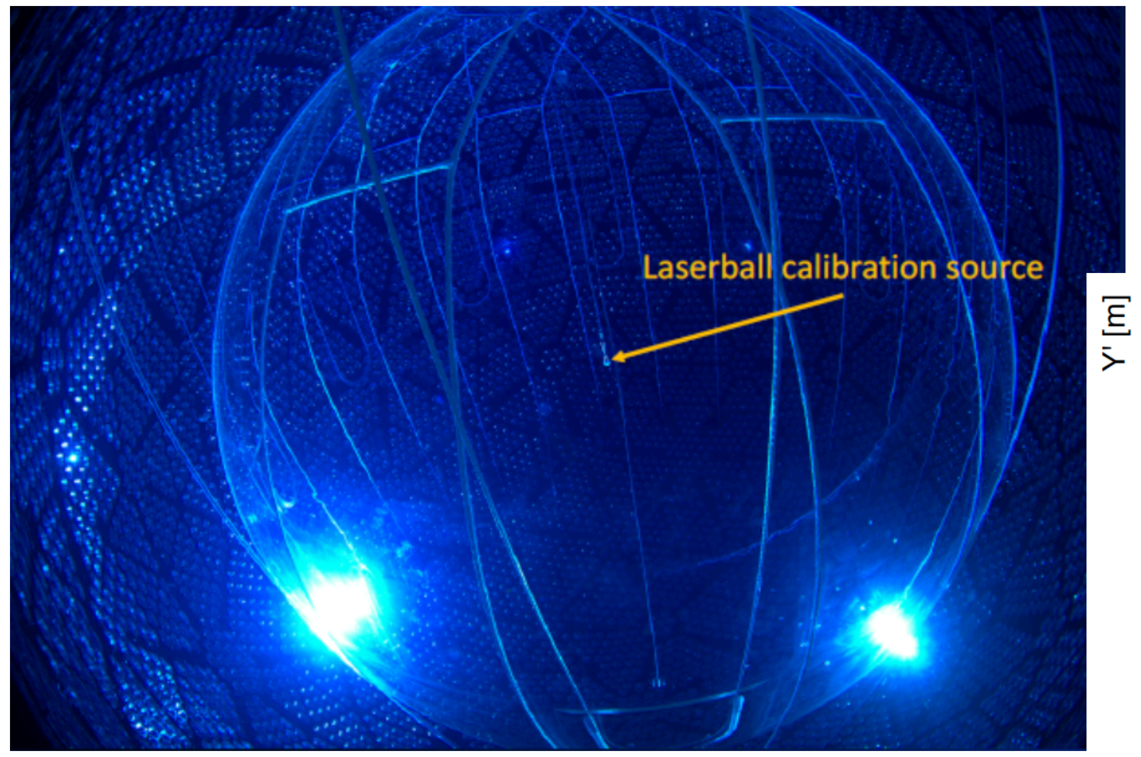
Detector calibrations

Full internal scan with laserball, photos from underwater cameras



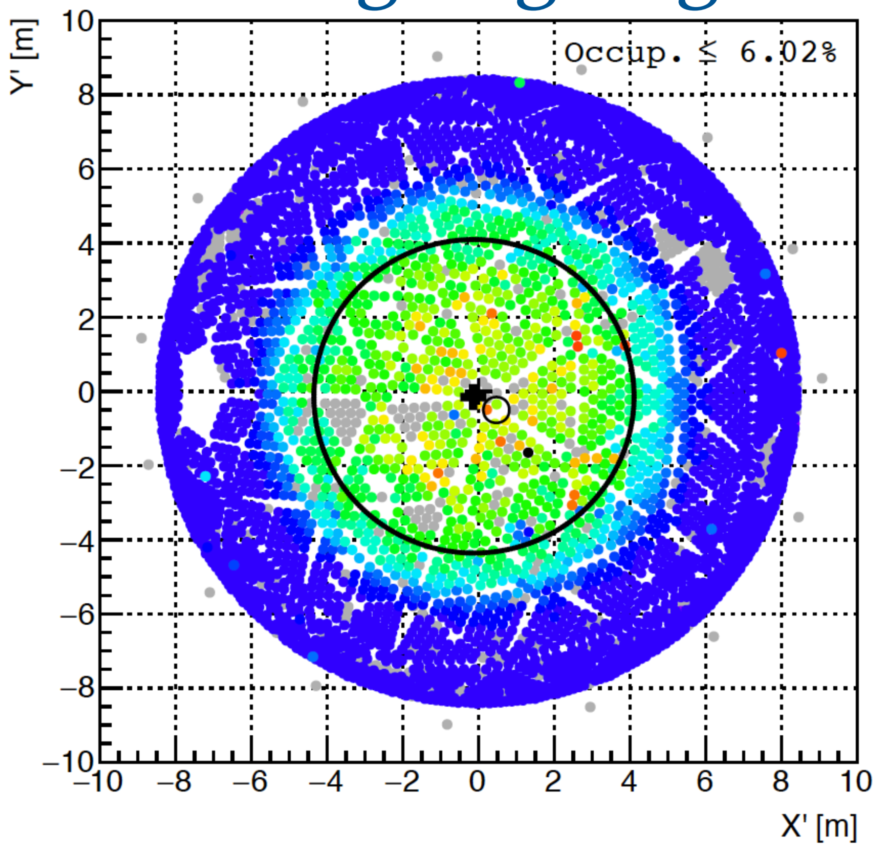
Cherenkov source deployed



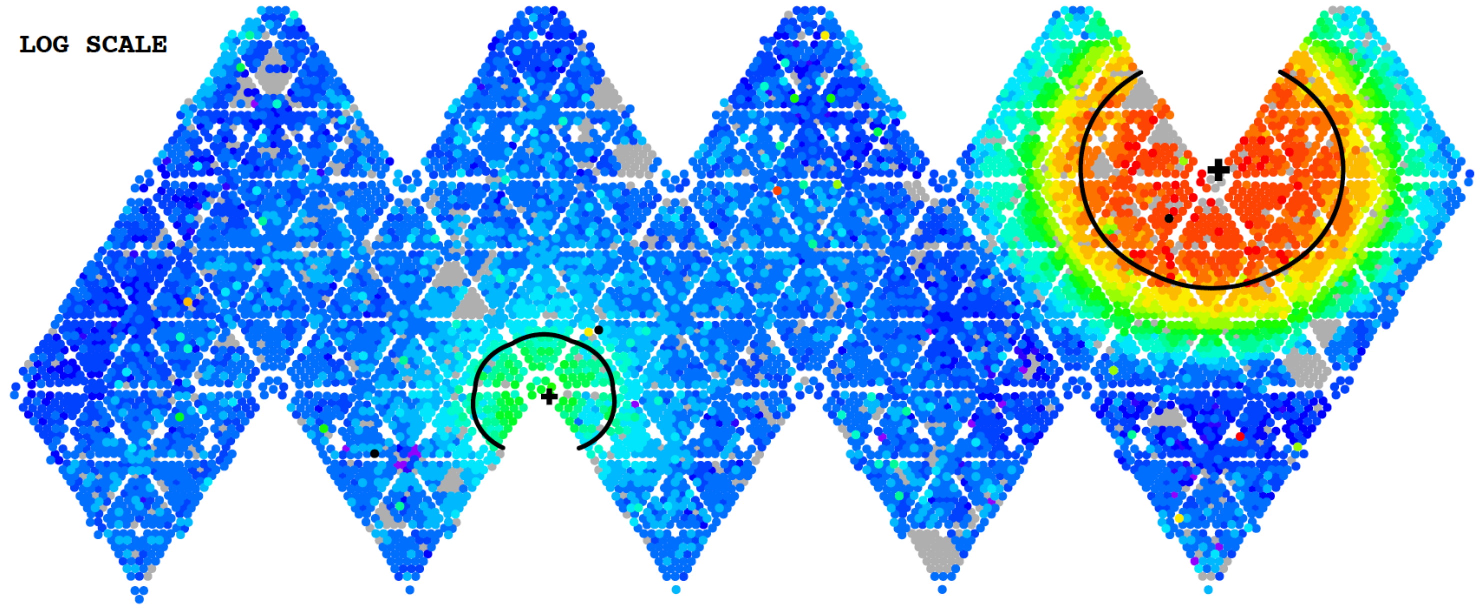


Poster #73
Calibration of the SNO+ Detector with a Light Diffusing Source in the Water Phase
A. Inacio

Fibre data taking ongoing

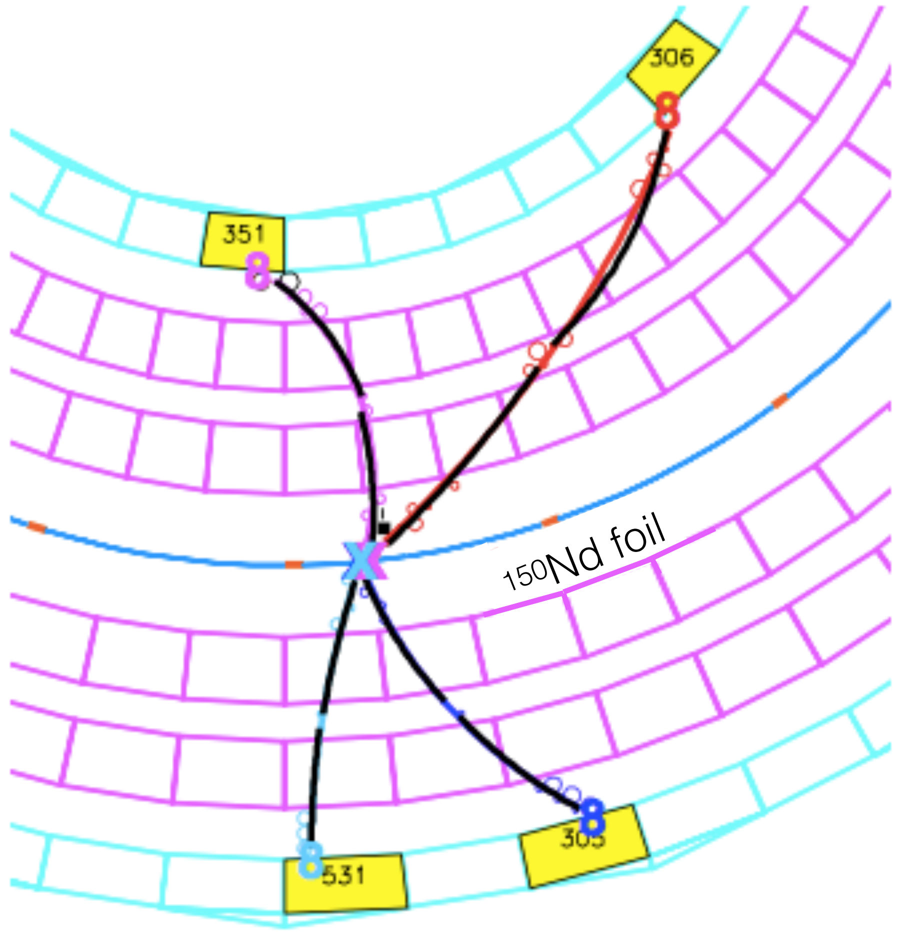


Poster #83
SMELLIE: A Laser Calibration System for SNO+
E. Turner



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)

