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SFB 1258 Neutrinos Dark Matter Messengers

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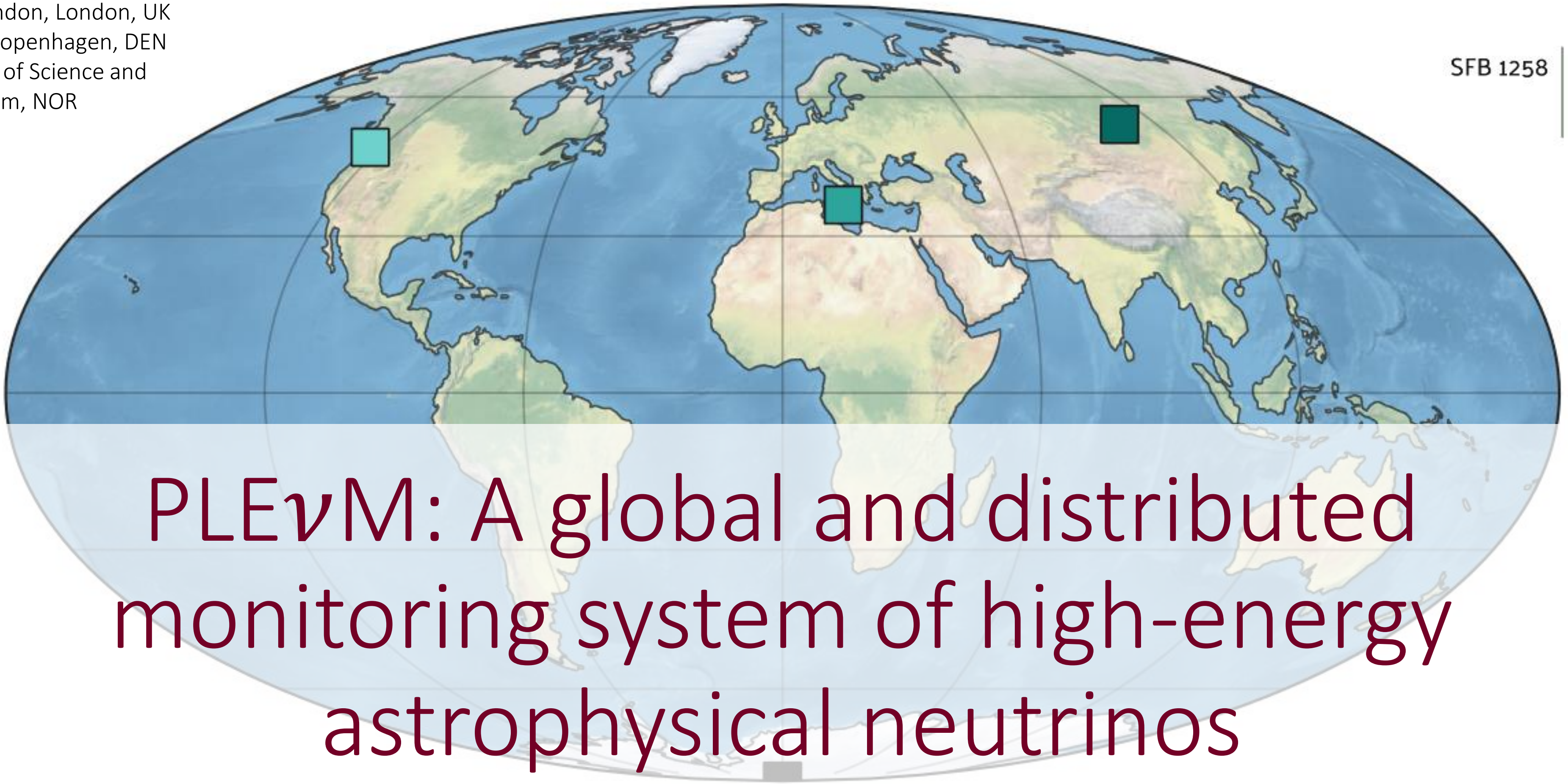
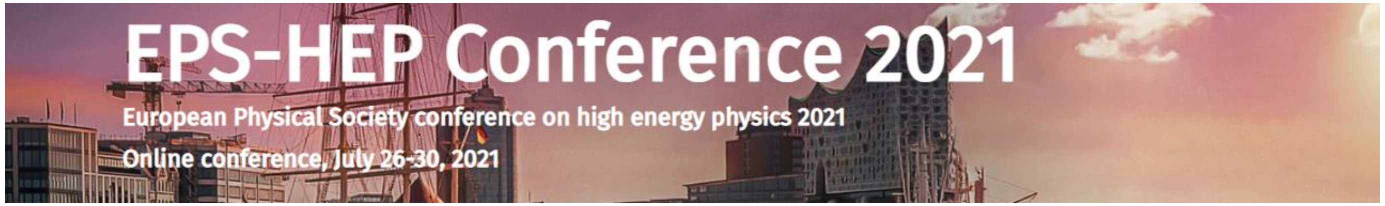
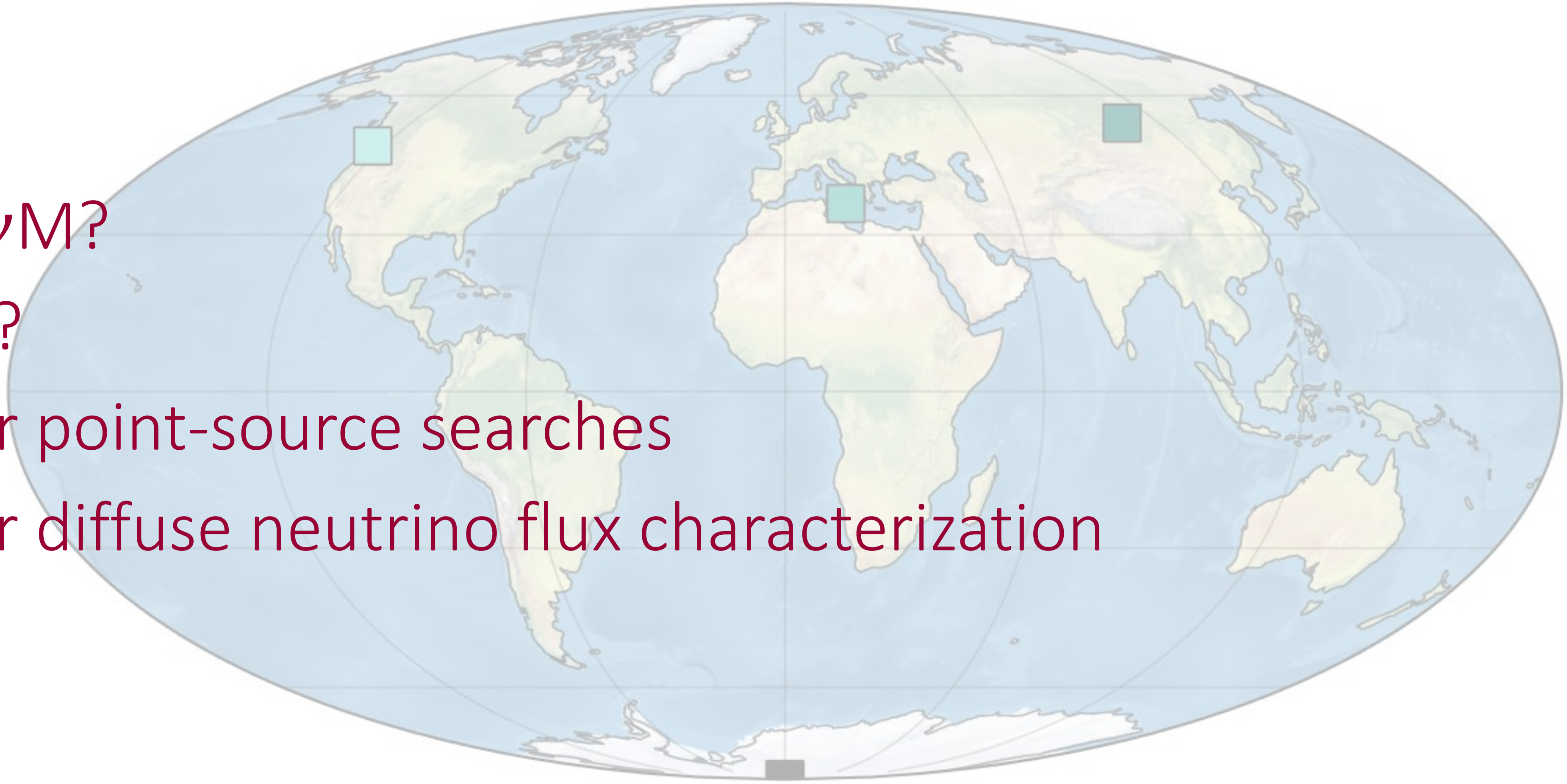


PLEνM: A global and distributed monitoring system of high-energy astrophysical neutrinos

Lisa Schumacher*, Matthias Huber*, Matteo Agostini[1], Mauricio Bustamante[2], Foteini Oikonomou[3], Elisa Resconi*



