Search for high-energy neutrinos from Active Galactic Nuclei with IceCube

Federica Bradascio (IRFU-CEA)

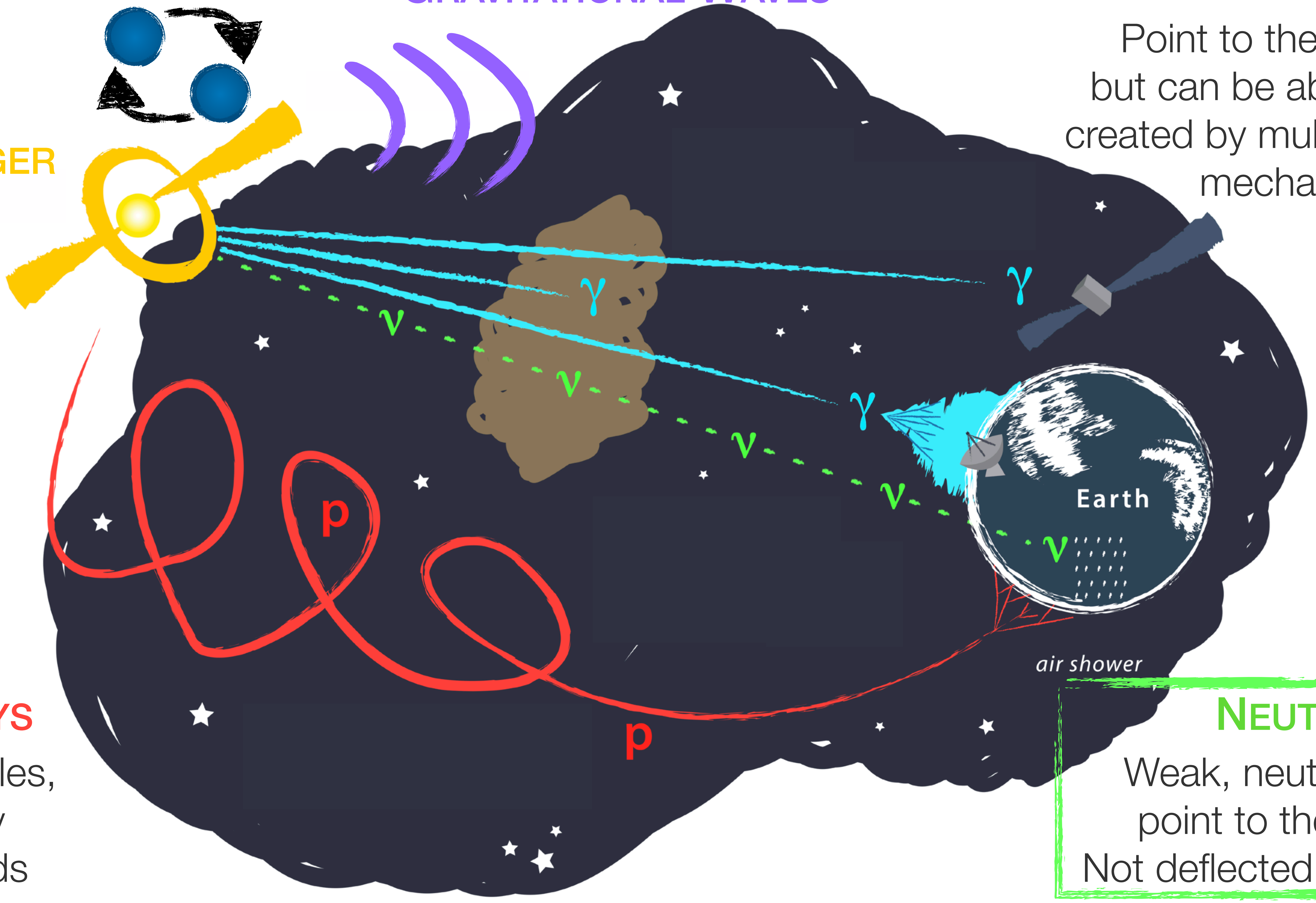
Séminaires du DPhP, IRFU-CEA
27 March, 2023


M106
Radio
Optical
IR
X-ray

Multimessenger astronomy

GRAVITATIONAL WAVES

MULTIMESSENGER SOURCE



GAMMA RAYS

Point to their sources, but can be absorbed and created by multiple emission mechanisms

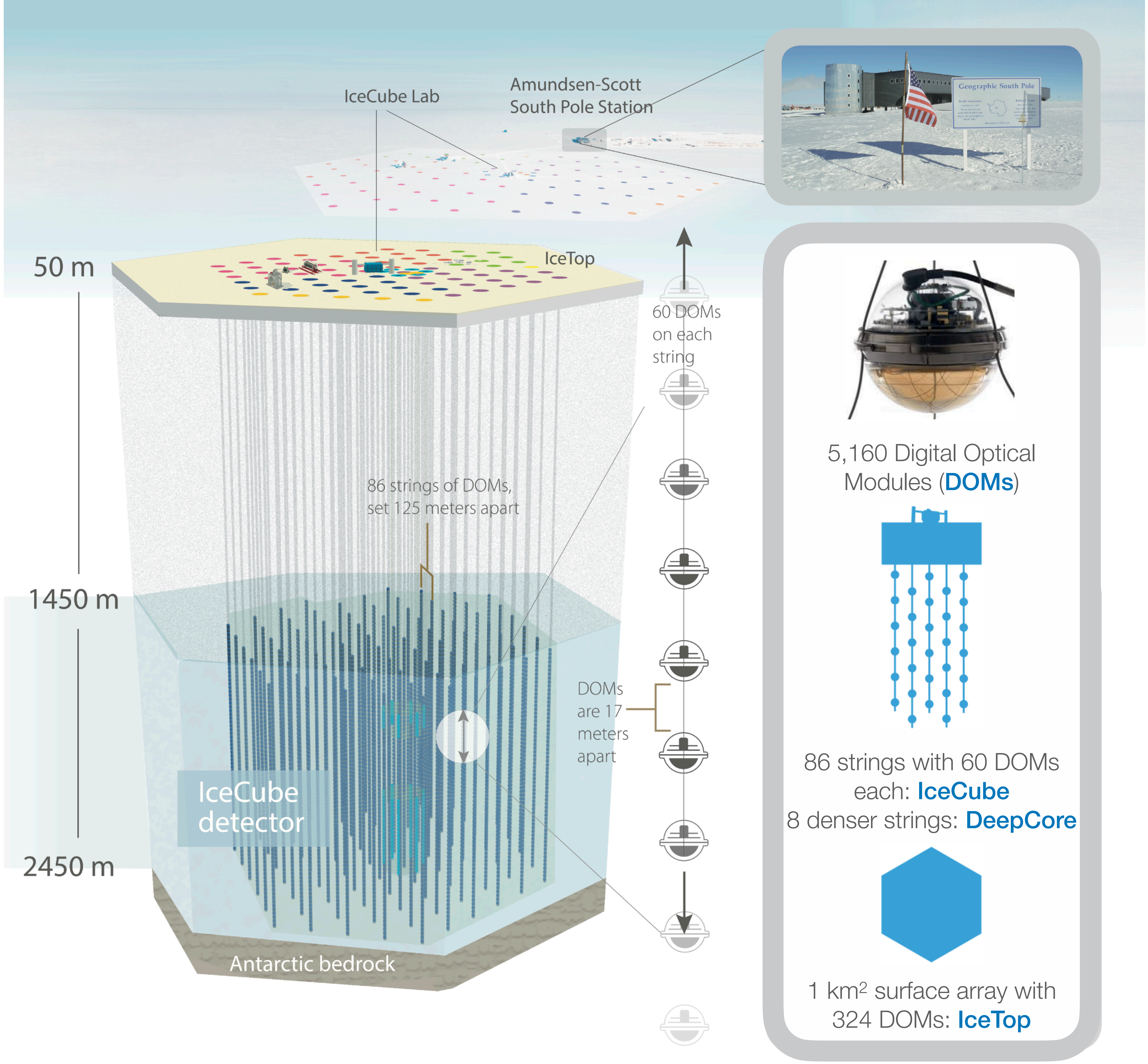
COSMIC RAYS

Charged particles, deflected by magnetic fields

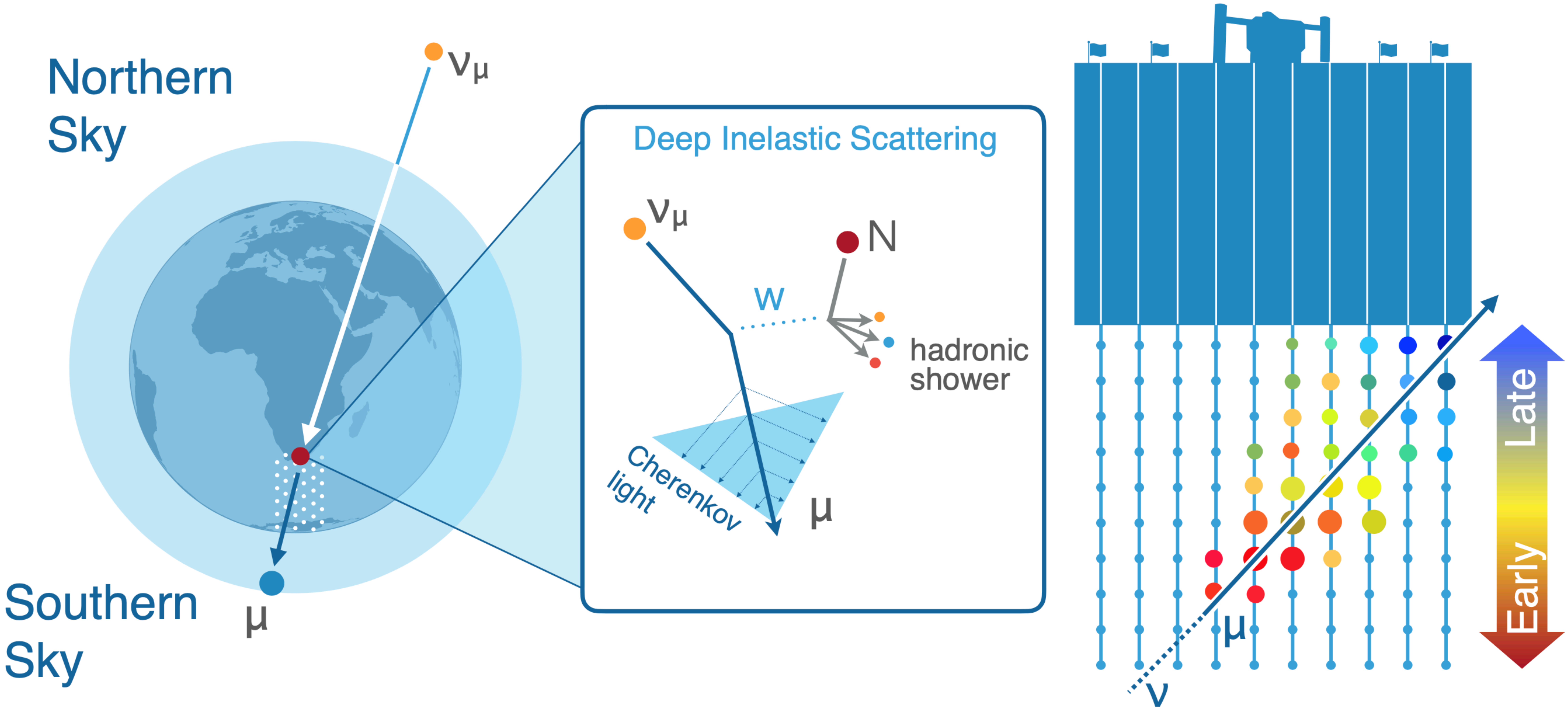
NEUTRINOS

Weak, neutral particles, point to their sources, Not deflected, not absorbed

The IceCube Neutrino Observatory

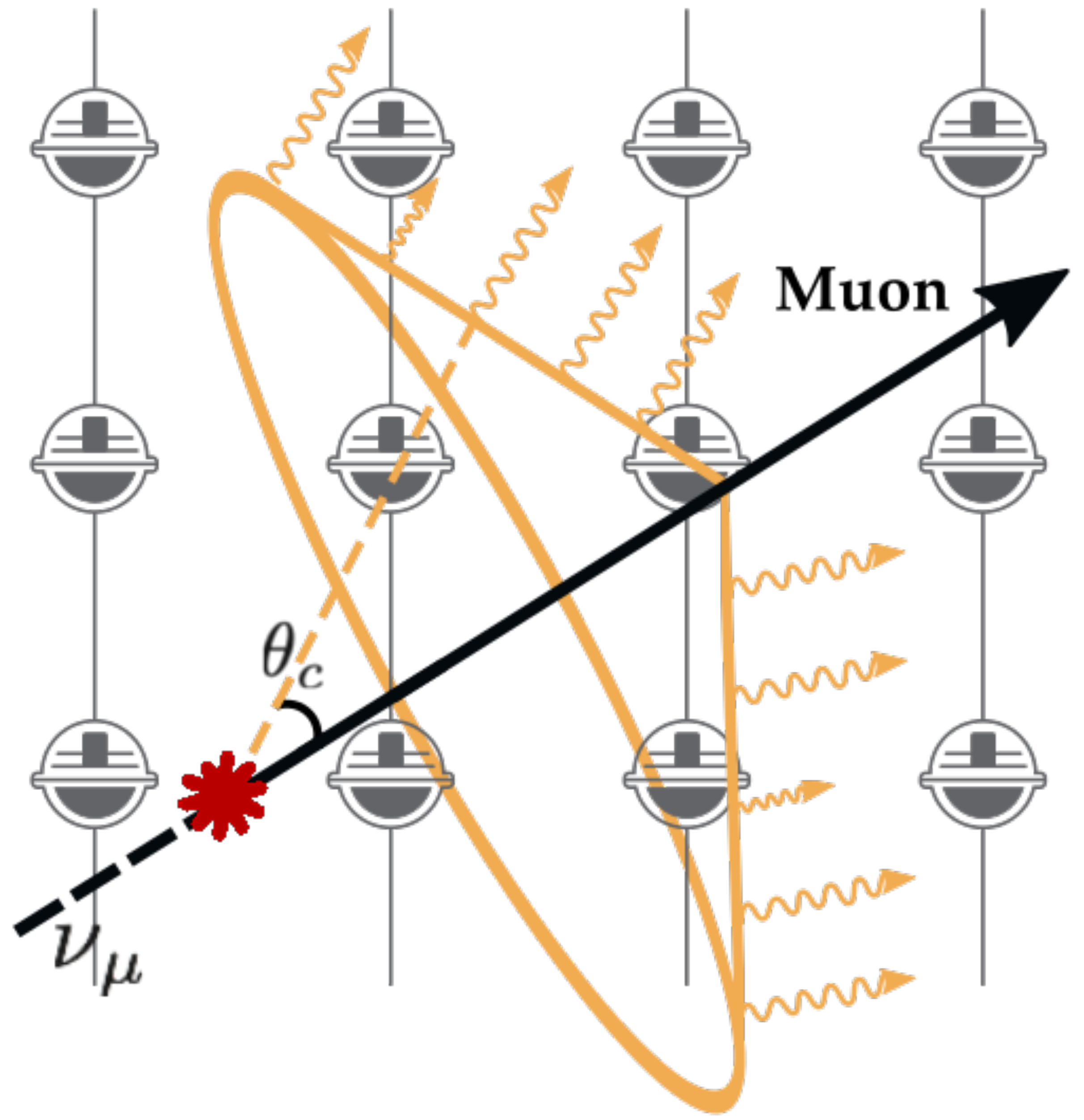


Neutrino detection principle



Neutrino event signature

Tracks

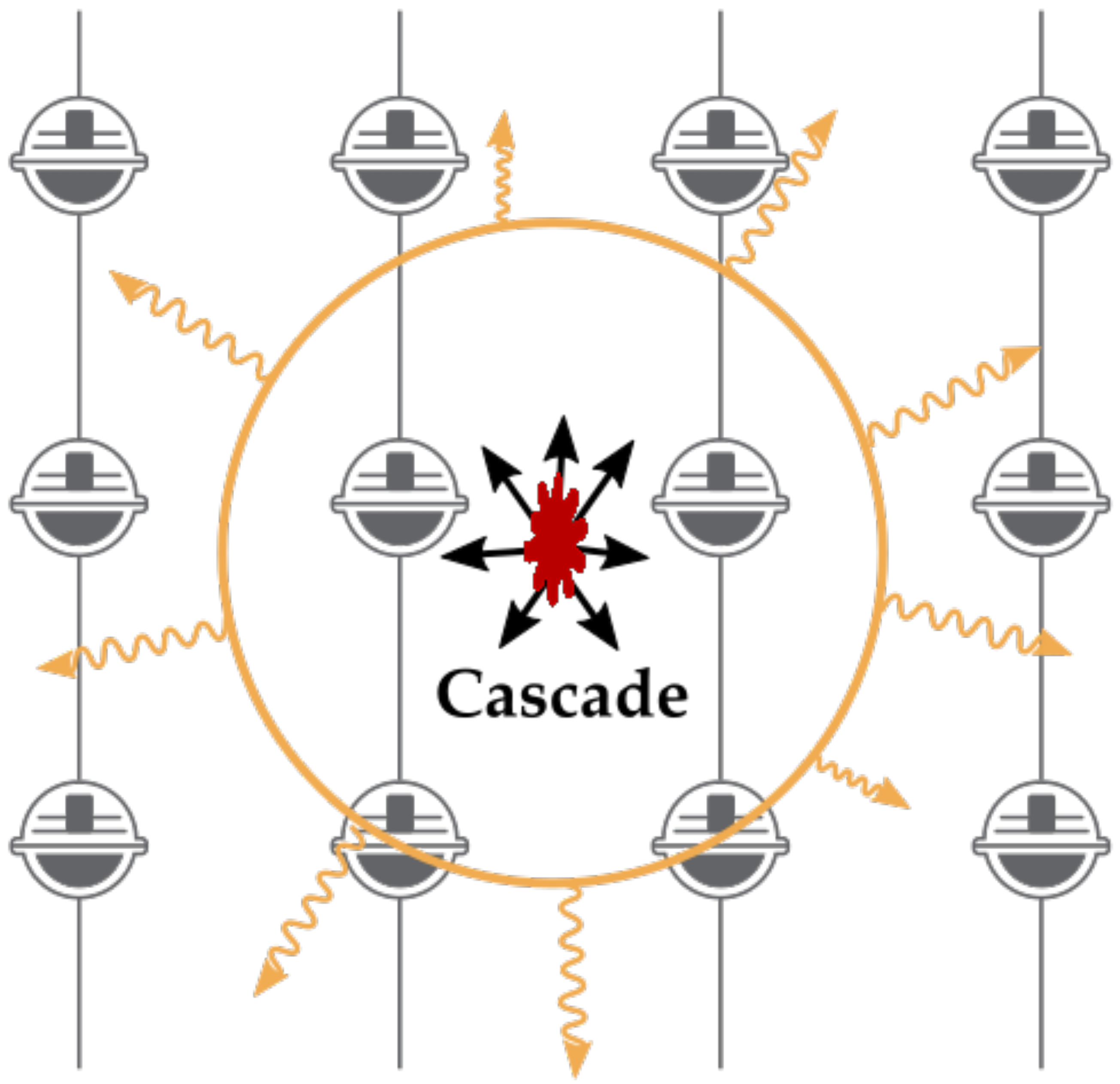


$$\nu_\mu + N \rightarrow \mu + X$$

Good angular resolution 0.1-1 deg

Neutrino astronomy

Cascades



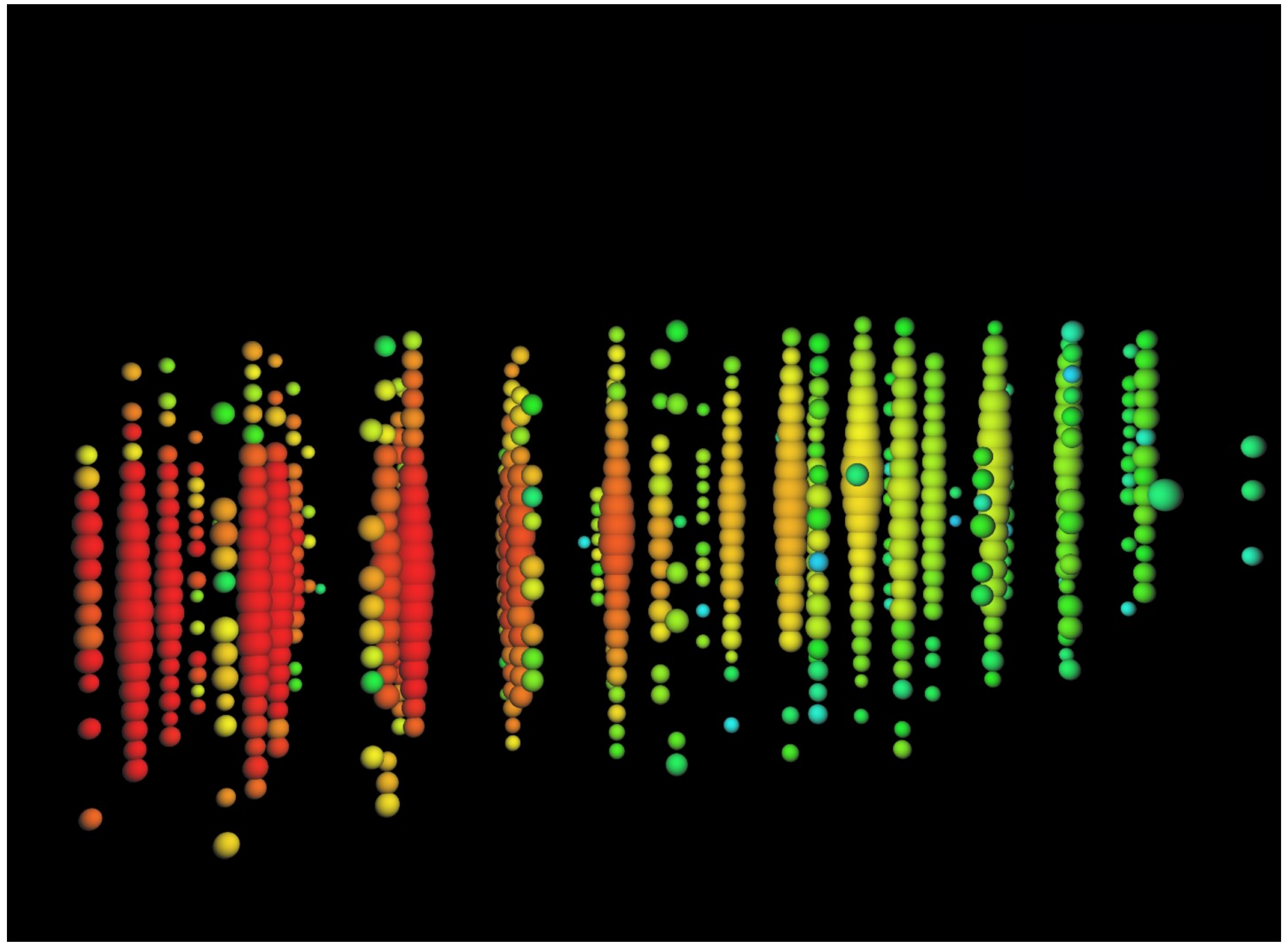
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

