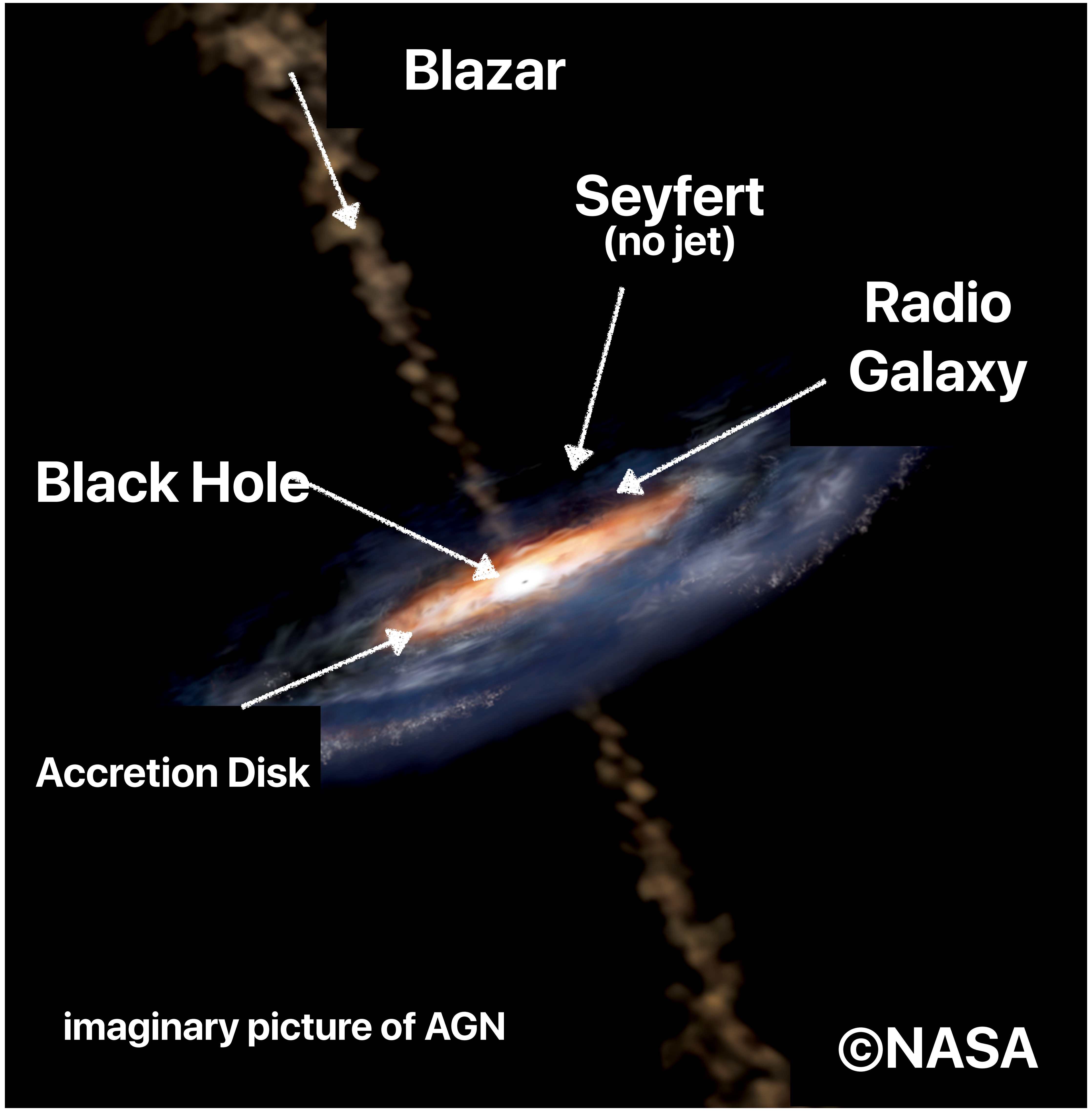
Prospects for Observations of Jetted and Unjetted AGNs with LST

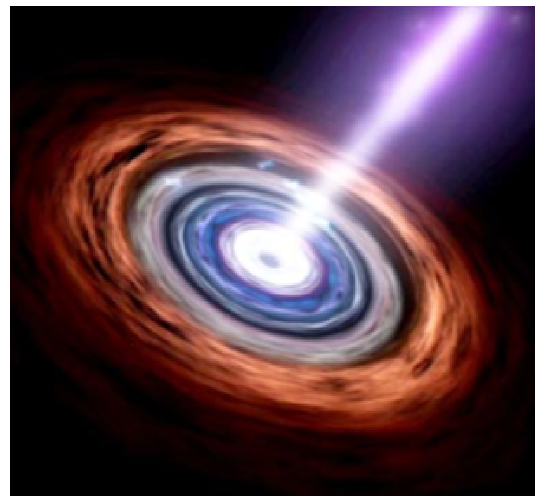
Yoshiyuki Inoue

CTA-Japan Meeting @ Kashiwa, 2023-02-07

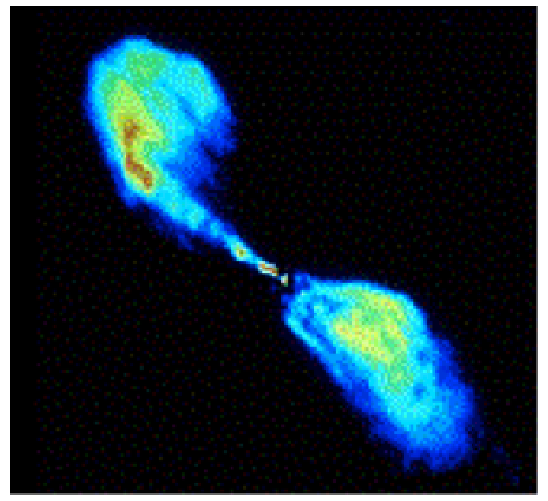
Contents

Main aims of AGN studies





- Blazar (~0.1% of AGNs)
  - Jet property

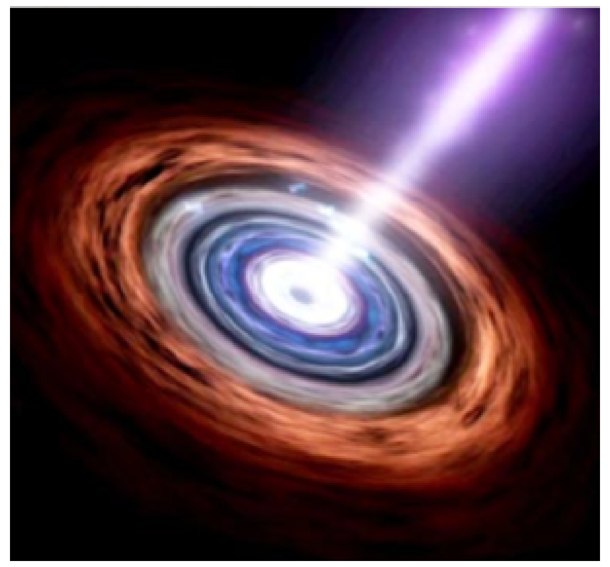


- Radio galaxy (~10% of AGNs)
  - Link between accretion and jet

- Seyfert (~90% of AGNs)
  - Accretion process

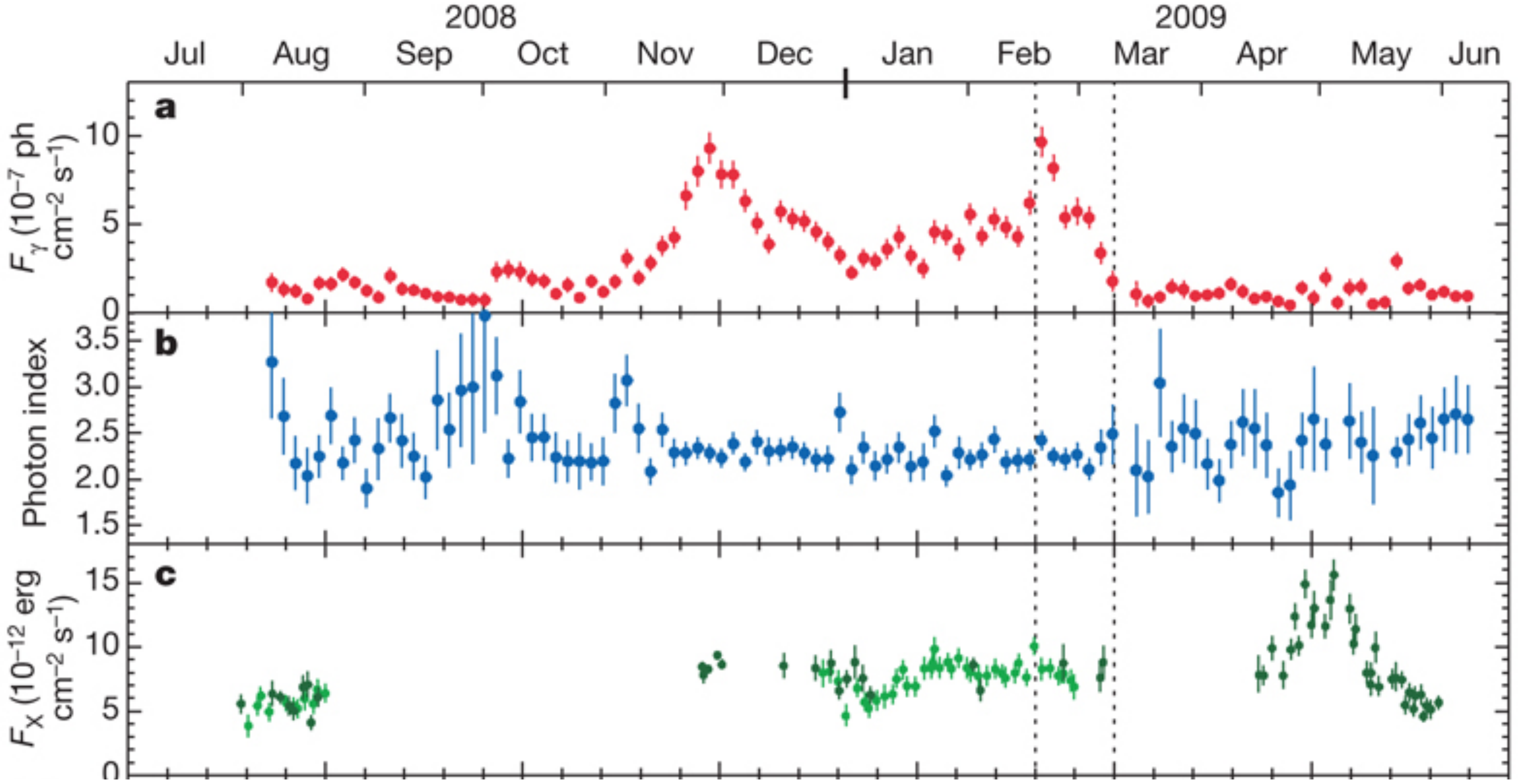
See Vovk's talk for the cosmological aspect

Jetted AGN Science

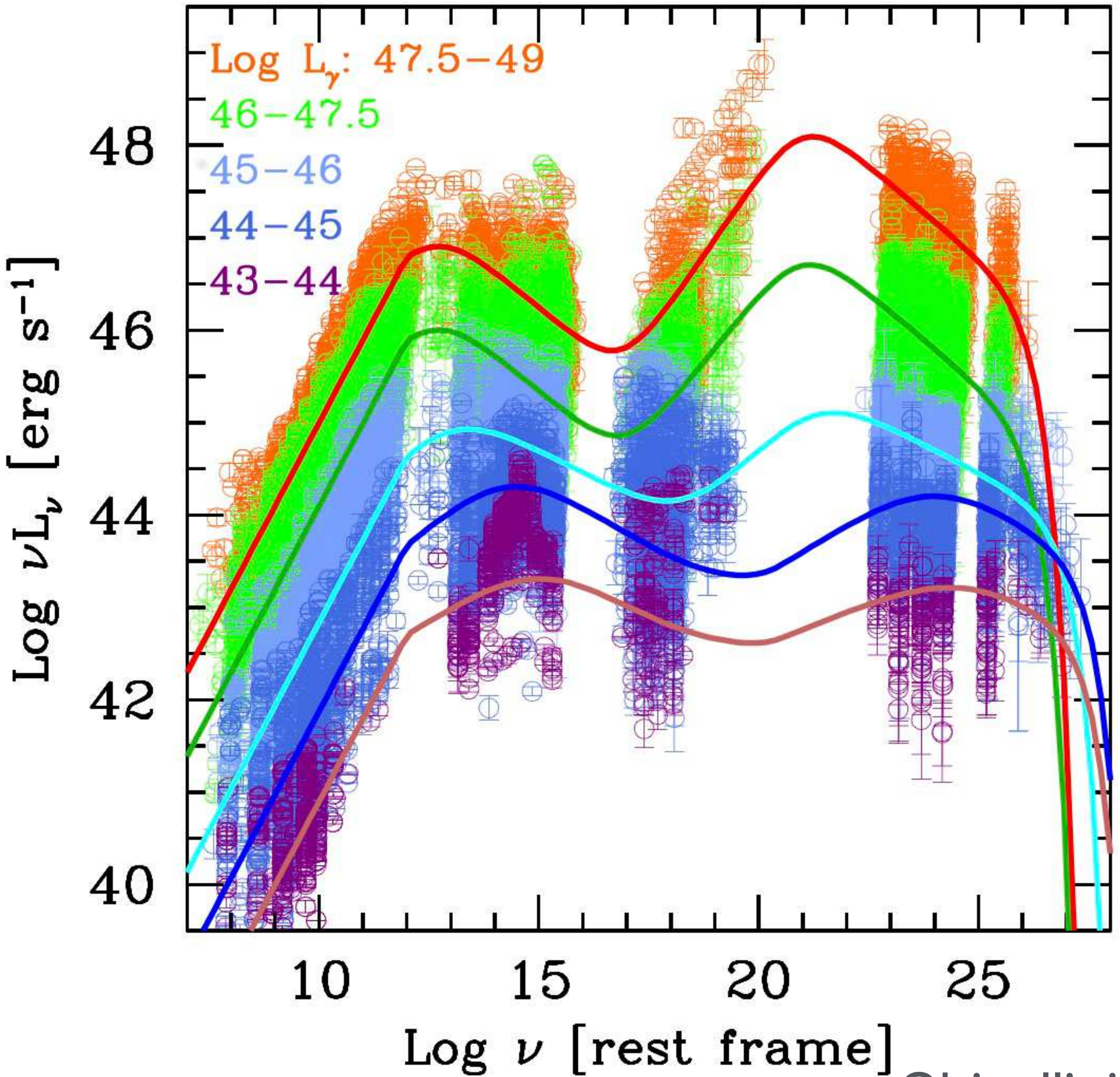


Blazars

Jet pointing toward the Earth



Abdo+'10



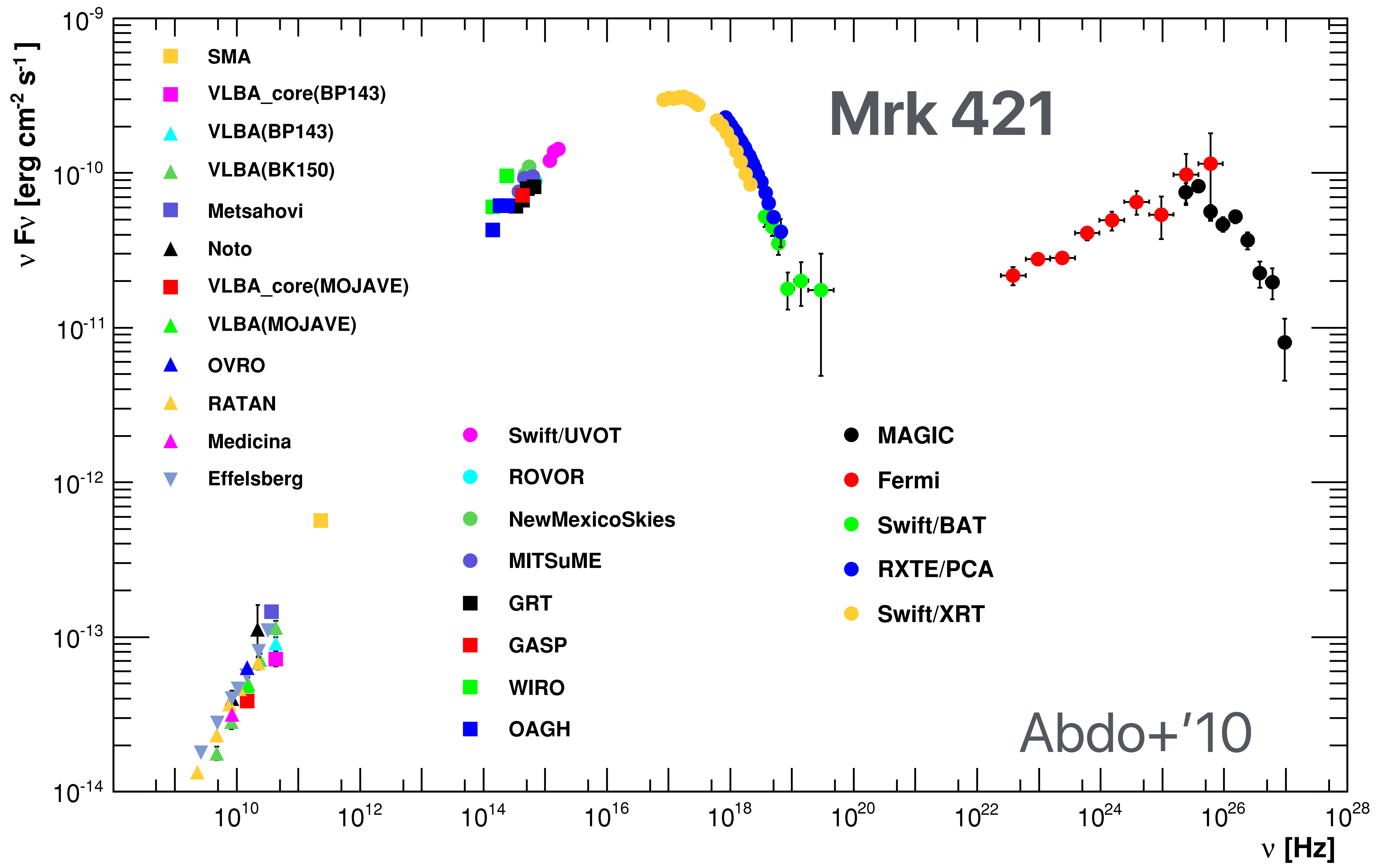
Ghisellini+'17

- Highly variable $\Delta t \sim 1$ day
- Non-thermal emission from radio to gamma
- Two spectral bumps
- Luminous blazars tend to have lower peak energies (Fossati+'98, Kubo+'98, Donato+'01, Ghisellini+'17)

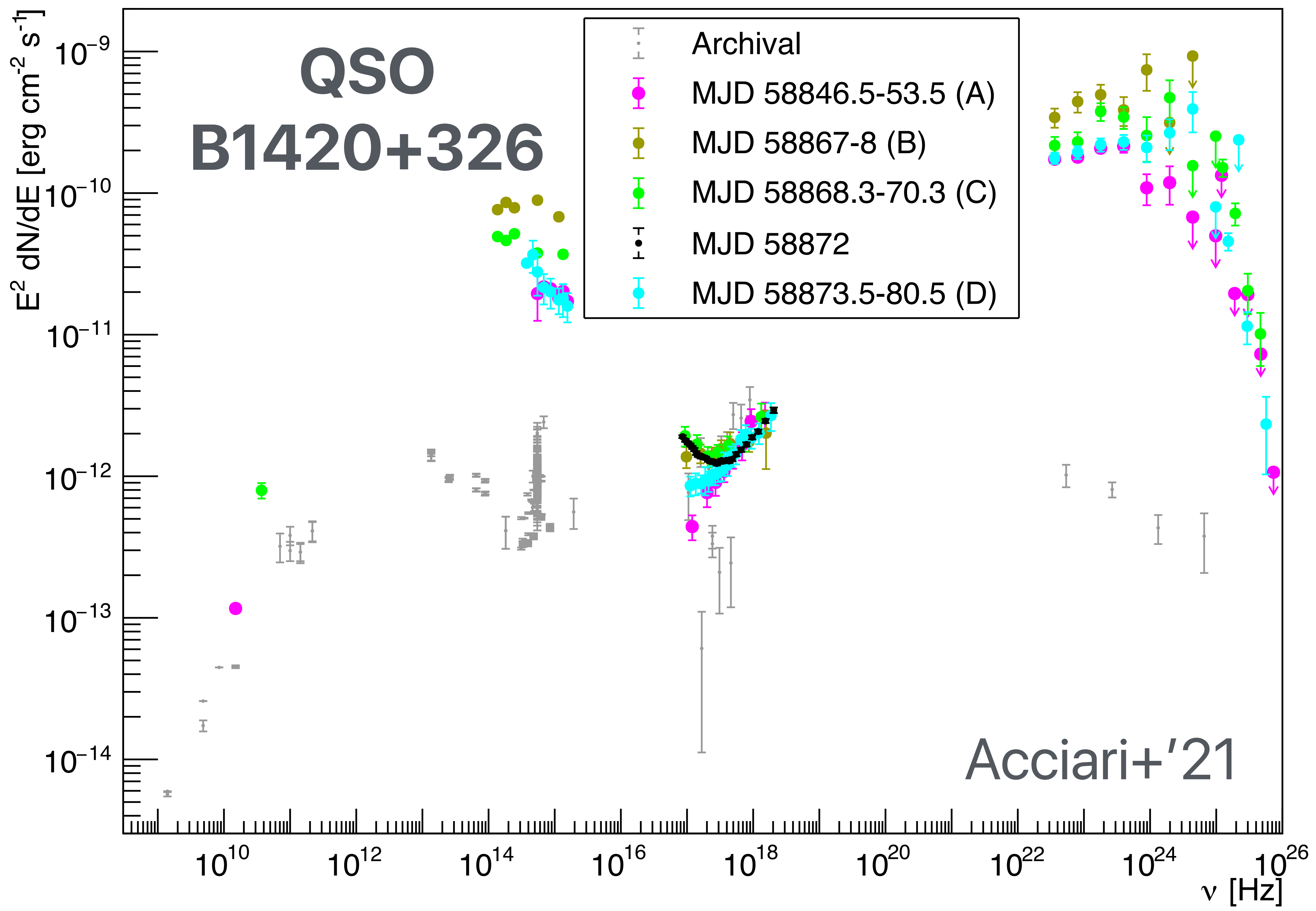
Multi-Wavelength Blazar Spectra

Radio to Gamma-ray (and even neutrino) data is available now

BL Lacs
emissions up to VHE/TeV

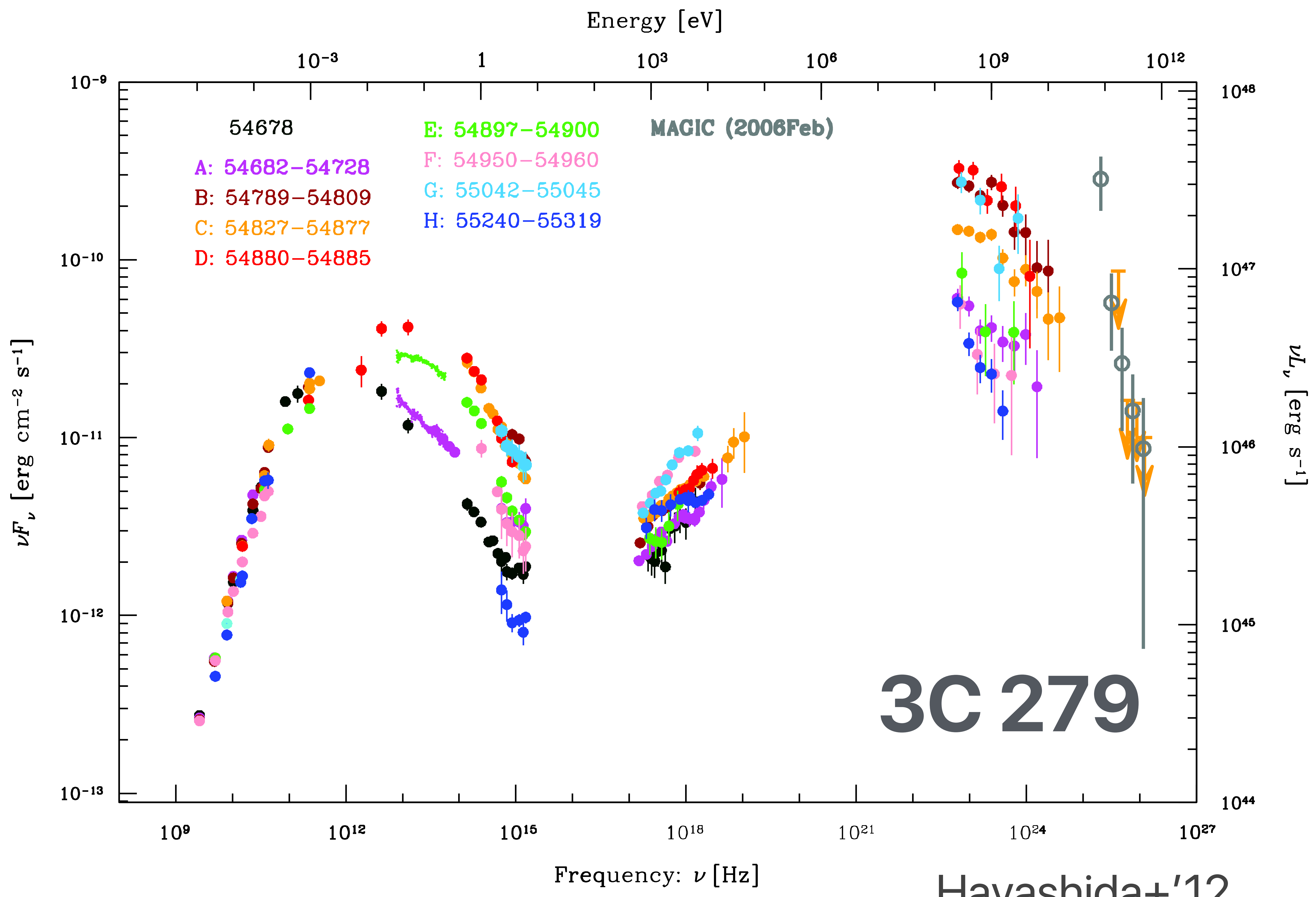


FSRQs
GeV cutoff (w/ VHE flares)



