

# Neutrinoless double-beta decay and non-accelerator neutrinos

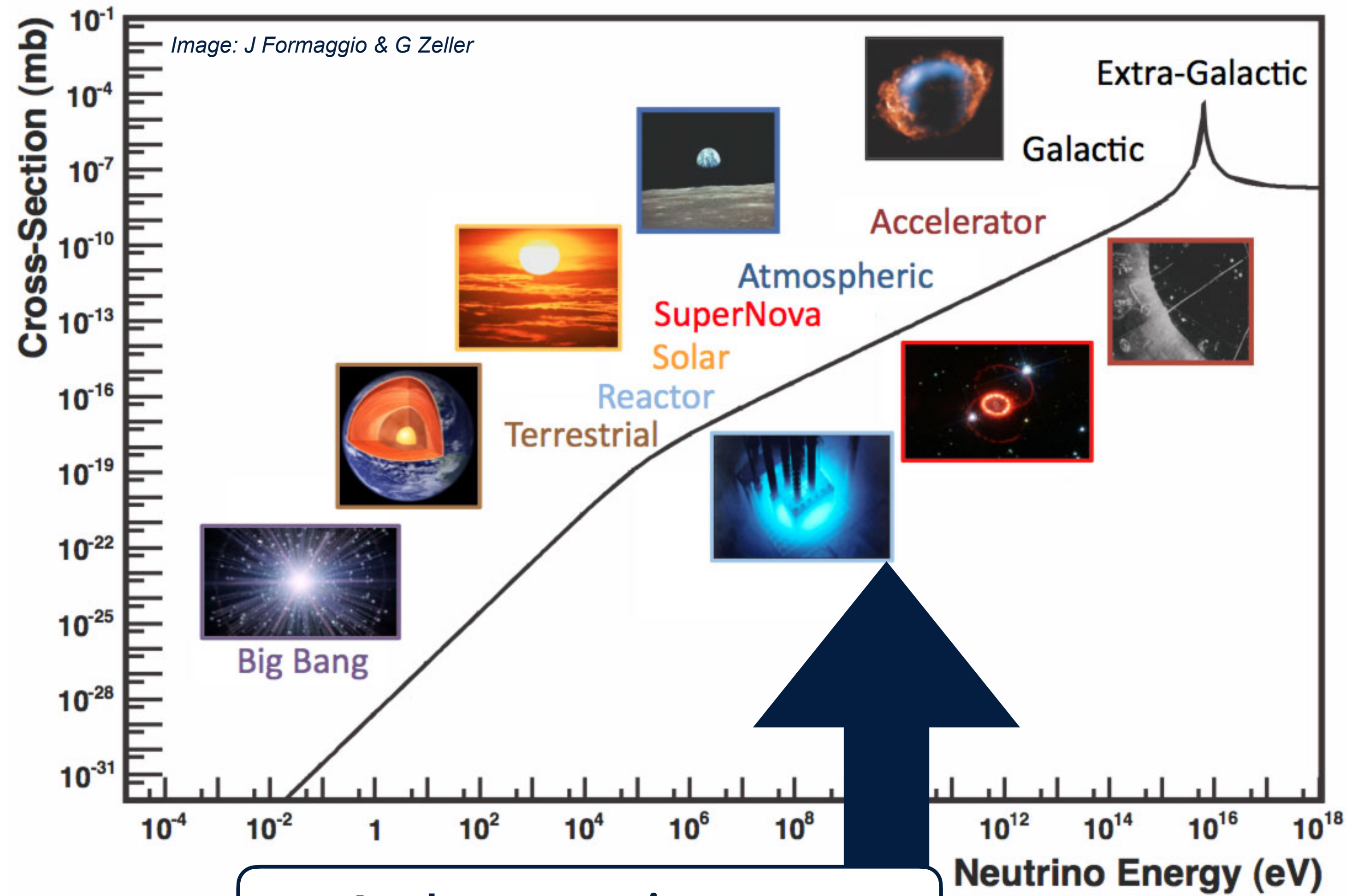
Dr Cheryl Patrick

STFC Ernest Rutherford Fellow, University of Edinburgh



THE UNIVERSITY  
of EDINBURGH

# accelerator neutrinos



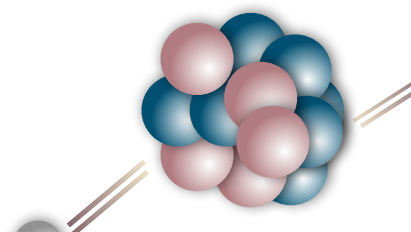
**Accelerator neutrinos**

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

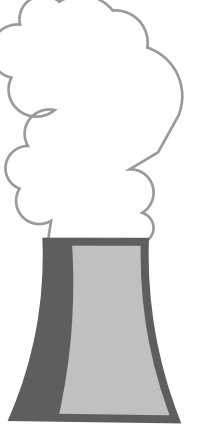
HYPER-K

# Non-accelerator neutrinos

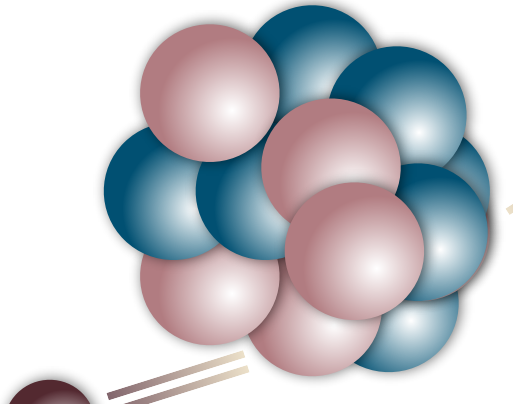
**Nuclear processes**



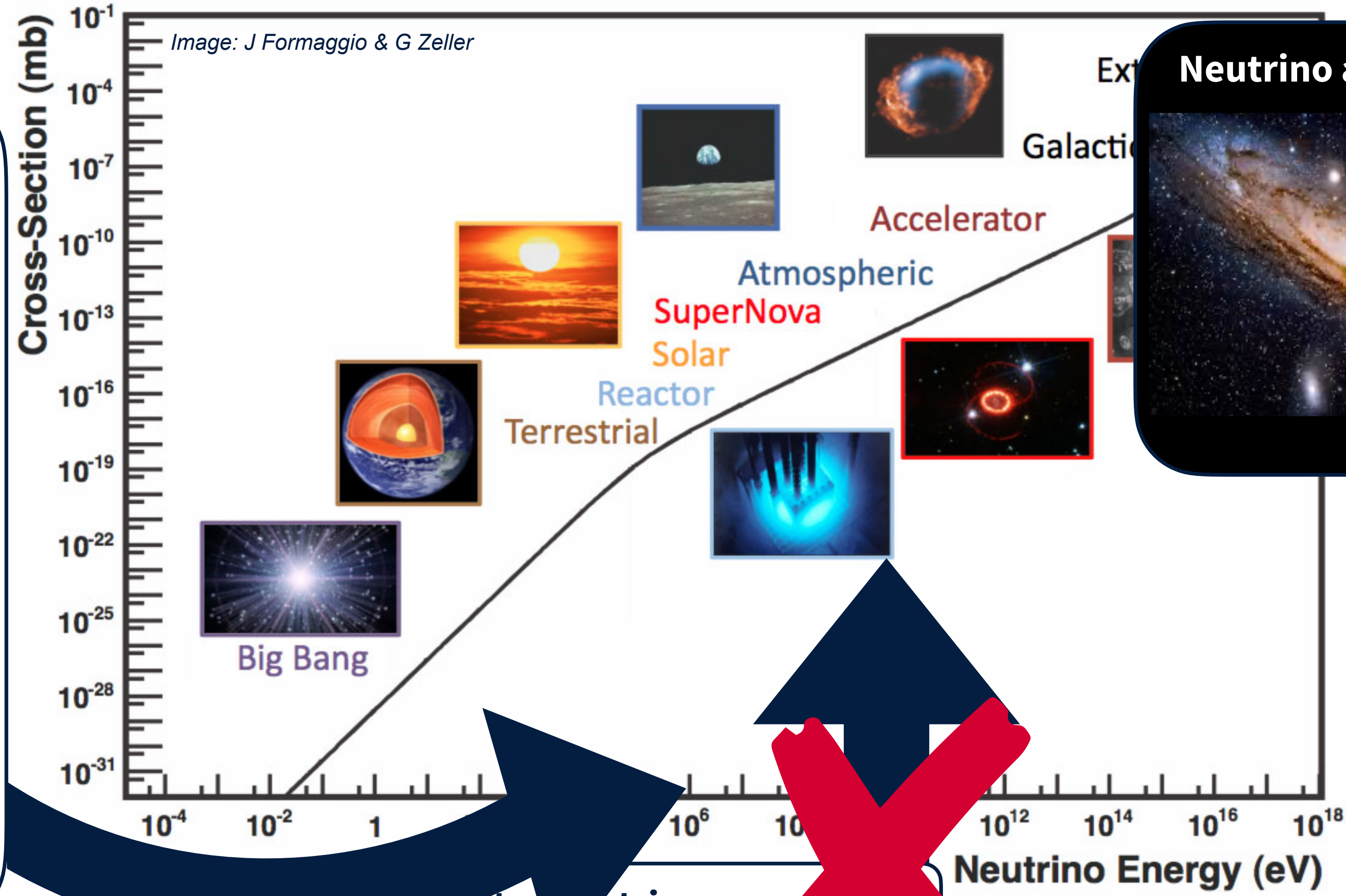
Beta decay (QTNM)



Reactor neutrinos



(Neutrinoless) double-beta decay



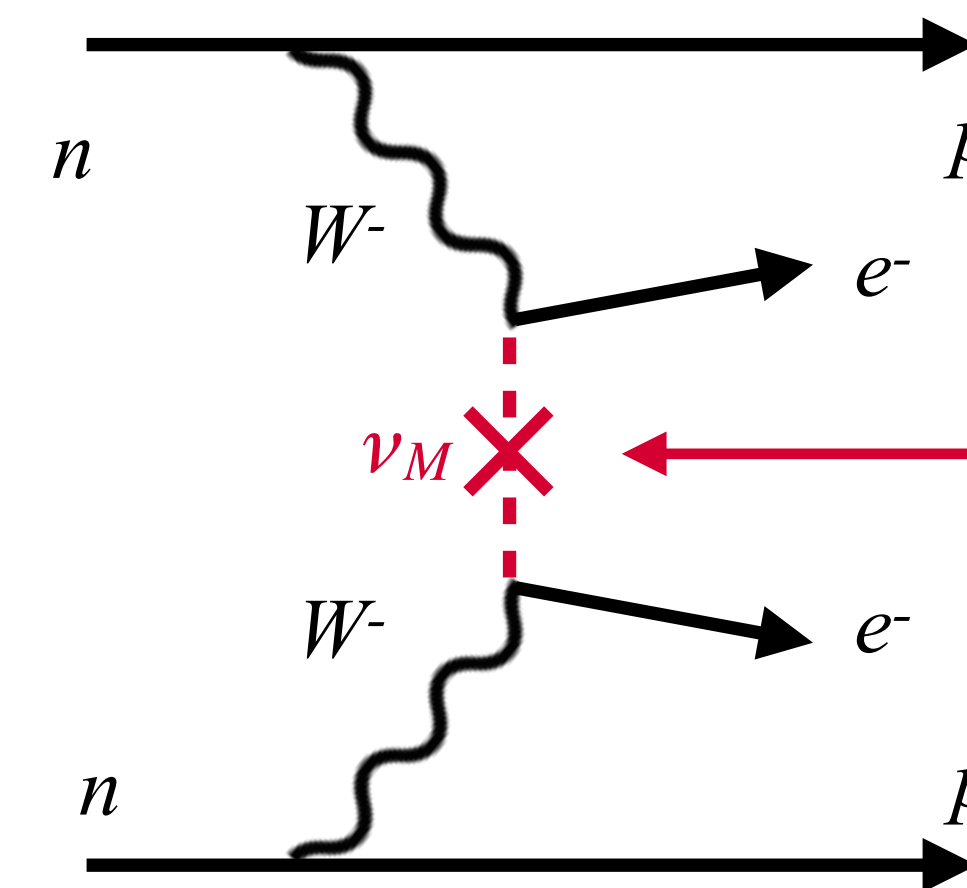
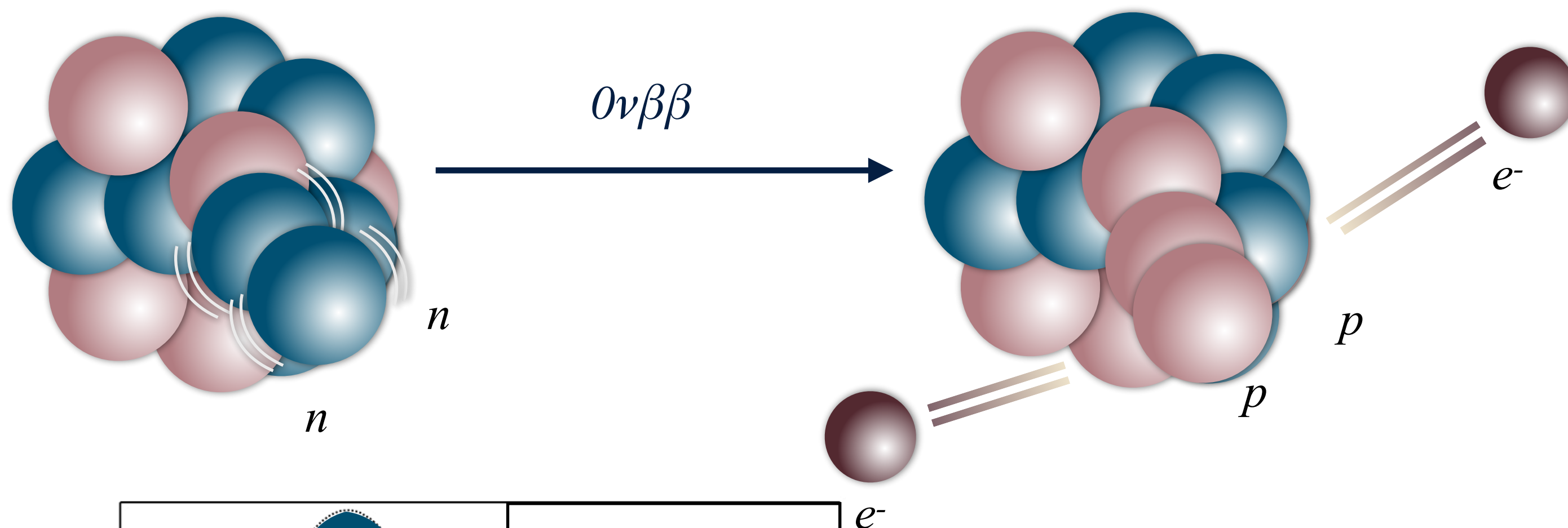
Accelerator neutrinos



**DUNE** DEEP UNDERGROUND NEUTRINO EXPERIMENT



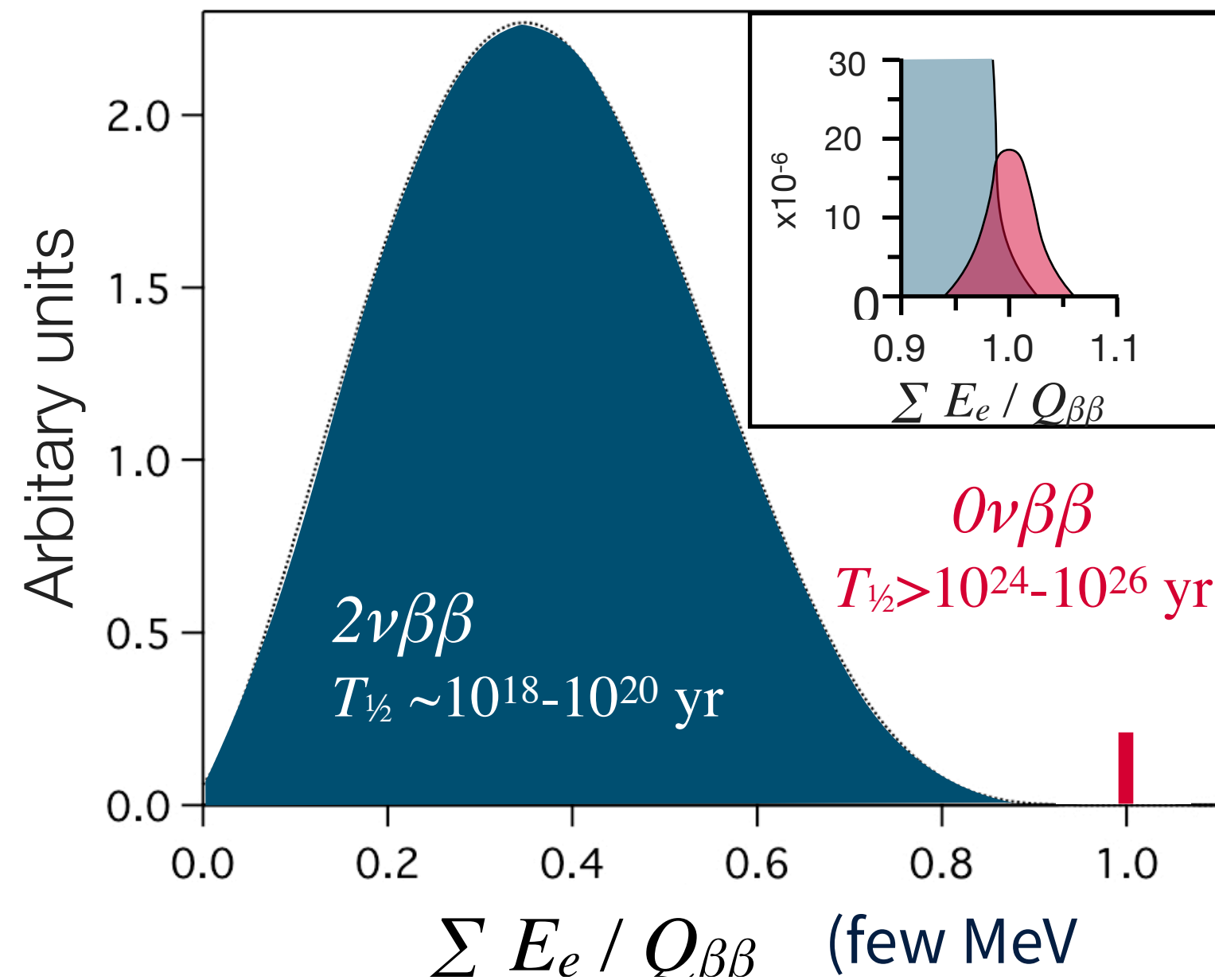
# Neutrinoless double-beta decay ( $0\nu\beta\beta$ )



