Technical University of Munich

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

SFB 1258 Neutrinos Dark Matter Messengers

γ 2022
7th Heidelberg International Symposium on
High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022

Search for neutrino point sources in the Northern Sky

with the IceCube Neutrino Observatory

Chiara Bellenghi, Theo Glauch, Hans Niederhausen,
Tomas Kontrimas, Martin Wolf, Christian Haack
on behalf of the IceCube Collaboration

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy - Barcelona, 07/07/2022

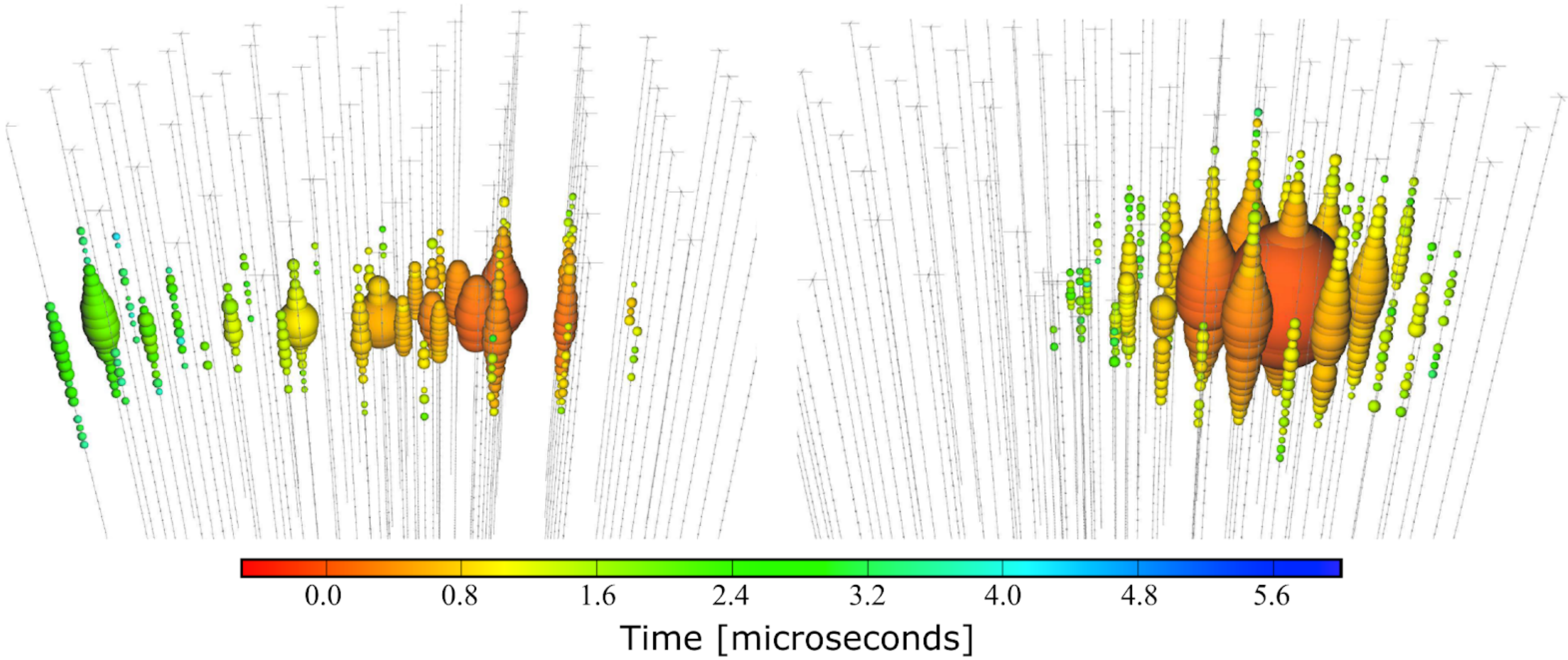
IceCube

Muon tracks

- High-energy neutrinos interact in the ice producing charged particles.
- Detect the Cherenkov radiation emitted by the secondary particles with PMTs.

TRACK (muons):
Good angular resolution
Excellent for pointing!

CASCADE (Hadronic/EM showers):
Good energy resolution

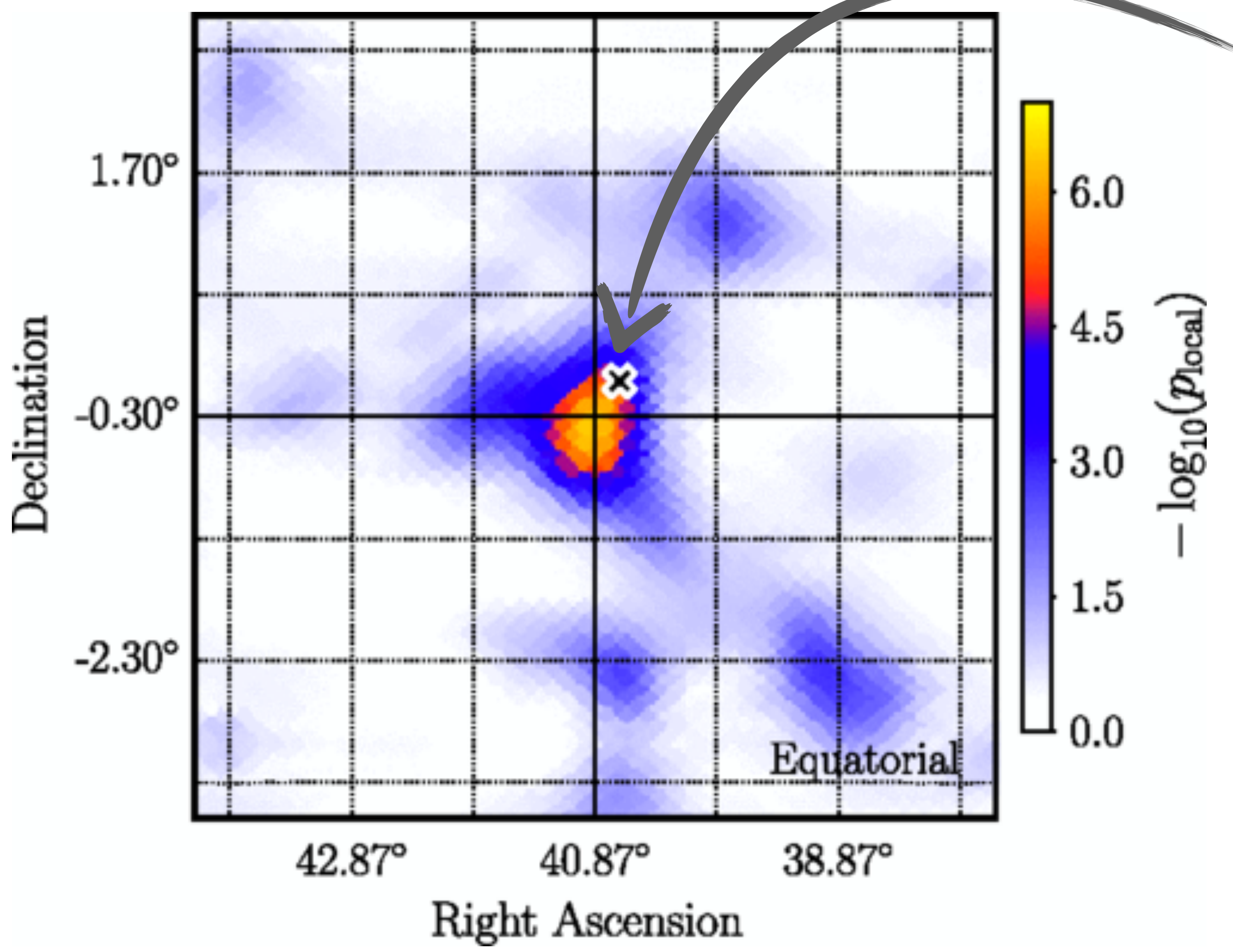


IceCube

Latest results

Phys. Rev. Lett. 124, 051103

- 2013: Discovery of a diffuse flux of astrophysical neutrinos. [Science 342 (2013)]
- 2018: TXS 0506+056 identified as the first compelling source of astrophysical neutrinos after observing a high-energy neutrino in coincidence with a gamma-ray flare. [Science 361 (2018) no.6398, 147-151, Science 361 (2018) no.6398]
- 2020: 2.9σ indication for neutrino emission from NGC 1068 with power law spectral index $\gamma \approx 3.2$. [Phys. Rev. Lett. 124, 051103]



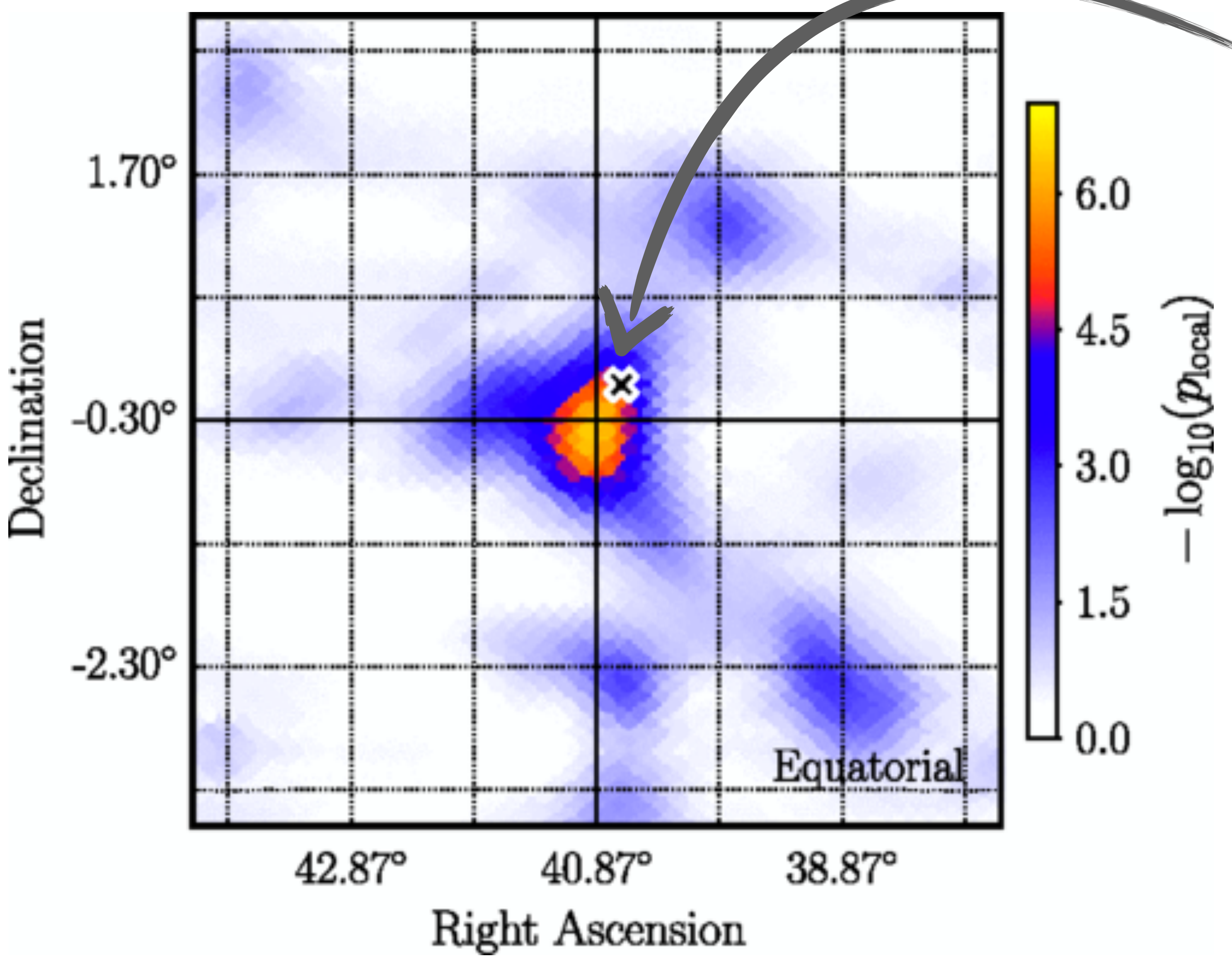
NGC 1068
One of the most famous Seyferts 2 in the sky!

