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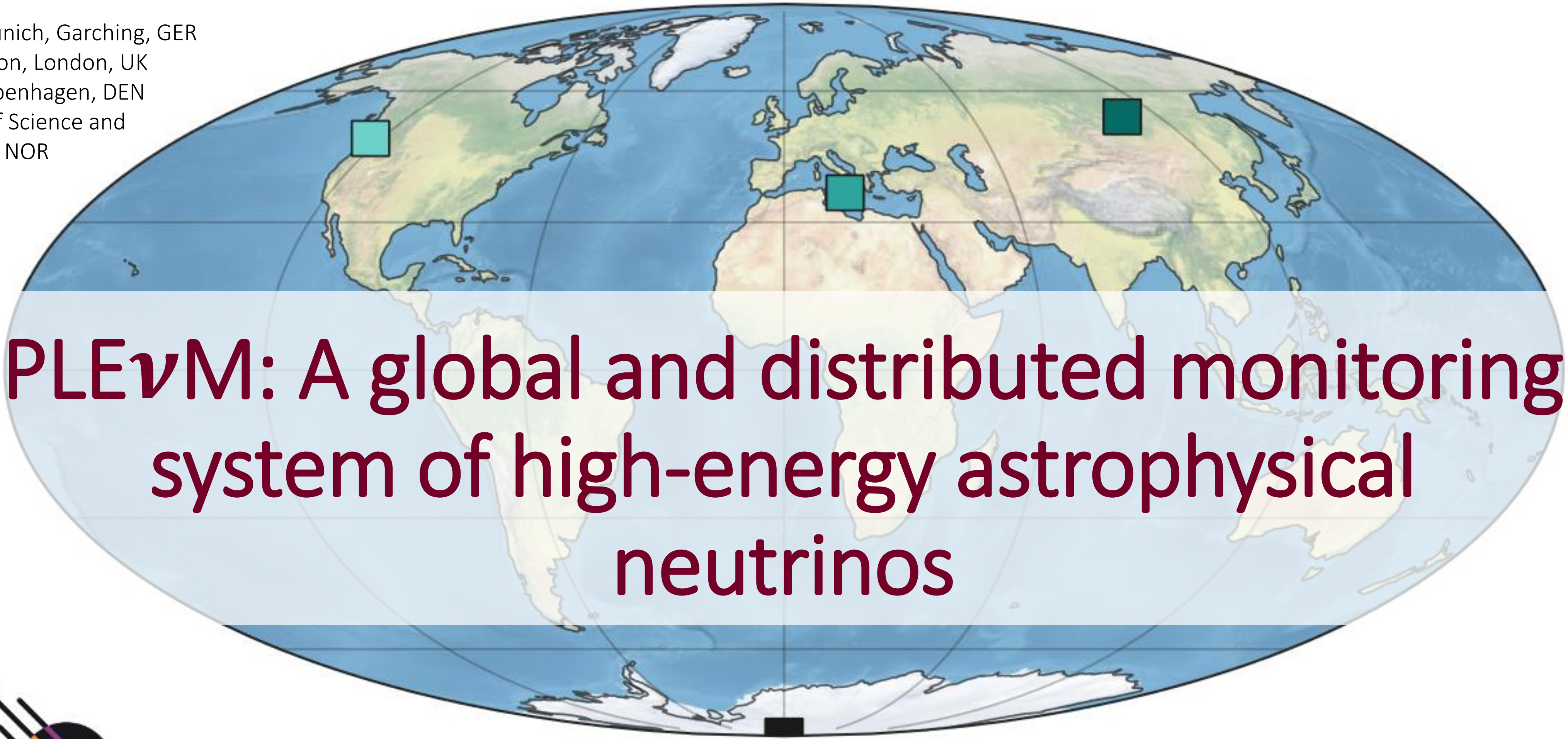

PLEνM: A global and distributed monitoring system of high-energy astrophysical neutrinos

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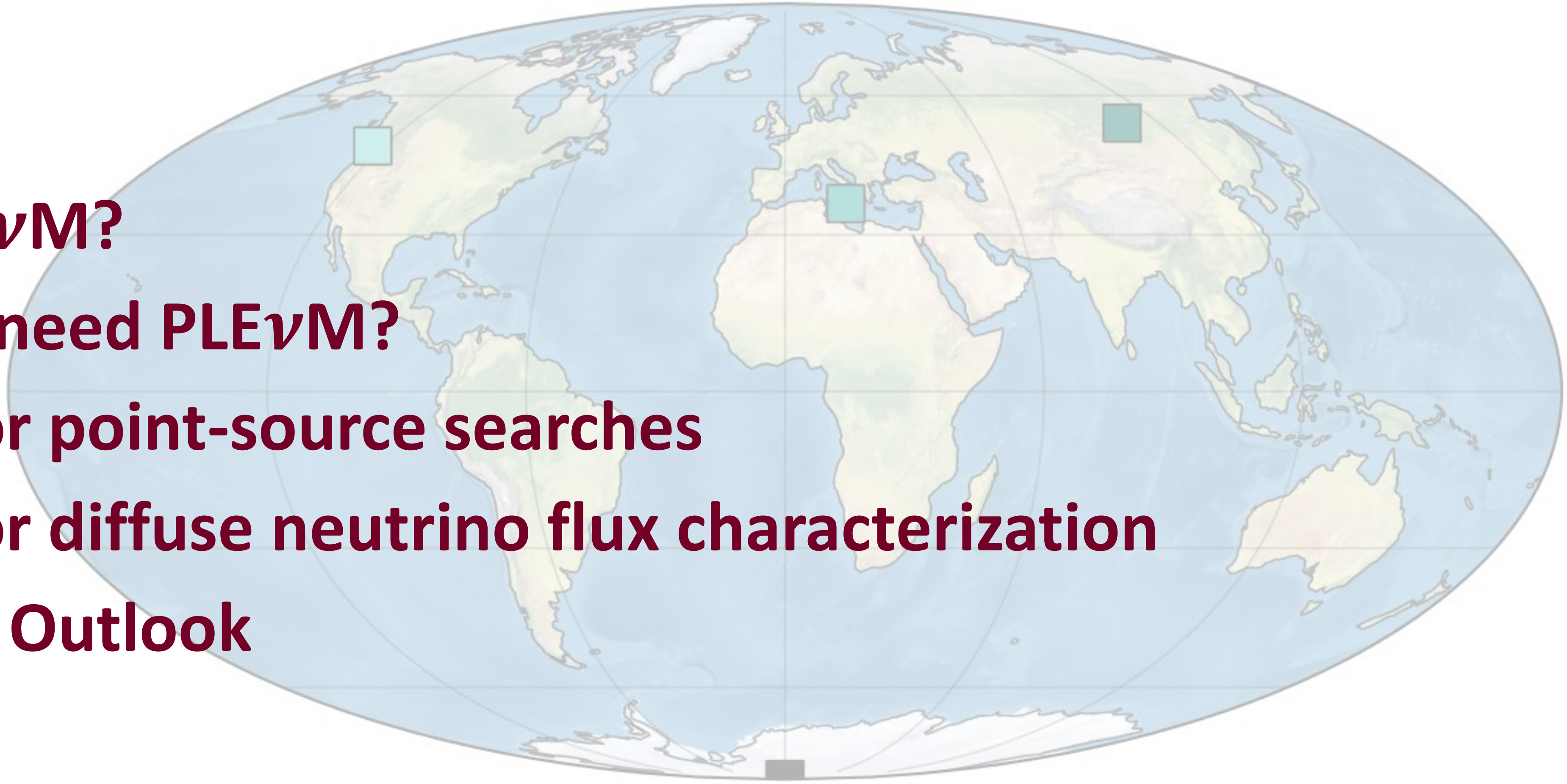
TECHNISCHE UNIVERSITÄT MÜNCHEN