Good energy resolution ~15%

Neutrino event signature

Tracks

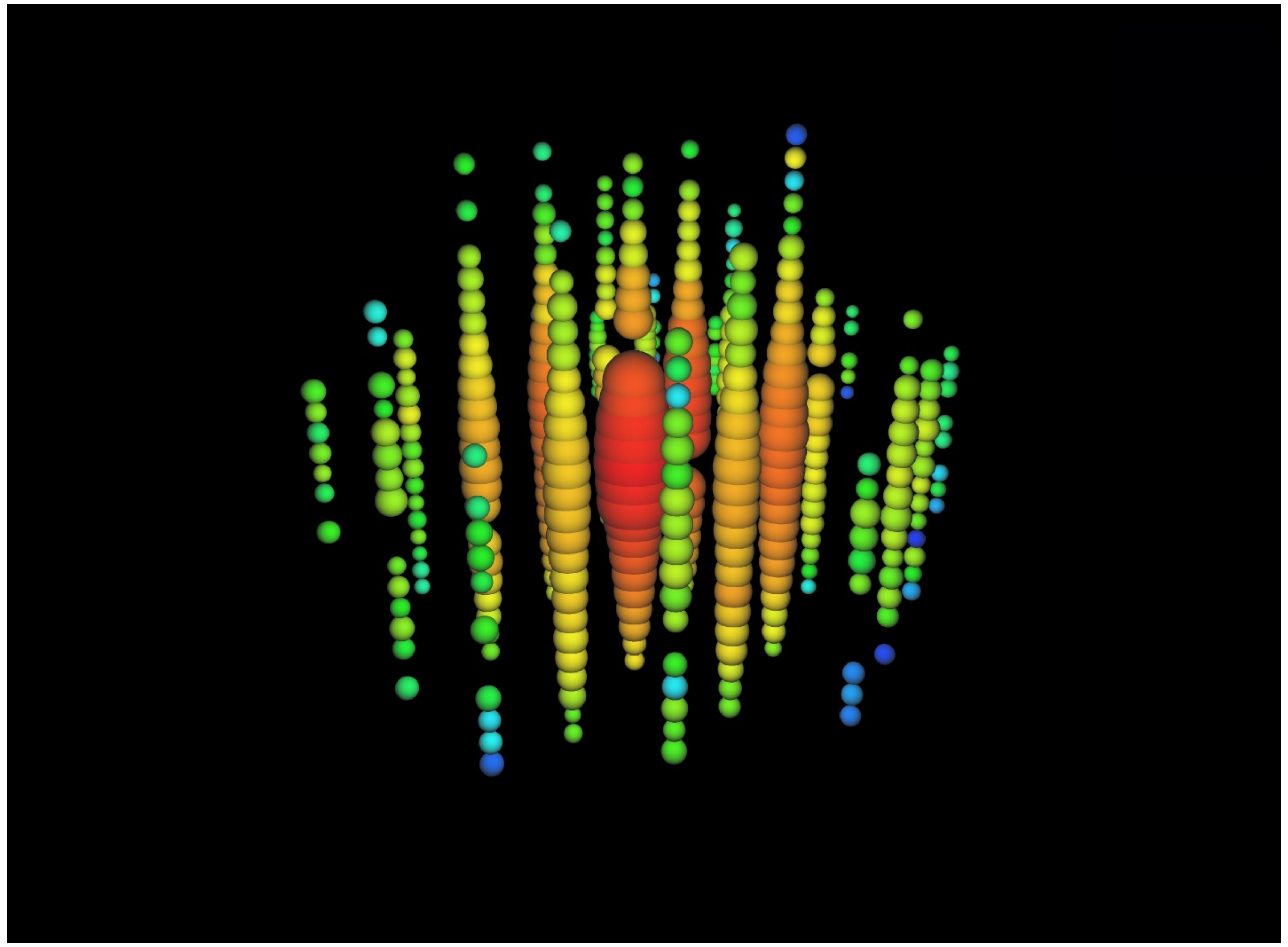


$$\nu_\mu + N \rightarrow \mu + X$$

Good angular resolution 0.1-1 deg

Neutrino astronomy

Cascades



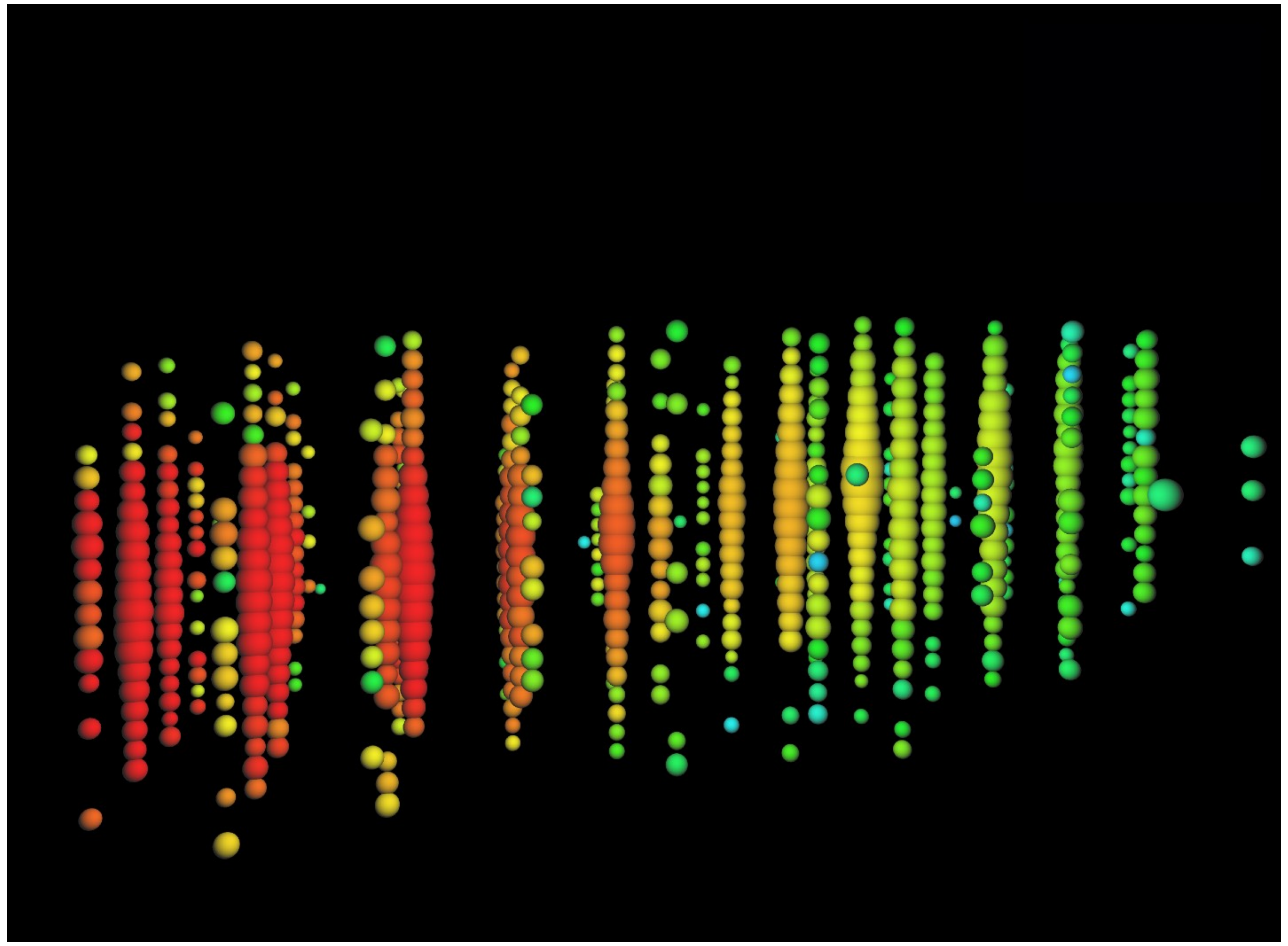
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

Good energy resolution ~15%

Neutrino event signature

Tracks

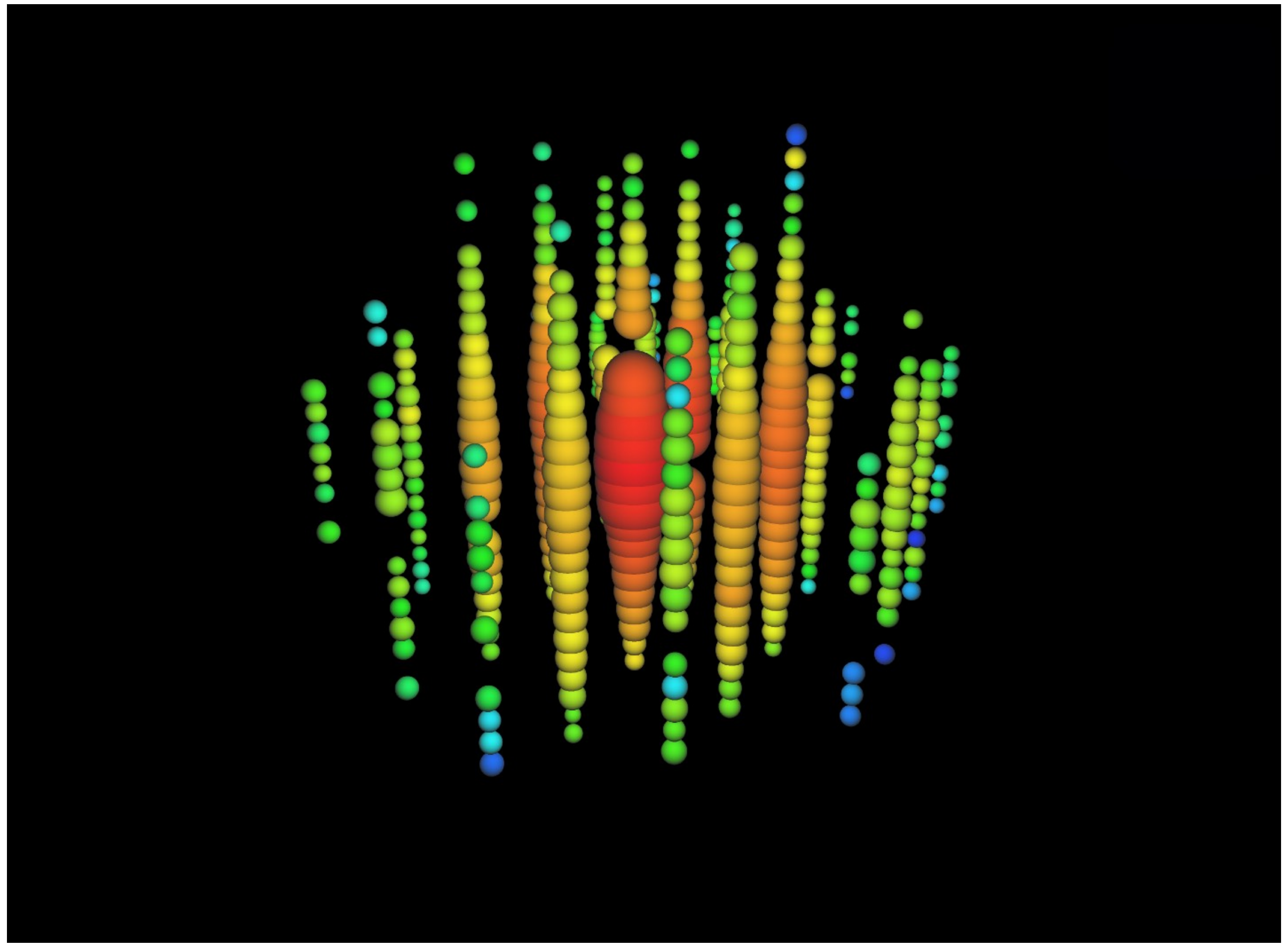


$$\nu_\mu + N \rightarrow \mu + X$$

Good angular resolution 0.1-1 deg

Neutrino astronomy

Cascades



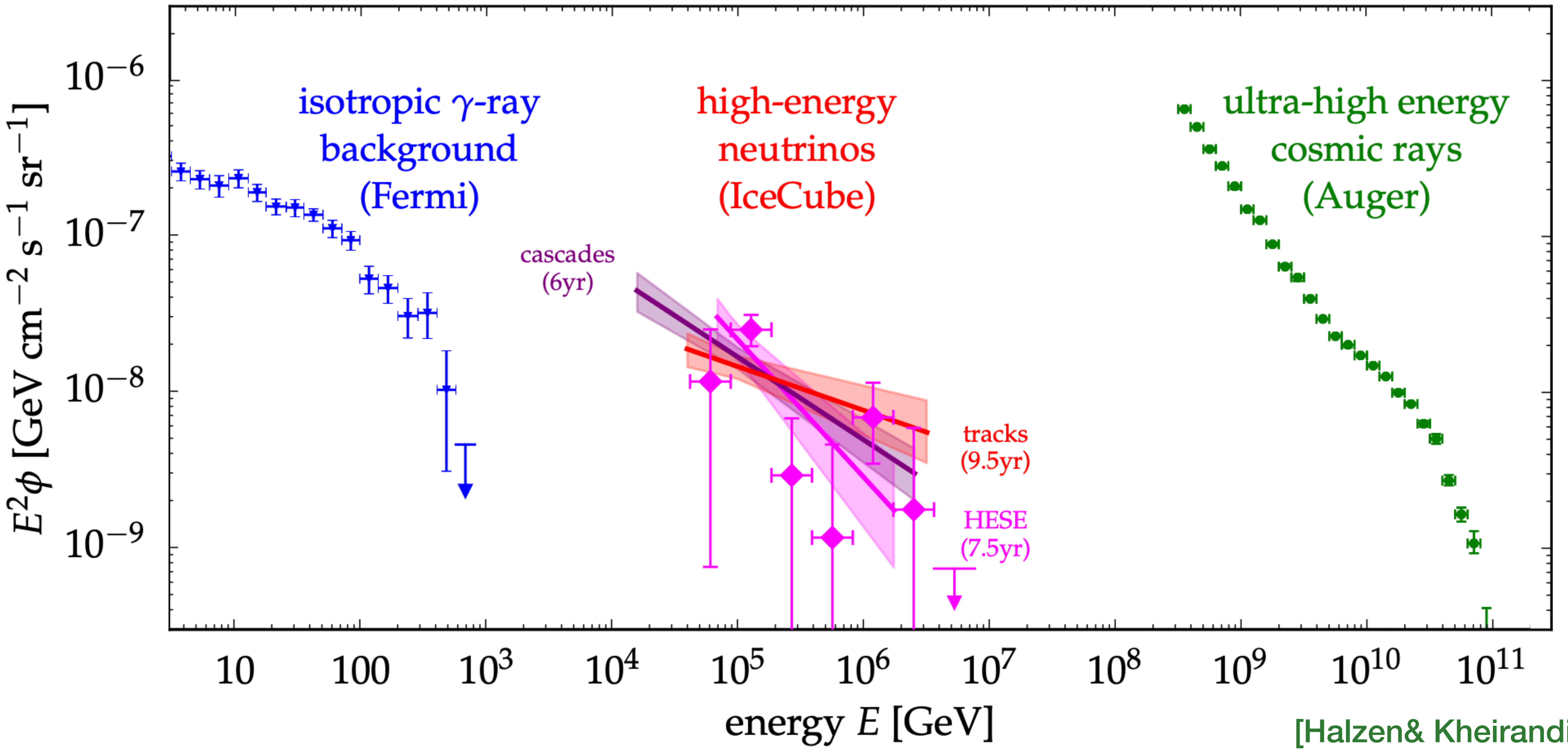
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

Good energy resolution ~15%

Astrophysical diffuse TeV-PeV neutrinos

In the multimessenger picture

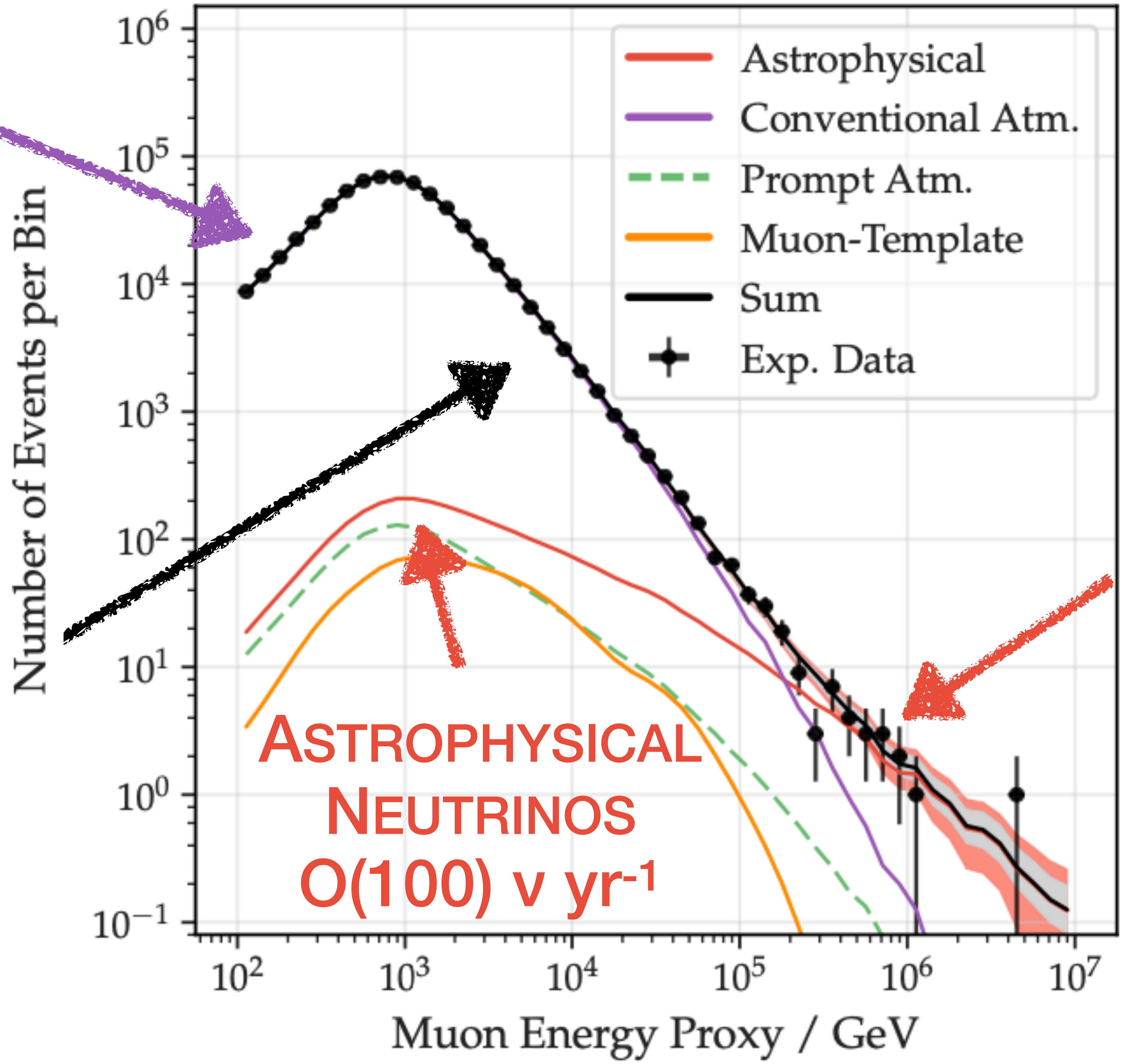


[Halzen& Kheirandish, arXiv/2202.00694]

Similar energies in γ-rays, neutrinos and CRs injected into our Universe!

How to search of neutrino sources?

ATMOSPHERIC BACKGROUND
O(10^5) ν yr^{-1}



Muon neutrino events using 9.5yr of IceCube data

ASTROPHYSICAL NEUTRINOS
O(100) ν yr^{-1}

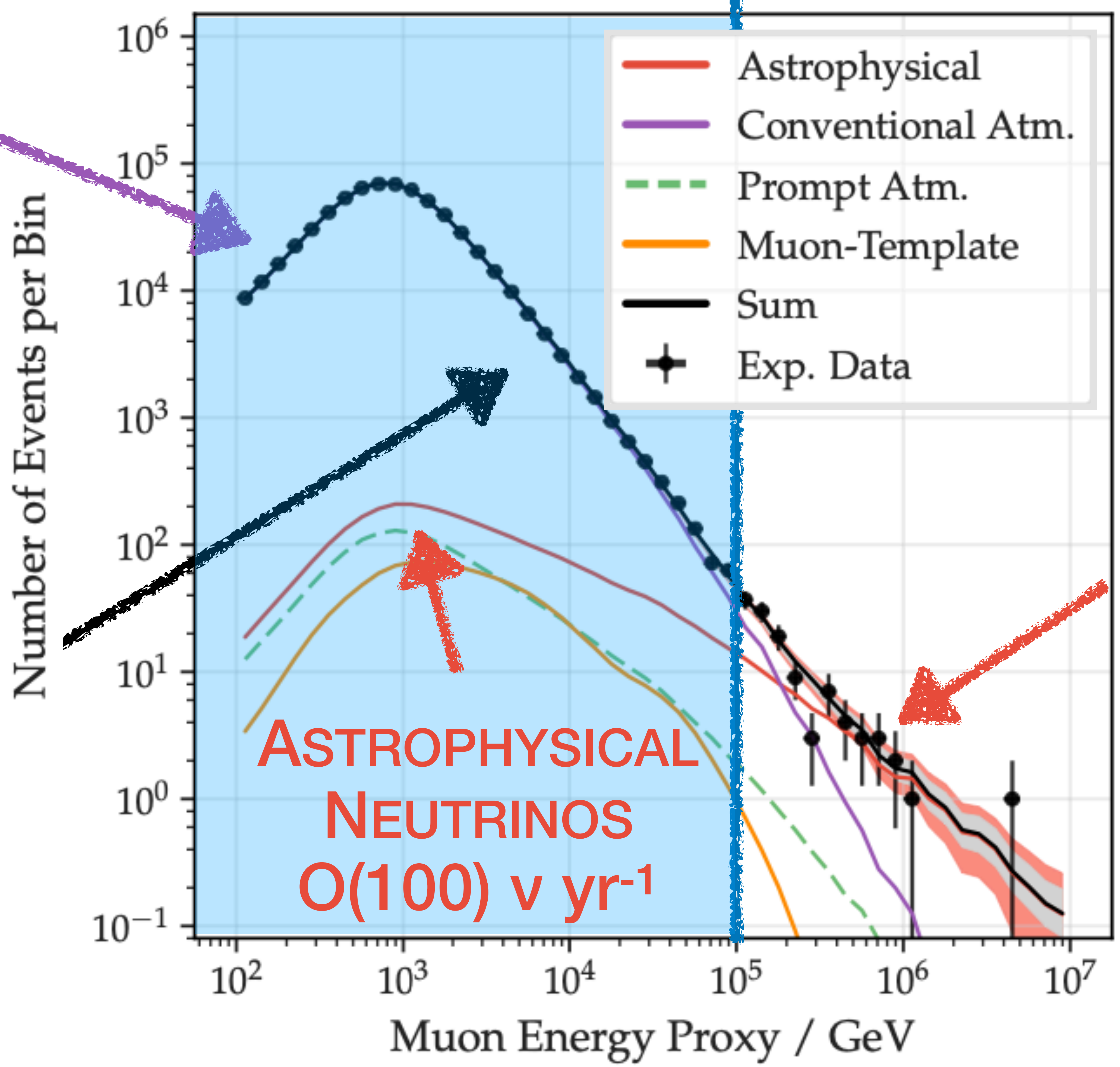
ASTROPHYSICAL NEUTRINOS
O(10) ν yr^{-1}

[Icecube 2022 *ApJ* **928** 50]

How to search of neutrino sources?

Atmospheric Background $O(10^5)$ ν yr^{-1}

Clustering

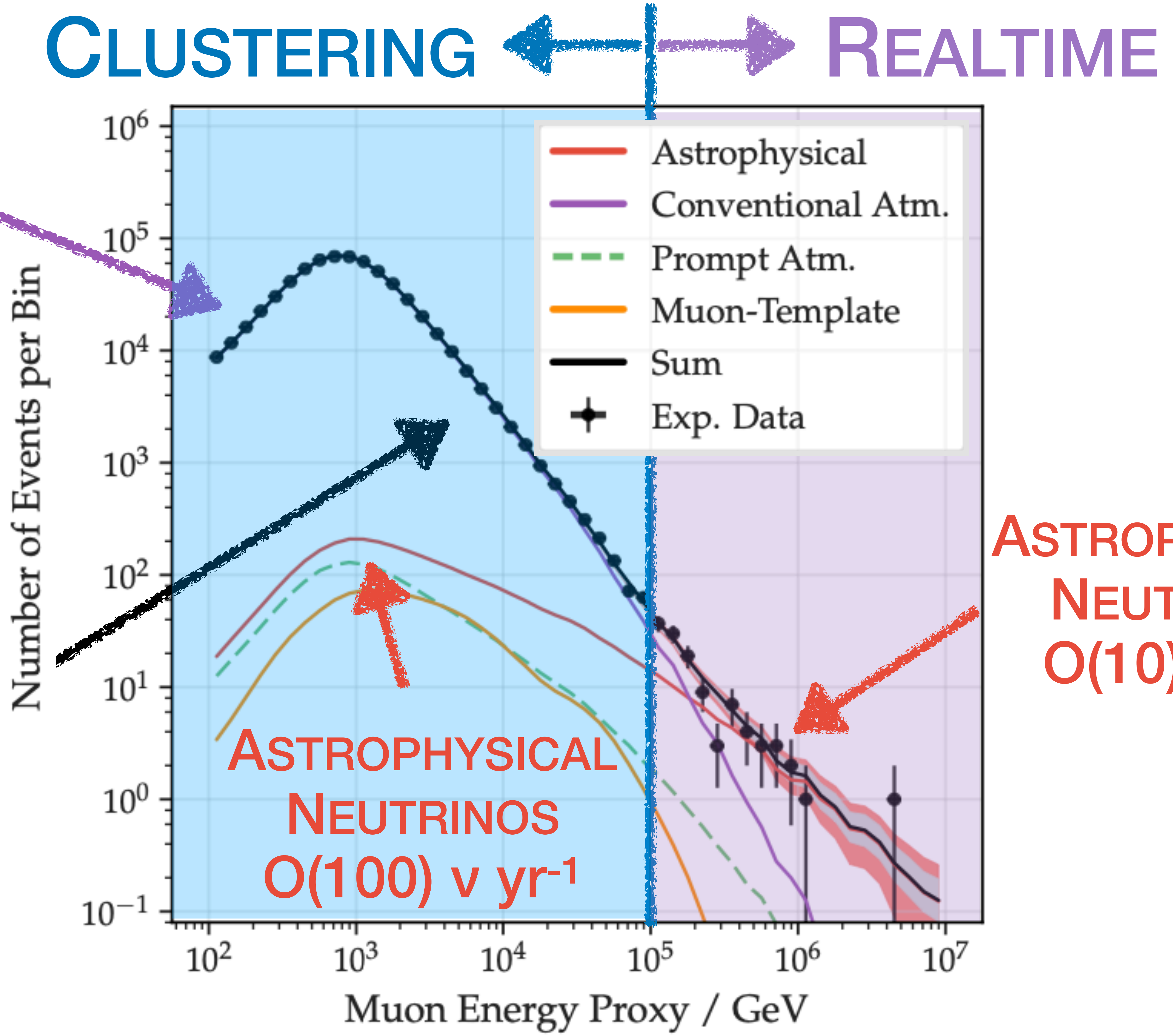


Astrophysical Neutrinos $O(10)$ ν yr^{-1}

Muon neutrino events using 9.5yr of IceCube data

[Icecube 2022 *ApJ* **928** 50]

How to search of neutrino sources?



