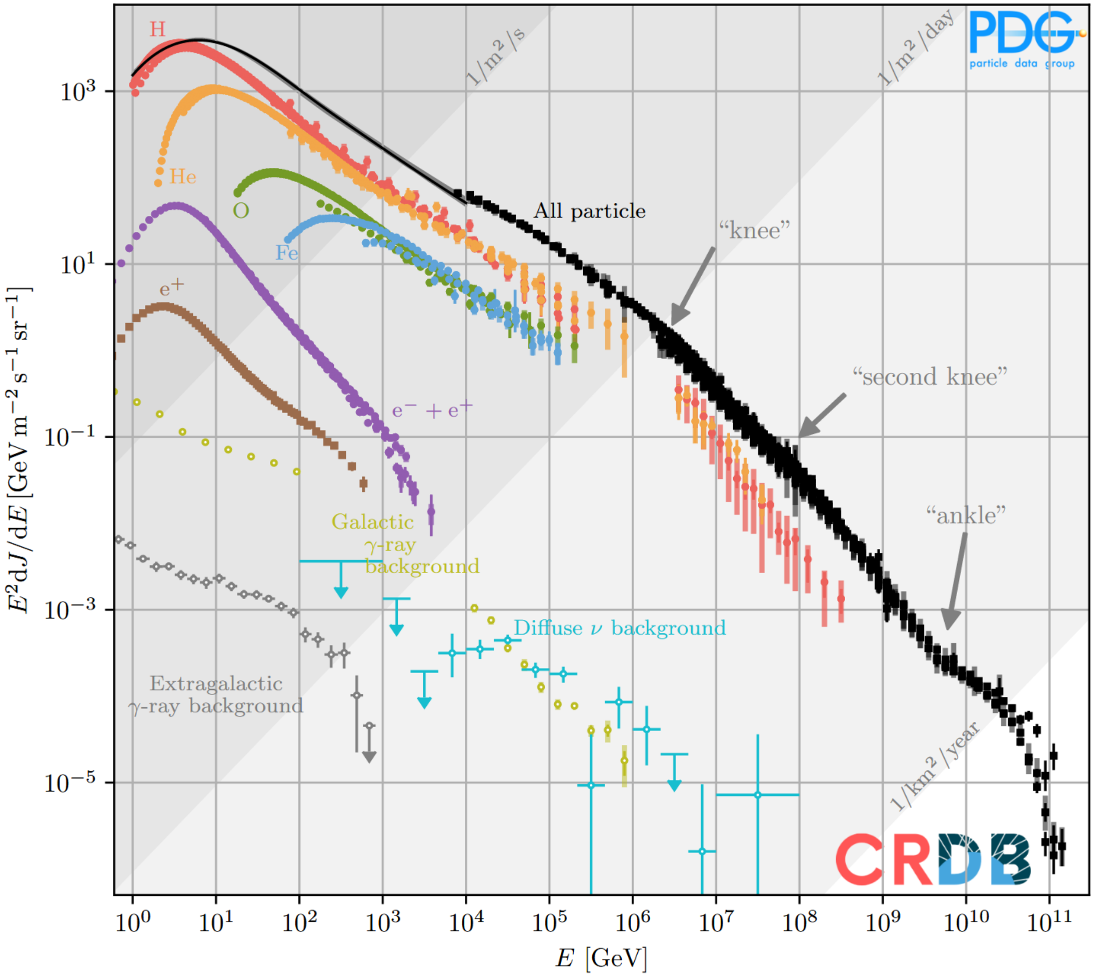
Large Volume Neutrino Telescopes - Current Status and Future Outlook

Christian Haack, ECAP FAU Erlangen-Nürnberg
christian.haack@fau.de

The Cosmic Ray Puzzle



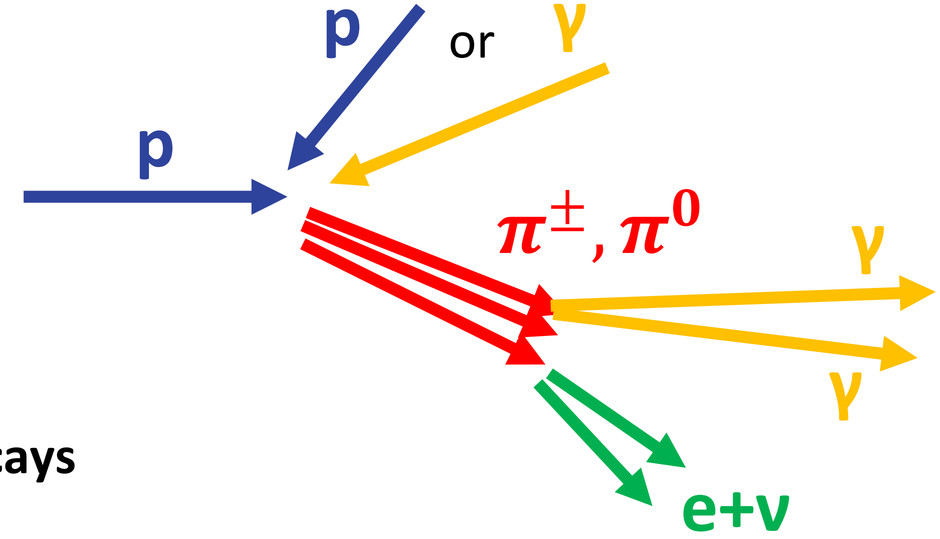
PDG 2024

Where and how are cosmic rays accelerated?

The Cosmic Ray Connection

Accelerator (AGN, SNR, GRB, ..)

DESY



Idealized scenarios

$$p + p \rightarrow X + \begin{cases} \pi^+ & 1/3 \\ \pi^- & 1/3 \\ \pi^0 & 1/3 \end{cases}$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 & 1/3 \\ n + \pi^+ & 2/3 \end{cases}$$

Pion Decays

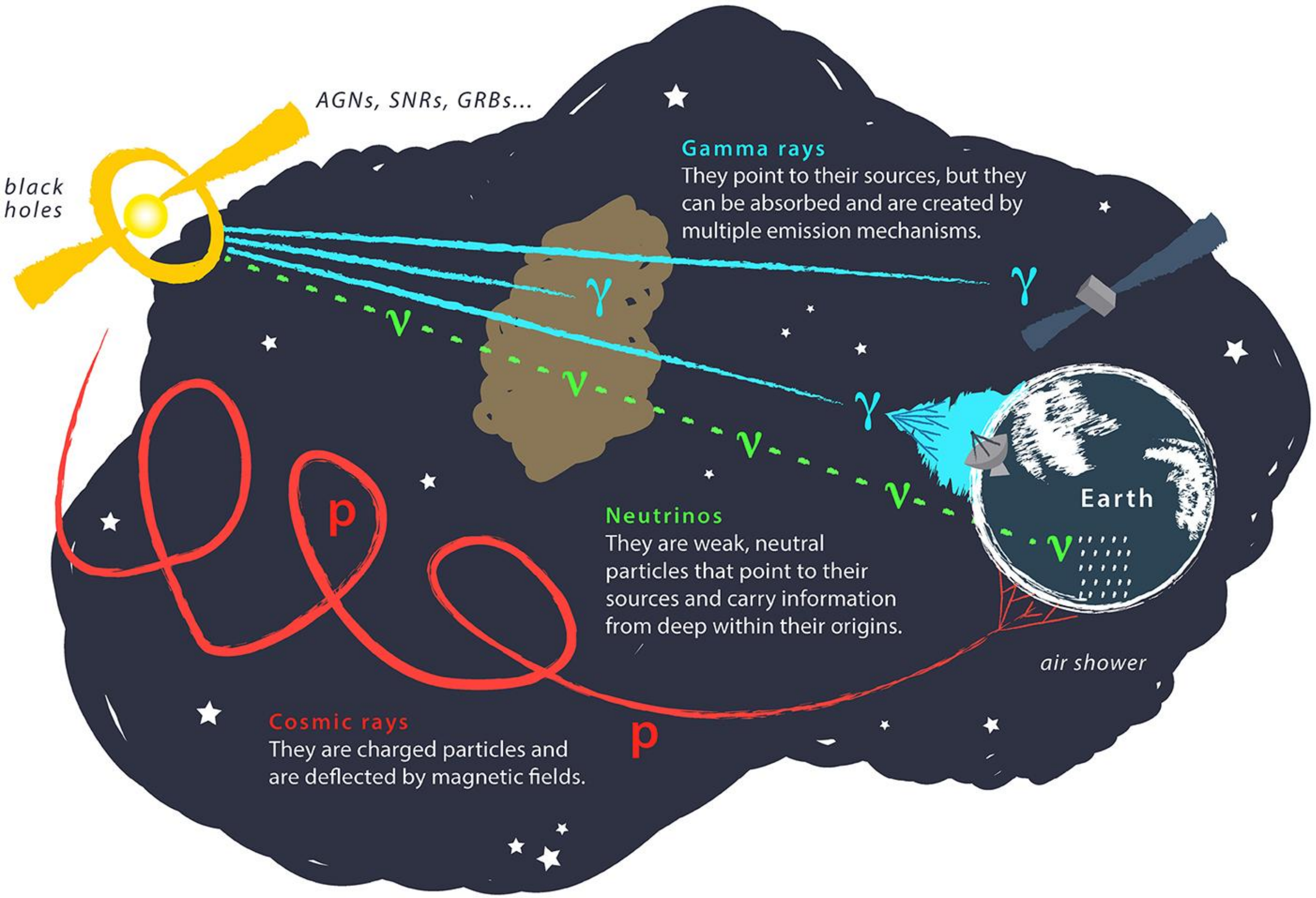
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

Interaction of accelerated CR naturally leads to production of neutrinos and gamma rays

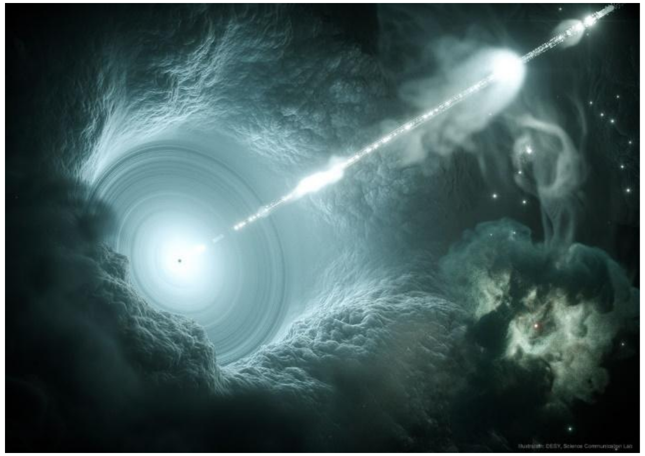
Neutrinos are Ideal Messengers



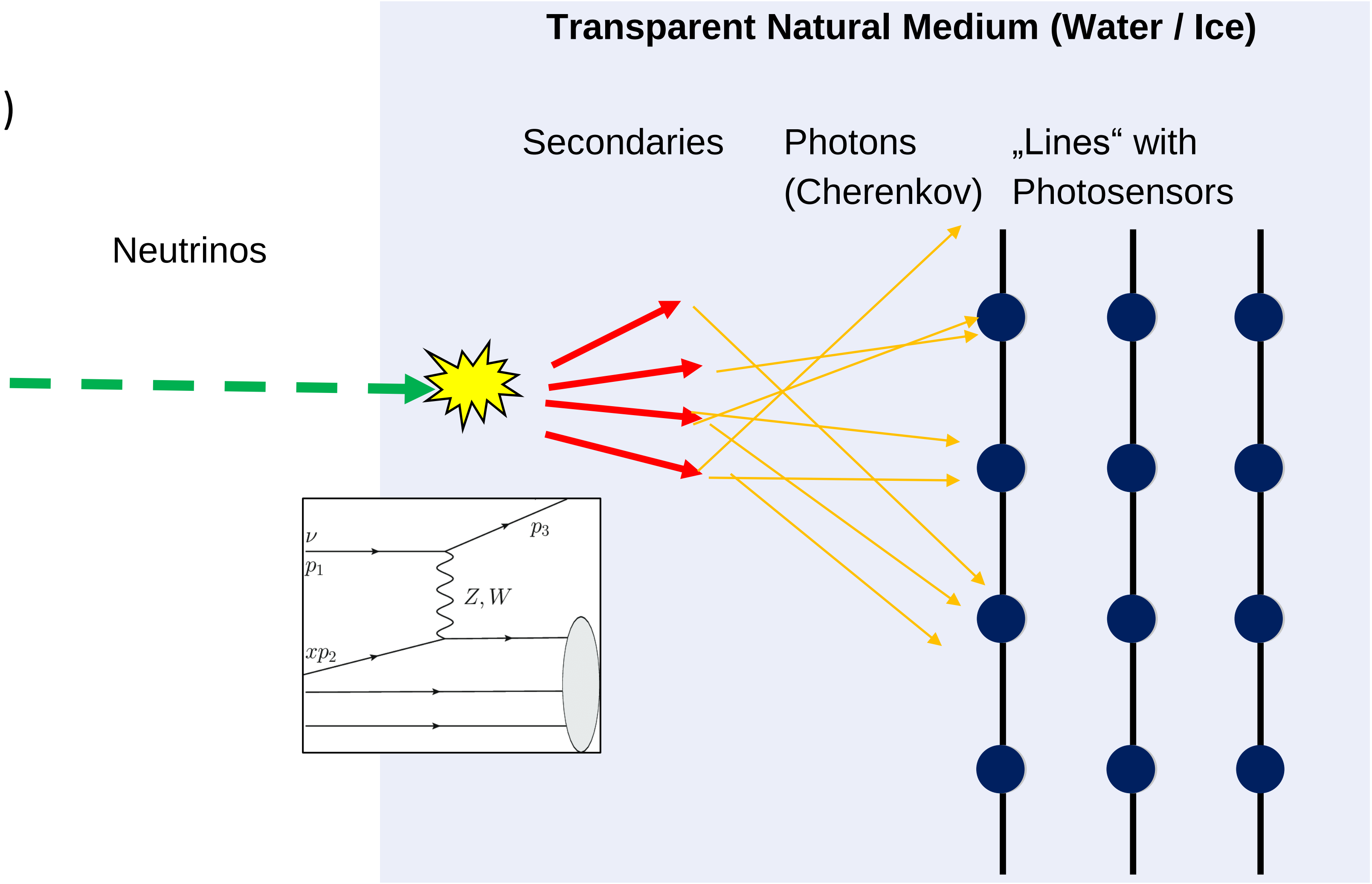
IceCube Collaboration/WIPAC, Juan Antonio Aguilar, and Jamie Yang

Detection Method

Accelerator (AGN, SNR, GRB, ..)



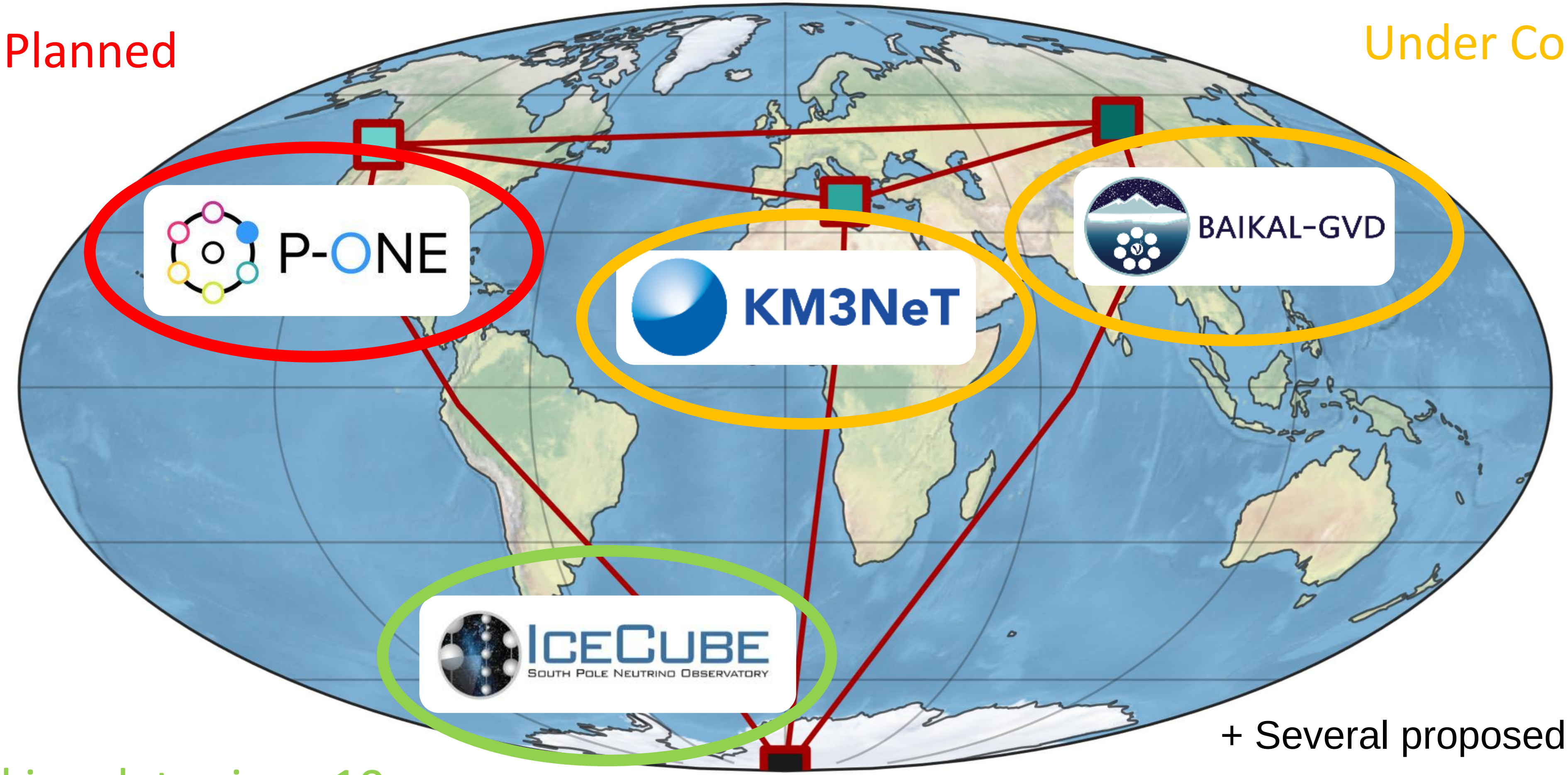
DESY



Neutrino Telescopes

Planned

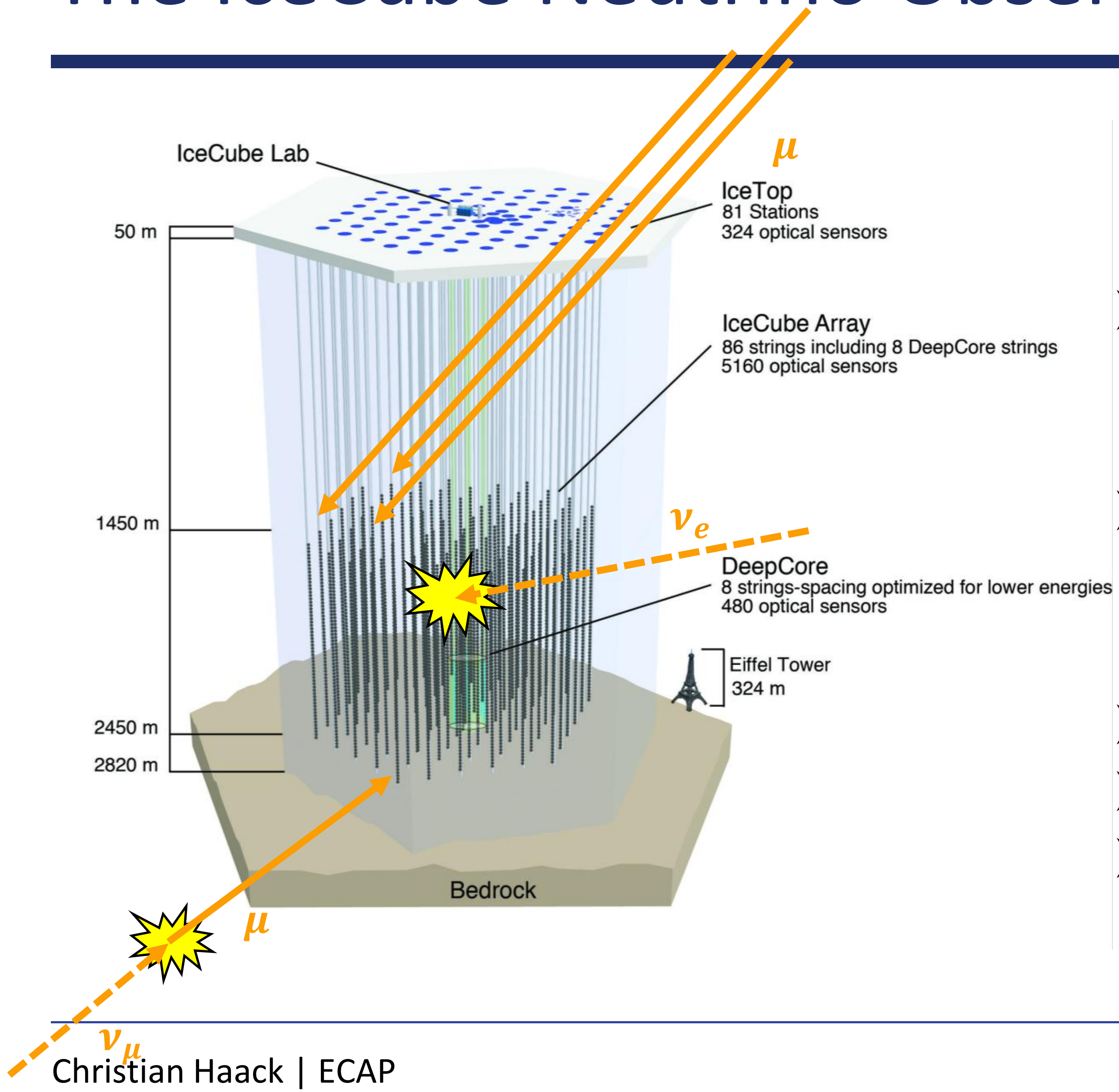
Under Construction



+ Several proposed Chinese projects

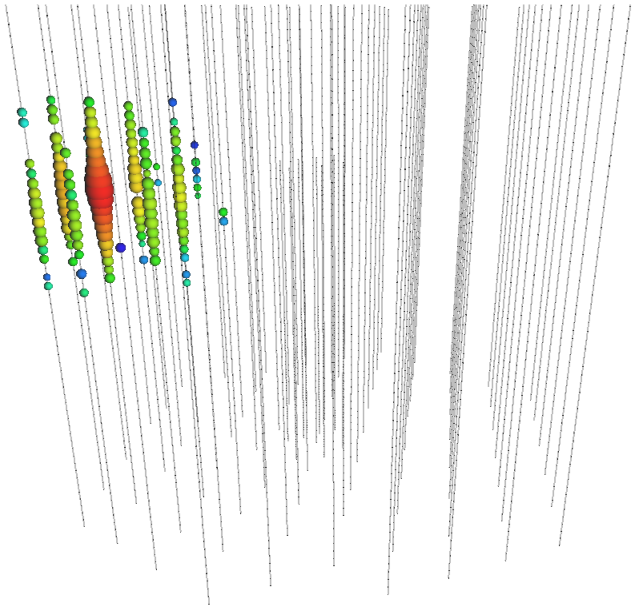
Taking data since 10+ years

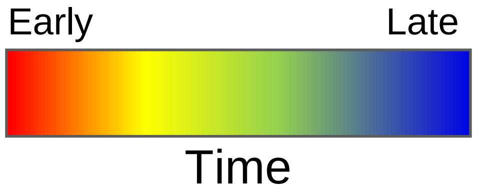
The IceCube Neutrino Observatory

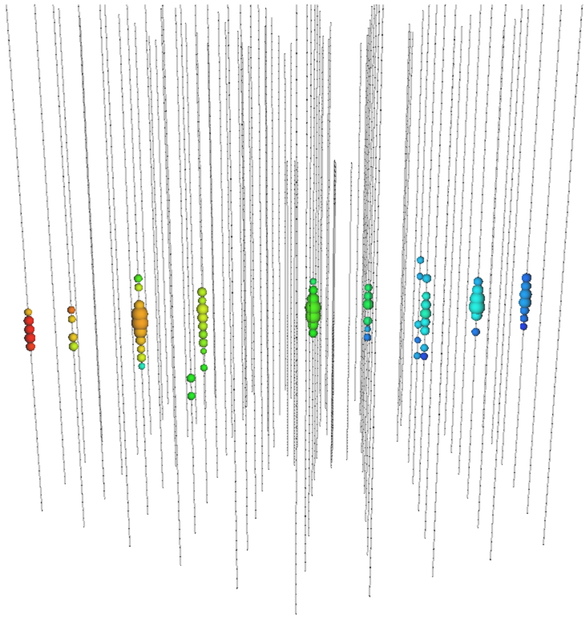


- 86 Strings with 60 Digital Optical Modules (DOMs)
- Full configuration running with > 99% uptime since 2011
- 3000 atmospheric μ per second
- 1 atmospheric ν per minute
- 1 astrophysical ν per day

Event Channels







(EM / Hadronic) Cascades

Neutral Current (NC) & ν_e (ν_τ) Charged Current (CC)

+ Energy resolution
+ High Purity

Throughgoing Tracks (muons)

