Neutrinos: First, Second and Third order

Elisa Resconi
Technical University of Munich
10.05.2024

https://www.ph.nat.tum.de/cosmic-particles/experimental-physics-with-cosmic-particles/

Neutrinos

1st order:

understand neutrino properties

2nd order:

neutrinos as a probe of cosmic objects
& understand neutrino properties

3rd order:

neutrinos as a probe of cosmic populations
& probe of cosmic objects, dark matter, relic neutrinos
& understand neutrino properties

Neutrinos

1st order:

understand neutrino properties

large volume neutrino experiments

2nd order:

neutrinos as a probe of cosmic objects
& understand neutrino properties

very large volume neutrino experiments

3rd order:

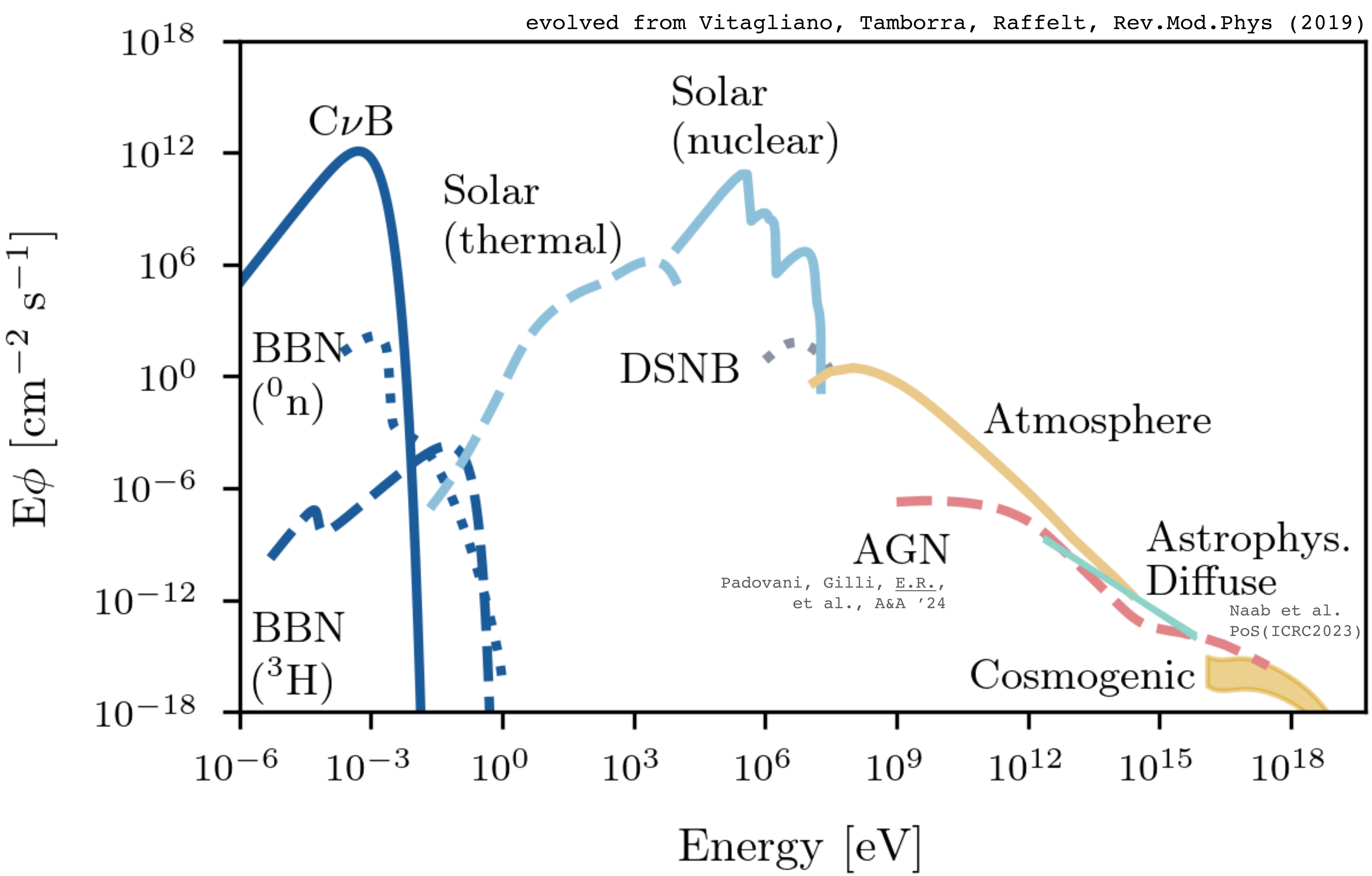
neutrinos as a probe of cosmic populations
& probe of cosmic objects, dark matter, relic neutrinos
& understand neutrino properties

several smart & very large volume neutrino experiments

0th order: Neutrino Sources

Neutrino Sources: natural ones

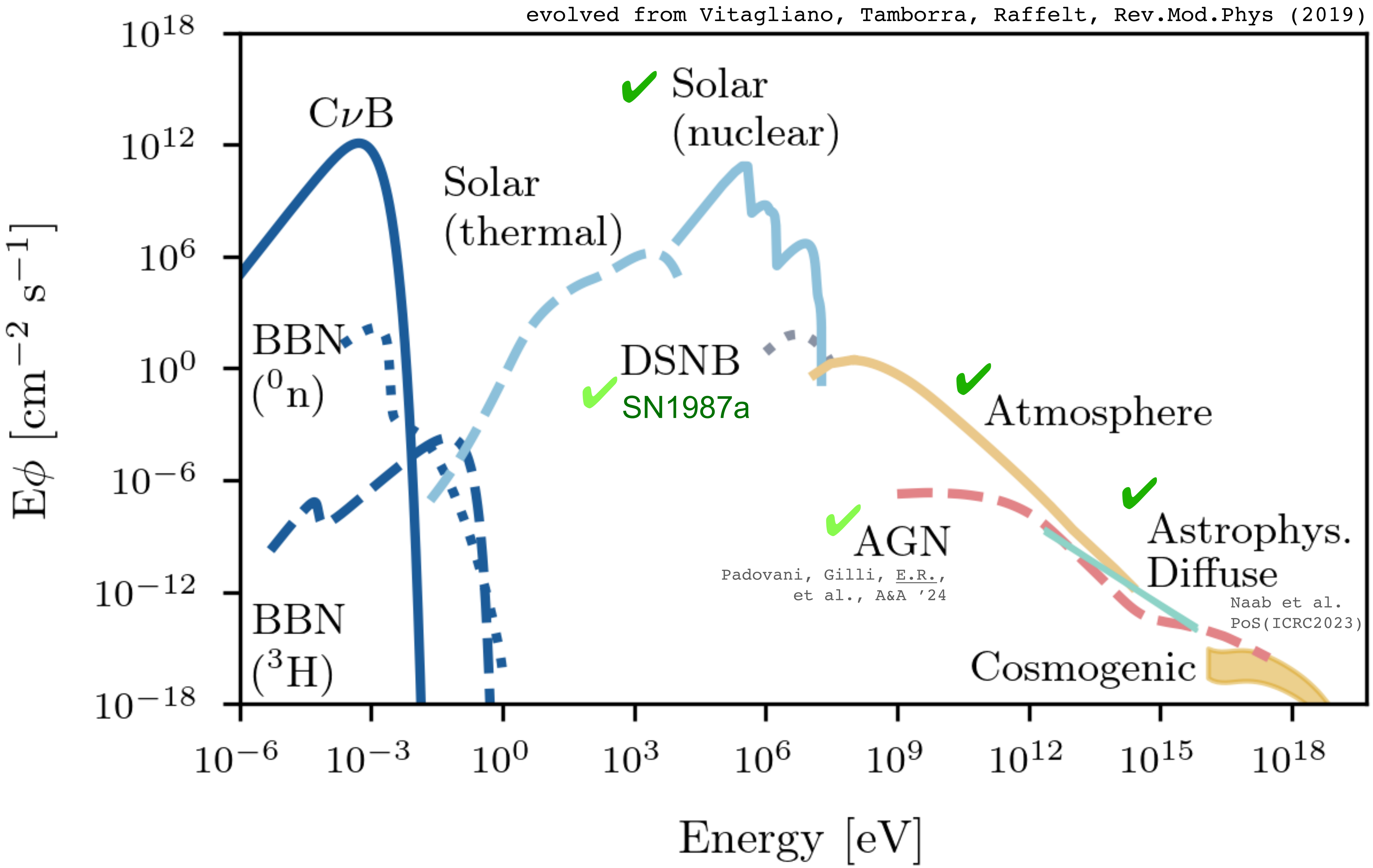
Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavors



Neutrino Sources: natural ones

Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavors

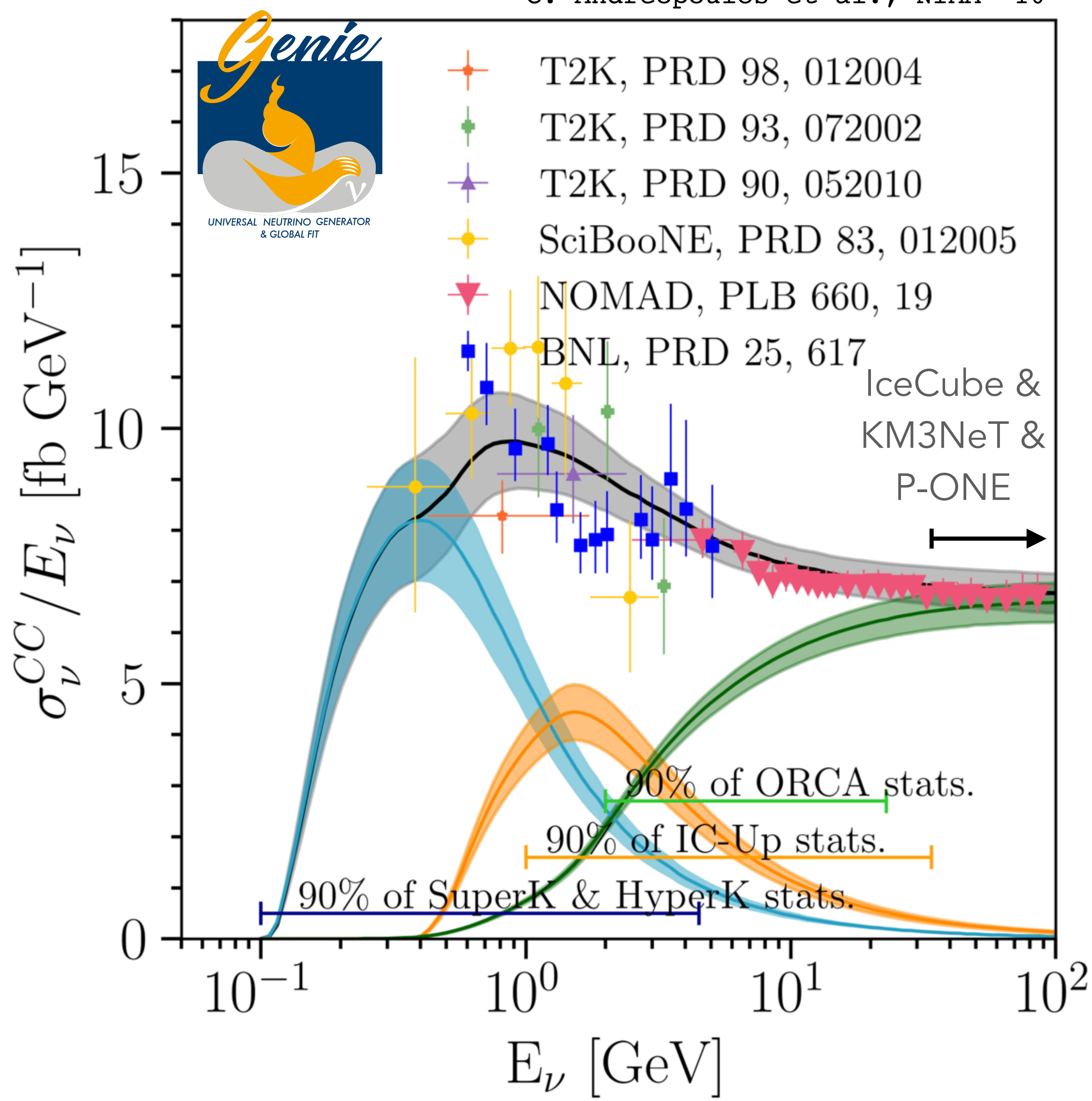
✔ Detected ✔ Associated



Neutrino Cross Sections

Charged-current ν_μ cross section per nucleon as a function of the neutrino energy

C. Andreopoulos et al., NIMA '10



0^{th} order: Neutrino Experiments

Neutrino experiments: precision and high energy

Snowmass Whitepaper, Beyond the Standard Model effects on Neutrino Flavor, ArXiv: 2203.10811

Energy Range	Experiment	Technology	Detected Flavor
$\lesssim 10^3$ GeV	JUNO	Liquid scintillator	All Flavors
$\lesssim 10^3$ GeV	DUNE	LArTPC	All Flavors
$\lesssim 10^3$ GeV	THEIA	WbLS	All Flavors
$\lesssim 10^3$ GeV	Super-Kamiokande	Gd-loaded Water C	All Flavors
$\lesssim 10^4$ GeV	Hyper-Kamiokande	Water Cherenkov	All Flavors
$\lesssim 10^5$ GeV	ANTARES	Sea-Water Cherenkov	ν_μ, $\bar{\nu}_\mu$ (CC)
$\lesssim 10^6$ GeV	IceCube/IceCube-Gen2	Ice Cherenkov	All Flavors
$\lesssim 10^6$ GeV	KM3NeT	Sea-Water Cherenkov	All Flavors
$\lesssim 10^6$ GeV	Baikal-GVD	Lake-Water Cherenkov	All Flavors
$\lesssim 10^6$ GeV	P-ONE	Sea-Water Cherenkov	All Flavors
$1 - 100$ PeV	TAMBO	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)
$\gtrsim 1$ PeV	Trinity	Earth-skimming Image	ν_τ, $\bar{\nu}_\tau$ (CC)
$\gtrsim 10$ PeV	RET-N	Radar echo	All Flavors
$\gtrsim 10$ PeV	IceCube-Gen2	In-ice Radio	All Flavors
$\gtrsim 10$ PeV	ARIANNA-200	On-ice Radio	All Flavors
$\gtrsim 20$ PeV	POEMMA	Space Air-shower Image	ν_τ, $\bar{\nu}_\tau$ (CC)
$\gtrsim 100$ PeV	RNO-G	In-ice Radio	All Flavors
$\gtrsim 100$ PeV	ANITA/PUEO	Balloon Radio	All Flavors
$\gtrsim 100$ PeV	Auger/GCOS	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)
$\gtrsim 100$ PeV	Beacon	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)
$\gtrsim 100$ PeV	GRAND	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)

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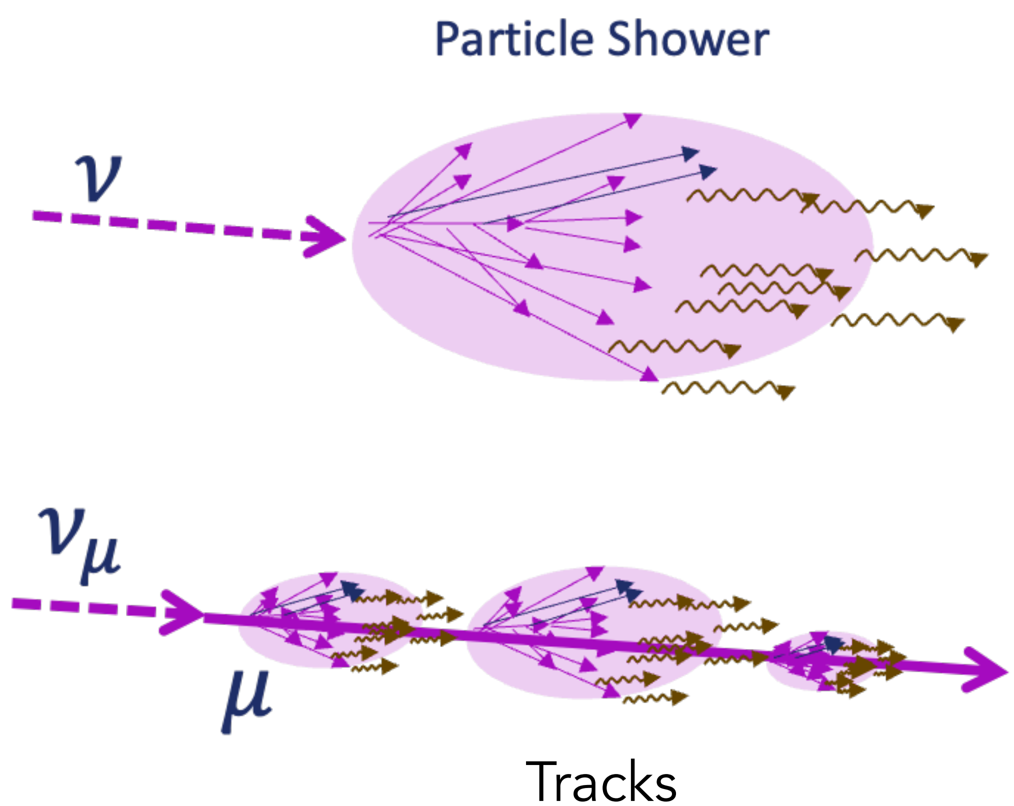
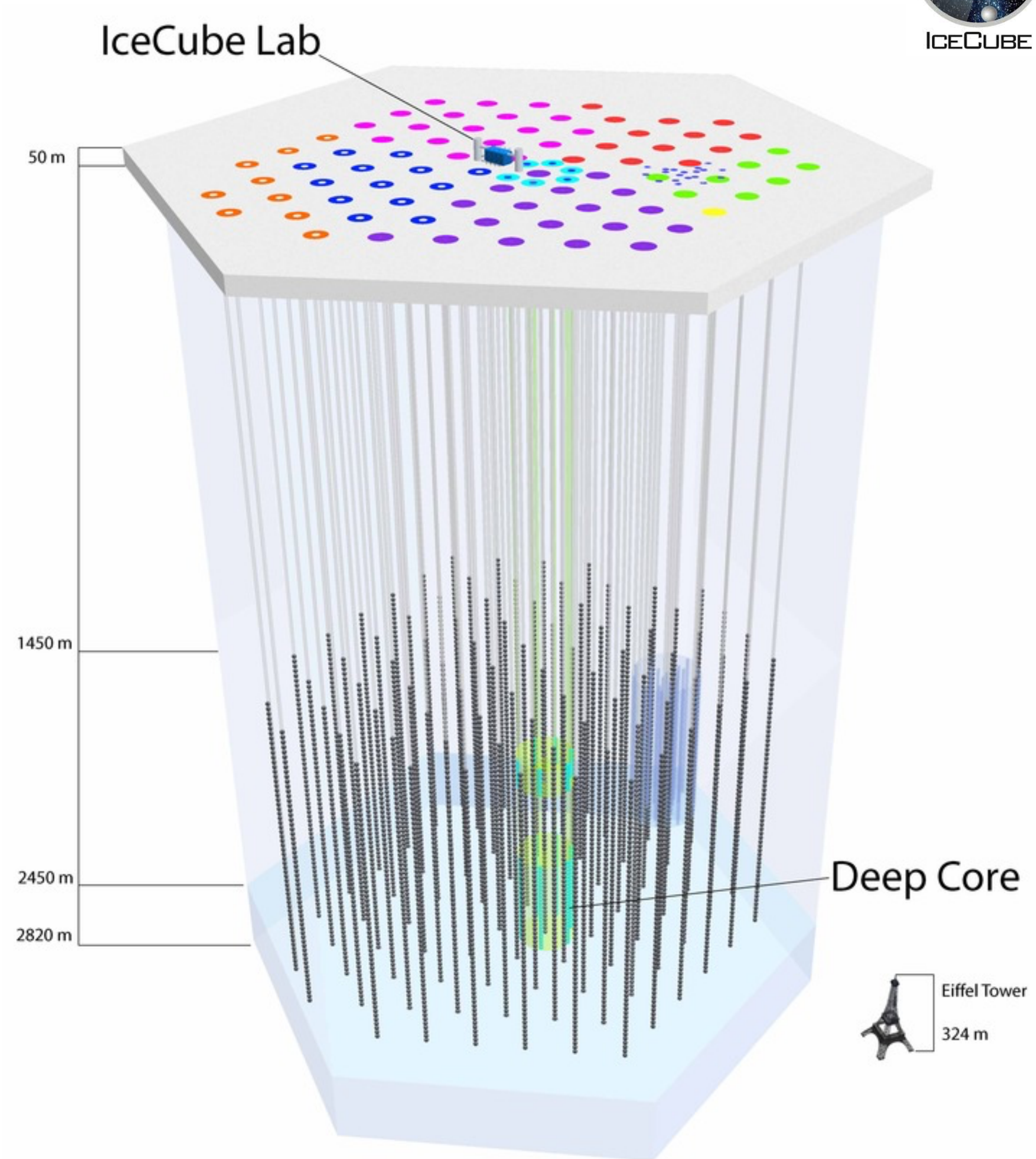
$\gtrsim 100$ PeV	Beacon	Earth-skimming Radio	$\nu_\tau, \bar{\nu}_\tau$ (CC)
$\gtrsim 100$ PeV	GRAND	Earth-skimming Radio	$\nu_\tau, \bar{\nu}_\tau$ (CC)

DeepCore & IceCube Upgrade

IceCube Neutrino Observatory

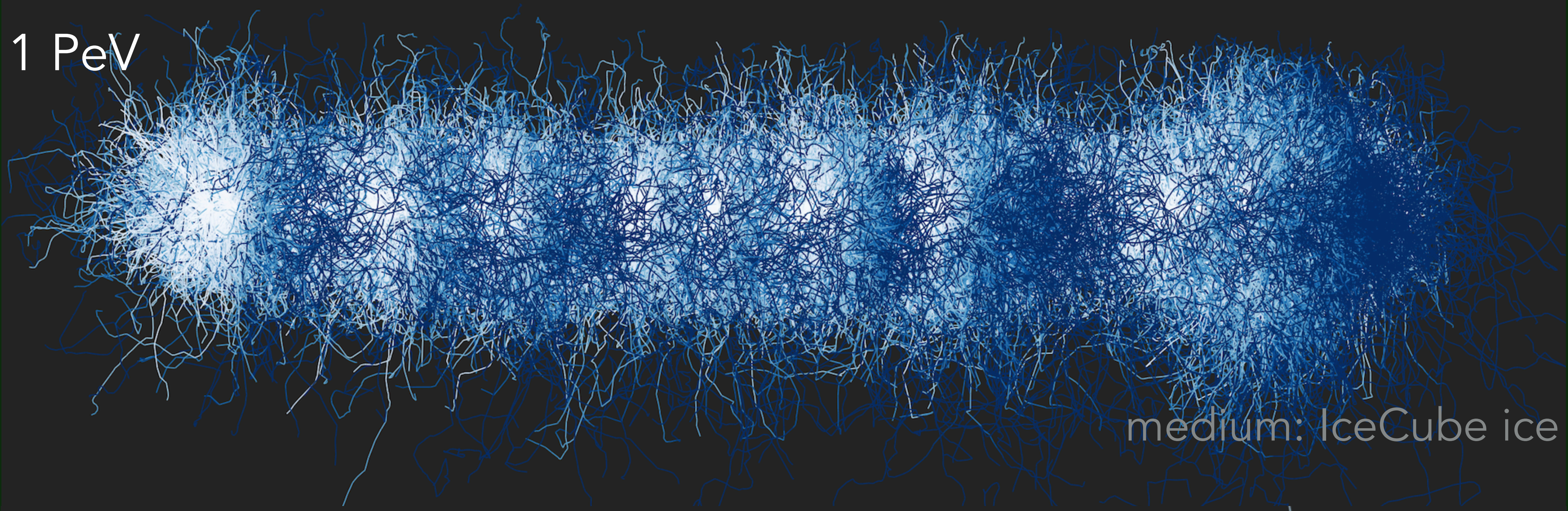
Two topological channels

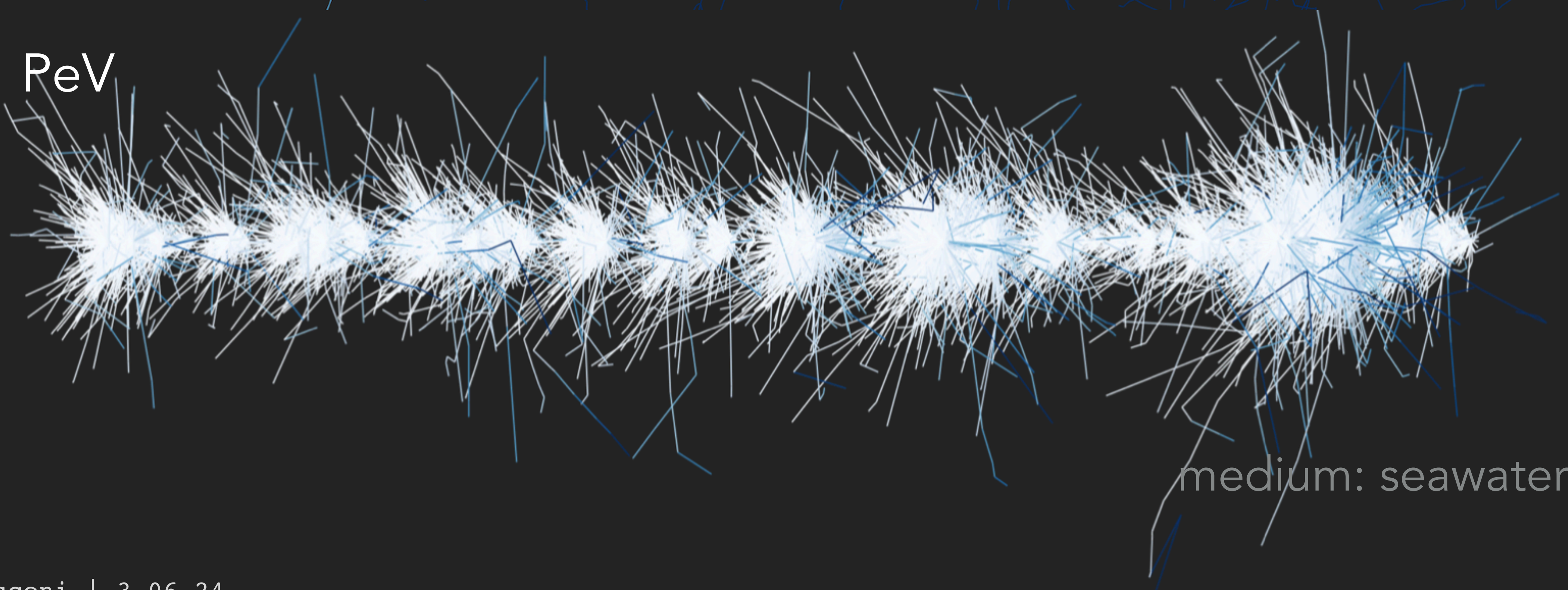




Measuring high energy muons

Driven by photosensors areas, timing, medium





1st order: understand neutrino properties

The Leptonic Mixing Matrix: status

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, et al., ***JHEP*** 2020

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar

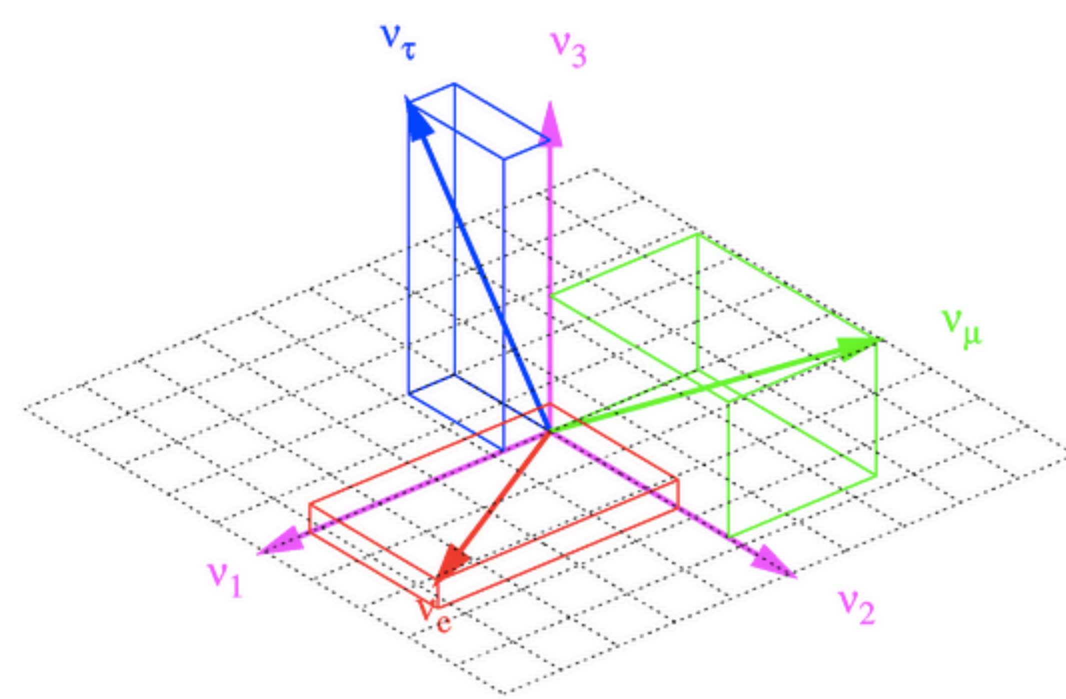
$$\Delta m^2_{ij} \equiv m^2_i - m^2_j \quad (i, j = 1, 2, 3,\ i > j)$$

NuFIT 5.3 (2024)

$$|U|^{\text{with SK-atm}}_{3\sigma} = \begin{pmatrix} 0.801 \to 0.842 & 0.518 \to 0.580 & 0.143 \to 0.155 \\ 0.244 \to 0.500 & 0.498 \to 0.690 & 0.634 \to 0.770 \\ 0.276 \to 0.521 & 0.473 \to 0.672 & 0.621 \to 0.759 \end{pmatrix}$$

www.nu-fit.org

Reactor/accelerator **Atmospheric**



The Leptonic Mixing Matrix and Neutrino Mass Ordering

Ongoing Measurements and Future Tests

Solar

NuFIT 5.3 (2024)

$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.801 \to 0.842 & 0.518 \to 0.580 & 0.143 \to 0.155 \\ 0.244 \to 0.500 & 0.498 \to 0.690 & 0.634 \to 0.770 \\ 0.276 \to 0.521 & 0.473 \to 0.672 & 0.621 \to 0.759 \end{pmatrix}$$

www.nu-fit.org

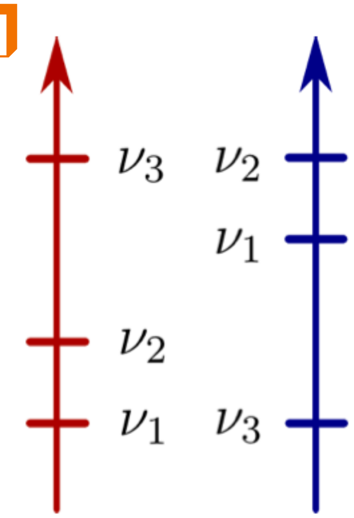
Reactor/accelerator

Atmospheric

Unknown:

δ_{CP}?