Several possible mechanisms, all need Majorana neutrino

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

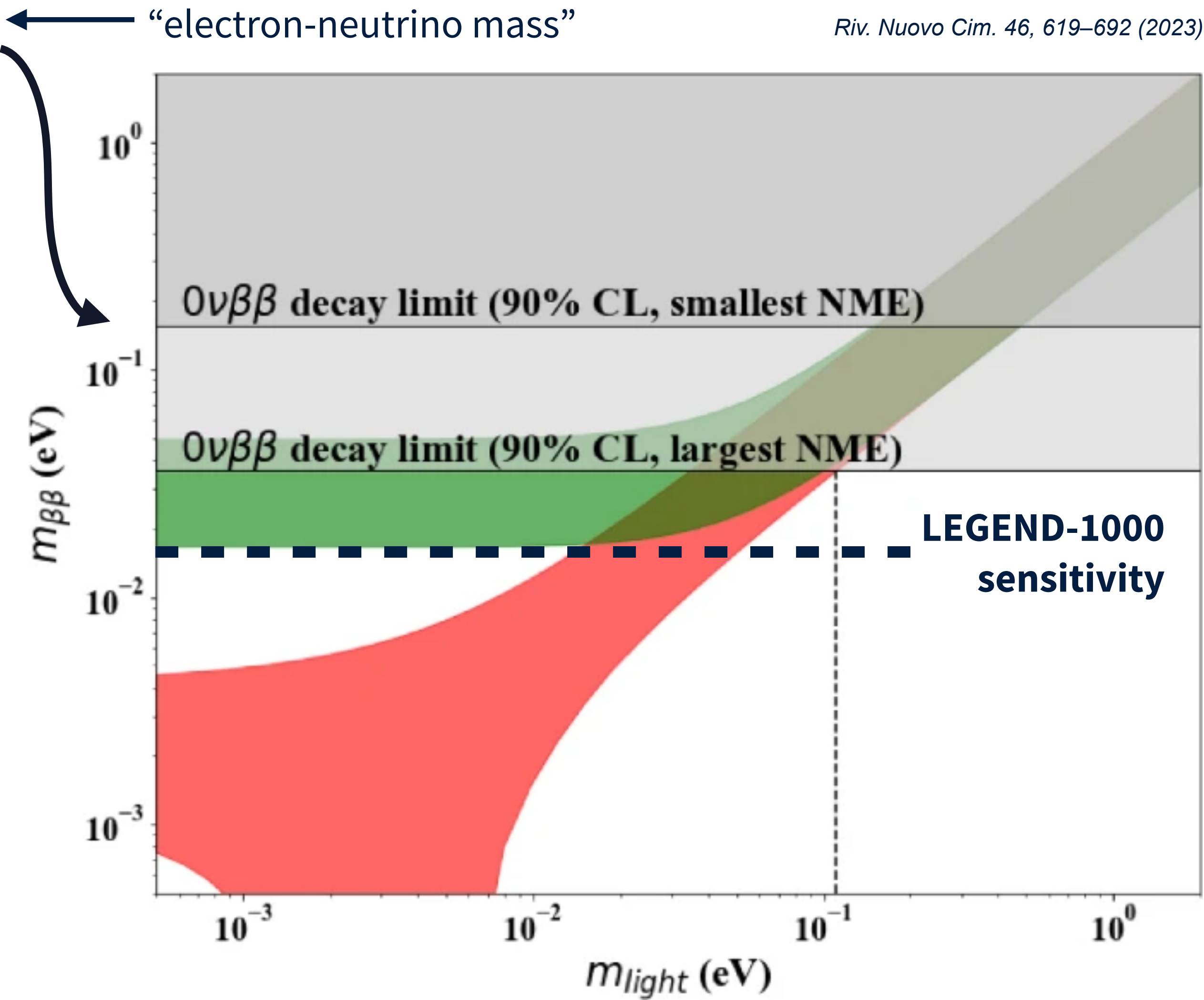
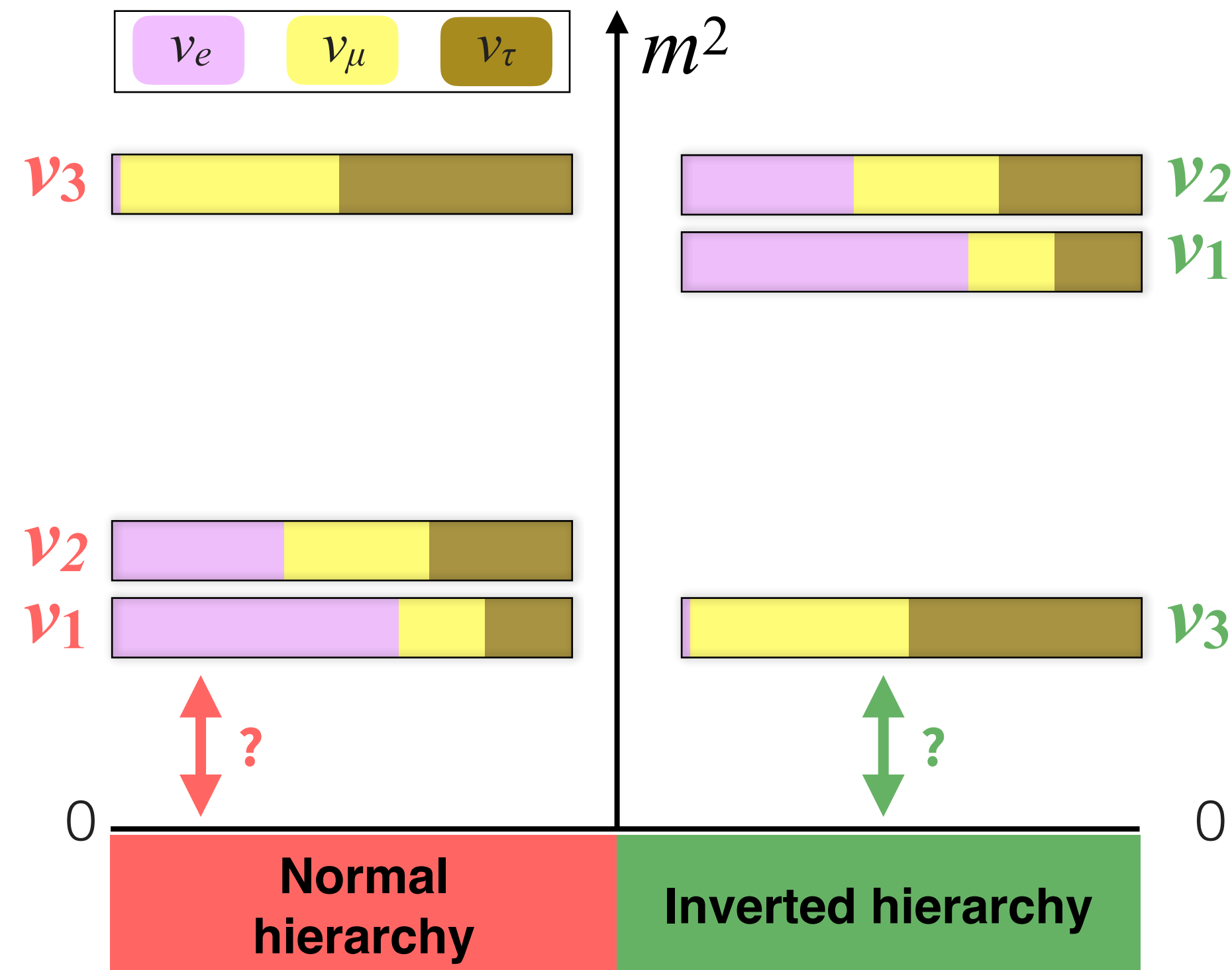
- be the first process observed to create matter without antimatter
- prove that neutrinos are Majorana fermions
- tell us about absolute neutrino mass



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

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

“electron-neutrino mass”



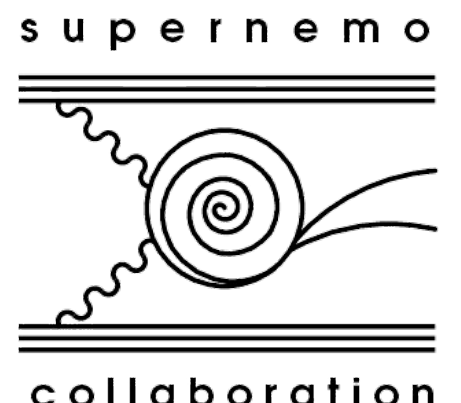
# The core UK strategy



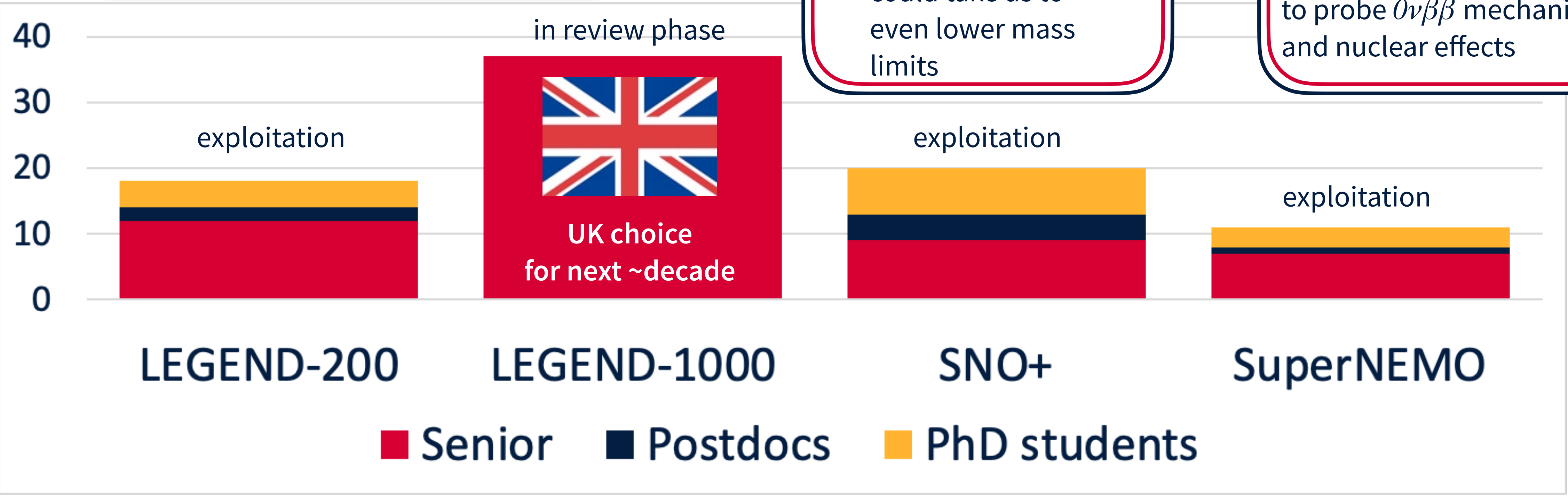

**LEGEND: a discovery machine** to explore the full inverted hierarchy regime



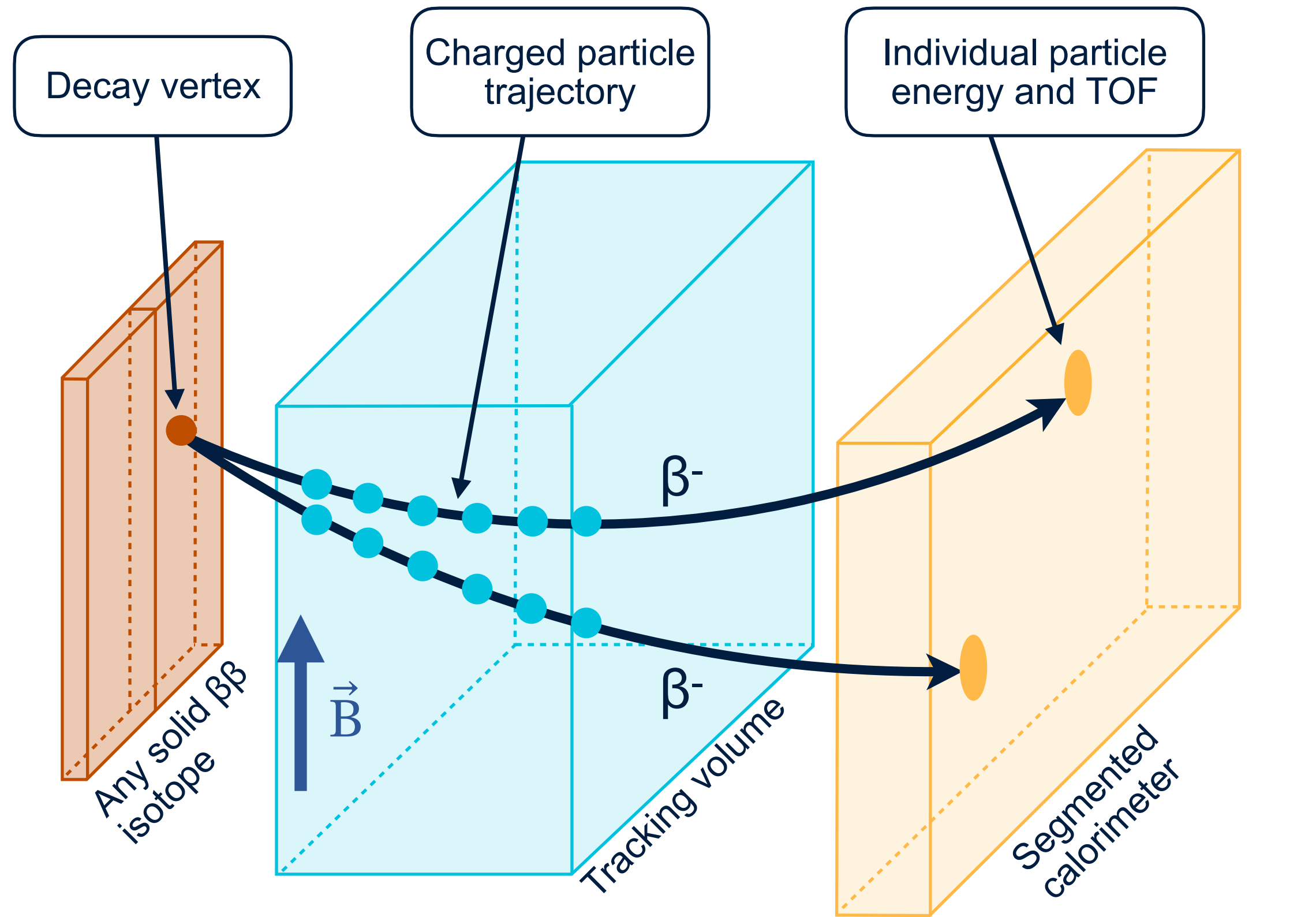

**SNO+**: a scalable technology that could take us to even lower mass limits

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



# SuperNEMO Demonstrator at LSM, France



6.1kg  $^{82}\text{Se}$

2034 Geiger cells with  
He, Ar, ethanol mix

712 optical modules

## Proof of concept for future tracking detectors:

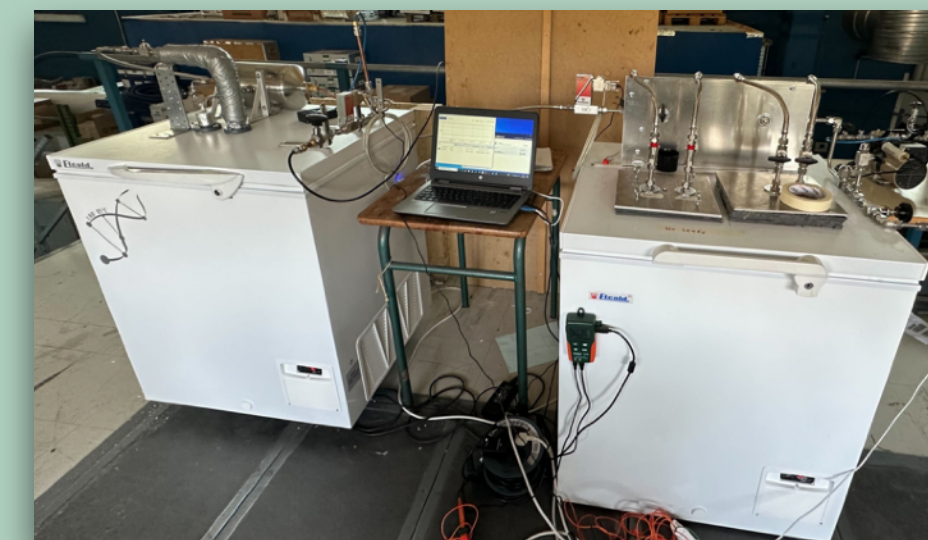
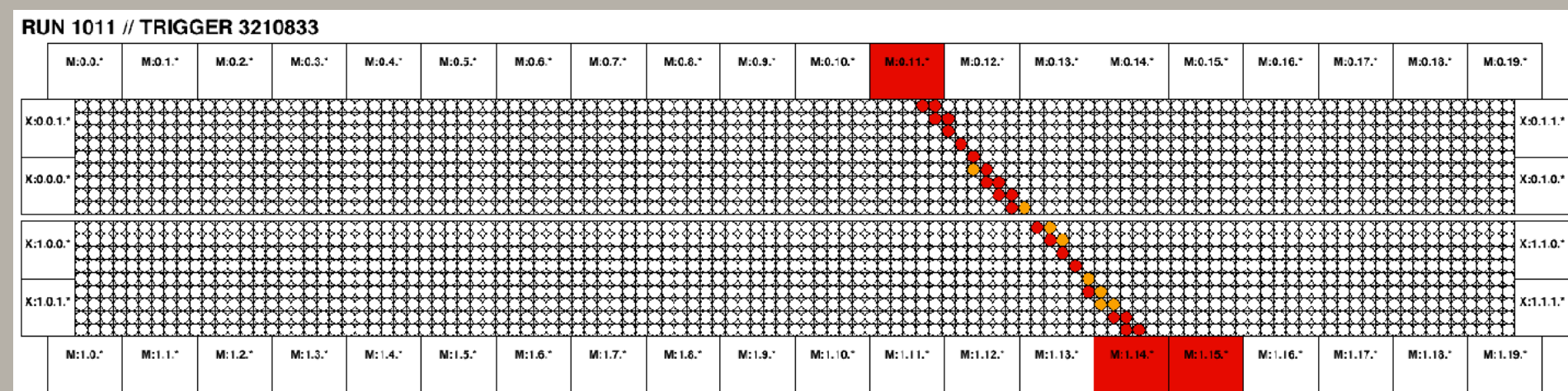
- (Nearly) **isotope-agnostic**
- Full topological reconstruction and particle ID
- Unique  $2\nu\beta\beta$  measurements:
  - **nuclear effects** ( $g_A$  constraint, SSD vs HSD)
  - **exotic decays & new physics**
- Could **probe  $0\nu\beta\beta$  mechanism** if discovered

## UK responsibilities

- Tracking detector
- Neutron shielding,
- Helium recycling
- Software and analysis
- **3 spokespeople**

# SuperNEMO status

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



Helium recycling system being installed



August-October 2024

2023-Feb 2024

March-August 2024

Sep-Oct 2024

November 2024 - 2027



Gamma shielding (iron) fully installed

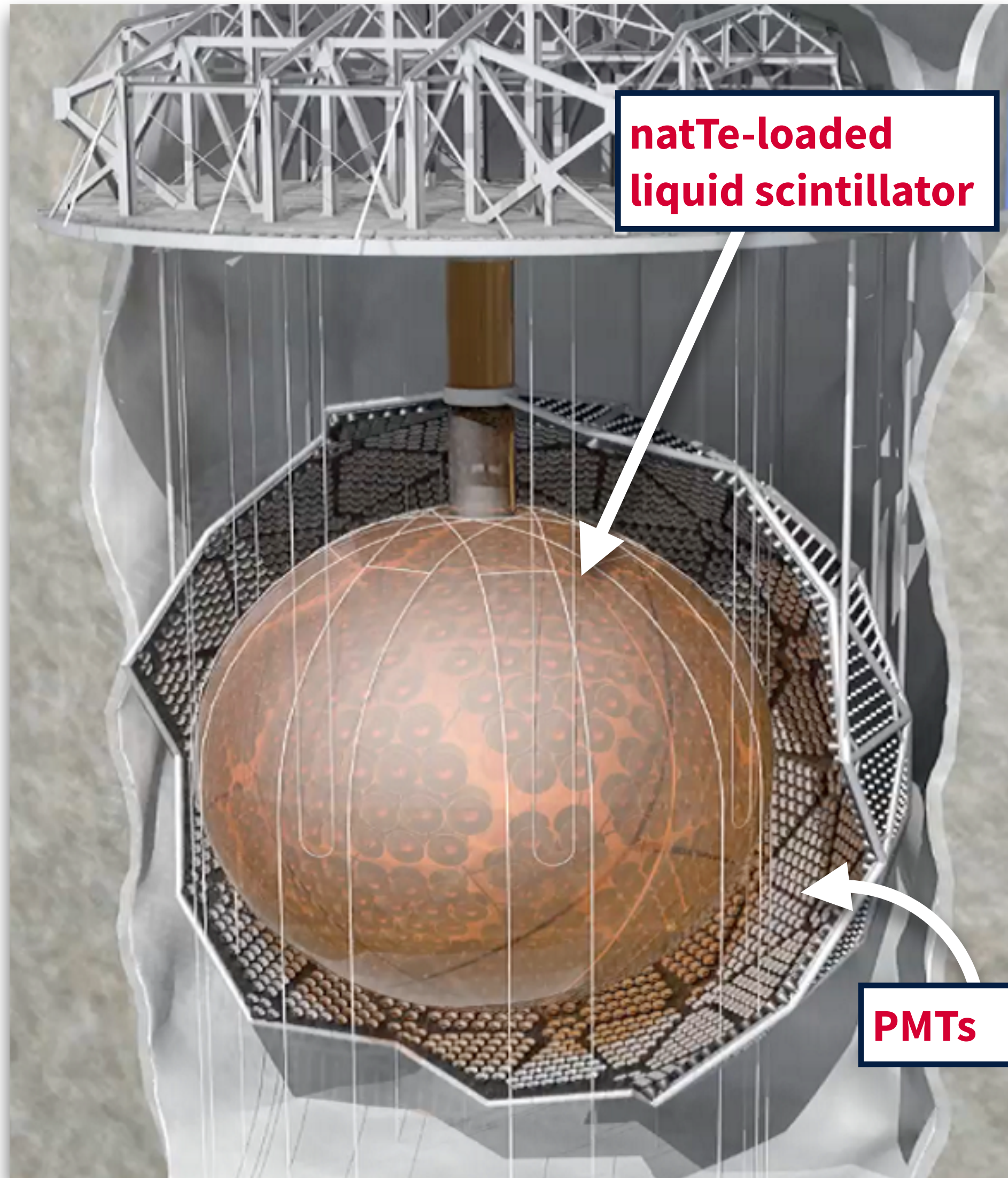
Neutron shielding (water / polyethylene) installation in progress



**$\beta\beta$  data taking**

*Stop project after Demonstrator, but if  $0\nu\beta\beta$  discovered, build new NEMO detector to discover mechanism*





## Cost-effective

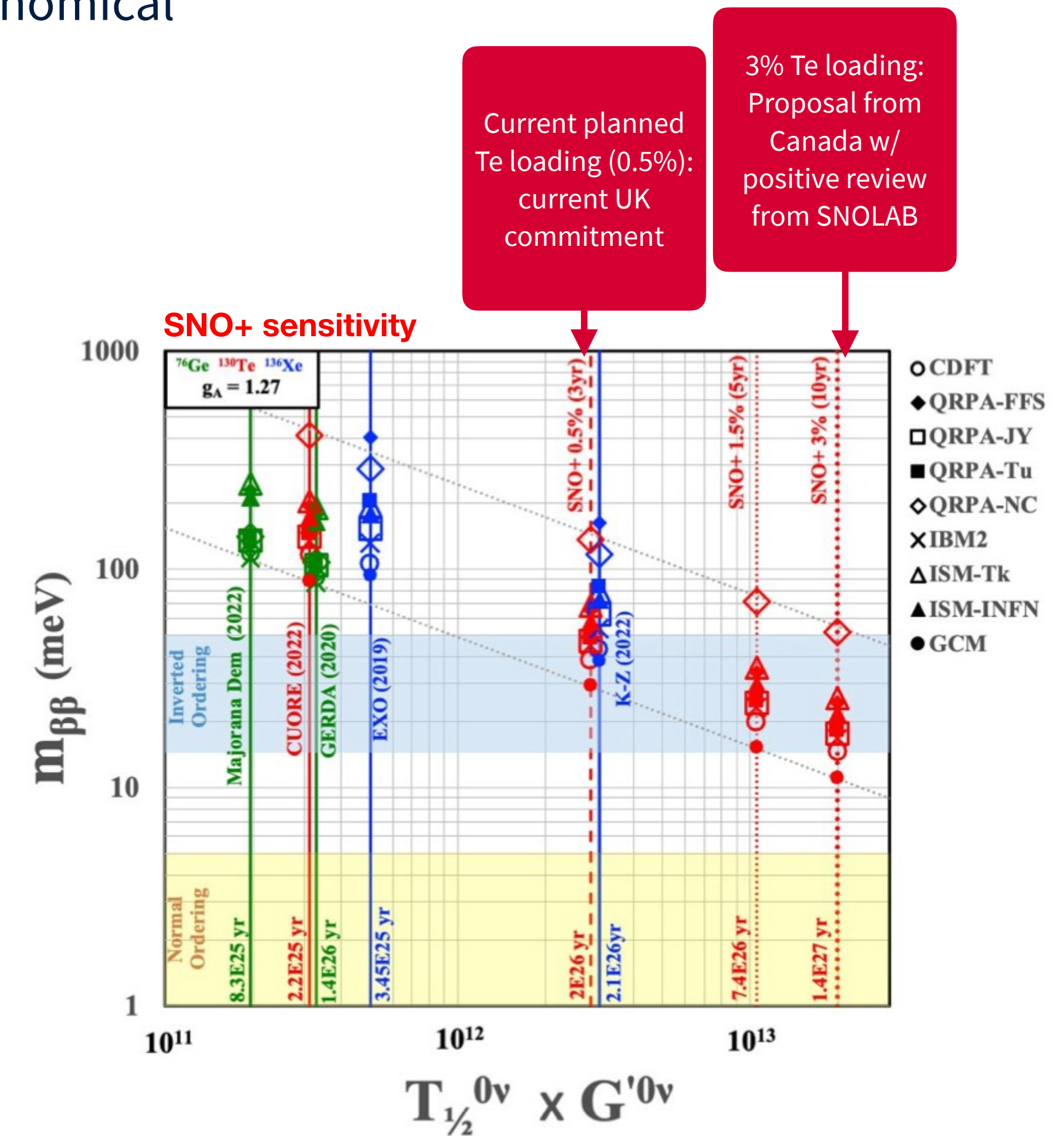
- $\beta\beta$  isotope has high (34%) natural abundance
- Liquid scintillator is also economical