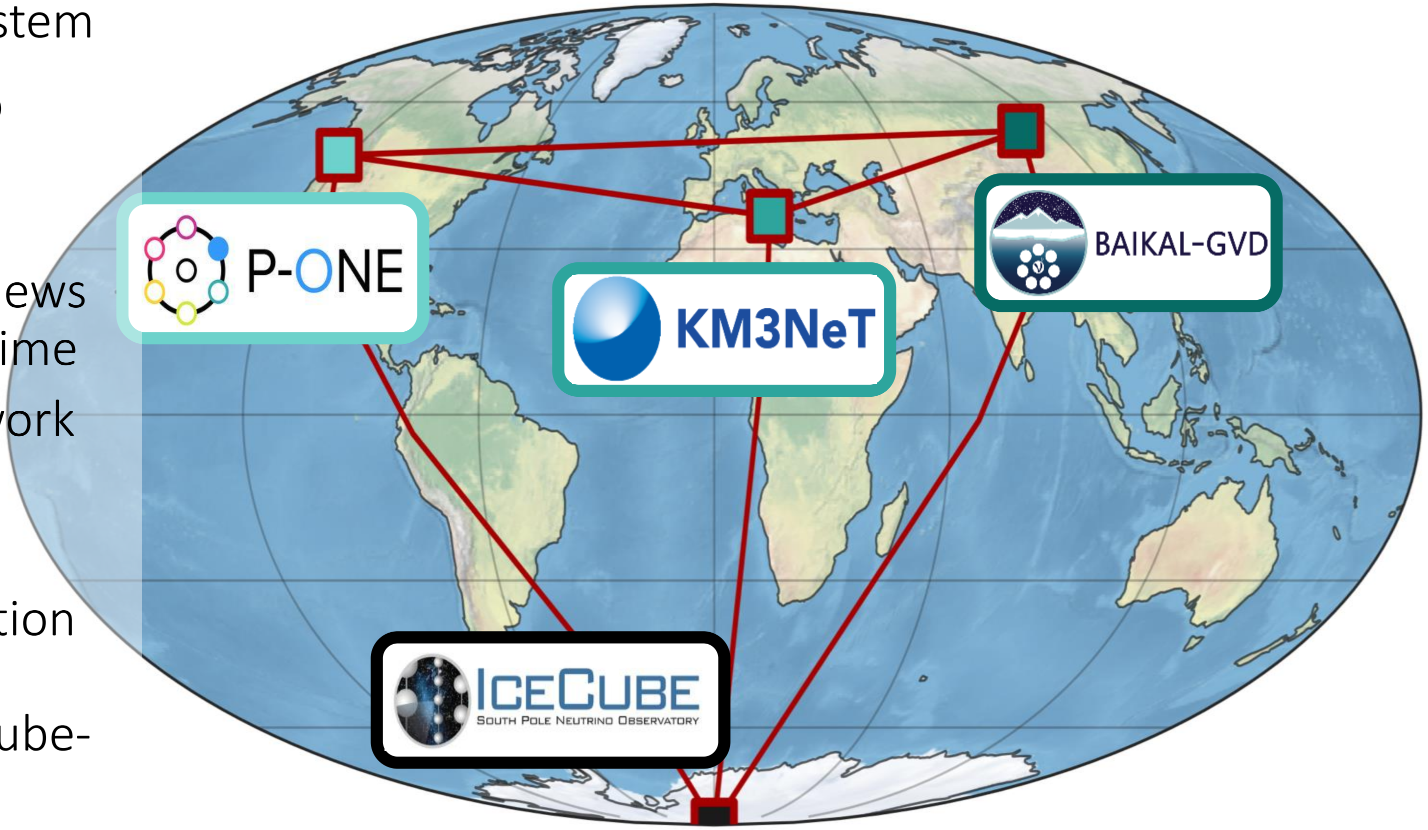
Outline



- What is PLEνM?
- Why PLEνM?
- Prospects for point-source searches
- Prospects for diffuse neutrino flux characterization
- Summary

What is PLEνM?

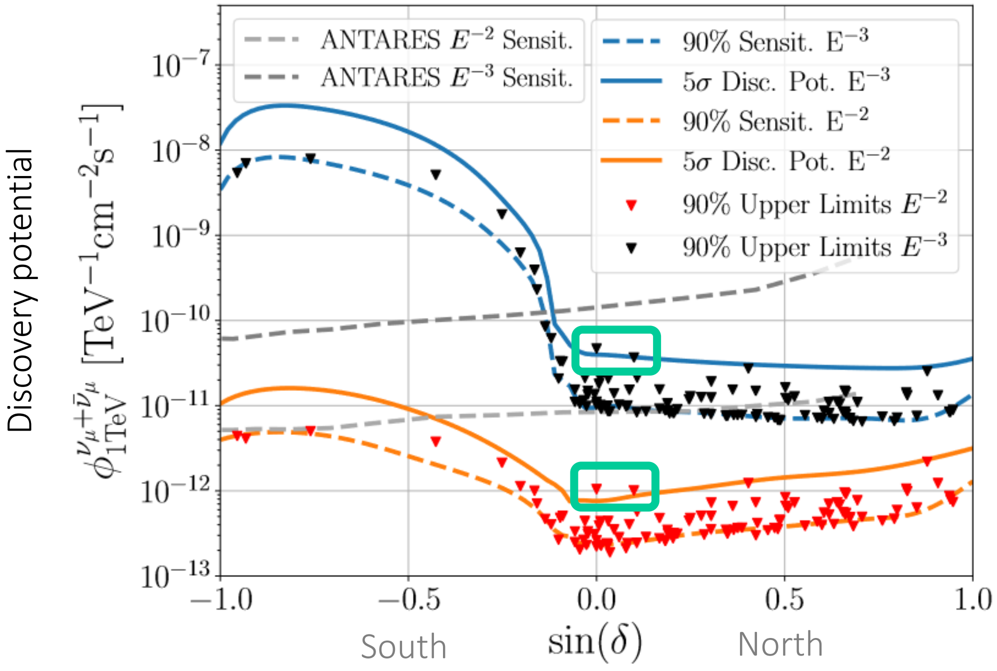
- PLEνM = PLanEtary neutrino (ν) Monitoring system
- Concept for repository of high-energy neutrino observations of current and future neutrino telescopes:
  - Combine data sets with different field of views to cover the whole sky offline and in real-time
  - Provide a platform for easy collaborative work between all contributing experiments
- Current approach:
  Combine exposure from telescopes at the location of
  P-ONE, KM3NeT, Baikal-GVD and IceCube/IceCube-Gen2
- Based on work by Matthias Huber



Why PLEνM? (1)

Open questions in Neutrino Astronomy due to limited statistics:

- Population of Galactic and Extragalactic Neutrino Sources?
- Distinct features in astrophysical neutrino spectrum?
- Flavor ratio of astrophysical neutrinos?
- Physics beyond the standard model with astrophysical neutrinos?
- …

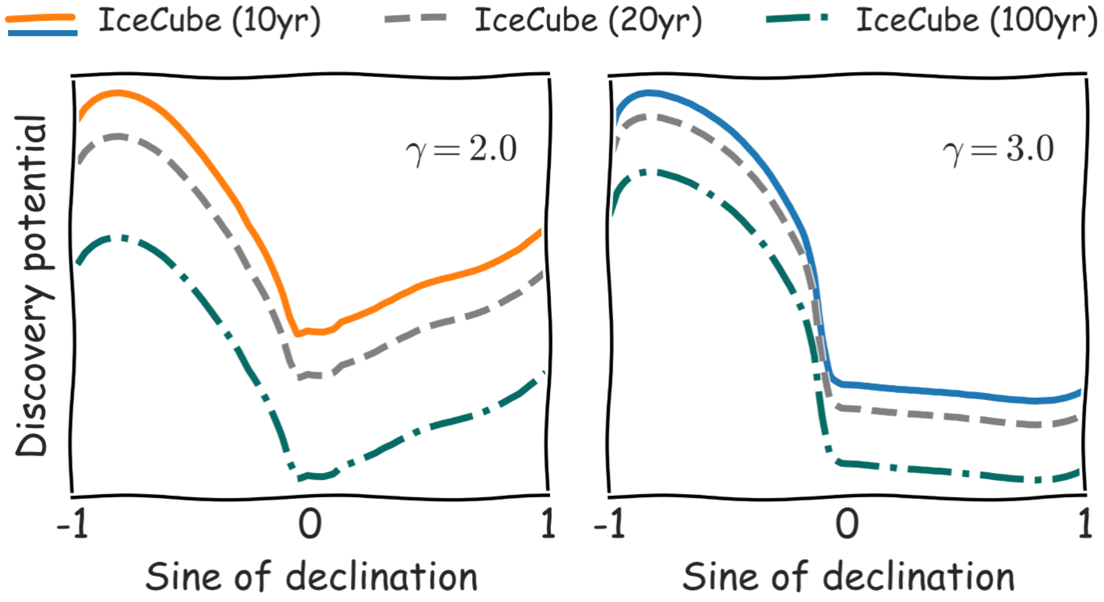


"Time-integrated Neutrino Source Searches with 10 years of IceCube Data" arXiv:1910.08488

Example: IceCube point-source searches with muon neutrinos

- Best sensitivity to point-like neutrino sources around horizon
  → Sources in the South must be orders of magnitude stronger to be discovered
- Two neutrino source candidates:
  TXS 0506+056 and NGC 1068 are close to the horizon
  → Are there sources we missed due to IceCube's location?
- <u>100 years of data is not enough to reach in the South a discovery potential as good as currently achieved at the horizon</u>

arXiv:1910.08488



Why PLEνM? (2)

