UPPSALA
UNIVERSITET

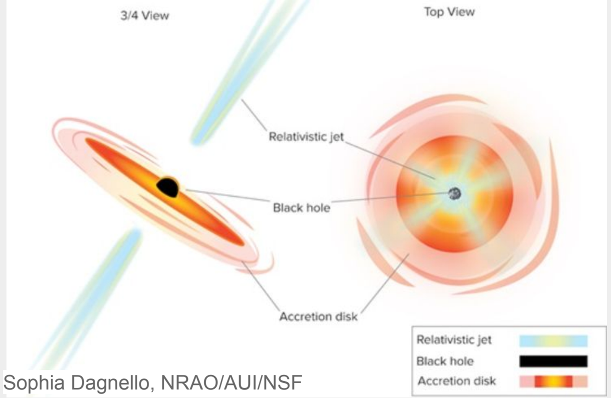
Testing the blazar sky visible to IceCube

Adithya S
2nd February

Project guide-
Ankur Sharma,
Antonio Marinelli

ICECUBE

What are Blazars?



Sophia Dagnello, NRAO/AUI/NSF

- Class of AGN with the relativistic jets pointed towards the Earth
- Intrinsically variable; short to long duration flares in diff. wavelengths

❖ **Observations of gamma ray flaring of blazar TXS0506+056 coincident with high energy IceCube neutrino IC-170922A**

- Jets - Broadband emission
- Broadline region- Optical, UV and soft X-rays

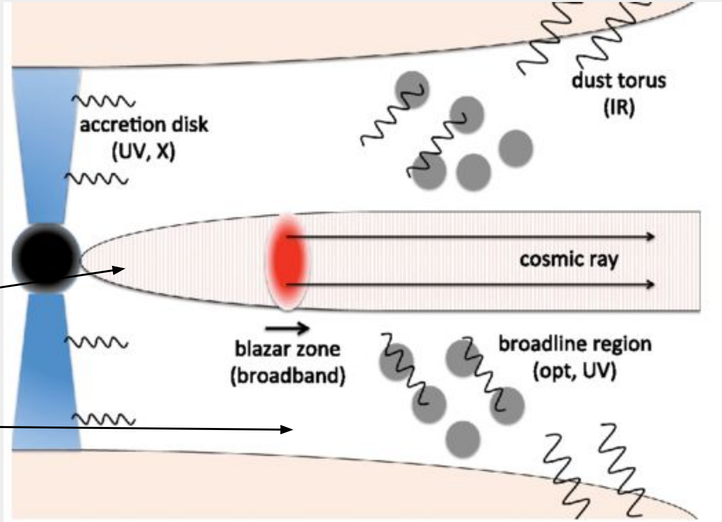


Image source - Murase et al, Phys. Rev. D 90, 023007 (2014).

Neutrino production in Blazars

- Blazar SED has 2 distinct peaks

$$p\,\gamma \to \pi^o,\ \pi^{+/-} \to \gamma + \nu_l + l$$

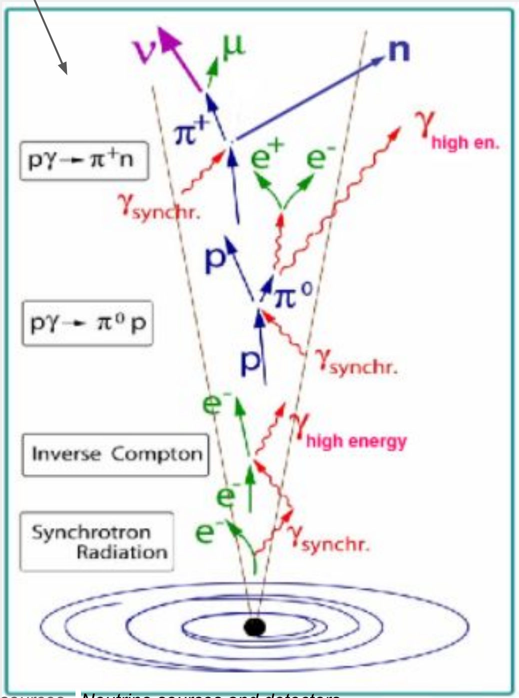
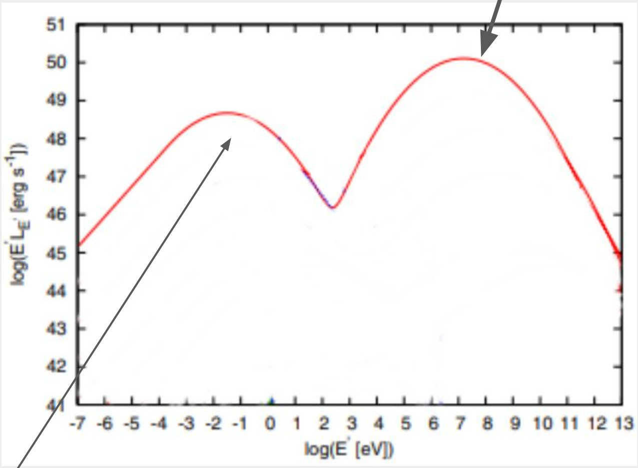


Image sources - Neutrino sources and detectors

- *Leptonic Models* - High energy peak - compton upscattering of synchrotron e-

- *Lepto-Hadronic Models*
  High energy peak can have contributions from hadronic/proton sync. γ rays

- Target photons for pγ interactions can be internal or external to the jet



Low energy peak - electron synchrotron emission

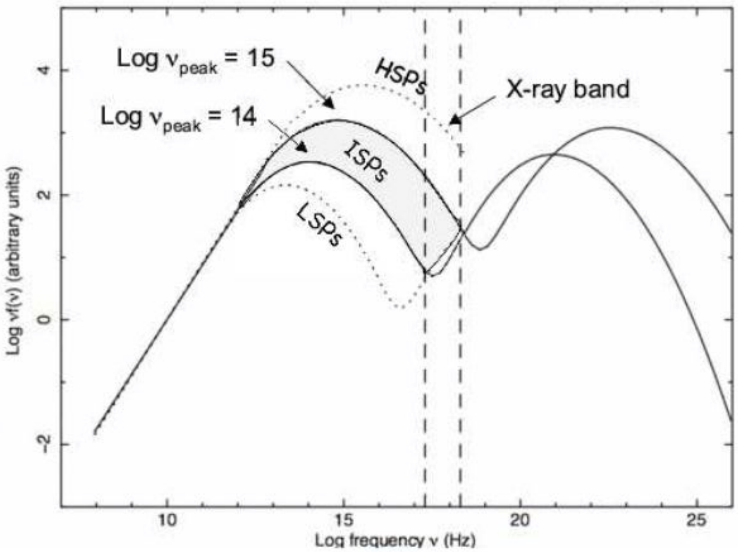
Types of Blazars

Based on difference in **optical spectrum**

- BL Lacs - Weak emission lines in optical spectrum
- Flat Spectrum Radio Quasars (FSRQs) -
  Strong broad emission lines in optical spectrum

Based on location of **synchrotron peak**

- LSP - $\nu^{s}_{peak} < 10^{14} Hz \mid < 0.4eV$
- ISP - $10^{14Hz} < \nu^{s}_{peak} < 10^{15} Hz \mid 0.4eV < \nu^{s}_{peak} < 4eV$
- HSP - $\nu^{s}_{peak} > 10^{15} HZ \mid > 4eV$



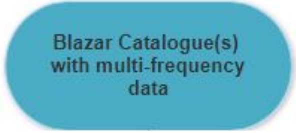
Stevenson, Marc , et al.- The definition of different blazar types based on the peak | Download Scientific Diagram

Project Outline

- Main aim of the project is to see which class of blazars IceCube is more sensitive to
- Compare the diff. sub-classes of blazars (***LSP, ISP, HSP***; ***BL Lacs, FSRQs***)

- Extend the prediction to higher energies by using IceCube Gen2
- sensitivity

prl/10.1103/PhysRevLett.117.241101



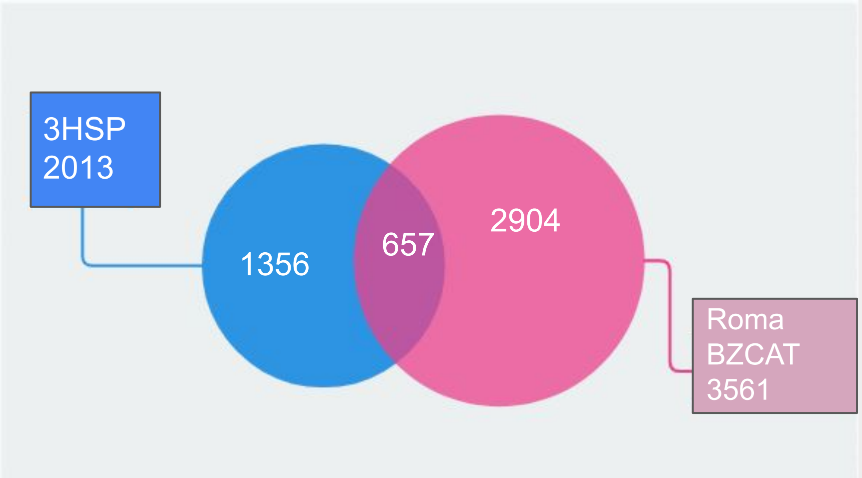
Catalogues under consideration

3HSP blazar catalogue

- Hint for correlation between IceCube neutrinos and HSP blazars {3HSP catalogue}
- Synchrotron peak , redshift and multi-frequency data available
- Contains 2013 blazars
- X-ray data @ 1.0 keV