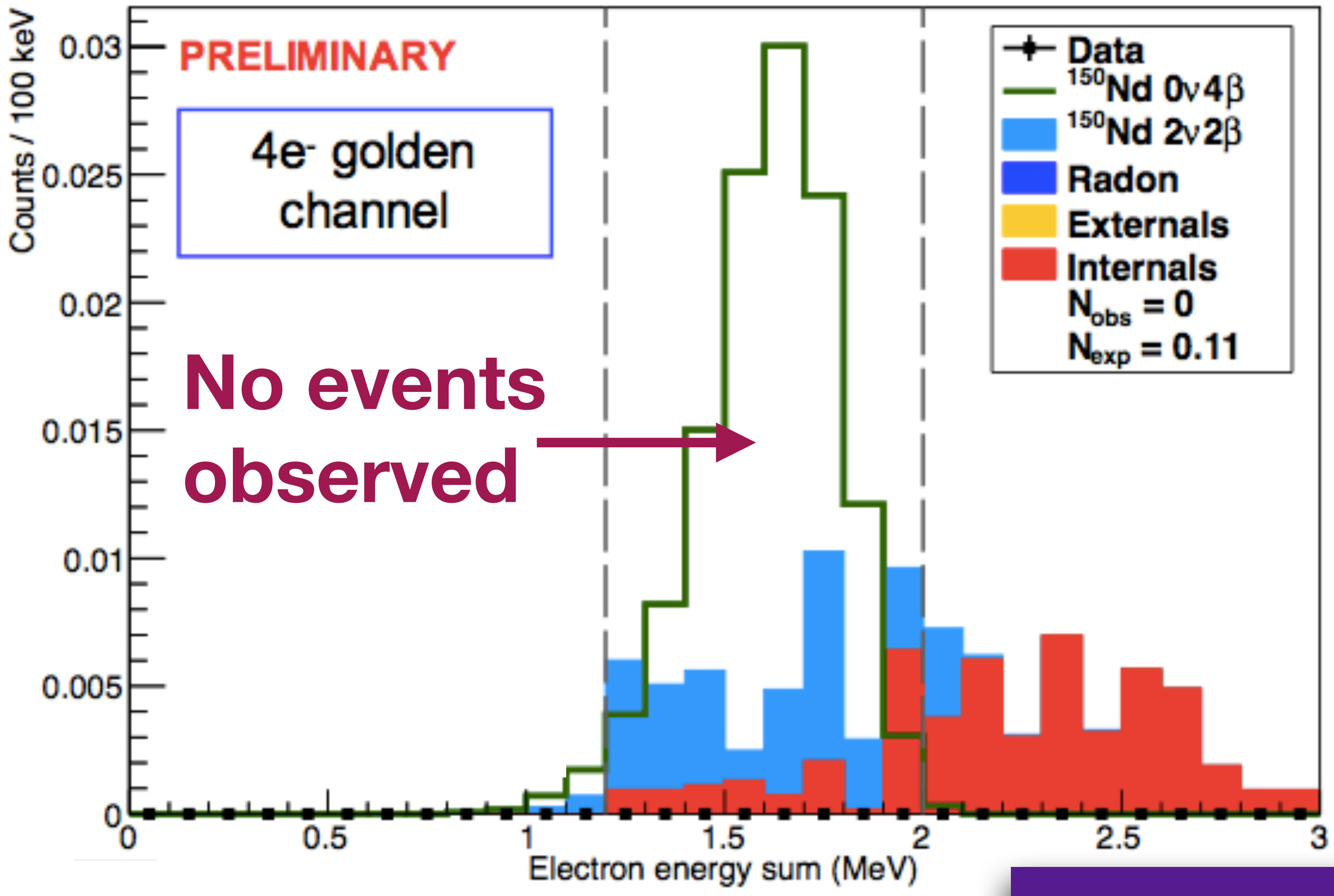


0ν4β decays would violate lepton number, but could occur even if neutrinos are **Dirac** fermions

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

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

Low background strategy: reduce, remove, reject

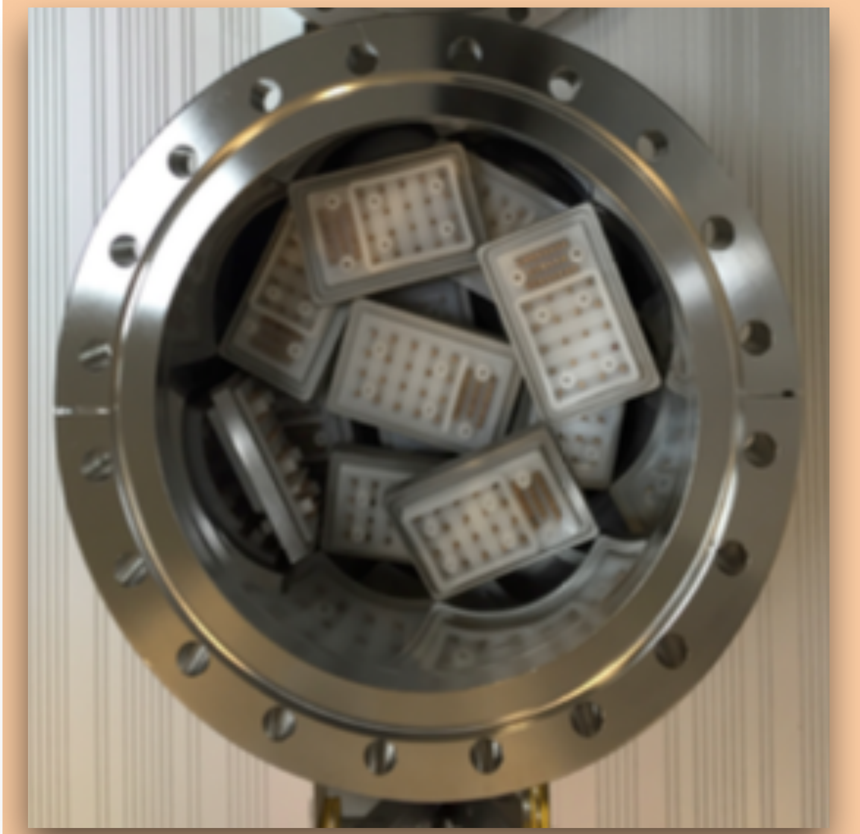
Radon 222 (from U decay chain): target activity **150 µBq / m^3**

~ 30 times lower than NEMO-3

Low background strategy: reduce, remove, reject

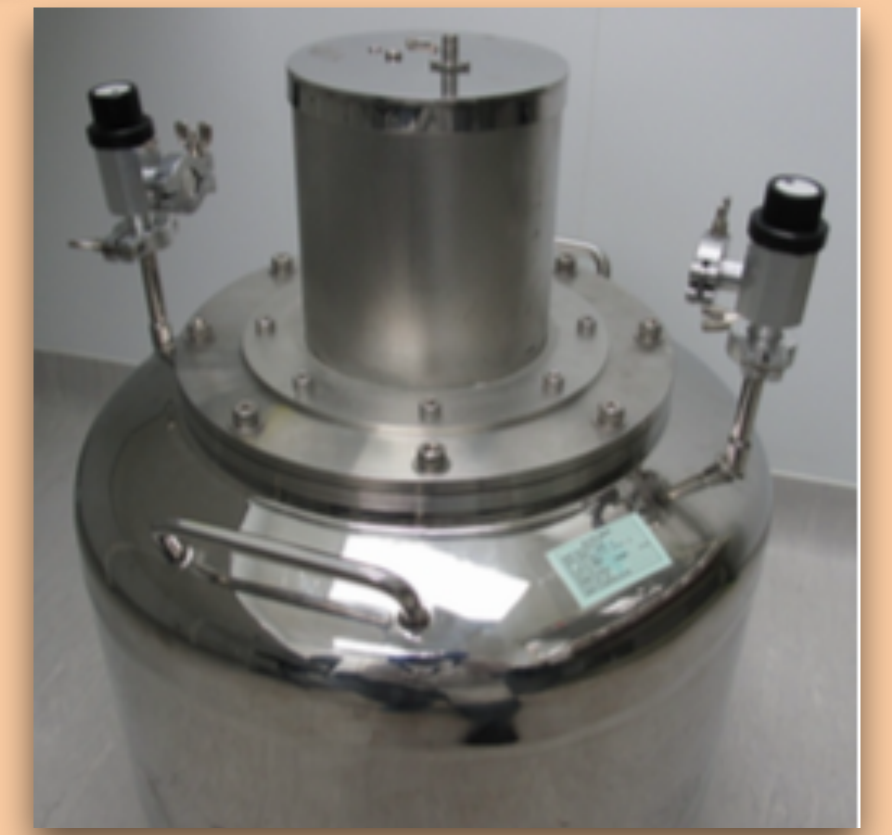
Radon 222 (from U decay chain): target activity 150 µBq / m^3