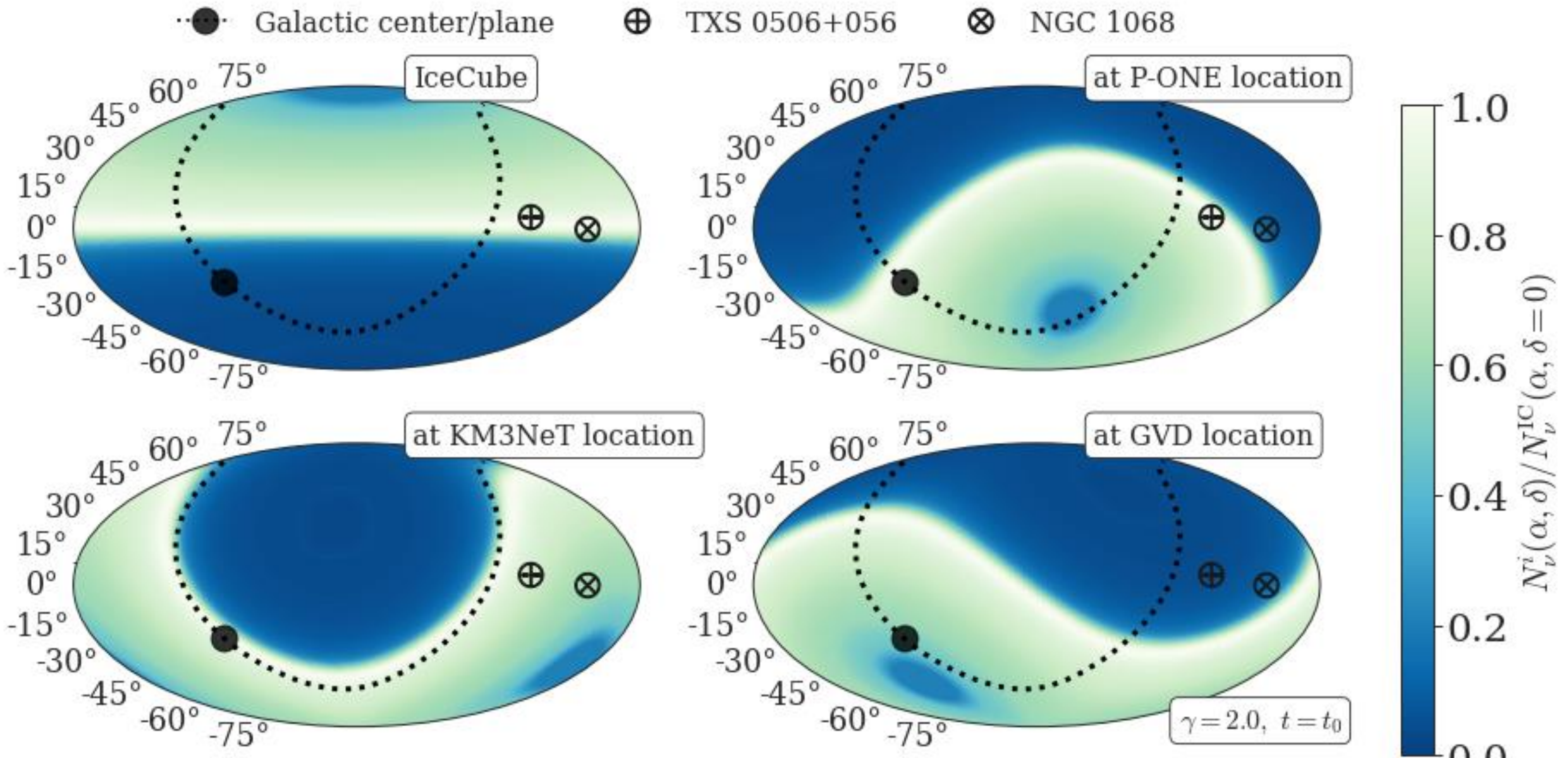
Illustration: Number of neutrinos relative to IceCube's number of neutrinos <u>at horizon</u>

Solution:

- More neutrino telescopes at different locations:
  → Three telescopes are being built or planned in the Northern Hemisphere: KM3NeT, Baikal-GVD, P-One; + IceCube-Gen2 at the South Pole
- Combine their field of view:
  → Reach a uniform exposure of the sky

➢ Combine the efforts of multiple telescopes to reach better sensitivity to astrophysical neutrinos

➢ This study: combine effective areas!

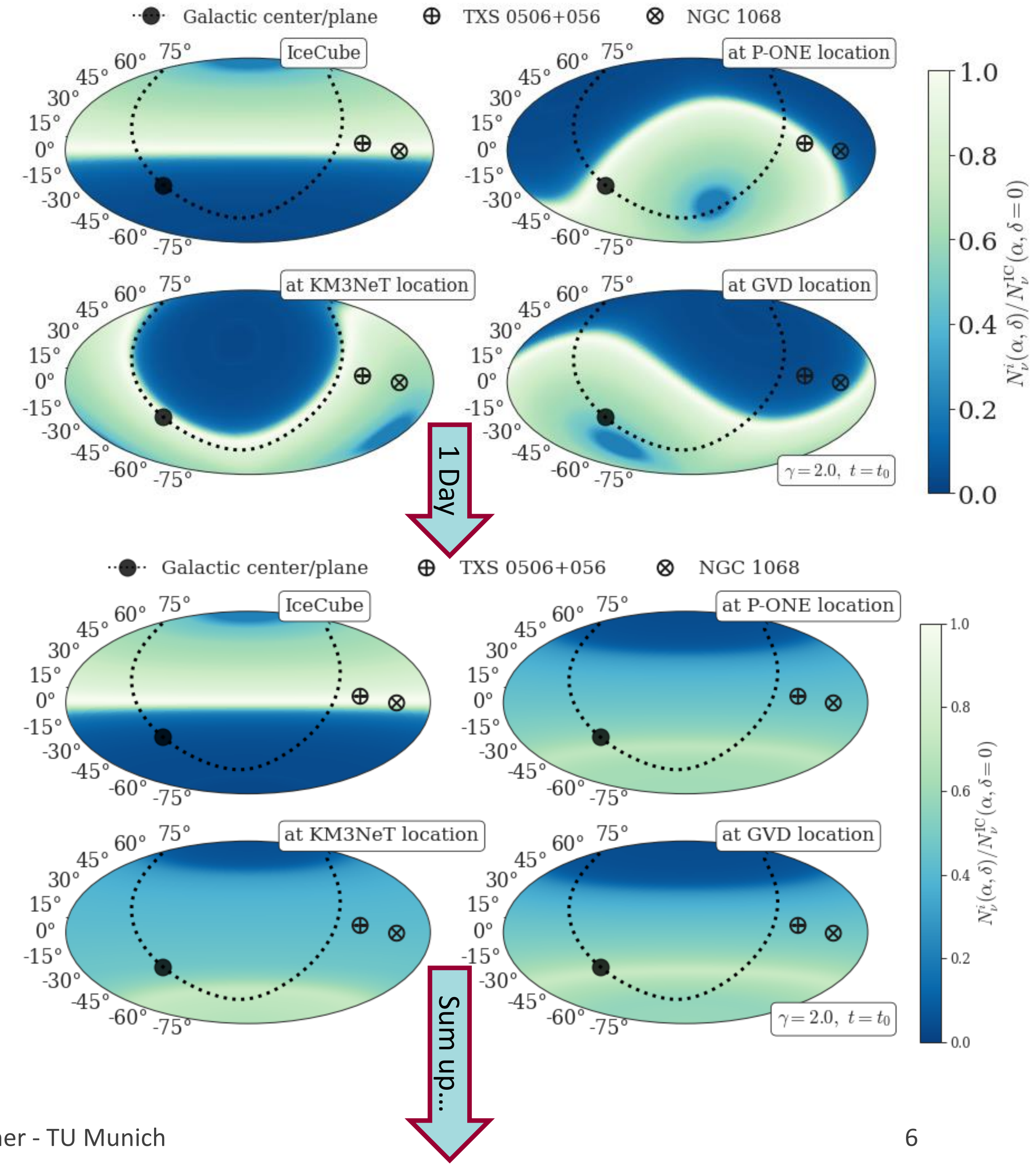


Concept: generate new effective areas at different locations on Earth

1) Assume IceCube's effective area for through-going muon neutrinos* at different locations around the globe
2) Integrate local effective area over one sidereal day to get a time-independent effective area per telescope
3) Sum up all contributions to estimate PLEνM's effective area

Important: currently all effective areas are based on IceCube's data release*

* "All-sky point-source IceCube data: years 2008-2018" http://doi.org/DOI:10.21234/sxvs-mt83

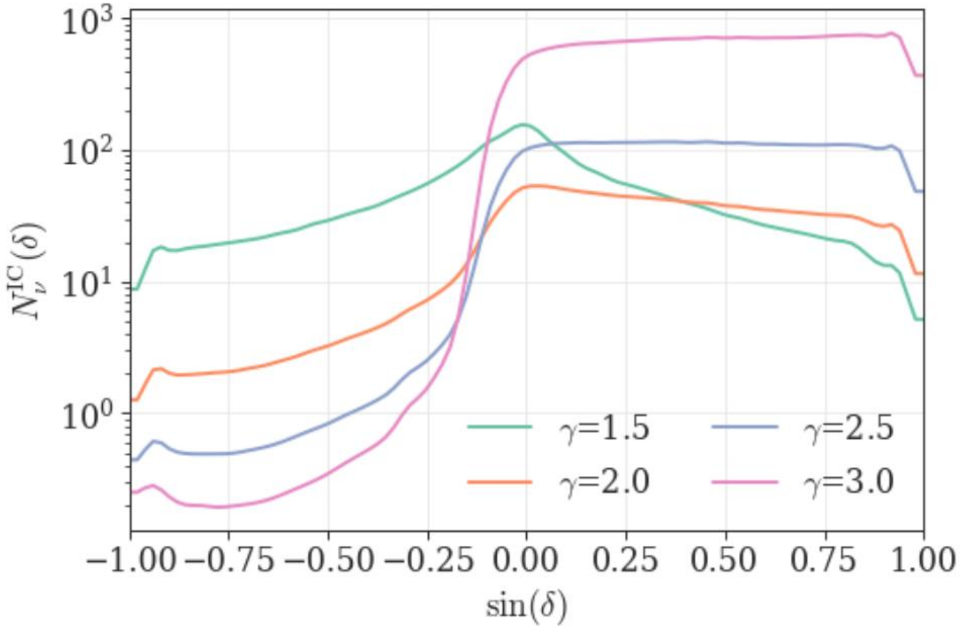


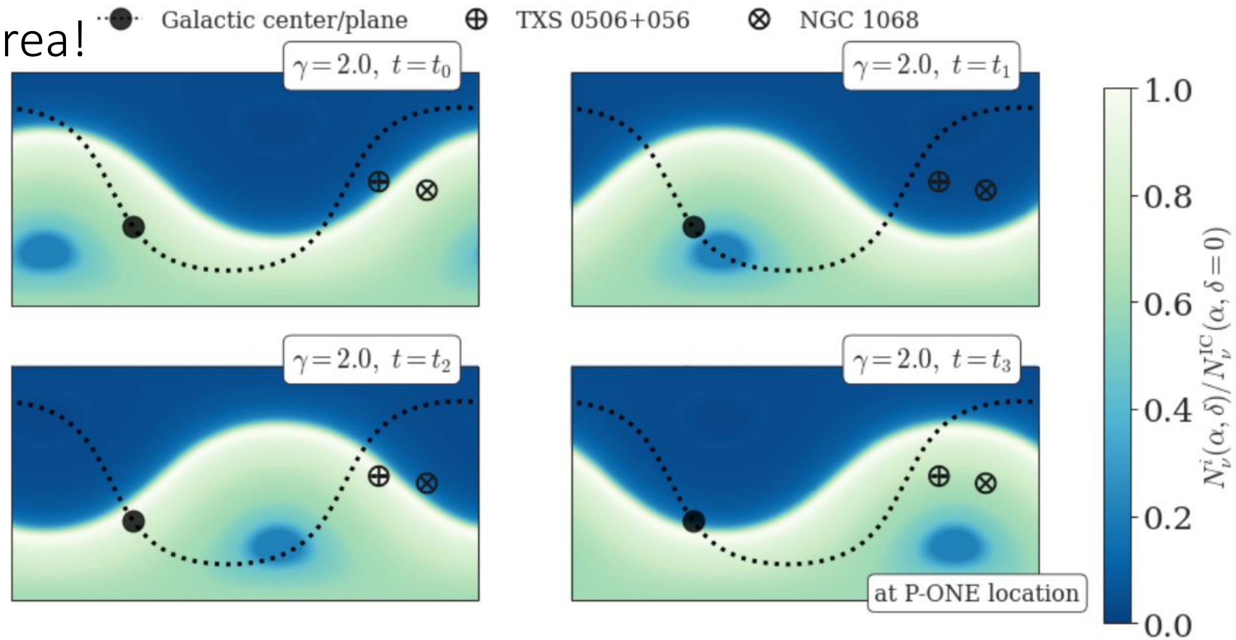
Can we simply add up the effective areas?

