A breakthrough in progress

Active Galactic Nuclei as Counterparts of IceCube Neutrinos

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Bundesministerium für Bildung und Forschung
European Research Council
MAX-PLANCK-GESELLSCHAFT
B 1258 Neutrinos Dark Matter Messengers
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;

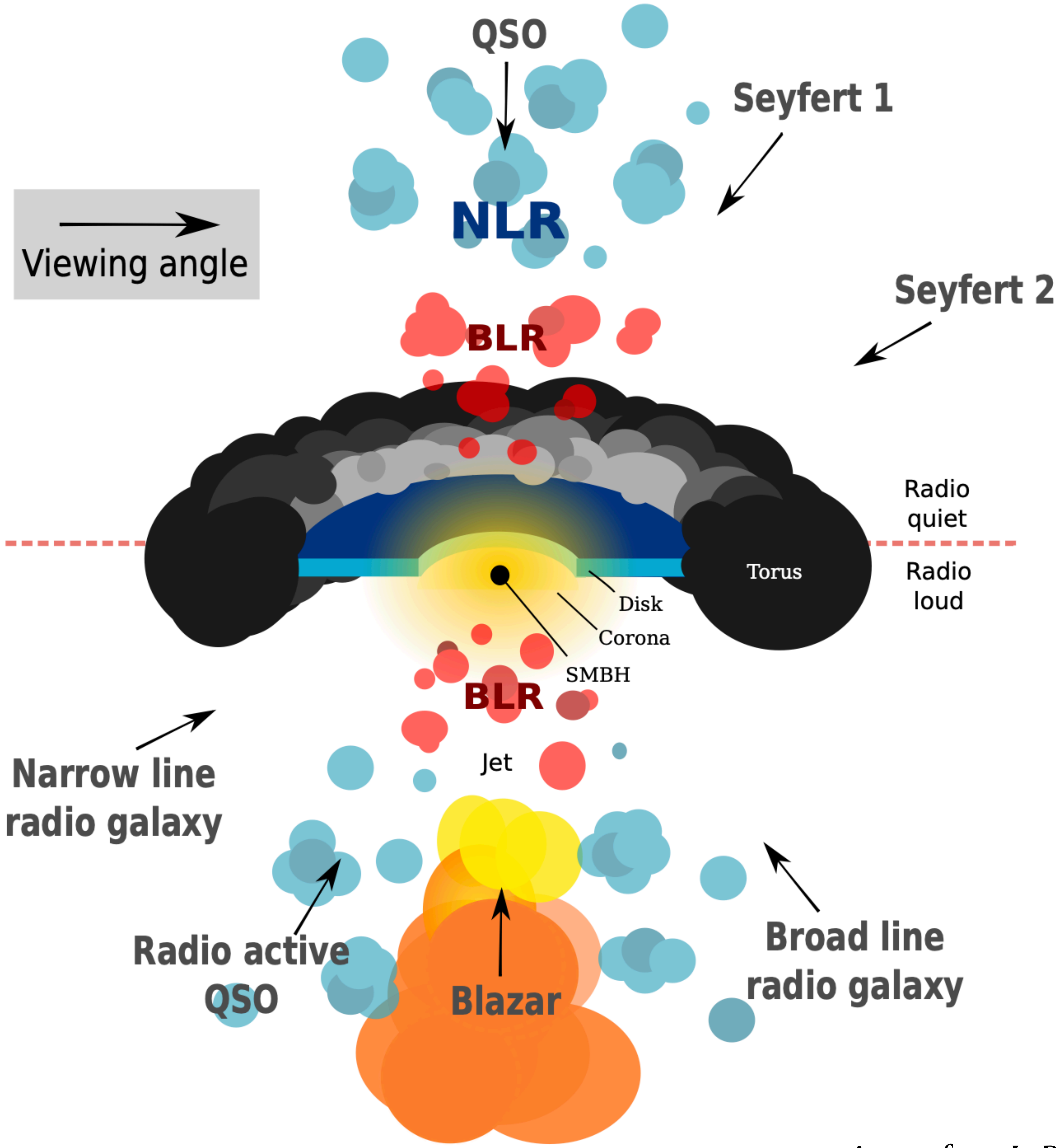
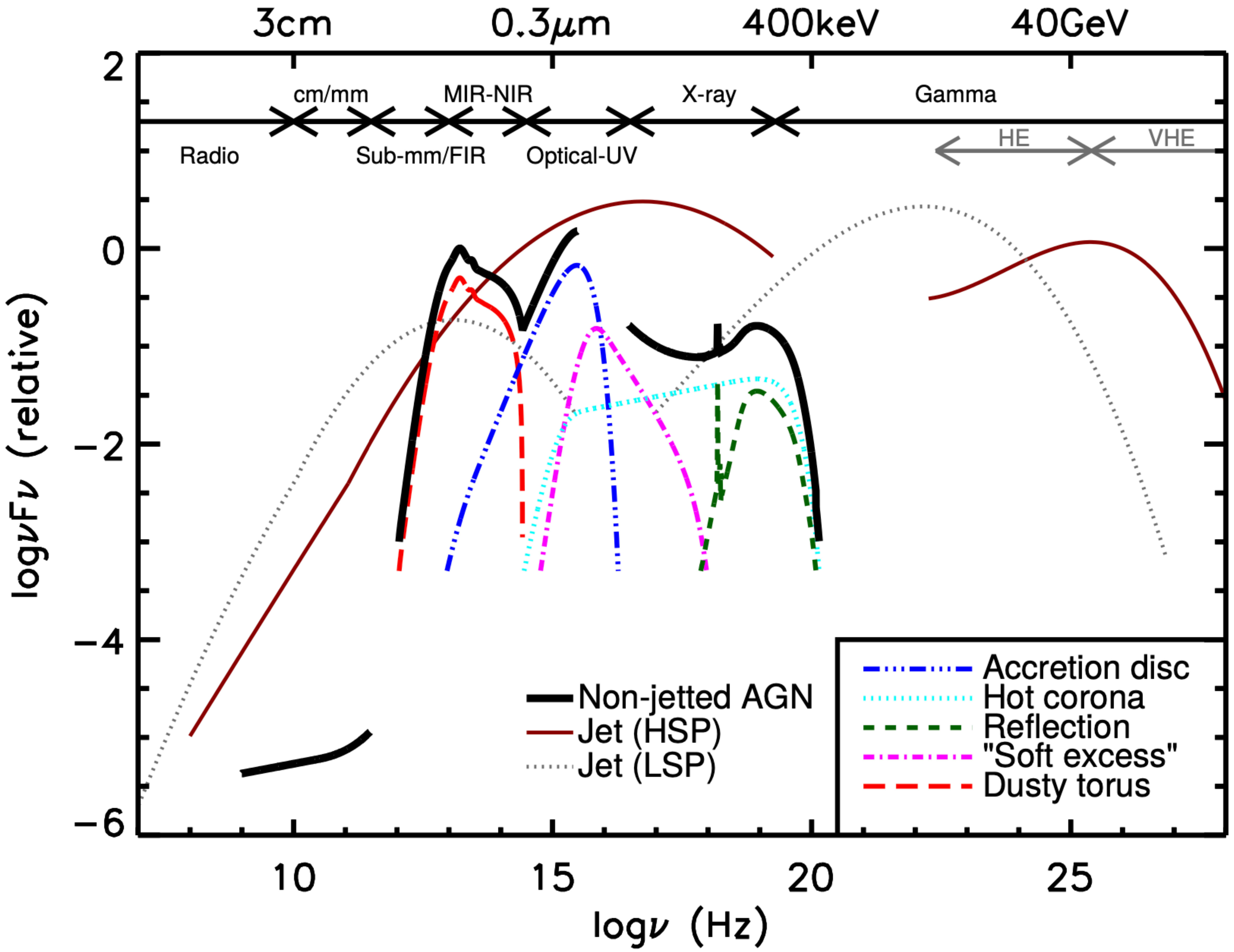


image from L. Baronchelli

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



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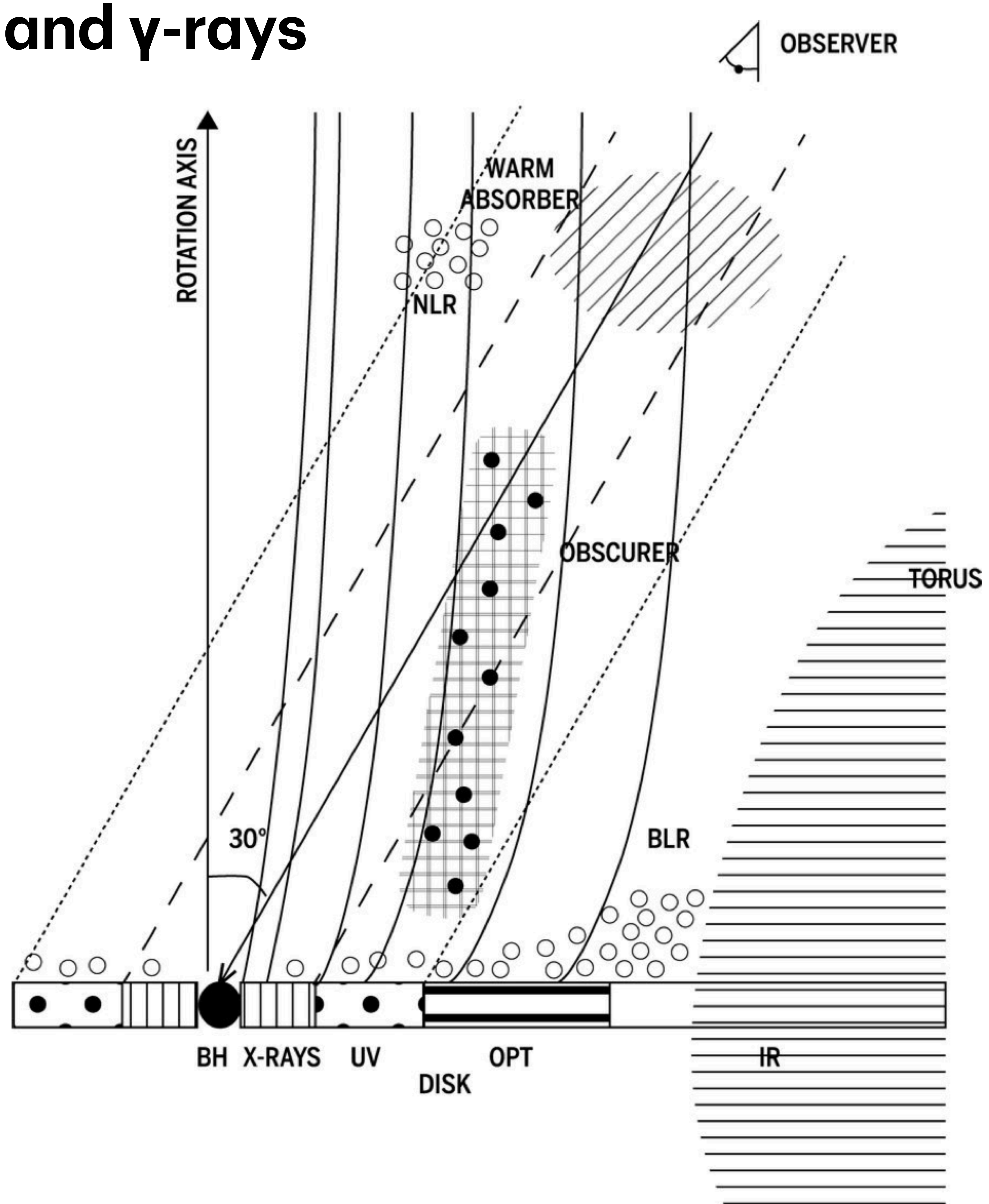
Active Galactic Nuclei

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

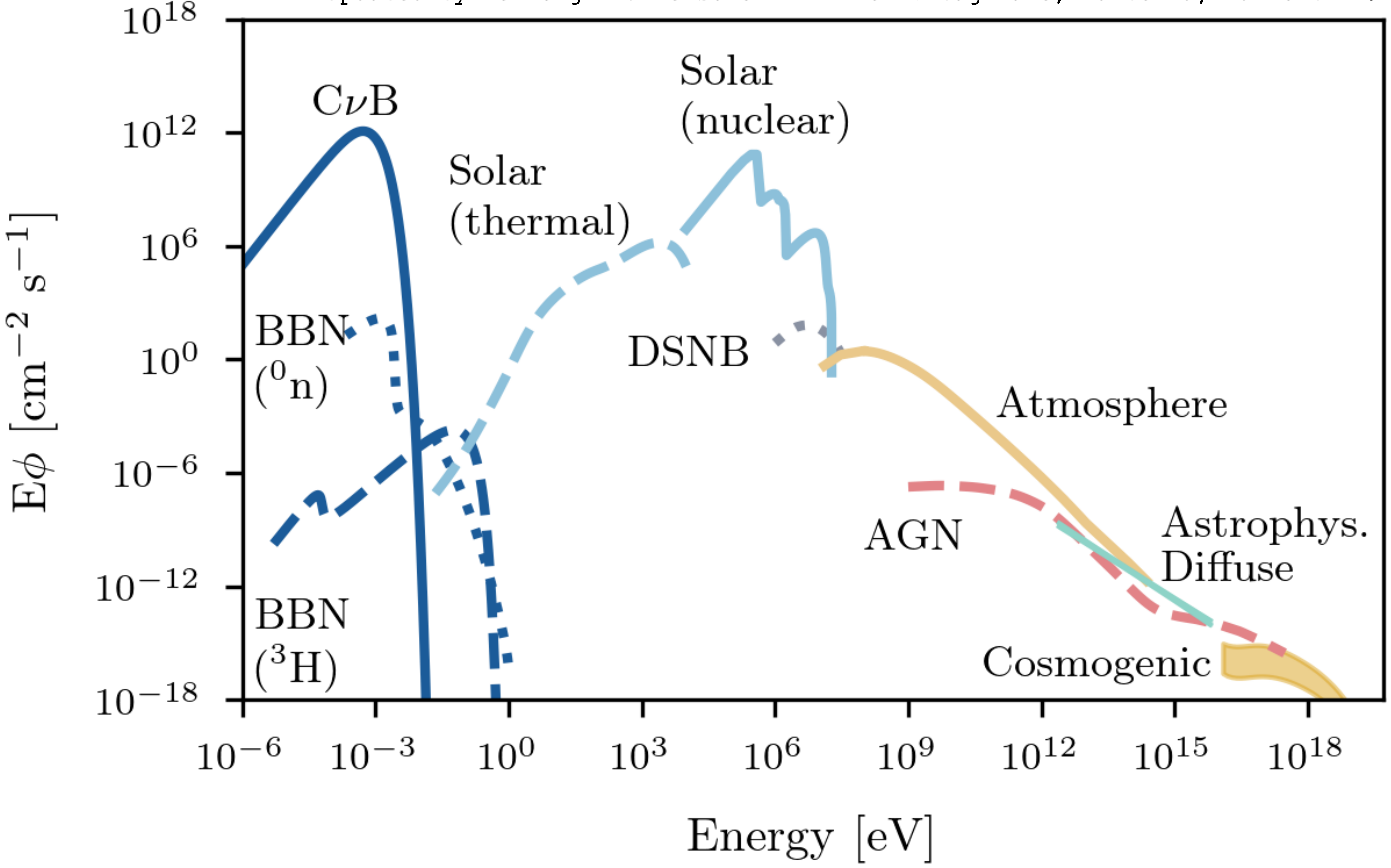
open questions

- **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

updated by Bellenghi & Kerscher '24 from Vitagliano, Tamborra, Raffelt '19



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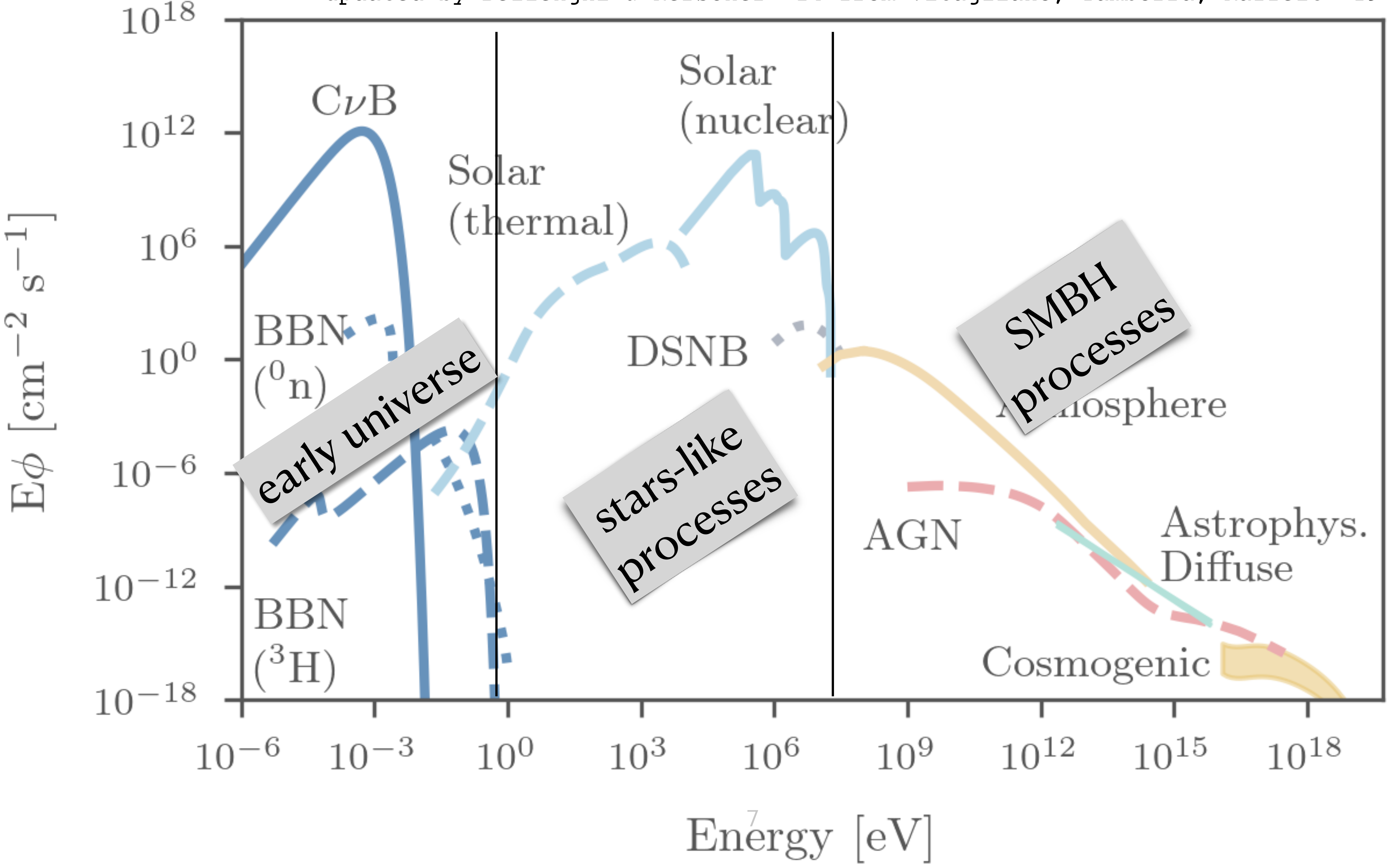