SFB 1258 Neutrinos Dark Matter Messengers

2021 TEV Particle Astrophysics Conference

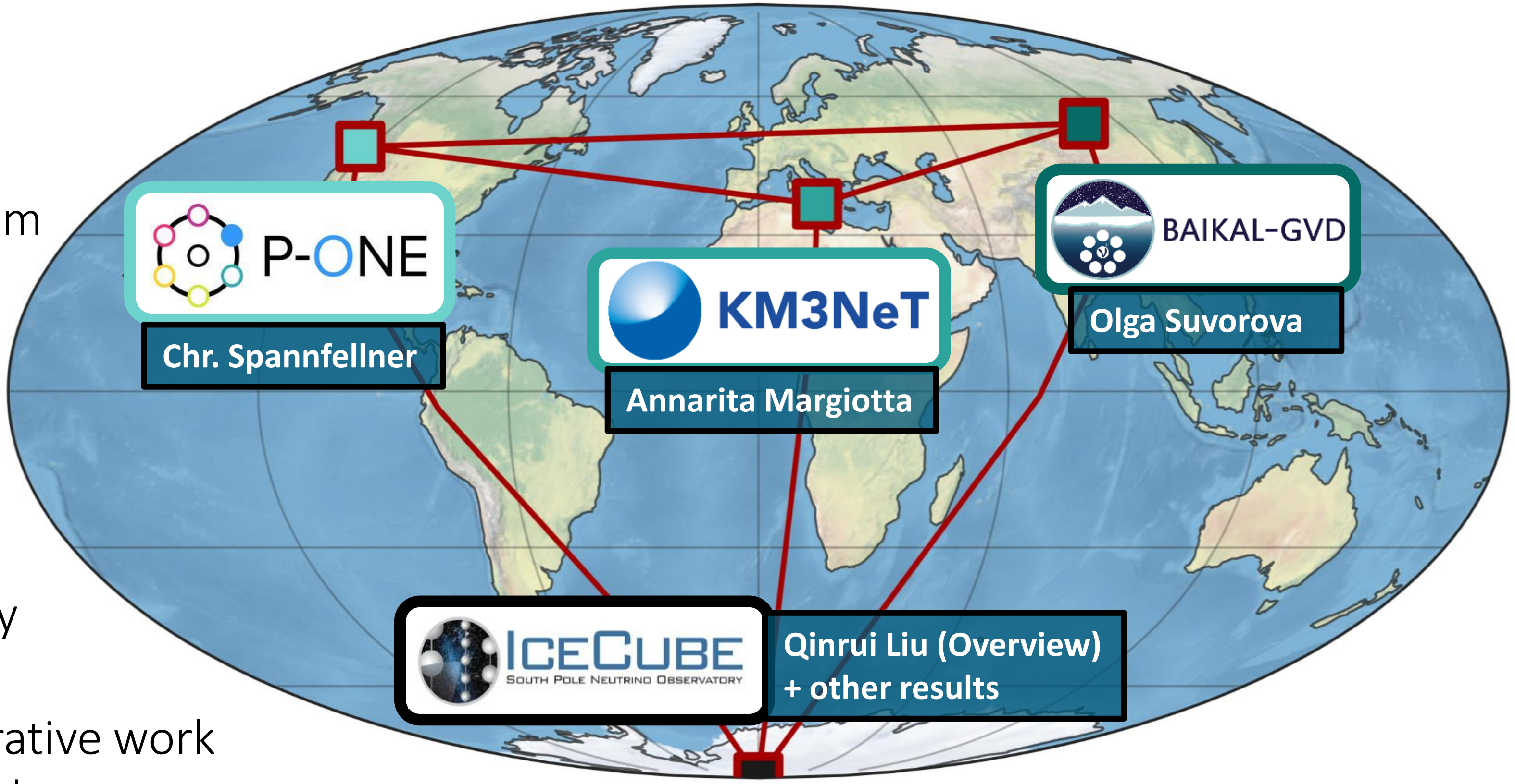
Outline



- **What is PLEνM?**
- **Why do we need PLEνM?**
- **Prospects for point-source searches**
- **Prospects for diffuse neutrino flux characterization**
- **Summary & Outlook**

What is PLEνM?

- PLanEtary neutrino (ν) Monitoring system
- Concept for repository of high-energy neutrino observations of current and future neutrino telescopes
- Goals:
  - 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



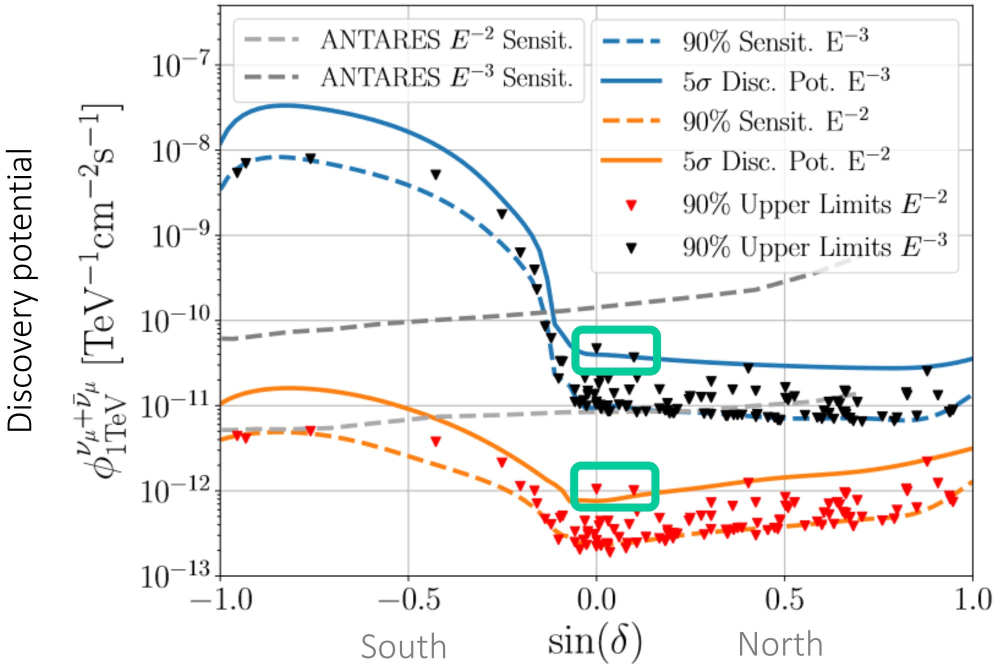
- Current approach: Combine exposure from telescopes at the location of P-ONE, KM3NeT, Baikal-GVD and IceCube/IceCube-Gen2
- Based on work by Matthias Huber to answer the question: are multiple neutrino telescopes all over the globe better than one telescope?

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?
- …

See talk by Qinrui Liu on recent IceCube results!

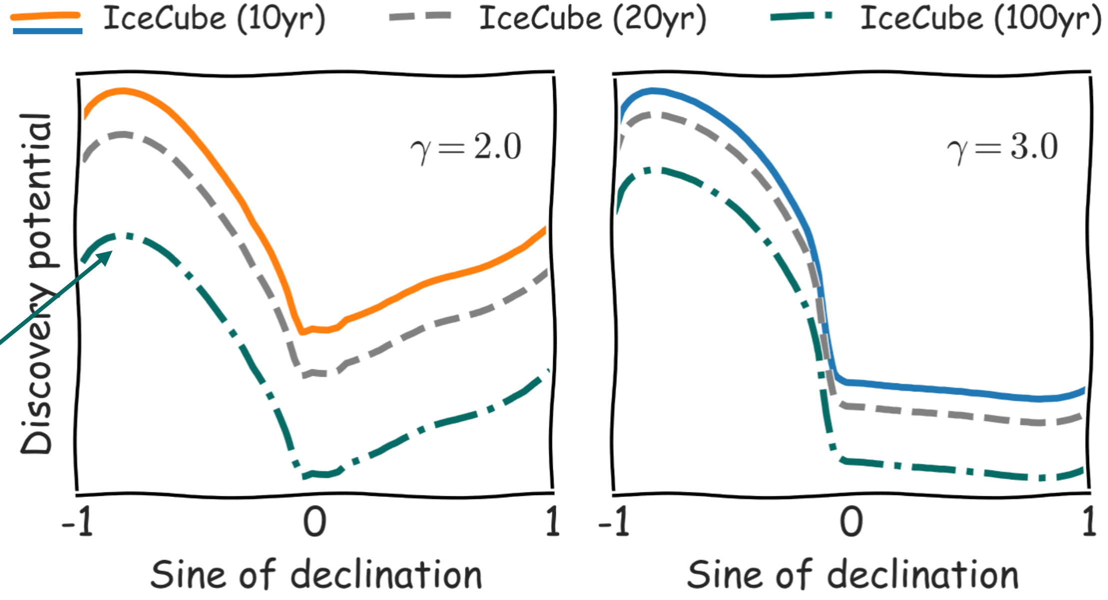


"Time-integrated Neutrino Source Searches with 10 years of IceCube Data" arXiv:1910.08488

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 miss due to IceCube's FoV?
- 100 years of data is not enough to reach a discovery potential in the South as good as 10 years of data at the horizon

arXiv:1910.08488



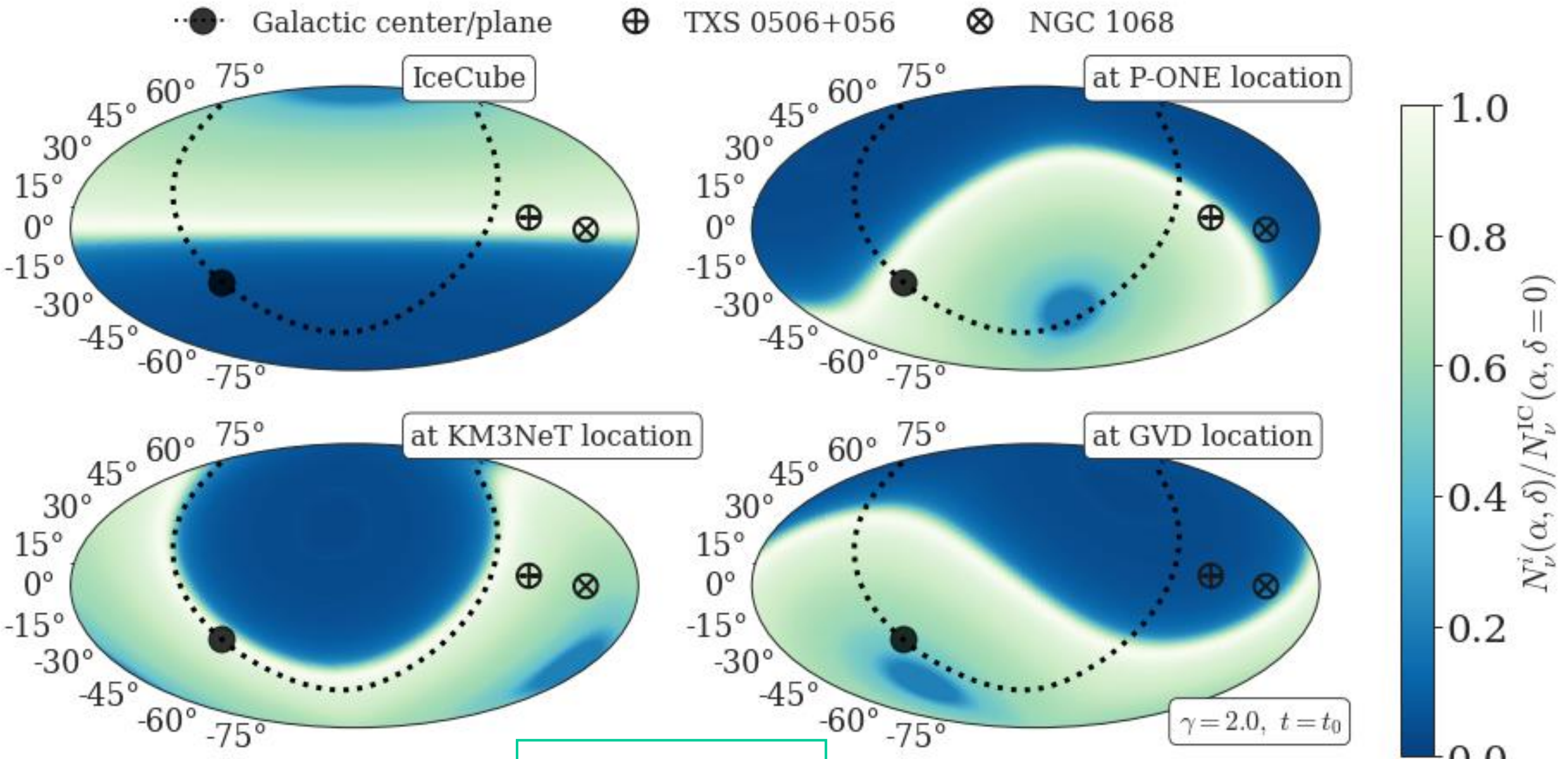
Why PLEνM? (2)