IceCube

Latest results

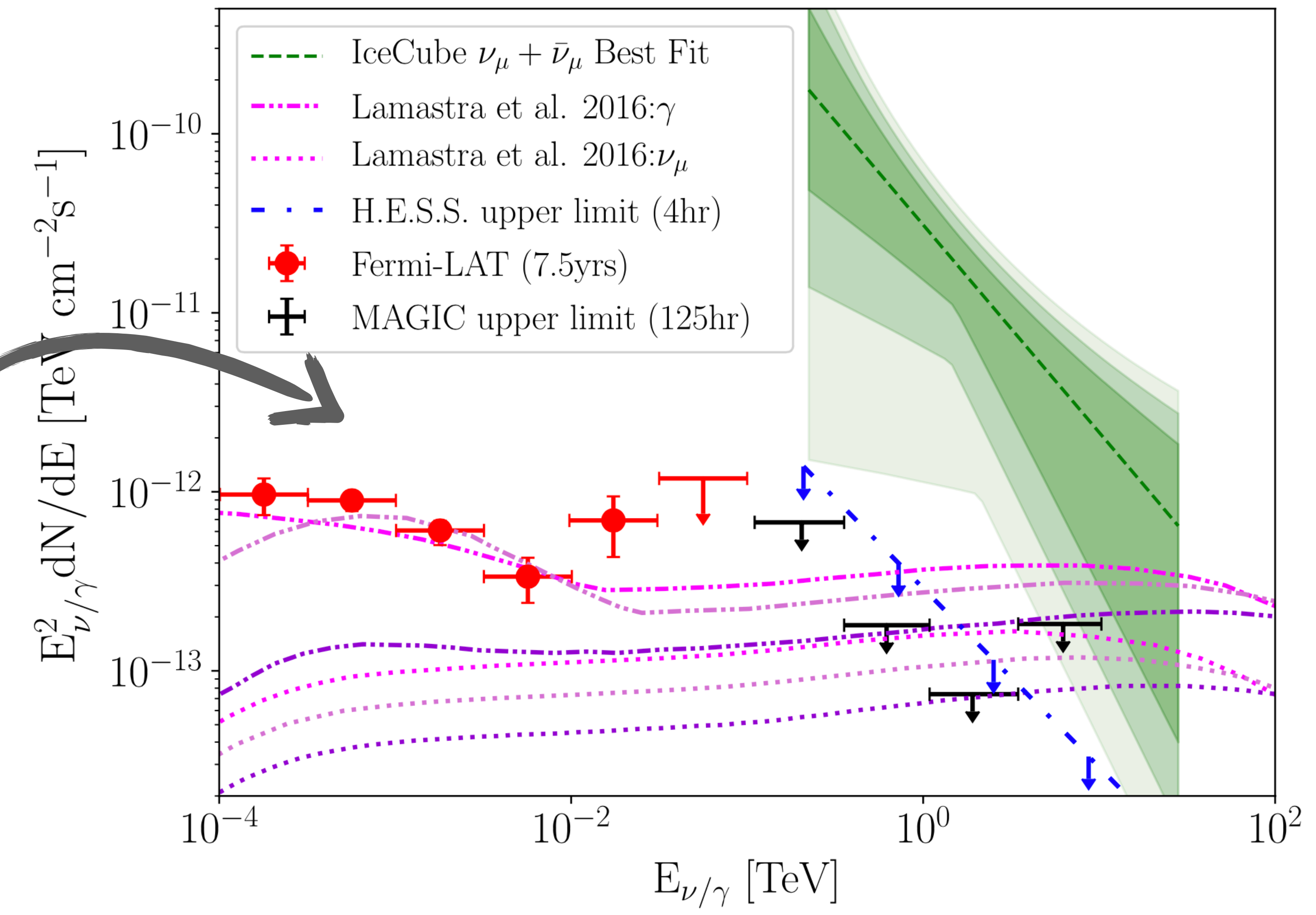
Phys. Rev. Lett. 124, 051103

- 2013: Discovery of a diffuse flux of astrophysical neutrinos. [Science 342 (2013)]
- 2018: TXS 0506+056 identified as the first compelling source of astrophysical neutrinos after observing a high-energy neutrino in coincidence with a gamma-ray flare. [Science 361 (2018) no.6398, 147-151, Science 361 (2018) no.6398]
- 2020: 2.9σ indication for neutrino emission from NGC 1068 with power law spectral index ɣ≈3.2. [Phys. Rev. Lett. 124, 051103]



NGC 1068
One of the most famous Seyferts 2 in the sky!

The neutrino flux outshines the measured gamma-ray emission. Simple hadronuclear/photomeson acceleration process can't explain it.



NGC 1068

As a neutrino source candidate

- "There are several classes of galaxies with compact nuclei and huge energy output from these nuclei […]. Seyferts of class 2, however, are so heavily obscured by dust and gas that their non-thermal nature is not established. It is shown that neutrino astronomy would help ascertain the nature of class 2 Seyferts."
- **The core of the AGN is optically thick for gamma-rays**, which undergo pair production reactions with the very abundant soft X-rays. Neutrinos can escape!
- A conclusive statement on whether NGC 1068 is a high-energy neutrino source or not, could shed light on the mechanisms producing the observed spectra.

ICRC PoS from 1979!

NEUTRINOS AS A PROBE FOR THE NATURE OF

AND PROCESSES IN ACTIVE GALACTIC NUCLEI

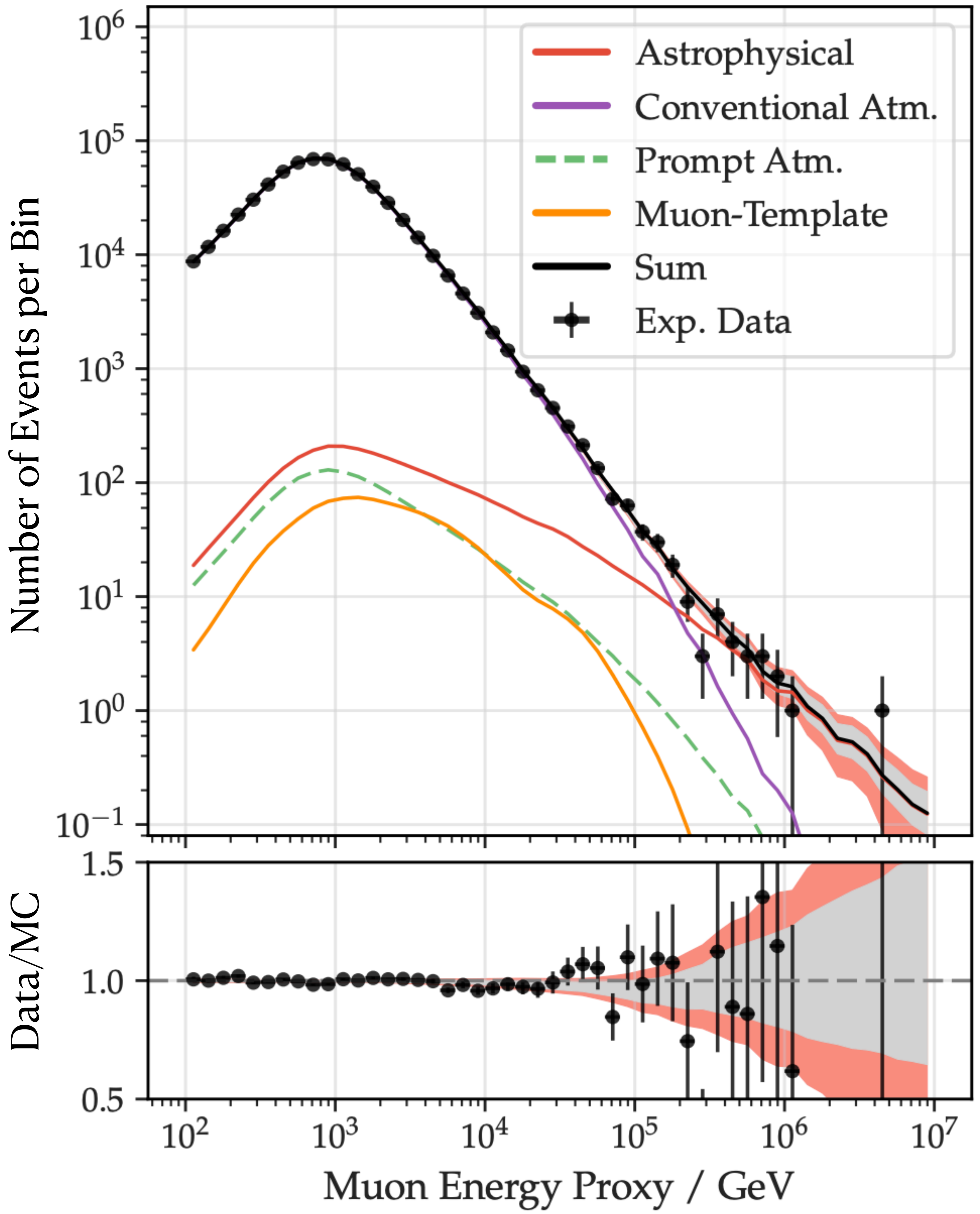
R. Silberberg and M. M. Shapiro
Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D. C. 20375, U.S.A.

Point Source analysis

The concept

- **The challenge:** strongly dominating atmospheric background.

