Towards the era of high-energy neutrino astronomy with P-ONE and PLEnuM

Lisa Schumacher, Erlangen Centre for Astroparticle Physics

DESY-Zeuthen AP Seminar, May 03, 2024

Towards the era of high-energy neutrino astronomy with P-ONE and PLEnuM

and KM3NeT!

Or: why do we need another neutrino telescope?

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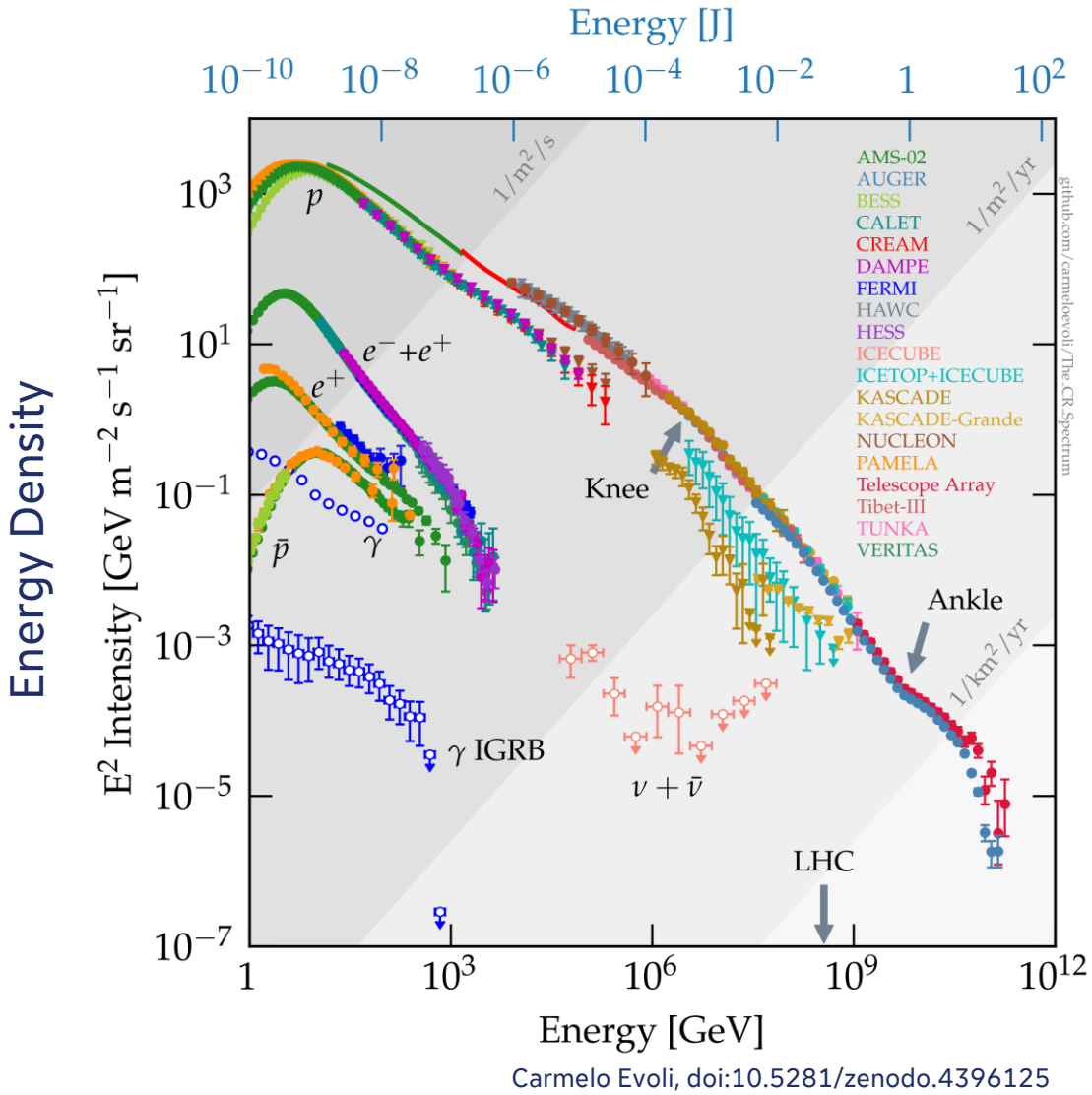
Outline

1) Introduction to Neutrino Astronomy
2) Pacific Ocean Neutrino Experiment (P-ONE)
3) Planetary Neutrino Monitoring (PLEnuM)

The Cosmic Ray Puzzle



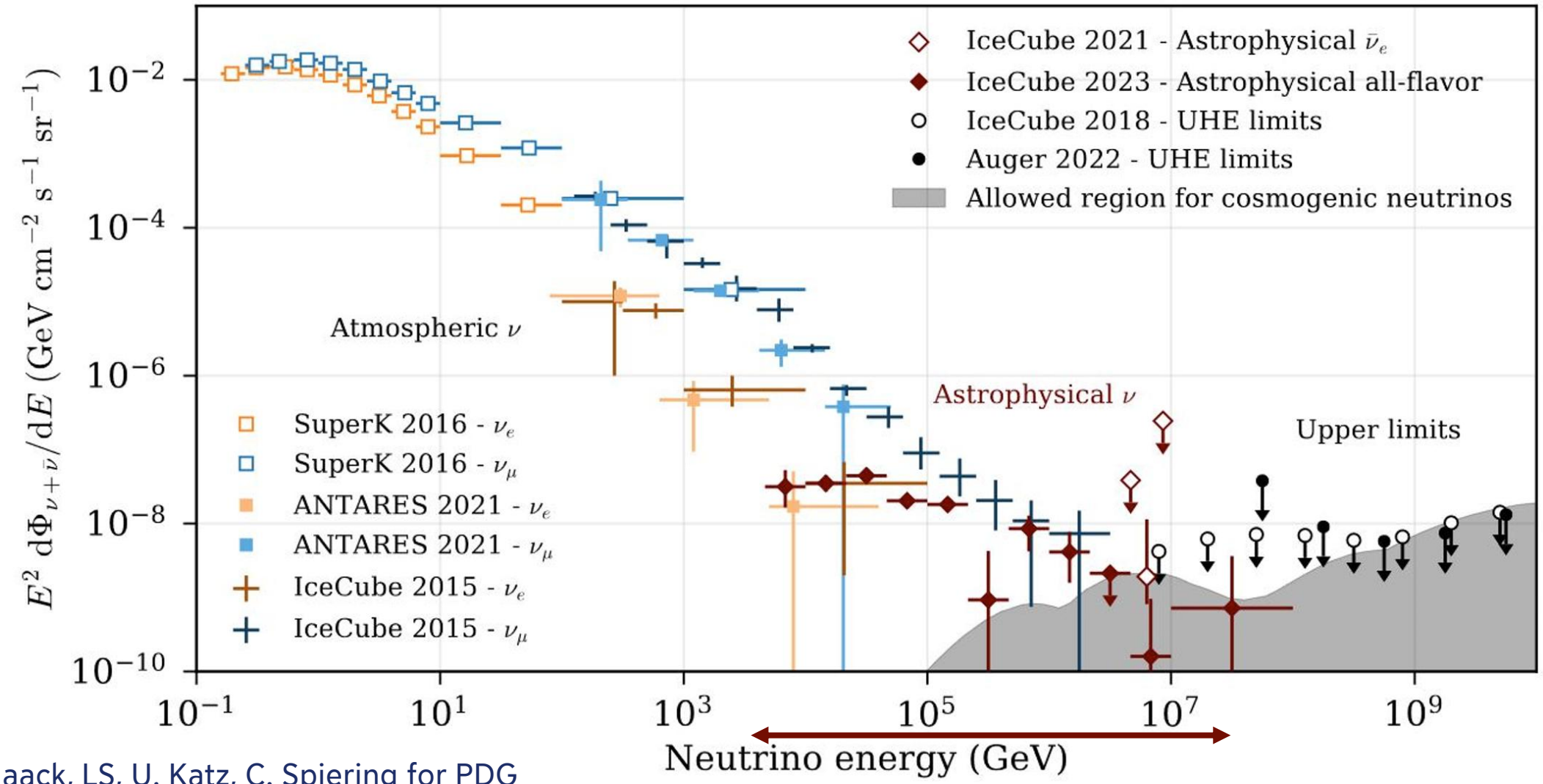
Carmelo Evoli, doi:10.5281/zenodo.4396125

Where and how are cosmic rays accelerated?
Where and how are neutrinos produced?

Why are neutrinos interesting?

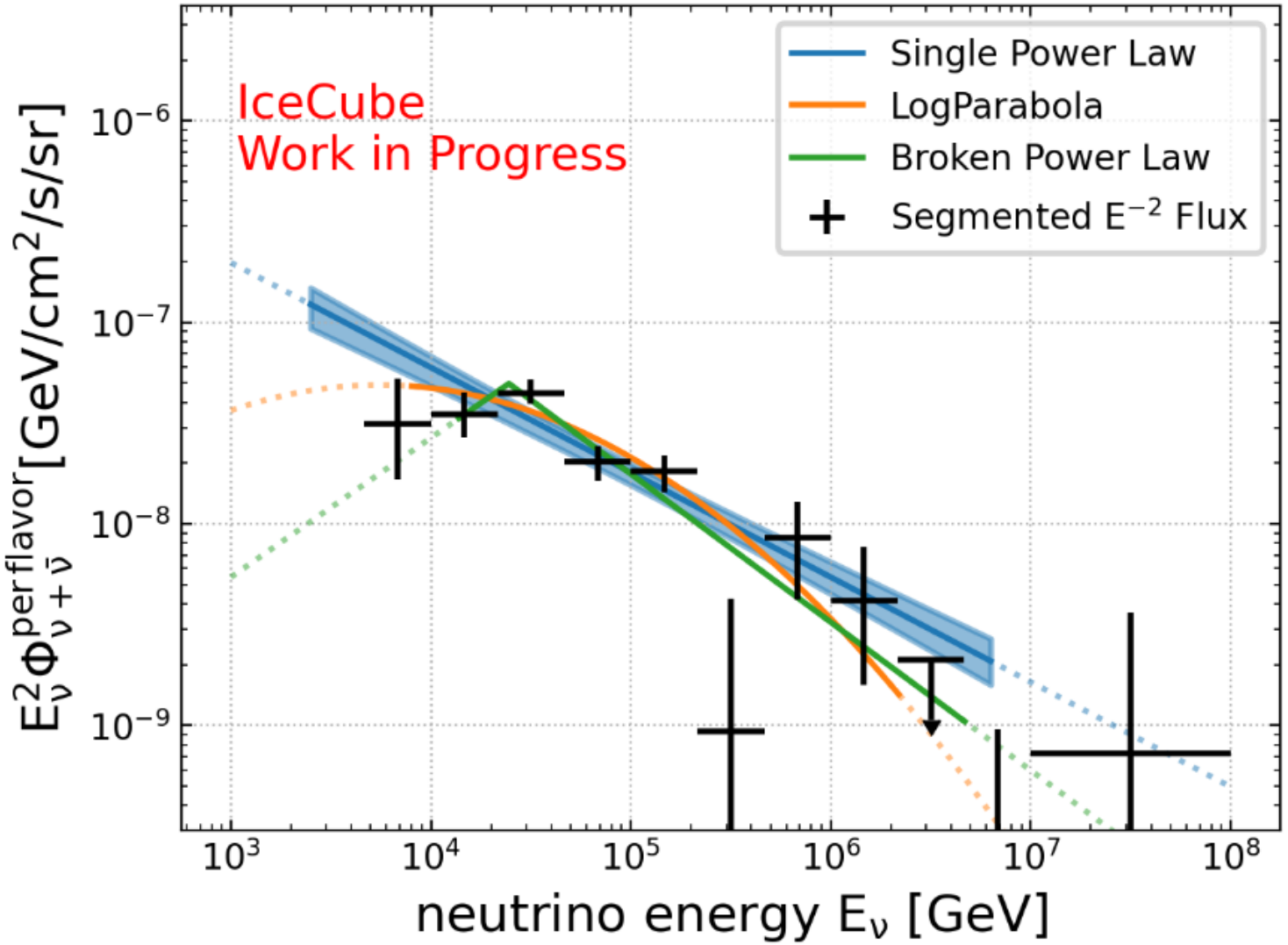
1) Neutrinos are unambiguous tracers of hadronic processes of CRs
2) Neutrinos can travel cosmological distances and through dense environments without absorption or deflection
3) Non-zero neutrino masses already point to physics beyond the standard model – what else are they hiding?

Where do these neutrinos come from?



