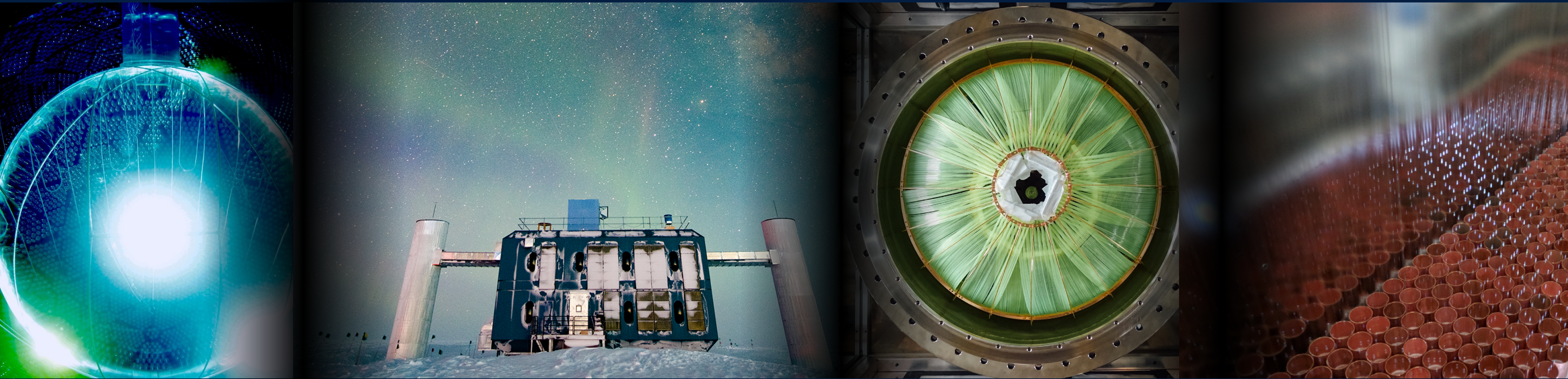




Non-accelerator neutrino physics

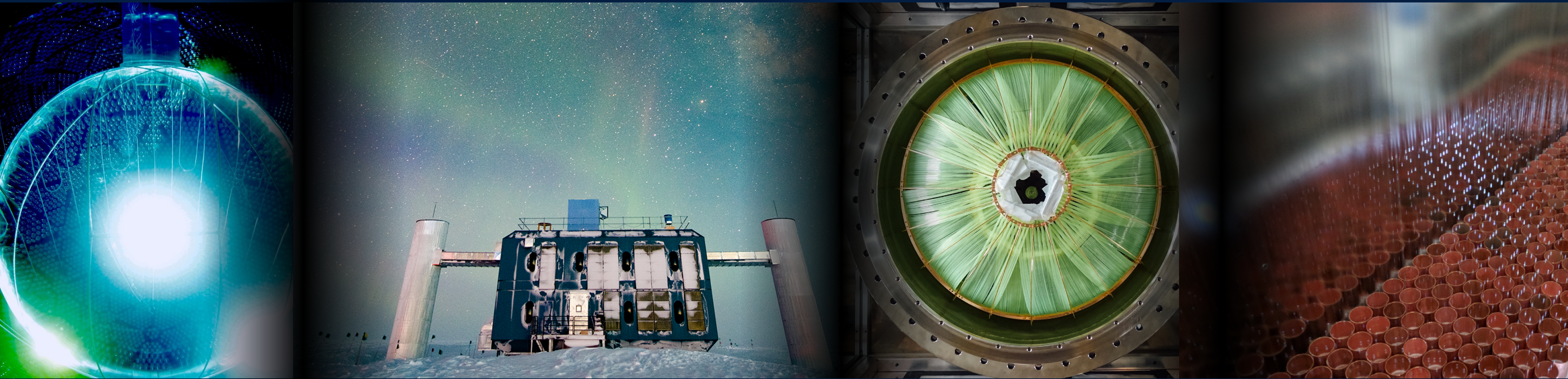
Dr Cheryl Patrick

STFC Ernest Rutherford Fellow, University of Edinburgh



THE UNIVERSITY
of EDINBURGH

Thank you for contributions

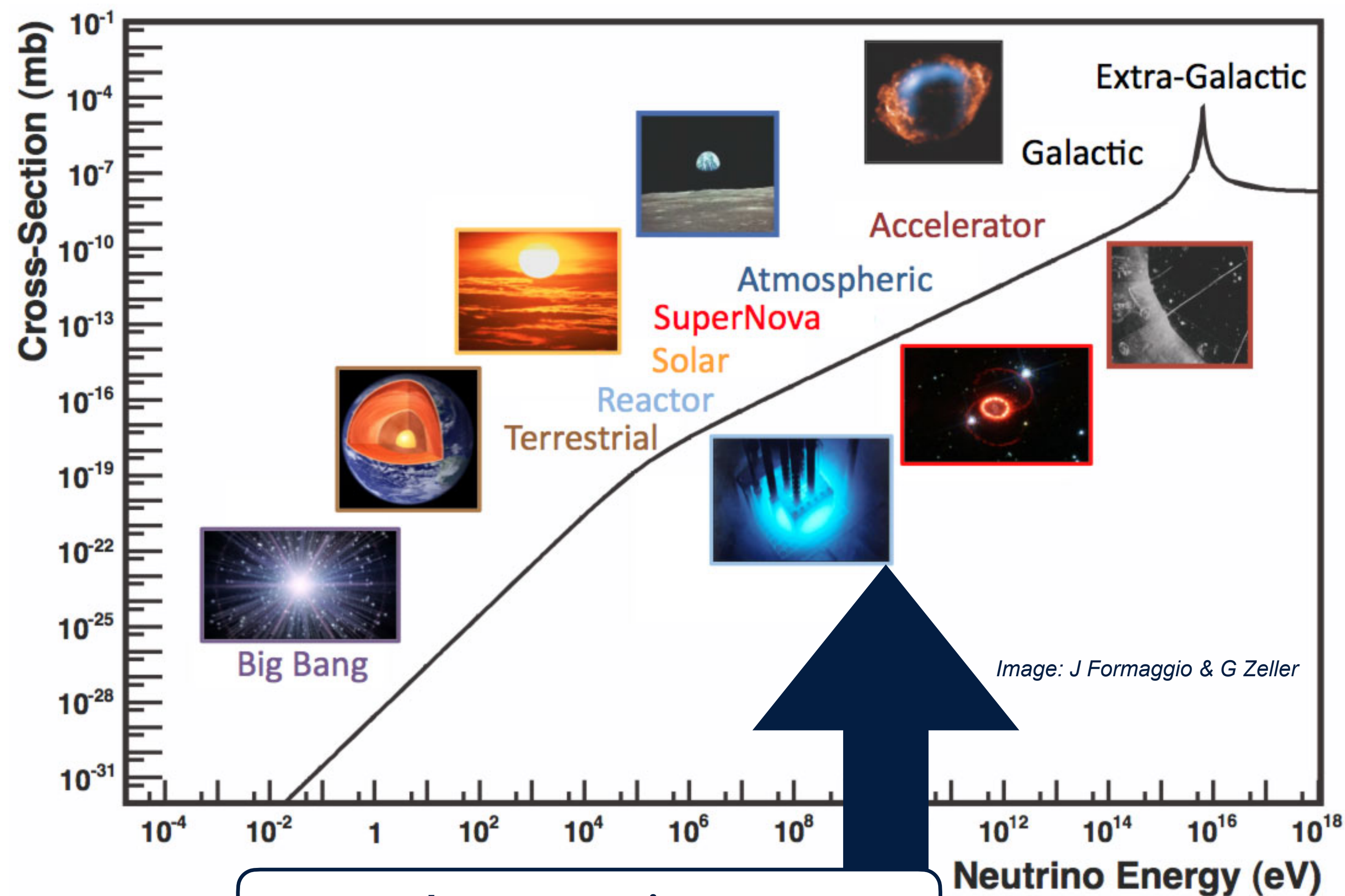


T Katori, KCL (IceCube)
J Wilson, KCL (SNO+)
W Quinn, UCL (LEGEND)
R Nichol, UCL (PUEO)
H Araújo, Imperial (XLZD)

R Guenette, Manchester (NEXT)
R Saakyan, UCL (QTNM)
J Hartnell, Sussex (CLOUD)
J Monroe, Oxford (DarkSide)
X Lu, Warwick (JUNO)

Helen O'Keefe, Lancaster (Kamioka)
M Nebot Guinot, Edinburgh (SBND)
V Basque, Edinburgh (DUNE)
M Agostini, UCL (P-ONE)

accelerator neutrinos



Accelerator neutrinos

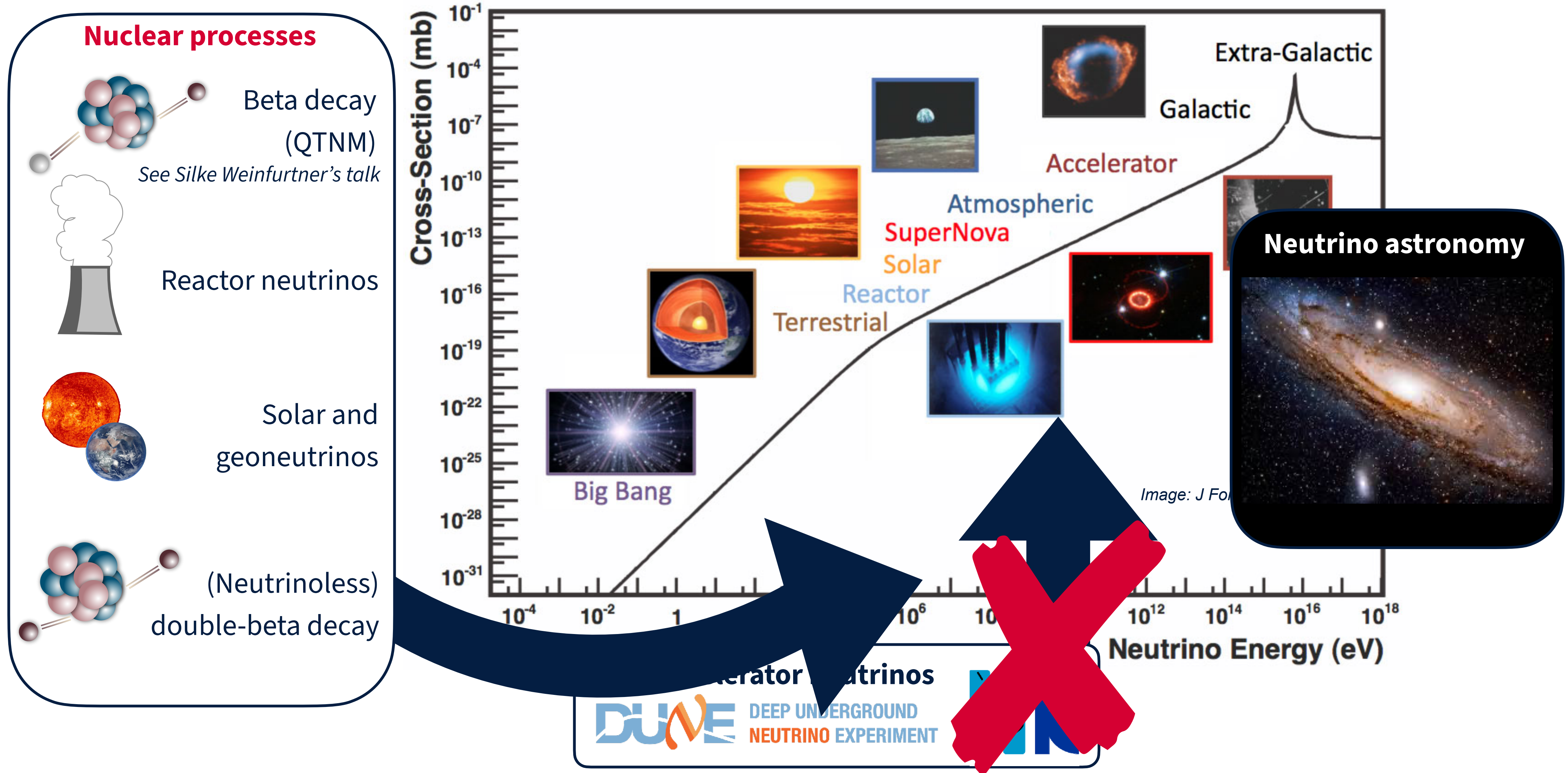


**DEEP UNDERGROUND
NEUTRINO EXPERIMENT**

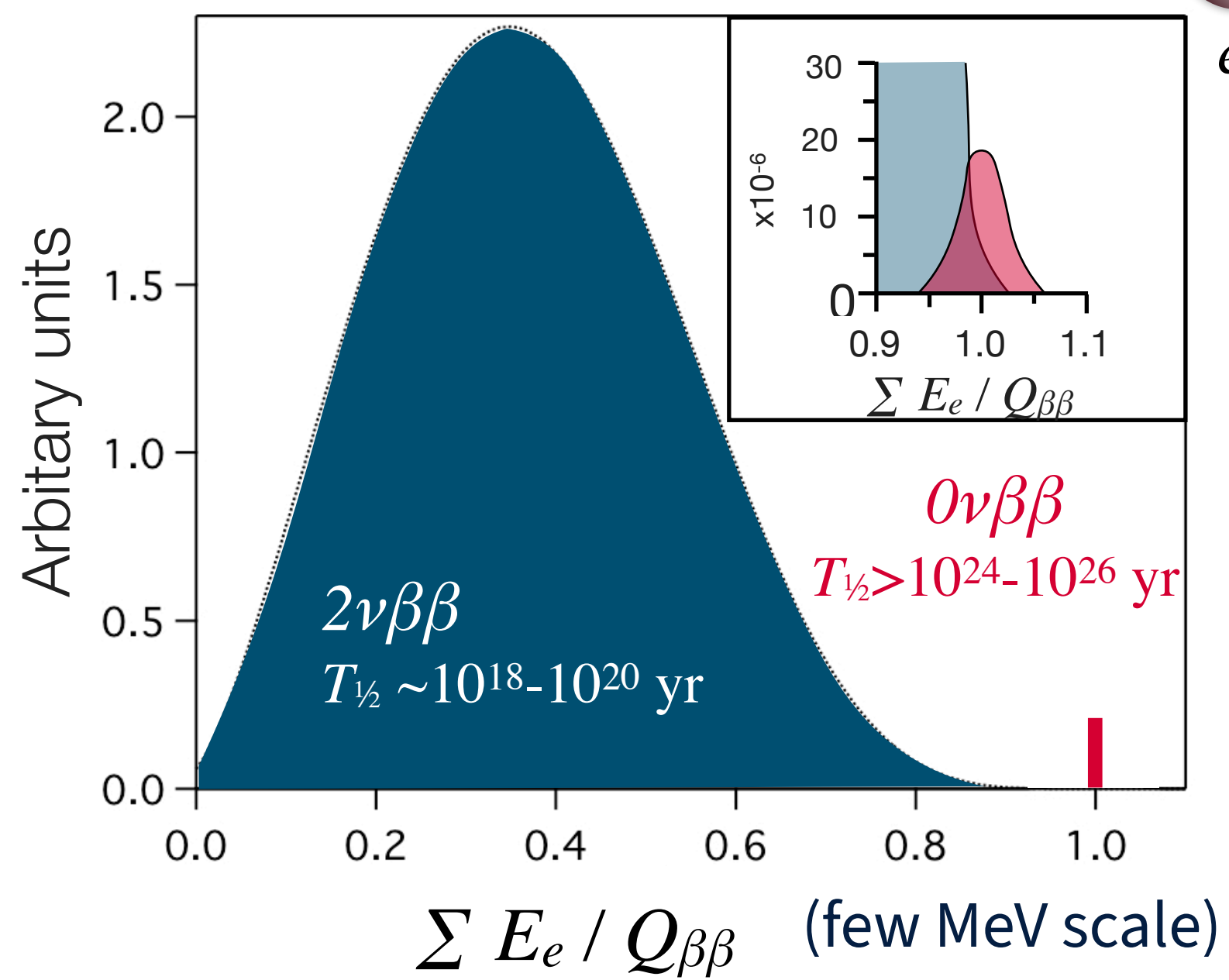
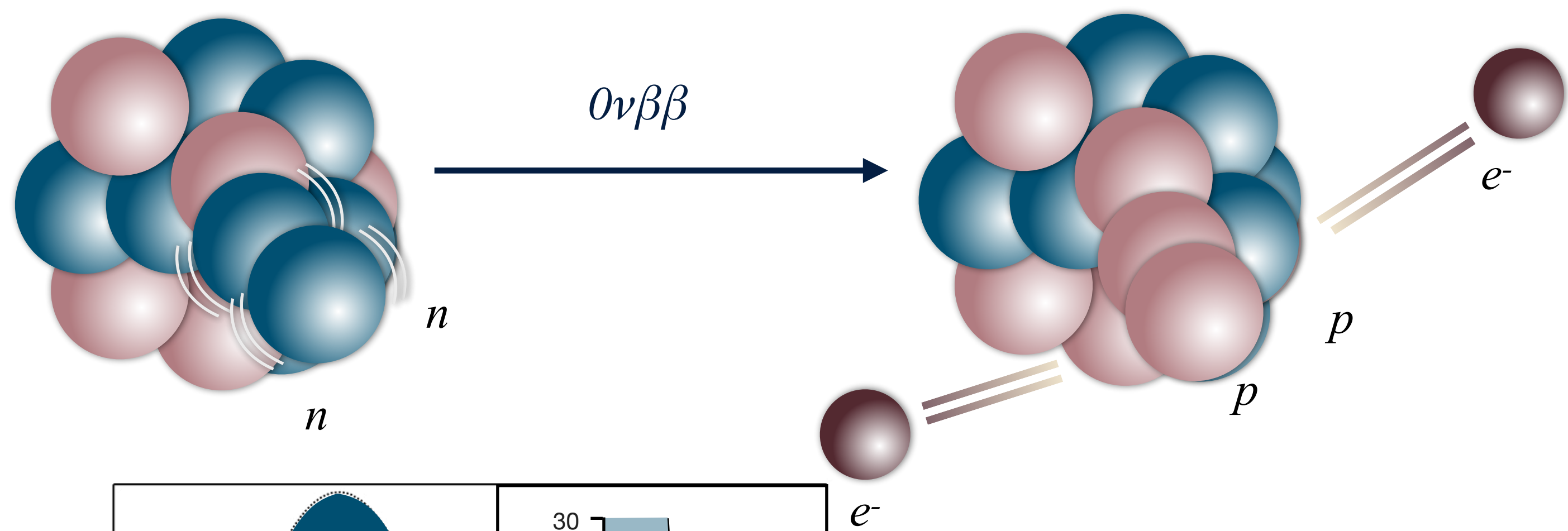


HYPER-K

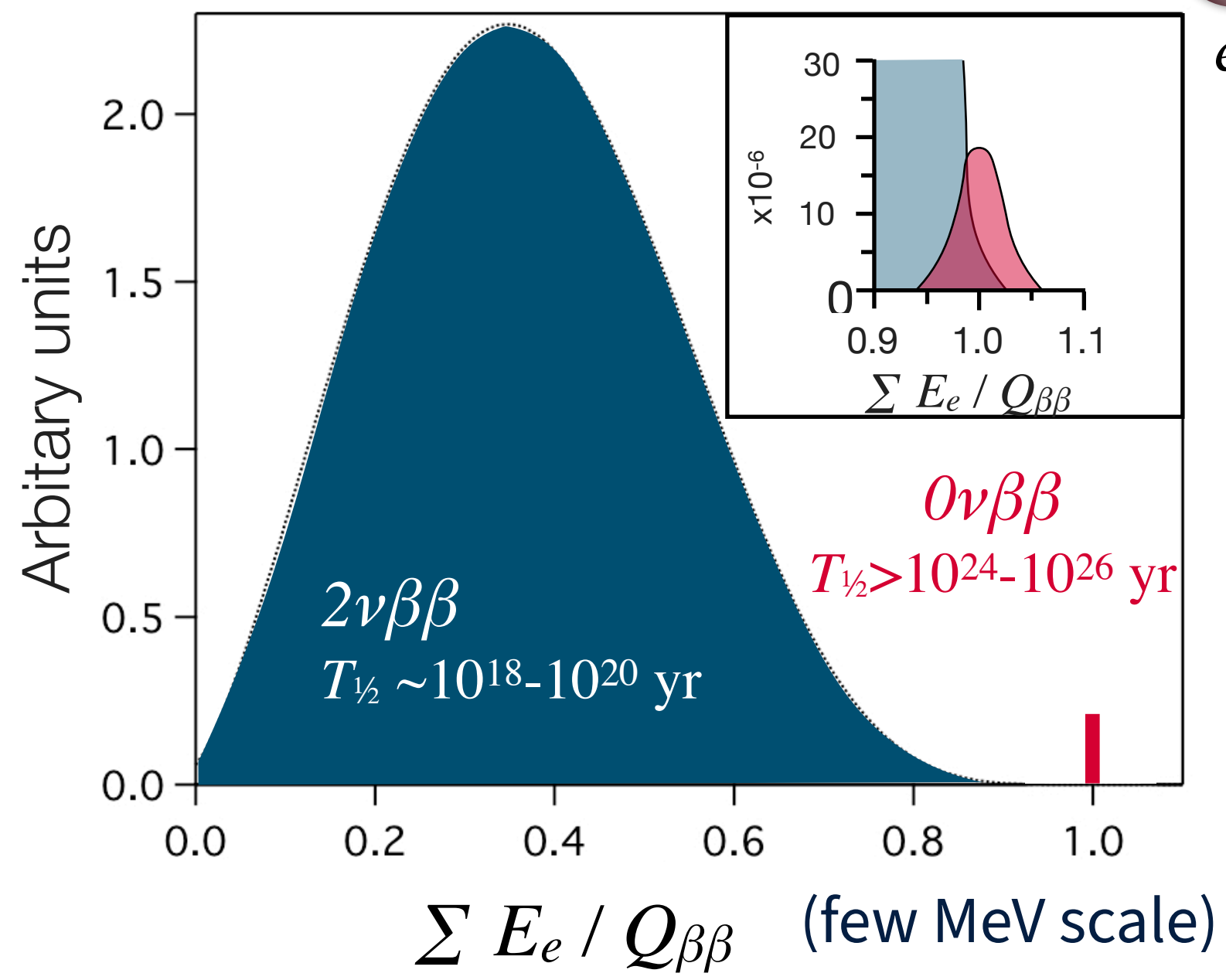
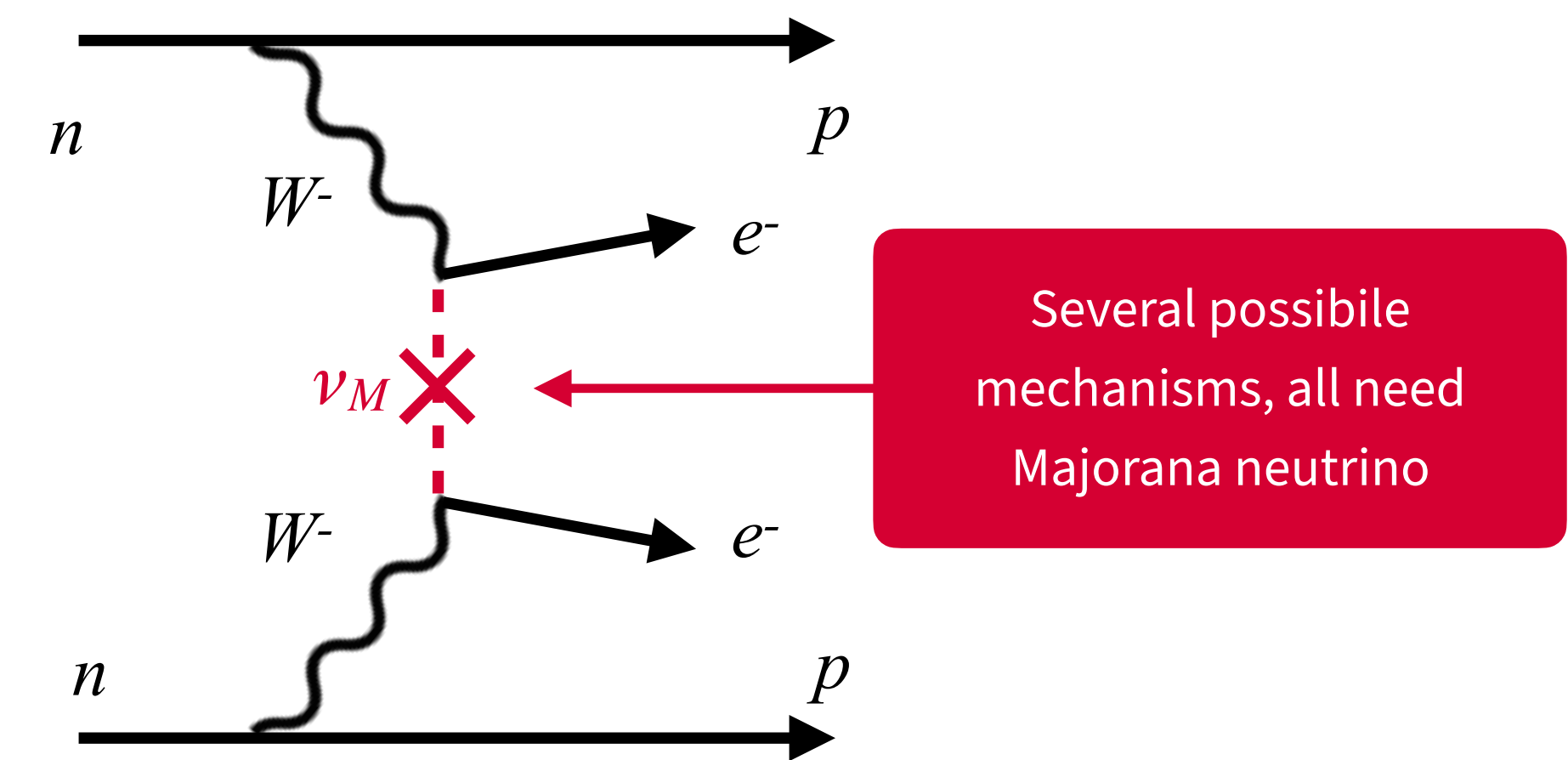
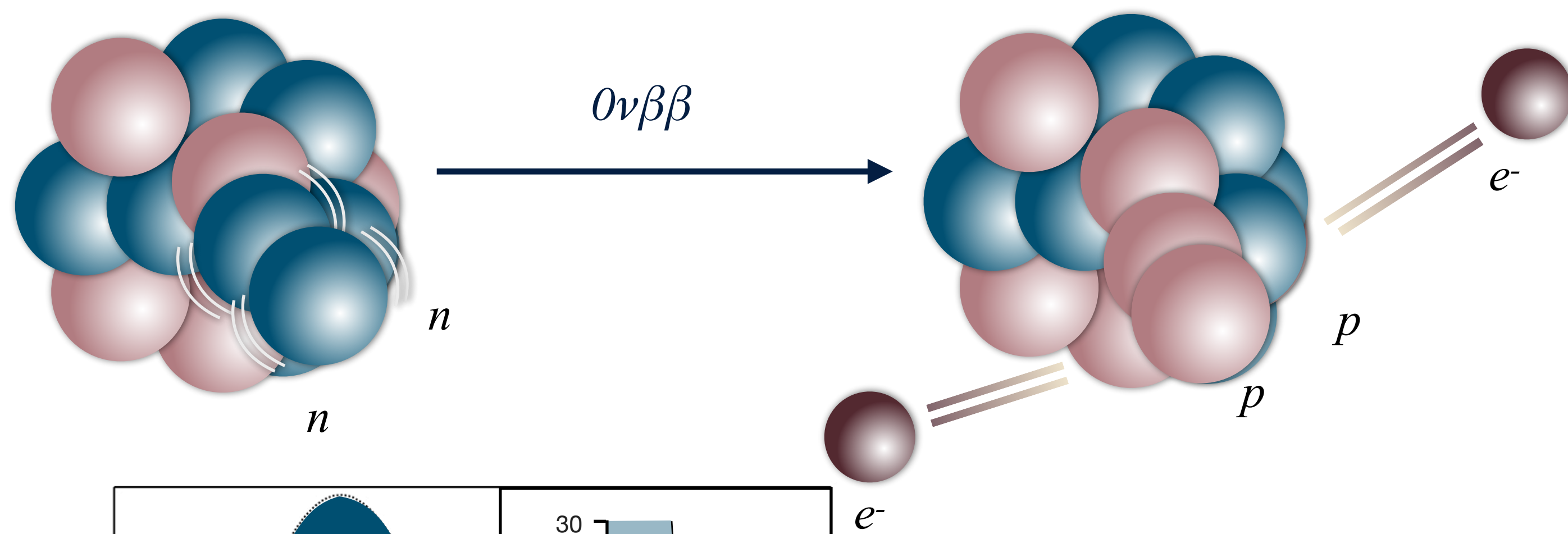
Non-accelerator neutrinos