- Number of neutrinos detected
  $N_\nu = T_{live} \cdot \int_{\Delta\Omega} d\Omega \int_{E_{min}}^{E_{max}} dE\, A_{eff}(E, \sin(\delta)) \cdot \frac{d\Phi}{dE}$
  with power-law spectrum $\frac{d\Phi}{dE} = \Phi_0 \cdot \left(\frac{E}{1TeV}\right)^{-\gamma}$
  $\Rightarrow N_\nu^{IC} + N_\nu^{P-ONE} \sim A_{eff}^{IC} + A_{eff}^{P-ONE}$

➢ Number of neutrinos linear in livetime and effective area!

- Note: effective areas are in general also time-dependent in equatorial coordinates!
- Not accounted for:
  - Different geometries
  - Different energy range/resolution
  - Different angular resolution
  - Different systematic uncertainties



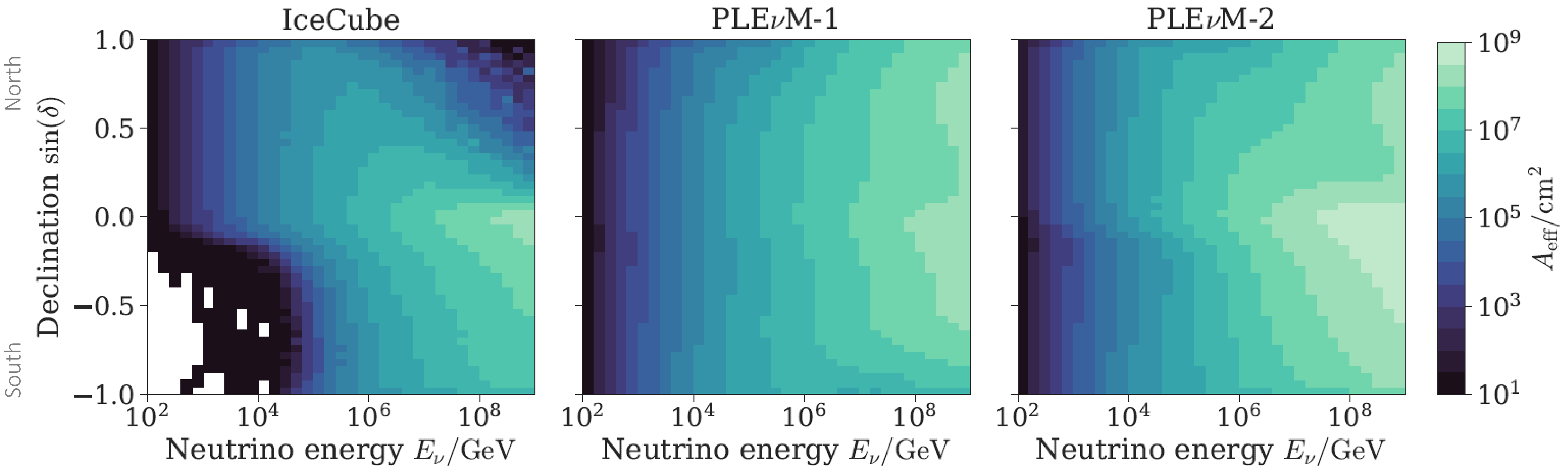


Combined effective areas of PLEνM

IceCube A_{eff} for through-going muon neutrinos

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

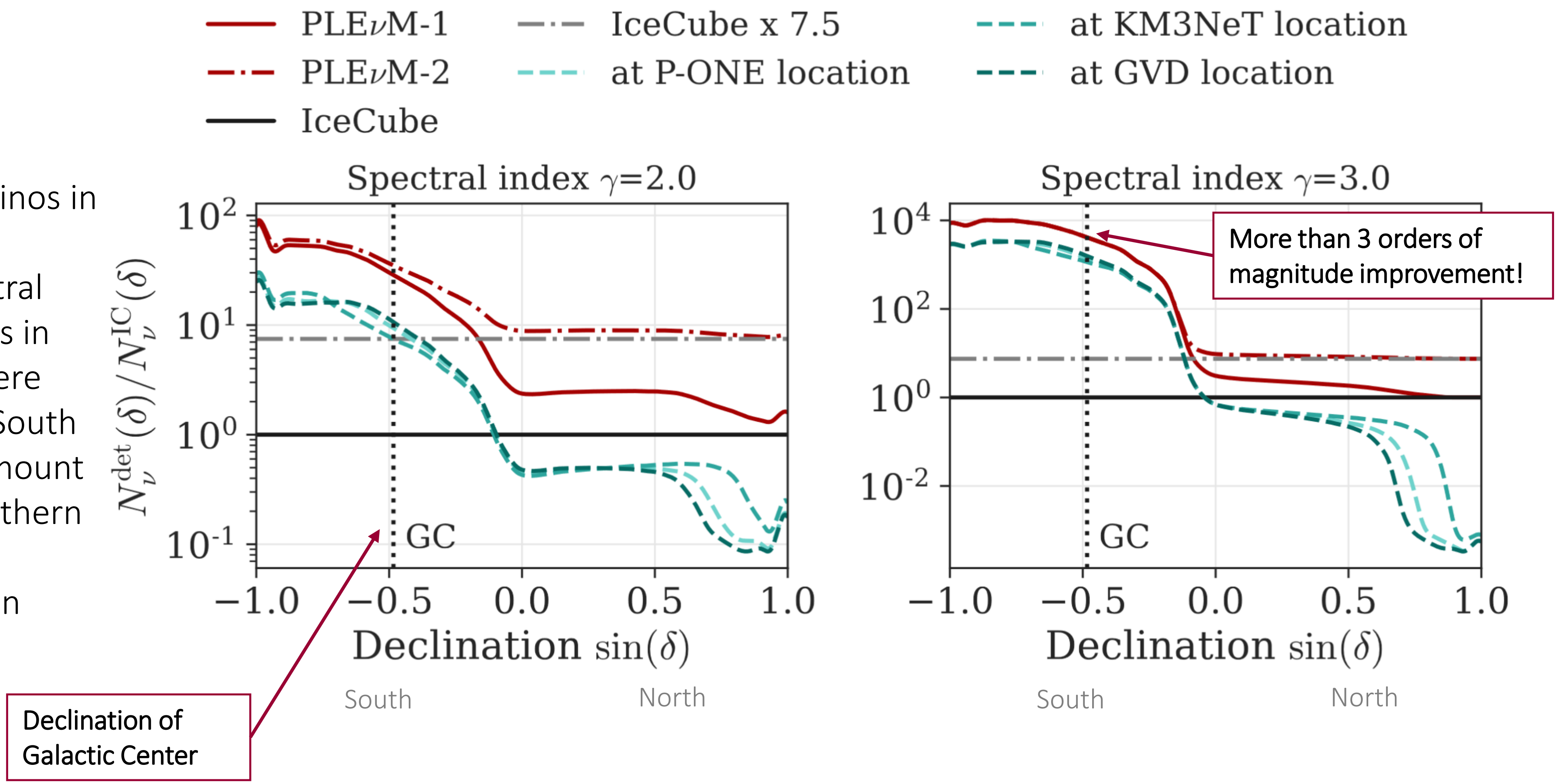
PLEνM-2: replace IceCube's contribution with Potential future telescope at South Pole: 7.5 x IceCube A_{eff} *



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

Expected number of neutrinos relative to IceCube

- Significant increase of number of muon neutrinos in Southern Hemisphere, especially for soft spectral indices due to detectors in the Northern Hemisphere
- Larger detector at the South Pole adds significant amount of neutrinos to the Northern Hemisphere
- (more spectral indices in back-up)



