Coronal Magnetic Activity in nearby Active Supermassive Black Holes

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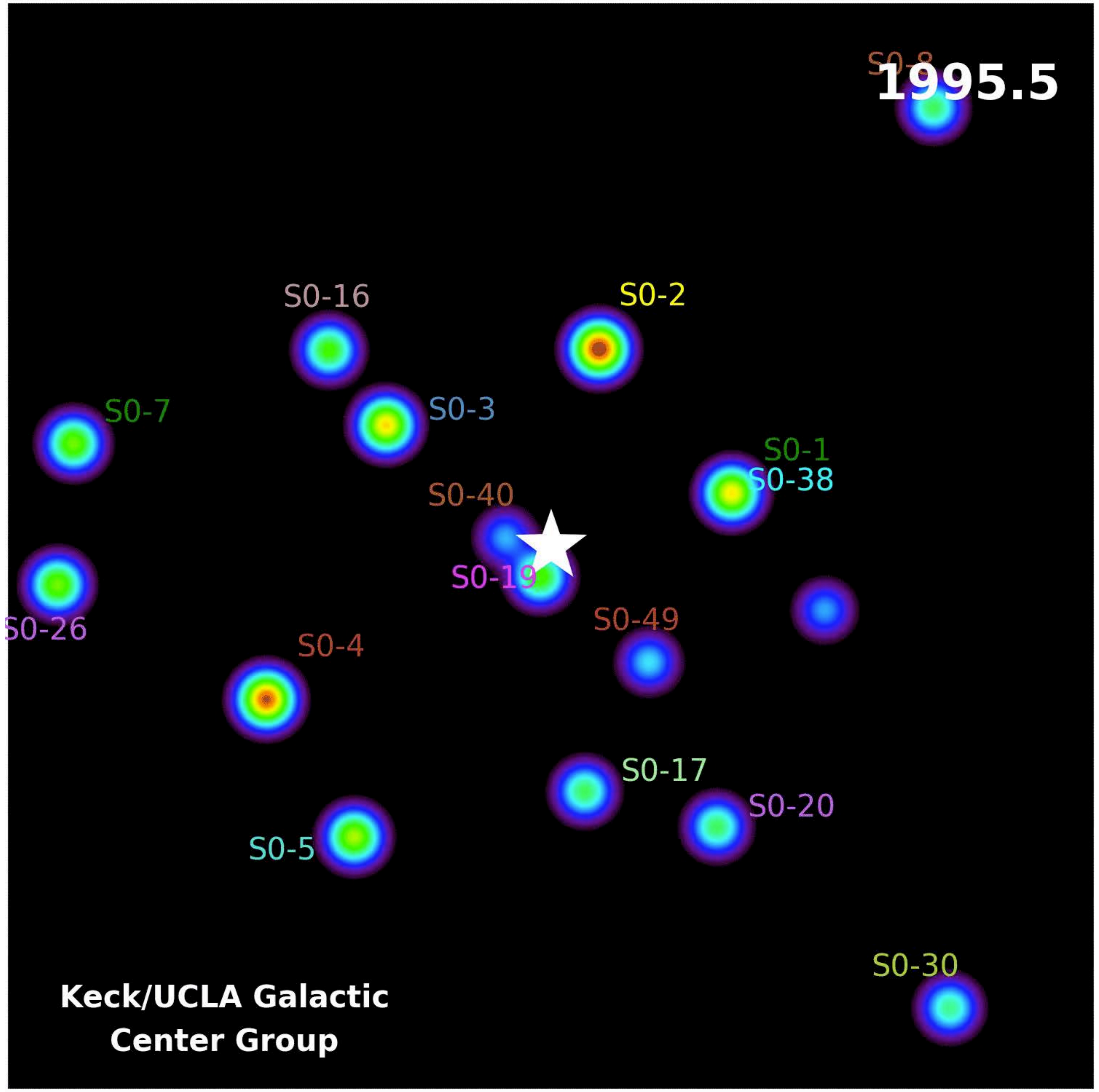
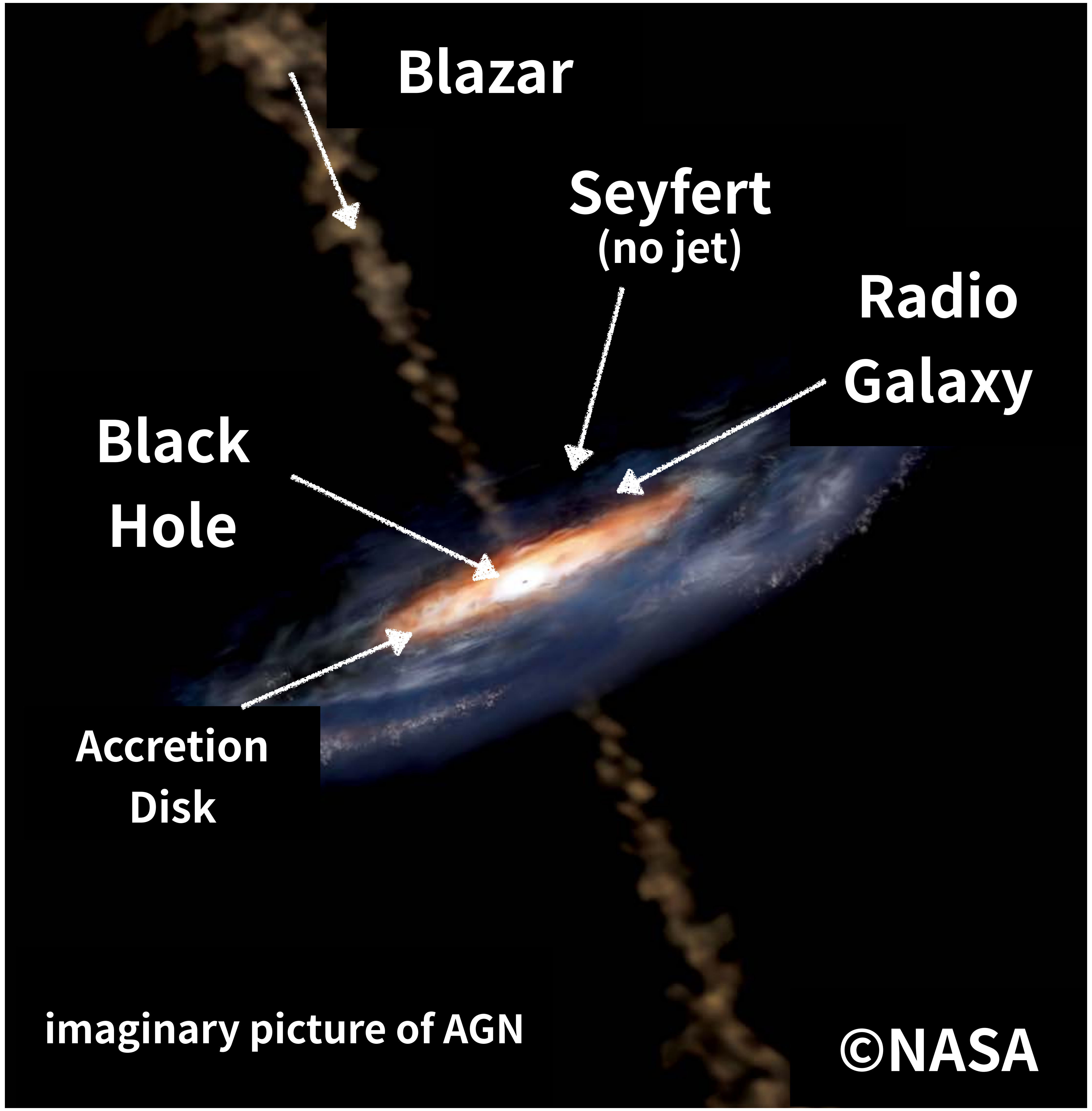
Supermassive Black Hole at the Center of the Galaxy

- Kepler motion of stars by the gravity of the central black hole
- Supermassive (>10^6 solar mass) black holes @ galactic center
  - In the Milky way,
    - $M_{\rm BH} \sim 4 \times 10^6 M_\odot$

Motion of Stars at the Galactic center



Supermassive Black Holes are Active

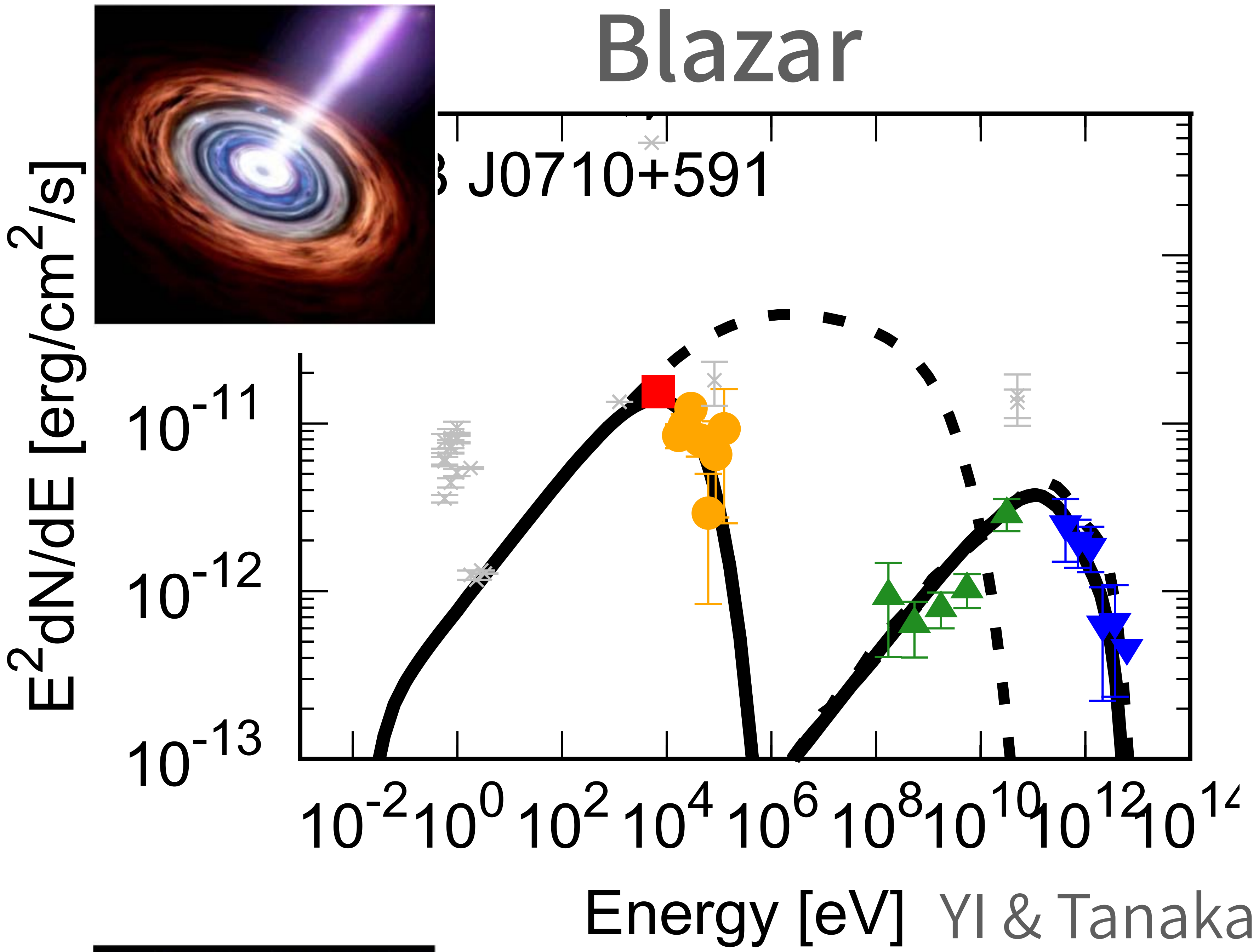


- Gas accretion
  ➡brighter than galaxy
- **Active Galactic Nuclei (AGNs)**
- Various populations
  - Blazar, Radio galaxy, Seyfert
- Unsolved mysteries of AGNs
  - Evolution? Power? Jet? Corona?,,,,