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



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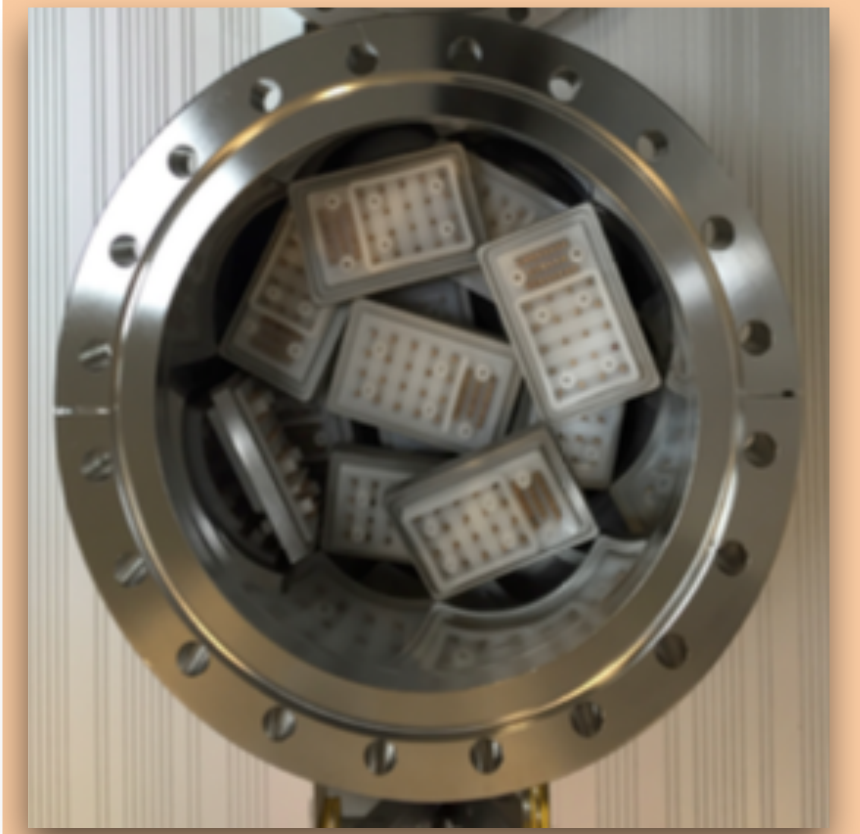

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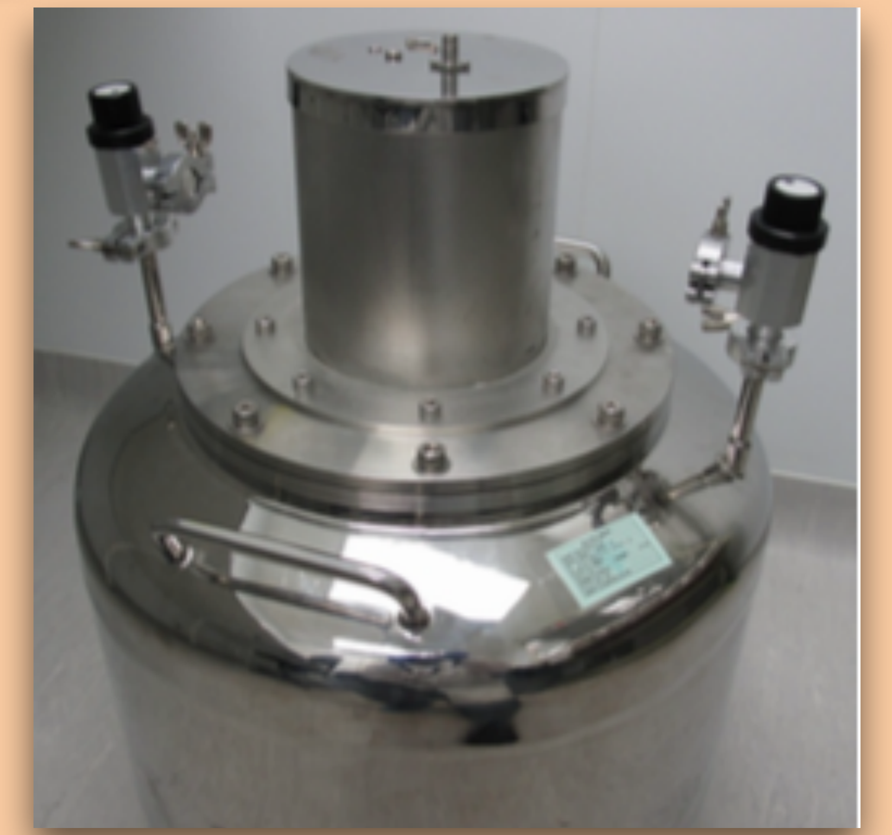
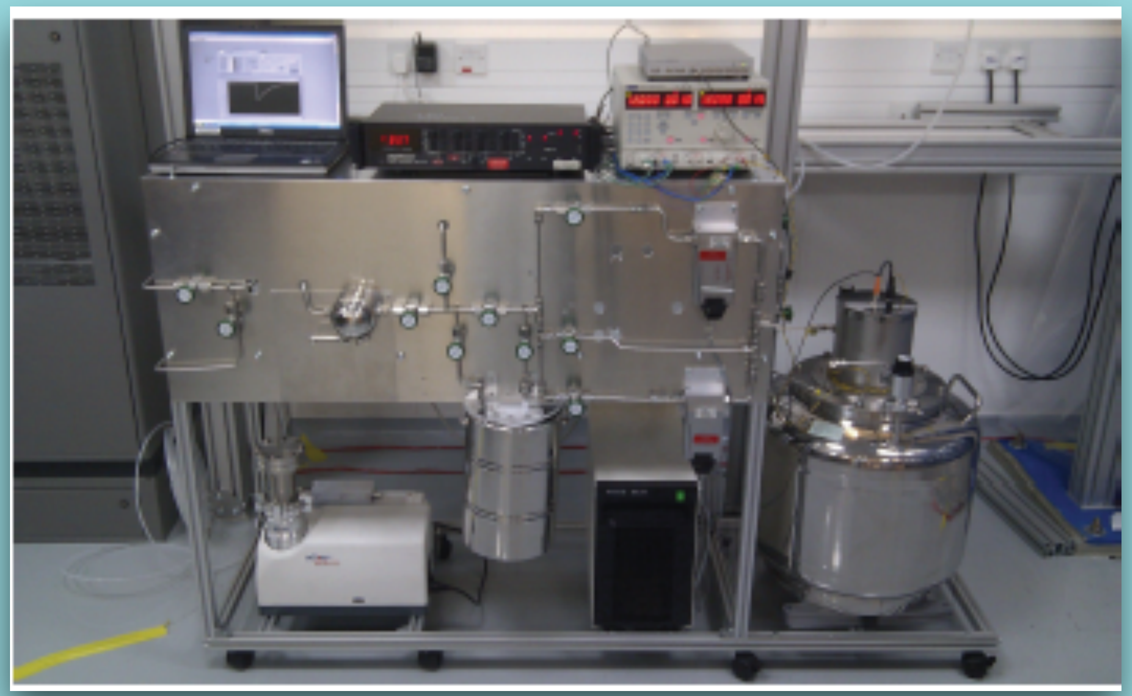


Remove radon from tracker gas
(95% helium, 1% argon, 4% ethanol)

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

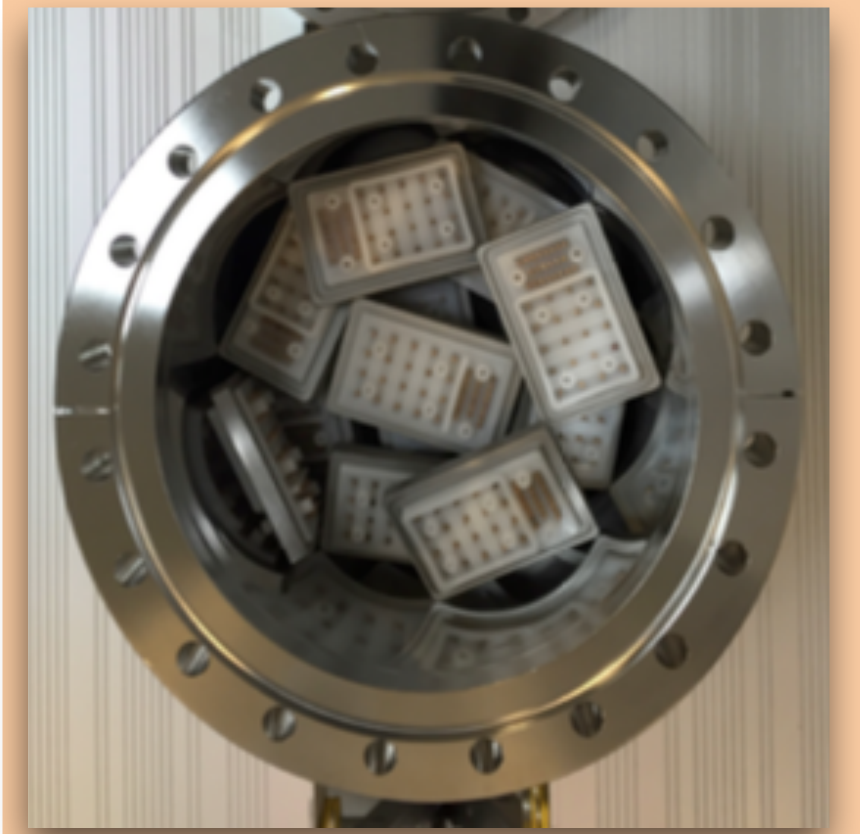
Flush with He: 2 m^3 / hour

Resulting activity: 0.15 mBq / m^3

Low background strategy: reduce, remove, reject

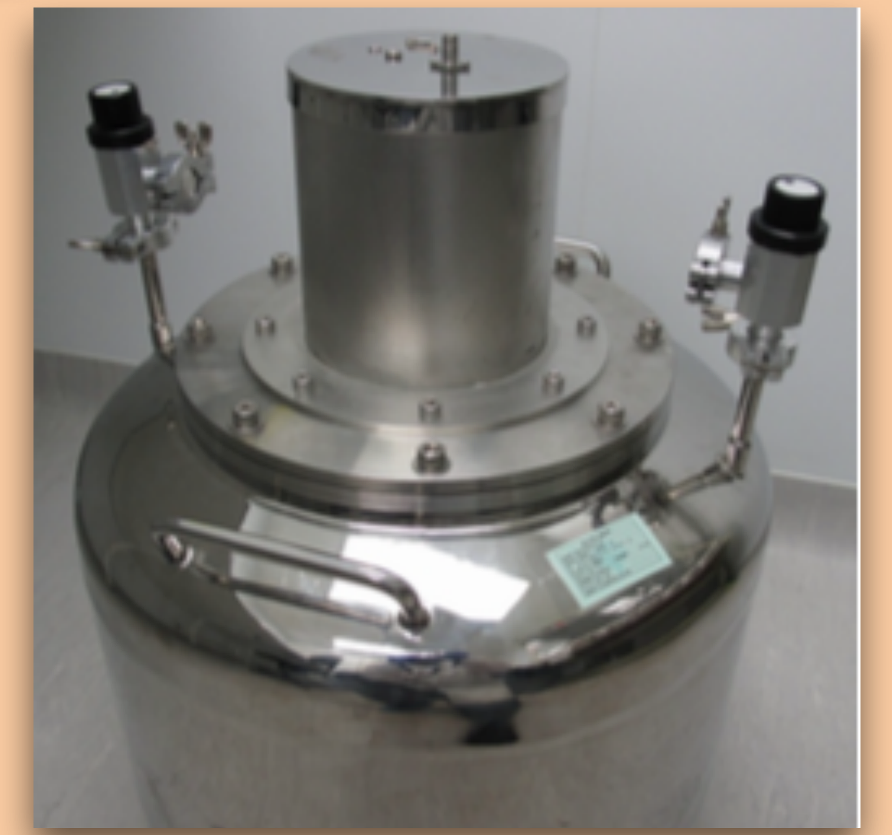
Radon 222 (from U decay chain): target activity 150 μBq / m³