$\theta_{23} \begin{cases} \text{octant?} \\ \text{maximal?} \end{cases}$

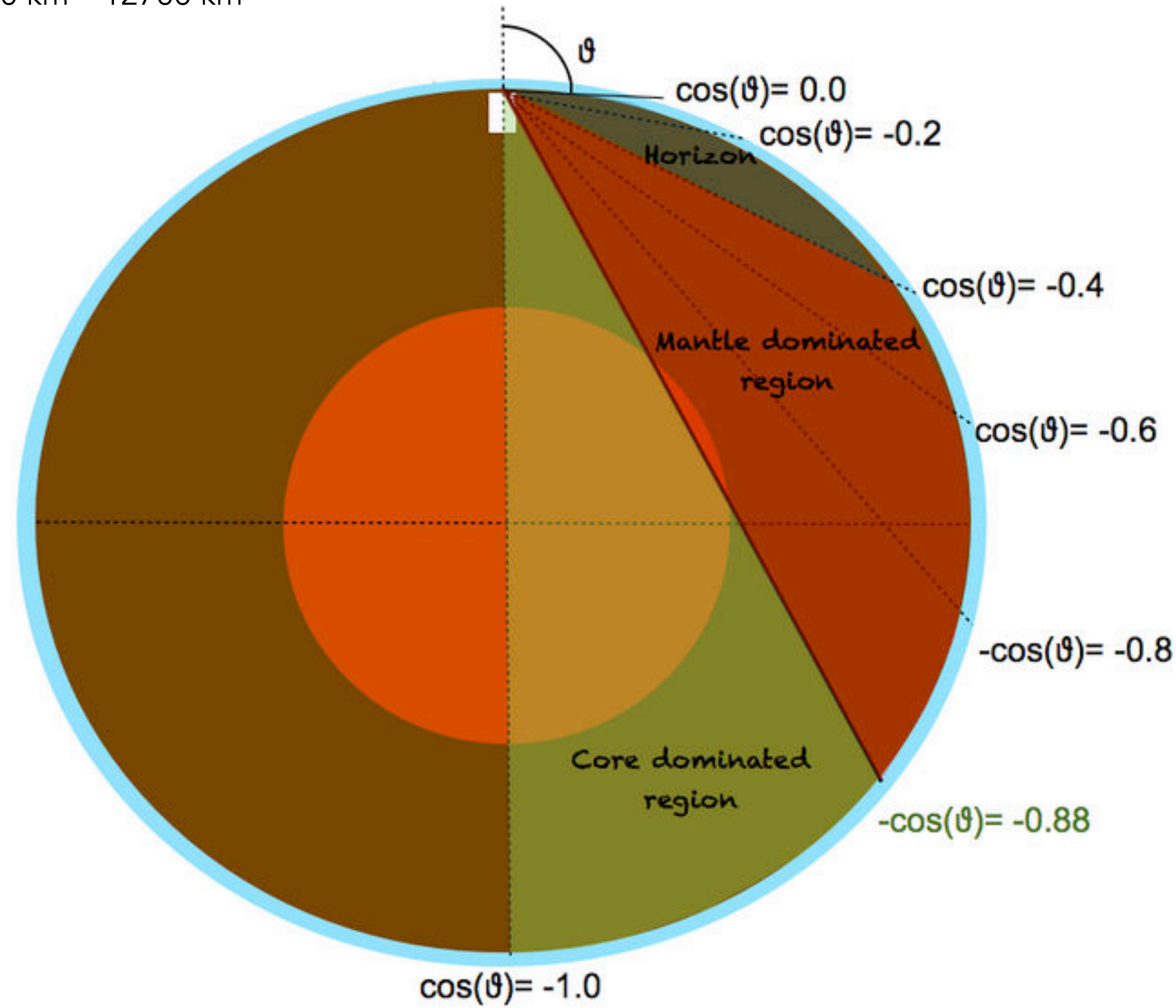


Unitarity?

Life time?

Atmospheric Neutrinos for Oscillation

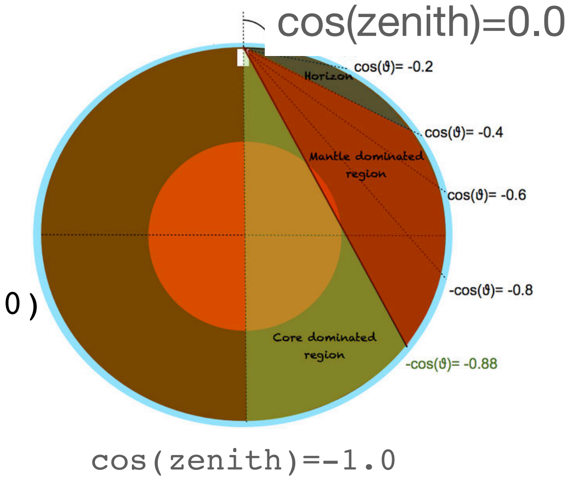
Baselines from ~20 km – 12700 km



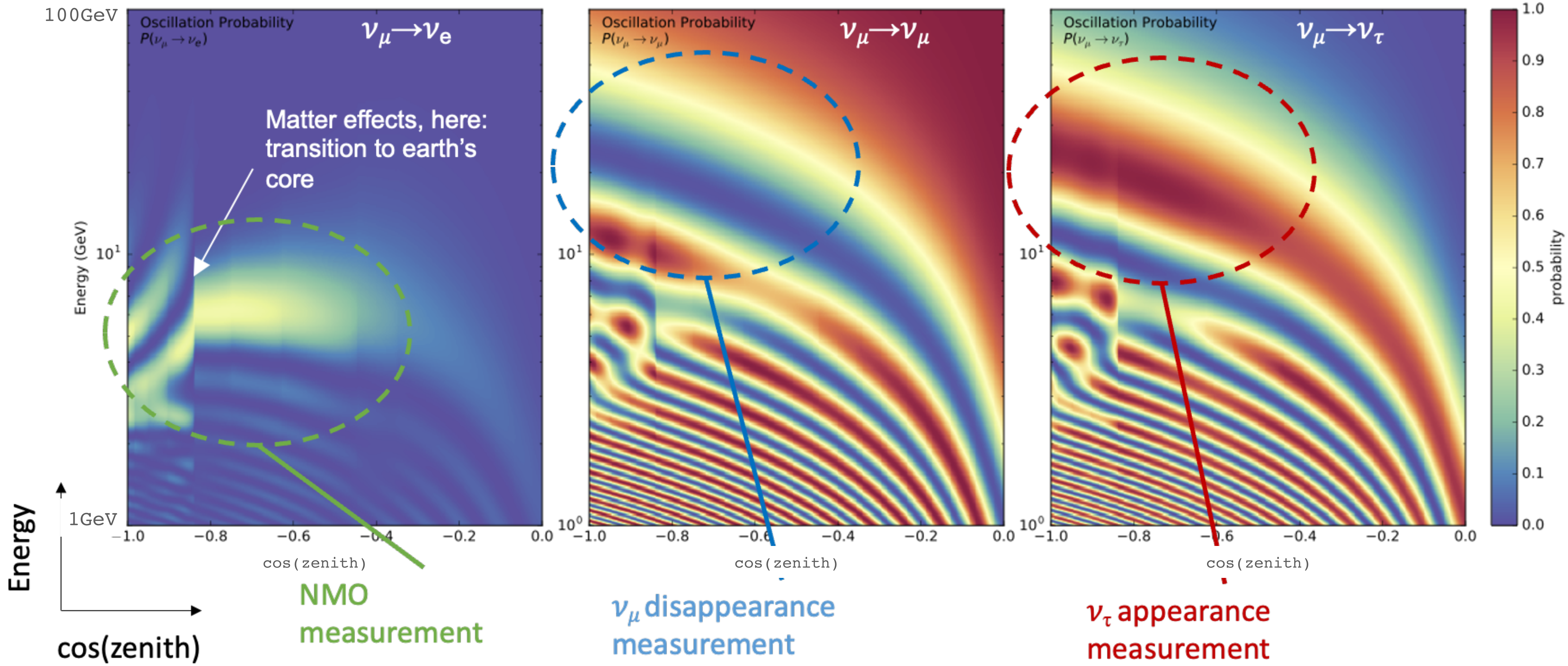
Atmospheric Neutrinos for Oscillation

Baselines from ~20 km – 12700 km

E. R. et al., ***NIMA*** 2013. J. Leute, E.R. et al, PoS ICRC23.
IceCube Coll., ***PRL*** 2013. IceCube Coll., ***J.Phys.G*** 2017. IceCube Coll., ***PRD*** 101 (2020)

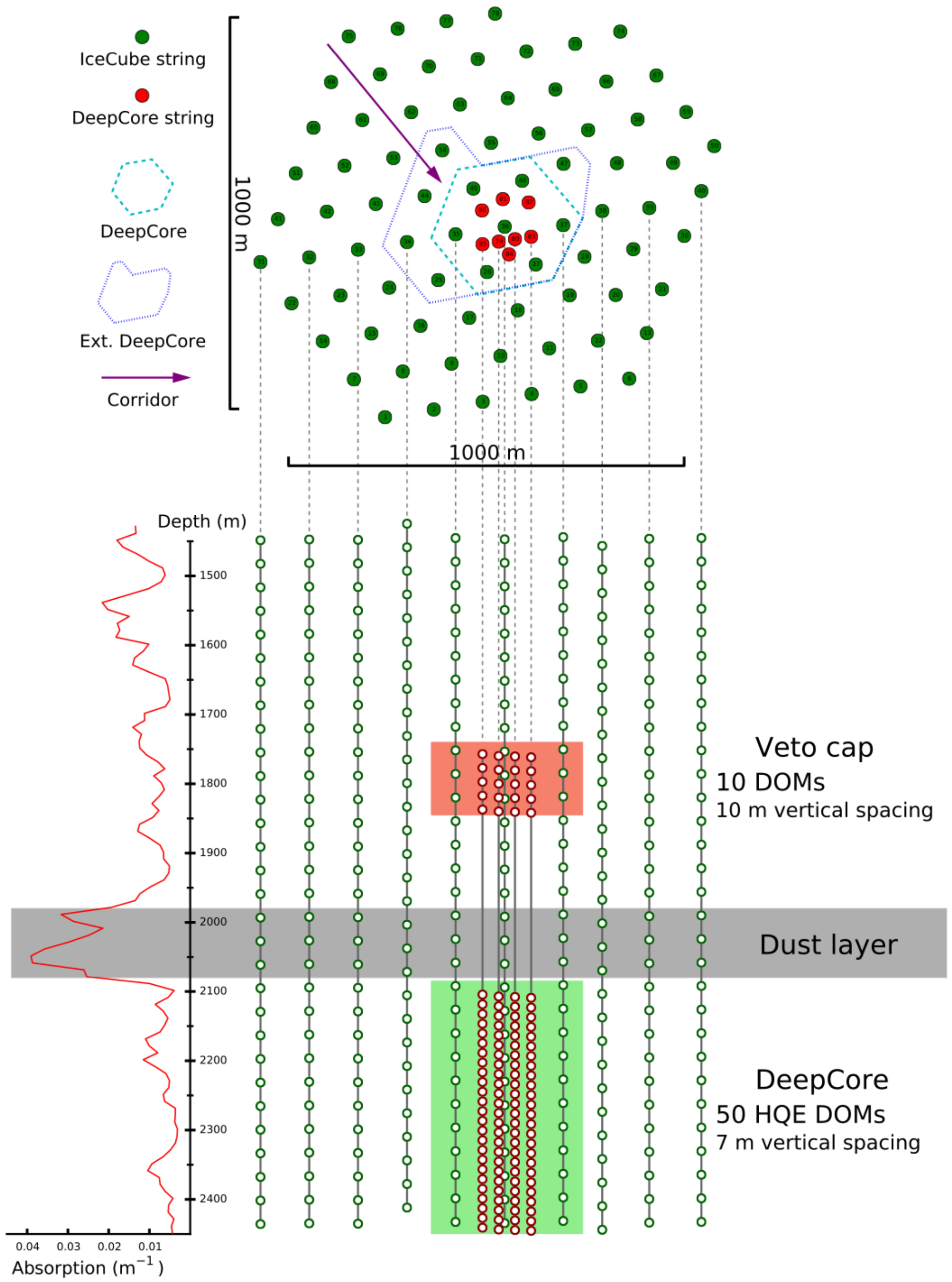


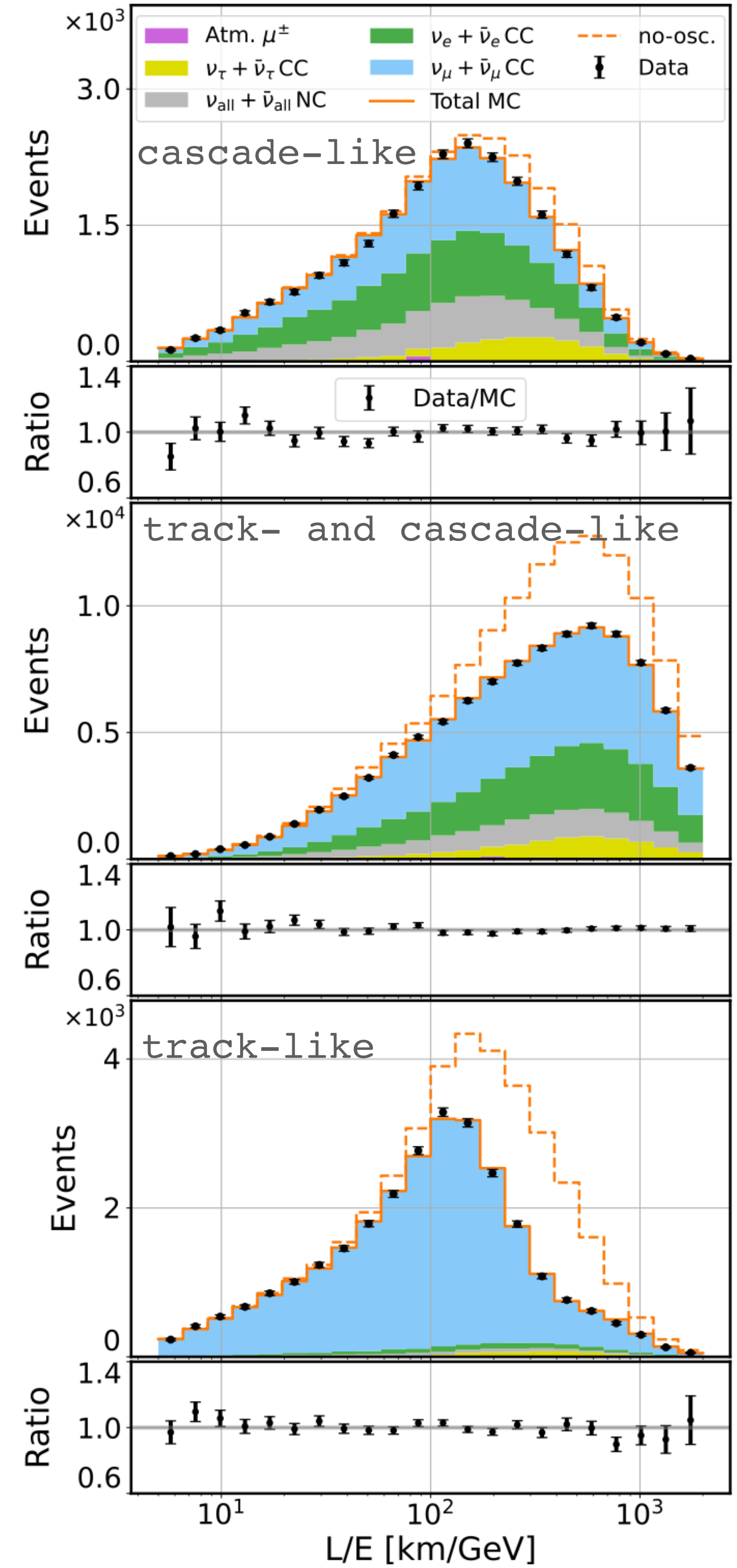
P. Eller et al., PoS ICRC2023



Atmospheric Neutrinos for Oscillation in IceCube/DeepCore

IceCube Coll– PRELIMINARY – submitted to PRL
3,387 days (2012-2021), 150257 neutrino candidates





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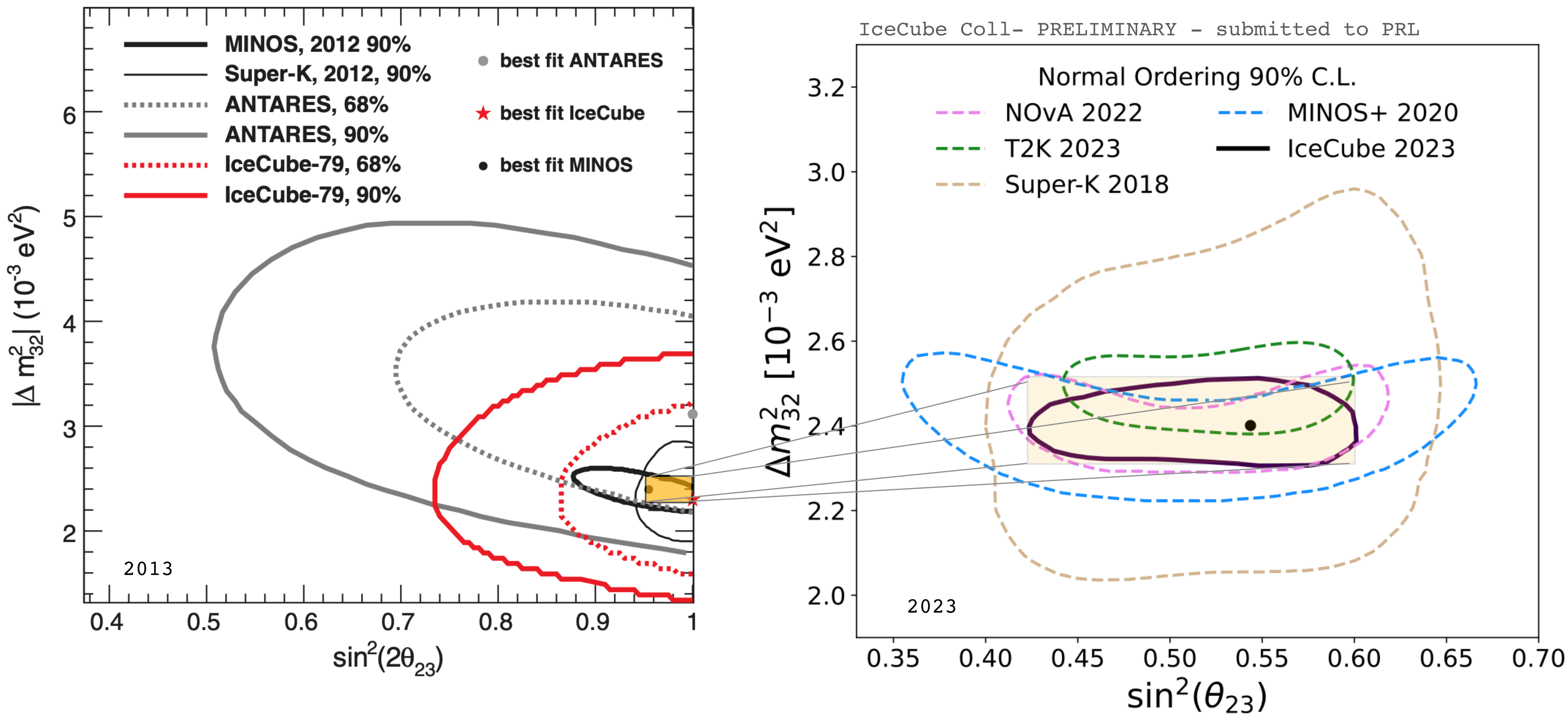
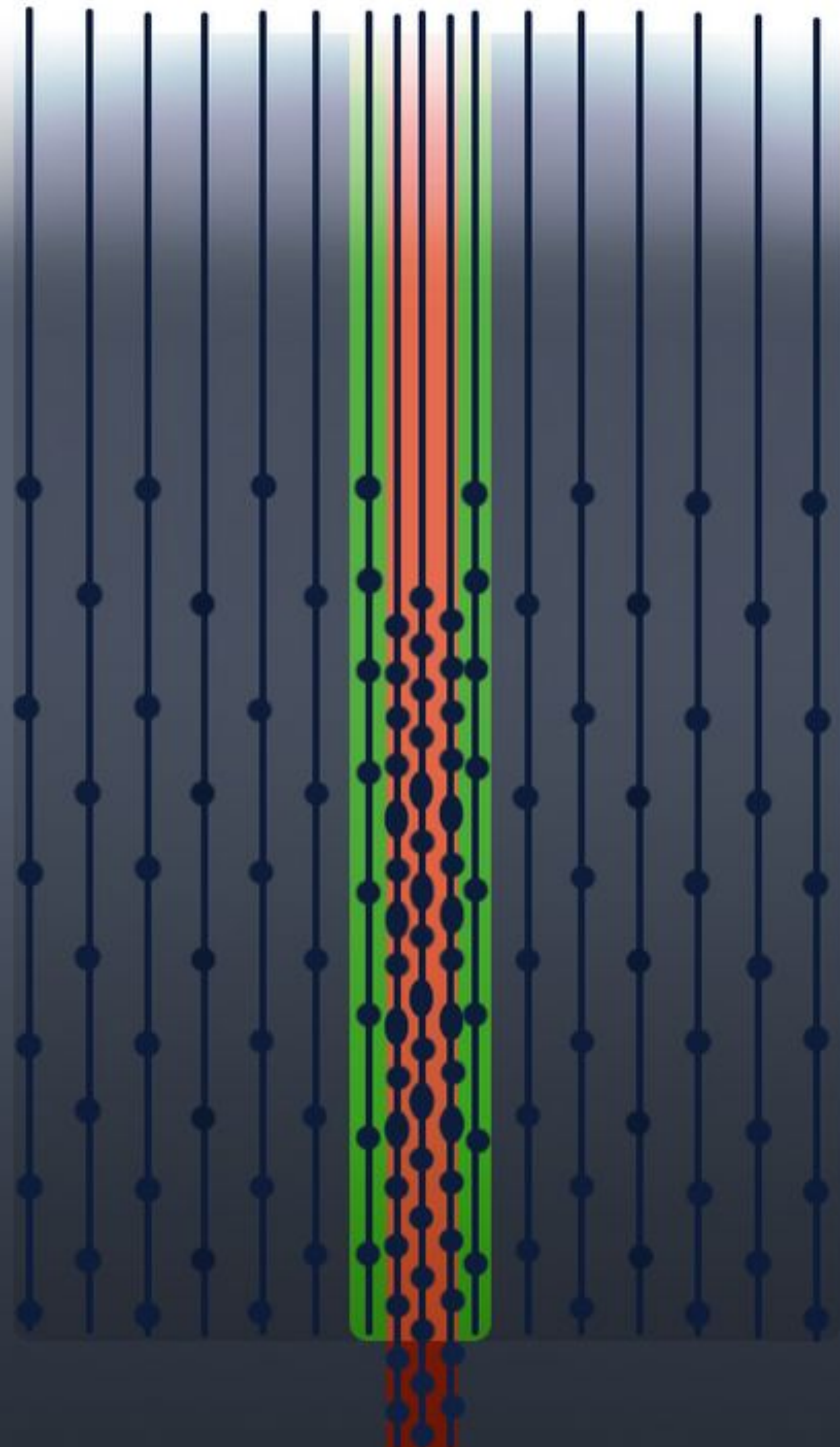
IceCube Coll., ***PRL*** 2013. IceCube Coll., ***J.Phys.G*** 2017. IceCube Coll., ***PRD*** 101 (2020)

'How it Started … How it's Going'



Atmospheric Neutrinos Oscillation in IceCube/DeepCore

+ IceCube Upgrade



To be installed in 25/26

700 new optical & calibration modules

IceCube Detector

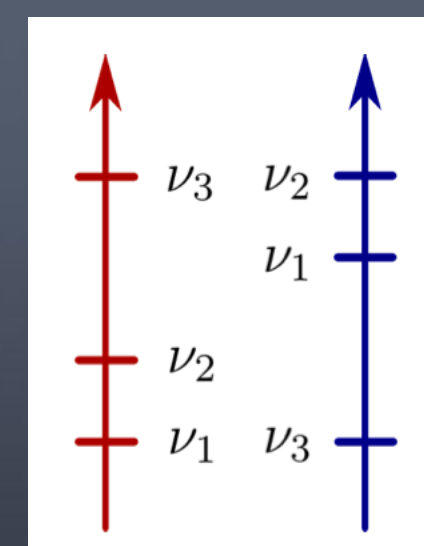
DeepCore

IceCube Upgrade

$\mathrm{sgn}(\Delta m^2_{31})$?

θ_{23} { octant? maximal?

Unitarity?



Atmospheric Neutrinos Oscillation in IceCube/DeepCore

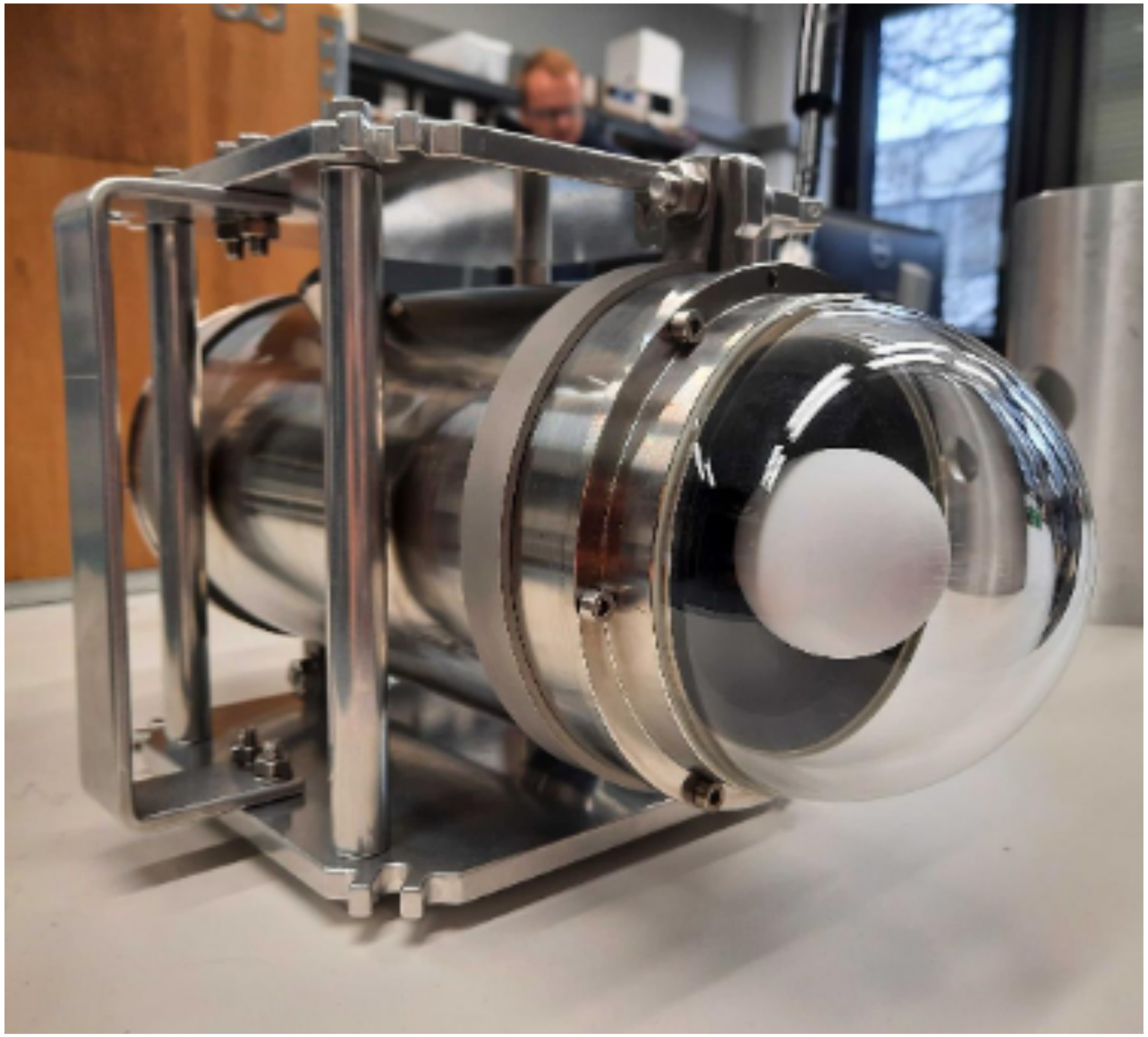
+ IceCube Upgrade

Photo: IceCube/NSF, '23/'24 Field Season

ICECUBE UPGRADE

The Precision Optical Calibration Modules (POCAMs) for **IceCube Upgrade**

J. Bedard, E.R. et al., JINST 14 (2019)



In production: 30 calibration modules

Target Systematic Uncertainties:

- Optical Module Efficiency:
  10% → 1.2%
- Bulk Ice Scattering & Absorption:
  5% → 0.5%
- Refrozen Borehole Ice:
  Unconstrained → Constrained

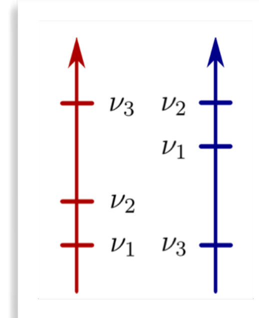
Sensitivity Studies for PMNS, NMO, mixing parameters

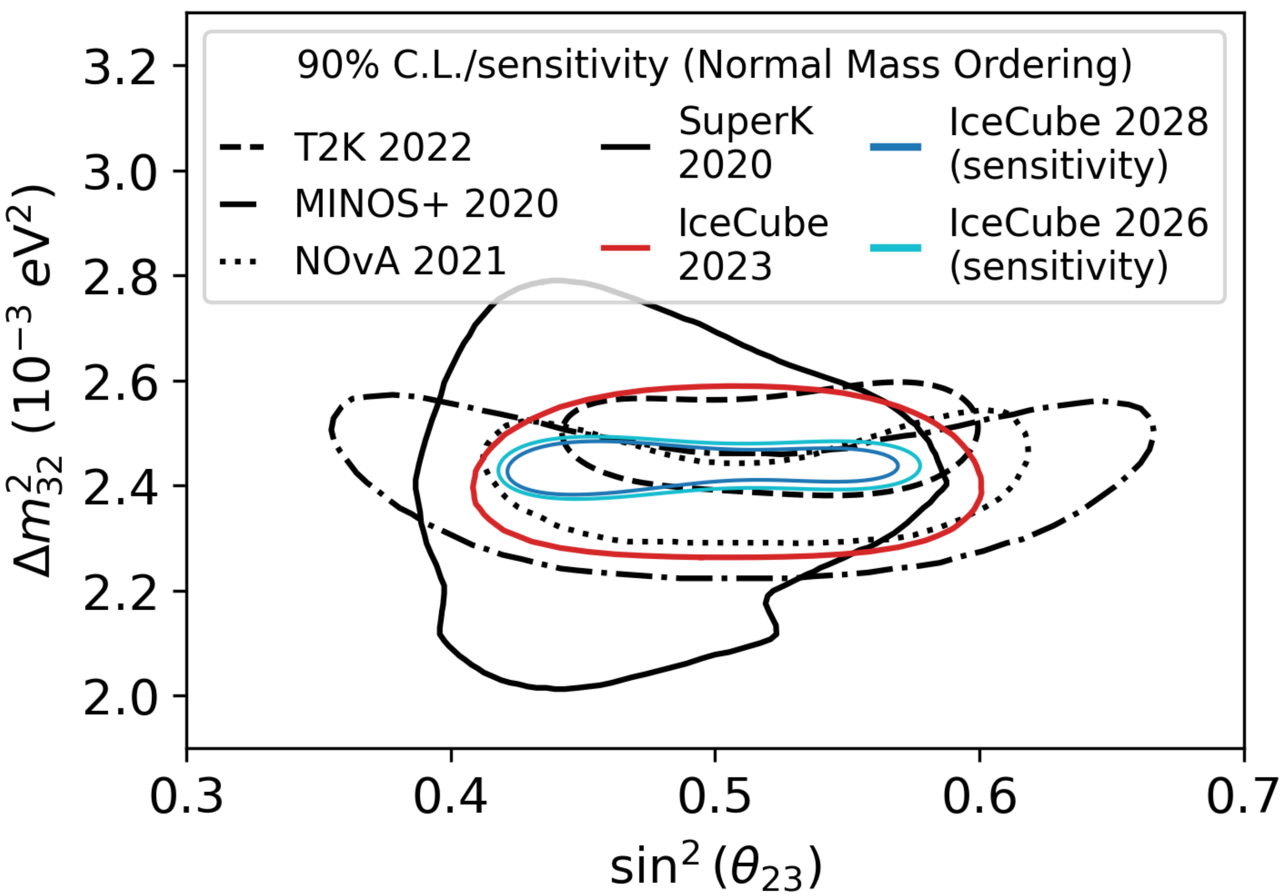
P. Eller et al., PoS ICRC2023

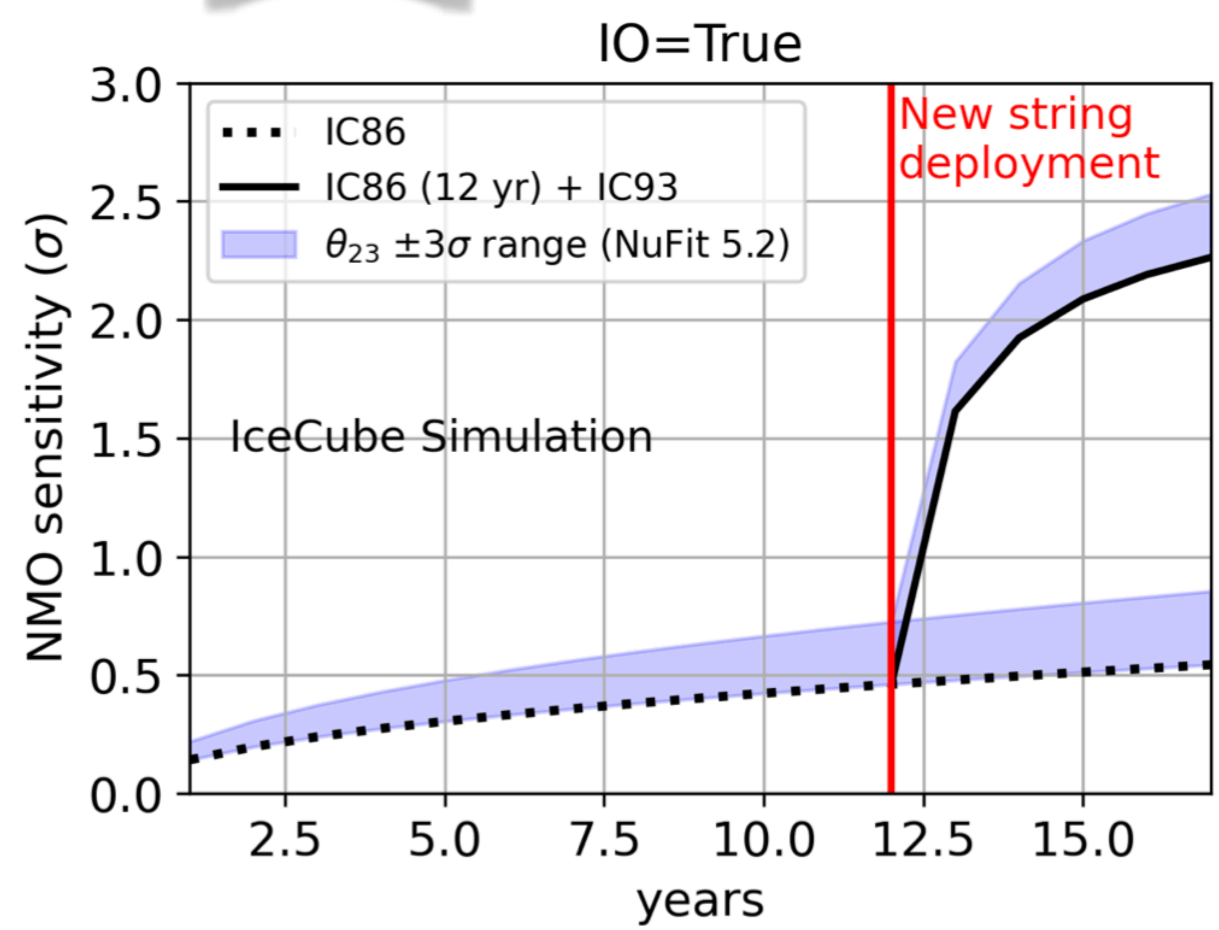
GraphNeT
Graph Neural Networks for Neutrino Telescope Event Reconstruction