Millimeter Excess in Nearby Seyferts

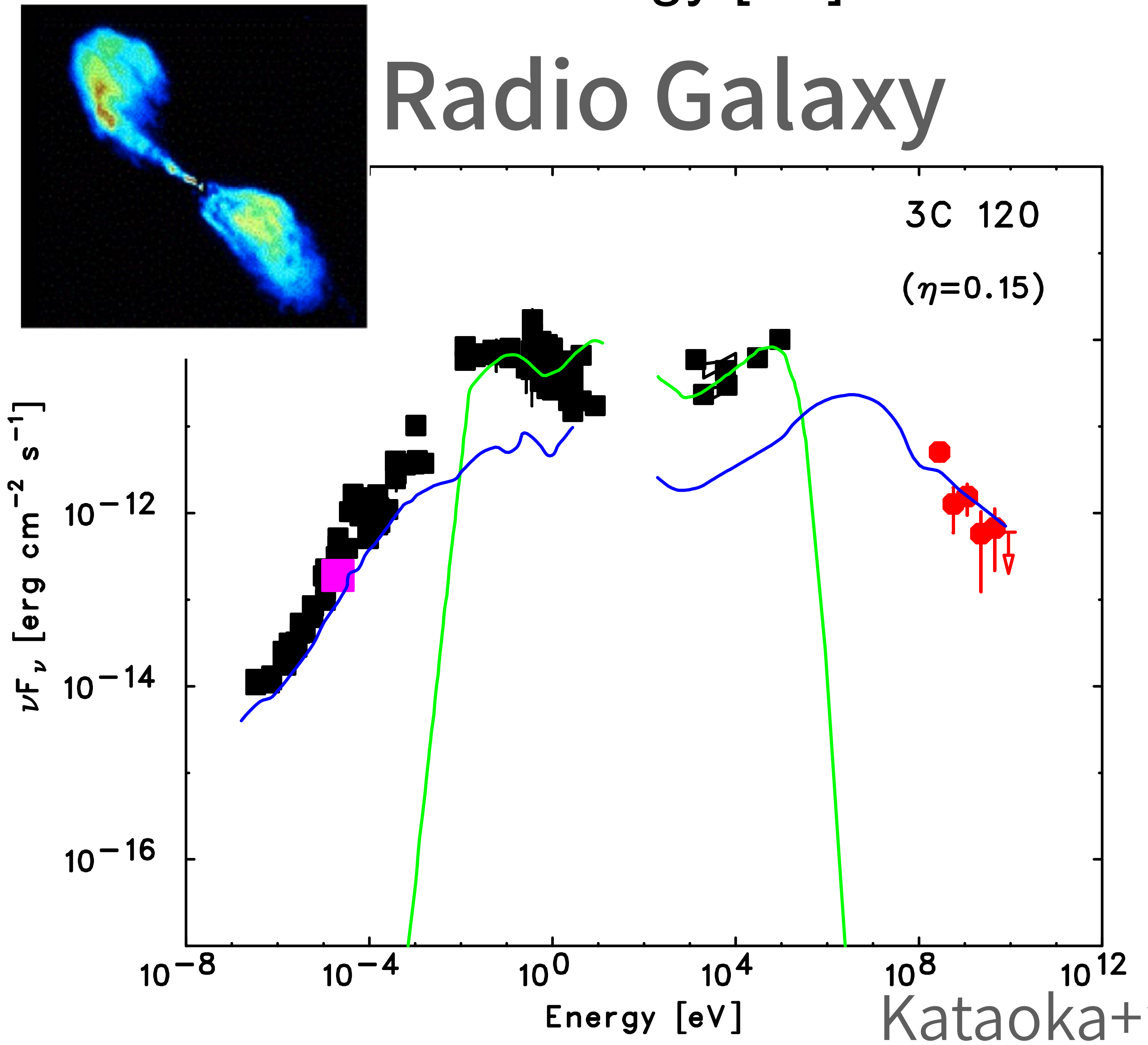
Multi-wavelength spectrum of AGNs

Blazar



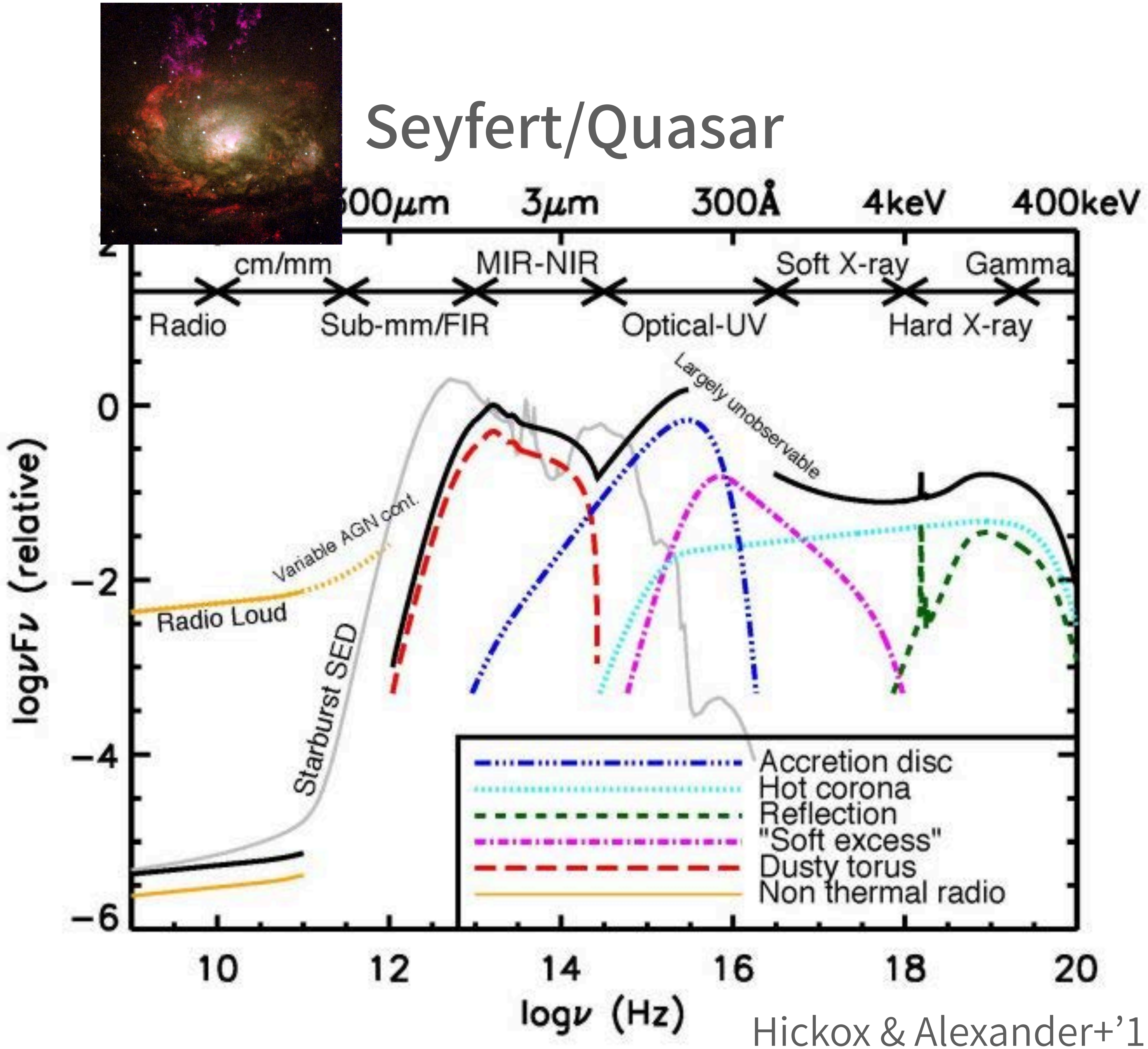
YI & Tanaka '16

Radio Galaxy



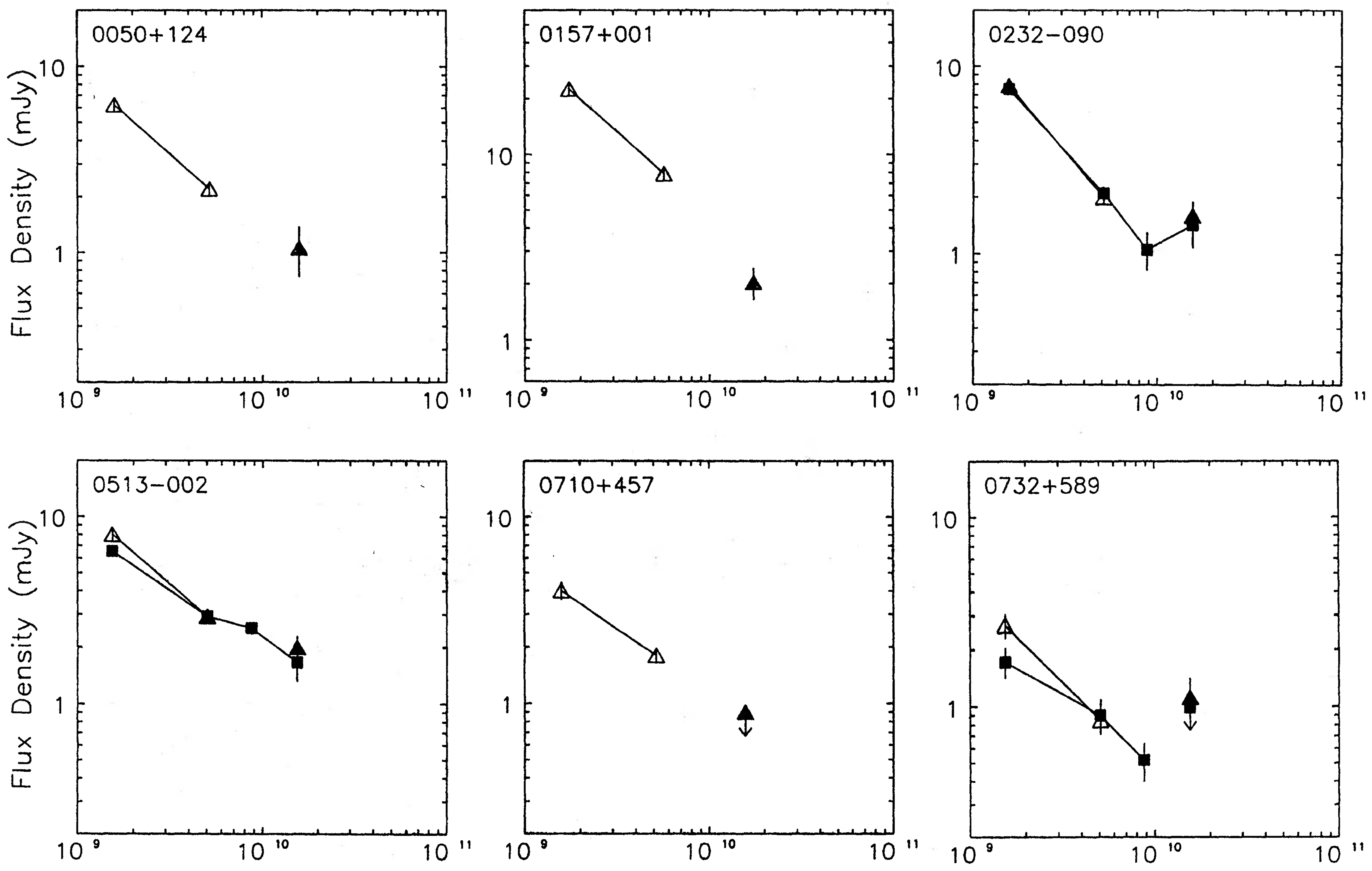
Kataoka+'11

Seyfert/Quasar

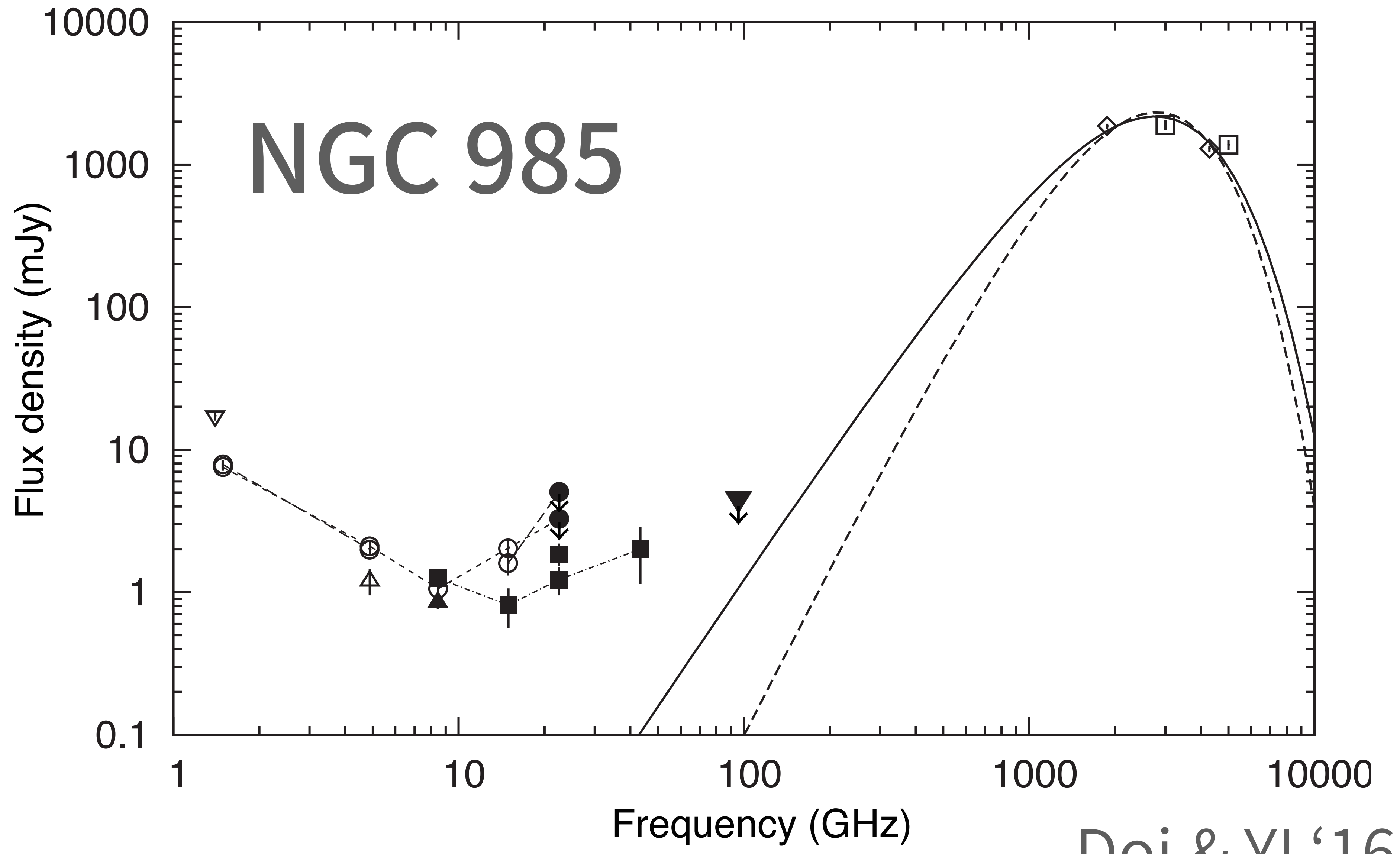


Hickox & Alexander+'16

Millimeter excess in nearby Seyferts



Barvainis+'96



Doi & YI '16

- Spectral excess in the mm-band

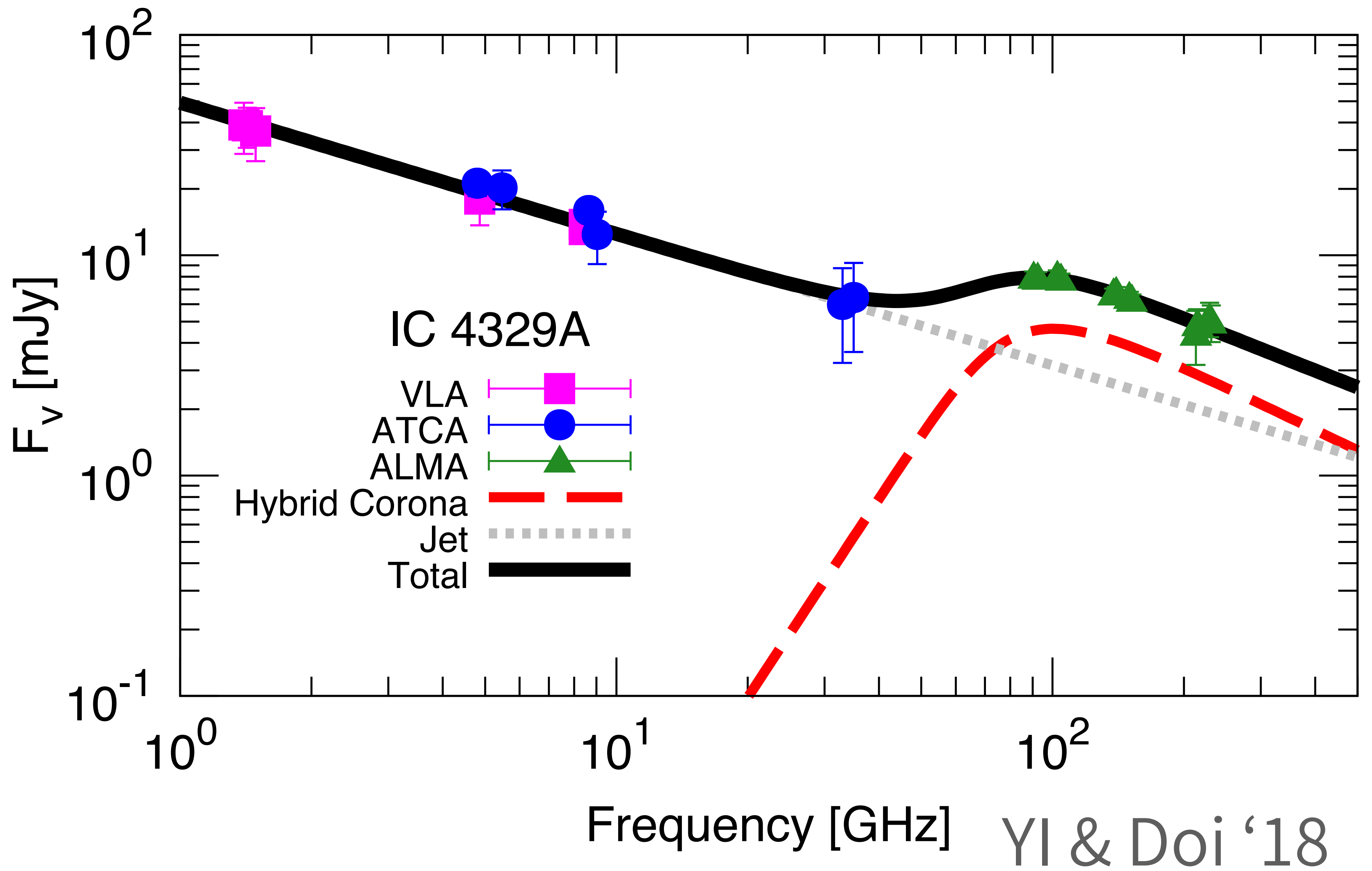
