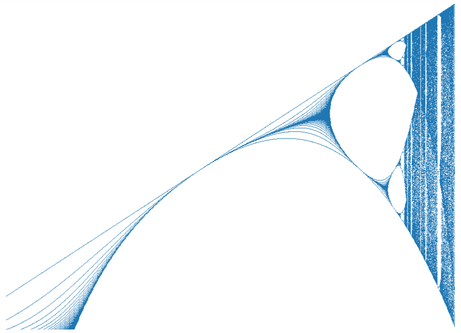
Conference in memory of Veniamin Sergeyevich Berezinsky



# Observations of Neutrino Emission from Active Galactic Nuclei: the Berezinsky Galaxies

Elisa Resconi
Technical University of Munich
03.09.2024

DFG | Bundesministerium für Bildung und Forschung | erc European Research Council | MAX-PLANCK-GESELLSCHAFT | B 1258 Neutrinos Dark Matter Messengers | TUM LMU ORIGINS Excellence Cluster

S. Bianchi, V. Mainieri, P. Padovani
https://arxiv.org/pdf/2203.16846

# Active Galactic Nuclei

## Main characteristics, classification

- most powerful, non-explosive sources in the Universe;
- emission unrelated to the nuclear fusion powering stars, connected to an actively accreting central supermassive (> $10^6$ M⊙) black hole (SMBH);
- jetted and non-jetted, radiative efficient or not, view under different angles;

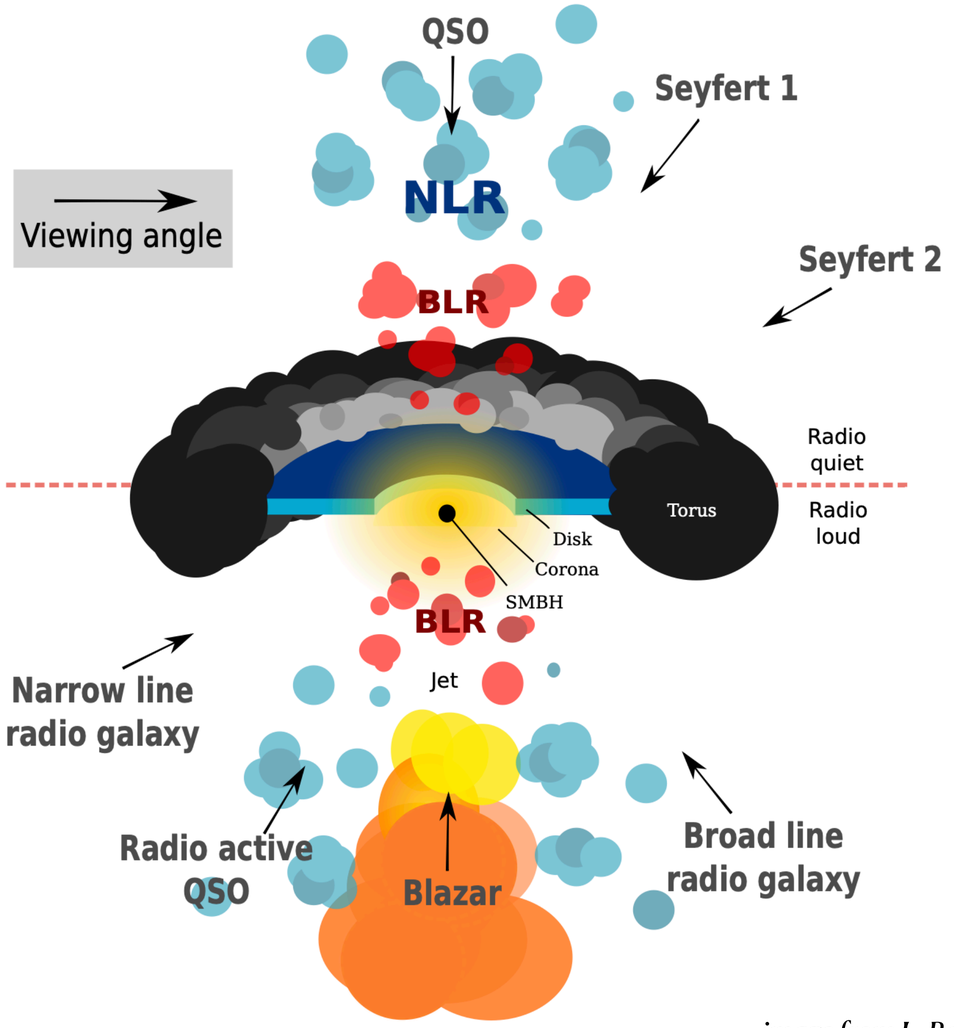


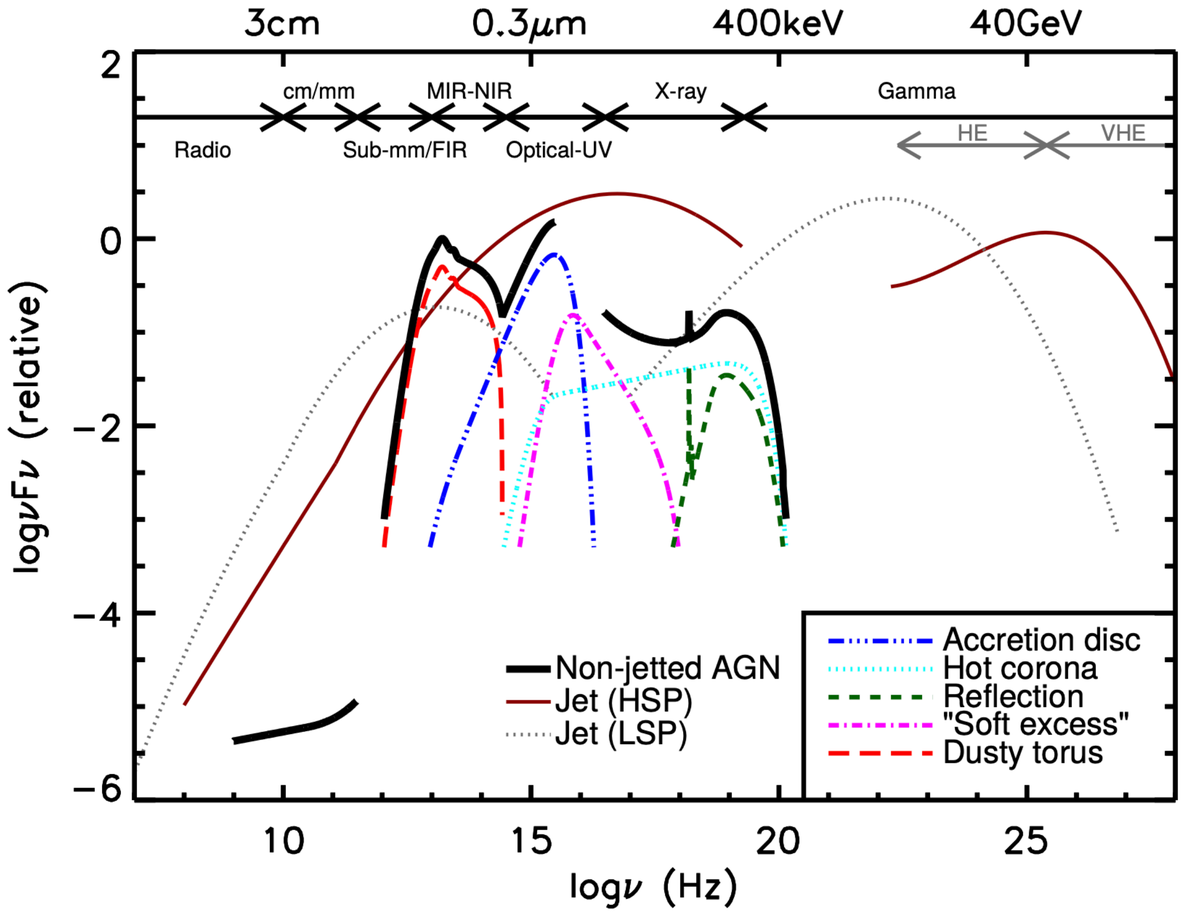

*image from L. Baronchelli*

S. Bianchi, V. Mainieri, P. Padovani
https://arxiv.org/pdf/2203.16846

# Active Galactic Nuclei

## Minimal classification

- covering the whole electromagnetic spectrum ... and more;
- very different characteristic SEDs;
  - non-jetted: up to X-ray
  - jetted: also γ-rays

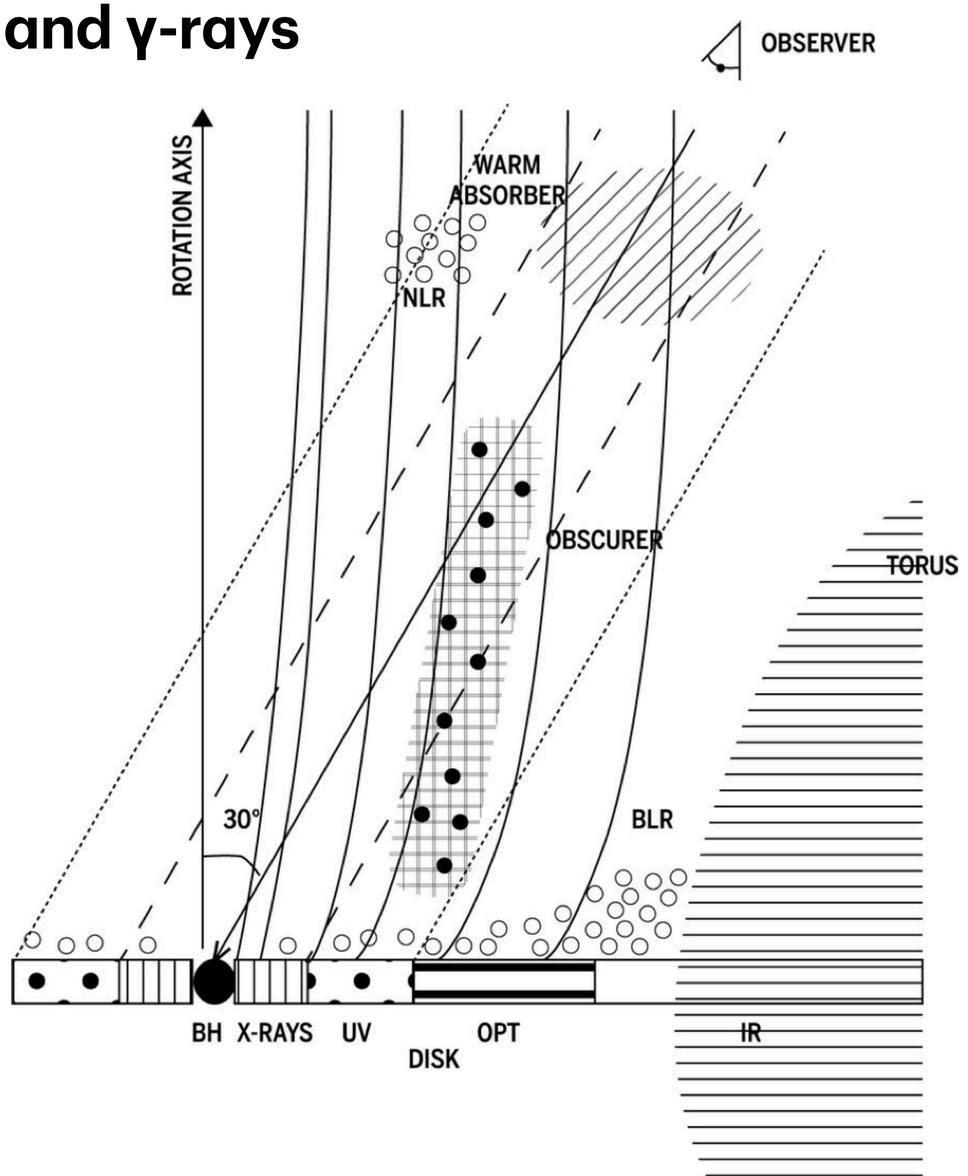


S. Bianchi, V. Mainieri, P. Padovani
https://arxiv.org/pdf/2203.16846

# Active Galactic Nuclei

## Central region, X-ray and γ-rays

- optically opaque torus located on parsec scales and multiple absorbers, on different physical scales;
- each wavelength traces a different part;
- X-ray ‘universality’: tracing Comptonized emission from a hot corona;
- X-ray obscuration: Compton-thick fraction ≈ 30%;
- γ-rays AGN driven by blazars, strong non-thermal radiation coming from relativistic jet.



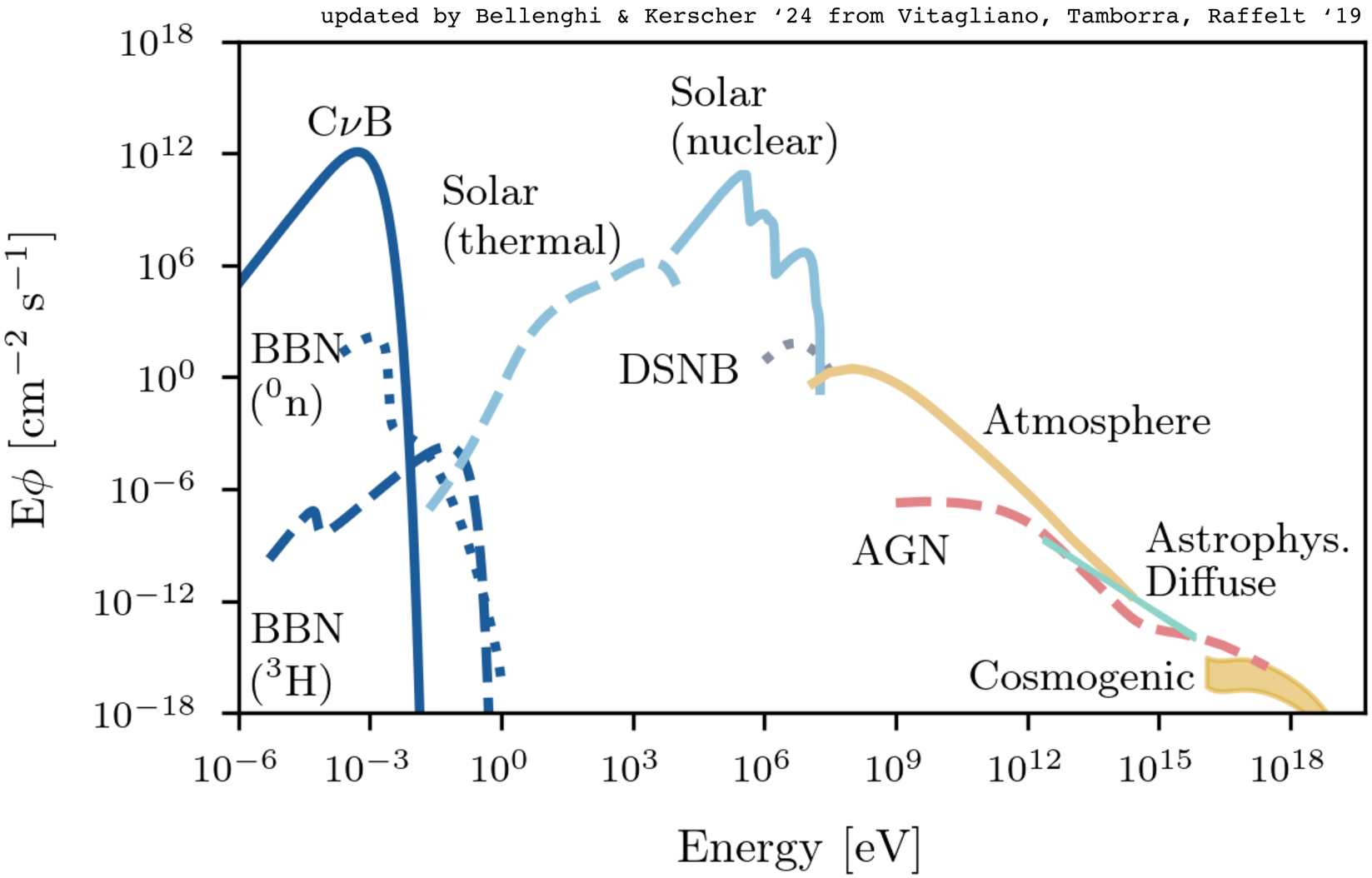
# Active Galactic Nuclei

## open questions

- **Role of the Supermassive Black Hole (SMBH)**: central engine driving extreme astrophysical phenomena
- **Accretion Processes**: accretion disk,  conversion of gravitational energy into radiation and kinetic energy
- **Jet Formation Mechanisms**:  magnetic fields, interaction between accretion disk and magnetic fields, launching relativistic jets.
- **Particles acceleration mechanisms**: magnetic reconnection and shock waves, energy amplification through interactions with turbulent fields.
- **Energy Scales Reached:**  Beyond TeV scales,  production mechanisms, observational signatures.
- **Exploration of New Physics**: dark matter, beyond the Standard Model, extreme environments and conditions

