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A search for neutrino emission from cores of Active Galactic Nuclei

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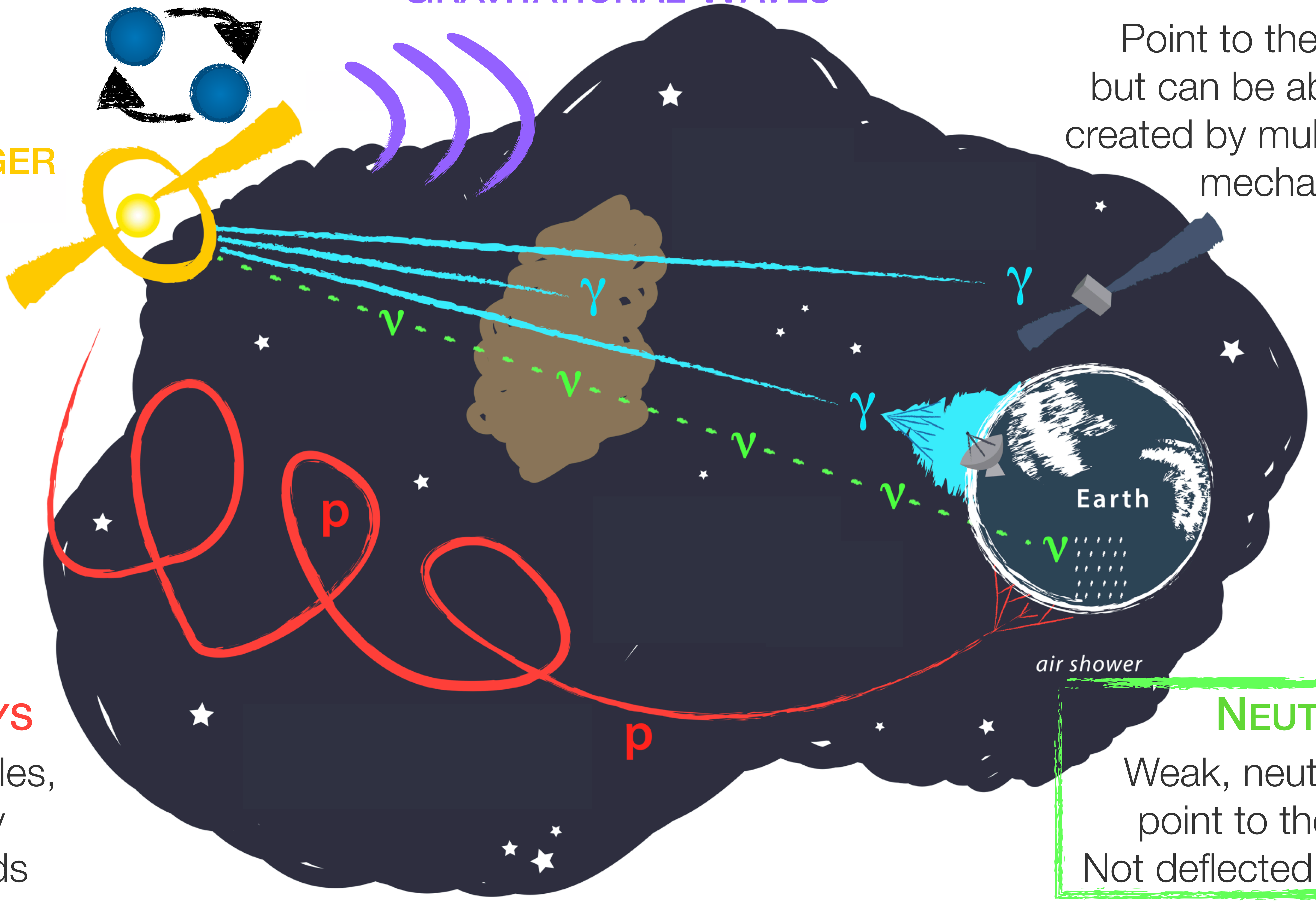
ICECUBE

DESY.

Multimessenger astronomy

GRAVITATIONAL WAVES

MULTIMESSENGER SOURCE



GAMMA RAYS

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

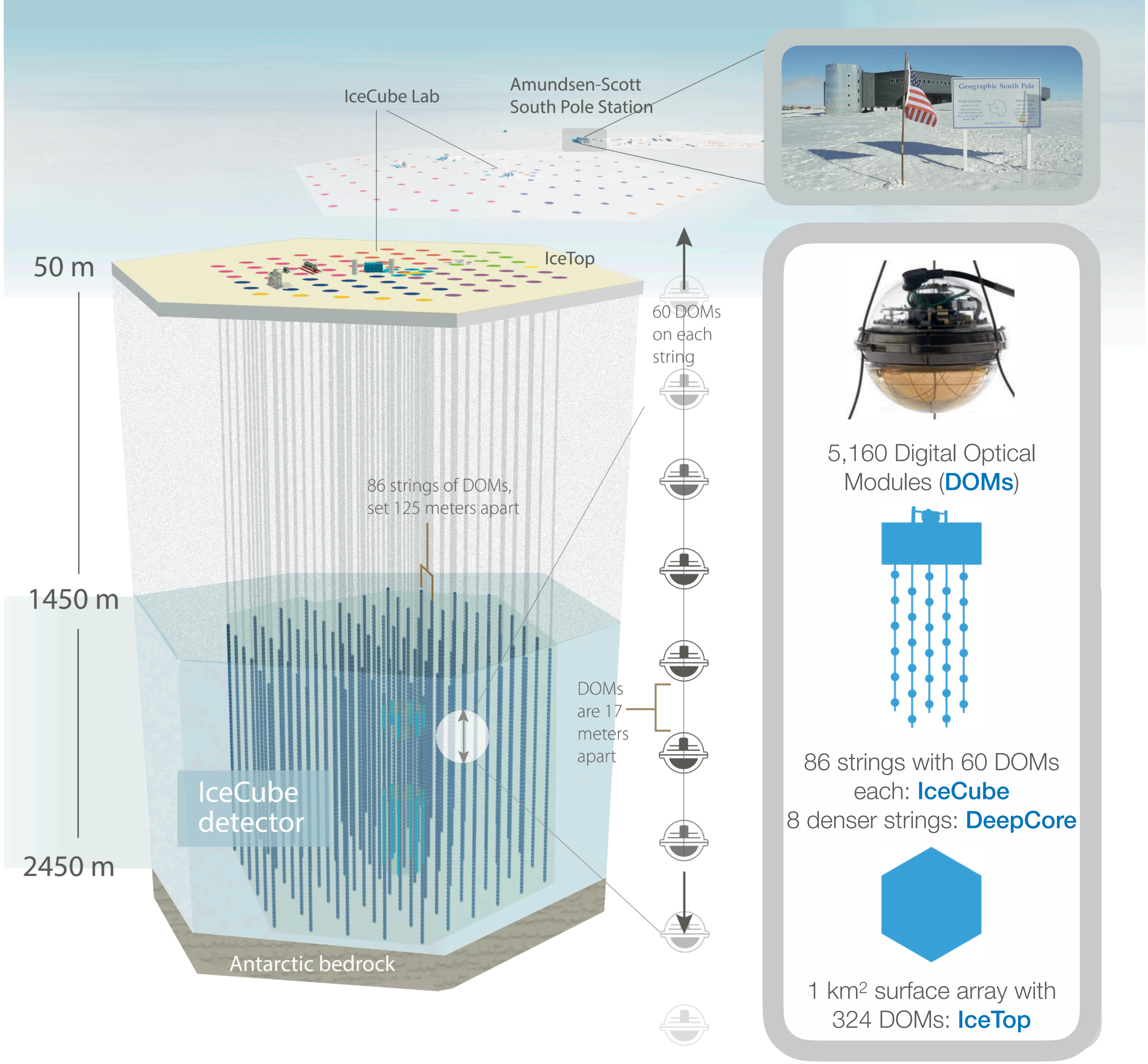
COSMIC RAYS

Charged particles, deflected by magnetic fields

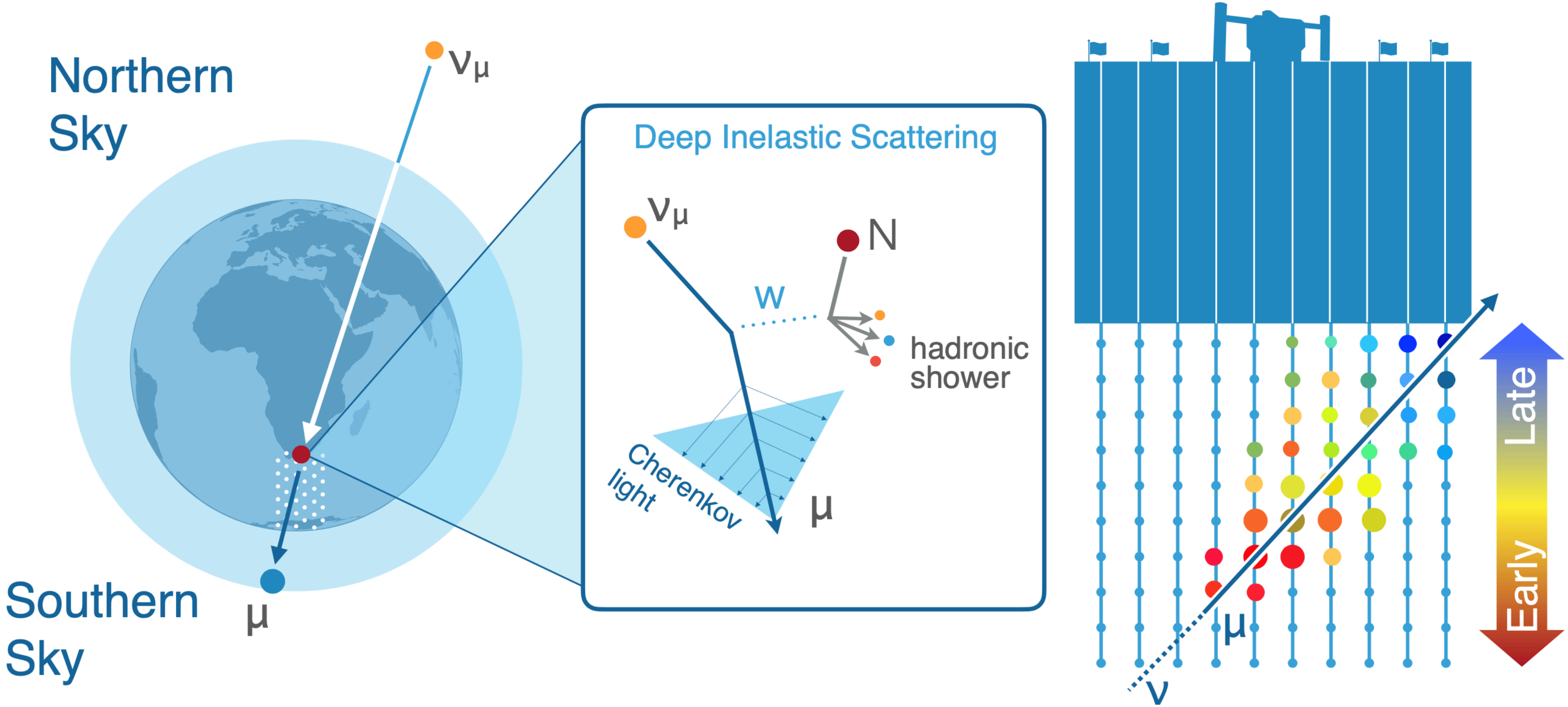
NEUTRINOS

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

The IceCube Neutrino Observatory



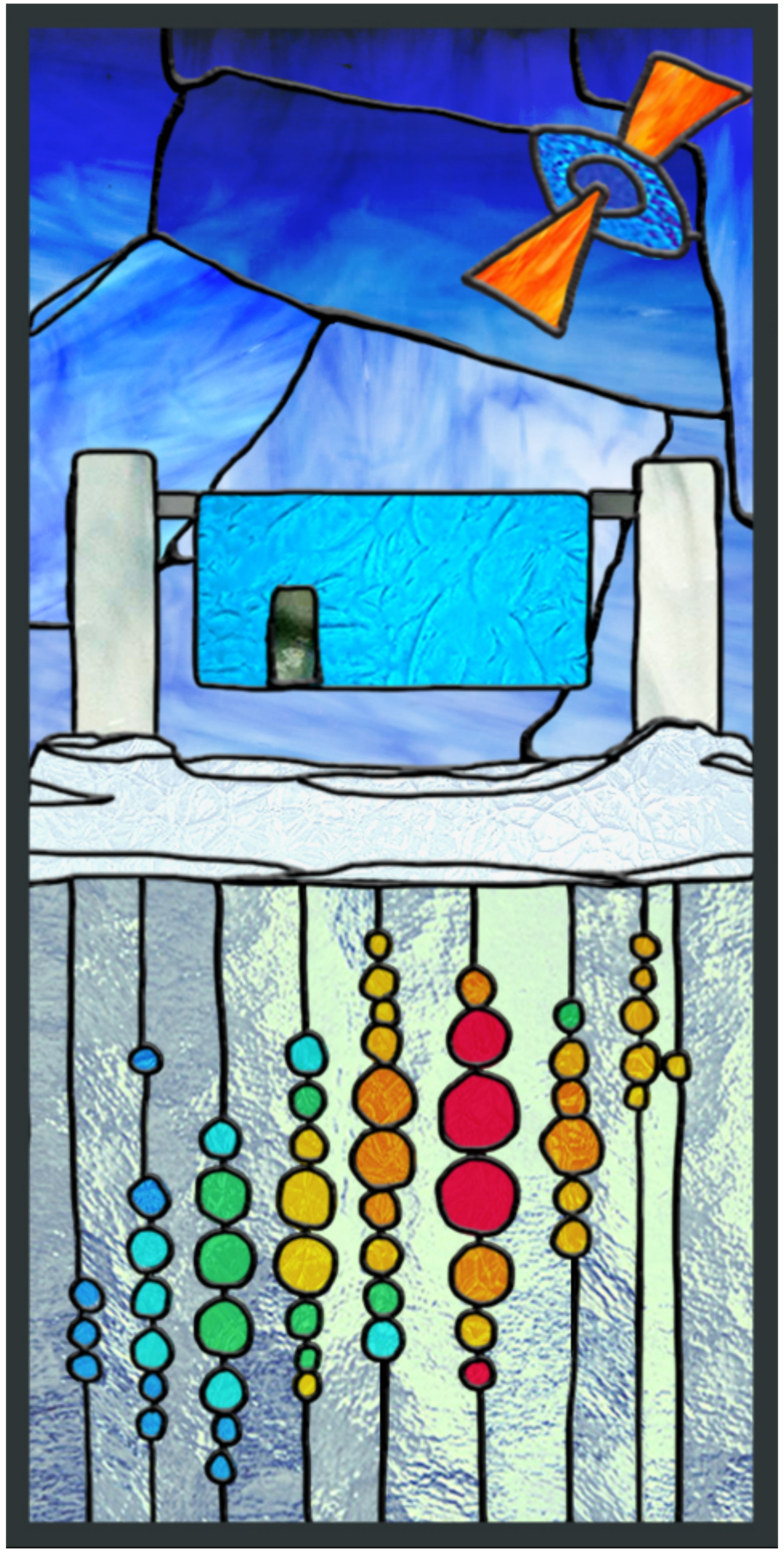
Neutrino detection principle



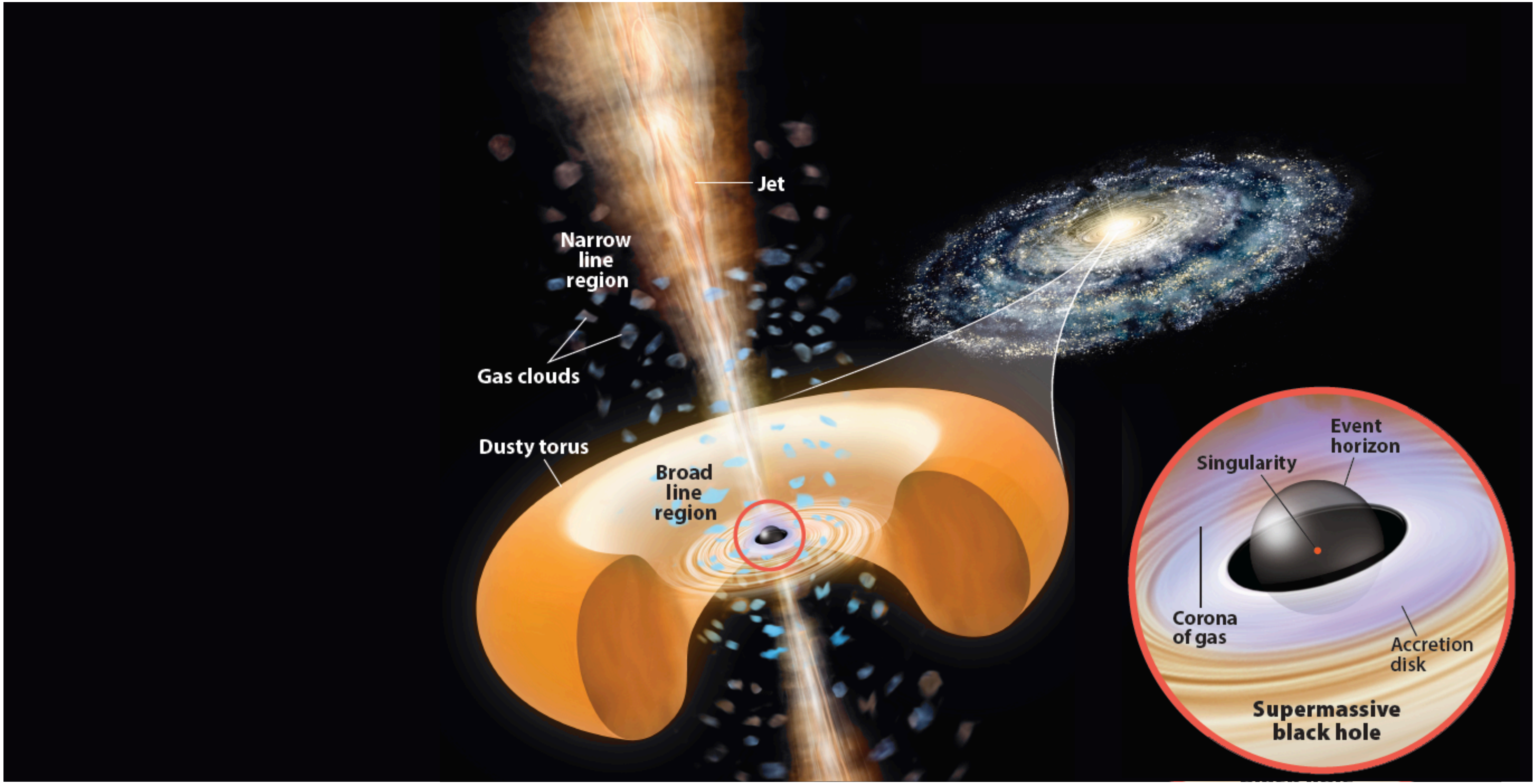
Cosmic Neutrinos

IceCube hunt for sources

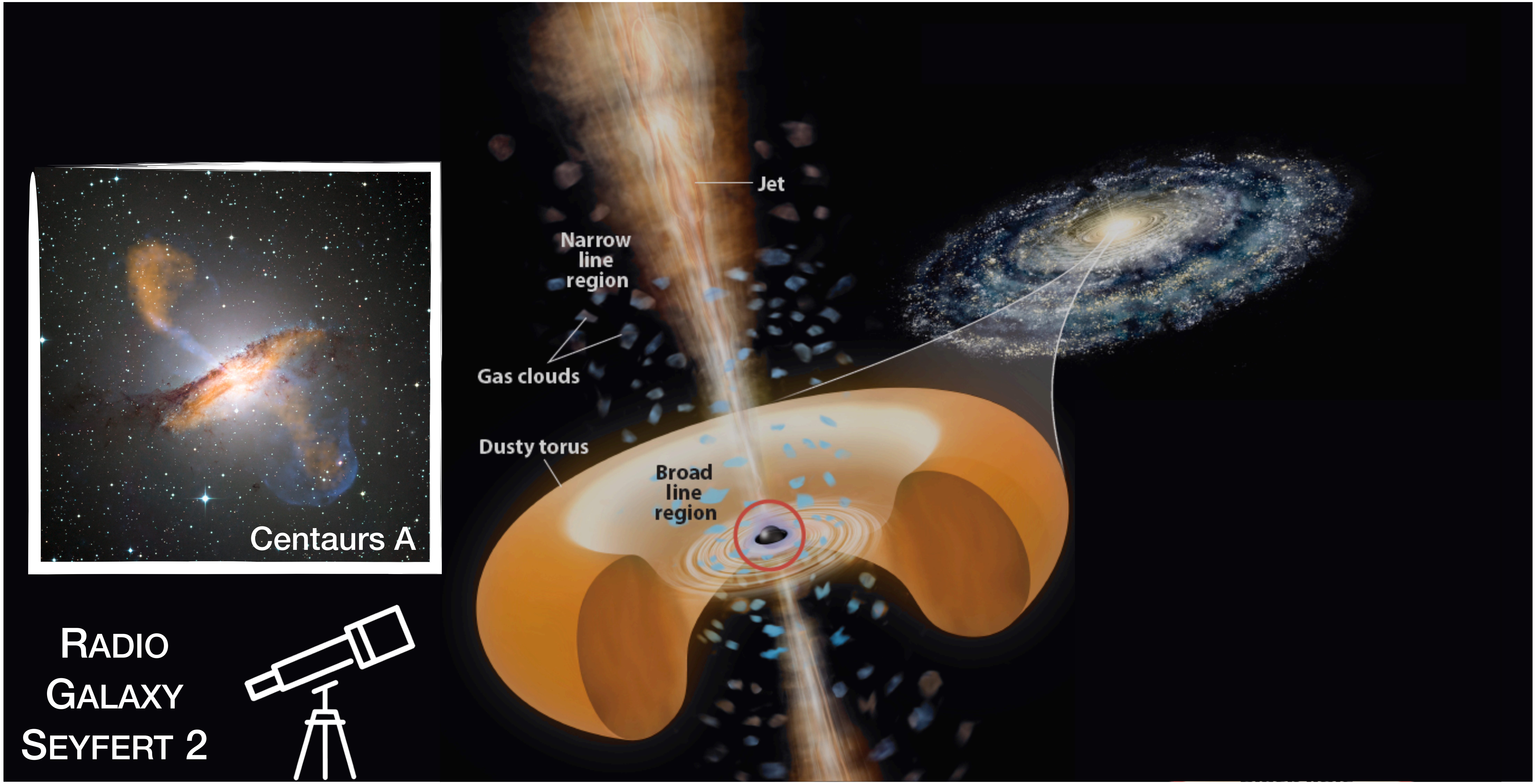
- Diffuse TeV-PeV neutrino flux of unknown origin
- TXS 0506+056 first compelling evidence of neutrino emission from blazars
- *Fermi*-LAT blazars can only be responsible for a small fraction of the observed neutrinos



AGN as Neutrino Sources



AGN as Neutrino Sources



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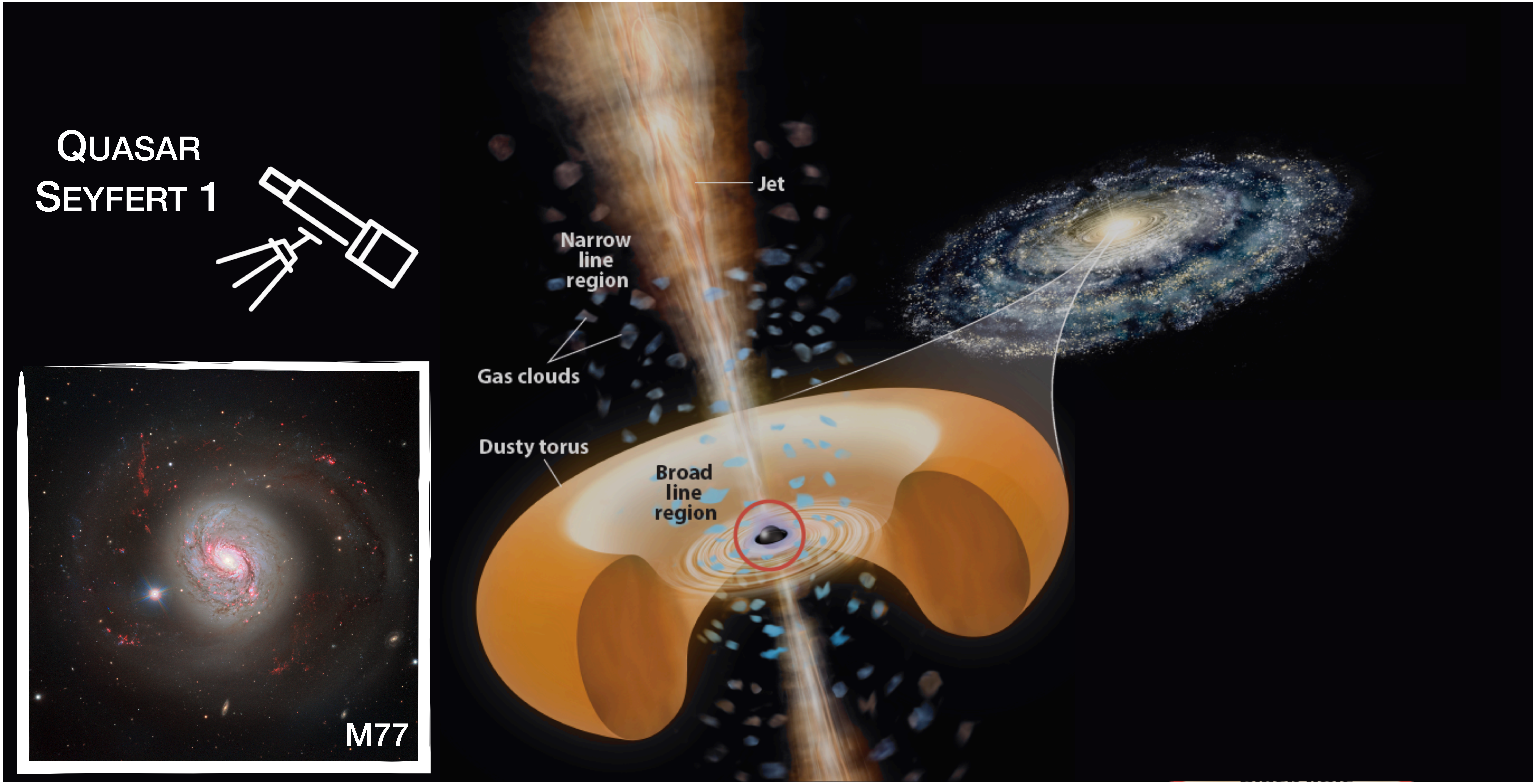
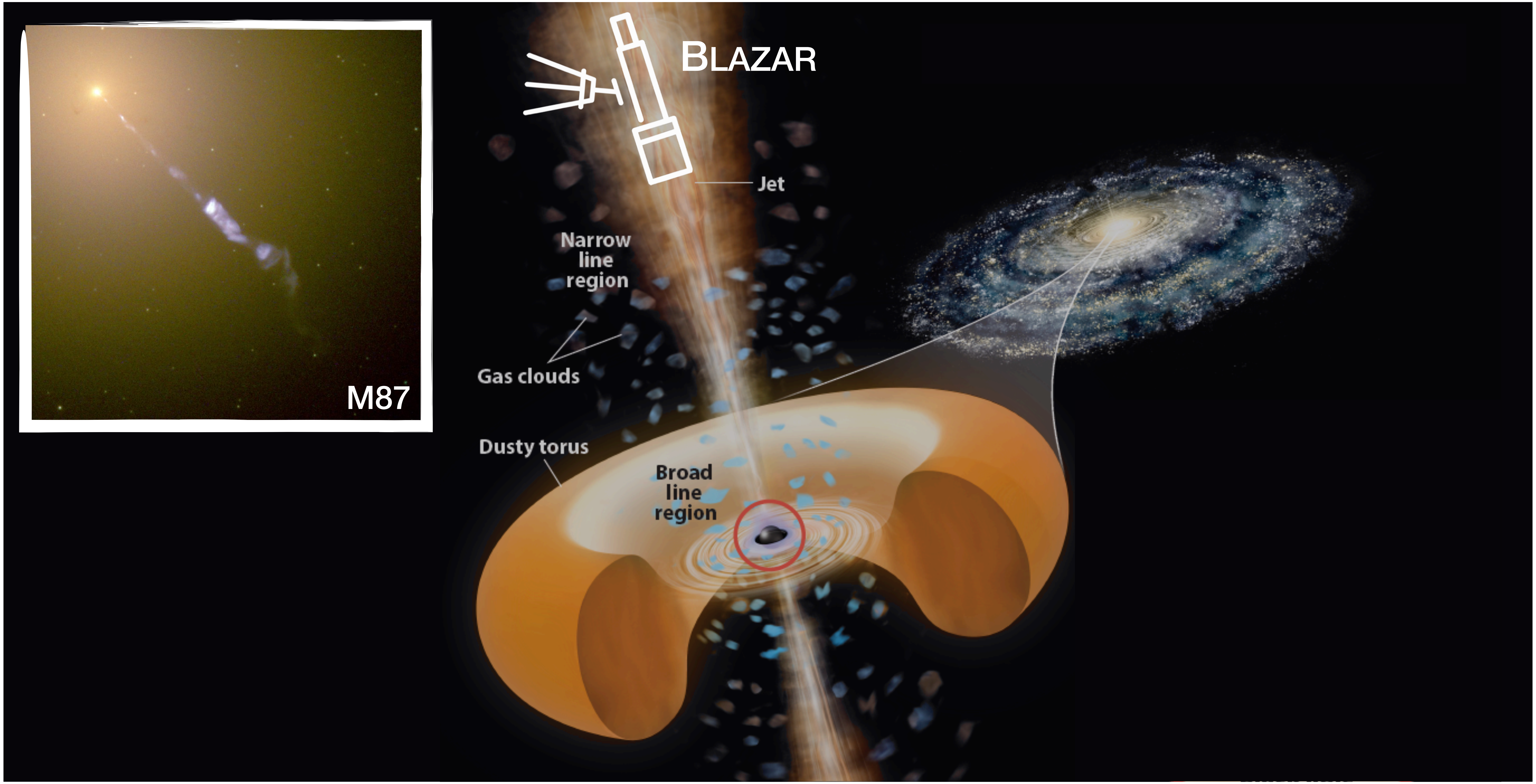
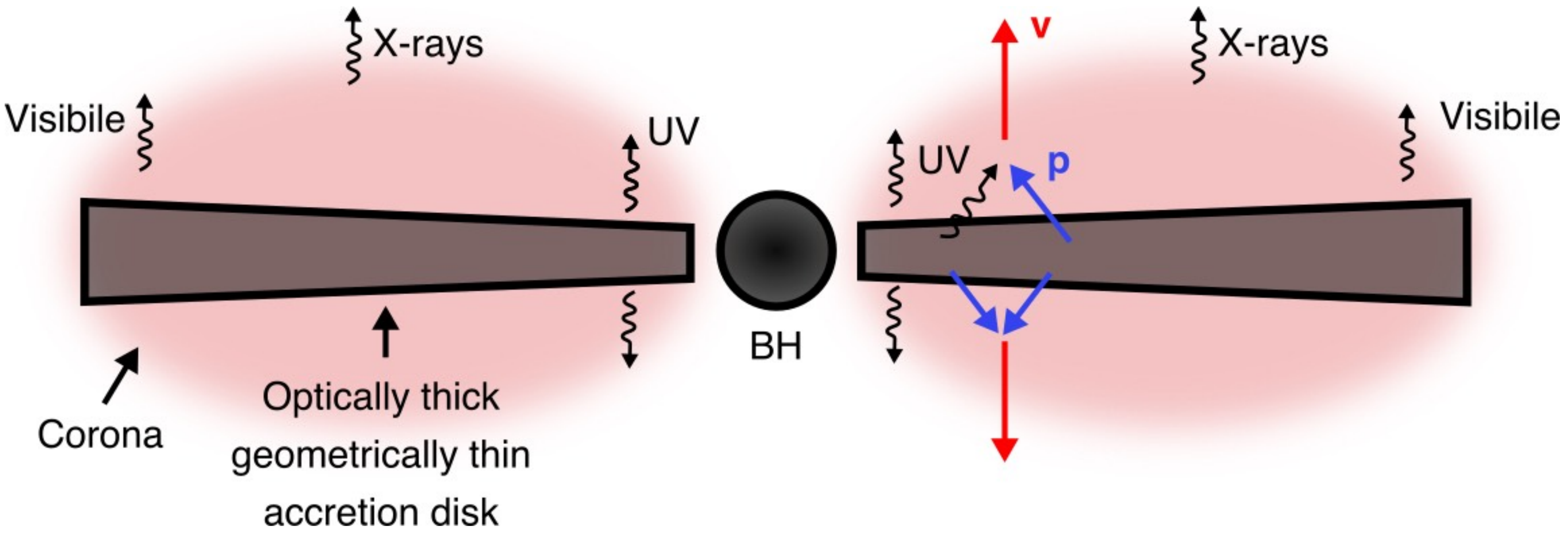


AGN as Neutrino Sources



Neutrinos from Cores of Luminous AGN

AGN with Shakura-Sunyaev accretion disk

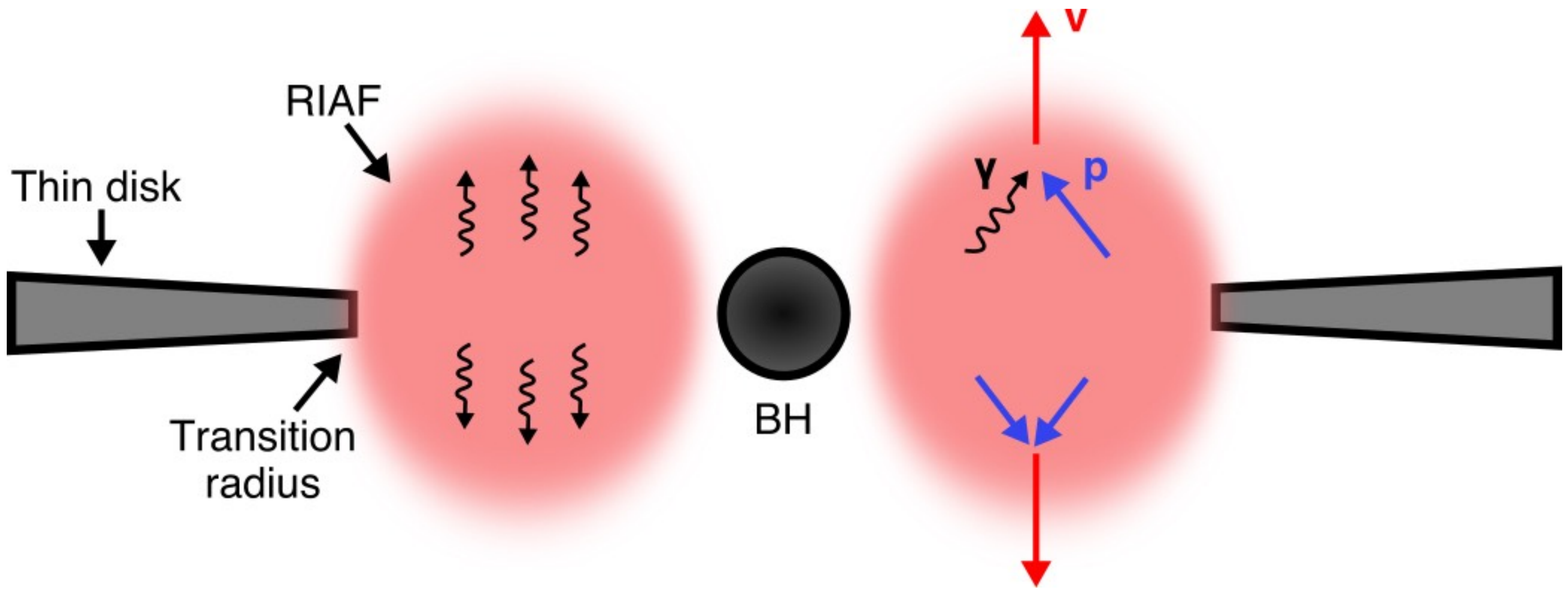


Neutrino luminosity approximated by X-ray luminosity

[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

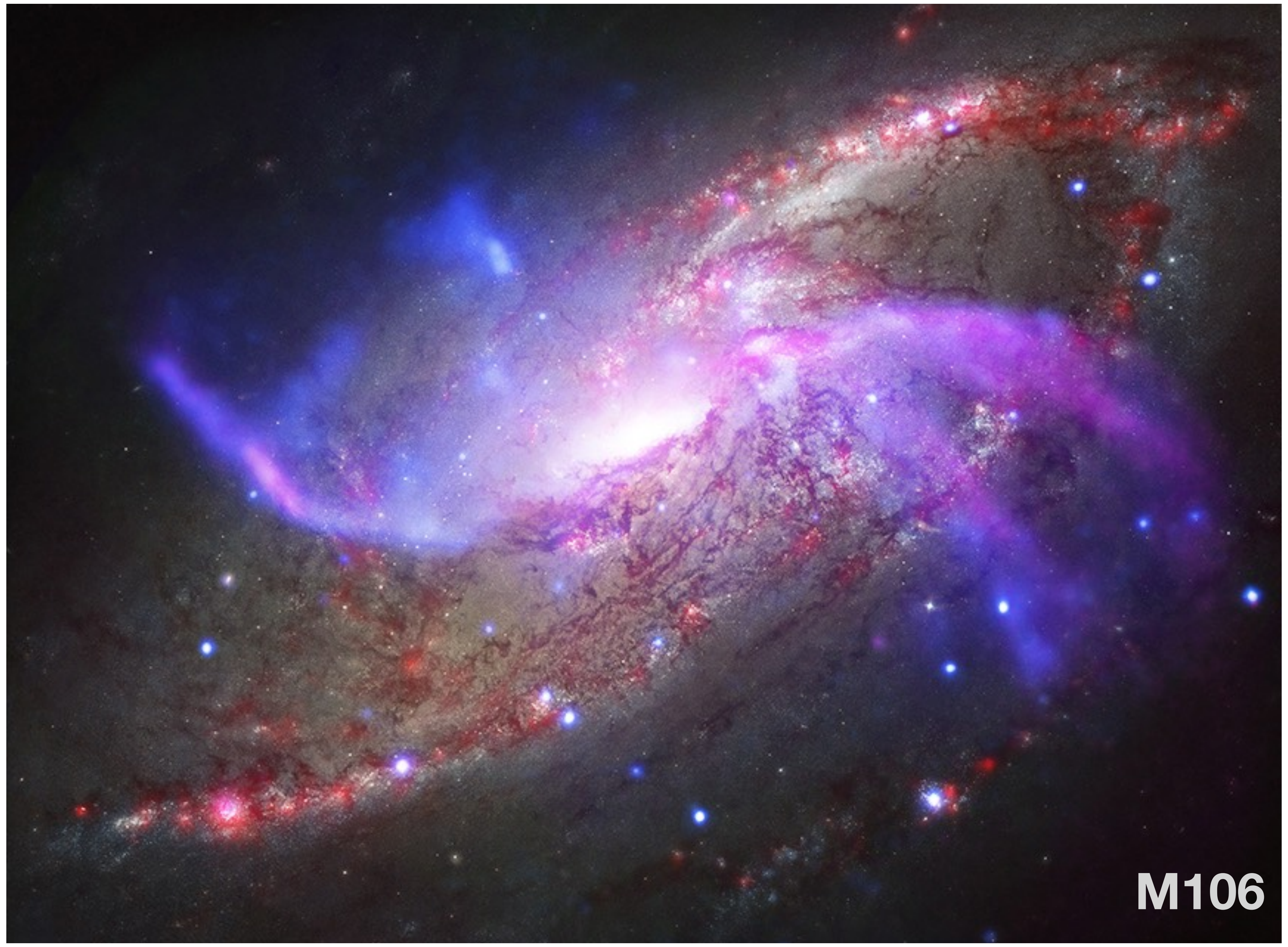
[Kimura et al. (2015)]

Which AGN?

Luminous AGN

Radio Galaxies

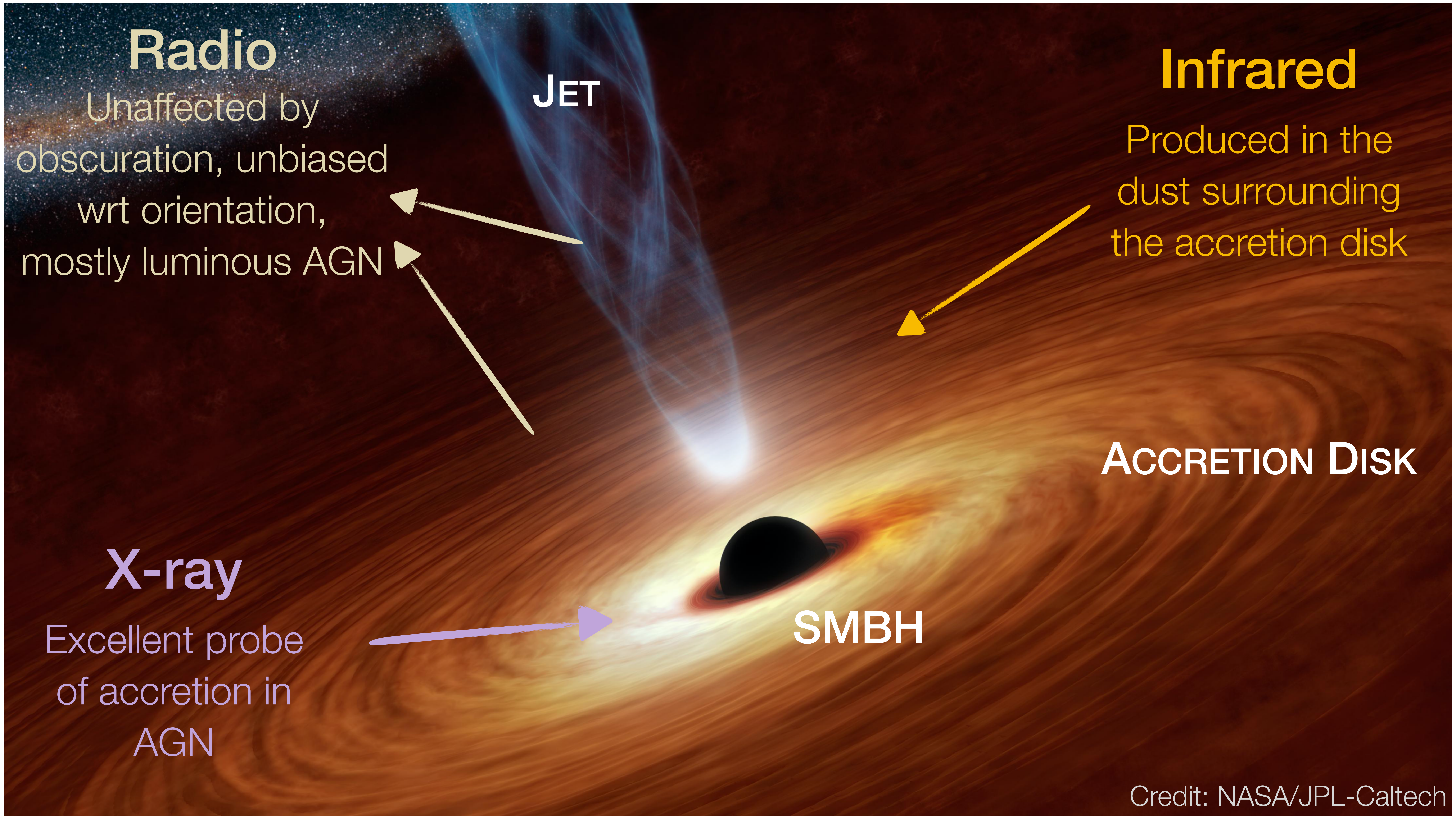
Low-Luminosity AGN (LLAGN)



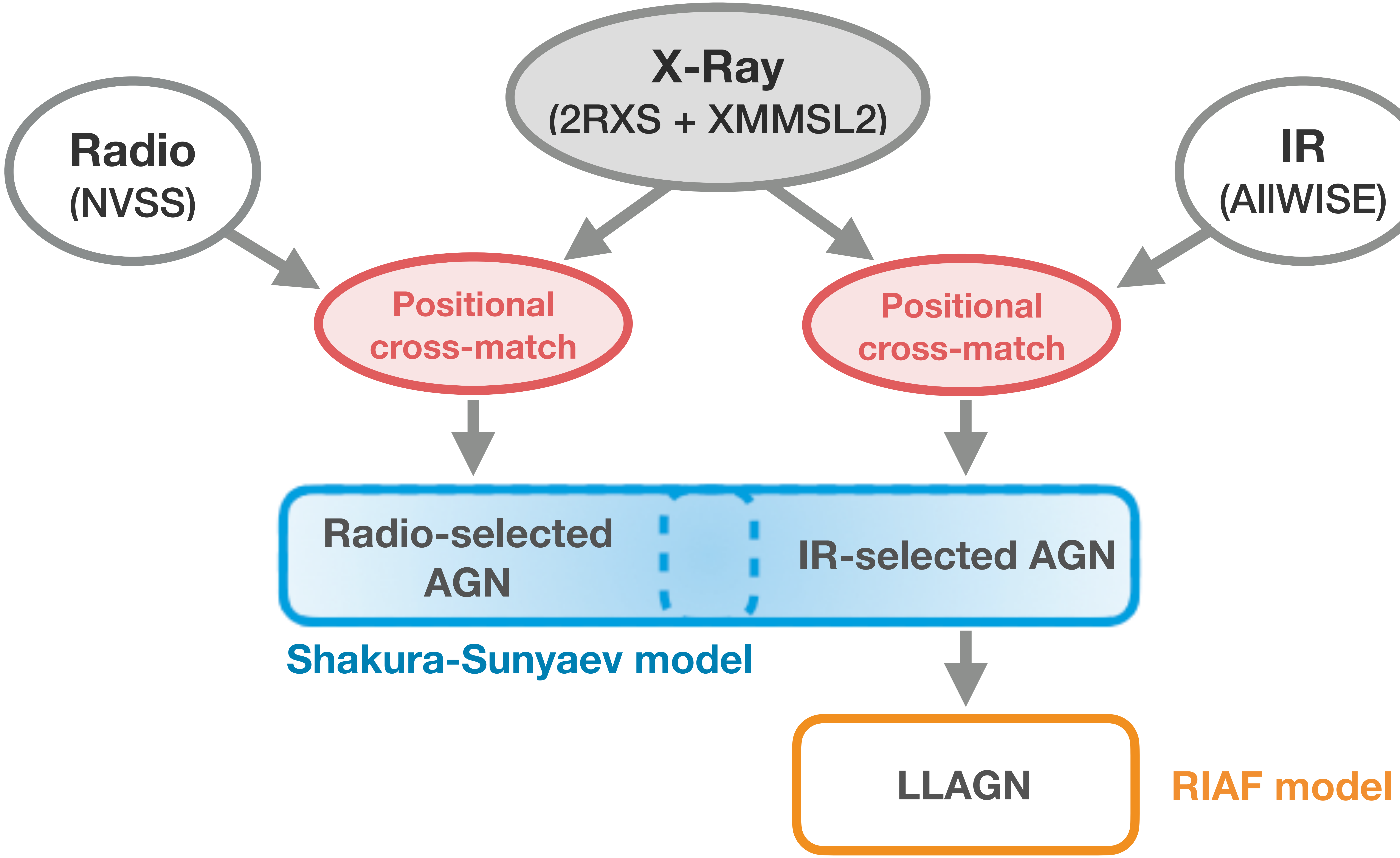
Seyfert Galaxies

How to select AGN?