SFB 1258 | Neutrinos Dark Matter Messengers

$$\theta_{23} \begin{cases} \text{octant?} \\ \text{maximal?} \end{cases}$$







JUNO Coll, Arxiv: 2405.18008
3σ sensitivity NMO,
6.5 years × 26.6 GW thermal power

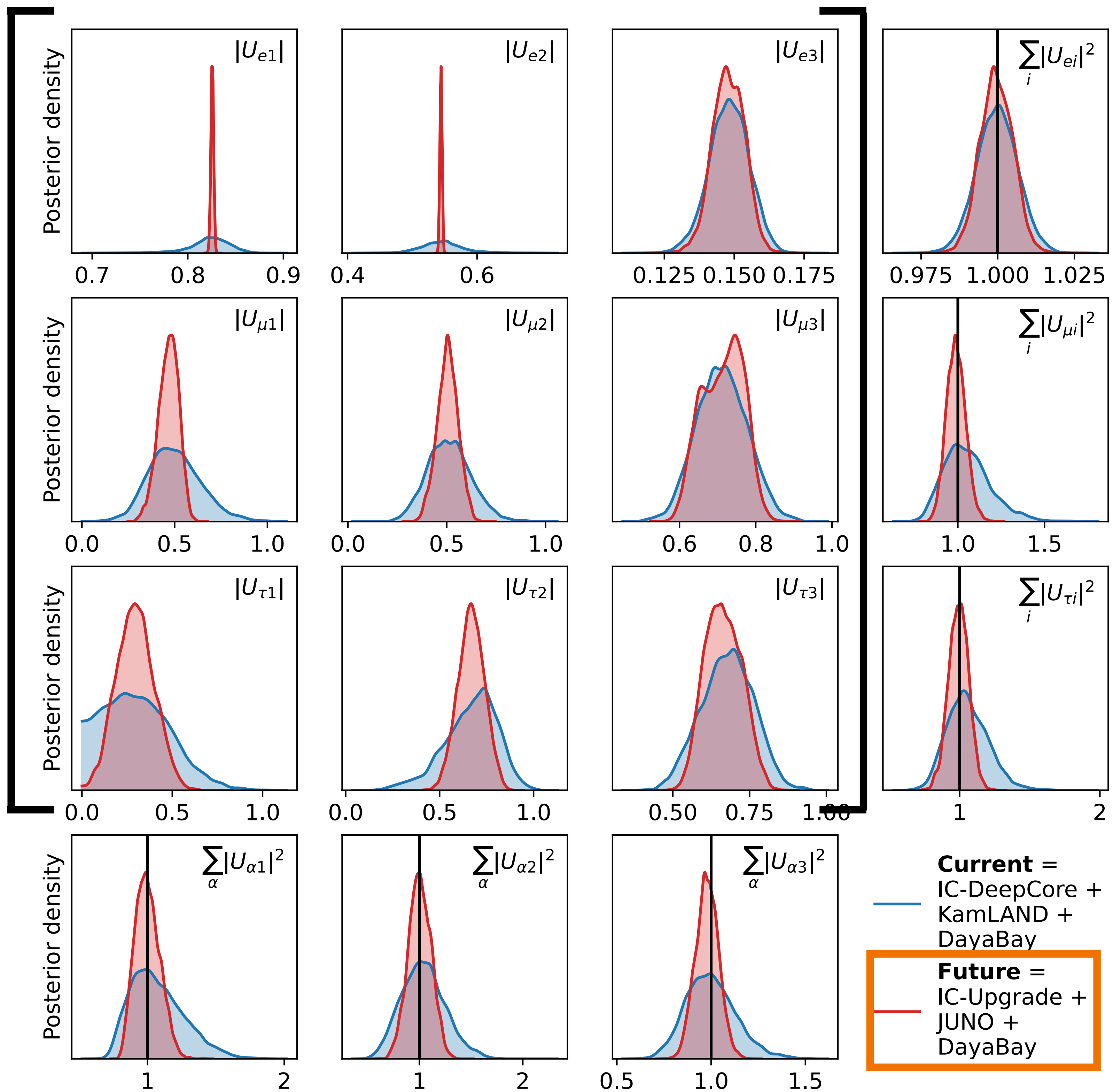
Unitarity test: global approach needed

P. Eller et al., PoS ICRC2023

Bayesian posterior densities for the normalizations of individual leptonic mixing matrix elements

Unitarity?

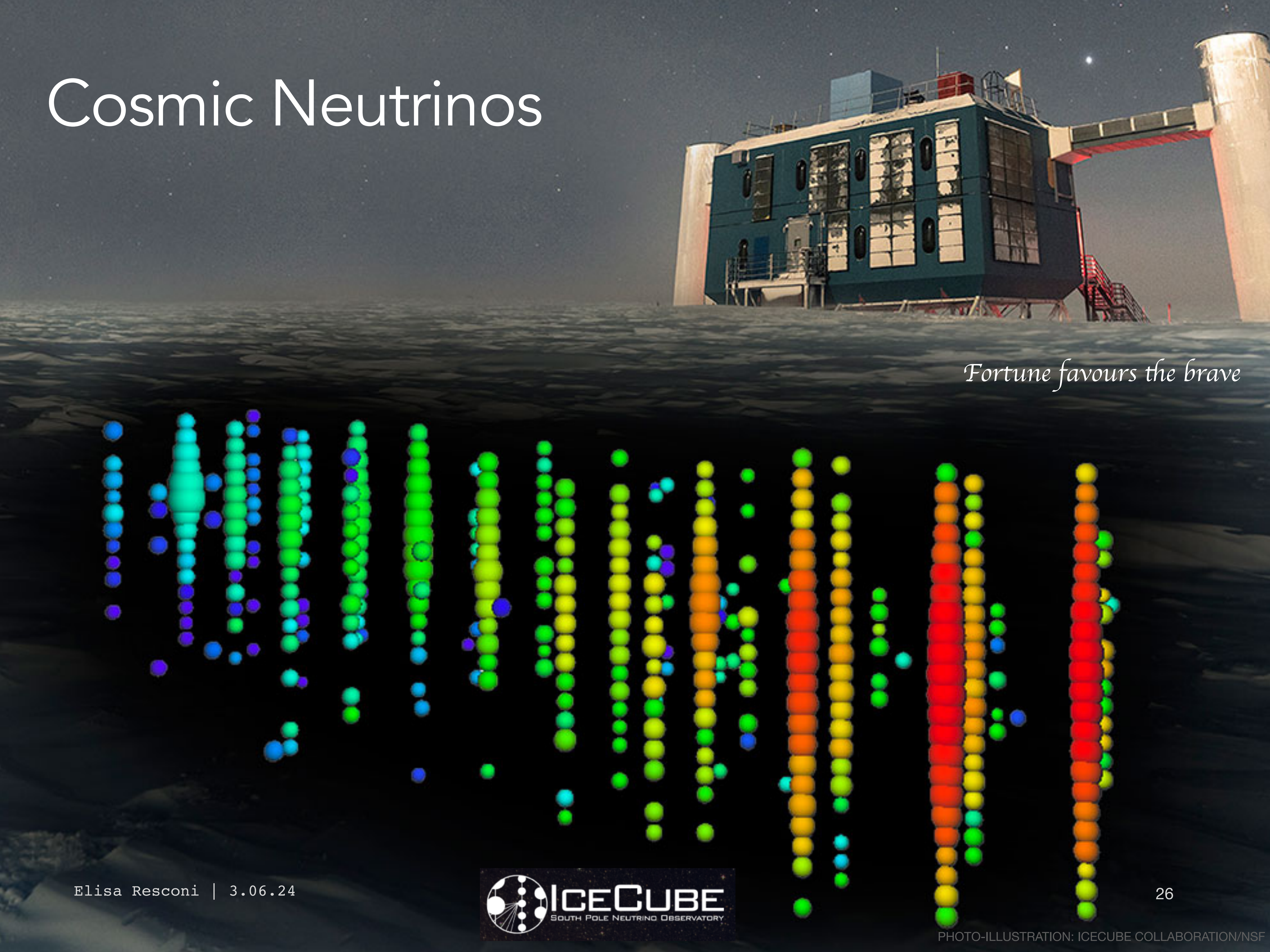
$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix} =$$



2nd order:

neutrinos as a probe of cosmic objects
& understand neutrino properties

Cosmic Neutrinos



Fortune favours the brave

PHOTO-ILLUSTRATION: ICECUBE COLLABORATION/NSF

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Cosmic Neutrinos
IceCube milestones

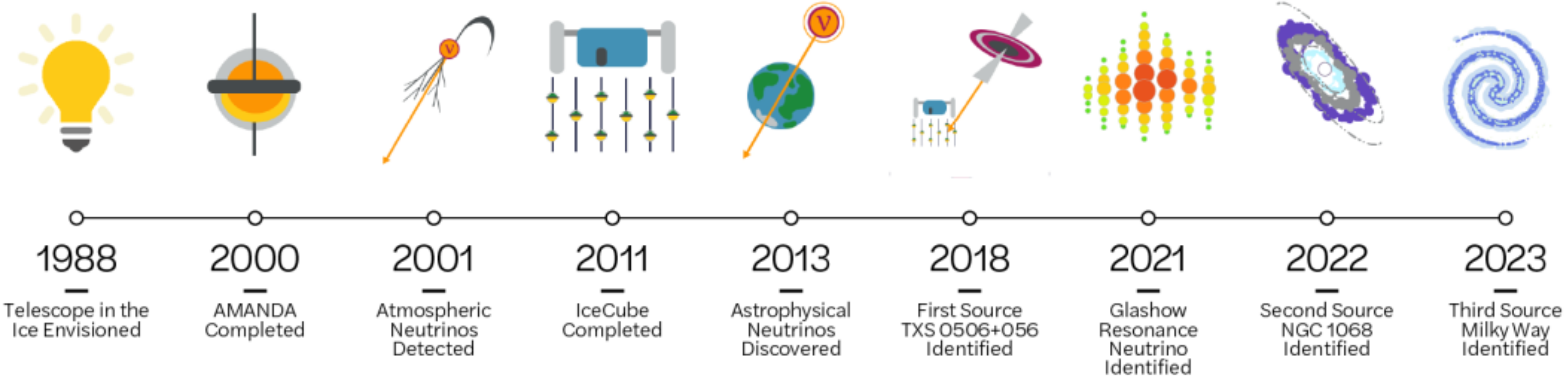
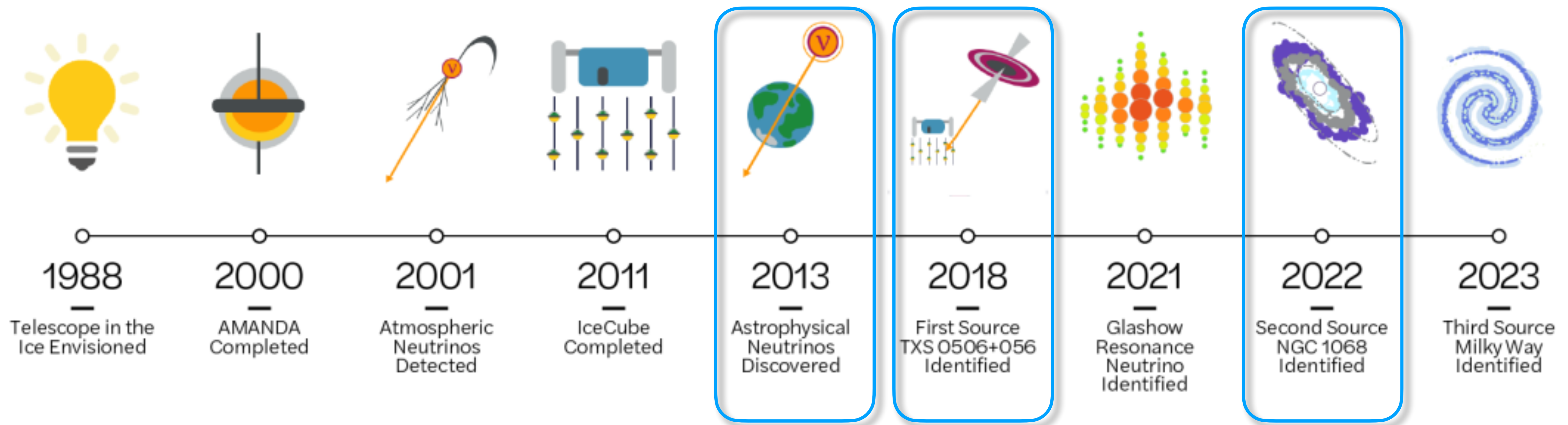


PHOTO-ILLUSTRATION: ICECUBE COLLABORATION/NSF

Cosmic Neutrinos

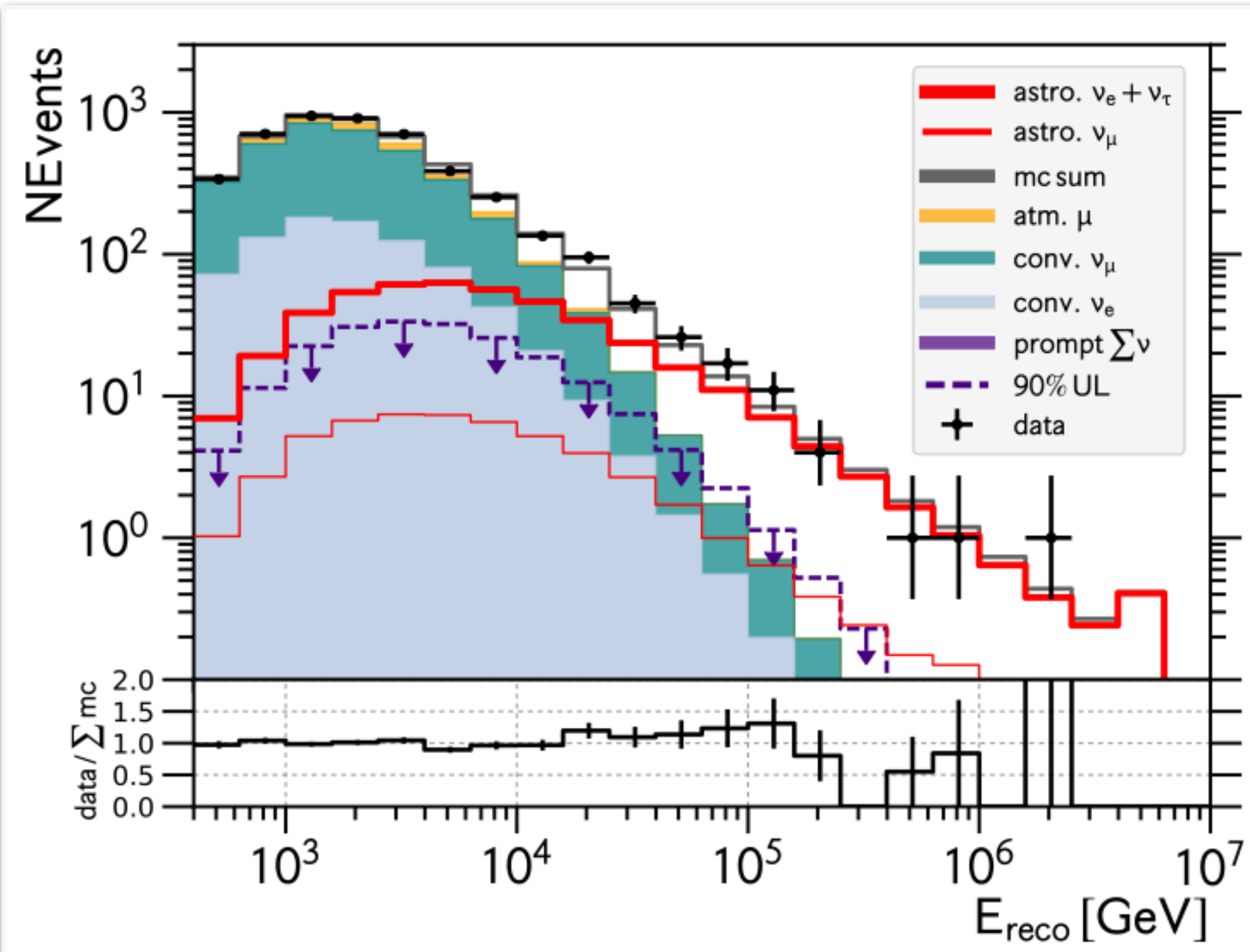
Event Rates in IceCube:
For every 1 Cosmic Neutrino,
~10^9 Atmospheric Muons
~10^3 Atmospheric Neutrinos



The cosmic neutrino diffuse signal

The IceCube Coll., ***PRL*** '20. The IceCube Coll., ***ApJ*** '22
The IceCube Coll., ***Nature*** '21

9.9σ excess



Record events:

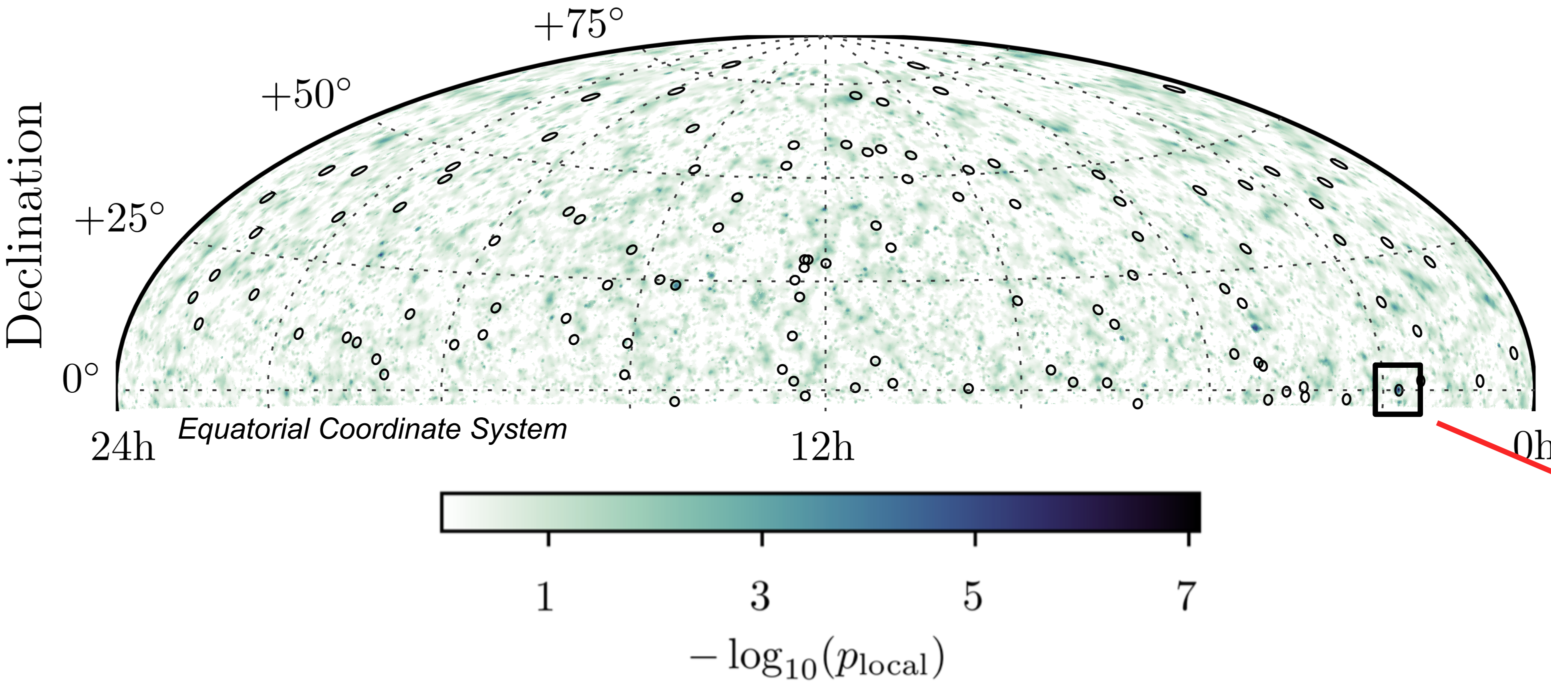
- 8.7 PeV track-like event
- 6.4 PeV shower-like
- 7 high-energy double peaked

First evidences for source association

IceCube first association: **TXS 0506+056** - alert event (~290 TeV) and neutrino flare (2015-2016)

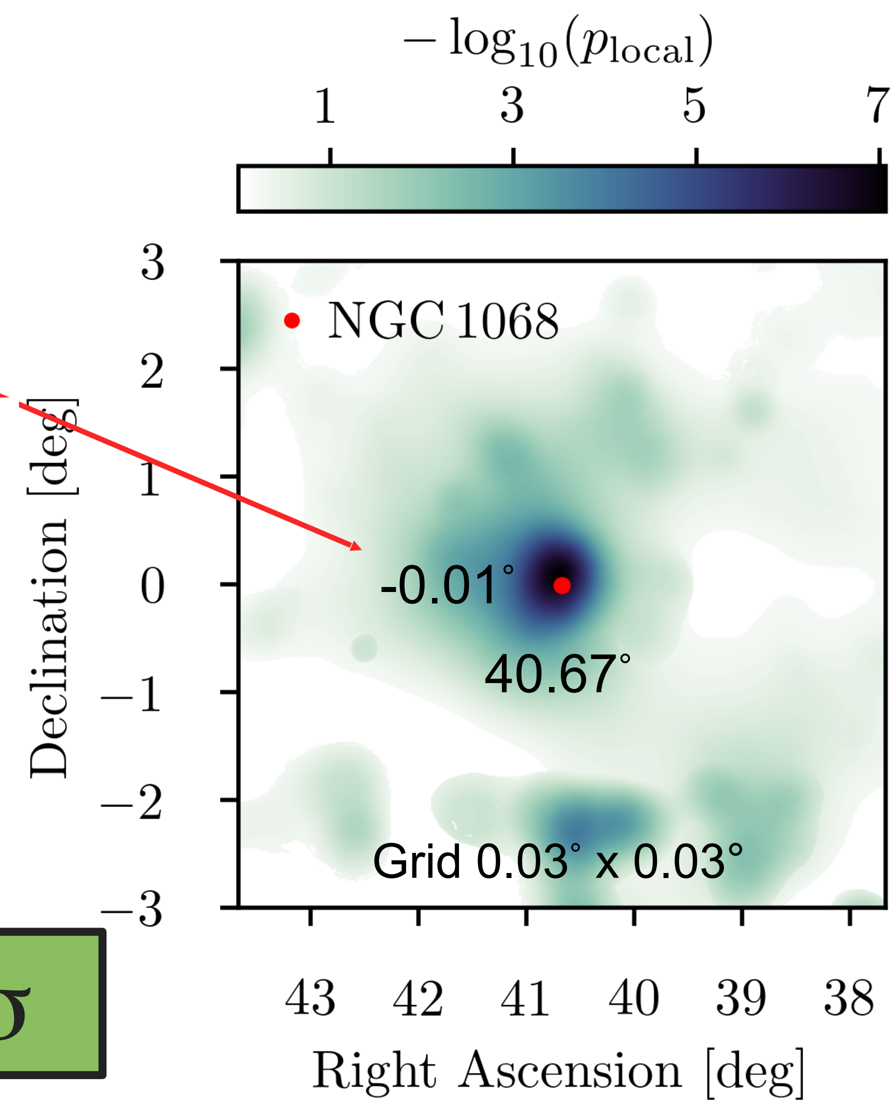
The IceCube Coll. and others, ***Science*** 361 (2018)
The IceCube Coll., ***Science*** 361 (2018)
The IceCube Coll., ***Science*** 378 (2022)

110 candidate sources



At the **NGC1068** location:

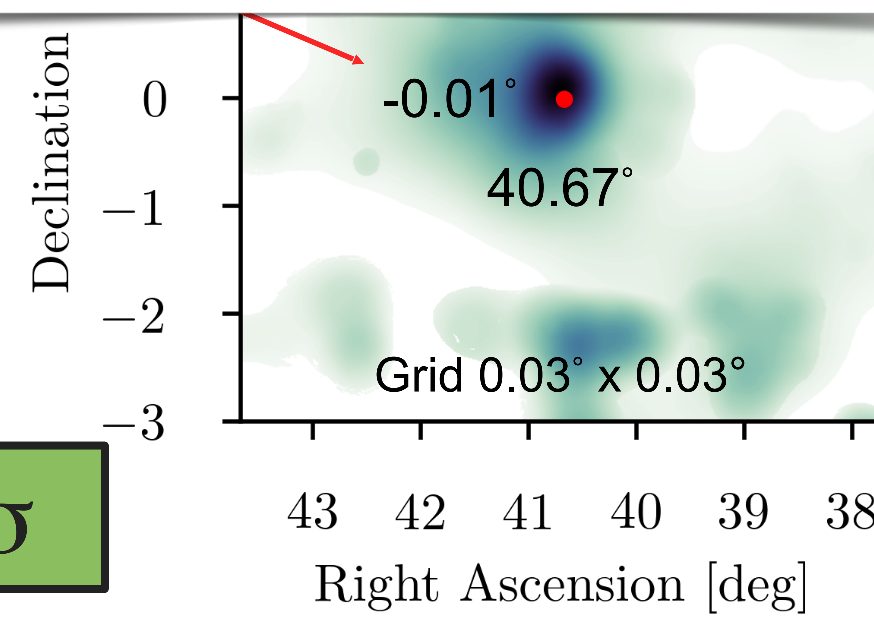
- Astrophysical neutrino events = 79^{+22}_{-20}
- Spectral index = 3.2 ± 0.2



Global significance **4.2σ**

First evidences for source association

IceCube Press Release UW, 03.11.22



Global significance **4.2σ**

NGC 1068 (D_L = 10.1 ± 1.8 Mpc)

Neutrinos from an obscured super massive black hole

P. Padovani, E.R., M. Ajello, et al., accepted in ***Nature Astronomy*, *arXiv:2405.20146***

p-p & p-γ

E_p~100 TeV

target γ~ X-ray domain

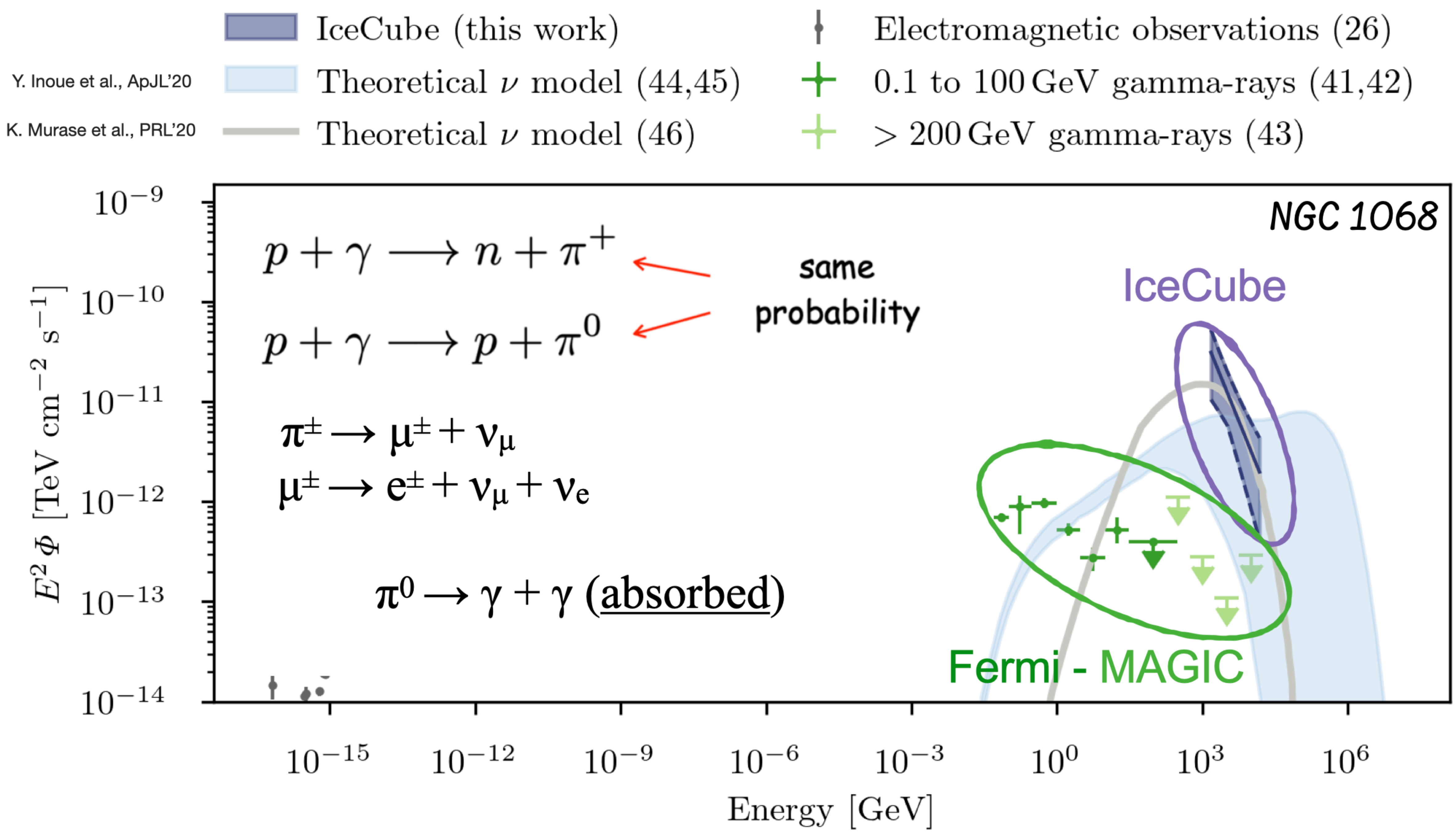
(Corona component)

super massive black hole are the future laboratories

Credit: NASA/JPL-Caltech

NGC1068 is not a Gamma Ray Source

The IceCube Coll., ***Science*** 378 (2022)