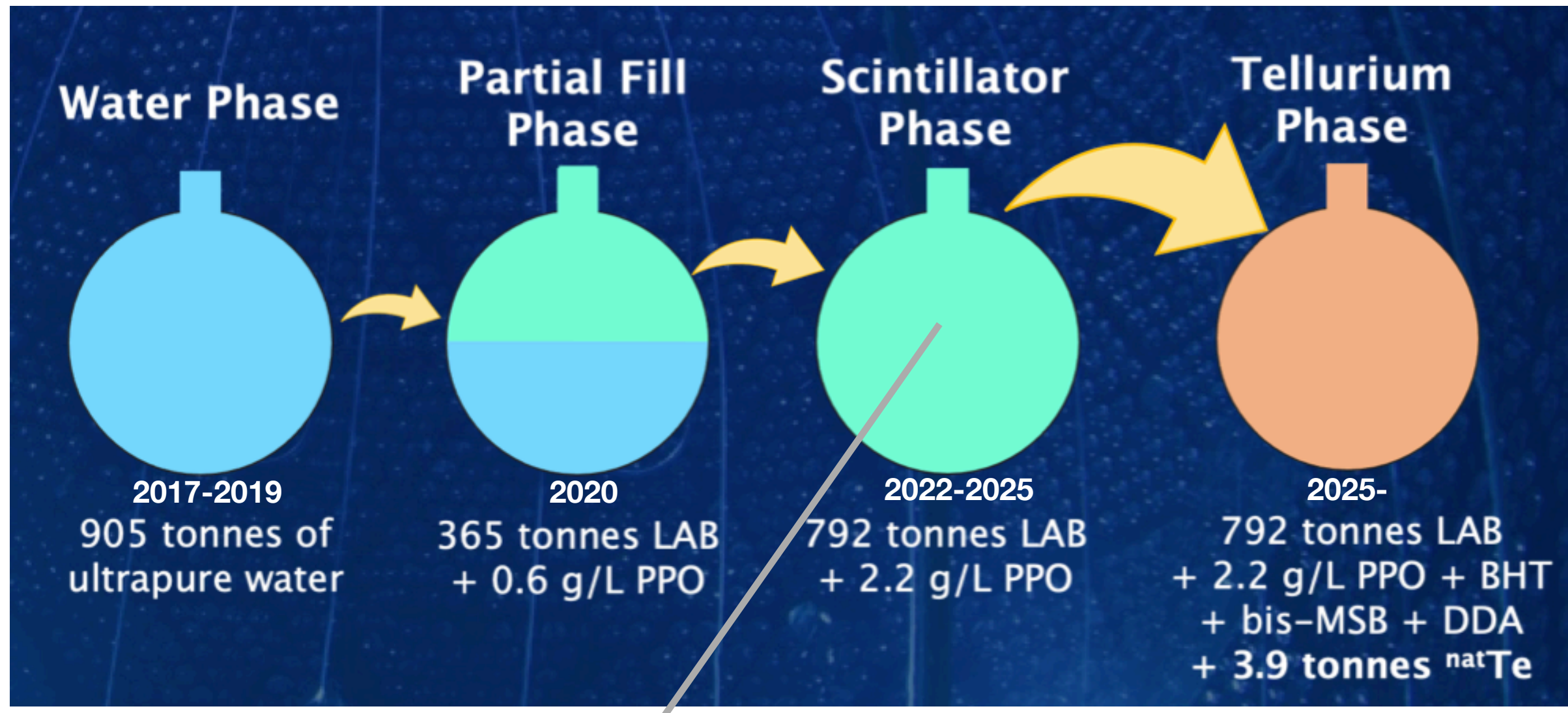
## Scalable

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



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





In **exploitation phase** -  
Te loading to start 2025



TeBD Synthesis Plant

Great advantage to study backgrounds without the target

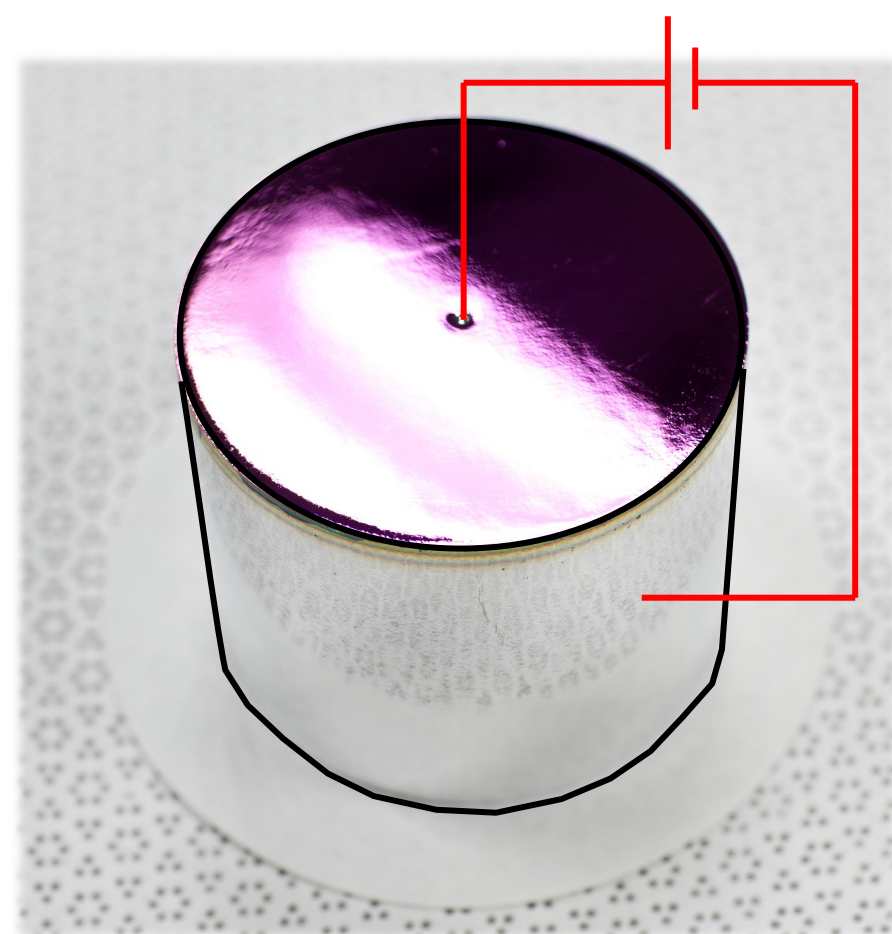
- <sup>8</sup>B solar neutrinos
- Reactor-neutrino oscillation measurements
- Invisible nucleon decay mode limits

- ## UK responsibilities
- Tellurium loading
  - Calibration system
  - Software
  - Data analysis
  - Analysis coordinator, board & executive committee chair

# LEGEND-200 $^{76}\text{Ge}$ semiconductor detector at LNGS, Italy

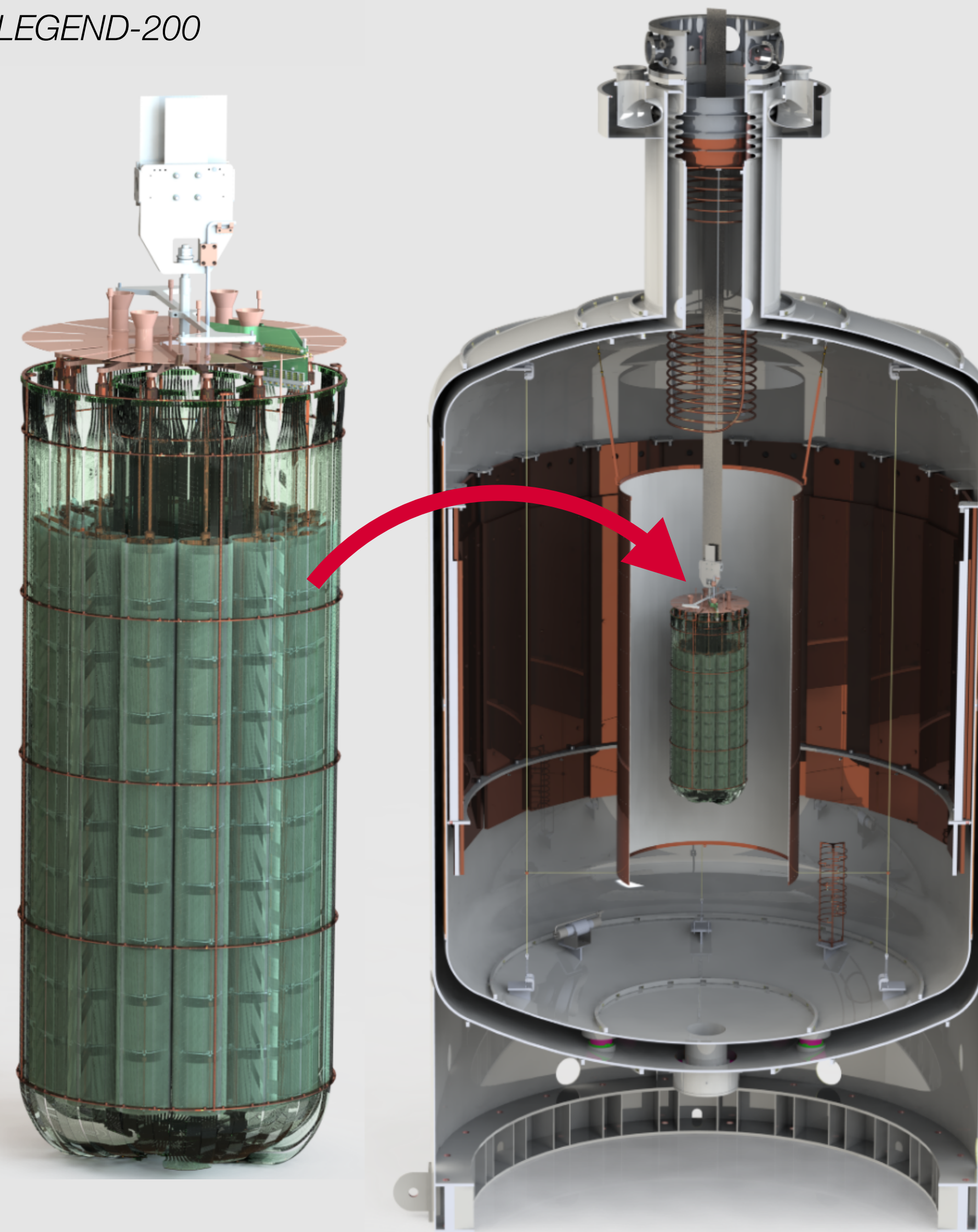
## High-Purity $^{76}\text{Ge}$ -enriched detectors:

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



S Mertens ICHEP 2024

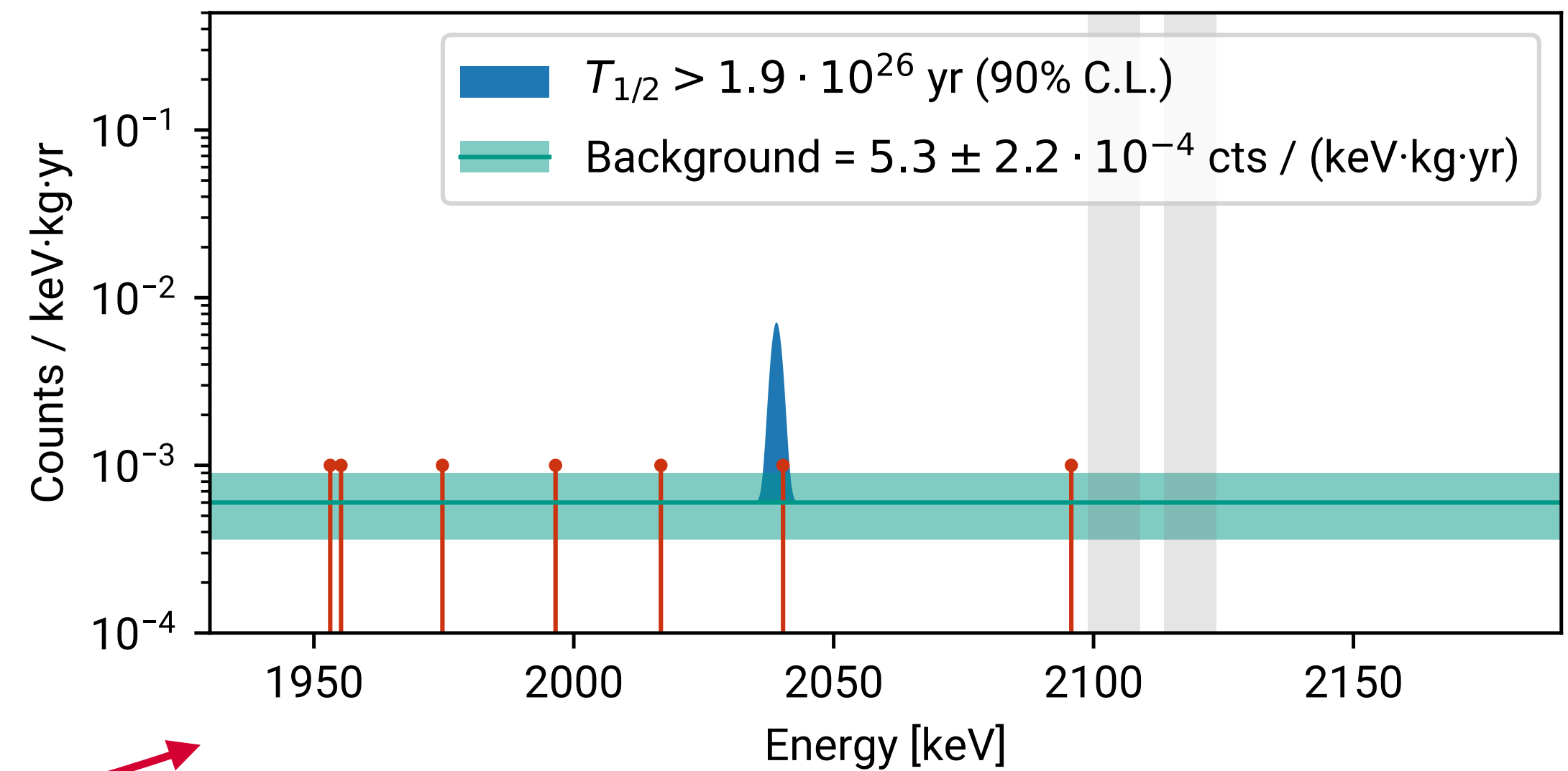
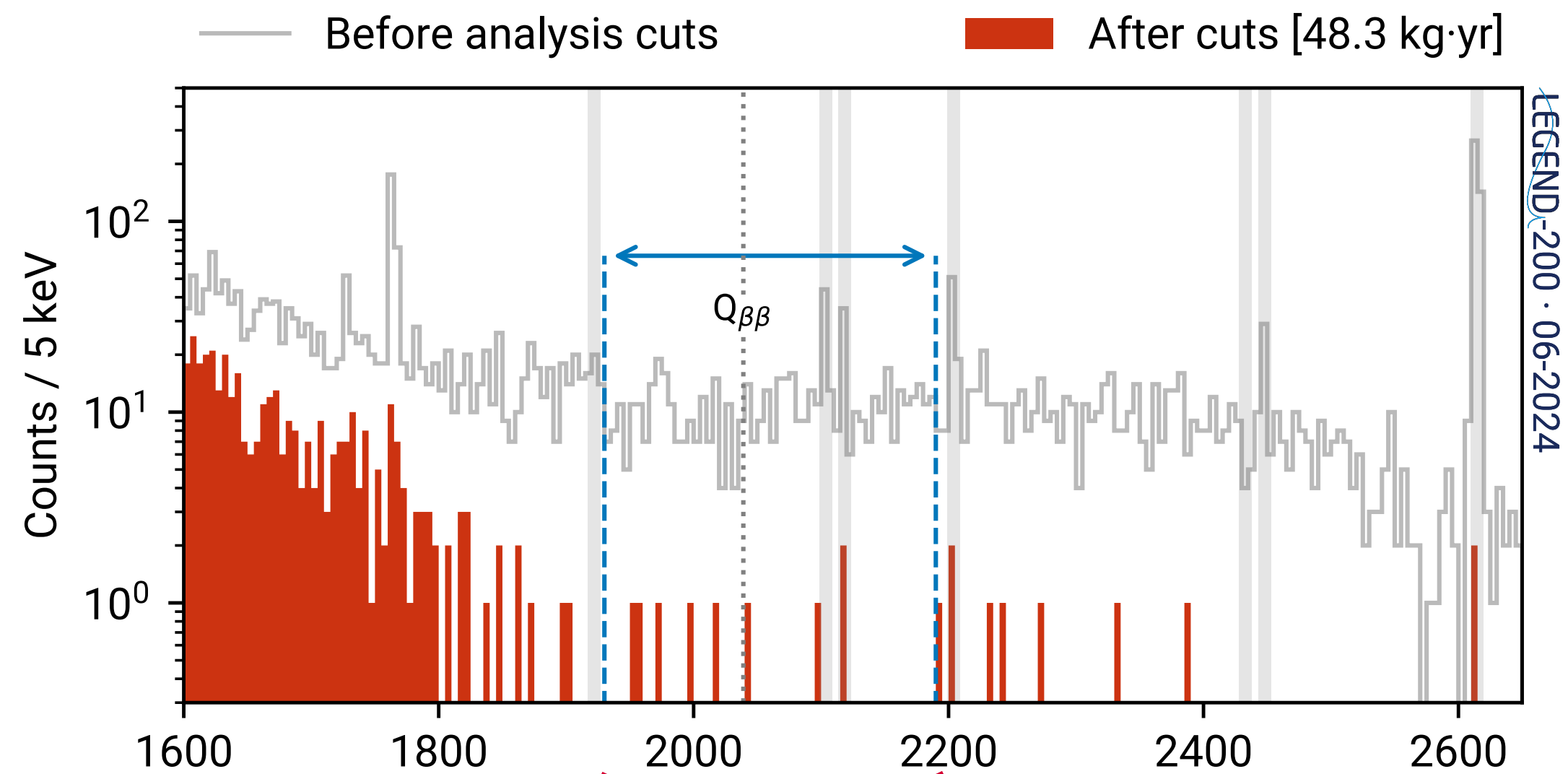
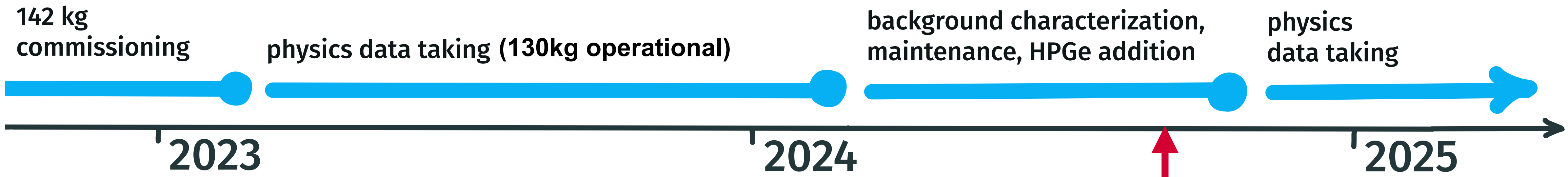
LEGEND-200



**UK responsibilities**

- 2 IB chairs, 1 analysis coordinator
- First results shown at Neutrino 2024 with UK leadership