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



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



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

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

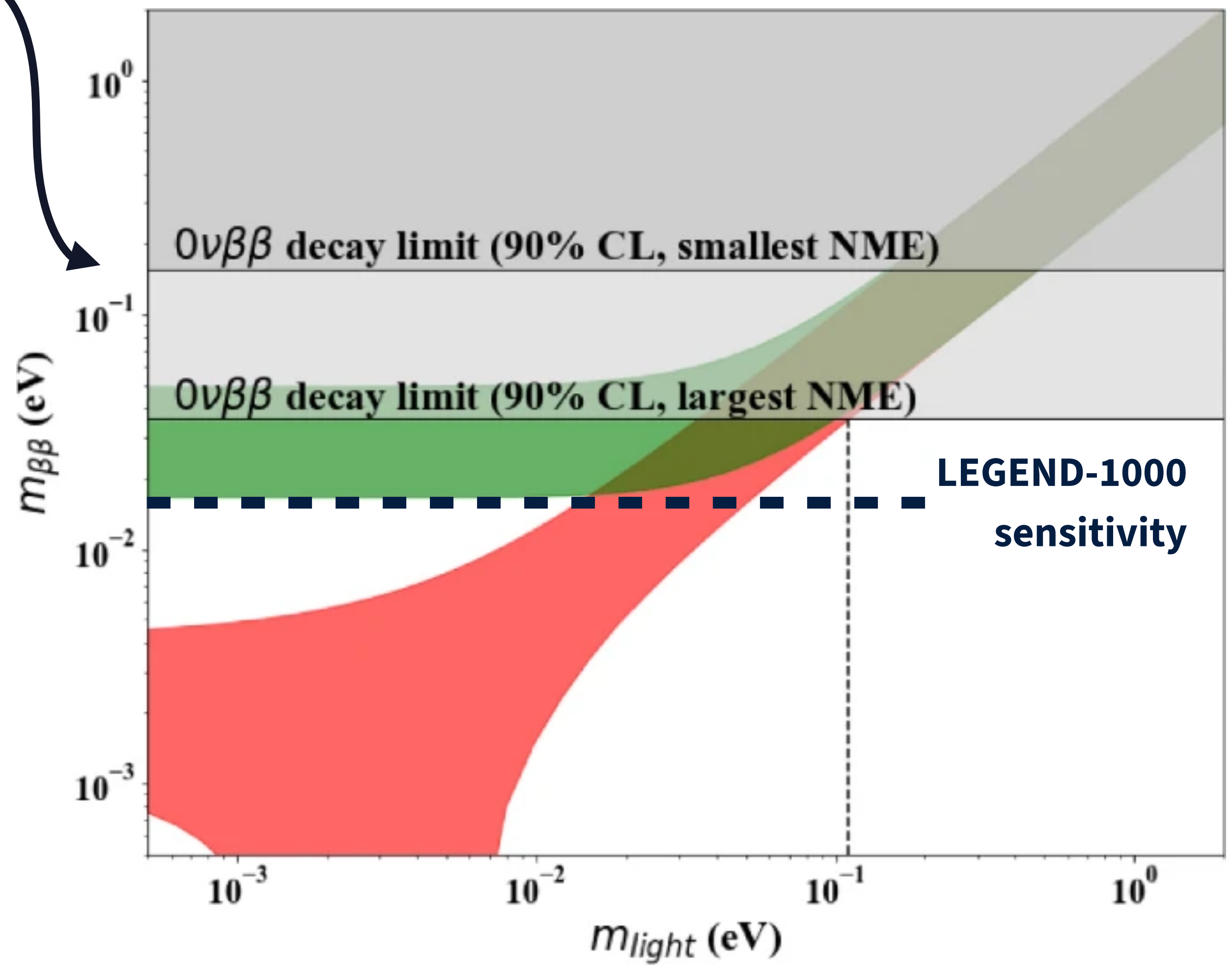
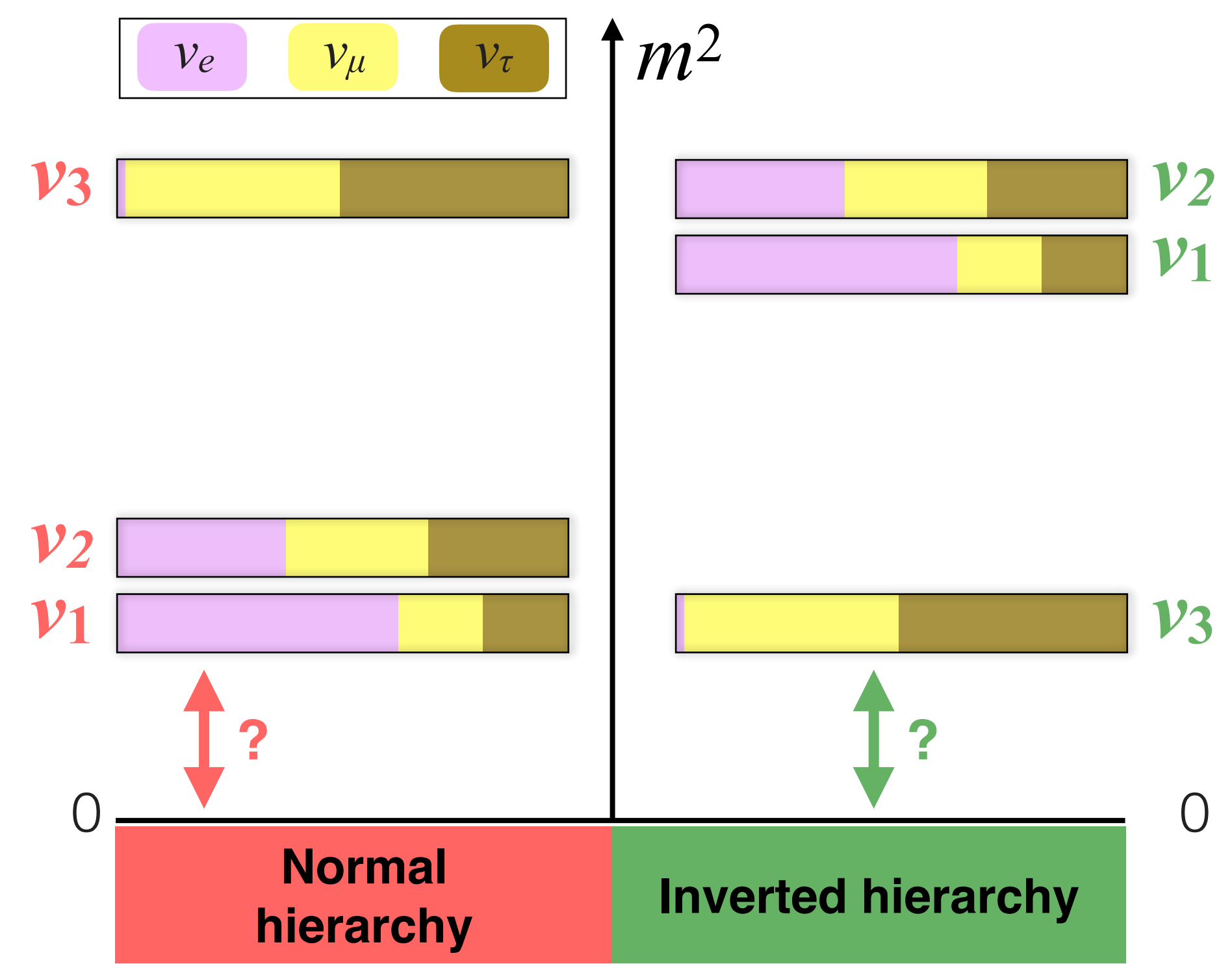
$0\nu\beta\beta$ and neutrino mass

Riv. Nuovo Cim. 46, 619–692 (2023)

$0\nu\beta\beta \text{ rate}$

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

“electron-neutrino mass”



The core UK strategy





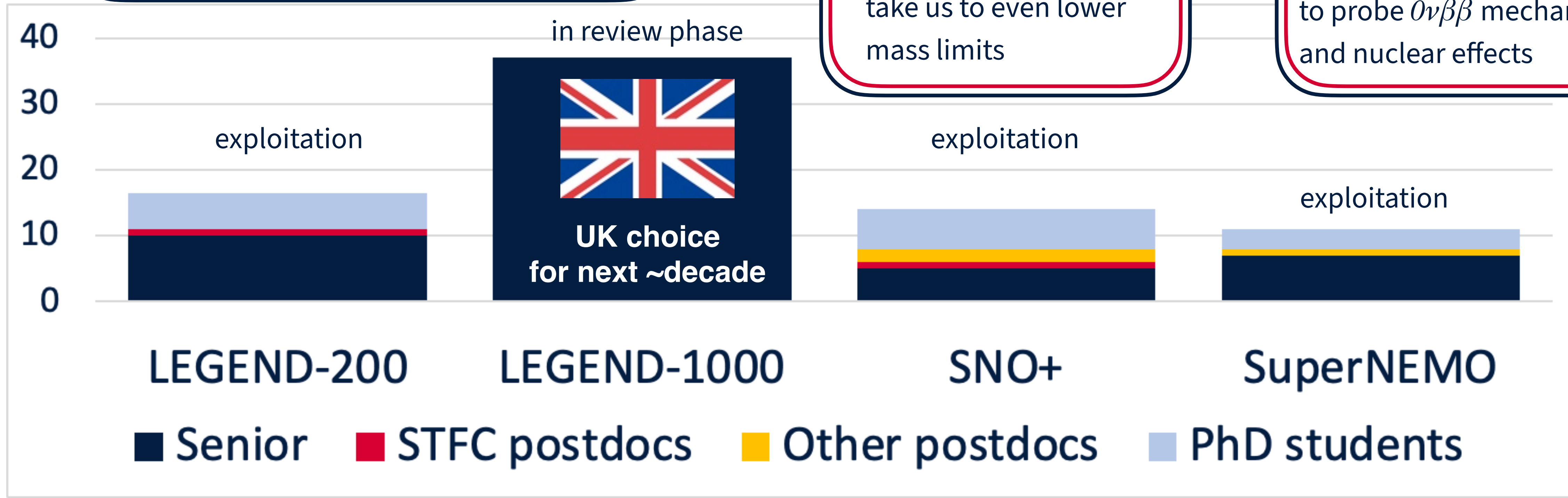
LEGEND: a discovery machine to explore the full inverted hierarchy regime



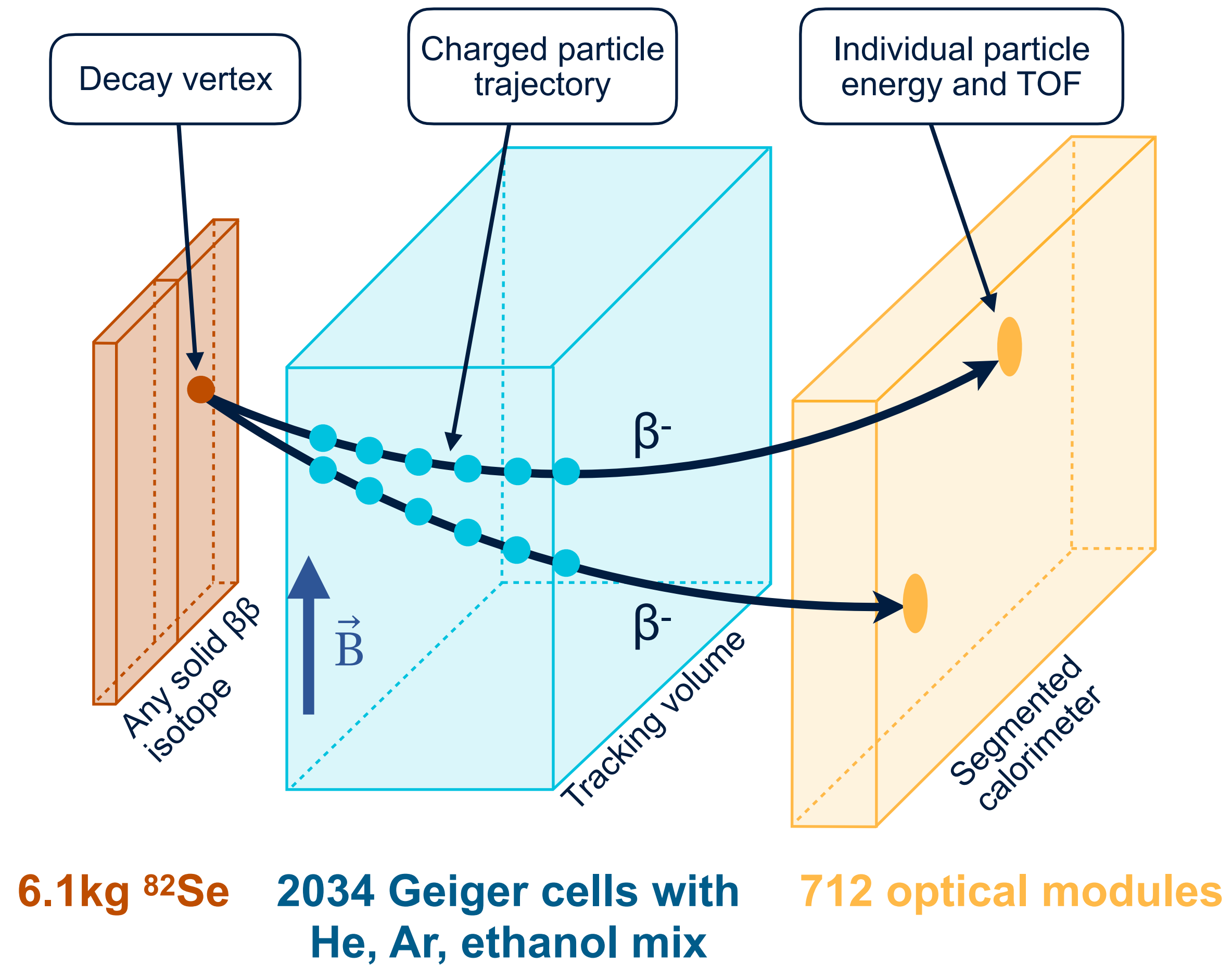
SNO+: a scalable technology that could take us to even lower mass limits



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



SuperNEMO Demonstrator at LSM, France



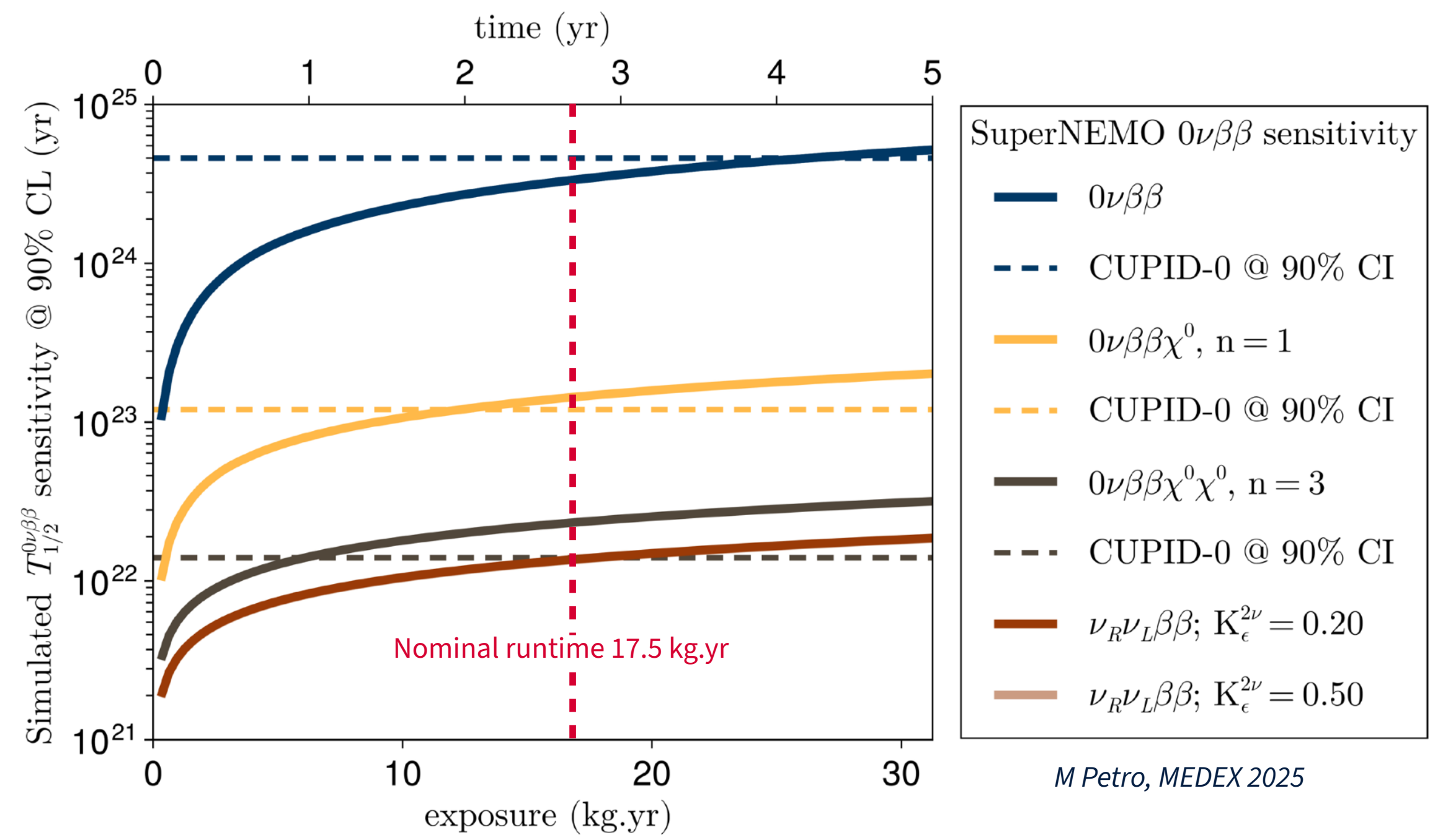
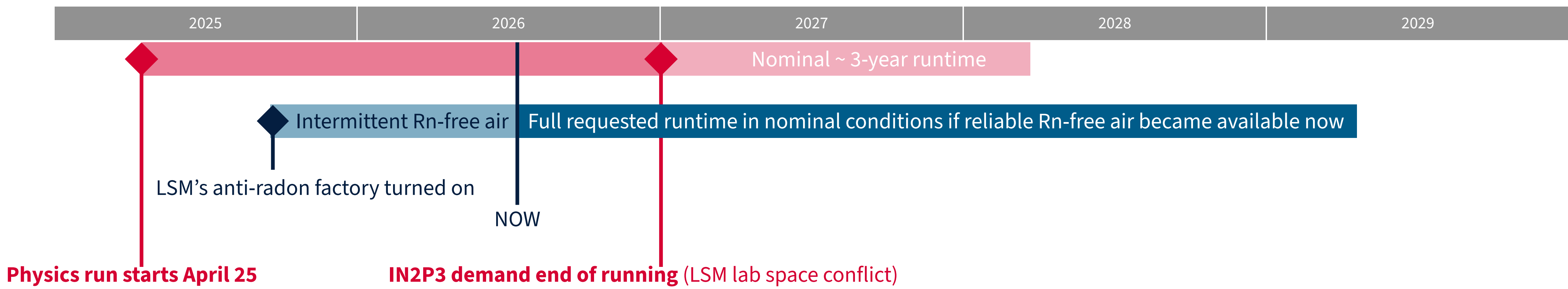
Proof of concept for future tracking detectors:

- (Nearly) **isotope-agnostic**
- Full topological reconstruction and particle ID
- Unique $2\nu\beta\beta$ measurements:
 - **nuclear effects** (g_A constraint, excited states)
 - **exotic decays** & new physics
- Could **probe $0\nu\beta\beta$ mechanism** if discovered

UK responsibilities

- Tracking detector
- Neutron shielding
- Helium recycling
- Software and analysis
- **1** current, **2** former spokespeople

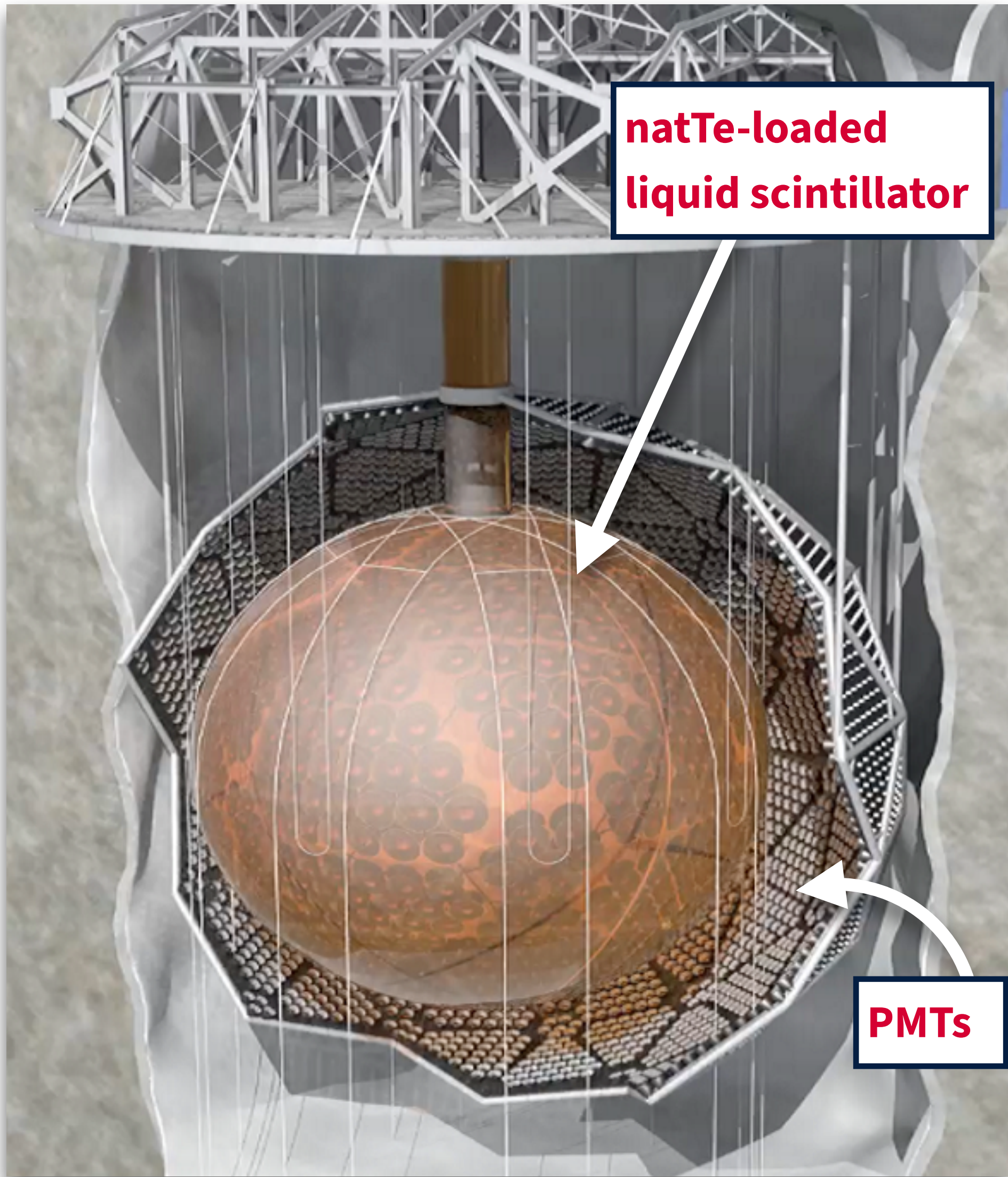
SuperNEMO running status



World's best BSM searches achievable in nominal ~3-year run

This potential is severely threatened by:

- IN2P3's imposed schedule
- Lack of radon-free air provided by LSM



Cost-effective

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

Scalable

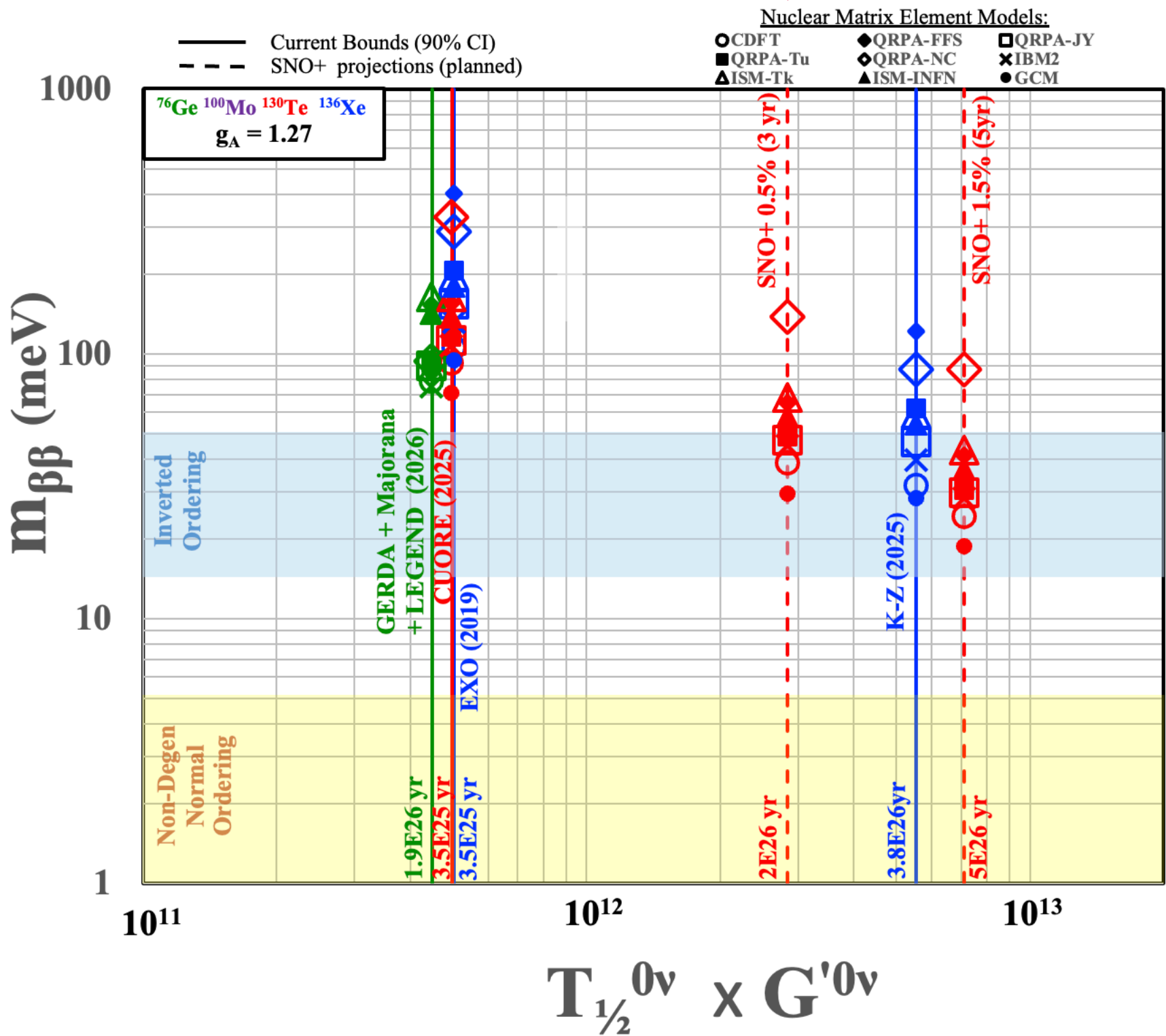
- Detector design can be scaled up dramatically
- UK-developed techniques can increase **tellurium loading**

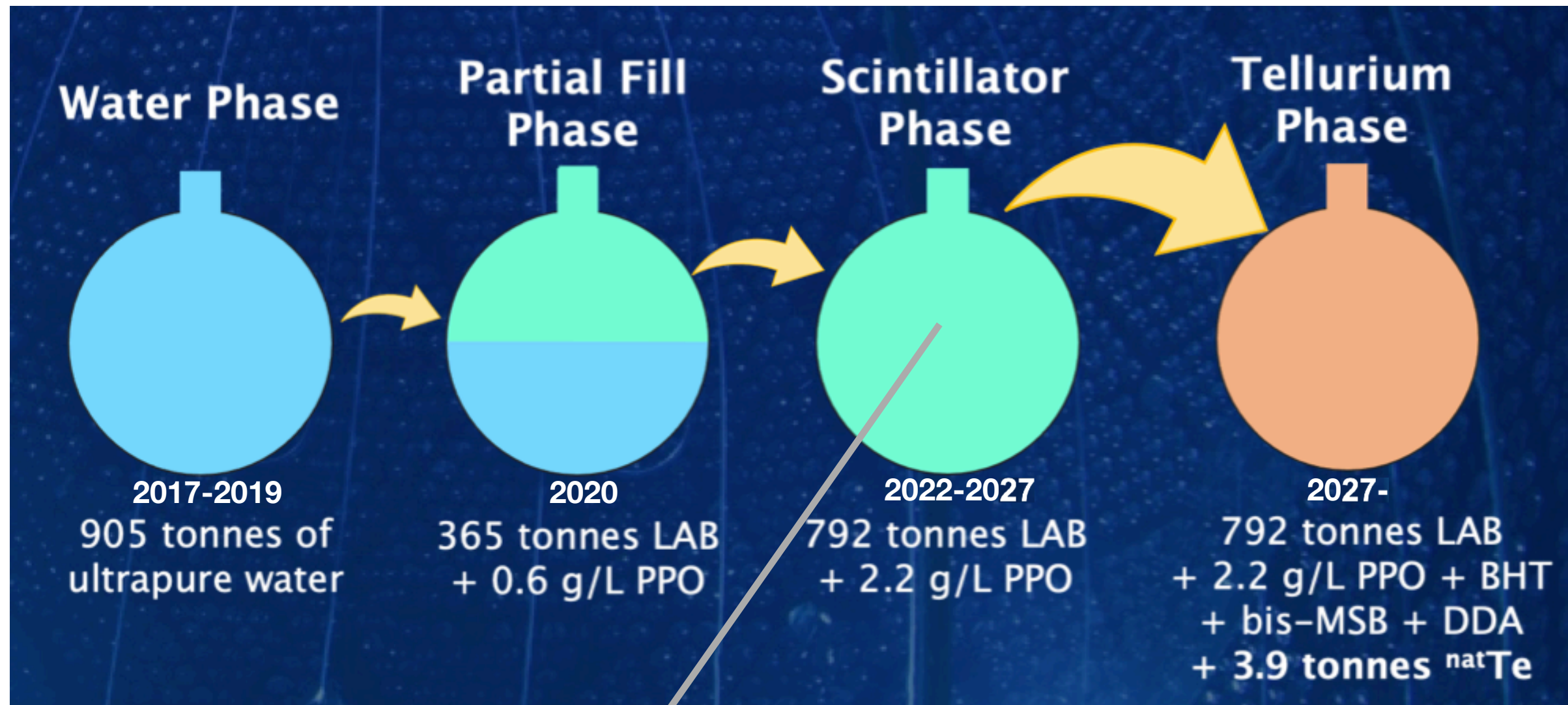


Could probe normal-hierarchy region with high enough Te loading!

