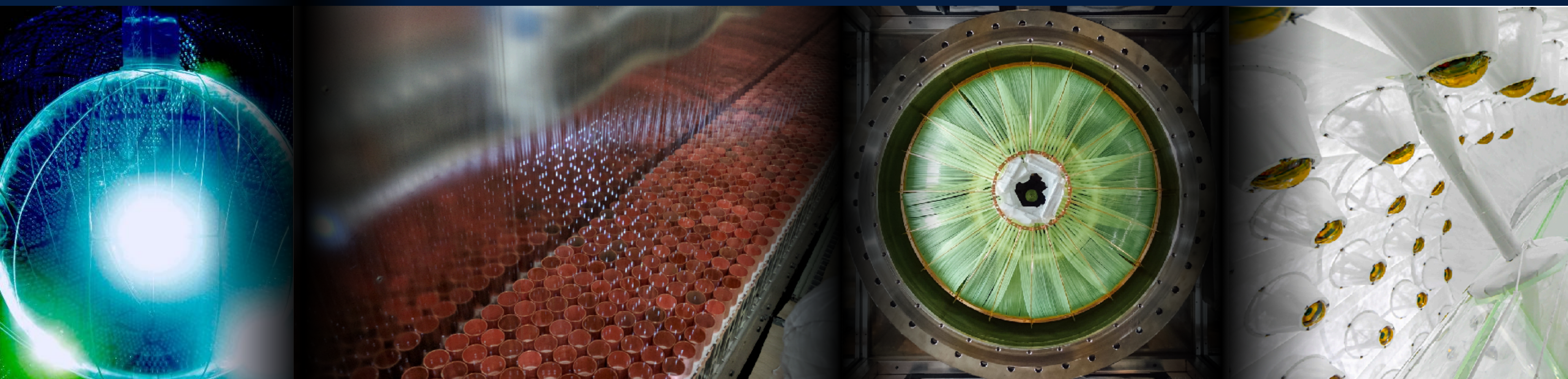




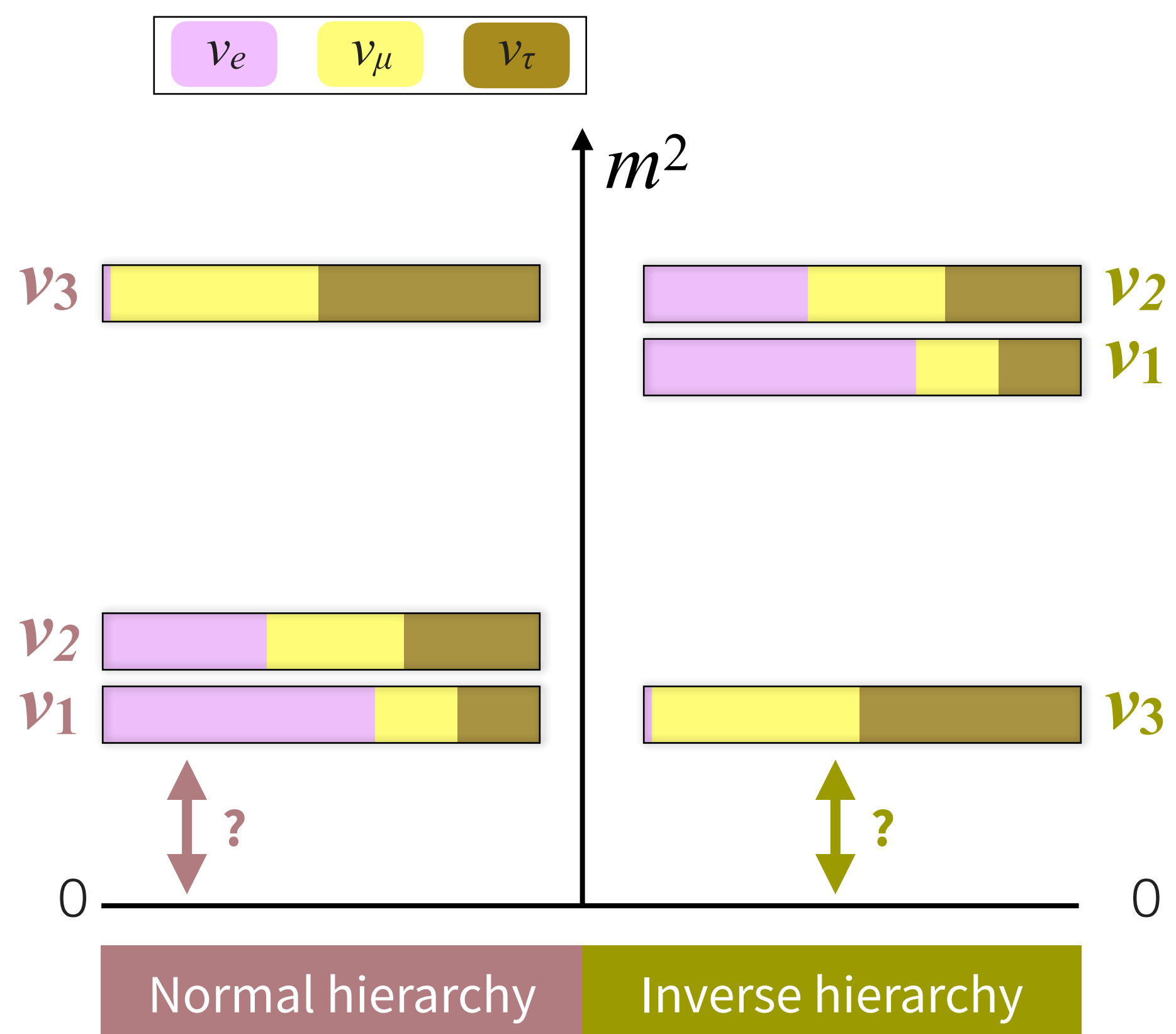
Neutrinoless double-beta decay

Cheryl Patrick STFC Ernest Rutherford Fellow, University of Edinburgh

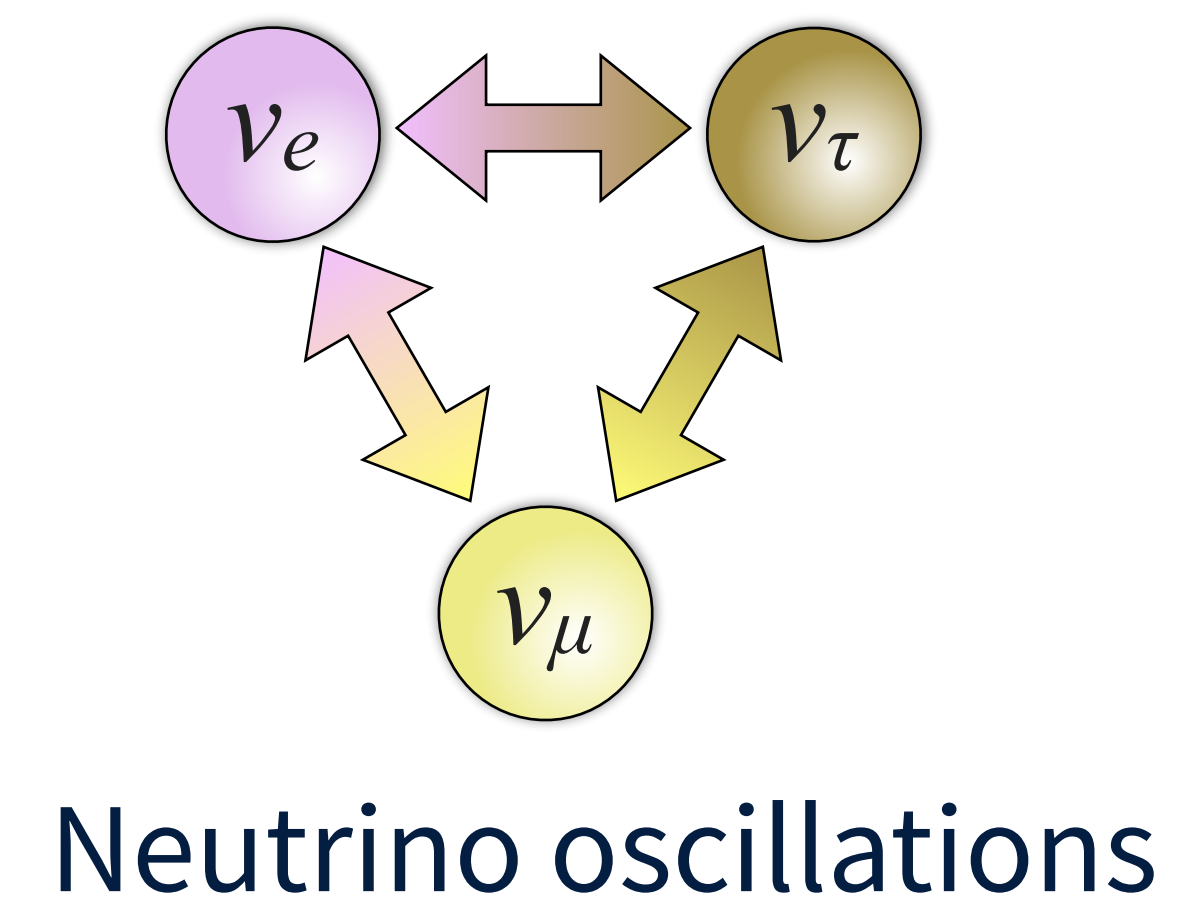


THE UNIVERSITY
of EDINBURGH

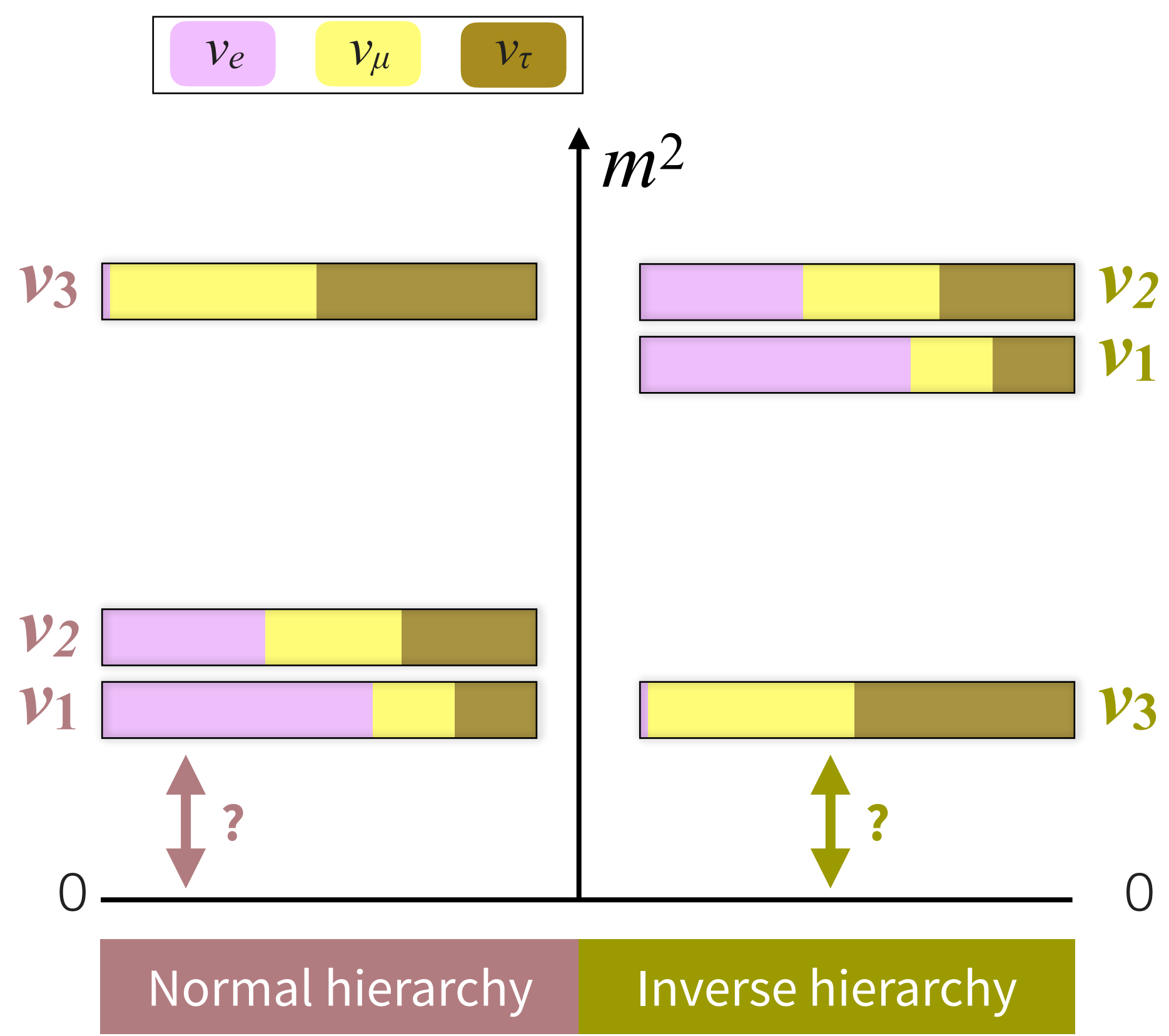
Neutrinos - unanswered questions



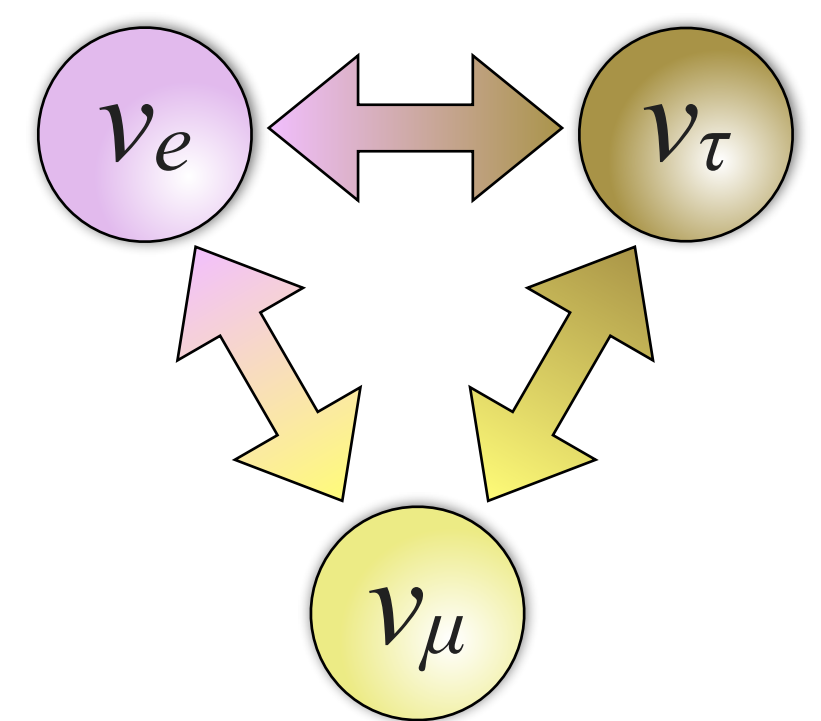
- Which neutrino is lightest?
- Do neutrinos violate CP symmetry?
- What's the absolute mass scale?
- How do neutrinos get their mass?



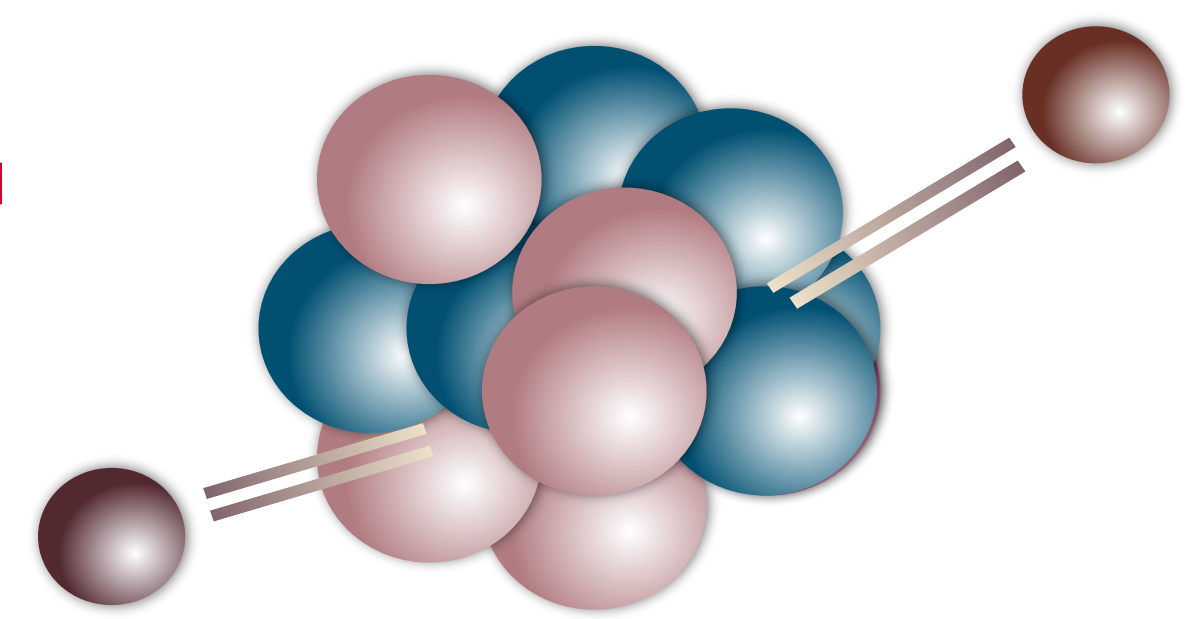
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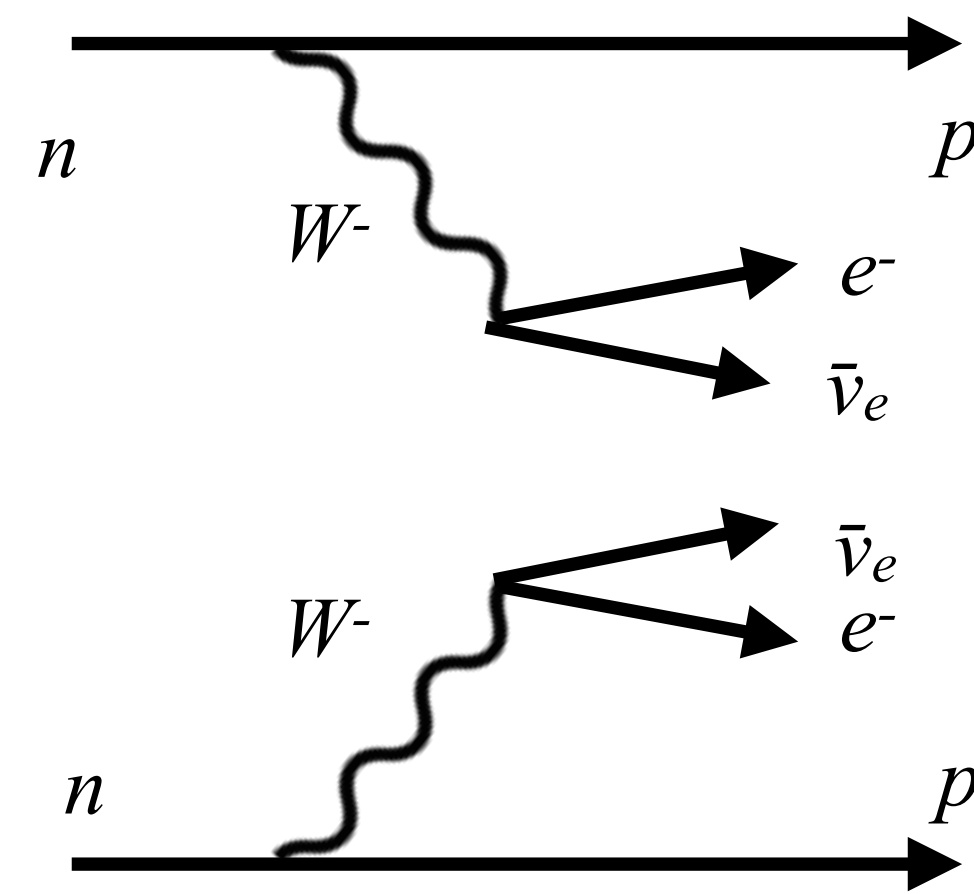
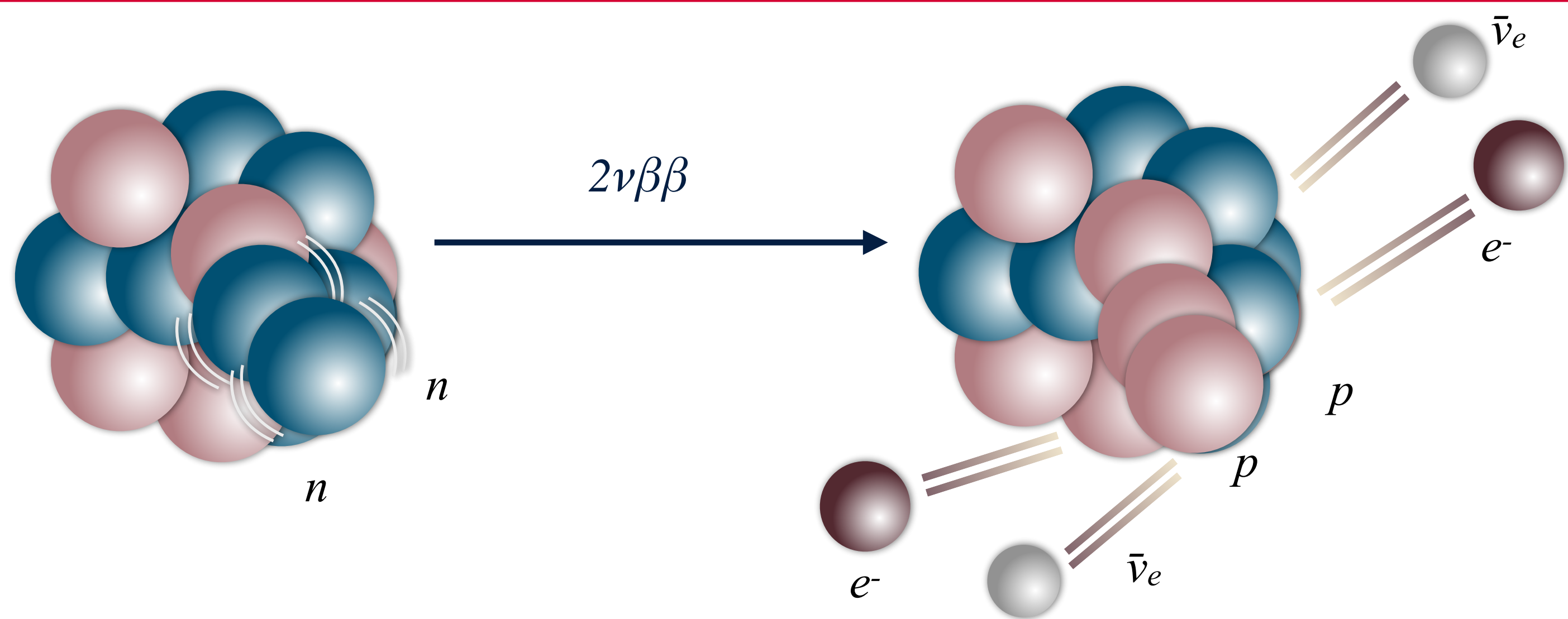


Neutrino oscillations



Neutrinoless double-beta decay

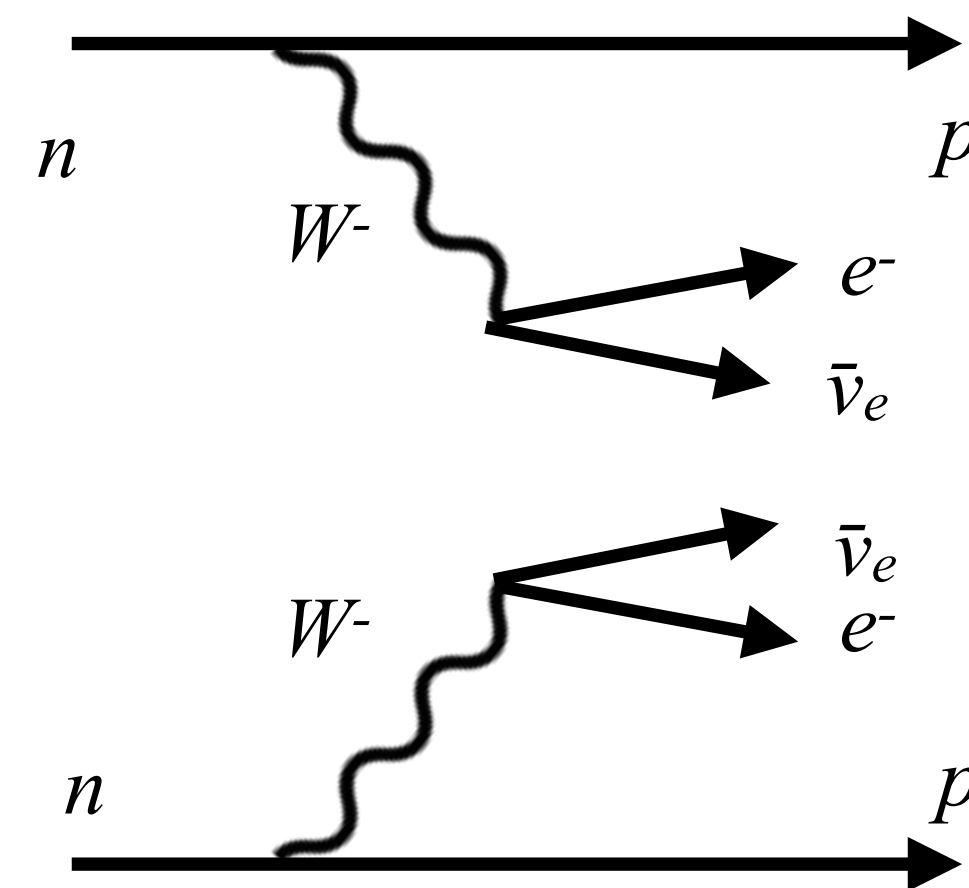
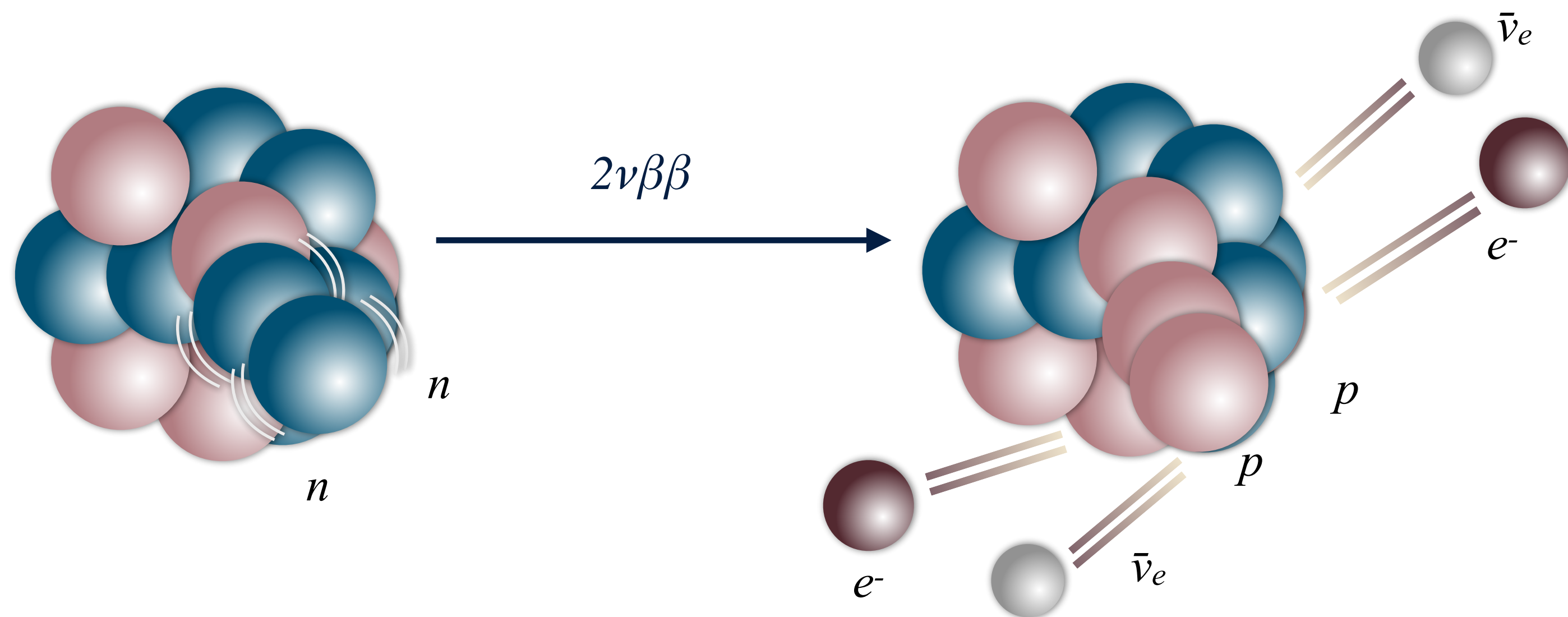
Standard-model double-beta decay ($2\nu\beta\beta$)



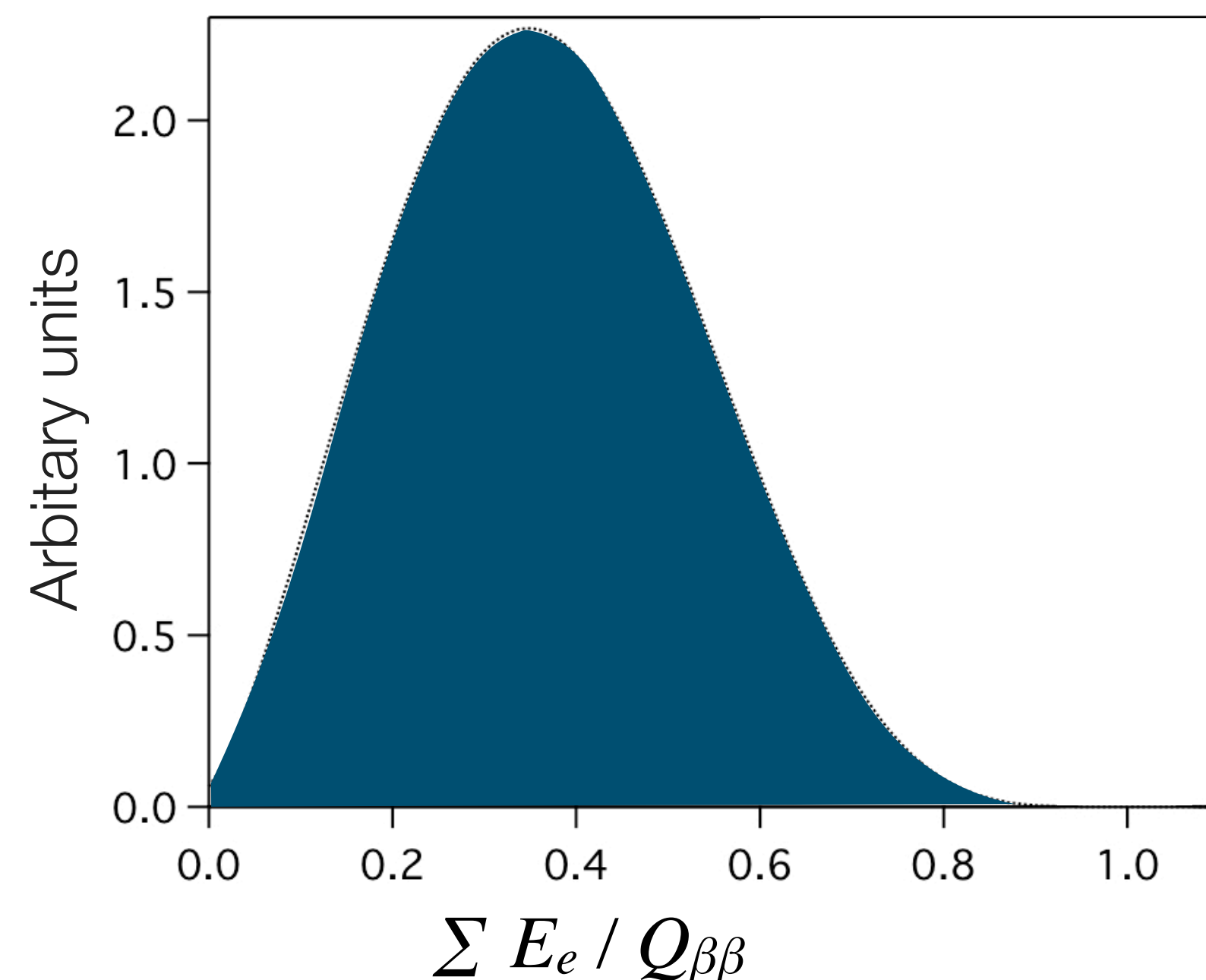
- Standard Model process
- Lepton number conserved
- Doubly weak = long half-life
- Observed in several isotopes; $T_{1/2} \sim 10^{20}$ years

1																	18						
1 H 1.008	2																2 He 4.0026						
3 Li 6.94	4 Be 9.0122																	5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
11 Na 22.990	12 Mg 24.305																	13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	18 Ar 39.948
19 K 39.098	48Ca	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	76Ge	33 As 74.922	82Se	35 Br 79.904	36 Kr 83.798						
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	96Zr	41 Nb 92.906	100Mo	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	110Pd	47 Ag 107.87	116Cd	49 In 114.82	124Sn	51 Sb 121.76	128, 130Te	53 I 126.90	134, 136Xe						
55 Cs 132.91	56 Ba 137.33	57-71 *	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)						
87 Fr (223)	88 Ra (226)	89-103 #	104 Rf (265)	105 Db (268)	106 Sg (271)	107 Bh (270)	108 Hs (277)	109 Mt (276)	110 Ds (281)	111 Rg (280)	112 Cn (285)	113 Nh (286)	114 Fl (289)	115 Mc (289)	116 Lv (293)	117 Ts (294)	118 Og (294)						
* Lanthanide series			57 La 138.91	58 Ce 140.12	59 Pr 140.91	150Nd	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.05	71 Lu 174.97						
# Actinide series			89 Ac (227)	90 Th 232.04	91 Pa 231.04	238U	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)						

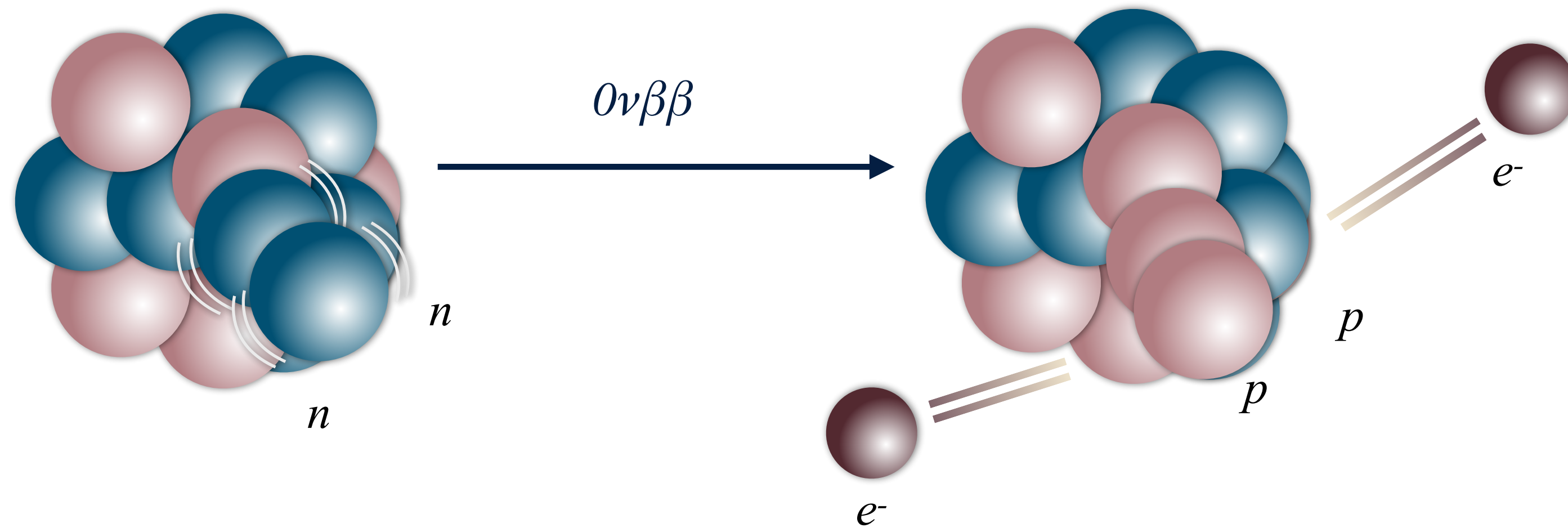
Standard-model double-beta decay ($2\nu\beta\beta$)



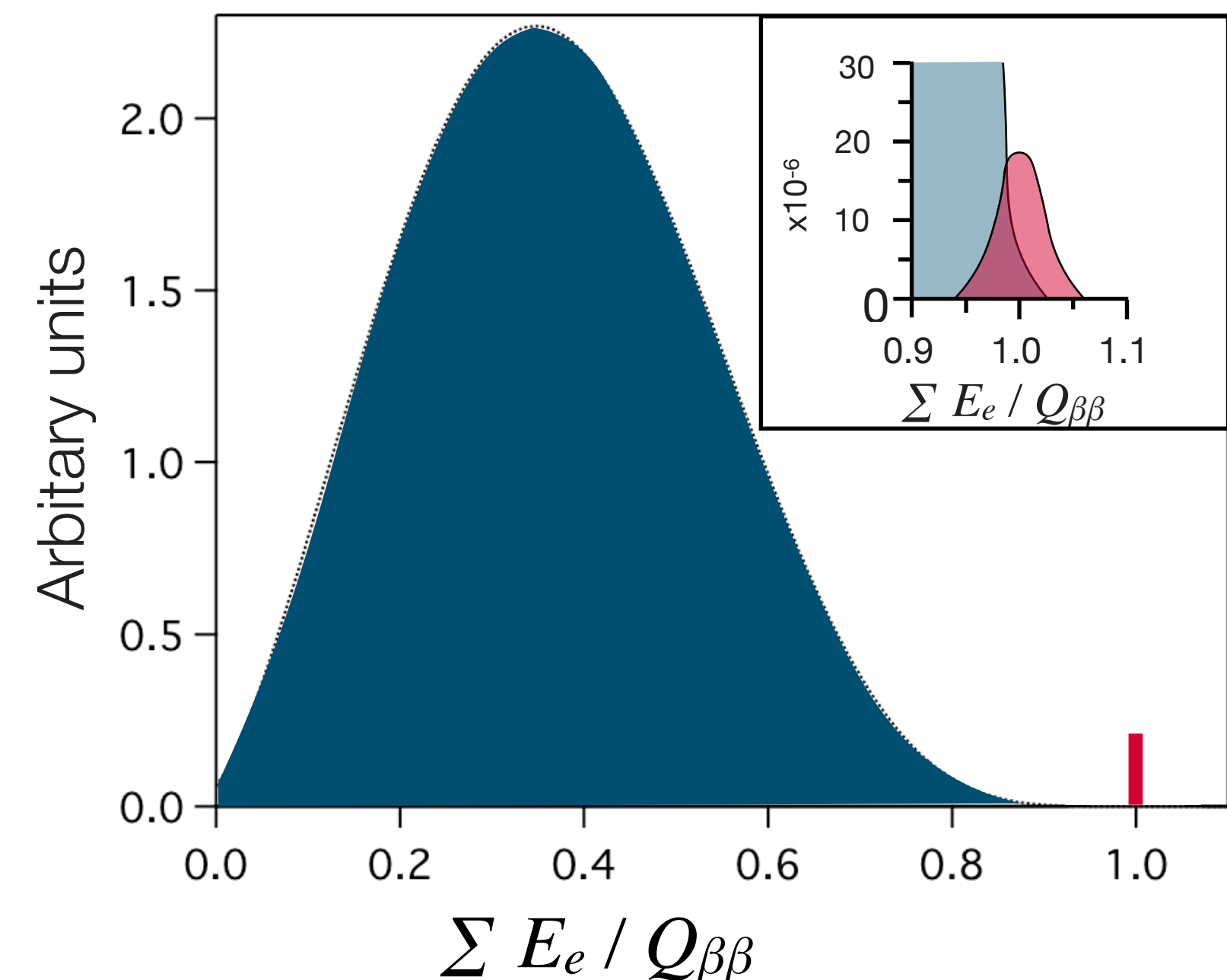
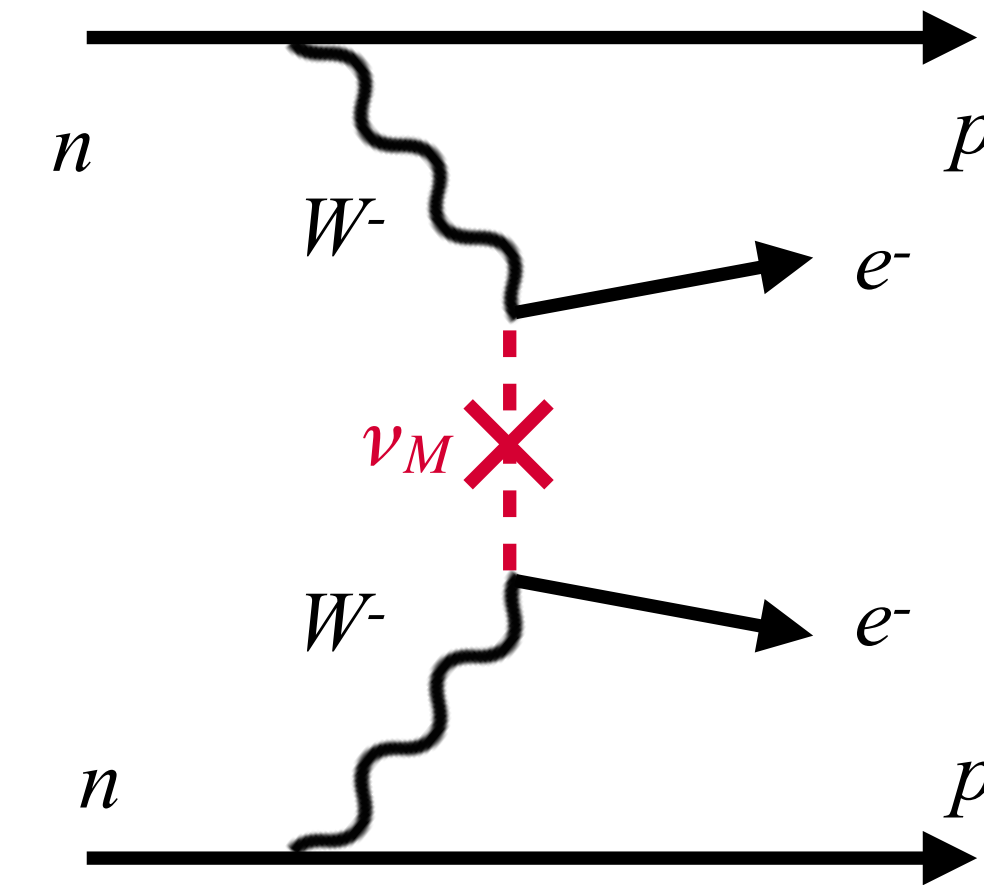
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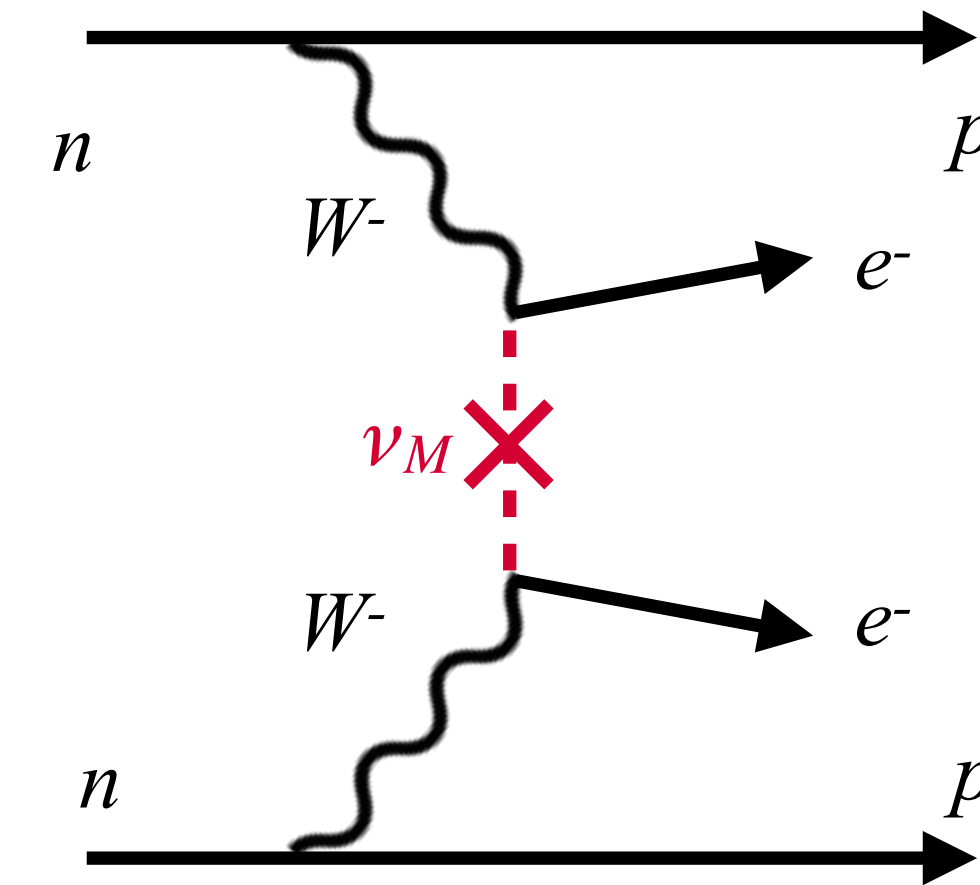
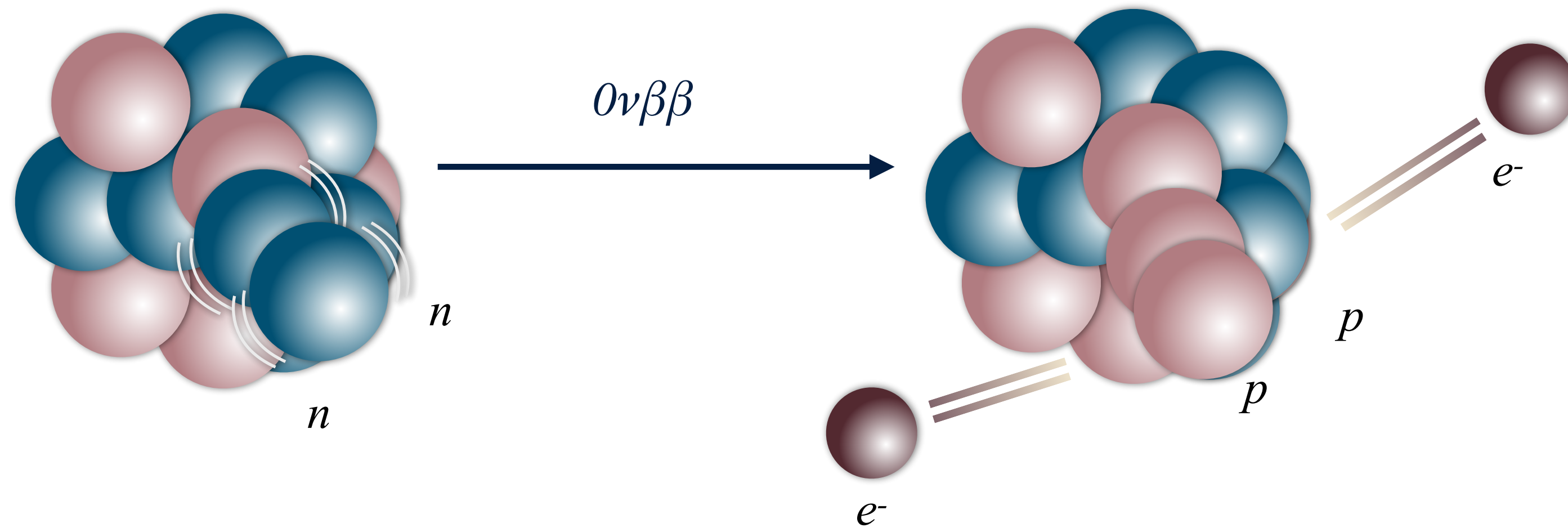
Neutrinoless double-beta decay ($0\nu\beta\beta$)



