SNO+/LEGEND/IceCube/ANITA

Slide courtesy
- Jeanne Wilson (SNO+)
- Matteo Agostini (LEGEND, P-ONE)
- Ryan Nichol (ANITA)

Teppei Katori
King's College London
PPAP townhall meeting, Jan. 7, 2021

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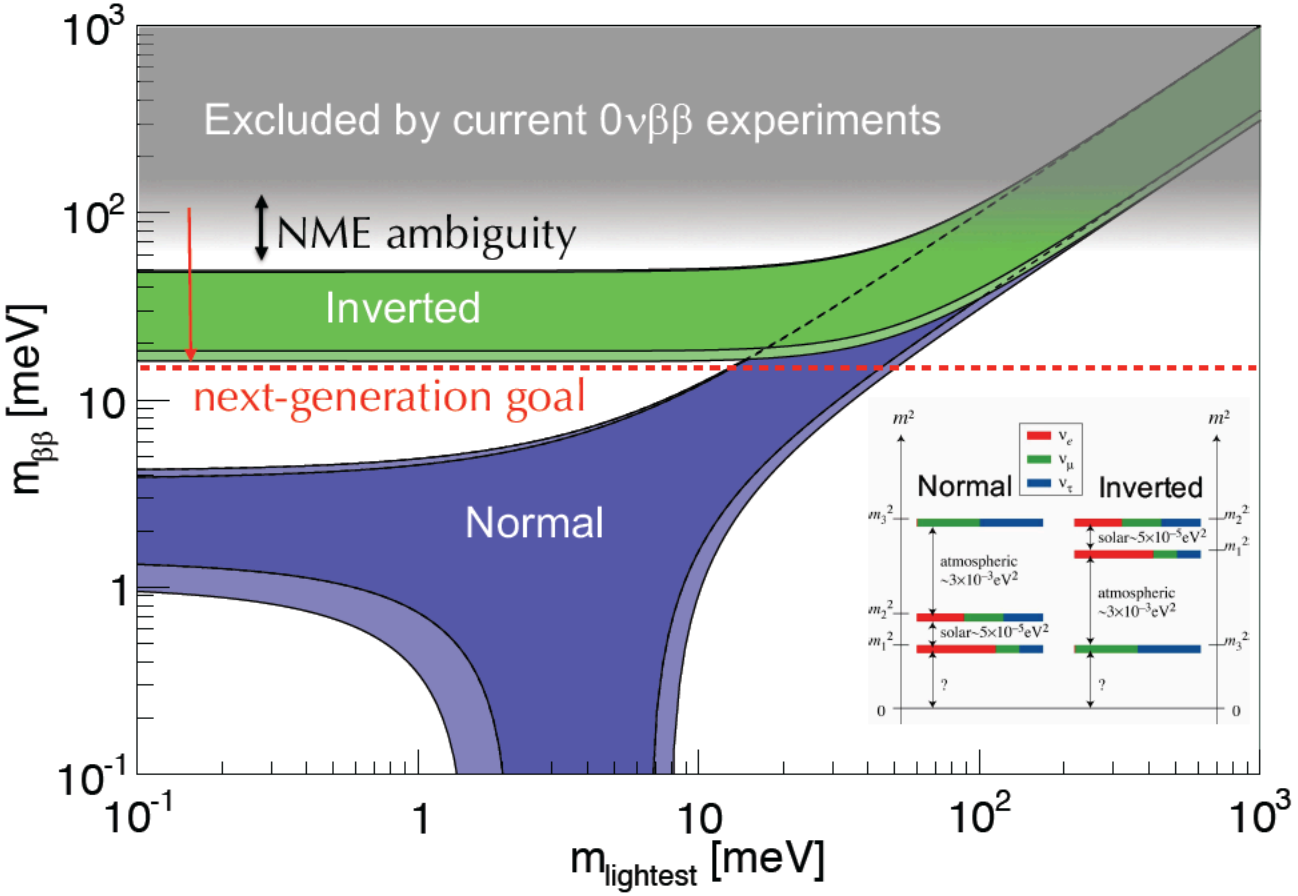
0νββ experiment

Next generation experiments' goal
- Cover all IO region
- Explore 50% of NO phase space

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{NN}\, m_\pi^2}{g_A^2} M^{0\nu}_{cont} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

Collaboration	Isotope	Technique
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers
GERDA	^{76}Ge	Point contact Ge in active LAr
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead
LEGEND 200	^{76}Ge	Point contact Ge in active LAr
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr
SuperNEMO Demonstrator	^{82}Se	Foils with tracking
SELENA	^{82}Se	Se CCDs
NvDEx	^{82}Se	SeF_6 high pressure gas TPC
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors
CUORE	^{130}Te	TeO_2 Bolometer
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator
EXO-200	^{136}Xe	Xe liquid TPC
nEXO	^{136}Xe	Xe liquid TPC
NEXT-WHITE	^{136}Xe	High pressure GXe TPC
NEXT-100	^{136}Xe	High pressure GXe TPC
PandaX	^{136}Xe	High pressure GXe TPC
AXEL	^{136}Xe	High pressure GXe TPC
DARWIN	^{136}Xe	^{nat}Xe liquid TPC
LZ	^{136}Xe	^{nat}Xe liquid TPC
Theia-Xe	^{136}Xe	3% in liquid scintillator

R&D | Construction | Operating

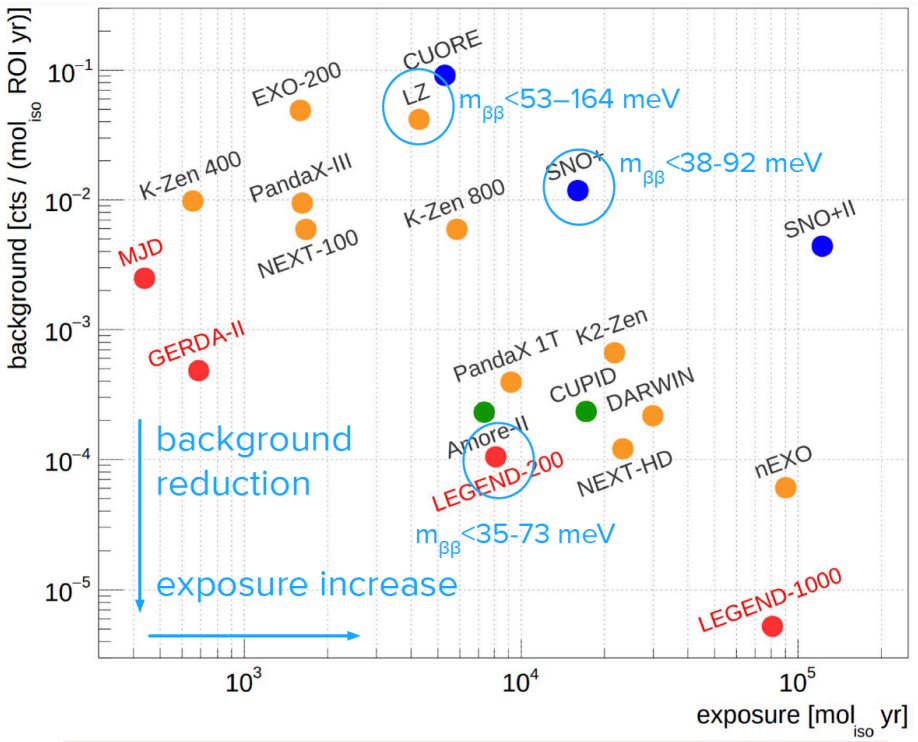


Detwiler, Neutrino 2020

UK 0νββ Decay Experiments

Iso	EXPERIMENT	STATUS	TECHNOLOGY
^{76}Ge	LEGEND	in construction (L200)	semiconductor detectors
^{82}Se	SuperNEMO	commissioning	Trackers & Calorimeters
^{100}Mo	NEMO-3	completed	
^{130}Te	SNO+	in construction (Phase I)	Loaded Scintillator
	Watchman	R&D	Loaded Scintillator
^{136}Xe	LZ	commissioning	Time Projection Chamber

Experimental Strategies:
Mass Scalability vs. Background Level
Calorimetry vs. Tracking

