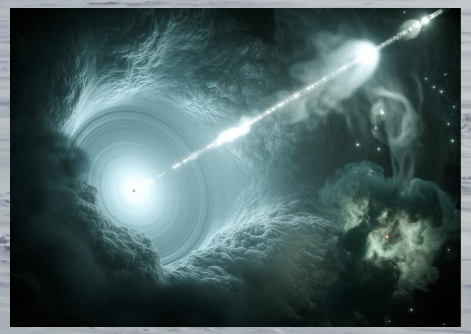
A New Search for Neutrino Point Sources with IceCube

Theo Glauch [1]
Chiara Bellenghi [1]
Martin Wolf [1]
Hans Niederhausen [1,3]
Tomas Kontrimas [1]
Matthias Huber [1]
Christian Haack [1]
Rene Reimann [2]

[1] Technical University of Munich
[2] University of Mainz
[3] Michigan State University

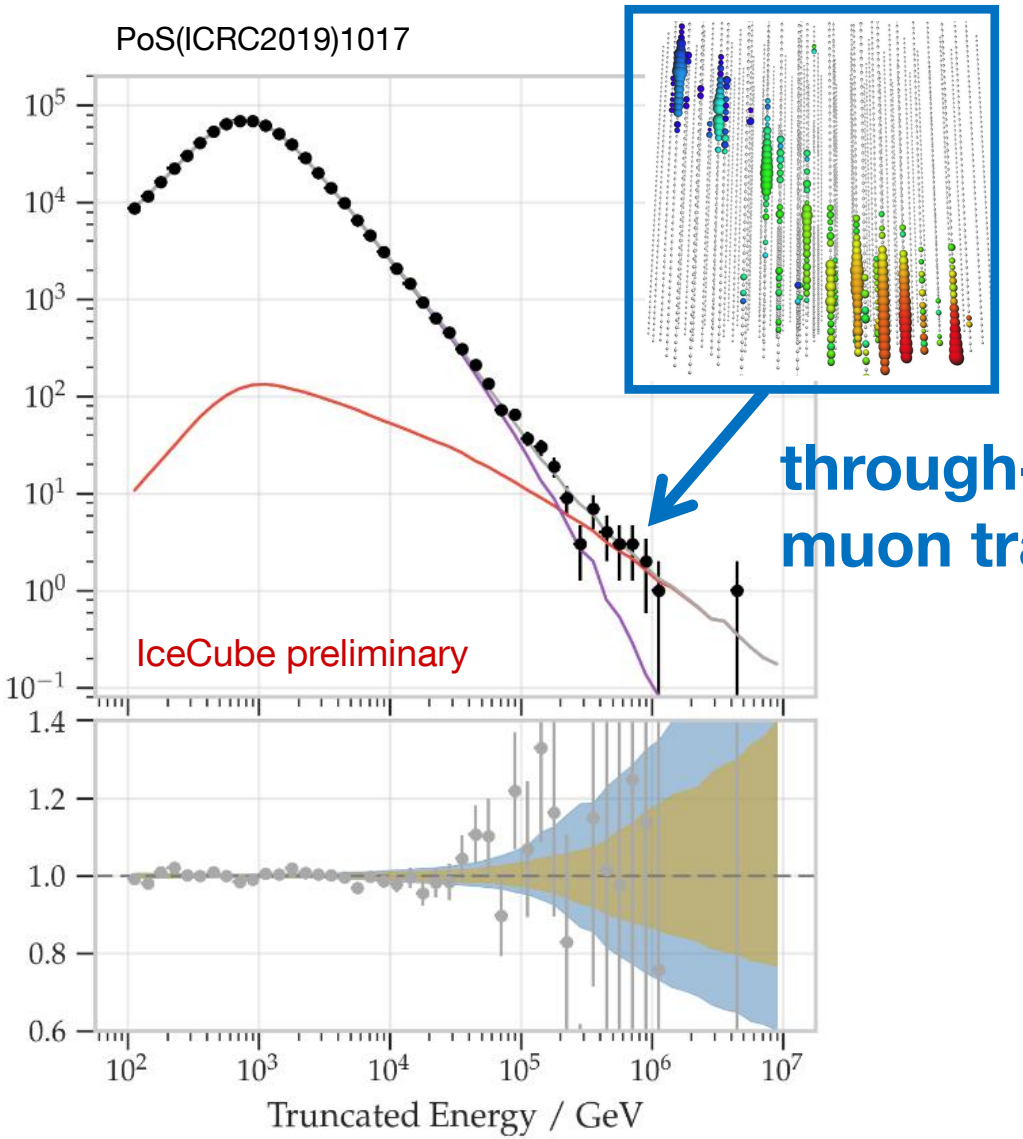
for the IceCube Collaboration



South Pole

37th International Cosmic Ray Conference, 12-23 July 2021, Germany, Berlin

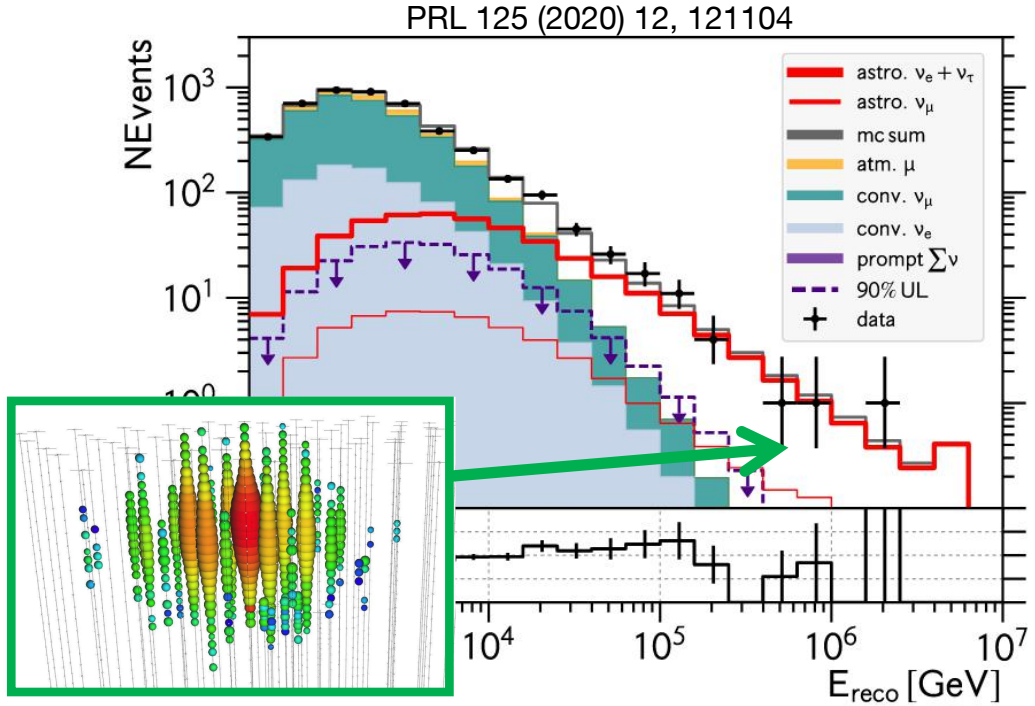
PoS(ICRC2019)1017