see **E. Yildizci** talk, this conference

Status of neutrino observations

The IceCube Neutrino Observatory

Two topological channels

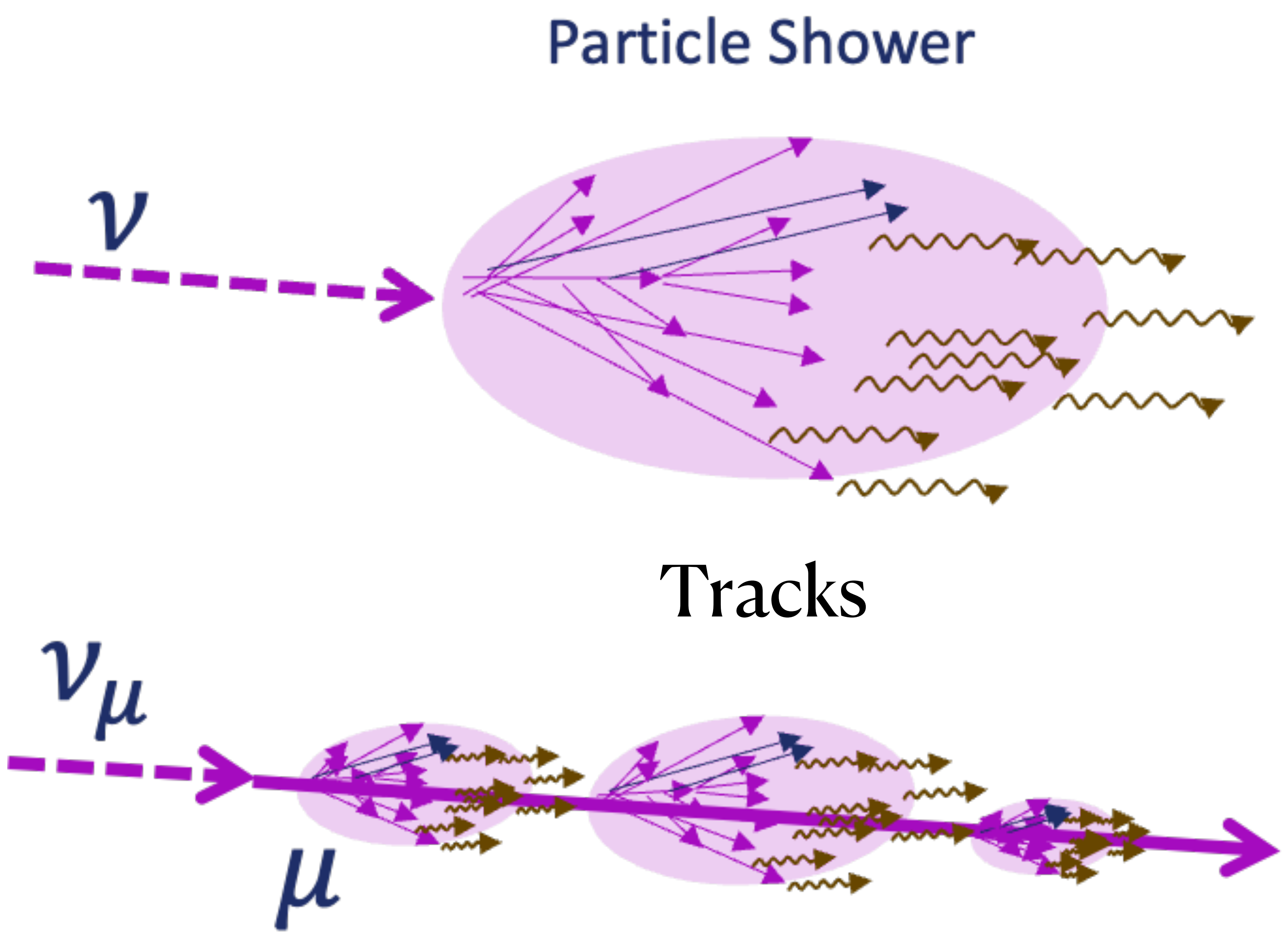
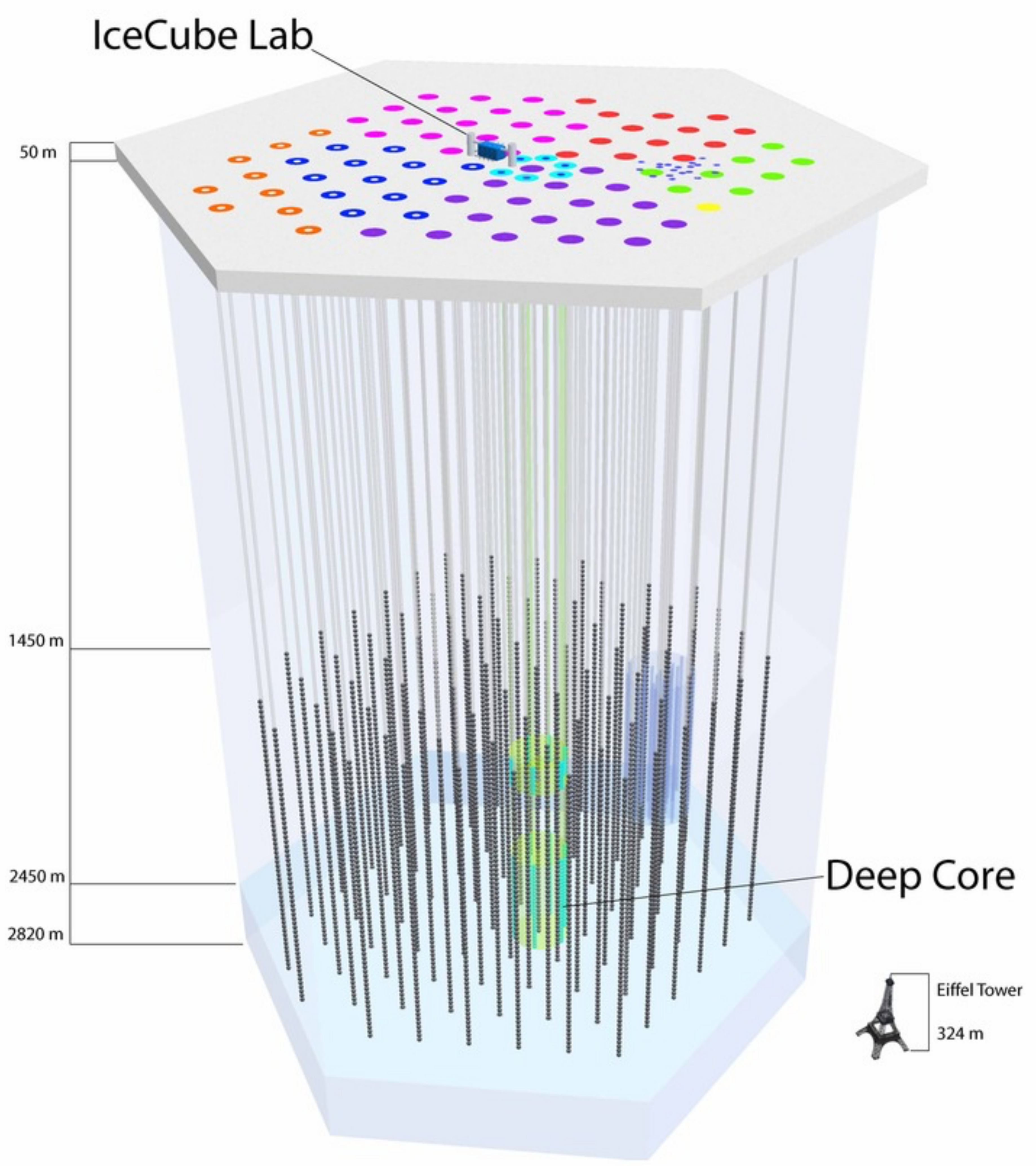


image from C. Haack



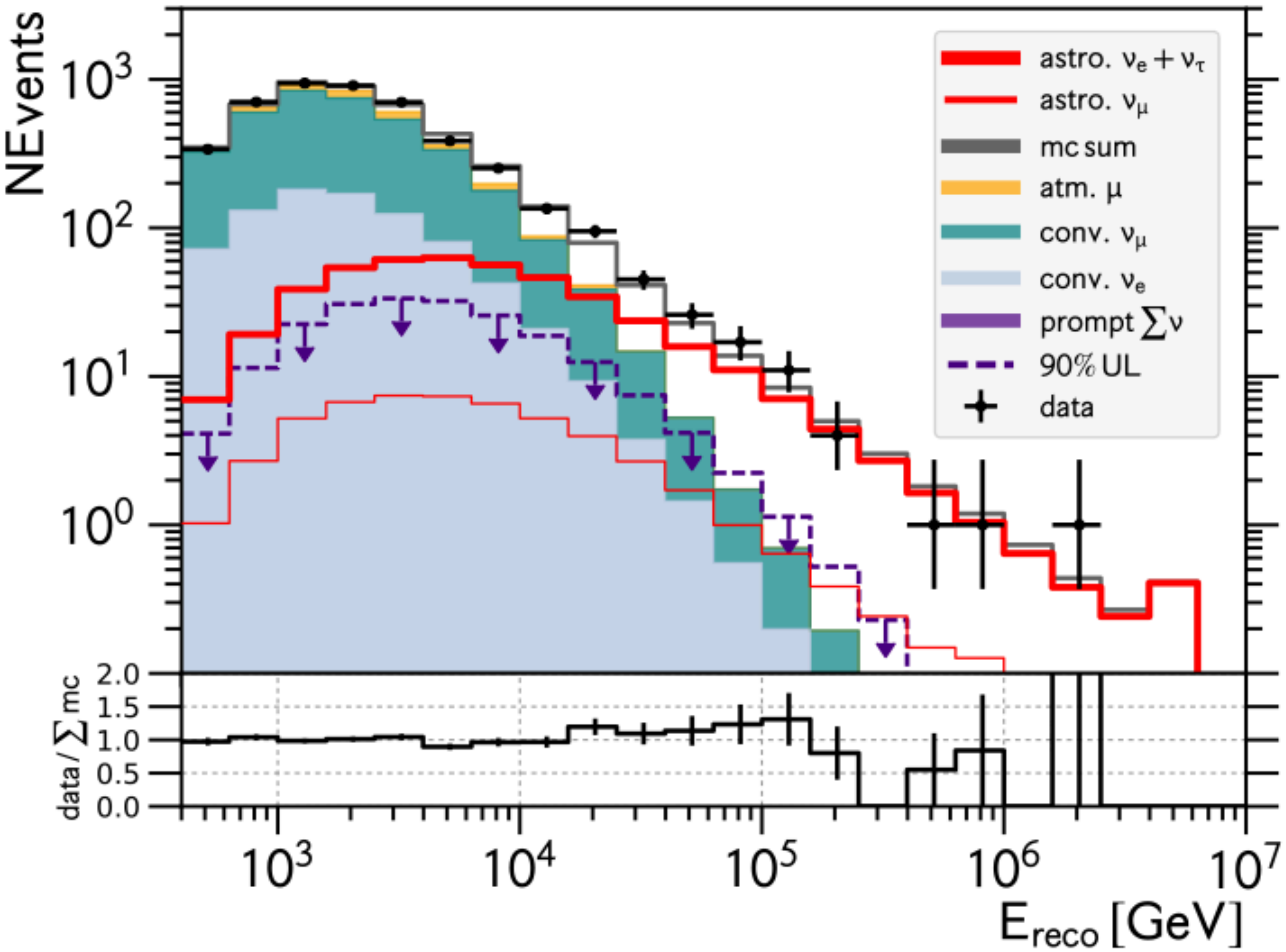
The IceCube Coll., ***PRL*** '20. The IceCube Coll., ***ApJ*** '22
The IceCube Coll., ***Nature*** '21