Using various bands of the electromagnetic spectrum



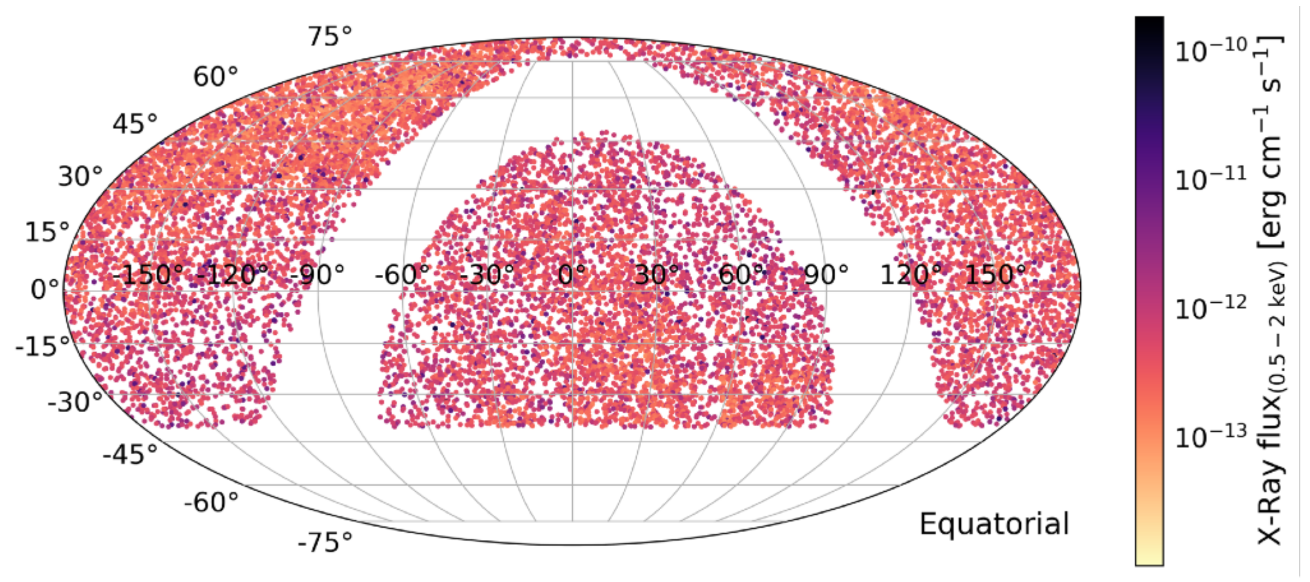
Creation of the AGN samples



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

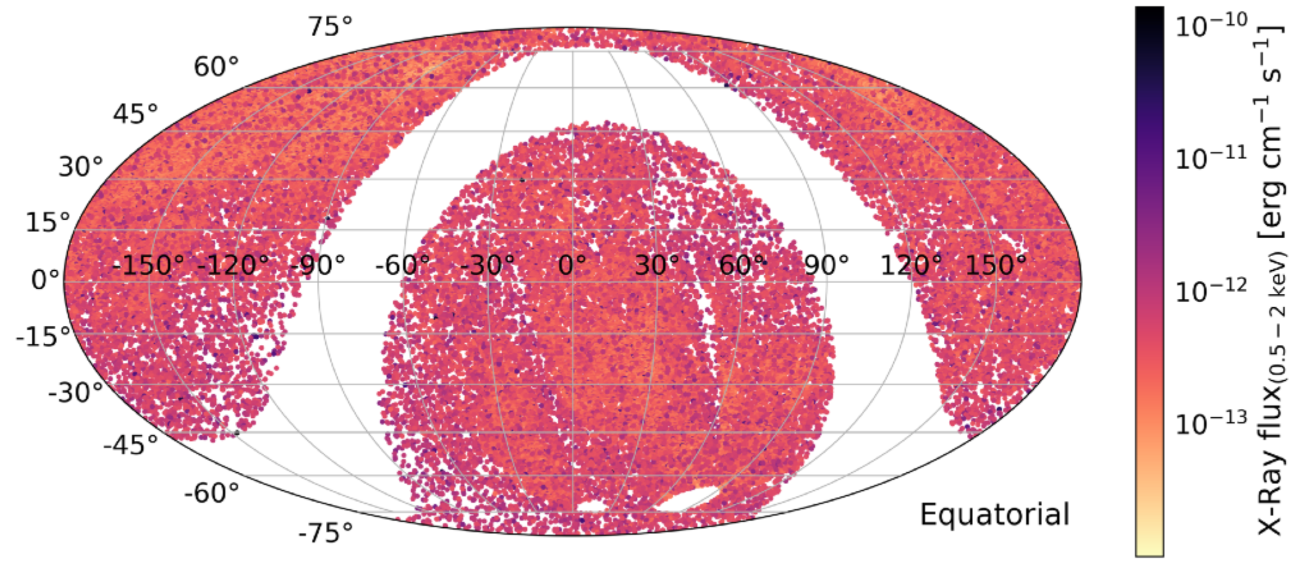
AGN final samples

Radio-selected AGN



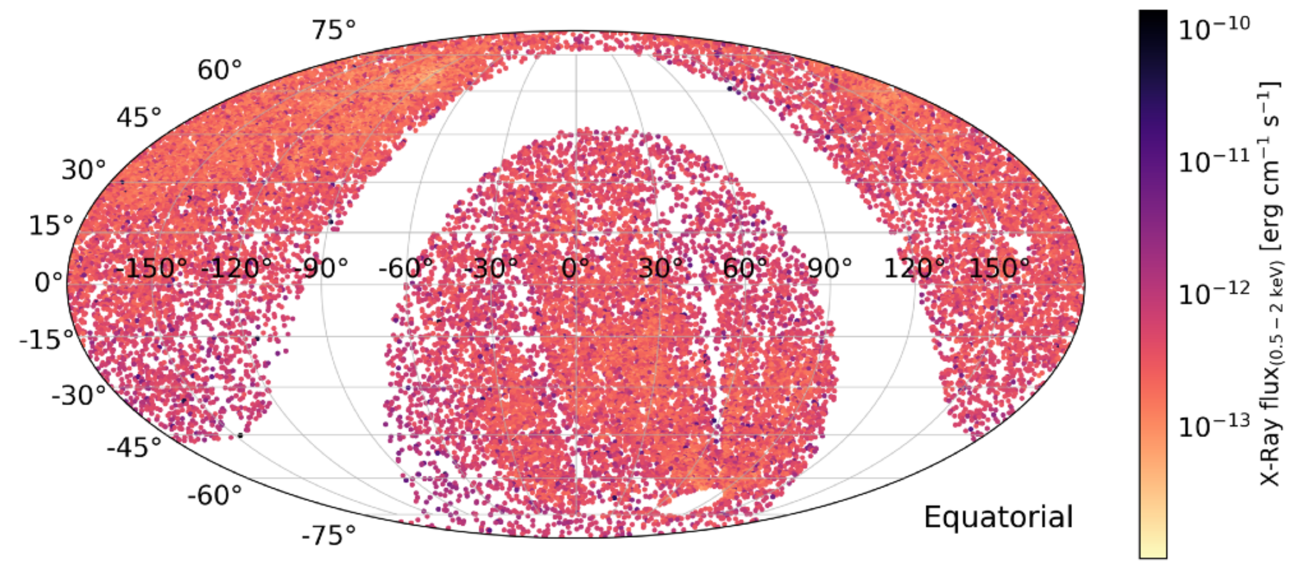
13,972 sources

IR-selected AGN



52,835 sources

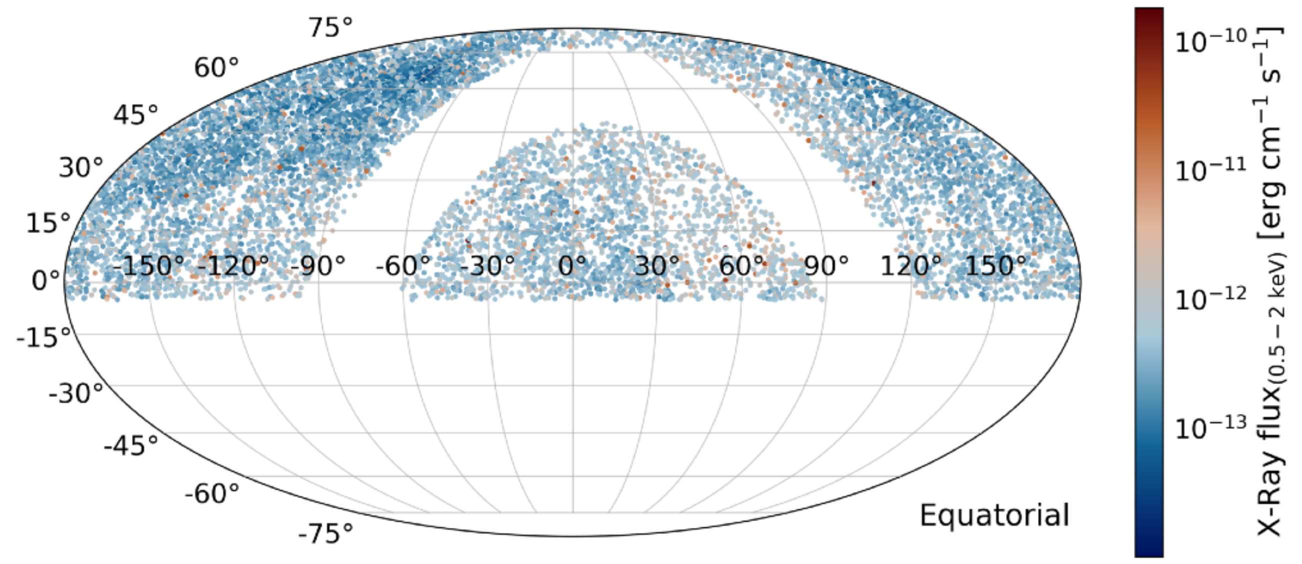
LLAGN



25,648 sources

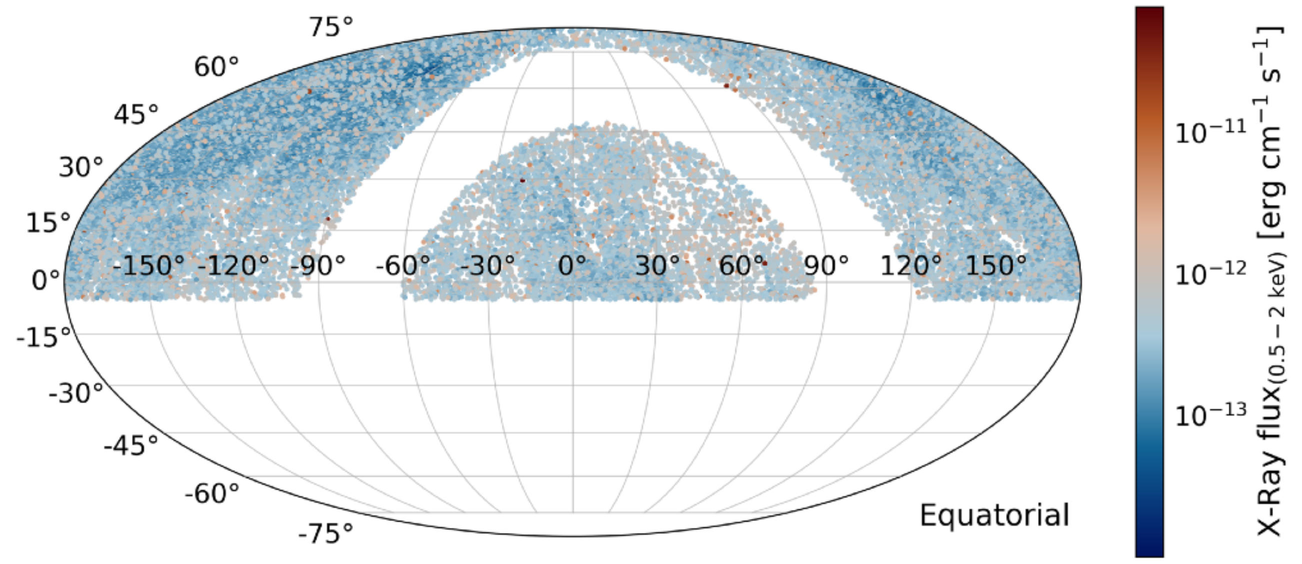
AGN final samples

Radio-selected AGN



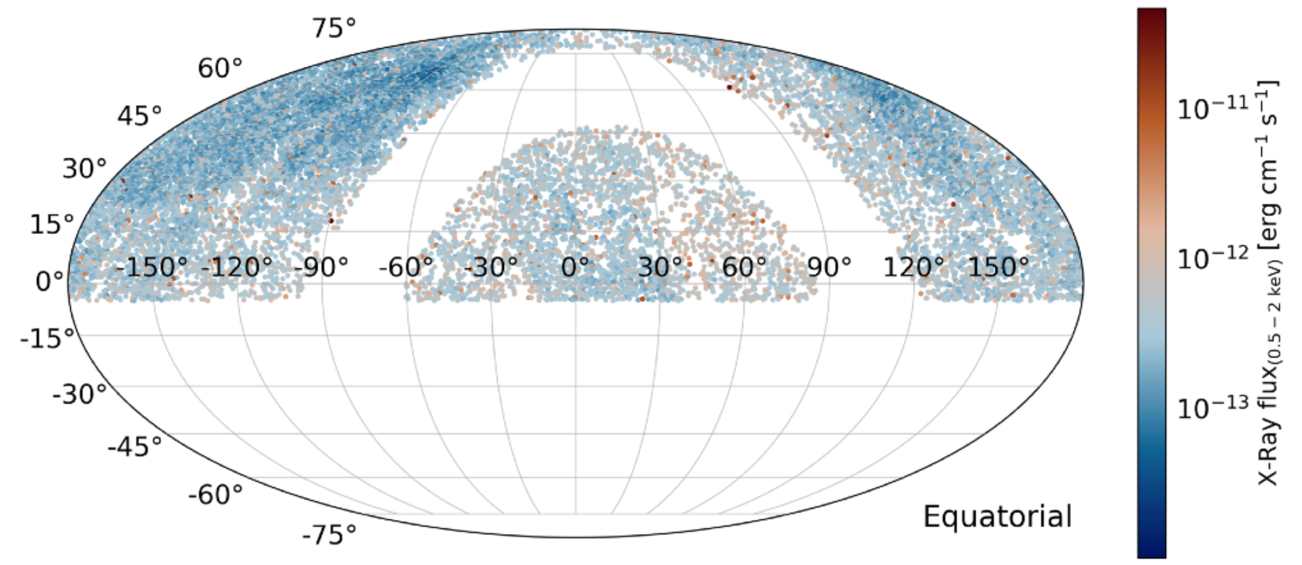
13,972 sources
9,749 sources

IR-selected AGN



52,835 sources
32,249 sources

LLAGN



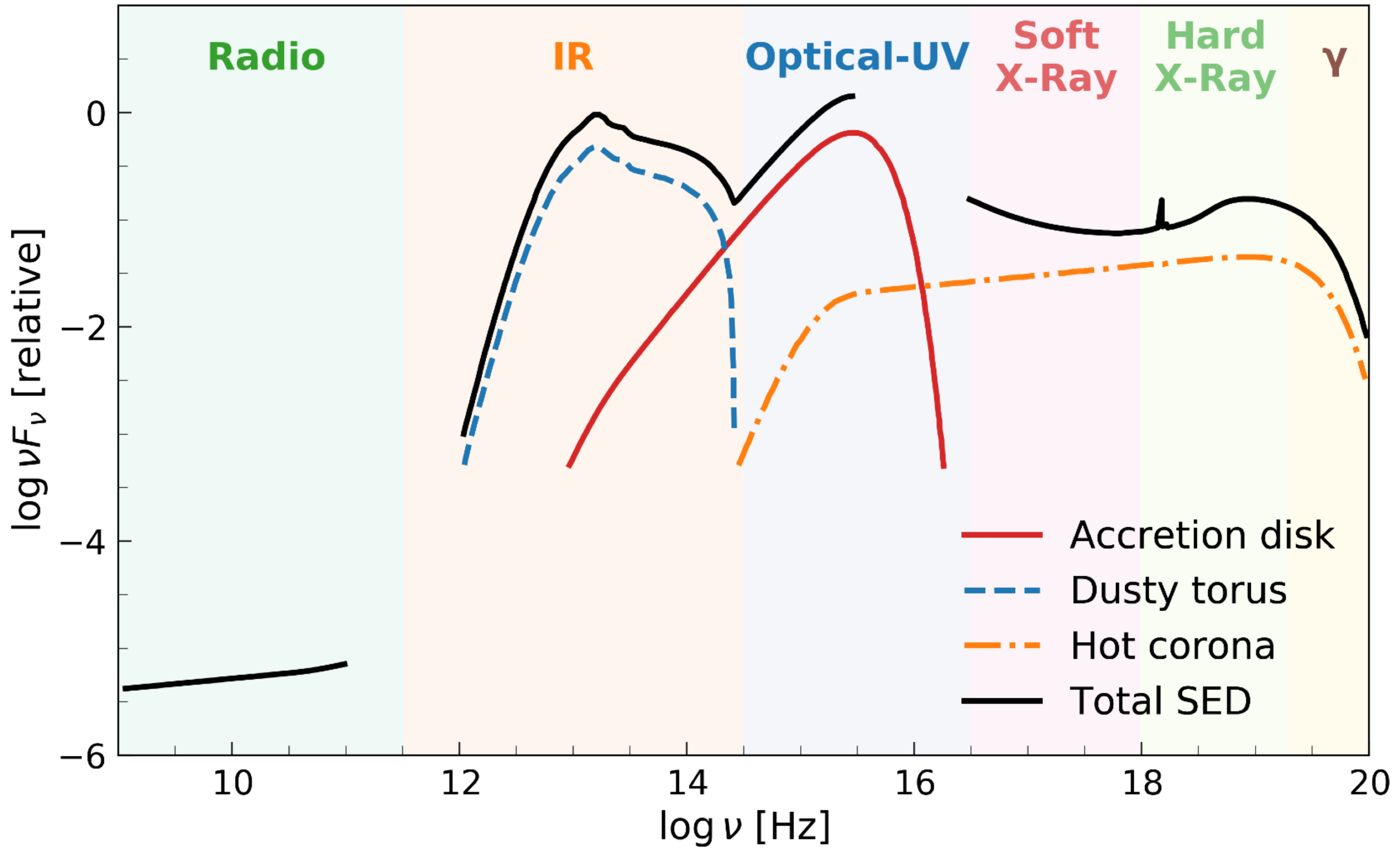
25,648 sources
15,887 sources

Stacking analysis to test the combined emission of all sources

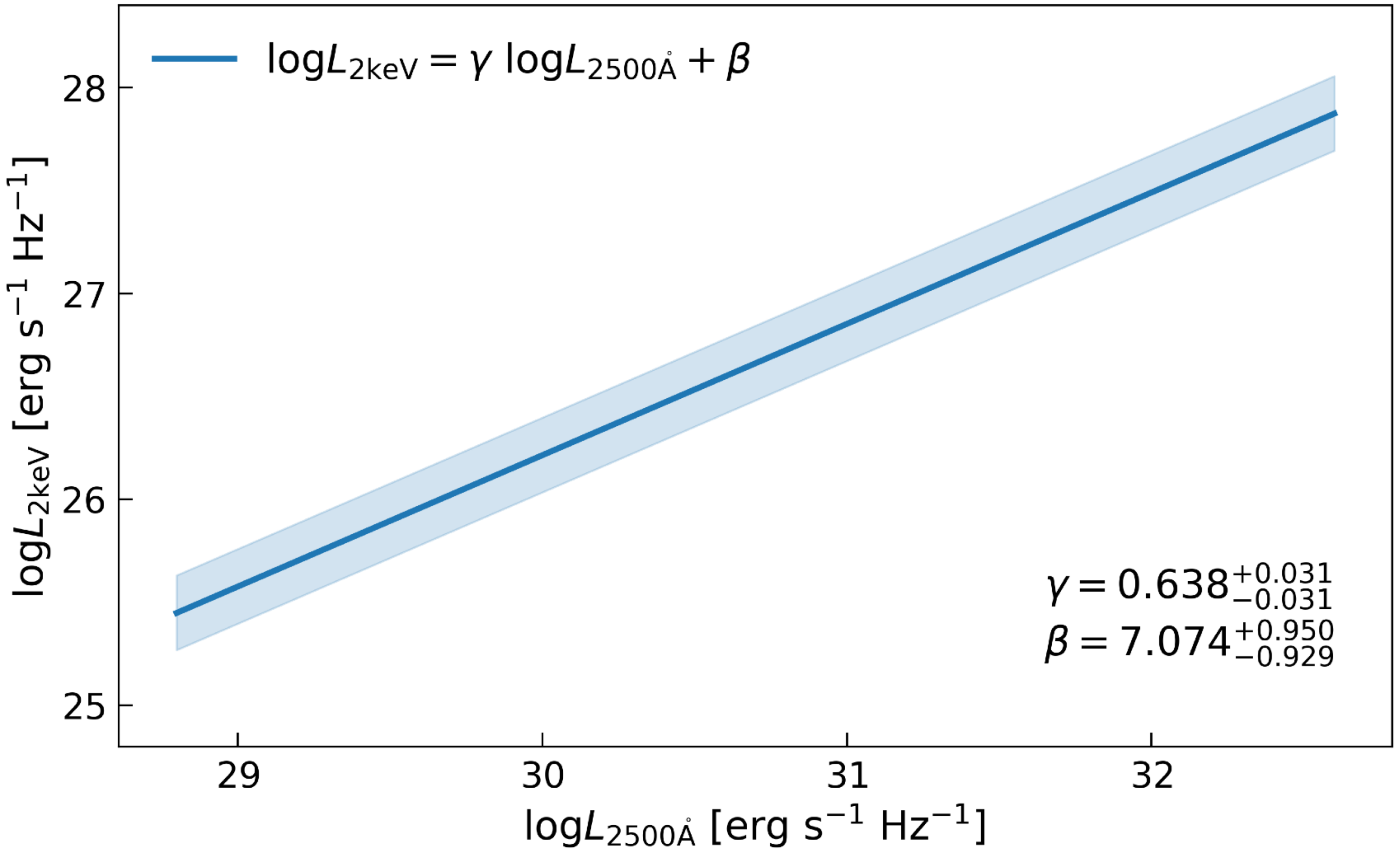
How many neutrinos from each AGN?

X-ray flux as neutrino flux proxy

Padovani et al. 2017



E. Lusso & Risaliti 2016



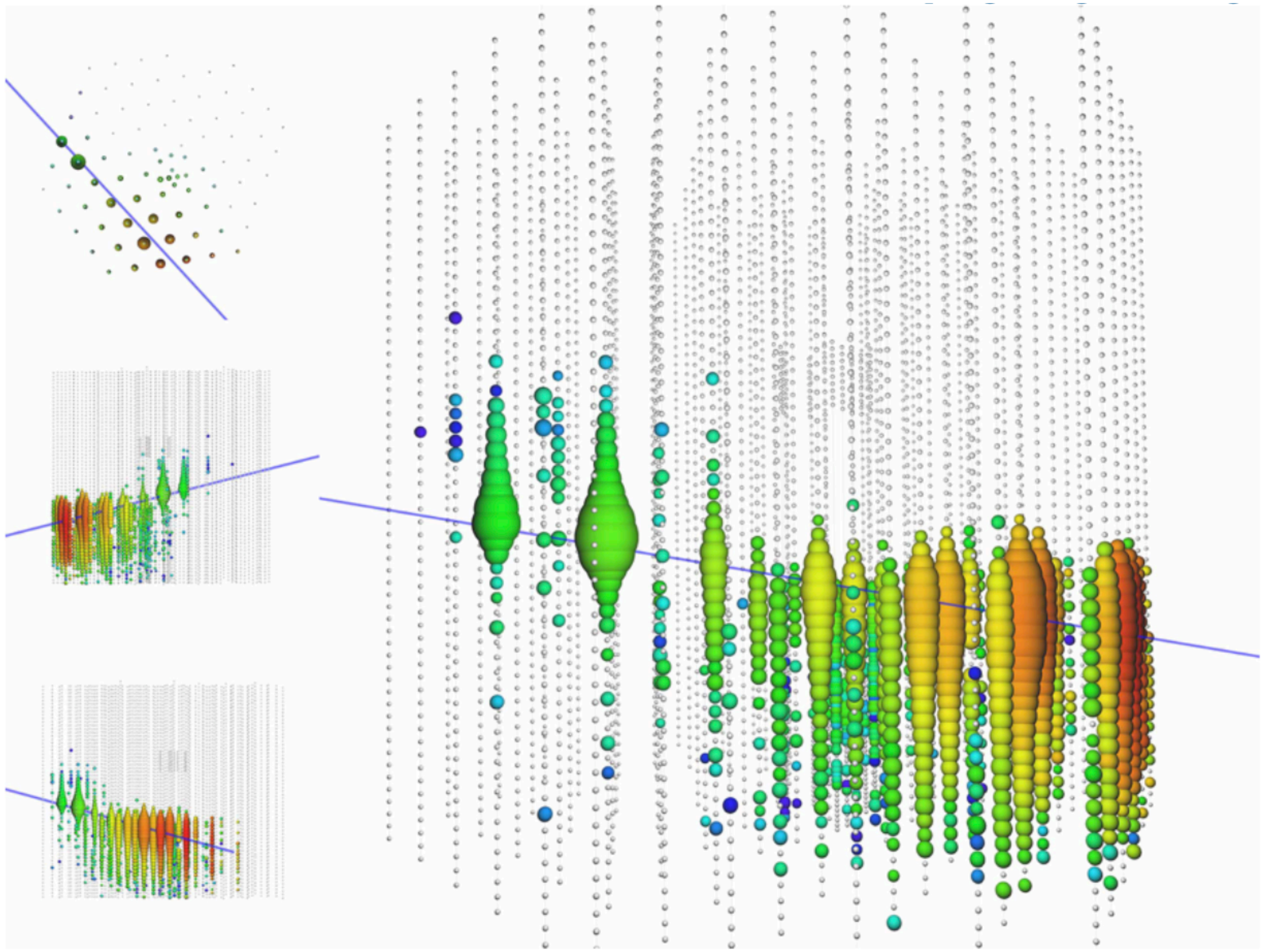
Accretion disk emission peaks at UV wavelength

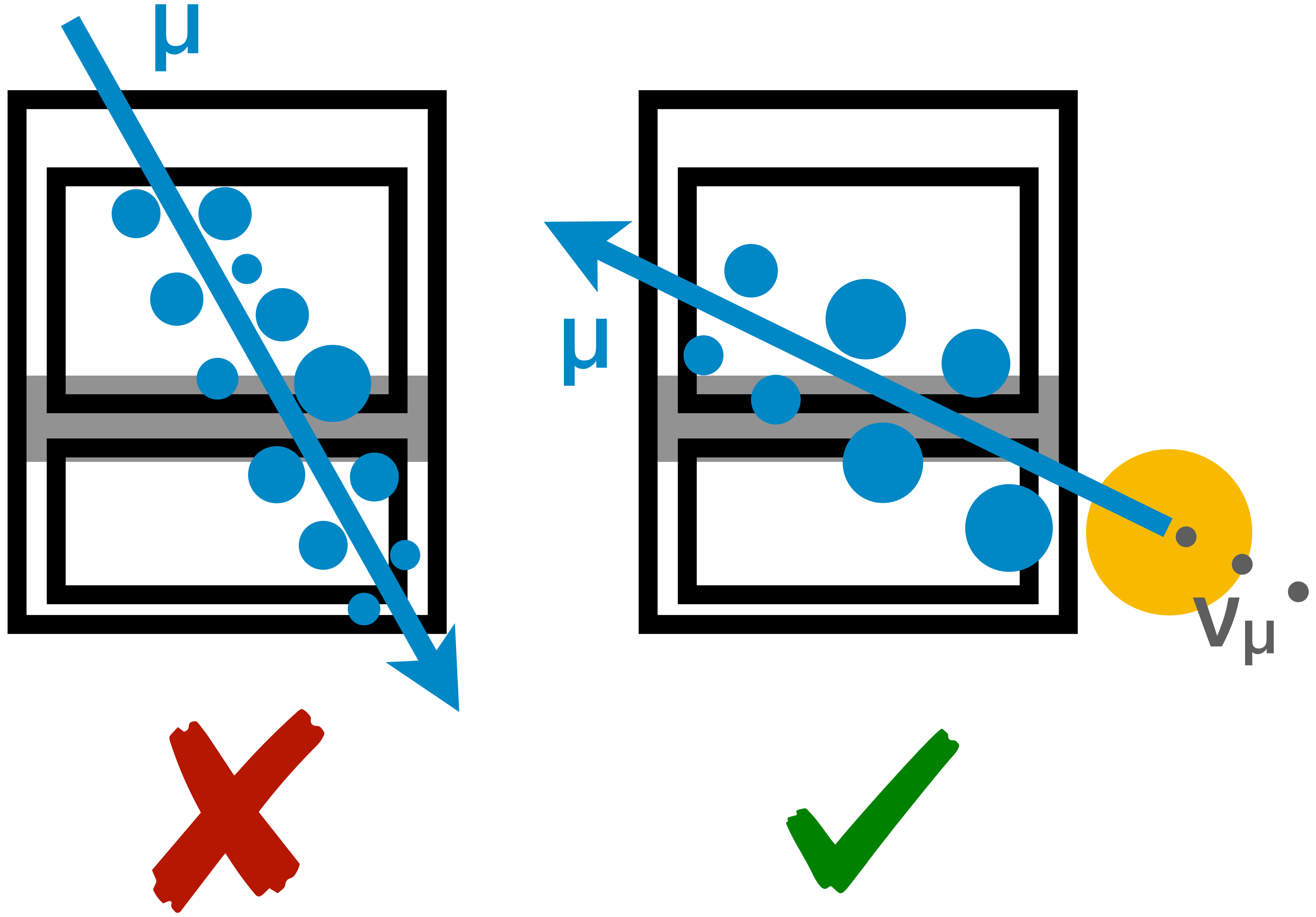
Tight relationship between X-ray and UV–optical emission

NEUTRINO LUMINOSITY → ACCRETION DISK LUMINOSITY → UV LUMINOSITY → X-RAY LUMINOSITY

Northern-Tracks dataset

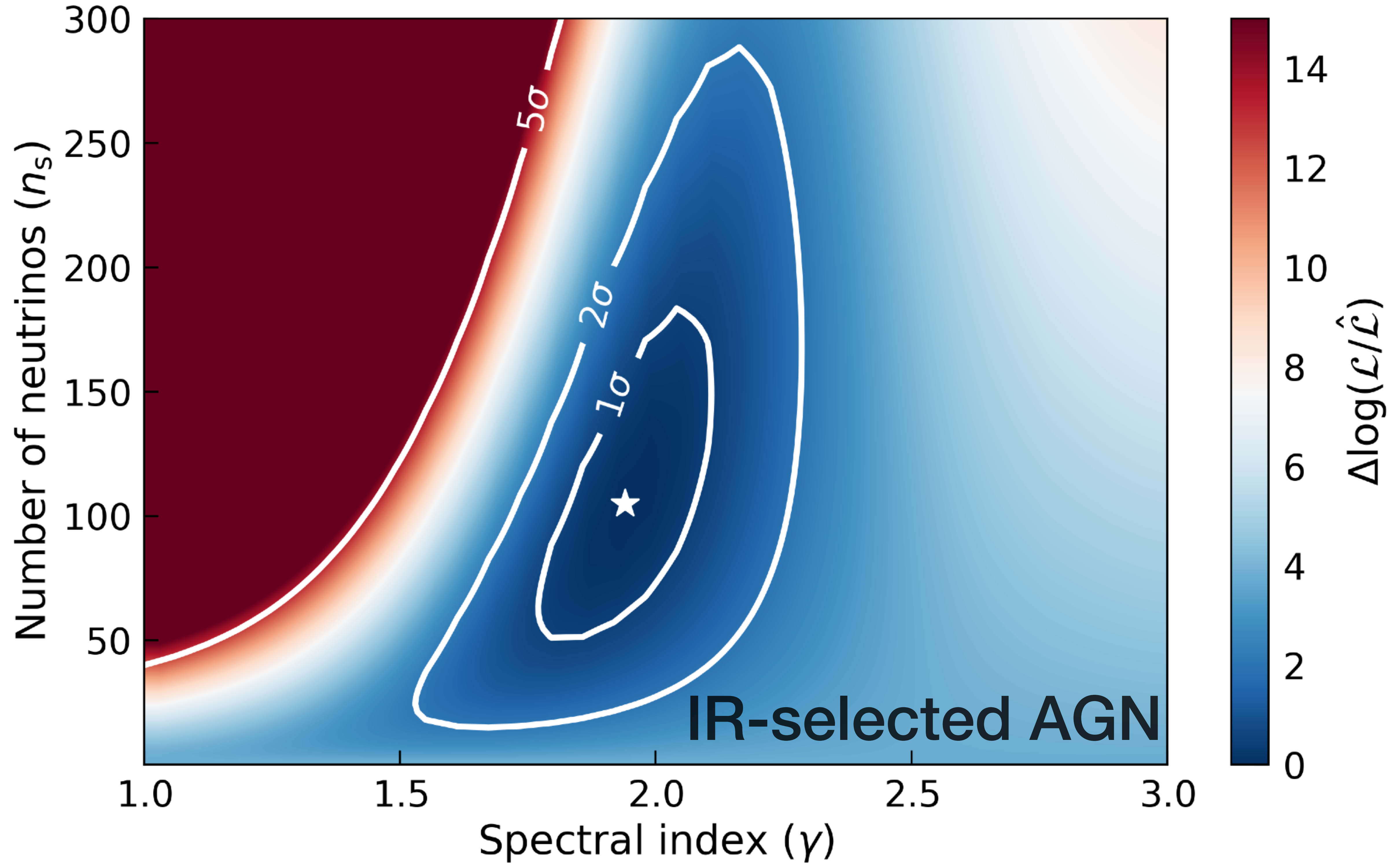
Upgoing through-going muons travelled through the Earth





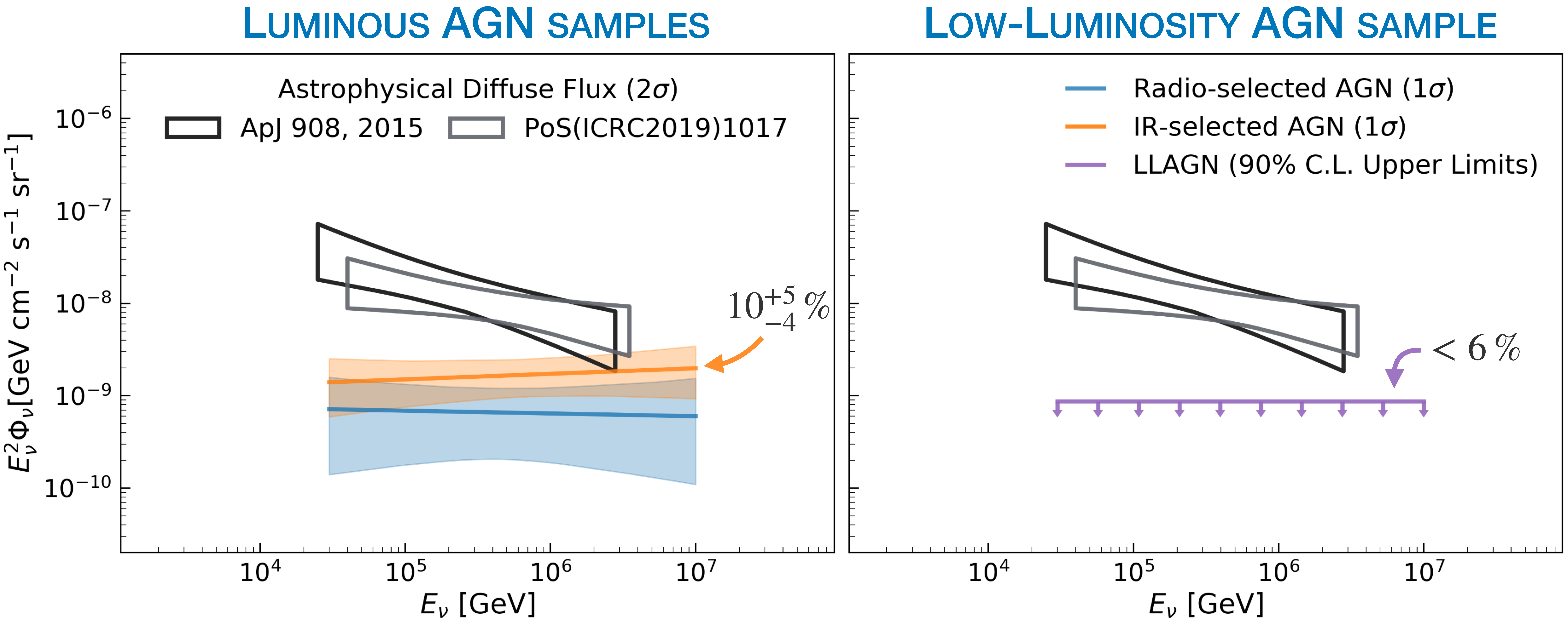
8 years of data
(2009-2017)
~ 497k events

Results: n_s, γ and p-value



	Radio-selected AGN	IR-selected AGN	LLAGN
n_s	53	105	28
γ	2.03	1.94	1.96
Post-trial p-value	5.85×10^{-2} (**1.6σ**)	4.64×10^{-3} (**2.6σ**)	0.16 (**1.0σ**)

