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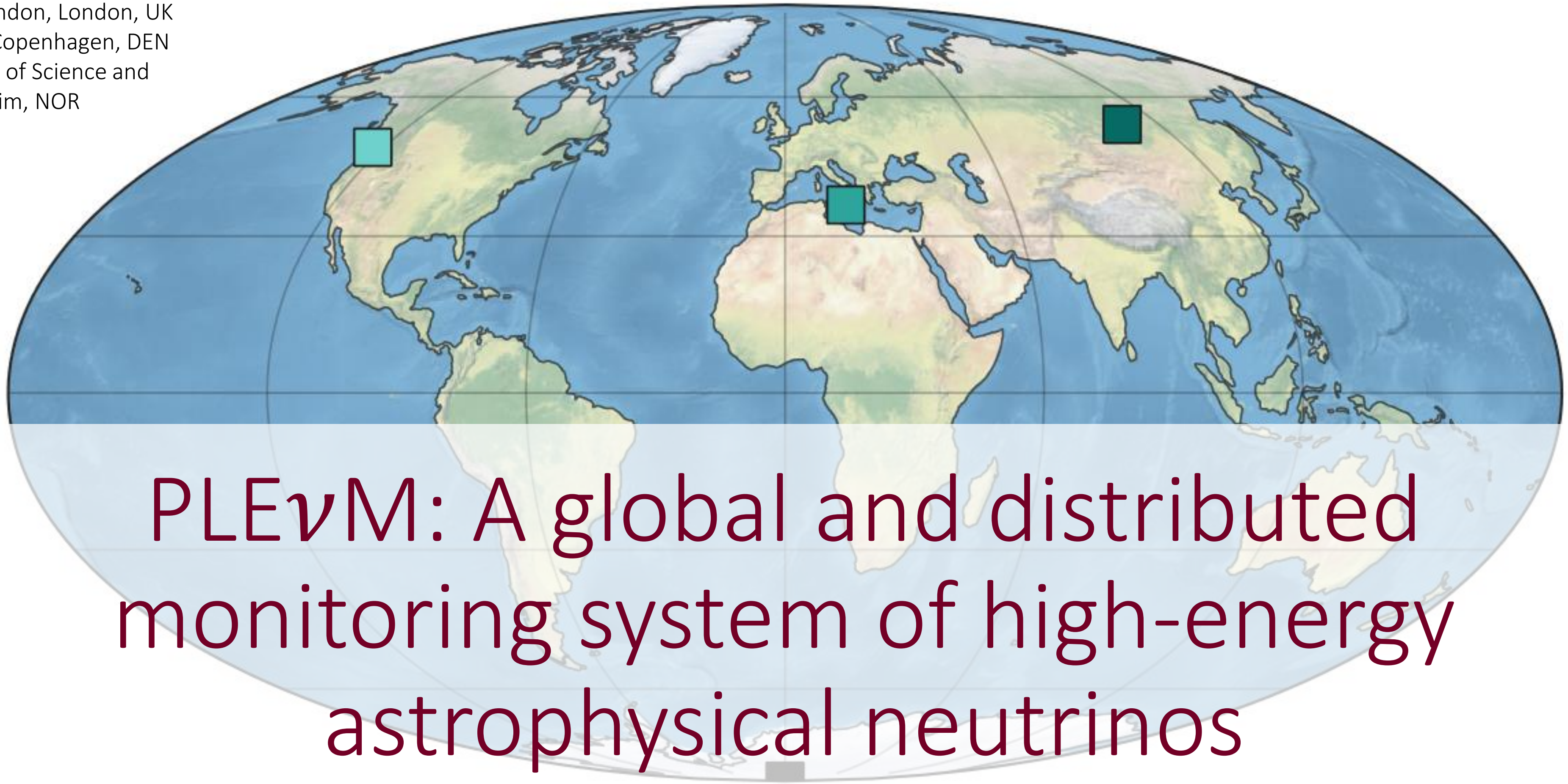

PLEνM: A global and distributed monitoring system of high-energy astrophysical neutrinos

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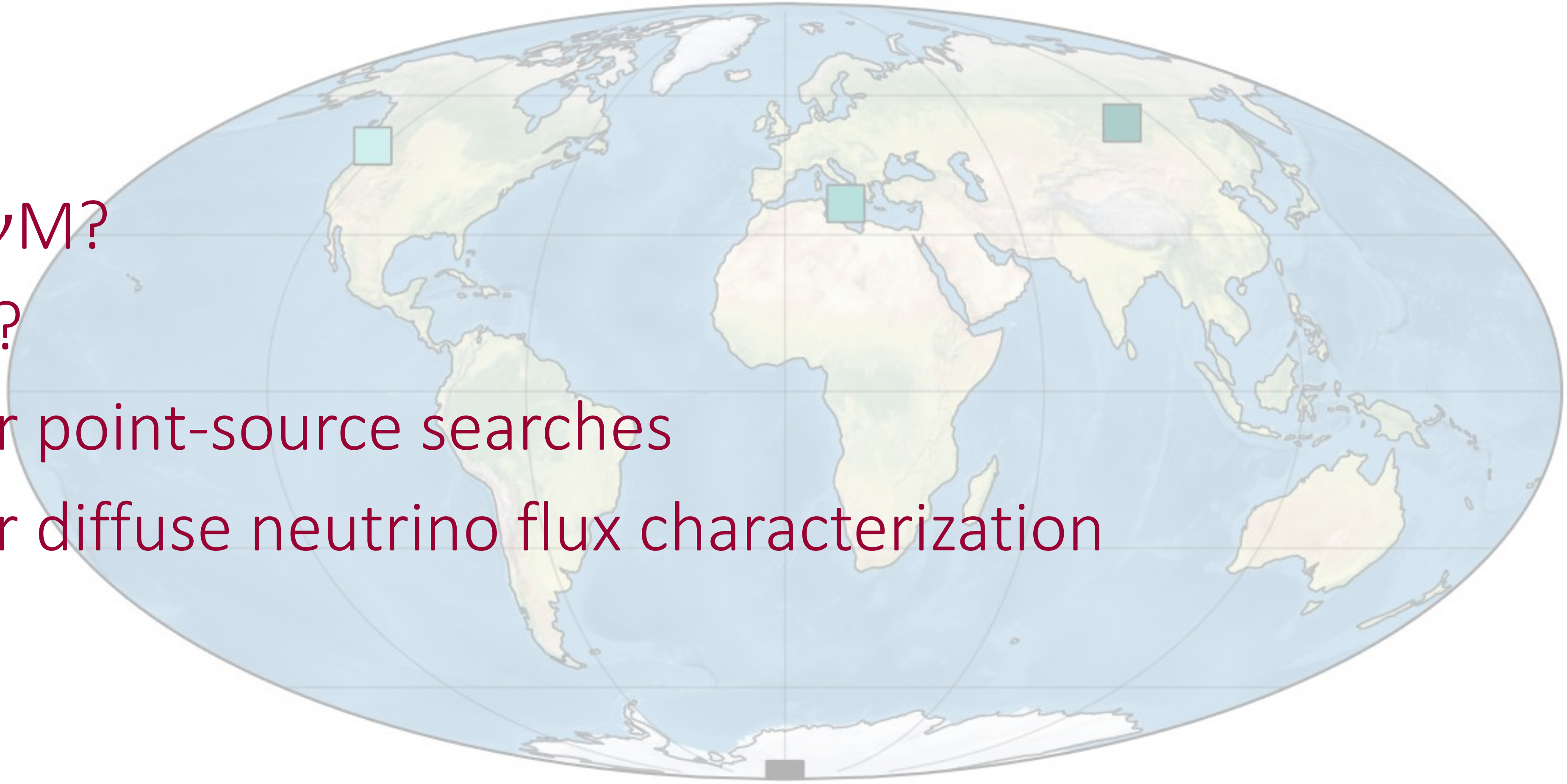
SFB 1258 Neutrinos Dark Matter Messengers