Roma BZCAT

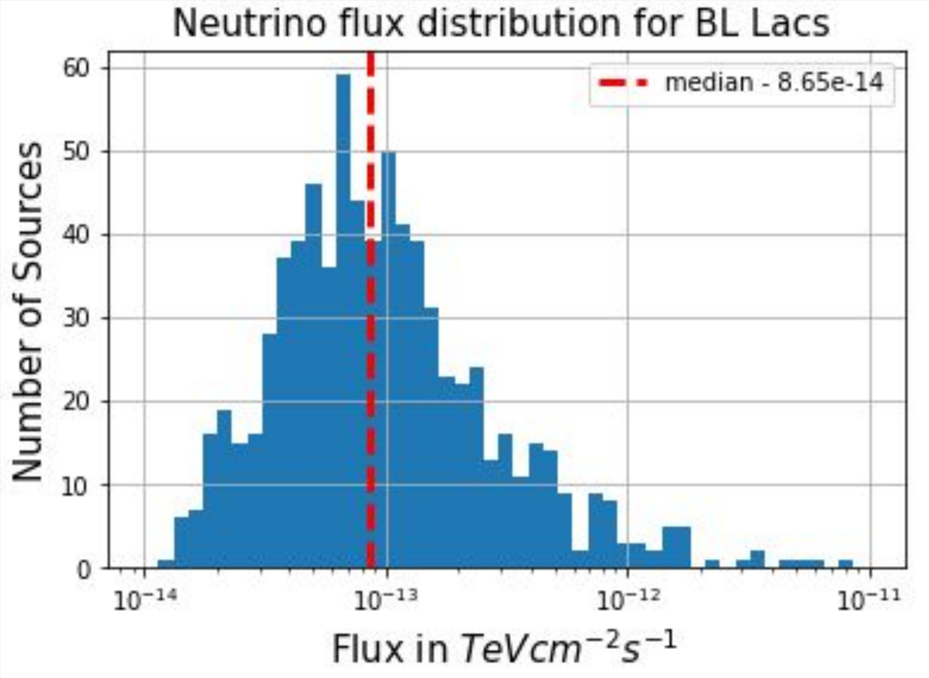
- 3561 blazars with data in X-rays (0.1-2.4 keV), γ - rays (1-100 GeV), Radio waves (1.4GHz)
- BL Lacs - 1285, FSRQs - 1909, BCUs - 367
- Sync. peaks not available

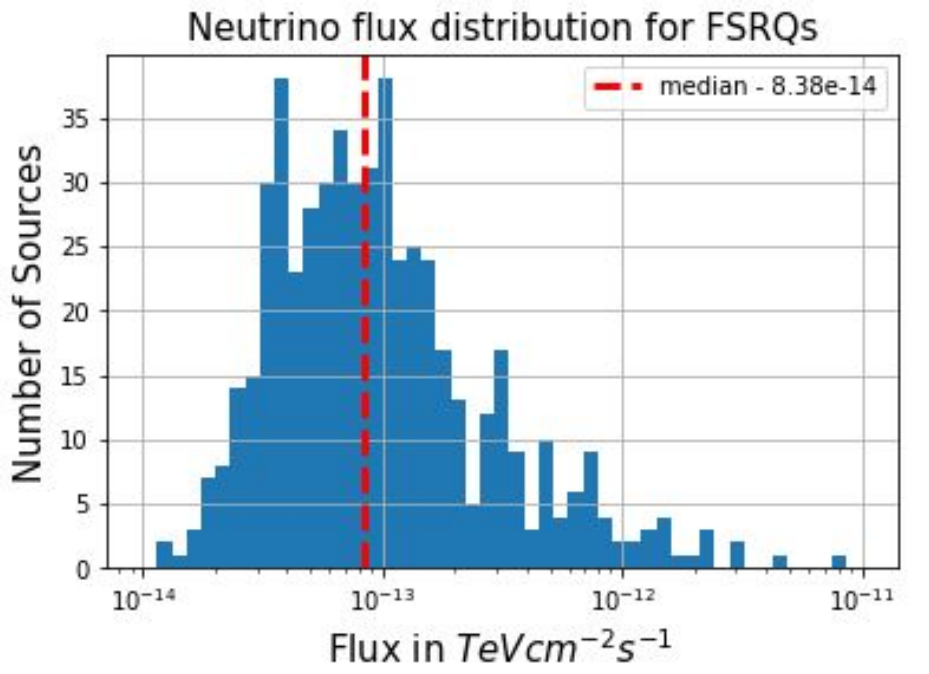


ν flux from γ-ray flux

Roma BZCAT - BL Lacs & FSRQs

$f(\nu)_{(10\ \text{TeV - 10 PeV})} = 0.1 * f(\gamma)_{(50\ \text{MeV - 300 GeV})}$





Roma BZCAT - BL Lacs & FSRQs

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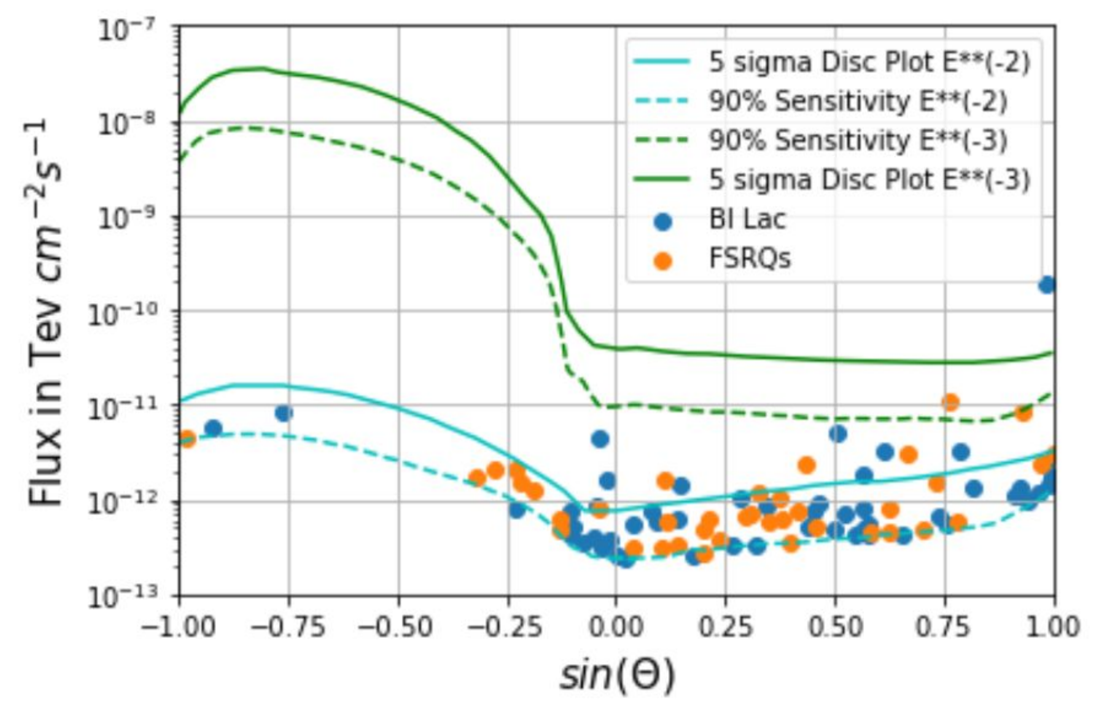


No. of sources with flux > IceCube 90% C.L. sensitivity (E^{-2})