ν_μ CC, atmospheric μ

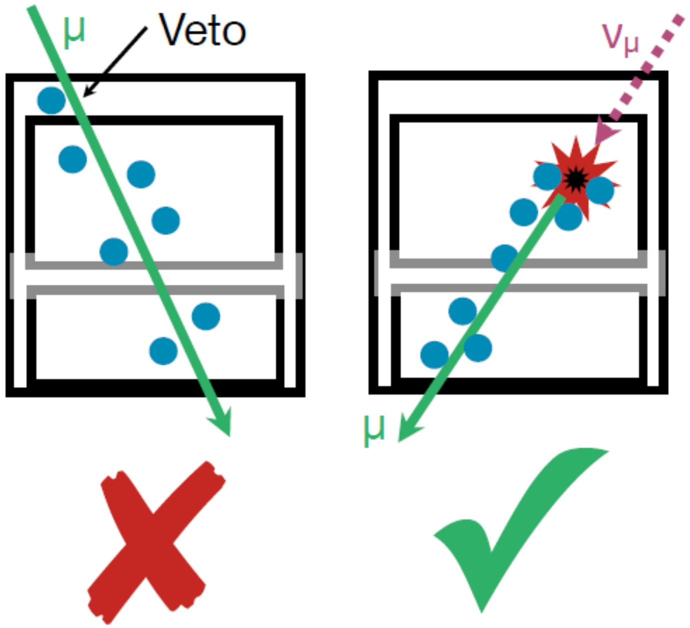
+ Angular resolution
+ Large effective area

Event Selection Strategies

Fiducialization

Starting Tracks, Cascades

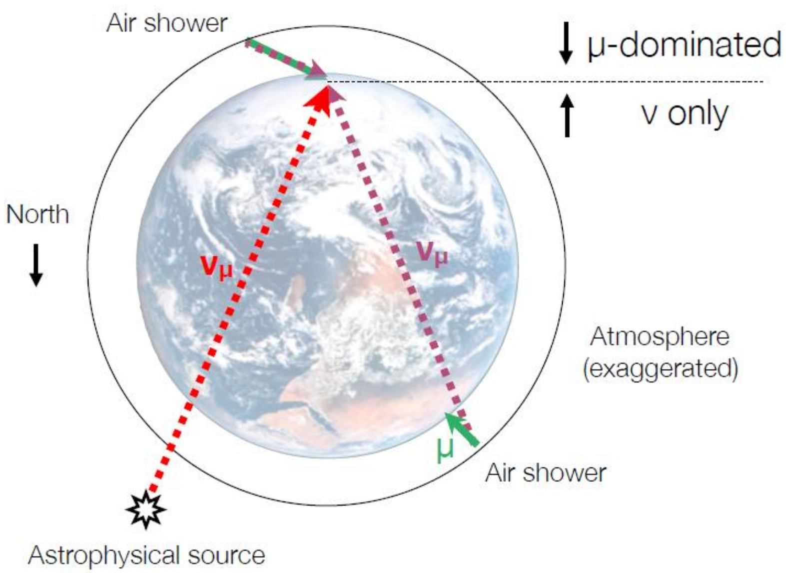
Morphology-based BG discrimination



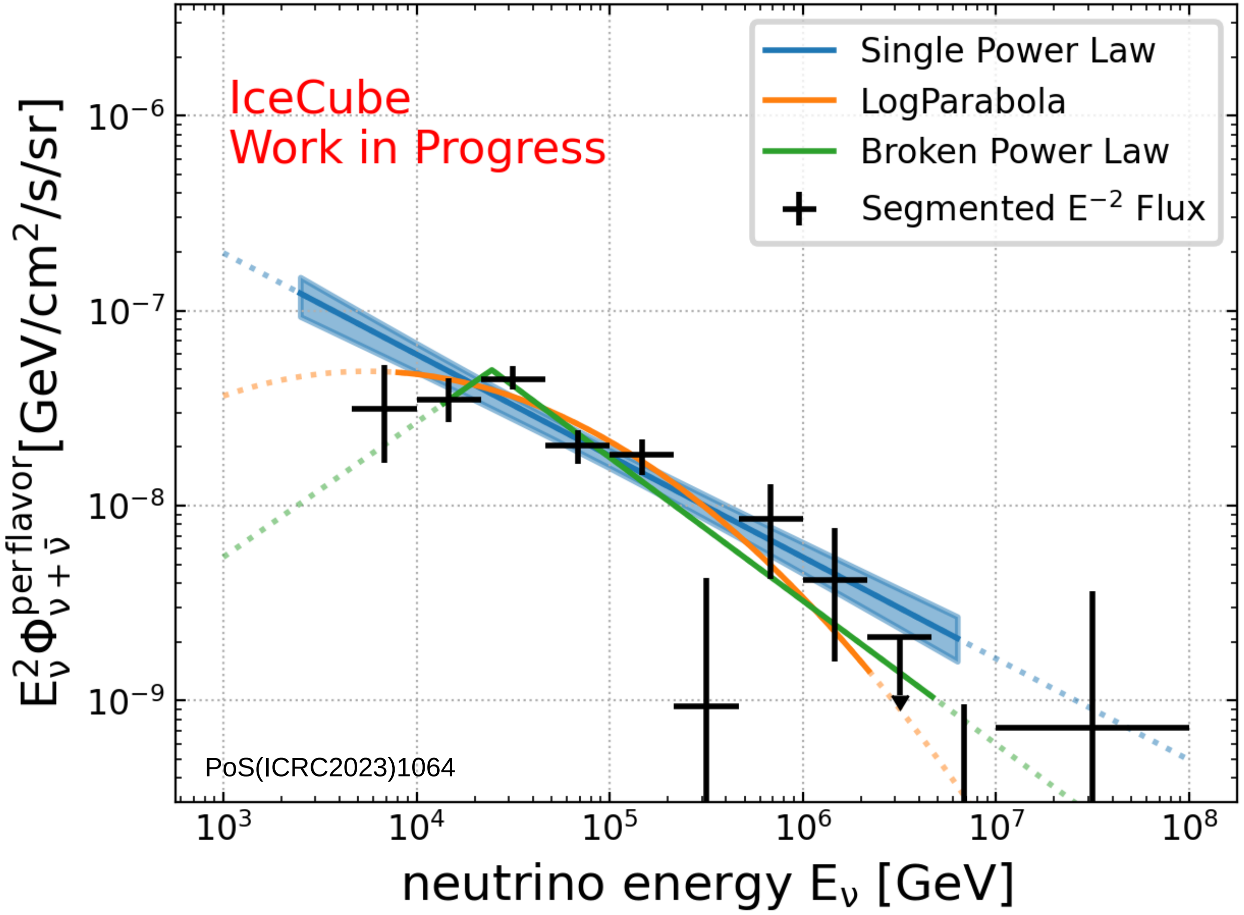
Using Earth as shield

“Upgoing” tracks

Direction based BG discrimination

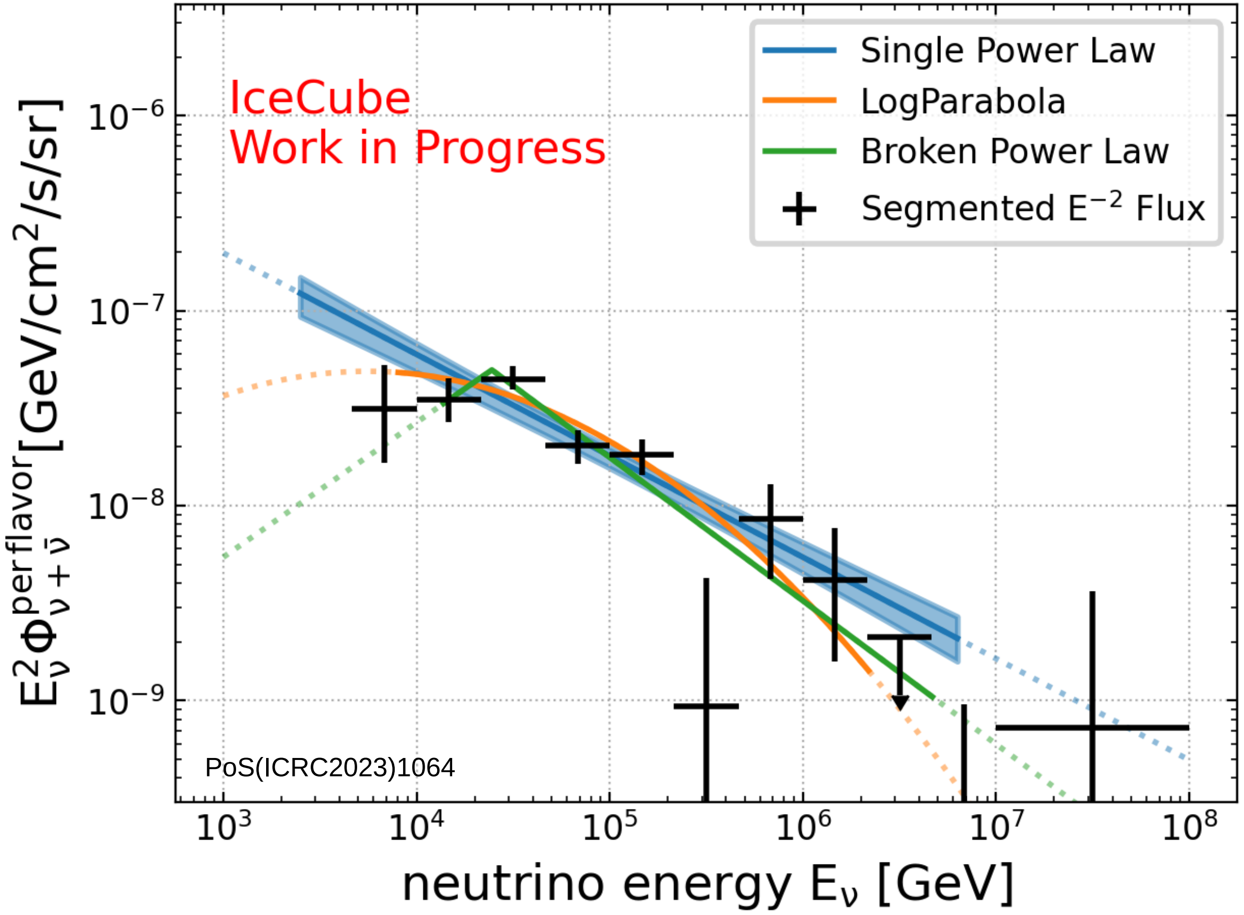


Cosmic Neutrino Spectrum



- ❑ Combined fit of tracks / cascades with unified systematic uncertainty treatment
- ❑ Indications for structure in energy spectrum

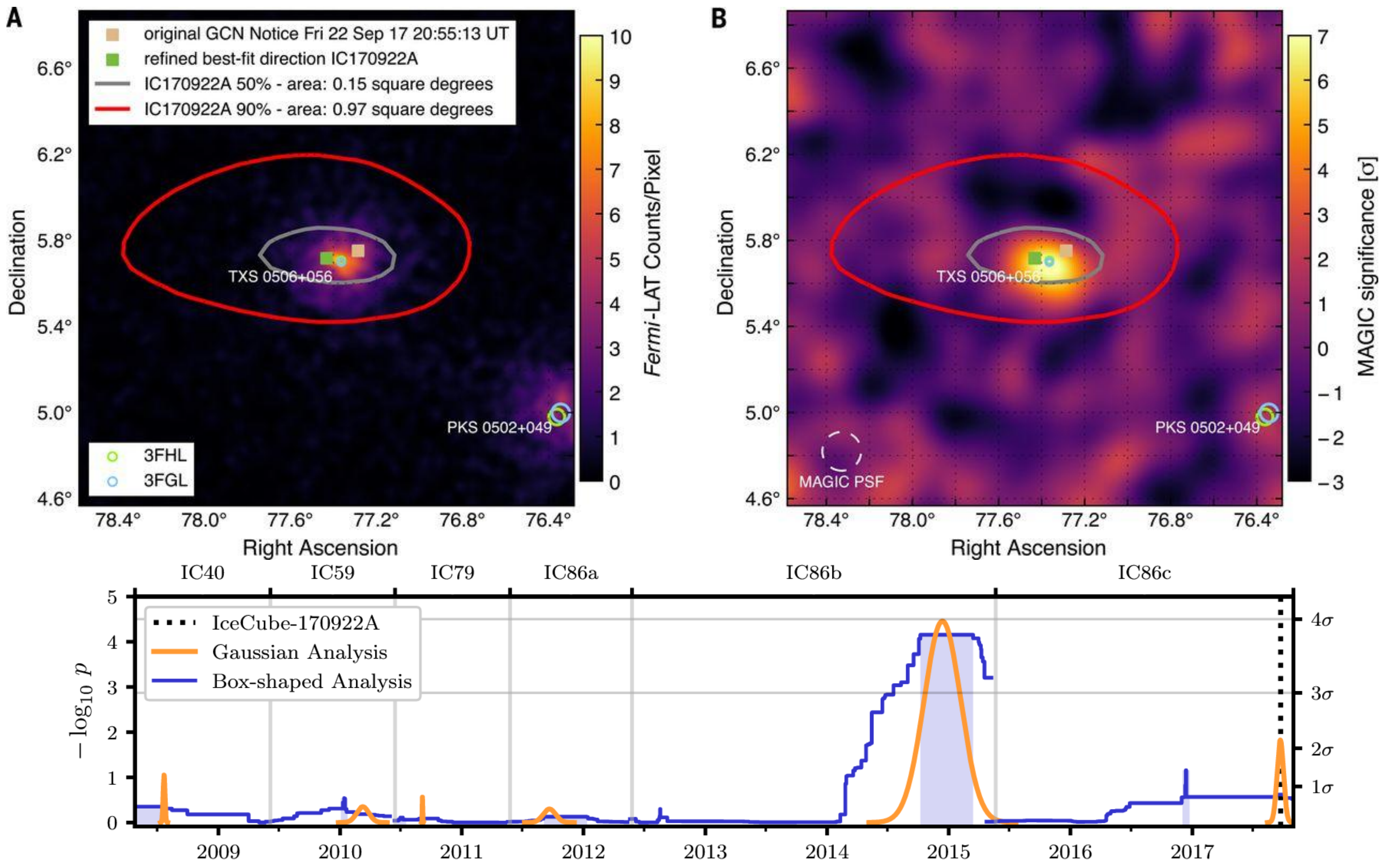
Cosmic Neutrino Spectrum



- ❑ Combined fit of tracks / cascades with unified systematic uncertainty treatment
- ❑ Indications for structure in energy spectrum

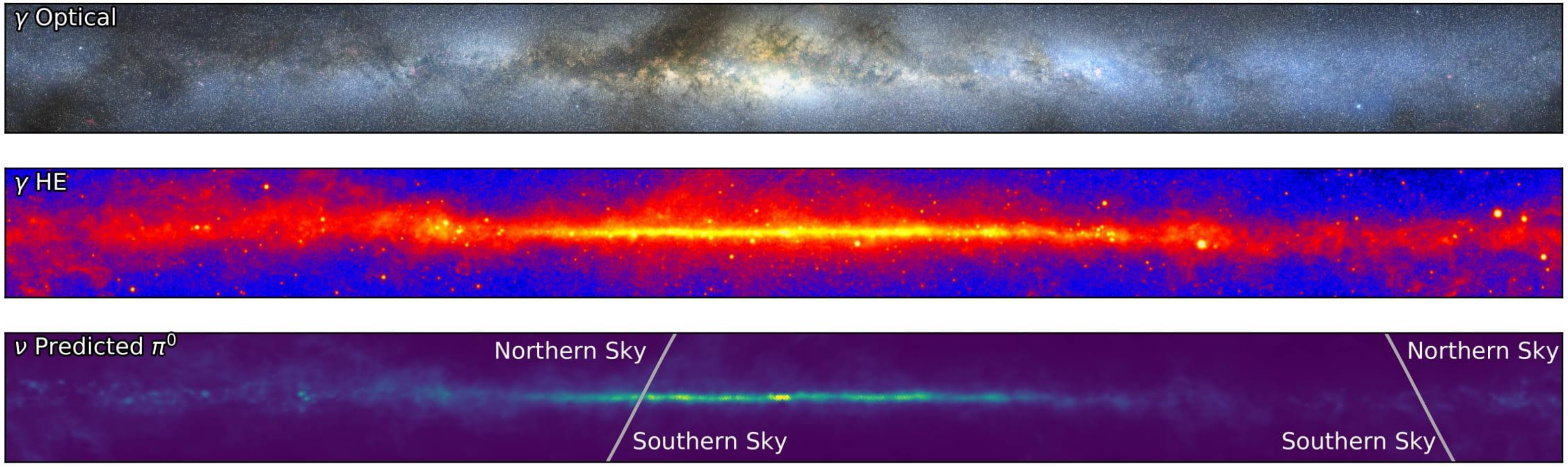
What are the sources of these neutrinos?

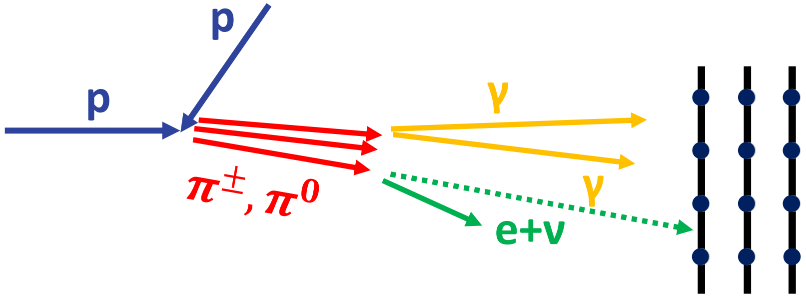
The First Neutrino Source: TXS 056+056



Neutrinos from the Galactic Plane

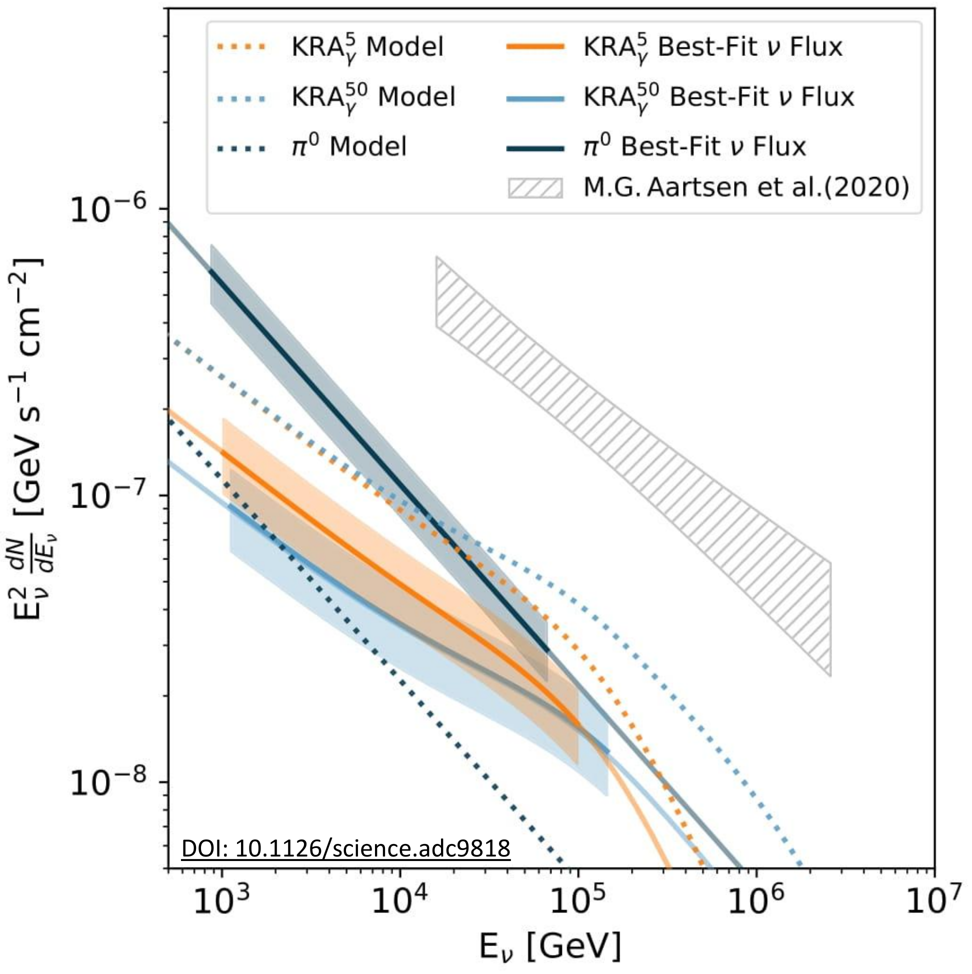
DOI: 10.1126/science.adc9818



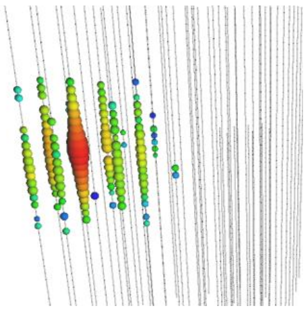


Galactic diffuse neutrino emission is a "guaranteed" flux

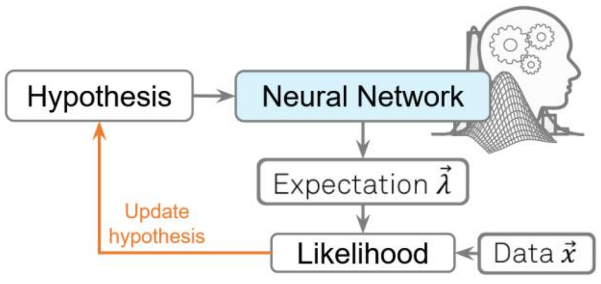
Evidence for Galactic Neutrino Emission



Cascade channel



Deep Learning



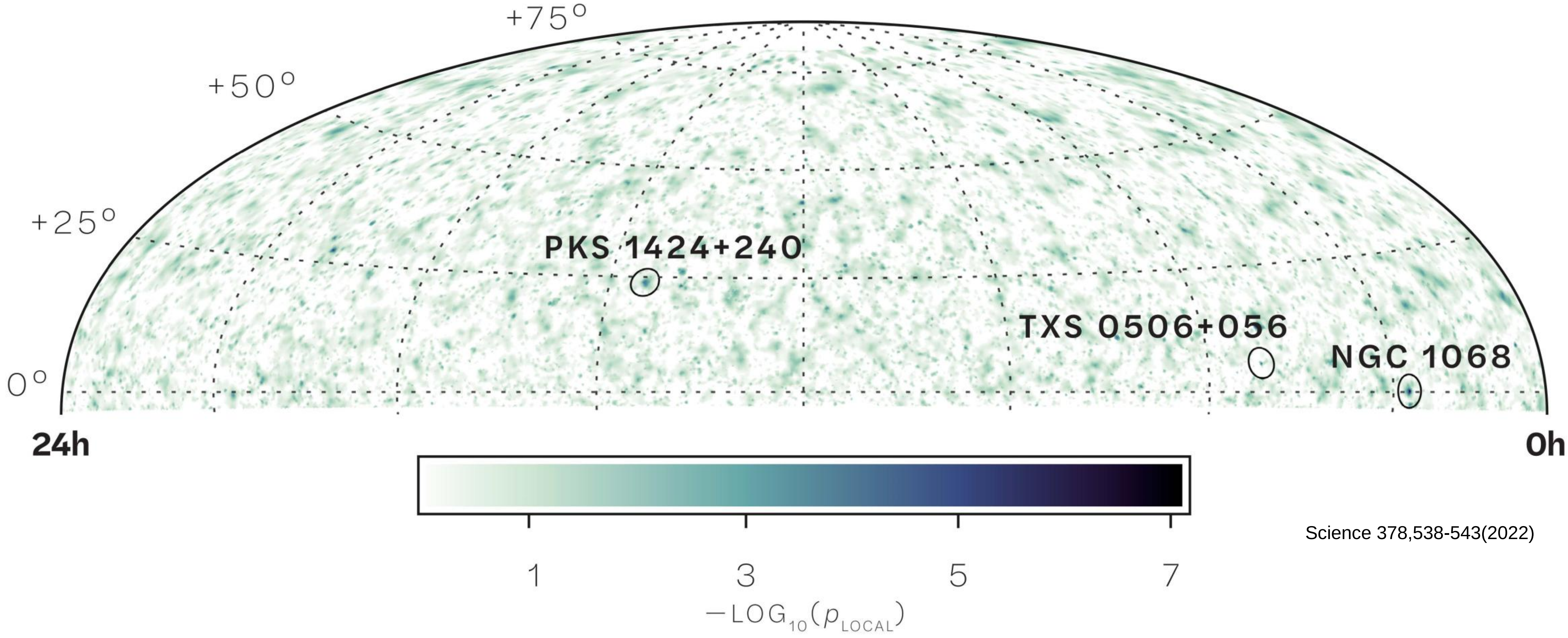
Credit: Mirco Huennefeld

4.5σ exclusion of pure isotropic hypothesis
6-13% of the total diffuse neutrino flux

Not yet enough statistical power to distinguish models or unresolved sources

The Muon-Neutrino Sky

Searching for clustering and deviation from atmospheric ν spectrum at every point in the sky



Science 378,538-543(2022)