(e.g., Antonucci & Barvainis'88; Barvainis+'96; Doi & Inoue '16; Behar+'18).

- Contamination of extended components?
- Multi-frequency property?

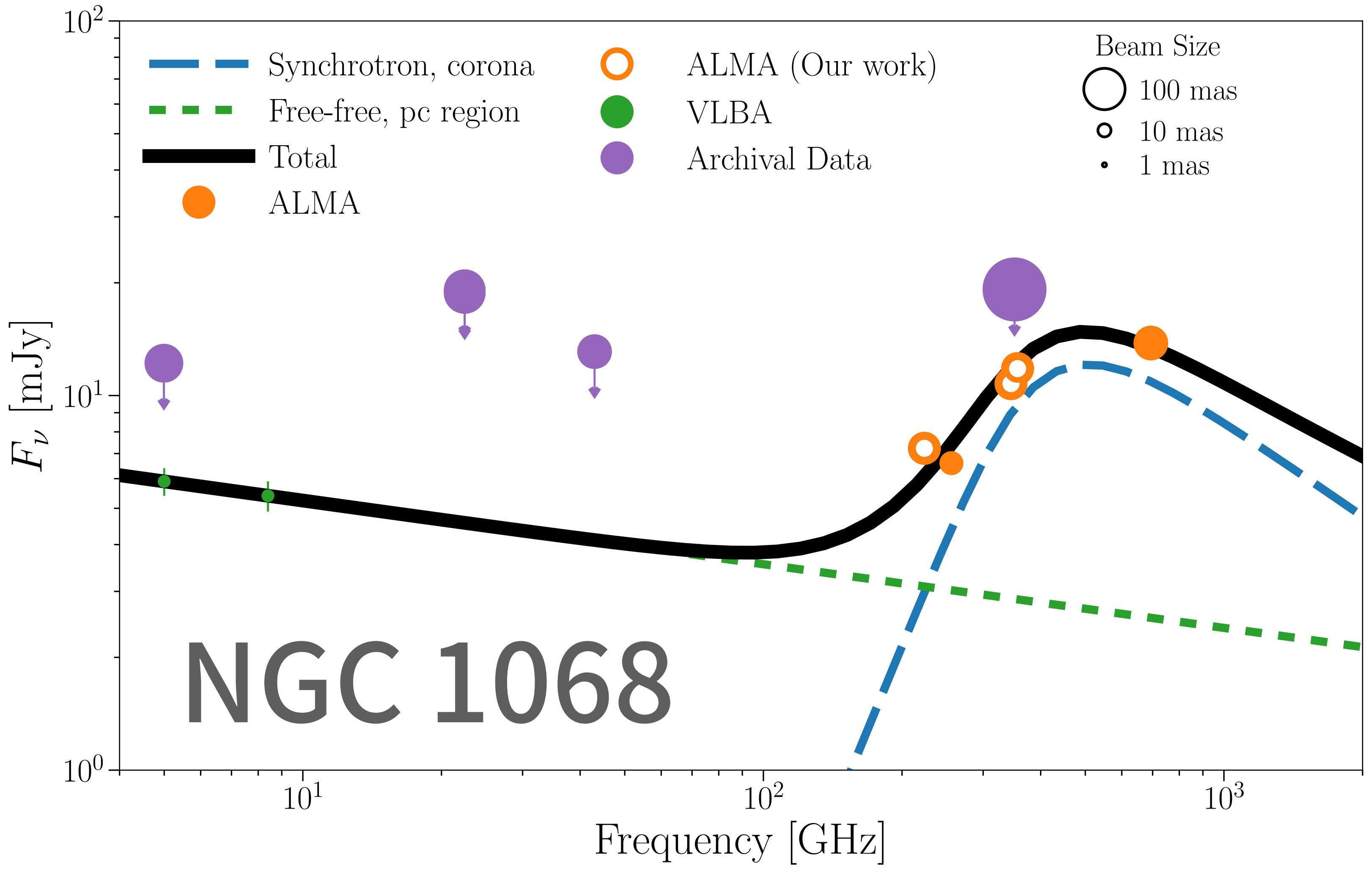
Now we live in the ALMA era.

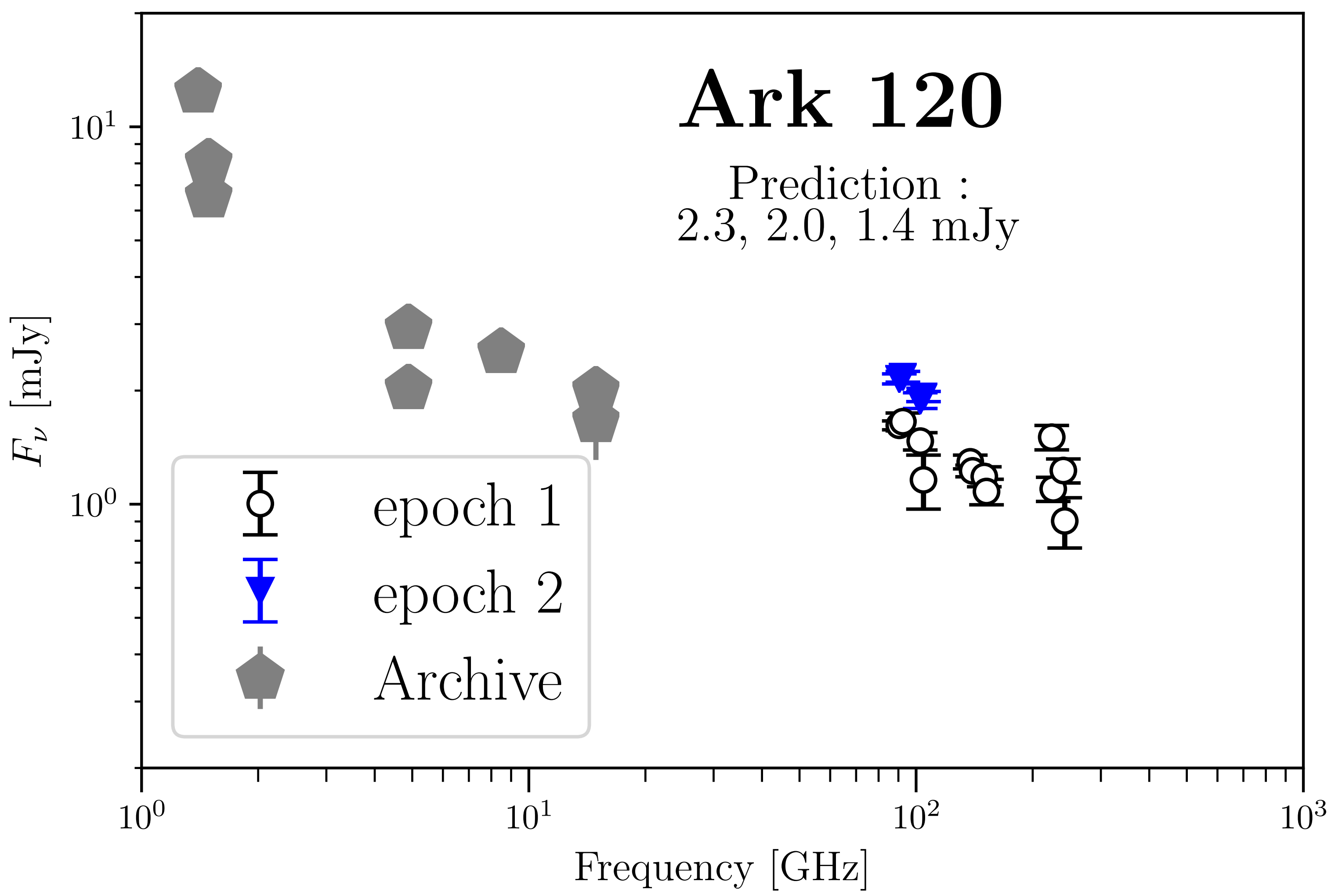
- The **Atacama Large Millimeter/submillimeter Array** (**ALMA**) is an astronomical interferometer of 66 radio telescopes in the Atacama Desert of northern Chile (from wikipedia).
- Covers millimeter and submillimeter bands.
- Has much higher sensitivity and higher resolution than before.

