Neutrinos from AGN cores

Federica Bradascio
for the IceCube Collaboration
ICRC 2019, 27 July

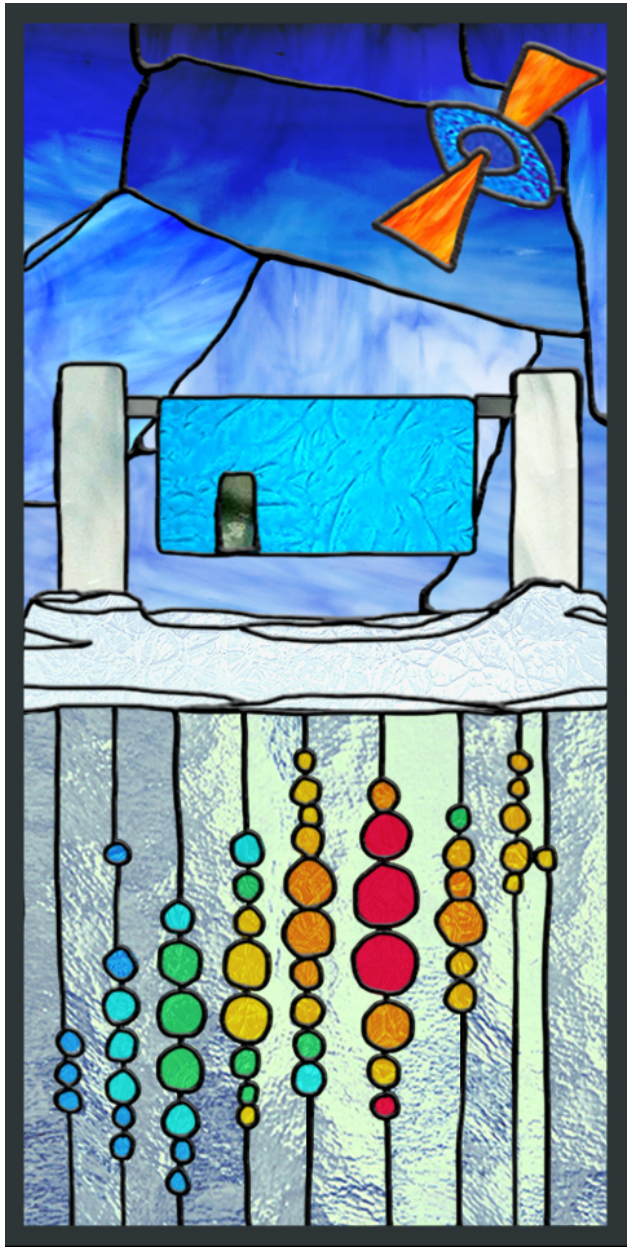
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Cosmic neutrinos

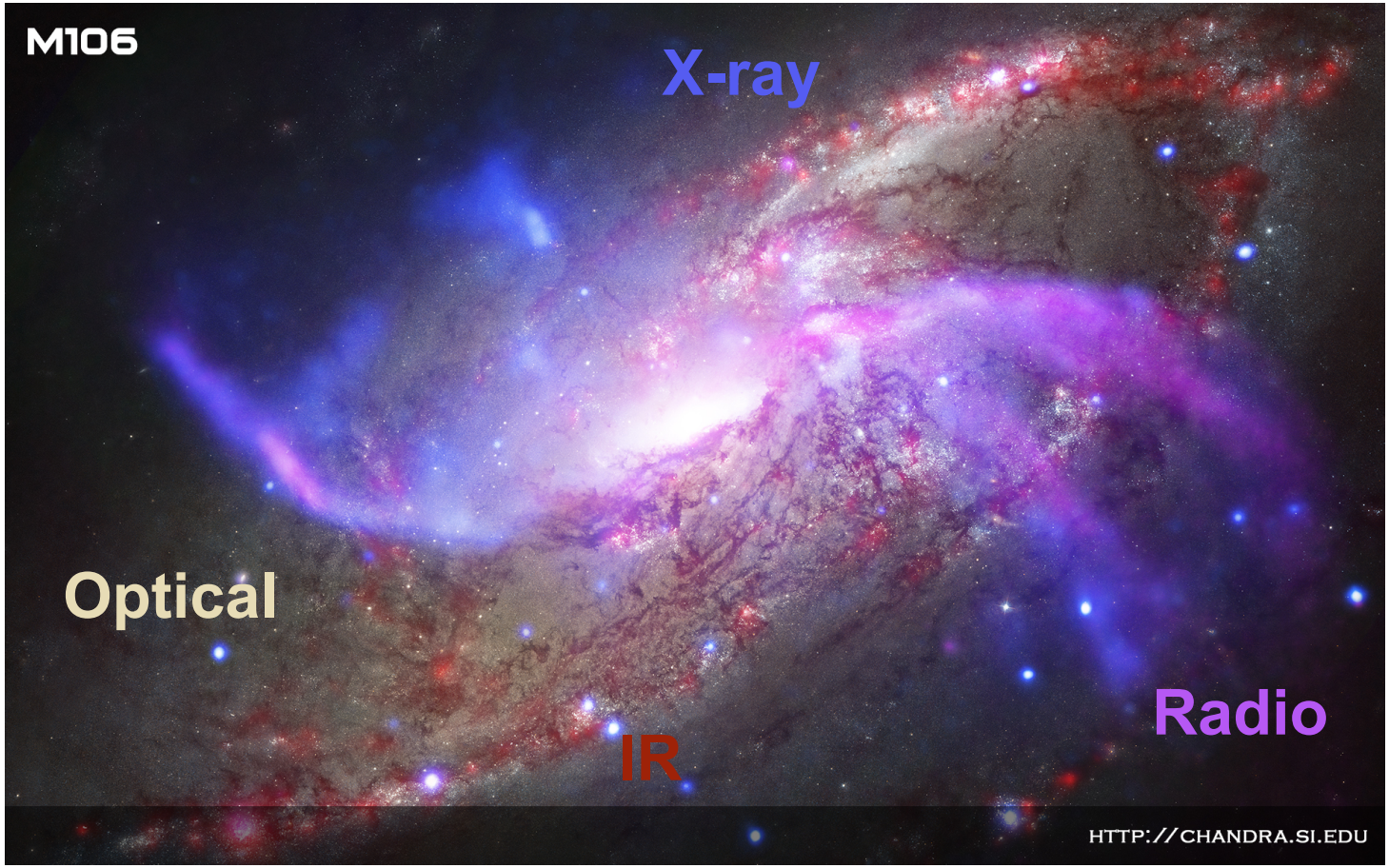
IceCube hunt for the sources

- Diffuse TeV-PeV neutrino flux of unknown origin
- First compelling evidence of neutrino emission from a flaring blazar
- *Fermi*-LAT blazars can only be responsible for a small fraction of the observed neutrinos



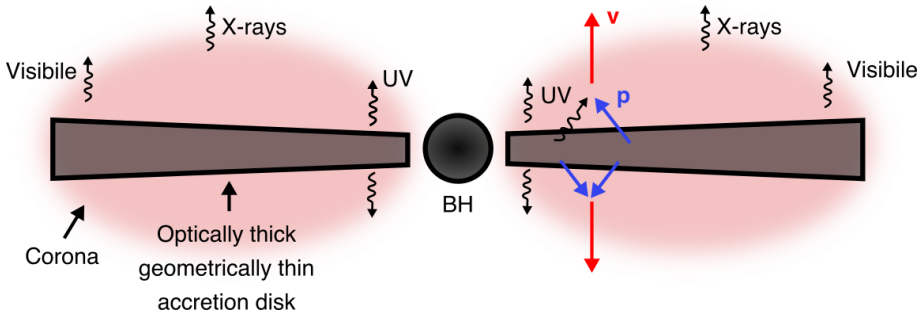
AGN cores

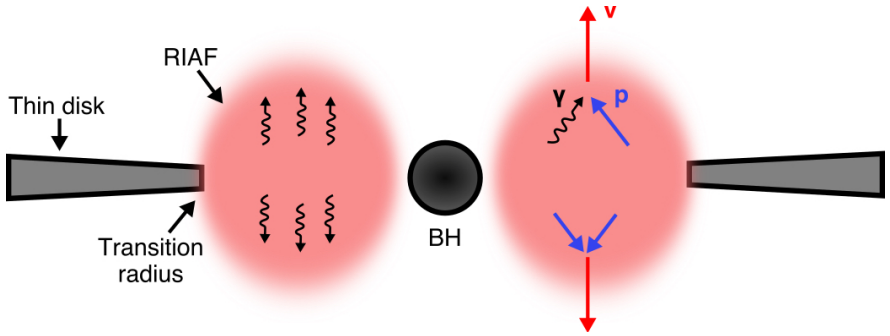
Prime candidates for neutrino production