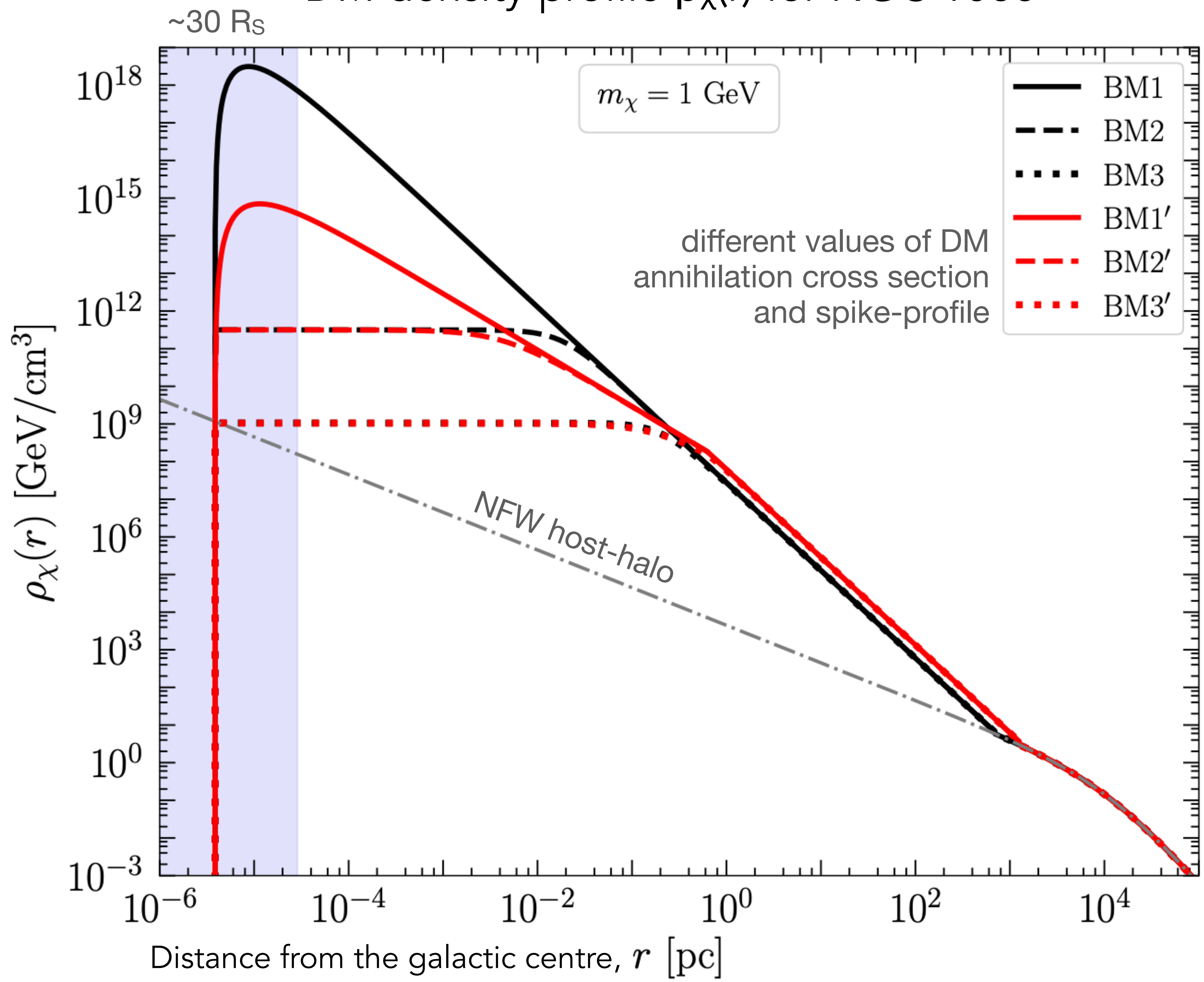
NGC1068: Neutrinos, Gamma-ray scattering on Dark Matter

Fuzzy DM scenarios: where quantum effects become apparent on large scales

J. M. Cline, M. Puel, JCAP 2023

G. Herrera, A. Ibarra, E.R., in preparation

DM density profile $\rho_\chi(r)$ for NGC 1068



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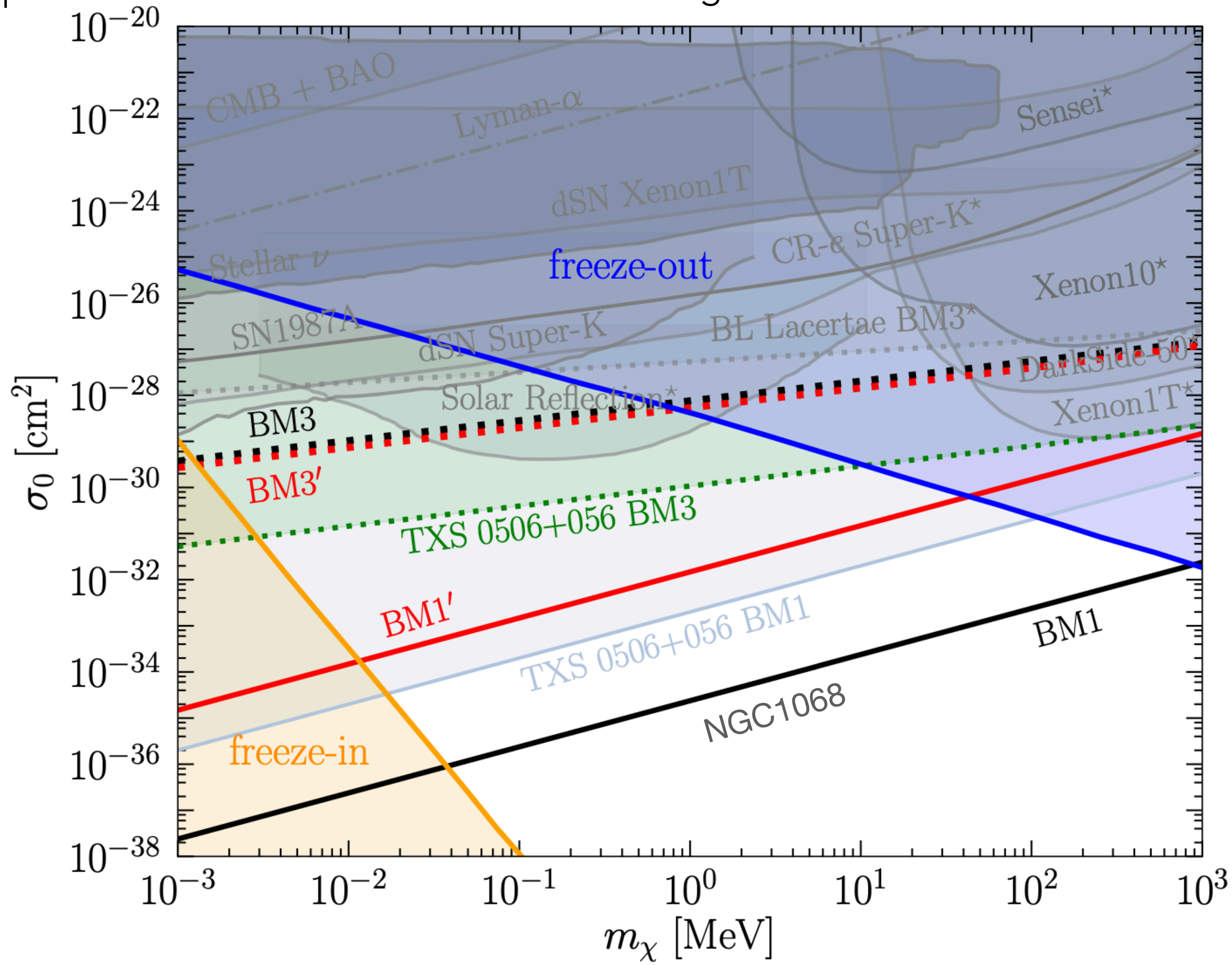
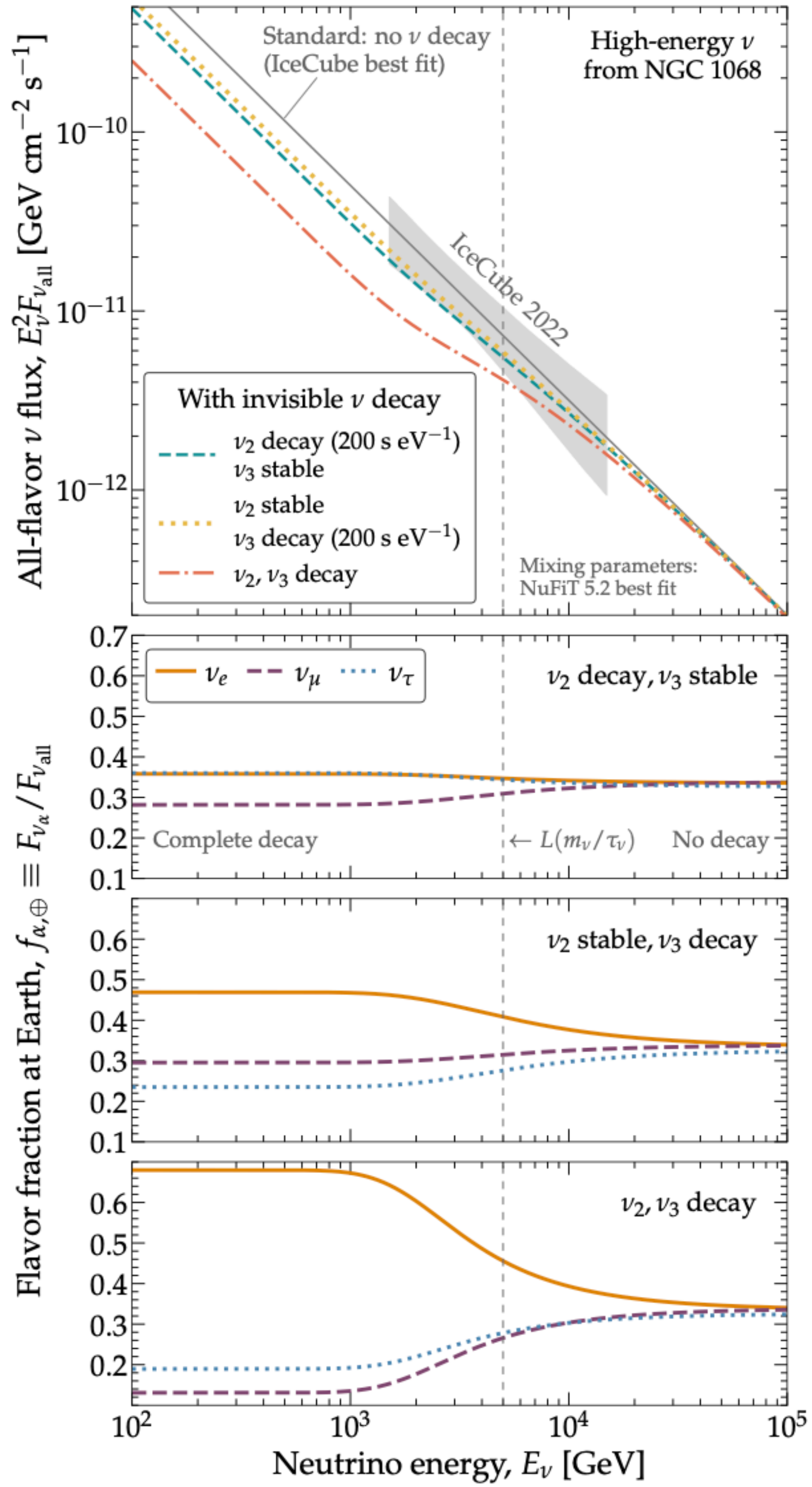
90% C.L. upper limits on the ν-DM and e-DM scattering cross sections at the reference energy E_o = 10 TeV



NGC1068: searches for neutrino decay

V. B. Valera , D. Fiorillo , I. Esteban, and M. Bustamante, e-Print: 2405.14826



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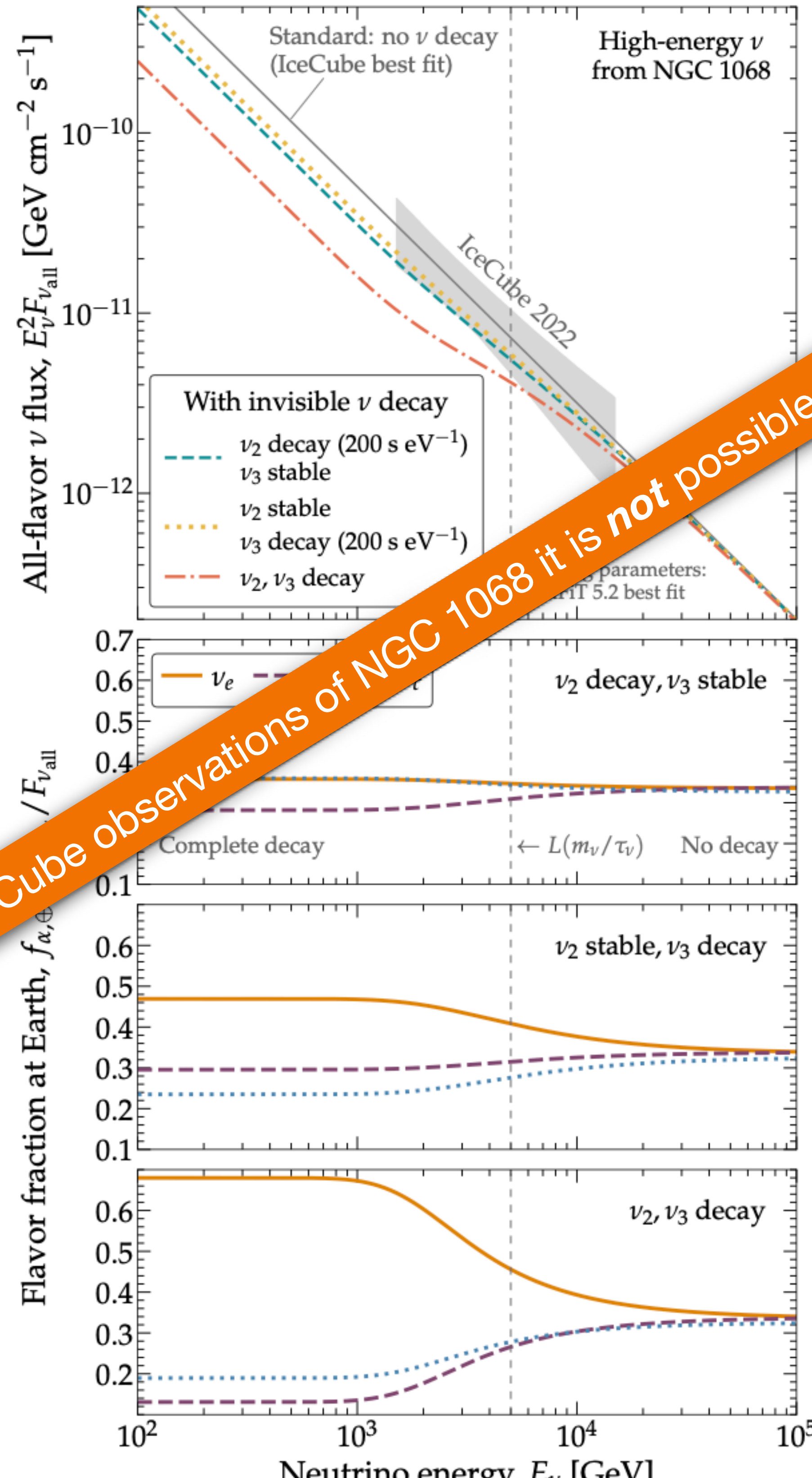


Using present-day IceCube observations of NGC 1068 it is ***not*** possible to constrain neutrino decay.

3rd order:

neutrinos as a probe of cosmic populations

& probe of cosmic objects, dark matter, relic neutrinos

& understand neutrino properties

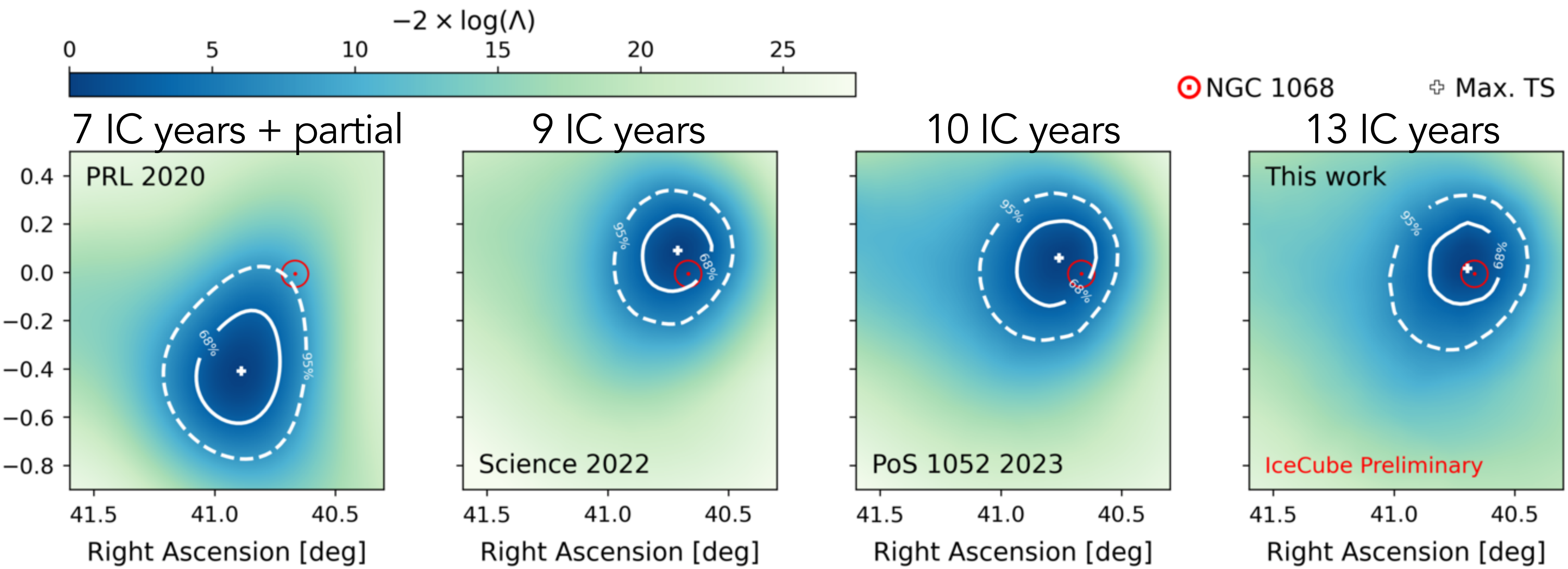
👉 new IceCube results

PRELIMINARY

From 9 years to 13 years of IceCube exposure

Hottest spot and global significance evolution of NGC1068

C. Bellenghi, E. Manao, T. Kontrimas, M. Ha Minh, E.R., M. Wolf (TUM) & the IceCube Coll., in preparation

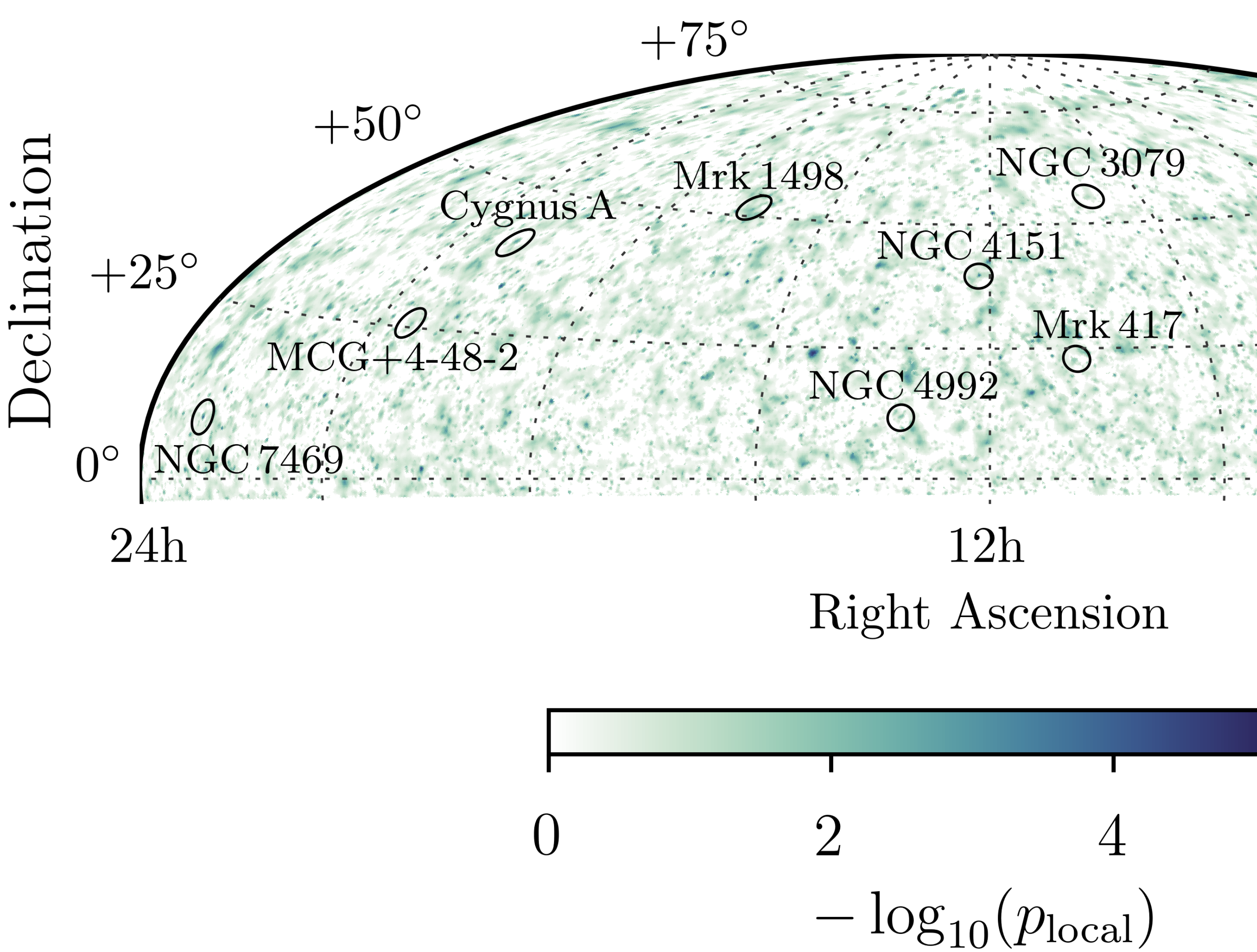


2.9σ 4.2σ 4.3σ 4.0σ

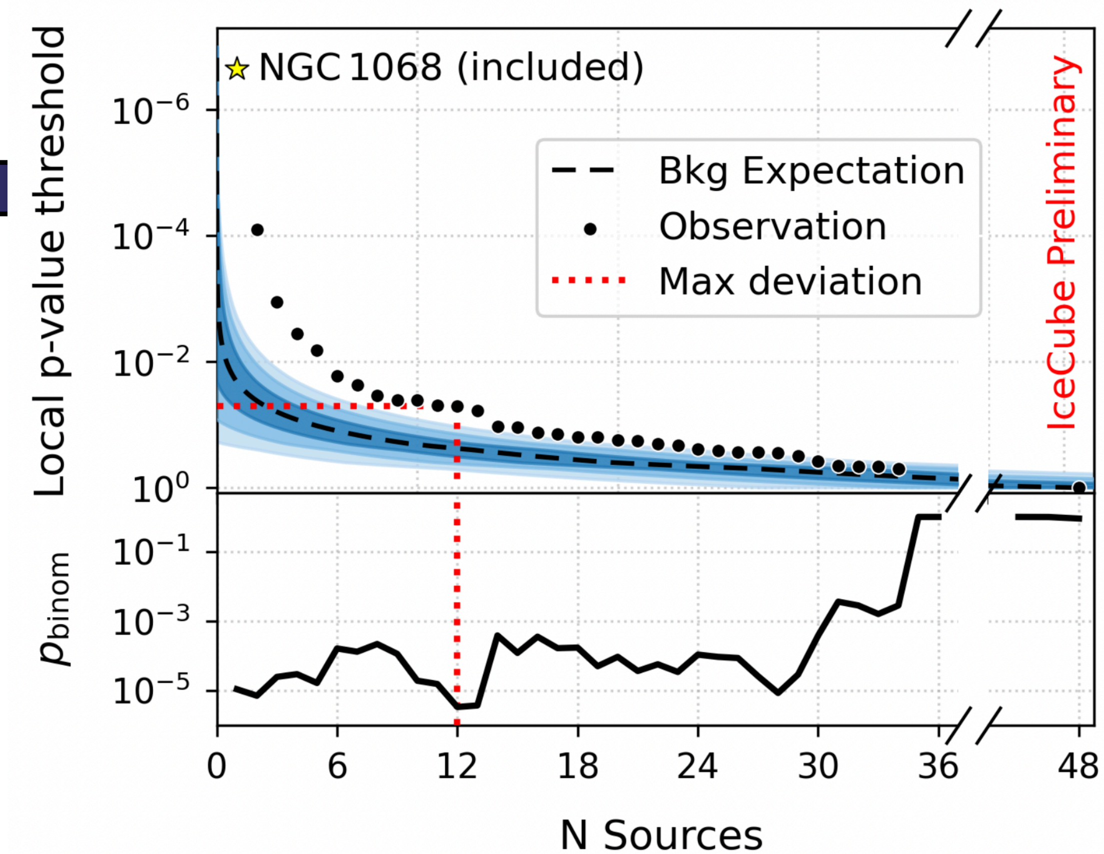
What about other similar AGN as NGC1068?

Selected a new list of 47 X-ray bright AGN

C. Bellenghi, E. Manao, T. Kontrimas, M. Ha Minh, E.R., M. Wolf (TUM) & the IceCube Coll., in preparation



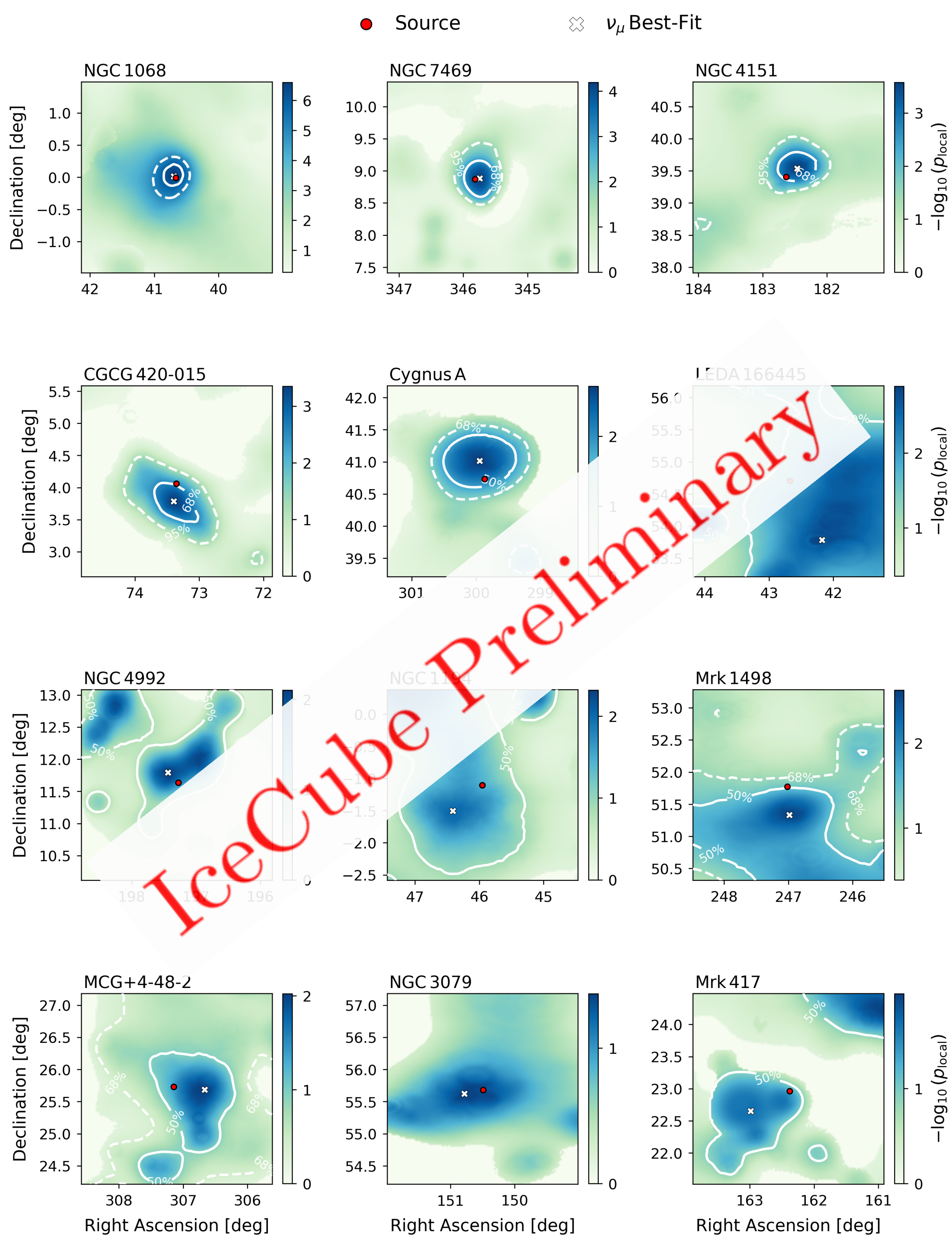
11+ 1 objects emerging



Global significance 3.3σ

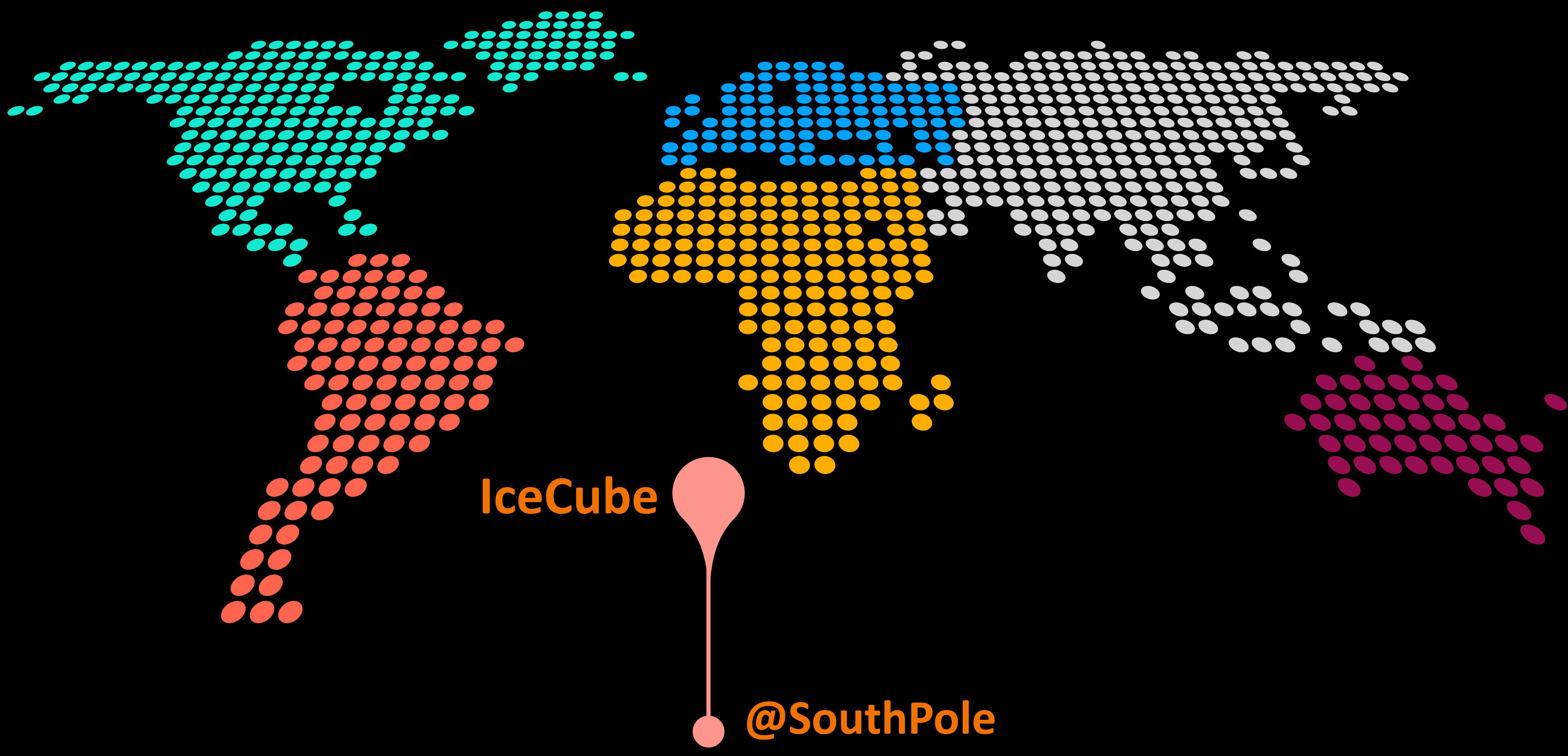
Emerging of a population of HE neutrino sources?