ATMOSPHERIC BACKGROUND O(10^5) ν yr^{-1}

Muon neutrino events using 9.5yr of IceCube data

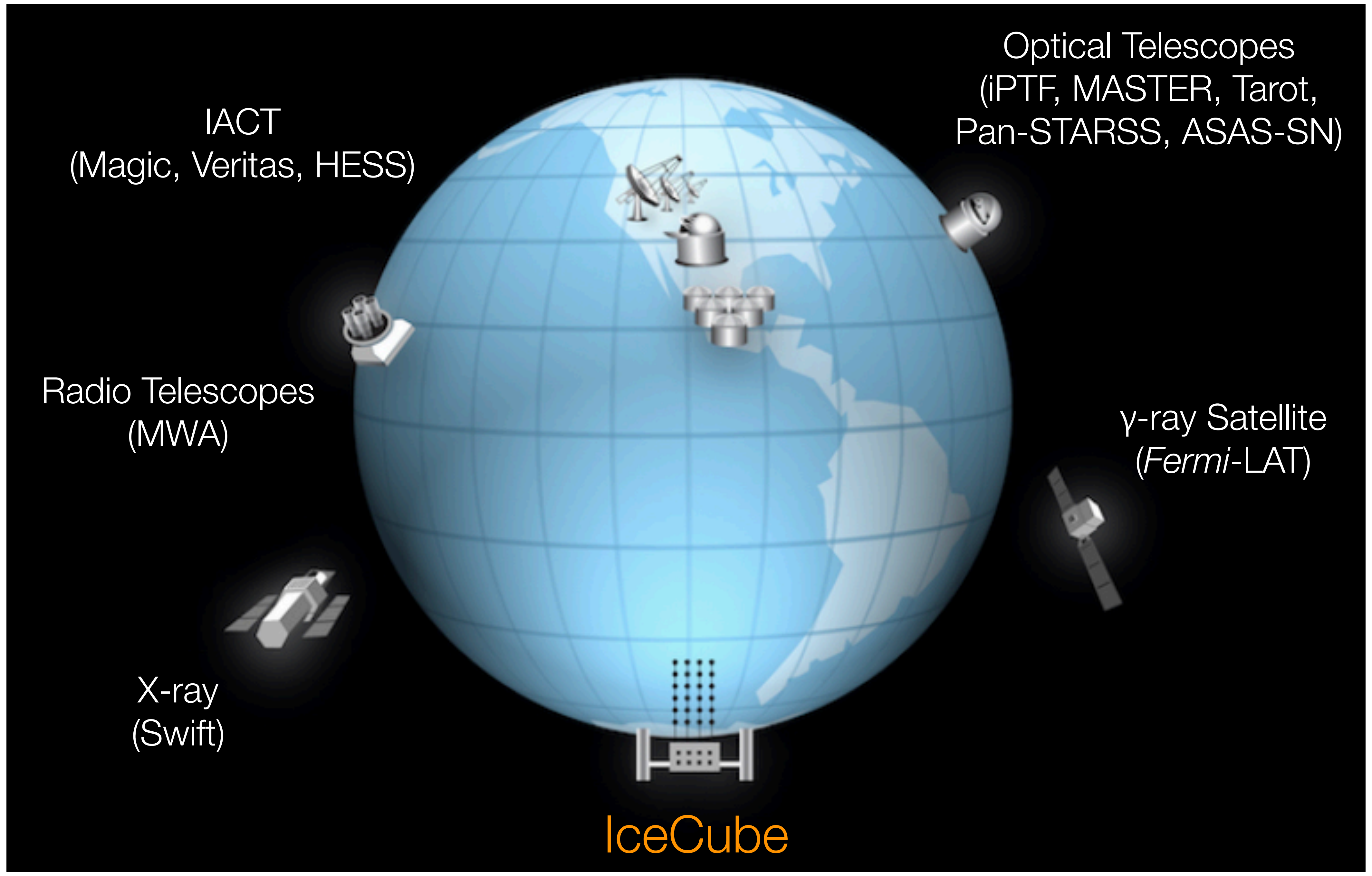
ASTROPHYSICAL NEUTRINOS O(10) ν yr^{-1}

[Icecube 2022 *ApJ* **928** 50]

Realtime searches

Follow-up of astrophysical neutrino events

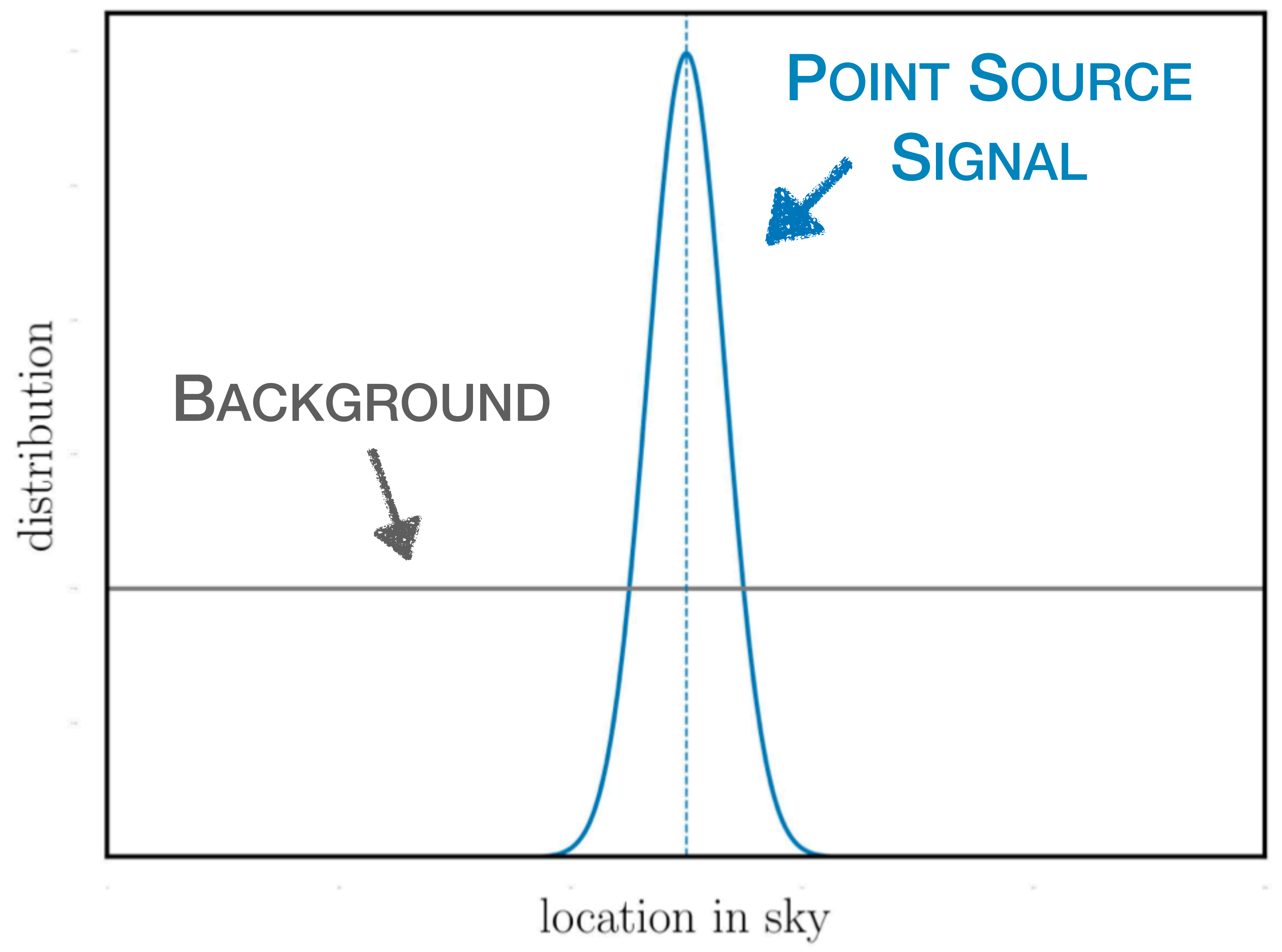
- Single high-energy muon track events with high probability of being astrophysical ($E \gtrsim 100$ TeV)
- Since 2016, alerts are distributed through GCN network to ground and space-based observatories for rapid follow-ups
- Average alerts rate of ~2/month
- Median latency ~30 sec



Goal: find electromagnetic counterpart

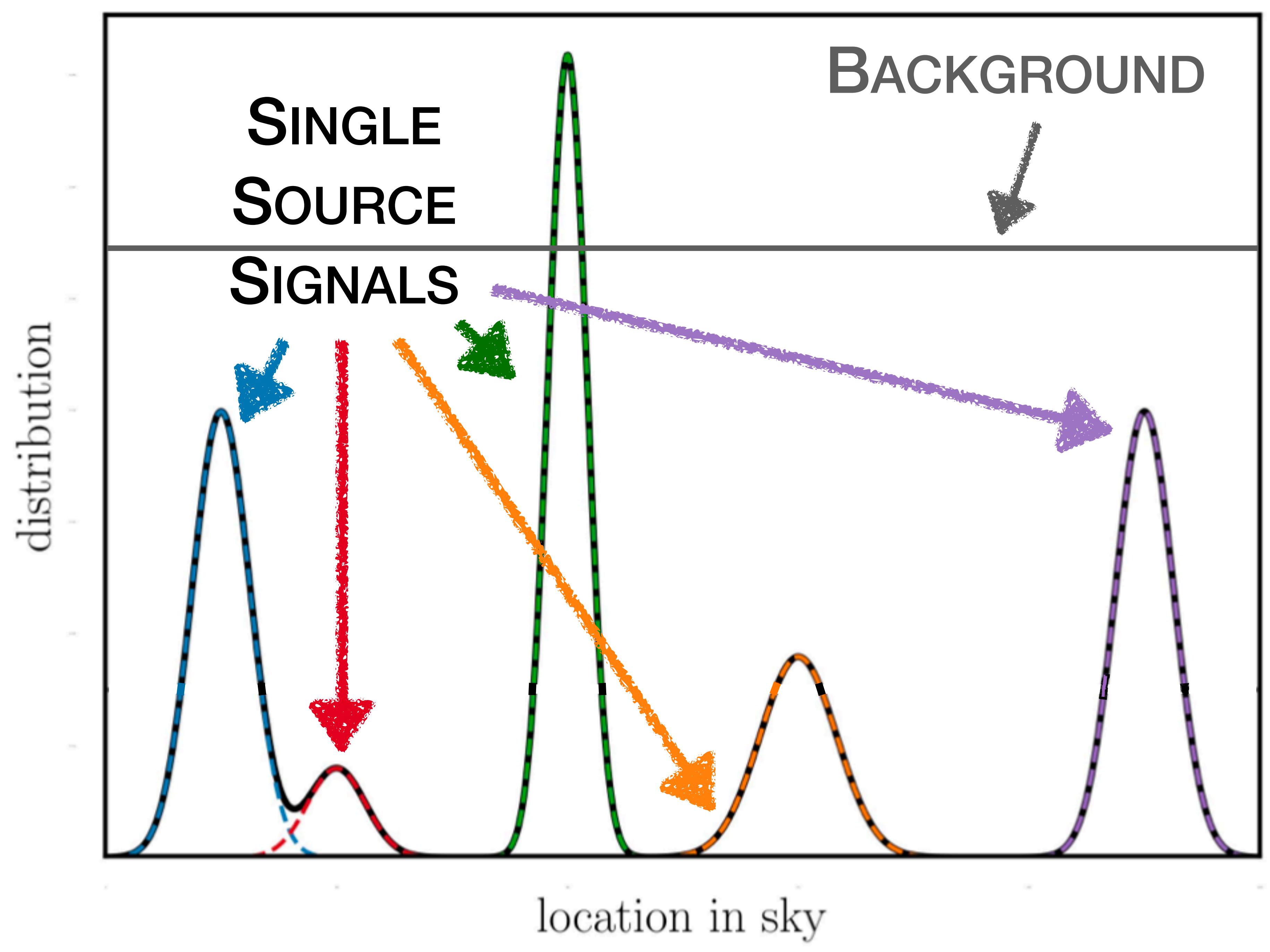
Clustering searches

SINGLE SOURCE SEARCH / CATALOGUE SEARCH



Search N sources individually
⇒ Identify hotspots in the neutrino sky

STACKING SEARCH

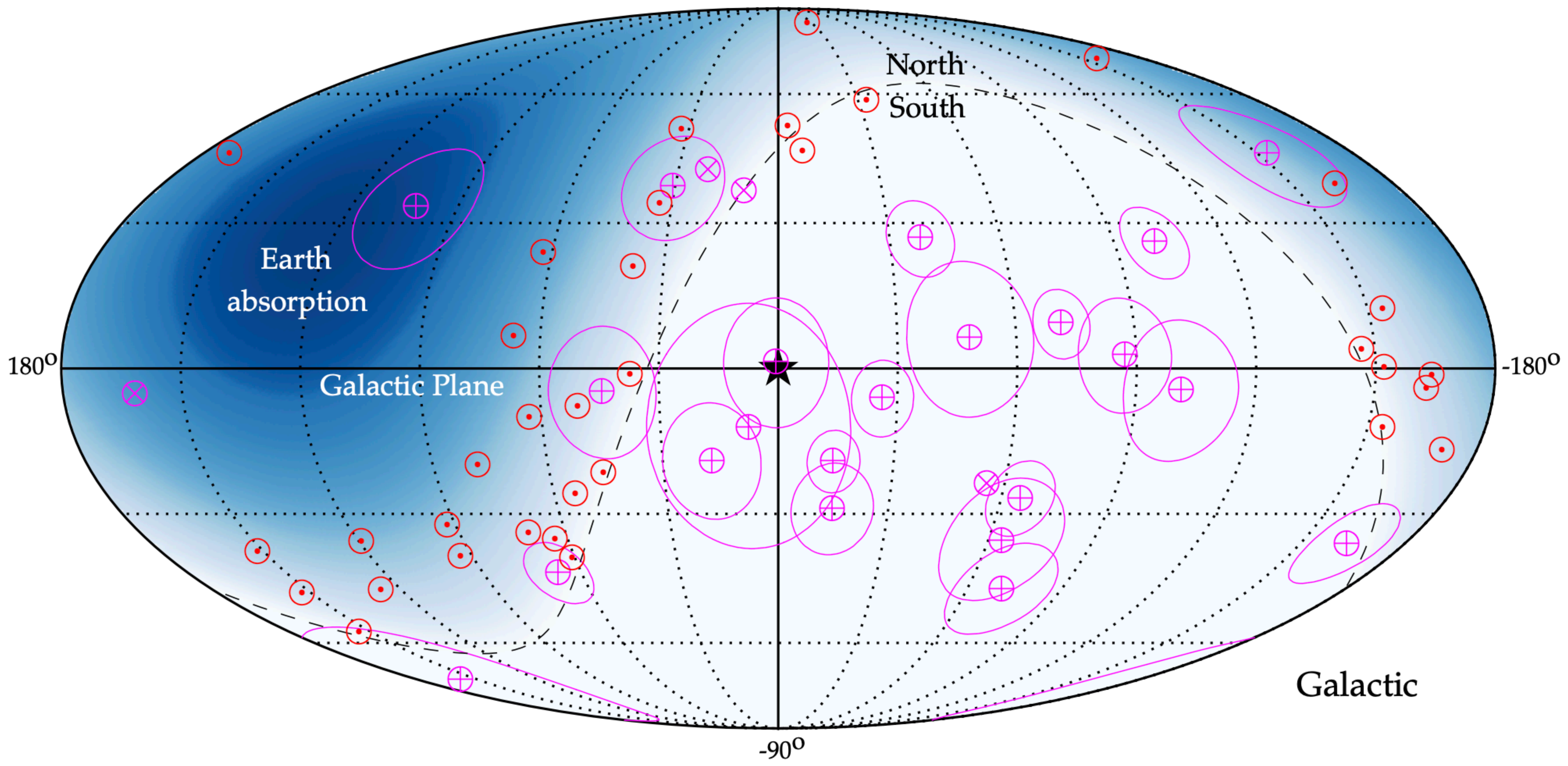


Search for combined signal from N sources from catalogues ⇒ Each source is weighted

Status of neutrino astronomy

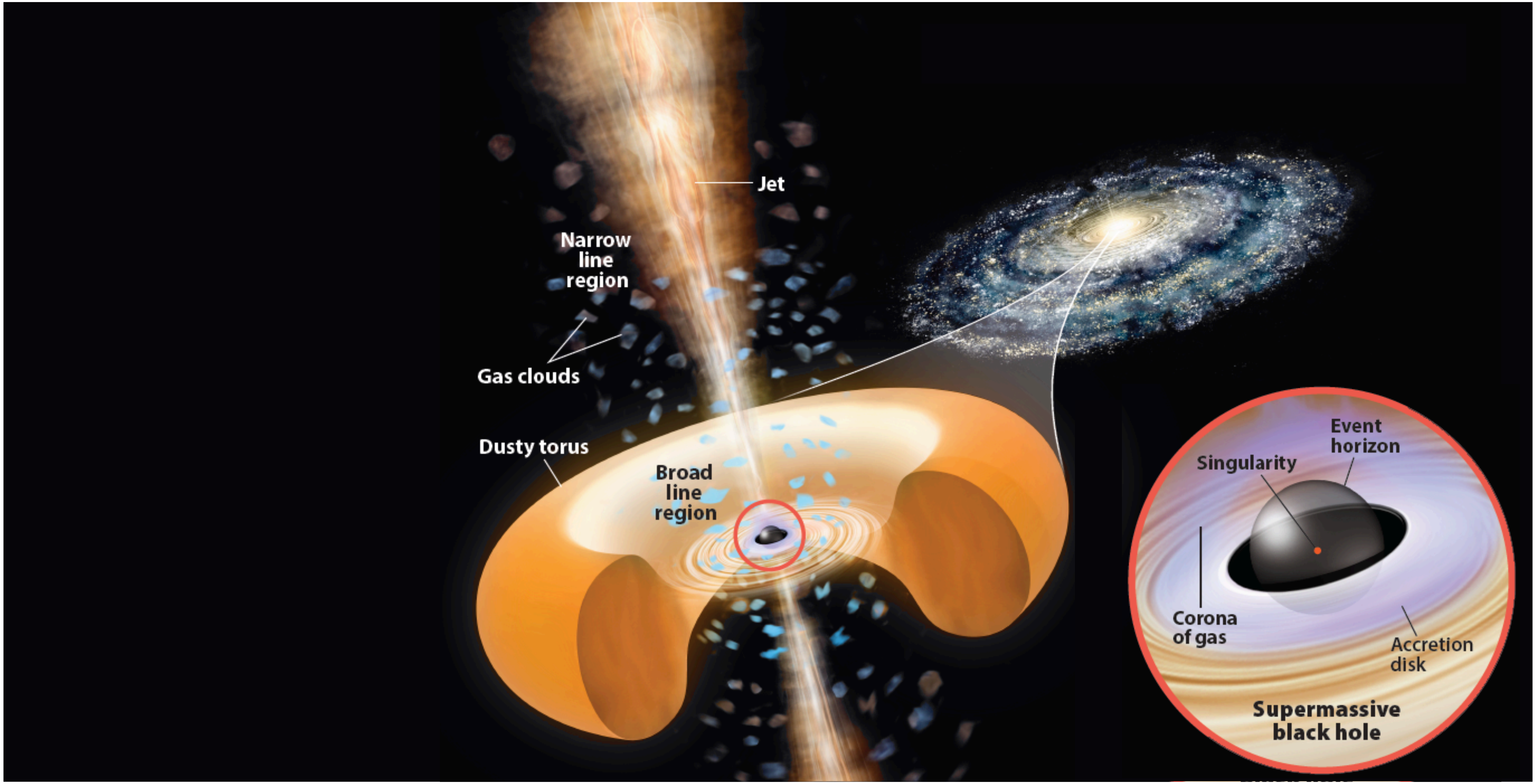
Extragalactic origin favoured by quasi-isotropic distribution

Most energetic neutrino events HESE 6yr (magenta) & $\nu_\mu + \bar{\nu}_\mu$ 8yr (red)