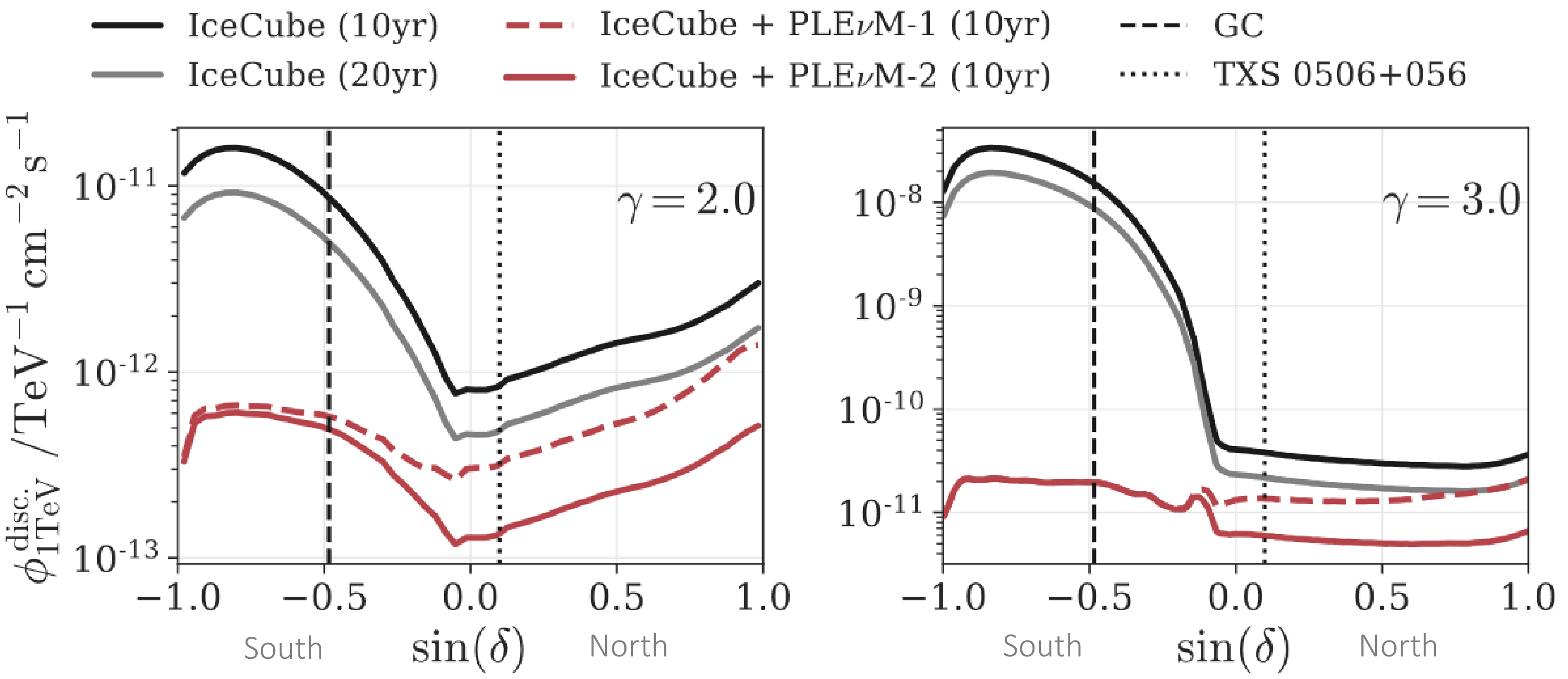
Prospects: Point-source searches

- Discovery Potential (DP): Neutrino flux per source with power-law spectrum* needed to claim a 5σ discovery

- Larger A_{eff}/livetime
  → better (=smaller) DP flux
- Scale known DP of IceCube to PLEνM: $\Phi^{\mathrm{disc}}_{\mathrm{PLE\nu M}} \propto \Phi^{\mathrm{disc}}_{\mathrm{IC}} \cdot A^{-0.8}_{\mathrm{eff}}$ (more info in backup)

- Extraordinary improvement in Southern hemisphere, especially for soft spectral indices
- Significant improvement in Northern Hemisphere with PLEνM-2

Discovery potential of "Time-integrated Neutrino Source Searches with 10 years of IceCube Data" (black) arXiv:1910.08488



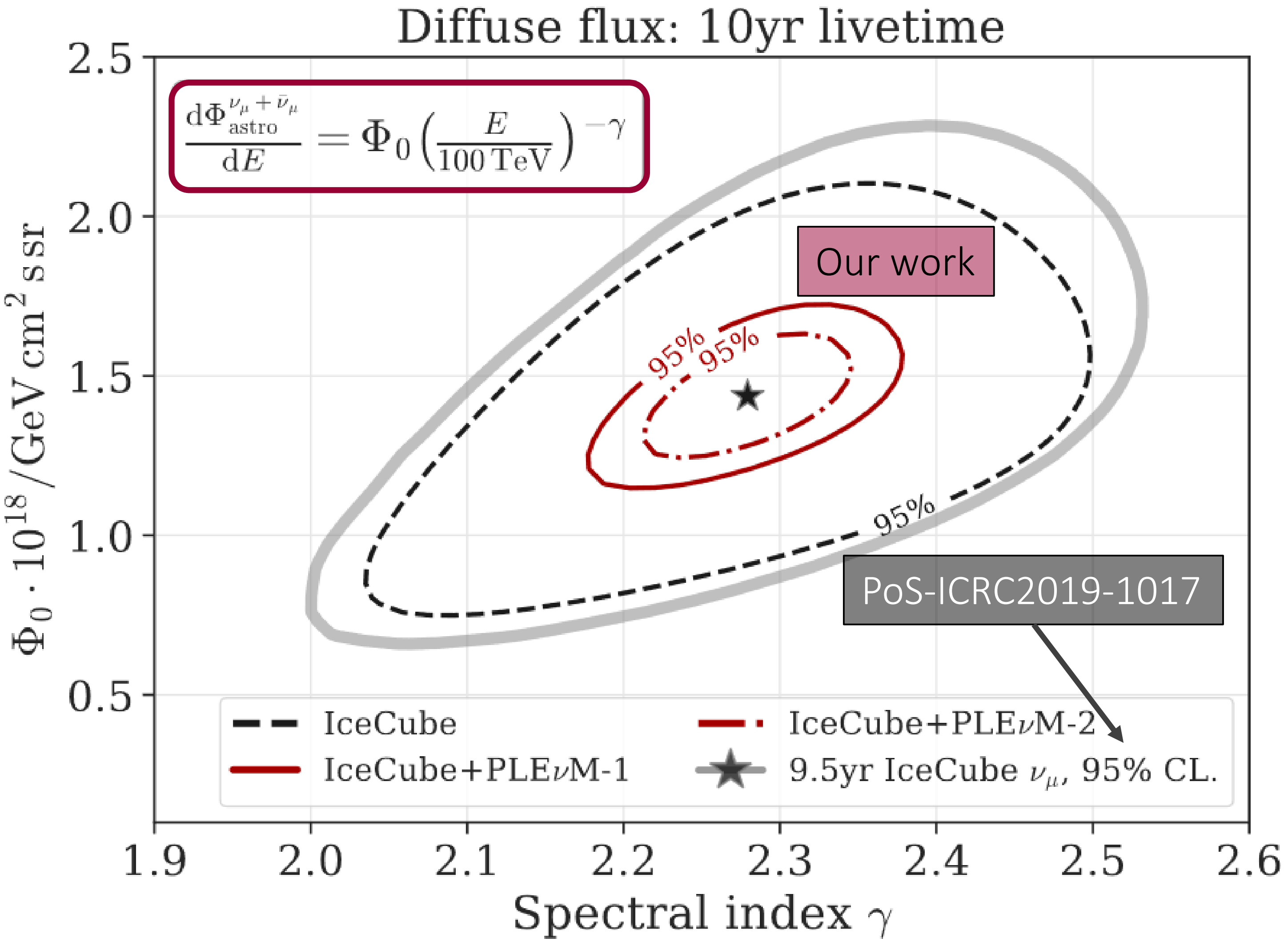
*Neutrino flux per source: $d\Phi/dE = \Phi^{\mathrm{disc.}} \cdot (E/1\,\mathrm{TeV})^{-\gamma}$ at 1 TeV

Prospects: Diffuse astrophysical neutrino flux

- Binned maximum likelihood method using poisson statistics and Asimov data/Wilks' theorem (more info in back-up)

$$\Lambda(data\ k \mid hypothesis\ \mu) = \prod_{bin\ i} \frac{\mu_i^{k_i}}{k_i!} \cdot \exp(-\mu_i)$$

- Contours: likelihood ratio of $\Lambda(\gamma_{scan}, \Phi_{scan})$ and $\Lambda(\gamma_{best}, \Phi_{best})$ ★
- Significance: likelihood ratio of $\Lambda(\gamma_{best}, \Phi_{best})$ and $\Lambda(\Phi_0 = 0)$
- Verified our approach: 95% C.L. contours (black) comparable to IceCube's diffuse analysis contours (gray)
- Expect significant improvement of contours with PLEνM-1/2 (~factor 2 in both parameters)