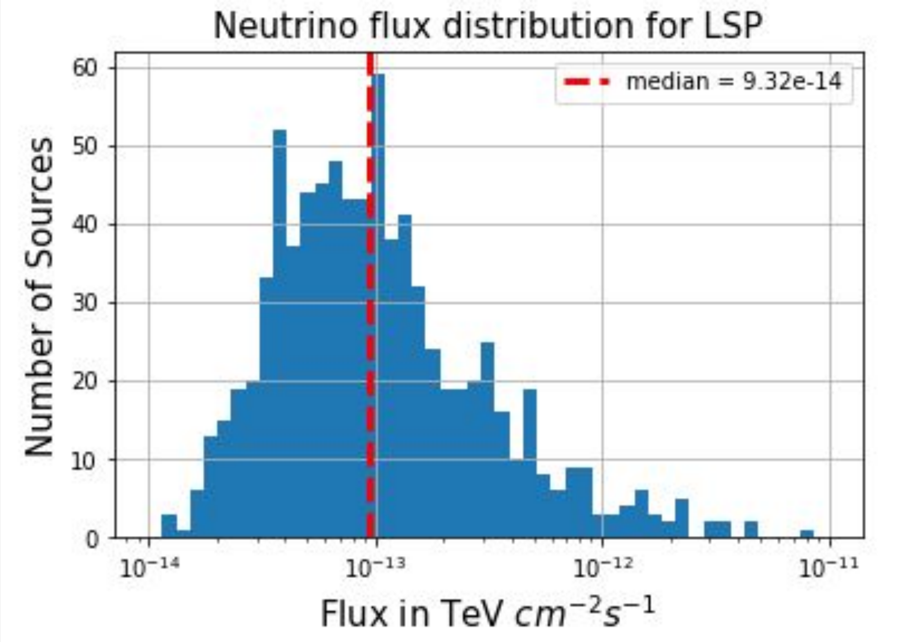
BL Lacs -
78/762 , 11.2%

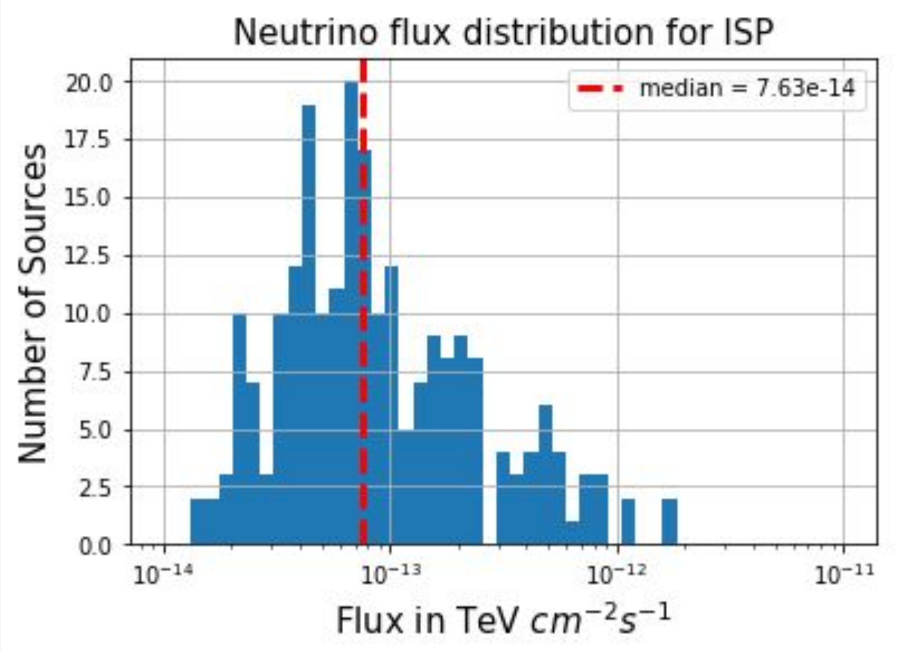
FSRQs -
56/535, 10.4%

No significant difference b/w FSRQs and BL Lacs

Romz BZCAT - LSP, ISP & HSP

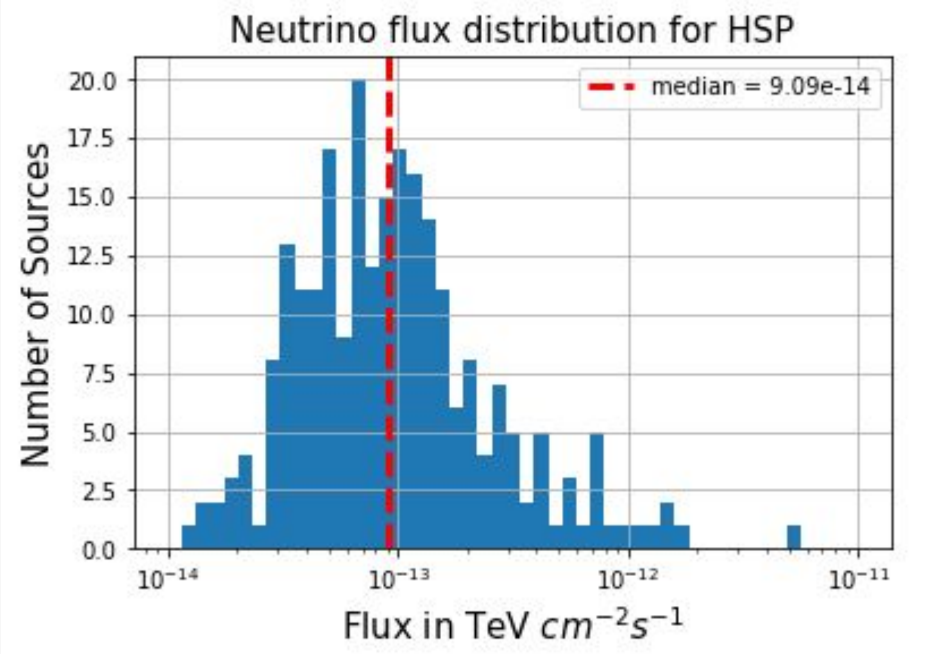
$f(\nu)_{(10\ \text{TeV - 10 PeV})} = 0.1 * f(\gamma)_{(50\ \text{MeV - 300 GeV})}$

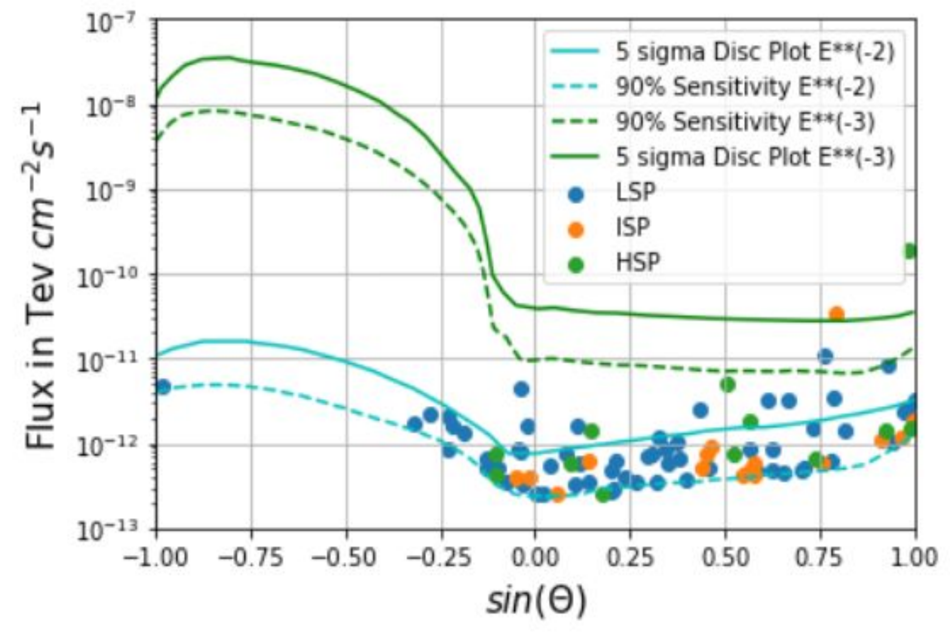




Romz BZCAT - LSP, ISP & HSP

$f(\nu)_{(10\ \text{TeV - } 10\ \text{PeV})} = 0.1 * f(\gamma)_{(50\ \text{MeV - } 300\ \text{GeV})}$





Romz BZCAT - LSP, ISP & HSP

No. of sources with
flux > IceCube 90% C.L. sensitivity (E^{-2})