# LEGEND-200 status: first results shown at Neutrino 2024



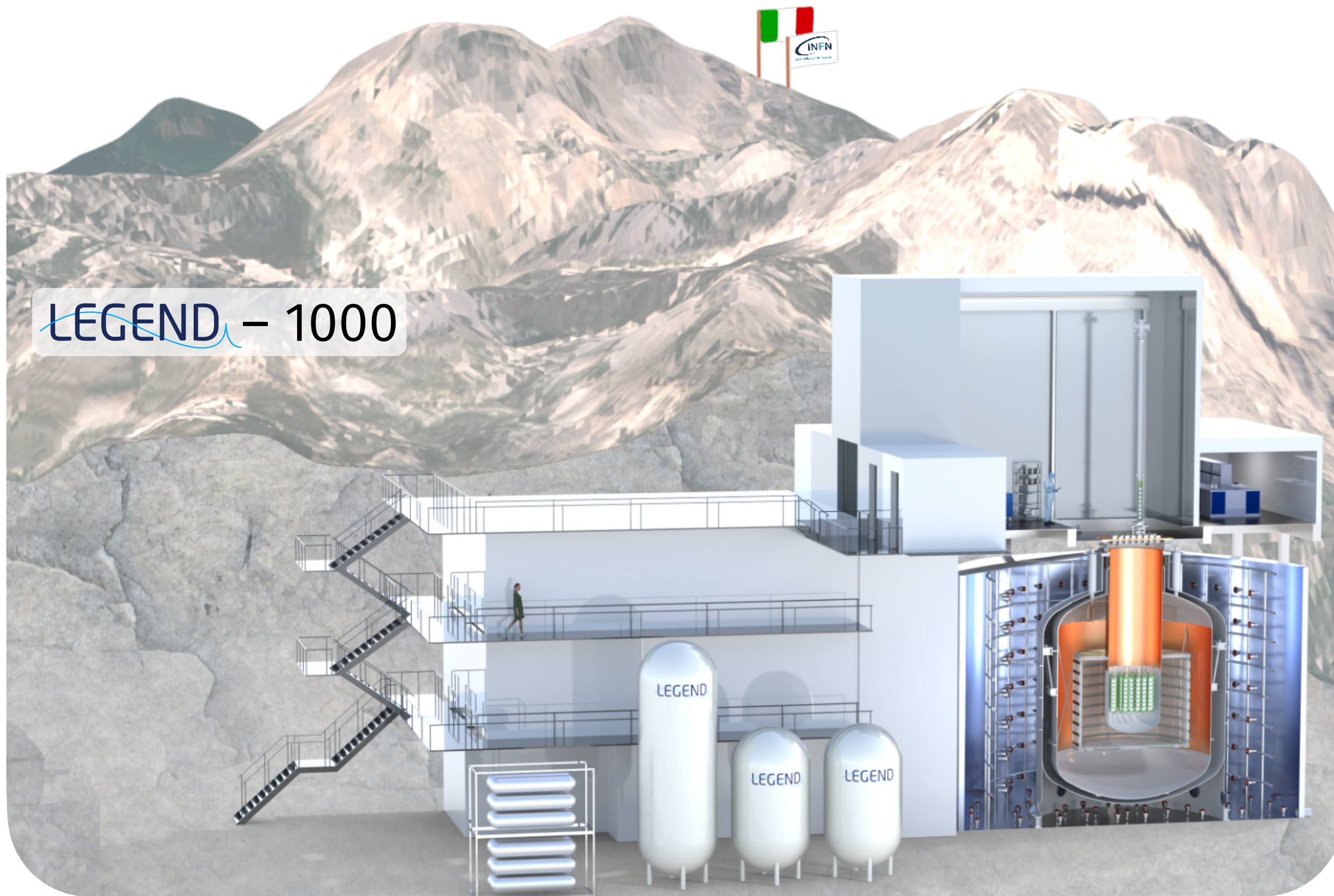
L Pertoldi, Neutrino 24

Background comparable to GERDA; detailed background model and radio assays during maintenance should allow it to be mitigated

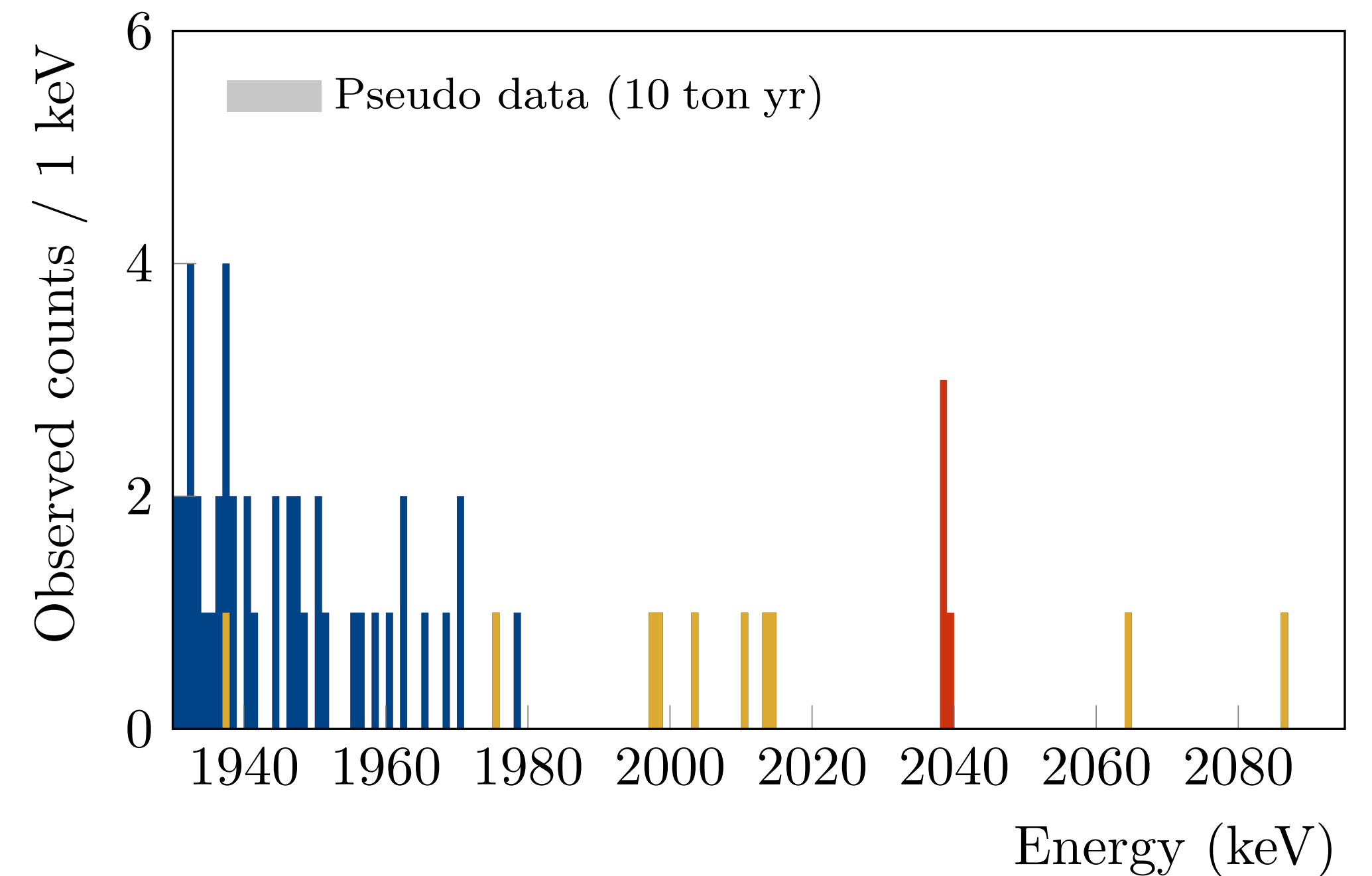
# Future prospect: LEGEND-1000 - discovery machine

L Pertoldi, Neutrino 24

## LEGEND 1000



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

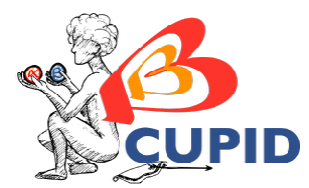


# LEGEND-1000 - world's leading choice for next generation



**APPEC**  
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.”



“The plan is to create an international virtual laboratory that would then coordinate the efficient and cost-effective deployment of CUPID, **LEGEND-1000**, and nEXO, with ton-scale experiments at LNGS and SNOLAB.”



(Highest priority due to top score in 2021 portfolio review)

- Technical design ready
- DOE CD1 this year
- NSF funding under review

2023   2024   2025   2026   2027   2028   2029   2030   2031   2032   2033   2034   2035   2036

Design & Reviews

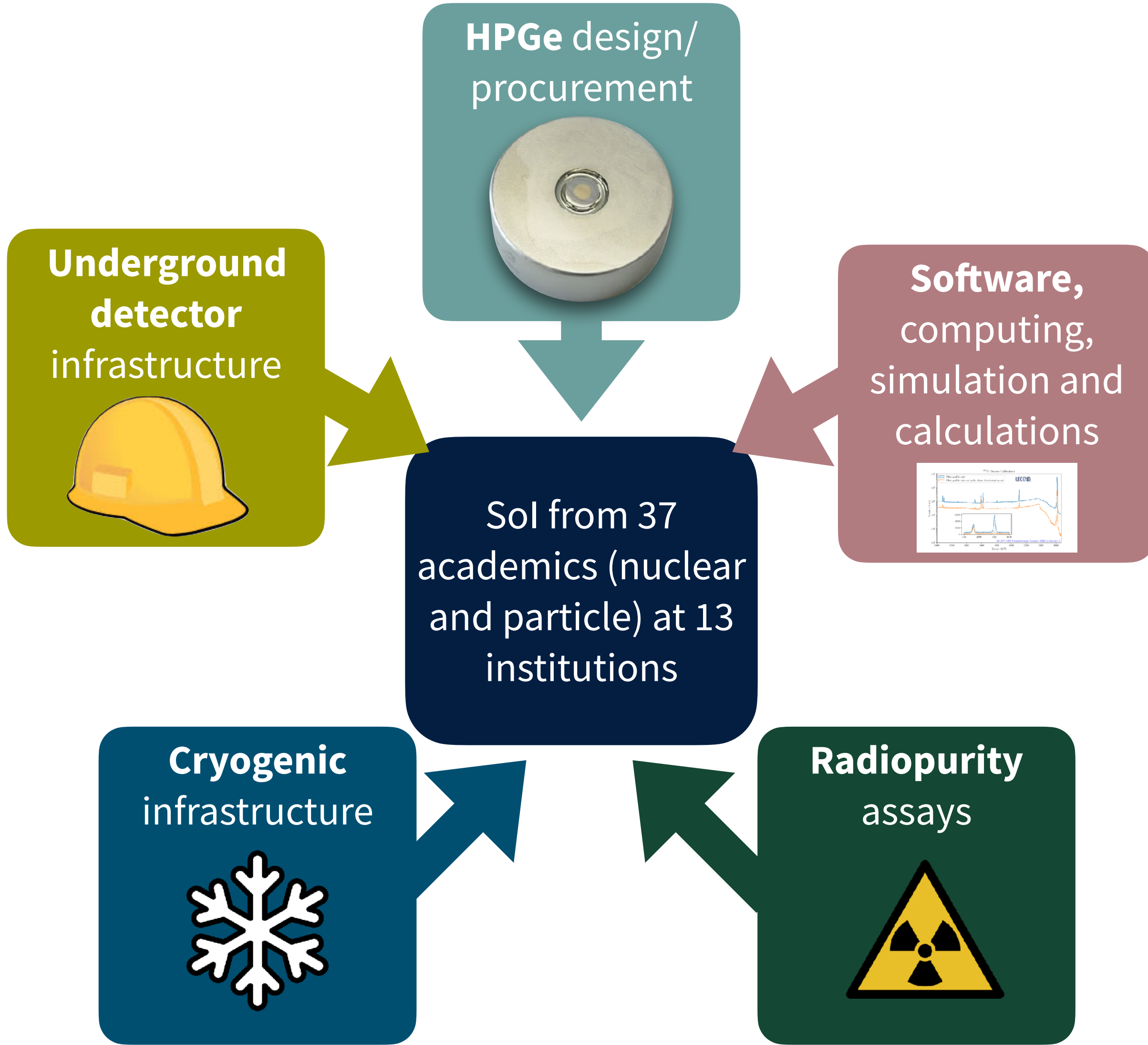
First Data

Full Data Taking

Construction, Detector Production & Installation

\*Technically driven schedule

# LEGEND-1000 in the UK



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



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



1 academic, 3 PDRA,  
3 PhD students

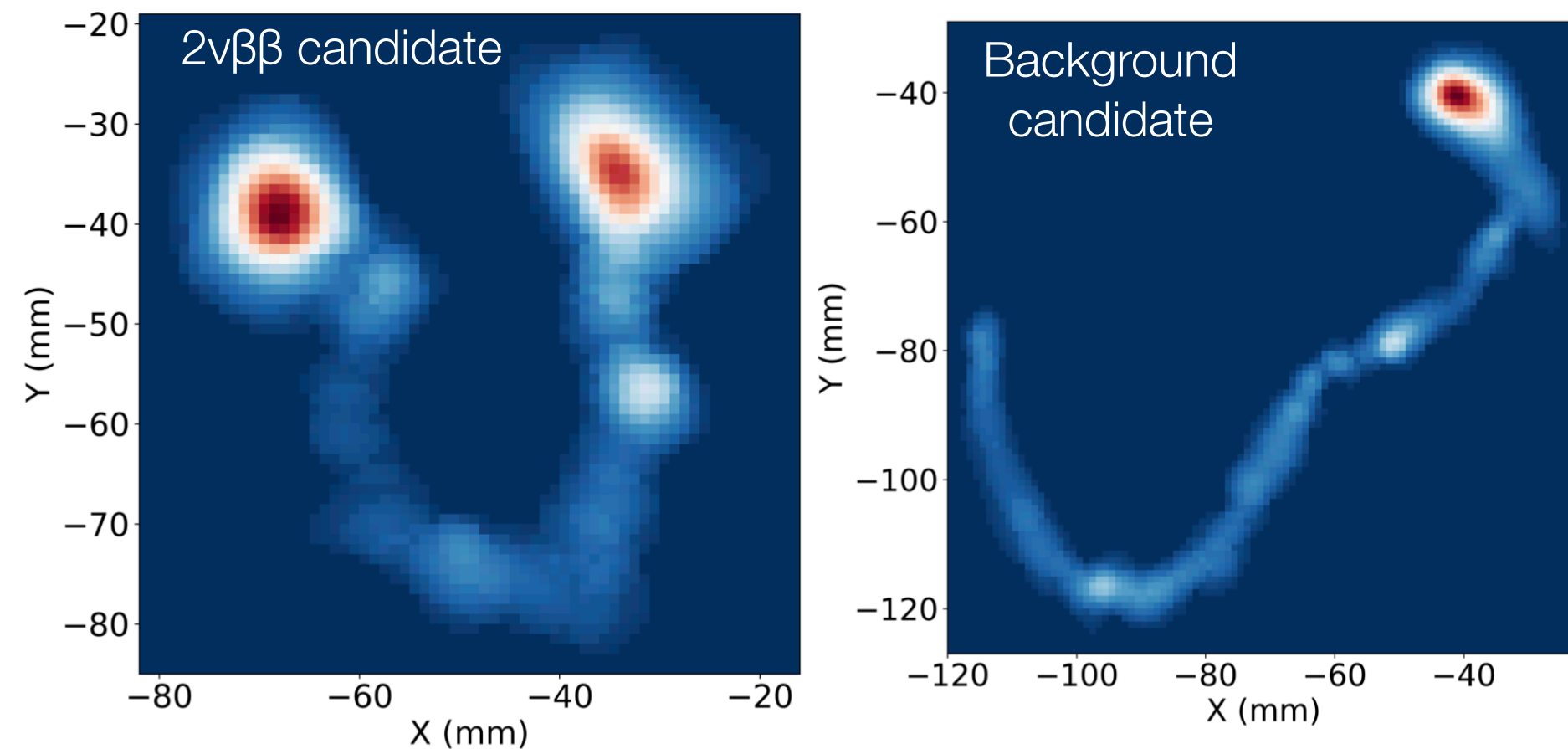


The University of Manchester



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

NEXT-White data



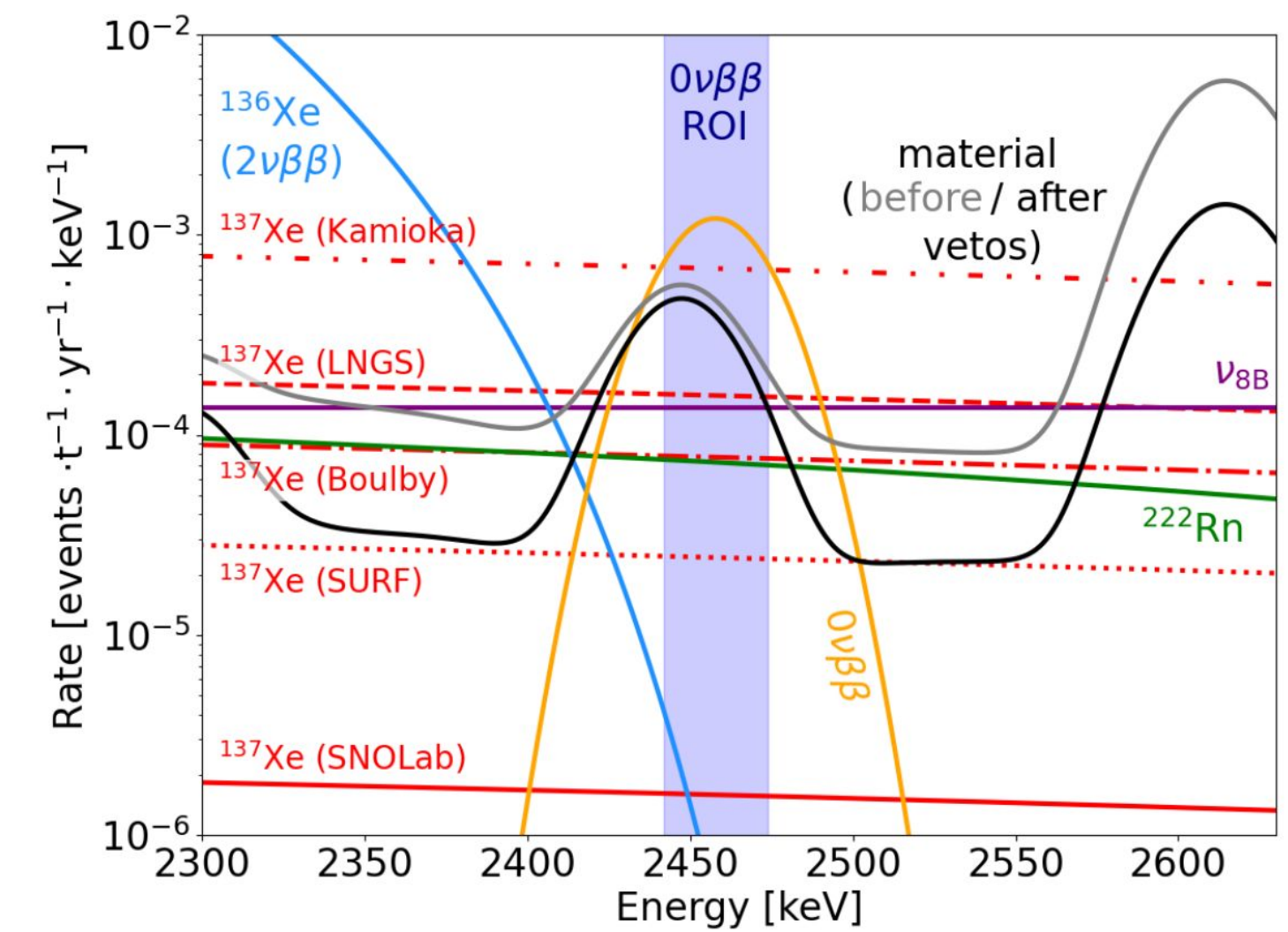
- NEXT-100 now taking commissioning data
- Ton-scale R&D underway: focus on Ba tagging
- In European roadmap (considered next-generation by US)



Statement of Interest from 22  
UK institutions

Proposed Xe TPC principally for  
**dark-matter** searches, proposed  
for Boulby

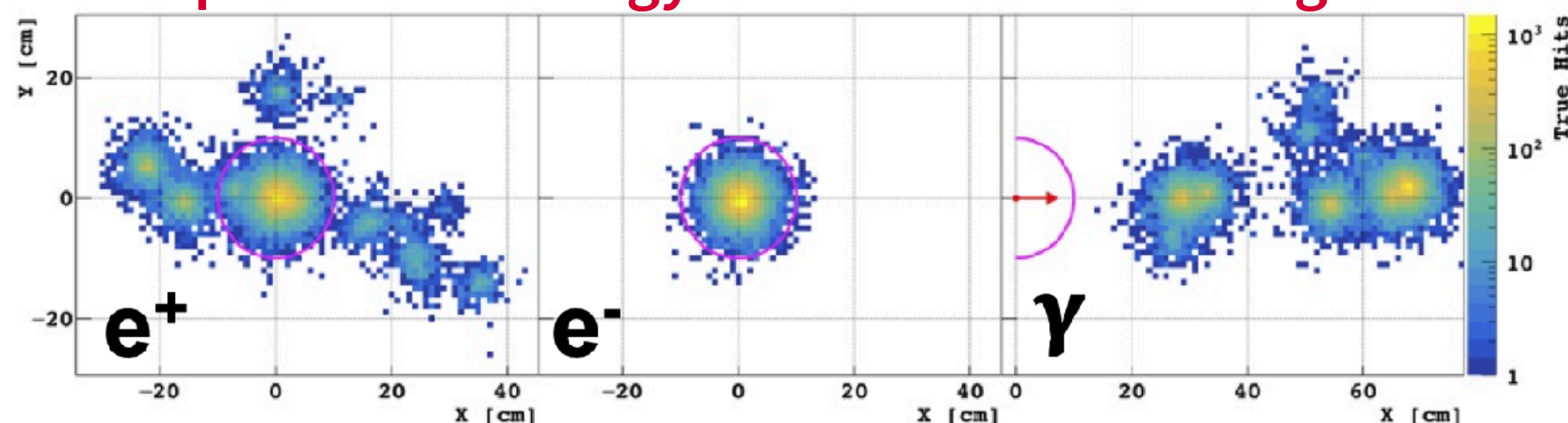
- 60-80 tonnes of Xe  
(9%  $^{136}\text{Xe}$ )
- Self-shielding
- Sensitivity  
comparable to nEXO





# Other low-energy physics - reactor neutrinos

## Liquid-O technology for reactor monitoring



Opaque liquid scintillator for particle discrimination

C L U D

US

UNIVERSITY OF SUSSEX

UKRI Science and Technology Facilities Council

European Innovation Council



UK Research and Innovation

(Multi-year project funded from: Dec/22)

### 3-phase project:

- Characterise reactor (U/Pu)

- Reactor  $\nu_e$  production with indium loading

- Low-energy IBD (for  $^{40}\text{K}$  geoneutrino search)

- Use tech for  $0\nu\beta\beta$  and more?