Current planned Te loading (0.5%): current UK commitment

1.5% Te loading: Proposal from Canada w/ positive review from SNOLAB





Great advantage to study backgrounds without the target

- ⁸B solar neutrinos (ES & CC on ¹³C)
- Reactor-neutrino oscillation measurements
- Invisible nucleon decay mode limits
- Geoneutrinos



TeBD Synthesis Plant

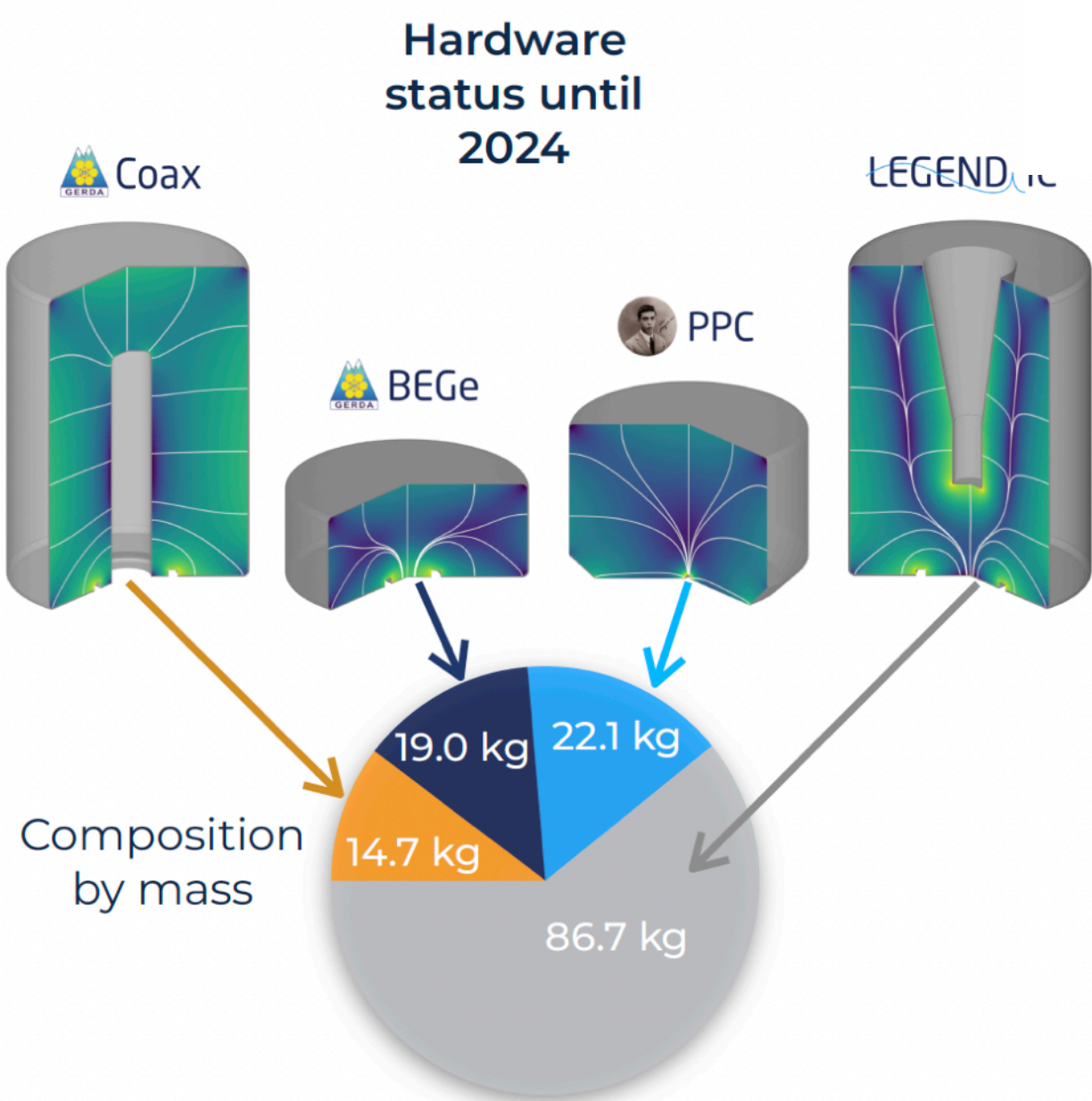
In **exploitation phase** -
Te loading to start Sep 2027
*Delay due to small leak in acrylic vessel:
drain / fix / refill in progress*

UK responsibilities

- Tellurium loading
- Calibration system
- Software
- Data analysis
- **1** analysis coordinator
- **6** working-group leads

High-Purity ^{76}Ge -enriched detectors:

- low background
- source = detector: high efficiency
- excellent (0.1%) energy resolution
- topological discrimination



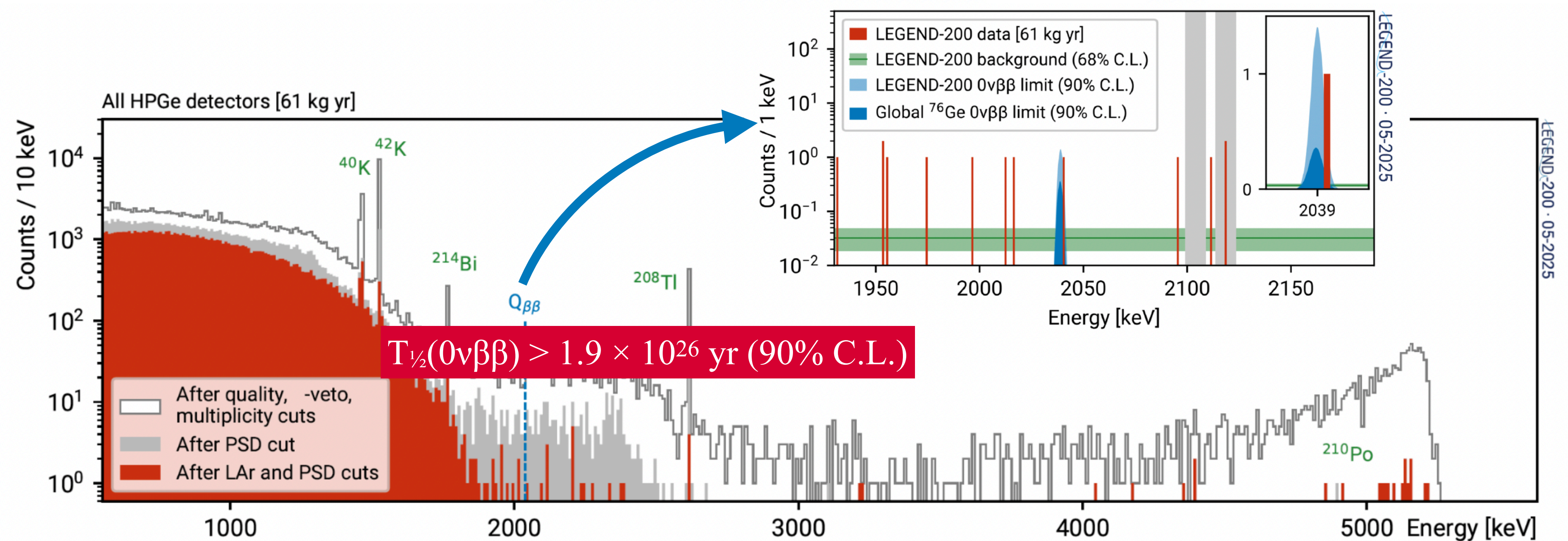
C Romo-Luque Neutrino 2026



UK responsibilities

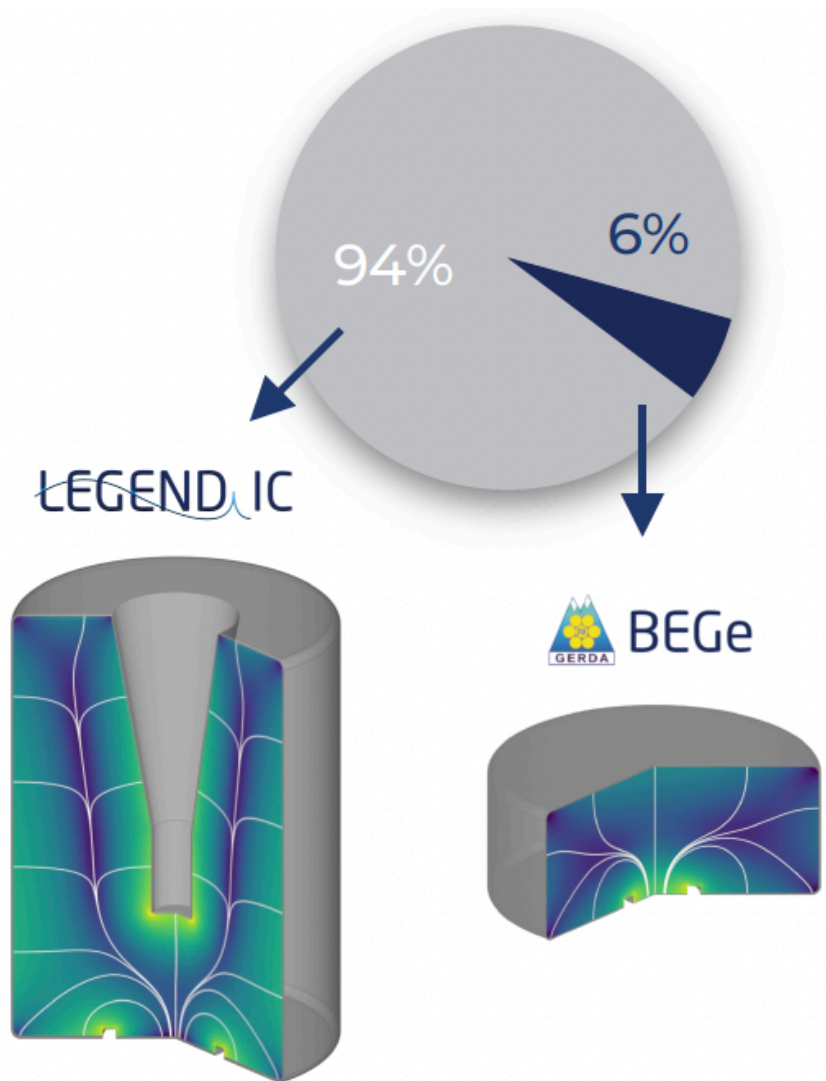
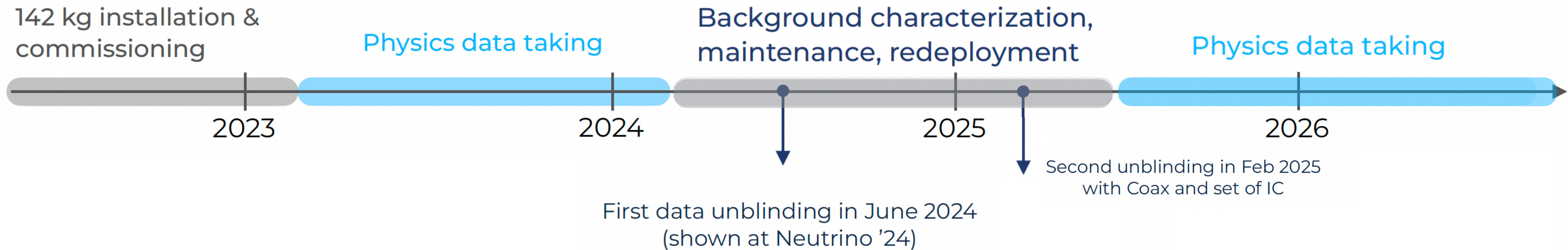
- 1 physics coordinator & background control manager
- 1 L-200 analysis convener
- 2 steering committee members
- (L2 for LEGEND-1000)

LEGEND

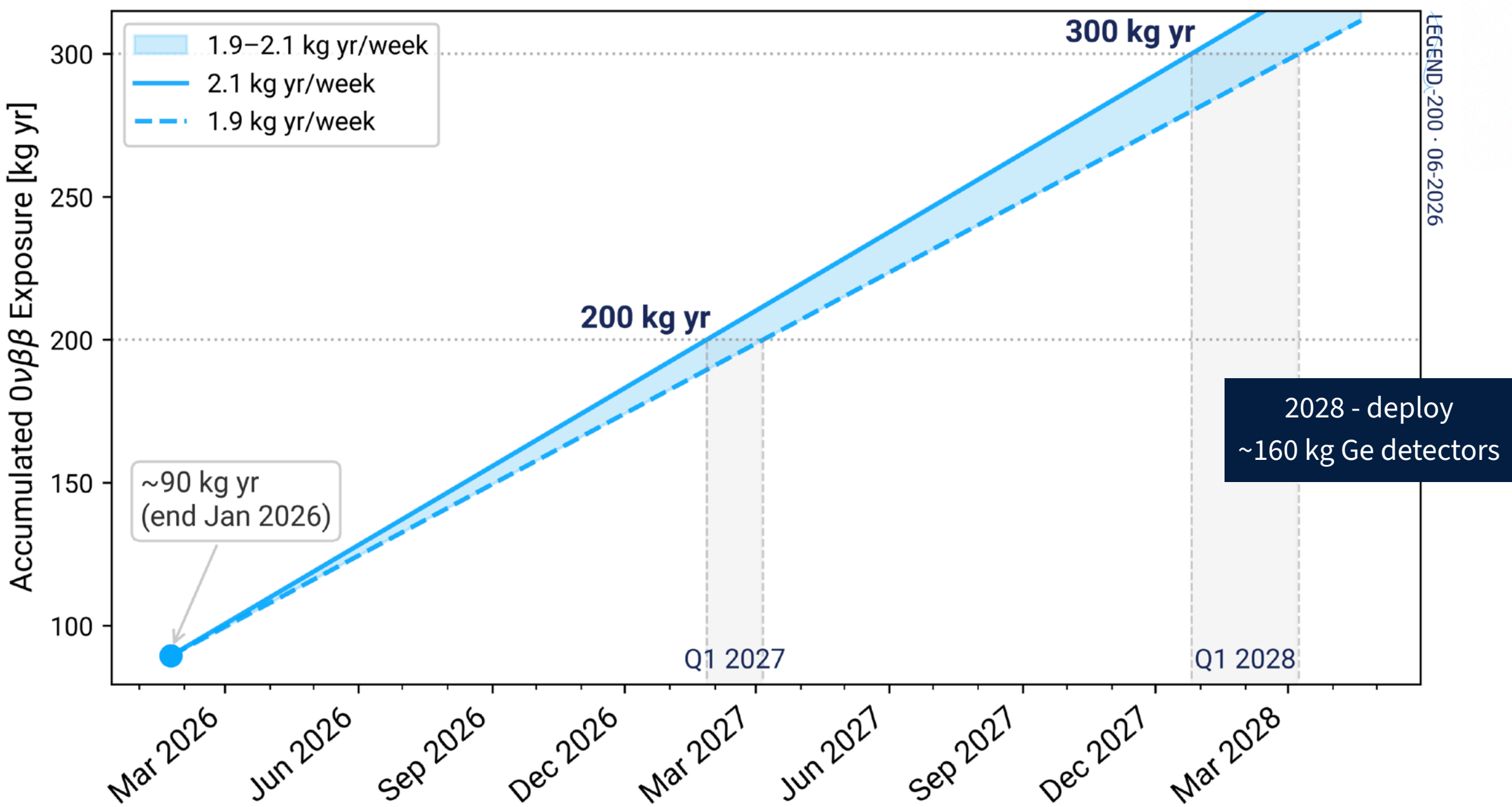


arXiv:2605.22479

LEGEND-200 redeployment and new data taking



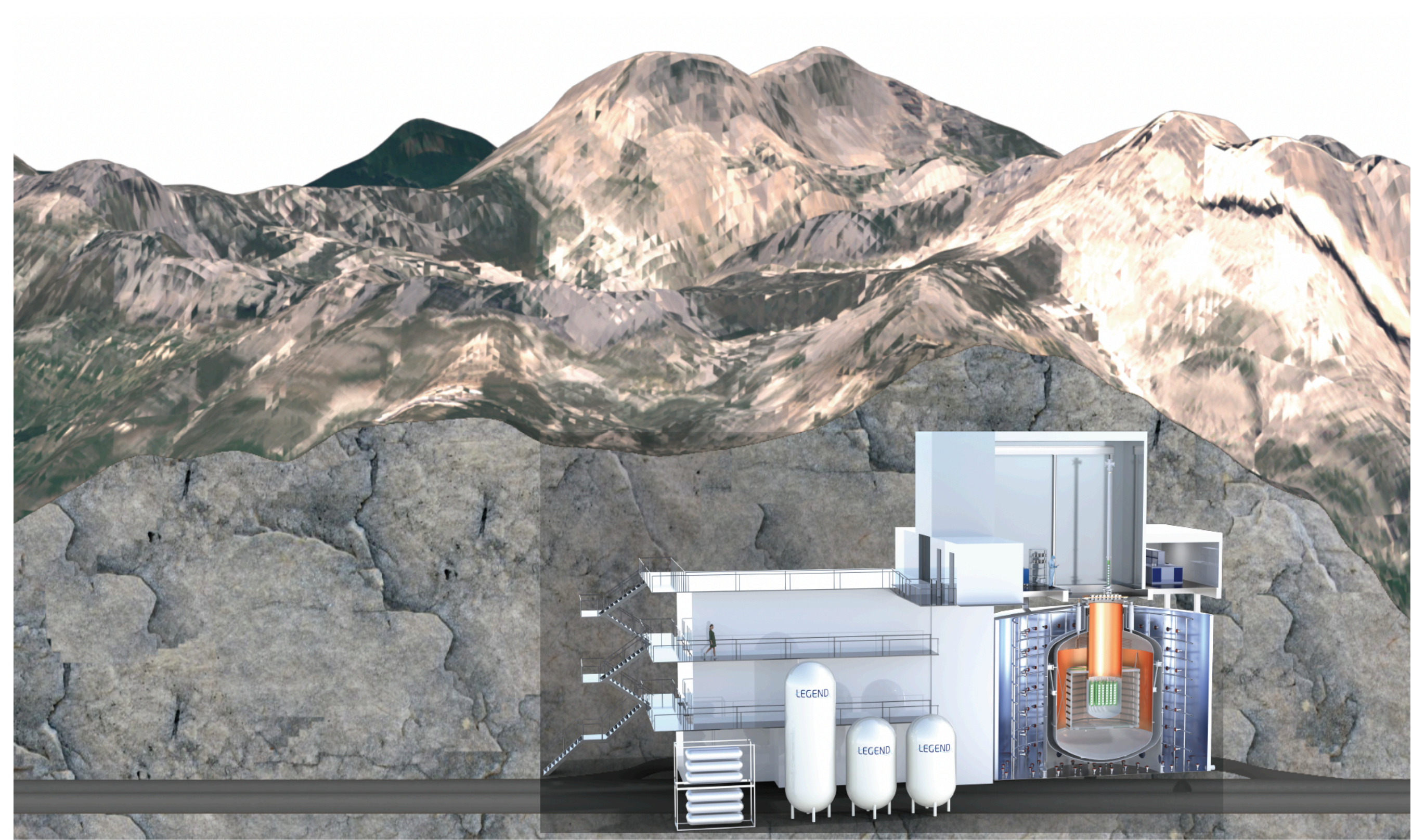
- **Data-taking restarted** Autumn 2025
- **Improved detectors** (total 138kg)
- **Background reduction**
 - Assays revealed surface contamination
 - Components re-etched / leached
 - ^{214}Bi background reduced 5 times
 - ^{208}Tl background eliminated



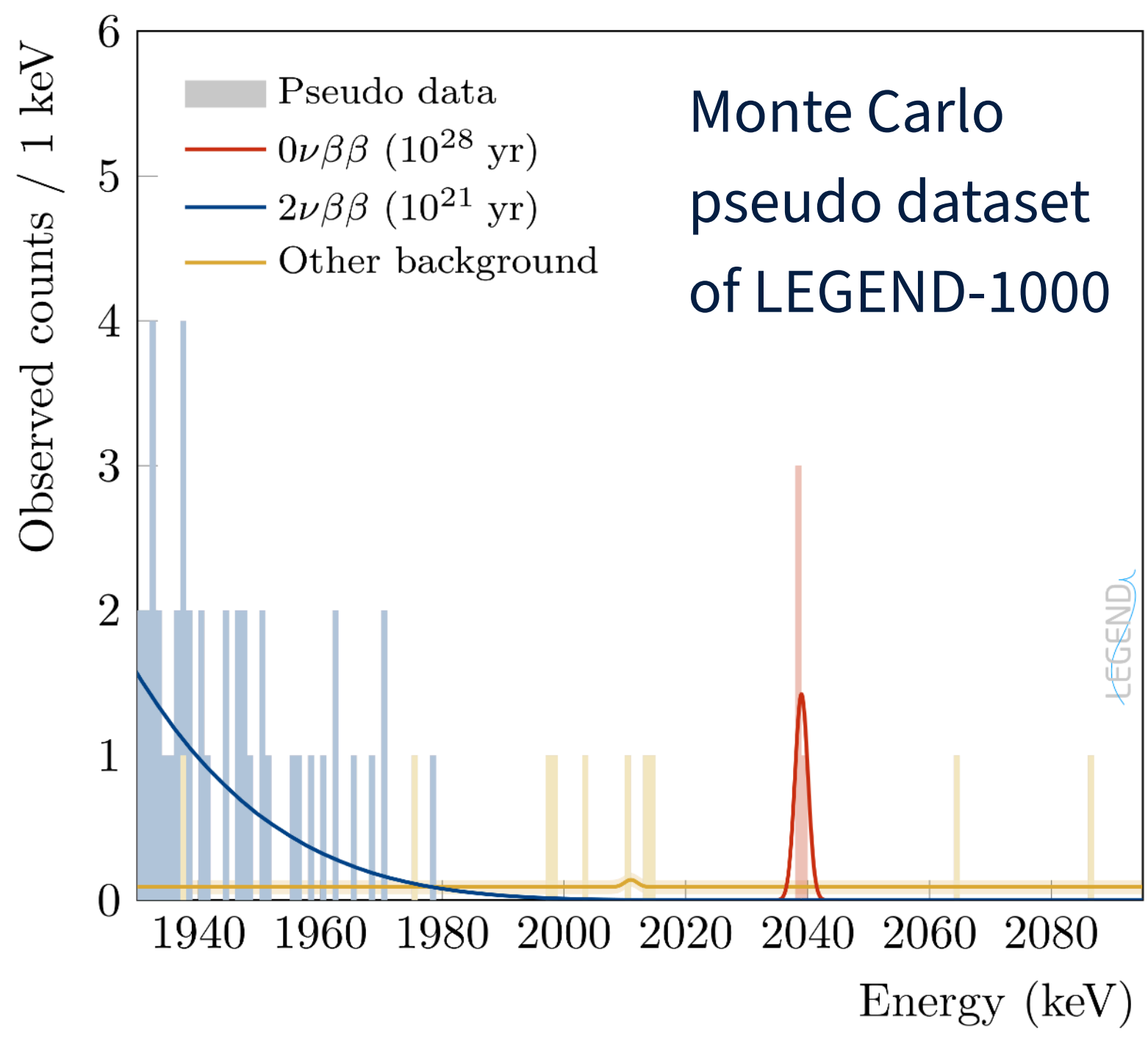
Future prospect: LEGEND-1000 - discovery machine



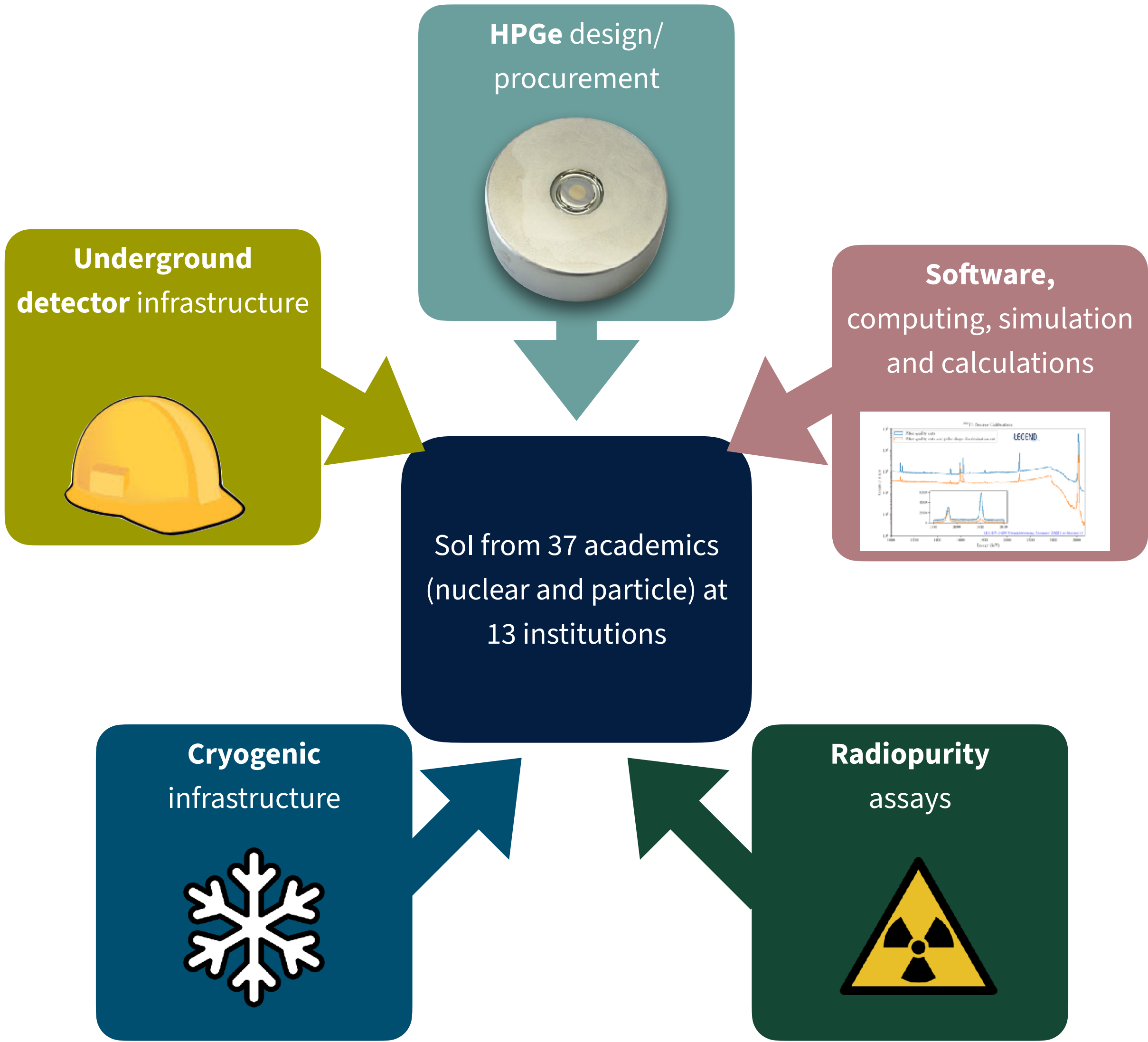
LEGEND 1000



- **1 tonne** of ^{76}Ge isotope
- **Full inverted-hierarchy $T_{1/2}(0\nu\beta\beta)$ sensitivity** (10^{28} years)
- **Quasi-background-free** for 10-year exposure (10^{-5} background events / keV.kg.yr)
- **Low-risk:** tech proven in LEGEND-200, GERDA & Majorana



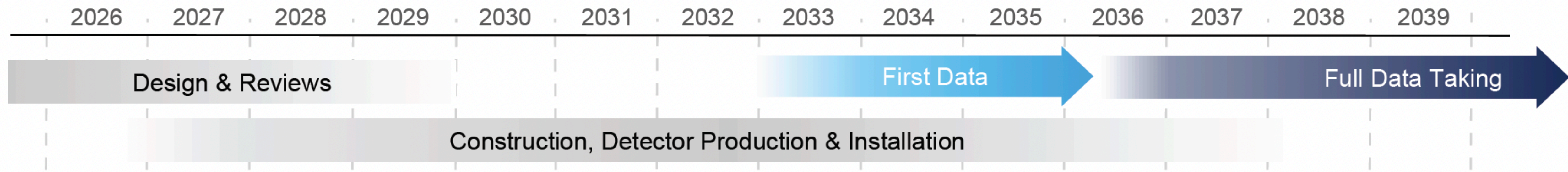
LEGEND-1000 in the UK



The UK community has converged on LEGEND-1000 for the next decade, but **needs funding**



LEGEND-1000 - world's leading choice for next generation



NSF (final design phase MREFC) & DOE (CD-1 review)

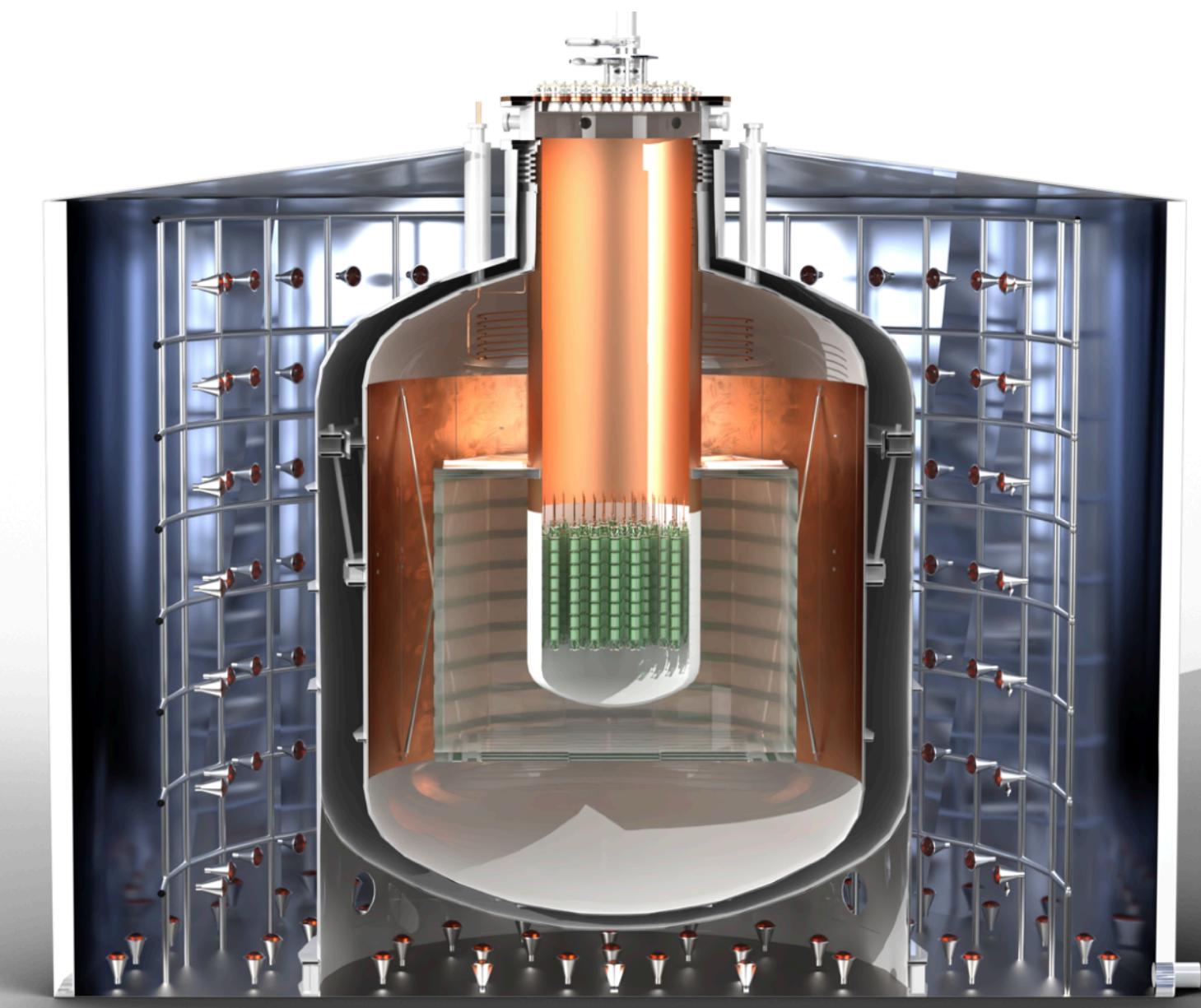


- MPG and DFG support
- German FIS National Research Infrastructure process (decision July 2026)
- INFN flagship project;
- Contributions from Switzerland and Poland