- No neutrinos in final state
- Virtual Majorana neutrino exchanged (various models available)
- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed - $T_{1/2} > 10^{24} - 10^{26}$ years



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If seen, $0\nu\beta\beta$ would:

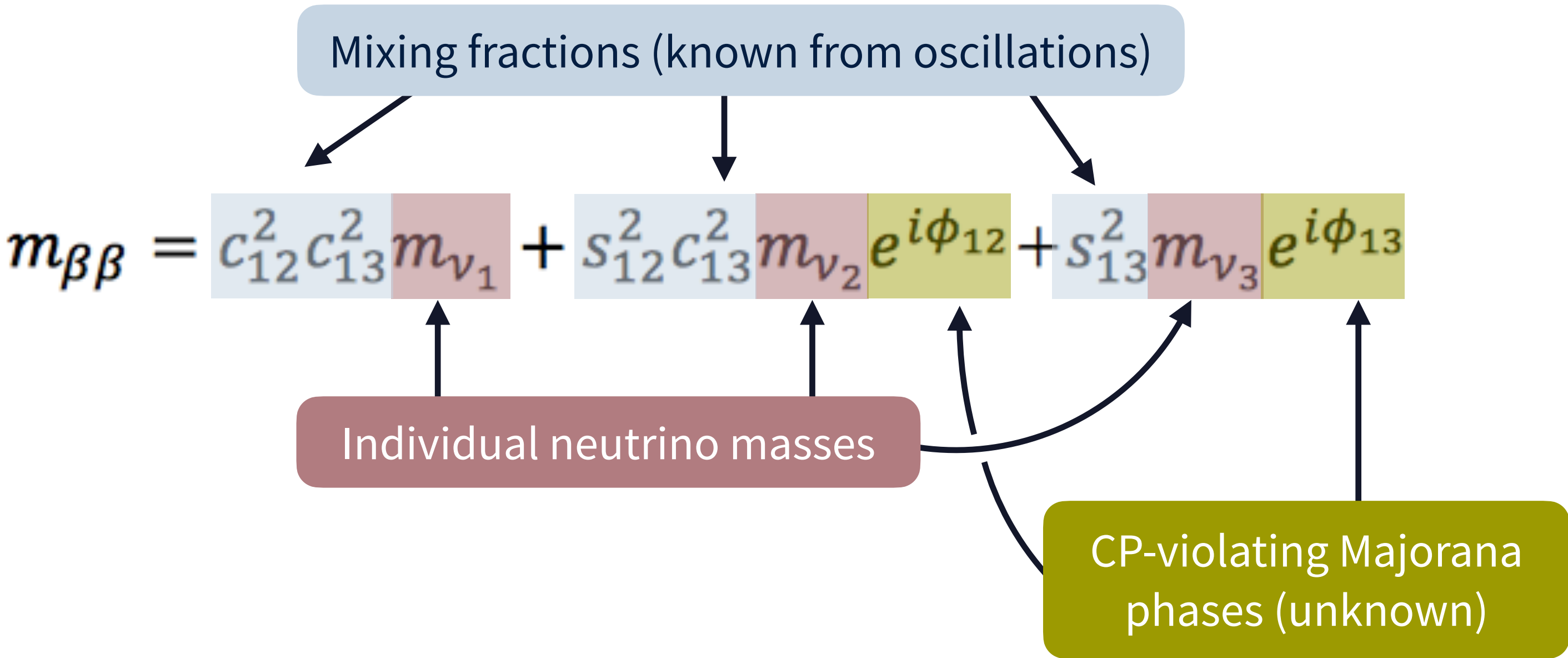
- be the first process observed to create matter without antimatter
- prove that neutrinos are Majorana fermions
- tell us about absolute neutrino mass

$0\nu\beta\beta$ and neutrino mass

$0\nu\beta\beta$ rate $\frac{1}{T_{1/2}^{0\nu\beta\beta}} = \underbrace{G_{0\nu}(Q_{\beta\beta}, Z)g_A^4|M_{0\nu}|^2}_{\text{Isotope-dependent}} \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$

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Mixing fractions (known from oscillations)

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

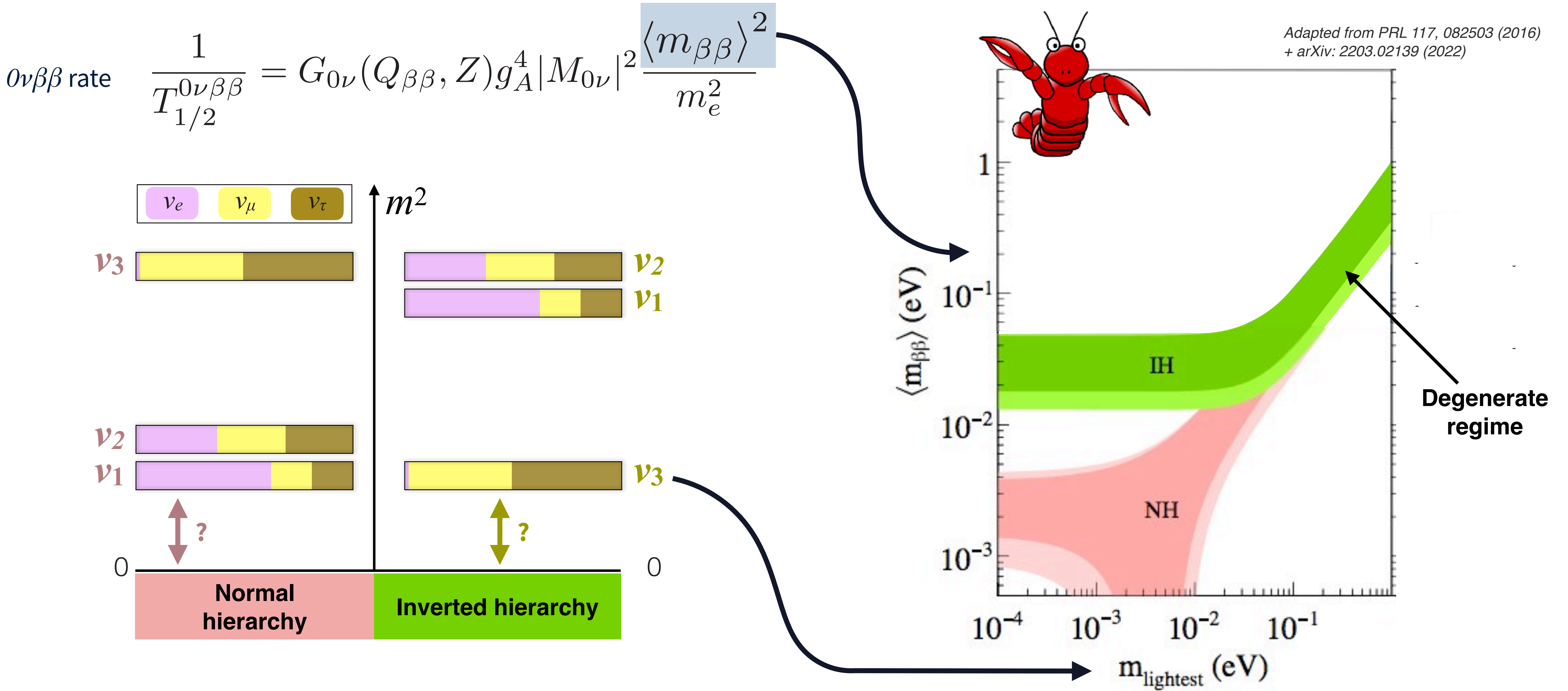
Individual neutrino masses

CP-violating Majorana phases (unknown)

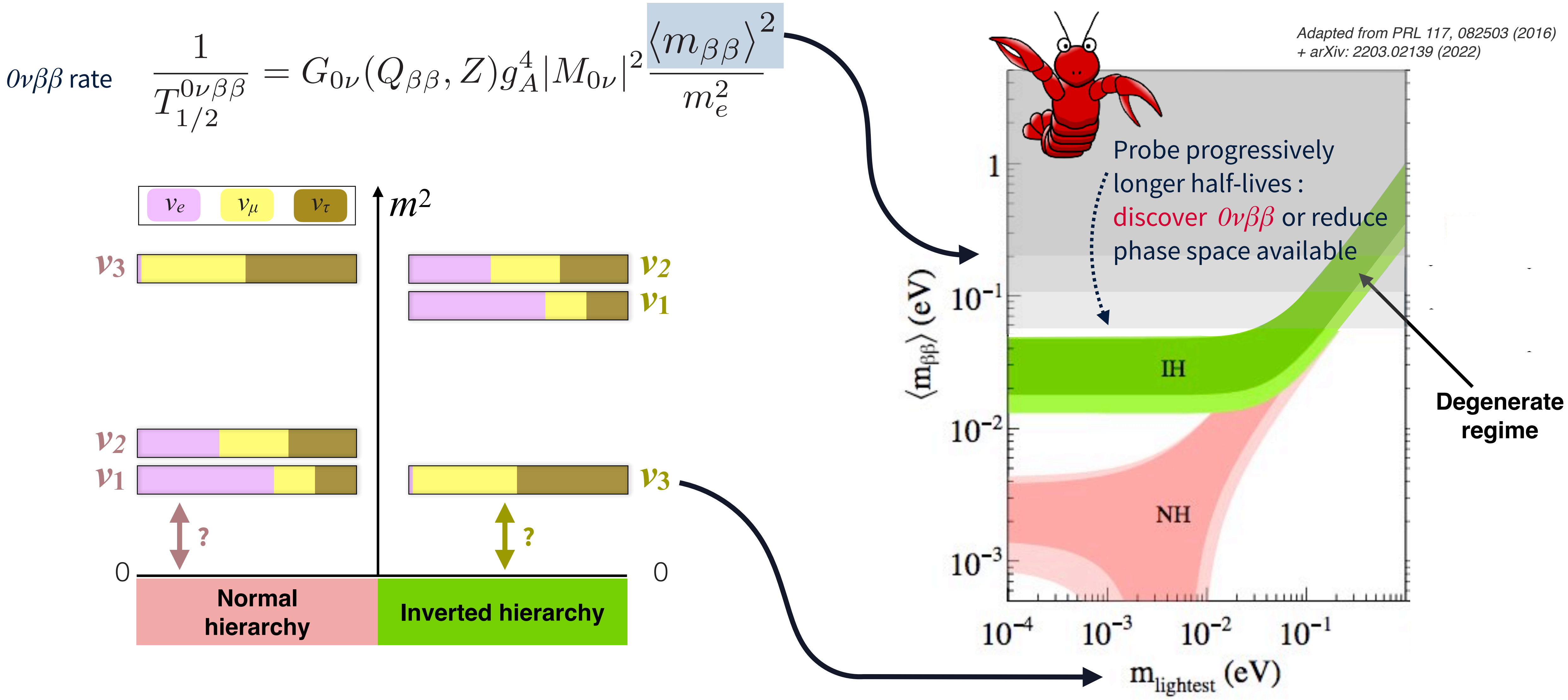
Complementary to:

- Oscillations
- Cosmology
- β decay endpoints

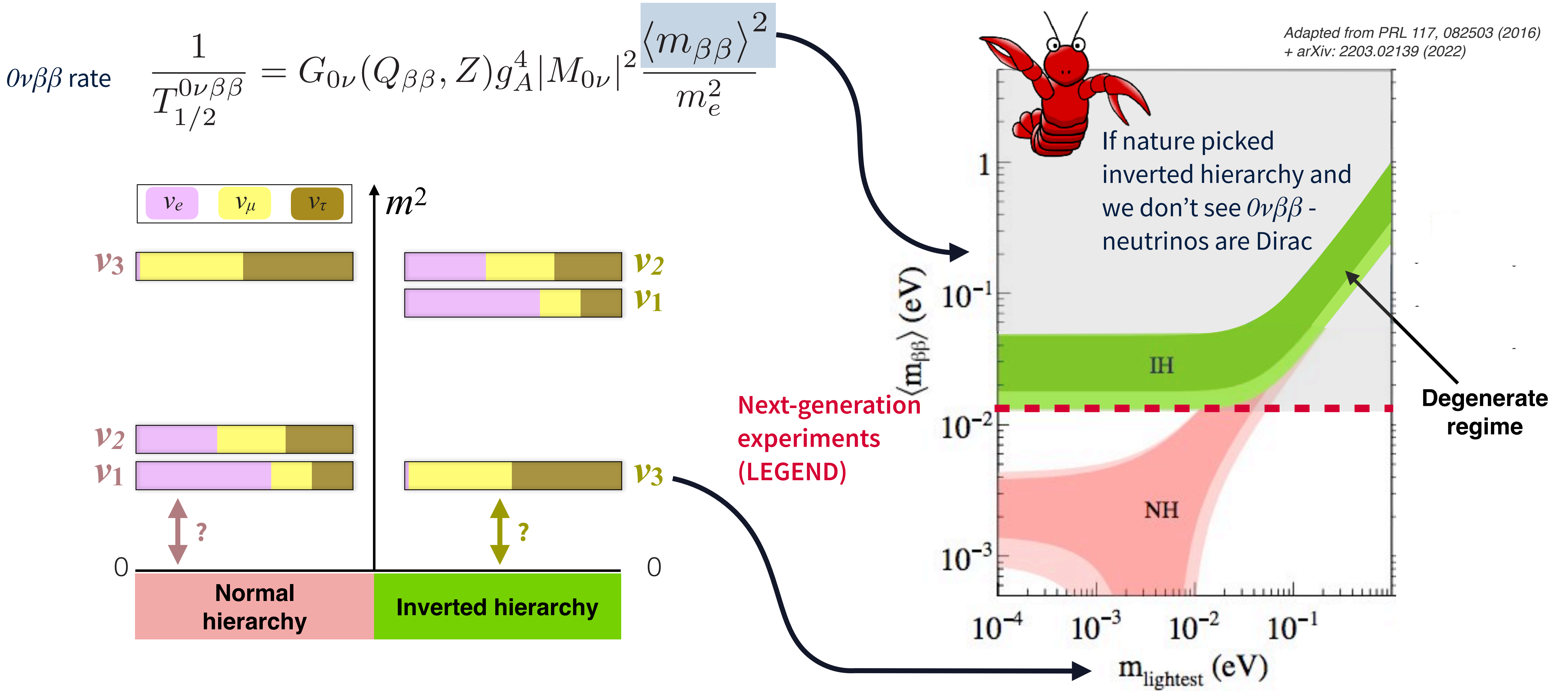
$0\nu\beta\beta$ and neutrino mass



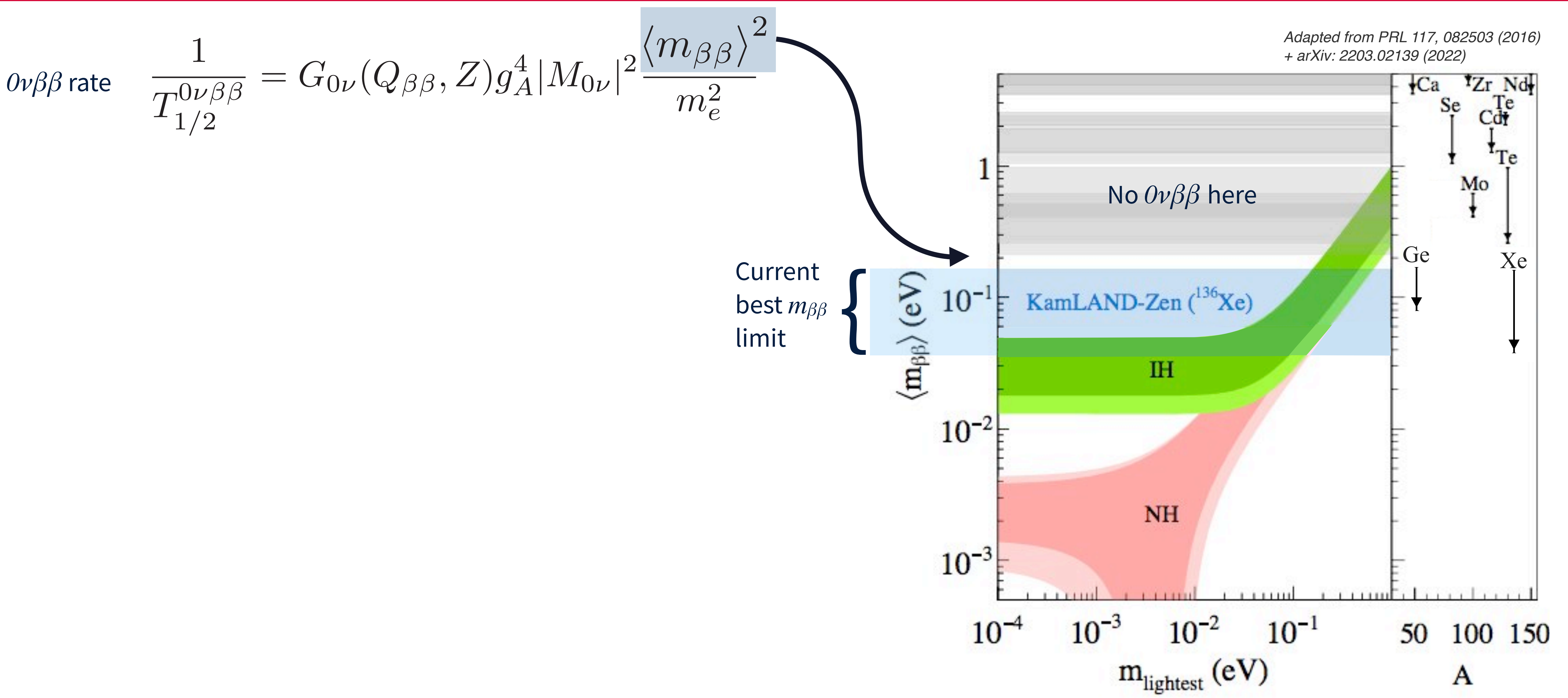
$0\nu\beta\beta$ and neutrino mass



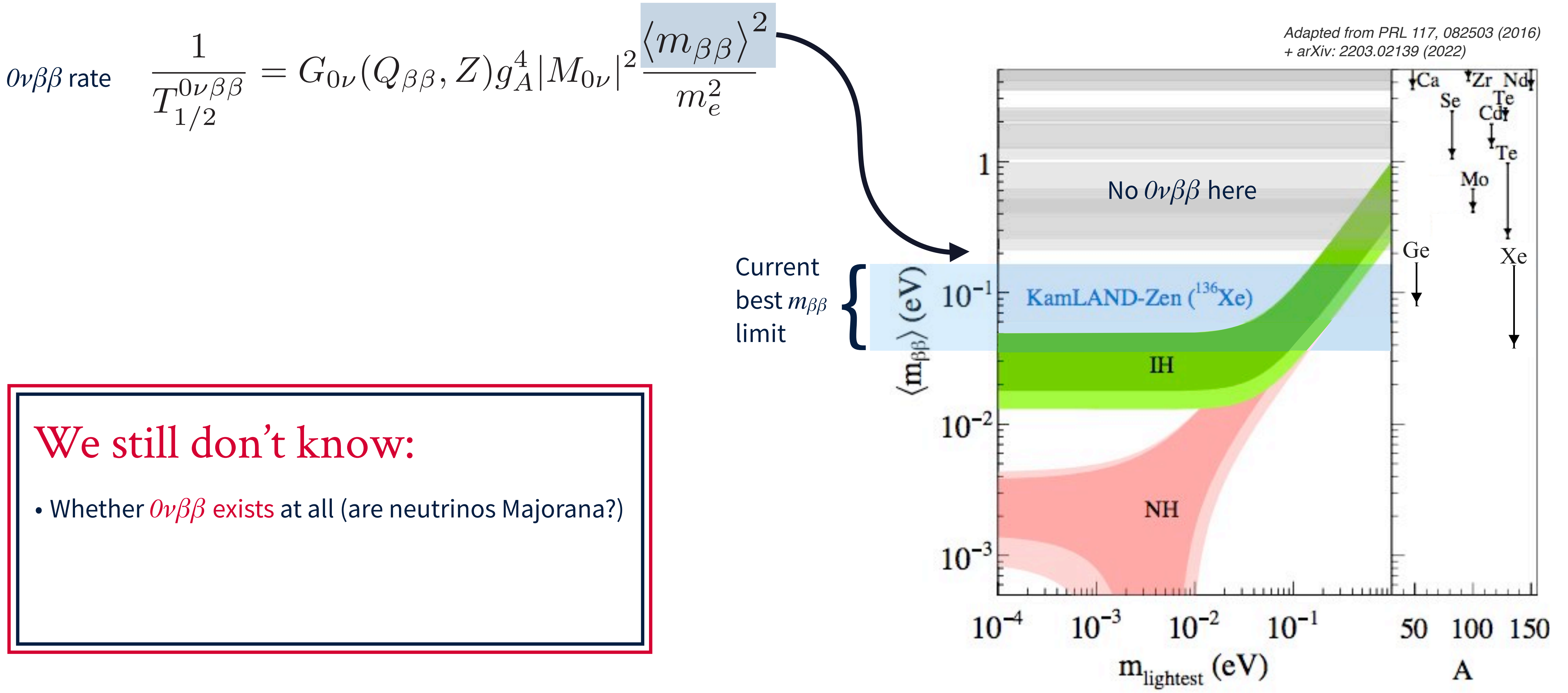
$0\nu\beta\beta$ and neutrino mass



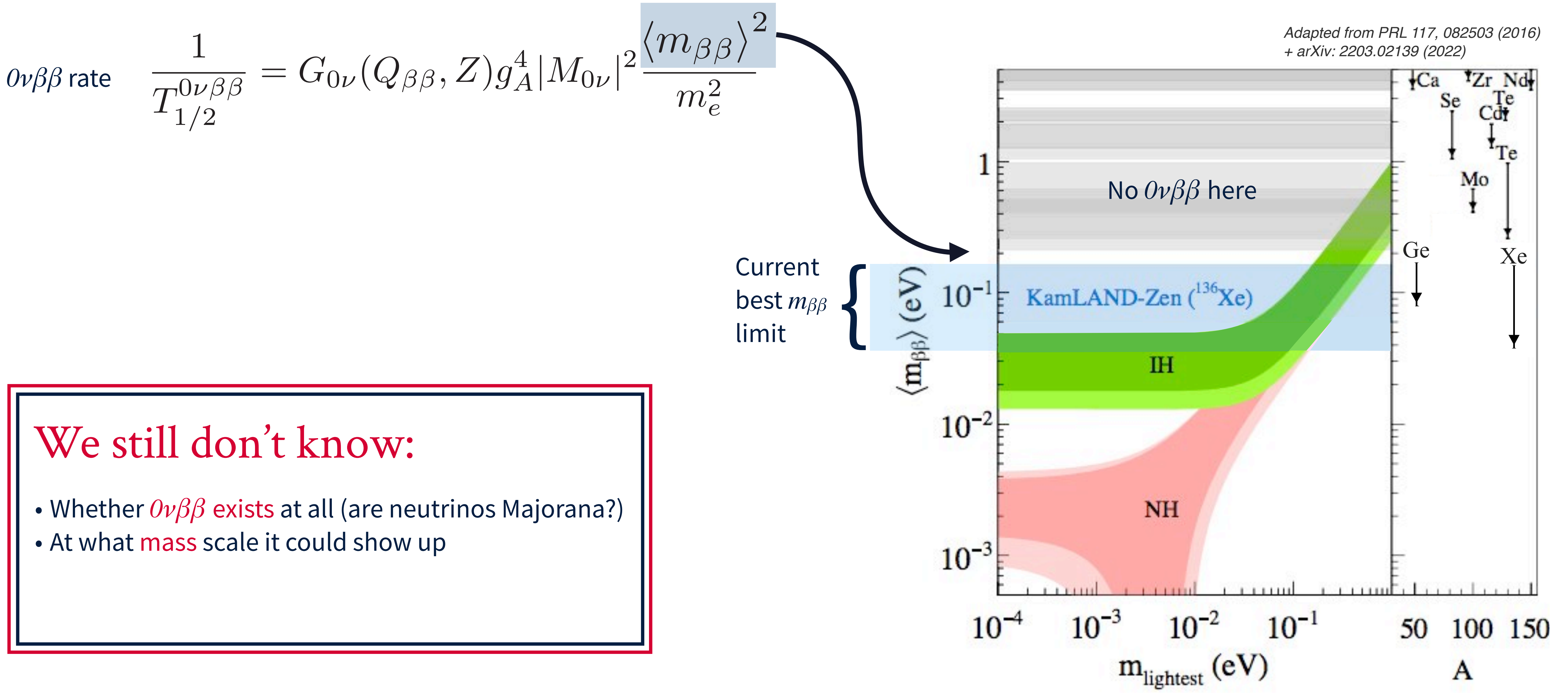
What do we know?



What do we know? And what don't we know?



What do we know? And what don't we know?

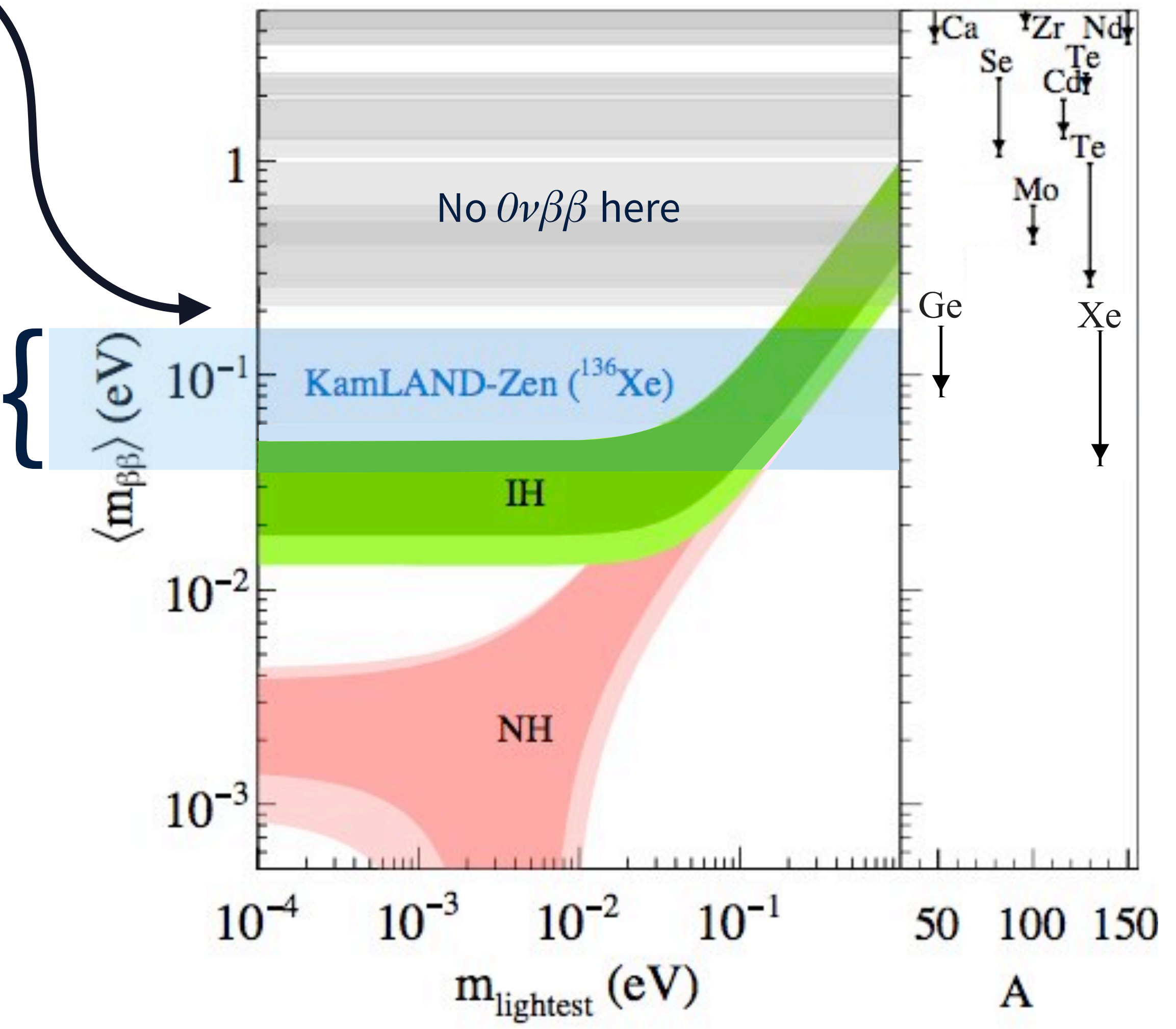


What do we know? And what don't we know?

$0\nu\beta\beta$ rate $\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)g_A^4|M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$

Adapted from PRL 117, 082503 (2016)
+ arXiv: 2203.02139 (2022)

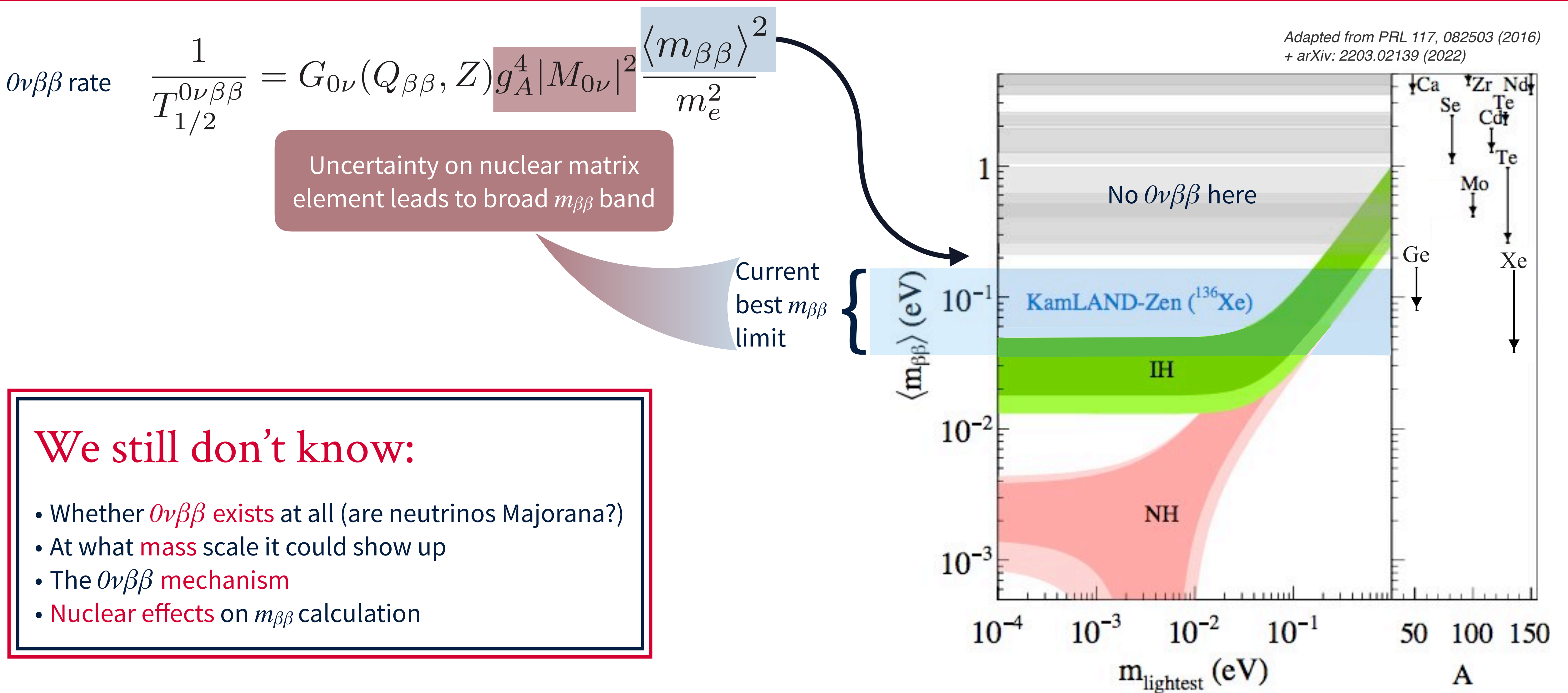
Current
best $m_{\beta\beta}$
limit



We still don't know:

- Whether $0\nu\beta\beta$ exists at all (are neutrinos Majorana?)
- At what mass scale it could show up
- The $0\nu\beta\beta$ mechanism

What do we know? And what don't we know?



The UK's strategic approach

Core UK strategy



We still don't know:

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- Nuclear effects on $m_{\beta\beta}$ calculation

The UK's strategic approach

Core UK strategy



LEGEND

**LEGEND: a
discovery machine**
to explore the full
inverted hierarchy
regime

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LEGEND: a discovery machine to explore the full inverted hierarchy regime

SNO+

SNO+: a scalable technology that could take us to even lower mass limits

supernemo
collaboration

SuperNEMO: a technique to probe $0\nu\beta\beta$ mechanism and nuclear effects

We still don't know:

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LEGEND at LNGS, Italy (so far...)



^{76}Ge

LEGEND

A discovery machine that will search the entire inverted hierarchy region

Thanks to Matteo Agostini for content

How does LEGEND work?

Semiconductor HPGe Detectors:

- solid state TPC
- mm-scale event topology



How does LEGEND work?