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

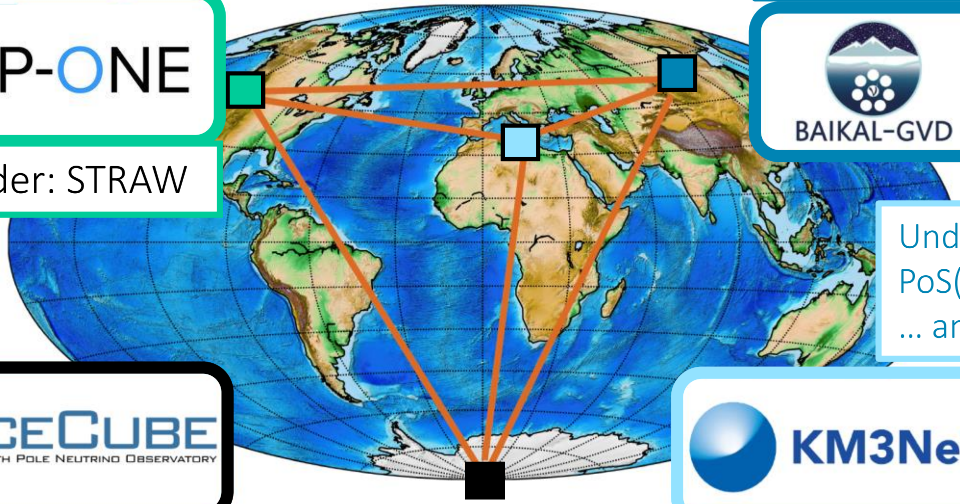
PoS(ICRC2021)002 (I. Belolaptikov)
… and many more

P-ONE

Pathfinder: STRAW

BAIKAL-GVD

PoS(ICRC2021)024 (E. Resconi)
PoS(ICRC2021)1092 (I.C. Rea)
PoS(ICRC2021)1197 (C. Spannfellner)
PoS(ICRC2021)1160 (C. Fruck)



Underwater Neutrino Telescopes:
PoS(ICRC2021)042 (P. Coyle)
… and many more

PoS(ICRC2021)022 (M. Kowalski)
… and many more

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

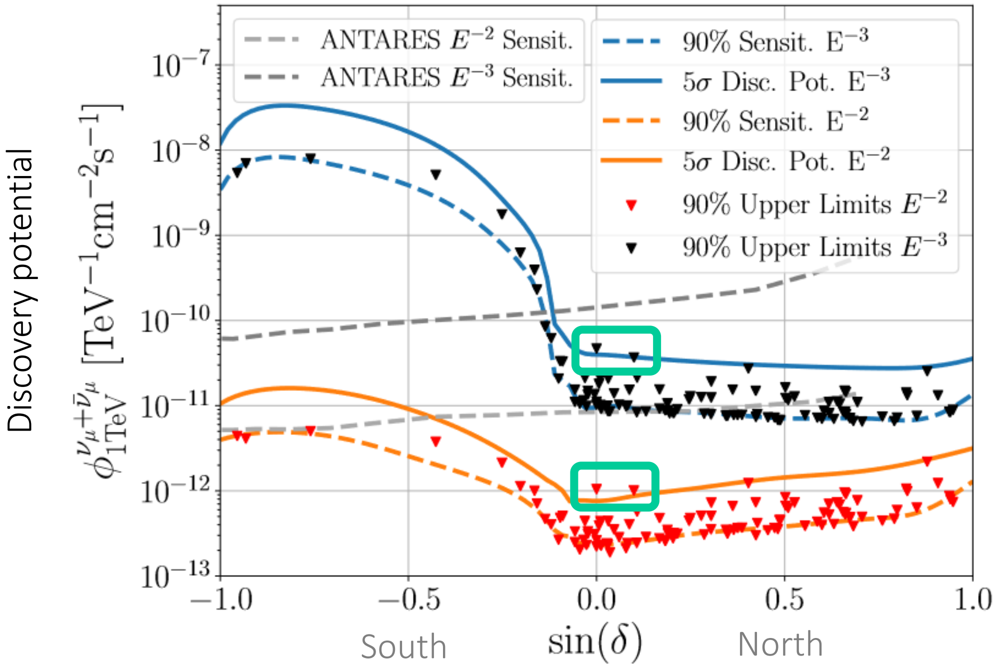
KM3NeT

PhD thesis M. Huber, TUM

Why PLEνM? (1)

Open questions in Neutrino Astronomy due to limited statistics:

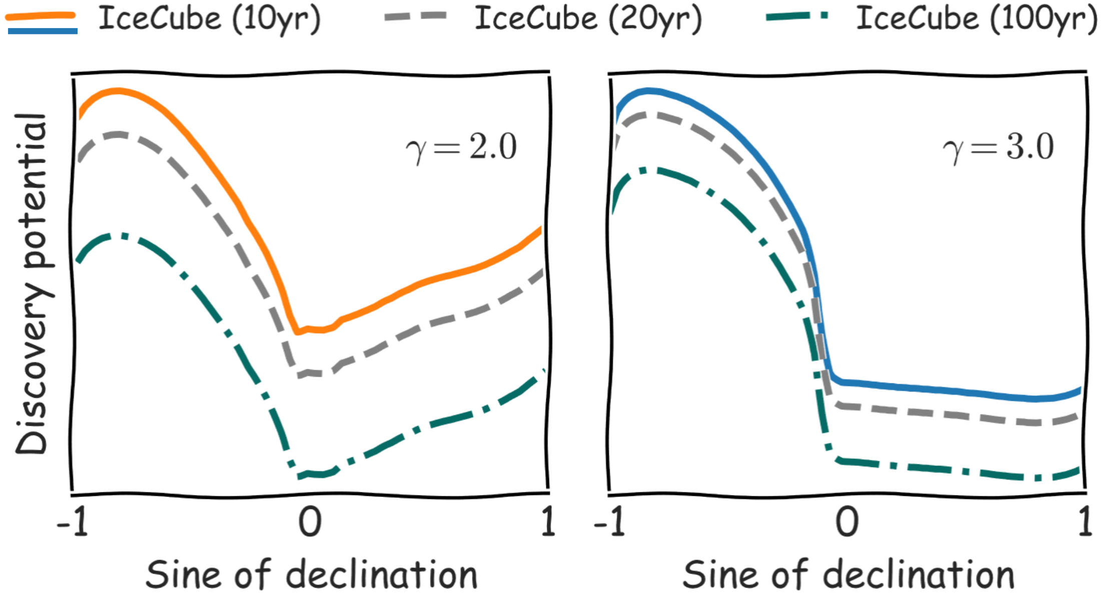
- Population of Galactic and Extragalactic Neutrino Sources?
- Distinct features in astrophysical neutrino spectrum?
- Flavor ratio of astrophysical neutrinos?
- Physics beyond the standard model with astrophysical neutrinos?
- …