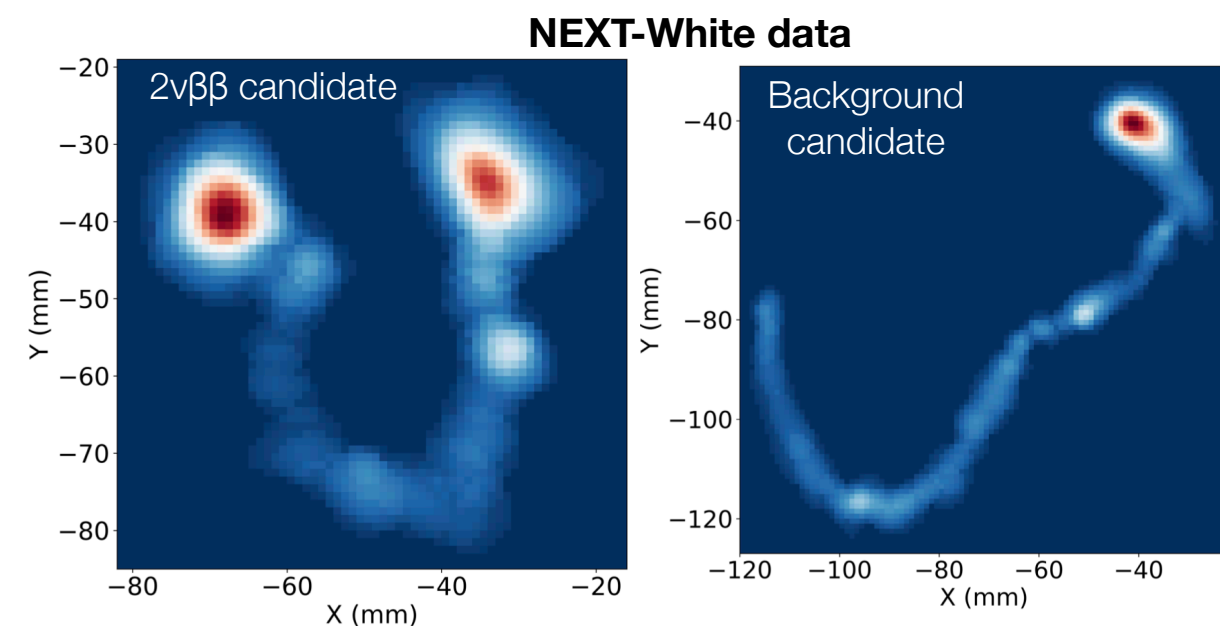


Mid-term update 2023

*“APPEC strongly supports the CUPID and **LEGEND 1000** double-beta decay experiments selected in the US- European process and endorses the development of **NEXT**.”*



Other next-generation $0\nu\beta\beta$ activity in the UK



High-pressure gas ^{136}Xe TPC with electroluminescence at Canfranc, Spain

2 academics, 3 PDRAs,
4 PhD students



- **NEXT-100** physics runs start this summer
 - $\beta\beta$ data-taking at 10 bars
- Detector working well at 4 bars:
 - The NEXT-100 Detector *Eur. Phys. J. C* 86, 114 (2026)
 - First results with ^{83}mKr decays *Eur. Phys. J. C* 86, 739 (2026)
 - Radon-induced backgrounds *Arxiv:2604.19616* (2026)
 - Energy resolution *Arxiv:2511.02467* (2026)

- Ton-scale R&D underway: focus on **Ba tagging**
 - Ba demonstrator currently at Manchester
 - Potential to operate at Boulby
- In European roadmap (next-gen for USA)

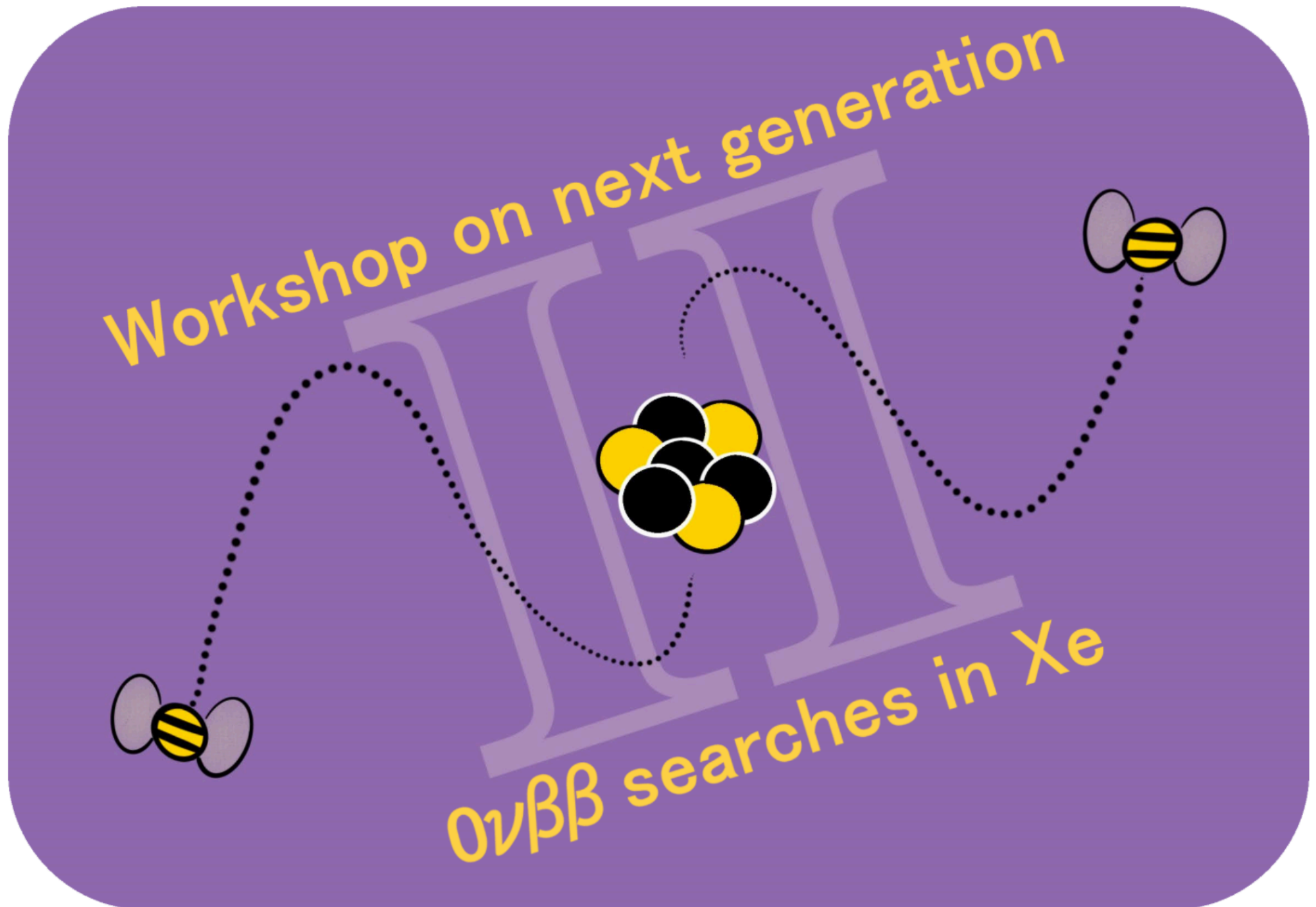


Second Workshop on $0\nu\beta\beta$ searches in Xe - next-generation experiments

Second Workshop on Neutrinoless double beta decay search in Xe - next-generation experiment

Sep 14 – 18, 2026
Old Trafford
Europe/London timezone

- Overview
- Timetable
- Call for Abstracts
- Registration
- Participant List
- Travel information
 - Visa Requirements
 - About Manchester
- Code of conduct



Link: <https://indico.global/event/17139/>

- Follows Montreal workshop in November 2025
- Strong community agreement to work together

14-18 September, Old Trafford

- National communities' strategies
- Experiment statuses
- Discussion sessions
- Community building

Consider joining!

Other noble-element TPCs: LZ to XLZD



LZ reaches 4.5σ evidence for solar ^8B neutrino detection via CEvNS

[\[2512.08065\]](#)

LZ $\rightarrow$ XLZD: 10-fold upscale
probing neutrino sources & properties
alongside dedicated experiments

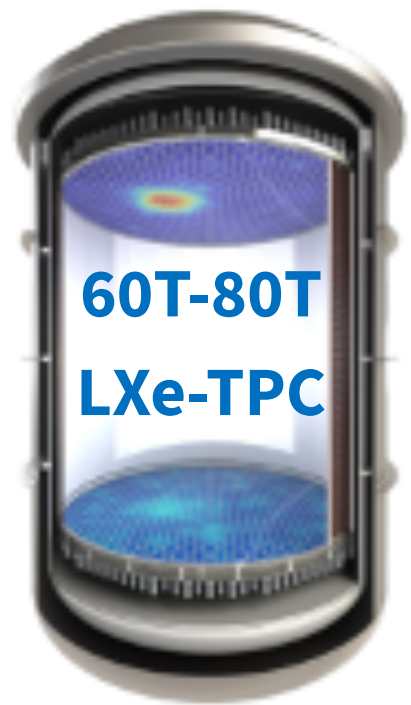
Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons



Neutrino nature
Neutrinoless double
beta decay
Neutrino magnetic
moment
Double electron
capture



**XLZD Rare Event Observatory
for dark matter & neutrino physics**



Supernovae
Early alert
Supernova neutrinos
Multi-messenger
astrophysics

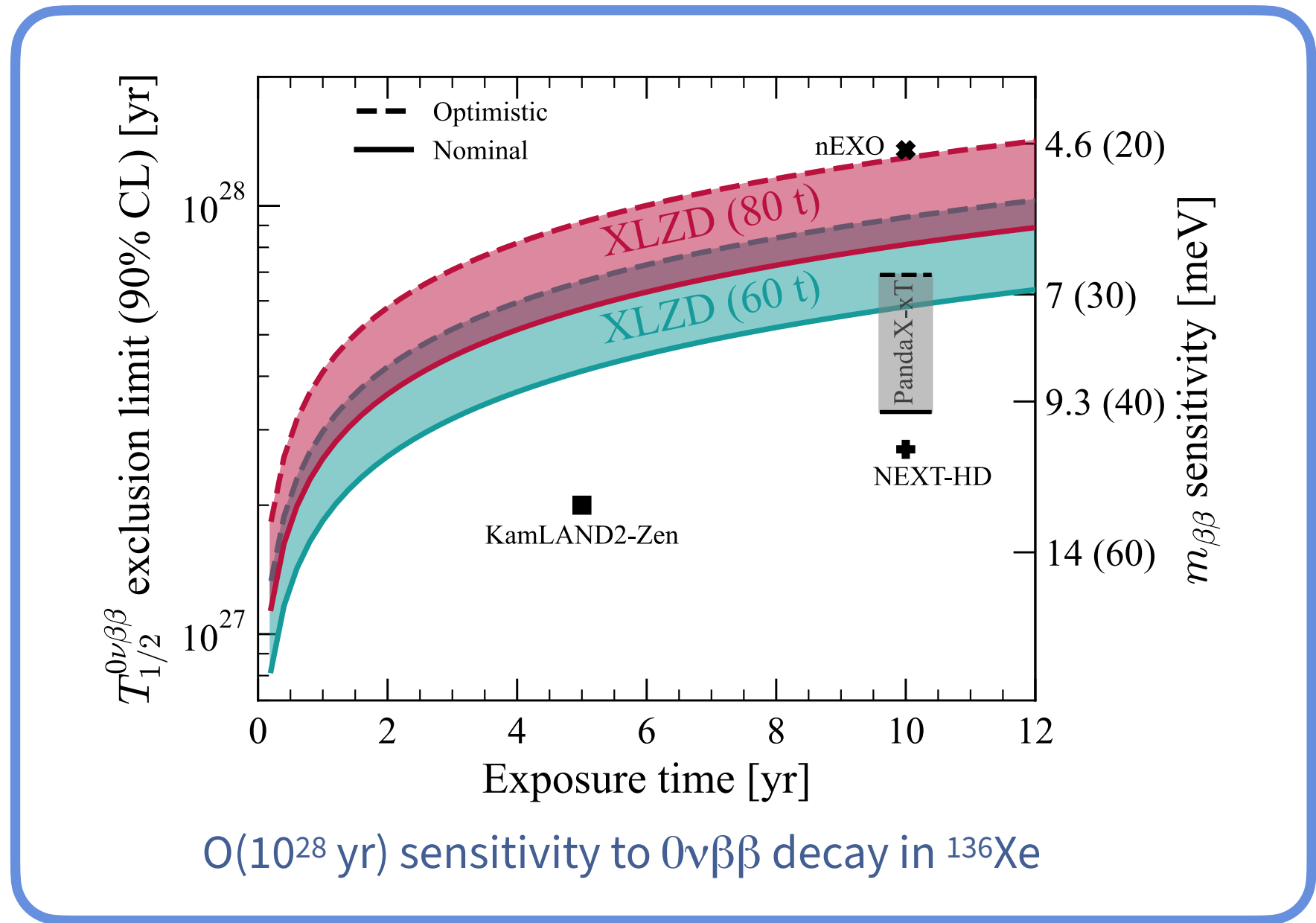


Sun
pp neutrinos
Solar metallicity
 ^7Be , ^8B , hep



Supernova neutrino detection via CEvNS

Solar pp neutrino measurement (ν -e)



XLZD@BOULBY

Opportunity for UK
neutrino community!

Other noble-element TPCs: DarkSide-20K



With >700 tonne of argon, DarkSide-20k will be a dark matter **and neutrino** observatory

Supernova neutrino detection

- Neutral current CEvNS in TPC volume: 100s of events for galactic (10kPc) supernova
- Charged current Rate due to 700-tonne veto volume! [\[JCAP 03 \(2021\) 043\]](#)
- Mass hierarchy sensitivity through CC/NC comparison
- Neutrino absorption on Ar (DUNE supernova channel) [\[2605.12769\]](#)

Solar neutrinos

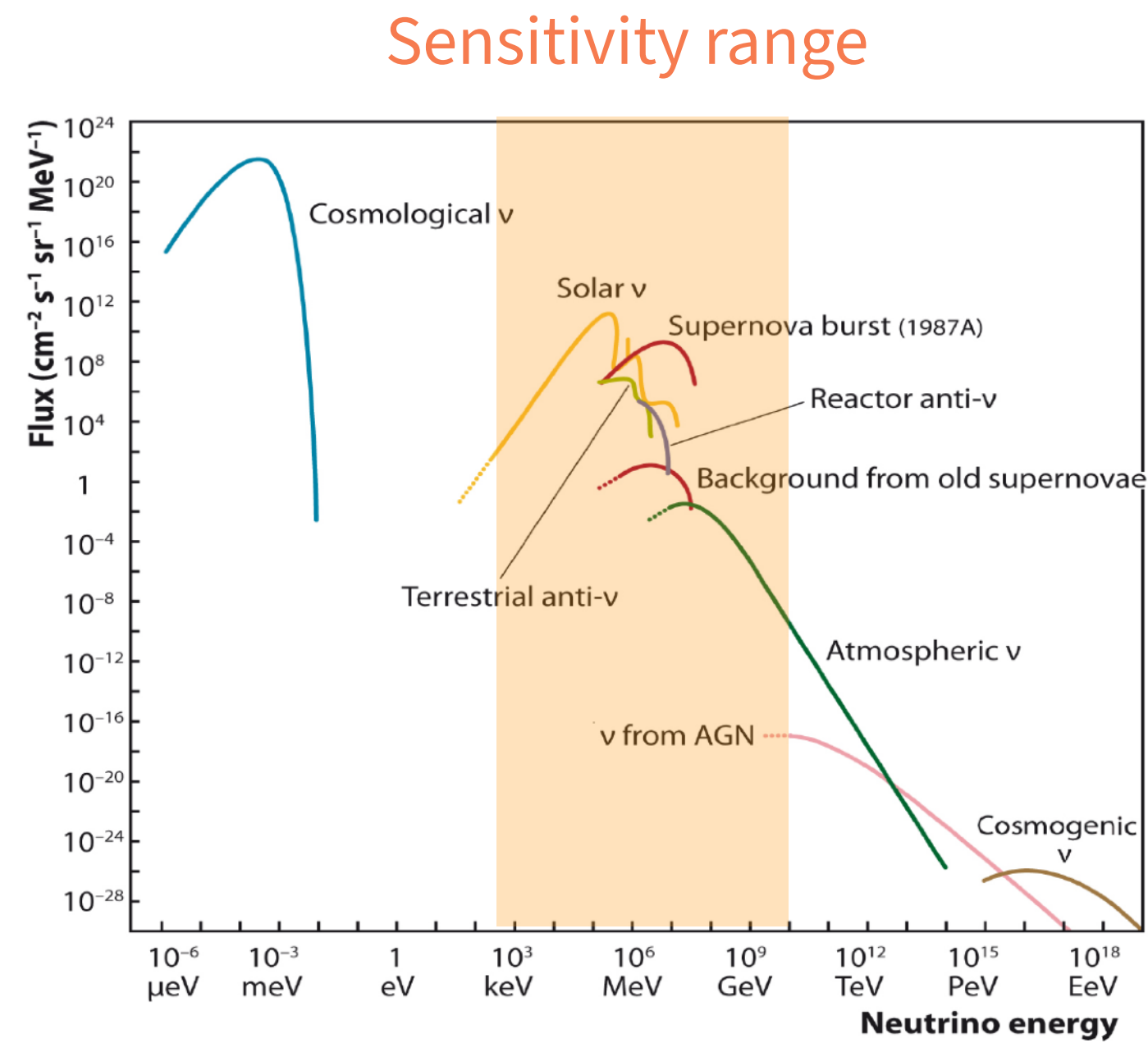
- >10,000 solar neutrino scattering interactions
- Potential to measure CNO vs ^7Be
- Non-standard interaction channels

Sterile neutrinos

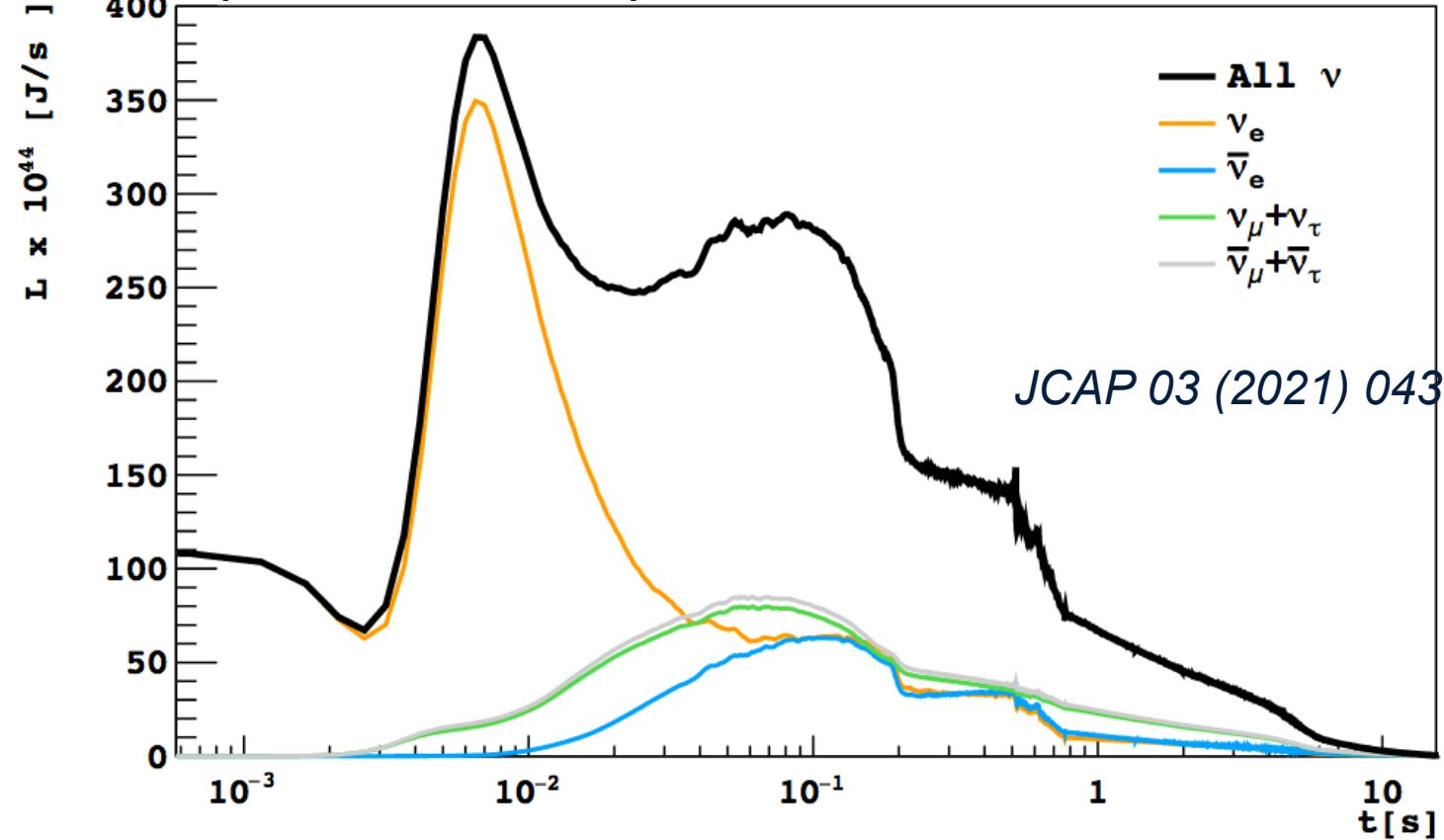
- Sensitive to keV-mass sterile neutrino-electron scattering [Phys. Rev. Lett. 130, 101002 \(2023\)](#)

$0\nu\beta\beta$

- Investigating xenon doping in phase 2

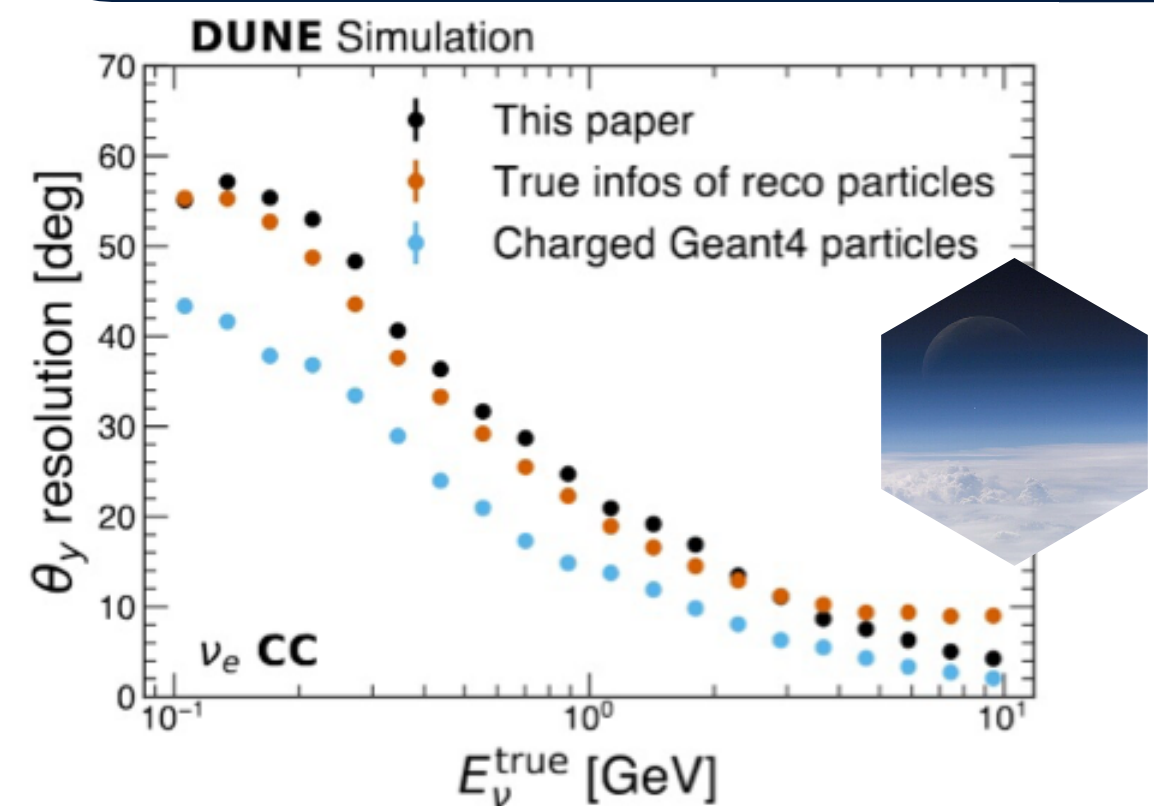


Supernova development vs time, in neutrinos!



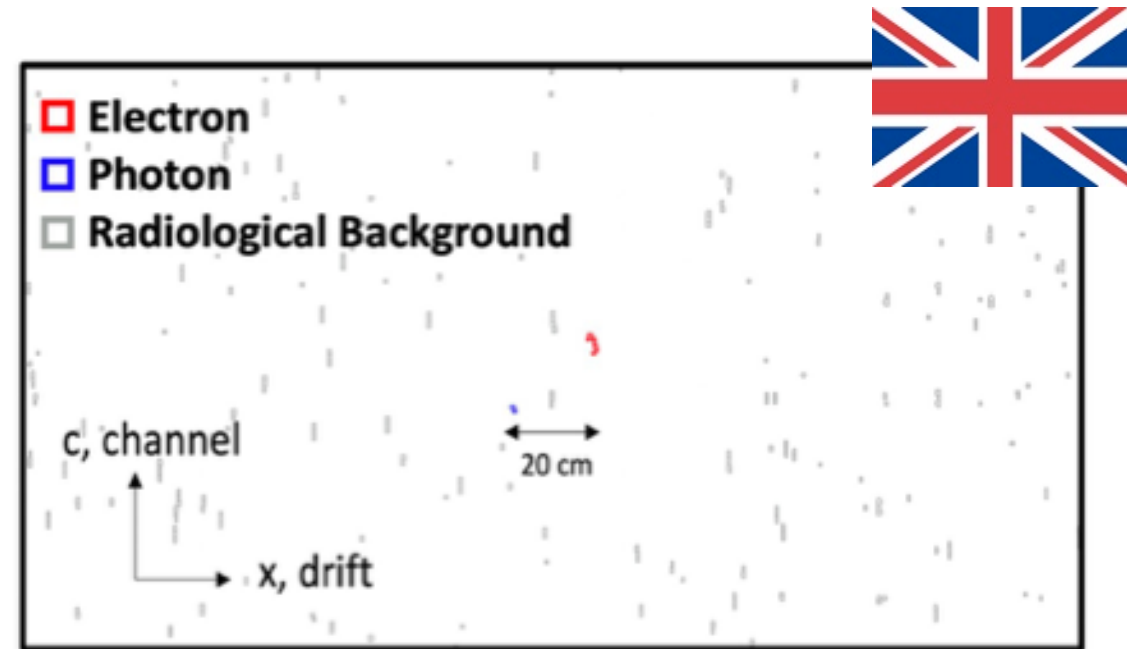
Non-accelerator neutrinos at accelerator-based detectors

DUNE Astro, atmospheric, and BSM program starts as soon as the far detector turns on



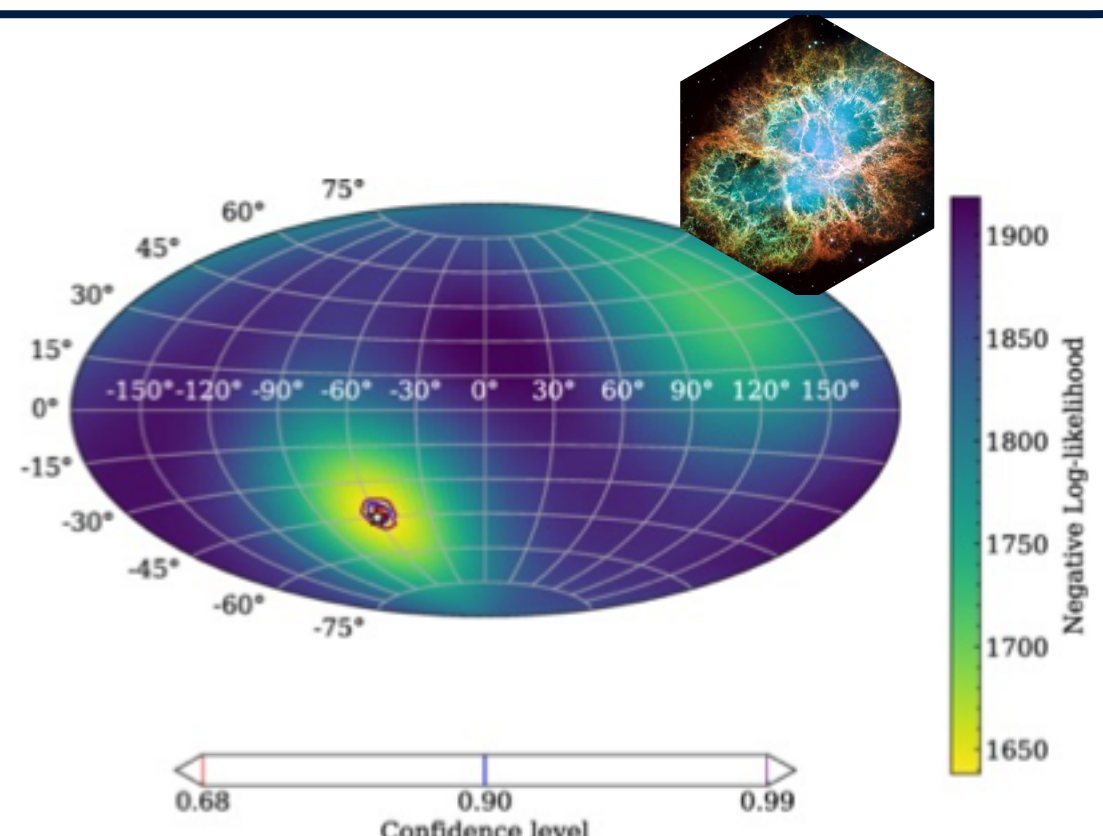
Atmospheric neutrinos

Simulation / reconstruction chain
demo [arXiv 2601.05697]