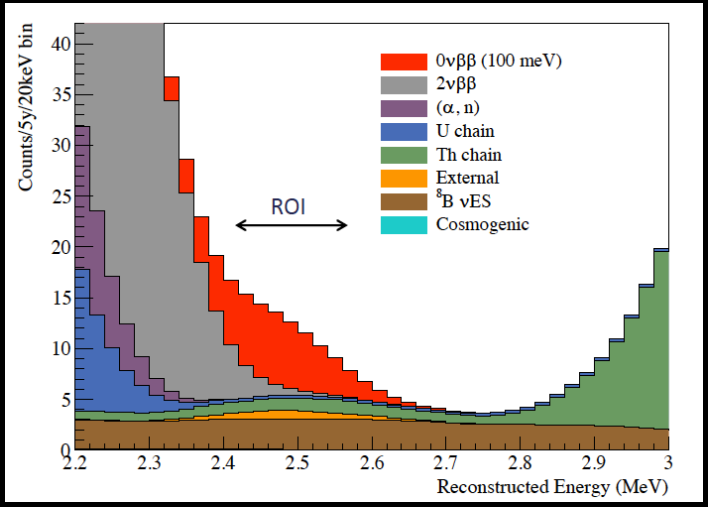


Different background/exposure combinations can lead to similar $m_{\beta\beta}$ sensitivities

SNO+

^{130}Te-loaded LS 0νββ experiment
- scalable, cost-effective
- statistically identify 0νββ over well understood background

Sensitivity (0.5% ^{130}Te, 3-yr)
- $T_{1/2} > 2 \times 10^{26}$ yr → - $m_{\beta\beta}$~37-89 meV



2km underground in SNOLAB, ~6000 MWE

780 tons of **Liquid scintillator**

Loaded with 0.5% double beta decay Isotope (Te130)

Contained in an **Acrylic vessel (AV)** 12 m diameter

Held-down by new rope system

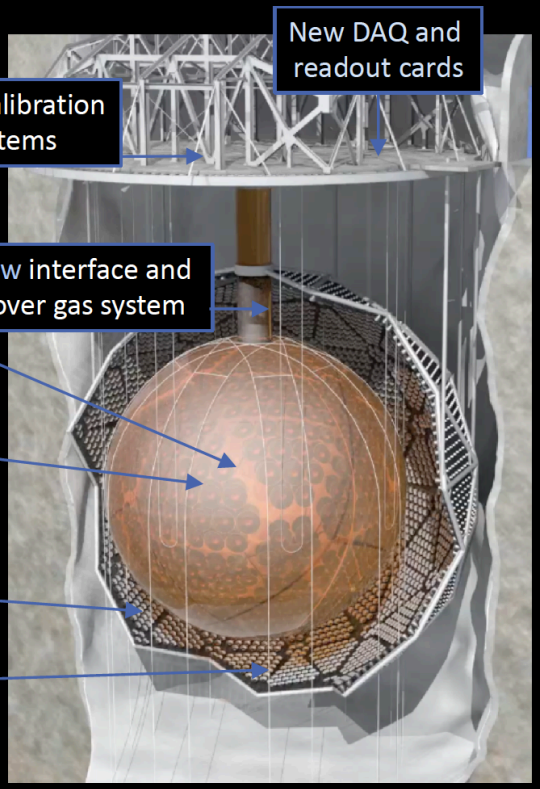
Shielded by 7 kT Ultra-pure water

Viewed by **~9300 PMTs** (8") mounted on 17 m diam. Structure

New calibration systems

New DAQ and readout cards

New interface and cover gas system

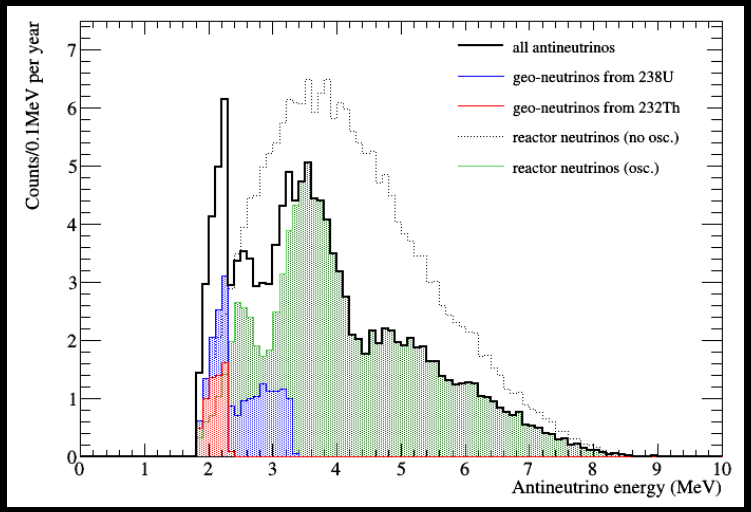


SNO+

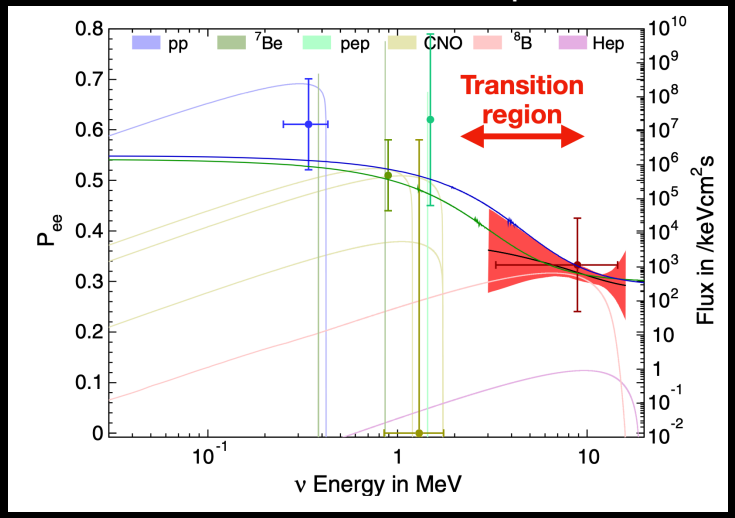
^{130}Te-loaded LS 0νββ experiment
- scalable, cost-effective
- statistically identify 0νββ over well understood background

Multi-purpose detector
- Solar neutrinos
- Geo neutrinos
- Supernova neutrinos
- Reactor neutrinos
- Invisible nucleon decay

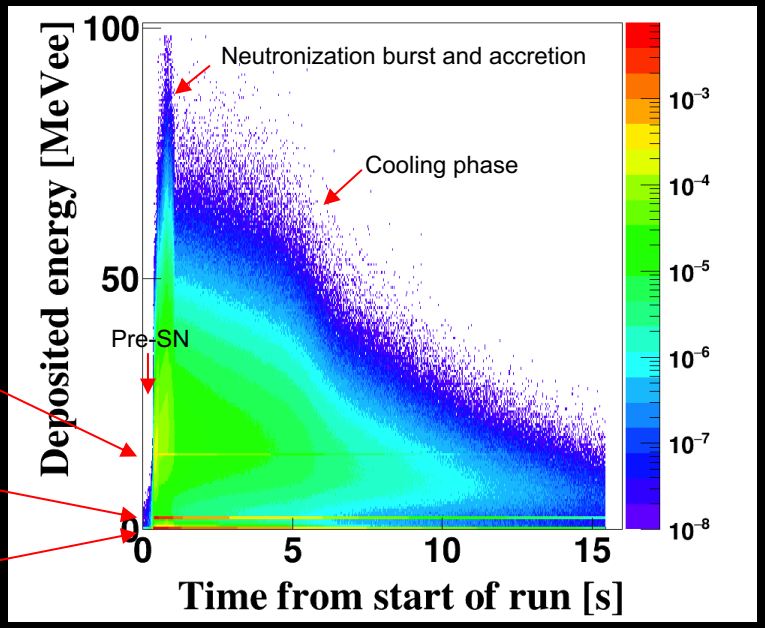
First geo-neutrino identification in American continent