through-going muon tracks

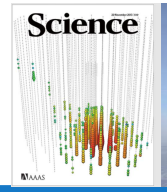
reconstructed track energy

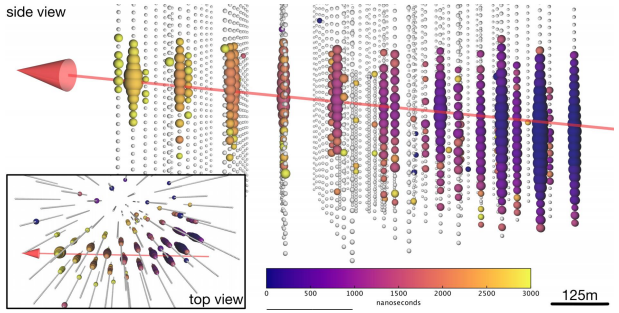
PRL 125 (2020) 12, 121104



cascades

IceCube has been studying a **diffuse flux** of high energy **astrophysical neutrinos** for almost a decade!



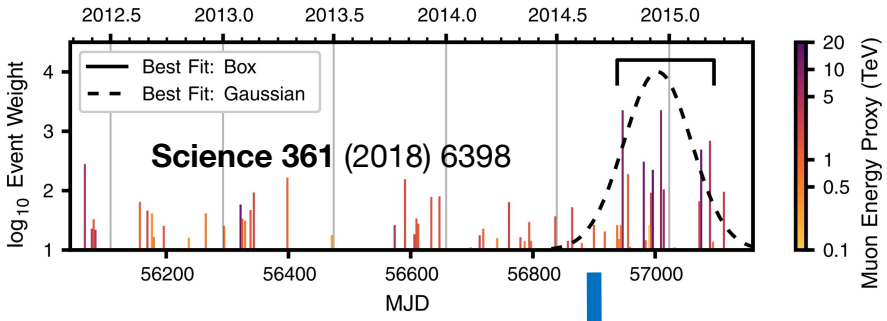


Science 361 (2018) 1378

γ-ray flare coincident with **high energy neutrino** in September 2017

Eν ~ 290 TeV

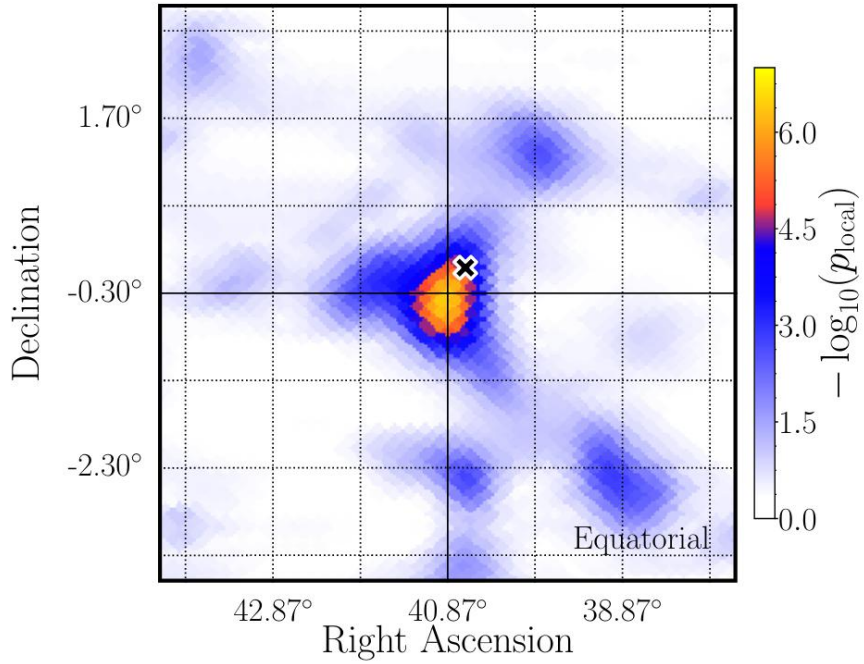
spatial + temporal clustering of neutrinos in 2014/5 at 3.5σ significance



