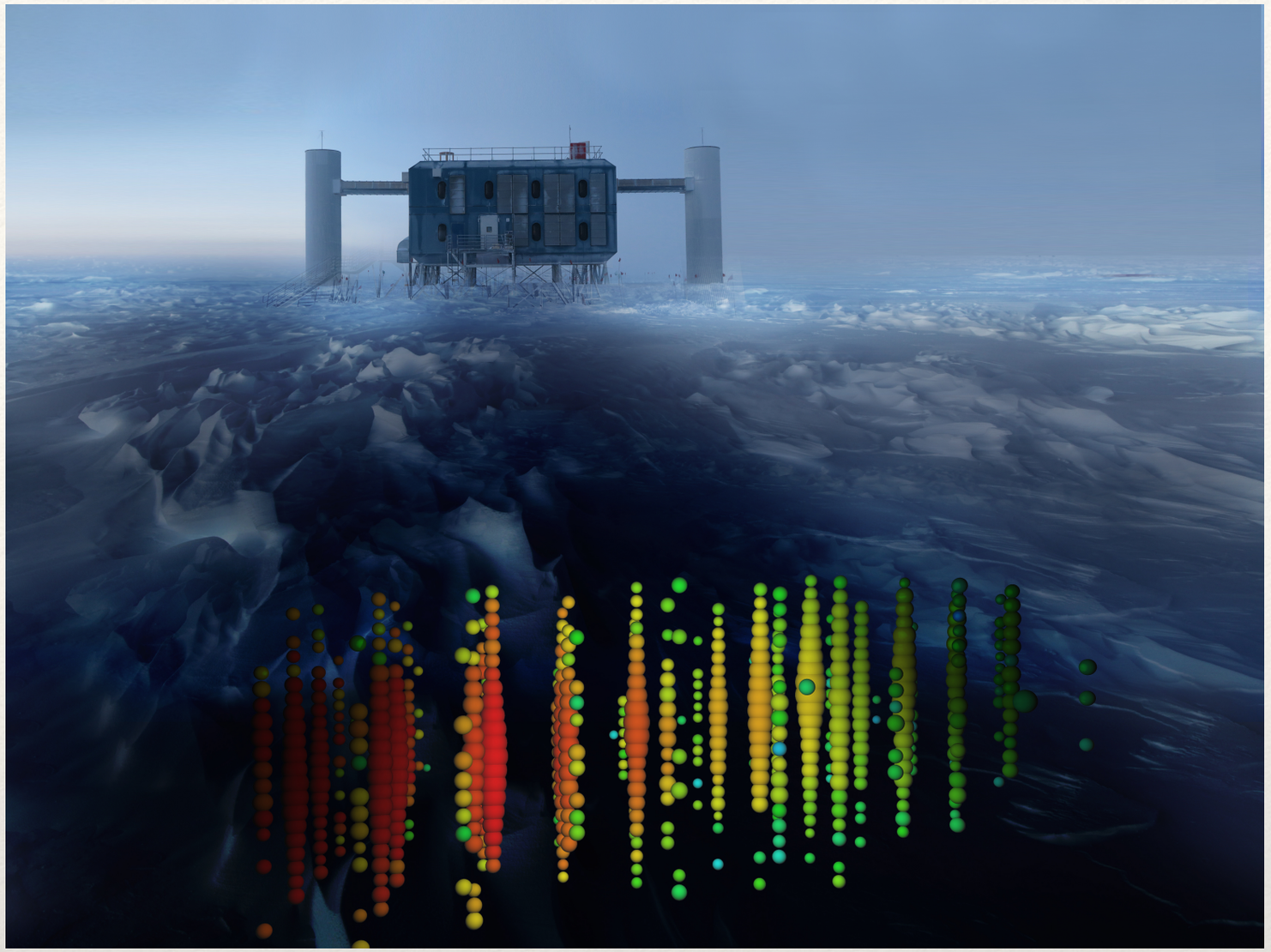


Multi-Messenger and Multi-Wavelength Studies with Active Galactic Nuclei

Abhishek Desai
Fermi Symposium
Sept 11th 2024

Our team: Stefano Marchesi, Justin Vandenbroucke, Ke Fang, Marco Ajello, Regina Caputo, Dieter Hartmann, Kavic R Kumar, Jessie Thwaites and Sam Hori

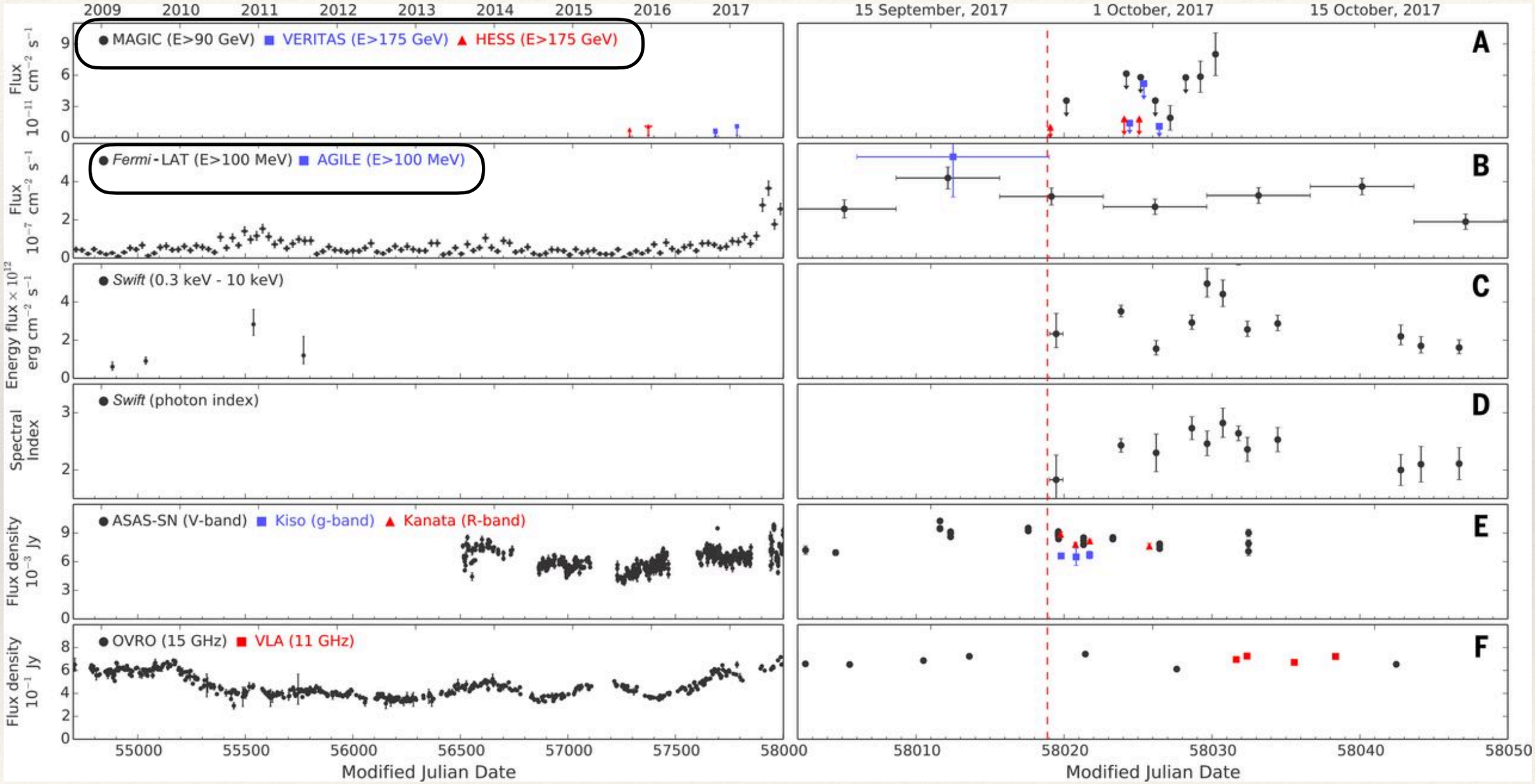
NPP
NASA Postdoctoral Program

NASA Goddard Space Flight Center

Why AGN Became So Interesting For Neutrino Studies:

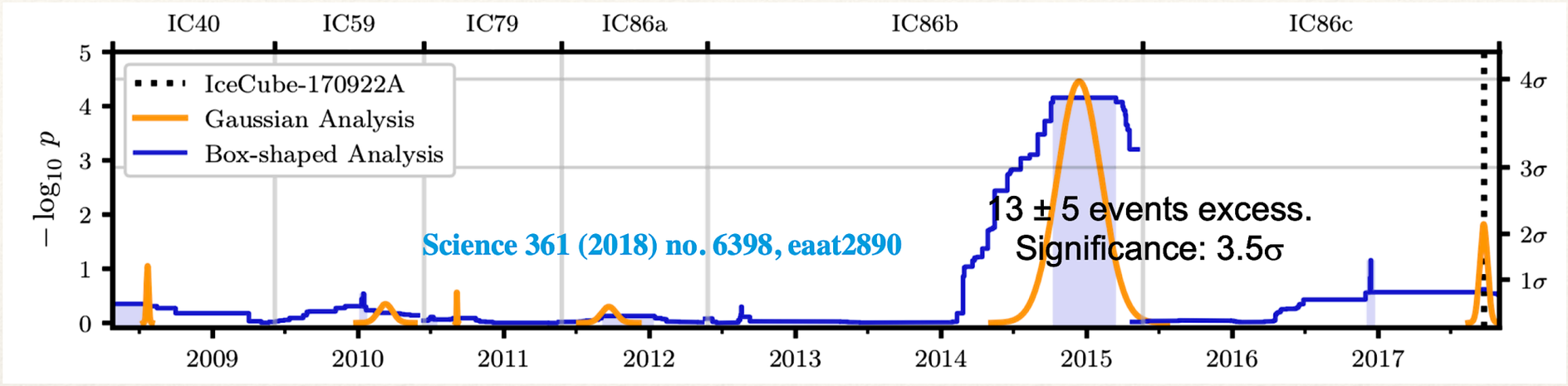
- Neutrino Alert: IC-170922A (Red dashed line); AGN: **TXS 0506+056**

Coincident detection with a *Fermi*-LAT Flare.