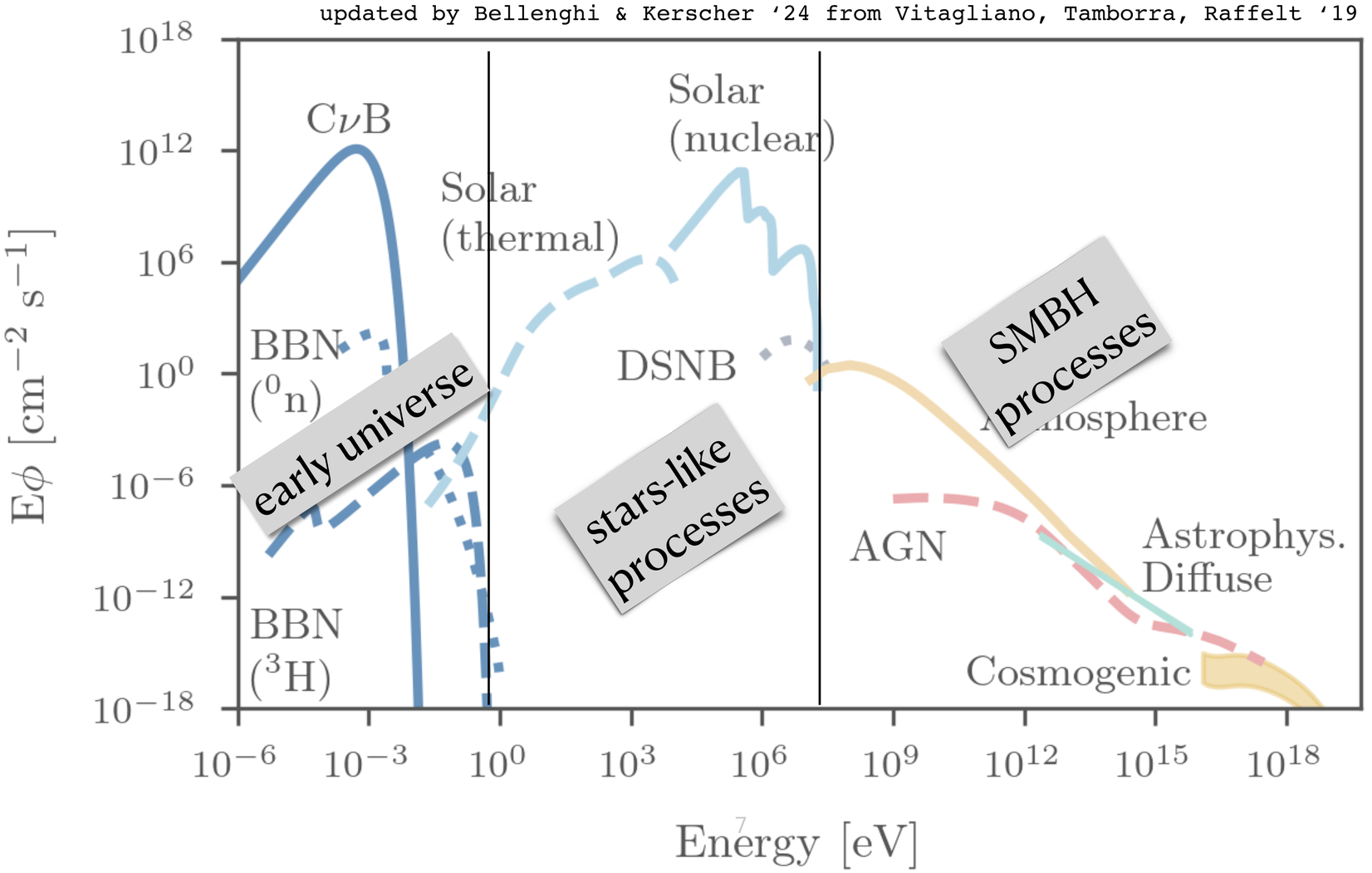
# AGN: why neutrinos?

## seeing beyond any obscuration regions



# AGN: why neutrinos?

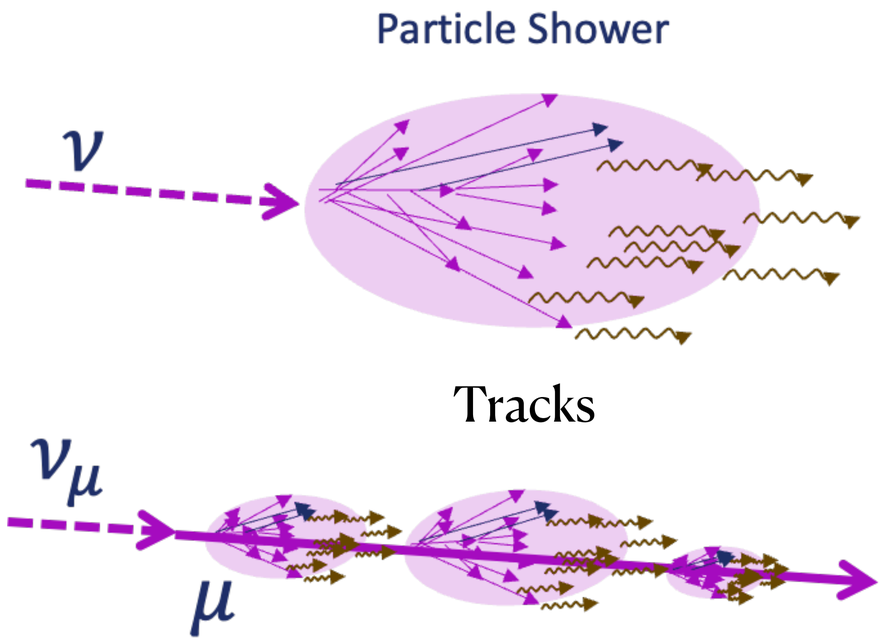
## seeing beyond any obscuration regions

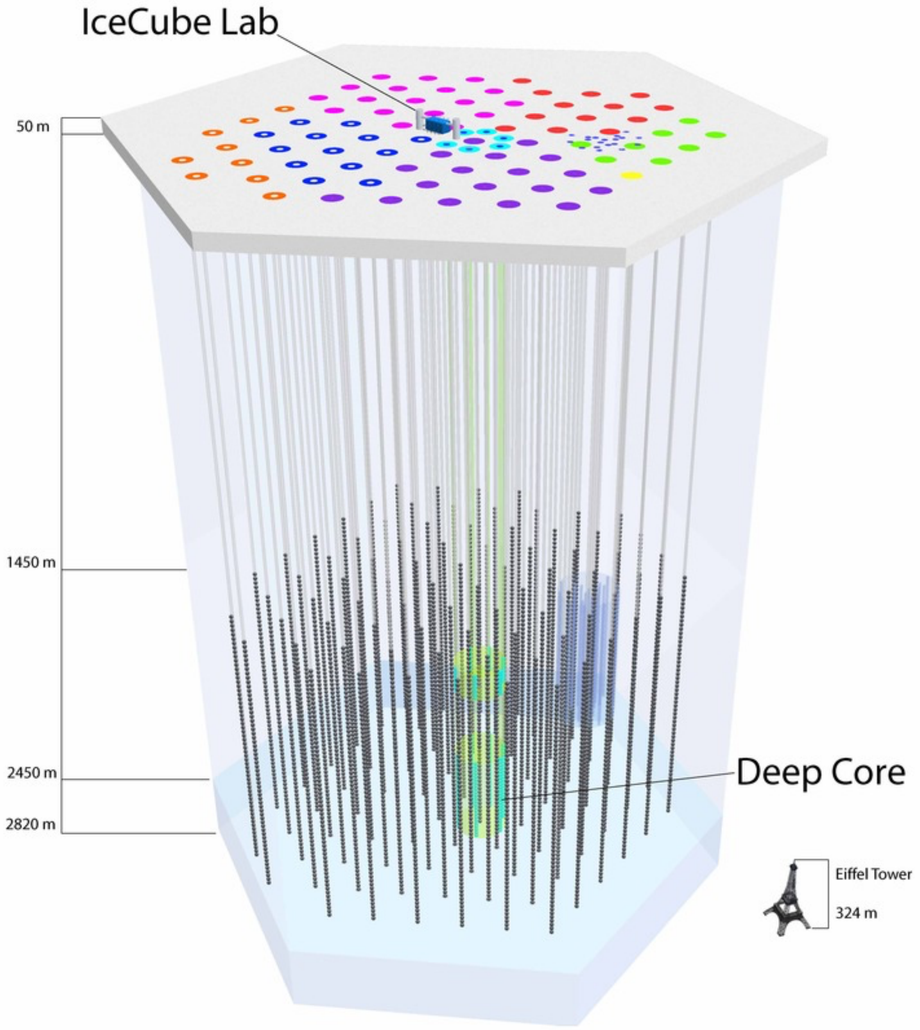


# Status of neutrino observations

## The IceCube Neutrino Observatory

Two topological channels



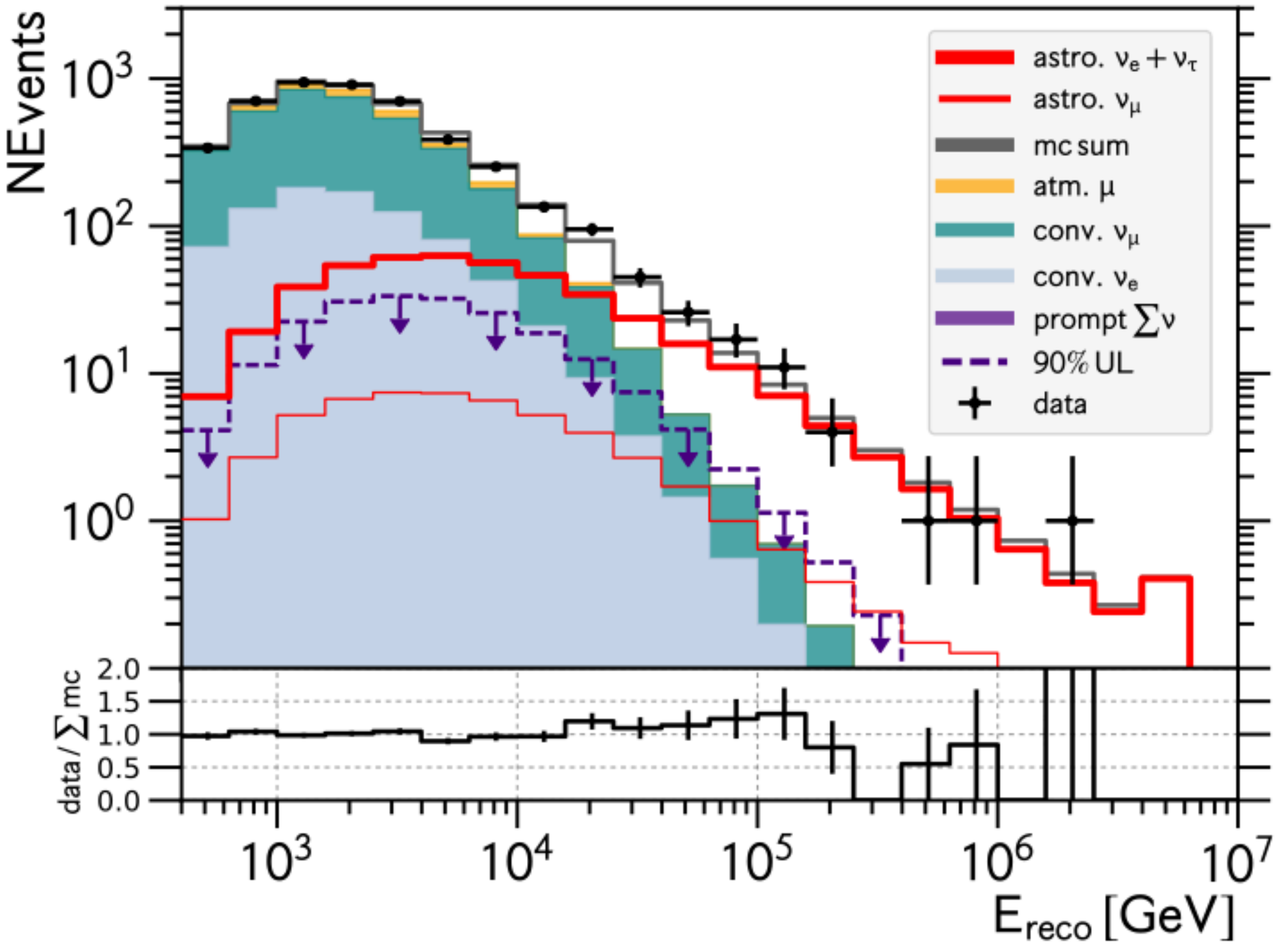



The IceCube Coll., ***PRL*** '20. The IceCube Coll., ***ApJ*** '22
The IceCube Coll., ***Nature*** '21

# Status of neutrino observations

## Finding astrophysical neutrinos

Event Rates in IceCube:
For every 1 cosmic neutrino,
~$10^9$ atmospheric muons
~$10^3$ atmospheric neutrinos

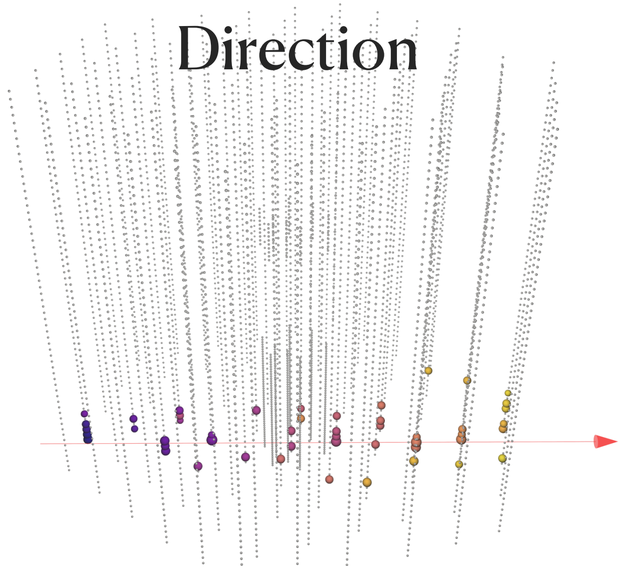


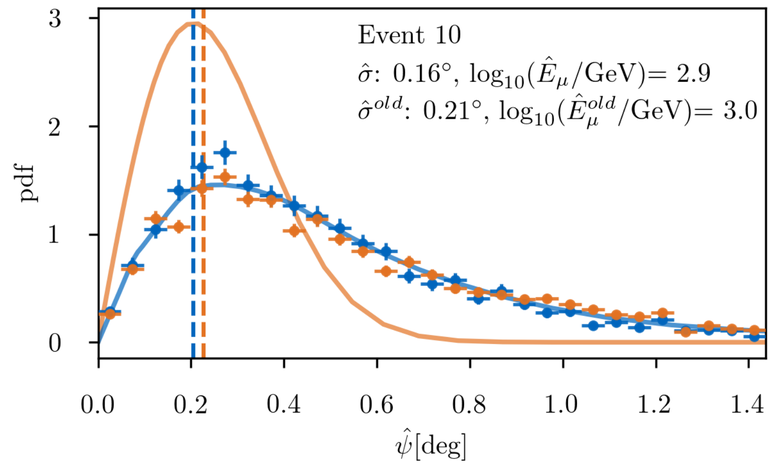
# Status of neutrino observations

## Finding astrophysical neutrino sources

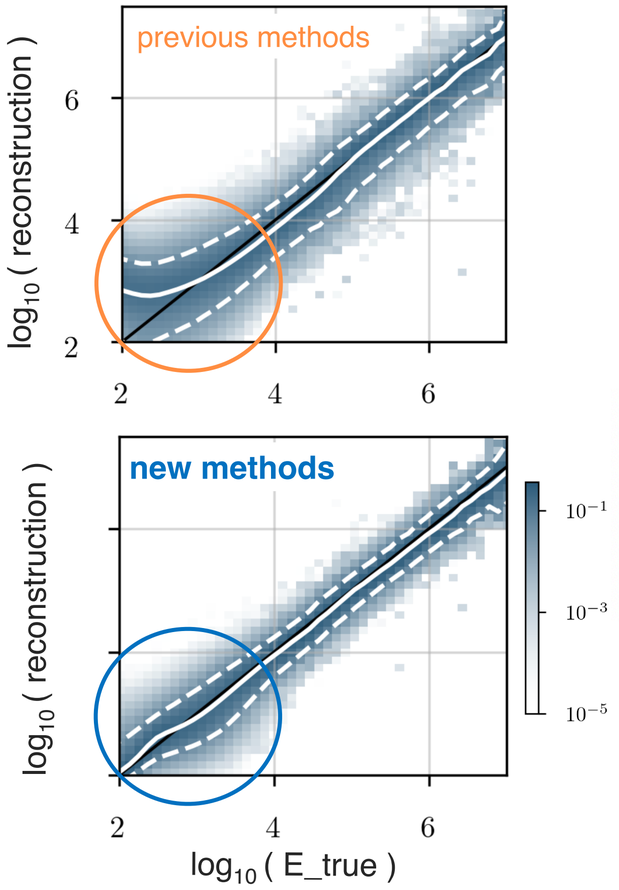
**A**

### Direction






### Energy




### Method

$$\mathcal{L}(\boldsymbol{\theta}|\boldsymbol{x}) = \prod_i f(x_i|\boldsymbol{\theta})$$

