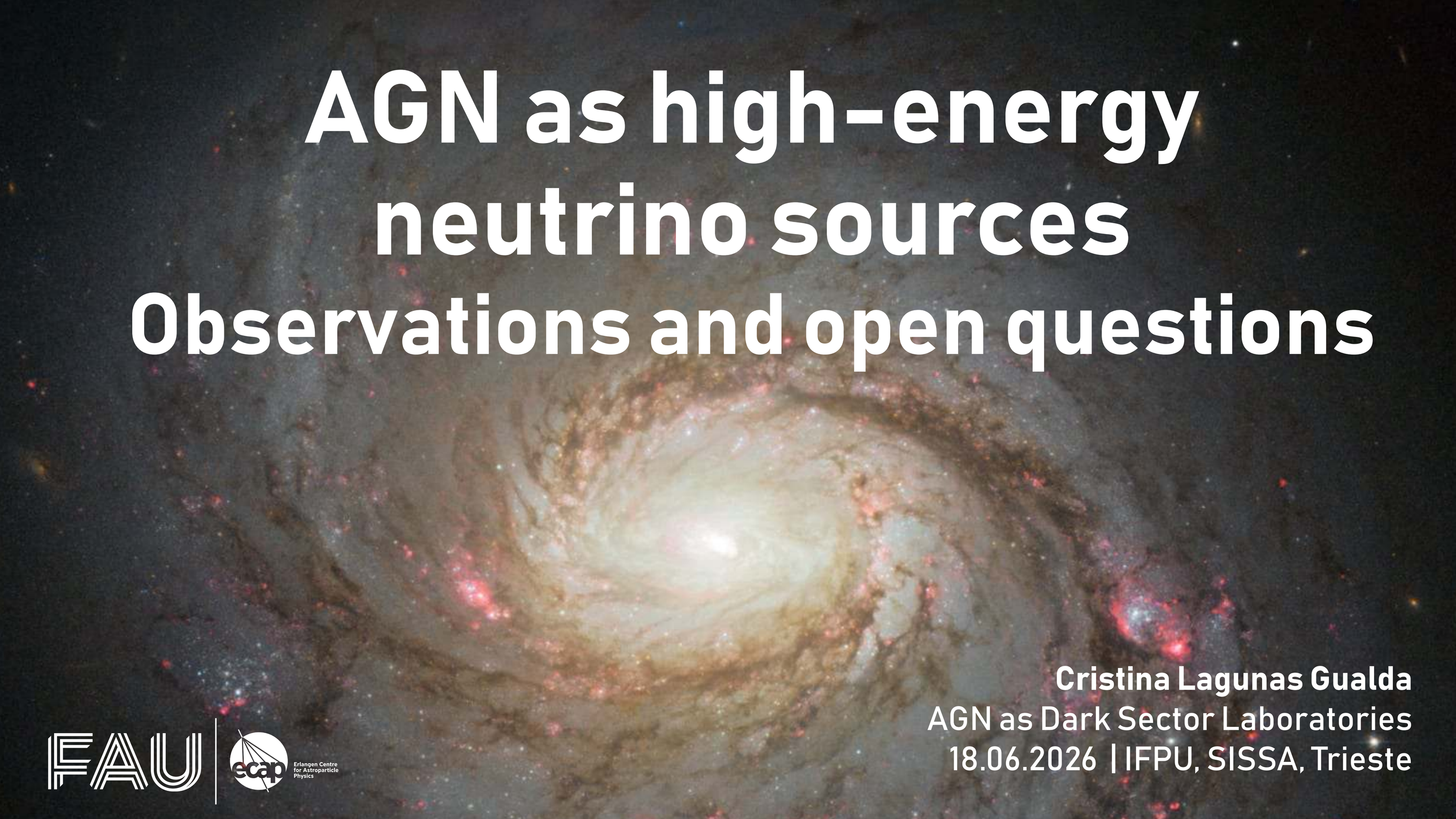
AGN as high-energy neutrino sources
Observations and open questions



Cristina Lagunas Gualda

AGN as Dark Sector Laboratories

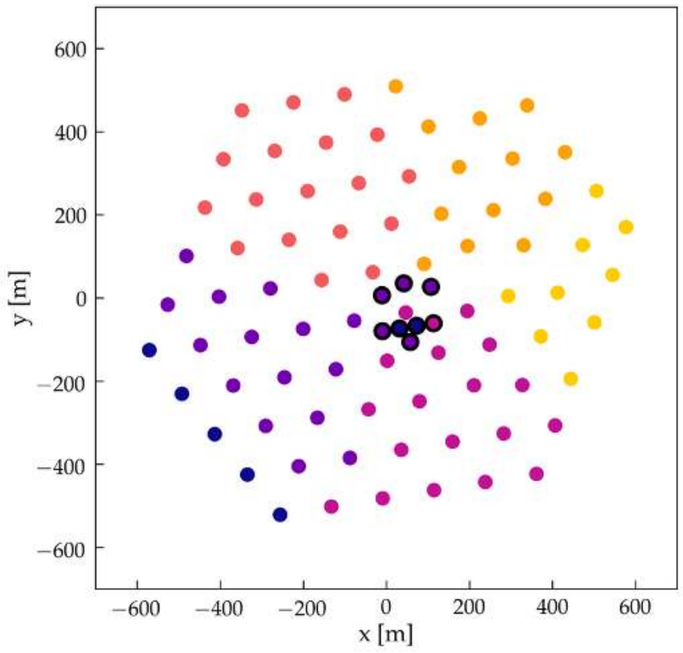
18.06.2026 | IFPU, SISSA, Trieste

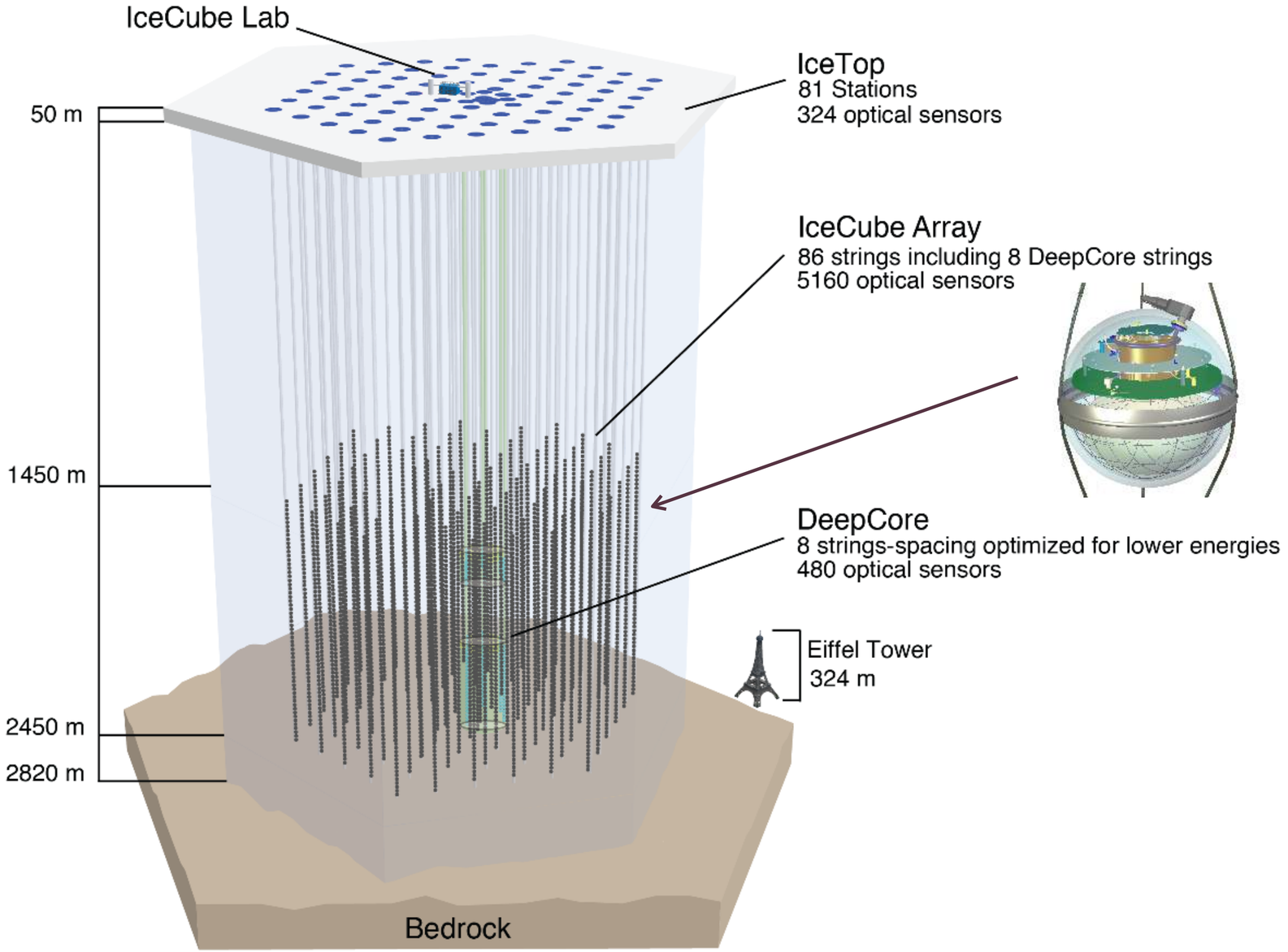
FAU | ecap Erlangen Centre for Astroparticle Physics

Neutrino detection

The IceCube Neutrino Observatory

- Largest telescope to date (1 km³)
- South Pole (sensitive to Northern sky)
- TeV-PeV neutrinos





