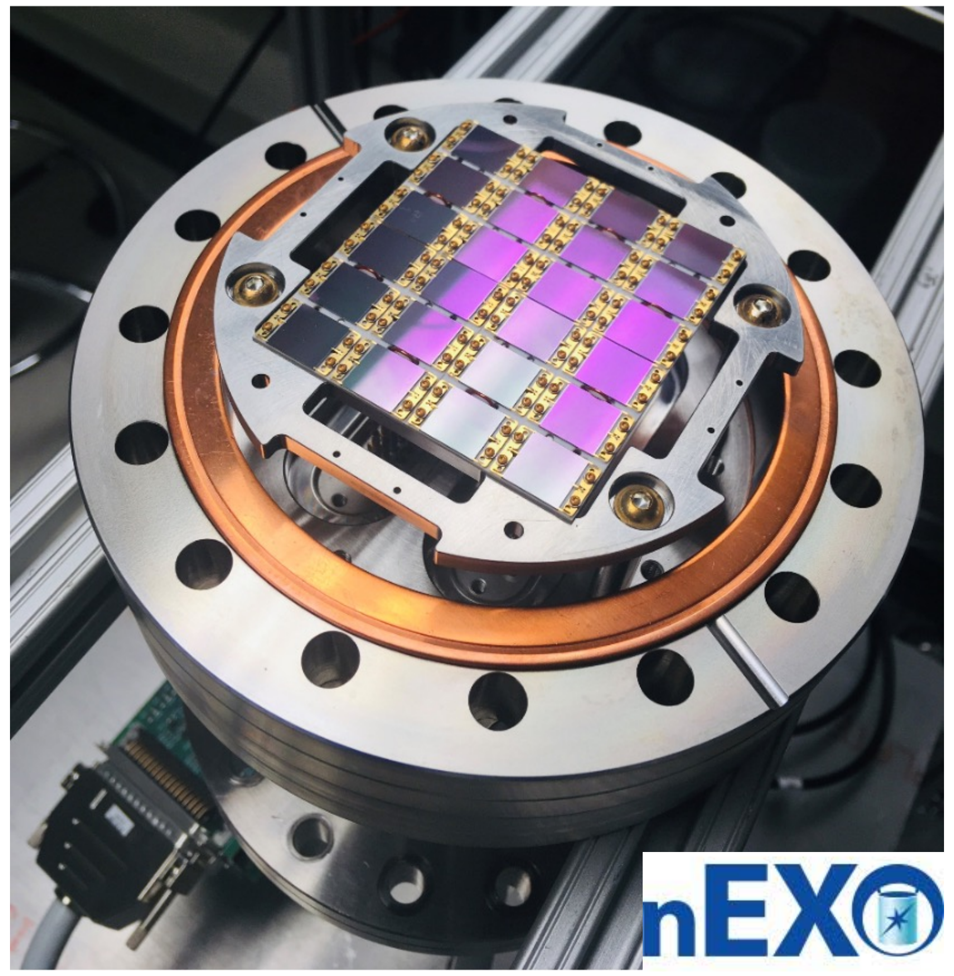
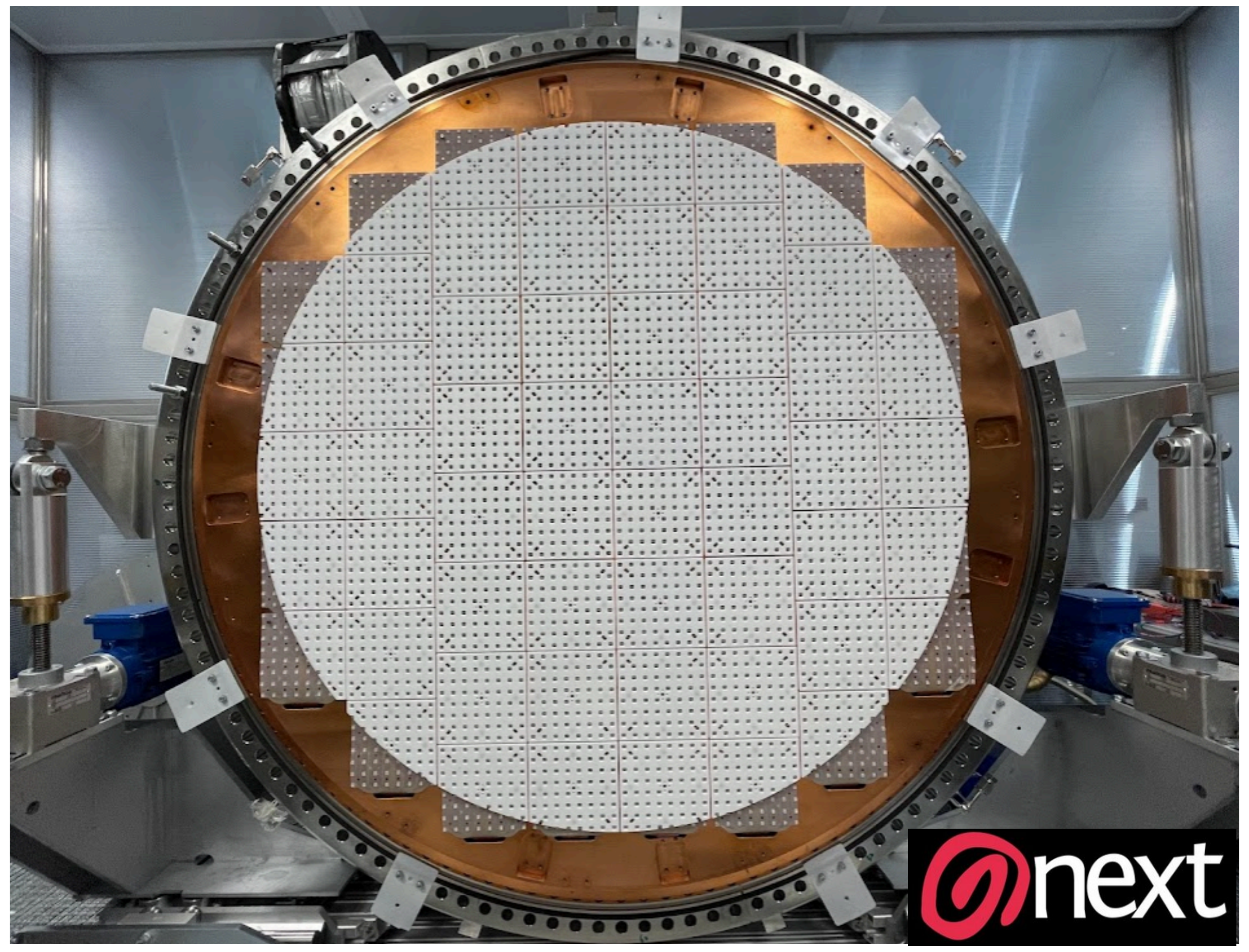
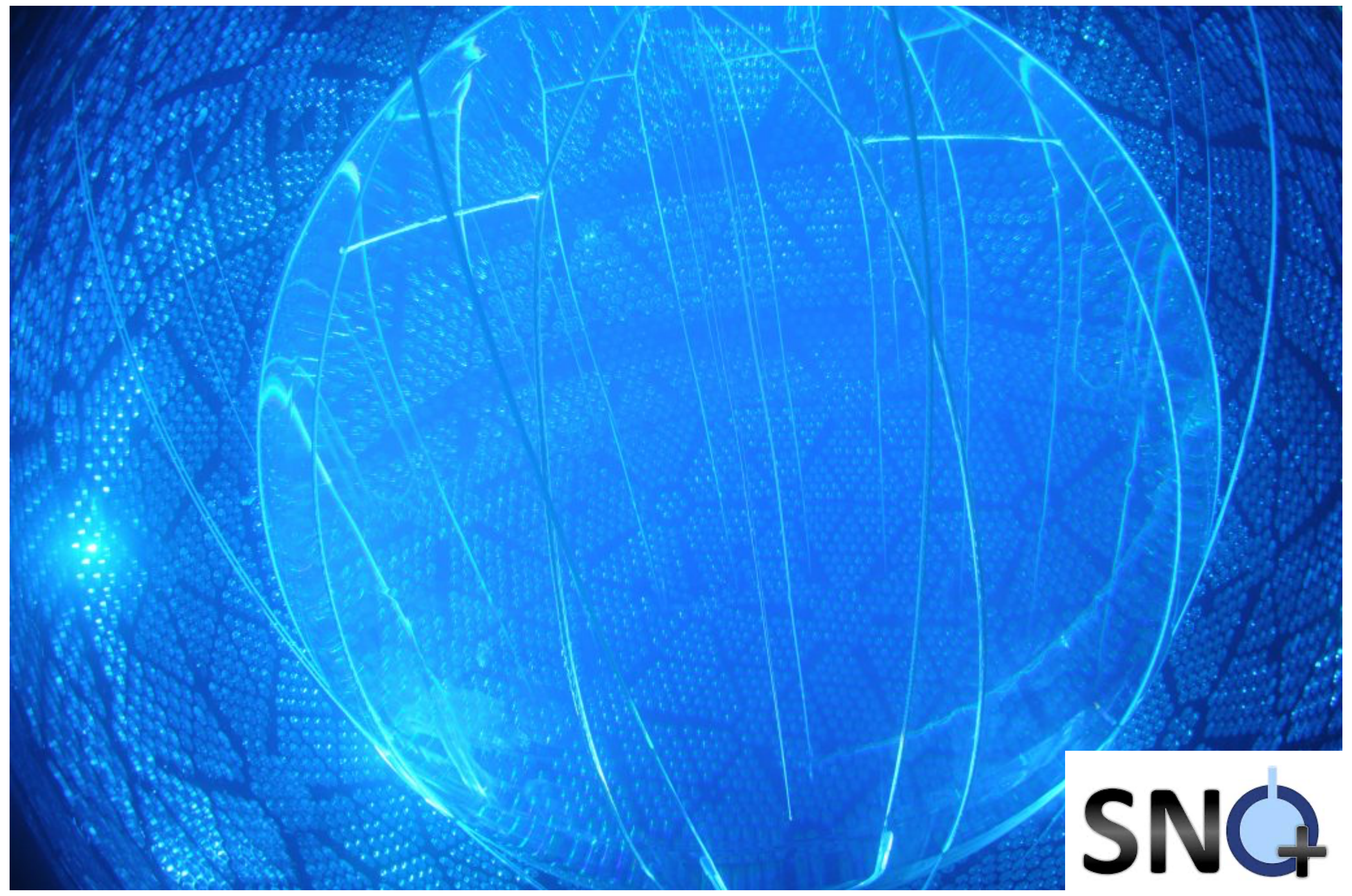






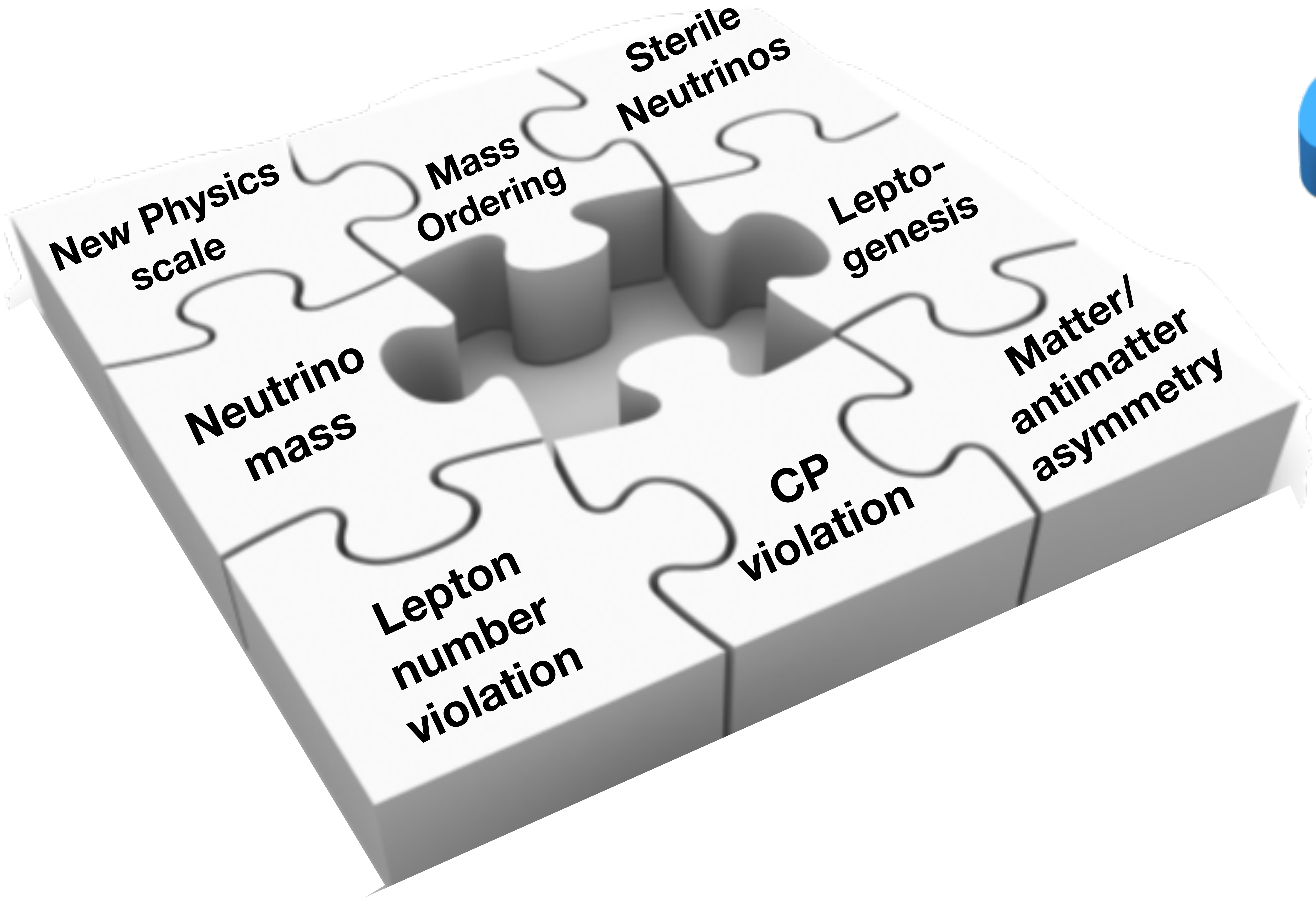
Other present and future 0νββ experiments

Roxanne Guénette

MANCHESTER 1824
The University of Manchester

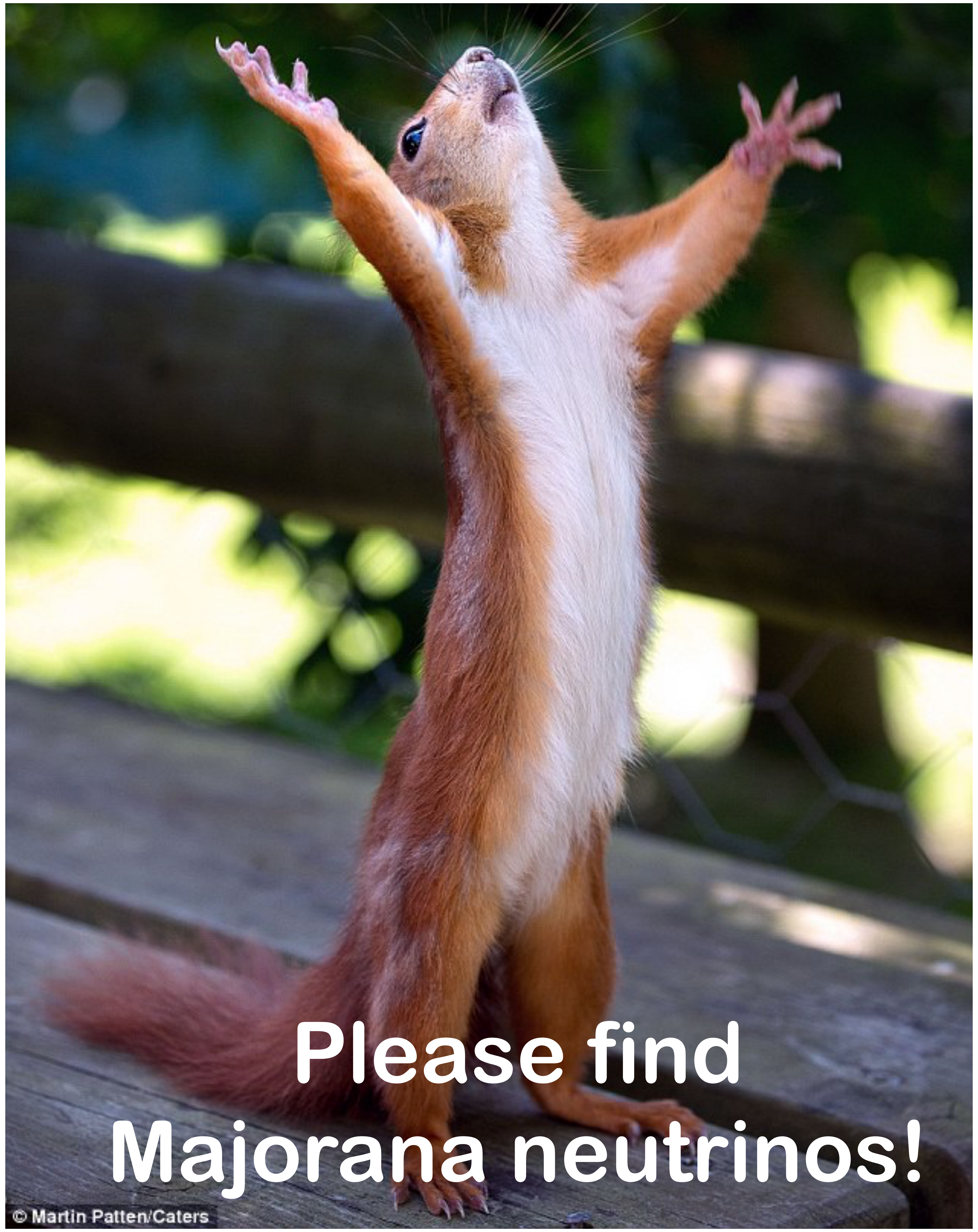
NEUTRINO 2024
18 June 2024

Importance of searching for 0νββ



See J. Menendez's talk

Importance of searching for 0νββ



The road to a Majorana neutrino

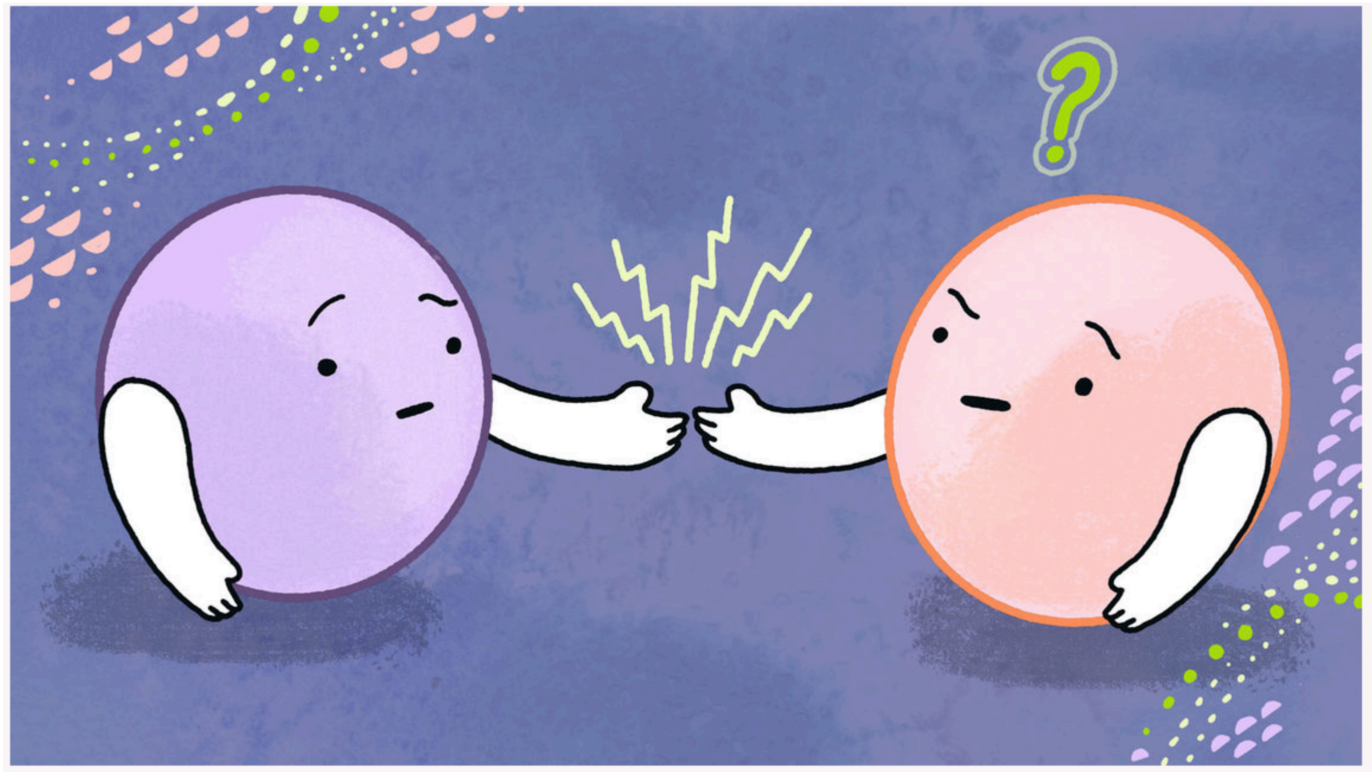
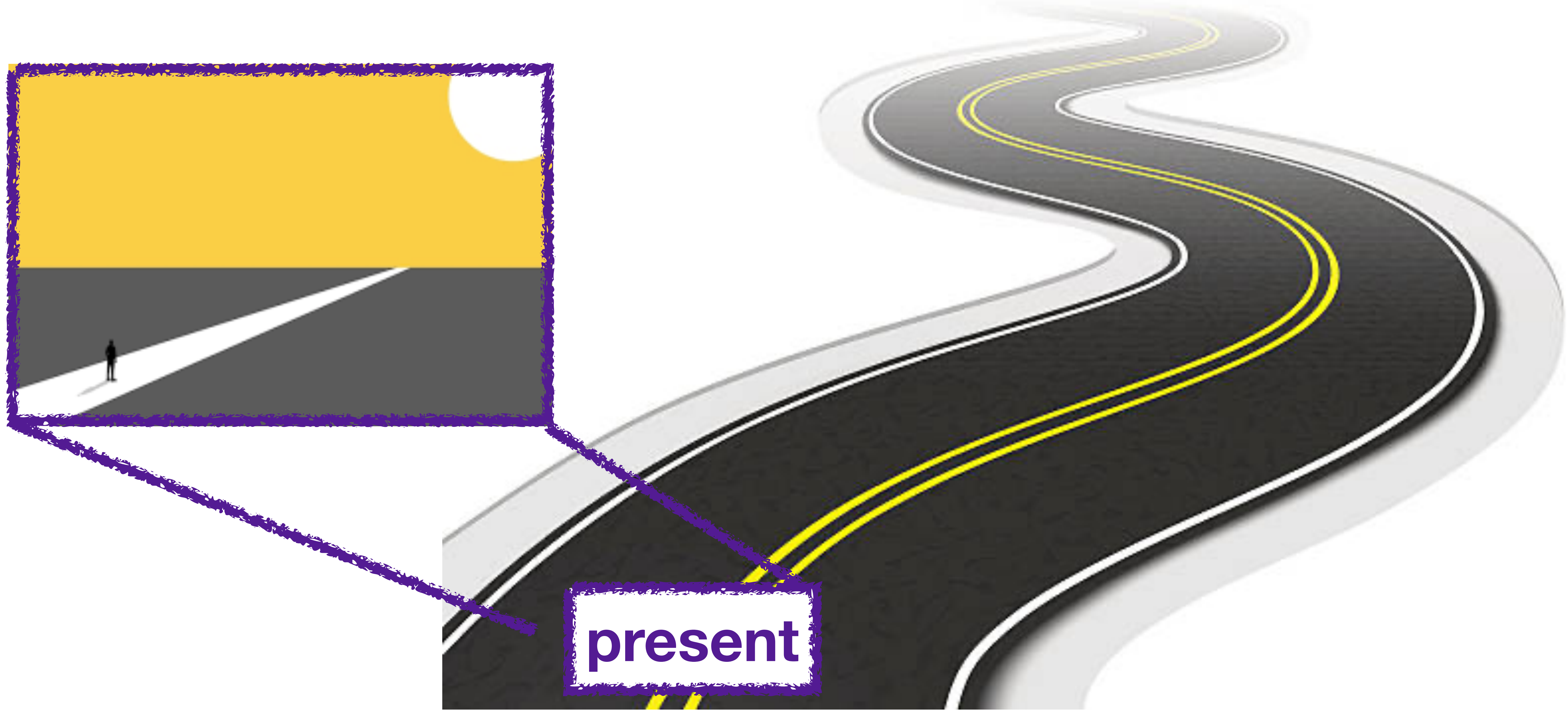
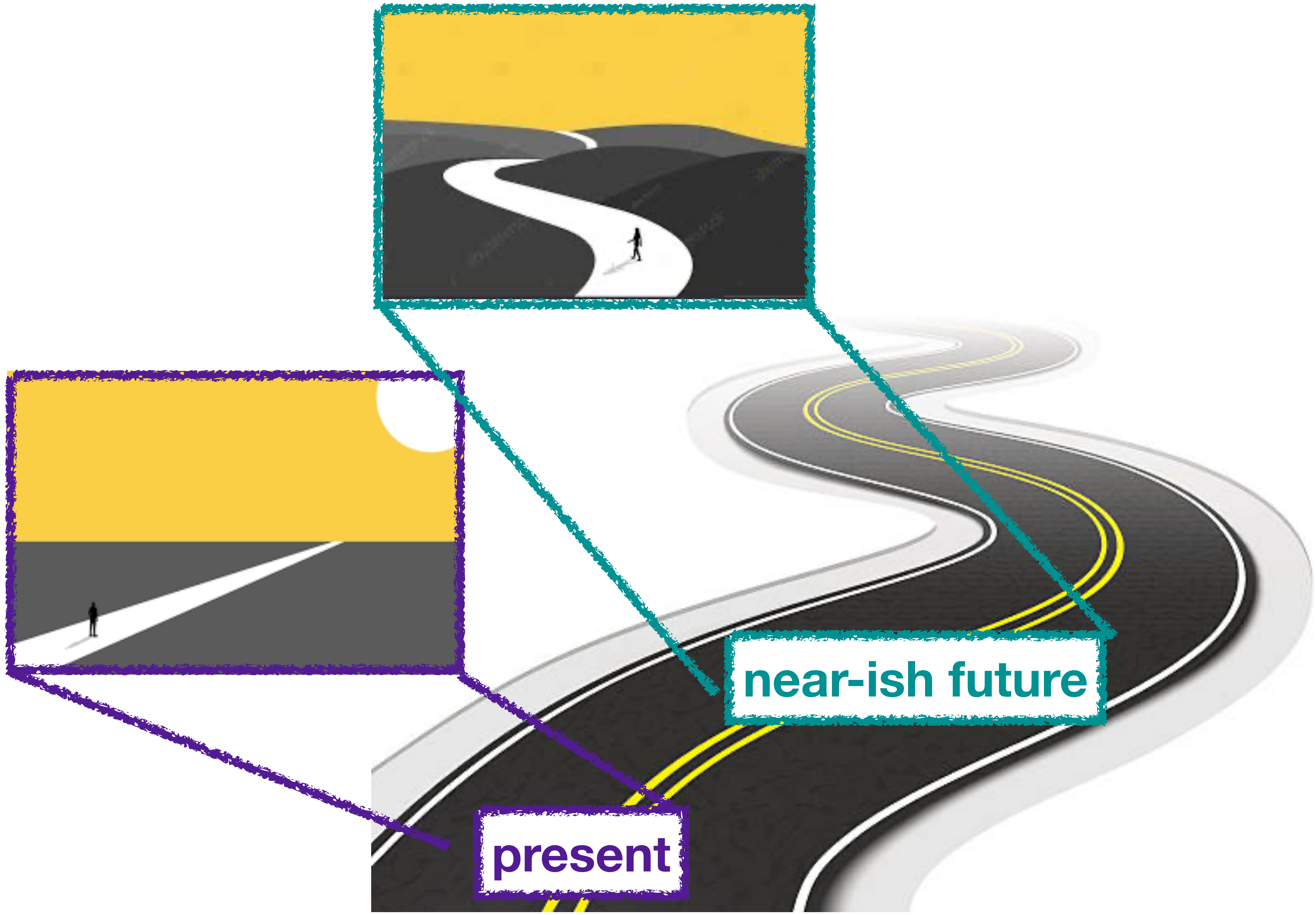


Illustration by Sandbox Studio, Chicago with Corinne Mucha

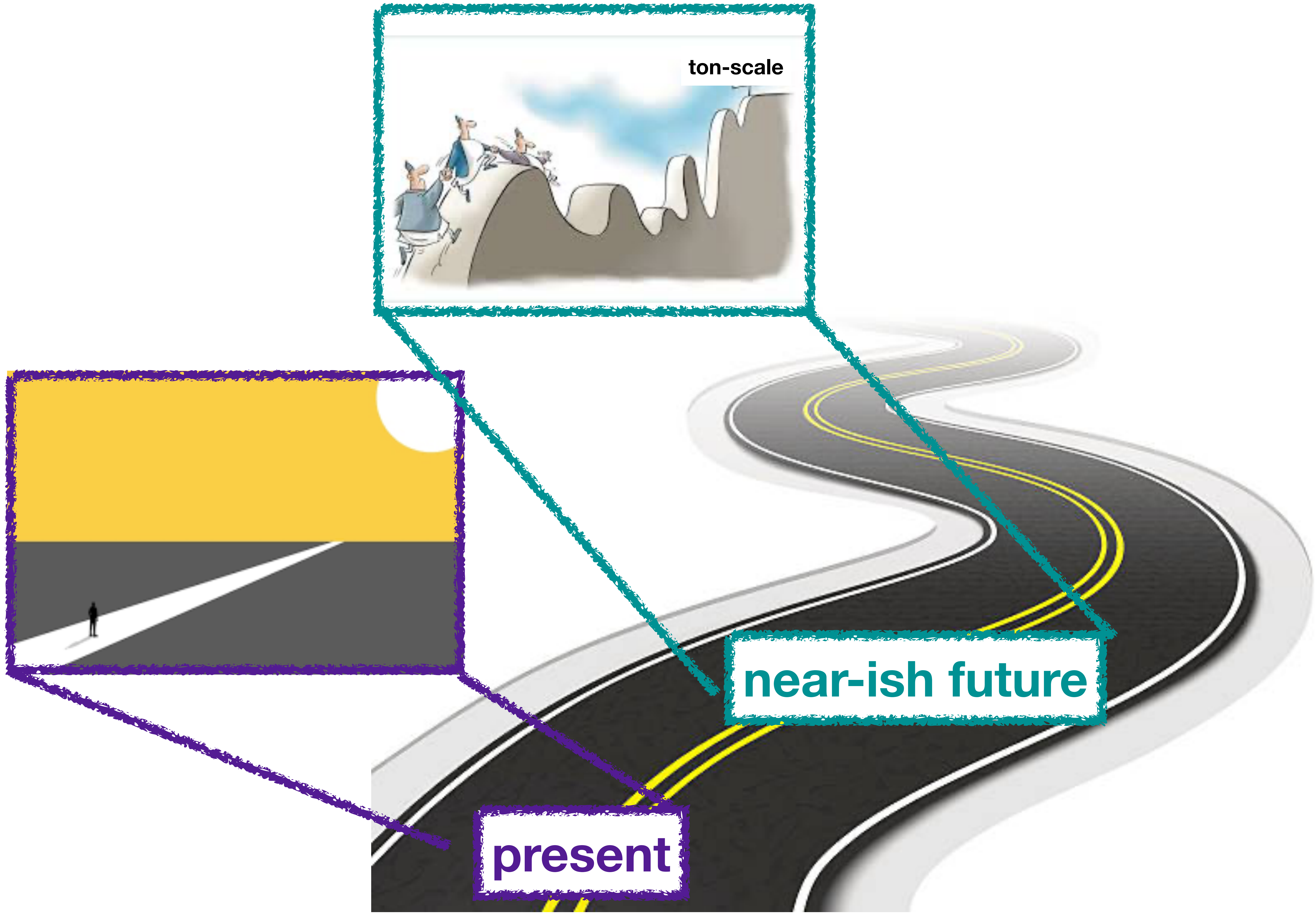
The road to a Majorana neutrino



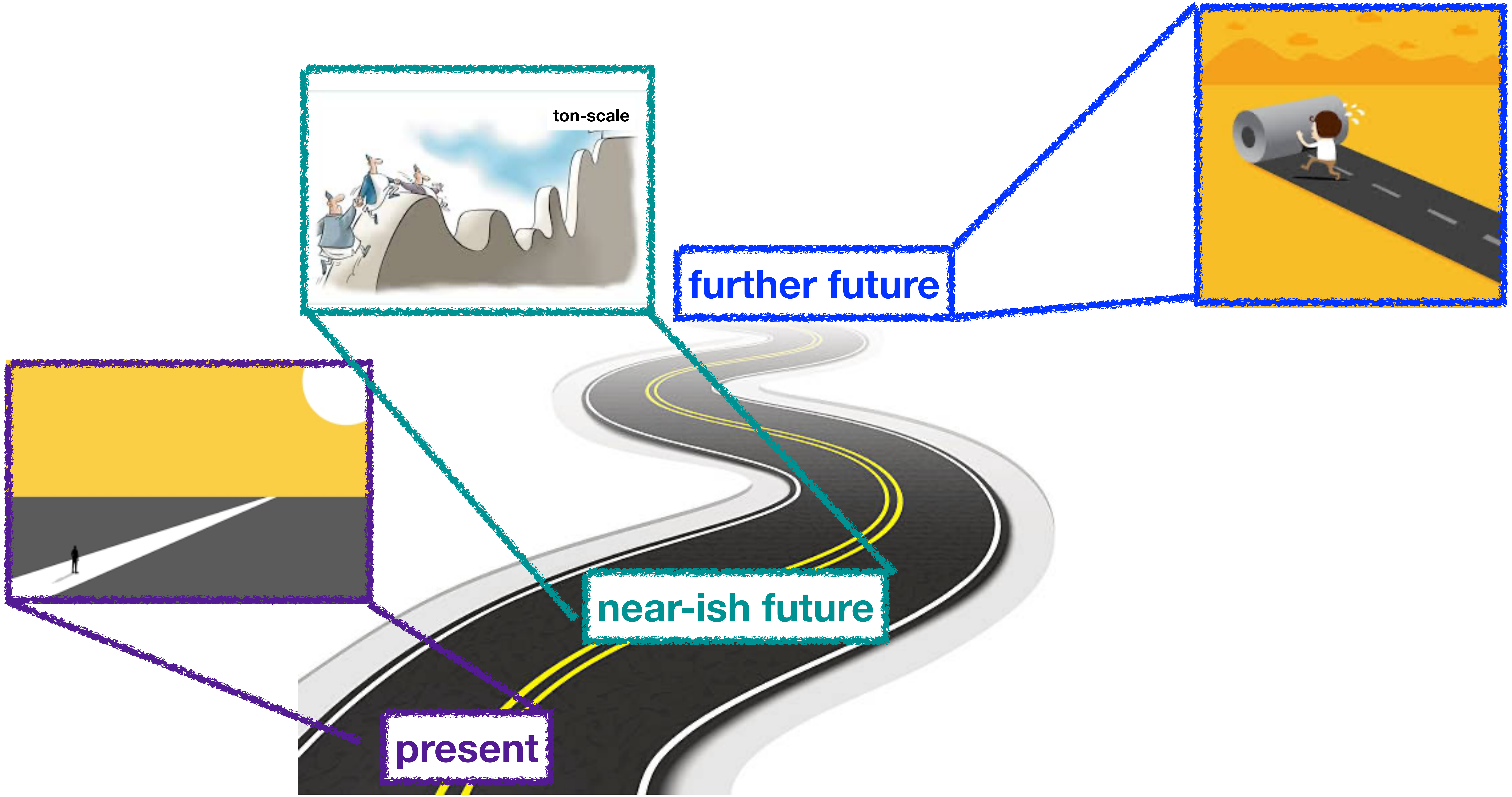
The road to a Majorana neutrino



The road to a Majorana neutrino



The road to a Majorana neutrino



The road to a Majorana neutrino

present

How to search for 0vββ

- Isotope choice:
  - Highest $Q_{\beta\beta}$ value (lower backgrounds)
  - Highest abundance (lower cost)

Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)

M. Agostini, et al., (2023) Rev. Mod. Phys. 95, 025002

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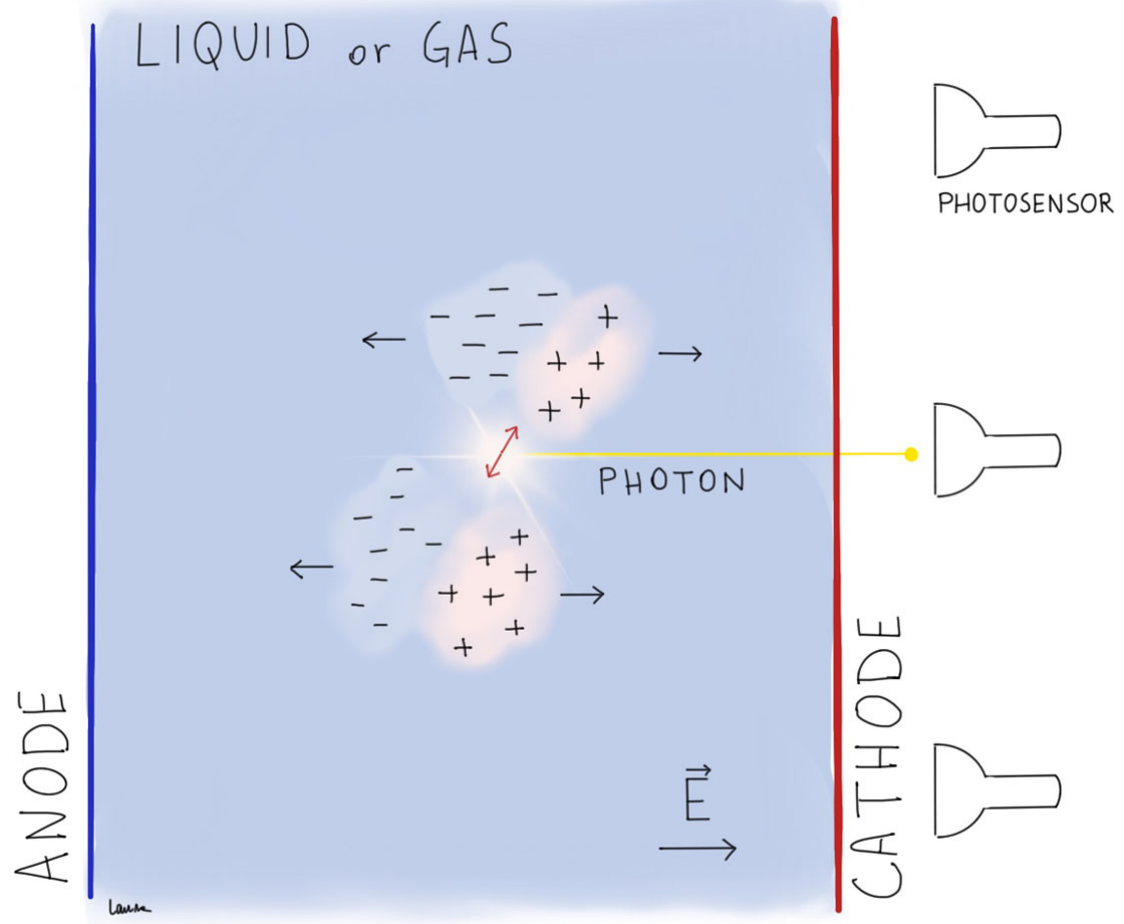
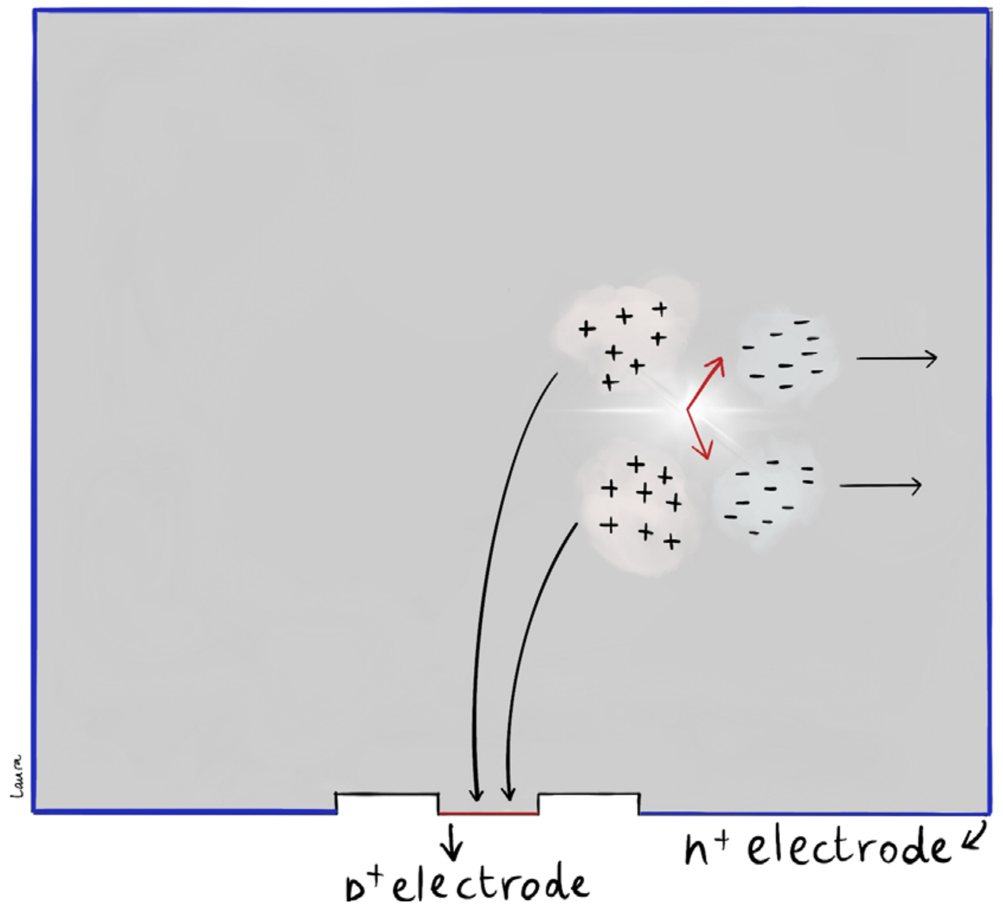
- Detector technology choice:
  - Best energy resolution
  - Lowest backgrounds
  - Most scalable

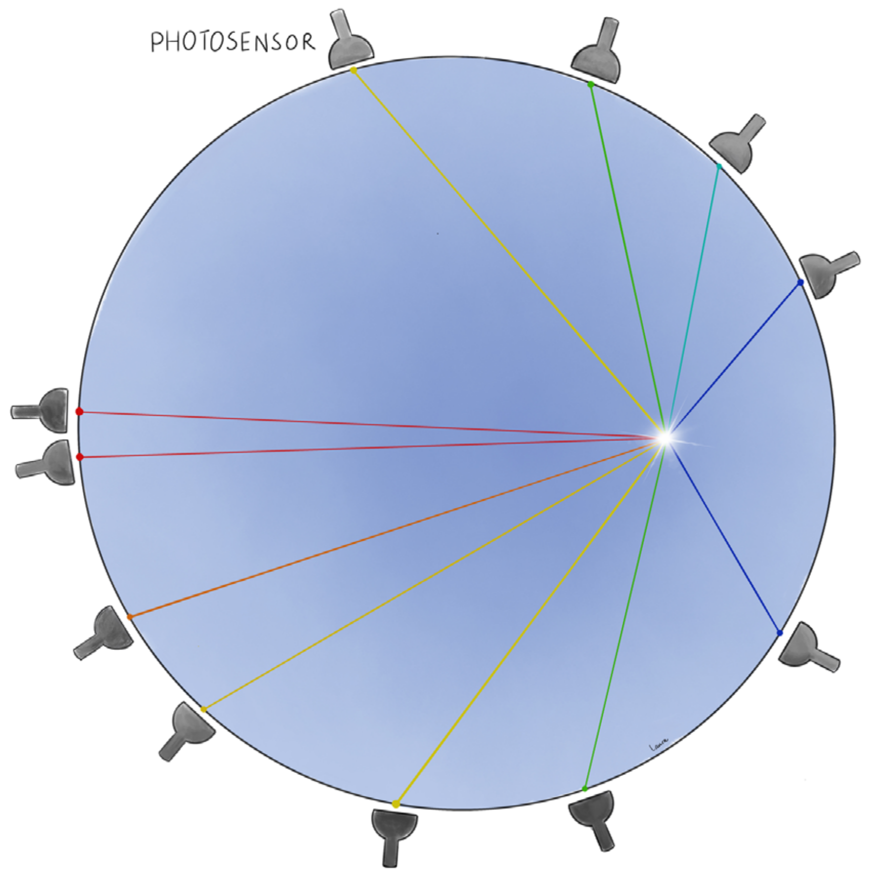
Xenon TPC



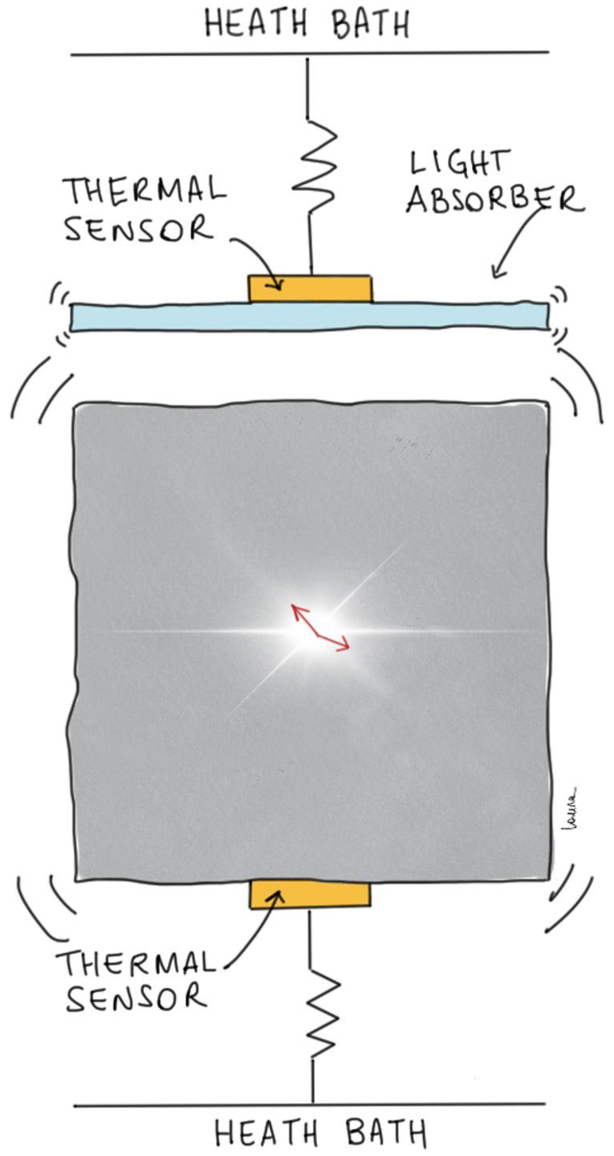
Semi-conductors



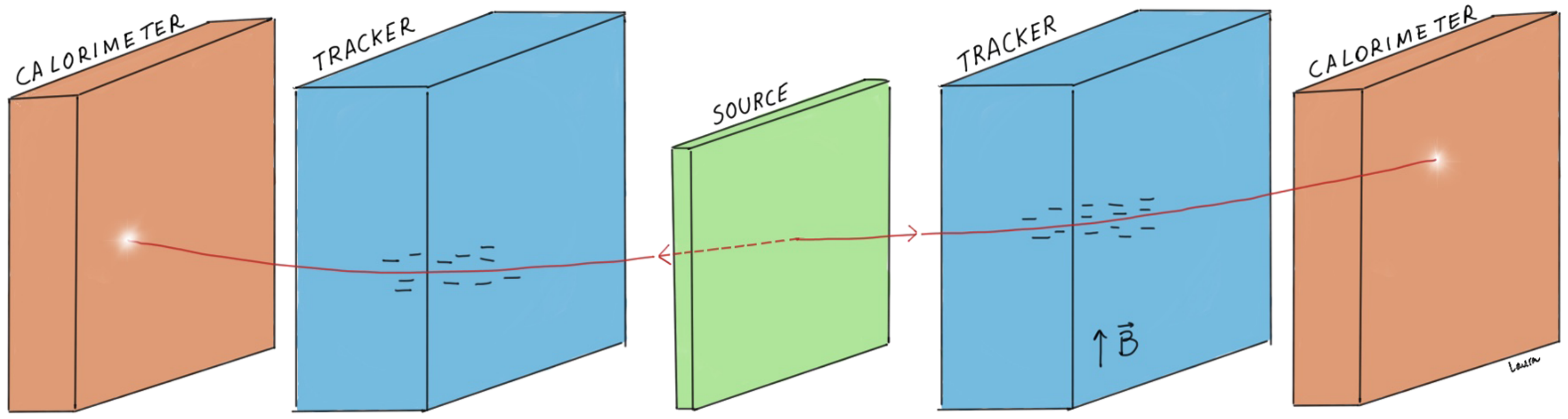
Liquid Scintillator



Cryogenic bolometers



Tracking calorimeters



M. Agostini, et al., (2023) Rev. Mod. Phys. 95, 025002

Drawings: Laura Manenti

How to search for 0νββ

- Isotope choice:
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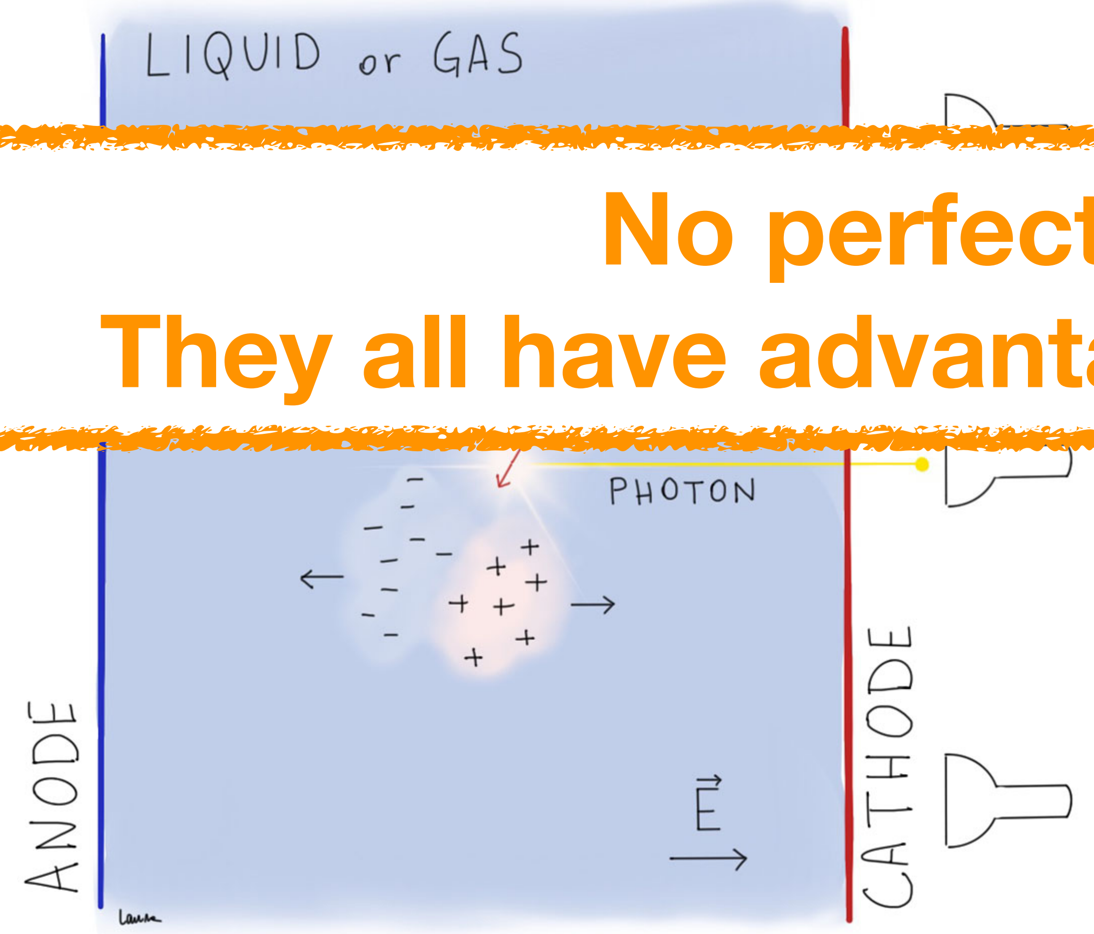
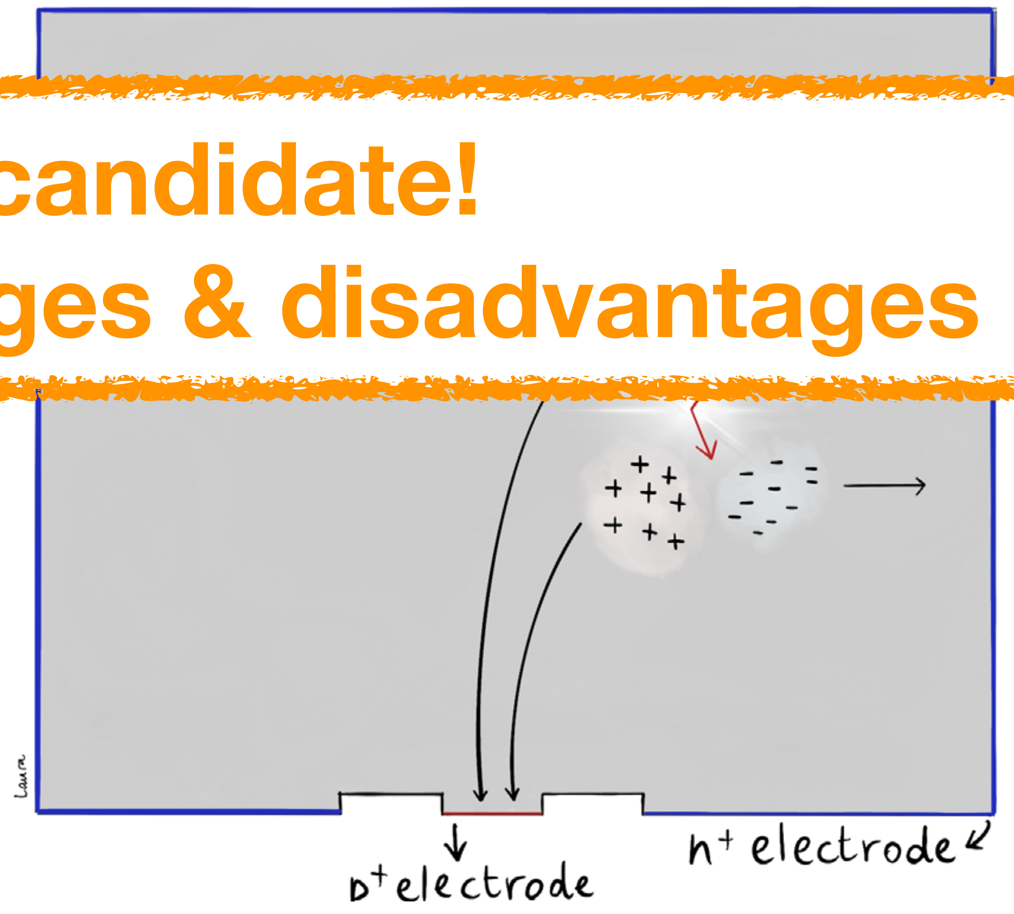
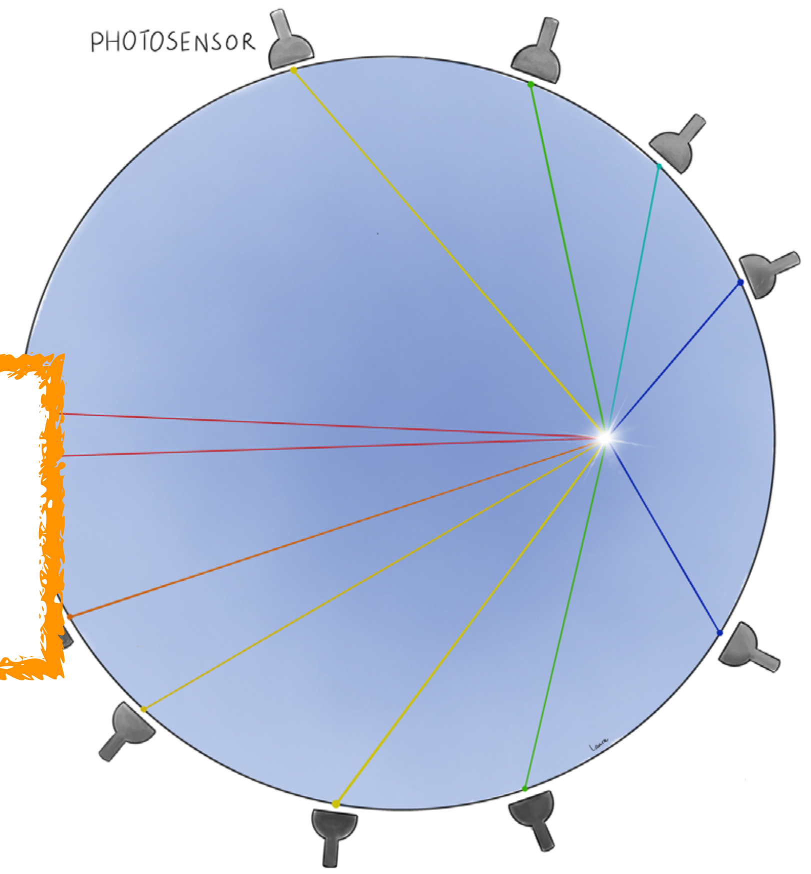


Semi-conductors

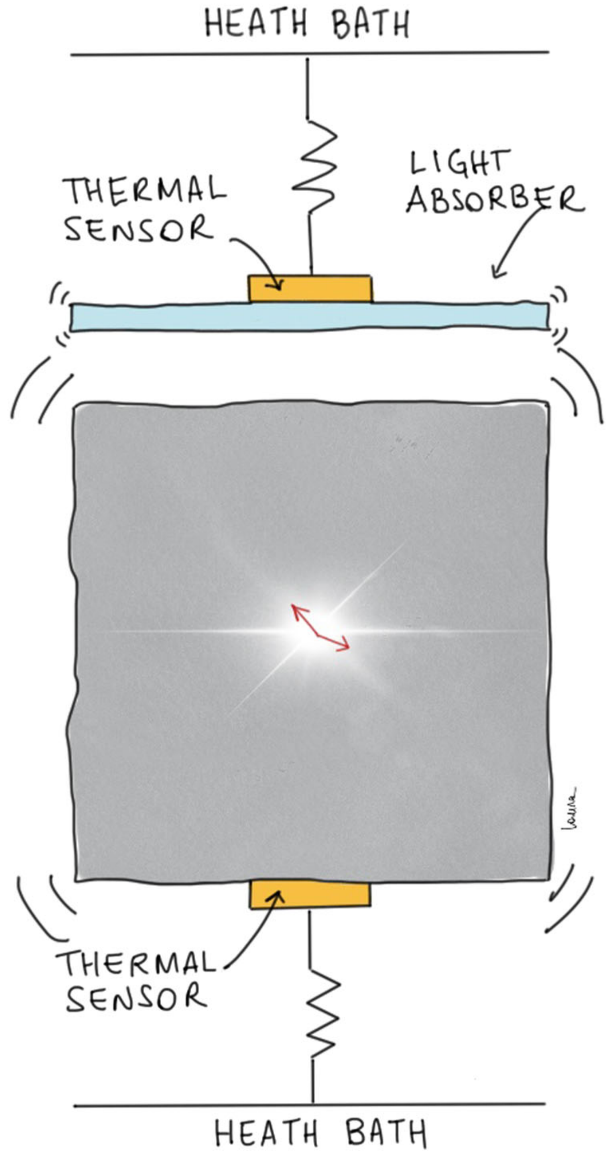


Liquid Scintillator



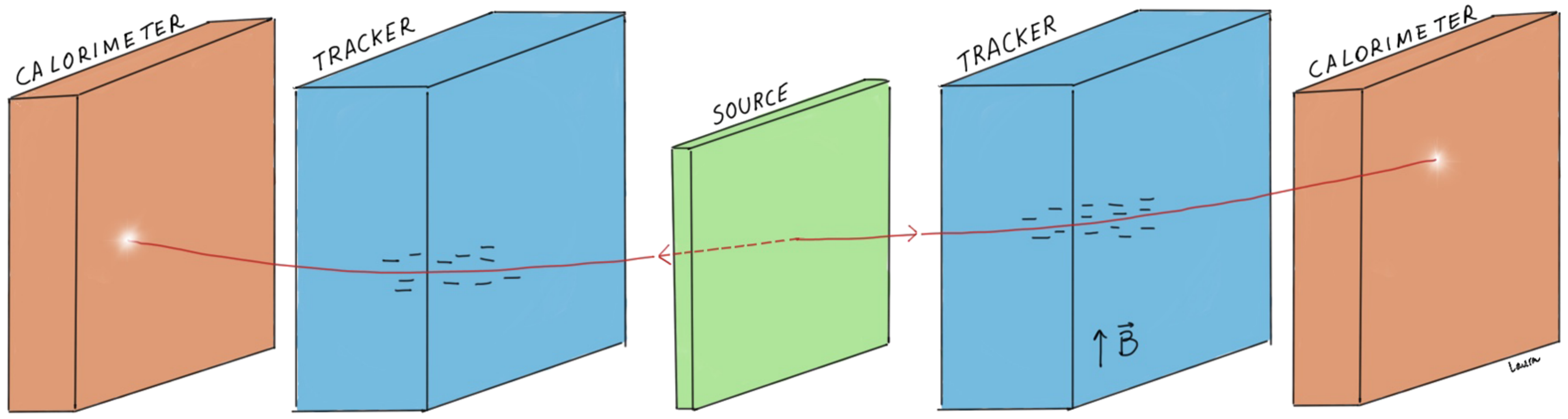
No perfect candidate!
They all have advantages & disadvantages

