Are X-rays the new γ-rays in neutrino astronomy?

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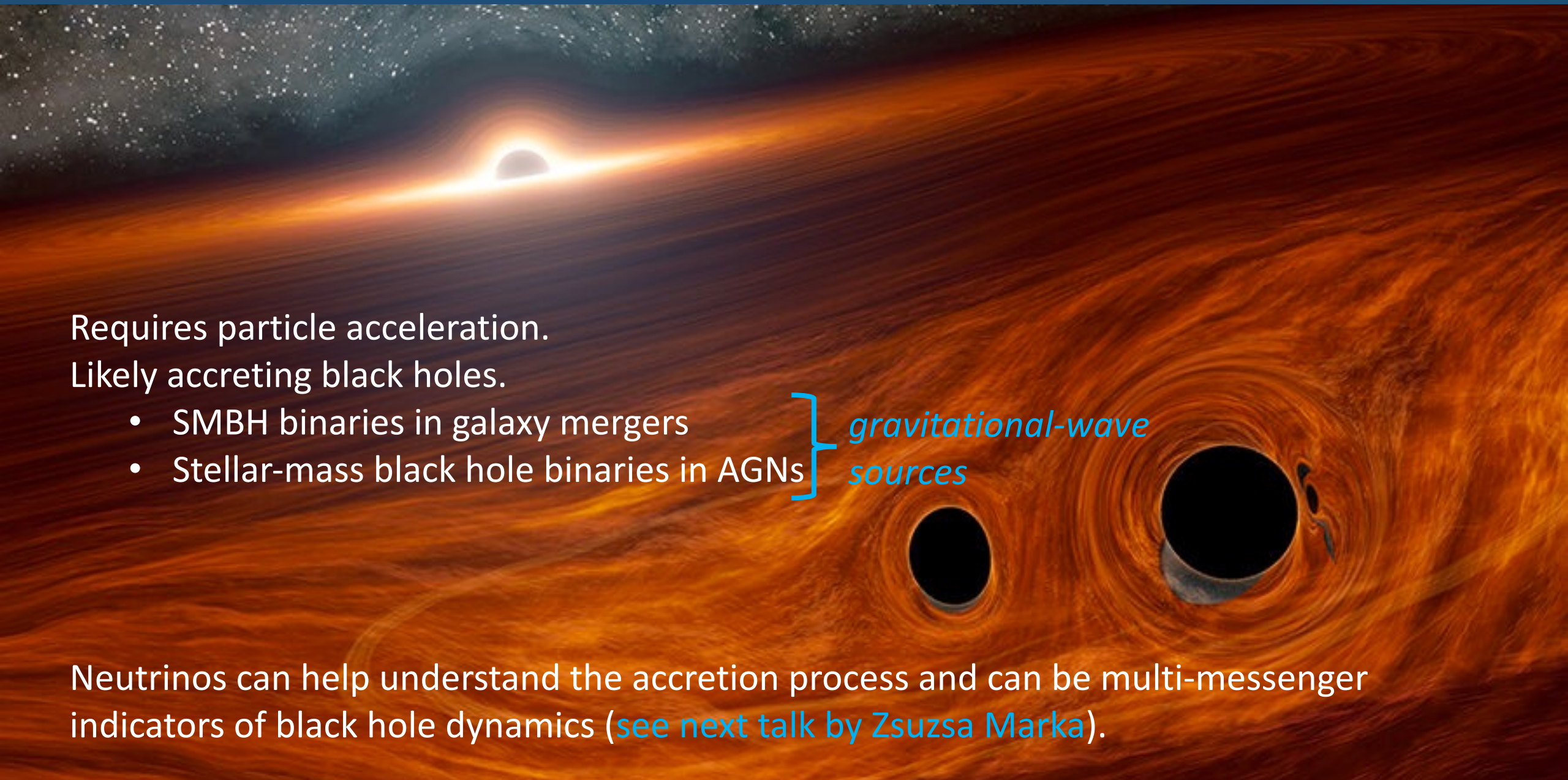
High-energy neutrino production and gravity



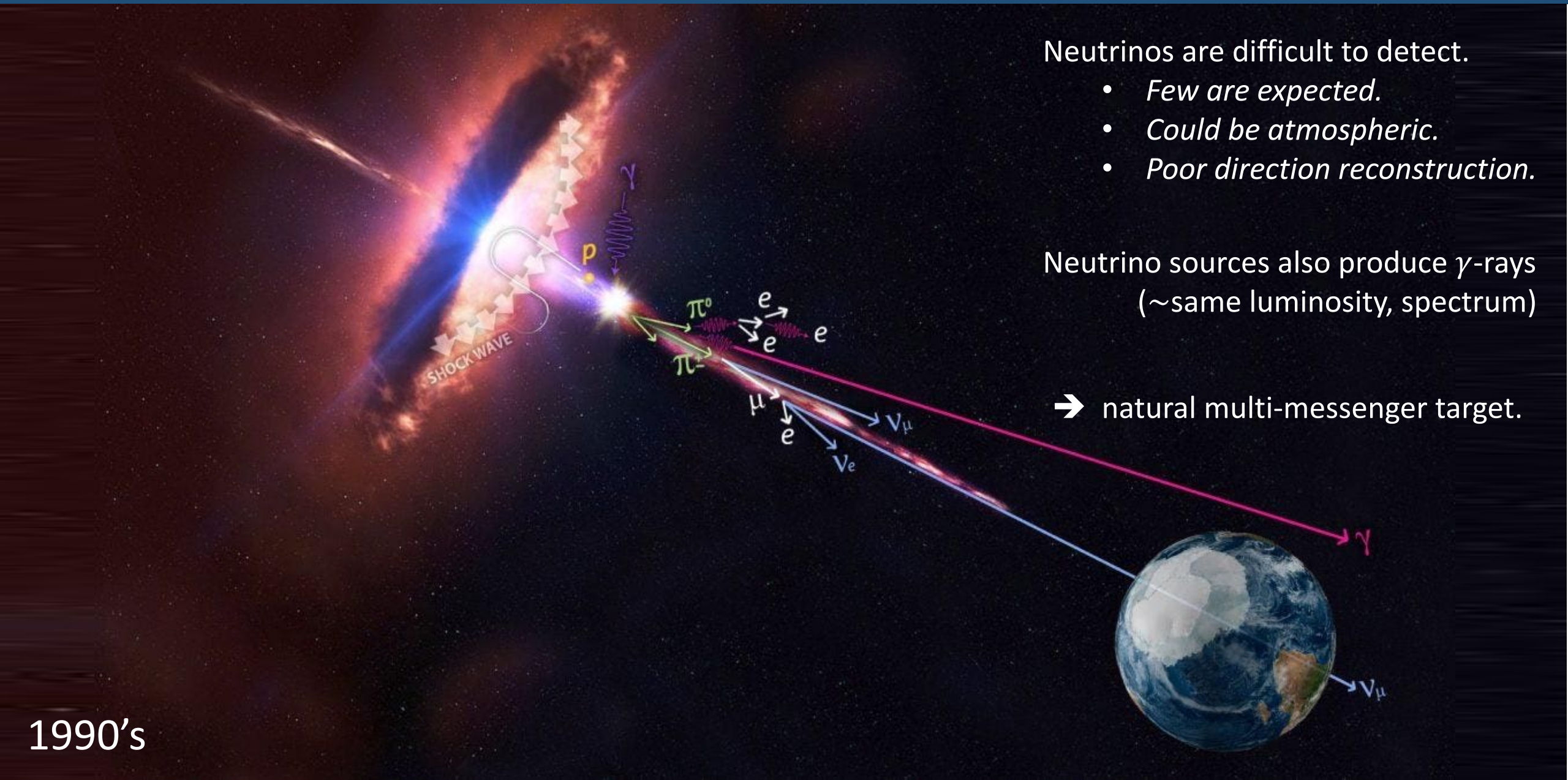
Requires particle acceleration.
Likely accreting black holes.