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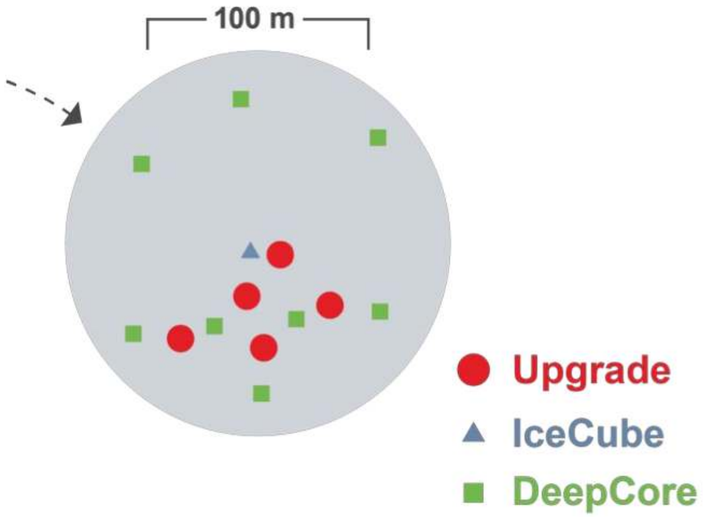
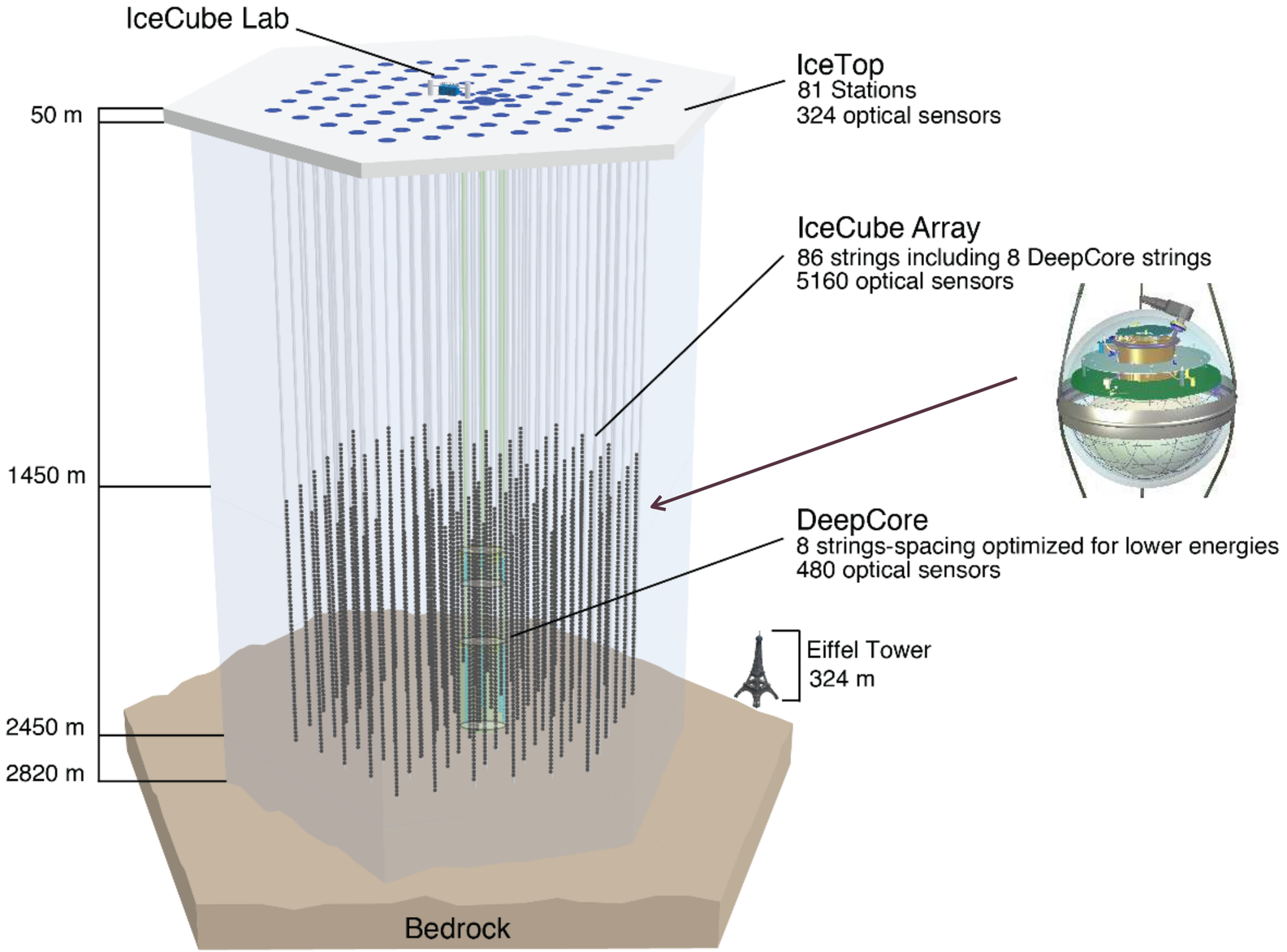
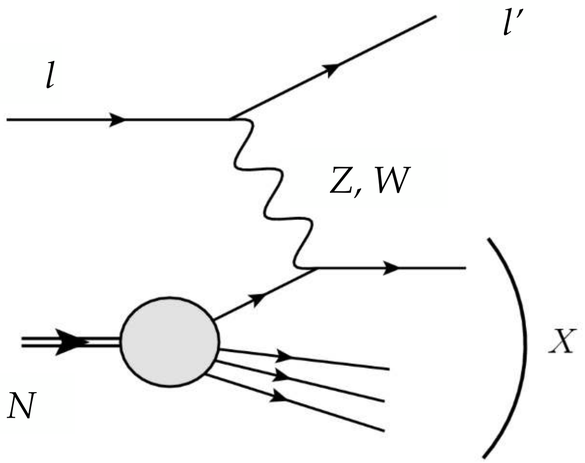
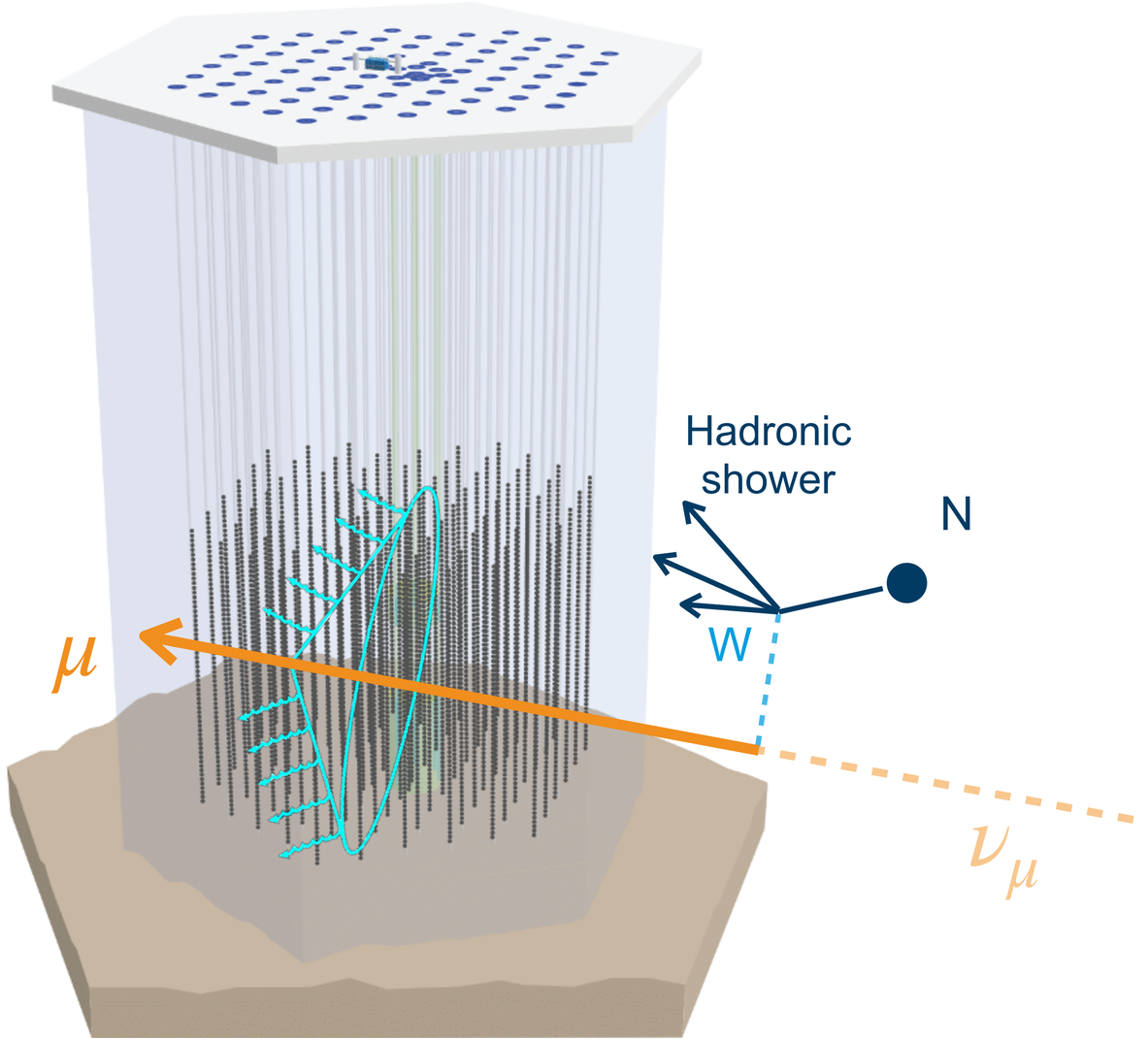




The IceCube Neutrino Observatory

- Neutrino interaction in ice
  - Deep inelastic scattering





The IceCube Neutrino Observatory

- Neutrino interaction in ice
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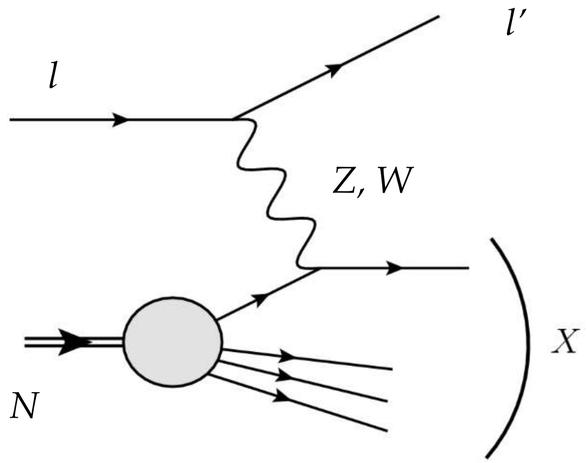
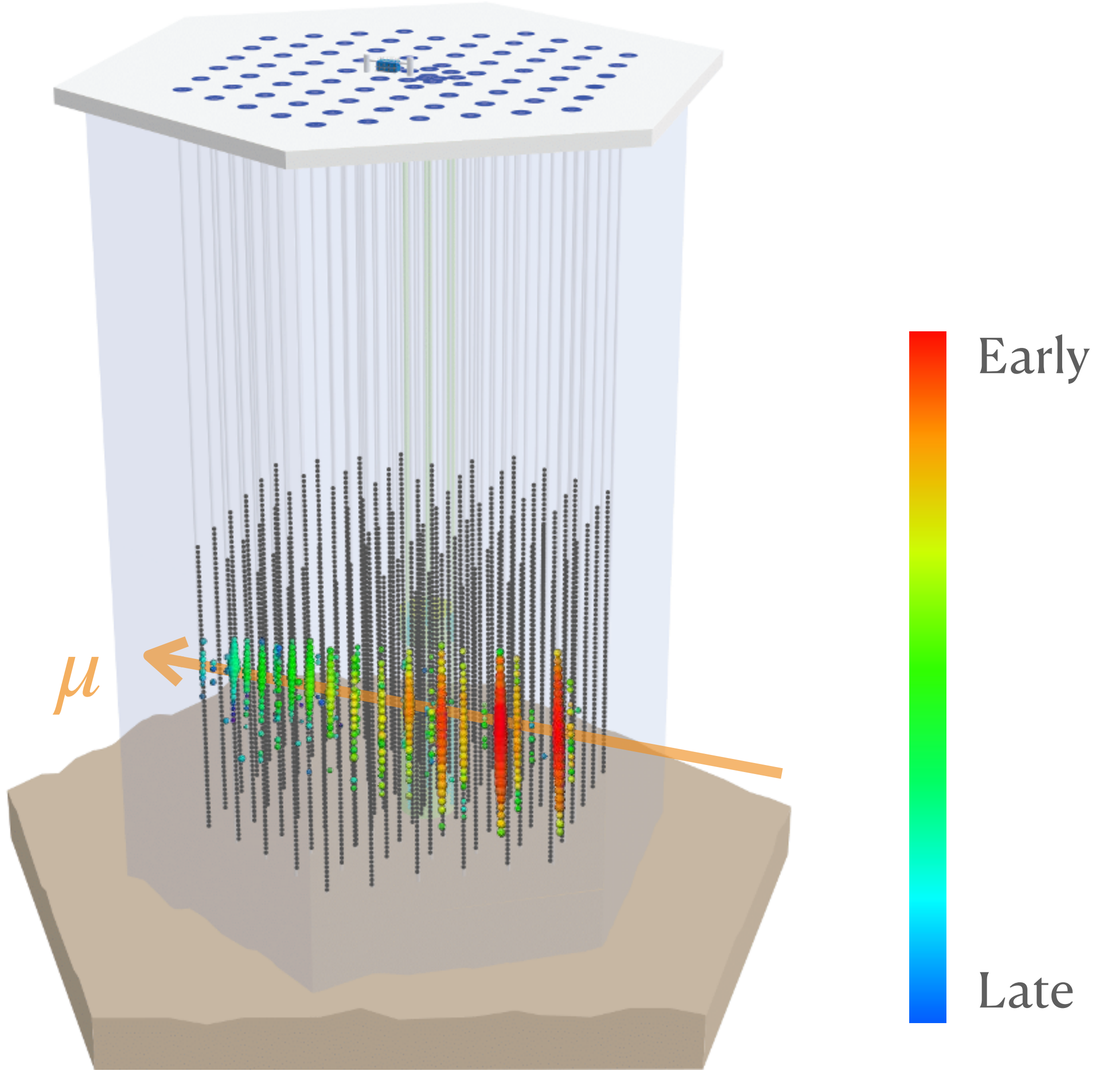
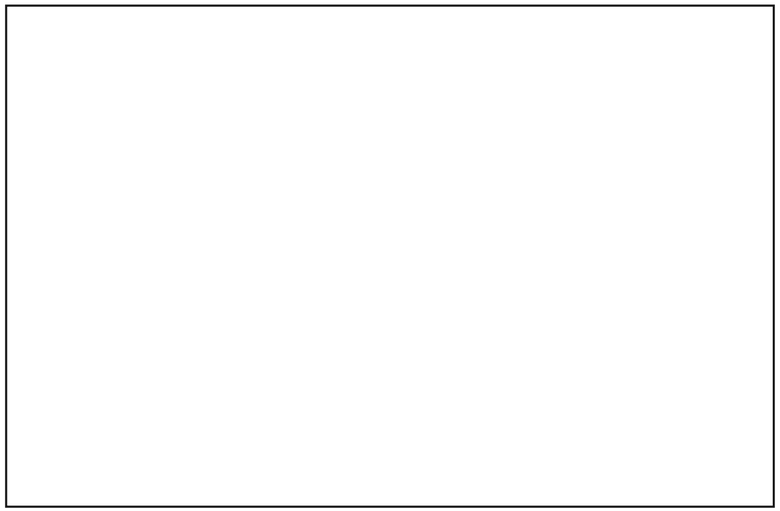
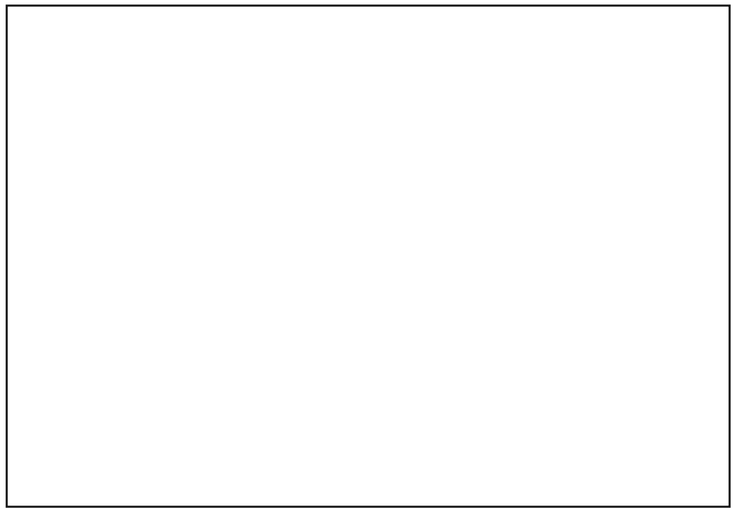


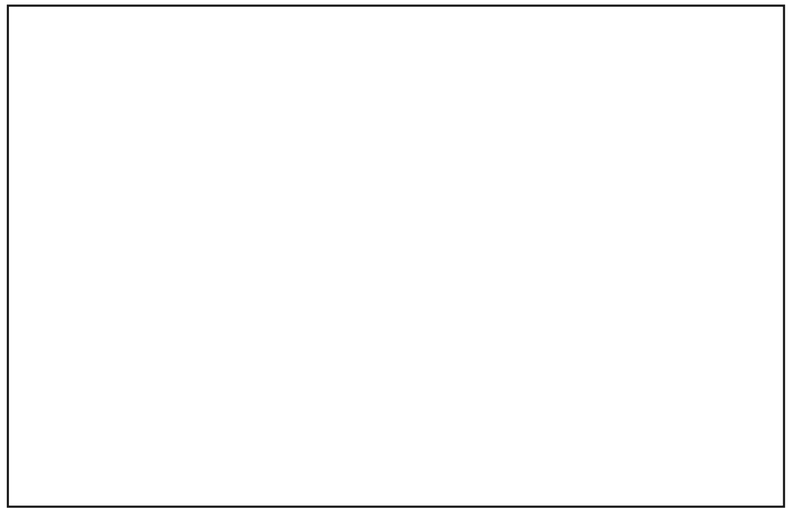
- Cherenkov radiation



Event topologies







Tracks

- CC muon neutrino interaction
- Good angular resolution (< 1 deg)
- Bad energy resolution (0.25 log E)