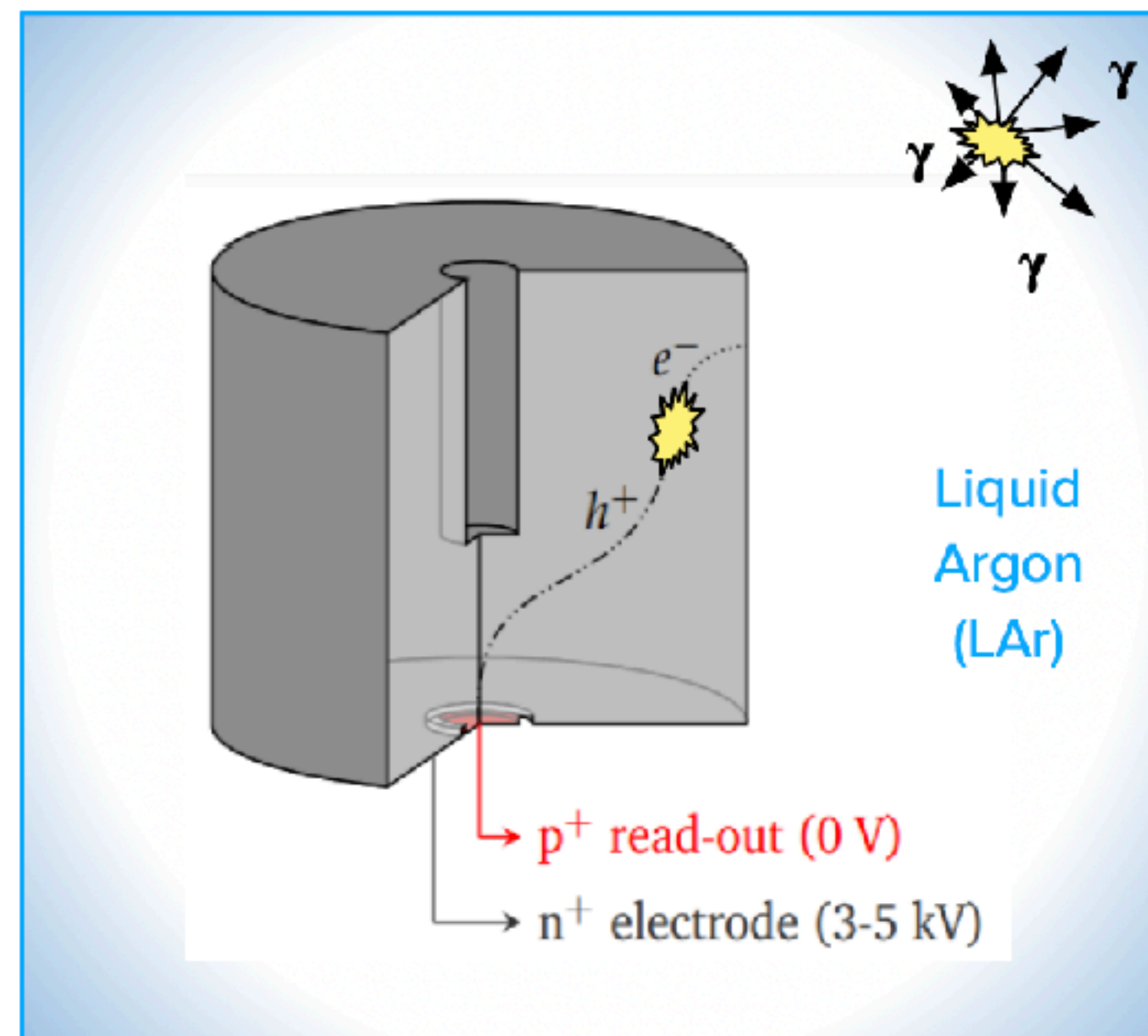
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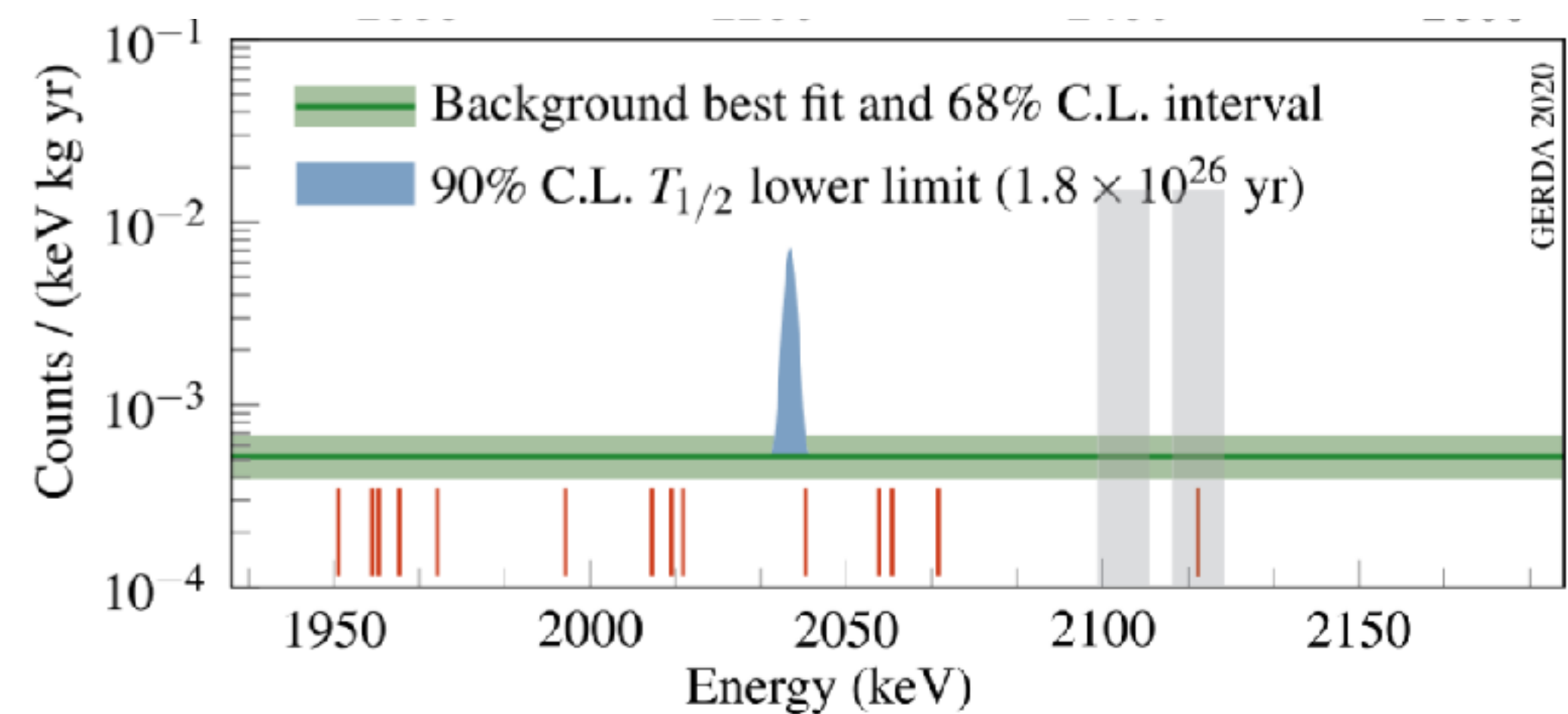
Liquid-argon Scintillation Detector:

- ultra-clean, cryogenic liquid
- isotropic emission of XUV photons
- calorimetric energy measurement

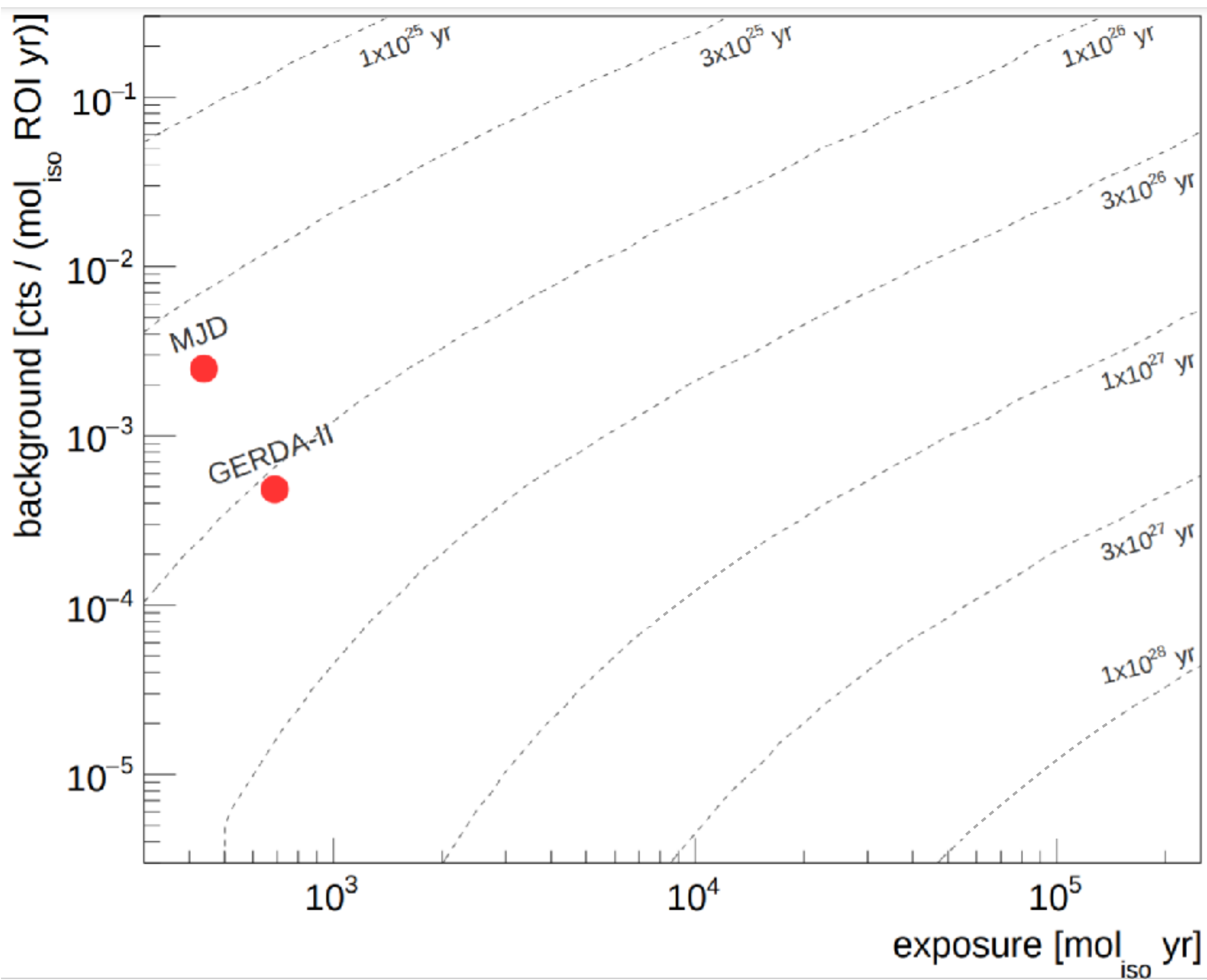


GERDA/MAJORANA (40/30 kg)

- **Lowest background** level in the field
- Best **energy resolution** in the field
- Best **discovery power** so far



Phys.Rev.Lett. 125 (2020) 25, 252502



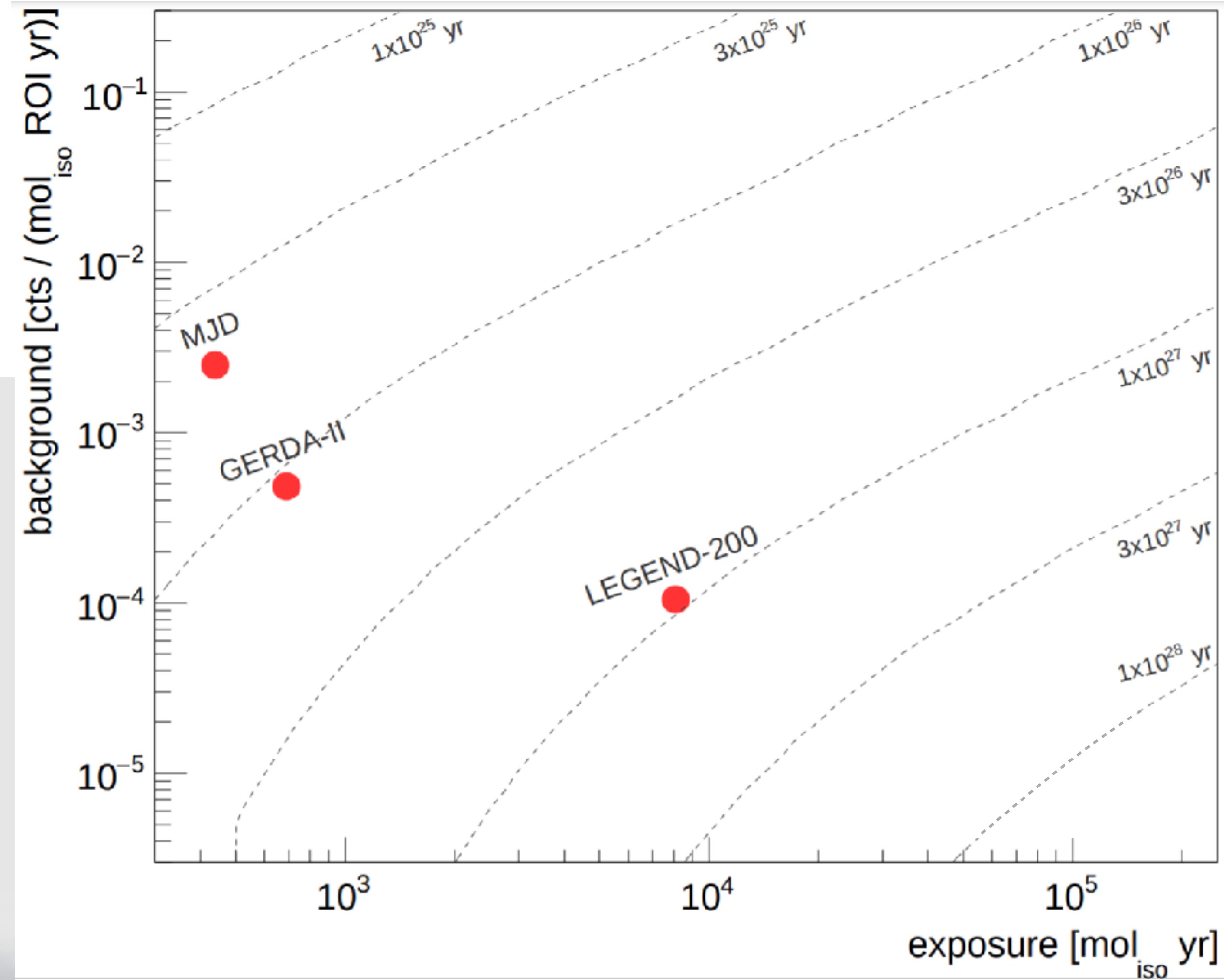
^{76}Ge - innovation and breakthroughs: past, present

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LEGEND-200 (200 kg)

- Approaching physics data taking
- Leading experiment for the next 5 years



^{76}Ge - innovation and breakthroughs: past, present, and future

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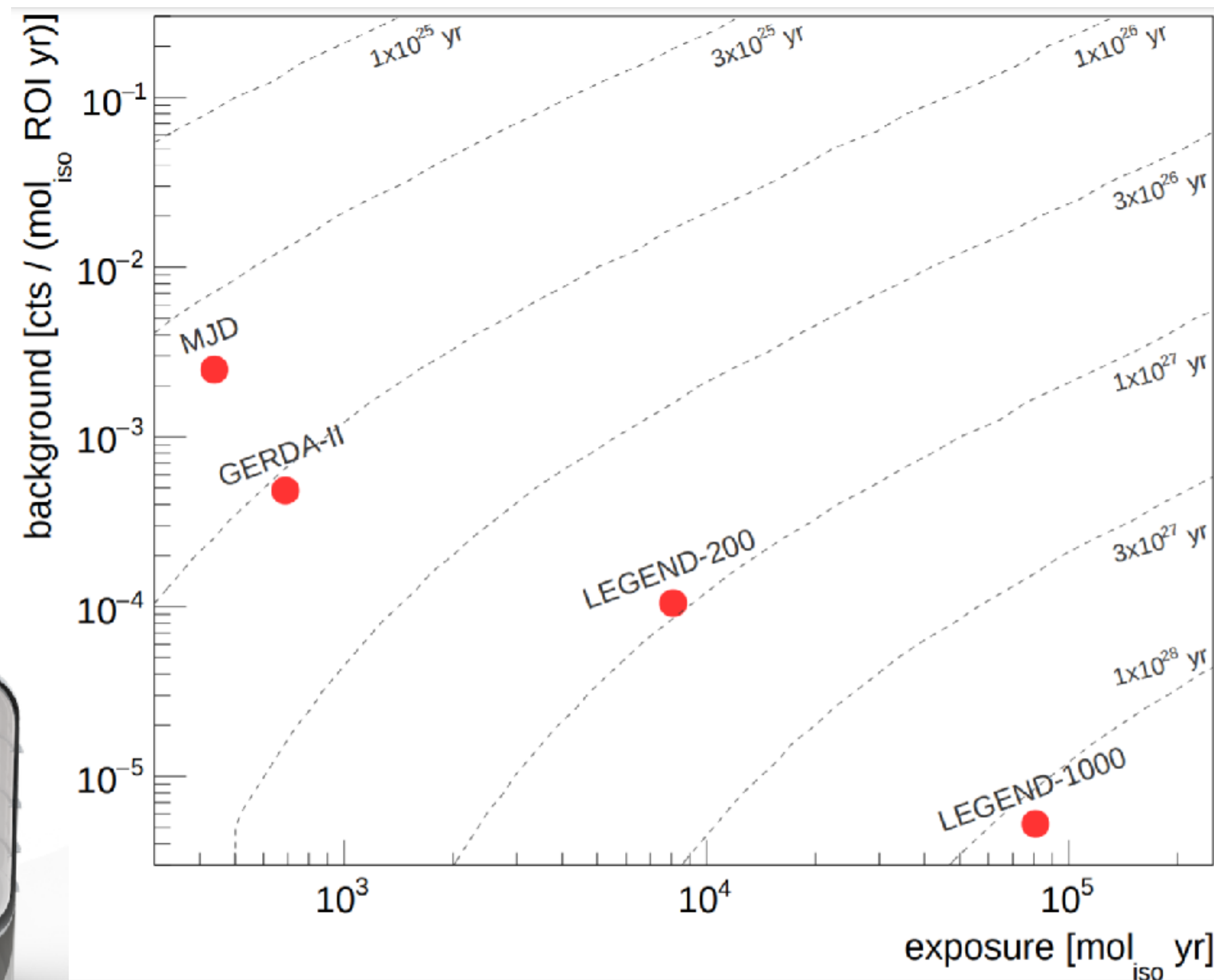
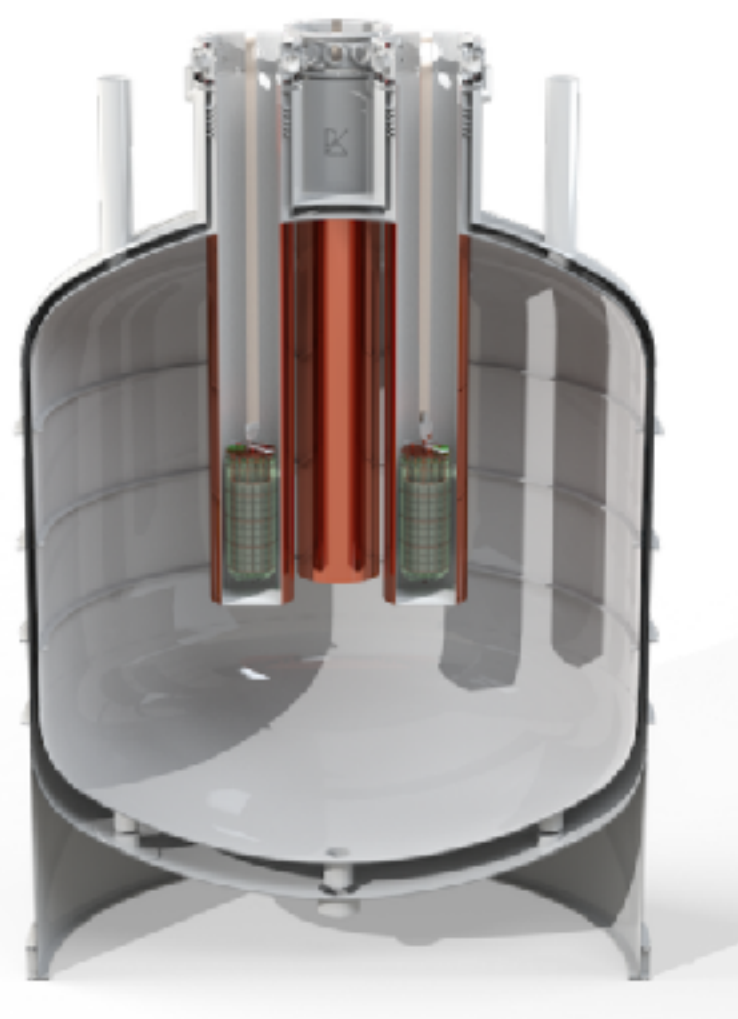
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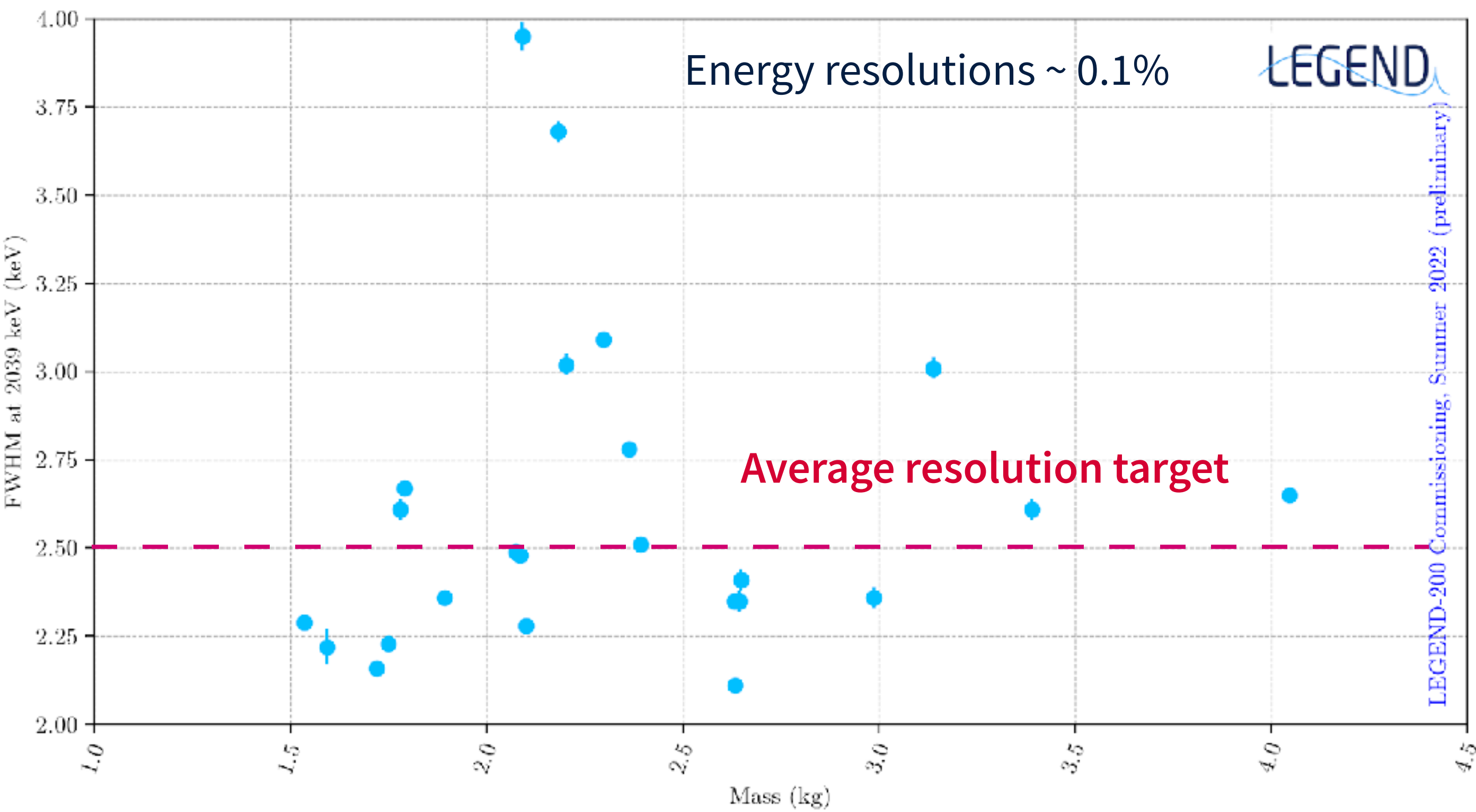
LEGEND-1000 (1 ton)

- Inverted-hierarchy explorer: $m_{\beta\beta}=18$ meV
- Only experiment in both the EU APPEC roadmap and DOE long term plan



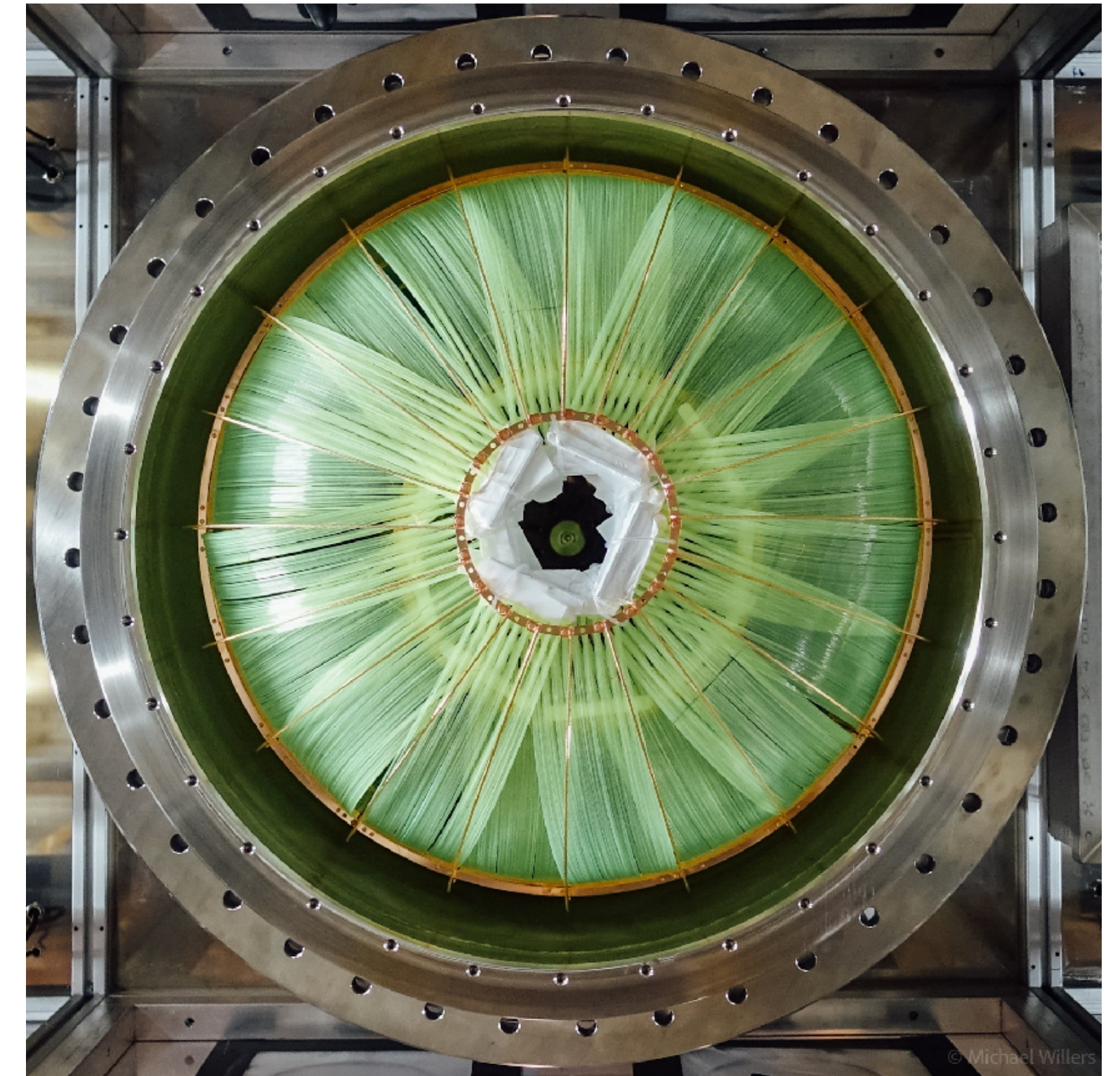
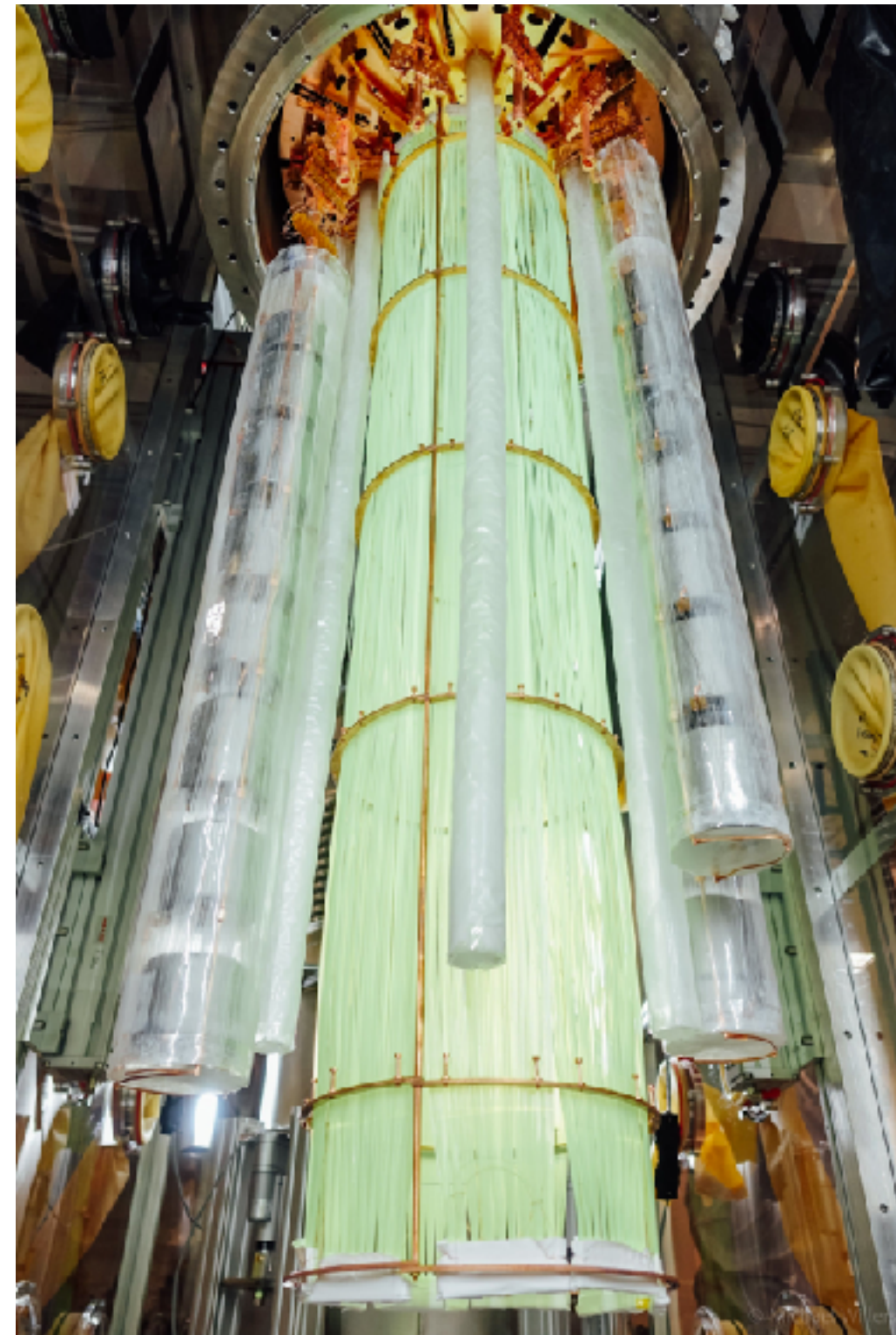
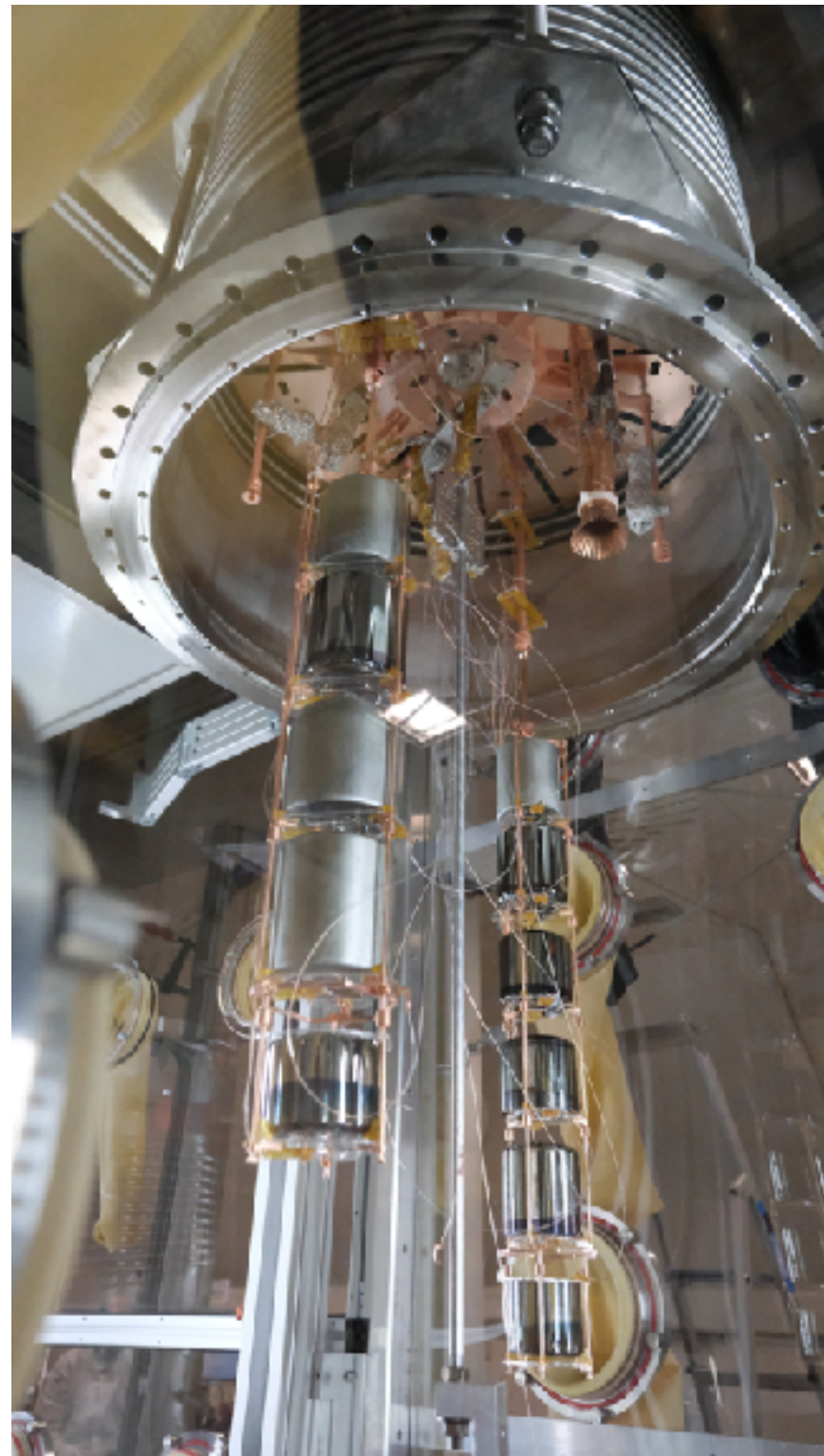
Summer 2022 LEGEND-200 integration runs:

- 24 detectors (60kg) used for background studies



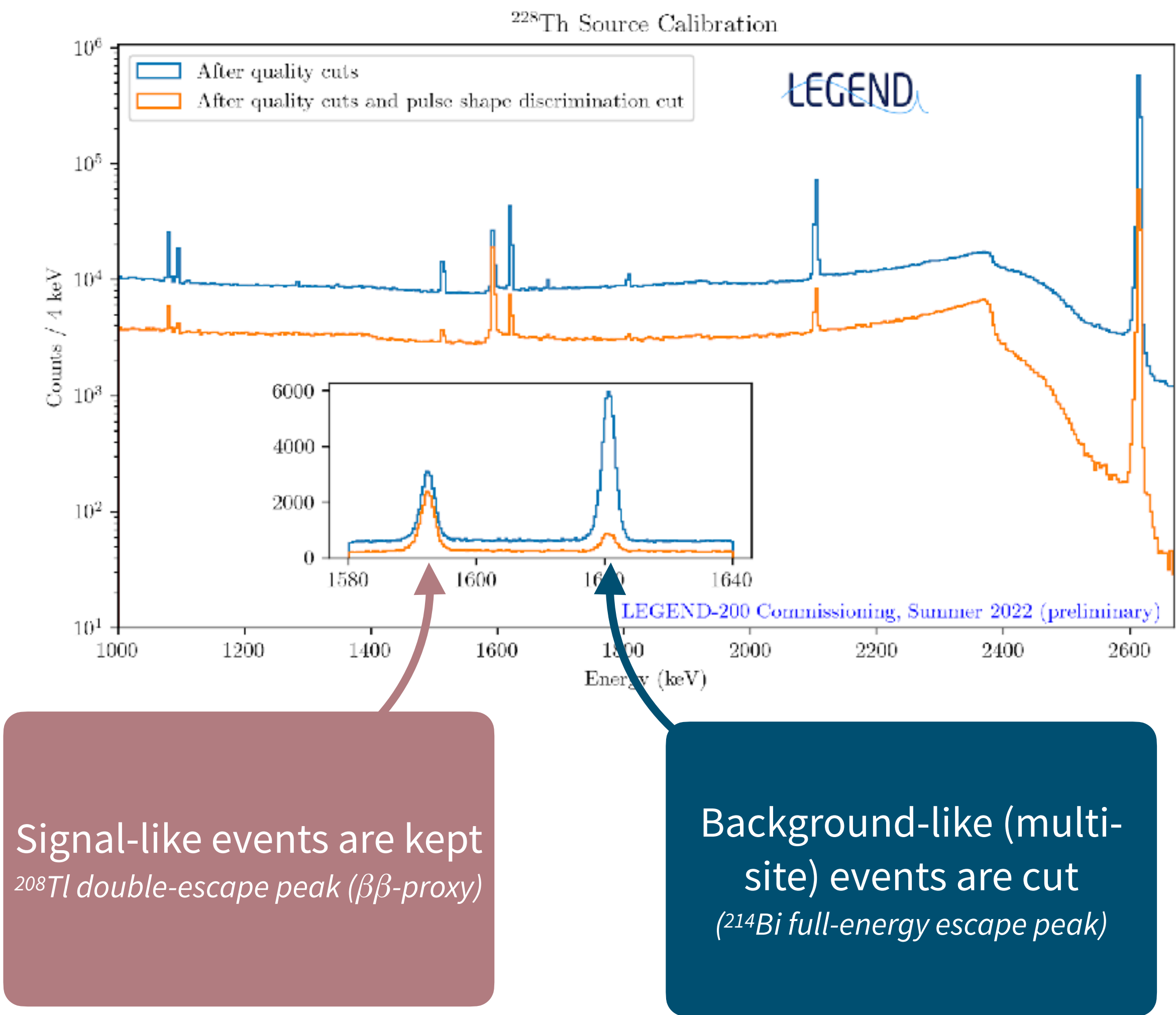
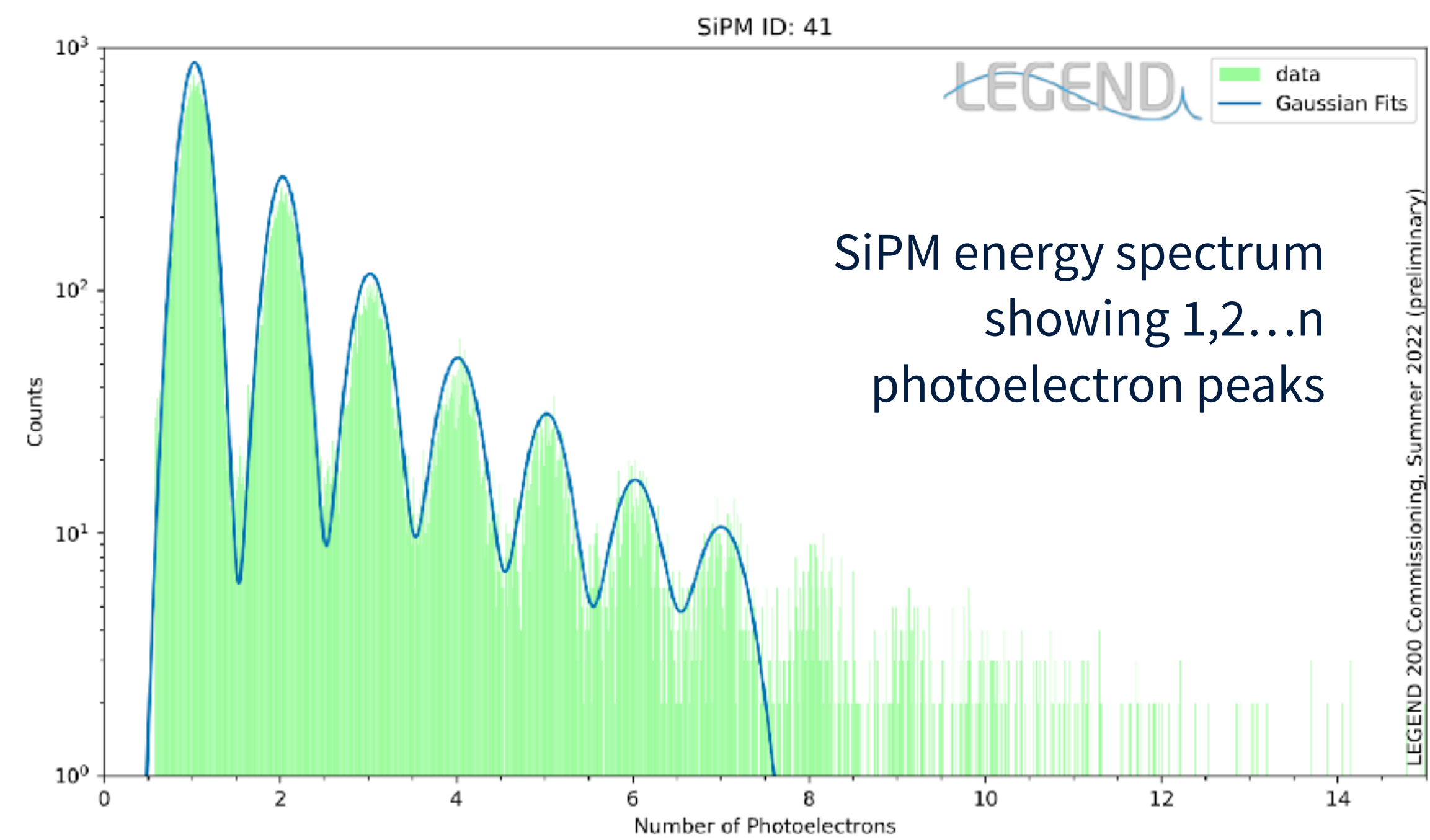
Summer 2022 LEGEND-200 integration runs:

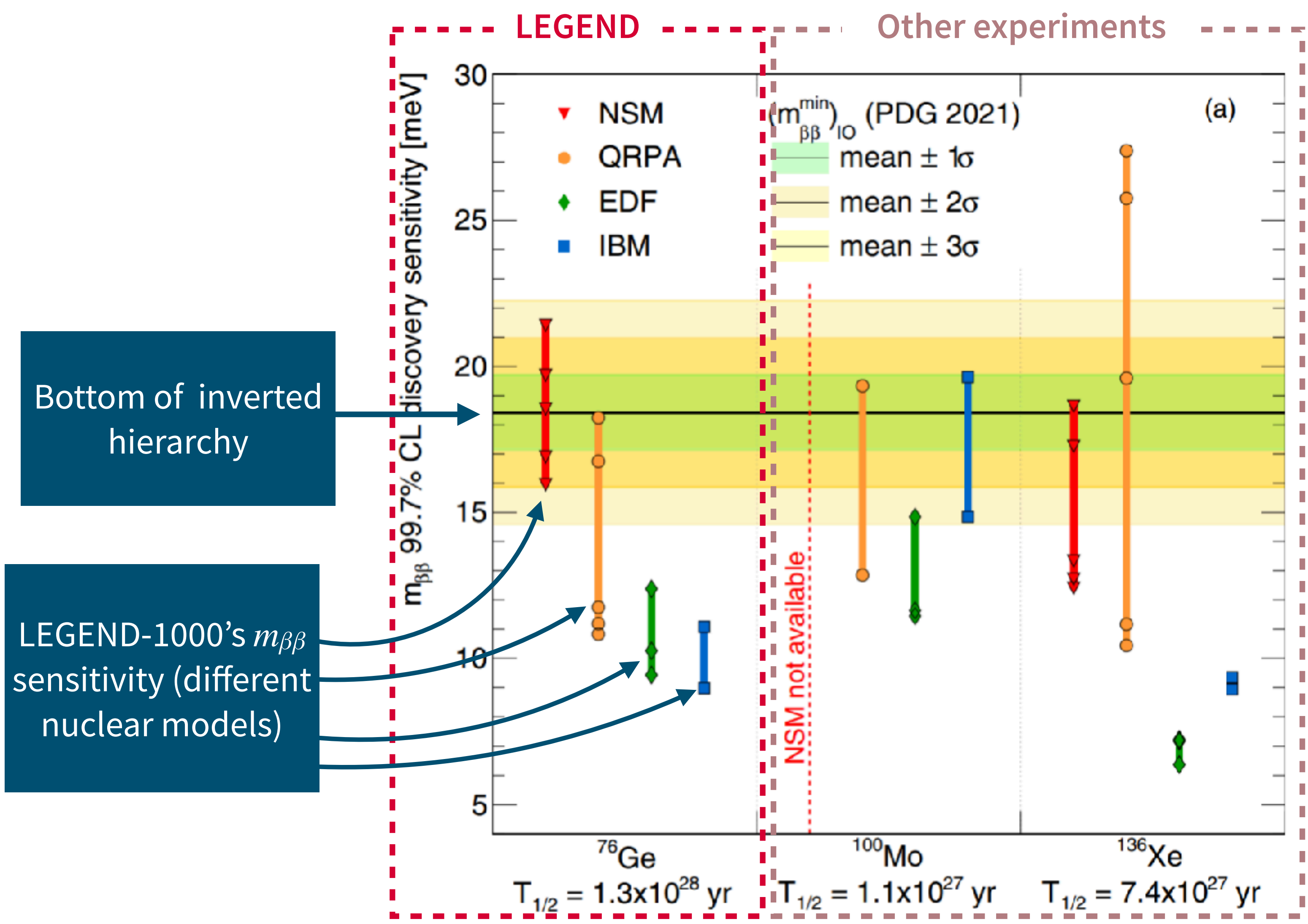
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Summer 2022 LEGEND-200 integration runs:

- 24 detectors (60kg) used for background studies
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- Analysis pipeline