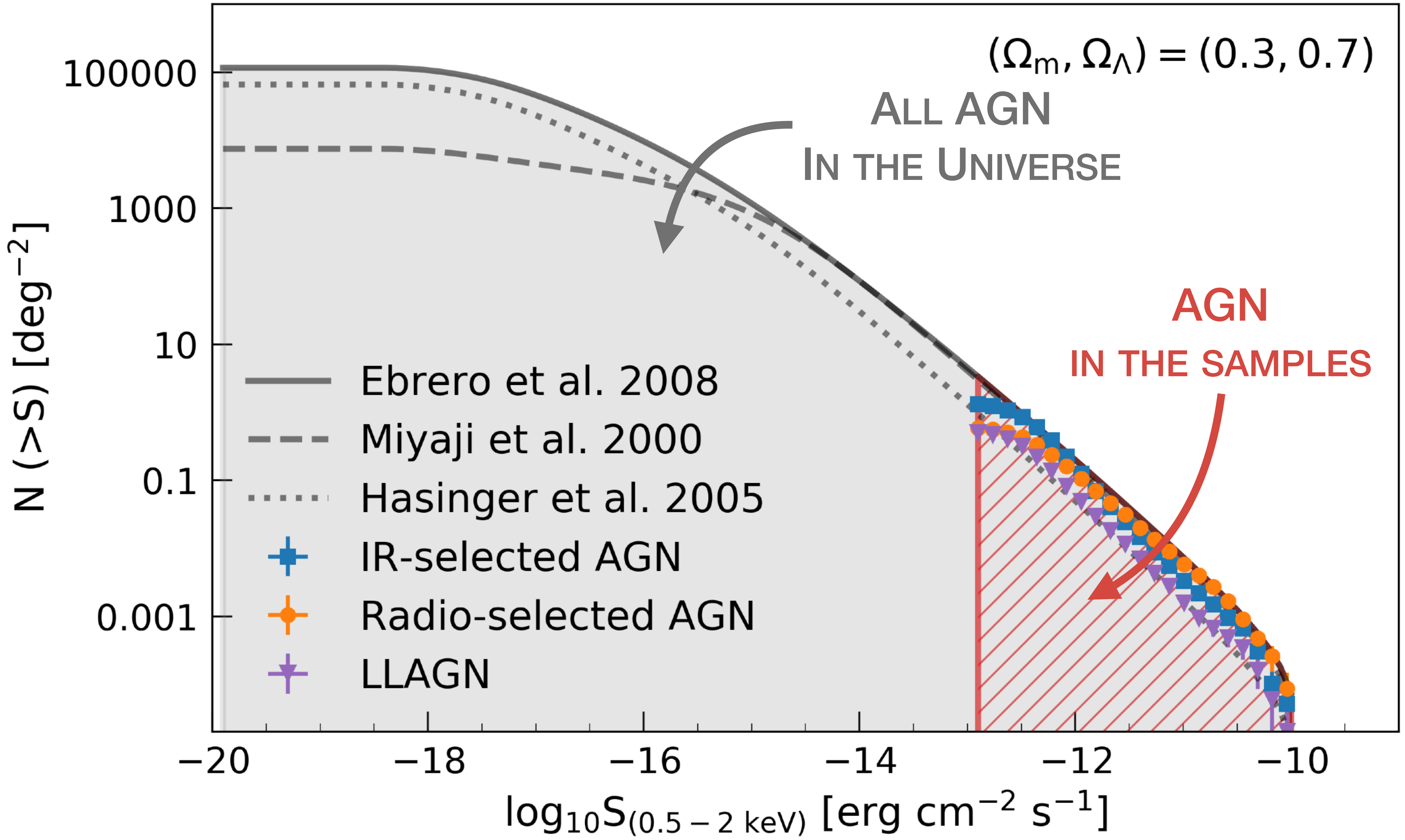
Neutrino spectrum



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

From AGN samples to AGN population

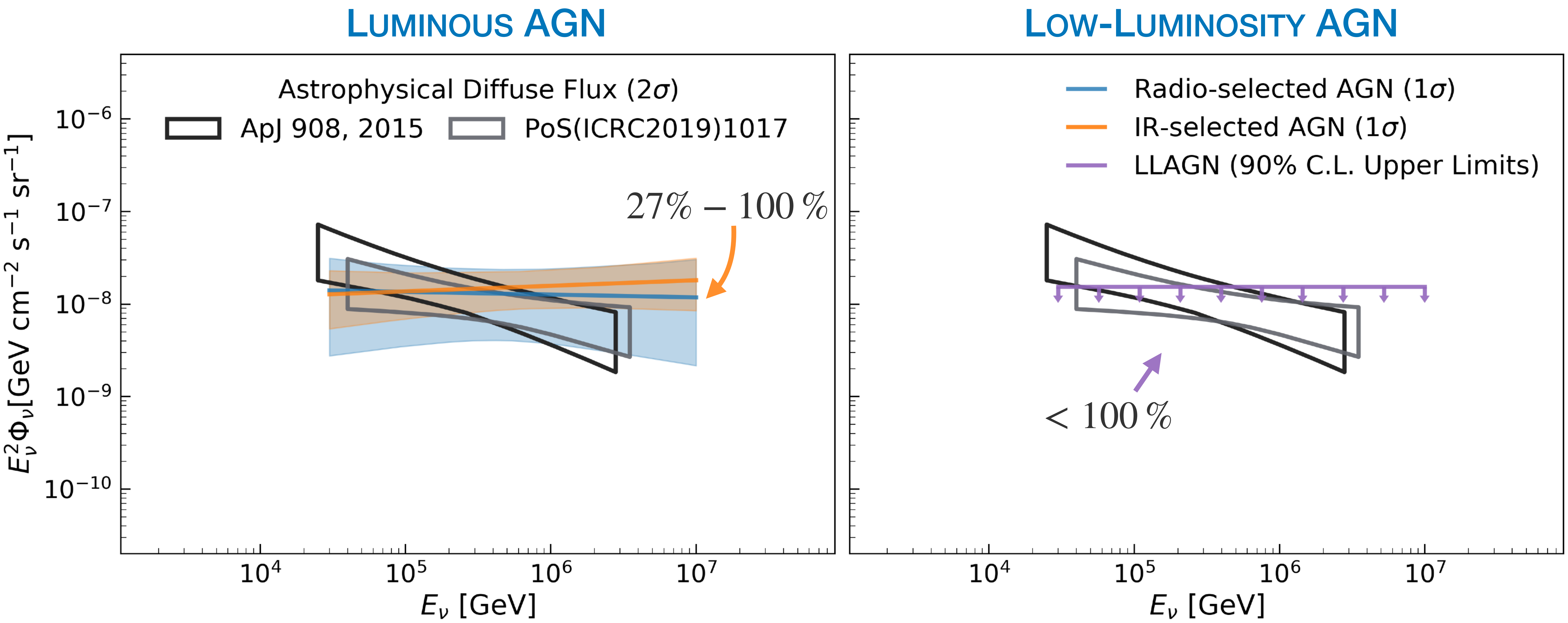
Through the ***completeness*** factor



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

	Completeness
Radio-selected AGN	~5%
IR-selected AGN	~11%
LLAGN	~7%

Neutrino spectrum for AGN population



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

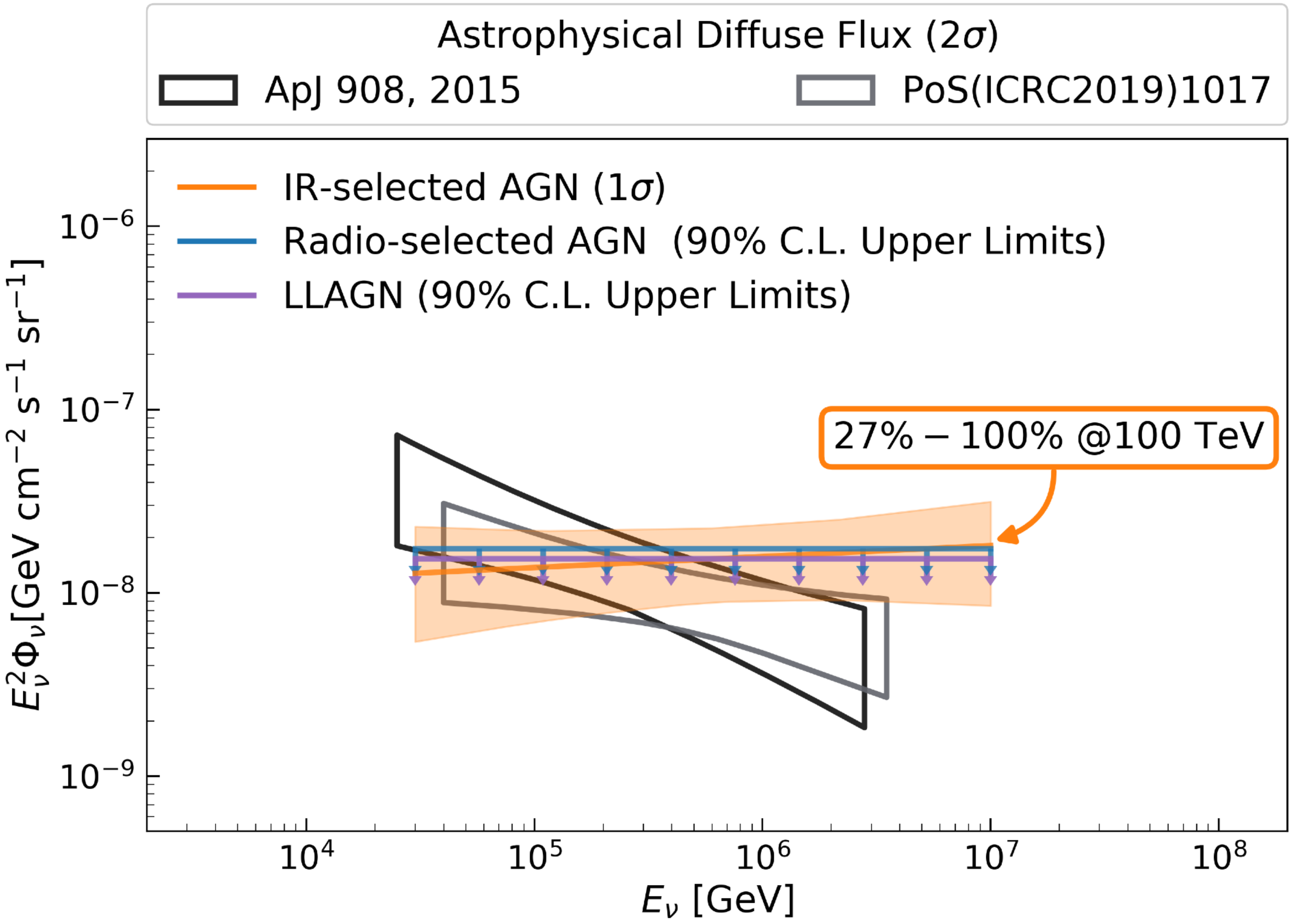
Cores of LLAGN can explain **<100%** of the diffuse neutrino flux **@100 TeV**

Conclusions

- **First direct hint** that cosmic rays accelerated in the **AGN core regions** are responsible for the bulk of the astrophysical neutrino flux observed by IceCube above 100 TeV

- **AGN population** dominates the sources of high-energy astrophysical neutrinos

- Sources of high-energy astrophysical neutrinos should be **opaque to GeV–TeV gamma rays**



Backup

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:

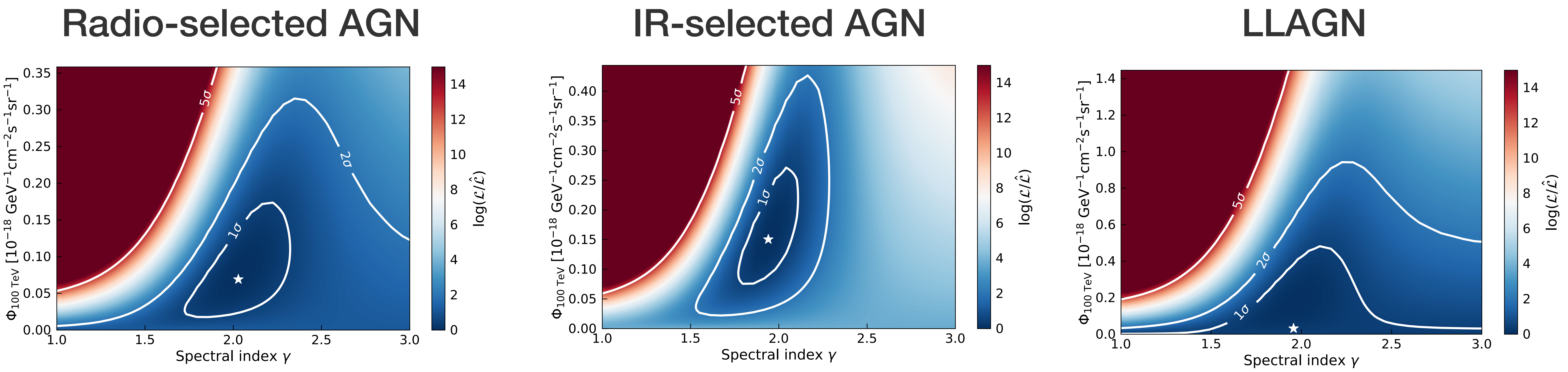
$$\frac{dN}{dE} \propto E^{-\gamma}$$

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

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

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

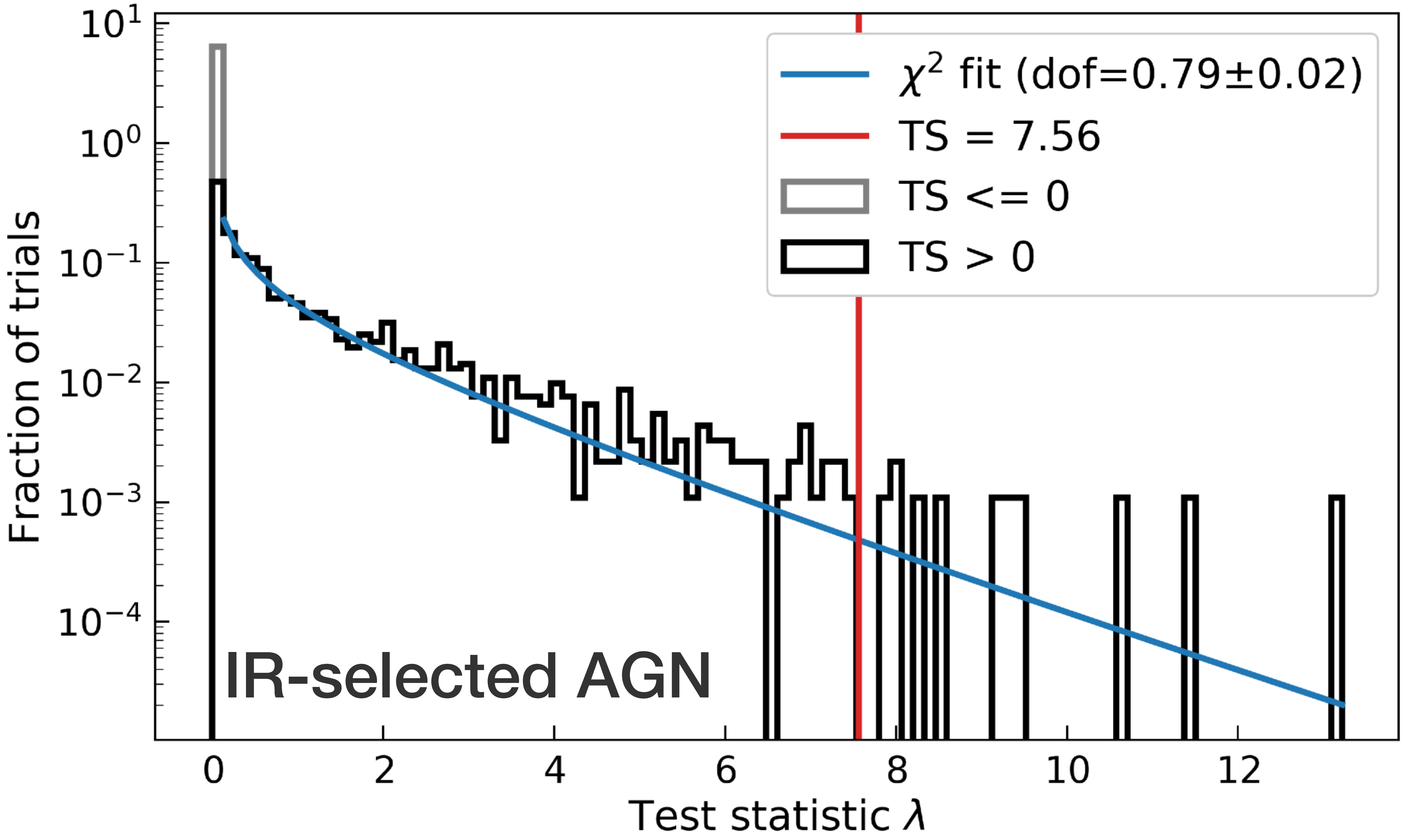
	Radio-selected AGN	IR-selected AGN	LLAGN
n_s	53	105	35
γ	2.03	1.94	1.96

Results: p-values

Probability that results are due to background alone

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

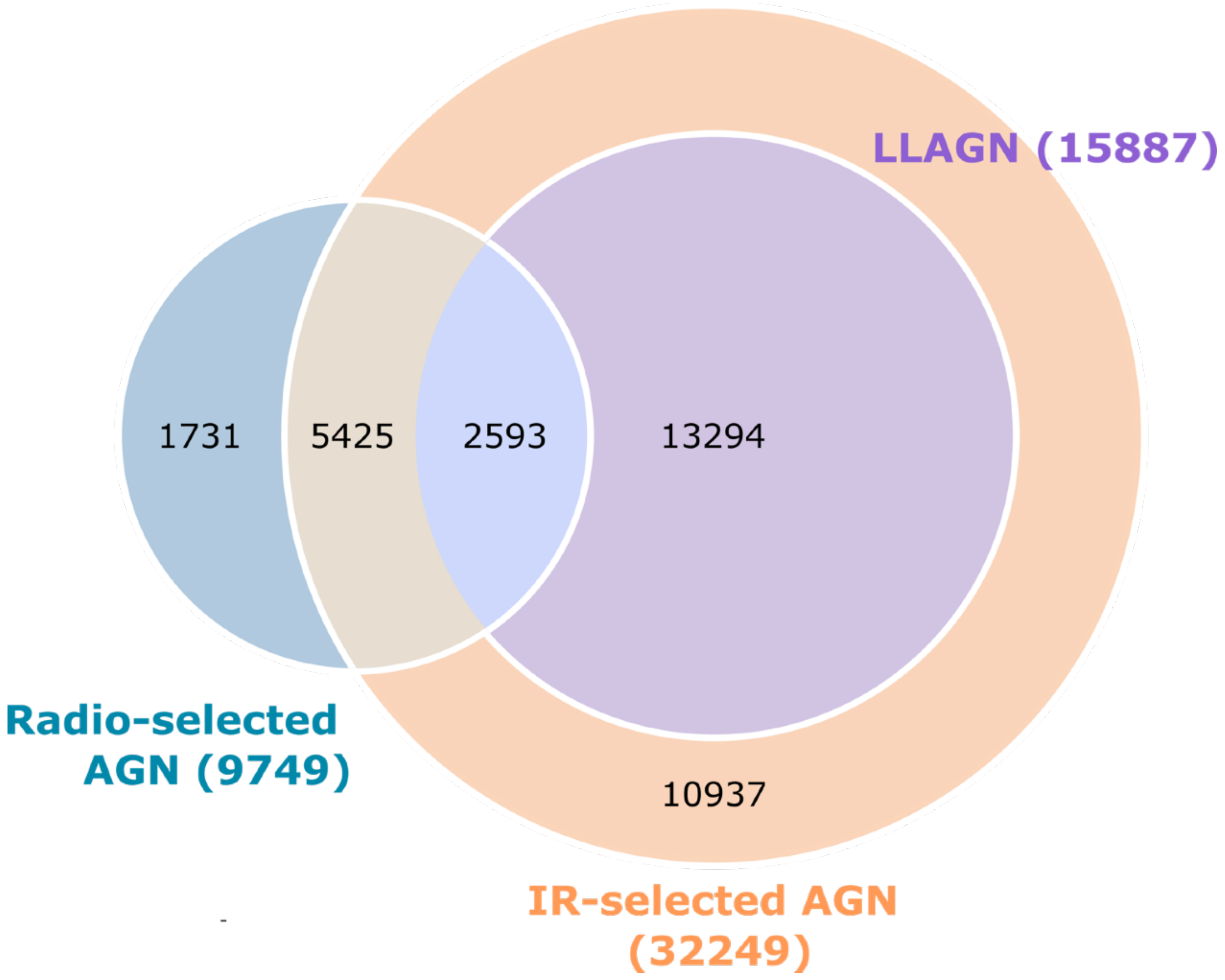
Normalized TS distribution

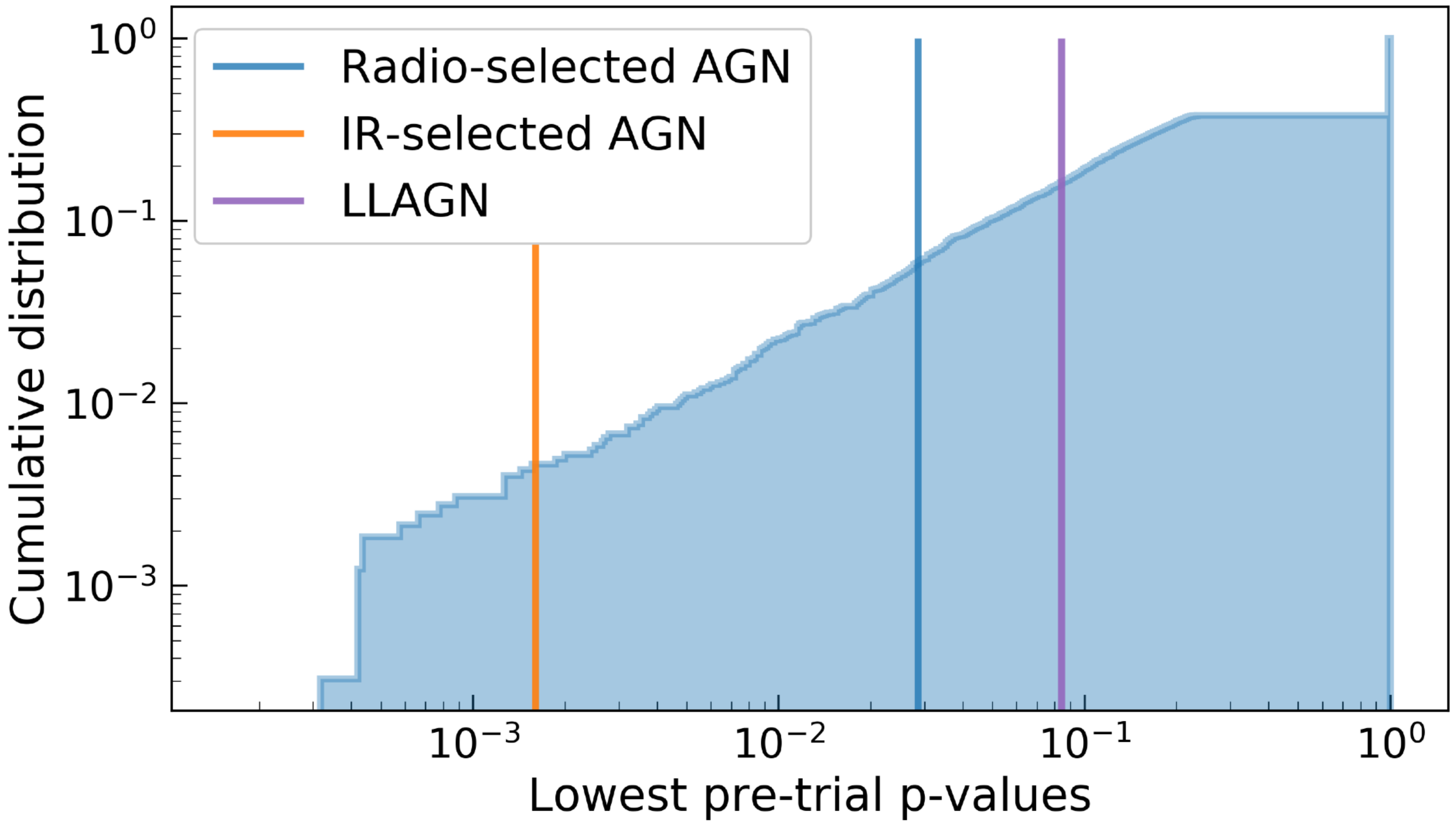


	Radio-selected AGN	IR-selected AGN	LLAGN
TS	2.39	7.56	0.51
Pre-trial p-value	2.84×10^{-2} (**1.9σ**)	1.59×10^{-3} (**2.9σ**)	0.08 (**1.4σ**)

Results: trial correction

“Look elsewhere” effect: have our results arisen by chance?





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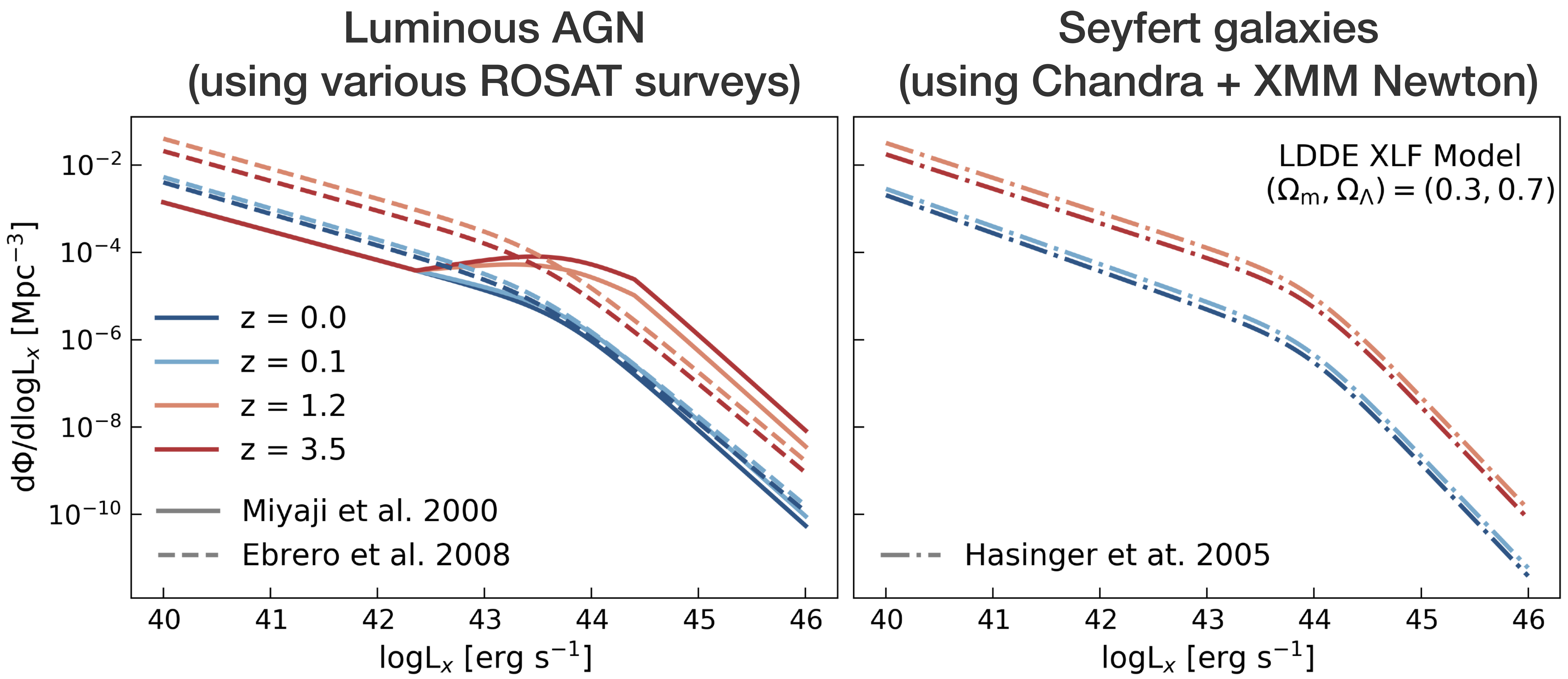
Post-trial p-value	5.85×10^{-2} (**1.6σ**)	4.64×10^{-3} (**2.6σ**)	0.16 (**1.0σ**)

Luminosity Function $\Phi(L, z)dL$

- Specifies the way in which the members of a class are distributed wrt their luminosity
- Defined as number density of objects with a luminosity in $[L, L+dL]$
- **Positive/Negative Evolution** = number density increases/decreases with larger redshift z
- **SXLF** = Soft X-ray Luminosity Function in the energy range 0.5-2 keV
- SXLF used to derive the total X-ray flux expected from all AGN in the 3 samples

Soft X-ray Luminosity Function

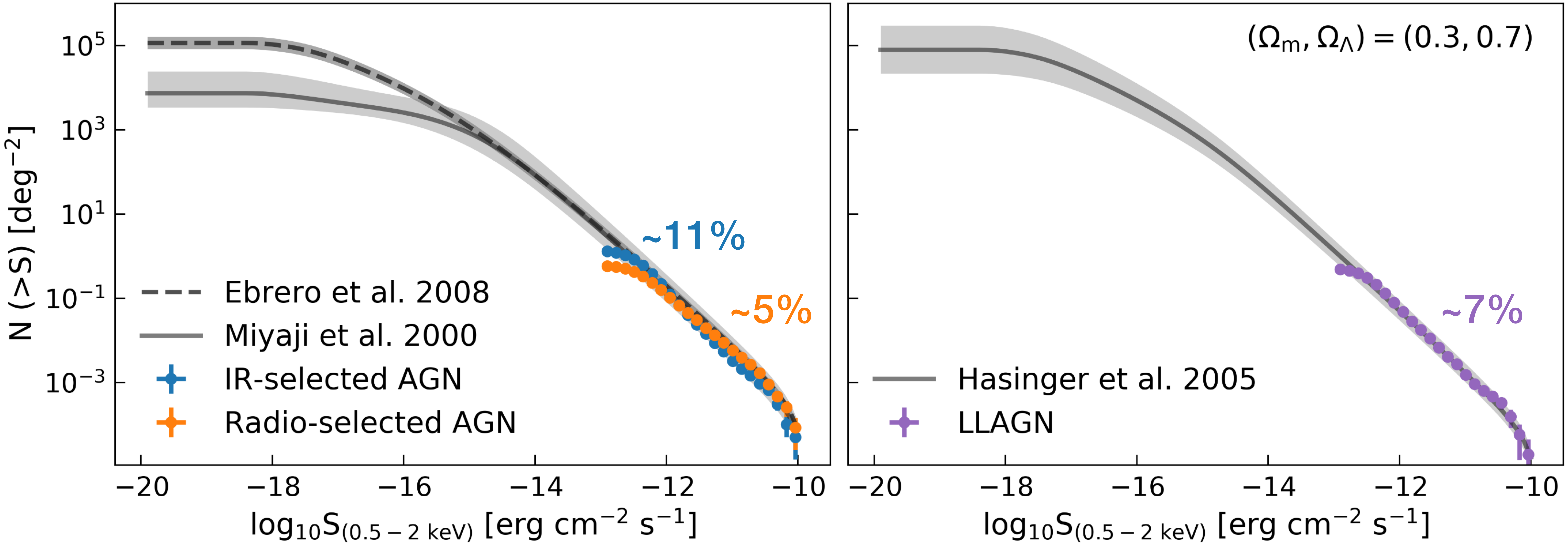
Described by the Luminosity-Dependent Density Evolution (LDDE)



From AGN samples to AGN population

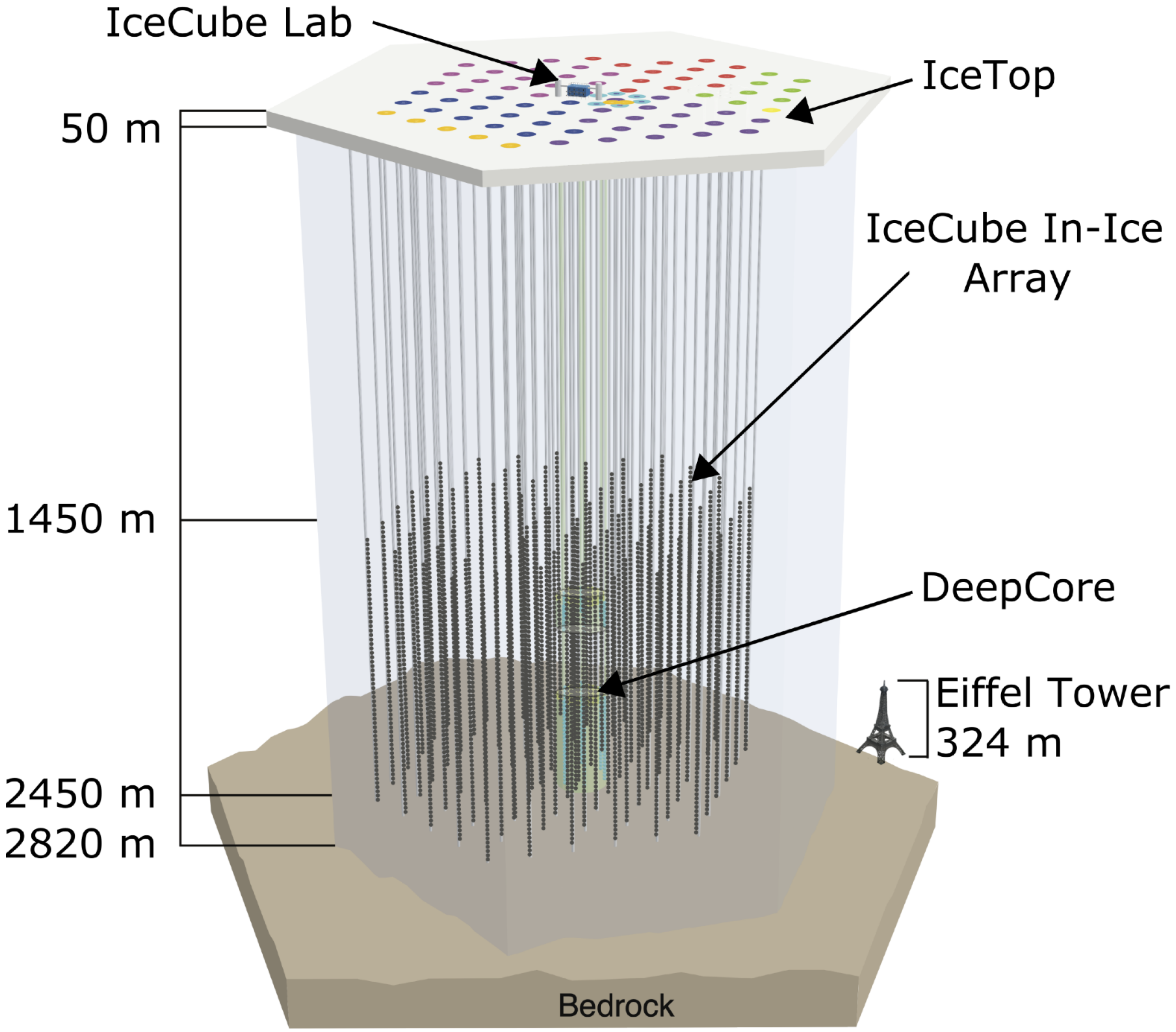
Through the *completeness* factor

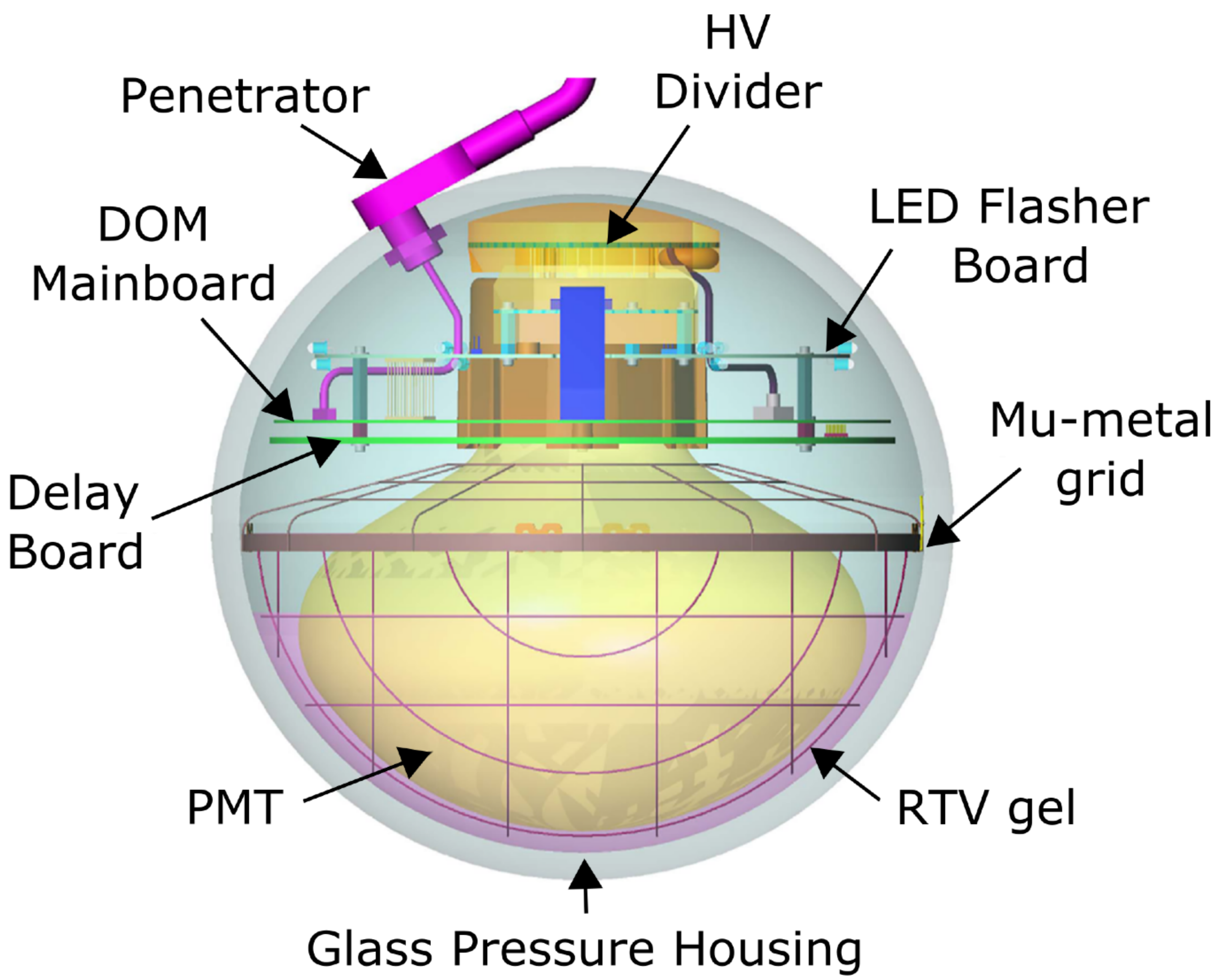
- Account for sources not making in the samples
- X-ray flux expected from all AGN in the entire Universe estimated through X-ray luminosity functions



IceCube

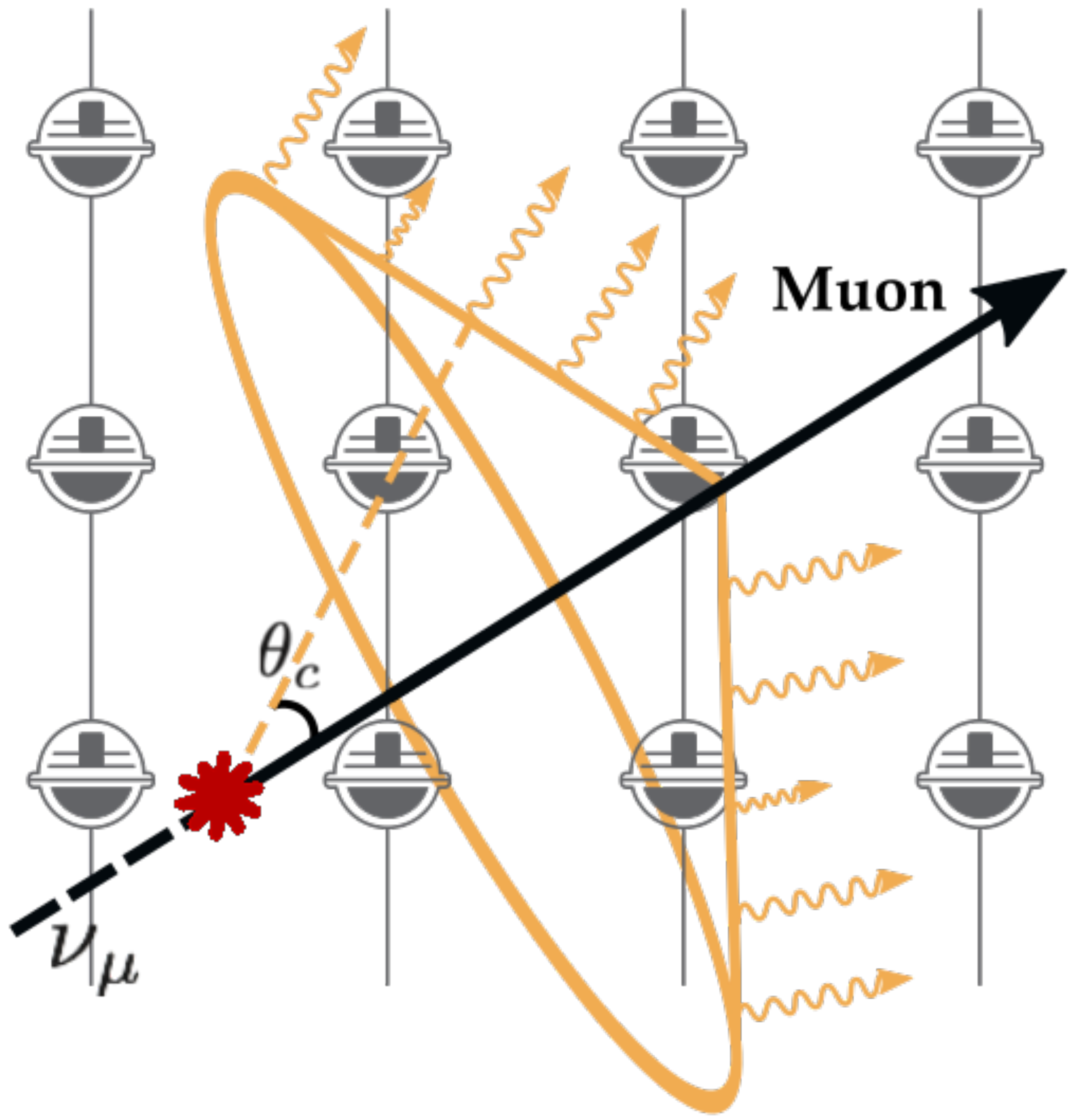
Instrumentation





Neutrino event signature

Tracks

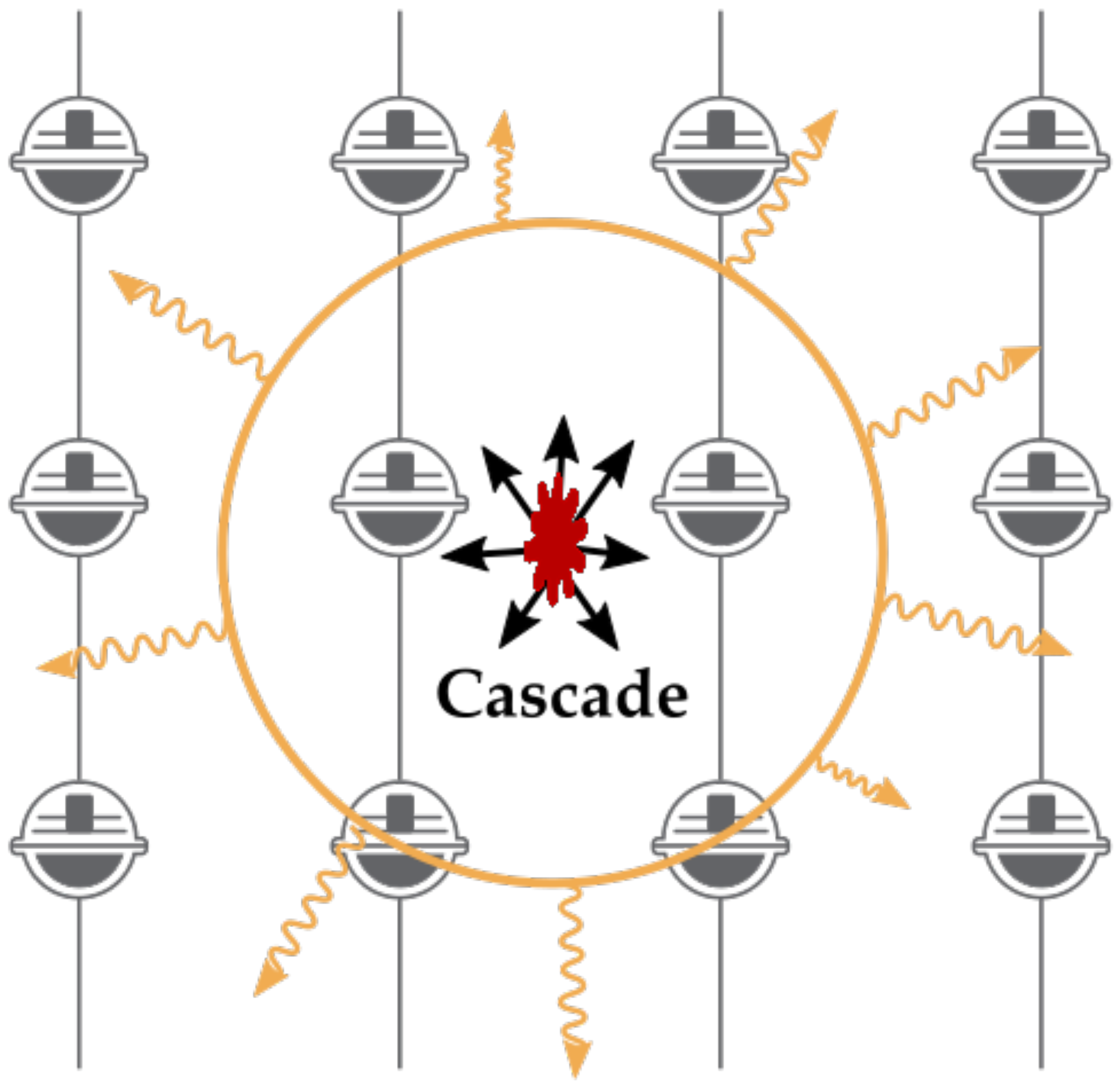


$$\nu_\mu + N \rightarrow \mu + X$$

Good angular resolution 0.1-1 deg

Neutrino astronomy

Cascades



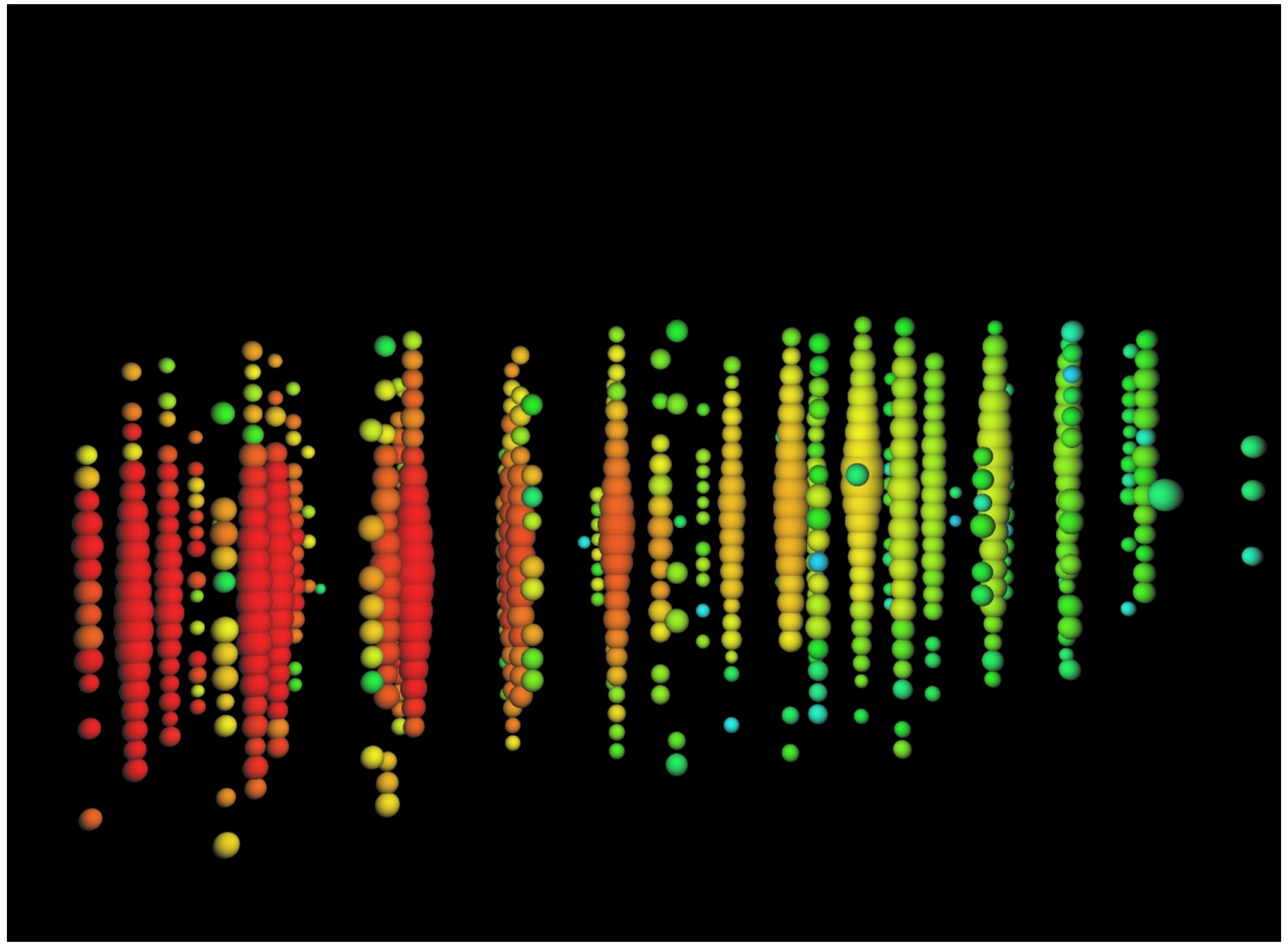
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