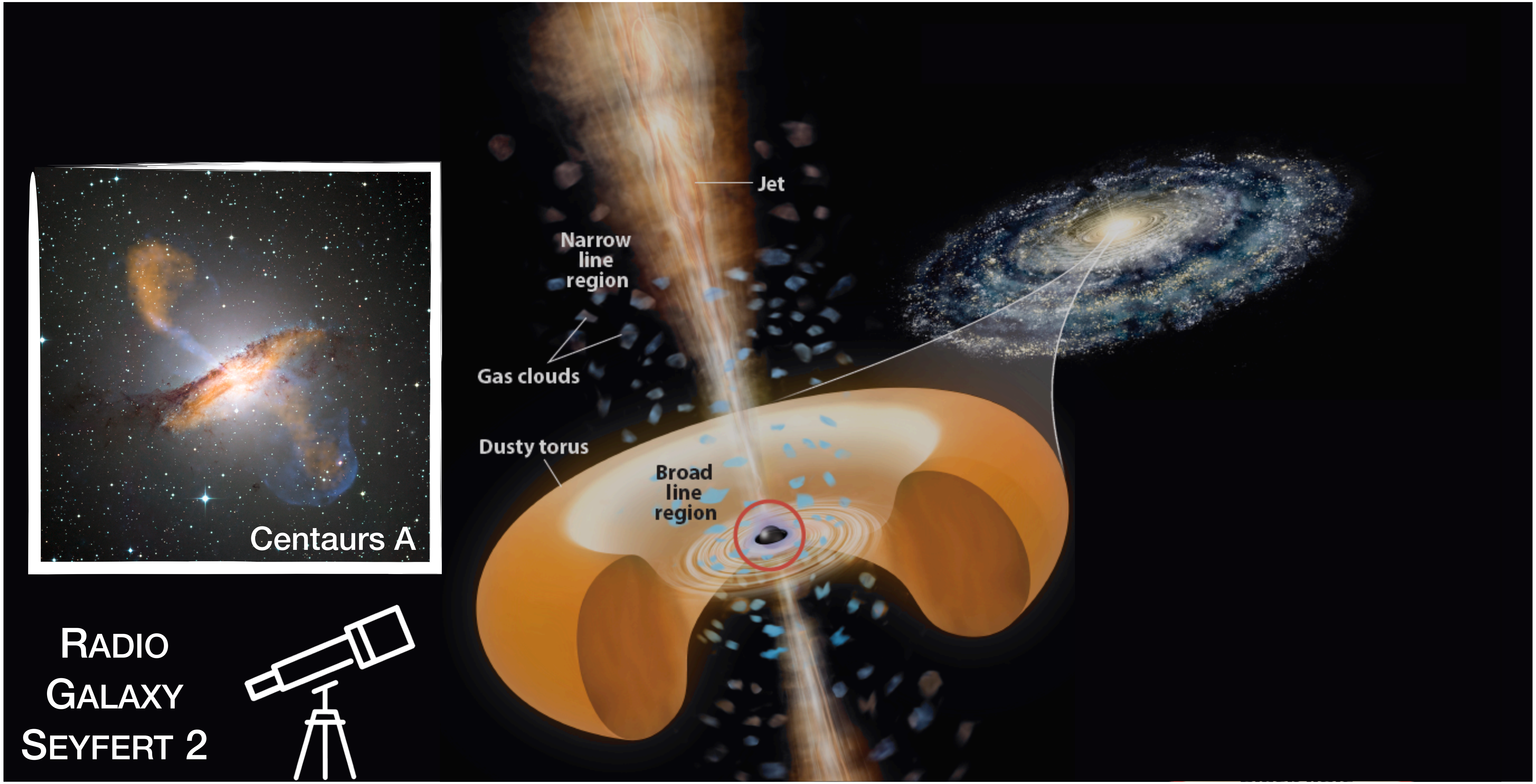


No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates (e.g. AGN)**

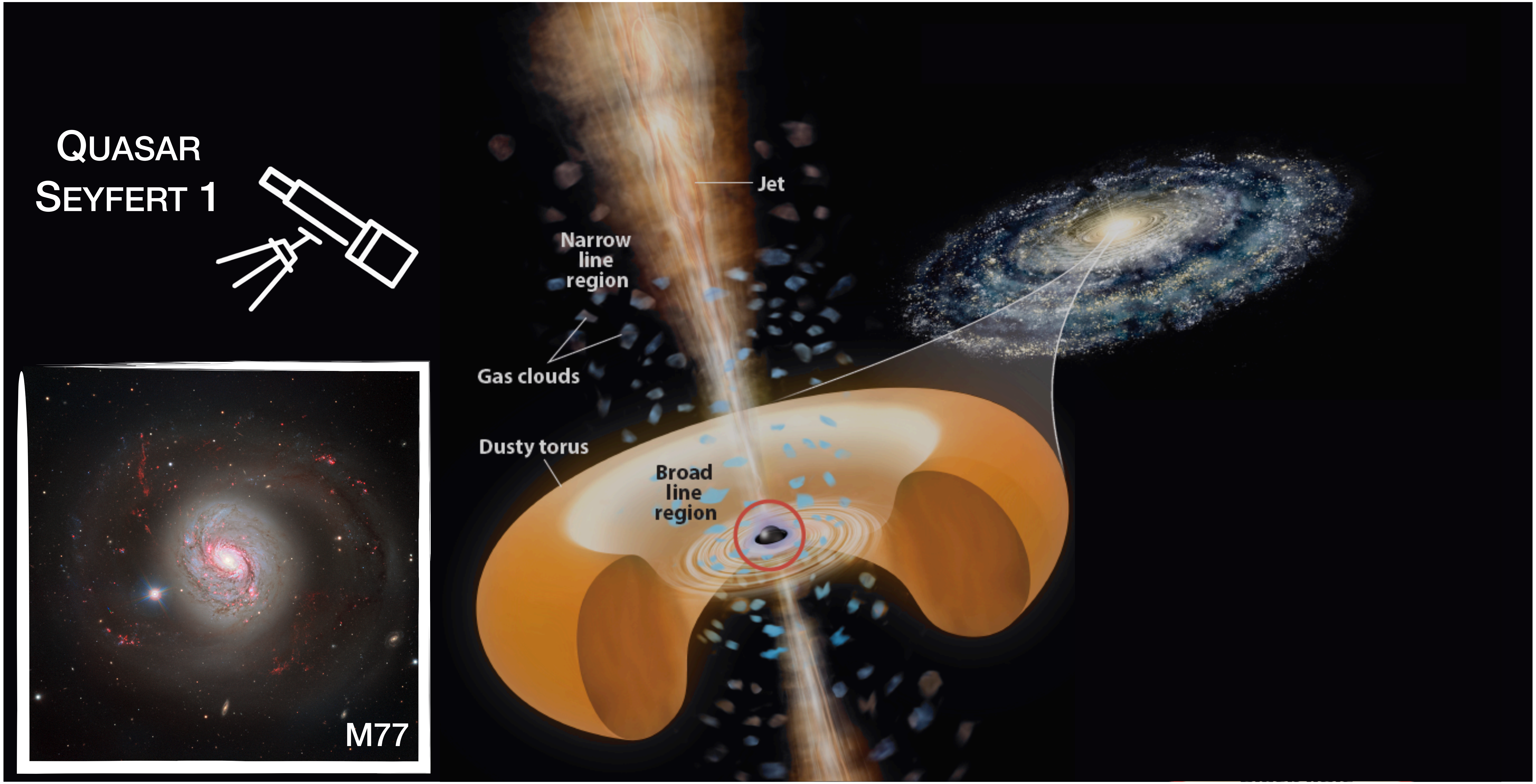
AGN as Neutrino Sources



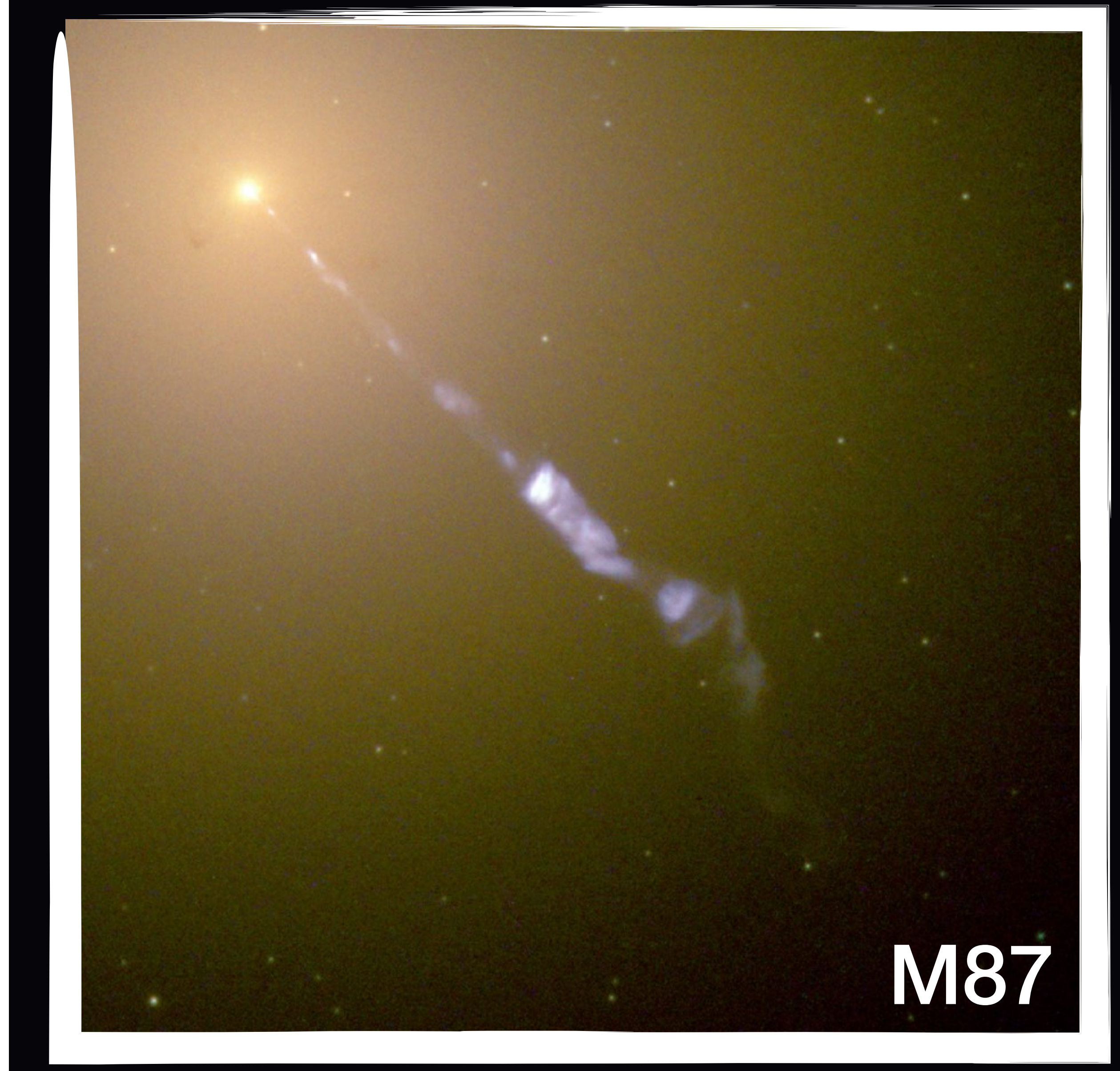
AGN as Neutrino Sources

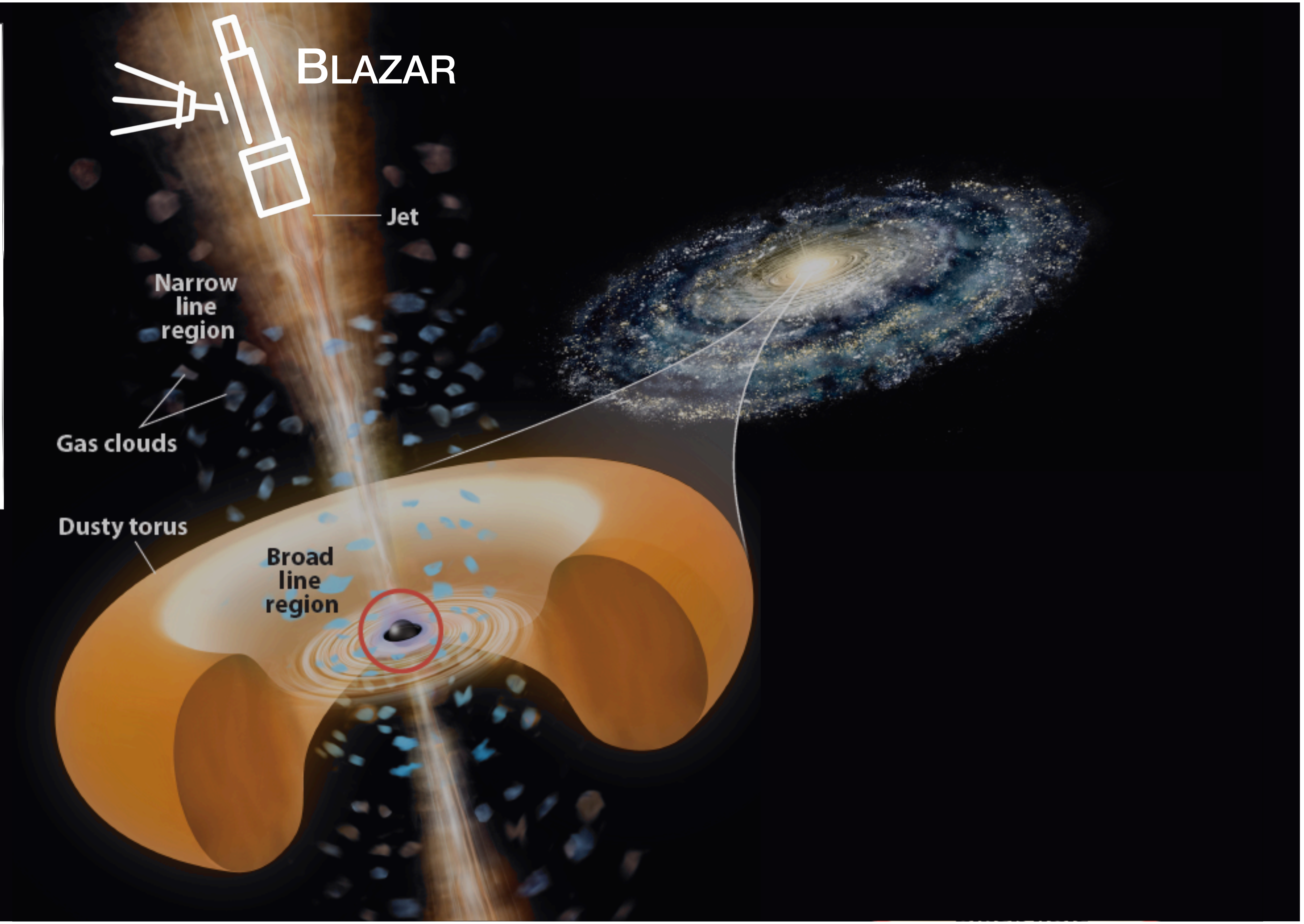


AGN as Neutrino Sources



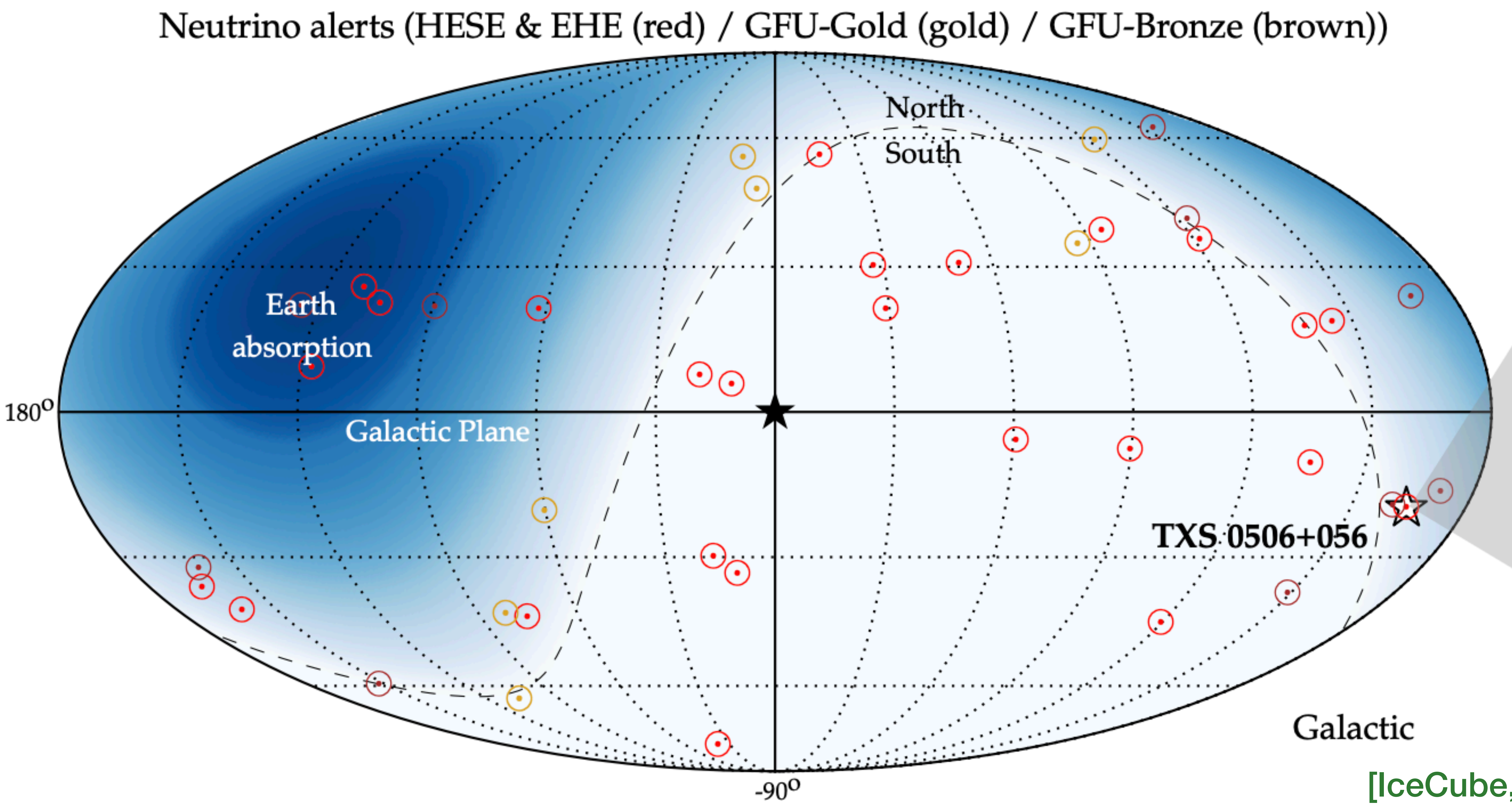
AGN as Neutrino Sources

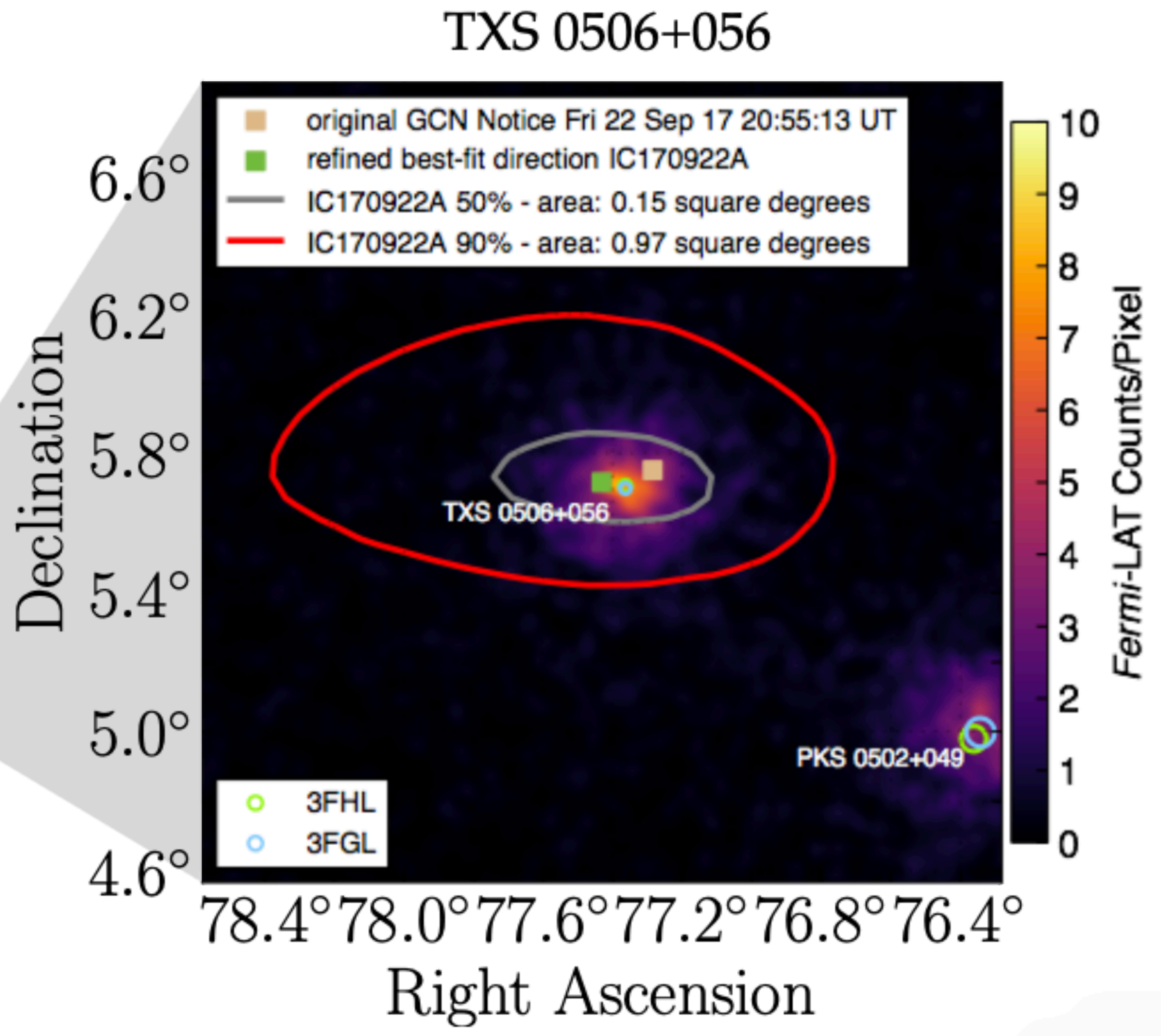




TXS 0506+056: realtime MM coincidence

IC-170922A observed in coincidence with flaring **gamma-ray blazar**

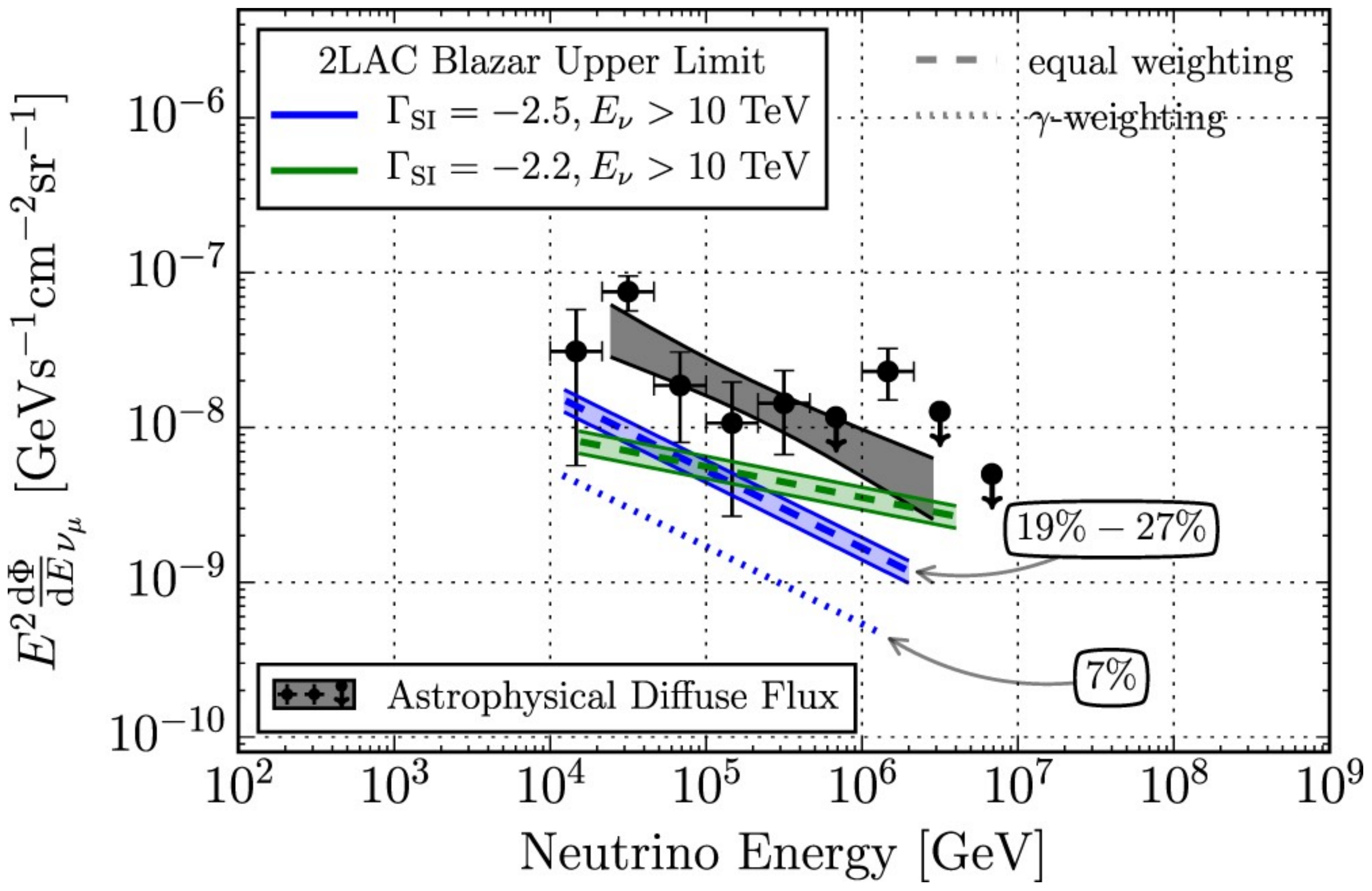




[IceCube, PoS (ICRC2019) 1021; Science 361(2018)6398]

Chance correlation can be rejected at the 3σ-level

Fermi-LAT blazar stacking

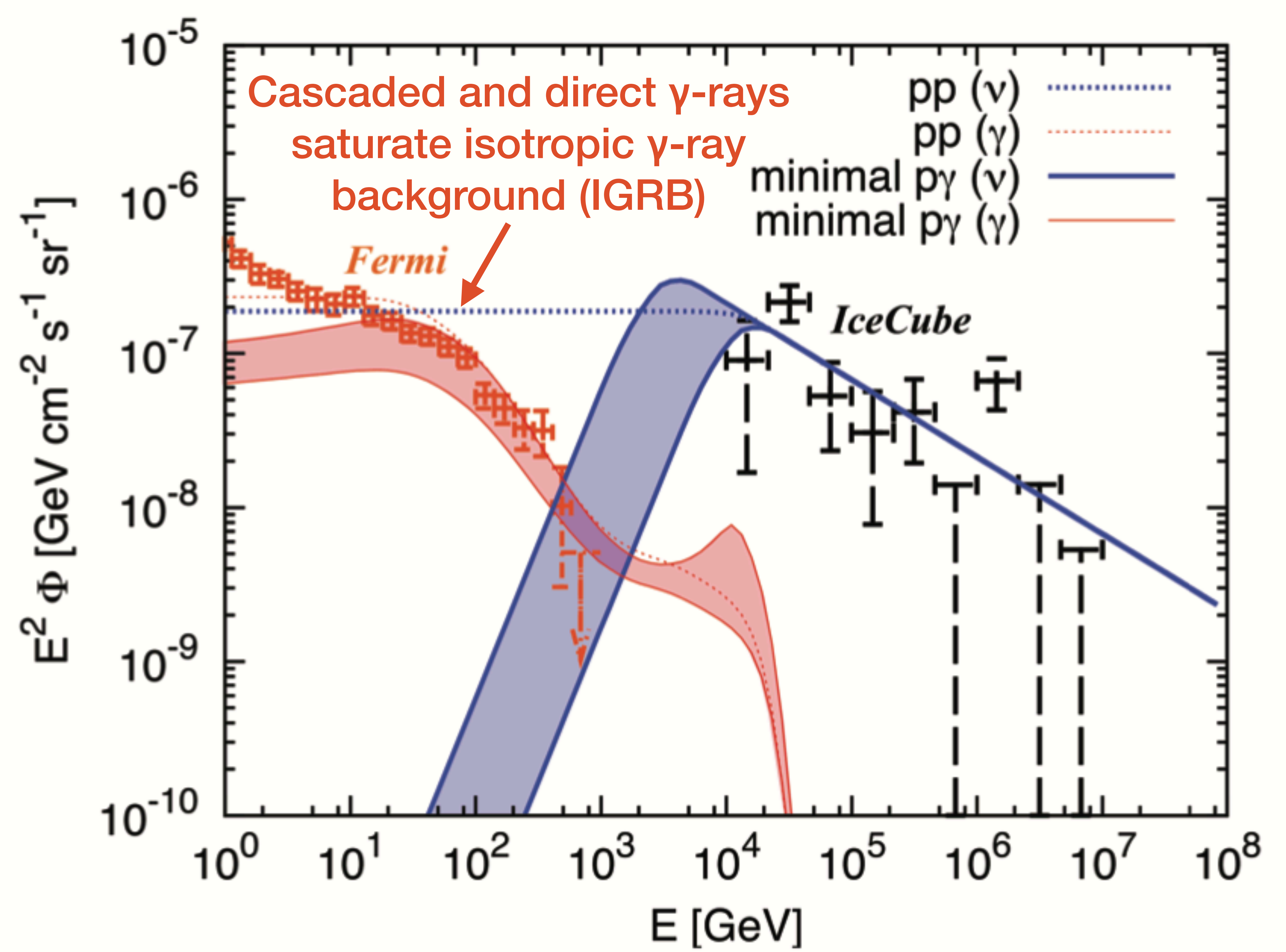


[IceCube, ApJ 435(2017)45]

Combined contribution of 862 *Fermi*-LAT balzars (2LAC)
below **27%** of the isotropic TeV-PeV neutrino flux

Neutrinos from hidden sources?