compelling evidence identifies blazar **TXS 0506+056** as **first neutrino source**

likely time variable

PRL 124 (2020) 5, 051103

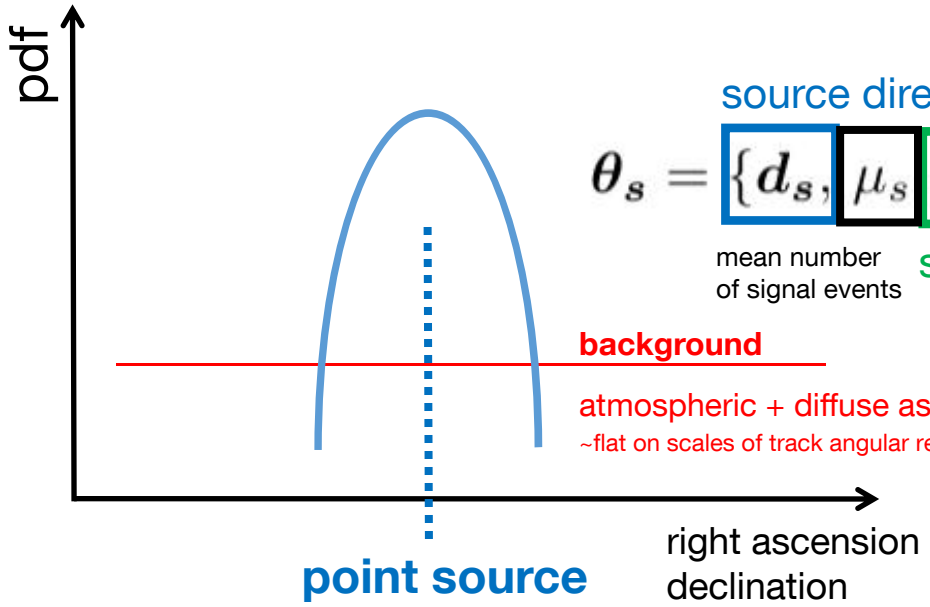


excess clustering of ~TeV νs near **NGC 1068** during a 10 years period (2.9σ @ NGC 1068) !

origin of vast majority of astro νs remains unknown!

hunting for the sources

directional clustering



source direction

$$\boldsymbol{\theta_s} = \{\boldsymbol{d_s}, \mu_s, \gamma_s\}$$

mean number of signal events

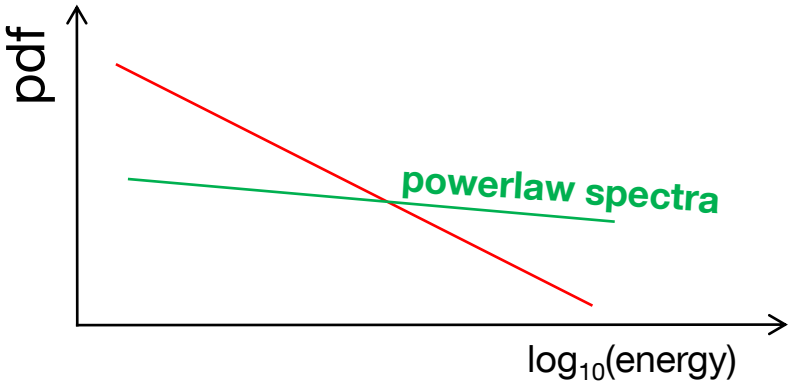
source spectral index

background

atmospheric + diffuse astrophysical

~flat on scales of track angular resolution (~1 deg)

different energy spectrum



Braun et al., Astropart. Phys. 29 (2008) 299305

$$L\left(\boldsymbol{\theta_s} \,|\, \hat{\boldsymbol{E}}, \hat{\boldsymbol{\sigma}}, \hat{\boldsymbol{d}}\right) = \prod_{i=1}^{N} \left\{ \frac{\mu_s}{N} \times \frac{1}{2\pi\hat{\sigma}_i^2} \exp\left(-\frac{1}{2\hat{\sigma}_i^2} \left|\hat{\boldsymbol{d}}_i - \boldsymbol{d_s}\right|^2\right) f_s\left(\hat{E}_i; \gamma\right) + \left(1 - \frac{\mu_s}{N}\right) \times f_b\left(\hat{E}_i, \hat{\boldsymbol{d}}_i\right) \right\}$$