"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>



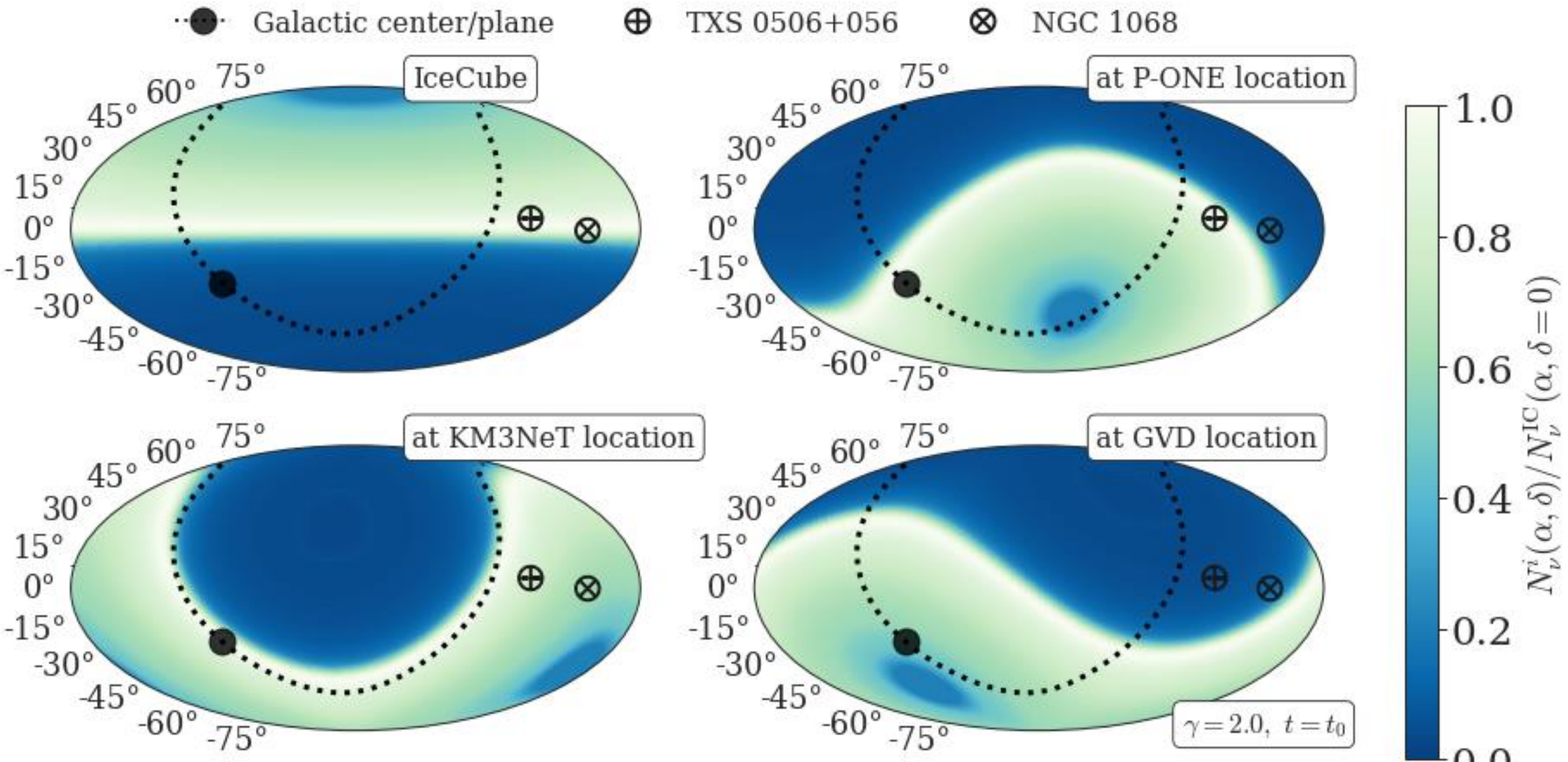
Why PLEνM? (2)

Illustration: Number of neutrinos relative to IceCube's number of neutrinos at horizon