Cryogenic bolometers



Trac

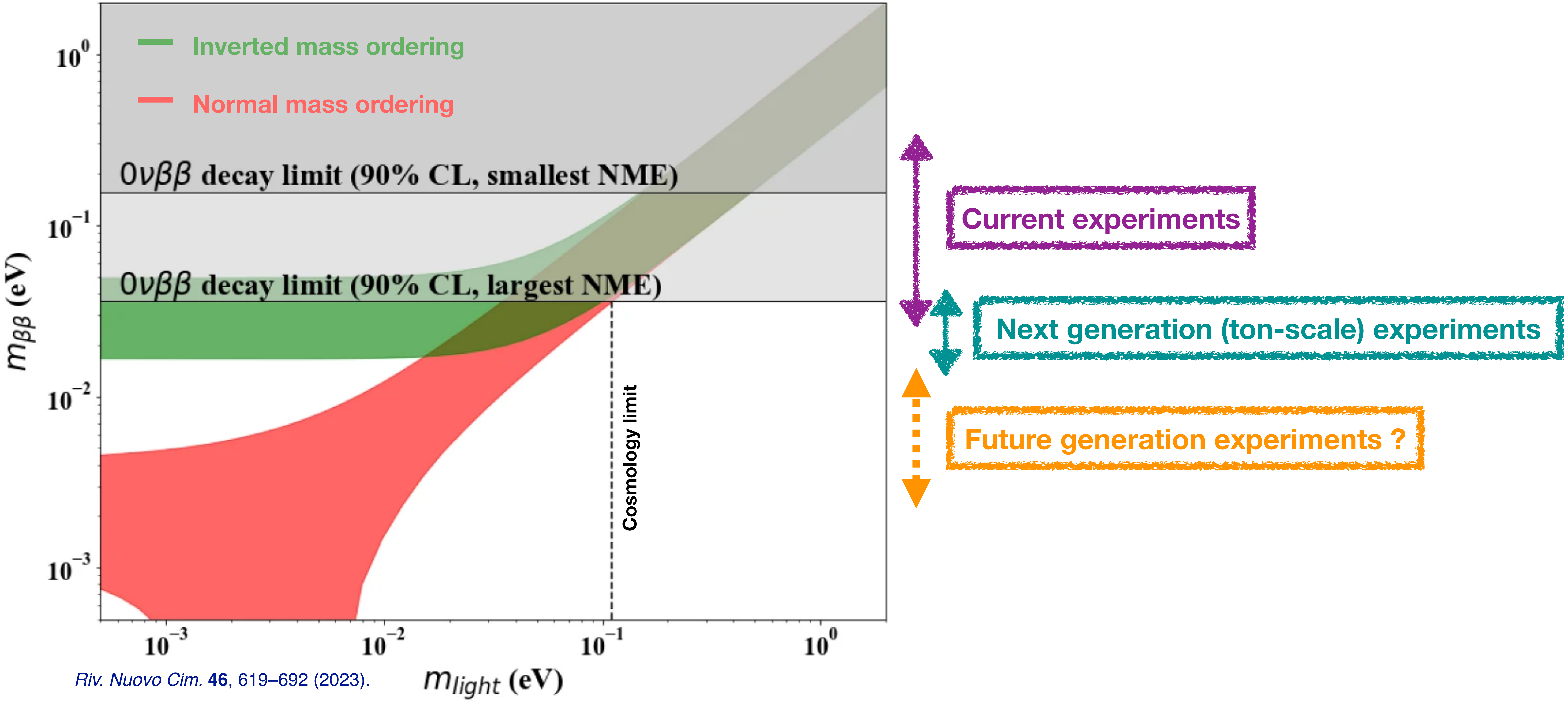
We need to pursue several of them



M. Agostini, et al., (2023) Rev. Mod. Phys. 95, 025002

Drawings: Laura Manenti

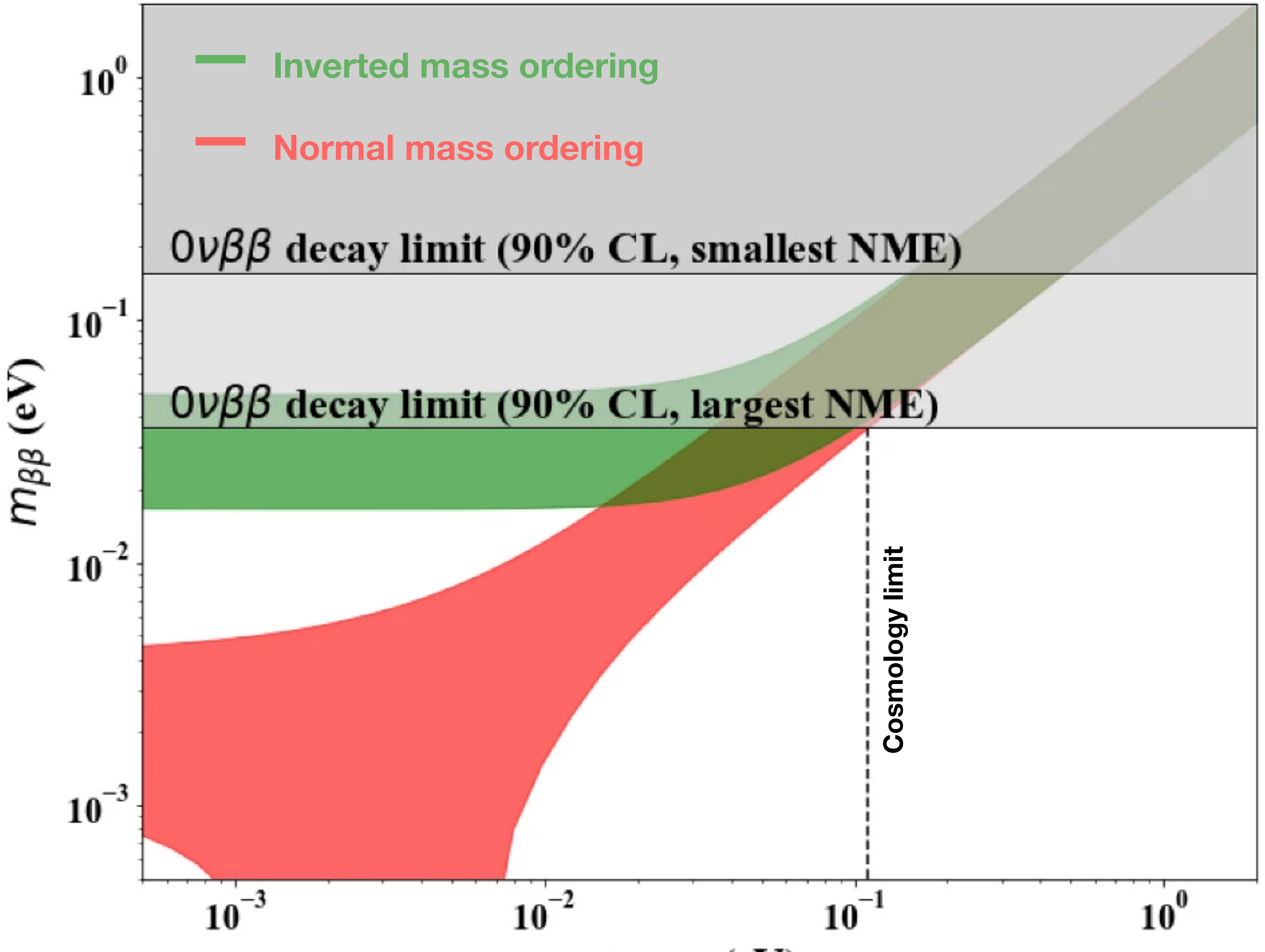
Where to search for 0νββ



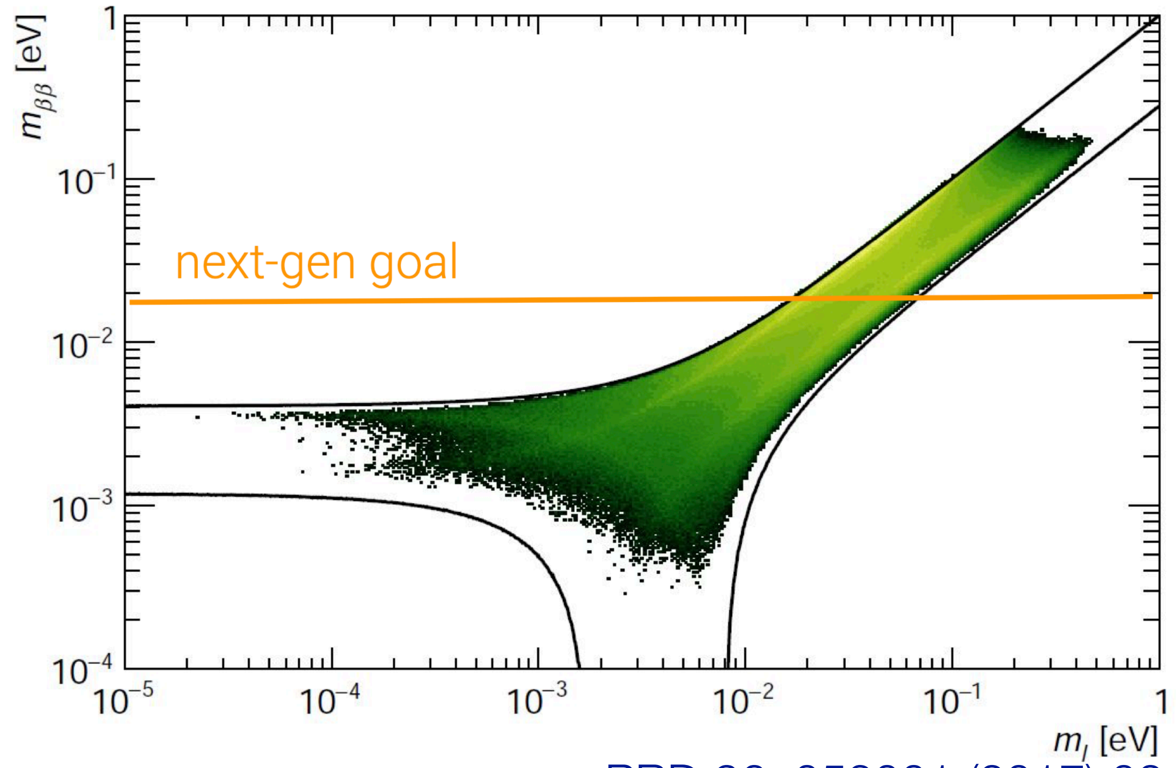
Riv. Nuovo Cim. **46**, 619–692 (2023).

Where to search for 0νββ

Not all parameter space has the same probability!



Riv. Nuovo Cim. **46**, 619–692 (2023).



PRD 96, 053001 (2017) 02

Current experiments

Next generation (ton-scale) experiments

Future generation experiments ?

**** This plot is just one example of parameter space… It does not mean that is exactly where the Majorana neutrino is! ****

Current running experiments

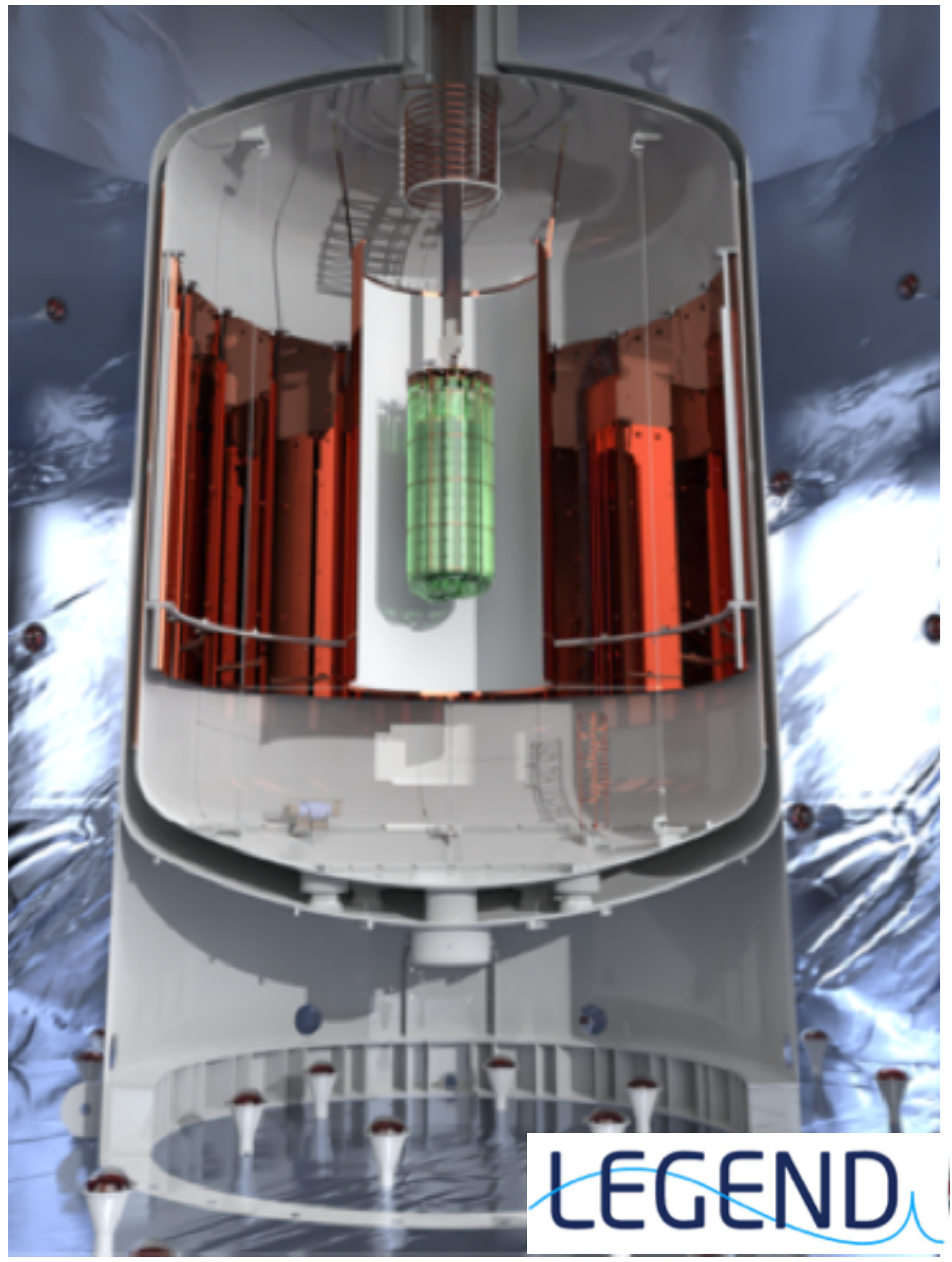
KamLAND-Zen

See I. Shimizu's talk

CUORE

See C. Bucci's talk

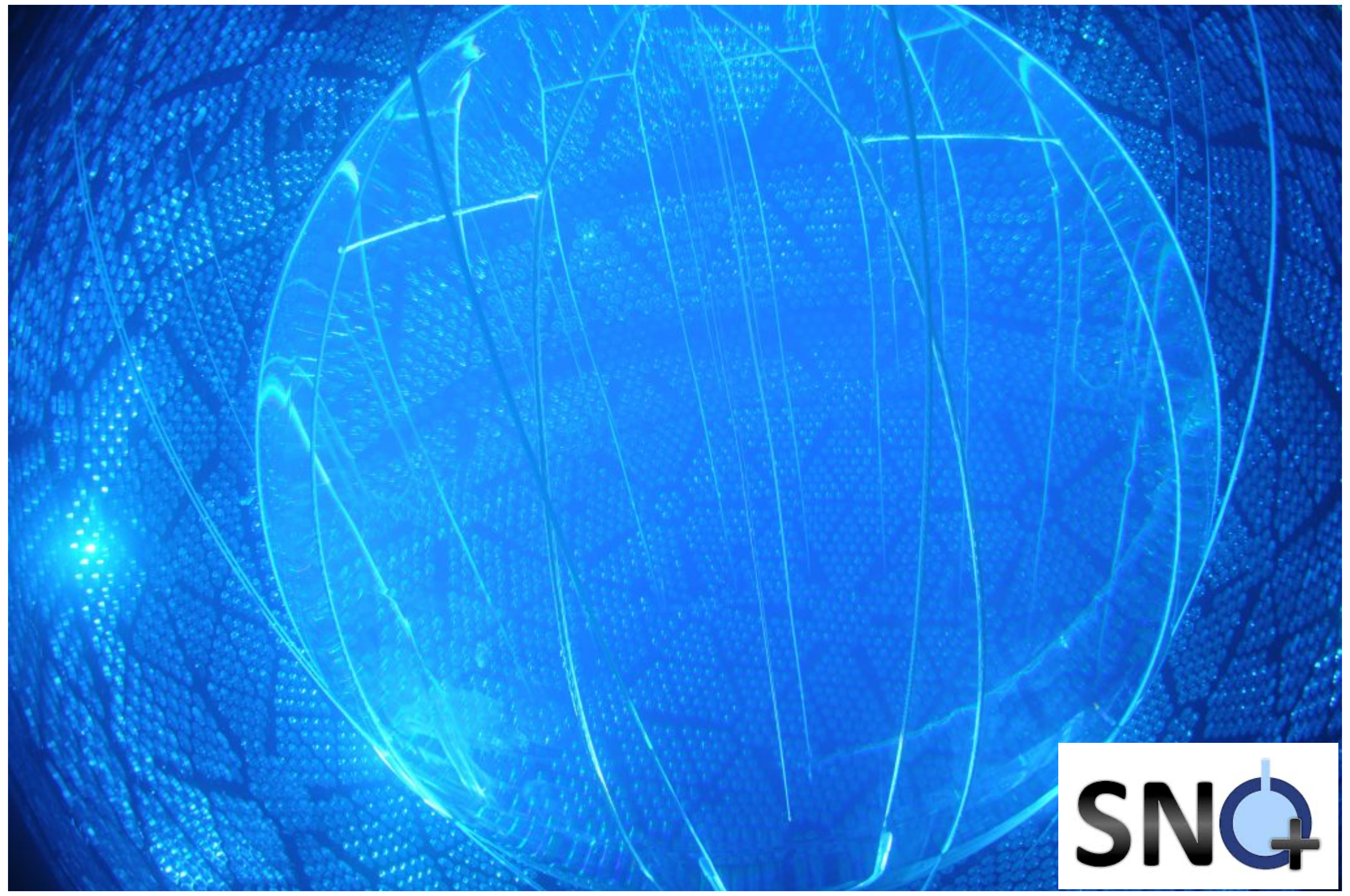
LEGEND-200



See L. Pertoldi's talk

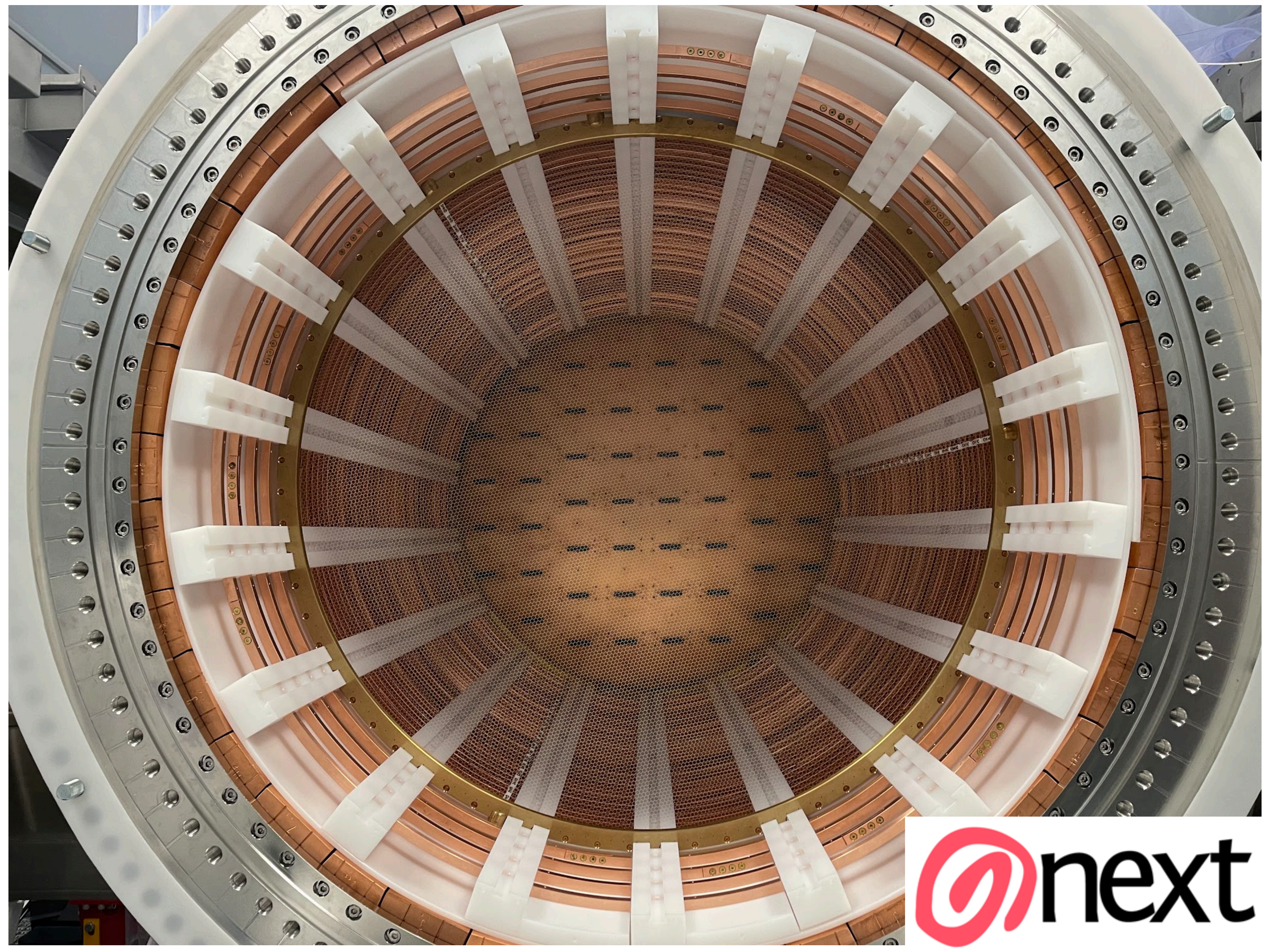
Current *(almost)* running experiments

SNO+



SUPERNEMO

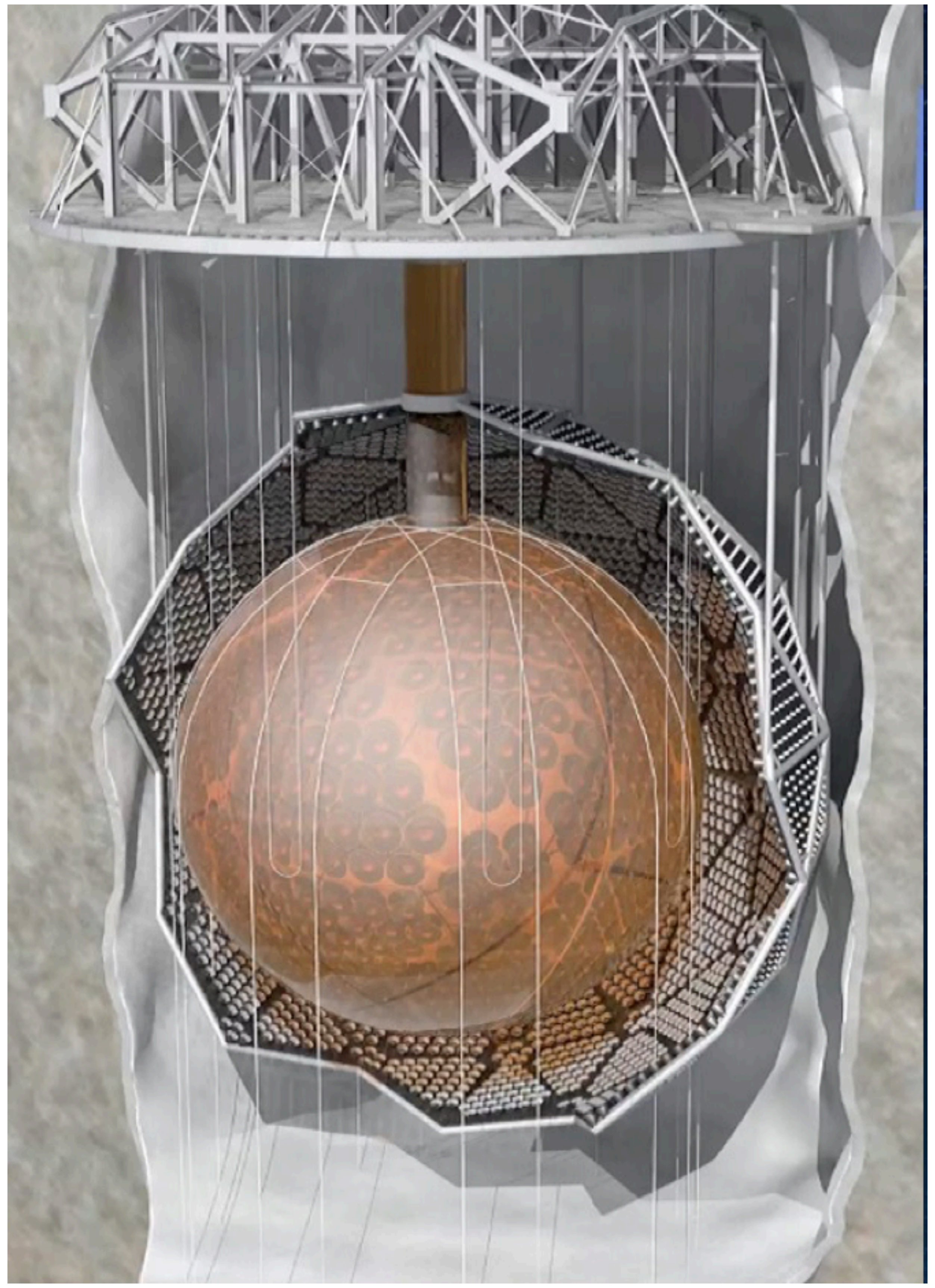
NEXT-100

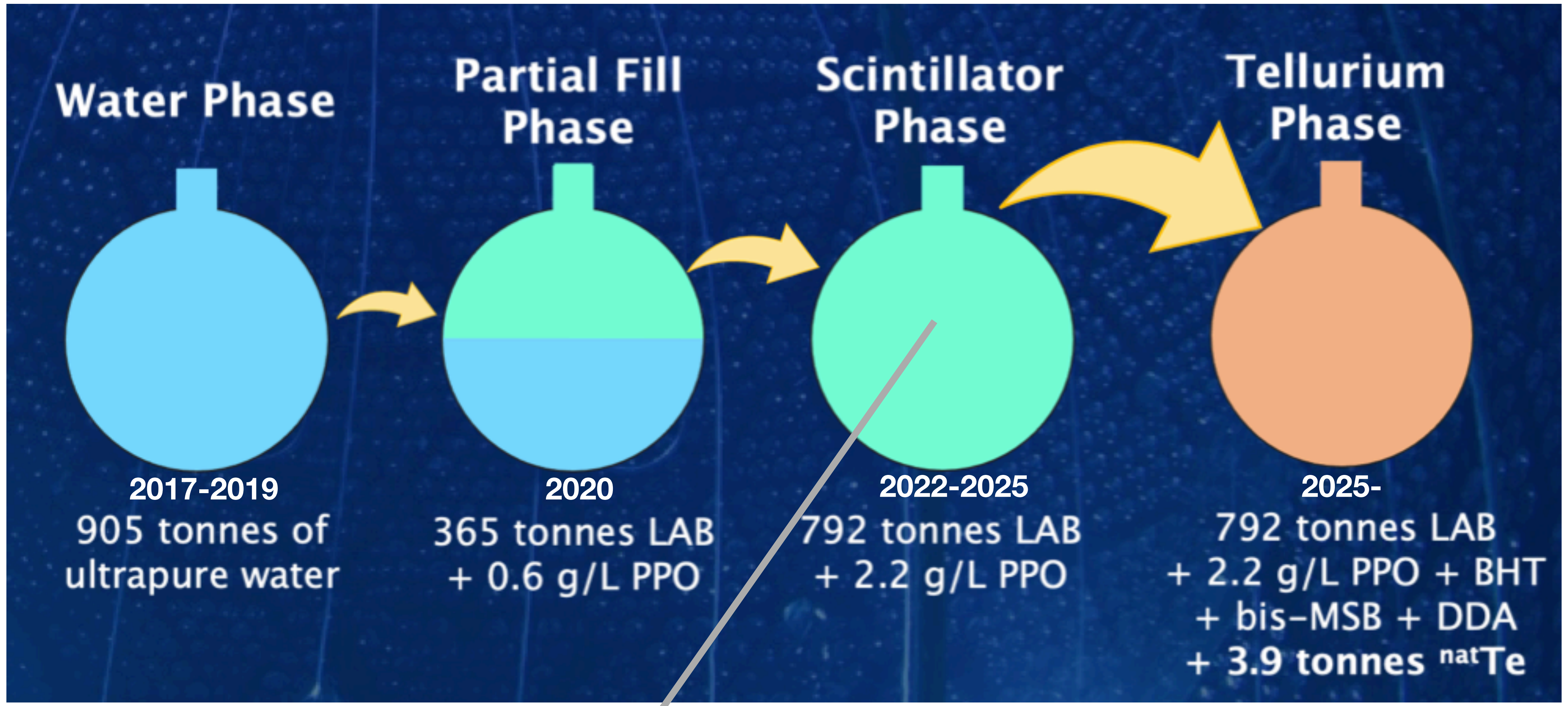


SNO+

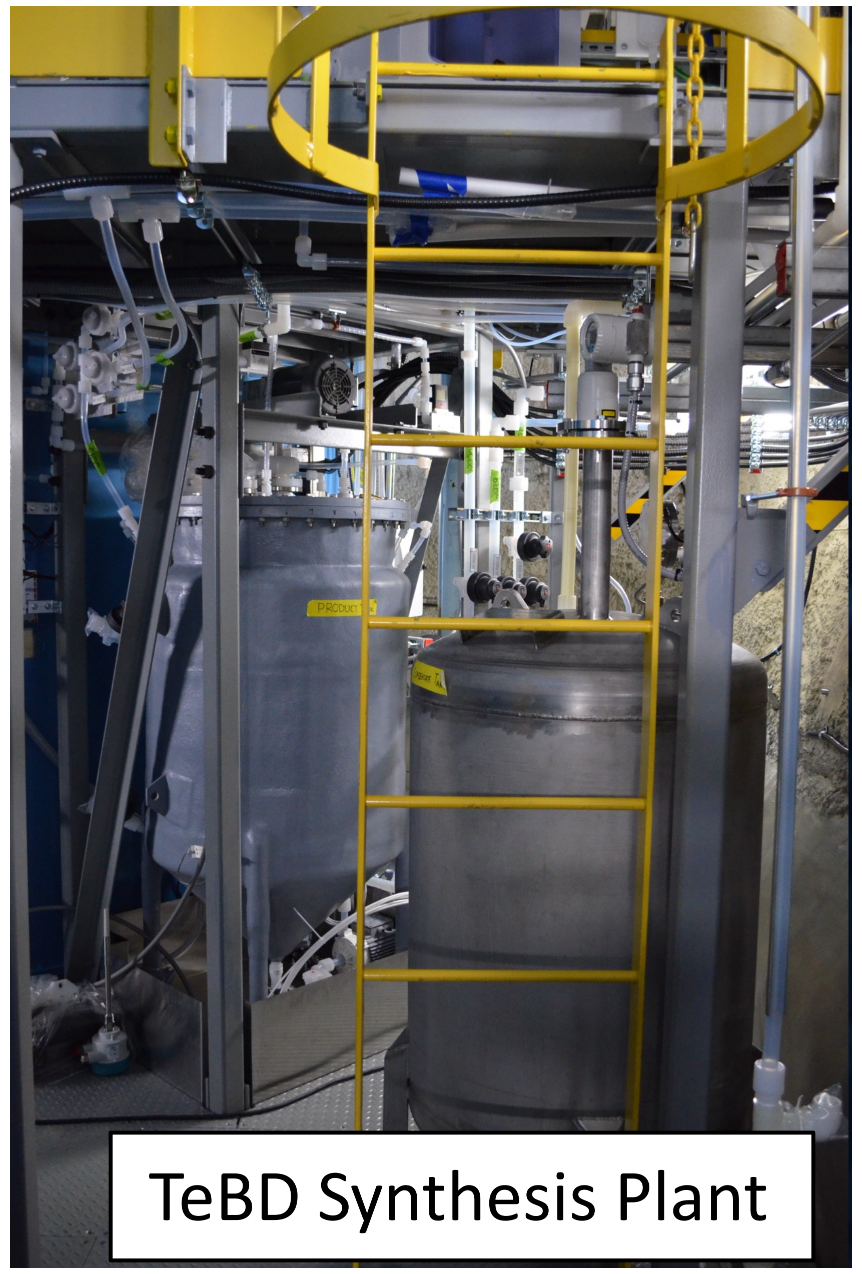
- Isotope of ^{130}Te → highest abundance, good $Q_{\beta\beta}$ (2.53MeV)

Te loading:
Phase 1: 0.5%
Phase 2: 1.5%
Phase 3: 3%





Great advantage to study backgrounds without the target



under commissioning

Poster 581:
The SNO+ Tellurium Deployment Programme

See J. Maneira's talk on Thursday for more details on SNO+ capabilities

Thanks to J. Maneira, S.Biller and M.Chen for input

SNO+

- Isotope of ^{130}Te → highest abundance, good $Q_{\beta\beta}$ (2.53MeV)