Illustration: Number of muon neutrinos relative to IceCube's number of neutrinos at horizon at one time of the day, t_0

Solution:

- More neutrino telescopes at different locations:
  → Multiple telescopes with target volume $\mathrm{V} > \mathrm{km}^3$ are under construction/planning in the Northern Hemisphere: KM3NeT, Baikal-GVD, P-One;
  + at the South Pole:
  IceCube-Upgrade/Gen2
- Combine their field of view (FoV):
  → Reach a uniform exposure of the sky

➢ **Combine the efforts of multiple telescopes to reach better sensitivity and FoV for astrophysical neutrinos – both instantaneous and time integrated!**



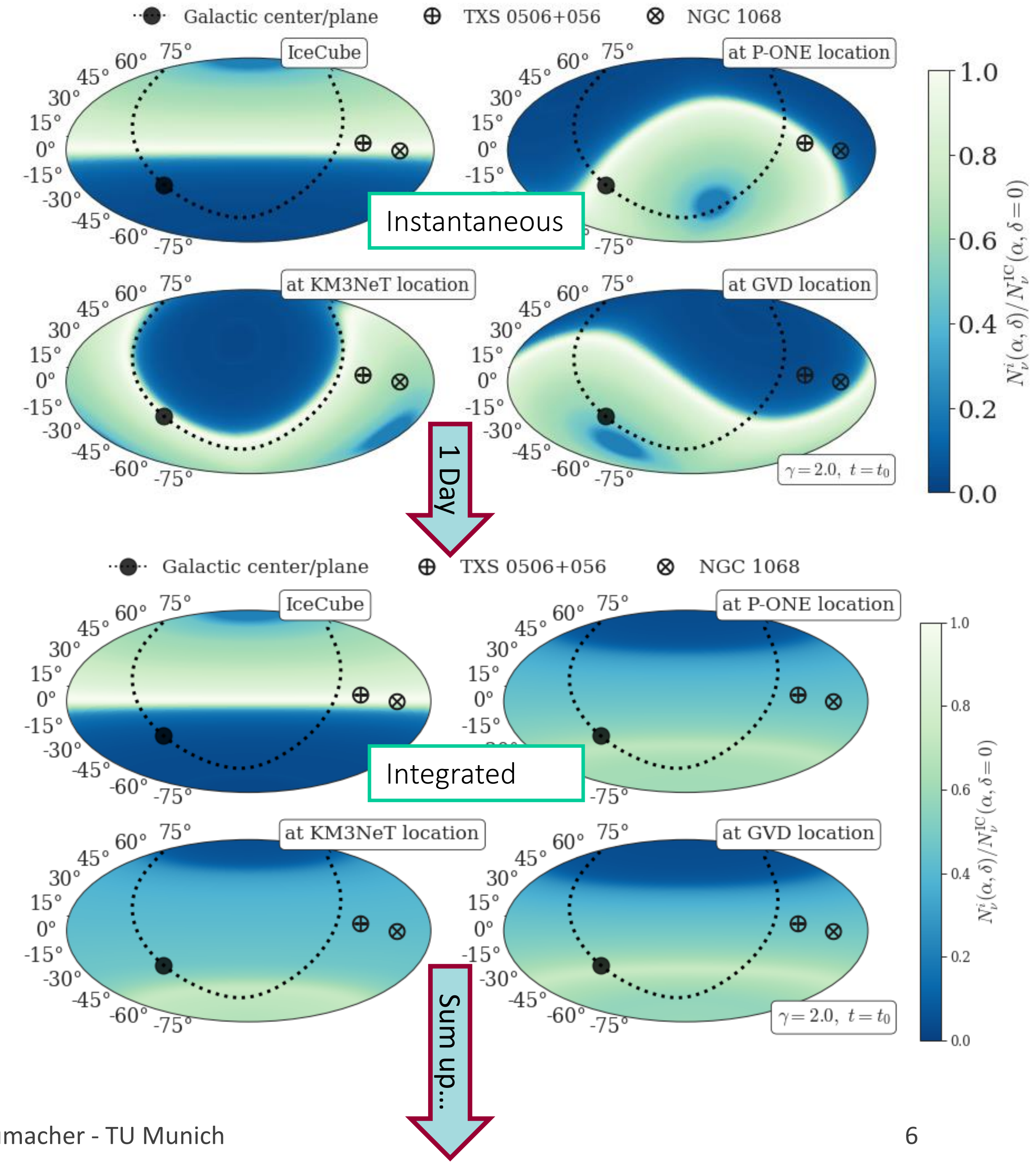
Instantaneous

Preliminary 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

Currently all effective areas are based on IceCube's data release of through-going muon neutrinos*

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



Can we add up effective areas?

- Number of neutrinos detected with power-law spectrum $\frac{d\Phi}{dE} = \Phi_0 \cdot \left(\frac{E}{1TeV}\right)^{-\gamma}$

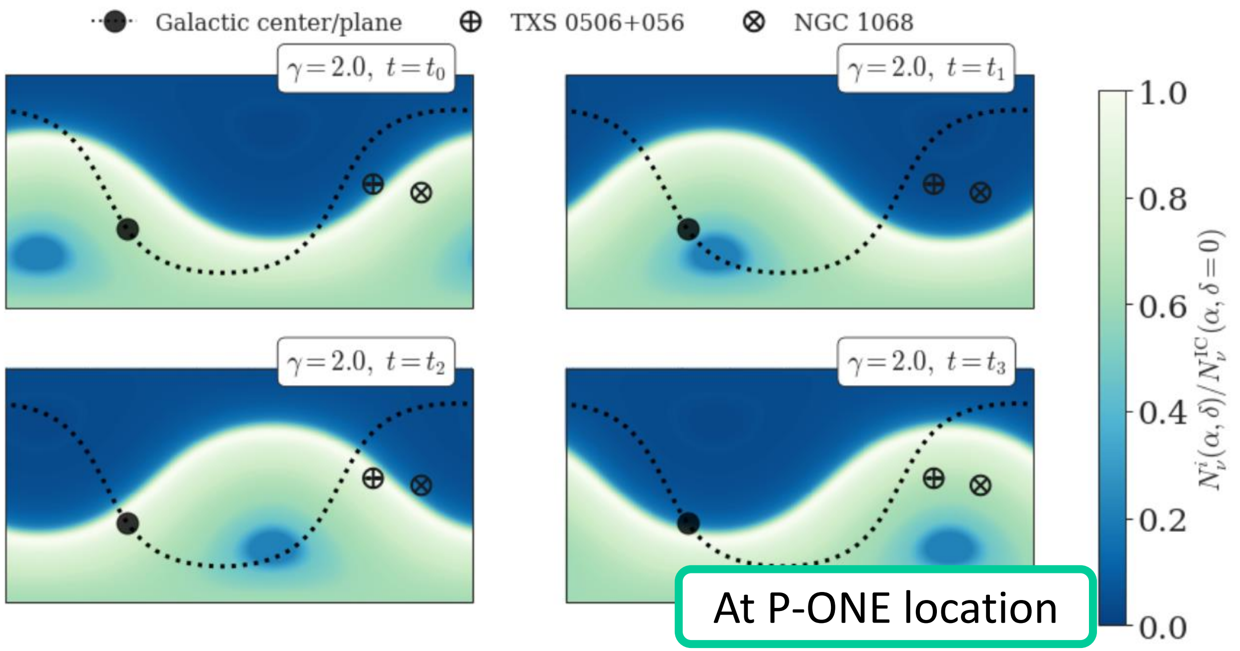
$$N_\nu = T_{live} \cdot \int_{\Delta\Omega} d\Omega \int_{E_{min}}^{E_{max}} dE\, A_{eff}(E, \sin(\delta)) \cdot \frac{d\Phi}{dE} \Rightarrow \sum N_\nu^{det} \propto \sum A_{eff}^{det}$$

➢ Number of neutrinos linear in livetime and effective area!

- Note: effective areas are in general also time-dependent in equatorial coordinates >> current studies are time-integrated!

- Not accounted for:
  - Different detector geometries
  - Different energy range/resolution
  - Different angular resolution
  - Different systematic uncertainties

Work in progress!