Why Gamma-ray for Blazars?

Energetic, Variable, Highest energy



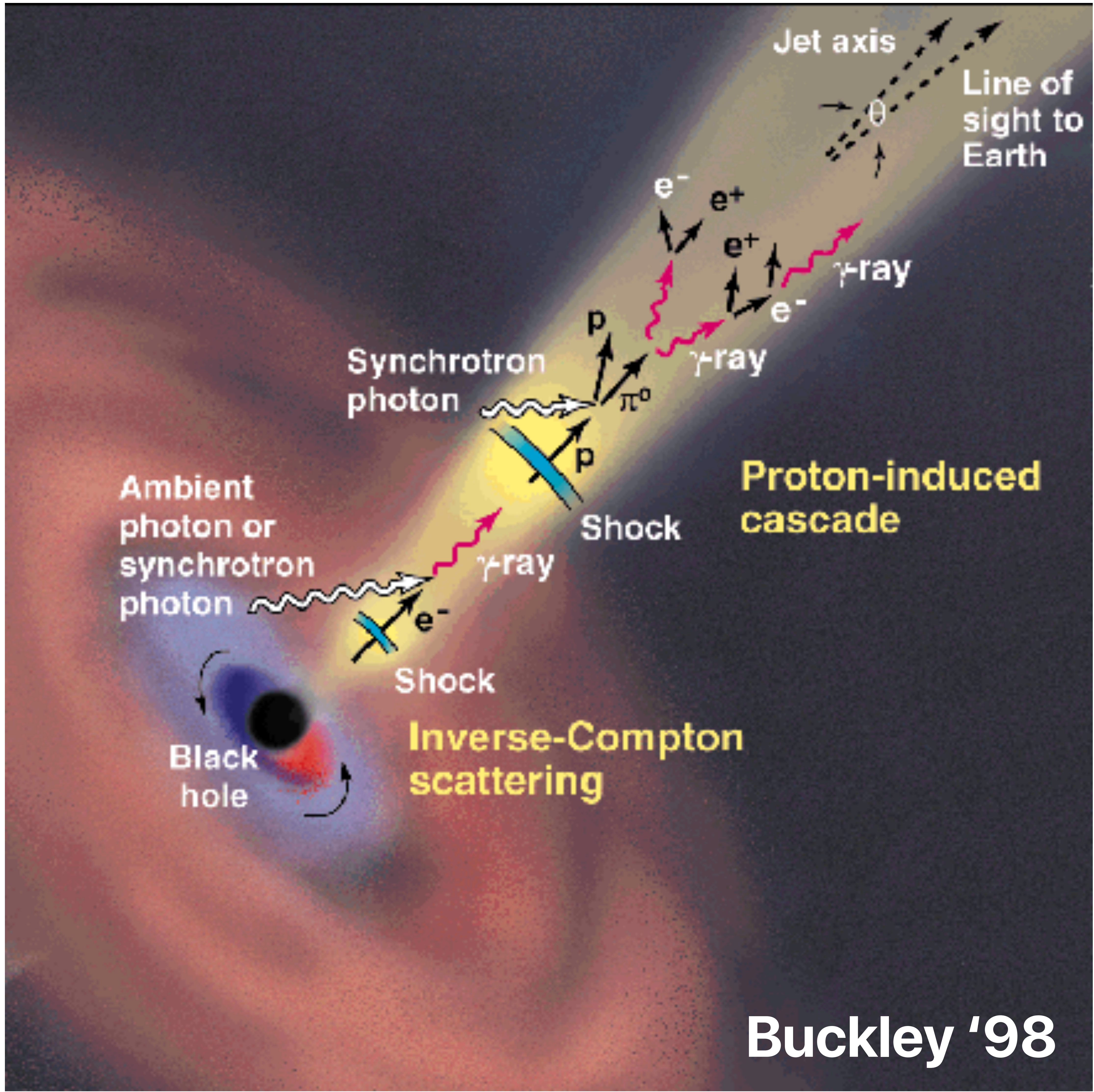
Hayashida+'12

- Energetic
  - Dominated by gamma-ray
- Variable
  - >x10 variability
- Highest energy
  - Energy frontier in photons

Blazar Gamma-ray Emission Mechanism

Leptonic? Hadronic?

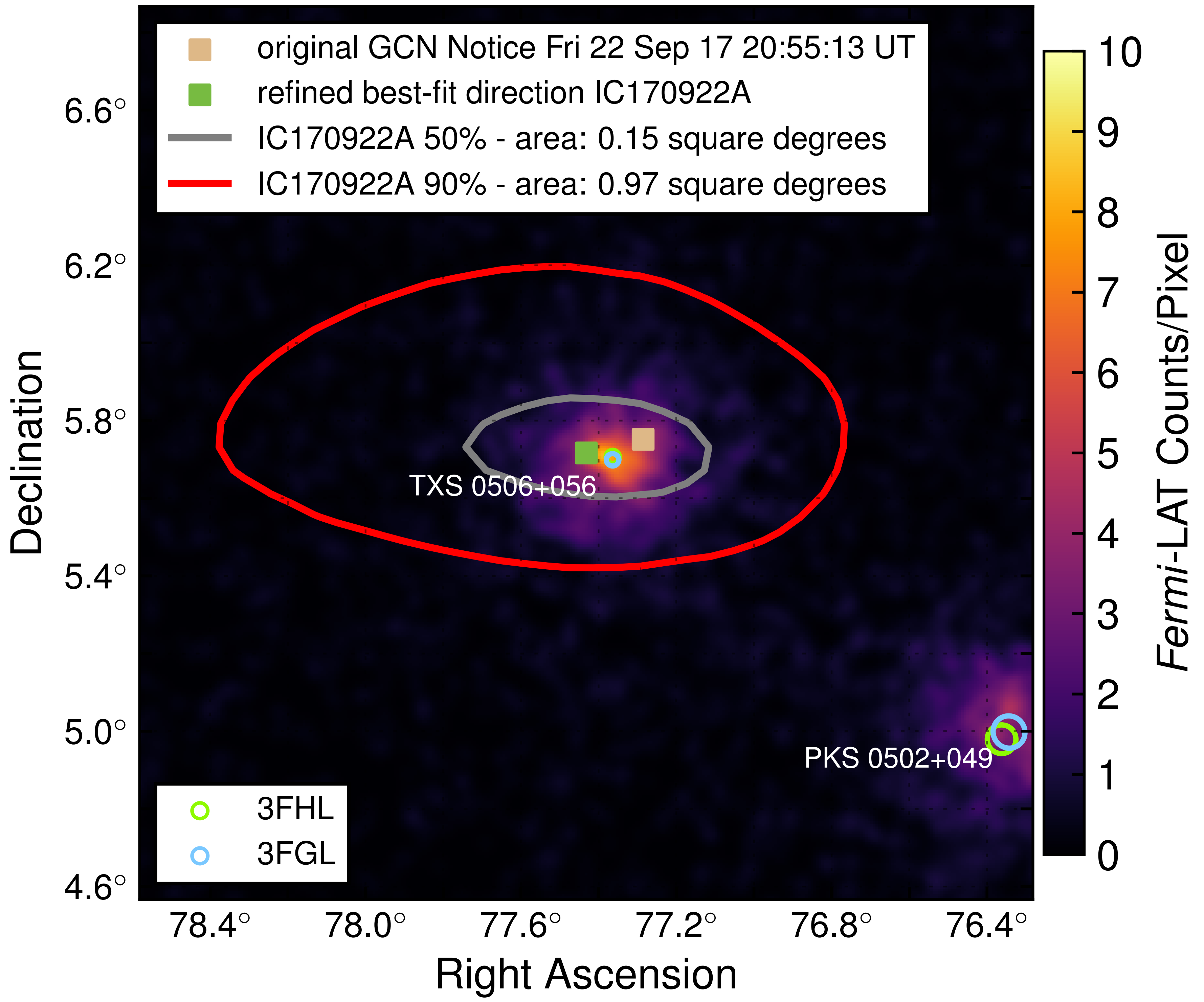
- **Leptonic scenario**
  - Synchrotron Self-Compton (SSC)
    - Jones, O'Dell, & Stein '74; Maraschi, Ghisellini, & Celotti '92
  - External Compton (EC)
    - Dermer & Schlickeiser '93; Sikora, Begelman, & Rees '94
- **Hadronic scenario**
  - Proton synchrotron, Photomeson
    - Mannheim '93; Aharonian '00; Mücke & Protheroe '01