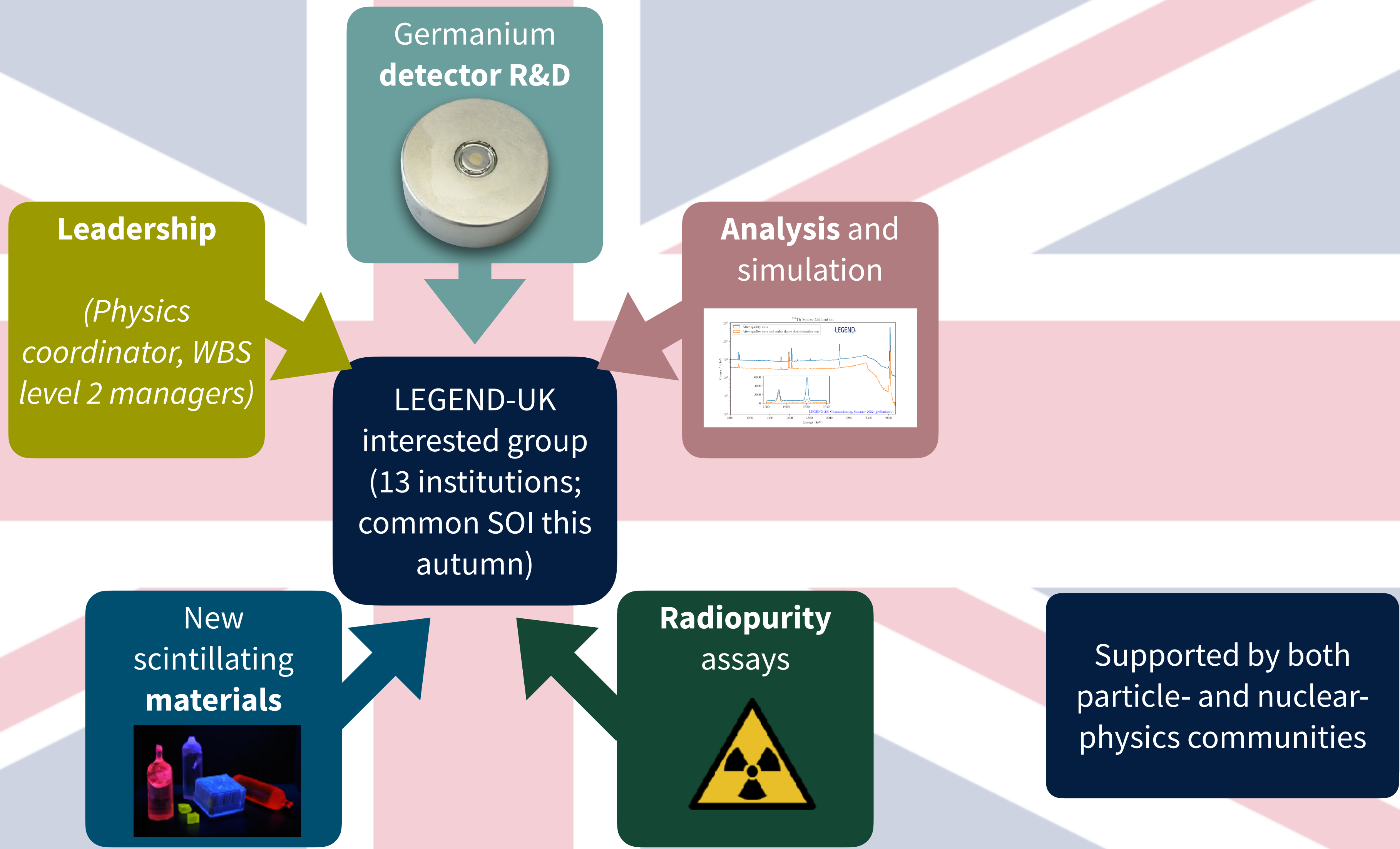
LEGEND-200 (under construction,
first data this year)



LEGEND-1000 (construction 2023-2030, first
data in 2028, 10 years of operations)

LEGEND won DOE portfolio review

- DOE fully committed to LEGEND and will prioritise it over any other $0\nu\beta\beta$ experiments
- CD1 and CD3 review next year



SNO+ at Sudbury, Canada

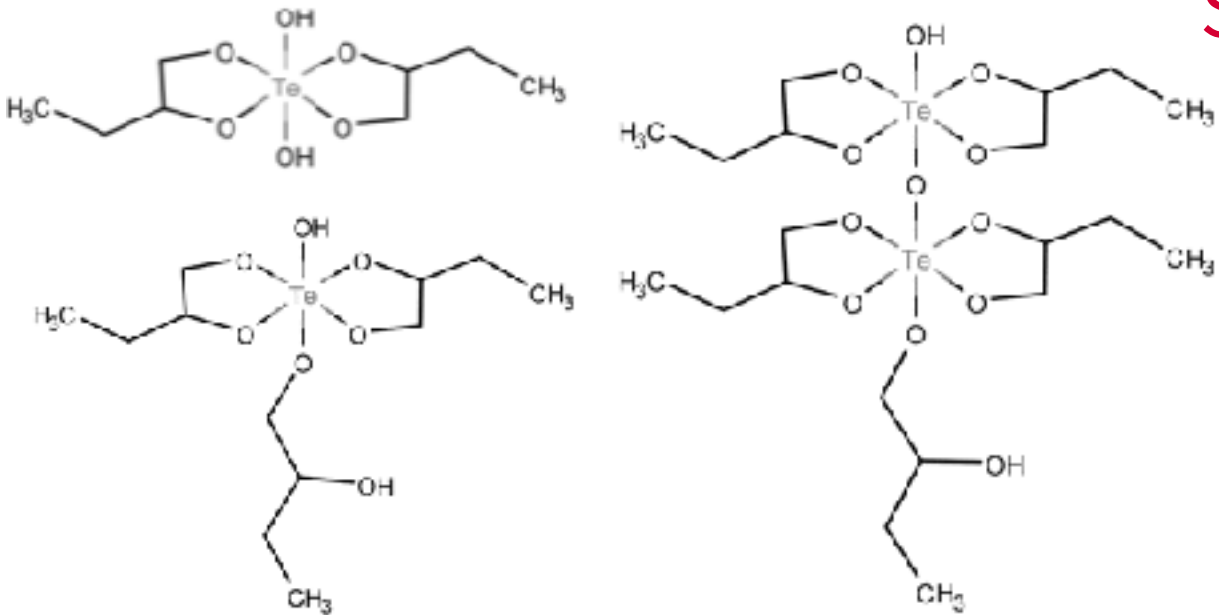
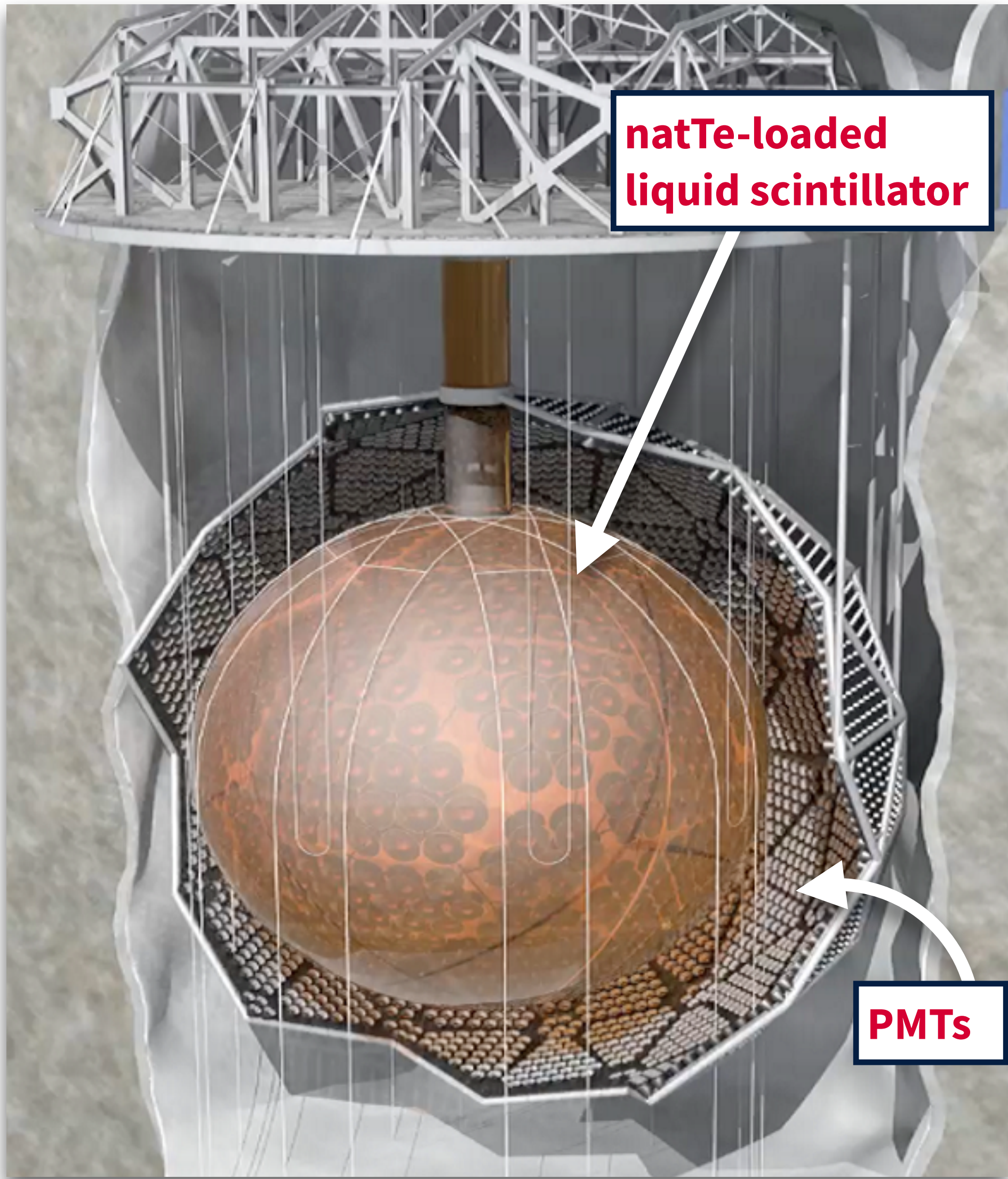


Thanks to Steve Biller for content

A highly scalable, cost-effective and sensitive approach to $0\nu\beta\beta$ (concept developed in the UK)

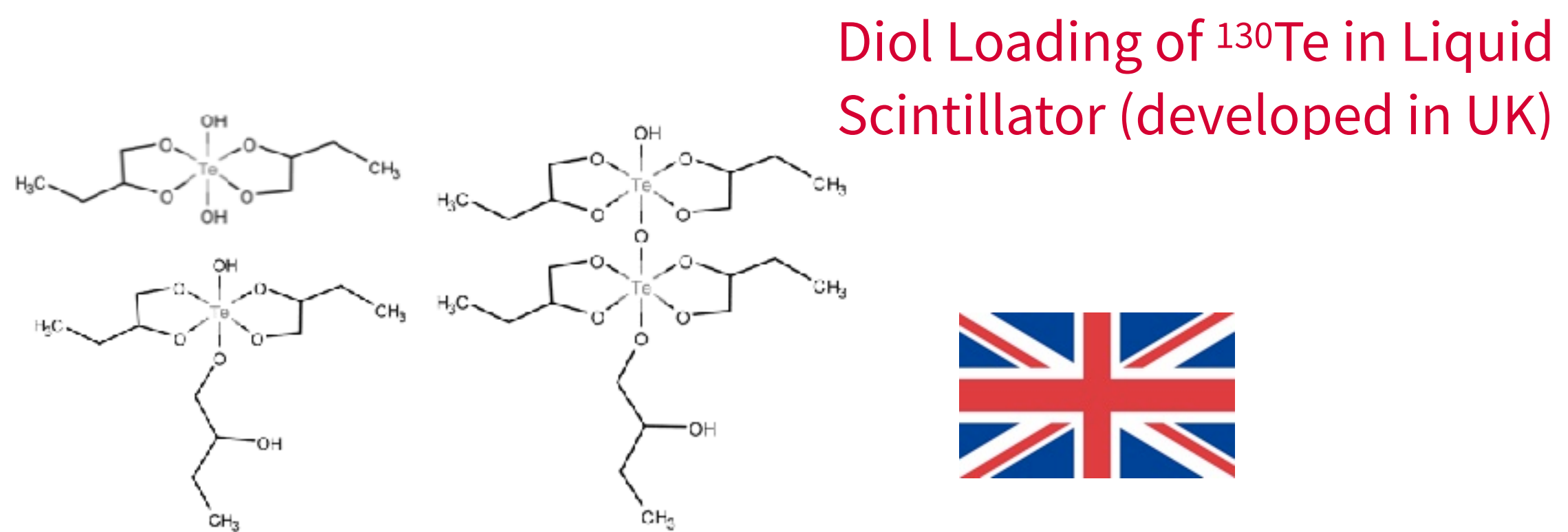
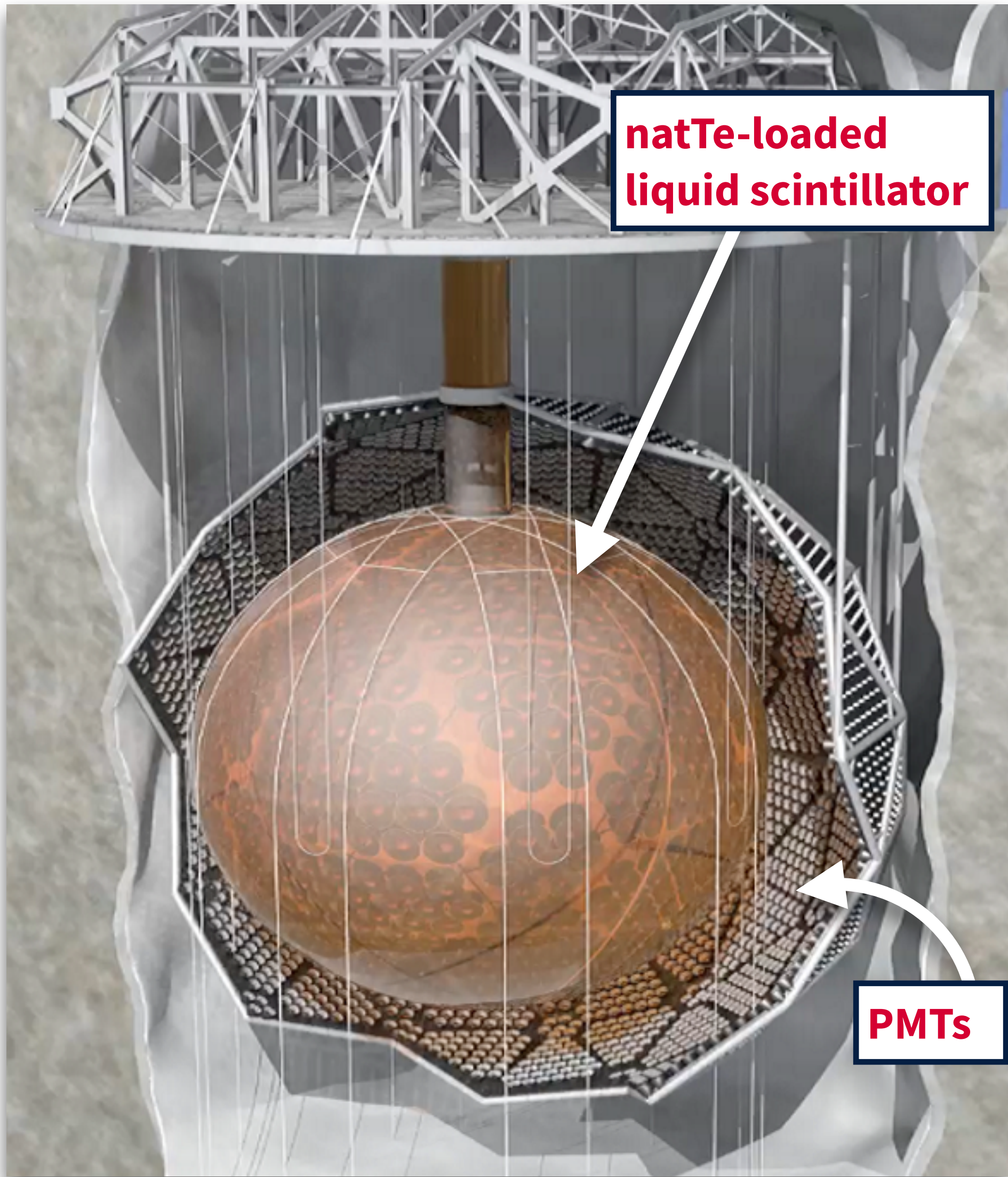


How SNO+ works



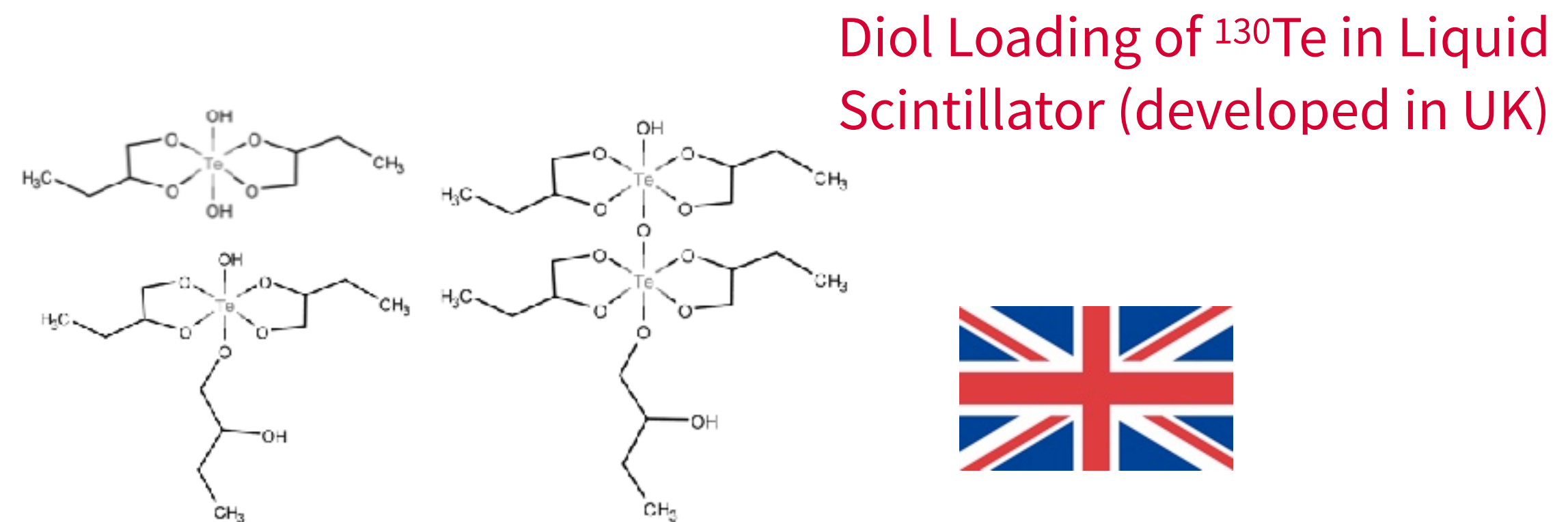
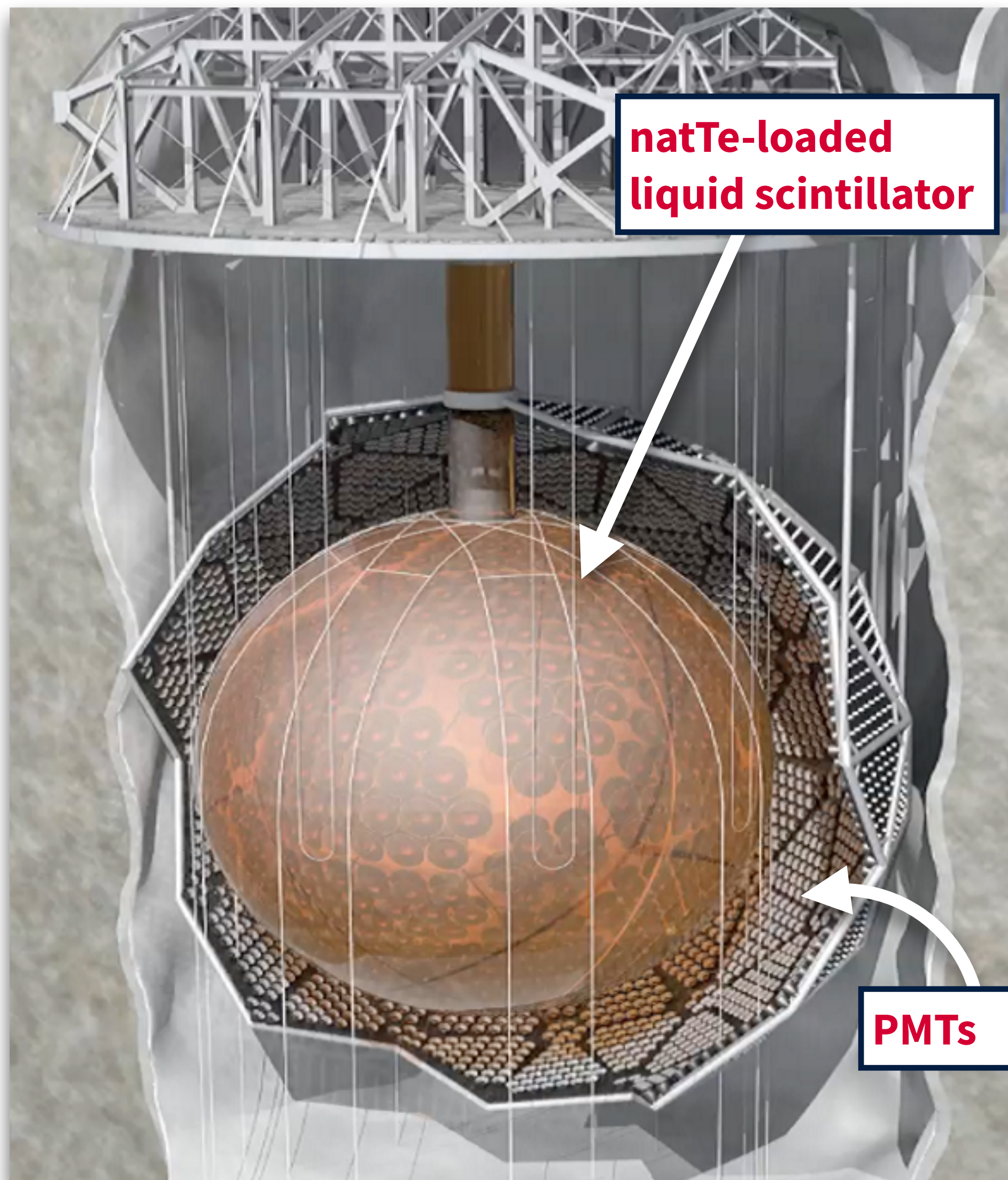
Diol Loading of ^{130}Te in Liquid Scintillator (developed in UK)





Cost-effective

- $\beta\beta$ isotope has high (34%) natural abundance
- Liquid scintillator is also economical

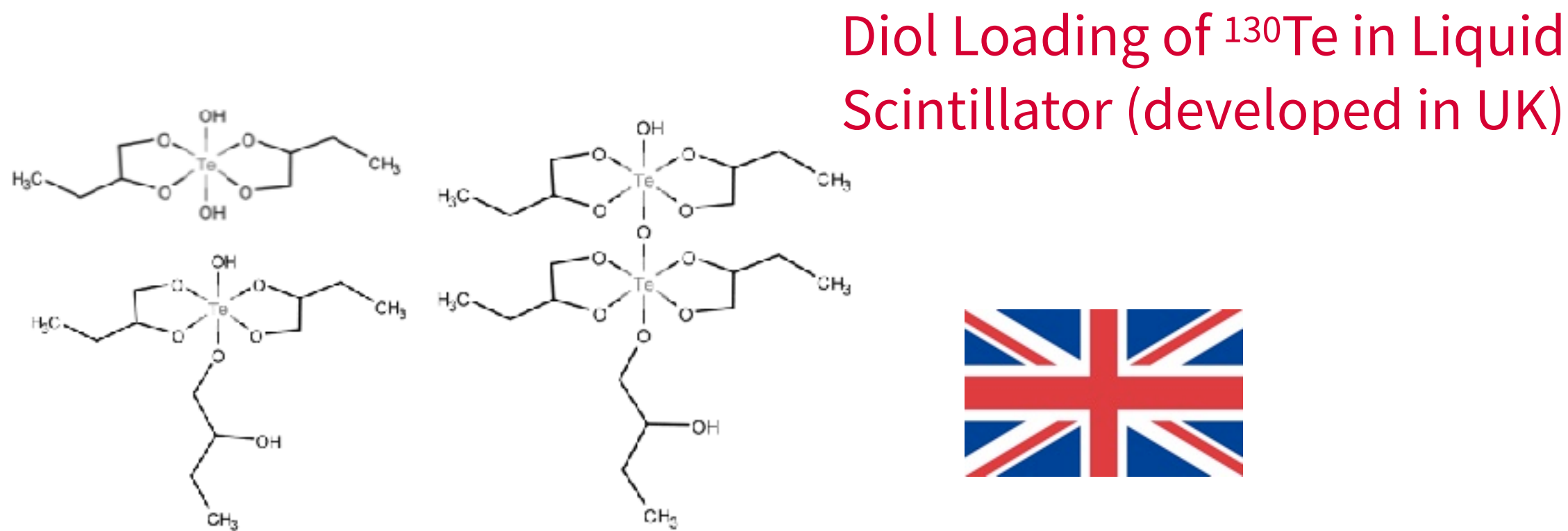
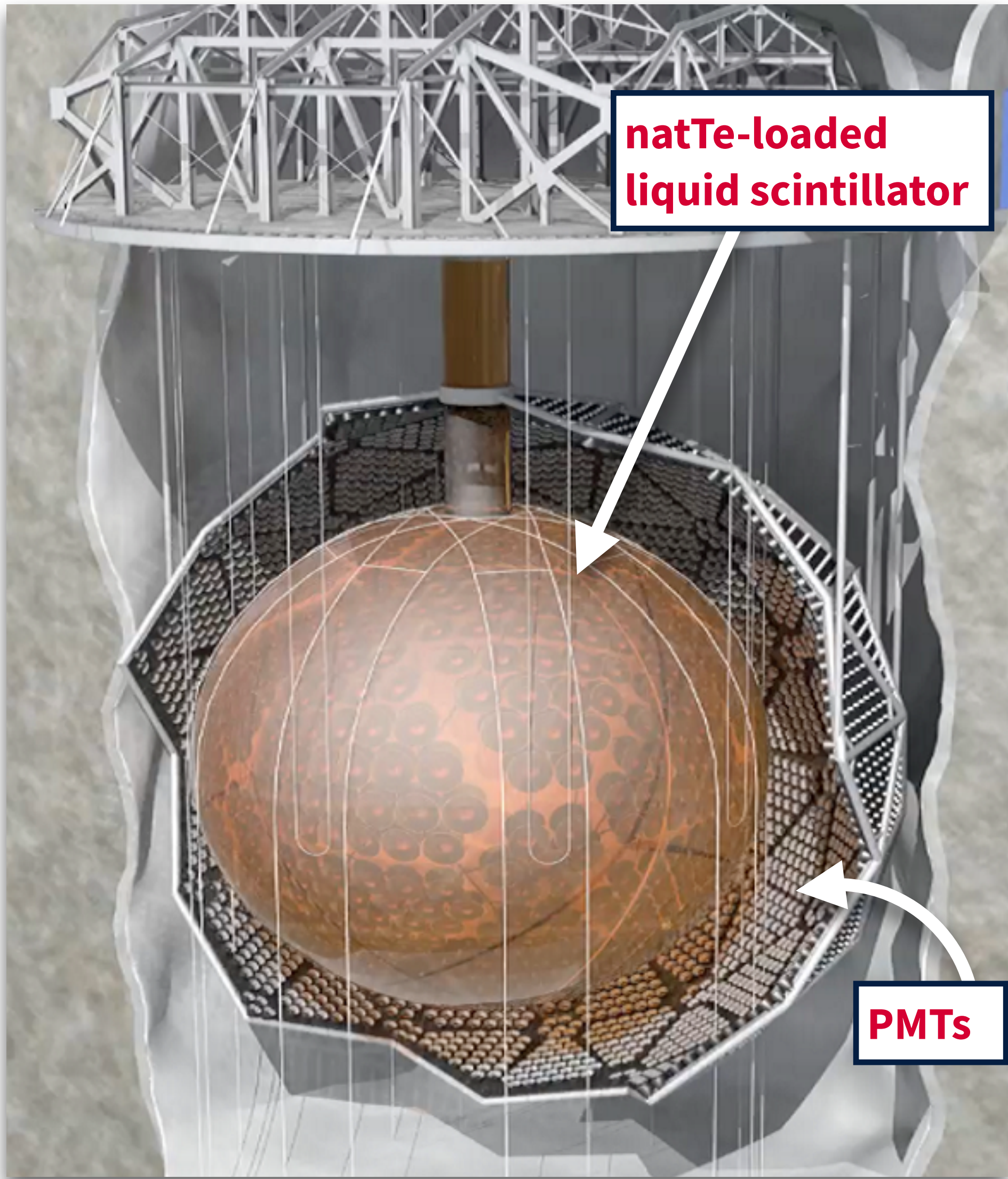


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Scalable

- Detector **design** can be scaled up dramatically
- UK-developed techniques can increase **tellurium loading**



Cost-effective

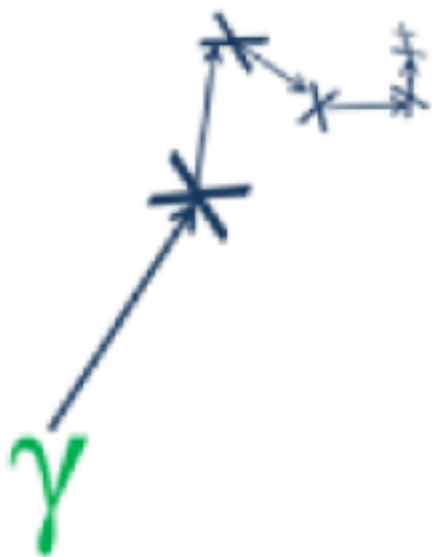
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Sensitive

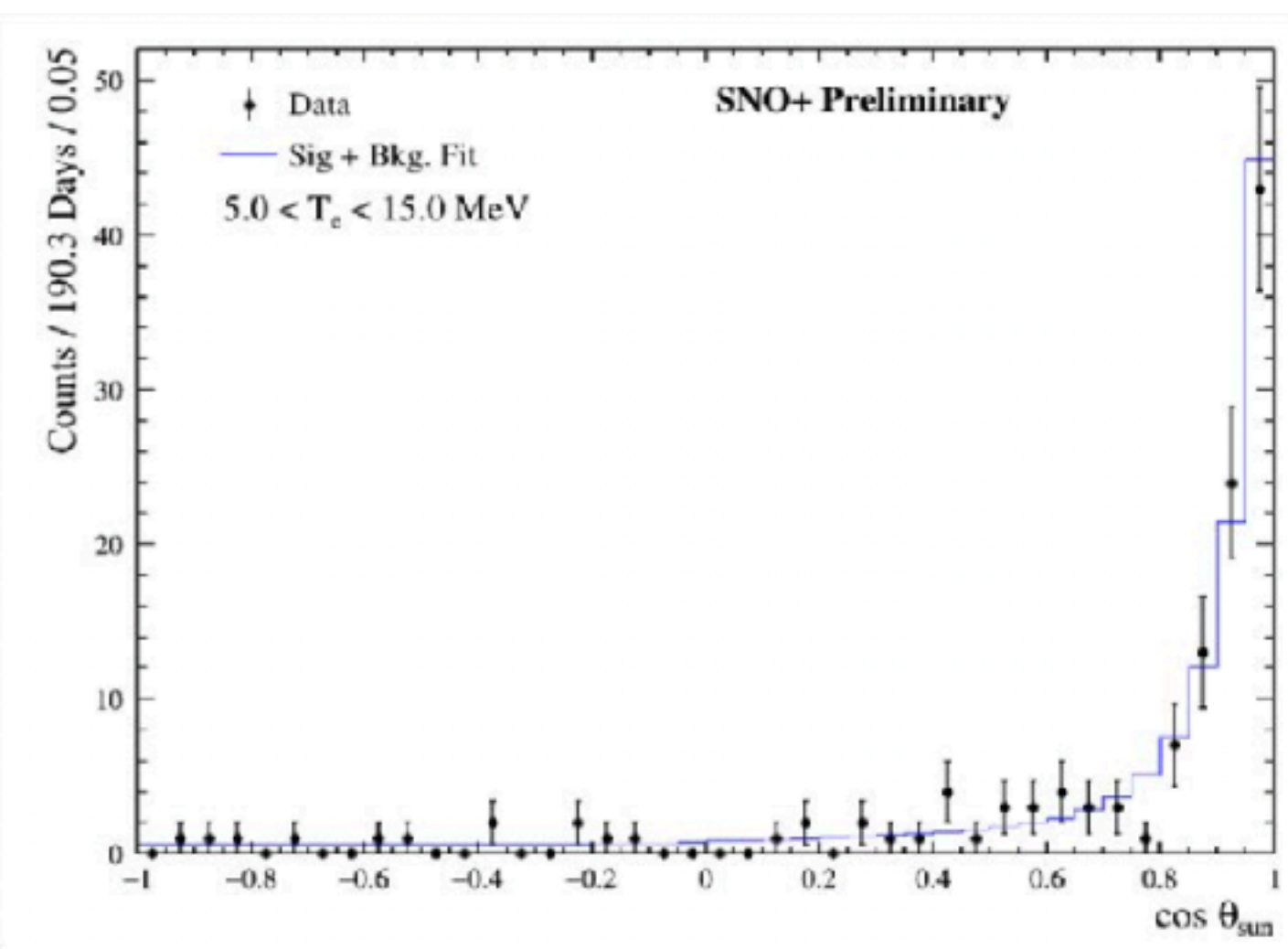
- Single- vs multi-site discrimination keeps backgrounds low



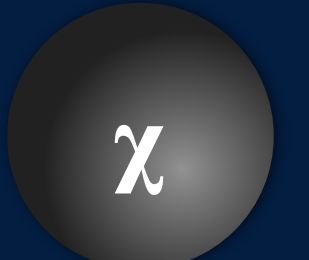
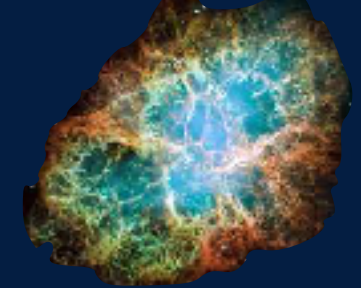
NIM, 943, 162420 (2019)

Initial phase - water-Cherenkov detector

Since April 2021- full liquid-scintillator detector

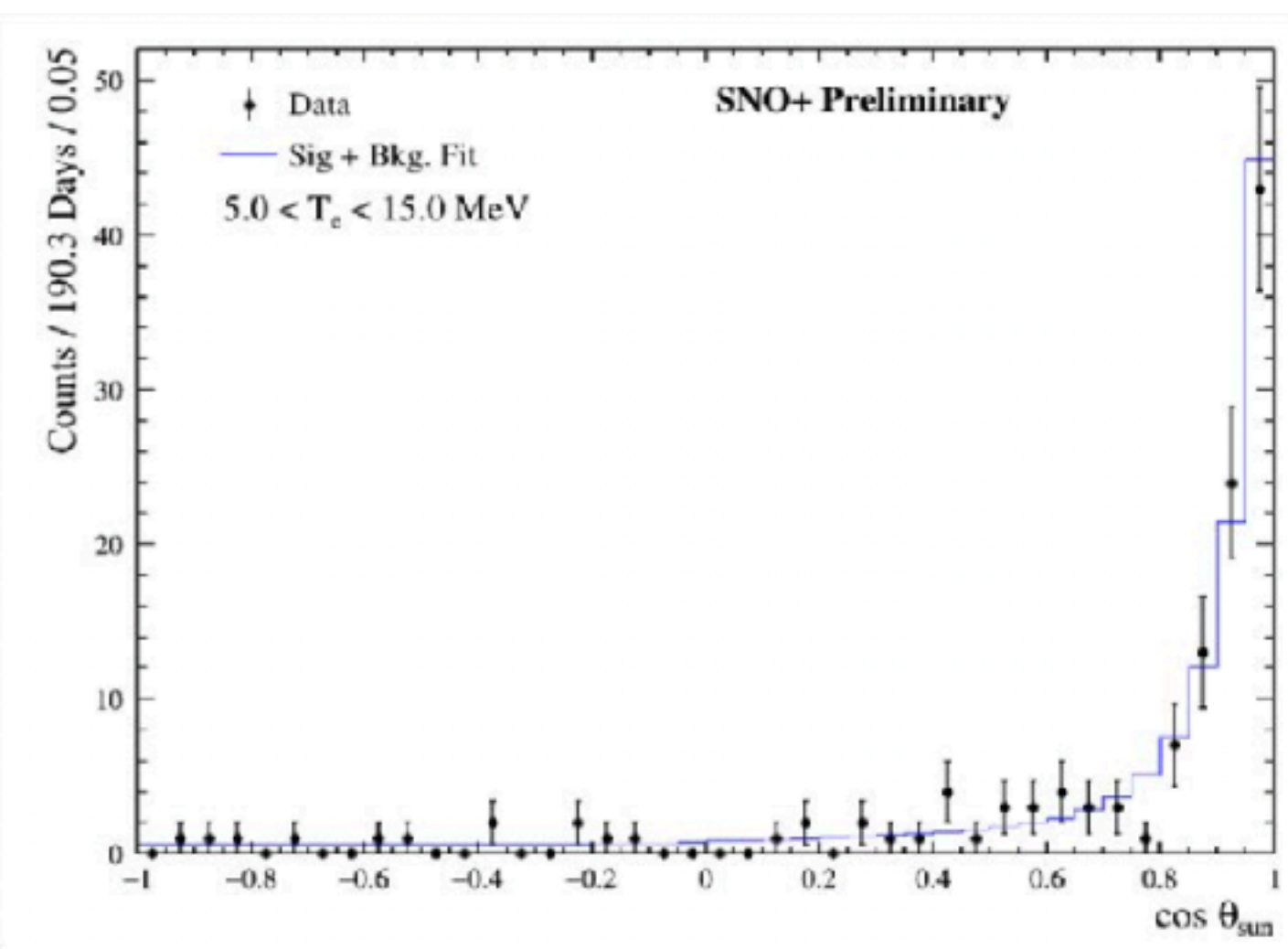


^8B solar neutrinos with extremely low backgrounds!