Good energy resolution ~15%

Neutrino event signature

Tracks



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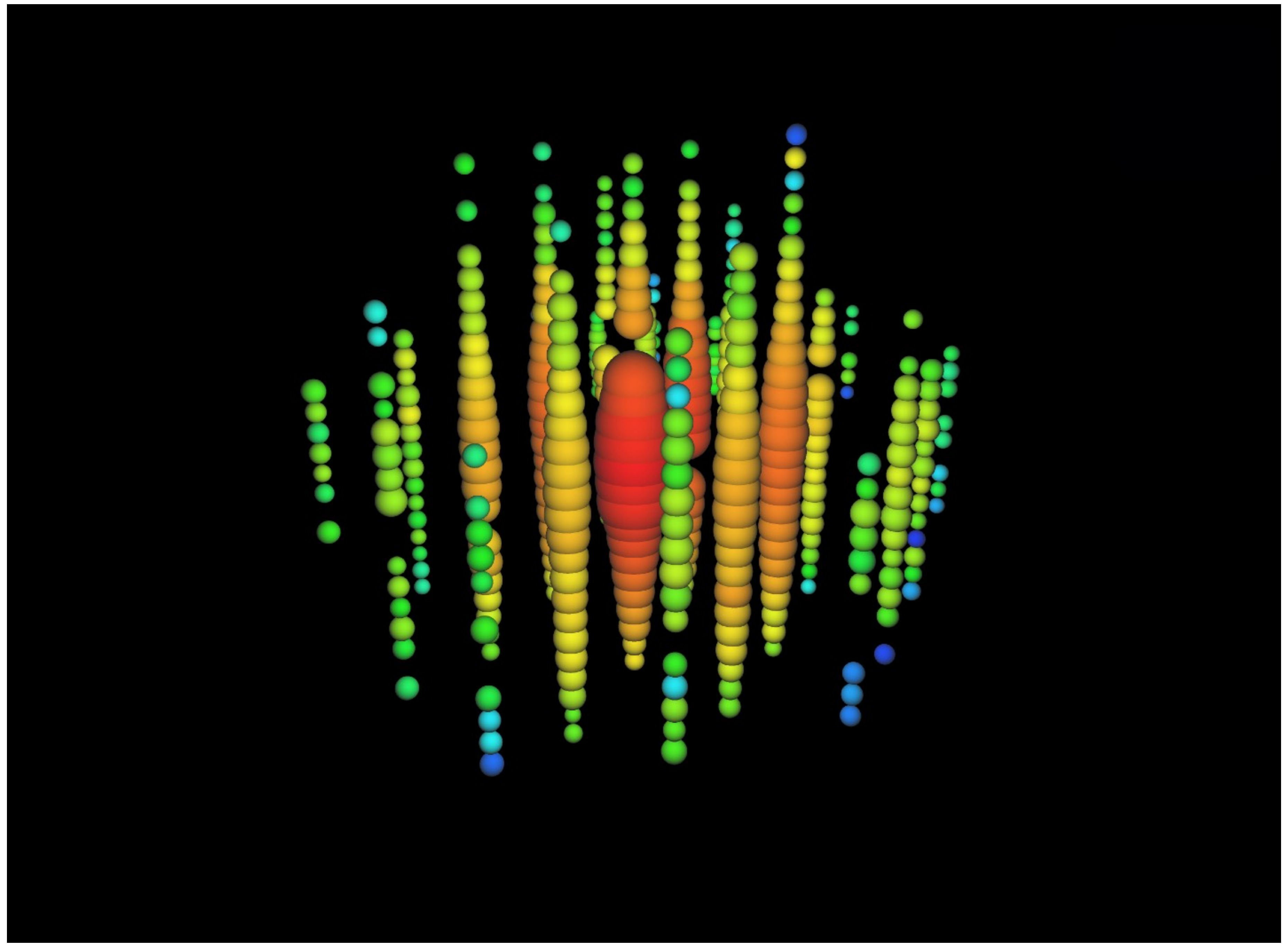
Neutrino astronomy

Cascades



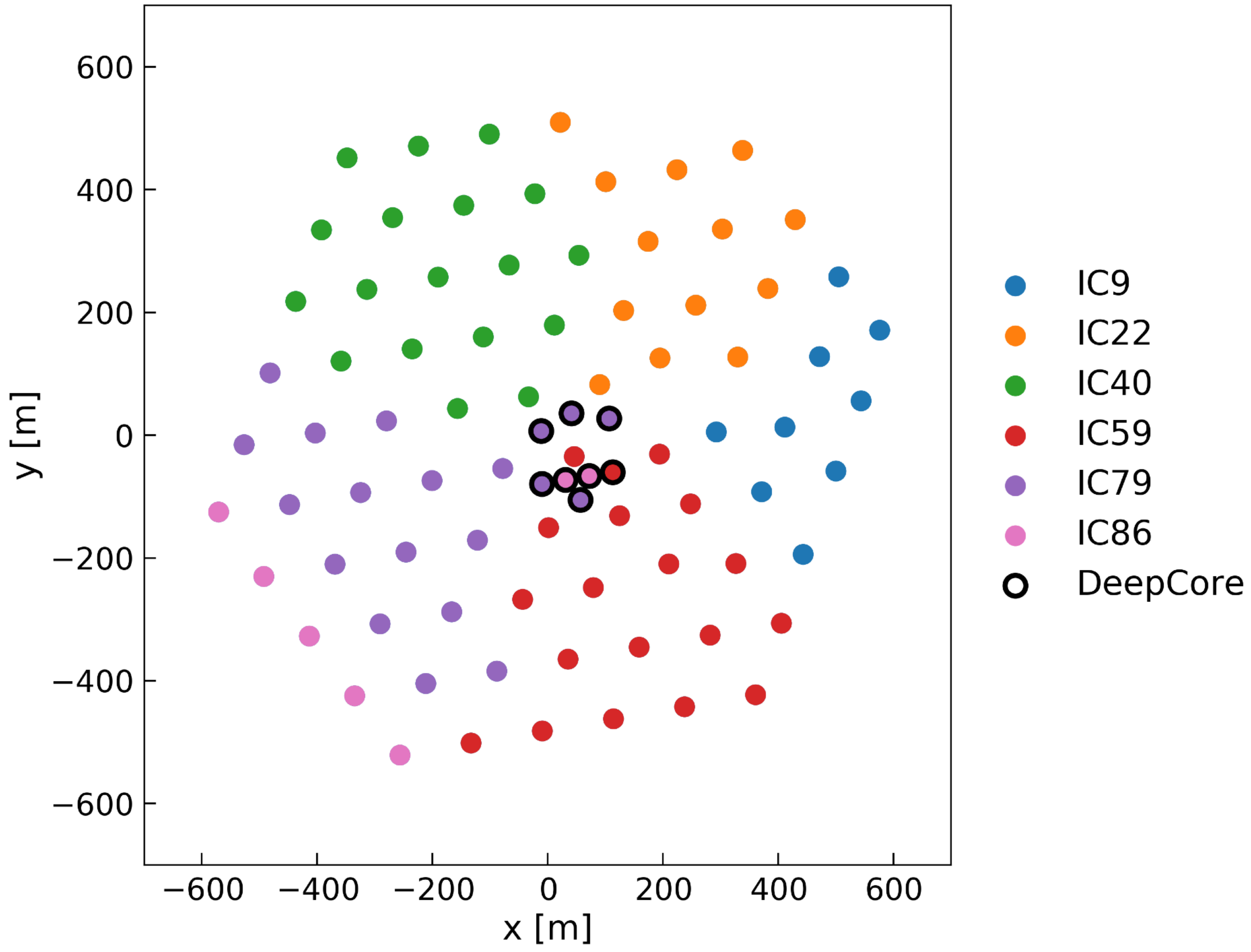
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

Good energy resolution ~15%

IceCube

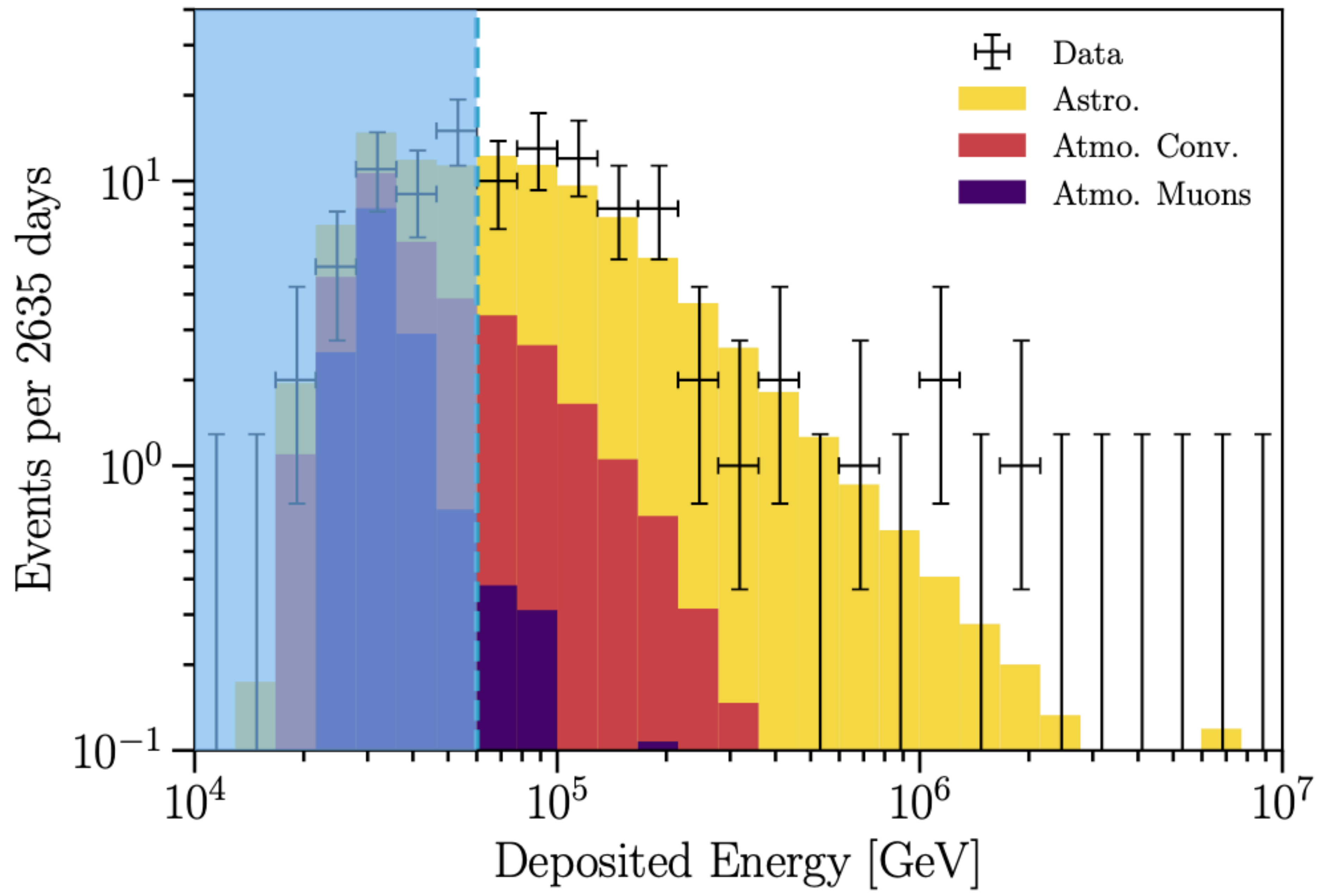
Strings and season deployments



Season	Strings	Name
2004-2005	1	IC1
2005-2006	9	IC9
2006-2007	22	IC22
2007-2008	40	IC40
2008-2009	59	IC59
2009-2010	79	IC79
2010-2011	86	IC86

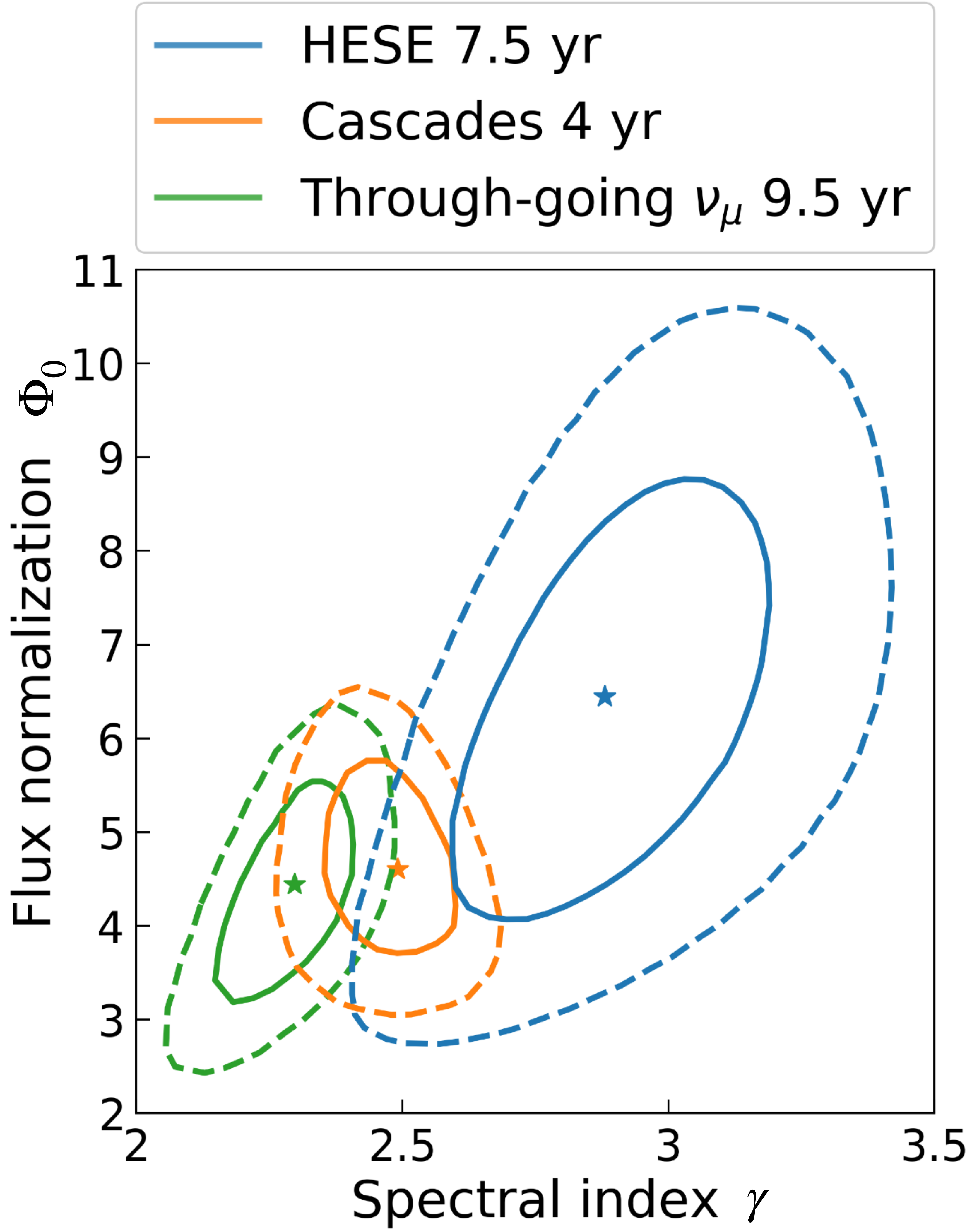
IceCube diffuse flux

HESE 7.5 yr diffuse flux measurement:
100+ contained events about 60 TeV (8yr)



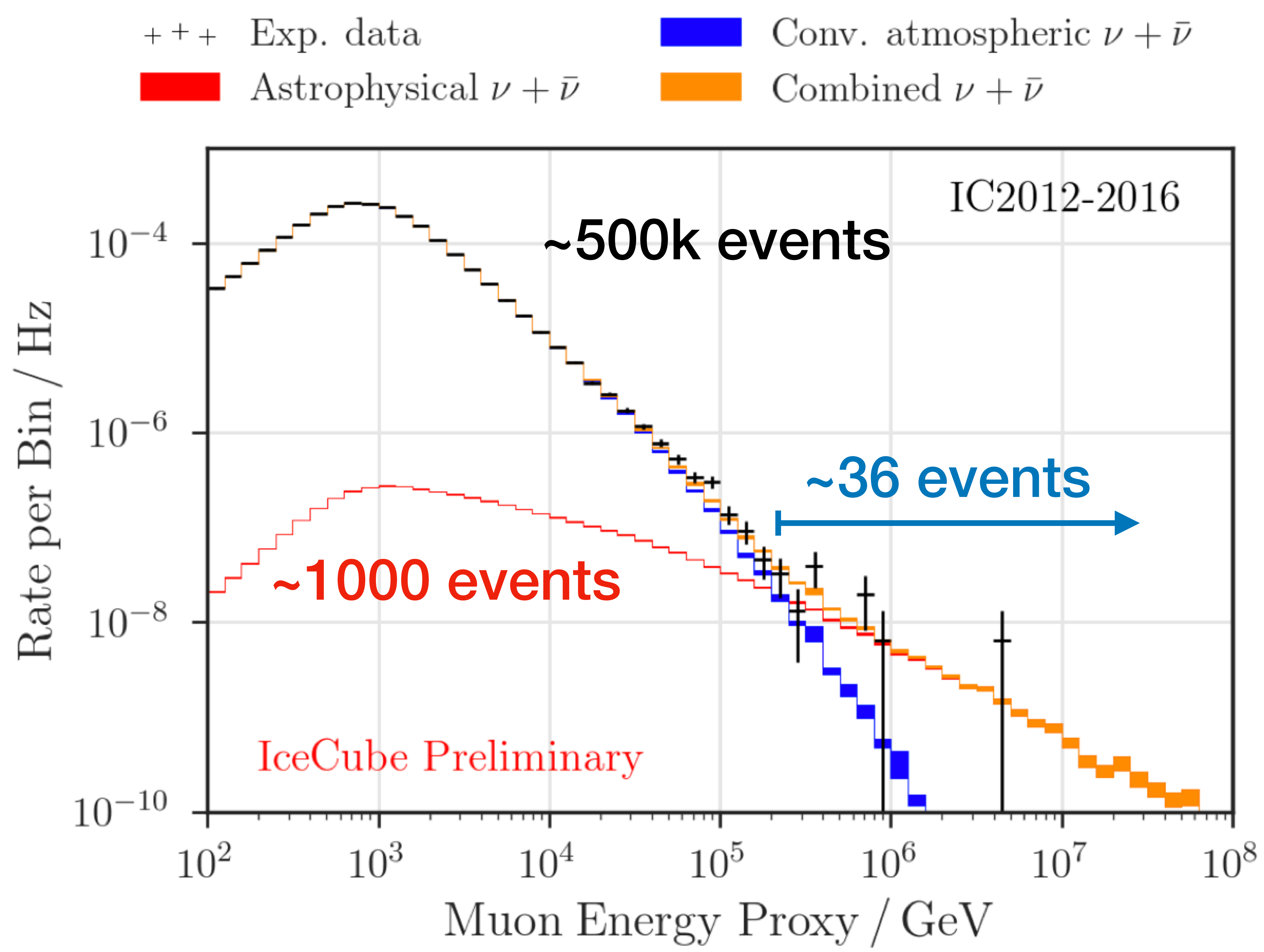
Single, unbroken power-law flux:

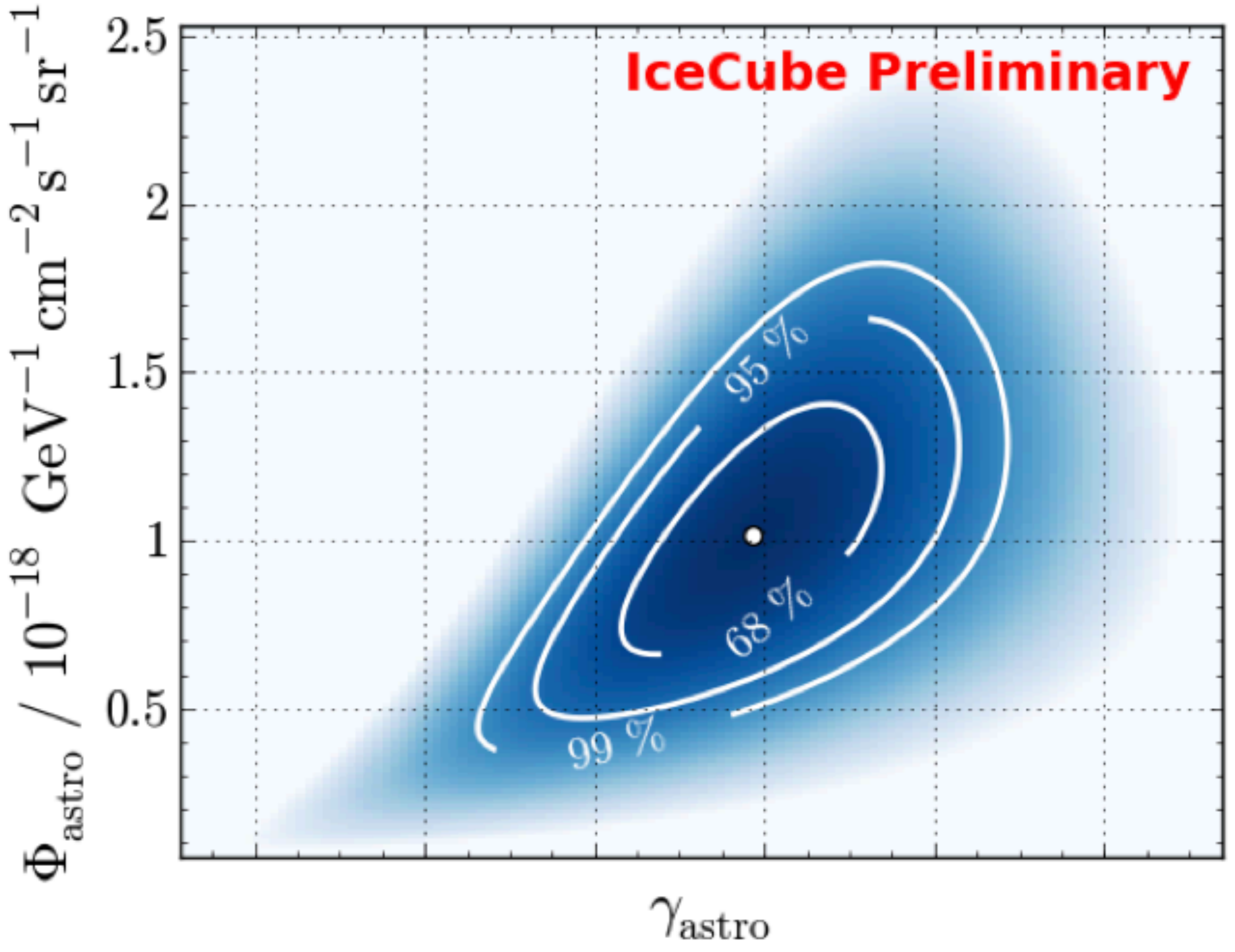
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \Phi_0 \left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma} \cdot 10^{-18} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$



Northern-Tracks dataset

Upgoing through-going muons — 8 years (2009-2017)





- ~500k neutrino events, purity >99.7%
- Exclusion of atmospheric origin @6.7σ
- Clear high energy excess (36 neutrinos) above 200 TeV
- Total ~1k astrophysical neutrinos with good pointing

$$\phi_{\nu+\bar{\nu}}\Big|_{100\ \mathrm{TeV}} = 1.01^{+0.26}_{-0.23} \times 10^{-18} \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

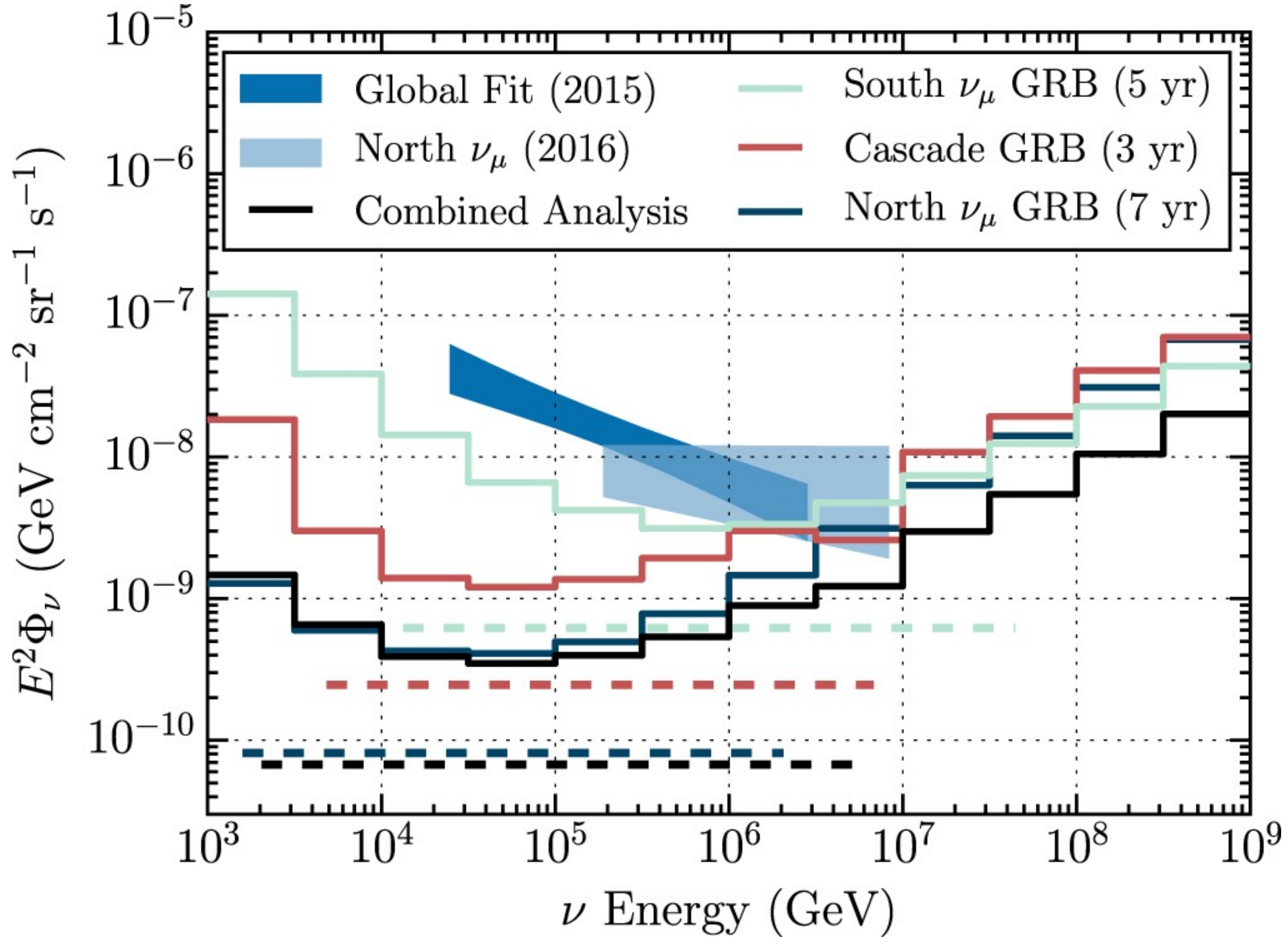
$$\gamma_{\mathrm{astro}} = 2.19 \pm 0.10$$

Search for neutrinos from AGN cores

Search for IceCube neutrino sources

Gamma-Ray Bursts and blazars - ***not*** dominant

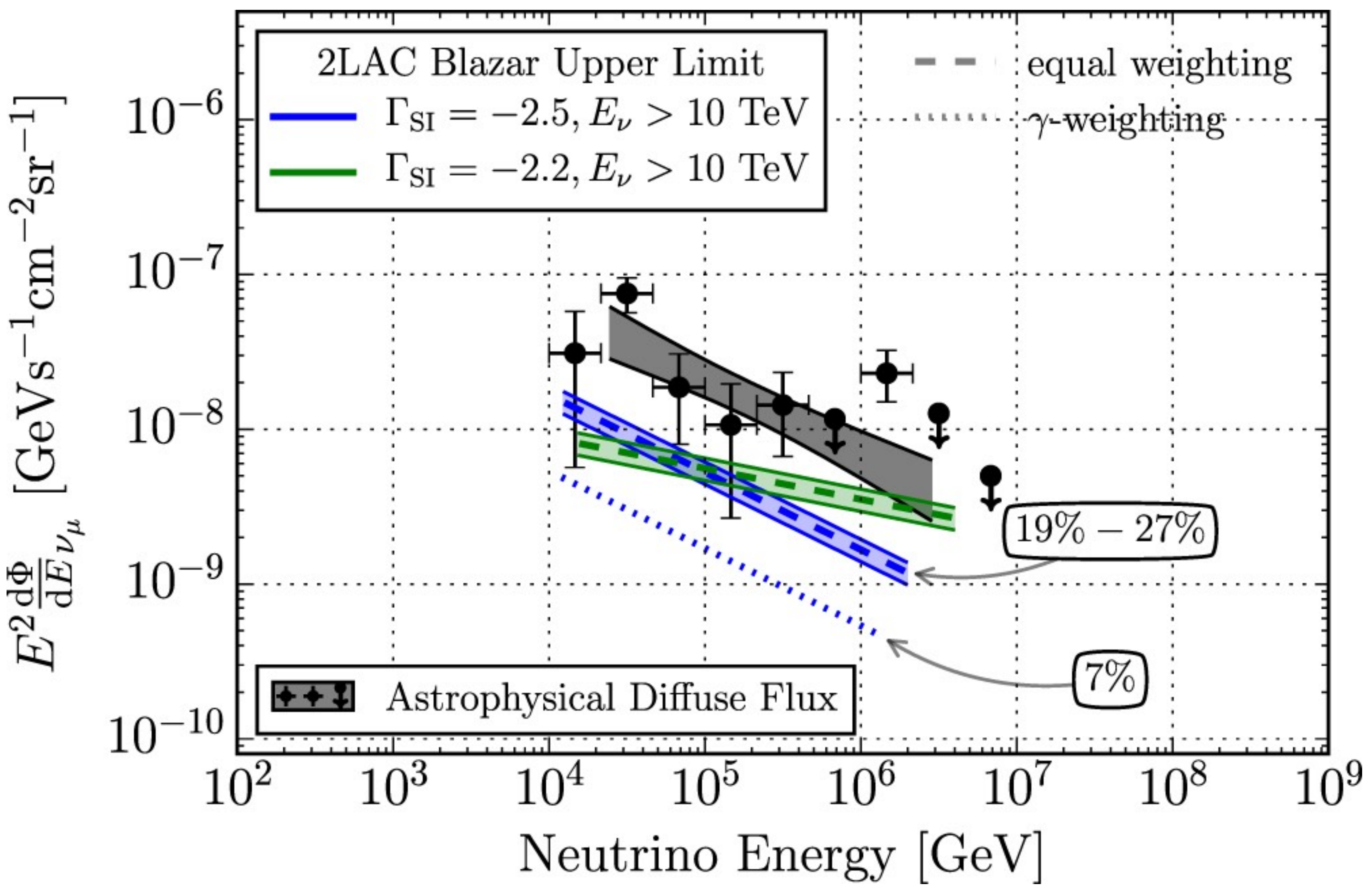
Gamma-Ray Bursts



1172 GRBs inspected, no correlation found
< 1% contribution to diffuse flux

[IceCube, ApJ 843(2017)2]

Blazars



862 blazars inspected, no correlation found
< 27% contribution to diffuse flux

[IceCube, ApJ 435(2017)45]

Active Galactic Nuclei

Supermassive Black Hole

$M_{\mathrm{SMBH}} \sim 10^6 - 10^9 M_\odot$

$L_{\mathrm{AGN}} = \epsilon \dot{M} c^2 \geq 10^{-5} L_{\mathrm{Edd}}$

$L_{\mathrm{Edd}} \approx 1.26 \times 10^{45} \left(M/10^7 M_\odot\right)\ \mathrm{erg\ s^{-1}}$

Narrow-Line Region

Lower-velocity ionised gas, not obscured by the torus

Corona

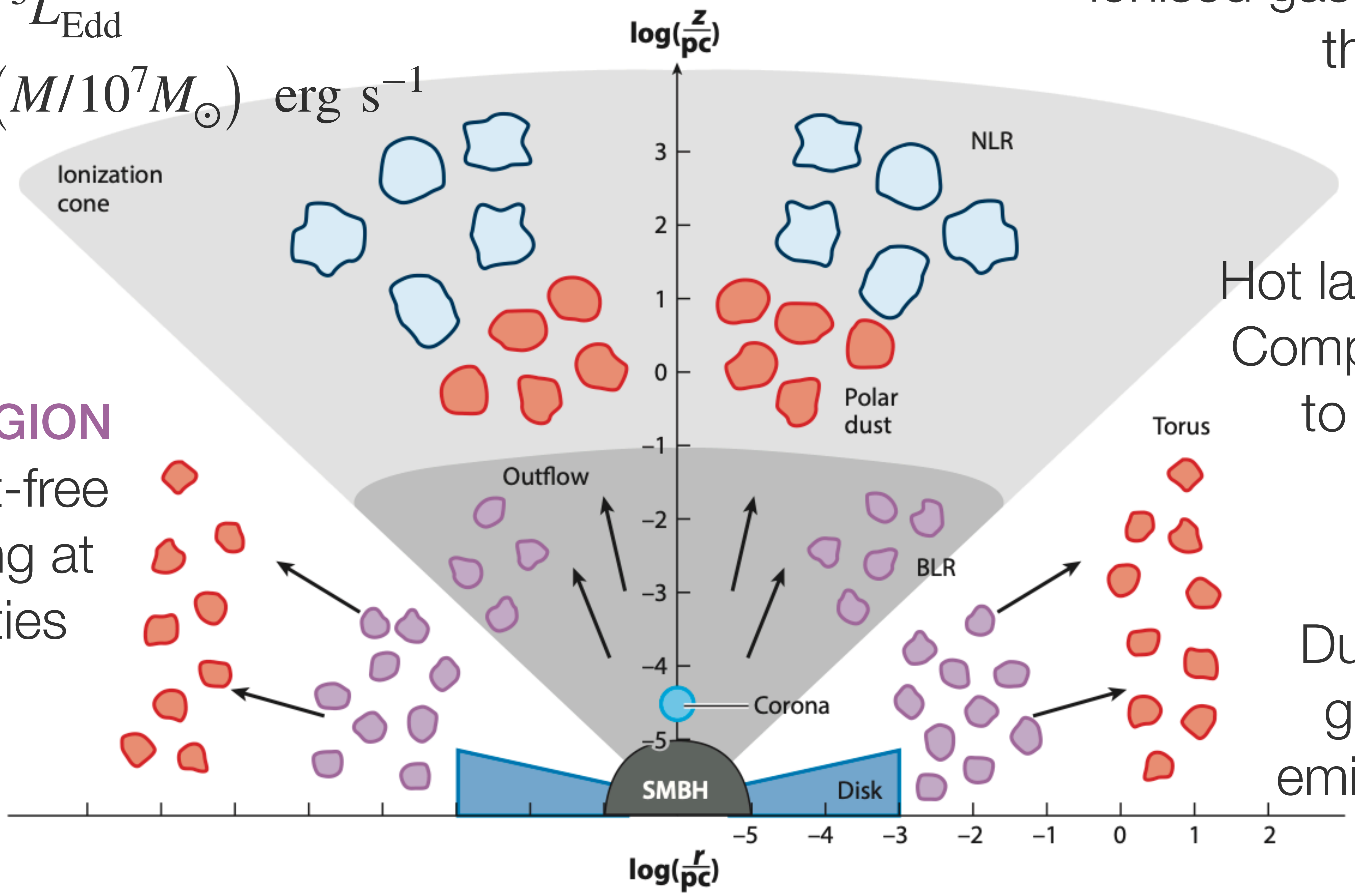
Hot layer of gas, inverse Compton scatters γ up to X-ray energies

Broad-Line Region

High-density, dust-free gas clouds moving at Keplerian velocities

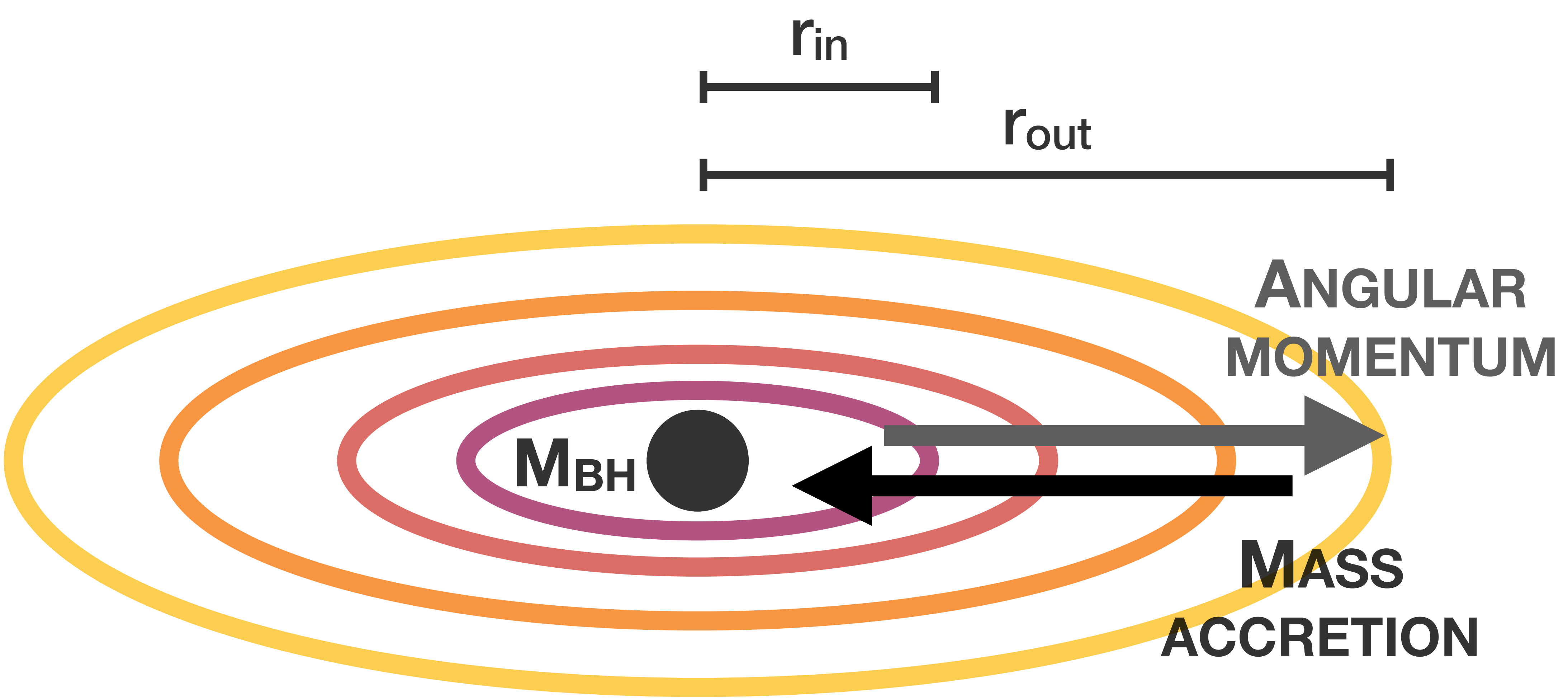
Torus

Dust and molecular gas, can obscure emission from the AD



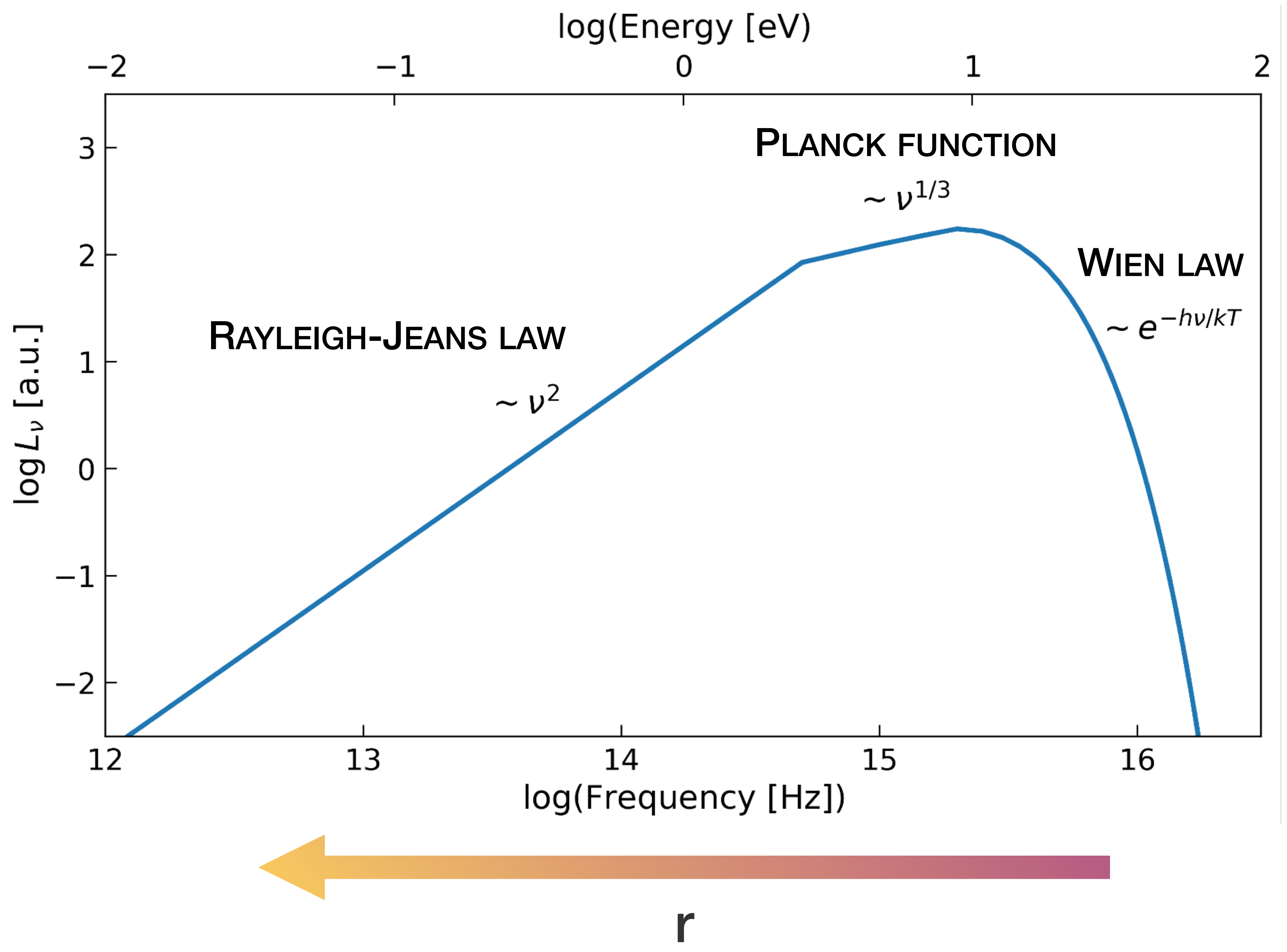
Shakura-Sunyaev Accretion Disk

Geometrically thin, optically thick (standard)