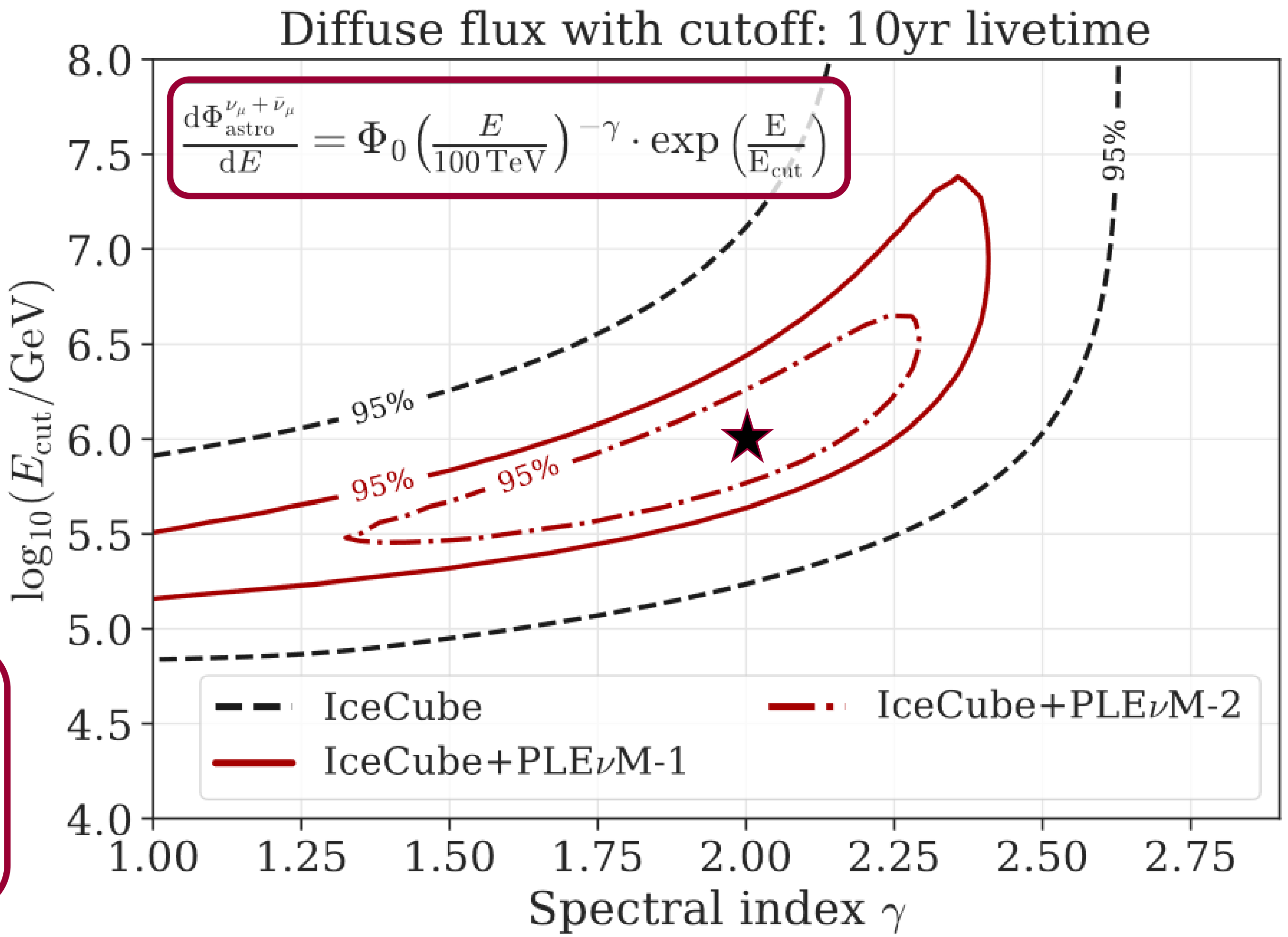


*https://github.com/afedynitch/MCEq with hadronic model Sibyll-2.3c and atmosphere: NRLMSISE-00 Model2001

Beyond the single power law: exponential cutoff

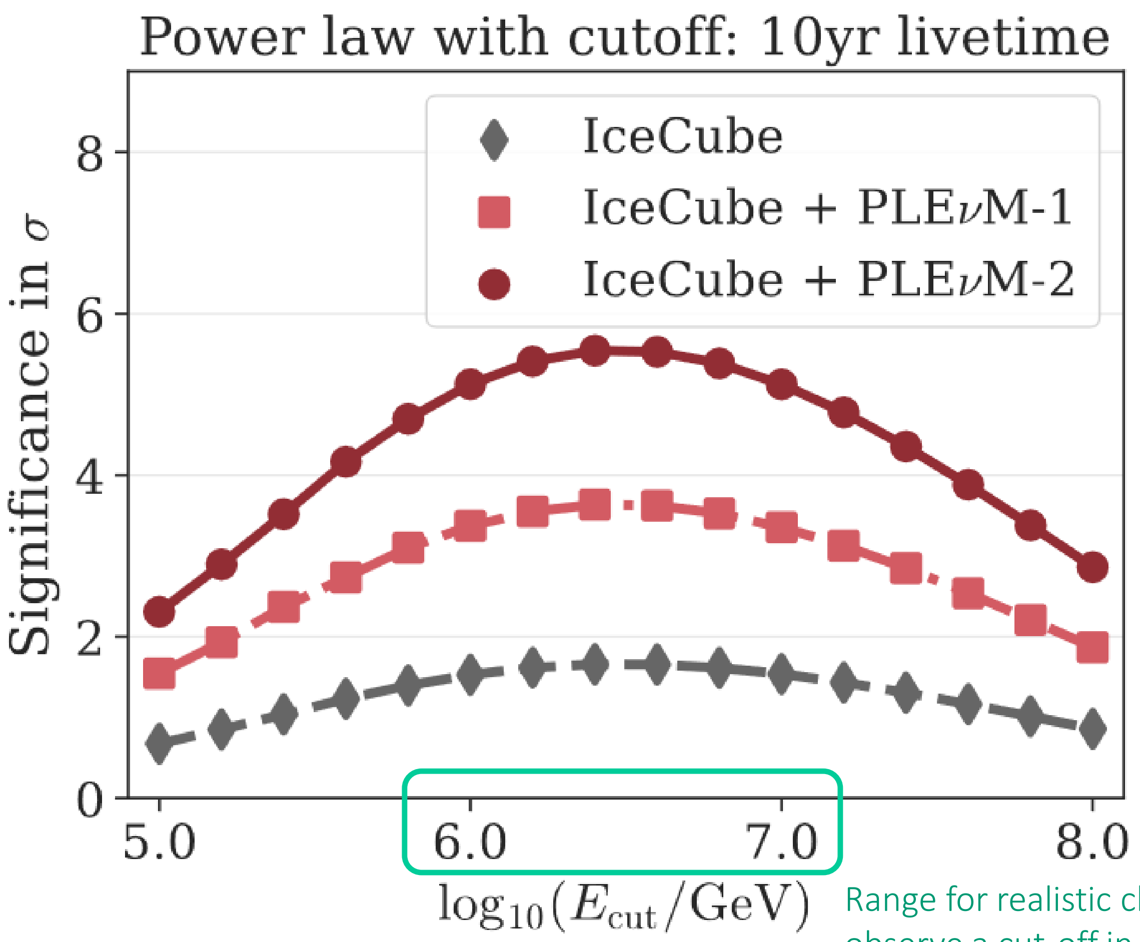
- Baseline model parameters:
  - Atmospheric neutrinos with MCEq
  - Astrophysical flux normalization $1.5 \cdot 10^{-18} / (\mathrm{GeV\ cm^2\ s\ sr})$
  - Spectral index $\gamma = 2.0$
  - Cut-off energy $E_{cut} = 1\ \mathrm{PeV}$ } ★
- Significance: likelihood ratio of $\Lambda(\gamma_{best}, \Phi_{best}, E_{cut,\,best})$ and $\Lambda(E_{cut} = \infty)$ (=pure power law)

- **Estimated significances wrt. pure power law:**
  - **IceCube: $< 2\sigma$**
  - **PLEνM-1: 3σ**
  - **PLEνM-2: 5σ**