2-D Gaussian

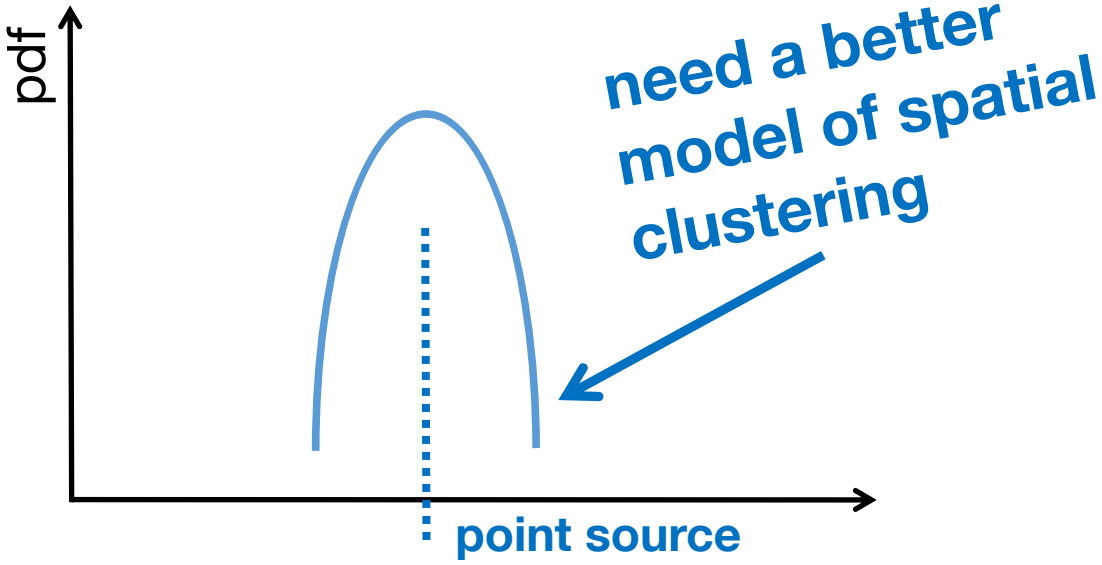
(independent of spectral index)

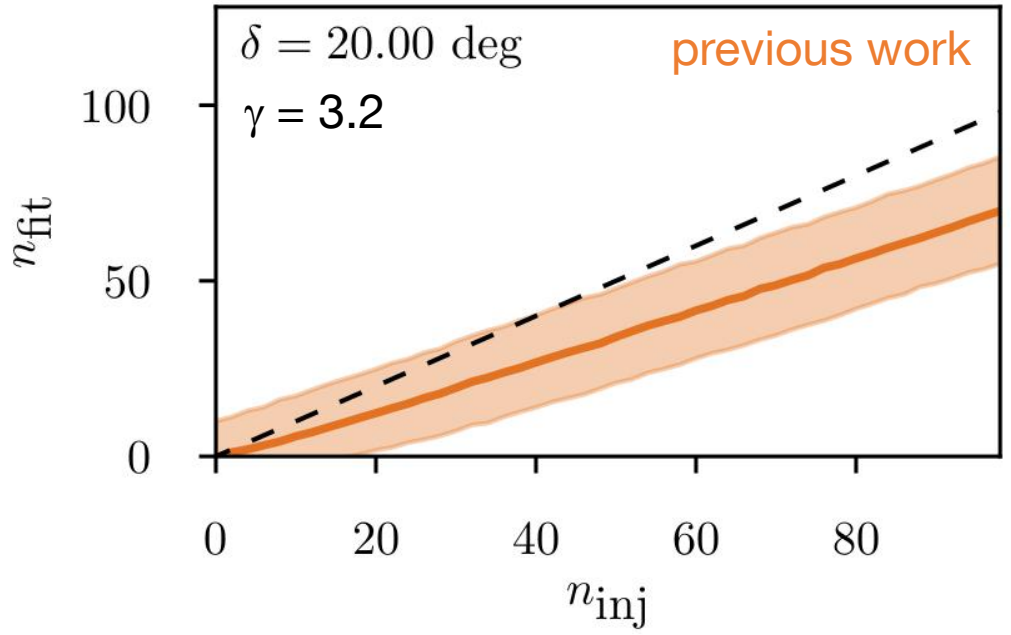
Braun et al. "**PointSource Likelihood**" has been a **reliable workhorse** for > decade

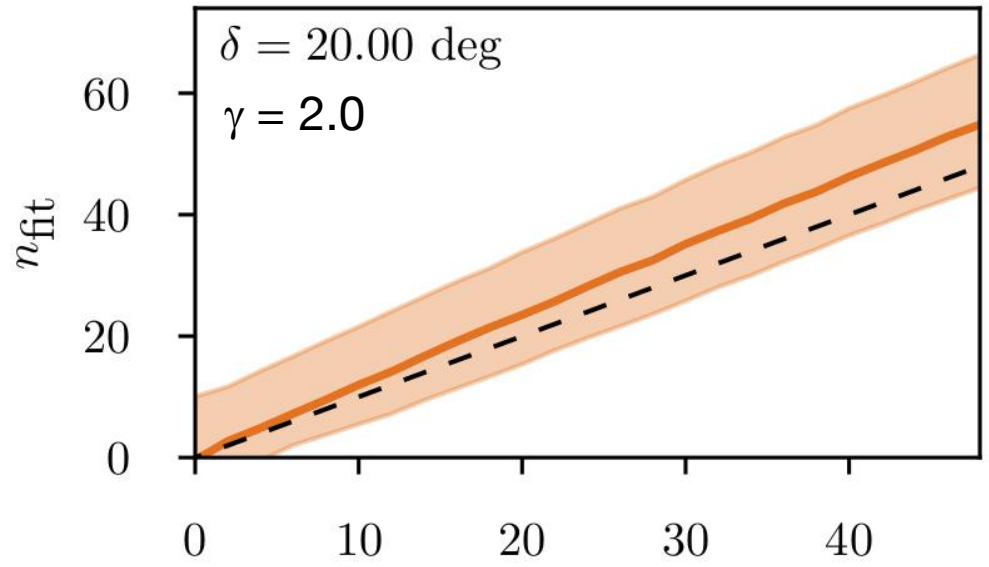
powerful method to identify point sources
correct p-values (by construction)

known limitations => room for improvement!