## JUNO, Jiameng, China

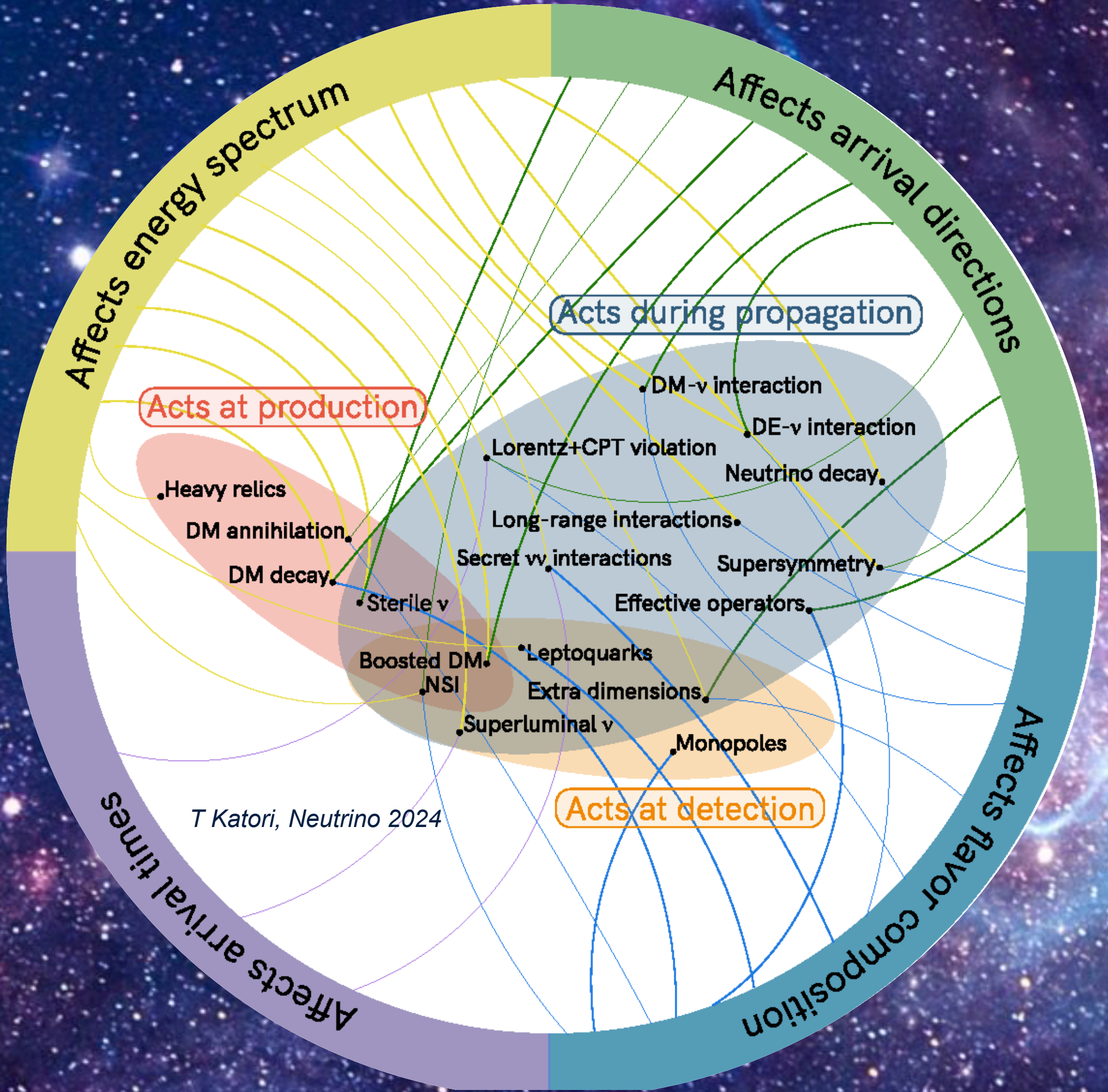
- Determine **mass hierarchy**
- Measure **3 $\nu$ -oscillation parameters**
- Solar / SN / geo-neutrinos, nucleon decays

## UK contributions



- Working-group convenor
- Neutrino interaction simulations / systematic studies
- Atmospheric oscillation analysis
- ML-based neutrino event reconstruction

# Neutrino astronomy



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

# UK High-energy Neutrino Consortium



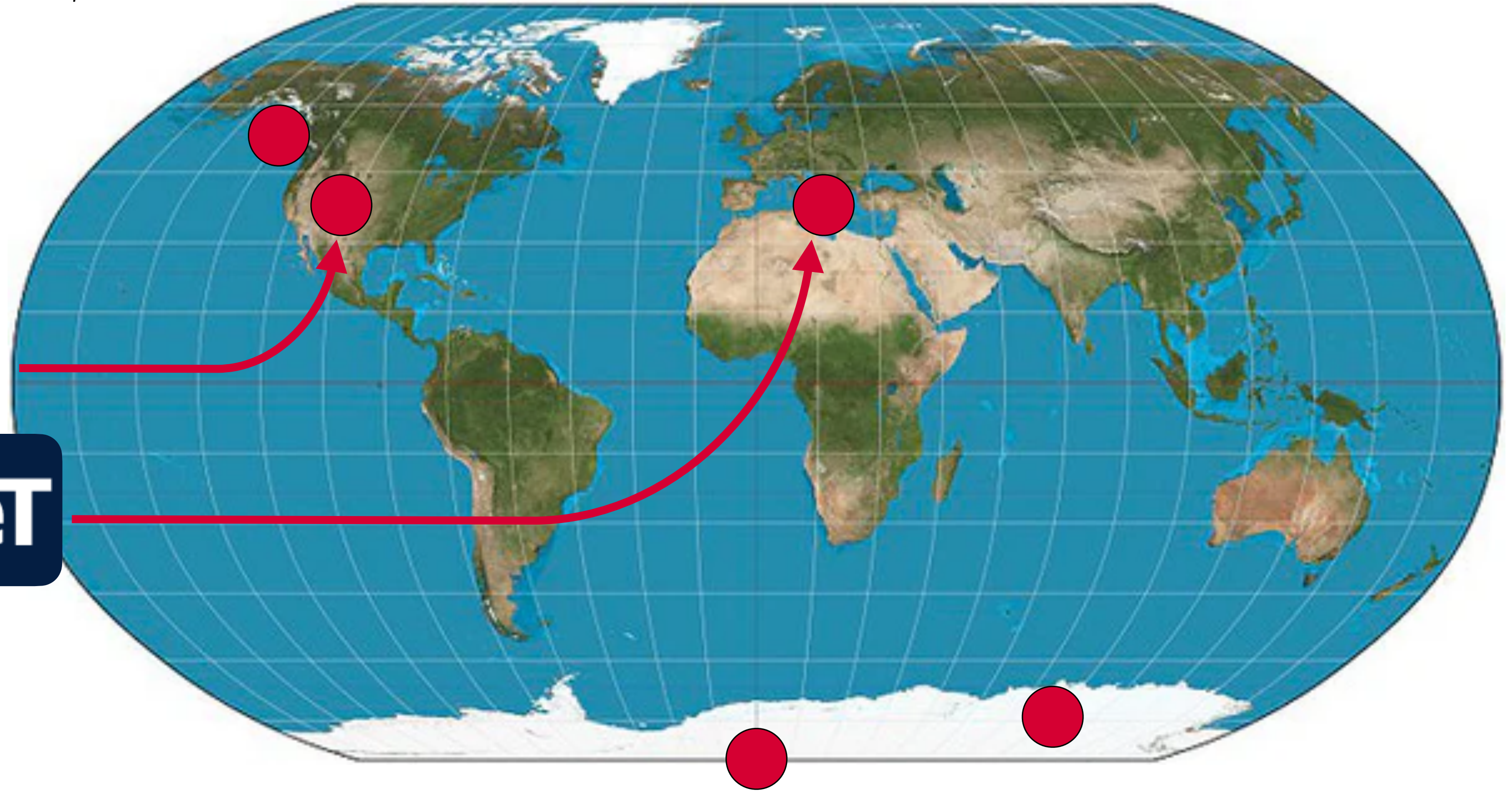
**P-ONE**  
*Pacific Ocean Neutrino Experiment*



**Trinity**



**KM3NeT**



**ICECUBE**  
NEUTRINO OBSERVATORY

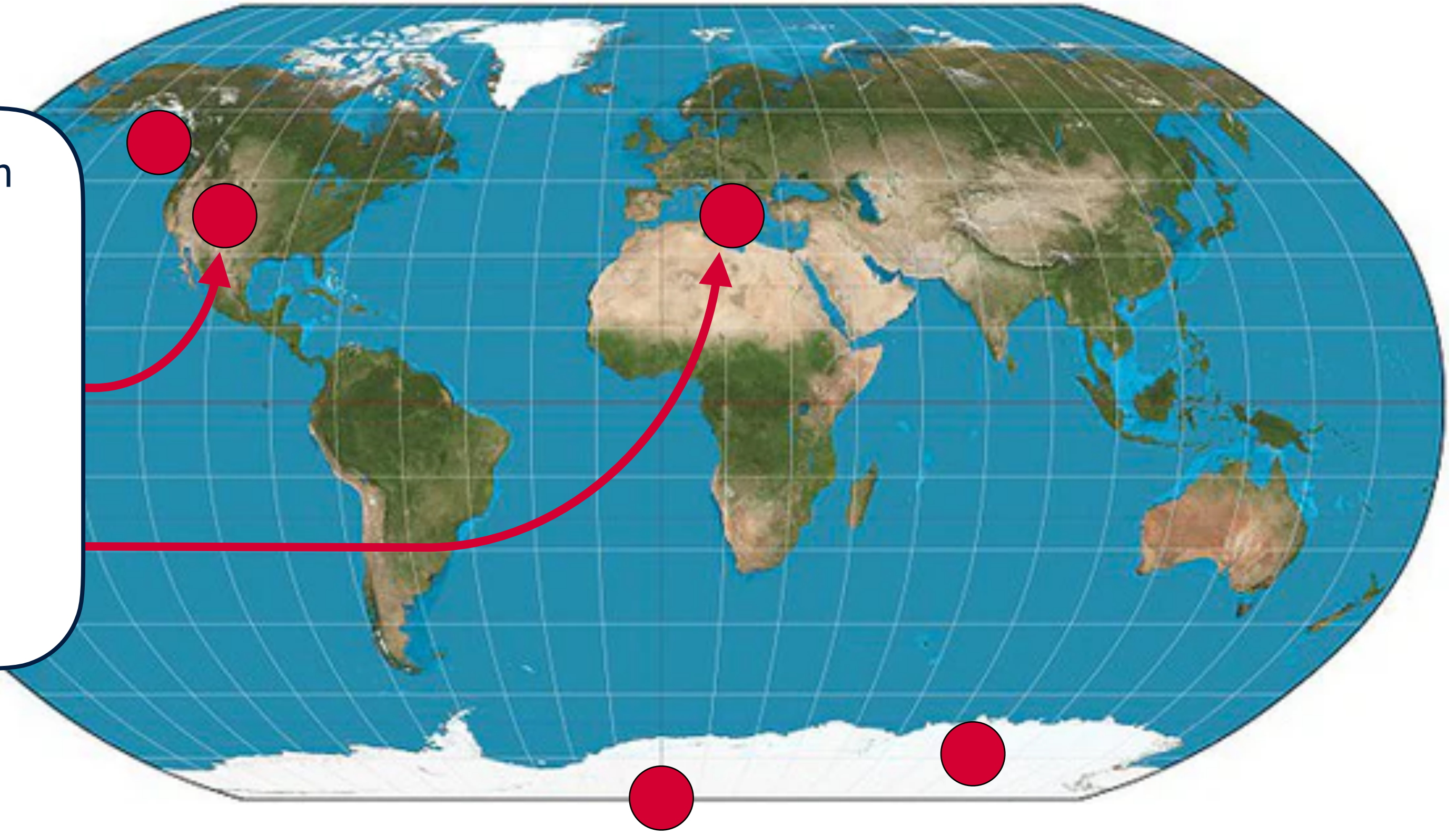


**PUEO**

# UK High-energy Neutrino Consortium



Limited UK involvement through astronomy

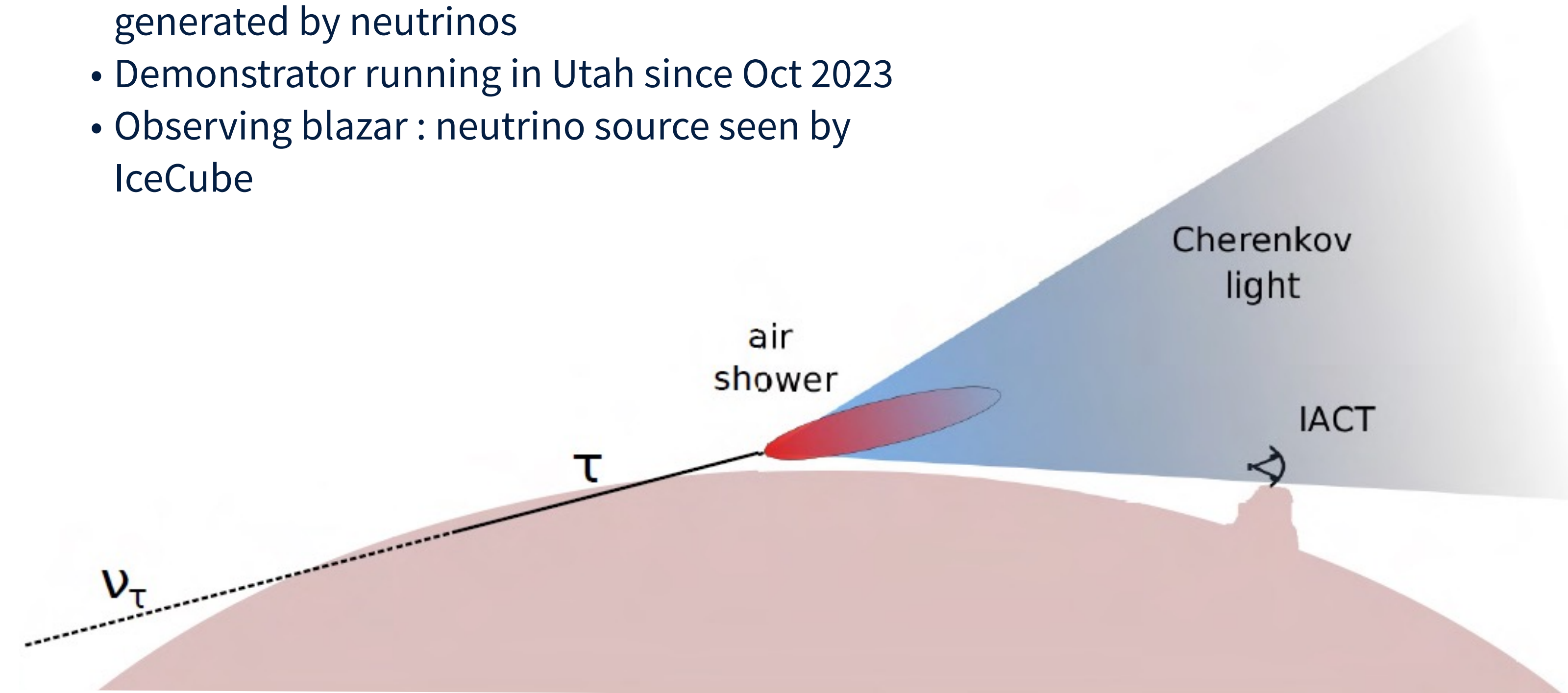


# Trinity - the PeV neutrino observatory

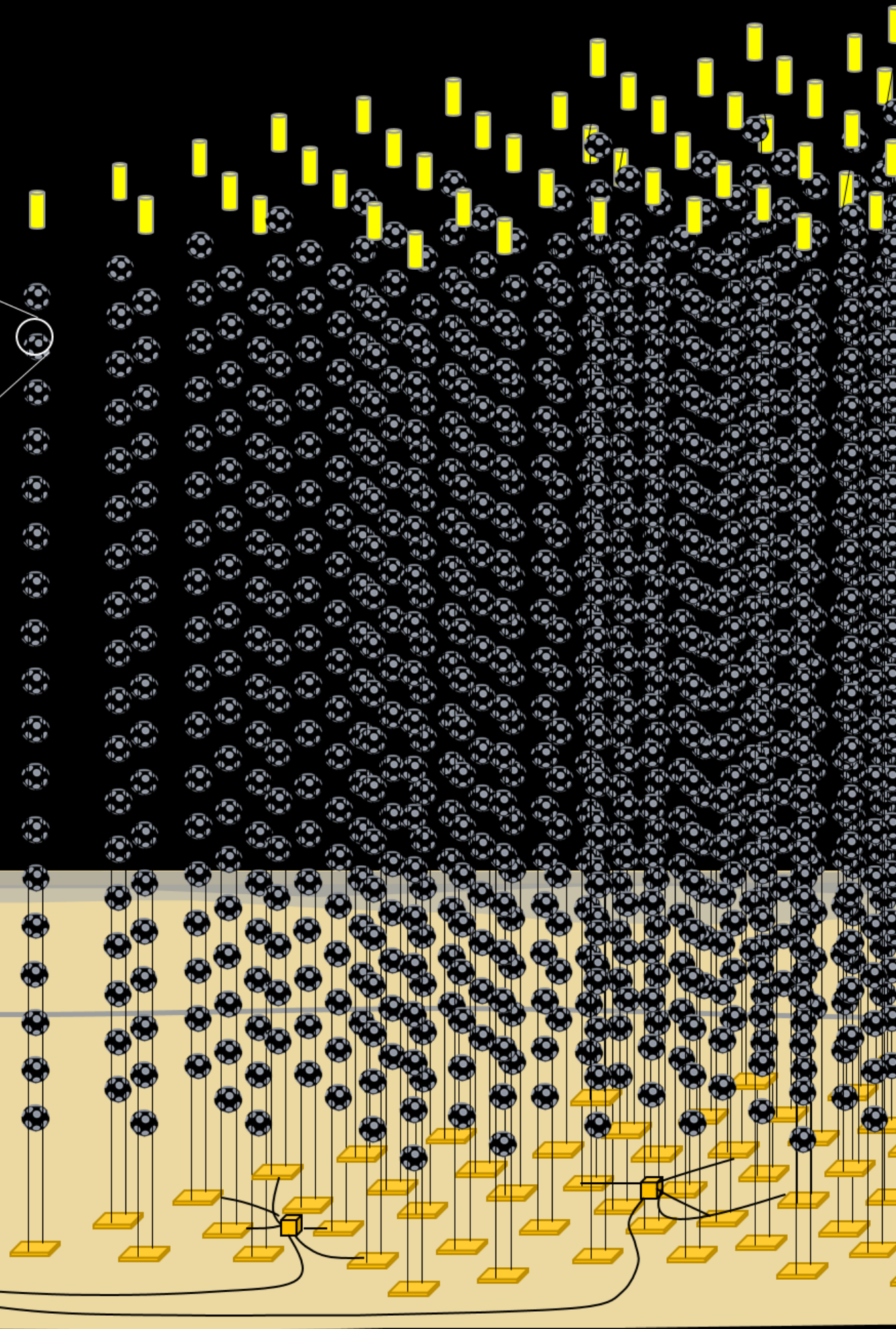


(1 astronomer)