Sensitive to MSW up-turn



Expected signals for 10kpc SN-II



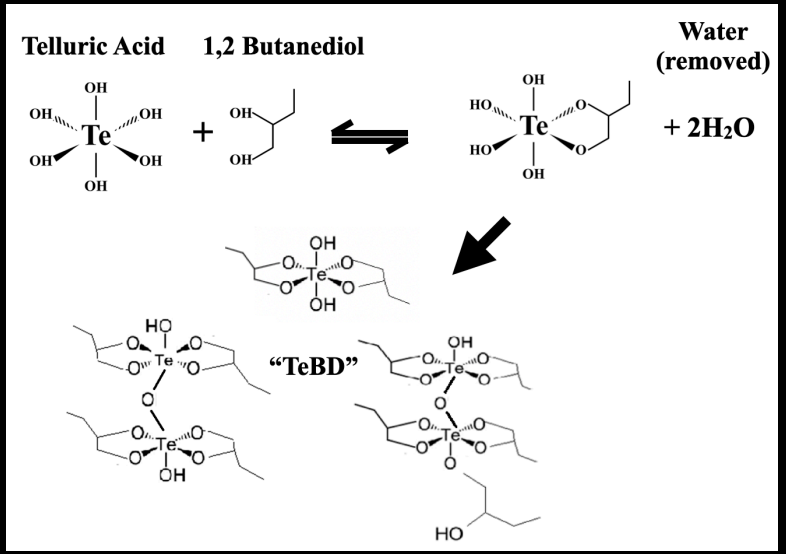
SNO+

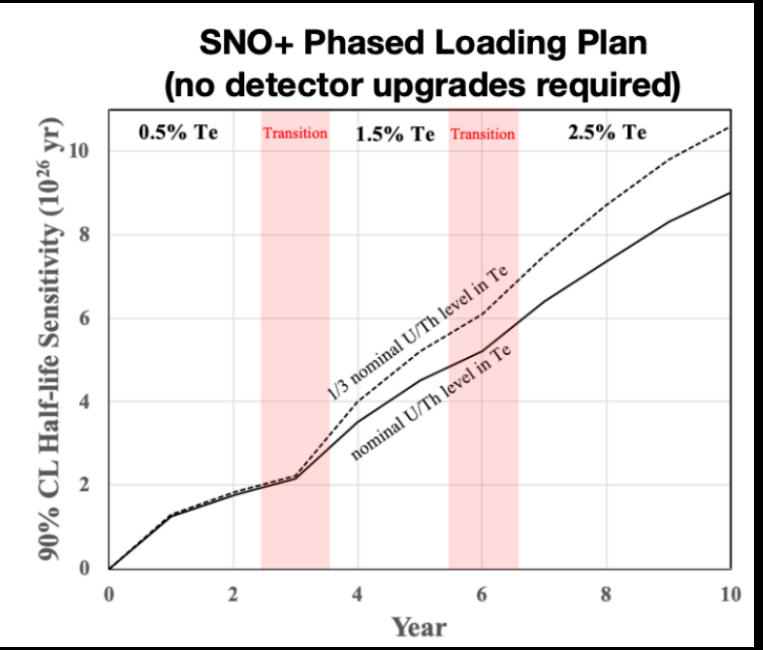
Water phase
- 2017-2019 (305 days)
- Low E water Cherenkov detector
- Physics result PRC102 (2020)014002, PRD100(2019)112005, PRD99(2019)032008

Scintillator filling
- 2019 → Apr 2020 (stop) → resume (~75% done)

Tellurium loading
- UK developed
- TeDiol (TeBD) will be mixed in LAB (0.5%)
- Staged Te-loading for background study

SNO+ UK
- Many leadership roles (analysis coordinator, leading software, reconstruction, calibration)
- Significant contributions both for analysis (supernova neutrinos, solar neutrinos, reactor neutrinos, etc)





LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

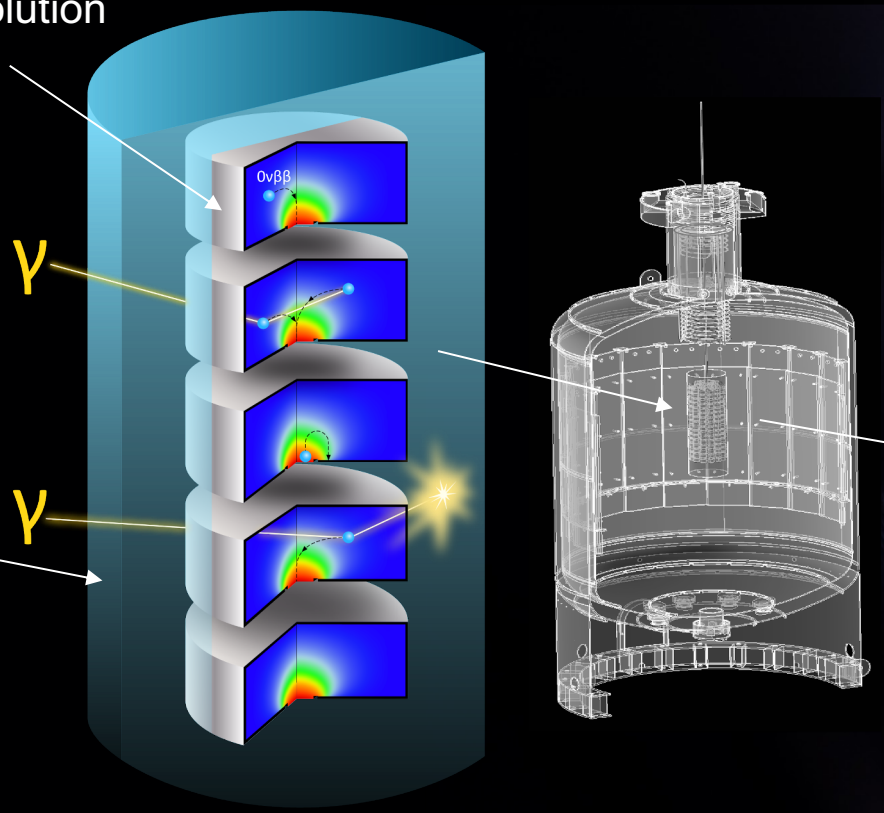
240 collaborators
48 institutions
worldwide

Ge detectors

- high efficiency
- <0.1% energy resolution
- event topology

Liquid Ar bath

- active shield
- scintillation light



A Background-free Discovery Machine!

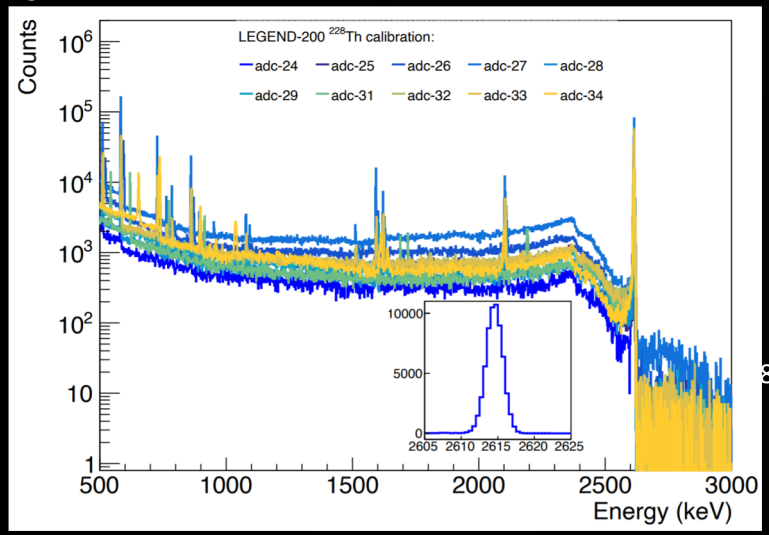
LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Staged Approach:

- GERDA/MAJORANA (40 kg of detectors, $T_{1/2} > 10^{26}$ y)
- LEGEND-200 ($T_{1/2} > 10^{27}$ y / $m_{\beta\beta} <$ 35-73 meV)
  - 200 kg of detector mass at LNGS
  - ongoing upgrade of GERDA infrastructure
  - **physics data taking in 2021**
- LEGEND-1000 ($T_{1/2} > 10^{28}$ y / $m_{\beta\beta} <$ 10-20 meV)
  - 1 ton of detector mass
  - Conceptual Design Report under preparation for US down-selection (now Portfolio Review)

LEGEND-200 integration tests in 2020 (20 detectors / 4 strings)



LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Lancaster University

UNIVERSITY OF LIVERPOOL

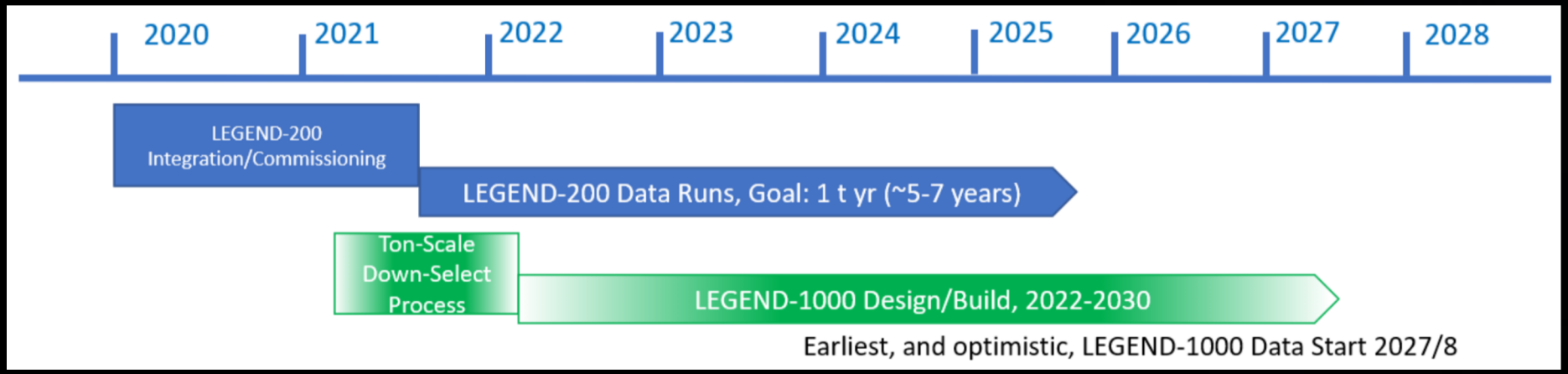
UCL

THE UNIVERSITY OF WARWICK

UK contributions:

- Ge detector characterisation
- Novel HPGe detector development
- Radio-assays
- Software and Analysis
- Novel Scintillating materials (PEN)

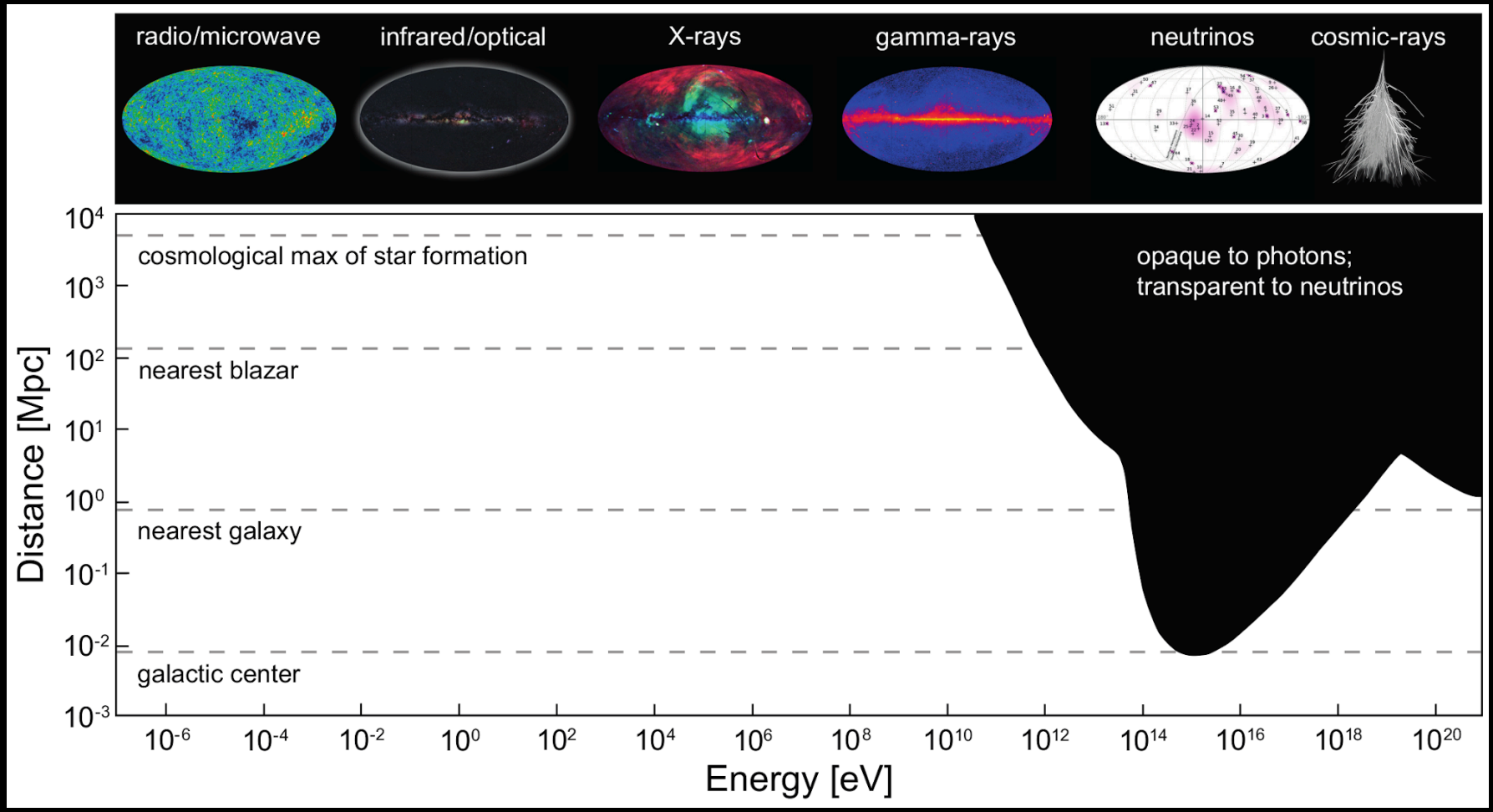
- Founding members of LEGEND
- Leadership roles (Analysis Coordinator, IB Chair, Steering Committee)
- Leveraging UK investment in nuclear physics, low-background, detector technologies, as well seed corn STFC Opportunities funding (£140k)