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

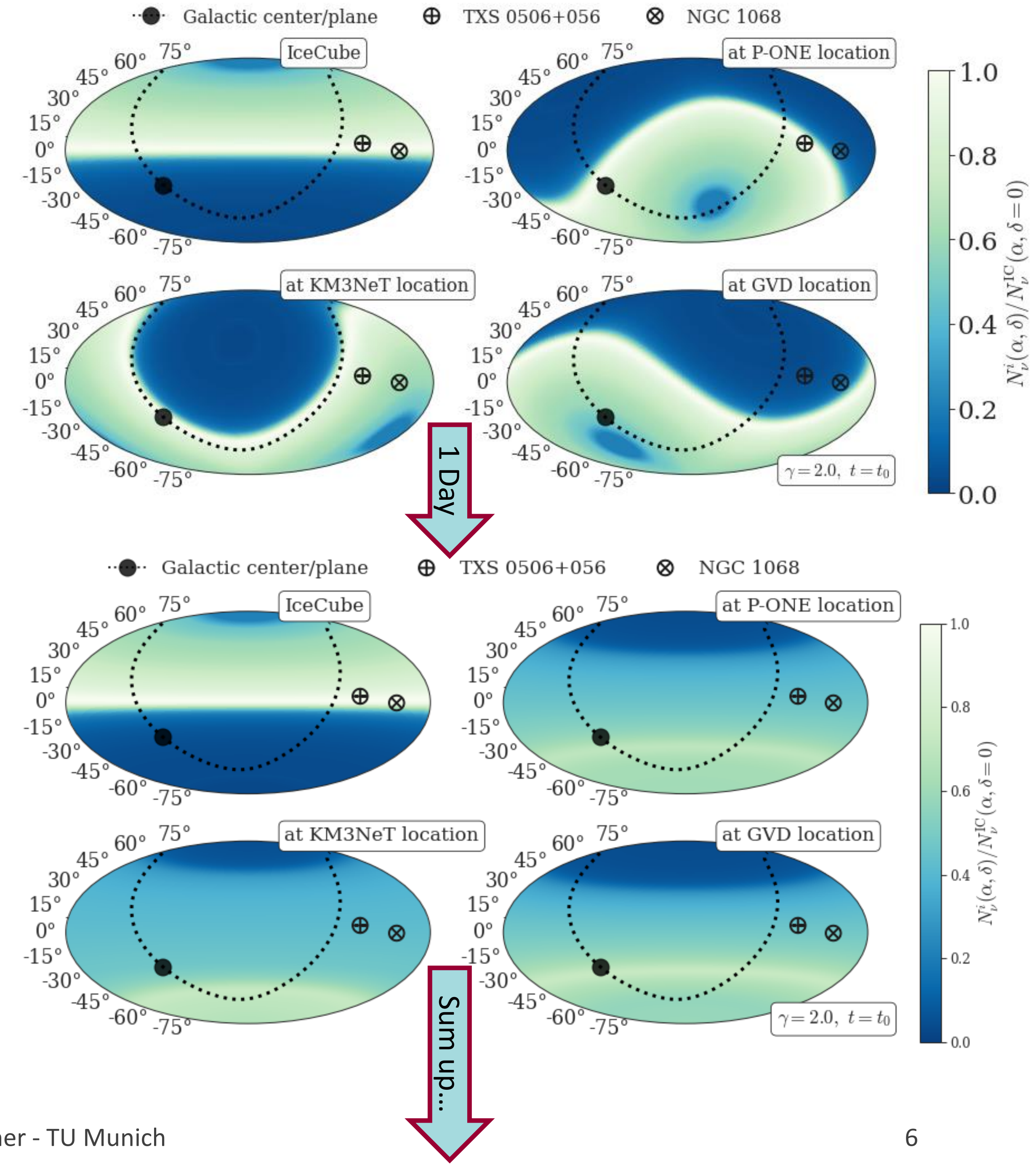


Concept: generate new effective areas at different locations on Earth

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

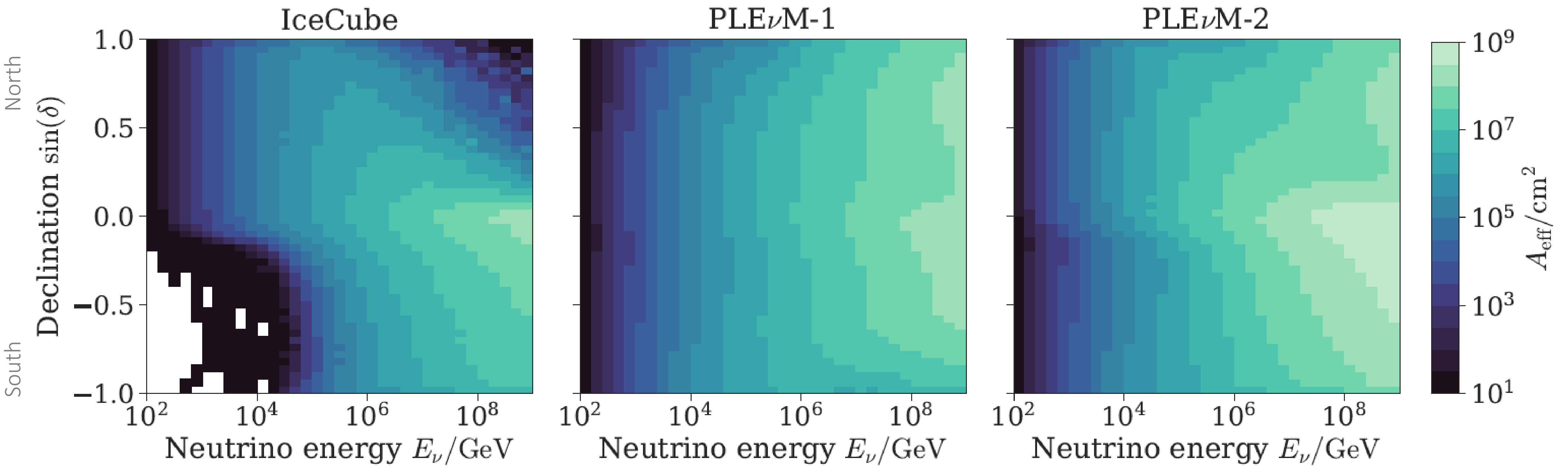


Combined effective areas of PLEνM

IceCube A_{eff} for through-going muon neutrinos

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

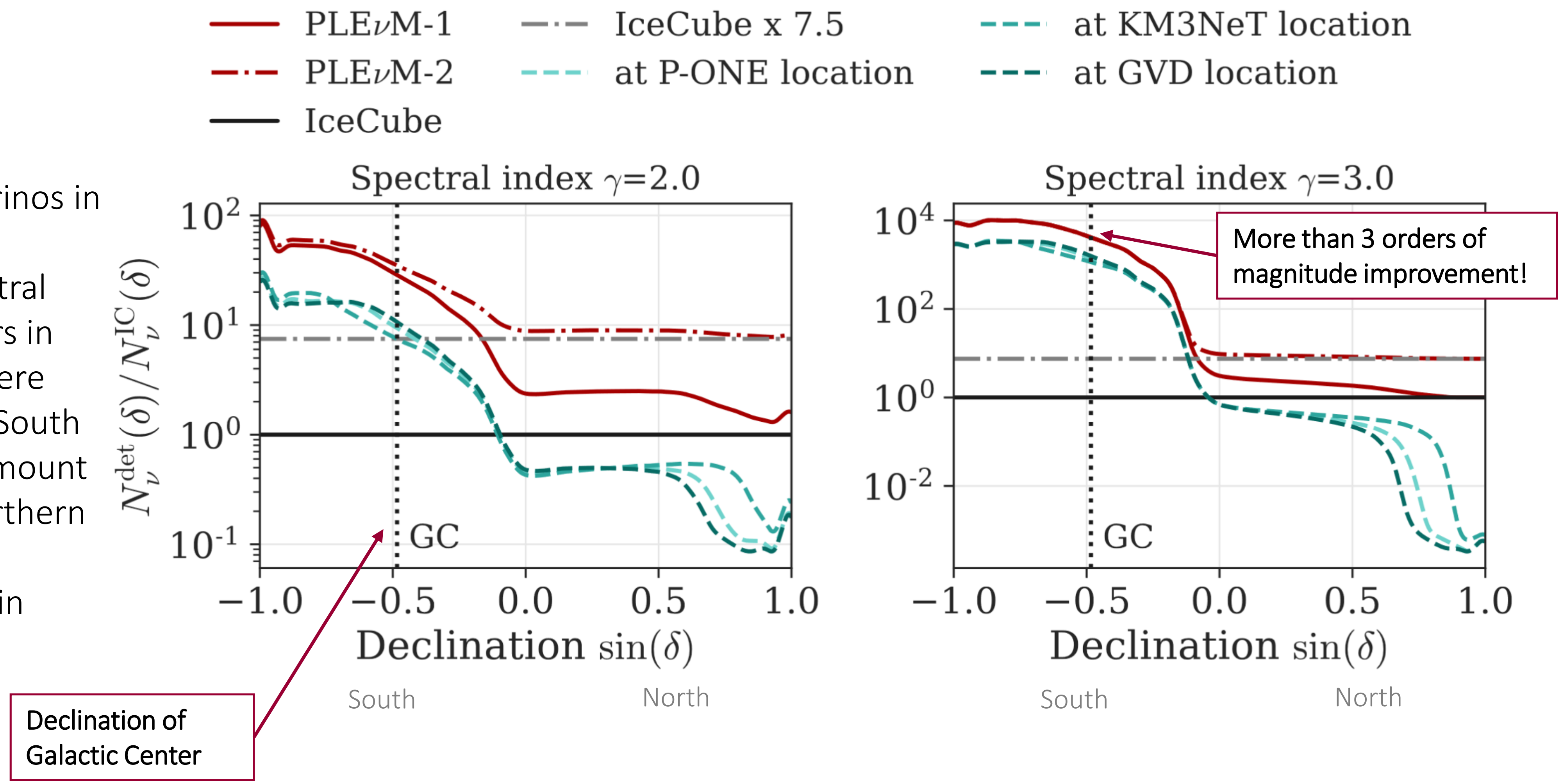
PLEνM-2: replace IceCube's contribution with Potential future telescope at South Pole: 7.5 x IceCube A_{eff} *