- SMBH binaries in galaxy mergers
- Stellar-mass black hole binaries in AGNs

} *gravitational-wave sources*

Neutrinos can help understand the accretion process and can be multi-messenger indicators of black hole dynamics (see next talk by Zsuzsa Marka).

γ-rays as multi-messenger counterparts



Neutrinos are difficult to detect.

- *Few are expected.*
- *Could be atmospheric.*
- *Poor direction reconstruction.*

Neutrino sources also produce γ-rays (~same luminosity, spectrum)

➔ natural multi-messenger target.

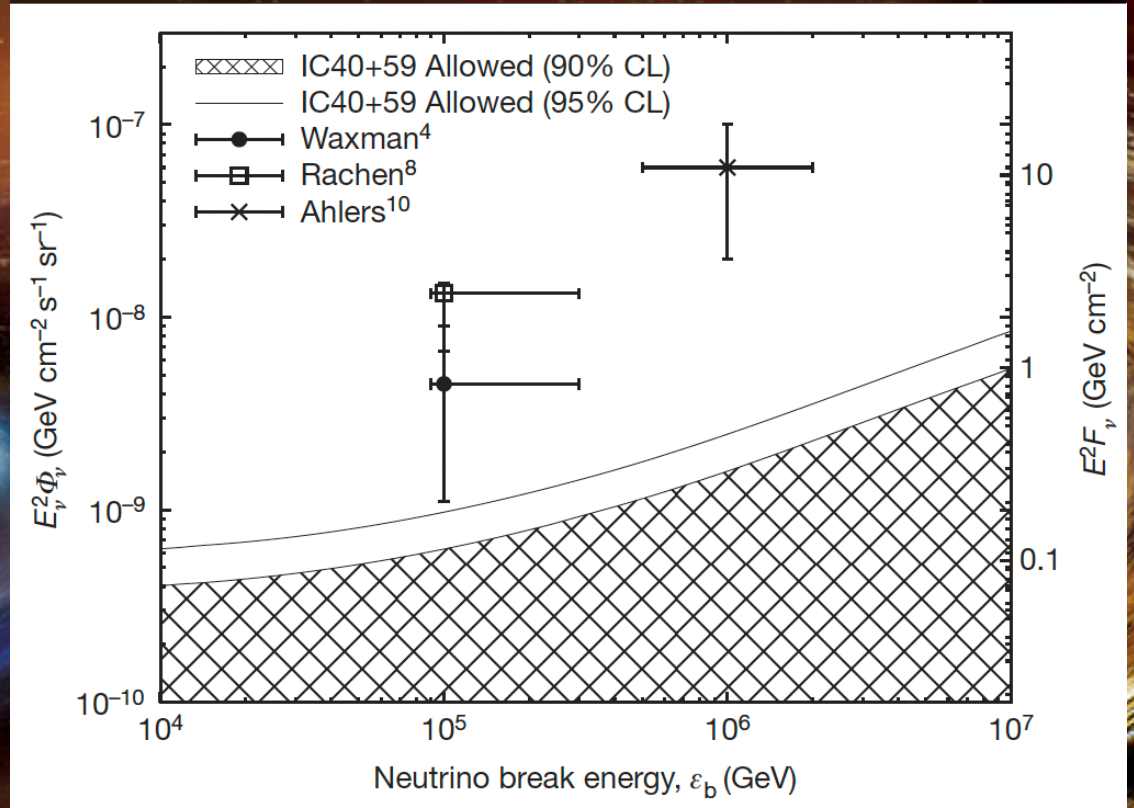
1990's

Gamma-ray bursts?

Multi-messenger neutrino sources?

- Bright in γ-rays
- Total γ-ray energy production comparable to that of cosmic-rays (Waxman & Bahcall 1997)
- Short transients ➔ ~no background

IceCube Nature 2012



An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

Blazars?

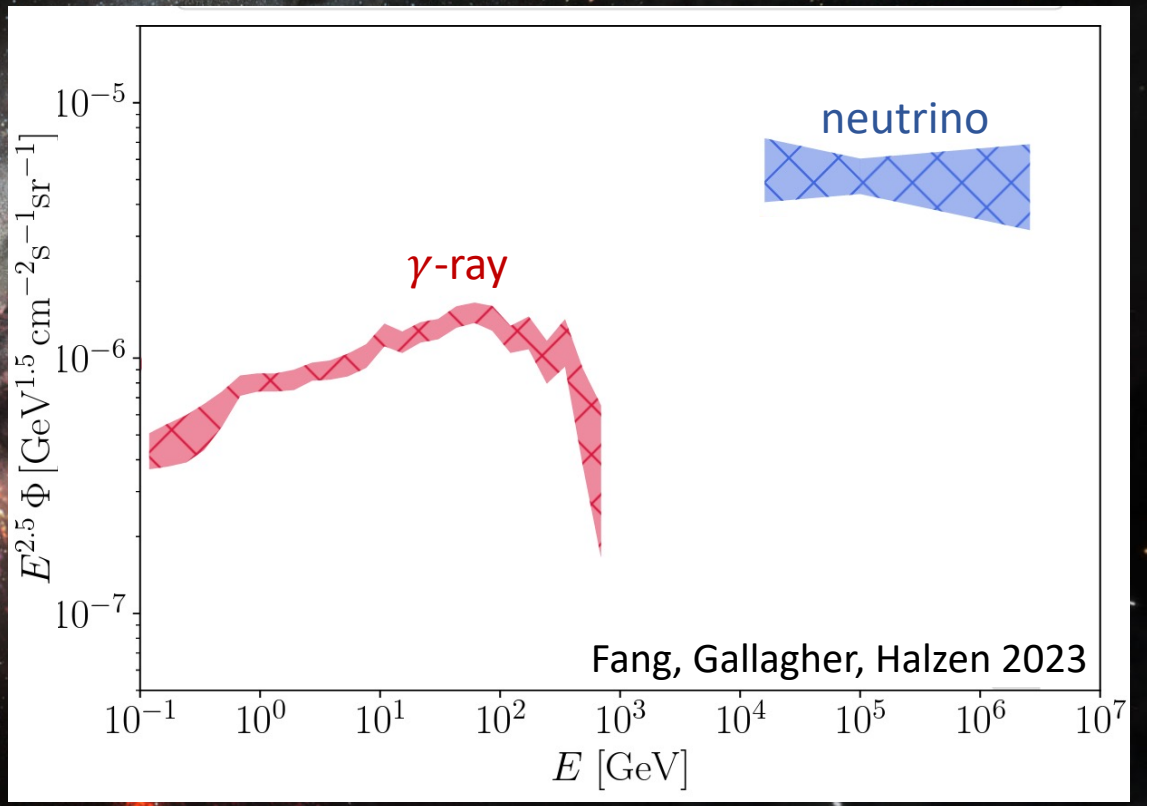
Active galactic nuclei with jets pointing towards Earth.