9

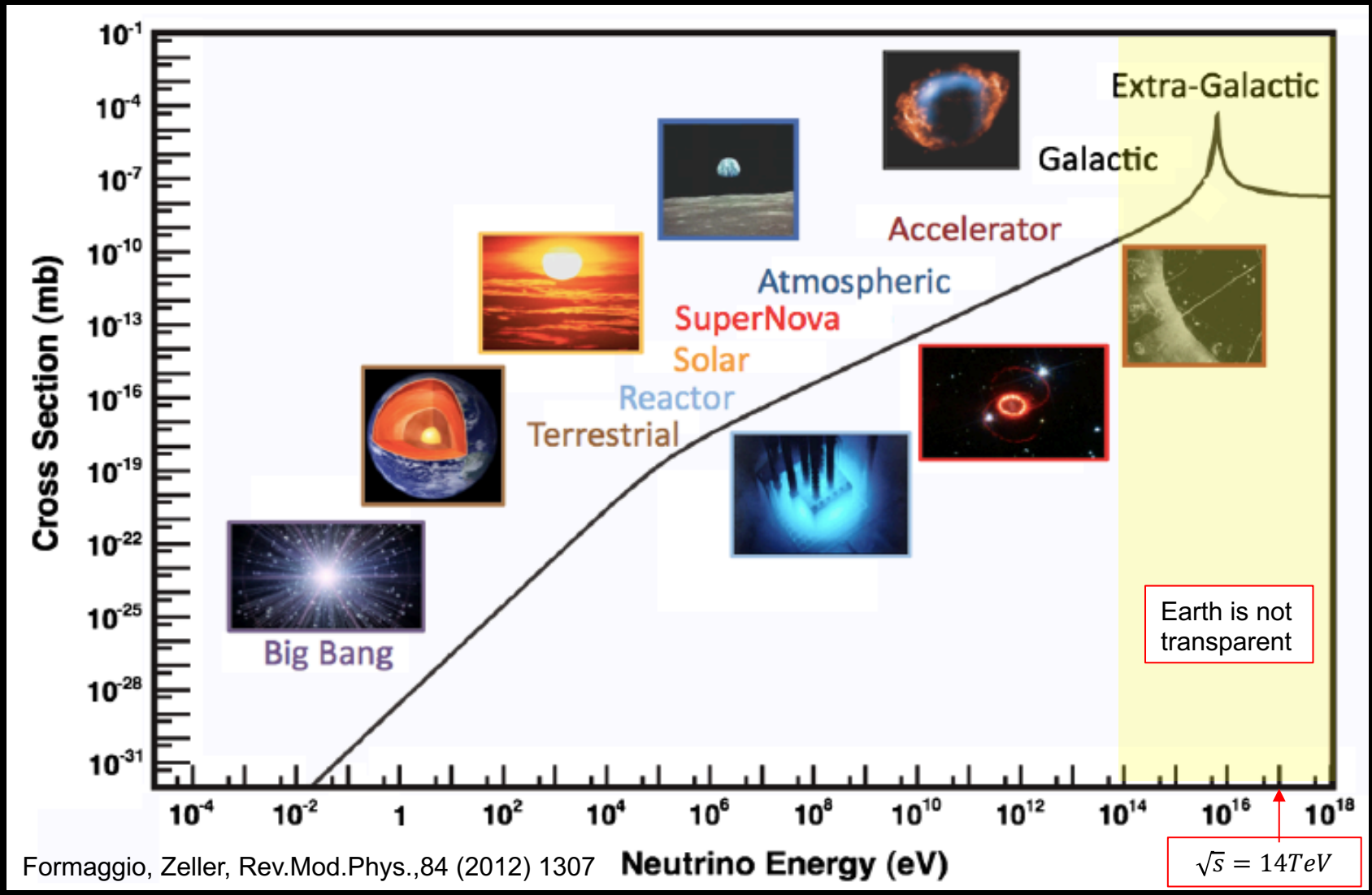
High-Energy Neutrino Astronomy

Above ~100 TeV neutrinos are only direct messengers



High-Energy Neutrino Astronomy

Above ~100 TeV neutrinos are only direct messengers

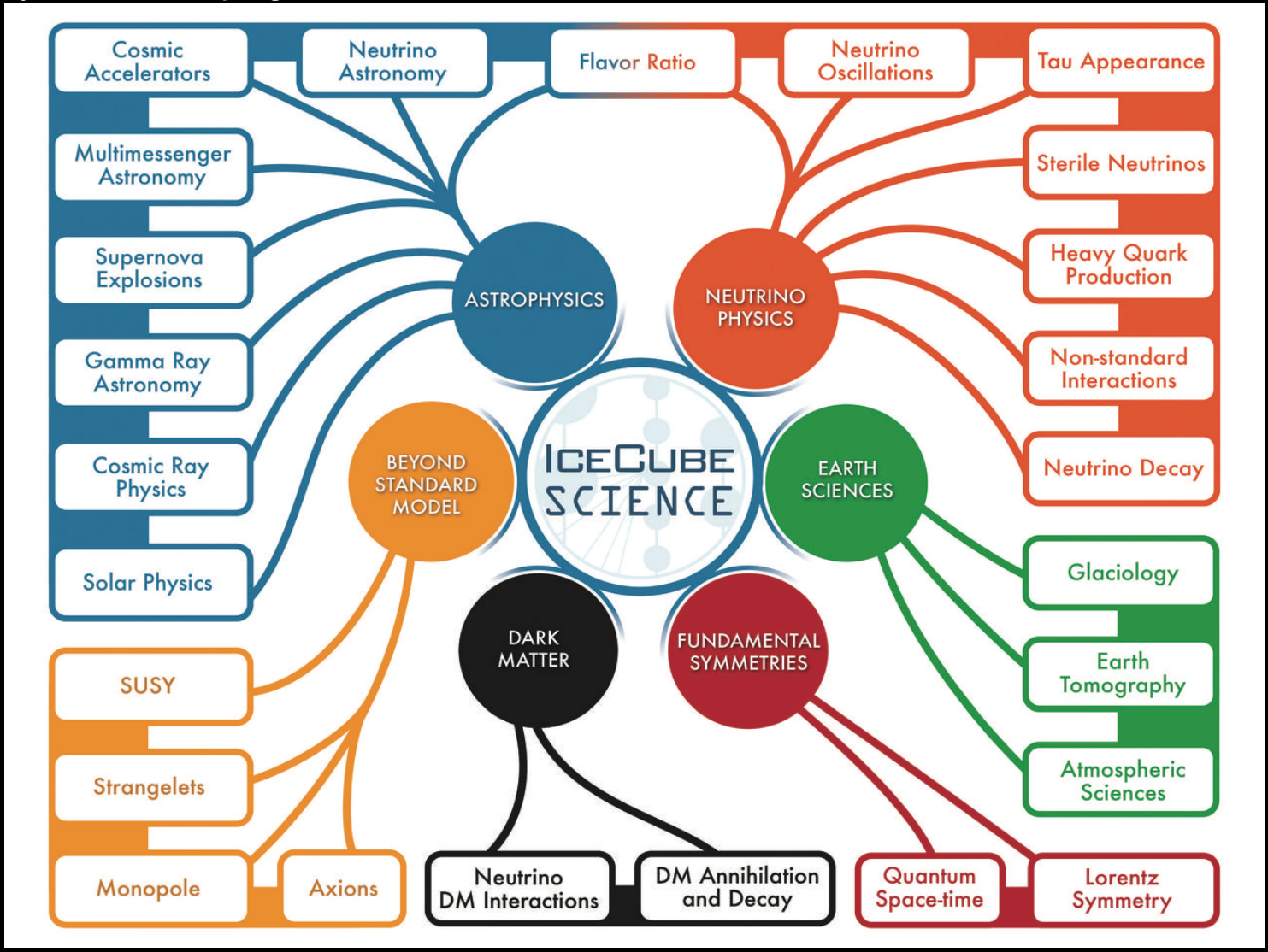


Formaggio, Zeller, Rev.Mod.Phys.,84 (2012) 1307

High-Energy Neutrino Astronomy

Above ~100 TeV neutrinos are only direct messengers

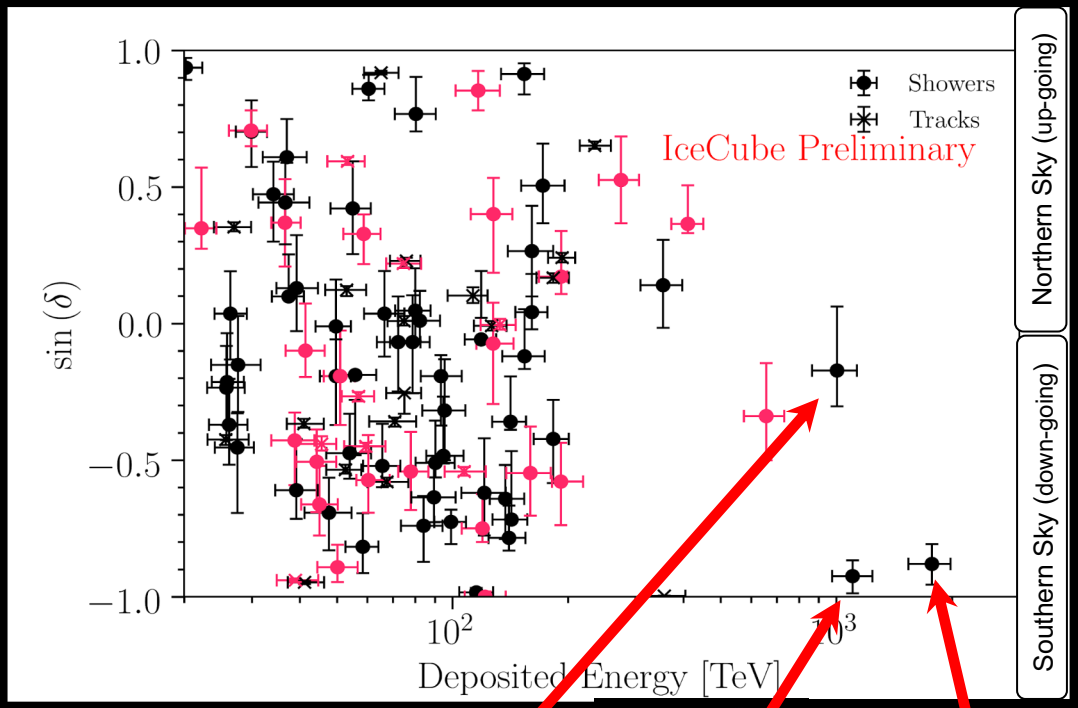
Extremely rich science program

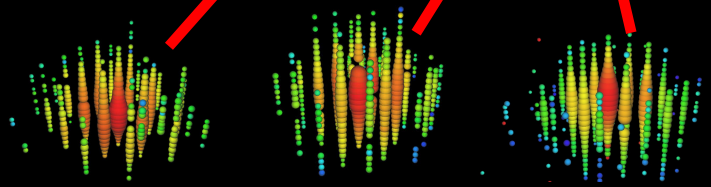


IceCube,ArXiv:2011.03545,2011.03560,2011.03561

IceCube

Diffuse events
- Data set major update (2020)
- Improved reconstruction and systematics
- low energy events for oscillation physics