$$H_0 : \boldsymbol{\theta} = \boldsymbol{\theta}_\mathrm{b}$$

$$H_1 : \boldsymbol{\theta} = \boldsymbol{\theta}_\mathrm{s}$$

$$\boldsymbol{r}_\mathrm{src} = (\alpha_\mathrm{src}, \delta_\mathrm{src}), \qquad \phi(E) = \phi_0 \times E^{-\gamma}.$$

$$\mathcal{L}(\boldsymbol{\theta}|\boldsymbol{x}) = \frac{(n_\mathrm{s}+n_\mathrm{b})^N}{N!} e^{-(n_\mathrm{s}+n_\mathrm{b})} \times \prod_i^N \left\{ \frac{n_\mathrm{s}}{n_\mathrm{s}+n_\mathrm{b}} f_\mathrm{s}(x_i|\boldsymbol{\theta}_\mathrm{s}) + \frac{n_\mathrm{b}}{n_\mathrm{s}+n_\mathrm{b}} f_\mathrm{b}(x_i|\boldsymbol{\theta}_\mathrm{b}) \right\}$$

# Status of neutrino observations

IceCube Data (dots) vs simulation (solid lines)  comparison: excellent agreement

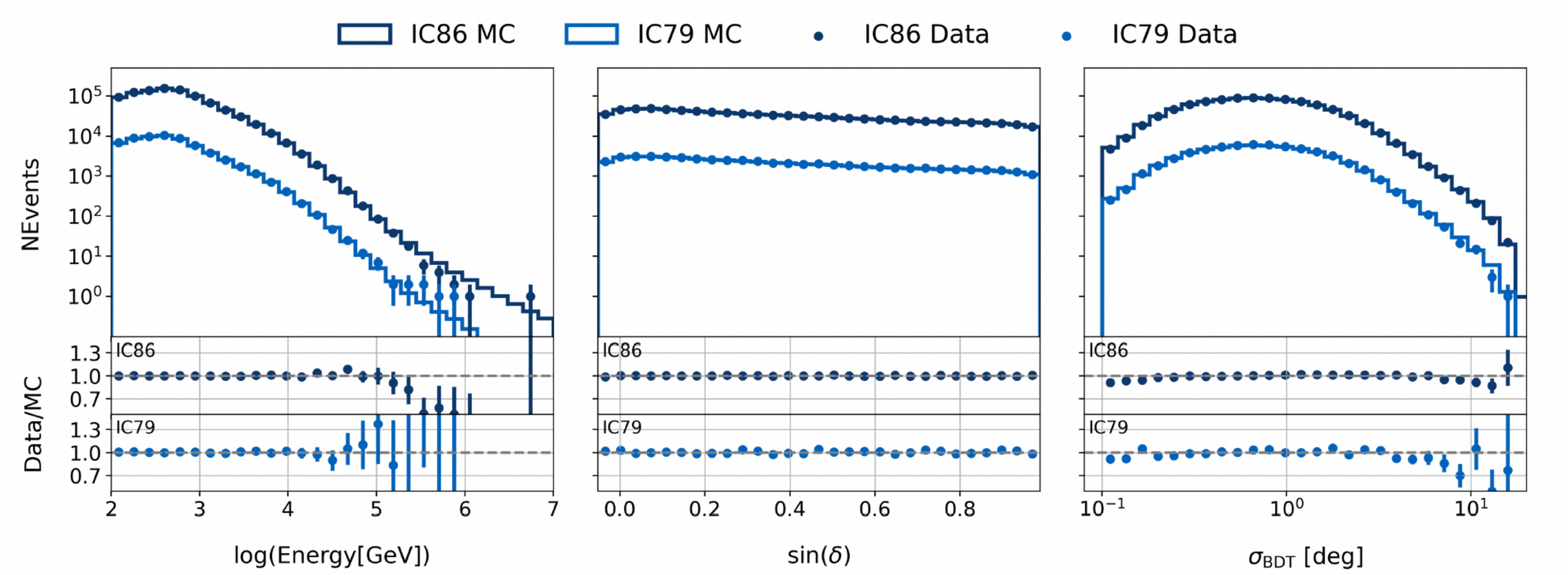
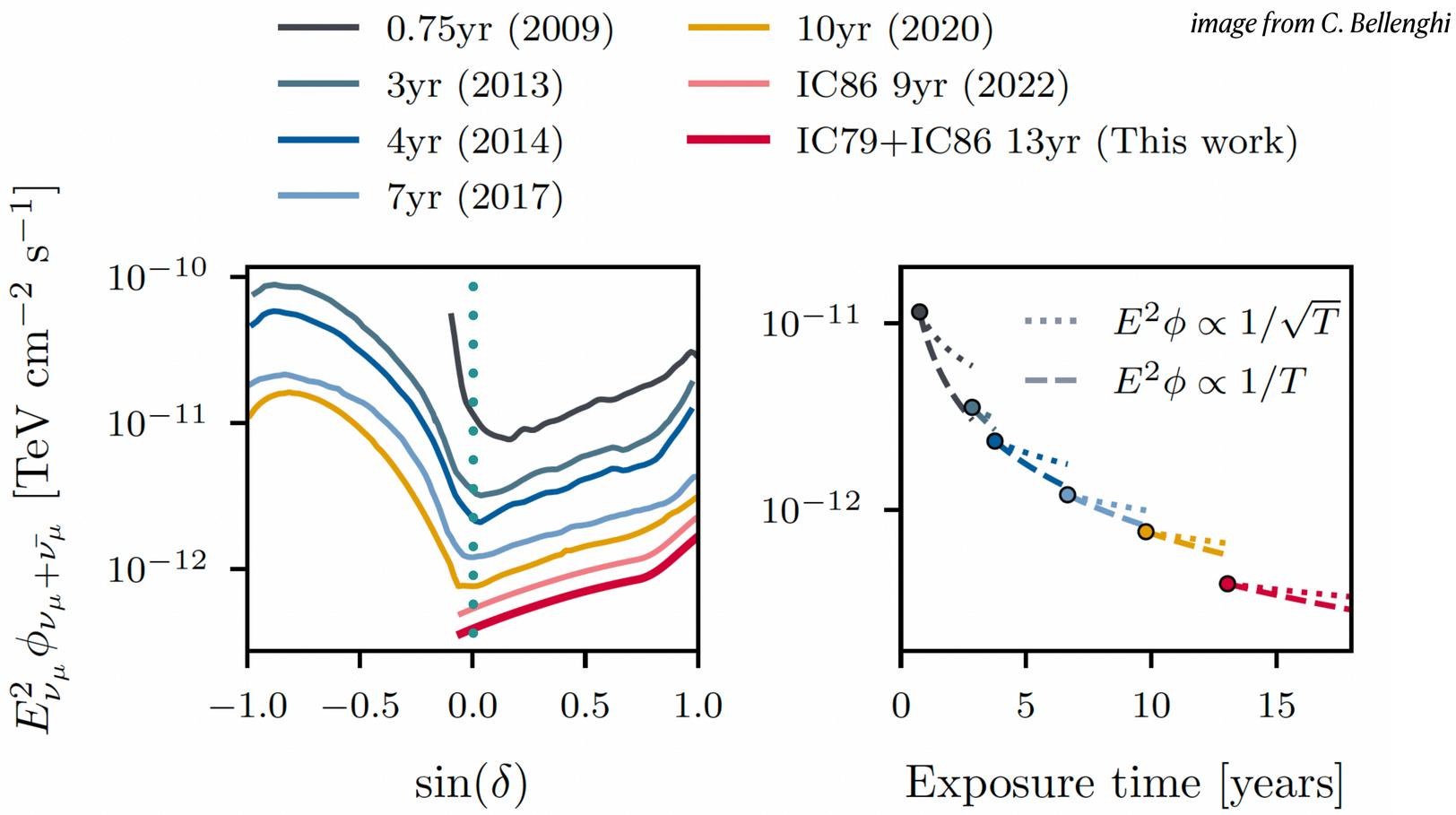



*image from C. Haack*

# Status of neutrino observations

## Discovery potential as a function of the source declination and exposure time

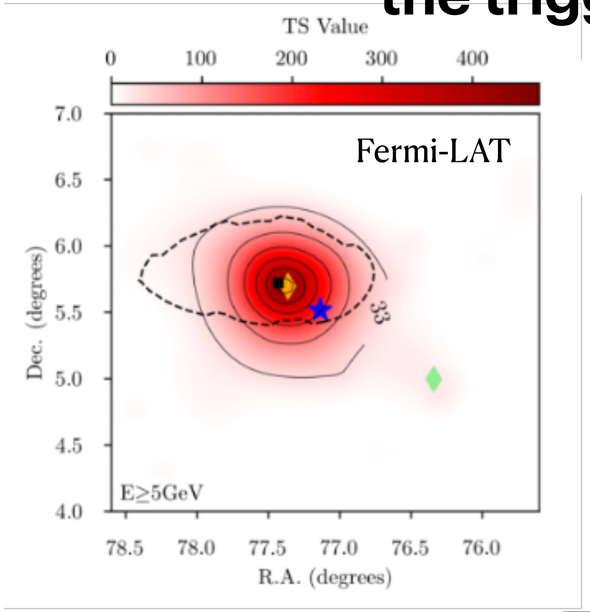
*image from C. Bellenghi*

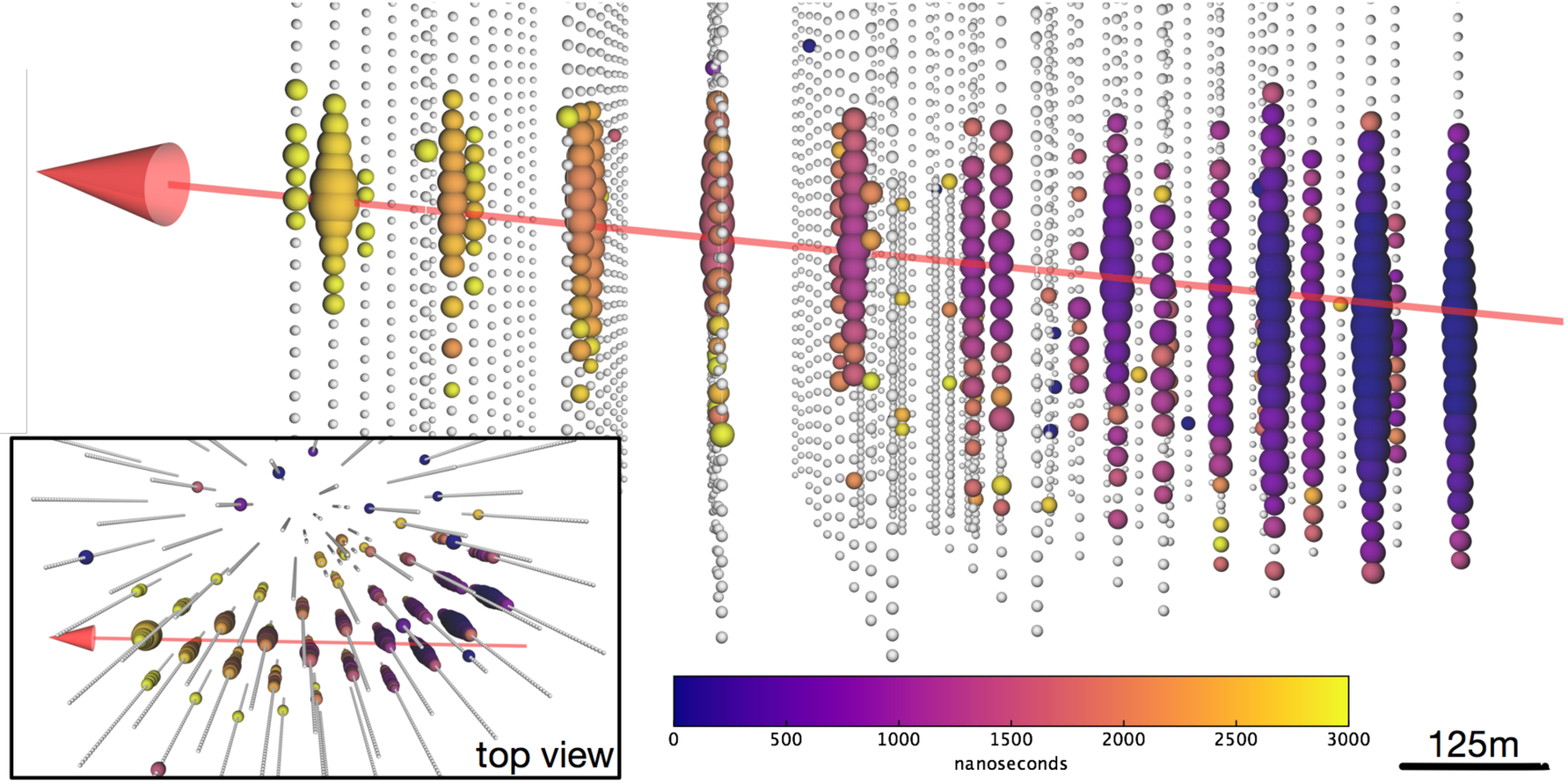


The IceCube Coll., ***Science*** '18
P.Padovani,P. Giommi, E.R., et al., ***MNRAS*** '18