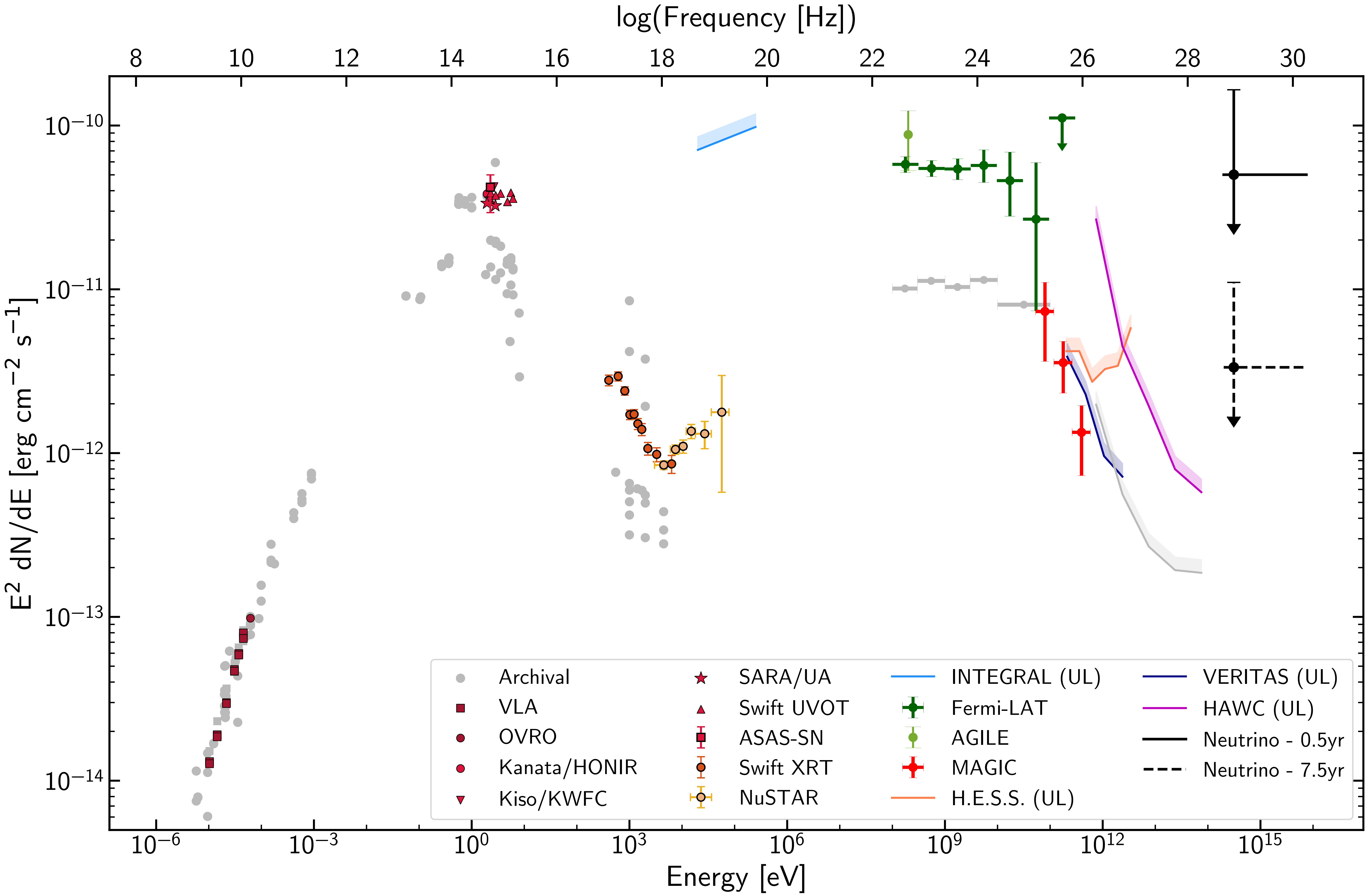


Buckley '98

Smoking Gun Event: TXS 0506+056

Discovery of the first ever neutrino associated blazar



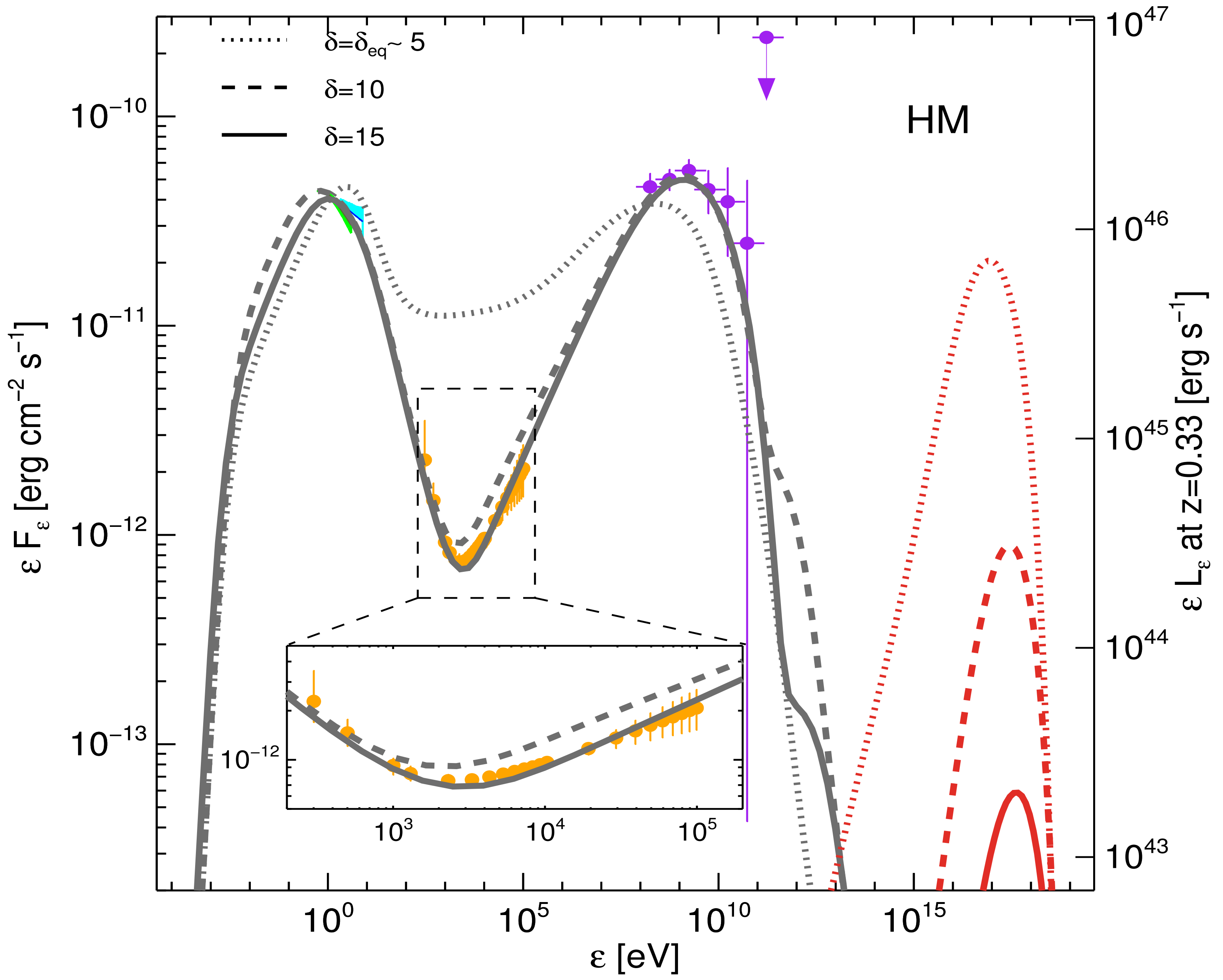


- "A" ~300 TeV neutrino
- "3"-sigma association

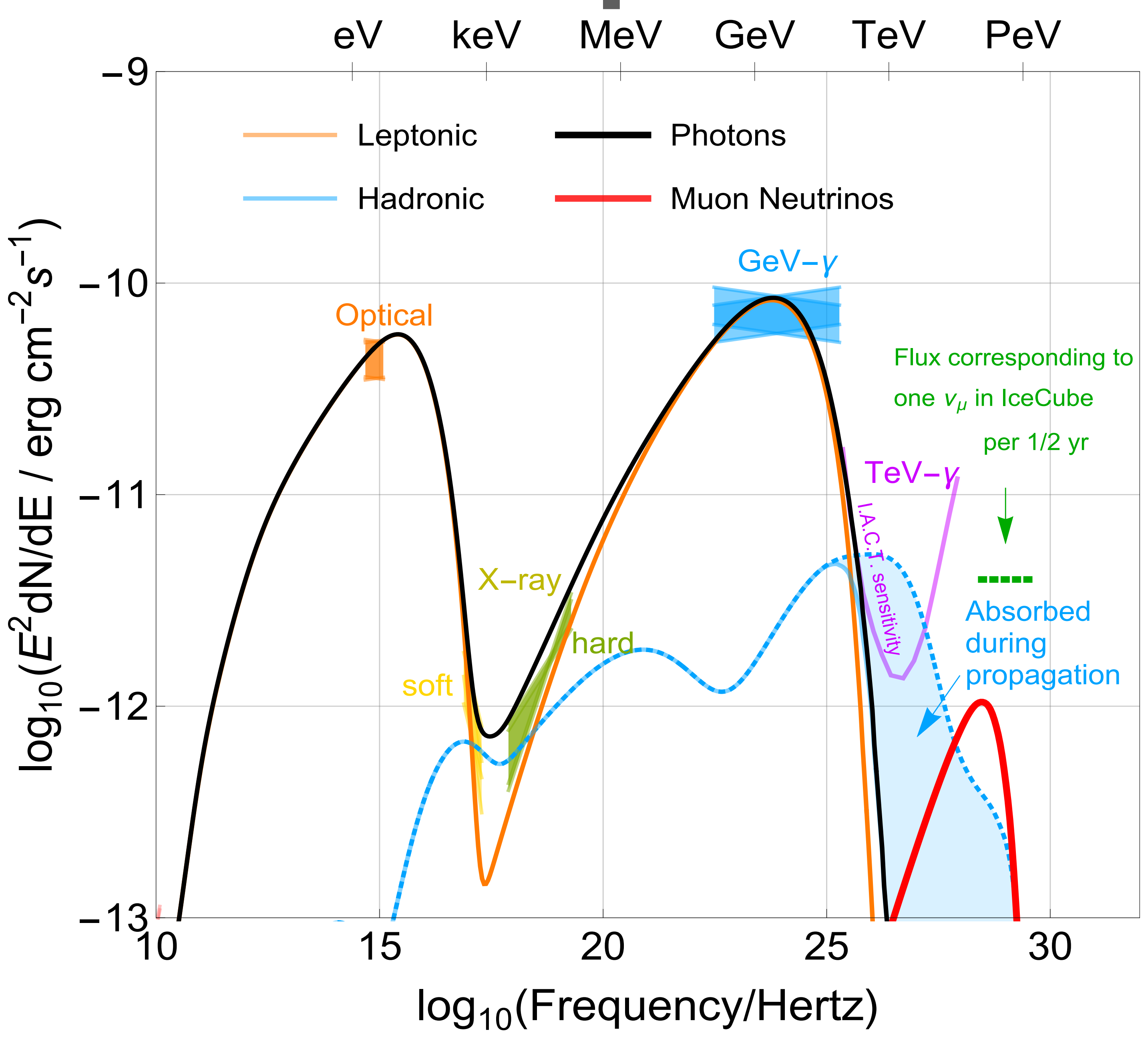
IceCube 2018

Theoretical Interpretation

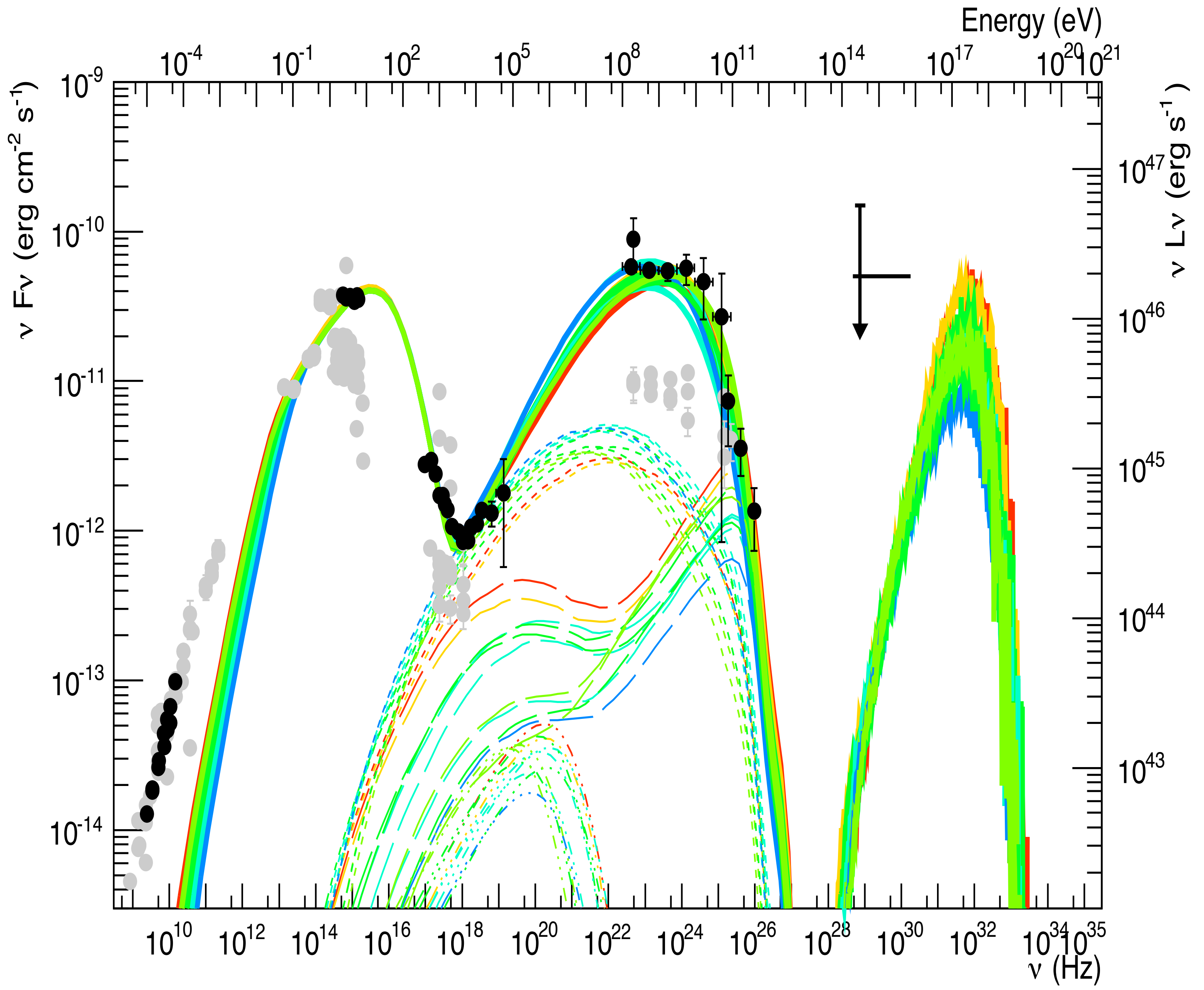
Hard X-ray Constrains Hadronic Component



Keivani+'18



Gao+'18

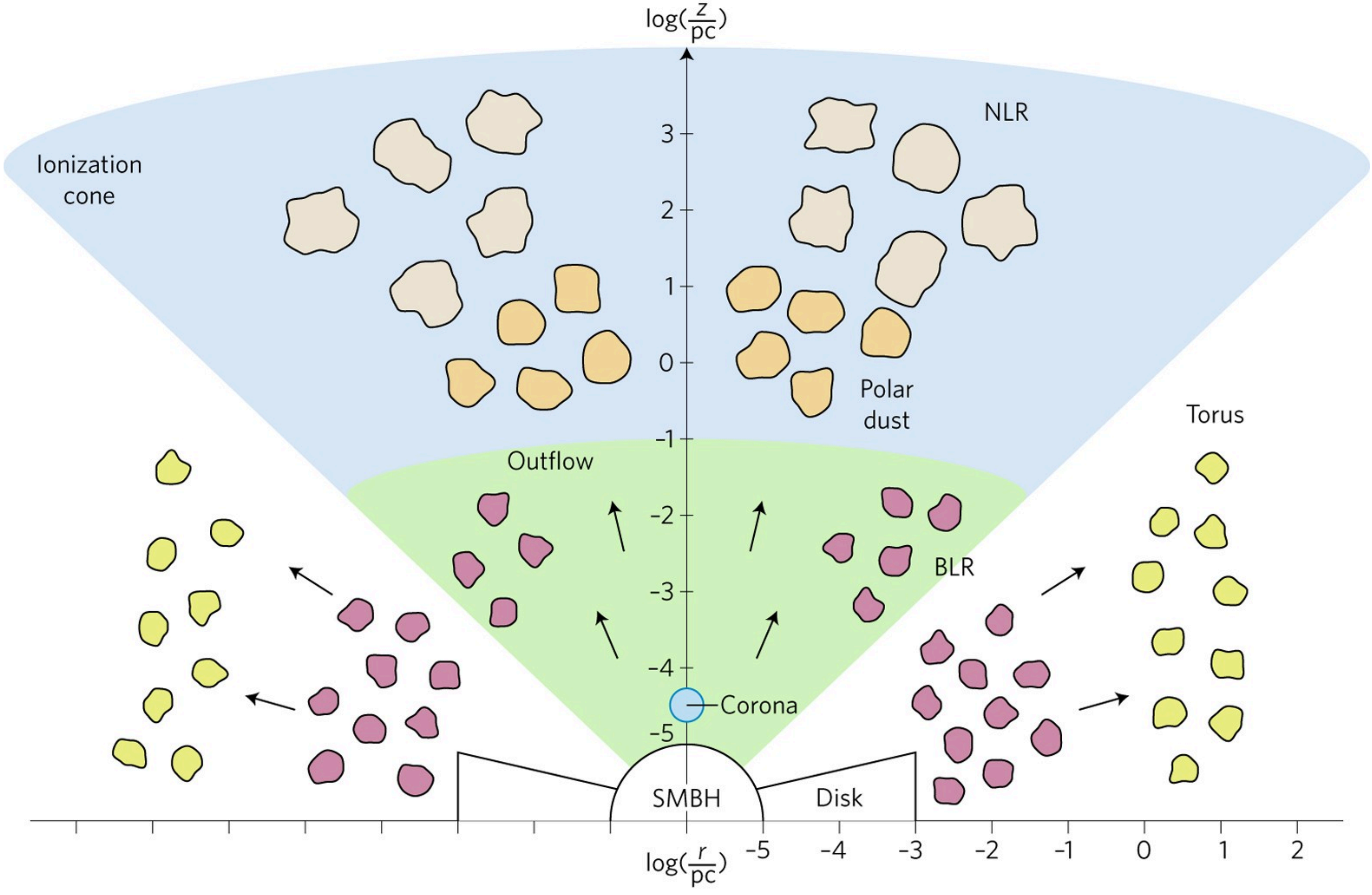


Cerruti+'18

- **<u>Pure hadronic model is ruled out</u>** because too much X-rays
  - Hadronic component is subdominant (e.g., Keivani+'18;Cerruti+'18;Gao+'18,,,,).
- Hard X-ray and MeV gamma-ray data will be also important.

Where is the Gamma-ray Emission Region?

Toward the understanding of the energy dissipation process



Ramos-Almeida & Ricci '17

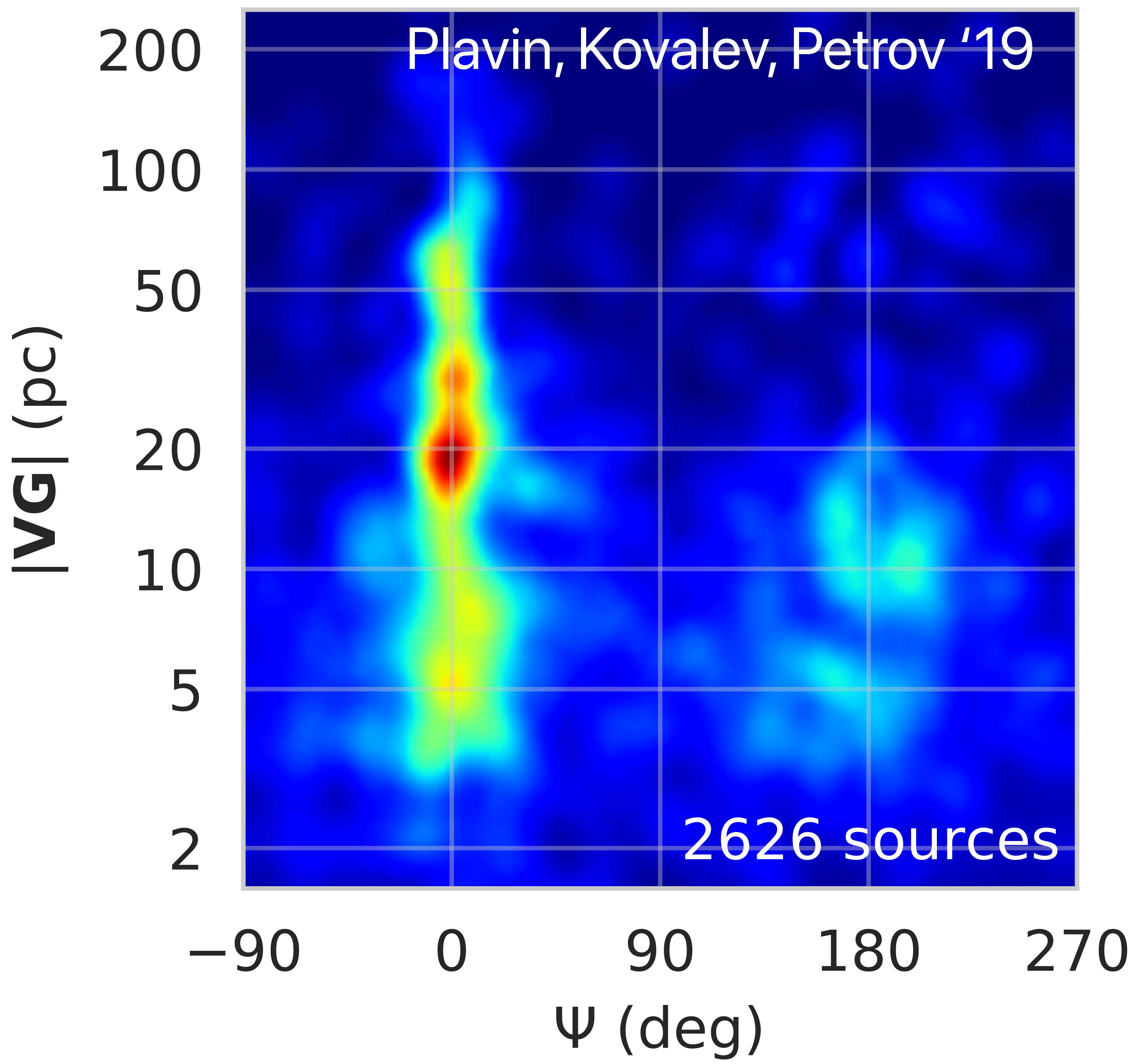
- Dust torus
  - > pc scale
- BLR region
  - > sub-pc scale
- Accretion disk
  - < sub-pc scale

Blazar Emission Region?

>pc region???

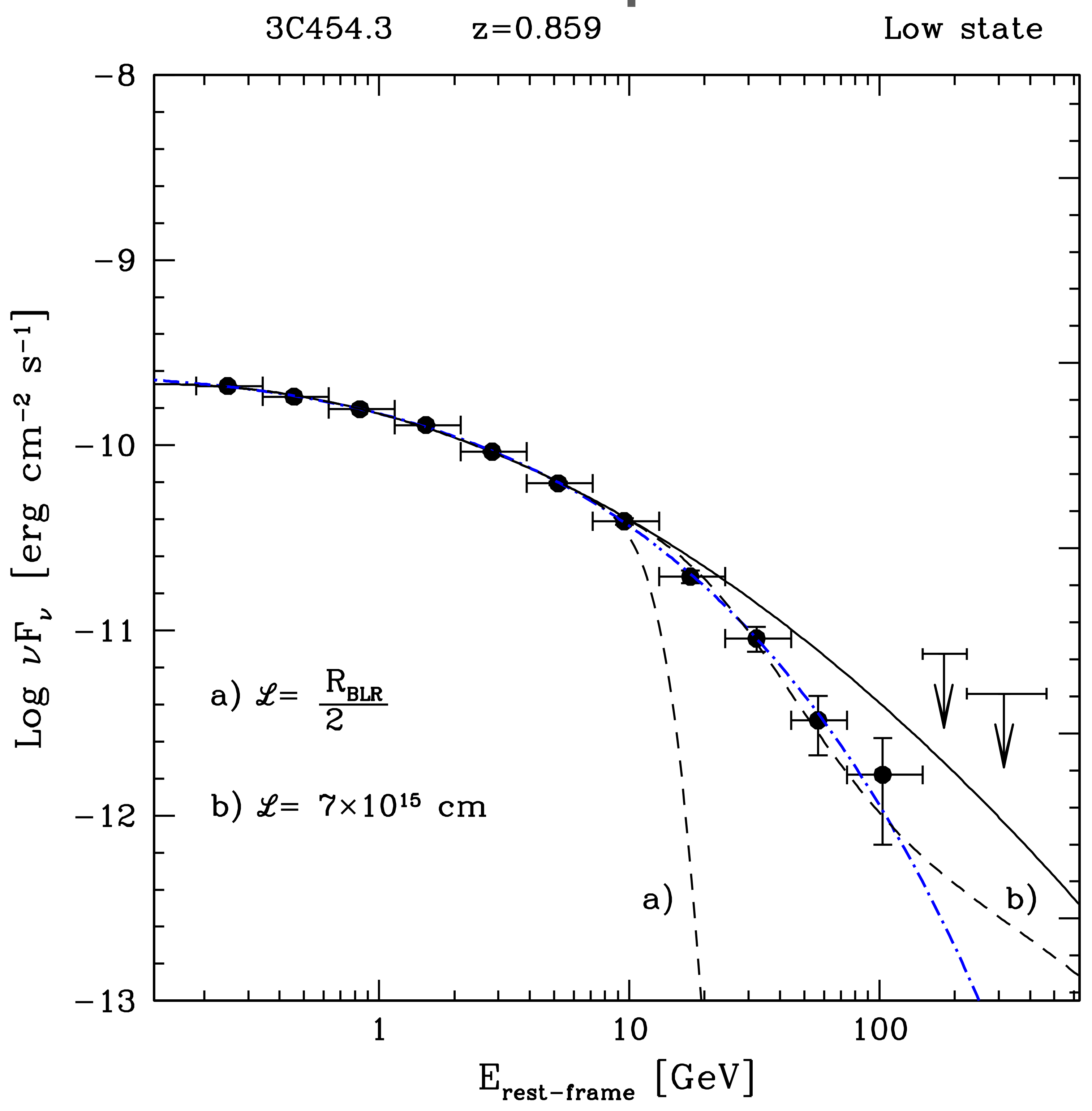
- Gaia (optical) emission locates ~20-50 pc away from the VLBI (radio) core ? (Plavin, Kovalev, Petrov '19)
- Lack of broad-line region photon attenuation signature in GeV ? (Costamante+'18)

Gaia - VLBI Distance



Offset relative to jet

Fermi GeV Spectrum



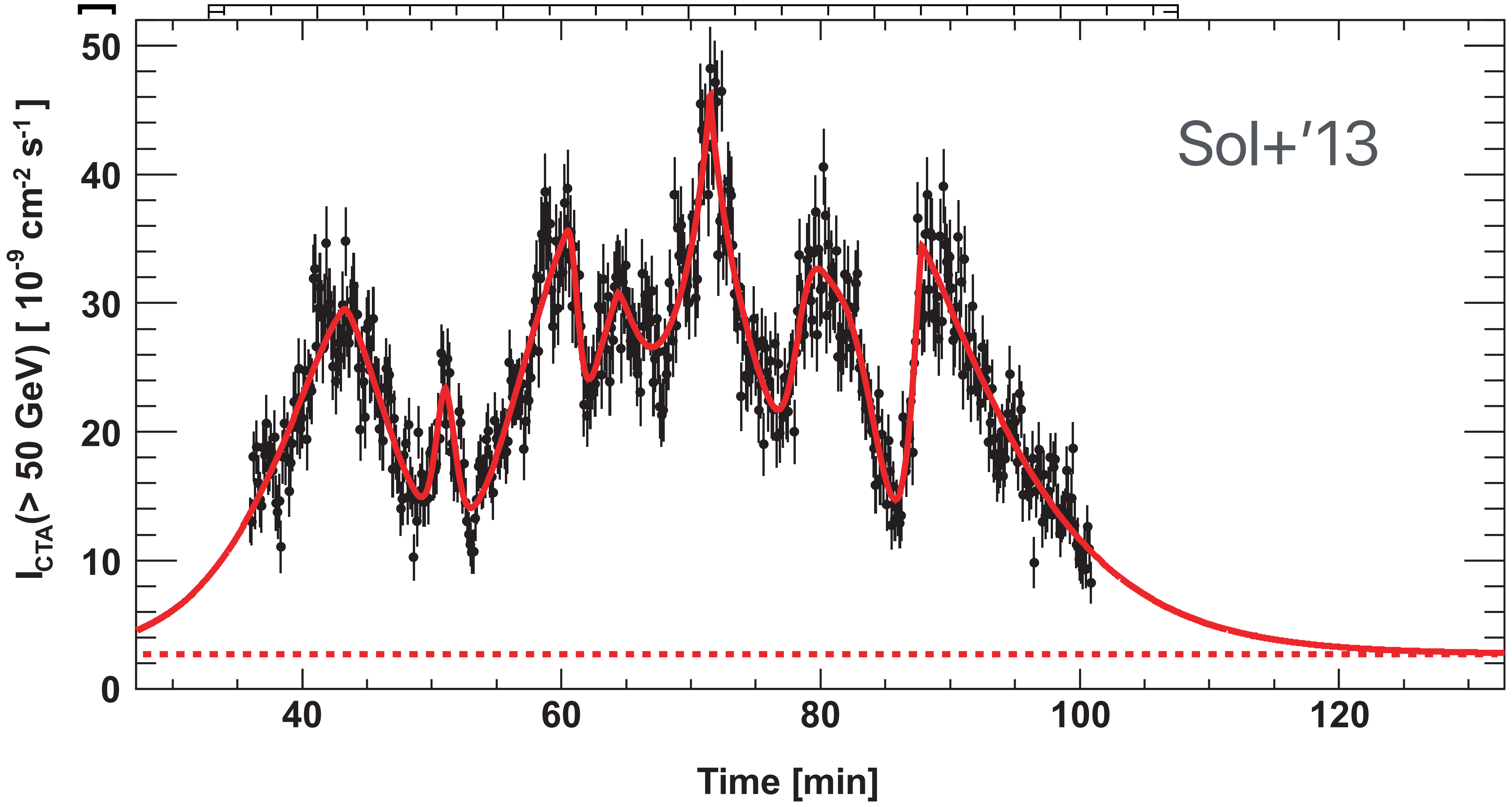
Costamante+'18

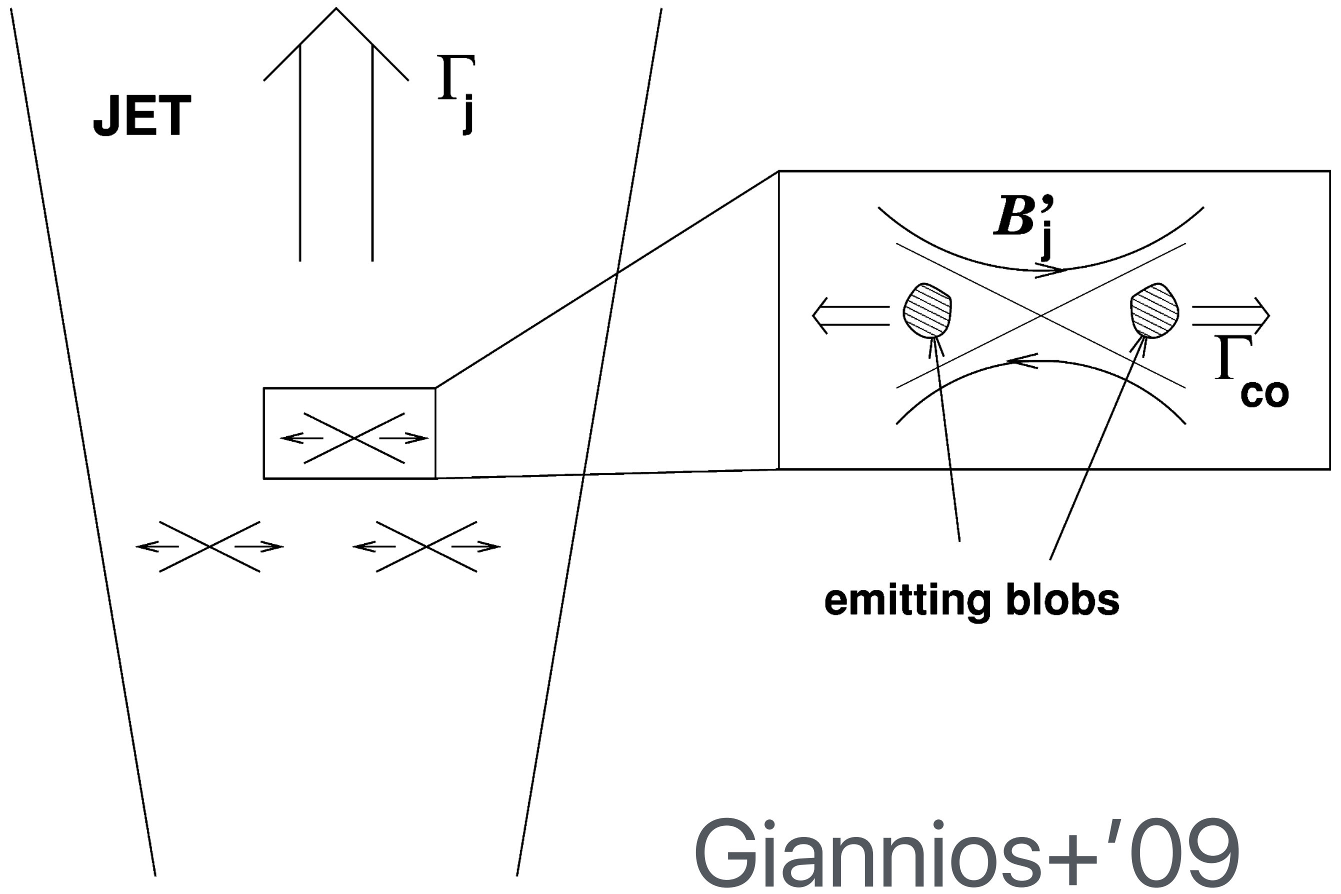
Spectral determination by LST will pin down the emission region.