C. Bellenghi, E. Manao, T. Kontrimas, M. Ha Minh, E.R., M. Wolf (TUM) & the IceCube Coll., in preparation



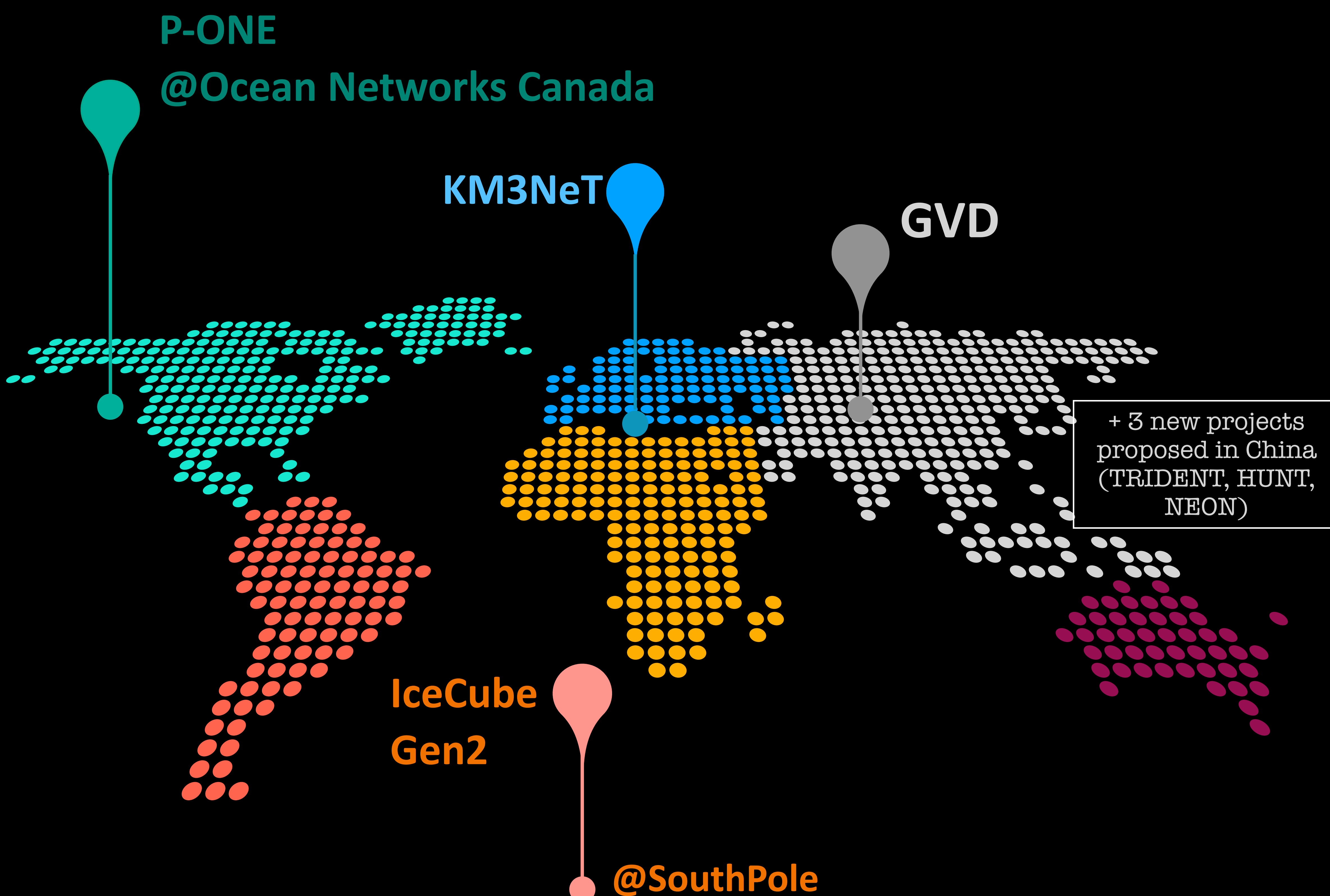
11+ 1 objects emerging

Neutrino experiments sensitive to cosmic fluxes



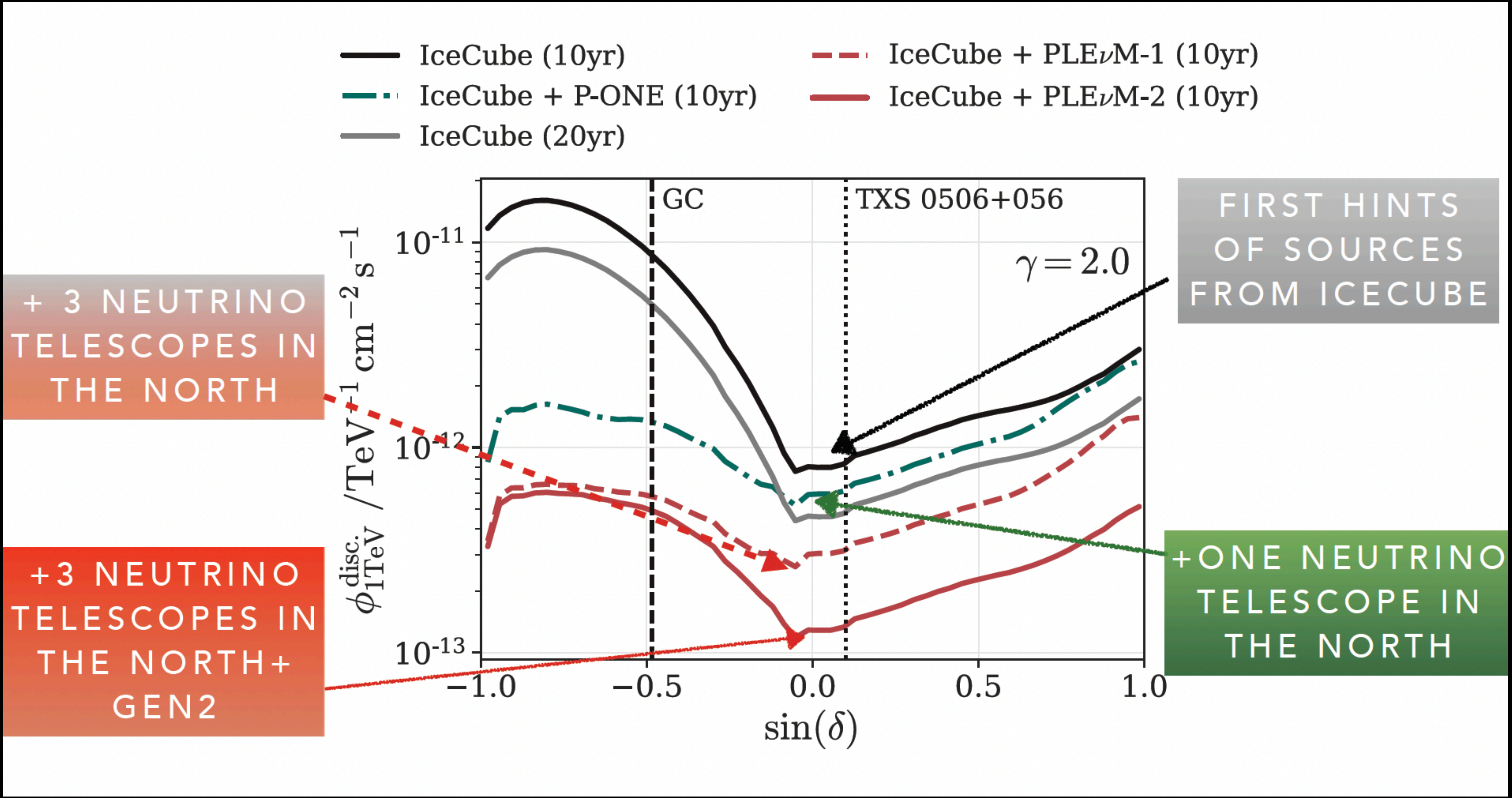
We need multiple LV neutrino experiments

L. Schumacher et al., PLEnuM, https://github.com/PLEnuM-group/Plenum



We need multiple LV neutrino experiments

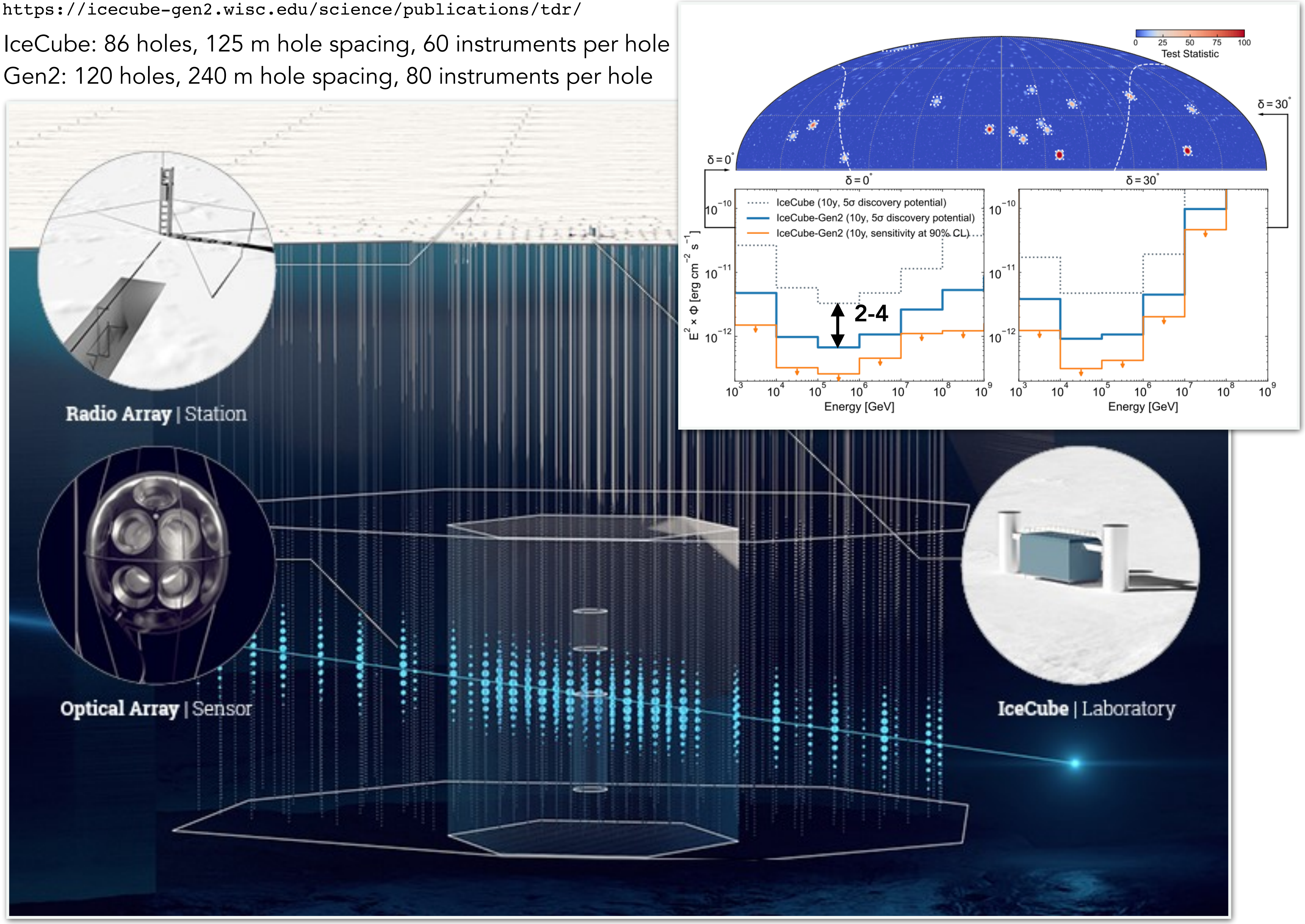
L. Schumacher et al., PLEnuM, https://github.com/PLEnuM-group/Plenum



IceCube Gen2: scale in **volume**

https://icecube-gen2.wisc.edu/science/publications/tdr/

IceCube: 86 holes, 125 m hole spacing, 60 instruments per hole
Gen2: 120 holes, 240 m hole spacing, 80 instruments per hole



IceCube Gen2: scale in **volume**

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IceCube: 86 holes, 125 m hole spacing, 60 instruments per hole

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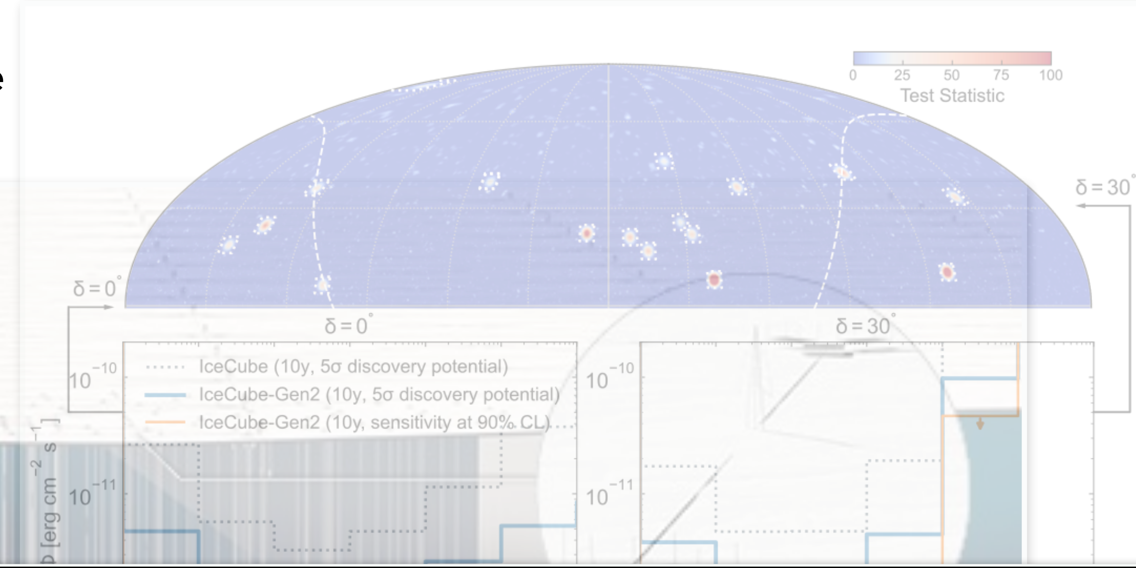


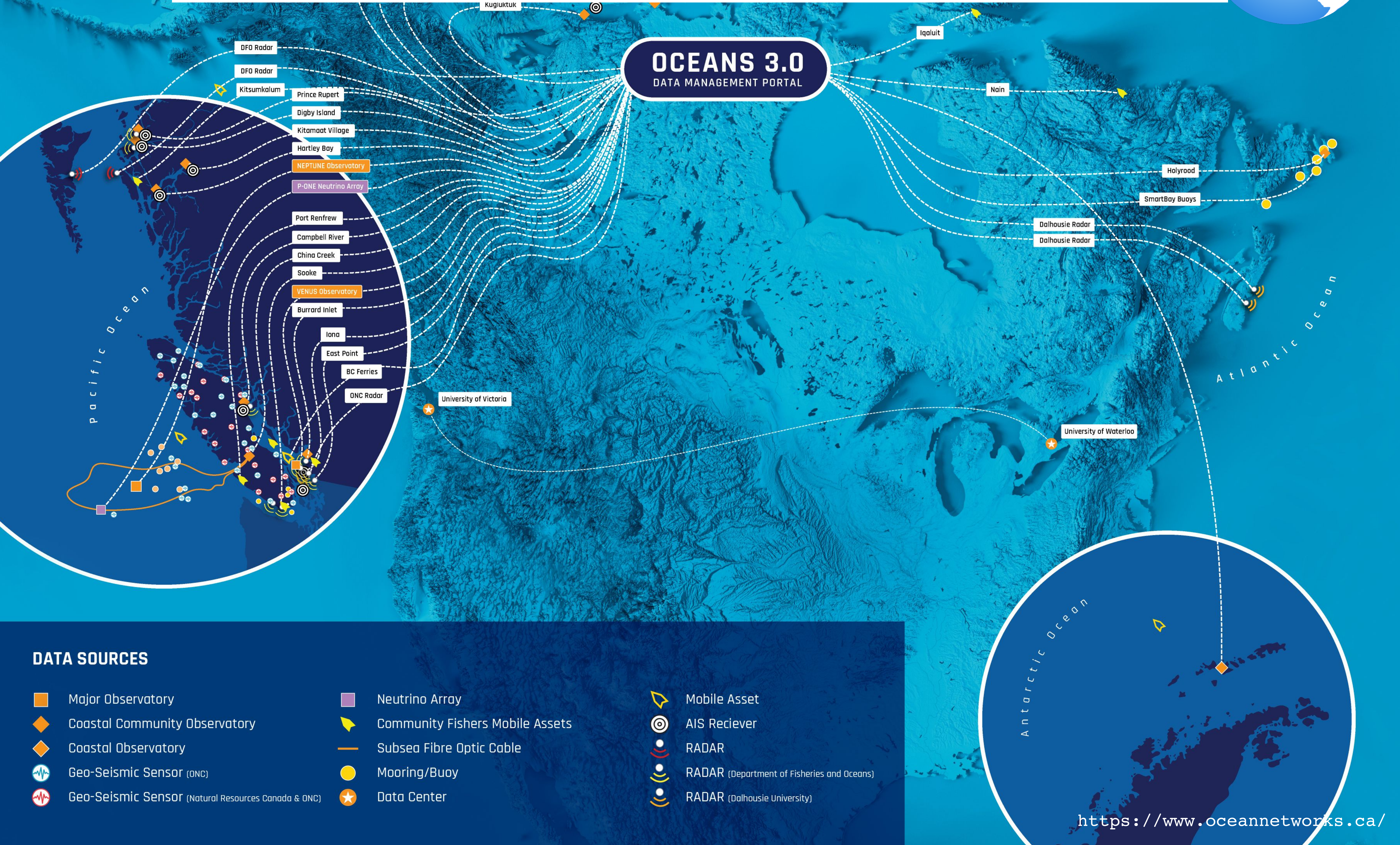
NSF perspective: *NSF has determined that the South Pole is essentially closed for any significant new construction of scientific equipment beyond what is already committed for at least the next 10 years (CMB-S4)*

- There is currently no defined timescale for IceCube-Gen2, although we know that Antarctic infrastructure needs provides an important constraint.
- Currently, we are focused on completing the ongoing IceCube upgrade. Results from that upgrade will inform any future plans for IceCube-Gen2

Saul Gonzalez, Division Director, Division of Physics, National Science Foundation HEPAP Meeting – May 9, 2024

11

The Pacific Ocean Neutrino Experiment @ Ocean Networks Canada



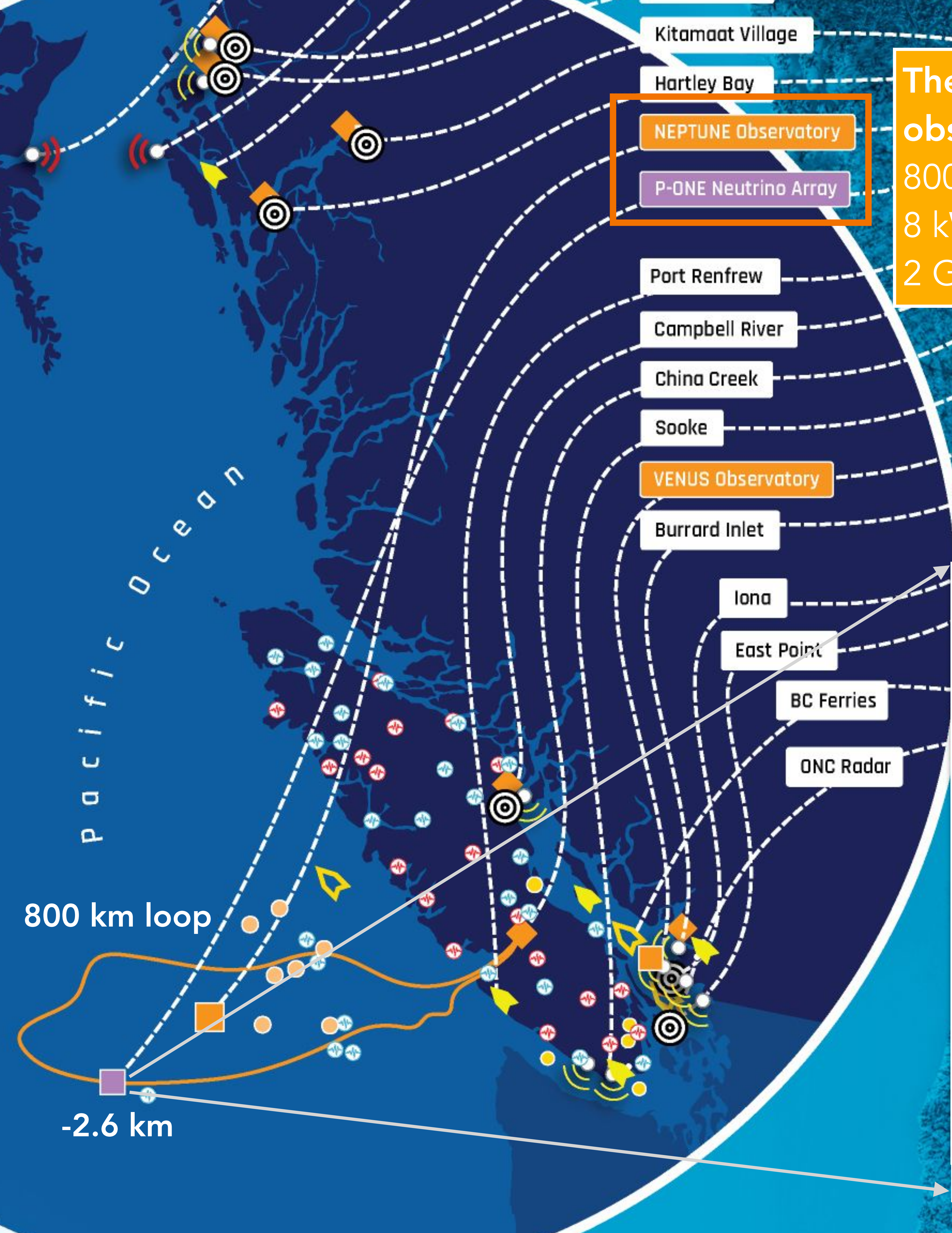
https://www.oceannetworks.ca/

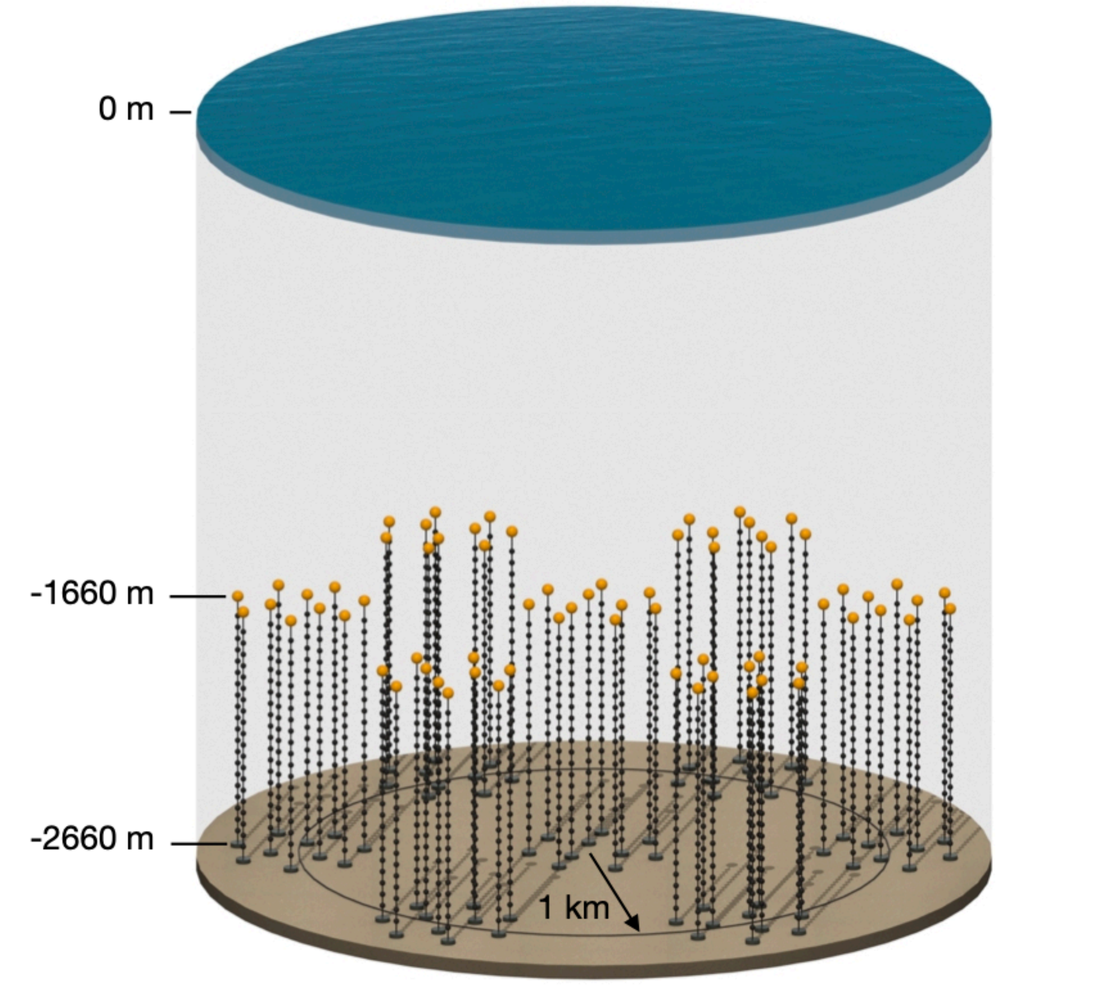
The world's largest undersea, real-time observatory network -

800 km loop of fibre-optic cables,

8 kW x 6 nodes,

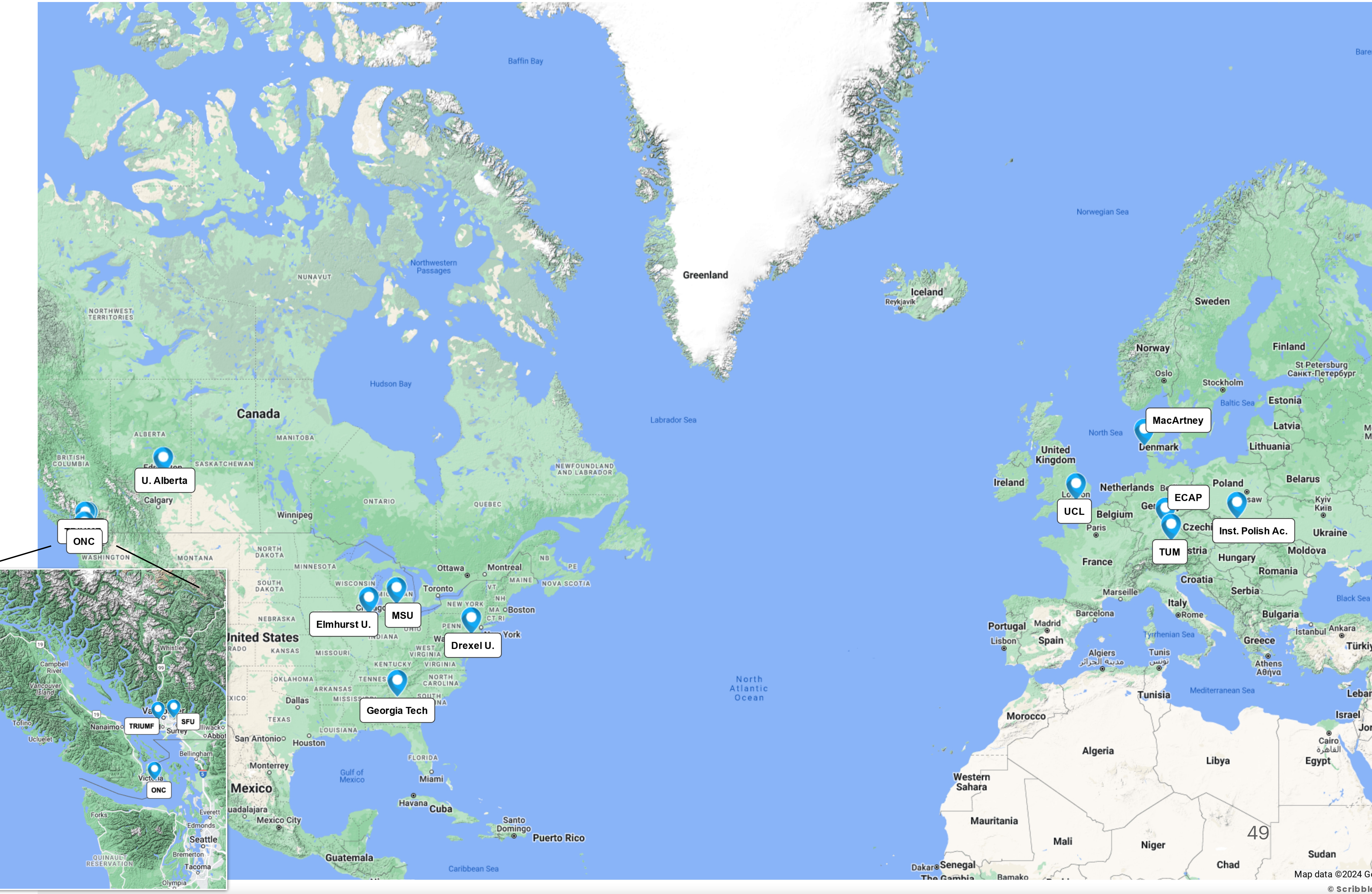
2 Gbit





P-ONE Collaboration, Nature Astron. 2020

P-ONE Collaboration & Major Partners on the Map



The Pacific Ocean Neutrino Experiment (P-ONE): pathfinders

STRAW — Deployed 2018

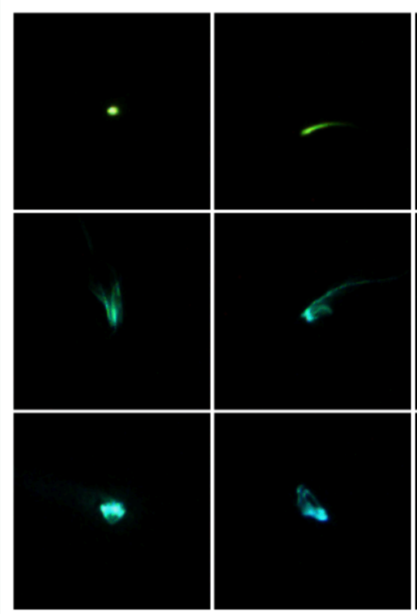
STRAW$_b$ — Deployed 2020

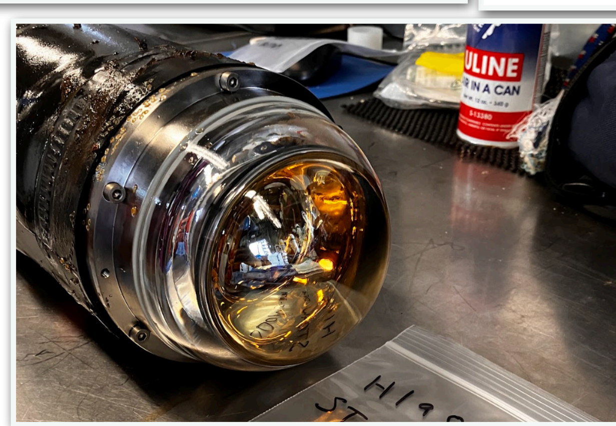
STRAW, STRAW$_b$ — Recovered 2023

1st pathfinder

2nd pathfinder

Papers in preparatic





JINST — Published by IOP Publishing for Sissa Medialab

Received: November 20, 2018
Accepted: January 28, 2019
Published: February 13, 2019

STRAW (STRings for Absorption length in Water): pathfinder for a neutrino telescope in the deep Pacific Ocean

comment

The Pacific Ocean Neutrino Experiment

The Pacific Ocean Neutrino Experiment is a new initiative towards constructing a multi-cubic-kilometre neutrino telescope to expand our observable window of the Universe to the highest energies, and will be installed within the deep Pacific Ocean underwater infrastructure of Ocean Networks Canada.