The Muon-Neutrino Sky

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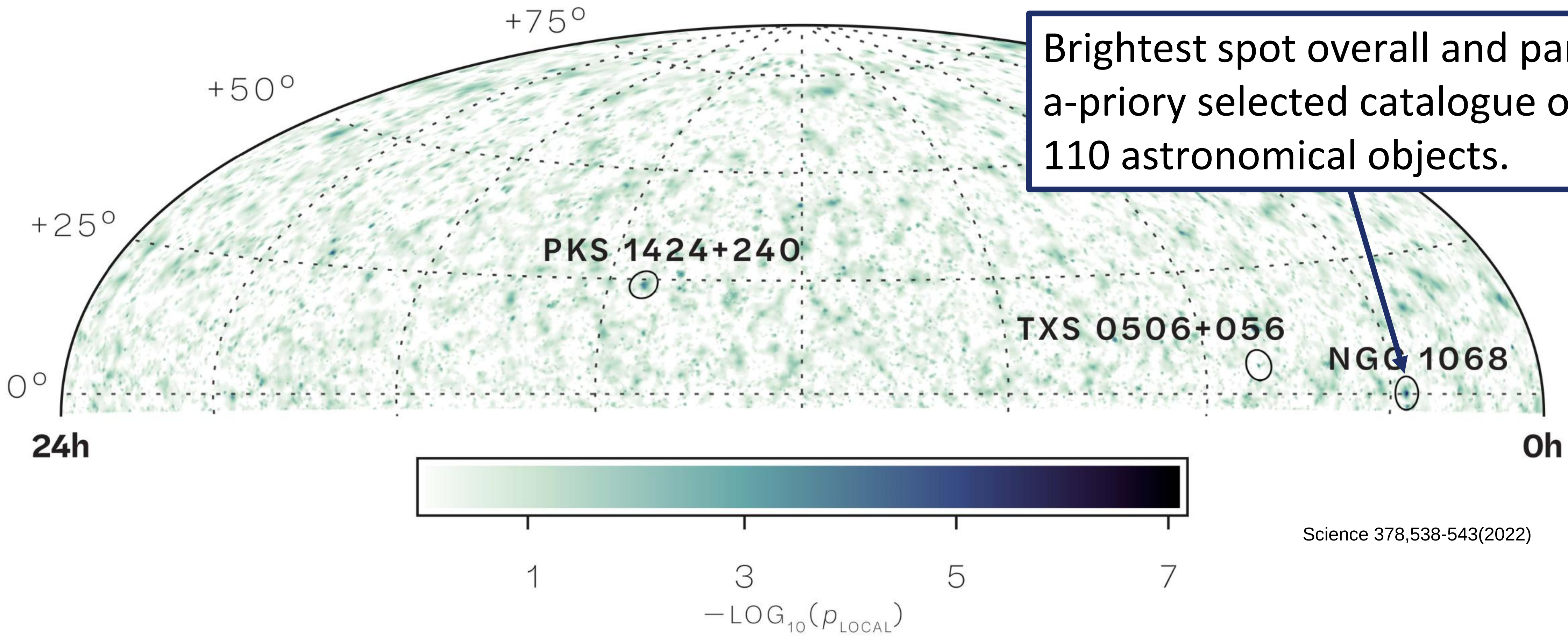


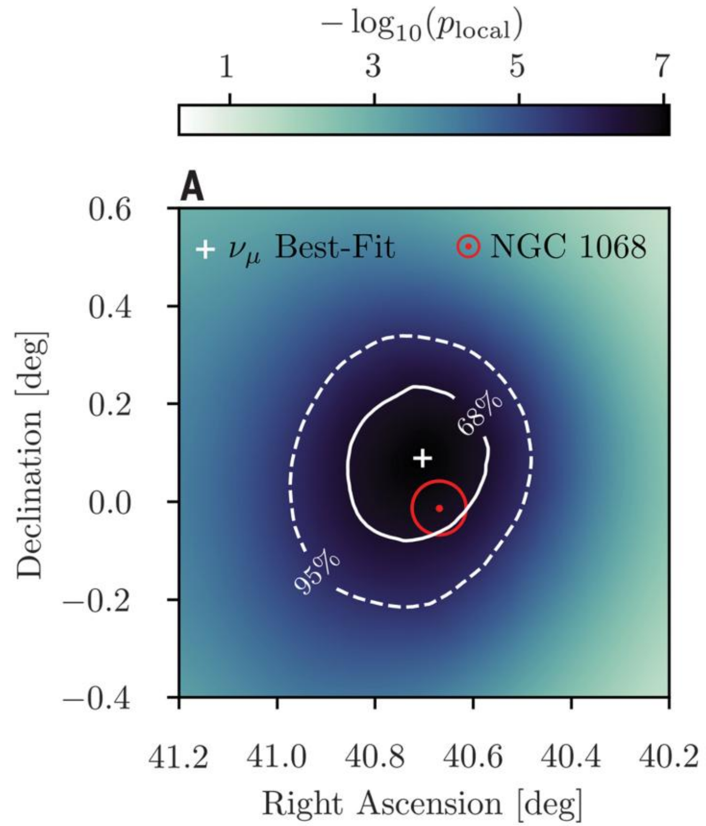
Brightest spot overall and part of a-priory selected catalogue of 110 astronomical objects.

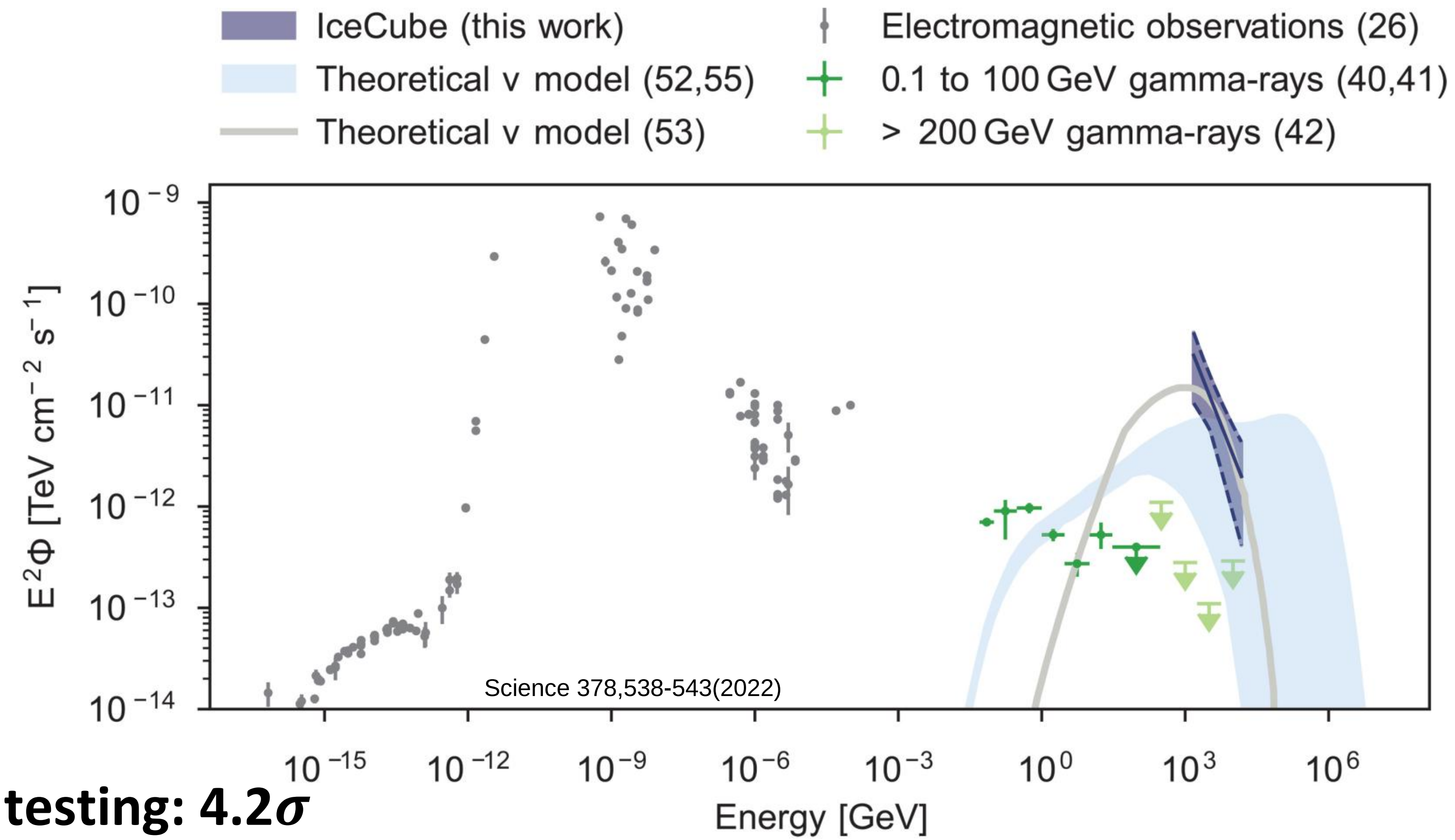
Science 378,538-543(2022)

NGC1068

- ❑ Type II Seyfert Galaxy
- ❑ d=14.4Mpc
- ❑ Compton-thick AGN
- ❑ Intrinsic X-ray photons in corona can provide target for ν production

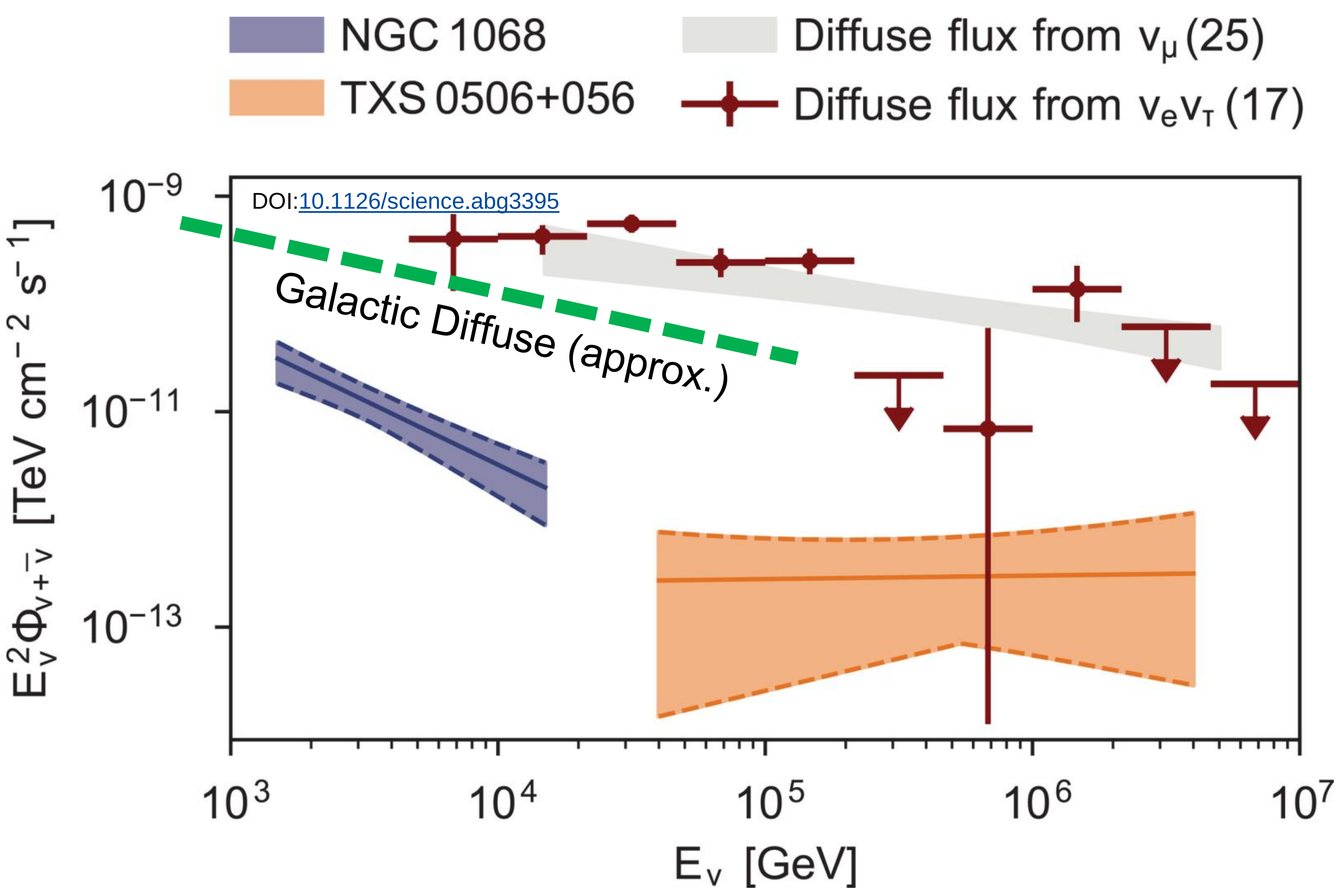
Neutrino Emission from NGC1068



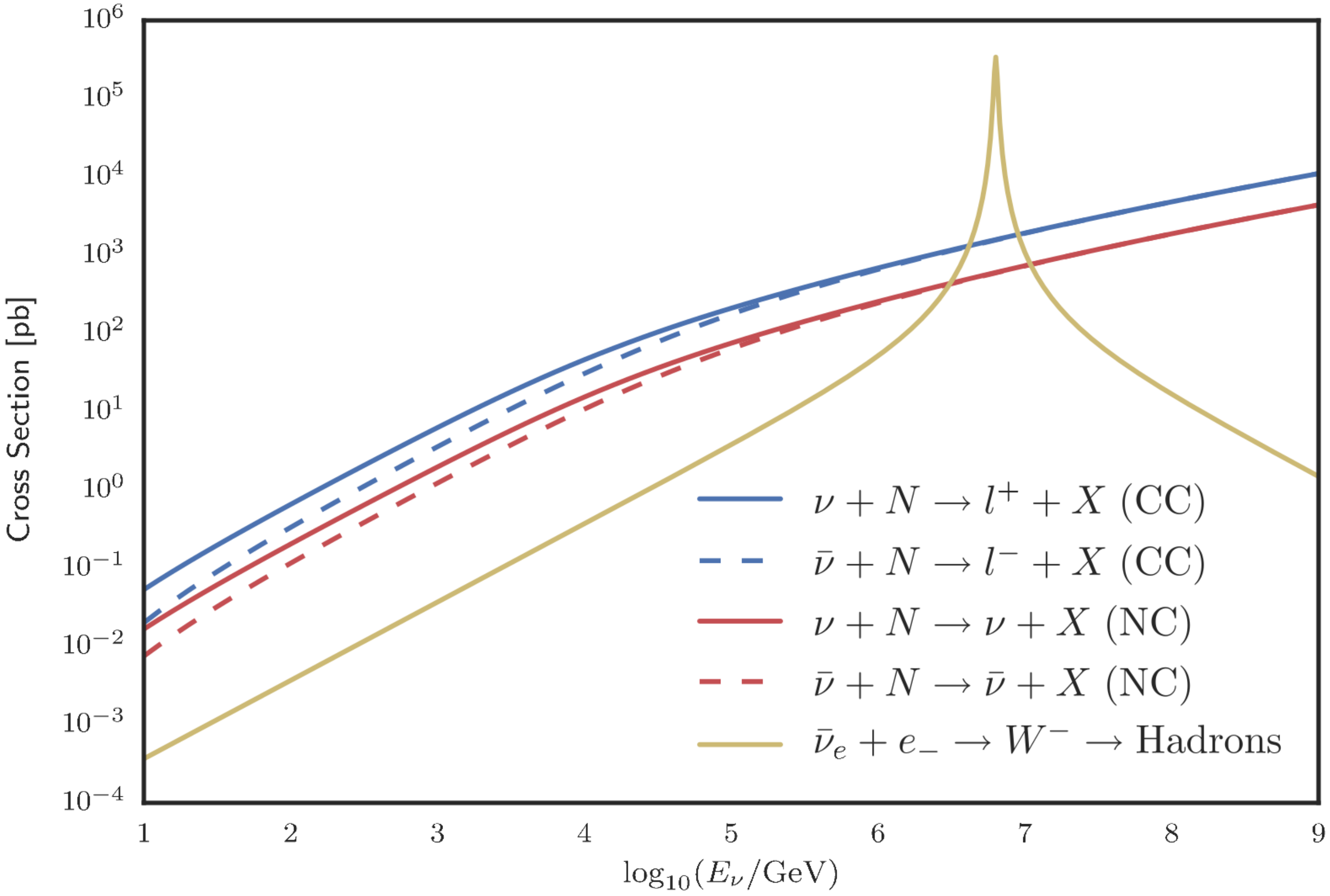


After correction for multiple testing: 4.2σ

Neutrino Fluxes



The Glashow Resonance

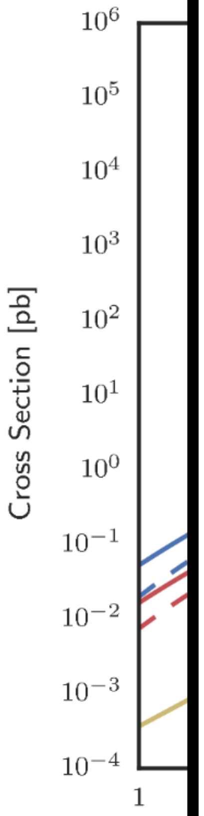


- Resonant W^--production in $\bar{\nu}_e - \mathrm{e}^-$ interactions at 6.3 PeV neutrino energy (electron at rest)

$$\bar{\nu}_e + e^- \to W^- \to \begin{cases} \text{Hadrons (67\%)} \\ \text{Leptons (33\%)} \end{cases}$$

- x200 increase over DIS in $\bar{\nu}_e$ cross section
- So far not observed experimentally, despite being fundamental Standard Model process
- Allows (statistical) measurement of $\frac{\bar{\nu}_e}{\nu_e}$ ratio (1:1 for pp, 4:14 for pγ)

The Glashow Resonance



Cosmic neutrino and the possibility of searching for *W* bosons with masses 30–100 GeV in underwater experiments

V. S. Berezinskiĭ and A. Z. Gazizov

Institute of Nuclear Reseach, USSR Academy of Sciences

(Submitted February 3, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 5, 276–278 (5 March 1977)

The possibility is discussed for searching for *W* bosons in underwater experiments with the aid of the resonant reaction $\bar{\nu}_e + e^- \to W^- \to$ hadrons. The resonance production of *W* bosons manifests itself as a narrow peak in the energy spectrum of the underwater nuclear-electromagnetic cascades. For *W*-boson masses 30–100 GeV (resonant antineutrino energies $9\times10^{14} - 1\times10^{16}$ eV) the resonant effect should exceed by more than one order of magnitude the background due to the nonresonant neutrino events.

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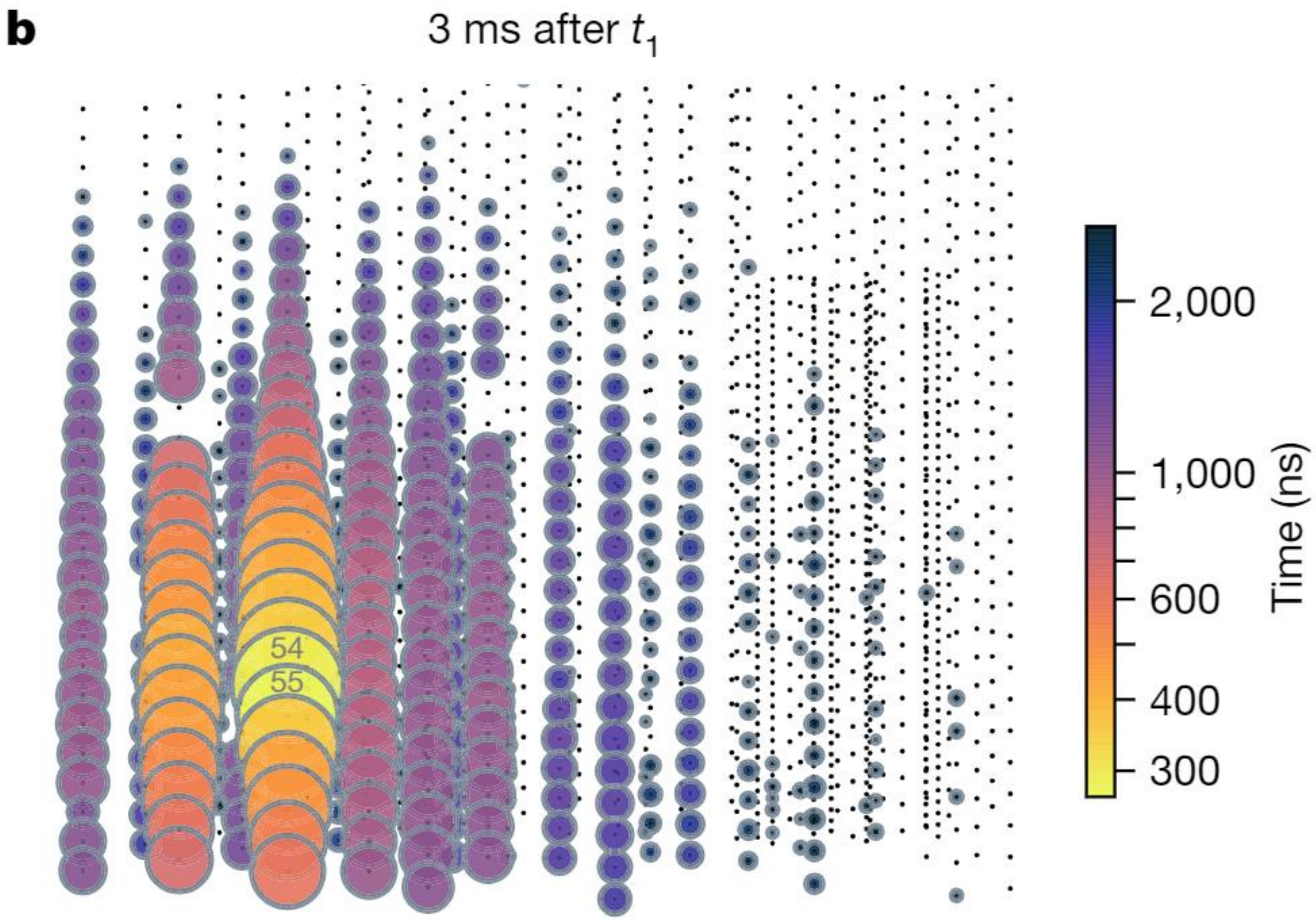
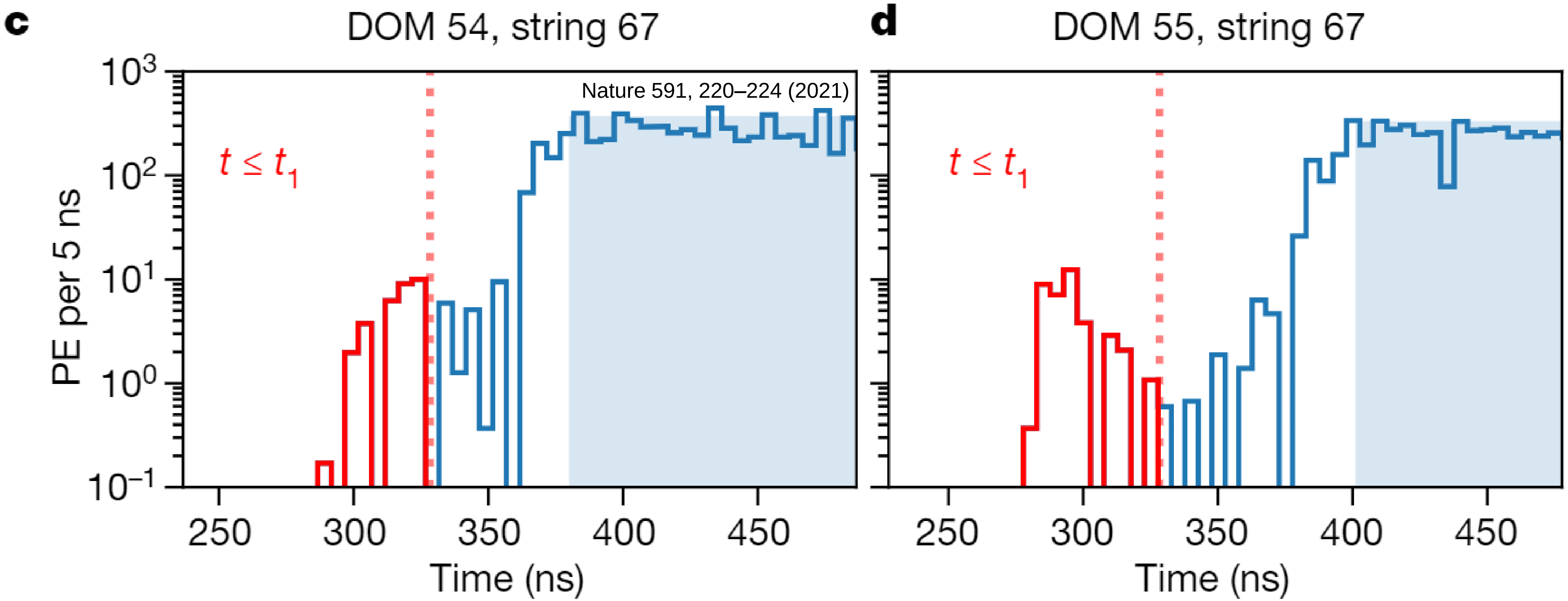
A Particle Cascade at 6PeV



Nature 591, 220–224 (2021)