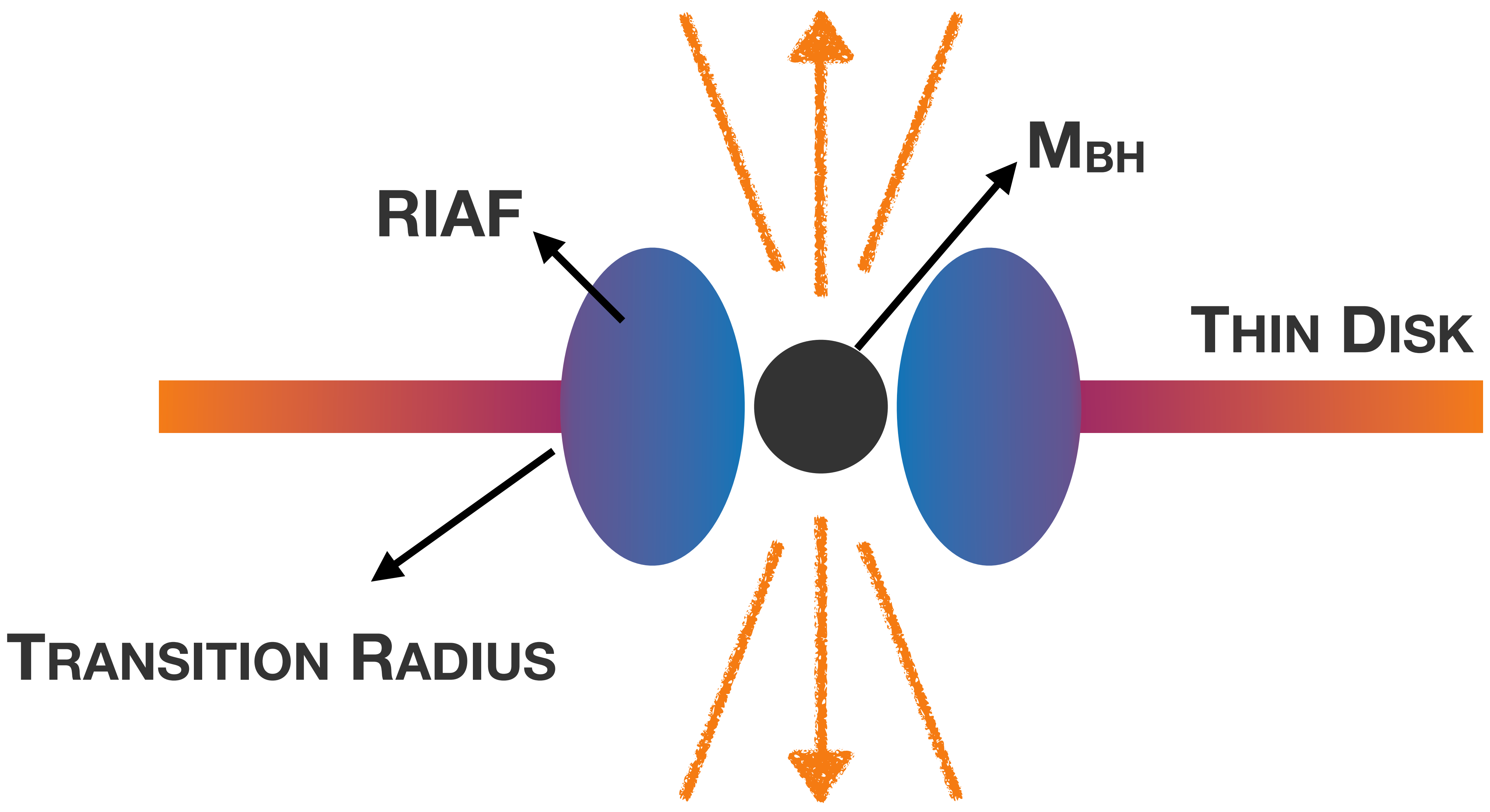
$$T_{\mathrm{eff}}(r) = \left[\frac{3GM\dot{M}}{8\pi\sigma r^3}\left(1-\sqrt{\frac{r_{\mathrm{in}}}{r}}\right)\right]^{1/4} \underset{r\gg r_{\mathrm{in}}}{\propto} r^{-3/4}$$

$$L_{\mathrm{standard}} \propto \dot{M}$$



Radiative Inefficient Accretion Flows (RIAF)

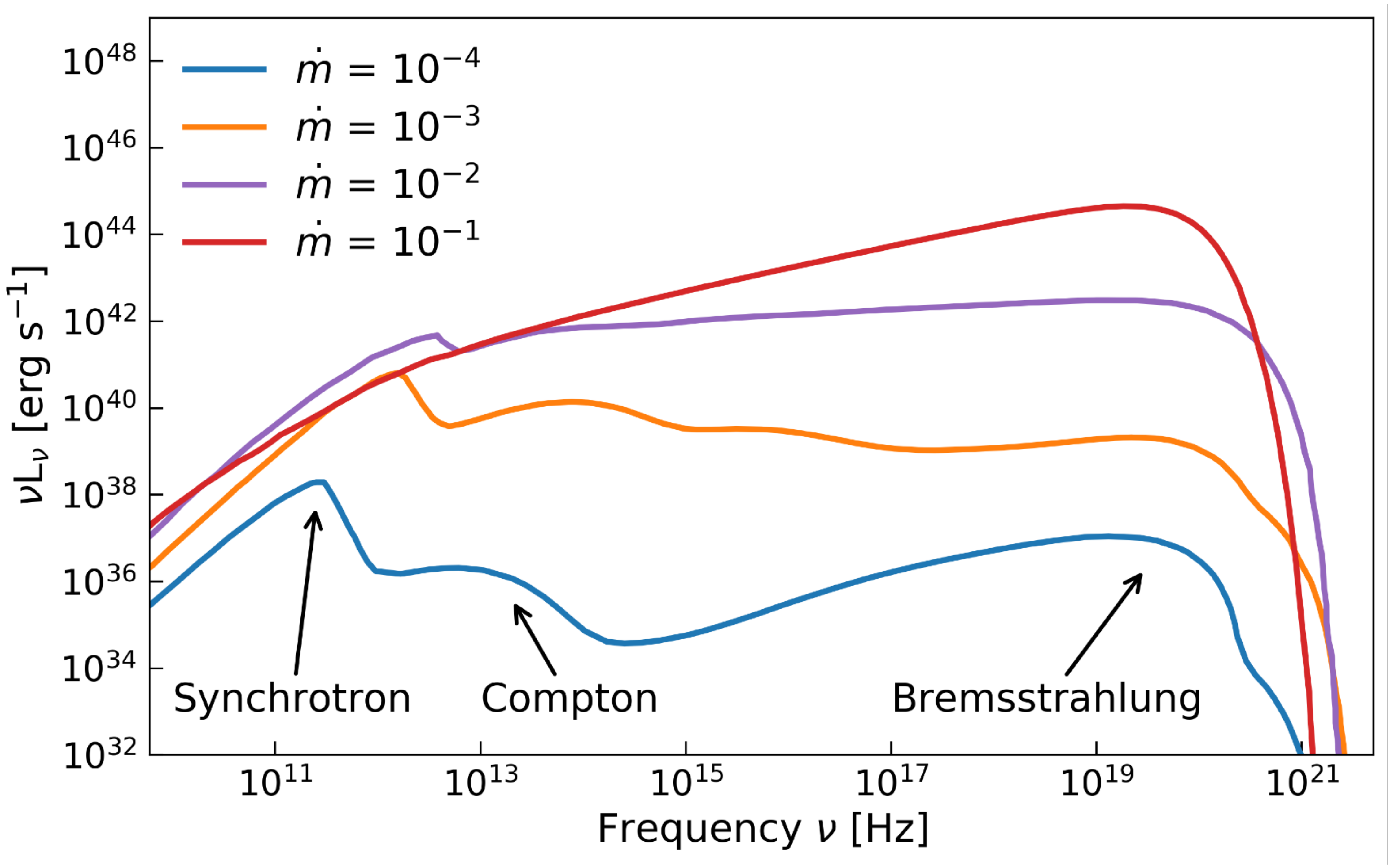
Truncated thin disk with low accretion rate



$$\dot{m} < \frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} \sim \alpha^2, \alpha \sim 0.2 - 0.3$$

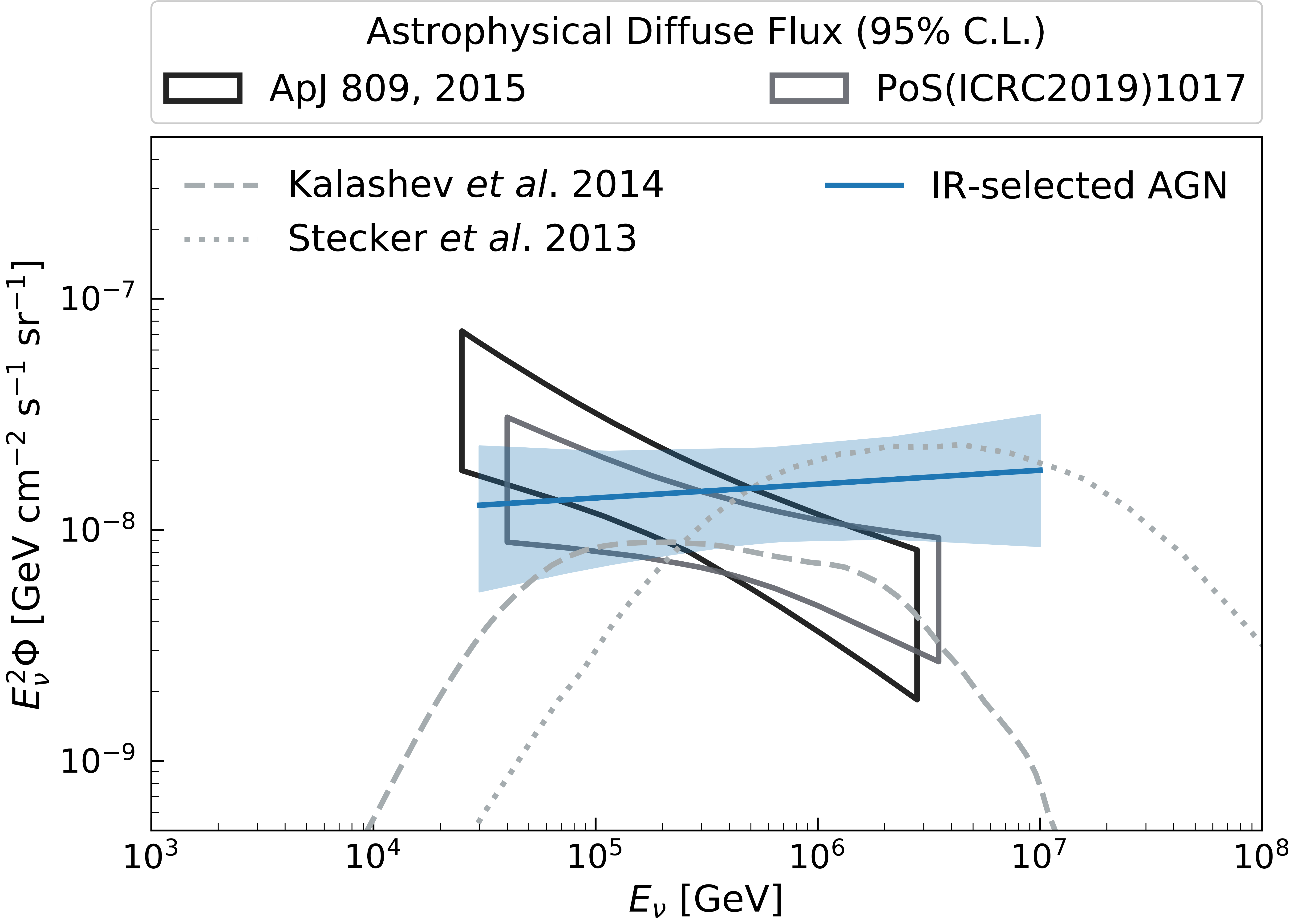
$$L_{\mathrm{ADAF}} \sim \dot{M}^2$$

ADAF ACCRETION DISK SPECTRUM FOR $M_{BH} = 10^9\ M_\odot$



Neutrinos from Cores of Luminous AGN

AGN with Shakura-Sunyaev accretion disk

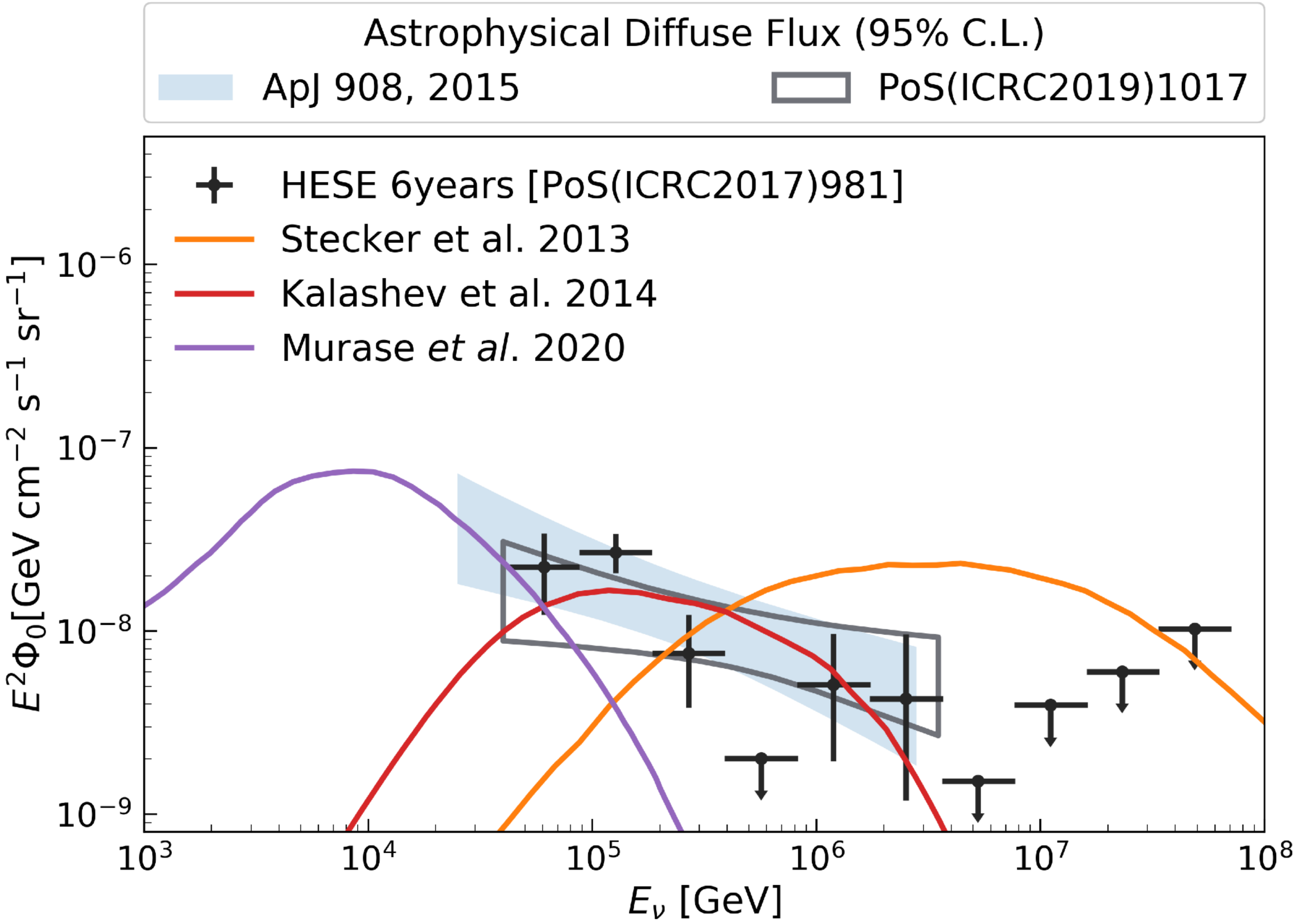


Neutrinos from Cores of Luminous AGN

AGN with Shakura-Sunyaev accretion disk

Stecker et al. (2013)

- Mainly pγ interactions in cores of luminous AGN
- Shock acceleration leading to maximum energies -> PeV neutrinos produced mainly through photomeson production with disk photons
- Neutrino luminosity approximated by X-ray luminosity

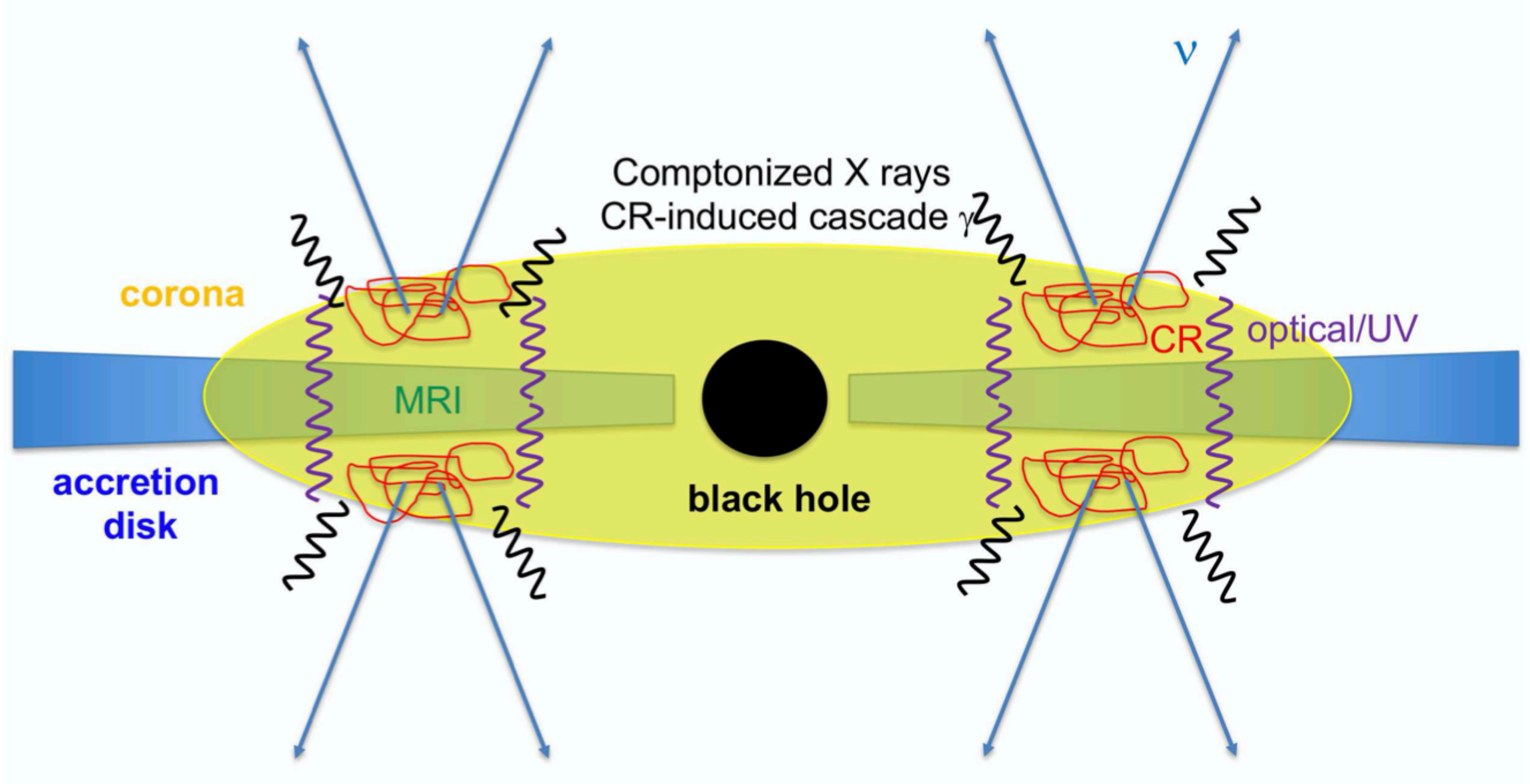


Neutrinos from Cores of Luminous AGN

AGN with Shakura-Sunyaev accretion disk

Murase et al. (2020)

- AGN corona model explaining the medium-energy neutrino data
- Coronal X-rays provide target photons for the photomeson production
- Protons in corona plasma accelerated up to 10 PeV (0.1-10 PeV) by plasma turbulence and produce 5–50 TeV neutrinos and cascaded gamma rays via interactions with matter and radiation

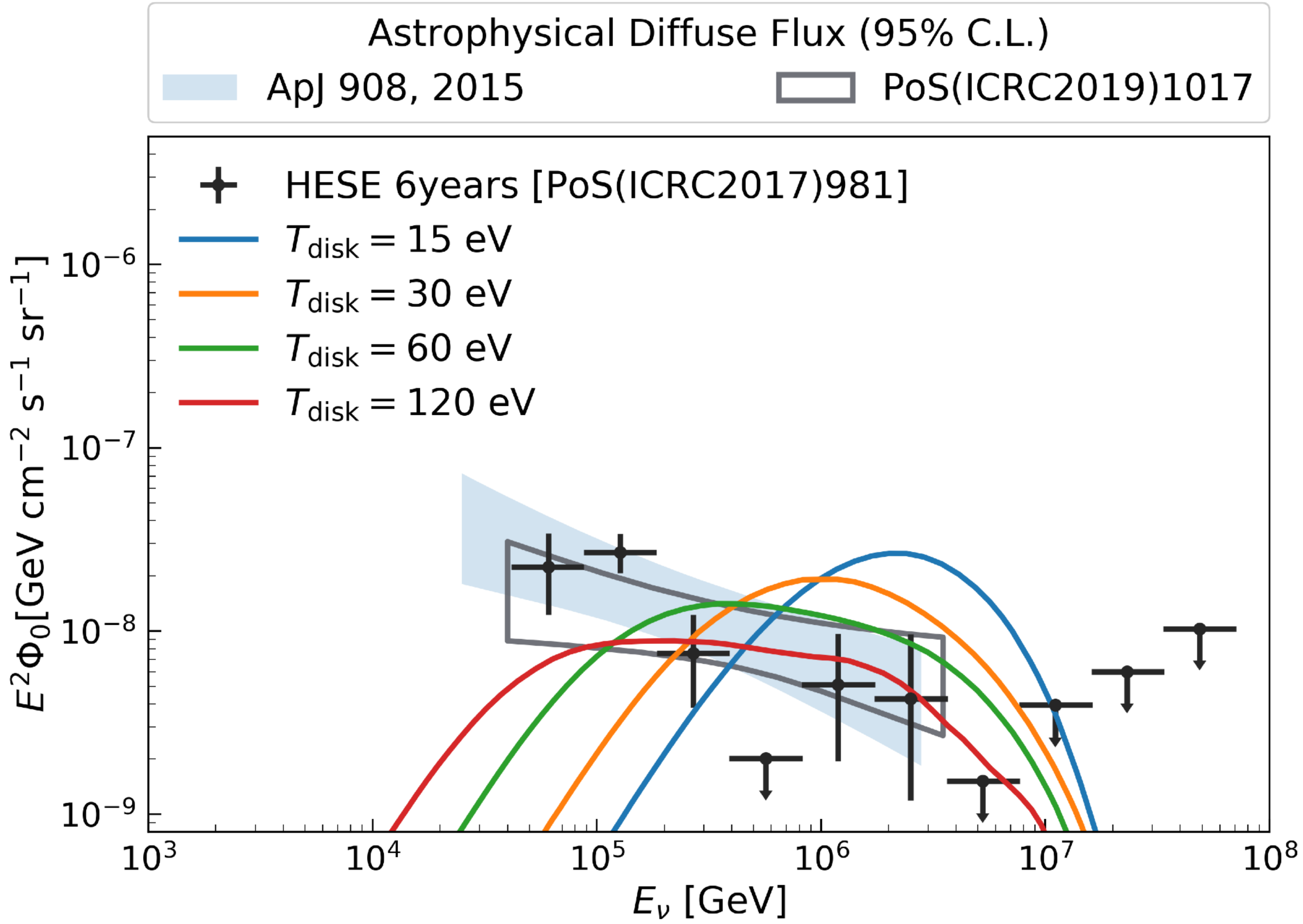


Neutrinos from Cores of Luminous AGN

AGN with Shakura-Sunyaev accretion disk

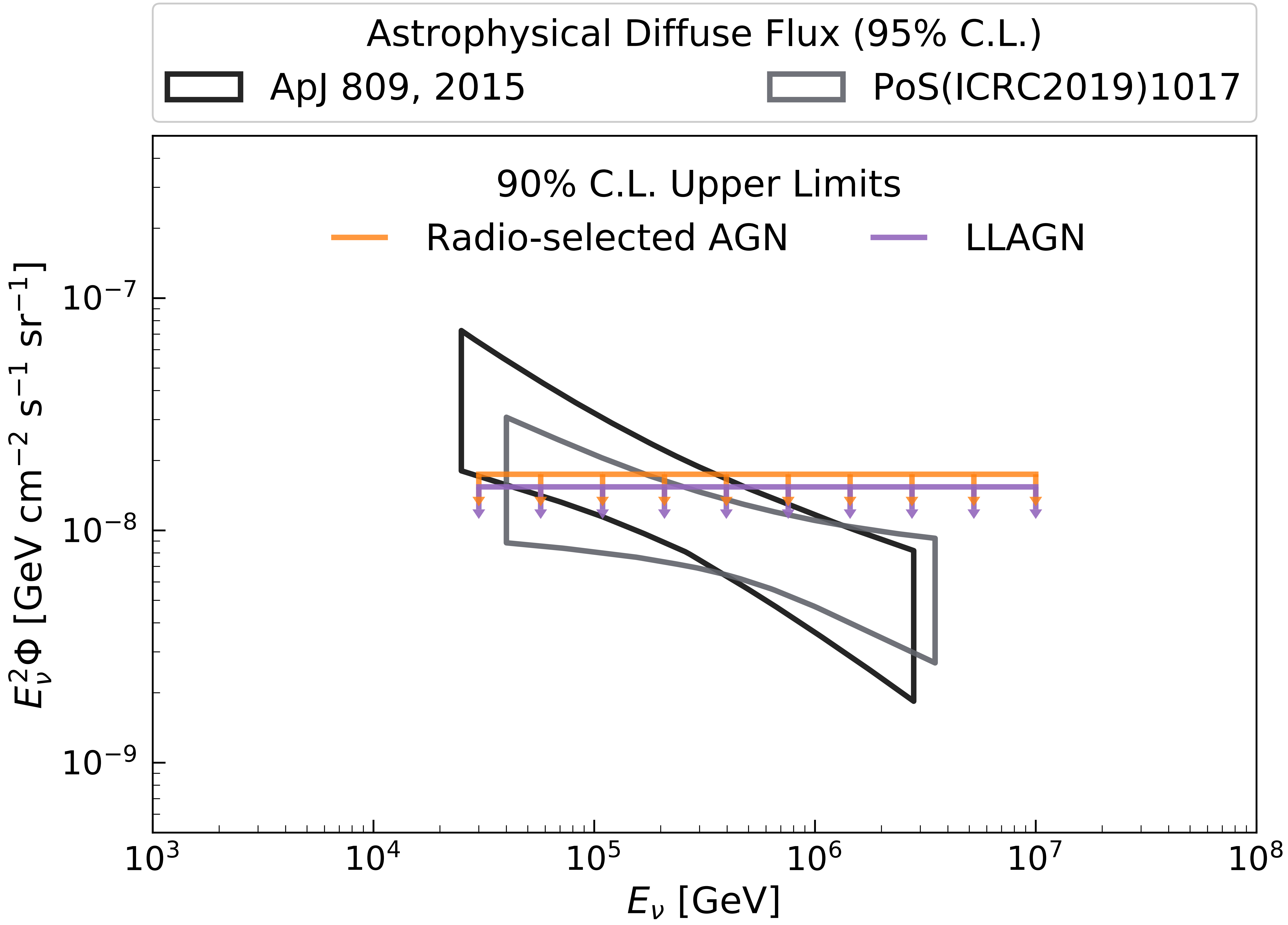
Kalashev et al. (2014)

- Protons accelerated by electric fields in close vicinity of the BH horizon, resulting in a E^{-2} spectrum
- Electric acceleration in a gap formed in the magnetosphere
- Neutrino flux depends on the assumed max proton energy and disk temperature



Neutrinos from Cores of Low-Luminosity AGN

AGN with Radiative Inefficient Accretion Flows

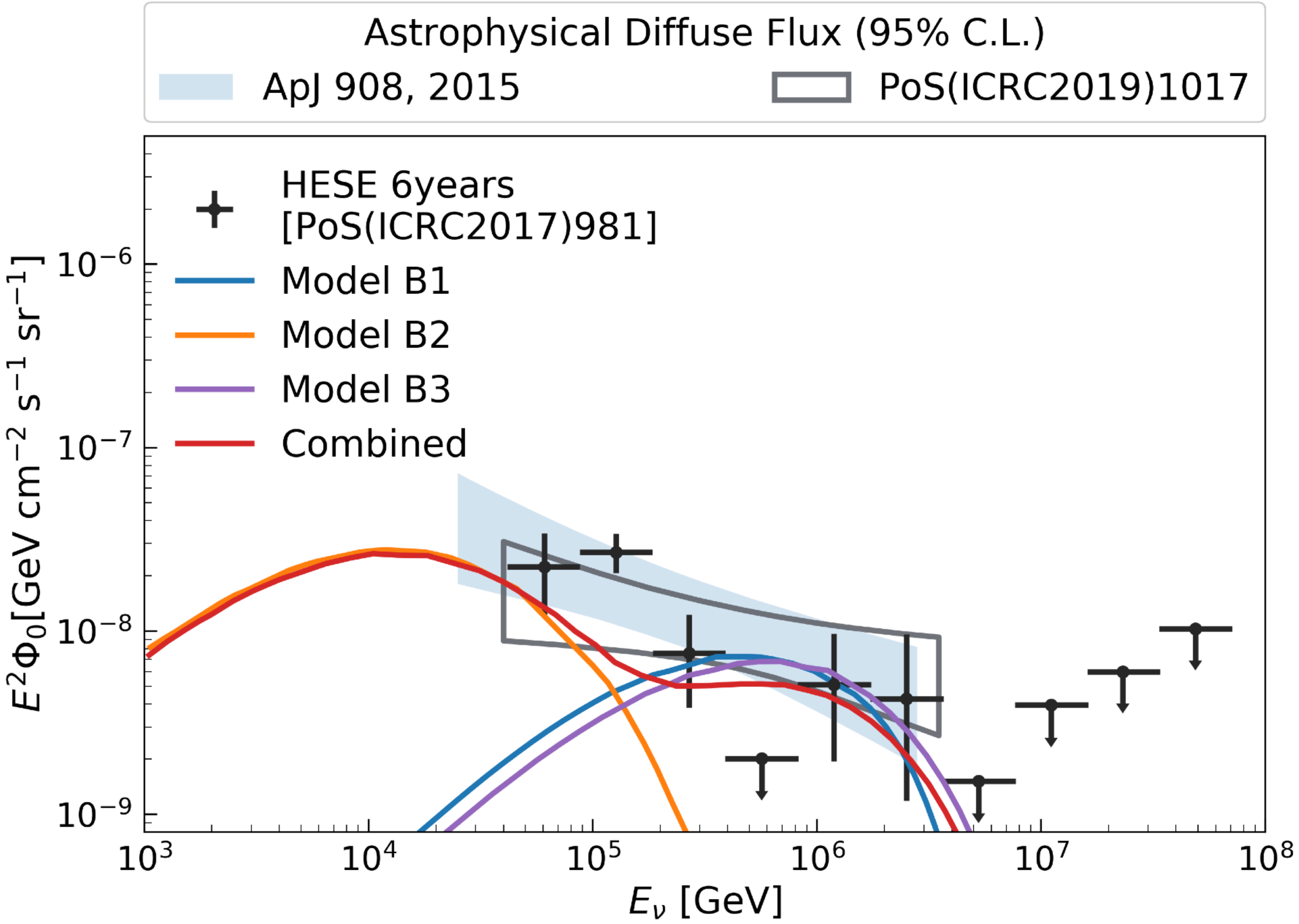


Neutrinos from Cores of Low-Luminosity AGN

AGN with Radiative Inefficient Accretion Flows

Kimura et al. (2015)

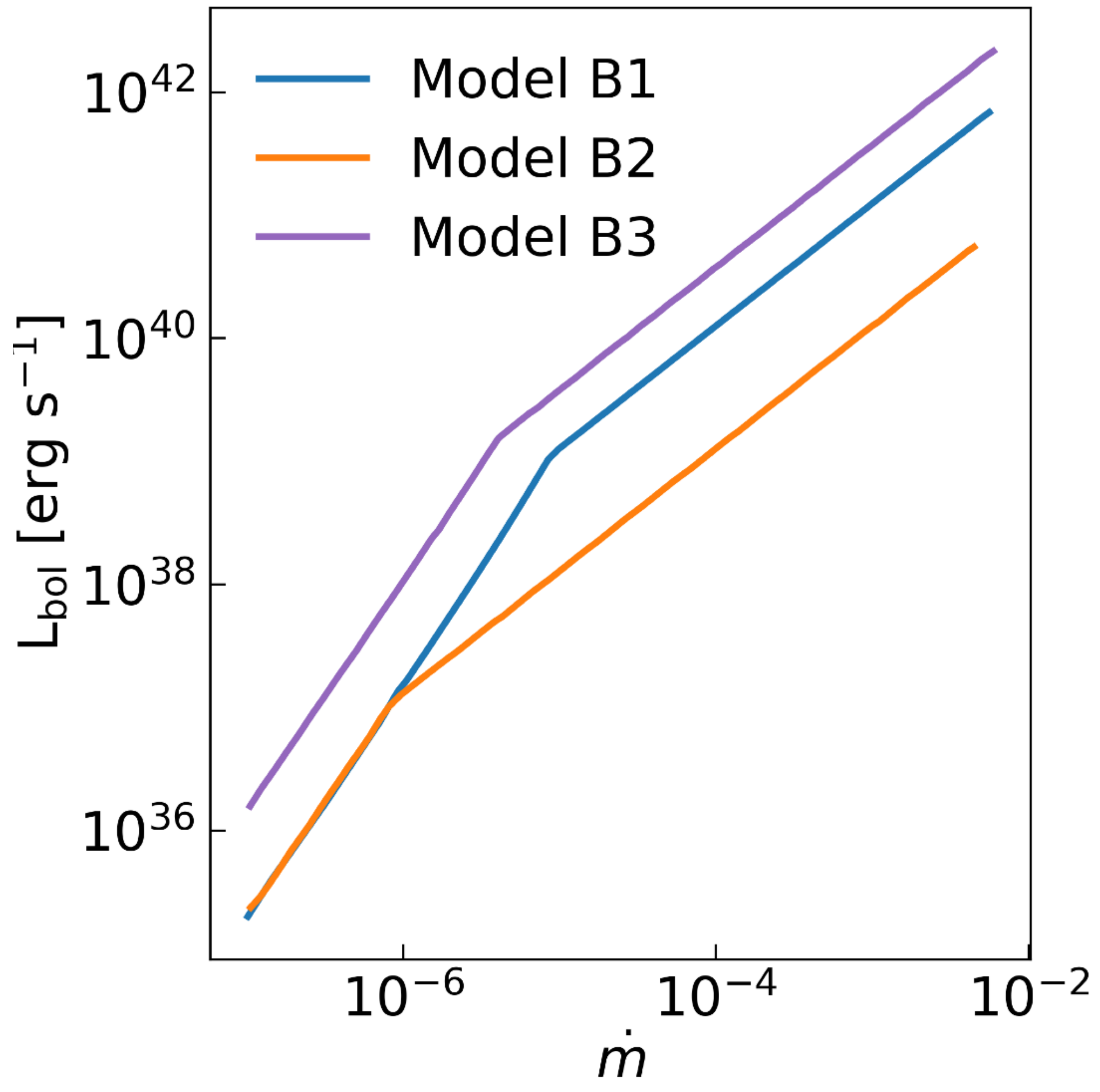
- Cosmic ray protons accelerated in RIAF via stochastic process or magnetic reconnection
- Neutrino production through mainly *pp* interactions
- Protons are not thermal
- Model depends on Bolometric luminosity and accretion rate of the RIAF

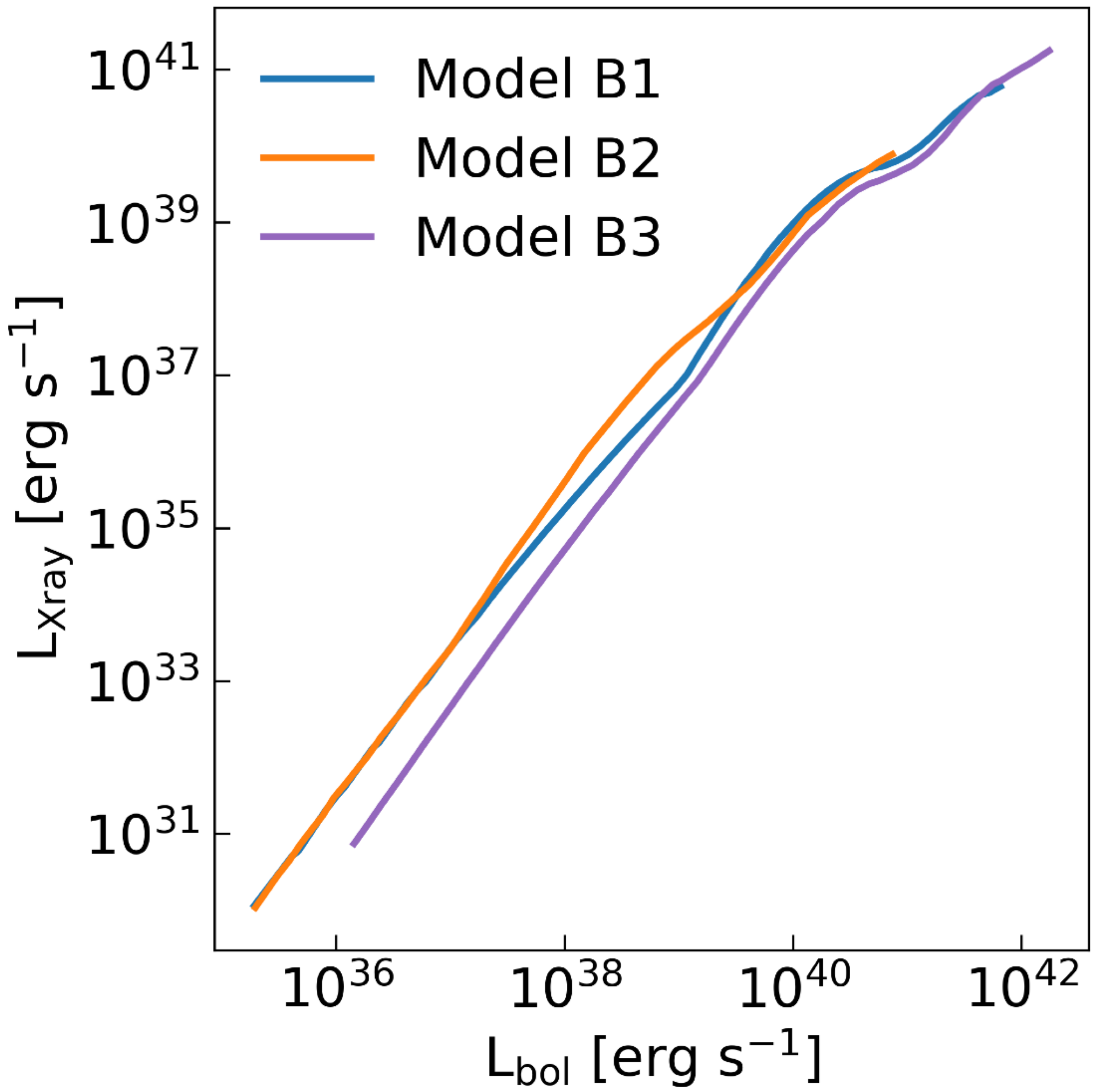


Neutrinos from Cores of Low-Luminosity AGN

AGN with Radiative Inefficient Accretion Flows

Kimura et al. (2015)



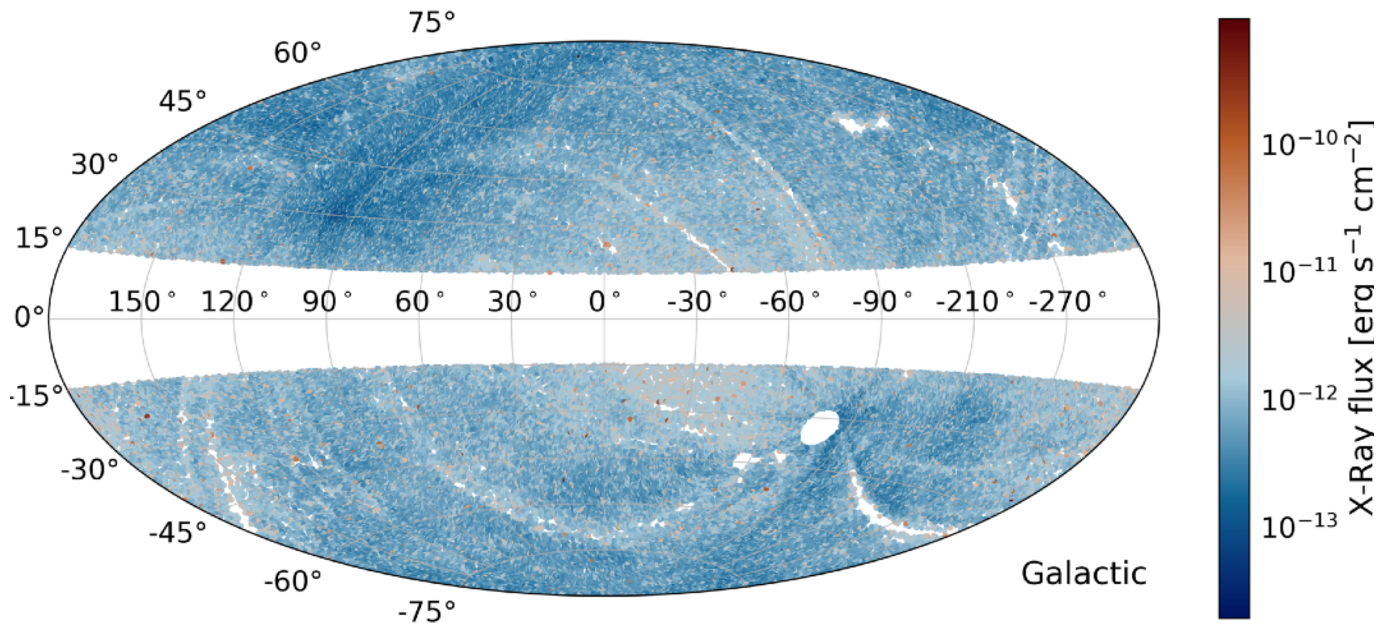


How to select AGN?