C. Haack, LS, U. Katz, C. Spiering for PDG

The road so far

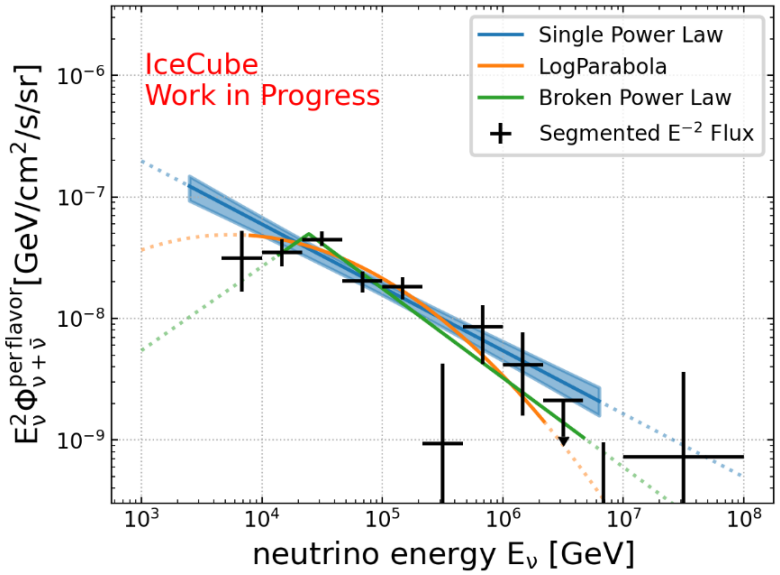


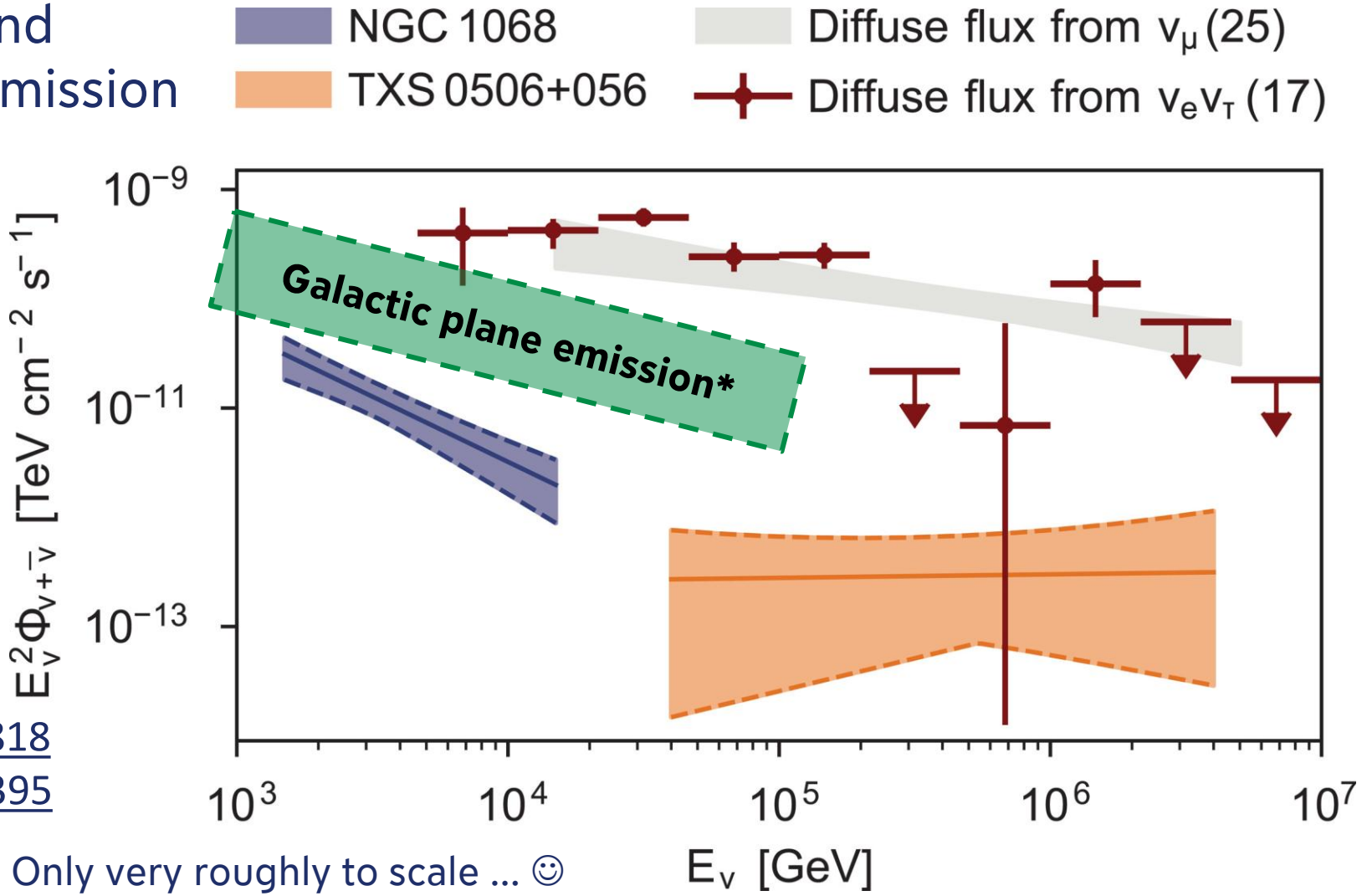
First hint of spectral features in the diffuse astrophysical neutrino flux

https://doi.org/10.22323/1.444.1064

The road so far

First galactic and extragalactic emission





https://doi.org/10.1126/science.adc9818
https://doi.org/10.1126/science.abg3395

* Only very roughly to scale … ☺

Open Questions

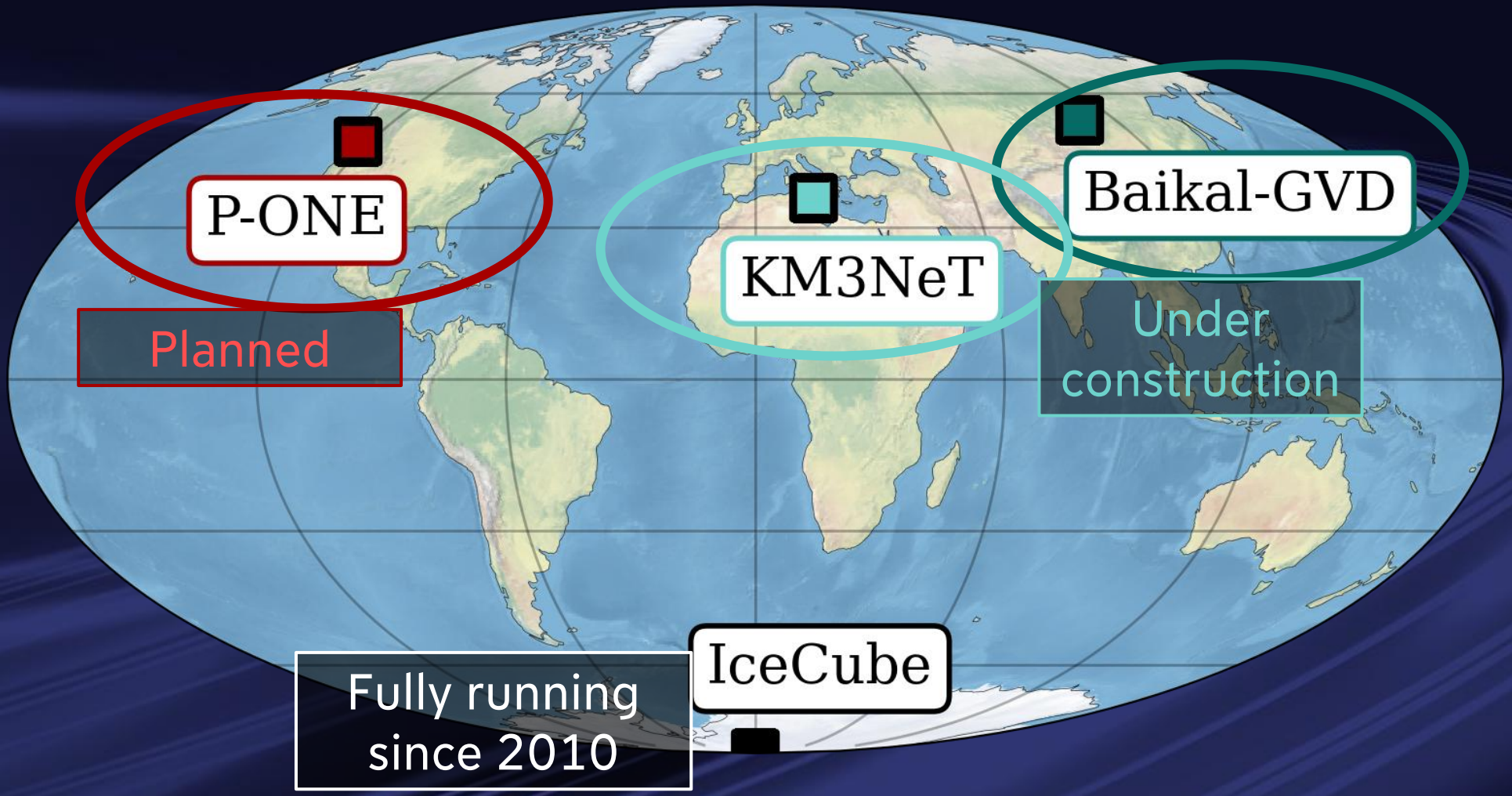
- Are TXS056+056 and NGC1068 just the brightest sources of an entire population of similar sources? Or are they special in another way?
- Are there other source populations?
- How does CR acceleration and neutrino production work in these sources?
- Is the Galactic-Plane emission truly diffuse or are there also smaller-scale sources?

Open Questions

- Are TXS056+056 and NGC1068 just the brightest sources of an entire population of similar sources? Or are they special in another way?
- Are there
- How does hese sources?
- Is the Gal maller-scale sour

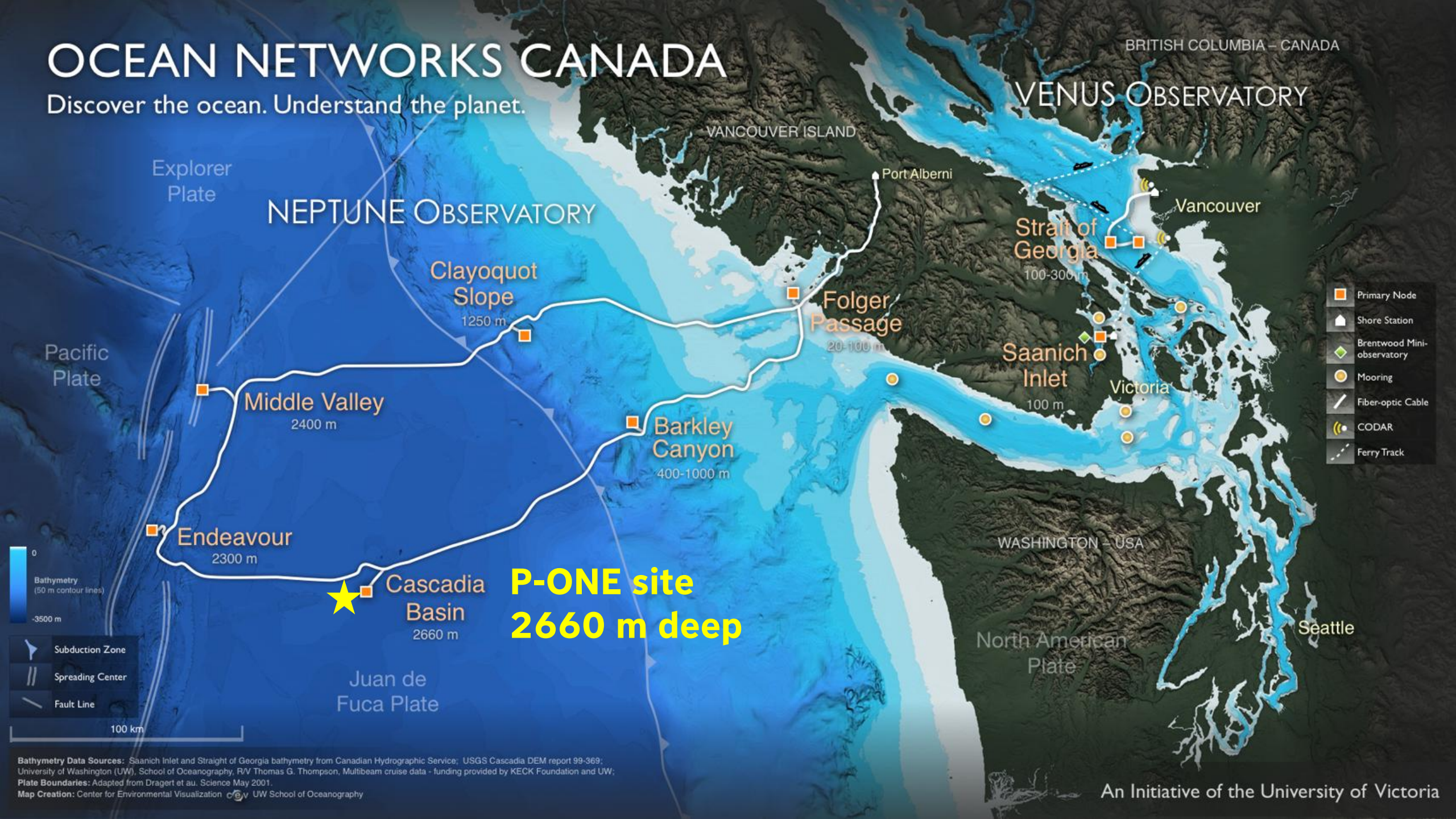
IceCube gathered data for more than a decade and progress based on livetime alone will slow down
We need more telescopes!
But how much more, exactly?