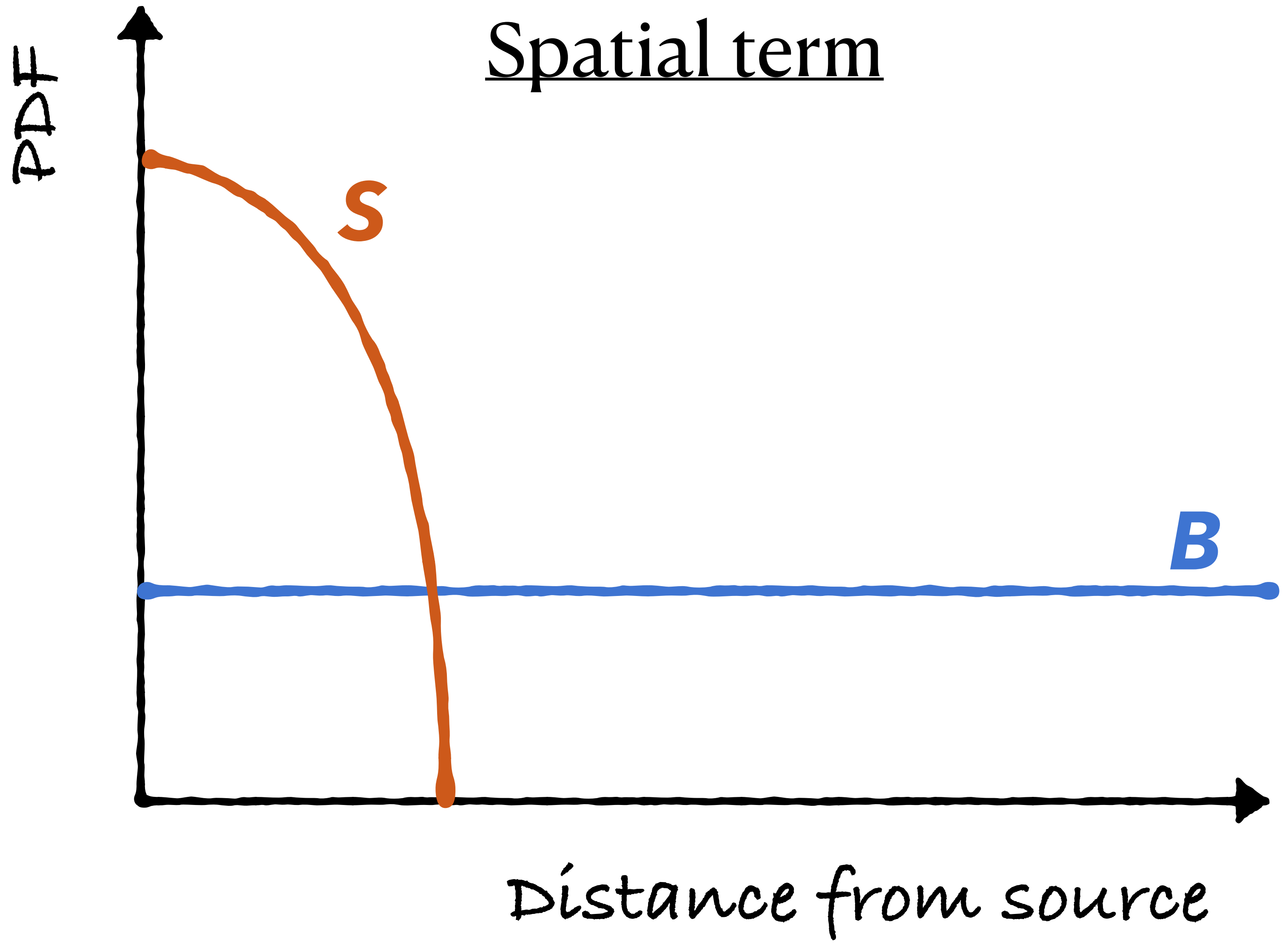
Abbasi et al 2022 ApJ 928 50

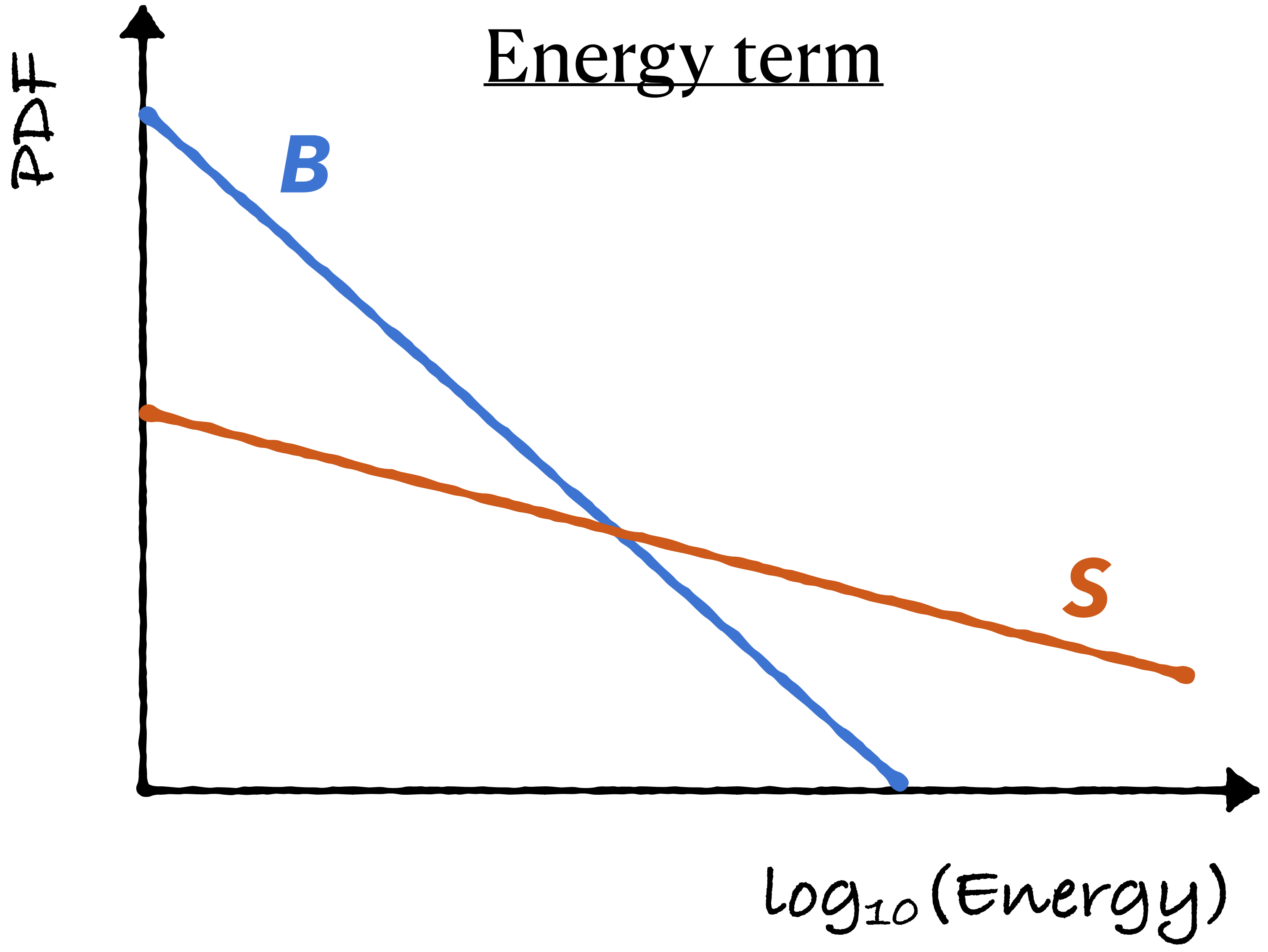


Point Source analysis

The concept

- **The challenge:** strongly dominating atmospheric background.
- **The tools:** Unbinned likelihood-ratio test to discriminate signal from background: $\mathscr{L} = \prod_i^N \left[\frac{n_s}{N} \boxed{S_i} + \left(1 - \frac{n_s}{N}\right) \cdot \boxed{B_i} \right]$





Point Source analysis

Current status and prospects

- **Currently:**
  - Very high statistics.
  - Simple and efficient calculation of the signal likelihood via Gaussian approximation for the spatial term.
  - The approximation leads to biases in the maximum likelihood estimators (number of signal events n_s, spectral index γ).
  - Soft spectral indices not well constrained, but NGC 1068 seems to be a soft source!

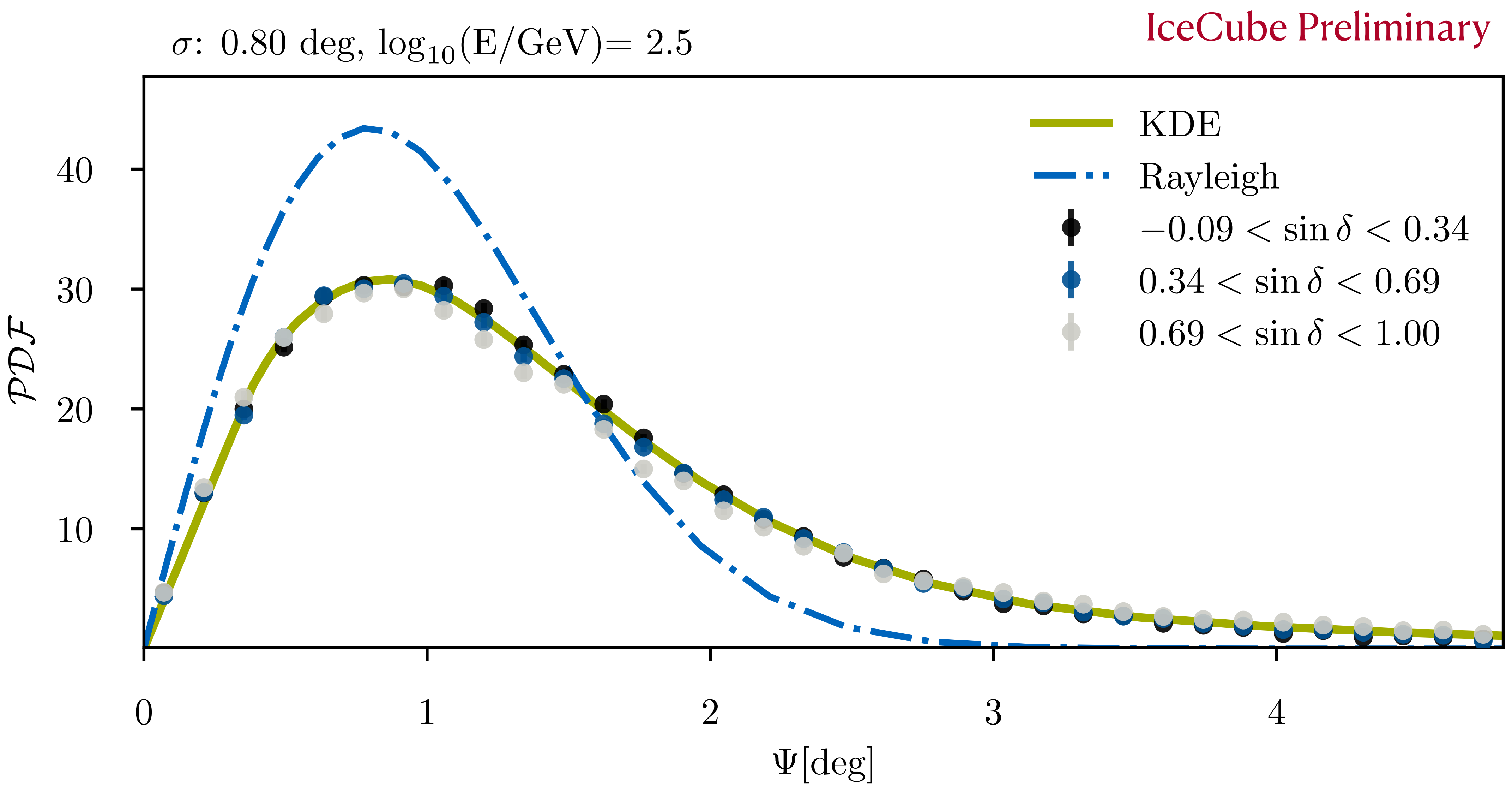
Point Source analysis

Current status and prospects

- **Currently:**
  - Very high statistics.
  - Simple and efficient calculation of the signal likelihood via Gaussian approximation for the spatial term.
  - The approximation leads to biases in the maximum likelihood estimators (number of signal events n_s, spectral index γ).
  - Soft spectral indices not well constrained, but NGC 1068 seems to be a soft source!
- **New developments:**
  - Room for methodological improvements in the analysis technique to overcome the known limitations:
    - Improved description of the signal likelihood;
    - Improved estimation of the reconstructed muon observables (energy and angular uncertainty on the direction).
  - Reprocessed the dataset to the latest detector calibration.