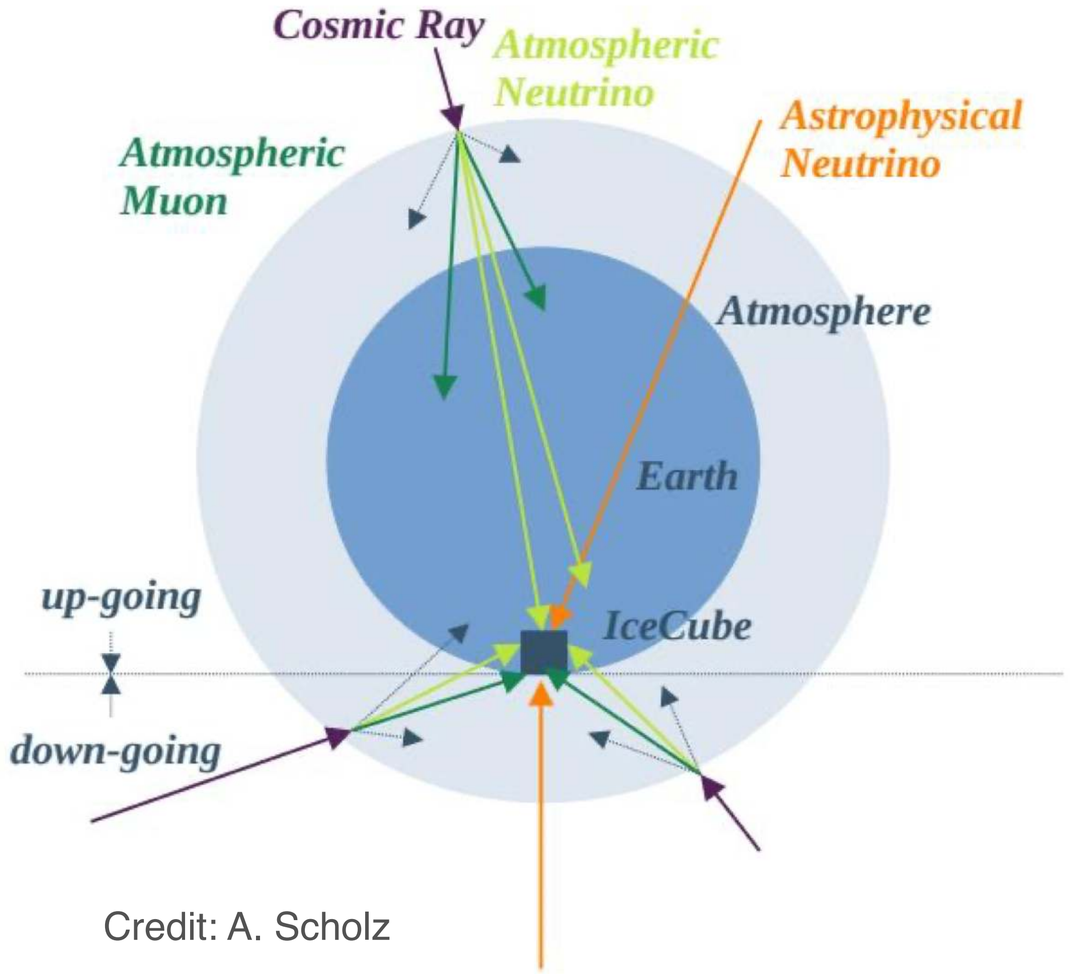
Cascades

- CC electron or tau neutrino interaction, NC interaction all flavors
- Bad angular resolution
- Good energy resolution

Double-bang

- CC tau neutrino interaction at high E

Backgrounds



Credit: A. Scholz

- Most sensitive in the northern sky (remove muons from CR)
- Can use outer layers as a veto (starting events)
- Best angular resolution from through-going tracks

Datasets

- NorthernTracks:
  - Muon neutrino tracks from the Northern sky (dec > -5 deg)
  - Used for diffuse and neutrino source analyses
- IceTracks:
  - Muon neutrino tracks, all sky
- HESE/ESTES:
  - Starting events (tracks), all sky, high purity
- IceCat:
  - Muon neutrino tracks, high probability of being astrophysical (alert events)
  - High energies (>100s TeV)
- DNNCascades/ICEMAN:
  - Cascades, all sky, galactic plane analyses

Datasets

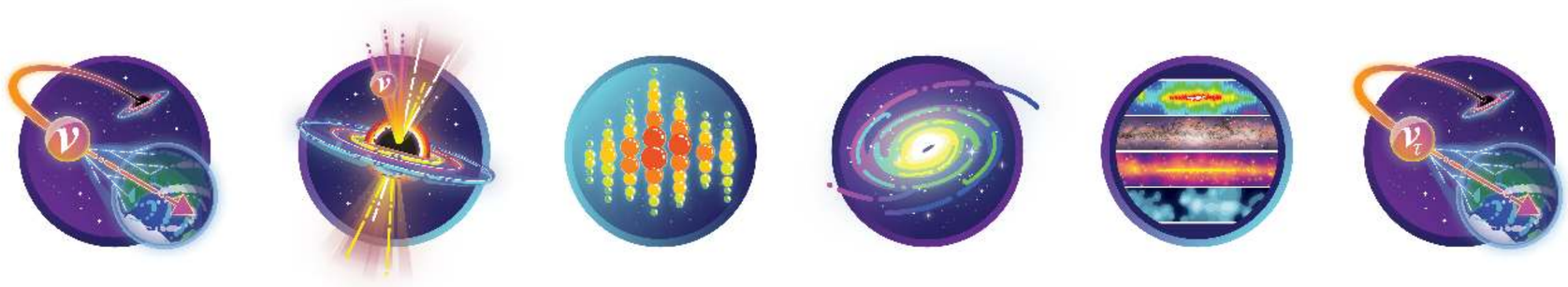
- **NorthernTracks (data):**
  - Muon neutrino tracks from the Northern sky (dec > -5 deg)
  - Used for diffuse and neutrino source analyses
- **IceTracks (data, paper):**
  - Muon neutrino tracks, all sky
- **HESE (data)**/ESTES:
  - Starting events (tracks), high purity
- **IceCat (data, v2 coming soon):**
  - Muon neutrino tracks, high probability of being astrophysical (alert events)
  - High energies (>100s TeV)
- DNNCascades/ICEMAN:
  - Cascades, all sky, galactic plane analyses

SkyLLH - analysis framework (Github)

Chronology

THE HISTORY OF

Neutrino Astronomy in Antarctica



2013
ASTROPHYSICAL NEUTRINOS
DISCOVERED

2018
BLAZAR TXS 0506+056
NEUTRINO EMISSION IDENTIFIED

2021
GLASHOW RESONANCE
NEUTRINO IDENTIFIED

2022
ACTIVE GALAXY NGC 1068
NEUTRINO EMISSION IDENTIFIED

2023
MILKY WAY
NEUTRINO EMISSION IDENTIFIED

2024
ASTROPHYSICAL TAU NEUTRINOS
IDENTIFIED

NSF | IceCube Neutrino Observatory

Chronology

+ Diffuse flux established with a broken power-law

+ Hints of a population of neutrino sources

Blazar searches

TXS 0506+056

First compelling evidence:
Coincidence of neutrino IC170922A with blazar TXS 0506+056 flaring in gamma rays

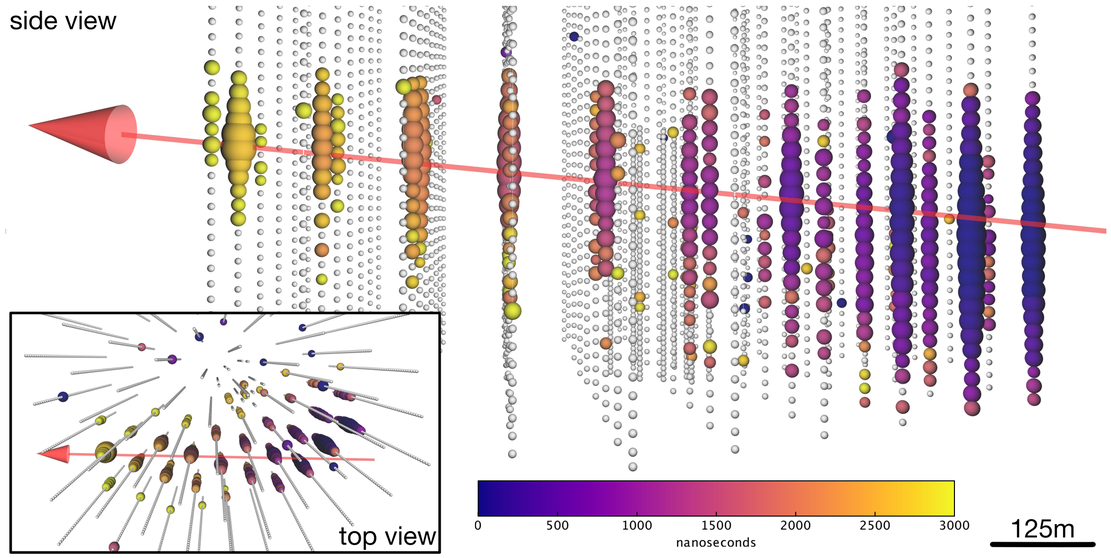
NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

TXS 0506+056

- Neutrino alert IC170922A
- Signalness of 56.5%
- Energy of 290 TeV
- Triggered a multi messenger campaign

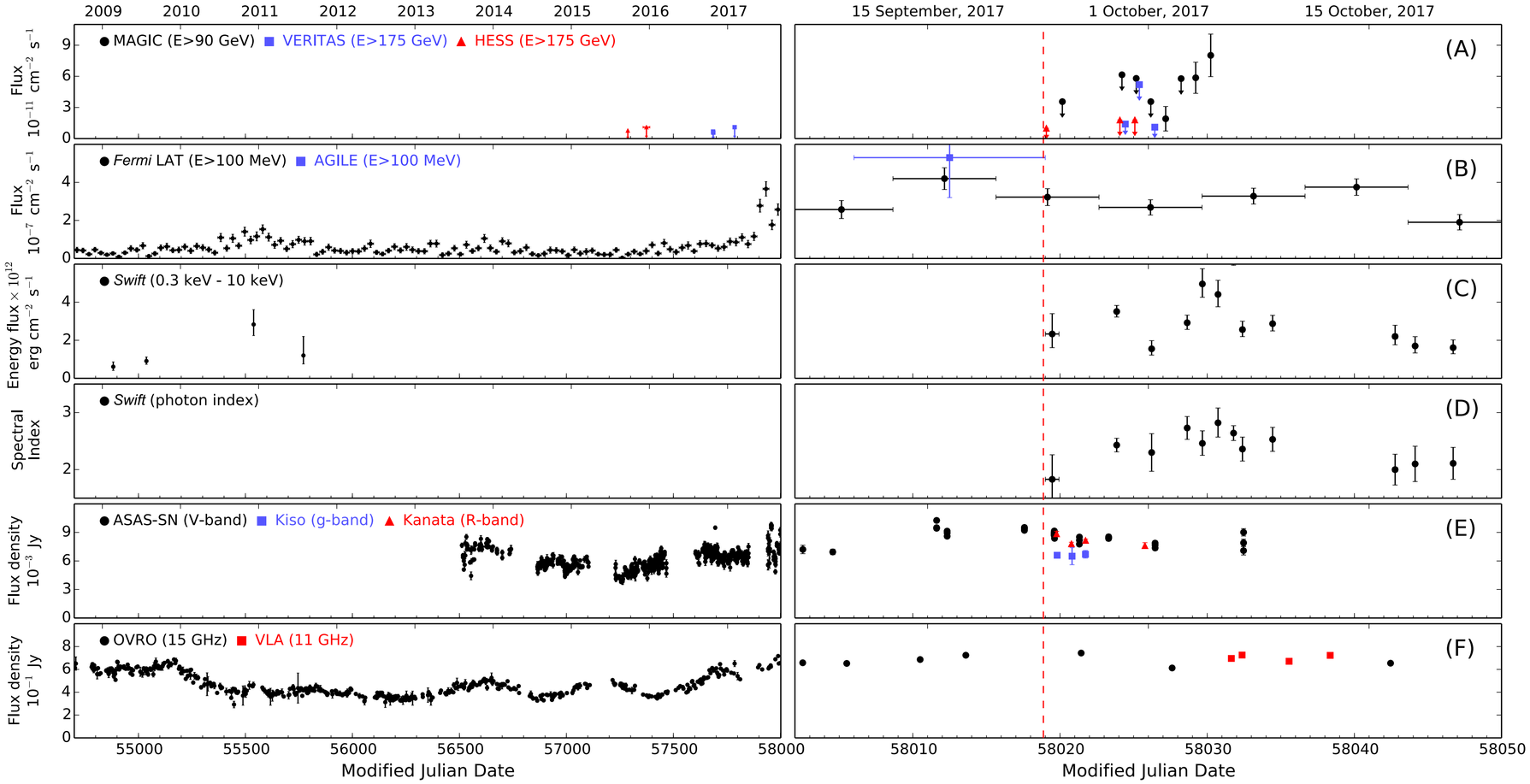


Science, 361 (6398) (2018), p. eaat1378

TXS 0506+056

Science, 361 (6398) (2018), p. eaat1378

- TXS 0506+056 flaring in gamma rays

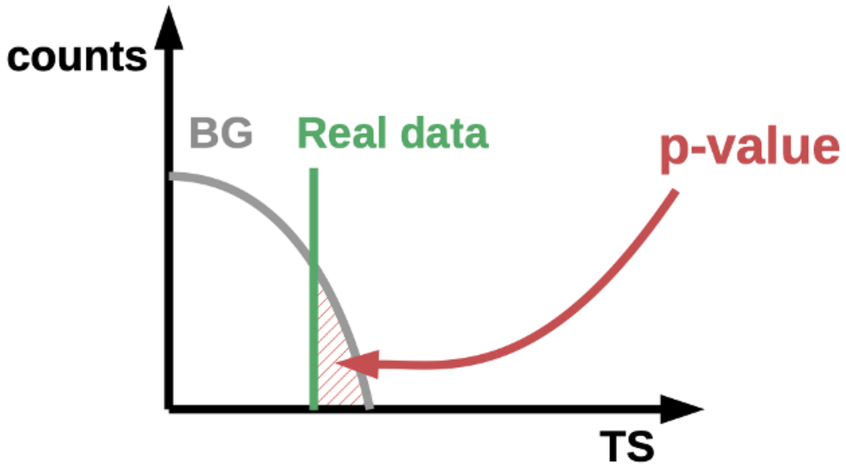


TXS 0506+056

- Standard point source likelihood

$$\mathcal{L} = \prod_i^N \left(\frac{n_s}{N} \mathcal{S} + (1 - \frac{n_s}{N}) \mathcal{B} \right), \quad \mathcal{S}(\vec{x}, t) = \sum_s \frac{1}{2\pi\sigma^2} e^{-|\vec{x}_s - \vec{x}|^2/(2\sigma^2)} \, w_s(t) \, w_{\mathrm{acc}}(\theta_s), \quad TS = 2 \log \frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2 \log \frac{\mathcal{S}}{\mathcal{B}}.$$