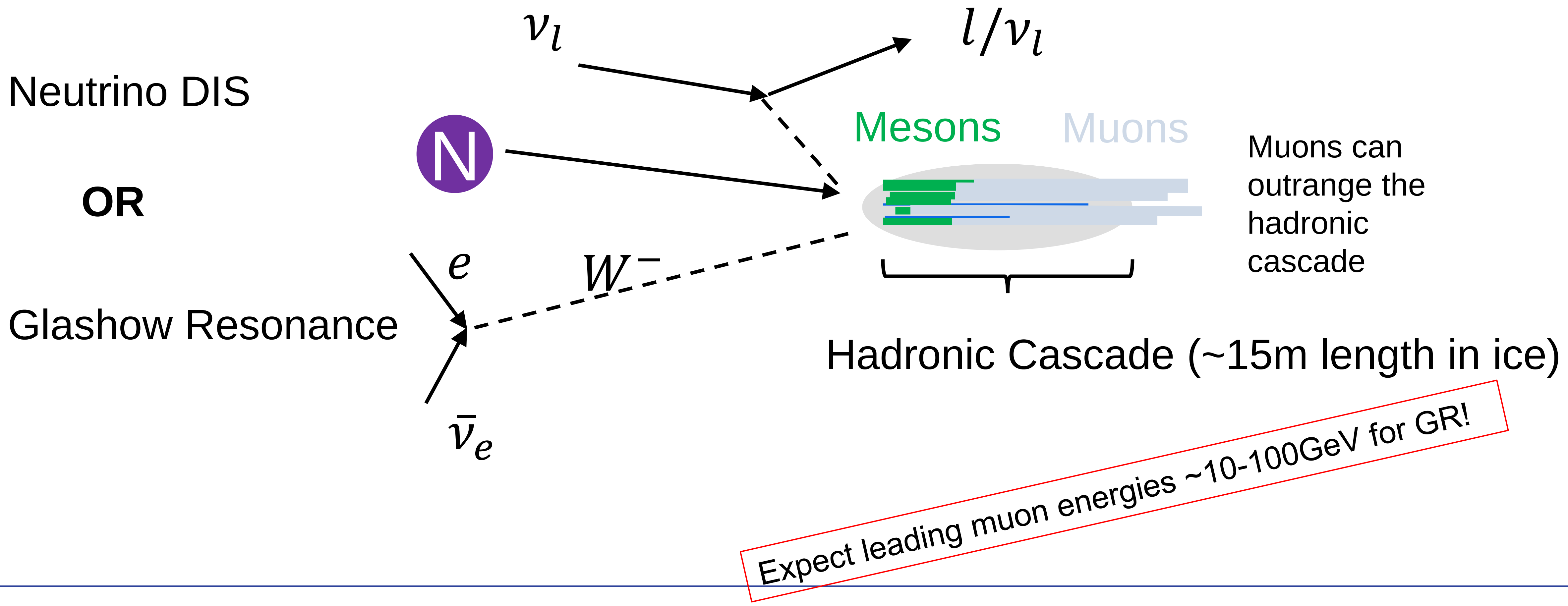
Early Pulses



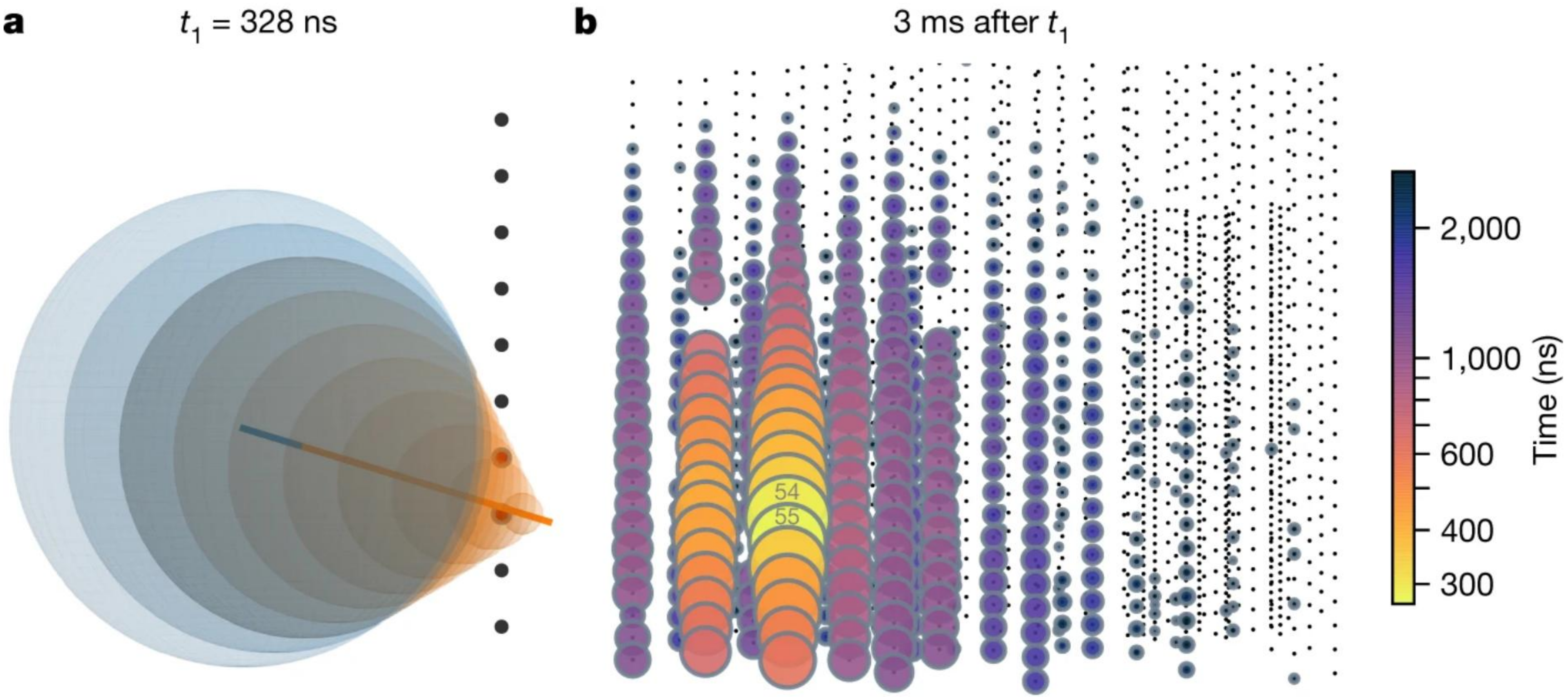
Could it be prepulses? -> No!

Careful analysis rules out PMT prepulses (timing & charge doesn‘t match PMT prepulse characteristics)

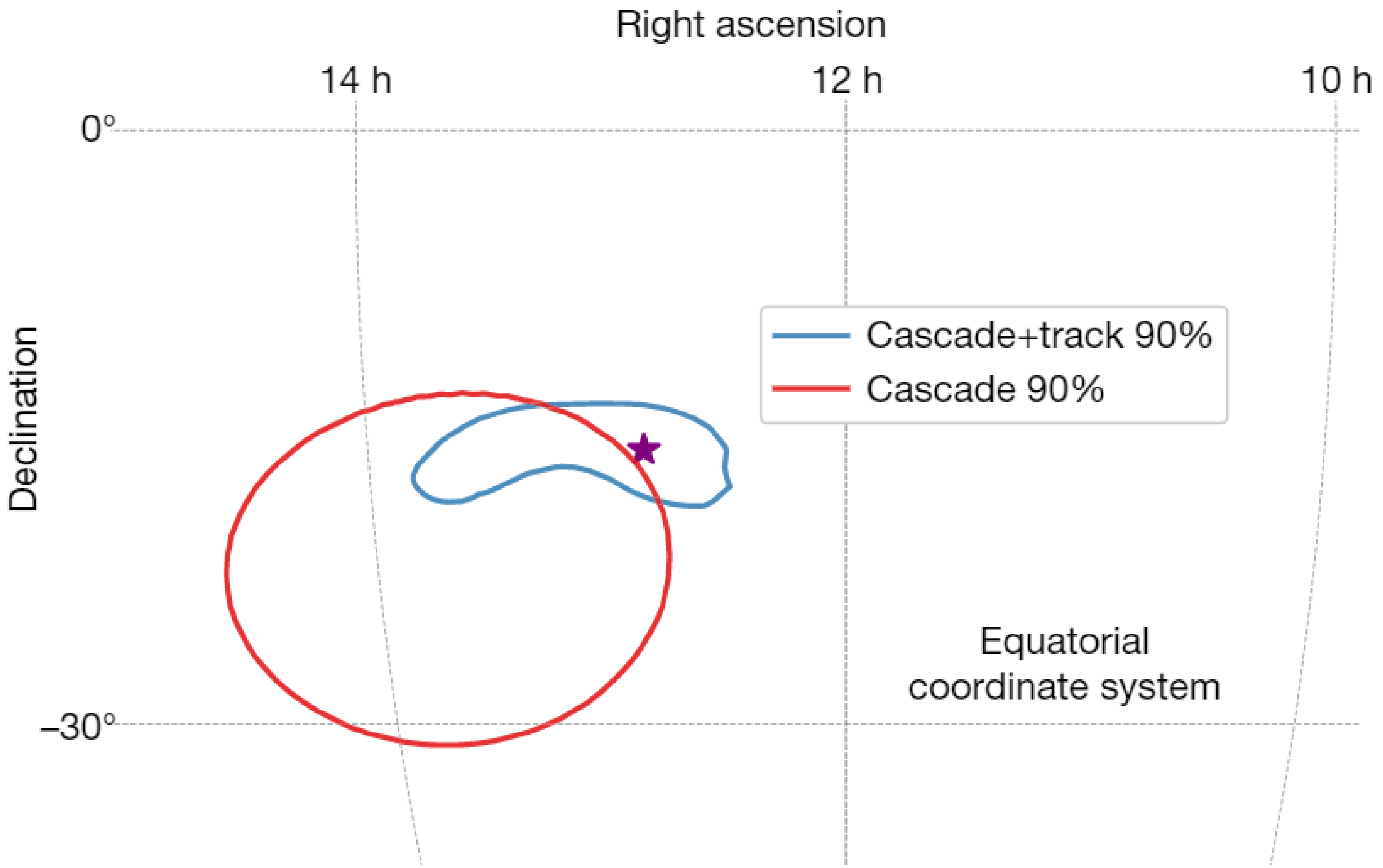
Muon Production in Hadronic Cascades



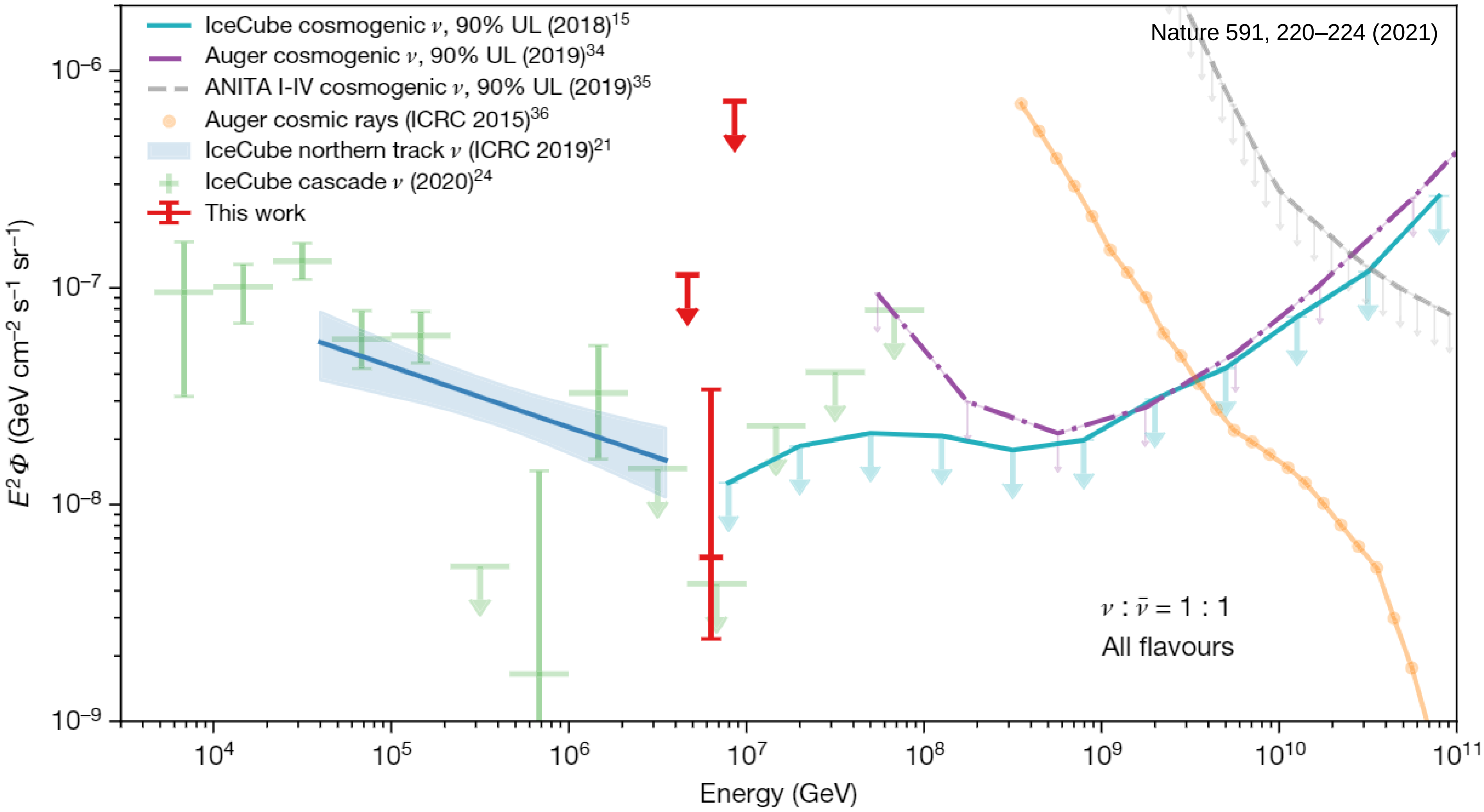
Early Pulses from Muonic Component



Independent Reconstruction of Muonic and Hadronic Component



The Astrophysical Neutrino Spectrum

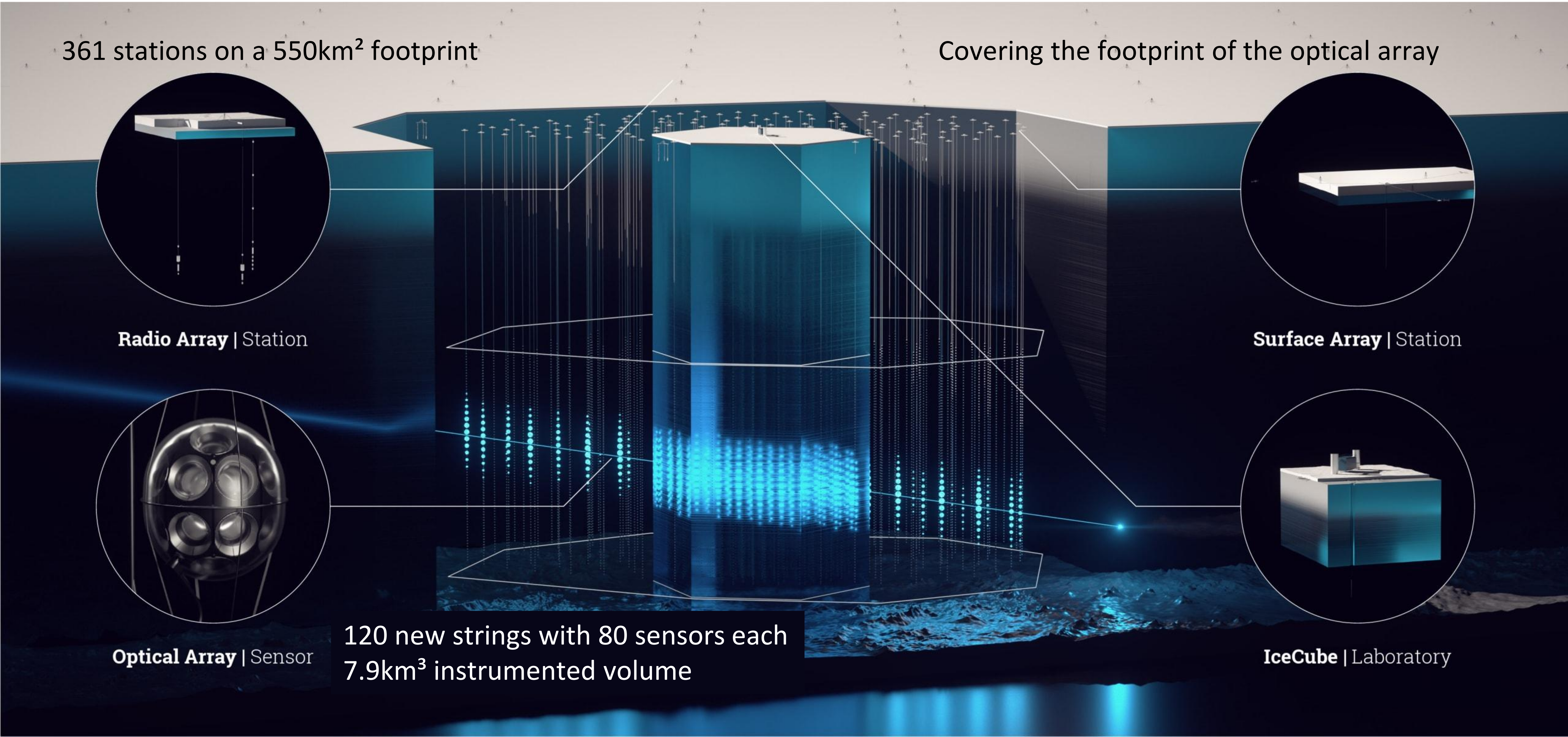


Open Questions

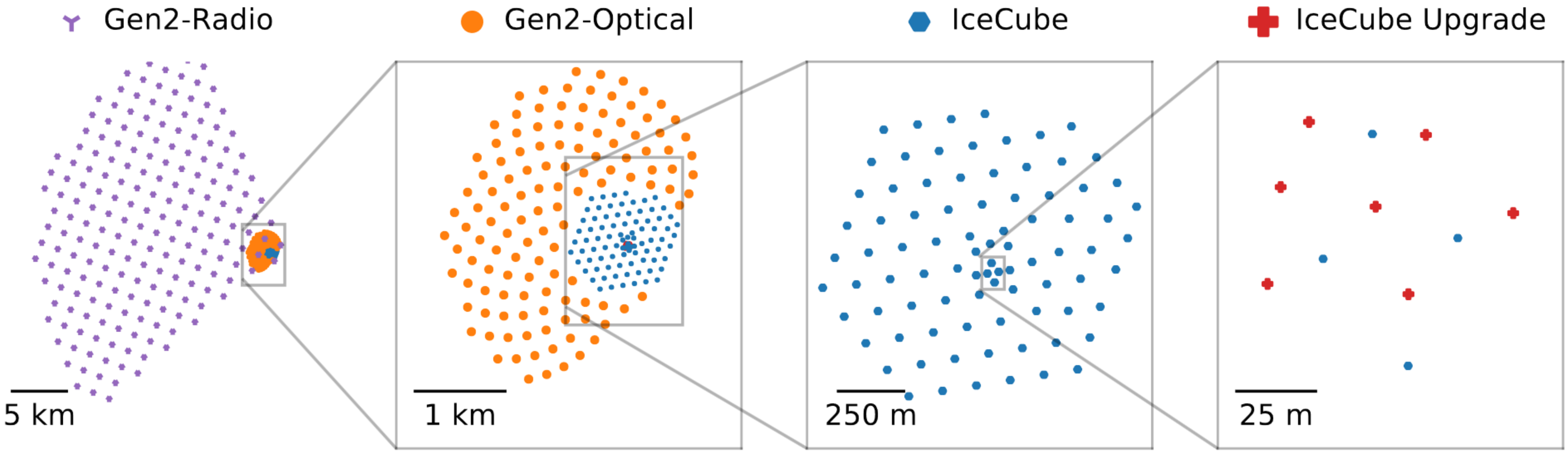
- Are TXS056+056 and NGC1068 just the brightest sources of an entire population of similar sources? Or are they special in another way?
- Are there other source populations?
- How does CR acceleration work in these sources?
- Do we see diffuse emission from the Galactic plane or unresolves sources?

We need more telescopes!

IceCube-Gen2 Neutrino Observatory

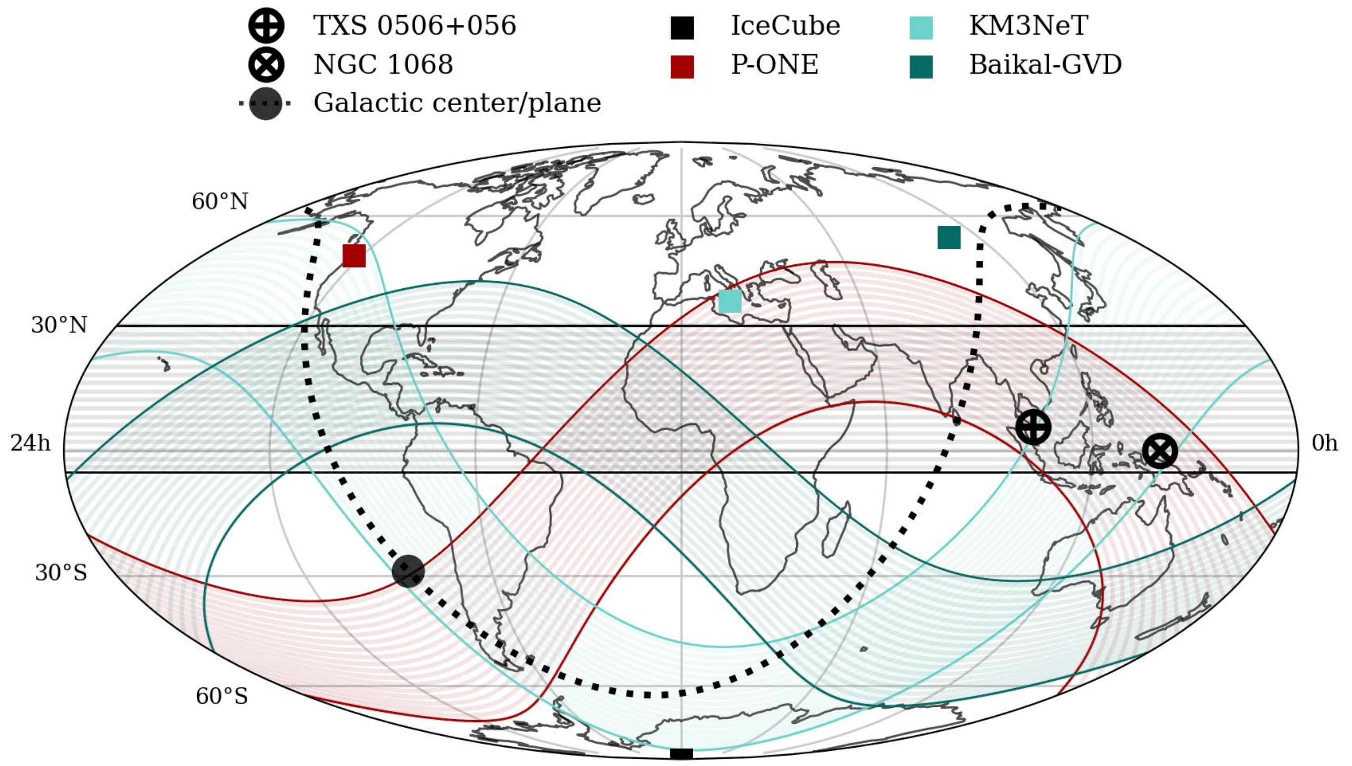


IceCube-Gen2

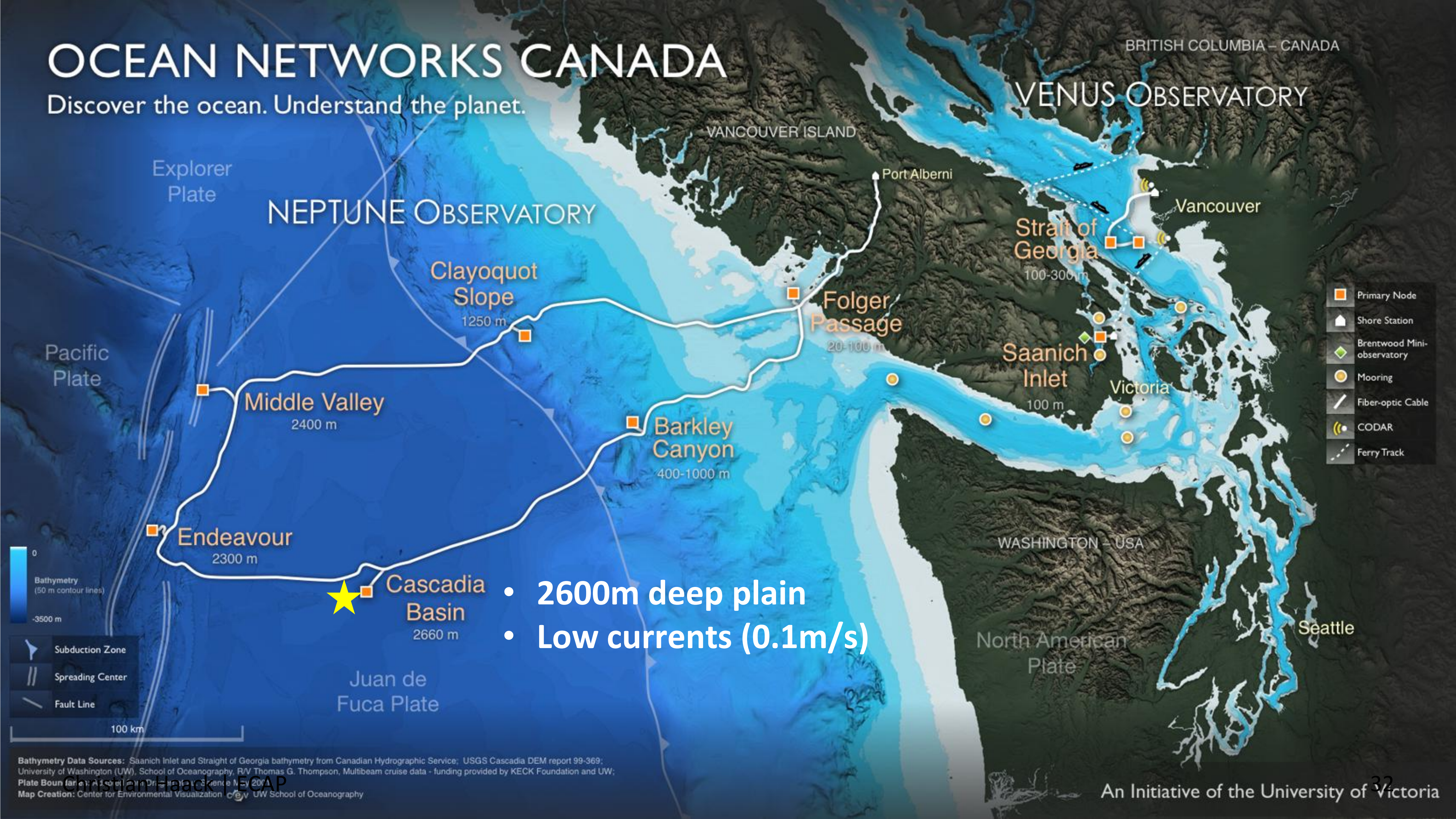


> 30 PeV **> 3 TeV** **> 0.1 TeV** **> GeV**

Telescope Complementarity



Lisa Schumacher

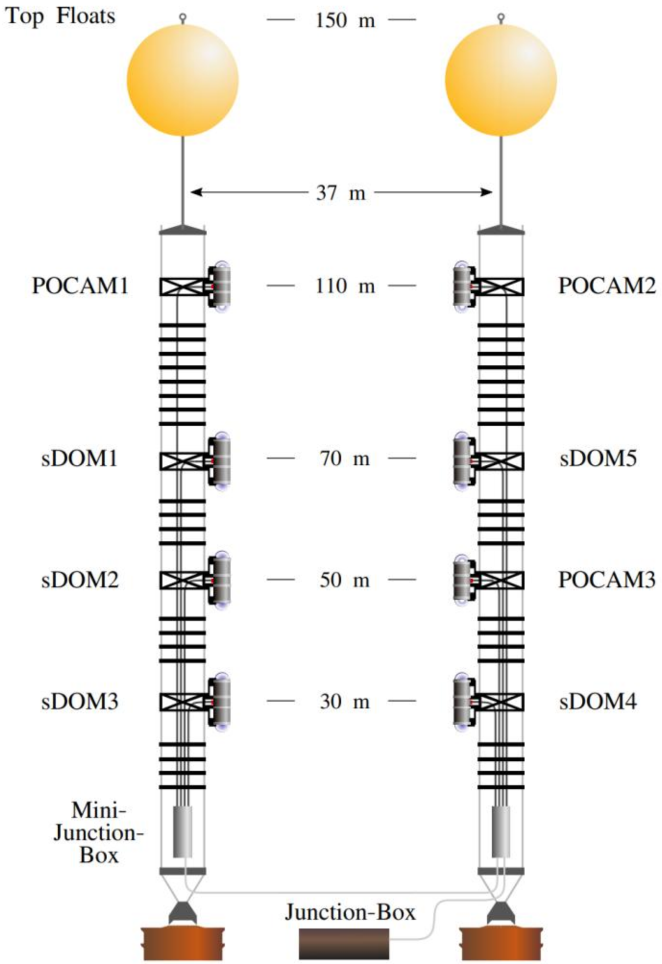


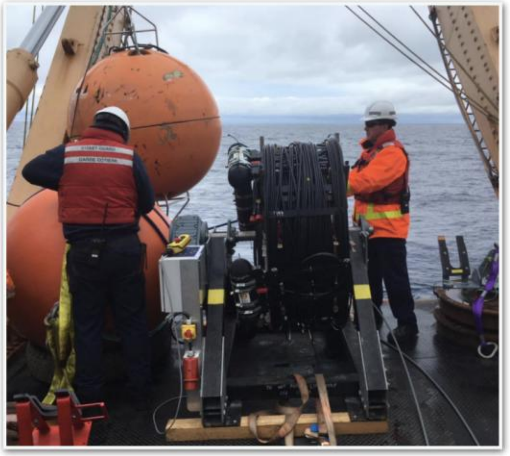
- 2600m deep plain
- Low currents (0.1m/s)