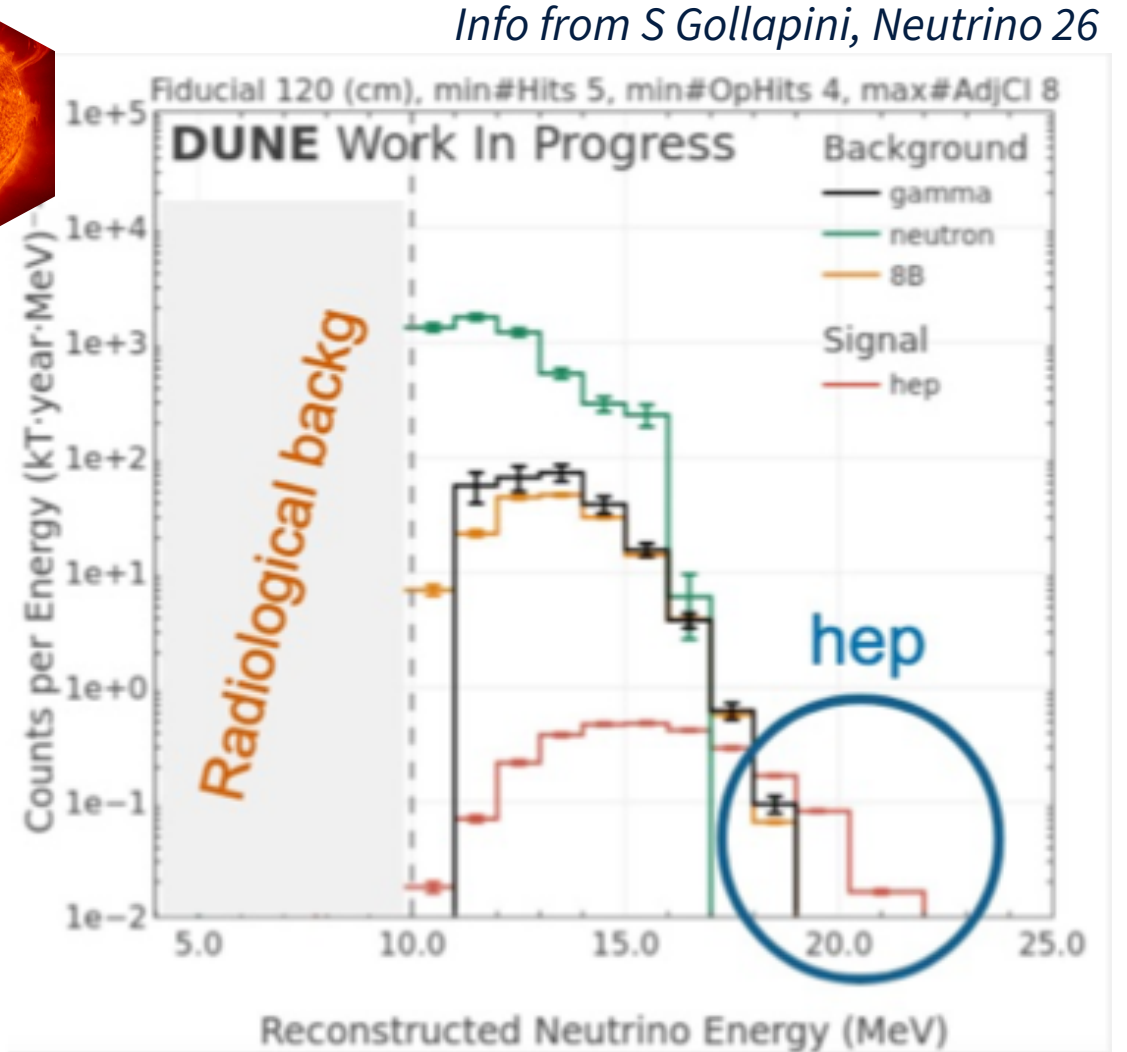
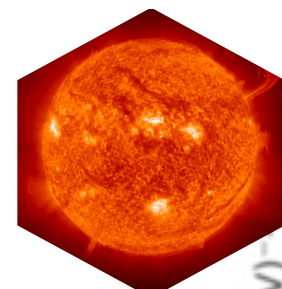
Low-energy reconstruction (4-70 MeV)

workflows for far detectors (paper in review)



Supernova pointing

~5° resolution for 40 kt, 10 kpc
(PRD 111 (2025) 9, 092006)

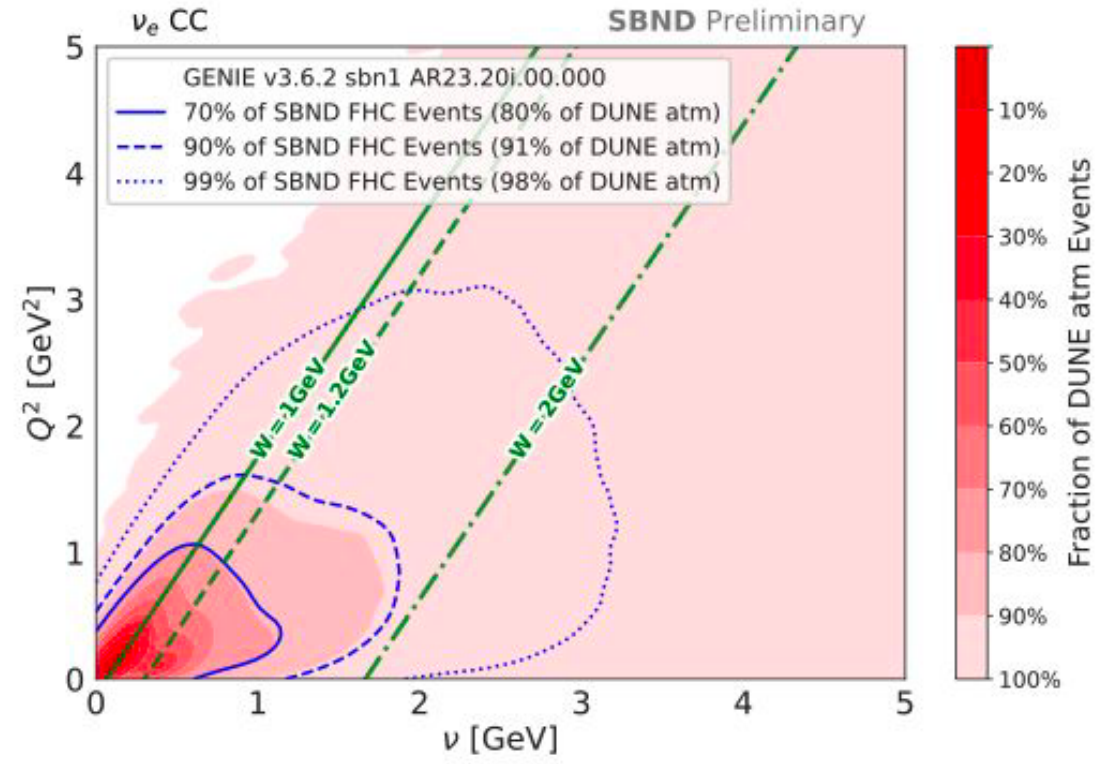


Sensitivity to solar neutrinos

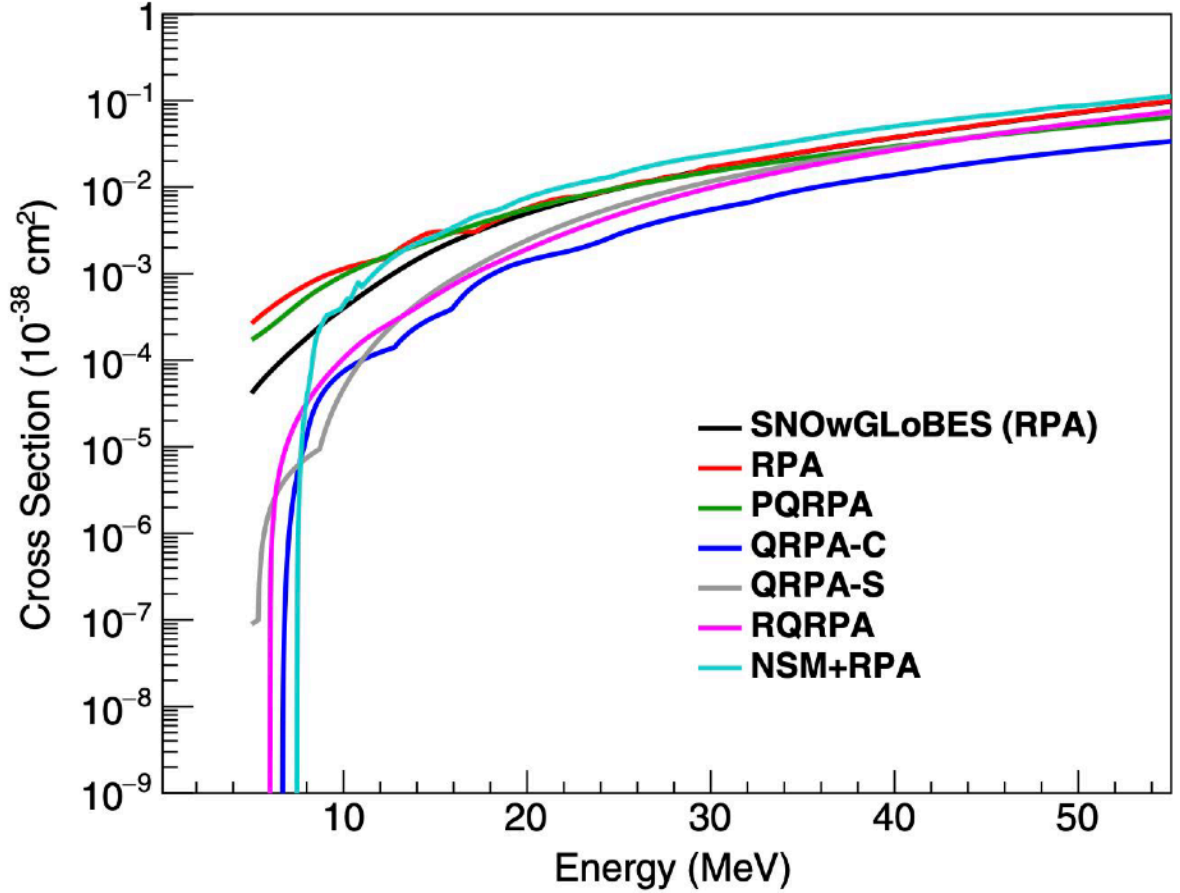
⁸B sensitivity >10 MeV; hep flux discovery sensitivity



ν -Ar cross-section measurements are crucial inputs for DUNE analyses



SBND beam flux mimics DUNE atmospheric flux



- Huge uncertainty between ν -Ar interaction models at supernova energies
- SBND cross sections (e.g. from μ DAR) can explore this phase space



PRD 107, 112012 (2023)



Super-Kamiokande

Gadolinium loading improves neutron tagging:

- 1st loading (2020): 0.011% Gd in water by mass.
- 2nd loading (2022): 0.033% Gd in water by mass.

Recent non-accelerator highlights with major UK involvement:



- **Diffuse supernova neutrino background** search

K. Abe et al. 2026 ApJ 1005 101

- **Reactor / solar** neutrino measurement comparison
(pub in progress)

1.94 σ agreement between SK I-IV solar neutrino and SK VI-VII reactor neutrino data.

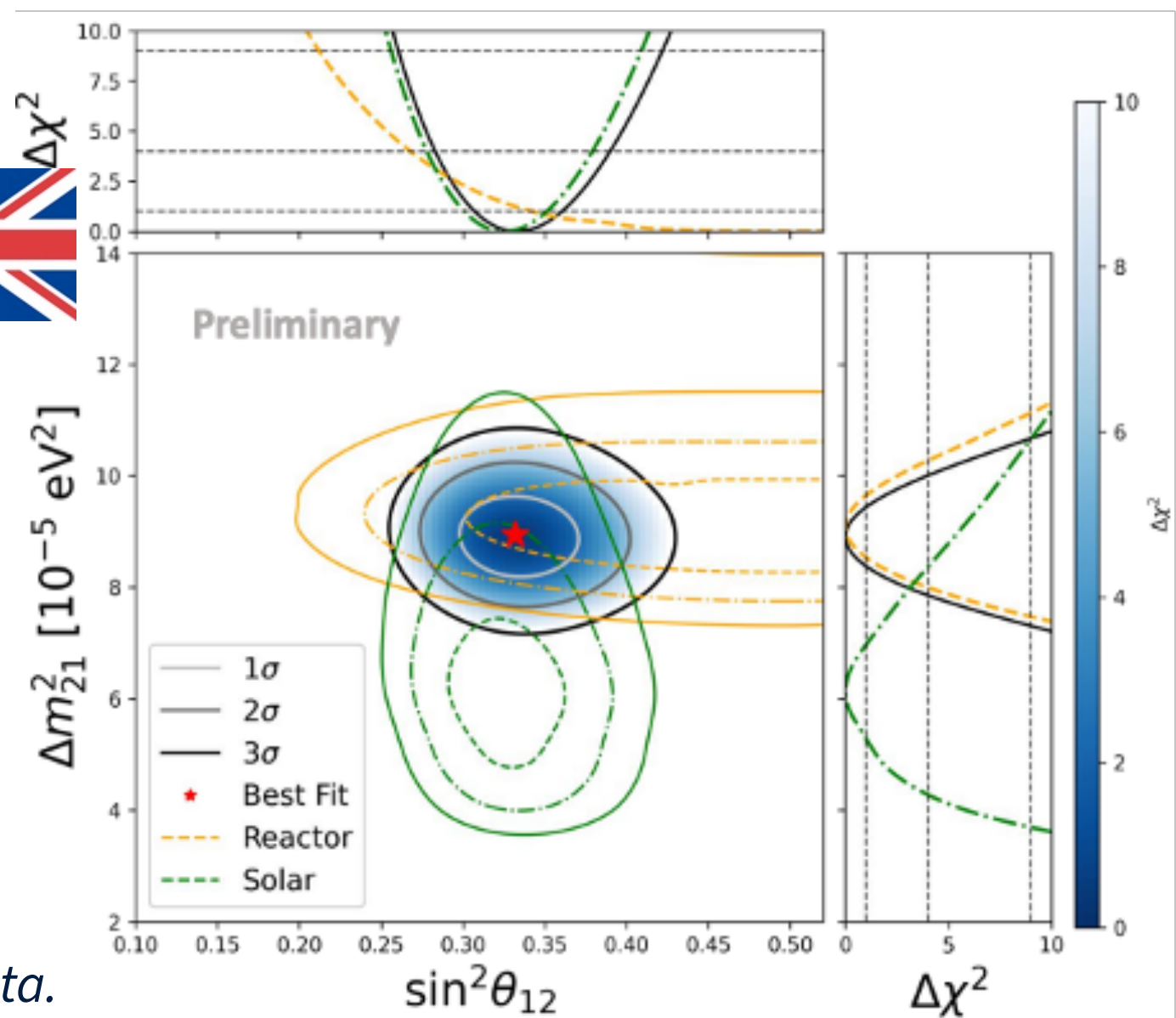


Figure from Super-K presentation at Neutrino 2026: [LINK](#)



Hyper-Kamiokande

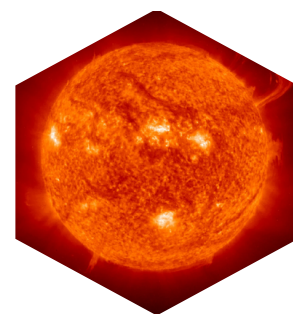


Significant UK involvement with non-accelerator programme.



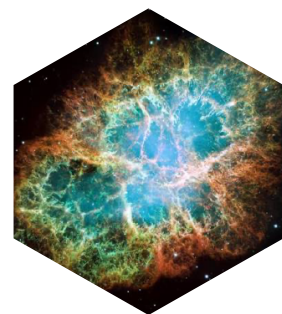
Atmospheric neutrinos

- Sensitivity to mass ordering and octant.
- Joint atmospheric/accelerator analysis can break degeneracies.



Solar neutrinos

- $>3\sigma$ sensitivity to MSW ^8B spectrum upturn in 10 years.

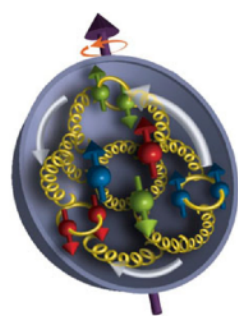


Supernova

- $\sim 70,000$ events expected at 10 kpc.

Diffuse Supernova Neutrino Background

- Supernova burst monitor: alert for multi-messenger observation.
- Pre-supernova sensitivity studies are ongoing.



Proton decay

- 3σ discovery potential for $p \rightarrow e^+ \pi^0$ and $p \rightarrow \bar{\nu} K^+$.



JUNO, Jiangmen, China

- Determine mass hierarchy
- Measure 3ν -oscillation parameters
- **Solar / SN / geo-neutrinos**, nucleon decays

UK contributions



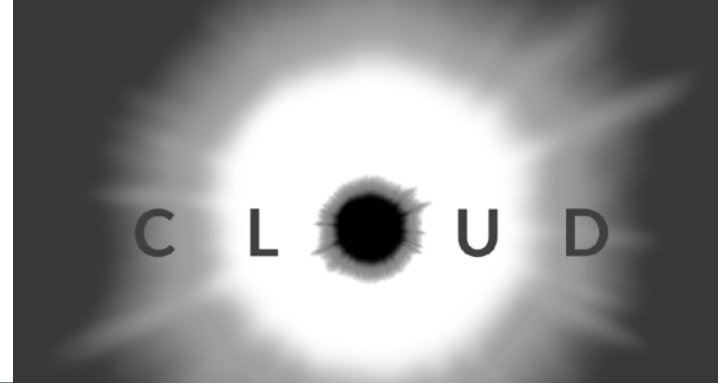
UNIVERSITY OF
LIVERPOOL



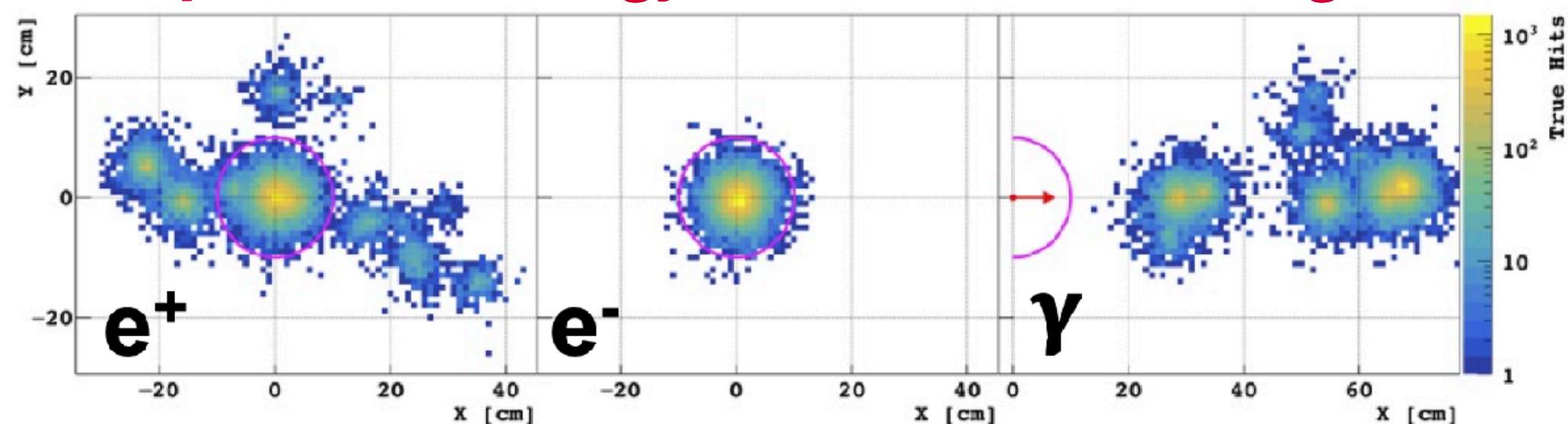
UNIVERSITY OF
OXFORD

- Working-group convenor
- Neutrino interaction simulations / systematic studies
- Atmospheric oscillation analysis
- Diffuse supernova background & proton-decay analyses
- ML-based neutrino event reconstruction

Other low-energy physics - reactor neutrinos



Liquid-O technology for reactor monitoring



Opaque liquid scintillator for particle discrimination ($\sim 2\text{MeV}$)

- Spokesperson
- CLOUD vessel designed at RAL



Science and
Technology
Facilities Council



UNIVERSITY
OF SUSSEX

(RAL, TD)



2m Liquid-O prototype at Sussex

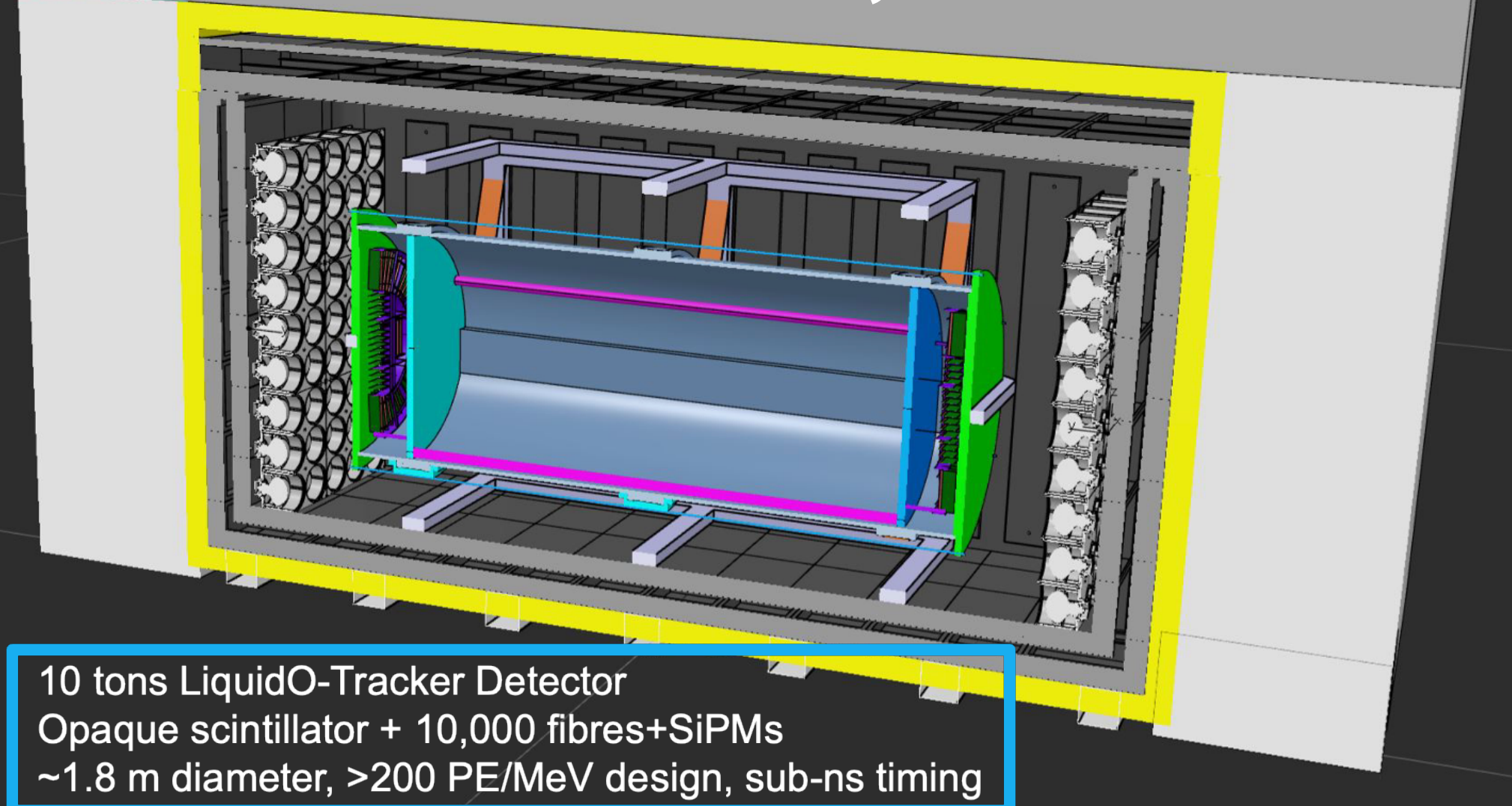
CLOUD

Reactor monitoring ($10,000 \bar{\nu}_e/\text{day}$)

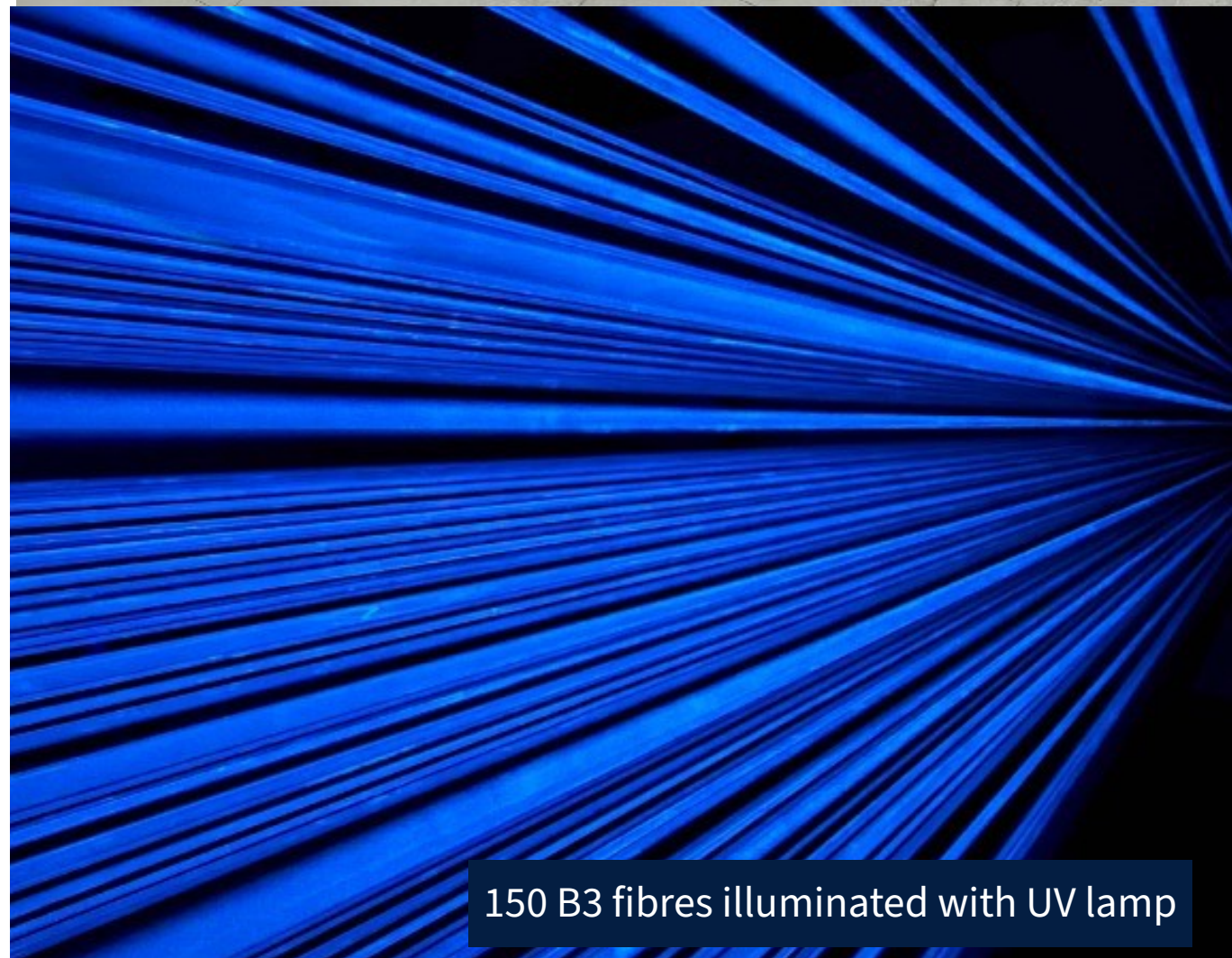
LIQUID-O potential for neutrinos

- Solar
- Geoneutrinos
- Supernova
- Reactor
- Atmospheric
- Accelerator
- $0\nu\beta\beta$

CLOUD at Chooz reactor, France

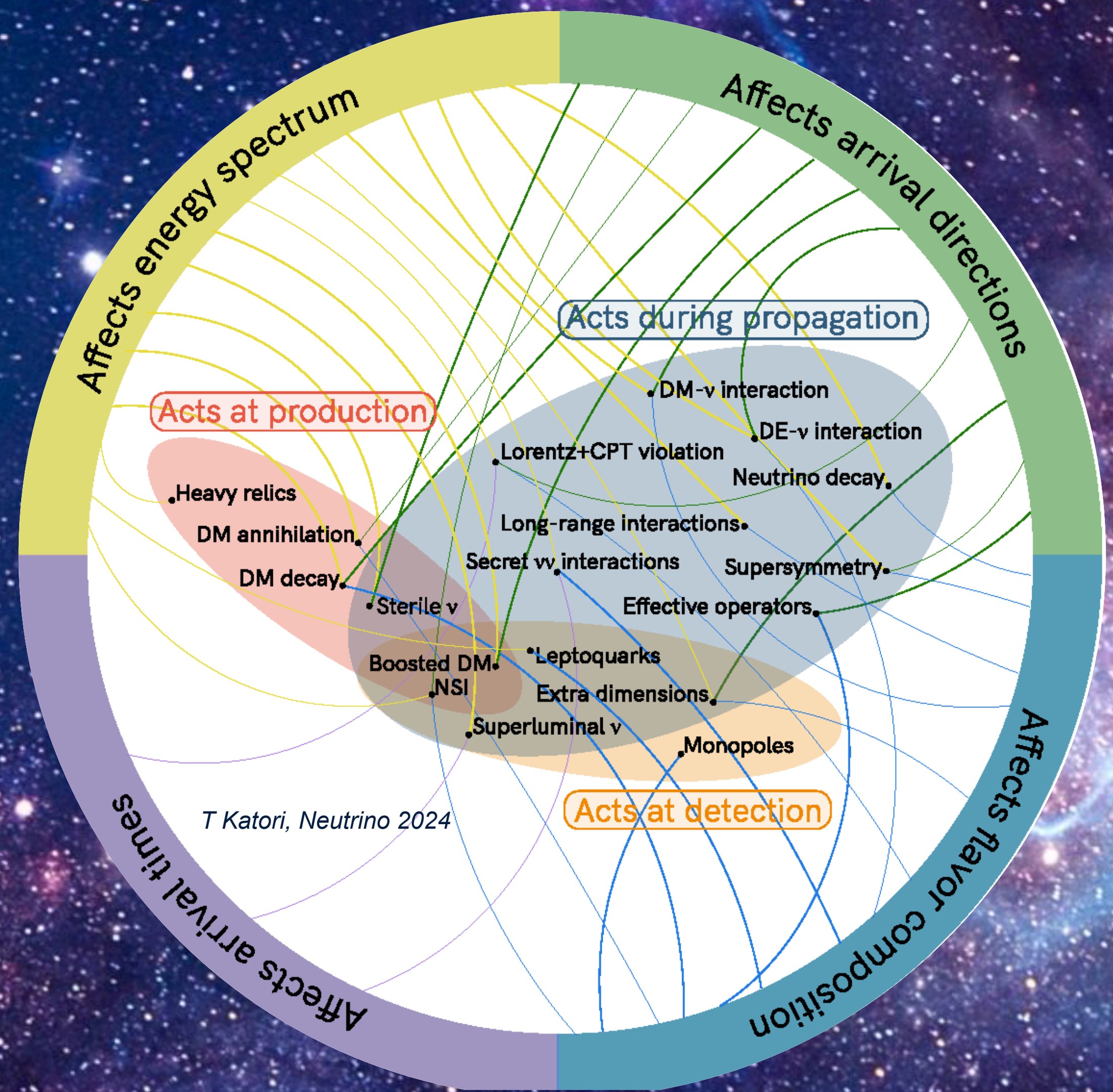


10 tons LiquidO-Tracker Detector
Opaque scintillator + 10,000 fibres+SiPMs
 $\sim 1.8\text{ m}$ diameter, $>200\text{ PE/MeV}$ design, sub-ns timing