JINST — Published by IOP Publishing for Sissa Medialab

Received: October 26, 2023
Revised: February 7, 2024
Accepted: March 16, 2024
Published: May 28, 2024

STRAW-b (STRings for Absorption length in Water-b): the second pathfinder mission for the Pacific Ocean Neutrino Experiment

K. Holzapfel,[a,*] C. Spannfellner,[a] O. Aghaei,[b] A. Baron,[b] J. Bedard,[b] M. Böhmer,[a] J. Bosma,[b] N. Deis,[b] C. Fink,[a] C. Fruck,[a] A. Gärtner,[c] R. Gernhäuser,[a] F. Henningsen,[d] R. Hotte,[b] R. Jenkyns,[b] M. Karl,[a] Na. Khera,[e] Ni. Khera,[f] I. Kulin,[b] A. Lam,[b] T. Lavallee,[b] K. Leismüller,[a] L. Papp,[a] B. Pirenne,[b] E. Price,[b] T. Qiu,[b] I.C. Rea,[g] E. Resconi,[a] A. Round,[b] C. Rott,[h,i] A. Ruskey,[b] L. Ruohan,[a] K. Sasaki,[b] M. Tradewell,[b] M. Traxler,[j] D. Vivolo,[g,k] S. Wagner,[b] E.L. Winter[a] and M. Wolf[a]

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[d] Department of Physics, Simon Fraser University, 8888 University Drive, Burnaby, Canada
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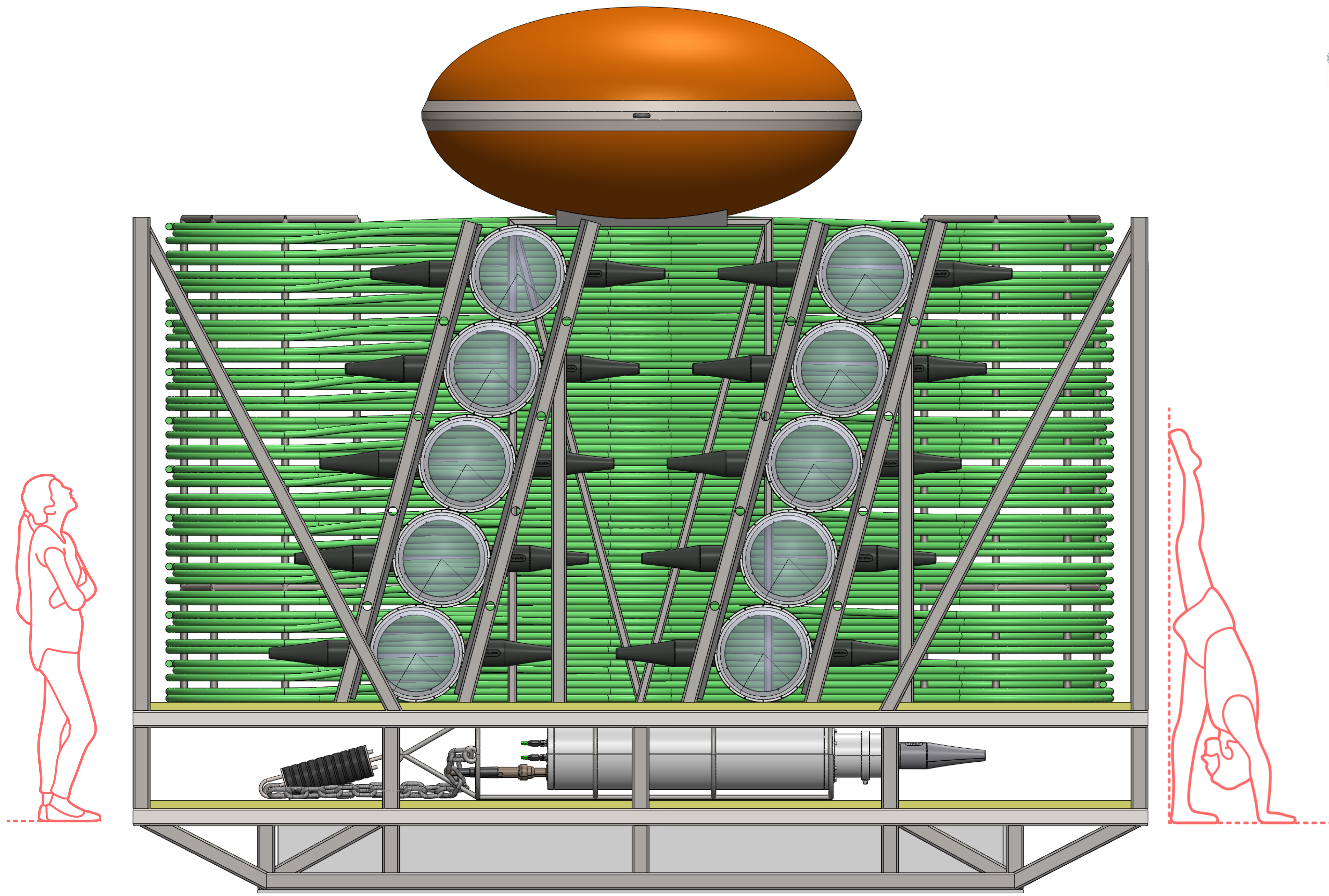
2024 JINST 19 P0

The Pacific Ocean Neutrino Experiment (P-ONE)

The Element: A 1 km Tall Instrumented Line Compactly Designed to Fit in a Transport Container

P-ONE Coll., ***Nature Astron.*** 2020;
C. Spannfellner et al., PoS ICRC23.

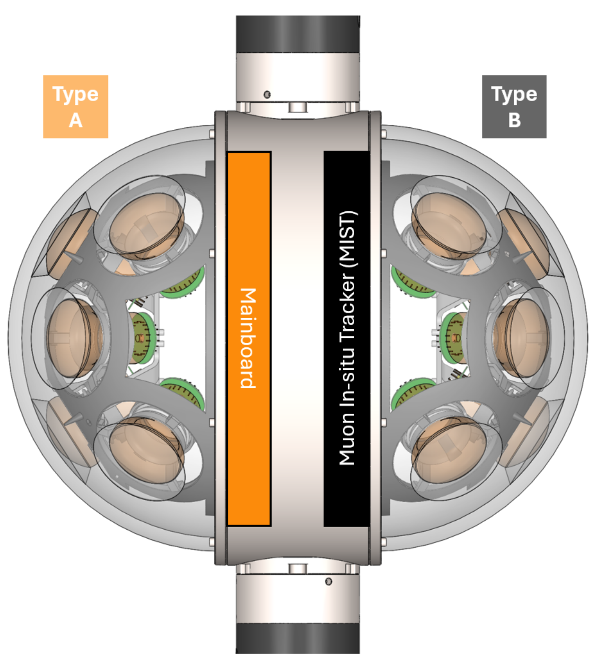


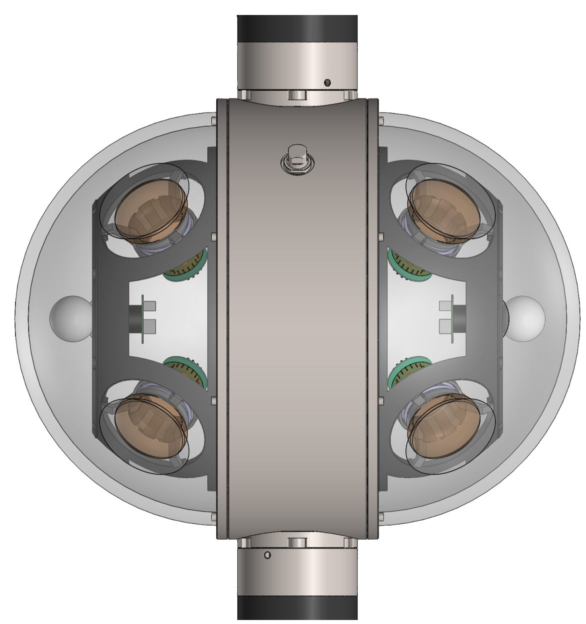
P-ONE System: Oceanography and Neutrino Experiments

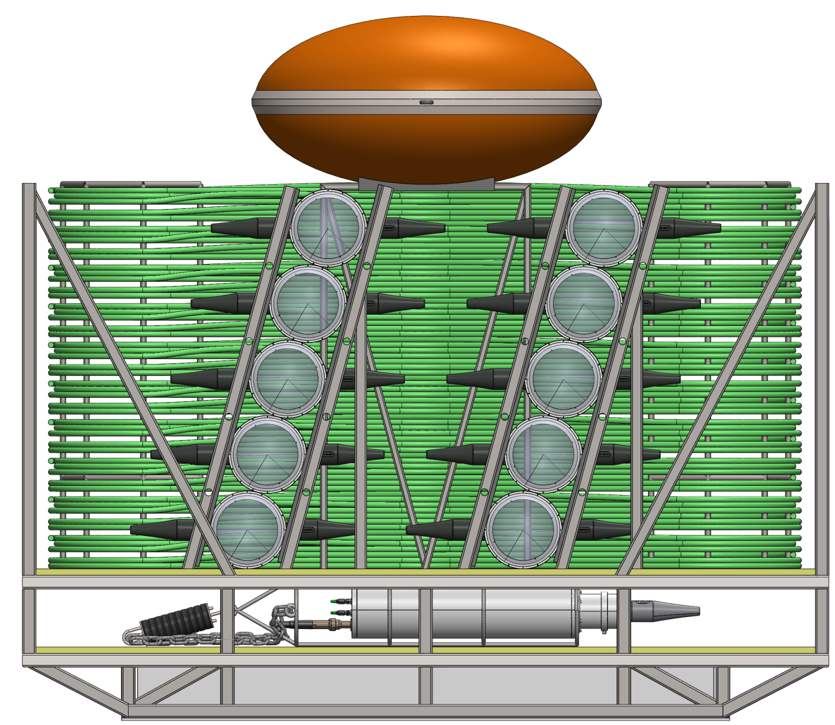
C. Spannfellner et al., PoS ICRC23; F. Henningsenn et al., PoS ICRC23.

- ***Integrated System***: Fully integrated assembly, transport, deployment, and anchor system.
- ***Advanced Waterproofing***: Connectorless, patented triple waterproof system.
- ***Precision Data***: Full waveform readout, sub-nanosecond timing, self-calibrated.
- ***Environmental Monitoring***: Integrated external environmental sensors by design.

1:1 spooling test, ’23 (TUM)



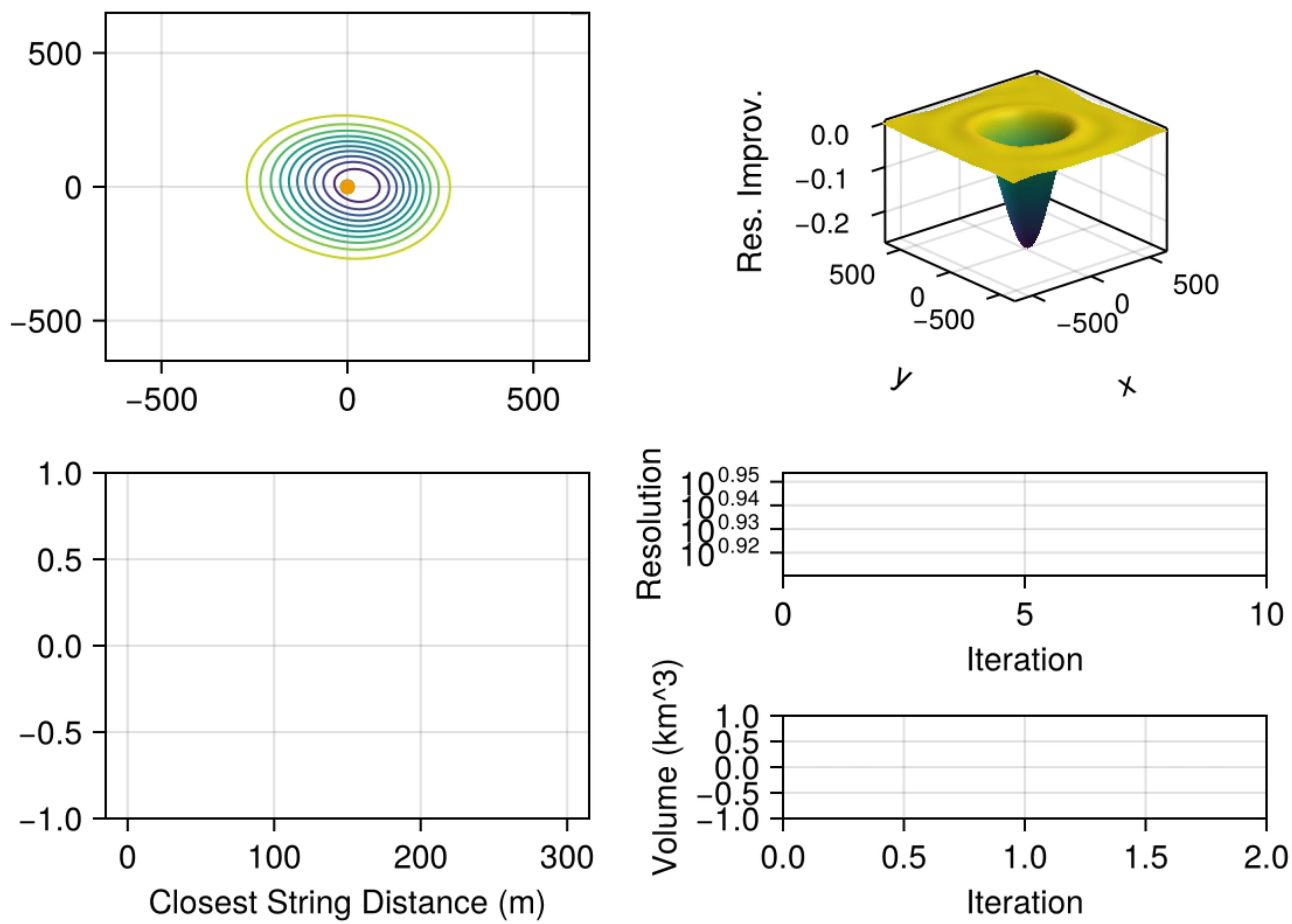




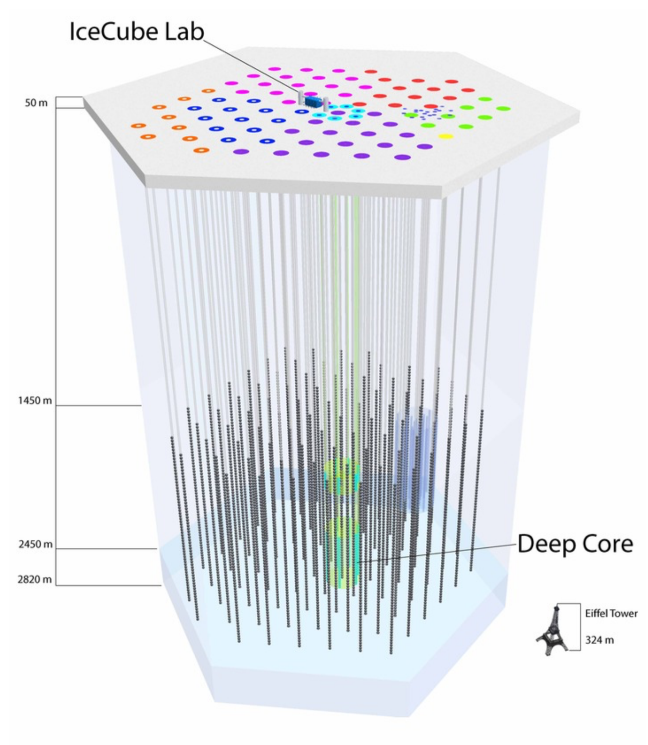
P-ONE Array Optimization: Surrogate Model

C. Haack et al., PoS ICRC23

- ***Present Optimal Geometry***: Calculated for best resolution.
- ***Discovery Potential***: Next, optimizing for best discovery potential, including full simulation of all background sources.

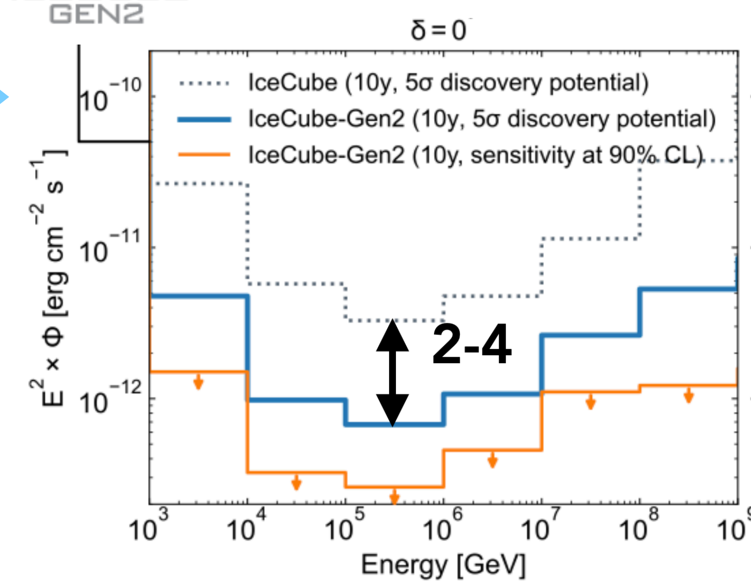


P-ONE as ***next generation neutrino experiment***

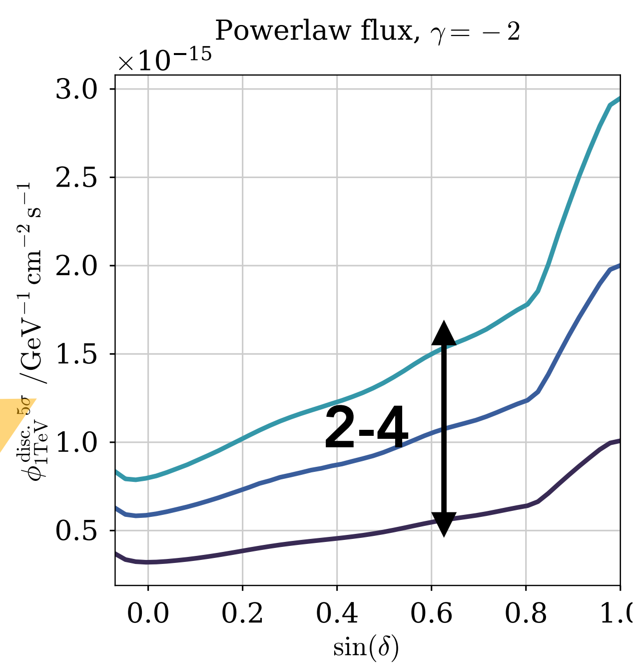


VOLUME

ICECUBE GEN2



ANGULAR RES.



P-ONE

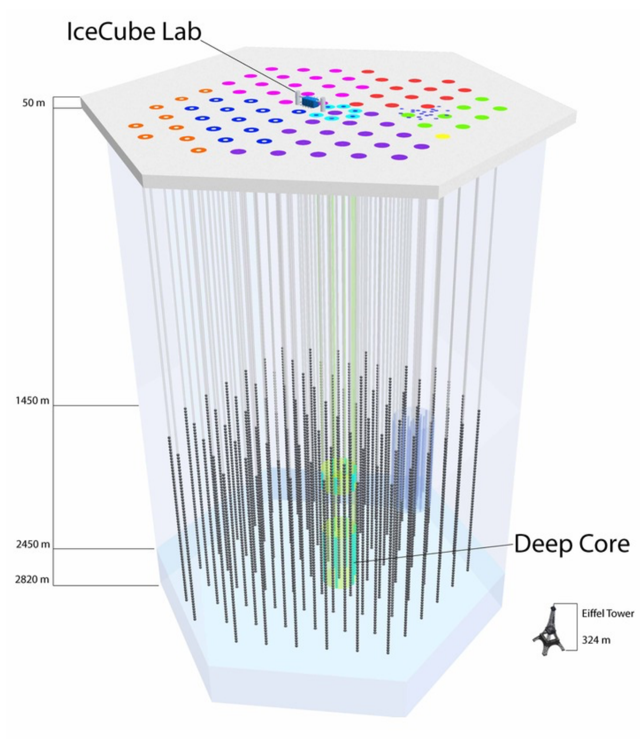
Challenges for Implementation:

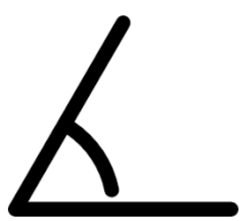
- IceCube: Impacted by ice scattering
- KM3NeT: Uses PMTs and Time-over-Threshold (ToT) technology

P-ONE as ***next generation neutrino experiment***

Gain through boost of ***Angular Resolution***

Gain through boost of ***Timing***

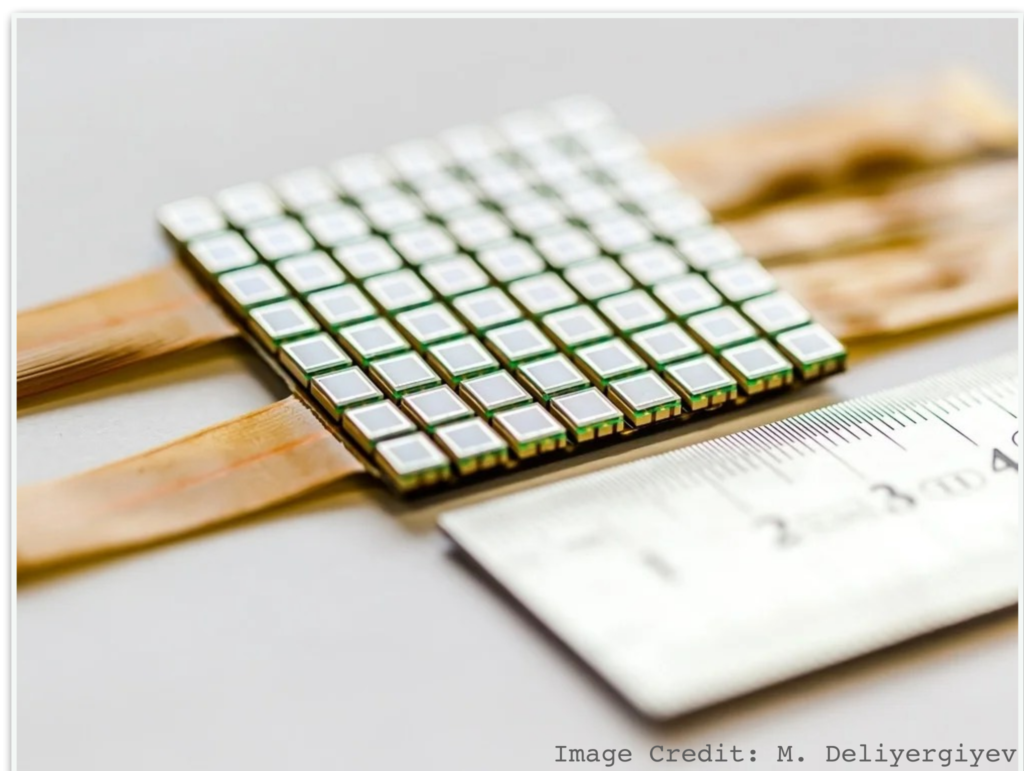




P-ONE

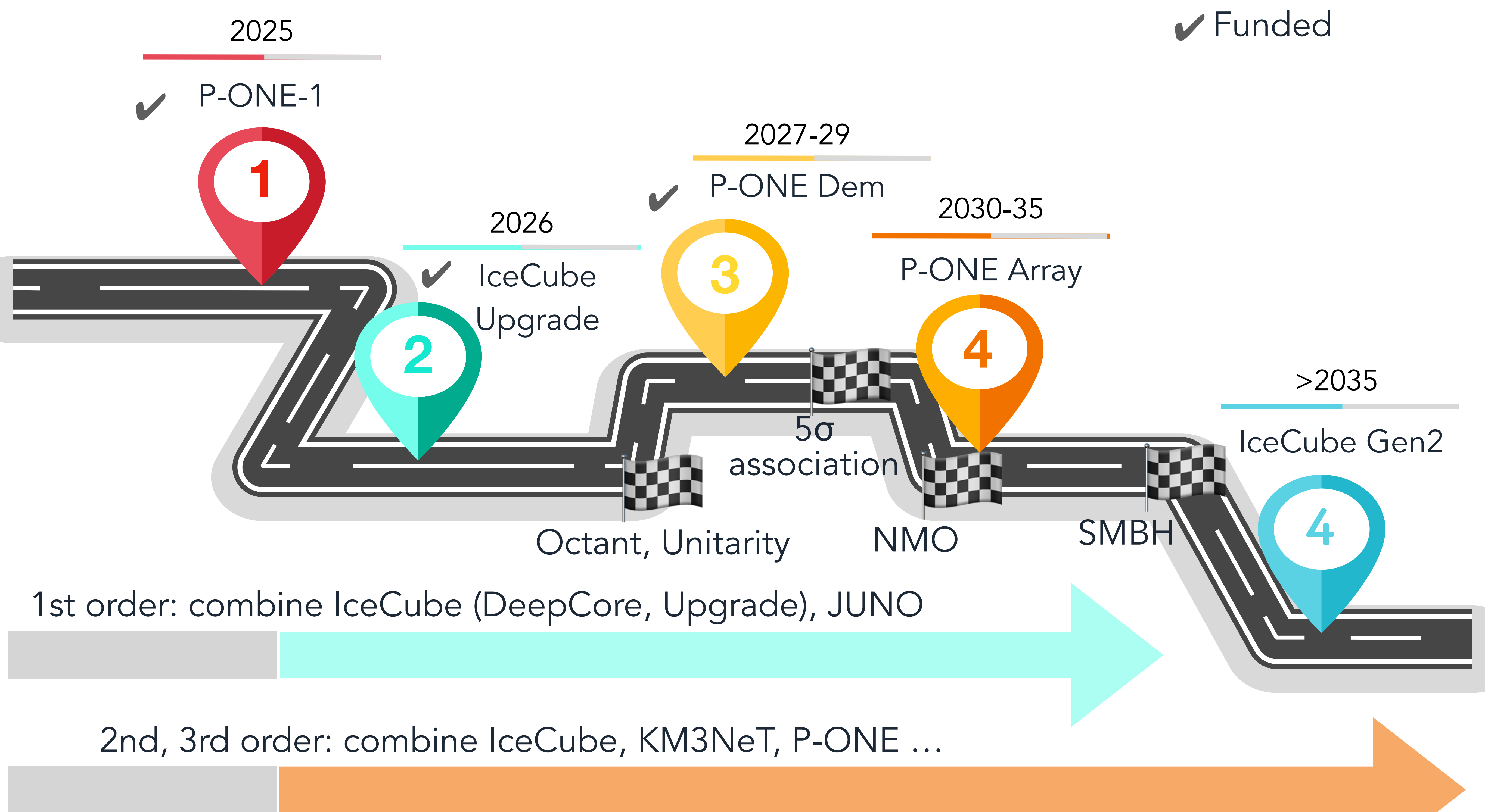
TTS ~ 1.5 - 1.7 nsec

NEW TECHNOLOGY REQUIRED



R&D on SiPMTs for large area, extreme conditions and ***sub-ns***

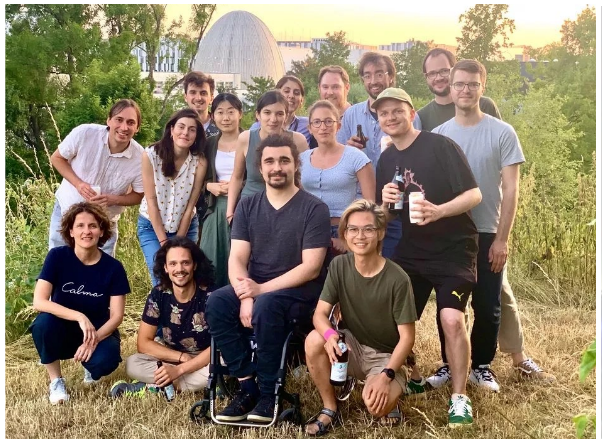
Strategic Roadmap to Unlocking Neutrino Secrets



Large-area sub-nanosecond SiPMTs for high-energy neutrino detection promise a groundbreaking breakthrough.

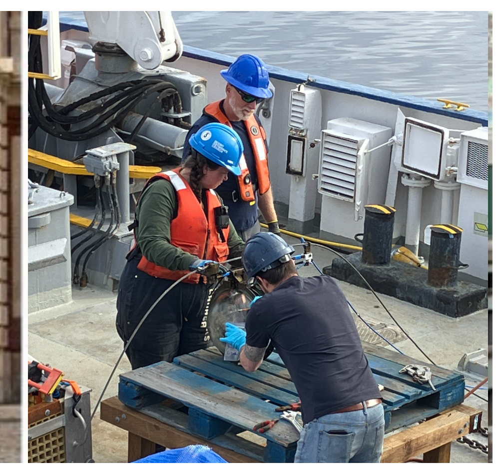
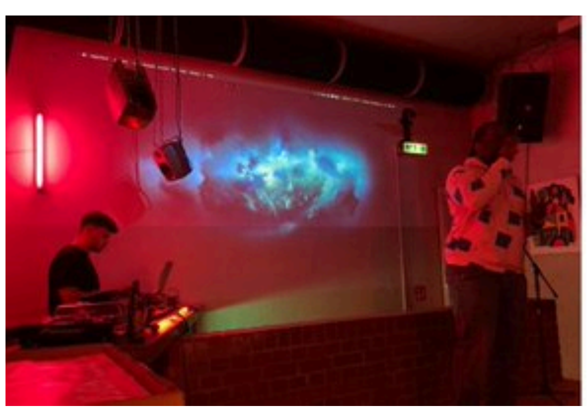
It takes a village ….

TUM/ECP, SFB1258, IceCube, P-ONE







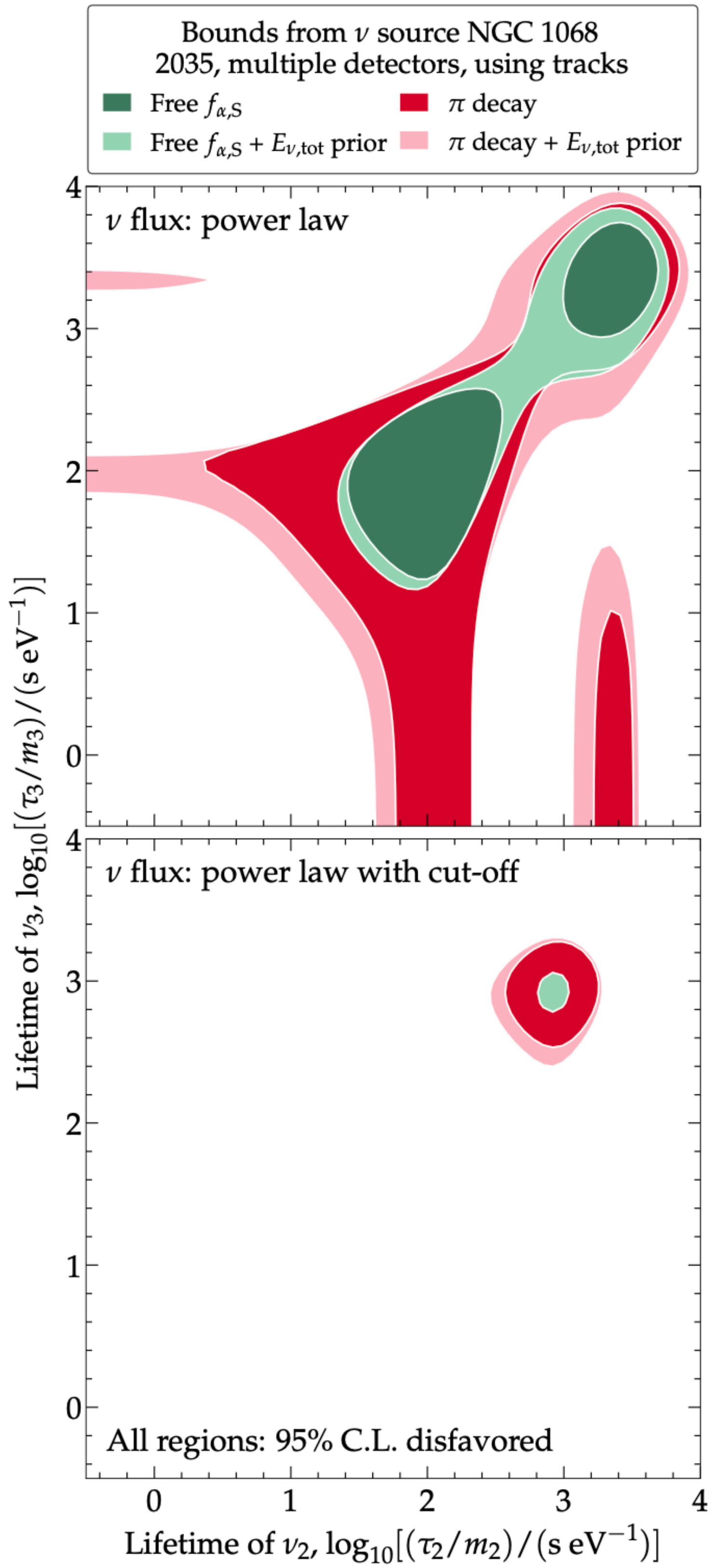
In conclusion

- “The neutrino sector is as intriguing and important as ever." - Saul Gonzalez, NSF
- My program covers IceCube/Upgrade, P-ONE, (potentially) JUNO and combined
- New **High Energy Neutrinos division** at MPP will drive groundbreaking discoveries and profound insights into the universe.
- Very natural synergy with MAGIC/LST/Fermi and the photosensors tradition.
- Privileged environment, specialized workshops & people, advanced semiconductor lab for high-performance detectors.