estimates of a source's **signal strength can be biased** due to use of spectral index independent **2-D Gaussian spatial PDF**







$$L\left(\boldsymbol{\theta_s} \,|\, \hat{\boldsymbol{E}}, \hat{\boldsymbol{\sigma}}, \hat{\boldsymbol{d}}\right) = \prod_{i=1}^{N} \left\{ \frac{\mu_s}{N} \times \frac{1}{2\pi\hat{\sigma}_i^2} \exp\left(-\frac{1}{2\hat{\sigma}_i^2} \left| \hat{\boldsymbol{d}}_{\boldsymbol{i}} - \boldsymbol{d_s} \right|^2 \right) f_s\left(\hat{E}_i; \gamma\right) + \left(1 - \frac{\mu_s}{N}\right) \times f_b\left(\hat{E}_i, \hat{\boldsymbol{d}}_{\boldsymbol{i}}\right) \right\}$$

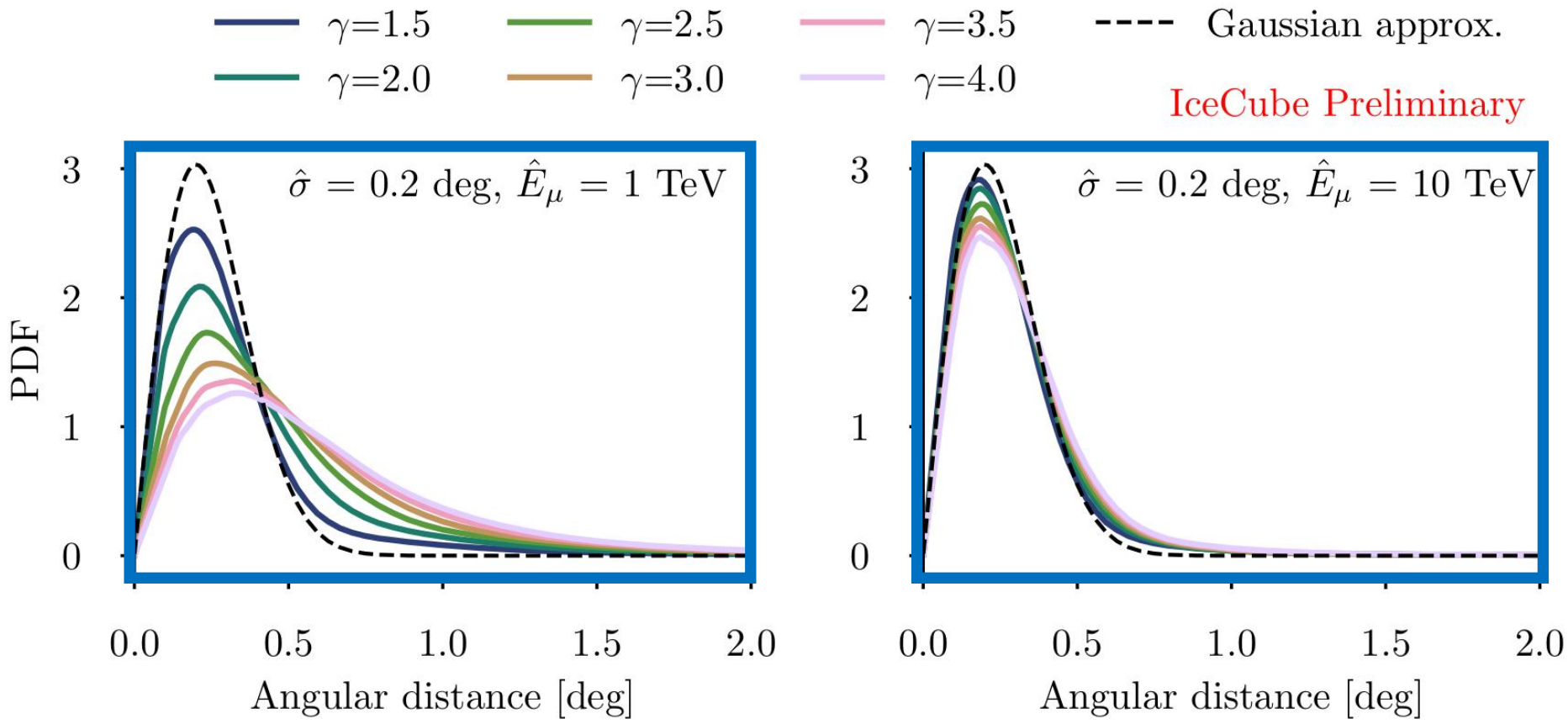
~~2-D Gaussian~~

final likelihood reads

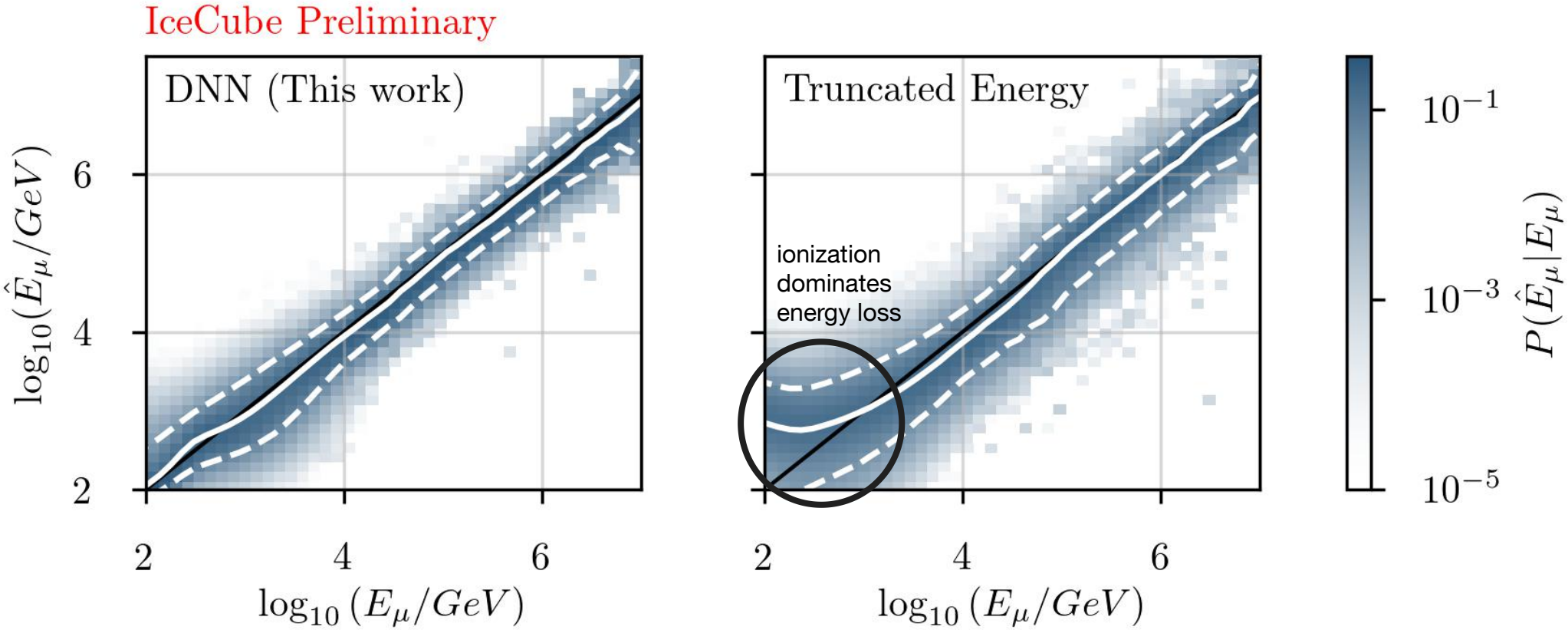
$$\prod_{i=1}^{N} \left\{ \frac{\mu_s}{N} \times \frac{1}{2\pi \sin\hat{\psi}} f_s\left(\psi\left(\hat{\boldsymbol{d}}_i, \boldsymbol{d}_s\right) | \hat{\sigma}_i, \hat{E}_i, \gamma\right) f_s\left(\hat{E}_i | \gamma\right) + \left(1 - \frac{\mu_s}{N}\right) \times f_b\left(\hat{E}_i, \hat{\boldsymbol{d}}_i\right) \right\}$$

spatial pdf describes **separation conditional** on **angular error** and **energy**