LSPs -

89/810, 10.98%

ISPs -

21/227, 9.25%

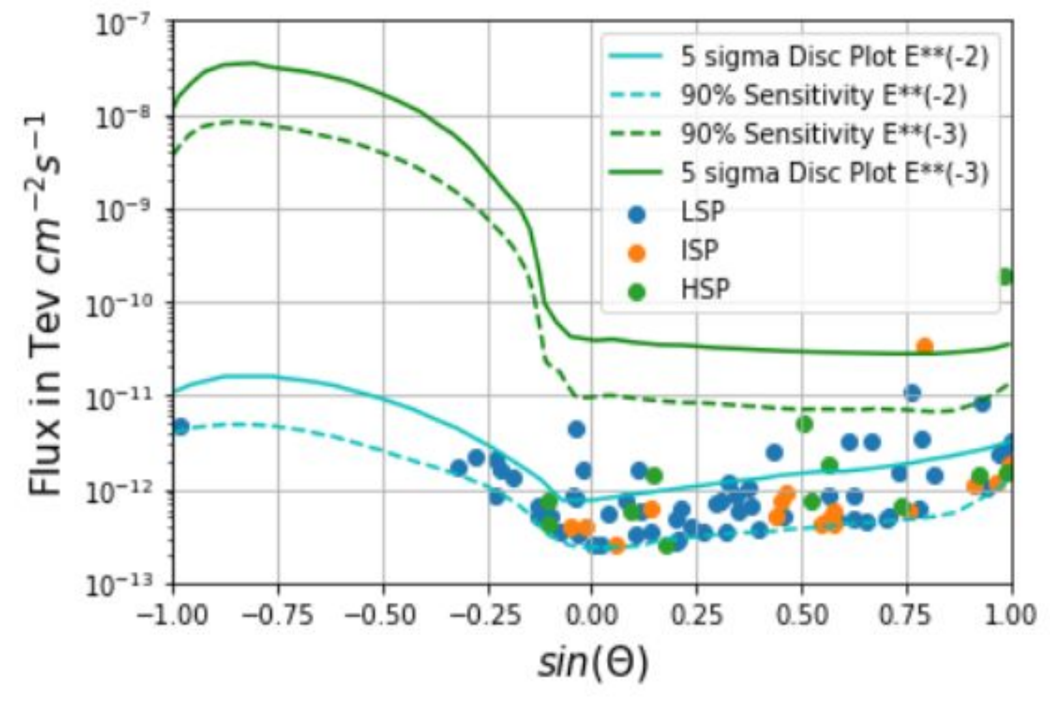
HSPs -

20/243, 8.23%

Total -

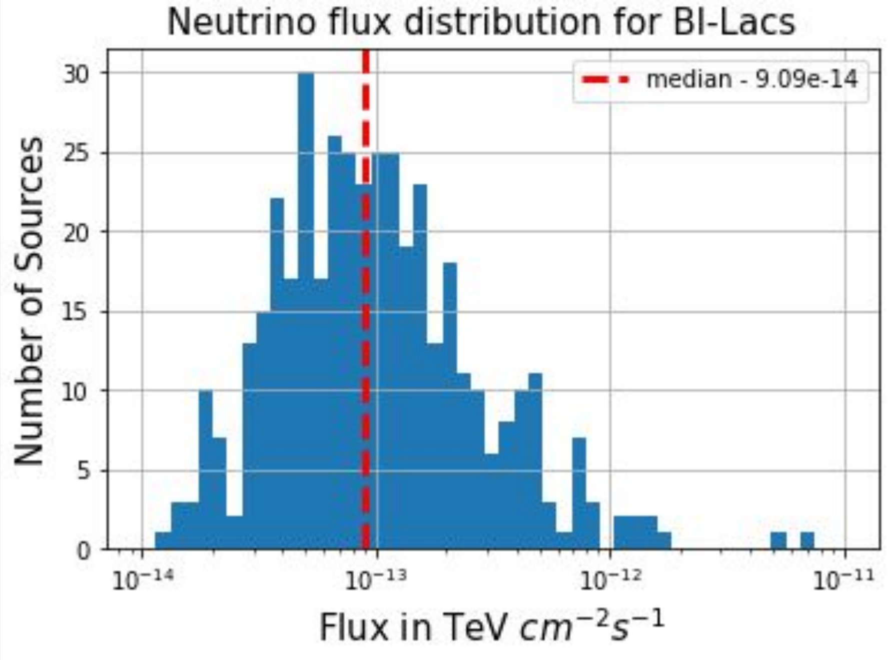
130/1280, 10.15%

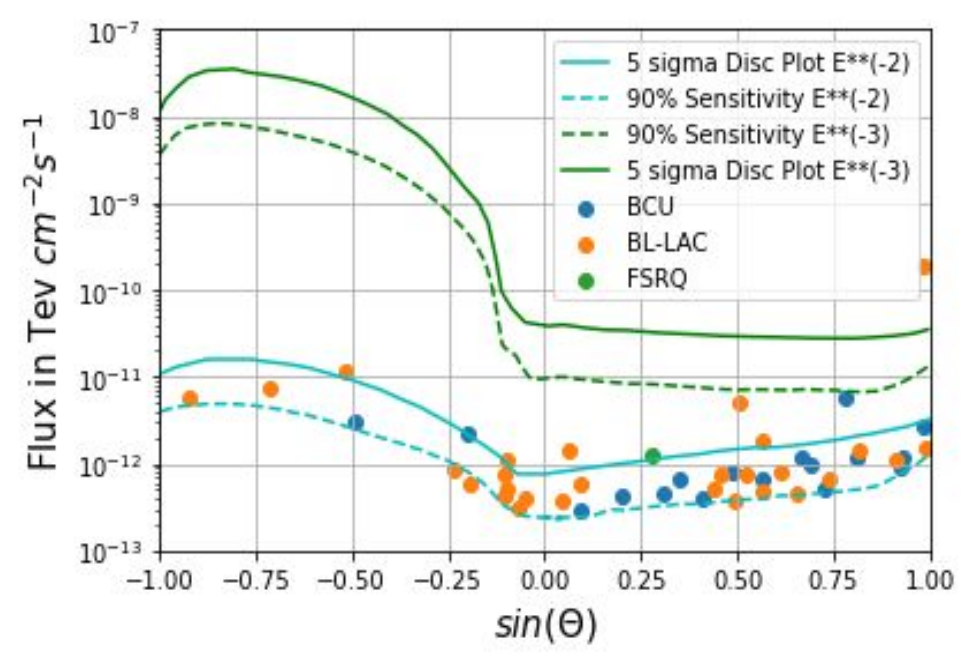
$f(\nu)_{(10\ \mathrm{TeV}\ -\ 10\ \mathrm{PeV})} = 0.1 * f(\gamma)_{(50\ \mathrm{MeV}\ -\ 300\ \mathrm{GeV})}$



3HSP catalog

$$f(\nu)_{(10\ \text{TeV - }10\ \text{PeV})} = 0.1 * f(\gamma)_{(50\ \text{MeV - }300\ \text{GeV})}$$





3HSP catalog

$f(\nu)_{(10\ \mathrm{TeV}\ -\ 10\ \mathrm{PeV})} = 0.1 * f(\gamma)_{(50\ \mathrm{MeV}\ -\ 300\ \mathrm{GeV})}$

No. of sources with
flux > IceCube 90% C.L. sensitivity (E^{-2})