Neutrinos from AGN Accretion Disks

Two models to test





AGN with Shakura-Sunyaev accretion disk

[Stecker et al. 1991, Kolashev et al. 2015]

Low Luminosity AGN with RIAF (Radiative Inefficient Accretion Flows)

[Kimura, Murase & Toma 2015]

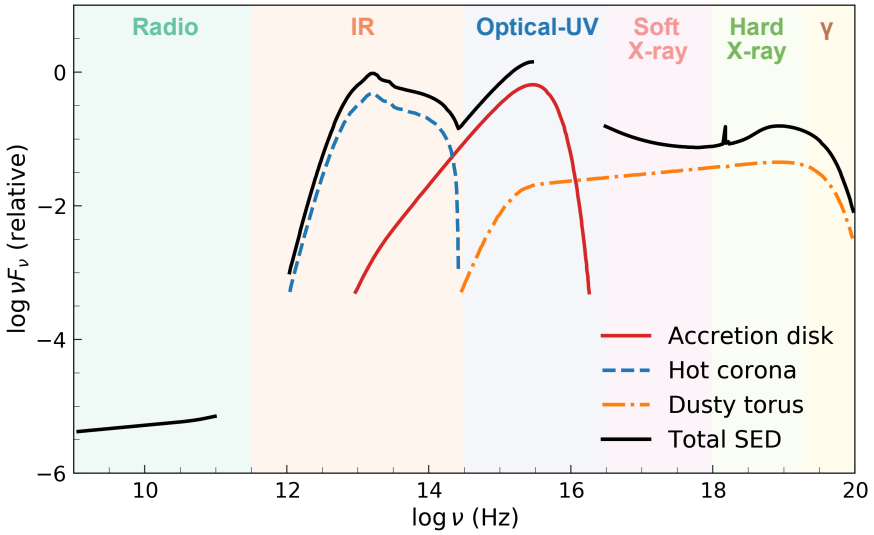
Both *pγ* and *pp* interactions should occur

>10 GeV gamma-rays do not escape

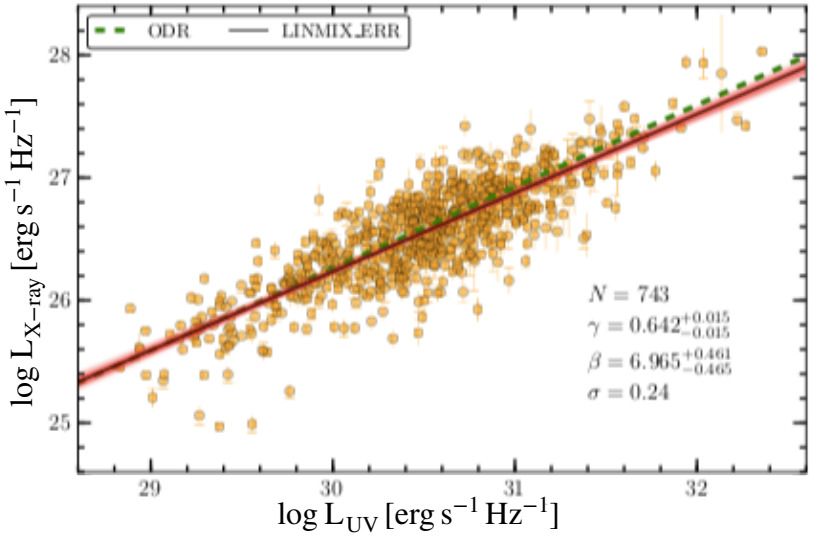
Which wavelength for AGN cores?