=> **generated from** Monte Carlo **simulations** of track events in IceCube



we also **improved** the **track energy** reconstruction

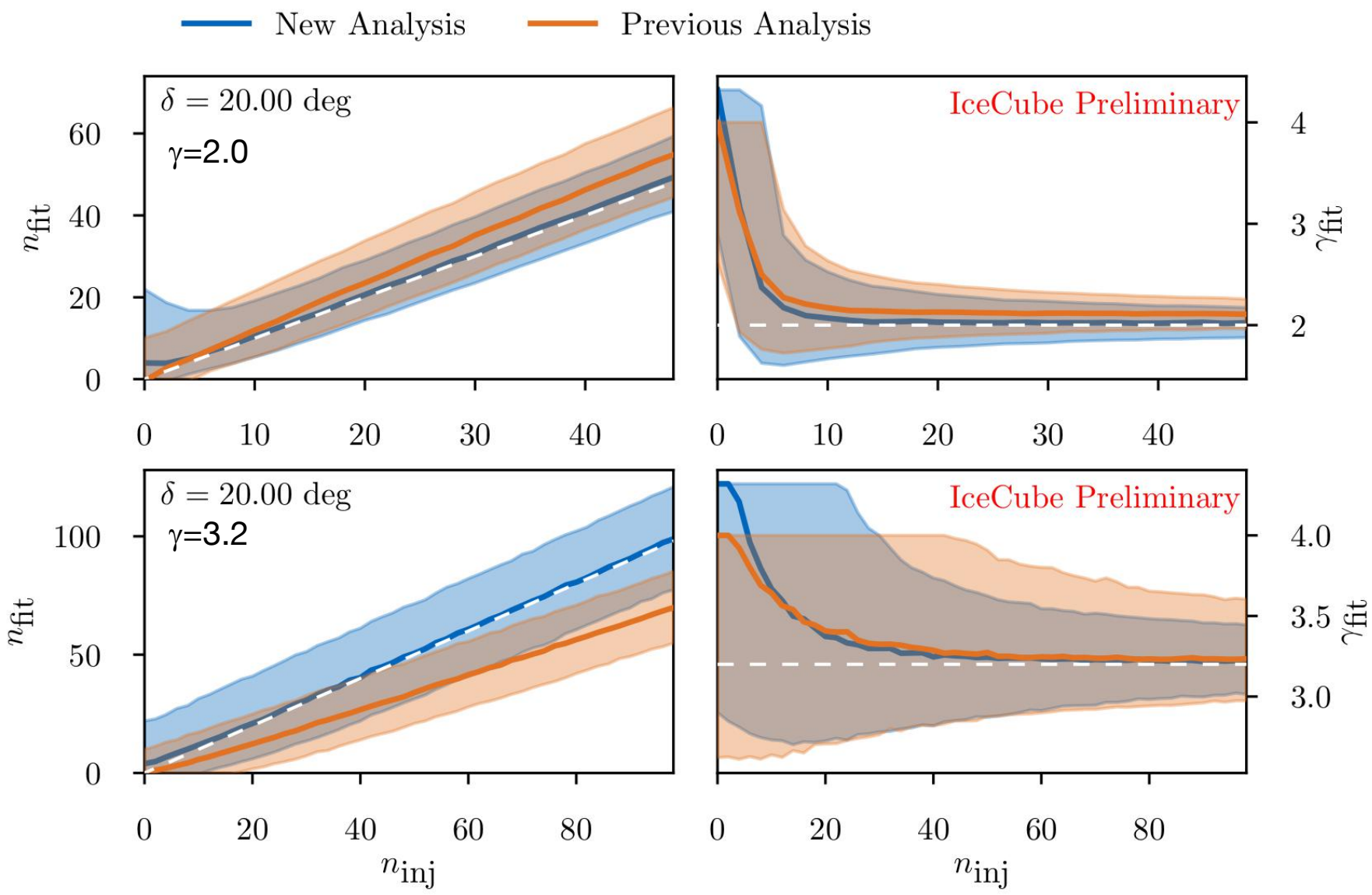


a **deep neural network** (DNN) ...

... improves **energy resolution by ~40%** at all energies
... **resolves bias**/degeneracy at few TeV and below

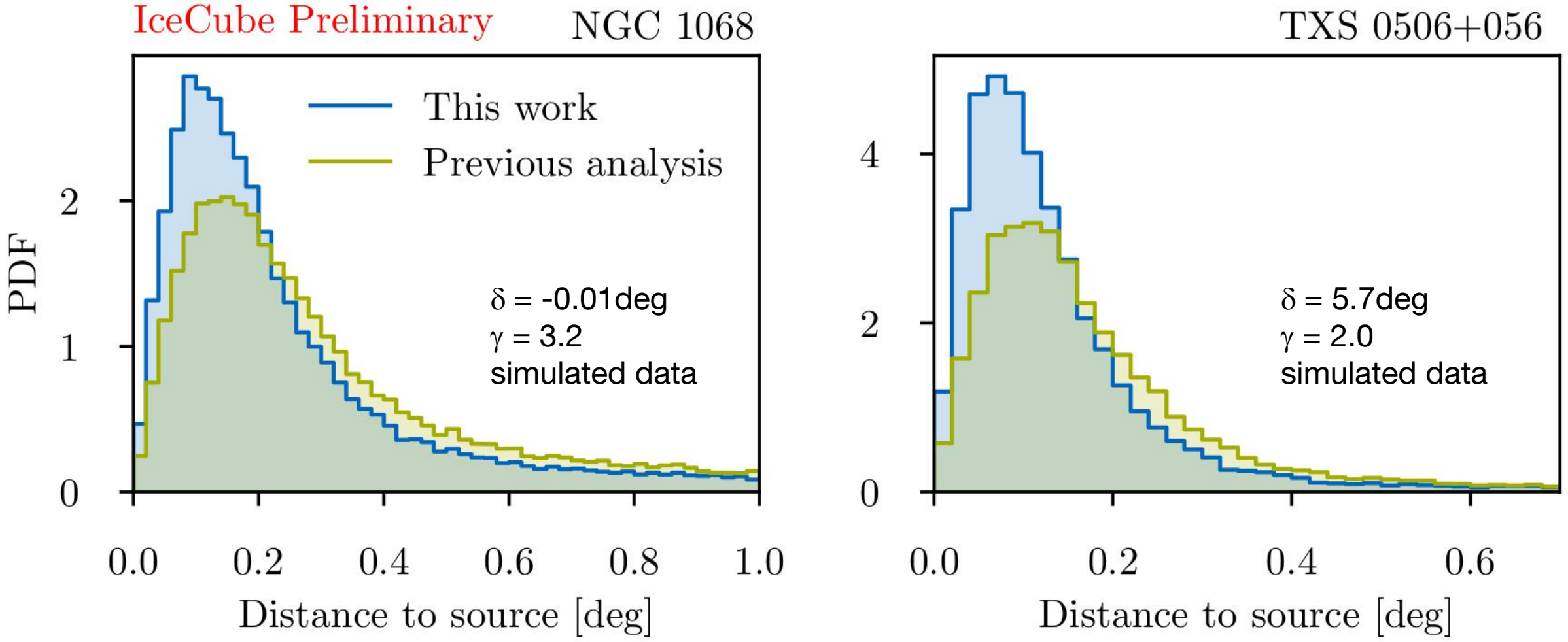
other analysis changes and improvements

- a **BDT angular error estimator** better characterizes directional track reconstruction as a function of several event characteristics
  (e.g. energy, energy loss, declination, position in detector, etc)
- latest detector **calibration** / data quality (“Pass-2”)
- **unified filtering** across entire data taking period
- track data sample developed for diffuse flux measurement in Northern Sky
- 9 years of data w/ **full detector configuration** (IC86-2011 to IC86-2019)
- replaced “data scrambling” by full Monte Carlo simulations