Blazar Emission Region?

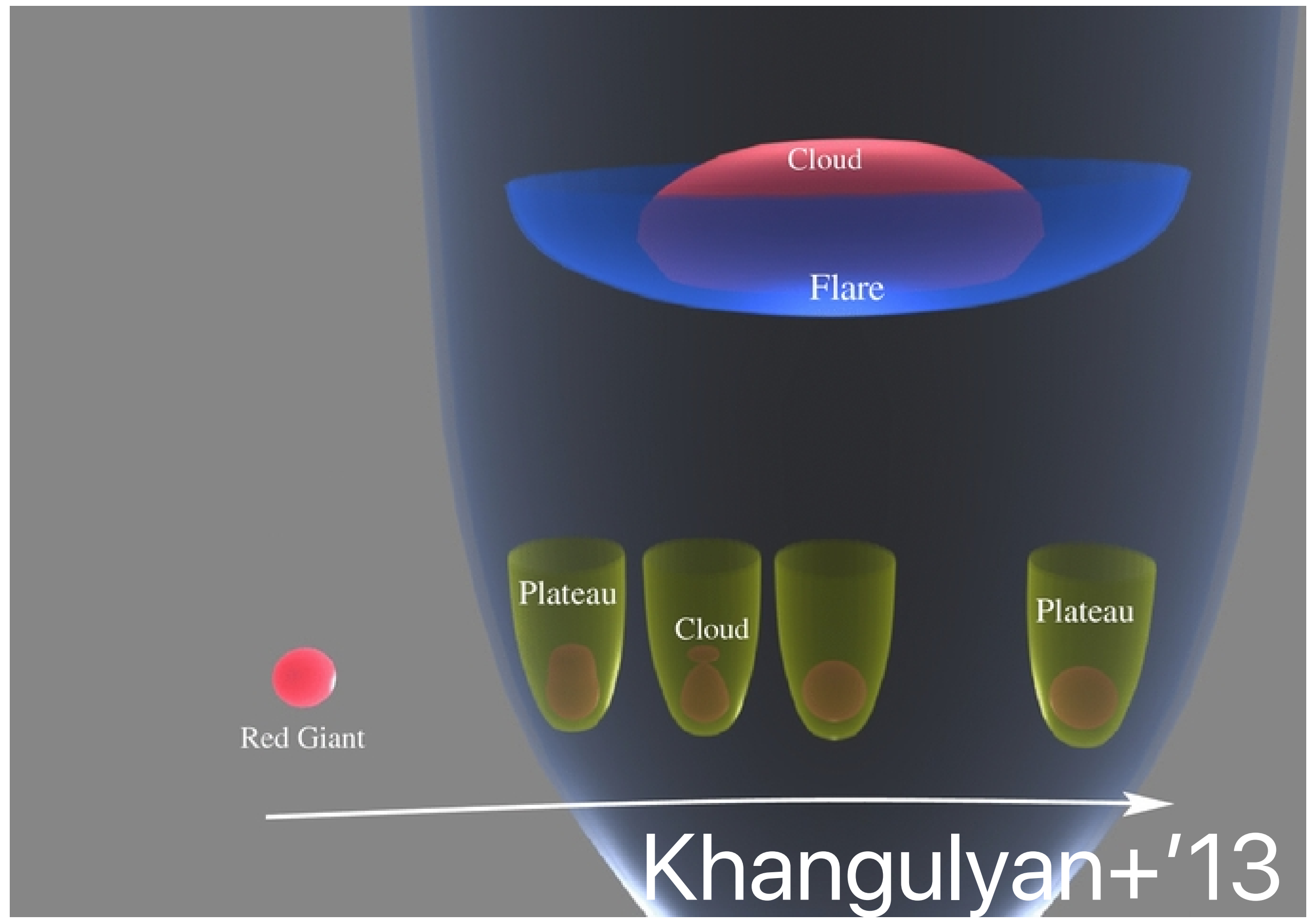
<pc region???

- Fast variabilities ~200 s
  (Aharonian+'07, Albert+'08)
  - Very compact emitting region?
- Closer region?
  - Jet-in-Jet (Giannios+'09) ?
  - Jet-Star interaction
    (Khangulyan+'13)?





Giannios+'09

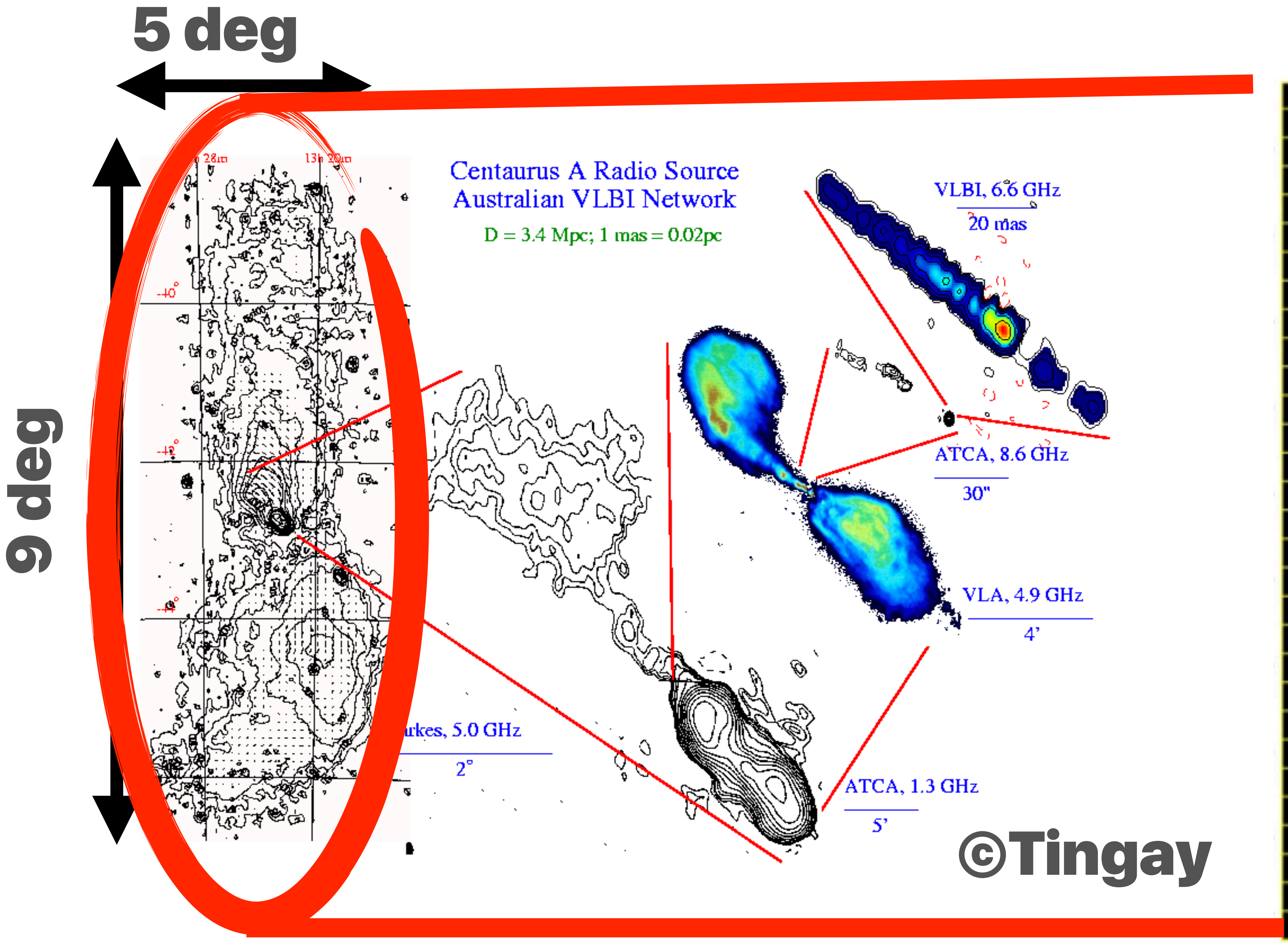


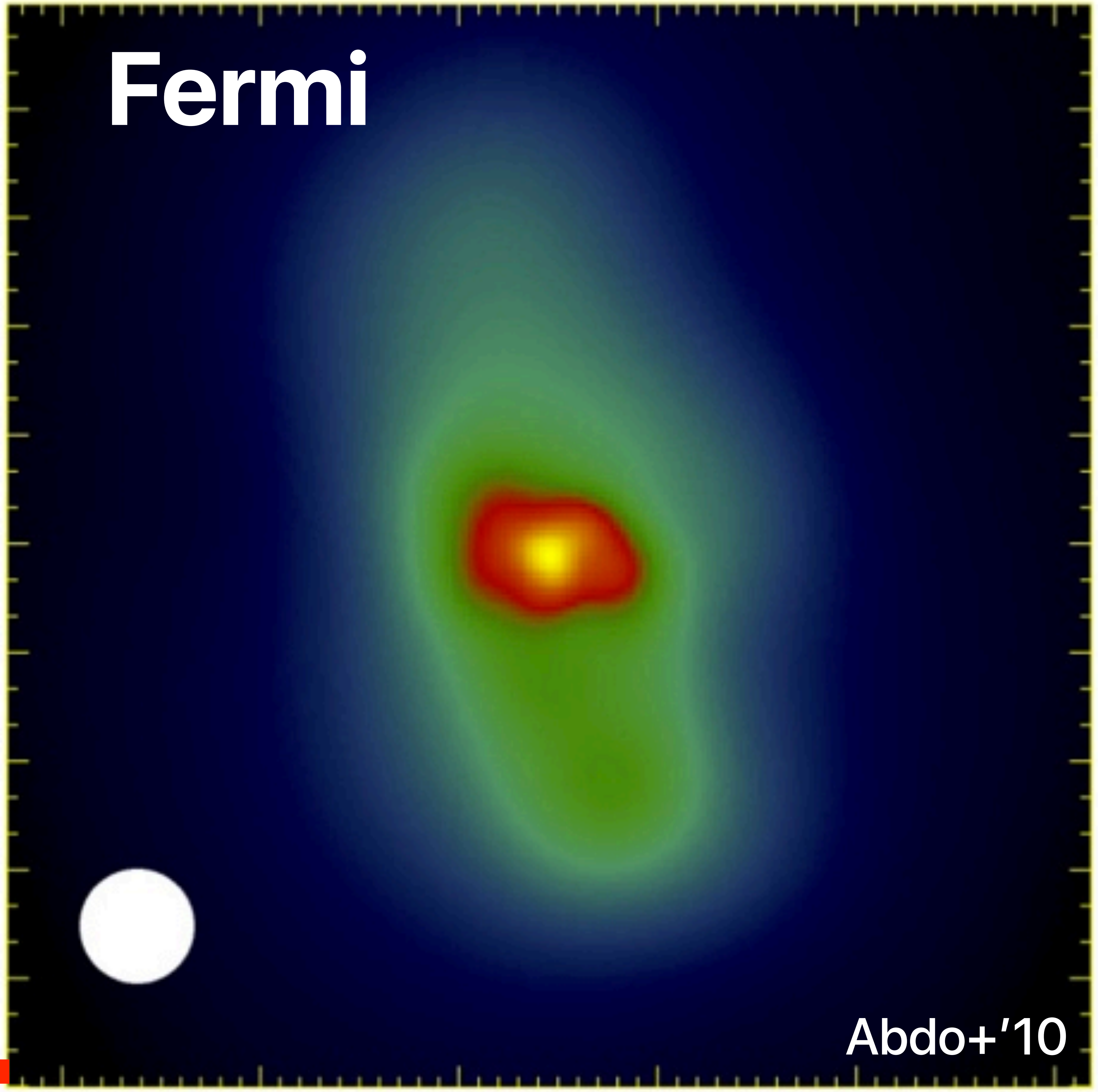
Khangulyan+'13

Photon statistics by LST will probe the smallest scale in the jet

Gamma-ray Emission from Large-Scale Jets

Spatial Extension of Cen A Seen by Fermi and H.E.S.S.





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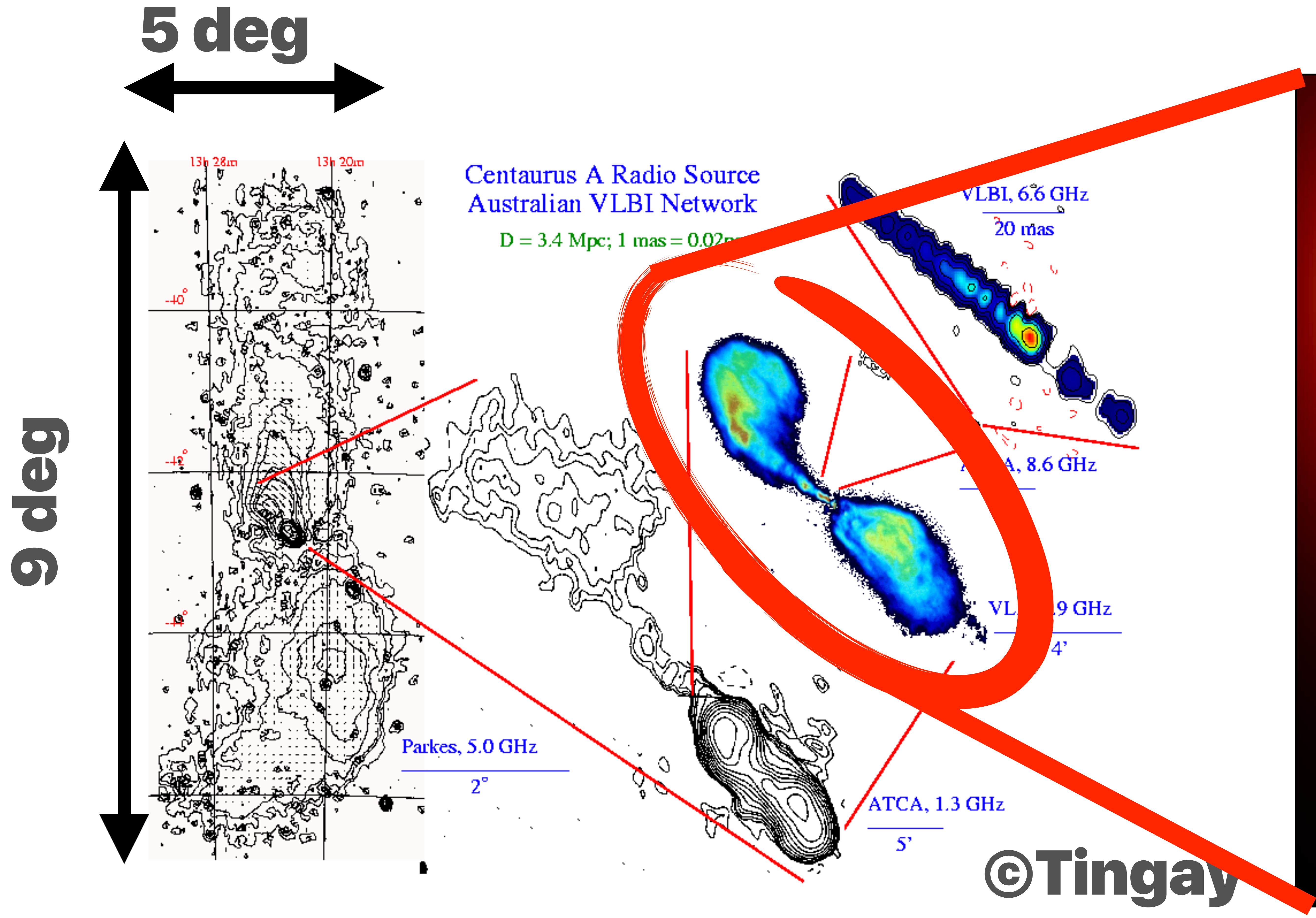
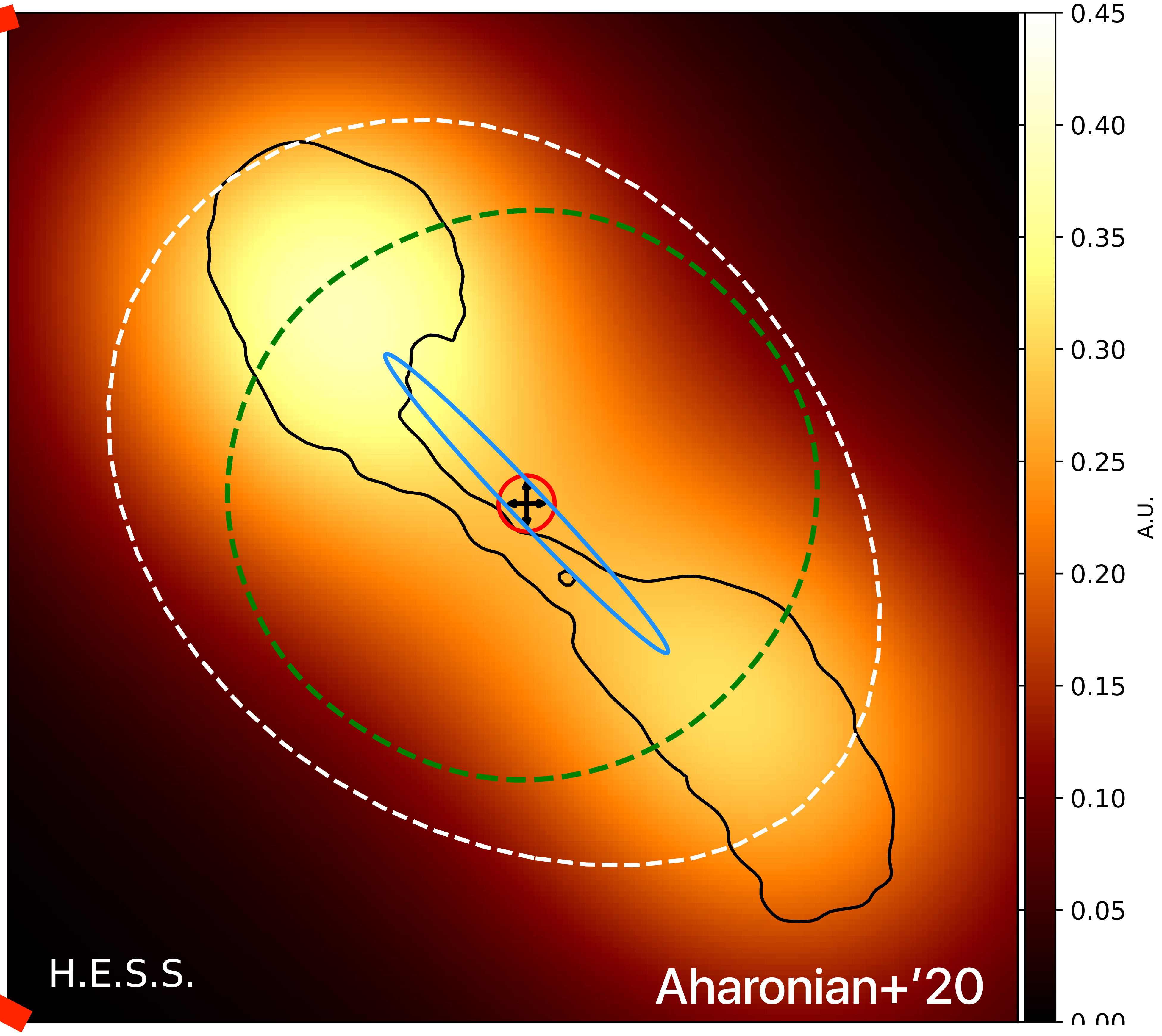
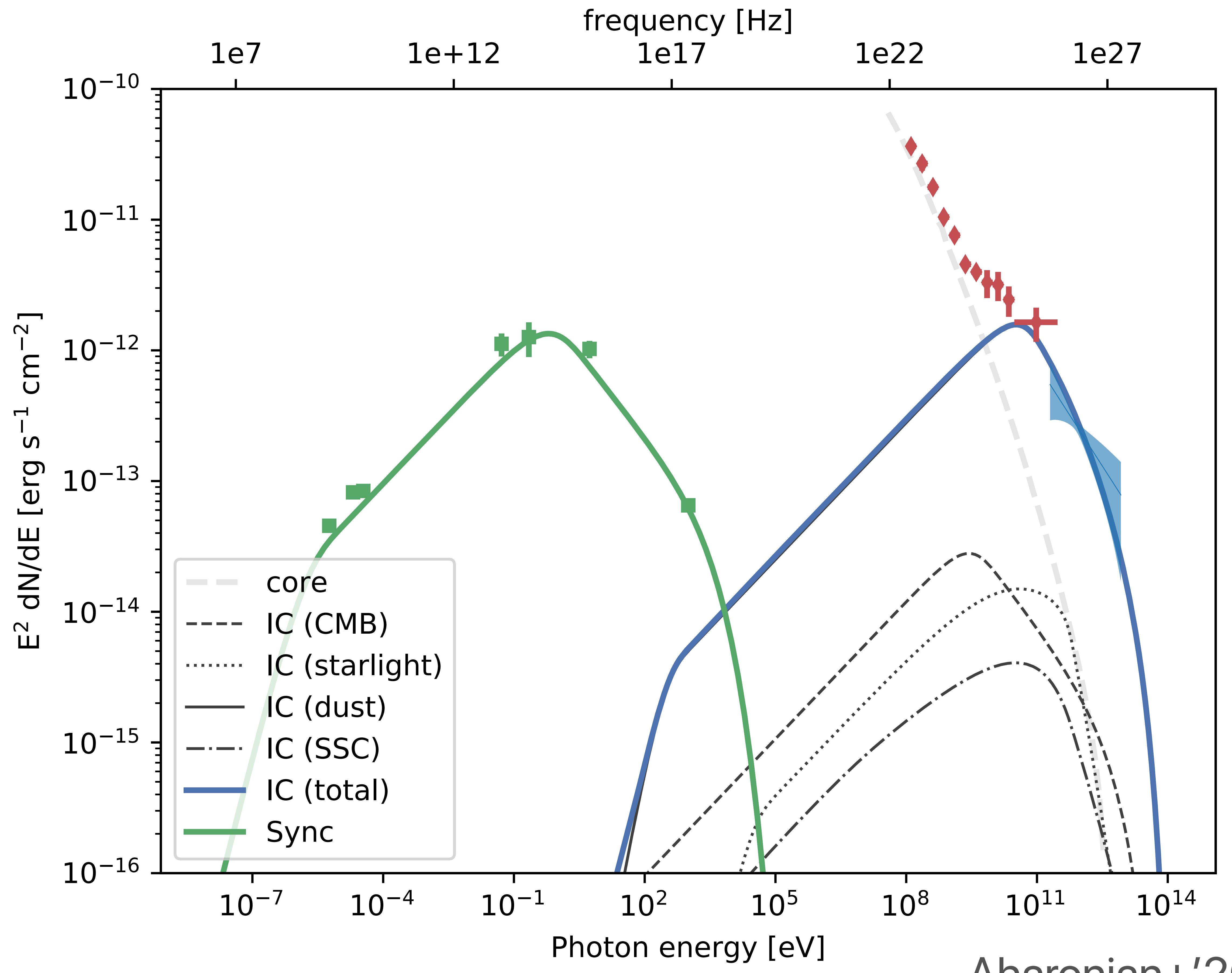