Beyond the single power law: exponential cutoff

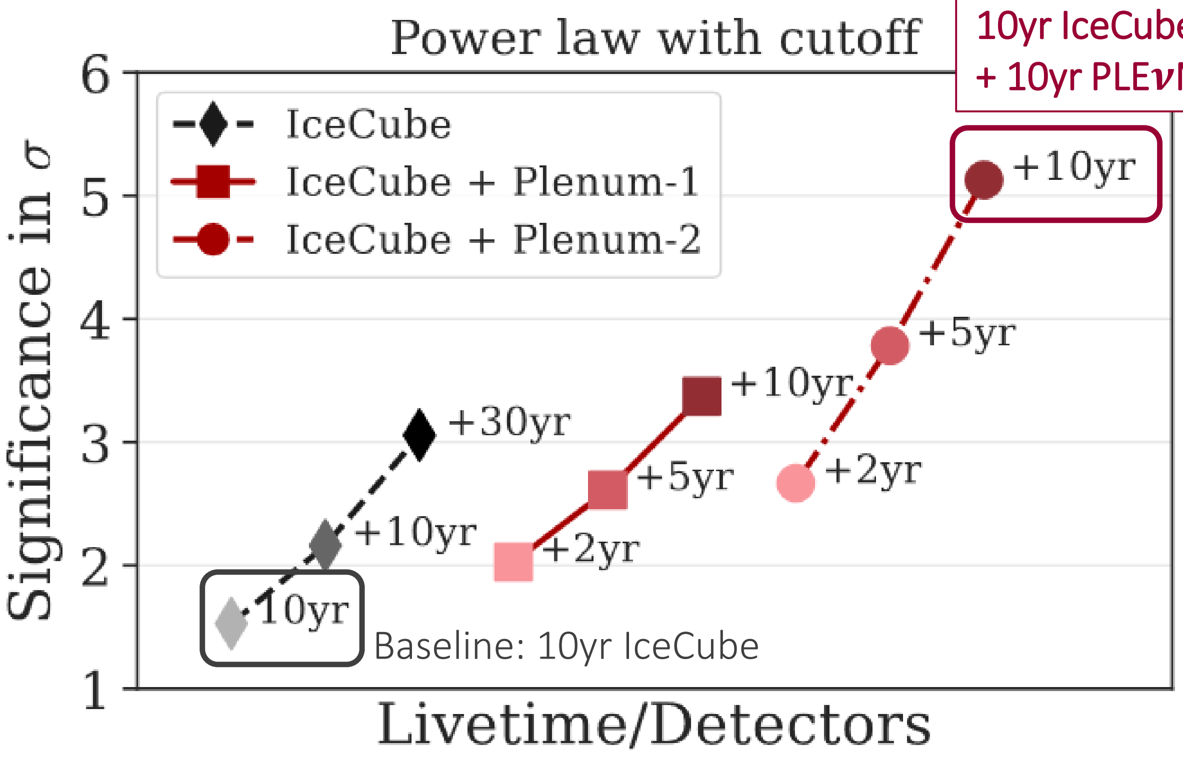
Significance vs. cut-off energy



Range for realistic chance to observe a cut-off in energy: 1 PeV – 10 PeV

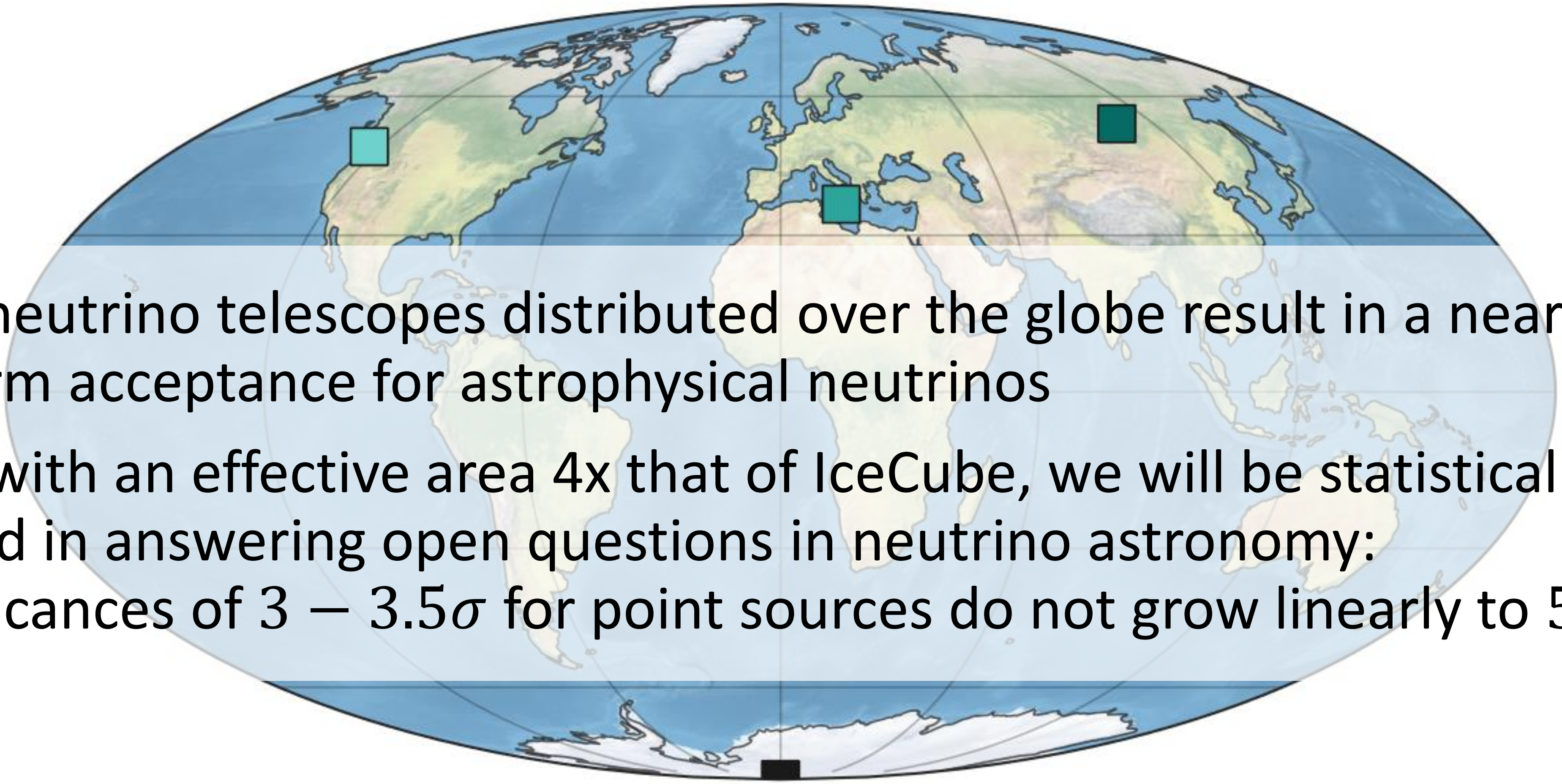
Significance vs. livetimes, $E_{cut} = 1\text{PeV}$

10yr IceCube
+ 10yr PLEνM-2



Key message:
A lot of data is needed to distinguish a cut-off spectrum from a pure power law at 5σ level!

Key messages



1) Four neutrino telescopes distributed over the globe result in a nearly uniform acceptance for astrophysical neutrinos
2) Even with an effective area 4x that of IceCube, we will be statistically limited in answering open questions in neutrino astronomy: Significances of $3 - 3.5\sigma$ for point sources do not grow linearly to 5σ!!

Summary

- PLEνM is a concept for combining data and efforts to improve sensitivity to astrophysical neutrinos compared to single observatories
- Feasibility and performance study based on IceCube's effective area and locations of future telescopes: P-ONE, KM3NeT, Baikal-GVD

Key results

Point-like sources:

- Discovery potential in the South profits significantly from combination of P-ONE, KM3NeT, Baikal-GVD
- Discovery potential in the North profits significantly from a large detector at the South pole like IceCube-Gen2

Diffuse flux:

- Realistic chance to observe a cut-off between 1 and 10 PeV in astrophysical neutrino spectrum with PLEνM
- Large amount of data combined from all neutrino telescopes needed to distinguish a power law with cut-off from a pure power law on 5σ level

Outlook

- Galactic/LHAASO sources
- Galactic plane diffuse emission
- Extragalactic source populations
- Transient neutrino sources
- Neutrino flavor, Particle physics, …
- Public code currently under development: https://github.com/mhuber89/Plenum

Back up slides

References

- "All-sky point-source IceCube data: years 2008-2018" (IceCube Collaboration), http://doi.org/DOI:10.21234/sxvs-mt83
- "Time-integrated Neutrino Source Searches with 10 years of IceCube Data" (IceCube Collaboration), https://doi.org/10.1103/PhysRevLett.124.051103
- "All-sky Search for Time-integrated Neutrino Emission from Astrophysical Sources with 7 yr of IceCube Data" (IceCube Collaboration), https://doi.org/10.3847/1538-4357/835/2/151
- "Measurement of the diffuse astrophysical muon-neutrino spectrum with ten years of IceCube data" (Stettner for the IceCube Collaboration), https://doi.org/10.22323/1.358.1017
- "IceCube-Gen2: the window to the extreme Universe" (IceCube-Gen2 Collaboration), https://doi.org/10.1088/1361-6471/abbd48
- "Letter of intent for KM3NeT 2.0" (KM3NeT Collaboration), https://doi.org/10.1088/0954-3899/43/8/084001
- "Neutrino telescope in Lake Baikal: Present and Future" (Baikal-GVD Collaboration), https://doi.org/10.22323/1.358.1011
- "The Pacific Ocean Neutrino Experiment" (P-ONE Collaboration), https://doi.org/10.1038/s41550-020-1182-4
- "PLEnuM: A global and distributed monitoring system of high-energy astrophysical neutrinos" (Schumacher et al.) https://doi.org/10.22323/1.395.1185
- "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert" (IceCube Collaboration), https://doi.org/10.1126/science.aat2890
- "Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A" (The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403 teams), https://doi.org/10.1126/science.aat1378

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- Significant increase of number of muon neutrinos in Southern Hemisphere, especially for soft spectral indices due to detectors in the Northern Hemisphere
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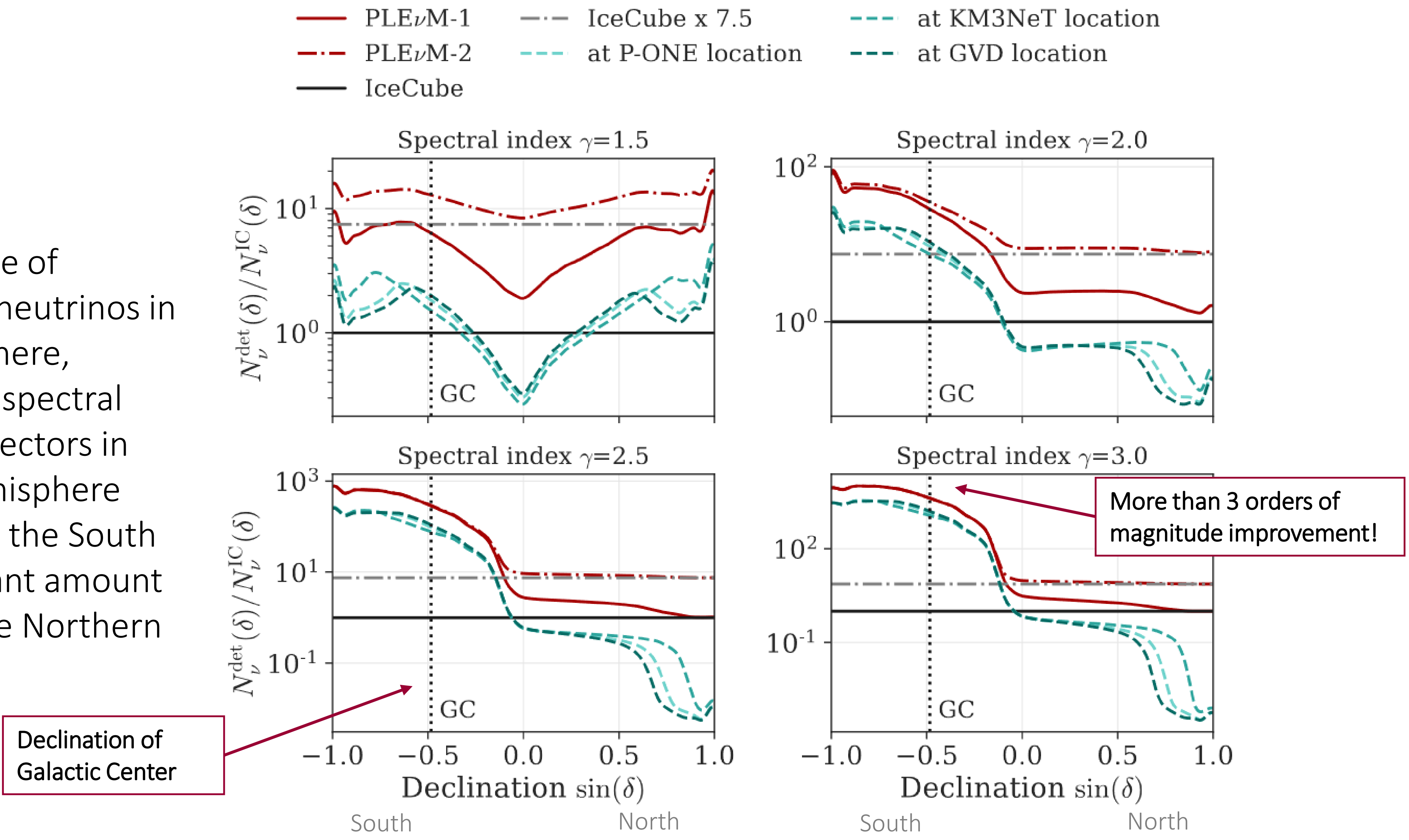