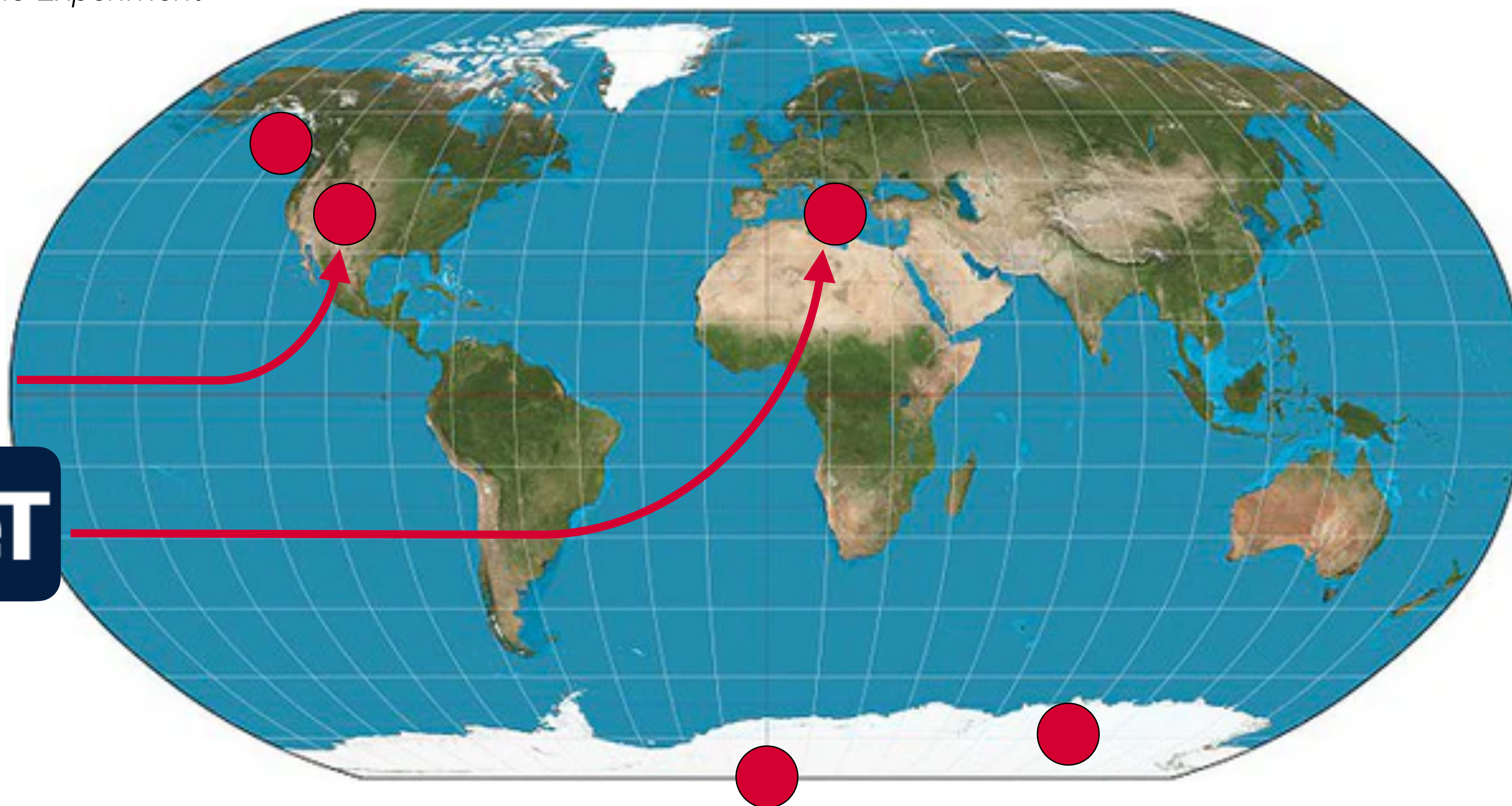
150 B3 fibres illuminated with UV lamp

Neutrino astronomy



- Can access many BSM physics topics
- Contributes to multi-messenger astronomy
- Synergy with oscillation experiments

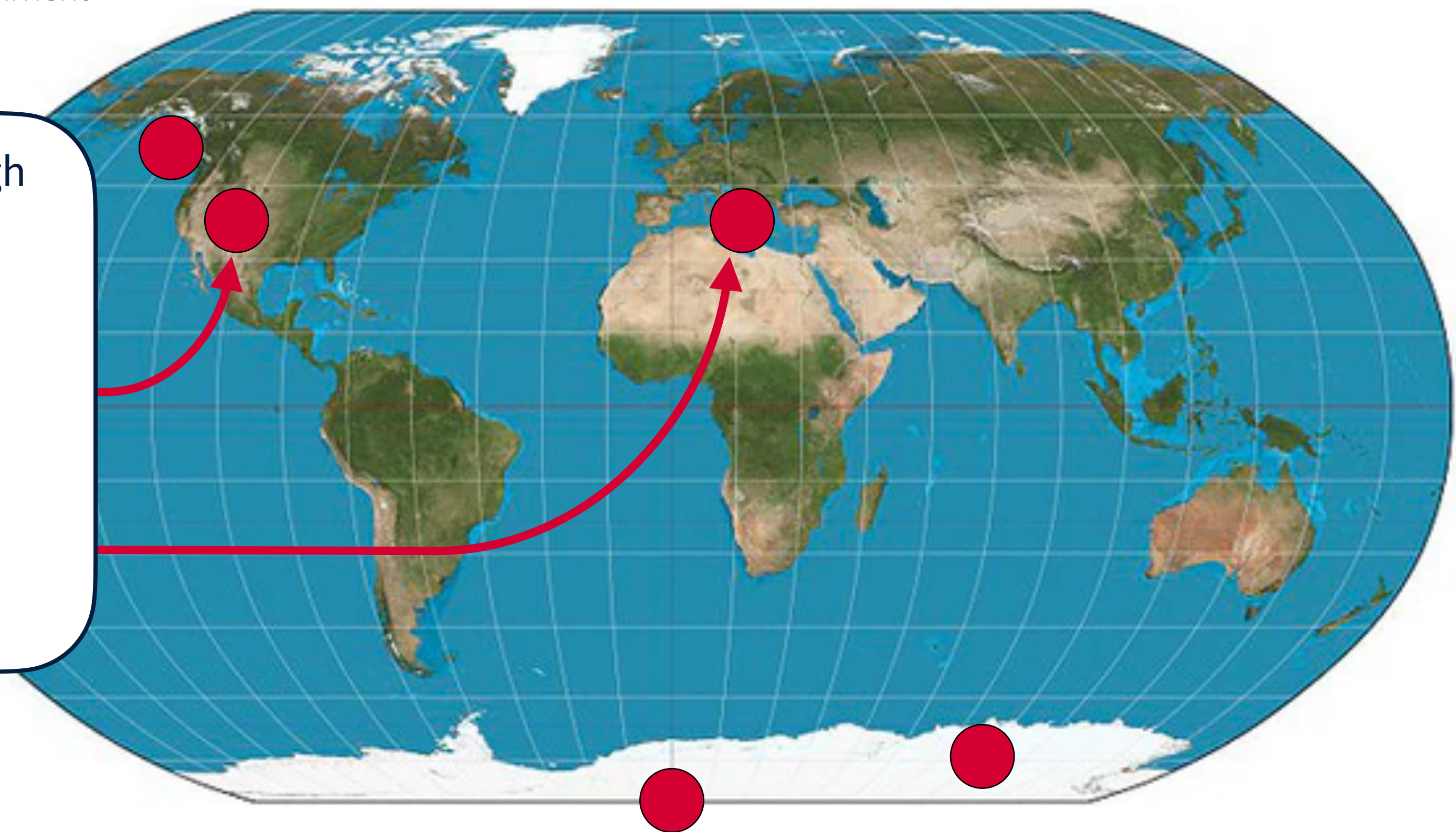
UK High-energy Neutrino Consortium



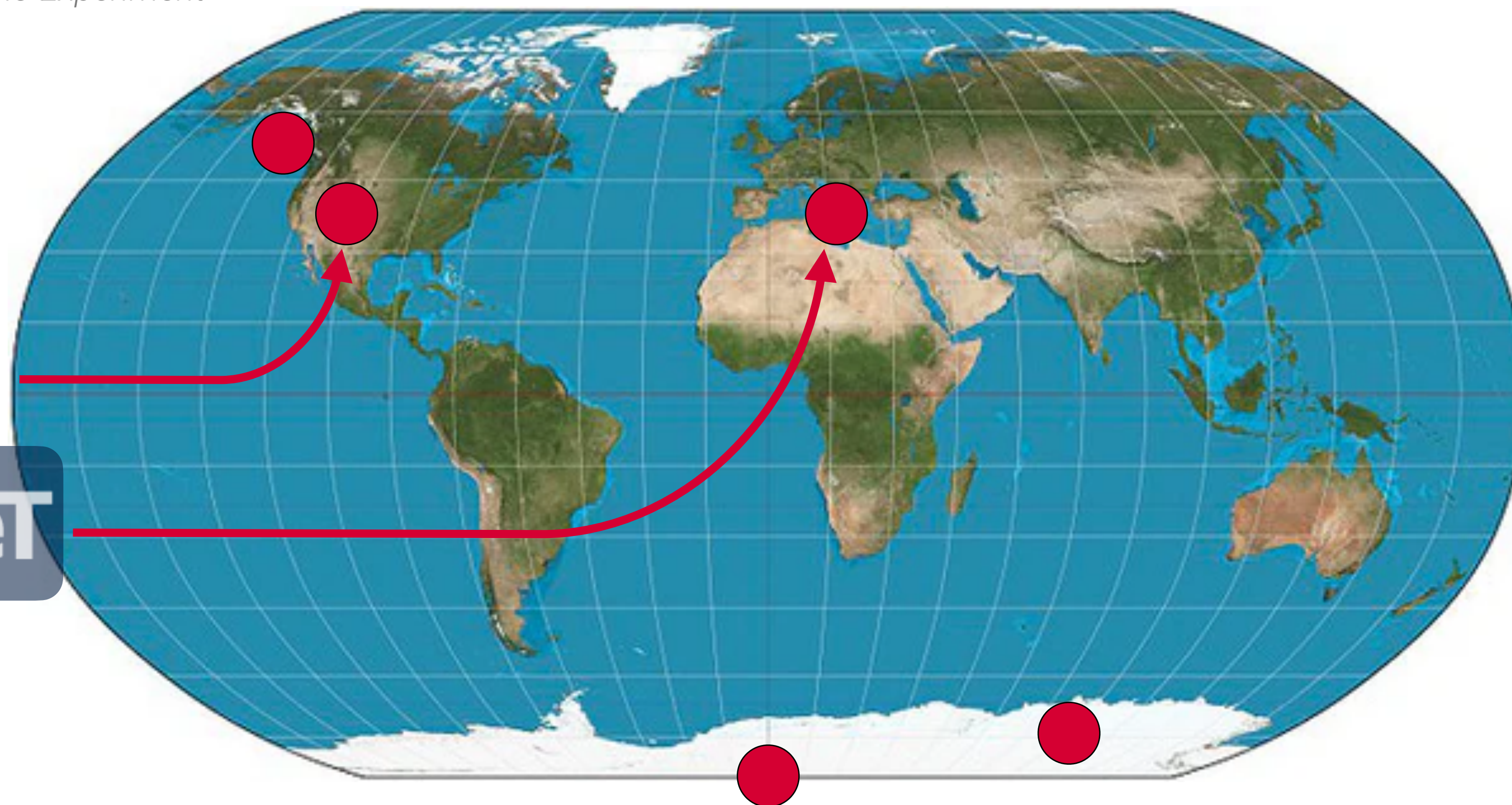
UK High-energy Neutrino Consortium



Limited UK involvement through astronomy



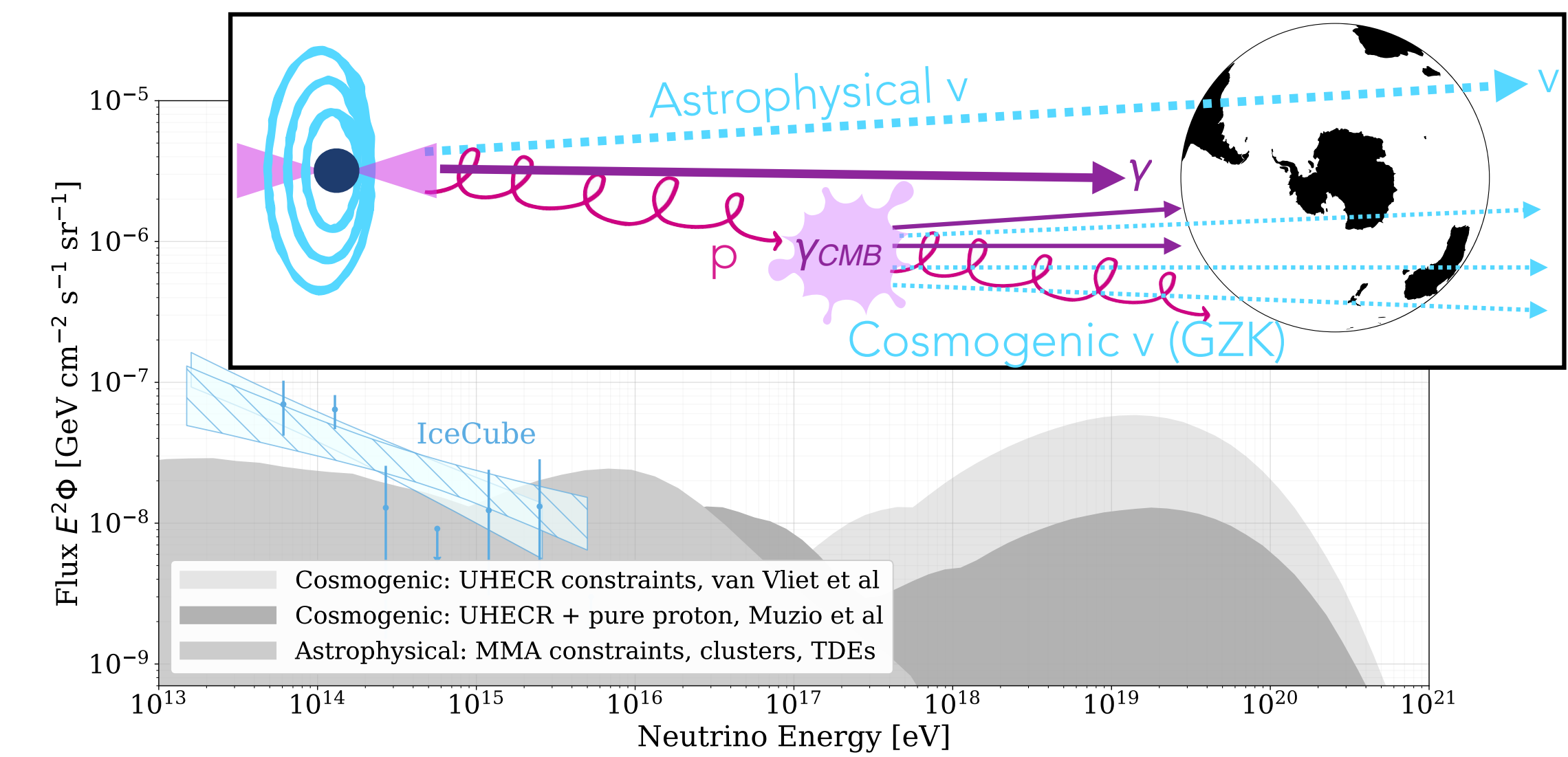
UK High-energy Neutrino Consortium



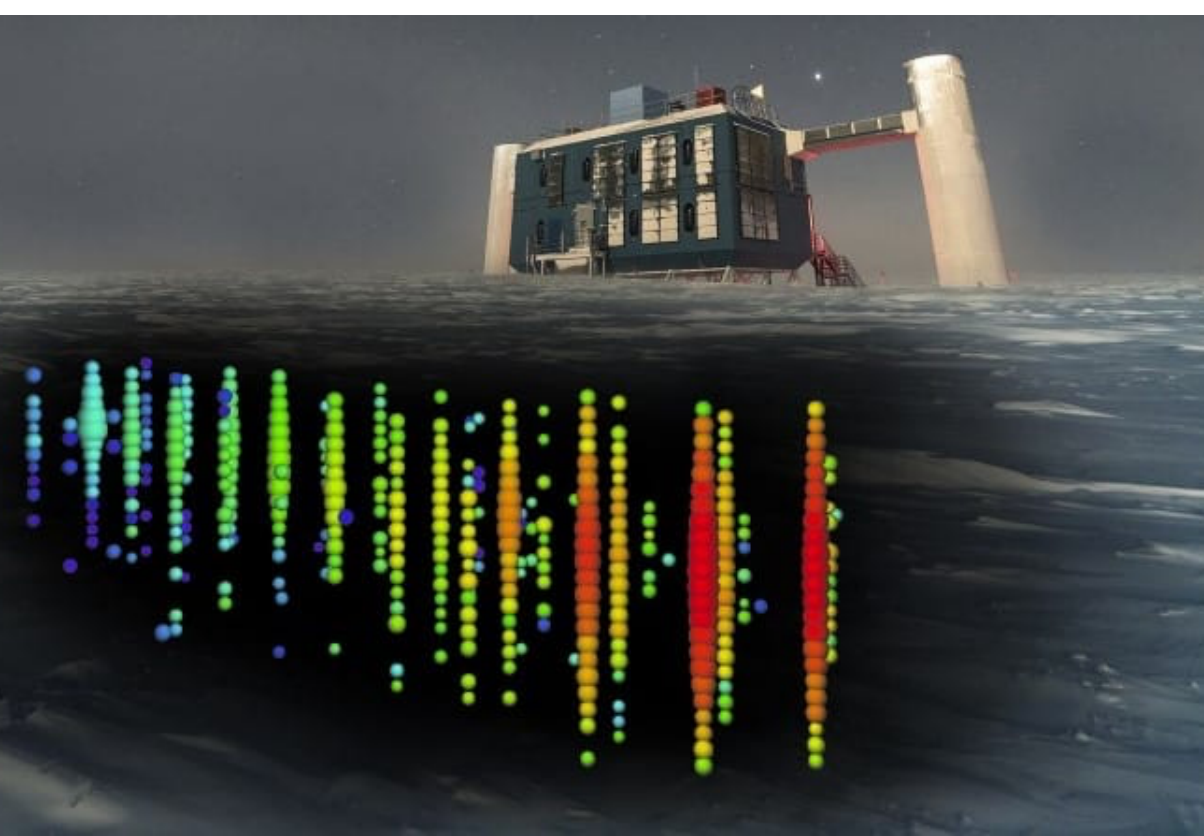
Sustained UK-HEP involvement



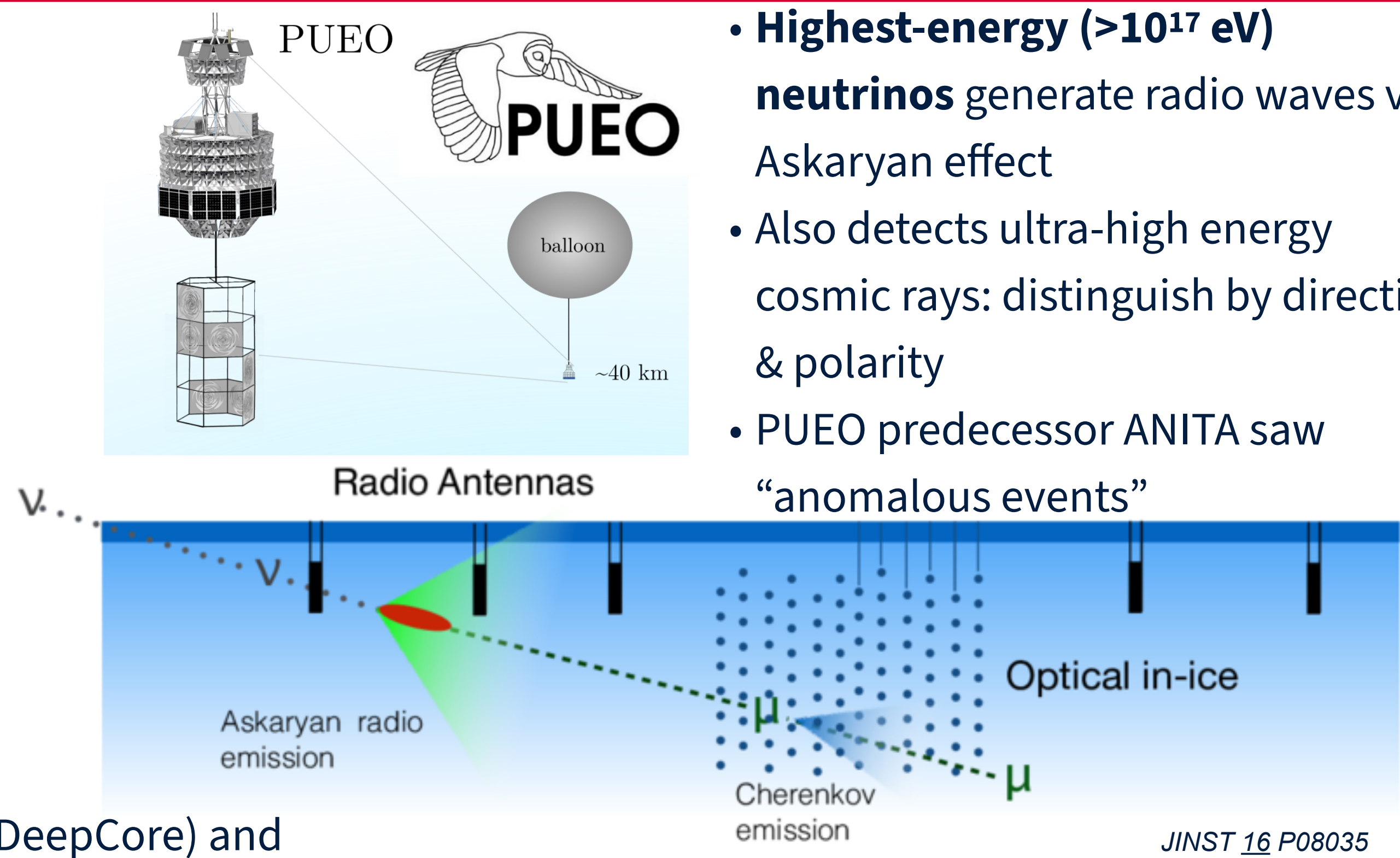
Antarctic ice as a neutrino detector



J.P. Yáñez, Neutrino 24



- Running since 2010 at **GeV** (DeepCore) and **TeV** (IceCube) energies
- Atmospheric oscillations, sterile ν , ν astronomy (point sources, diffuse neutrinos, galactic neutrinos)



- **Highest-energy ($>10^{17}$ eV) neutrinos** generate radio waves via Askaryan effect
- Also detects ultra-high energy cosmic rays: distinguish by direction & polarity
- PUEO predecessor ANITA saw “anomalous events”

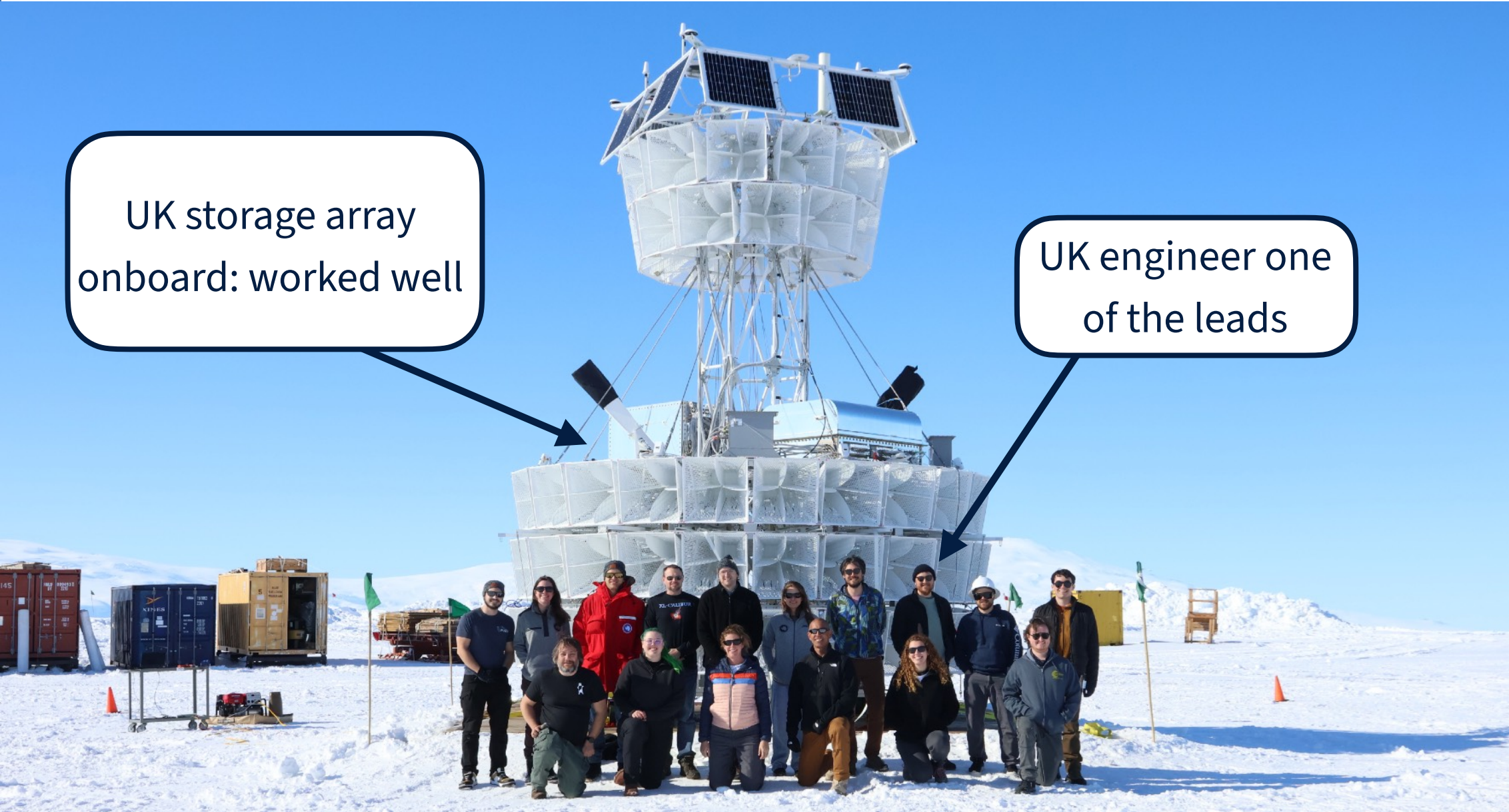


PUEO launch, Dec 2025:
successful flight with
in-flight support from UK



4	Physicists	2	PhD students
3	Engineers	4	Undergrads

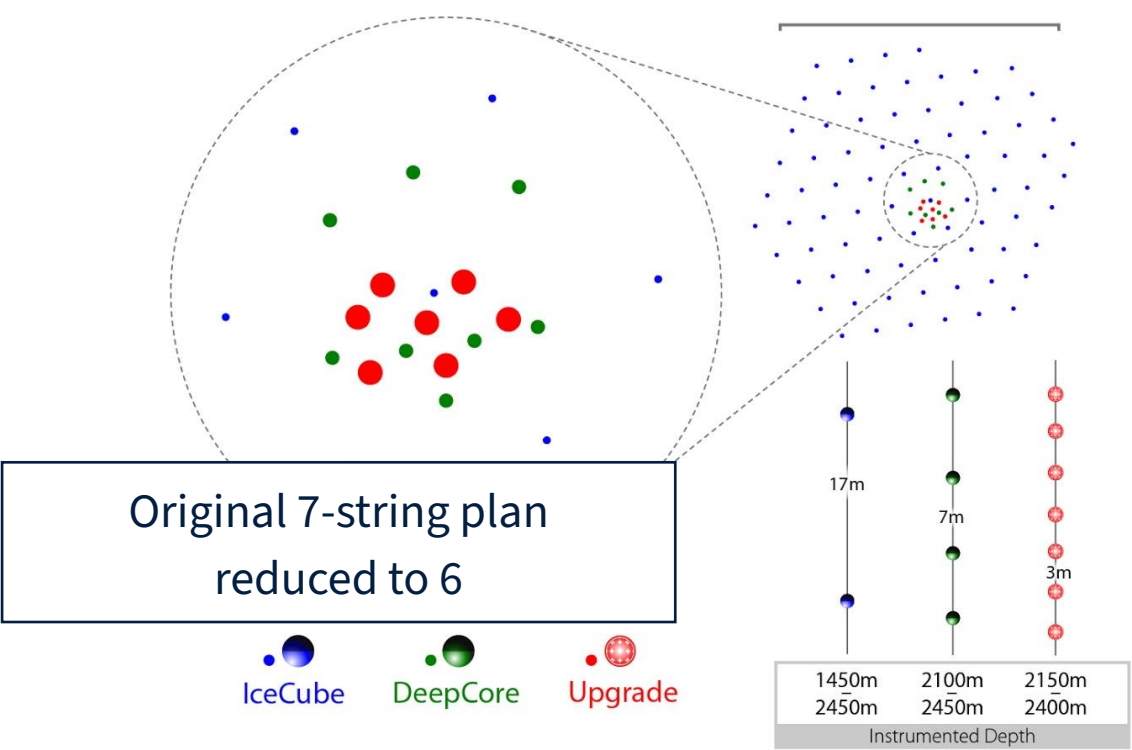
- Analysis ongoing - first results within 12 months
- Trigger paper submitted to arXiv <https://arxiv.org/abs/2607.05285>



- IceCube Upgrade to 6-string deployment completed
- Atmospheric neutrino sensitivity published

Phys. Rev. D 113, 072009

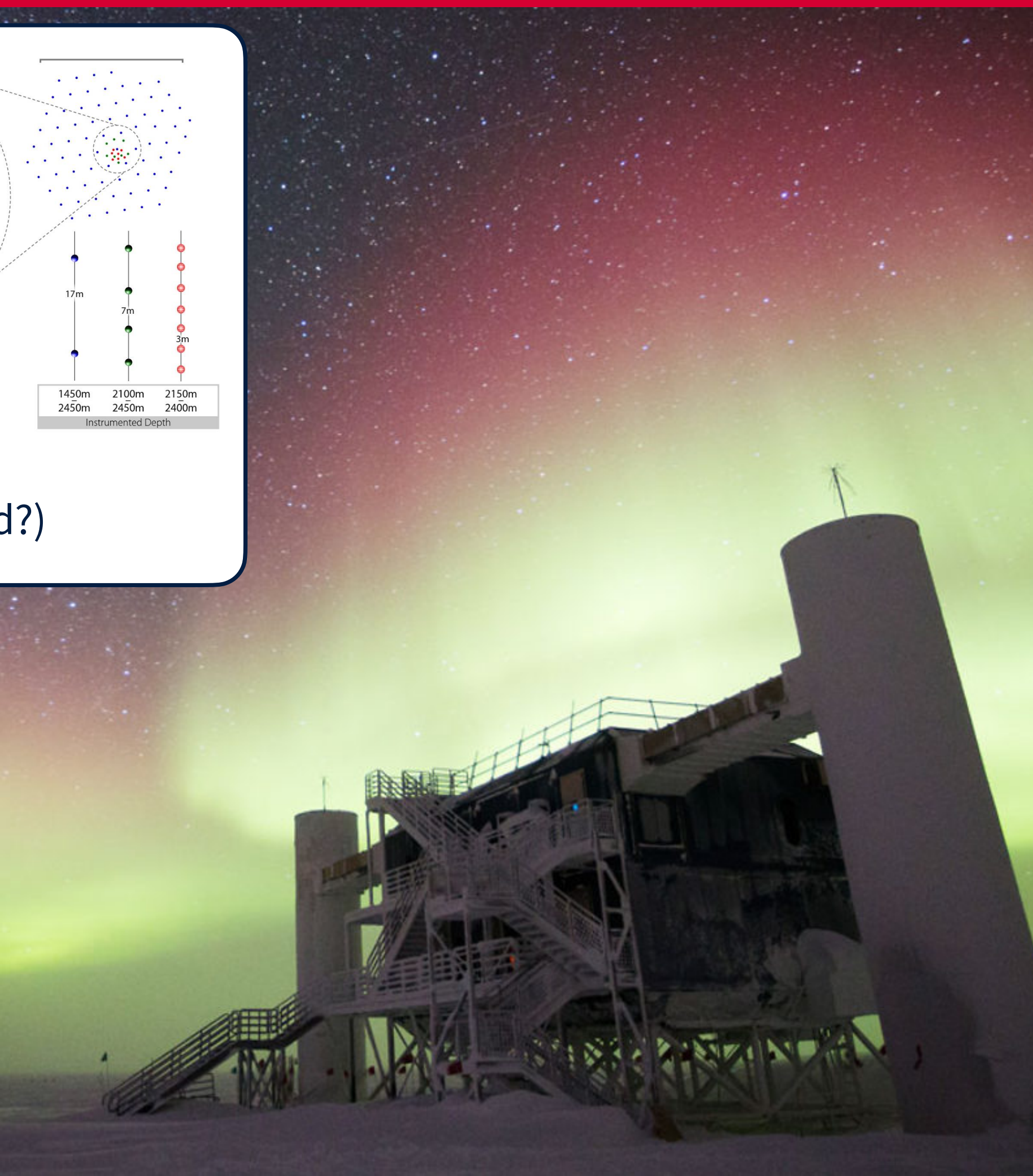
- IceCube Gen2 planned (but will it be funded?)