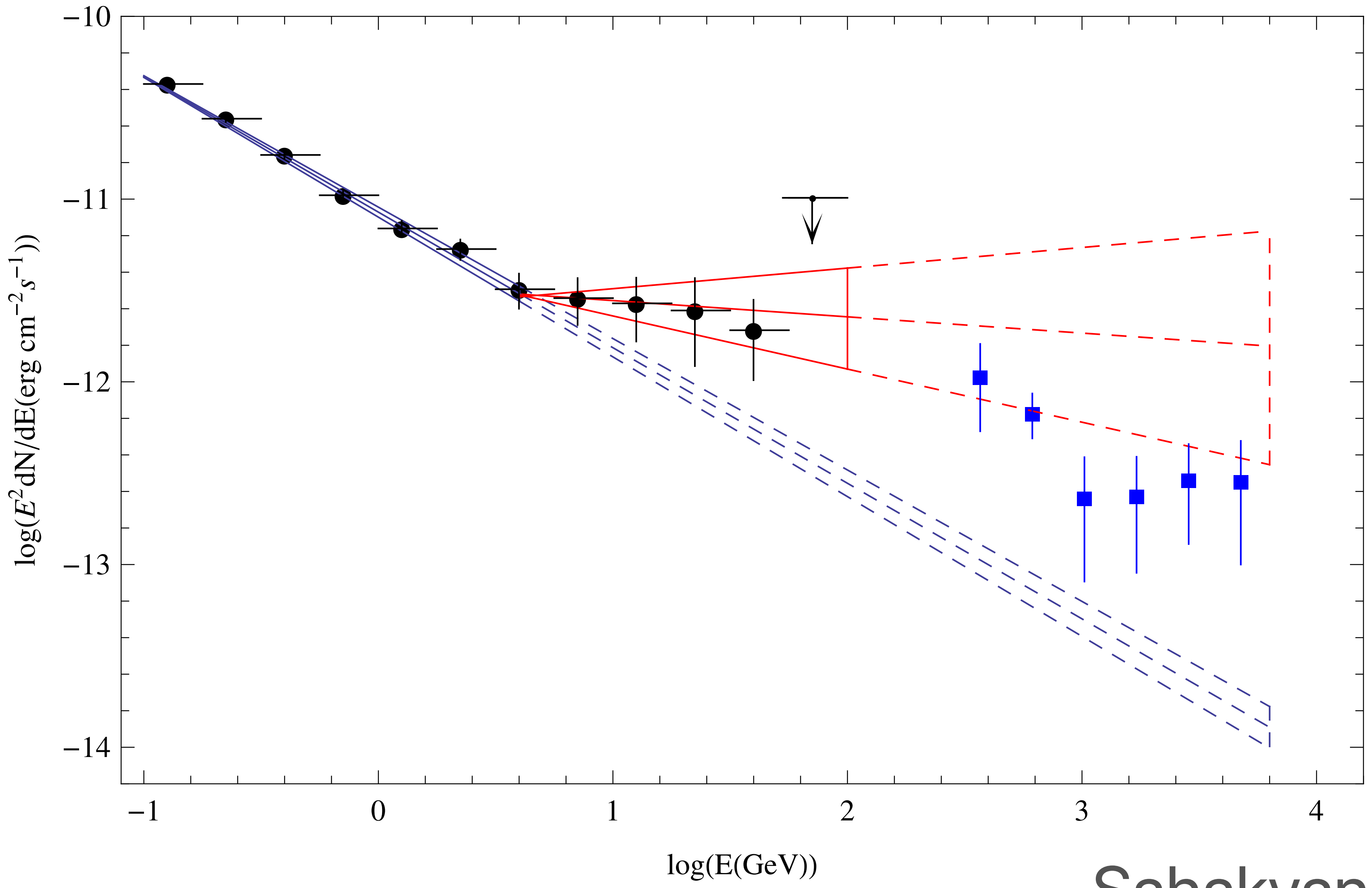
NOTE: Color scale is radio!
HESS region is WHITE circle.

Unusual Spectral Hardening in the Cen A Spectrum

LST/MST mapping would help us to understand jet kinematics.



Aharonian+'20



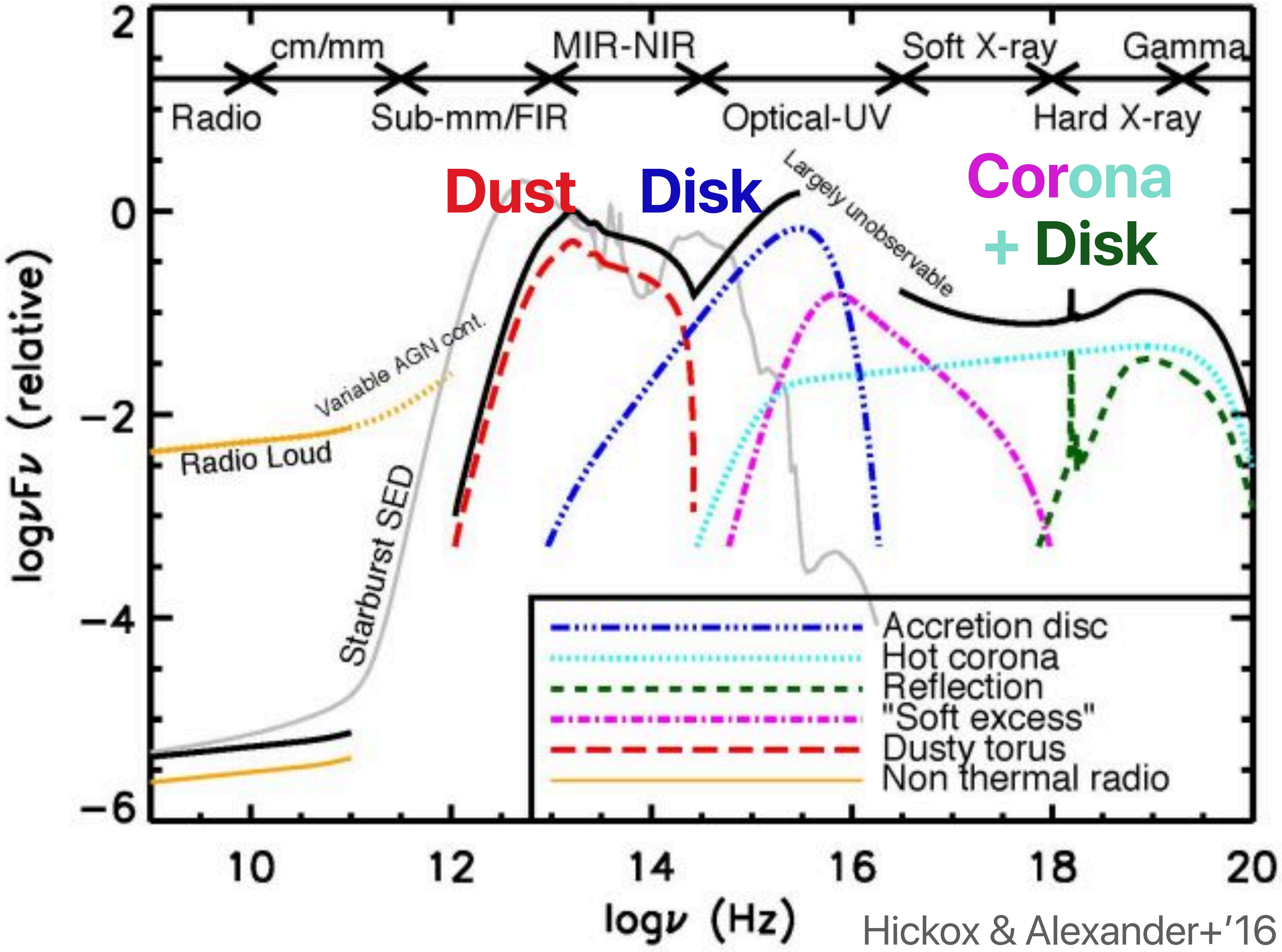
Sahakyan+'13

- Spectral hardening by the kpc jet?
- Diffuse jet should be weakly magnetized $\eta_B \sim 10^{-2}$ (Sudoh, Khangulyan, & YI '20)

Unjetted AGN Science

Multi-wavelength spectrum of Unjetted AGNs

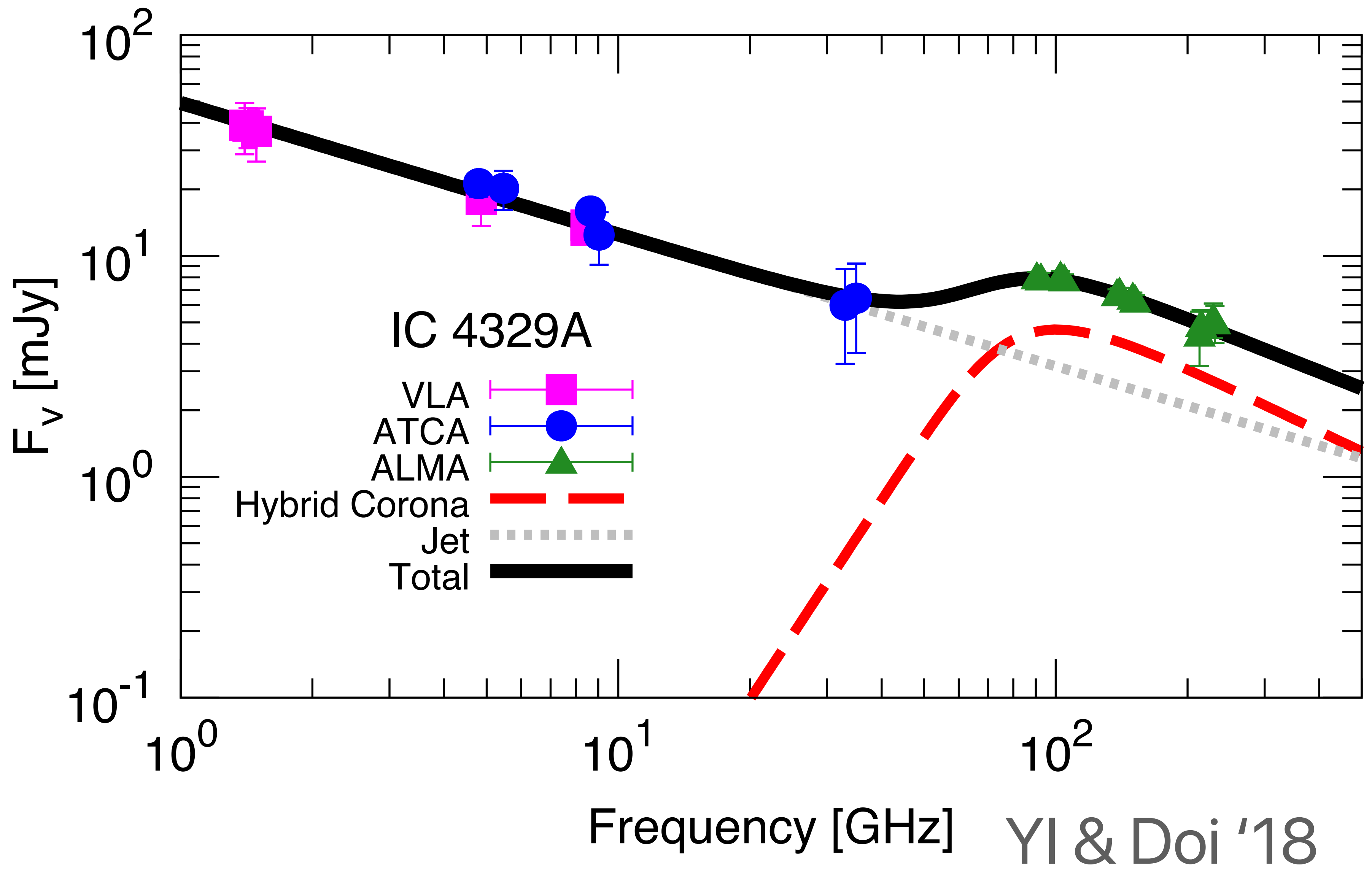
Thermal emission dominates.



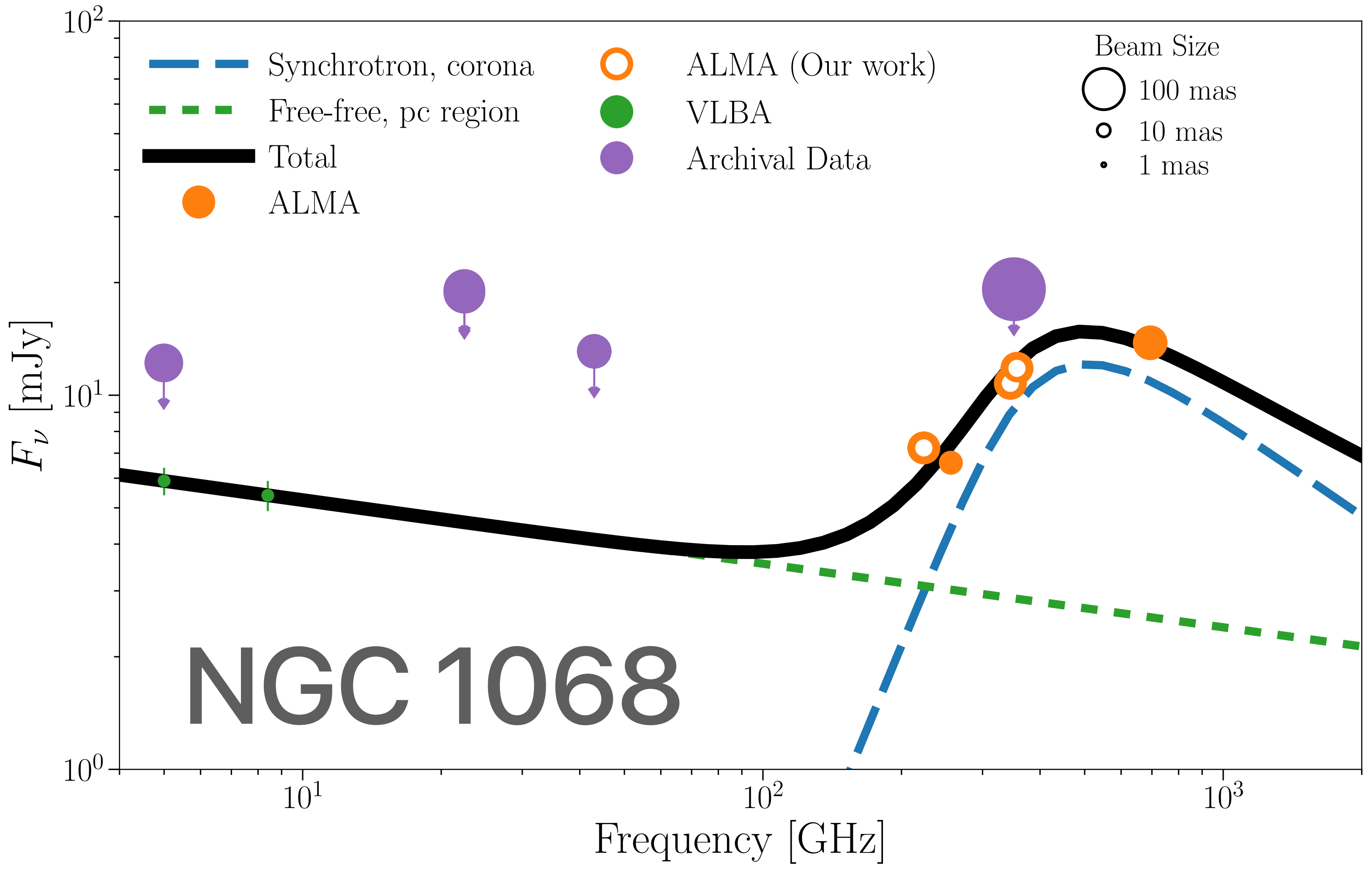
Hickox & Alexander+'16

- If unjetted AGNs are gamma-ray/neutrino sources,
  - we should see non-thermal EM emission.
- BUT, in unjetted AGNs,
  - thermal emission is everything "so far".
- **Where is non-thermal signature?**

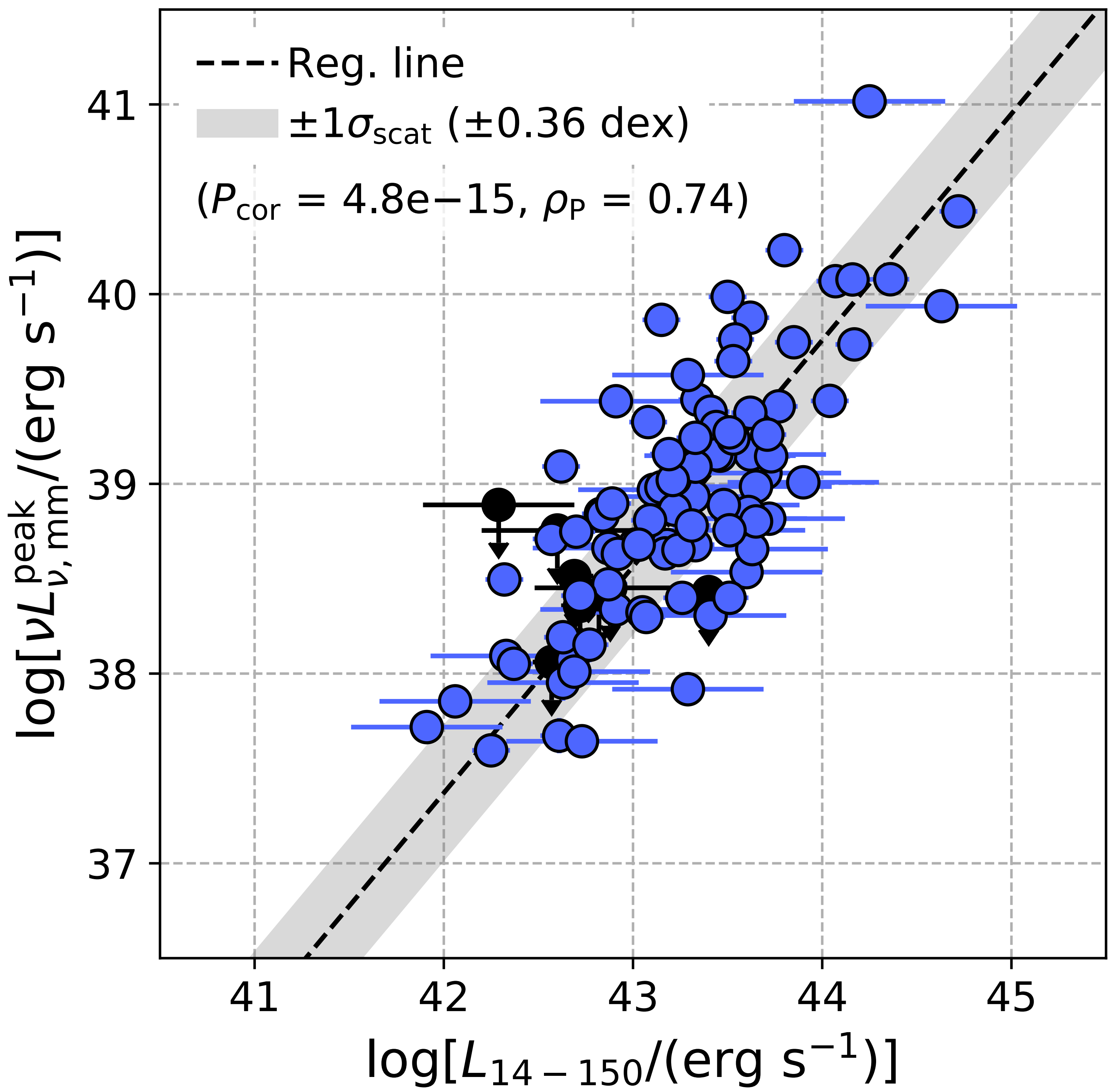
ALMA observations toward nearby Seyferts