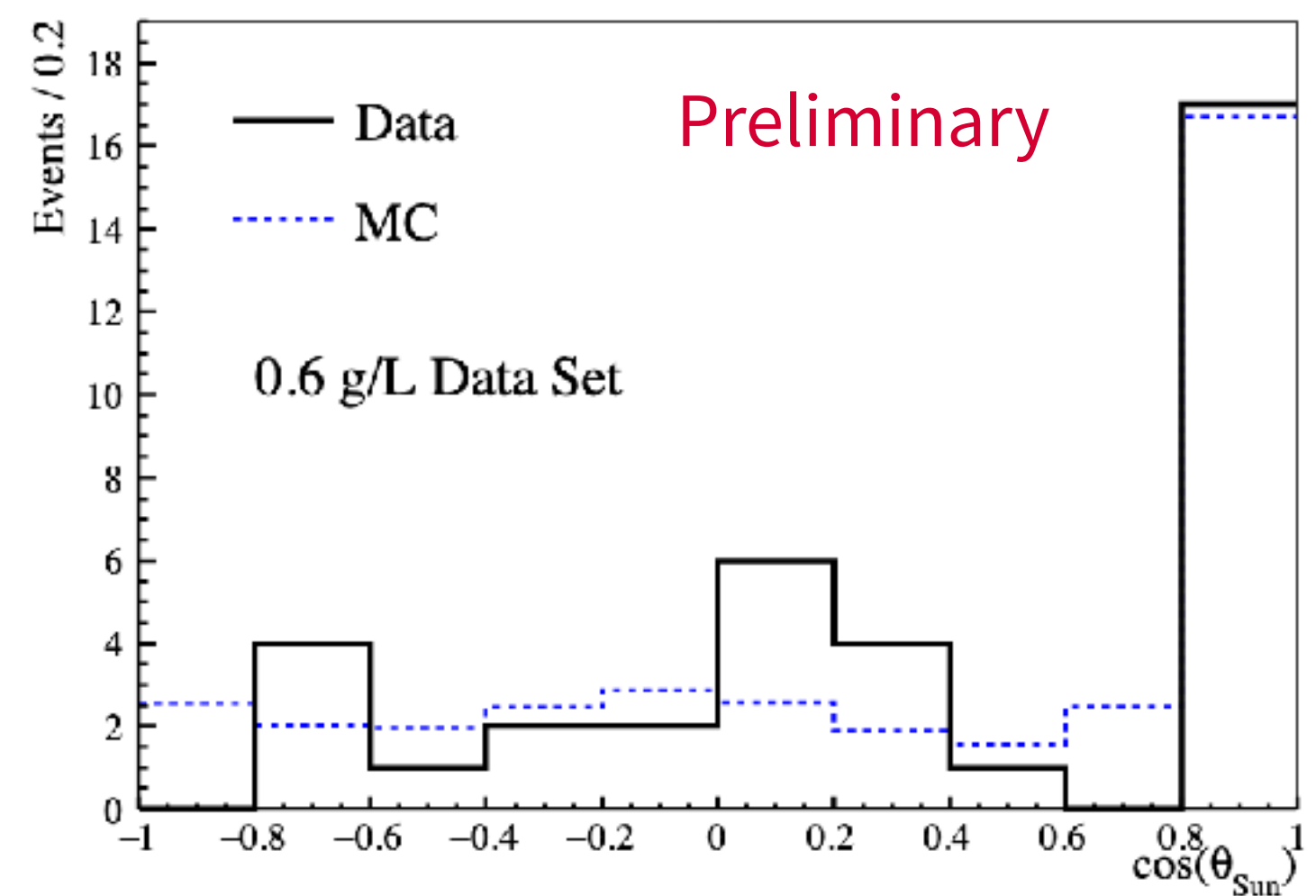
Solar neutrinos 	Reactor neutrinos 	Up-scattered dark matter 
Geo-neutrinos 	Supernova neutrinos 	"Invisible" nucleon decay

Initial phase - water-Cherenkov detector

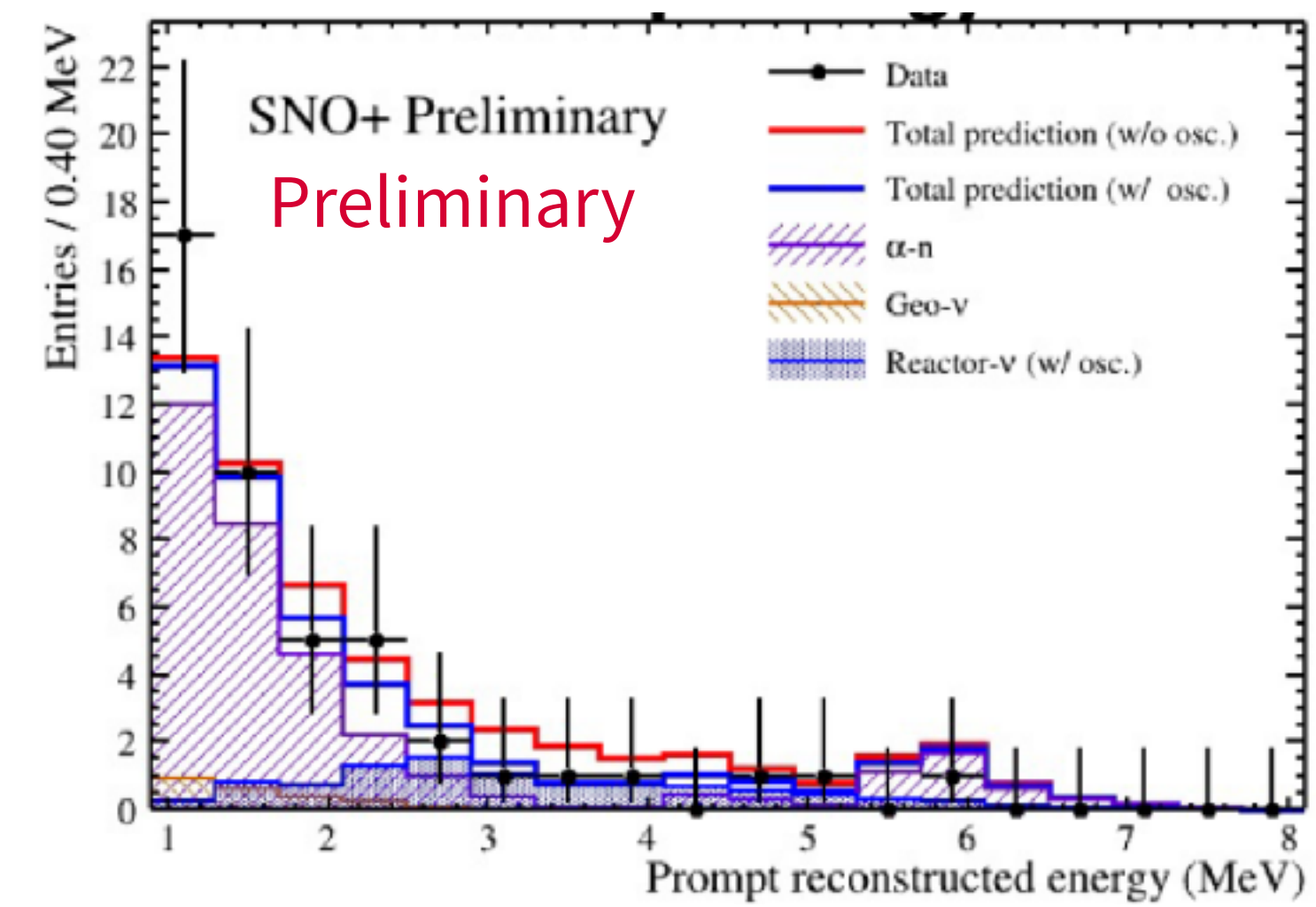
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Solar neutrinos

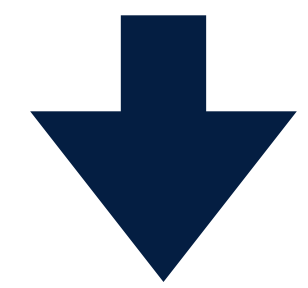


Reactor neutrinos

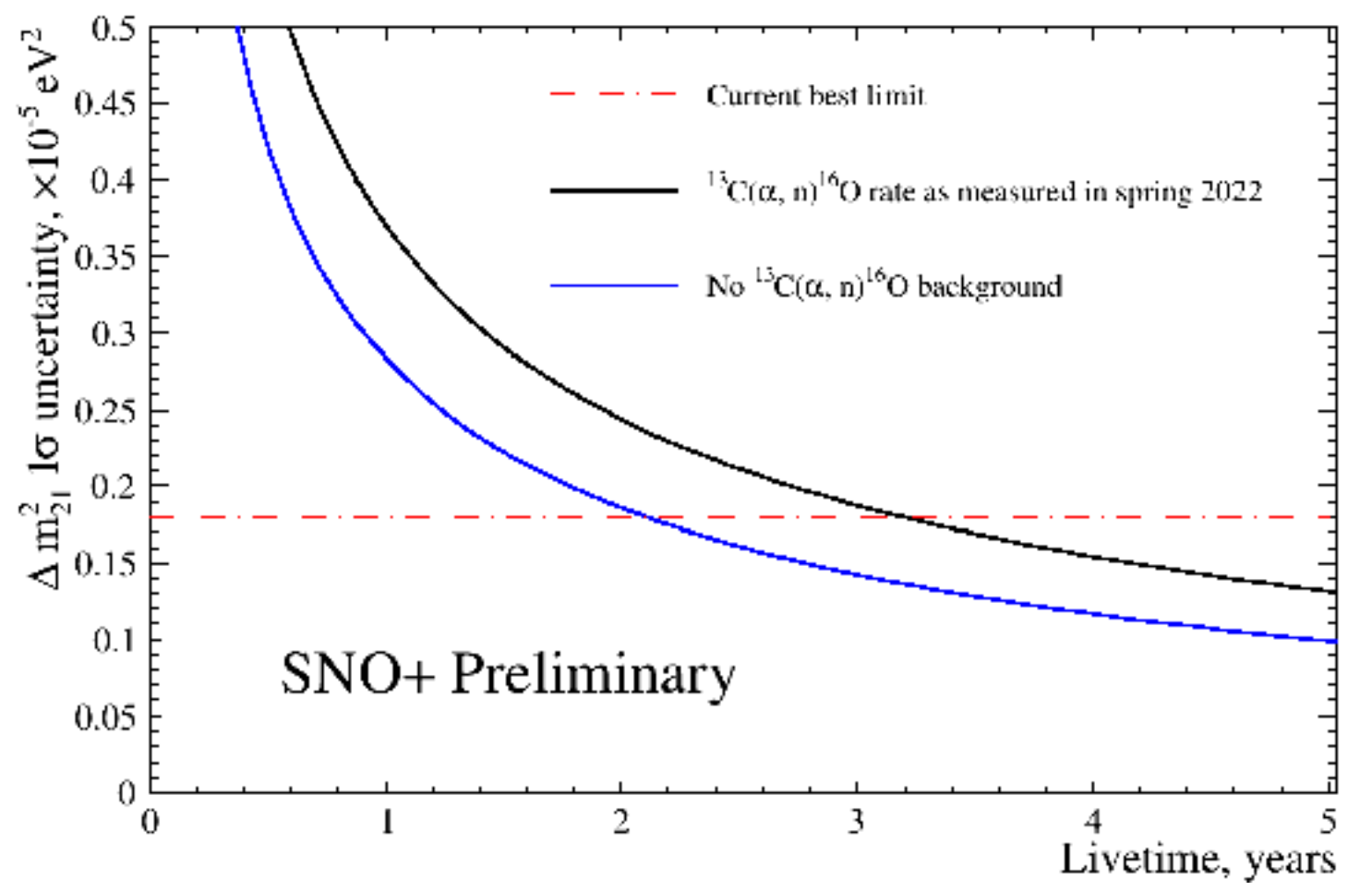


First ever demonstration of event-by-event solar ν directional reconstruction in high light-yield LS

Initial SNO+ observation of reactor $\bar{\nu}$ oscillation

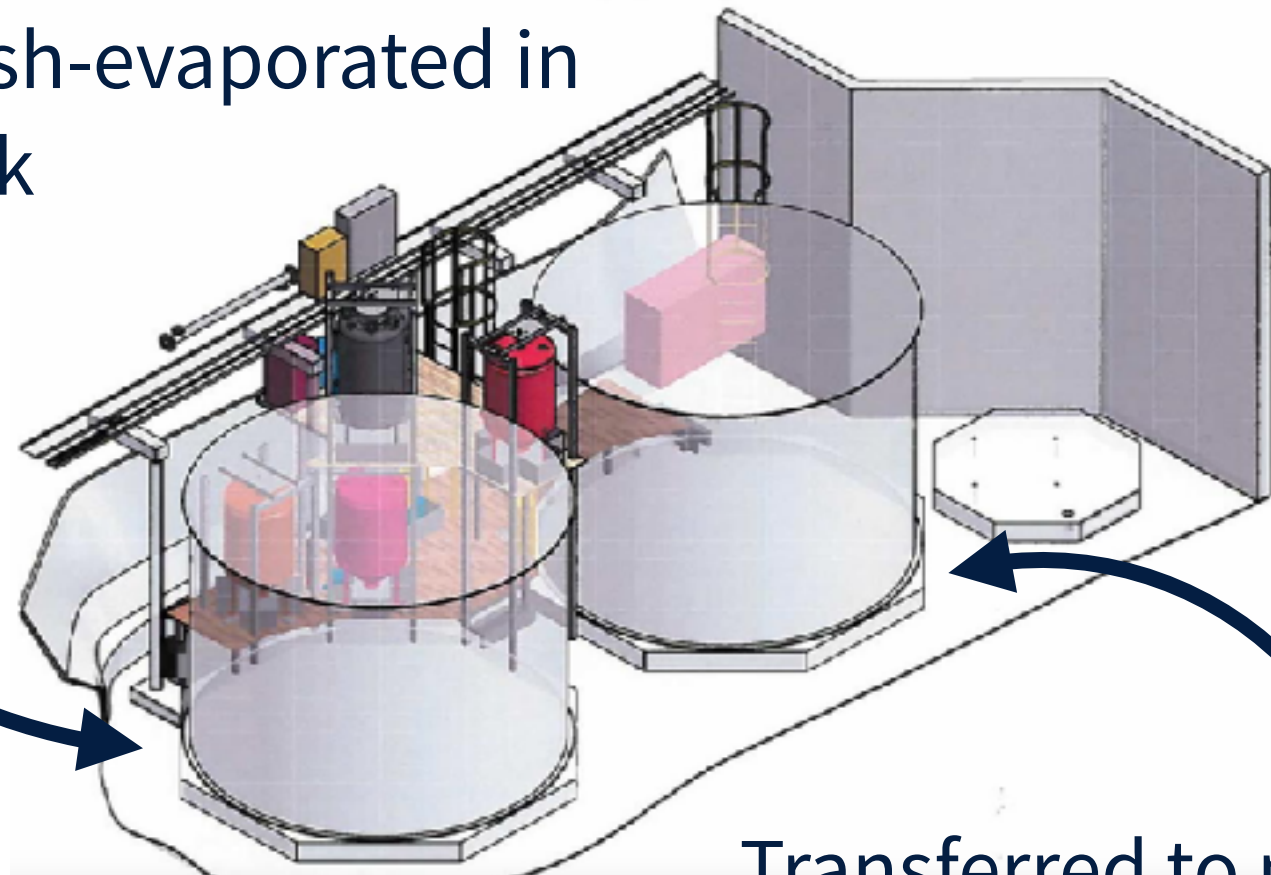


Best Δm^2_{12} constraints within a couple of years!



Preparing for $\beta\beta$ -decay

Mixture of telluric acid in water and distilled butanediol is heated while water is flash-evaporated in the synthesis tank



Transferred to mixing tank near solubility point to combine with LAB and 0.25mol DDA to complete solubilisation



Te purification and loading systems constructed and starting commissioning

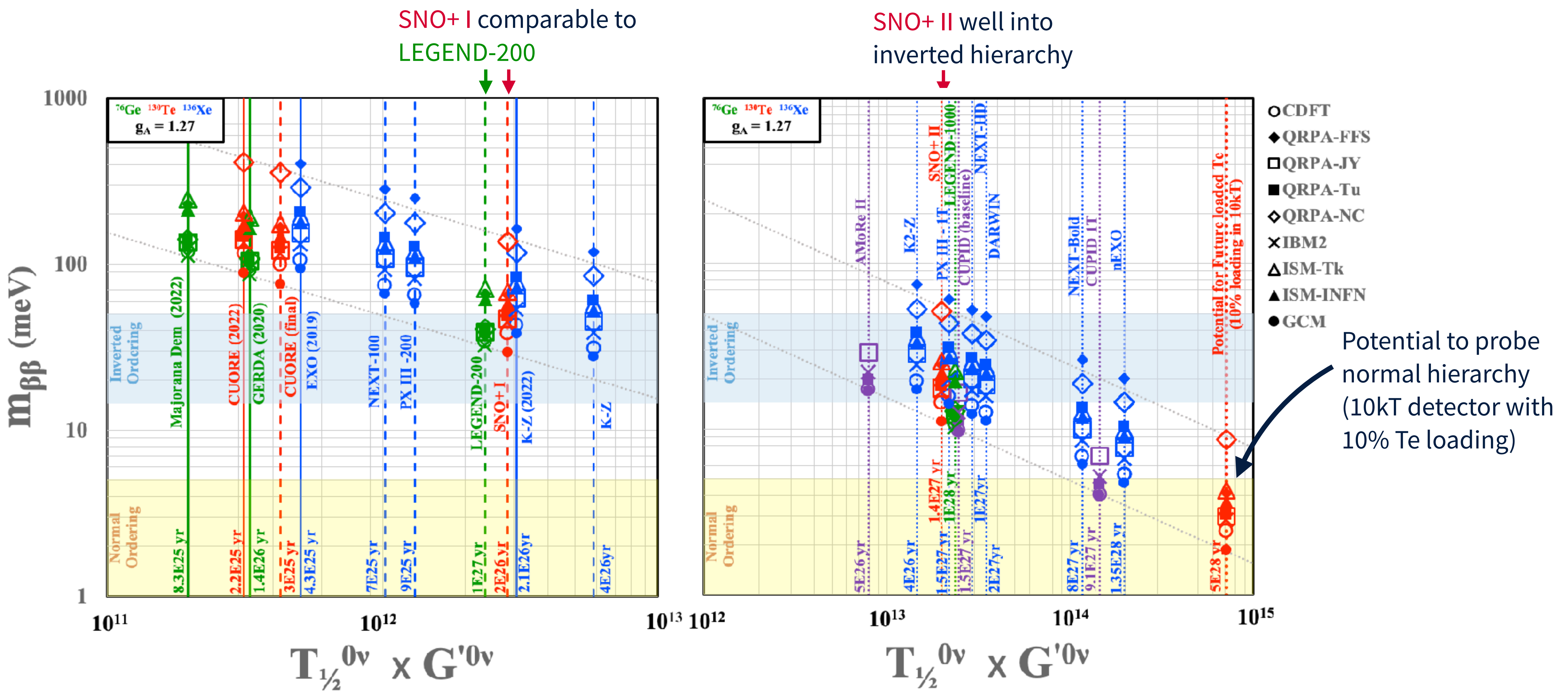


Delays to Te deployment:

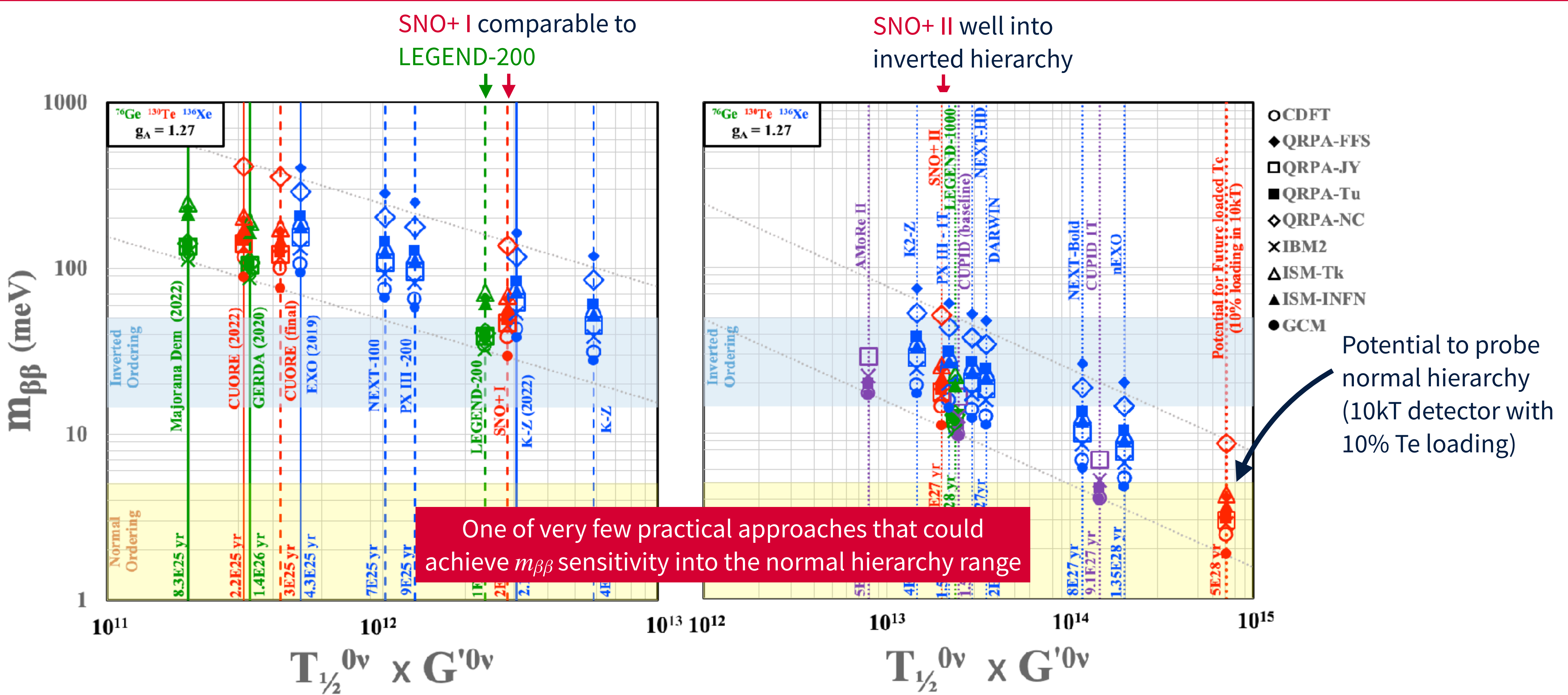
- COVID disruption of supply chains
- Loss of key engineers at SNOLAB
- Extended commissioning & safety review
- Site access limitations

Loading to start in late 2024/early 2025

SNO+ sensitivity



SNO+ sensitivity



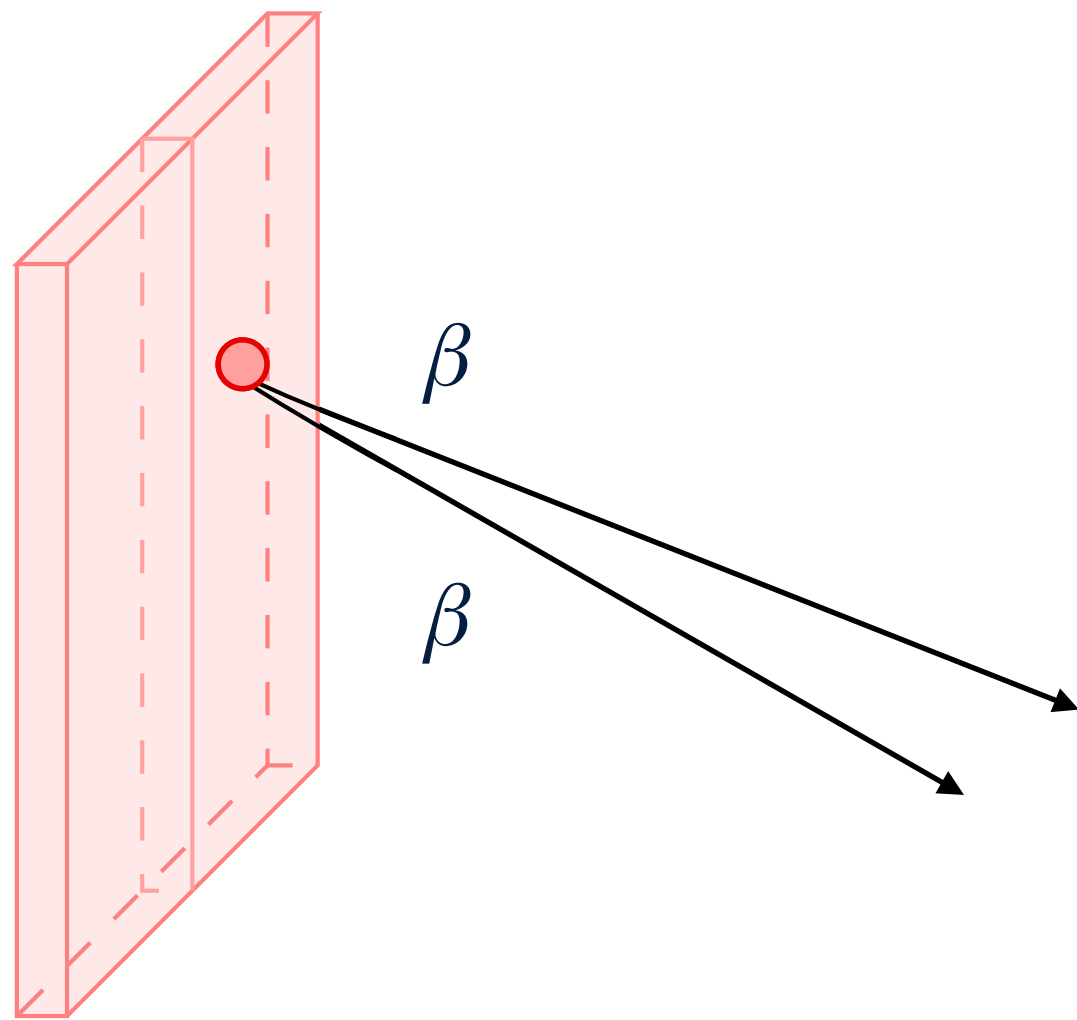
SuperNEMO, at LSM, French Alps



An isotope-agnostic technique to distinguish individual particles, and probe $0\nu\beta\beta$ mechanisms and nuclear effects

The NEMO principle

$\beta\beta$ source

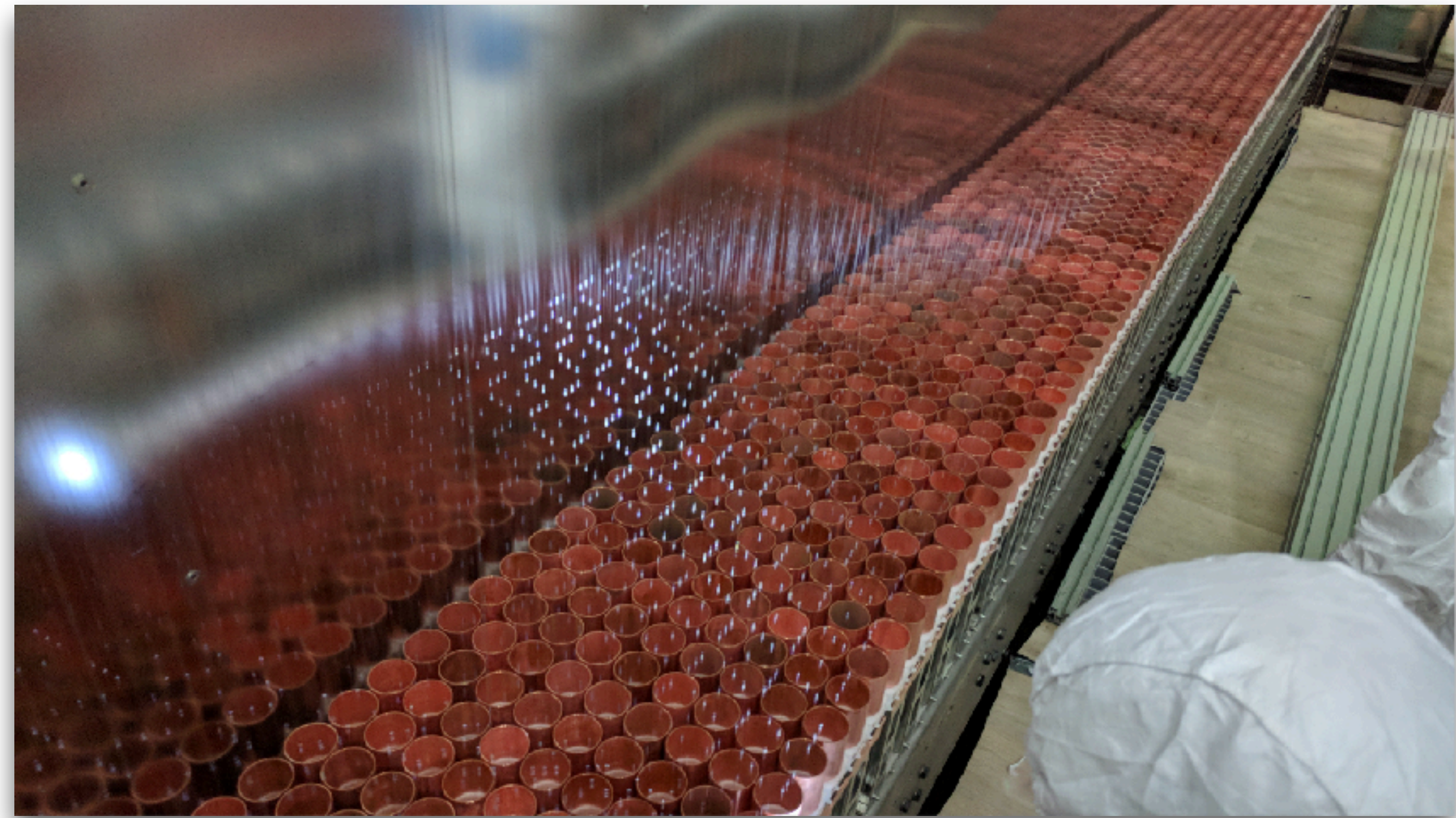
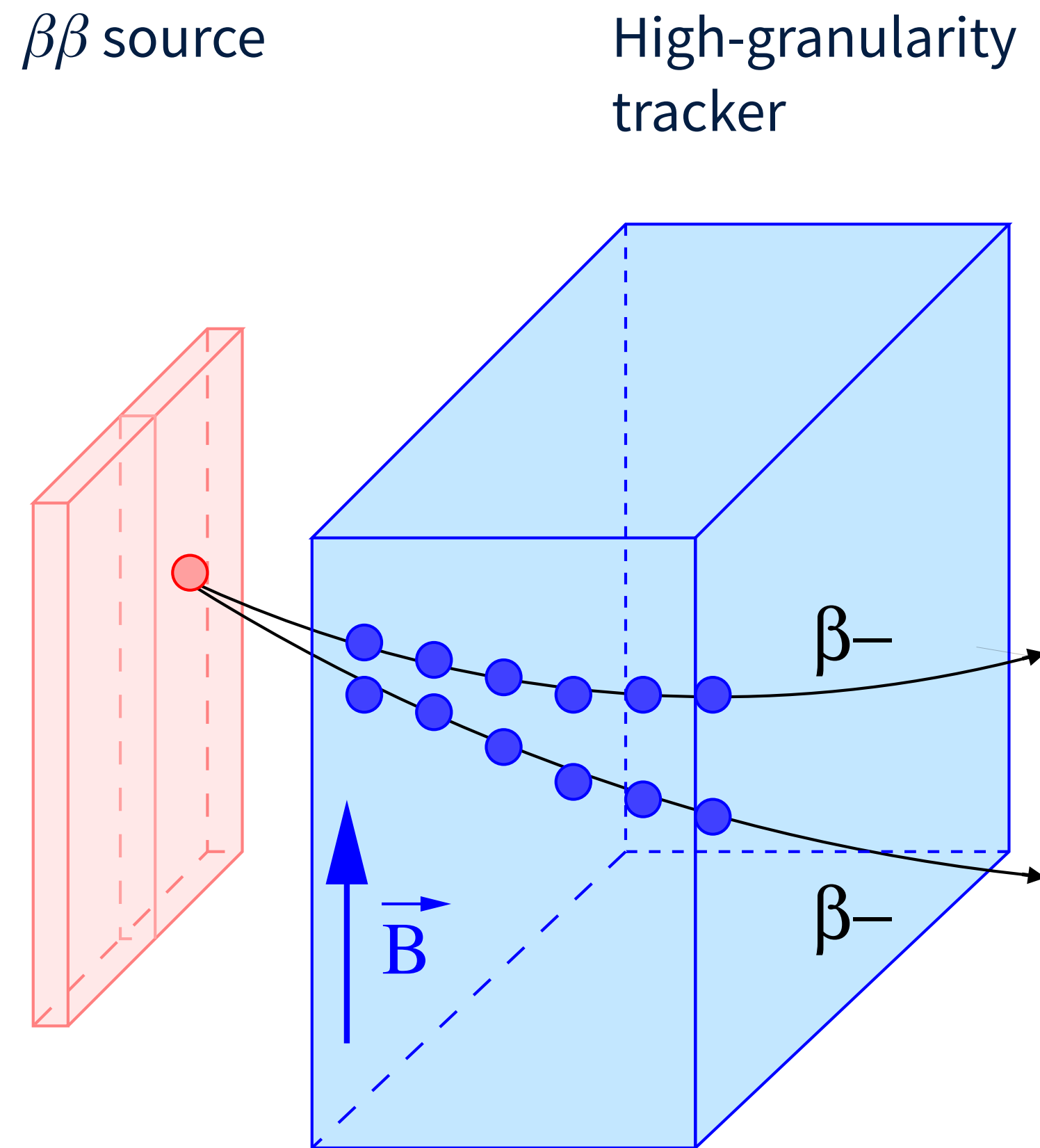


Any solid $\beta\beta$ isotope



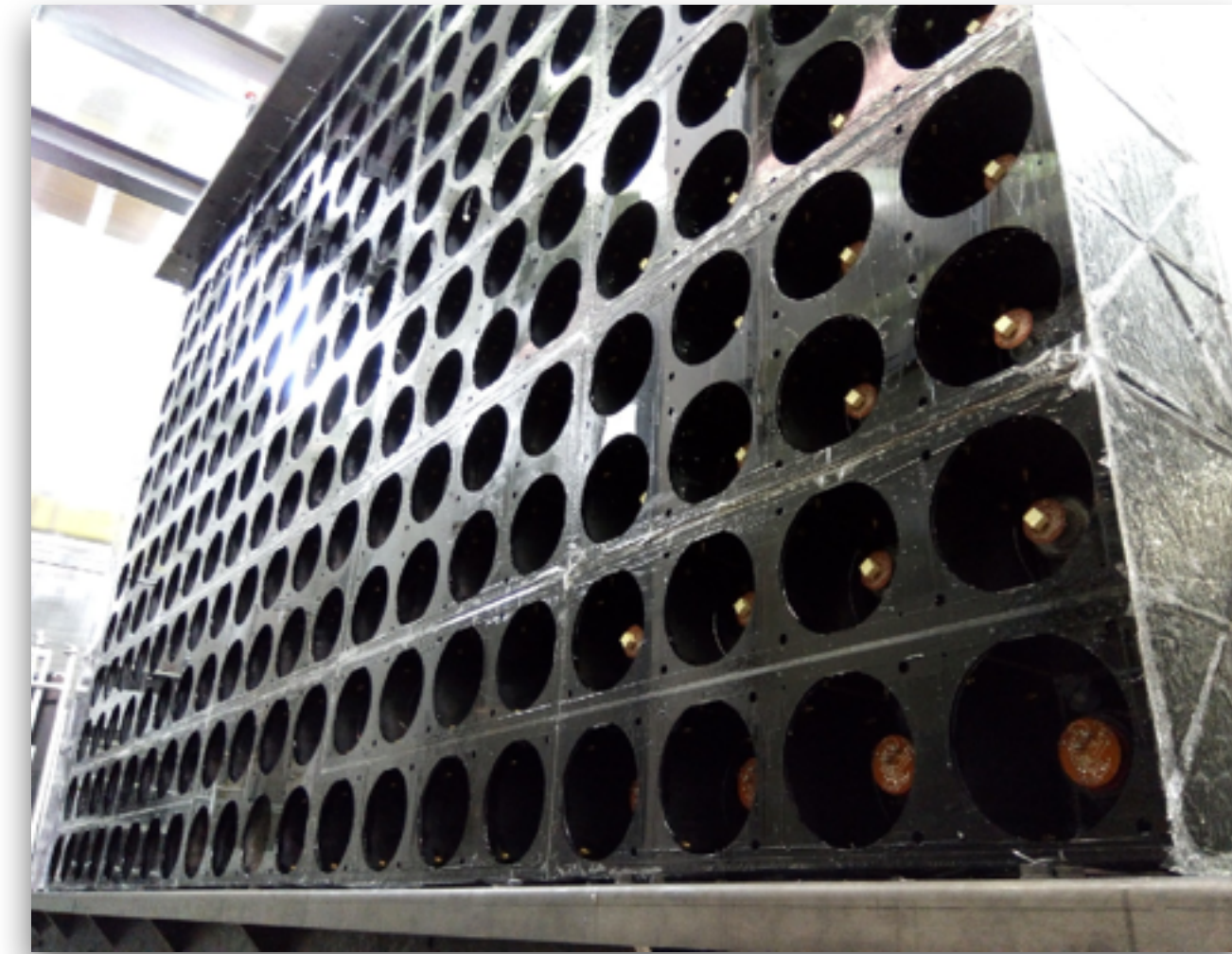
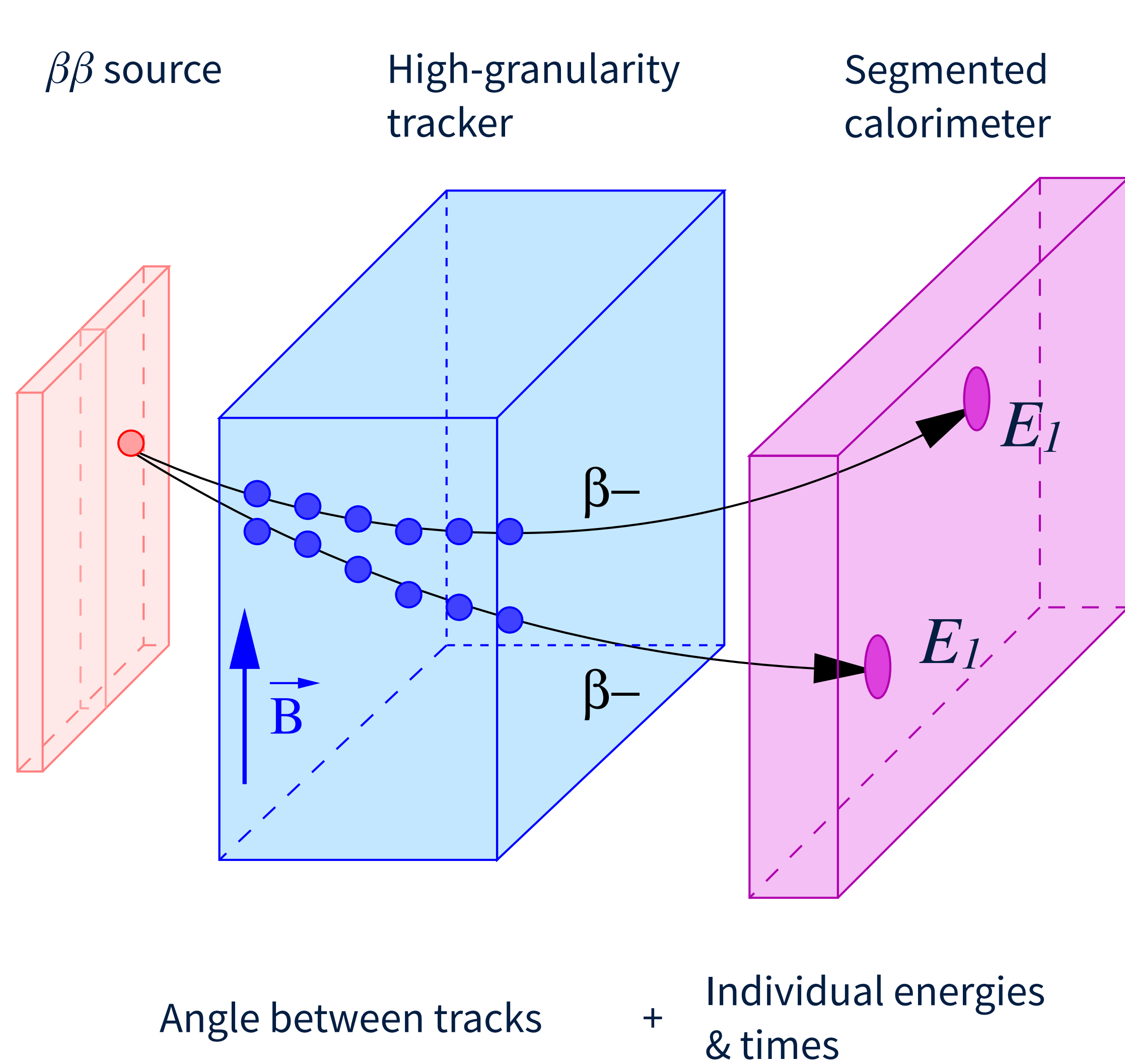
SuperNEMO Demonstrator - 6.23kg ^{82}Se

The NEMO principle



SuperNEMO Demonstrator - 2034 Geiger cells

How SuperNEMO works

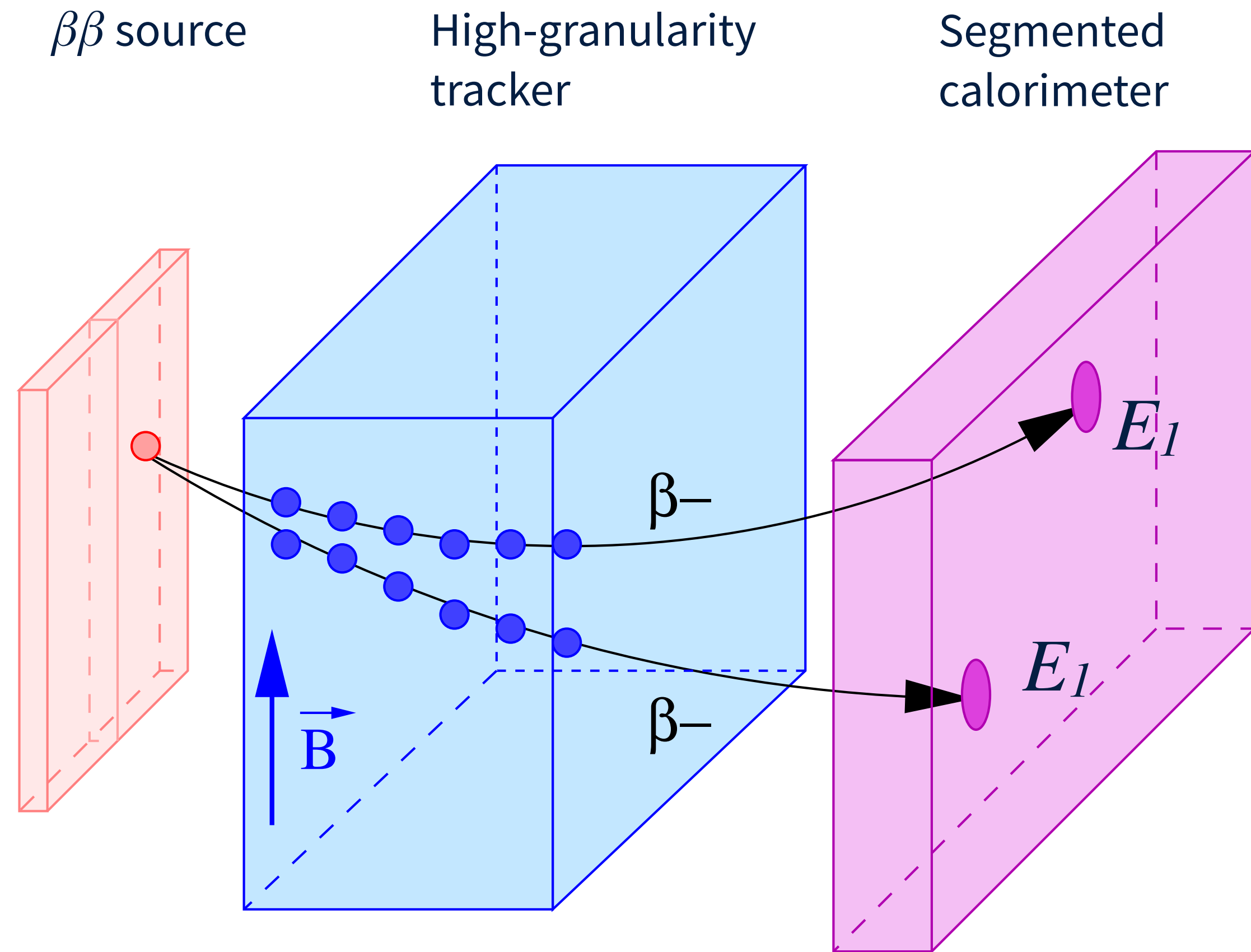


712 optical modules

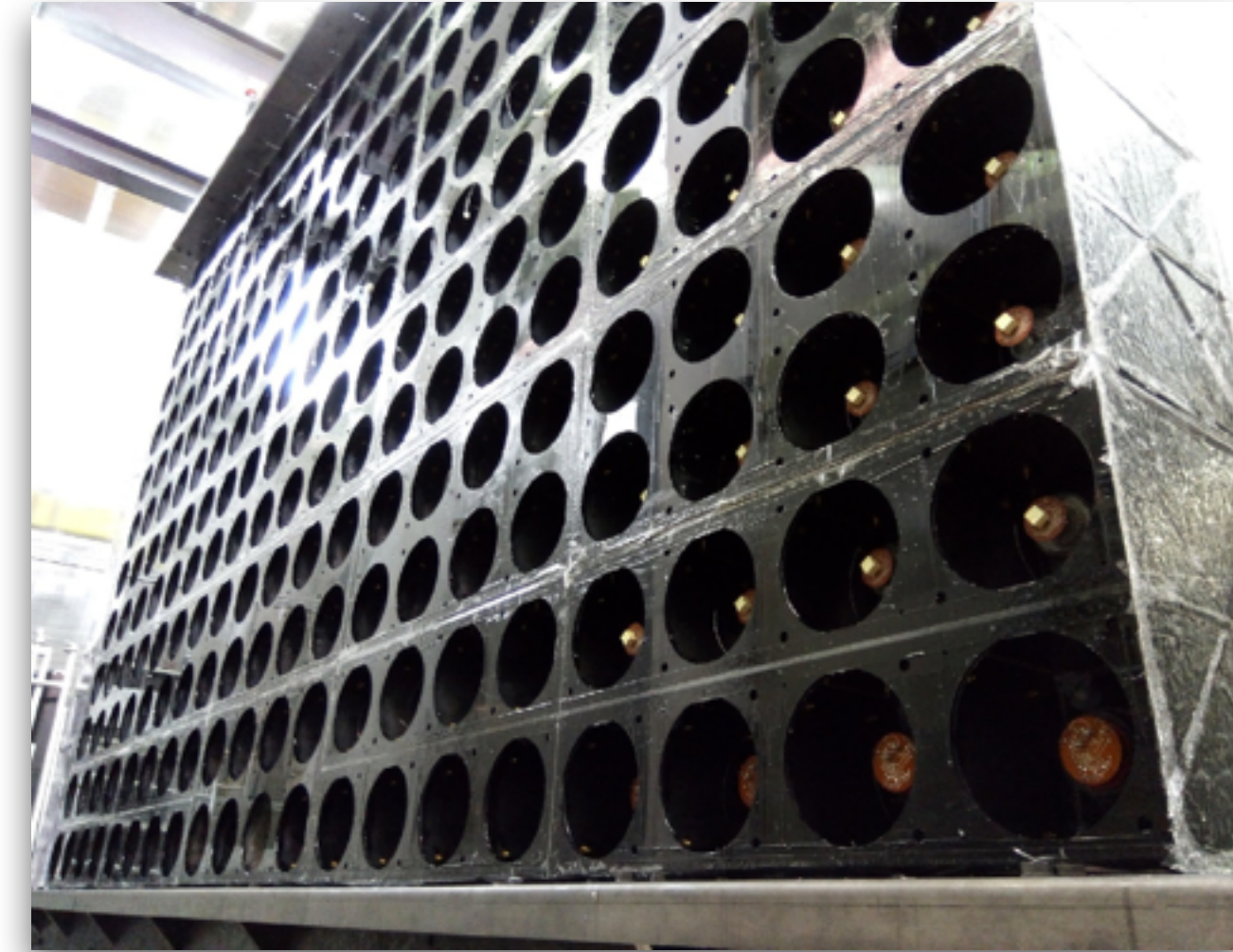
σ/E 1.8% at 3 MeV



How SuperNEMO works



Angle between tracks + Individual energies & times = discrimination between $\beta\beta$ mechanisms and nuclear effects; background rejection