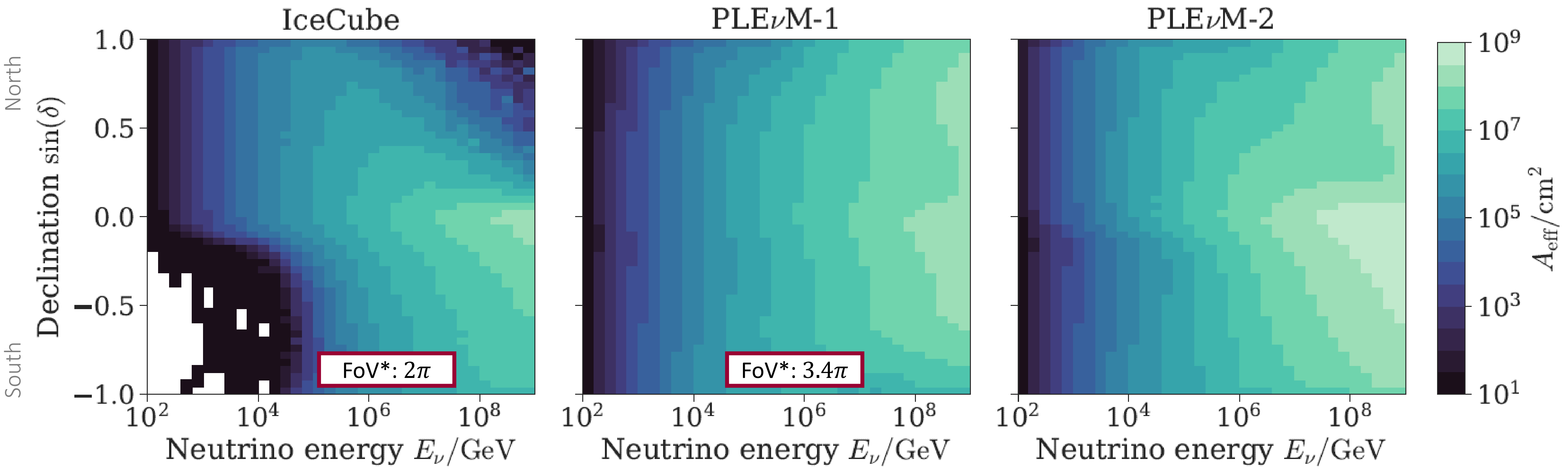


Combined effective areas of PLEνM

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}^{+}

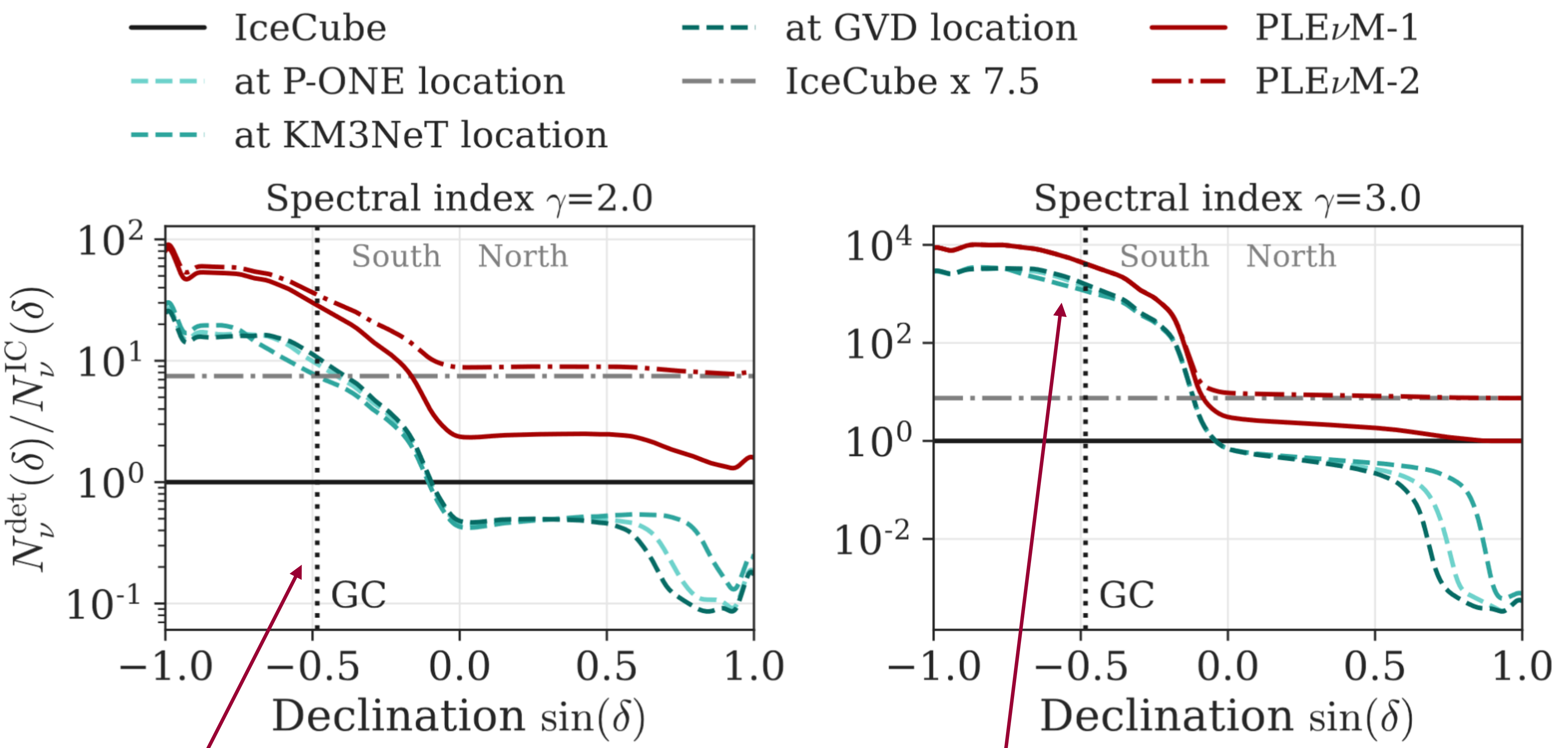


*FoV: Area of the sky where the daily average of the number of neutrinos ($\Phi \propto E^{-2}$) is at least as large as 50% of the max(number of neutrinos)

+ 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)



Declination of Galactic Center

More than 3 orders of magnitude improvement!