Current & future neutrino telescopes



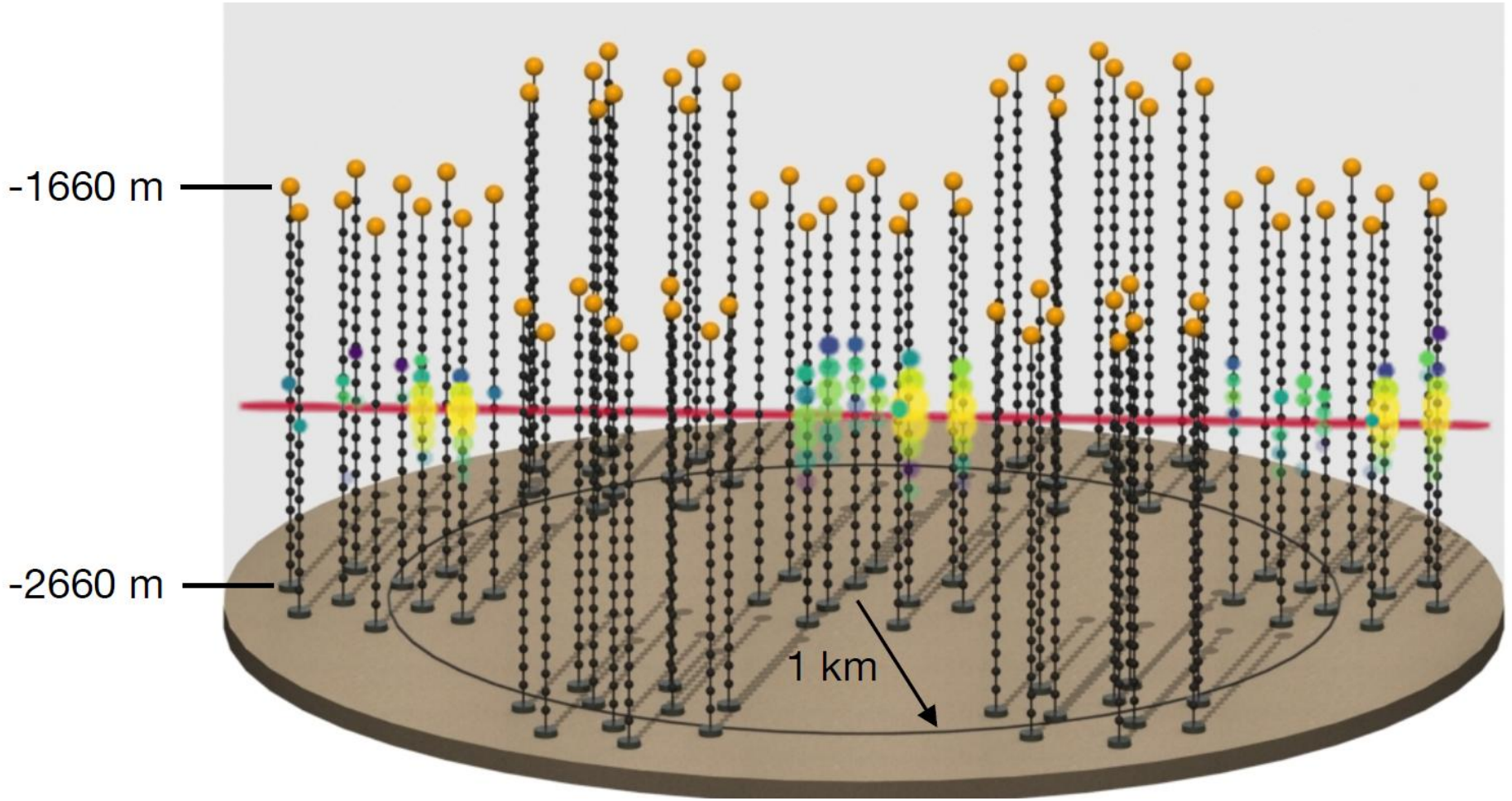
Pacific Ocean Neutrino Experiment
P-ONE

https://www.pacific-neutrino.org/

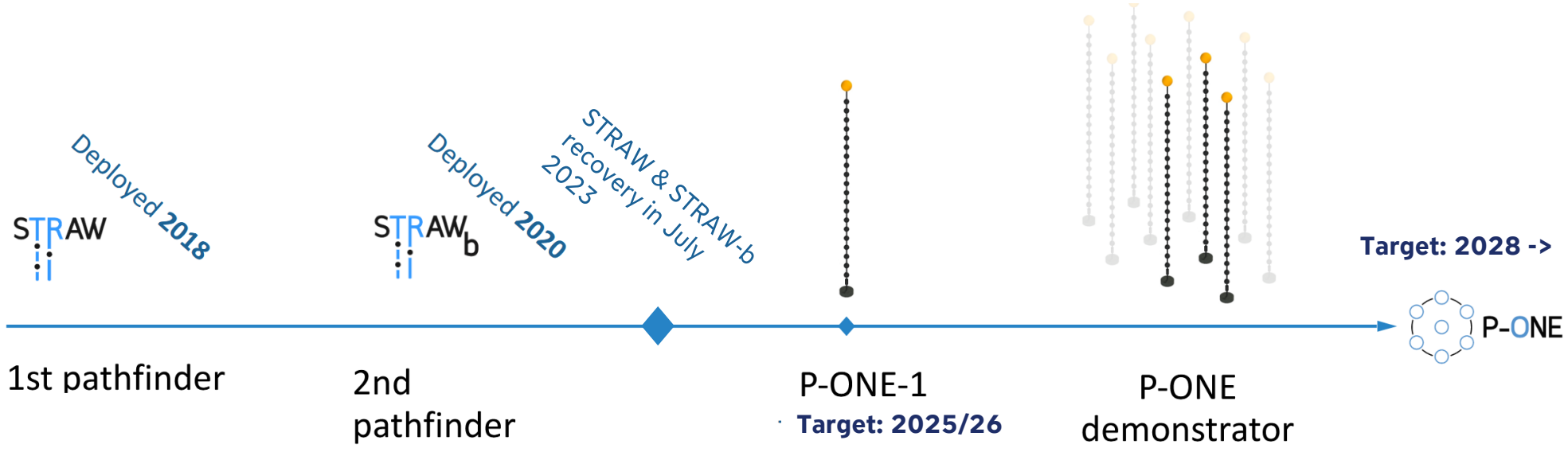

OCEAN NETWORKS CANADA
Discover the ocean. Understand the planet.
BRITISH COLUMBIA – CANADA
VENUS OBSERVATORY
VANCOUVER ISLAND
Port Alberni
Vancouver
Strait of Georgia
100-300 m
Explorer Plate
NEPTUNE OBSERVATORY
Clayoquot Slope
1250 m
Folger Passage
20-100 m
Saanich Inlet
100 m
Victoria
Pacific Plate
Middle Valley
2400 m
Barkley Canyon
400-1000 m
Endeavour
2300 m
Cascadia Basin
2660 m
P-ONE site
2660 m deep
WASHINGTON – USA
Seattle
North American Plate
Juan de Fuca Plate
Primary Node
Shore Station
Brentwood Mini-observatory
Mooring
Fiber-optic Cable
CODAR
Ferry Track
0
Bathymetry
(50 m contour lines)
-3500 m
Subduction Zone
Spreading Center
Fault Line
100 km
Bathymetry Data Sources: Saanich Inlet and Straight of Georgia bathymetry from Canadian Hydrographic Service; USGS Cascadia DEM report 99-369; University of Washington (UW), School of Oceanography, R/V Thomas G. Thompson, Multibeam cruise data - funding provided by KECK Foundation and UW;
Plate Boundaries: Adapted from Dragert et au. Science May 2001.
Map Creation: Center for Environmental Visualization UW School of Oceanography
An Initiative of the University of Victoria

The vision of P-ONE

Multi-km^3 detector integrated into ONC infrastructure



P-ONE Timeline



Goals of P-ONE-1:

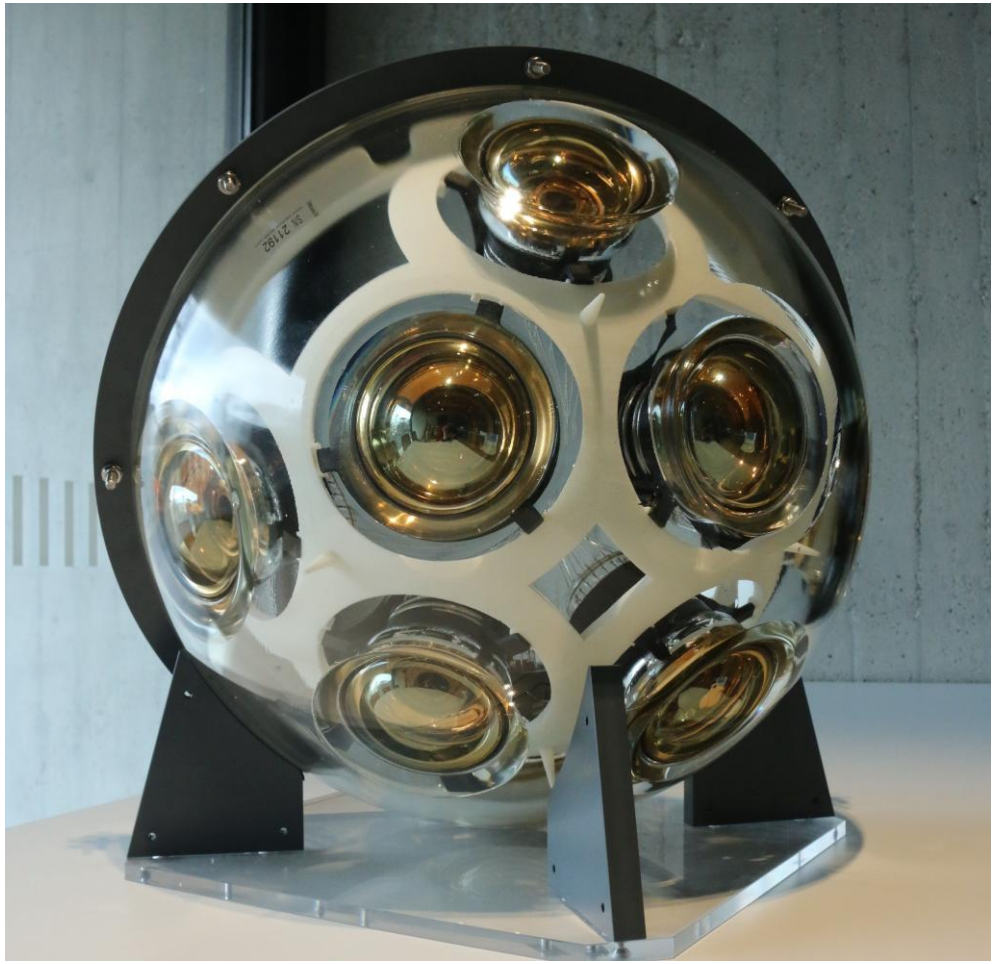
- Demonstrate that hardware, technical & mechanical design, deployment, data transfer, trigger… are working and scalable
- (Re-)measure optical properties over 1km depth
- Measure first atmospheric muons
- Determine background rates:
  - Bioluminescence rate & variability
  - K40 decay

First string:

- 20 modules with 16 PMTs each
- 1000 m length

Integrated hemisphere

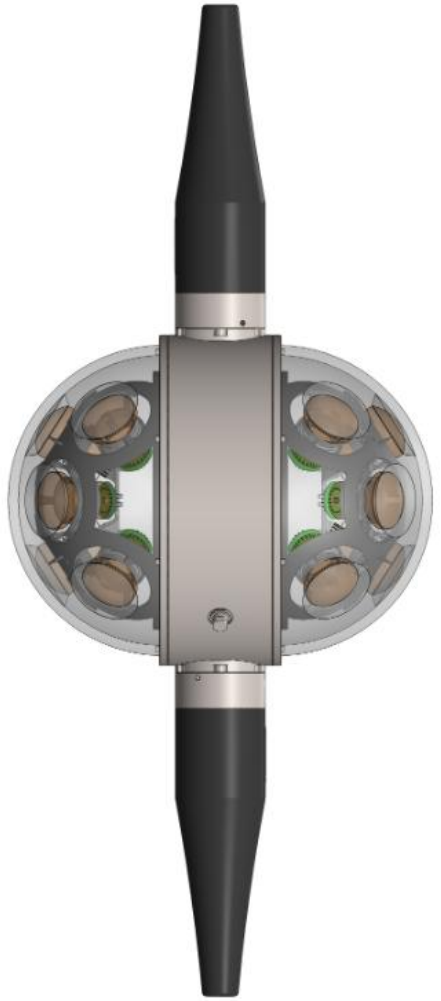
Titanium Ring + Hemisphere



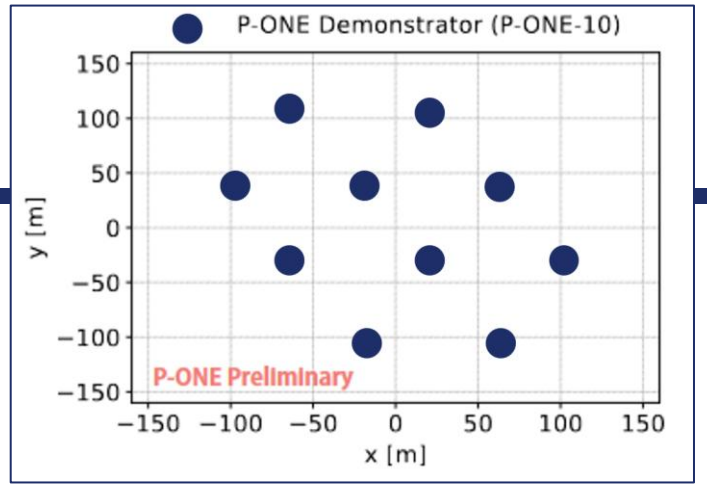
https://doi.org/10.22323/1.444.1219
PoS(ICRC2023)1219

What is special about P-ONE?

- Existing infrastructure and maintanance (ONC)
- Connectorless module design
- Full waveform digitization + off-shore data reduction
  - Tau neutrino identification („double bang“)
  - Particle shower sub-structure?
- Field of view:
  - P-ONE‘s latitude will be similar to KM3NeT, so on average they observe the same sky declinations
  - However: Instantaneous field of view is complementary to KM3NeT