- Background TS constructed with MC neutrino events
- Look-elsewhere effect corrected by considering previous alerts and alert-like events (51 including IC170922A) ~IceCat
- **Chance coincidence disfavored at the 3σ level**

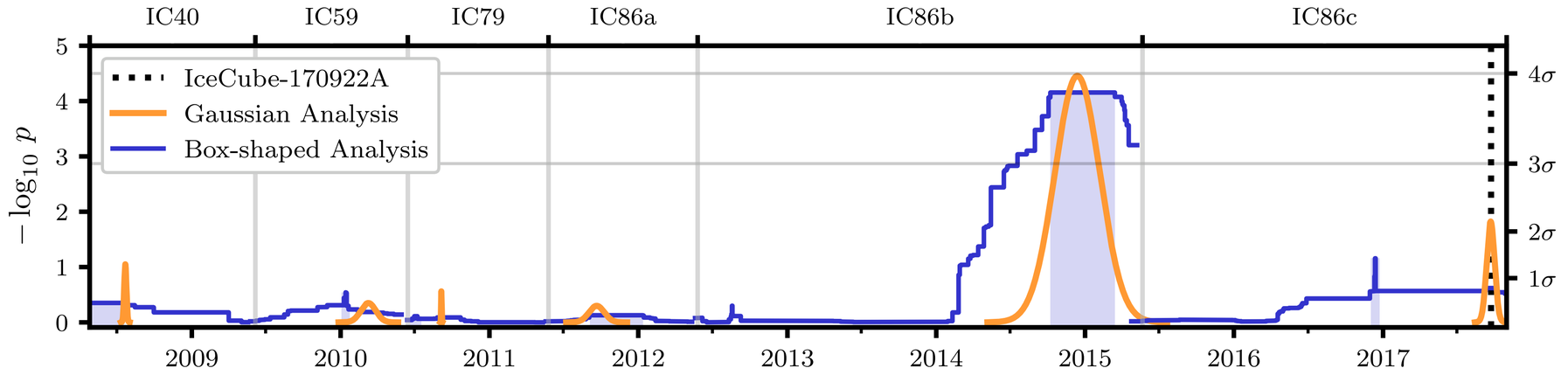


TXS 0506+056

Science 361,147-151(2018)

~NorthernTracks

- Neutrino flare prior to the alert (2014-2015)
- 3.5 σ evidence of neutrino excess (~150 days, 13±5 events)



- No gamma-ray counterpart during this flare
- **Hidden sources?**

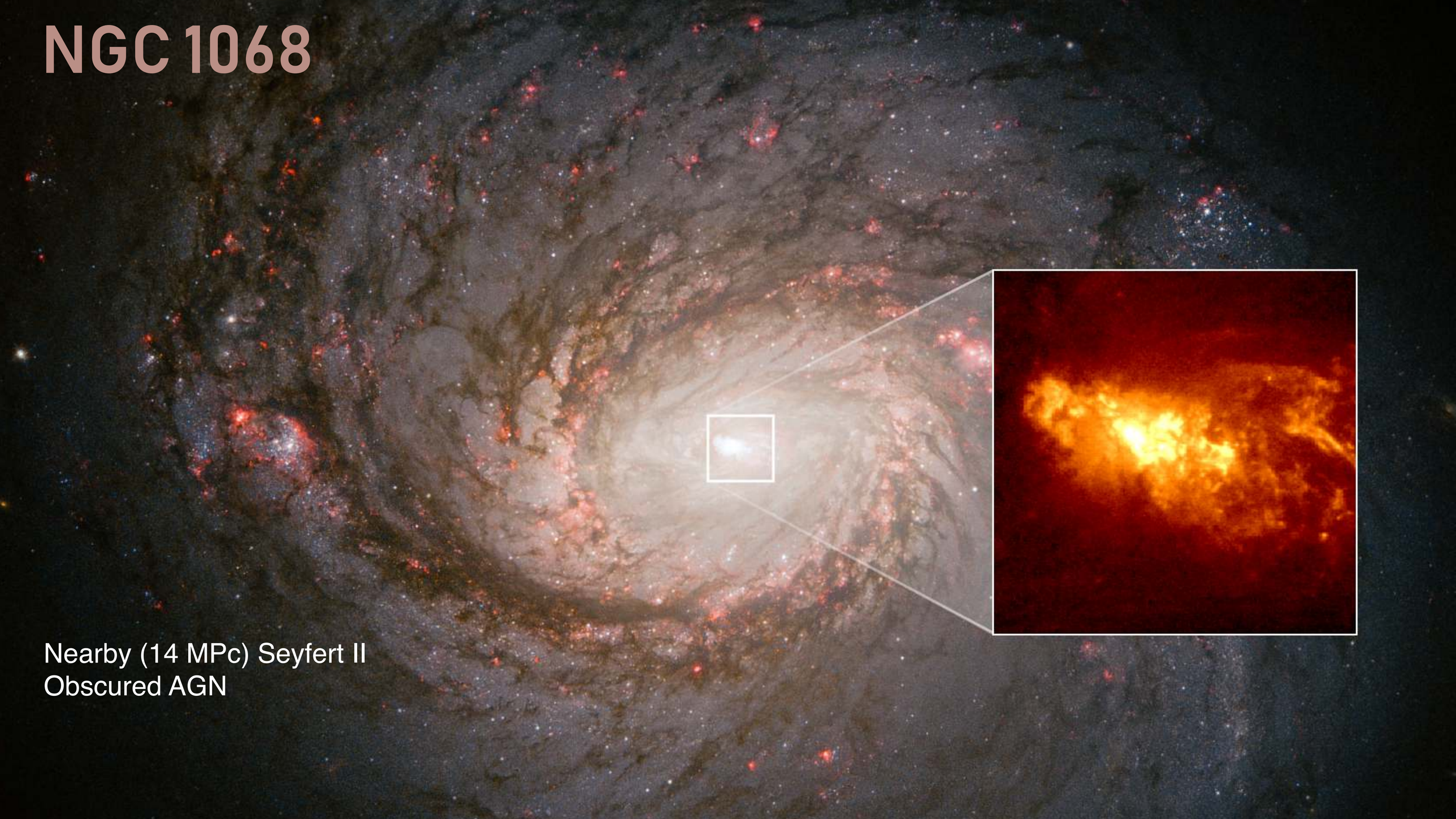
Population studies

- Many population studies have been performed, both **inside** and **outside** the IceCube Collaboration:
  - Blazar catalogs (Fermi-LAT, BZCat..,)
    - arXiv:2305.11263, ApJL 955 L32, PoS-ICRC2025-933
  - Radio-loud AGN (RFC)
    - MNRAS 523 2, ApJ 954 75A
- Some hints, but not always consistent
    - Most results are background compatible

- **Blazars cannot explain the entire diffuse neutrino flux**
- **What are the missing sources?**

NGC 1068

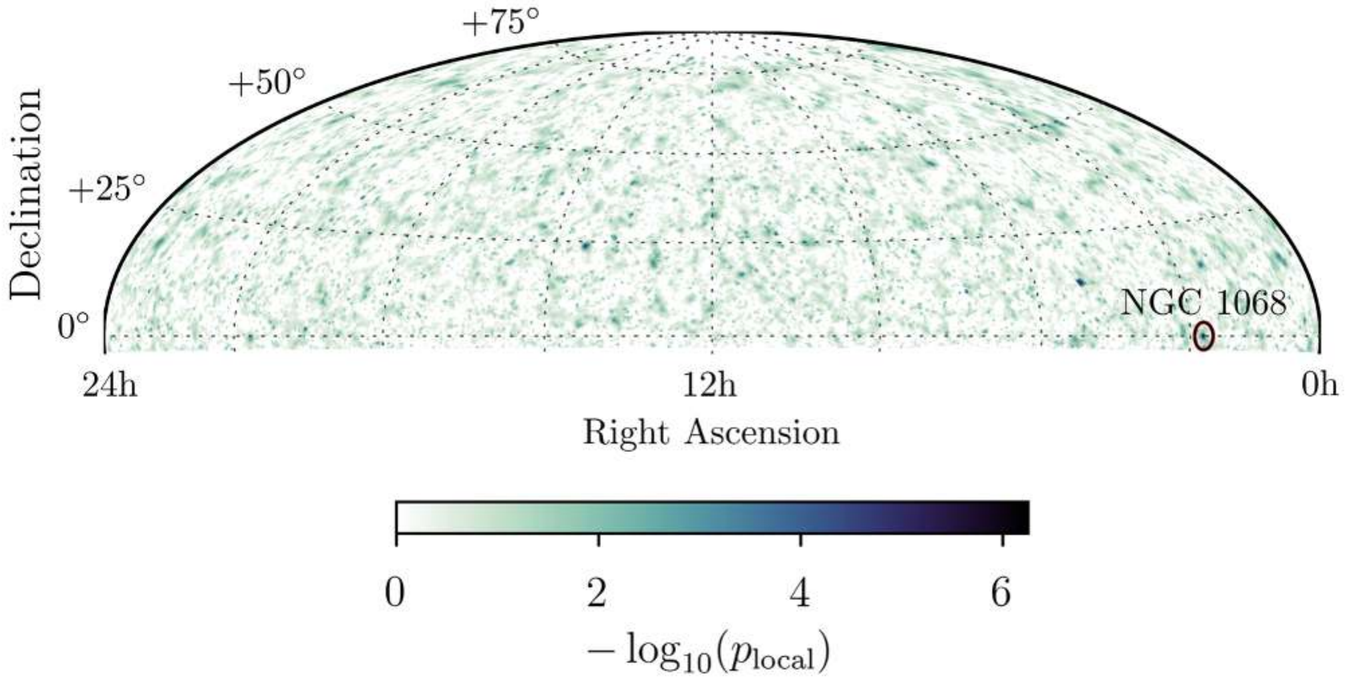
NGC 1068



Nearby (14 MPc) Seyfert II
Obscured AGN

All-sky search

- 13.1 years of Northern Tracks (–3 deg < δ < 81 deg)
- Grid of pixels of ≈0.052 deg^2, find best-fit values ns, γ, and TS
- 20 most significant hotspots scanned finer (≈0.003 deg^2)



$$\mathcal{L} = \prod_{i}^{N} \left(\frac{n_s}{N} \mathcal{S} + (1 - \frac{n_s}{N}) \mathcal{B} \right)$$

$S(E_i, d_i, \sigma_i \,|\, d_{src}, \gamma)$ $\quad$ $B(E_i, d_i, \sigma_i)$

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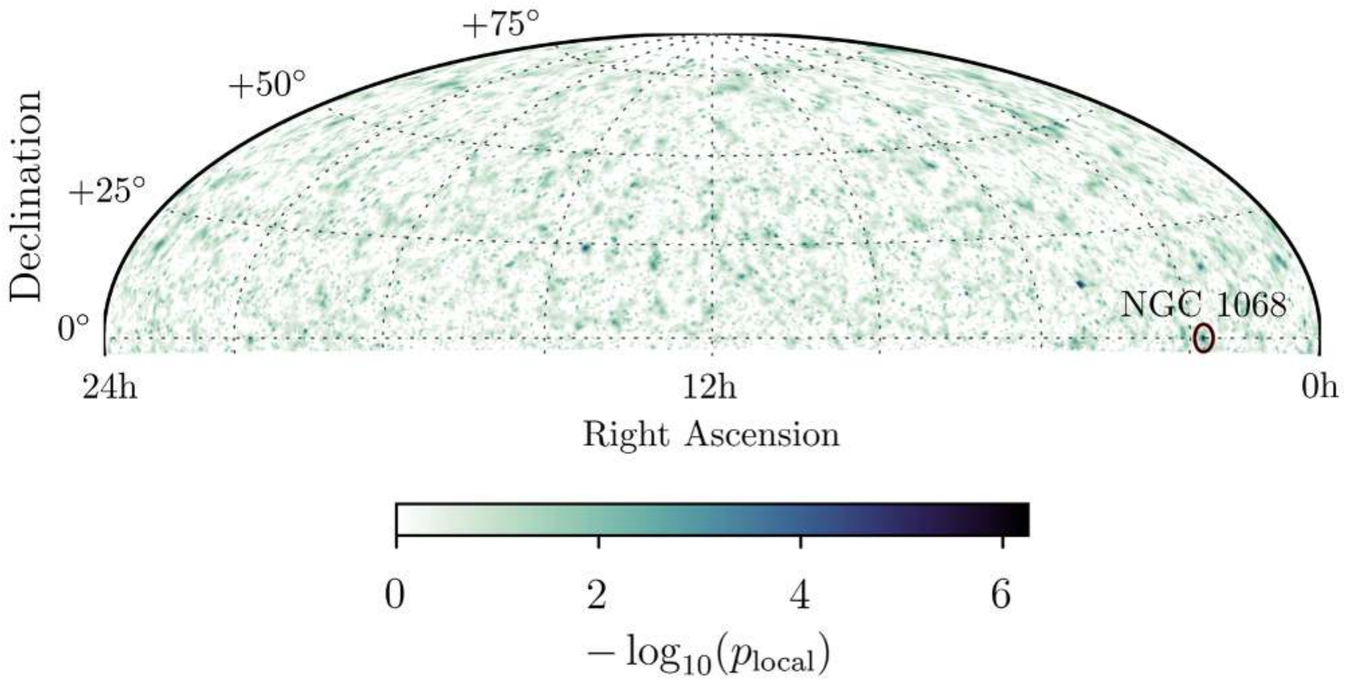