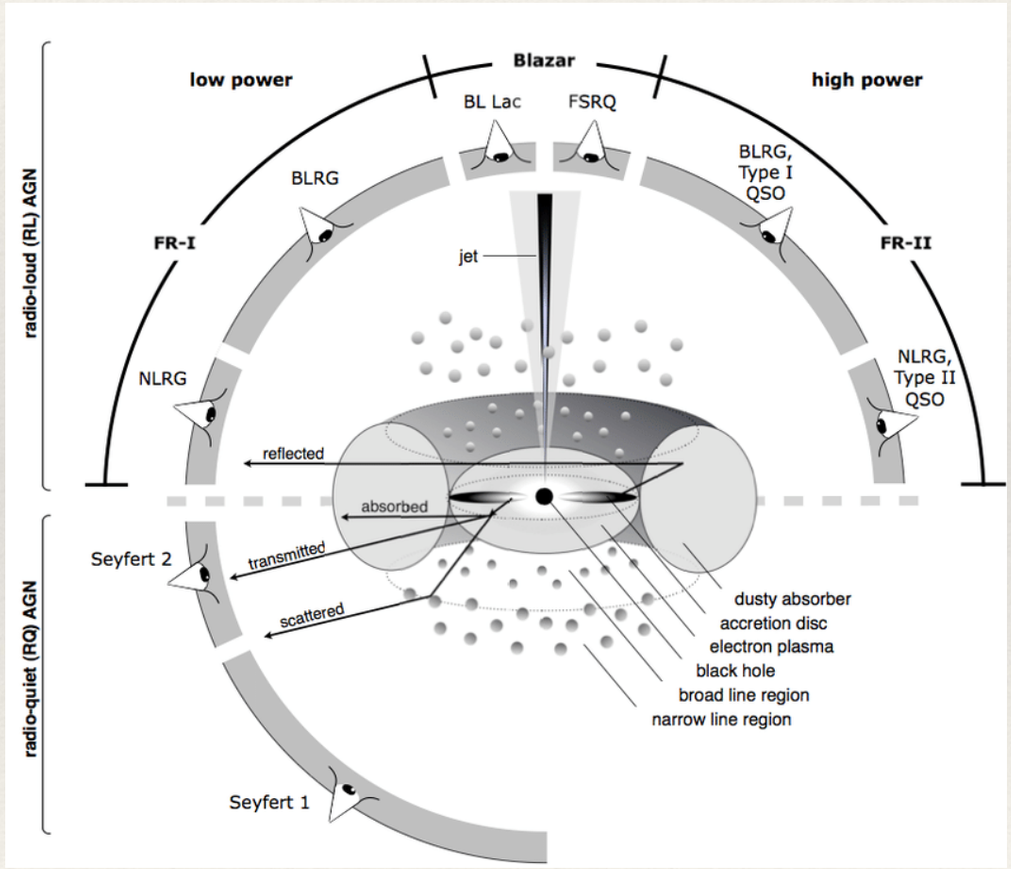


The IceCube Collaboration. Science 2018, 361

Blazars or Seyferts?

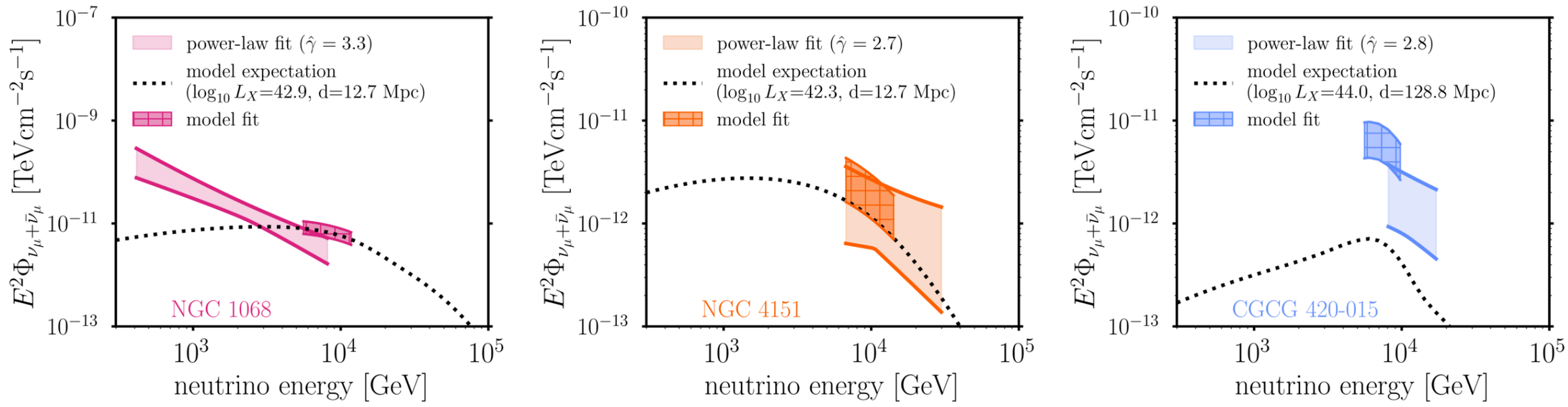


- **TXS0506+056**: Archival analysis detected neutrino emission also in 2014-2015 but no flaring activity reported by *Fermi*-LAT.
- Additionally, a Seyfert (and starburst) galaxy NGC 1068 was found to be a significant neutrino source using a 10 year time integrated analysis



Credit: Beckmann & Shrader (2012).

X-ray Bright Seyferts:

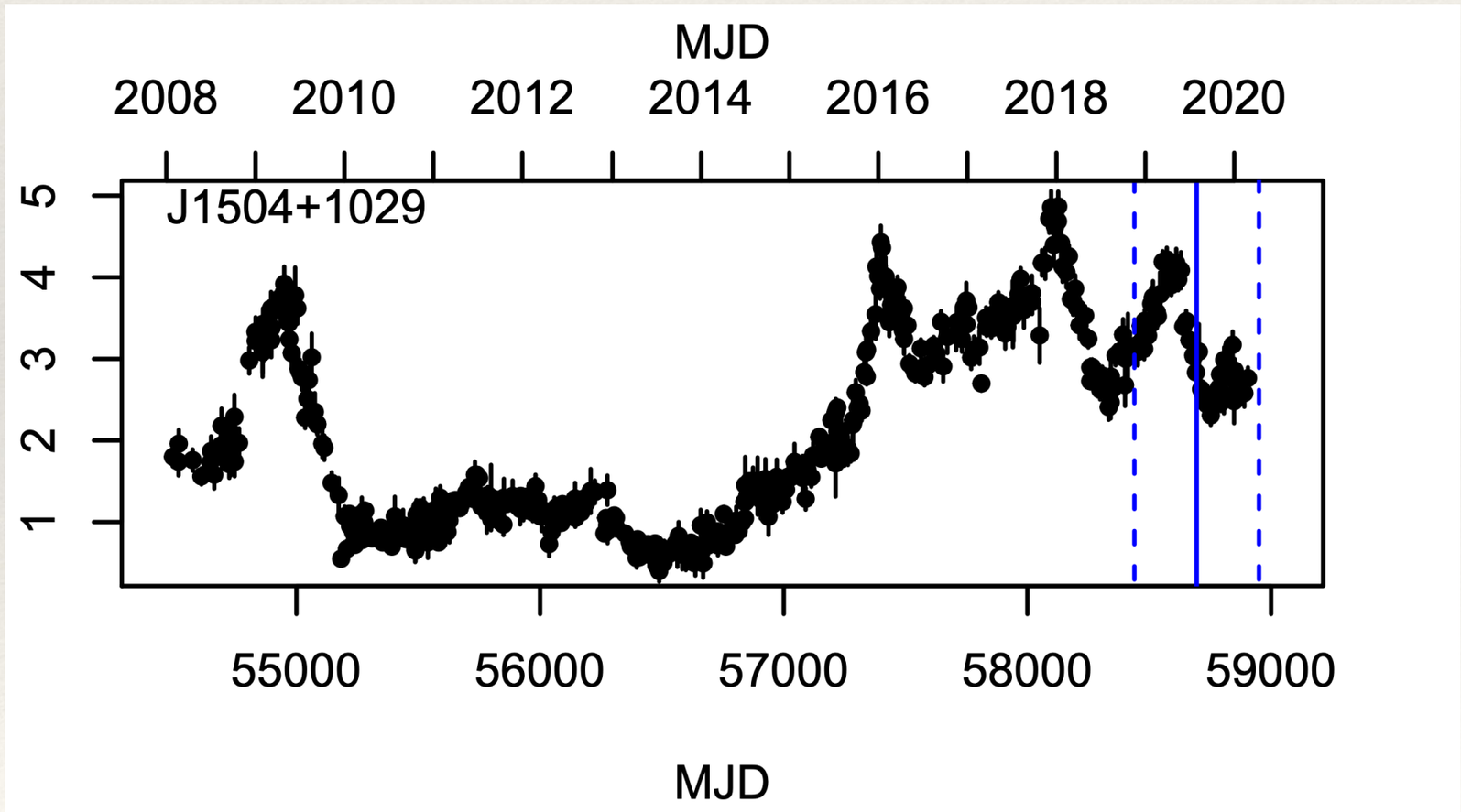


https://arxiv.org/abs/2406.07601

	spectral model	$n_{\rm exp}$	TS	$\hat{n}_{\rm s}$	$\hat{\gamma}$	$p_{\rm local}$	$p_{\rm global}$	$n_{\rm UL}$
Stacking Searches								
Stacking (excl.)	disk-corona	154.0	0.1	5	–	2.4×10^{-1} ($0.7\,\sigma$)	2.4×10^{-1} ($0.7\,\sigma$)	51.1
Stacking (incl.) (*)	disk-corona	199.0	11.2	77	–	1.1×10^{-4} ($3.7\,\sigma$)	–	128.0
Catalog Search 1								
CGCG 420-015	disk-corona	3.2	11.0	31	–	2.4×10^{-4} ($3.5\,\sigma$)	6.5×10^{-3} ($2.5\,\sigma$)	46.4
NGC 4151	disk-corona	13.1	9.0	23	–	6.4×10^{-4} ($3.2\,\sigma$)	–	39.5
NGC 1068 (*)	disk-corona	44.6	23.4	48	–	3.0×10^{-7} (5.0σ)	–	61.4
Catalog Search 2								
NGC 4151	power-law	–	7.4	30	2.7	6.4×10^{-4} ($3.2\,\sigma$)	1.7×10^{-2} ($2.1\,\sigma$)	61.4
CGCG 420-015	power-law	–	9.2	35	2.8	3.0×10^{-3} ($2.7\,\sigma$)	–	62.1
NGC 1068 (*)	power-law	–	29.5	94	3.3	8.0×10^{-8} ($5.2\,\sigma$)	–	94.9

One more intersting Blazar:

- Blazar PKS1502+106 was found to have a possible correlation with an IceCube alert (IC190730A: ATel #12967) .
- At the time of the alert, the radio observations of the FSRQ were seen reaching an all time peak flux of 4 Jy (S. Kiehlmann et al. ATel #12996)



Hovatta et al. 21

Theory behind neutrino production:

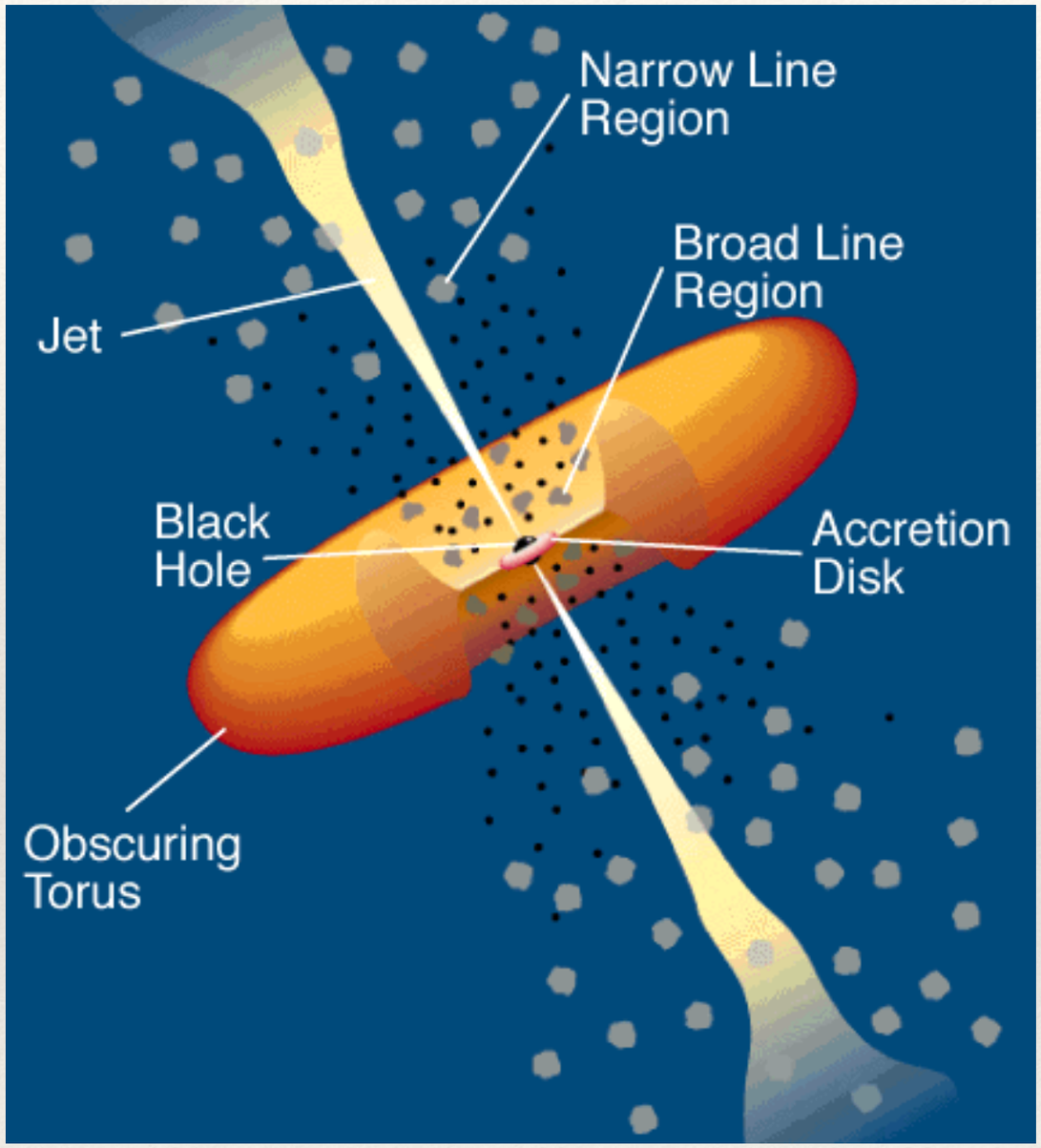
A theory to explain:

- Radio-neutrino correlation

- X-ray - neutrino correlation

over

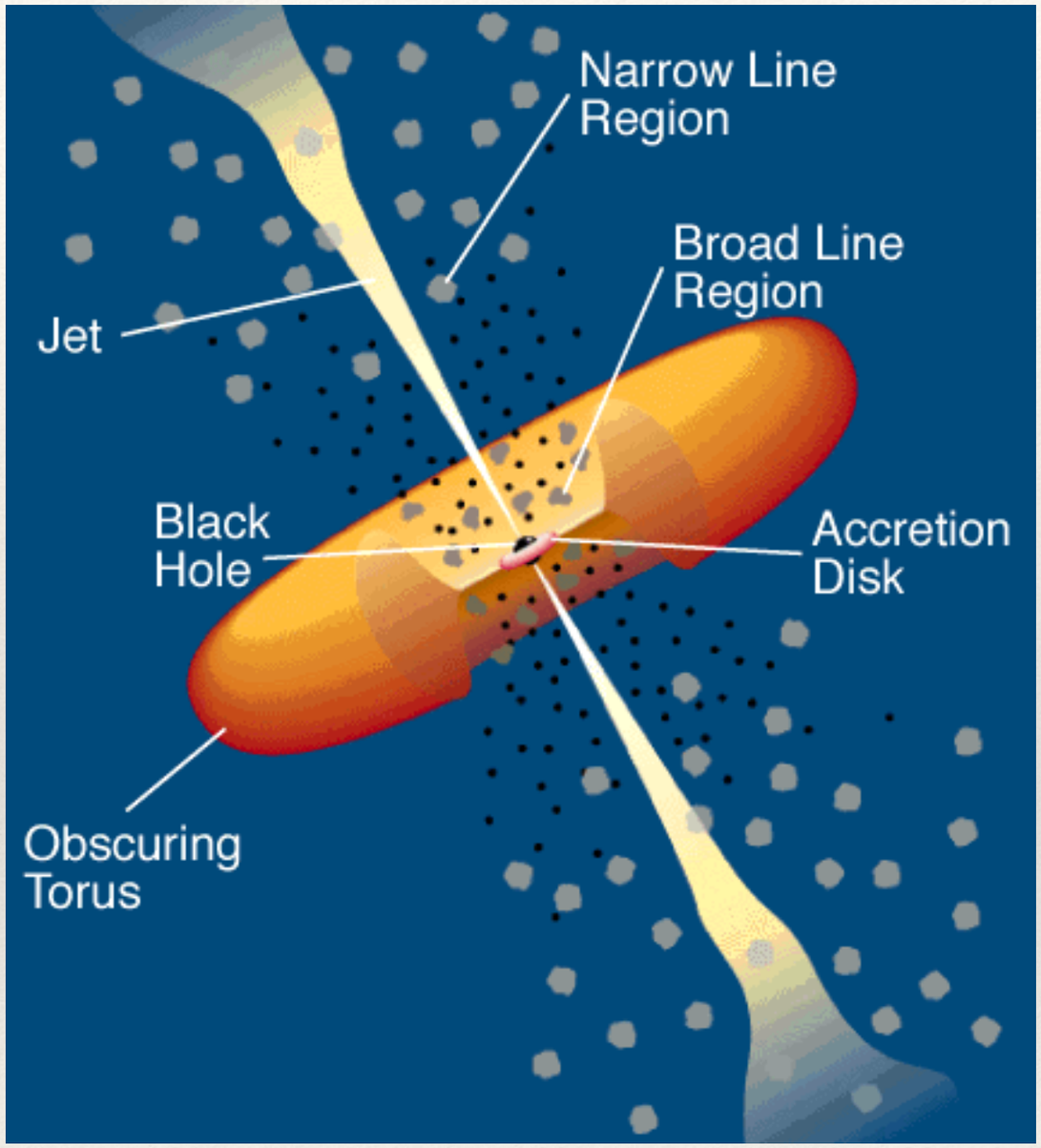
- Gamma-ray - neutrino correlation



Credit: C.M. Urry and P. Padovani

Theory behind neutrino production:

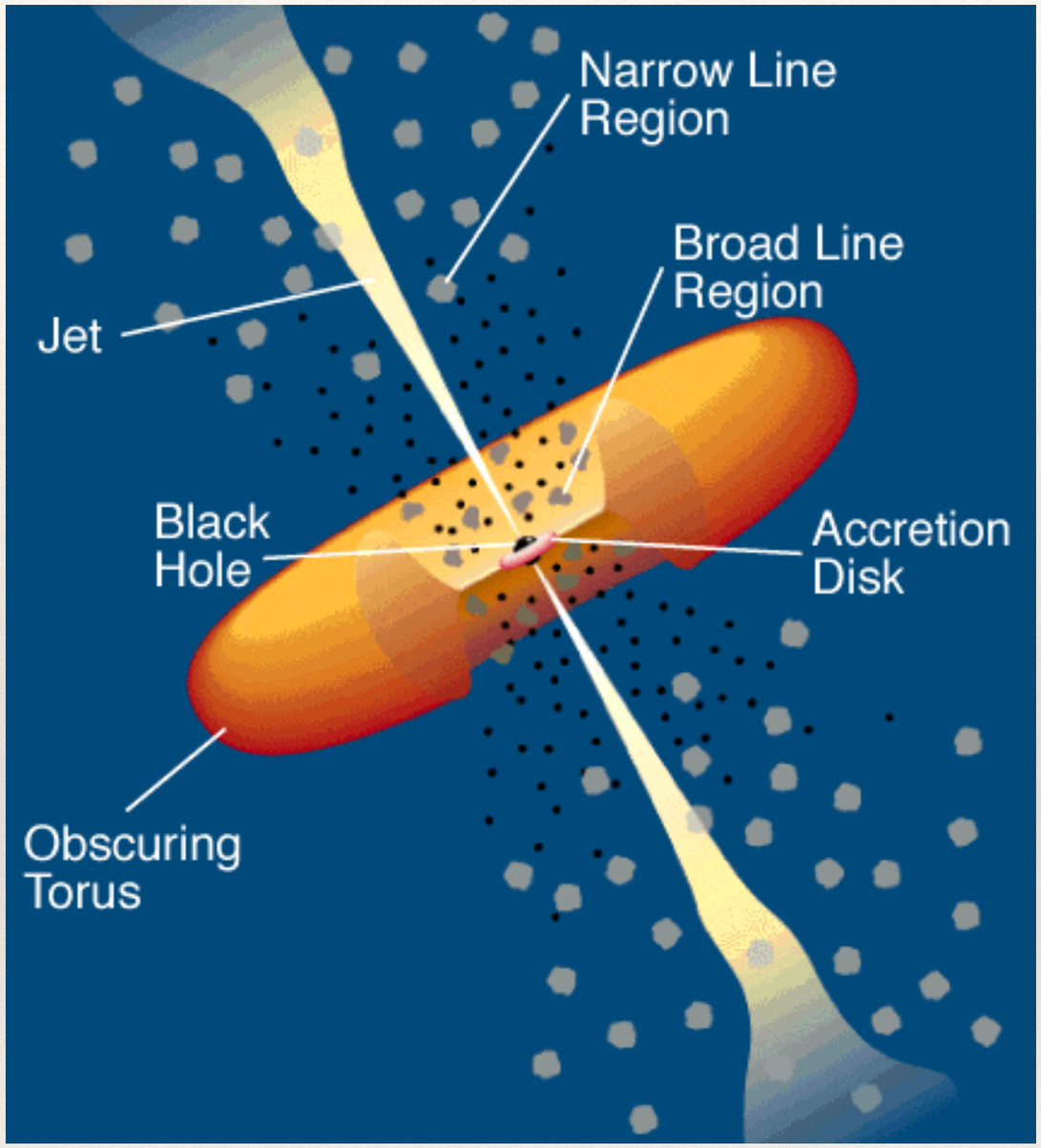
- Synchrotron radiation for radio Photon Creation
- Compton scattering to higher energy photons.
- In case of a pγ interation close to the center of the AGN:
  - These X-ray photons interact with protons
  - Resultant pions decay to give gamma-rays and neutrinos.



Credit: C.M. Urry and P. Padovani

Theory behind neutrino production:

- Synchrotron radiation for radio Photon Creation
- They undergo Inverse Comption Scattering to form higher energy photons.
- In case of a pγ interation close to the center of the AGN:
  - These X-ray photons interact with protons
  - Resultant pions decay to give gamma-rays and neutrinos.