KING'S
College
LONDON

1

Physicist
IceCube-KM3NeT joint NMO fit working group
- neutrino cross-section convener



UK High-energy Neutrino Consortium

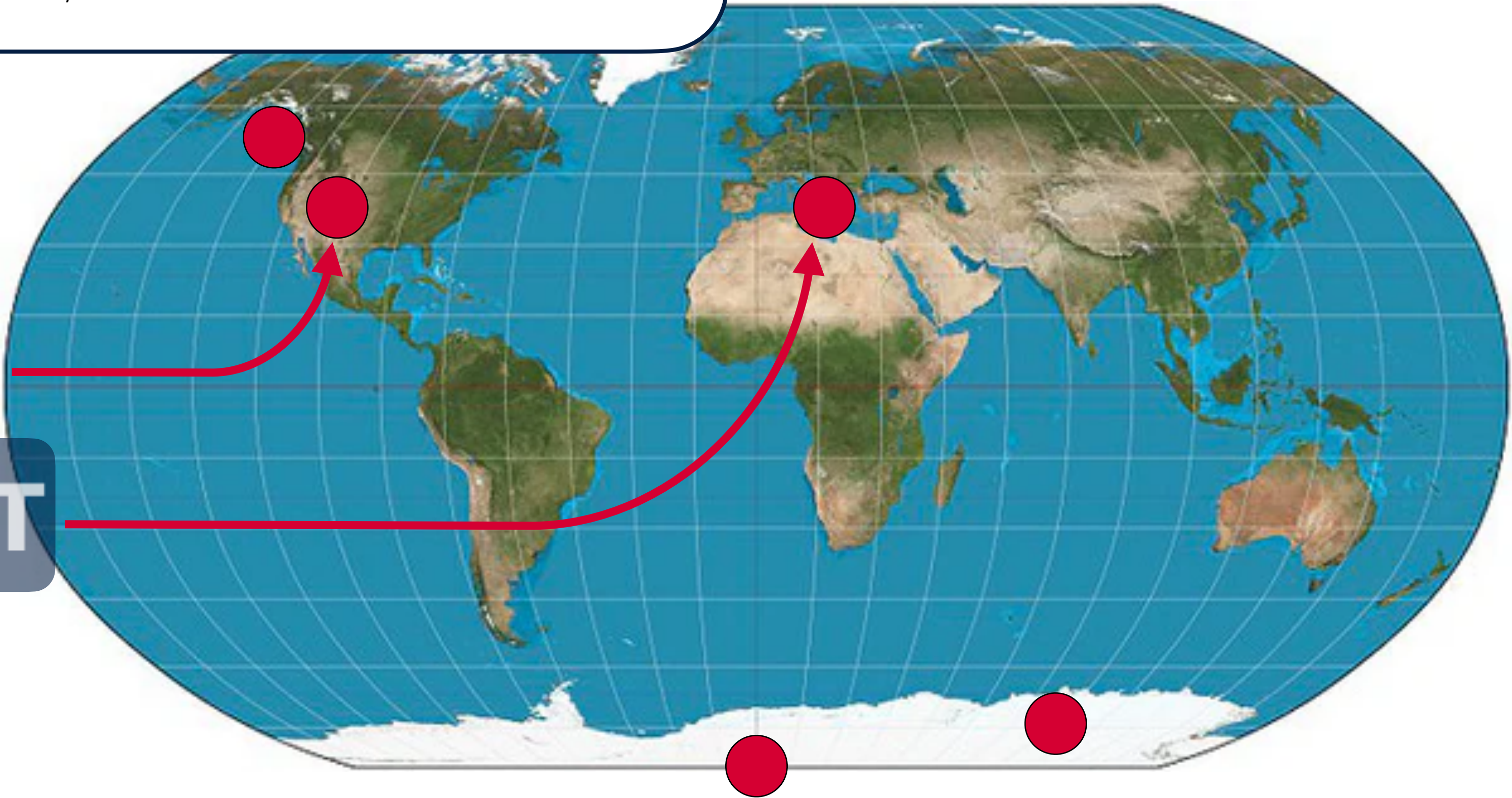


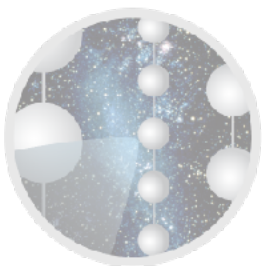
P-ONE
Pacific Ocean Neutrino Experiment

Preferred UK medium-term experiment

**Trinity**

**KM3NeT**



**ICECUBE**
NEUTRINO OBSERVATORY

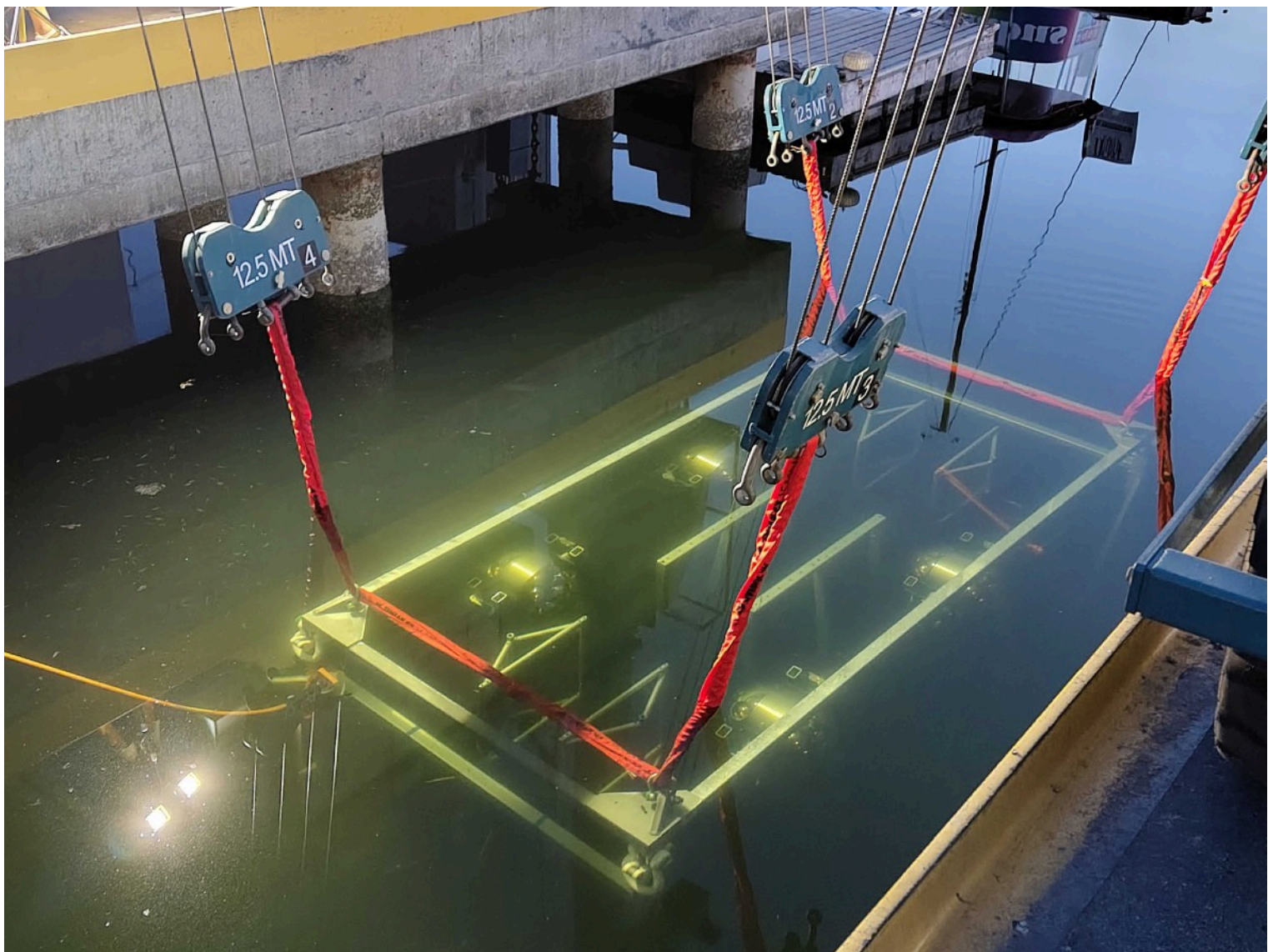
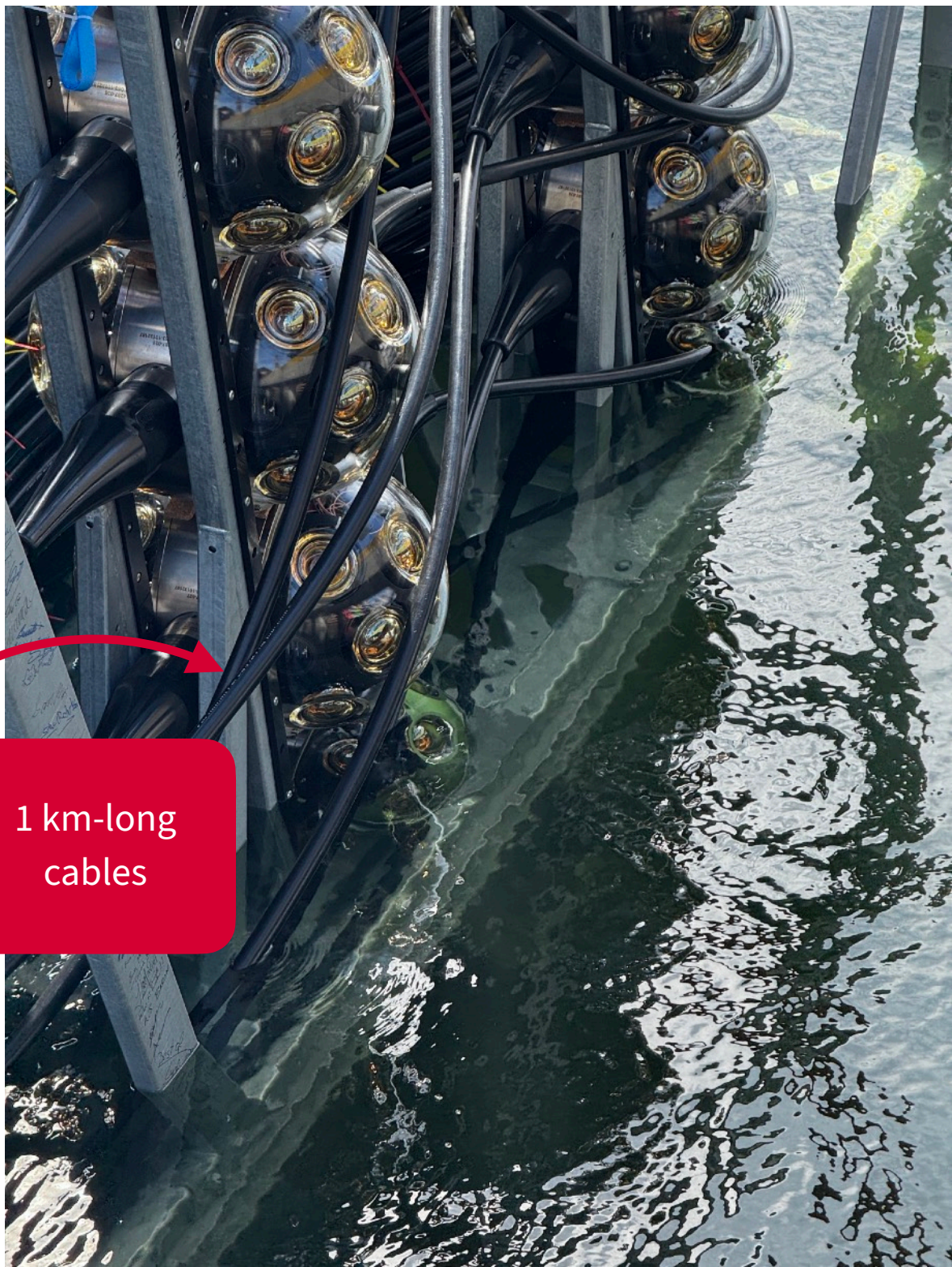
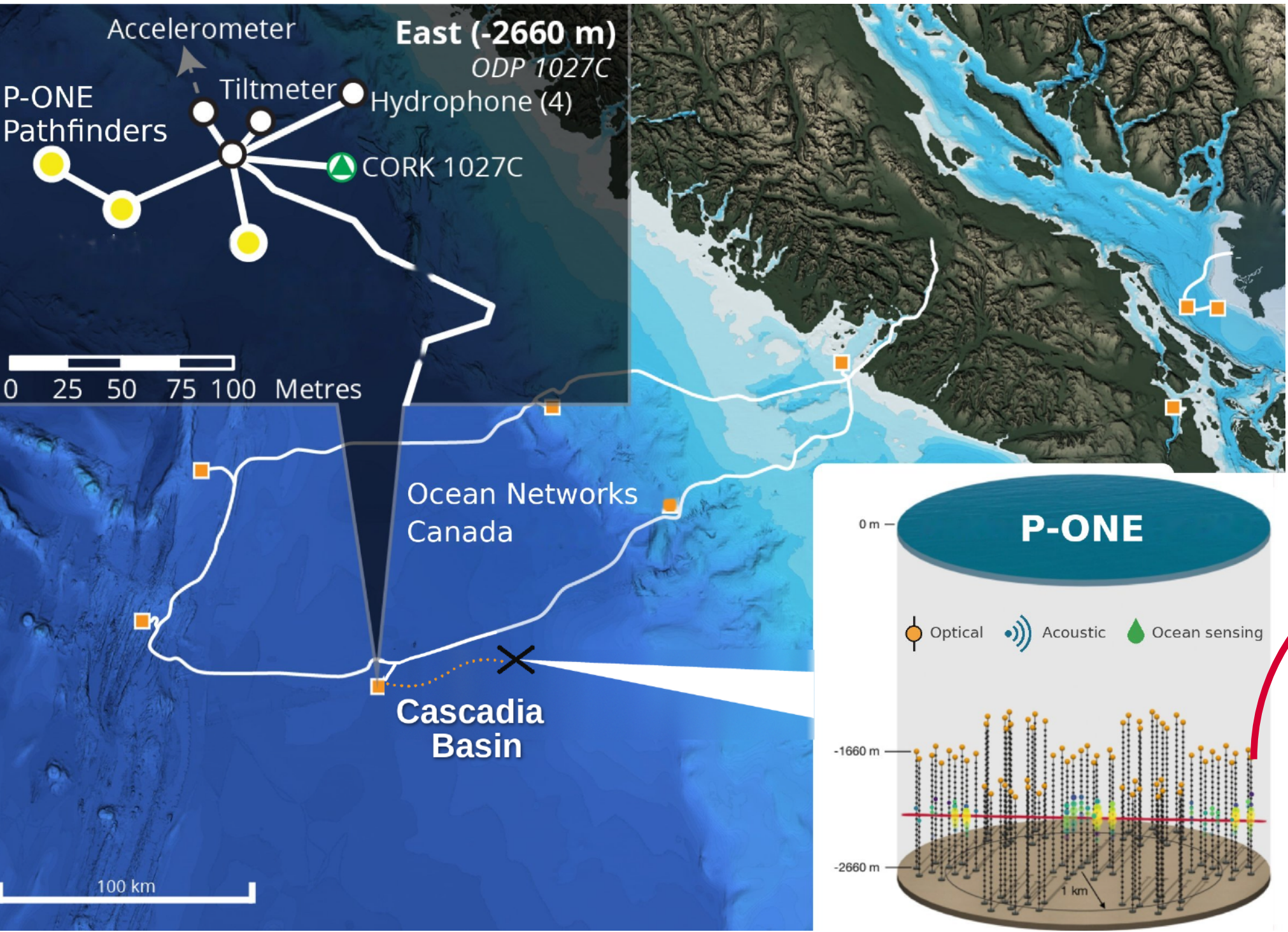
**PUEO**

P-ONE - first neutrino telescope in the Pacific

- Neutrino properties (8kpc oscillation experiment?)
- Neutrino astrophysics
- Marine biology - biologists in collaboration
- Acoustic sensors for UHE ν (and whales...)



- Pilot line to be deployed 2.6 km under the sea by end of August
- 1st cluster of lines (fully funded), including a submarine junction box for distributed logic, to be deployed in 2027-28.



P-ONE is the UK opportunity to lead one of the key neutrino and multimessenger infrastructures in the coming decades.



- First-line assembly & commissioning
- Particle- and astrophysics of ν from galactic centre
- Interplay with multi-messenger network

UK non-accelerator neutrino plan - but we need funding to support it!

Neutrino astronomy



Fully exploit existing experiments



... then converge on long-term project



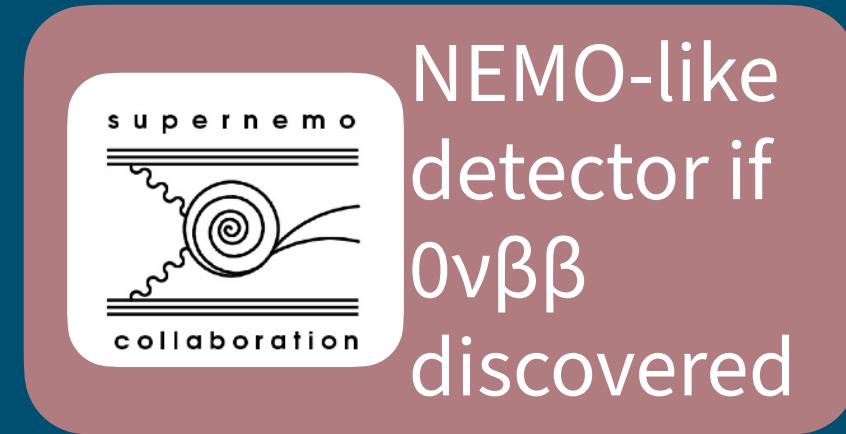
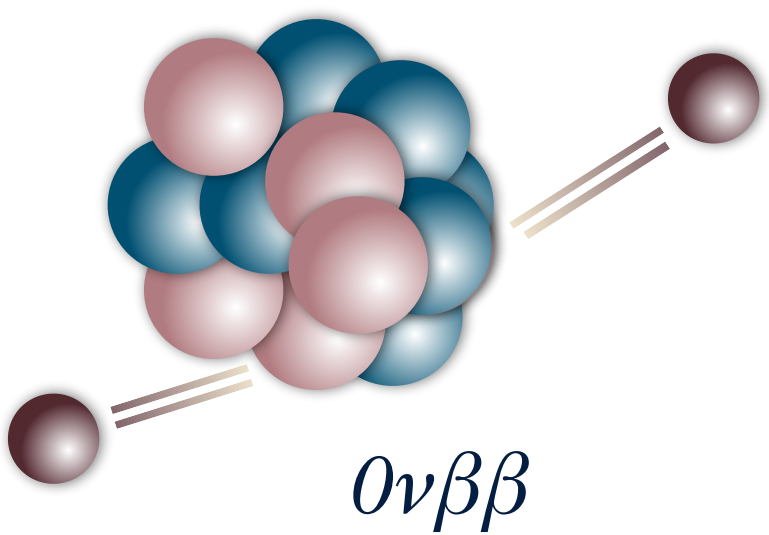
UK non-accelerator neutrino plan - but we need funding to support it!

Neutrino astronomy



Fully exploit existing experiments

... then converge on long-term project



Tellurium loading development

UK non-accelerator neutrino plan - but we need funding to support it!

Neutrino astronomy



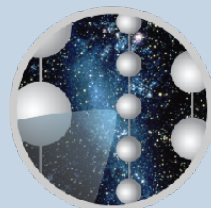
Fully exploit existing experiments

... then converge on long-term project



P-ONE

Pacific Ocean Neutrino Experiment

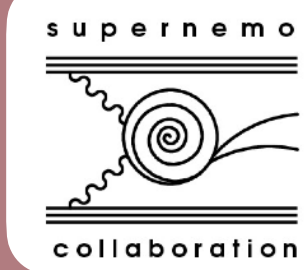


ICECUBE
NEUTRINO OBSERVATORY



LEGEND 200

LEGEND 1000



NEMO-like
detector if
 $0\nu\beta\beta$
discovered

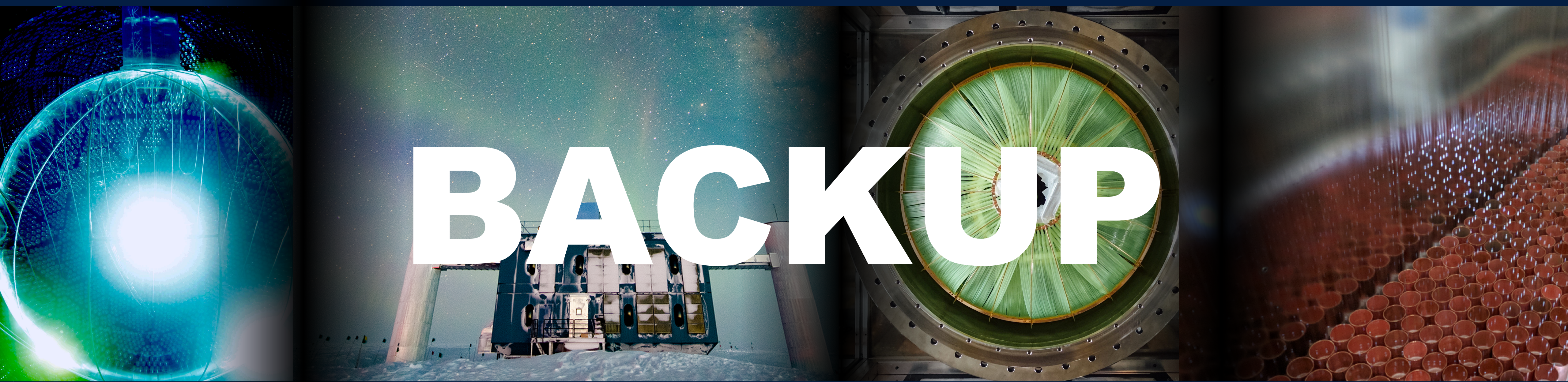
SNO+

Tellurium loading development



...and more



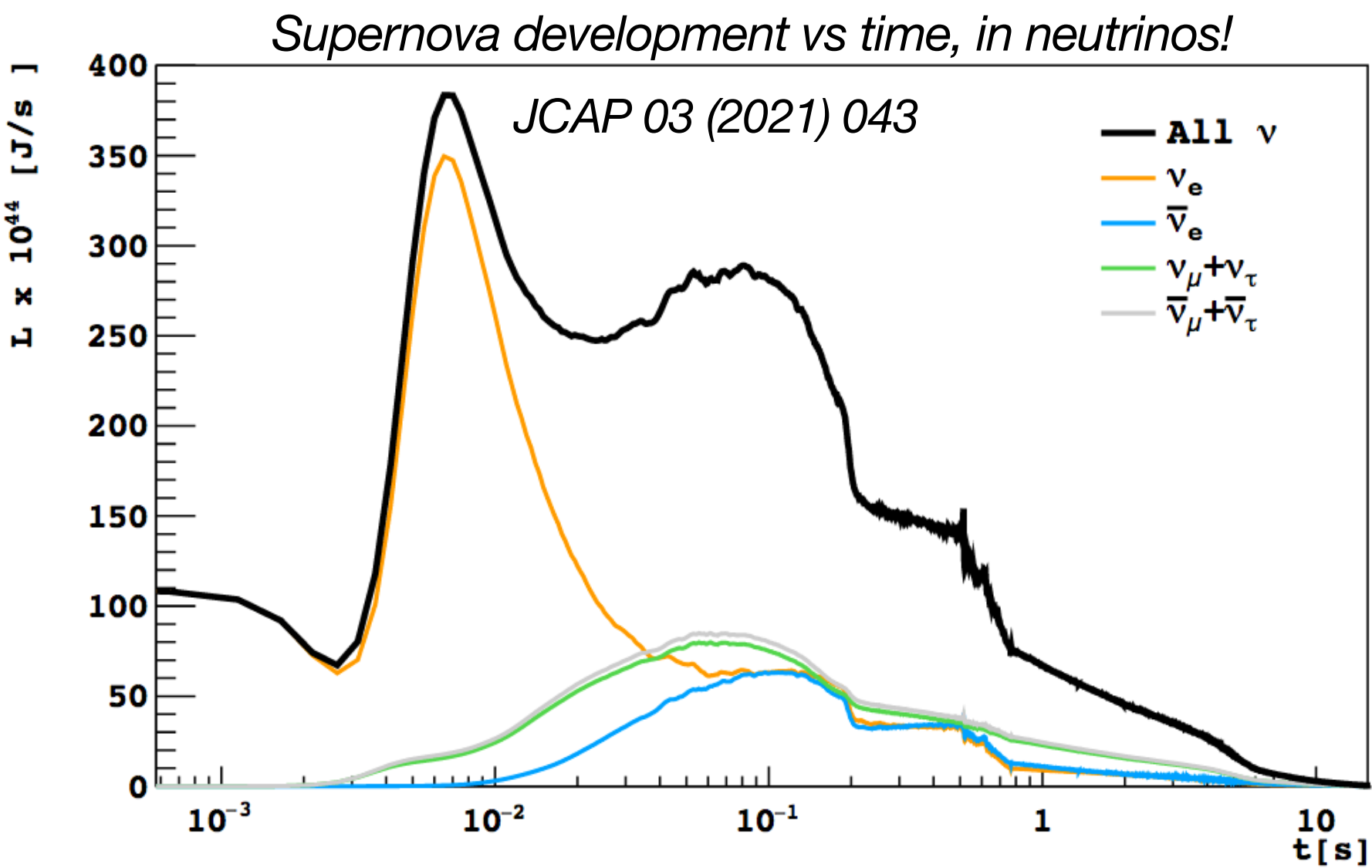
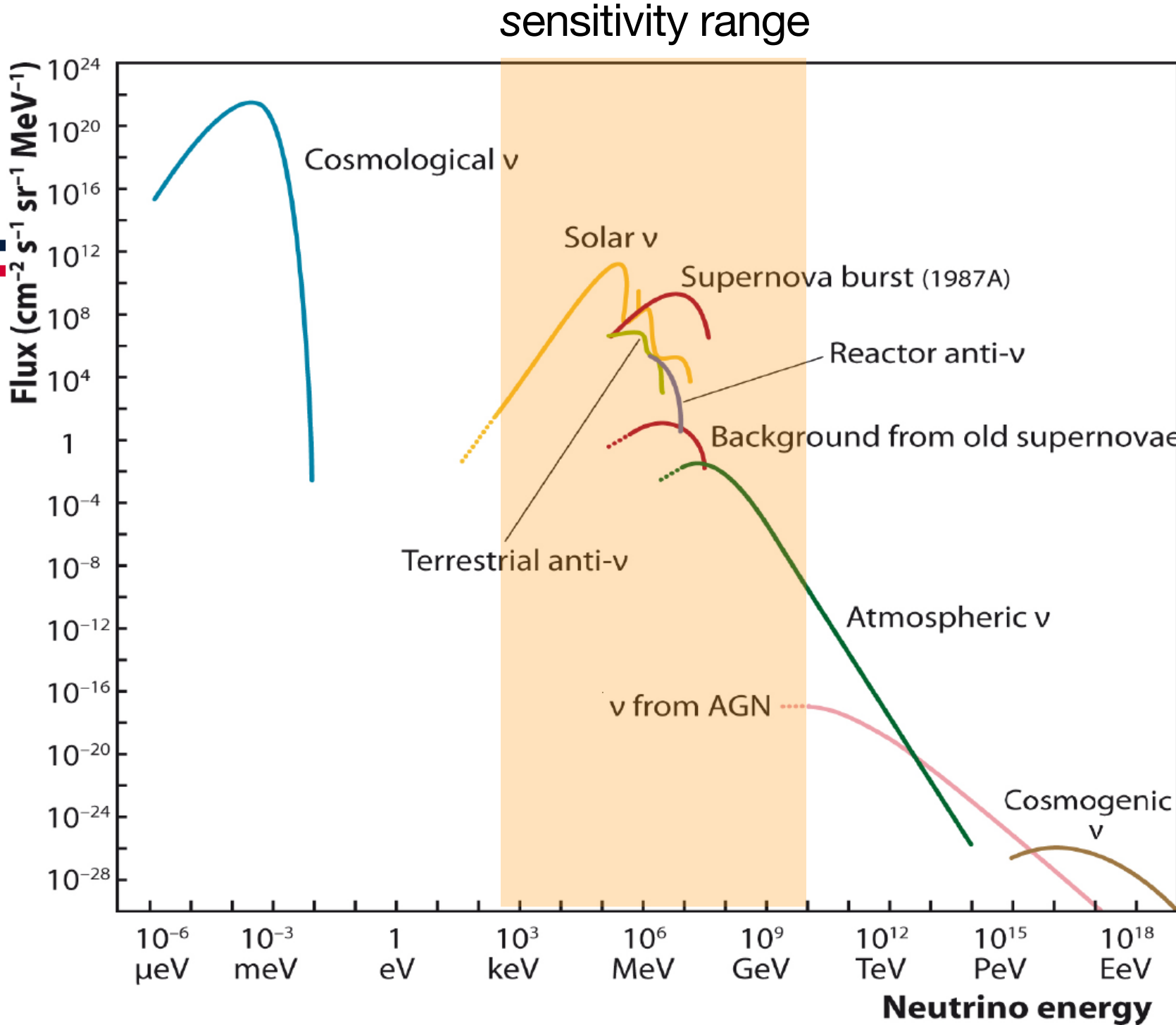


Neutrino Physics in DarkSide-20k

With >700 t of argon, DarkSide-20k will be a dark matter **and neutrino observatory**

Neutrino physics in DarkSide-20k

- Supernova neutrino detection in neutral current (via CEvNS In TPC volume, 100s of events for galactic supernova at 10 kPc) *and* charged current channels (rate due to 700t veto volume!) [JCAP 03 (2021) 043]
- Exploration of sensitivity to the neutrino mass hierarchy with supernova neutrinos, through comparing NC to CC interactions
- Recent first measurement of neutrino absorption on argon! [arXiv: 2605.12769] — a key supernova neutrino channel for DUNE
- >10,000 solar neutrino scattering interactions, giving interesting sensitivity to non-standard neutrino interaction models (analysis developed for SOLAIRE) and potential to measure CNO vs Be-7
- Sensitivity to scattering of keV-mass sterile neutrinos with electrons [published first search for warm sterile neutrino dark matter: Phys.Rev.Lett. 130 (2023) 10, 1]





Non-Accelerator physics with Super-Kamiokande and Hyper-Kamiokande

Rich, diverse non-accelerator physics programmes at both experiments.