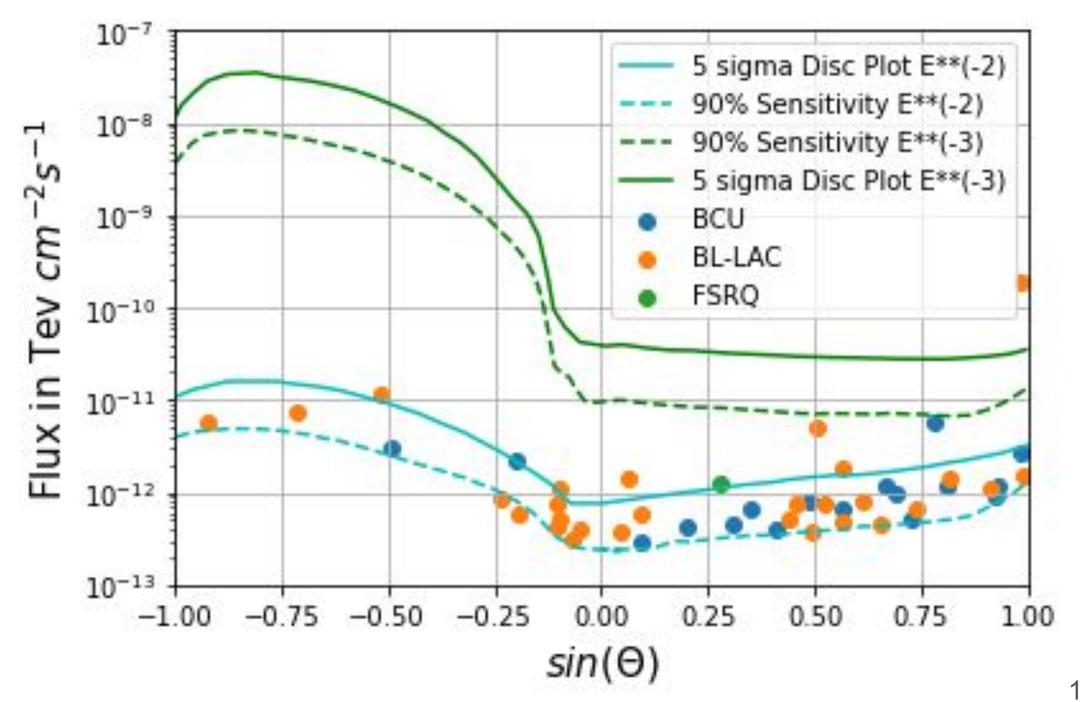
FSRQ -
1/5, 20%

BL Lac -
28/496, 5.6%

BUC -
17/251, 6.7%

Total-
45/752, 5.98%

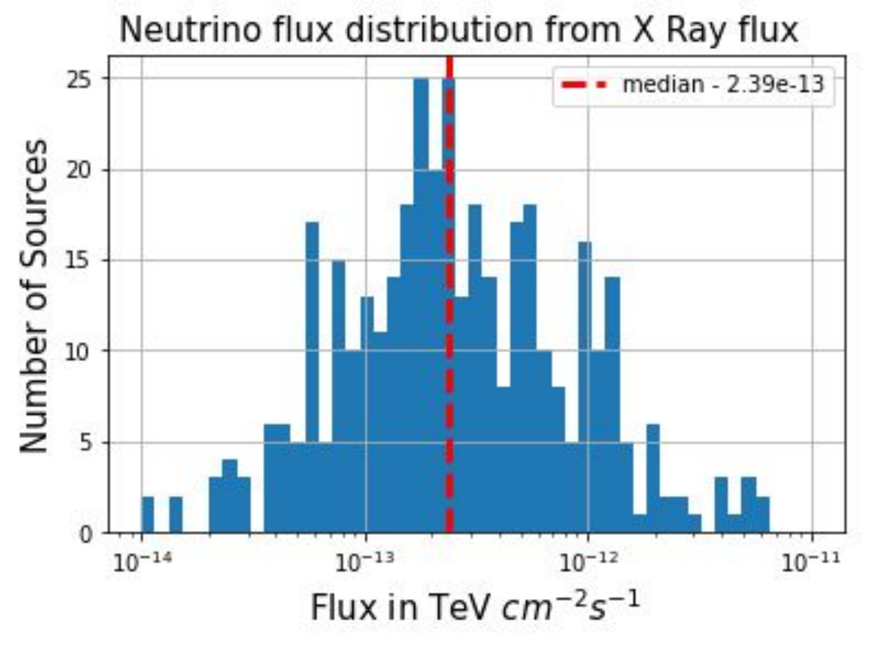
Not statistically significant

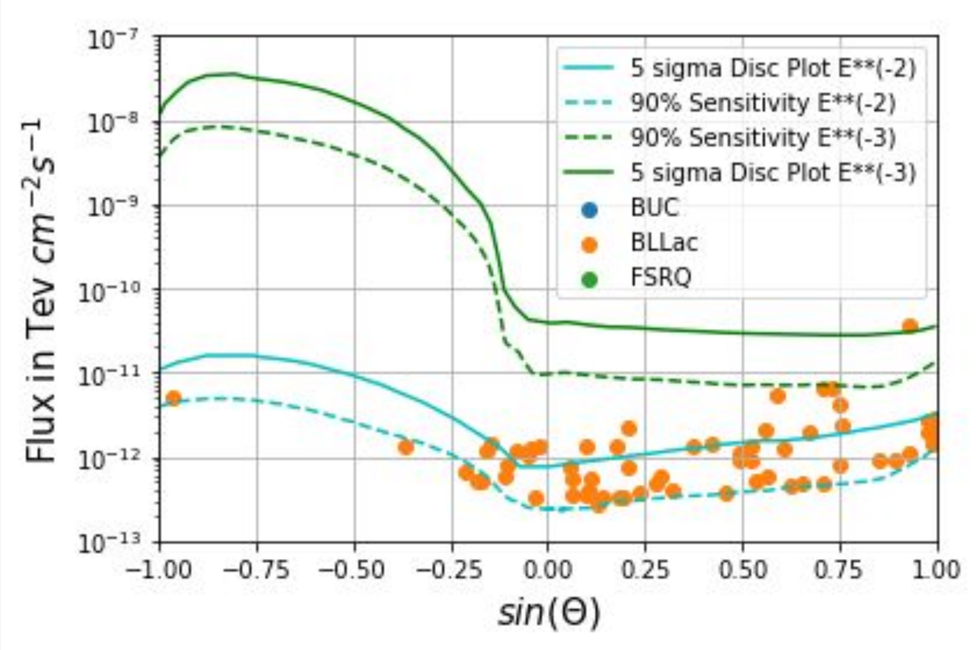


ν flux from X-ray flux

3HSP catalog

$f(\nu)_{(10TeV\ -\ 10\ PeV)} = f(\mathbf{X})_{(0.1keV\ -\ 2.4keV)}$





3HSP catalog

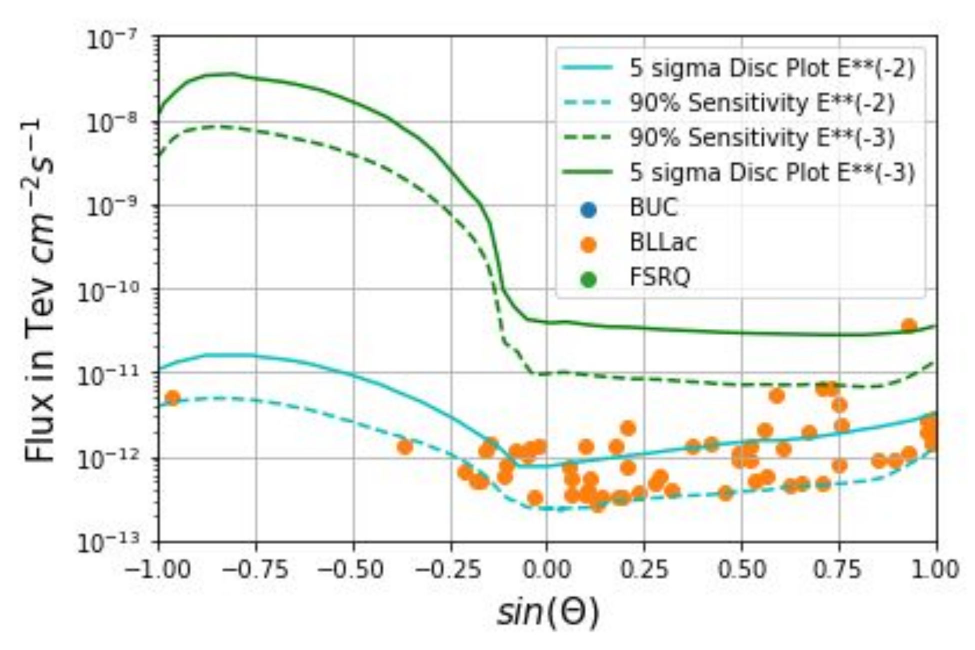
$f(\nu)_{(10\text{TeV - }10\text{ PeV})} = f(\mathbf{X})_{(0.1\text{keV - }2.4\text{keV})}$

No. of sources with
flux > IceCube 90% C.L. sensitivity (E^{-2})

BL-Lacs - 64/418, 15.31%

FSRQs - 0/5, 0%

BUCs - 0/ 251, 0%



Roma BZCAT

$f(\nu)_{(10TeV\ -\ 10\ PeV)} = f(\mathbf{X})_{(0.1keV\ -\ 2.4keV)}$

No. of sources with
flux > IceCube 90% C.L. sensitivity (E^{-2})

FSRQs -

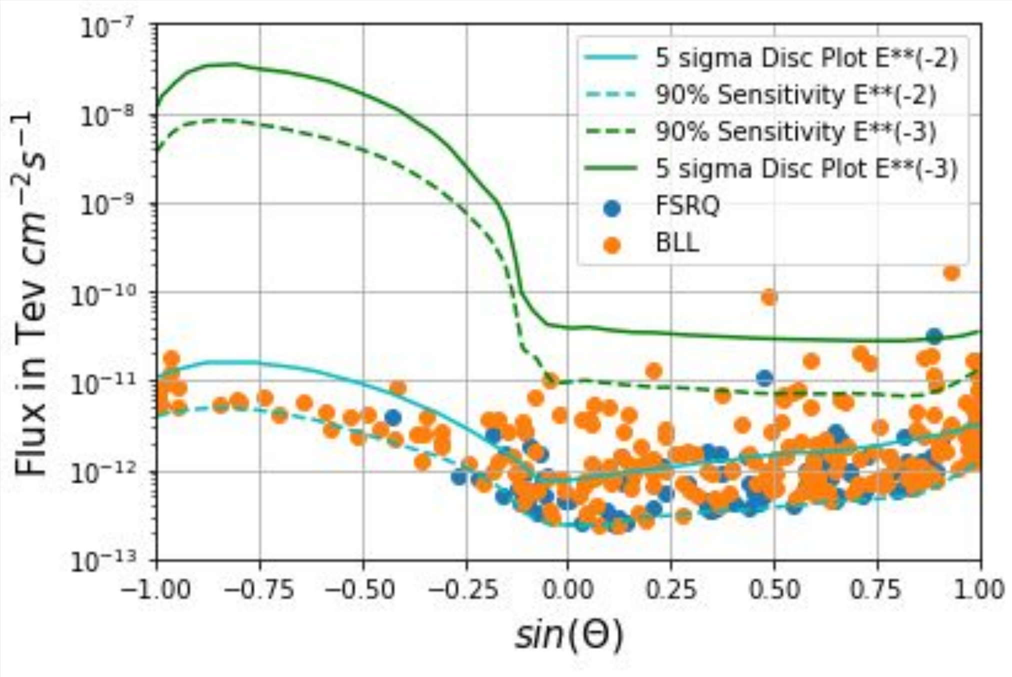
93/1909, (4.8%)

BL Lac -

273/1285, (21.2%)

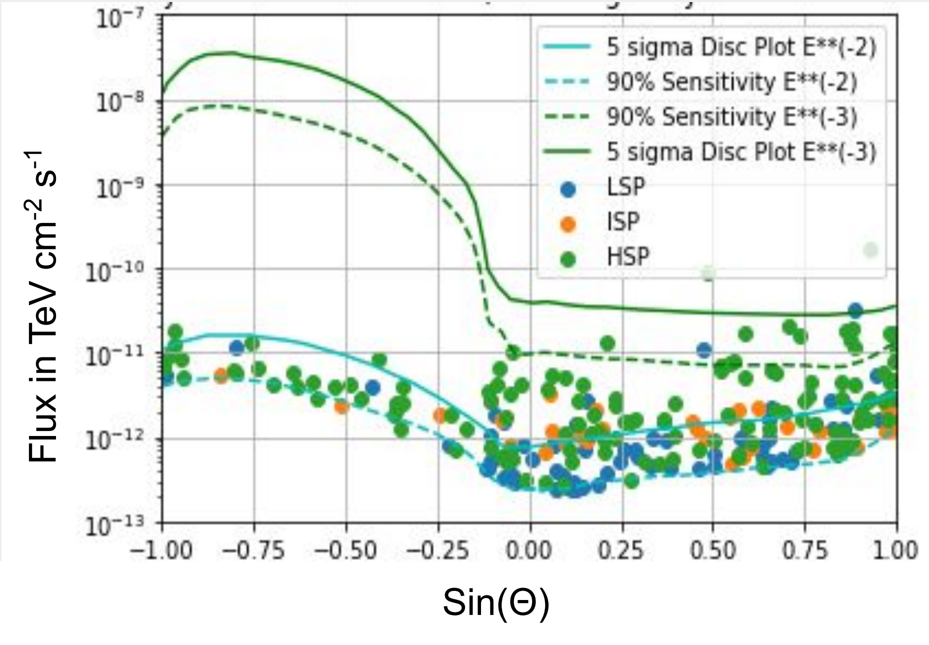
Total -

366/3194, (11.45%)



Roma BZCAT

$f(\nu)_{(10TeV - 10\ PeV)} = f(\mathbf{X})_{(0.1keV - 2.4keV)}$



No. of sources with flux > IceCube 90% C.L. sensitivity (E^{-2})

LSPs -
70/810, (8.64%)

ISPs -
34/227, (14.94%)

HSPs -
133/243, (54.73%)

Total-
237/1170, (20.25%)

Results

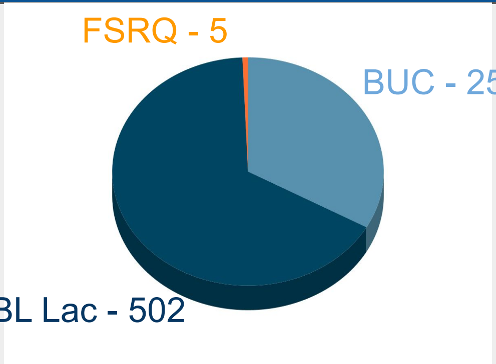
Class	X Rays		Gamma Rays	
	3HSP	Roma BZCAT	3HSP	Roma BZCAT
FSRQs	0%	4.80%	20%	11.20%
BL Lacs	15.31%	20.25%	5.60%	10.40%
LSP	-	8.64%	-	10.98%
ISP	-	14.94%	-	9.25%
HSP	-	54.73%	-	8.23%

ν flux from Sync. peak/ BLR

Catalogue down-selection (to calculate differential flux)

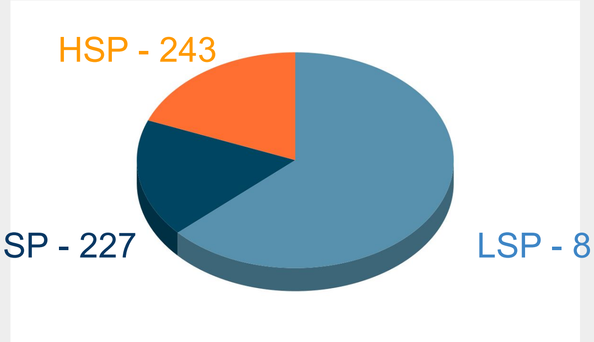
3HSP

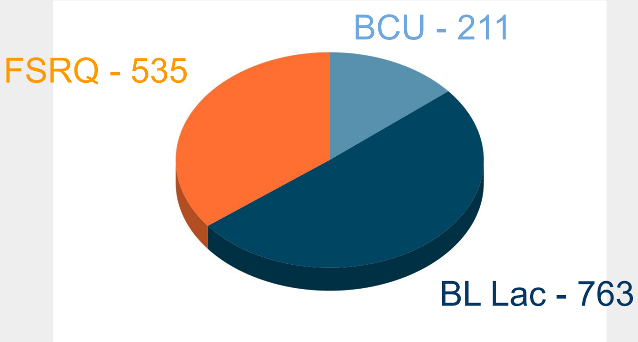
- Cross-correlated with 4FGL catalogue obtain energy flux in γ rays - 758
- 758 after down-selection