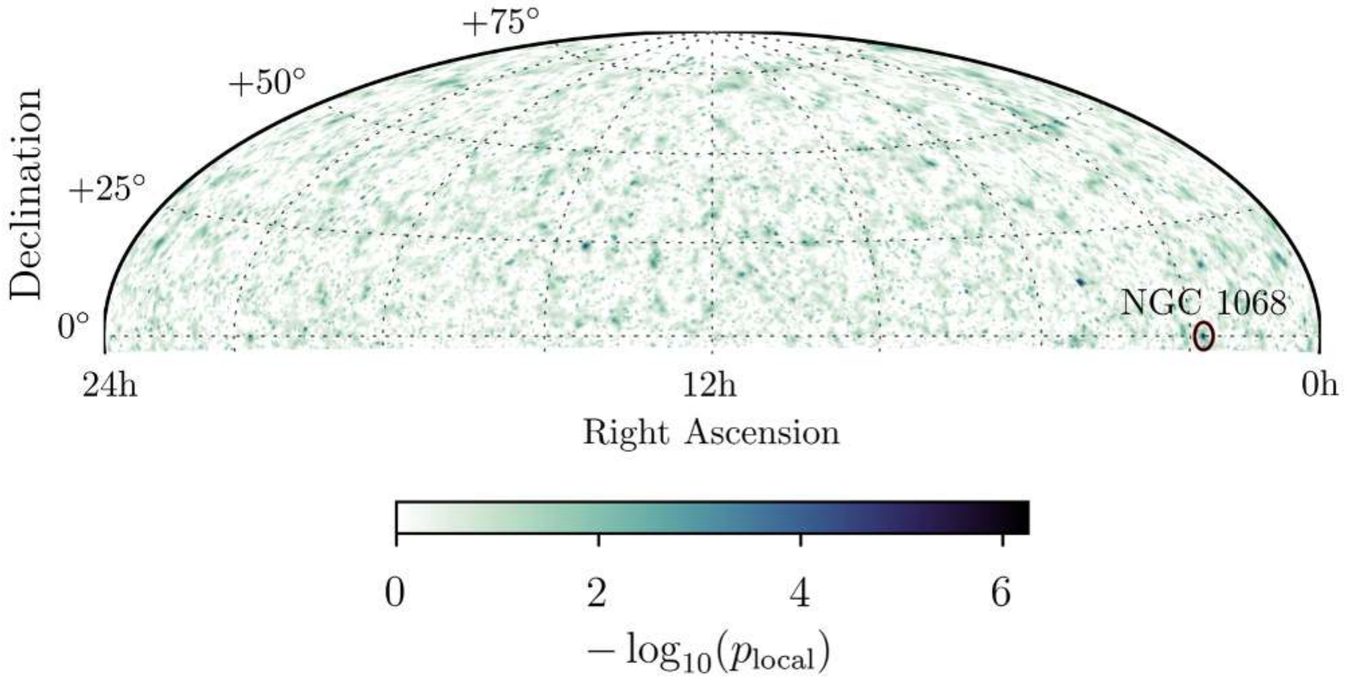
$$\mathcal{L} = \prod_{i}^{N} \left(\frac{n_s}{N} \mathcal{S} + (1 - \frac{n_s}{N}) \mathcal{B} \right)$$

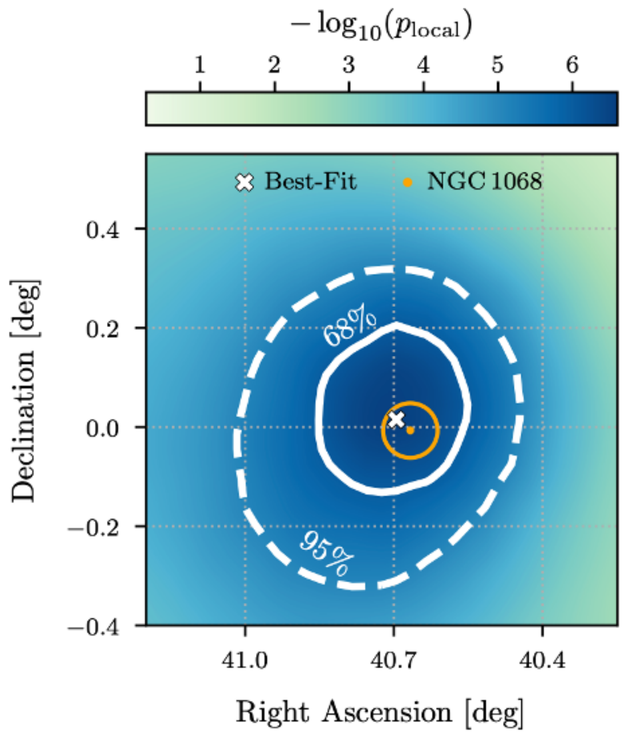
- Hottest spot coincident with location of NGC 1068
- Local significance of 5 σ, global 1.4 σ

Catalog search

ApJL 1000 L26

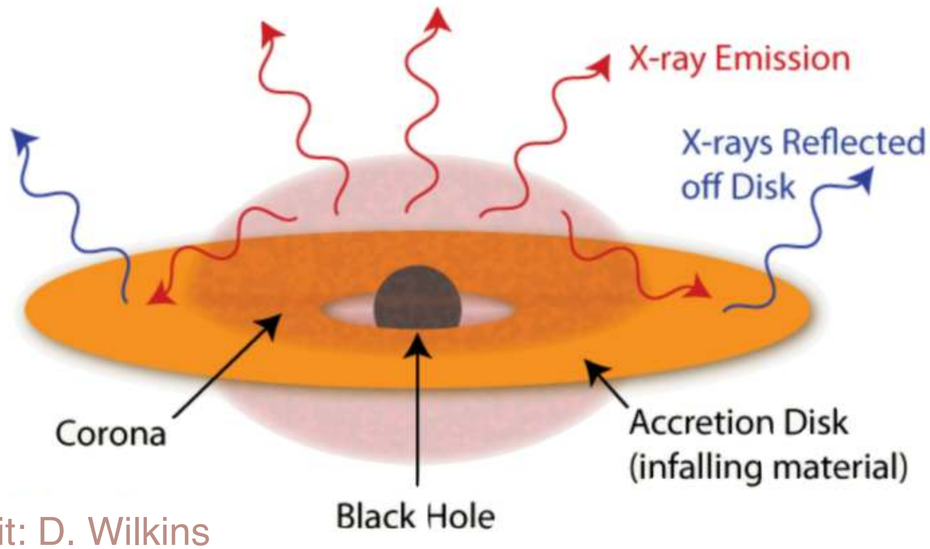
- 110 gamma-ray sources: most significant emission from Seyfert galaxy NGC 1068
- Persistent emission (ns from 79 to 102)
- Global significance of 4 σ (assuming PL)





NGC 1068

- In Seyfert galaxies, magnetized coronae are formed due to accretion and magnetic dissipation
- Gamma rays cascade down to lower energies
- Intrinsic X-ray luminosity can be used to predict neutrino flux

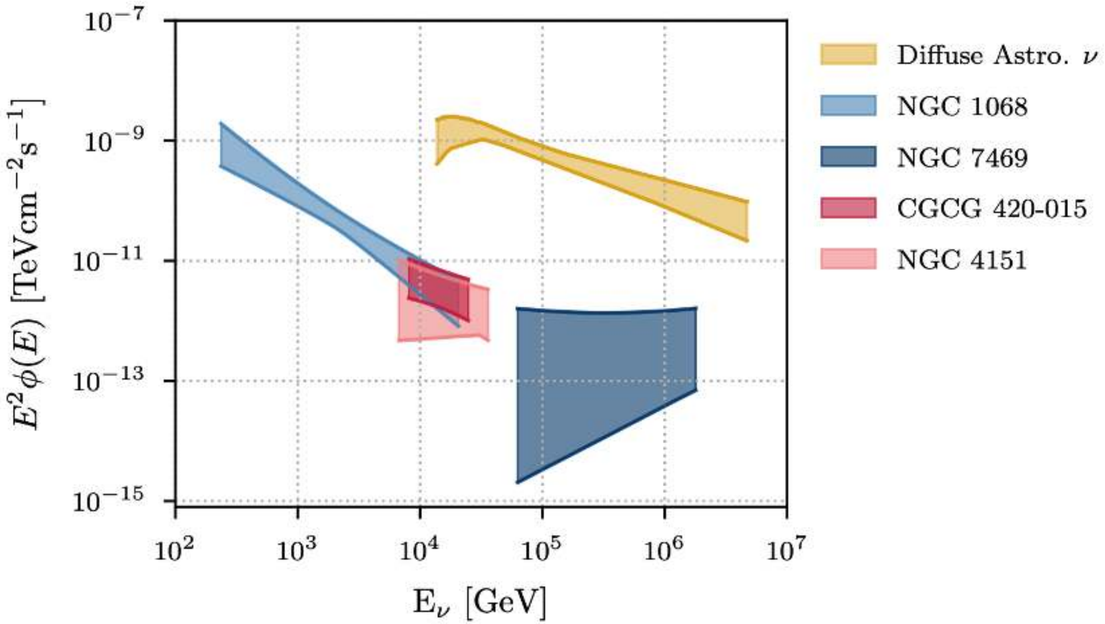


Credit: D. Wilkins

Seyfert galaxies

ApJL 1000 L26

- Binomial test to study Seyfert sources
- BASS Seyfert galaxies with $F_X^{20-50\ \mathrm{keV}} > 20\,\%$ of NGC1068
  - Selection to optimise sensitivity vs thermal cutoff
- Two hypothesis: core-corona model and power-law with free index
- 3.3 σ excess from ensemble of 11 sources with PL



		R.A.	Dec.	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$-\log_{10} p_{\mathrm{global}}$
47 X-ray bright AGN							
Most significant source	NGC 7469	345.82	8.87	5.5	1.9	4.1 (3.8σ)	2.1 (2.4σ)
Binomial test	11 Sources					4.8 (4.2σ)	3.3 (3.3σ)
Other sources in binomial excess	NGC 4151*	182.64	39.41	27.6	2.7	2.9 (3.1σ)	–
	CGCG 420-015*	73.36	4.06	35.3	2.7	2.4 (2.7σ)	–
	Cygnus A*	299.87	40.73	3.4	1.6	2.2 (2.5σ)	–
	LEDA 166445	42.68	54.70	57.1	4.4	1.8 (2.1σ)	–
	NGC 4992	197.27	11.63	27.3	2.9	1.6 (2.0σ)	–
	NGC 1194*	45.95	−1.10	43.2	4.4	1.5 (1.8σ)	–
	Mrk 1498	247.02	51.78	39.9	3.6	1.4 (1.7σ)	–
	MCG +4-48-2*	307.15	25.73	36.7	3.2	1.4 (1.7σ)	–
	NGC 3079	150.49	55.68	33.8	3.6	1.3 (1.7σ)	–
	Mrk 417	162.38	22.96	4.4	2.0	1.3 (1.6σ)	–

Picture emerging?

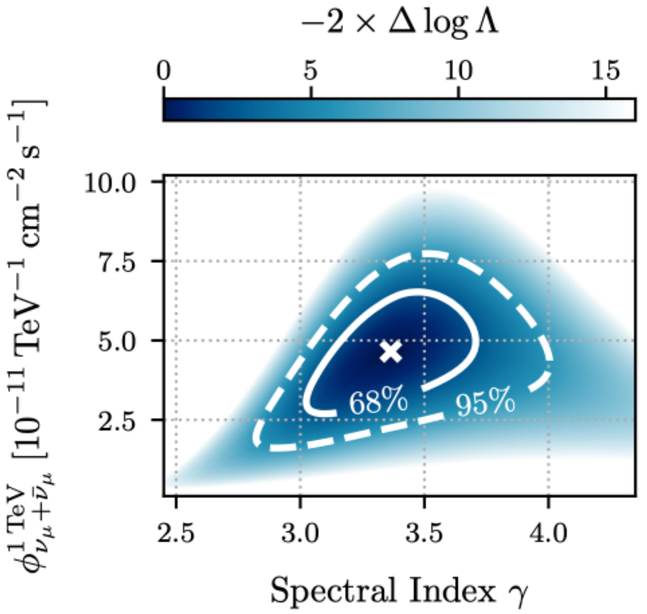
- Other IceCube analyses:
  - 2.7 σ from Northern Sky (ApJ (988) 141)
  - 2.9 σ from Hard X-ray (ApJ (981) 131)
  - 3.0 σ from Southern Sky (ApJL 1000 L37)
- KM3Net analysis:
  - Upper limits (PoS(ICRC2025)1065)

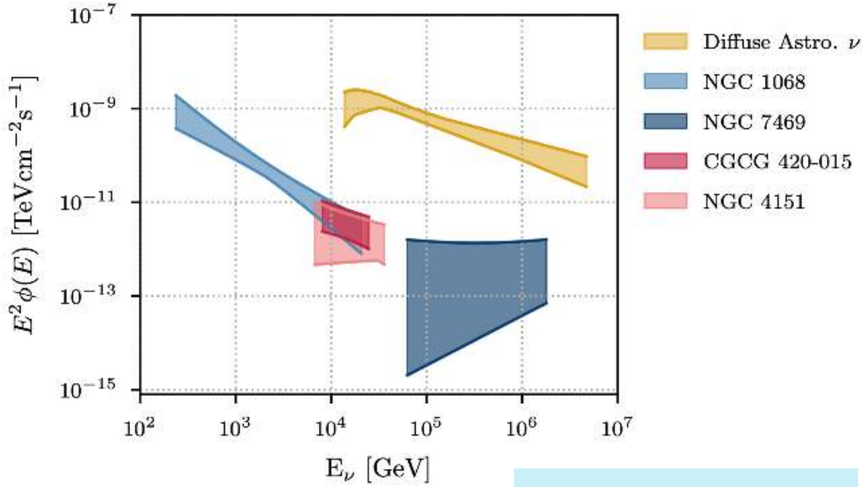
- **First indication of a neutrino source class**

IceCube constraints

- We know about NGC 1068:
  - Soft spectrum
  - Steady emission
  - Potentially part of a population

- **Any dark-sector interpretation must:**
  - NGC 1068 neutrino flux
  - Non-observation in other sources
  - Gamma-ray constraints
  - Not overshoot diffuse flux