Status of neutrino observations

Finding astrophysical neutrinos

see **Z. Rechav** talk, this conference
see **Lu Lu** talk, this conference

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

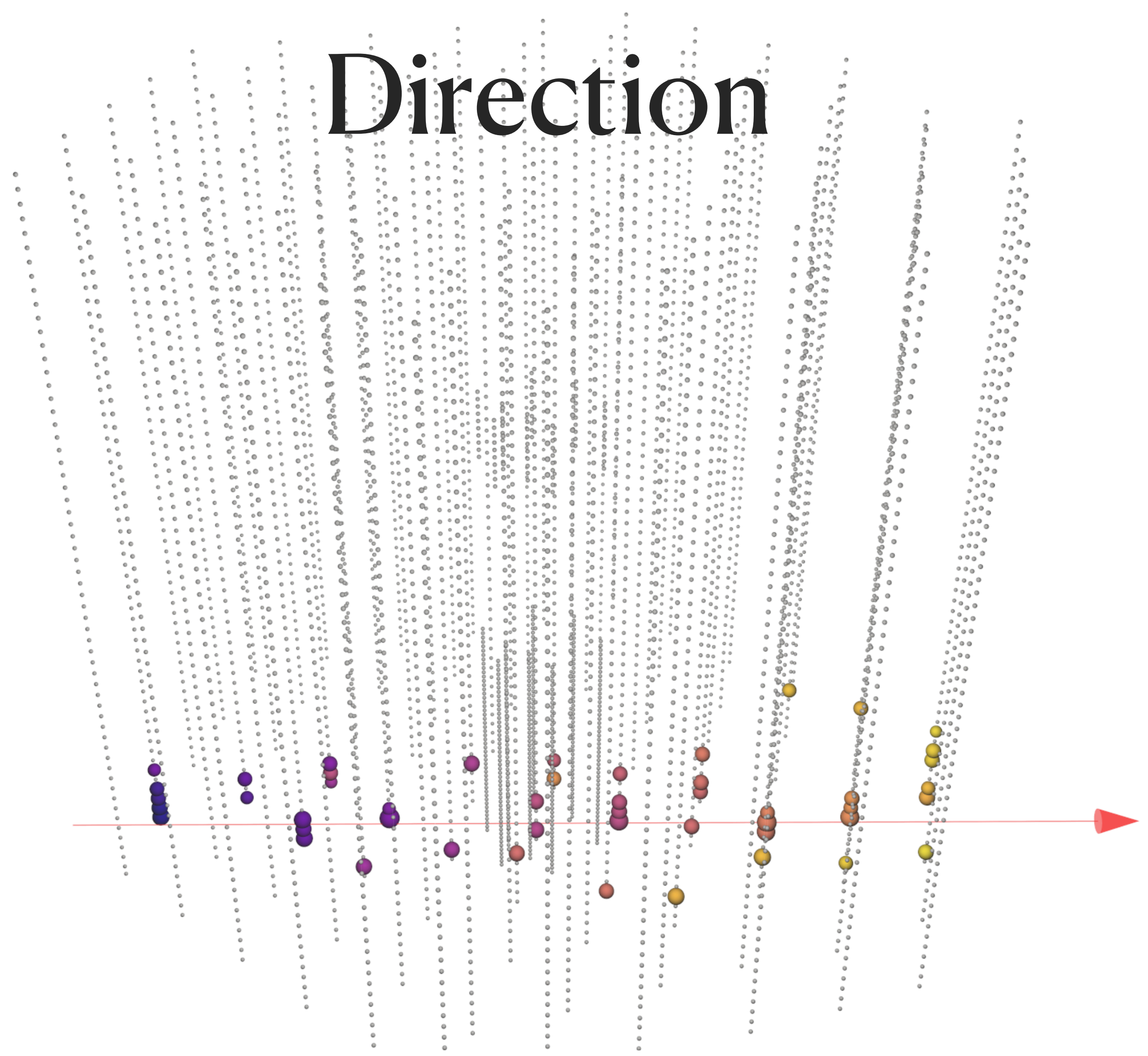


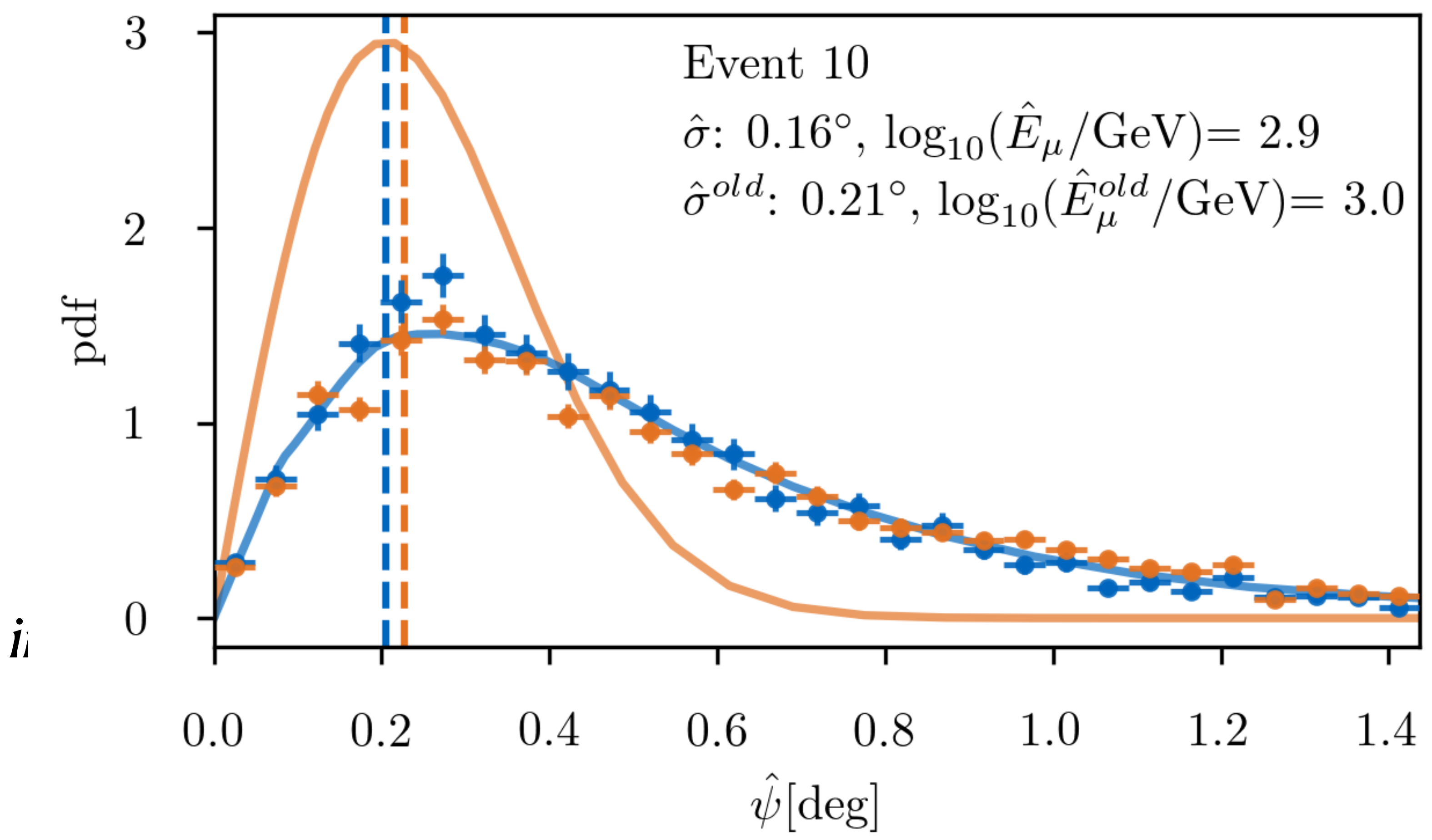
Status of neutrino observations

Finding astrophysical neutrino sources

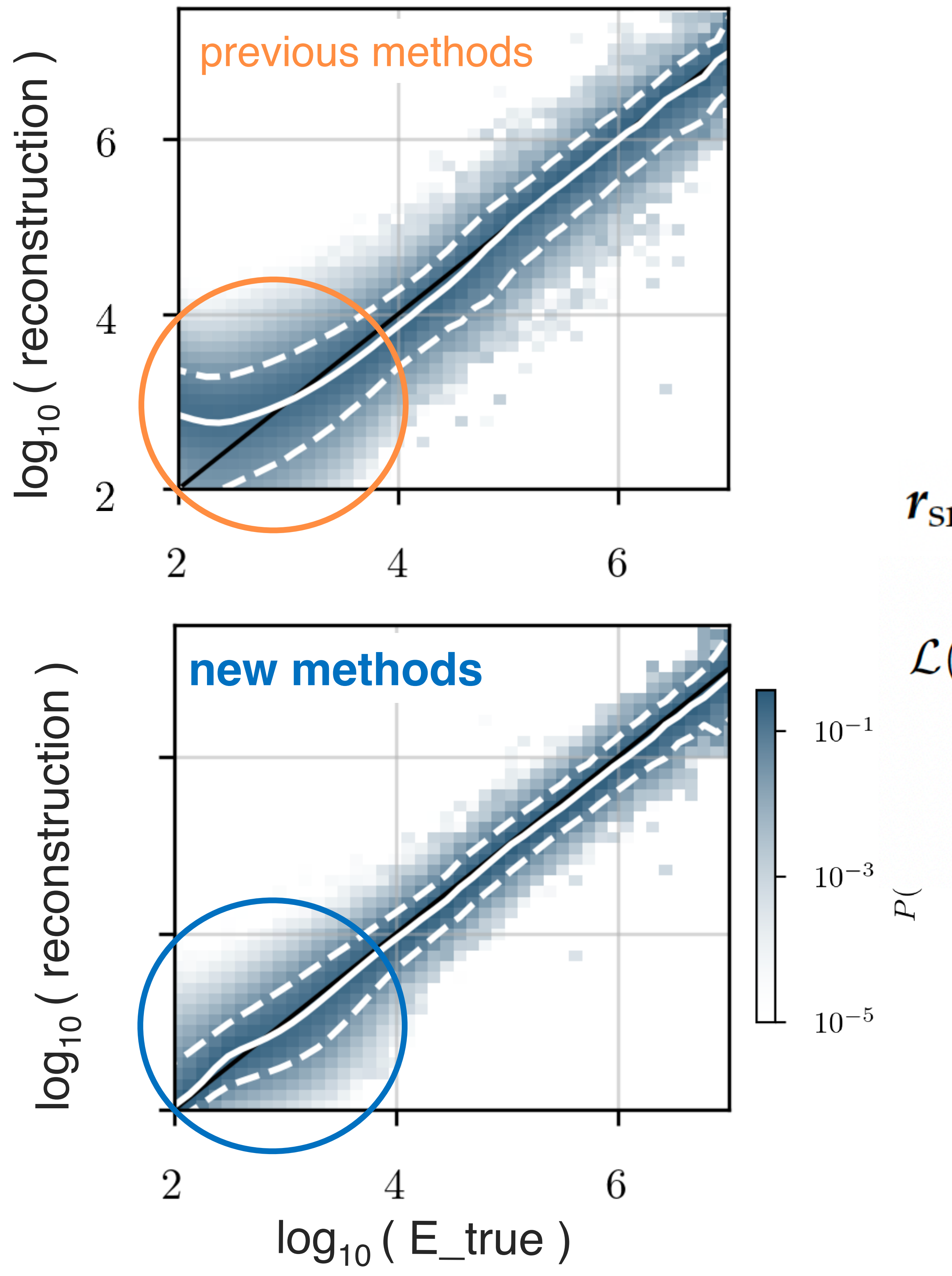
A

Direction





Energy



Method

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

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

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

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

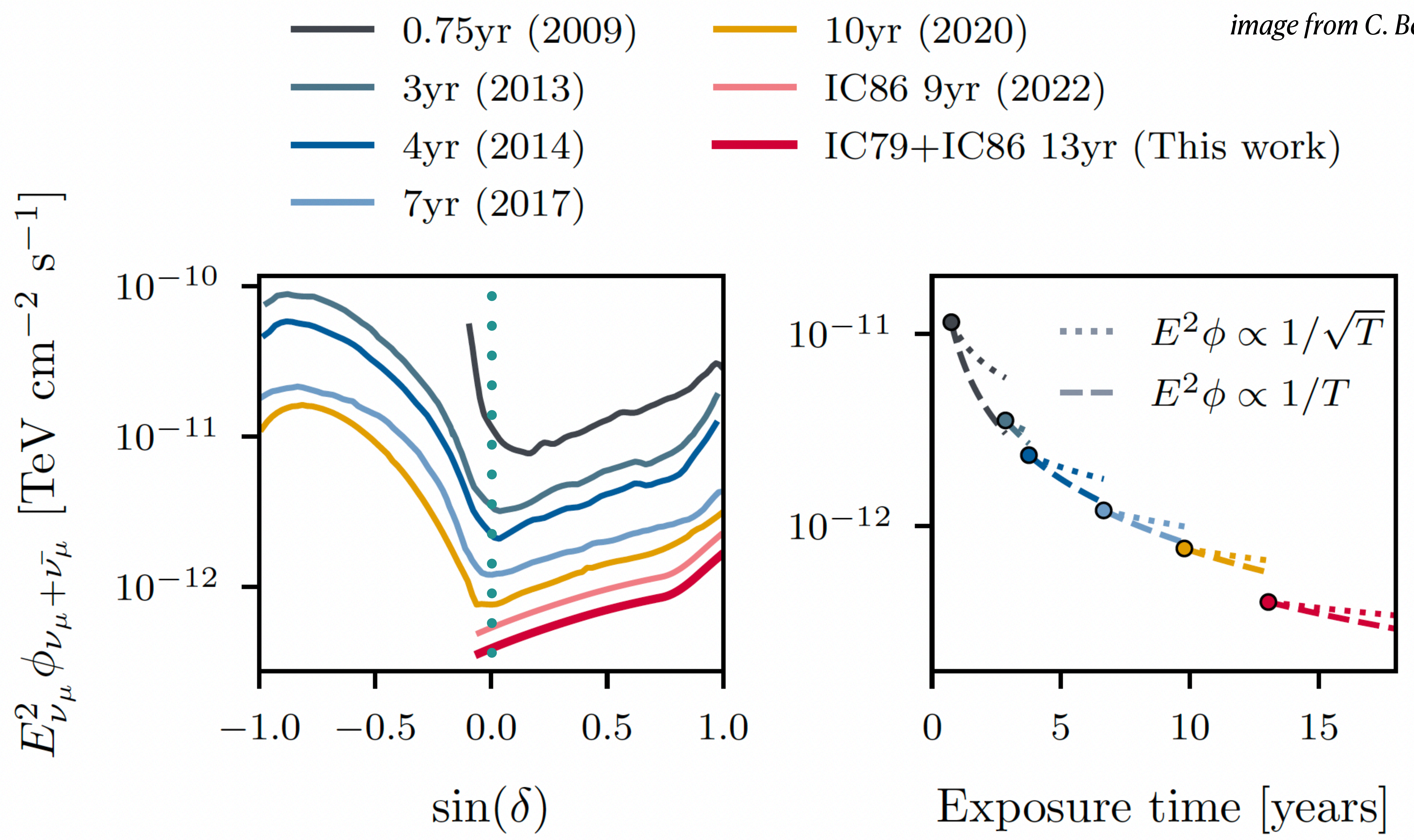
$$\mathcal{L}(\boldsymbol{\theta}|\boldsymbol{x}) = \frac{(n_\mathrm{s}+n_\mathrm{b})^N}{N!} e^{-(n_\mathrm{s}+n_\mathrm{b})} \times \prod_i^N \left\{ \frac{n_\mathrm{s}}{n_\mathrm{s}+n_\mathrm{b}} f_\mathrm{s}(x_i|\boldsymbol{\theta}_\mathrm{s}) + \frac{n_\mathrm{b}}{n_\mathrm{s}+n_\mathrm{b}} f_\mathrm{b}(x_i|\boldsymbol{\theta}_\mathrm{b})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