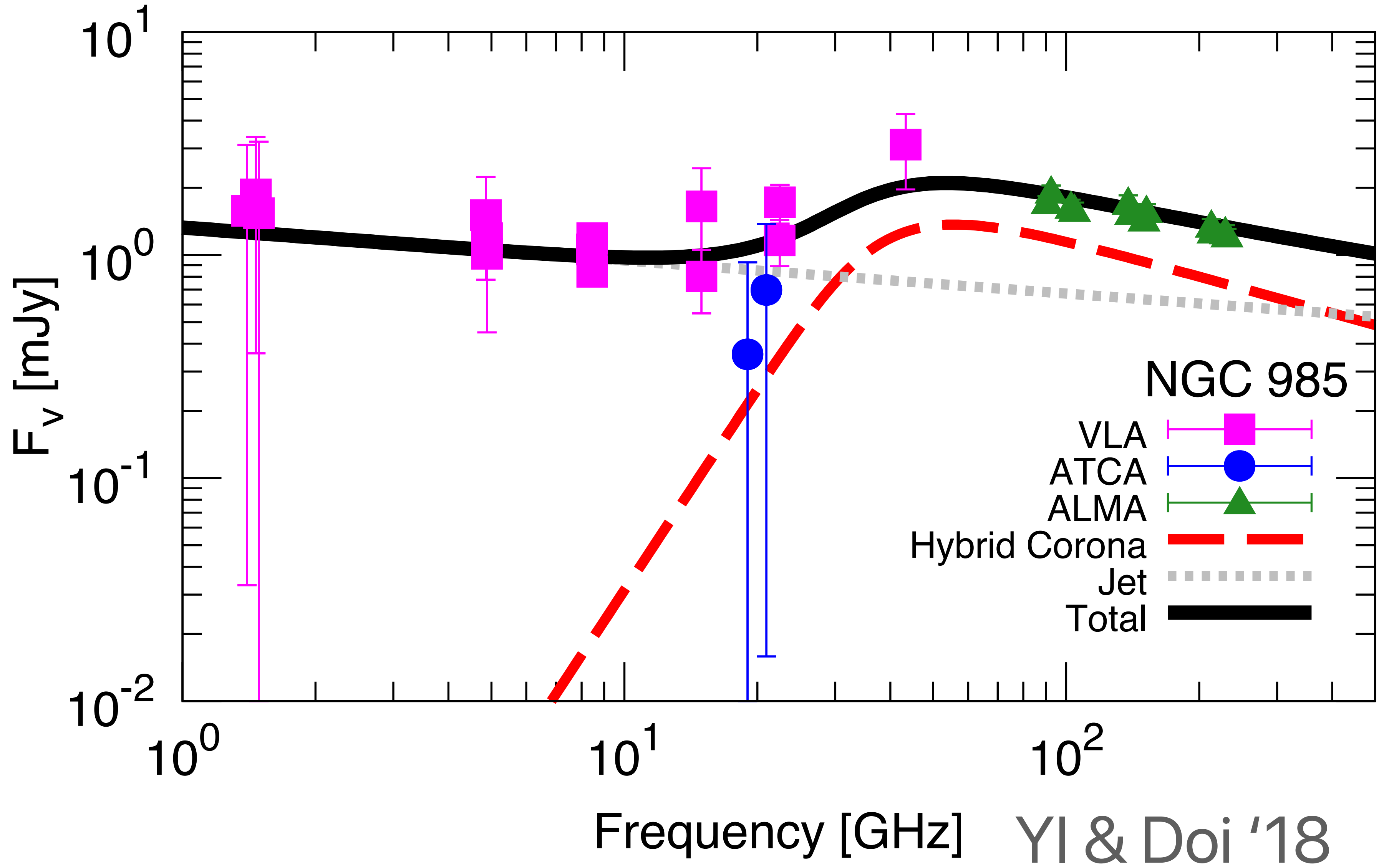
YI & Doi '18



YI, Khangulyan, & Doi '20



Kawamuro+'22

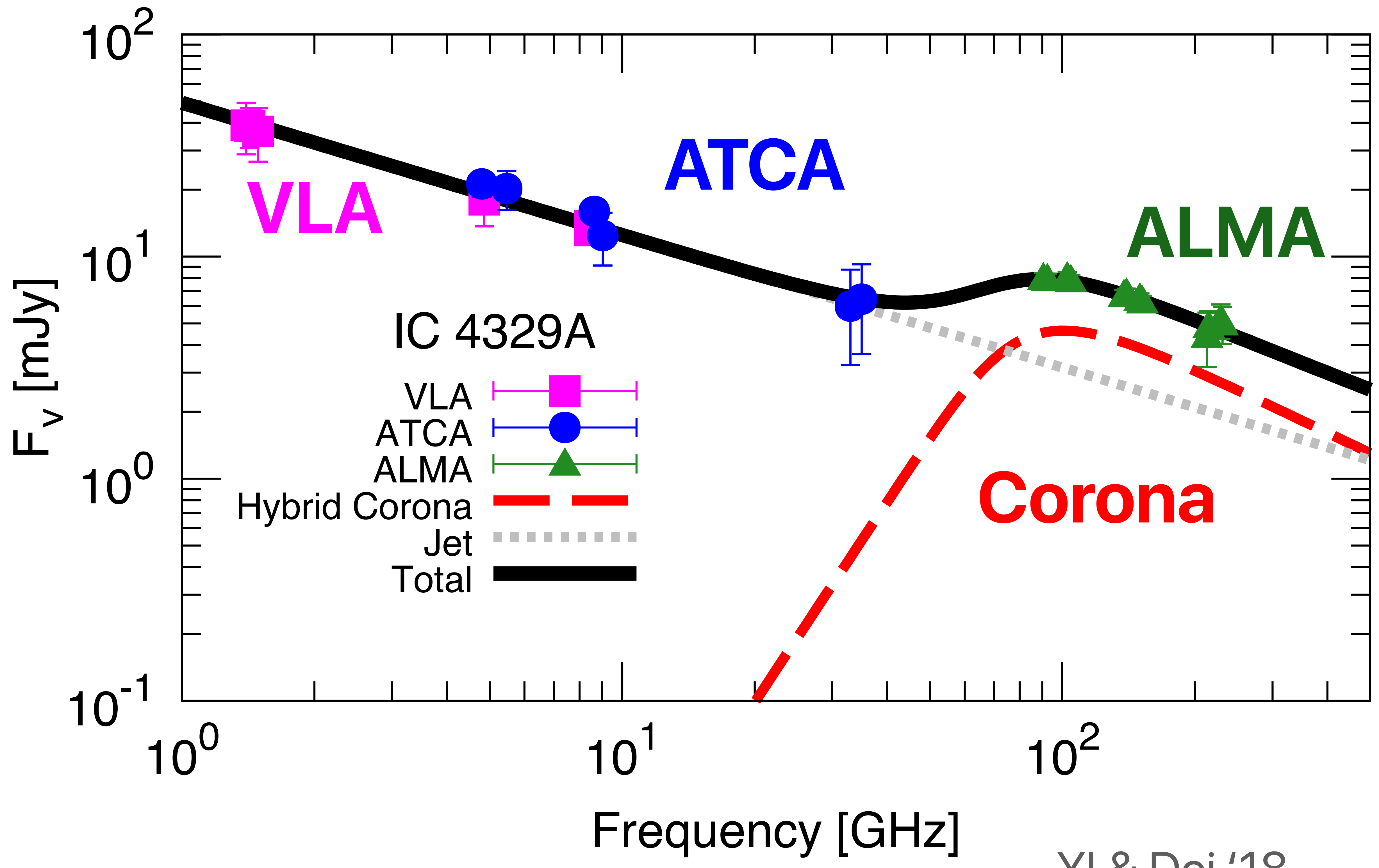


YI & Doi '18

- Clear excess in nearby Seyferts
  (YI & Doi '18; YI, Khangulyan, & Doi '20; Kawamuro+'22; Michiyama+in prep.)
- Flux ~ 1-10 mJy peaking @ a few tens GHz
- Some shows time variability ~1 week
  (Michiyama,YI+ in prep., see also Behar+'20)
- Correlation b/w mm and X-ray luminosities (Kawamuro+'22)
- Size : < 10 pc → Nucleus

cm-mm spectrum of AGN core

A case of IC 4329A

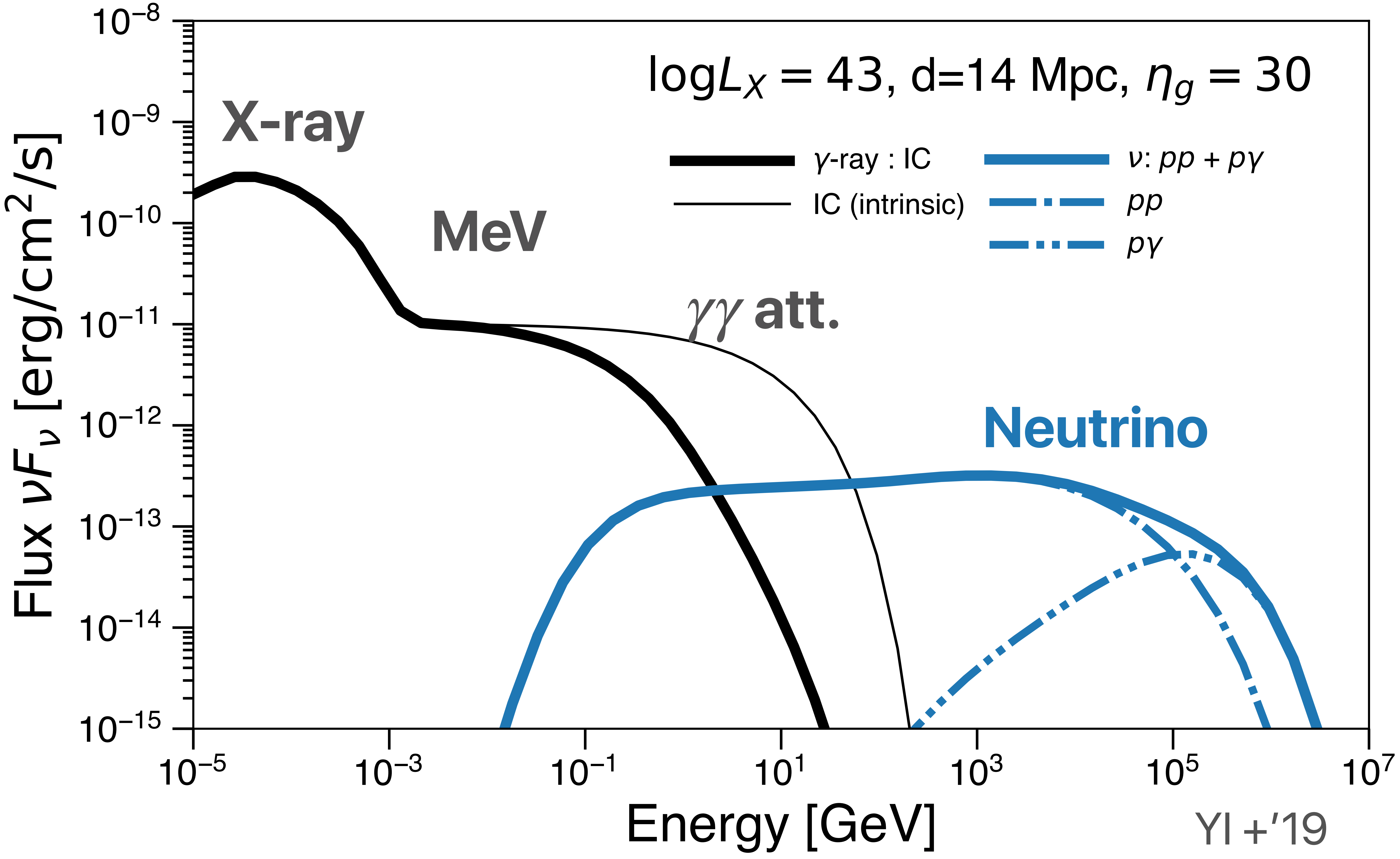


YI & Doi '18

- Hybrid (thermal + non-thermal) corona model (YI & Doi '14)
- Non-thermal electron fraction
  - 0.03 (fixed)
  - Consistent with the MeV gamma-ray background spectrum (YI, Totani, & Ueda '08; YI+'19)
- Non-thermal photon index: 2.9
- Size: 40 r_s
- B-field strength : 10 G

High energy emission from AGN coronae

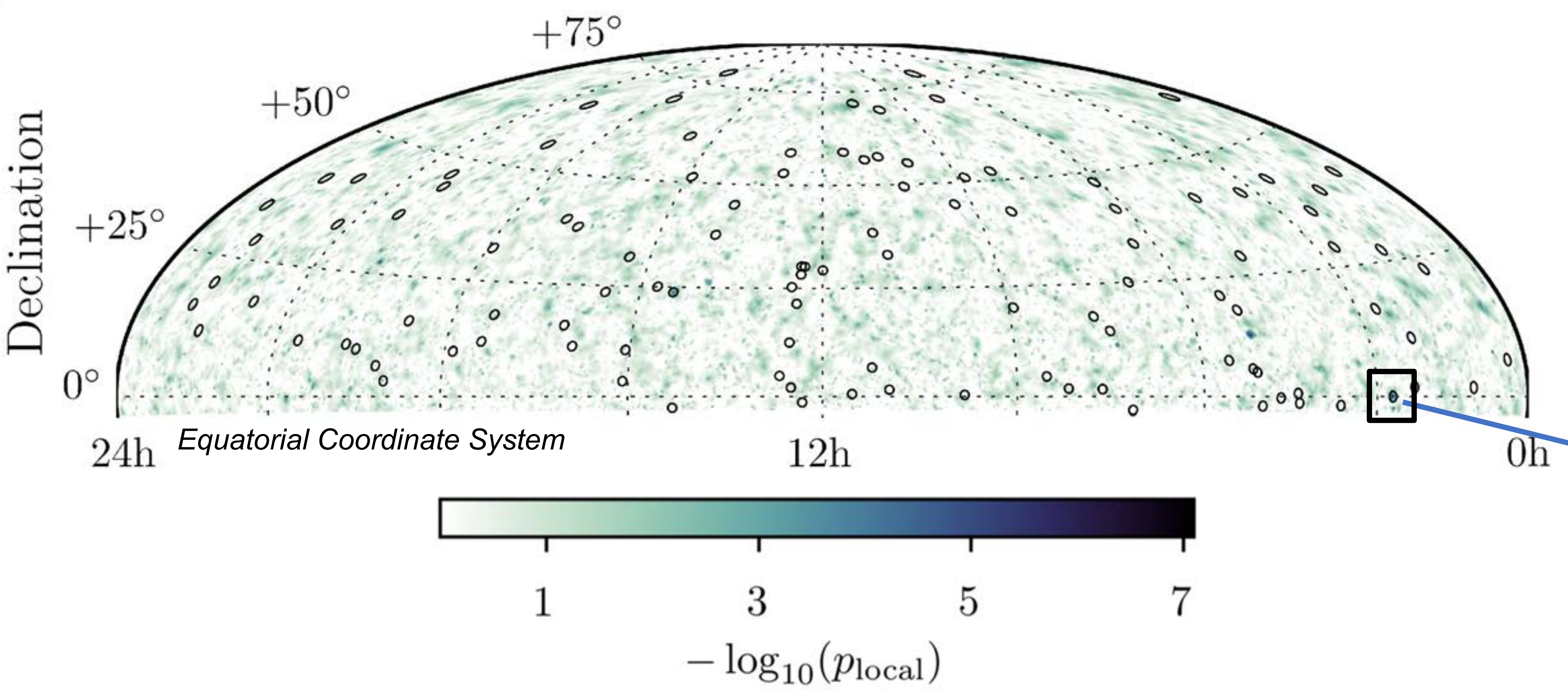
Multi-messenger Signature: MeV Gamma-ray & TeV Neutrinos

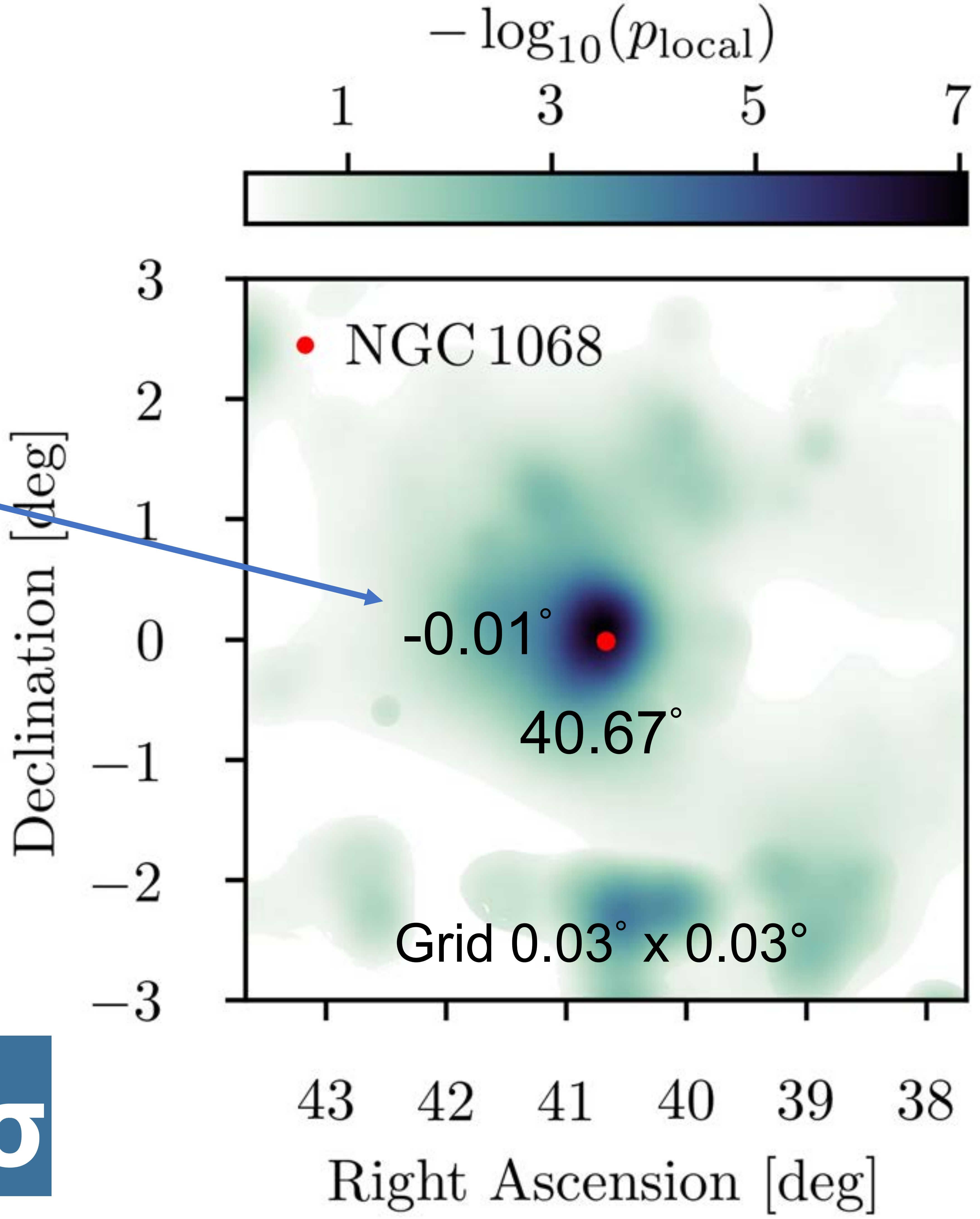


YI +'19

- MeV emission
  - but, no GeV emission
- Protons would be accelerated simultaneously
  - Generation of high energy neutrinos
- See also Begelman+'90; Stecker+'91, '92, '05, '13; Kalashev+'15; Murase+'20; Gutiérrez +'21; Kheirandish+'21

Evidence for neutrino emission from NGC 1068

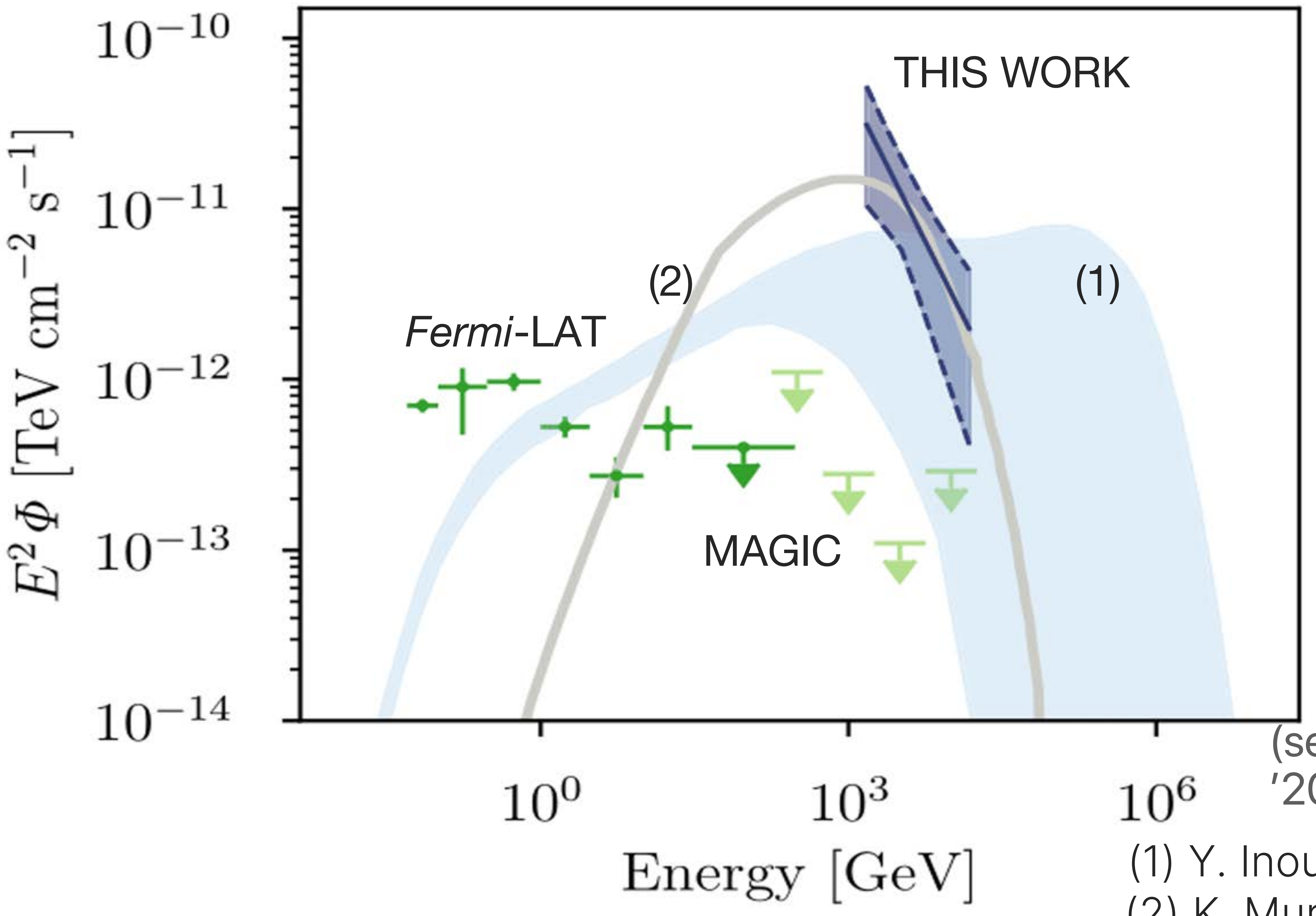




At the NGC 1068 location:
Astrophysical neutrino events = 79^{+22}_{-20}
Spectral index = 3.2 ± 0.2

Global significance 4.2σ

NGC 1068: a cosmic obscured accelerator



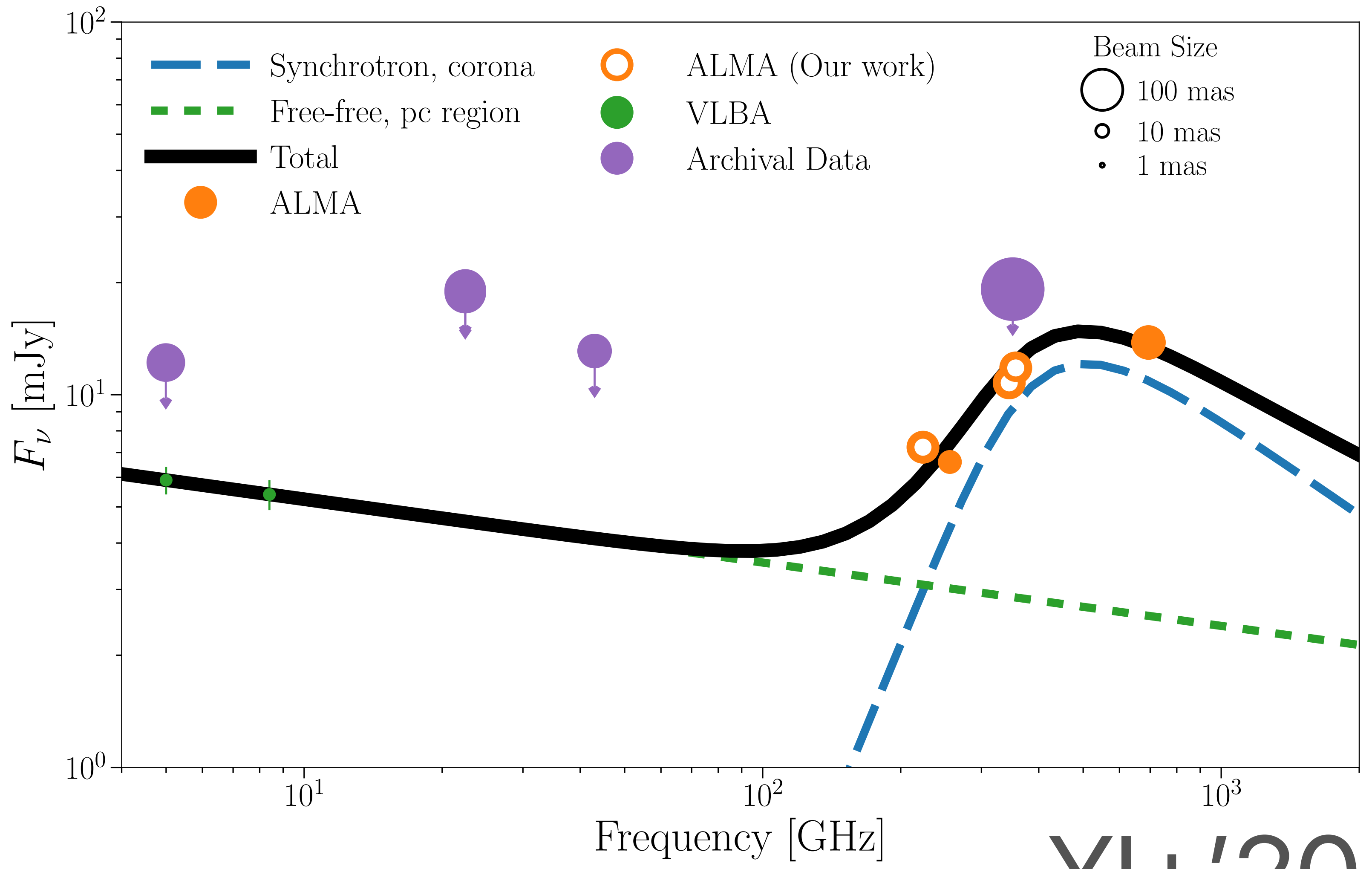
(see also Müller & Romero '20, Eichmann+'22)

(1) Y. Inoue et al., ApJL'20
(2) K. Murase et al., PRL'20

How can we test the model?