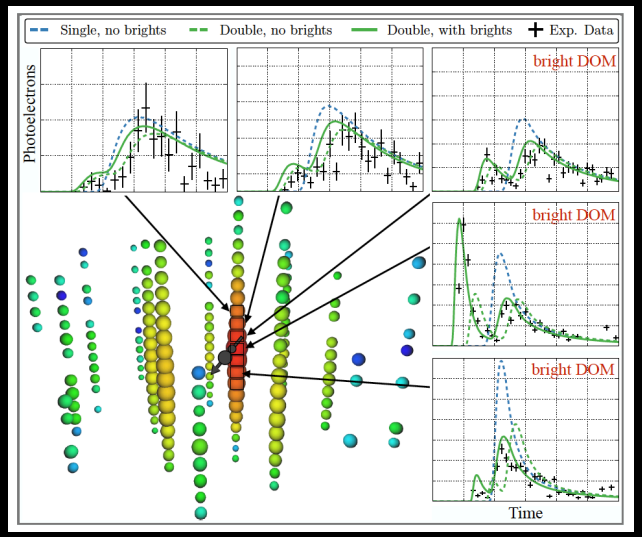


"Bert"
1.1 PeV

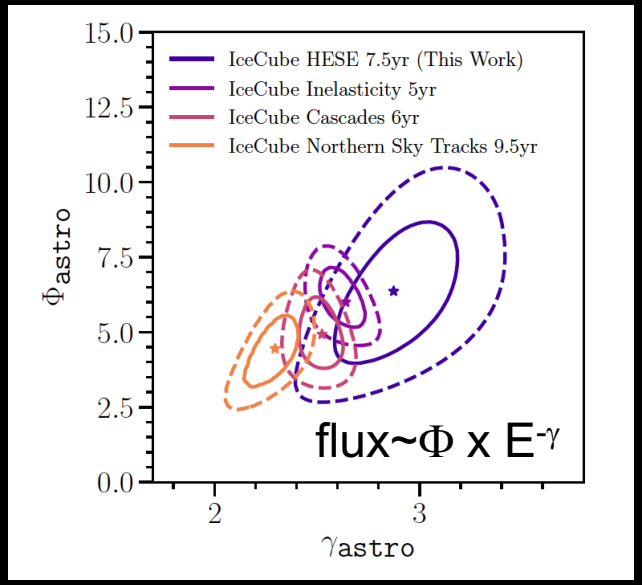
"Ernie"
1.0 PeV

"Big Bird"
2.0 PeV

"Double Double"
tau-neutrino candidate



Spectrum index

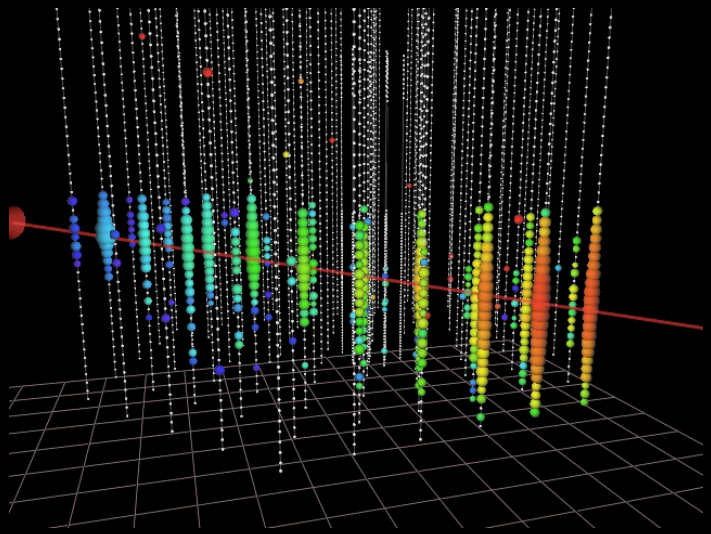


IceCube,ArXiv:2011.03545,2011.03560,2011.03561
IceCube,Science361(2018)147, IceCube et al,(2018)eaat1378

IceCube

Diffuse events
- Data set major update (2020)
- Improved reconstruction and systematics
- low energy events for oscillation physics

Point source & transient events
- Multi-messenger astronomy (optics, GW)
- Realtime alert (2016)
- Blazar neutrino (2018)



IC170922A (290TeV)

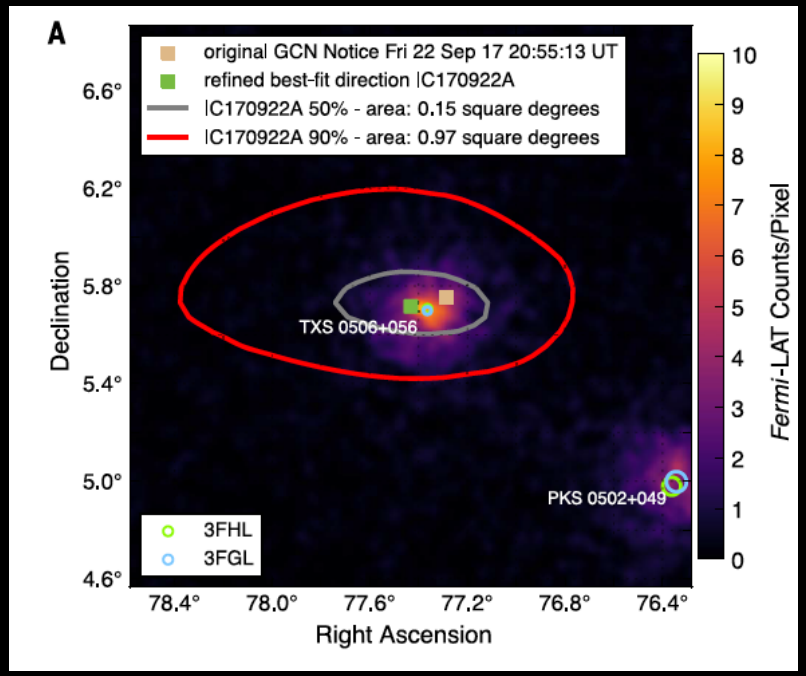
Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

Fermi-LAT



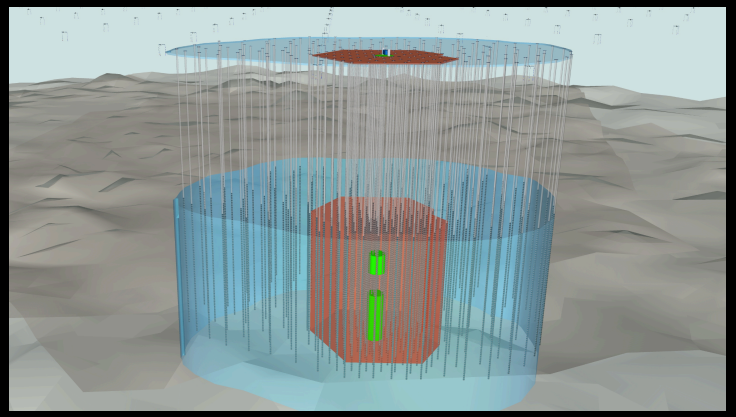
Full coverage, radio wavelength to gamma rays by everyone: Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403