ALMA observations toward nearby Seyferts



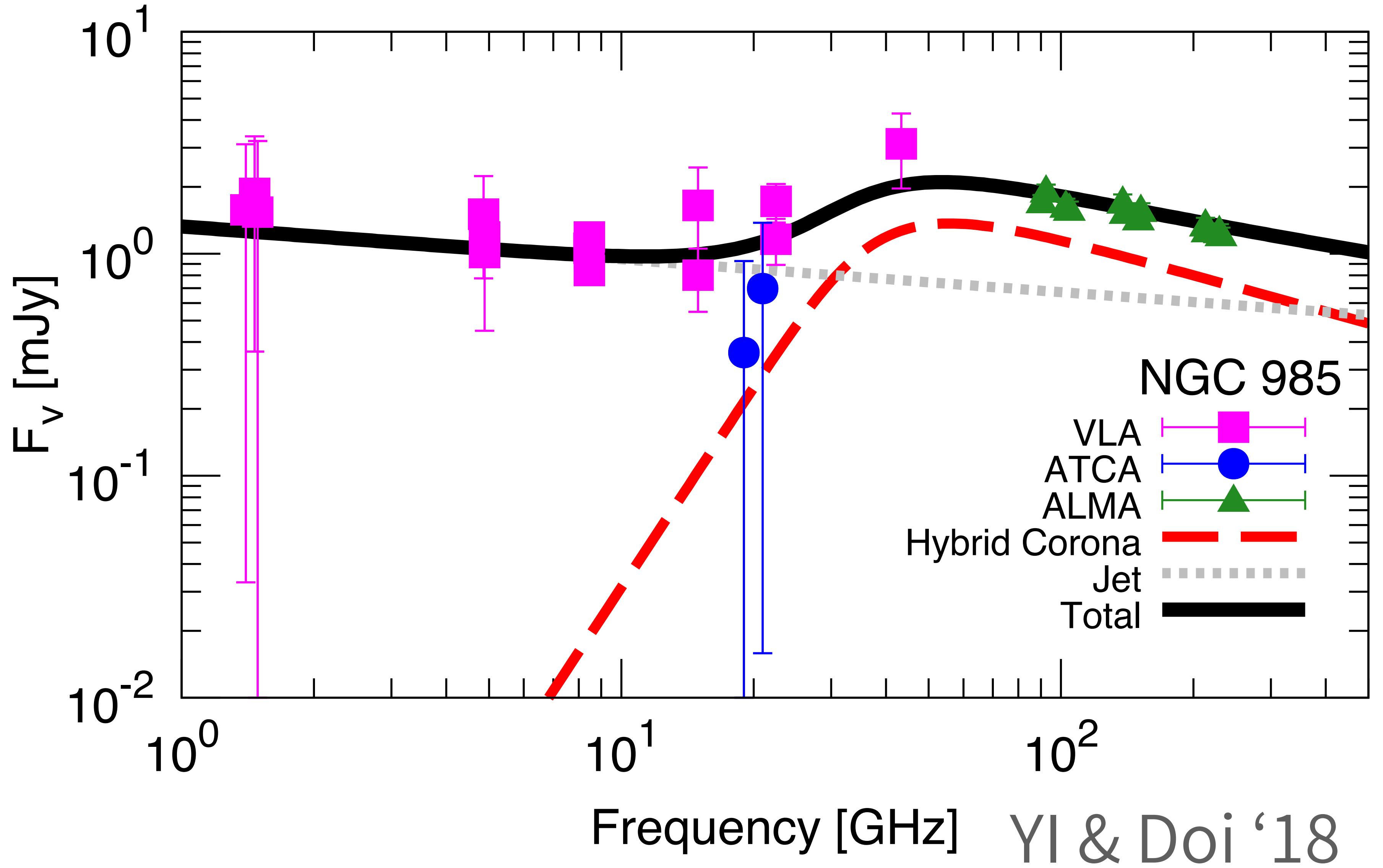
YI & Doi ‘18





YI, Khangulyan, & Doi ‘20

YI+’in prep.

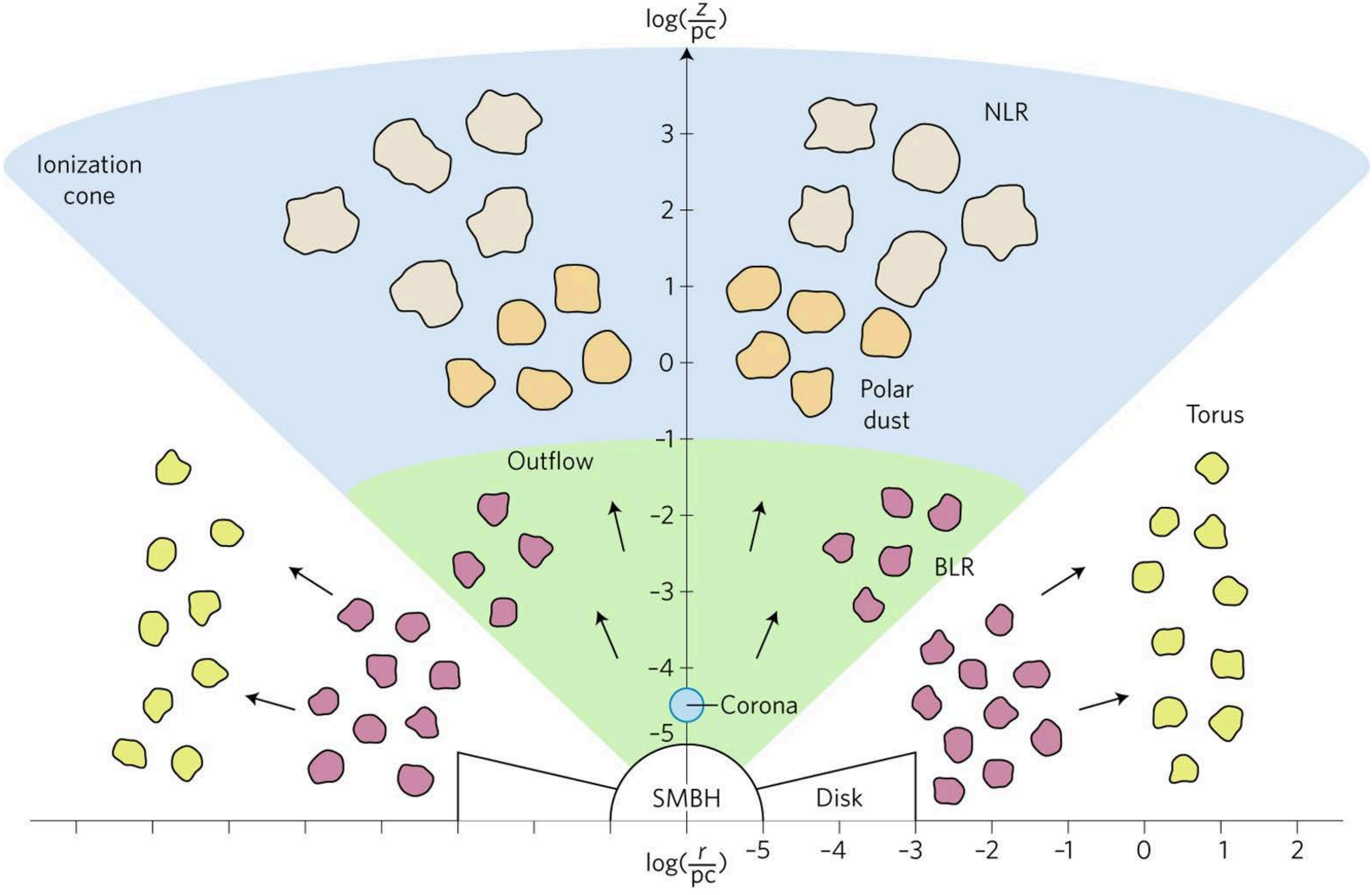


YI & Doi ‘18

- Clear excess in nearby Seyferts
  (YI & Doi ’18; YI, Khangulyan, & Doi ’20; YI+in prep.)
- Flux ~ 1-10 mJy peaking @ a few tens GHz
- Some shows time variability ~1 month
  (see also Behar+’20)
- Size : < 10 pc → Nucleus

Structure of AGN core in the <10 pc scale

Where is the origin of the mm excess?

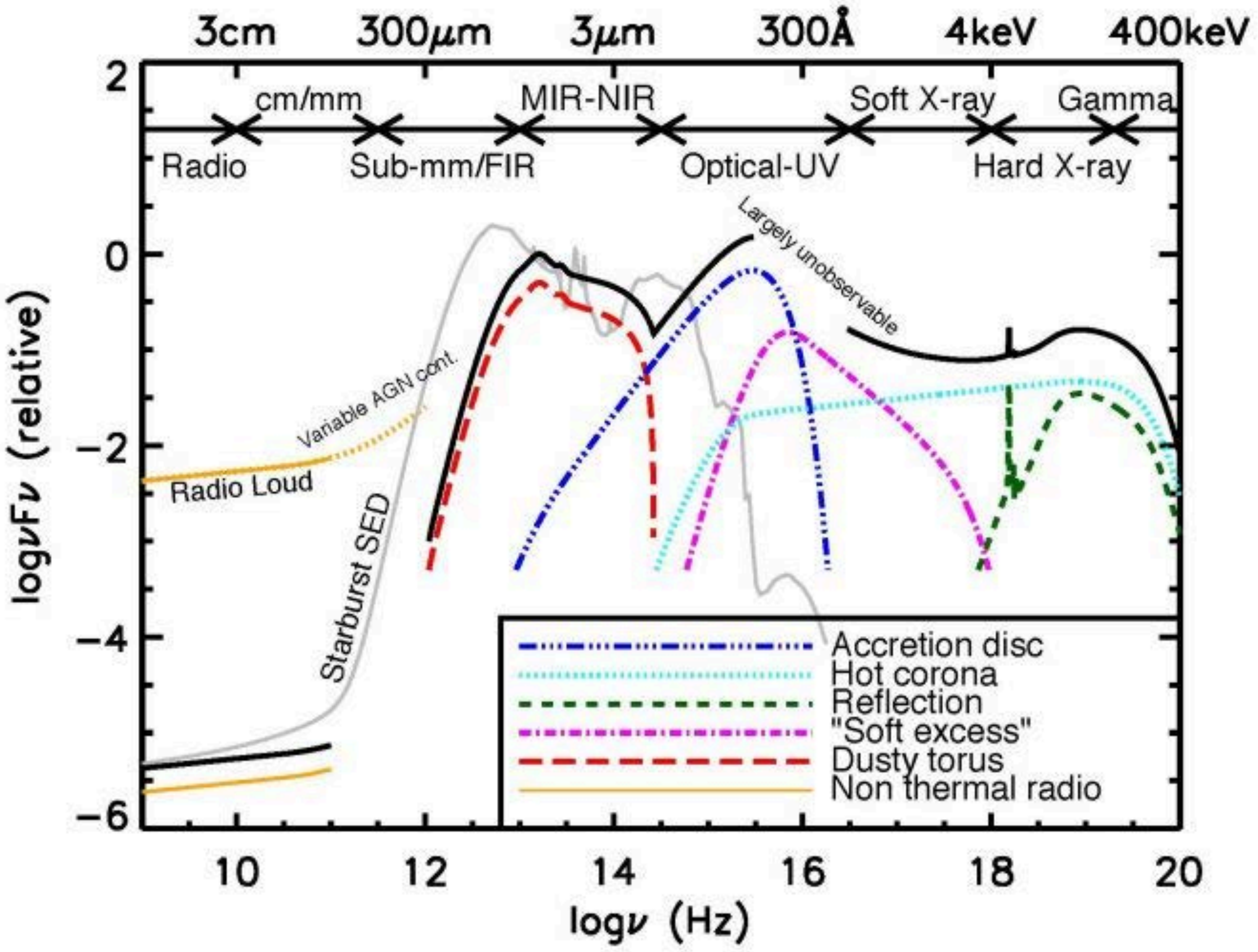


Ramos-Almeida & Ricci '17

- Dust torus?
  - spectral shape, not enough, variability
- Free-free?
  - spectral shape, not enough
- Jet?
  - radio-quiet, no blazar like activity
- Corona?