Point Source analysis

New methods - MC-based numerical construction of the PDFs

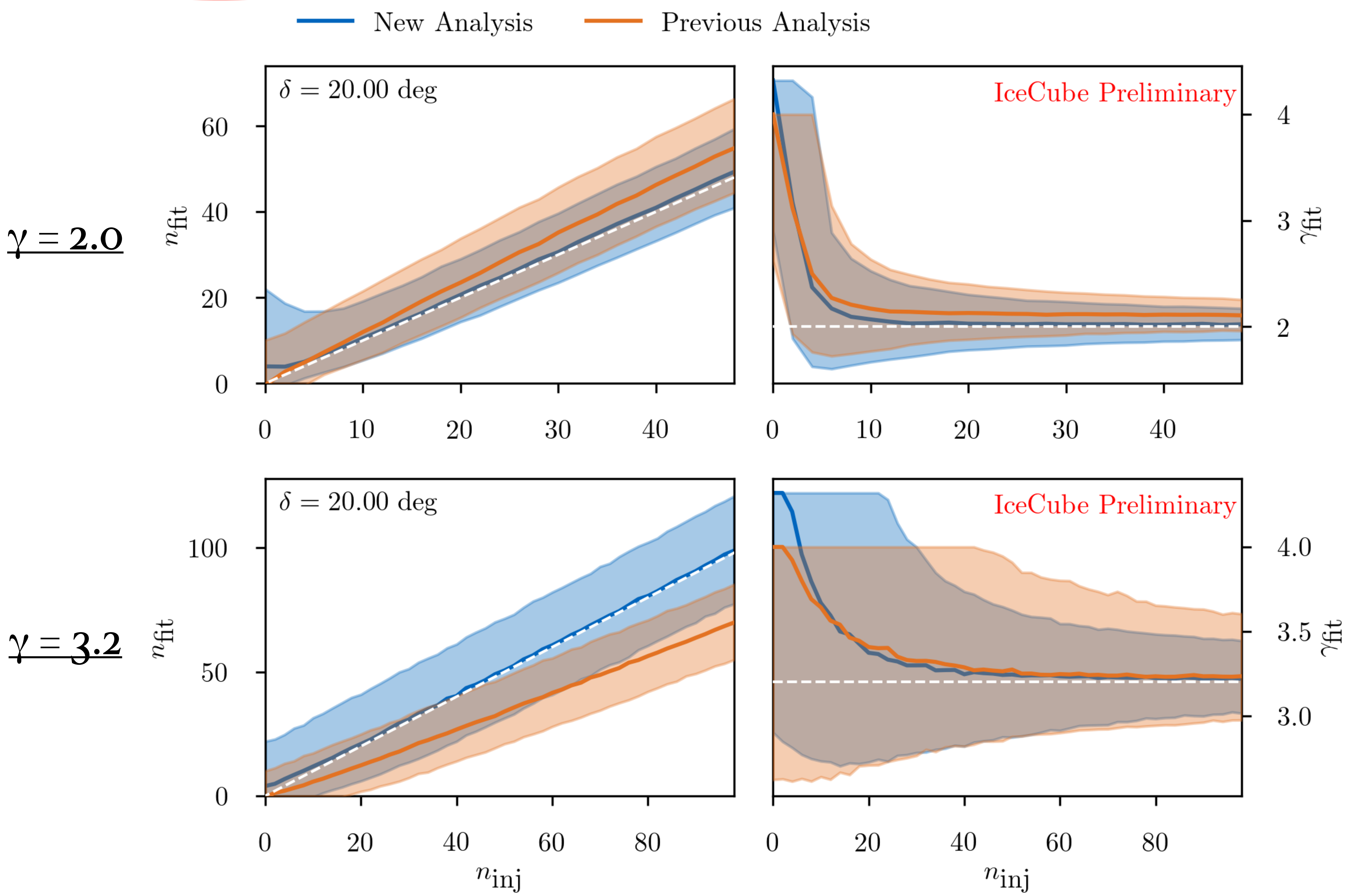


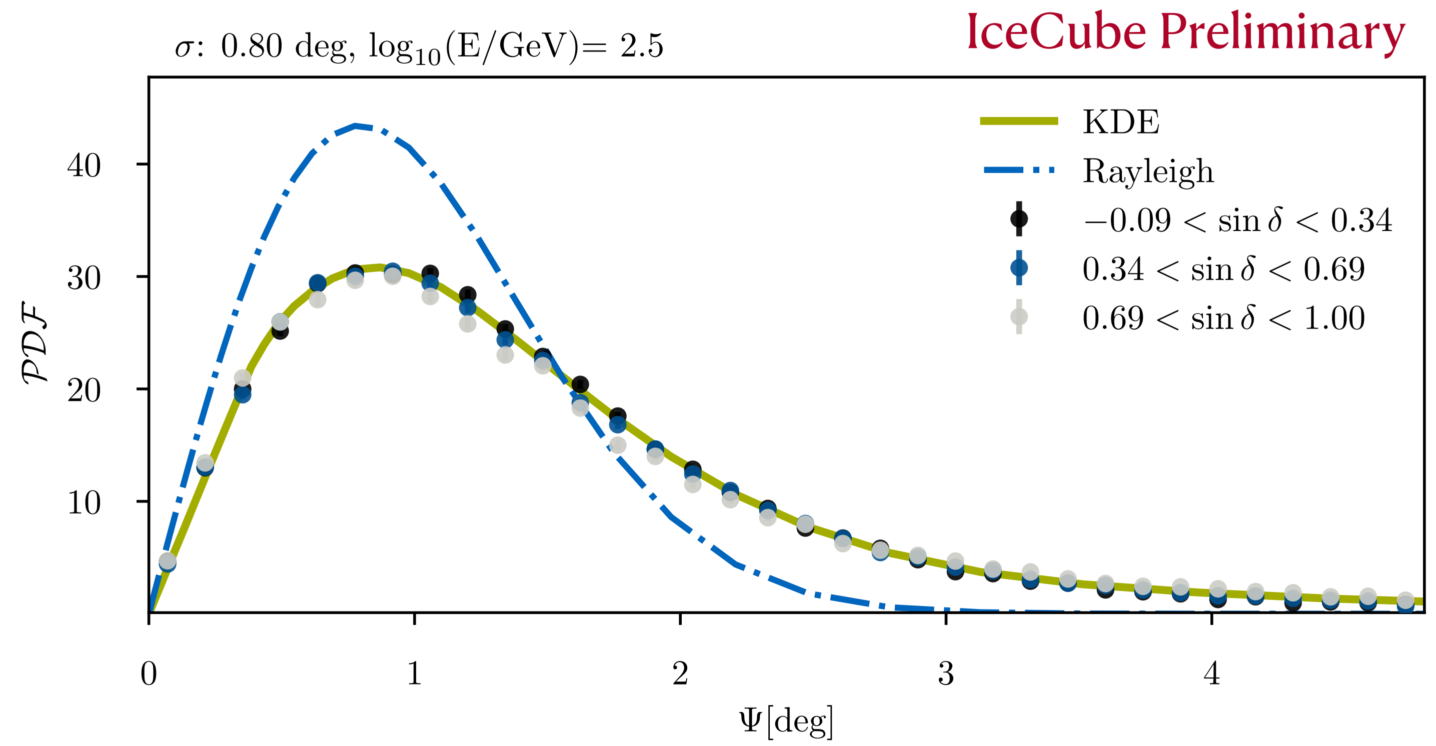
Legend:
Reyleigh = Phys. Rev. Lett. 124, 051103
KDE = The new analysis, PoS (ICRC 2021) 1138
JINST 16 (2021) C11002

- Rayleigh (1D-projection of 2D Gauss) doesn't describe our simulations properly, especially at lower energies!
- Numerical non-parametrical construction of the PDFs based on MC using Kernel Density Estimation (KDE).
- More improvements (see backup):
  - New DNN-based energy estimate (by T. Glauch)
  - New BDT-based angular uncertainty estimate (by H. Niederhausen)

Point Source analysis

New performances - unbiased Maximum Likelihood Estimators



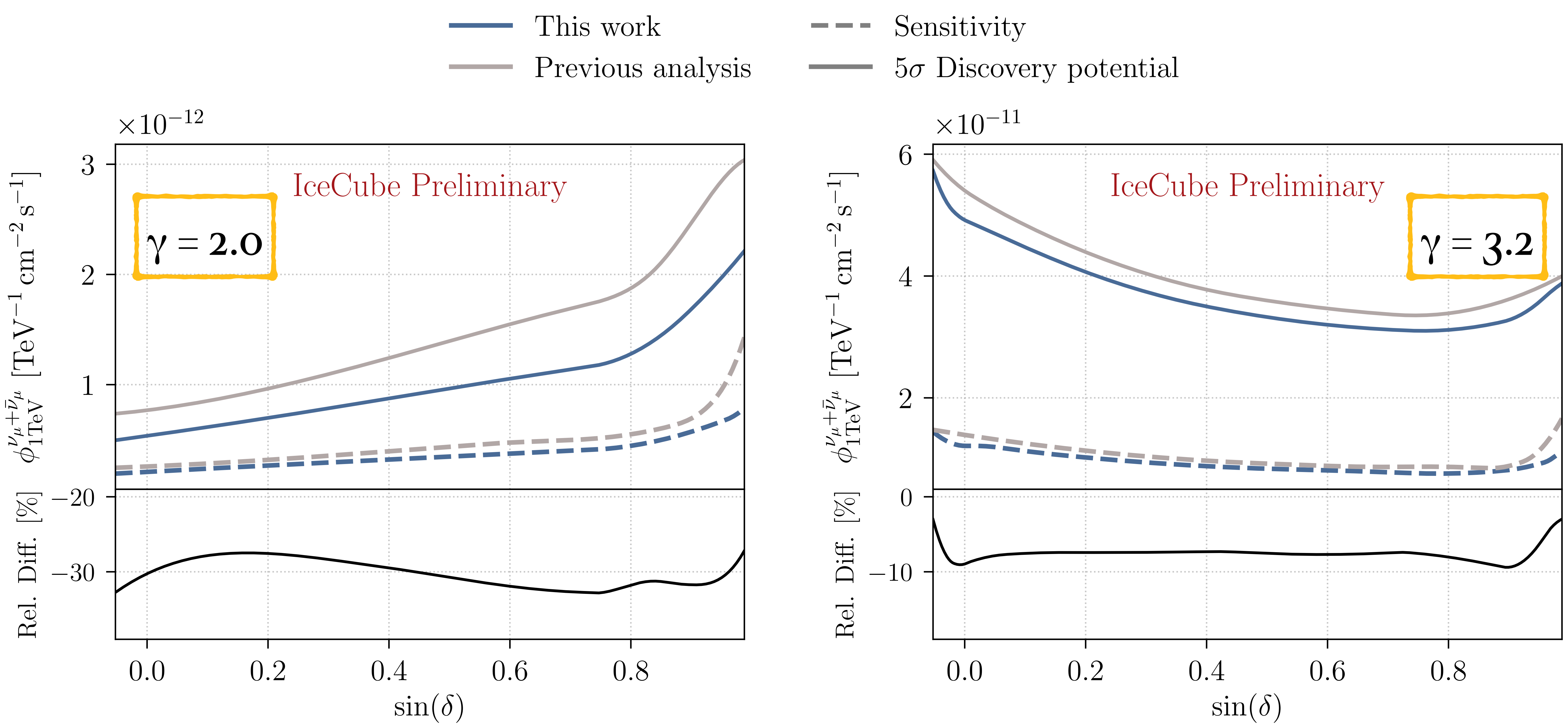


- Bias in the fit parameters of the point source likelihood is solved, thanks to a better description of the signal pdf.
- The coverage of the tail of the pdf recovers many low energy events, curing the large bias in the number of fitted events, especially for soft spectra.
- The improved energy estimation contributes to better constrain soft spectral indices .
- **Overall, the new analysis proves to be better at characterizing the source spectral emission!**

Point Source analysis

Potentially detectable flux

- Analysis: Test the **Northern Sky** - where IceCube is most sensitive to astrophysical signals - for high-energy neutrino emission.
- Sample: **9 years of muon tracks** reprocessed to the latest detector calibration.



- Thanks to the improved methods and new data processing, the discovery potential of the new point source analysis increases by ~30% (~10%) over previous works for hard (soft) spectra.

Summary

- **NGC 1068** was reported as an interesting neutrino source candidate by the IceCube Collaboration.
- Neutrinos are the probe for testing acceleration scenarios happening in obscured Seyfert galaxies.
- We developed a new and improved point source analysis method, to analyse an ultra pure sample of muon tracks in the Northern Sky reprocessed to the latest detector calibration.
  - Biases in the fit parameters characterizing the source emission are solved.
  - from ~10% to ~30% more likely to make a 5σ discovery, depending on the emission spectral index compared to the previous analysis.
- RESULTS are being published, COMING SOON!
- P.S. Very cool poster by Dr. Martina Karl on a new method to find flares (applied to neutrinos but maybe not only...!).

Backup

NGC 1068

As a neutrino source candidate

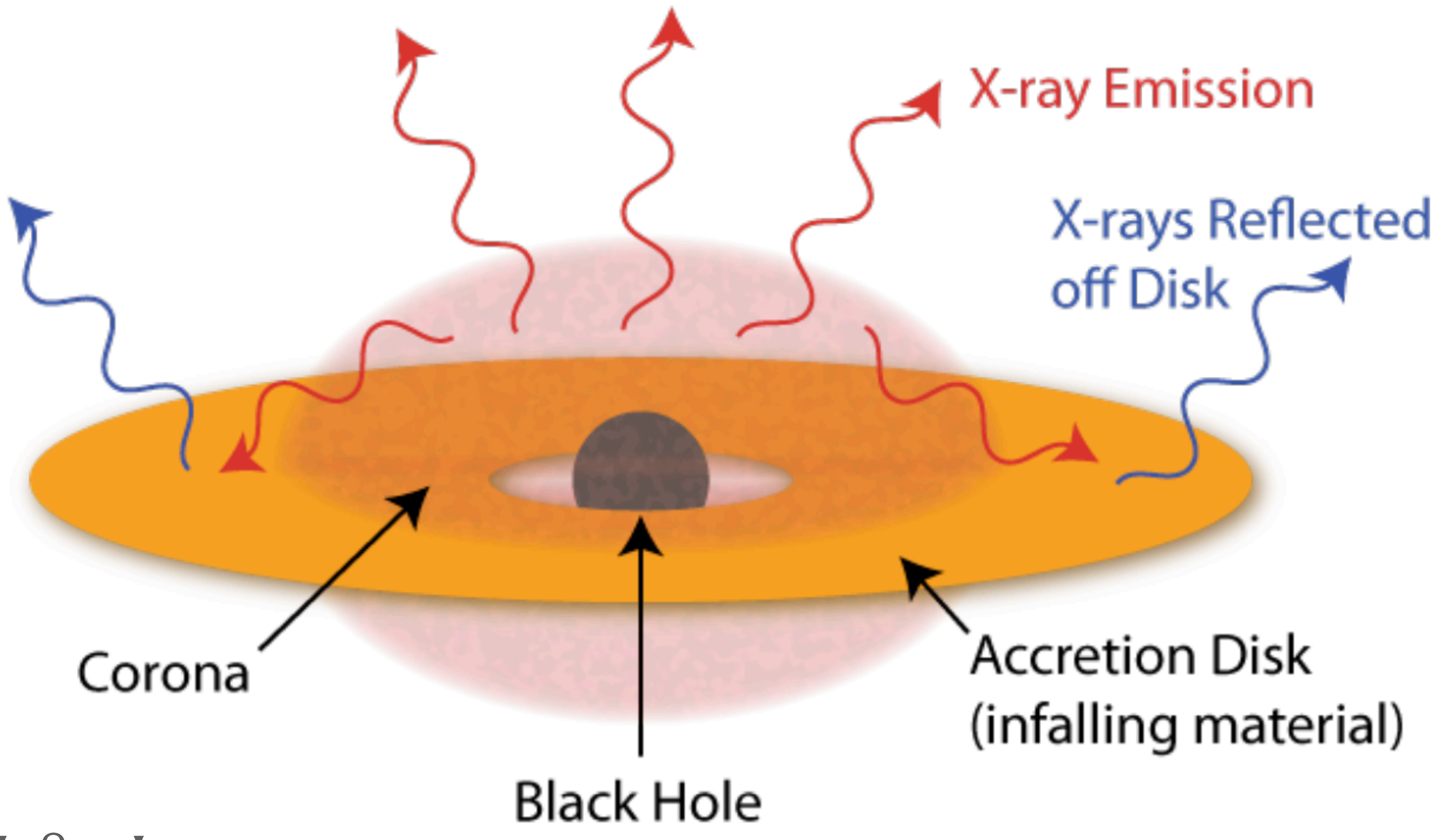
- "There are several classes of galaxies with compact nuclei and huge energy output from these nuclei […]. Seyferts of class 2, however, are so heavily obscured by dust and gas that their non-thermal nature is not established. It is shown that neutrino astronomy would help ascertain the nature of class 2 Seyferts."
- **The core of the AGN is optically thick for gamma-rays**, which undergo pair production reactions with the very abundant soft X-rays. Neutrinos can escape!
- Non-thermal activity in hot, turbulent AGN coronae? *
- A conclusive statement on whether NGC 1068 is a high-energy neutrino source or not, could shed light on the mechanisms producing the observed spectra.