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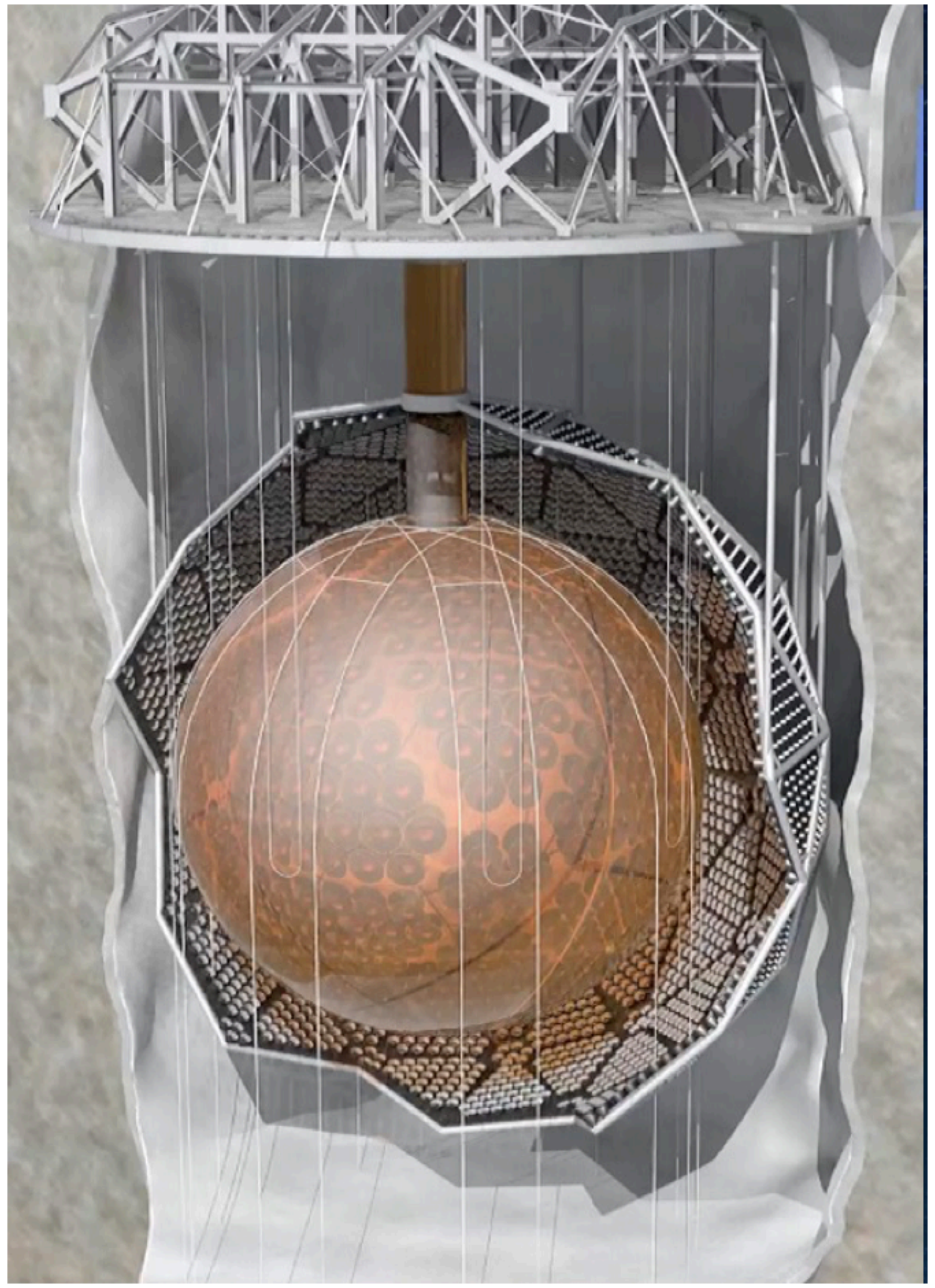
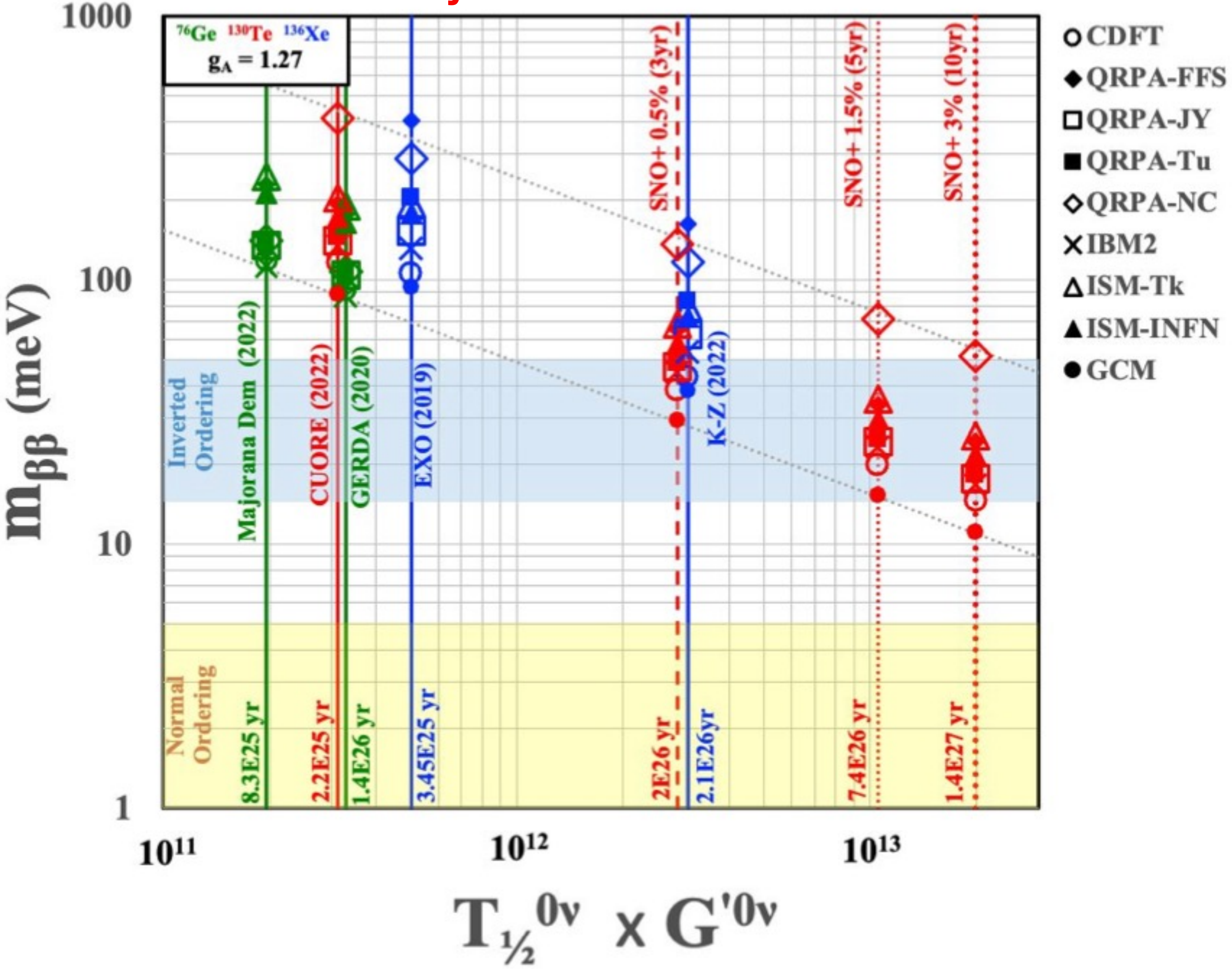
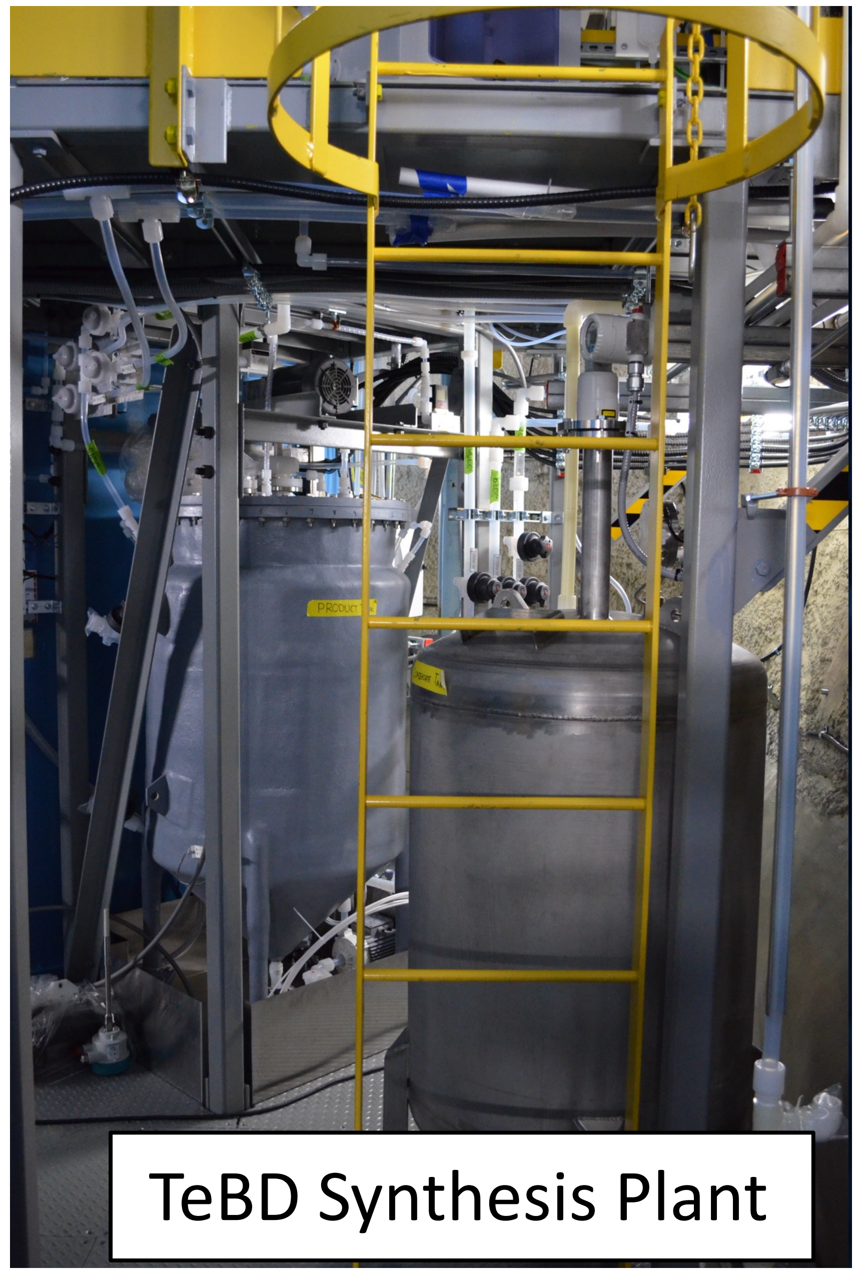


Poster 581:
The SNO+ Tellurium Deployment Programme

SNO+ sensitivity





TeBD Synthesis Plant

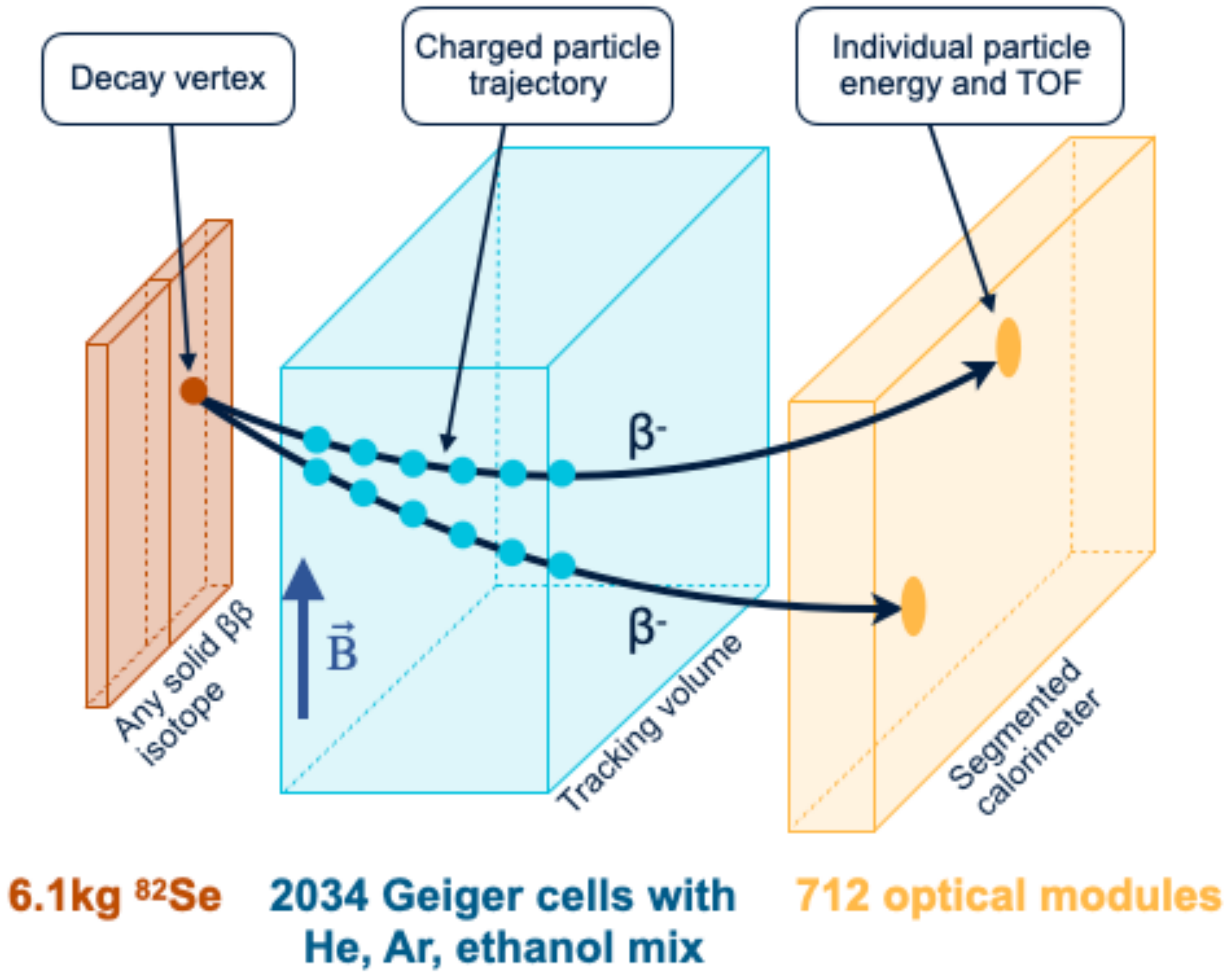
under commissioning

Thanks to J. Maneira, S.Biller and M.Chen for input

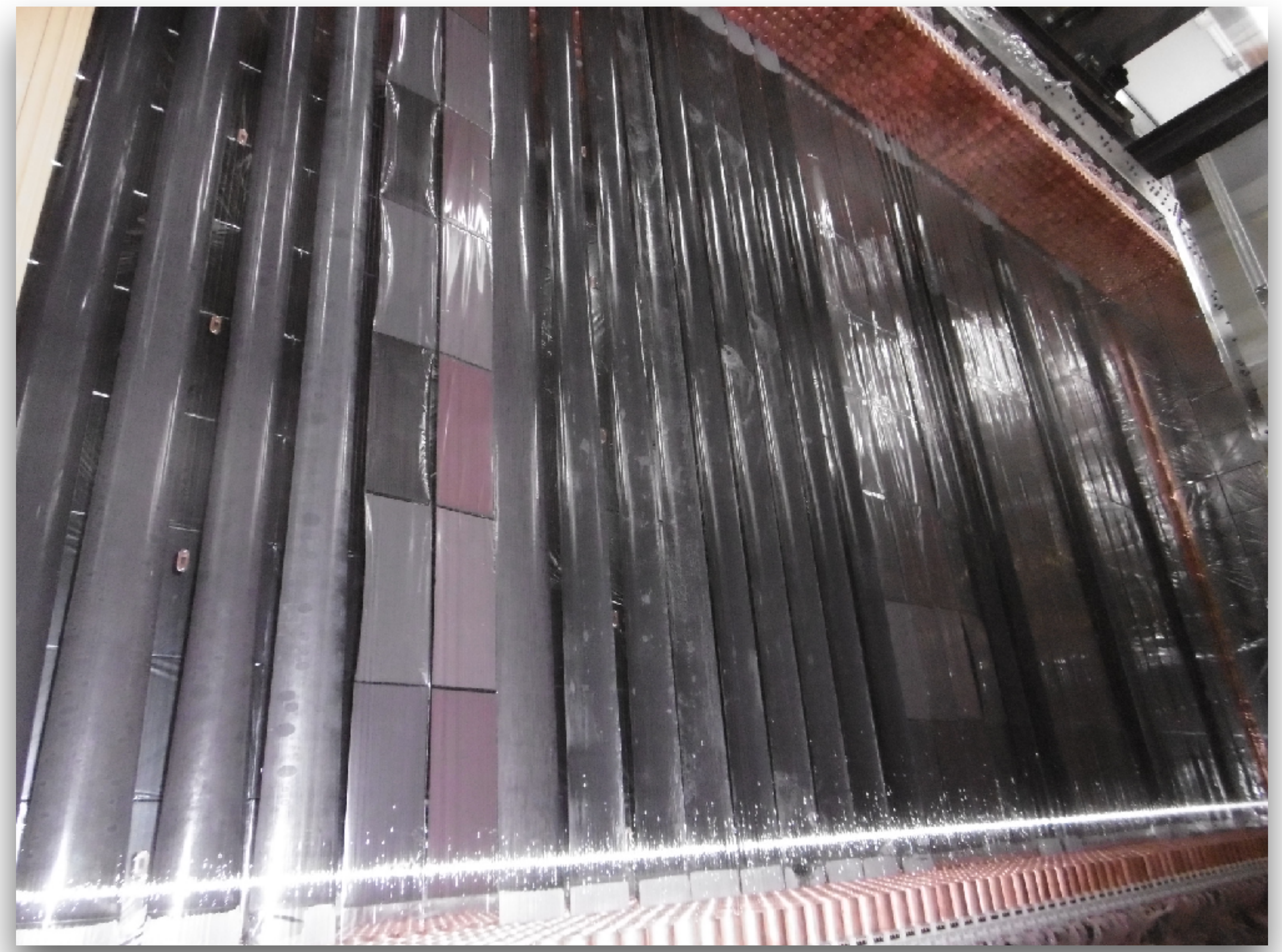
See J. Maneira's talk on Thursday for more details on SNO+ capabilities

SuperNEMO (demonstrator)

- Modular concept that builds on predecessor NEMO-3 located at LSM (France)



- (Nearly) isotope-agnostic
- Full topological reconstruction and particle ID
- Unique 2νββ measurements:
  - nuclear effects
  - exotic decays & new physics
- Could probe 0νββ mechanism if discovered
- Proof of concept for future tracking detectors

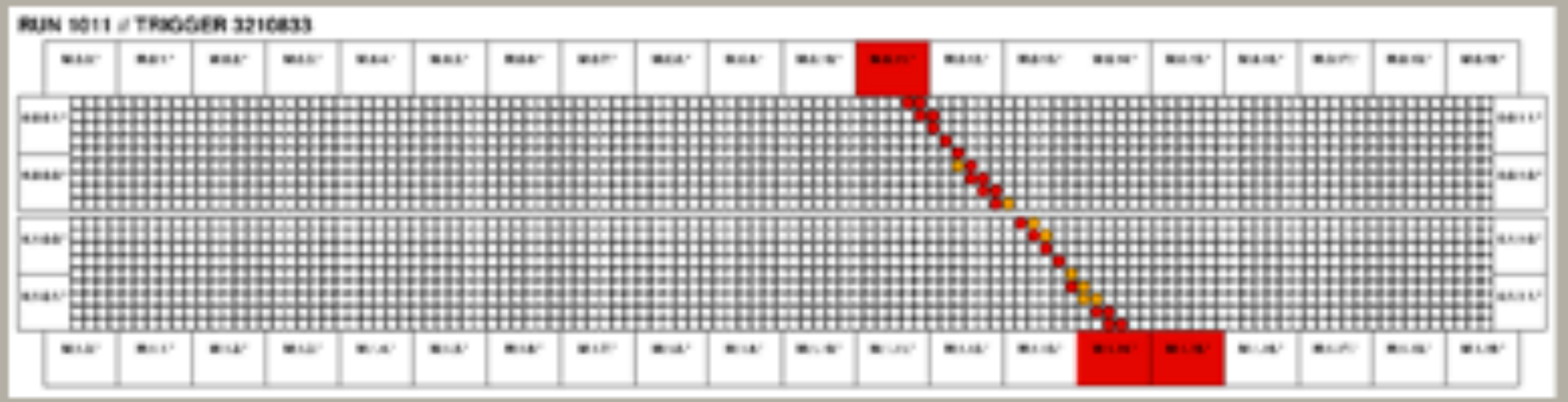


Thanks to Cheryl Patrick for the slides!

SuperNEMO (demonstrator)

supernemo collaboration

Taking calibration and background data - 99% of tracker & 98% of calorimeter channels live!



Install helium recycling system

2023-Feb 2024	March-June 2024	June-August 2024	September 2024 - 2027

Gamma shielding (iron) currently being installed

Install neutron shielding (water / polyethylene)

ββ data taking

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

Poster #41
Identification, measurement, and mitigation strategy

Poster #382
Reconstructing particle energies from measured charges and track topologies

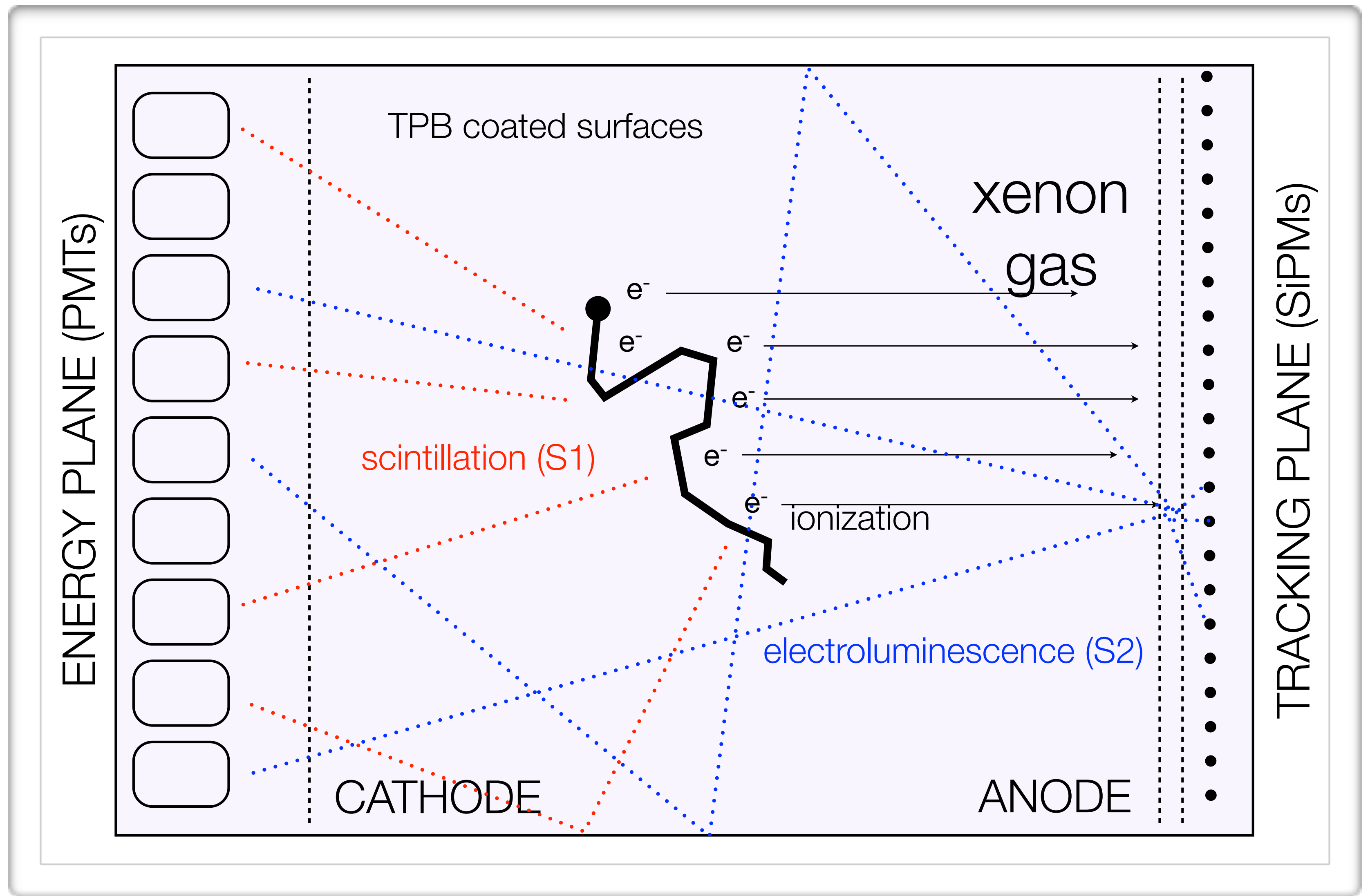
Poster #397
SuperNEMO's background model, and a new measurement of the γ background at LSM using SuperNEMO

Poster #451
More detail on SuperNEMO's capabilities and status

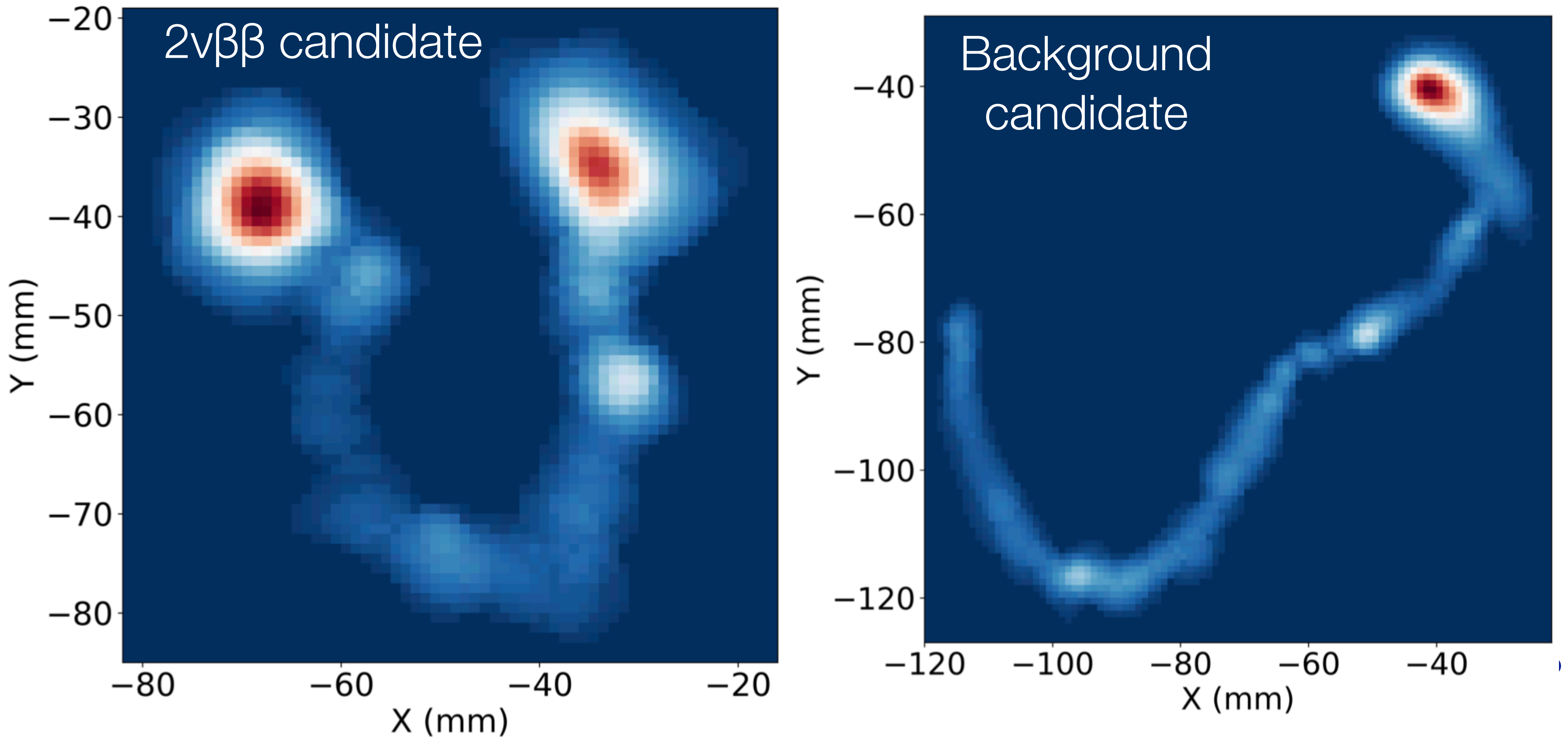
Thanks to Cheryl Patrick for the slides!

NEXT-100

- High pressure xenon gas TPC with electroluminescence



NEXT-White data



✓ Gas → great energy resolution (sub-percent FWHM) *JHEP* 10 (2019) 230

✓ Kr calibration *JINST* **13** (2018) P10014

All demonstrated by NEXT-White

✓ Tracking plane → topological signal/background separation *JHEP* 07 (2021) 146, *JHEP* 01 (2021) 189, *JHEP* 10 (2019) 052

✓ Background control → runs with depleted/enriched Xe JHEP 10 (2019) 51,Phys. Rev. C 105, 055501 (2022), JHEP 09 (2023) 190

✓ Scalability **Goal of NEXT-100**

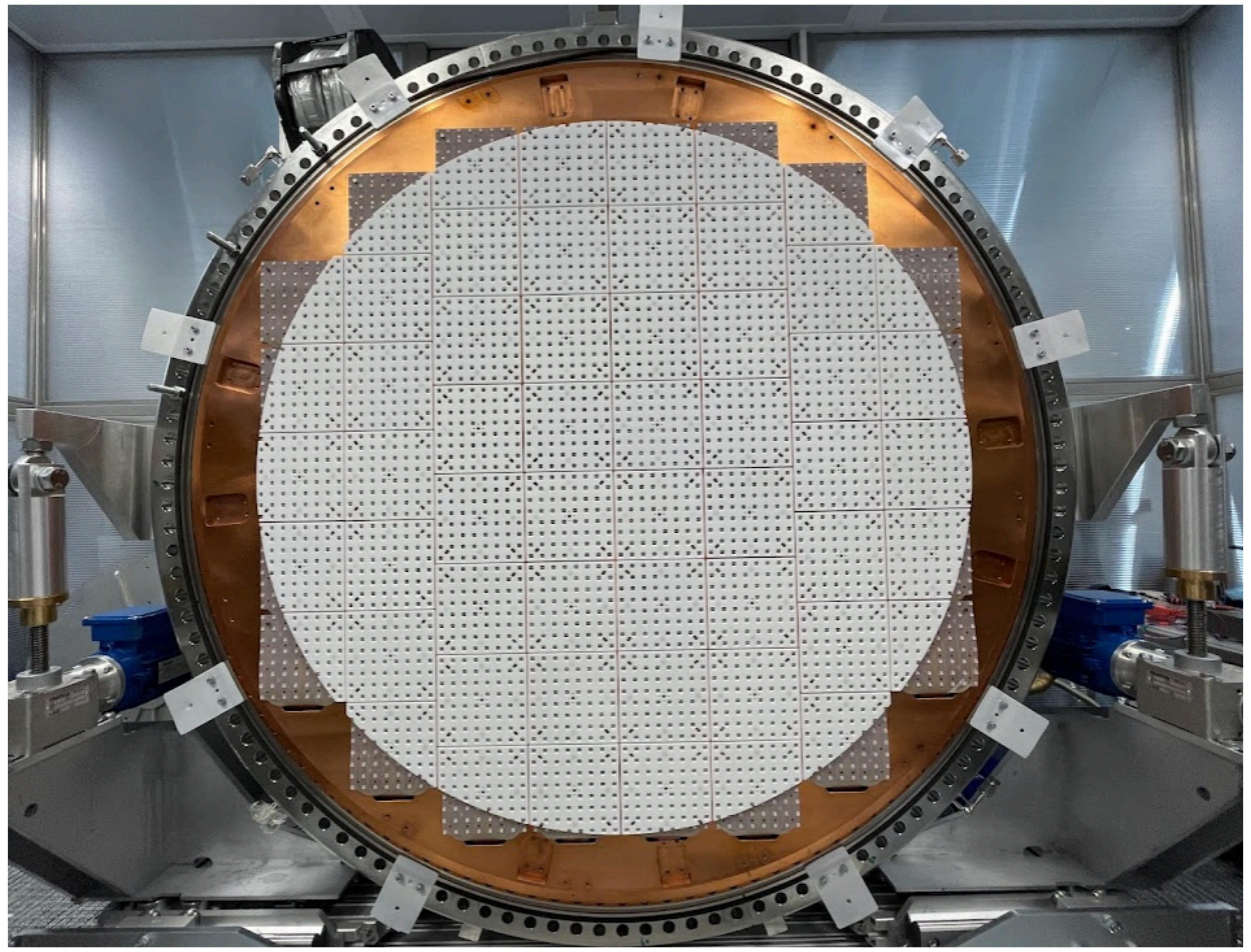
NEXT-100 sensitivity: 4.1 x 10^{25} yr

JHEP **1605** (2015) 159

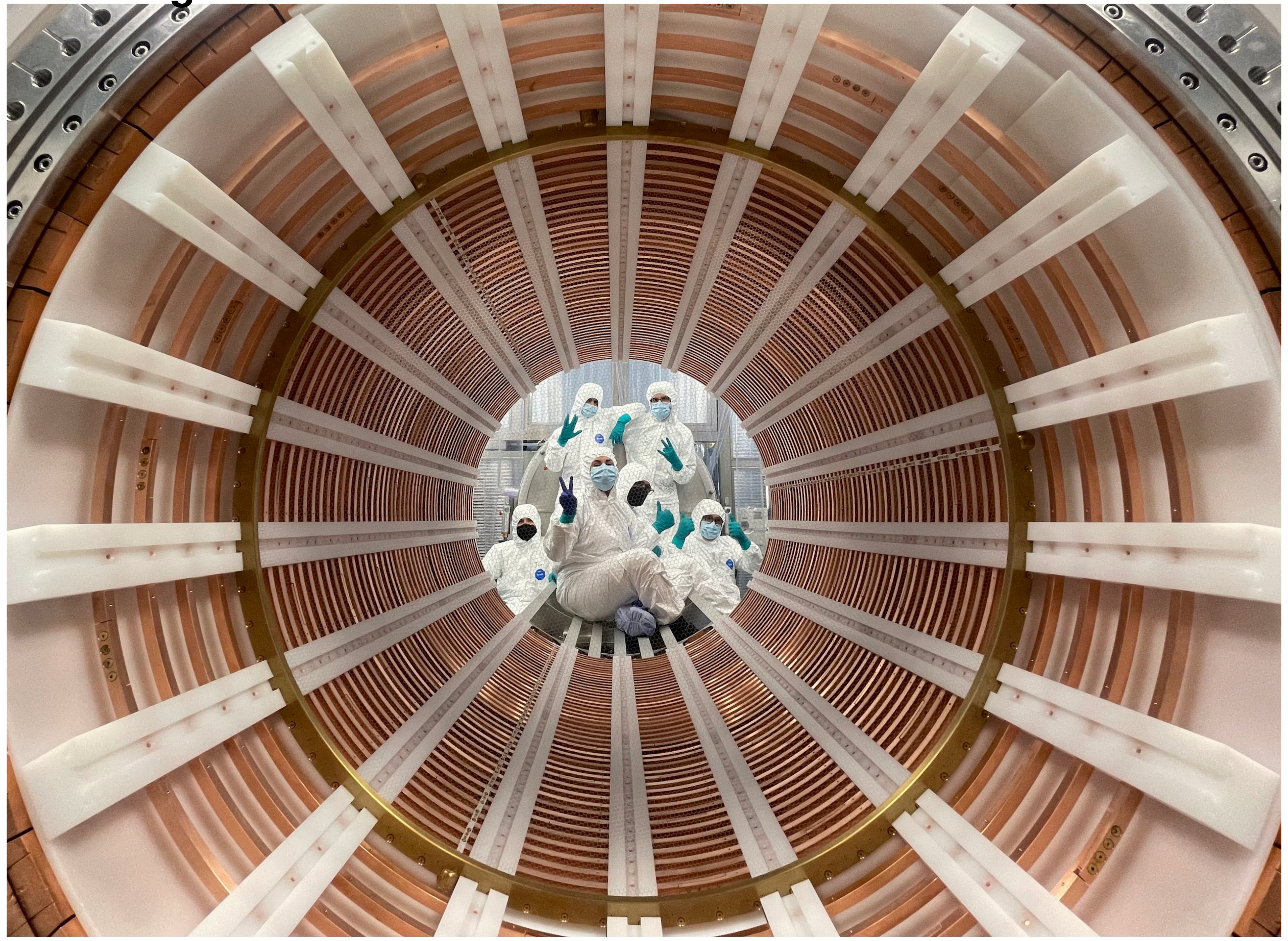
Status of NEXT-100

- Detector fully built and under commissioning!
- First runs in Ar gas in May 2024
- Xenon runs to start shortly