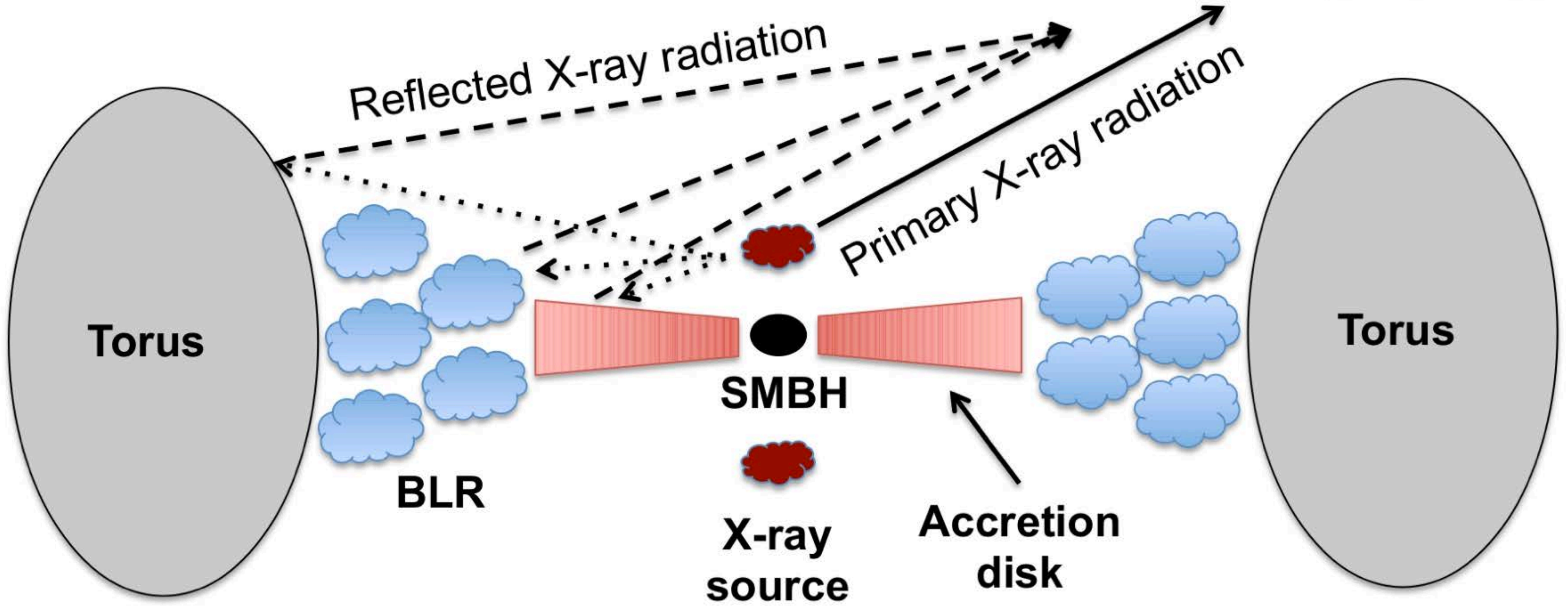
Coronal Synchrotron Emission

X-ray emission from black hole corona



Hickox & Alexander+'16

- Power-law continuum is generated by Comptonization of disk photons in the **corona**.



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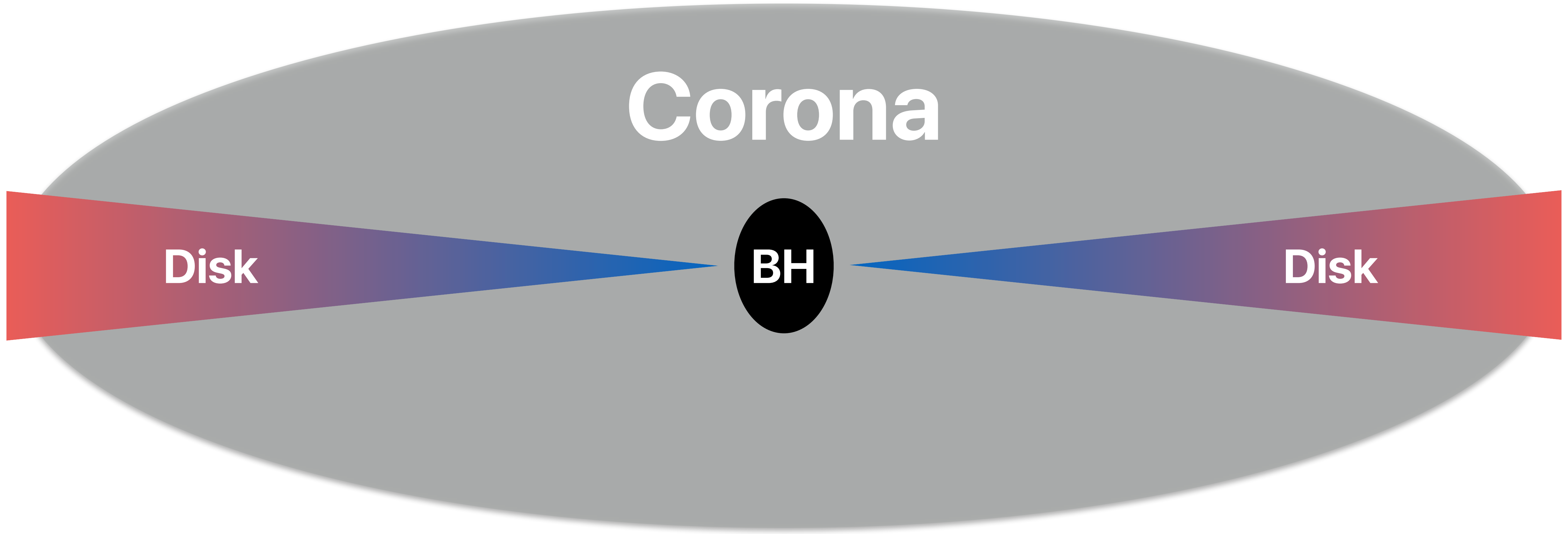
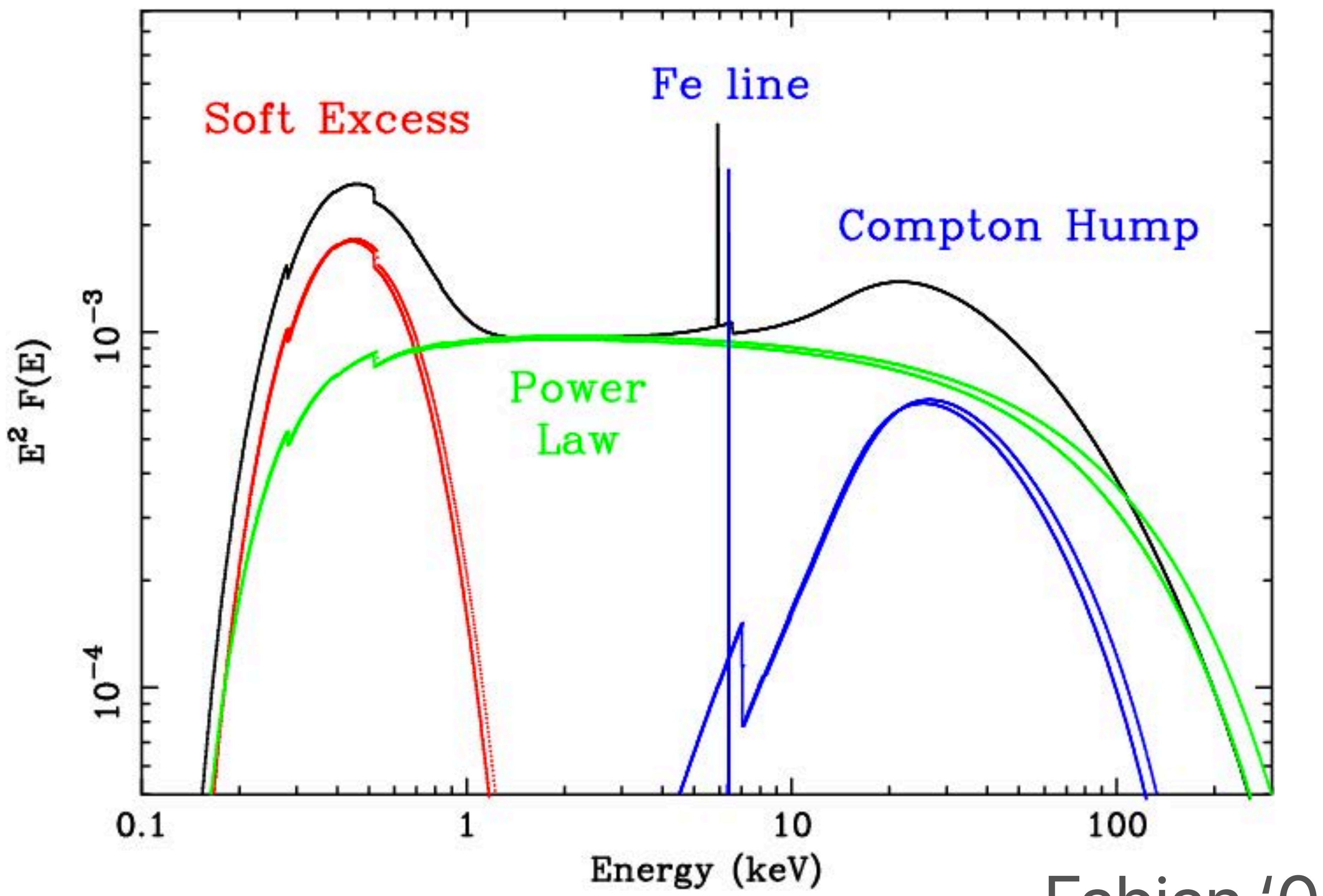
Black Hole Accretion disk corona