ICRC PoS from 1979!

NEUTRINOS AS A PROBE FOR THE NATURE OF

AND PROCESSES IN ACTIVE GALACTIC NUCLEI

R. Silberberg and M. M. Shapiro
Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D. C. 20375, U.S.A.



* [Inoue et al 2020 ApJL 891 L33, Murase et al 2020 PRL 125, 011101, Kheirandish et al 2021 ApJ 922 45, …]

Backup

The Point-Source Likelihood

Signal PDF

Background PDF

$$f(\{x\}, N|\theta) = \frac{(\mu_s + \mu_b)^N}{N!} e^{-(\mu_s+\mu_b)} \times \prod_{i=1}^{N} \left[\frac{\mu_s}{\mu_s + \mu_b} \boxed{f_s(x_i|\theta_s)} + \frac{\mu_b}{\mu_s + \mu_b} \boxed{f_b(x_i|\theta_b)} \right]$$

The observables:

$$x_i = \{E_\mu, \vec{d}_\mu, \sigma\}$$

Signal Likelihood

2 free parameters:

- spectral index γ
- source strength μ_s

Background Likelihood

No free parameters.

Background flux expectations fixed through atmospheric models

$$f_s(E_\mu, \vec{d}_\mu, \sigma|\theta_s) = \frac{1}{2\pi \sin\psi} f_s(\psi|\sigma, E_\mu, \theta_s) \cdot f_s(E_\mu, \sigma|\theta_s)$$

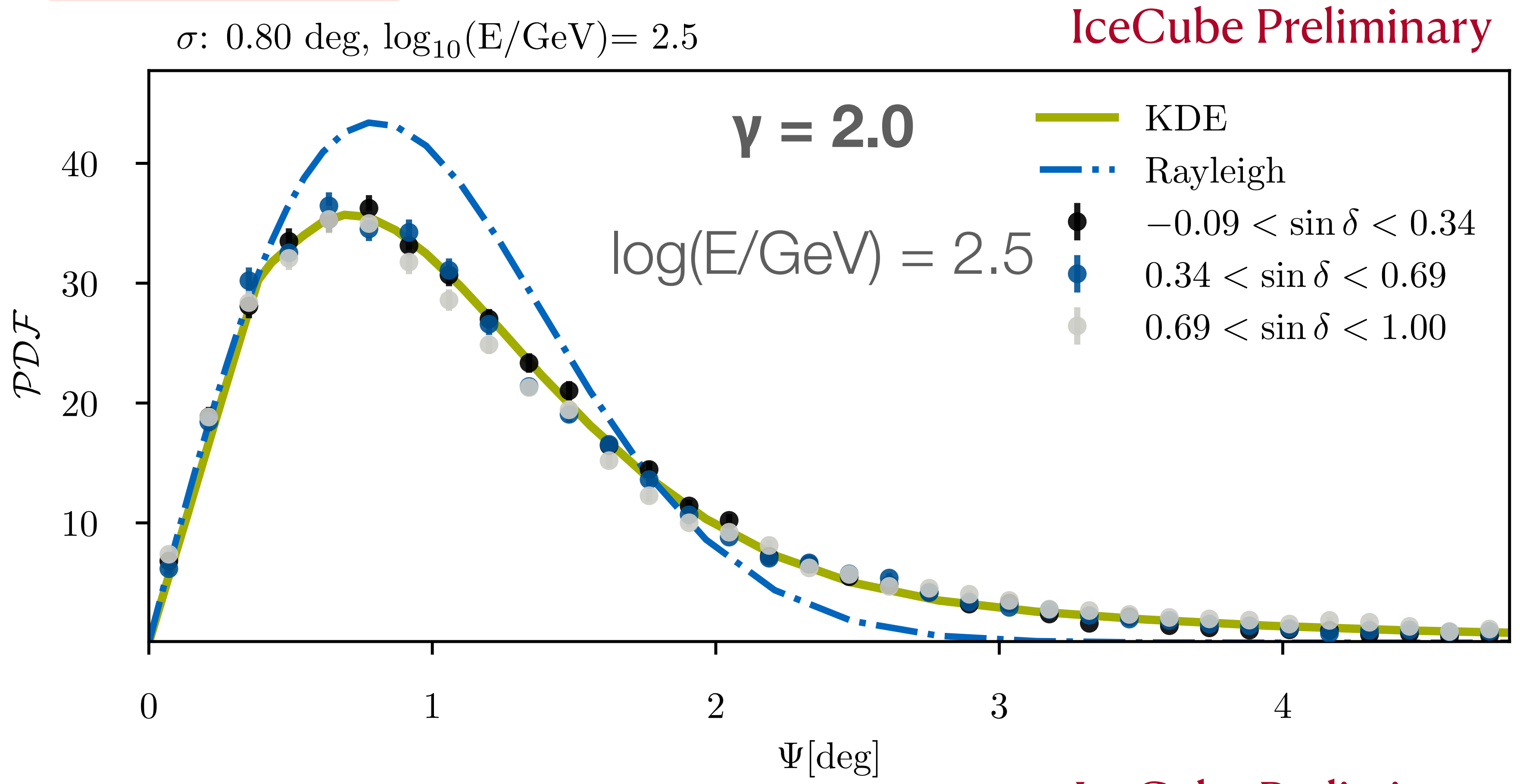
$$= \mathcal{S}(E_\mu, \psi, \sigma|\theta_s) \cdot \mathcal{E}(E_\mu, \cancel{\sigma}|\theta_s)$$

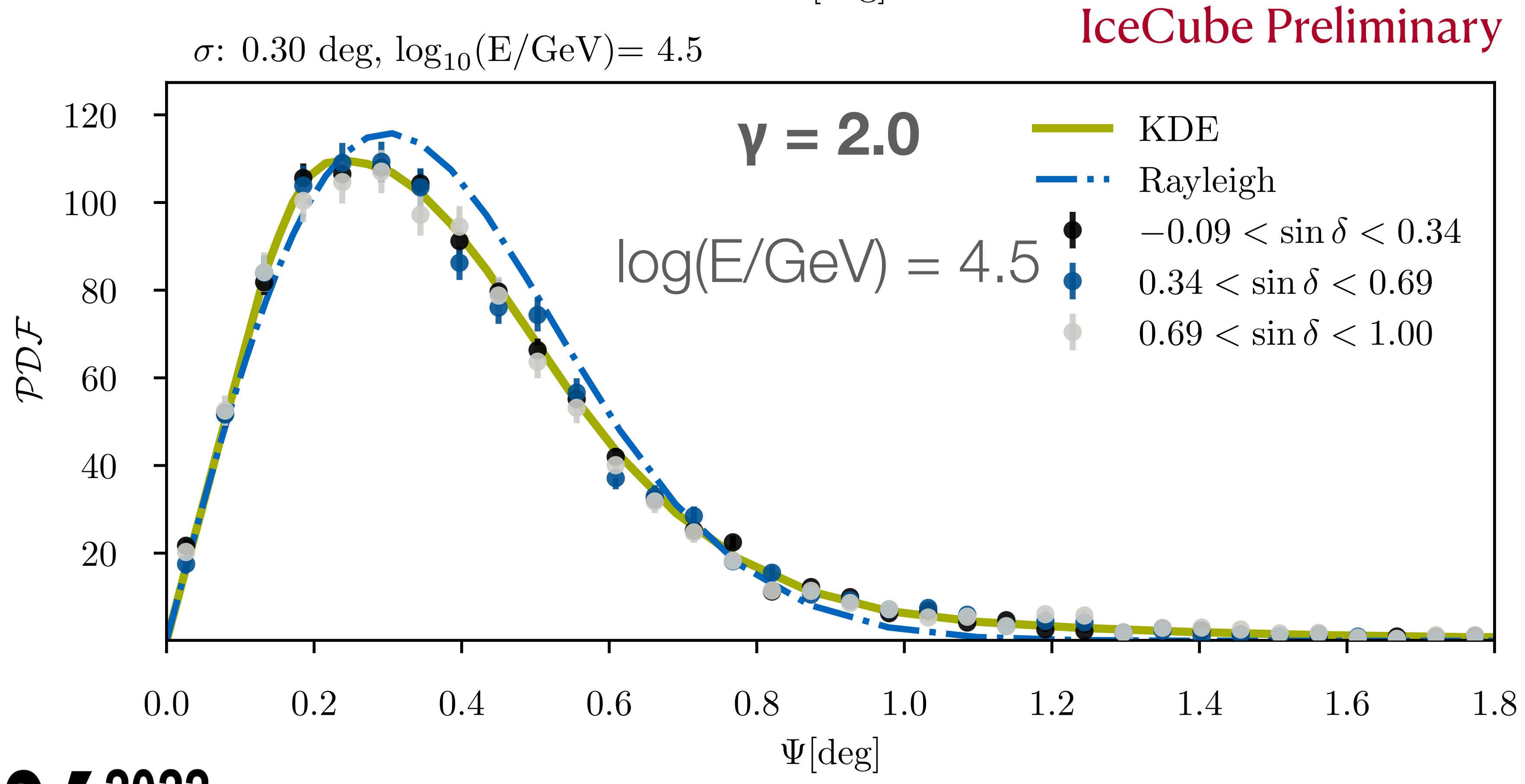
$$f_b(E_\mu, \vec{d}_\mu, \sigma|\theta_b) = \frac{1}{2\pi} f_b(E_\mu, \sin\delta_\mu, \cancel{\sigma}|\theta_b)$$

Point Source analysis

New methods - MC-based numerical construction of the PDFs

Legend:
Reyleigh = Phys. Rev. Lett. 124, 051103
KDE = The new analysis, PoS (ICRC 2021) 1138
JINST 16 (2021) C11002