Promising option:

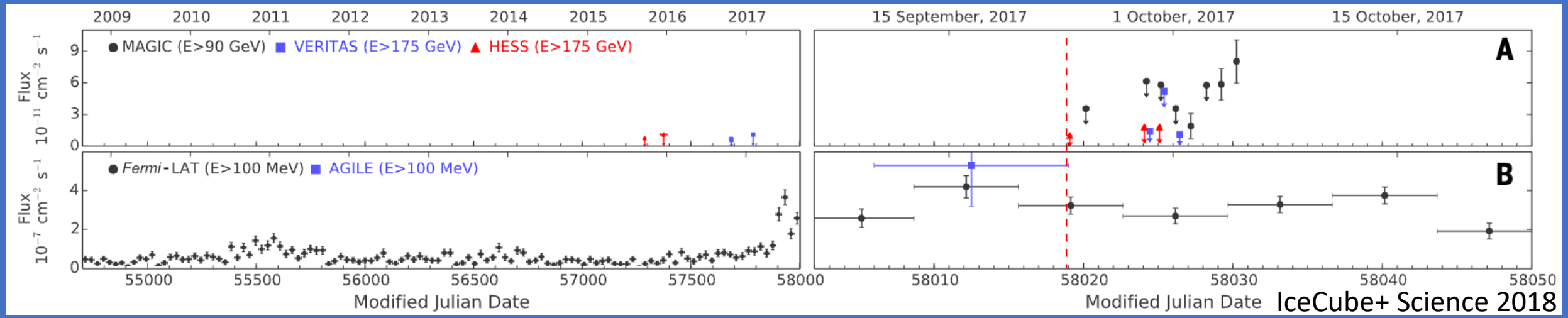
- **Few sources can accelerate particles to >PeV**
- **Majority of cosmic γ-rays**
  (Fermi-LAT; $86^{+16}_{-14}\%$ for > 50GeV; Mauro 2016)

γ-ray diffuse flux might be mostly cascaded emission from neutrino source.

Stacked analyses put **limits** on blazar contribution (e.g. $< 30\%$, Fermi 2LAC blazars; Aartsen+ 2017)



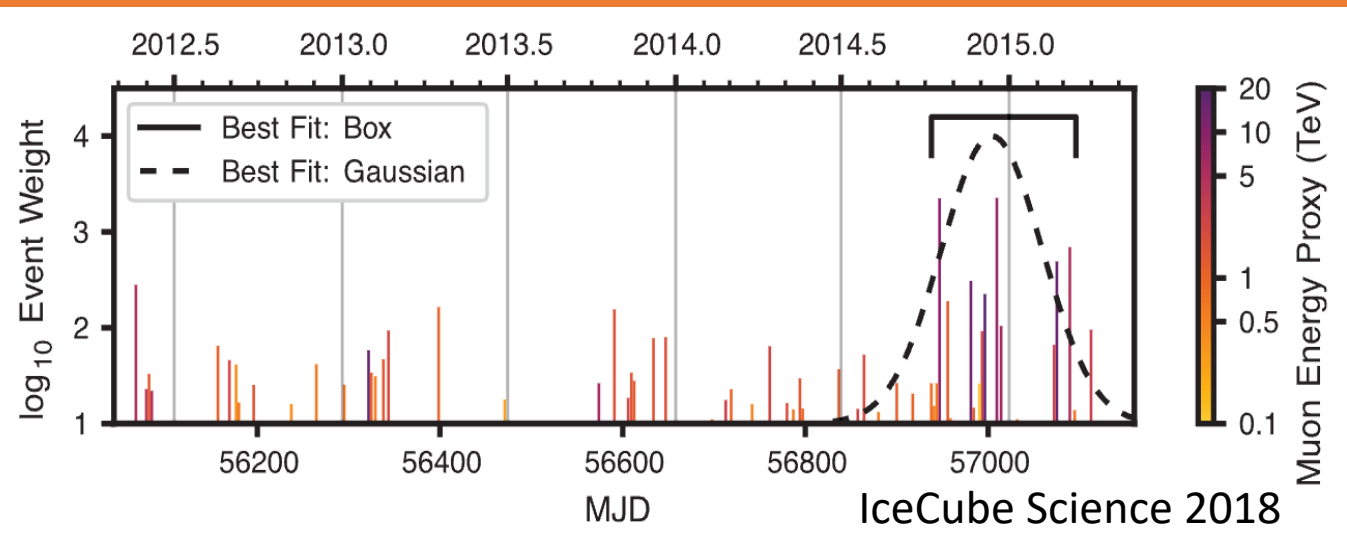
Multi-messenger discovery – blazar TXS0506+056



- Neutrino alert: IceCube-170922A (290 TeV)
- Direction coincident with blazar TXS 0506+056
- Blazar was in flaring state