Status of neutrino observations

ν_μ

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

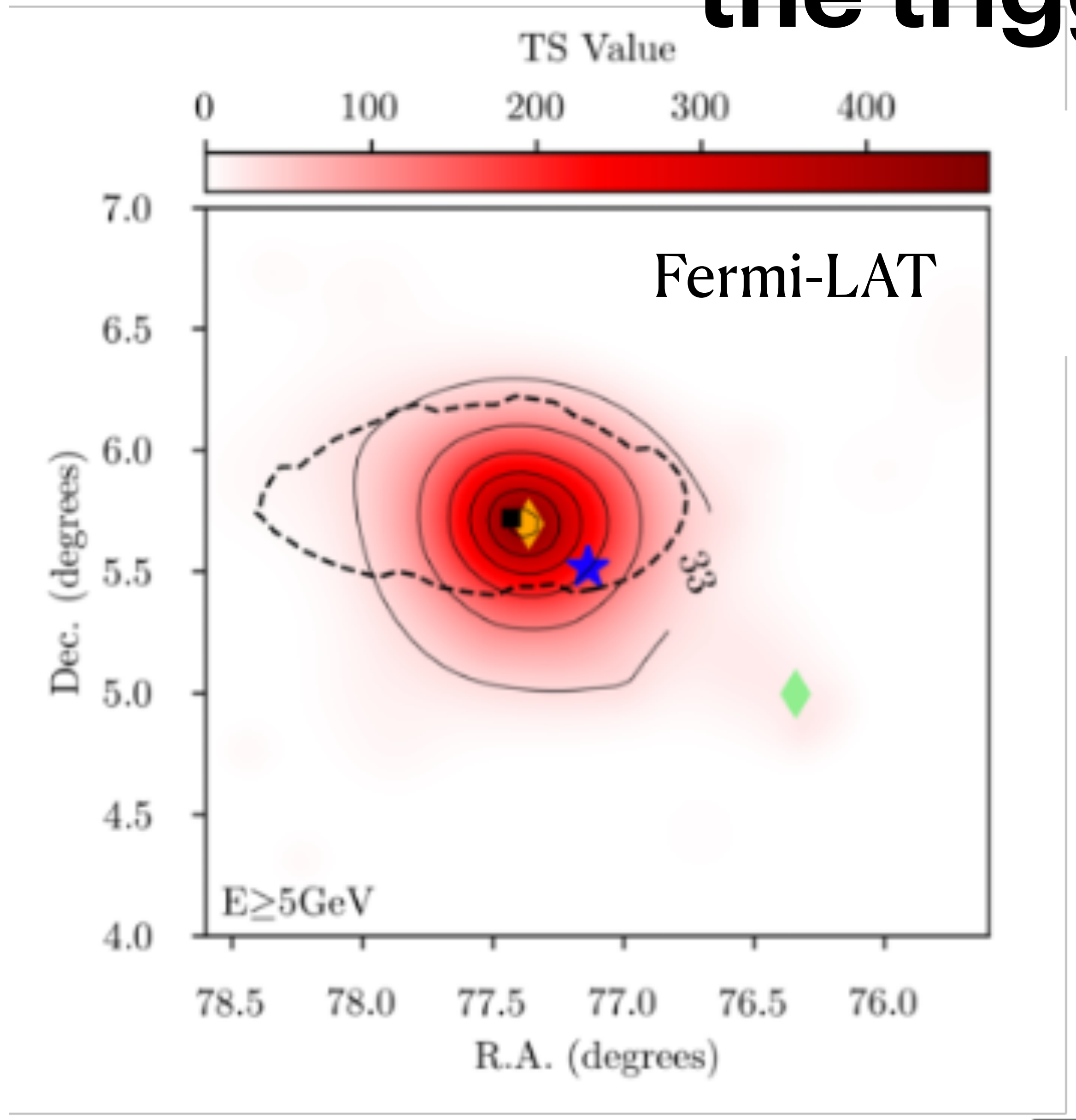
image from C. Bellenghi

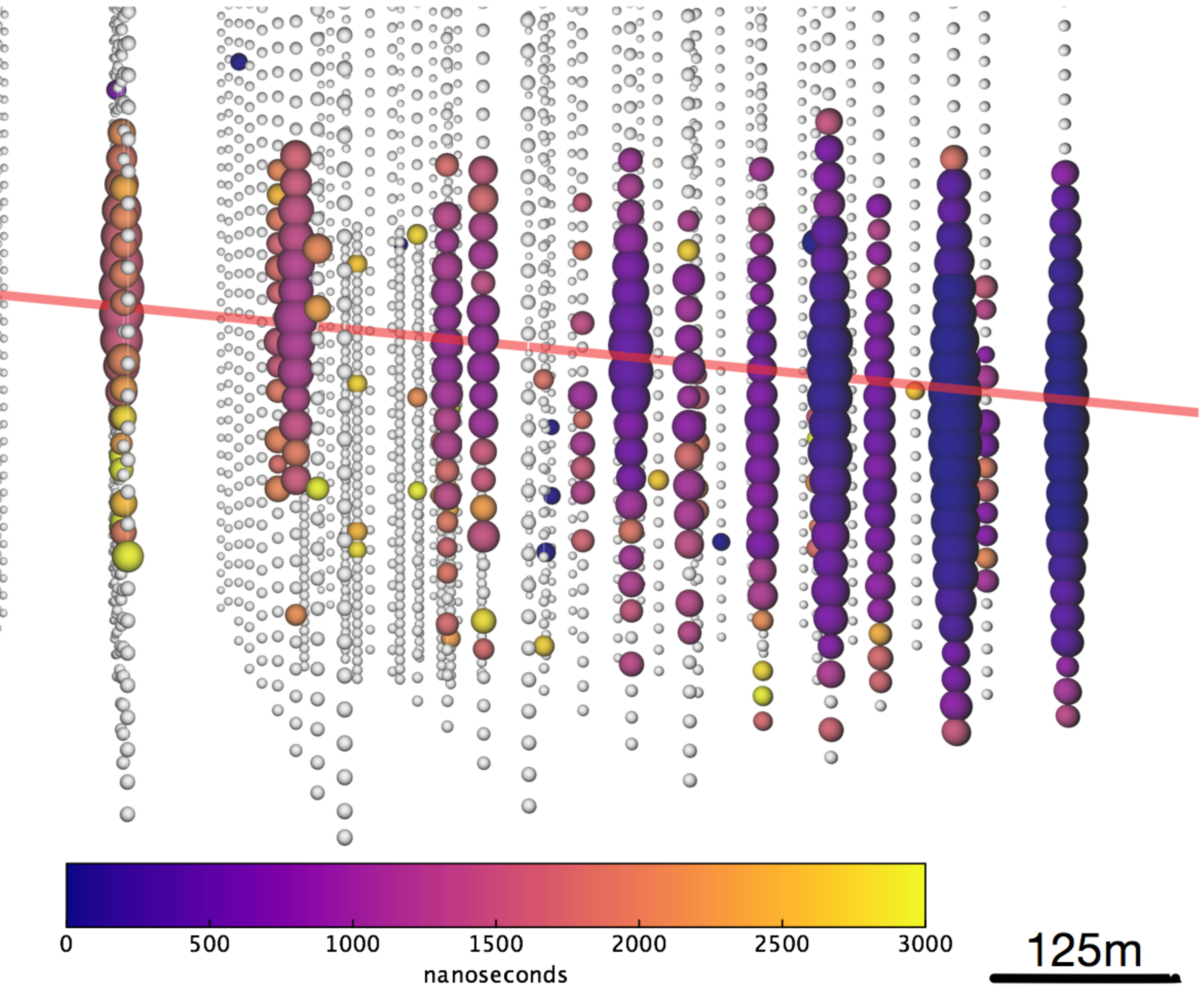


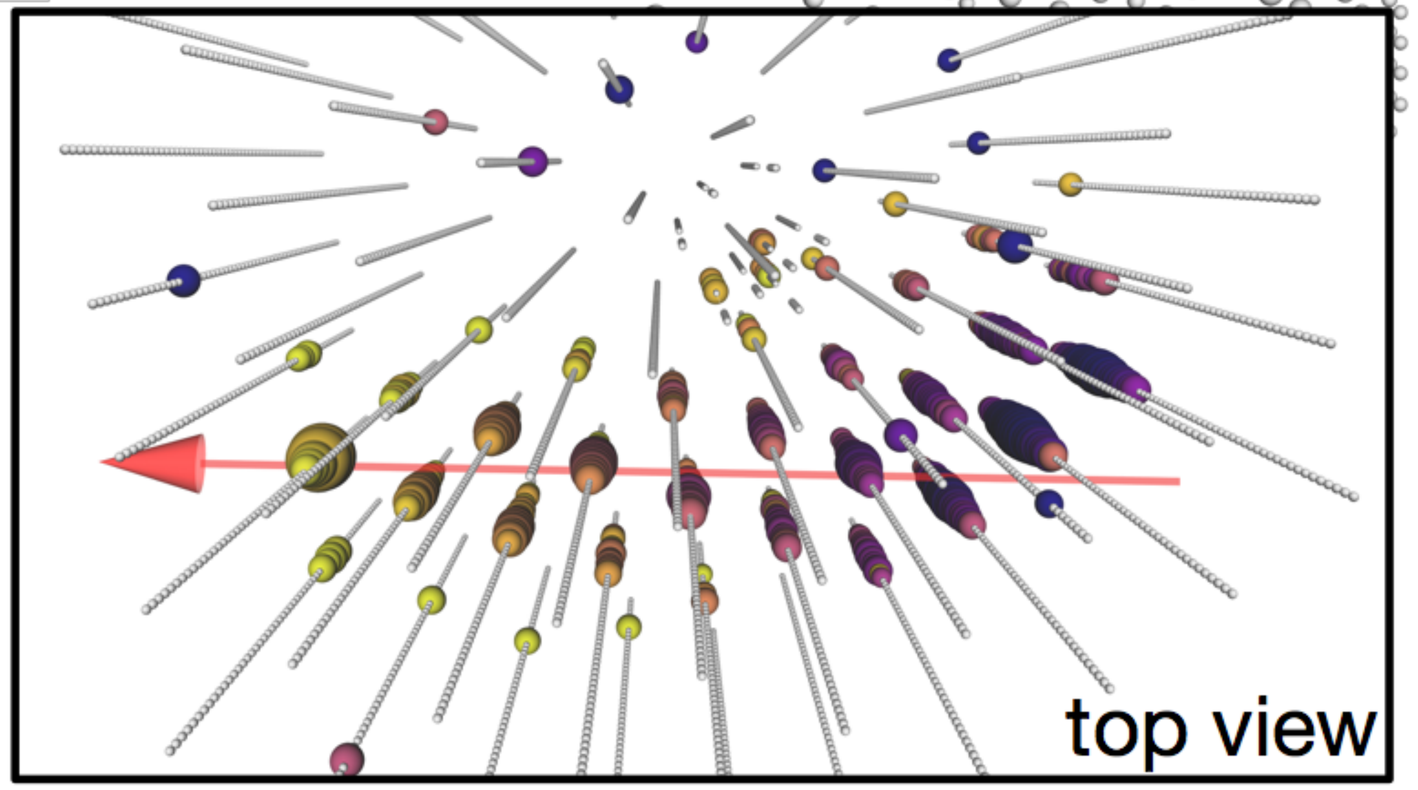
The IceCube Coll., ***Science*** '18
P.Padovani, P. Giommi, E.R., et al., ***MNRAS*** '18

Neutrino associations to jetted AGN

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

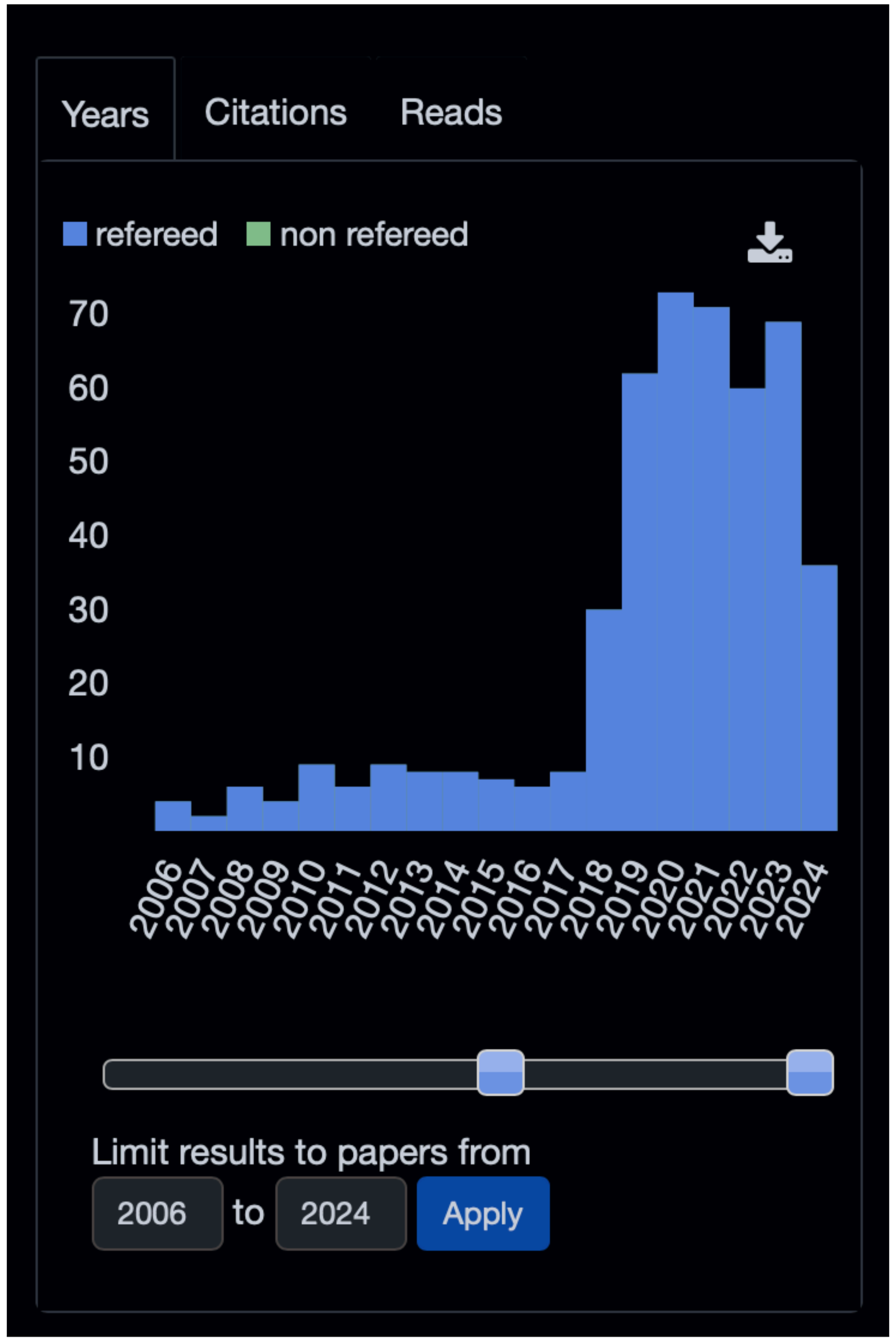






IceCube-170922A: neutrino alert [~290 TeV, Dec ~5.72 deg]

NASA ADS: papers related to TXS 0506

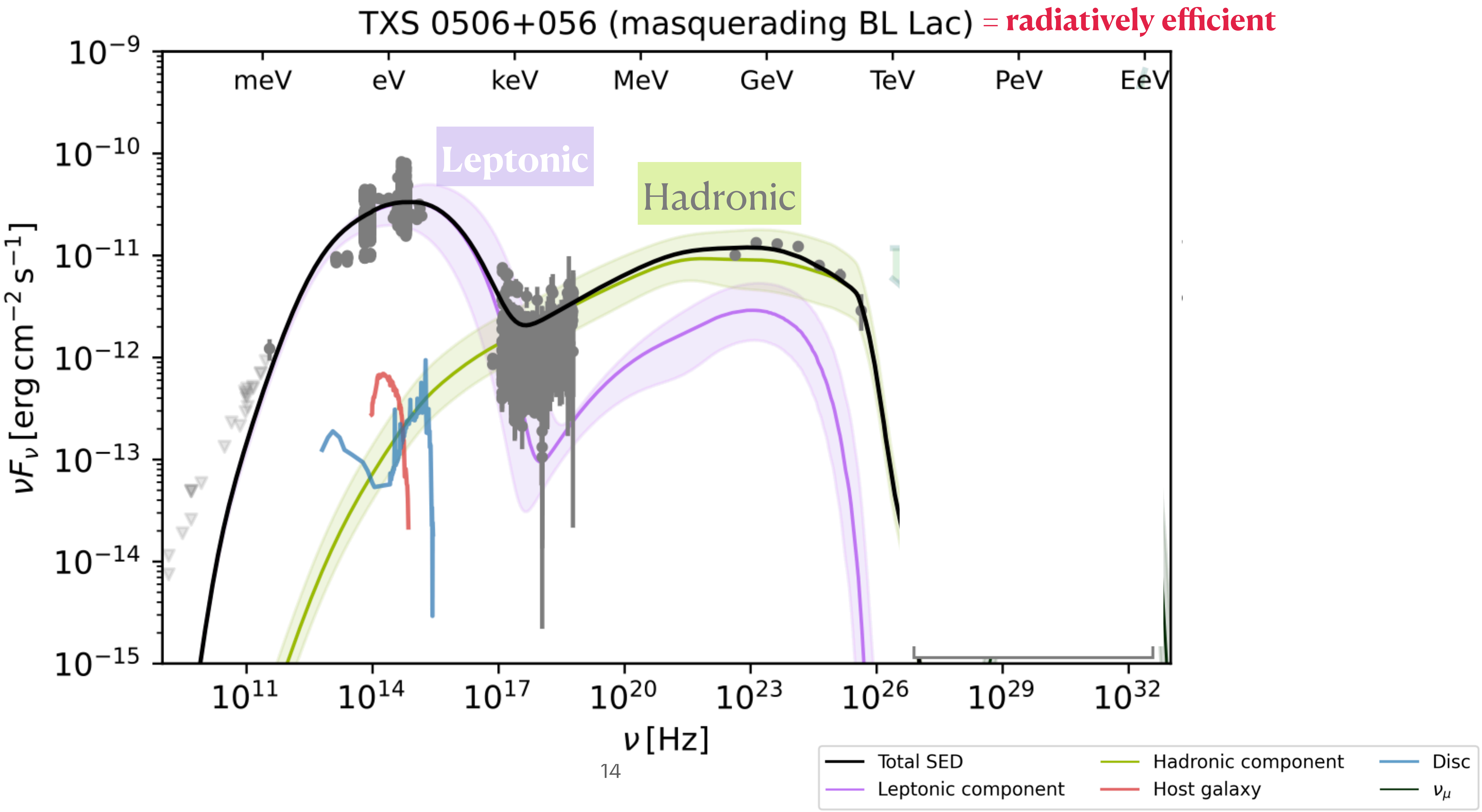


https://ui.adsabs.harvard.edu/search/filter_property_fq_property=AND&filter_property_fq_property=property:"refereed"&fq={!type=aqp v=$fq_database}&fq={!type=aqp v=$fq_property}&fq_database=(database:astronomy OR database:physics)&fq_property=(property:"refereed")&q=((=abs:"TXS 0506+056" OR simbid:"769351" OR nedid:"WISEA_J050925.96+054135.3") database:astronomy)&sort=date desc, bibcode desc&p_=0

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

TXS 0506+056: classification

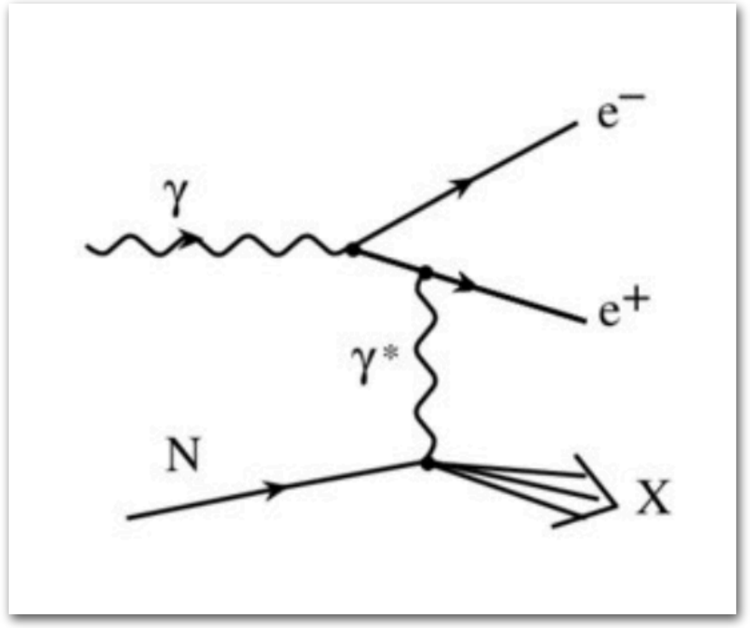
leptonic, hadronic? is one zone enough?



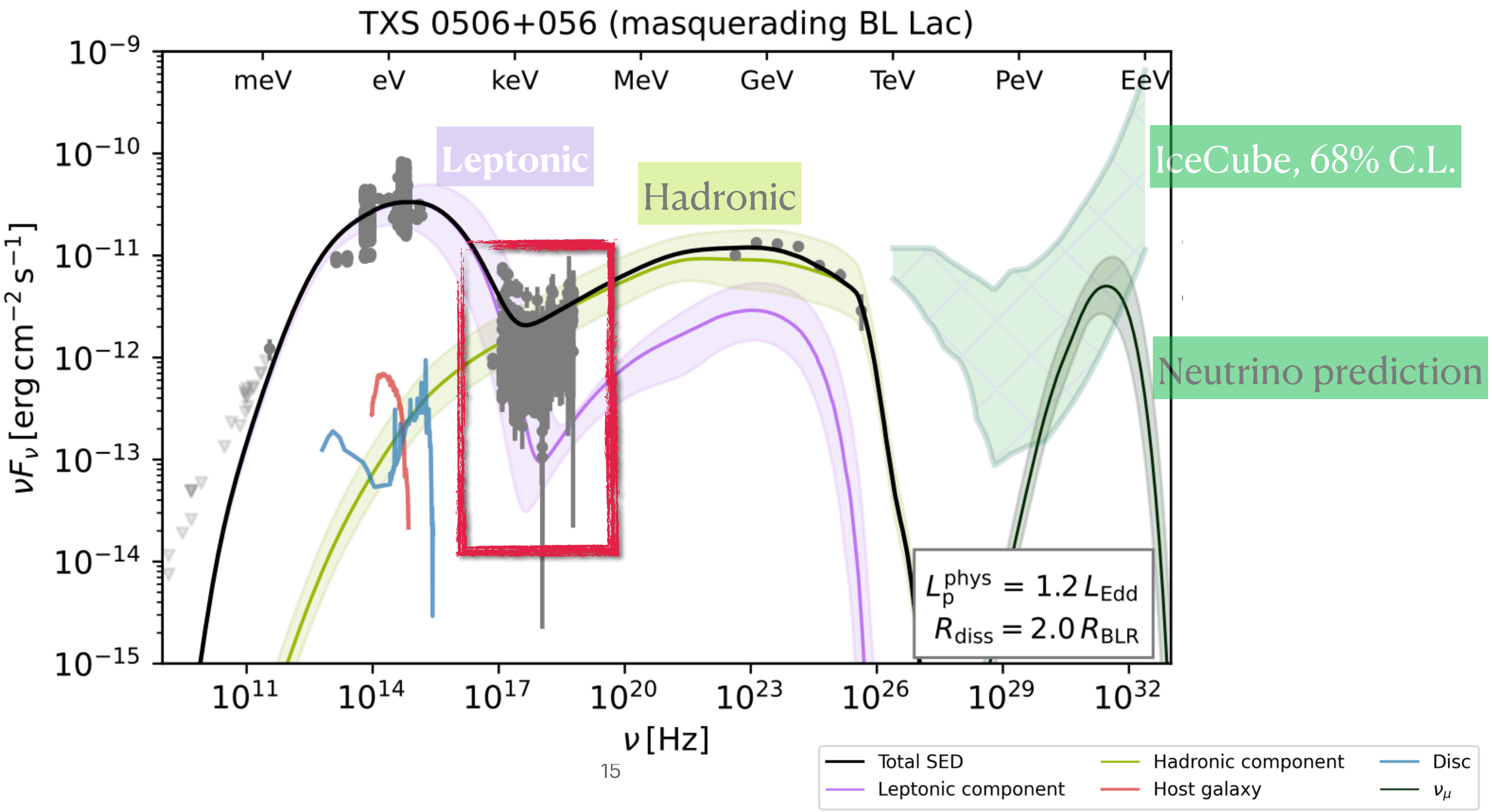
X. Rodrigues, M. Karl, P. Padovani et al., **A&A** '24
D. Karavolaa M. Petropoulou, **JCAP** '24