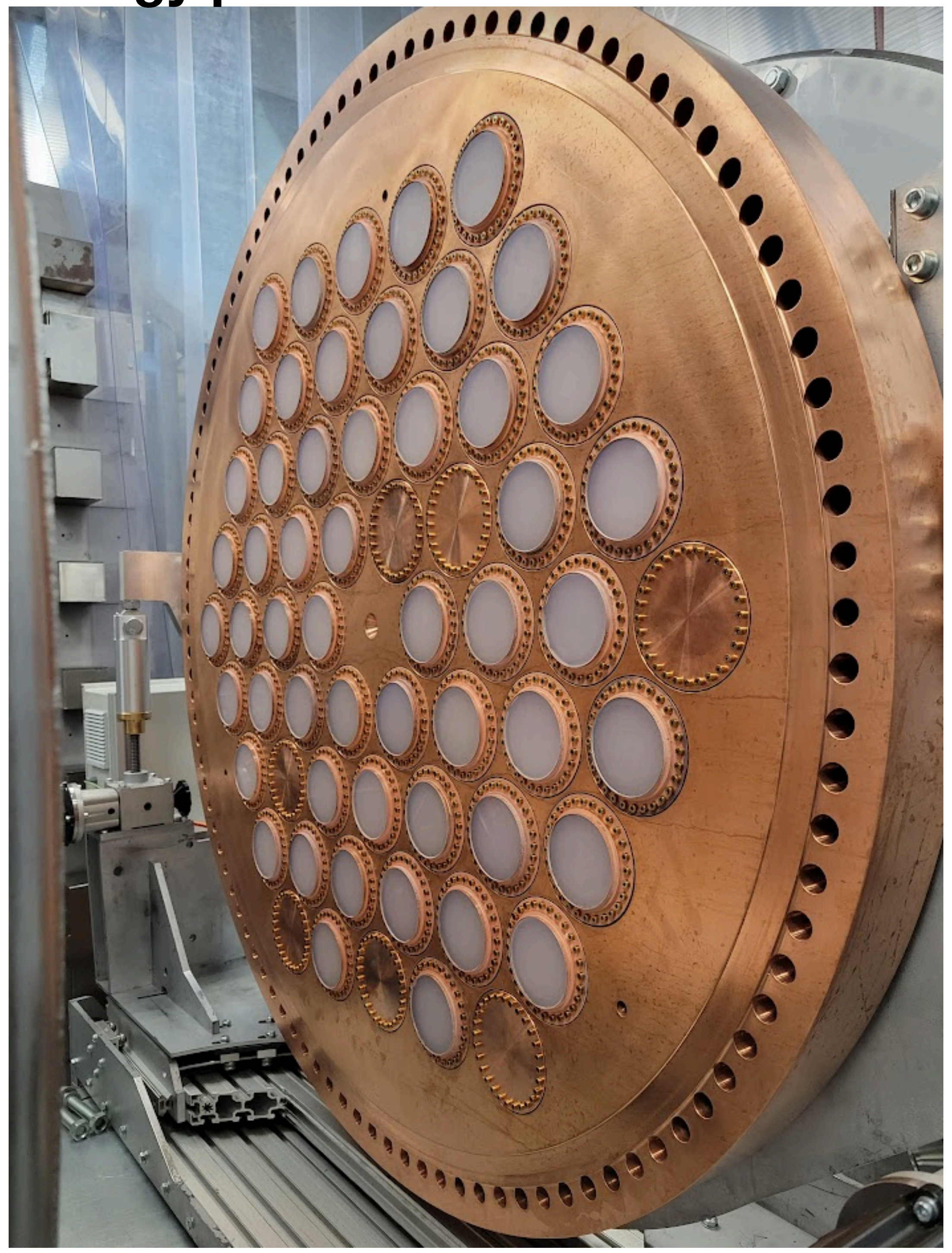
Tracking plane



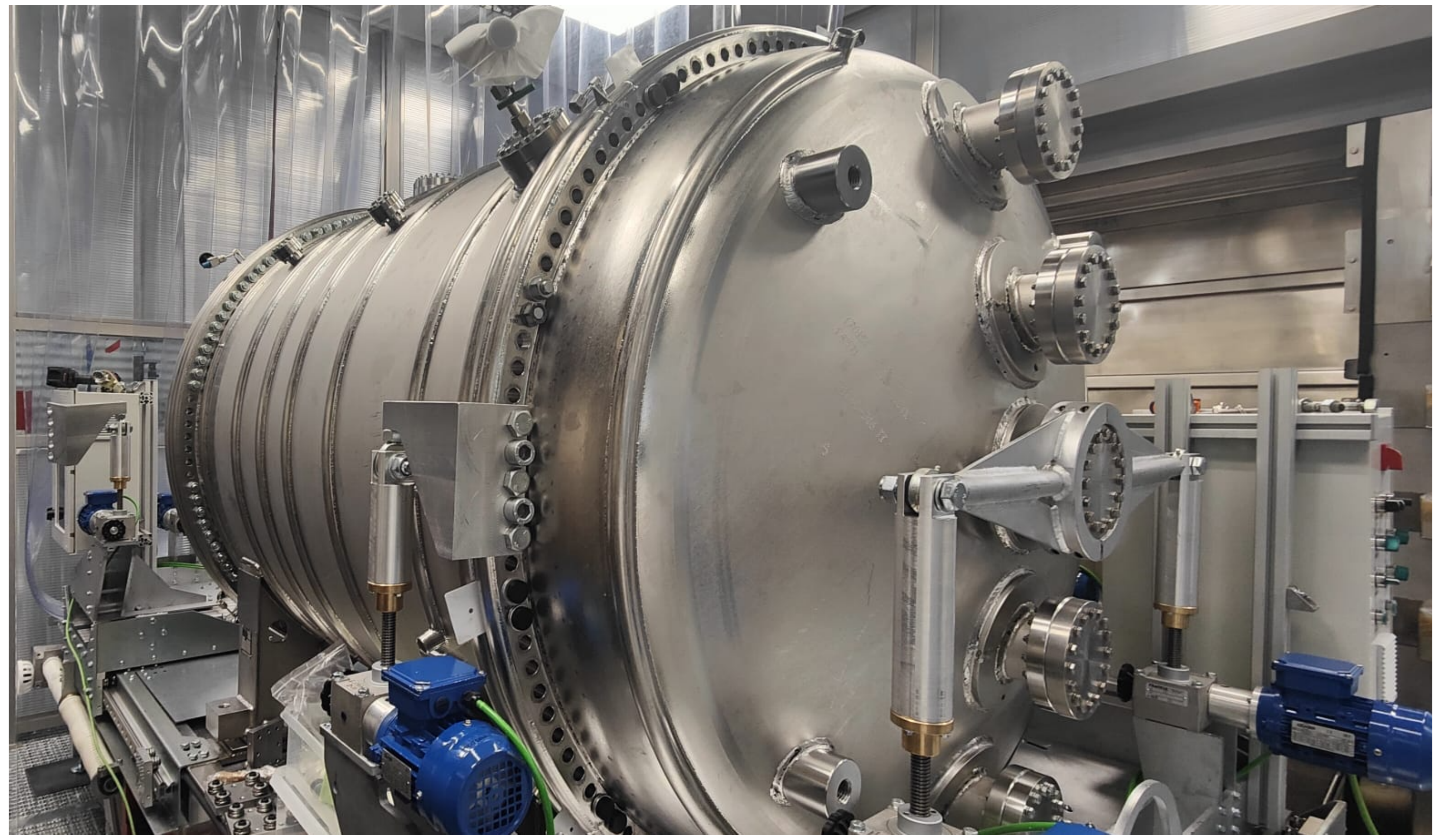
Field cage



Energy plane



Vessel

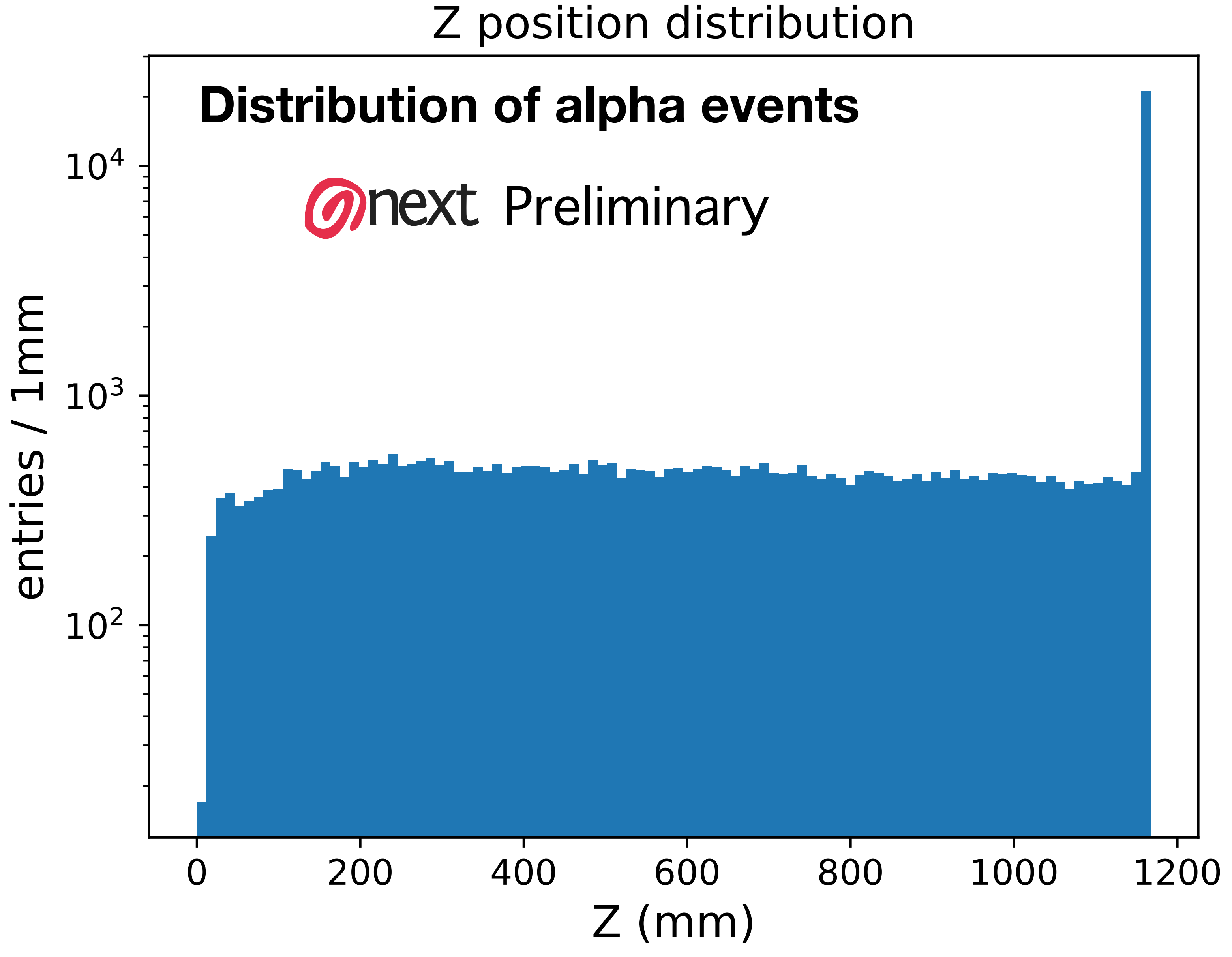


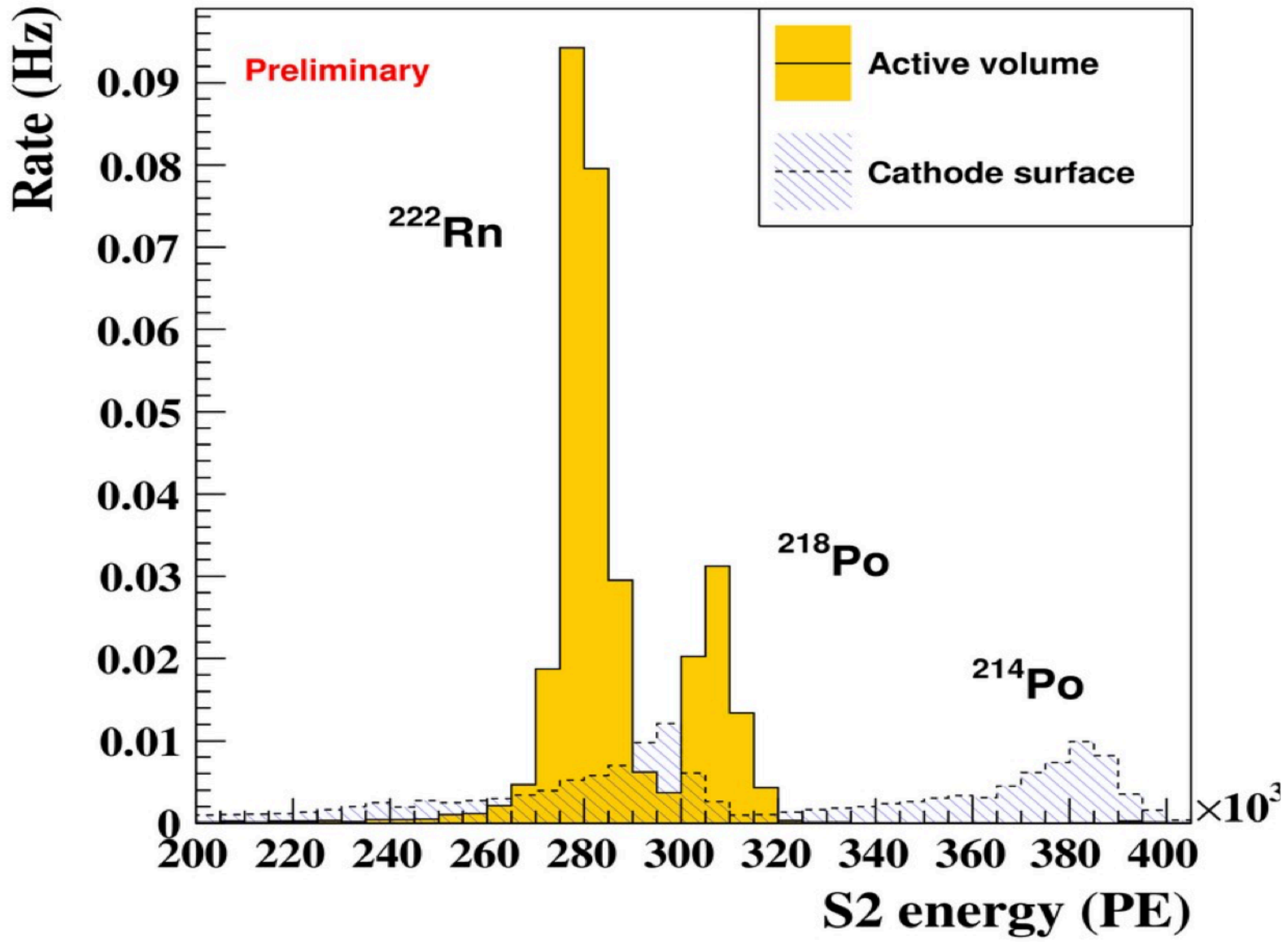
Poster 362: Searching for the neutrinoless double beta decay with NEXT-100 by P.Novella

Status of NEXT-100

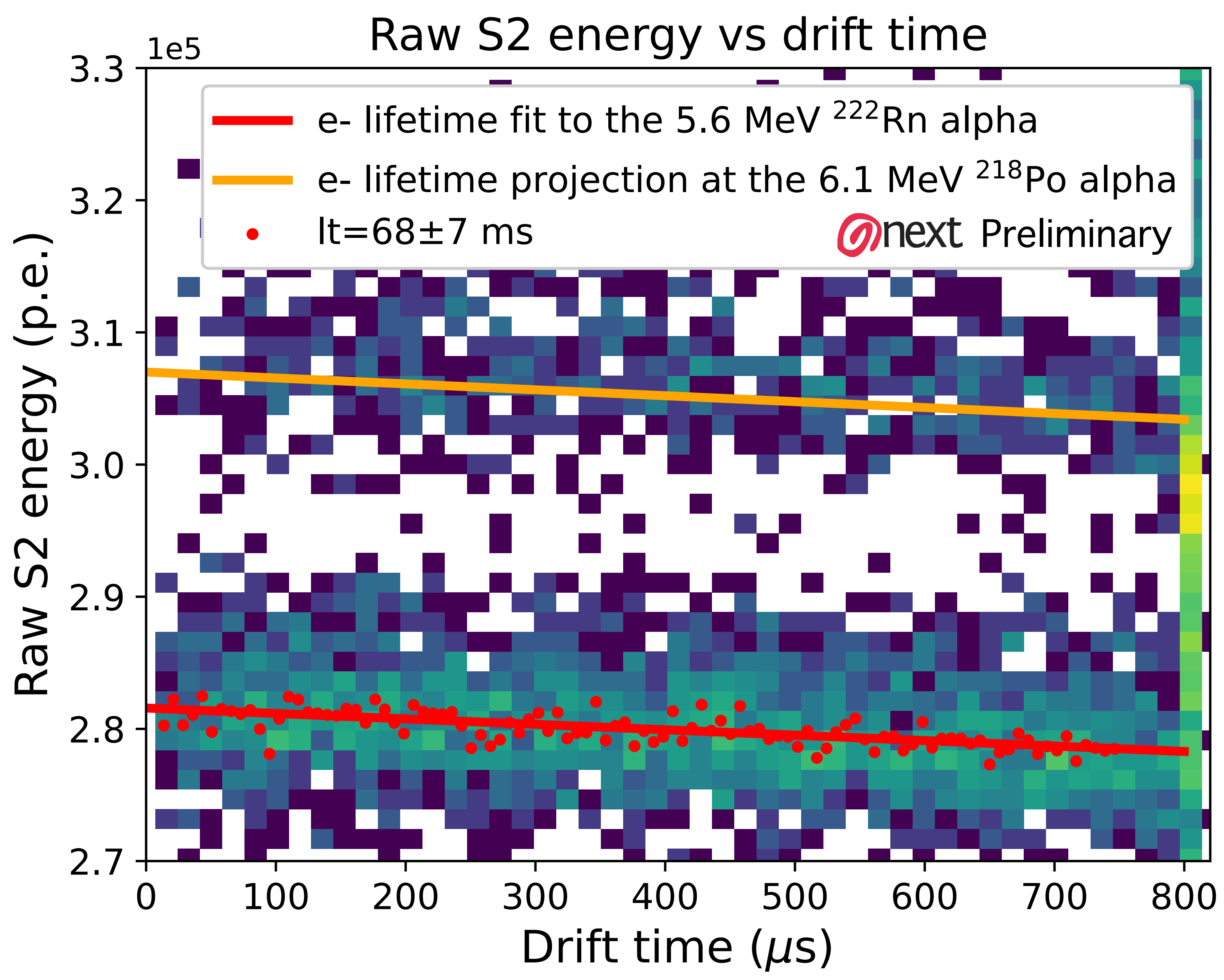
- Detector fully built and under commissioning!
- First runs in Ar gas in May 2024
- Xenon runs to start shortly

Very recent detector response on alpha particles from ^{222}Rn





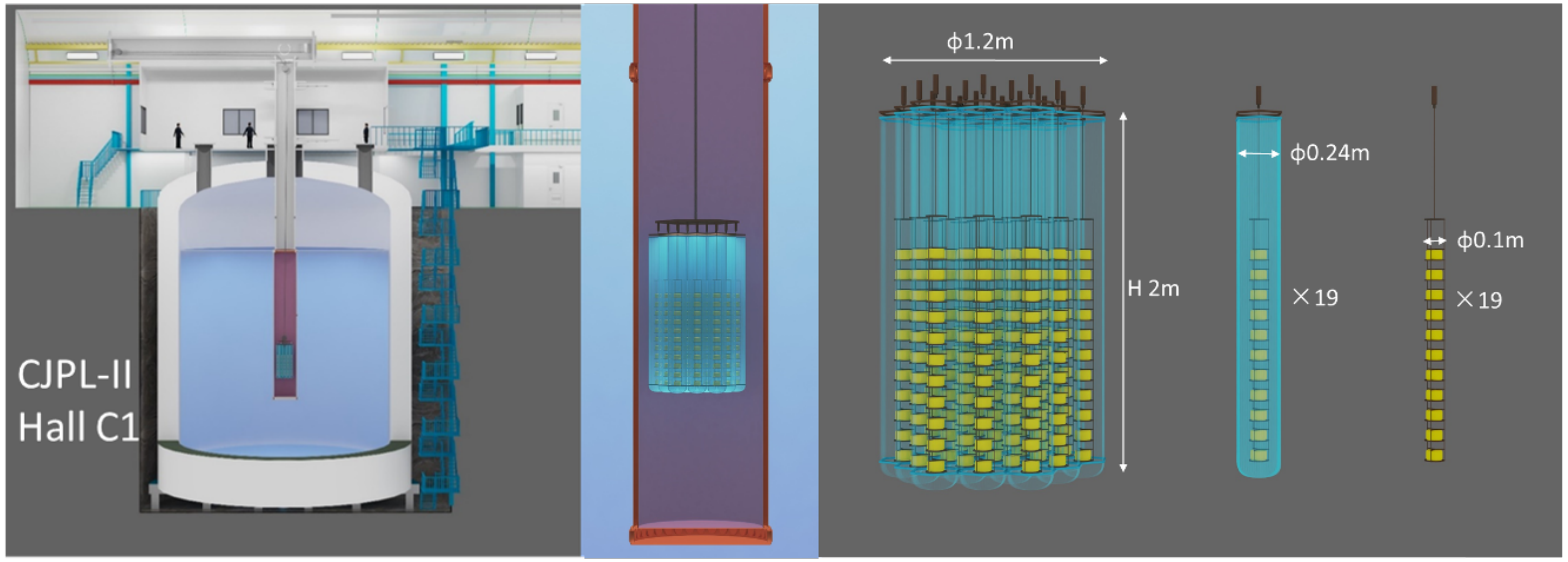
Lifetime measurement



Poster 362: Searching for the neutrinoless double beta decay with NEXT-100 by P.Novella

Coming soon: CDEX-300v

- Enr-Ge detectors test started in 2022 @ CJPL-I
- Test and operate LAr test facility in early 2024
- Hall C1 ready for experiment this June
- Experimental setup in 2024
- First batch of Ge detector installation and test in 2024
- Expected 1.3×10^{27} yr half-life sensitivity with 5 yr running

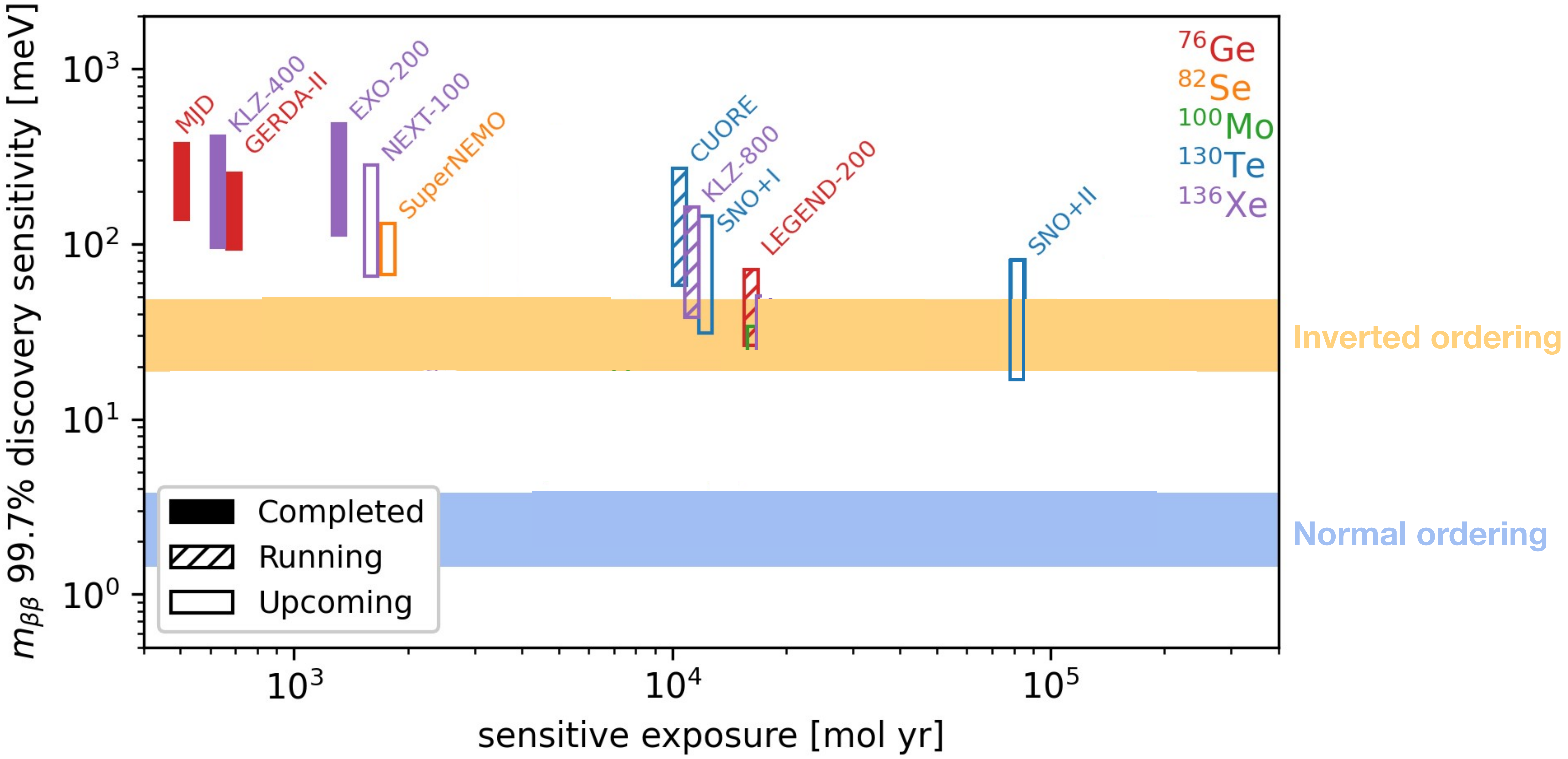


1725 m³ Liquid Nitrogen LAr tube Enriched Ge array

Thanks to Hao Ma for the slide!

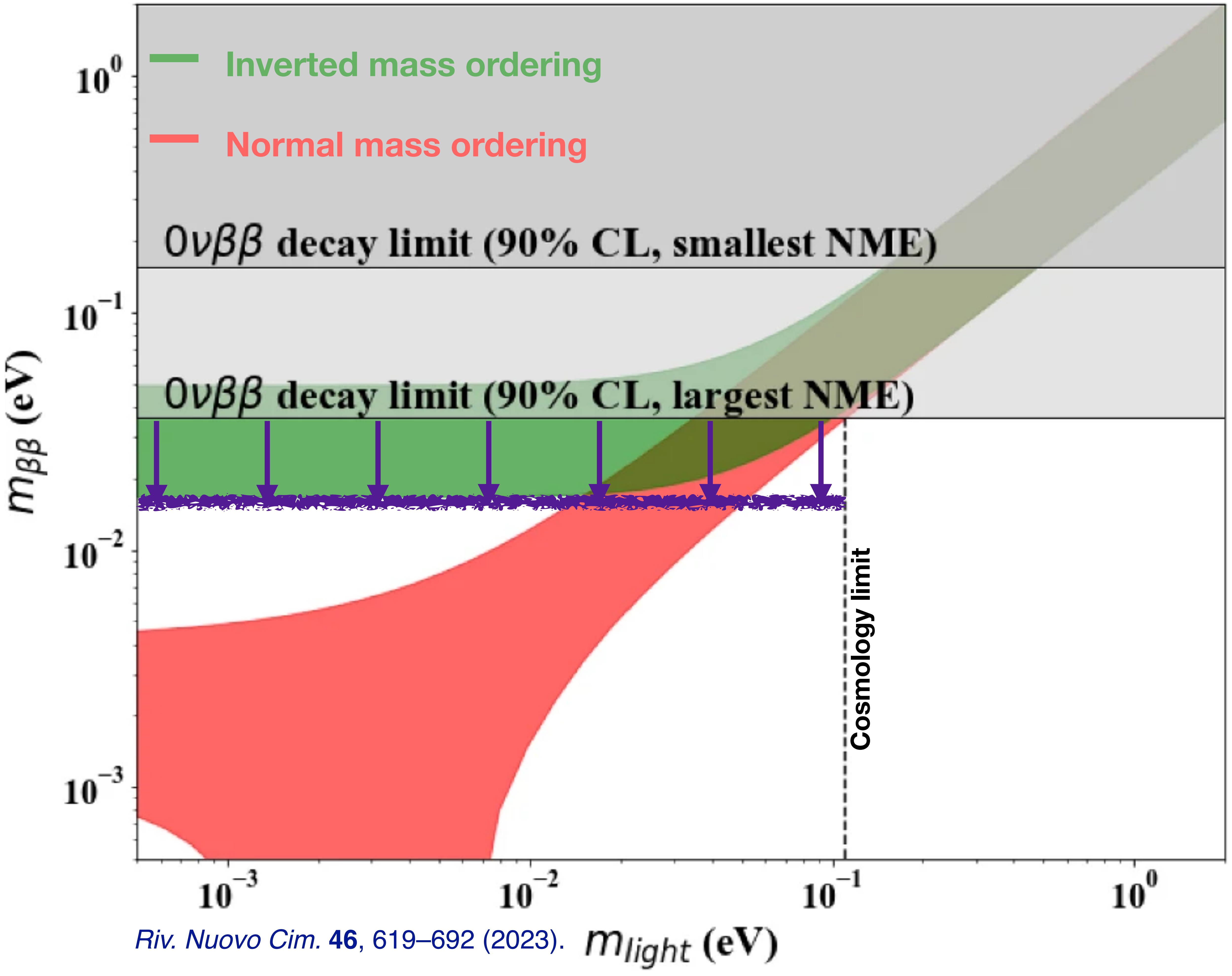
Current generation sensitivity

- Unless we are lucky, this generation may not get there…



Adapted from the Long Range Plan for Nuclear Physics 2023: arxiv:2304.03451

Next step: Conquer the Inverted Ordering



Riv. Nuovo Cim. **46**, 619–692 (2023).

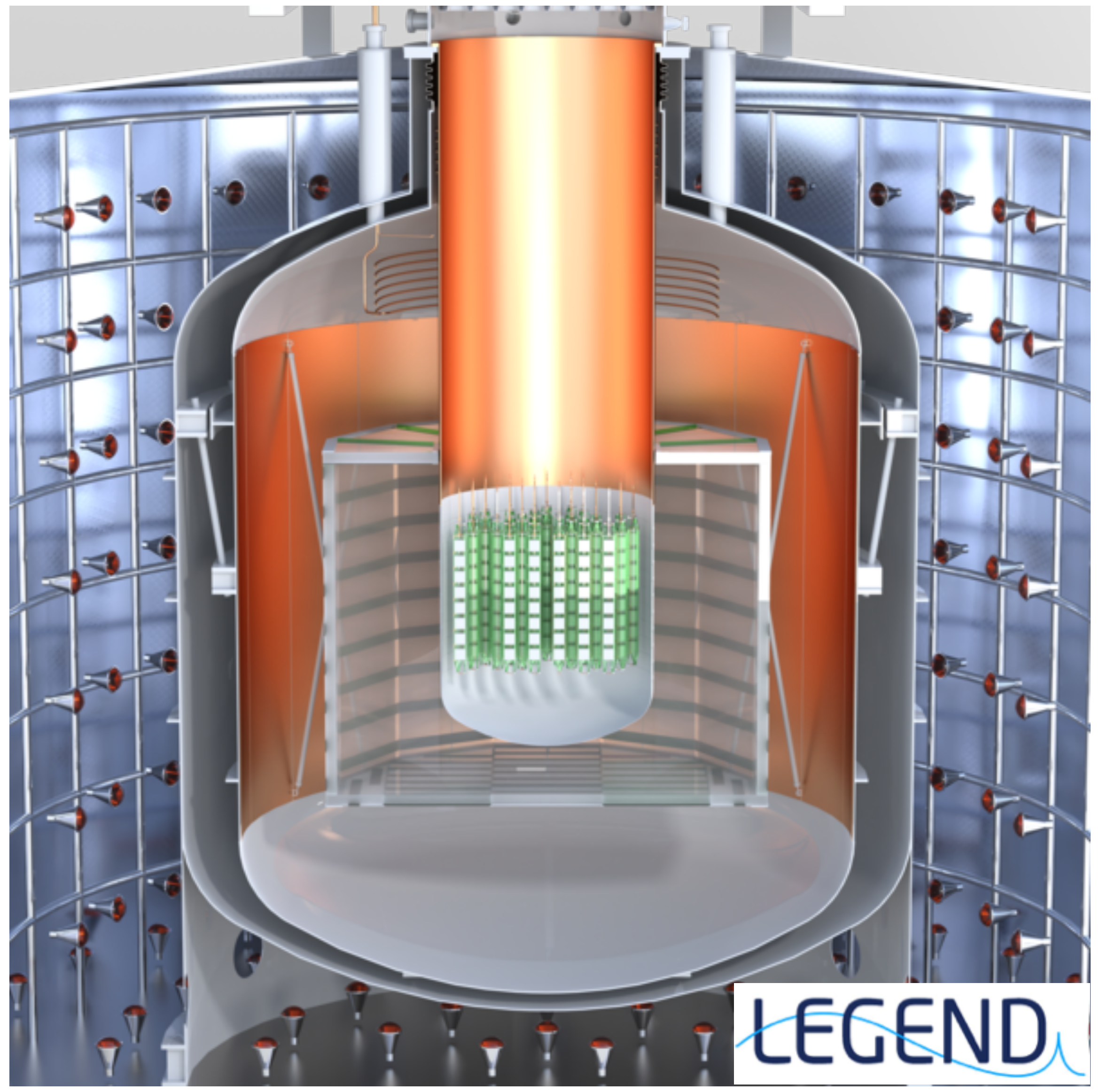
Need tonne-scale experiments!