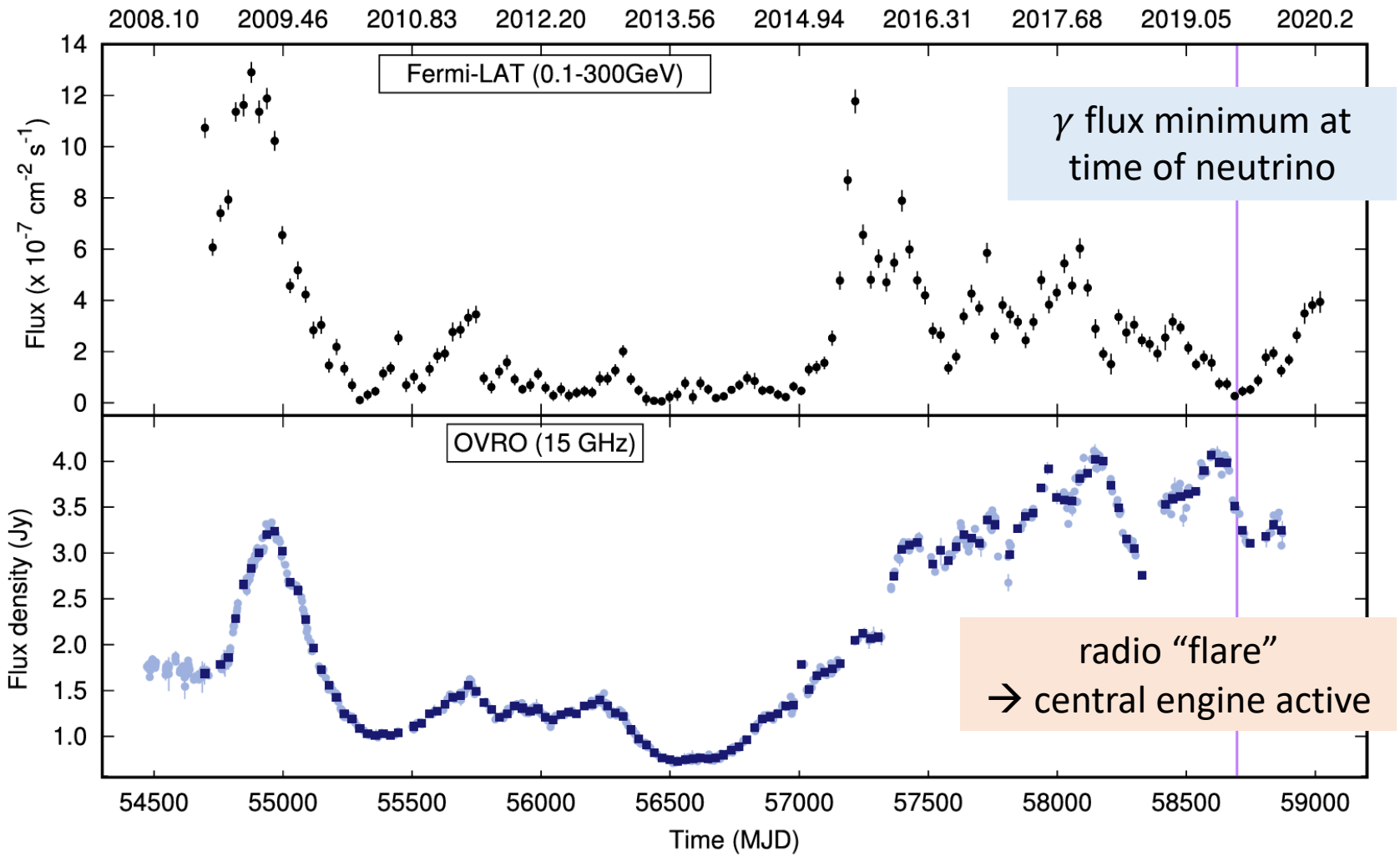
- Variability? (e.g. MASTER flare 2h after ν)

- Further neutrinos detected in 2014-2015.
  - ❑ No flare ☹



γ-suppressed blazars?

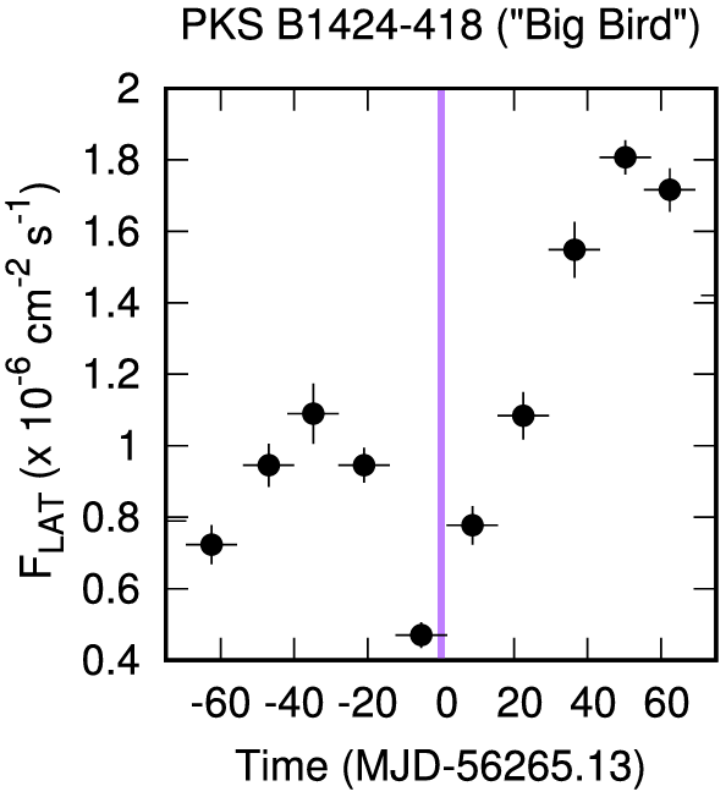
New association: blazar **PKS1502+106** coincident with neutrino IceCube-190730A.



γ flux minimum at time of neutrino

radio "flare"
→ central engine active

Other blazar associations: similar minima / suppression.