Hot plasma around BH





Fabian '06

- High energy cutoff

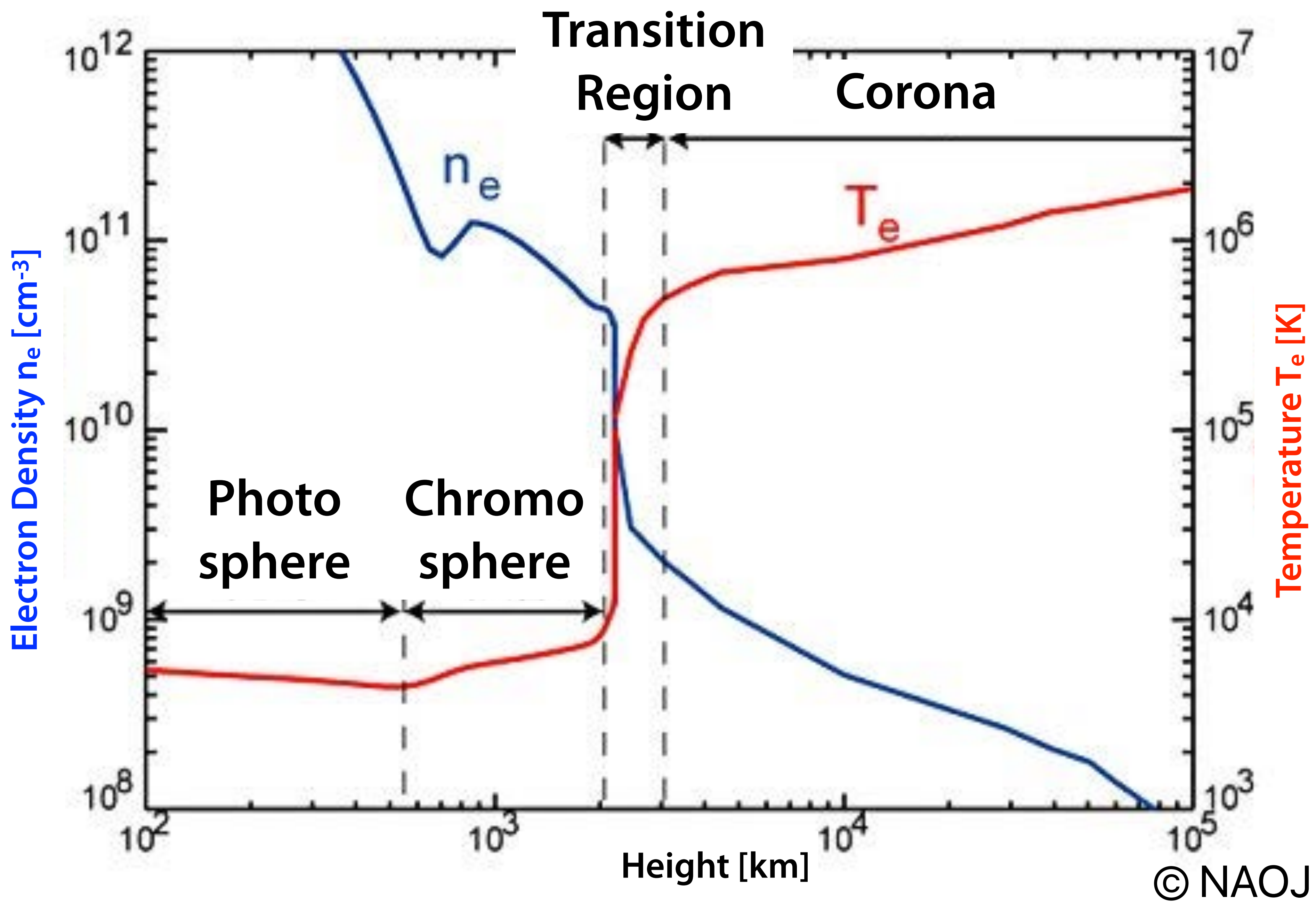
$$\checkmark\ k_B T_e \sim 10^9\ \mathrm{K} \sim 100\ \mathrm{keV}$$

- Power-law spectrum: Compton y-parameter

$$\checkmark\ n_e \sim 10^9 \left(\frac{k_B T_e}{100\ \mathrm{keV}}\right)\left(\frac{M_{\mathrm{BH}}}{10^8 M_\odot}\right)^{-1}\ \mathrm{cm}^{-3}$$

Solar corona heating

Dissipation of magnetic energy



- Magnetic activity heats the solar corona to ~10^6 K.
- Magnetic fields transfer interior convection energy to the corona (e.g., Matsumoto & Suzuki ’14).

Magnetic Reconnection Heated Corona Model

Haardt & Maraschi '91; Liu, Mineshige, & Shibata '02

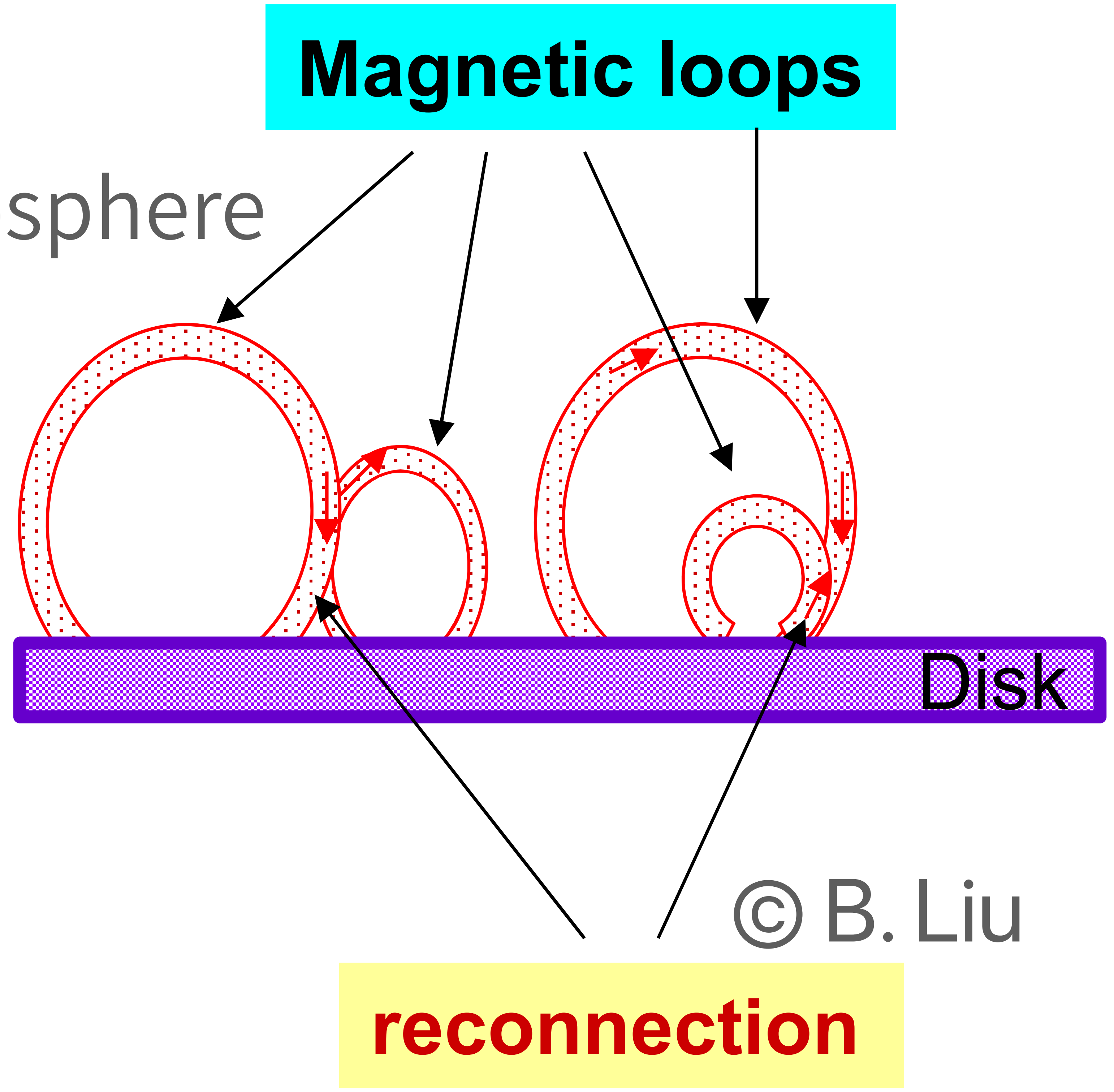
1. Reconnection heating = Compton cooling in corona

✓ $$\frac{B^2}{4\pi}V_A \approx \frac{4k_BT_e}{m_ec^2}n_e\sigma_T cU_{\rm seed}l \sim ycU_{\rm seed}$$

2. Conduction heating = Evaporation cooling in disk chromosphere

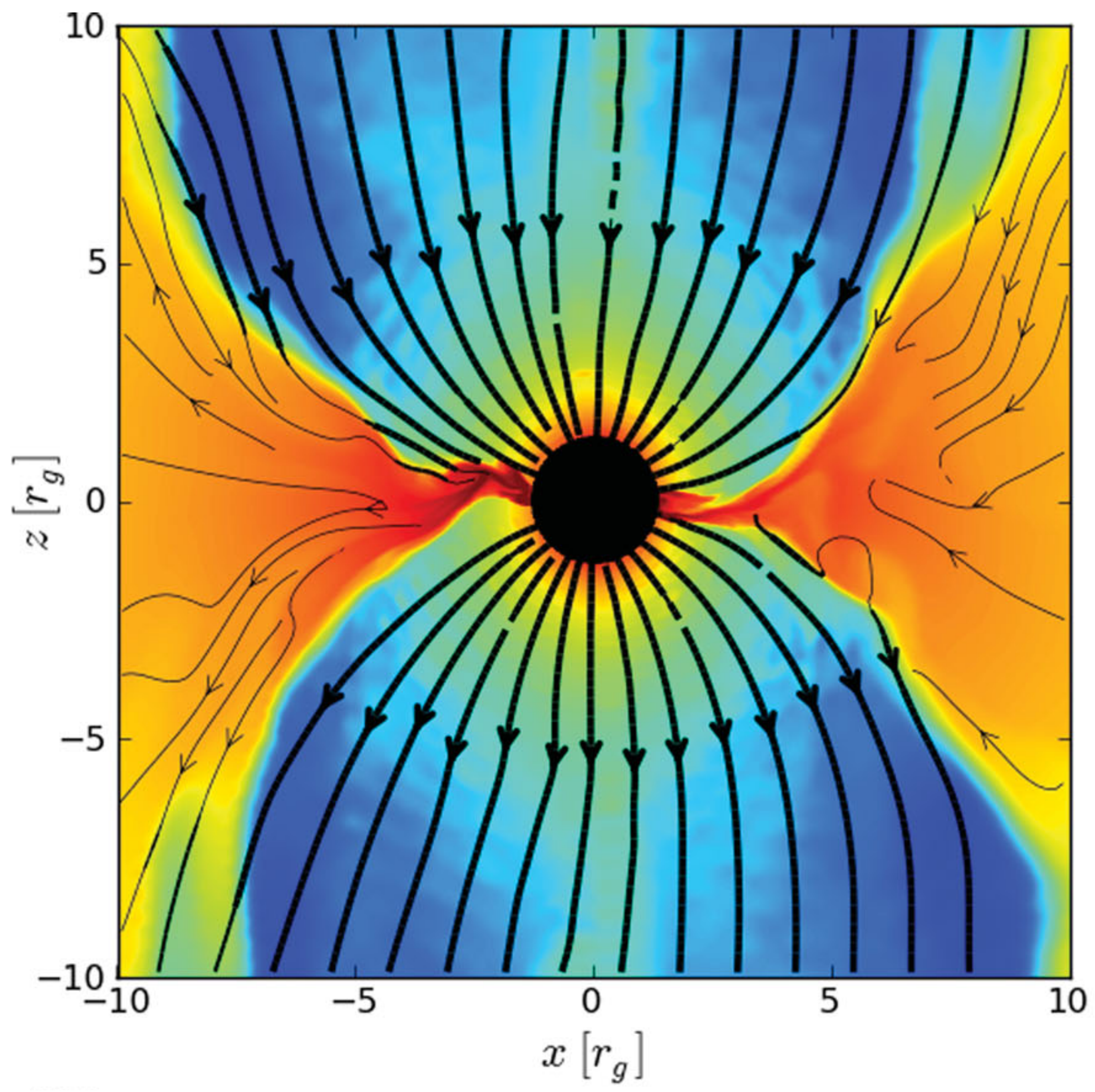
✓ $$\frac{k_0T^{7/2}}{l} \approx \frac{\gamma}{\gamma-1}n_ek_BT_e\left(\frac{k_BT_e}{m_H}\right)^{1/2}$$

➡ $$\begin{cases} T_e \sim 10^9 \left(\frac{B}{10^3\ \rm G}\right)^{3/4}\left(\frac{l}{10^{14}\ \rm cm}\right)^{1/8}\left(\frac{U_{\rm seed}}{10^5\ \rm erg/cm^3}\right)^{-1/4}\ \rm K \\ n_e \sim 10^9 \left(\frac{B}{10^3\ \rm G}\right)^{3/2}\left(\frac{l}{10^{14}\ \rm cm}\right)^{-3/4}\left(\frac{U_{\rm seed}}{10^5\ \rm erg/cm^3}\right)^{-1/2}\ \rm cm^{-3} \end{cases}$$