* 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)



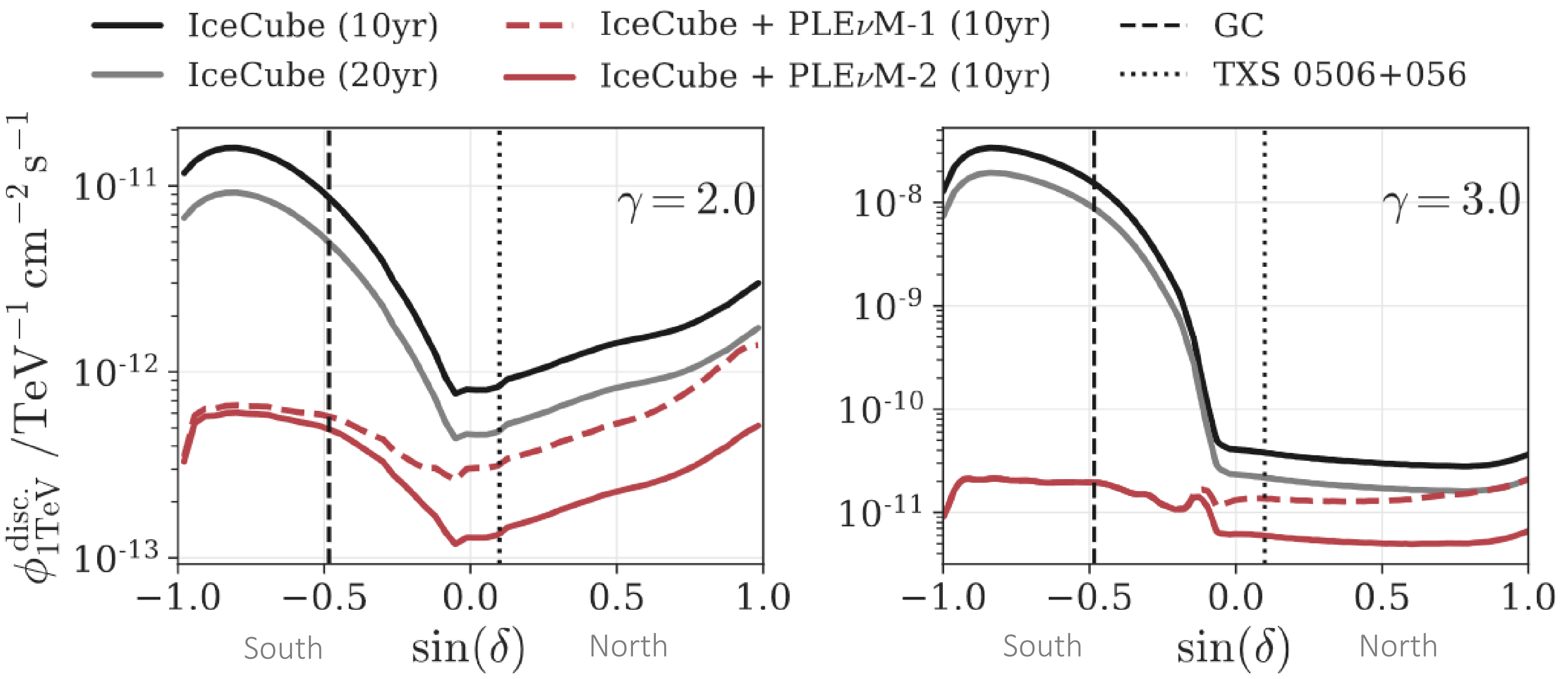
Prospects: Point-source searches

- 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: $\Phi^{\text{disc}}_{\text{PLE}\nu\text{M}} \propto \Phi^{\text{disc}}_{\text{IC}} \cdot A_{\text{eff}}^{-0.8}$ (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



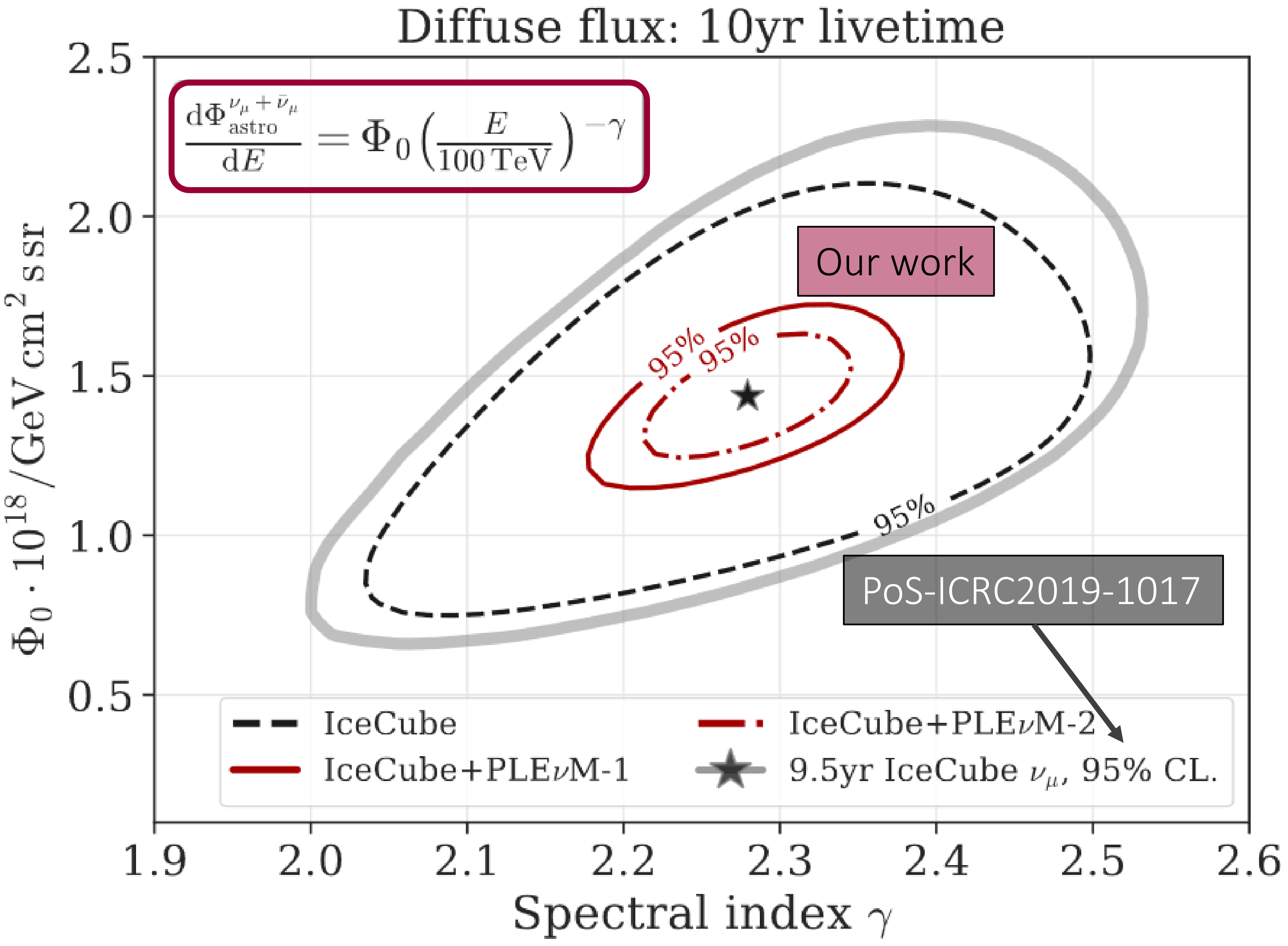
*Neutrino flux per source: $d\Phi/dE = \Phi^{\text{disc.}} \cdot (E/1\,\text{TeV})^{-\gamma}$ at 1 TeV