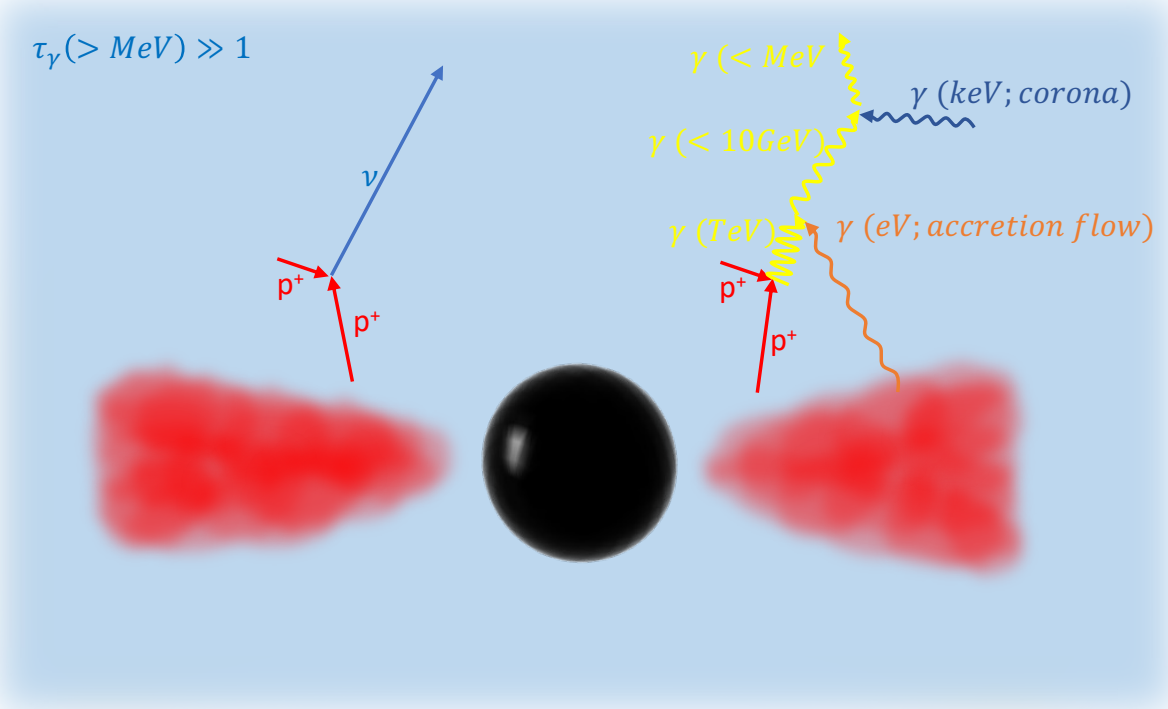


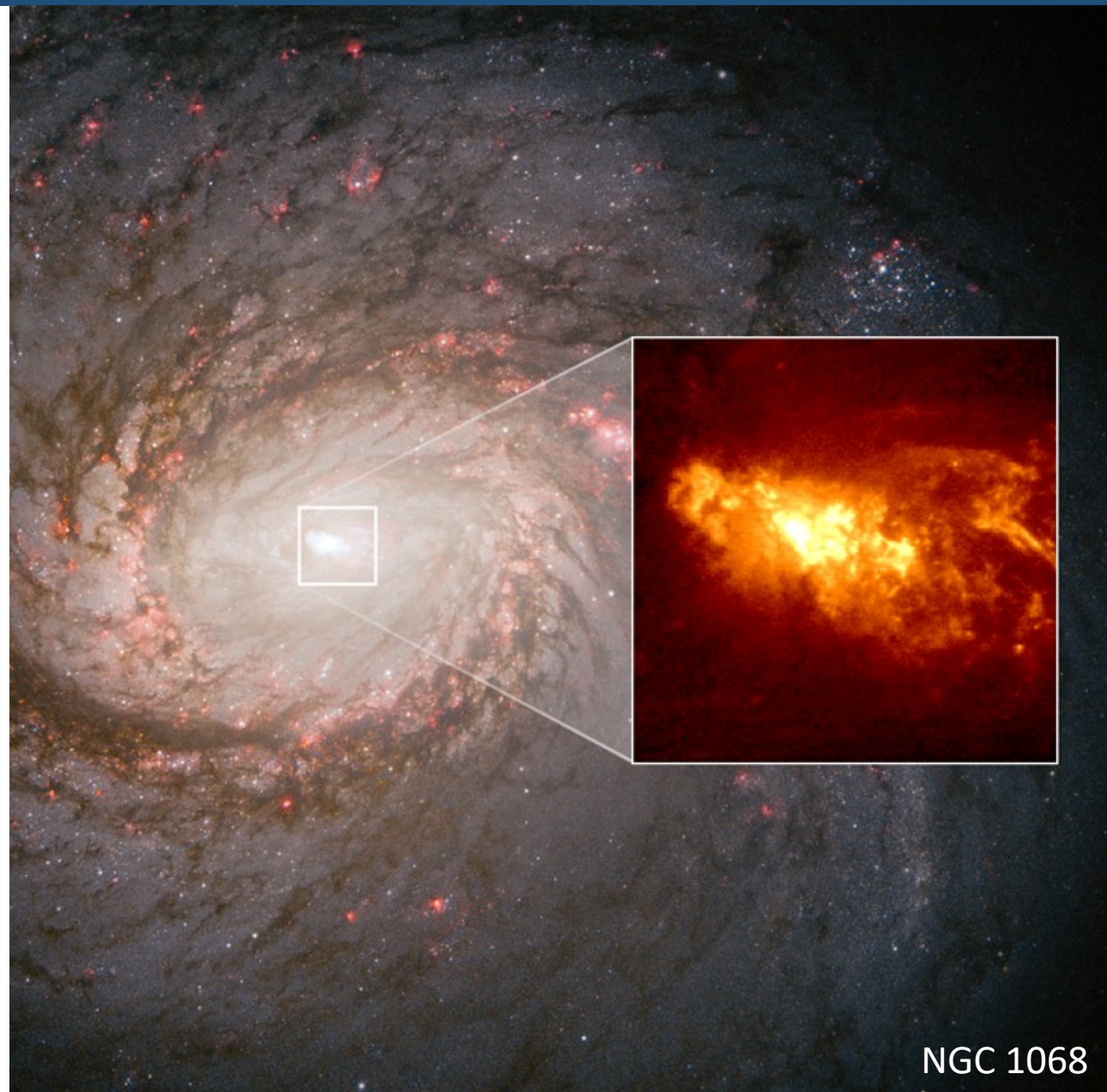
More neutrinos when source is γ-obscure?

Kun, Bartos, Becker Tjus, Biermann, Halzen, Mezo ApJ Lett 2021

(non-blazar) AGNs as neutrino sources

- Seyfert **NGC 1068:** detected as bright neutrino source.
- Neutrino flux: $\sim 100\times$ greater than γ-ray flux (MAGIC)
- Most Seyferts are radio quiet – no jet?
- Attenuation due to accretion flow + corona ➔ Hard X-ray?