X-ray emission as neutrino flux proxy

Padovani et al. 2017



E. Lusso & Risaliti 2016

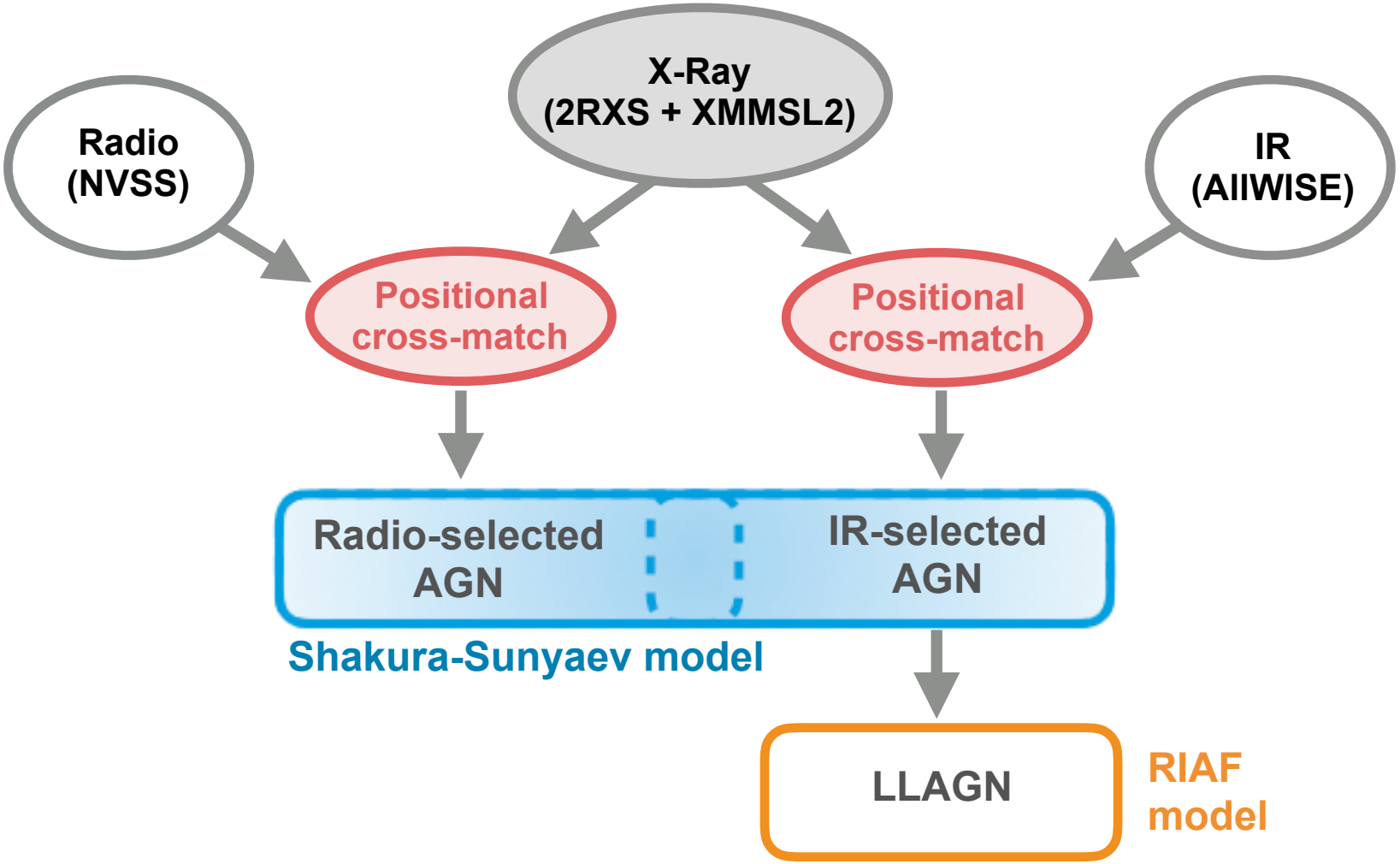


Accretion disk emission peaks at UV wavelength

Tight relationship between X-ray and UV–optical emission

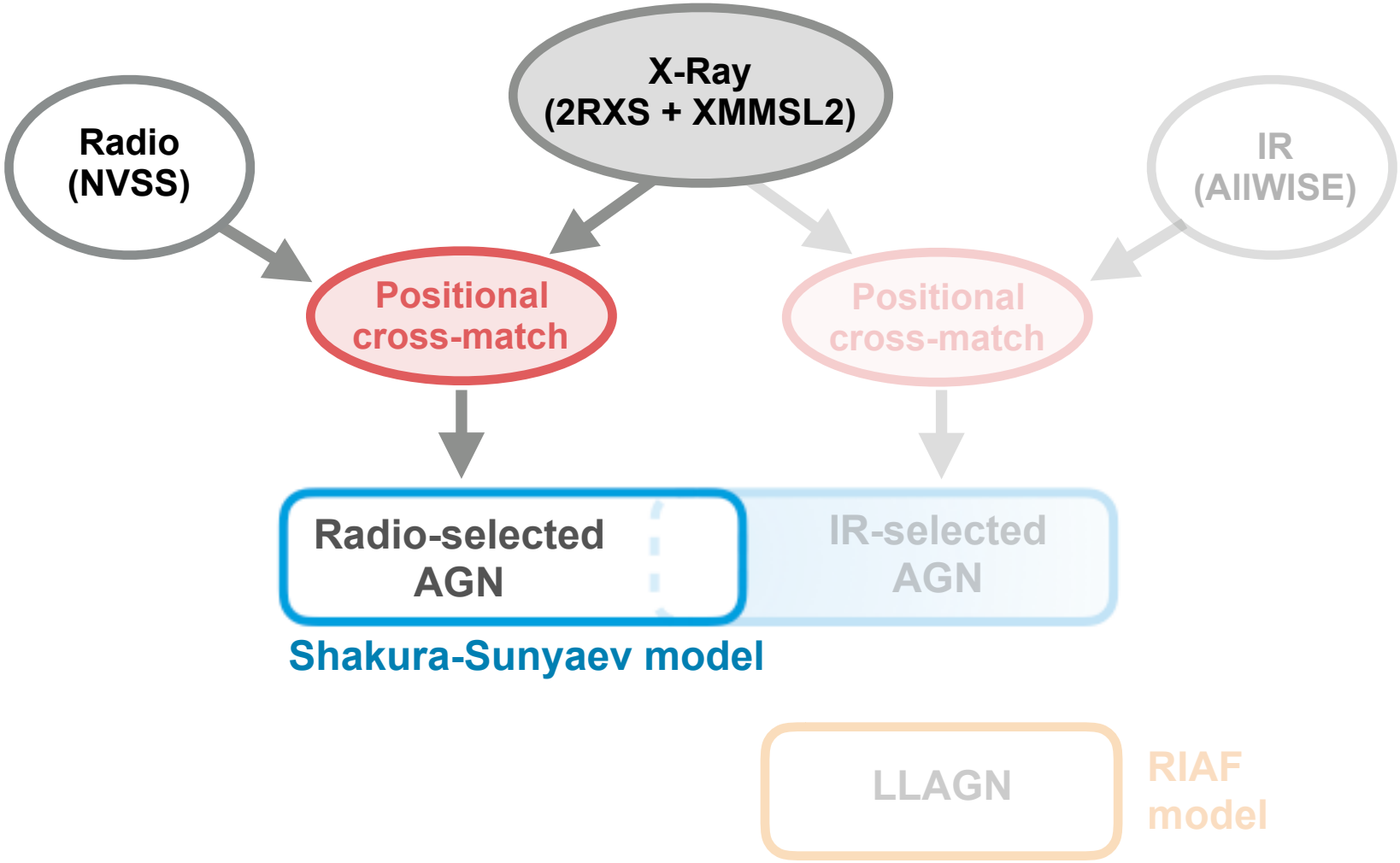
NEUTRINO LUMINOSITY → **ACCRETION DISK LUMINOSITY** → **UV LUMINOSITY** → **X-RAY LUMINOSITY**

Creation of the AGN samples



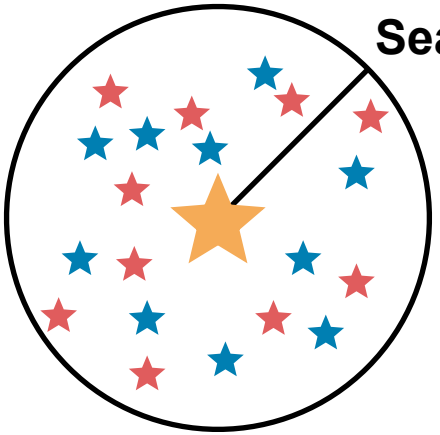
3LAC *Fermi*-LAT blazars are removed in all samples

Radio-selected AGN

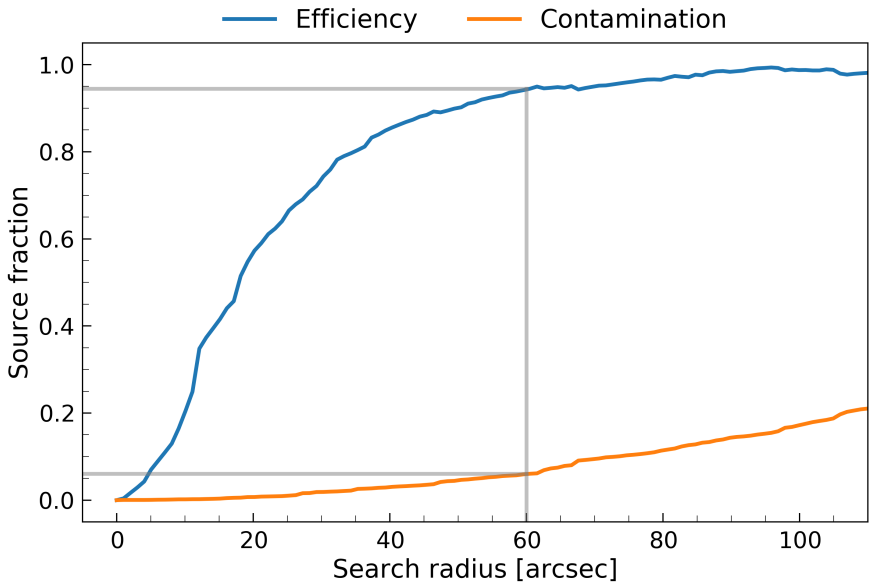


Radio-selected AGN

Through X-ray and Radio positional cross-match



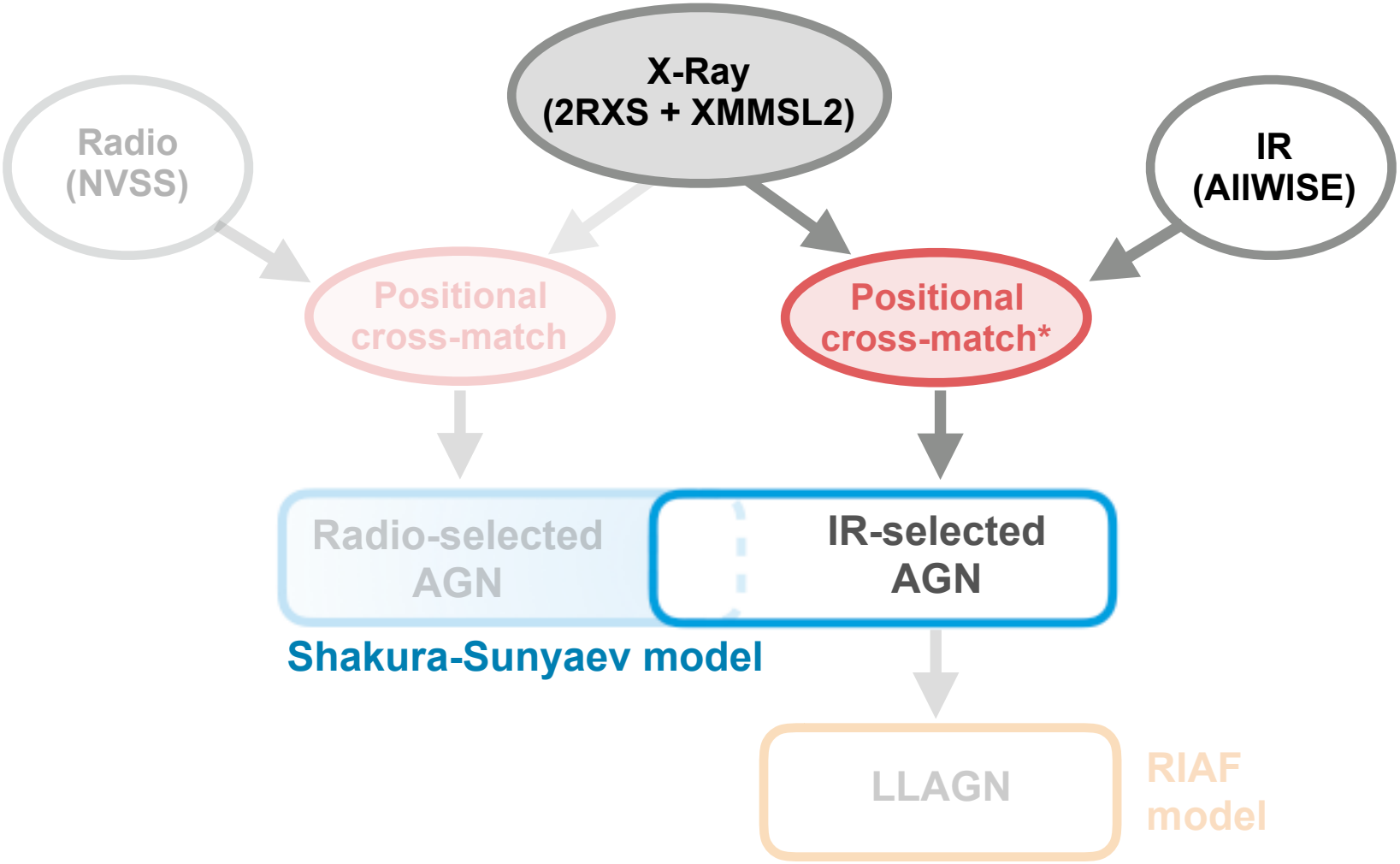
X-ray source
NVSS sources
Random sources