**** This plot is just one example of parameter space… It does not mean that is exactly where the Majorana neutrino is! ****

Conquering the inverted ordering

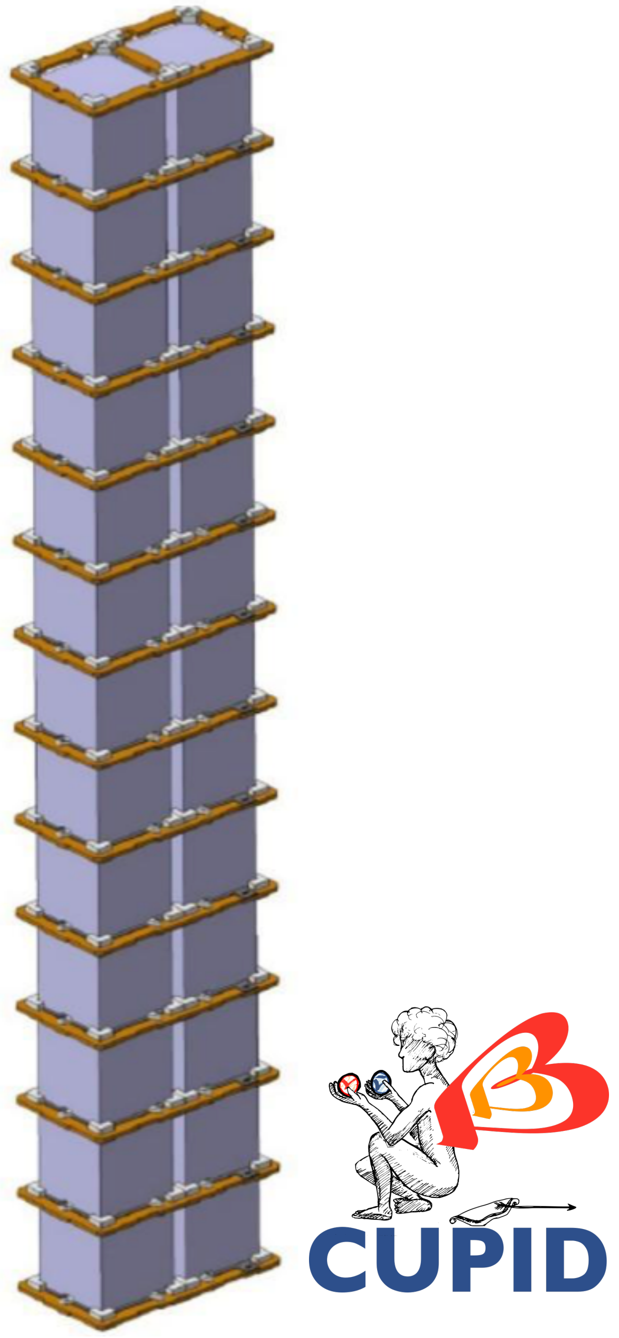
- Currently proposed tonne-scale experiments:

LEGEND-1000



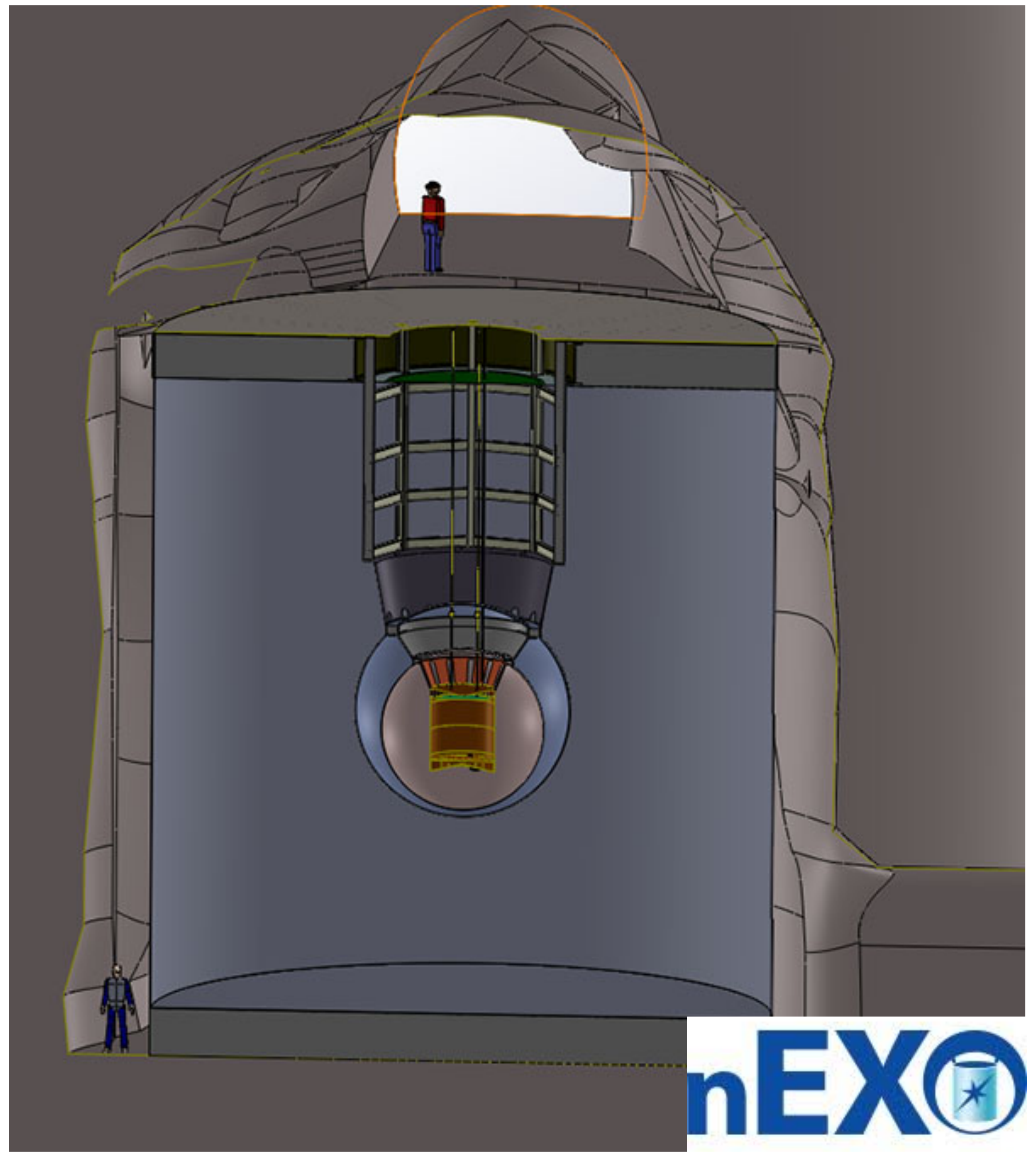
See L. Pertoldi's talk

CUPID



See C. Bucci's talk

nEXO

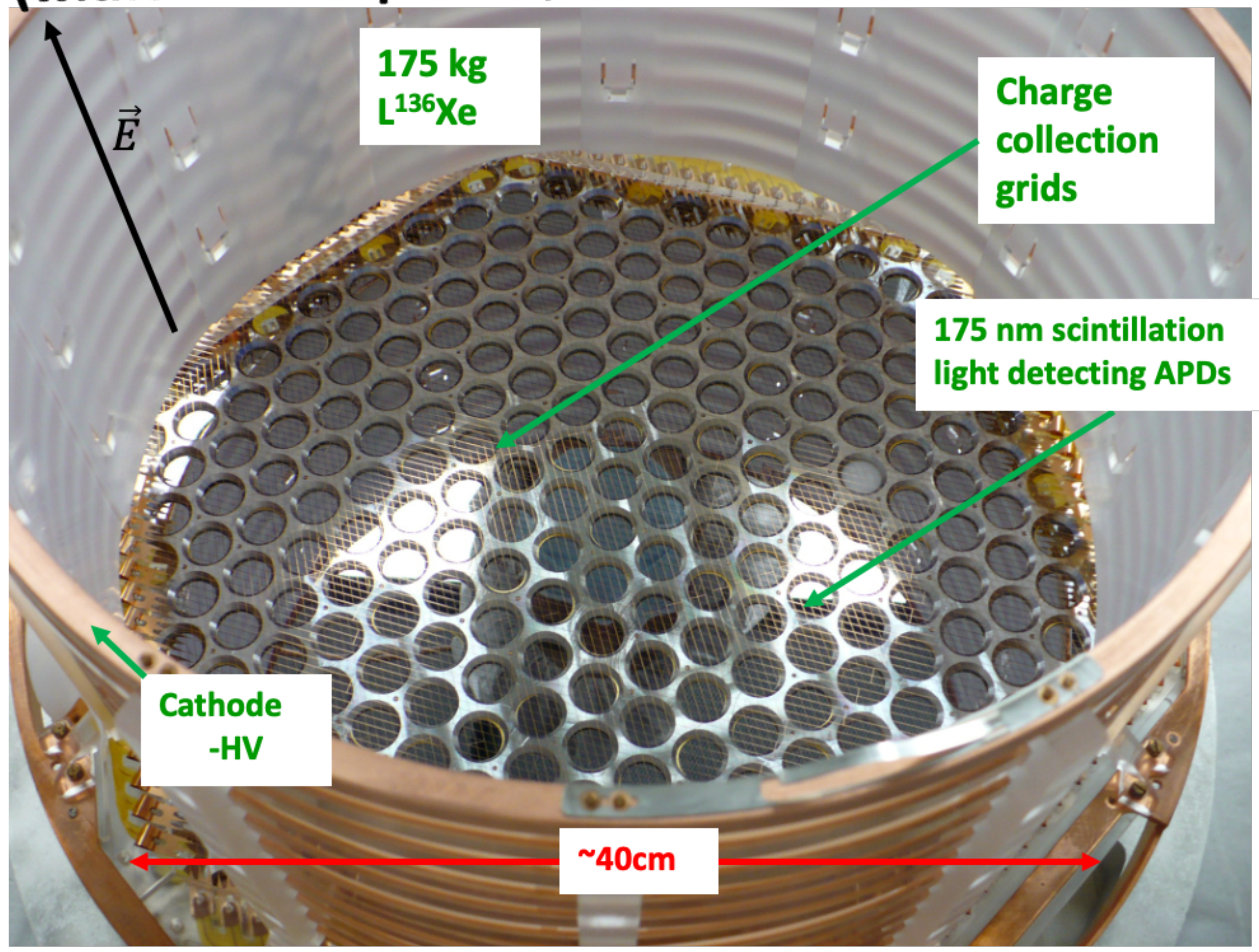


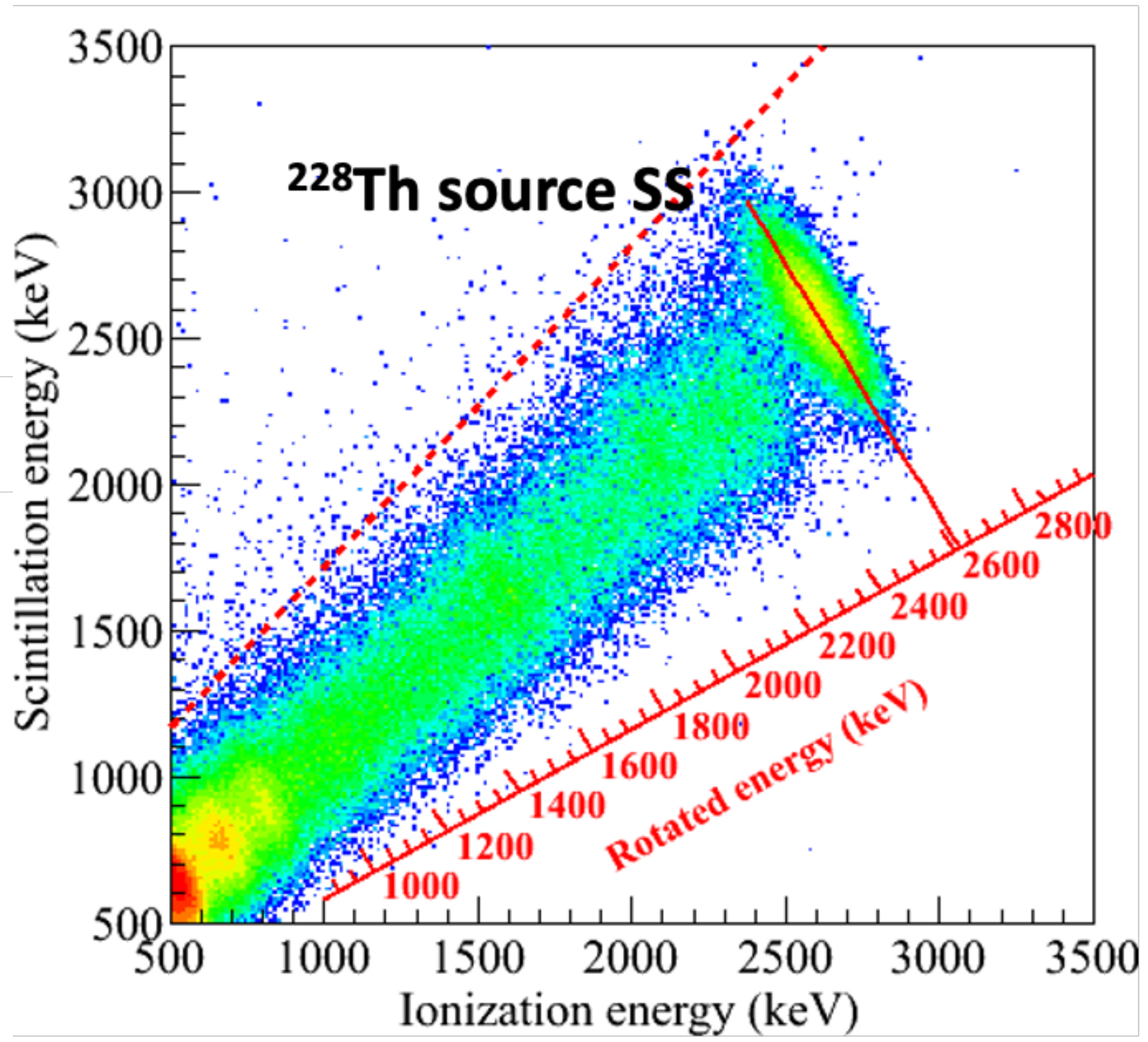
NEXT-HD

nEXO

- Builds (directly extrapolated) on successful EXO-200 predecessor
- 5 tonnes of enriched LXe TPC (^{136}Xe)

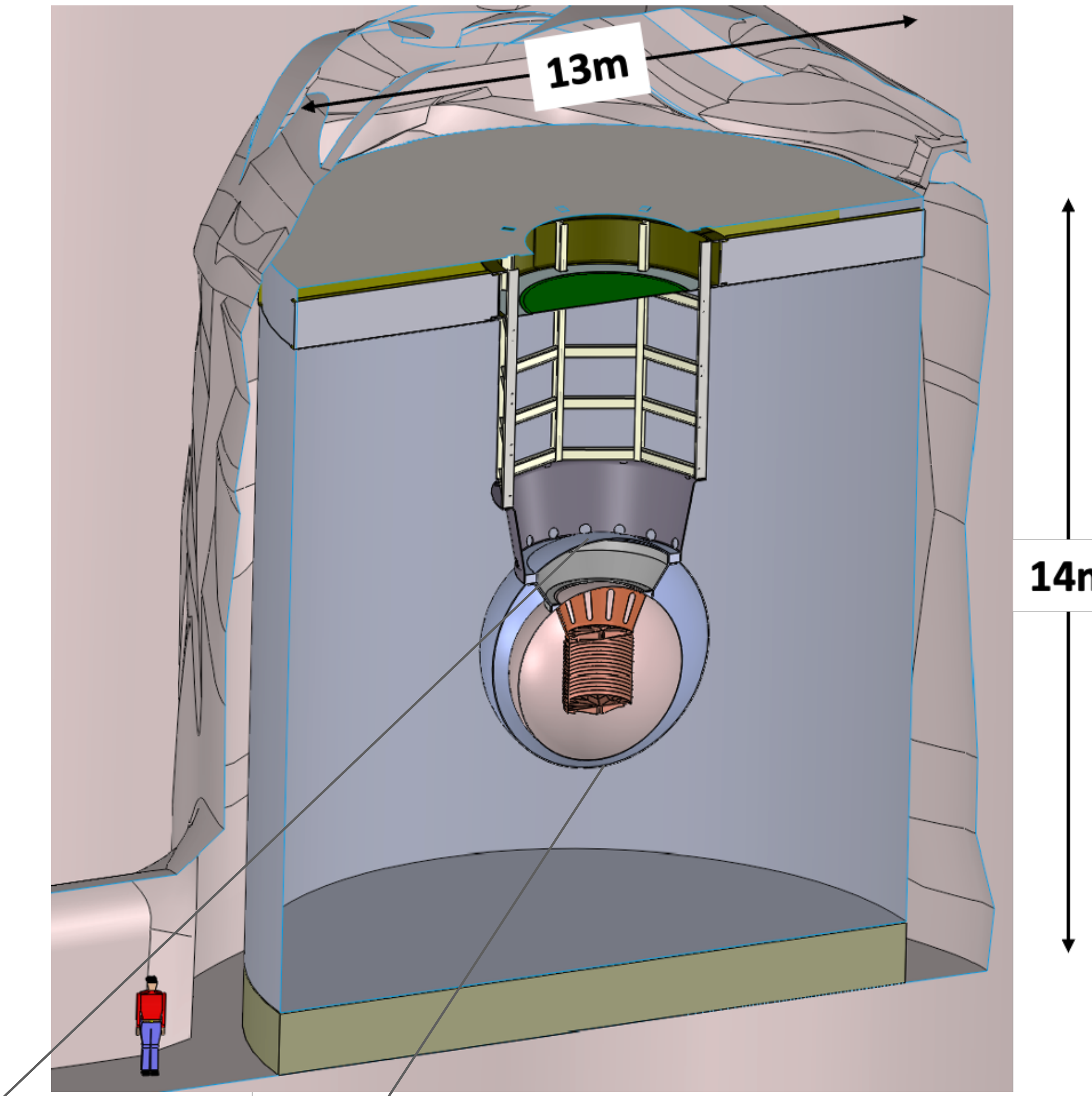
(1/2 of) the EXO-200 TPC (without the liquid Xe)

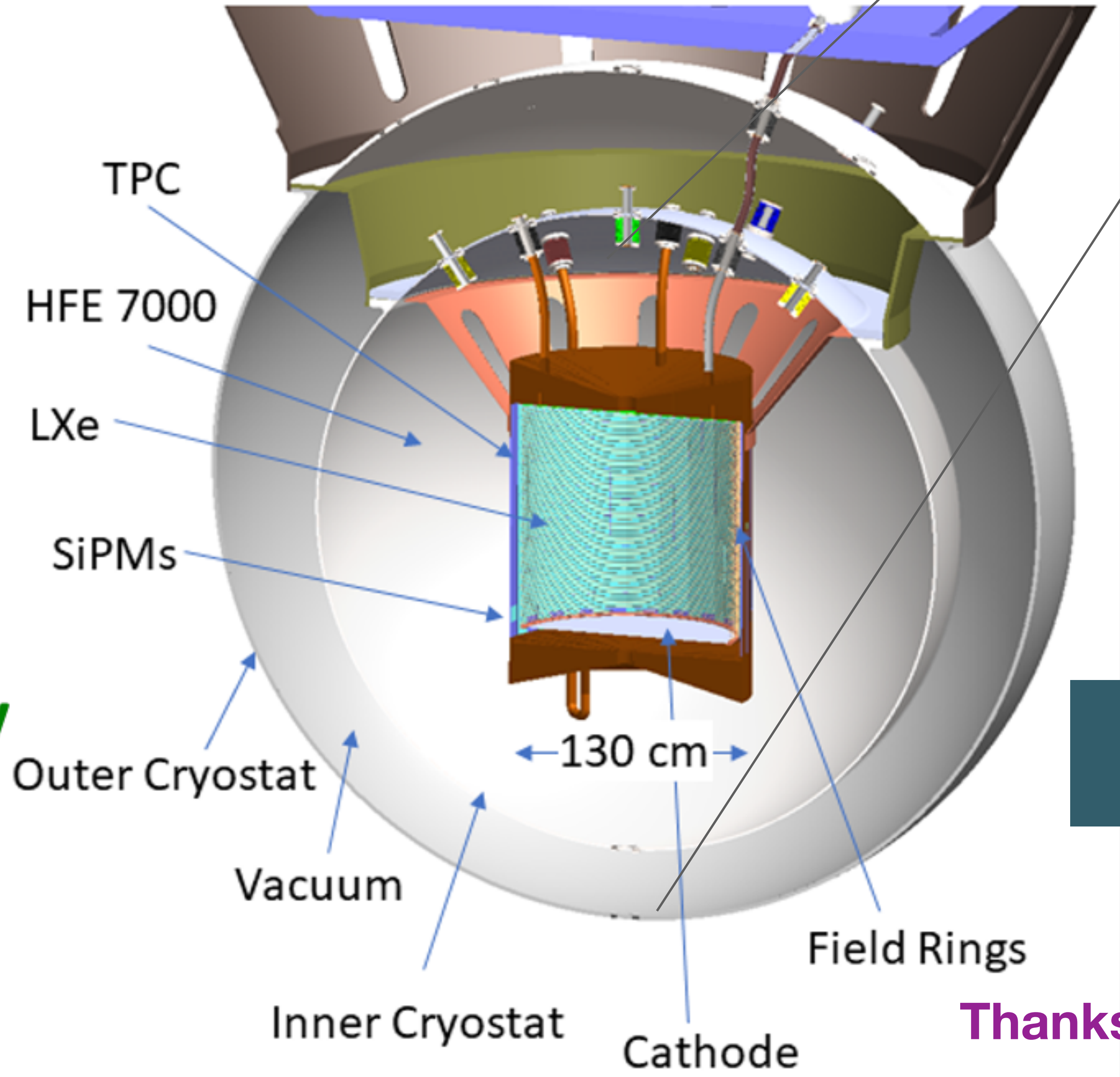




Rotation angle chosen to optimize energy resolution near $Q_{\beta\beta}$=2457.83 keV

2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys. Rev. Lett. 123 (2019) 161802



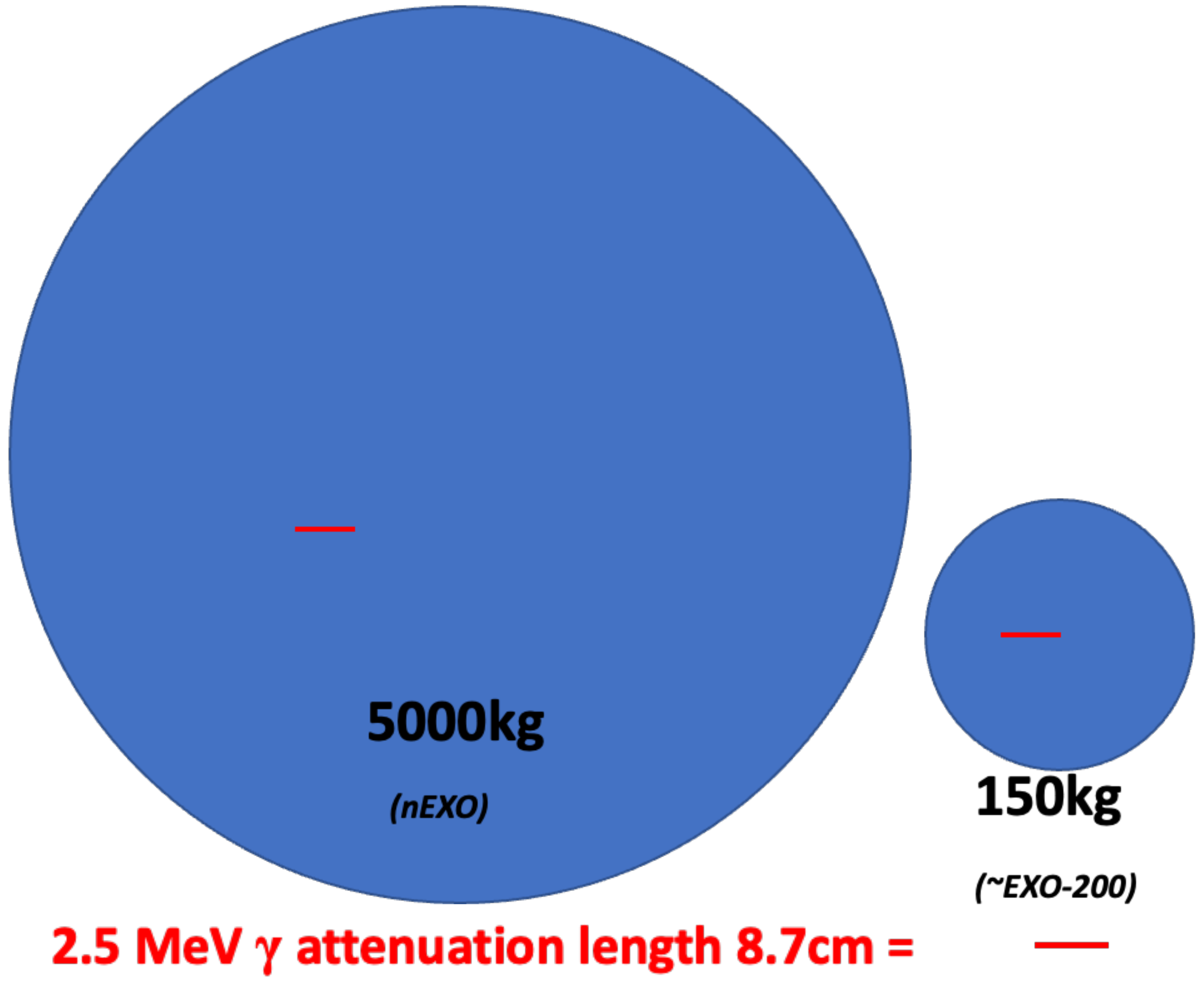


Posters # 478, 447, 294

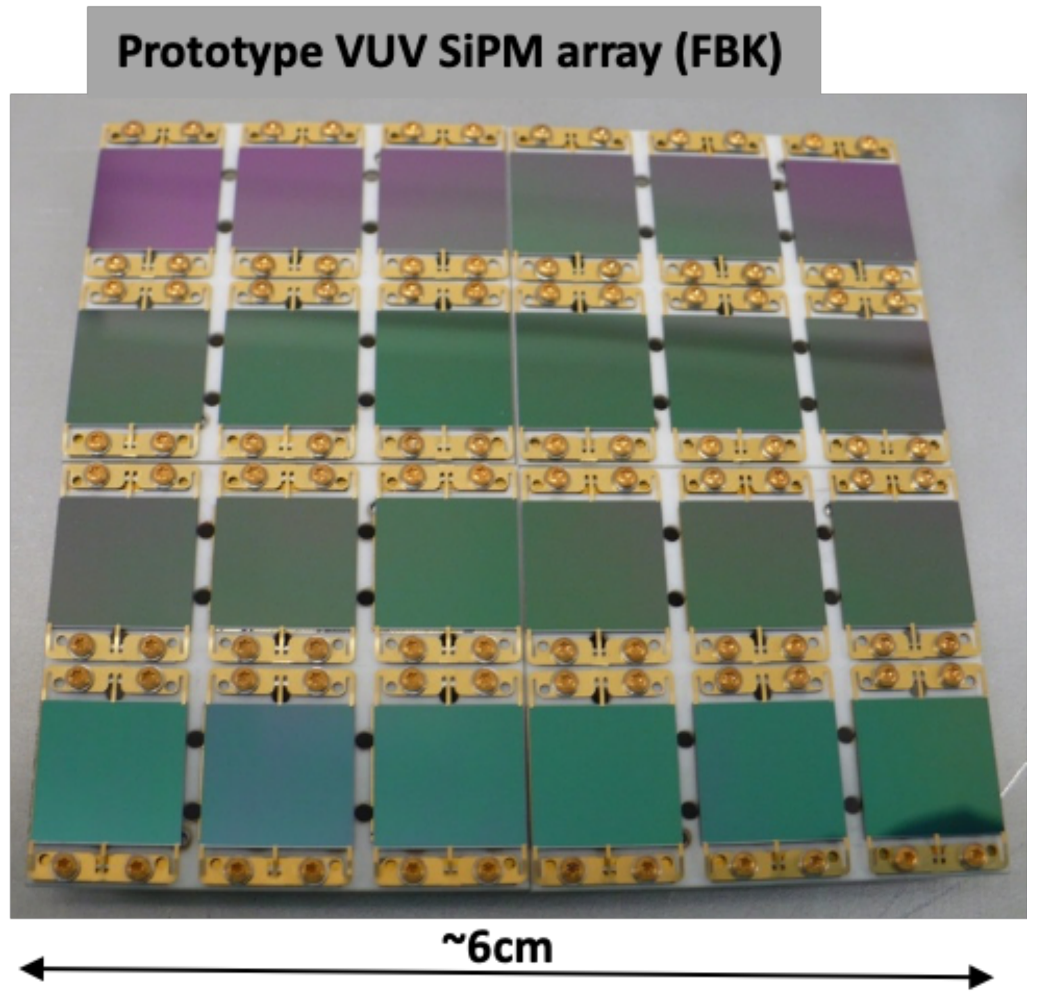
Thanks to G. Gratta for the slides!

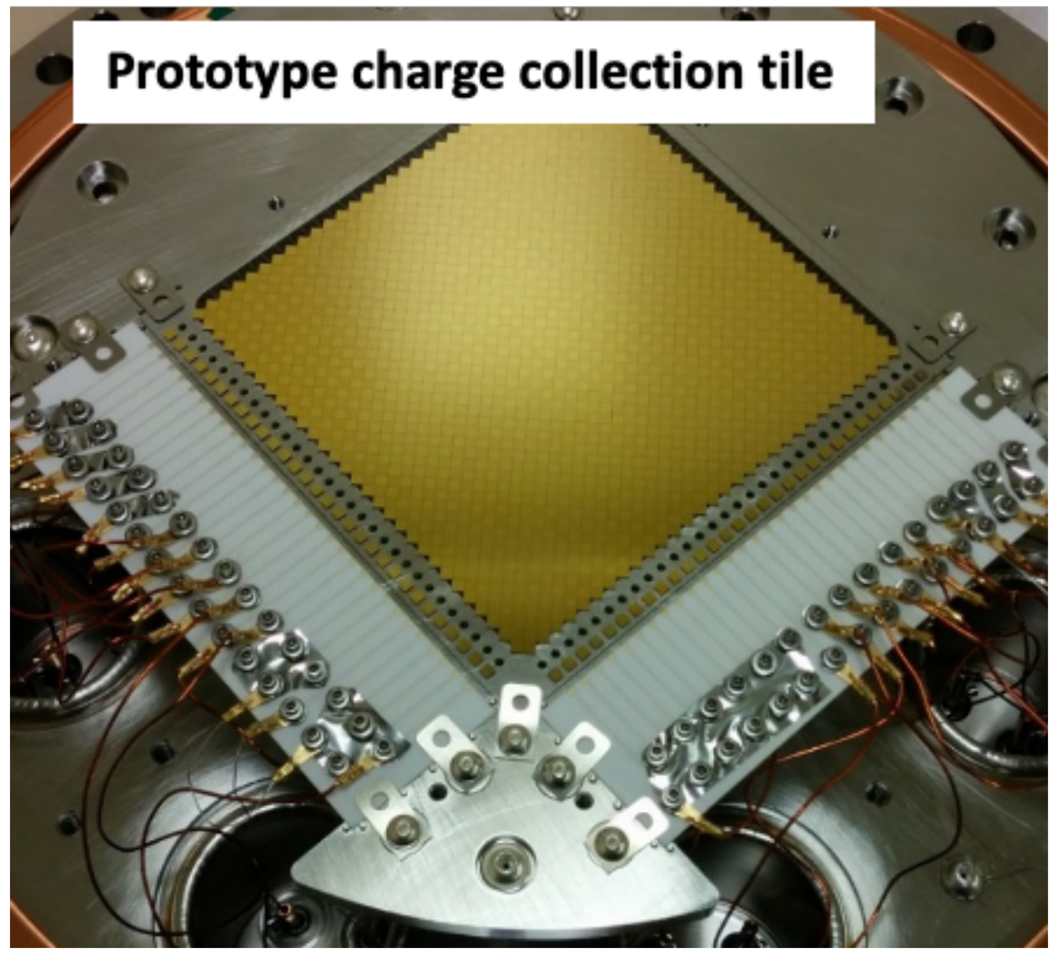
nEXO

Great self-shielding power with LXe



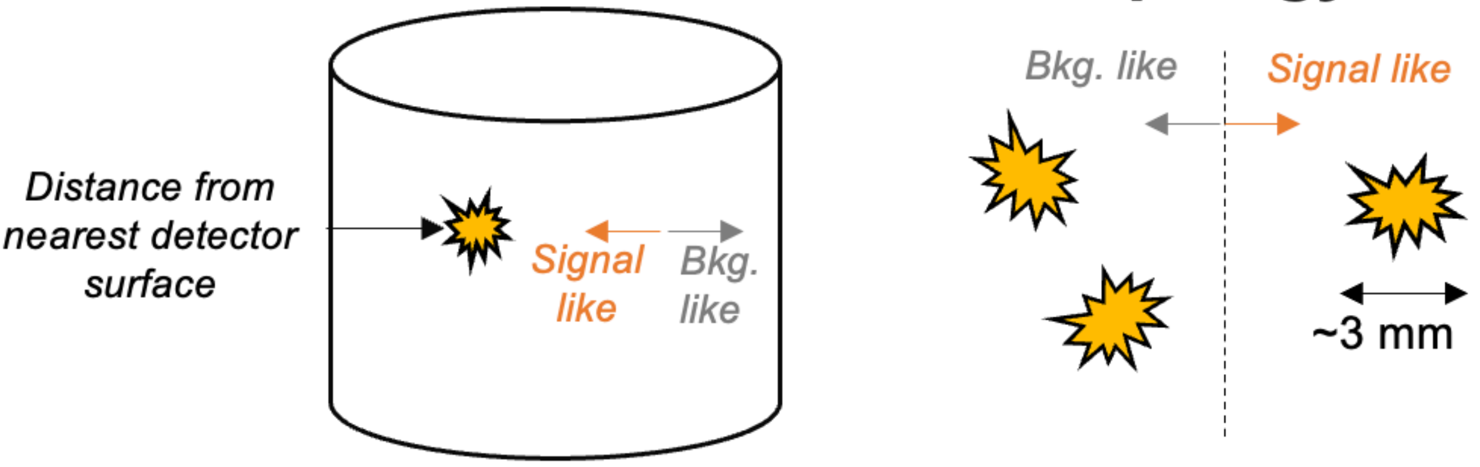
New readout technologies





Signal vs background

Standoff: **Topology:**



	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)	*Cu clad polyimide (digital)*	Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission
e^- lifetime	3-5 ms	*5 ms (req.), 10 ms (goal)*	Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program
Charge collection	Crossed wires	*Gridless modular tiles*	R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed
Light collection	APDs + PTFE reflector	*SiPMs around TPC barrel*	SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors
Energy resolution	1.2%	*1.2% (req.), 0.8% (goal)*	Improved resolution due to SiPMs (negligible readout noise in light channels)
Electronics	Conventional room temp.	*In LXe ASIC-based design*	Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage
Background control	Measurement of all materials	*Measurement of all materials*	RBC program follows successful strategy demonstrated in EXO-200
Larger size	>2 atten. length at center	*>7 atten. length at center*	Exponential attenuation of external gammas and more fully contained Comptons