Using various bands of the electromagnetic spectrum

X-ray

Excellent probe of accretion in AGN

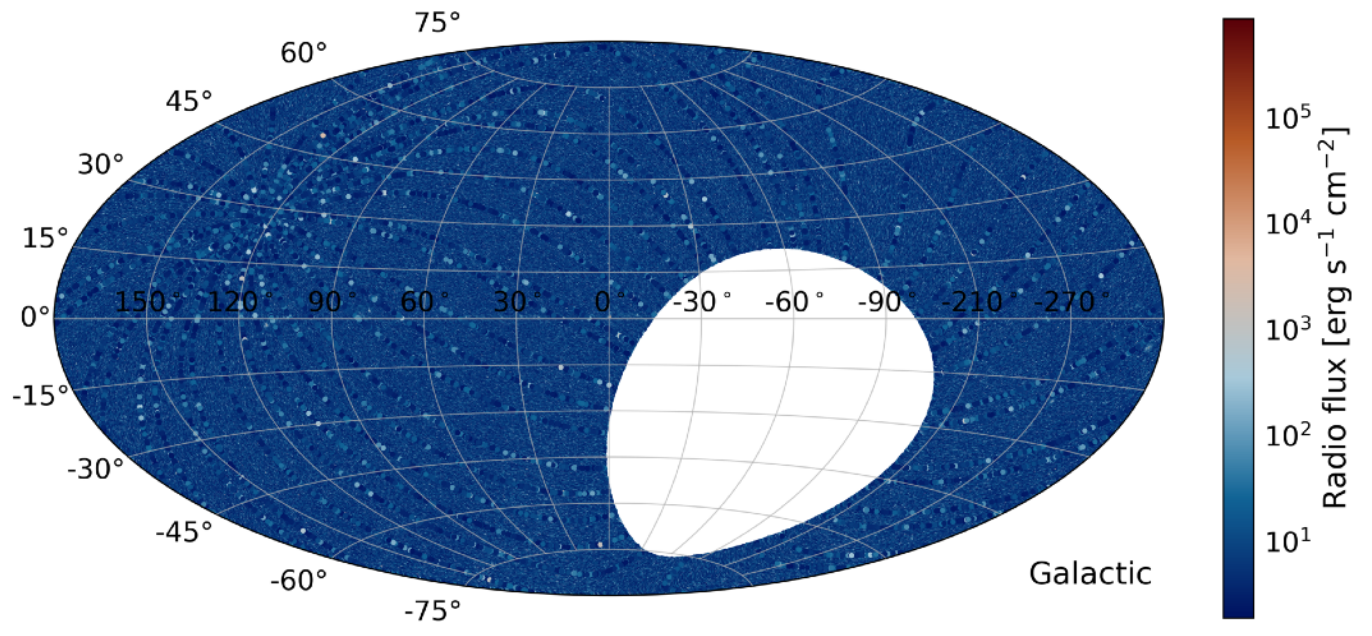


2RXS + AllWISE

~1.6 x 10^4 sources

Radio

Unaffected by obscuration and thus unbiased wrt orientation

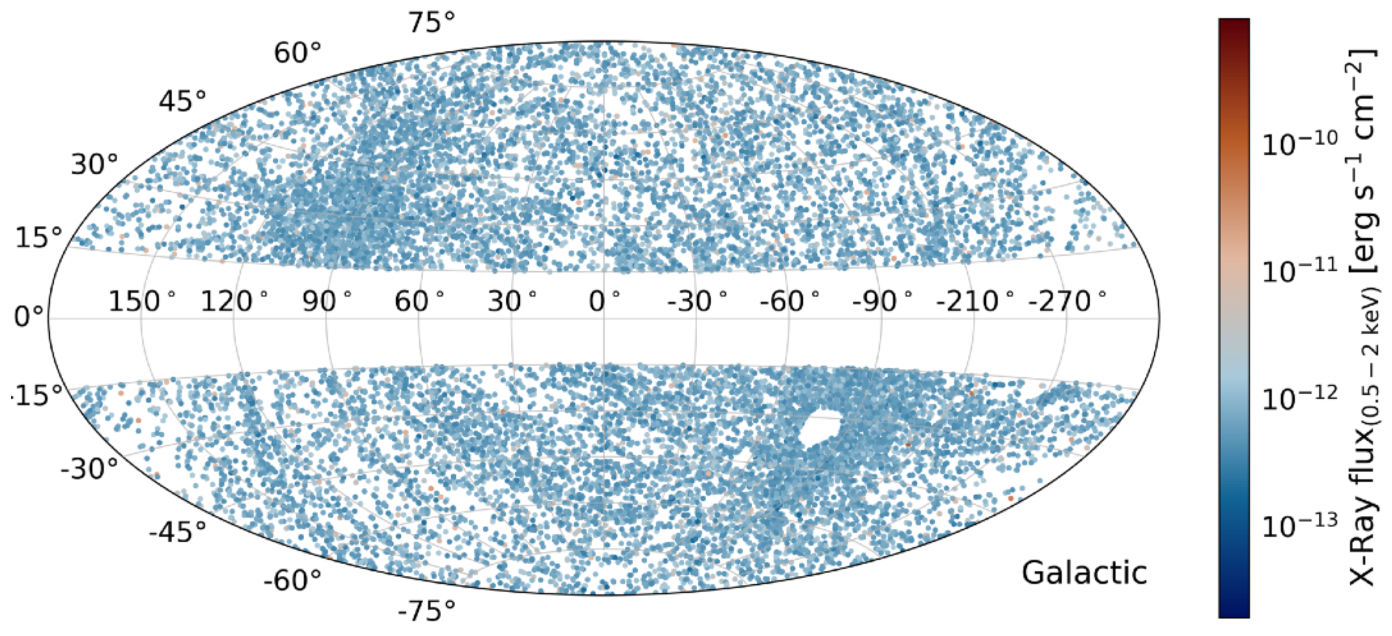


NVSS

~1.8 x 10^6 sources

Infrared

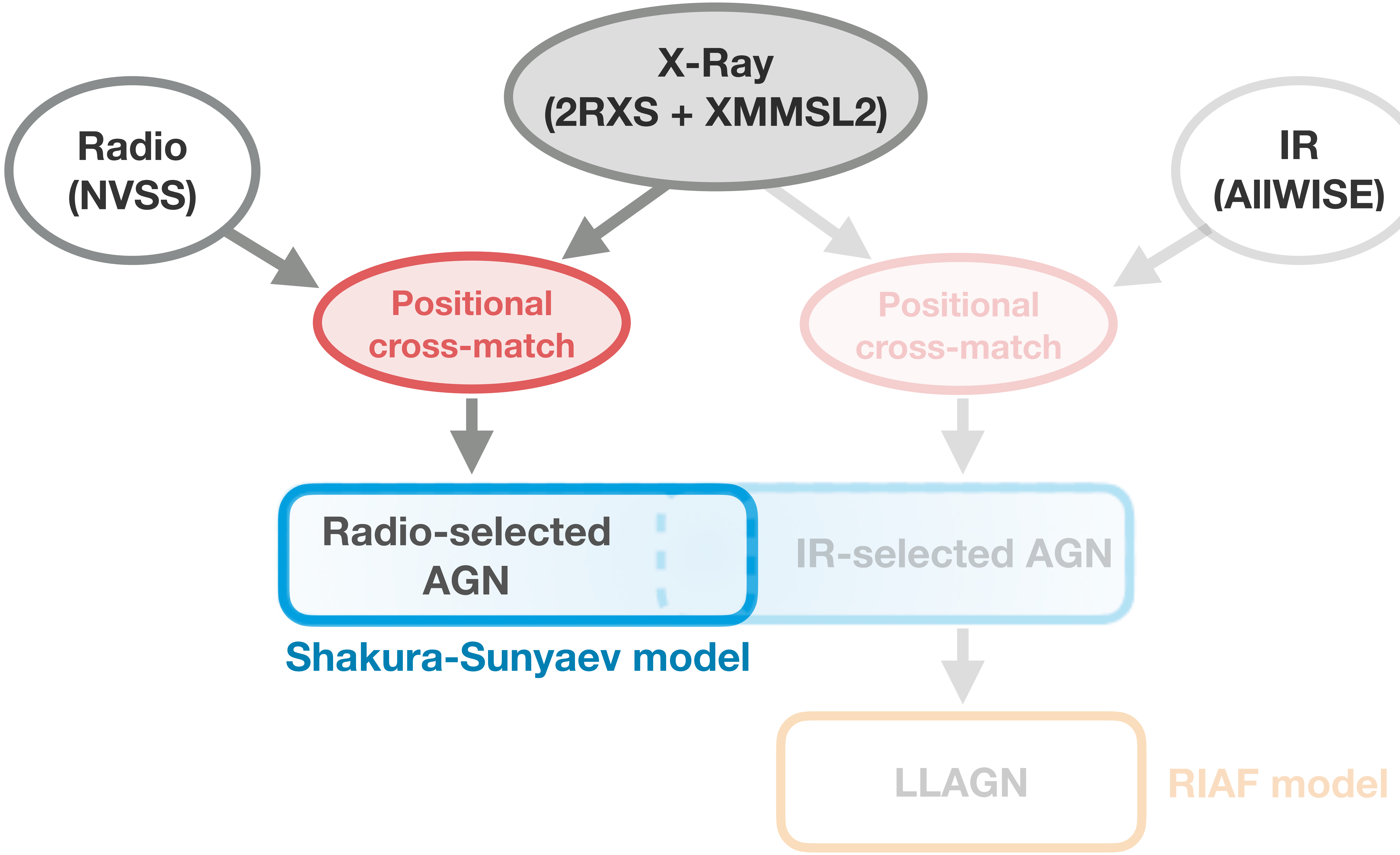
Produced in the dust surrounding the accretion disk



XMMSL2 + AllWISE

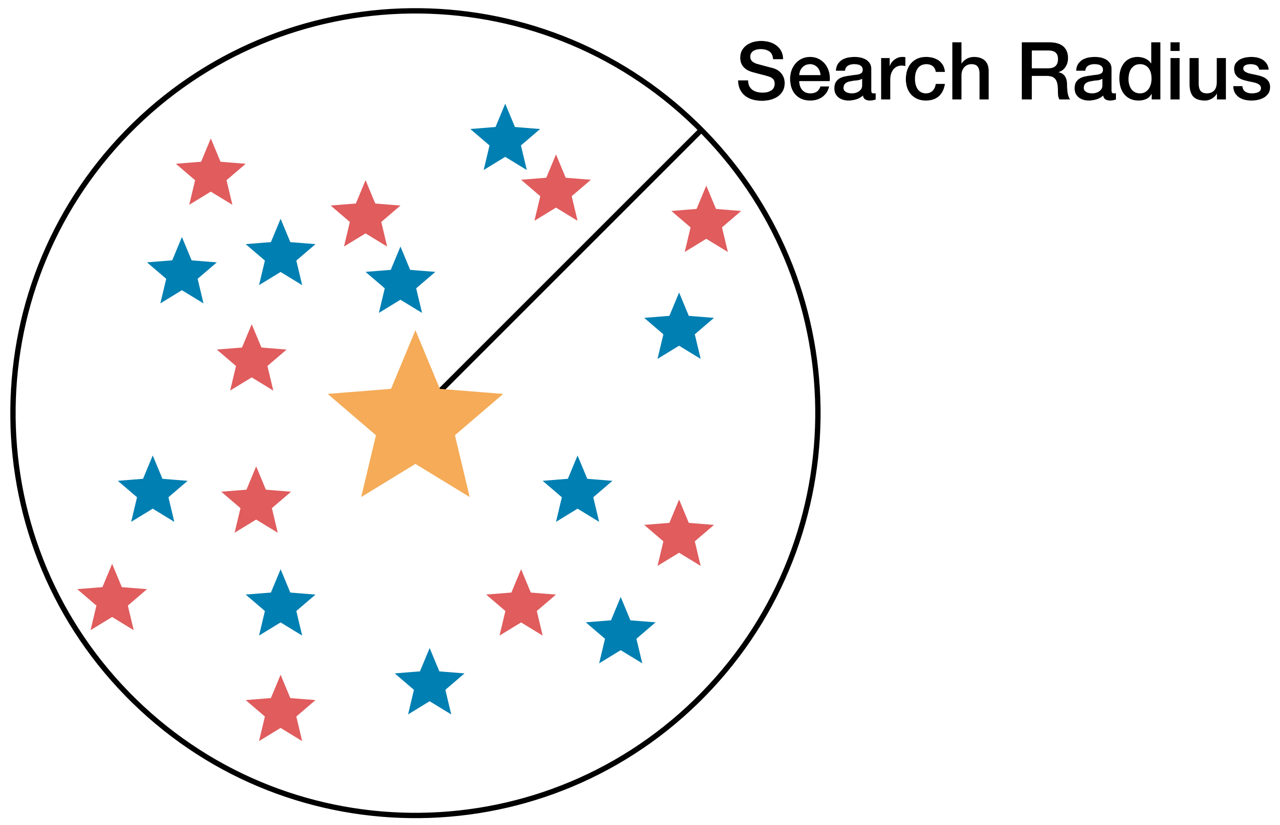
~1.9 x 10^3 sources

Radio-selected AGN

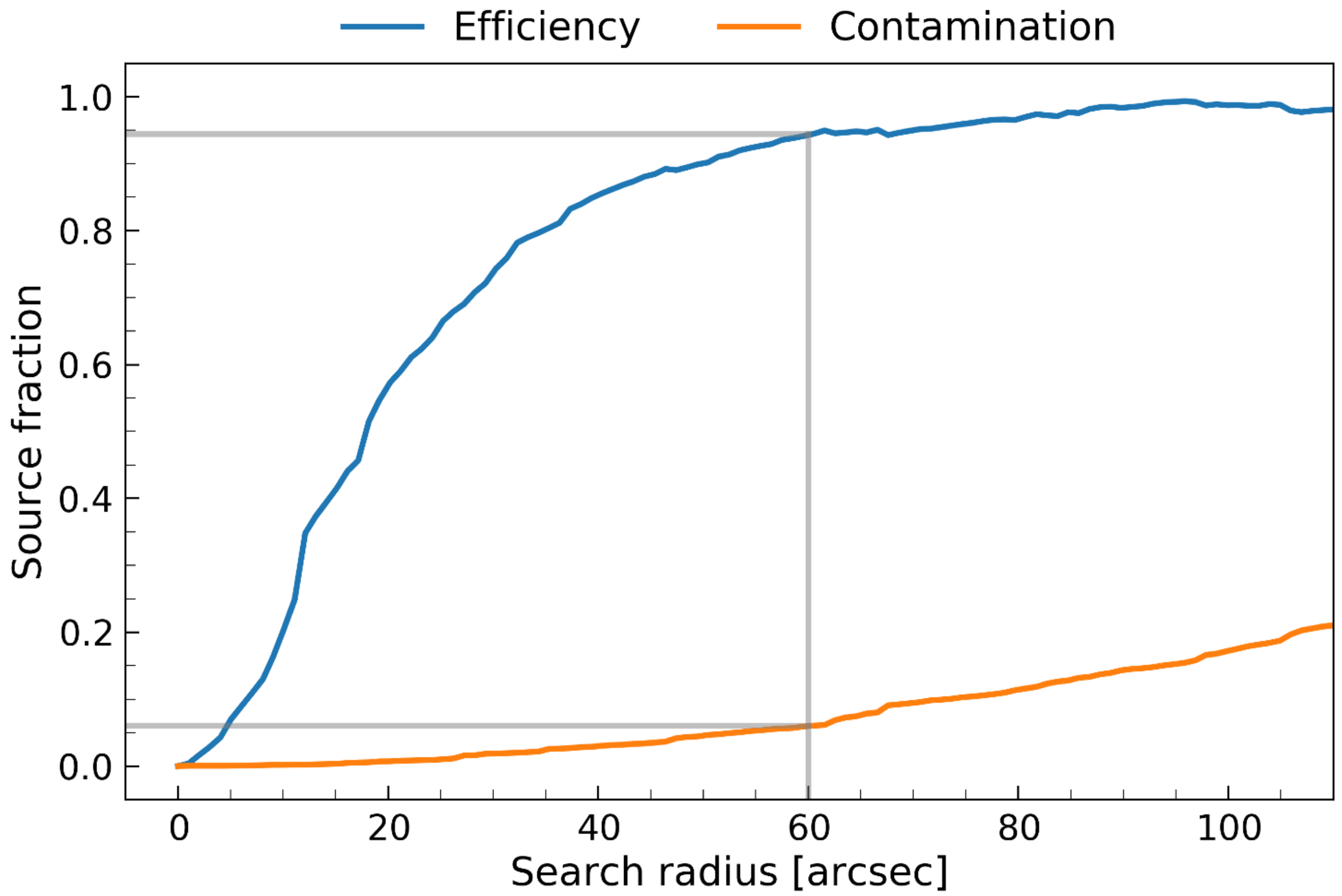


Radio-selected AGN

Through X-ray and Radio positional cross-match



X-ray source
NVSS sources
Random sources

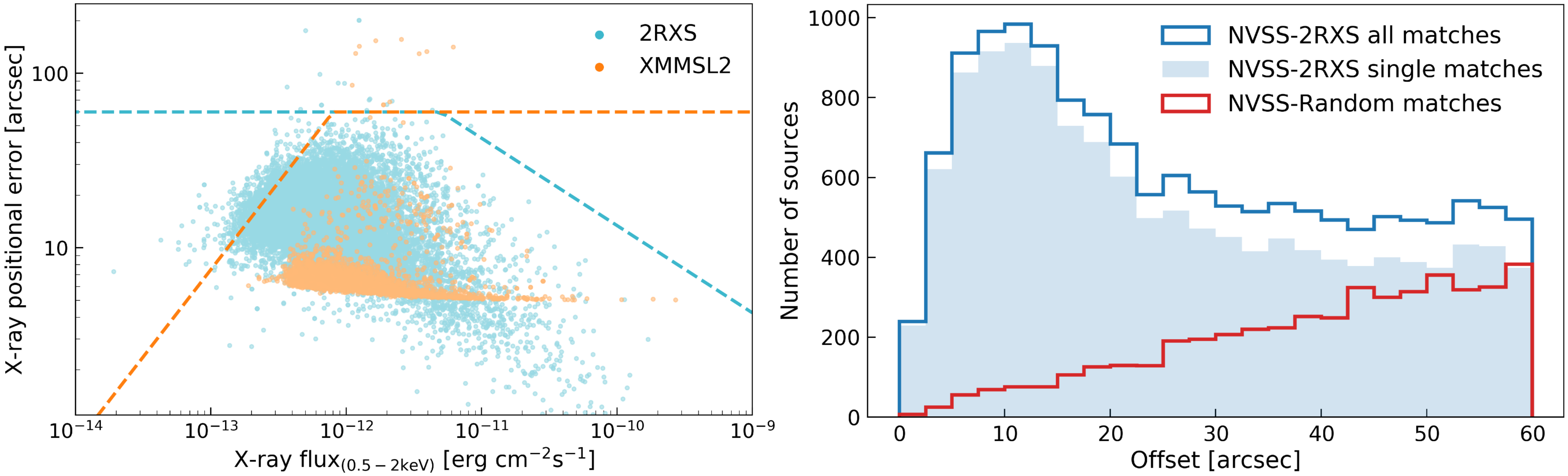


Search Radius ≤ 60 arcsec, chosen based on the X-ray positional error and flux

Contamination ≃ 5%
Efficiency ≃ 94%

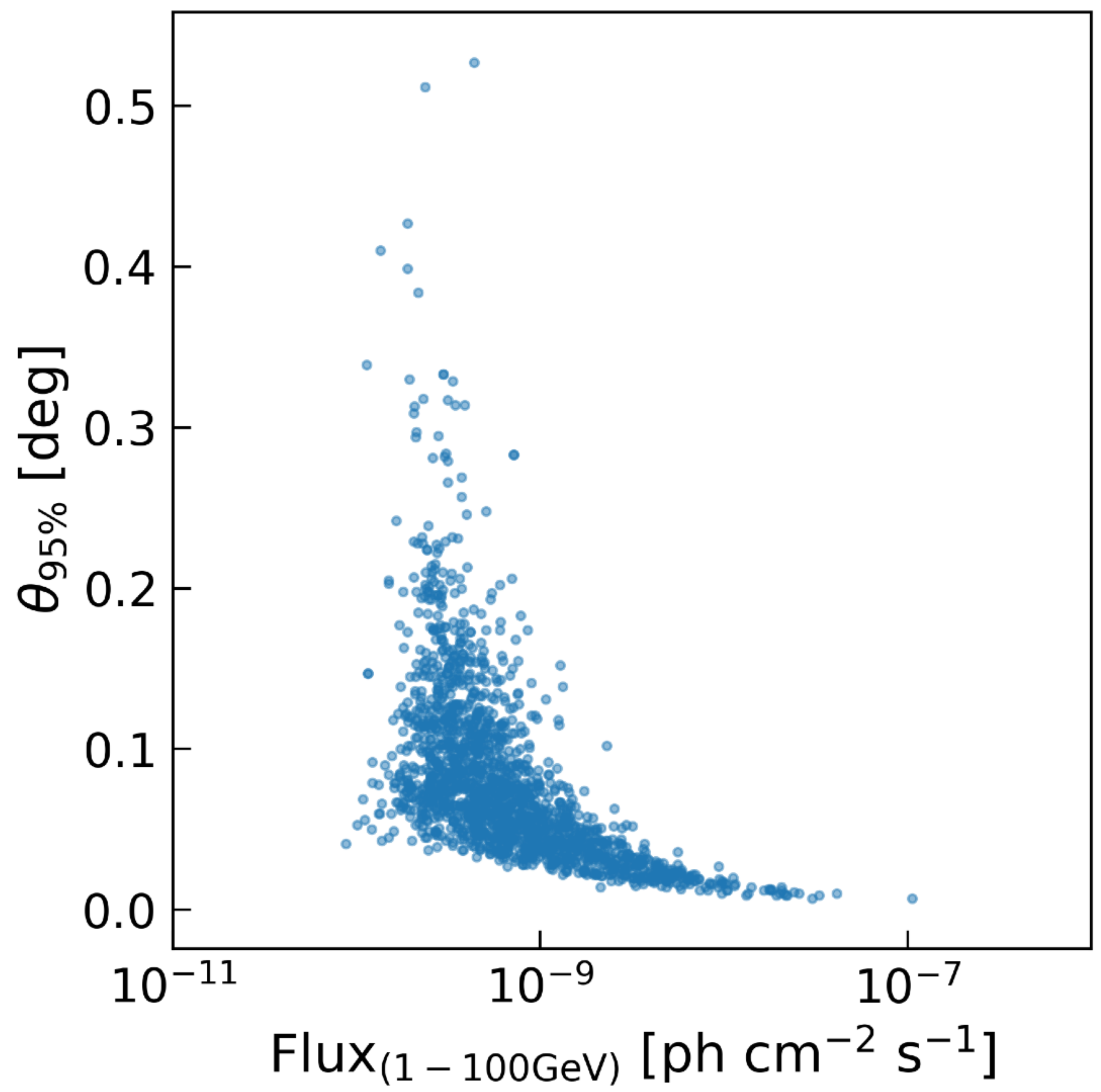
Radio-selected AGN

Through X-ray and Radio positional cross-match

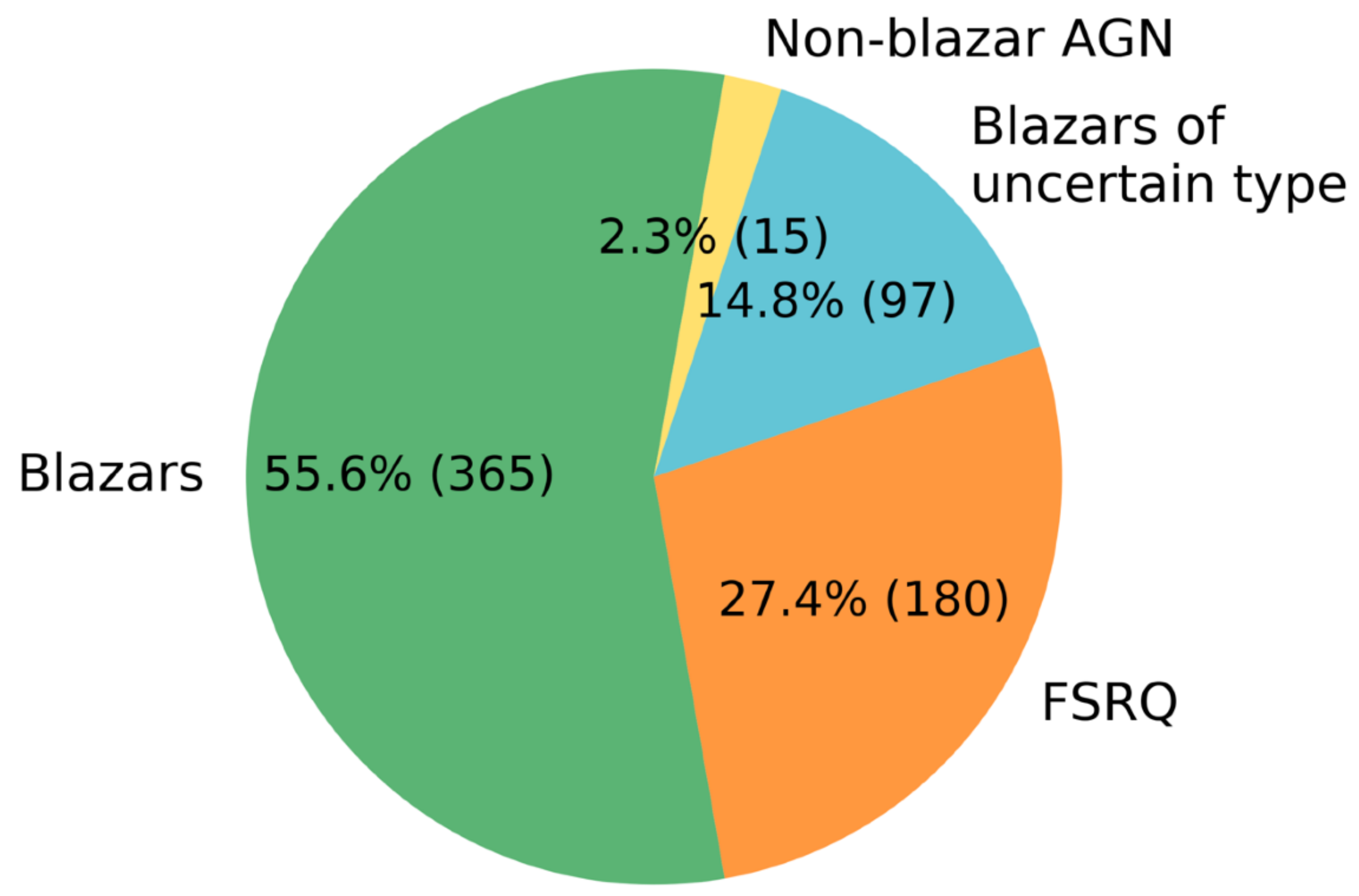


Radio-selected AGN

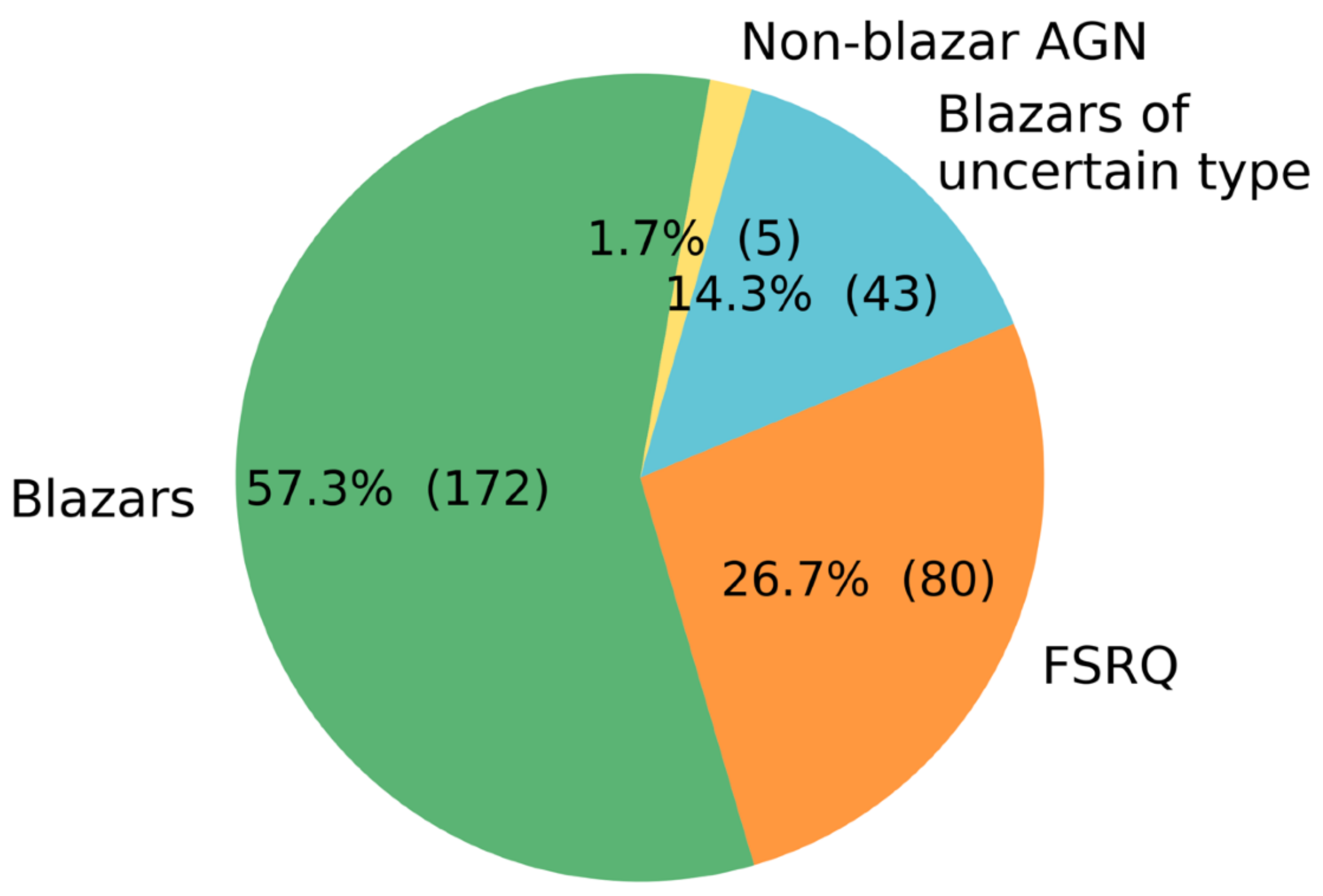
Removing Fermi-LAT blazars



FRACTION OF 3LAC MATCHED SOURCES



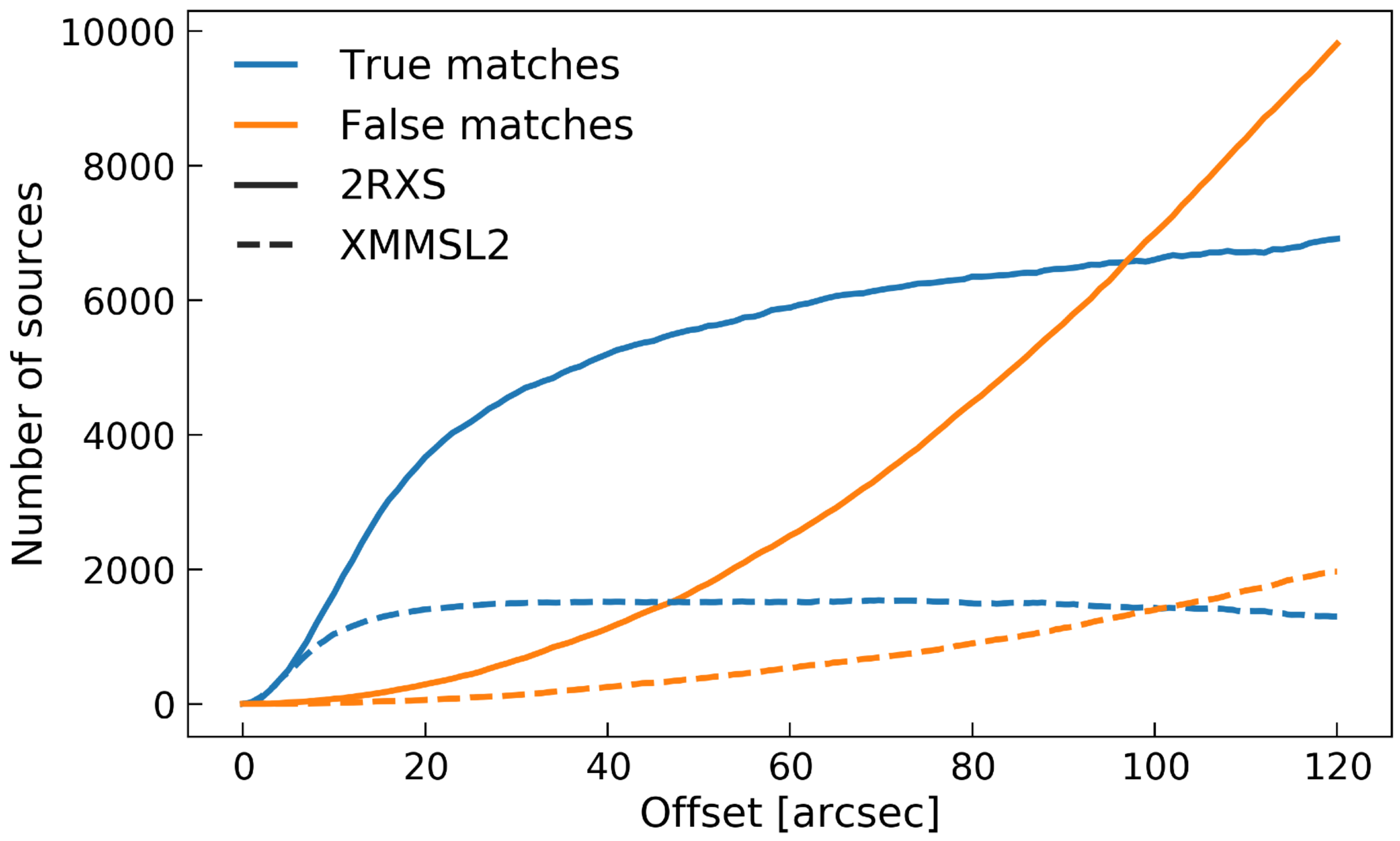
2RXS-NVSS

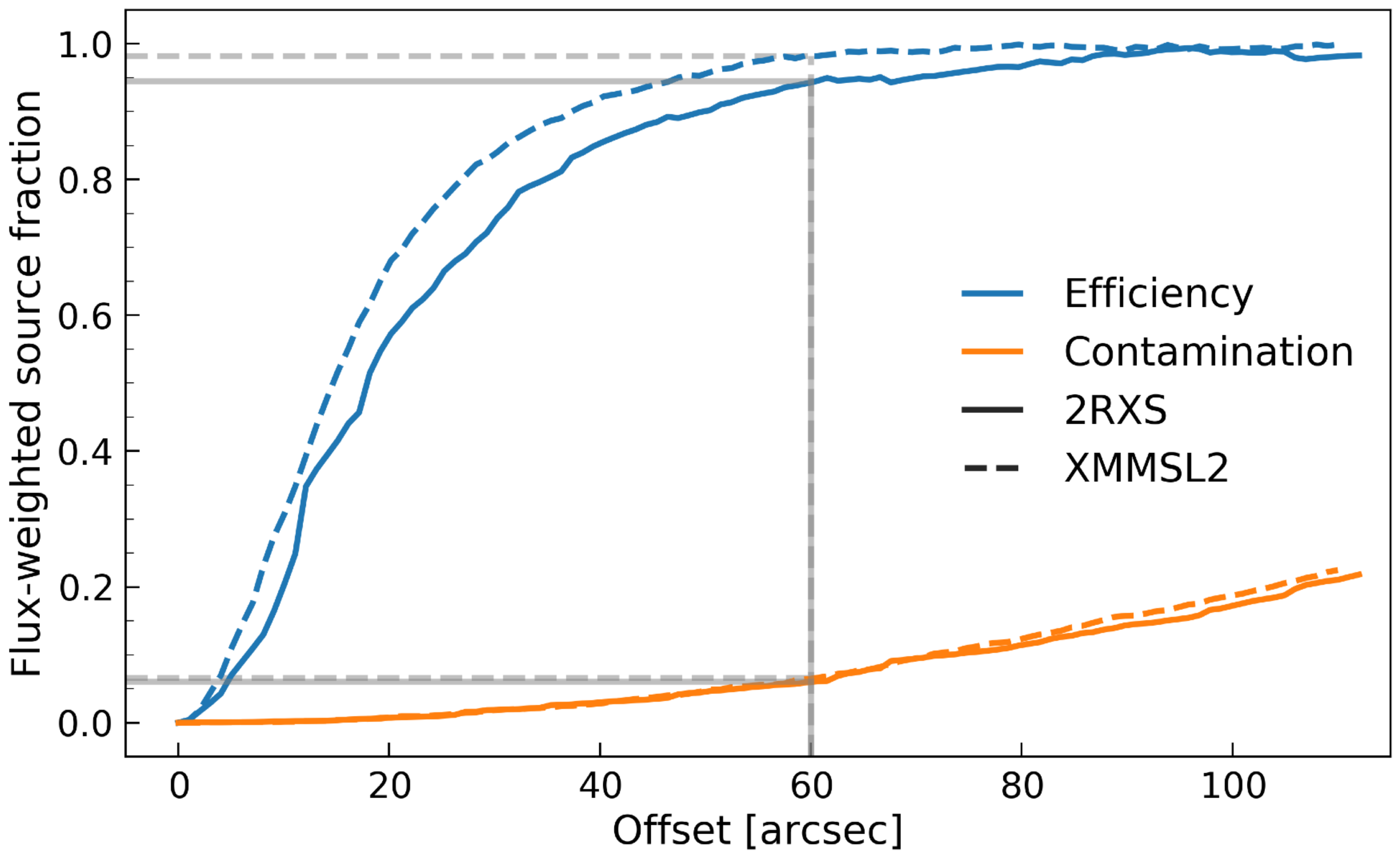


XMMSL2-NVSS

Radio-selected AGN

Contamination and Efficiency

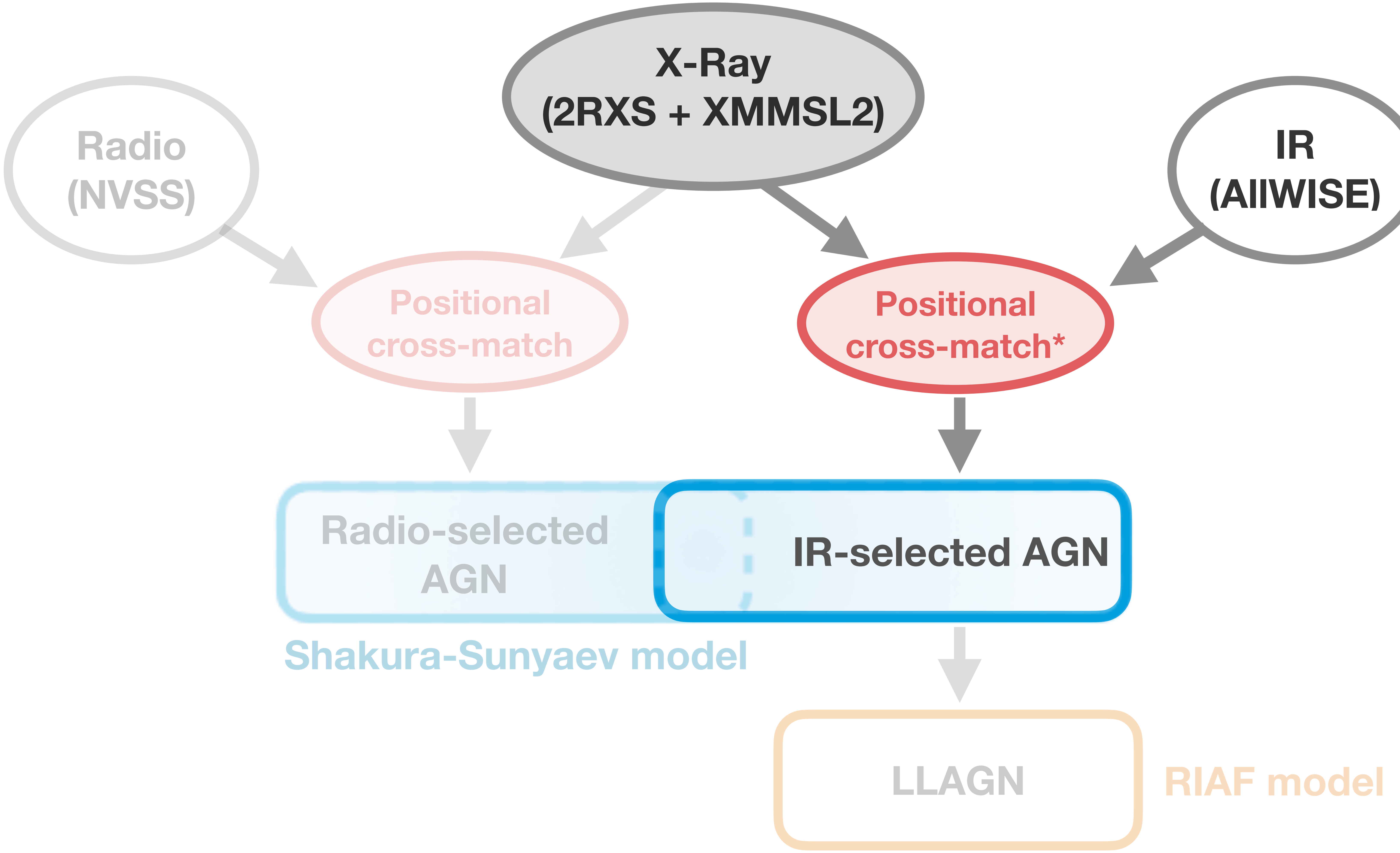




True matches = all matches - random matches
False matches = random matches

Efficiency = true matches normalized on all matches
Contamination = false matches normalized to crossing point