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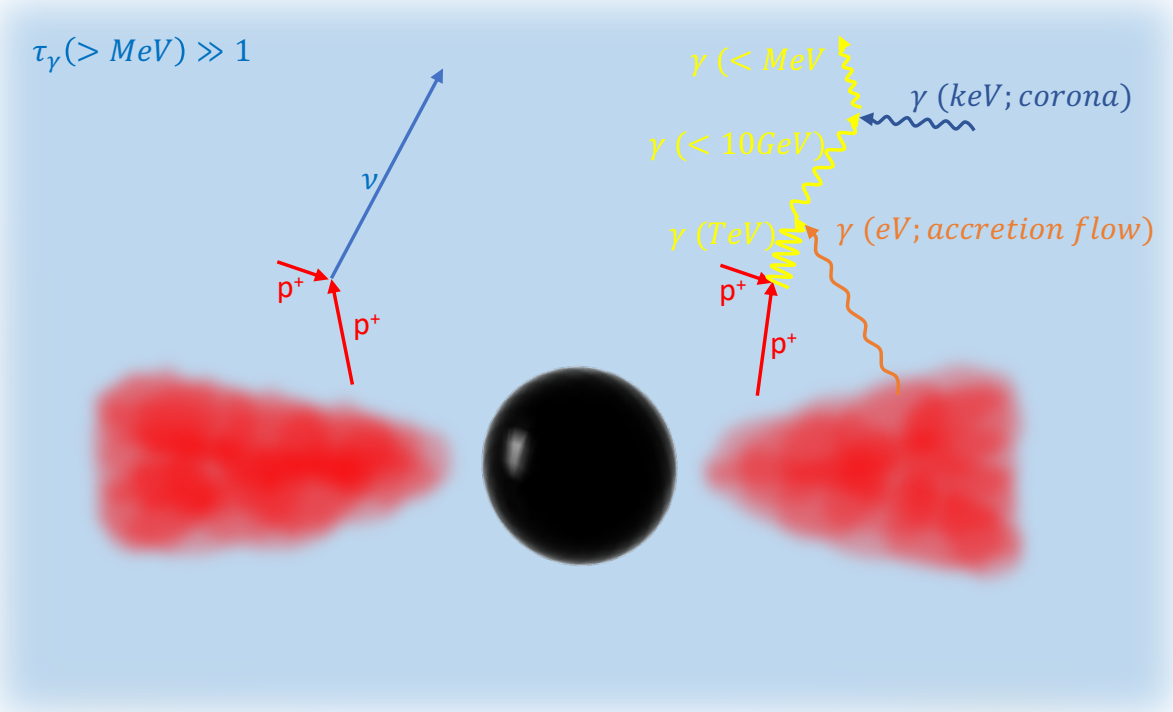
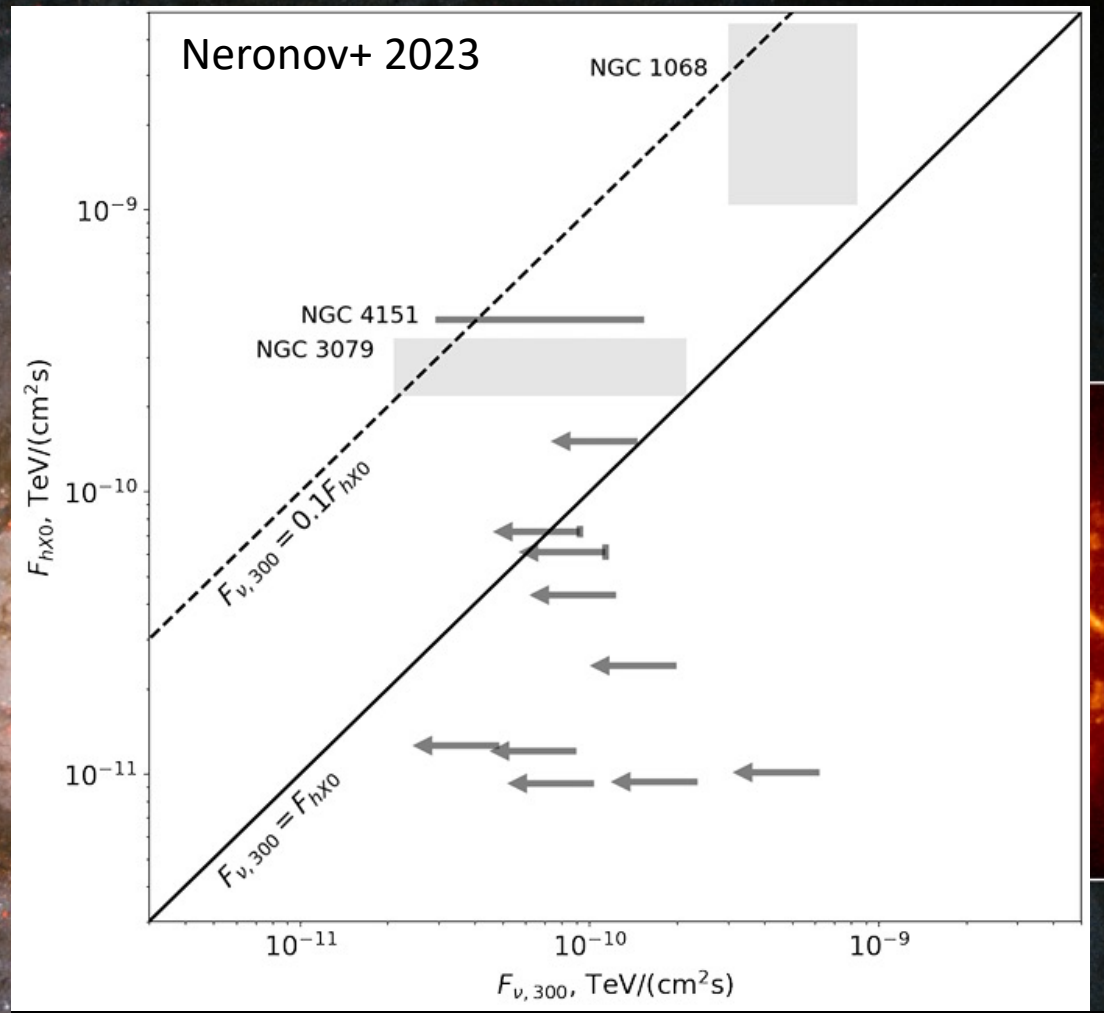
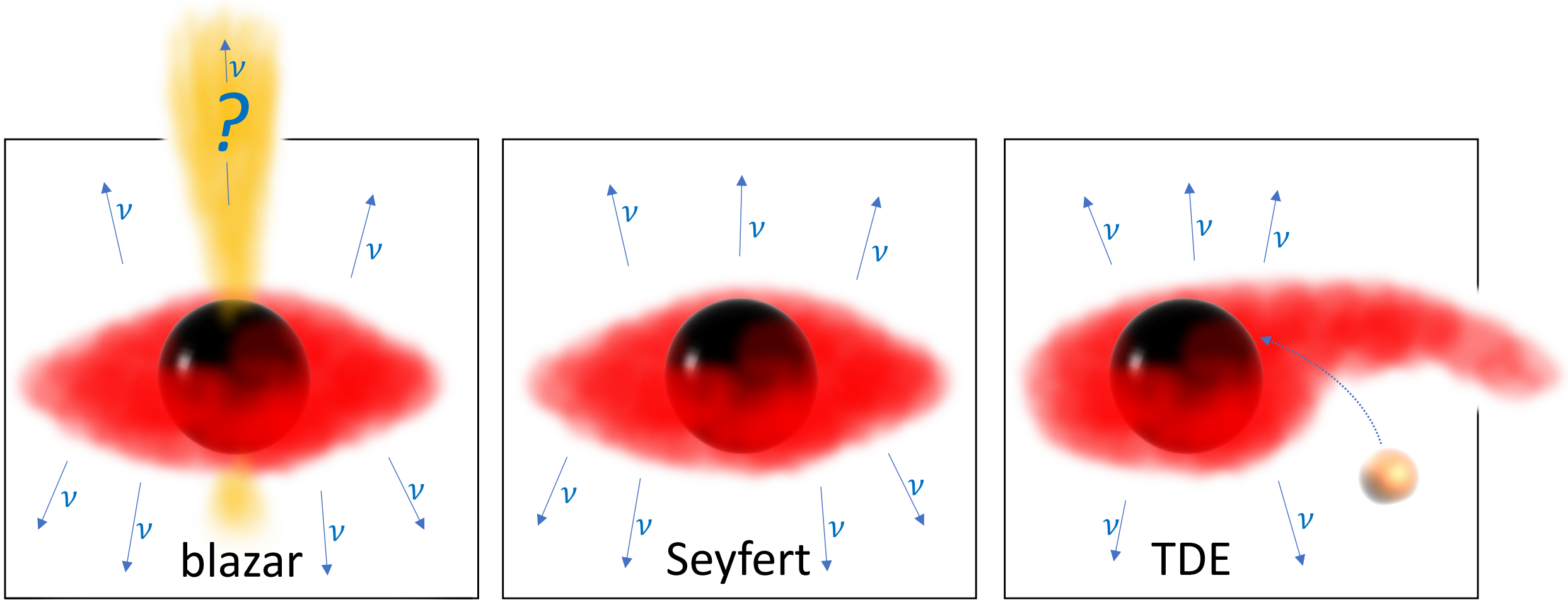