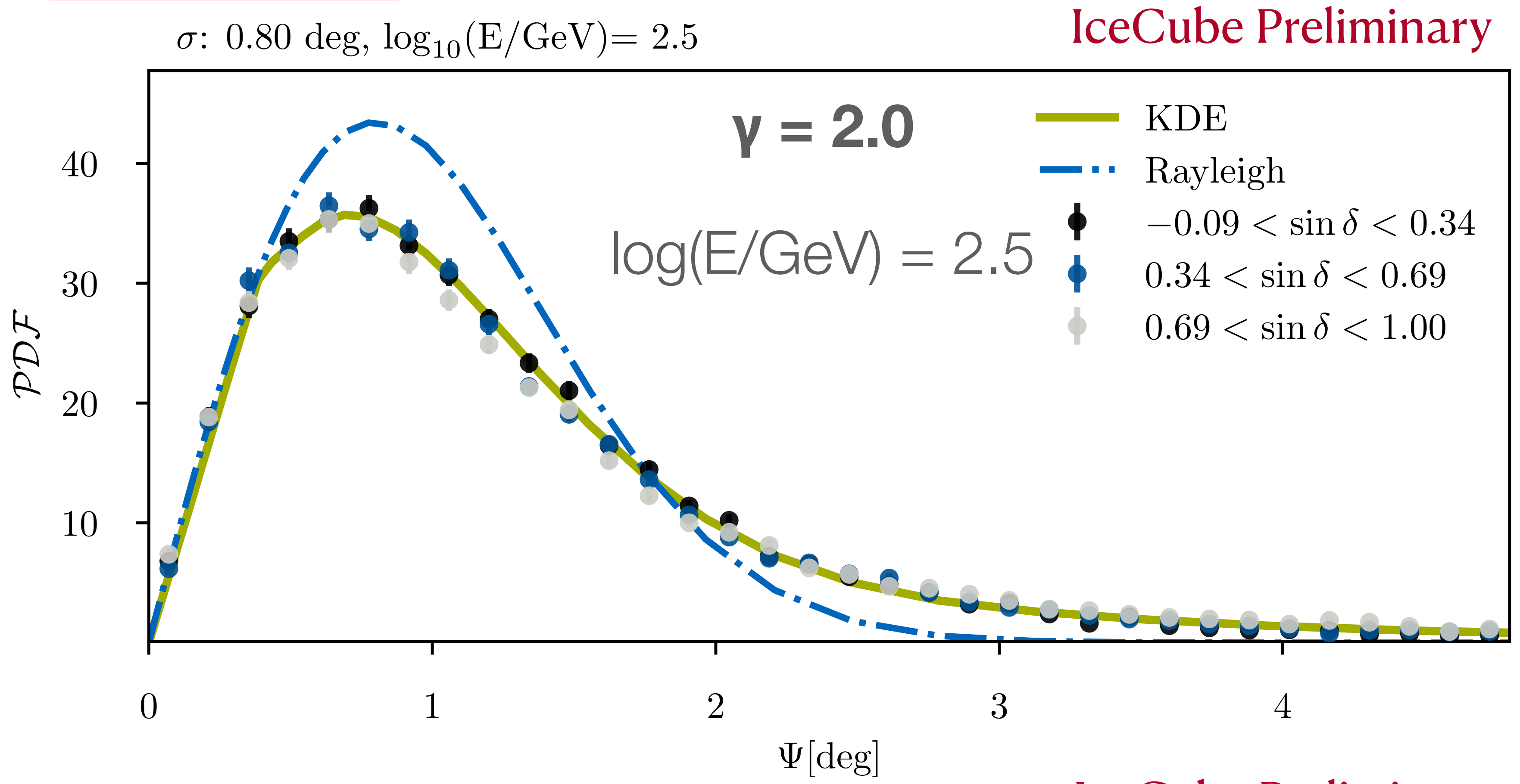


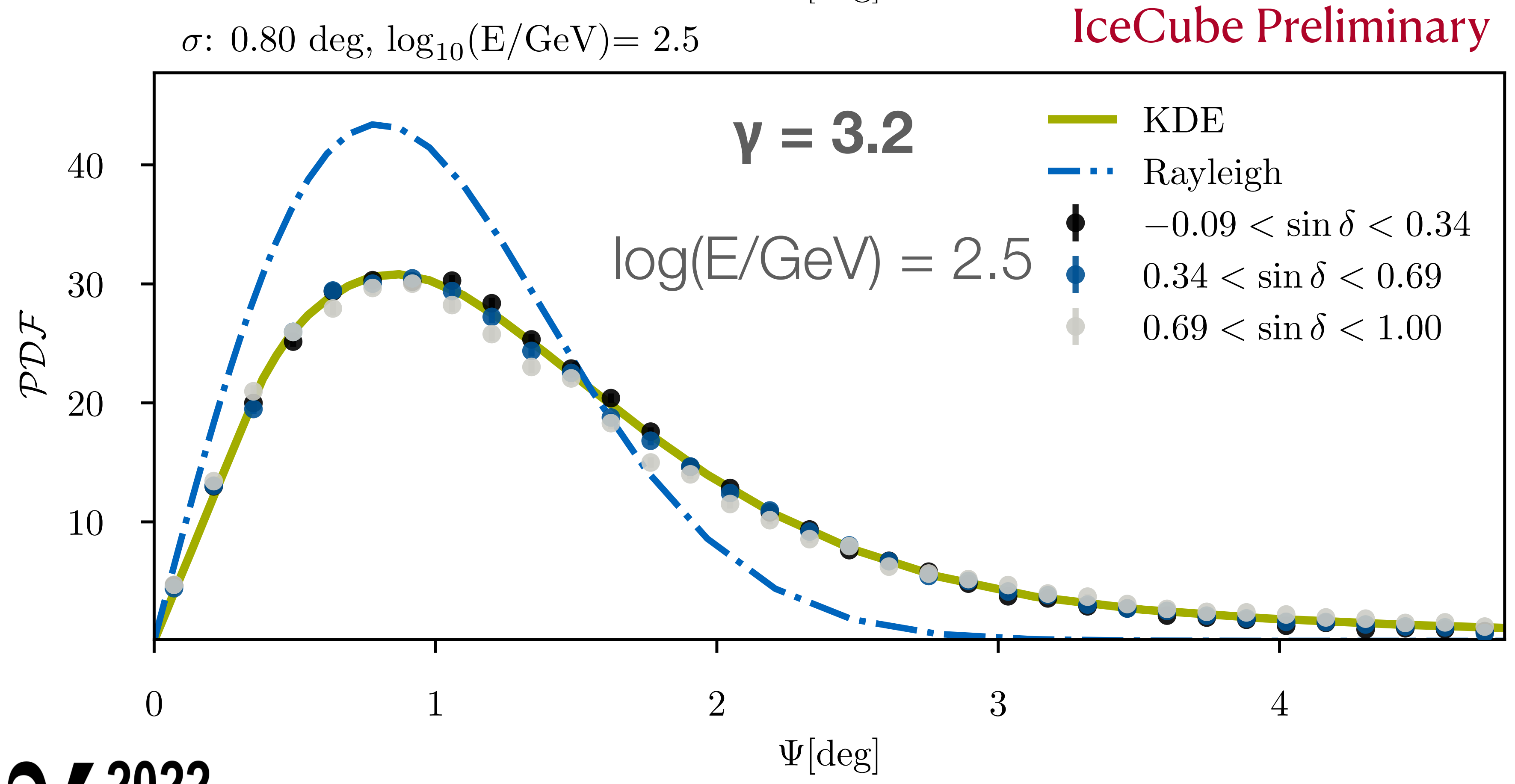
- Rayleigh (1D-projection of 2D Gauss) doesn't describe our simulations properly, especially at lower energies!
- Numerical non-parametrical construction of the PDFs based on MC using Kernel Density Estimation (KDE).
- Obtain a spectral index dependent description of the spatial term of the signal likelihood!
- More improvements (see backup):
  - New DNN-based energy estimate (by T. Glauch)
  - New BDT-based angular uncertainty estimate (by H. Niederhausen)

Point Source analysis

New methods - MC-based numerical construction of the PDFs

Legend:
Reyleigh = Phys. Rev. Lett. 124, 051103
KDE = The new analysis, PoS (ICRC 2021) 1138
JINST 16 (2021) C11002

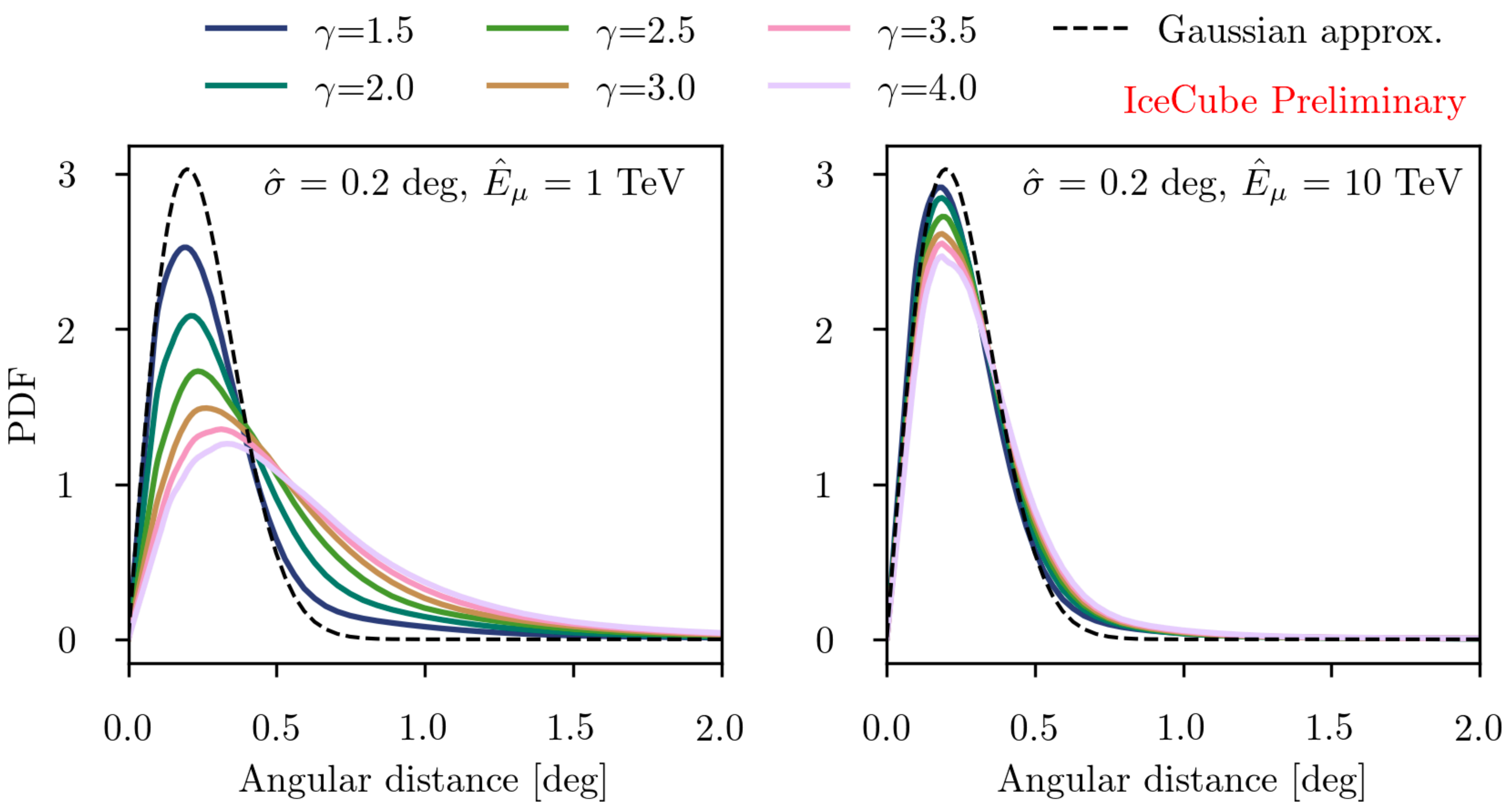




- Rayleigh (1D-projection of 2D Gauss) doesn't describe our simulations properly, especially at lower energies!
- Numerical non-parametrical construction of the PDFs based on MC using Kernel Density Estimation (KDE).
- Obtain a spectral index dependent description of the spatial term of the signal likelihood!
- More improvements (see backup):
  - New DNN-based energy estimate (by T. Glauch)
  - New BDT-based angular uncertainty estimate (by H. Niederhausen)

Backup

Spectral index dependence of the spatial signal pdf



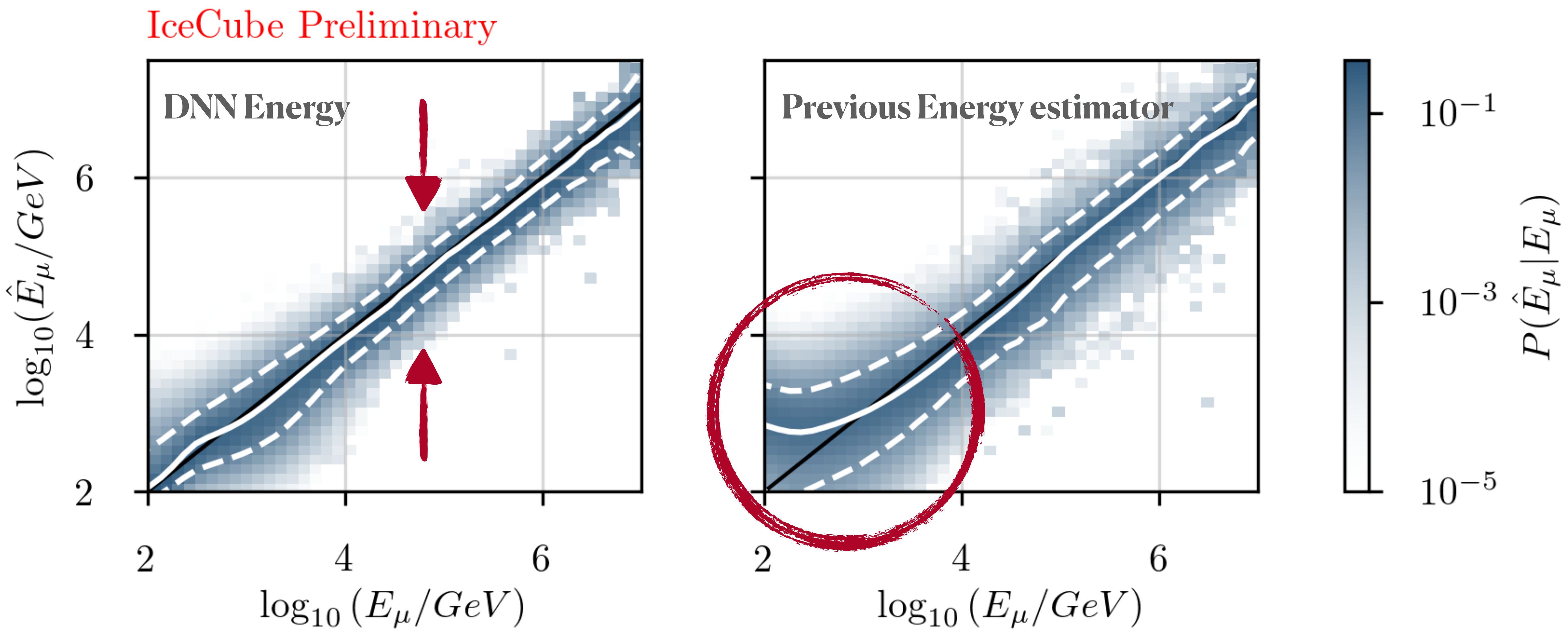
$$f_s(\hat{E}_\mu, \hat{\psi}, \hat{\sigma} \,|\, \sin(\delta_{src}), \gamma) \approx$$

$$\approx \frac{1}{2\pi \sin\hat{\psi}} f_s(\hat{\psi} \,|\, \hat{E}_\mu, \hat{\sigma}, \gamma) \cdot f_s(\hat{E}_\mu \,|\, \sin(\delta_{src}), \gamma)$$

- The angular uncertainty $\hat{\sigma}(\hat{E}_\mu, \gamma)$ combines the estimated reconstruction error and the kinematic angle (angular separation between the incoming neutrino and the secondary muon directions).
- At low energies, the quality of the reconstruction degrades enough that the kinematic angle becomes significant.