The P-ONE Collaboration

P-ONE Collaboration Meeting, Krakow 2023

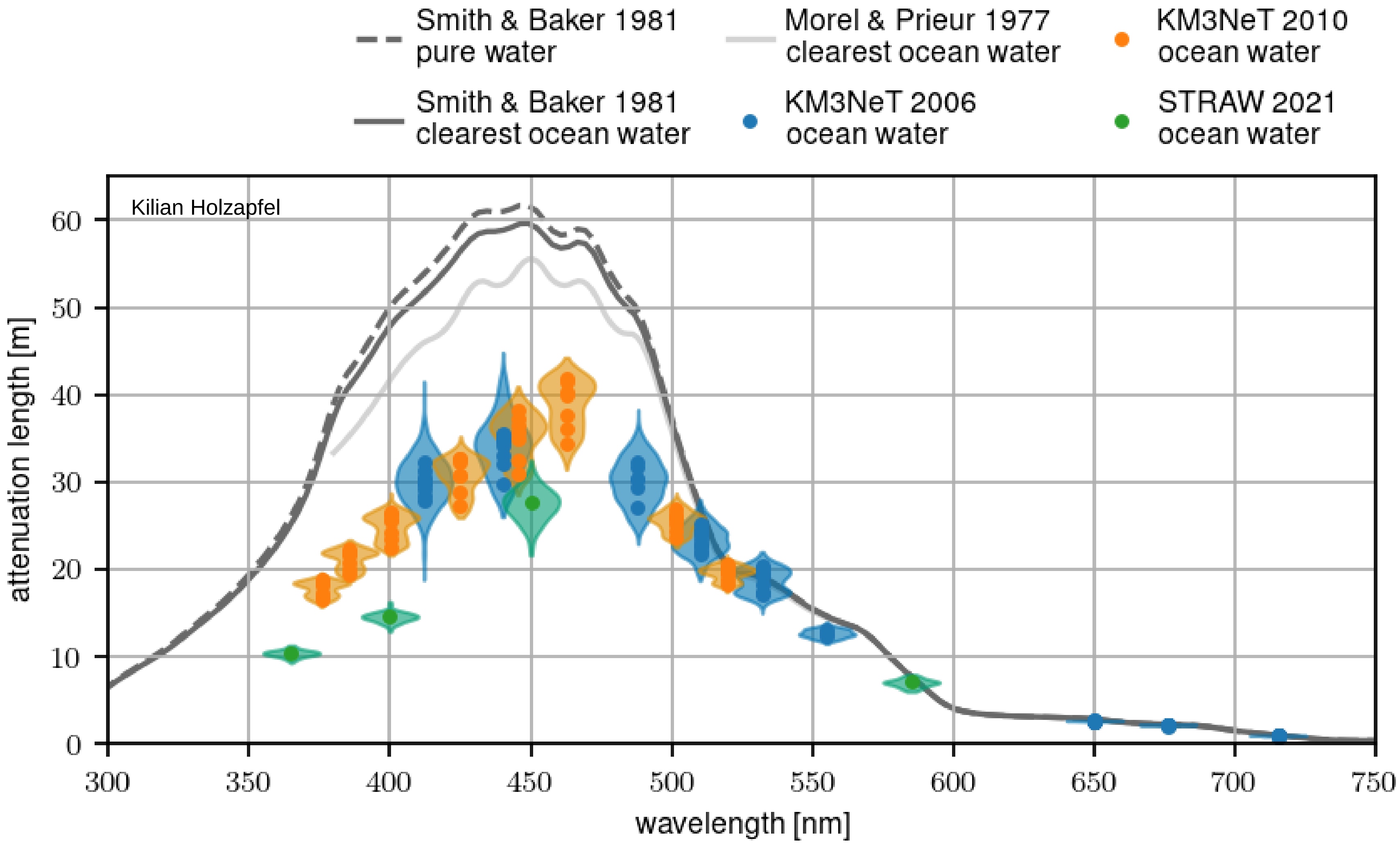
Precursor Experiment: STRAW
(STRings for Absorption length in Water)





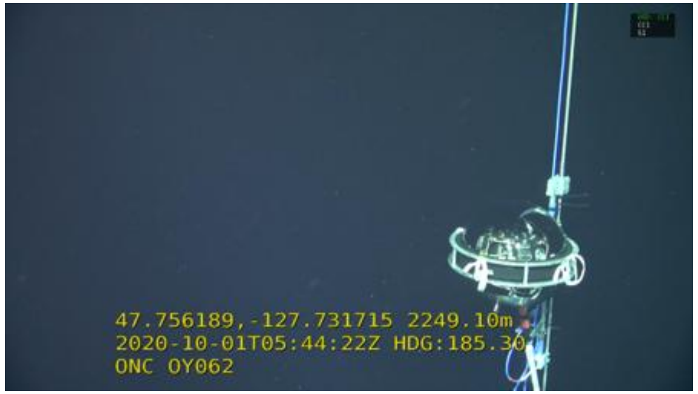
Deployed 2018

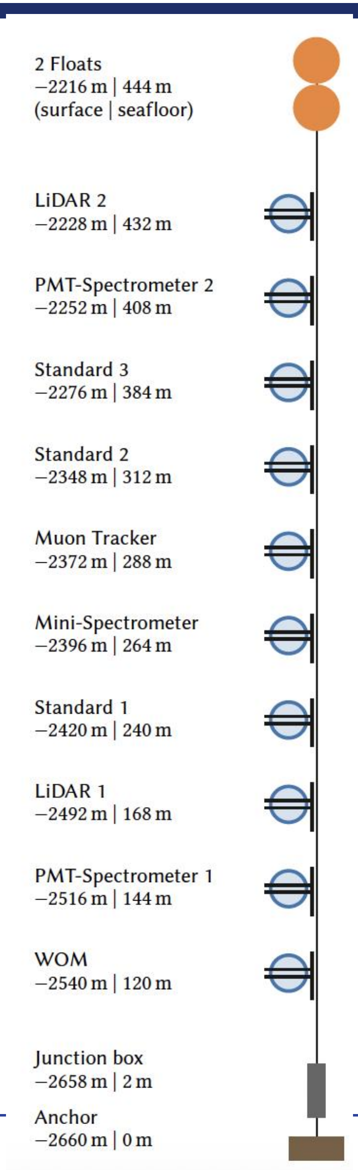
Optical Properties



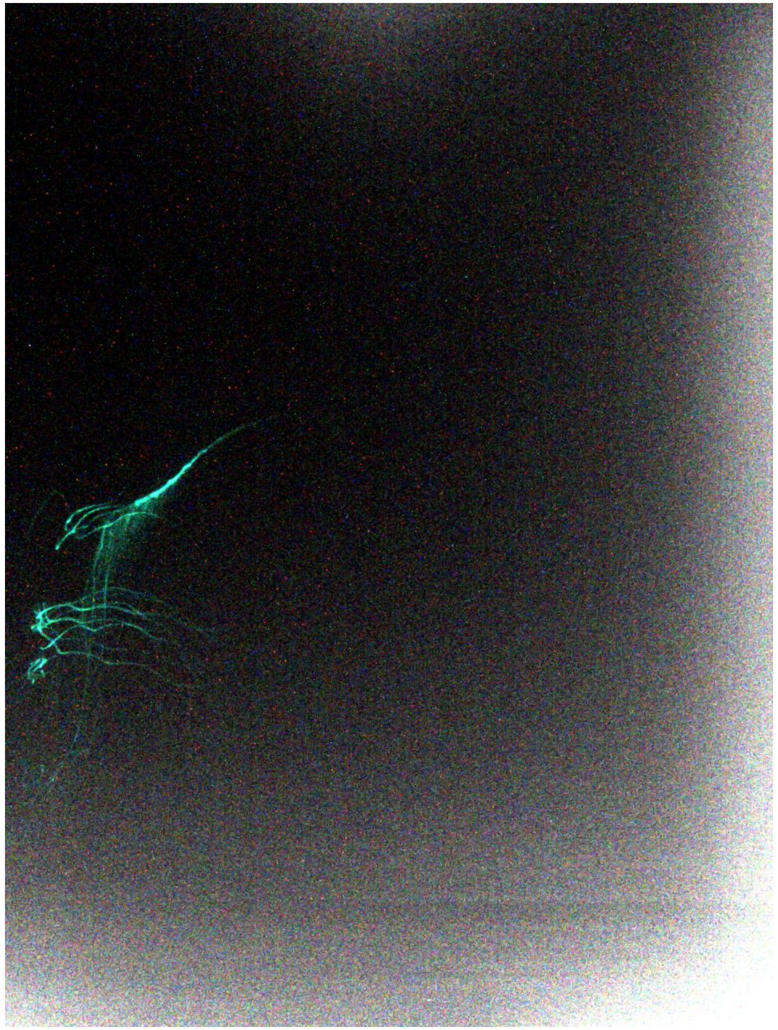
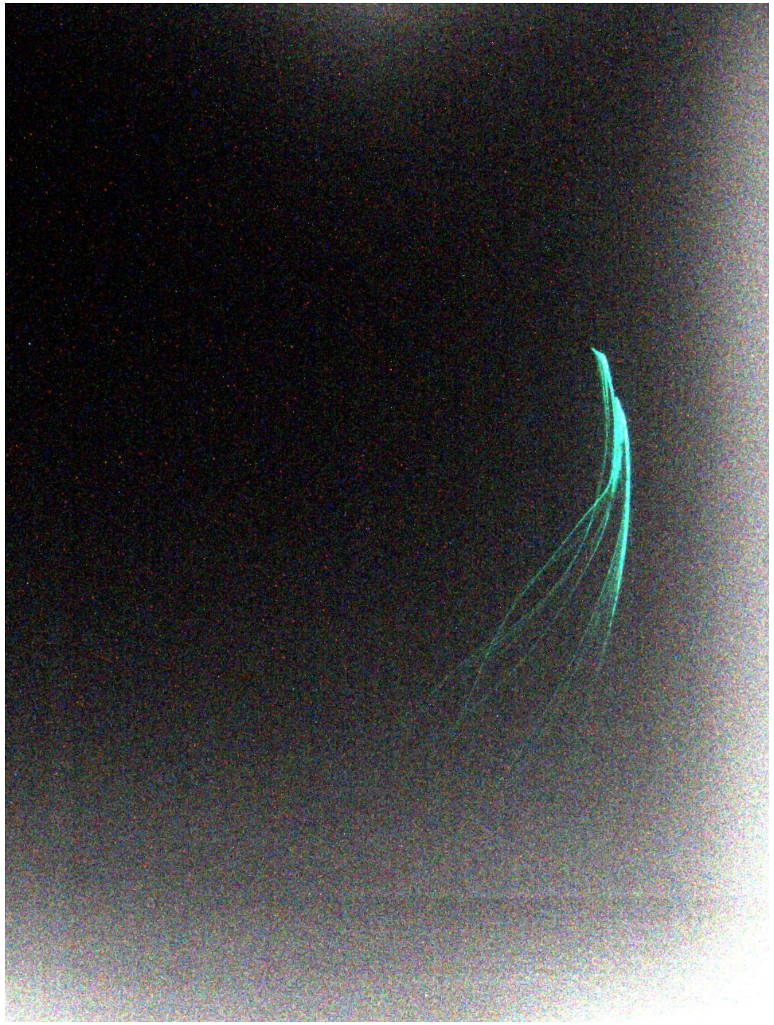
Second Precursor: STRAW-B

Camera



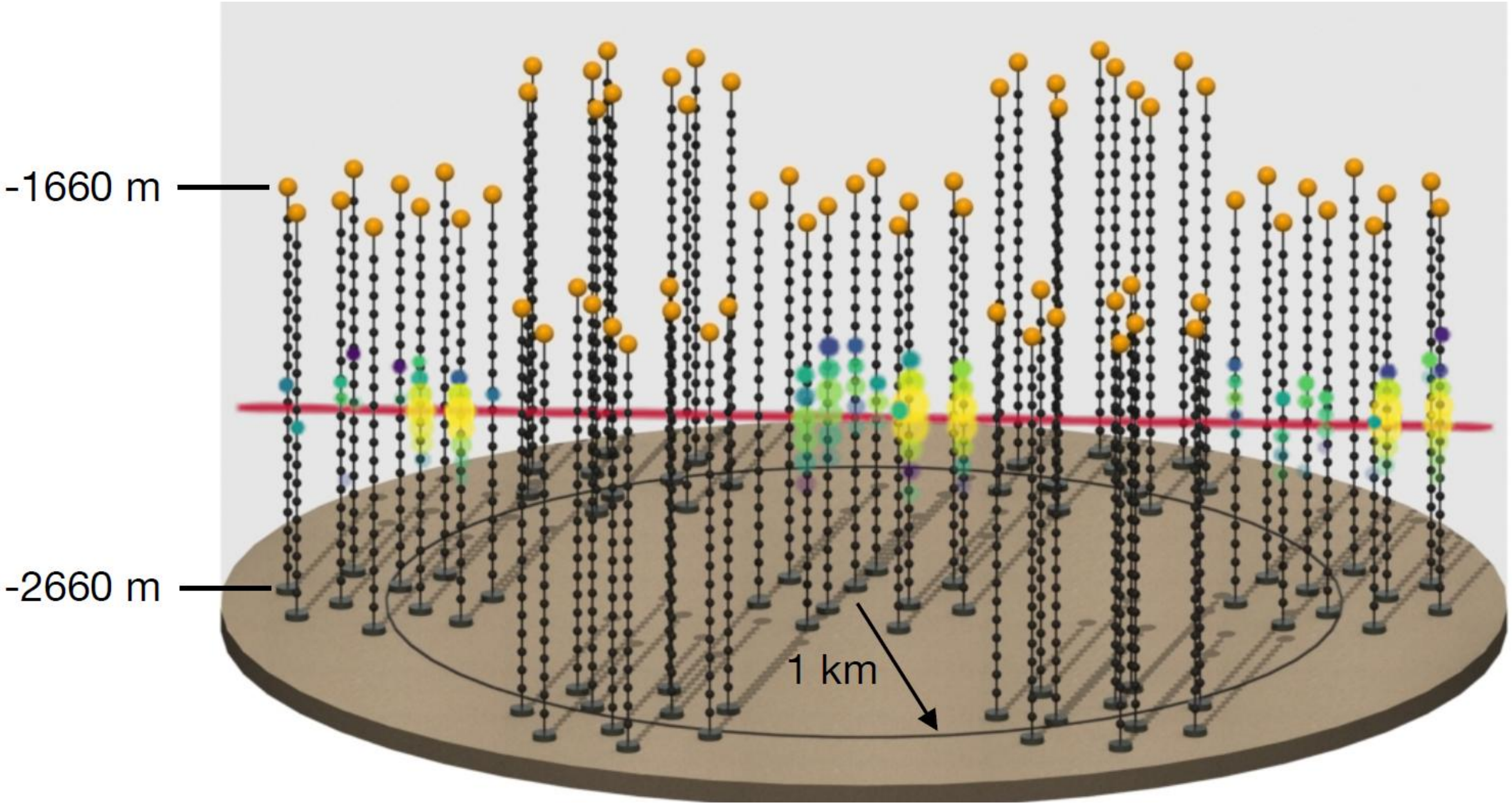


P-ONE Background

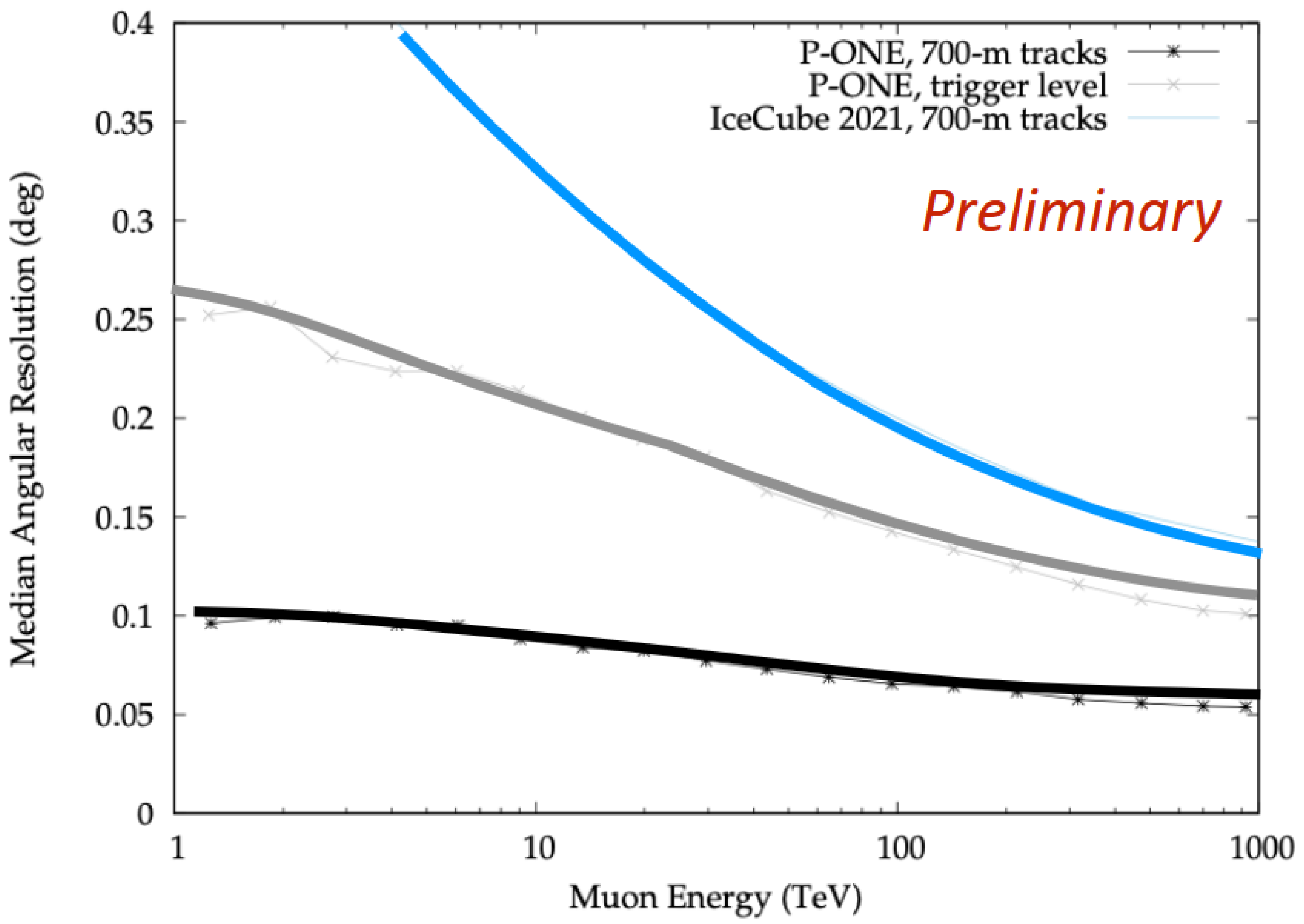




The Vision Of P-ONE

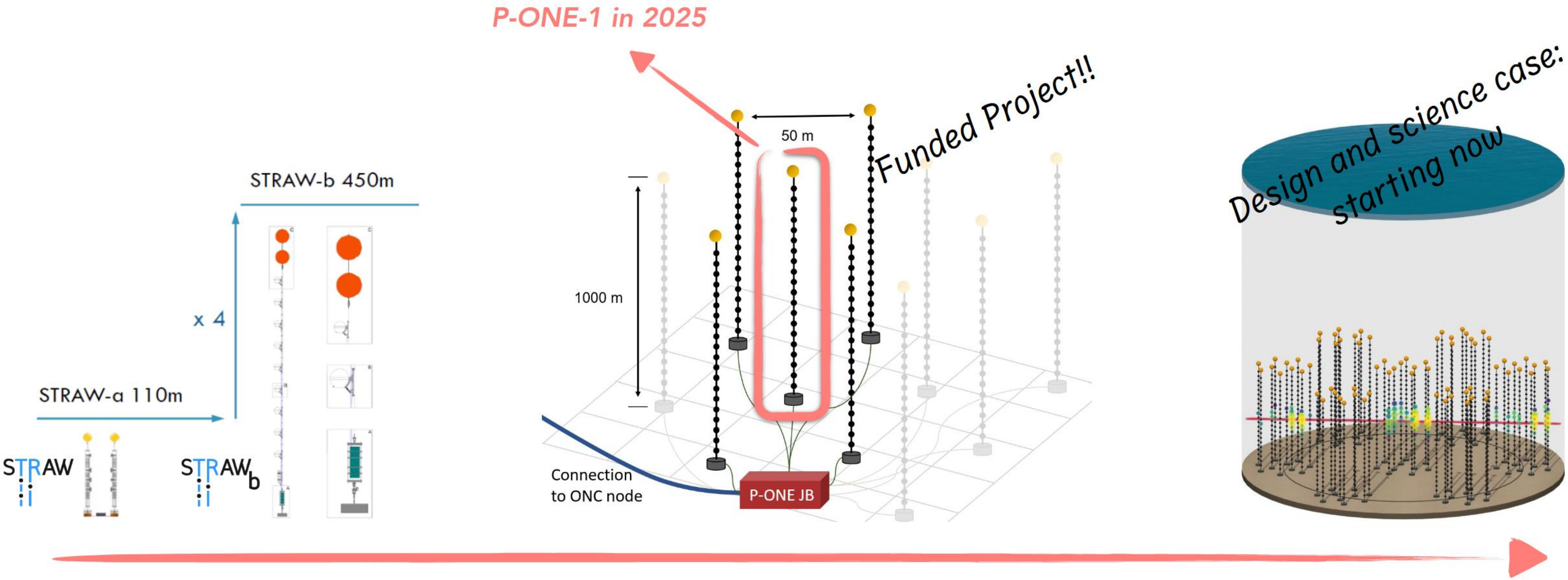
Multi-km^3 detector integrated into ONC infrastructure