# Neutrino associations to jetted AGN

## the trigger: 270 TeV neutrinos from blazar TXS 0506+056 in flare



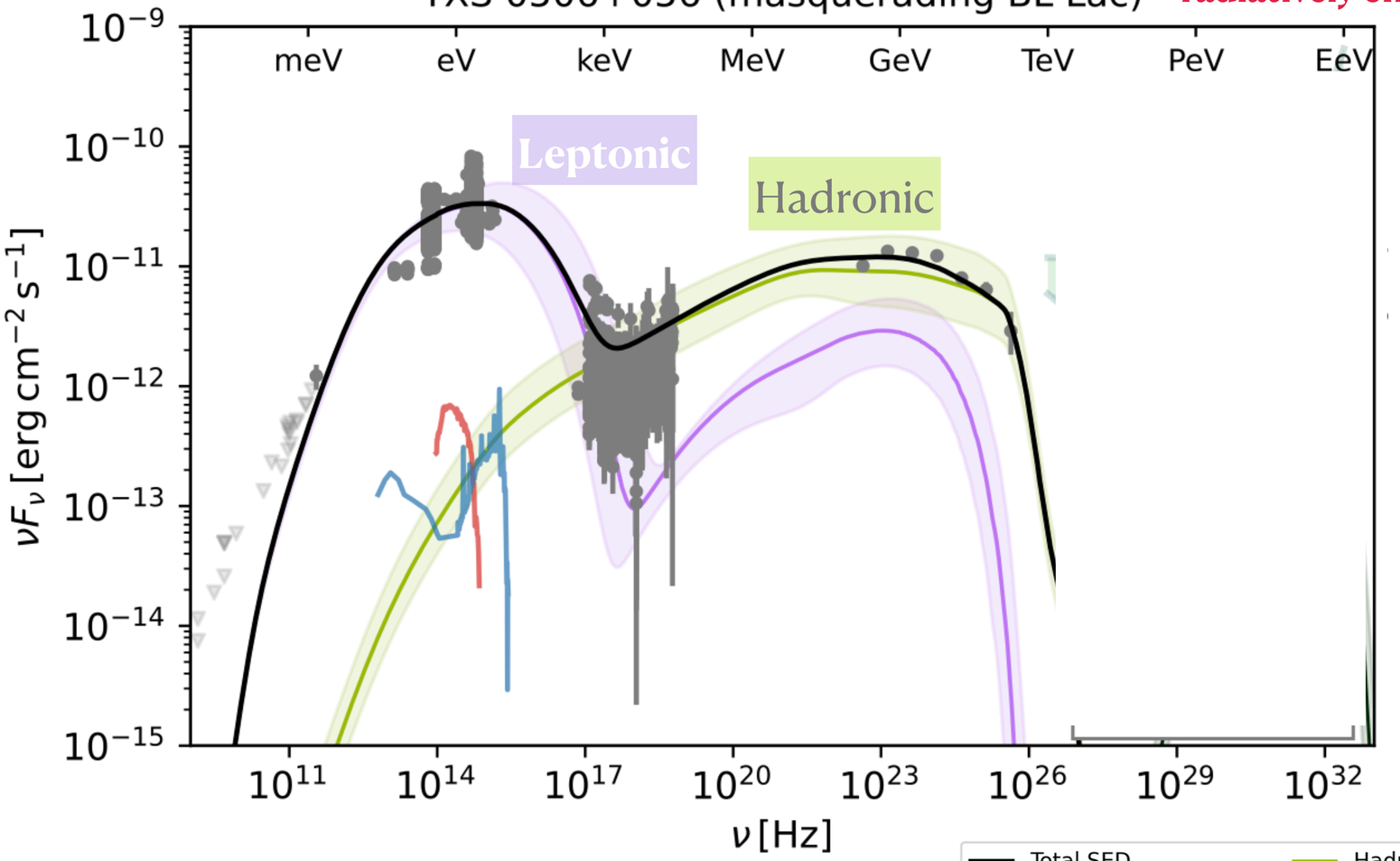

IceCube-170922A: neutrino alert [~290 TeV, Dec ~5.72 deg]

X. Rodrigues, M. Karl, P. Padovani et al., **A&A** '24
D. Karavolaa M. Petropoulou, **JCAP** '24

# TXS 0506+056: classification

## leptonic, hadronic? is one zone enough?

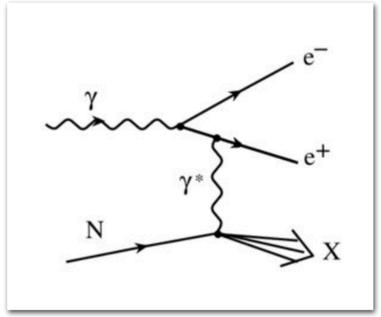
TXS 0506+056 (masquerading BL Lac) = **radiatively efficient**



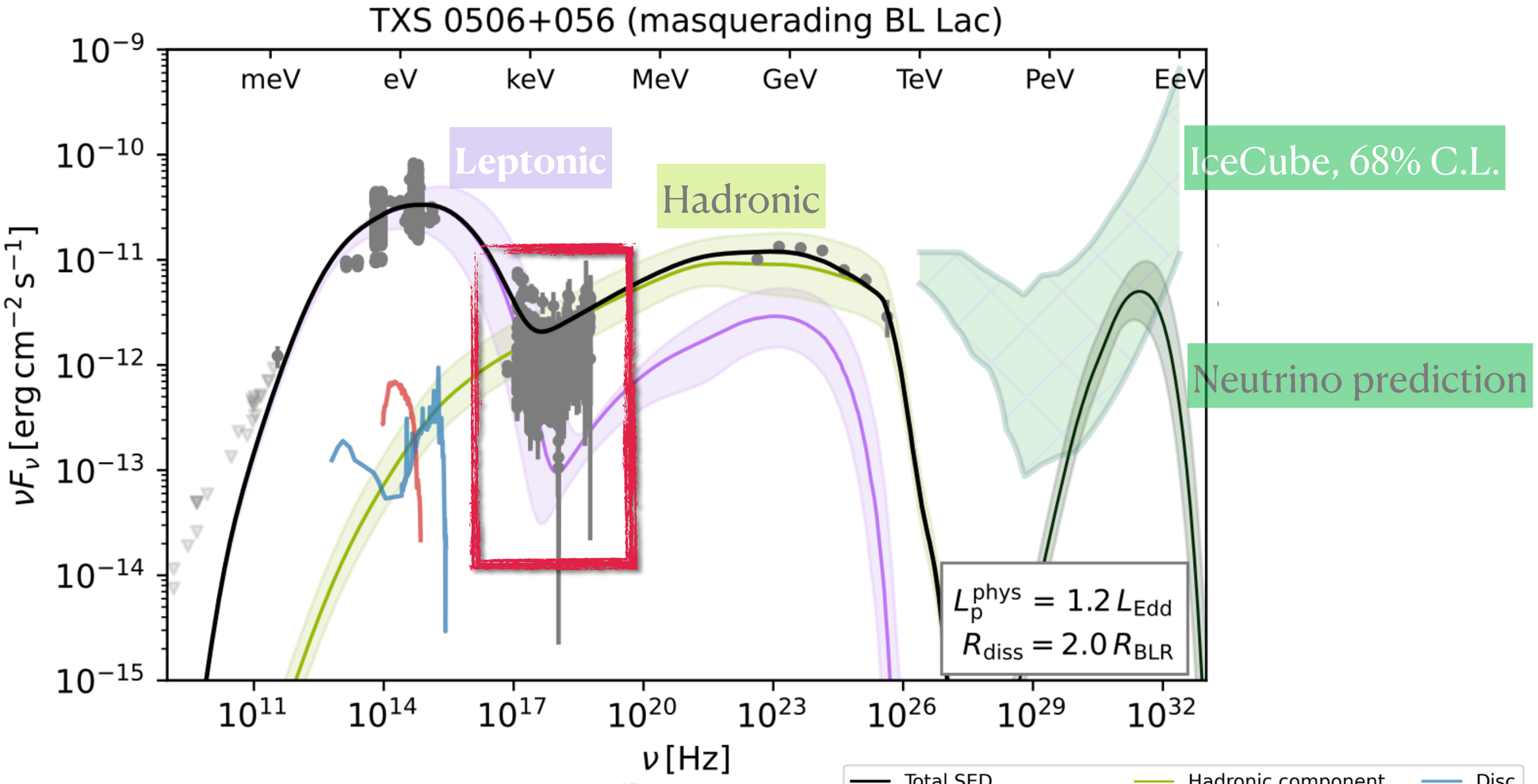
X. Rodrigues, M. Karl, P. Padovani et al., **A&A** '24
D. Karavolaa M. Petropoulou, **JCAP** '24

# TXS 0506+056: X-ray constrains

## Bethe-Heitler pairs



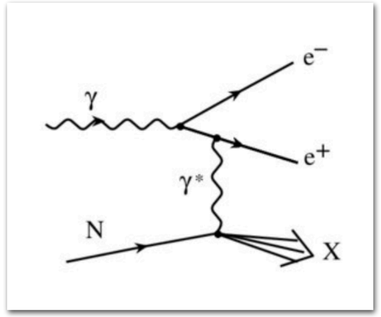

synchrotron emission from Bethe-Heitler pairs



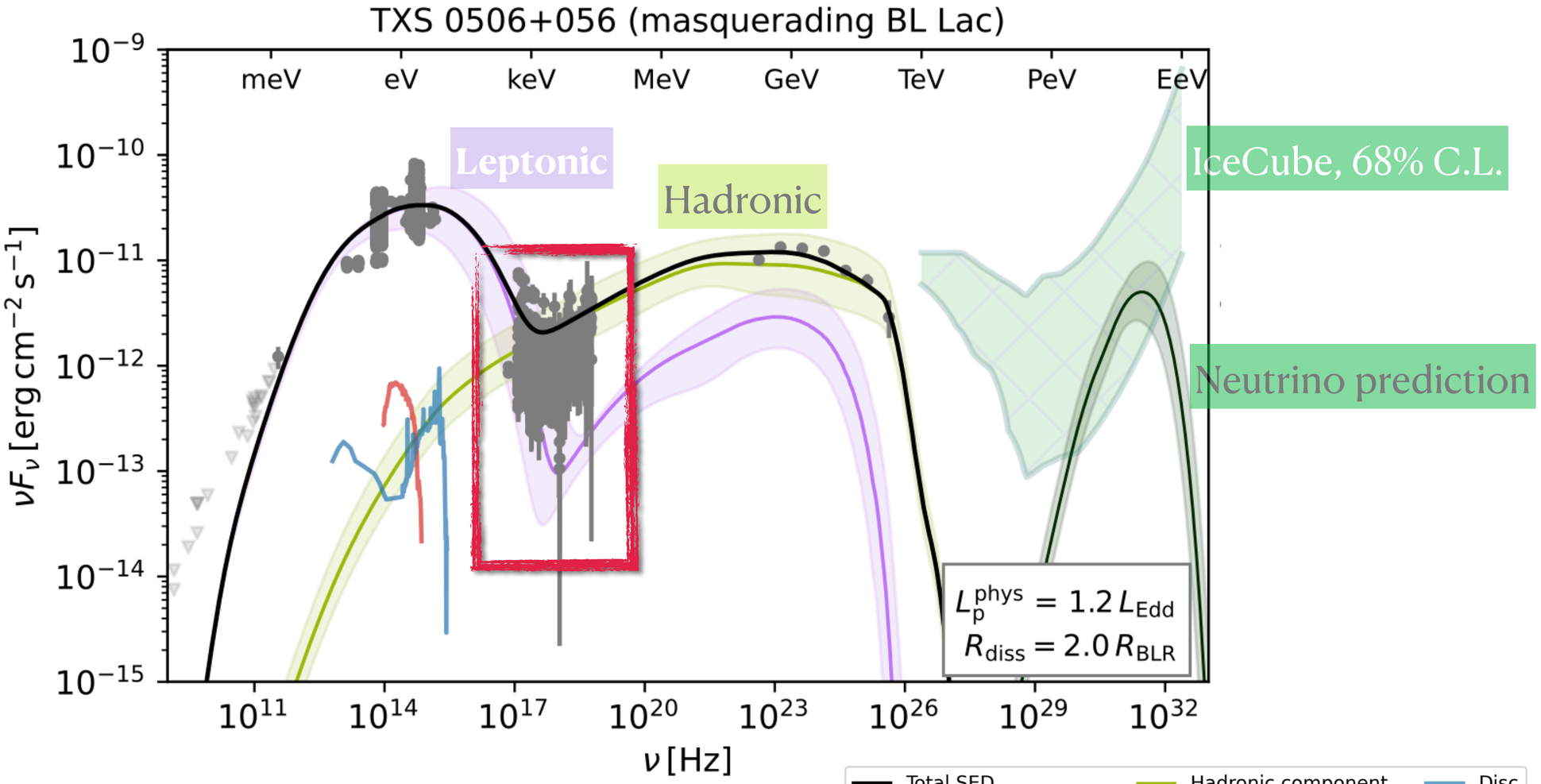
X. Rodrigues, M. Karl, P. Padovani et al., **A&A** '24
D. Karavolaa M. Petropoulou, **JCAP** '24

# TXS 0506+056 explained

**with one-zone leptohadronic!!**




synchrotron emission from Bethe-Heitler pairs

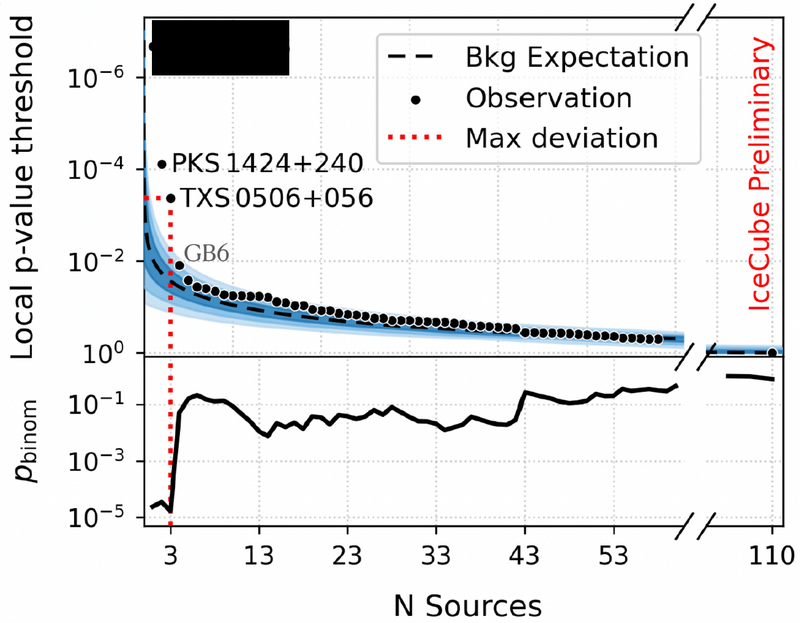


The IceCube Coll., ***Science*** 378 (2022)
The IceCube Coll., ***preliminary***

# What about other jetted AGN?

## IceCube ranking of most significant object in 110 gamma-ray emitters

| | NAME | TS | ns | gamma | pVal | Nsigma | |
|---|---|---|---|---|---|---|---|
| 1. | [redacted] | | | | | | |
| 2. | **PKS 1424+240** | 16,2 | 96,3 | 3,6 | 7,7E-05 | 3,78 | jetted AGN, masquerading BL Lac |
| 3. | **TXS 0506+056** | 12,6 | 4,9 | 1,9 | 4,3E-04 | 3,33 | jetted AGN, masquerading BL Lac |
| 4. | **GB6 J1542+6129** | 5,6 | 26,6 | 3,2 | 1,2E-02 | 2,24 | jetted AGN, masquerading BL Lac |



The IceCube Coll., ***Science*** 378 (2022)
The IceCube Coll., ***preliminary***

# What about other jetted AGN?

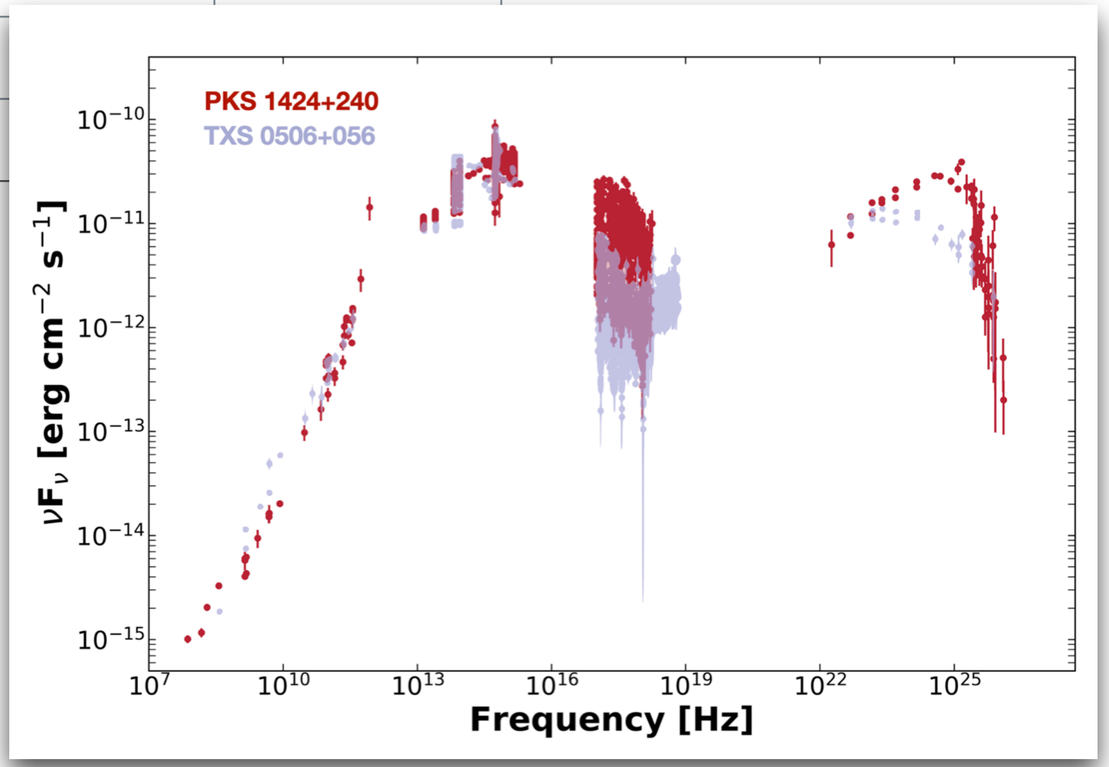
## IceCube ranking of most significant object in 110 gamma-ray emitters

| | NAME | TS | ns | gamma | pVal | Nsigma |
|---|---|---|---|---|---|---|
| 1. | [redacted] | | | | | |
| 2. | **PKS 1424+240** | 16,2 | 96,3 | 3,6 | 7,7E-05 | 3,78 |
| 3. | **TXS 0506+056** | 12,6 | 4,9 | 1,9 | | |
| 4. | **GB6 J1542+6129** | 5,6 | 26,6 | 3,2 | | |

P.Padovani et al., ***MNRAS*** '22

All three jetted AGN share **surprising similarities**: masquerading, SED, high powers, parsec scale properties.