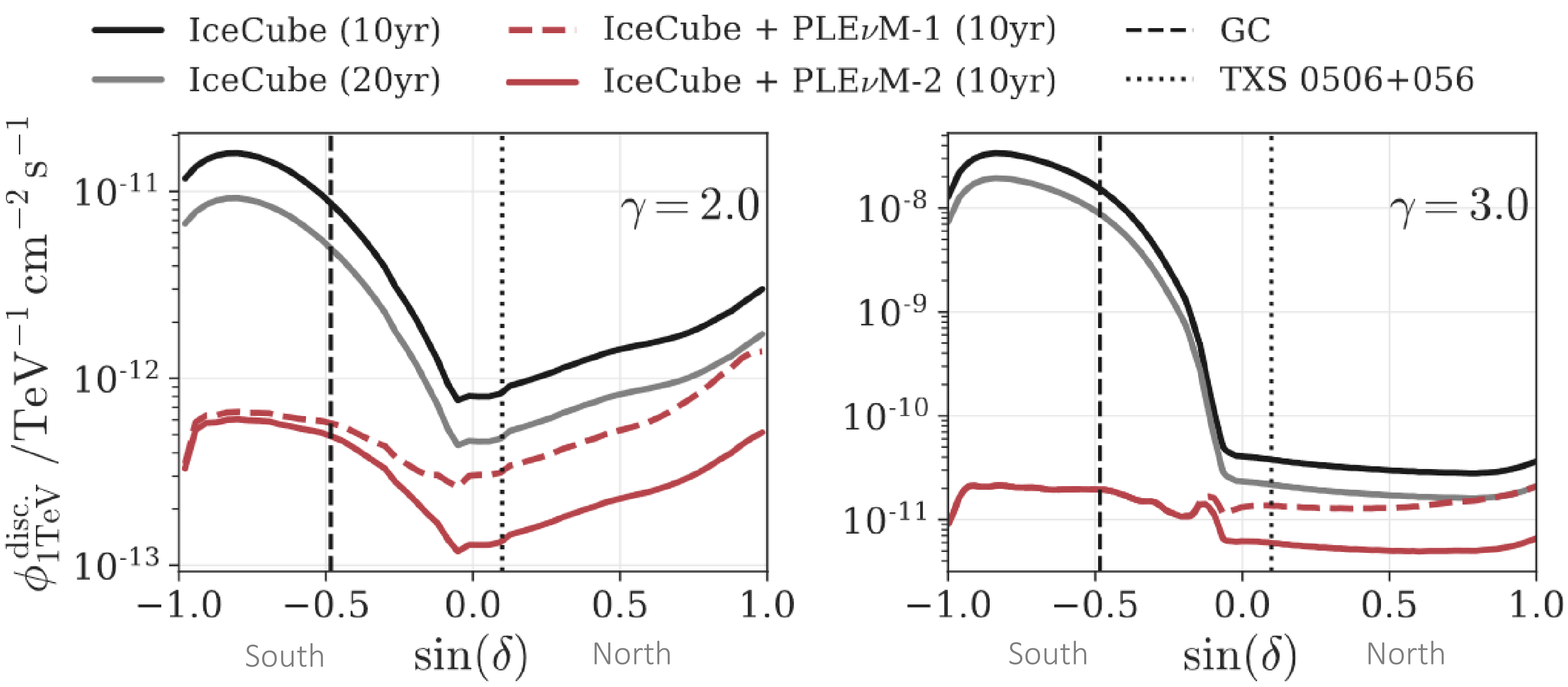
Prospects: Point-source searches

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



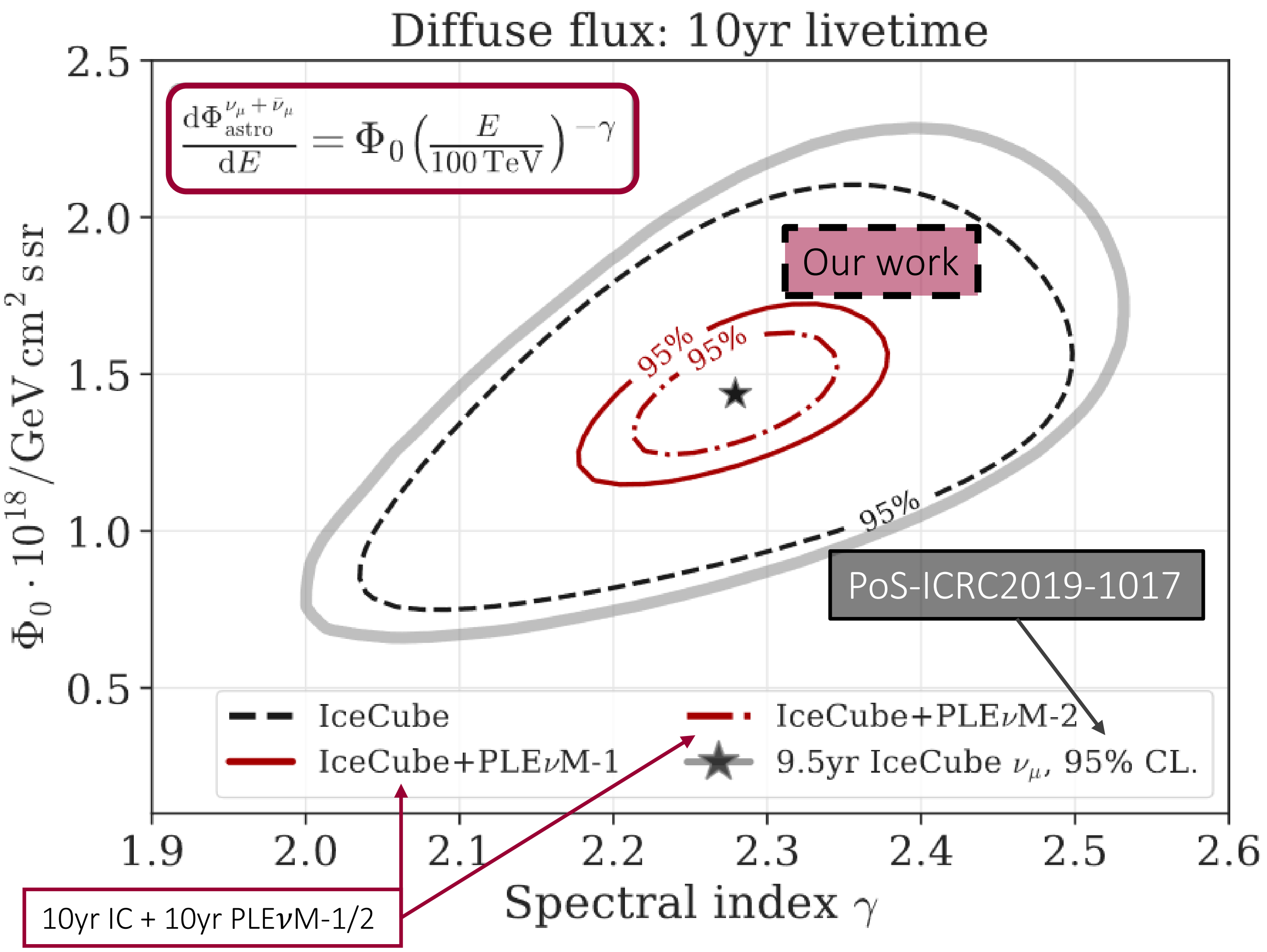
*Neutrino flux per source: $\frac{d\Phi}{dE} = \Phi^{disc}_{1TeV} \cdot \left(\frac{E}{1TeV}\right)^{-\gamma}$ at $E = 1TeV$

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)

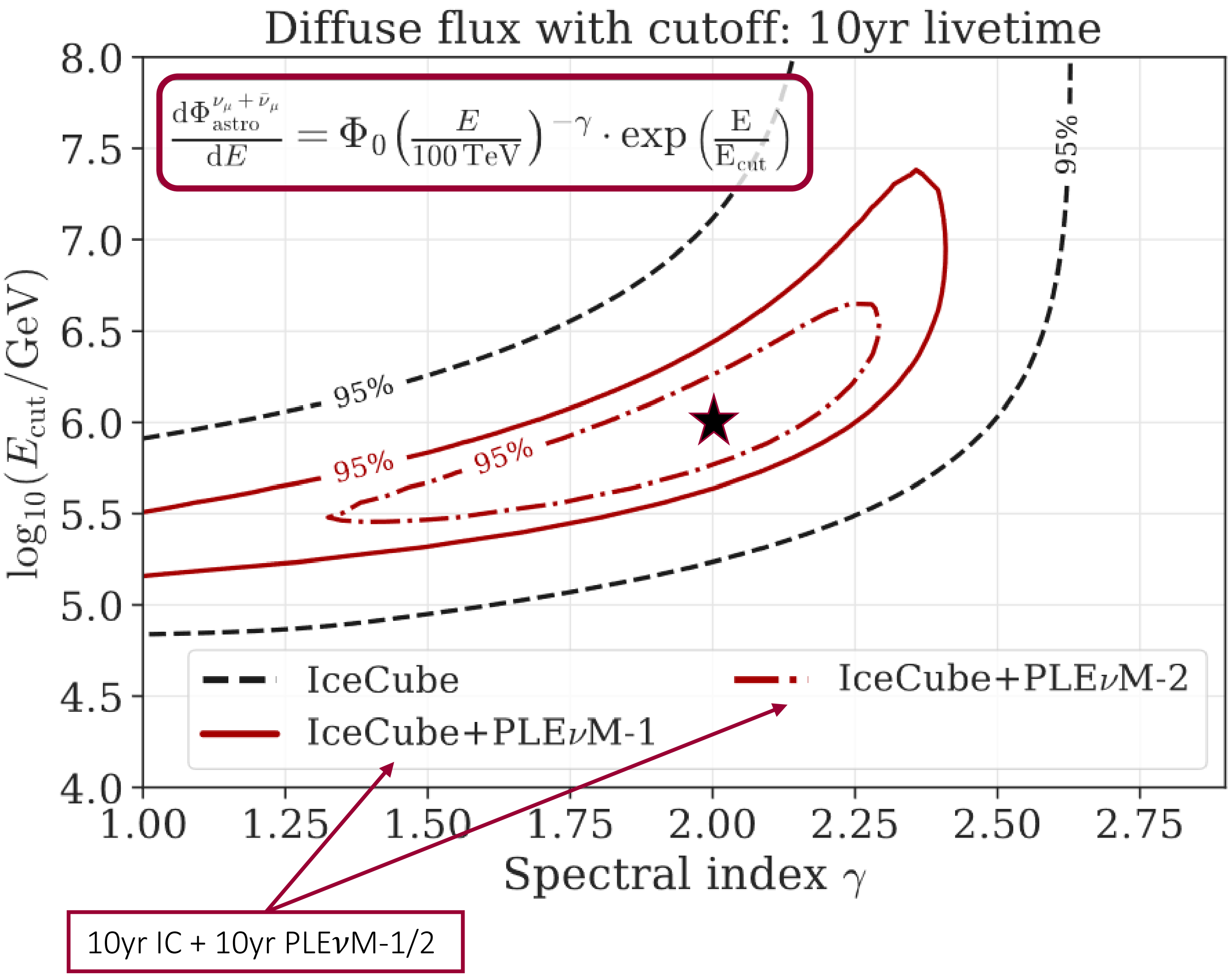


*https://github.com/afedynitch/MCEq with hadronic model Sibyll-2.3c and atmosphere: NRLMSISE-00 Model2001

Beyond the single power law: exponential cutoff

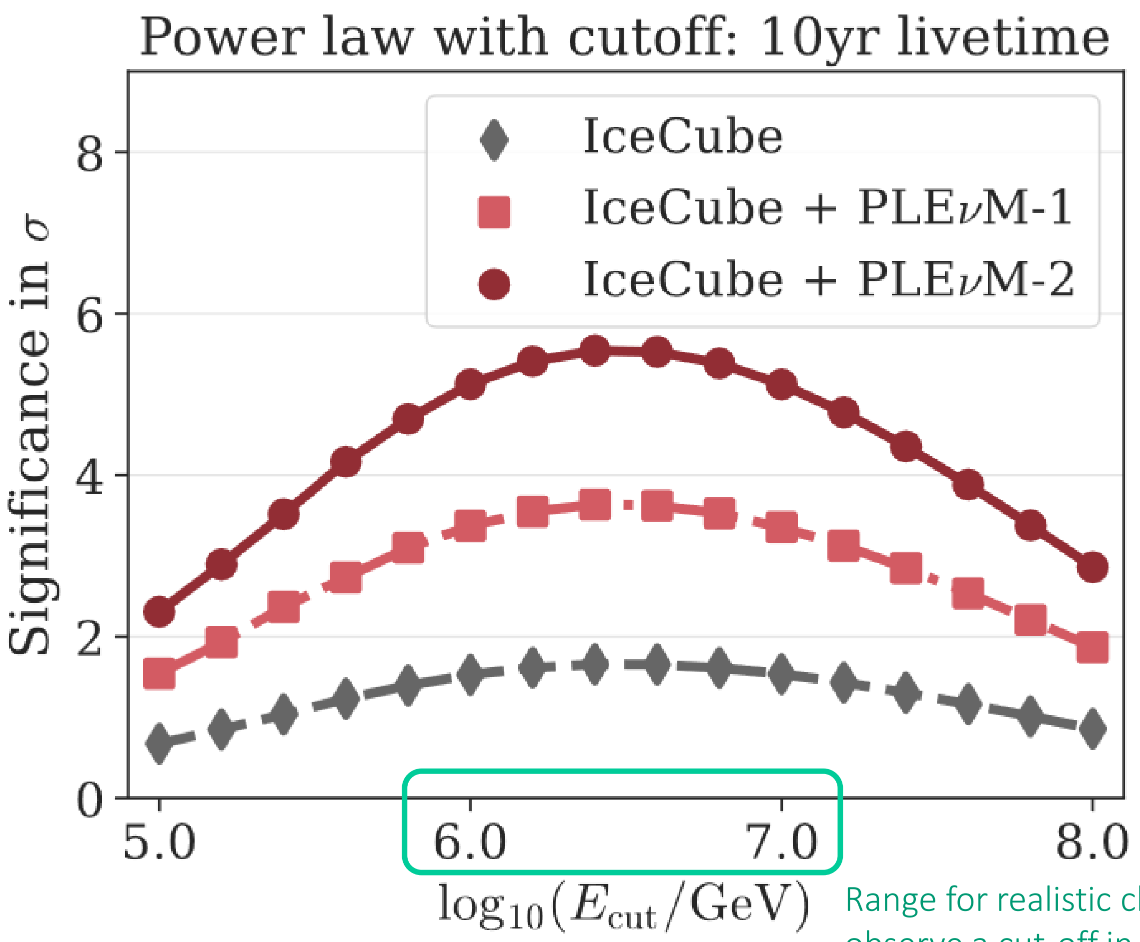
- Baseline model parameters:
  - Atmospheric neutrinos with MCEq
  - Astrophysical flux normalization $1.5 \cdot 10^{-18}/(\mathrm{GeV\ cm^2\ s\ sr})$
  - Spectral index $\gamma = 2.0$
  - Cut-off energy $E_{cut} = 1\ \mathrm{PeV}$ ★