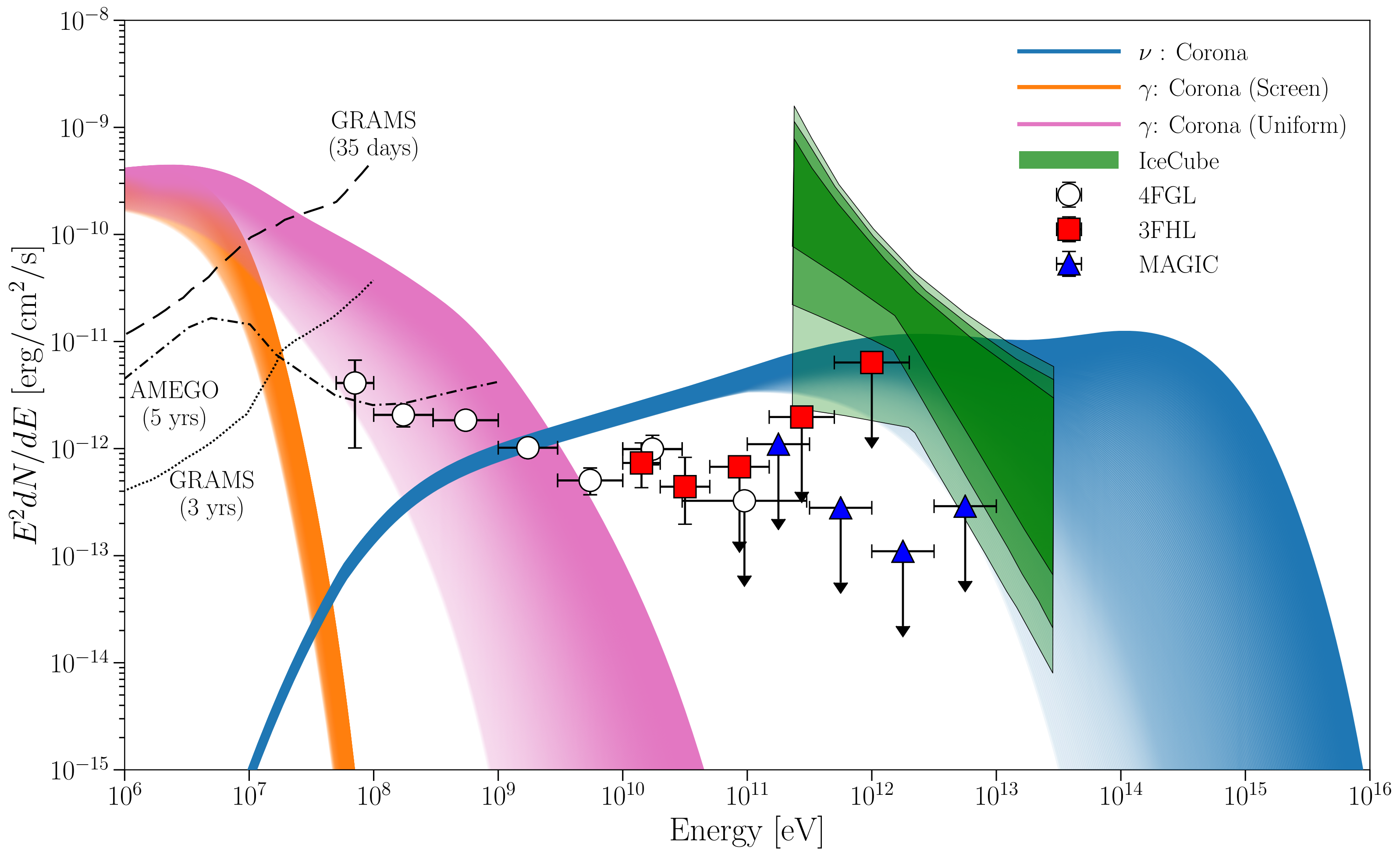
ALMA? ngVLA? FORCE? COSI-X? GRAMS? AMEGO? CTA? IceCube-Gen2? KM3Net? XRISM?

mm-band



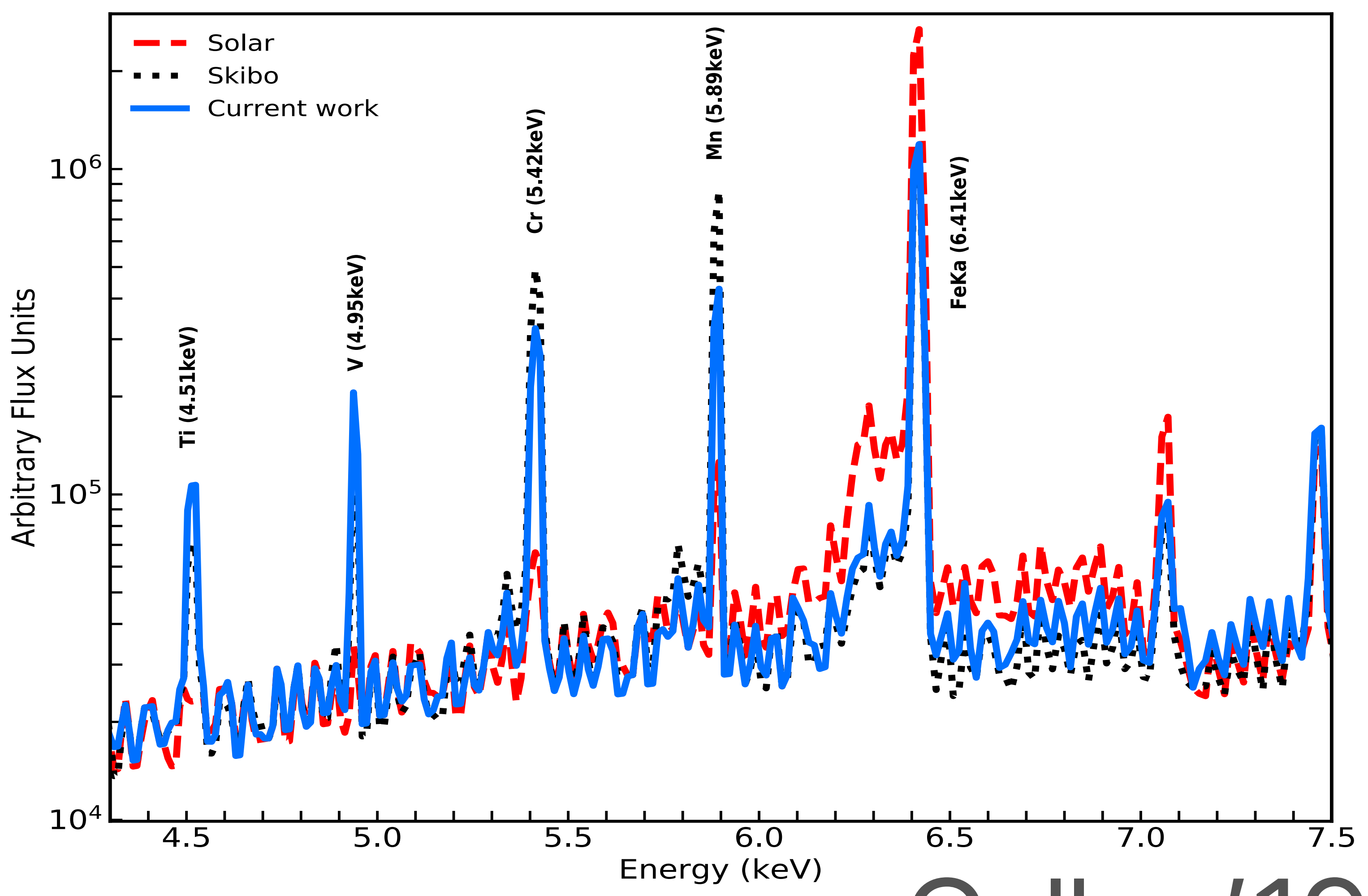
Yl+'20

MeV & TeV ν



Yl+'20

X-ray

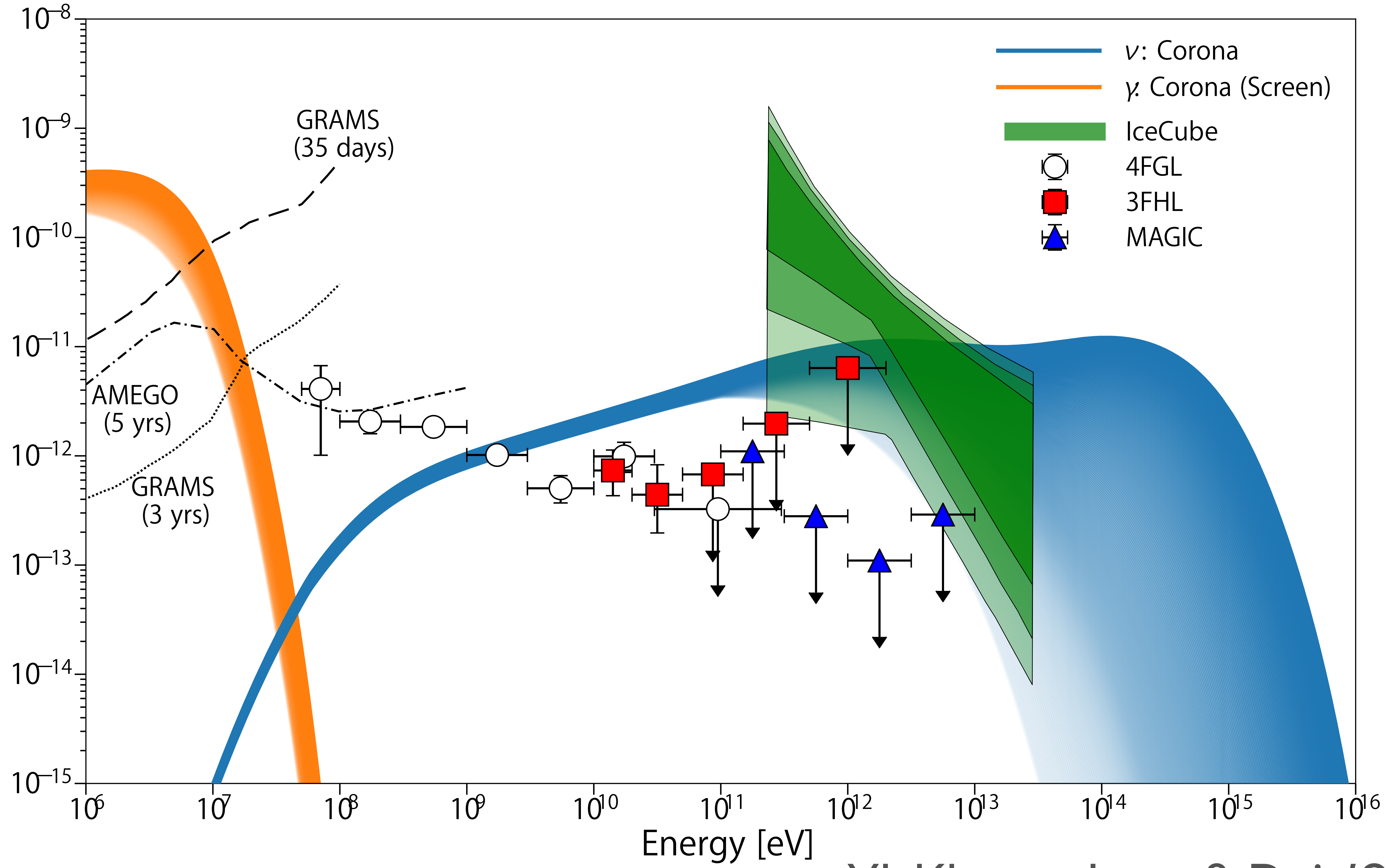


Gallo+'19

- mm-excess
- MeV PL tail
- **TeV ν without GeV-TeV γ**
- Nuclear spallation in X-ray

We see GeV-TeV gamma rays from NGC 1068

Simultaneous obs. of ALMA, Fermi, CTA, & IceCube will be the key

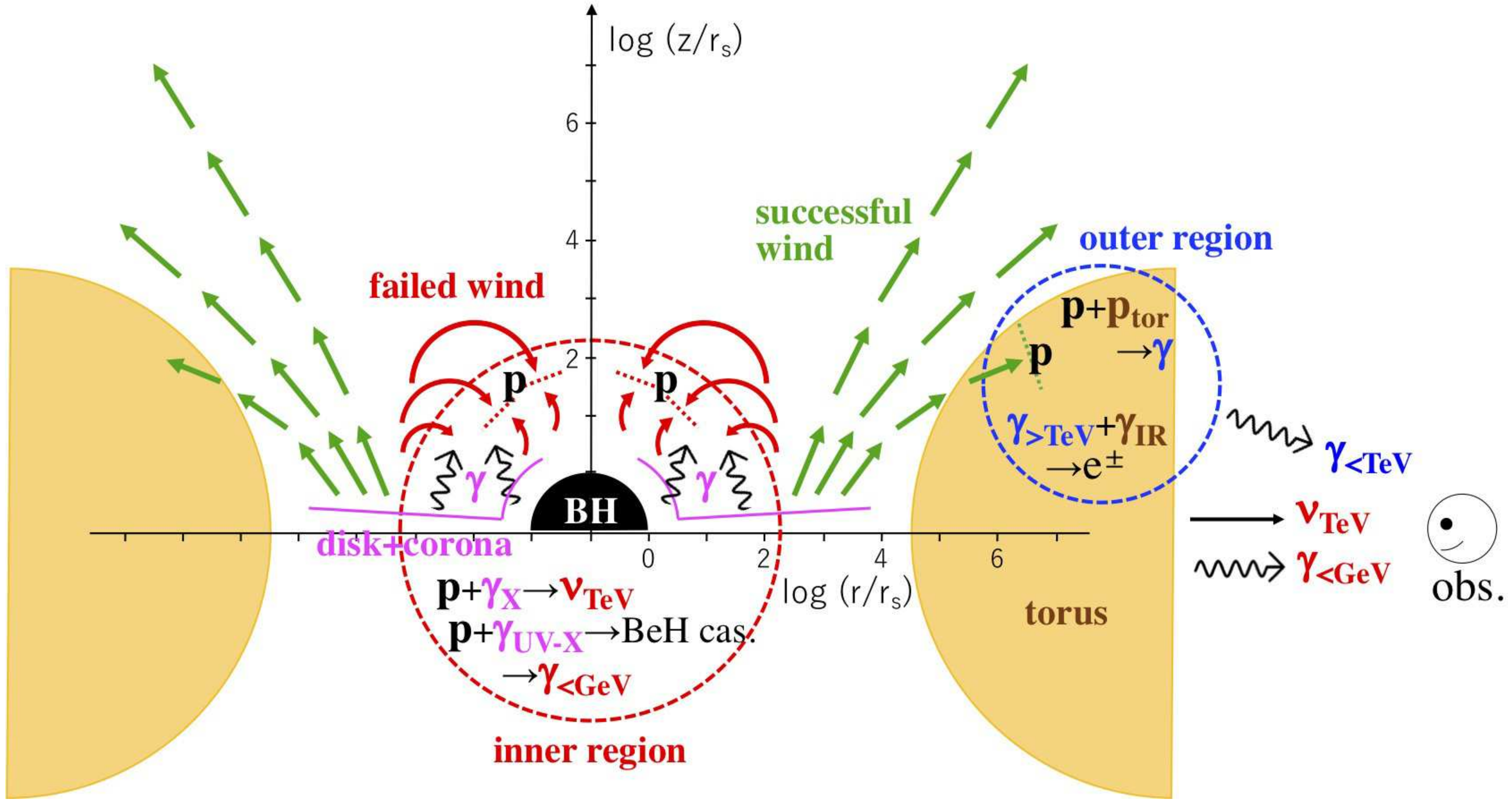


YI, Khangulyan, & Doi, '20

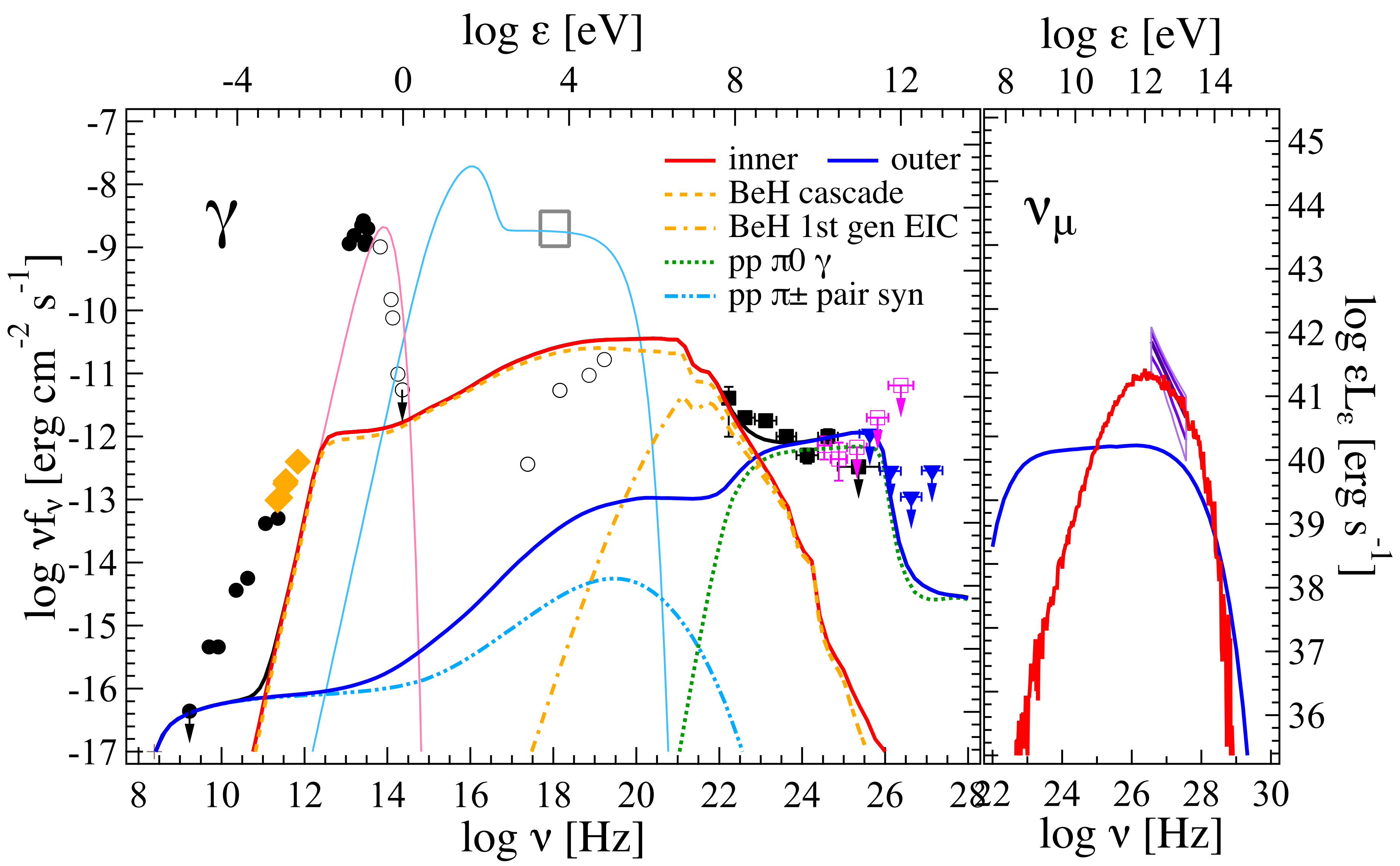
- We can not expect GeV-TeV gamma from AGN corona
  - because of internal γγ attenuation
- GeV - TeV gamma rays should be from outside of corona
  - starburst activity or disk wind

AGN Failed Wind? (S. Inoue+'22)