Reduce radon contamination with radio-pure components



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

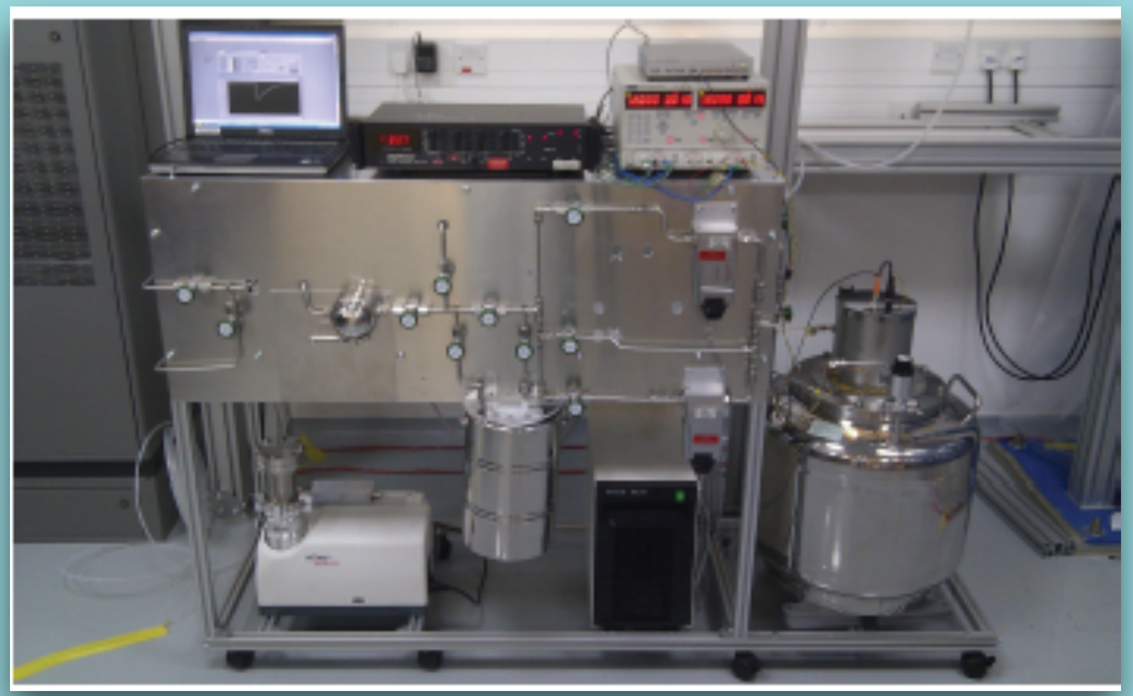
70 litre **electrostatic detector** sensitive down to 0.09mBq



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/m³



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

Measured activity: 2.7 ± 0.3 mBq / m³

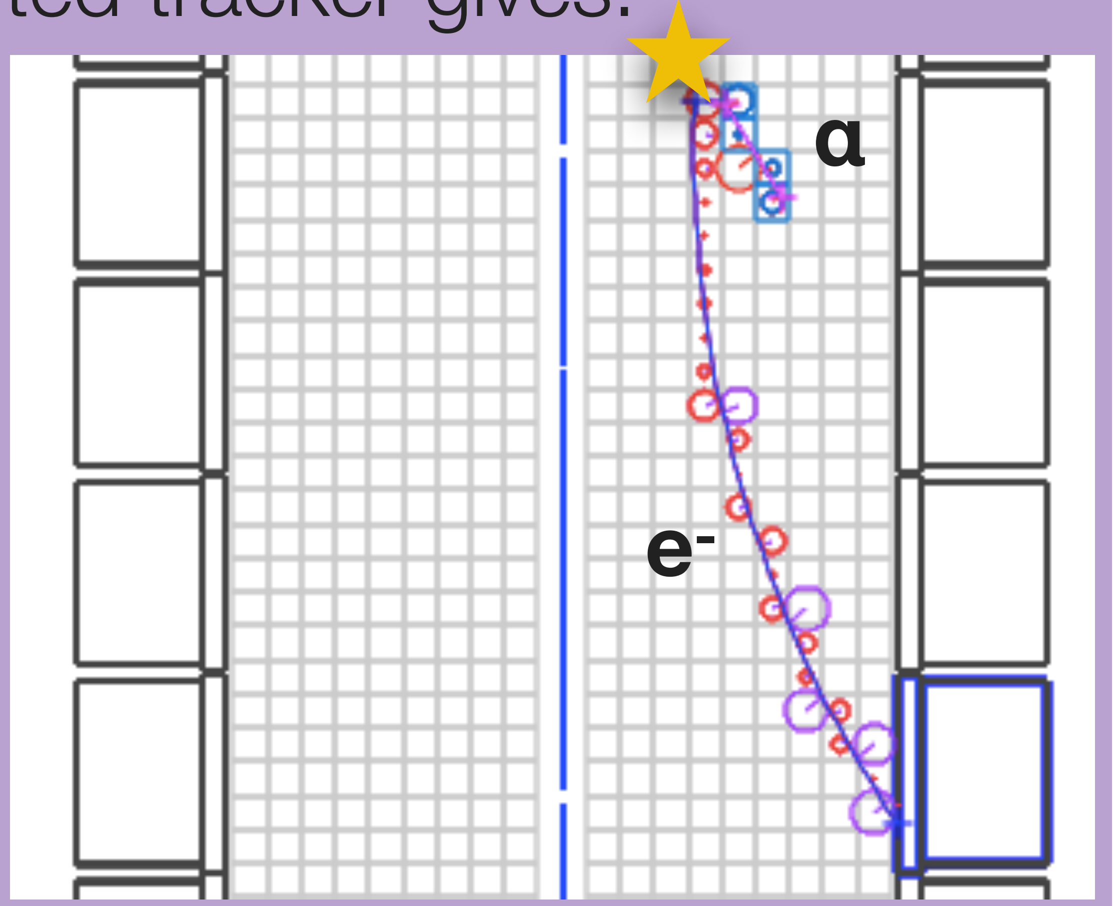
Flush with He: 2 m³ / hour

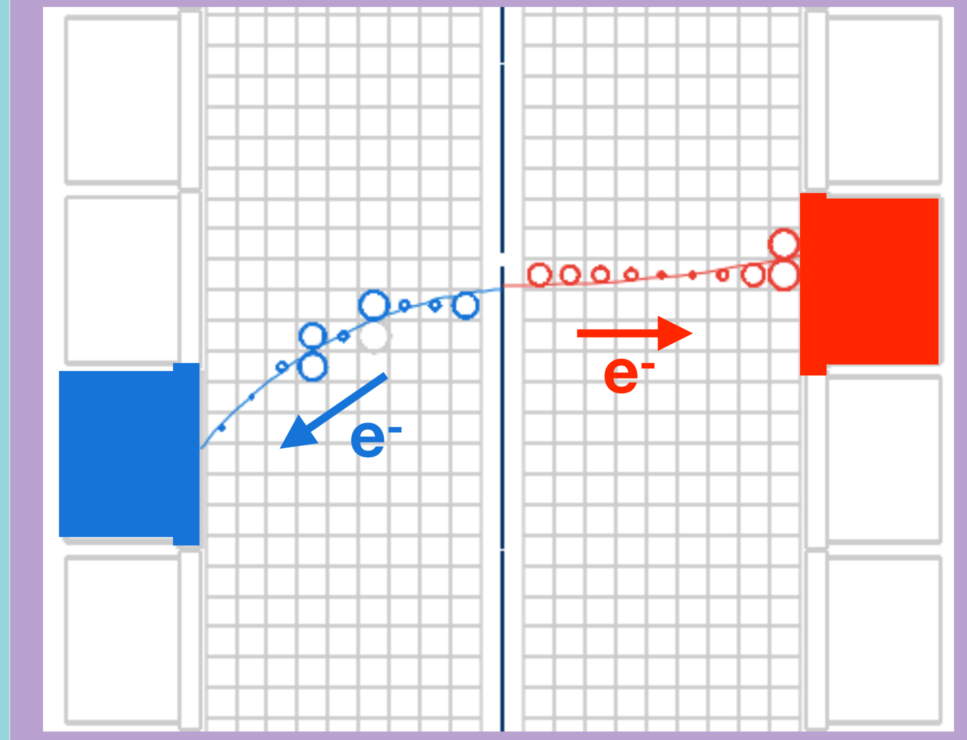
Resulting activity: 0.15 mBq / m³

Reject background events with topological and timing cuts

Fully-instrumented tracker gives:

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



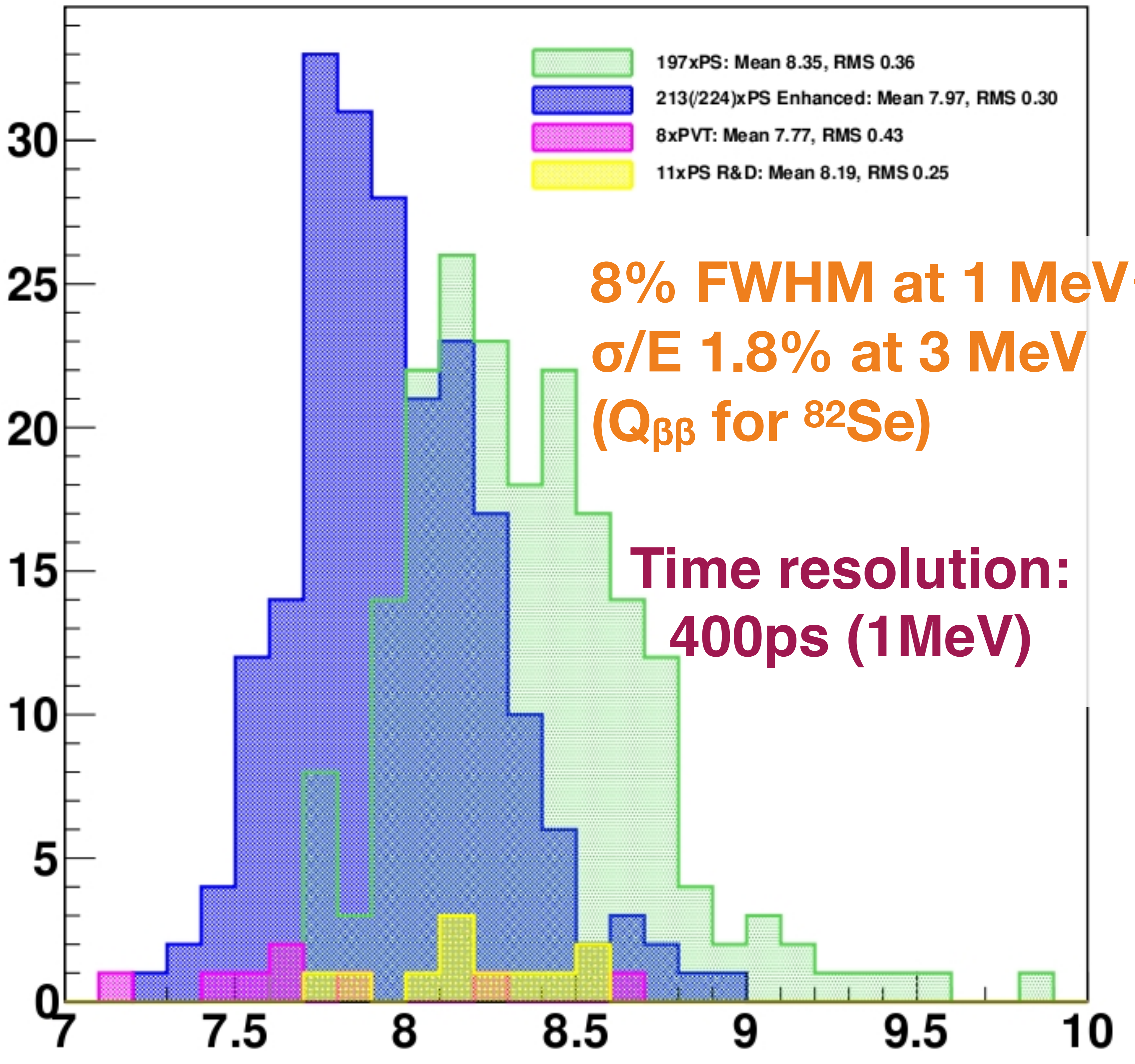


Reject non-ββ topologies at analysis time

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

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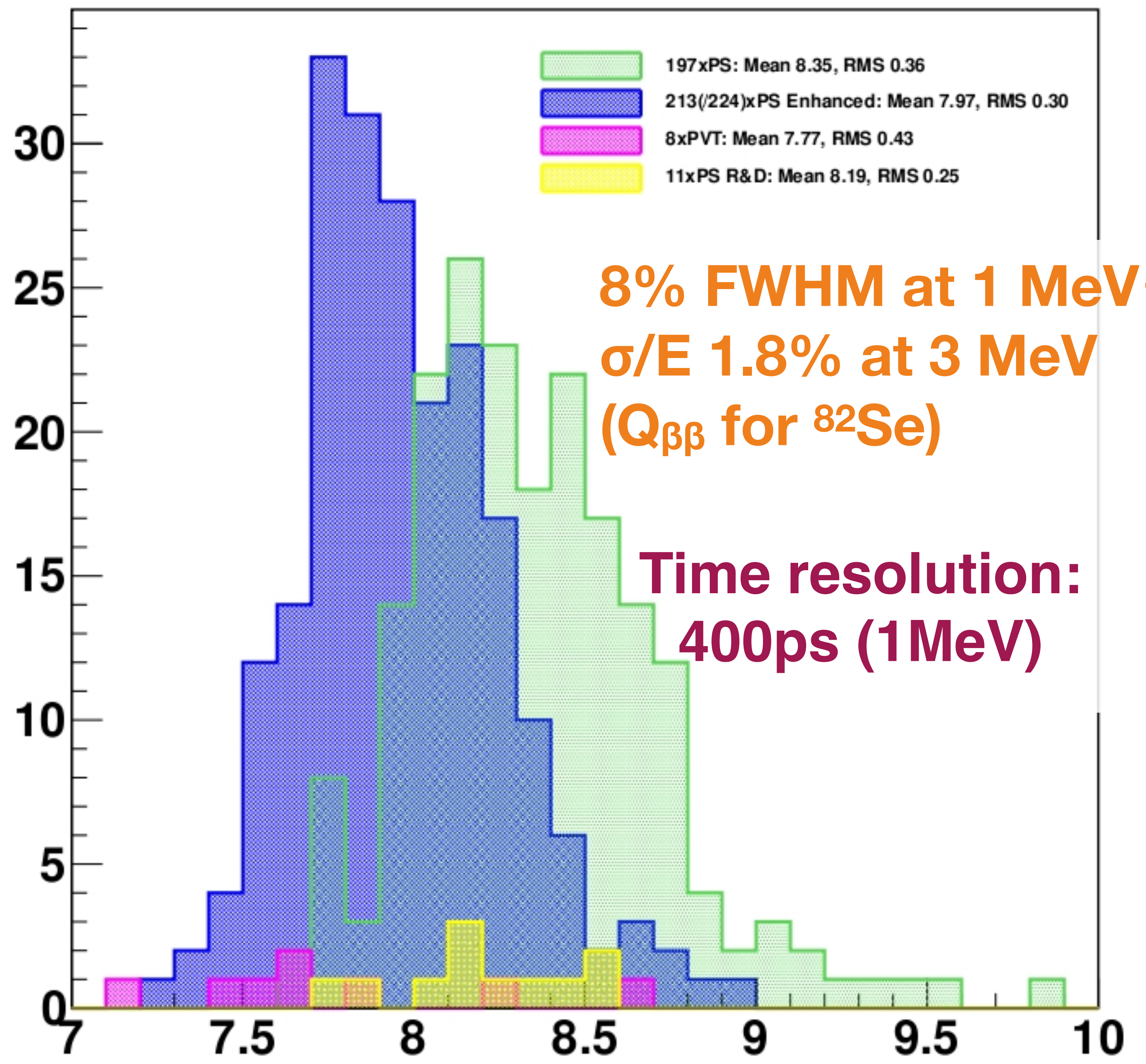
With side, top and bottoms: 712 modules total

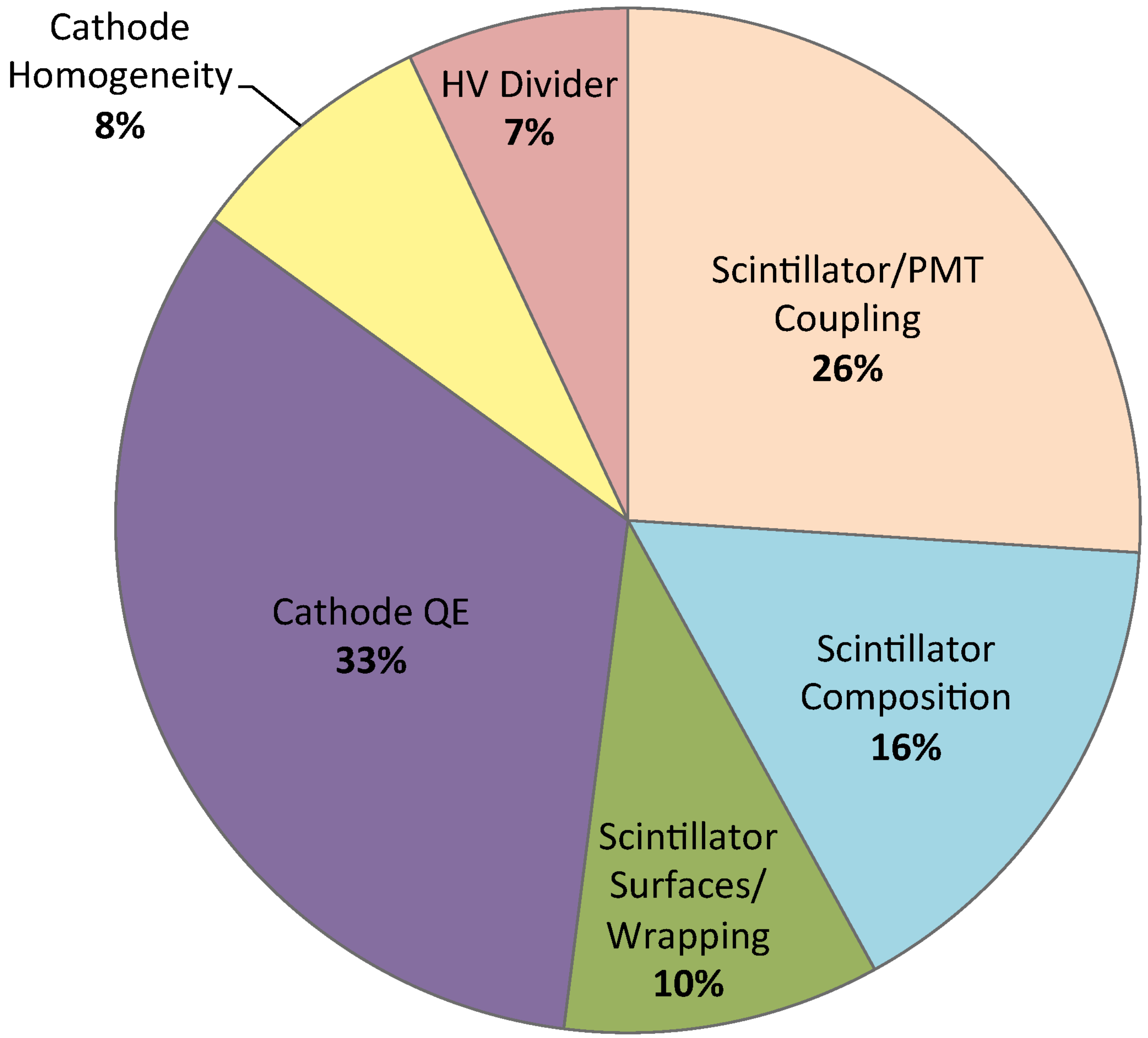
Nucl. Inst. Meth. A 868, 98-108 (2017)