These type of AGN are **very rear**, at most ≈ 20 Fermi-4LAC.

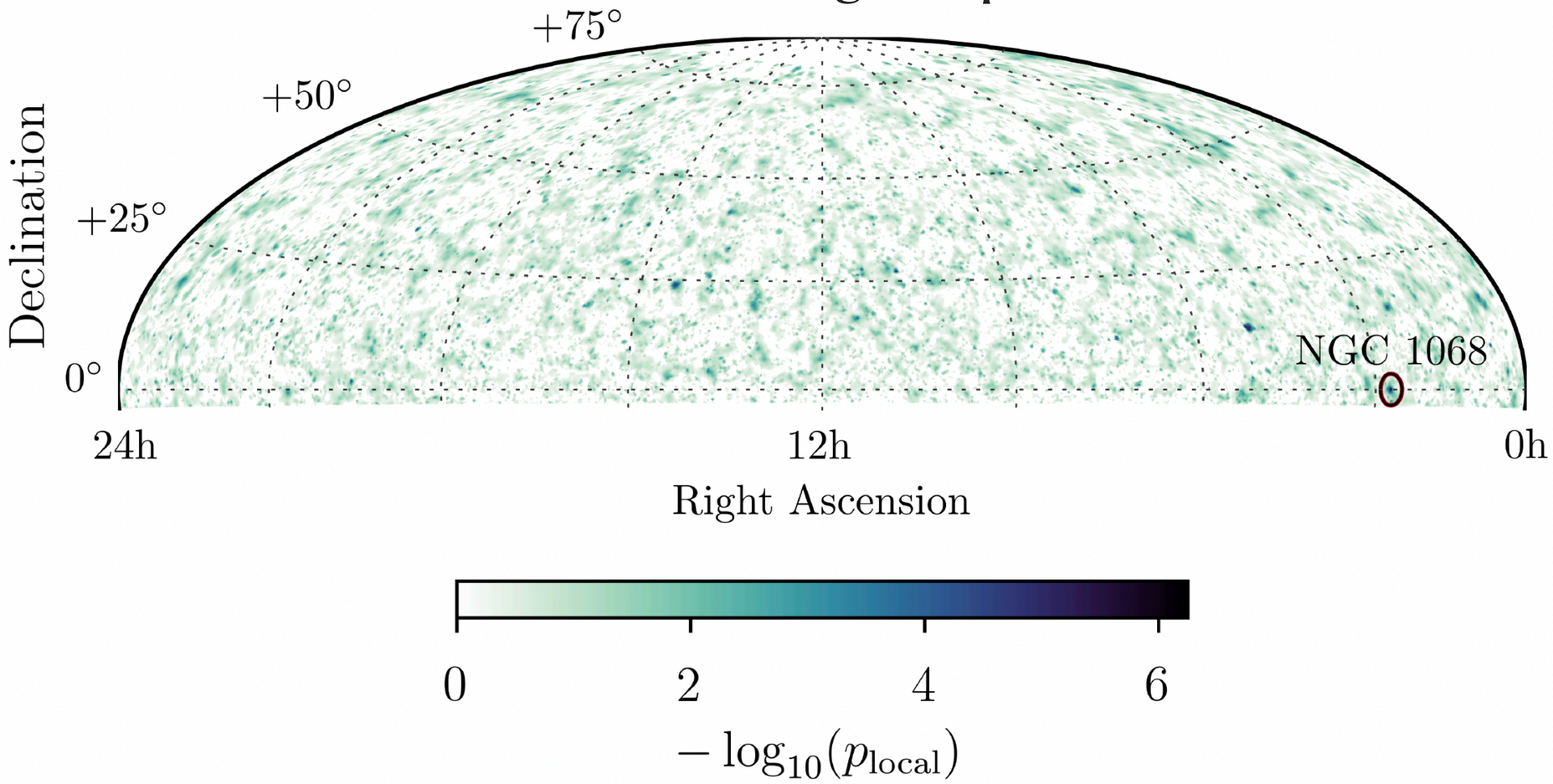


The IceCube Coll., ***Science*** 378 (2022)
The IceCube Coll., ***preliminary***

# Neutrino association: the top 1.

## NGC1068: a non-jetted AGN

at the 4σ level (global p-value)

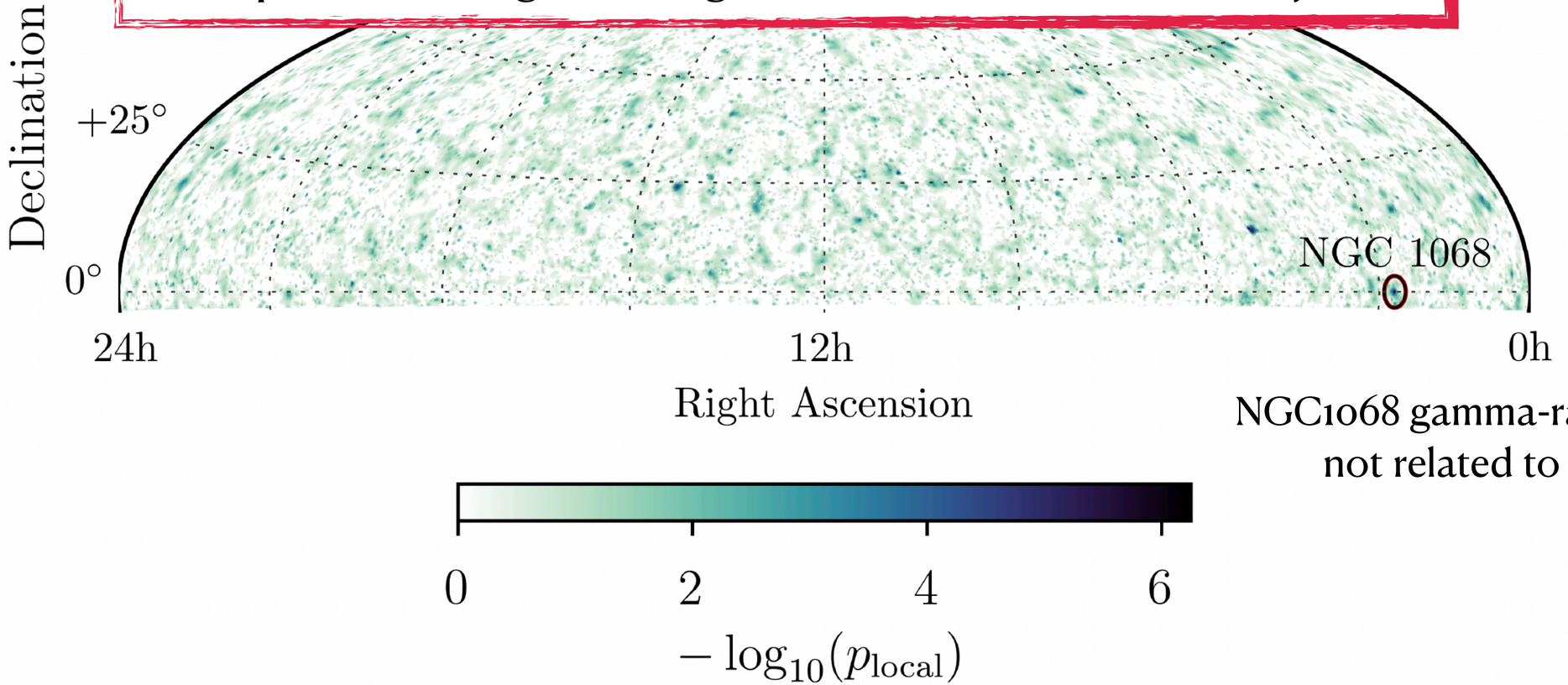


The IceCube Coll., ***Science*** 378 (2022)
The IceCube Coll., ***preliminary***

# Neutrino association: the top 1.

## NGC1068: a non-jetted AGN

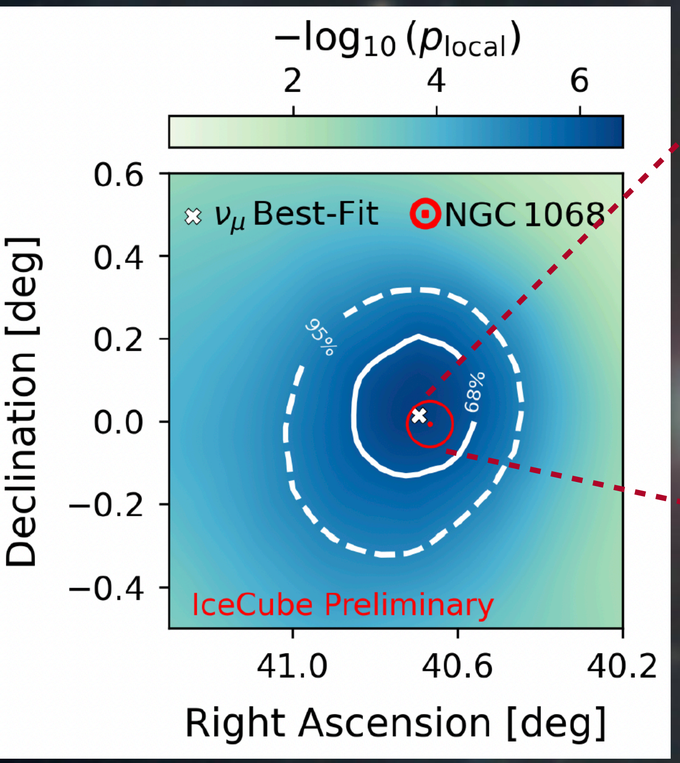
if “A theorist is usually a failed experimentalist”
“An experimentalist gets the signal first and worries about why later!”




NGC1068 gamma-ray part is probably not related to the neutrinos

# NGC 1068: An Archetype of Obscured AGN

**One of the nearest (D = 10.1 Mpc) and most studied Seyfert 2**




AGN

Halo

Circumnuclear disk
~200 pc in radius

Starburst activity:
~2 kpc starburst ring

Bar connecting CND and
starburst ring

IceCube can't resolve different emission components

NASA/JPL-Caltech/Roma Tre Univ.

# NGC 1068

## Spectral Energy Distribution: "hidden" source scenario

- Intense neutrino flux;
- No equivalent γ-rays;
- X-ray bright associated to a **corona** emission.

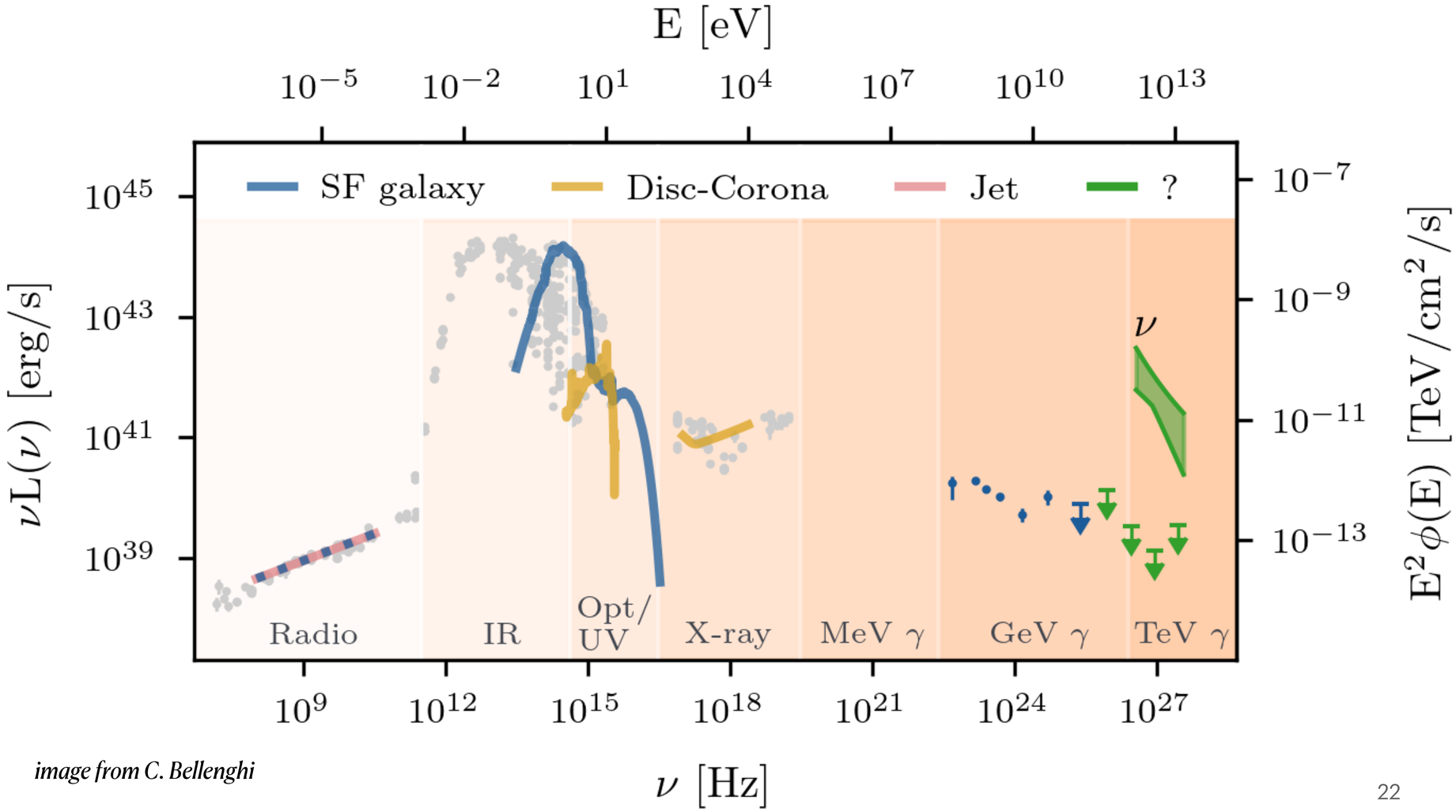
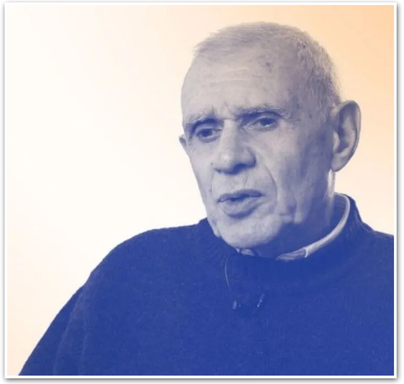