P-ONE: Aiming for Precision



P-ONE — project timeline



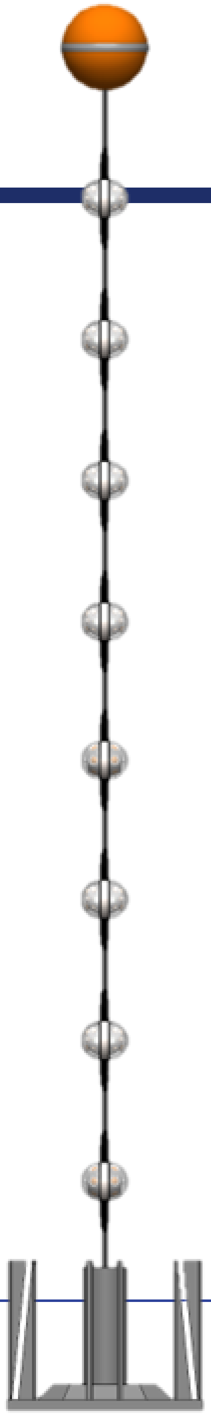
Pathfinder
Phase 1 (2018–2023)

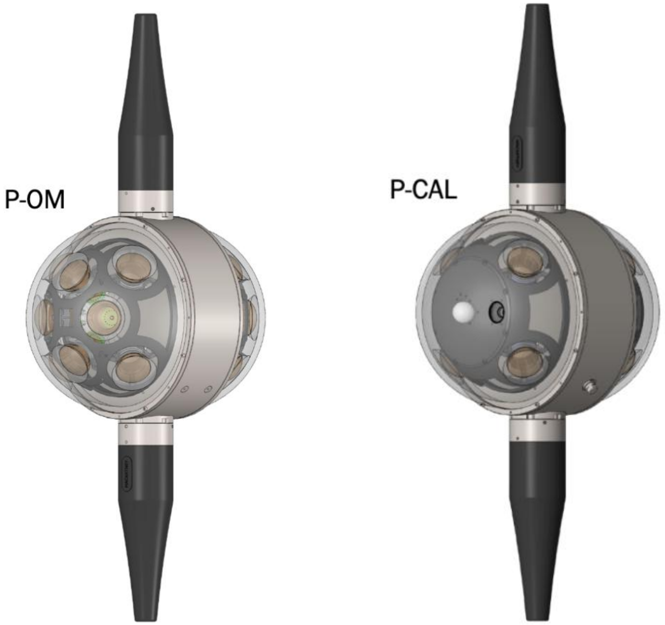
Demonstrator (7-10 lines)
Phase 2 (2023–2028)

P-ONE
Phase 3 (2028->)

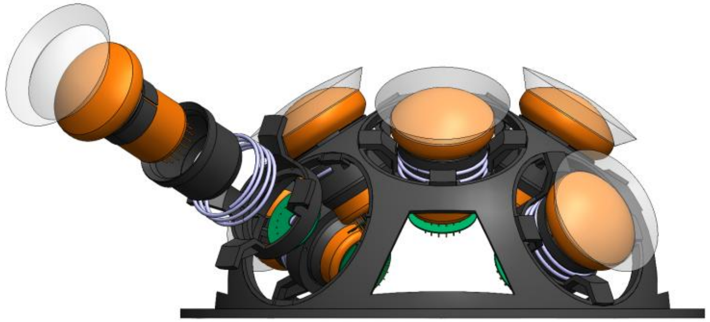
P-ONE 1

- 1km long mooring line with 20 modules
- 20 modules with 16 PMTs each.
- Onboard digitization & readout electronics
- Optical and calibration modules
- Connectorless cable design
- Sub-ns time synchronization





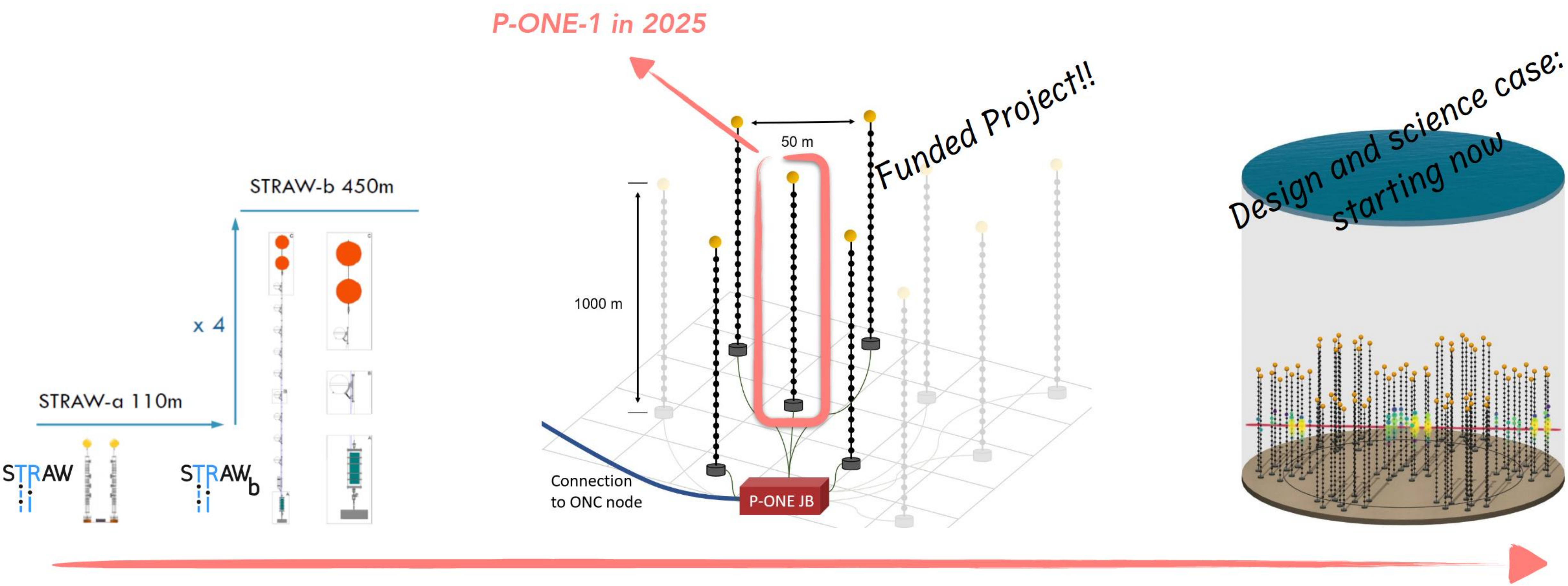
Integrated Hemisphere



- ❑ 16 Hamamatsu R14374-10 3” PMTs
- ❑ Modular, spring-loaded mounting structure
- ❑ Optical gel pads to increase light yield

- ❑ 16 channel ADC (full waveform digitization)
- ❑ 200 MHz sampling rate
- ❑ Local buffer (4GB)

P-ONE — project timeline



Pathfinder
Phase 1 (2018–2023)

Demonstrator (7-10 lines)
Phase 2 (2023–2028)

P-ONE
Phase 3 (2028->)

Summary / Outlook

- IceCube has started the era of neutrino astronomy:

  Two Neutrino Sources + Diffuse Emission from our Galaxy

- Lots of open questions to answer: More telescopes are needed
- Next Generation: KM3NeT + Baikal GVD under construction
- P-ONE aims to instrument a multi-km^3 volume in the Pacific Ocean, integrated into the Ocean Networks Canada infrastructure
- More plans are on the table: Multiple Chinese proposals + IceCube-Gen2

Backup

The Road to P-ONE

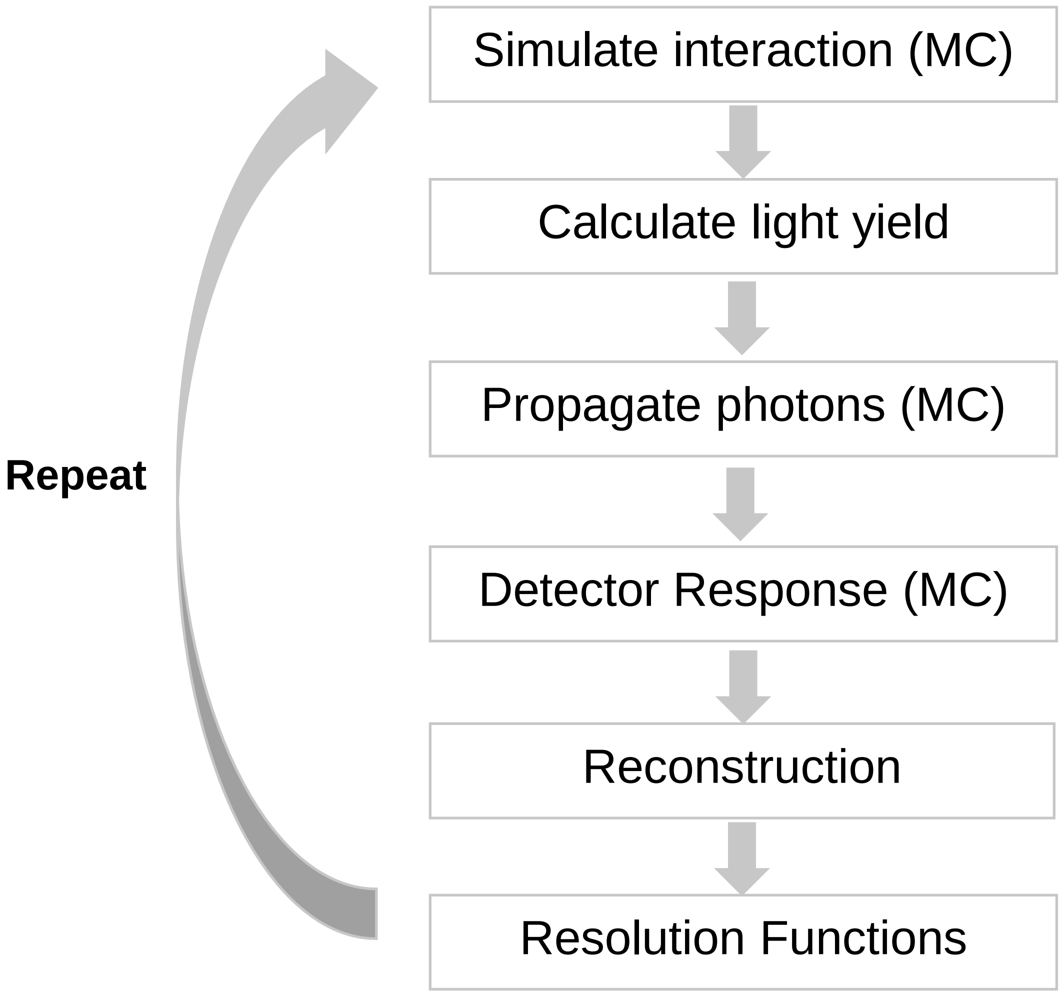
Detector Optimization

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

Optimization target: Resolution + Acceptance, Analysis Sensitivities

Optimization constraints: Cost, geometric constraints (sea-bottom cabling), …

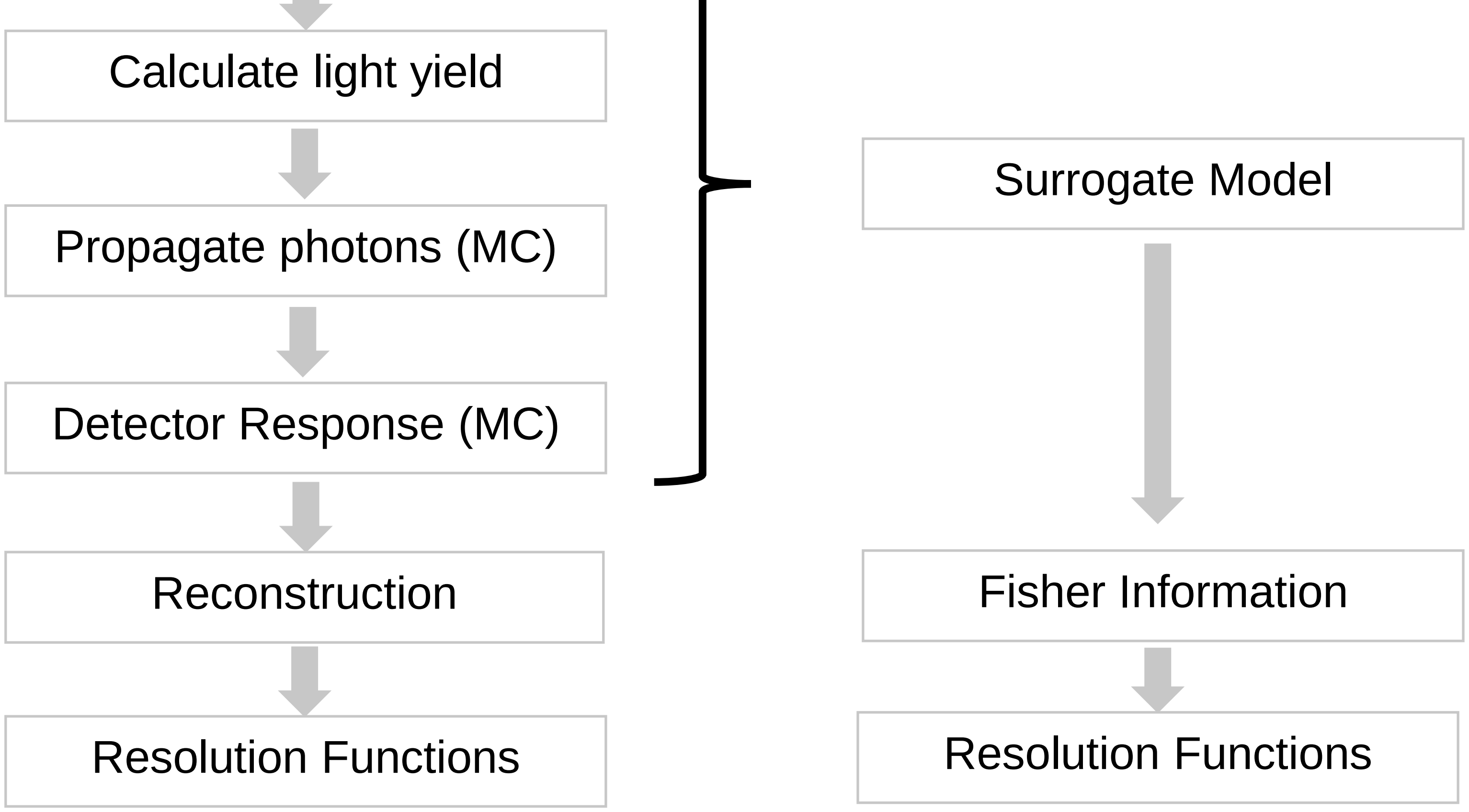
Conventional Optimization



- „Manual“ optimization.
- Discrete exploration of design parameter space
- Expensive MC campaigns

ML-Aided Optimization

Goal: $\frac{\partial \text{Analysis}}{\partial \text{Detector}}$

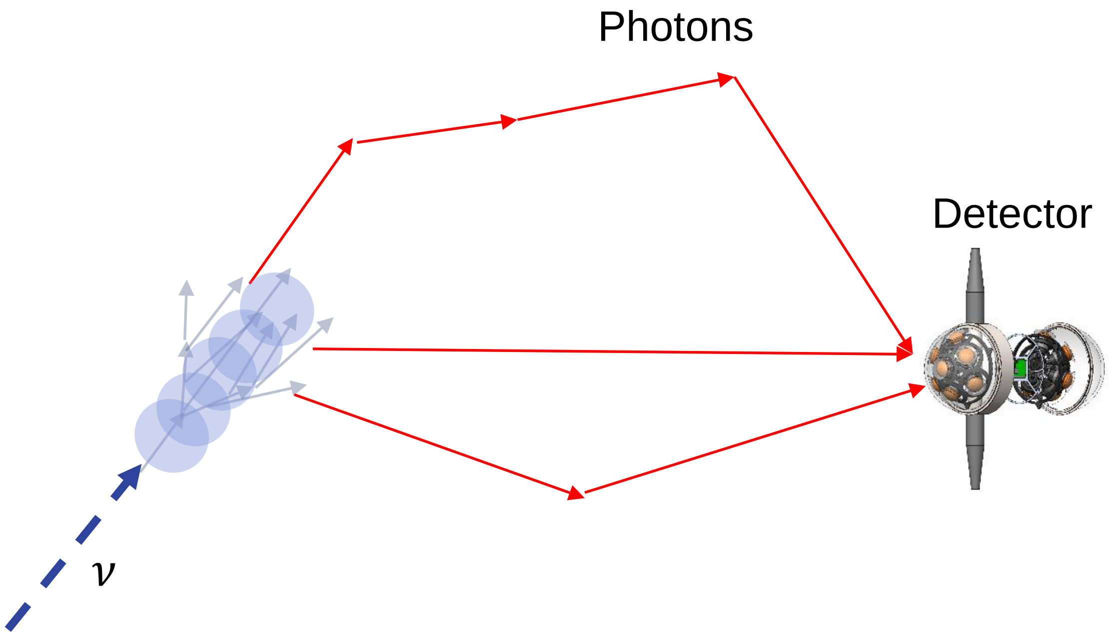


One (large) MC campaign to train model.

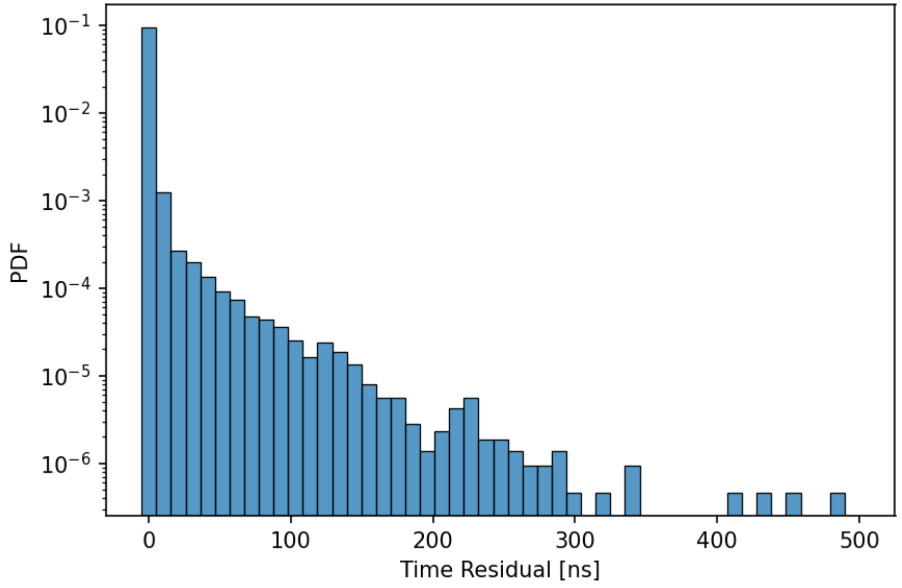
Exploration of parameter space is cheap.

No reconstruction algorithms needed

Surrogate Model



Our PMTs see this:



Relative photon arrival time

Arrival time distribution depends on:

- relative position / direction of emitter and receiver
- energy

Normalizing Flows

- Normalizing flows allow parametrization of PDFs.
  Idea: Change of variables formula.
  Start with samples x of known distribution $\pi(x)$(e.g. normal, gamma, …) and apply a function:

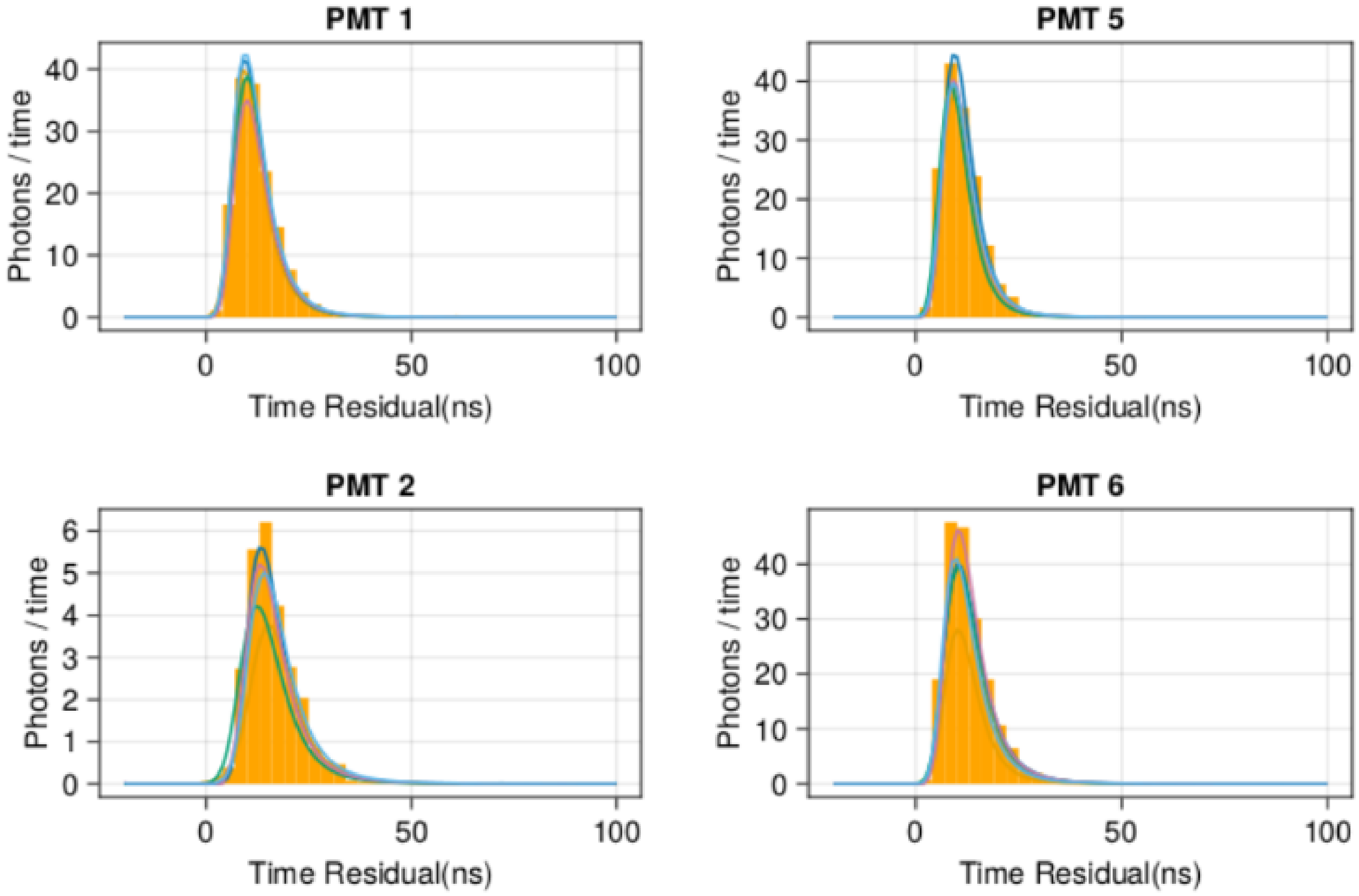
- $y = f(x),\ x \sim \pi(x)$

$$p(y) = \pi(f^{-1}(y)) \left| \det \frac{\partial f^{-1}}{\partial y} \right|$$

- $f(u)$ can be arbitrary, as long as invertible and differentiable.