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



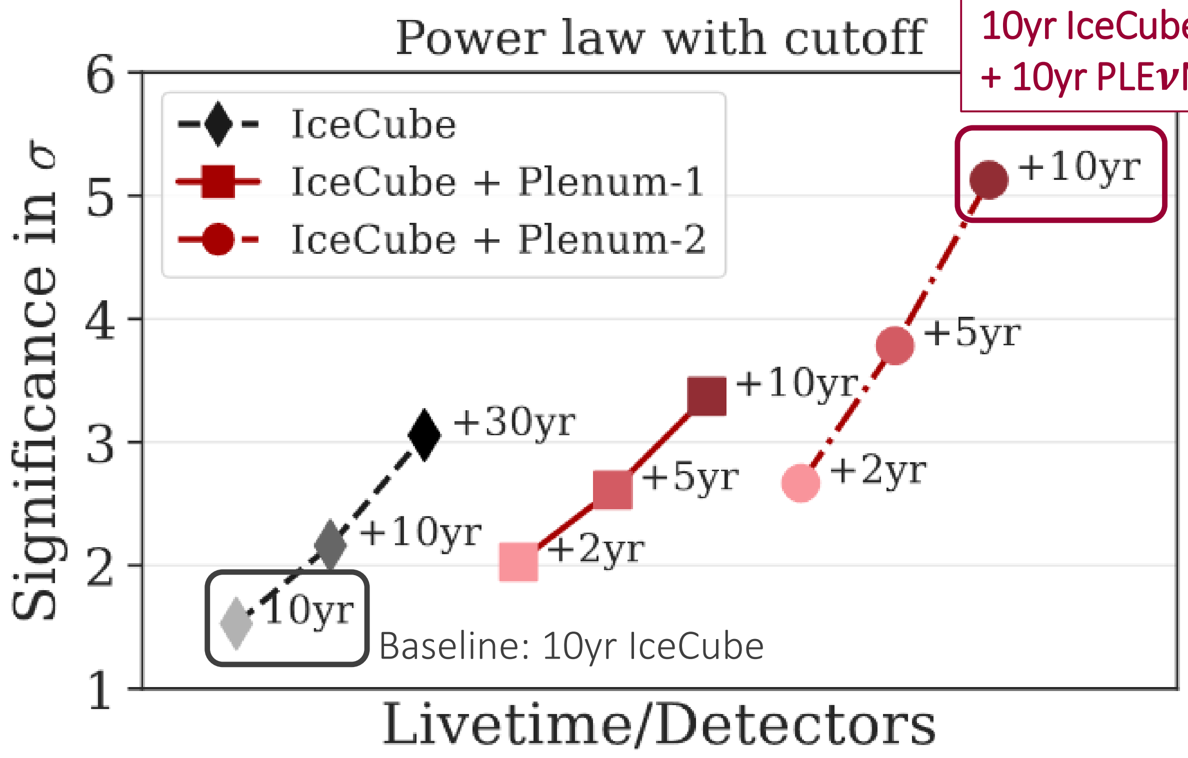
Beyond the single power law: exponential cutoff

Significance vs. cut-off energy



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

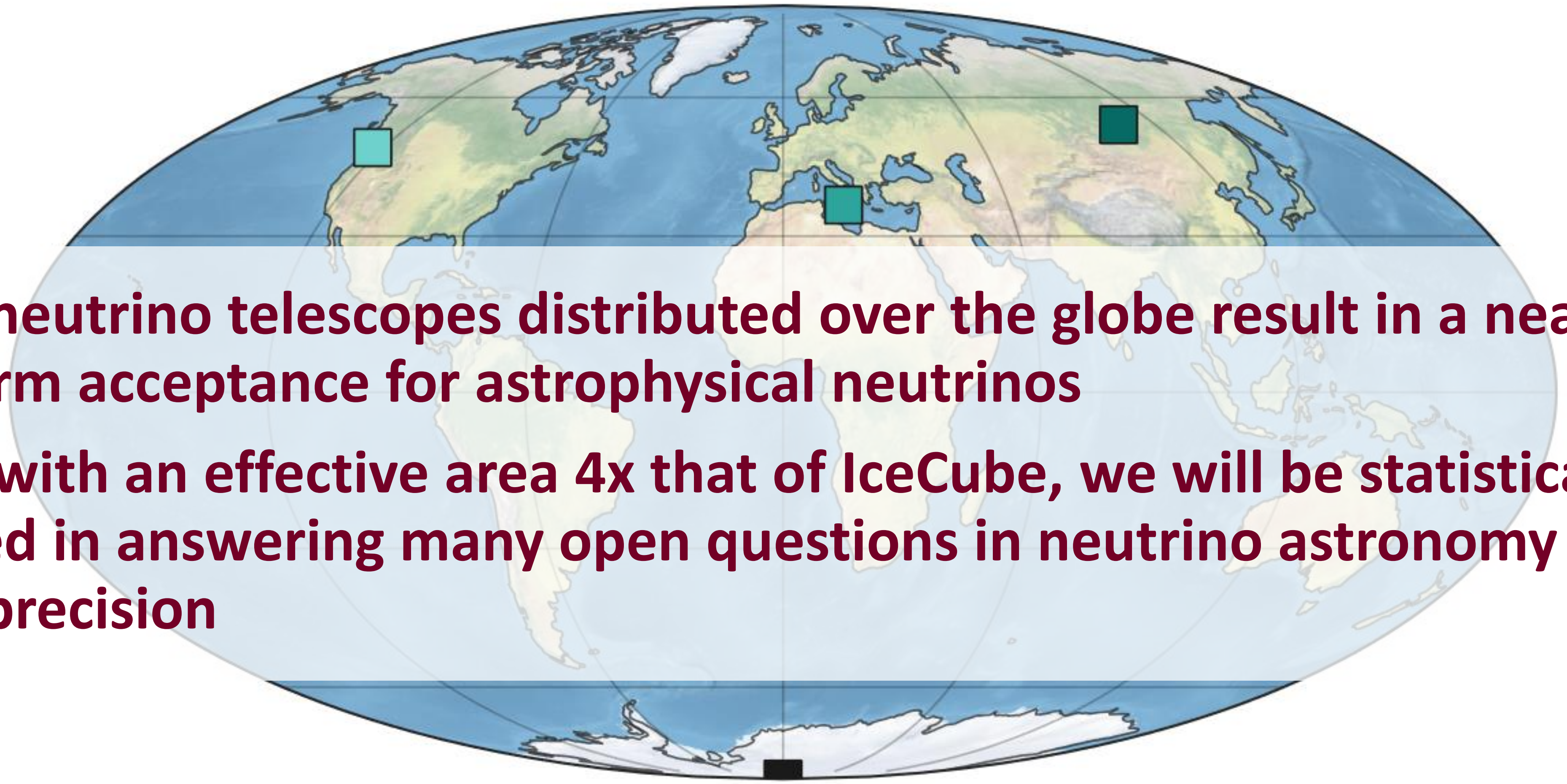
Significance vs. livetimes, $E_{cut} = 1\mathrm{PeV}$



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!

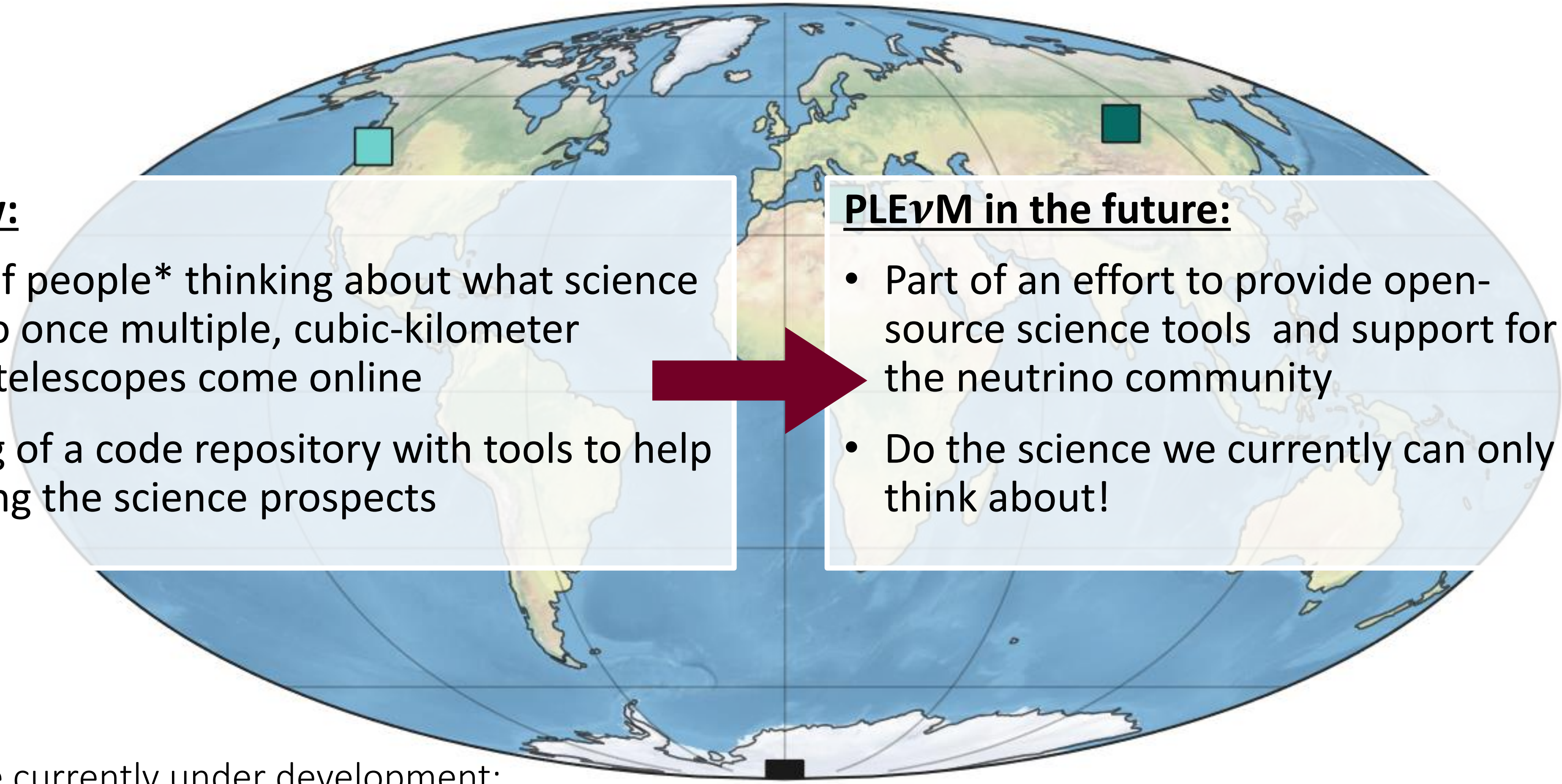
Key results



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 many open questions in neutrino astronomy with high precision