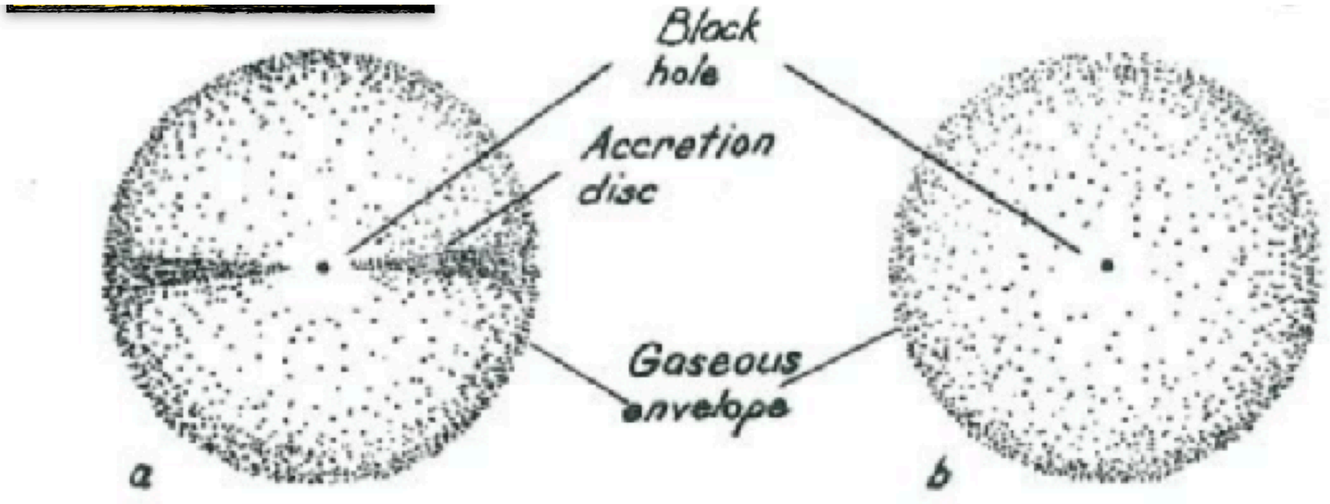

*image from C. Bellenghi*



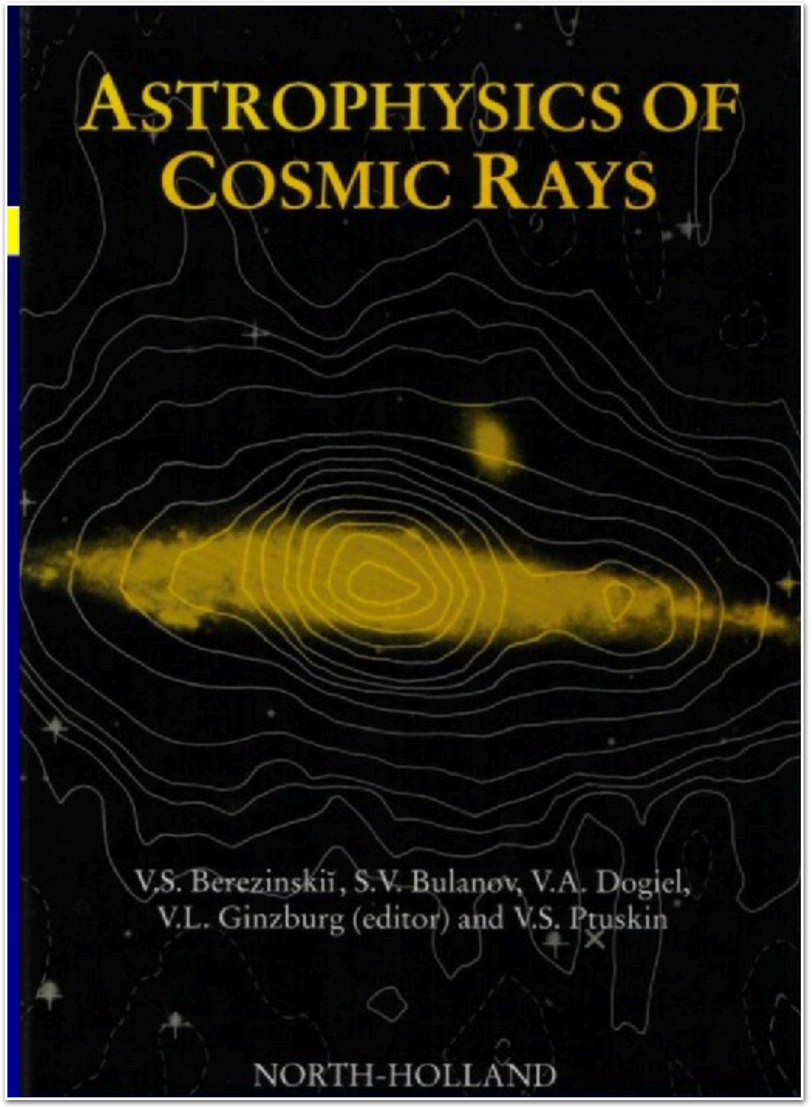
# The 'Hidden' source idea

## §9. Hidden sources

In the example of a massive black hole in a cocoon we encountered a model of a hidden source: an object which contains particles accelerated to high energies, but is not seen in high-energy electromagnetic radiation (X-ray and (or) gamma-ray radiation).




Berezinsky, Ginzburg, MNRAS 1981
Silberberg, Shapiro 1982



# NGC 1068

## Maximum neutrino power vs regions

**Table 3.** Estimated $\gamma$-ray and neutrino powers.

| Component | Scale | $L_\gamma$ (0.1 – 10 GeV) | $L_\nu$ (1.5 – 15 TeV) |
|---|---|---|---|
| Star formation | $>$ kpc | $\sim 10^{40.9}$ | $\lesssim 10^{40.1}$ |
| Jet | $\sim$ kpc | $< 10^{41.7}$ (M87-like) | $< 10^{40.9}$ |
| Outflow (UFO) | $\sim$ pc | $< 10^{41.2}$ | $< 10^{40.4}$ |
| BH vicinity | $\sim 0.03$ mpc ($\sim 50\ R_s$) | ? | ? |
| | Total | $\lesssim 10^{41.9}$ | $\ll 10^{41.1}$ |
| | Observed | $10^{40.92\pm0.03}$ | $10^{42.1\pm0.2}$ |

All powers in erg $s^{-1}$; $R_s$ is the Schwarzschild radius.

Y. Inoue et al., ***ApJL***'20; K. Murase et al., ***PRL***'20; Eichmann et al., ***Astrophys. J.*** '22

# NGC 1068

## The 'naive' scenario

<u>Step 1</u>: acceleration of protons (and electrons)

<u>Step 2</u>: p-γ (also p-p) interaction

e.g., $E_p \sim 100$ TeV

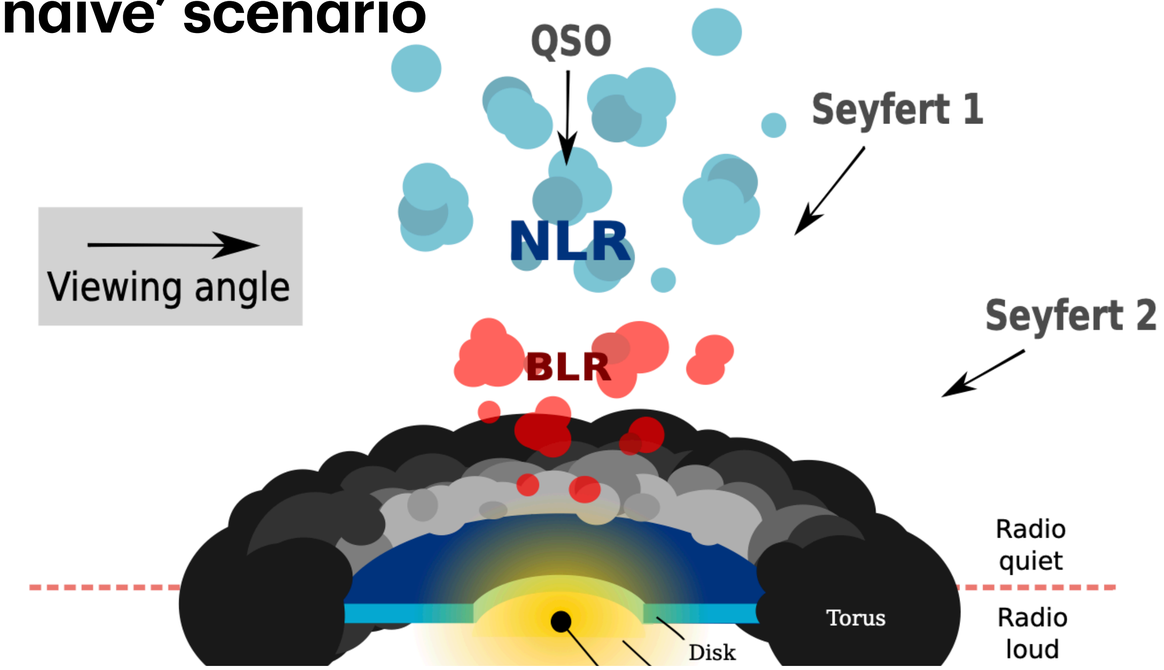
target γ ~ X-ray domain

(Corona component)

<u>Step 3</u>: mesons production

<u>Step 4</u>: γ-ray → degraded into **<u>MeV region</u>**

neutrinos stream through

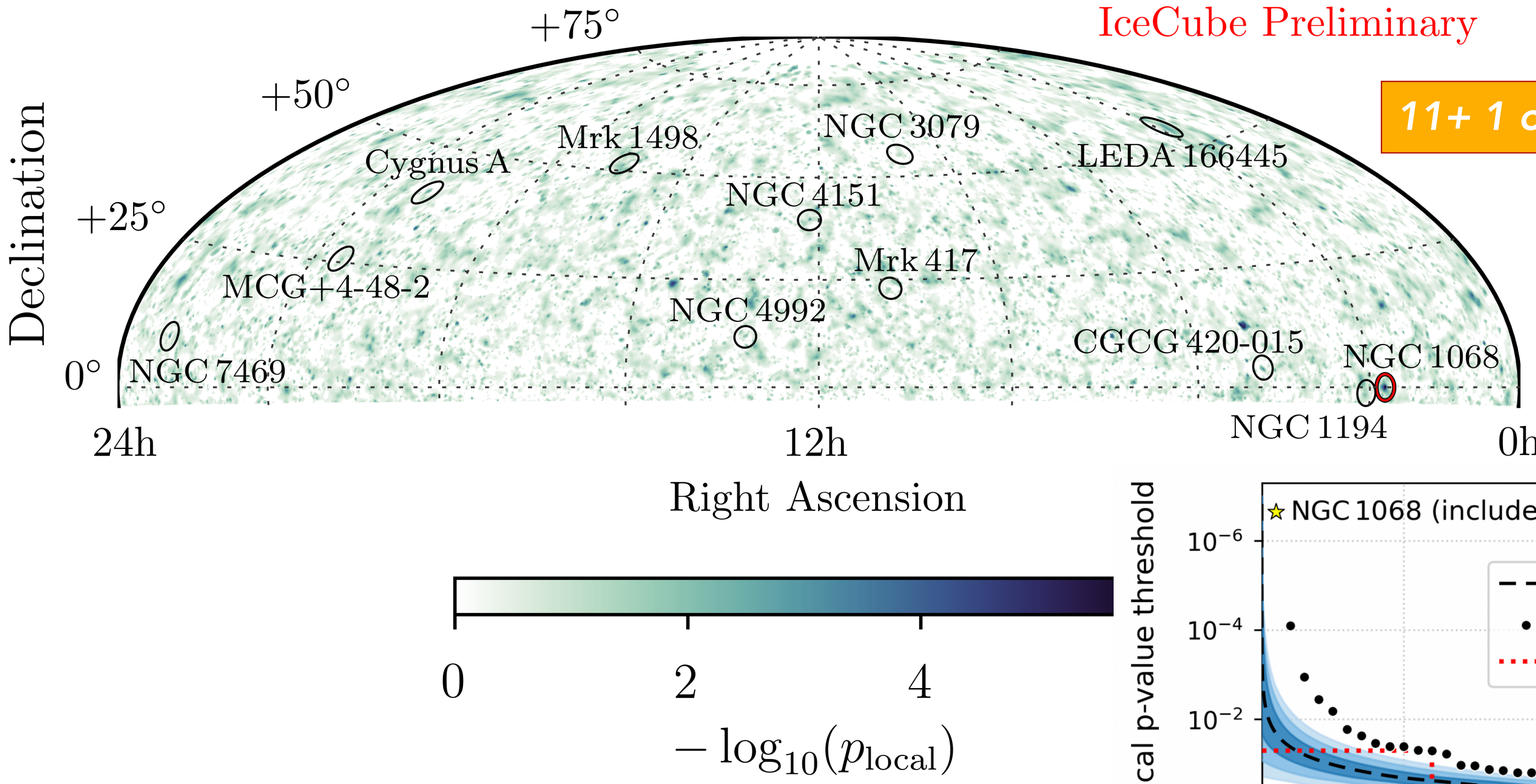



**Corona of hot electrons (X-ray)**

<u>Note</u>: the *Fermi*-LAT component most probably associated to the starburst component

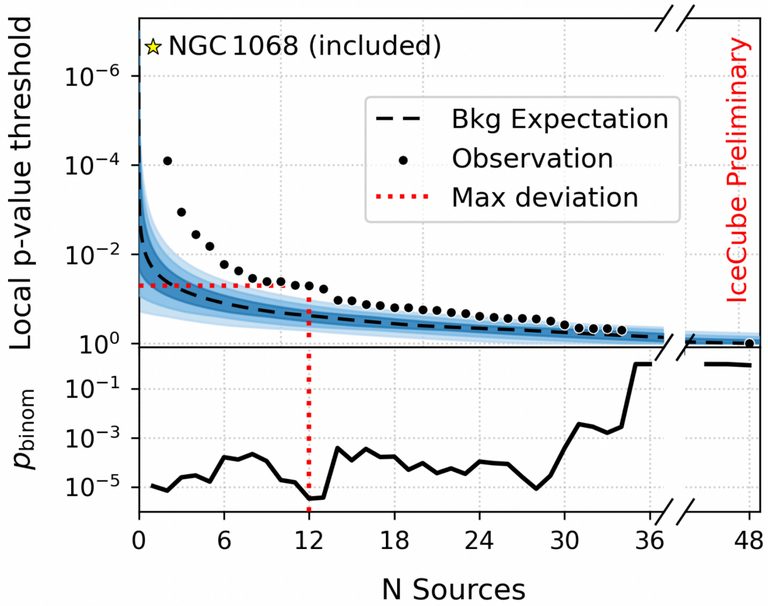
# And there are more!!