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

Contamination ≃ 5%
Efficiency ≃ 94%

IR-selected AGN

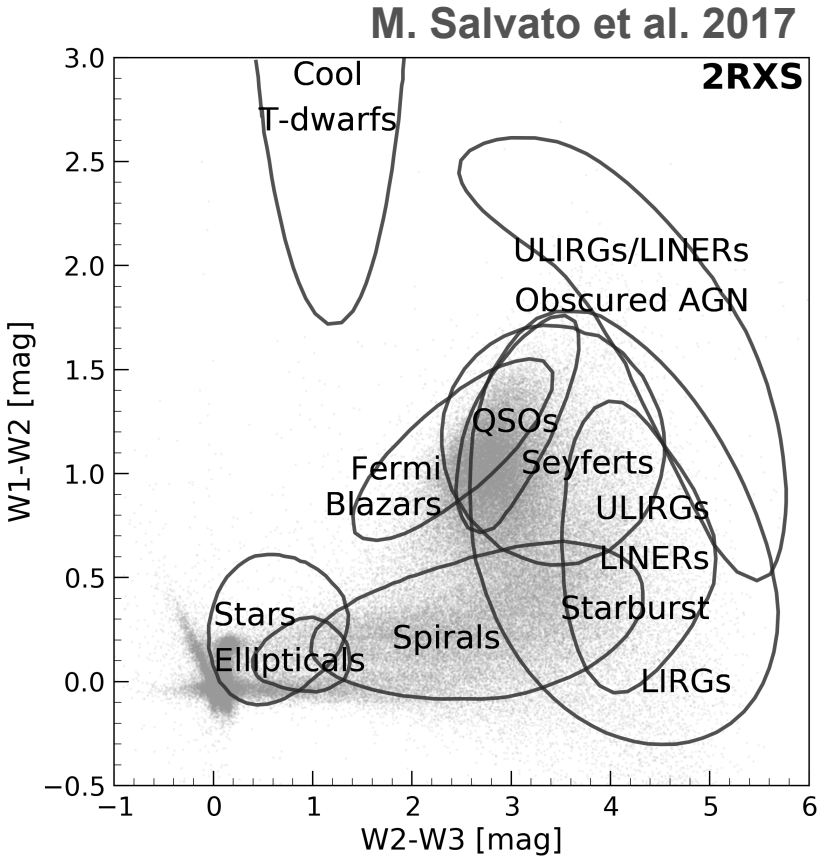


* From Salvato et al. 2017 (already cross-matched)

IR-selected AGN

Through X-ray and IR correlation

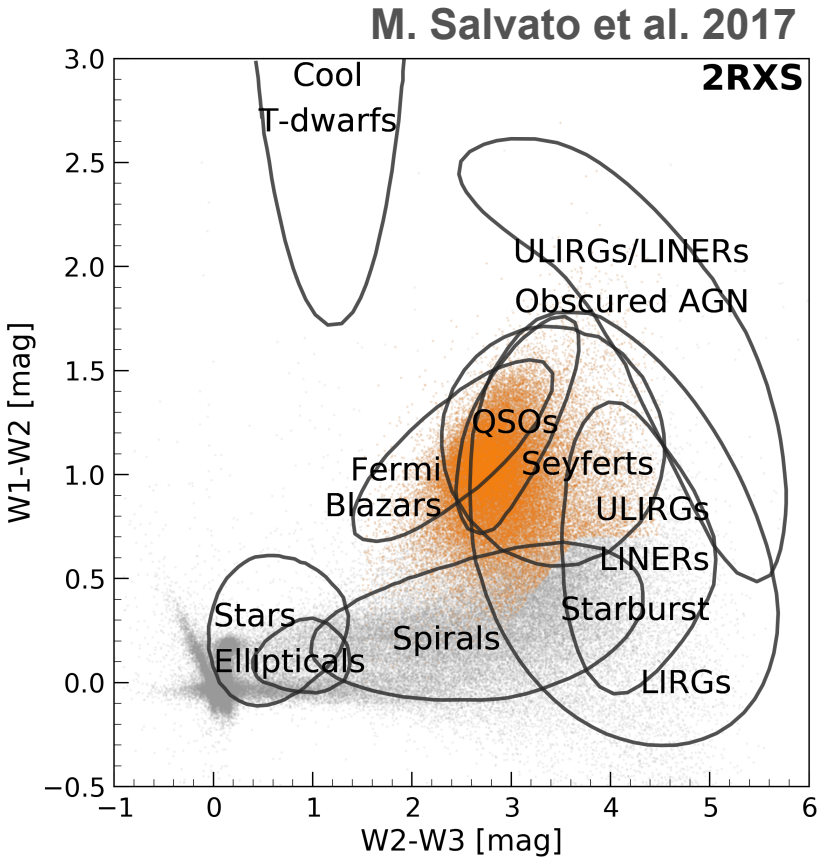
- Use IR color-color diagram to select AGN
- Use AGN classification from existing AGN catalogue **[Véron et al. 2010]**
- Remove 3LAC blazars