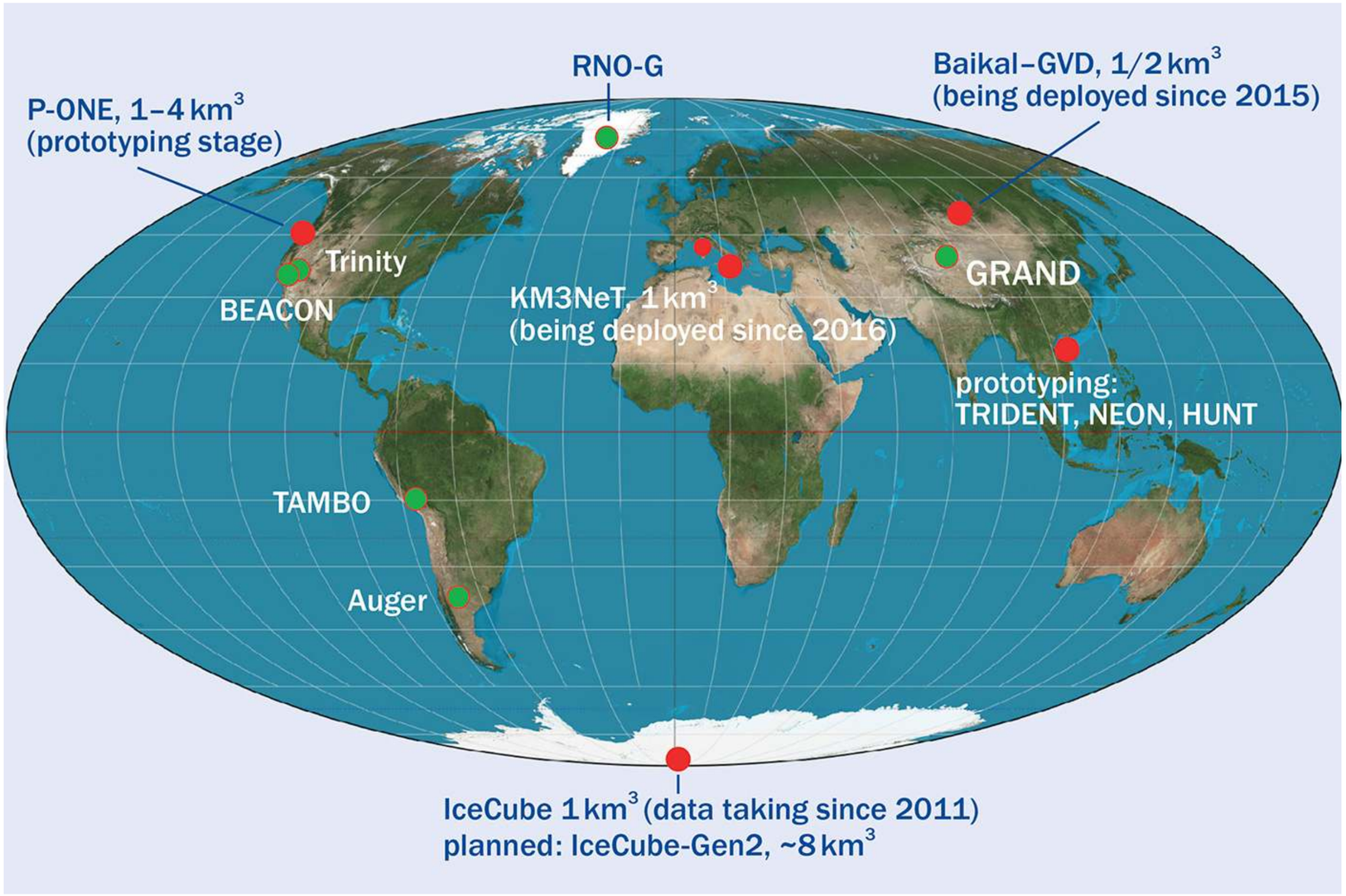




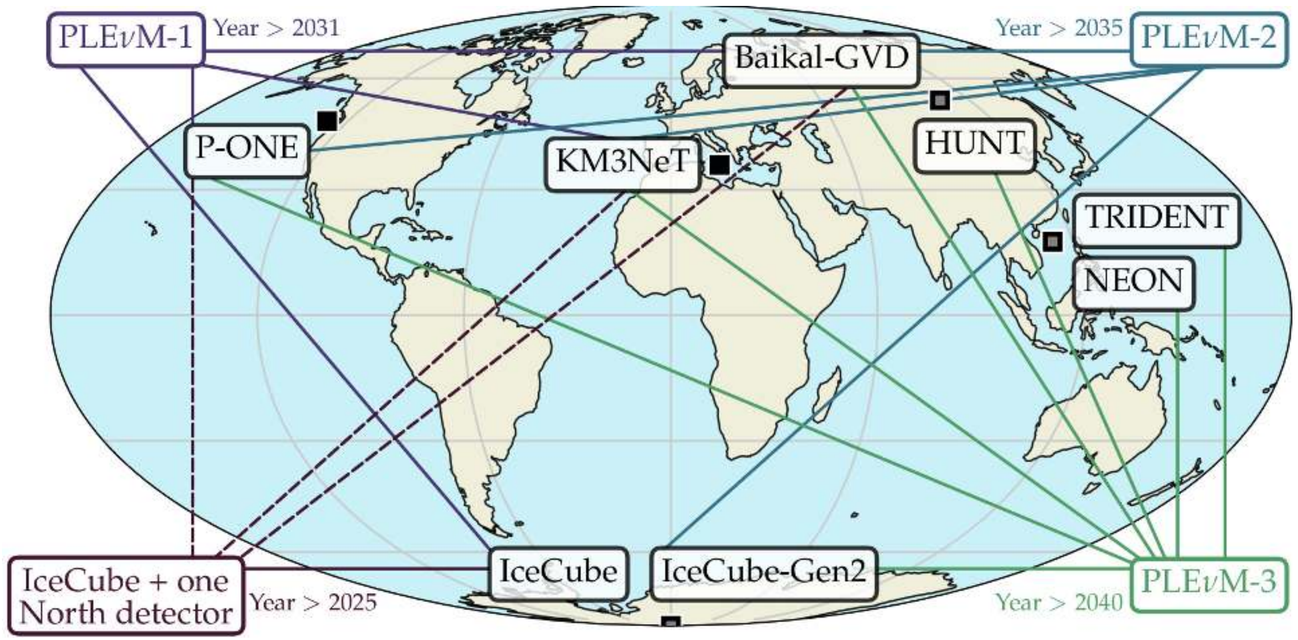
ApJL 1000 L26

Future prospects

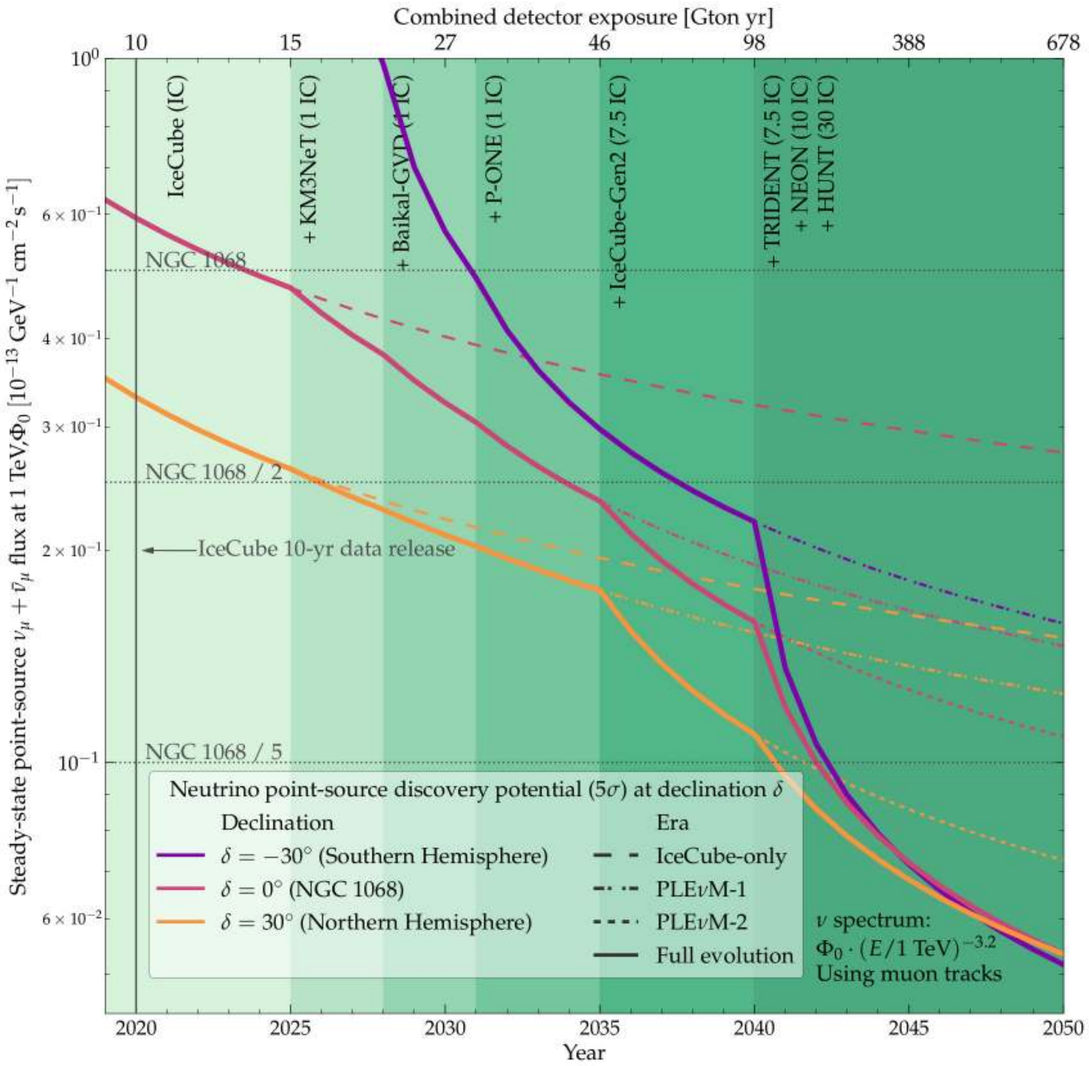
Next generation of detectors



Combining next generations



- More and fainter AGN correlations
- Population studies



arXiv:2503.07549

Summary

- Neutrino astronomy has evolved from hints of sources to population studies
- NGC 1068 is currently the most compelling hidden AGN neutrino source
- Its neutrino/gamma-ray tension motivates both astrophysical and dark-sector explanations
- Next generation telescopes will increasingly help discriminate between those

Summary

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- NGC 1068 is currently the most compelling hidden AGN neutrino source
- Its neutrino/gamma-ray tension motivates both astrophysical and dark-sector explanations
- Next generation telescopes will increasingly help discriminate between those

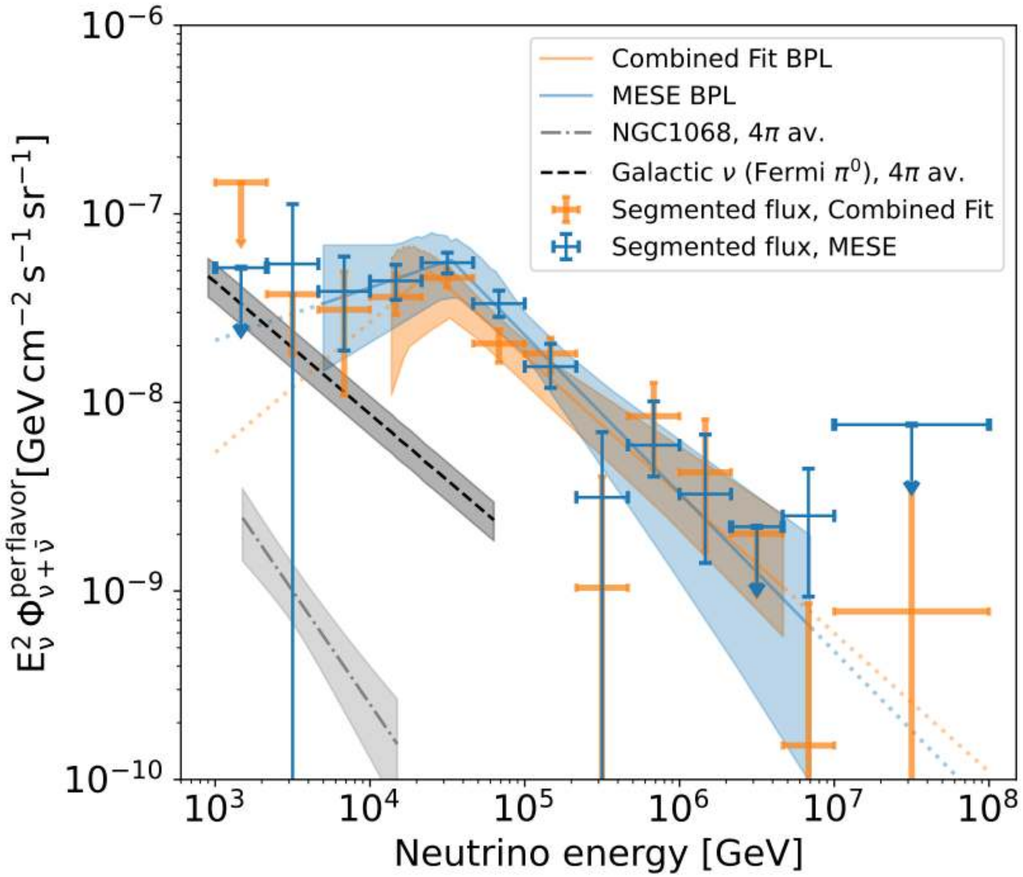
Thank you!