ν flux compared to low γ-ray diffuse flux point to γ-ray dark sources

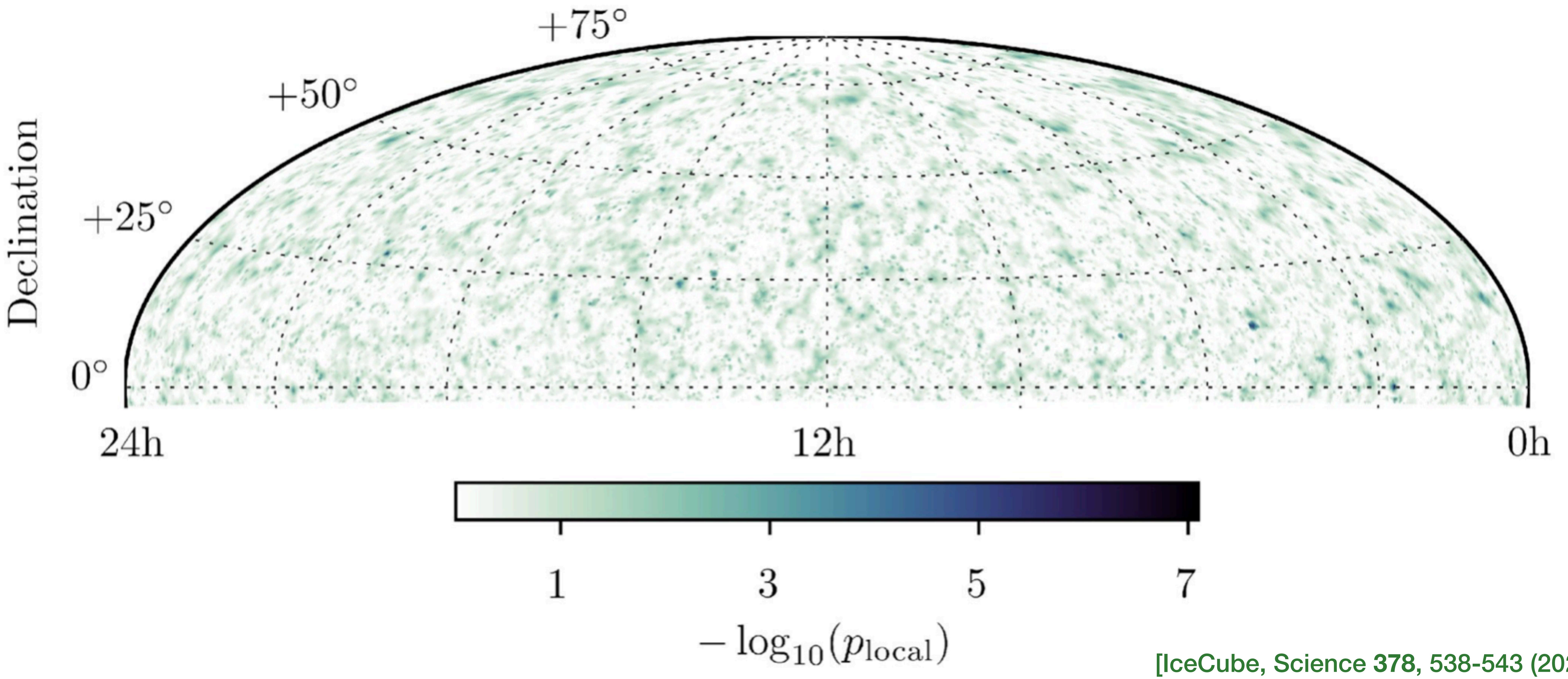


[Murase et al., PRL **116 (2016)**, 071101]

Efficient production of 10 TeV neutrinos in pγ scenario requires sources with strong X-ray backgrounds → **AGN core models**

IceCube 10 years (2011-2020) neutrino map

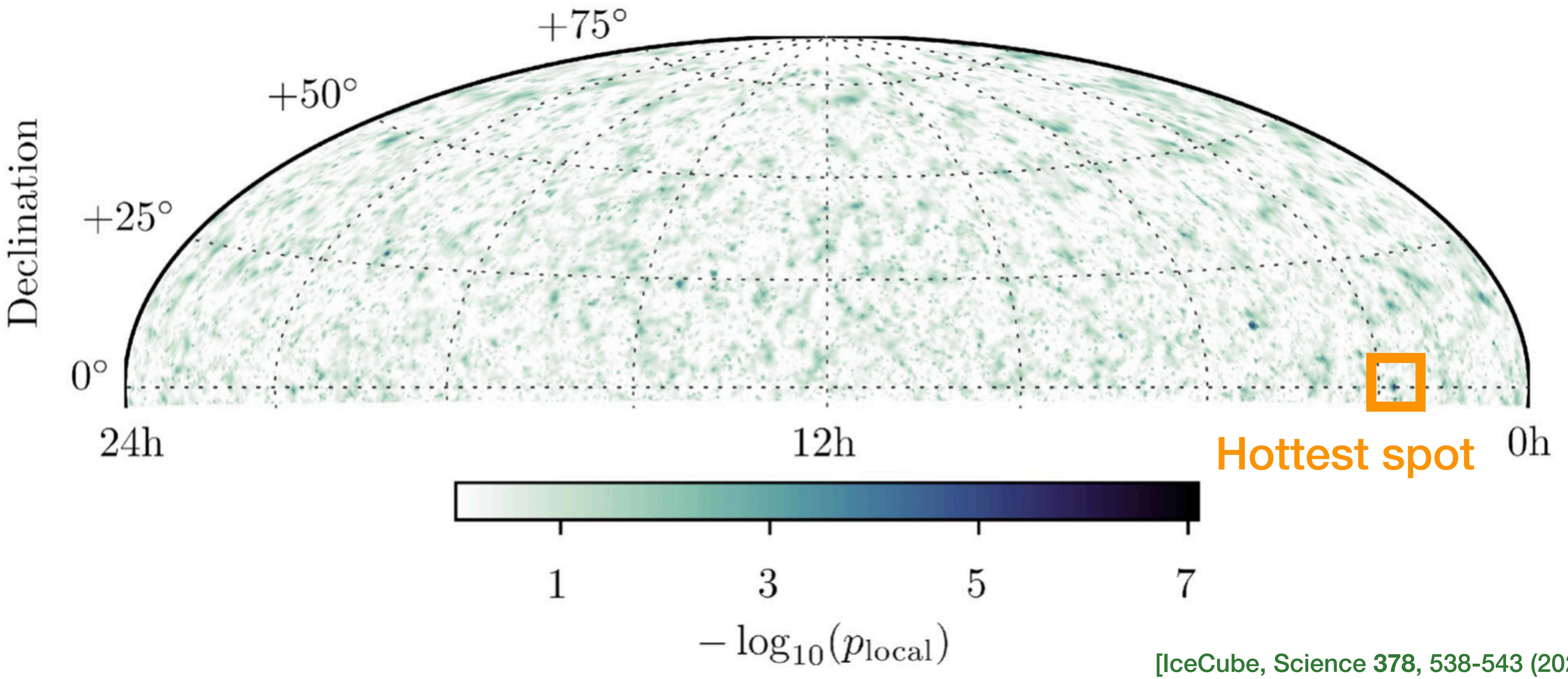
Northern-sky point source cluster search (6.7 x 10^5 events)



[IceCube, Science **378**, 538-543 (2022)]

IceCube 10 years (2011-2020) neutrino map

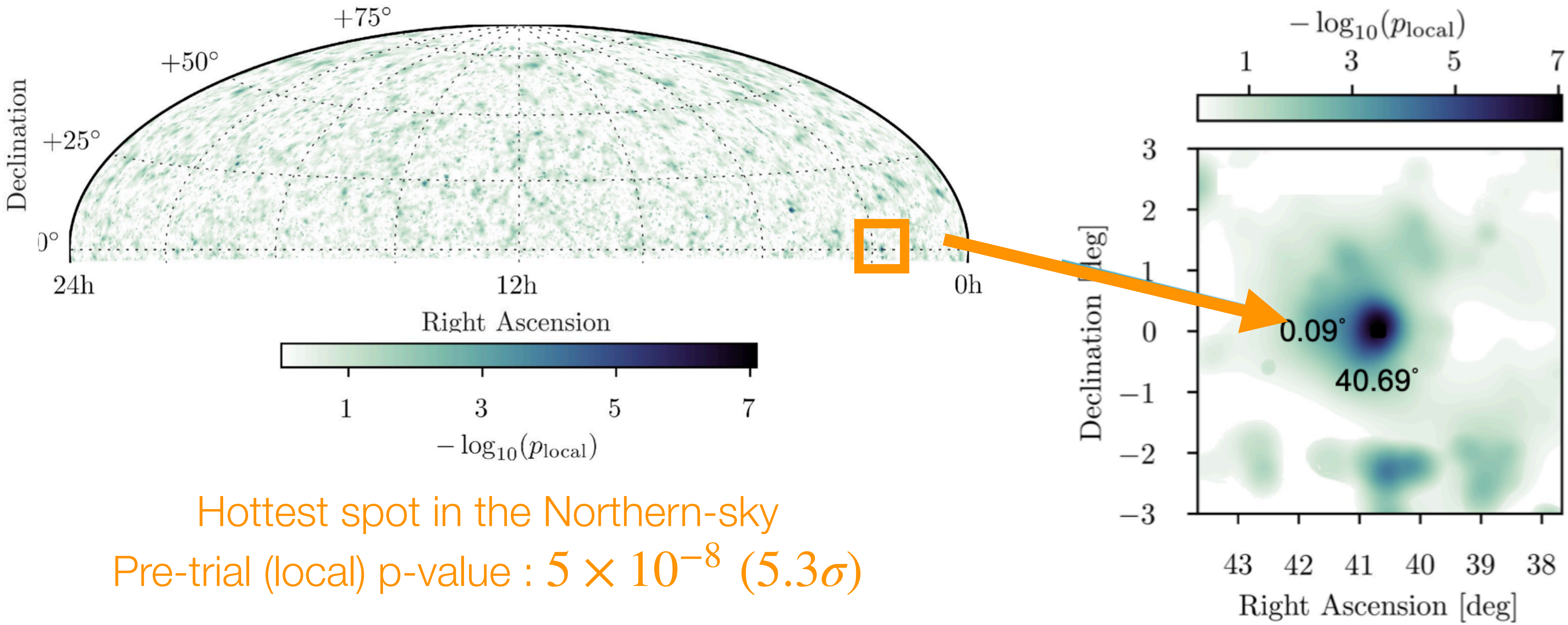
Northern-sky point source cluster search (6.7 x 10^5 events)



[IceCube, Science **378**, 538-543 (2022)]

IceCube 10 years (2011-2020) neutrino map

Northern-sky point source cluster search (6.7 x 10^5 events)



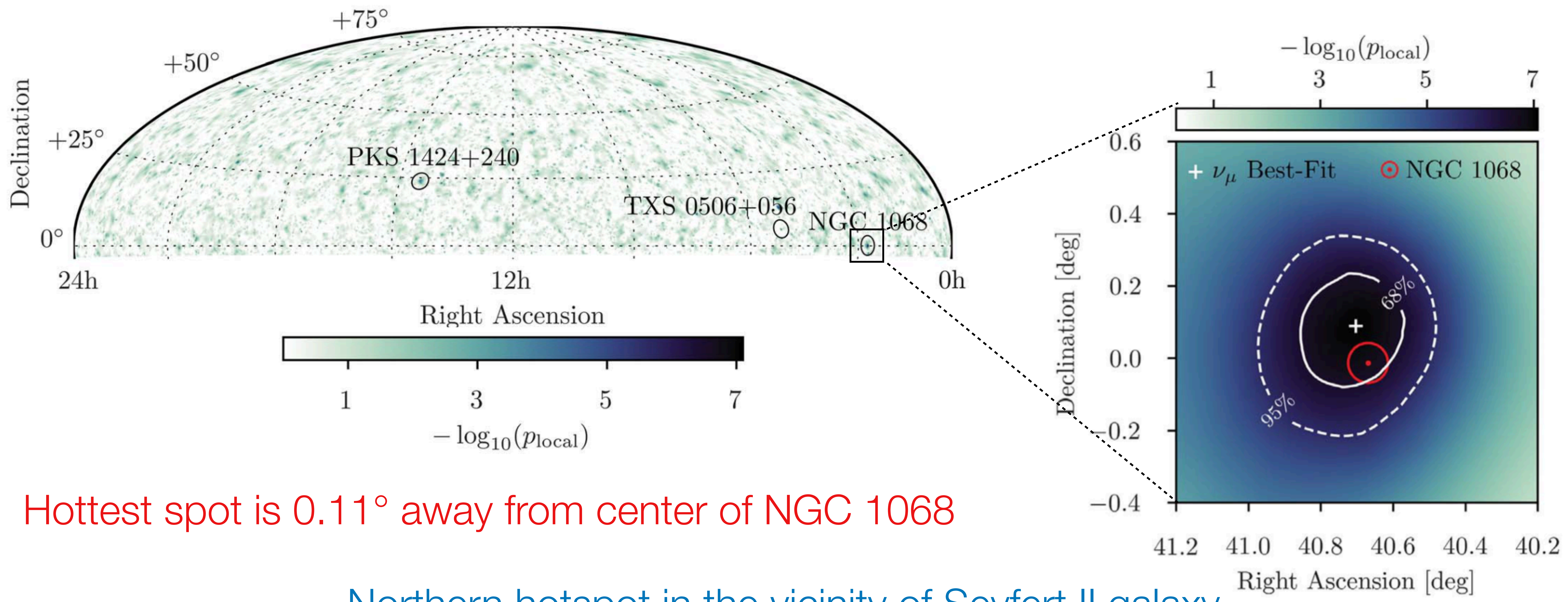
Hottest spot in the Northern-sky

Pre-trial (local) p-value : 5×10^{-8} (5.3σ)

After correcting for the look-elsewhere effect, global significance is **2.0 σ**

Excess from NGC 1068 (M77)

By looking only at 110 gamma-ray selected sources



Hottest spot is 0.11° away from center of NGC 1068

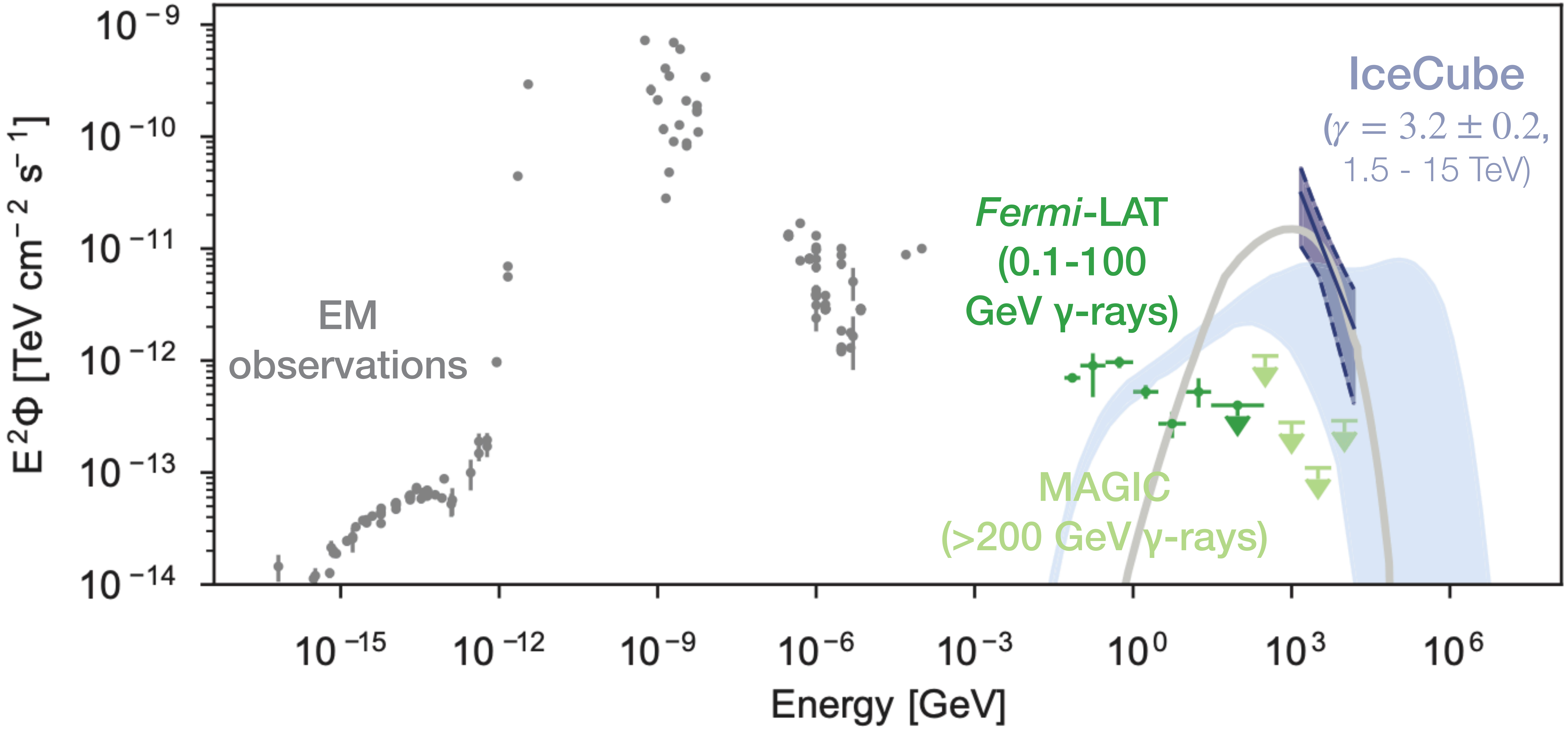
Northern hotspot in the vicinity of Seyfert II galaxy

NGC 1068 with significance of **4.2σ** (trial-corrected for 110 sources)

AGN corona model

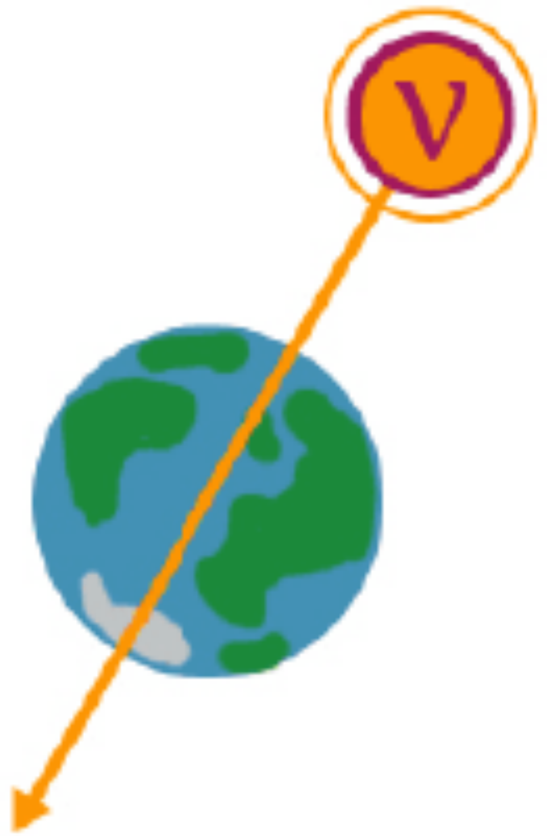
Measured neutrino flux exceeds TeV gamma-ray upper limits

[IceCube, Science **378**, 538-543 (2022)]

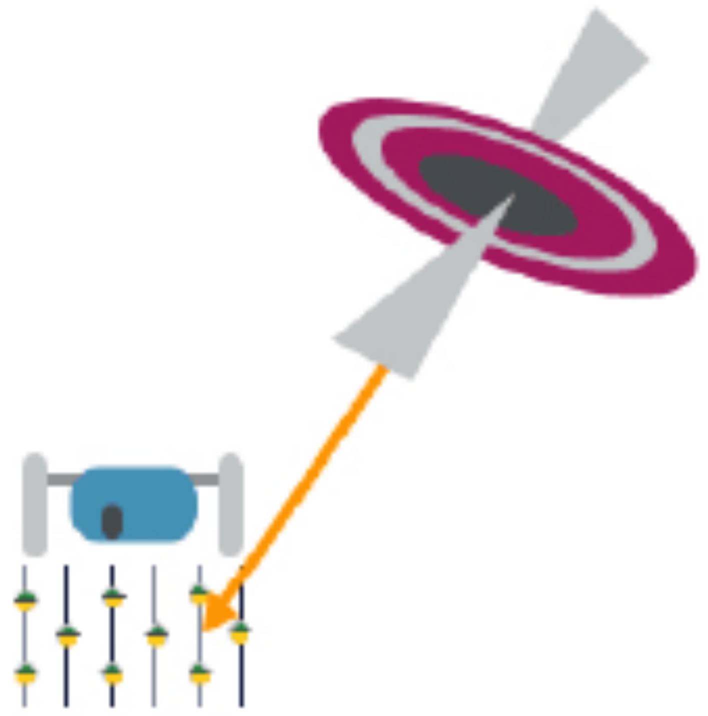


Neutrinos produced in gamma-ray obscured environment

Why searching neutrinos from AGN cores?

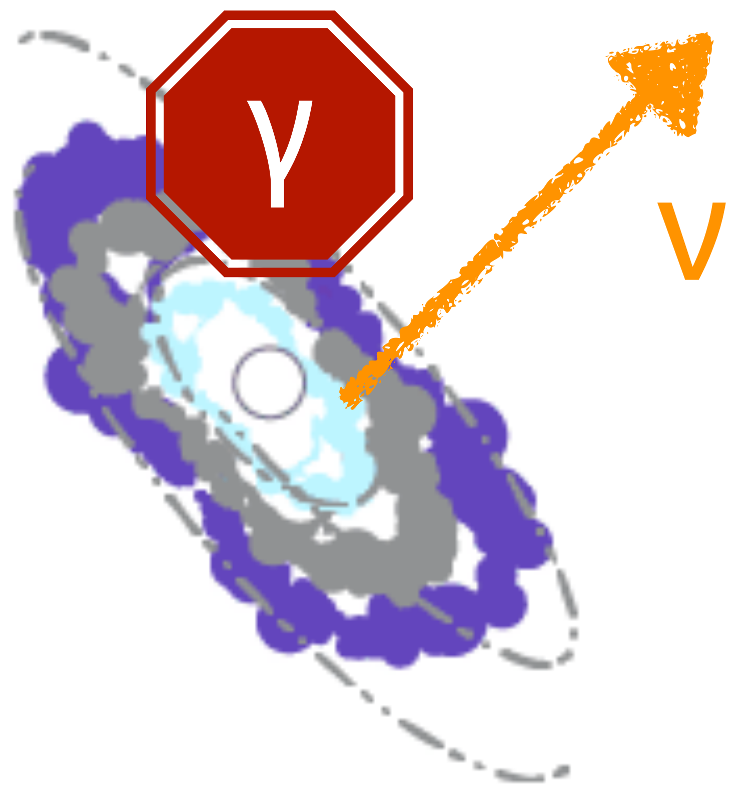


Astrophysical neutrinos discovered

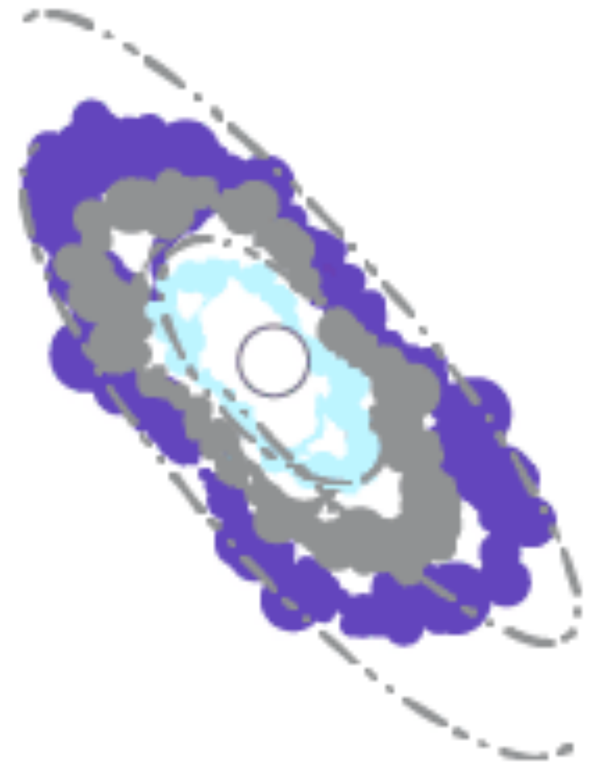


First source TXS 0506+056 identified

γ-ray blazars responsible for a small fraction of ν



Neutrinos produced in γ-ray opaque sources



Second source NGC 1068 identified

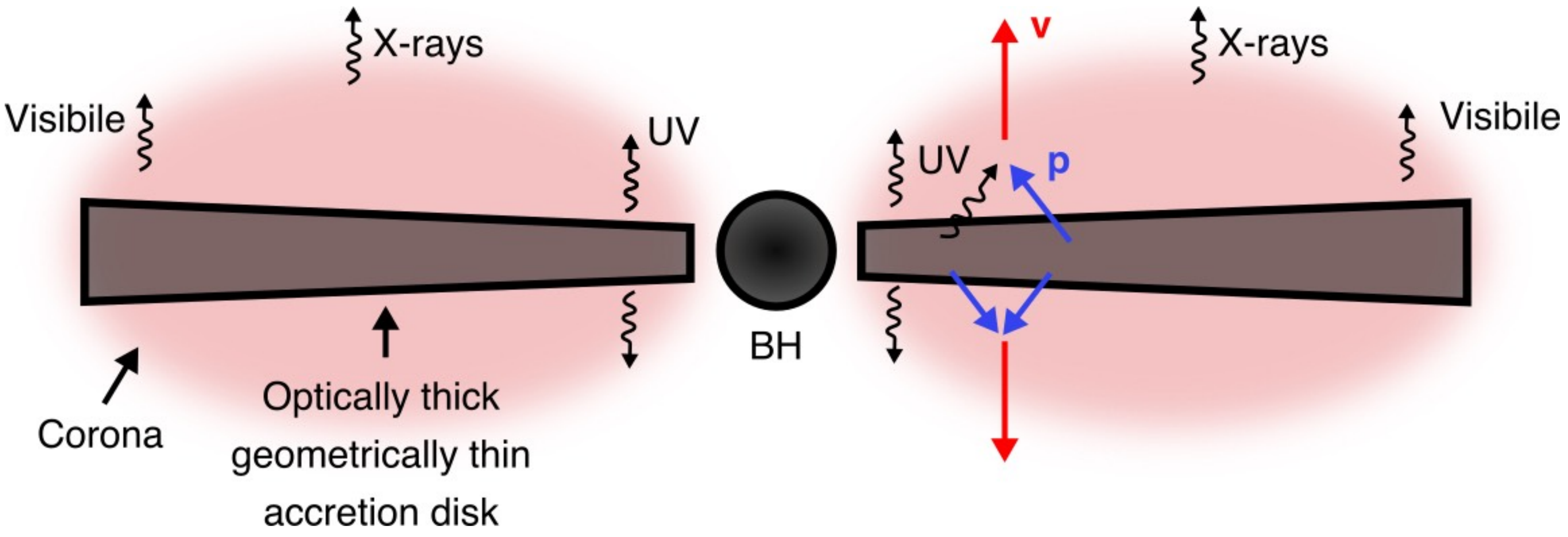
Production of ν in AGN corona

Neutrinos from AGN cores

[IceCube, PRD 106 (2022) 2]