- 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

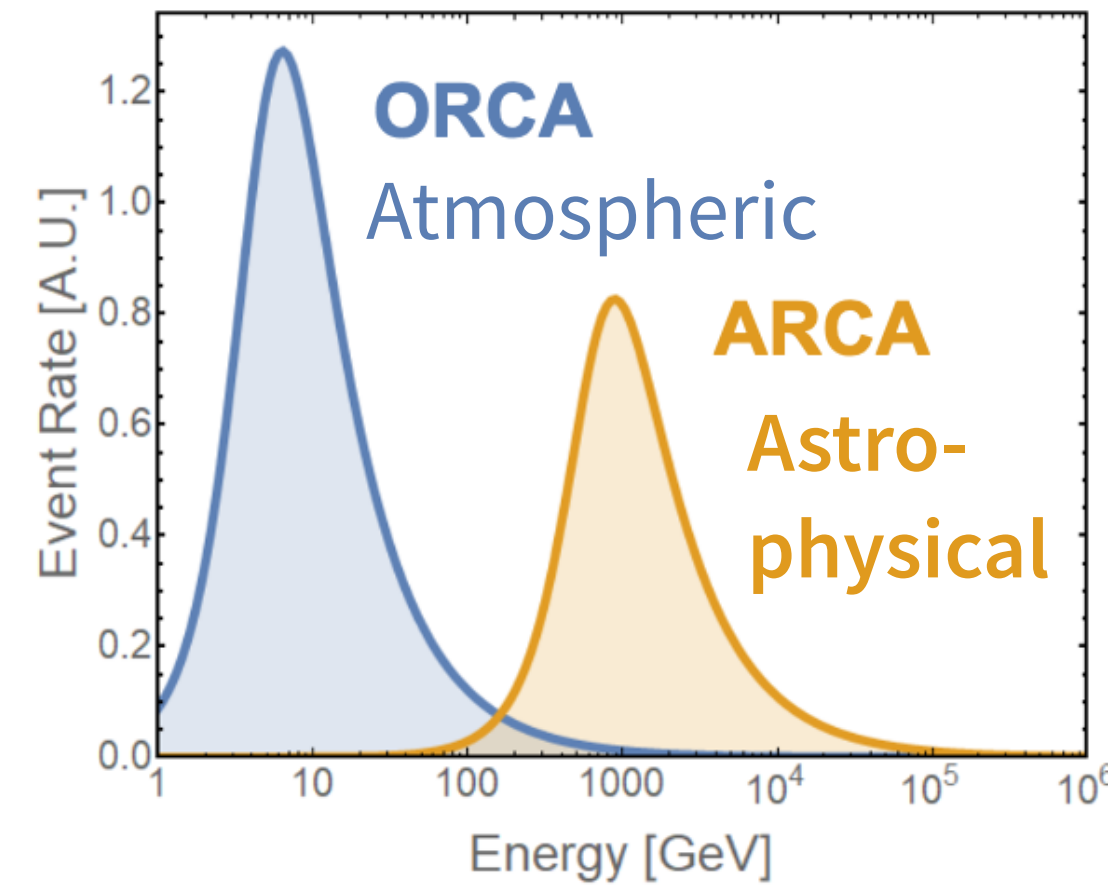


# KM3NeT neutrino telescope in the Mediterranean

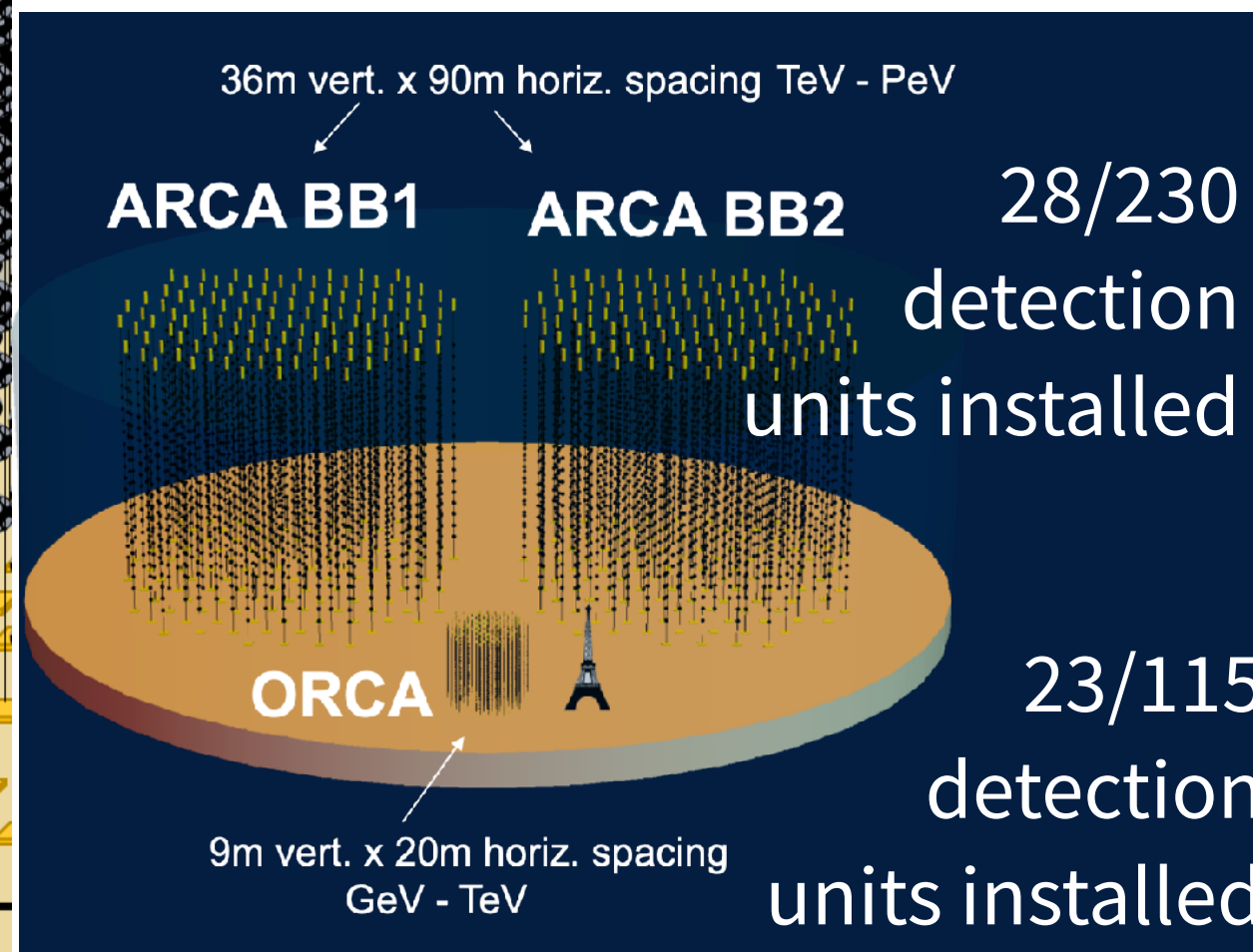
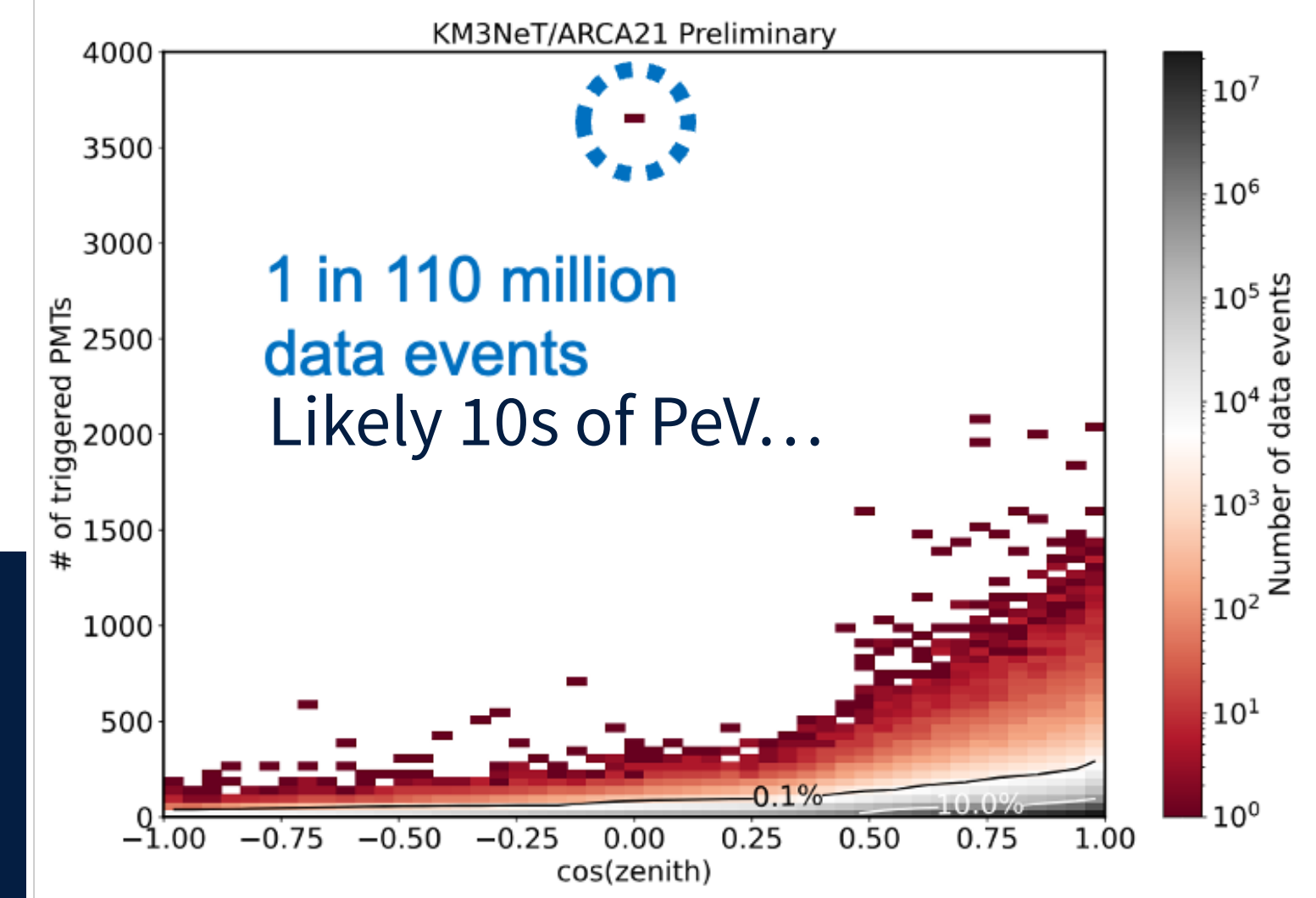




UNIVERSITY of HULL

(astronomers - computing & supernova detection)



(and whatever THIS is...)



KM3NeT would be keen for more UK involvement

J. Coelho, Neutrino24

# UK High-energy Neutrino Consortium



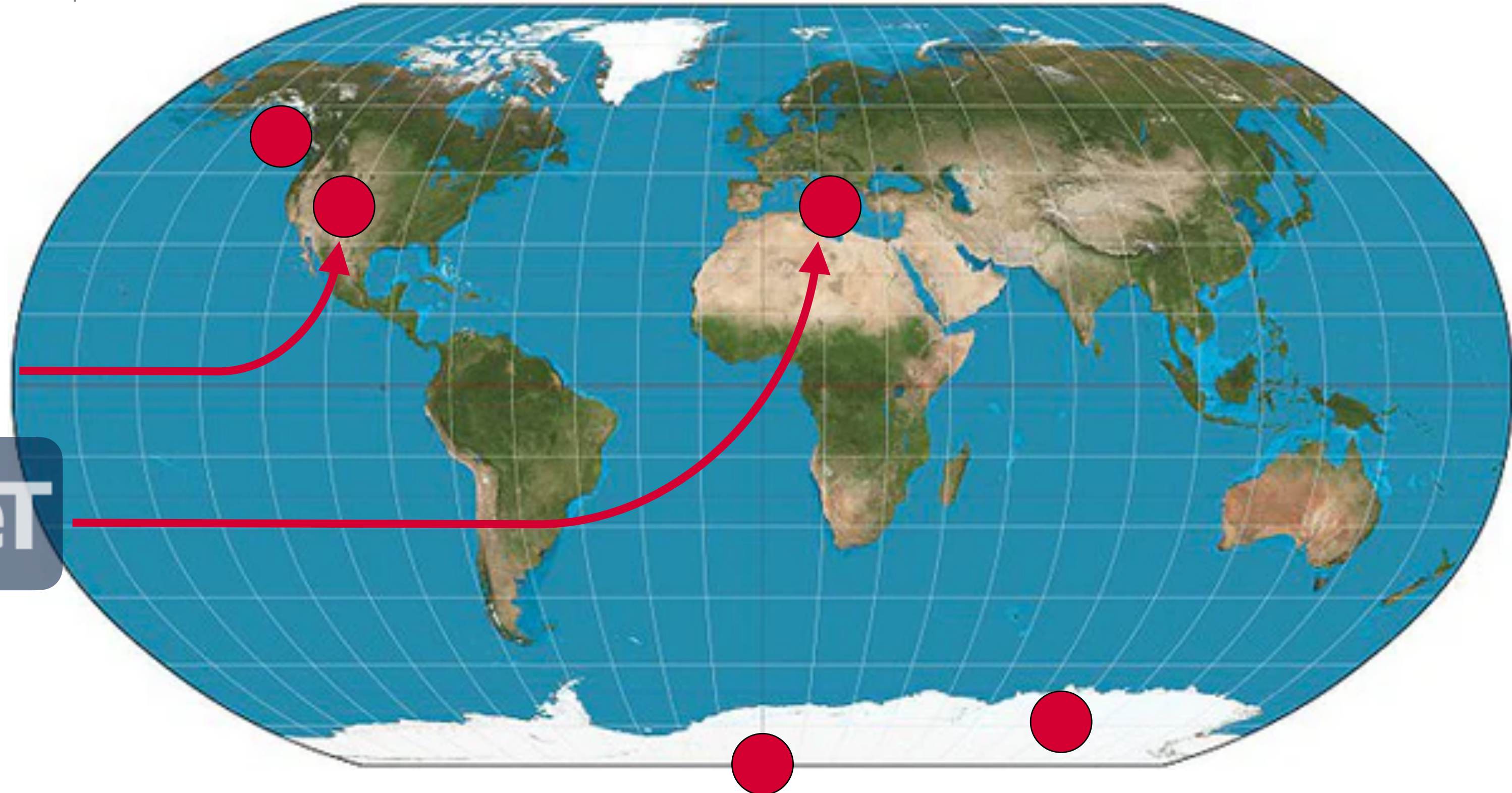
**P-ONE**  
*Pacific Ocean Neutrino Experiment*



**Trinity**



**KM3NeT**



Sustained UK-HEP involvement

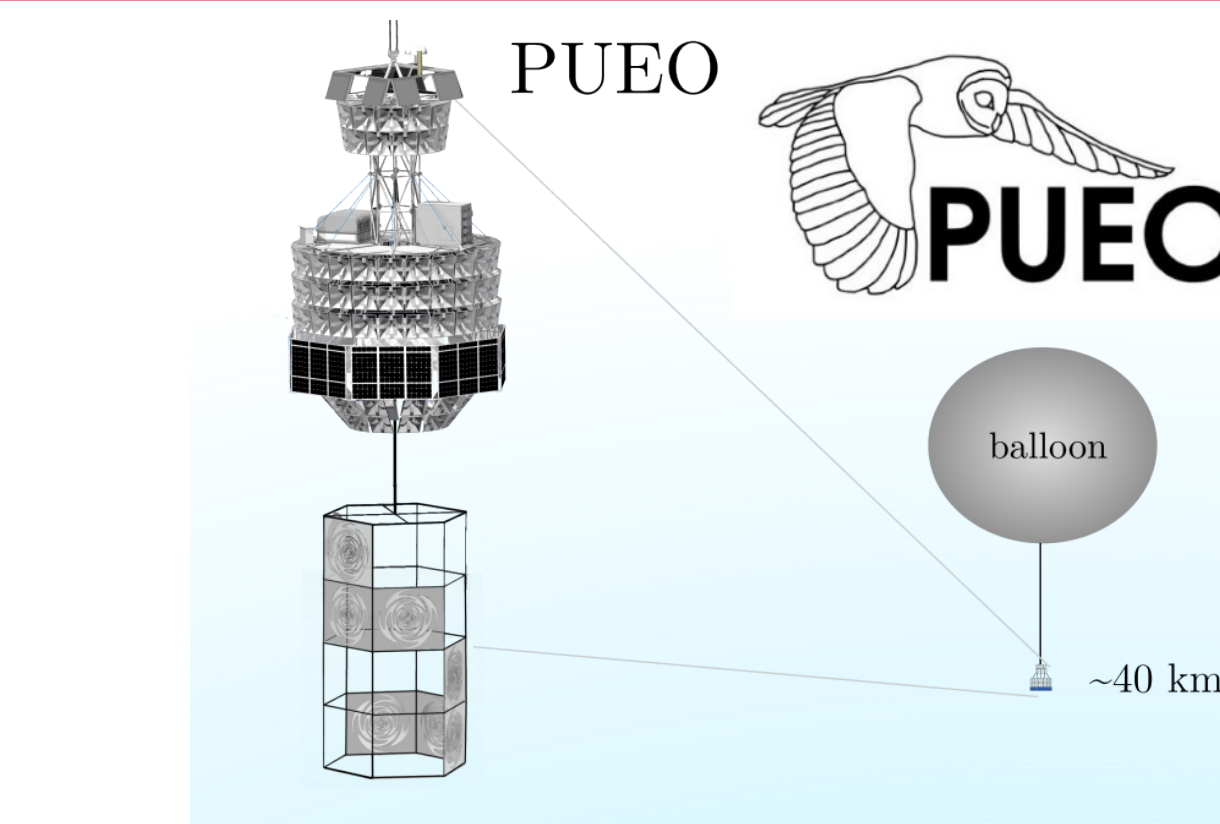
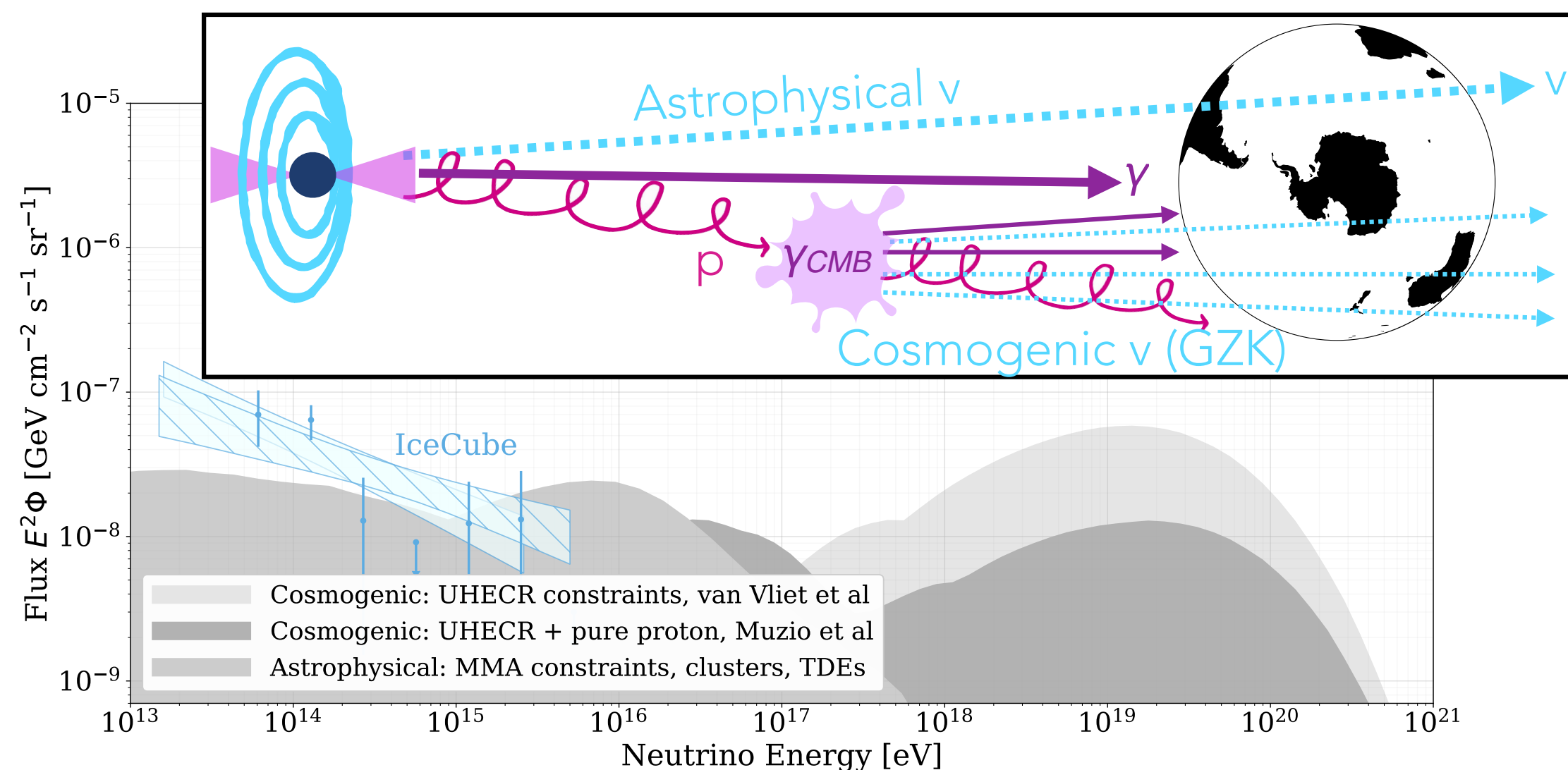