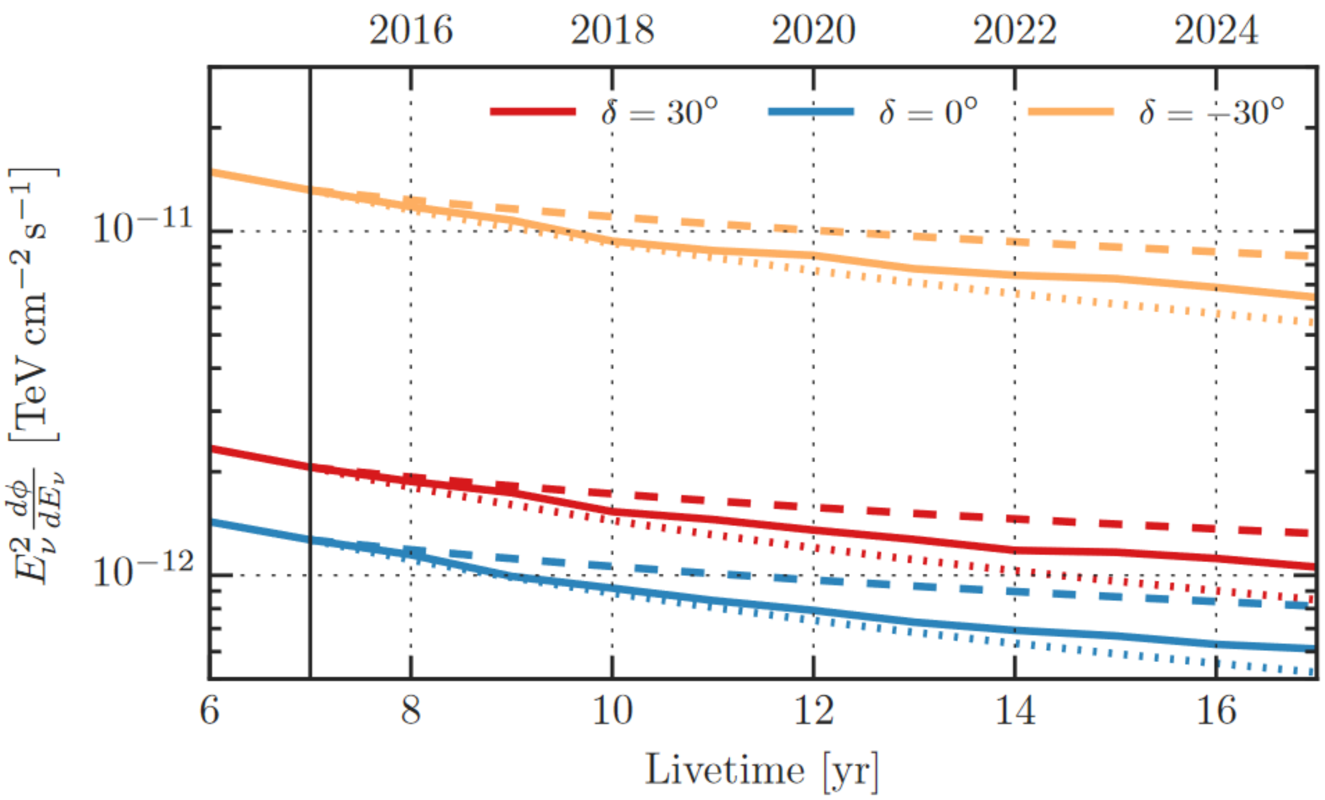
Prospects: Point-source searches

$$\mathrm{d}\Phi/\mathrm{d}E = \Phi^{\mathrm{disc.}} \cdot (E/1\,\mathrm{TeV})^{-\gamma} \text{ at } 1\,\mathrm{TeV}$$

- Scaling of discovery potential with time/effective area:
  See PhD theses of
  - S. Coenders (TUM)
  - R. Reimann (RWTH)
  - M. Huber (TUM)

$$\frac{\phi_0^{\mathrm{disc.}}(T_{\mathrm{live}} = T_0)}{\phi^{\mathrm{disc.}_1}(T_{\mathrm{live}} = T_1)} = \begin{cases} \left(\frac{T_0}{T_1}\right)^{-0.8} & \text{if } A_{\mathrm{eff}} = \text{const.} \\ \left(\frac{A_{\mathrm{eff},0}}{T_{\mathrm{eff},1}}\right)^{-0.8} & \text{if } T_{\mathrm{live}} = \text{const.} \end{cases}$$

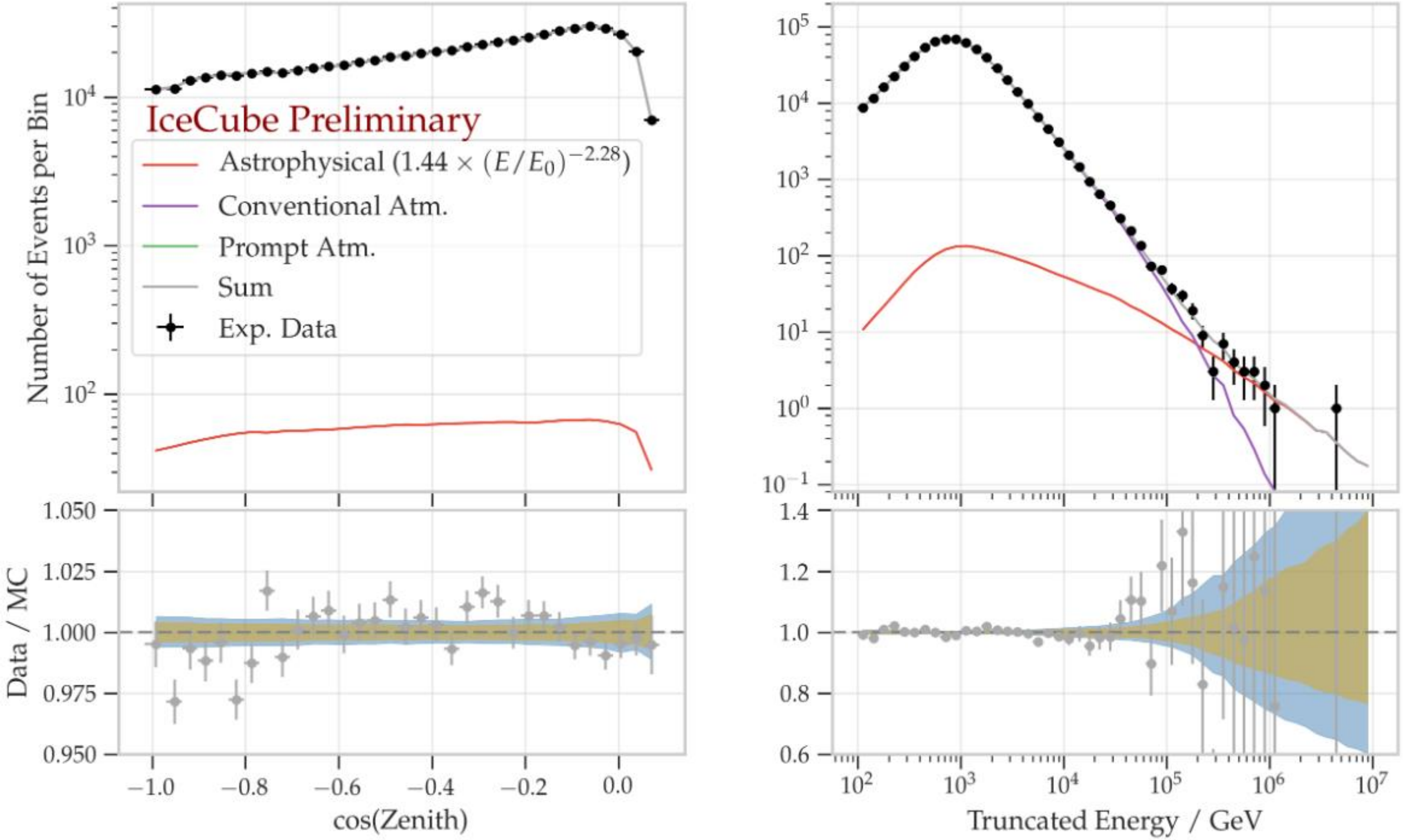
- Motivation:
  - Scaling with $1/T$ expected for analysis limited by signal statistics
  - Scaling with $1/\sqrt{T}$ expected for analysis limited due to background



ALL-SKY SEARCH FOR TIME-INTEGRATED NEUTRINO EMISSION FROM ASTROPHYSICAL SOURCESWITH 7 YR OF ICECUBE DATA
arXiv:1609.04981

Diffuse astrophysical neutrino flux

Measurement of the Diffuse Astrophysical Muon-Neutrino Spectrum with Ten Years of IceCube Data
arXiv:1908.09551



Method: Diffuse astrophysical neutrino flux

- Binned maximum likelihood method using poisson statistics and Asimov data/Wilks' theorem

$$\Lambda(data\ k \mid hypothesis\ \mu) = \prod_{bin\ i} \frac{\mu_i^{k_i}}{k_i!} \cdot \exp(-\mu_i)$$

- Binned in reconstructed energy and declination
- Analysis strategy similar to IceCube's method, but without systematic uncertainties
- Baseline parameters:
  - Atmospheric neutrino background calculated with MCEq*
  - Astrophysical flux normalization $\Phi_0 = 1.44 \cdot 10^{-18} / (\mathrm{GeV\ cm^2\ s\ sr})$
  - Spectral index $\gamma = 2.28$
  - Power law: $\frac{d\Phi}{dE} = \Phi_0 \cdot \left(\frac{E}{100TeV}\right)^{-\gamma}$

Asimov data k: "perfect" representative data set based on model parameters → good for calculating expectation values

Model with parameters:

$$\mu = \mu_{signal} + \mu_{background}$$
$$= \mu_{astro}(\Phi_0, \gamma) + \mu_{atmos}(\mathrm{const} \cdot \mathrm{MCEq})$$

Hypothesis test:

$$TS = -2 \log\left(\frac{\Lambda_0}{\Lambda_1}\right)$$

→ „Wilks' theorem offers an asymptotic distribution of the log-likelihood ratio statistic, which can be used to produce confidence intervals for maximum-likelihood estimates or as a test statistic for performing the likelihood-ratio test."

*https://github.com/afedynitch/MCEq with hadronic model Sibyll-2.3c and atmosphere: NRLMSISE-00 Model2001