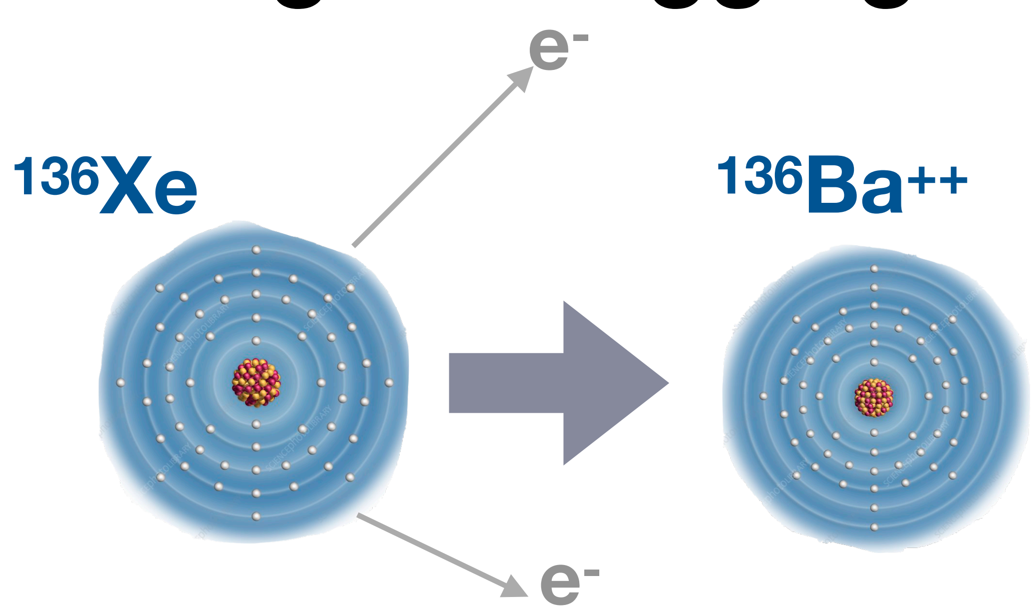
nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

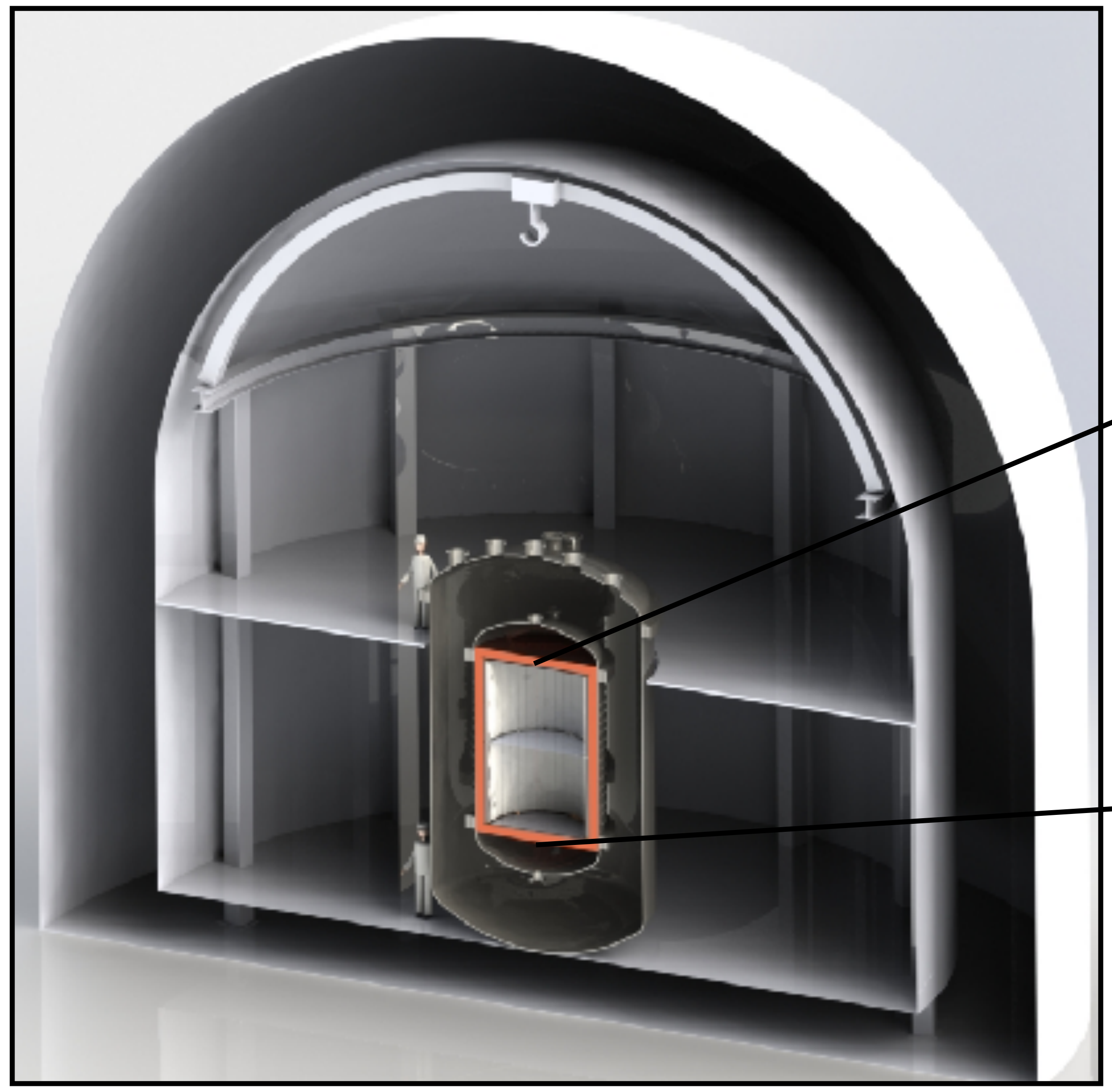
Thanks to G. Gratta for the slides!

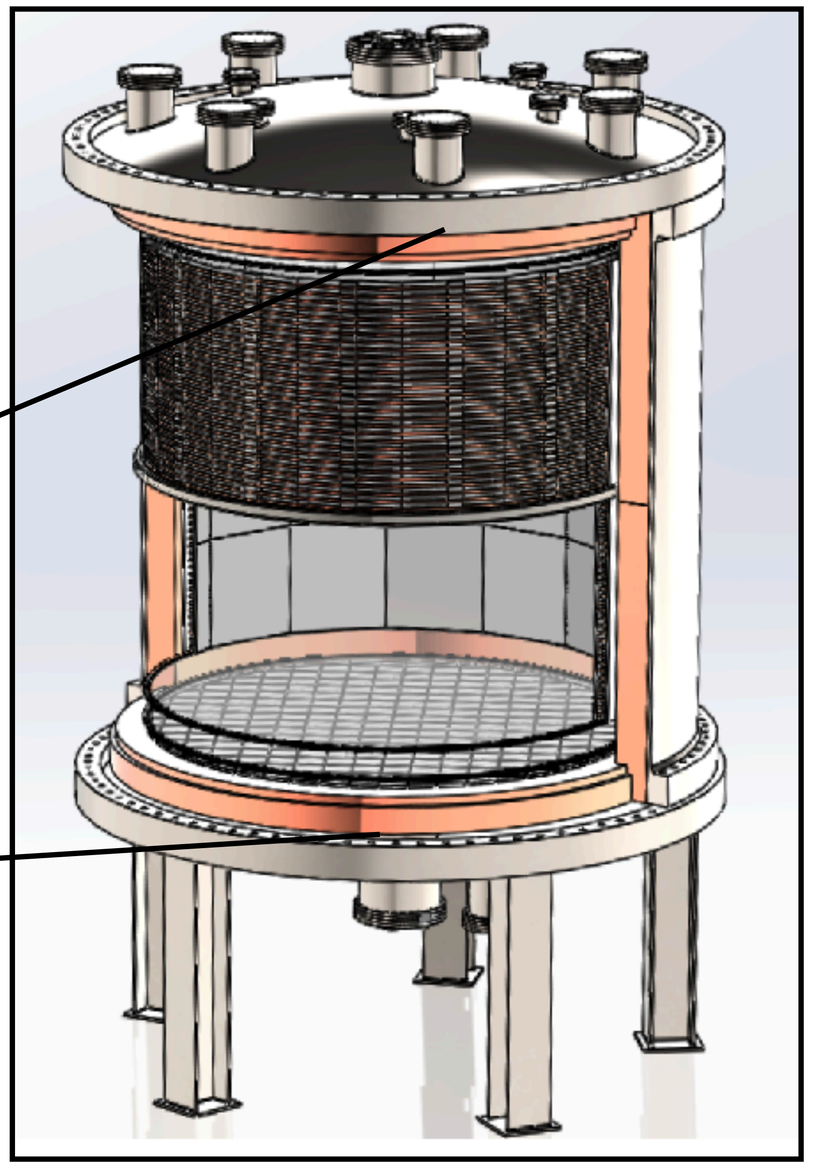
NEXT-HD (and NEXT-BOLD)

- Module(s) of 1 tonne of ^{136}Xe building in NEXT technologies (NEXT-HD)
- Designed to accommodate future Ba tagging (NEXT-BOLD)

Daughter tagging:

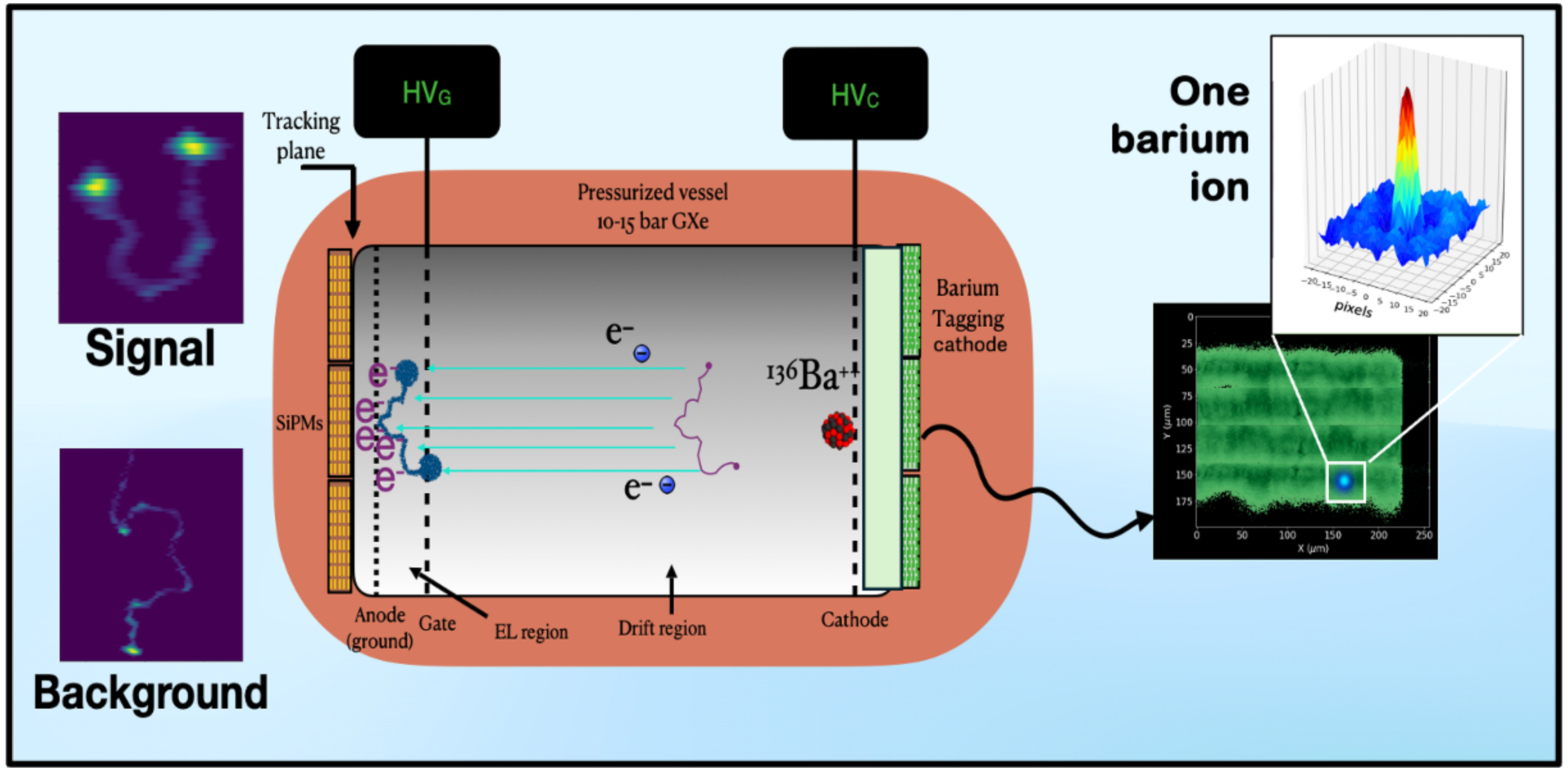






NEXT Collaboration, *JHEP* 164 (2021) 08

Letter of Intent to be submitted in 2025 to LSC

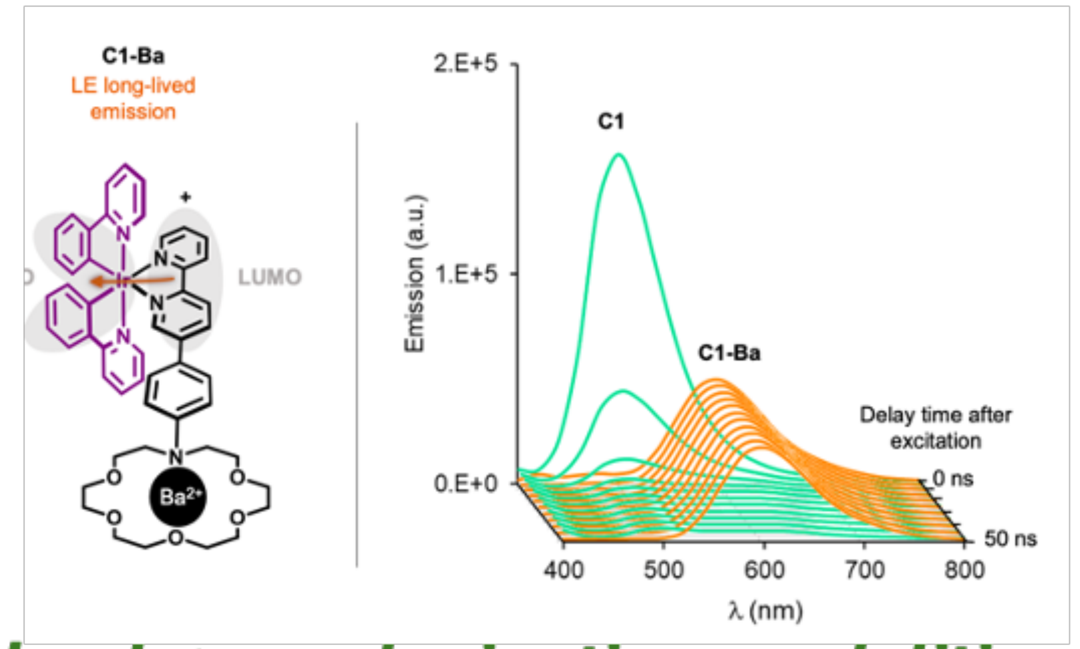


Poster 430: Optical Time Projection Chamber for the Realization of a Ton-Scale Neutrinoless Double Beta Decay Demonstratorby L. Rogers

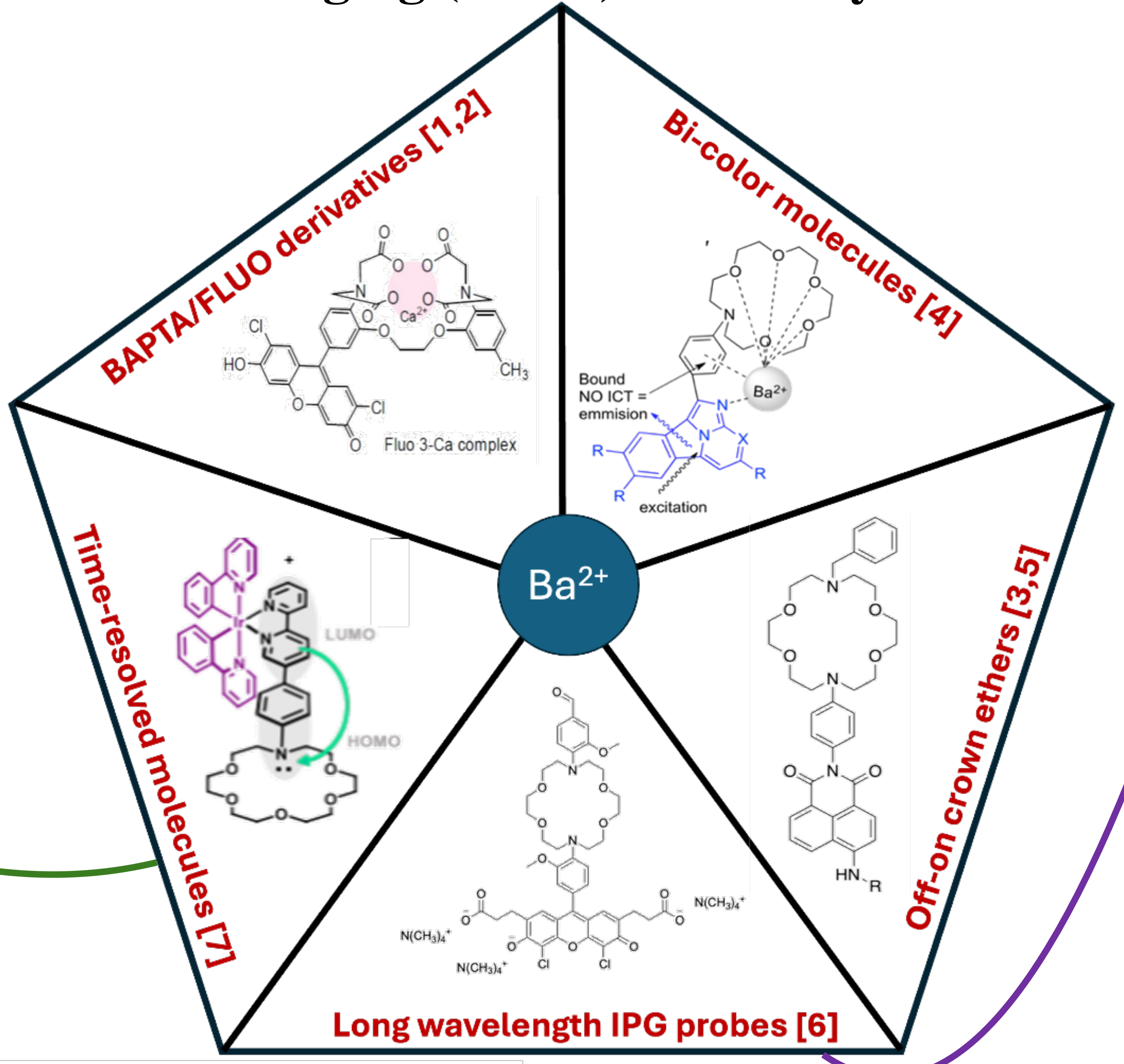
Barium ion is only produced in a true ββ decay, not in any other radioactive event →Identification of Ba ion with ~1% FWHM energy measurement would give a **background-free experiment**.

Very recent progress in Ba tagging

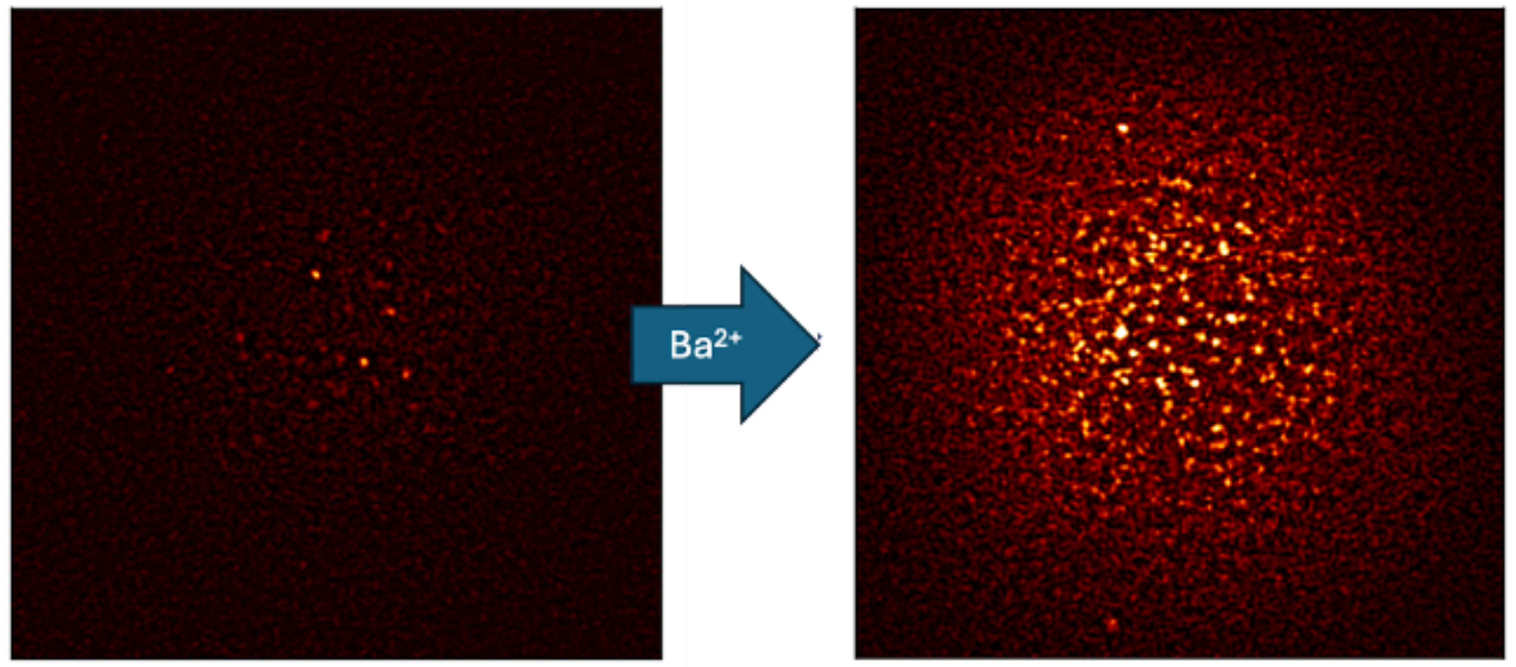
The NEXT approach uses single molecule fluorescence imaging (SMFI) to identify barium interacting the specially designed organic molecules.



New background rejection modalities, e.g. phosphorescence/fluorescence separation

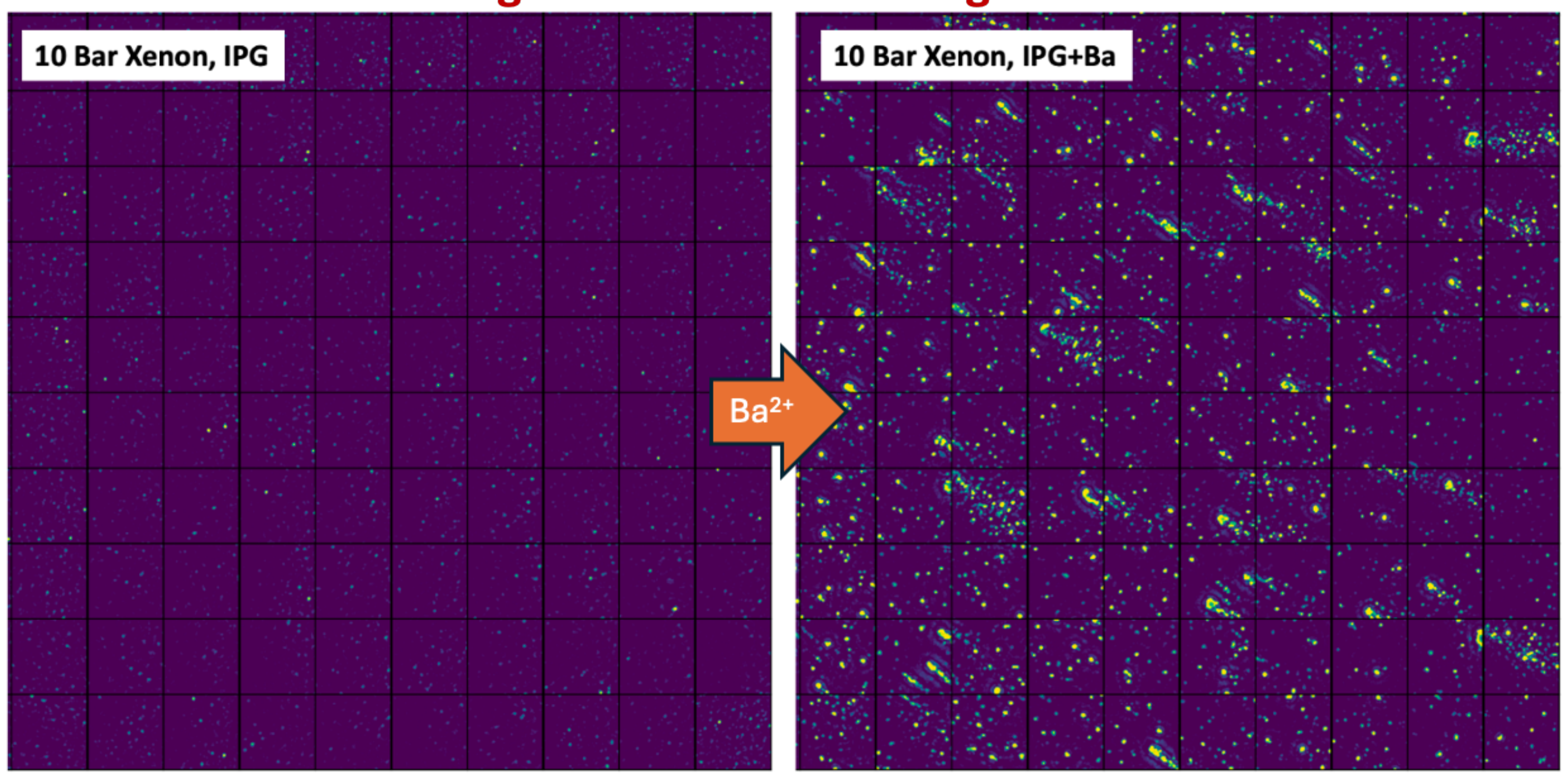


[1]. JINST 11 P12011 (2016)
[2]. Phys. Rev. Lett. 120, 132504 (2018)
[3]. Sci Rep 9: 15097 (2019)
[4]. Nature 583, 48 (2020)
[5]. ACS Sensors 6, 1, 192-20 (2021)
[6]. 10.26434/chemrxiv-2023-wxpbh (2023)
[7]. Publication in Preparation (2024)



New longer wavelength dyes enable higher quality single molecule imaging

Individual Ba^{2+} ions imaged in 10 bar of xenon gas



NEXT has built microscopy systems capable of imaging individual barium ions in high pressure xenon gas environments.

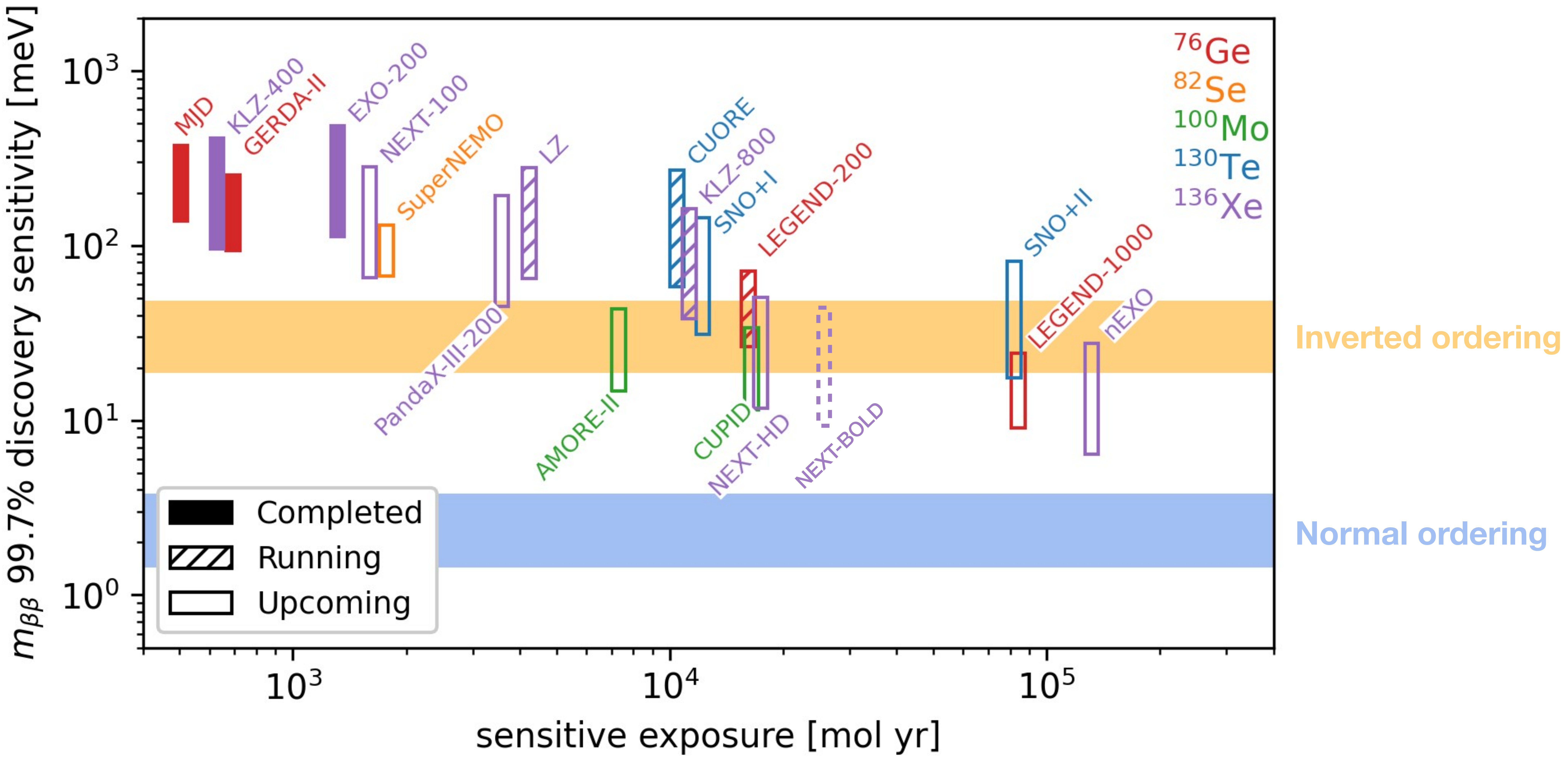
Multidisciplinary effort with physicists, chemists, material scientists

Poster 377: BOLD: three strategies for detecting single Ba ions in NEXT using molecular indicators by P. Herrero Gomez

Poster 391: Advancements in Single Barium Ion Capture and Imaging for Barium Tagging Sensors in NEXT Neutrinoless Double Beta Decay Studies by K. Navarro

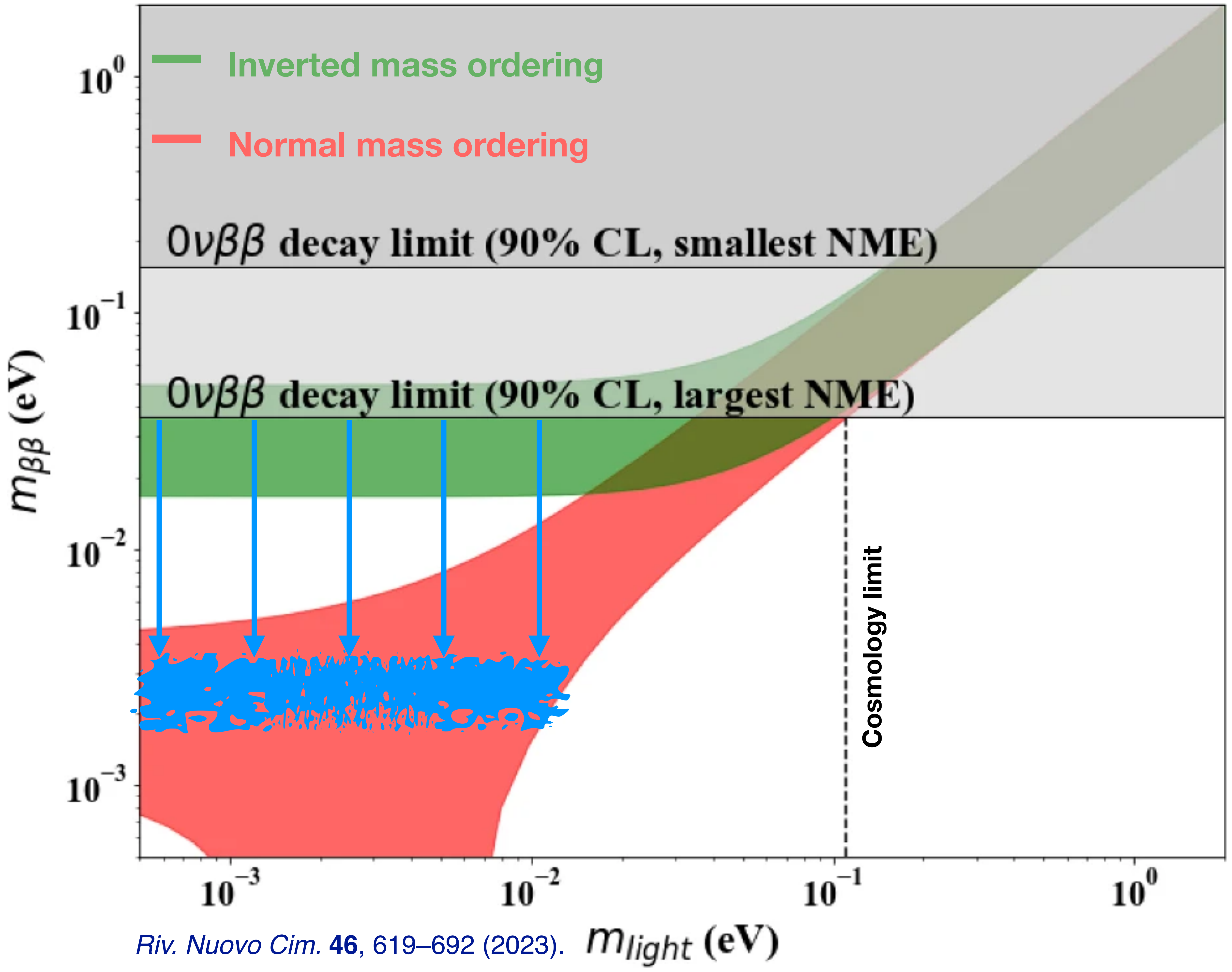
Conquering the inverted ordering

- Next generation will *cover* the inverted ordering



Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

Next next step: Attempt the Normal Ordering

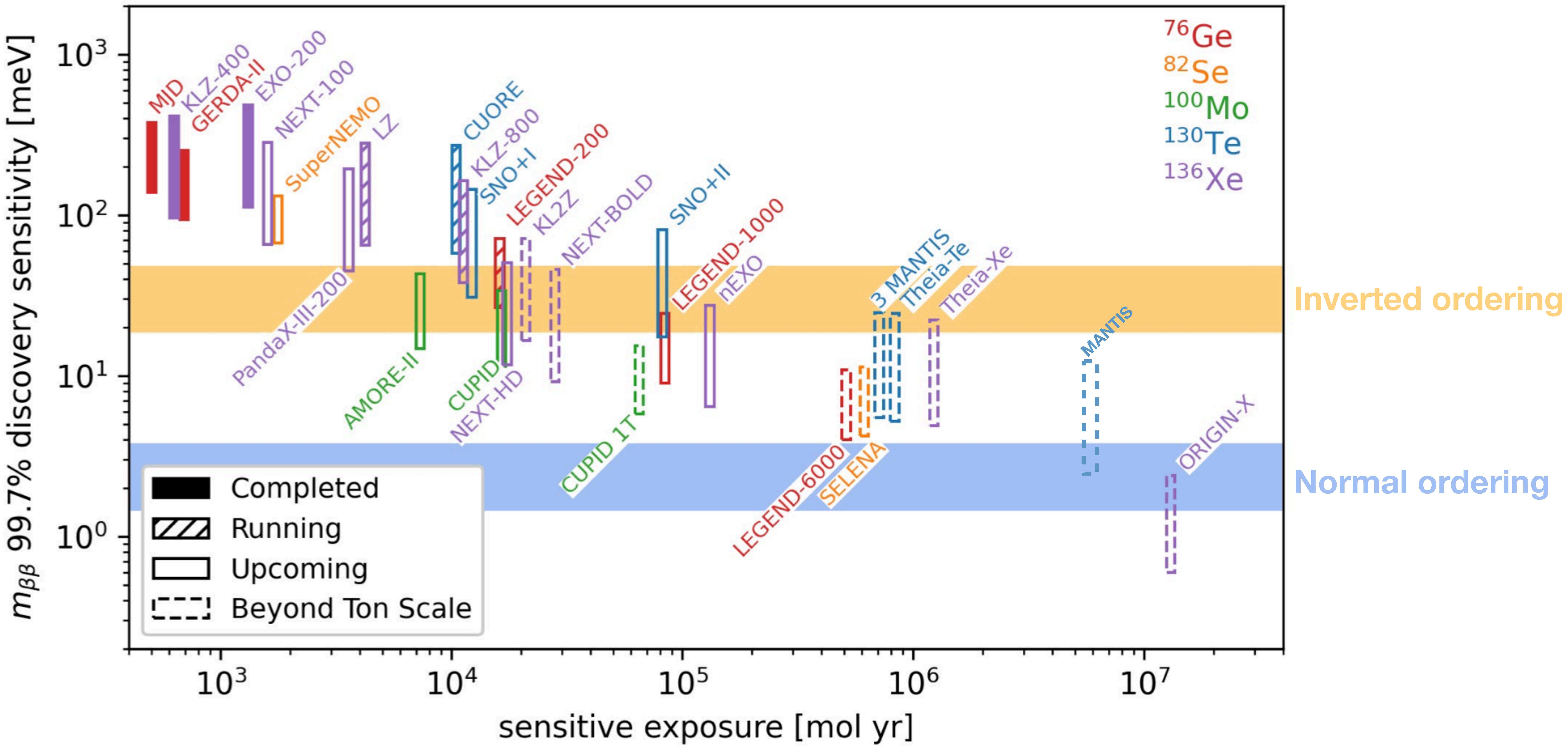


Riv. Nuovo Cim. **46**, 619–692 (2023).