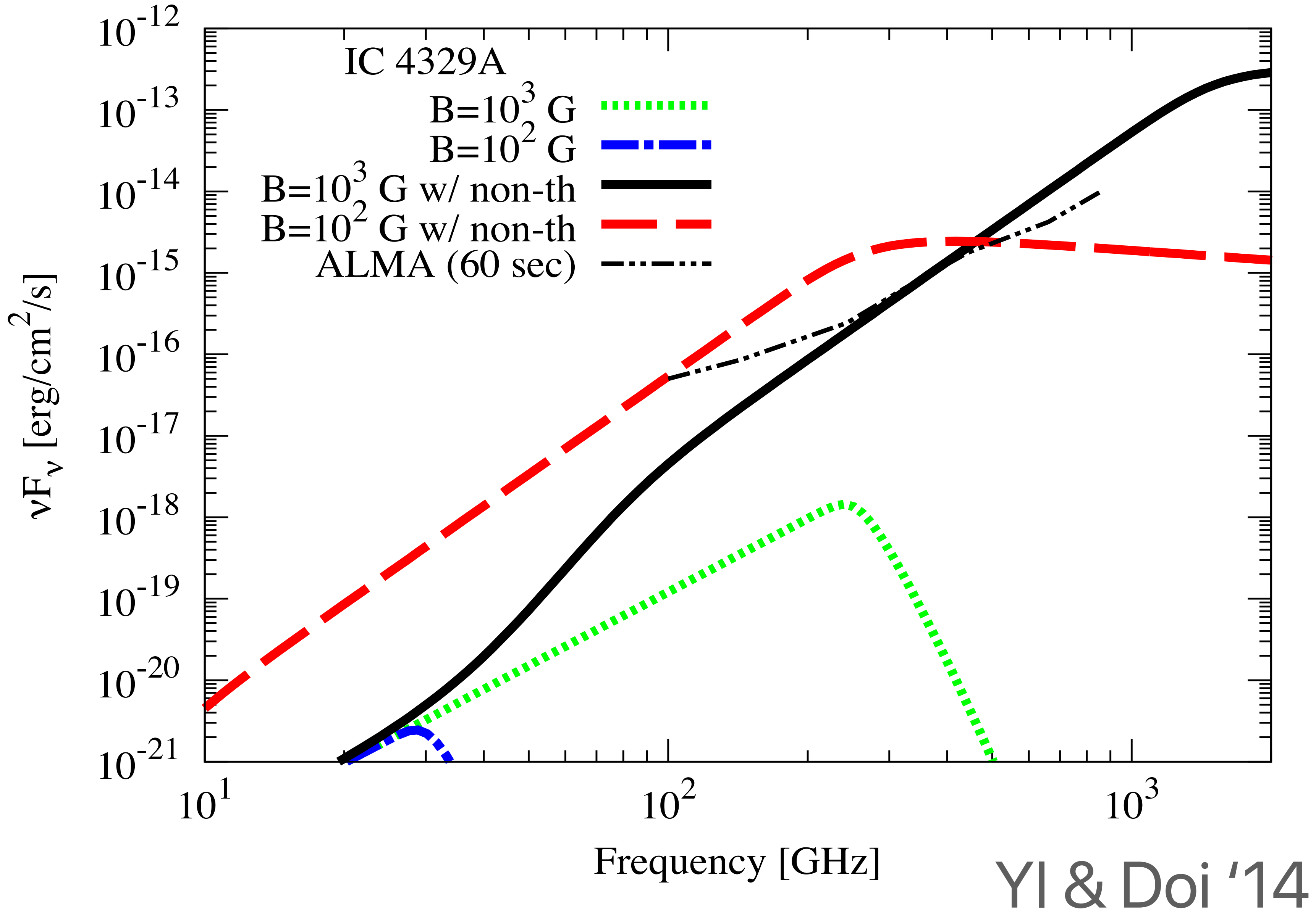


Magnetic Fields around SMBHs

- Key Parameter for
  - Corona heating
    (e.g., Haardt & Maraschi '91; Liu, Mineshige, & Shibata '02)
  - Jet launching
    (e.g., Blandford & Znajek '77; Tchekhovskoy+'10, '11)
- If the corona is magnetized
  - **coronal synchrotron radiation** is expected
    (Di Matteo+'97; YI & Doi '14; Raginski & Laor '16)
  - Spectral excess appears in the mm band



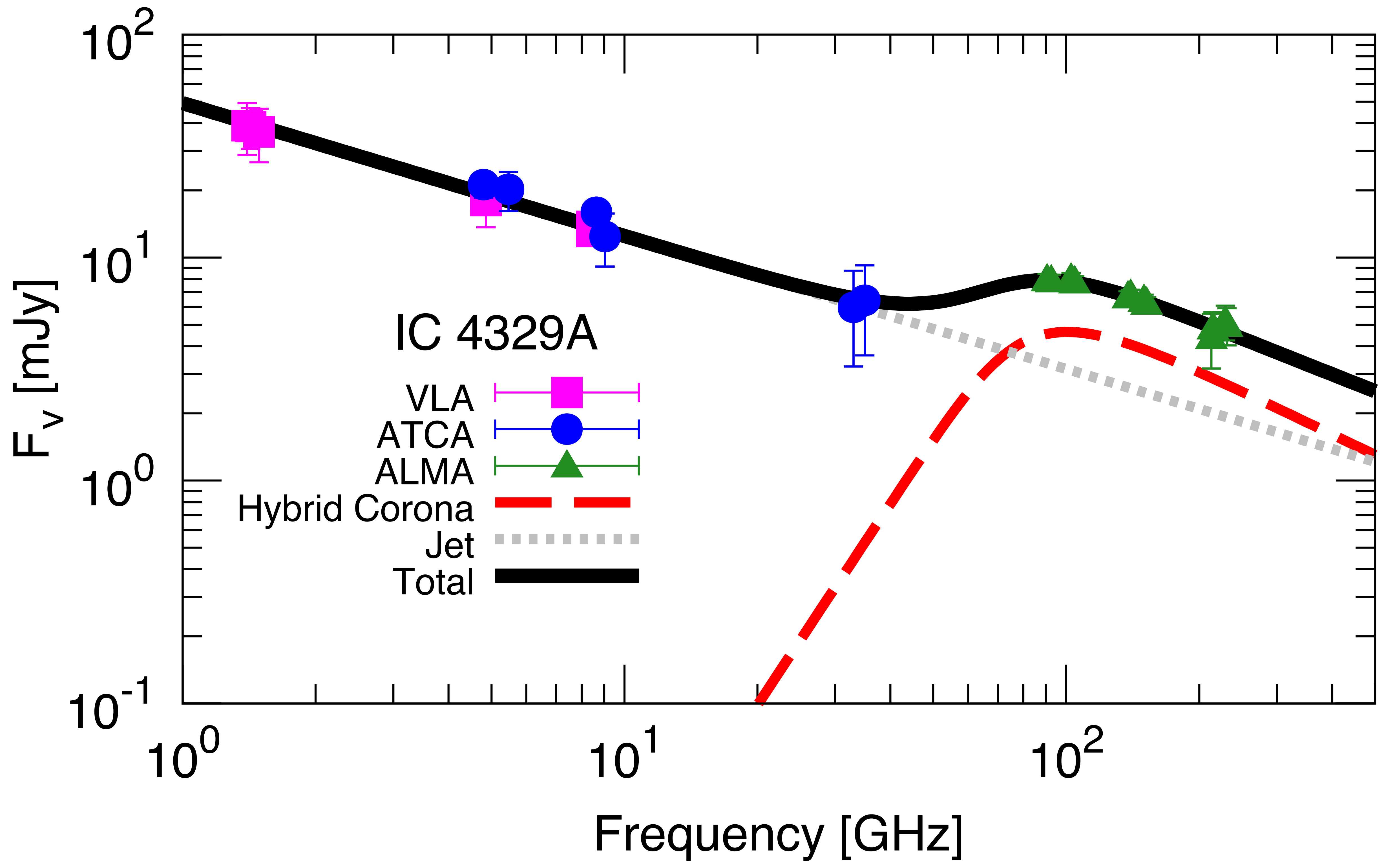
McKinney et al. '12



YI & Doi '14

cm-mm spectrum of AGN core

A case of IC 4329A



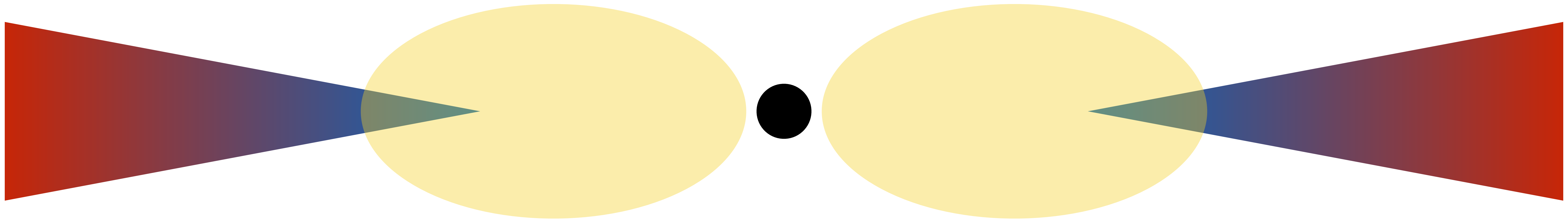
YI & Doi '18

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

Reconnection Corona Heating?

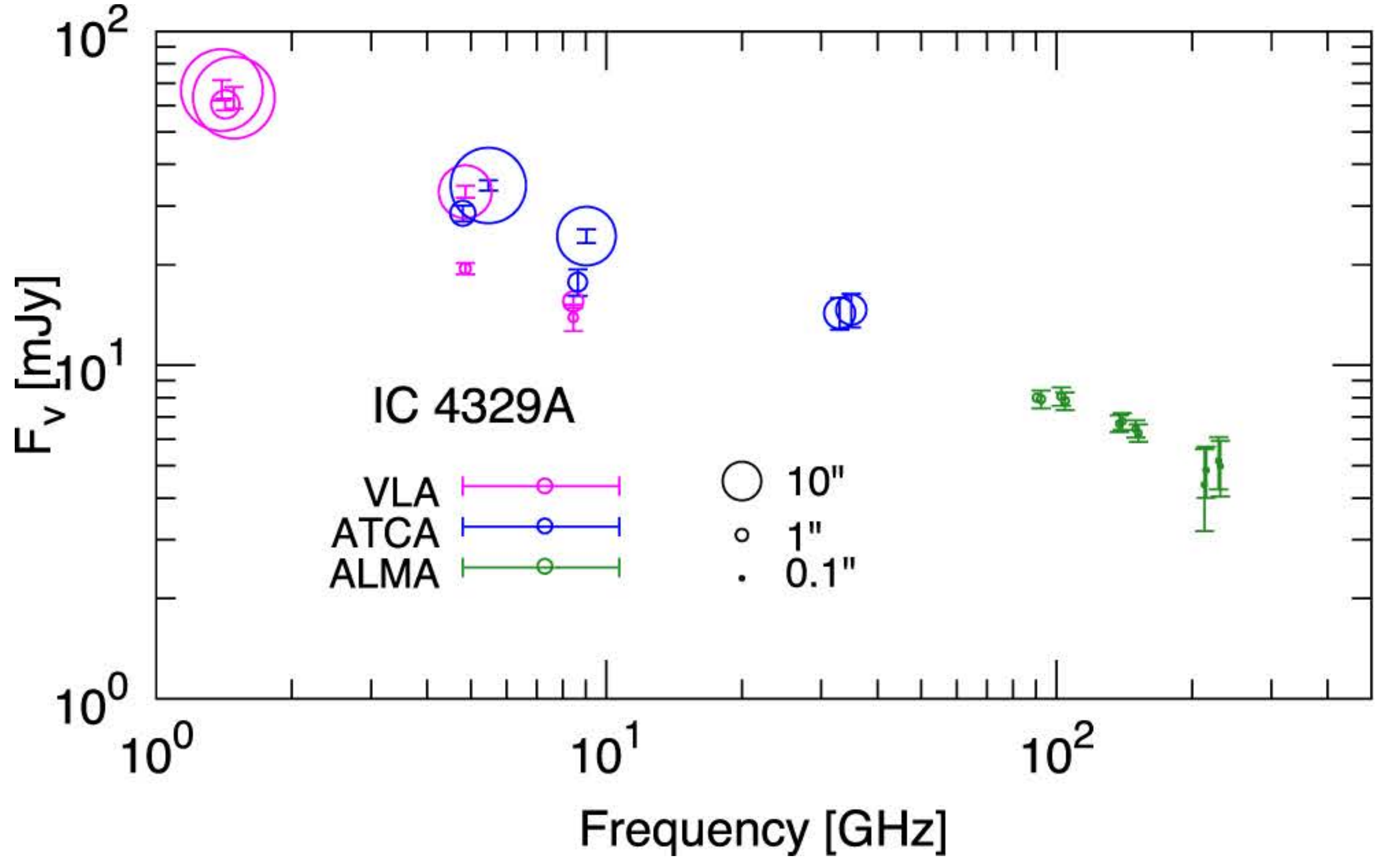
Implication for the truncated accretion disk structure.