The Big Picture

*Lisa Schumacher, Matthias Huber, Matteo Agostini,
Mauricio Bustamante, Foteini Oikonomou, Elisa Resconi
+ a couple of other people contributing ideas, feedback, …



PLEνM now:

- A group of people* thinking about what science we can do once multiple, cubic-kilometer neutrino telescopes come online
- Beginning of a code repository with tools to help quantifying the science prospects

PLEνM in the future:

- Part of an effort to provide open-source science tools and support for the neutrino community
- Do the science we currently can only think about!

Public code currently under development:
https://github.com/mhuber89/Plenum

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 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 powerlaw on 5σ level

Outlook & Ideas

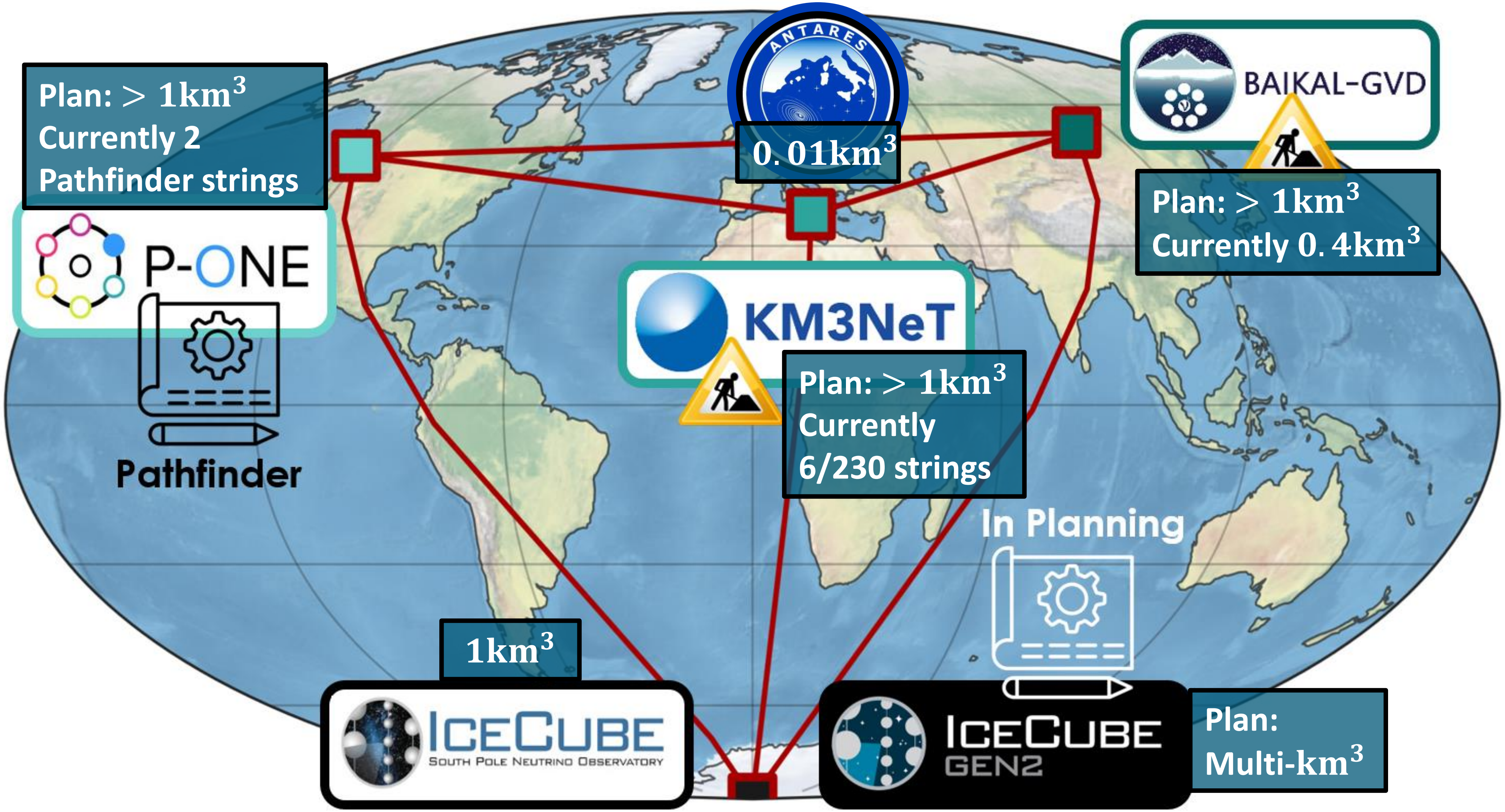
- Benchmark comparisons for TXS0506+056, NGC 1068 and other interesting sources
- Galactic/LHAASO sources
- Galactic plane diffuse emission
- Extragalactic source populations
- Transient neutrino sources
- Include UHE neutrino telescopes
- Neutrino flavor, Particle physics, …

Thanks for listening!

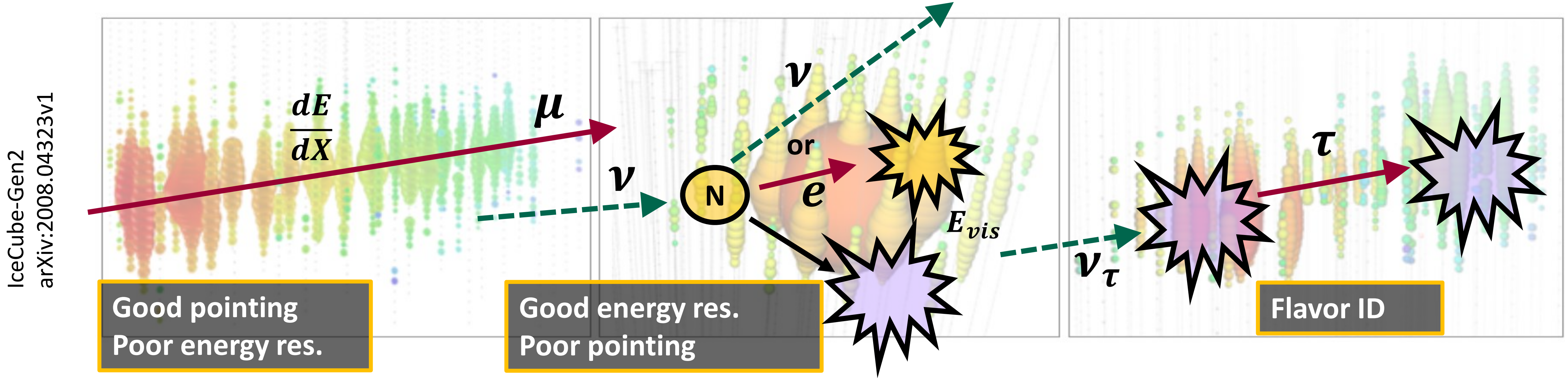
Public code currently under development: https://github.com/mhuber89/Plenum

Back up slides

Current & future Cherenkov neutrino telescopes



Neutrino signatures in Cherenkov detectors



"Tracks":

- Good directional resolution $< 1°$
- Poor energy resolution via $\frac{dE}{dX}$ of muon

"Cascades":

- CC ν_e interactions (+ NC all-flavor)
- Directional resolution $\sim 5 - 15°$
- Good resolution of visible energy: $\sim 10\%$ for CC ν_e