Neutrinos from Cores of Luminous AGN

AGN with Shakura-Sunyaev accretion disk

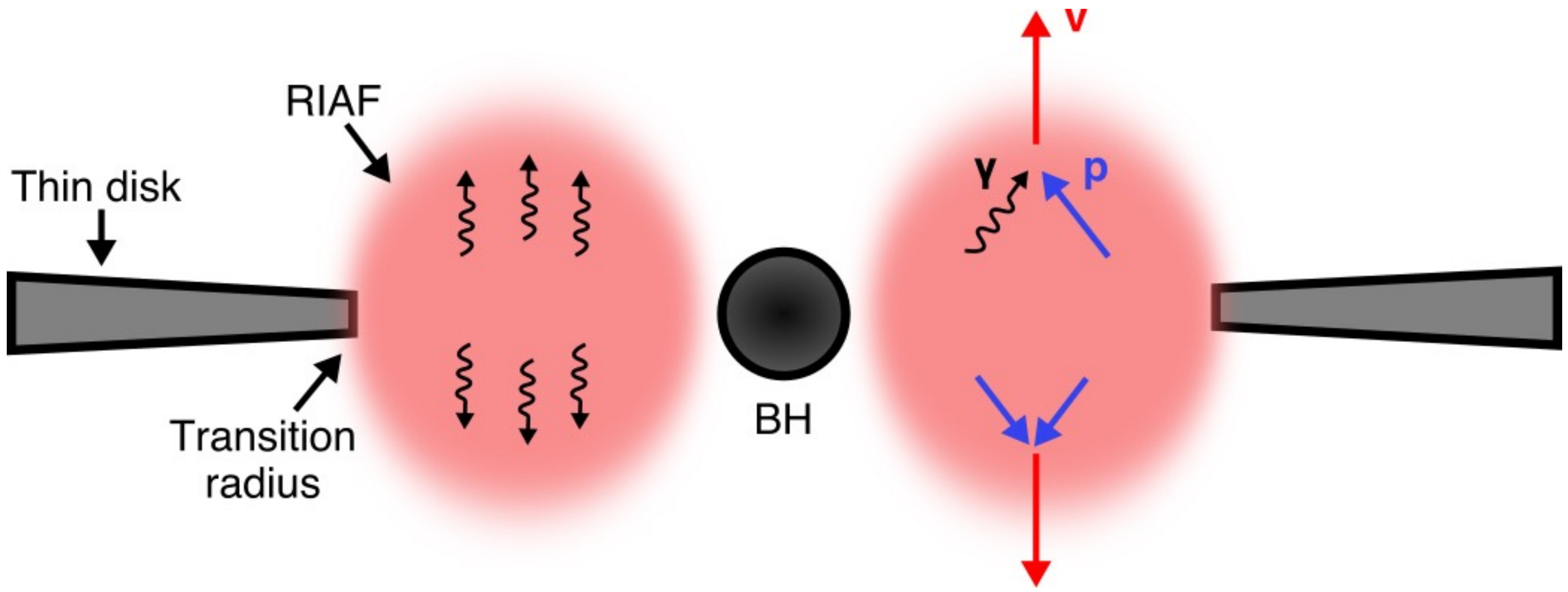


Neutrino luminosity approximated by X-ray luminosity

[Stecker et al. (2013), Kalashev et al. (2014)]

Neutrinos from Cores of Low-Luminosity AGN

AGN with Radiative Inefficient Accretion Flows (RIAFs)



Neutrino luminosity approximated by X-ray luminosity

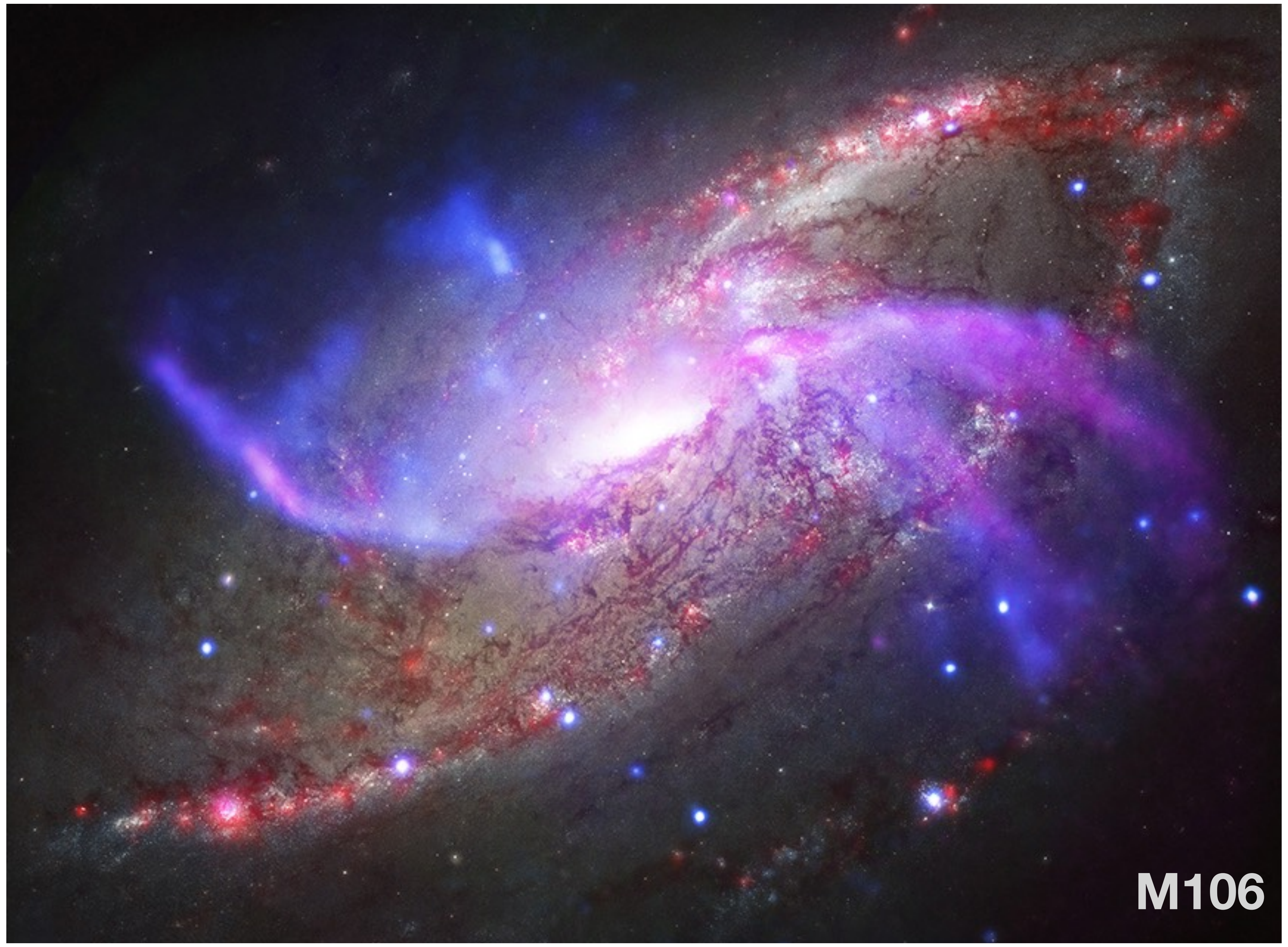
[Kimura et al. (2015)]

Which AGN?

Luminous AGN

Radio Galaxies

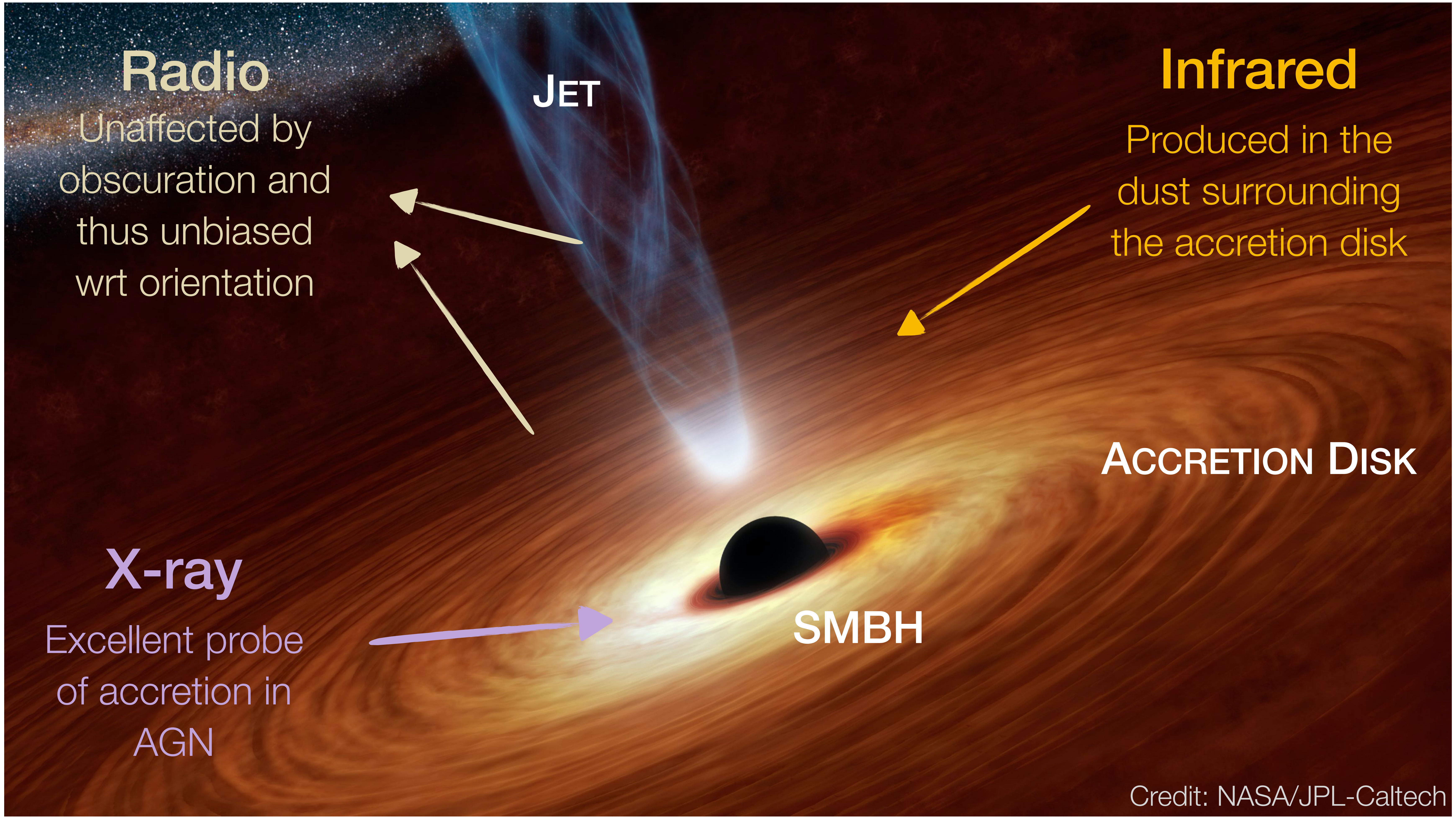
Low-Luminosity AGN (LLAGN)



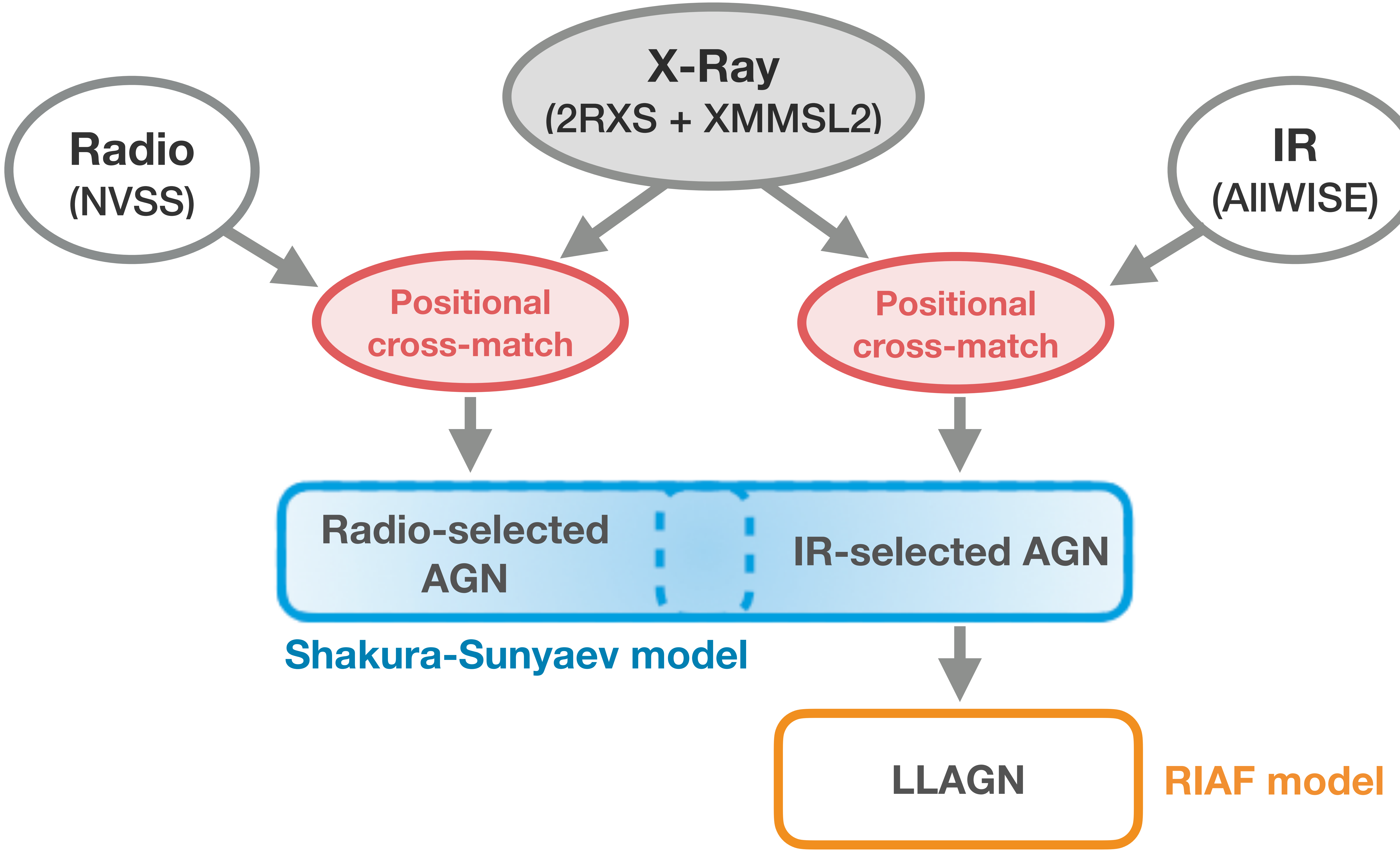
Seyfert Galaxies

How to select AGN?