Backup

NGC1068: searches for neutrino decay with multiple sources (and detectors)

V. B. Valera , D. Fiorillo , I. Esteban, and M. Bustamante, e-Print: 2405.14826



NSF Perspectives on P5, Saul Gonzalez Division Director, Division of Physics
National Science Foundation, HEPAP Meeting - May 9, 2024

Conclusion: The View from NSF

Exploring the Quantum Universe

- We must maximally exploit existing and new facilities
- There is a shift in the center of gravity of the field from collider techniques to cosmo/astro techniques. We heard that message and are thinking about how to follow that shift to these scientific opportunities.
  - This is healthy because it means the particle physics is dynamic, chasing the science, not the tools themselves. (see EPP2024 charge!)
- However, much community interest in Higgs factory and muon collider development
- There are opportunities for instrumentation development and cyberinfrastructure tools by leveraging emerging technologies and allied fields
- The neutrino sector is as intriguing and important as ever.
- There are budgetary constraints and technically-limited infrastructure constraints, so need to be realistic about what can be done when and where.
- We are excited about the future of particle physics!

NSF Perspectives on P5
Saul Gonzalez Division Director
Division of Physics
National Science Foundation
HEPAP Meeting - May 9, 2024

P5 Recommendation 2 (continued)

P5: *Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future. [in priority order:]*

e) IceCube-Gen2 for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool

NSF perspective:

- There is currently no defined timescale for IceCube-Gen2, although we know that Antarctic infrastructure needs provides an important constraint.
- Currently, we are focused on completing the ongoing IceCube upgrade. Results from that upgrade will inform any future plans for IceCube-Gen2

NSF Perspectives on P5
Saul Gonzalez Division Director
Division of Physics
National Science Foundation
HEPAP Meeting - May 9, 2024

P5 Recommendation 3

P5: ***Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.***

b) Continue Mid-Scale Research Infrastructure (MSRI) and Major Research Instrumentation (MRI) programs as a critical component of the NSF research and project portfolio.

NSF perspective:

- We agree. The FY 2025 President's Budget Request for NSF includes requests for MRI, MSRI-1, and MSRI-2. The Division has benefitted from these programs.

Photo Credits: University of Michigan

NGC1068: An Archetype of Obscured Active Galactic Nuclei

P. Padovani, E.R., M. Ajello, et al., accepted in ***Nature Astronomy, arXiv:2405.20146***

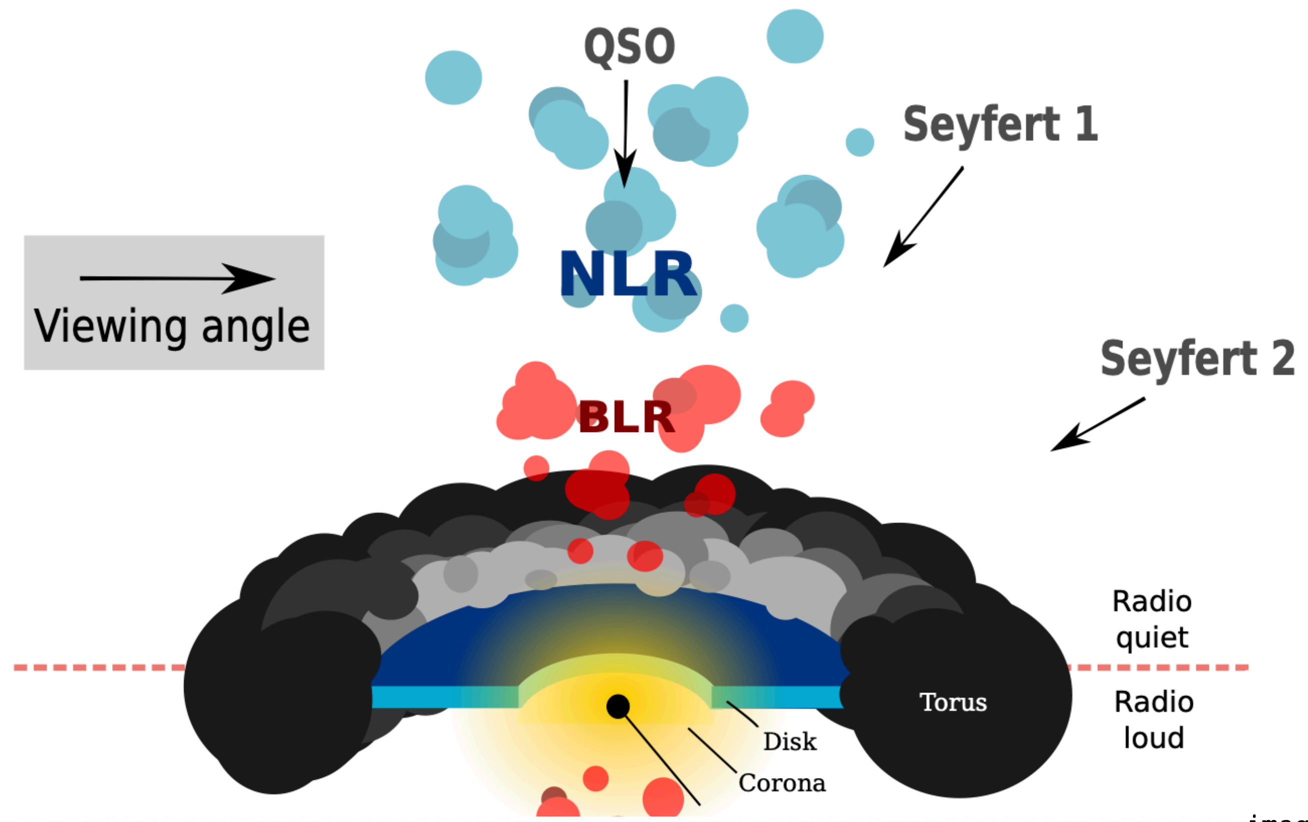


image from L. Baronchelli (MPE)

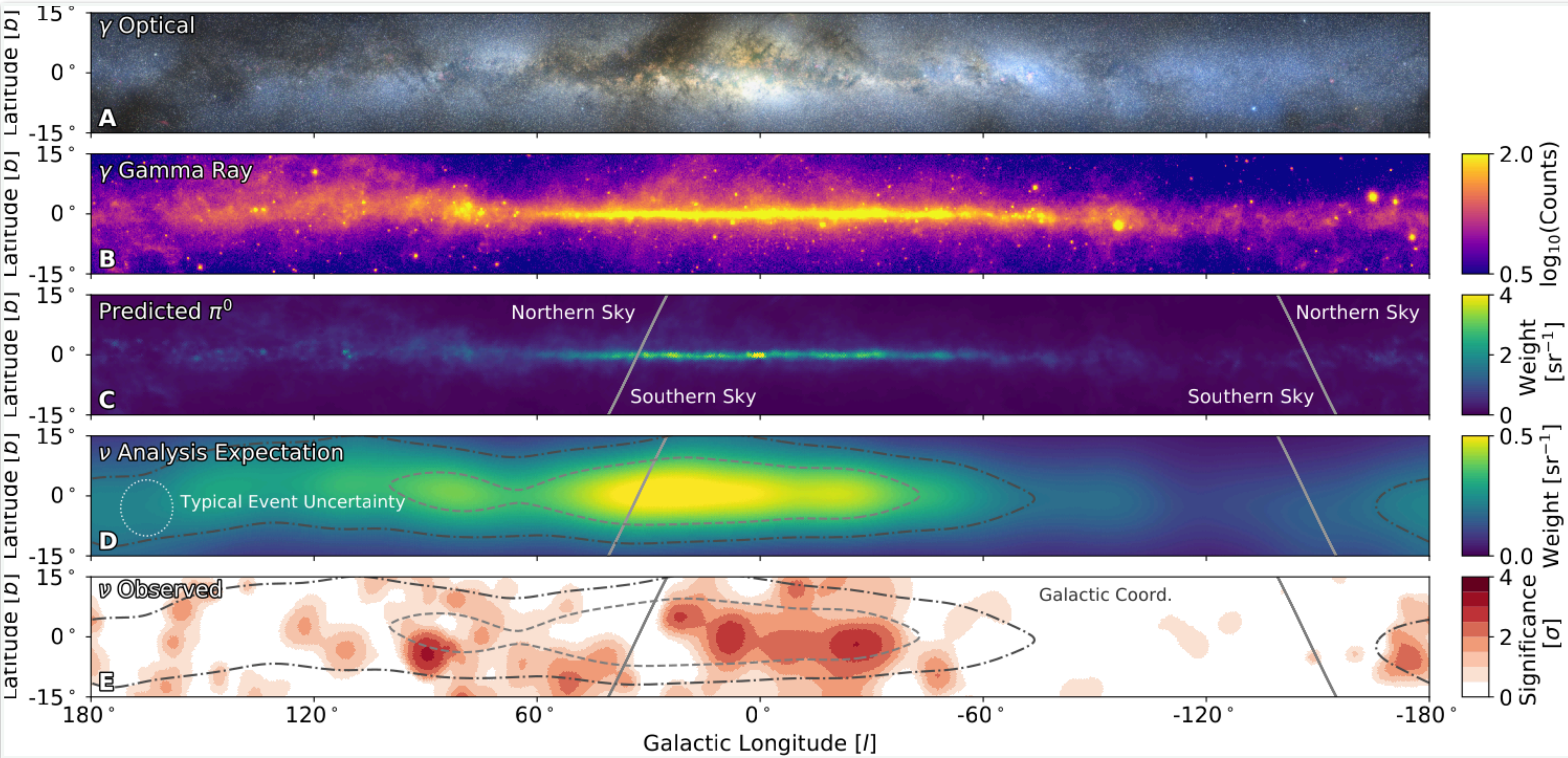
Table 3. Estimated γ-ray and neutrino powers.

Component	Scale	L_γ (0.1 – 10 GeV)	L_ν (1.5 – 15 TeV)
Star formation	$>$ kpc	$\sim 10^{40.9}$	$\lesssim 10^{40.1}$
Jet	$\sim$ kpc	$< 10^{41.7}$ (M87-like)	$< 10^{40.9}$
Outflow (UFO)	$\sim$ pc	$< 10^{41.2}$	$< 10^{40.4}$
BH vicinity	~ 0.03 mpc ($\sim 50\ R_s$)	?	?
	Total	$\lesssim 10^{41.9}$	$\ll 10^{41.1}$
	Observed	$10^{40.92\pm0.03}$	$10^{42.1\pm0.2}$

All powers in erg s^{-1}; R_s is the Schwarzschild radius.

The Galactic plane in neutrinos

The IceCube Coll., ***Science*** 380 (2023)



Global significance **4.5σ**

Paul de Jong (ANTARES)

The Galactic plane in neutrinos

The IceCube Coll., ***Science*** 380 (2023)

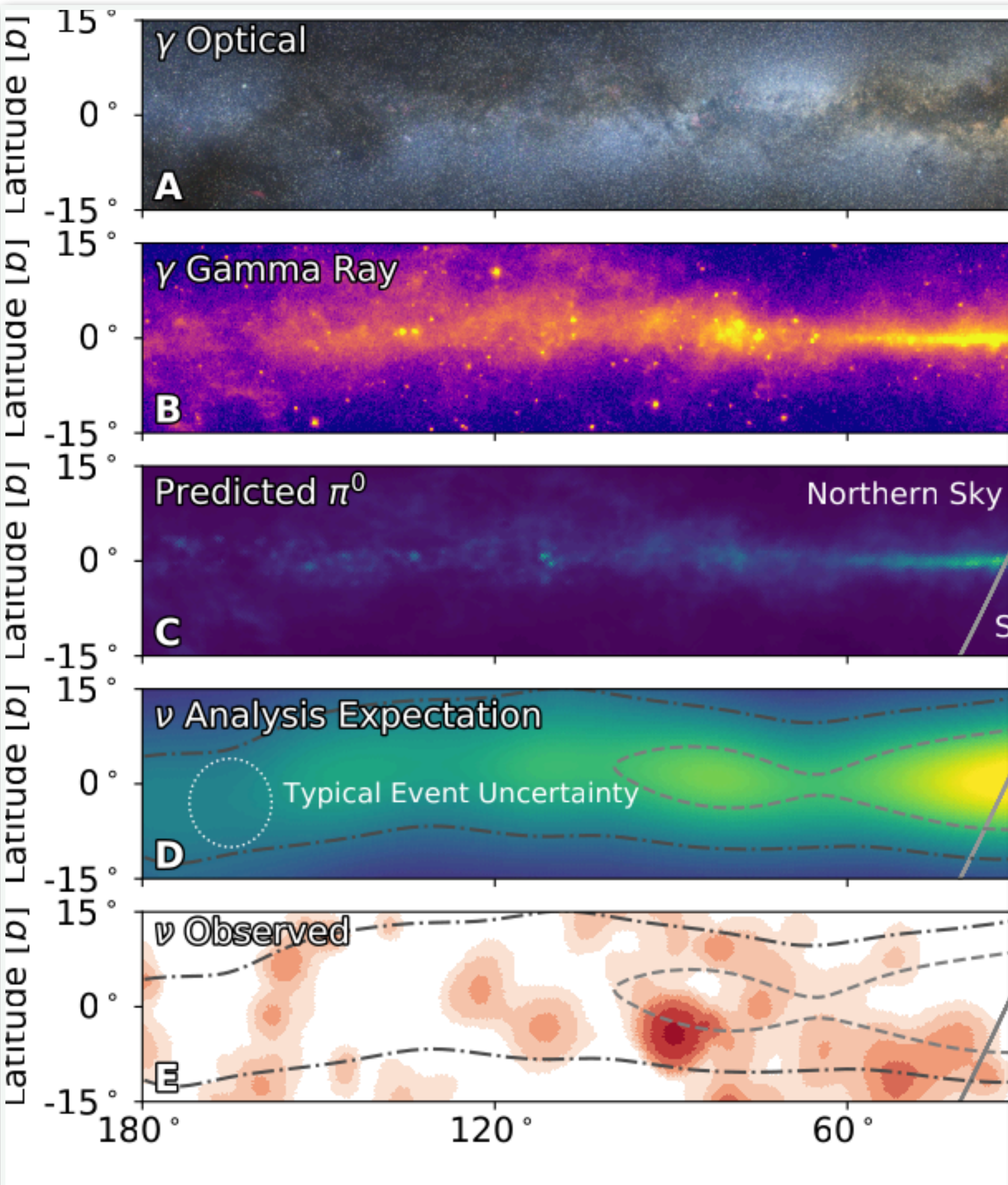
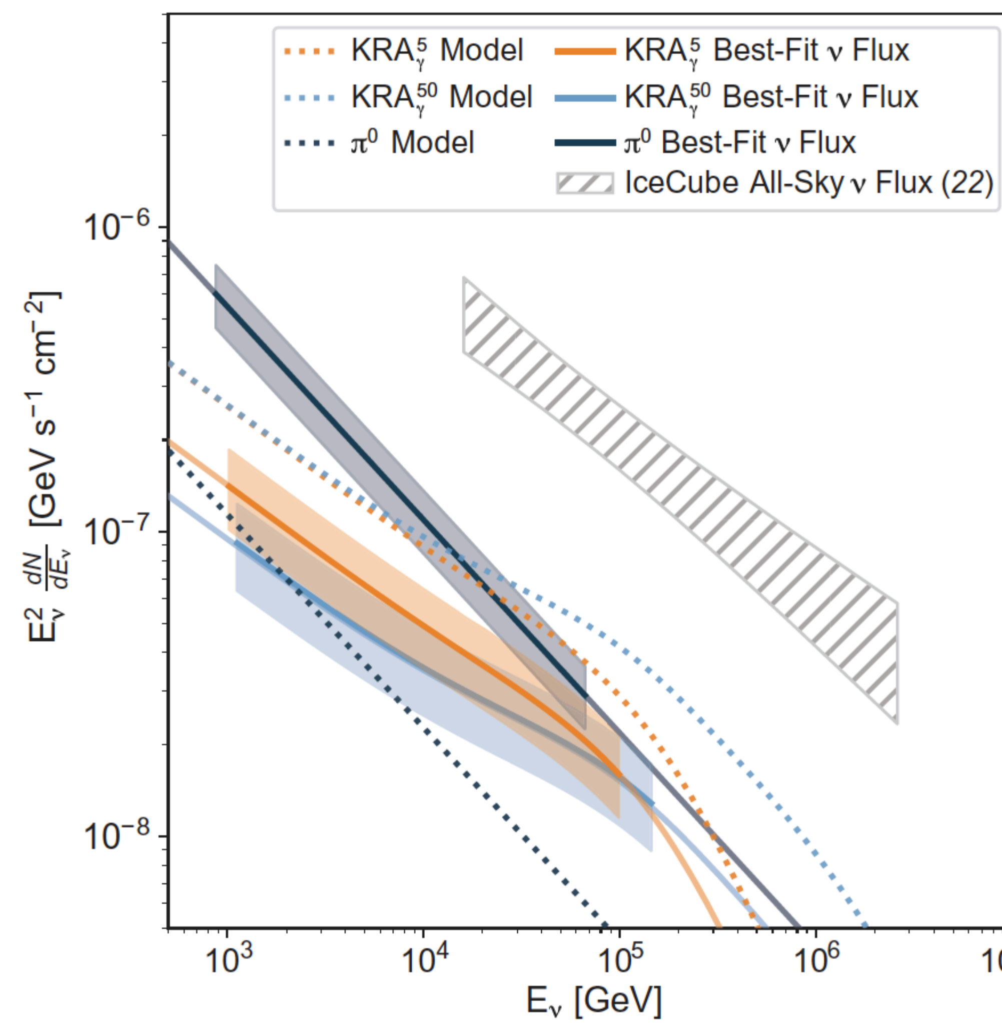


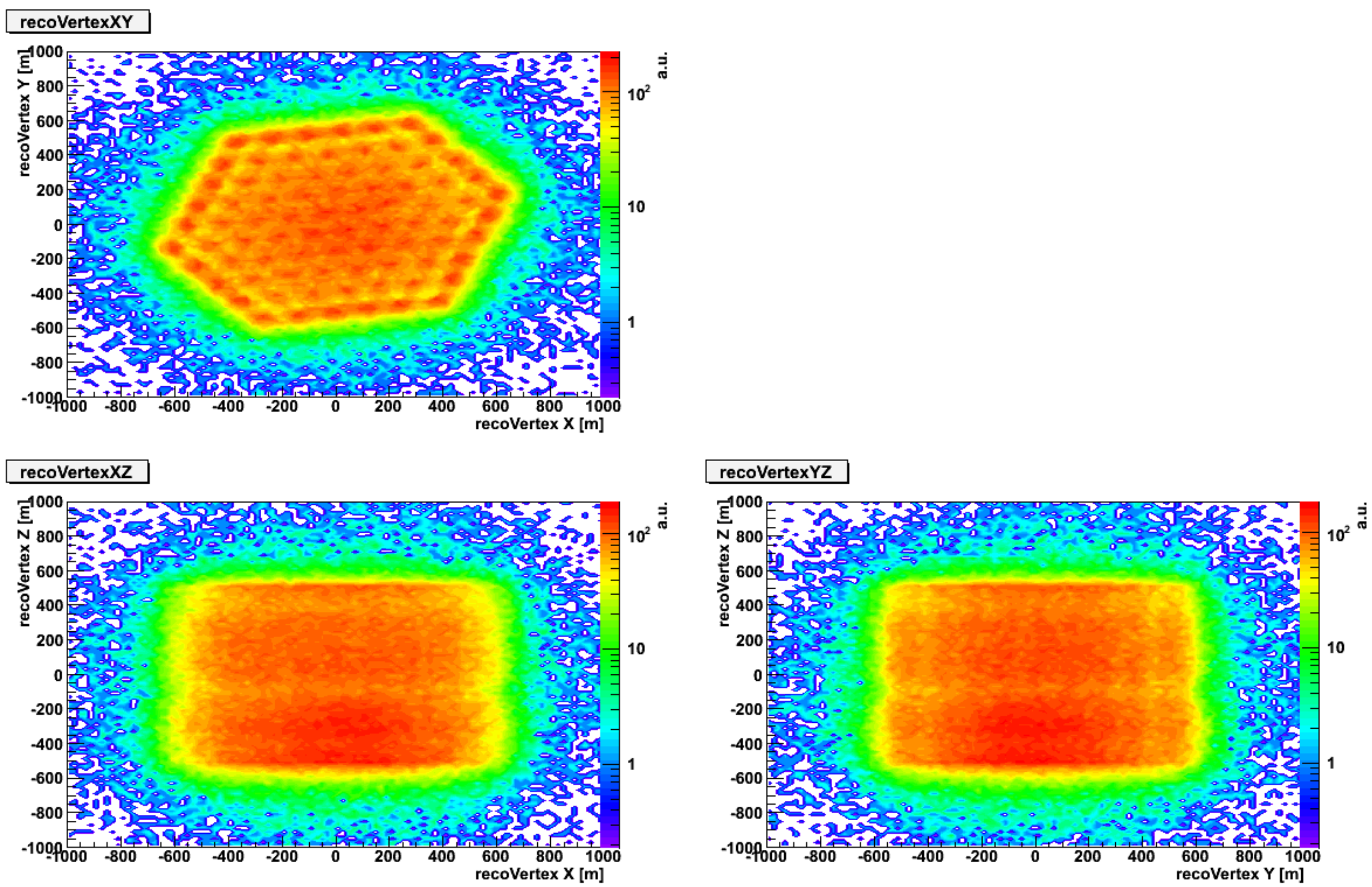
Fig. 5. Energy spectra for each of the Galactic plane models. Energy-scaled, sky-integrated, per-flavor neutrino flux is shown as a function of neutrino energy (E_ν) for each of the Galactic plane models. Dotted lines are the predicted values for the π^0 (dark blue), KRA^5_γ (orange), and KRA^{50}_γ (light blue) models. Solid lines are our best-fitting flux normalizations from the IceCube data. Shaded regions indicate the 1σ uncertainties; they extend over the energy range that contributes to 90% of the significance. These results are based on the all-sky (4π sr) template and are presented as an all-sky flux. For comparison, the gray hatching shows the IceCube total neutrino flux (*22*), scaled to an all-sky flux by multiplying by 4π, with its 1σ uncertainty.

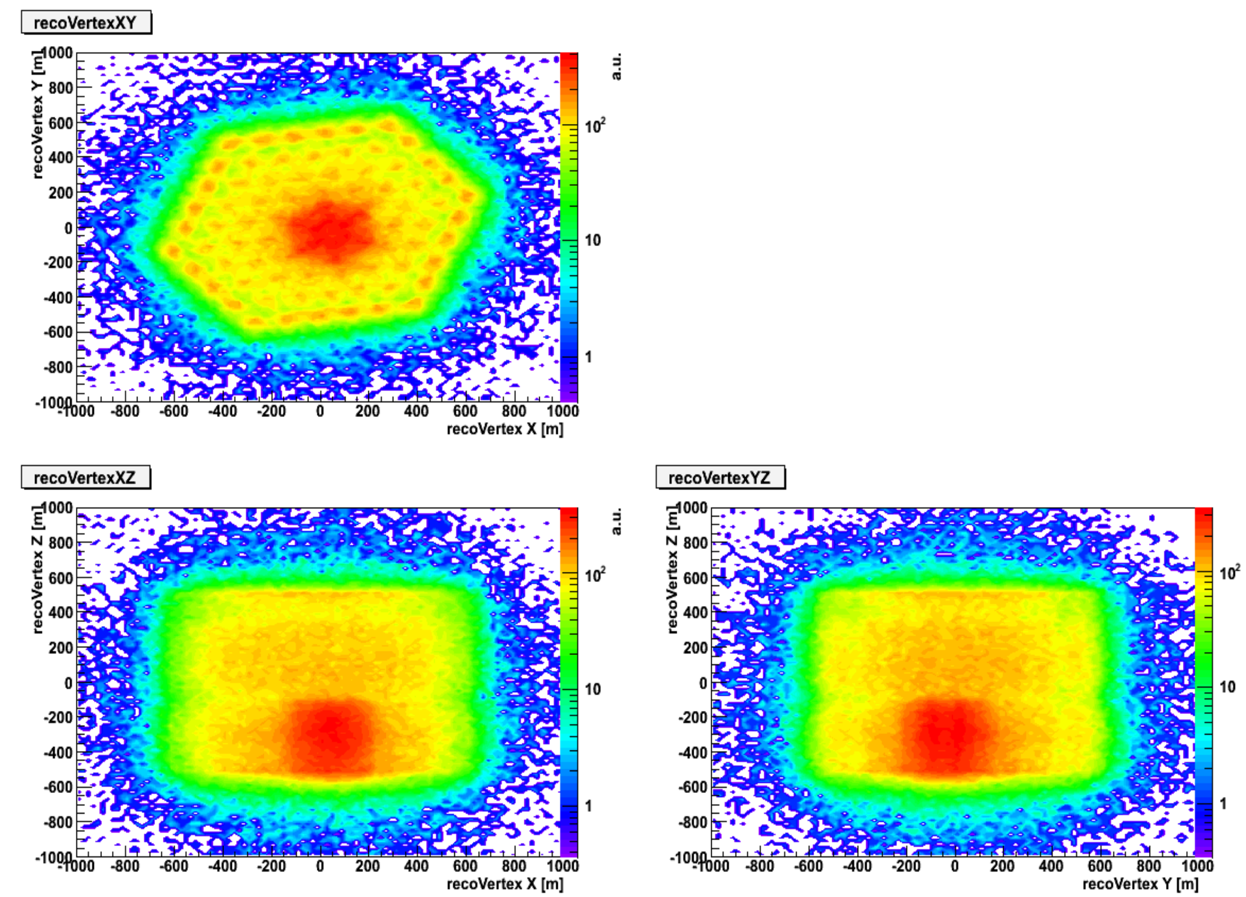


IceCube: DeepCore subarray

IC80 + 12 strings DeepCore

ν - vertex





E.R., from DeepCore design study meeting in Stockholm, 2008

The Point Source Search: analysis method

The IceCube Coll., Science 2022

Maximum likelihood technique, likelihood ratio hypothesis test

S: point-like neutrino emission (location, energy spectrum)
B: atmospheric & diffuse astrophysical neutrinos

Observables: muon direction, uncertainty and energy $\hat{\boldsymbol{d}} = (\hat{\alpha}, \hat{\delta})$, $\hat{\sigma}$, $\hat{E}_\mu$

$$\mathcal{L}(\boldsymbol{\theta} \,|\, \boldsymbol{x}, N) = f(\boldsymbol{x}, N \,|\, \boldsymbol{\theta}) = \prod_{i=1}^{N} f(\boldsymbol{x_i} \,|\, \boldsymbol{\theta})$$

$$\boldsymbol{x_i} = (\hat{\boldsymbol{d}}_i, \hat{\sigma}_i, \hat{E}_{\mu,i}). \qquad \Phi_{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = \Phi_0 \cdot (E_\nu/E_0)^{-\gamma}$$

$$\mathcal{L}(\mu_{ns}, \gamma \,|\, \boldsymbol{x}, N) = \prod_{i=1}^{N} \left\{ \frac{\mu_{ns}}{N} \cdot f_S(\boldsymbol{x_i} \,|\, \gamma) + \left(1 - \frac{\mu_{ns}}{N}\right) \cdot f_B(\boldsymbol{x_i}) \right\}$$

$$f_B(\boldsymbol{x_i}) = f_B(\hat{E}_{\mu,i}, \hat{\boldsymbol{d}}_i, \hat{\sigma}_i) = \frac{1}{2\pi} f_B(\hat{E}_{\mu,i}, \sin\hat{\delta}_i, \hat{\sigma}_i)$$

$$f_S\left(\hat{E}_{\mu,i}, \hat{\boldsymbol{d}}_i, \hat{\sigma}_i \,|\, \sin\delta_{src}, \gamma\right) = \frac{1}{2\pi \sin\hat{\psi}_i} f_S\left(\hat{E}_{\mu,i}, \hat{\psi}_i, \hat{\sigma}_i \,|\, \sin\delta_{src}, \gamma\right)$$

The Point Source Search: analysis method

The IceCube Coll., Science 2022

Maximum likelihood technique, likelihood ratio hypothesis test

S: point-like neutrino emission (location, energy spectrum)
B: atmospheric & diffuse astrophysical neutrinos

Observables: muon direction, uncertainty and energy $\hat{\boldsymbol{d}} = (\hat{\alpha}, \hat{\delta})$ $\hat{\sigma}$ $\hat{E}_\mu$

$$f_S\left(\hat{E}_{\mu,i},\, \hat{\boldsymbol{d}}_i,\, \hat{\sigma}_i \,|\, \sin\delta_{src},\, \gamma\right) \approx \frac{1}{2\pi\, \sin\hat{\psi}_i} f_S\left(\hat{\psi}_i \,|\, \hat{E}_{\mu,i},\, \hat{\sigma}_i,\, \gamma\right) \cdot f_S\left(\hat{E}_{\mu,i} \,|\, \sin\delta_{src},\, \gamma\right)$$

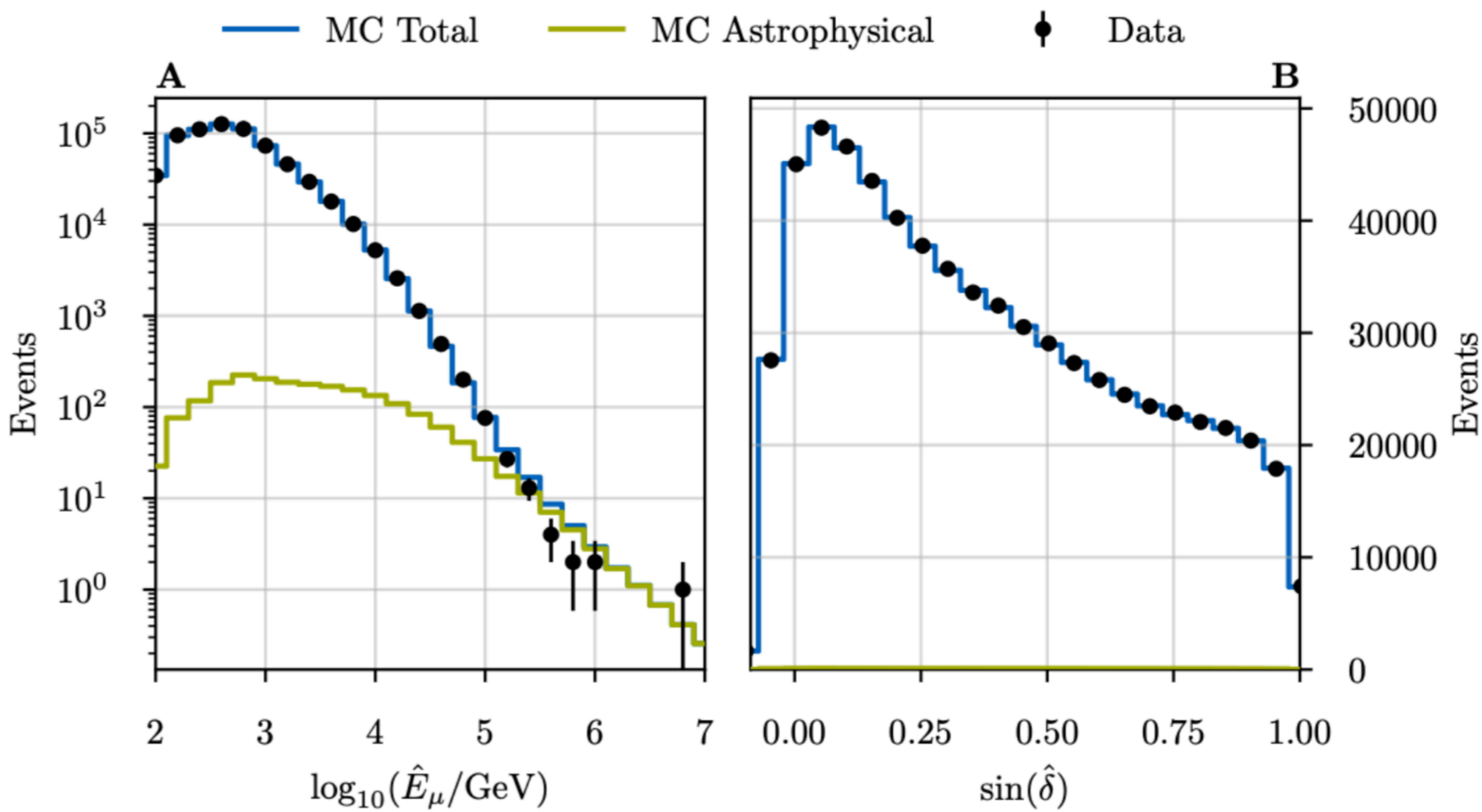
$$f_B(\hat{\boldsymbol{E}}_{\mu,i},\, \hat{\boldsymbol{d}}_i,\, \hat{\sigma}_i) \approx \frac{1}{2\pi} f_B(\hat{E}_{\mu,i},\, \sin\hat{\delta}_i).$$

angular error estimated using Boosted Decision Trees
pdfs non-parametrically via kernel density estimation (KDE) from Monte Carlo

$$TS(\boldsymbol{d}_{src}) \equiv -2 \times \log(\Lambda) = -2 \times \log\left(\frac{\mathcal{L}(\mu_{ns} = 0 \,|\, \boldsymbol{x})}{\sup_{\mu_{ns},\gamma} \mathcal{L}(\mu_{ns},\, \gamma,\, \boldsymbol{d}_{src} \,|\, \boldsymbol{x})}\right)$$