- Use AGN hard X-ray flux to look for neutrino sources.
- Two more AGNs: NGC 4151 & NGC 3079
- Hard X-ray (Swift-BAT extrapolated)

Difference between emission mechanisms?



All detected sources are accreting supermassive black holes.

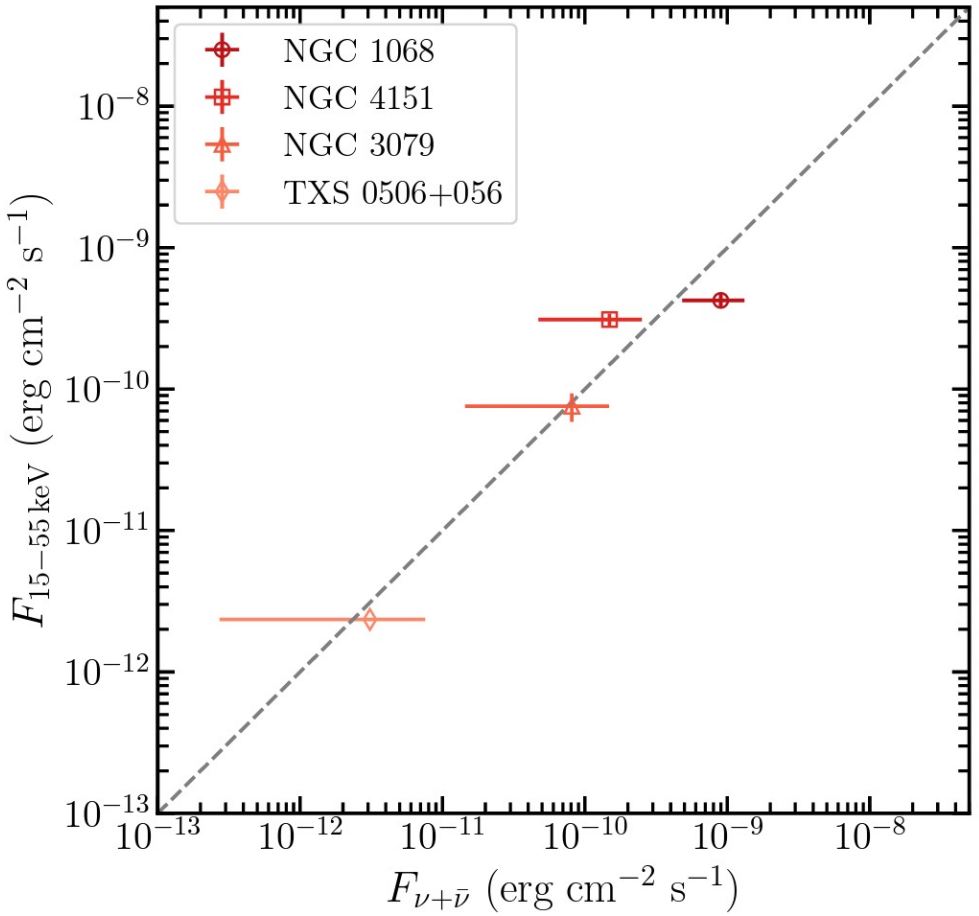
Whatever produces neutrinos in non-blazar AGNs should also work in blazars.