Roma BZCAT

- Cross-correlation with 4FGL to obtain energy flux in γ rays - 1506
- Cross-correlation with 4LAC to get the $\nu_{\text{sync.}}$ (peak) - 1407
- 1407 after down-selection





ν flux from BL Lacs

$$E_{\nu,p}(\delta, z, \nu^{s}_{peak}) \approx \frac{17.5\,PeV}{(1+z)^2}\left(\frac{\delta}{10}\right)^2\left(\frac{\nu^{s}_{peak}}{10^{16}Hz}\right)^{-1}$$

P.Padovani, et al. - https://arxiv.org/abs/1506.09135

Energy of neutrino SED peak is obtained from sync. peak energy

Flux at neutrino SED peak

$$F_\nu(E_\nu) = C \cdot E_\nu^{1-\Gamma_\nu}$$

C is obtained by assuming 1 event in IceCube at neutrino SED peak energy

ν flux from FSRQs

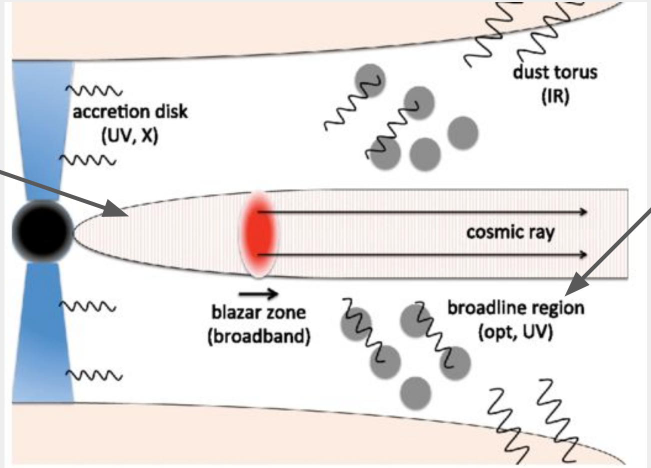
For FSRQs

$$E'^{b}_{\nu} \approx 0.05\, E'^{b}_{p} \approx 80\, PeV\, \Gamma_1^{\,2} (E'_s/10eV)^{-1}$$

Blazar zone

$$E'^{b}_{\nu} \approx 0.05(0.5 m_p c^2 \bar{\varepsilon}_{\Delta}/E'_{\mathrm{BL}}) \simeq 0.78\ \mathrm{PeV}$$

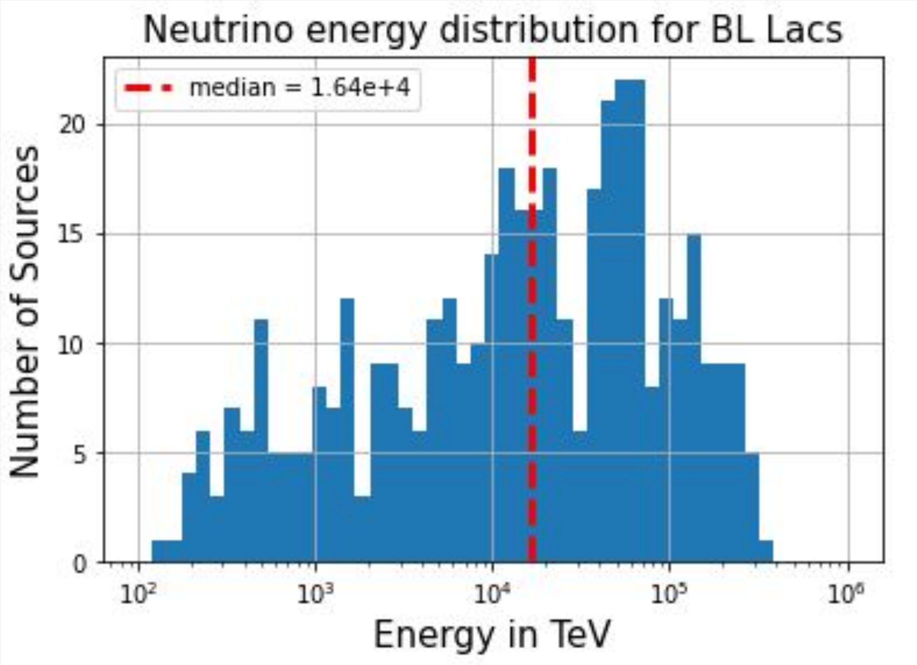
BLR - Broadline Region



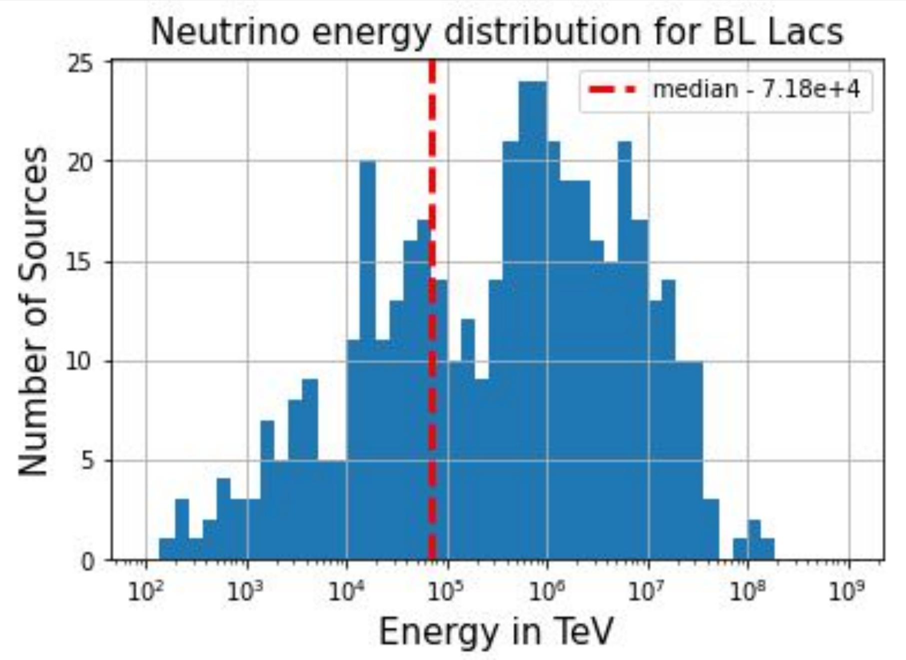
Murase et al, Phys. Rev. D 90, 023007 (2014) .

BL Lacs

3HSP



Roma BZCAT



Summary

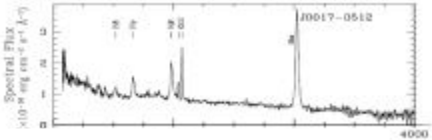
- We consider 2 multi-frequency catalogues to study the sensitivity of IceCube to classes of blazars
- Neutrino flux estimated by correlation with 1. Gamma-Ray flux, 2. X-Ray flux and 3. Sync peak freq. as target photon energy
- No evidence for preference of one sub-class over another when GeV gamma-ray flux used to obtain neutrino flux
- Using X-ray flux as a proxy, BL Lacs are 4 times more likely to be visible than FSRQs, while HSP blazars stand out over ISP and LSP
- All results can be explained if we consider HSP blazars have their peaks shifted to the right (hence a higher X-ray flux), and FSRQs are more likely to be ISP and LSP types

Next Steps

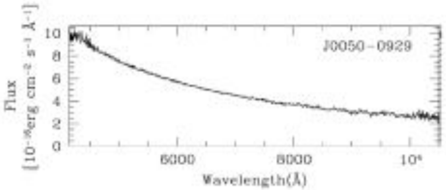
- Obtain estimates for differential neutrino flux at neutrino SED peak energy
- Calculate expected flux for FSRQs when target photons coming from BLR
- Compare differential fluxes with IceCube Gen2 sensitivity

Thank you!