Super-Kamiokande

Gadolinium loading improves neutron tagging.

1st loading (2020): 0.011% Gd in water by mass.

2nd loading (2022): 0.033% Gd in water by mass.

Physics highlights with major UK involvement:

Search for Diffuse Supernova Neutrino Background with 956.2 Days of Super-Kamiokande Gadolinium Dataset.

K. Abe et al. 2026 ApJ **1005** 101

Comparison of reactor antineutrino and solar neutrino measurements using a single detector.

1.94 σ agreement between SK I-IV solar neutrino and SK VI-VII reactor neutrino data.

Publication in preparation.

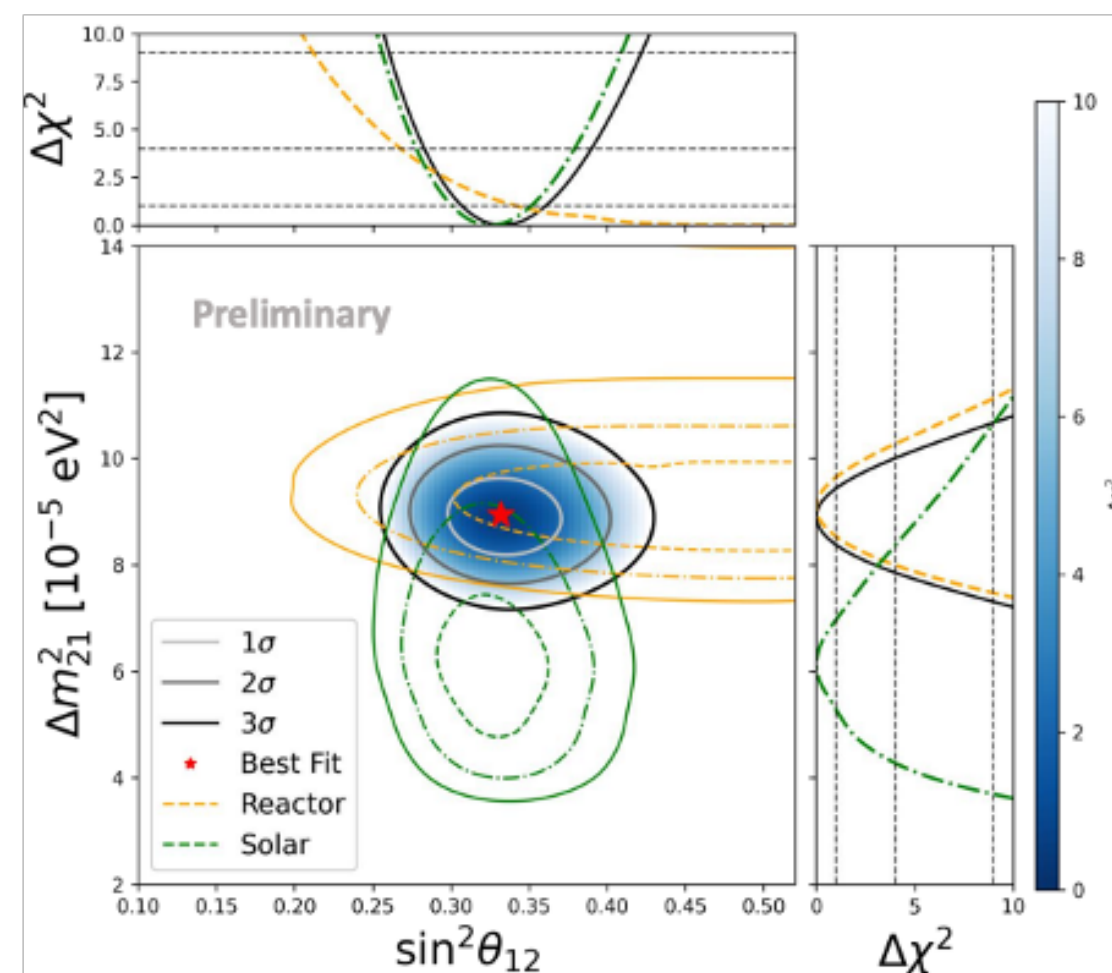


Figure from Super-K presentation at Neutrino 2026: [LINK](#)

Hyper-Kamiokande

Significant UK involvement with non-accelerator physics programme.

Atmospheric neutrinos

Sensitivity to mass ordering and octant.

Joint analysis of atmospheric and accelerator neutrinos can break degeneracies.

Solar neutrinos

> 3 σ sensitivity to MSW upturn in 10 years.

Supernova

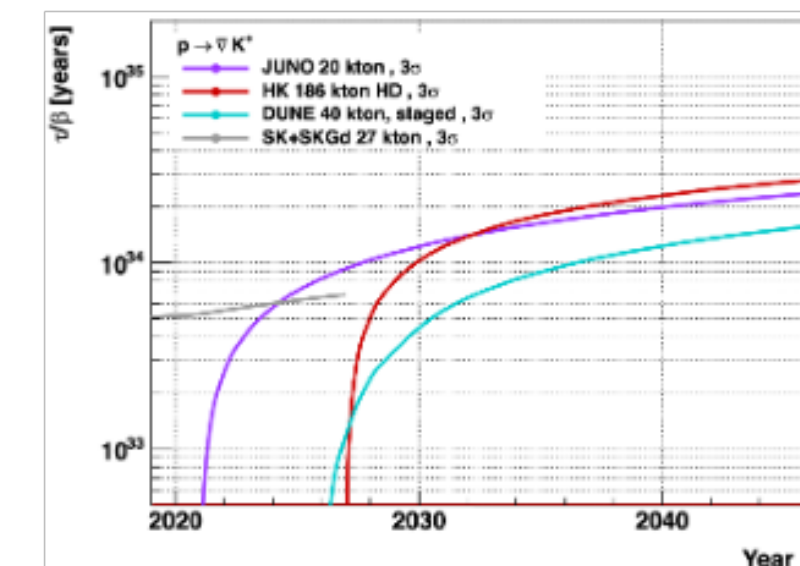
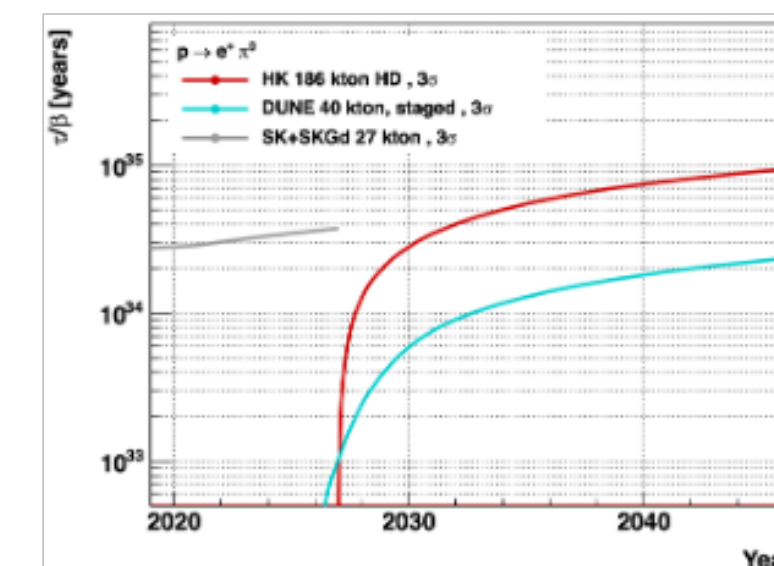
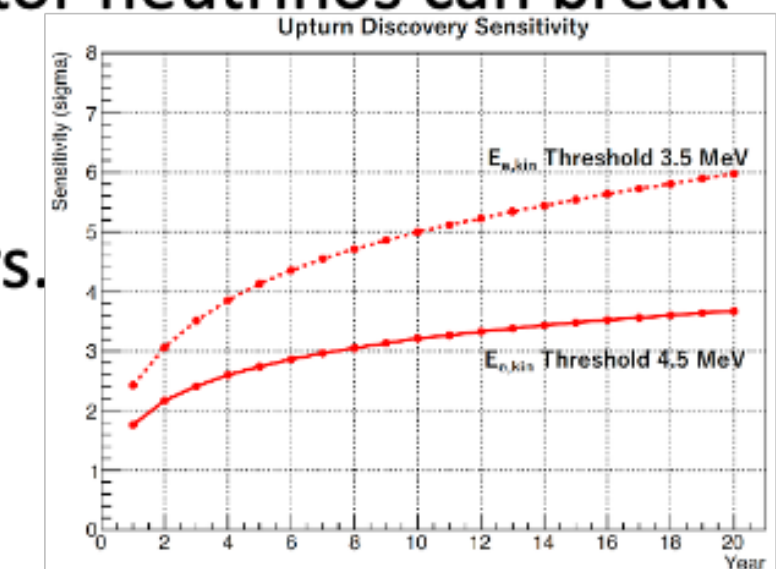
~70,000 events expected at 10 kpc.

Diffuse Supernova Neutrino Background.

Supernova burst monitor to provide alert for multi-messenger observation. Pre-supernova sensitivity studies are ongoing.

Proton decay

3 σ discovery potential for $p \rightarrow e^+ \pi^0$ and $p \rightarrow \bar{\nu} K^+$.



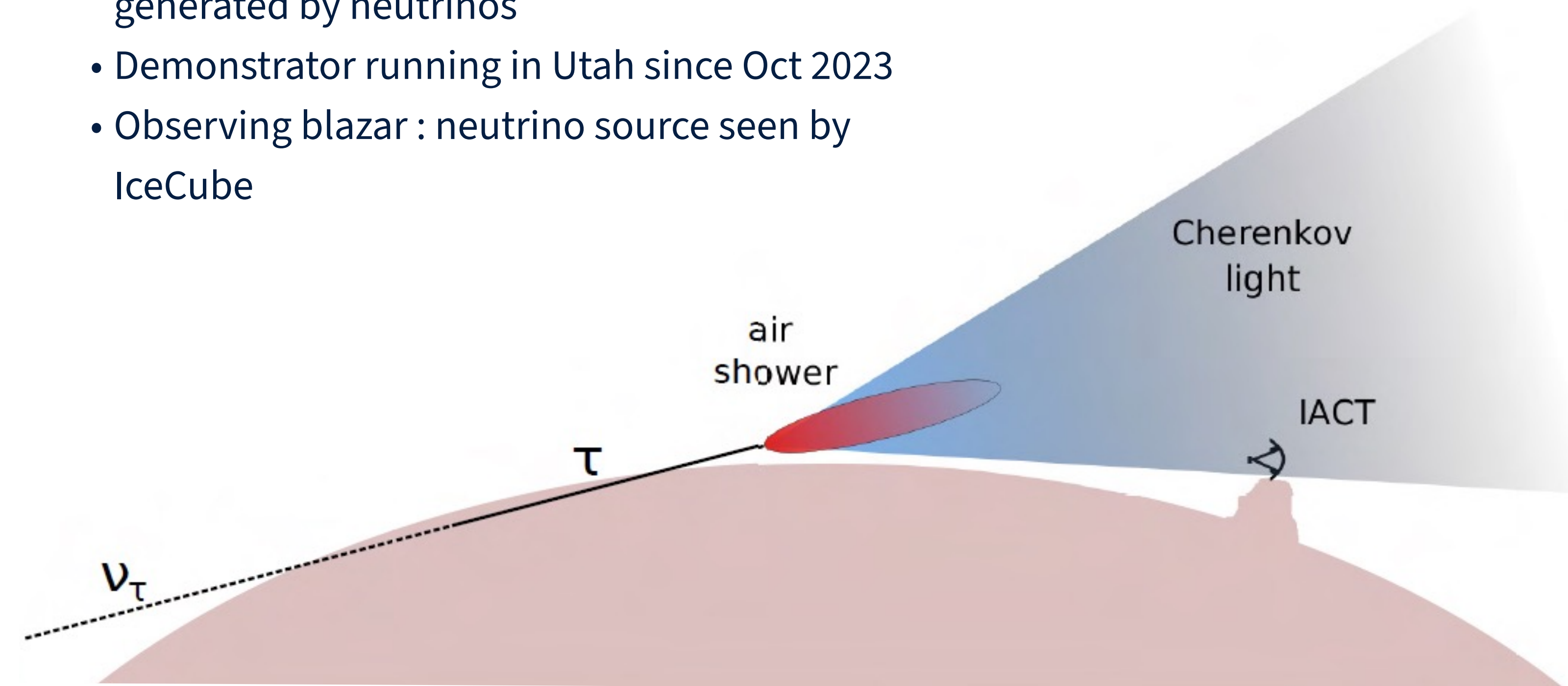
Figures from Hyper-Kamiokande collaboration

Trinity - the PeV neutrino observatory

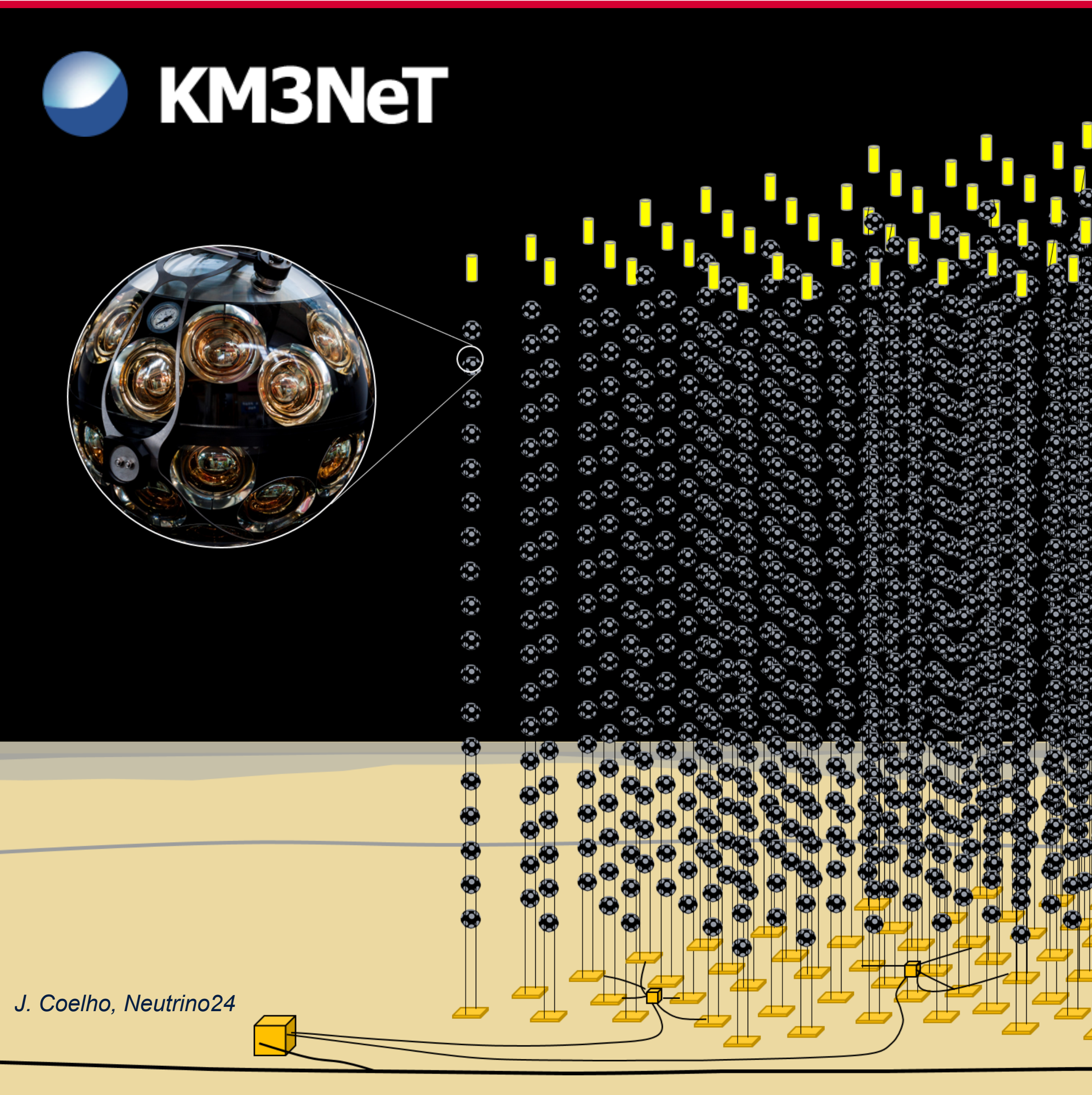


(1 astronomer)

- Uses CTA-like technology to detect air showers generated by neutrinos
- Demonstrator running in Utah since Oct 2023
- Observing blazar : neutrino source seen by IceCube

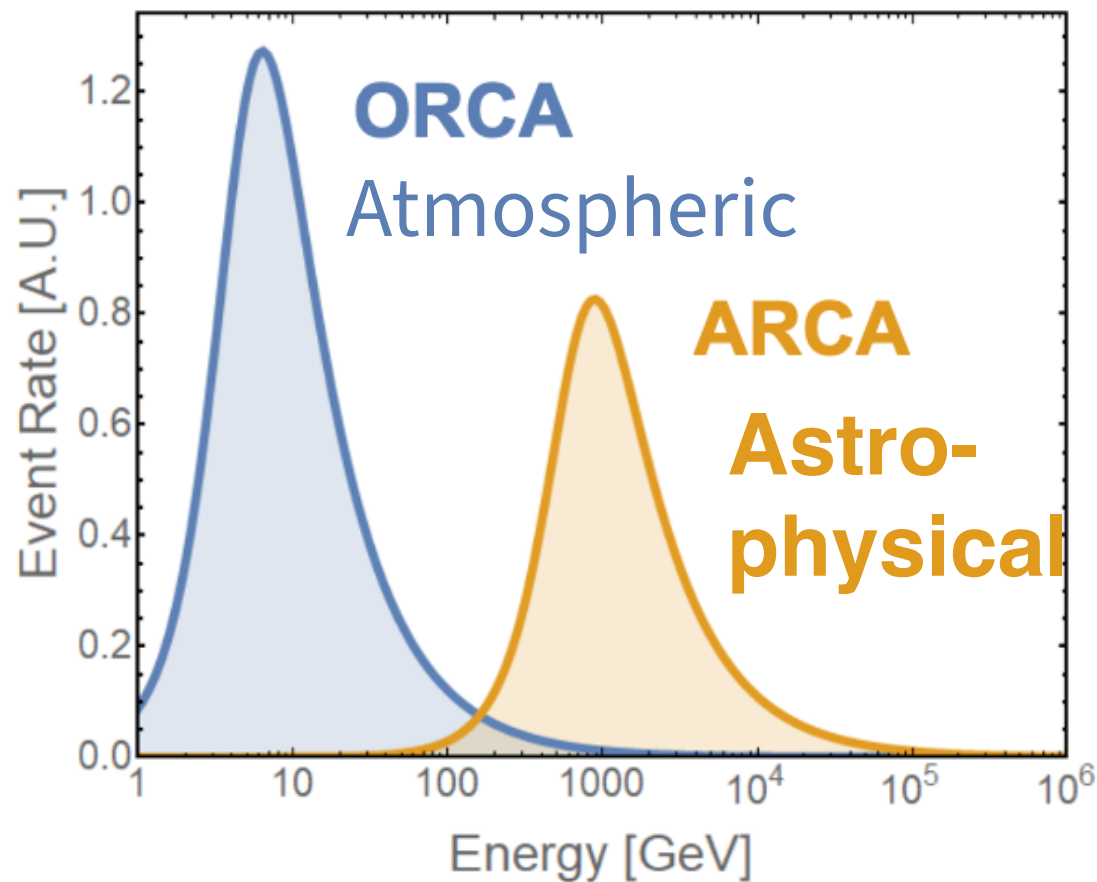


KM3NeT neutrino telescope in the Mediterranean

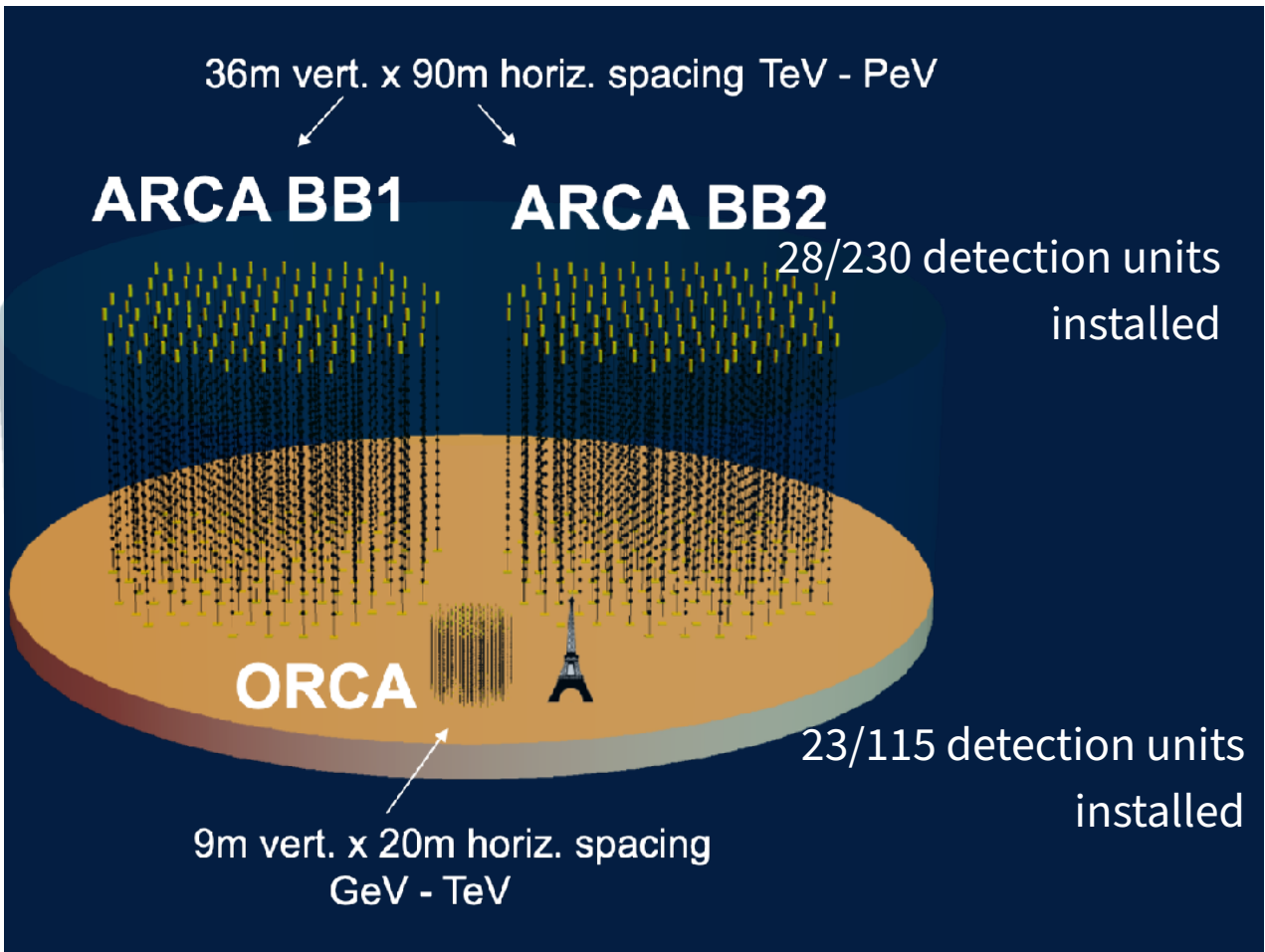
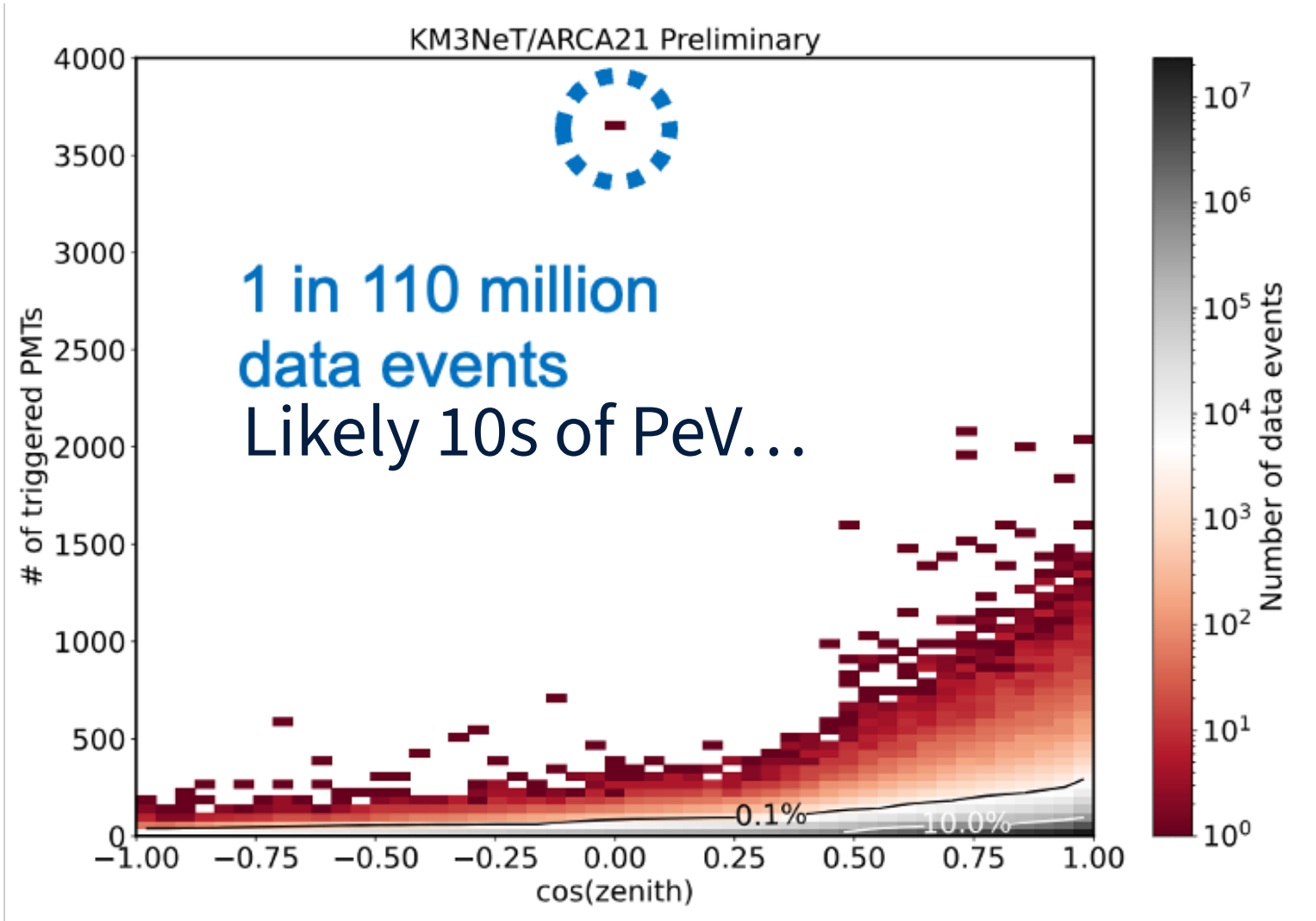


UNIVERSITY
of **HULL**

(astronomers - computing & supernova detection)



(and whatever THIS is...)



KM3NeT would be keen for more UK involvement