TXS 0506+056: X-ray constrains

Bethe-Heitler pairs



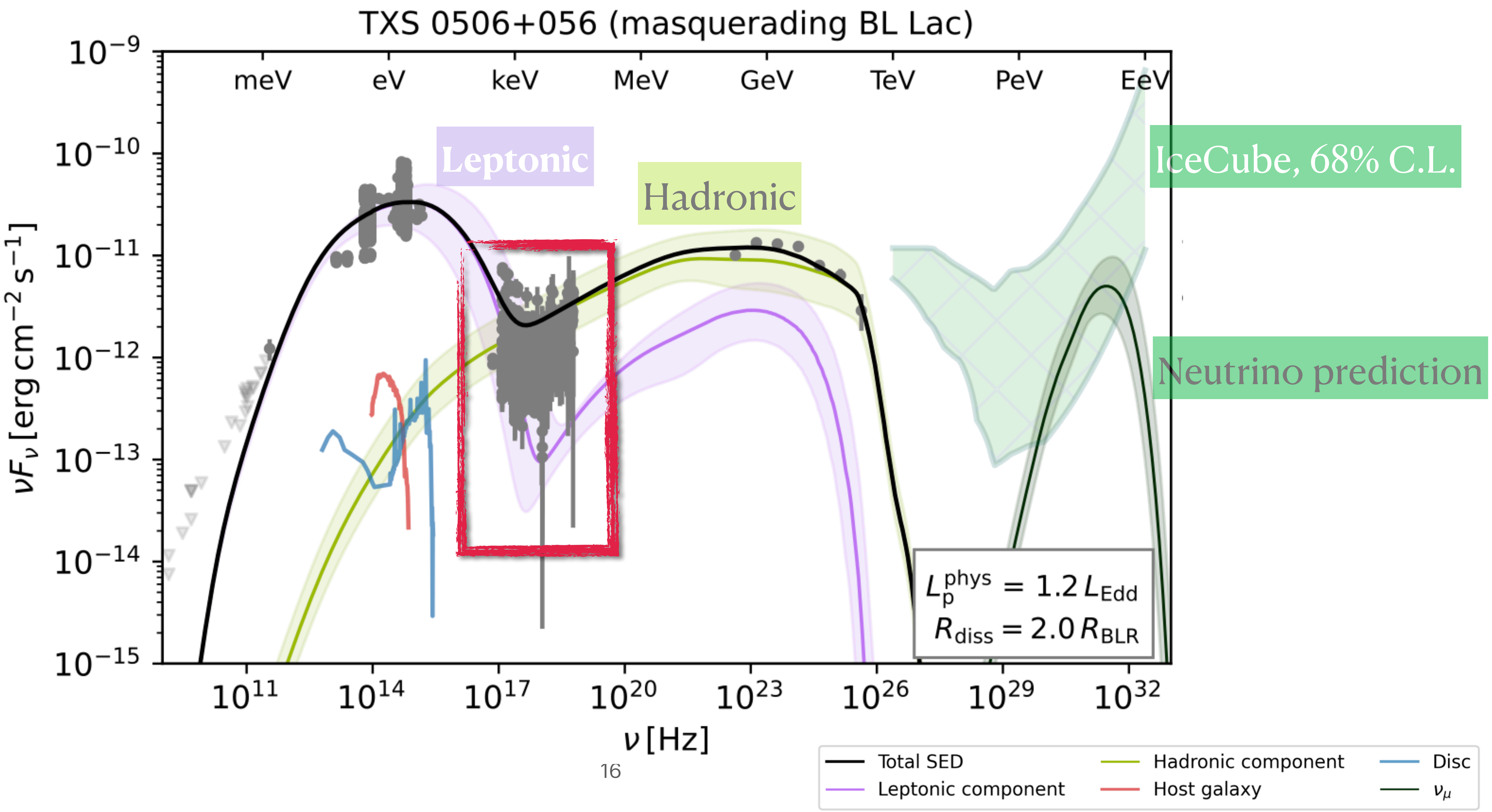
synchrotron emission from Bethe-Heitler pairs

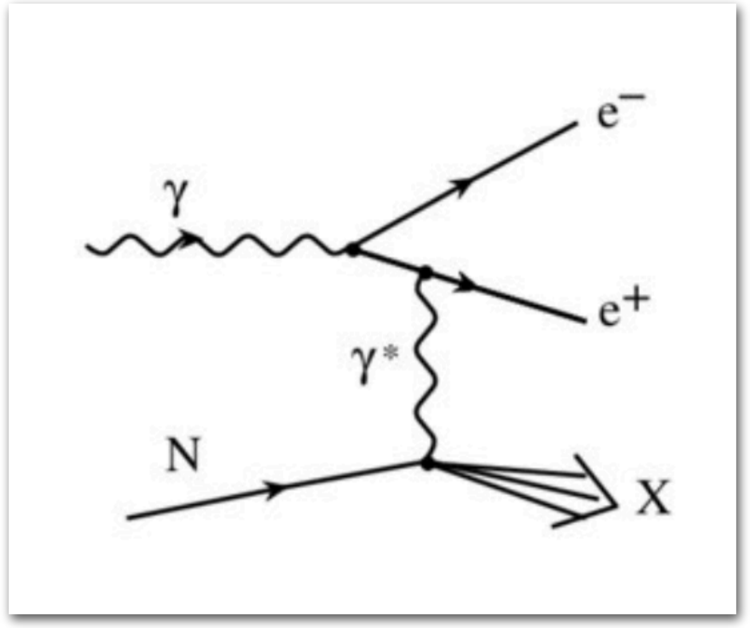


X. Rodrigues, M. Karl, P. Padovani et al., **A&A** '24
D. Karavolaa M. Petropoulou, **JCAP** '24

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***

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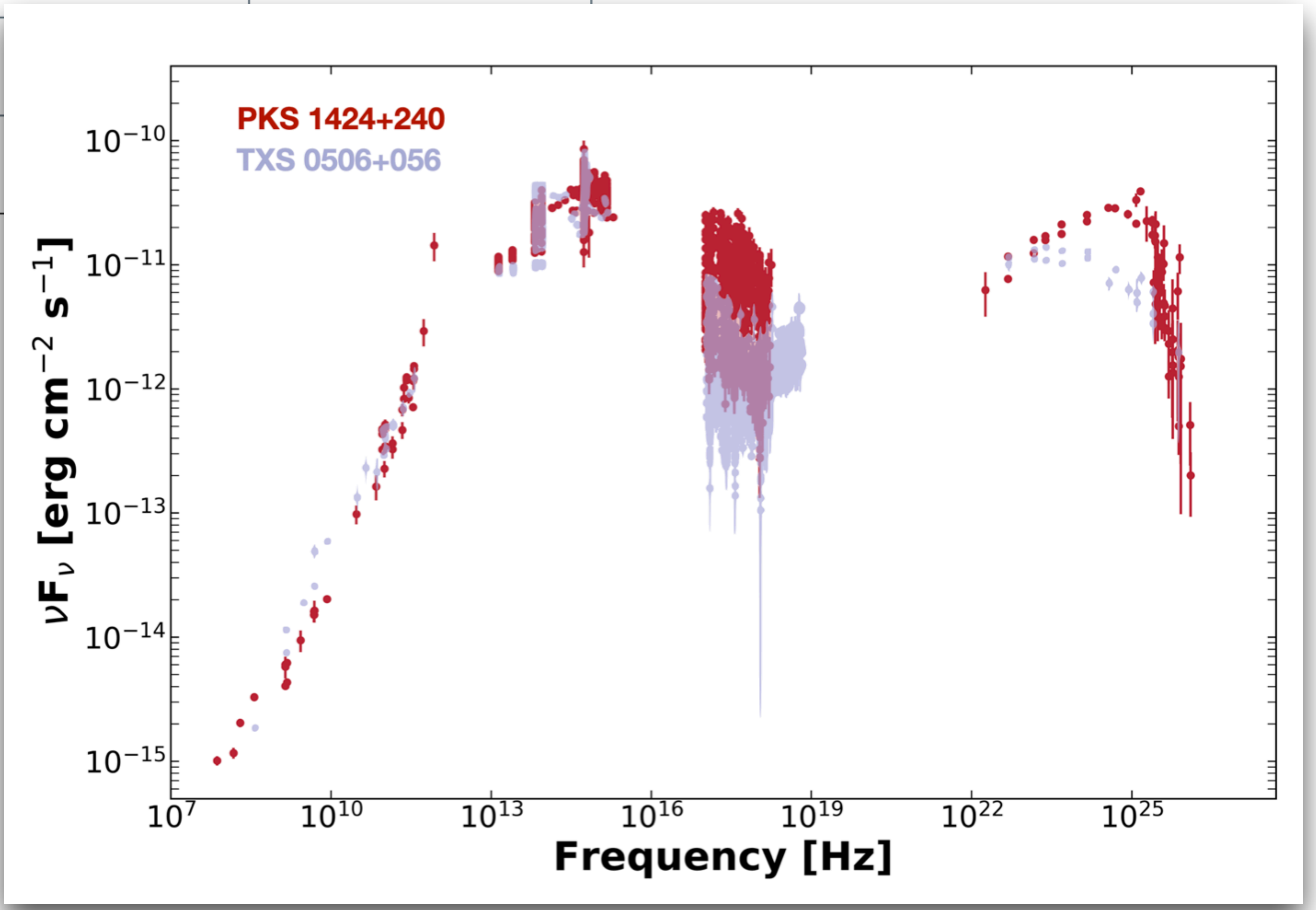
P.Padovani et al., ***MNRAS*** '22



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.

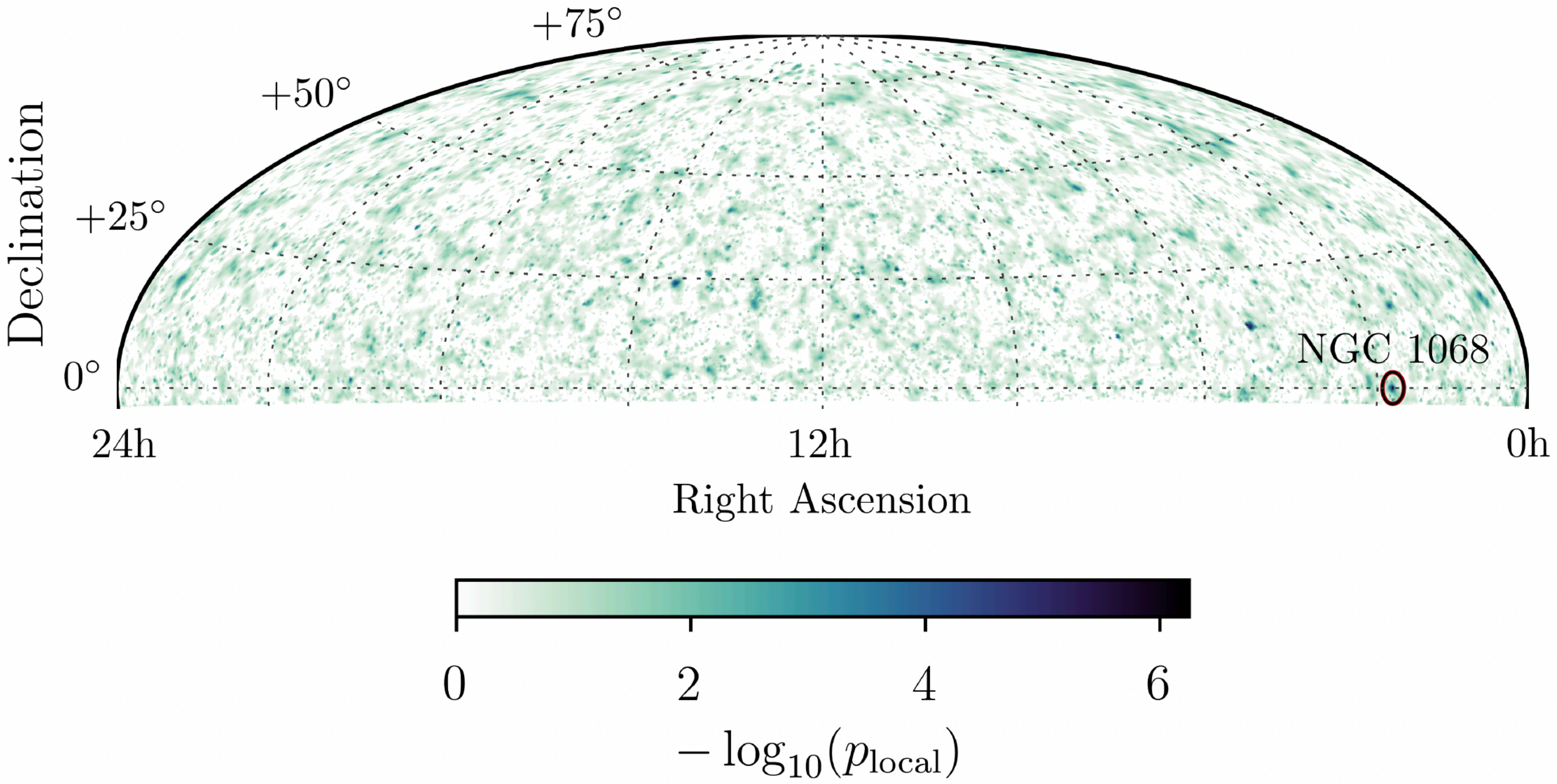
The IceCube Coll., *Science* 378 (2022)
The IceCube Coll., *preliminary*

Neutrino association: the top 1.

NGC1068: a non-jetted AGN

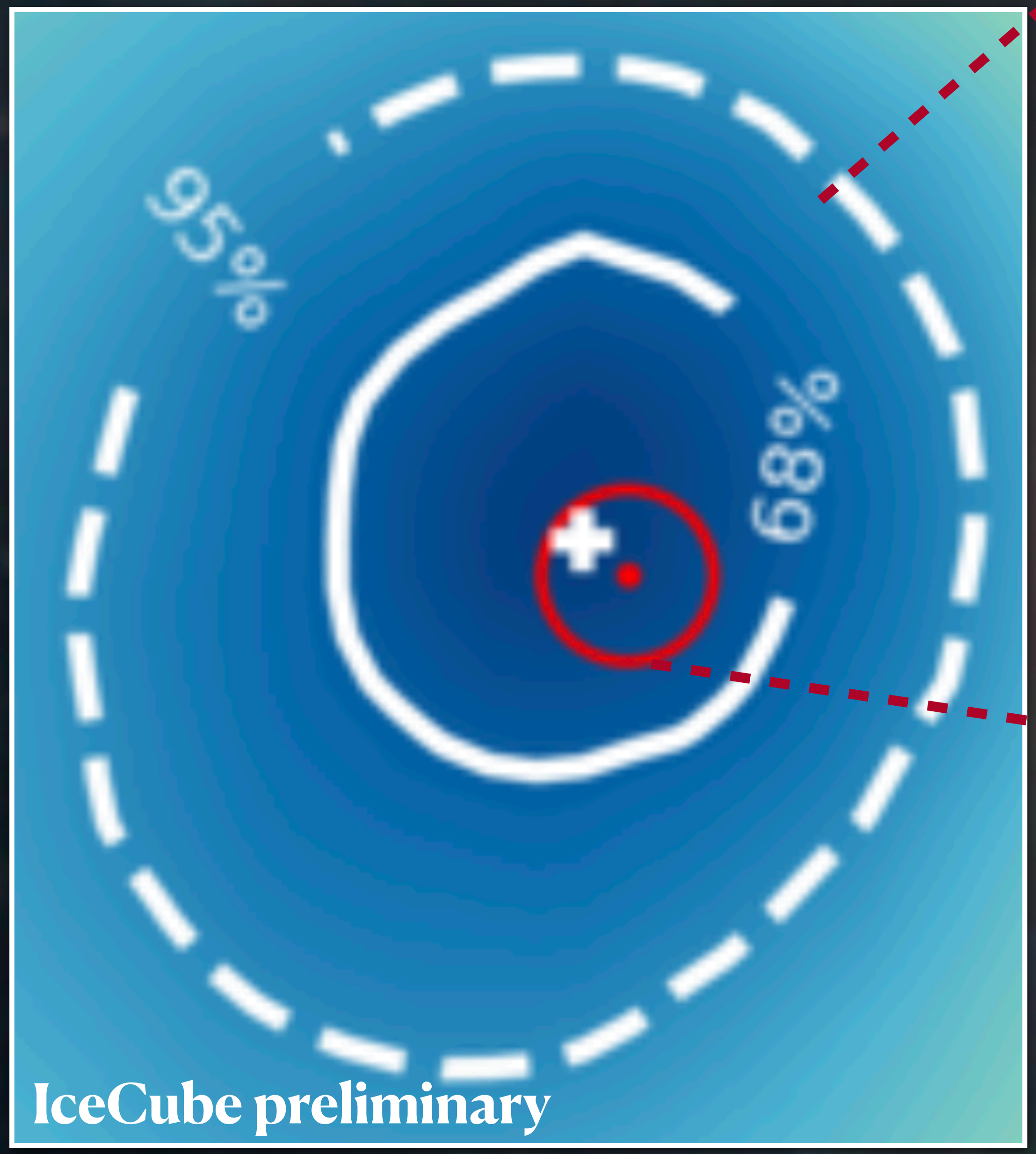
see **T. Kontrimas** talk, this conference

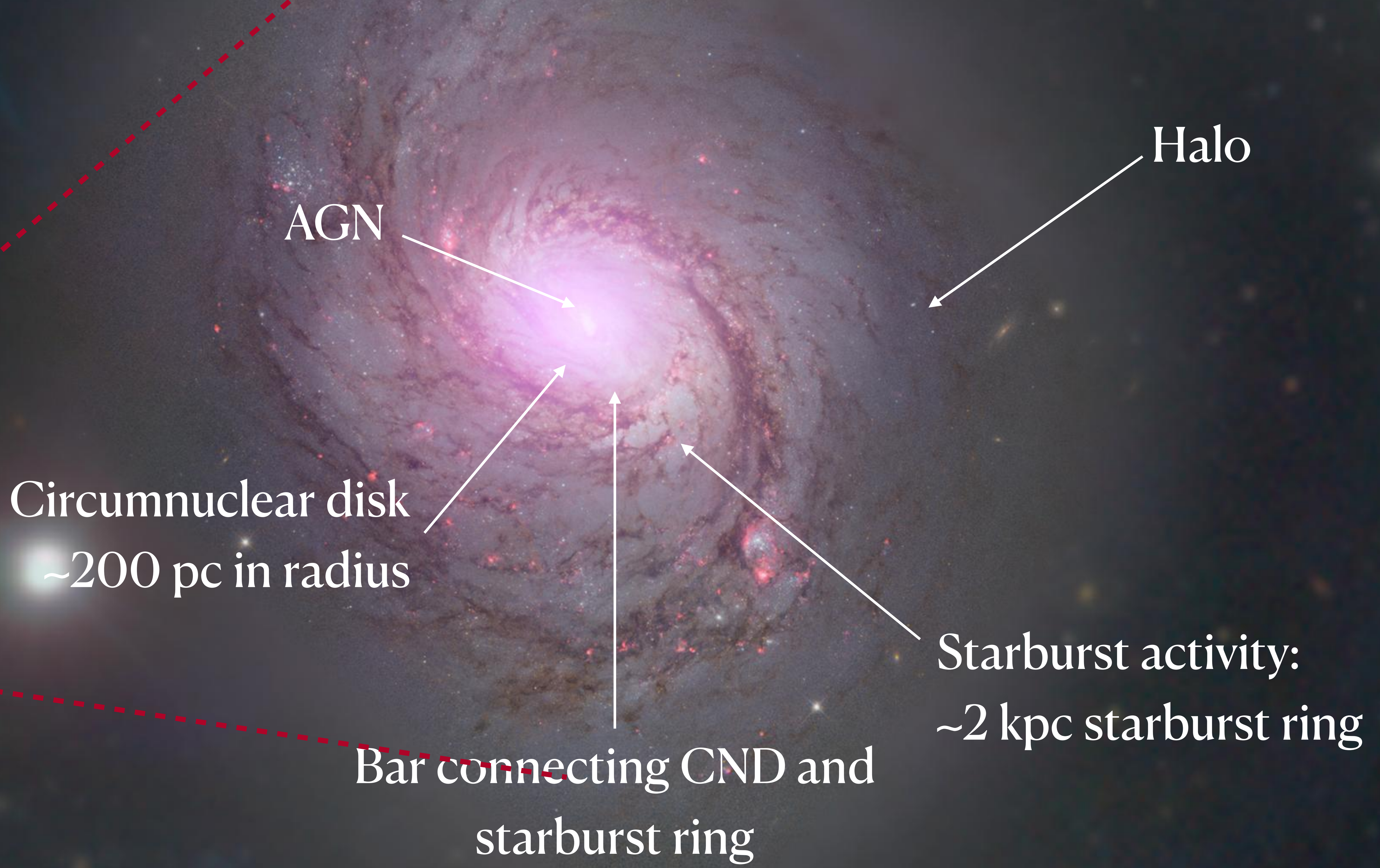
at the 4σ level



NGC 1068: An Archetype of Obscured AGN

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





IceCube can't resolve different emission components

NASA/JPL-Caltech/Roma Tre Univ.