IR-selected AGN



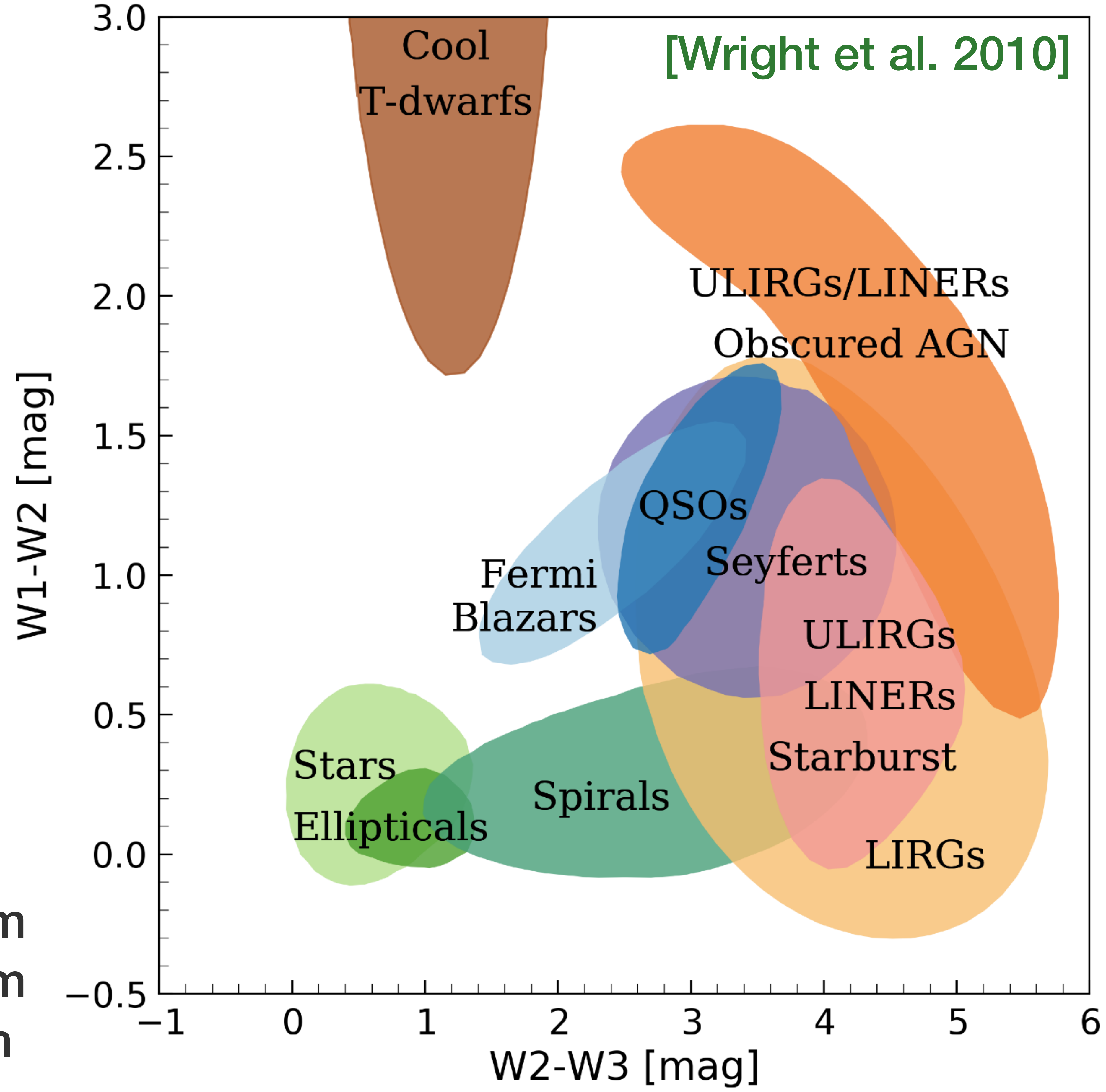
*From Salvato et al. 2017 (already cross-matched)

IR-selected AGN

Through X-ray and IR-colors correlation

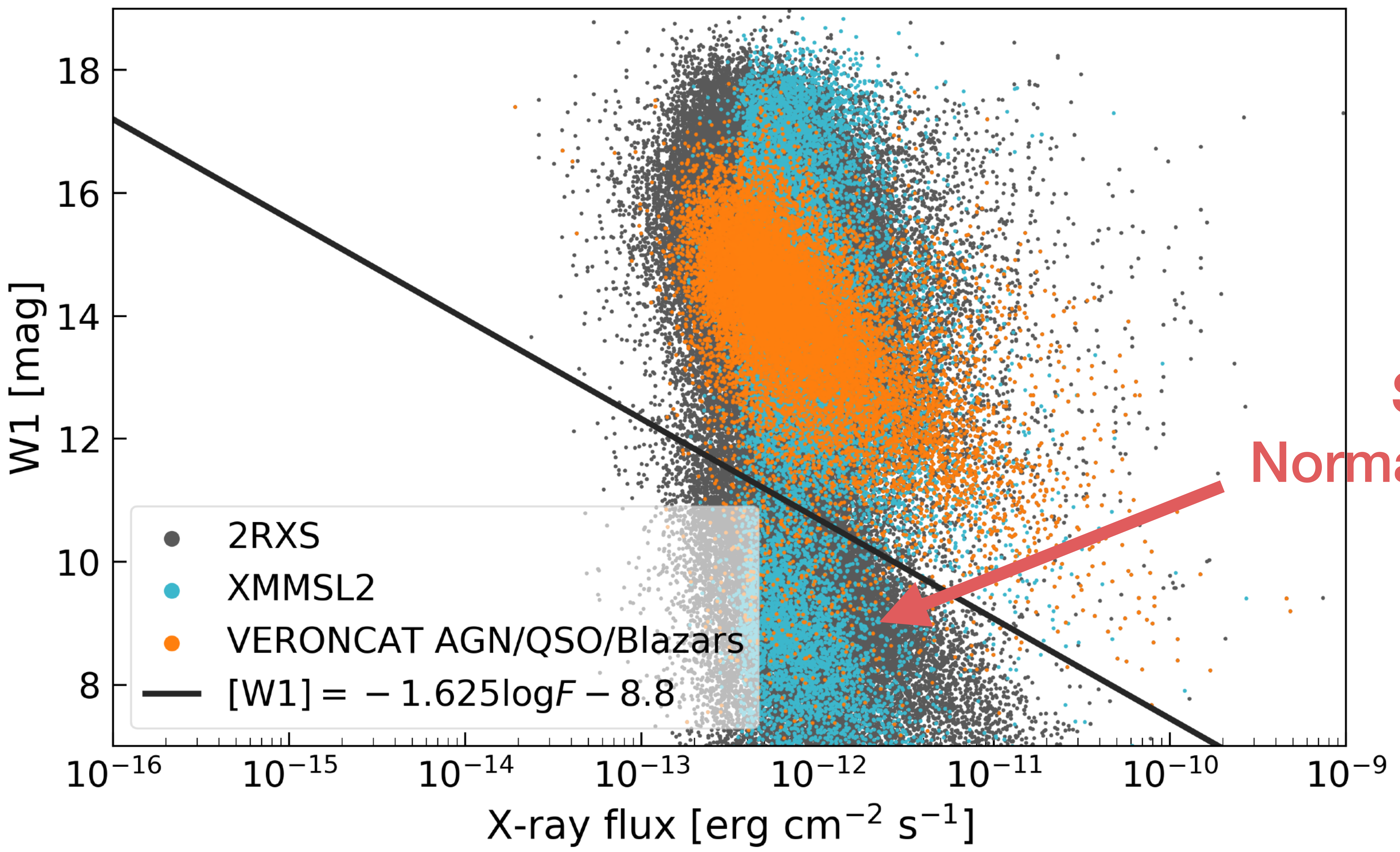
- Mid-IR emission produced in the warm dust torus
- IR colors = ratio of intensities between several mid-IR bands
- Use IR color-color diagram to select AGN
- Use AGN classification from existing AGN catalogue **[Véron et al. 2010]**
- Remove 3LAC blazars

W1 = 3.4 μm
W2 = 4.6 μm
W3 = 12 μm



IR-selected AGN

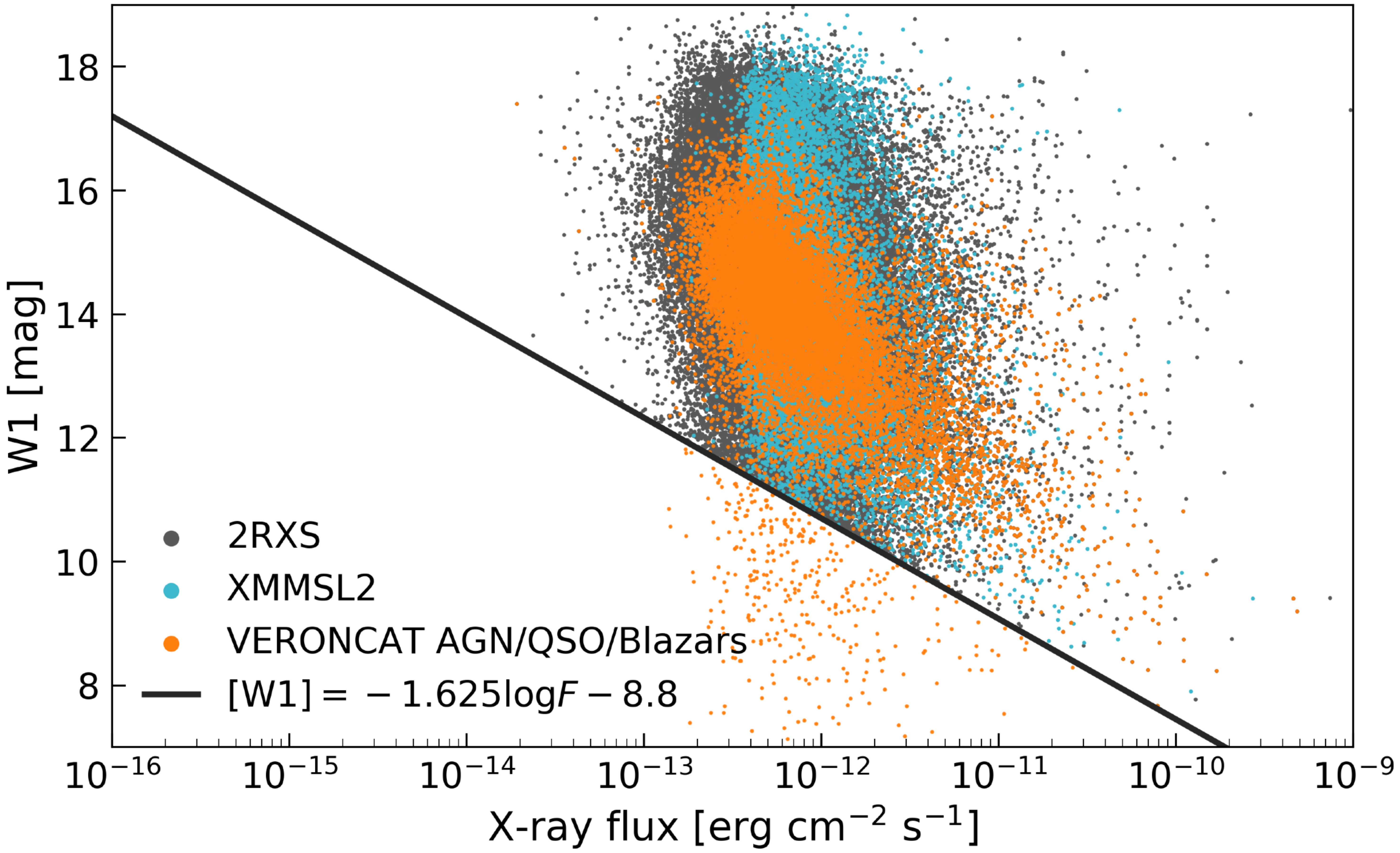
Cut on W1 (3.4 μm)



Stars
Normal galaxies

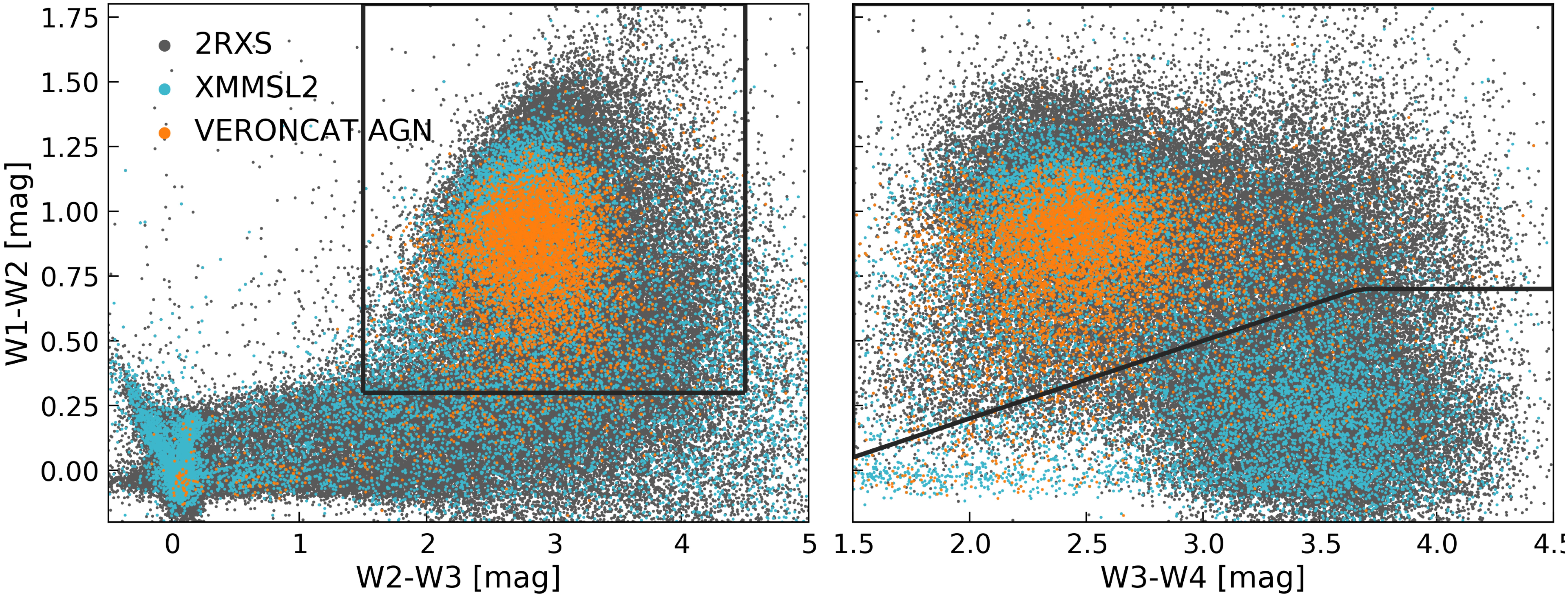
IR-selected AGN

Cut on W1 (3.4 μm)



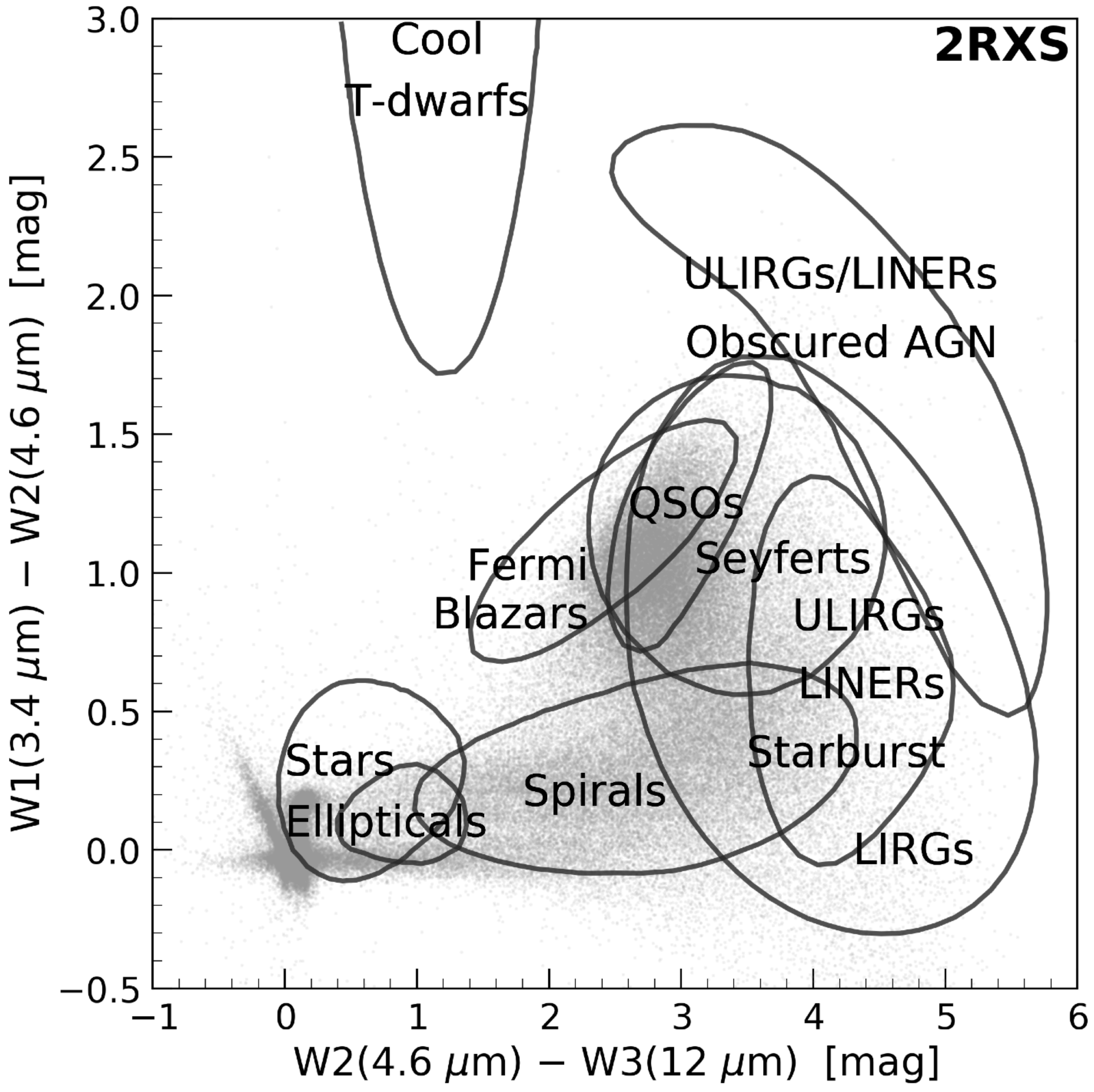
IR-selected AGN

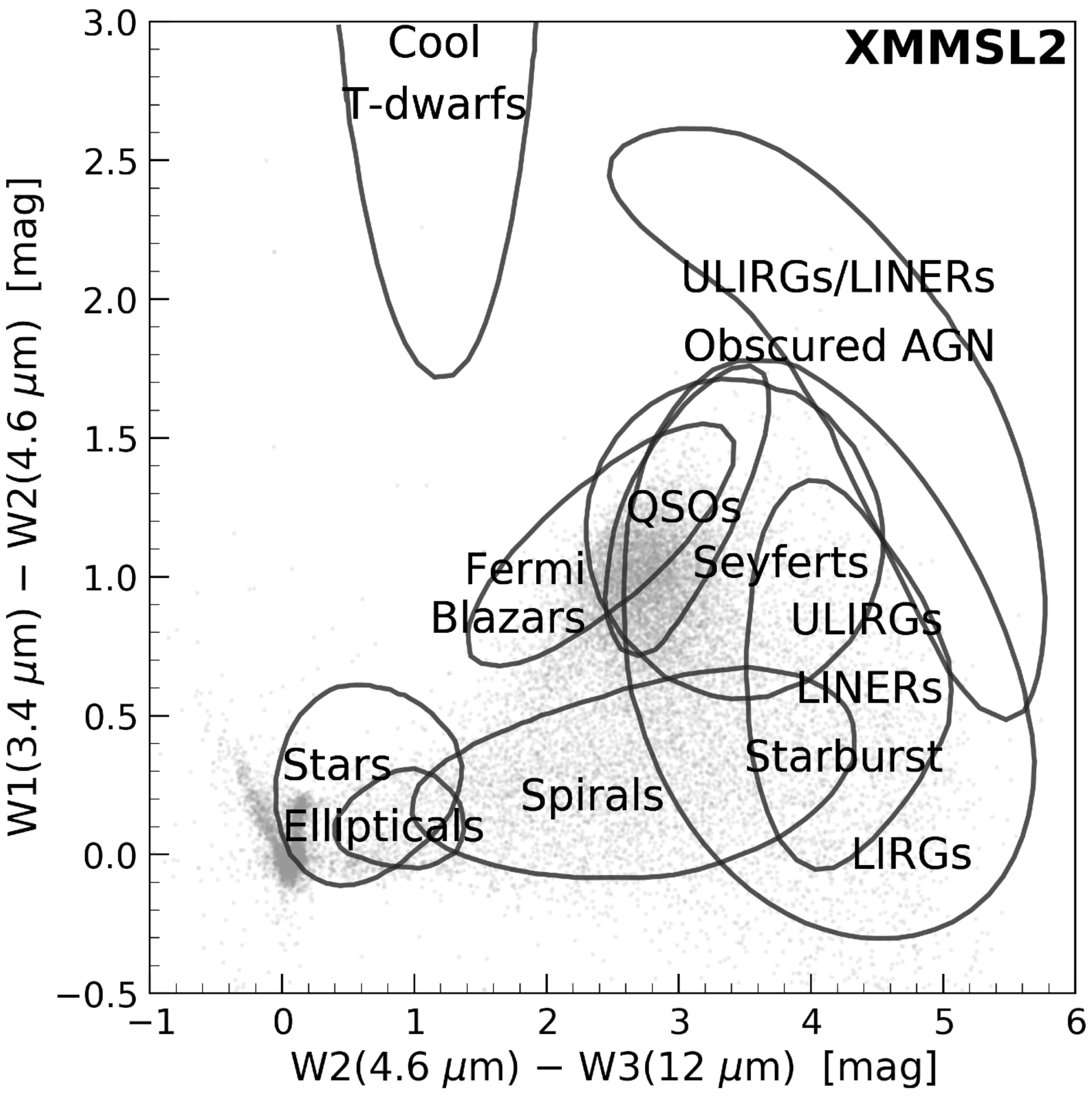
Cut on W1 (3.4 μm), W2 (4.6 μm), W3 (12 μm) and W4 (22 μm)



IR-selected AGN

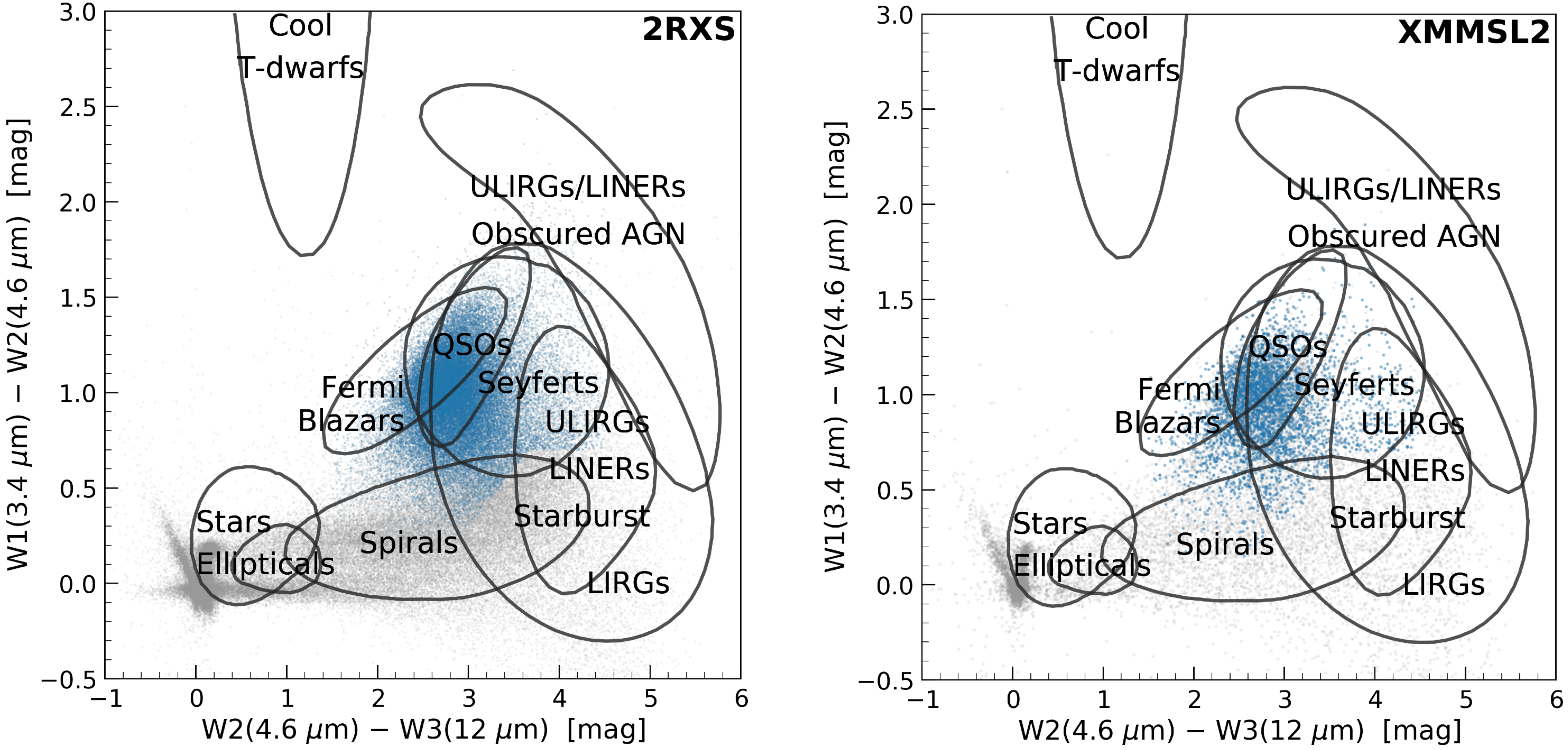
Before applying the cut





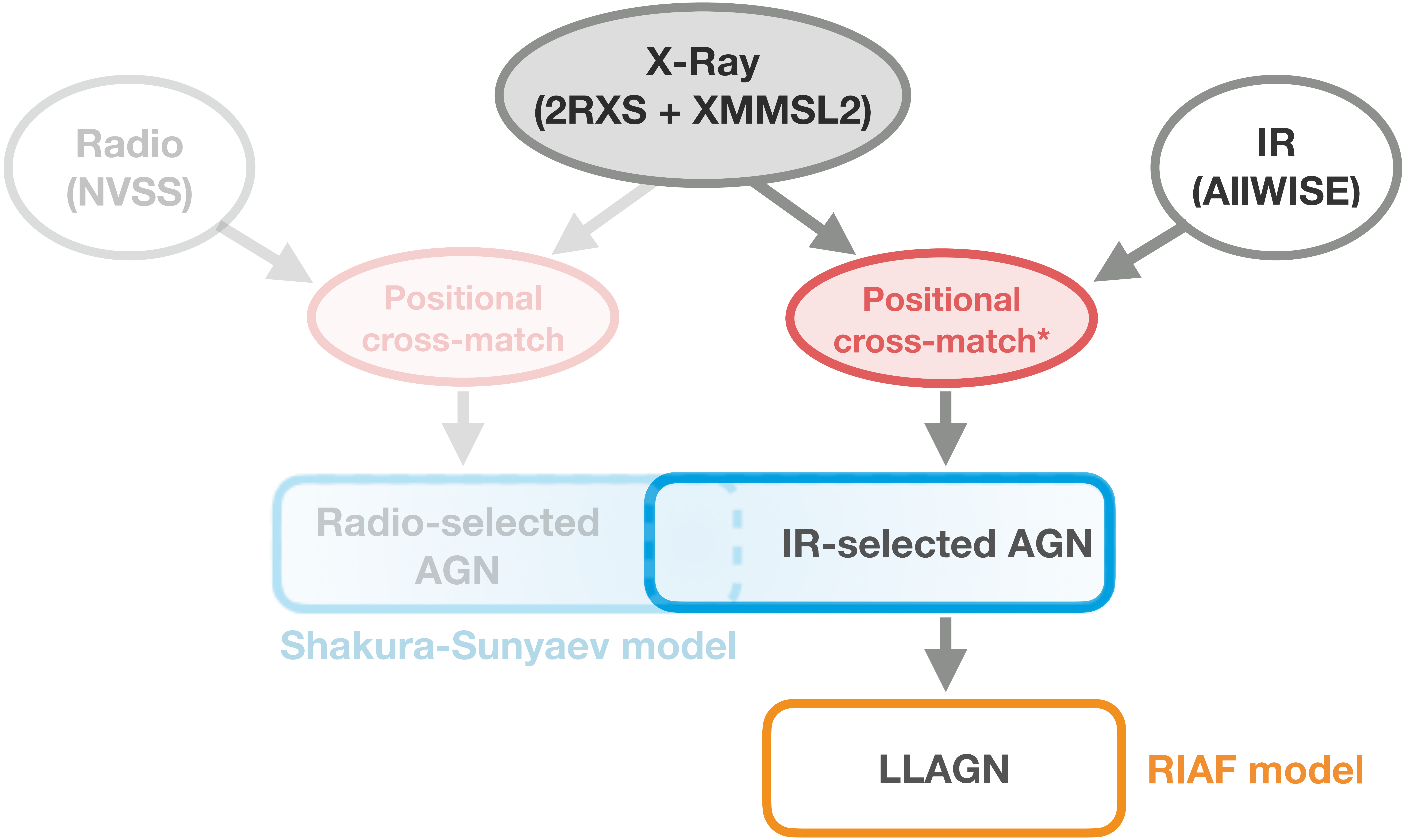
IR-selected AGN

After applying the cut



Contamination ≃ 6%, Efficiency ≃ 89%

LLAGN

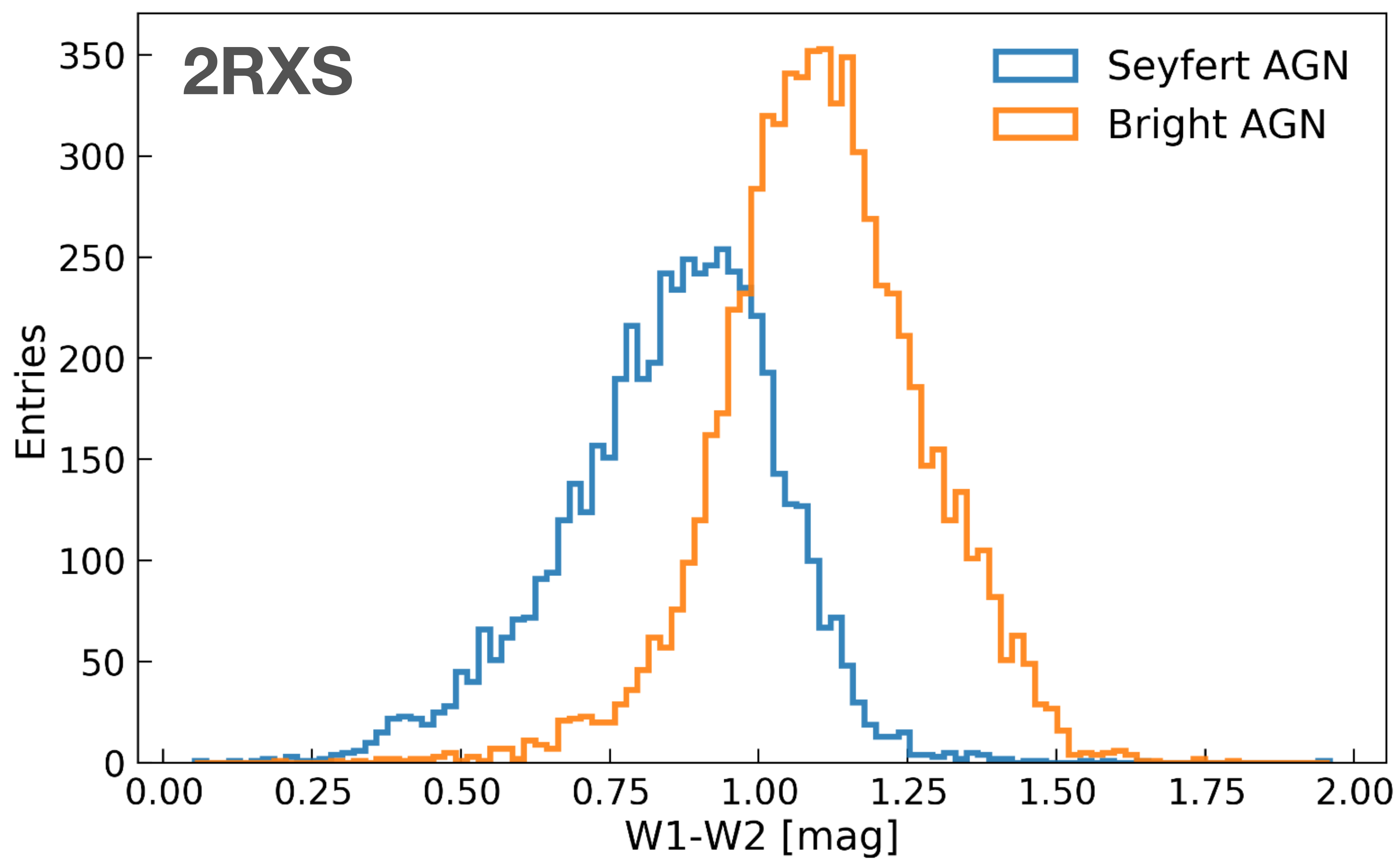


*From Salvato et al. 2017 (already cross-matched)

LLAGN (Seyfert Galaxies)

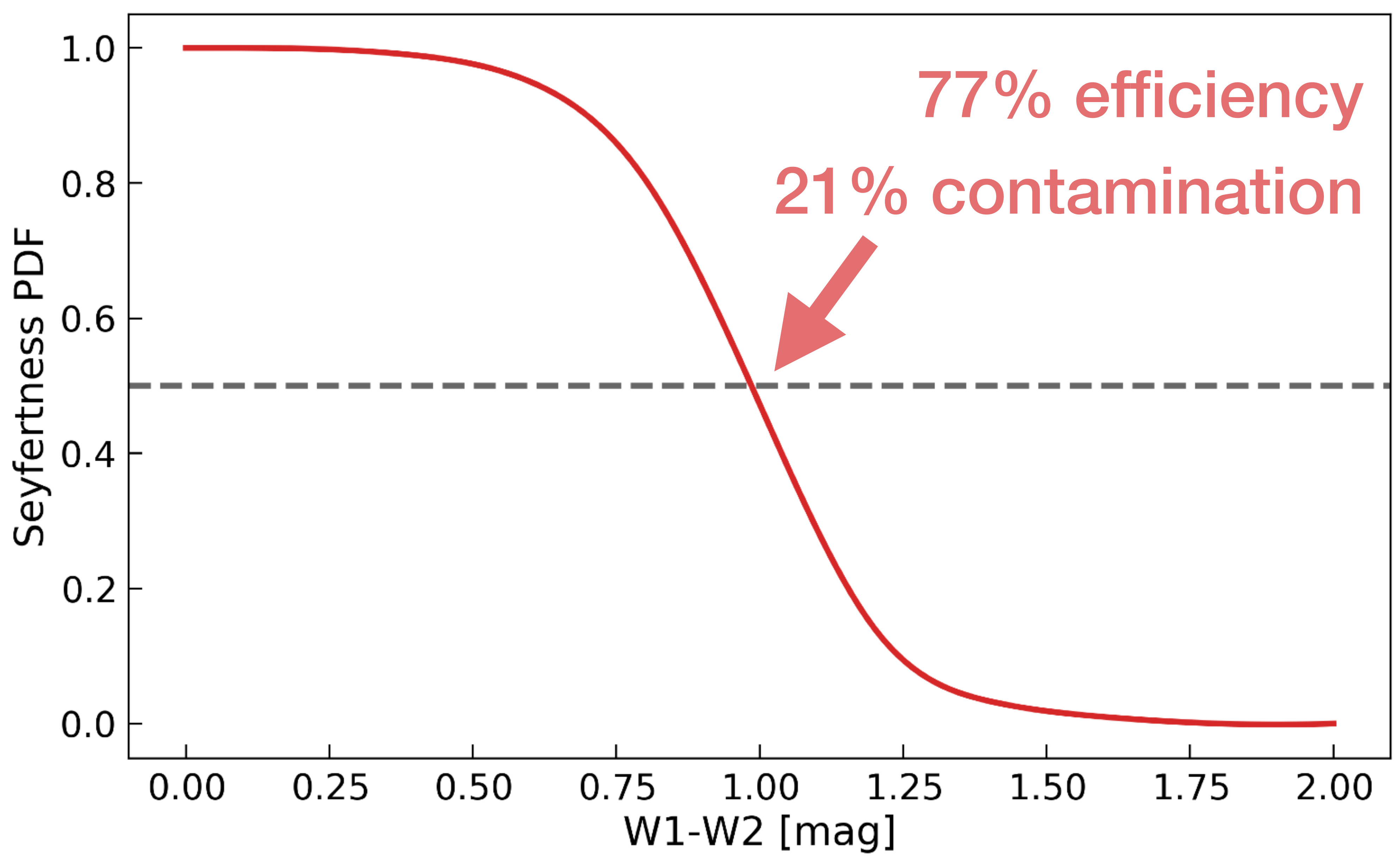
Through X-ray and IR correlation + Seyfertness PDF

2RXS sources classification from AGN catalogue [Véron et al. 2010]



$$\text{Seyfertness} = \frac{P(\text{Seyf})}{P(\text{Seyf}) + P(\text{Bright})}$$

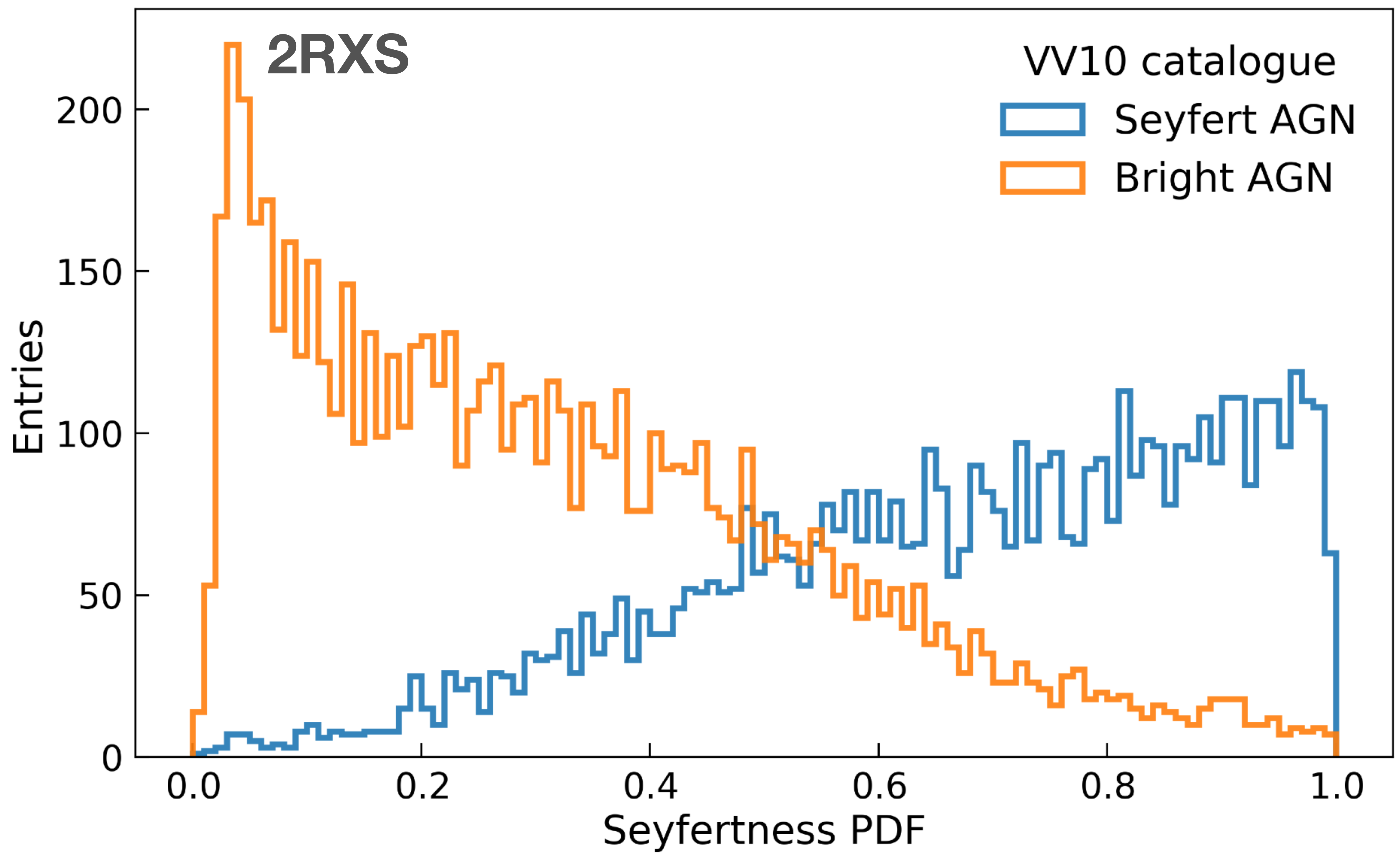
Seyfertness assigned to each source

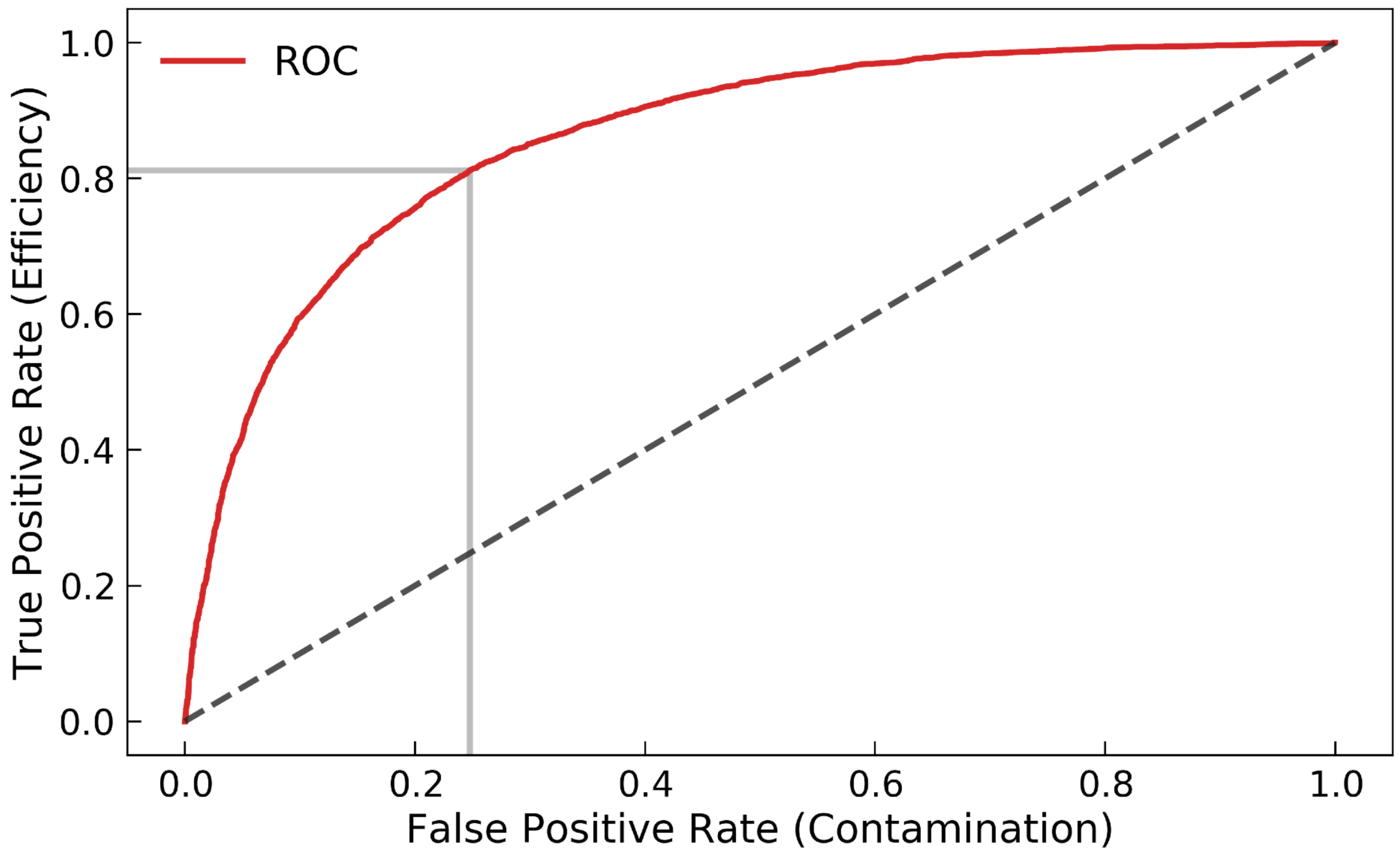


$$\text{Seyfertness} \geq 0.5$$

LLAGN (Seyfert Galaxies)