Prospects: Diffuse astrophysical neutrino flux

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

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

- Analysis strategy similar to IceCube's method, but without systematic uncertainties
- Model parameters:
  - Atmospheric neutrino background calculated with MCEq*
  - Astrophysical flux normalization Φ_0
  - Spectral index γ
- 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)

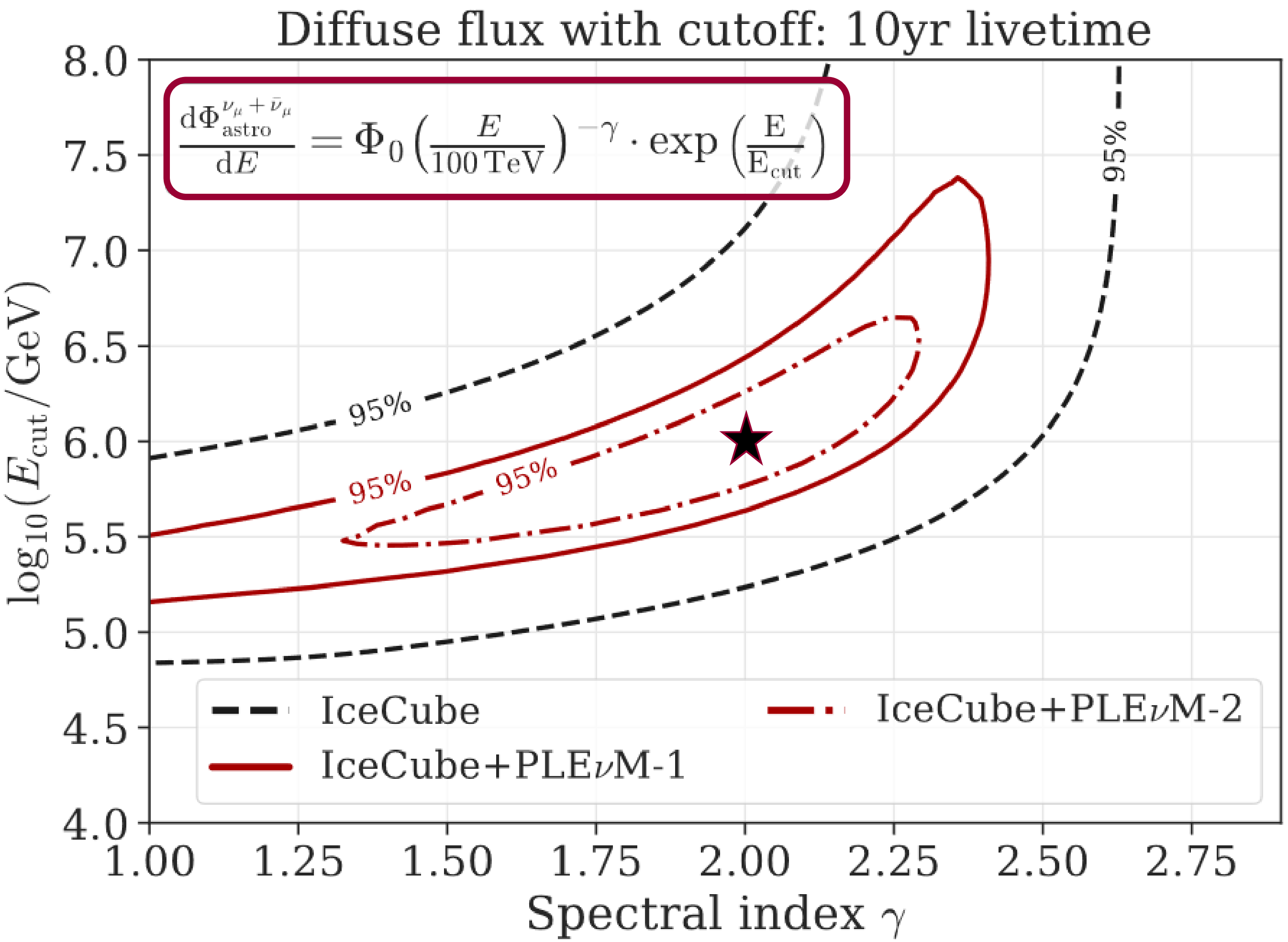


*https://github.com/afedynitch/MCEq with hadronic model Sibyll-2.3c and atmosphere: NRLMSISE-00 Model2001