Backup

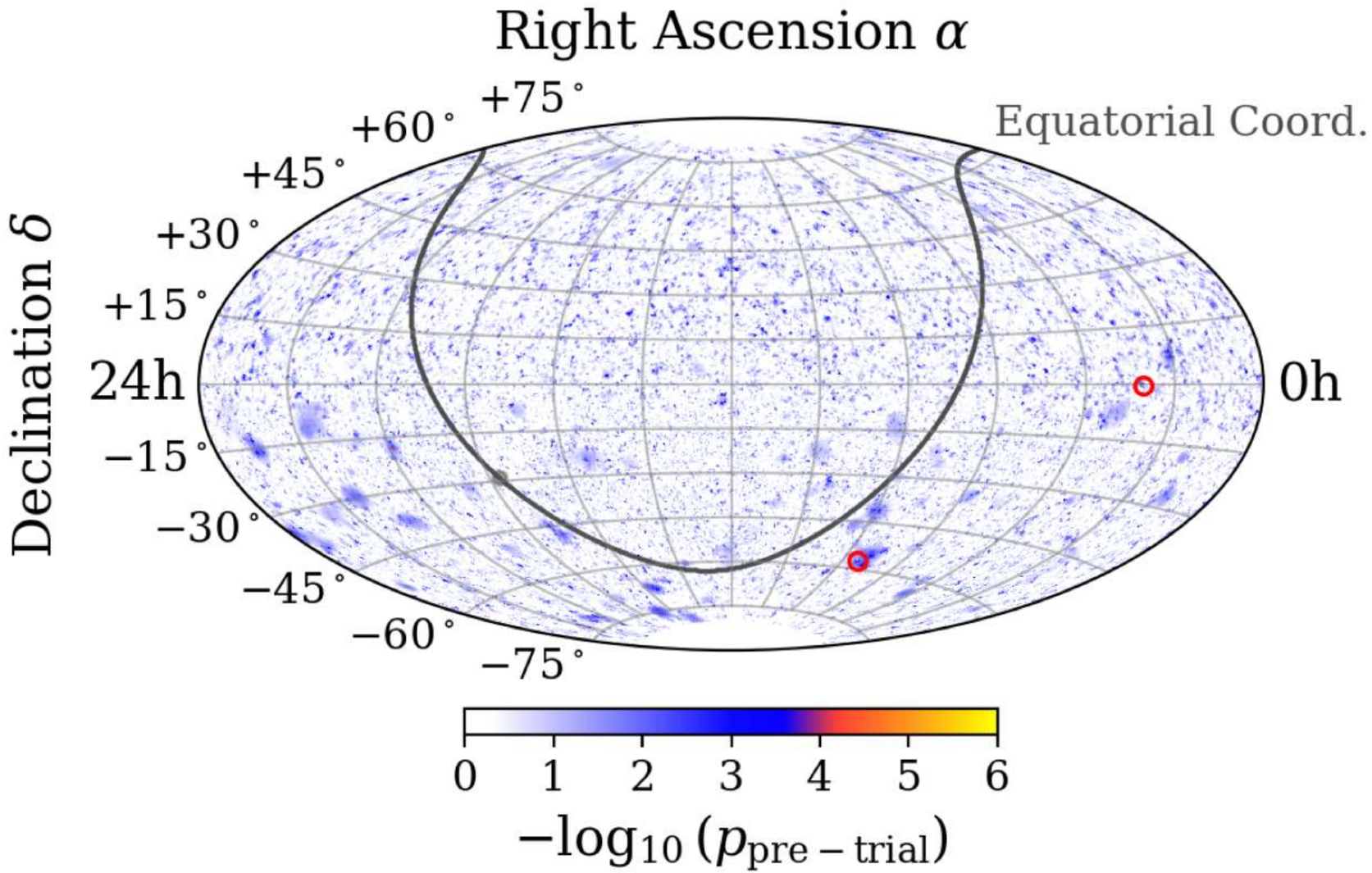
Diffuse flux BPL

$$\gamma_{\mathrm{BPL}} = \begin{cases} \gamma_1 \,, (E_\nu < E_{\mathrm{break}}) \\ \gamma_2 \,, (E_\nu > E_{\mathrm{break}}) \end{cases} \,, \text{ and } \phi_{0,\mathrm{broken}} = \phi_0 \begin{cases} (E_{\mathrm{break}}/100\,\mathrm{TeV})^{-\gamma_1} \,, (E_{\mathrm{break}} > 100\,\mathrm{TeV}) \\ (E_{\mathrm{break}}/100\,\mathrm{TeV})^{-\gamma_2} \,, (E_{\mathrm{break}} \leq 100\,\mathrm{TeV}) \end{cases}$$

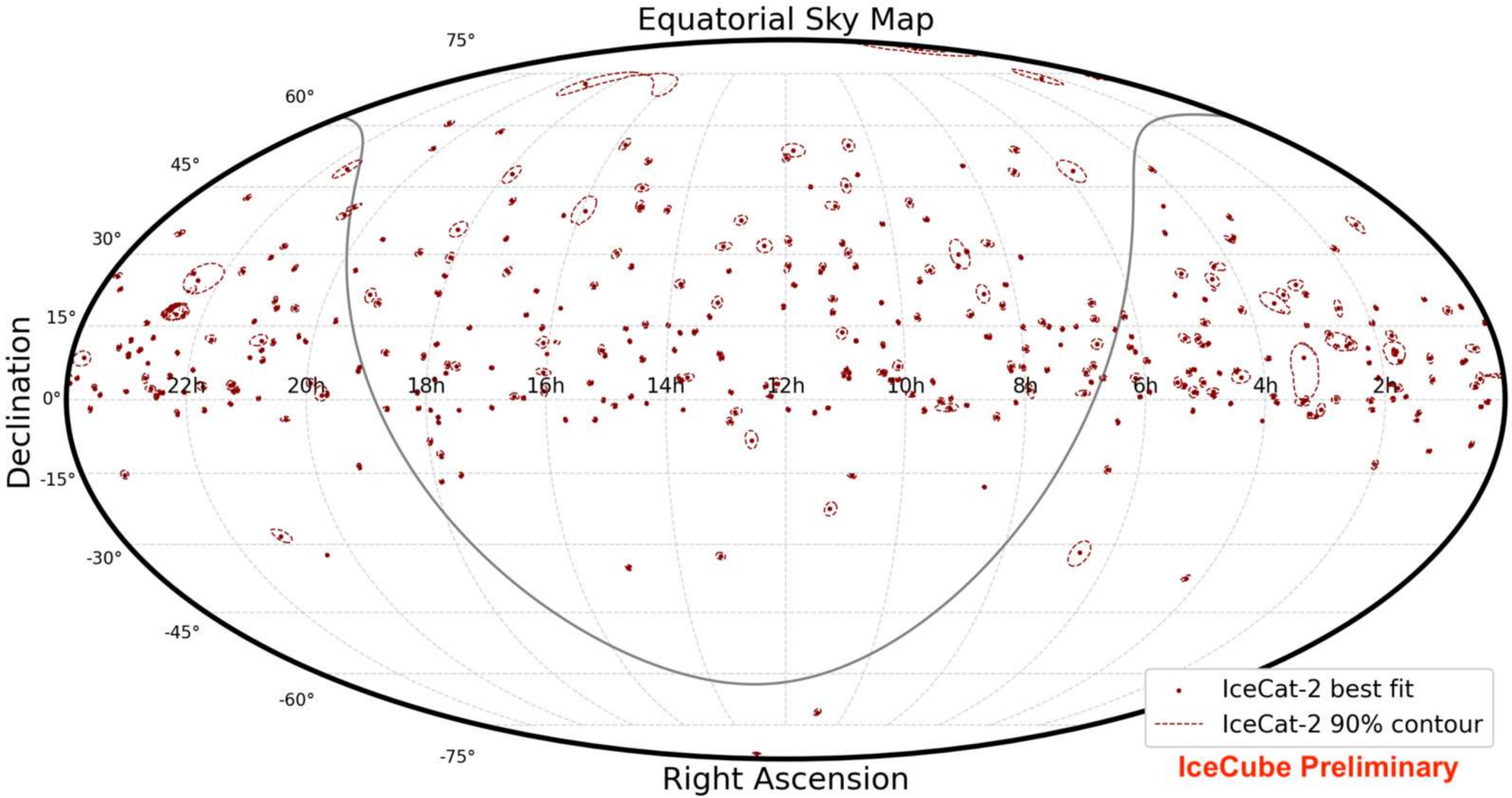
$$\begin{aligned} \phi_0 &= 1.77^{+0.15}_{-0.11} \\ \gamma_1 &= 1.31^{+0.50}_{-1.21} \\ \gamma_2 &= 2.74^{+0.06}_{-0.07} \\ \log_{10}(\tfrac{E_{\mathrm{break}}}{\mathrm{GeV}}) &= 4.39^{+0.09}_{-0.08} \end{aligned}$$



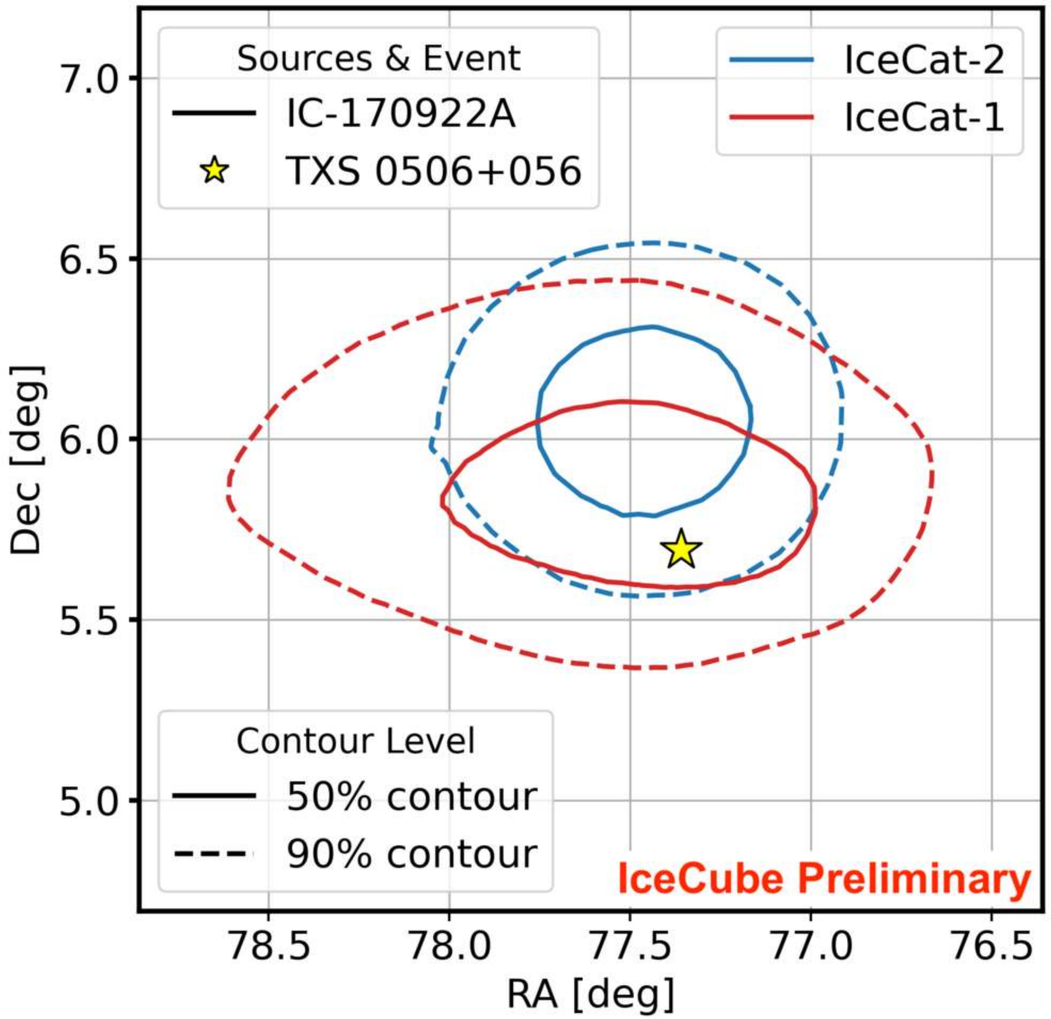
IceTracks-DR2



IceCat-v2


Equatorial Sky Map
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Declination
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
Right Ascension
IceCat-2 best fit
IceCat-2 90% contour
IceCube Preliminary

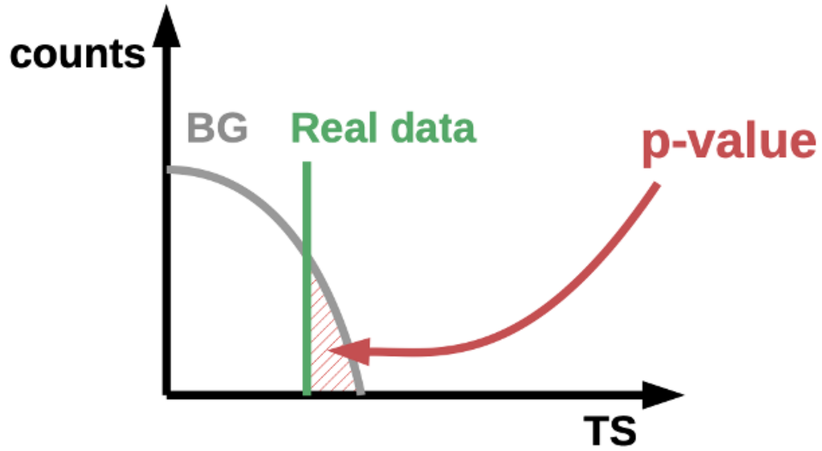
IceCat-v2


Sources & Event
IC-170922A
TXS 0506+056
IceCat-2
IceCat-1
Contour Level
50% contour
90% contour
IceCube Preliminary
Dec [deg]
RA [deg]
7.0
6.5
6.0
5.5
5.0
78.5
78.0
77.5
77.0
76.5