Credit: C.M. Urry and P. Padovani

Theory behind neutrino production:

- Synchrotron radiation for radio Photon Creation
- They undergo Inverse Comption Scattering to form higher energy photons.
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  - These X-ray photons interact with protons
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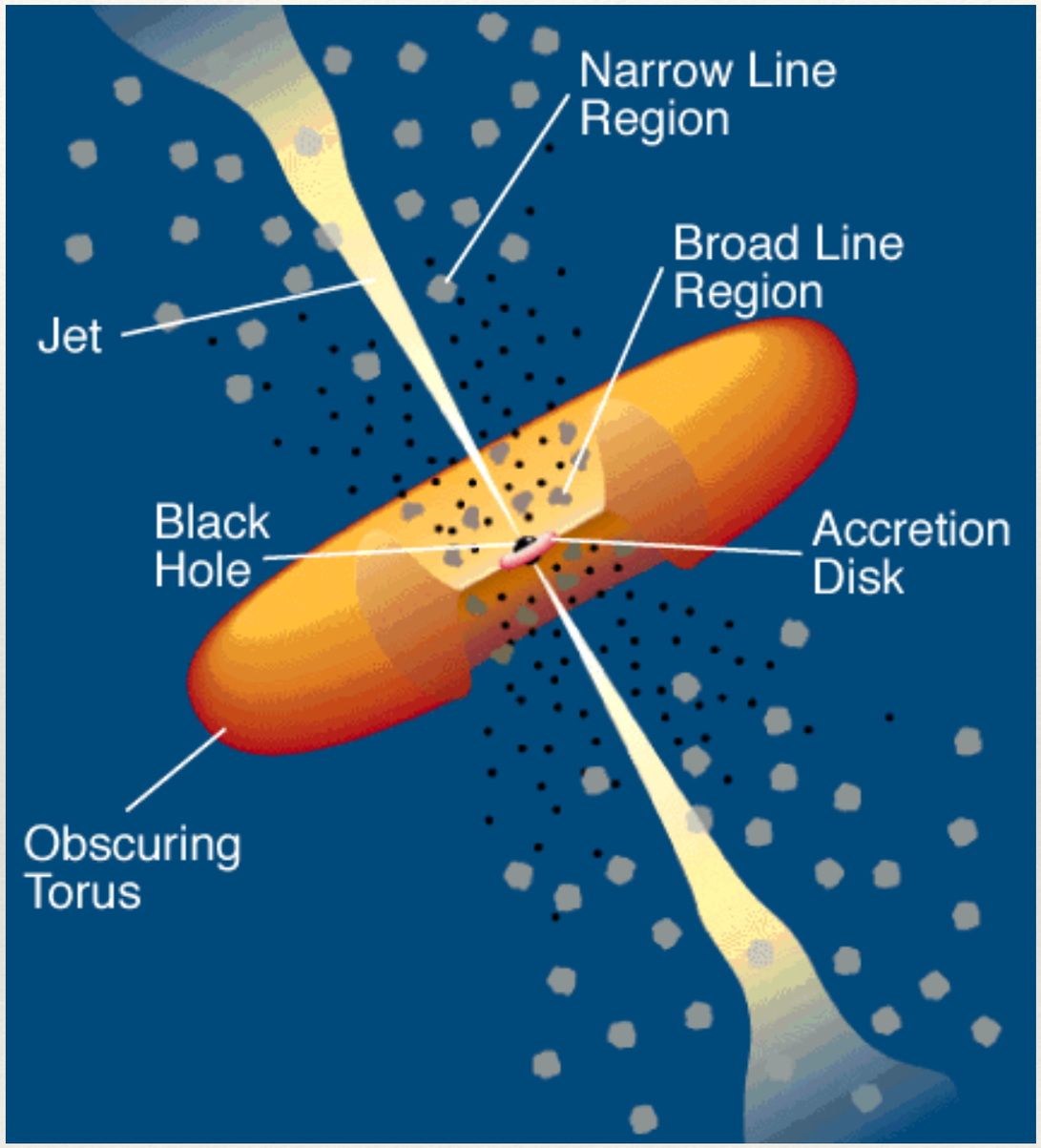
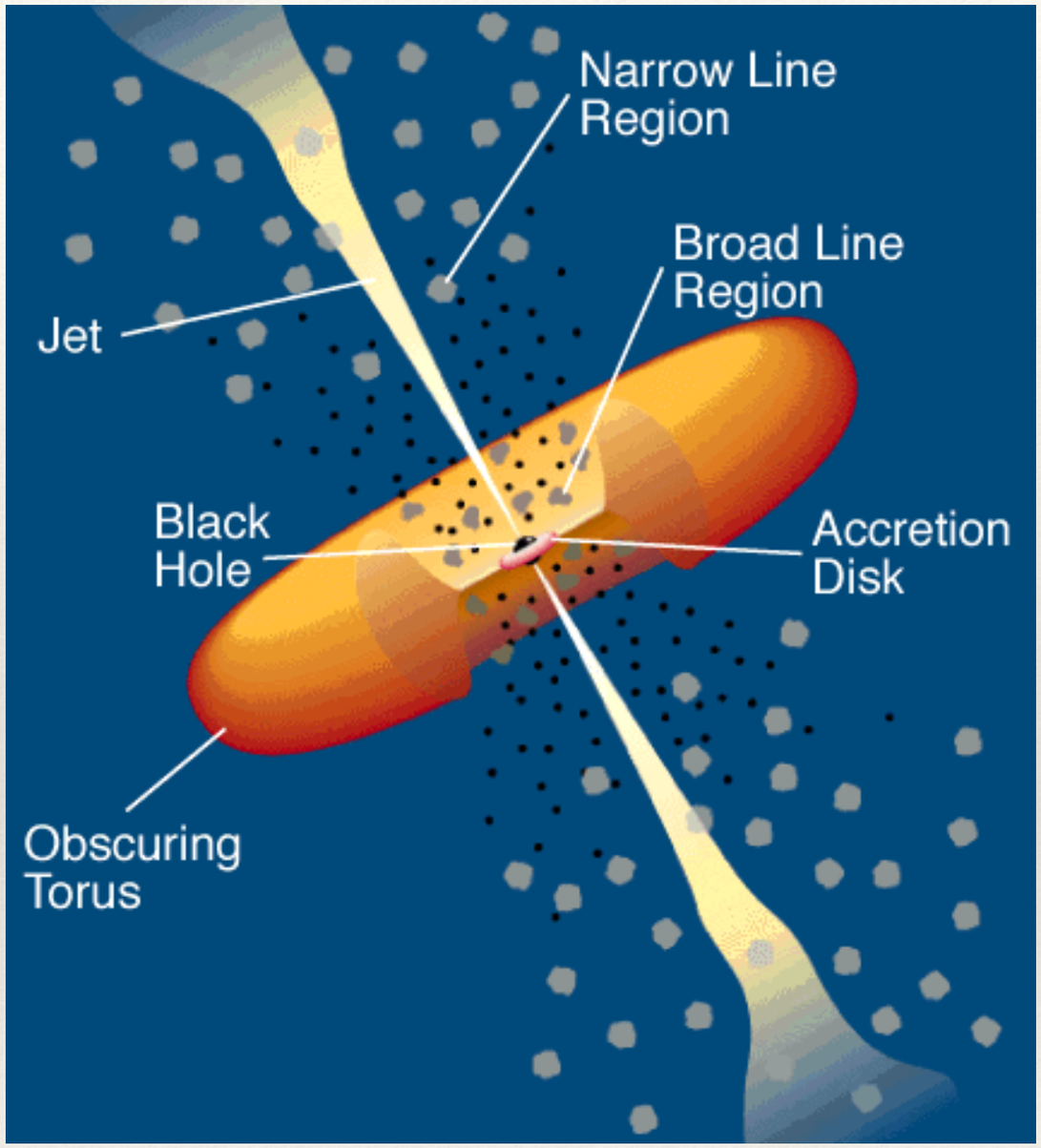


Credit: C.M. Urry and P. Padovani

Theory behind neutrino production:

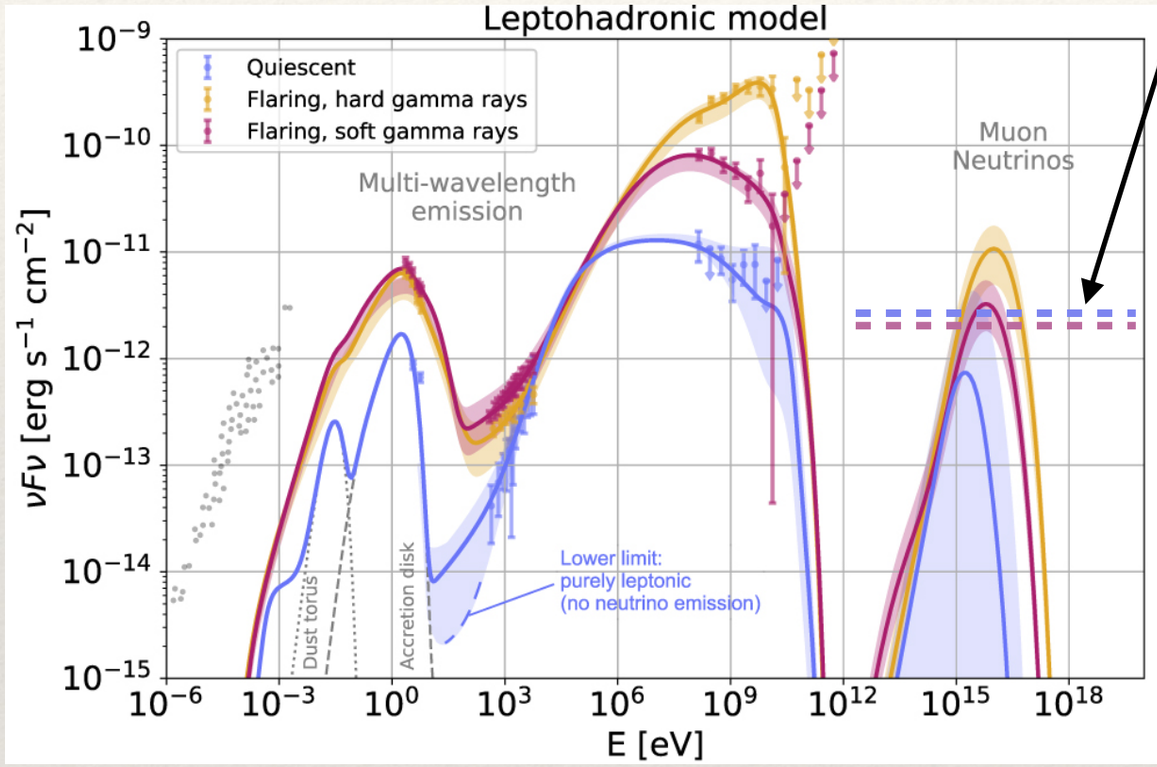
- Case 1 (Non-jetted or obscured AGN): The resultant gamma-ray photons cascade down to lower energies
  - Lower possibility of Gamma-ray and neutrino correlation.
  - Stronger correlation with X-ray (and radio) photons.
- Case 2 (Jetted AGN, specifically blazars).
  - Possibility of correlation with X-ray, Gamma-ray and radio photons
  - Neutrino production can also happen in the jet (which leads to a different model)