Contamination and Efficiency calculation





Stacking analysis

Likelihood ratio test as Test Statistic

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

Unbinned Likelihood

Nr. neutrino events

Nr. signal events

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

Unbinned likelihood

Signal PDF

Background PDF

Stacking of Weighted Sources

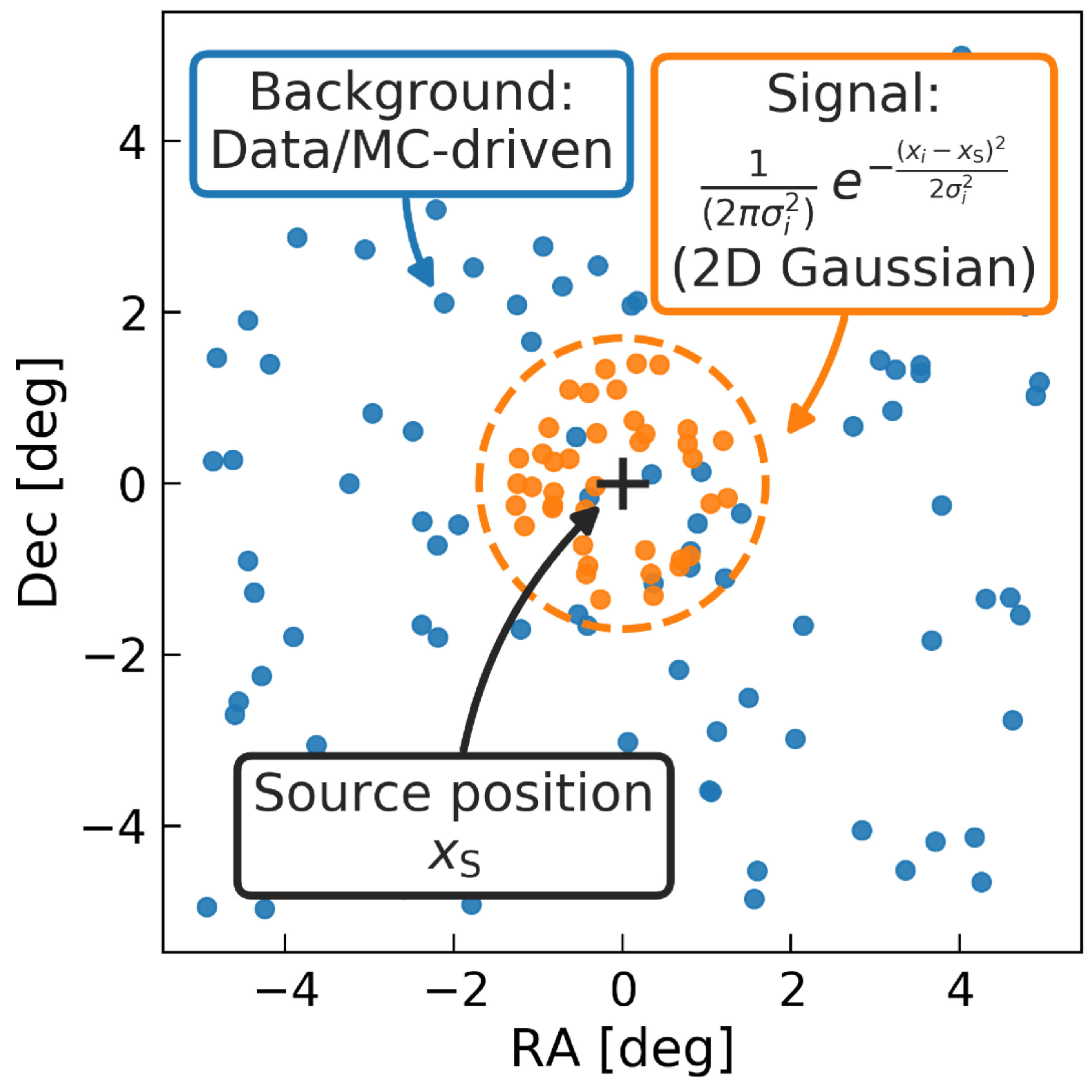
$$S(x_i, \gamma) = \frac{\sum_{k=1}^{M_{\rm AGN}} \omega_k \cdot S_k(x_i, \gamma)}{\sum_{k=1}^{M_{\rm AGN}} \omega_k}$$

Stacking analysis

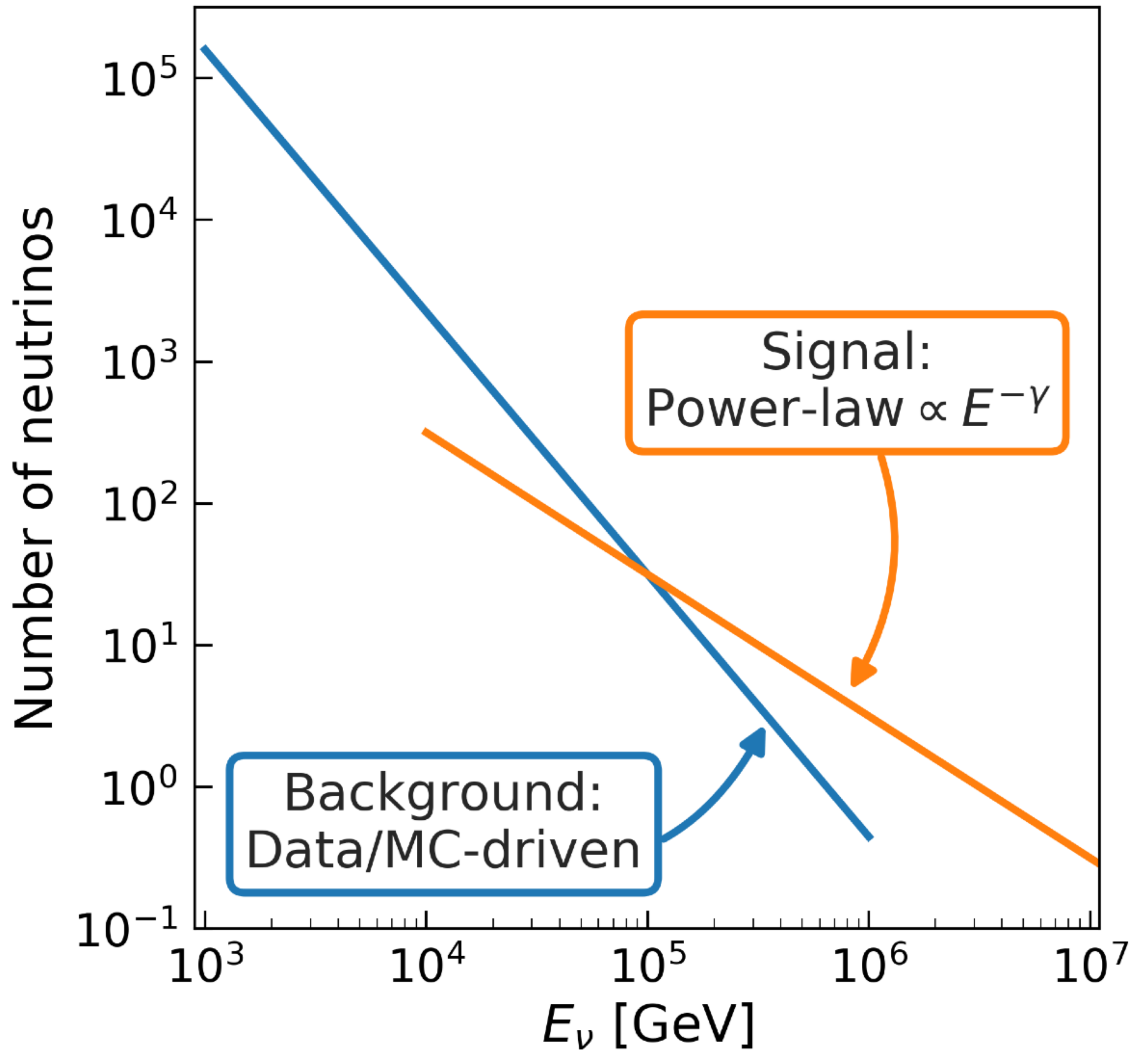
Signal PDF $S(x_i, \gamma) = S_{\text{spatial}} \cdot S_{\text{energy}}$

Background PDF $B(x_i, \gamma) = B_{\text{spatial}} \cdot B_{\text{energy}}$

Spatial PDF



Energy PDF



Stacking analysis

Likelihood ratio test as test statistic

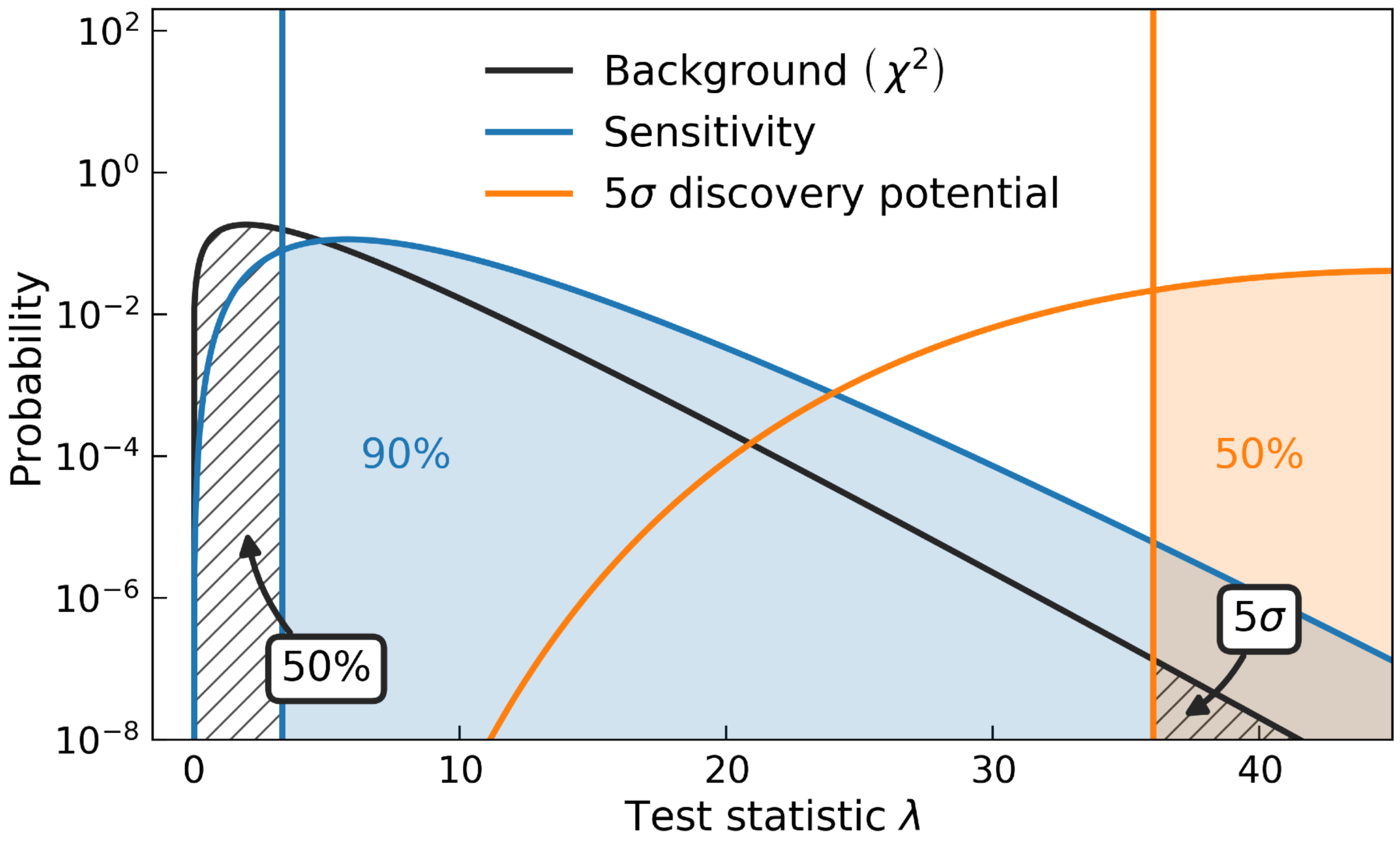
Test Statistic gives the significance of an excess of neutrinos above background expectations

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

Nr. signal events = strength of the signal

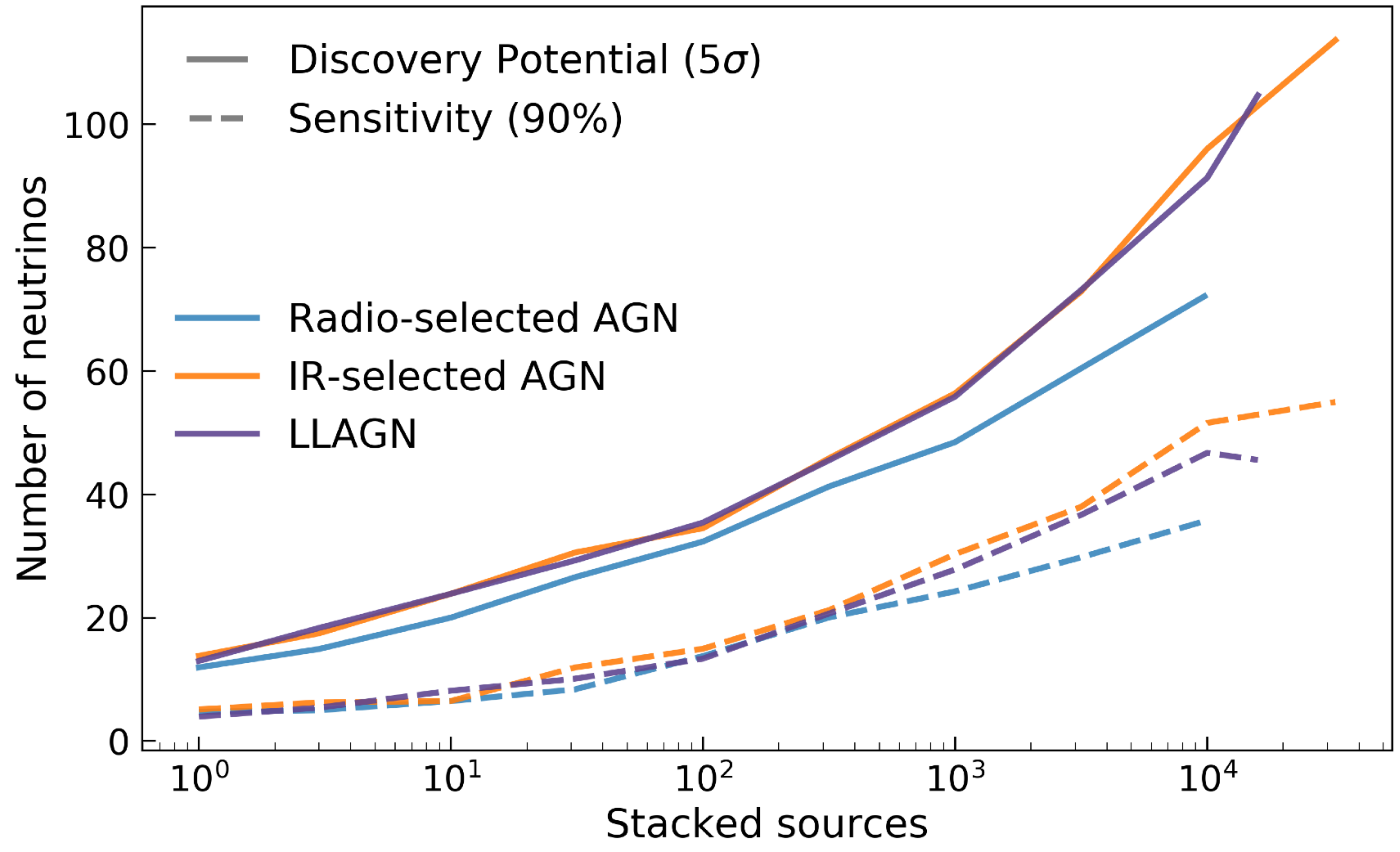
Spectral index of the signal $E^{-\gamma}$ spectrum

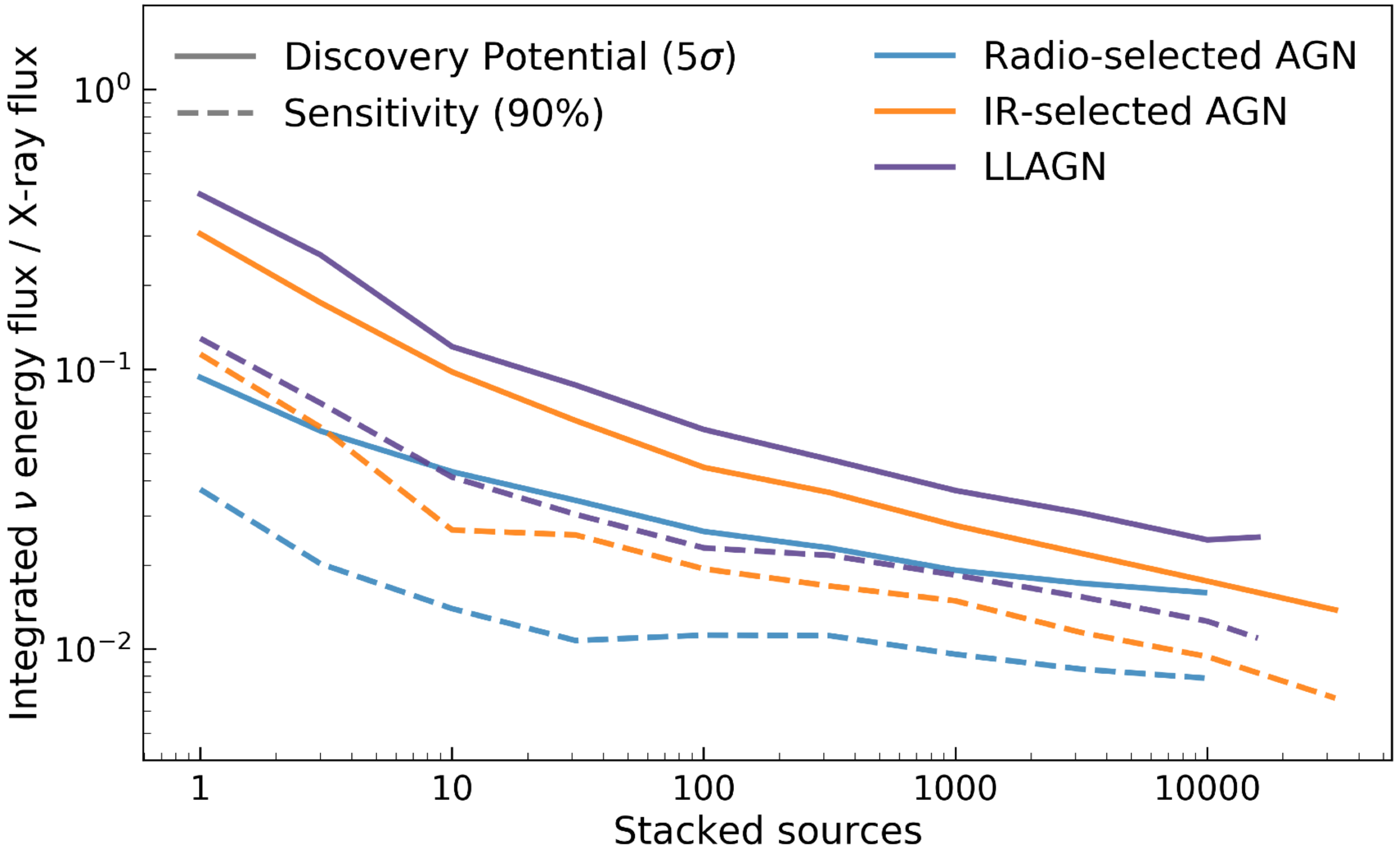
Test Statistic used to evaluate the **p-value** of the analysis by comparing the bkg-only TS distribution with the signal TS



Stacking analysis

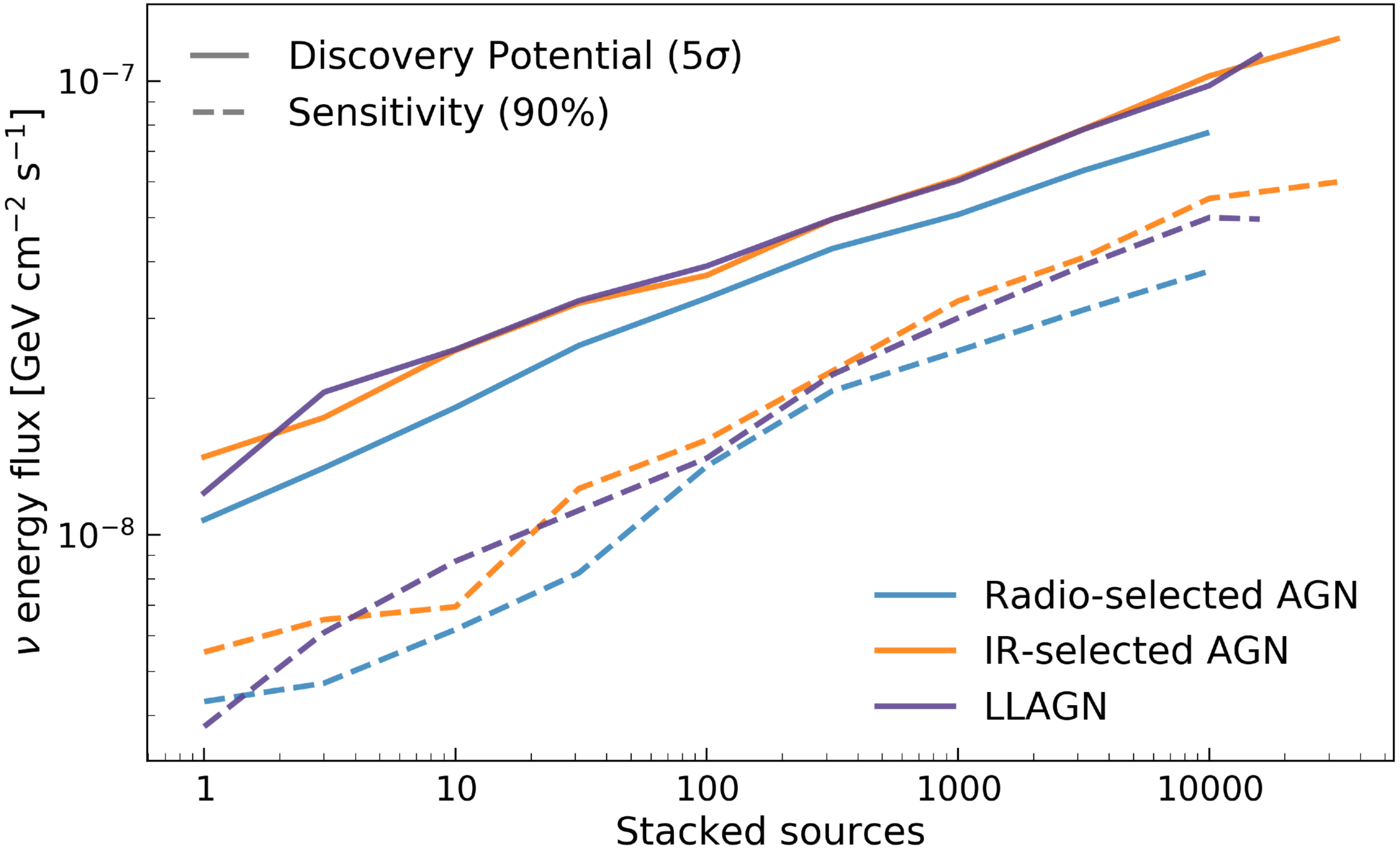
Advantage of a stacking analysis





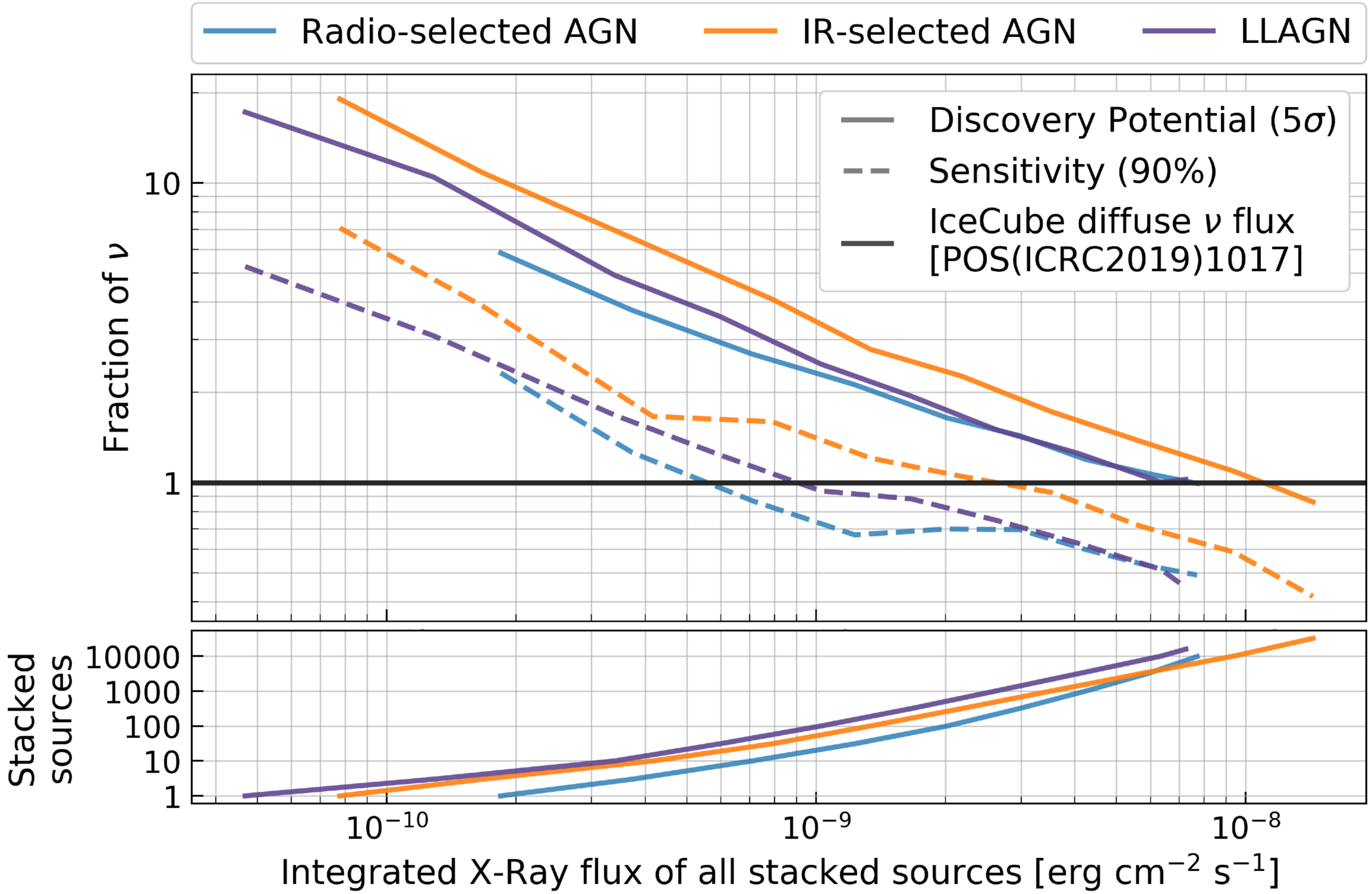
Stacking analysis of cores of AGN

Expected results



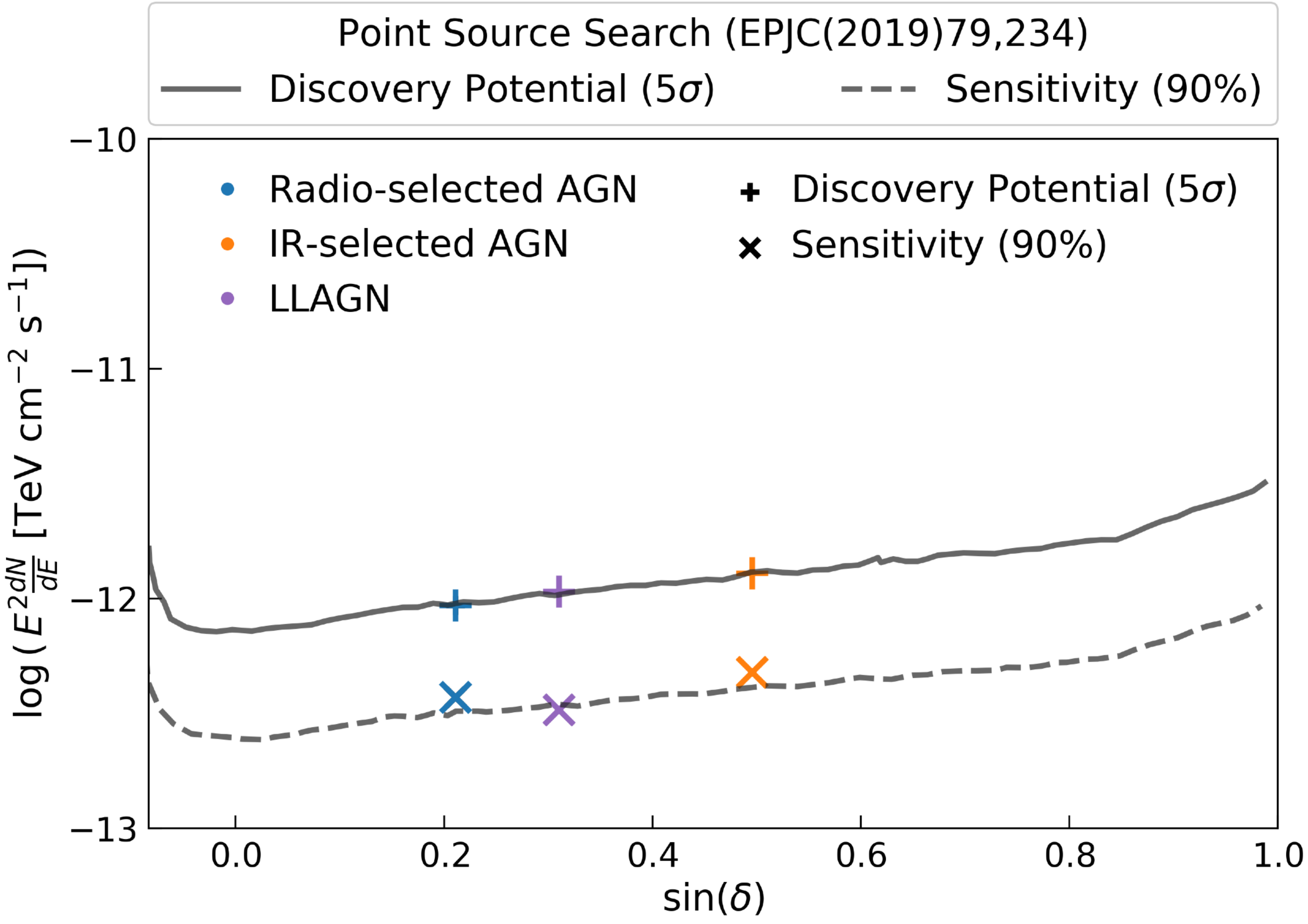
Stacking analysis of cores of AGN

Expected fraction of diffuse flux



Validation of the analysis

Comparison with 8yr PS stacking analysis



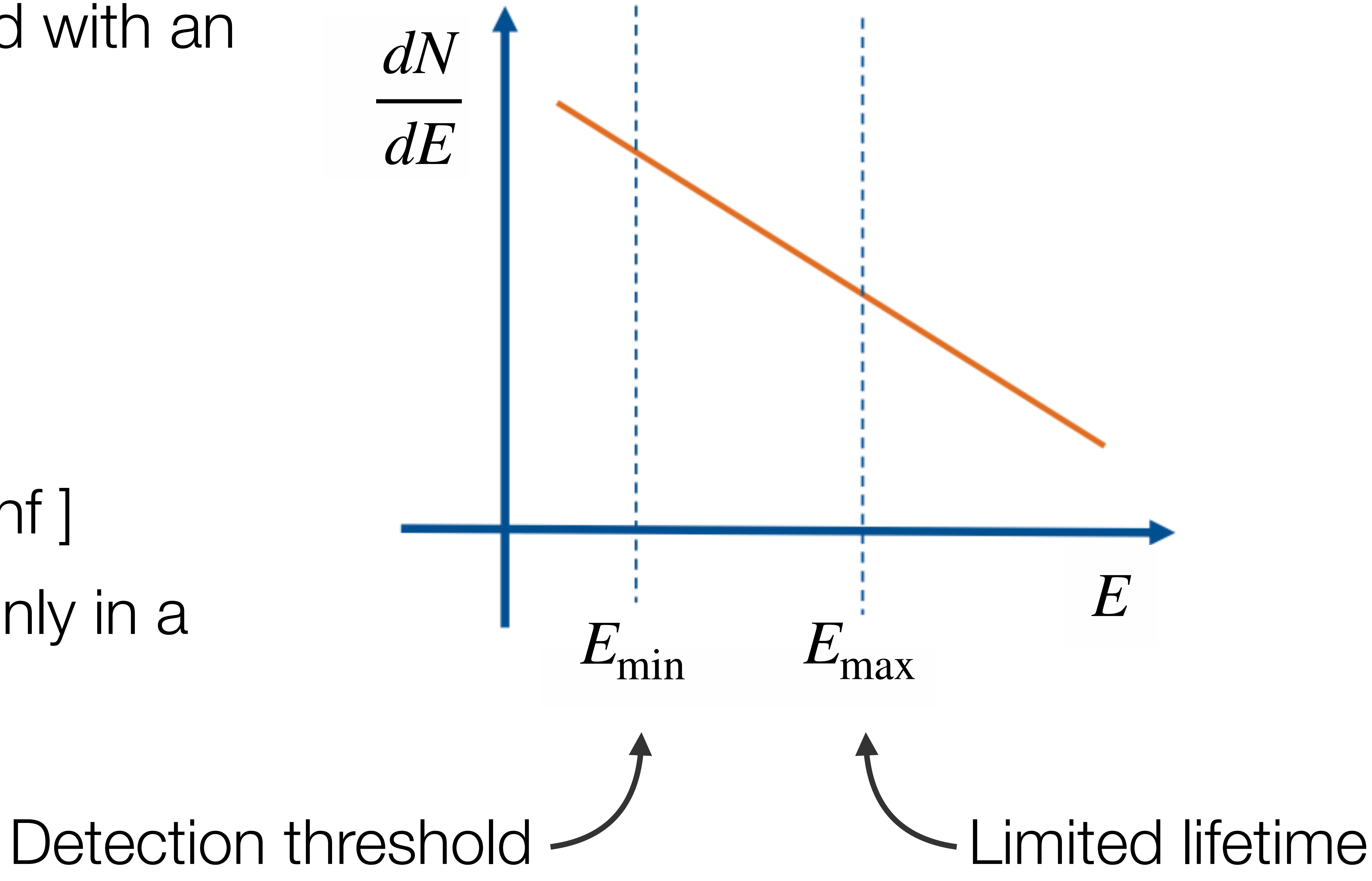
Neutrino Energy Range

Where our data is able to constrain the source spectrum

- The source spectrum is modelled with an unbroken powerlaw:

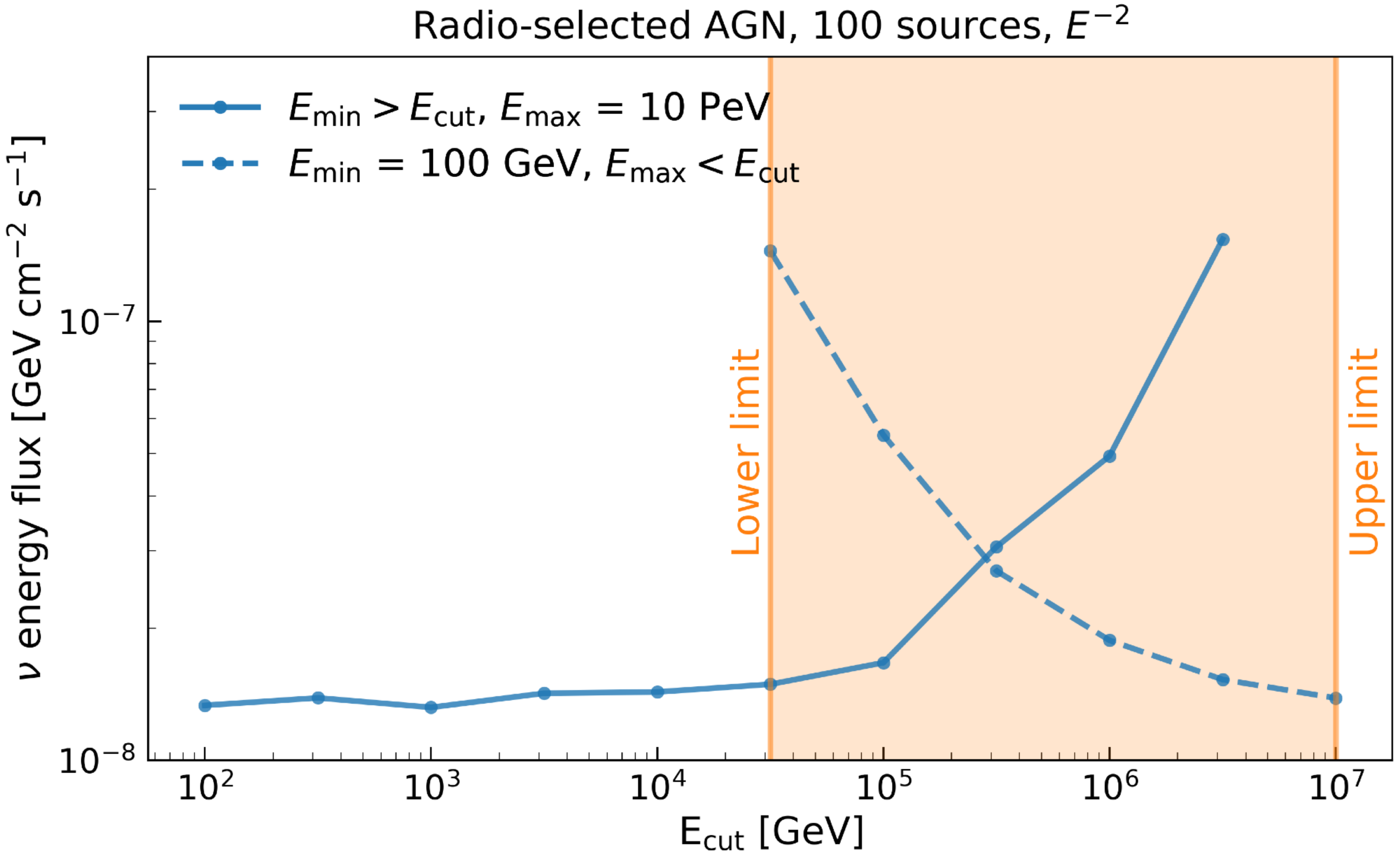
$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

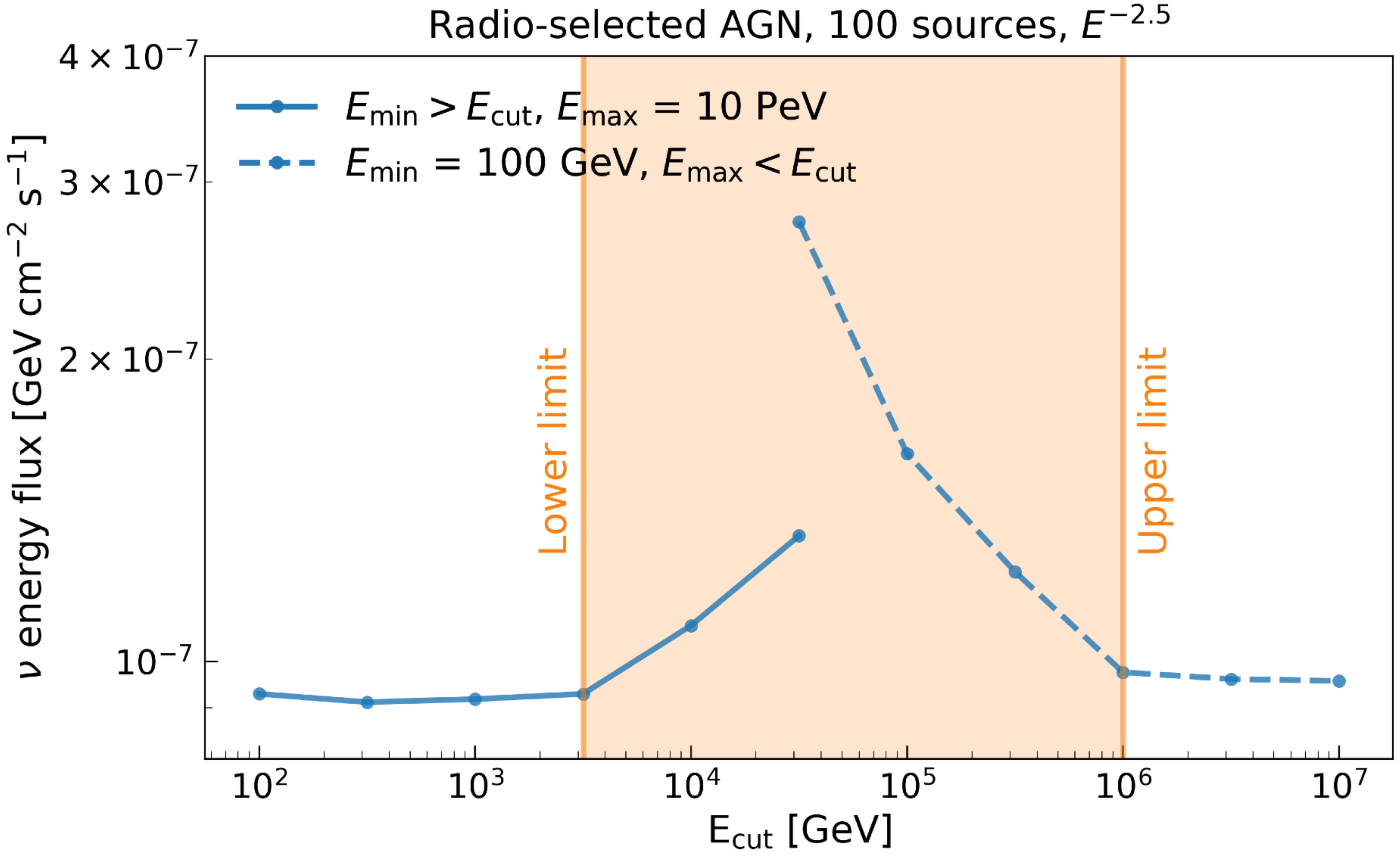
- This PDF has support on [E_0, + inf]
- But we can measure neutrinos only in a limited energy range **[E_{min}, E_{max}]**



Neutrino Energy Range

By progressively changing the energy range limits of injected neutrino signal





[30 TeV, 10 PeV] **[3 TeV, 1 PeV]**