Backup

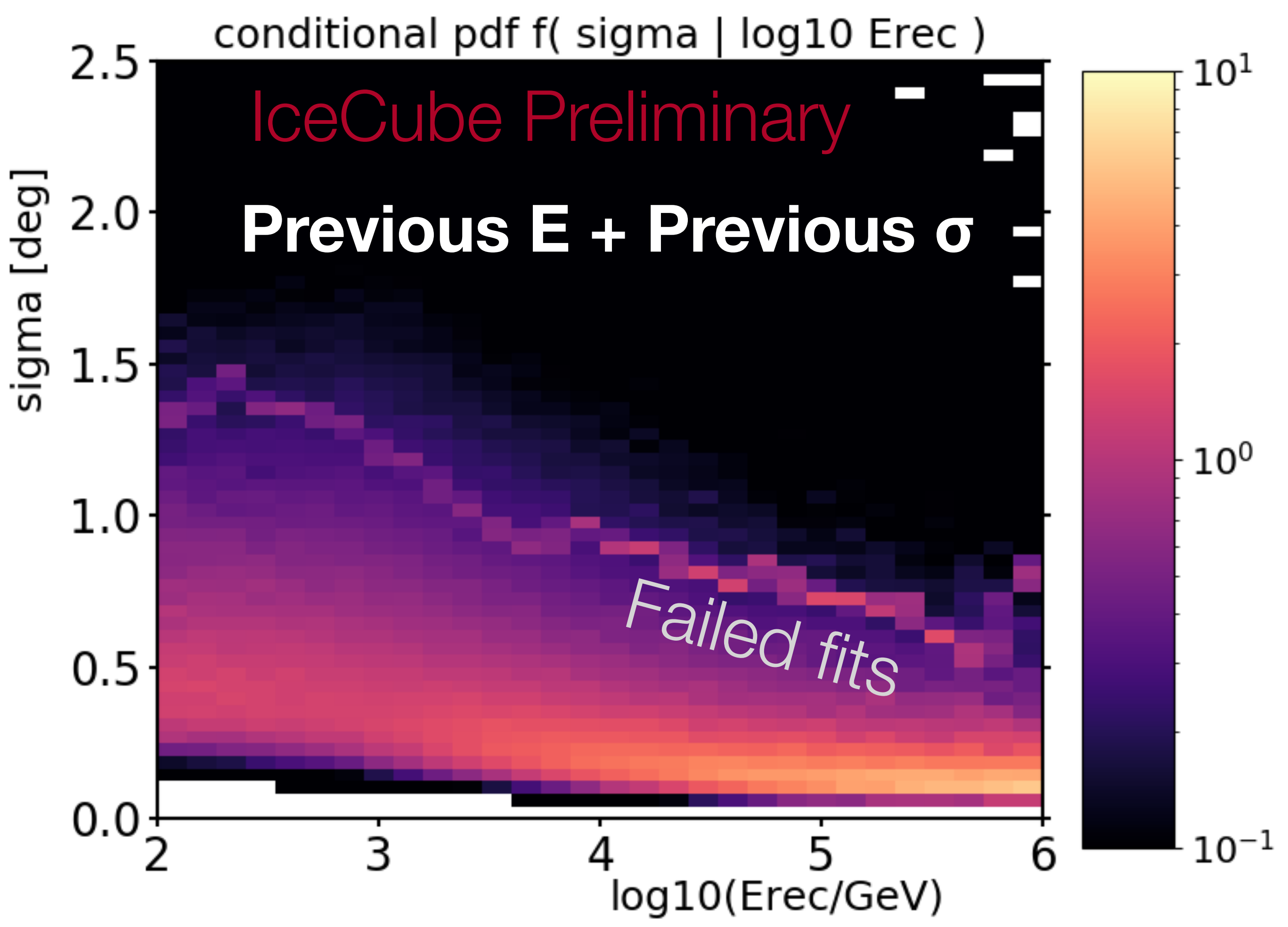
A new DNN-based energy estimator

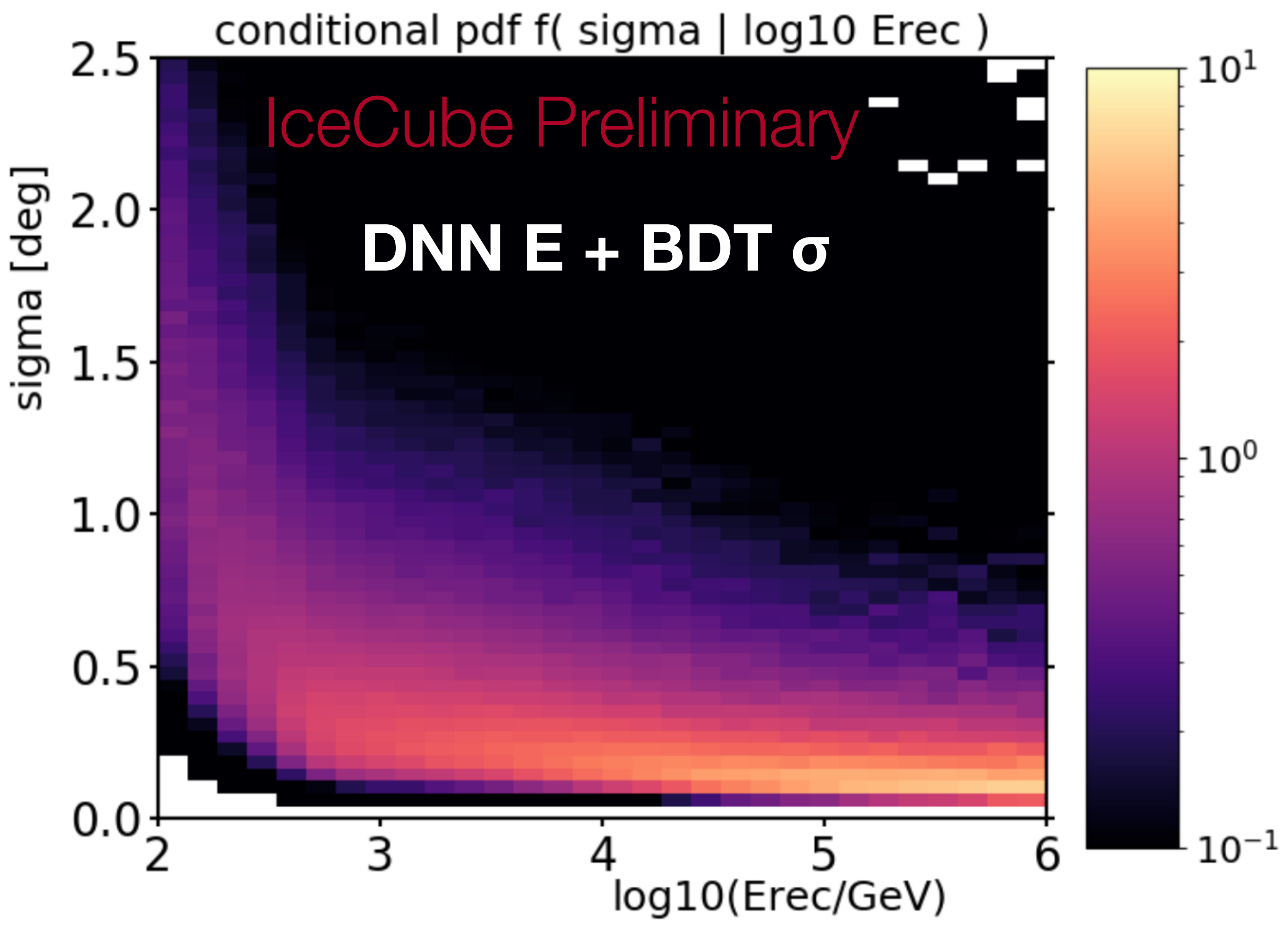


- Deep Neural Network energy estimator:
  - Able to resolve muon energy below 1TeV
  - Improves energy resolution by ~50% at all energies
- By removing the degeneracy in the energy reconstruction, we also improve the angular resolution, as the reconstructed energy carries information about the kinematic angle between muon and parent neutrino.
- Increased power in separating background fluctuations from signal.