P. Padovani, E.R., M. Ajello, C. Bellenghi et al., ***Nature Astr.*** '24

Berezinsky, Ginzburg, MNRAS 1981
Silberberg, Shapiro 1982

NGC 1068

Spectral Energy Distribution: "hidden" source scenario

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

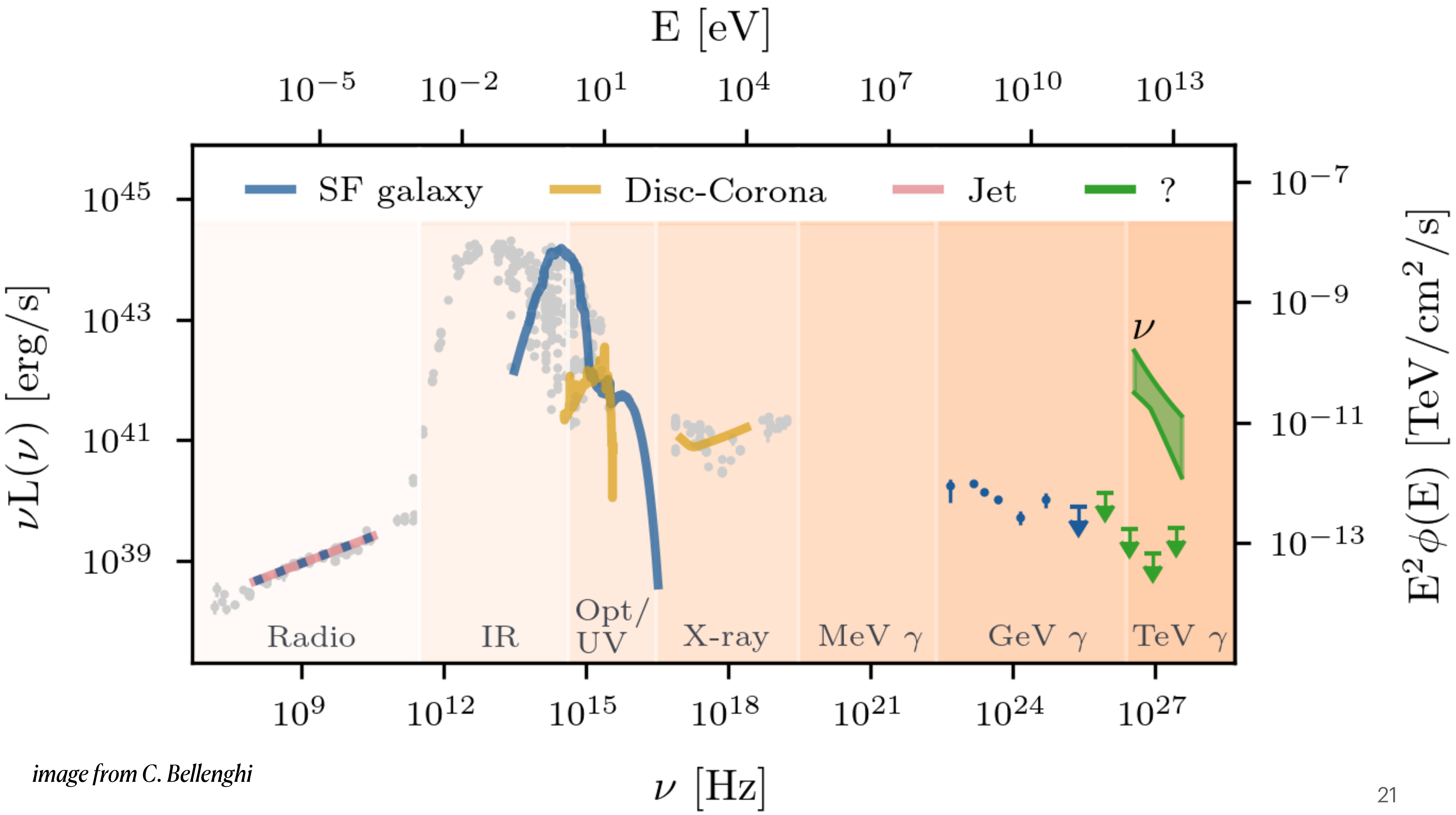


image from C. Bellenghi

NGC 1068

Maximum neutrino power vs regions

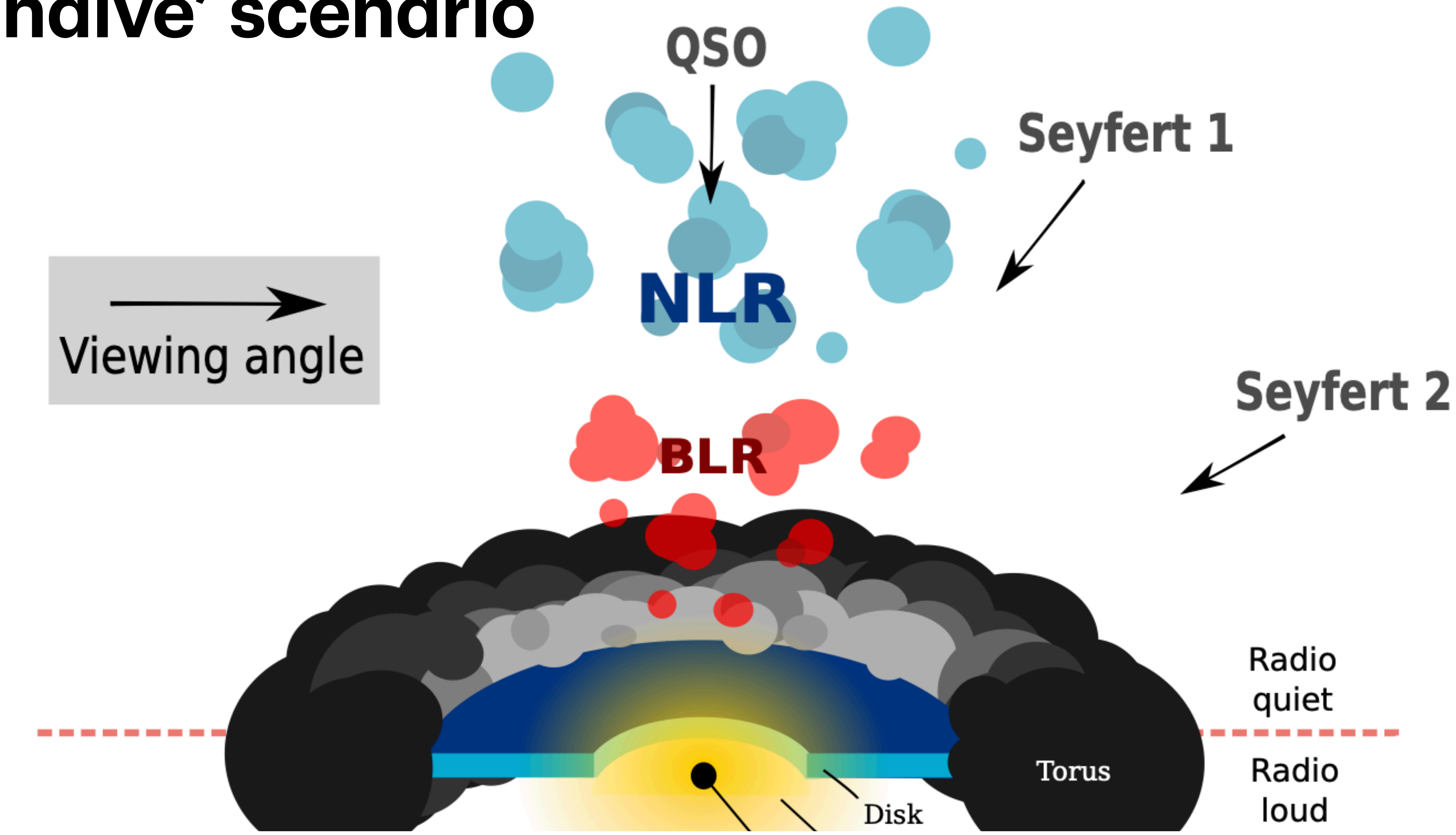
Table 3. Estimated γ-ray and neutrino powers.

Component	Scale	L_γ (0.1 – 10 GeV)	L_ν (1.5 – 15 TeV)
Star formation	$> \text{kpc}$	$\sim 10^{40.9}$	$\lesssim 10^{40.1}$
Jet	$\sim \text{kpc}$	$< 10^{41.7}$ (M87-like)	$< 10^{40.9}$
Outflow (UFO)	$\sim \text{pc}$	$< 10^{41.2}$	$< 10^{40.4}$
BH vicinity	~ 0.03 mpc ($\sim 50\ R_s$)	?	?
	Total	$\lesssim 10^{41.9}$	$\ll 10^{41.1}$
	Observed	$10^{40.92 \pm 0.03}$	$10^{42.1 \pm 0.2}$

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

NGC 1068

The 'naive' scenario



Corona of hot electrons (X-ray)

<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 $\gamma \sim$ X-ray domain

(Corona component)

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

<u>Step 4</u>: γ-ray $\rightarrow$ degraded into **<u>MeV region</u>**

neutrinos stream through

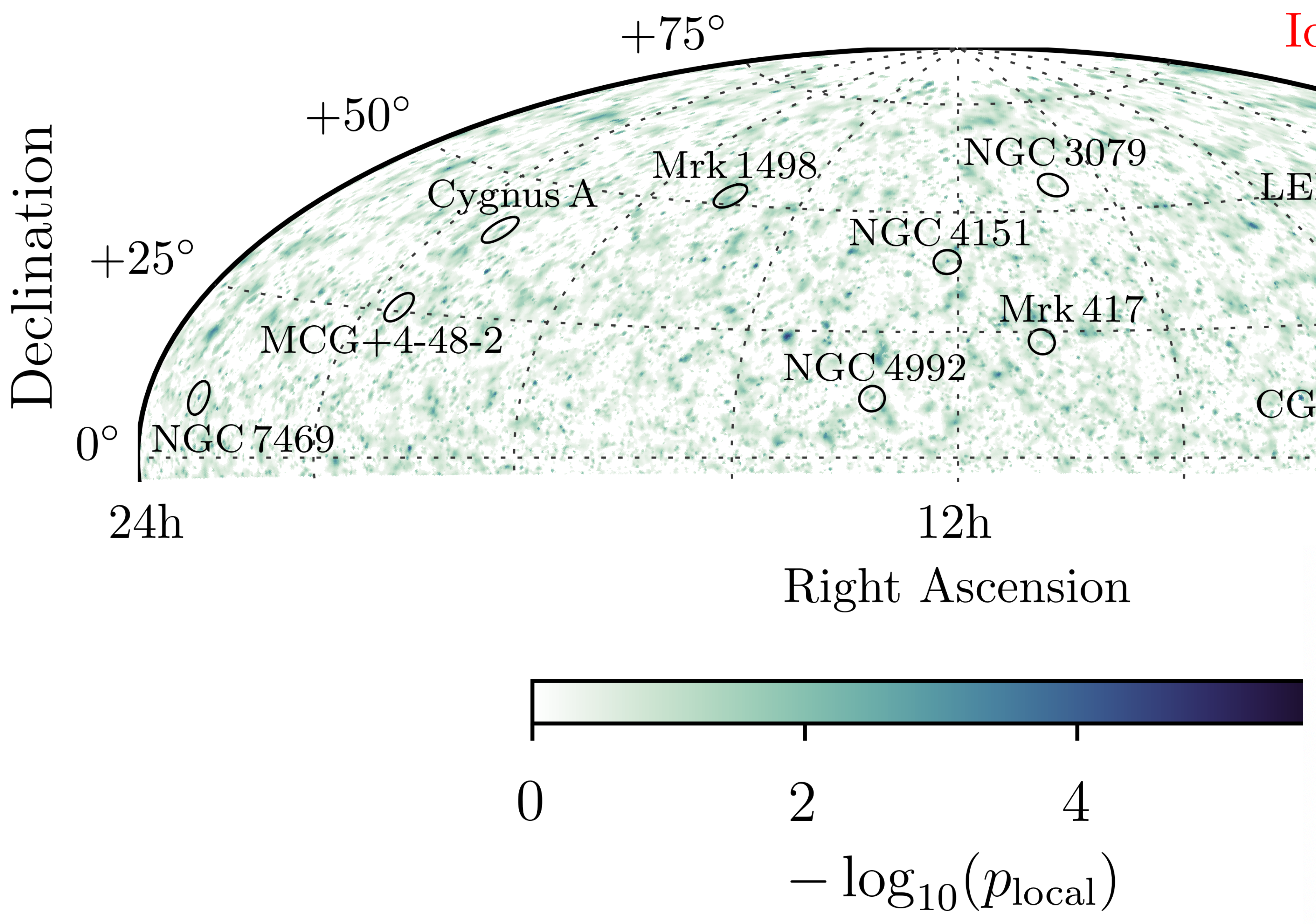
AMEGO-X

see **R. Caputo** talk, this conference

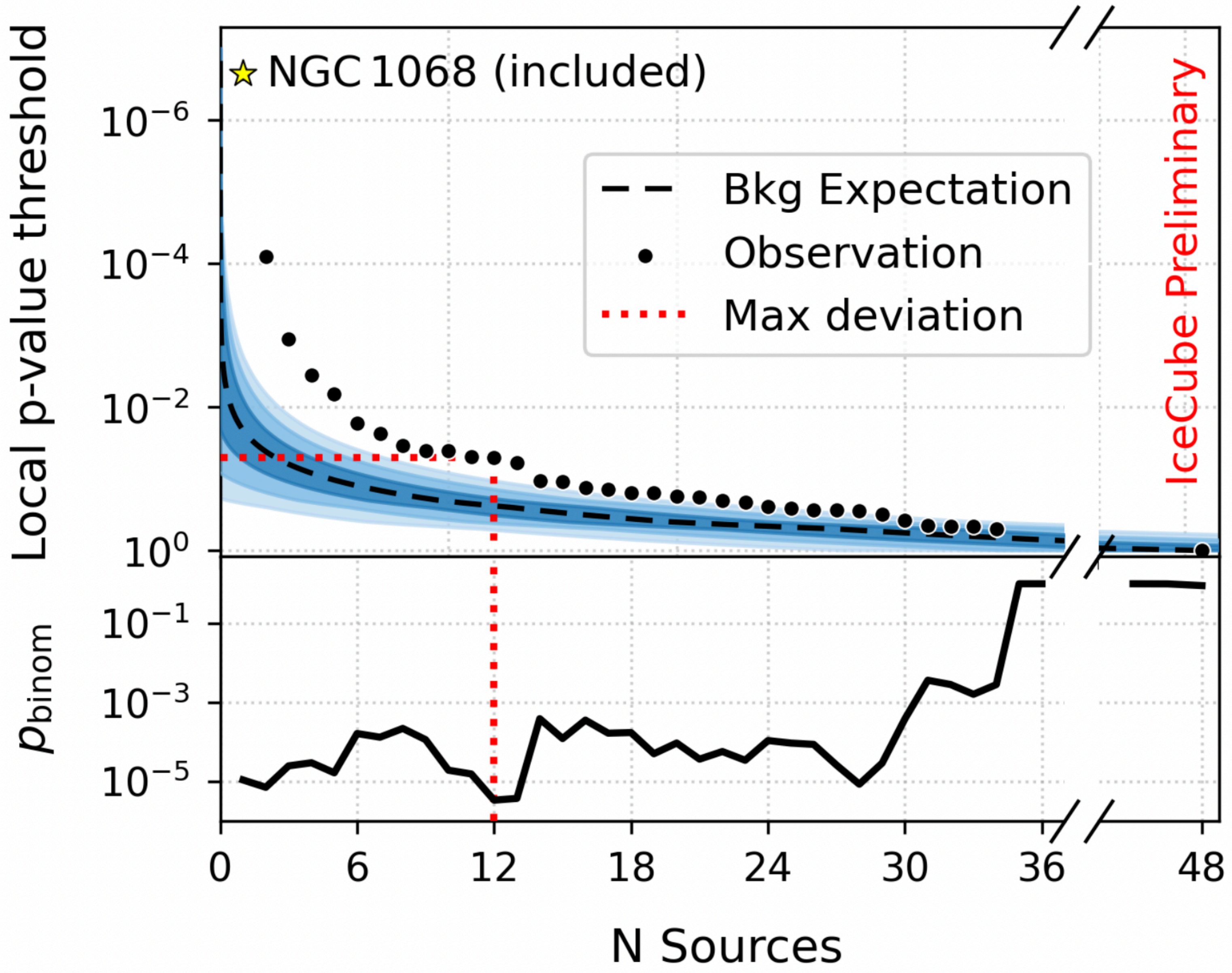
<u>Note</u>: the *Fermi*-LAT component most probably associated to the starburst component

And there are more!!