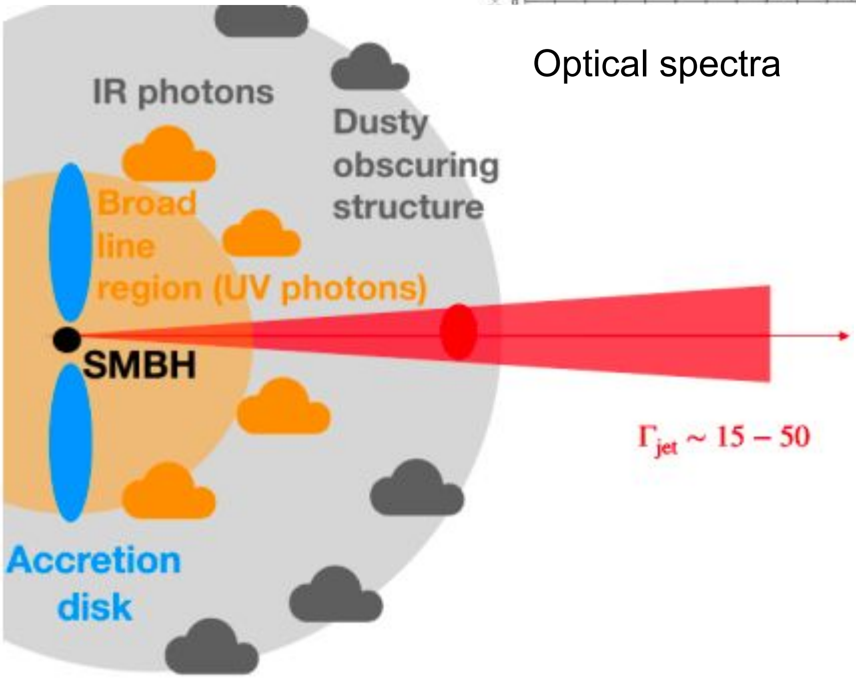
Backup

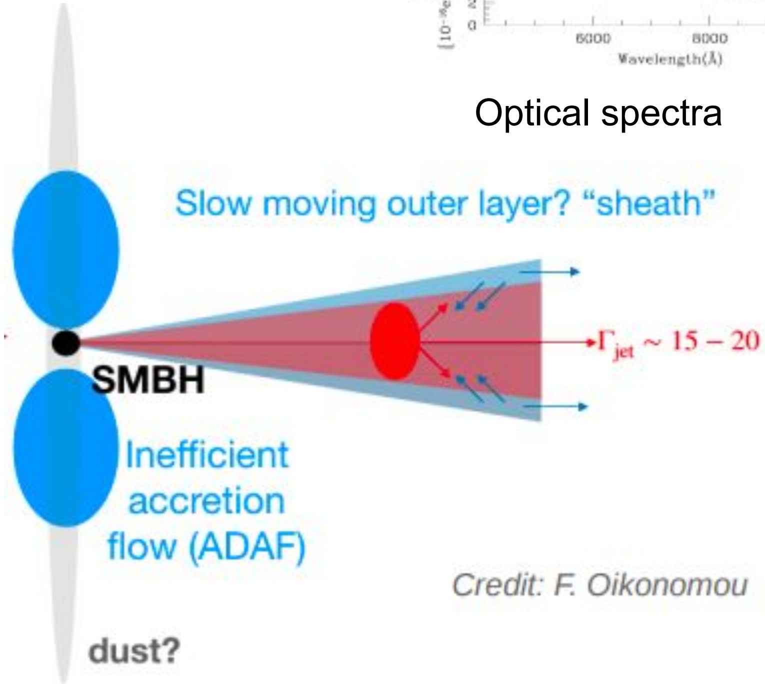


Optical spectra



Optical spectra





FSRQs

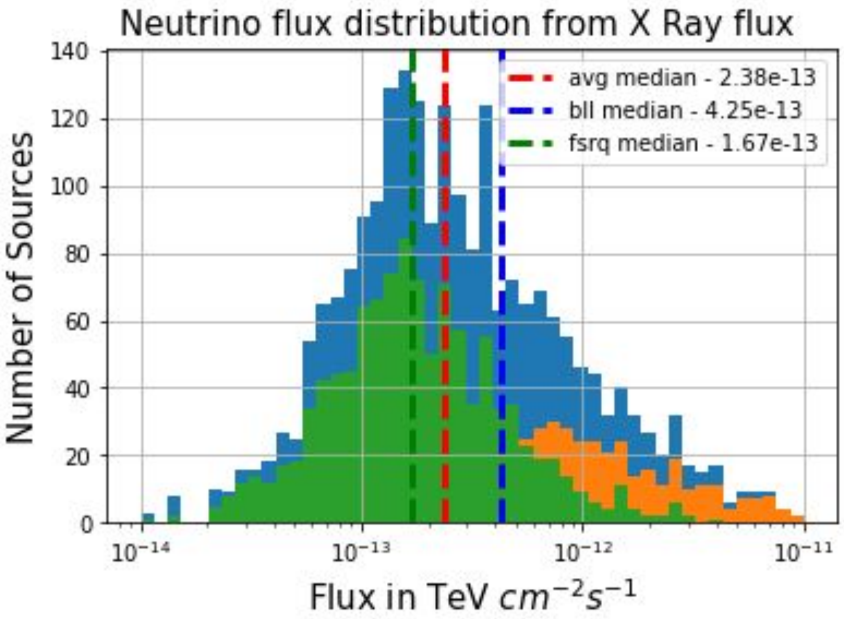
BL Lacs

Results

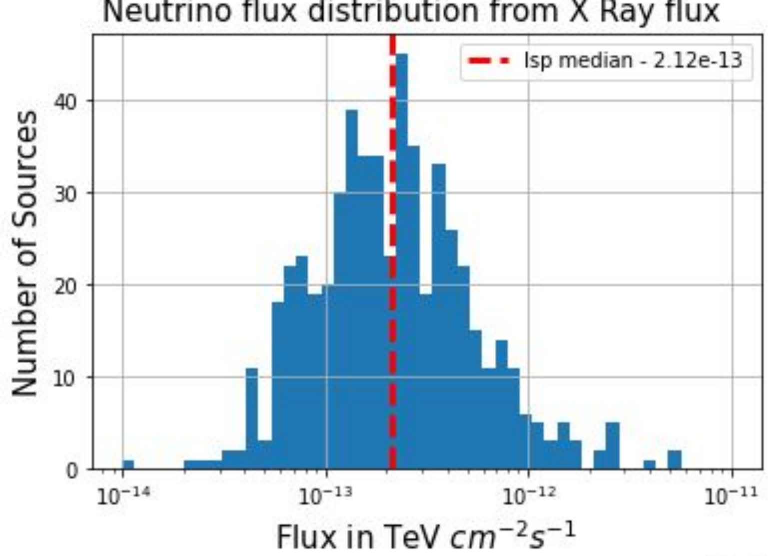
Class	X Rays		Gamma Rays	
	3HSP	Roma BZCAT	3HSP	Roma BZCAT
FSRQs	0/5	93/1909	1/5	78/762
BL Lacs	64/418	273/1285	28/496	56/535
LSP	-	70/810	-	89/810
ISP	-	34/227	-	21/227
HSP	-	133/243	-	20/243

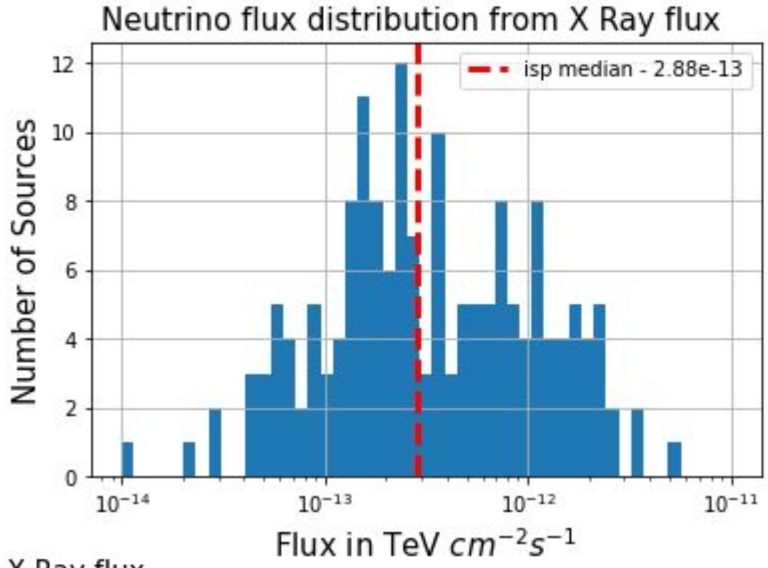
Results with number of sources

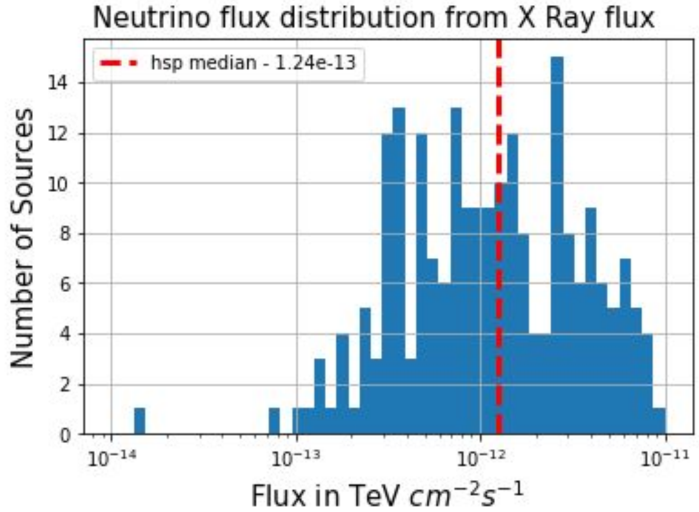
Roma BZCAT



Neutrino flux distribution from X Ray flux
avg median - 2.38e-13
bll median - 4.25e-13
fsrq median - 1.67e-13
Number of Sources
0
20
40
60
80
100
120
140
10^{-14}
10^{-13}
10^{-12}
10^{-11}
Flux in TeV $cm^{-2}s^{-1}$

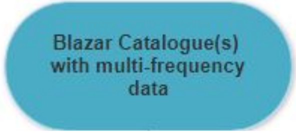

Neutrino flux distribution from X Ray flux
lsp median - 2.12e-13
Number of Sources
Flux in TeV $cm^{-2}s^{-1}$


Neutrino flux distribution from X Ray flux
isp median - 2.88e-13
Number of Sources
Flux in TeV $cm^{-2}s^{-1}$


Neutrino flux distribution from X Ray flux
hsp median - 1.24e-13
Number of Sources
Flux in TeV $cm^{-2}s^{-1}$

Project Outline

- Main aim of the project is to see which class of blazars IceCube is more sensitive to
- Compare the diff. sub-classes of blazars (***ISP, LSP, HSP***; ***BL Lacs, FSRQs***)
- Extend the prediction to higher energies by using IceCube Gen2 sensitivity