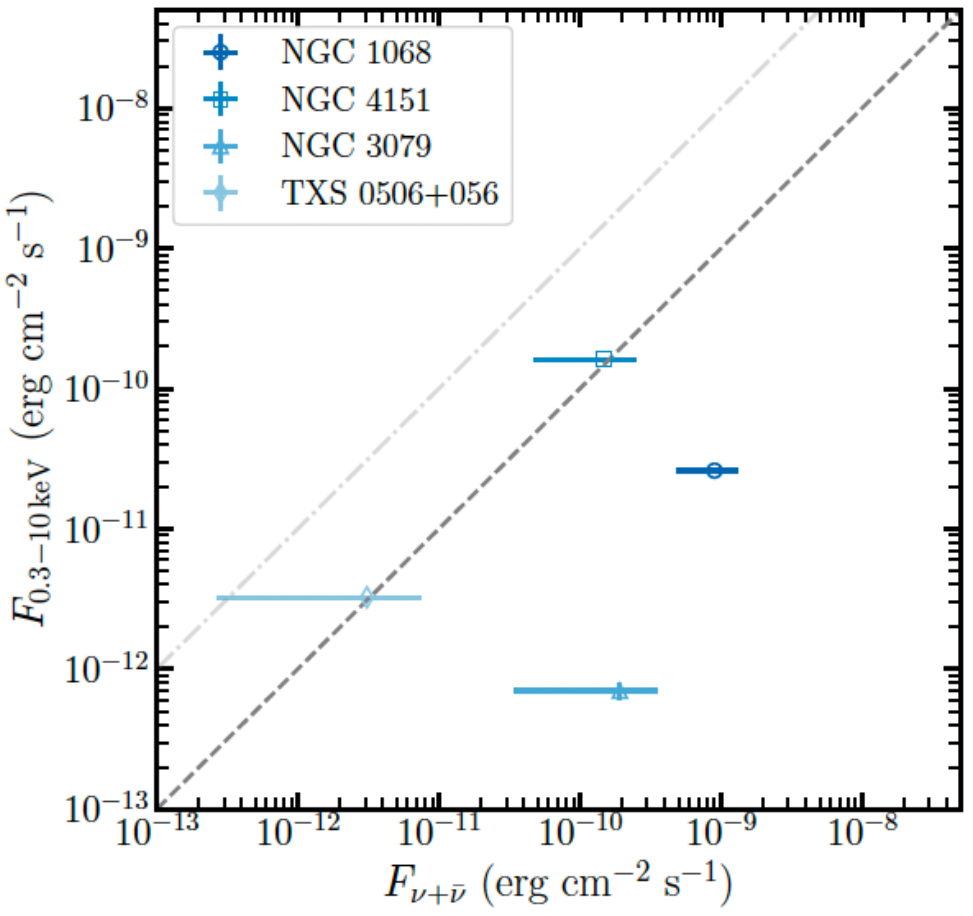
Difference between emission mechanisms?

Updated Seyfert hard X-ray using NuSTAR data – strengthened correlation

✓ Connection also works for TXS 0506+056

❑ No similar association for soft X-rays



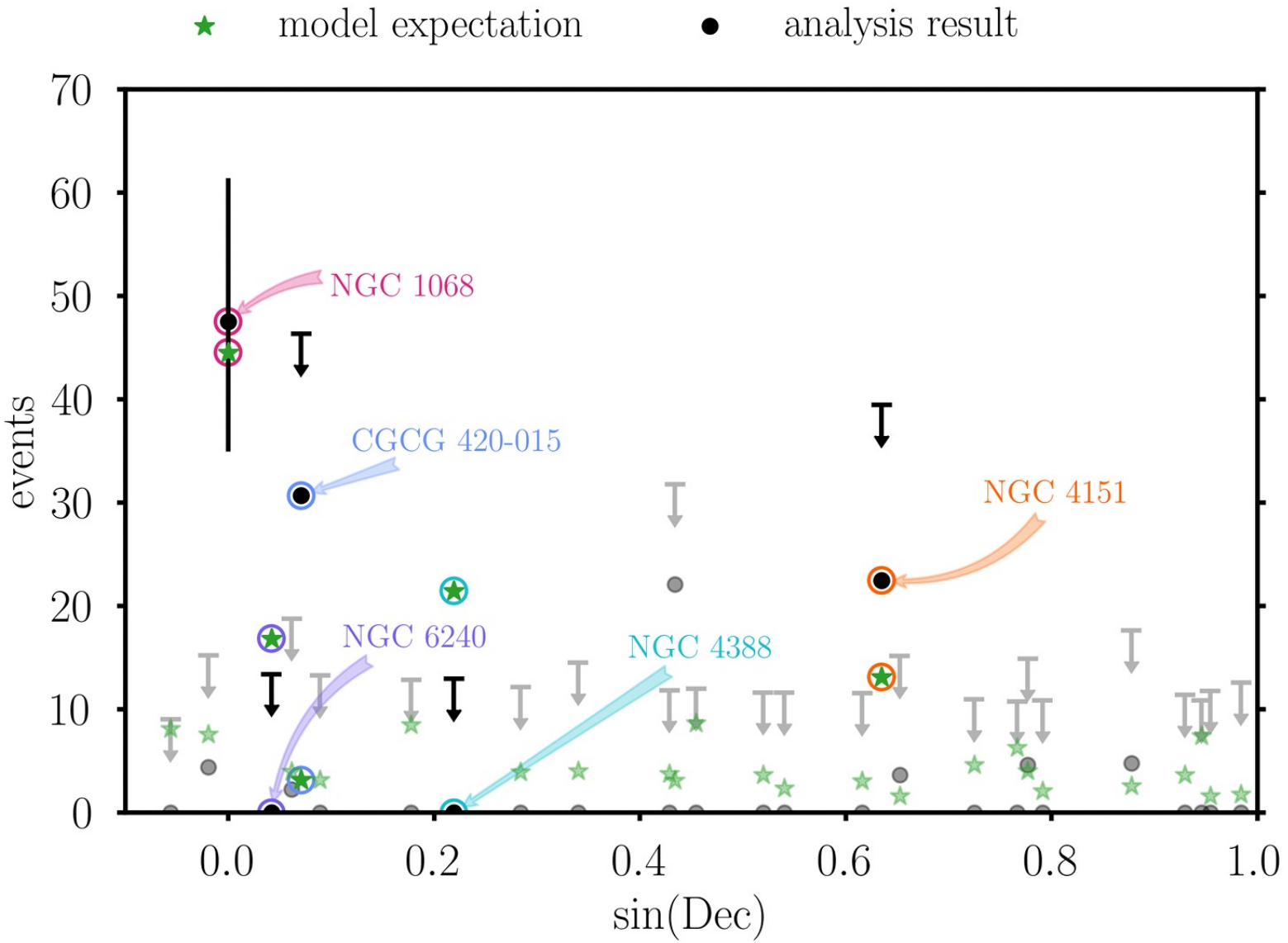


Kun, Bartos, Becker Tjus, Biermann, Franckowiak, Halzen, del Palacio 2024

Other AGNs?

IceCube neutrino search over X-ray-bright AGNs:

- Search only over the AGNs brightest in X-rays.
- Neutrino fluxes consistent with expectations based on X-ray flux
- More “borderline” AGNs that may rise over the detection in the near future.



IceCube 2024 (2406.07601)

Summary

- Neutrino sources appear to be γ-obscure
- All neutrino associations so far are accretion supermassive black holes (blazars, Seyferts, TDEs?)
- Could their neutrino production be similar?
- Blazar: individual neutrinos appear to occur in γ "dips"
  - Beam dump?
- Hard X-ray flux ≈ neutrino flux in 3 Seyferts & TXS 0506+056
  - They are γ obscure
  - X-ray emission can help identify neutrino sources.
  - Similar level of attenuation = similar process/location?
  - Could emission mechanism be related for blazars and Seyferts?