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



11+ 1 objects emerging

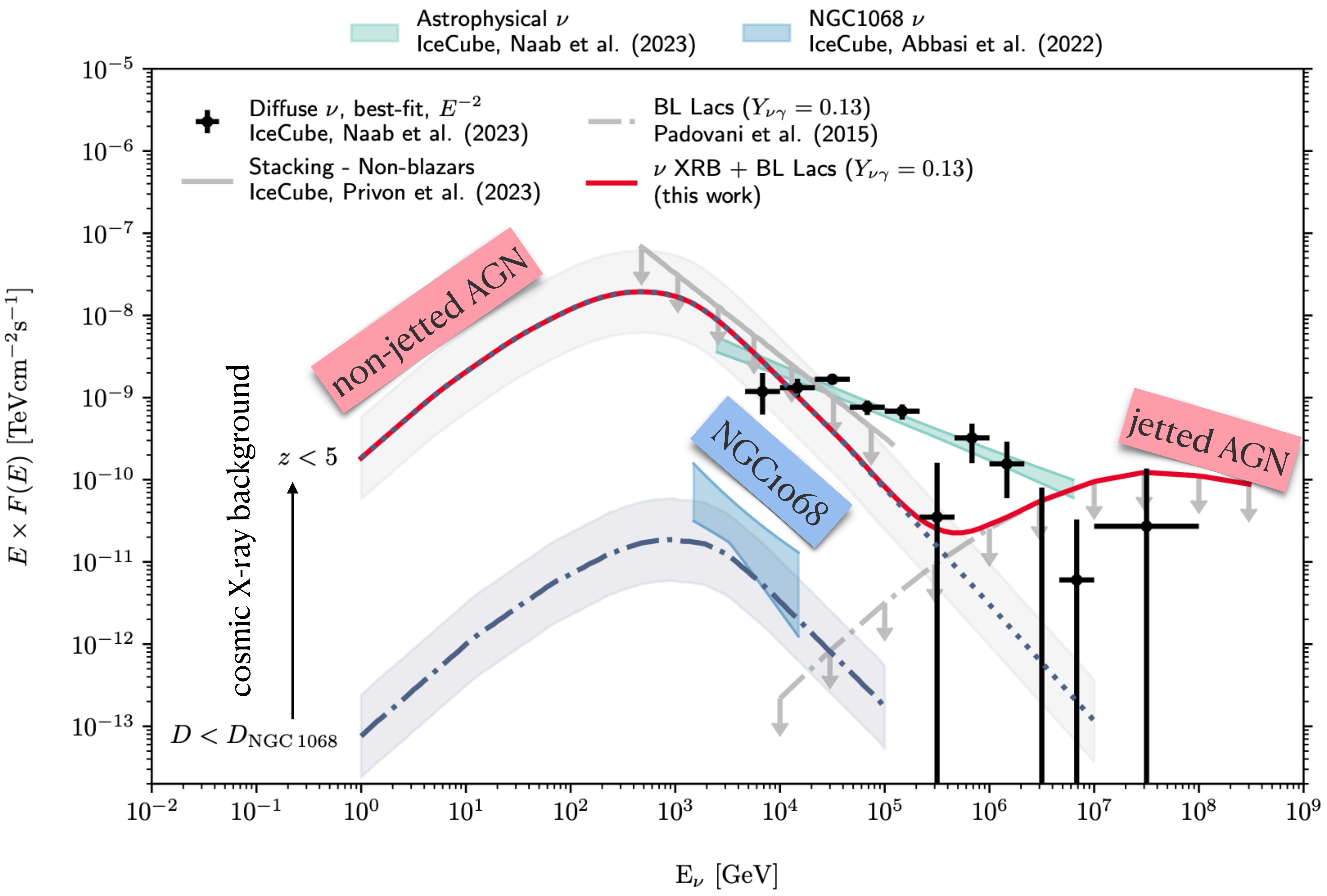


Global significance 3.3σ (NGC1068 excluded)

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

Can AGN explain the IceCube diffuse?

maybe



To be updated soon including recent IceCube results

Conclusions

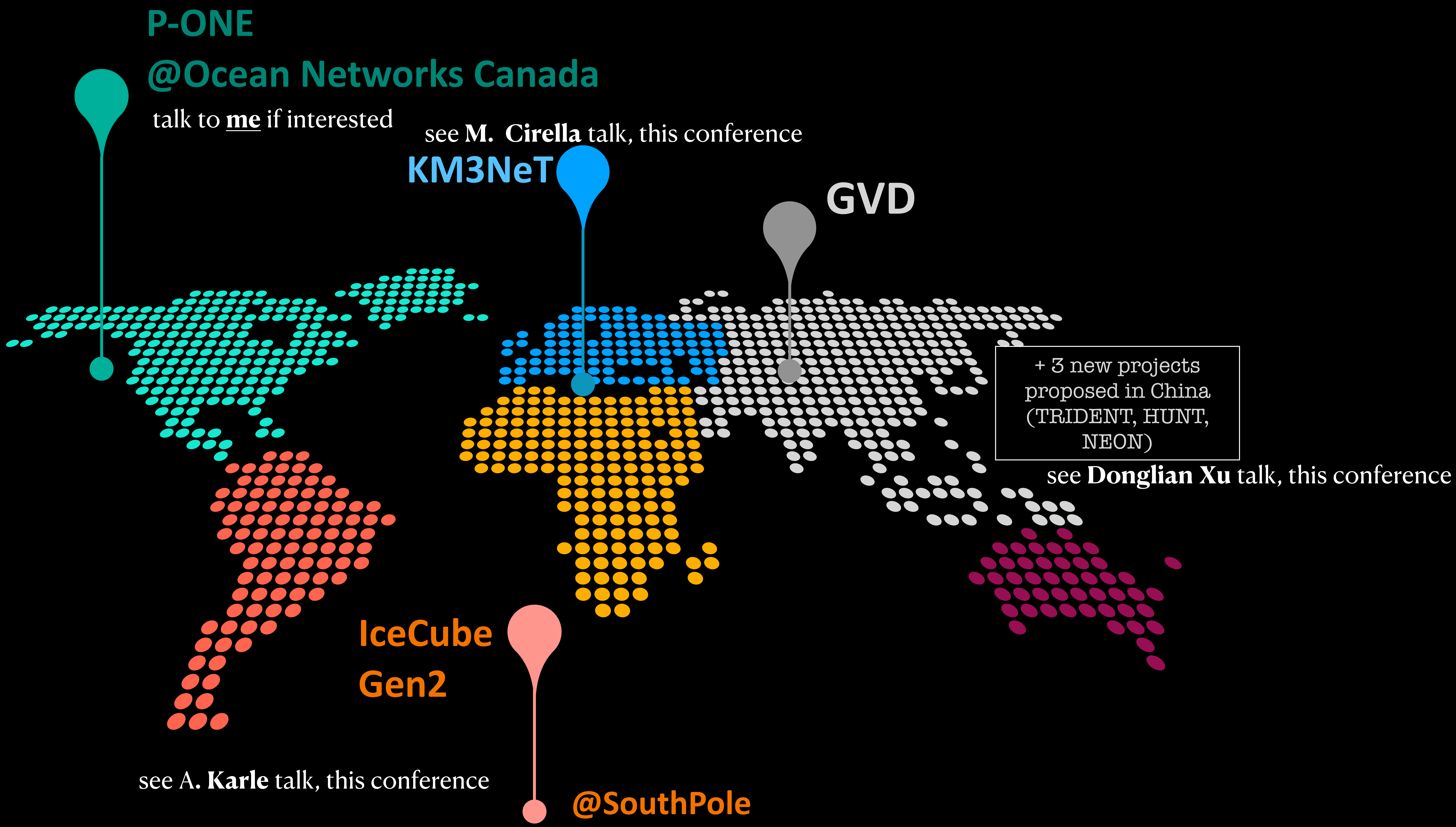
We are observing a breakthrough in progress

1. **AGNs as Neutrino Sources:** emerging evidence from
    - jetted (UHE neutrinos, rare, variable) and
    - non-jetted (lower energy neutrinos, numerous, steady) AGNs
      Berezinsky galaxies = non-jetted AGN with neutrino flux association -

2. **Cosmic Ray Models**: classic cosmic ray scenarios explain observed neutrino signals.

3. **Neutrino Impact**: neutrino observations enhance AGN classification and astrophysics.

Next-generation neutrino telescopes essential



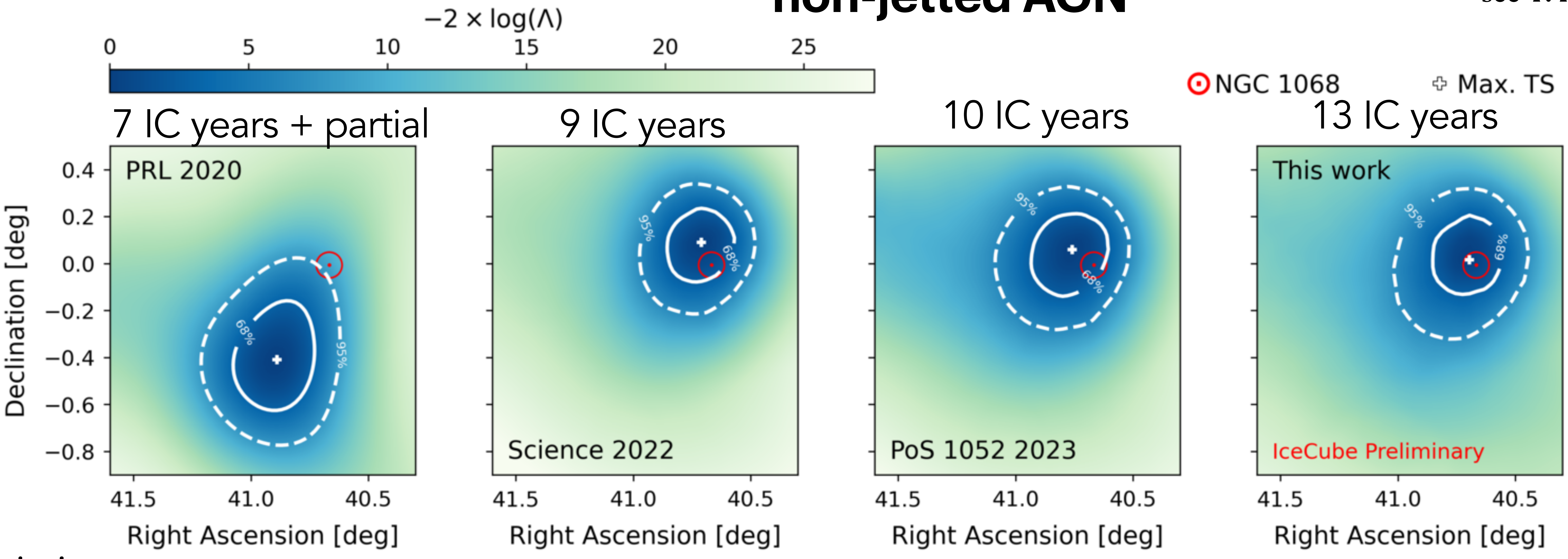
Extra

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

Status of neutrino observations

non-jetted AGN

see **T. Kontrimas** talk, this conference



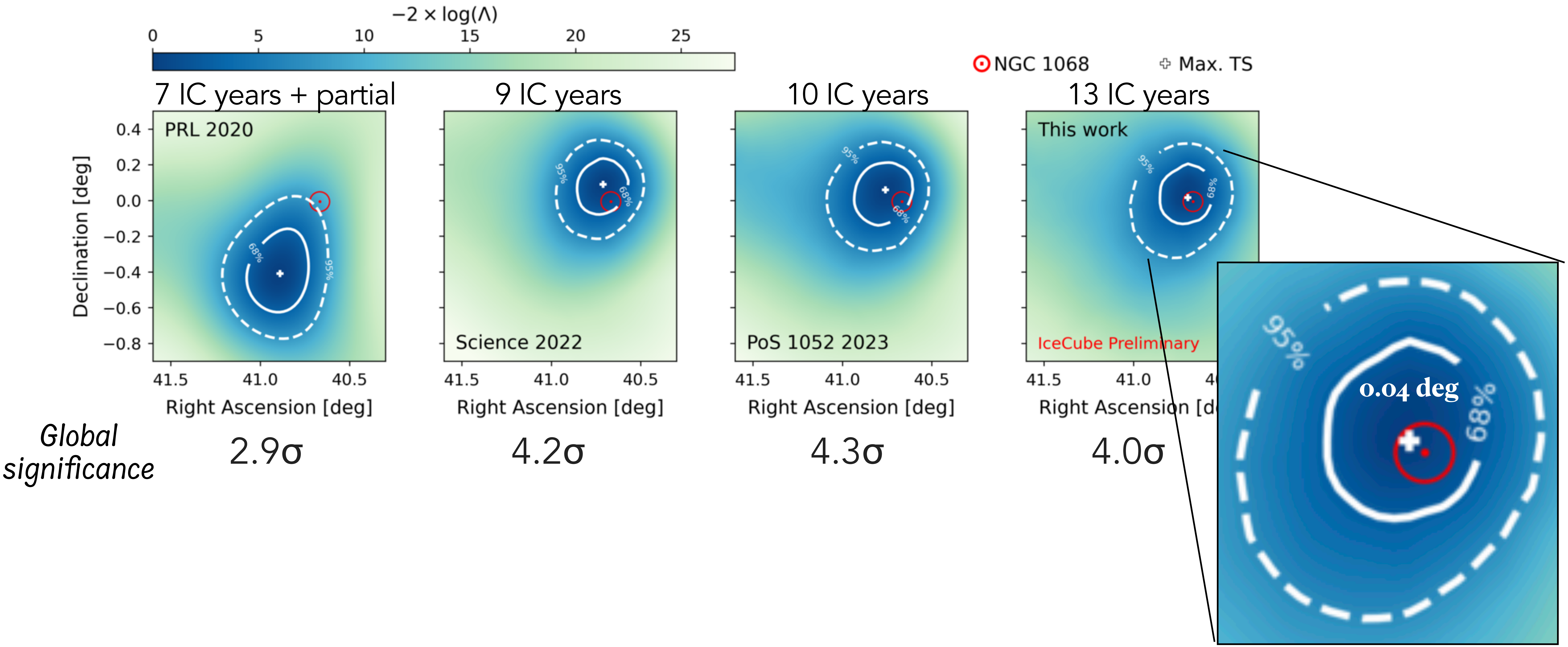
Global significance 2.9σ 4.2σ 4.3σ 4.0σ

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

From 9 years to 13 years of IceCube exposure

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

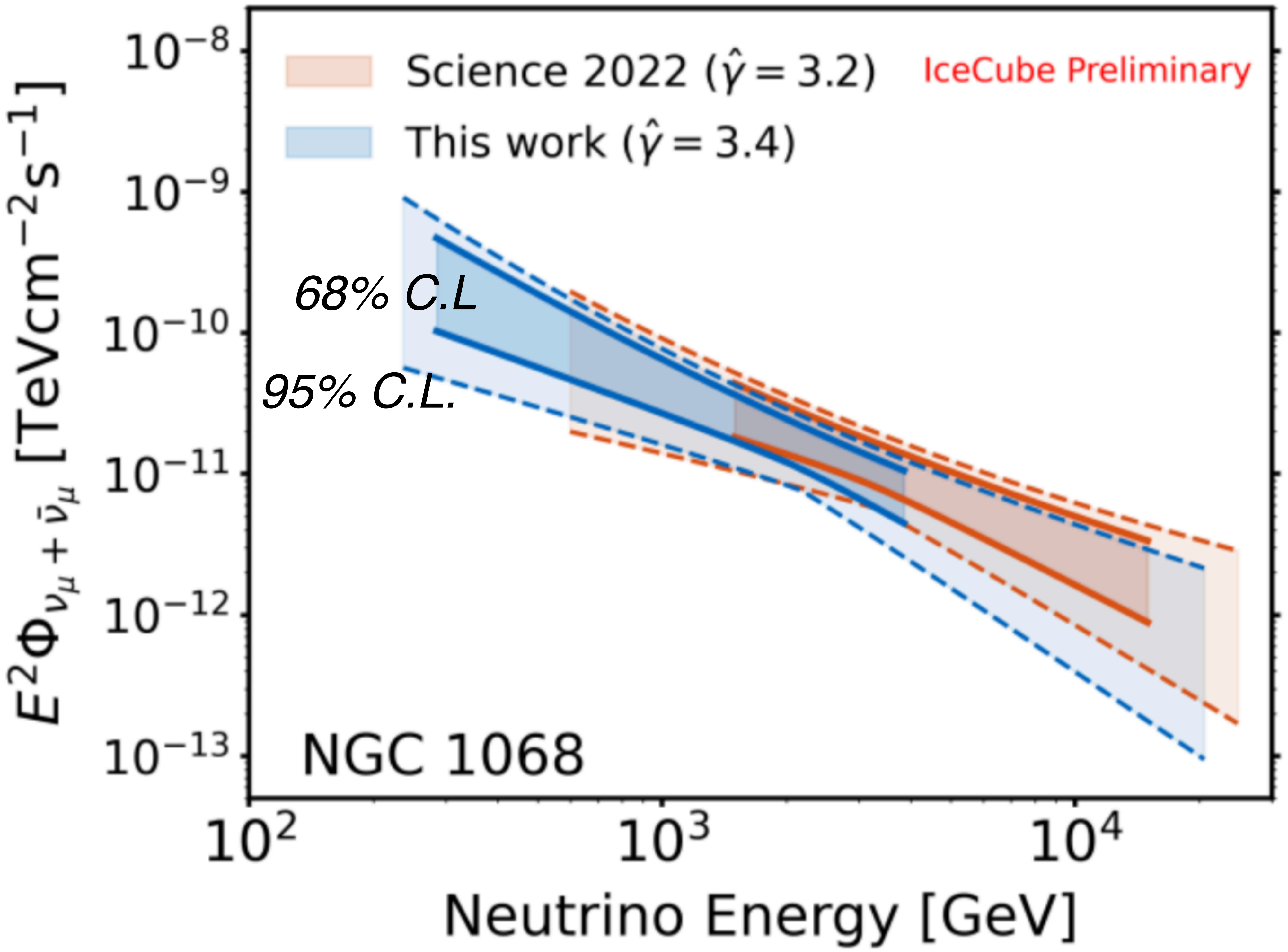
see **T. Kontrimas** talk, this conference