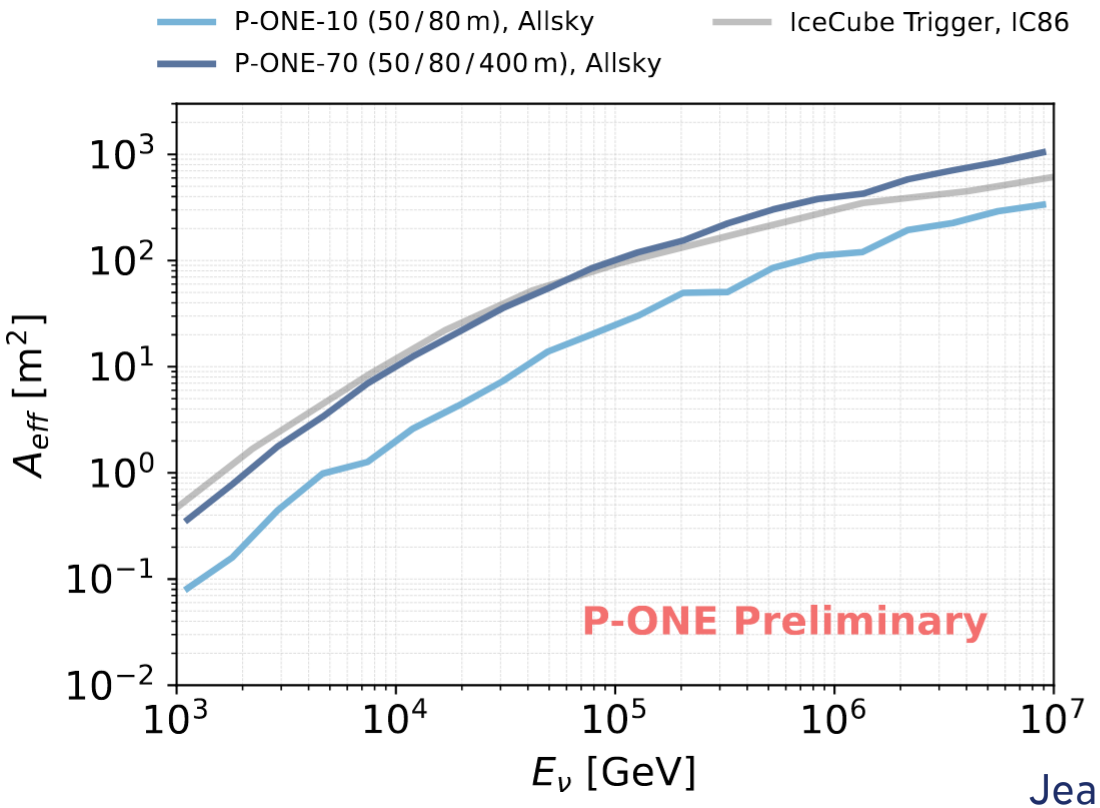


Performance

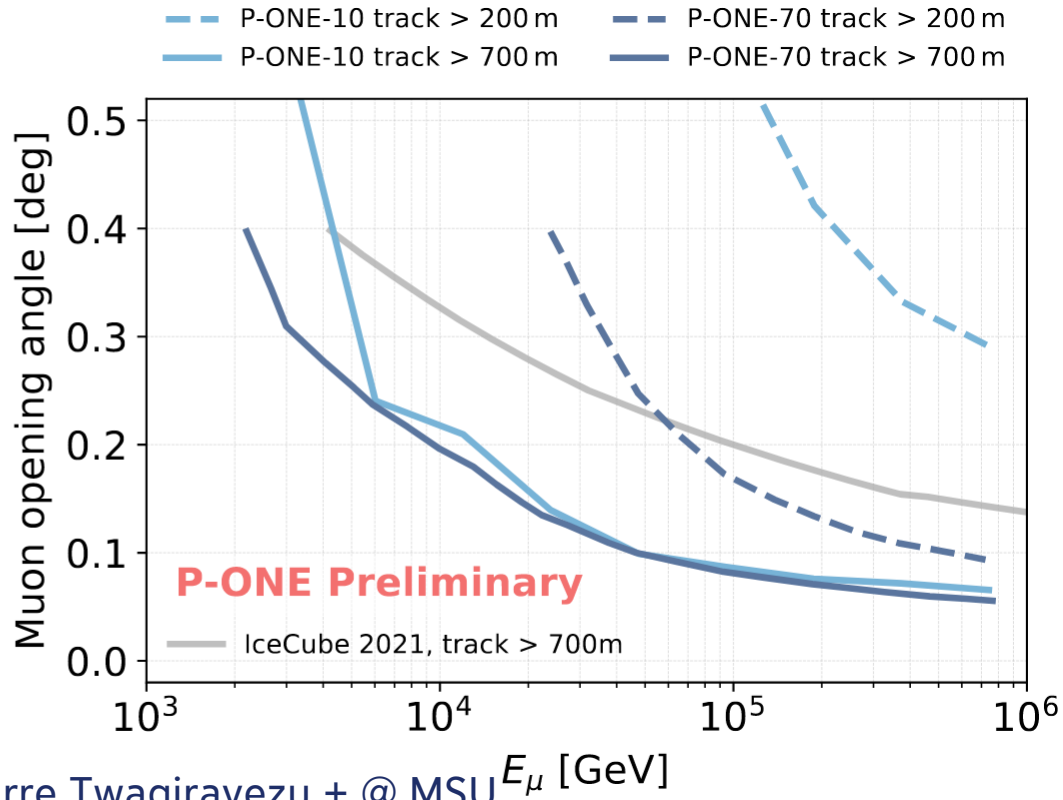


https://doi.org/10.22323/1.444.1053
PoS(ICRC2023)1053

Effective Area

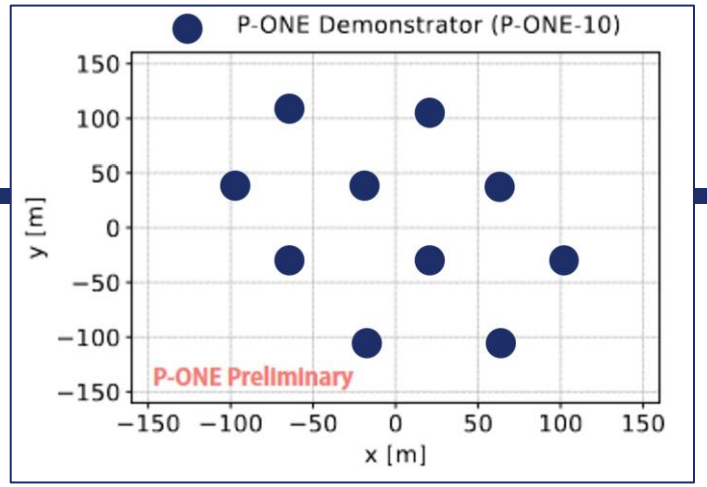


Muon-Neutrino directional resolution



Jean-Pierre Twagirayezu + @ MSU

Performance



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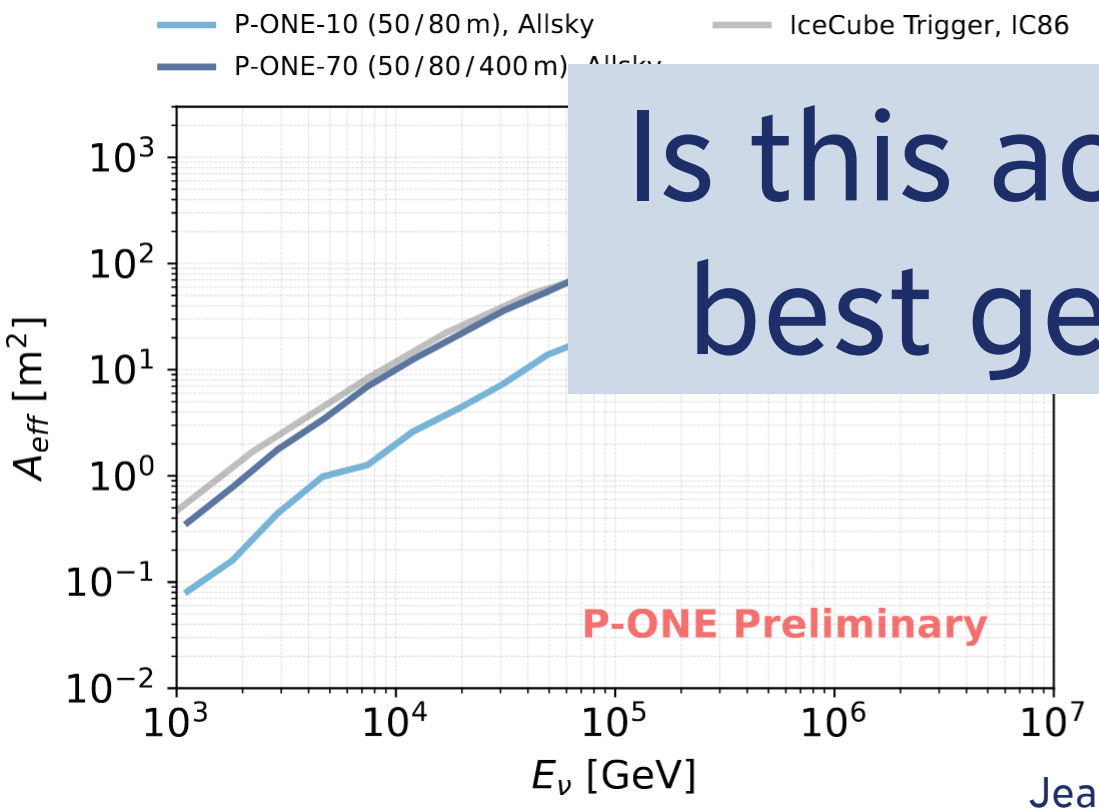
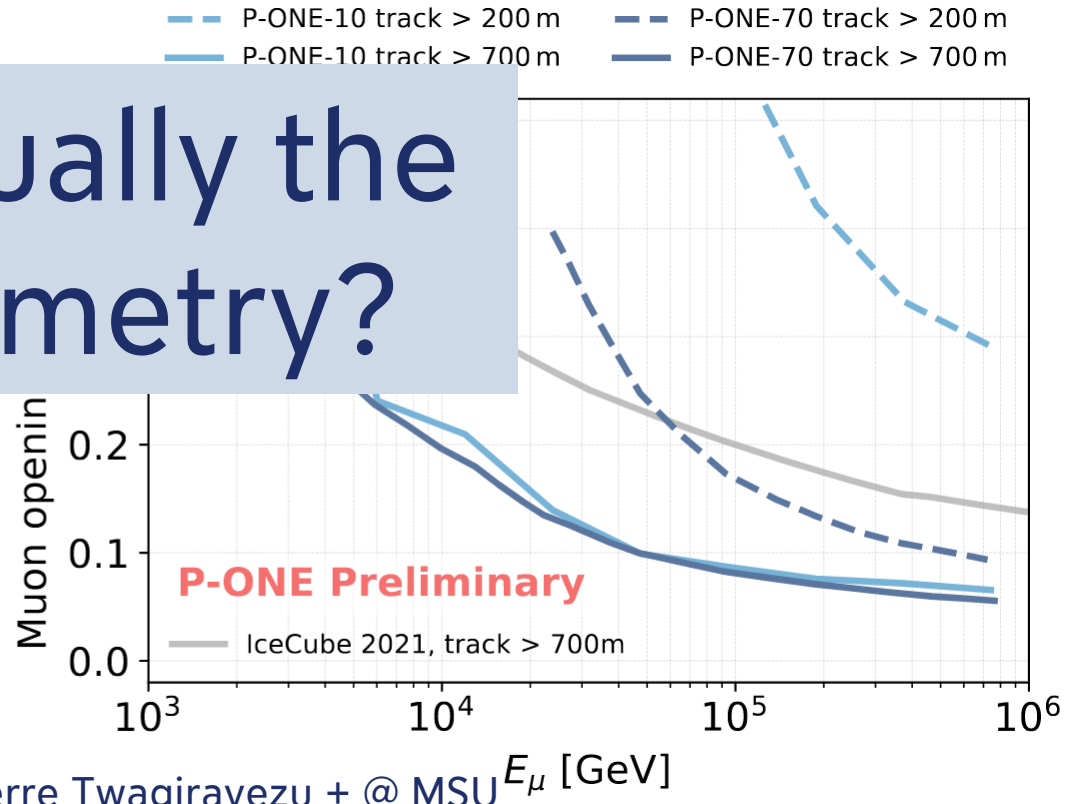
PoS(ICRC2023)1053

Effective Area



Muon-Neutrino directional resolution



Is this actually the best geometry?

Jean-Pierre Twagirayezu + @ MSU

Finding the best* geometry for P-ONE

* different physics cases -> different „best“ geometries

Work by Christian Haack (ECAP)

- **Idea:**
  ML-aided simulation (fast) replacing full MC-based simulation & LLH recos (slow)
- **Optimization target:** Resolution + Acceptance, Analysis Sensitivities
- **Optimization constraints:** Cost, geometric constraints (sea-bottom cabling), …
- **Goal:** $\frac{\partial \mathrm{Analysis}}{\partial \mathrm{Detector}}$

Detector Optimization Parameters:

- Horizontal spacing of detector lines
- Number of PMTs & placement per module
- Vertical spacing of modules on a line
- Placement & number of calibration instruments
- Trigger algorithm

Optimization of Neutrino Source Search

Work by Christian Haack and LS

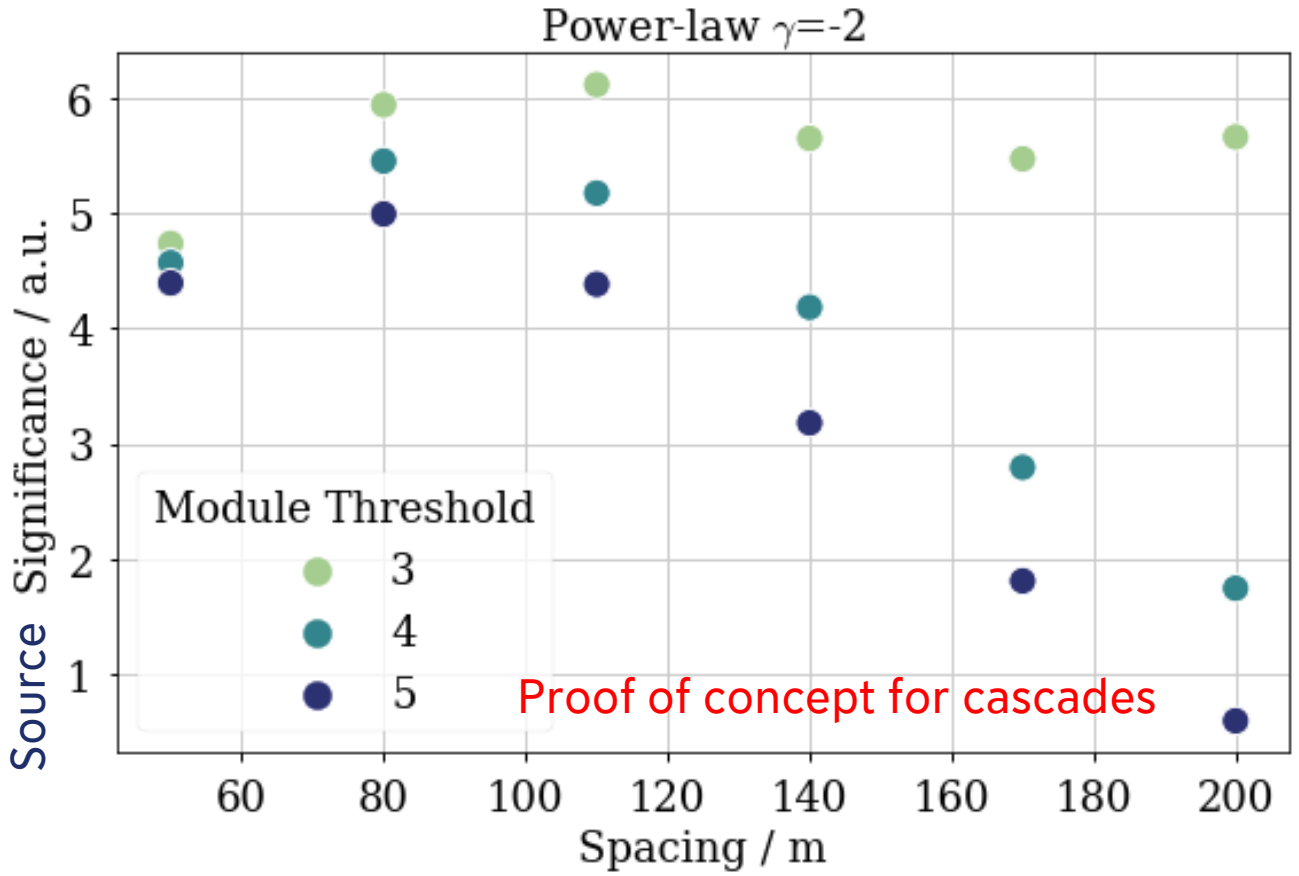
Inputs:

- Energy & directional resolution
- Acceptance

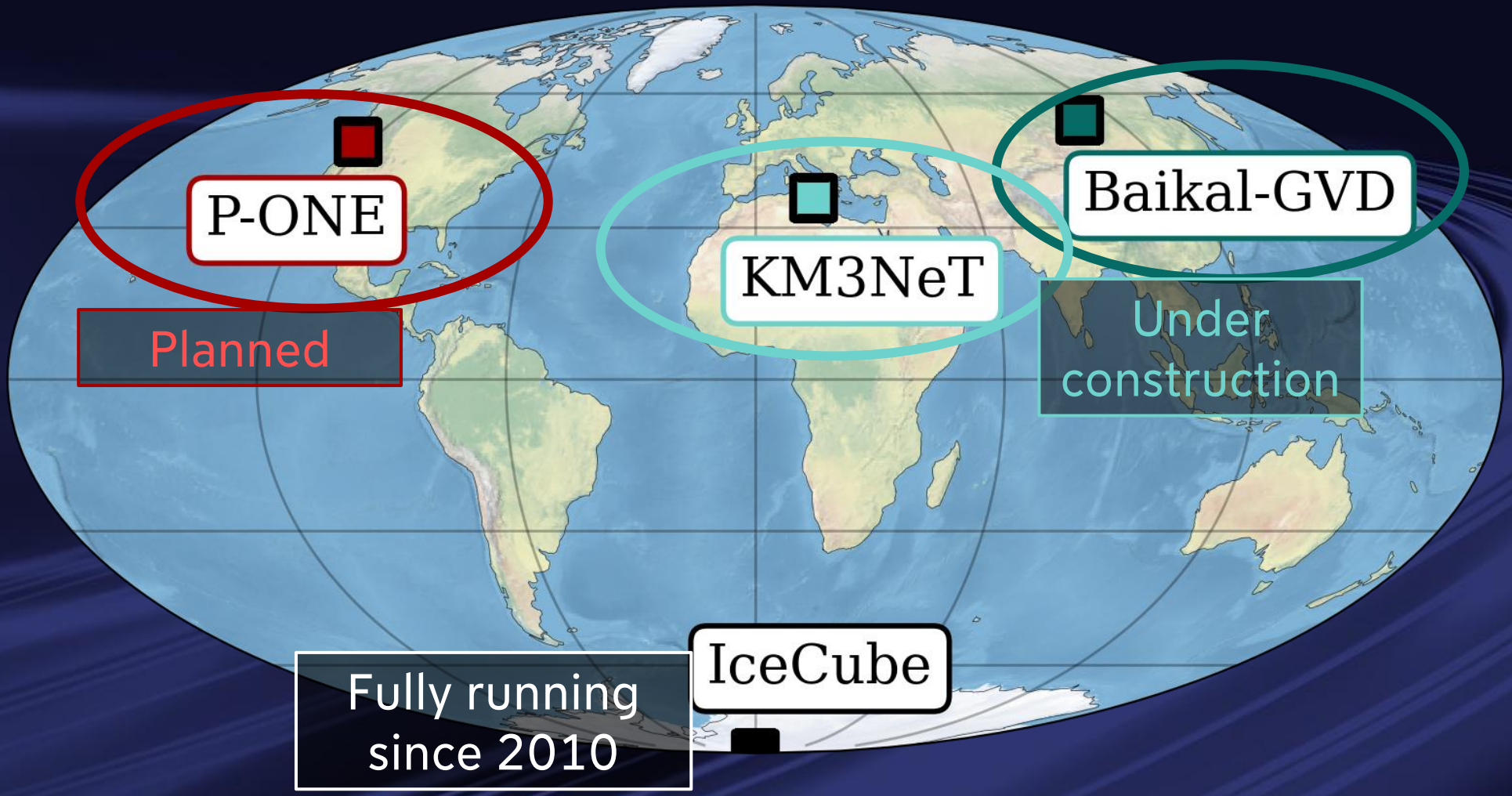
ML-based

- Simple trigger & event selection
- **Likelihood-based clustering analysis with PLEnuM software**