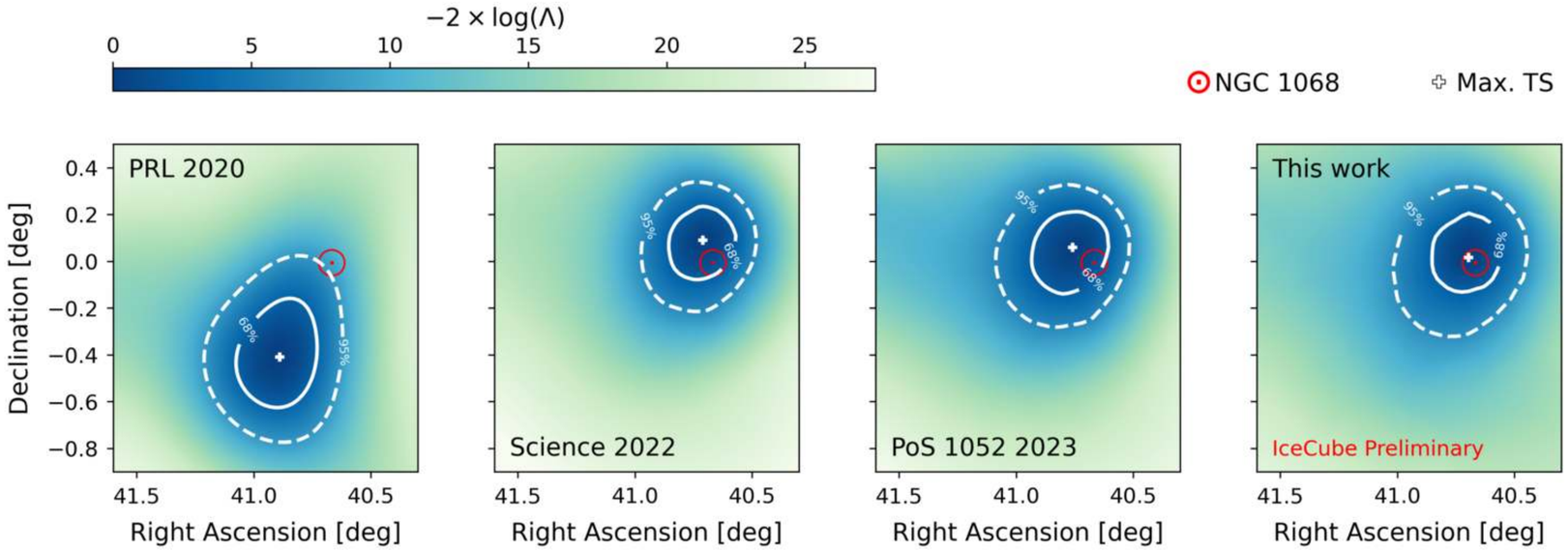
Point source LH

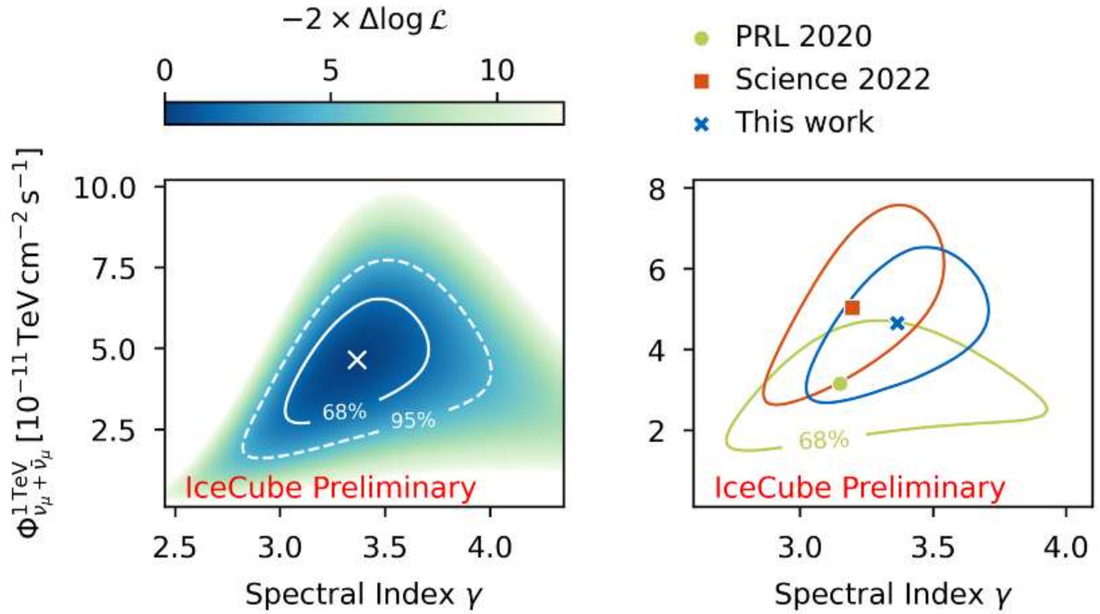
$$\mathcal{L}\left(n_{\mathrm{s}},\, \gamma,\, \boldsymbol{d}_{\mathrm{src}} \mid \boldsymbol{x}\right) = \prod_{i=1}^{N} \left\{ \frac{n_{\mathrm{s}}}{N} \cdot f_{\mathrm{S}}\left(\boldsymbol{x}_i \mid \gamma,\, \boldsymbol{d}_{\mathrm{src}}\right) + \left(1 - \frac{n_{\mathrm{s}}}{N}\right) \cdot f_{\mathrm{B}}\left(\boldsymbol{x}_i\right) \right\},$$

$$\mathrm{TS} = -2 \log \left(\frac{\mathcal{L}(n_{\mathrm{s}} = 0 \mid \boldsymbol{x})}{\mathcal{L}(\hat{n}_{\mathrm{s}},\, \hat{\gamma},\, \boldsymbol{d}_{\mathrm{src}} \mid \boldsymbol{x})} \right) = 2 \sum_{i}^{N} \log \left\{ \frac{\hat{n}_{\mathrm{s}}}{N} \left(\frac{f_{\mathrm{S}}(\boldsymbol{x}_i \mid \hat{\gamma},\, \boldsymbol{d}_{\mathrm{src}})}{f_{\mathrm{B}}(\boldsymbol{x}_i)} - 1 \right) + 1 \right\},$$

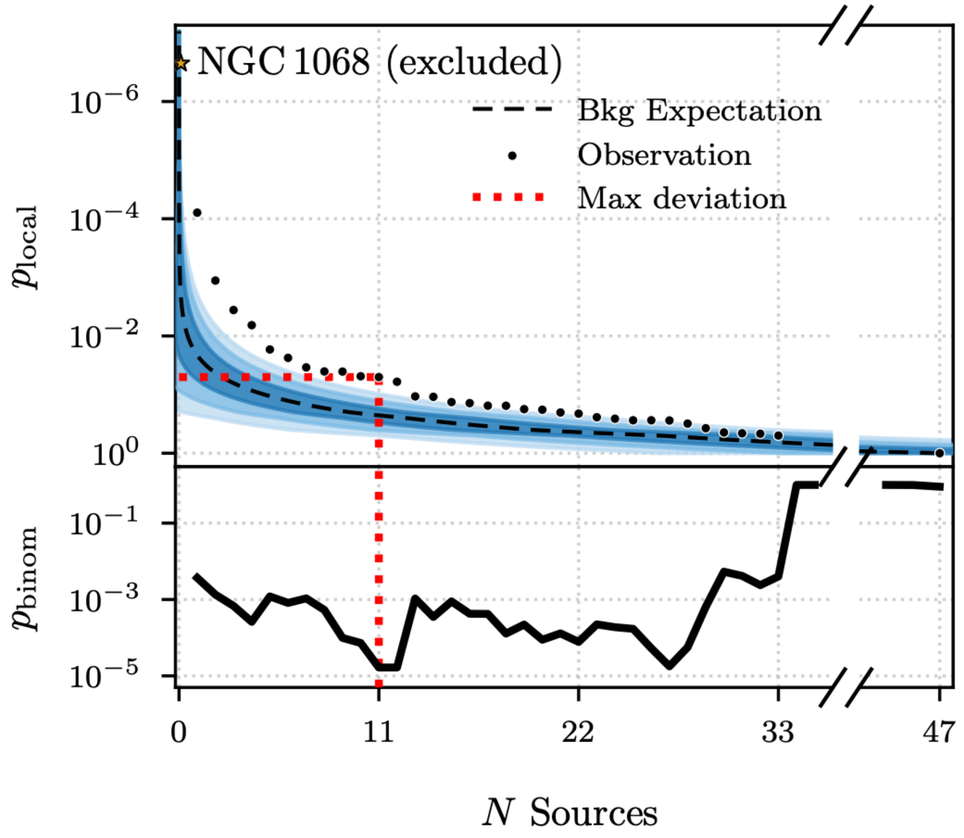


New in NGC 1068 analysis





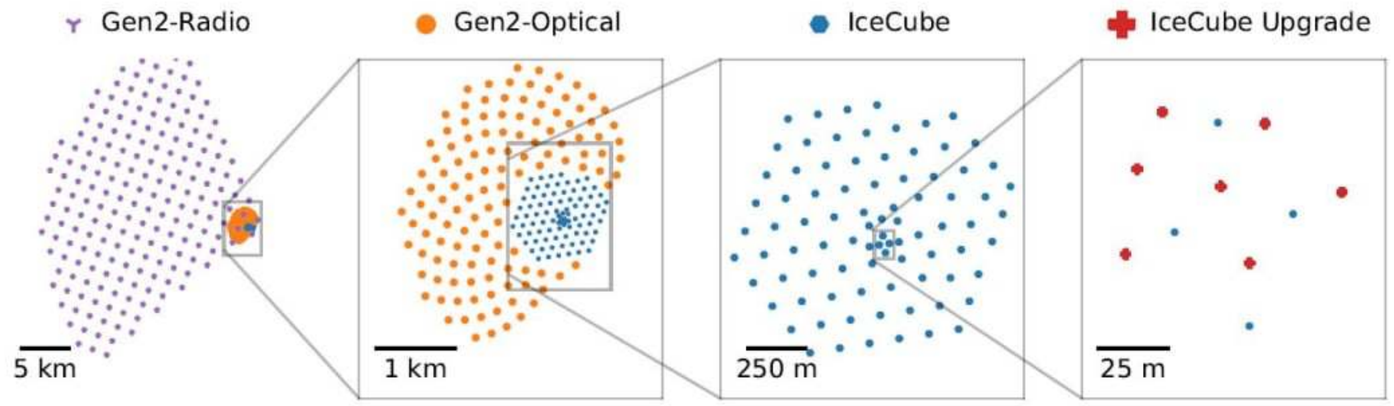
Binomial test

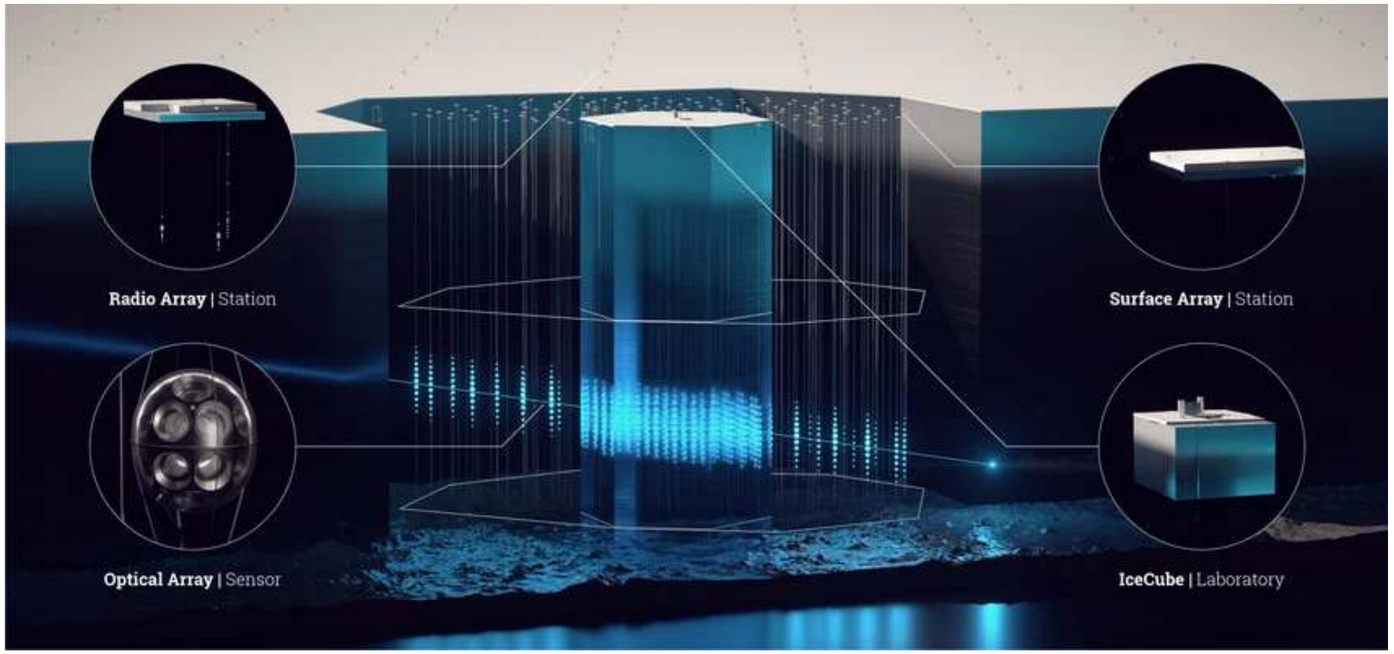


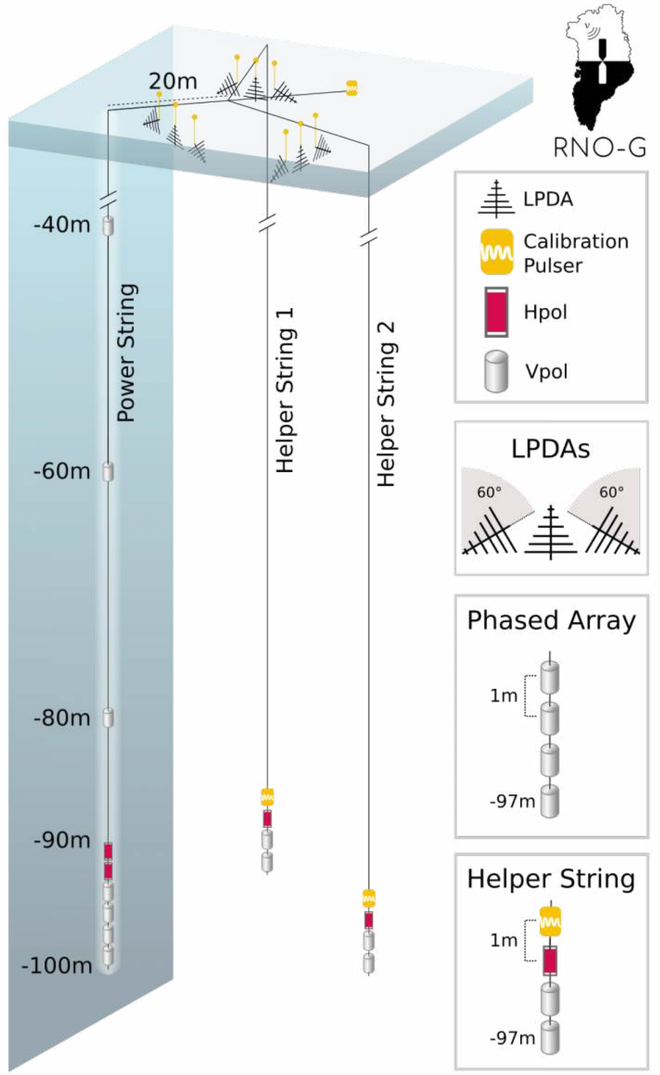
NGC 1068, other results

- Binomial on the 110 gamma-ray list: 3 sigma
- Binomial on 47 Seyferts with core-corona: local p-value of 0.001

Next generation of detectors







Next generation of detectors