Using various bands of the electromagnetic spectrum



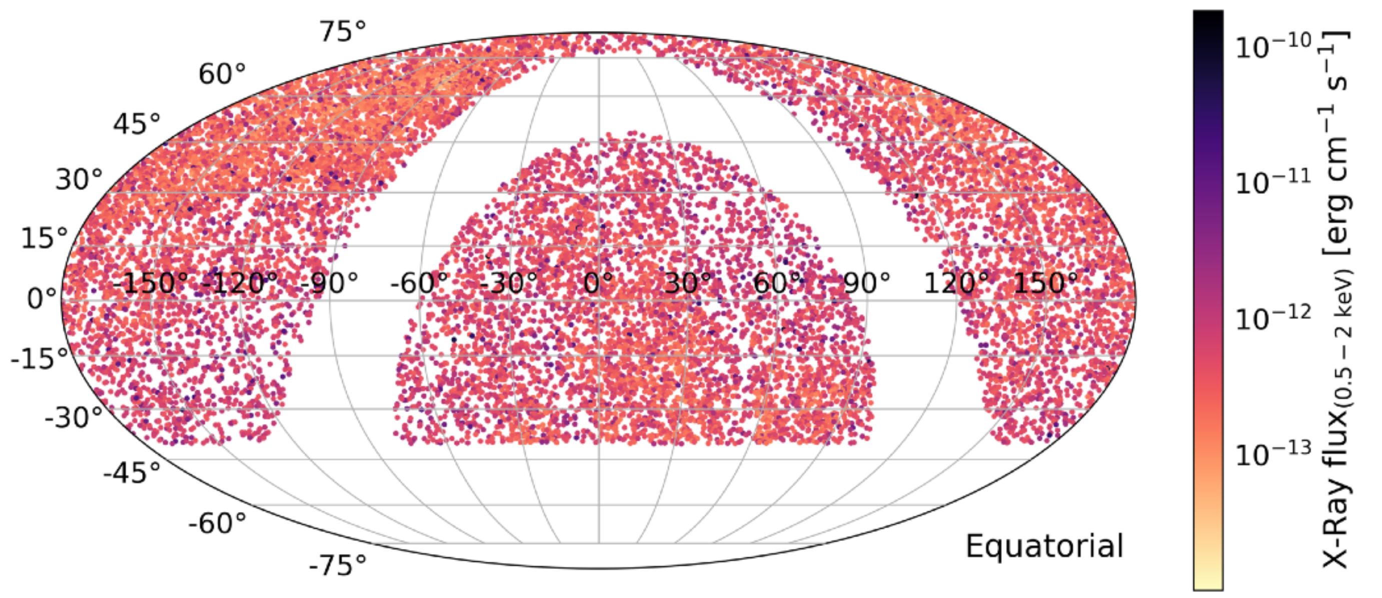
Creation of the AGN samples



3LAC *Fermi*-LAT blazars are removed in all samples

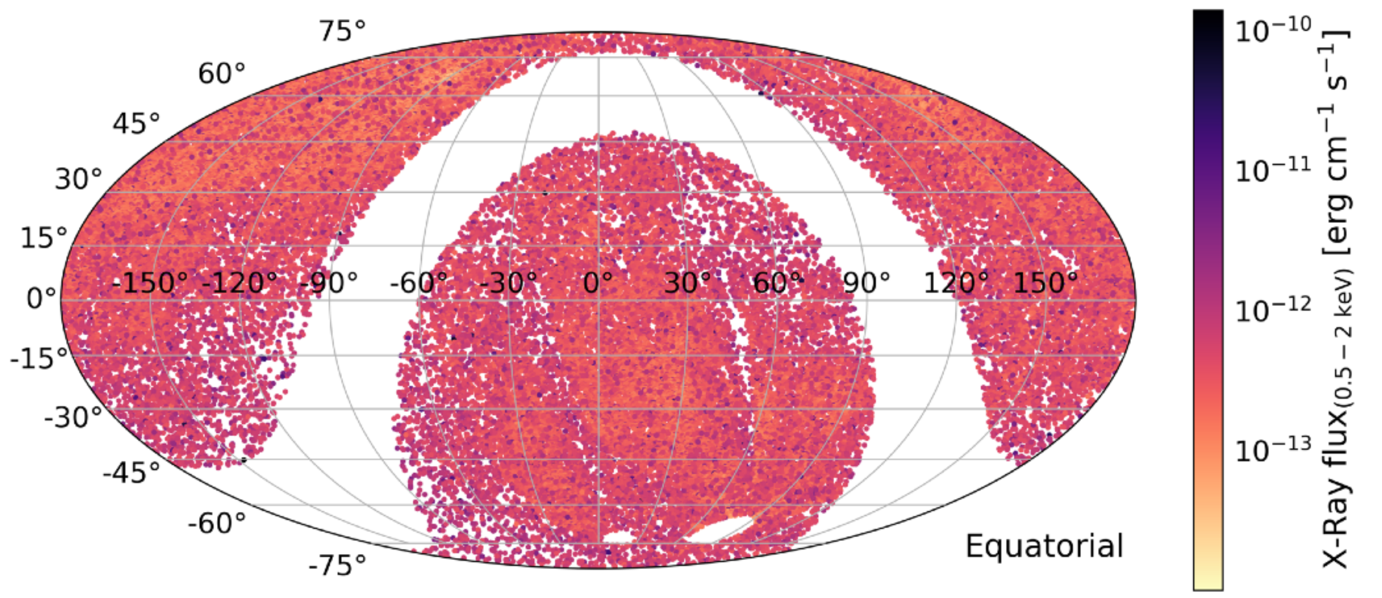
AGN final samples

Radio-selected AGN



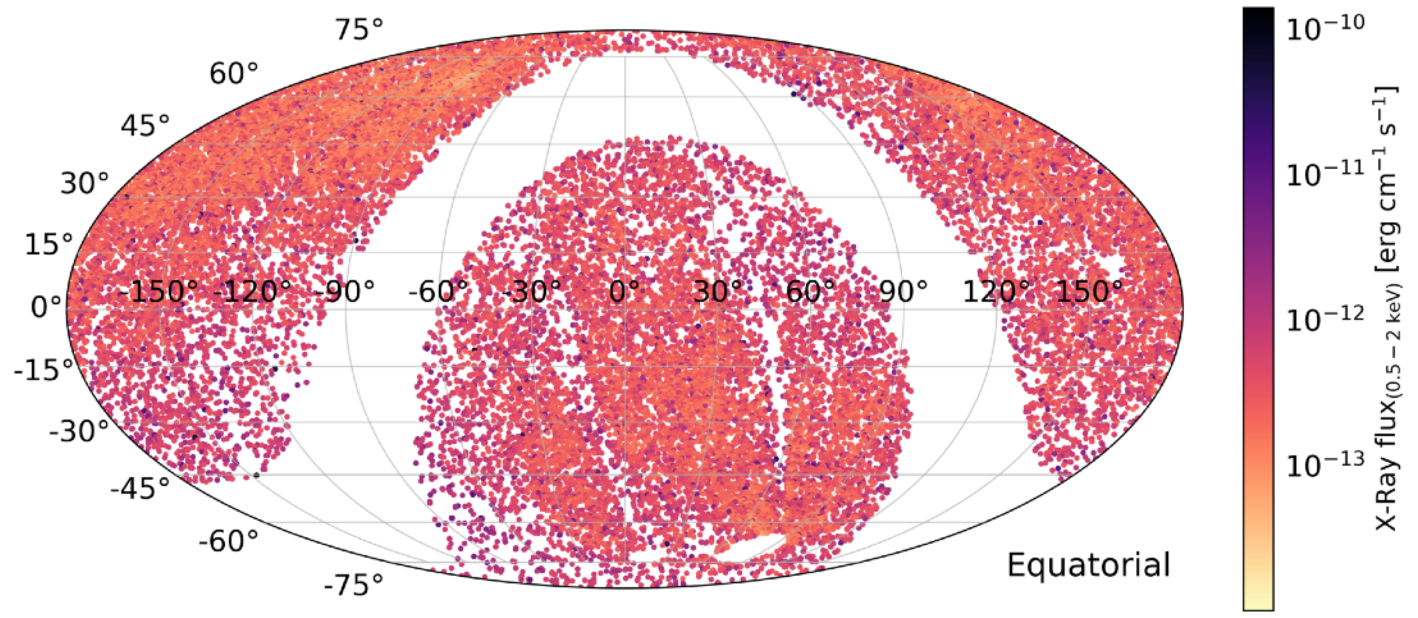
13,972 sources

IR-selected AGN



52,835 sources

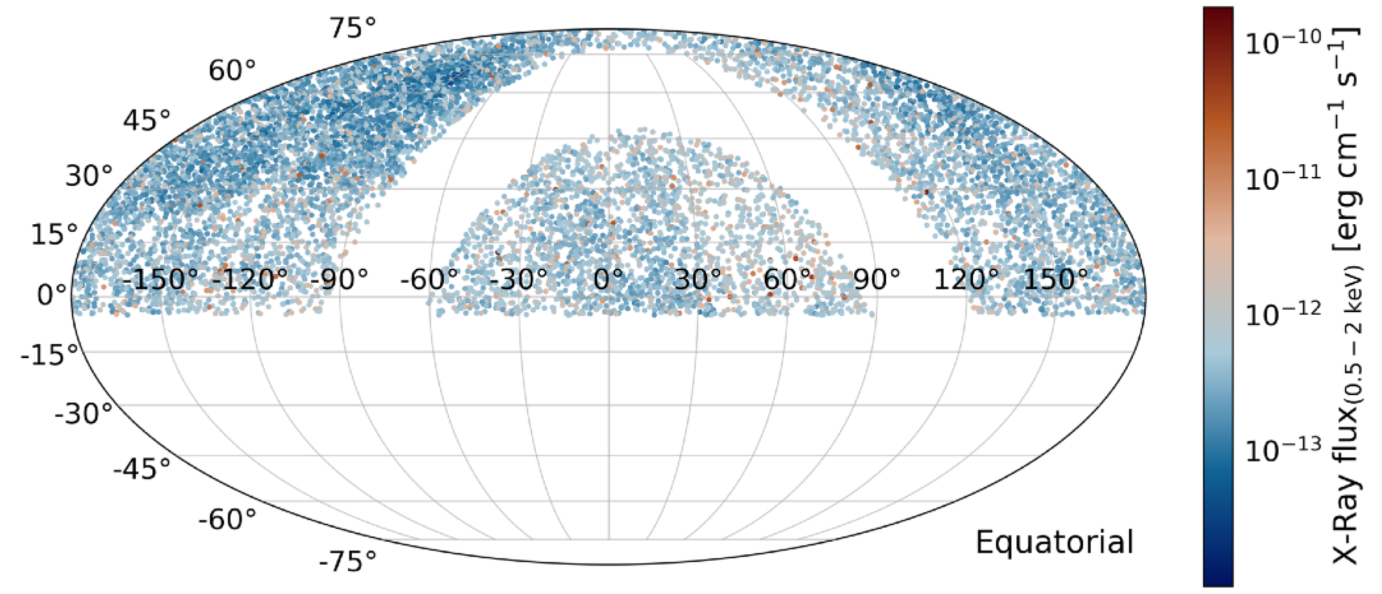
LLAGN



25,648 sources

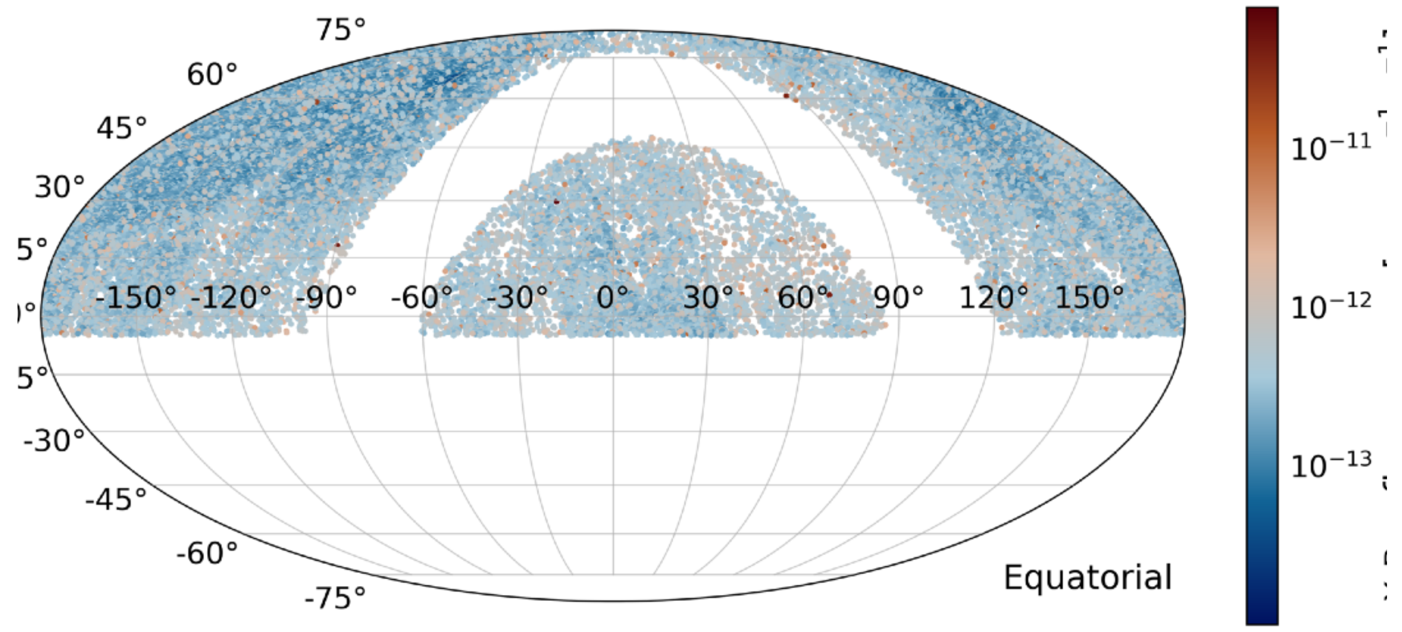
AGN final samples

Radio-selected AGN



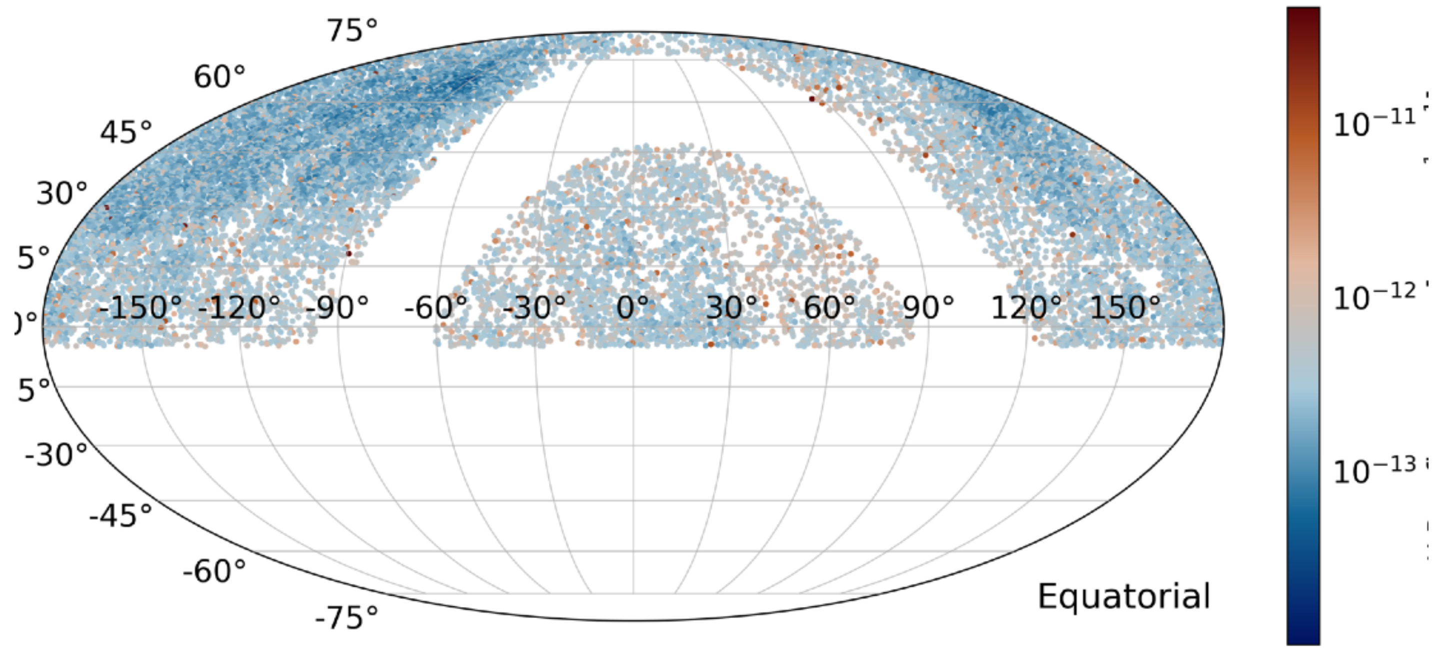
13,972 sources
9,749 sources

IR-selected AGN



52,835 sources
32,249 sources

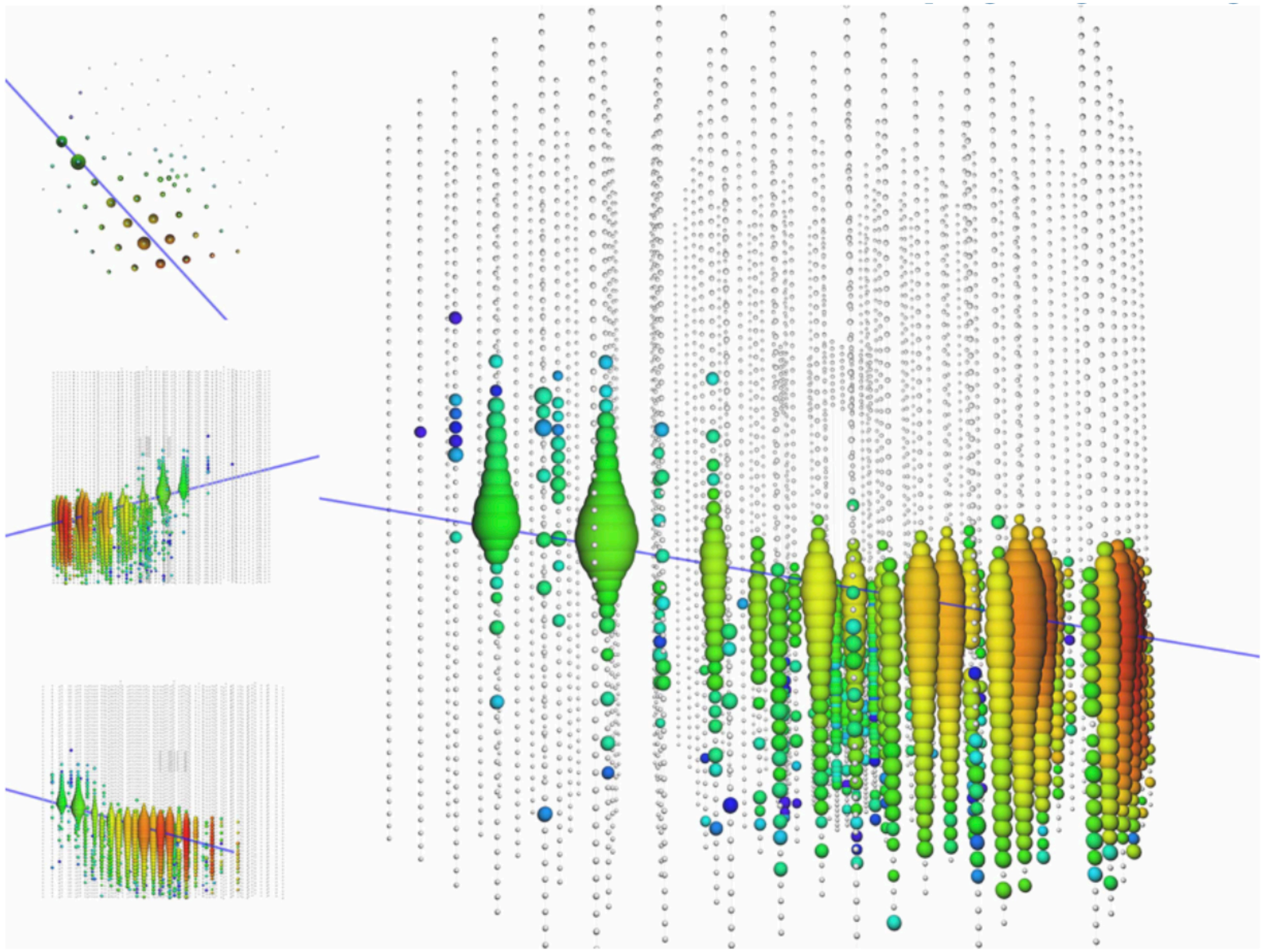
LLAGN

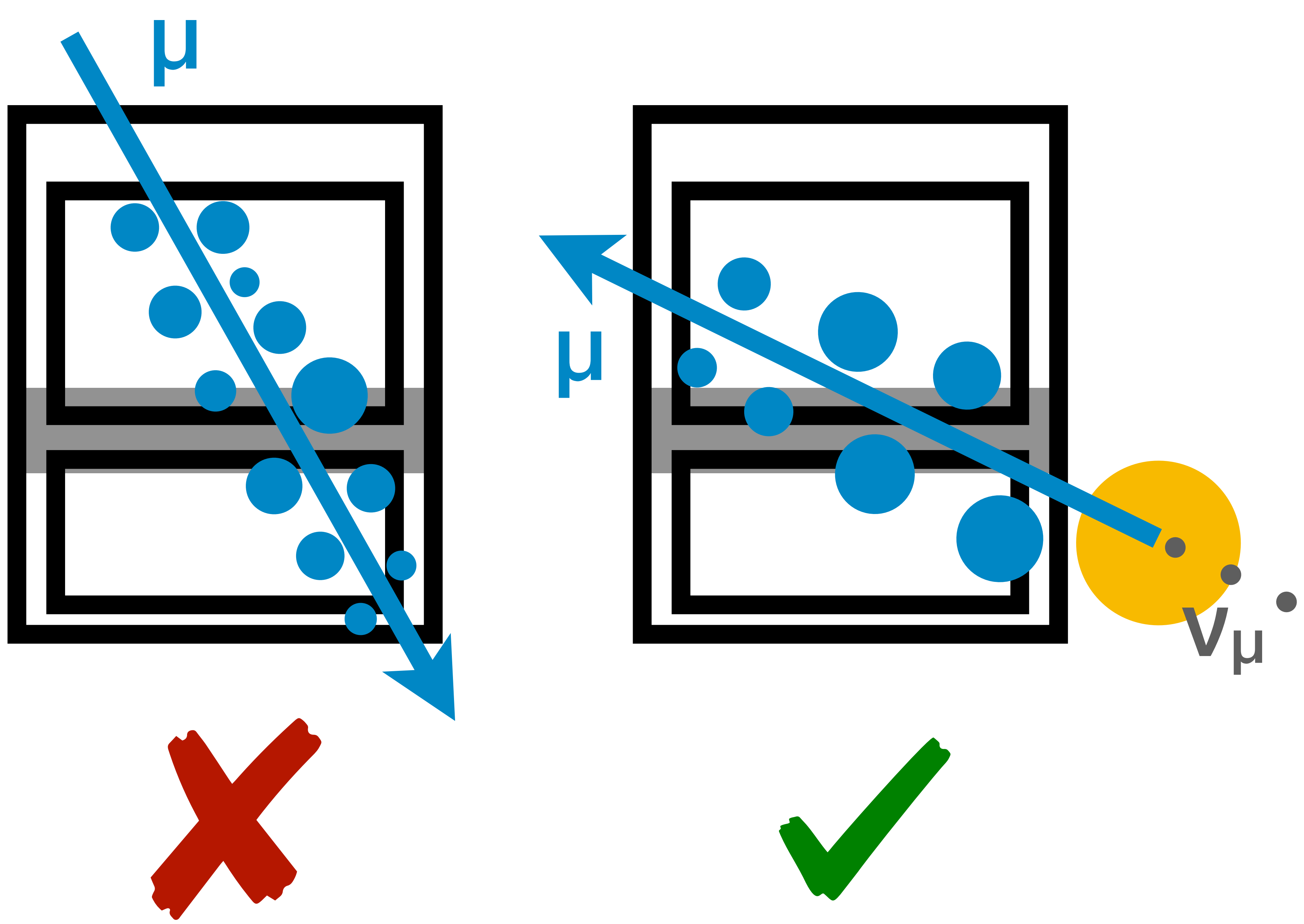


25,648 sources
15,887 sources

Northern-Tracks dataset

Upgoing through-going muons travelled through the Earth



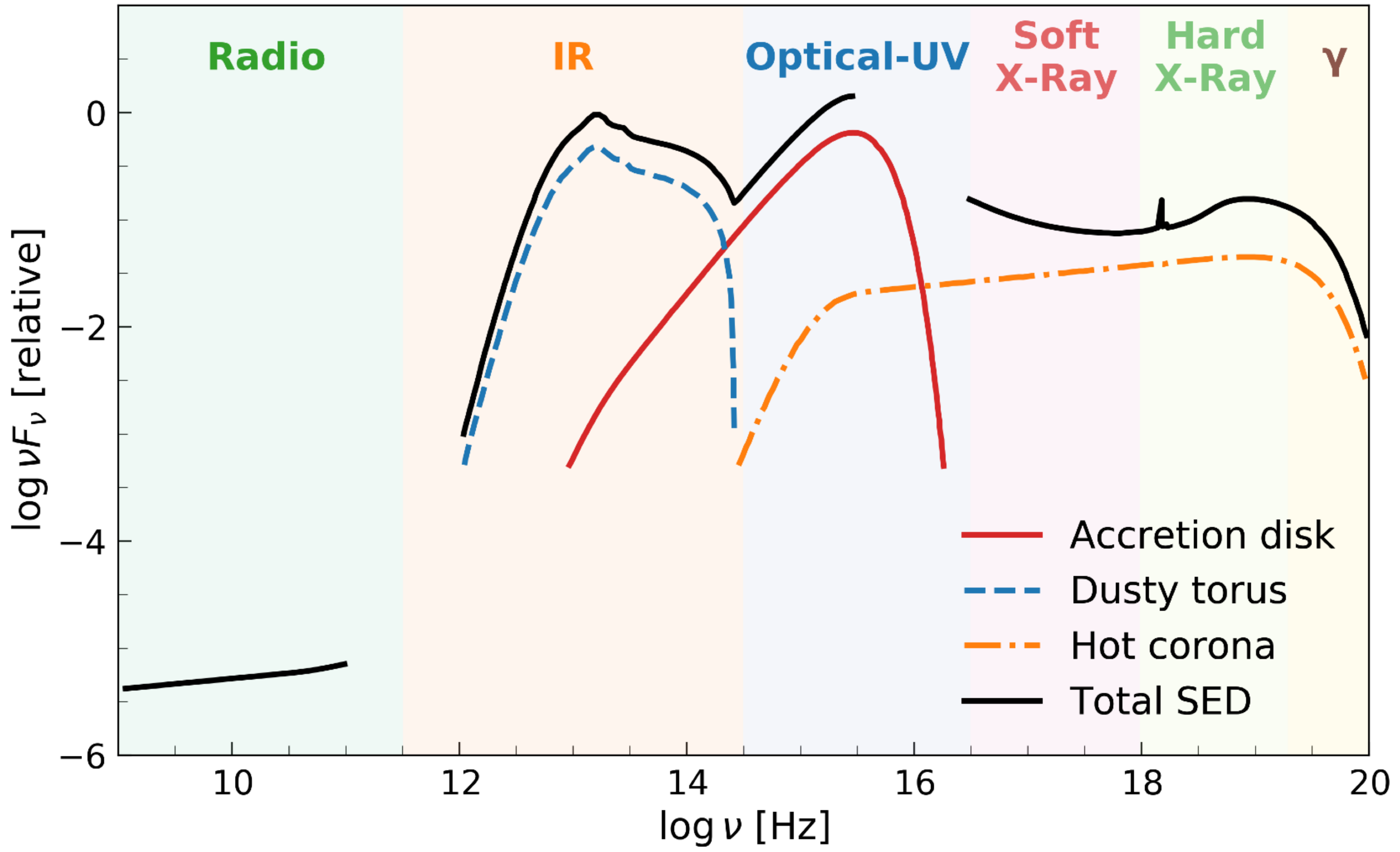


8 years of data
(2009-2017)
~ 497k events

How many neutrinos from each AGN?

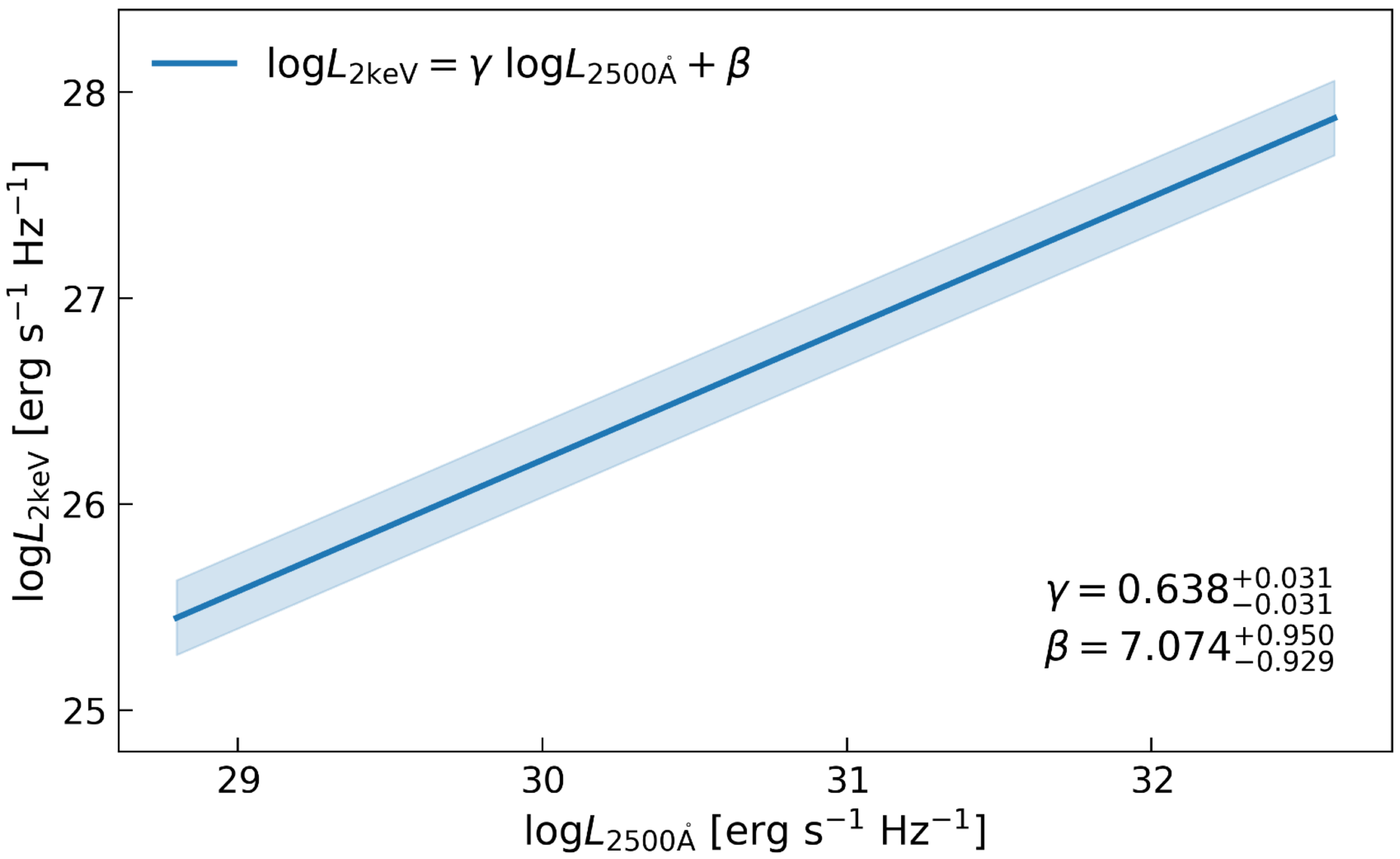
X-ray flux as neutrino flux proxy

Padovani et al. 2017



Accretion disk emission peaks at UV wavelength

E. Lusso & Risaliti 2016



Tight relationship between X-ray and UV–optical emission

Neutrino Luminosity → Accretion Disk Luminosity → UV Luminosity → X-ray Luminosity

How to search for correlation?