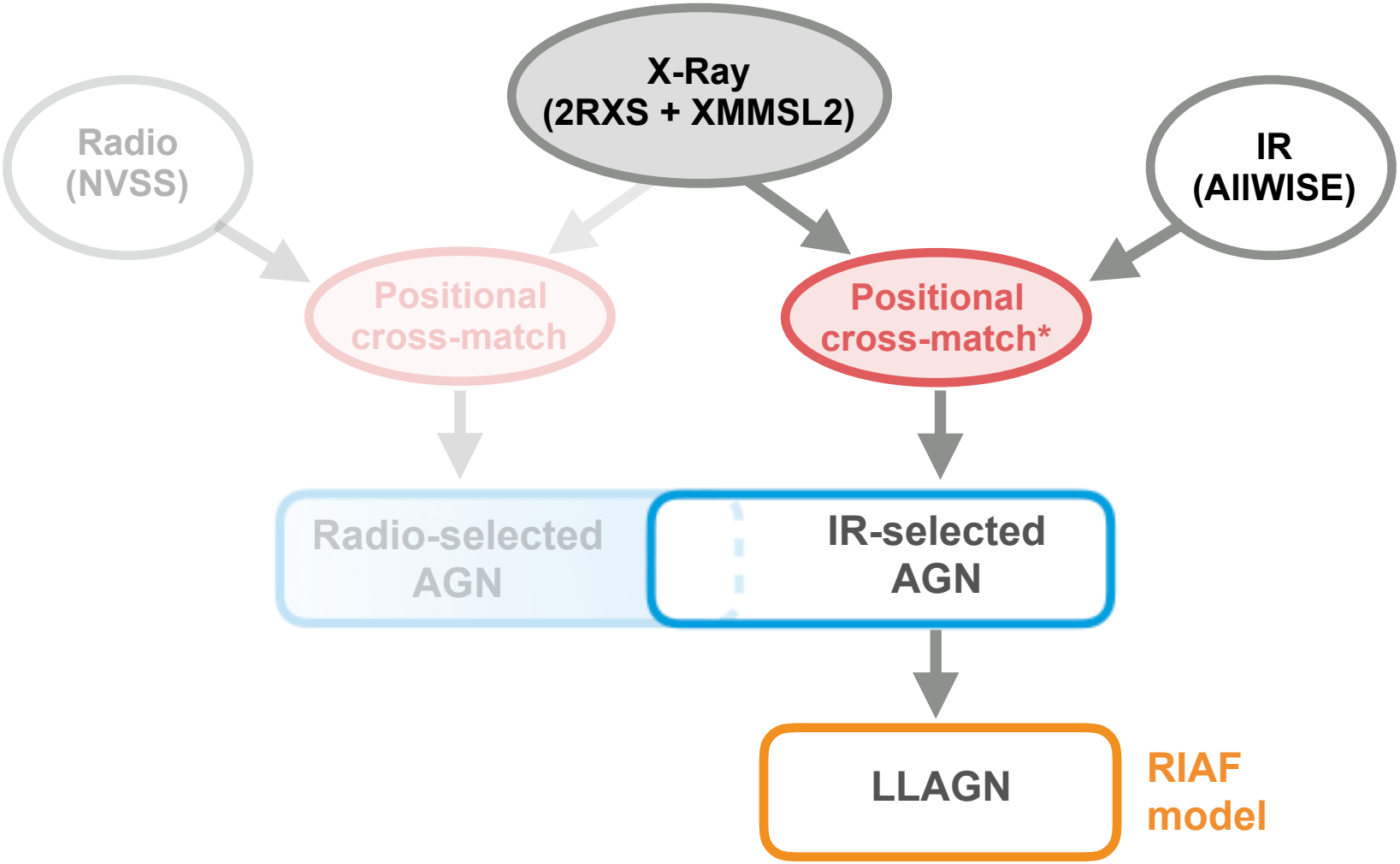
IR-selected AGN

Through X-ray and IR correlation

- Use IR color-color diagram to select AGN
- Use AGN classification from existing AGN catalogue **[Véron et al. 2010]**
- Remove 3LAC blazars



LLAGN

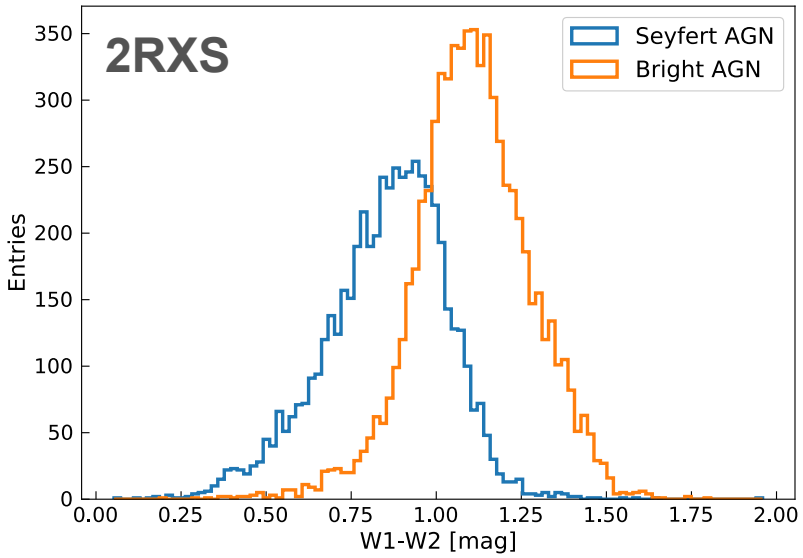


* From Salvato et al. 2017 (already cross-matched)

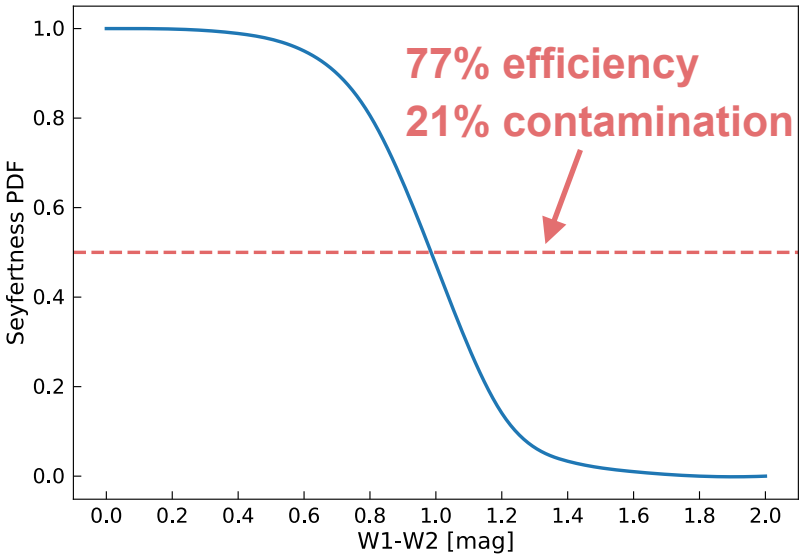
LLAGN (Seyfert Galaxies)

Through X-ray and IR correlation + Seyfertness PDF

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



Seyfertness assigned to each source

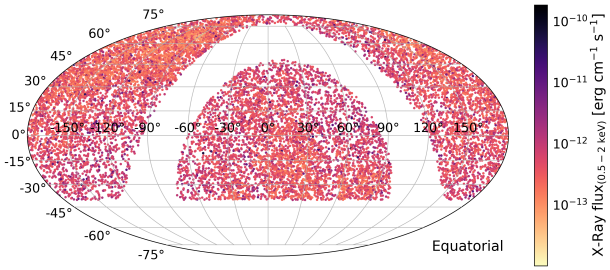


$$\text{Seyfertness} = \frac{P(\text{Seyf})}{P(\text{Seyf}) + P(\text{Bright})}$$