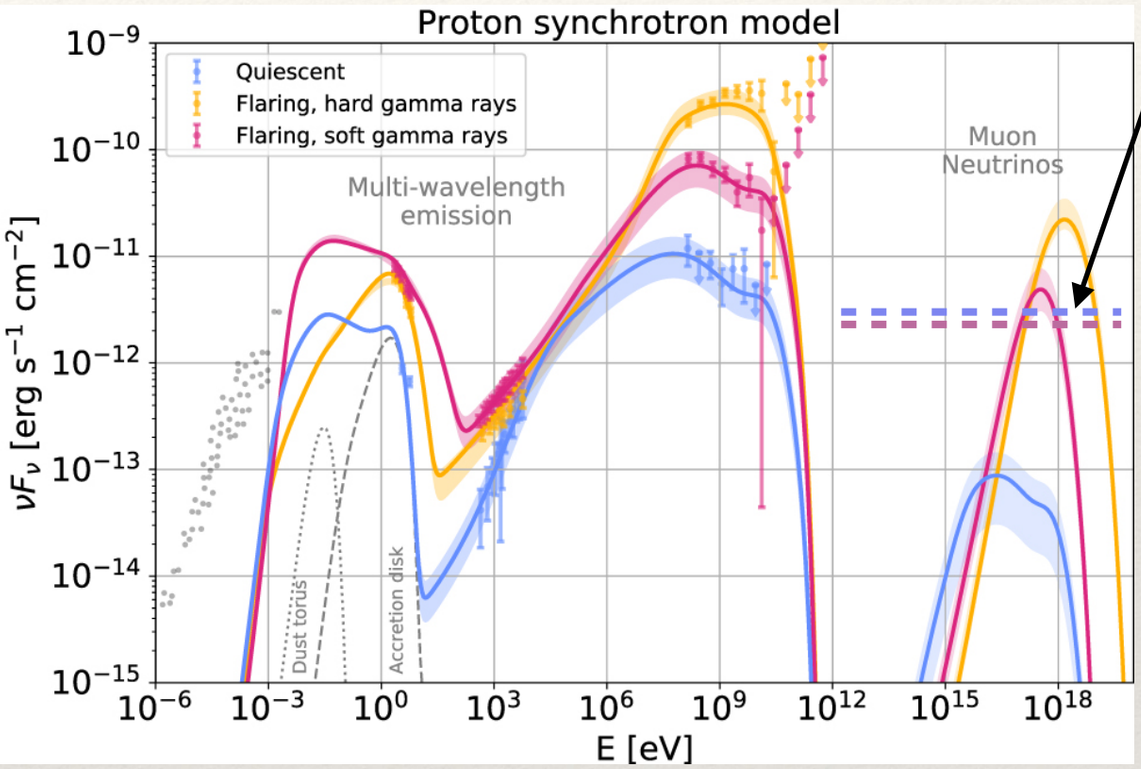
Credit: C.M. Urry and P. Padovani

Multi-wavelength+Multi-messenger Study:

Sensitivities from simulation

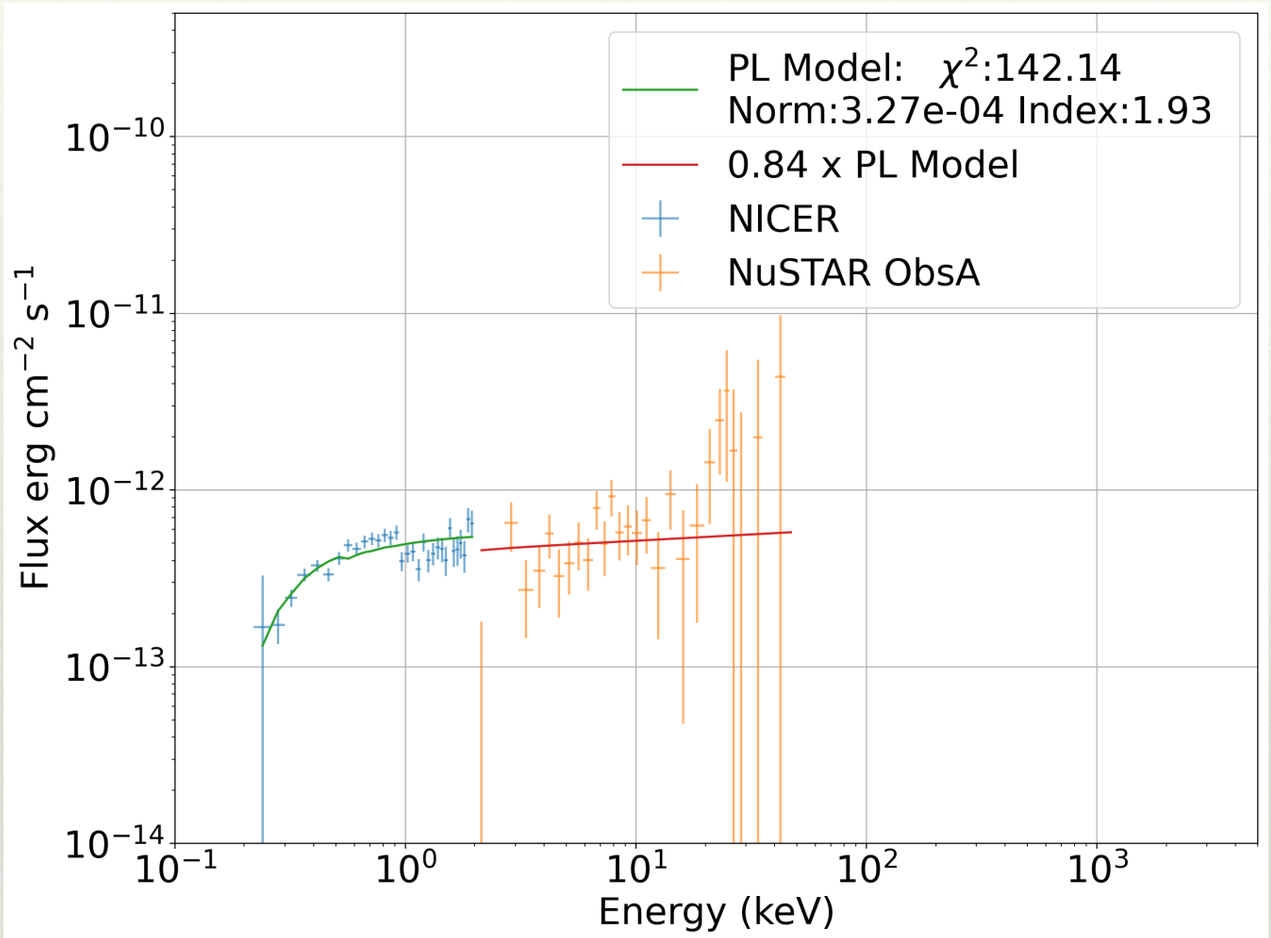


Sensitivities from simulation



PKS 1502+106 modeling by Rodrigues et al. 2021
(Dashed lines not part of model)

Multi-wavelength Results:

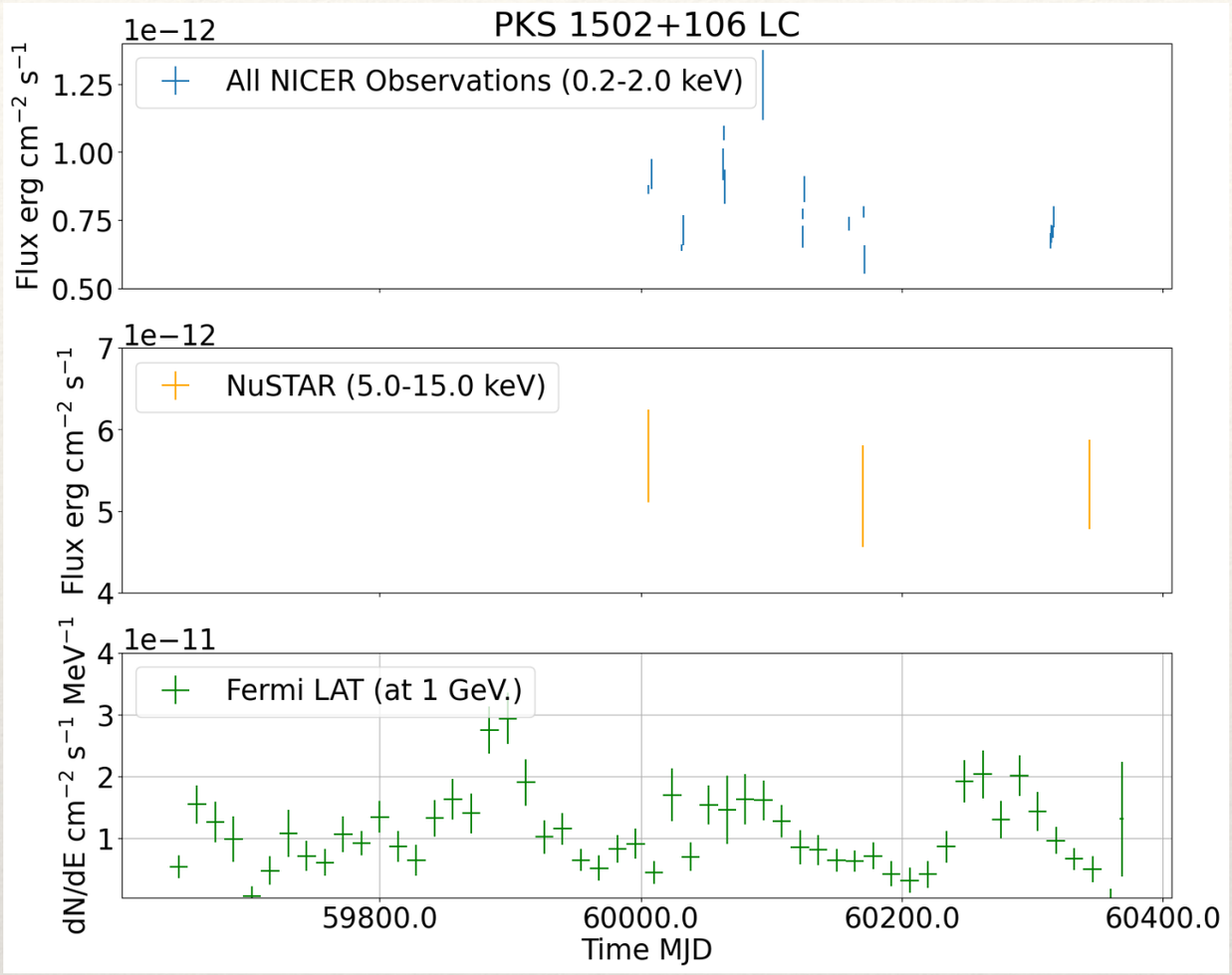


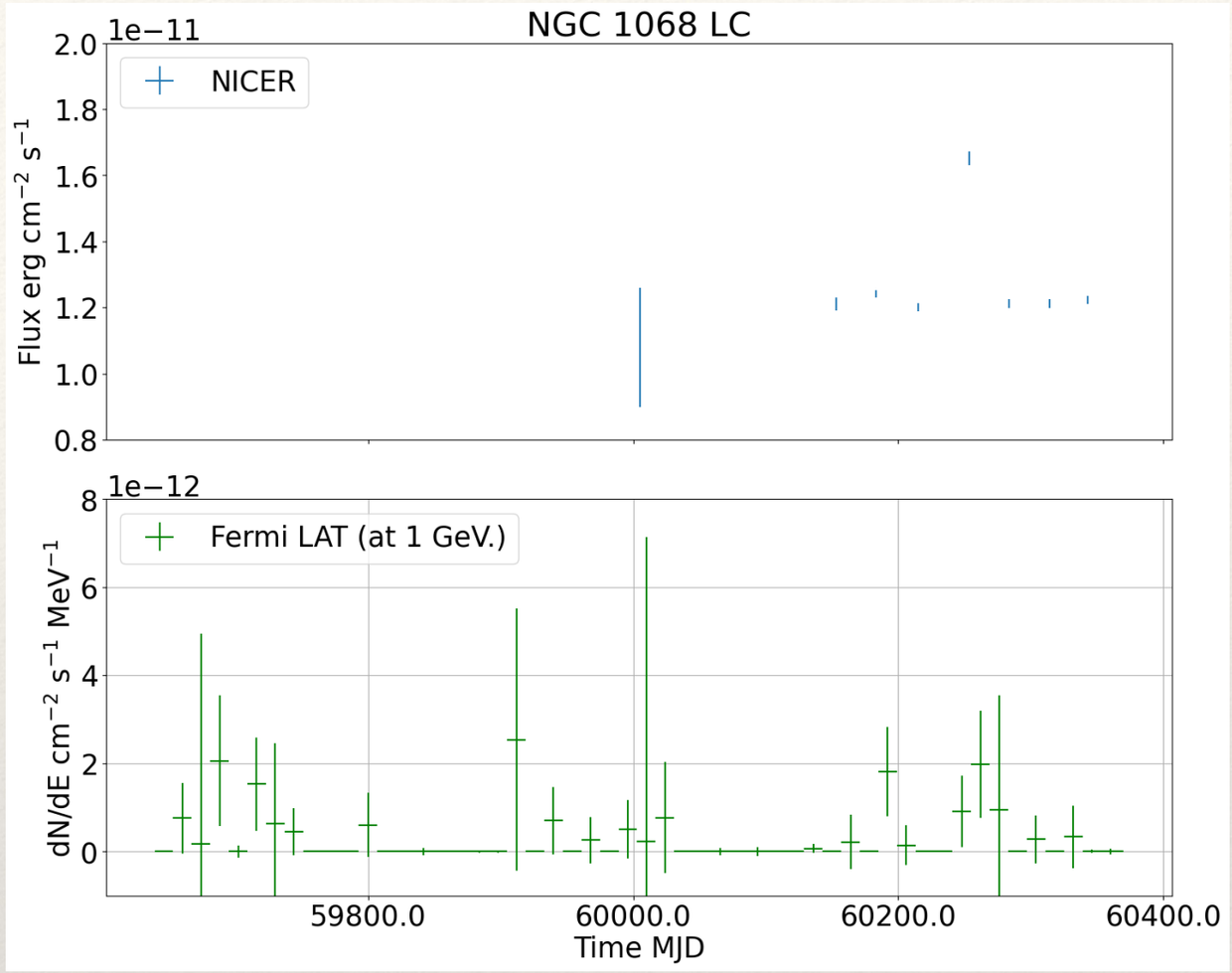
- PKS1502+106 observed using NICER+NuSTAR

- Current Work using Observations:
  - NICER + NuSTAR Data (X-ray)
  - *Fermi*-LAT Data (Gamma-rays)
  - Neutrino (IceCube)

- Sources:
  - NGC 1068
  - PKS 1502+106

Light Curves

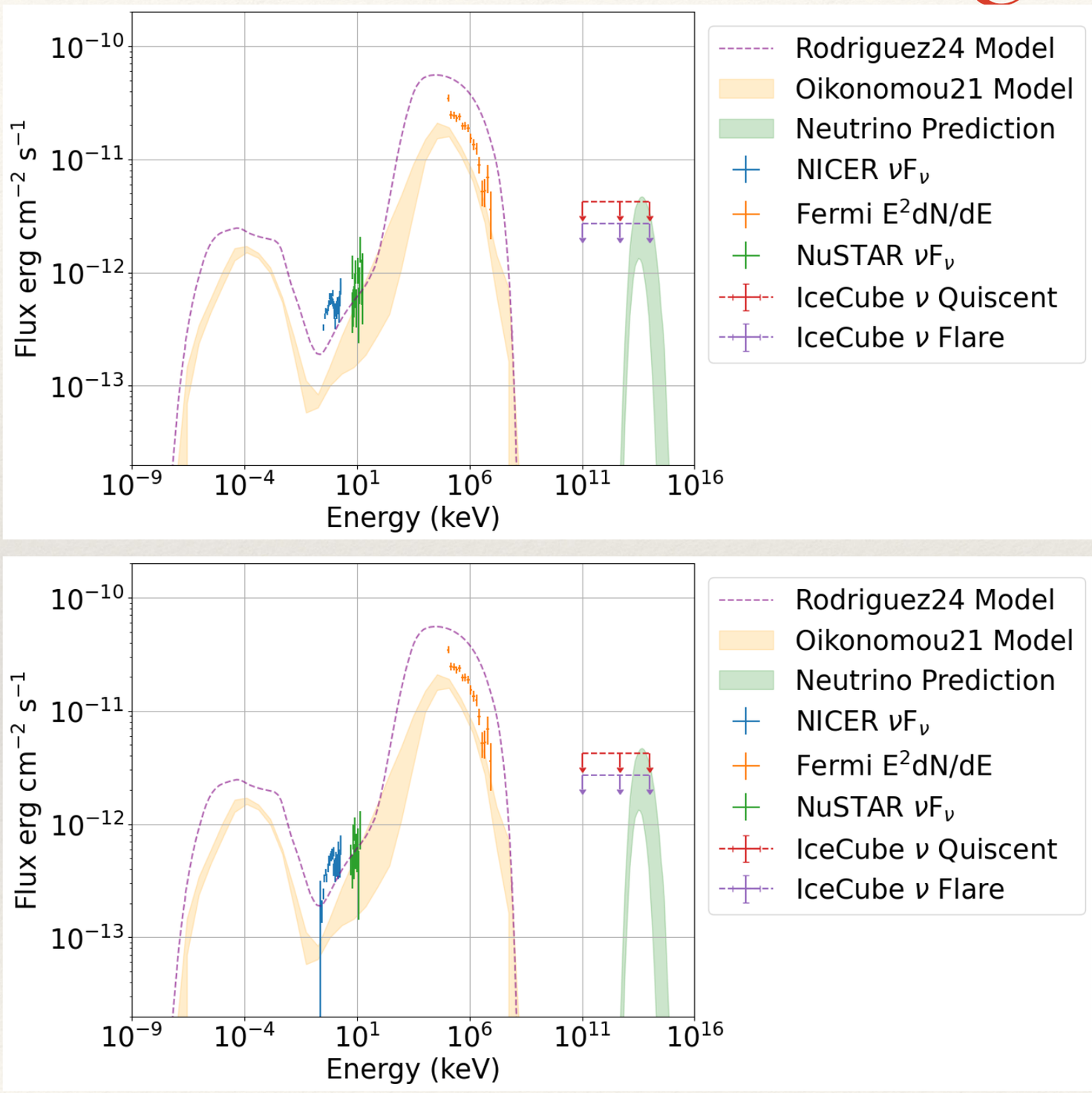




Preliminary results for Desai et al.

- Using NICER:
  - 21(-2) Observations of PKS1502+10633
  - 9(-1) for NGC 1068.
- 3 joint observations with NuSTAR:
  - One with zero exposure from NICER

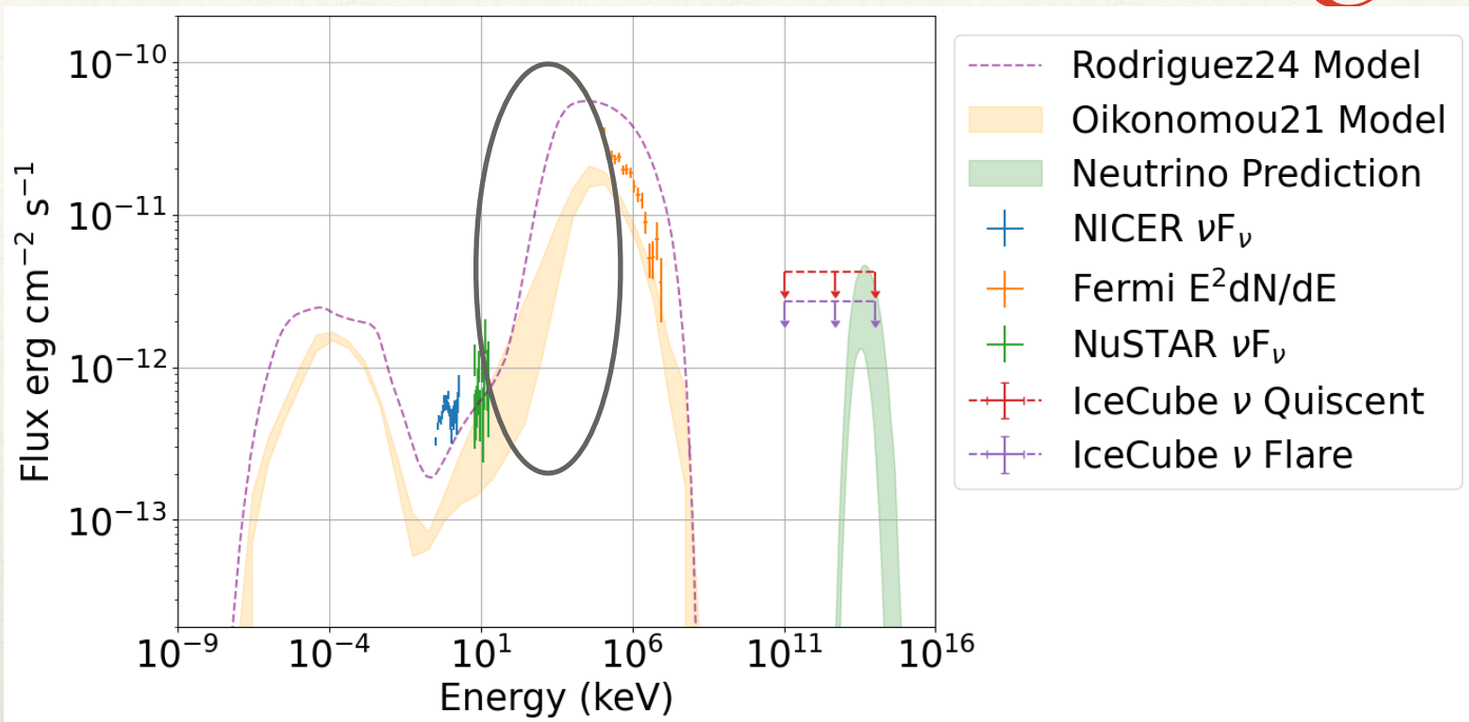
Multi-wavelength Results:



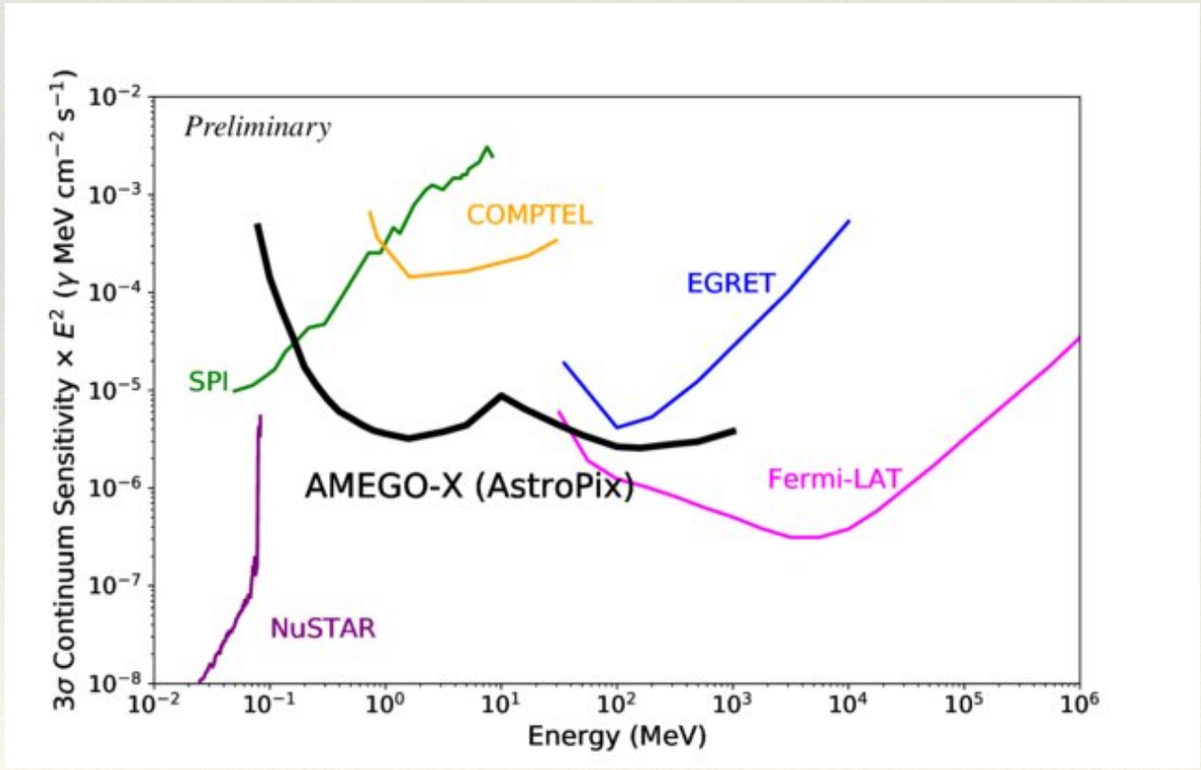
- Two Independent Observations with NICER+NuSTAR
- 2-year of Fermi LAT data is added (after accounting for varaibility).
- Models taken from Rodriguez, et al. 24 for comparision.

Desai et al. (In Prep)

Multi-wavelength Results:



- Importance of observing the (keV to MeV band)
- AMEGO should be able to put constraints on the model.



AMEGO-X
Mission Concept,
Caputo et al 2022

Both plots are E^2 dN/dE
and
1 MeV = 1.6e-6 ergs

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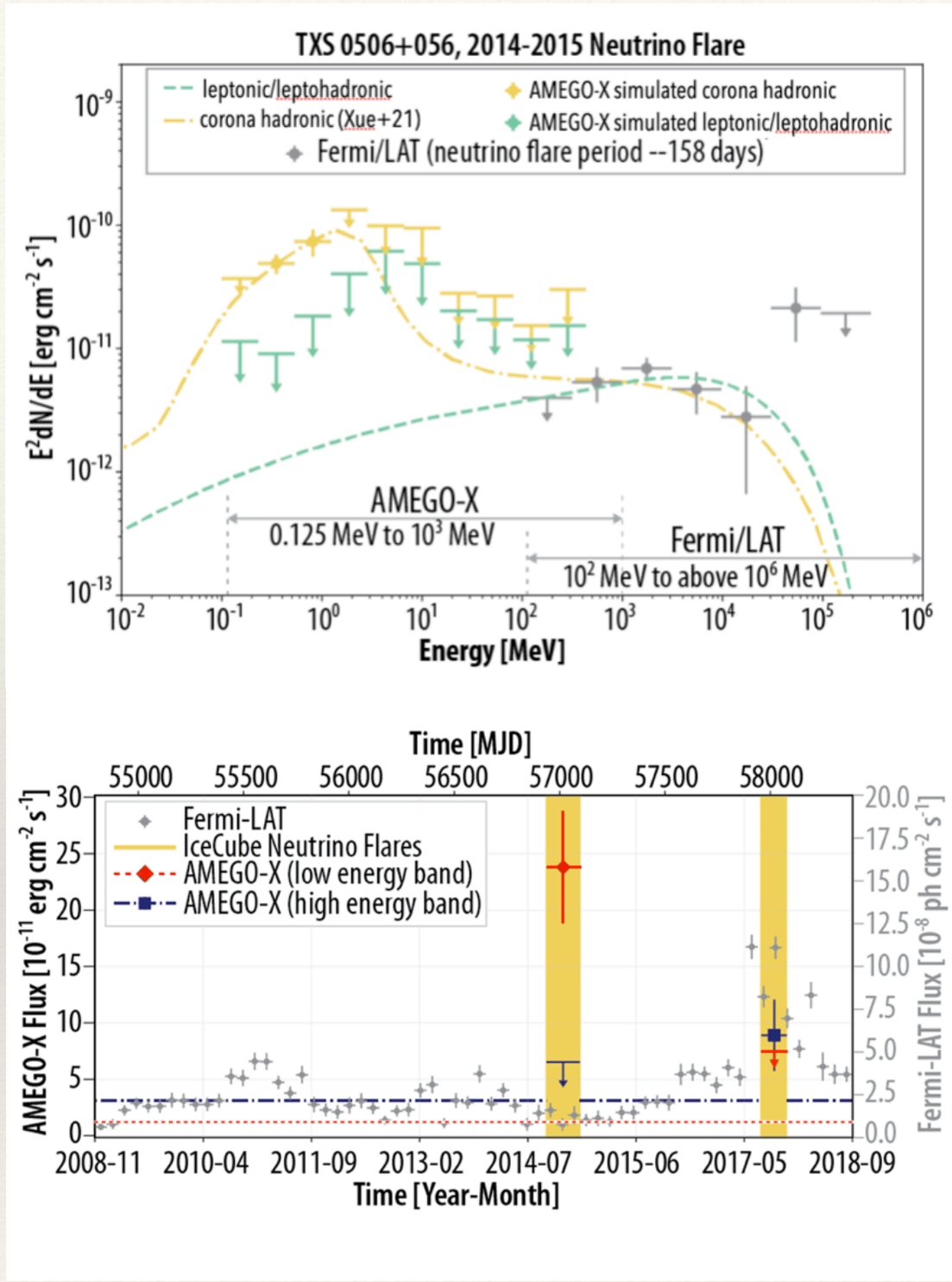
Importance of Future Missions:

- Advantages of missions like AMEGO for neutrino studies:
  - Realtime flare detection.
  - Stacking studies using MeV bright sources
  - Model limits which become extremely significant with multiwavelength data.
  - Archival studies after multi-year observations



AMEGO-X Mission Concept, Caputo et al 2022

Our Analysis Plan:

- Publish the studies (Multiwavelength and Multimessenger seperate papers)
- Expand source sample for multimessenger study
- Study both Blazars and Seyferts

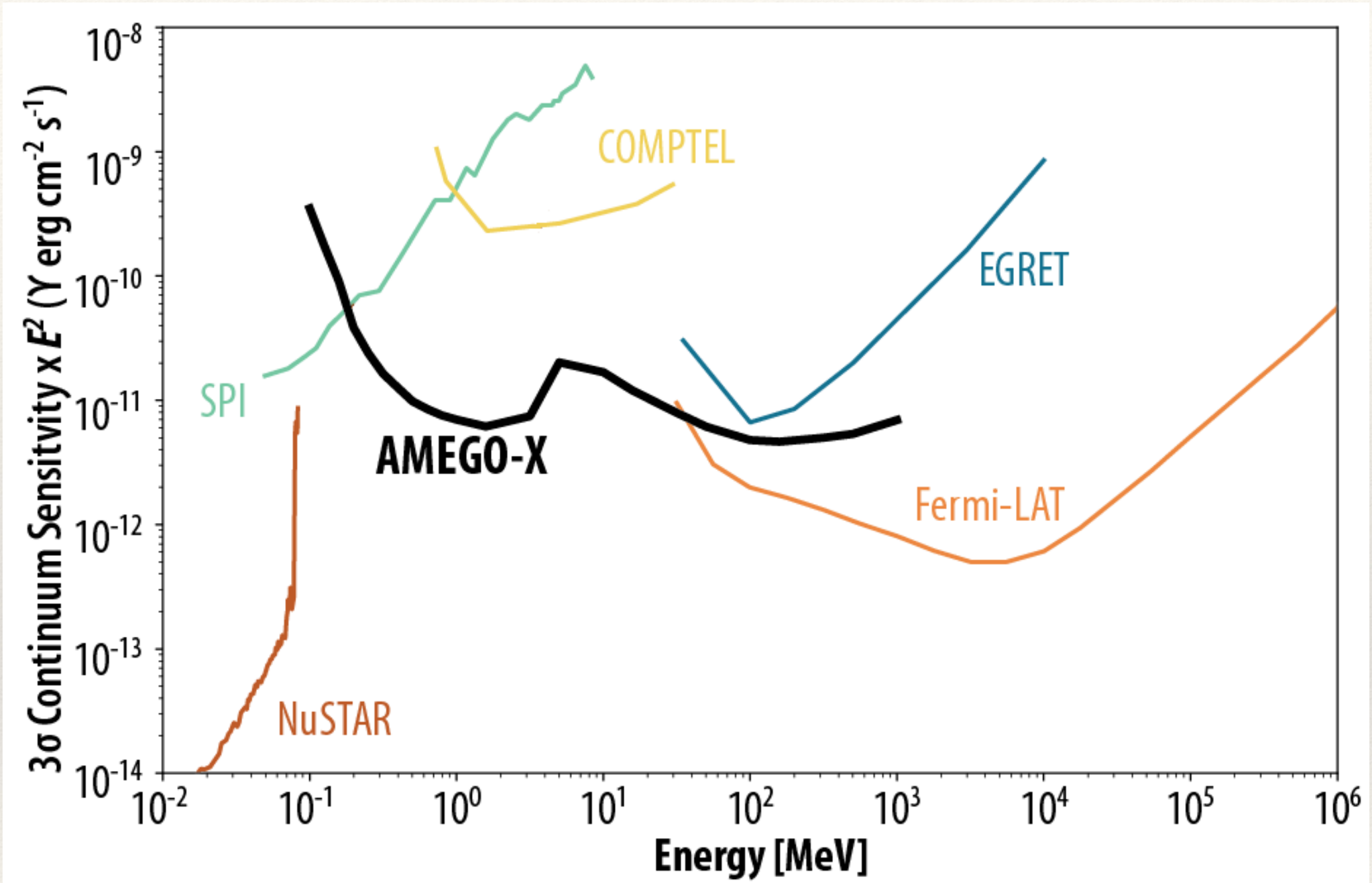
- Please feel free to contact me if you think your favourite AGN is a neutrino emitter and needs to be studied.