Surrogate Model

Predicting the arrival time distribution for a neutrino interaction



Histogram: MC Simulation
Lines: Surrogate Model(s)

Fisher Information

Given a PDF $f(X;\theta)$ of an observable X conditioned on a parameter vector θ, the Fisher Information Matrix is:

$$[\mathcal{I}(\theta)]_{ij} = E\left[\left(\frac{\partial}{\partial\theta_i}\log f(X;\theta)\right)\left(\frac{\partial}{\partial\theta_j}\log f(X;\theta)\right)\right]$$

$$E[f(x)] \approx \frac{1}{n}\sum_{i=1}^{n} f(x_i)$$

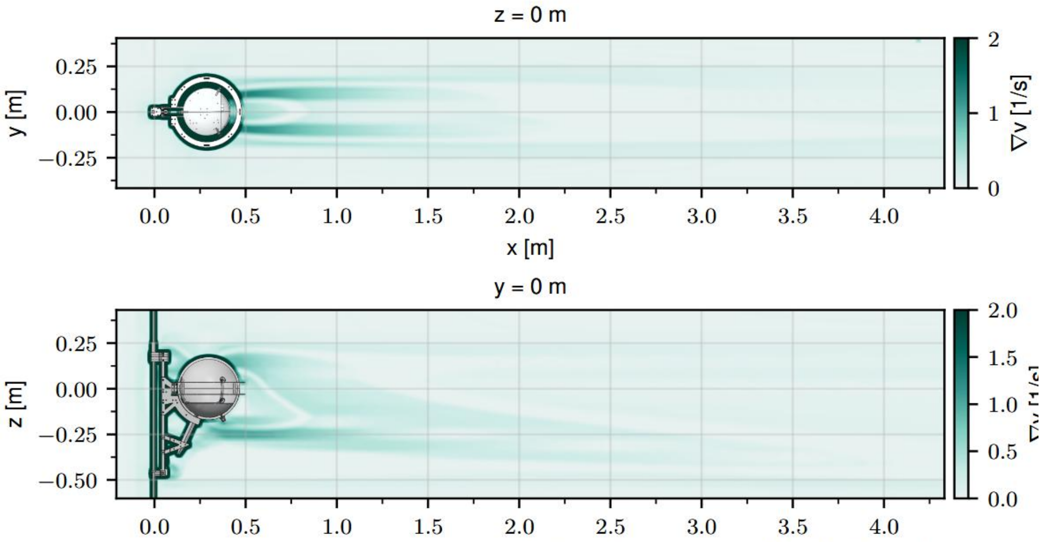
$\theta = (\text{Energy}, \text{Direction}, \text{Position}, \dots)$

$f(X;\theta)$: Surrogate Model

Cramer Rao Bound: $\text{cov}_\theta(\hat{\theta}) \geq \mathcal{I}(\theta)^{-1}$

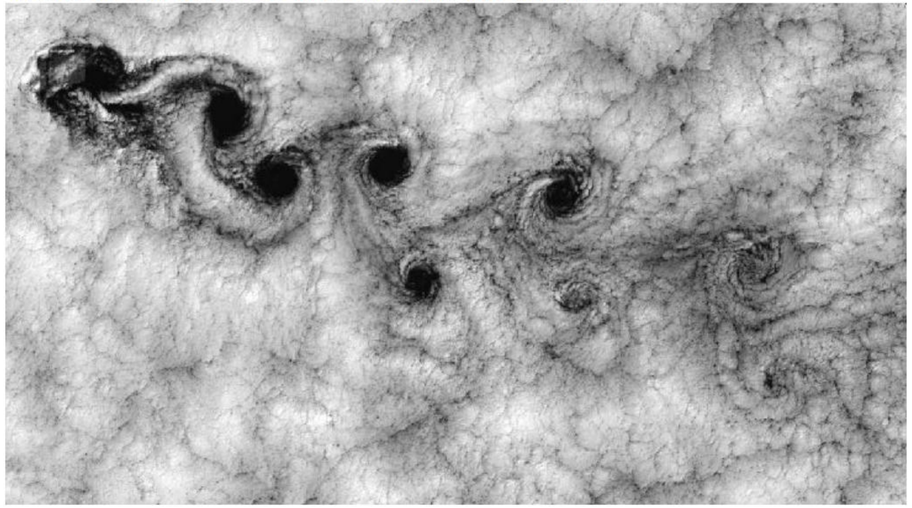
$\hat{\theta} = \textbf{Any}$ estimator of $(\text{Energy}, \text{Direction}, \text{Position}, \dots)$

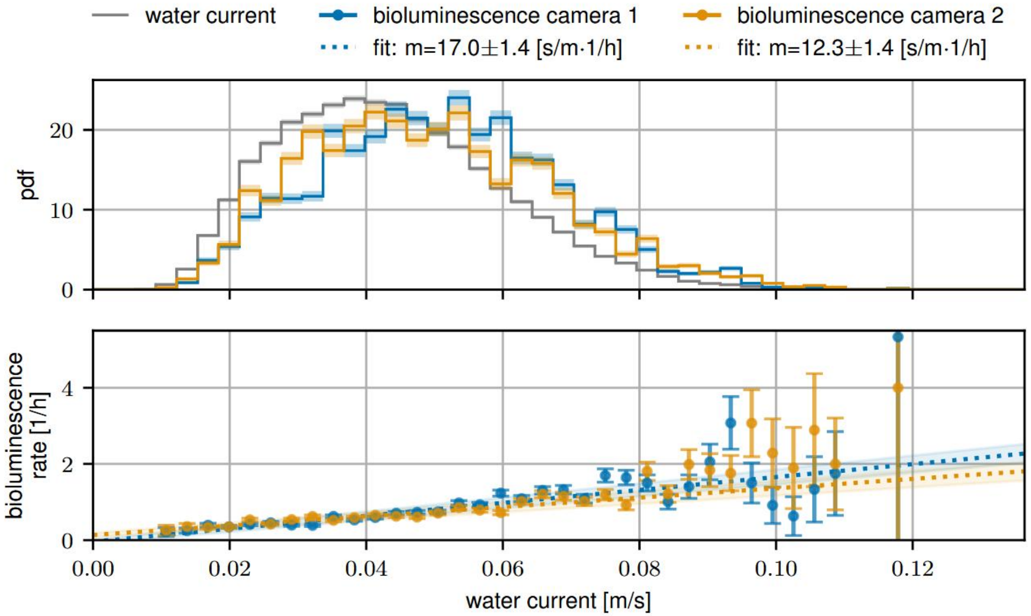
Predicting Bioluminescence



Simulation by Christian Spannfellner

Vertex streets downstream an Island

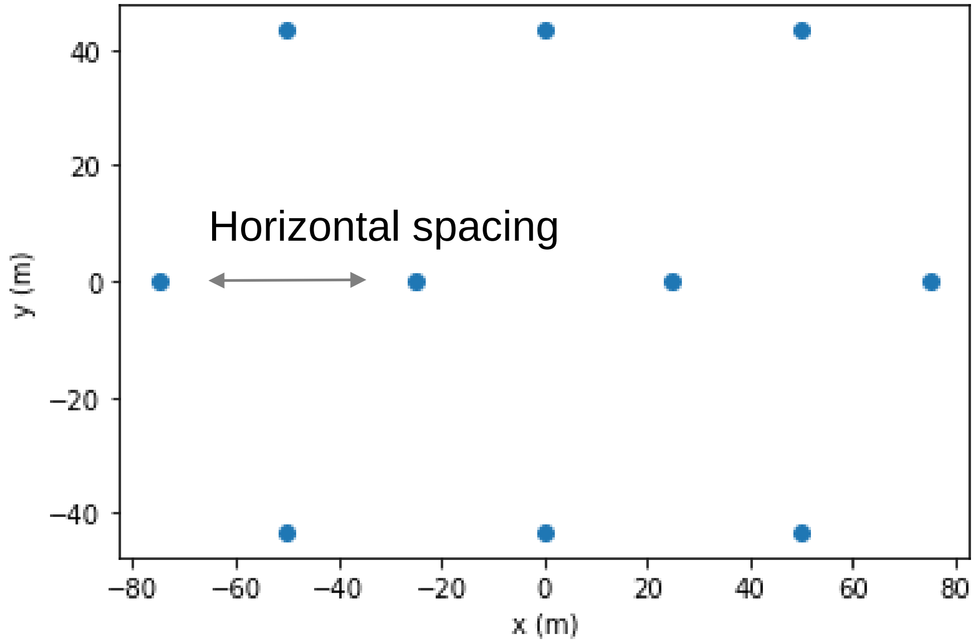




Kilian Holzapfel

Proof of Concept

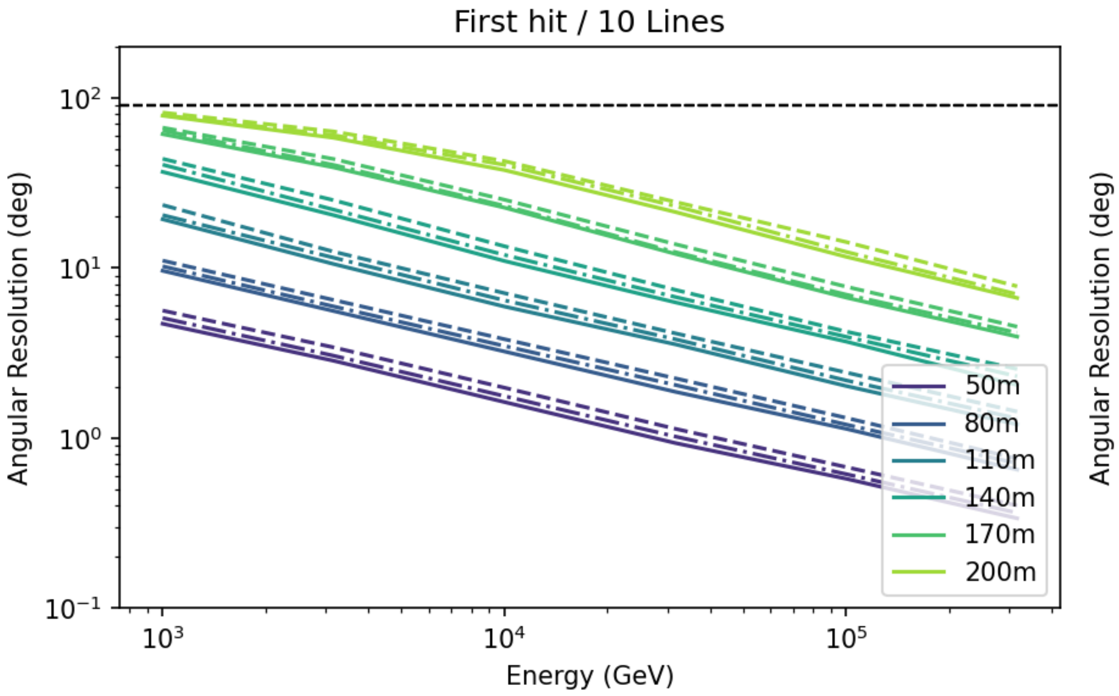
10-Line Detector, 20 modules per line, 50m vert. spacing

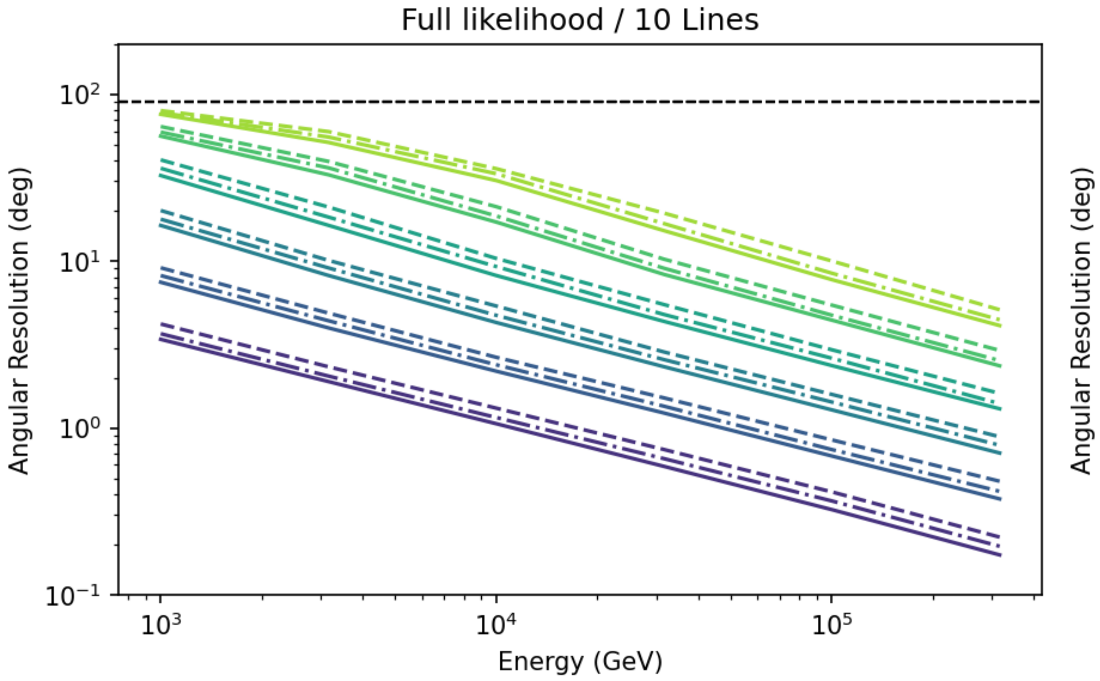


For EM cascades, study resolution scaling as function of:

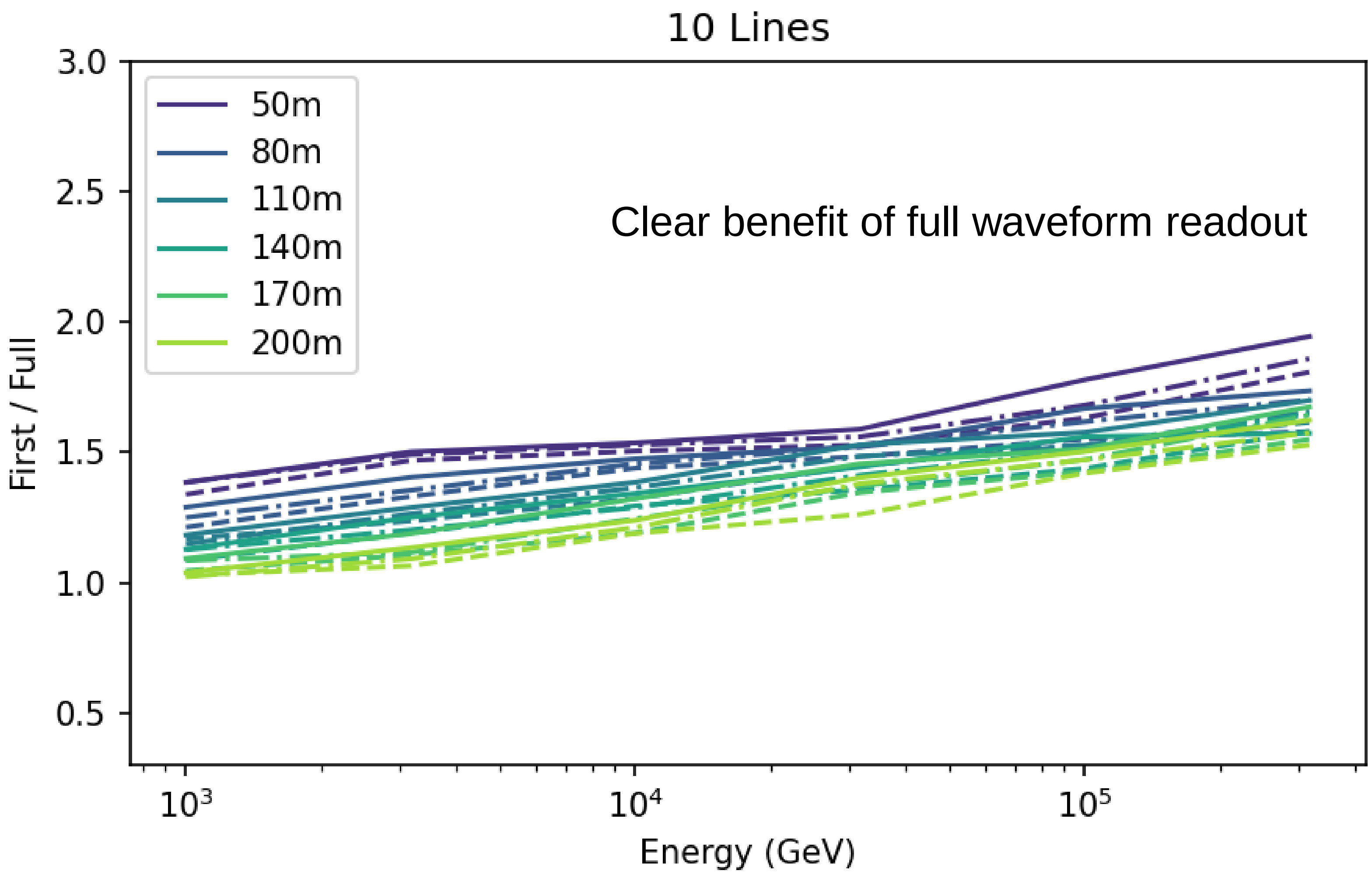
- Horizontal spacing
- Readout strategy (TOT vs. full waveform readout)
- Number of PMTs per module (photon collection efficiency /ignore pixelisation)

Fisher Resolutions





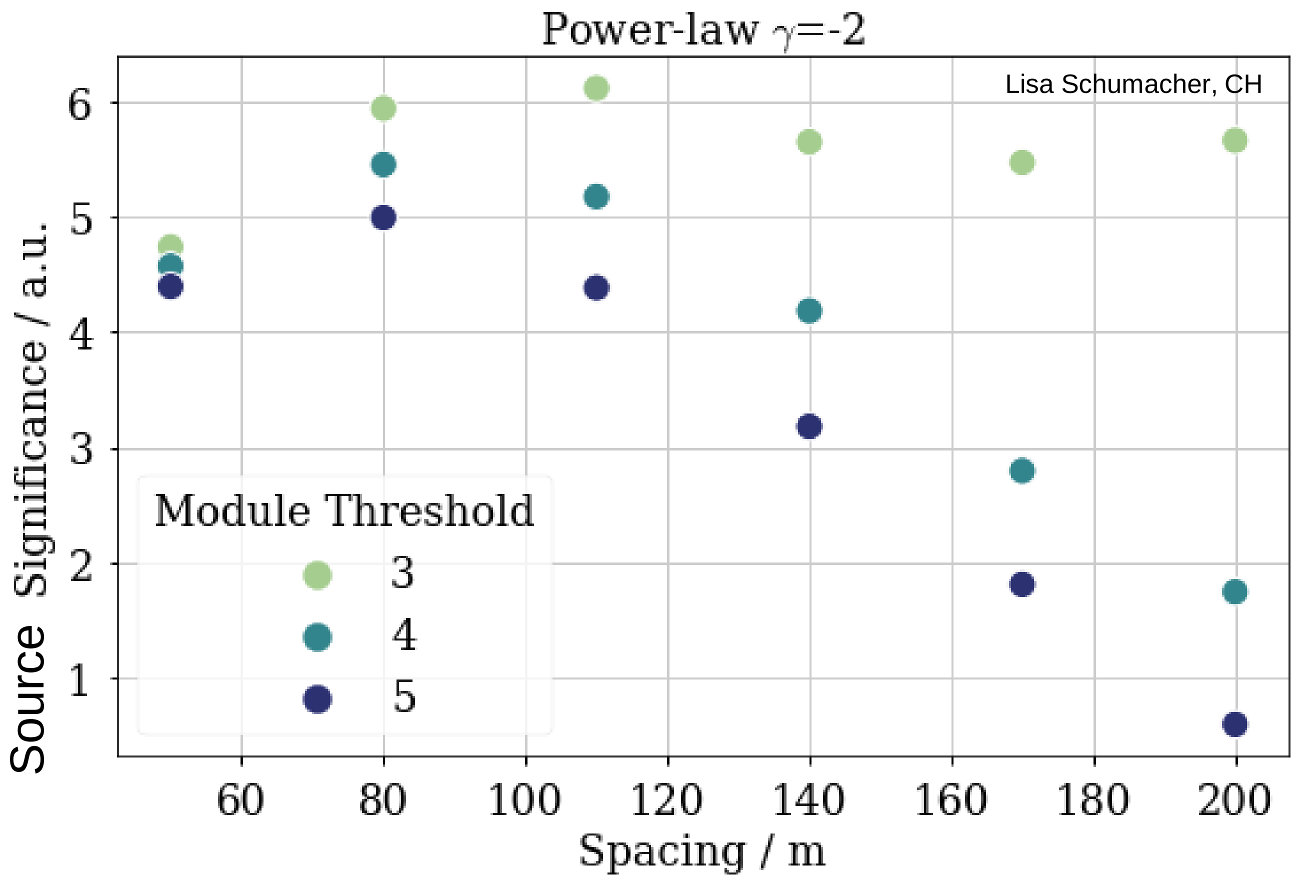
Fisher Resolutions

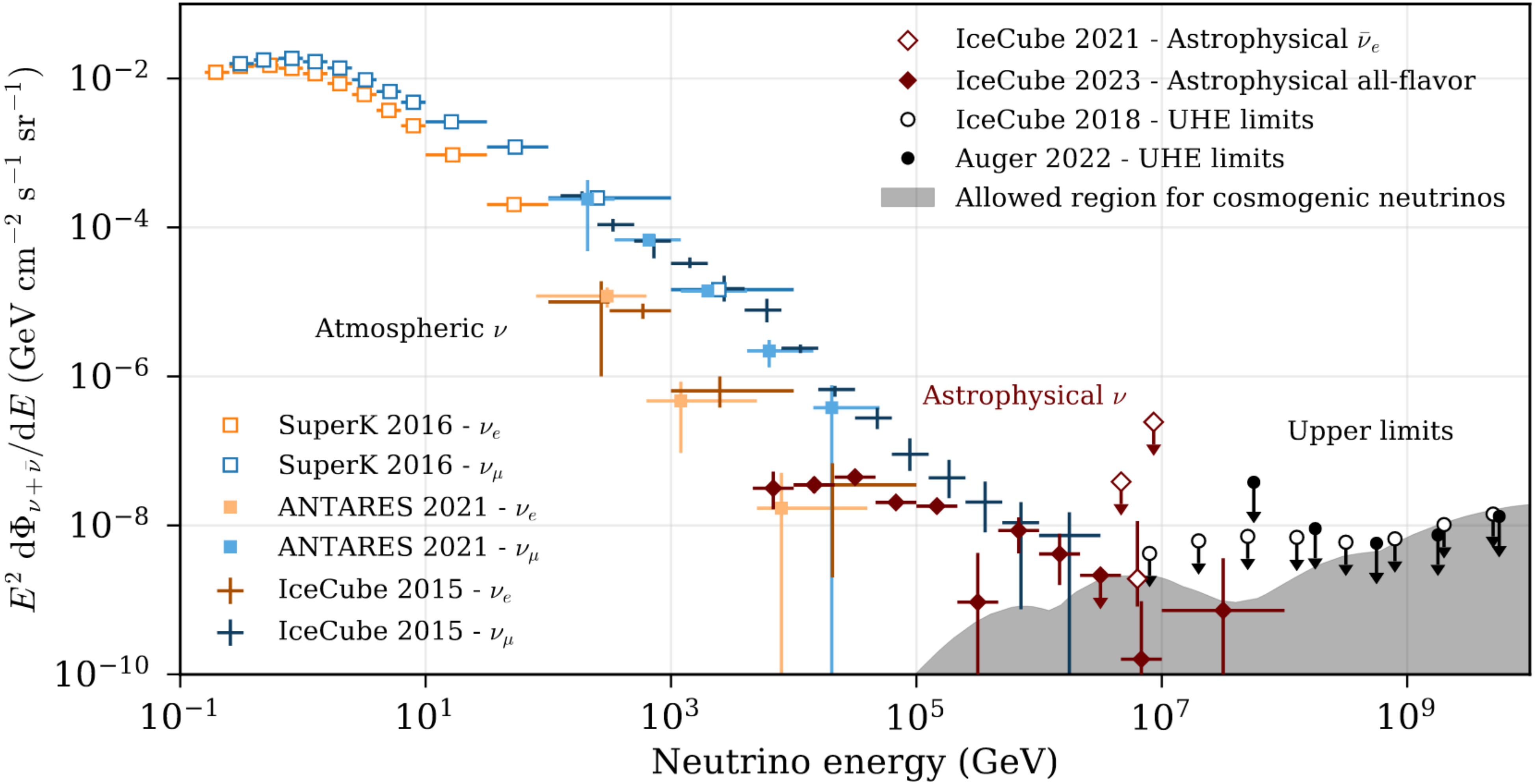


Toy Neutrino Source Search

Inputs:

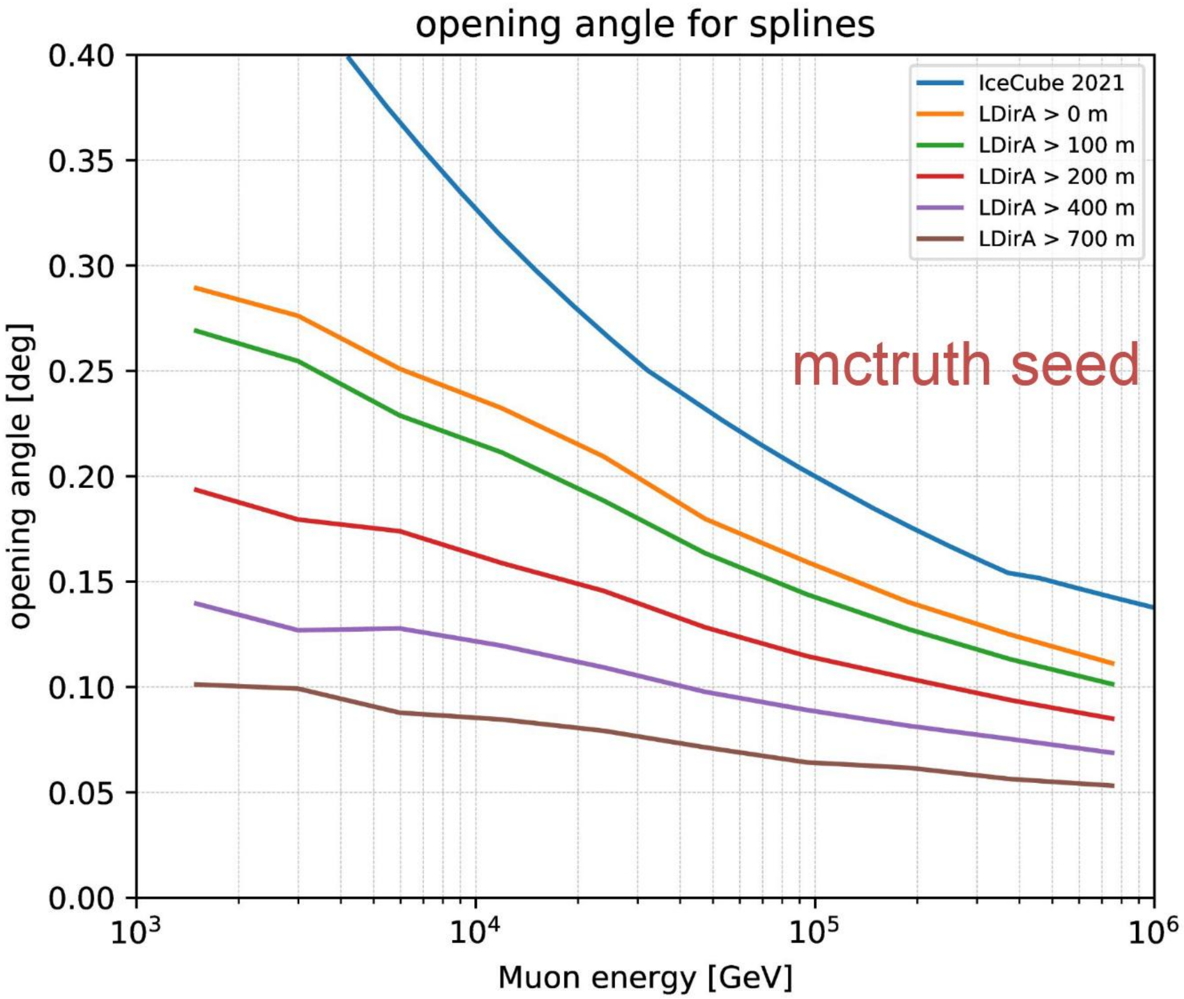
- Resolutions
- Effective Volume („Acceptance“)
- Simple trigger (Multiplicity)
- Simple event selection (cut on positional resolution)
- Likelihood-based clustering analysis