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

AGN final sample

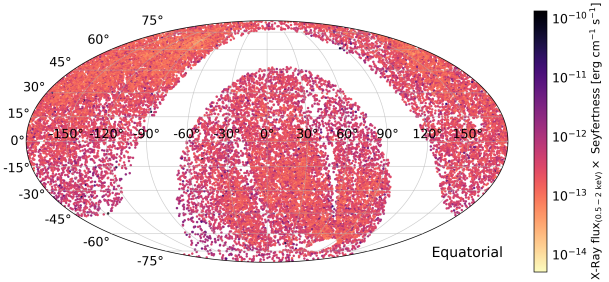
Radio-selected AGN



13,927 sources

X-ray flux

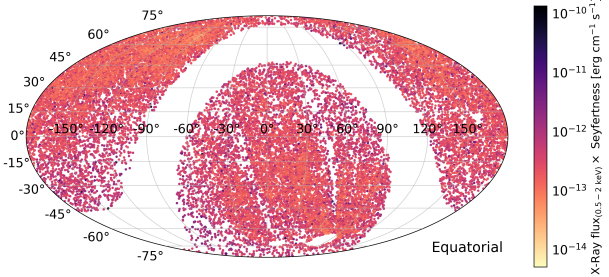
IR-selected AGN



52,835 sources

X-ray flux

LLAGN



25,648 sources

X-ray flux × Seyfertness

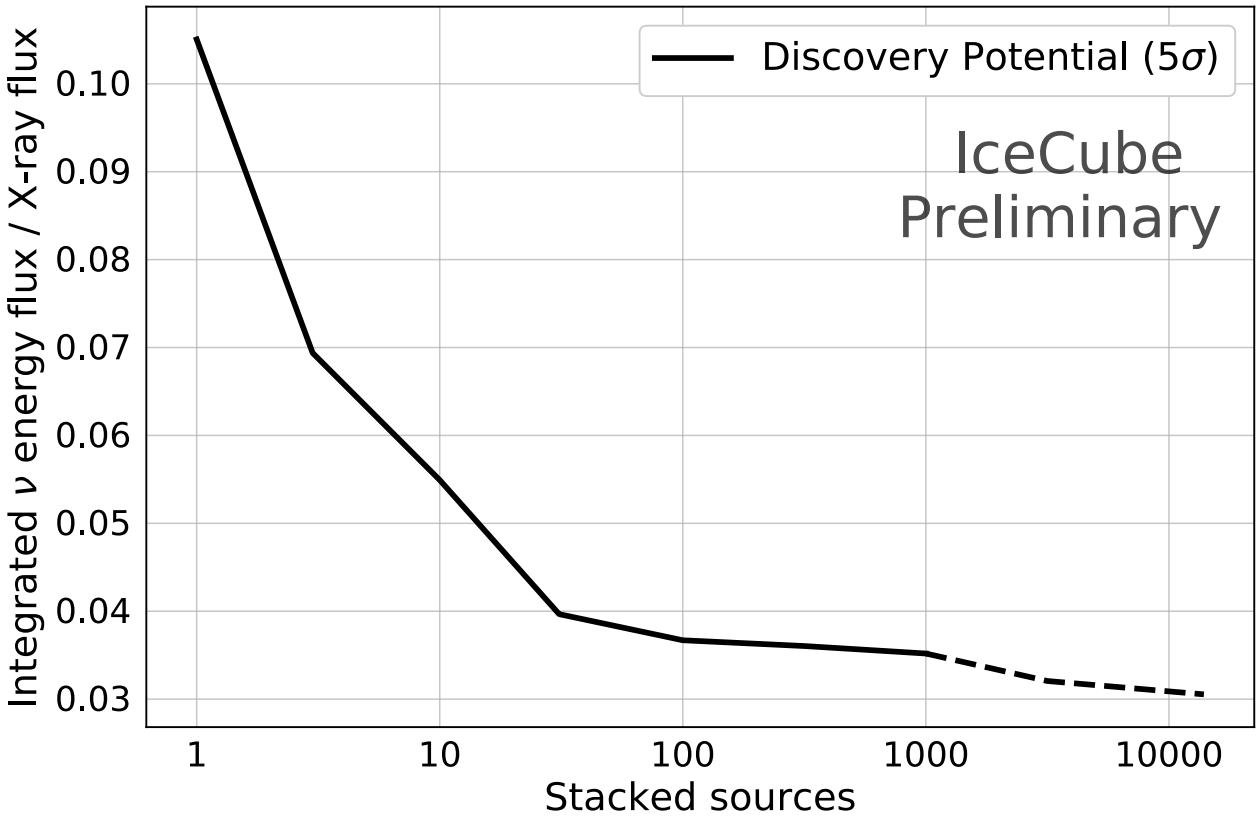
Stack the emission of all sources → **Very large samples** → **Weighting is the key!***

* Or using a **template analysis** [see talk NU3a by S. Sclafani]

Radio-selected AGN sample

Discovery potential study

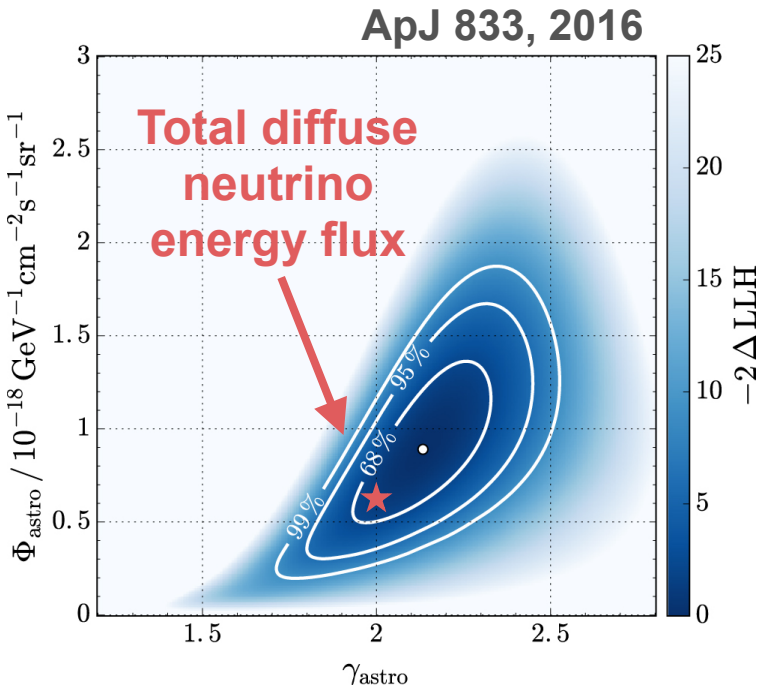
- 10 years of IceCube data [see talk NU5c by T. Carver]
- Injected neutrinos from E^{-2} spectrum