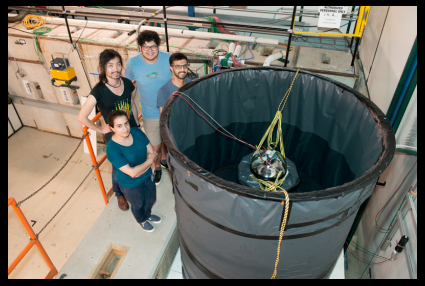
IceCube,ArXiv:2008.04323

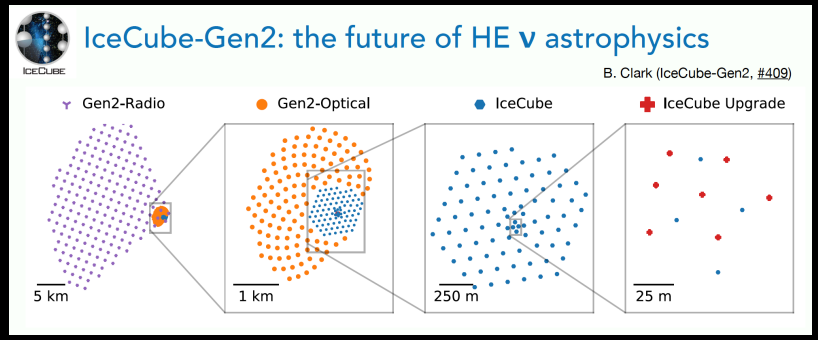
IceCube-Gen2

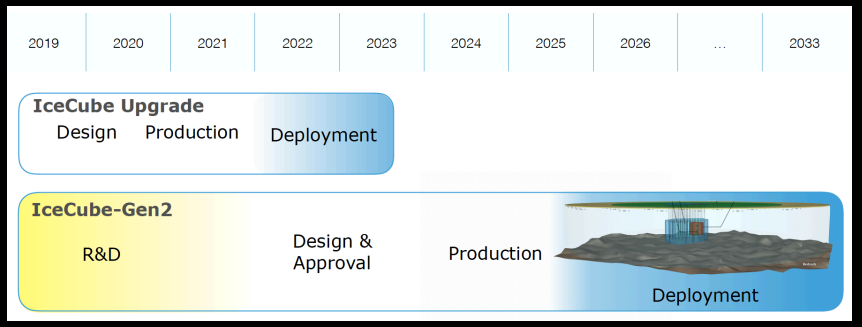
IceCube-Gen2 include many projects
- Larger IceCube array (~x8)
- ARA (Askaryan Radio-telescope Array)
- PINGU (oscillation physics)
  - IceCube Upgrade (7 new PINGU strings, 2023)
- New sensors, calibration devices, surface array

IceCube-UK
- Funding: CG, Royal Society, university
- Analyses: Oscillation EPJC80(2020)9 PRD101(2020)032006, BSM physics Nature Physics 14(2018)961, flux/xs studies PRD95(2017)023012 JPhysG42(2015)115004, etc
- Software: Oscillation fit code NIMA977(2020)164332, Bayesian BSM fit ArXiv:2011.03545, etc
- Hardware: Fermilab beam test JINST15(2020)T05002, etc



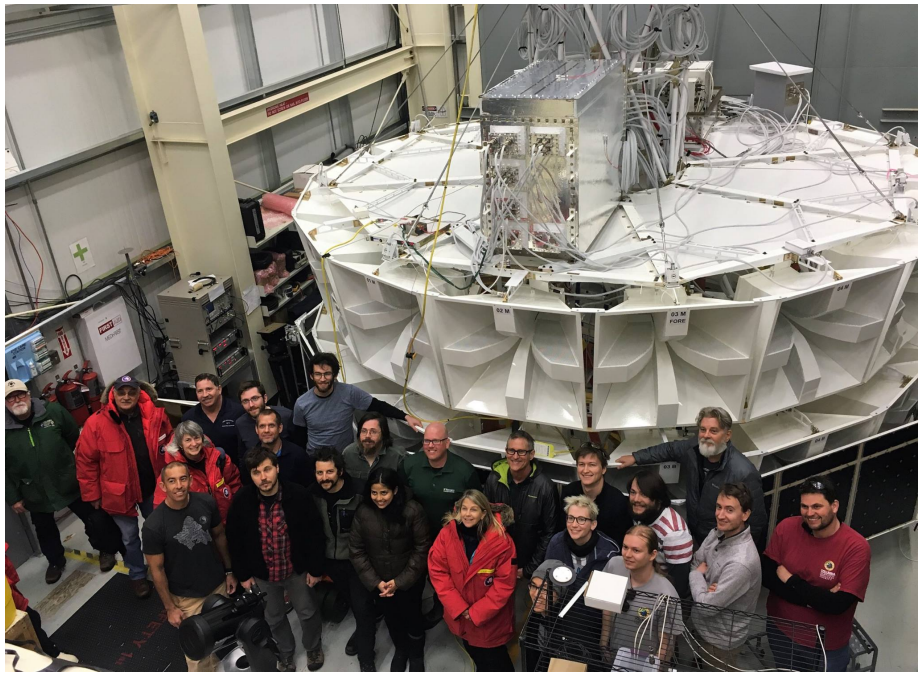


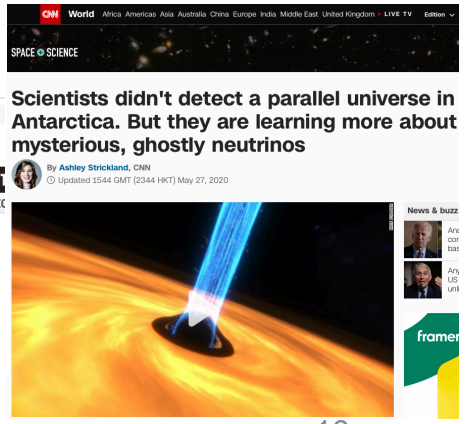




ANITA Past

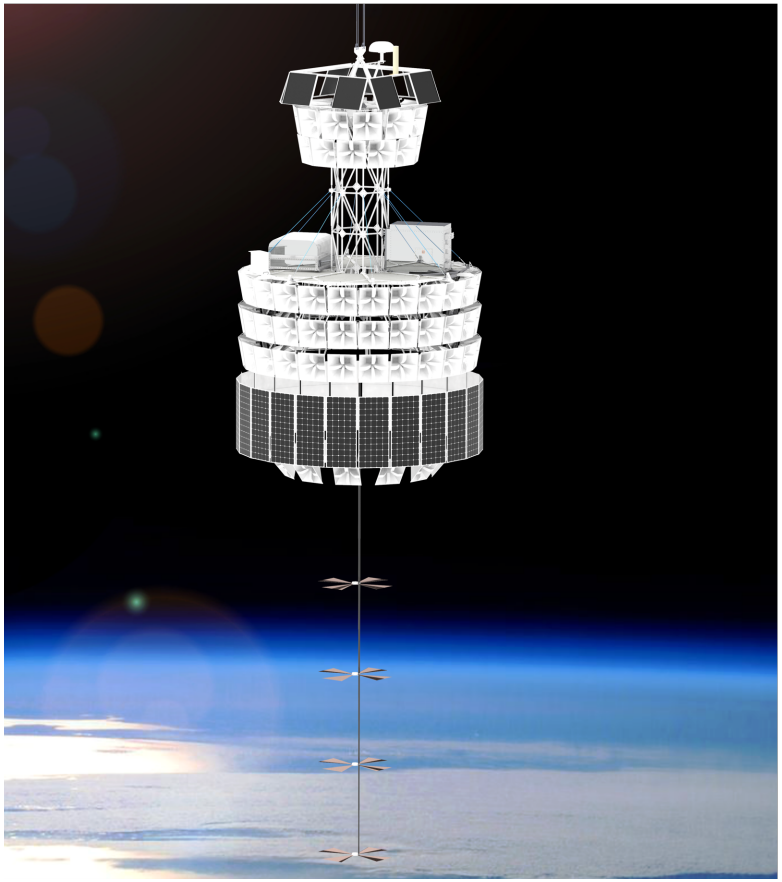
- Ultra-high energy neutrino search experiment using radio-Cherenkov technique
  - Searching for the neutrinos that come from the highest energy cosmic rays
- UK have been involved in all four ANITA flights (2006-2016/17)
  - Significant fraction of the collaboration (3/16th of on-ice effort)
  - Funded by STFC (PRD & CG), Royal Society and Leverhulme Trust
  - ‘Anomalous’ events which have resulted in ‘interesting’ theoretical interpretations… caused some fun headlines in 2019/2020.