Beyond the single power law: exponential cutoff

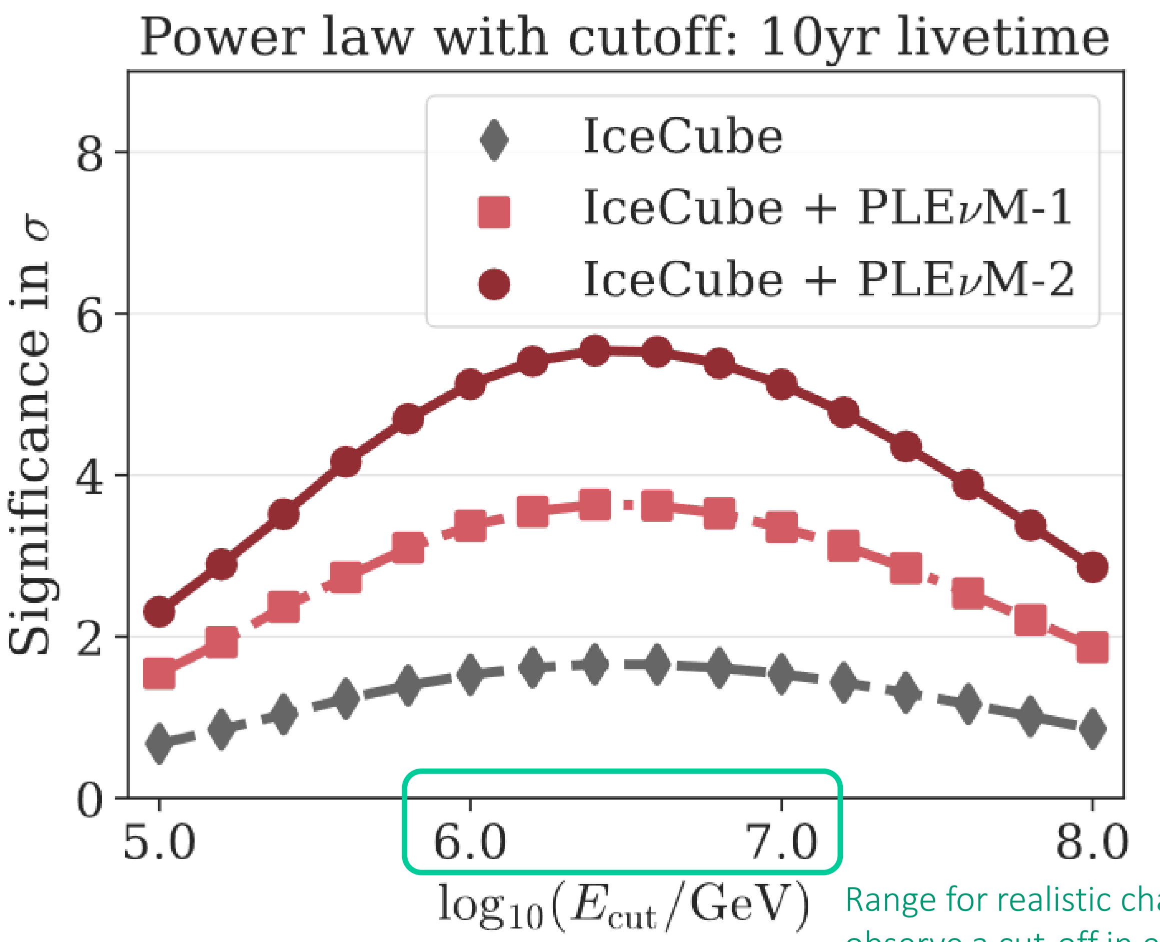
- Baseline model parameters:
  - Atmospheric neutrinos with MCEq
  - Astrophysical flux normalization $1.5 \cdot 10^{-18}/(\mathrm{GeV\ cm^2\ s\ sr})$
  - Spectral index $\gamma = 2.0$ } ★
  - Cut-off energy $E_{cut} = 1\ \mathrm{PeV}$

- Estimated significances wrt. pure power law:
  - IceCube: $< \mathbf{2\sigma}$
  - PLEνM-1: $\mathbf{3\sigma}$
  - PLEνM-2: $\mathbf{5\sigma}$



Beyond the single power law: exponential cutoff

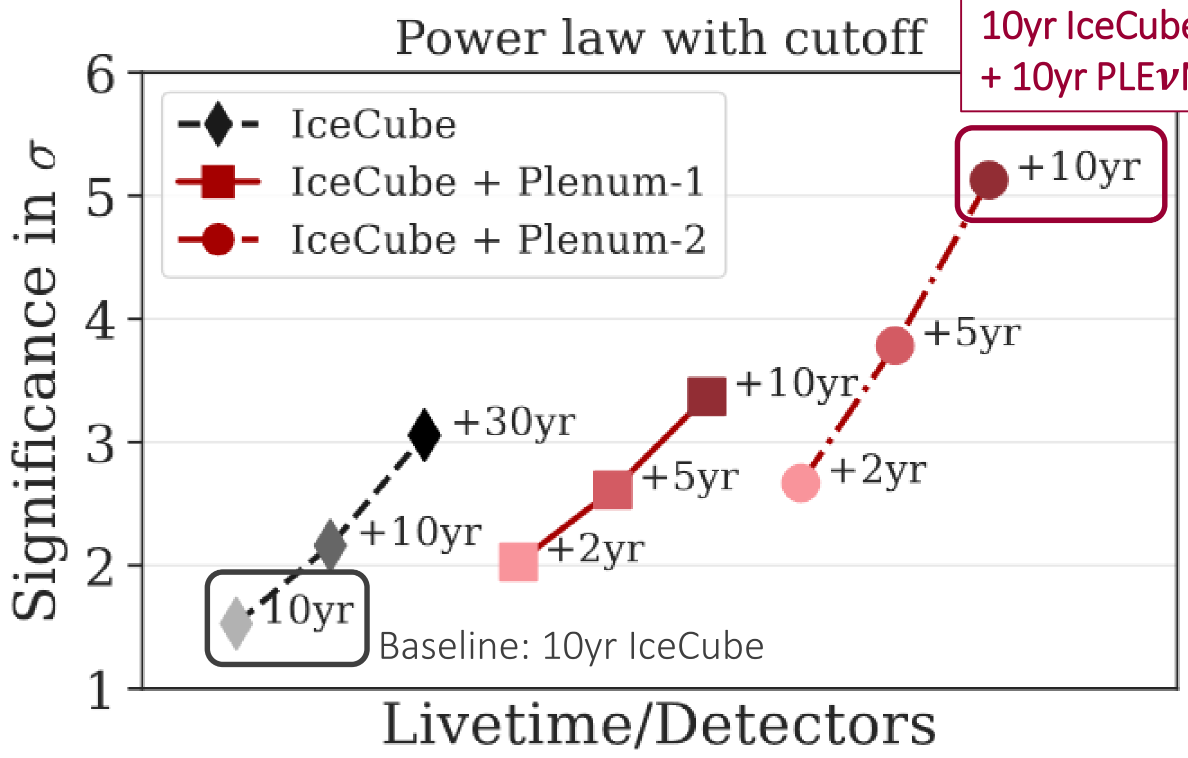
Significance vs. cut-off energy



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



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

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 powerlaw 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