Backup

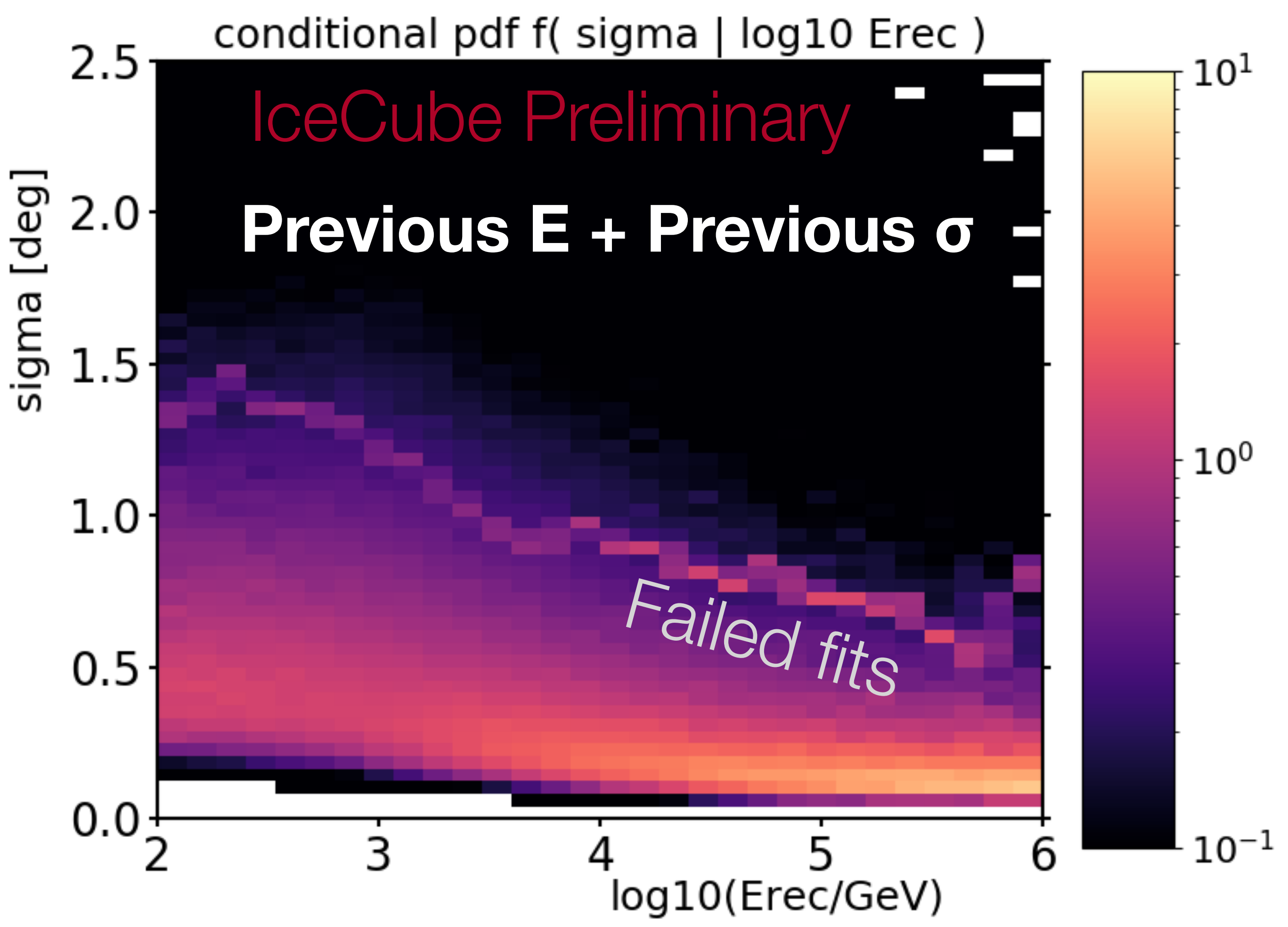
The new angular error estimator

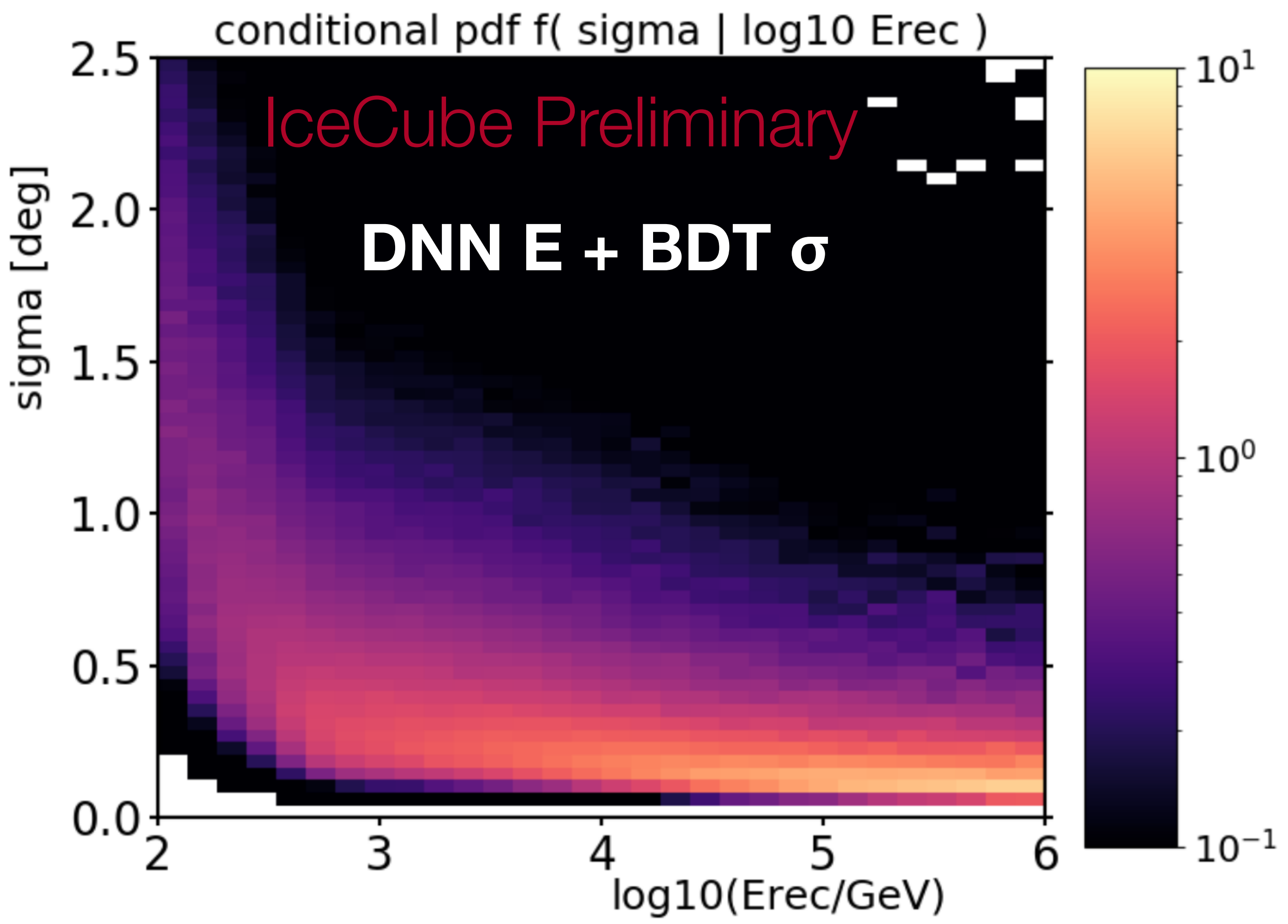




Backup

The new angular error estimator





- **Boosted Decision Tree angular uncertainty (σ) estimator:**
  - Very stable: no failed fits and no strong outliers
  - Absorbs zenith dependence of the spatial pdf, especially important for low energy events
- Trained on multiple variables all having excellent data/MC agreement in the sample, including:
  - Previous angular error estimator
  - Angular distance for different directional reconstructions
  - Different energy estimators
  - Location in the detector
  - Zenith angle
  - …

Backup

Some details about Kernel Density Estimation

- The pdfs in the point source likelihood can not be described analytically: **KDEs are a convenient non-parametric way to infer a PDF for a given sample**.

- KDEs don't depend much on the chosen **kernel**: we use a **n-D Gaussian.**

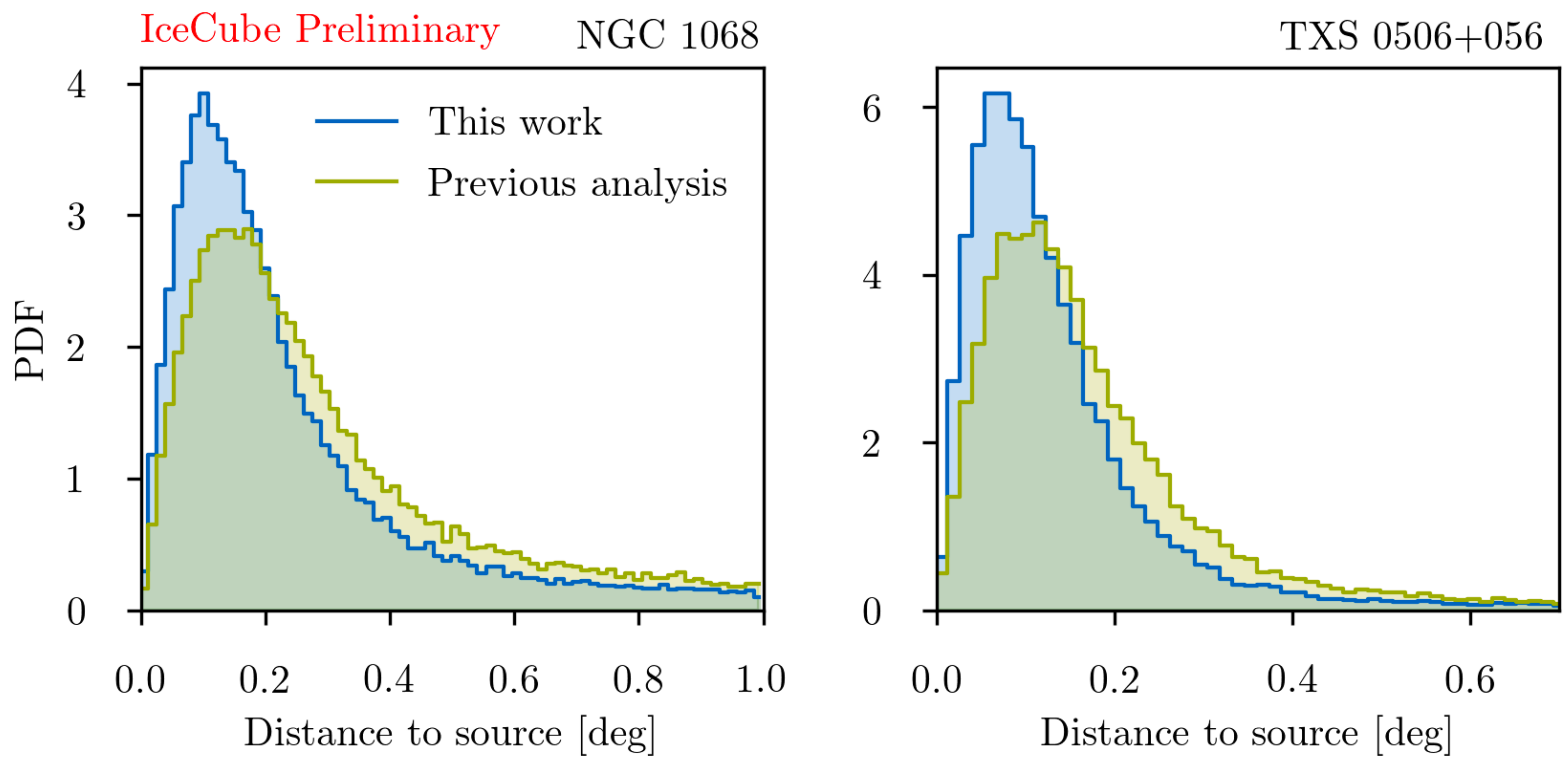
- **We use a smoothing parameter *h (bandwidth)* to account for the limited MC statistics**. The optimal bandwidth is chosen using a k-fold cross validation, splitting the sample in k-parts and in subsequent k iterations the KDE is then trained on $k - 1$ parts of the dataset (training dataset) and evaluated on the remaining part (test dataset).

Backup

Improvement in pointing capability

- Distribution of the angular distance from a source simulated at the location of NGC 1068 and TXS 0506+056 to the location where the global maximum of the likelihood is found.

- For NGC 1068, the hottest spot is found at a median distance of 0.24° from the simulated source instead of 0.35°, assuming the best fit flux reported in [Phys. Rev. Lett. 124, 051103]

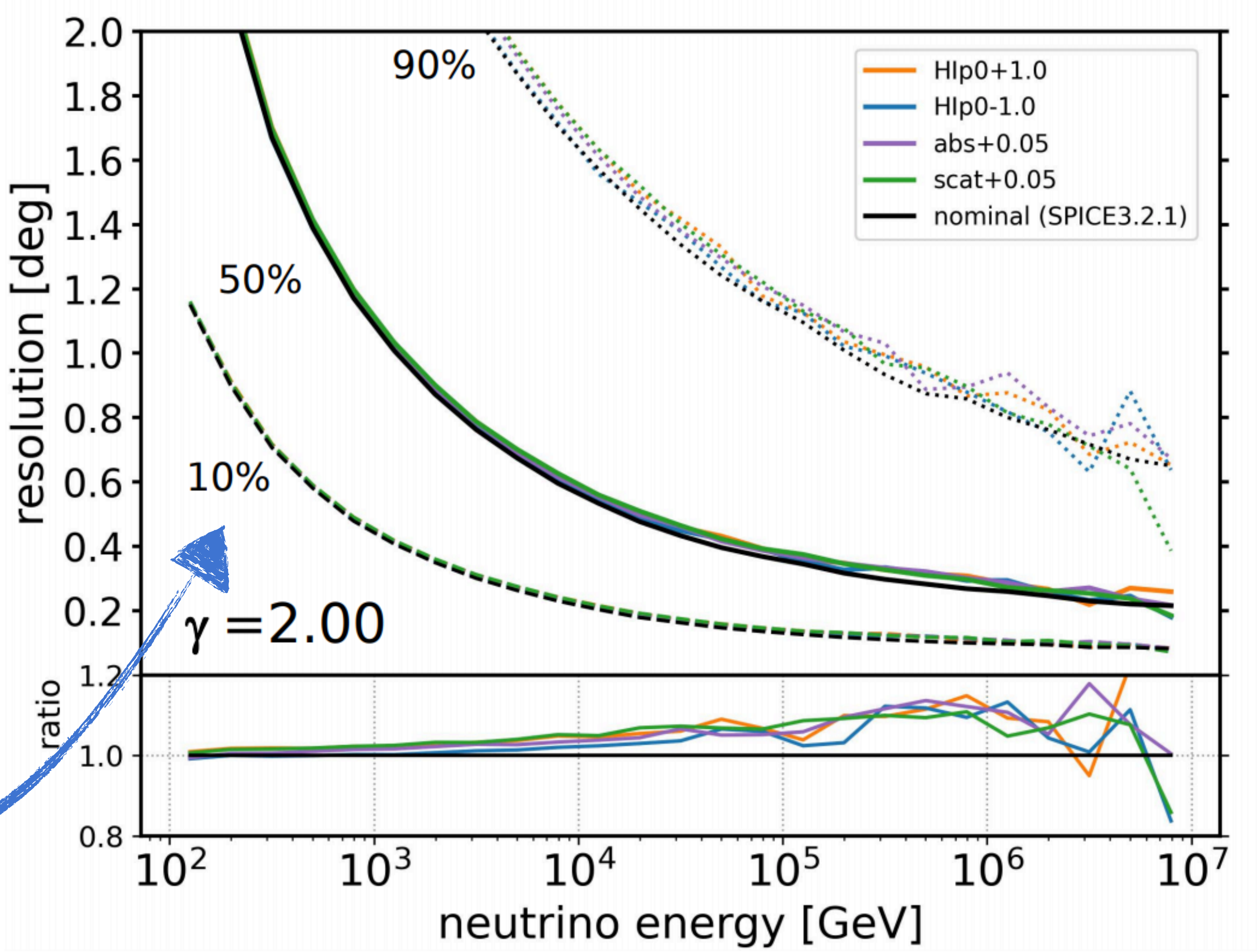


Backup

Stability against ice systematics

- The directional reconstruction proves to be fairly stable against the typical ice systematics.

Resolution = opening angle between the reconstructed muon direction and the true neutrino direction for different ice models, assuming a benchmark value for the energy spectral index of 2.0



Backup

A glance to a promising future - PLEνM

- PLEνM, the Plenary Neutrino Monitoring System [PoS (ICRC2021) 1185]:
  "a concept for a global repository of high-energy neutrino observations, in order to finally give firm answers to open questions."

- PLEνM-1 : IceCube + IceCube-like detectors at the locations of KM3Net, Baikal GVD and P-ONE.

- PLEνM-2 : Assume a detector with 7.5 times the IceCube's effective area instead of IceCube.

Neutrino flux for 5σ discovery potential