**ICECUBE**  
NEUTRINO OBSERVATORY

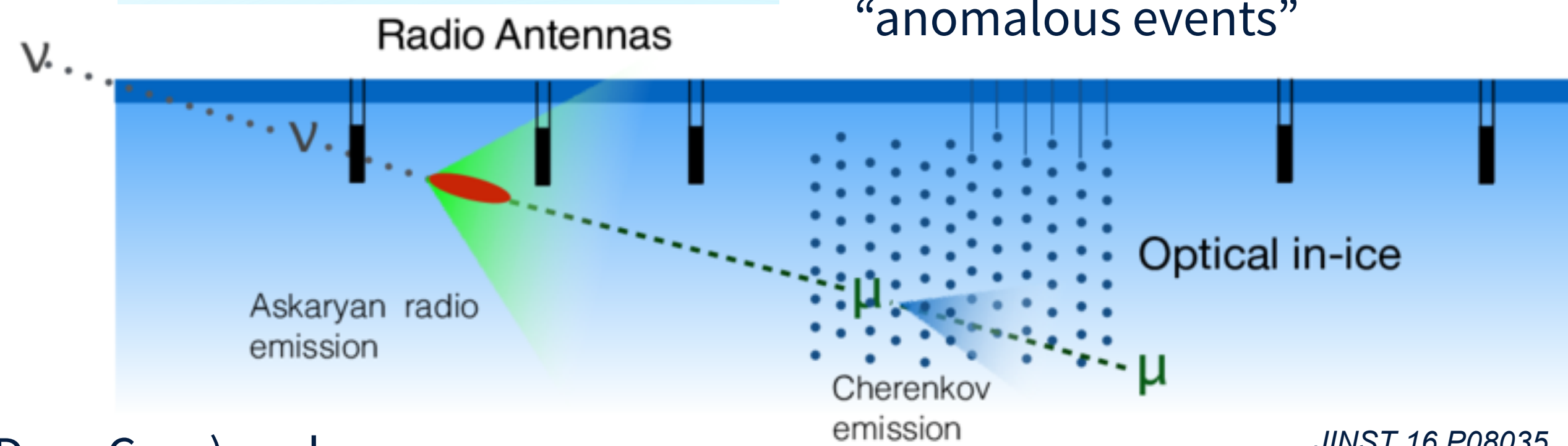


**PUEO**

# Antarctic ice as a neutrino detector



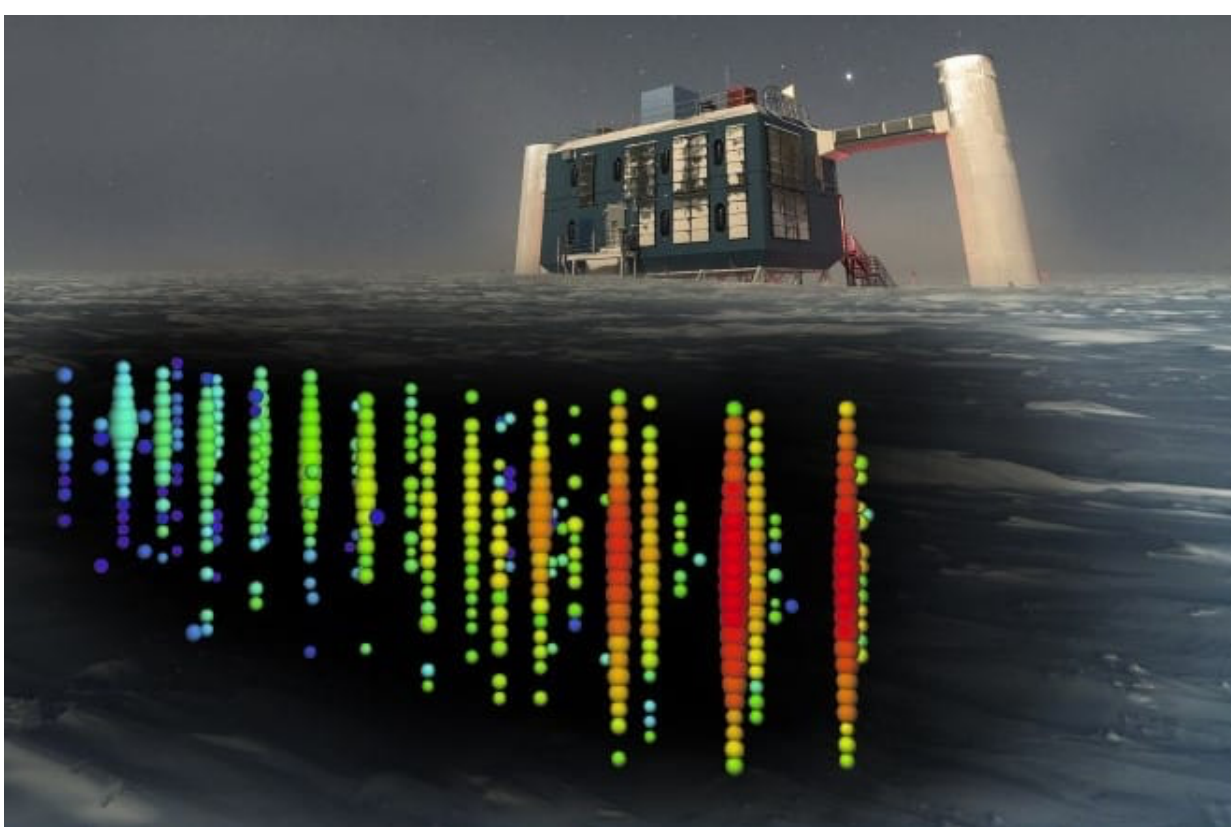
- **Highest-energy (>10<sup>17</sup> eV) neutrinos** generate radio waves via Askaryan effect
- Also detects ultra-high energy cosmic rays: distinguish by direction & polarity
- PUEO predecessor ANITA saw “anomalous events”



JINST 16 P08035



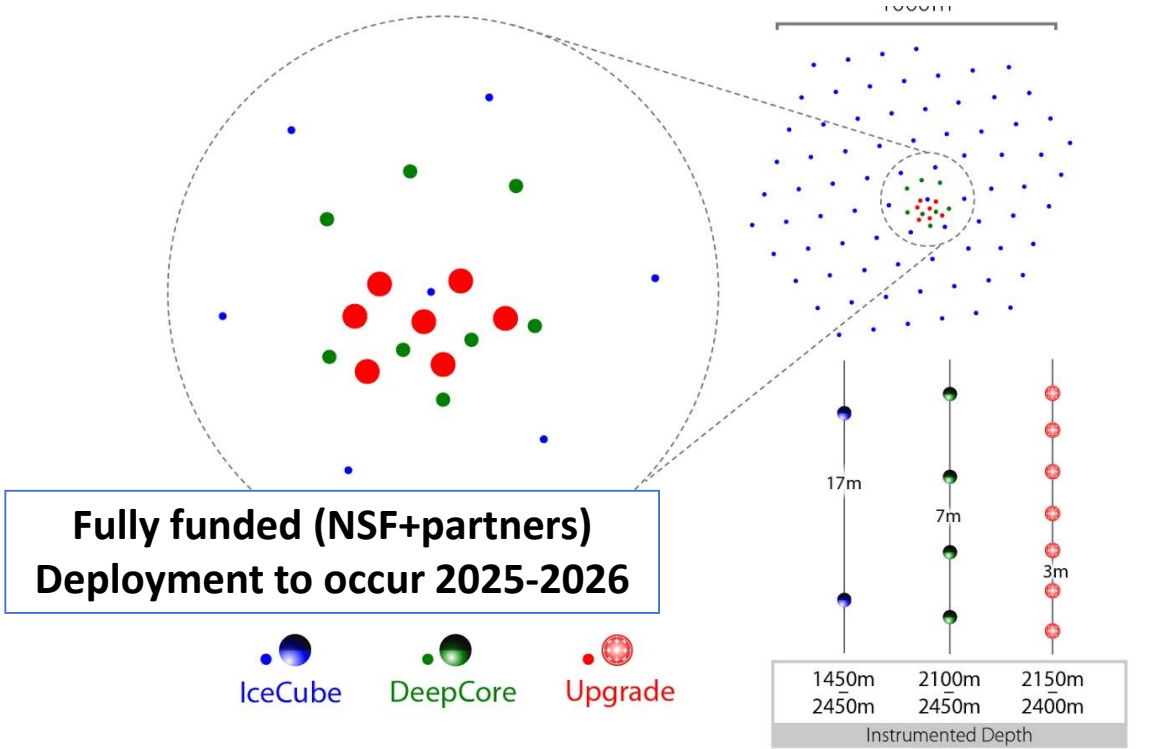
- Running since 2010 at **GeV** (DeepCore) and **TeV** (IceCube) energies
- Atmospheric oscillations, sterile  $\nu$ ,  $\nu$  astronomy (point sources, diffuse neutrinos, galactic neutrinos)



J.P. Yáñez, Neutrino 24



- IceCube Upgrade to deploy 2025-6
- IceCube-Gen2 planned
- NSF reports **ageing infrastructure at South Pole** - impact unclear

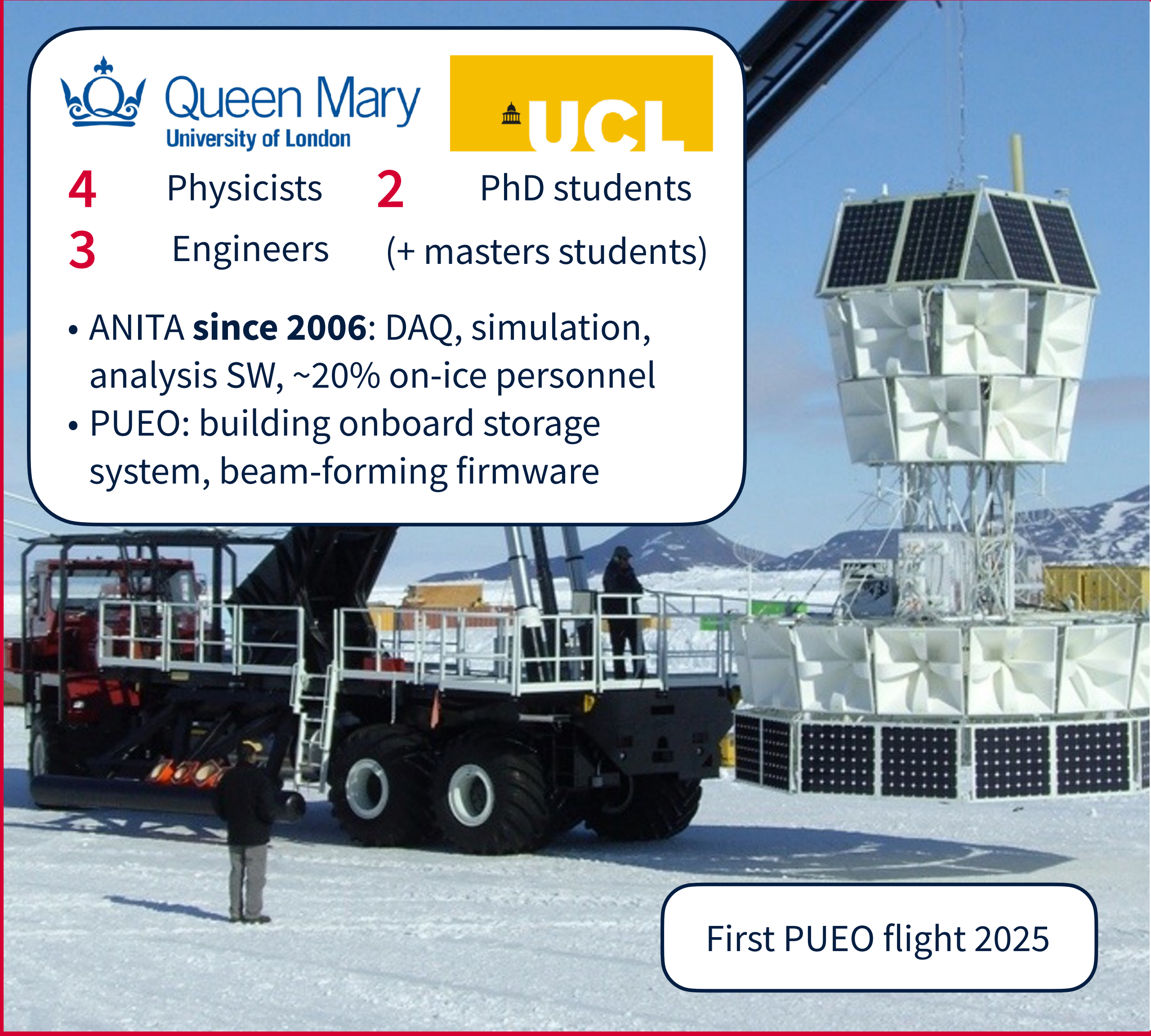


- 4** Physicists     **2** PhD students
- 3** Engineers     (+ masters students)

- ANITA **since 2006**: DAQ, simulation, analysis SW, ~20% on-ice personnel
- PUEO: building onboard storage system, beam-forming firmware



- 1** Physicist     **1** PhD student
- BSM physics analysis
- IceCube-Upgrade sensitivity
- Gen2 R&D (scintillator-based detector)



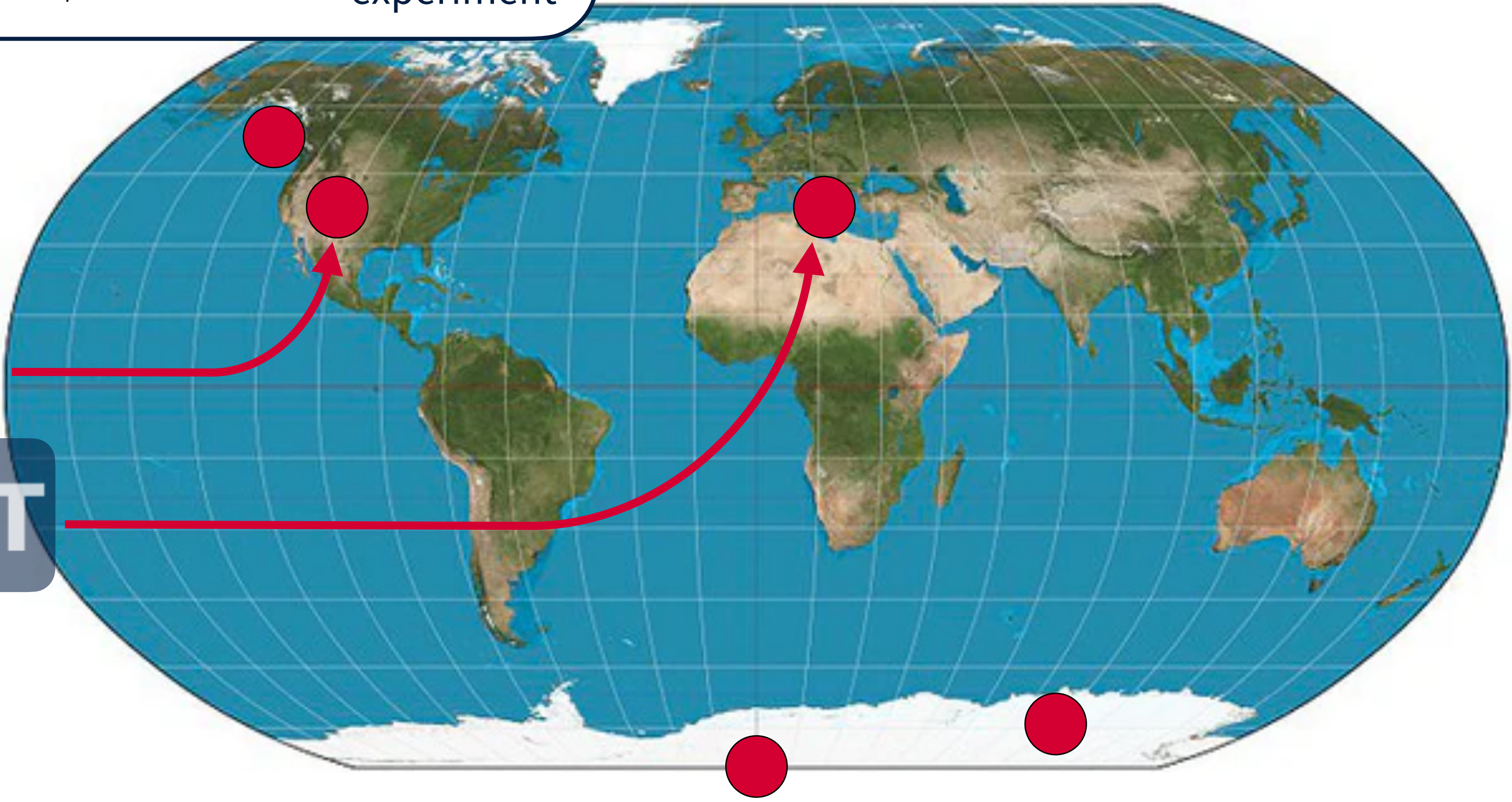
First PUEO flight 2025

# UK High-energy Neutrino Consortium



 **P-ONE**  
*Pacific Ocean Neutrino Experiment*

Preferred UK medium-term experiment



 **Trinity**

 **KM3NeT**

 **ICECUBE**  
NEUTRINO OBSERVATORY

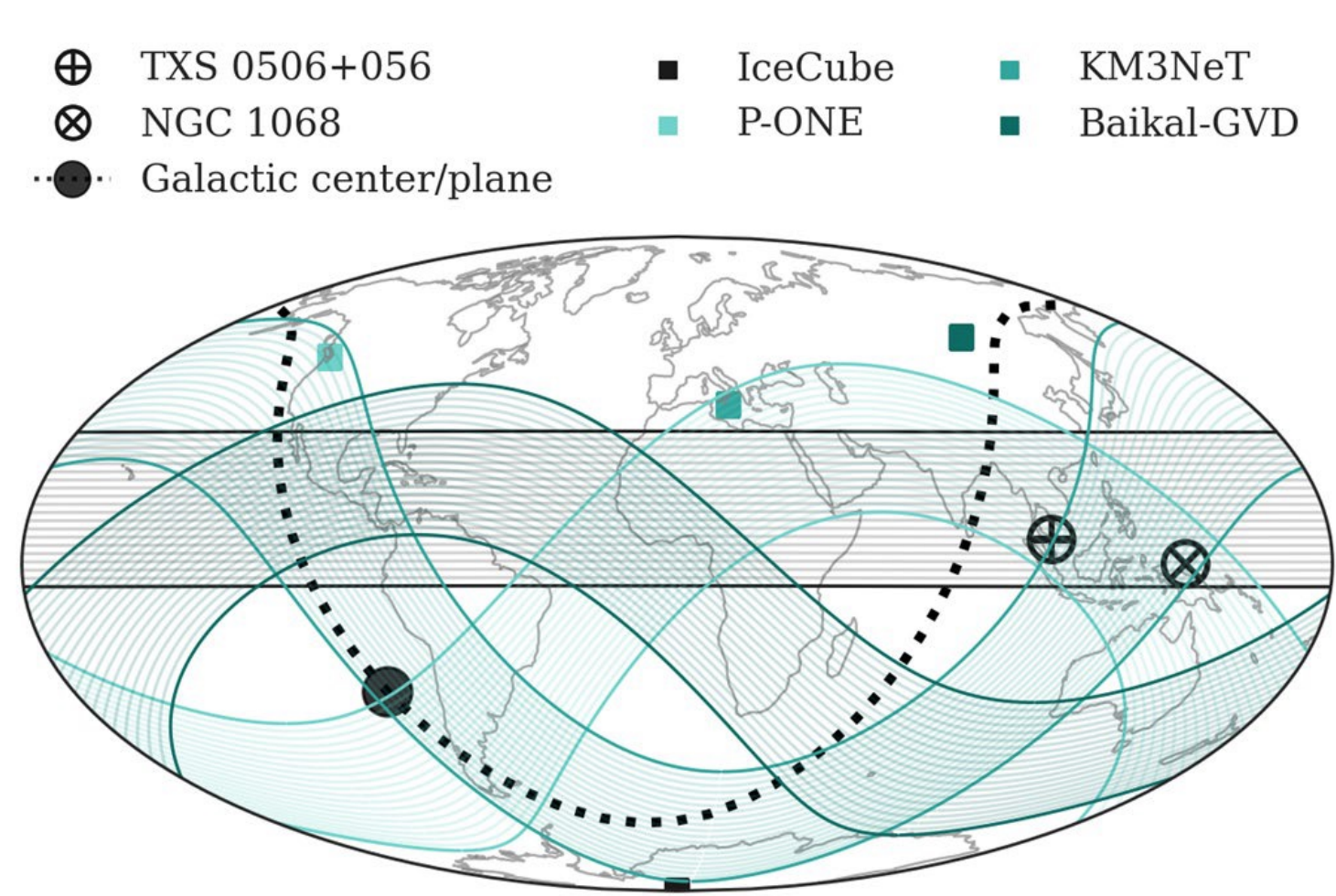
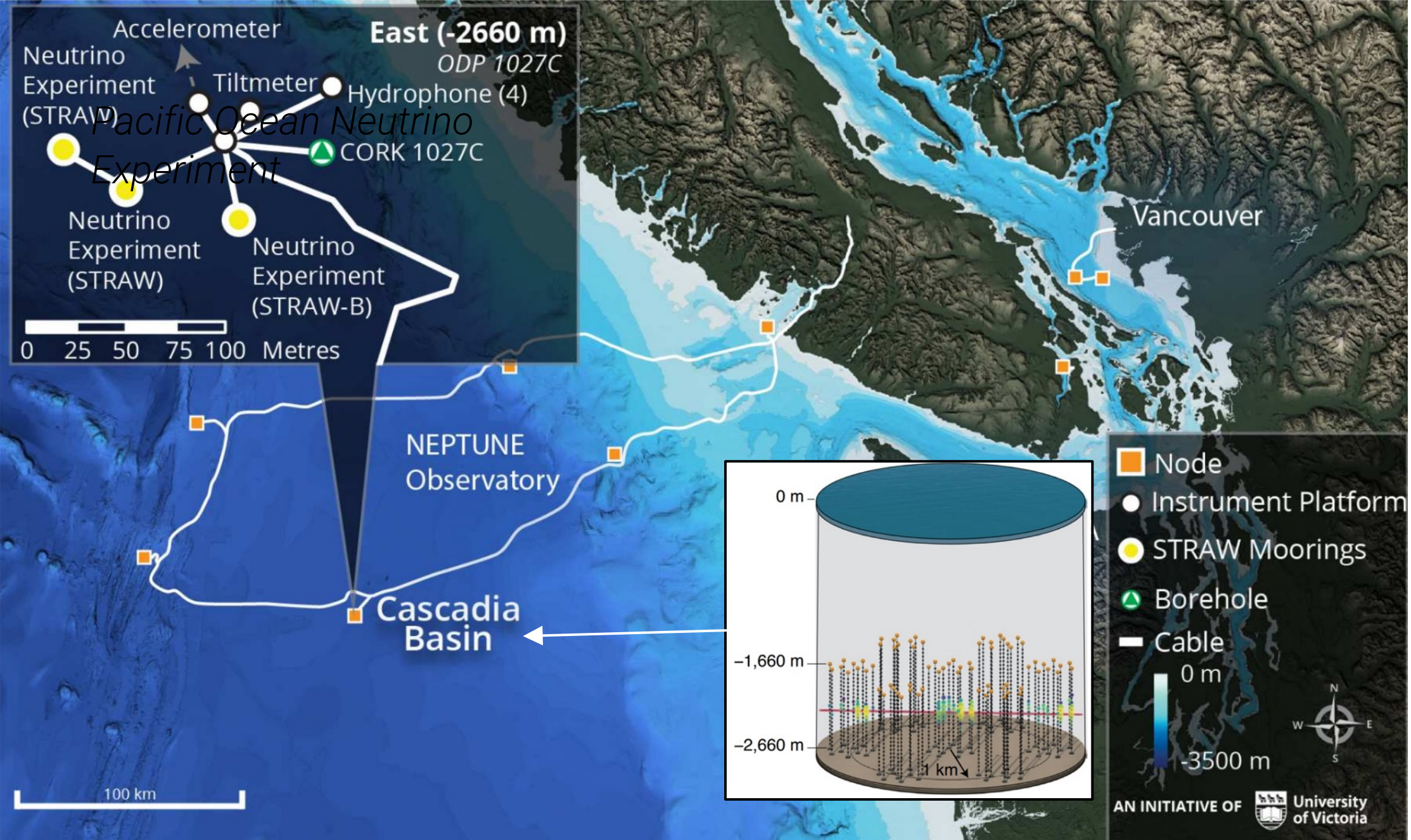
 **PUEO**