Need (significant) technological advances!

**** This plot is just one example of parameter space… It does not mean that is exactly where the Majorana neutrino is! ****

Next next step: Attempt the Normal Ordering



Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

Next next step: Attempt the Normal Ordering

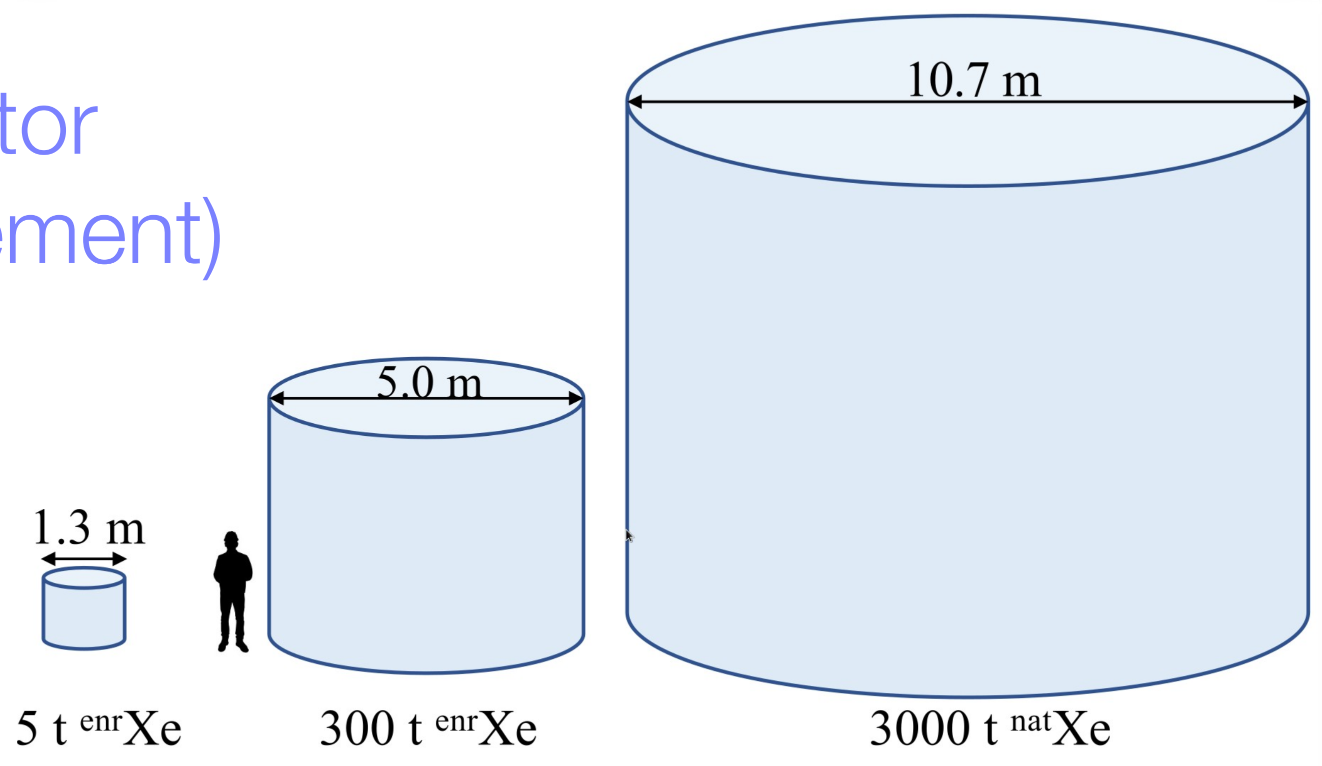
Next next step: Attempt the Normal Ordering

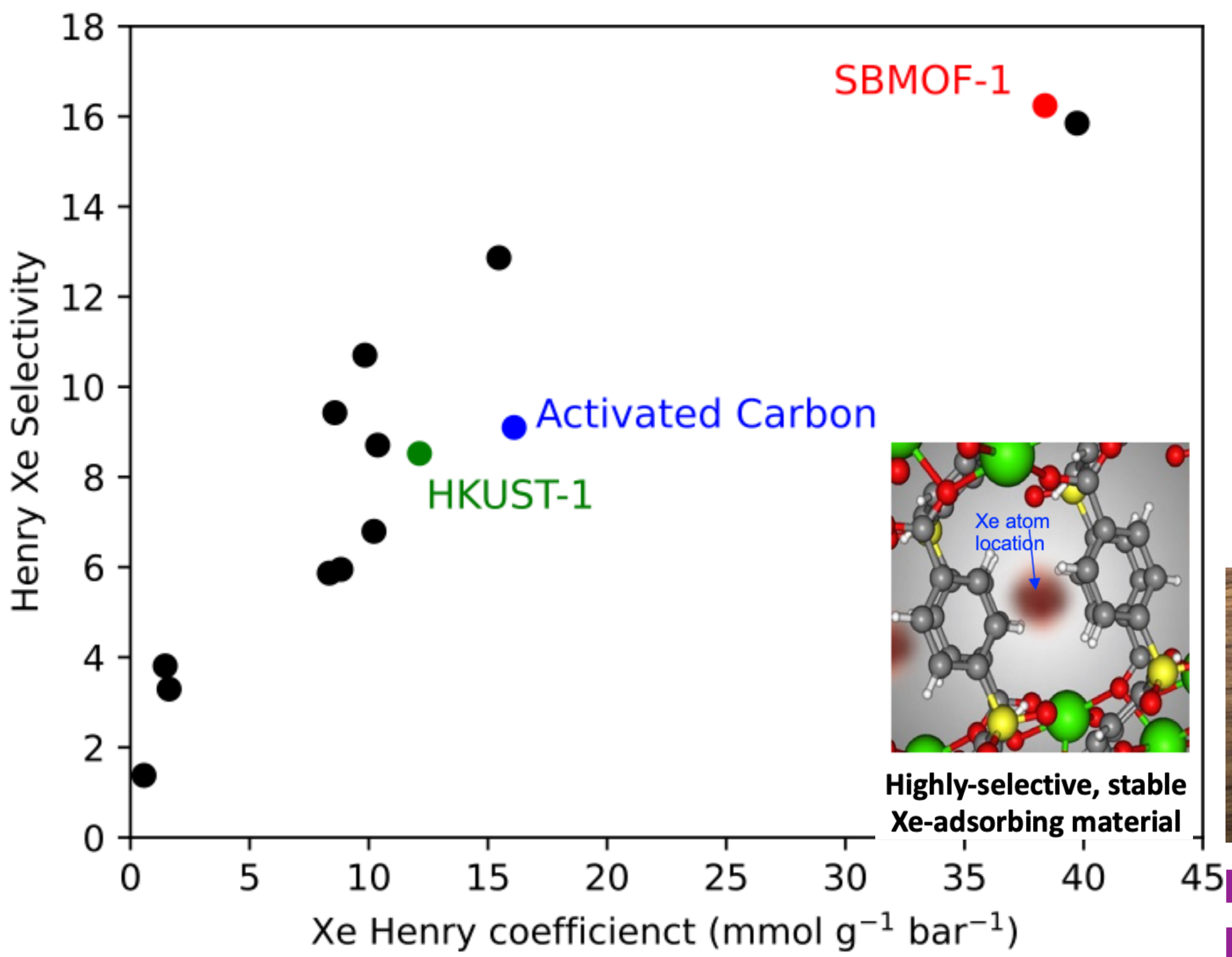
ORIGIN-X

Observing Rare Interactions with a GIaNt Xenon experiment

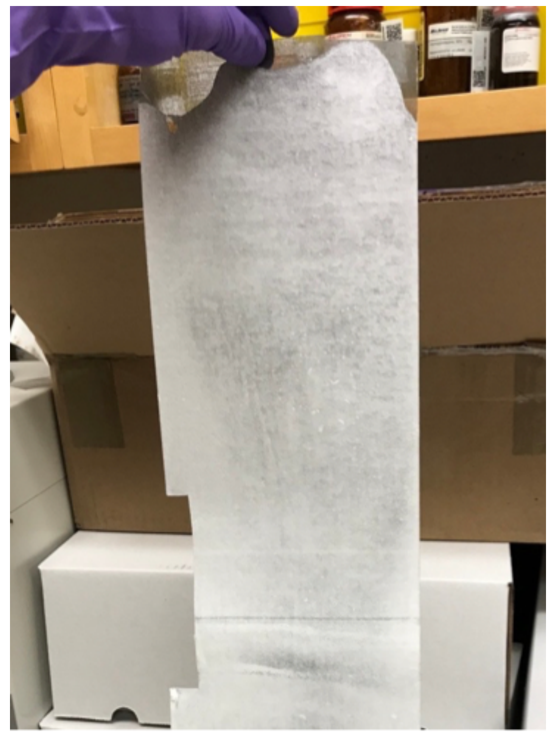
Kilotonne Xe detector
(Limited by Xe procurement)

R&D on more efficient
Xe extraction solutions



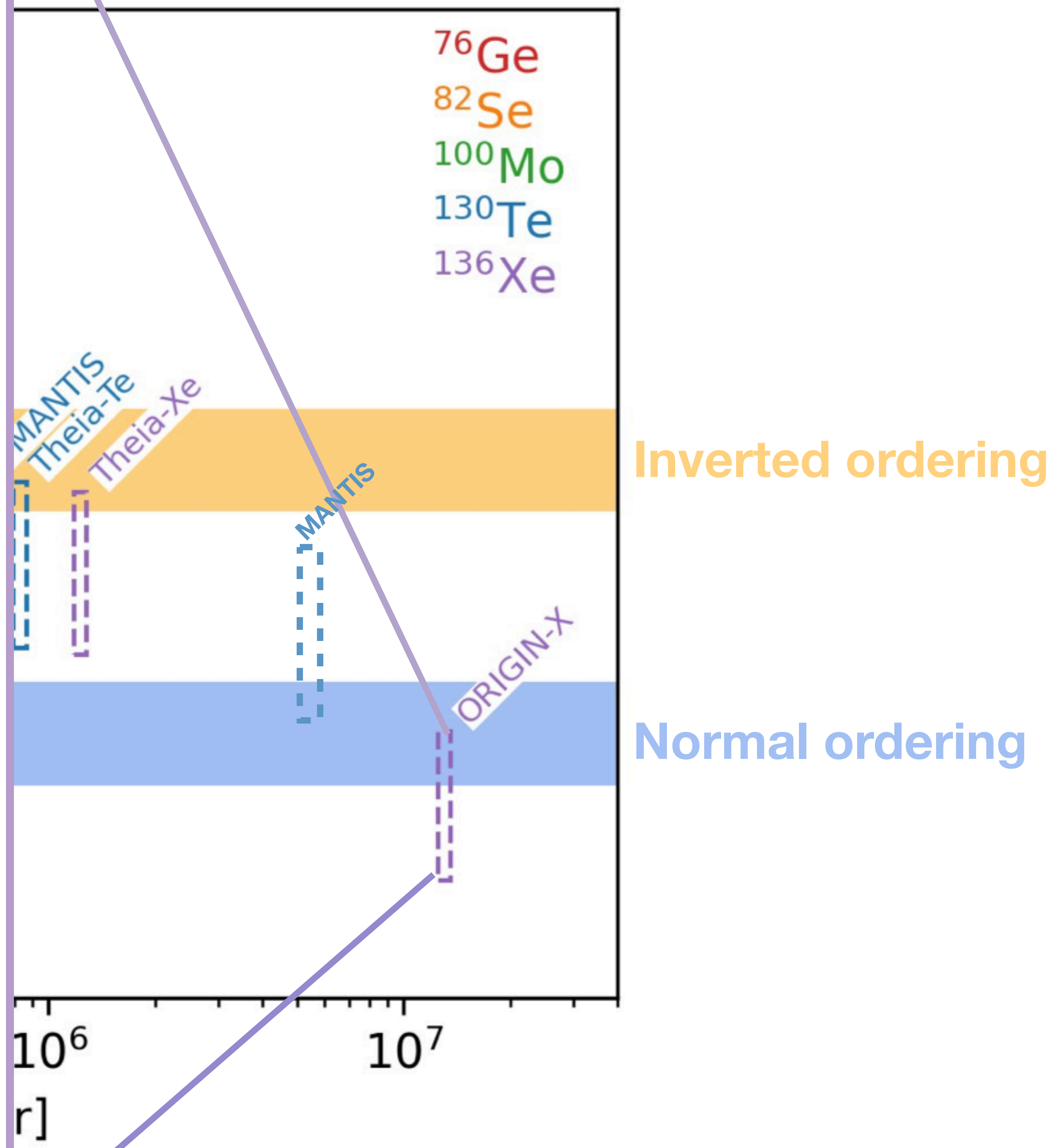


Highly-selective, stable Xe-adsorbing material



A. Avasthi *et al.* Phys. Rev. D 104, 112007 (2021)

More details at Workshop on Xenon Detector 0nbb searches: Steps towards the kilotonne scale



C Long Range Plan)

And many more ideas

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	^{48}Ca	305 kg	$^{nat}CaF_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300ν [125]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [126]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [127]	^{82}Se		^{enr}Se, CMOS	Development	
IFC [128]	^{82}Se		ion drift SeF_6 TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	Li$^{enr}MoO_4$,scint. bolom.	Prototype	LNGS
AMoRE-I [129]	^{100}Mo	6 kg	^{40}Ca$^{100}MoO_4$ bolometers	Operation	YangYang
AMoRE-II [129]	^{100}Mo	200 kg	^{40}Ca$^{100}MoO_4$ bolometers	Construction	Yemilab
CROSS [130]	^{100}Mo	5 kg	$Li_2{}^{100}MoO_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [131]	^{100}Mo		Li$^{enr}MoO_4$	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	Li$^{enr}MoO_4$,scint. bolom.	Proposal	LNGS
China-Europe [132]	^{116}Cd		$^{enr}CdWO_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	^{116}Cd		^{nat}CdTe. det.	Development	
TIN.TIN [135]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+ [136]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [137]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe disolved in liq. scint.	Development	Kamioka
LZ [139]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [143]	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA [145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	

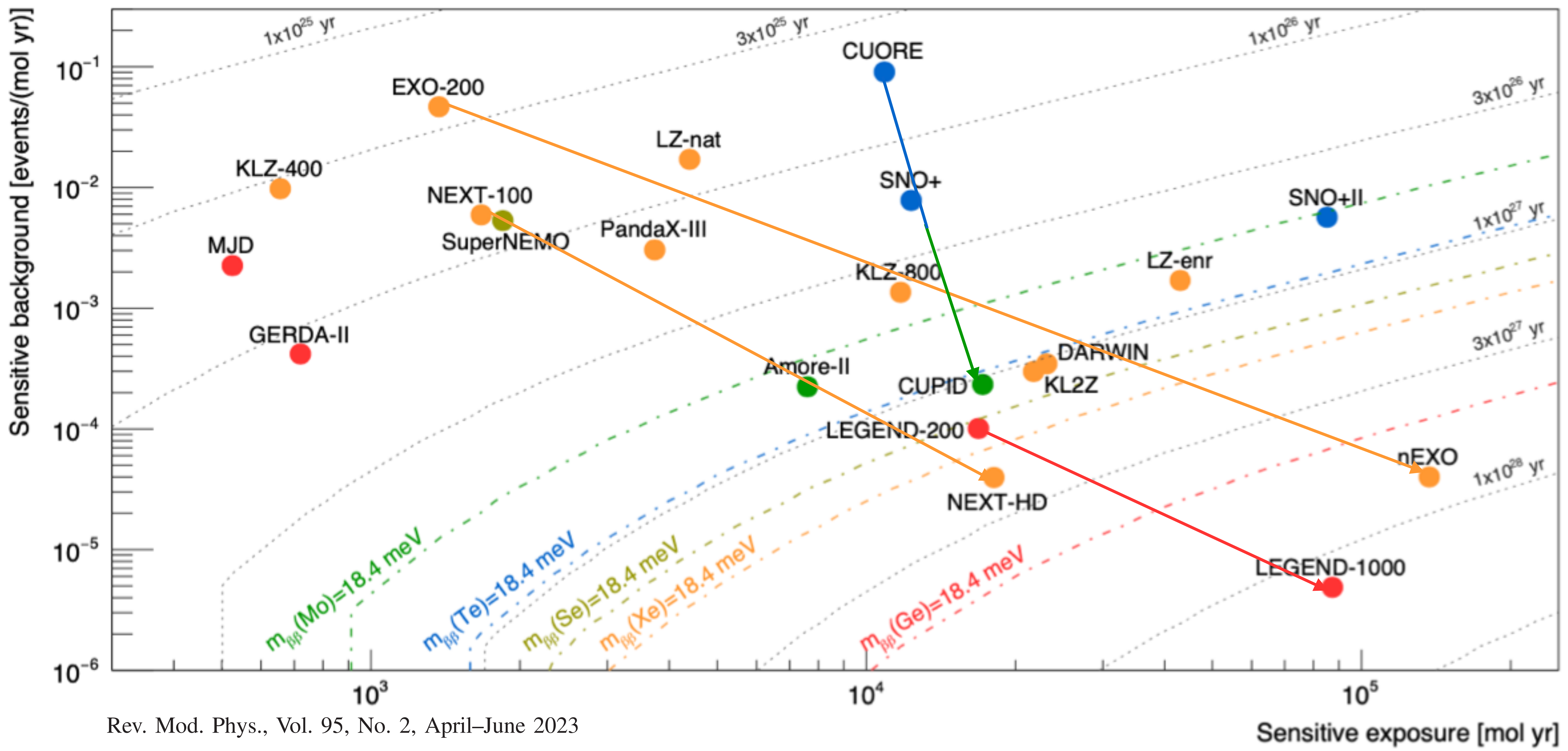
I did not have time to discuss these, but they all have unique features….

Opportunistic searches with Dark Matter experiments: L. Baudis' talk on Friday

arXiv:2212.11099

Reminder of the challenges ahead

- Very ambitious (technical) goals for the ton-scale experiments



Rev. Mod. Phys., Vol. 95, No. 2, April–June 2023

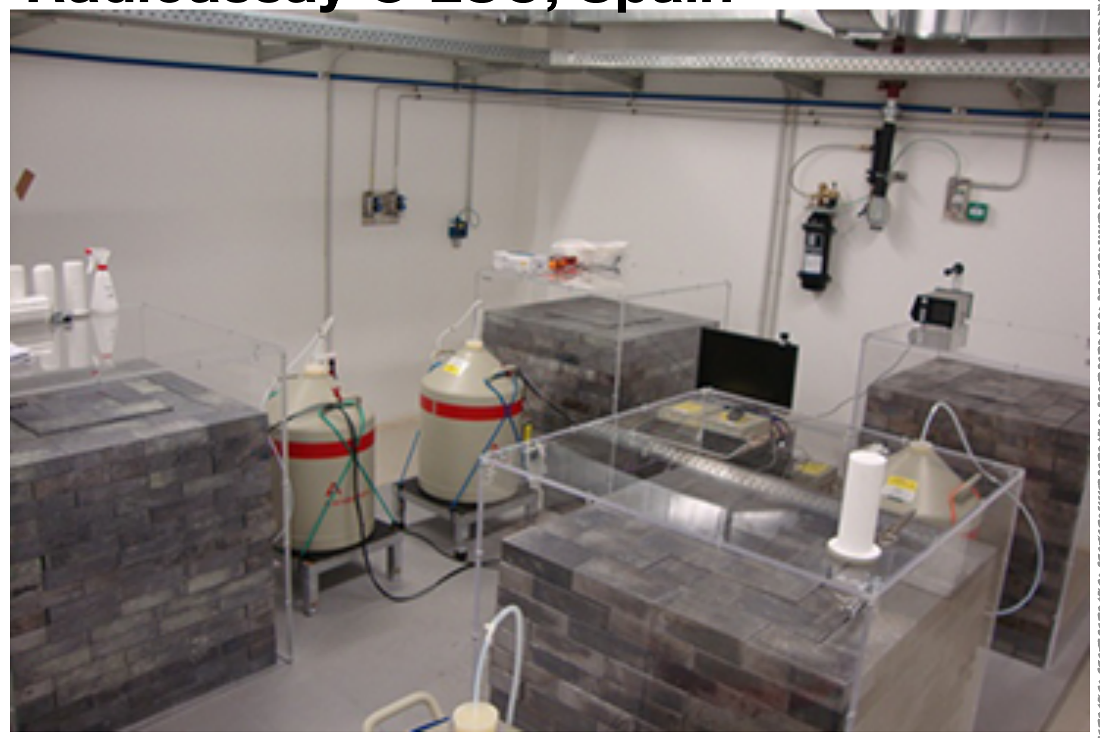
We need to continue our R&D efforts to develop mature technologies

Reminder of the challenges ahead

- Very ambitious (technical) goals for the ton-scale experiments
- Radiopurity requirements are pushing the limits of radioassay capabilities

Radioassay @ Boulby, UK

Radioassay @ LSC, Spain



We can build a strong network of facilities

Reminder of the challenges ahead

- Very ambitious (technical) goals for the ton-scale experiments
- Radiopurity requirements are pushing the limits of radioassay capabilities
- Working with industry is becoming more and more challenging (and expensive)

We can build a strong network of reliable companies

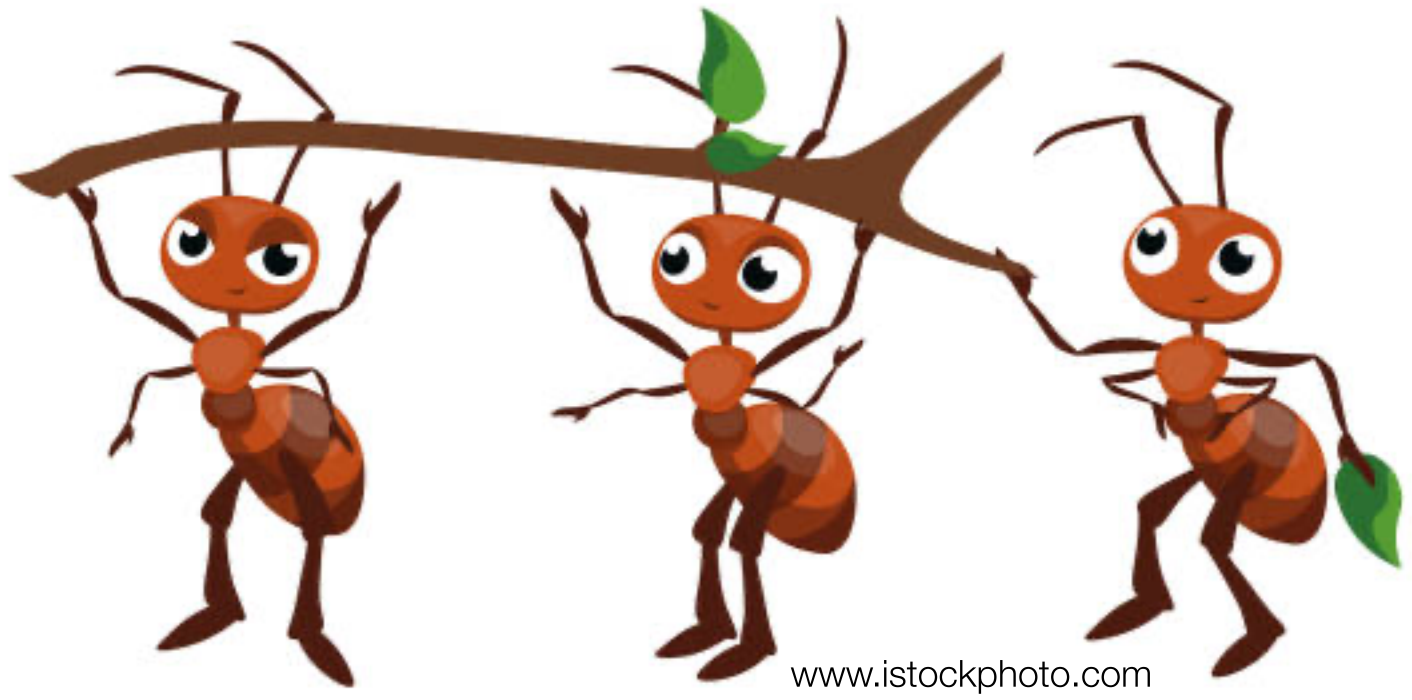
Reminder of the challenges ahead

- Very ambitious (technical) goals for the ton-scale experiments
- Radiopurity requirements are pushing the limits of radioassay capabilities
- Working with industry is becoming more and more challenging (and expensive)
- Funding situations for fundamental research across the globe is much lower than our scientific ambitions

Let's avoid to duplicate efforts

Reminder of the challenges ahead

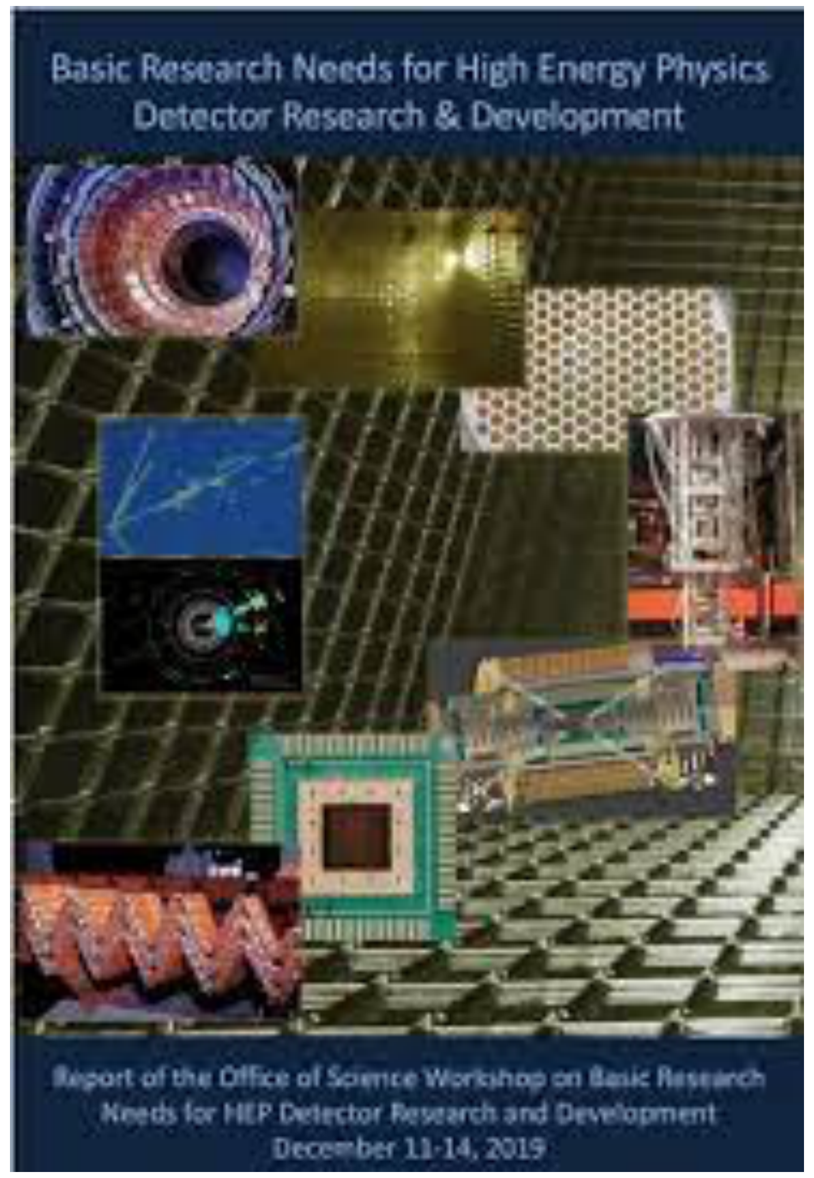
- Very ambitious (technical) goals for the ton-scale experiments
- Radiopurity requirements are pushing the limits of radioassay capabilities
- Working with industry is becoming more and more challenging (and expensive)
- Funding situations for fundamental research across the globe is much lower than our scientific ambitions
- Community(ies) need to come together to be stronger, while pushing on new technology development



www.istockphoto.com

Pushing the instrumentation frontier together

- Need for instrumentation development recognized worldwide



Basic Research Needs for HEP Detector R&D (2019)

ECFA Detector R&D Roadmap (2021)

Snowmass 2021

SNOWMASS Process (2021)
→ P5 Report (2023)

And more….

Pushing the instrumentation frontier together

- Need for instrumentation development recognized worldwide
- Creation of new Detector R&D Collaborations (2023) (approved by CERN council)
- Example: DRD2 - Liquid Detectors

Charge Readout	Light Readout	Target Properties	Scaling-up Challenges
Pixels & charge+light	Increased sensor quantum efficiency	Target properties and isotope loading of LS & WC	Radiopurity & background mitigation
Charge-to-light, electroluminescence & amplification	Higher efficiency WLS and collection		Detector and target procurement/production & purification
Ion detection	Improved sensors for LS & WC	Target properties and isotope loading of noble elements	Large-area readouts
			Material properties

Consider joining the DRD efforts!

Closing remarks

- Understanding the nature of neutrinos is of the utmost importance
- The next generation of experiments will *cover* the inverted neutrino mass ordering, but it will be technologically challenging
- To reach the normal neutrino mass ordering, transformative technologies are needed
- We need to continue to cast a wide net and explore different isotopes and technologies
- Given the technological limitations, the community needs to work together to avoid duplication of scarce ressources

Closing remarks

THANK YOU !