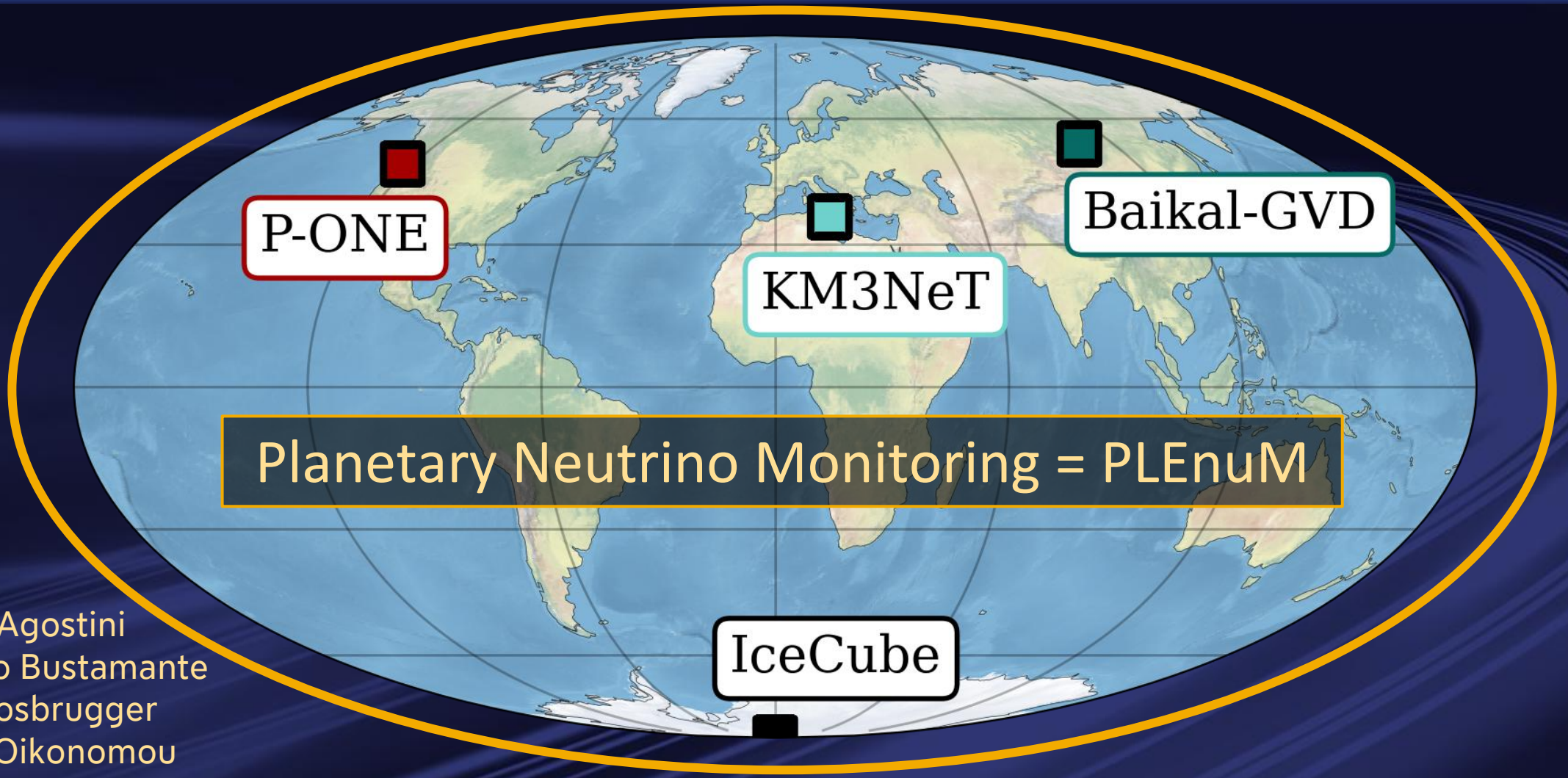
➢ Determine optimum of analysis performance wrt. string spacing



Current & future neutrino telescopes



Current & future neutrino telescopes



Matteo Agostini
Mauricio Bustamante
Anke Mosbrugger
Foteini Oikonomou
Elisa Resconi

What do we want to do?

<u>Physics goals:</u> How good will we be able to measure…

- Neutrino sources
- Diffuse flux
- Galactic diffuse & sources
- …

<u>Community goals:</u>

- Long-term, effective cooperation between collaborations
- Make data & analyses accessible for “outsiders”

<u>Software goals:</u>

- Open-source software for everyone
- Quickly estimate the power of (combined) analyses

https://github.com/PLEnuM-group/Plenum/tree/dev

Next steps in neutrino astronomy

(a non-exhaustive list)

- Source populations (steady, transient/time-variable)?
- Energy spectrum of astrophysical neutrinos beyond power law?
- Energy spectrum of single sources and populations?
- Astrophysical neutrino sources at 1 PeV and beyond?
- …

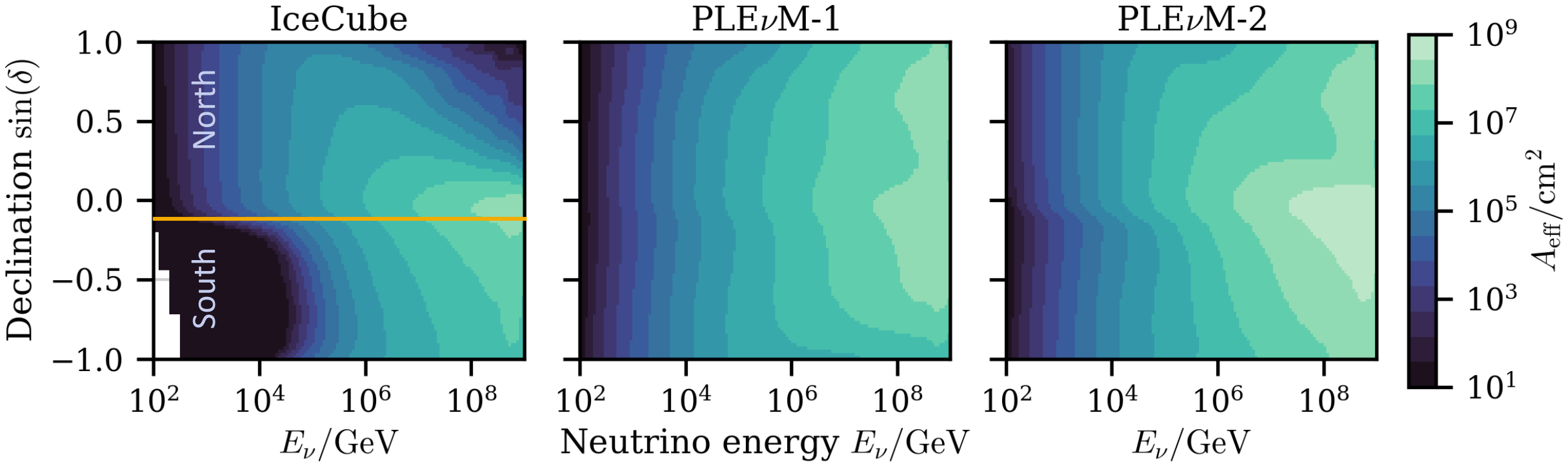
➢ How much data / exposure will we need to answer these questions?

Combined effective areas of PLEnuM

Baseline: IceCube A_{eff} for through-going muon neutrinos

PLEνM-1: equal contributions of detectors at IceCube, KM3NeT, P-ONE, Baikal-GVD locations

PLEνM-2: replace IceCube's contribution with potential future telescope at South Pole: 7.5 x IceCube A_{eff}*

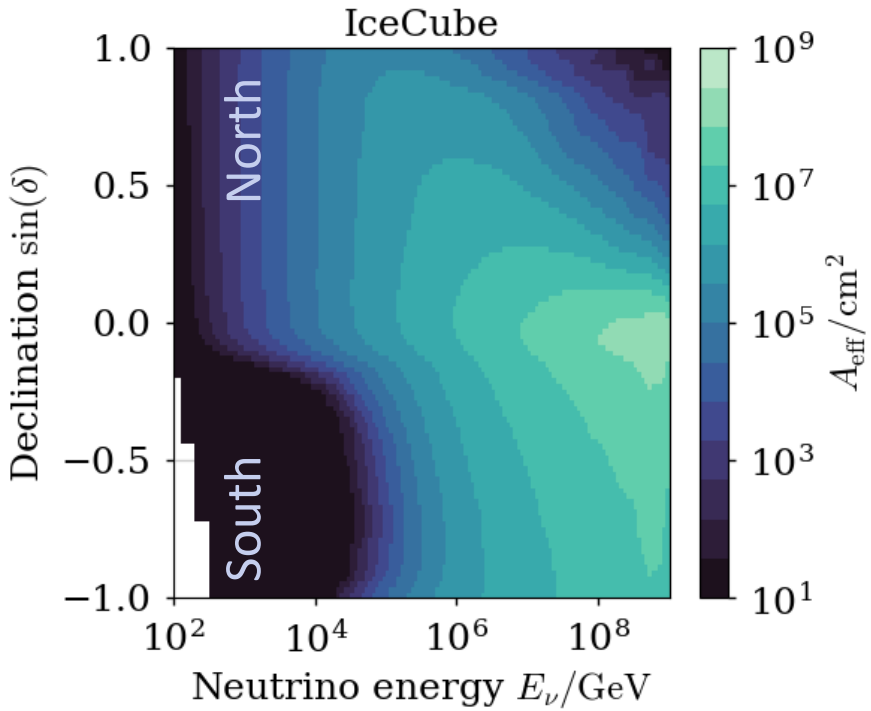


Important: currently everything is based on IceCube's data release of 10yr muon tracks http://doi.org/DOI:10.21234/sxvs-mt83

* Based on 5x better discovery potential for point-like sources (IceCube-Gen2: The Window to the Extreme Universe, arXiv:2008.04323)

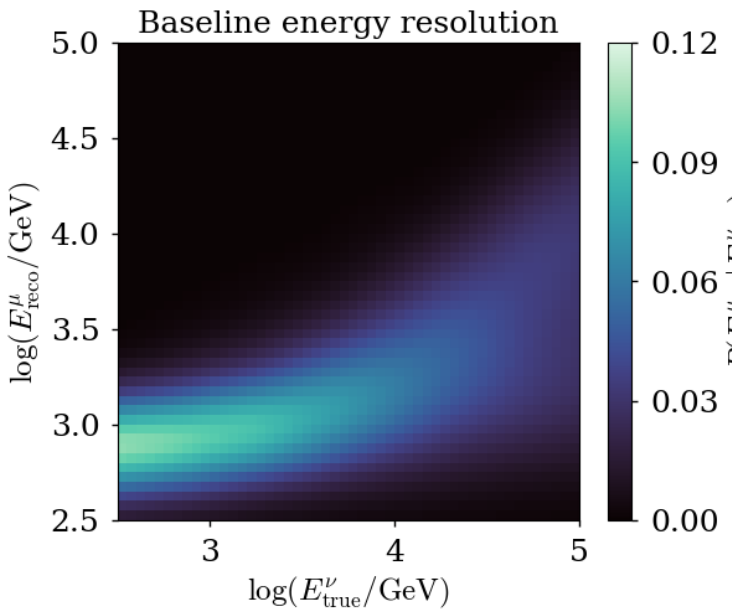
What input is needed for PLEnuM?

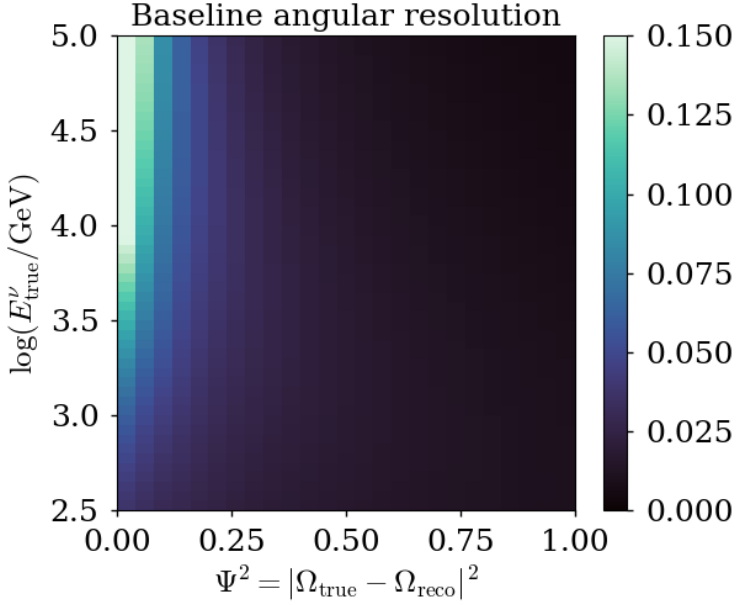
$$A_{\text{eff}}(E, \vec{\Omega}) = T_{\text{Earth}}(E_\nu, \vec{\Omega}) \otimes P_{\nu \to \mu}(E_\nu, E_\mu, R) \otimes \epsilon_{\text{select}}(E_\mu, \vec{\Omega}) \otimes A_{\text{geo}}(\vec{\Omega})$$



$$N_\nu(\sin(\delta_{\text{src}})) = T_{\text{live}} \cdot \int_{E_{\min}}^{E_{\max}} \mathrm{d}E \, A_{\text{eff}}\,(E, \sin(\delta_{\text{src}})) \cdot \frac{\mathrm{d}\Phi_{\text{src}}}{\mathrm{d}E}$$

- **Effective area:** rotated from local zenith to declination for other detectors based on IceCube's effective area
- **Energy resolution**
- **Angular resolution**





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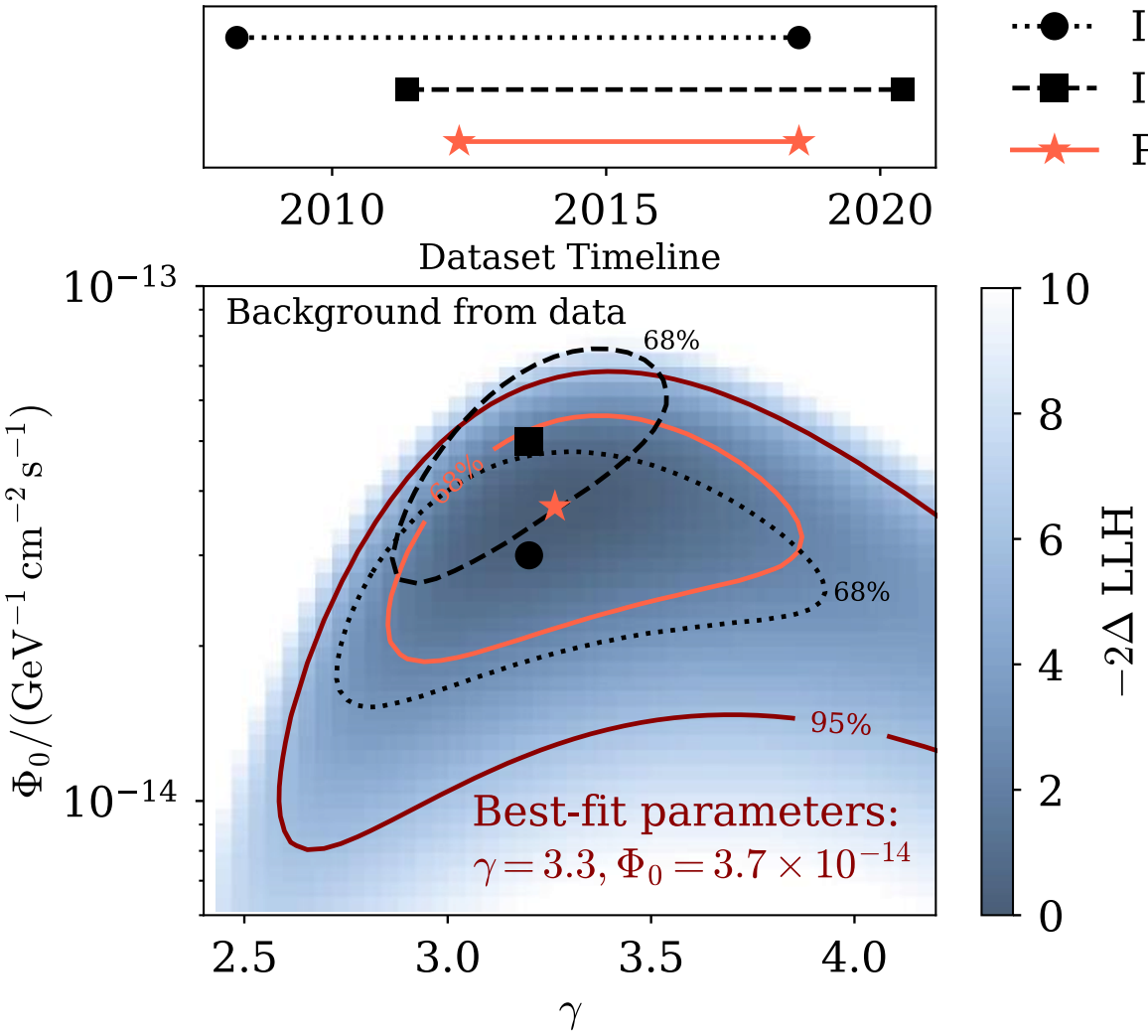
Reproduce NGC 1068 fit on public data