Interaction between Accretion Flows and Disk Winds



S. Inoue +'22

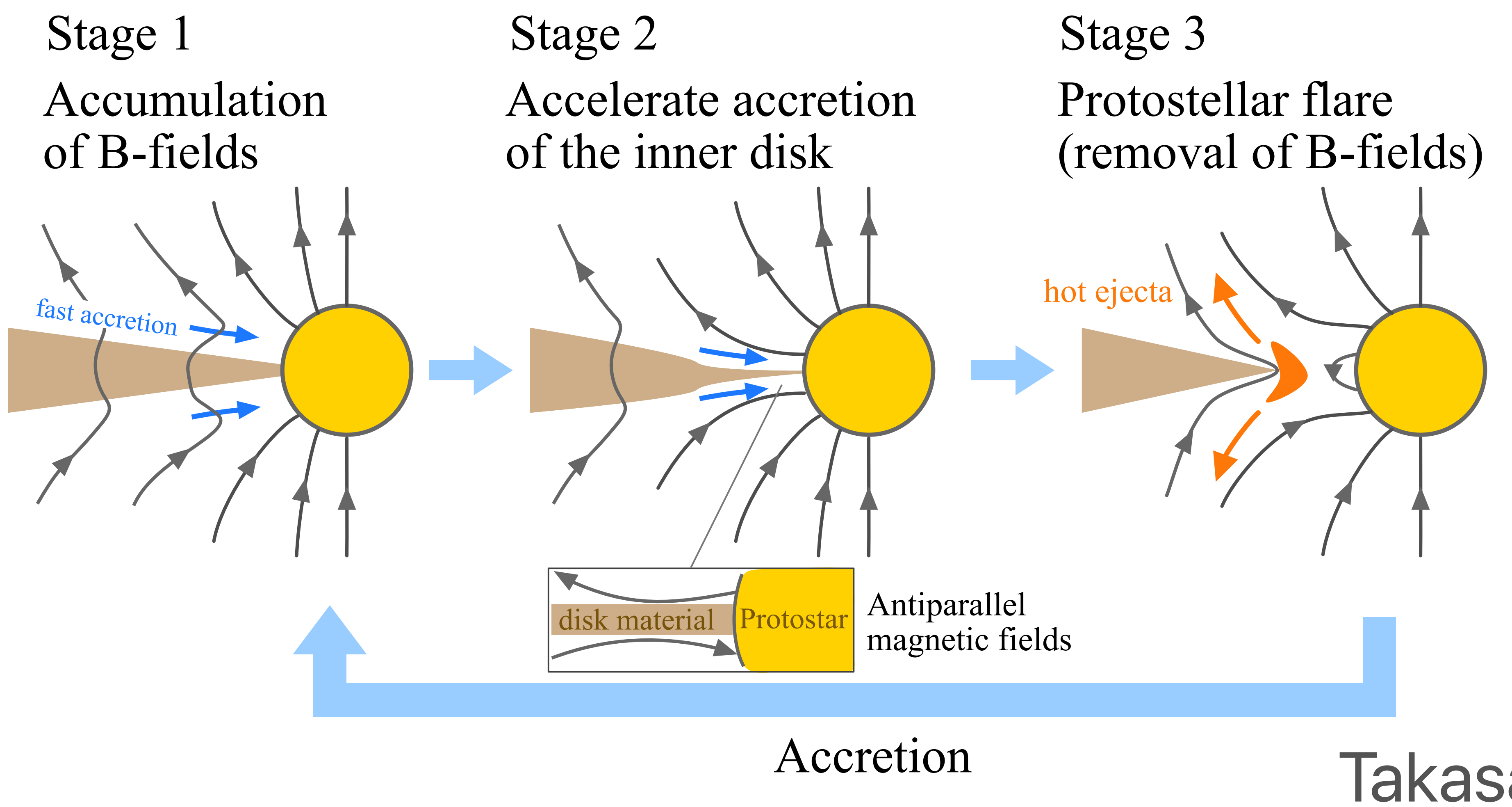


S. Inoue +'22

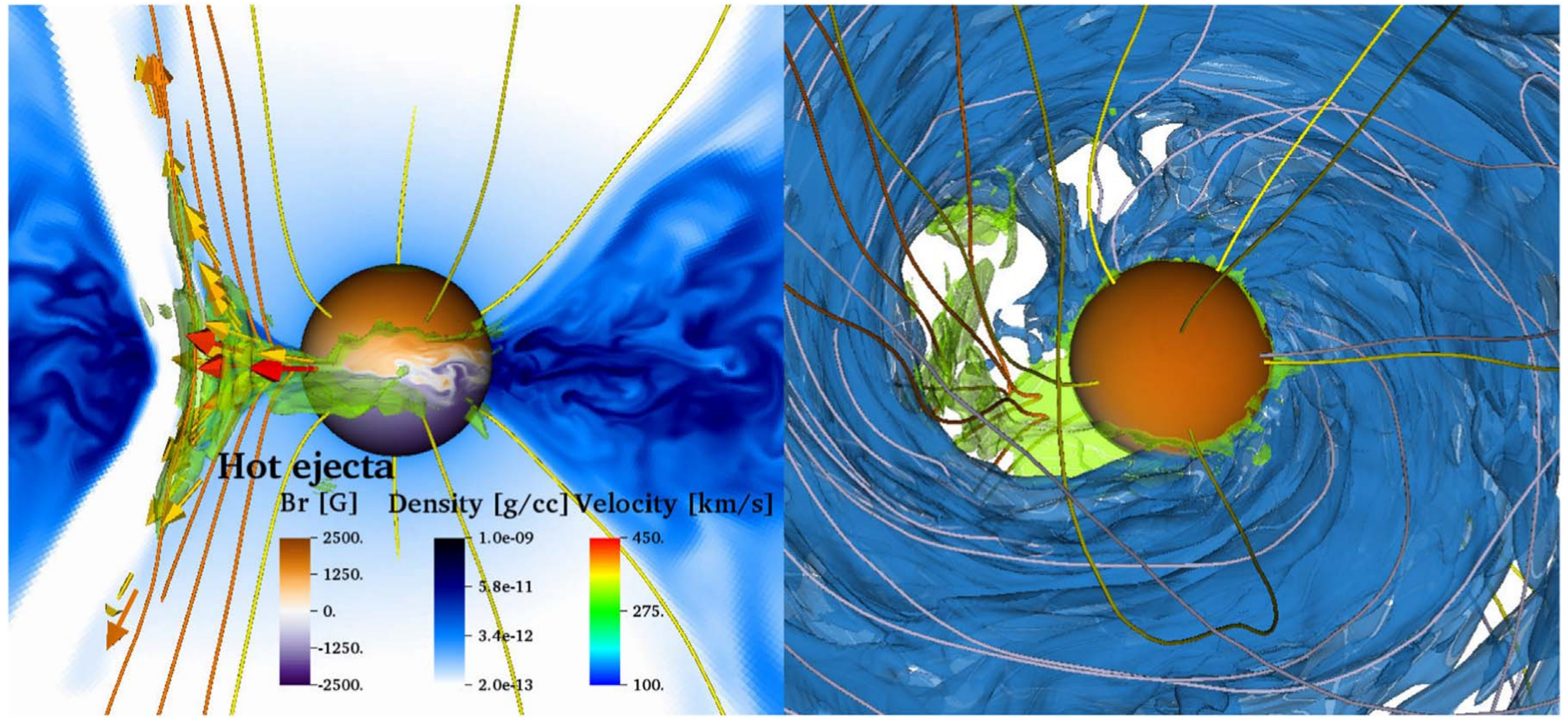
- Two wind components may explain both gamma-ray and neutrino data.

Reconnection Driven Flare (Takasao Flare) ?

A possible scenario for the radio galaxy IC 310 flare event?



Takasao +'19



Takasao +'19

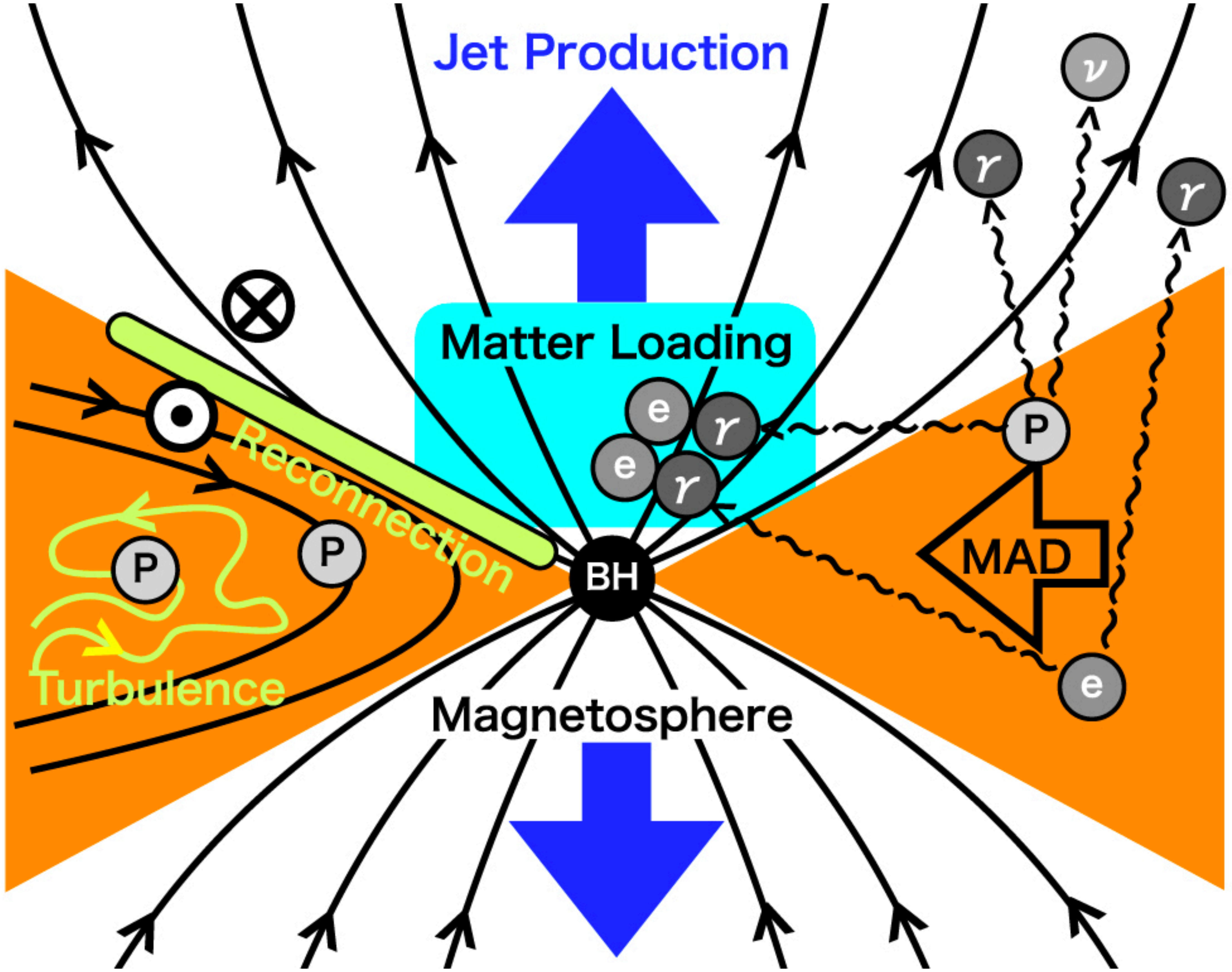
- 3D MHD simulation reveals a large reconnection flare for protostars (Takasao+'19)
  - Later, confirmed for SMBH systems (Porth+'21)
- Rough energetics estimate

$$E_{\rm flare} \approx f \frac{B^2 L^3}{8\pi}$$

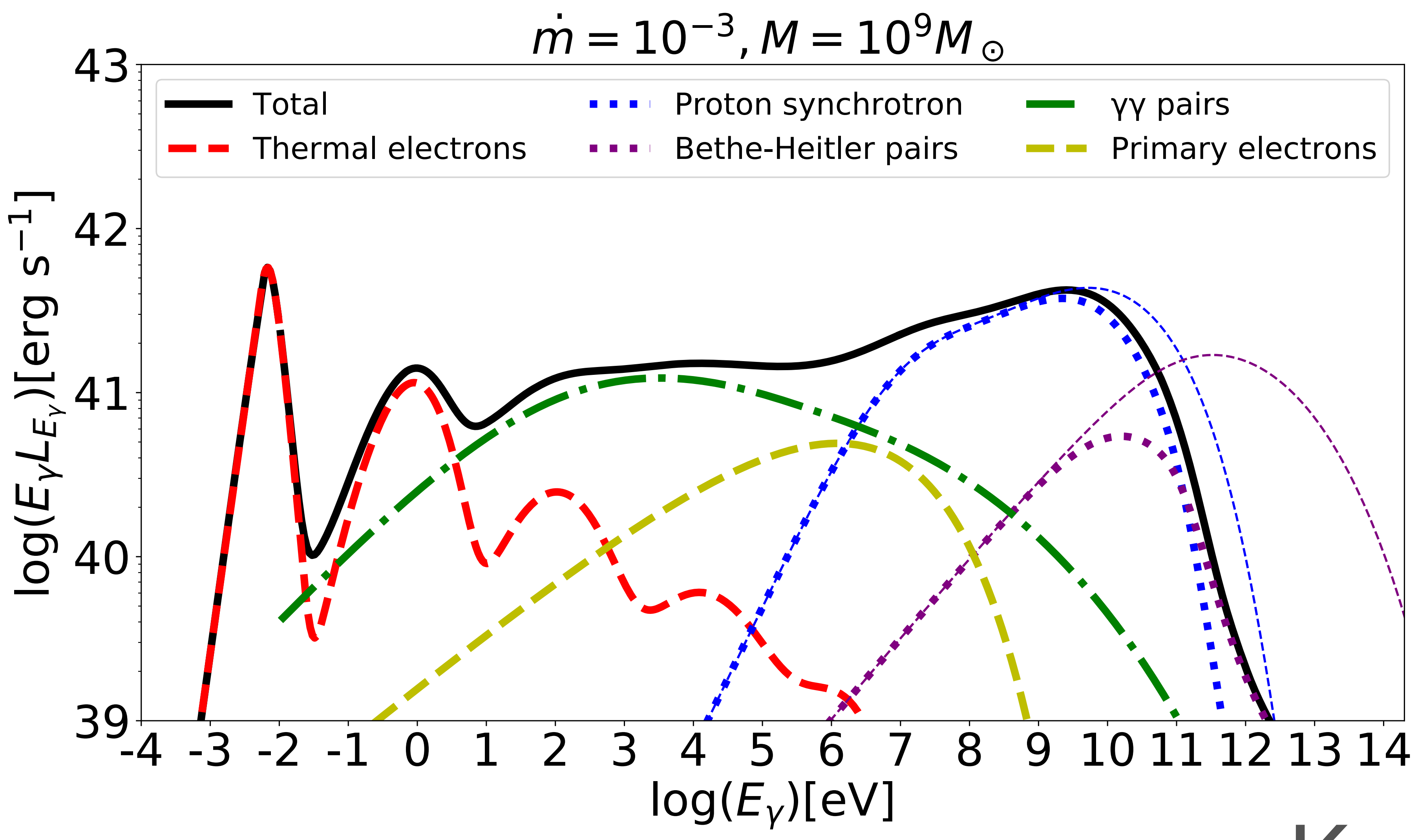
$$\approx 10^{47}\ {\rm erg} \left(\frac{f}{0.1}\right) \left(\frac{B}{10^4\ {\rm G}}\right)^2 \left(\frac{L}{3R_s(10^8 M_\odot)}\right)^3$$

Probing Magnetically-Arrested Disks (MAD) by CTA ?

Gamma-ray emission from MAD in nearby radio galaxies



Kimura & Toma '20

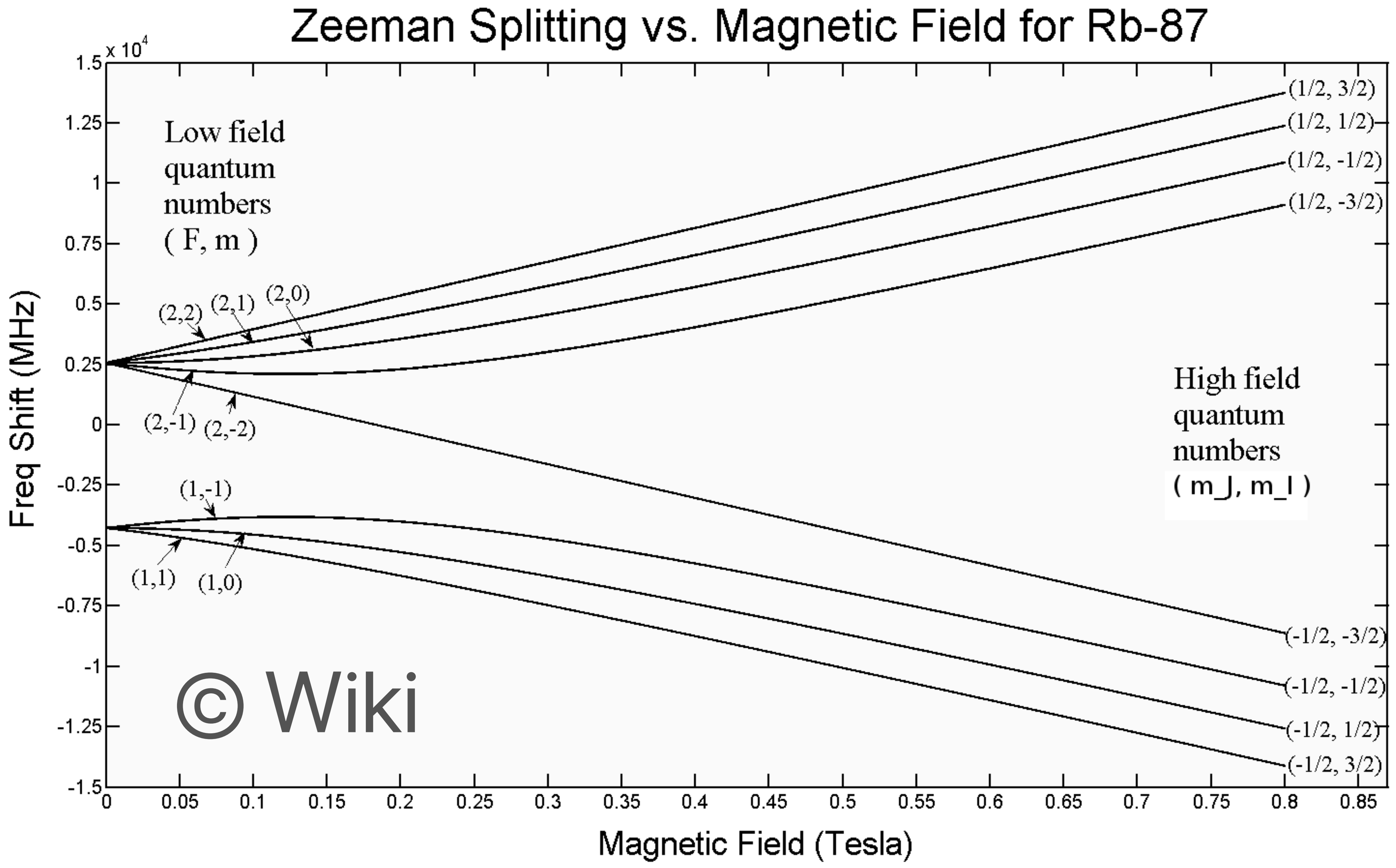


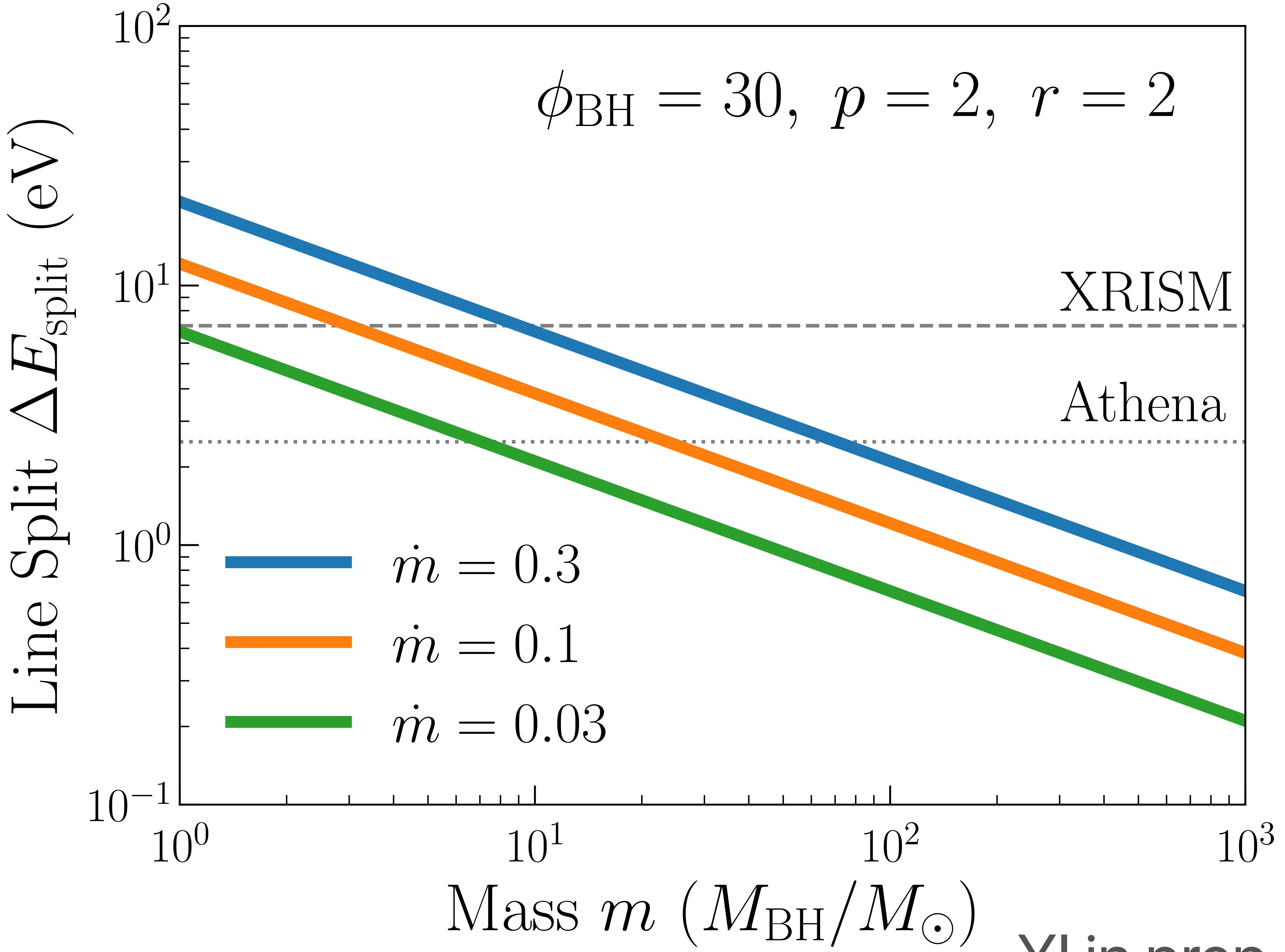
Kuze+'22

- MAD accumulates B-field for jet launch (e.g., Narayan+'03)
- RIAF-type MAD may produce hadronic signatures (Kimura & Toma '20; Kuze+'22)
- How to discriminate from jet / wind / corona ?

Probing MAD by XRISM and Athena

Zeeman Splitting Effect on the Fe Kα Line





YI in prep.

- Emission line will be split under strong magnetic field.
- MAD will split the Fe Kα line.

Summary

- Gamma-ray production processes in blazars are well understood now.
    - Leptonic dominant & hadronic sub-dominant for the TXS 0506+056 case
- Low-energy threshold, Large collection area, Fast slewing capability of LST will probe
    - Energy dissipation region in the jet
    - Jet energy distribution process in a galaxy
    - Origin of high-energy emission in unjetted AGNs
    - Disk accretion dynamics through reconnection process