Thank You,

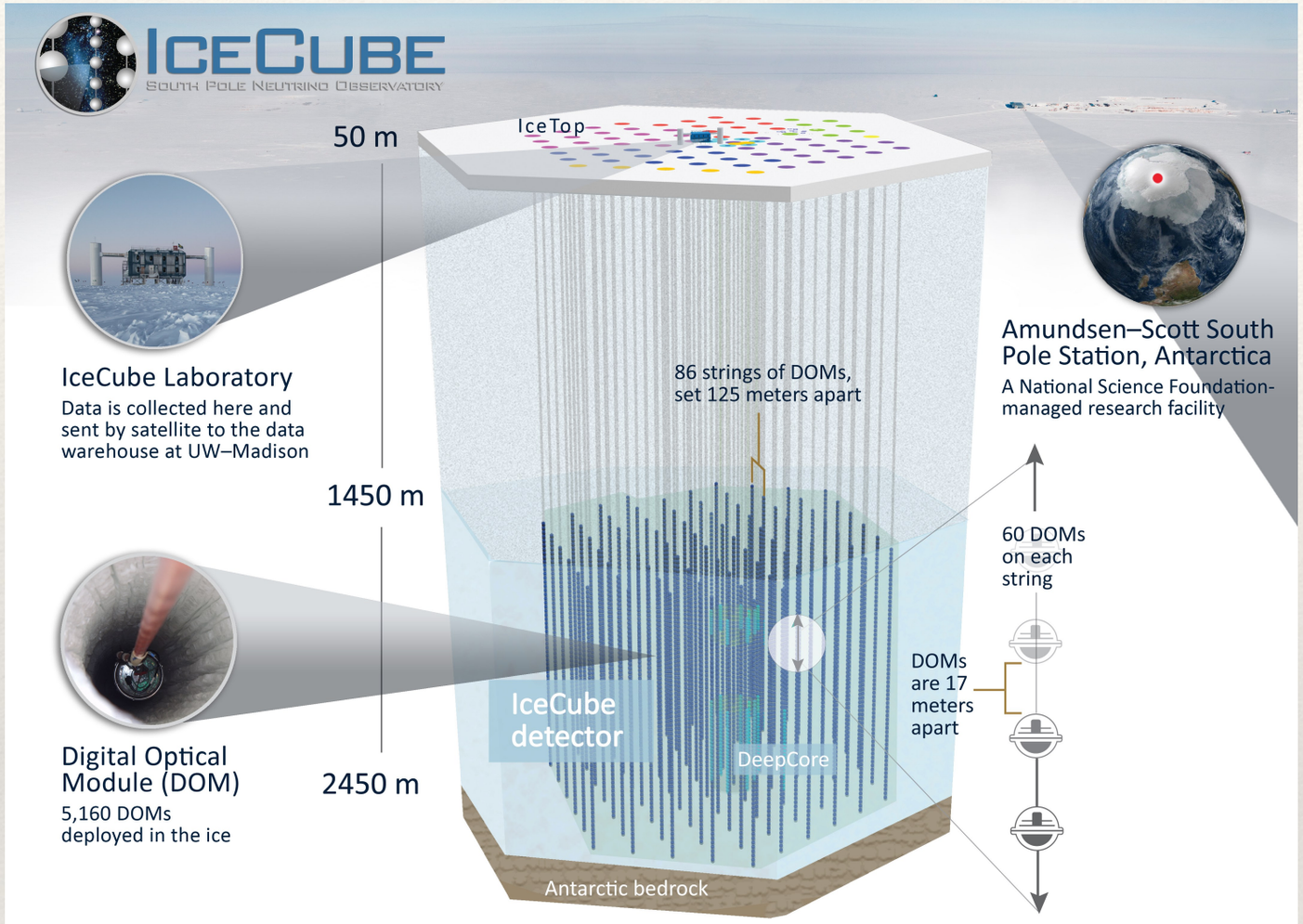
Questions?

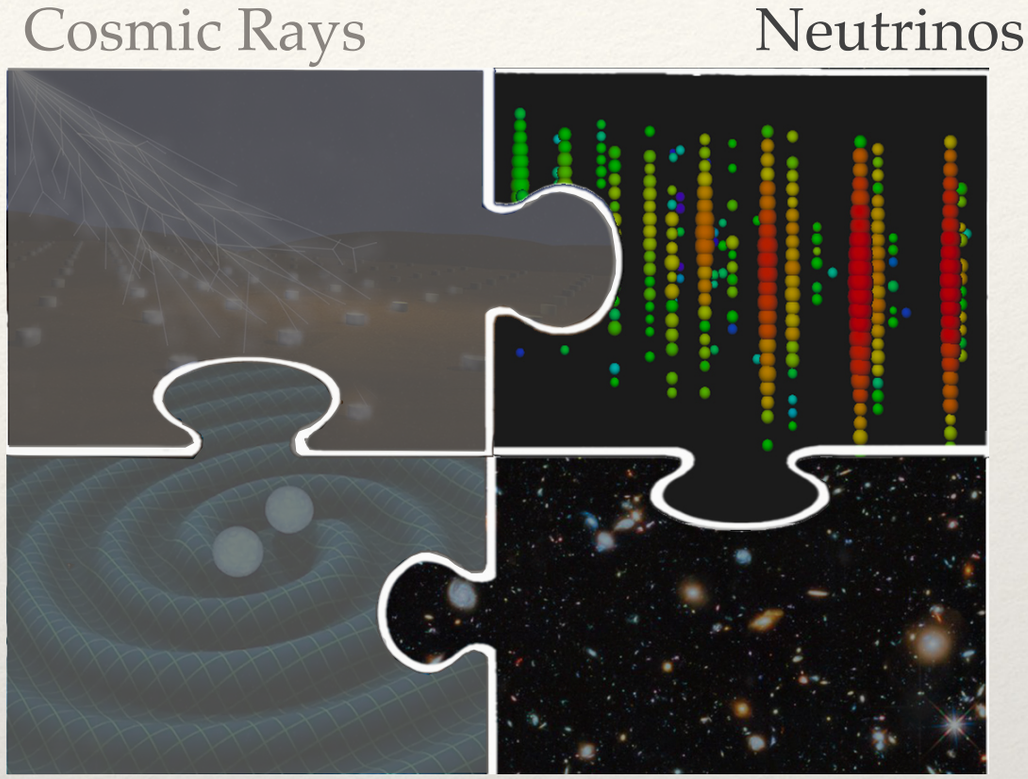
Backup Slides:

AMEGO Sensitivity:



The Multi-messenger Picture

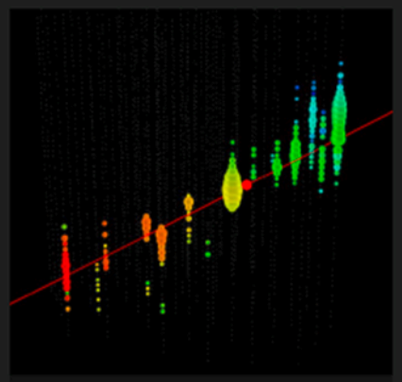




Neutral/Charged Current neutrinos

time

CC Muon Neutrino

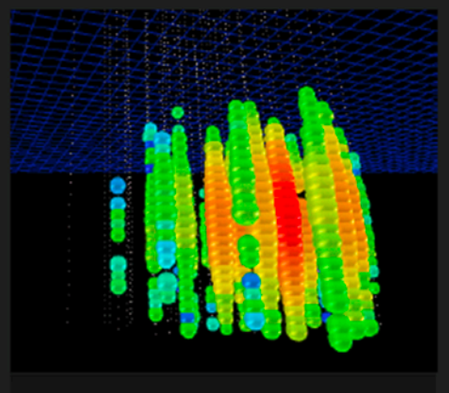


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino

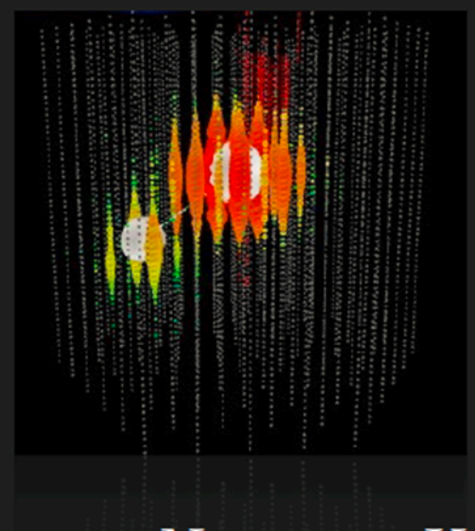


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino



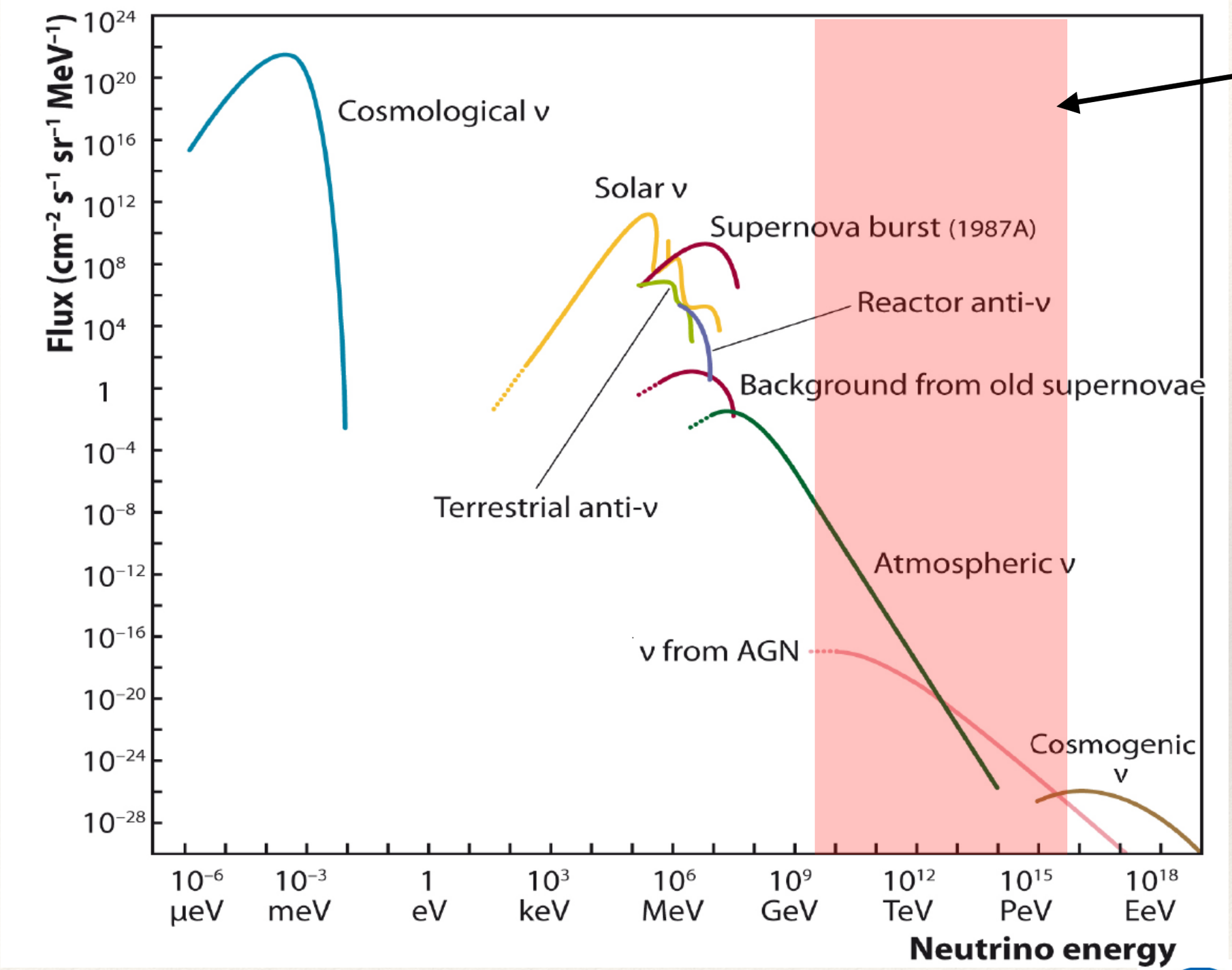
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" (≳10PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)

https://icecube.wisc.edu

IceCube Neutrino Energy



Can be detected by IceCube