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



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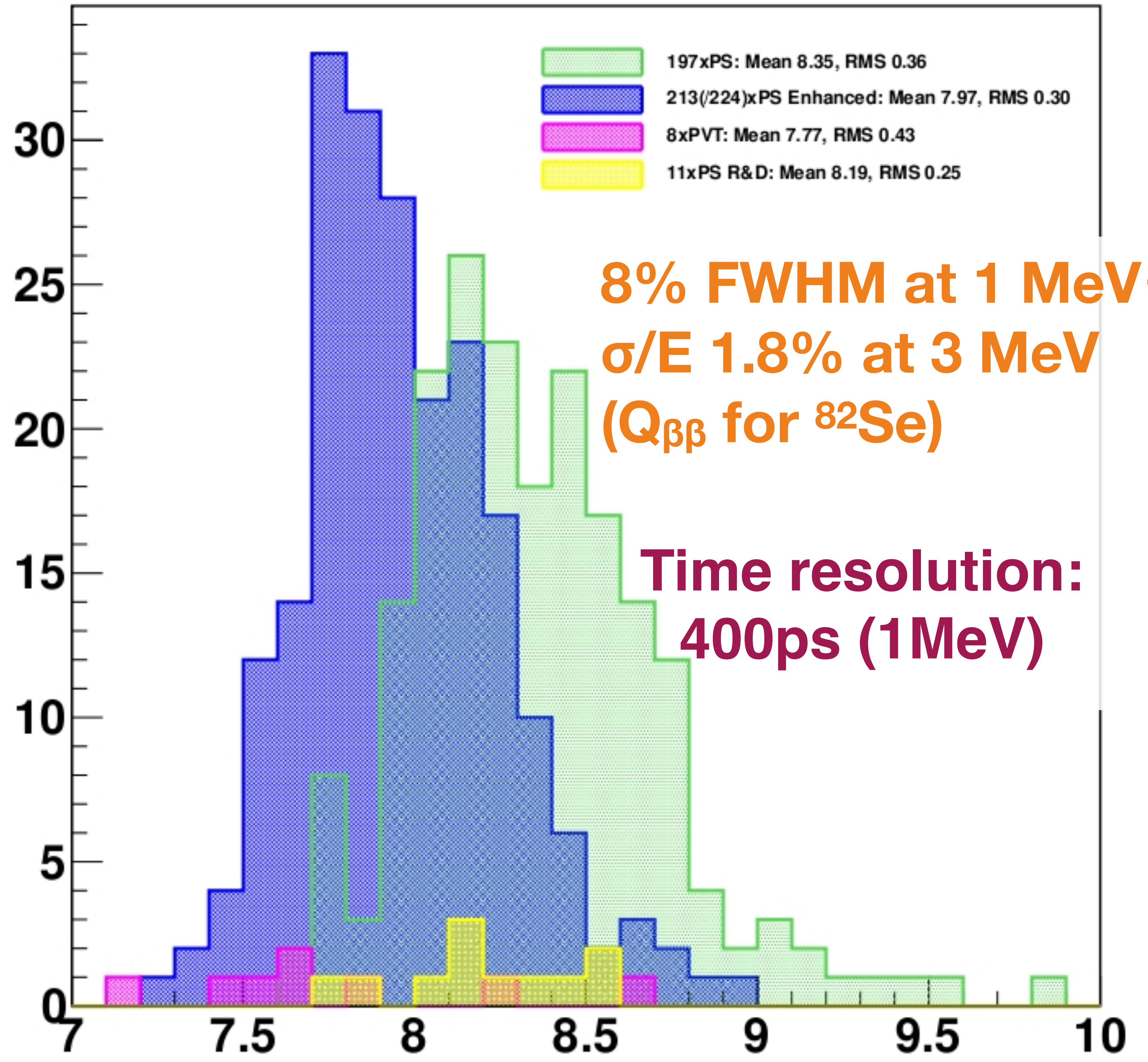
Nucl. Inst. Meth. A 868, 98-108 (2017)



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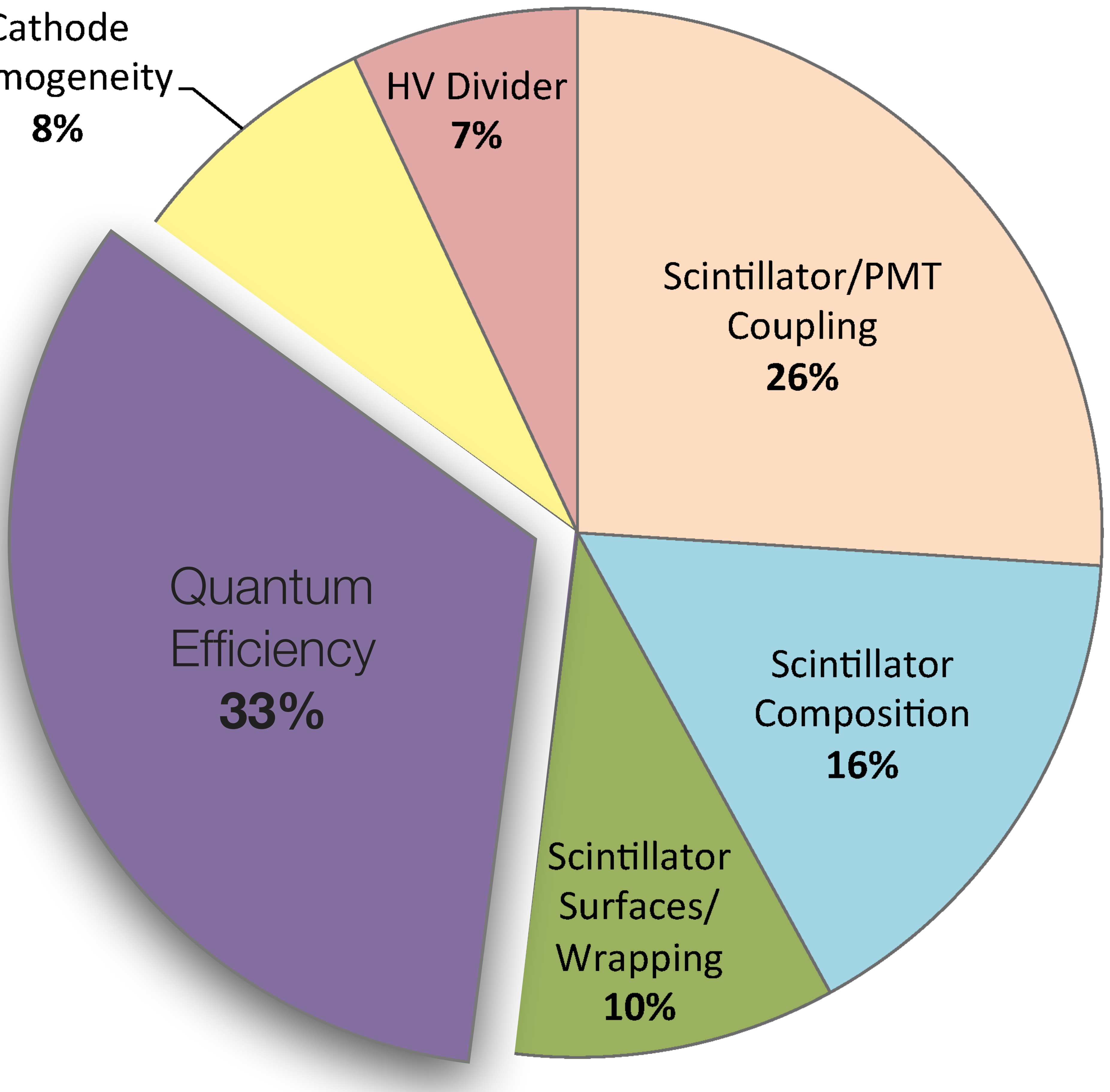
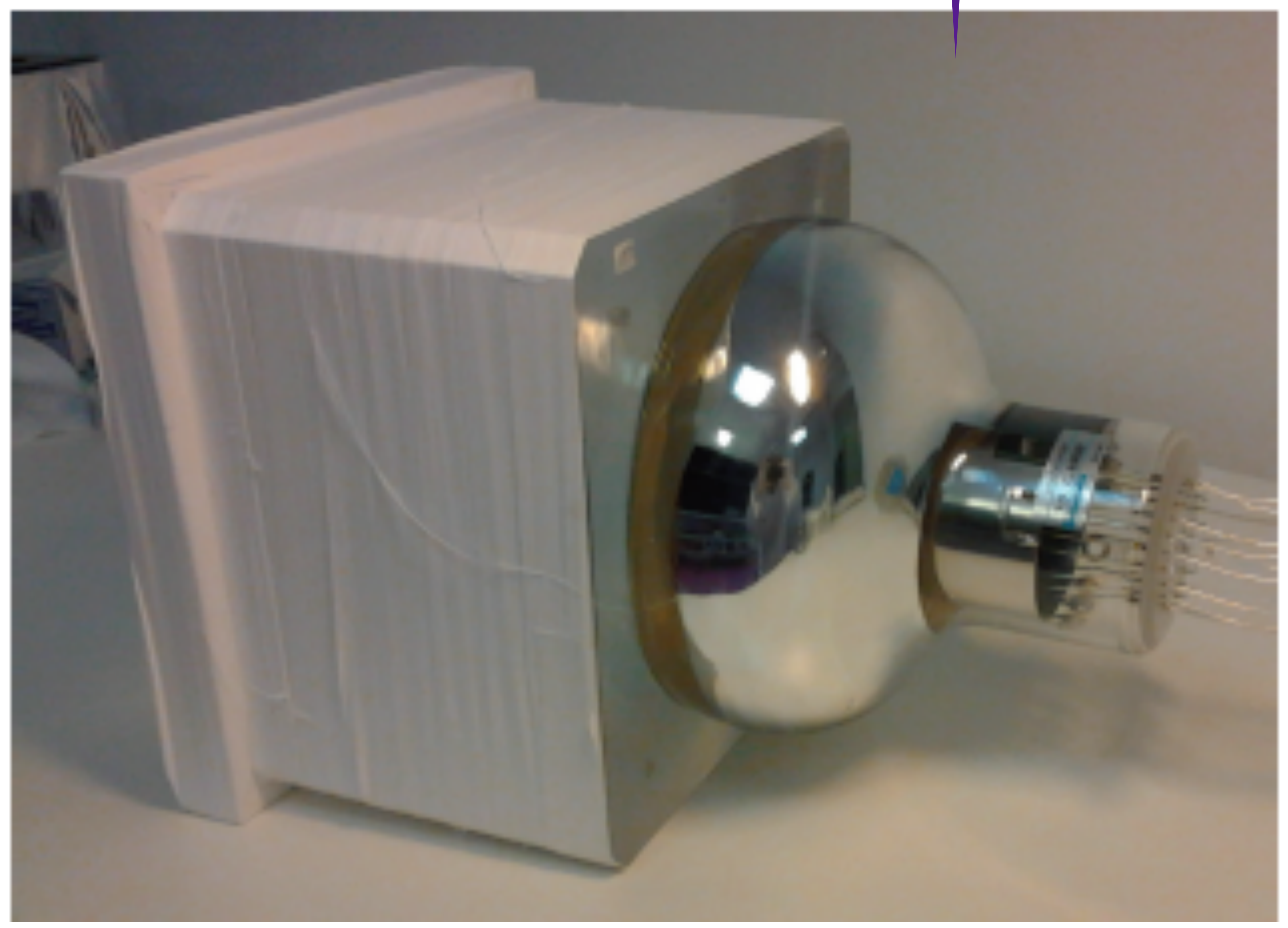
Time resolution: 400ps (1MeV)