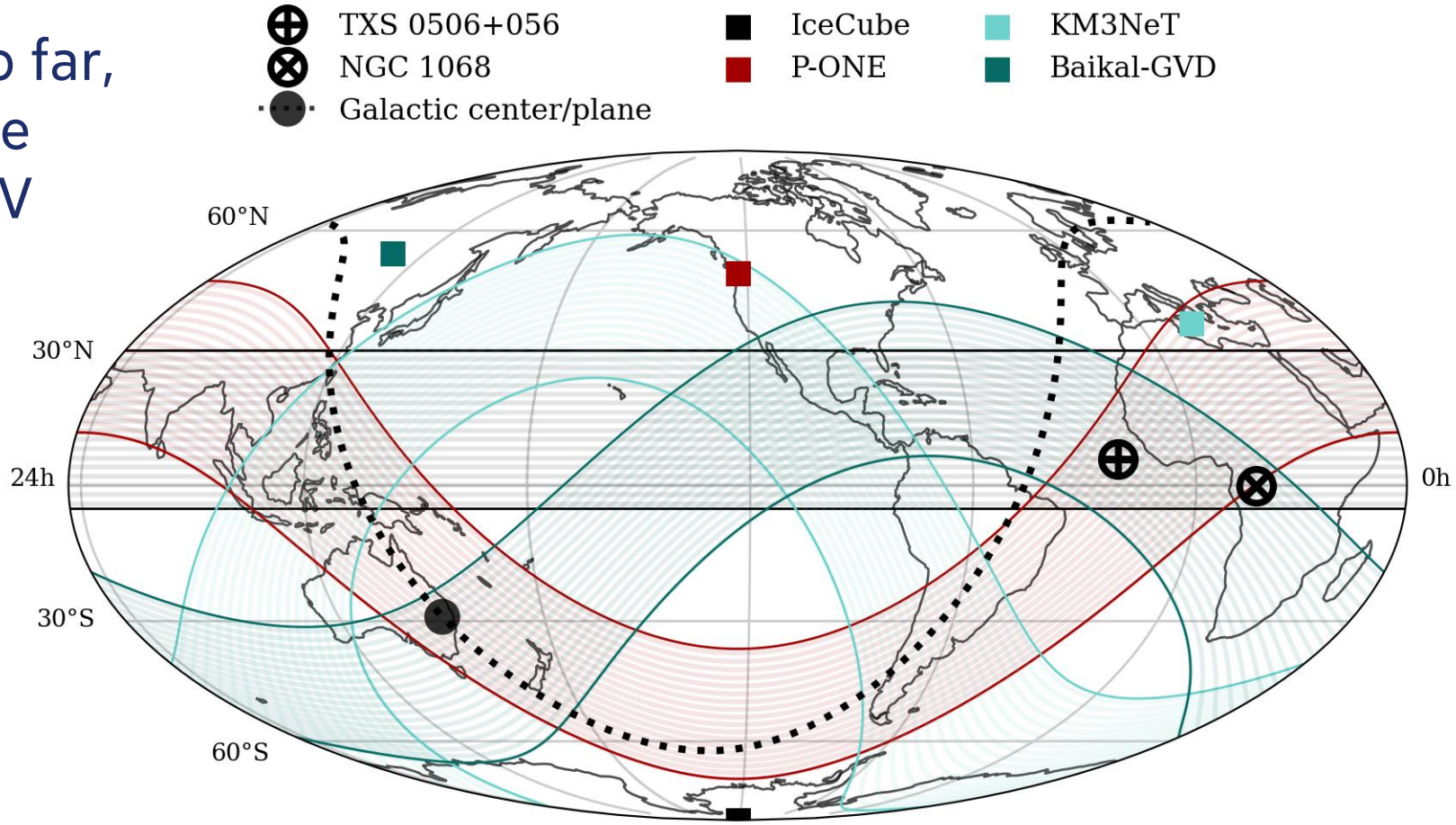


NGC 1068 in public IceCube data analysed with PLEnuM

Publication in preparation!

Best field of view for high-energy ν_μ

We used the integrated FOV so far, now we look at the instantaneous FOV



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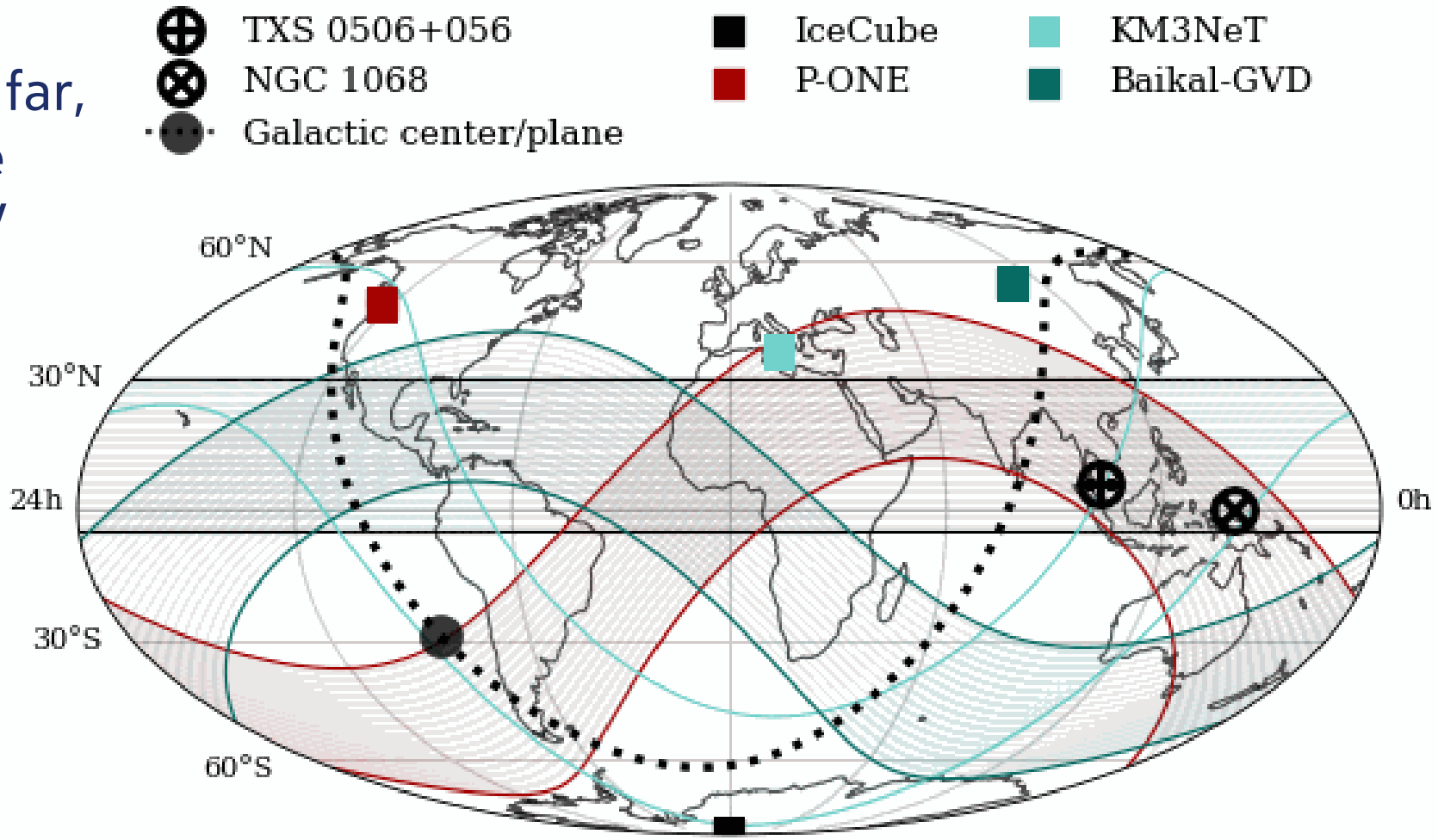
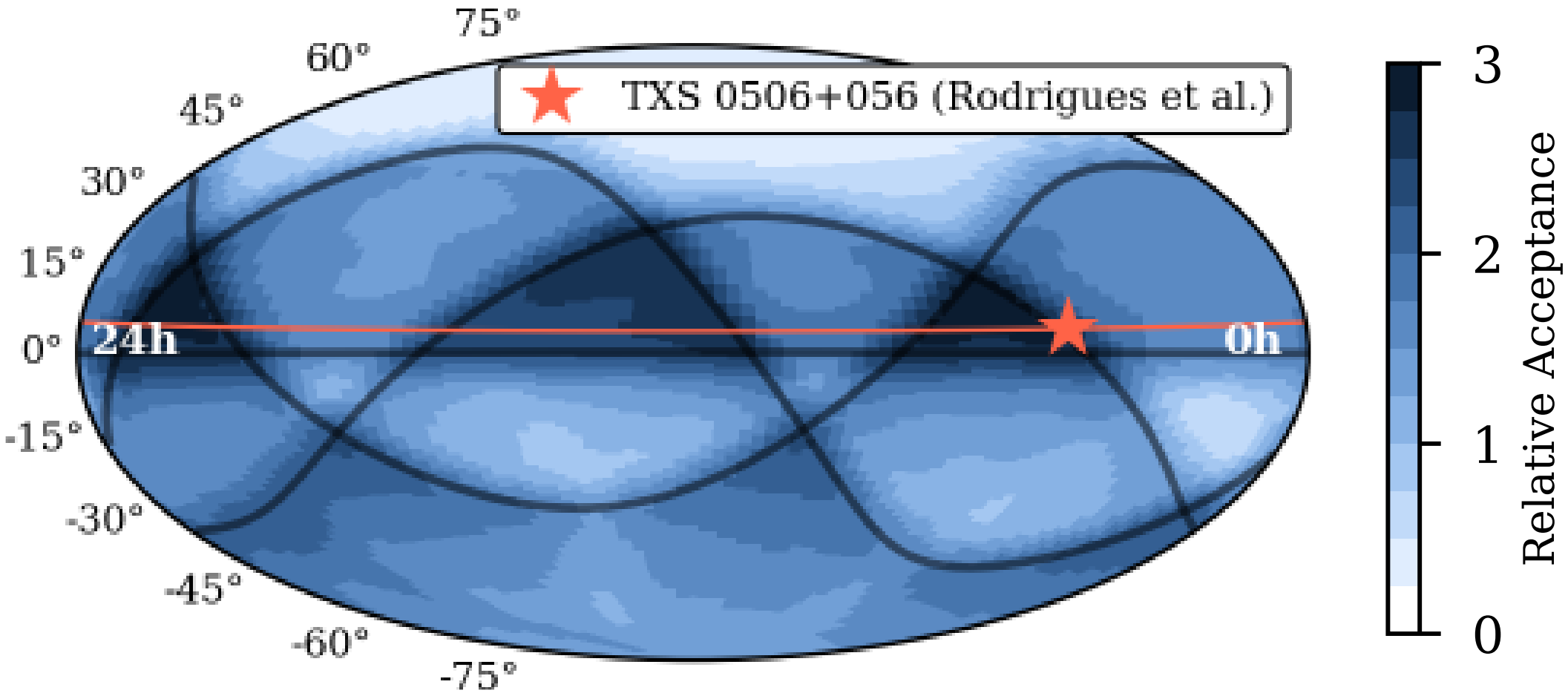
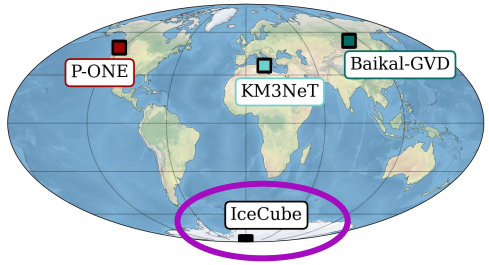


Instantaneous detection efficiency

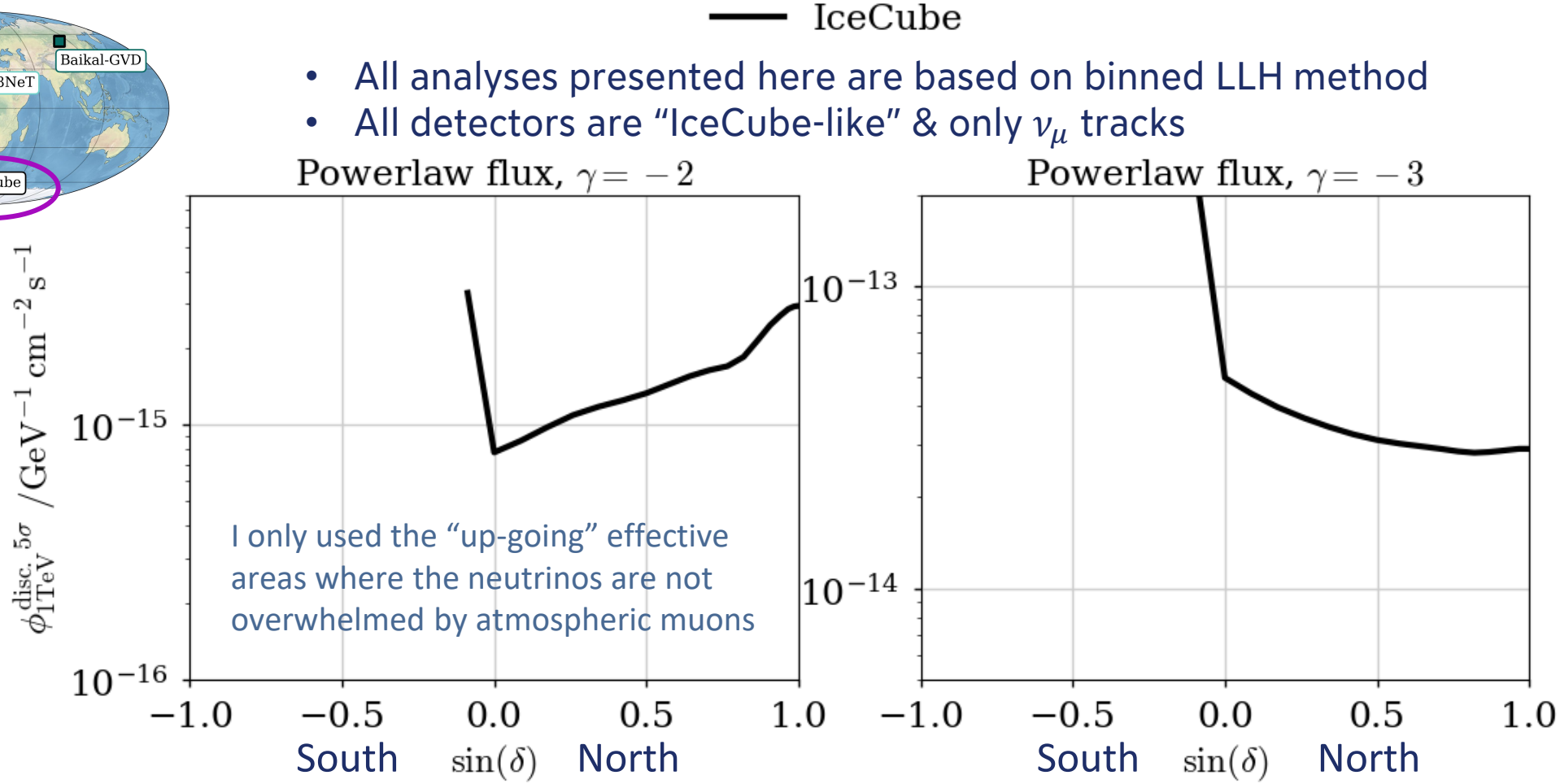


Discovery potential for point sources

… as function of declination and for hard and soft spectra



- All analyses presented here are based on binned LLH method
- All detectors are “IceCube-like” & only ν_μ tracks