Stacking Analysis: test the combined emission of all sources to identify neutrinos from a population

Nr. neutrino events → N; Nr. signal events → n_s

$$\mathscr{L}(n_s, \gamma) = \sum_i^N \left[\frac{n_s}{N} S(x_i, \gamma) + \left(1 - \frac{n_s}{N}\right) B(x_i) \right]$$

Unbinned likelihood — Signal PDF — Background PDF

Signal PDF assumes each source is point-like and follows a power law spectrum:

$$\frac{dN}{dE} \propto E^{-\gamma}$$

Signal PDF of all *M* AGN sources stacked together, weighted by ω_k:

$$S(x_i, \gamma) = \sum_{k=1}^{M_{\rm AGN}} \omega_k \cdot S_k(x_i, \gamma)$$

X-RAY FLUX (→ ω_k)

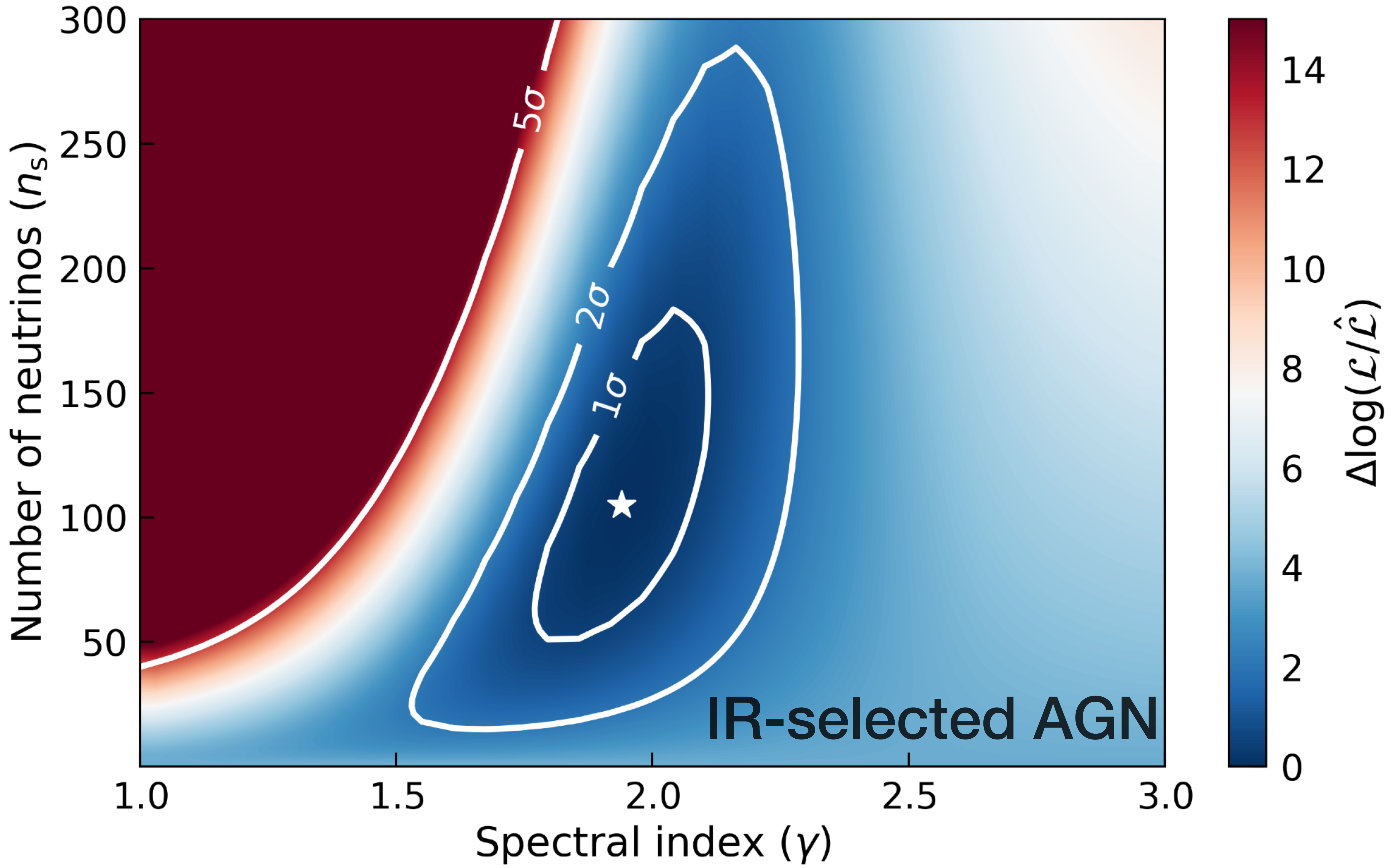
Results: n_s and γ

Test Statistic

$$\lambda = -2\log\left[\frac{\mathscr{L}(n_s = 0)}{\mathscr{L}(\hat{n}_s, \hat{\gamma})}\right]$$

Nr. signal events = strength of the signal → Neutrino flux $\Phi_{100\ \mathrm{TeV}}$

Spectral index of the signal $E^{-\gamma}$ spectrum



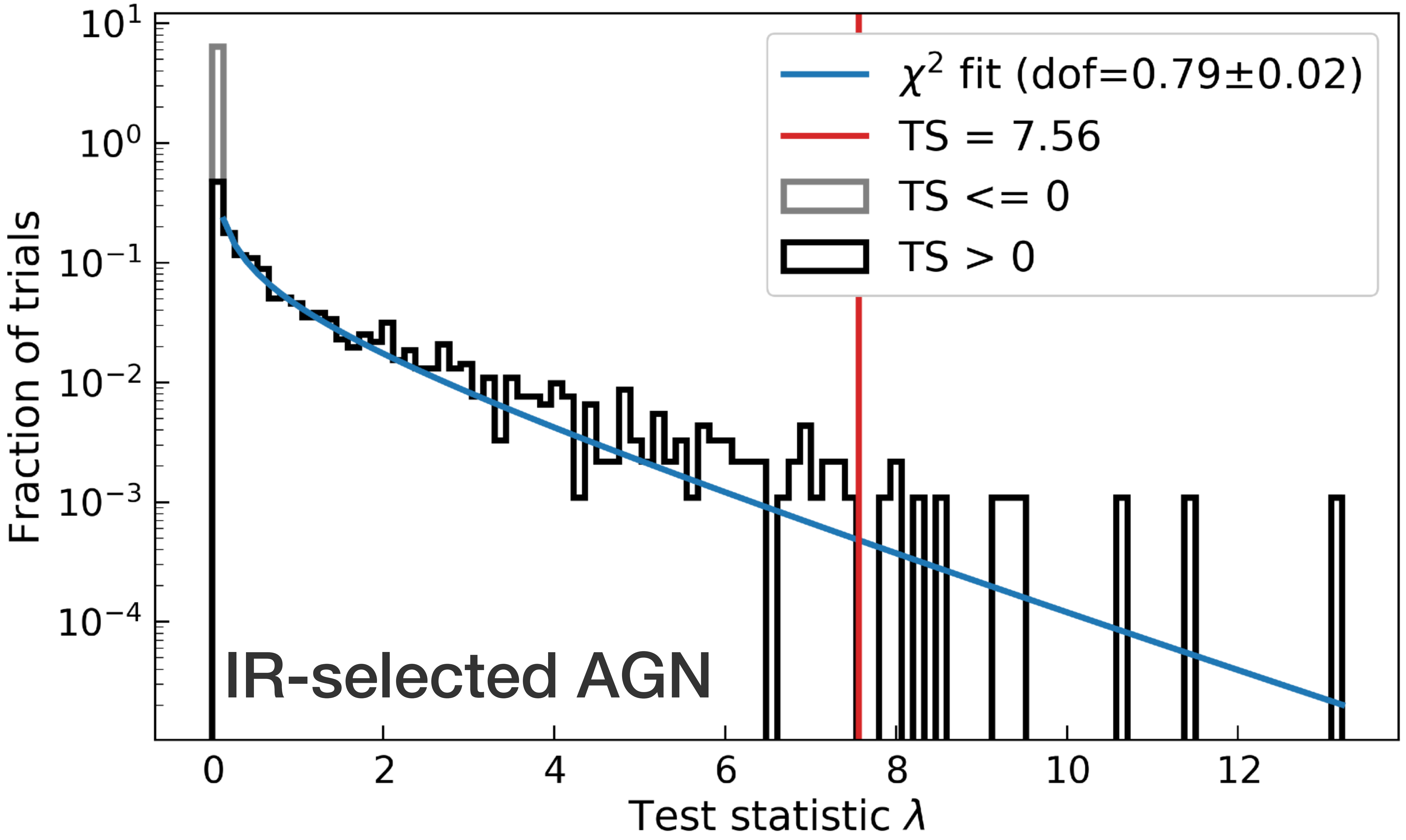
	Radio-selected AGN	IR-selected AGN	LLAGN
n_s	53	105	28
γ	2.03	1.94	1.96

Results: p-values

Probability that results are due to background alone

$$p_{\mathrm{value}} = \sum_{\lambda \geq \lambda_{\mathrm{obs}}} g(\lambda, H_0)$$

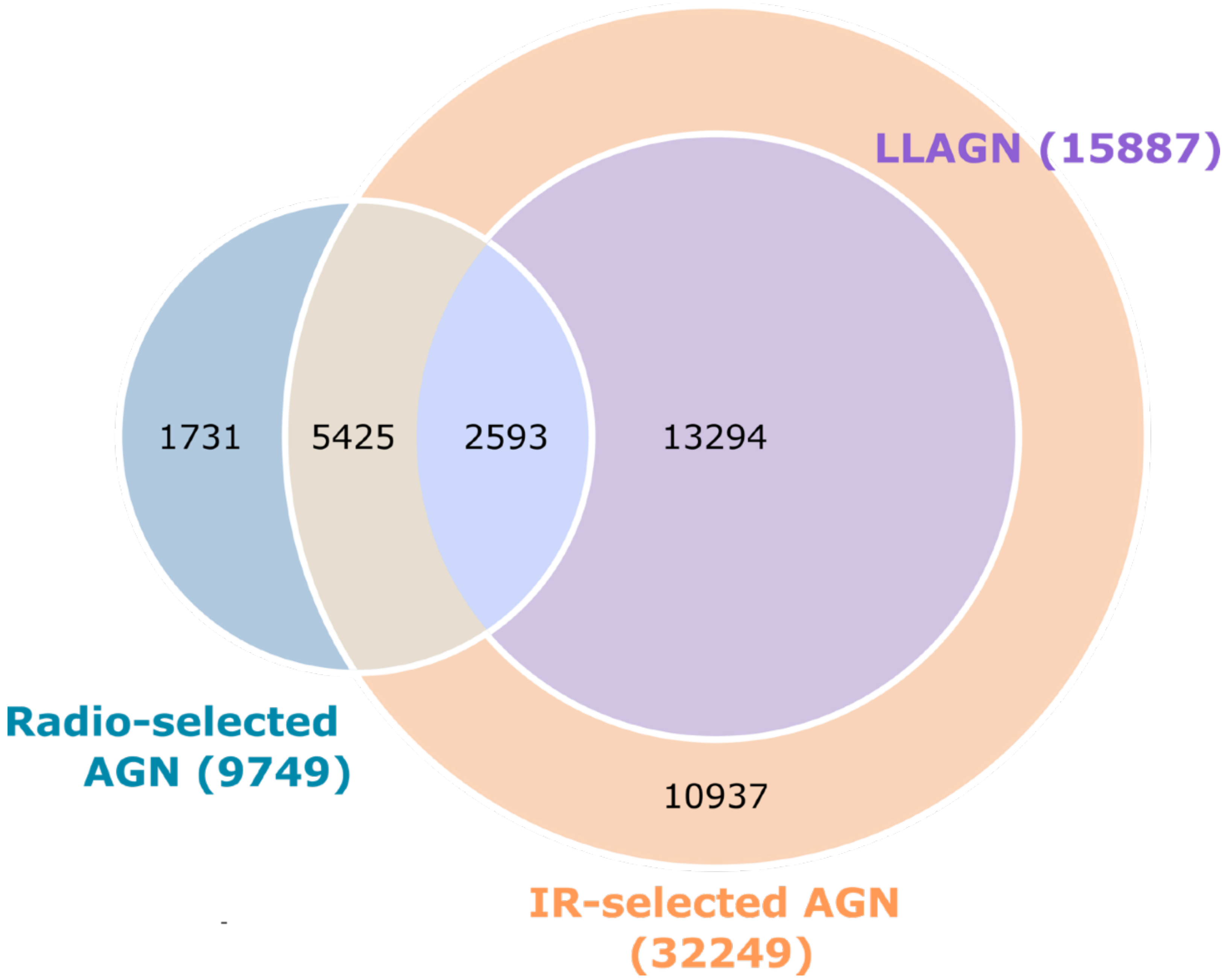
Normalized TS distribution

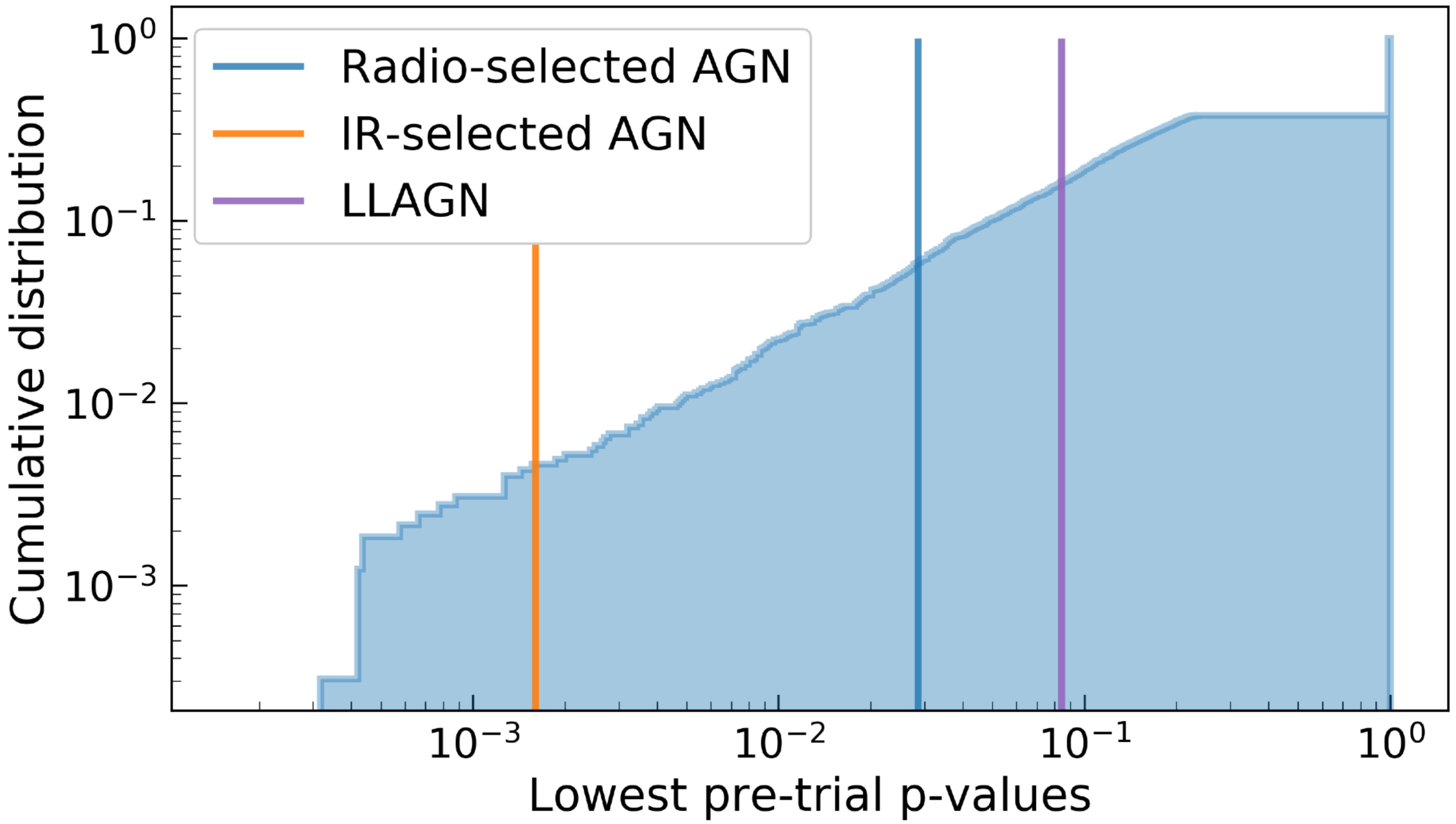


	Radio-selected AGN	IR-selected AGN	LLAGN
TS	2.39	7.56	0.51
Pre-trial p-value	2.84×10^{-2} (**1.9σ**)	1.59×10^{-3} (**2.9σ**)	0.08 (**1.4σ**)

Results: trial correction

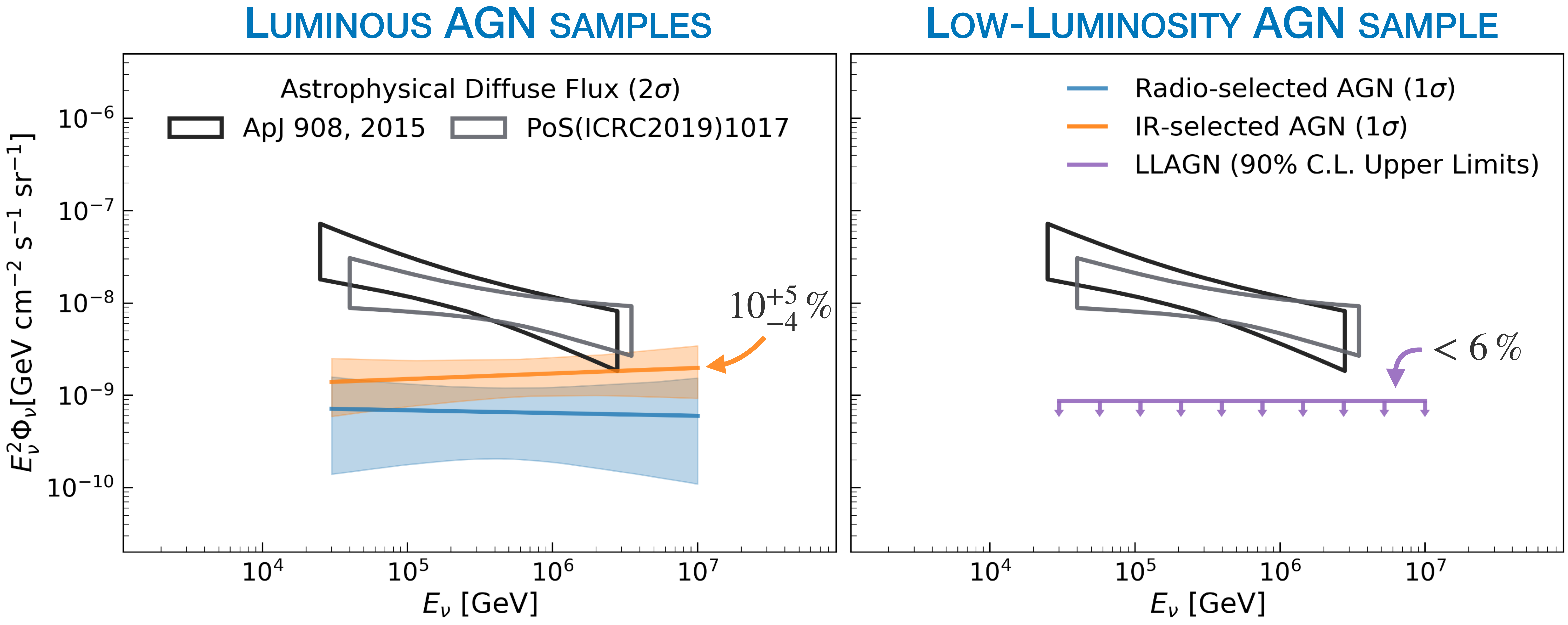
"Look elsewhere" effect: have our results arisen by chance?





	Radio-selected AGN	IR-selected AGN	LLAGN
Post-trial p-value	5.85×10^{-2} (**1.6σ**)	4.64×10^{-3} (**2.6σ**)	0.16 (**1.0σ**)

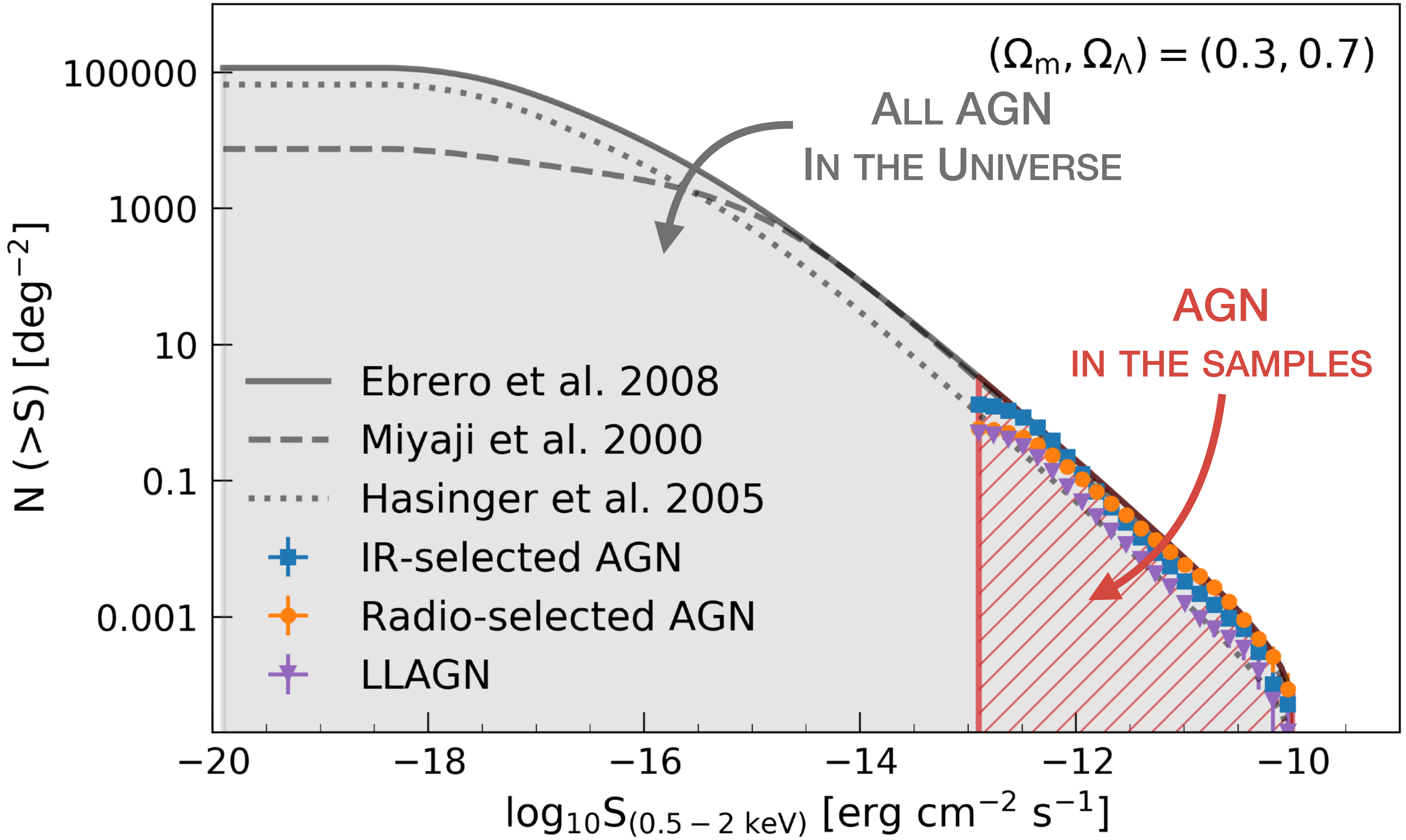
Neutrino spectrum



Minimum contribution to the IceCube diffuse flux @100TeV is of **~10%** from **Luminous AGN** and **<6%** from **LLAGN**

From AGN samples to AGN population

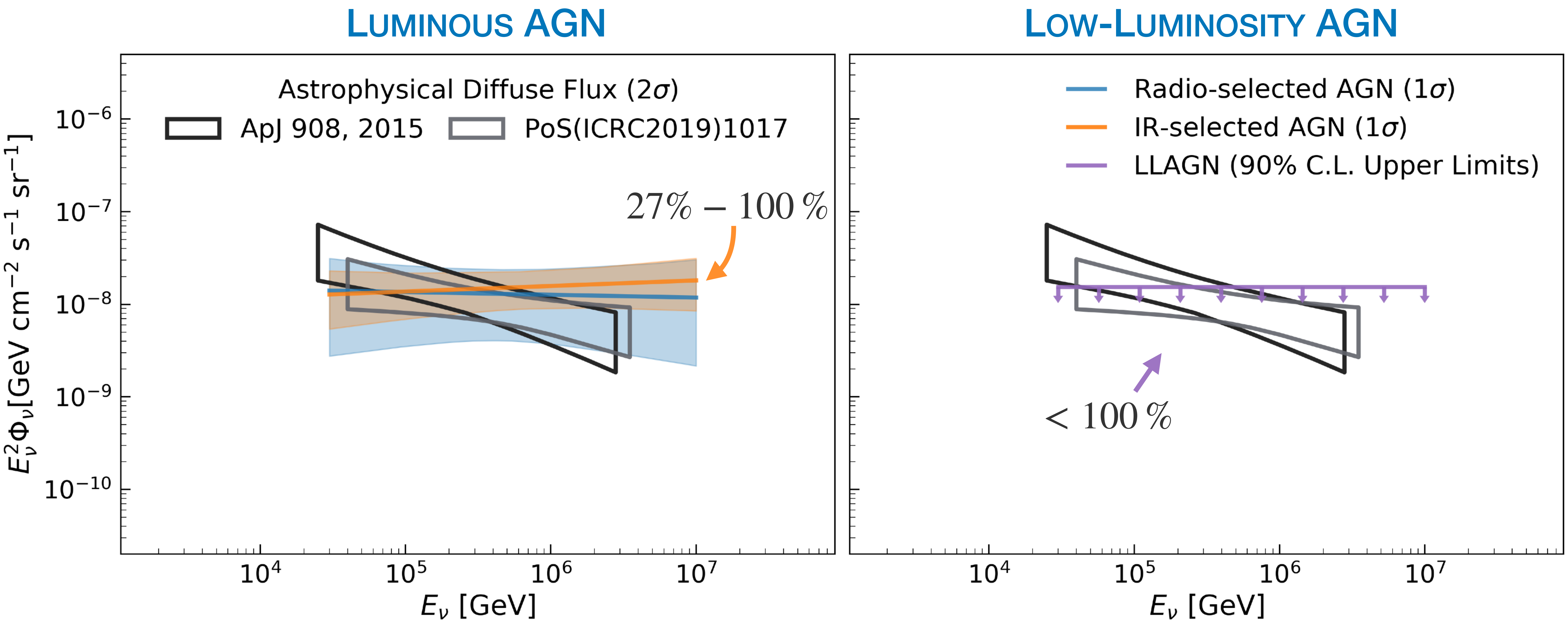
Through the ***completeness*** factor



$$\text{Completeness} = \frac{\text{AGN in samples}}{\text{All AGN}}$$

	Completeness
Radio-selected AGN	~5%
IR-selected AGN	~11%
LLAGN	~6%

Neutrino spectrum for AGN population



Cores of Luminous AGN can explain **27%—100%** of diffuse neutrino flux **@100 TeV**

Cores of LLAGN can explain **<100%** of the diffuse neutrino flux **@100 TeV**

Summary

- IceCube has been investigating a diffuse flux of astrophysical neutrinos > TeV for almost a decade
- Exiting results related to **Active Galactic Nuclei**:
    - Evidence for neutrinos from flaring blazar TXS 0506+056 (3σ)
    - Evidence for neutrinos from nearby Seyfert galaxy NGC 1068 (4.3σ)
    - Hint at cores of X-ray selected AGN as sources of IceCube neutrinos at energies > TeV (**2.6σ**)