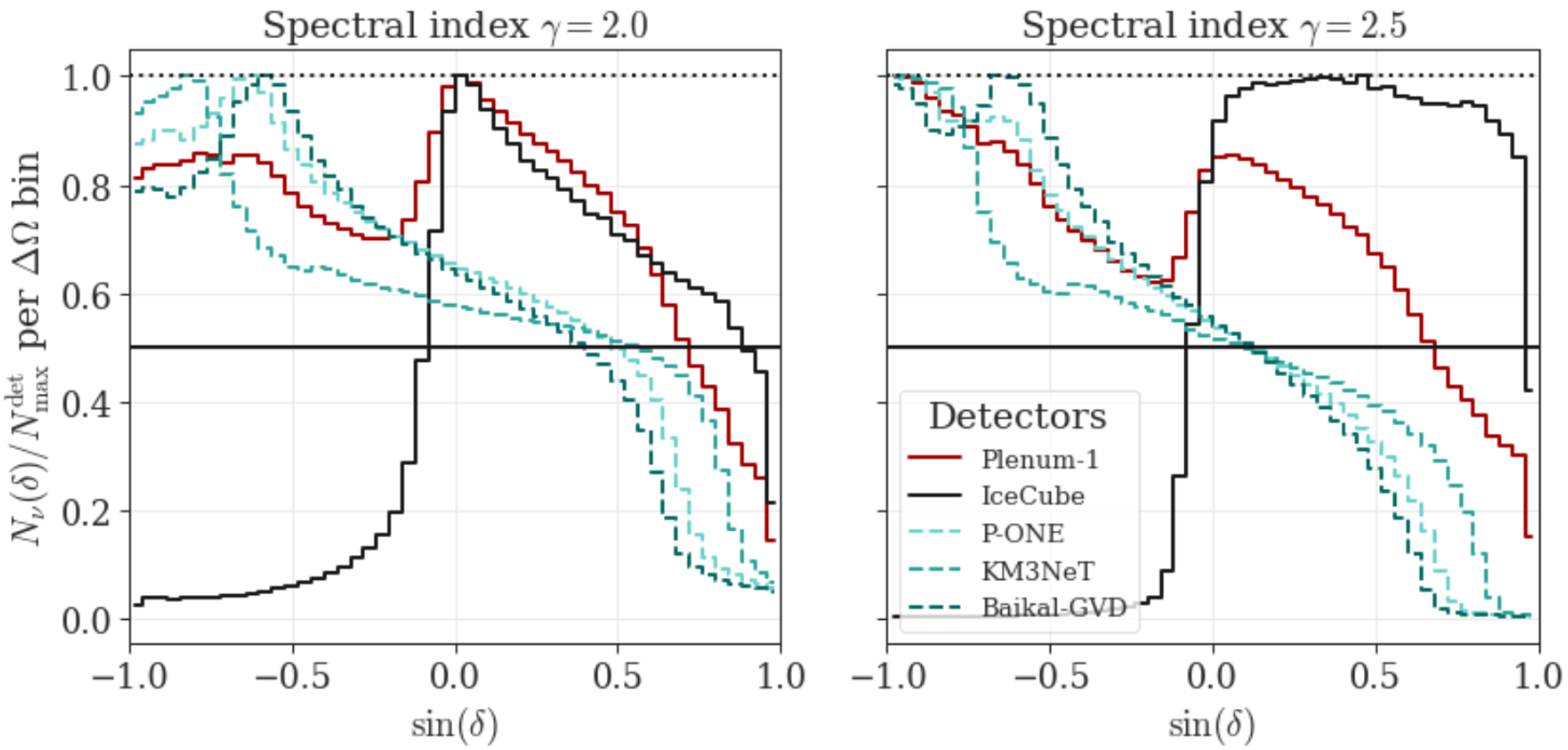
"Double Cascades":

- CC ν_τ interactions + τ decay
- Only resolvable at highest energies with distance

$$\sim 50\mathrm{m} \cdot \left(\frac{E}{\mathrm{PeV}}\right)$$

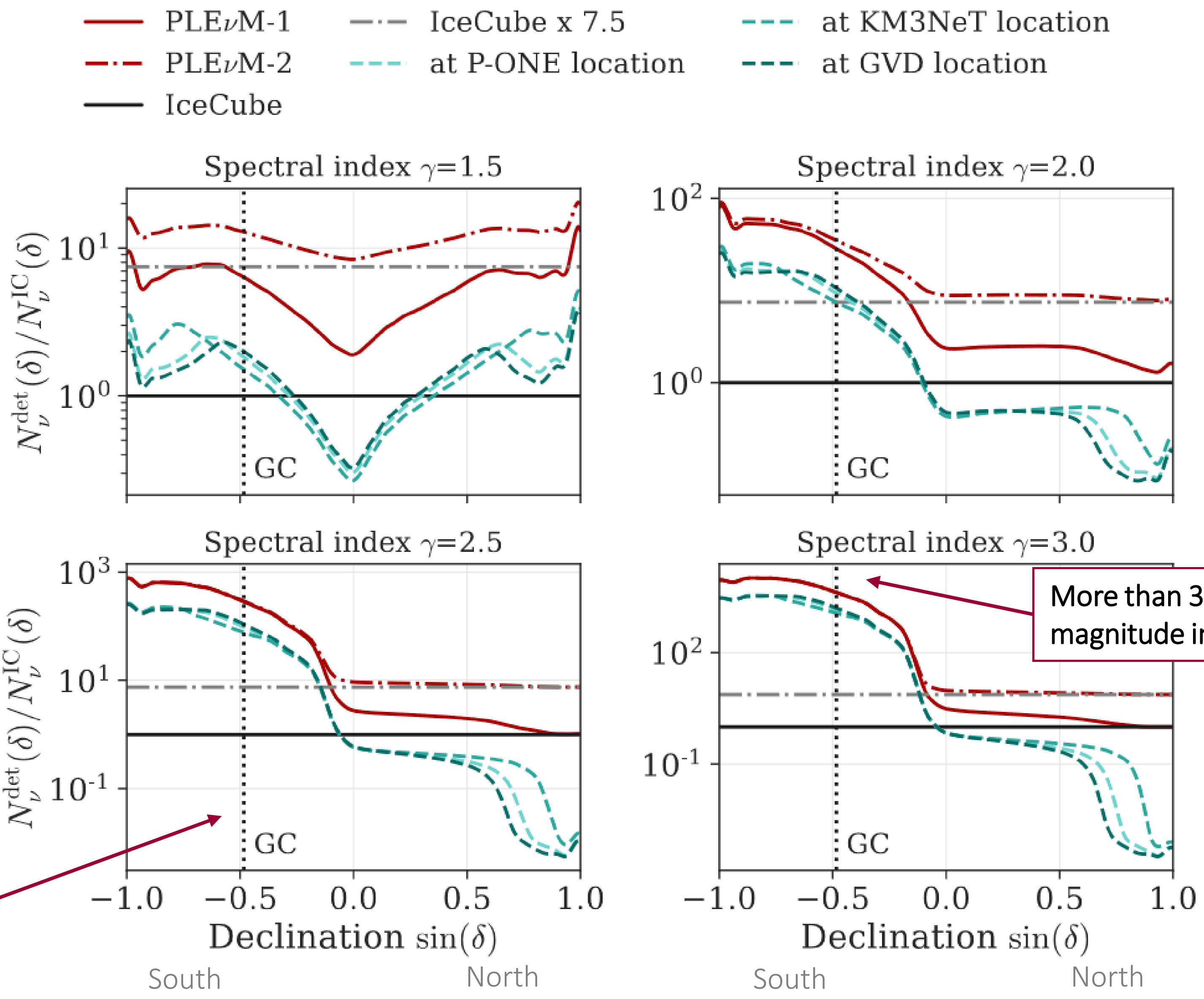
- 2 candidates identified by IceCube

Field of view: daily integrated & normalized to max.



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 than 3 orders of magnitude improvement!

Declination of Galactic Center

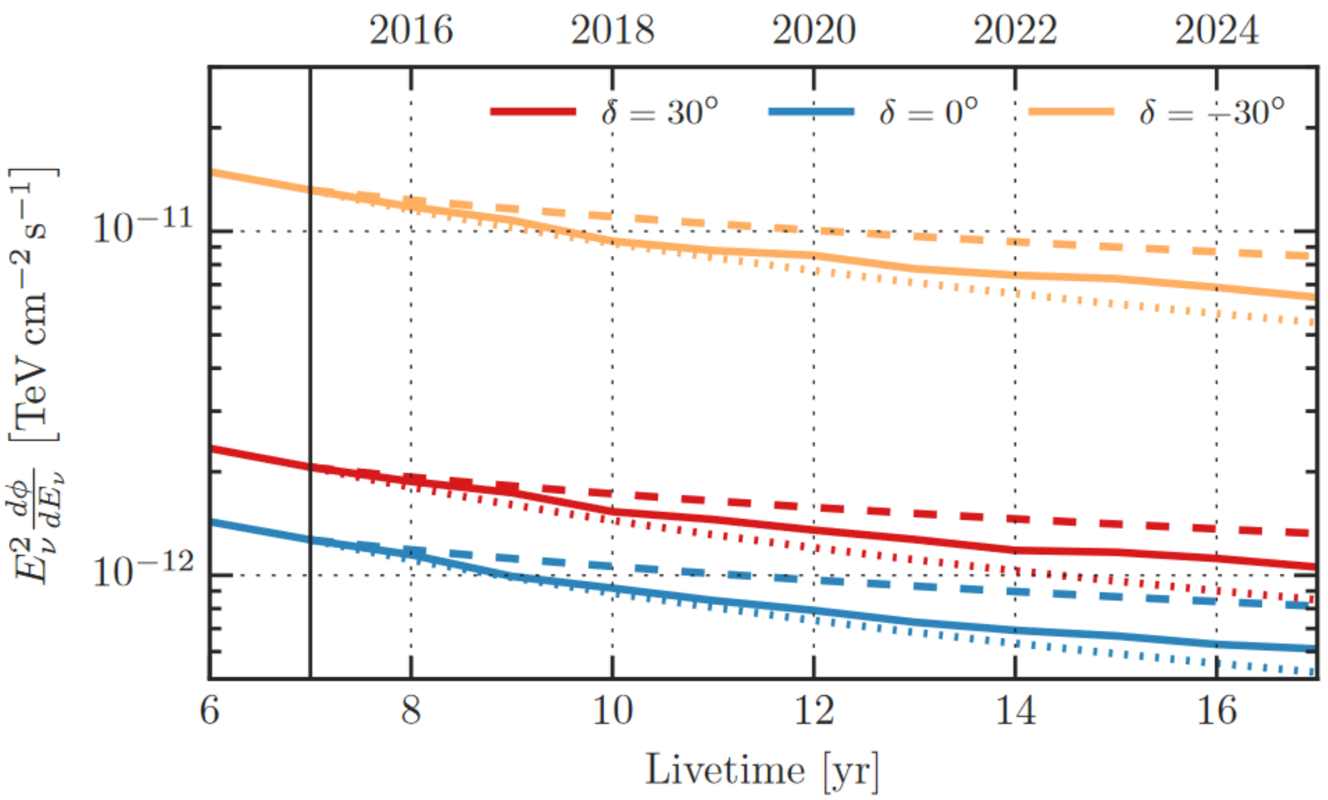
Prospects: Point-source searches

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

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

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

- 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

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