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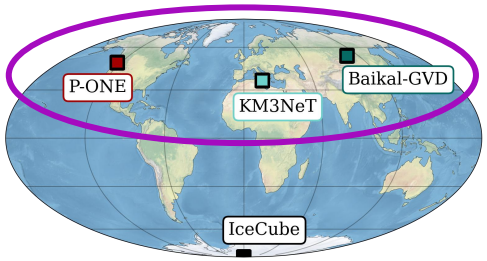

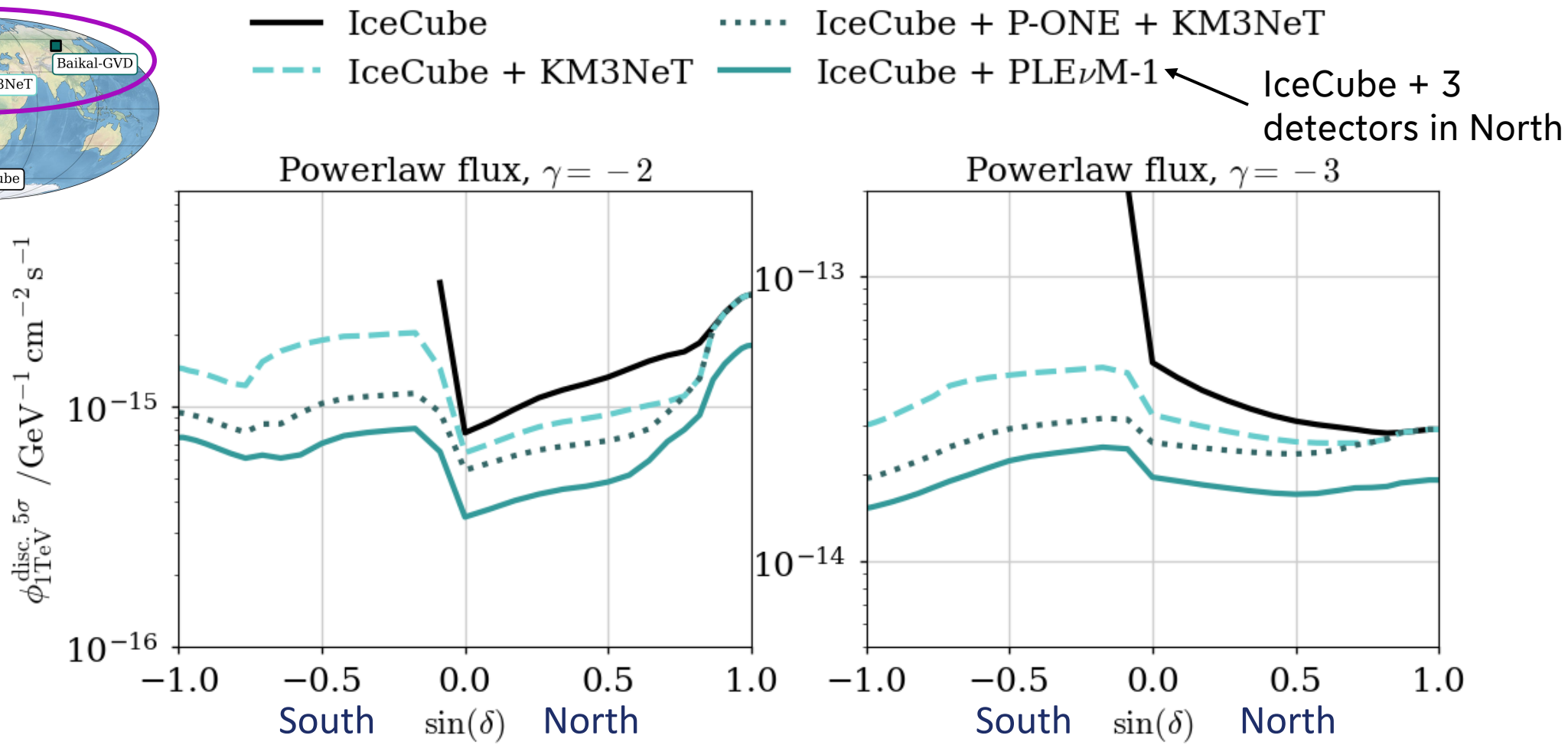

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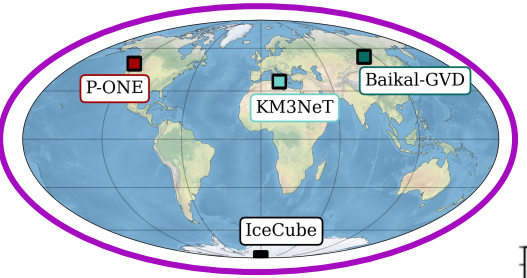
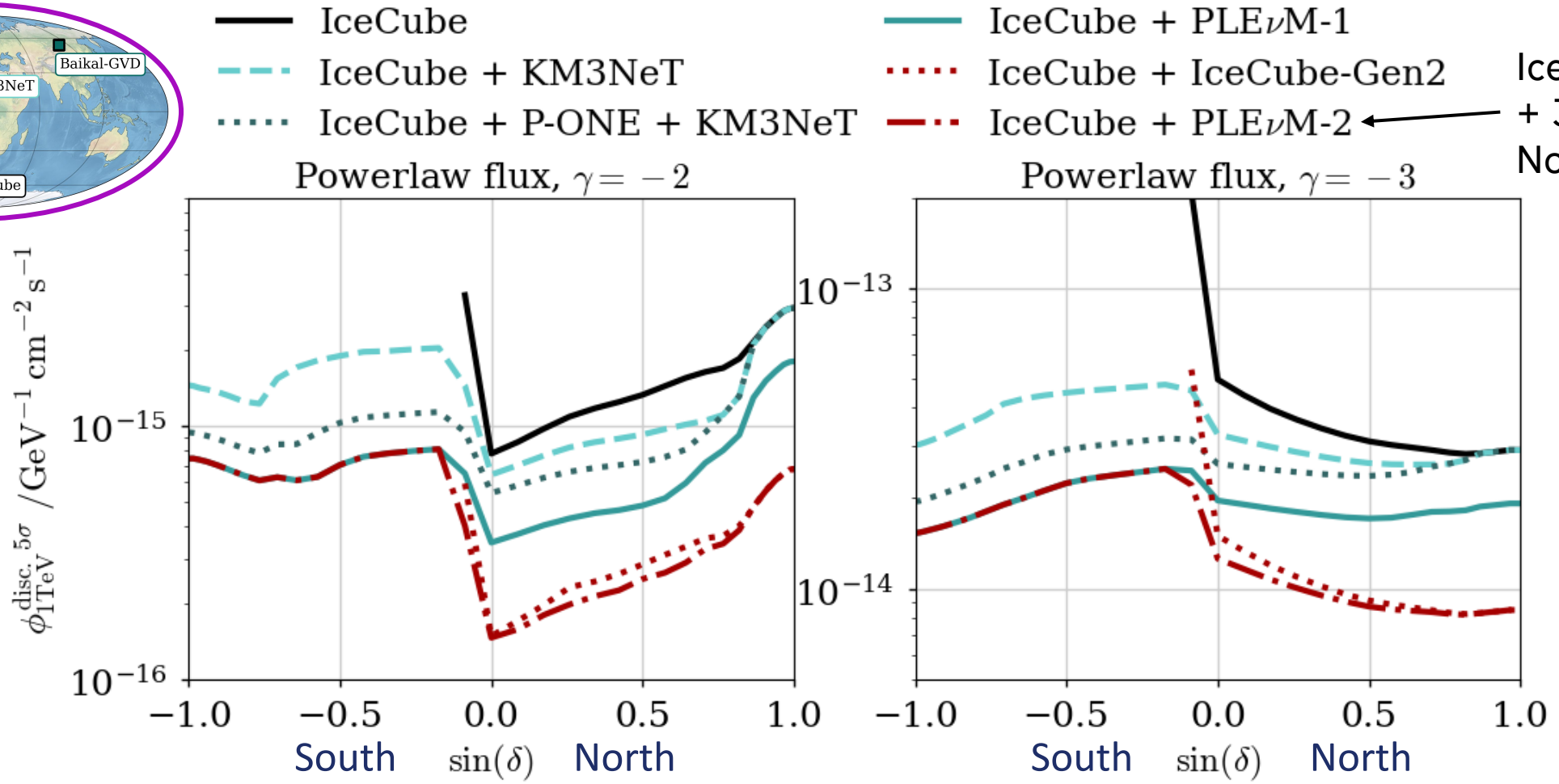


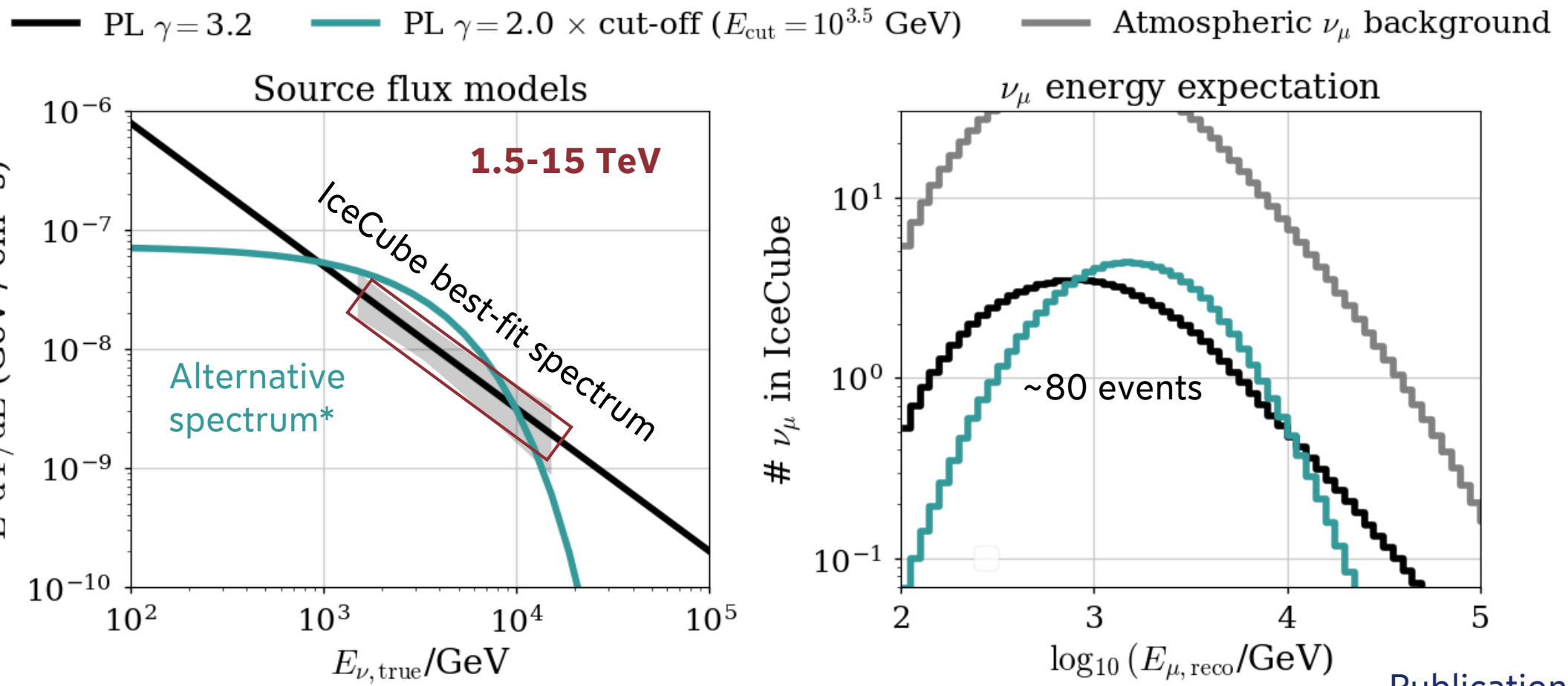
+Gen2



IceCube-Gen2 + 3 detectors in North

Beyond the single power law – NGC 1068

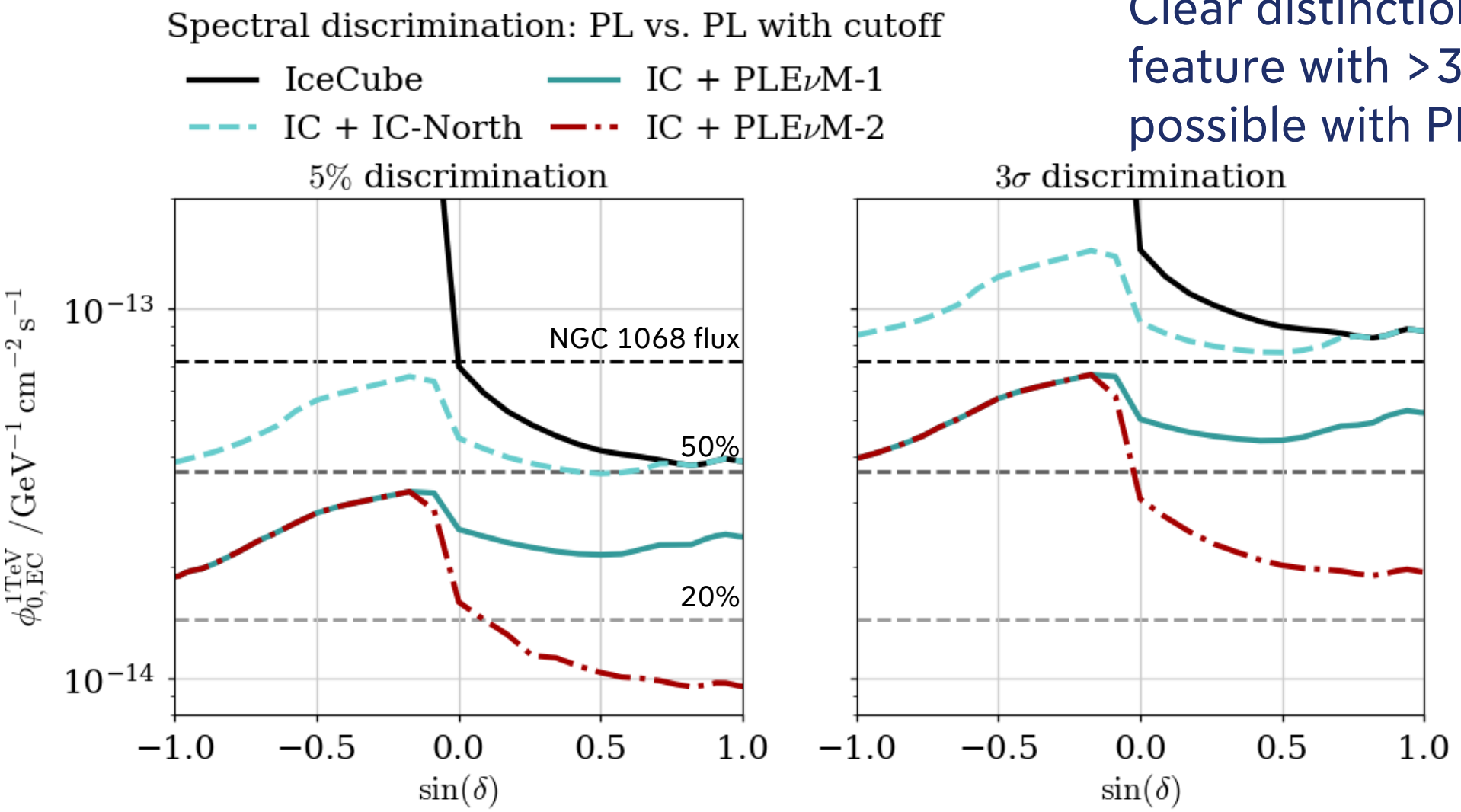
Spectral models



*motivated by Inoue+, PoS(ICRC2023)1161
And Kheirandish+, https://doi.org/10.3847/1538-4357/ac1c77