712 optical modules

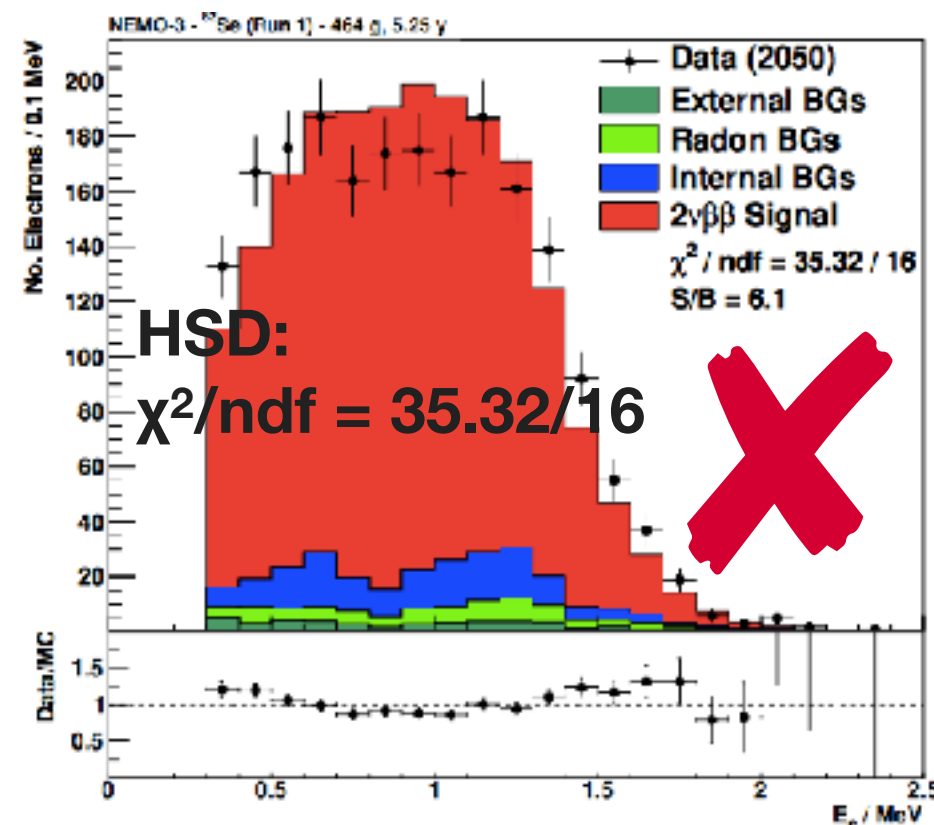
σ/E 1.8% at 3 MeV



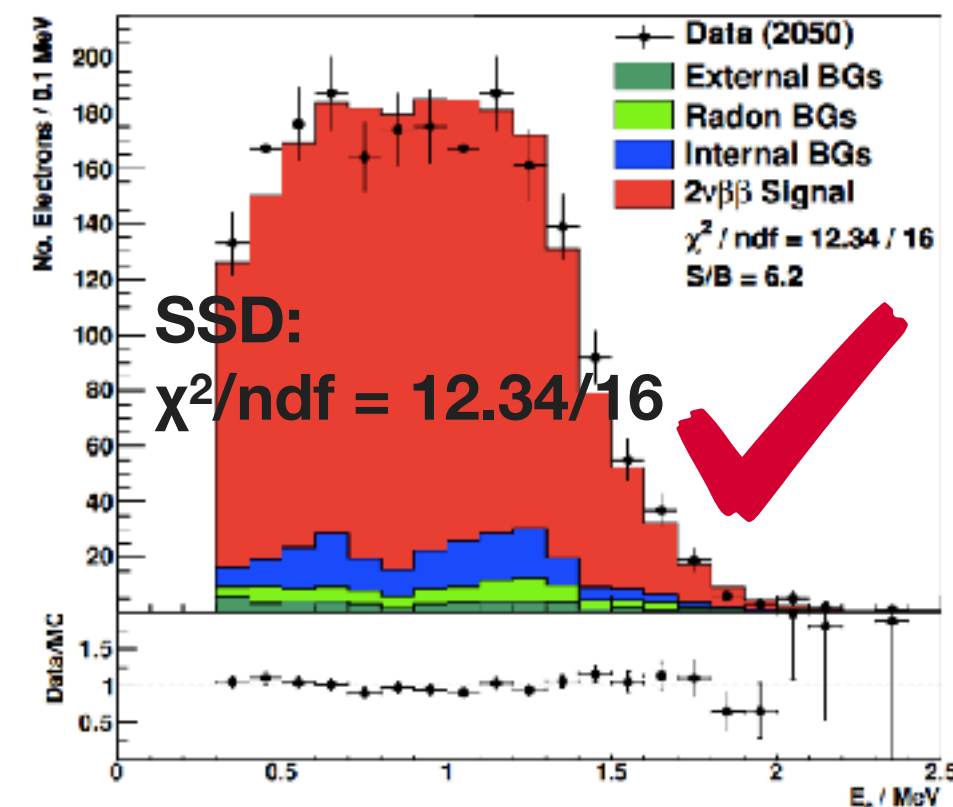
SuperNEMO for nuclear effects

Intermediate states in $2\nu\beta\beta$ decay

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



Various excited states



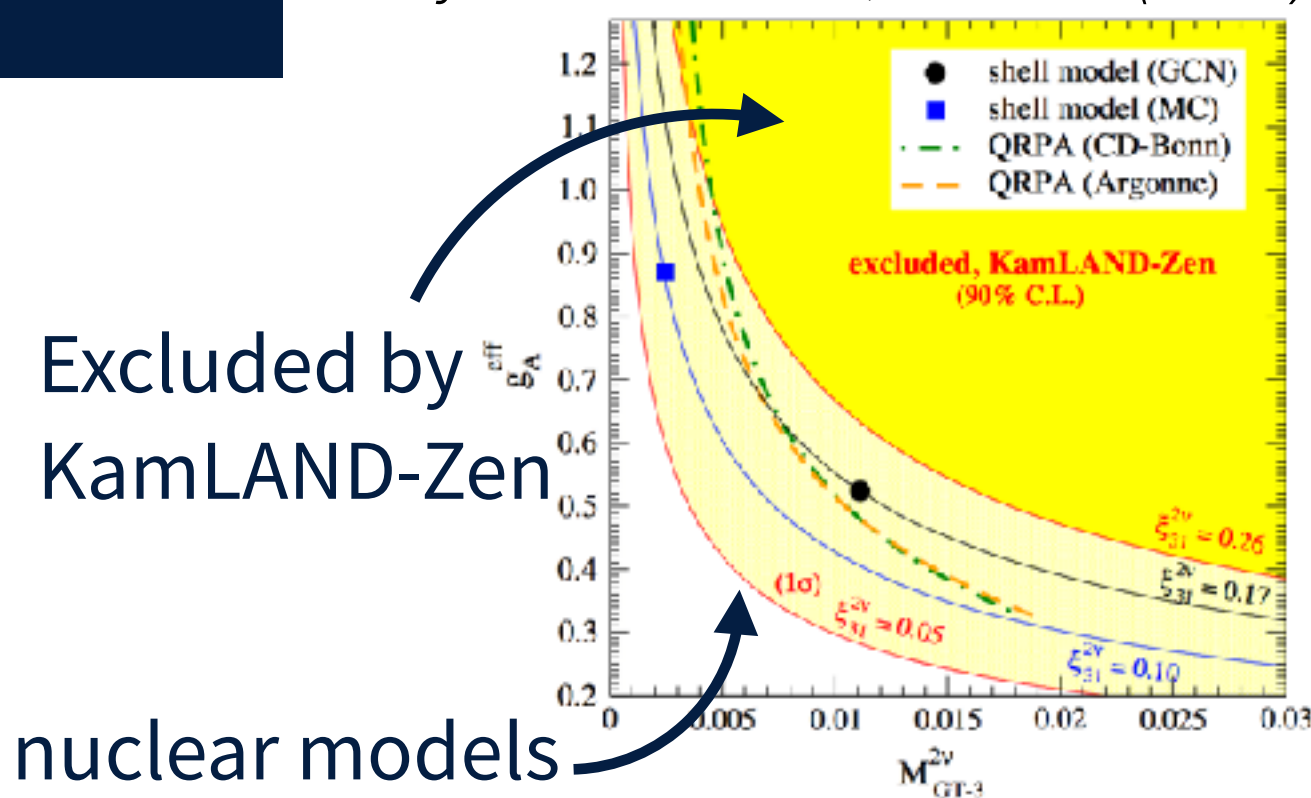
Mostly ground state

SuperNEMO will have 5σ sensitivity

g_A quenching

SuperNEMO's individual e^- spectrum will be more sensitive

Phys Rev Lett 122, 192501 (2019)



Excluded by KamLAND-Zen

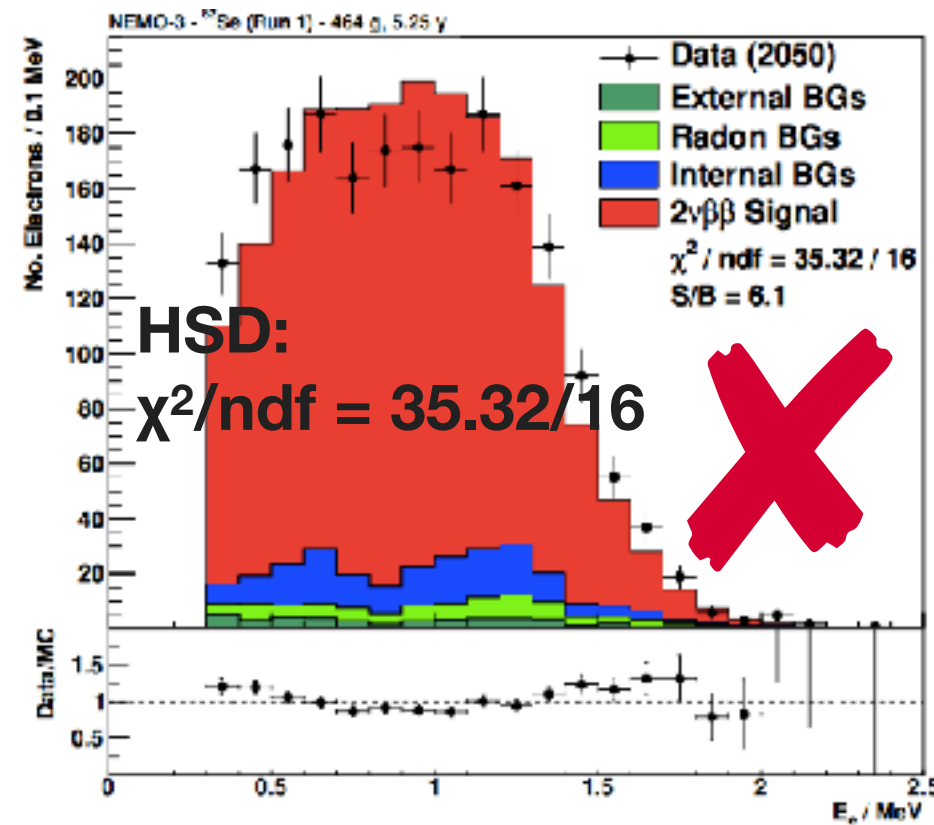
Lines and points → nuclear models

SuperNEMO for nuclear effects

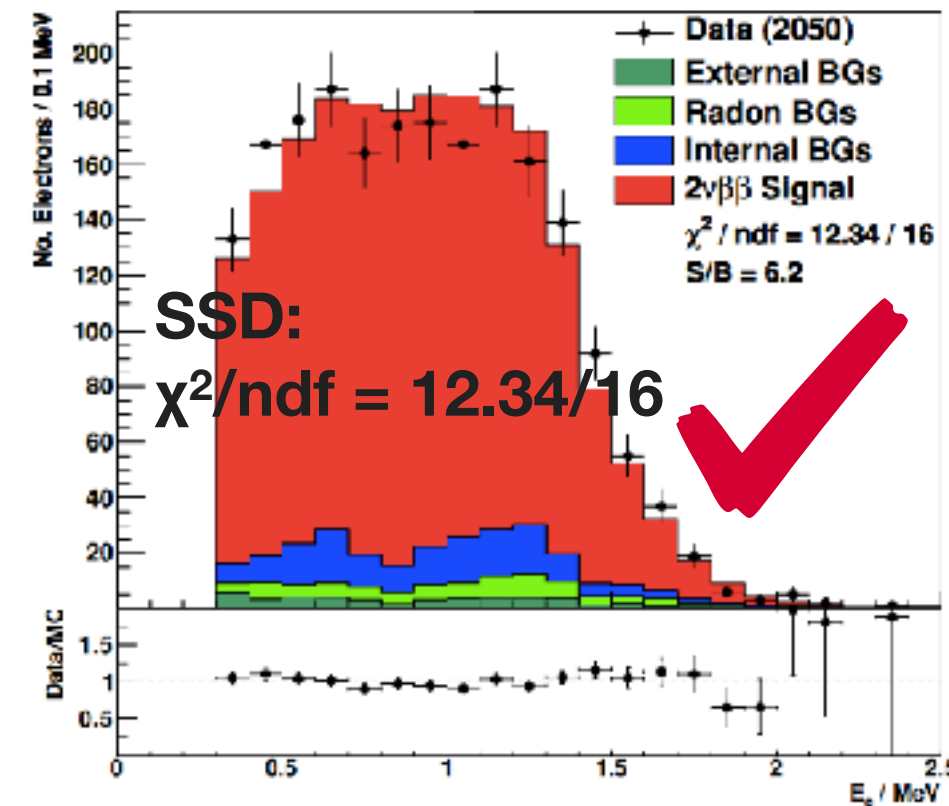
... and exotic physics

Intermediate states in $2\nu\beta\beta$ decay

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



Various excited states



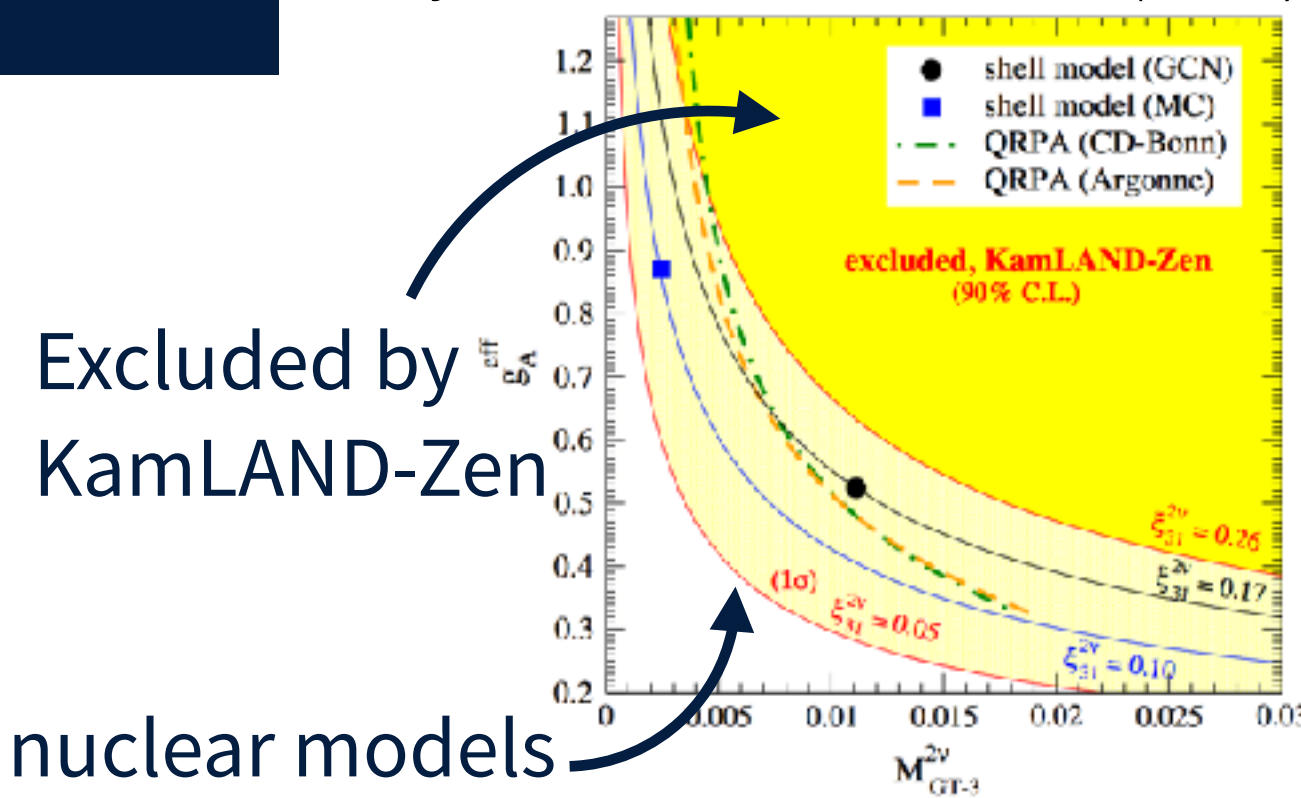
Mostly ground state

SuperNEMO will have 5σ sensitivity

g_A quenching

SuperNEMO's individual e^- spectrum will be more sensitive

Phys Rev Lett 122, 192501 (2019)

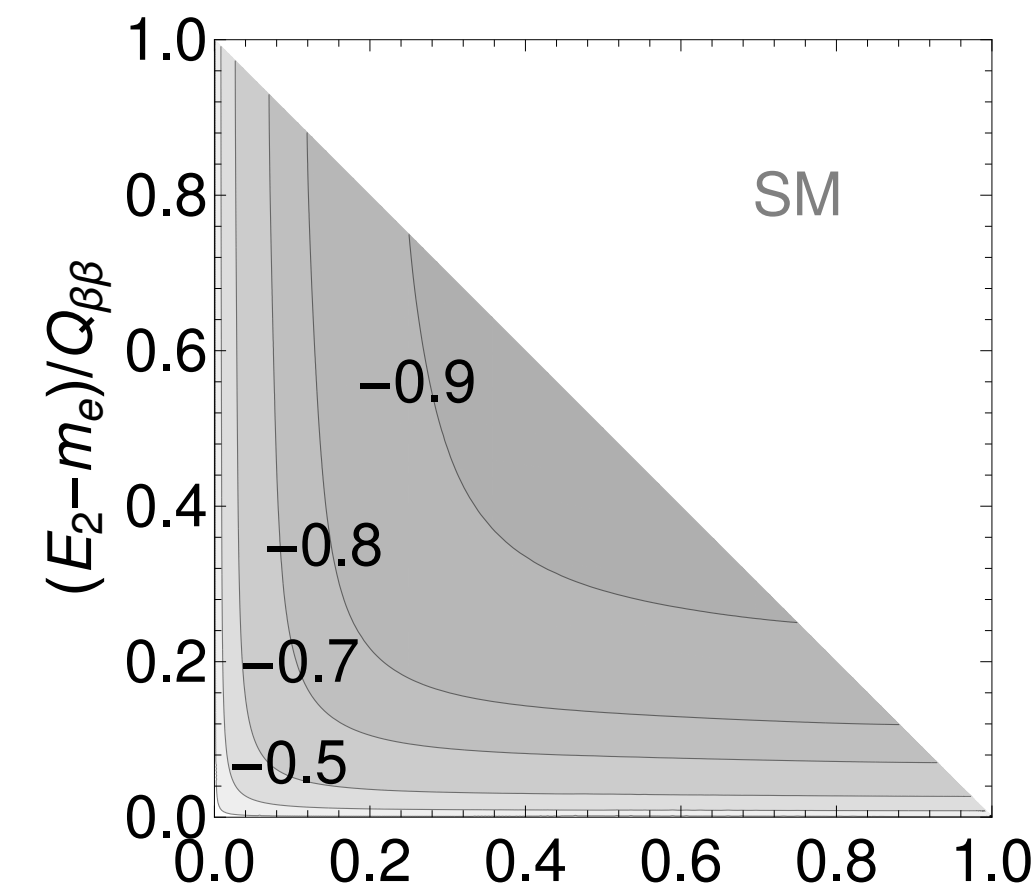


Lines and points → nuclear models

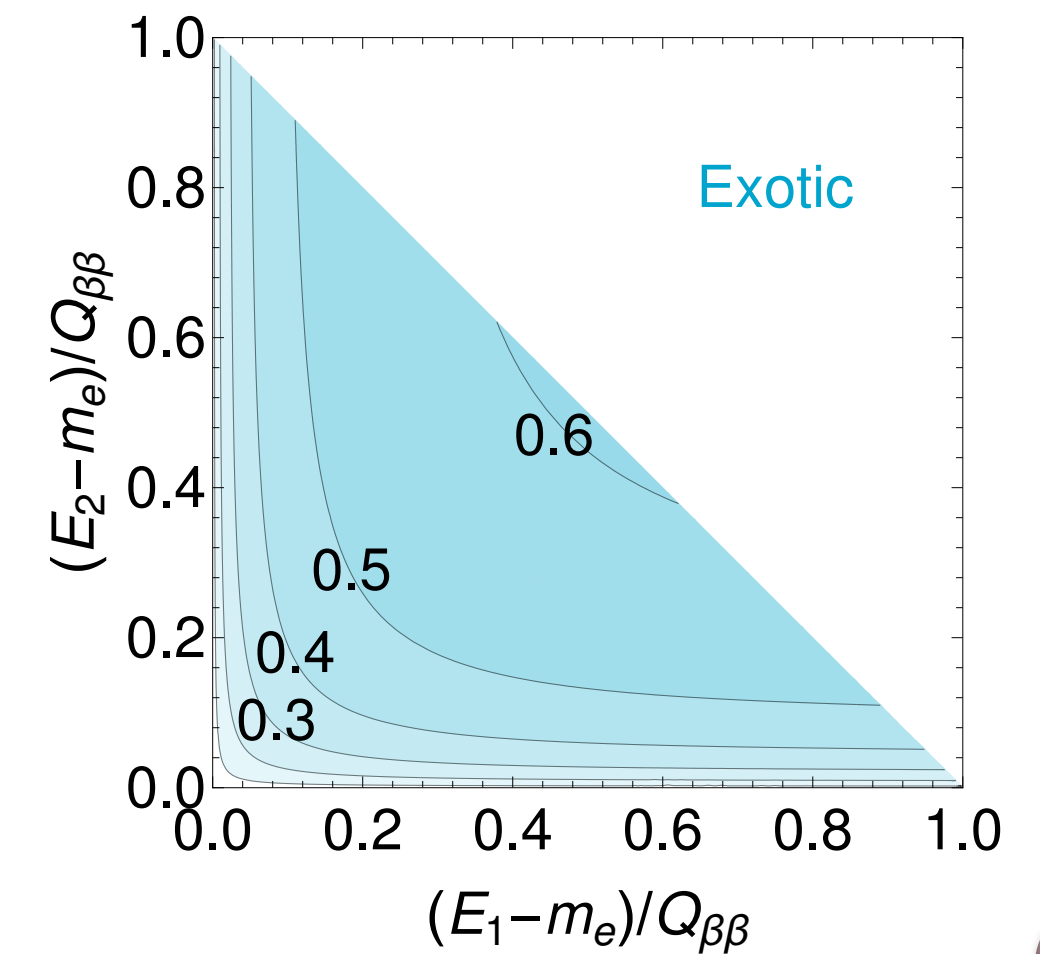
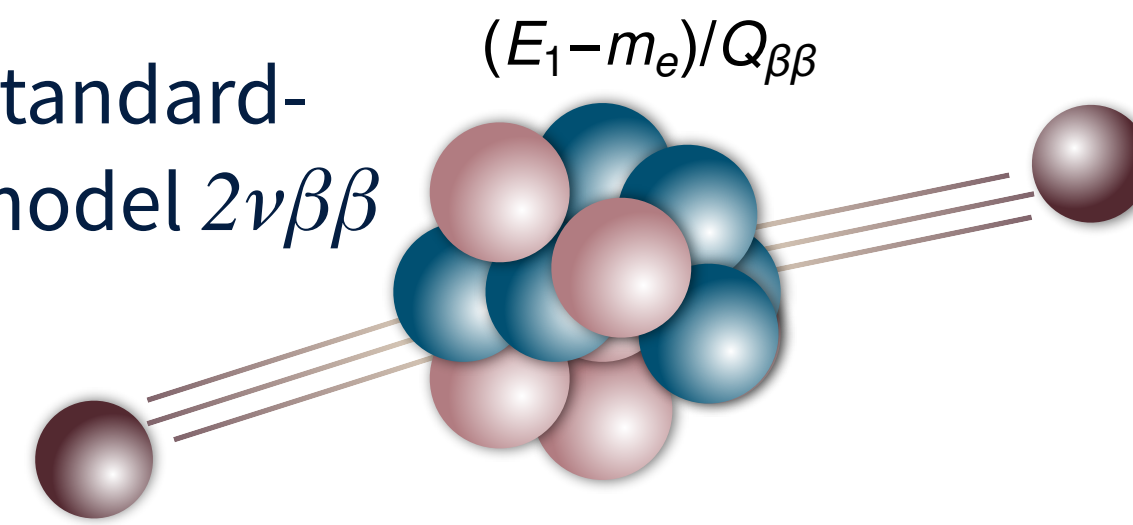
Precision $2\nu\beta\beta$ measurements can reveal BSM effects...

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

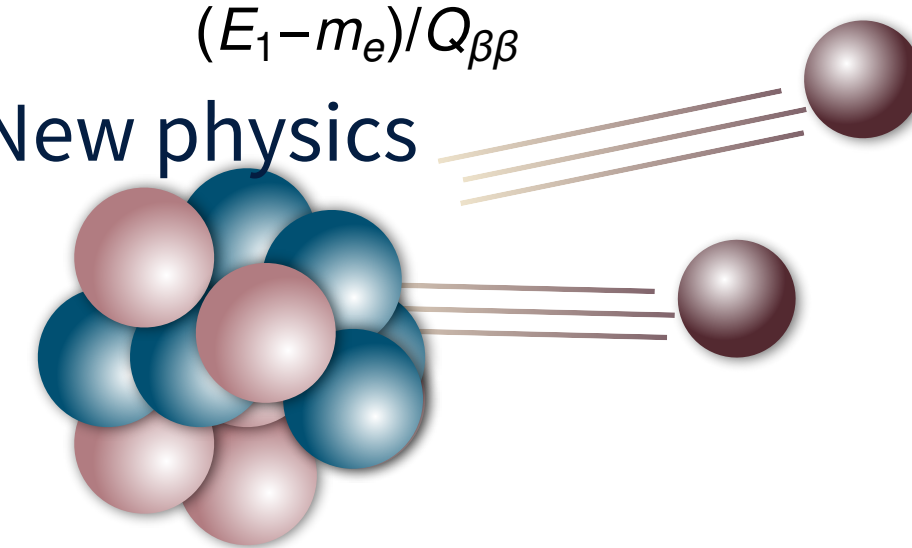
Phys. Rev. Lett. 125, 171801 (2020)
(UK-led study)



Standard-model $2\nu\beta\beta$



New physics



Best technology to understand $0\nu\beta\beta$ mechanism if it's discovered

SuperNEMO Demonstrator status: Calorimeter calibration

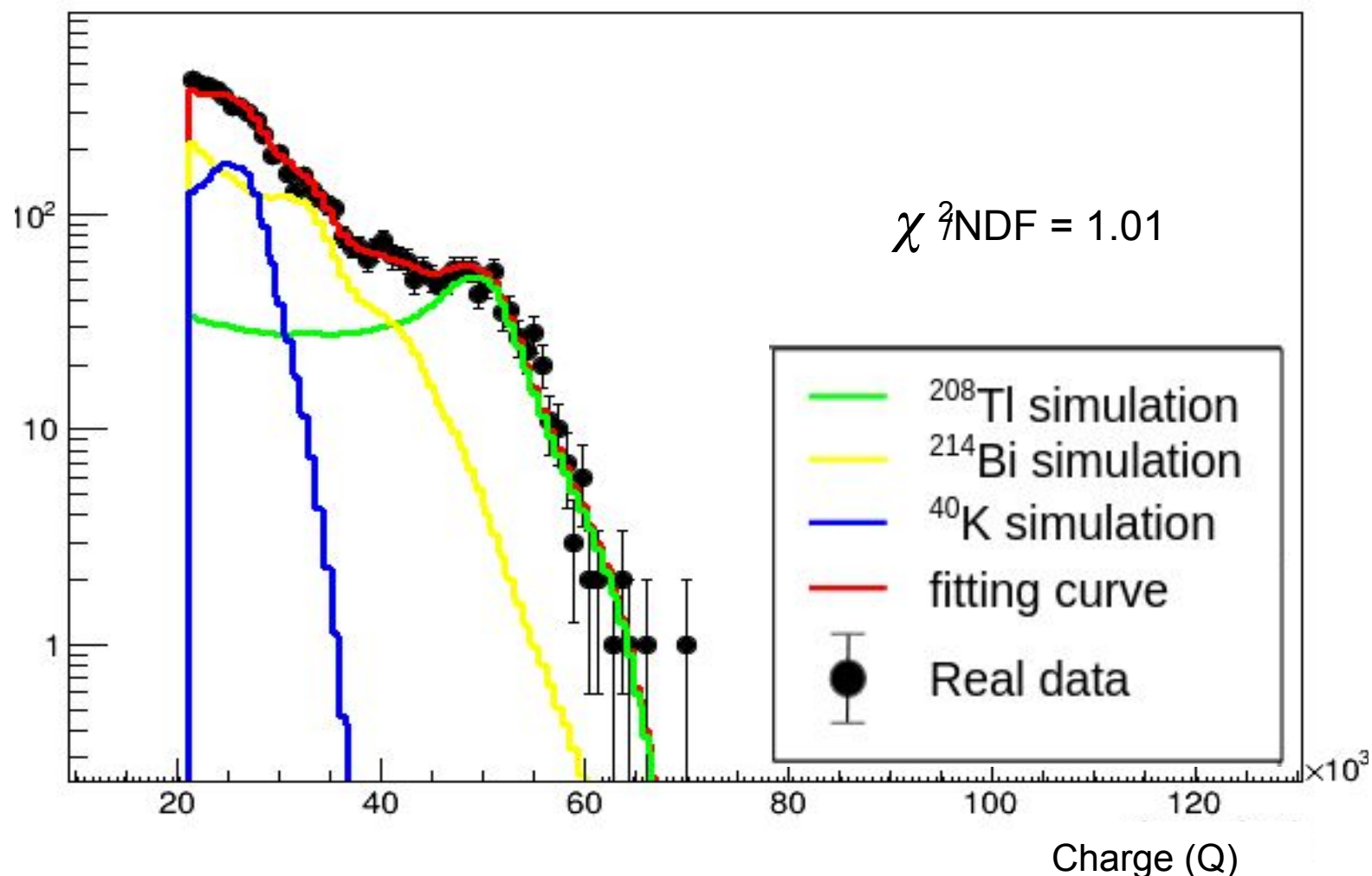
Timing

ITALY TUNNEL		G:0.1.15	G:0.1.14	G:0.1.13	G:0.1.12	G:0.1.11	G:0.1.10	G:0.1.9	G:0.1.8	G:0.1.7	G:0.1.6	G:0.1.5	G:0.1.4	G:0.1.3	G:0.1.2	G:0.1.1	G:0.1.0	MOUNTAIN							
X:0.1.15X:0.1.1.15		M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.11	M:0.10	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.1.15X:0.0.1.15			
		28.38	21.77	22.44	23.21	19.07	16.70	17.53	14.33	14.33	11.22	12.81	11.66	11.75	10.10	7.97	6.05	9.29	4.27	2.07	0.56	X:0.0.1.14X:0.0.1.14			
X:0.1.14X:0.1.1.14																						X:0.0.1.13X:0.0.1.13			
					17.60	16.71	13.80	11.53	15.26	13.35	12.27	12.08	8.86	9.65	6.41	4.10	3.89	4.79	1.32	-2.80	0.21	-1.18	-3.46	X:0.0.1.12X:0.0.1.12	
X:0.1.13X:0.1.1.13																						X:0.0.1.11X:0.0.1.11			
					M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.11	M:0.10	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.1.10X:0.0.1.10
X:0.1.12X:0.1.1.12																							X:0.0.1.09X:0.0.1.09		
					18.90	19.14	18.41	15.64	14.16		13.00	13.03	13.76	11.11	9.80	7.02	8.87	5.66	4.38	0.56	2.86	-1.08	0.91	-0.47	X:0.0.1.08X:0.0.1.08
X:0.1.11X:0.1.1.11																								X:0.0.1.07X:0.0.1.07	
					M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.1.06X:0.0.1.06		
X:0.1.10X:0.1.1.10																							X:0.0.1.05X:0.0.1.05		
					17.27	16.76	15.76	14.77	10.83	11.75	10.16	10.81	8.17	8.40	6.68	6.27	4.14	2.34		-1.14	-2.30	-4.21	-3.48	X:0.0.1.04X:0.0.1.04	
X:0.1.09X:0.1.1.9																							X:0.0.1.03X:0.0.1.03		
					M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.1.02X:0.0.1.02		
X:0.1.08X:0.1.1.8																							X:0.0.1.01X:0.0.1.01		
					18.70	15.22	17.00	13.42	8.05	13.62	9.30	9.31	6.66	6.48	4.18	3.08	1.99	-0.05	1.25	5.10	-2.78		-5.14	-3.97	X:0.0.1.00X:0.0.1.00
X:0.1.07X:0.1.1.7																							X:0.0.0.15X:0.0.0.15		
					M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.0.14X:0.0.0.14		
X:0.1.06X:0.1.1.6																							X:0.0.0.13X:0.0.0.13		
					14.56	13.02	12.28	12.10	11.81	9.31	8.04	5.99	4.96	3.97	1.76	0.55		-2.64	-1.61	-4.31	-7.69	-4.35	-4.95	-5.40	X:0.0.0.12X:0.0.0.12
X:0.1.05X:0.1.1.5																							X:0.0.0.11X:0.0.0.11		
					M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.0.10X:0.0.0.10		
X:0.1.04X:0.1.1.4																							X:0.0.0.09X:0.0.0.09		
					17.21	12.27	12.89	12.30	8.57	10.16	9.60	8.28	5.55										X:0.0.0.08X:0.0.0.08		
X:0.1.03X:0.1.1.3																							X:0.0.0.07X:0.0.0.07		
					M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.0.06X:0.0.0.06		
X:0.1.02X:0.1.1.2																							X:0.0.0.05X:0.0.0.05		
					11.67	9.77	7.88	6.46	6.21	5.54	6.09	3.23	4.66	4.58	-0.03	-0.69	-2.23	-1.24	-3.40	-2.52	-9.38	-7.02	-9.09	-9.57	X:0.0.0.04X:0.0.0.04
X:0.1.01X:0.1.1.1																							X:0.0.0.03X:0.0.0.03		
					M:0.19	M:0.18	M:0.17	M:0.16	M:0.15	M:0.14	M:0.13	M:0.12	M:0.9	M:0.8	M:0.7	M:0.6	M:0.5	M:0.4	M:0.3	M:0.2	M:0.1	M:0.0	X:0.0.0.02X:0.0.0.02		
X:0.1.00X:0.1.1.0																							X:0.0.0.01X:0.0.0.01		
					11.84	9.91	8.00	8.64	7.14	6.23	5.50	6.10	3.21	3.91	-2.08	0.29	2.31	-2.09	-3.83	-2.36	-7.13	-8.86	-7.34	-9.57	X:0.0.0.00X:0.0.0.00
X:0.0.1.15X:0.0.1.1.15																							X:0.0.0.1.15X:0.0.0.1.15		
																							X:0.0.0.1.14X:0.0.0.1.14		
X:0.0.1.14X:0.0.1.1.14																							X:0.0.0.1.13X:0.0.0.1.13		
																							X:0.0.0.1.12X:0.0.0.1.12		
X:0.0.1.13X:0.0.1.1.13																							X:0.0.0.1.11X:0.0.0.1.11		
																							X:0.0.0.1.10X:0.0.0.1.10		
X:0.0.1.12X:0.0.1.1.12																							X:0.0.0.1.09X:0.0.0.1.09		
X:0.0.1.11X:0.0.1.1.11																							X:0.0.0.1.08X:0.0.0.1.08		
																							X:0.0.0.1.07X:0.0.0.1.07		
X:0.0.1.10X:0.0.1.1.10																							X:0.0.0.1.06X:0.0.0.1.06		
																							X:0.0.0.1.05X:0.0.0.1.05		
X:0.0.1.09X:0.0.1.1.9																							X:0.0.0.1.04X:0.0.0.1.04		
																							X:0.0.0.1.03X:0.0.0.1.03		
X:0.0.1.08X:0.0.1.1.8																							X:0.0.0.1.02X:0.0.0.1.02		
																							X:0.0.0.1.01X:0.0.0.1.01		
X:0.0.1.07X:0.0.1.1.7																							X:0.0.0.1.00X:0.0.0.1.00		
																							X:0.0.0.0.15X:0.0.0.0.15		
X:0.0.1.06X:0.0.1.1.6																							X:0.0.0.0.14X:0.0.0.0.14		
																							X:0.0.0.0.13X:0.0.0.0.13		
X:0.0.1.05X:0.0.1.1.5																							X:0.0.0.0.12X:0.0.0.0.12		
X:0.0.1.04X:0.0.1.1.4																							X:0.0.0.0.11X:0.0.0.0.11		
																							X:0.0.0.0.10X:0.0.0.0.10		
X:0.0.1.03X:0.0.1.1.3																							X:0.0.0.0.09X:0.0.0.0.09		
																							X:0.0.0.0.08X:0.0.0.0.08		
X:0.0.1.02X:0.0.1.1.2																									

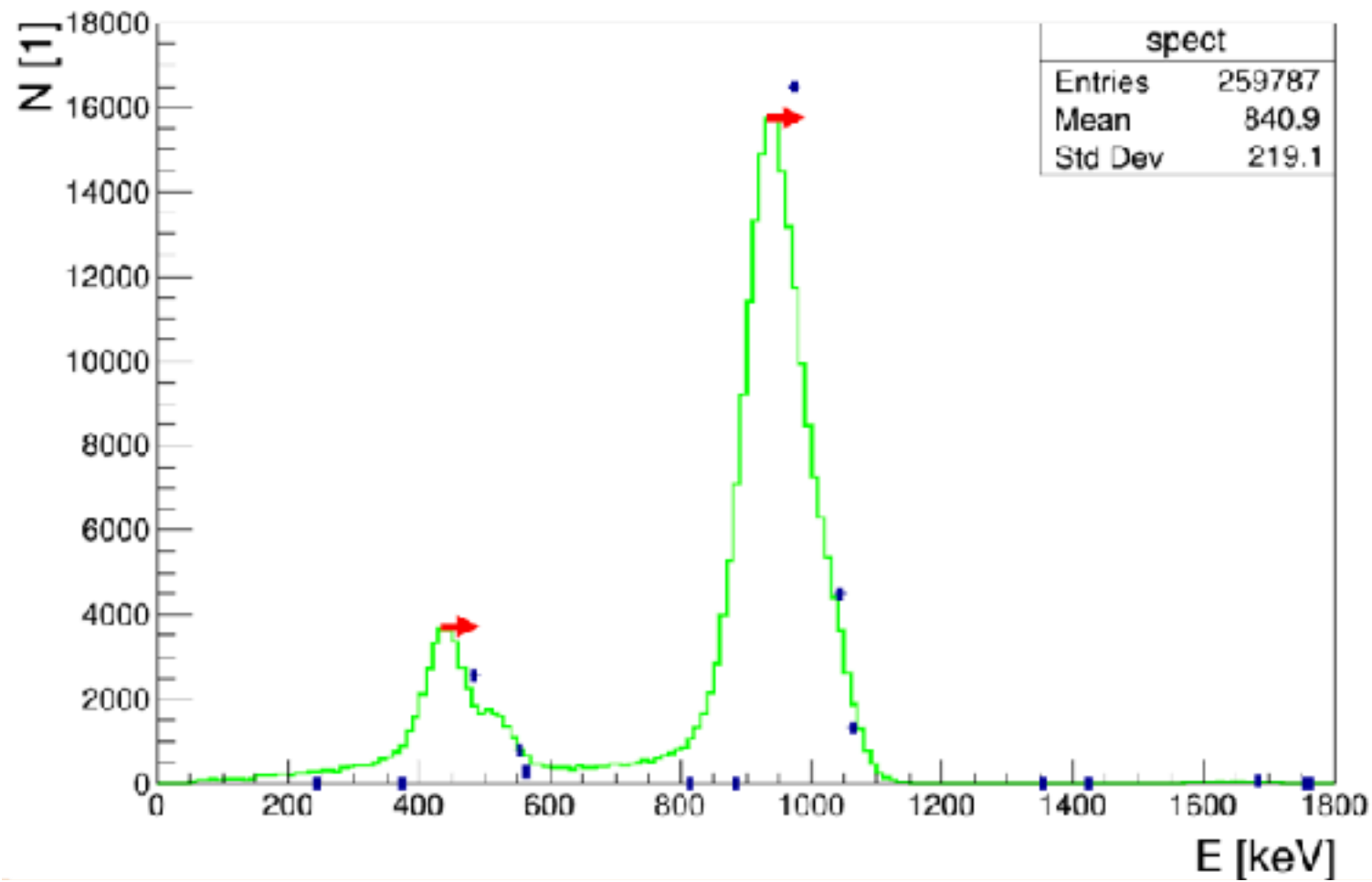
ITALY TUNNEL	G:0.1.15	G:0.1.14	G:0.1.13	G:0.1.12	G:0.1.11	G:0.1.10	G:0.1.9	G:0.1.8	G:0.1.7	G:0.1.6	G:0.1.5	G:0.1.4	G:0.1.3	G:0.1.2	G:0.1.1	G:0.1.0	MOUNTAIN				
	X:0.1.15	X:0.1.14	X:0.1.13	X:0.1.12	X:0.1.11	X:0.1.10	X:0.1.9	X:0.1.8	X:0.1.7	X:0.1.6	X:0.1.5	X:0.1.4	X:0.1.3	X:0.1.2	X:0.1.1	X:0.1.0					
X:0.1.15	0.84	1.07	0.71	0.76	0.68	0.80	0.65	0.81	0.76	0.78	0.91	0.79	1.02	0.75	1.06	0.73	0.68	0.90	0.92	0.90	X:0.0.15
X:0.1.14																					X:0.0.14
X:0.1.13	0.42	0.51	0.69	0.60	0.60	0.67	0.61	0.63	0.55	0.53	0.56	0.61	0.56	0.70	0.63	0.66	0.45	0.58	0.66		X:0.0.13
X:0.1.12	0.70	0.60	0.52	0.69	0.62		0.72	0.62	0.56	0.67	0.60	0.68	0.55	0.73	0.58	0.64	0.64	0.59	0.53	0.54	X:0.0.12
X:0.1.11	0.61	0.63	0.57	0.69	0.70	0.60	0.71	0.46	0.55	0.53	0.46	0.66	0.64	0.65	0.68	0.55	0.49	0.49			X:0.0.11
X:0.1.10	0.62	0.86	0.61	0.69	0.66	0.56	0.51	0.65	0.58	0.51	0.63	0.61	0.57	0.66	0.66	0.63	0.68				X:0.0.10
X:0.1.9	0.52	0.56	0.50	0.50	0.59	0.50	0.73	0.63	0.54	0.58	0.60	0.51		0.51	0.63	0.64	0.62	0.69	0.57	0.56	X:0.0.9
X:0.1.8	0.51	0.54	0.57	0.64	0.53	0.62	0.66	0.65	0.66	0.62	0.57	0.64	0.63	0.65	0.66	0.63	0.65	0.66	0.60	0.59	X:0.0.8
X:0.1.7	0.63	0.57	0.72	0.62	0.66	0.60	0.55	0.62	0.53	0.47	0.55	0.51	0.63	0.62	0.53	0.67	0.61	0.51	0.55	0.44	X:0.0.7
X:0.1.6	0.75	0.67	0.61	0.56	0.60	0.61	0.64	0.58	0.67	0.68	0.66	0.67	0.58	0.55	0.60	0.79	0.58	0.58	0.39	0.60	X:0.0.6
X:0.1.5	0.74	0.72	0.37	0.43	0.57	0.52	0.64	0.68		0.64	0.54	0.59	0.63	0.64	0.48	0.59	0.67	0.43	0.48	0.64	X:0.0.5
X:0.1.4	0.55	0.67	0.54	0.74	0.58	0.62	0.51	0.56	0.64	0.64		0.67	0.64				0.53	0.65	0.64	0.58	X:0.0.4
X:0.1.3	0.52	0.66	0.50	0.67	0.68	0.56	0.46	0.62	0.62	0.55	0.58	0.62	0.61	0.69	0.66	0.65	0.55	0.62	0.73	0.69	X:0.0.3
X:0.1.2	0.66	1.07	0.77	0.84	0.83	0.99	0.81	0.83	0.92	0.82	0.88	0.96	0.72	0.68	0.99	0.80	0.86	0.86	0.76	0.83	X:0.0.2
X:0.1.1																					X:0.0.1
X:0.1.0																					X:0.0.0
row	G:0.0.15	G:0.0.14	G:0.0.13	G:0.0.12	G:0.0.11	G:0.0.10	G:0.0.9	G:0.0.8	G:0.0.7	G:0.0.6	G:0.0.5	G:0.0.4	G:0.0.3	G:0.0.2	G:0.0.1	G:0.0.0	NOTATIONS: wall:module.side.col,row wall:module.col,row				
column	G:0.0.15	G:0.0.14	G:0.0.13	G:0.0.12	G:0.0.11	G:0.0.10	G:0.0.9	G:0.0.8	G:0.0.7	G:0.0.6	G:0.0.5	G:0.0.4	G:0.0.3	G:0.0.2	G:0.0.1	G:0.0.0					