Expected number of neutrinos relative to IceCube

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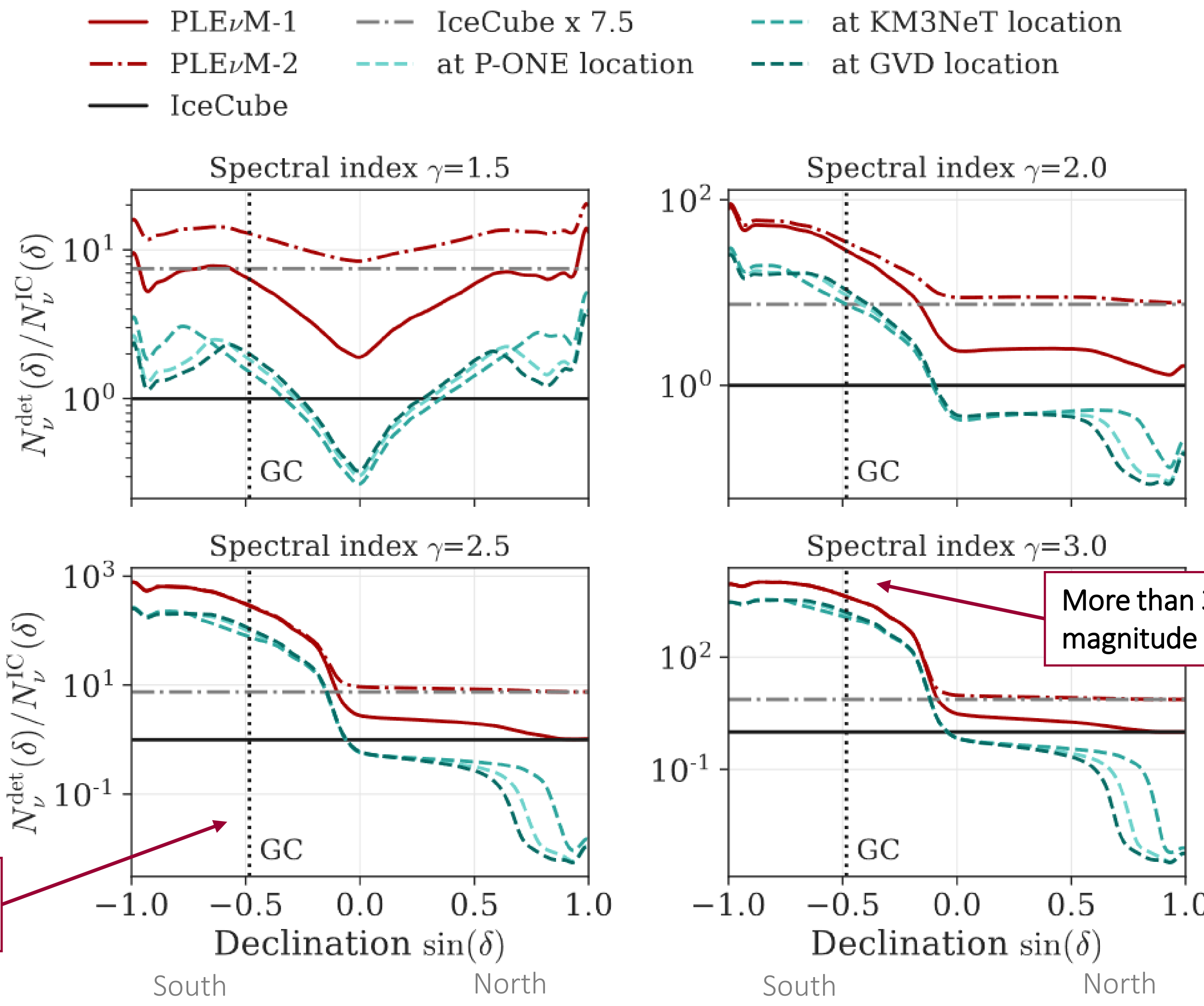


More than 3 orders of magnitude improvement!

Declination of Galactic Center

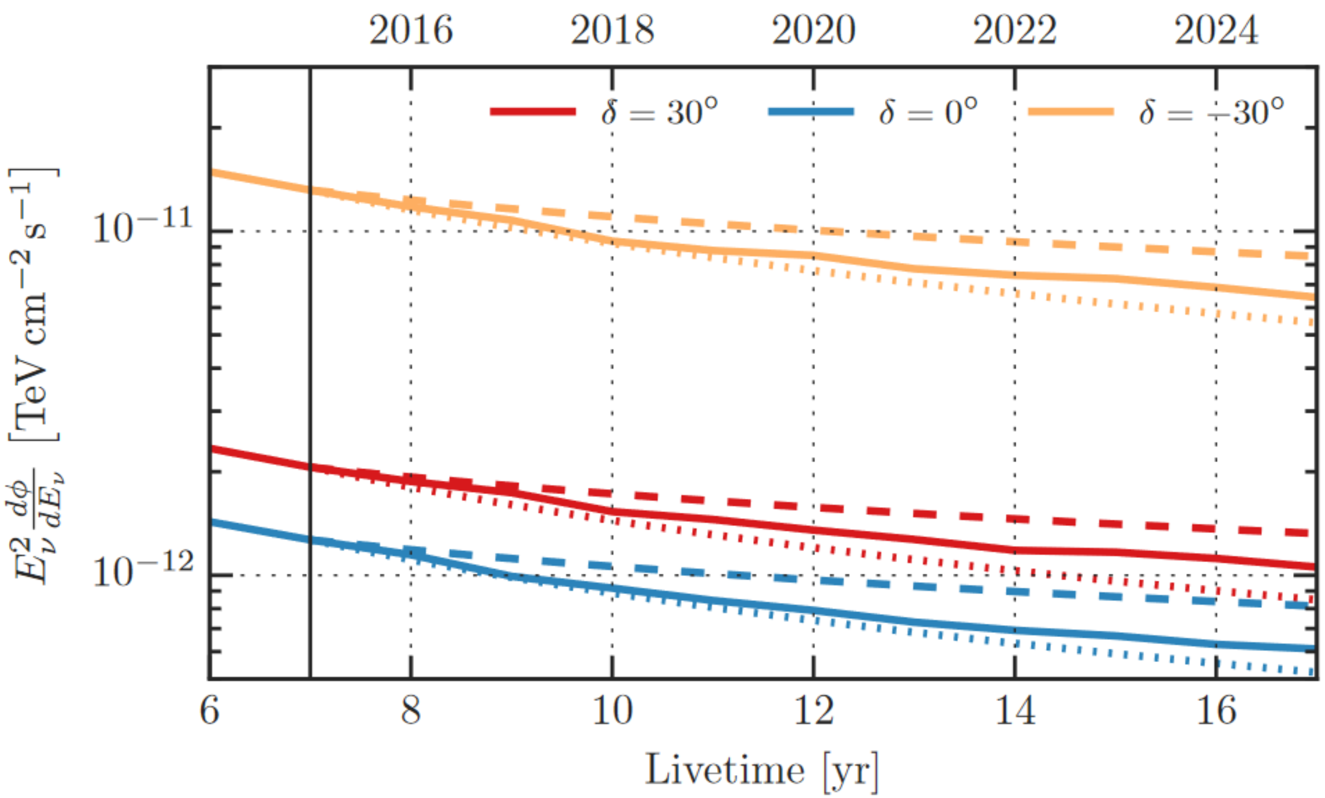
Prospects: Point-source searches

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

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

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

- 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