## Selected a new list of 47 X-ray bright non-jetted AGN




*11+ 1 objects emerging*

Global significance 3.3σ (NGC1068 excluded)

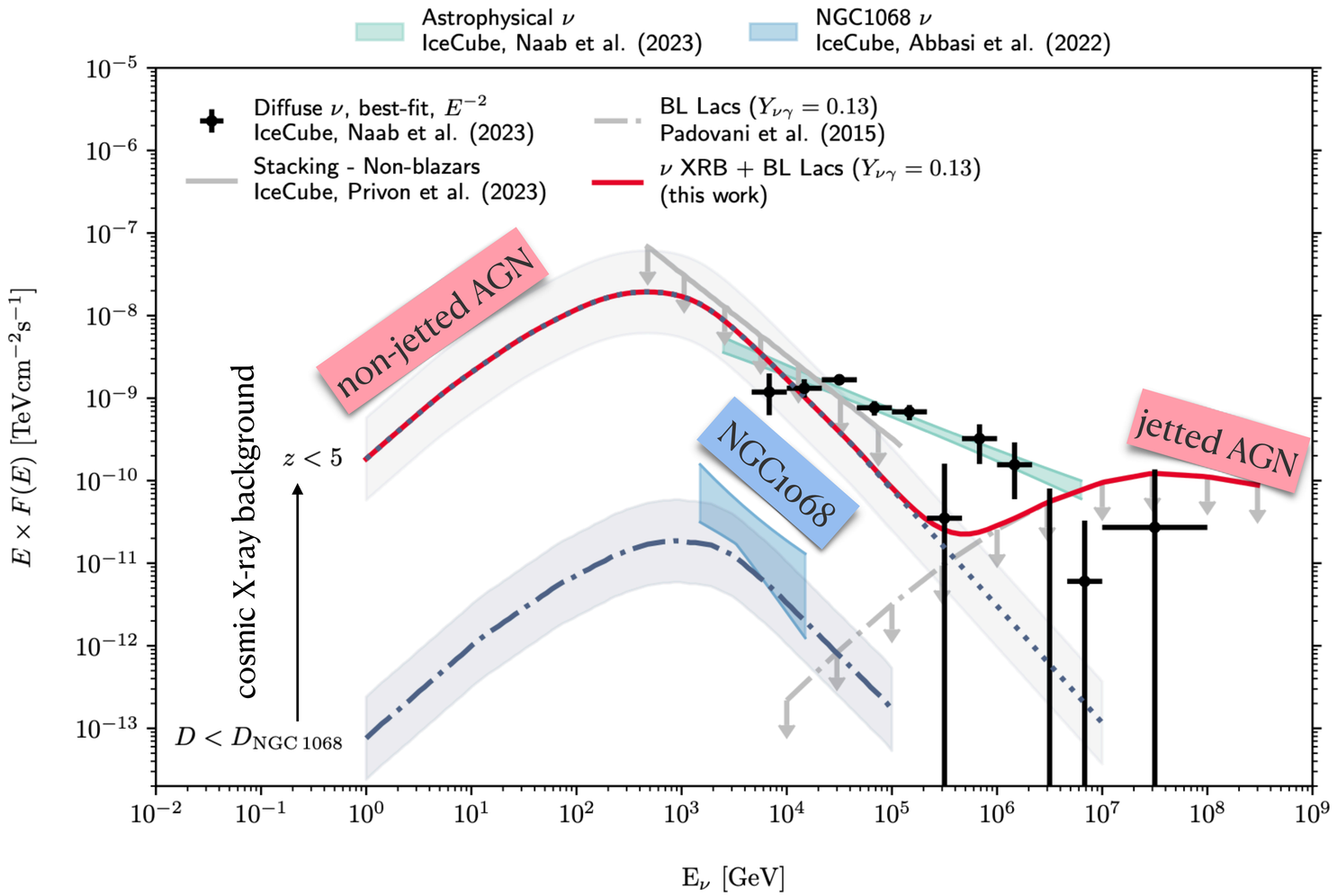


P. Padovani, R. Gilli, E. R., C. Bellenghi, and F. Henningsen, ***A&A*** L'24
P. Padovani, M. Petropoulou, P. Giommi, E. R., ***MNRAS*** '15

see also
A. Neronov et al., ***PRL*** '24
B. A. Ambrosone, ***JCAP***'24

# Can AGN explain the IceCube diffuse?

**maybe**




To be updated soon including recent IceCube results

# Conclusions

1. **AGNs as Neutrino Sources:** emerging evidence from IceCube for
    - jetted (UHE neutrinos, rare, variable) and
    - non-jetted (lower energy neutrinos, numerous, steady) AGNs
2. **Jetted AGN** (Blazars): when all processes included, emerging one-zone model
3. **Non-jetted AGN:** obscured / heavily absorbed objets; condition needed to provide target for neutrino production. ‘Hidden’ source idea originally from Venya emerging.

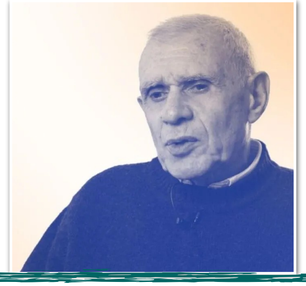
**Question remains: where are the source of cosmic rays?**

# Conclusions

1. **AGNs as Neutrino Sources:** emerging evidence from IceCube for
    - jetted (UHE neutrinos, rare, variable) and
    - non-jetted (lower energy neutrinos, numerous, steady) AGNs
2. **Jetted AGN** (Blazars): when all processes included, emerging one-zone model
3. **Non-jetted AGN:** obscured / heavily absorbed objets; condition needed to provide target for neutrino production. ‘Hidden’ source idea originally from Venya emerging.

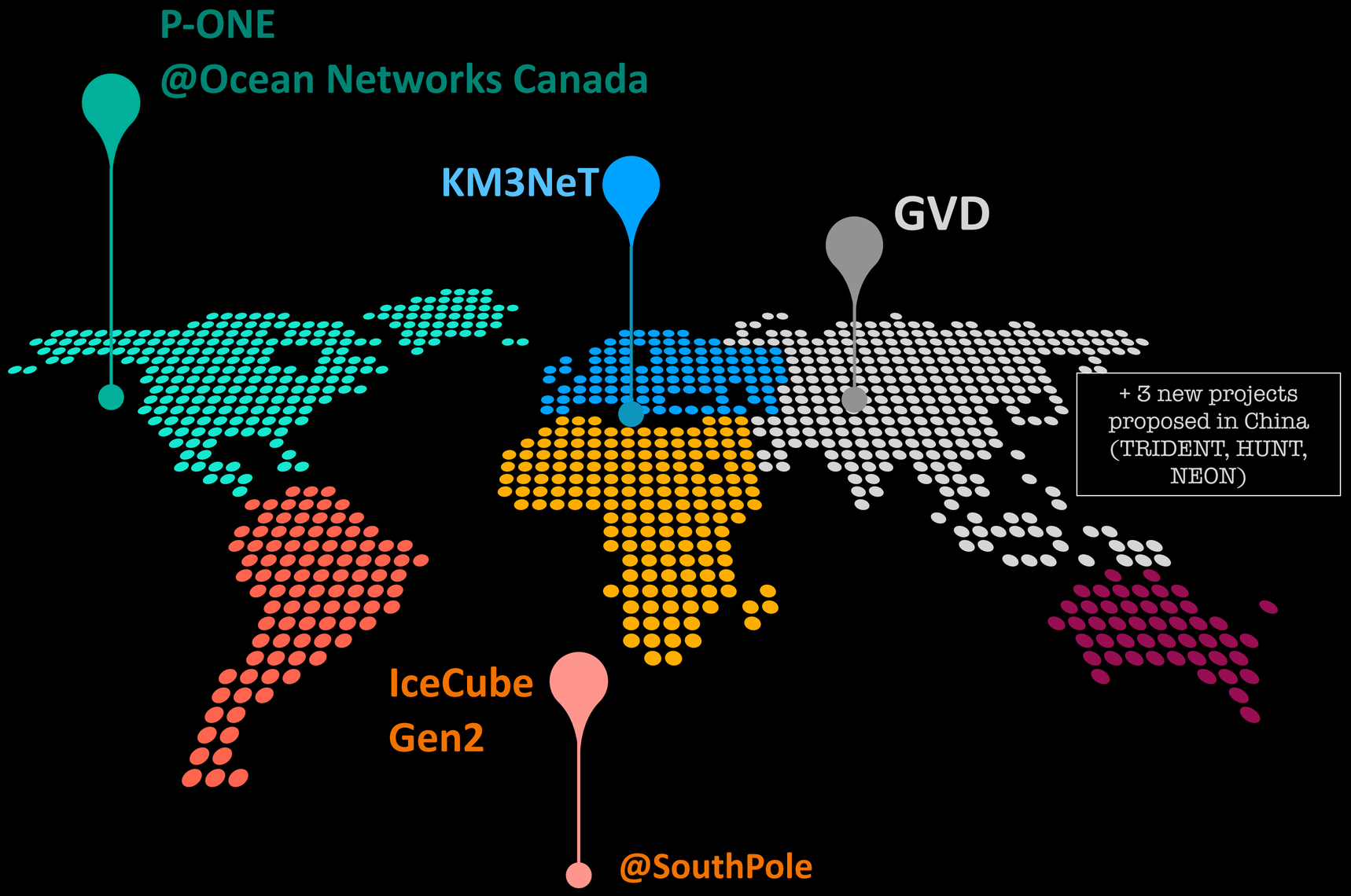
Proposal: name

**Berezinsky galaxies: non-jetted AGN with neutrino association -**



Extra

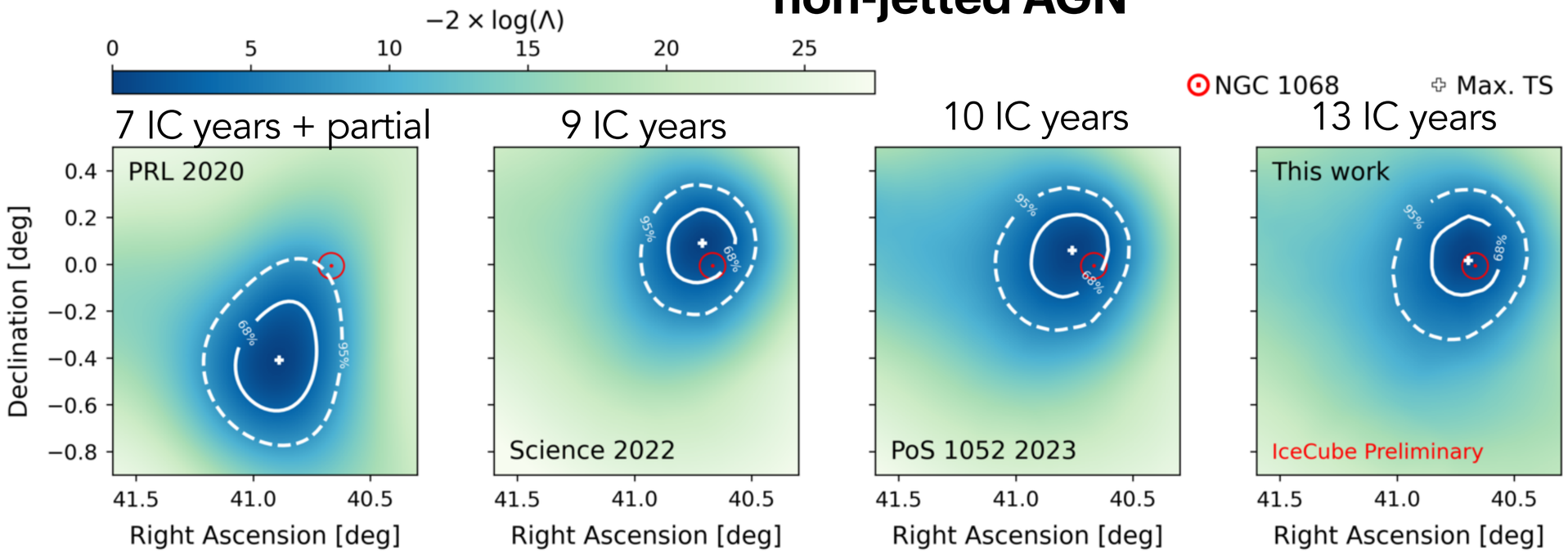
# Next-generation neutrino telescopes essential



The IceCube Coll., ***Science*** 378 (2022)
The IceCube Coll., ***preliminary***

# Status of neutrino observations

## non-jetted AGN



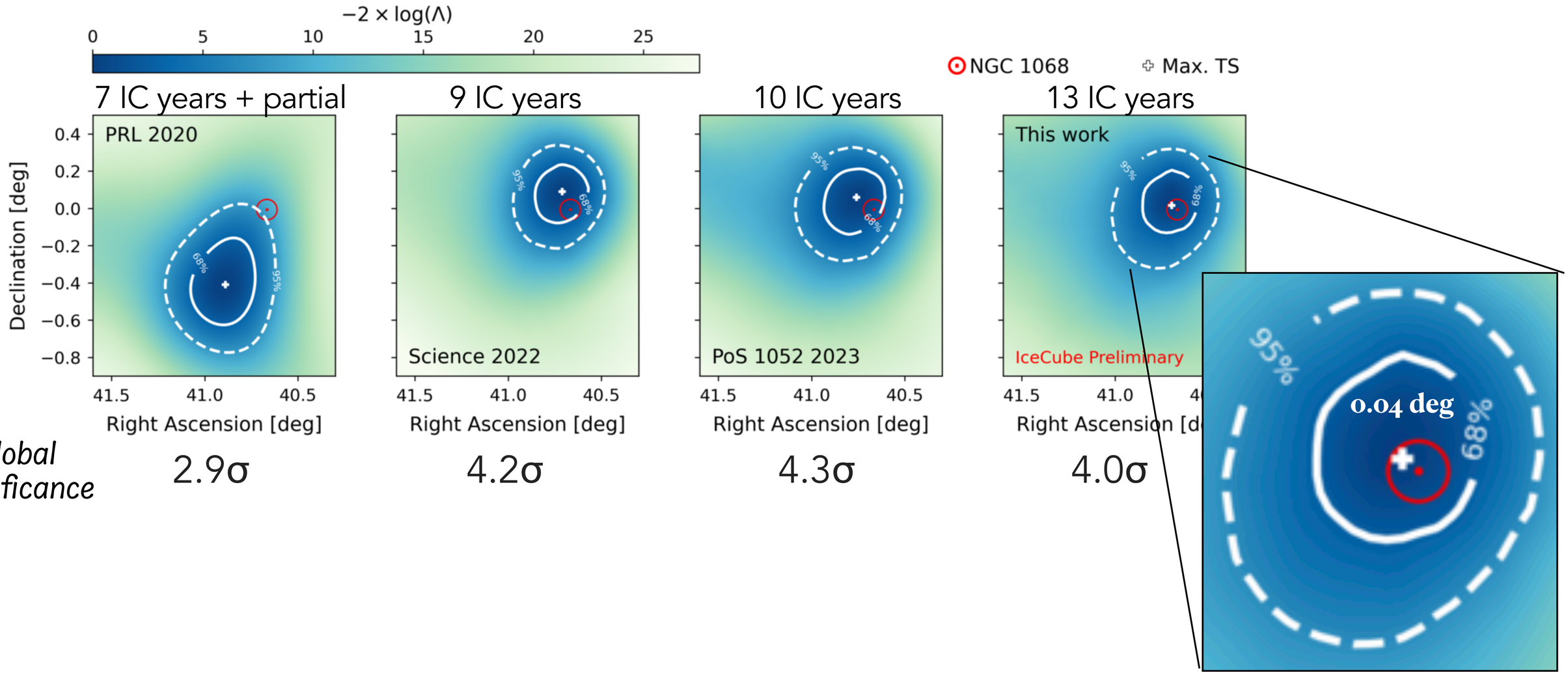

*Global significance*

2.9σ | 4.2σ | 4.3σ | 4.0σ

| Spectral hypothesis | R.A. | Dec. | $\hat{n}_s$ | $\hat{\gamma}$ | Local significance |
|---|---|---|---|---|---|
| Floating $\gamma$ | 40.69° | 0.02° | 102.6 | 3.4 | $5.0\,\sigma$ |
| $\gamma = 2.0$ | 77.01° | 12.98° | 16.8 | – | $4.9\,\sigma$ |
| $\gamma = 2.5$ | 161.48° | 27.32° | 34.3 | – | $4.5\,\sigma$ |