PUEO: Payload for Ultrahigh Energy Observations

- A new name and a new paradigm
  - Embracing the technological advances to implement a trigger based on high-bandwidth digital filtering and beam forming
  - Prototype digitisation system based on XILINX RFSoC (FPGA) under development at UCL (and in the US)
- NASA Astrophysics Pioneers announcement expected this week with a launch date of December 2024
  - UCL and QMUL collaborators



PUEO Sensitivity

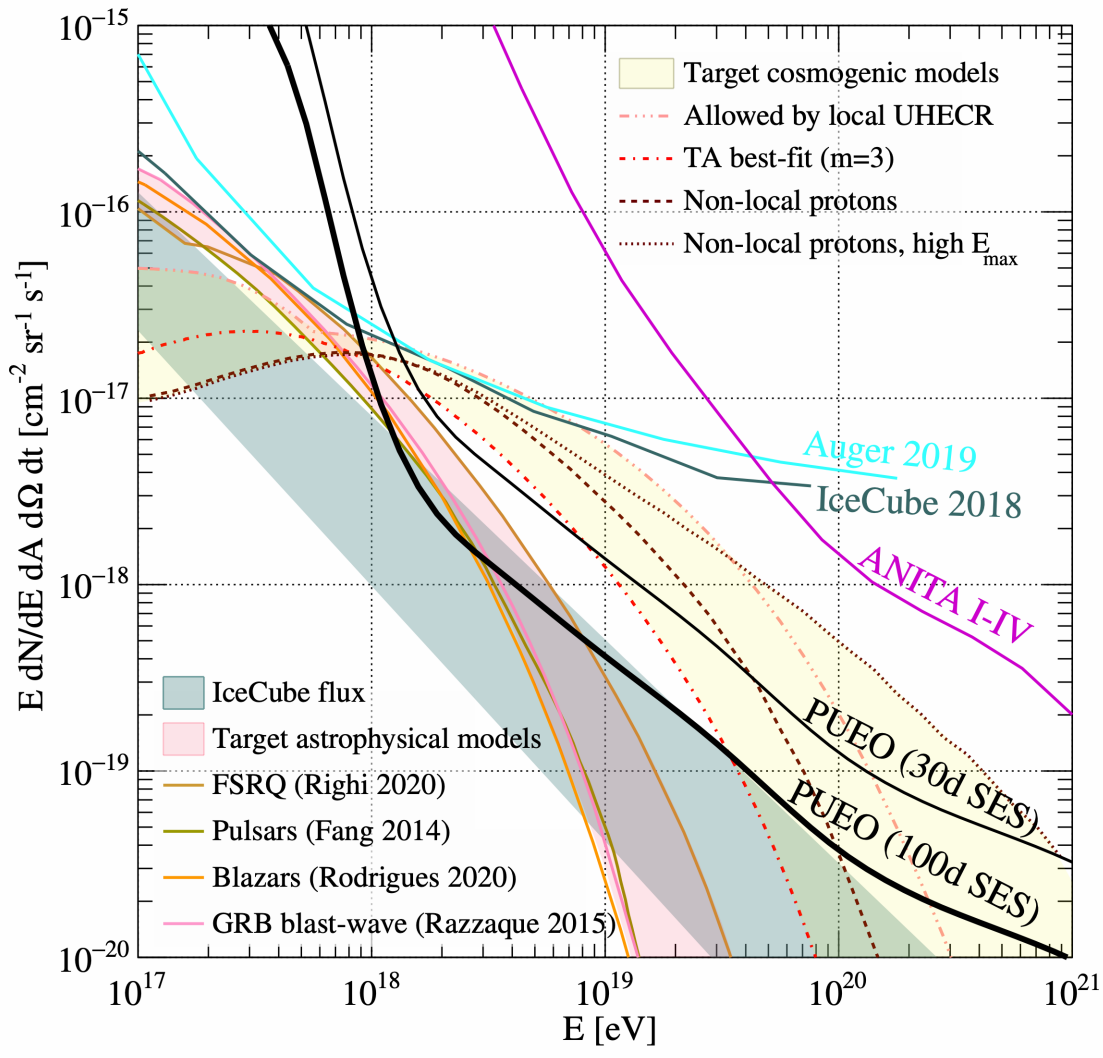
Astrophysical neutrinos

$$\left.\begin{matrix} p+p \\ p+\gamma \end{matrix}\right\} \rightarrow X + \pi \rightarrow \nu$$

Cosmogenic neutrinos

$$p + \gamma(CMB) \rightarrow p + \pi \rightarrow \nu$$

- World-leading cosmogenic neutrino sensitivity
- World-leading astrophysical neutrino sensitivity at EeV energies
- Dark matter sensitivity (e.g. decays of heavy DM particles)
- Unique energy regime for neutrino-nucleon cross-section measurements
- Other exotic searches (Lorentz violation, the anomalous ANITA events?)



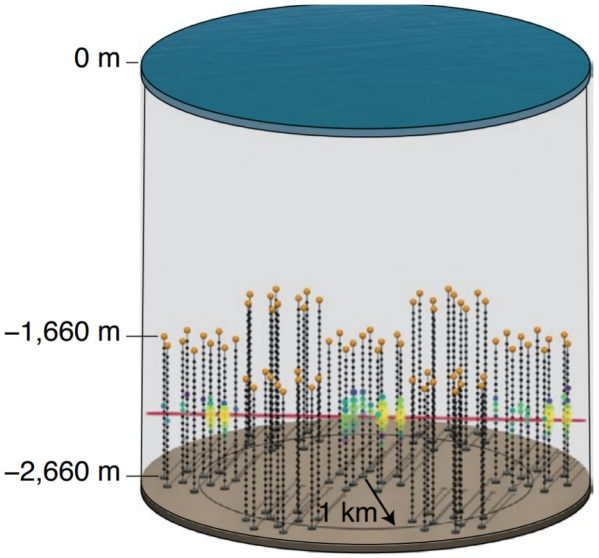
P-ONE, Nature Astronomy 4(2020)913

Pacific Ocean Neutrino Experiment

P-ONE

P-ONE:

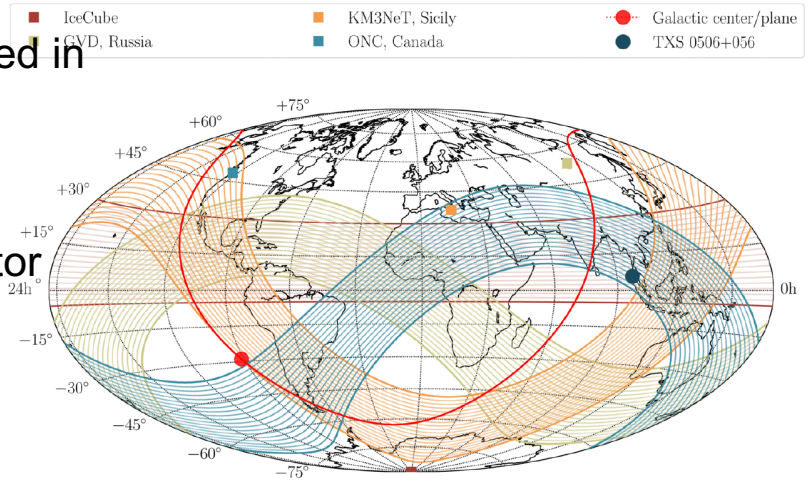
- Optimized for horizontal tracks, effective ~ IceCube
- **Reliable** underwater infrastructure & detector installation provided by Ocean Network Canada (Vancouver)
- Up to factor 10 coverage increase, sensitive to galactic center



Status:

- 2018: first string in situ, **verified** water properties (STRAW)
- 2023: installation of 10 strings, **funding** to be secured in 2021
- 2028: completion of detector

UCL initial contributions: STRAW data analysis, detector design and physics potential studies



UCL

M. Agostini (UCL)

UK High-Energy Neutrino Astronomy Consortium(?)

Many projects to cover variety of topics
- We are in the process to form a group beyond each collaboration.
- Realistic future plan of the UK high-energy neutrino astronomy