✓ **resolved parameter fit bias**

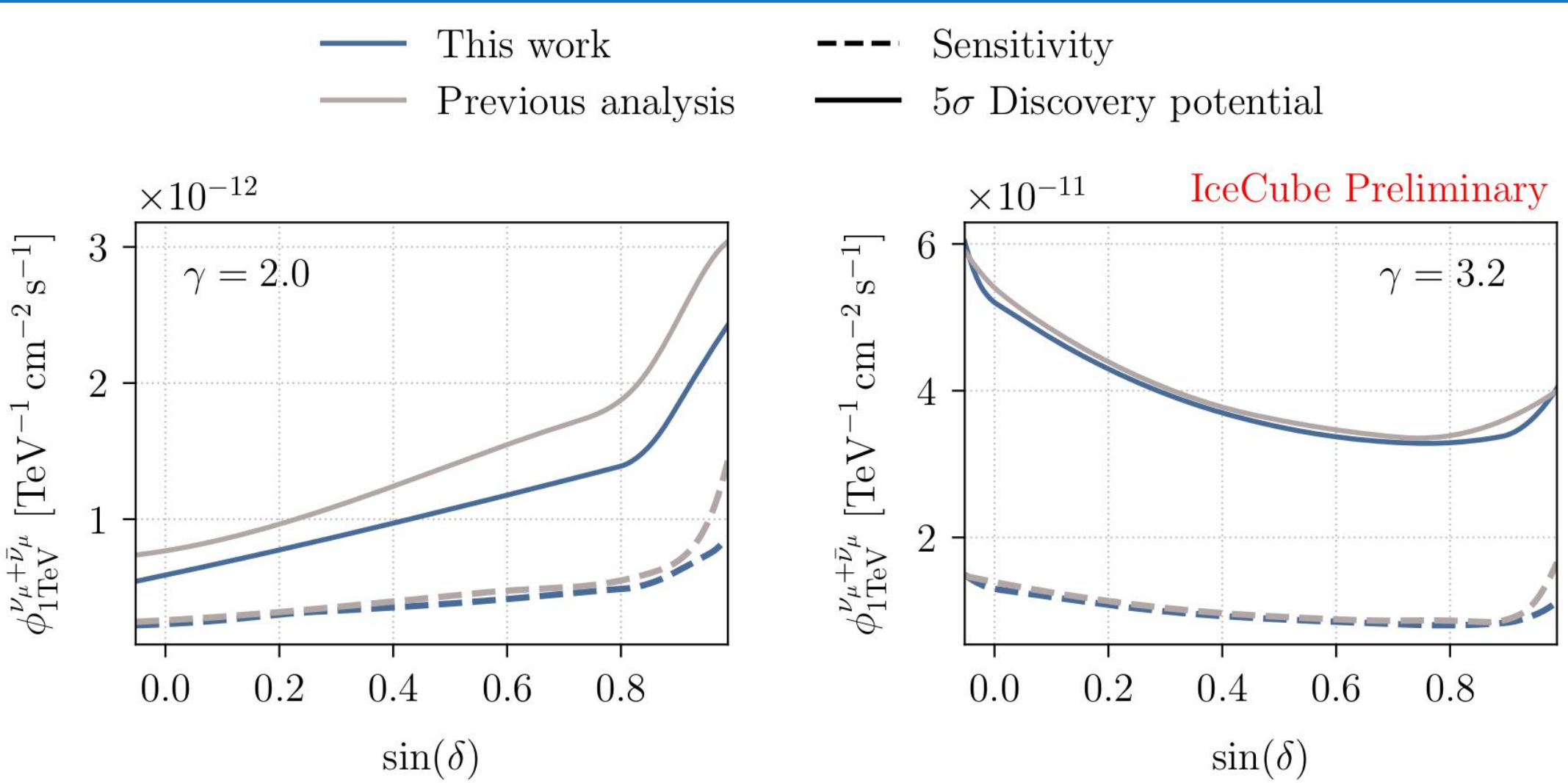
✓ better constraints on spectral index



✓ improved localization of sources

reduced median separation by 30-40%

from 0.35° (0.24°) to 0.21° (0.13°) for NGC 1068 (TXS 0506+056) like steady source



✓ **improved discovery potential**

20-30% **for γ=2.0**

~5% for γ=3.2

summary

developed new numerical tools to search for ν point sources

- **improved point source likelihood** function
  - point spread function from MC simulations
  - no gaussian assumption
- resolved parameter fit biases + improved precision of spectral index fits
  increased discovery potential by up to 30% (γ=2.0)
- applied techniques to **9 years of IceCube data** (full detector, 86 strings)
  ... including **latest detector calibrations**!

results will be public soon - stay tuned!


THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster
JAPAN
Chiba University
NEW ZEALAND
University of Canterbury
REPUBLIC OF KOREA
Sungkyunkwan University
SWEDEN
Stockholms universitet
Uppsala universitet
SWITZERLAND
Université de Genève
UNITED KINGDOM
University of Oxford
UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University
FUNDING AGENCIES
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
IceCube
South Pole Neutrino Observatory
icecube.wisc.edu