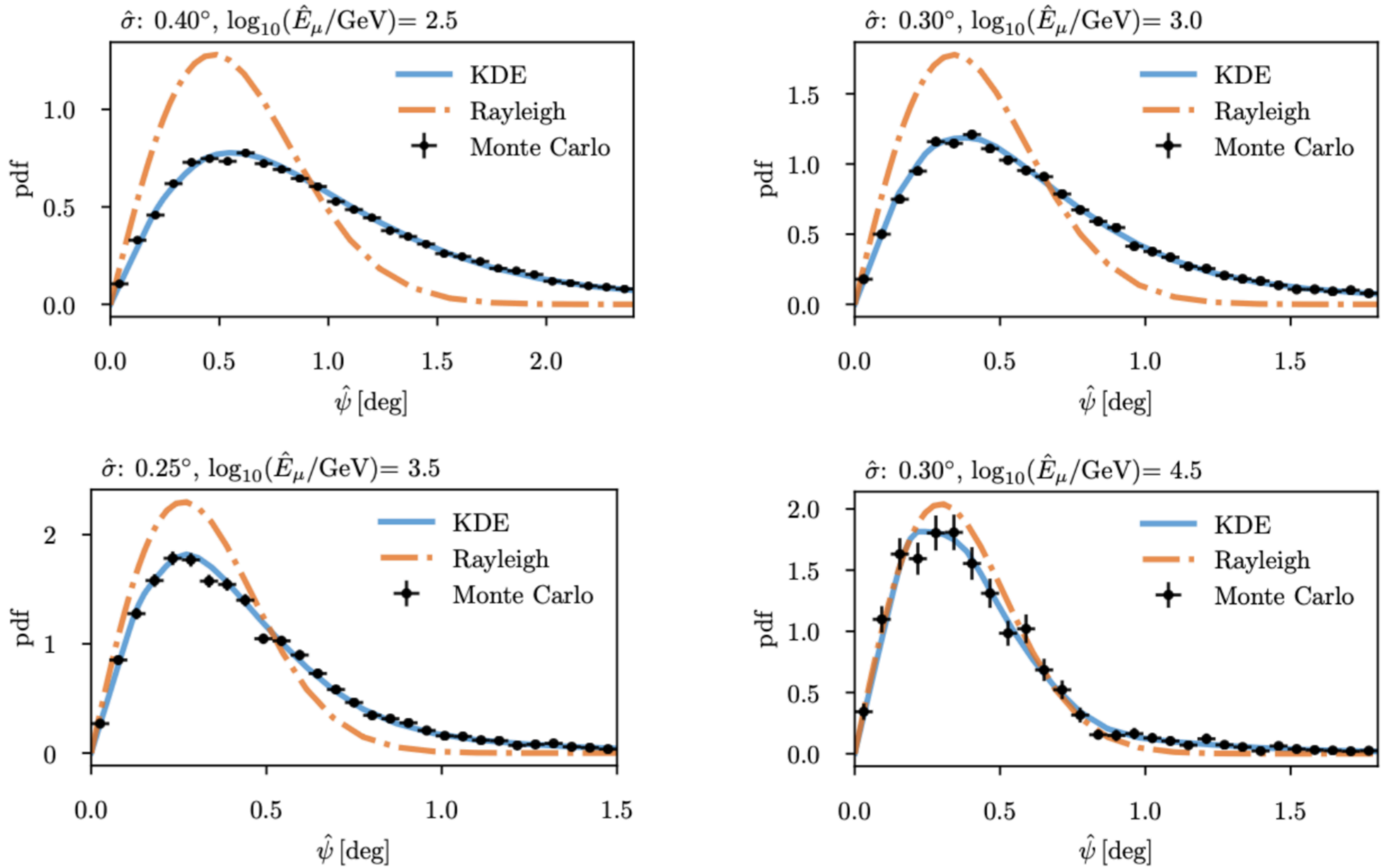
The Point Source Search: analysis method

The IceCube Coll., Science 2022



The Point Source Search: analysis method

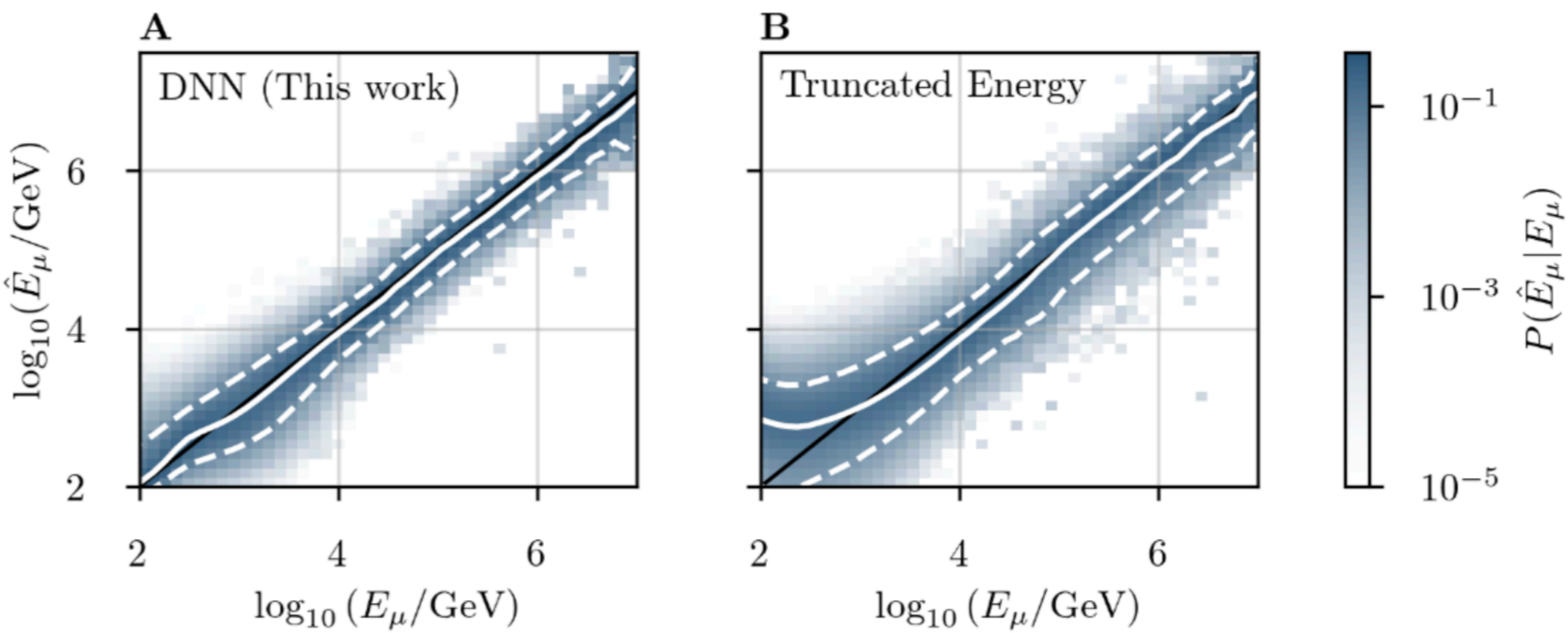
The IceCube Coll., Science 2022



The Point Source Search: analysis method

The IceCube Coll., Science 2022

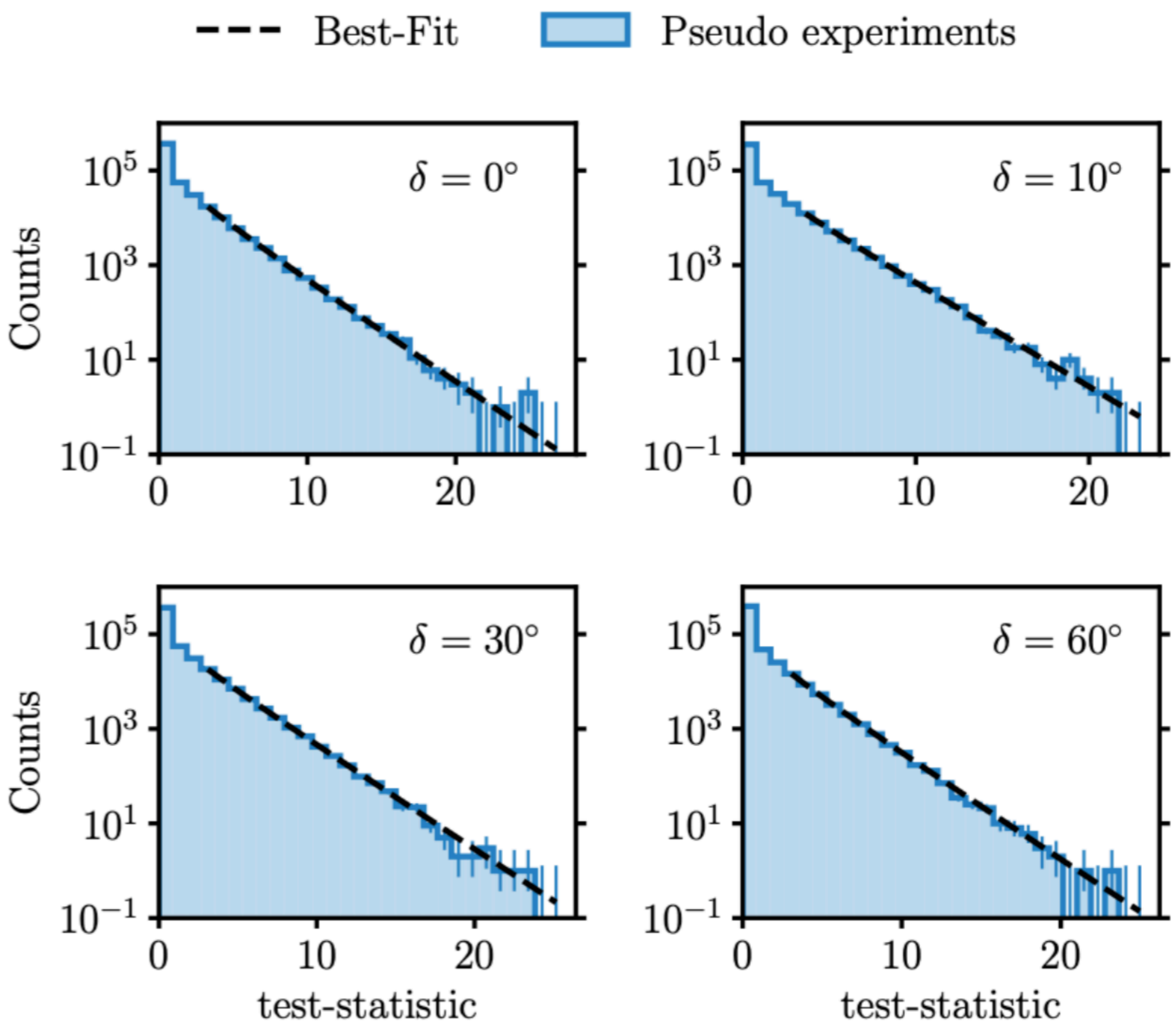
Muon Energy Estimation Using Deep Learning



The Point Source Search: analysis method

The IceCube Coll., Science 2022

Muon Energy Estimation Using Deep Learning



The PMNS Mixing Matrix

NuFIT 5.3 (2024)

Atmospheric | Reactor/accelerator | Solar | Majorana Phases

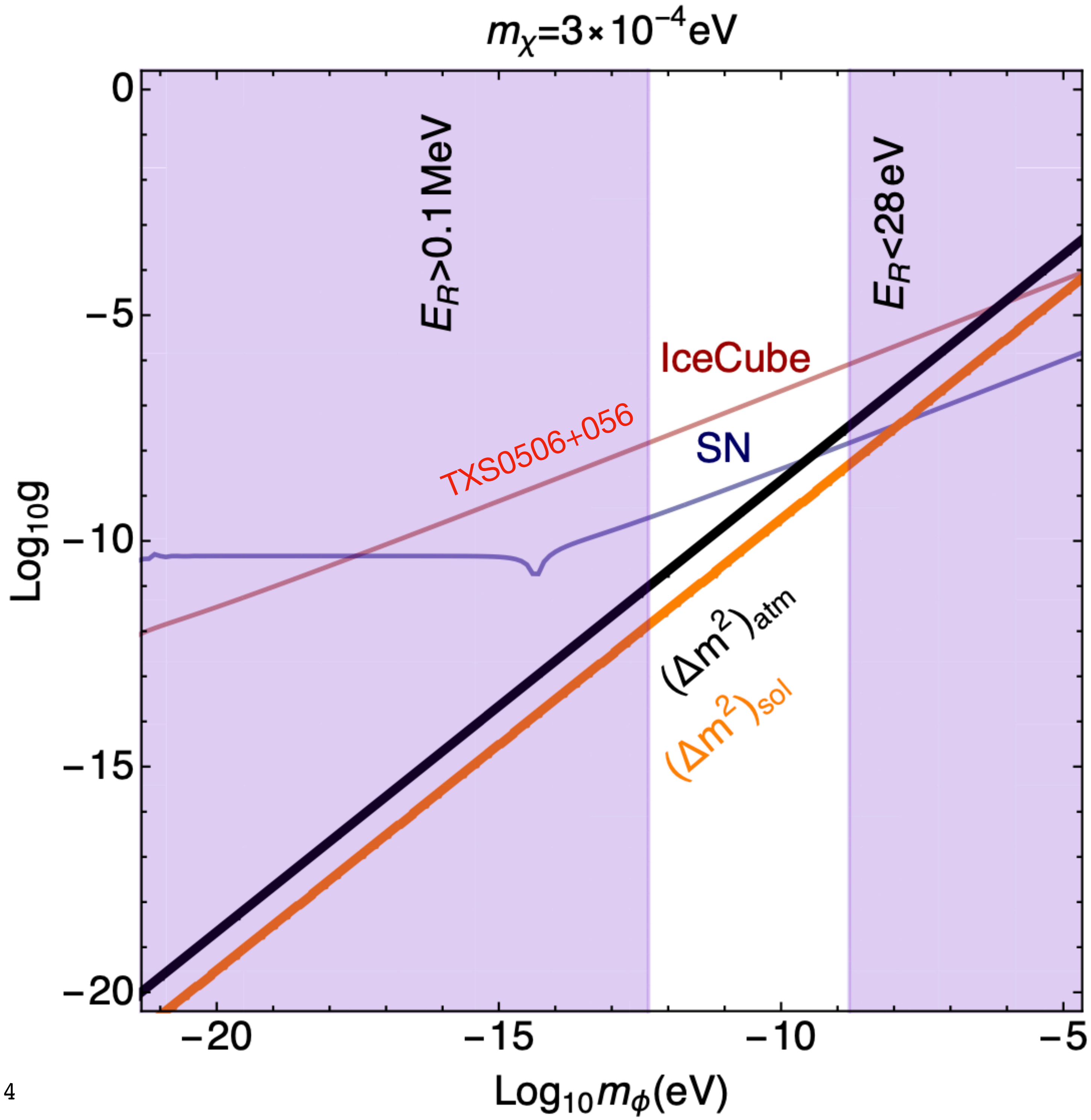
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
	$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
	$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
	$\delta_{CP}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.505^{+0.024}_{-0.026}$	$+2.426 \to +2.586$	$-2.487^{+0.027}_{-0.024}$	$-2.566 \to -2.407$

Neutrinos gaining mass due to refraction on ultralight DM

Manibrata Sen and Alexei Y. Smirnov JCAP 01(2024)040

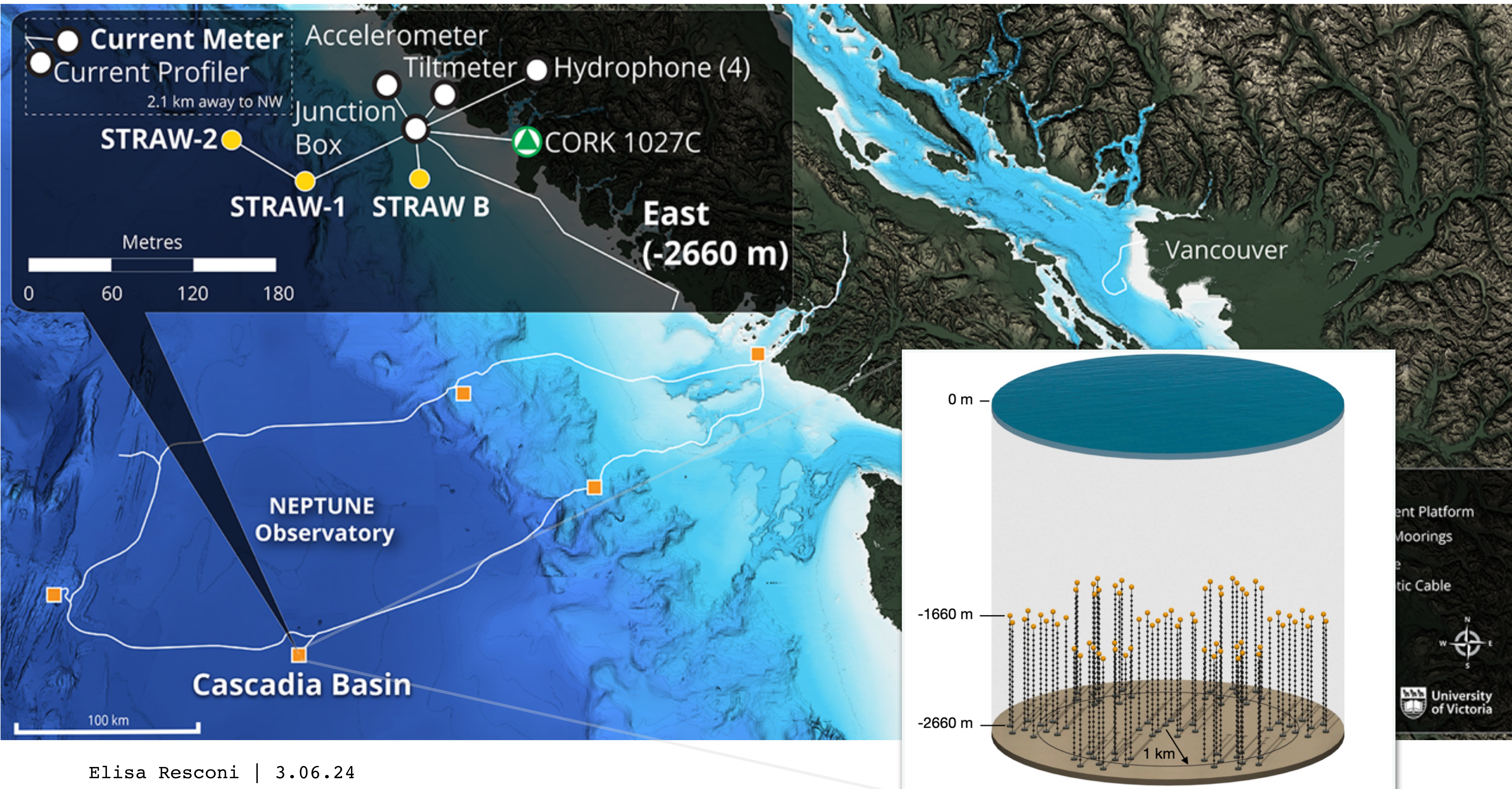
Fuzzy DM scenarios: where quantum effects become apparent on large scales



The Pacific Ocean Neutrino Experiment (P-ONE)

@***Ocean Networks Canada***: state-of-the-art underwater observatories and real-time data capabilities
Cabled ocean observatory: 800 km loop of fibre-optic cables ***in operation***

👉 ***the world's largest undersea observatory network***

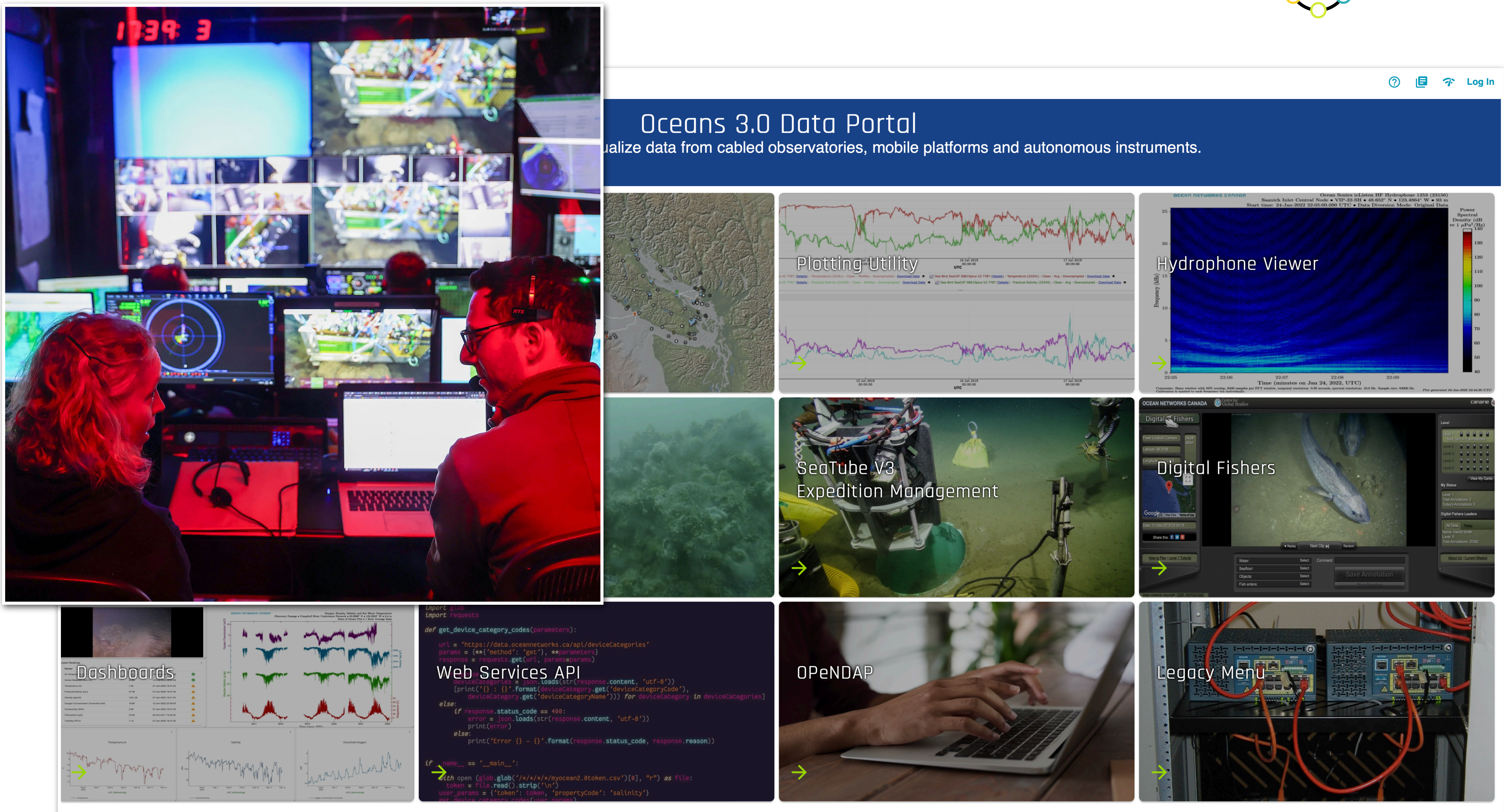


P-ONE Collaboration, Nature Astron. 2020

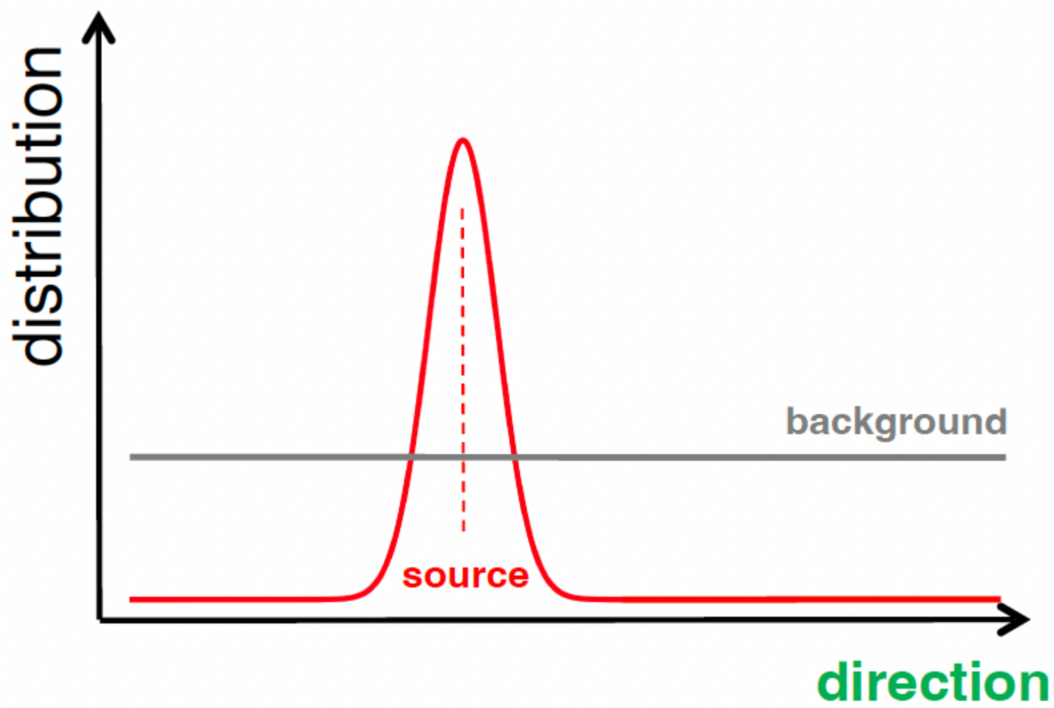
The Pacific Ocean Neutrino Experiment (P-ONE)

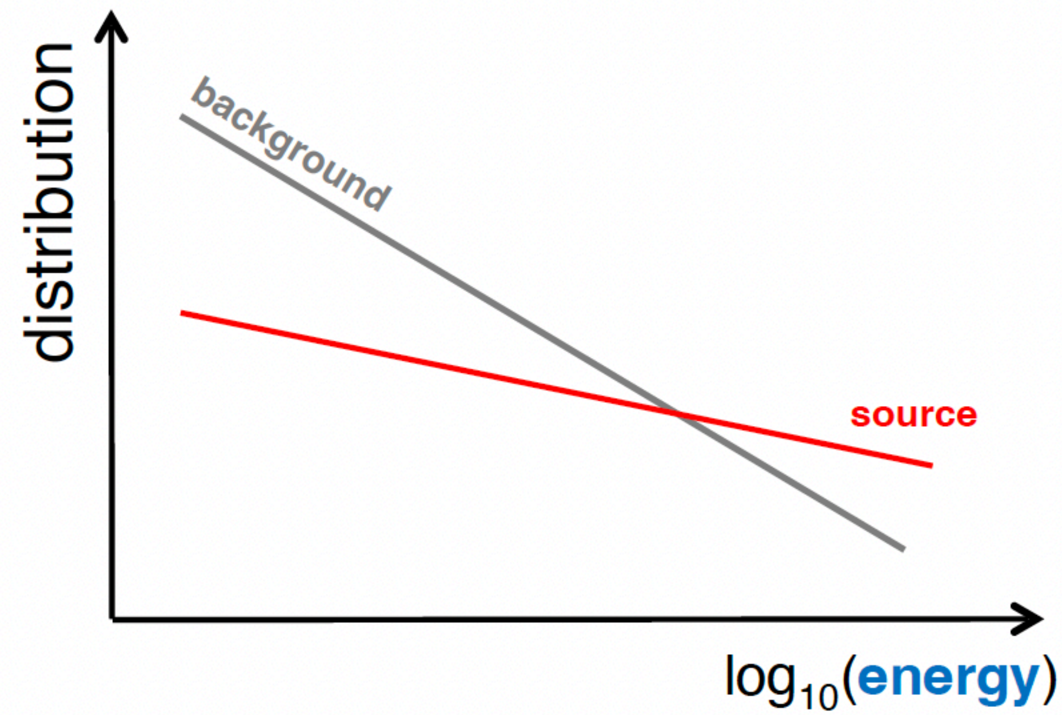
July'23 ONC sea expedition

The Pacific Ocean Neutrino Experiment (P-ONE)



https://data.oceannetworks.ca/home





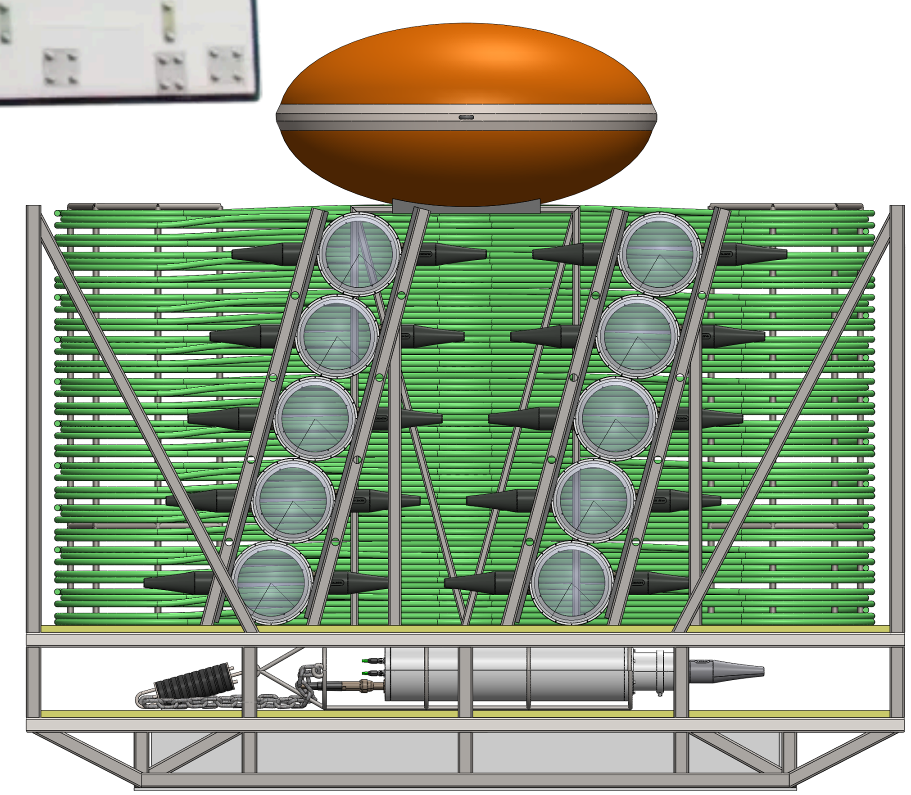
$$L\left(\boldsymbol{\theta_s} \mid \hat{\boldsymbol{E}}, \hat{\boldsymbol{\sigma}}, \hat{\boldsymbol{d}}\right) = \prod_{i=1}^{N} \left\{ \frac{\mu_s}{N} \times \frac{1}{2\pi\hat{\sigma}_i^2} \exp\left(-\frac{1}{2\hat{\sigma}_i^2} \left|\hat{\boldsymbol{d}}_{\boldsymbol{i}} - \boldsymbol{d_s}\right|^2\right) f_s\left(\hat{E}_i;\, \gamma\right) + \left(1 - \frac{\mu_s}{N}\right) \times f_b\left(\hat{E}_i,\, \hat{\boldsymbol{d}}_{\boldsymbol{i}}\right) \right\}$$

Braun et al., Astropart. Phys. 29 (2008) 299305

2-D Gaussian (until '20)

NEW: Connectorless, full waveform readout

The P-ONE Coll., ***Nature Astron.*** 2020



P-ONE