# P-ONE - underwater neutrino telescope in the Pacific

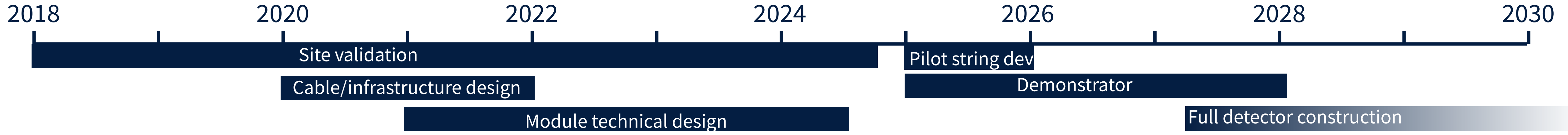
- KM3NeT multi-PMT technology
- Baikal-GVD-inspired string configuration
- IceCube expertise
- Available underwater infrastructure



- Physics coordinator
- Lead role in pathfinder analysis
- Forming multi-messenger community



The UK is converging on P-ONE as its future preferred project



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

## Neutrino astronomy



Fully exploit existing experiments



... then converge on long-term project



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

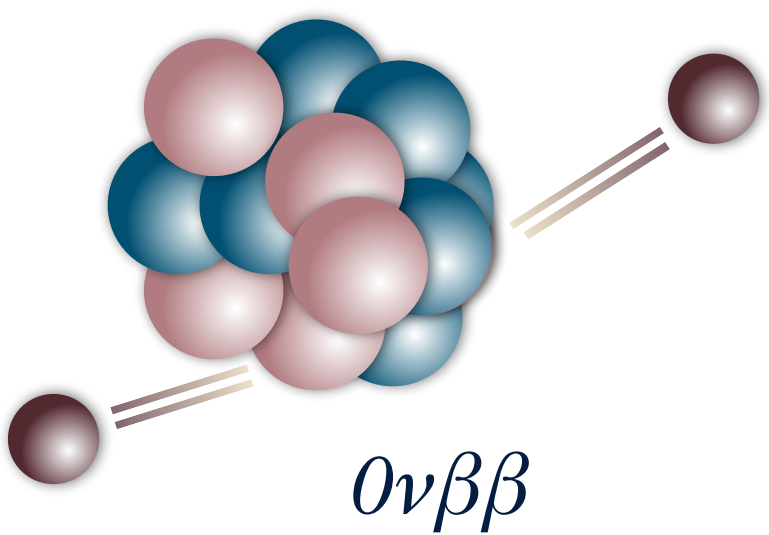
## Neutrino astronomy



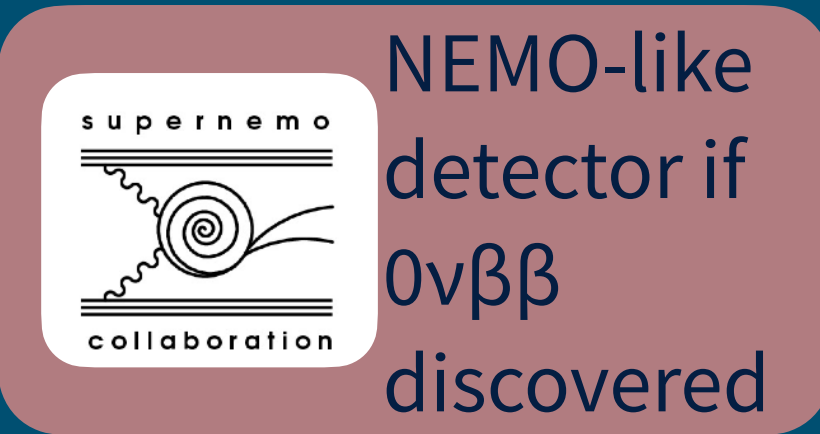
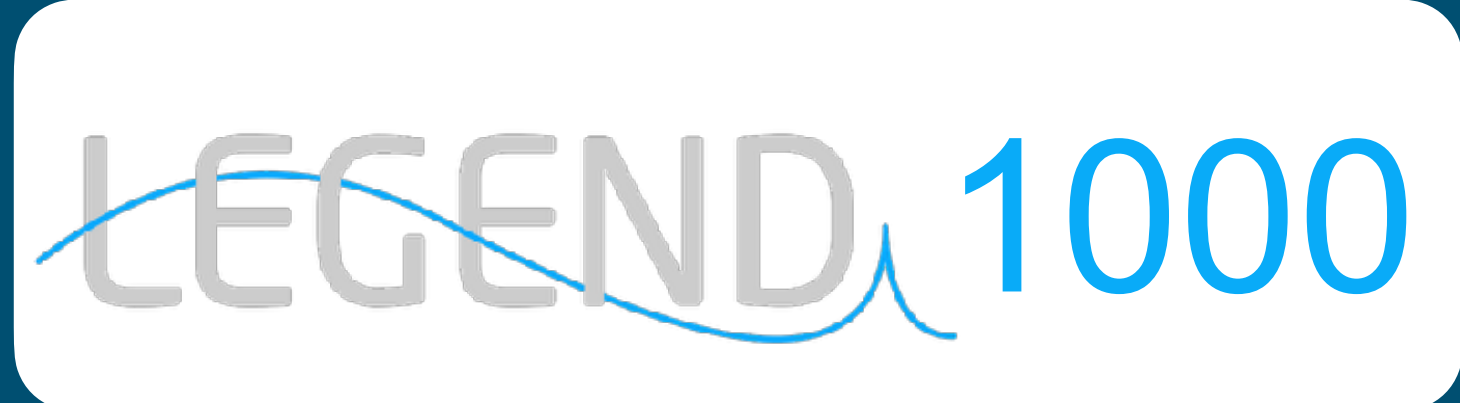
Fully exploit existing experiments



... then converge on long-term project



LEGEND 200



Tellurium loading development

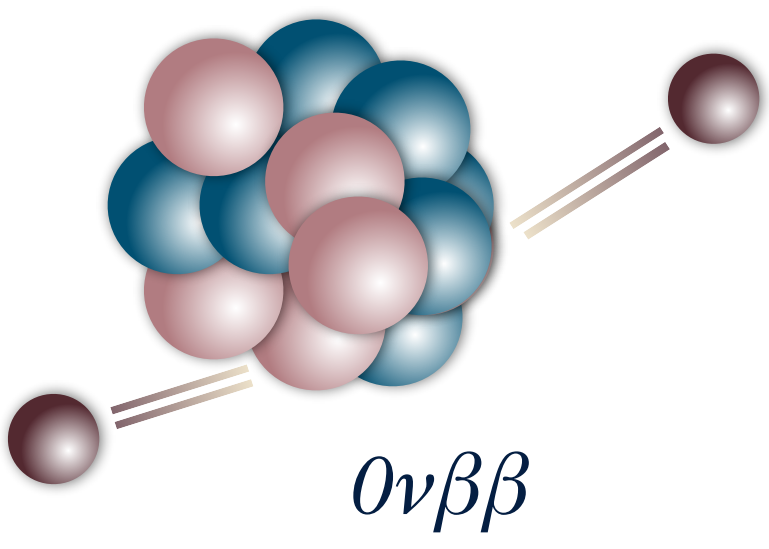
# UK non-accelerator neutrino community plan - but we need funding to support it!

## Neutrino astronomy



Fully exploit existing experiments

... then converge on long-term project



LEGEND 200

LEGEND 1000

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

SNO+

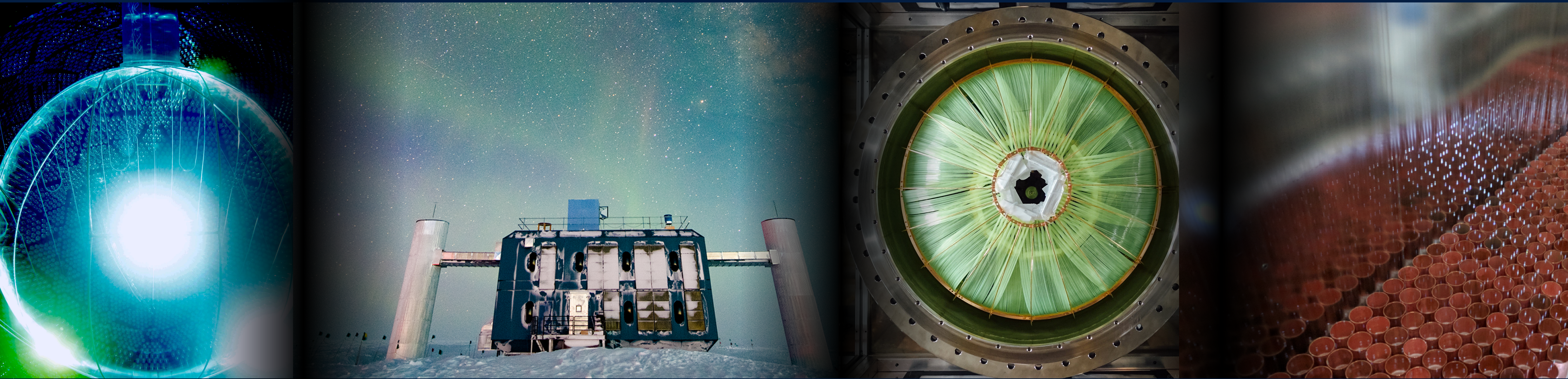
@next

Tellurium loading development

...and more

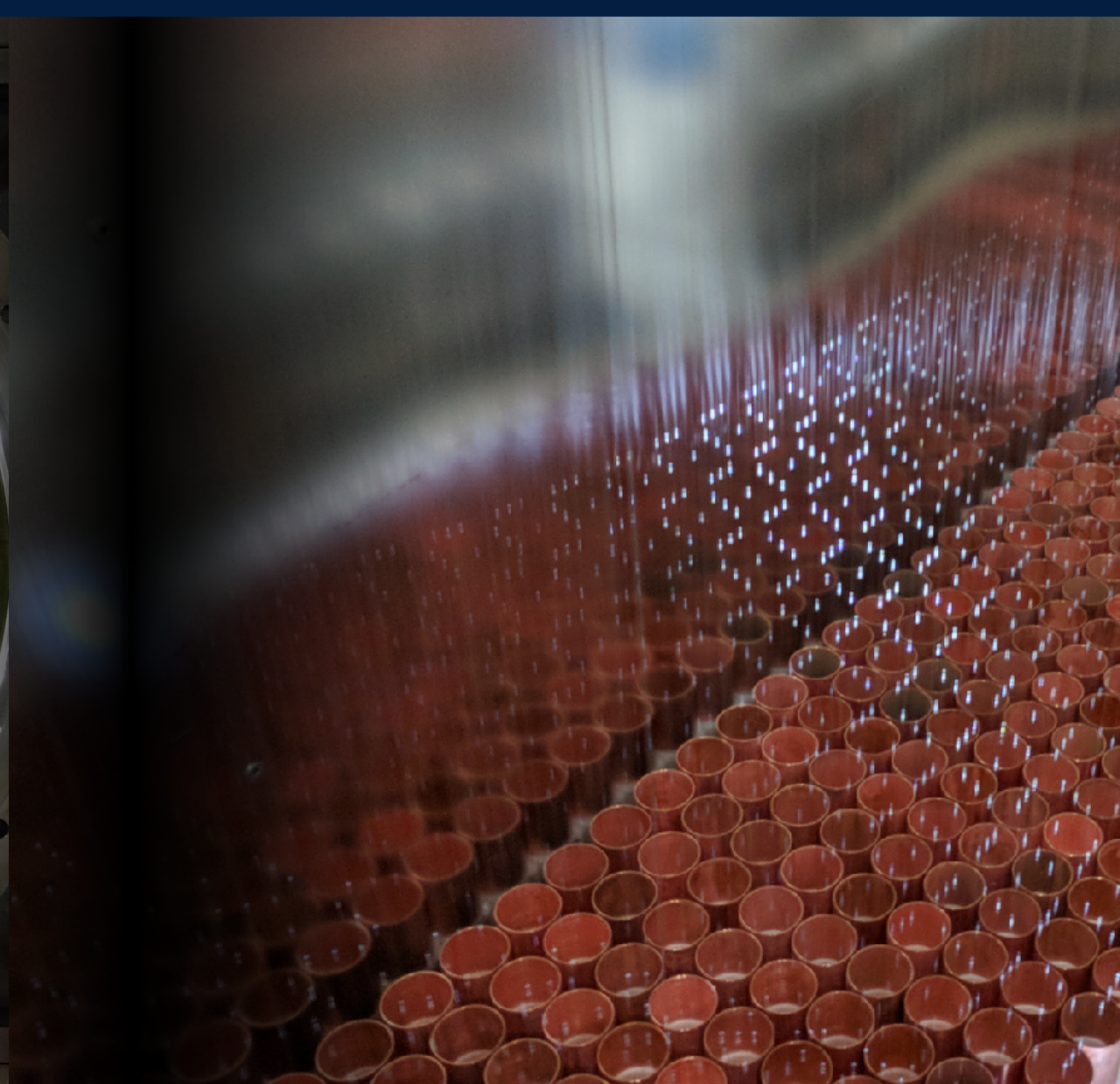


# Thank you for contributions



T Katori, King's College London  
J Wilson, King's College London  
M Agostini, UCL  
R Nichol, UCL

R Saakyan, UCL  
J Hartnell, University of Sussex,  
M Wascko, University of Oxford,  
X Lu, Warwick University







- 5 Institutions
- 7 Academics/senior researchers
- 1 PDRAs
- 3 PhD students

## UK responsibilities

- Tracking detector
- neutron shielding,
- helium recycling
- software and analysis
- 3 spokespeople, 1 analysis coordinator

## Future prospects

- **Data taking until ~ 2027**
- World-leading  $^{82}\text{Se}$  measurements of
  - $0\nu\beta\beta$  limit
  - $g_A$  constraint
  - Exotic decay-mode searches
- Proof of concept:
  - Modular design
  - Ultra-low background techniques
  - Helium-ethanol separation
  - Source-foil production techniques
- Build larger SuperNEMO-like detector if/when  $0\nu\beta\beta$  is discovered to investigate mechanism
- Until then, **pause project** after Demonstrator



- 4.5 Institutions
- 9 Academics/senior researchers
- 4 PDRAs
- 7 PhD students

## UK responsibilities

- Tellurium loading
- Calibration system
- Software
- Data analysis
- **1** analysis coordinator, board & executive committee chair

## Future prospects

- In **exploitation phase** - Te loading to start 2025
- **Current UK commitment is to demonstrate 0.5% Te loading**
- Canadian colleagues bidding to increase Te loading to 2.5-3% - positive review from SNOLAB Director
- **Potential to reach normal hierarchy** range with higher Te loading levels

# LEGEND-200 in the UK



- 6 Institutions
- 12 Academics/senior researchers
- 2 PDRAs
- 4 PhD students

- ### UK responsibilities
- First results shown at Neutrino 2024 with UK leadership
  - 2 IB chairs, 1 analysis coordinator




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# Other low-energy physics - CLOUD at CHOOZ, France

## Reactor Neutrinos



- 2 Institutions
  - 5 Academics / lab scientists
  - 1.5 PDRAs
  - 5 PhD students
  - 2 Engineers
- Spokesperson  
UK-based

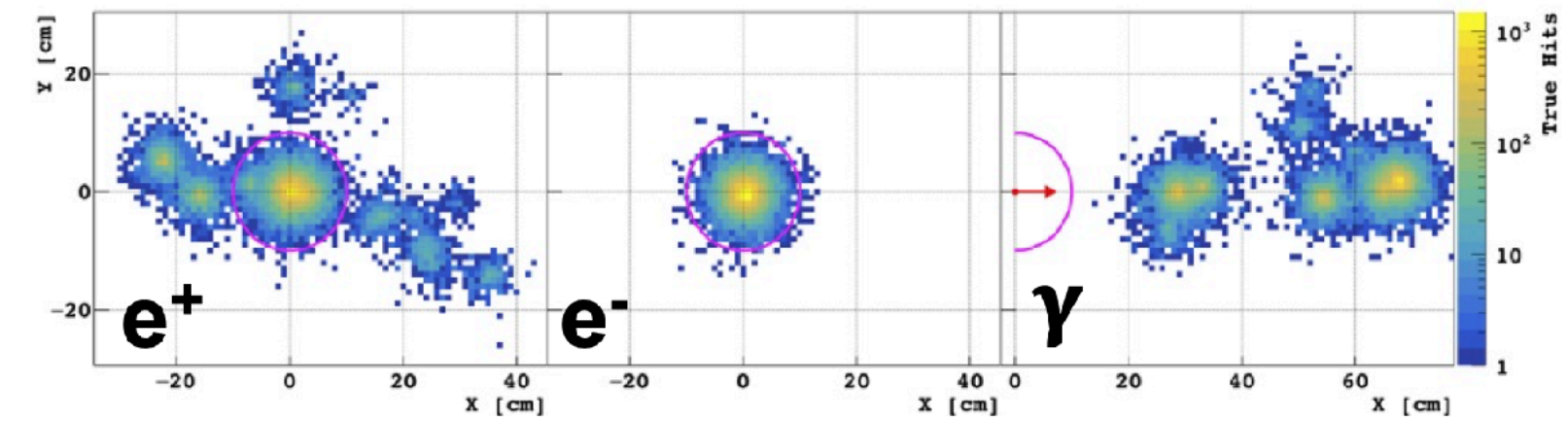
- ### Physics programme
- Funded to develop LiquidO technology for reactor monitoring
  - Phase 1 - reactor characterisation (U/Pu composition)
  - Phase 2 - indium loading: measure reactor  $\nu_e$  production
  - Phase 3 - copper loading: low-energy IBD detection first step for  $^{40}\text{K}$  geoneutrino search
  - Technology could be used for  $0\nu\beta\beta$  and more



Rutherford  
Appleton Lab

Funded by EIC  
and UKRI

### Liquid-O technology



Opaque scintillator for particle discrimination

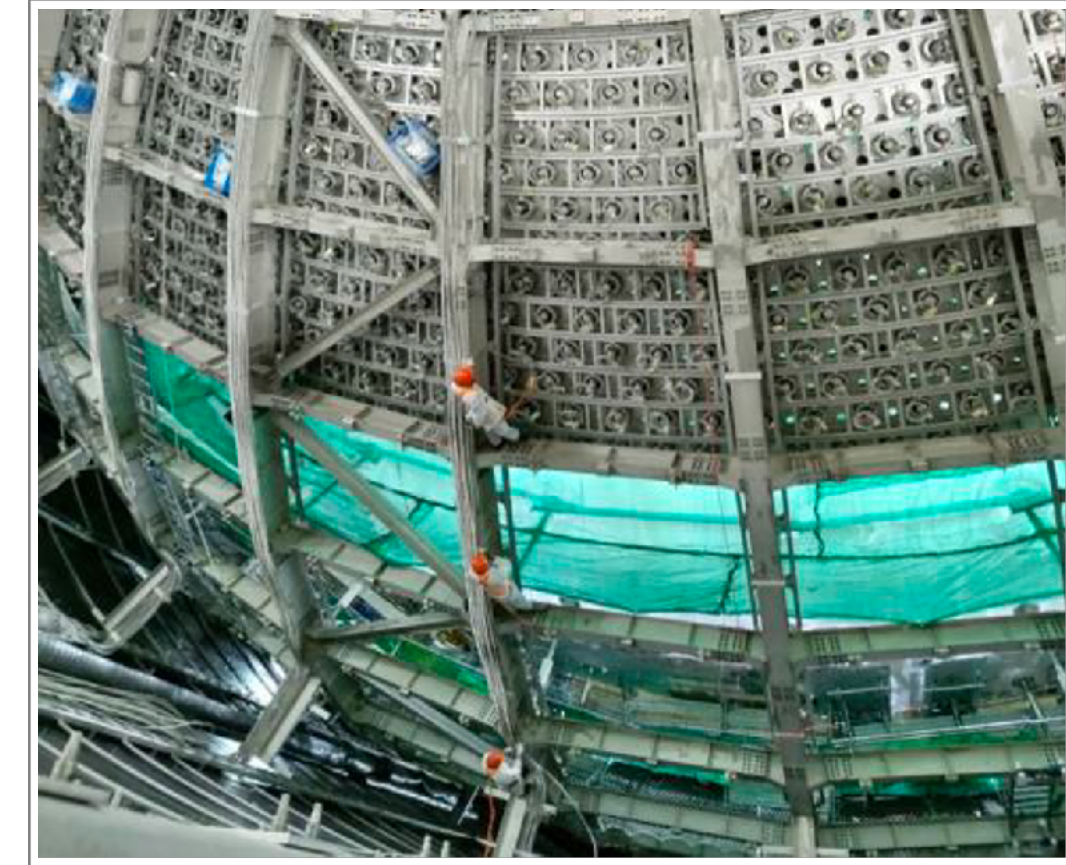
ject funded from: Dec/22)

## Reactor Neutrinos



## Physics programme

- Determine mass hierarchy
  - $3\sigma$  in 6 years with reactor neutrinos only
  - Improve sensitivity with atmospheric neutrinos
- Measure  $3\nu$ -oscillation parameters: 0.5% precision in 6 years
- Solar & supernova neutrinos, geo-neutrinos, nucleon decays



WARWICK  
THE UNIVERSITY OF WARWICK



UNIVERSITY OF  
LIVERPOOL

Funded by RS,  
STFC ERF, China  
Scholarship  
Council

- 2** Institutions
- 2** Academics
- 4** PhD students

## UK contributions

- Working-group convenor
- Neutrino interaction simulations and systematic studies
- Atmospheric neutrino oscillation analysis
- ML-based neutrino event reconstruction