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

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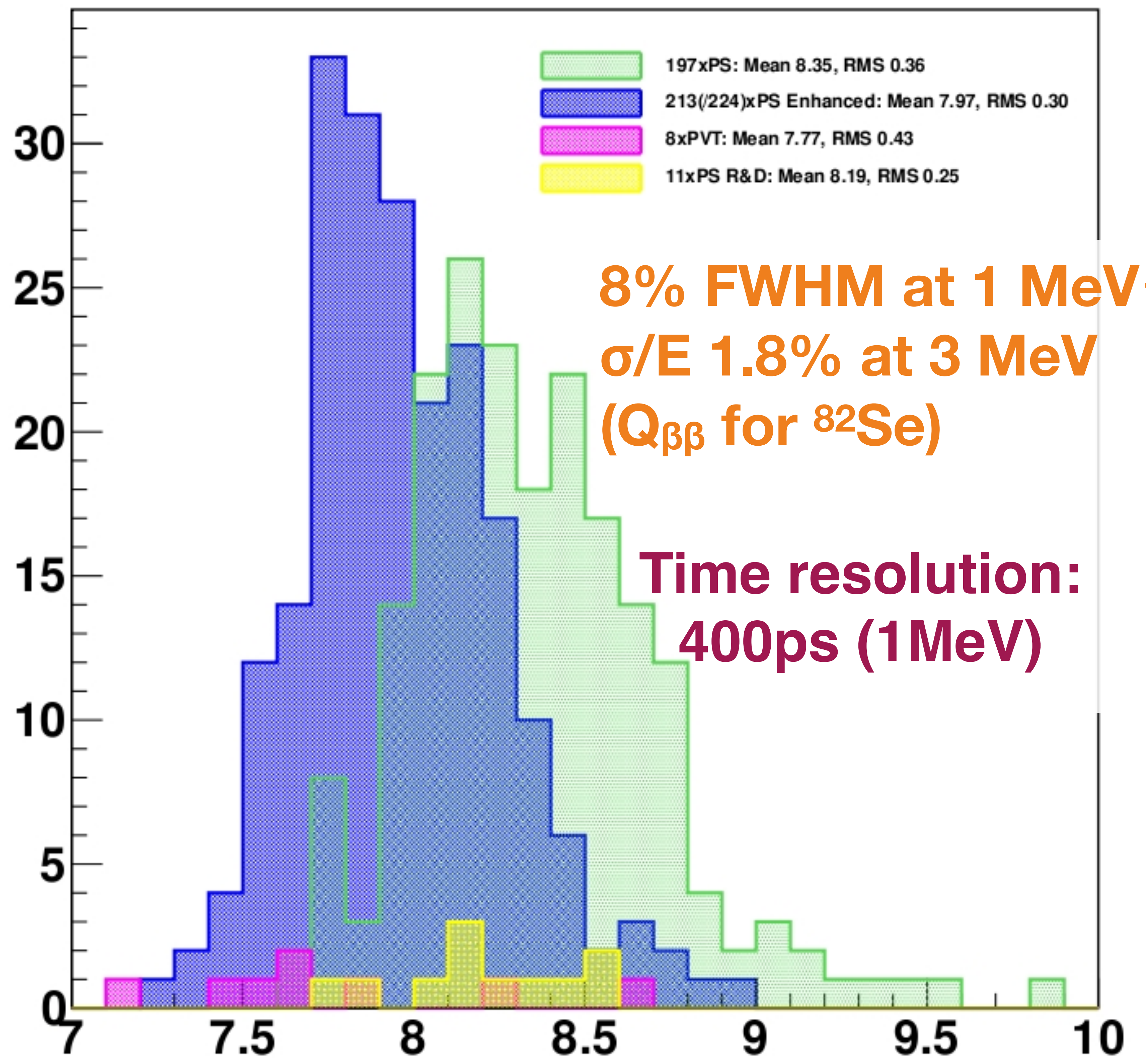
Nucl. Inst. Meth. A 868, 98-108 (2017)



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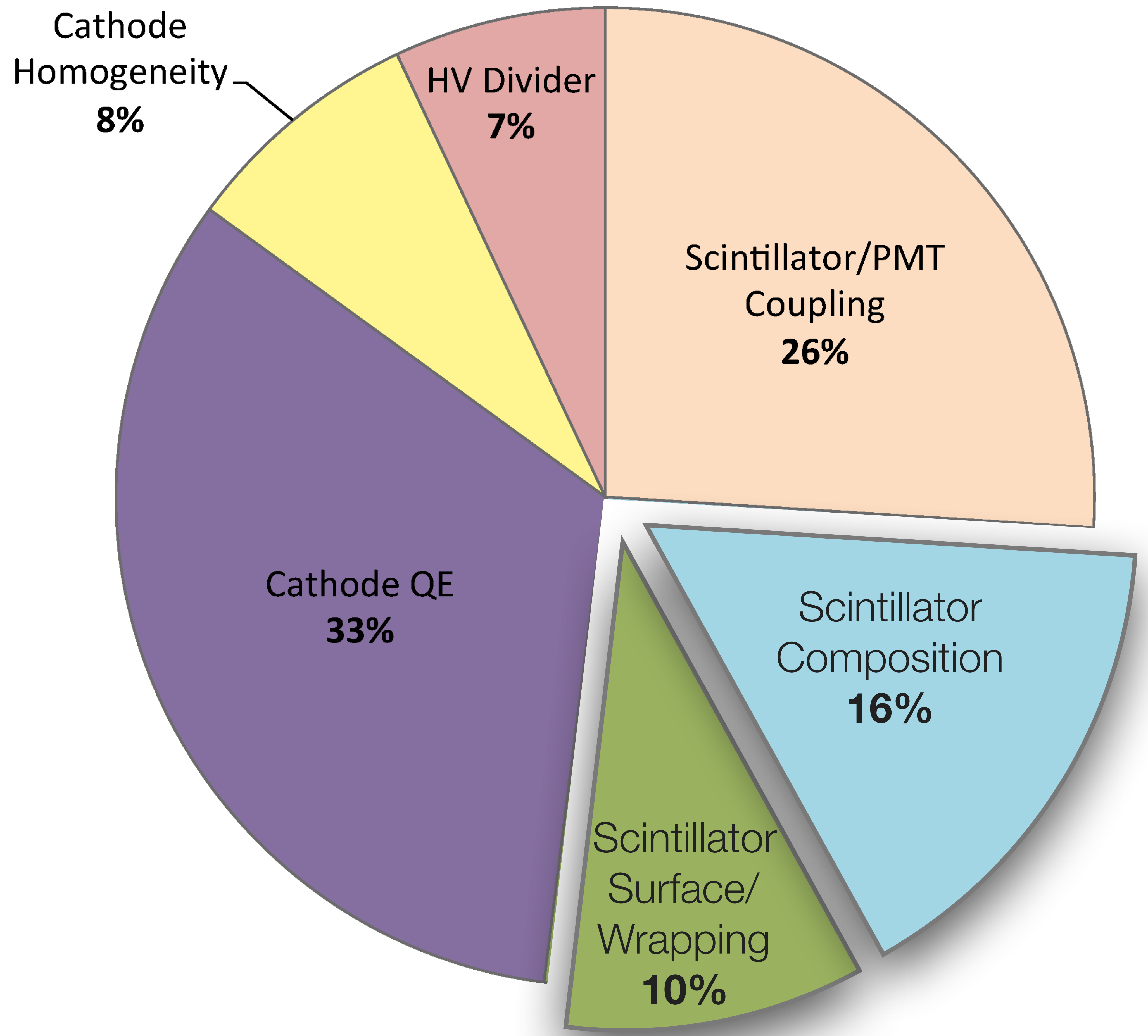
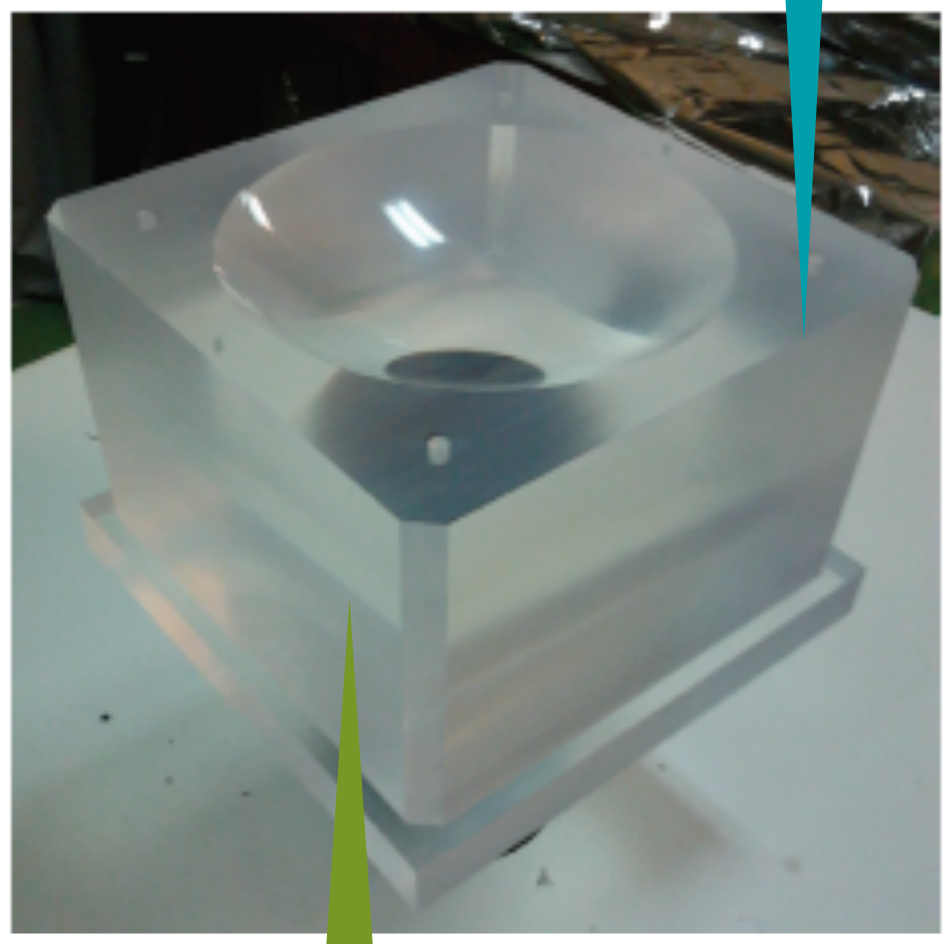
Time resolution:
400ps (1MeV)