Publication work in progress

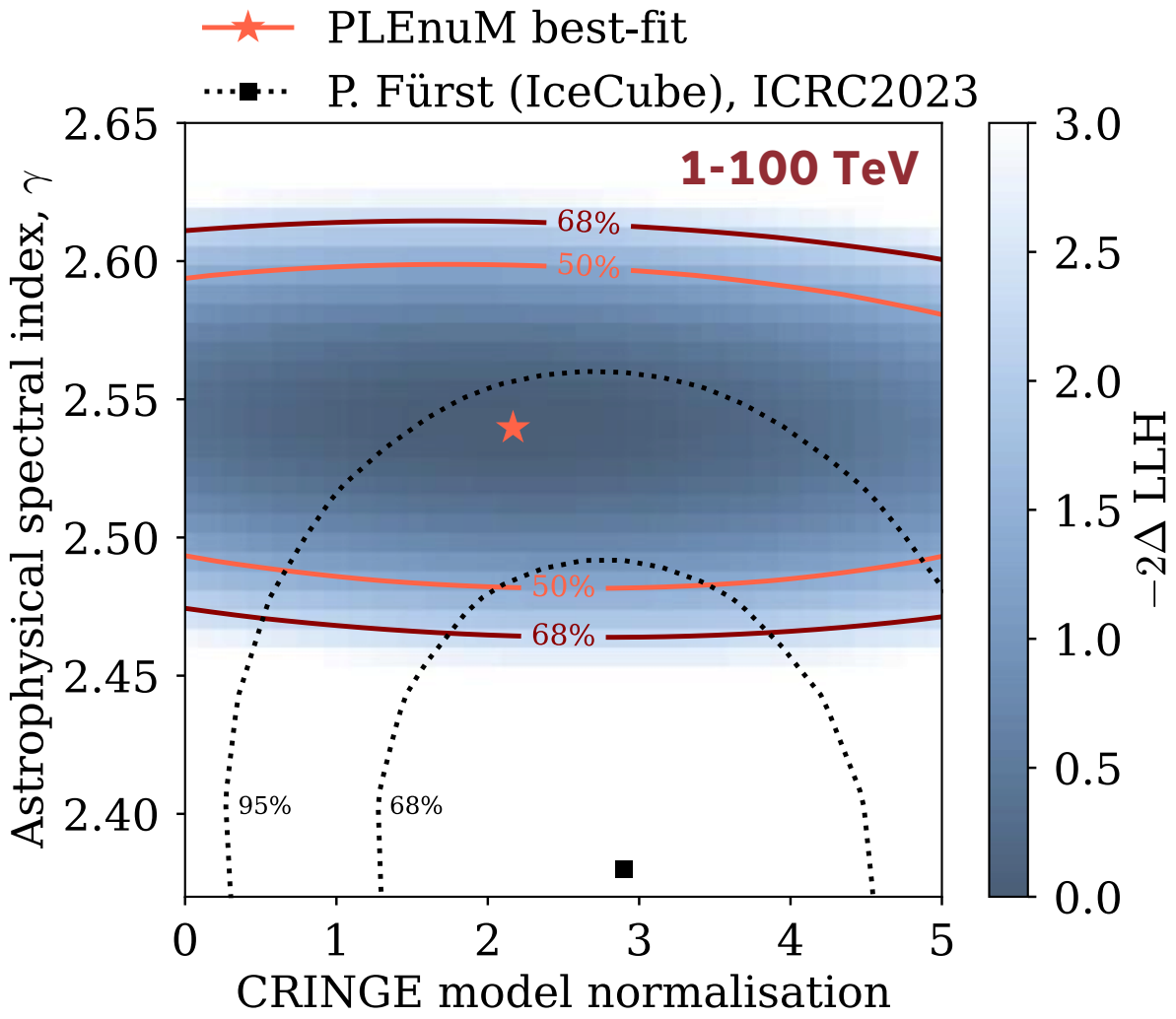
Beyond the single power law – NGC 1068



Clear distinction of cut-off feature with >3σ significance possible with PLEnuM!

Publication work in progress

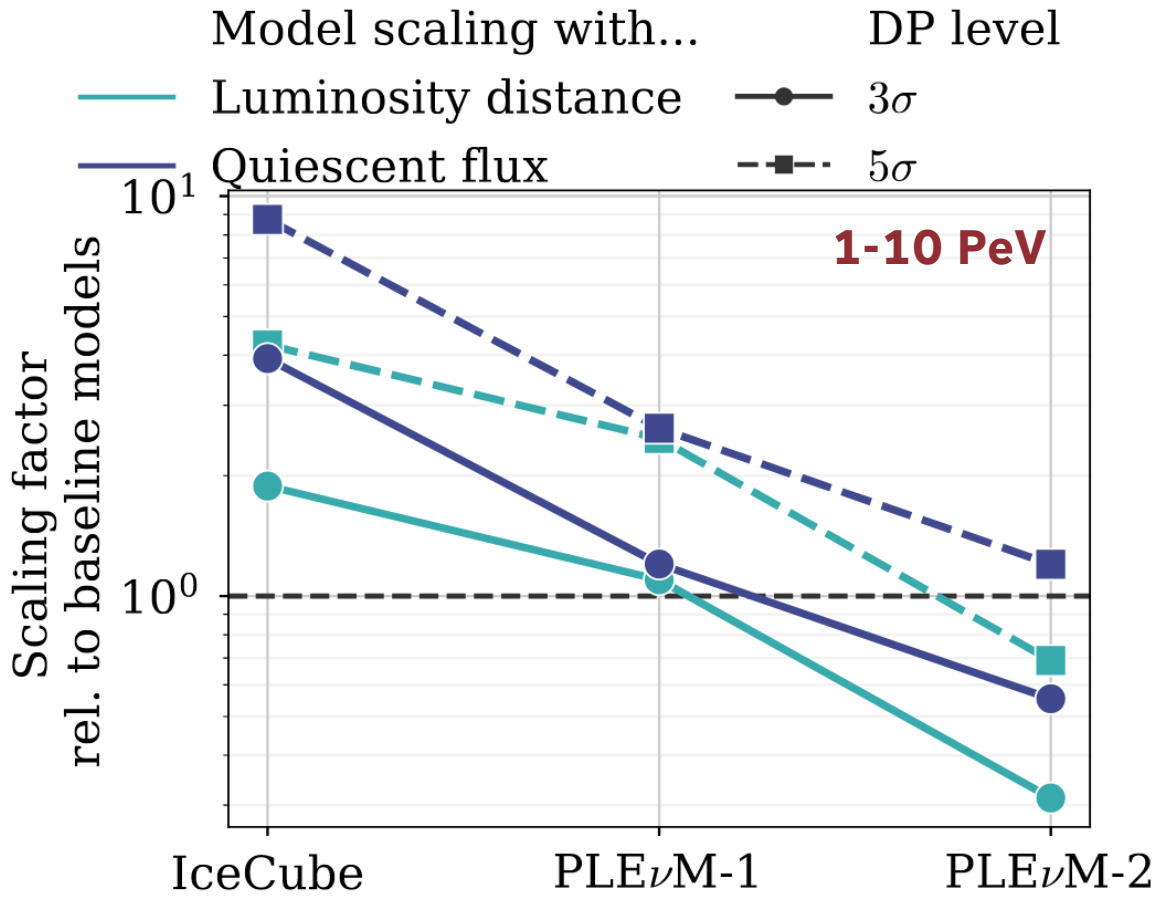
Galactic plane



Galactic Plane in public IceCube data analysed with PLEnuM

Work in progress by Anke Mosbrugger (ECAP)
CRINGE model (Schwefer et al.):
DOI 10.3847/1538-4357/acc1e2

Detecting FSRQs as neutrino sources



https://doi.org/10.22323/1.444.0991
ICRC 2023 F. Oikonomou, LS

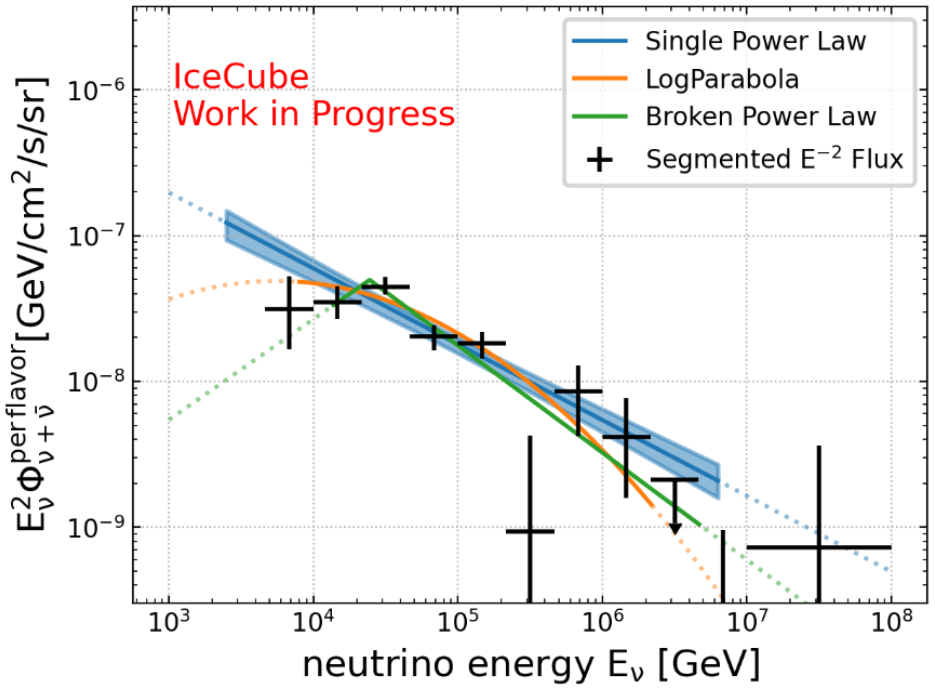
- 106 flat-spectrum radio quasars (incl. TXS 0506+056 as masquerading FSRQ)
- Assume a flaring duty cycle as in Yoshida+ https://doi.org/10.3847/1538-4357/acea74
- Spectral model: LMBB2b* for TXS -> scale all FSRQ fluxes relative to TXS based on luminosity distance or quiescent gamma-ray flux
- PLEnuM-1: reach 3σ discovery potential
- PLEnuM-2: reach 5σ discovery potential

https://doi.org/10.3847/1538-4357/aad59a
*A. Keivani+

Beyond the single power law - diffuse

- IceCube sees hints for features in the diffuse astrophysical neutrino spectrum already today!
- State-of-the-art analysis tool & simulations
- Including cascades with good energy resolution

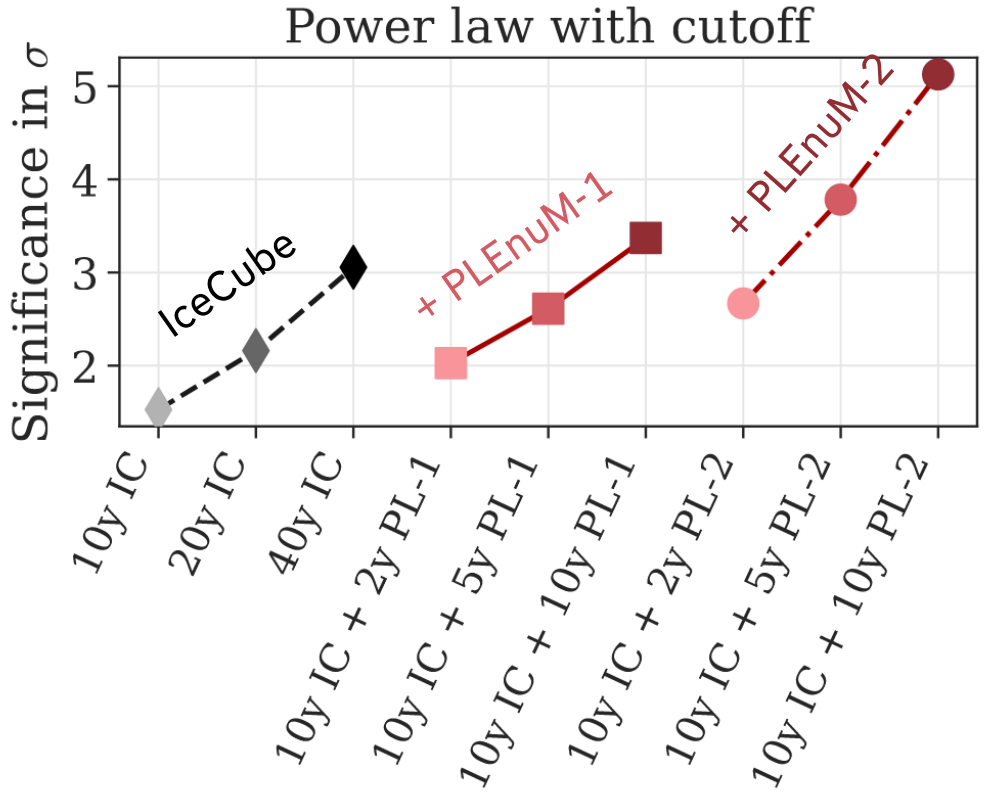
10TeV – 10 PeV



https://doi.org/10.22323/1.444.1064

https://doi.org/10.22323/1.395.1185
ICRC2021

- Projected significance of cut-off with PLEnuM
- Only muon neutrino tracks (no cascades)



Take away messages

1) The era of neutrino astronomy has just begun
2) The detectors coming online in the next decade(s) will enable discoveries over the whole sky and will push the frontier towards fainter sources
3) Beyond the first discoveries made by IceCube, much more neutrinos will be needed to really start digging into the characteristics of neutrino sources