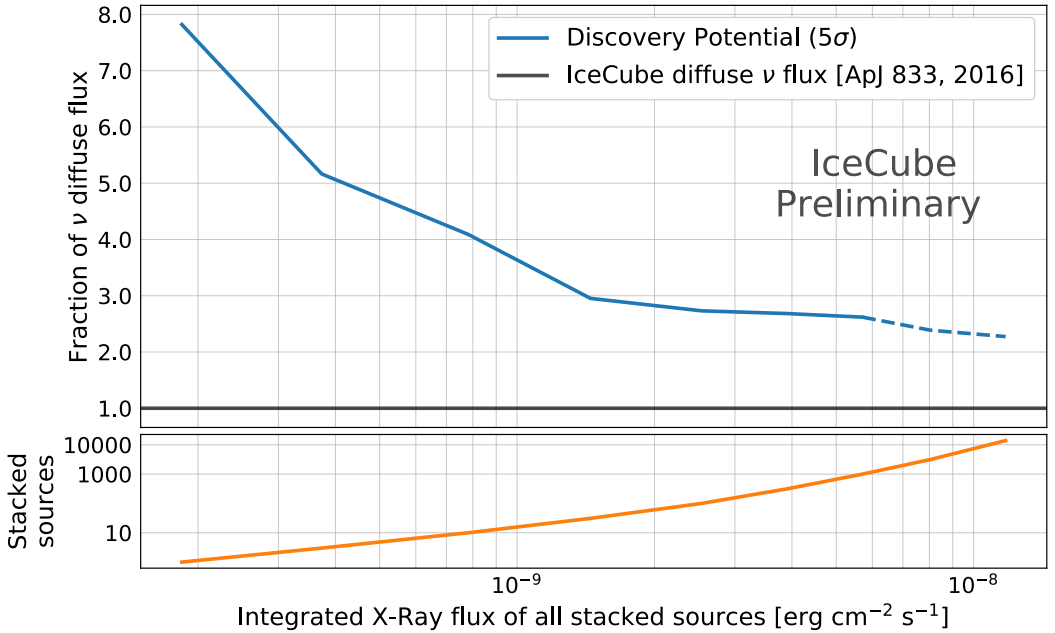


Fraction of diffuse neutrino flux

By accounting also for AGN not making it into the sample

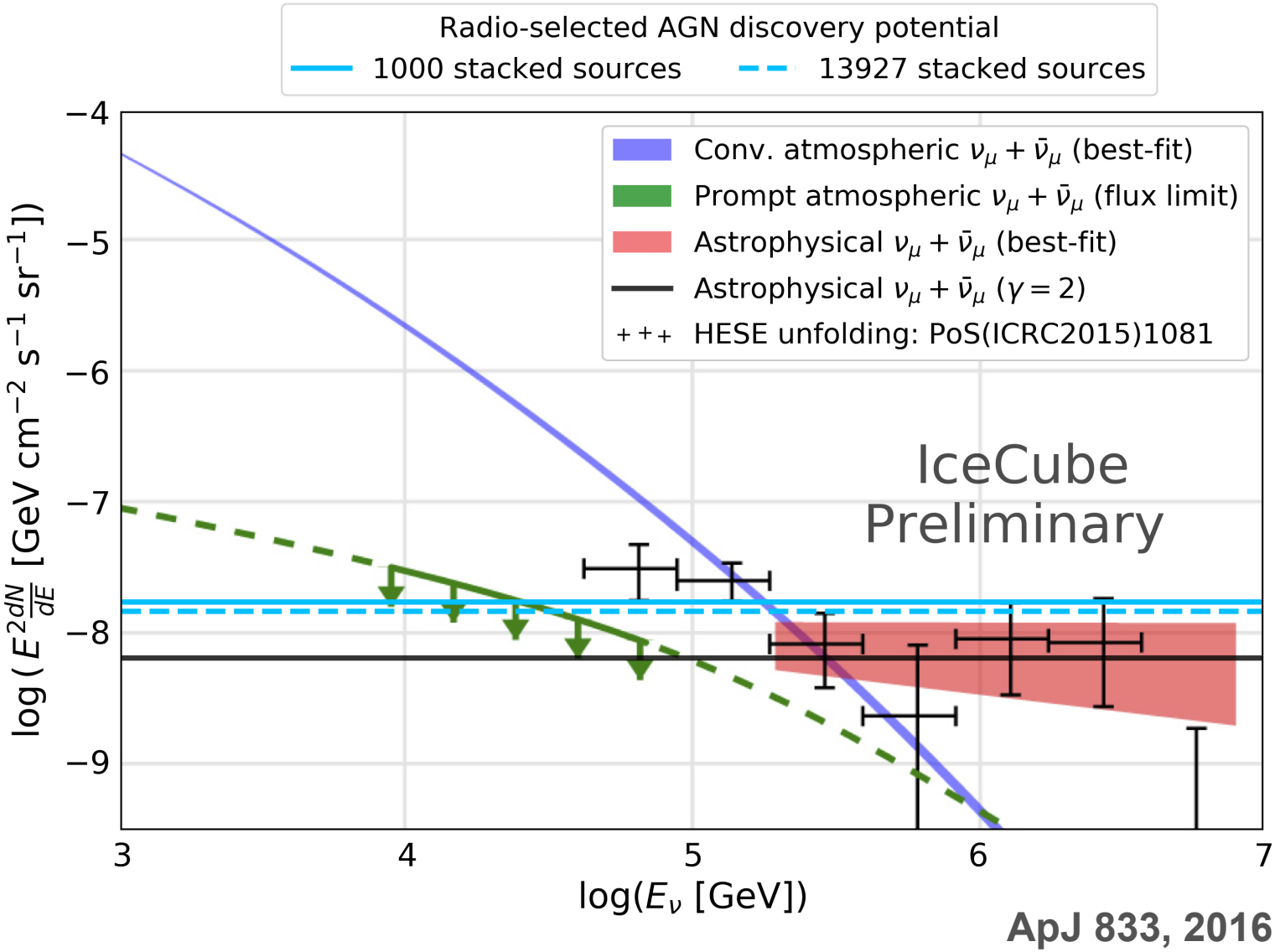
$$\text{Fraction of diffuse } \nu \text{ flux} = \frac{\dfrac{\nu \text{ energy flux}}{\text{X} - \text{Ray flux}}}{\dfrac{\text{Total diffuse } \nu \text{ energy flux}}{\text{Total AGN flux}}}$$





What fraction of the neutrino flux would the AGN have to produce in order for a discovery to be made?

How do we compare to the diffuse neutrino flux?

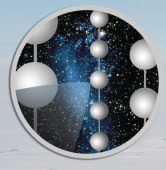


ApJ 833, 2016

Conclusions

- Search for neutrinos from:
  - AGN with Shakura-Sunyaev accretion disk
  - LLAGN with Radiative Inefficient Accretion Flows (RIAF)
- 3 AGN samples created based on radio emission, IR color properties and X-ray flux
- Sensitive to γ=2 radio-selected AGN sample from NVSS+2RXS+XMMSL2, but no discovery expected
- Remaining two samples and additional γ will be tested in the future

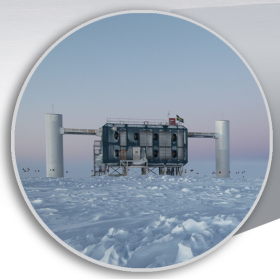
Backup



IceCube

South Pole Neutrino Observatory

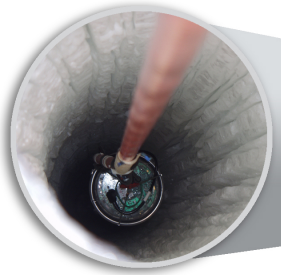
50 m



IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

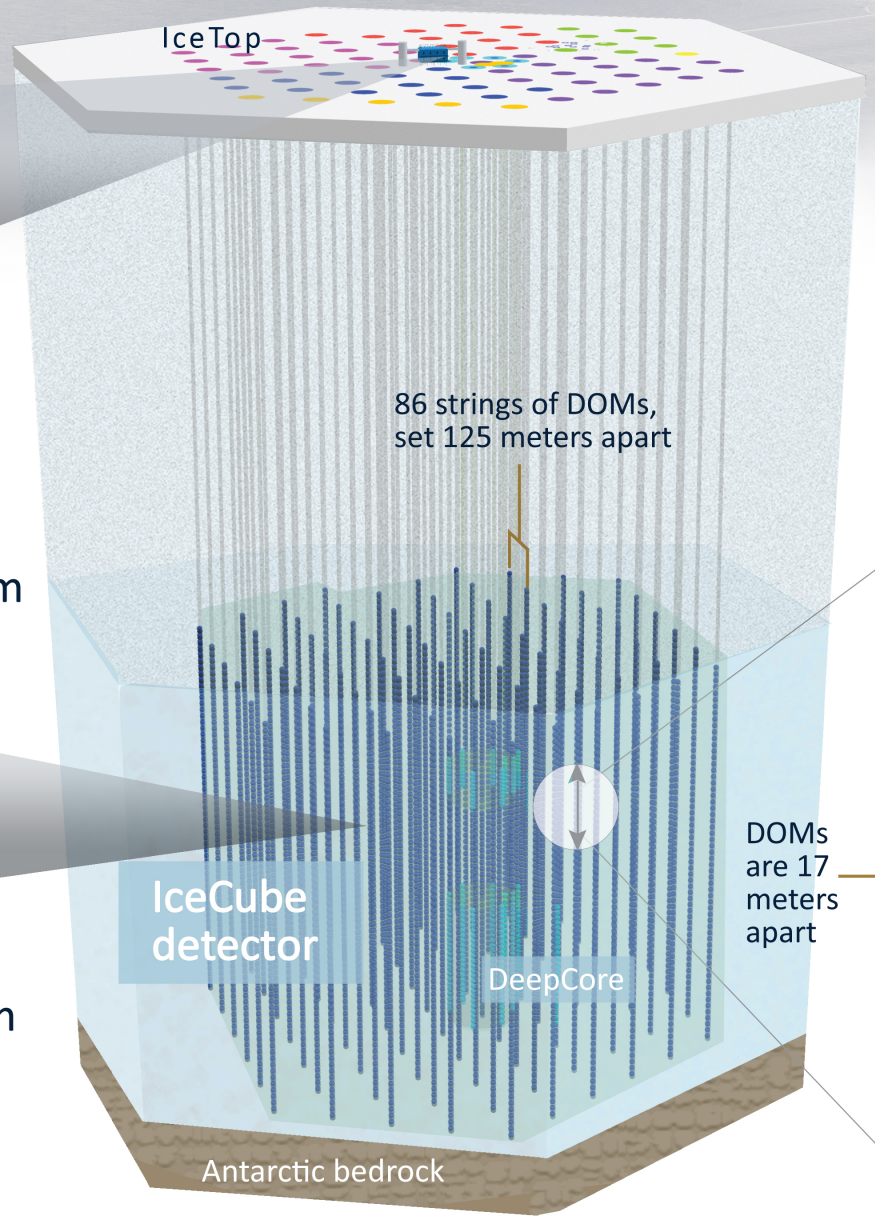
1450 m

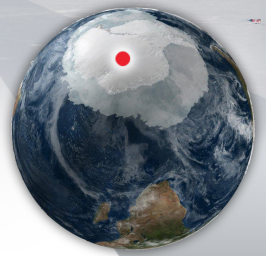


Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m





Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart

Catalogues used for selection

Radio

NVSS

- 10^3 sr of sky north of δ=-40 deg
- 1.4 GHz radio survey
- 1.8 x 10^6 sources
- Positional error ~45”