# From 9 years to 13 years of IceCube exposure

The IceCube Coll., ***preliminary***




*Global significance*

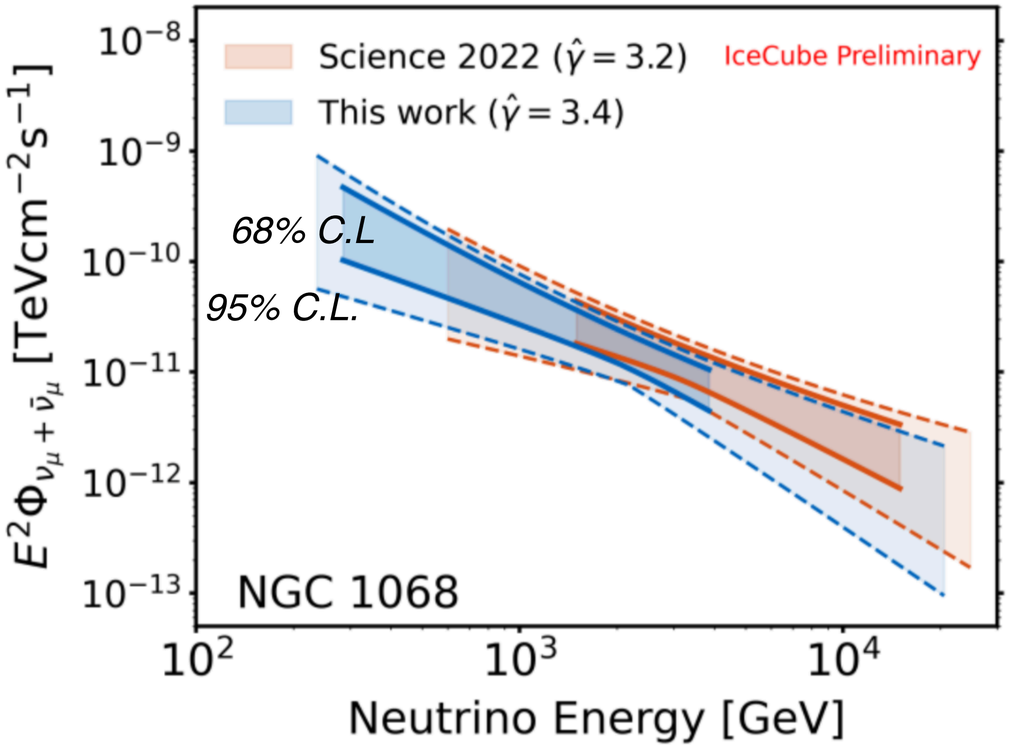
2.9σ | 4.2σ | 4.3σ | 4.0σ

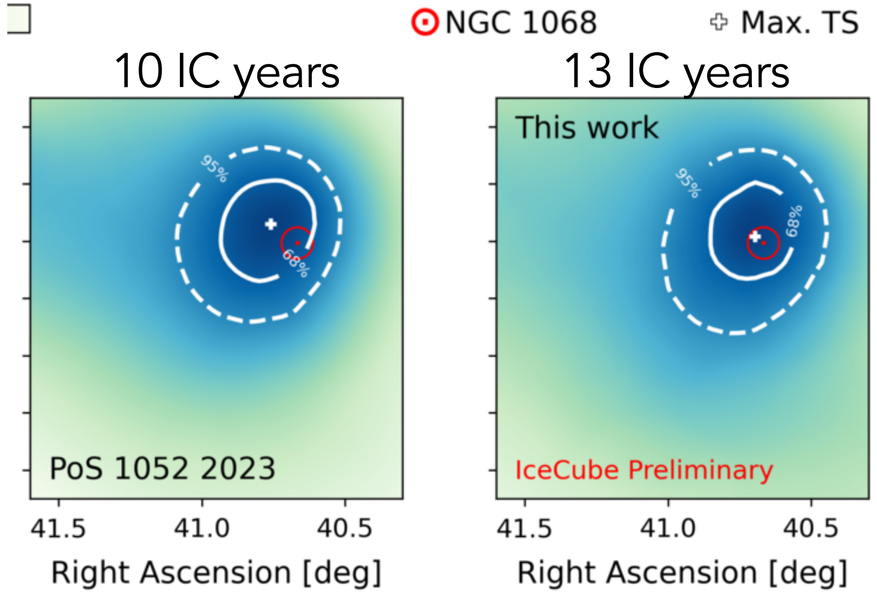


33

# From 9 years to 13 years of IceCube exposure

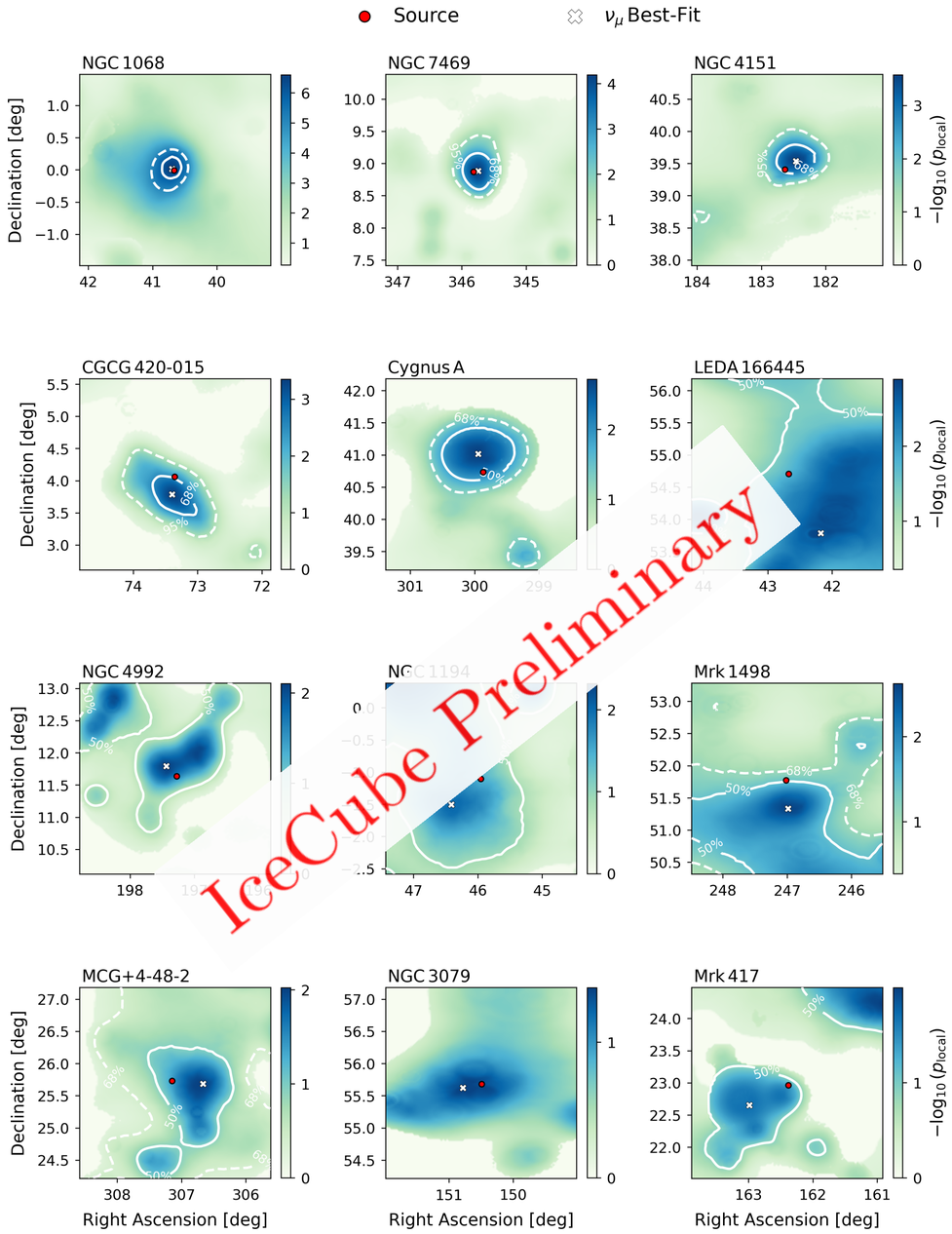
The IceCube Coll., ***preliminary***




4.3σ 4.0σ

| Spectral hypothesis | R.A. | Dec. | $\hat{n}_s$ | $\hat{\gamma}$ | Local significance |
|---|---|---|---|---|---|
| Floating $\gamma$ | 40.69° | 0.02° | 102.6 | 3.4 | $5.0\,\sigma$ |
| $\gamma = 2.0$ | 77.01° | 12.98° | 16.8 | – | $4.9\,\sigma$ |
| $\gamma = 2.5$ | 161.48° | 27.32° | 34.3 | – | $4.5\,\sigma$ |




*11+ 1 objects emerging*

# The Corona

see e.g., A.C. Fabian et al., MNRAS '15

- *NGC1068 X-ray Emission: Arises from scattered emission along our line of sight.*
- *Rapid X-ray Variability (2–10 keV): Implies a compact corona near the SMBH.*
- *Anisotropic Coronae: Influenced by corona position, black hole spin, and disc inclination.*

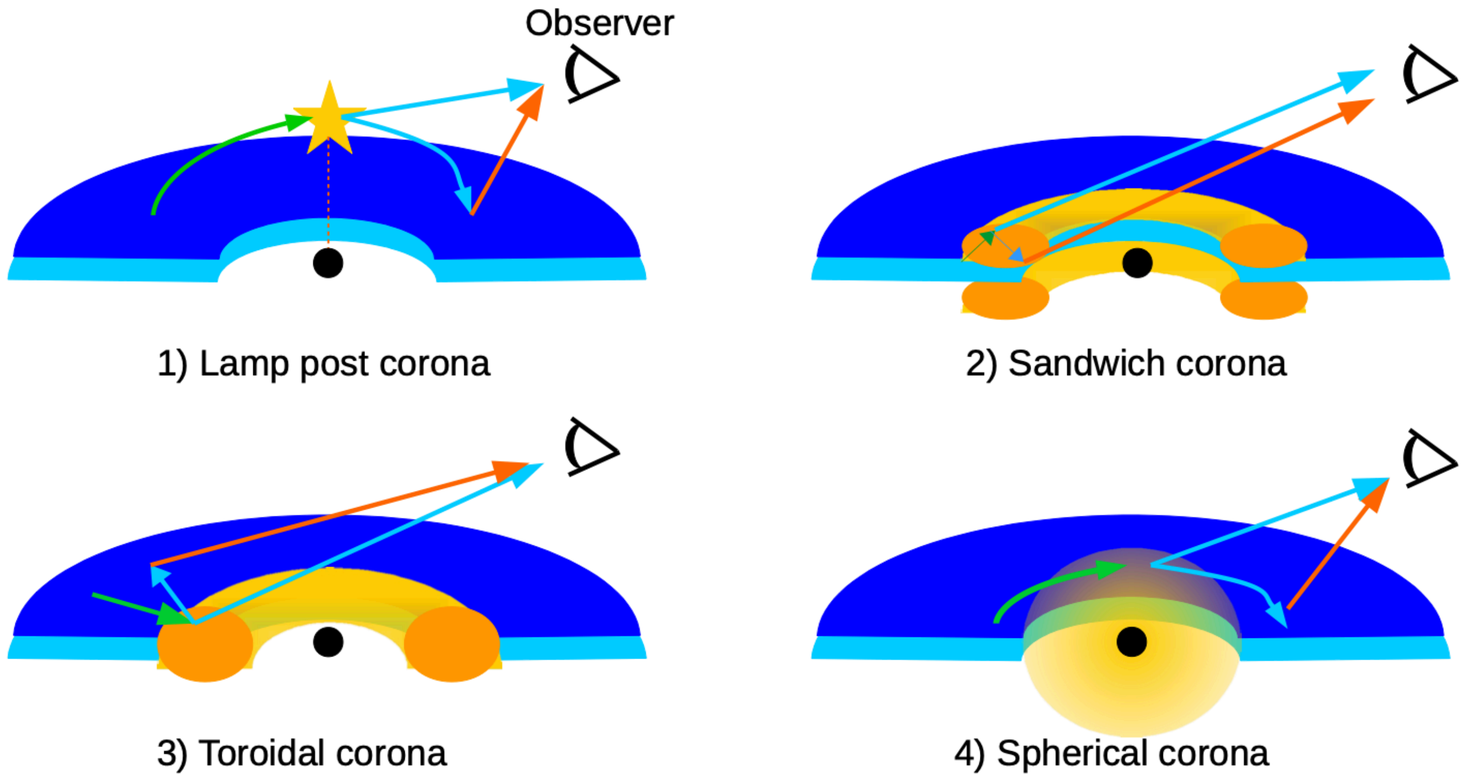



*image from L. Baronchelli*

# The Corona

see e.g., A.C. Fabian et al., MNRAS '15

- *NGC1068 X-ray Emission: Arises from scattered emission along our line of sight.*
- *Rapid X-ray Variability (2–10 keV): Implies a compact corona near the SMBH.*
- *Anisotropic Coronae: Influenced by corona position, black hole spin, and disc inclination.*
- *Coronae Placement: Many of the coronae are positioned within regions where*

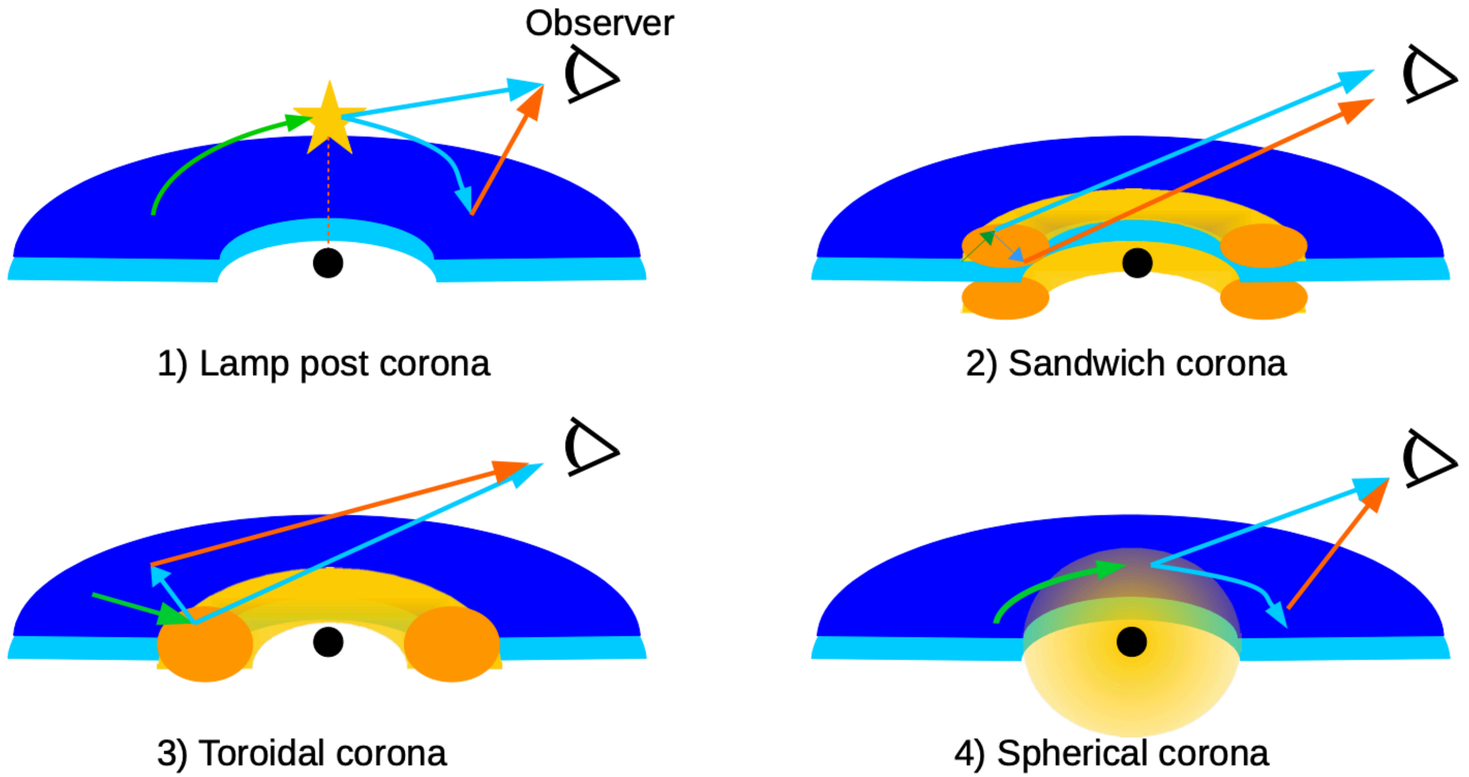



*image from L. Baronchelli*

➡ *General Relativistic Effects might play Crucial Roles. Strong gravity regime.*

see Tomas Kontrimas for IceCube, TeVPA 2024

# Seyfert related studies within IceCube

## The emergence of a population of sources?

- 2022: Evidence of neutrino emission from NGC 1068 (Science)
- 2024: IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies (**Northern sky**)
  - $2.7\,\sigma$ binomial excess from 2 sources: NGC 4151 and CGCG 420-015

arXiv:2406.07601

- 2024: ESTES **Southern Sky** Seyfert Search
  - $3.0\,\sigma$ from stacking 13 Southern Seyfert galaxies.

TeVPA, Tue 14:40

- 2024: Search for neutrino emission from **hard X-ray** AGN with IceCube
  - $2.9\,\sigma$ from NGC 4151

arXiv:2406.06684

- **This work**: $3.3\,\sigma$ **binomial excess for 11 sources** from an updated list of X-ray bright Seyfert Galaxies