Contributions to improved resolution



256 x 256 x 194 mm
Polysytrene scintillator block

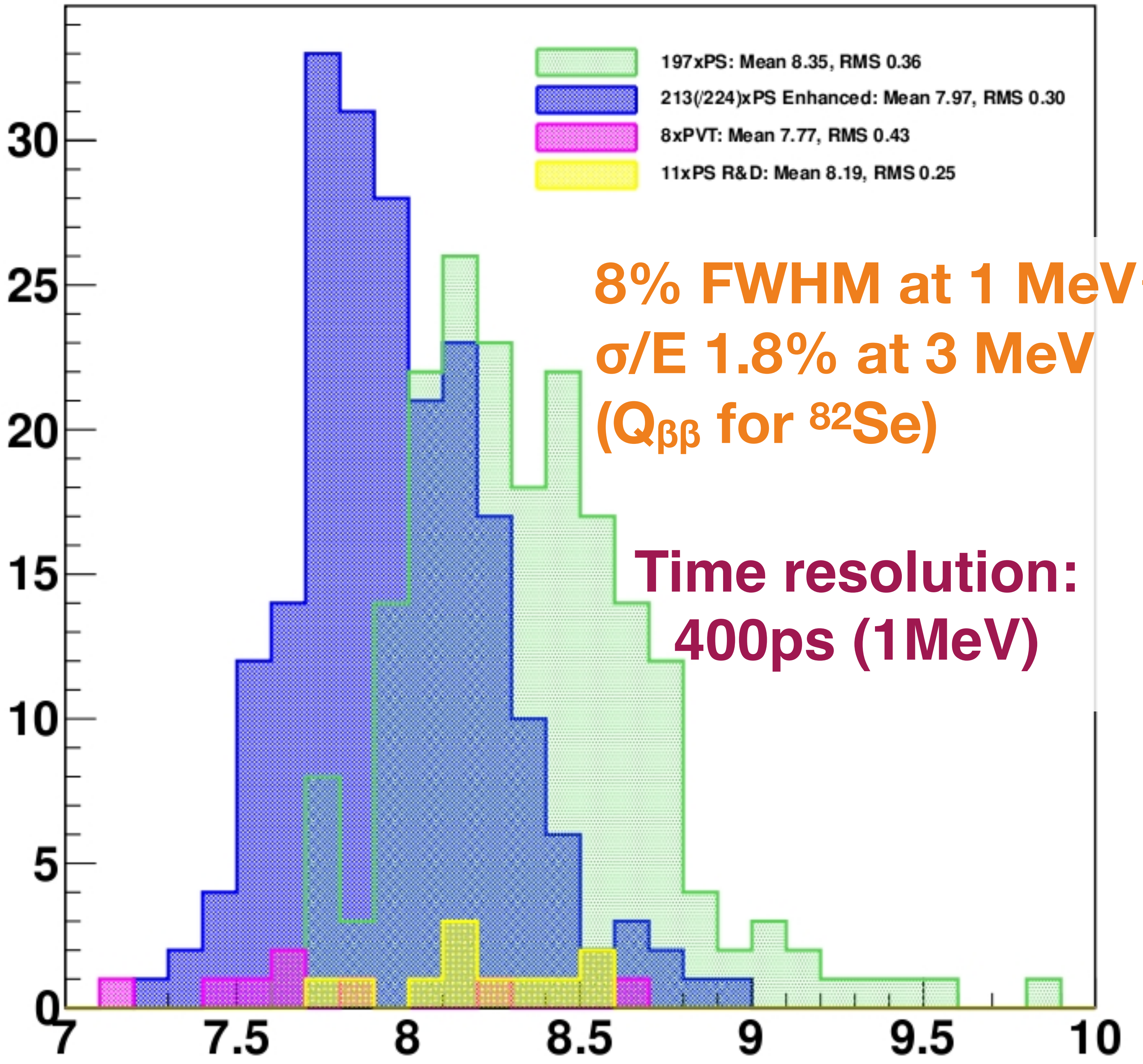


Optimised surface finish

Calorimeter development

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

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



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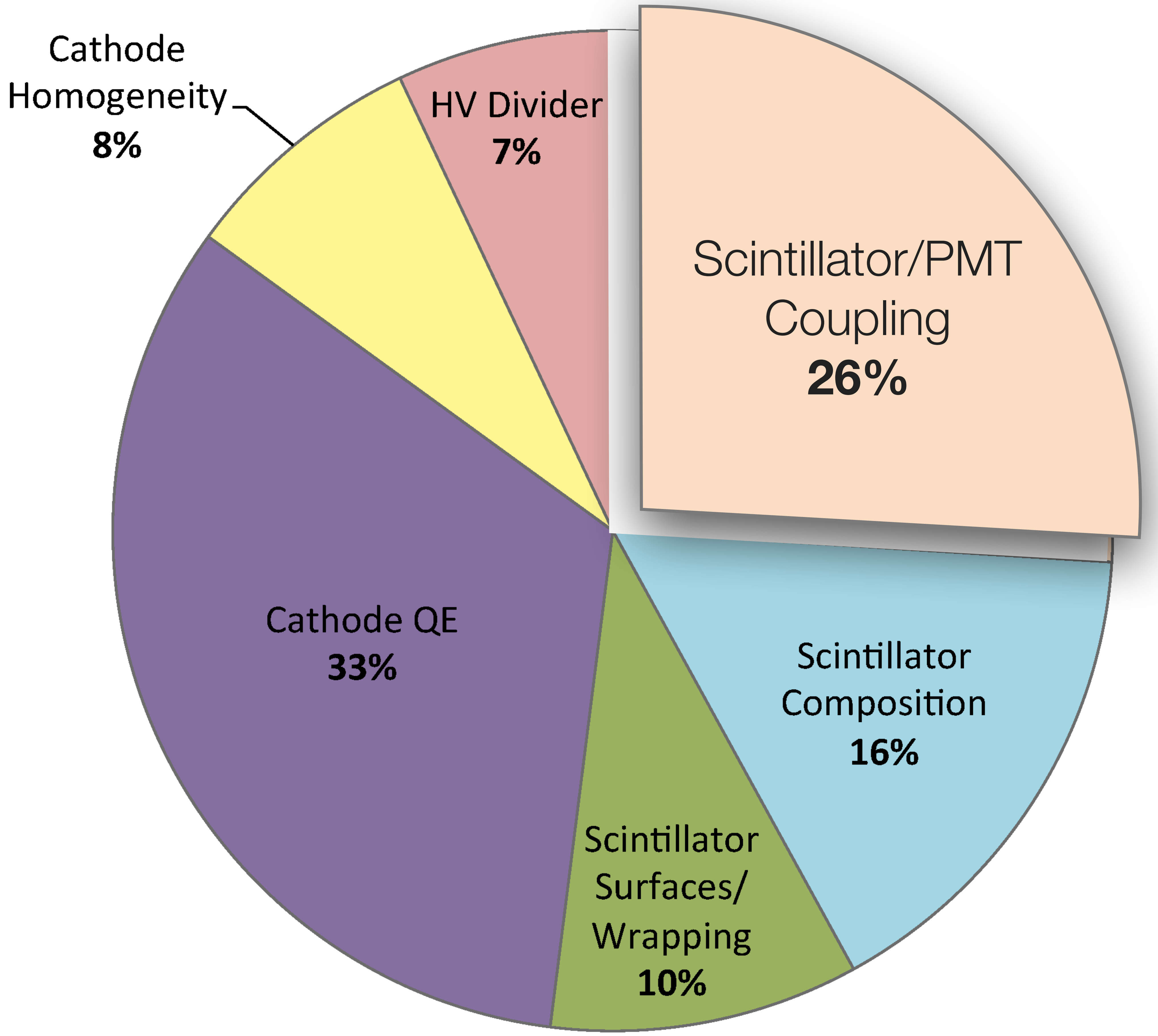
($Q_{\beta\beta}$ for ^{82}Se)

Time resolution: 400ps (1MeV)

Contributions to improved resolution



Directly coupled - no light-guide