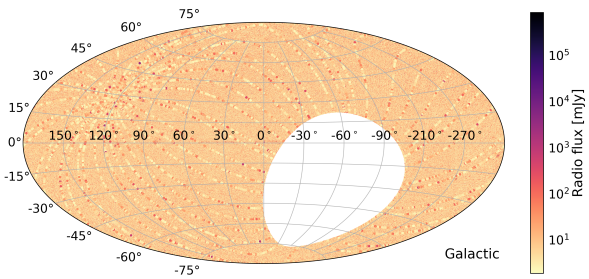
X-ray + IR

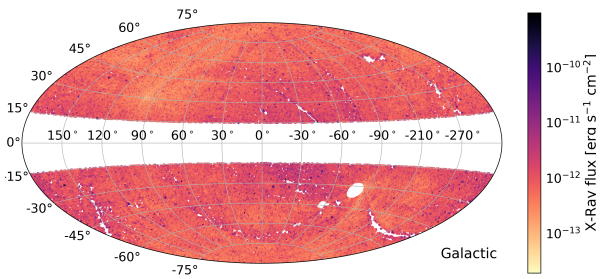
2RXS + AllWISE

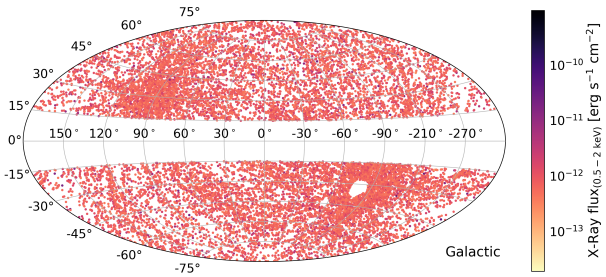
- All sky survey
- 0.1 - 2.4 keV energy range
- 106,573 sources
- Positional error ≤ 60”

XMMSL2 + AllWISE

- Slew survey
- 0.2 - 12 keV energy range
- 17,665 sources
- Positional error ≤ 50”



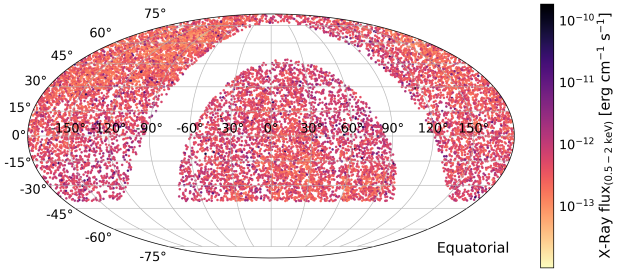




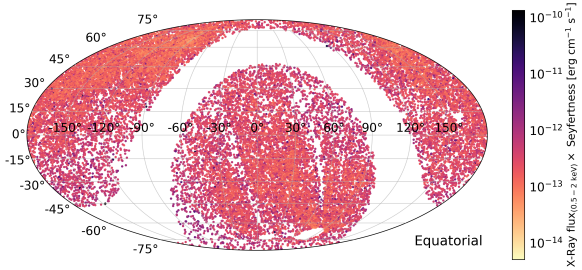
Catalogues from **M. Salvato et al., 2017**

AGN final samples

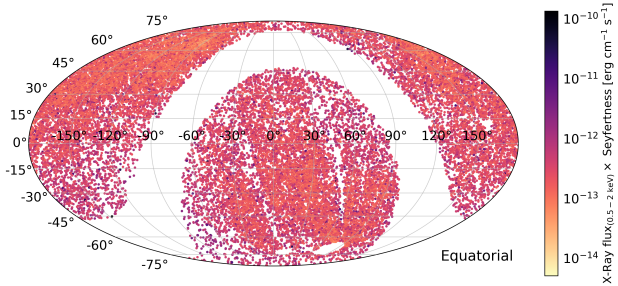
Radio-selected AGN



IR-selected AGN



LLAGN

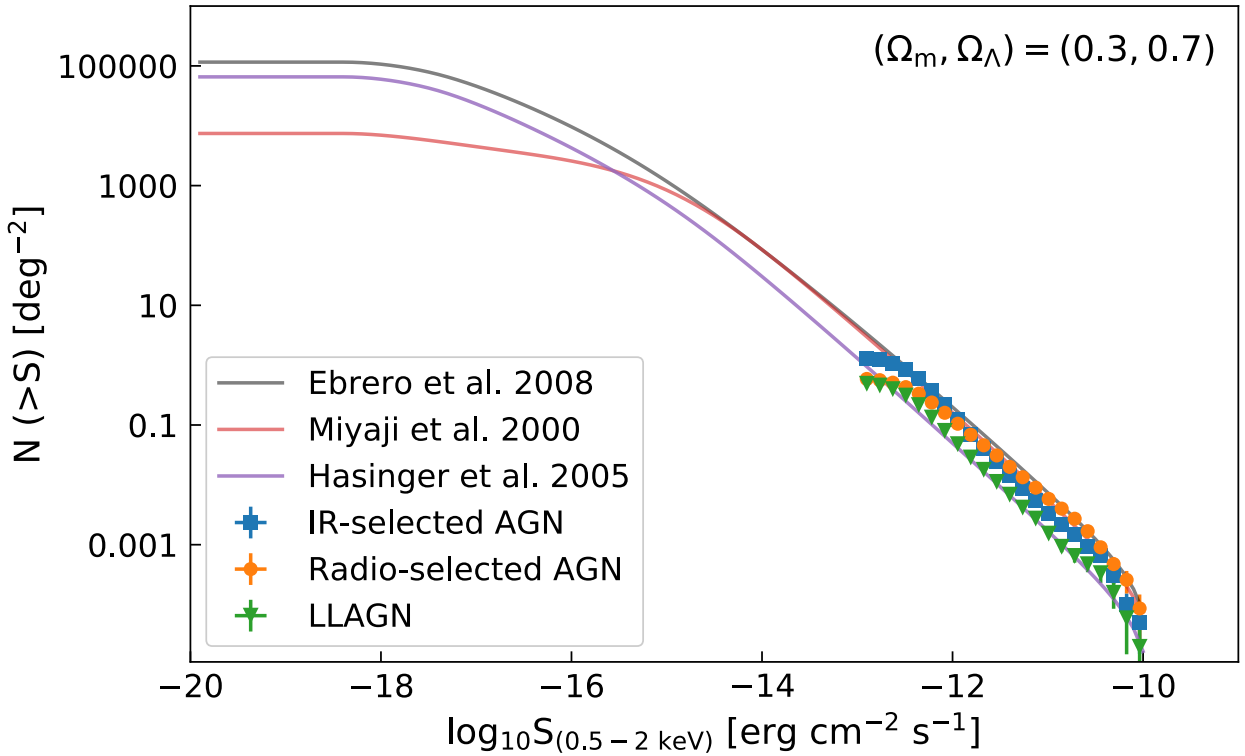


	Radio-selected AGN	IR-selected AGN	LLAGN
Matched catalogues	NVSS + 2RXS + XMMSL2	AllWISE + 2RXS + XMMSL2	2RXS + AllWISE
Sky Coverage	52%	82%	82%
Nr. of sources	**13,927**	**52,835**	**25,648**
Weight	X-ray flux	X-ray flux	X-ray flux × Seyfertness

Completeness of the samples

Correct for the samples' bias

- Account for sources not making in the samples
- Estimated total AGN X-ray flux expected from all AGN in the entire Universe
- Use X-ray luminosity function



Method: Stacking Analysis

Unbinned likelihood analysis

Test the combined emission of all sources to identify neutrinos from a population

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

N number of events in sample
n_s number of signal events
$B(x_i)$ signal PDF (constructed from data)
x_i data events (direction, energy)
γ signal spectral index
$S(x_i, \gamma)$ signal PDF (constructed from MC)

- Assume a power-law energy spectrum for the signal: $dN/dE \propto E^{-\gamma}$
- Signal PDF of all M AGN sources stacked together, weighted by w_k:

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

Method: Stacking Analysis

Likelihood ratio test as test statistic

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

Sensitivity:

Signal required to obtain $p \leq 0.5$ in 90% of the trials

Discovery Potential:

Signal required to obtain $p \leq 5.73 \times 10^{-7}$ (5σ) in 50% of the trials