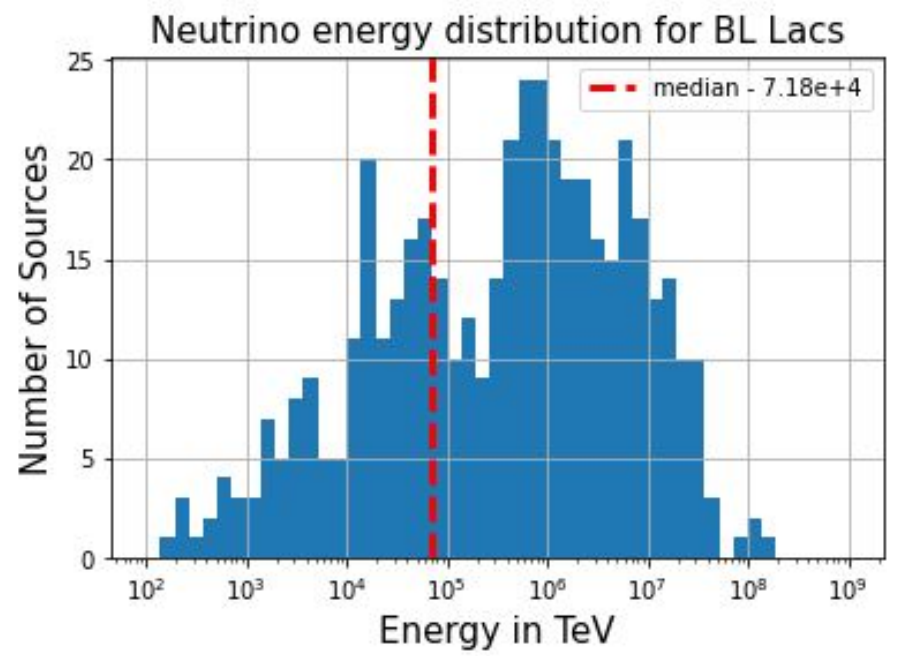


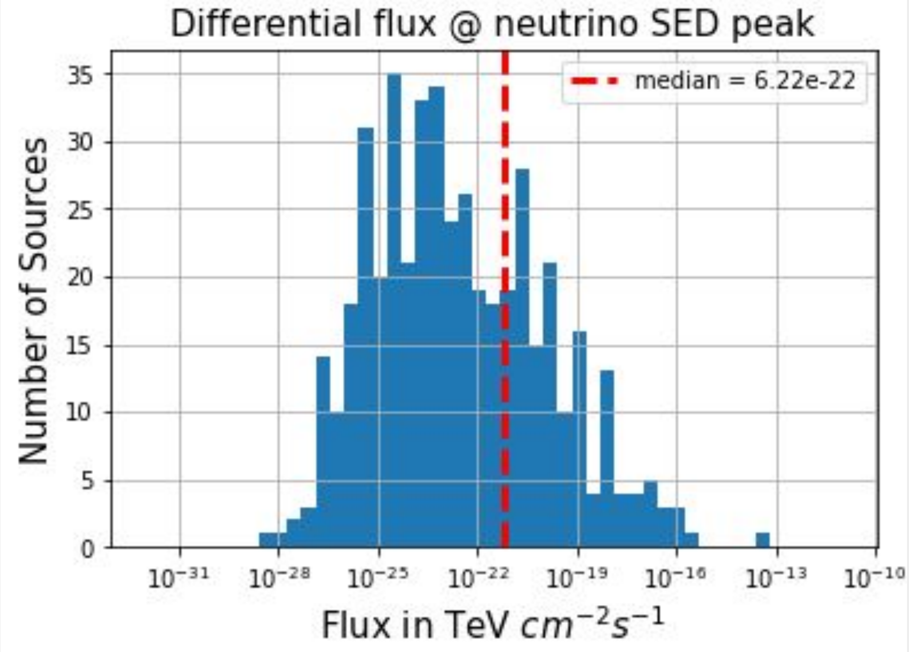
Roma BZCAT

BL Lacs

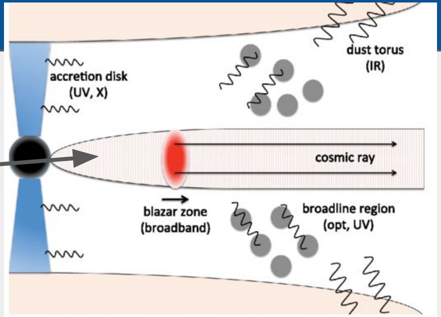
$$E_{\nu,p}(\delta, z, \nu^{s}_{peak}) \approx \frac{17.5\,PeV}{(1+z)^2}\left(\frac{\delta}{10}\right)^2\left(\frac{\nu^{s}_{peak}}{10^{16}Hz}\right)^{-1}$$

P.Padovani, et al. - https://arxiv.org/abs/1506.09135





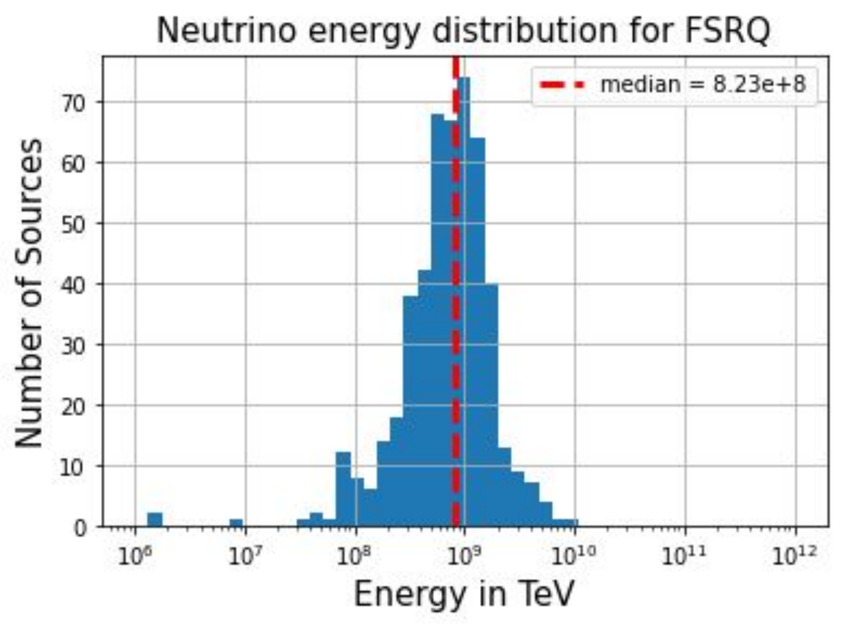
ν flux from Sync peak - FSRQ - Roma BZCAT

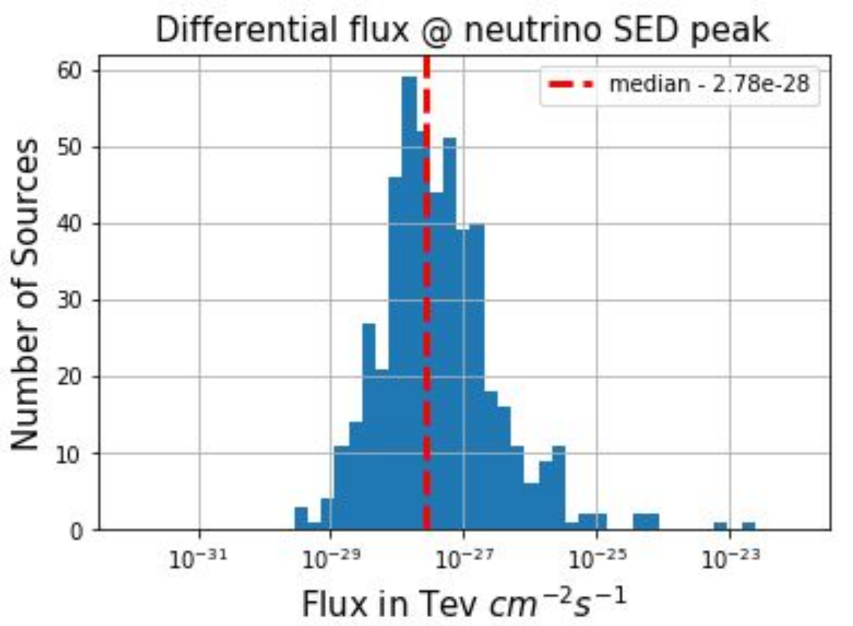


Blazar zone (FSRQs)

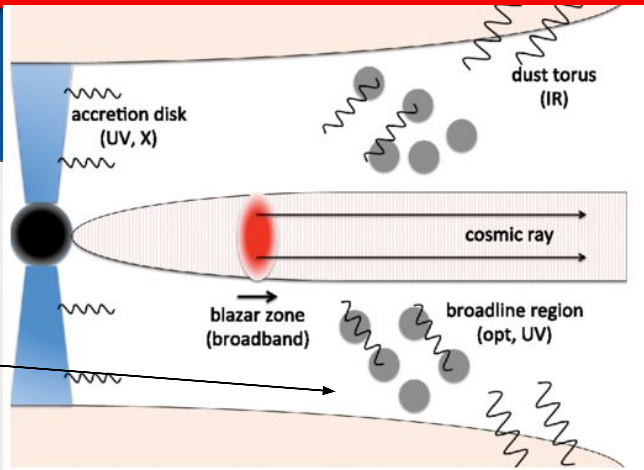
$$E'^{b}_{\nu} \approx 0.05\, E'^{b}_{p} \approx 80\, PeV\, \Gamma_1^{2} (E'_{s}/10eV)^{-1}$$

Roma Bzcat Catalogue





BLR region - FSRQs - Roma BZCAT



Broadline Region (FSRQs)

$$E'^{b}_{\nu} \approx 0.05(0.5 m_p c^2 \bar{\varepsilon}_{\Delta} / E'_{\rm BL}) \simeq 0.78 \text{ PeV}$$

The target photons (X-rays = 0.1 keV to 2.4 keV)

Corresponding neutrino SED peak = 79.74 PeV and 3.86 PeV