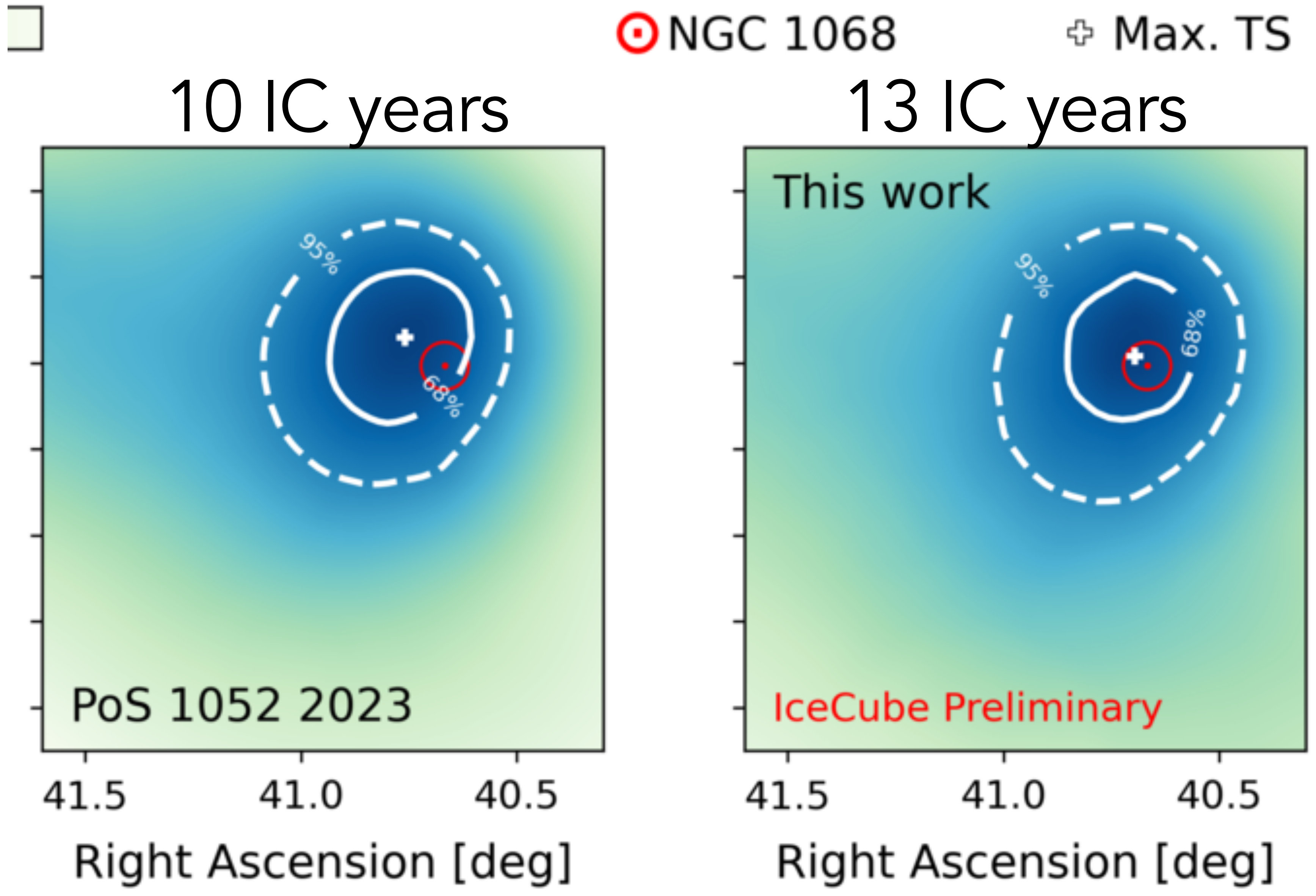


From 9 years to 13 years of IceCube exposure

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

see **T. Kontrimas** talk, this conference





4.3σ

4.0σ

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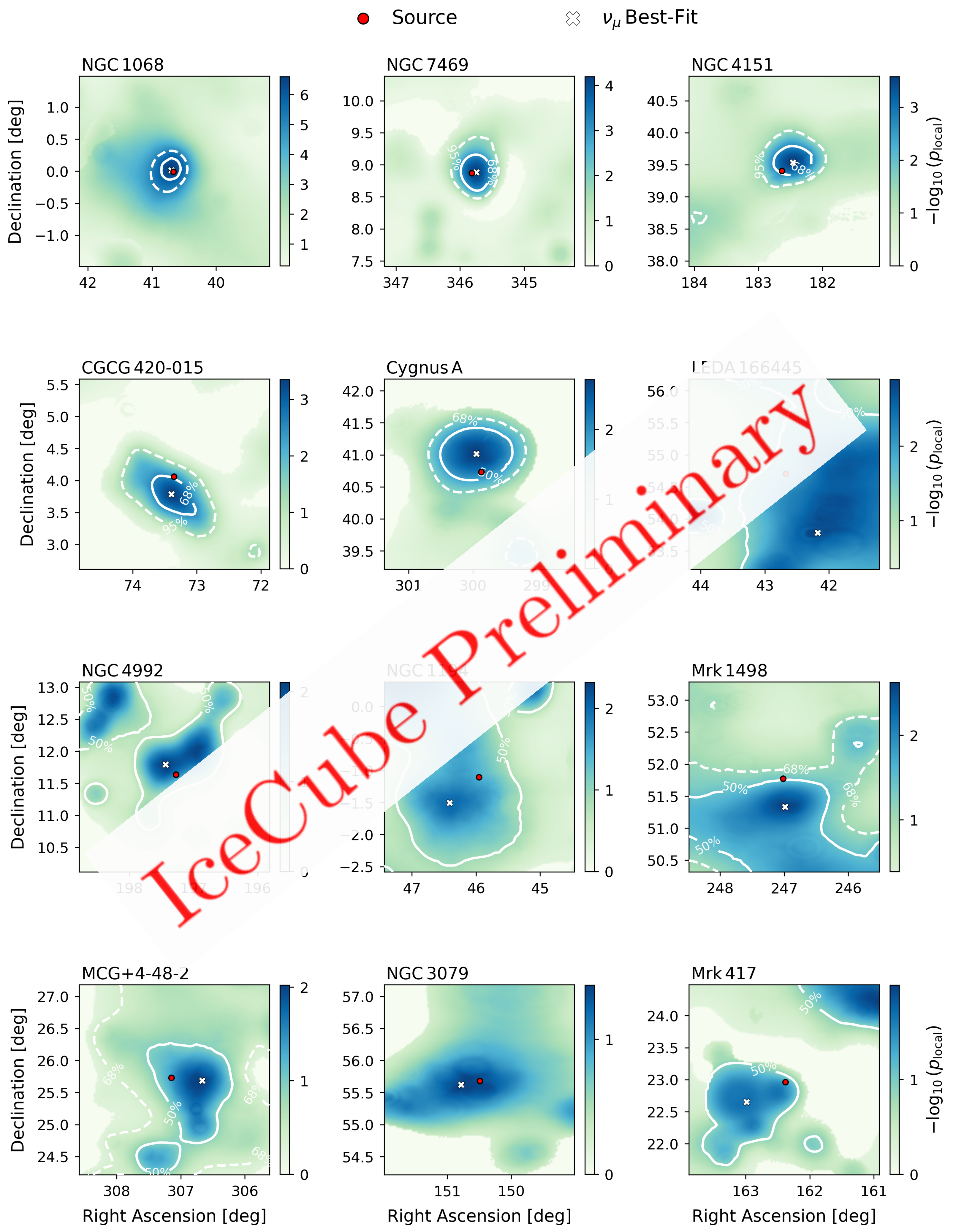
Emerging of a population of HE neutrino sources?

C. Bellenghi, E. Manao, T. Kontrimas, M. Ha Minh, E.R., M. Wolf (TUM) & the IceCube Coll., in preparation



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.

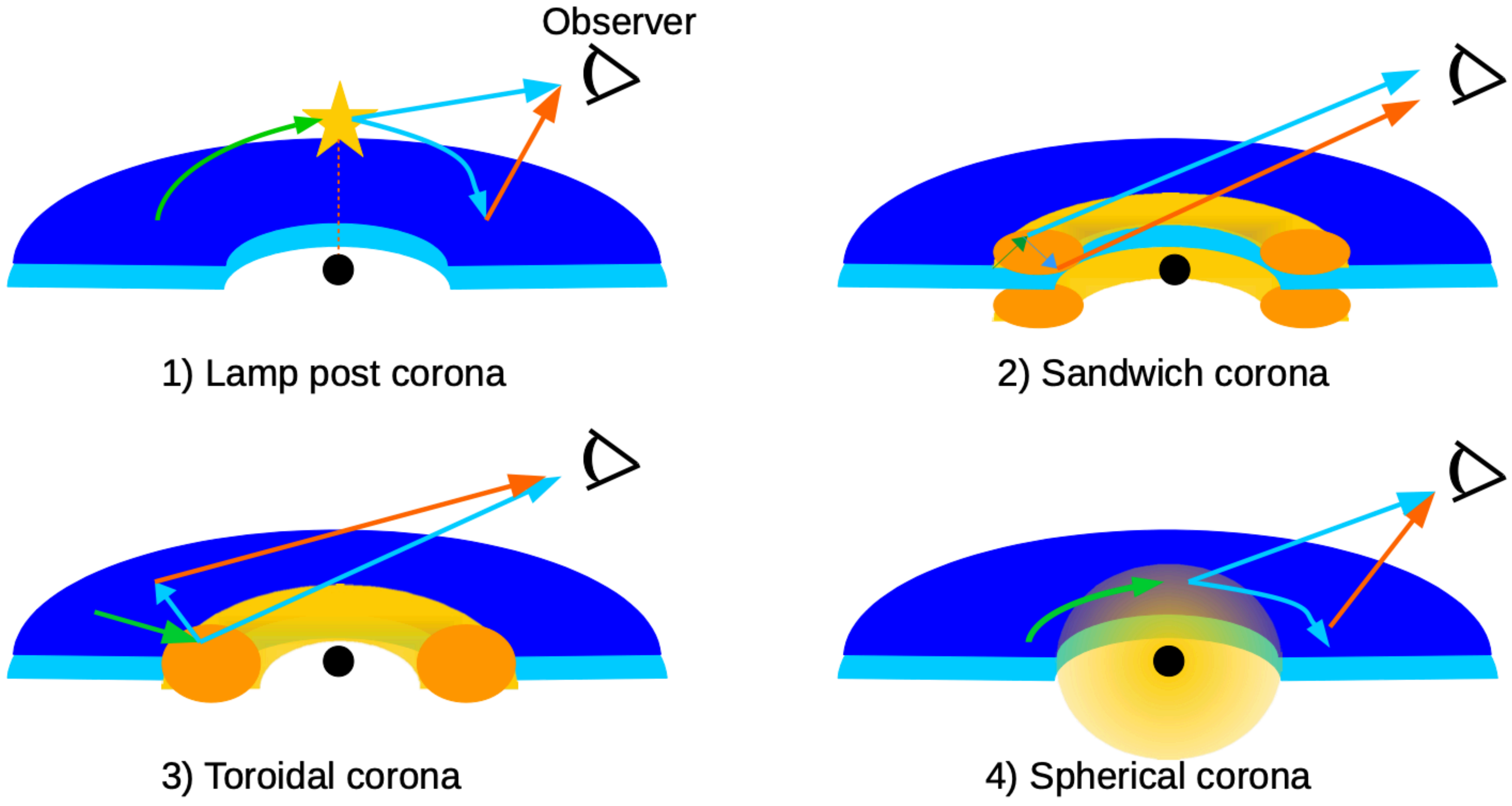


image from L. Baronchelli

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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

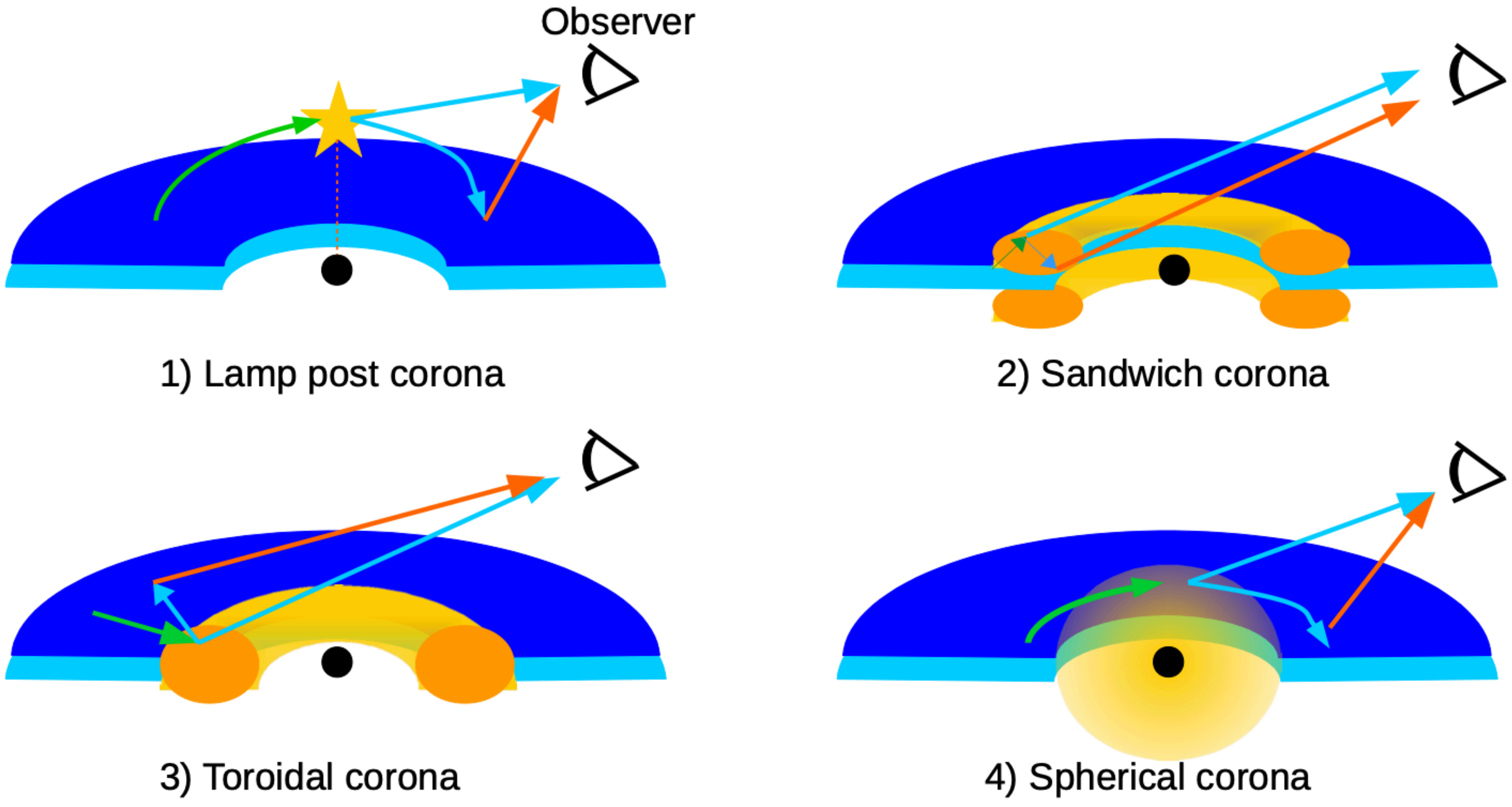


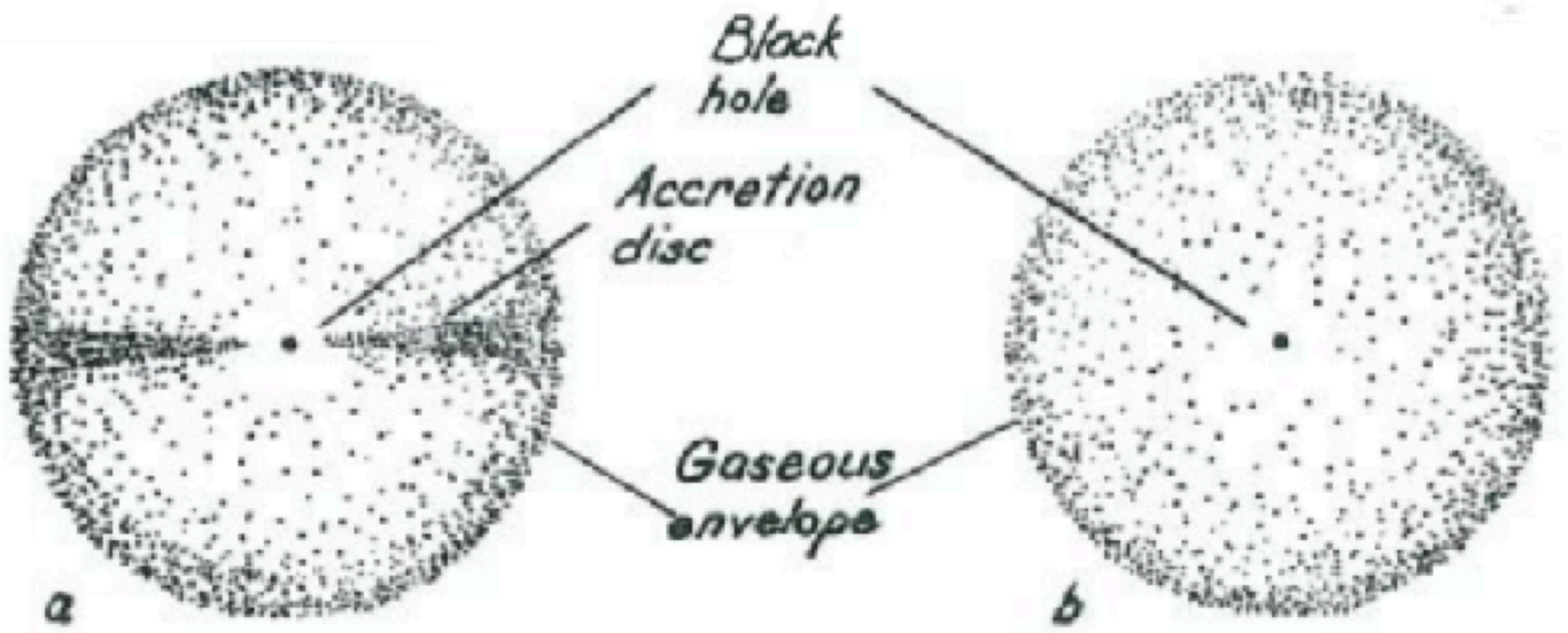
image from L. Baronchelli

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

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