Time-delay calibration

Energy calibration



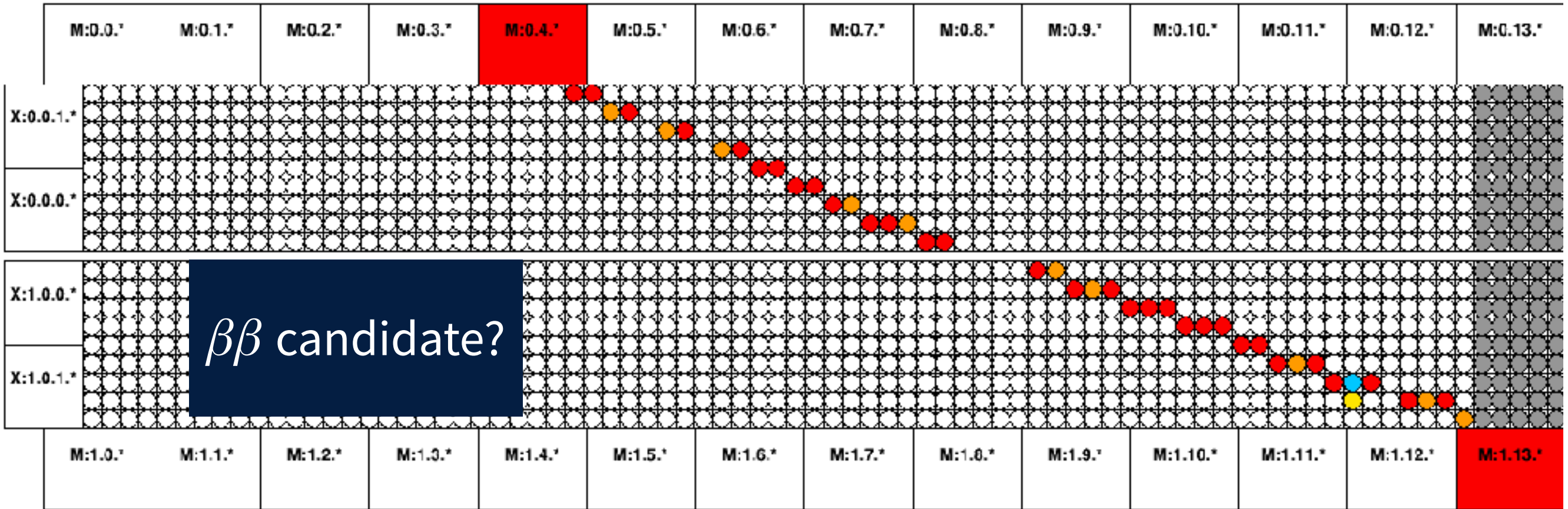
... with ambient sources



... with our automatic ^{207}Bi source deployment system

SuperNEMO Demonstrator status: Tracker

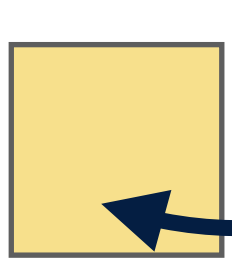
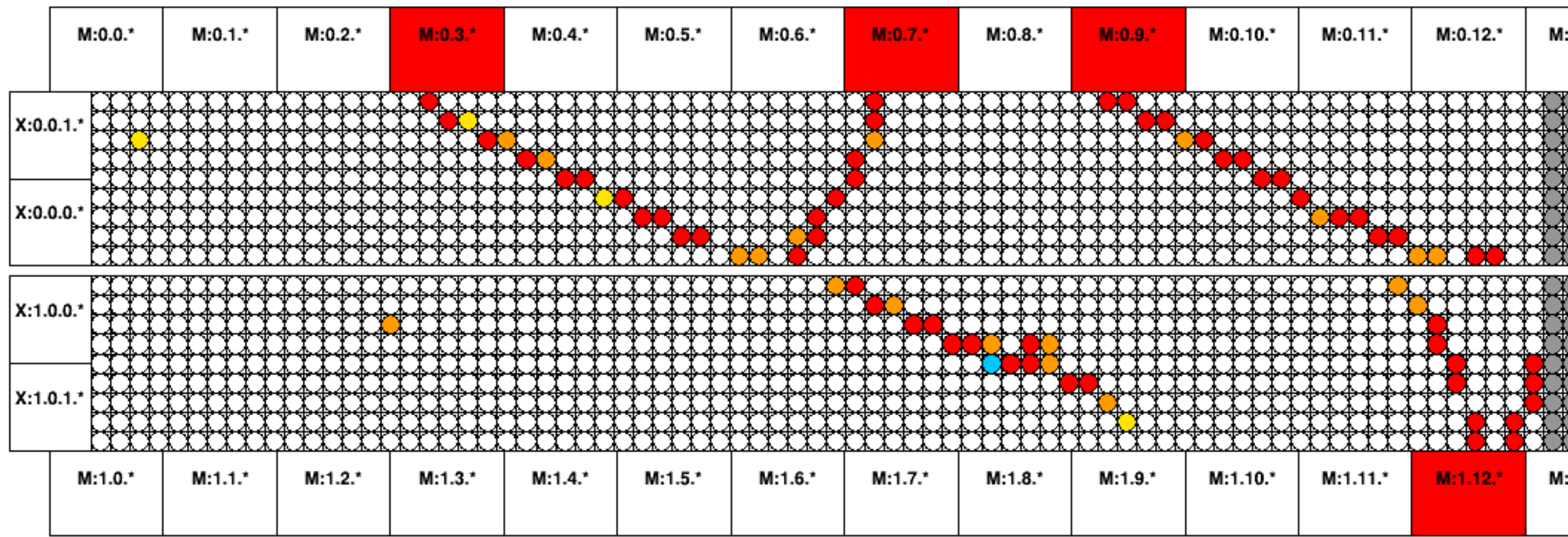
RUN 807 // TRIGGER 458



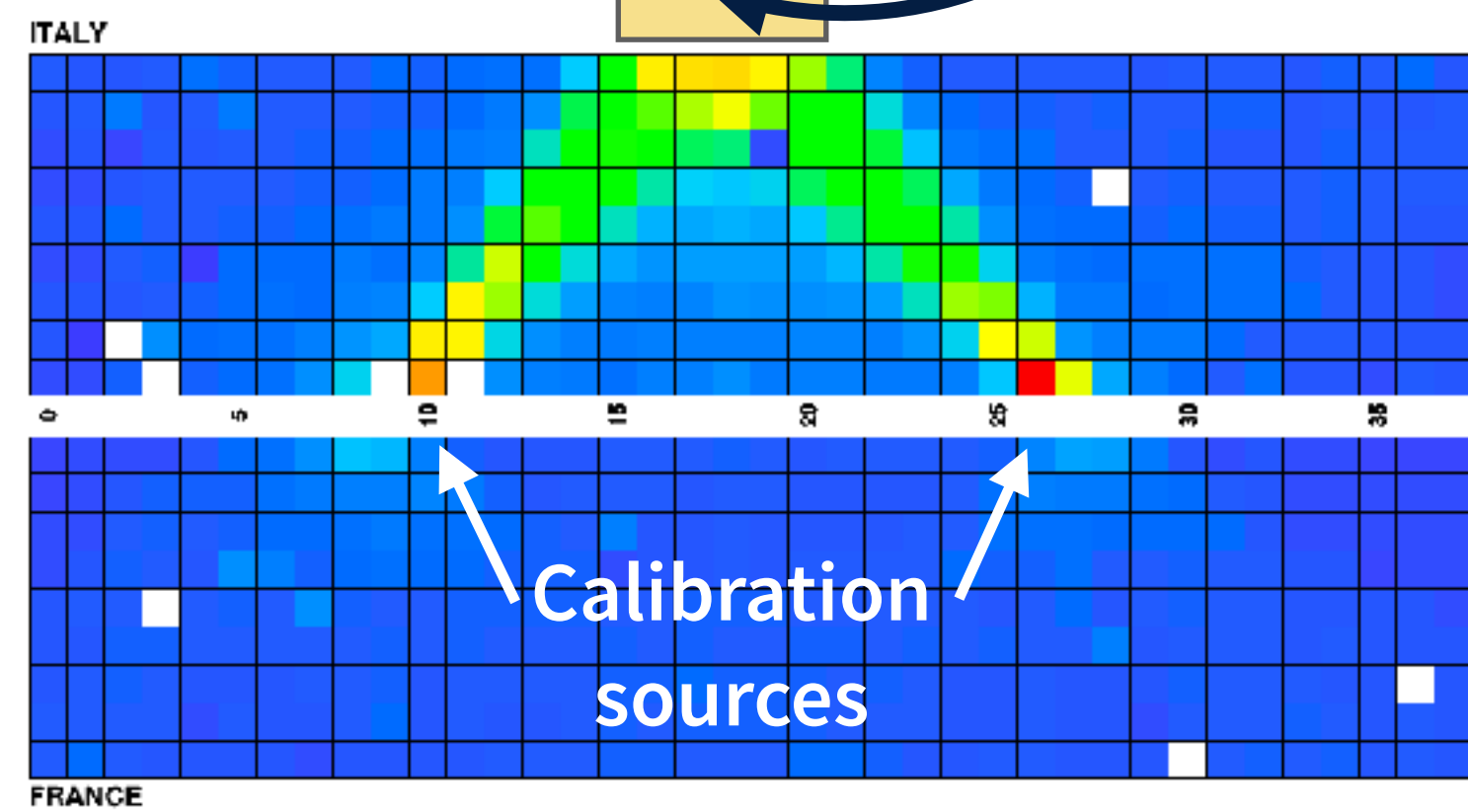
- **Dramatic progress** over the last year after setbacks due to Covid, faulty hardware...
- **Entire tracker successfully tested** at high voltage
- 2/3 of detector undergoing commissioning / calibration
- Final 1/3 to be connected shortly
- **~99% of connected channels operational**

Real tracker-calorimeter data!

RUN 807 // TRIGGER 840+841

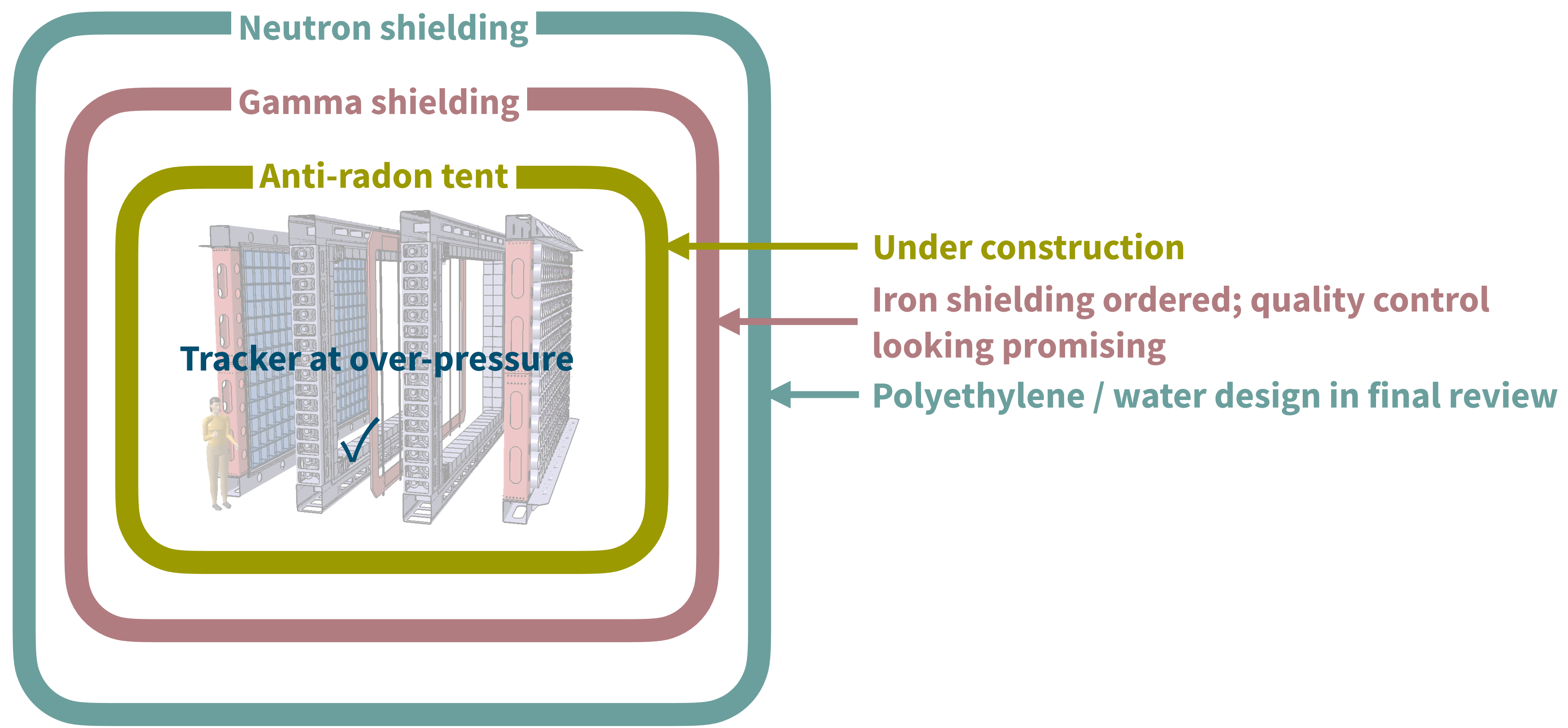


Tracker hits activating
this optical module

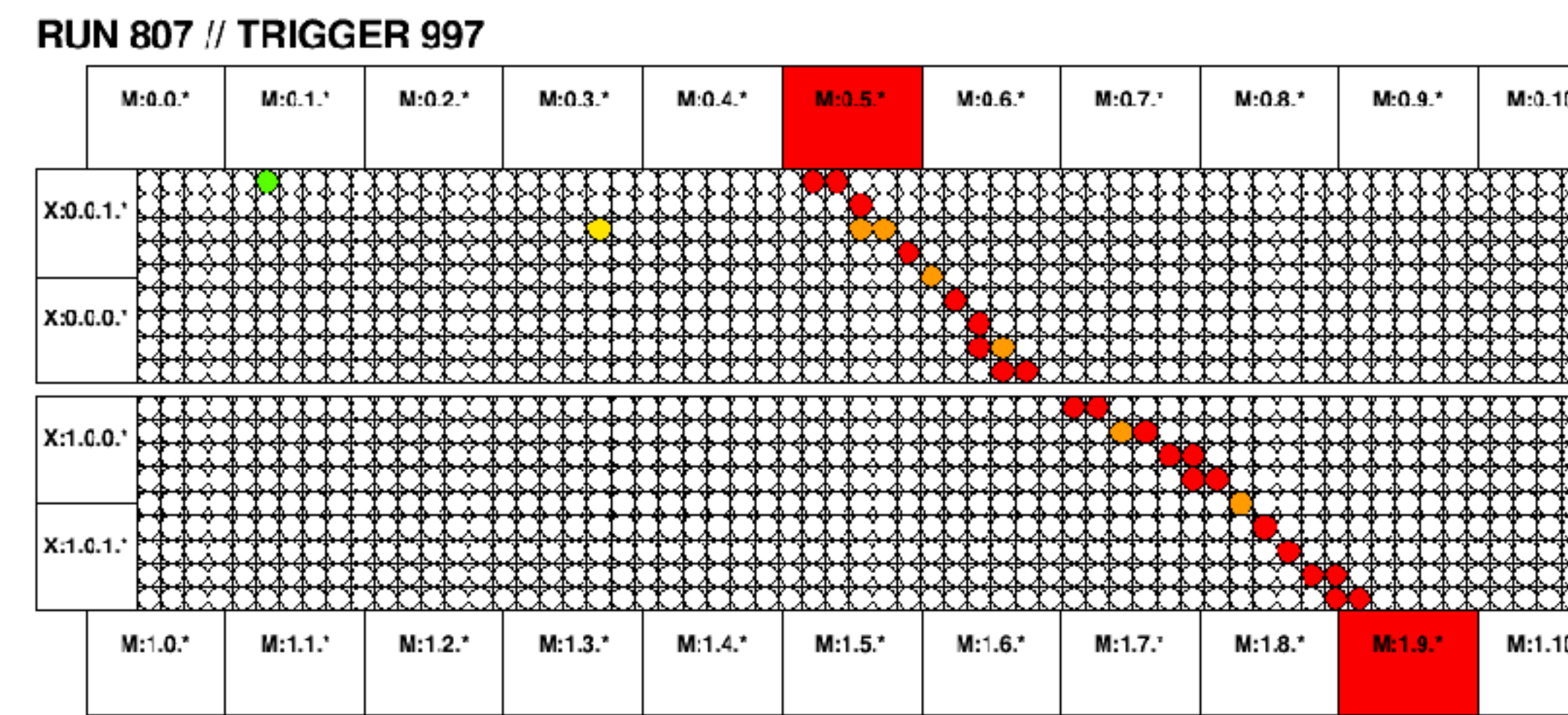
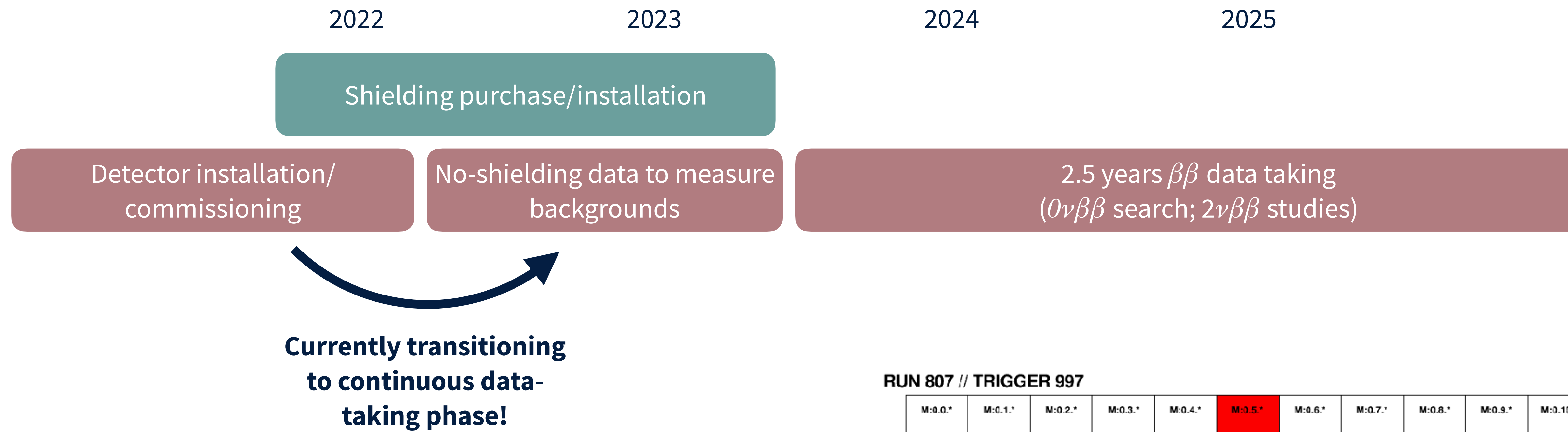


Automatic ^{207}Bi calibration system in action

Getting ready for physics data

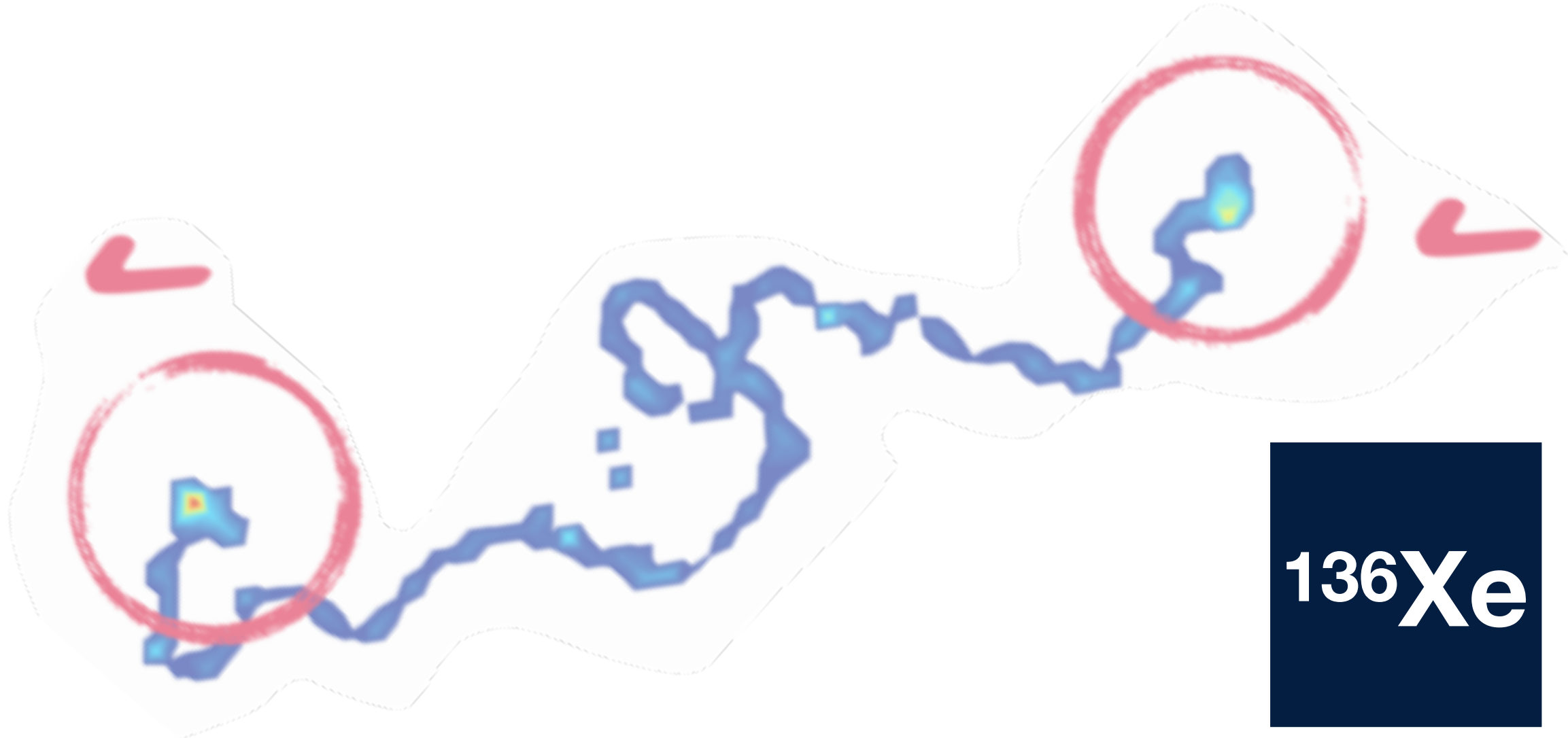


Getting ready for physics data



Other UK activities





^{136}Xe

^{134}Xe

Thanks to Roxanne Guenette for content



^{136}Xe

^{134}Xe

Thanks to Sally Shaw for content



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Of
Sheffield.

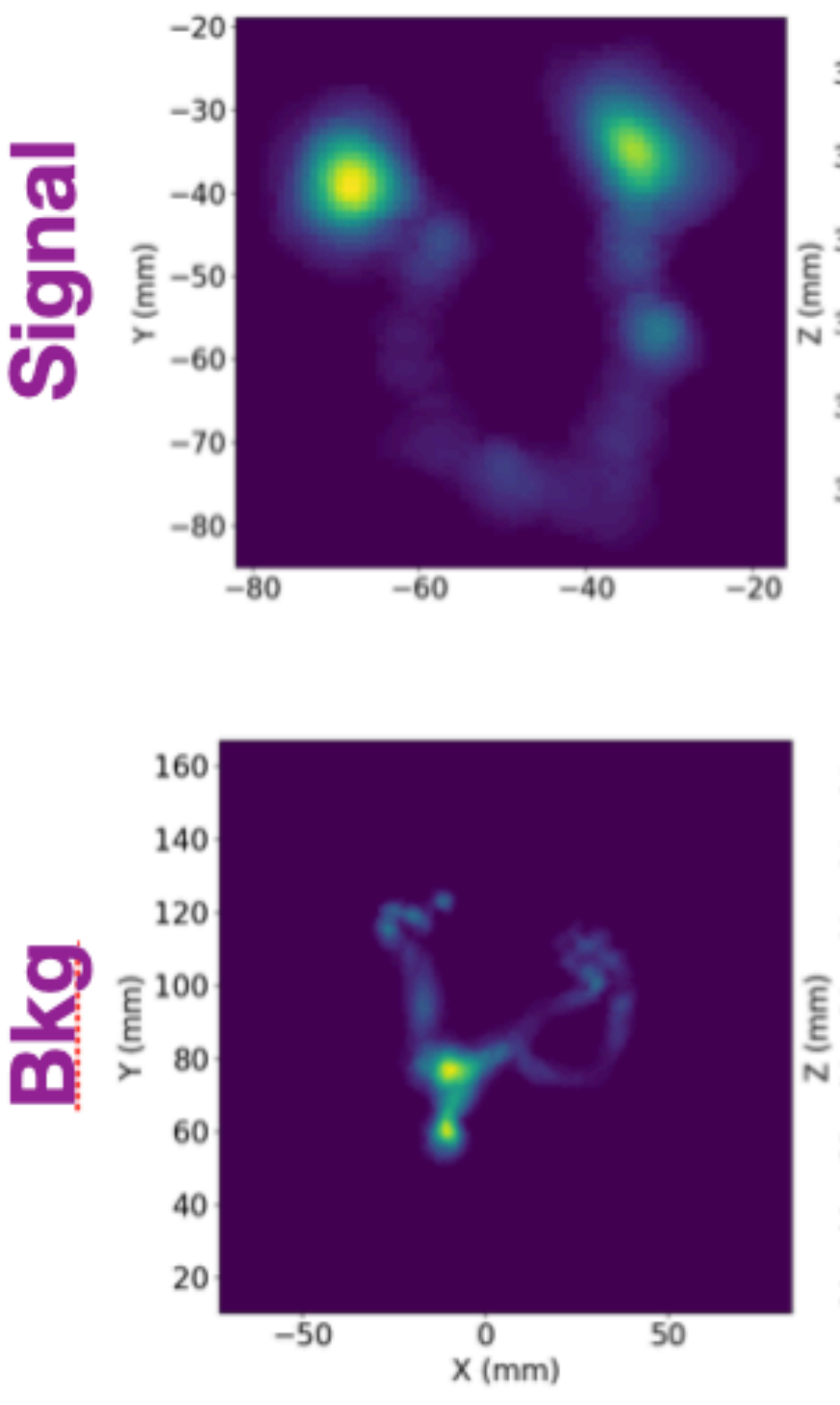


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OF LONDON

Imperial College
London

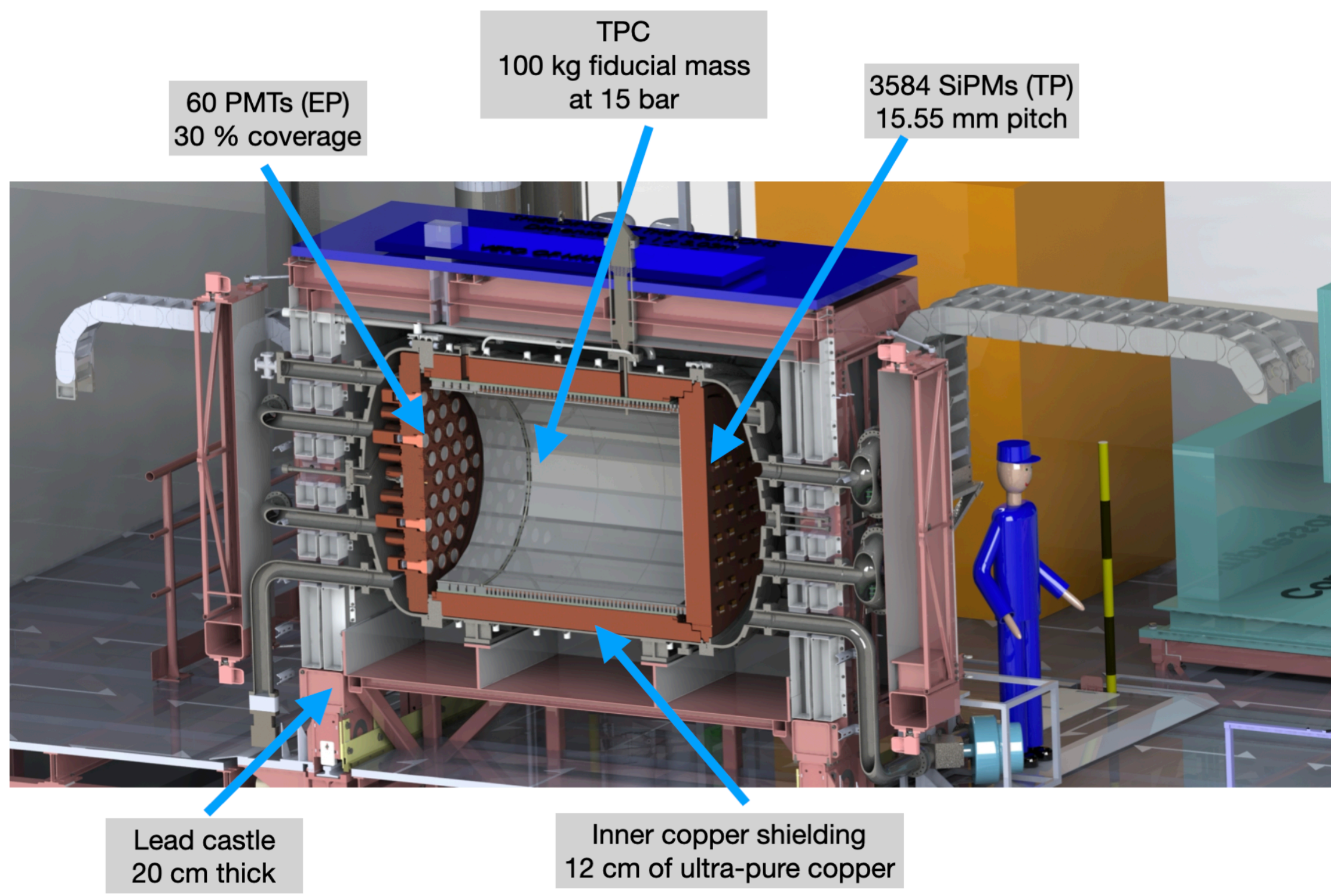
NEXT high-pressure gaseous ^{136}Xe TPC

Topological Identification

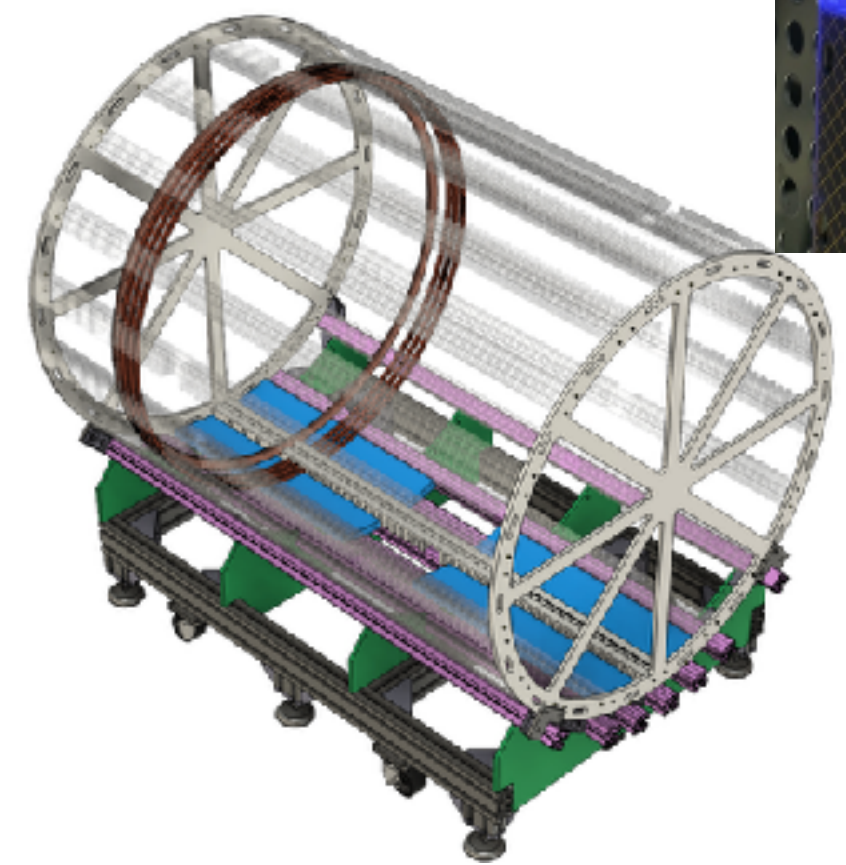
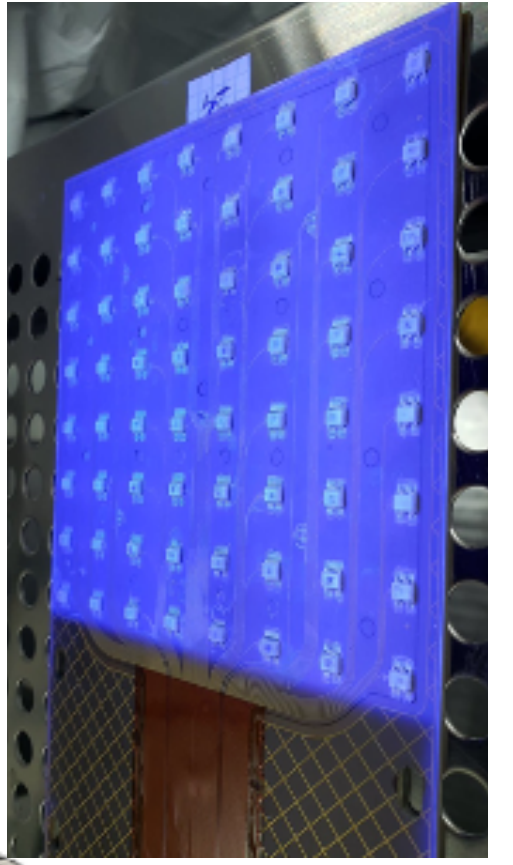
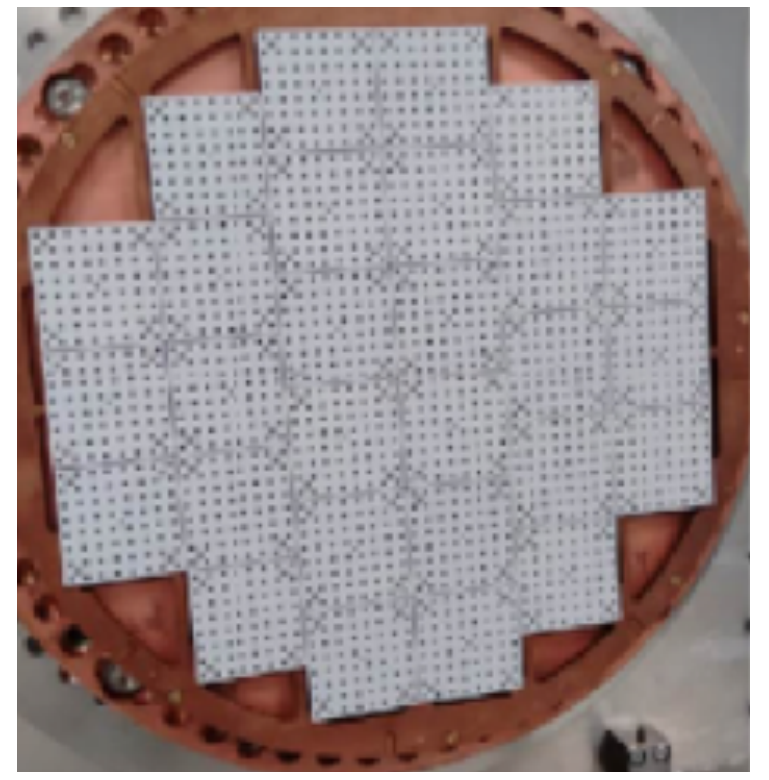


NEXT Collaboration, JHEP 01 (2021) 189
NEXT Collaboration, JHEP 10 (2019) 052

NEXT-100 (2022-2025) proves scalability

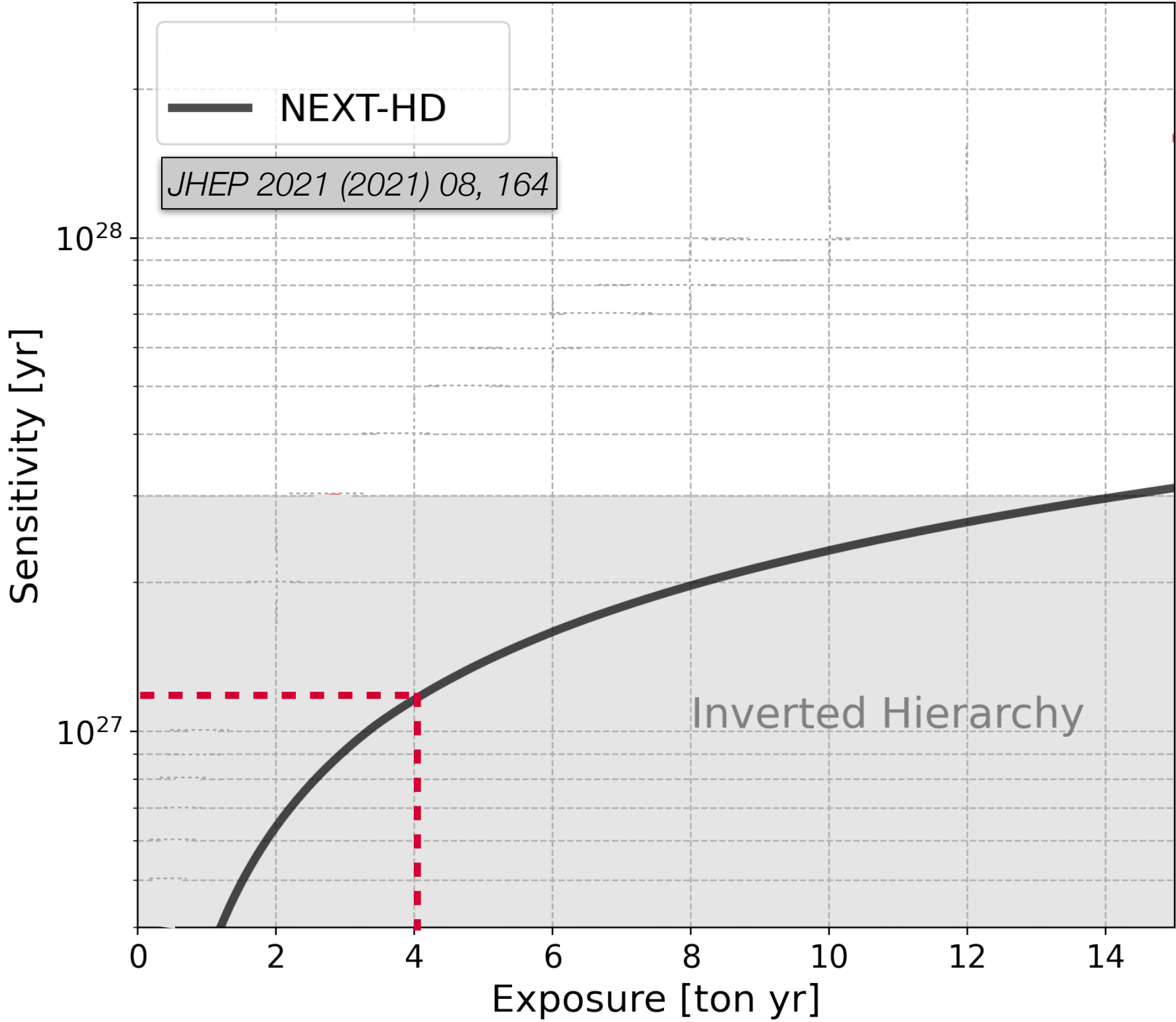


R&D on new tracking and energy plane with SiPMs



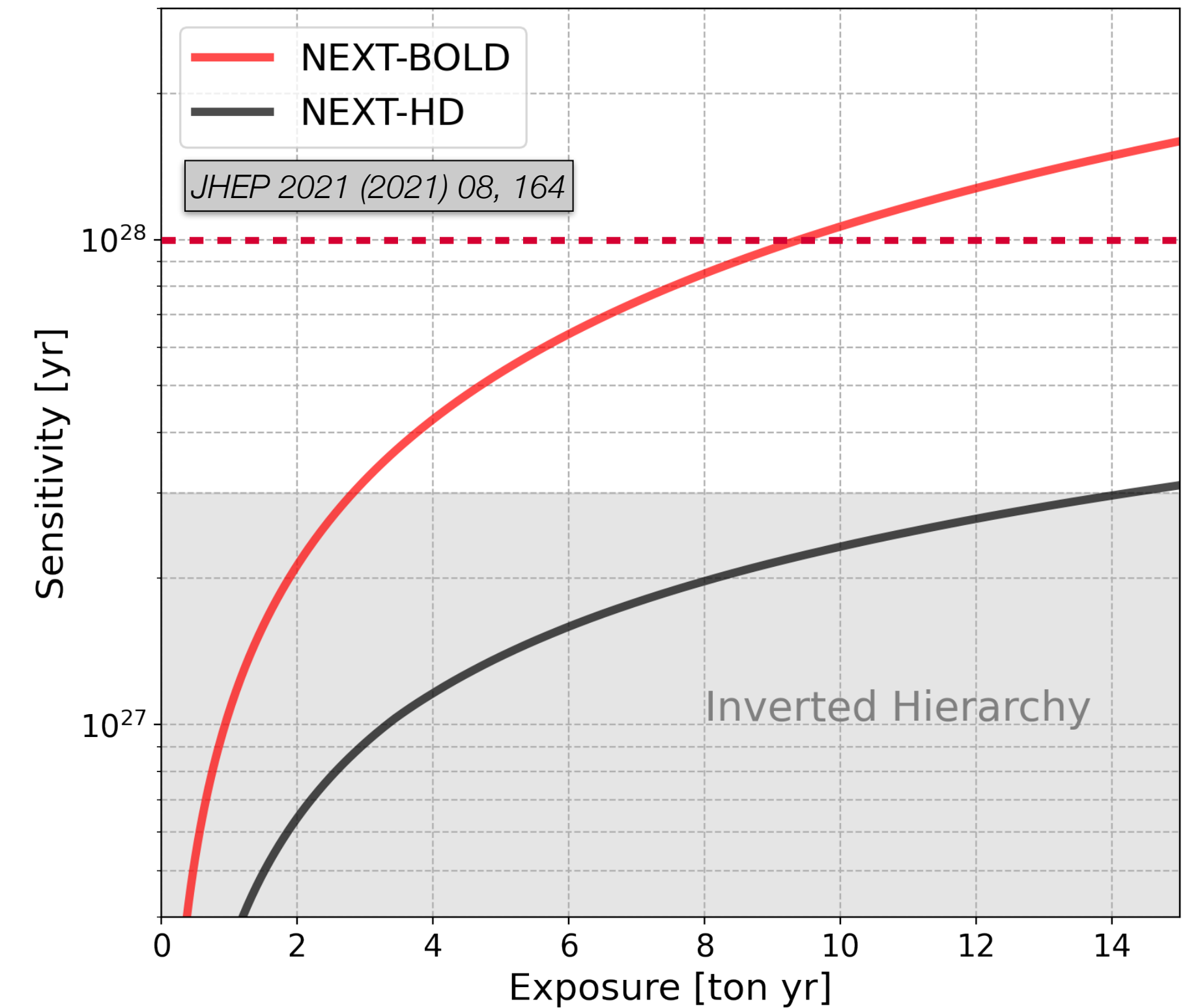
TPC installation UK-led

- NEXT-HD's first module can reach $T_{1/2} > \mathbf{10^{27} \text{ yr}}$ $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure