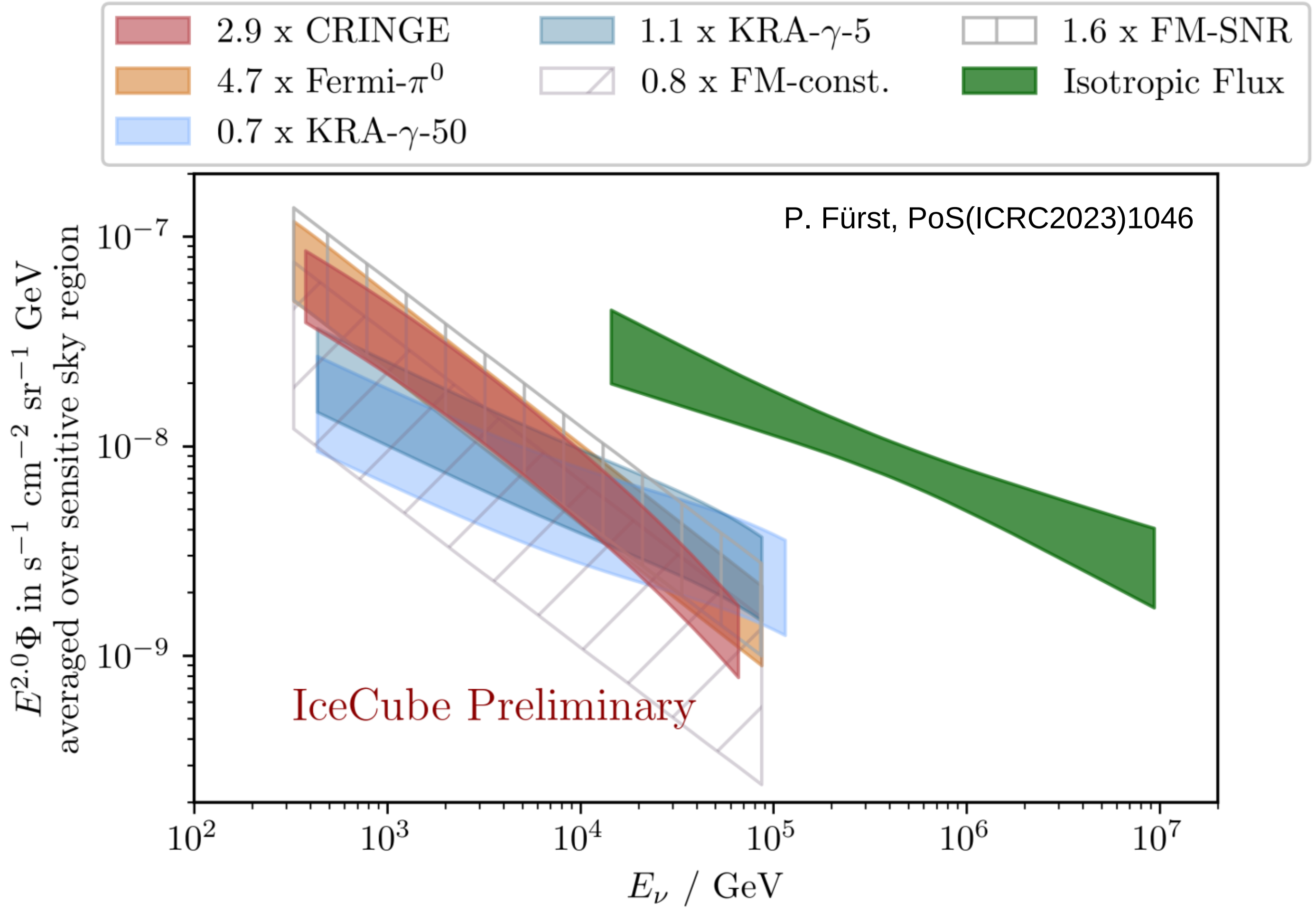


IceCube 2021 - Astrophysical $\bar{\nu}_e$
IceCube 2023 - Astrophysical all-flavor
IceCube 2018 - UHE limits
Auger 2022 - UHE limits
Allowed region for cosmogenic neutrinos
Atmospheric ν
Astrophysical ν
Upper limits
SuperK 2016 - ν_e
SuperK 2016 - ν_μ
ANTARES 2021 - ν_e
ANTARES 2021 - ν_μ
IceCube 2015 - ν_e
IceCube 2015 - ν_μ
$E^2\, \mathrm{d}\Phi_{\nu+\bar{\nu}}/\mathrm{d}E$ (GeV cm^{-2} s^{-1} sr^{-1})
Neutrino energy (GeV)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}

P-ONE Track Resolution



Galactic Plane in Track Channel

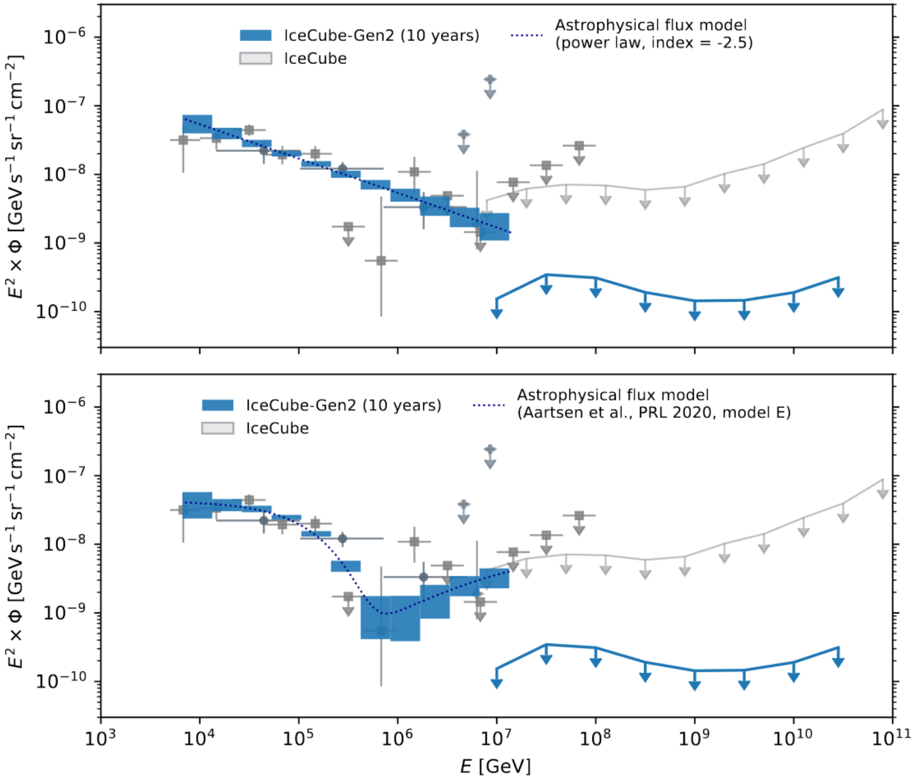


⬅ Multiple diffuse emission models tested

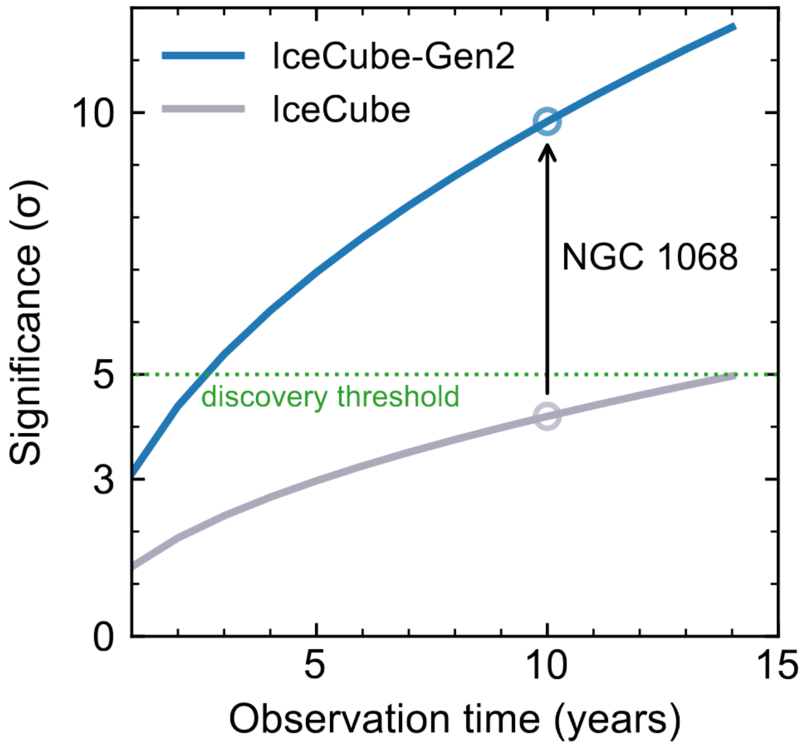
Supporting result by independent analysis using track channel (2.7σ)

Gen2 Science Highlights

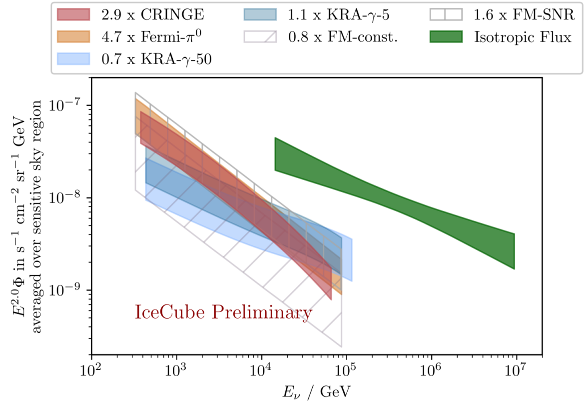
Precision measurement of the astrophysical neutrino spectrum



Resolving neutrino sources

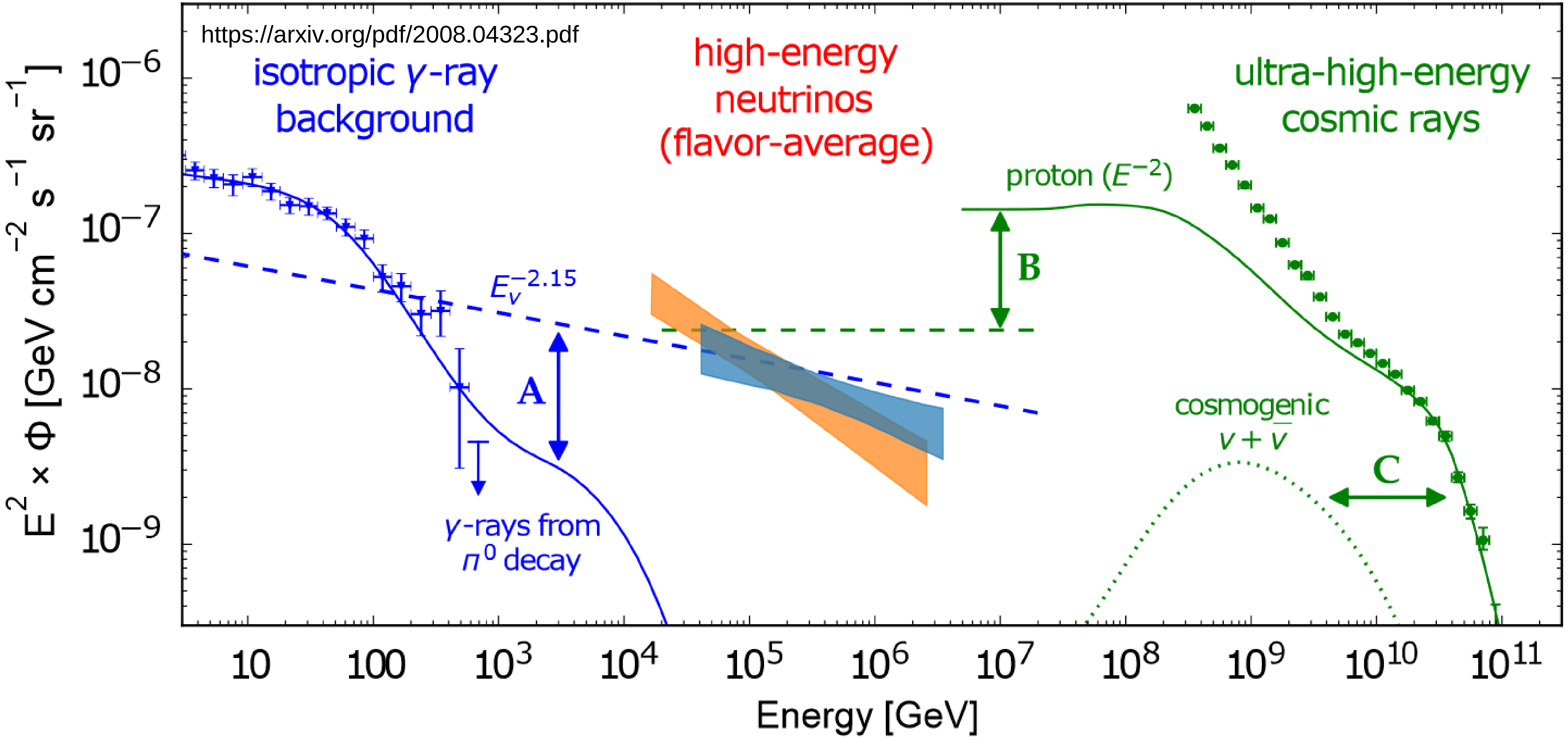


8.7σ for diffuse galactic emission after 10years.

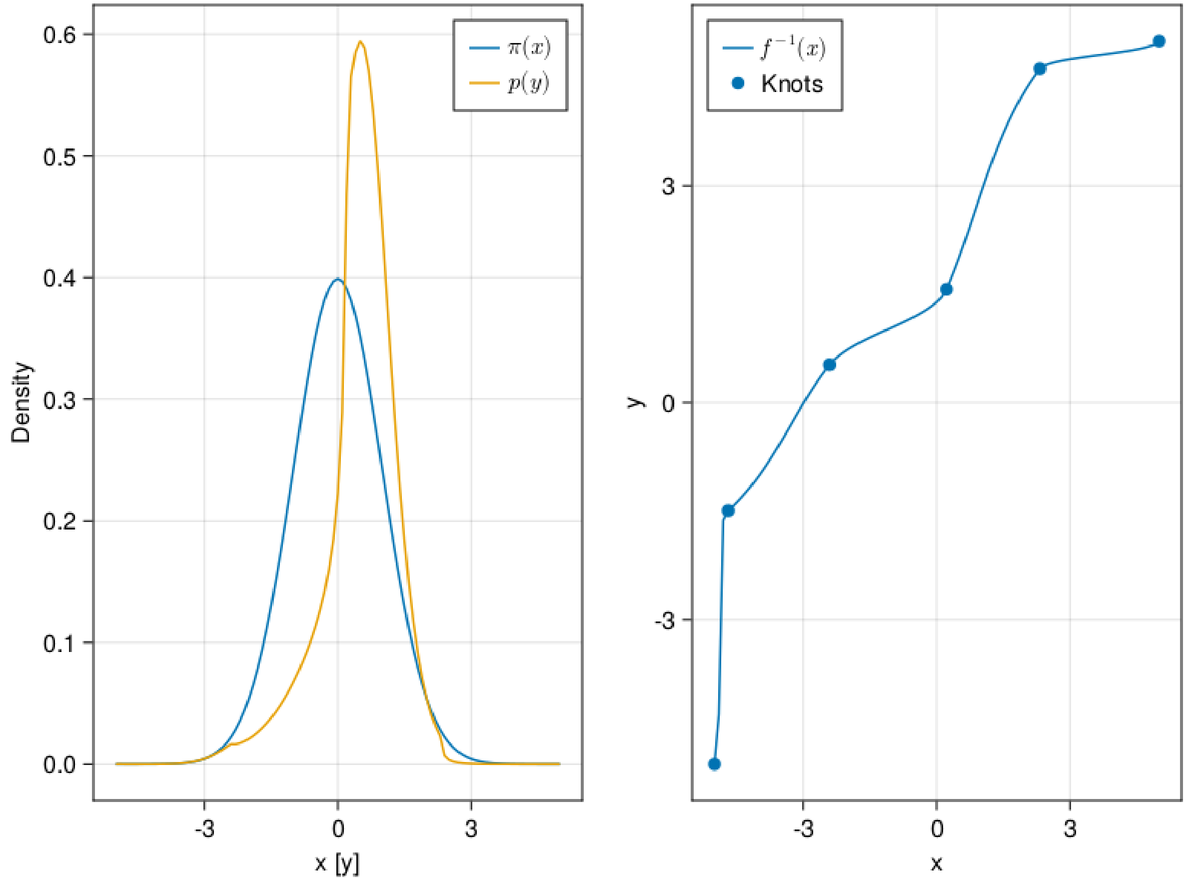


And much, much more.
Check out the TDR

Energy Density of Cosmic Messengers

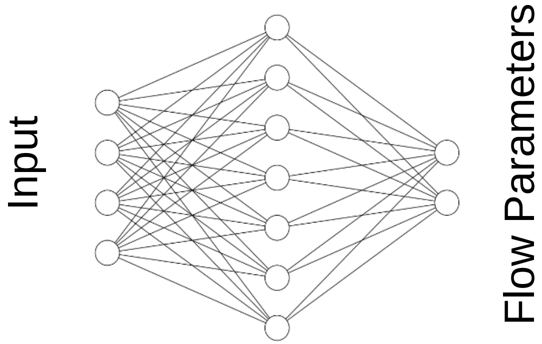


- For 1D PDFs, rational-quadratic (RQ) splines are useful normalizing flows:



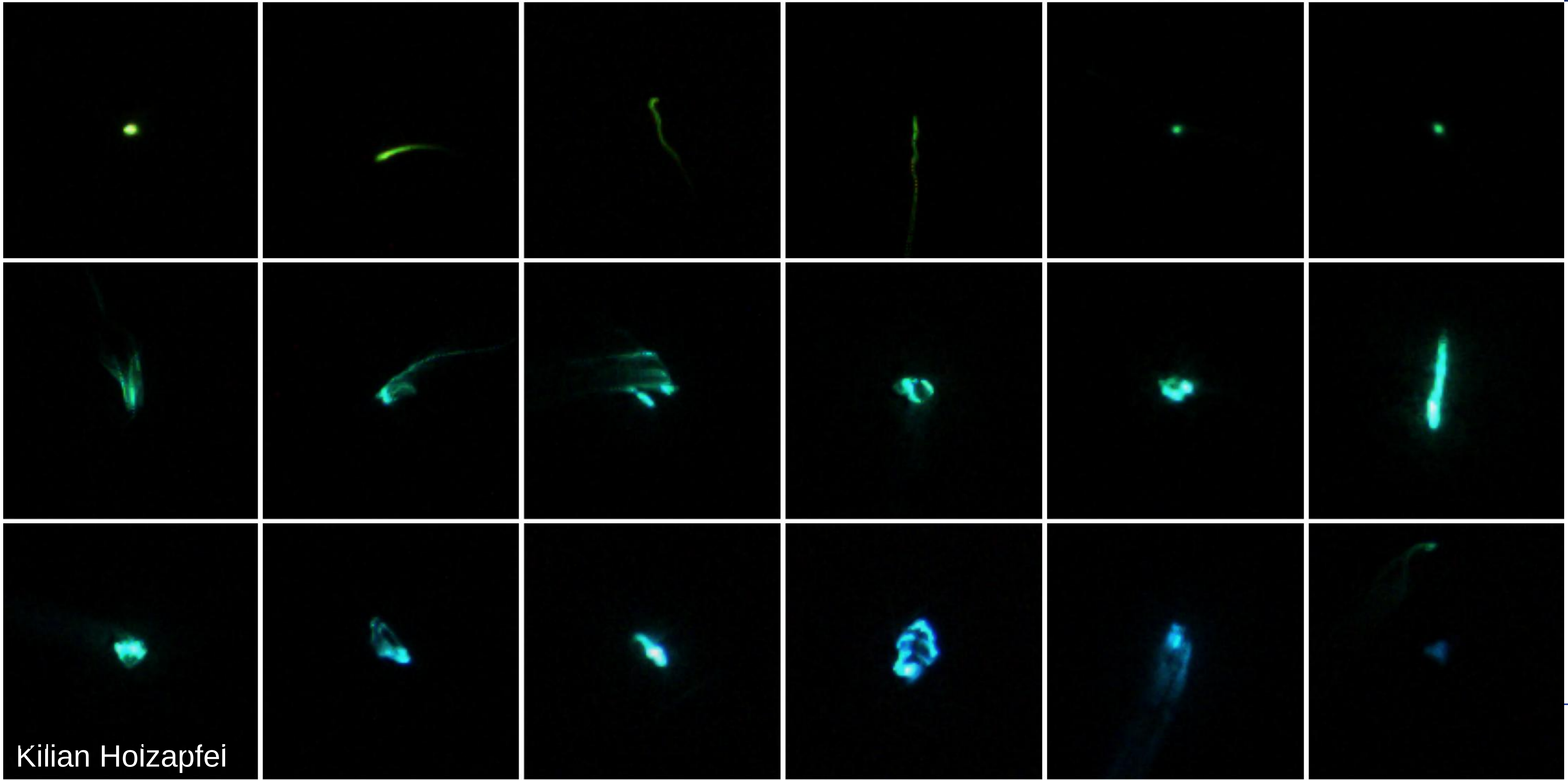
- K RQ-splines between K+1 boundary points (knots)
- Invertible & differentiable
- Naturally supports multimodality
- $3K + 1$ free parameters

NN Embedding

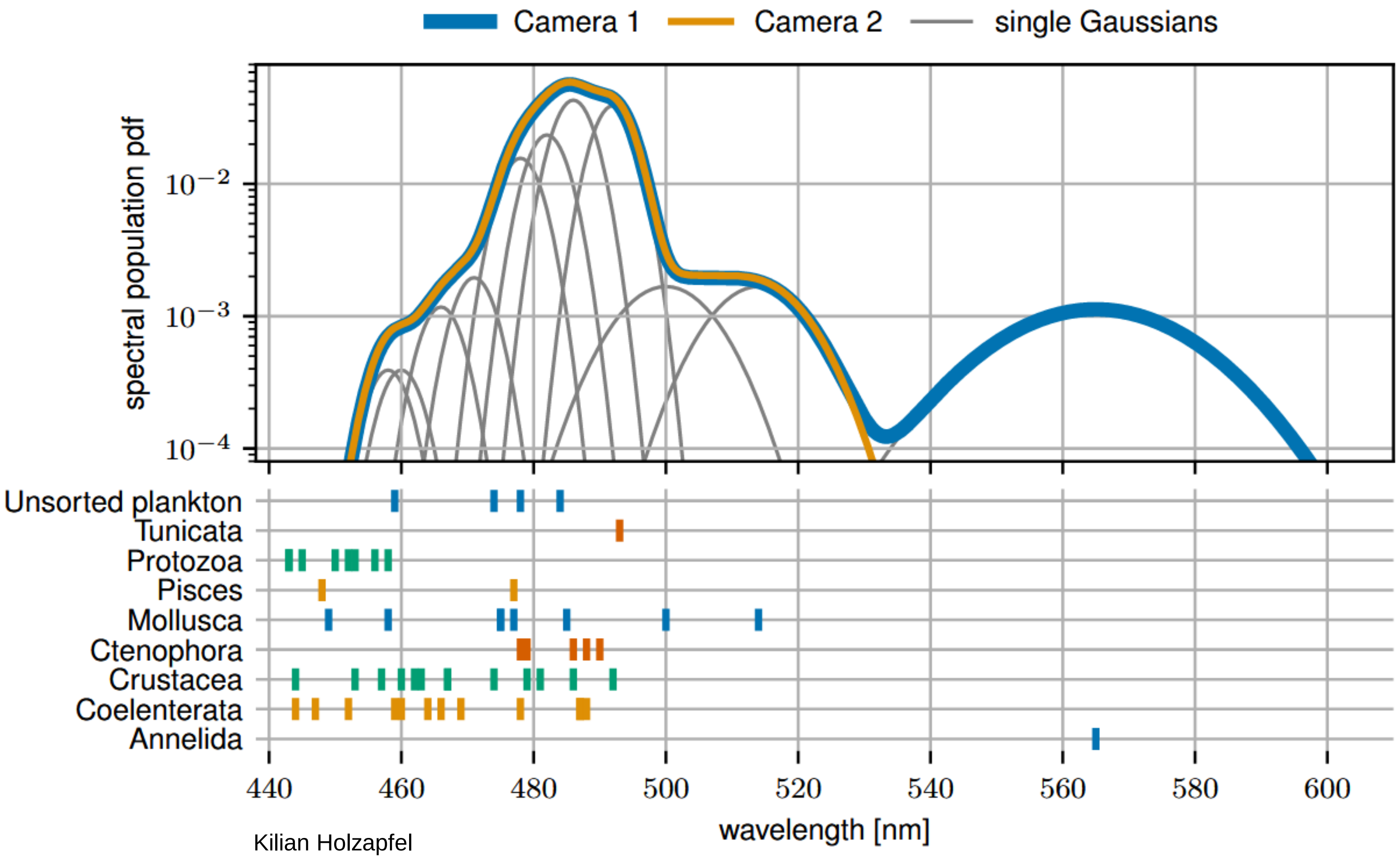


$$\min_{w,b} \mathcal{L}$$

Classifying Bioluminescence



Species Identification



Kilian Holzapfel