NEXT ton-scale and beyond

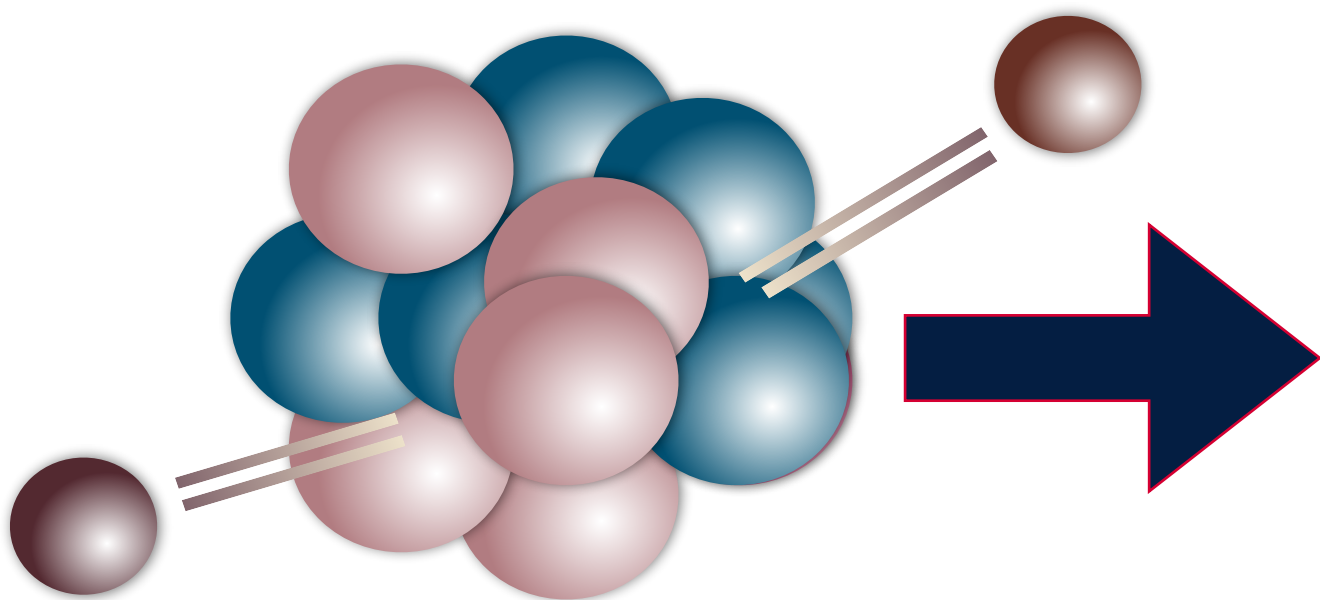
- NEXT-HD's first module can reach $T_{1/2} > \mathbf{10^{27} \text{ yr}}$ $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure
- NEXT-BOLD: seeks 10^{28} -year sensitivity through **barium tagging technology**



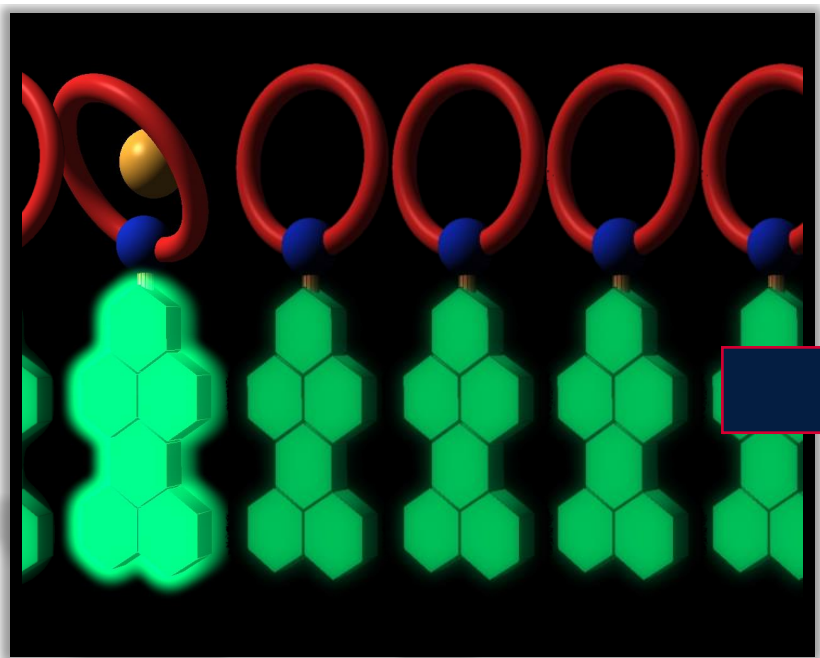
- NEXT-HD's first module can reach $T_{1/2} > 10^{27}$ yr $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure
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J. Phys.Conf.Ser 650 (2015) 1, 012002;
JINST 11 (2016) 12, P12011;
Phys.Rev.Lett 120 (2018) 13 132504;
Sci.Rep. 9 (2019) 1, 15097;
Nature 583 (2020) 7814 48-54;
ACS Sens. (2021) 6, 1, 192-202;
arXiv:2201.09099;
arXiv:2109.05902

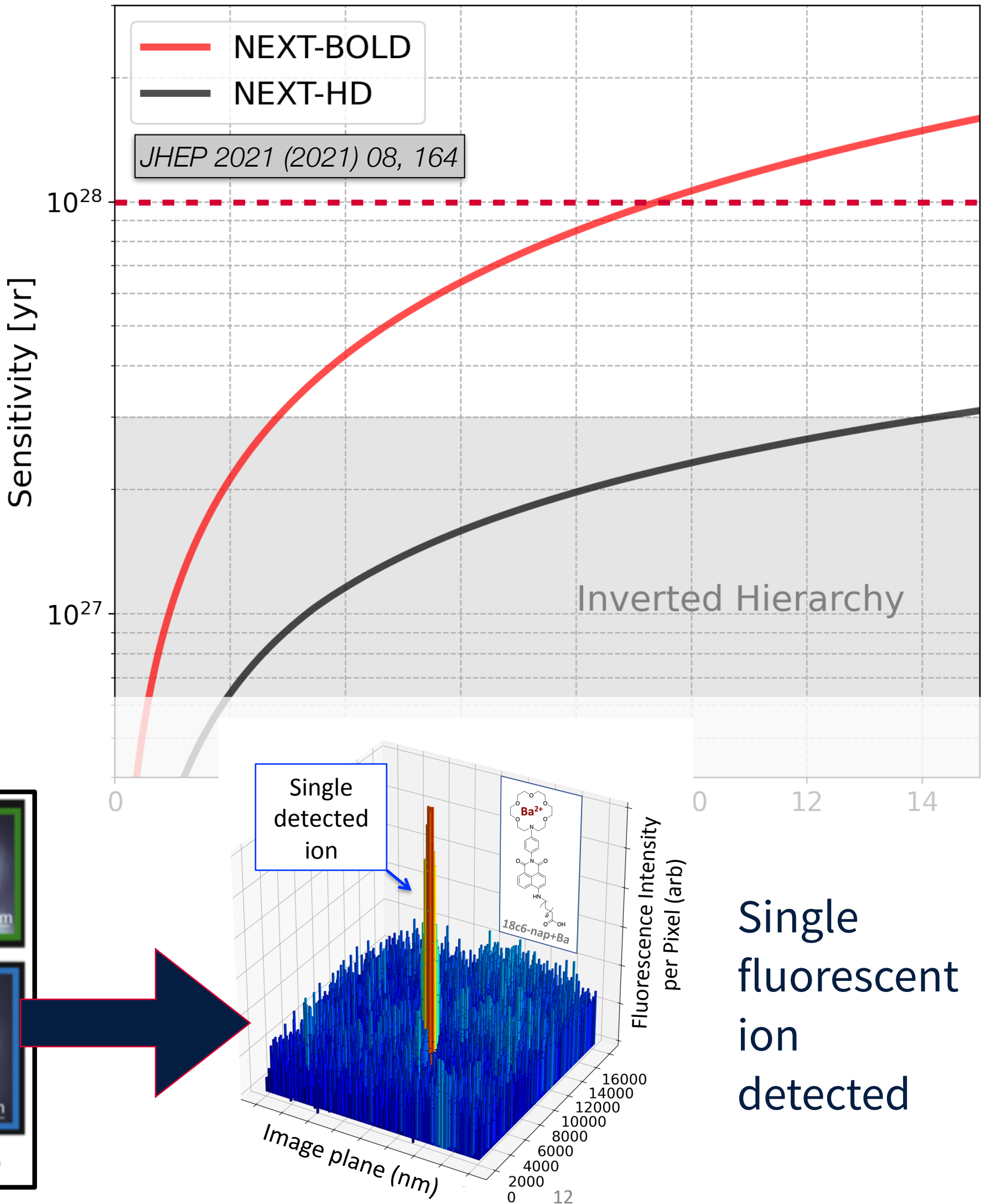
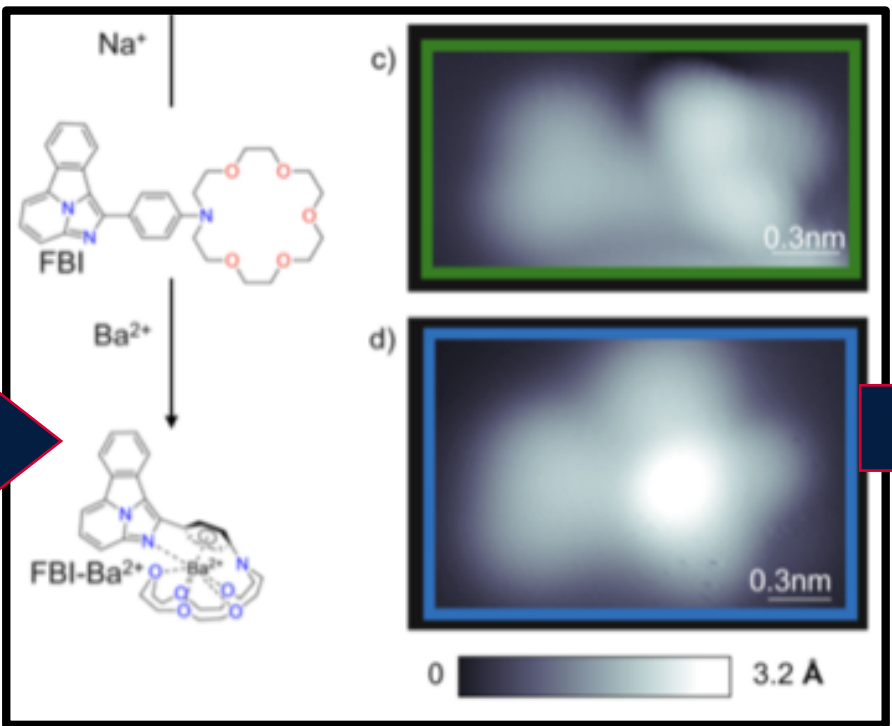
Ba²⁺ $\beta\beta$ decay product



Ba²⁺ chelation

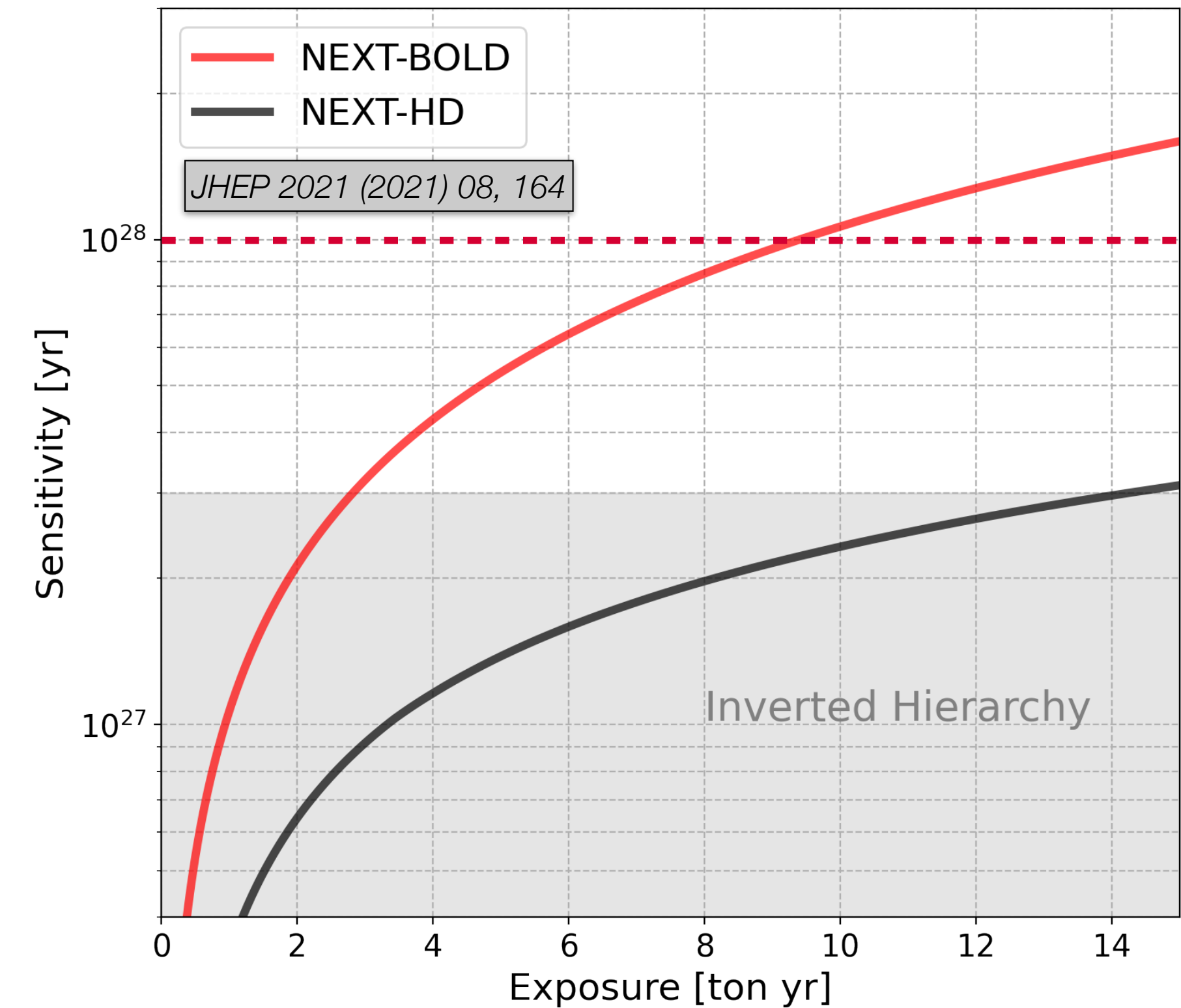


Molecule fluoresces



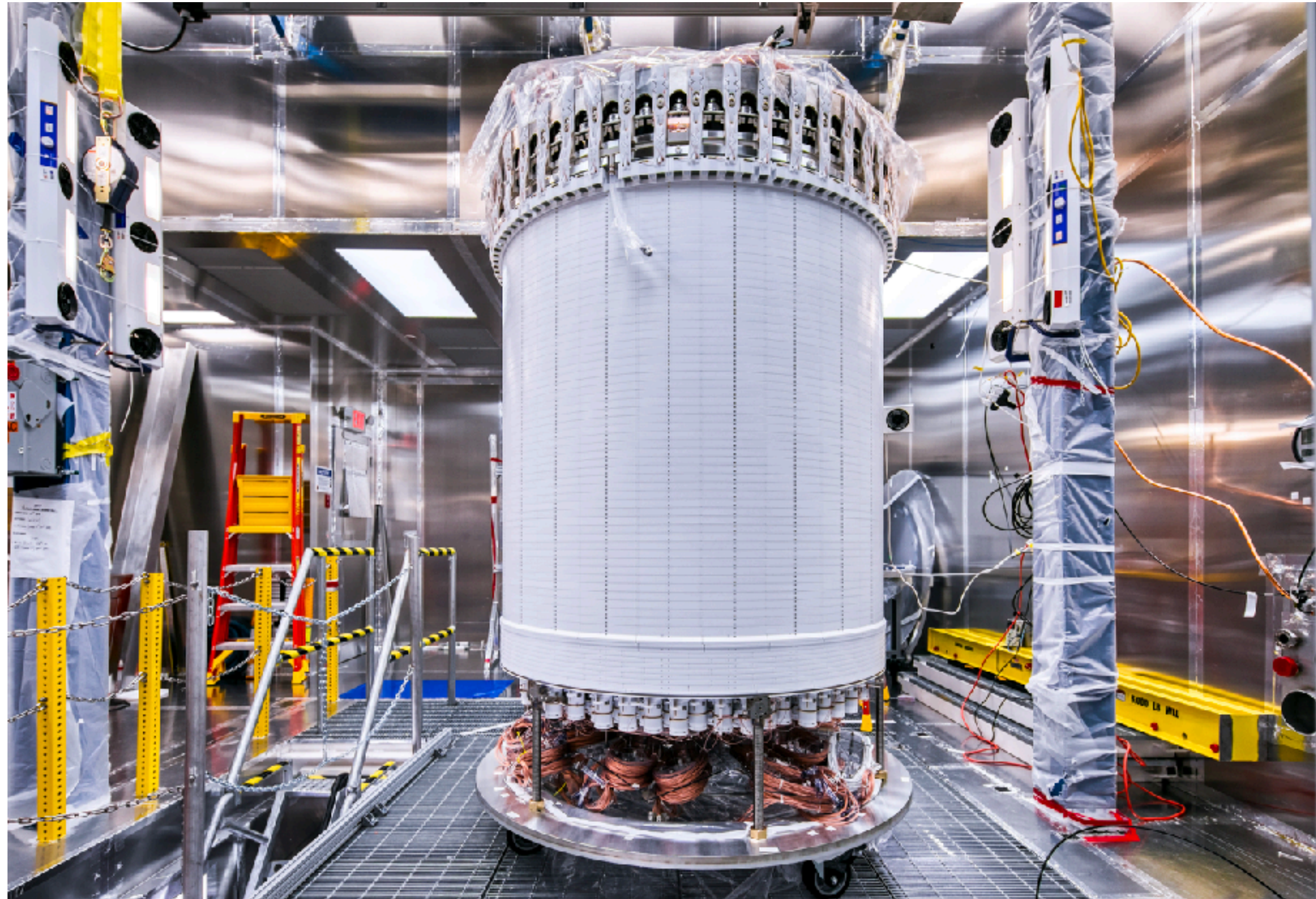
NEXT ton-scale and beyond

- NEXT-HD's first module can reach $T_{1/2} > \mathbf{10^{27} \text{ yr}}$ $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure
- NEXT-BOLD: seeks 10^{28} -year sensitivity through **barium tagging technology**
- Unambiguous signature for $\beta\beta \rightarrow$ background free
- R&D needed to scale up to 1-ton detectors...





LUX-ZEPLIN dark-matter detector



The day job:

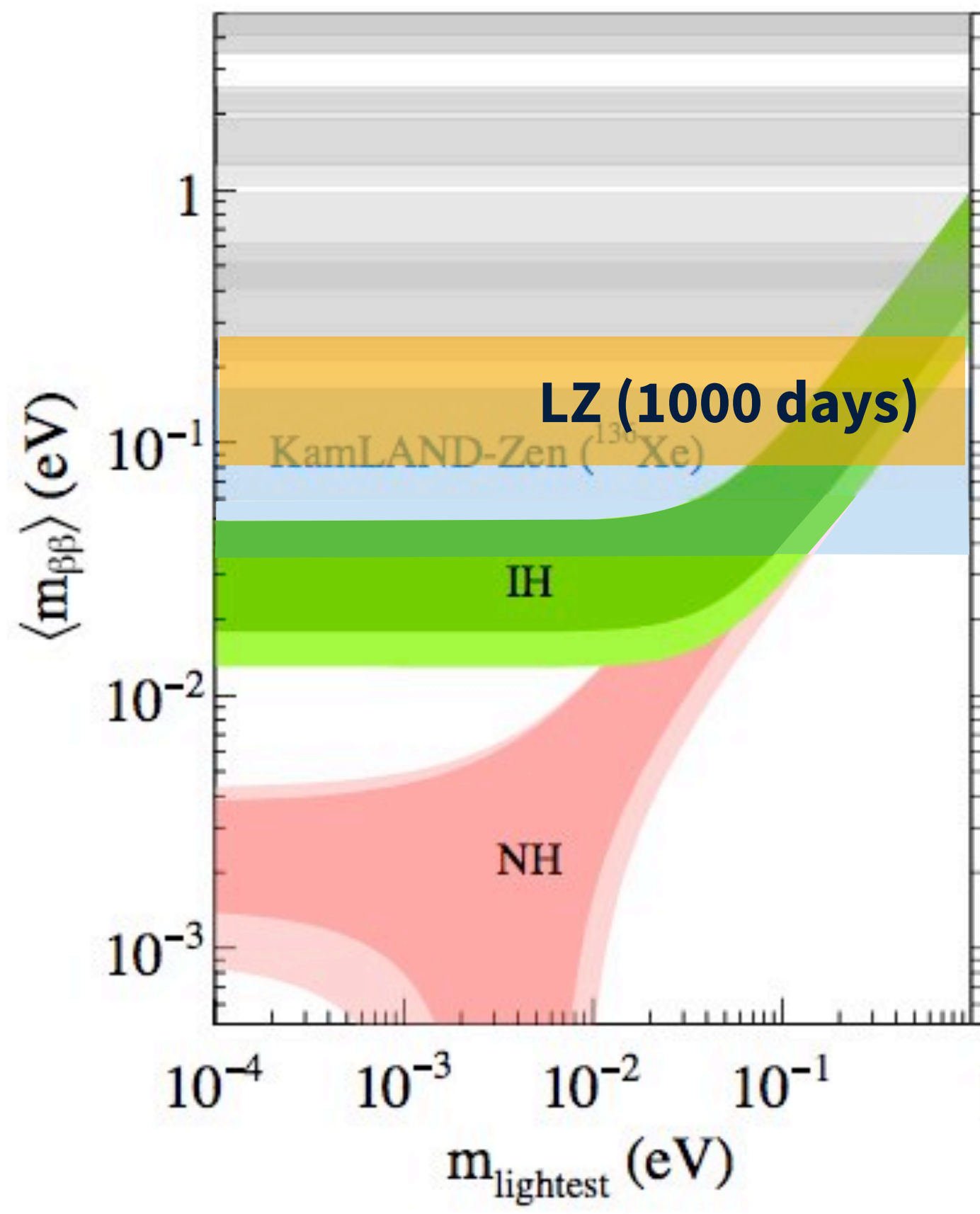
- 7-ton liquid-xenon TPC for direct dark-matter detection

The side hustles:

- Two $\beta\beta$ xenon isotopes: ^{134}Xe and ^{136}Xe

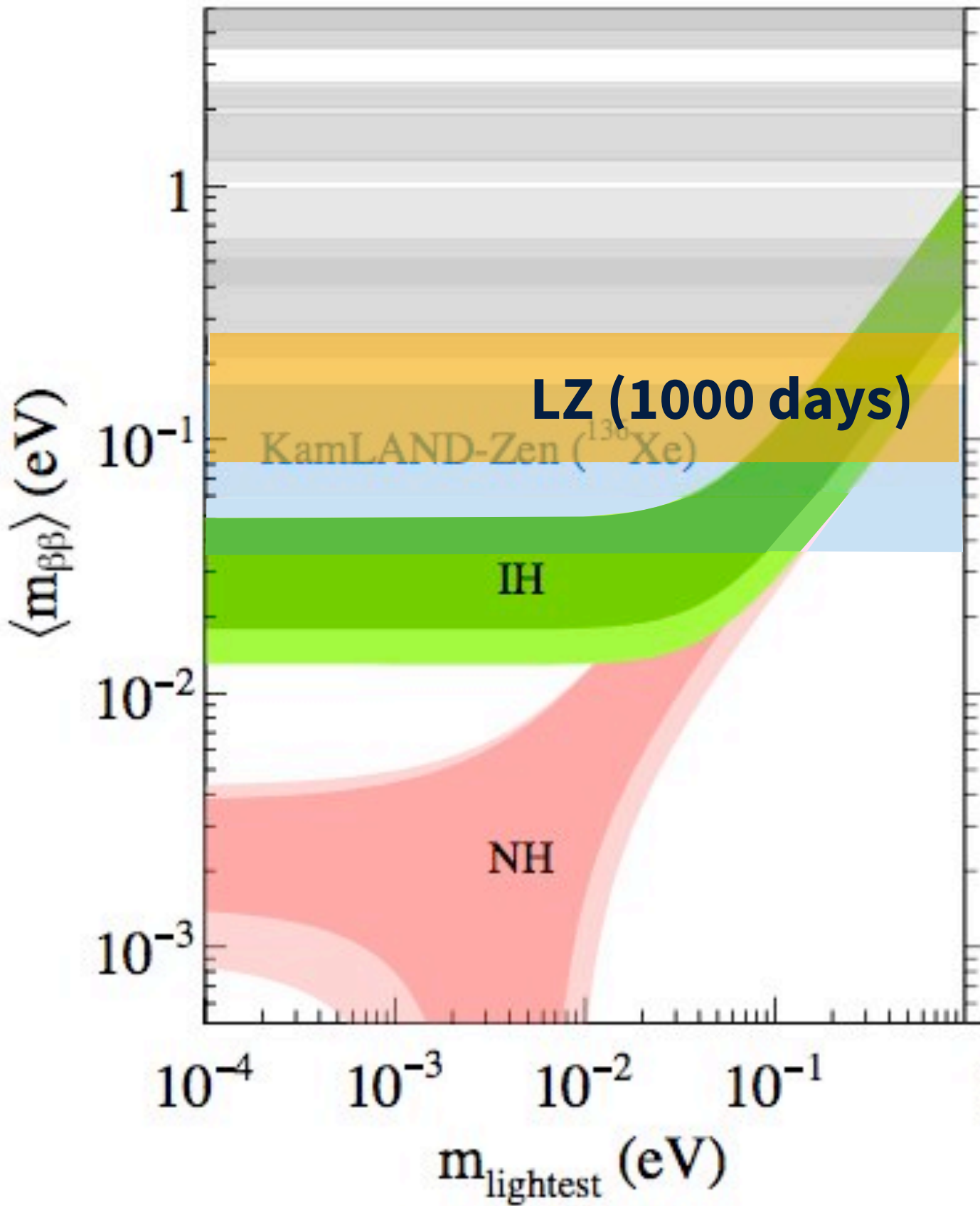


Current LZ xenon detector
(8.9% ^{136}Xe) won't see $0\nu\beta\beta$

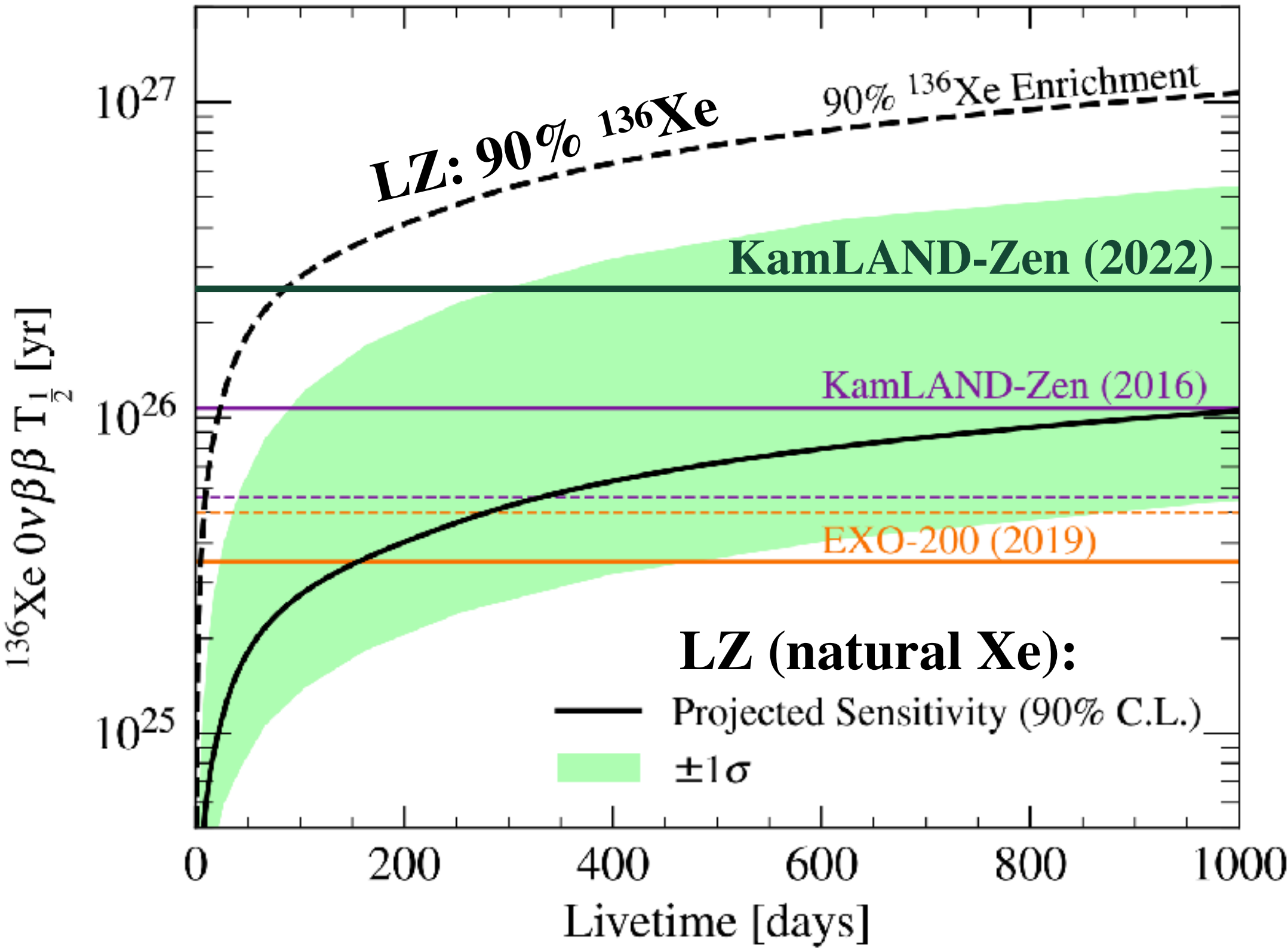




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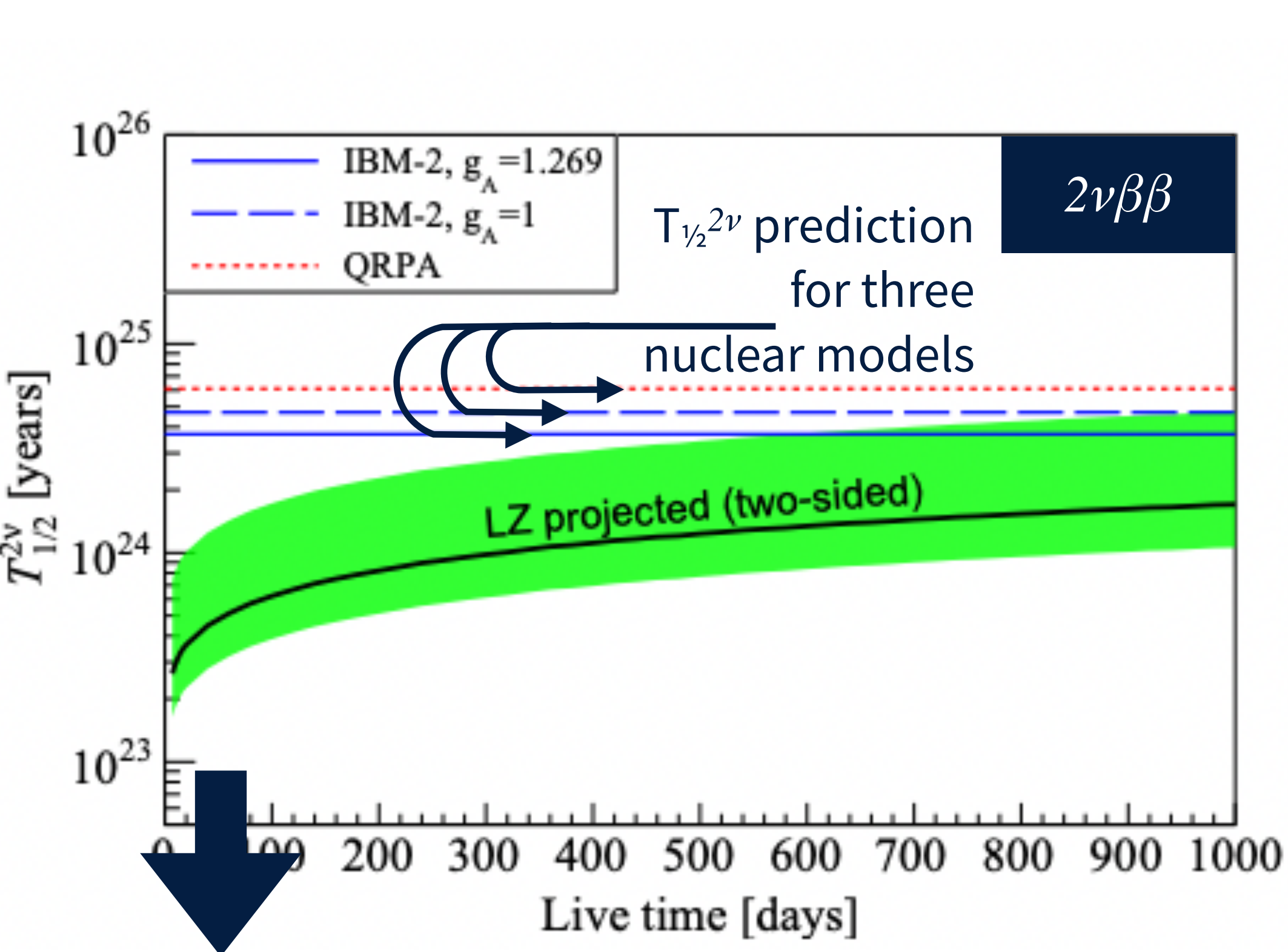


- **After WIMP search:** enrich with 90% ^{136}Xe ?
- Potential for 10^{27} -year sensitivity - beyond current best limit



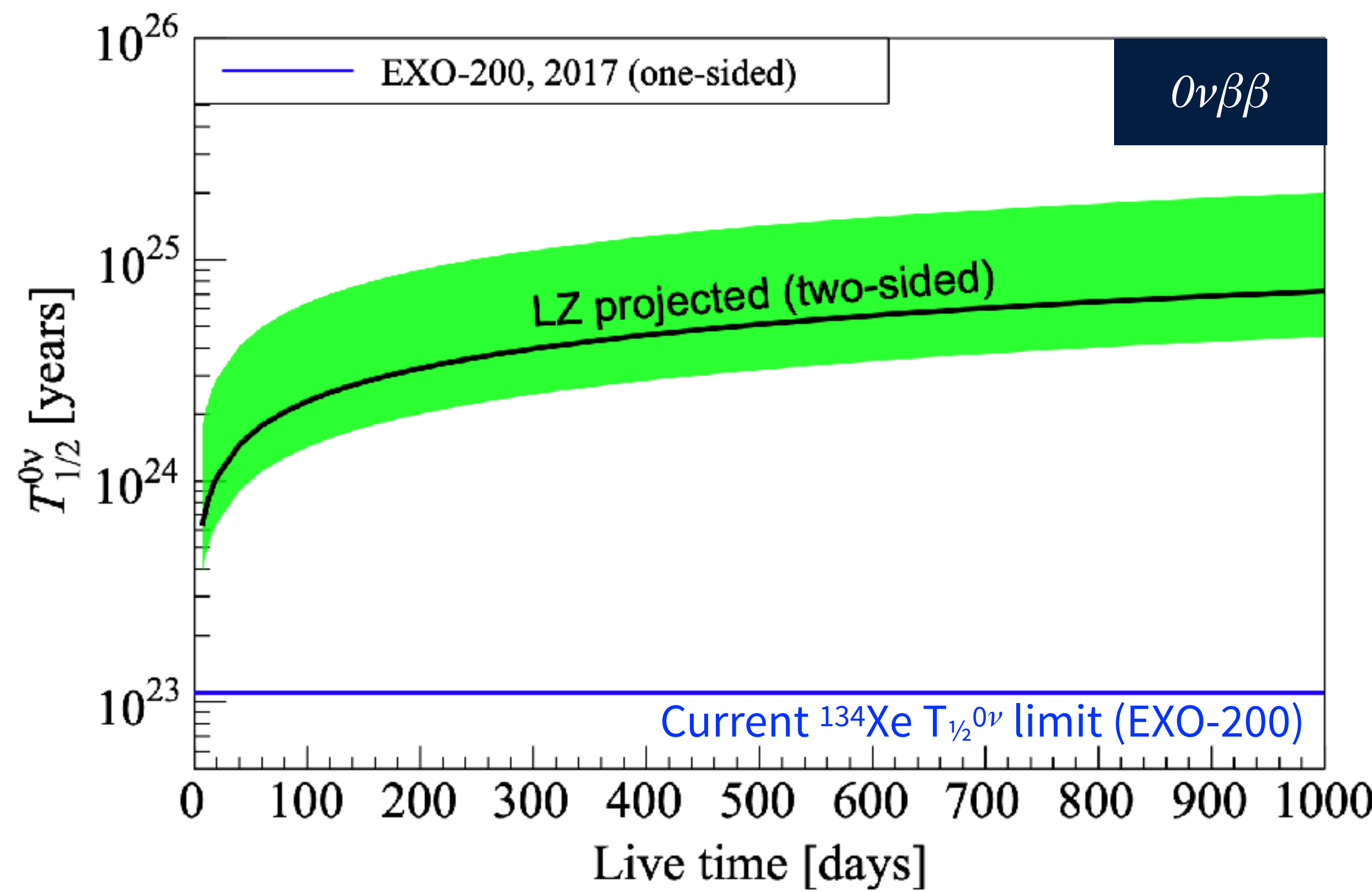


- Abundance 10.4%
- $2\nu\beta\beta$ predicted with very long half-life
- Experimental limit $T_{1/2}^{2\nu} > 8.7 \times 10^{20}$ years (EXO-200)



Experimental limit 100 times shorter

LZ's neutral-Xe detector could improve the limit at short exposure for $2\nu\beta\beta$ and $0\nu\beta\beta$

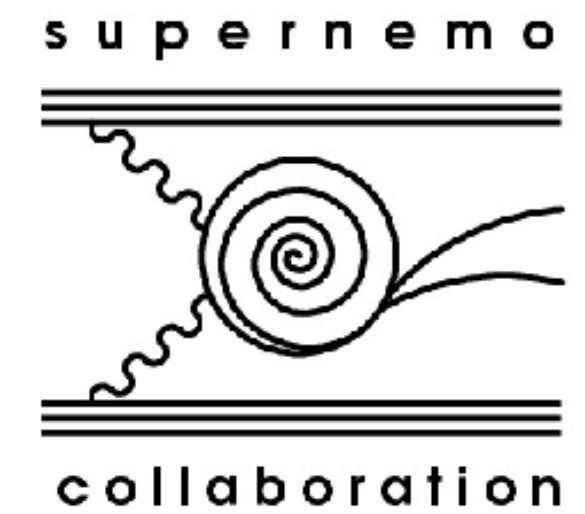


Summary of UK strategy

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- Substantial prior UK investment
- Two completely unique physics programmes



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2) Next-generation: LEGEND

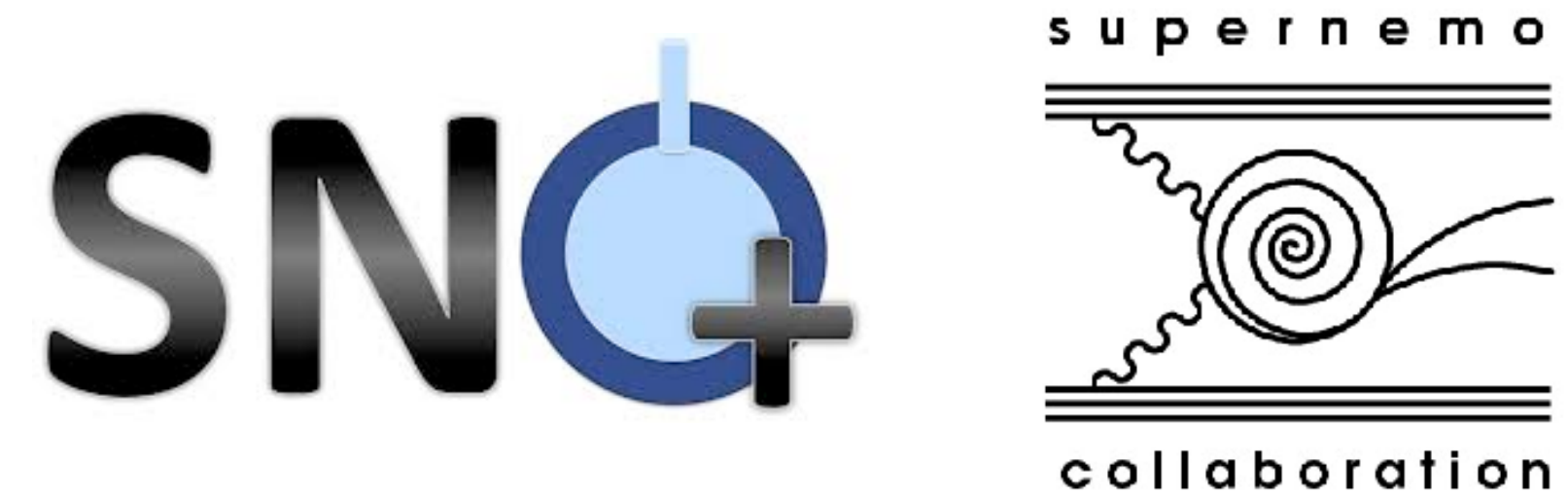
- Supported by both US and EU roadmaps
- LEGEND-200 exploitation
- LEGEND-1000 preparations



Summary of UK strategy

1) Continued support for SNO+ and SuperNEMO Demonstrator exploitation

- Substantial prior UK investment
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2) Next-generation: LEGEND

- Supported by both US and EU roadmaps
- LEGEND-200 exploitation
- LEGEND-1000 preparations



3) R&D: new techniques to go beyond inverted hierarchy

- Isotope-loaded liquid scintillator (SNO+ technique) especially promising
- and...?