- Heating and Cooling
  - Magnetic Heating: $B^2V_A/4\pi$
    - $Q_{B,\,heat} \sim 10^{10}$ erg/cm^2/s
  - Compton Cooling: $4kTn_e\sigma_T cU_{\rm rad}l/m_ec^2$
    - $Q_{IC,\,cool} \sim 10^{13}$ erg/cm^2/s
  - Magnetic field energy is **NOT** sufficient to keep coronae hot.
- Disk truncation at some radii (e.g. ~40 r_s)
  - The inner part = hot accretion flow (Ichimaru '77, Narayan & Yi '94, '95).
    - Heated by advection.
  - Suggested for Galactic X-ray binaries. (e.g. Poutanen+'97; Kawabata+'10; Yamada+'13).
- Simultaneous model fitting to X-ray and radio data is required (see also Gutierrez+'21).

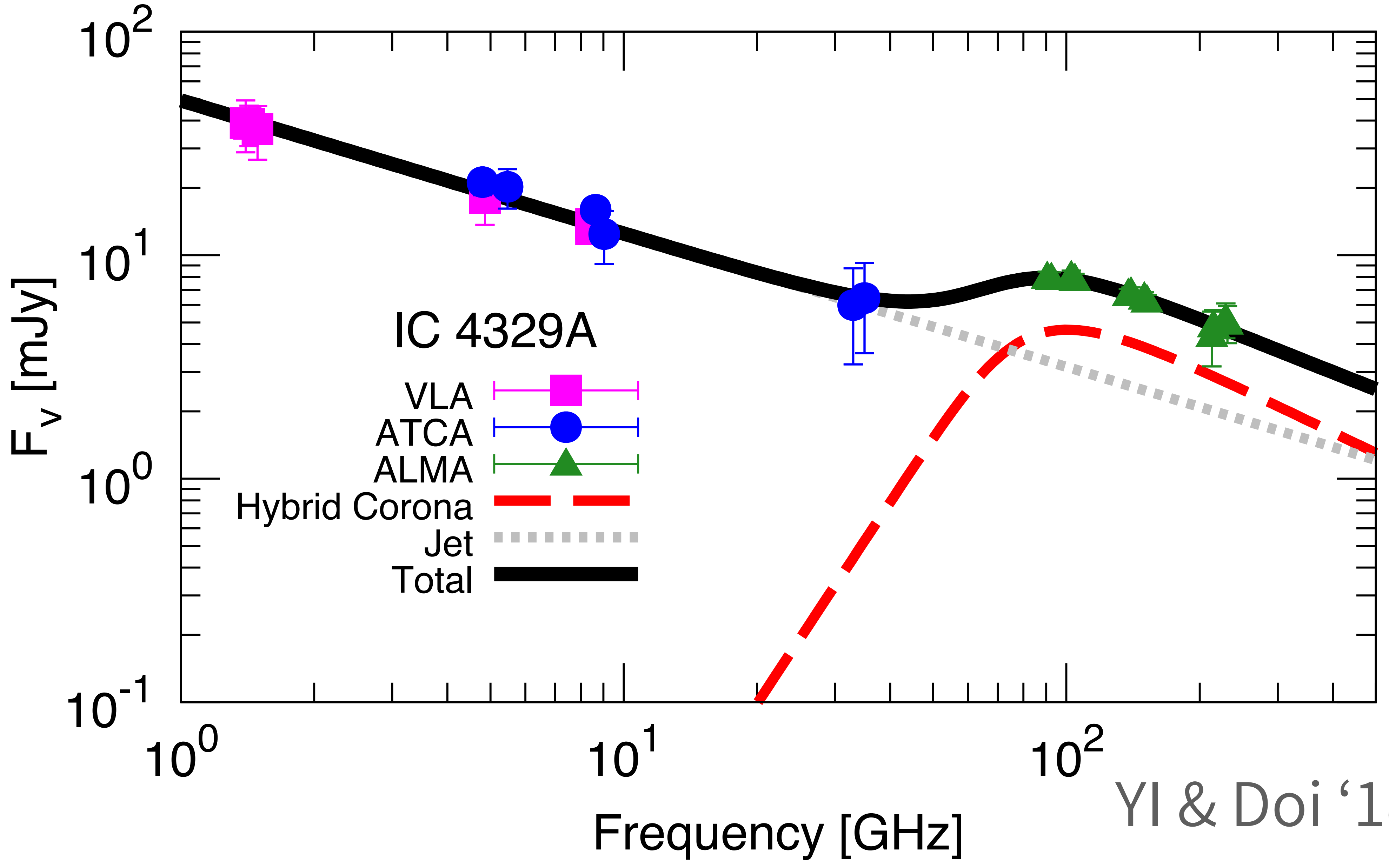


Radio Data analysis is not straightforward

Effect of different beam sizes



Remove extended components



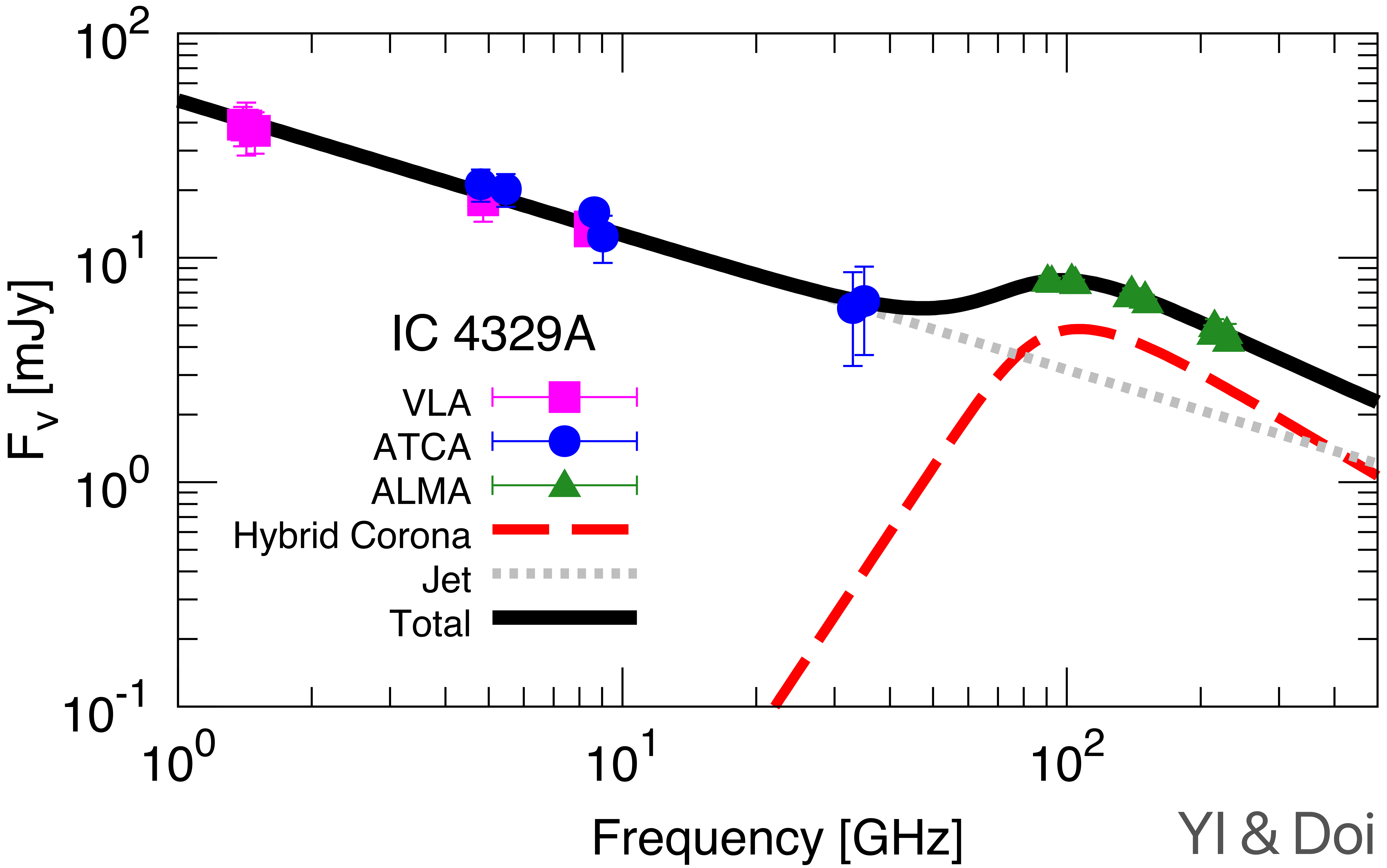
YI & Doi '18

- Beam size (~psf) of each data is different in radio.
- We remove extended component (star formation activity) by fitting.

High Energy Emission From Coronae

Radio Spectrum of AGN Core

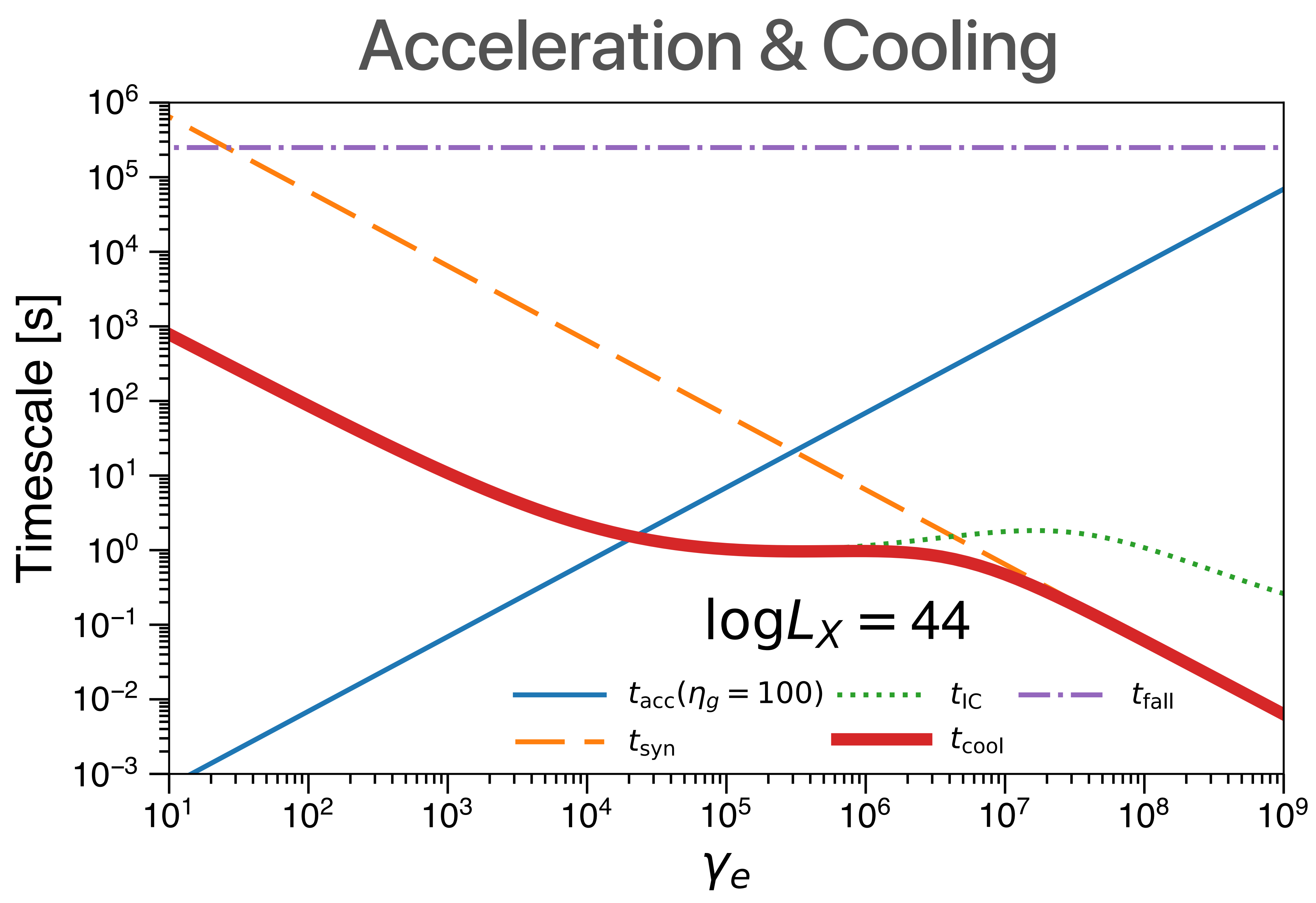
Non-thermal tail in the mm spectrum

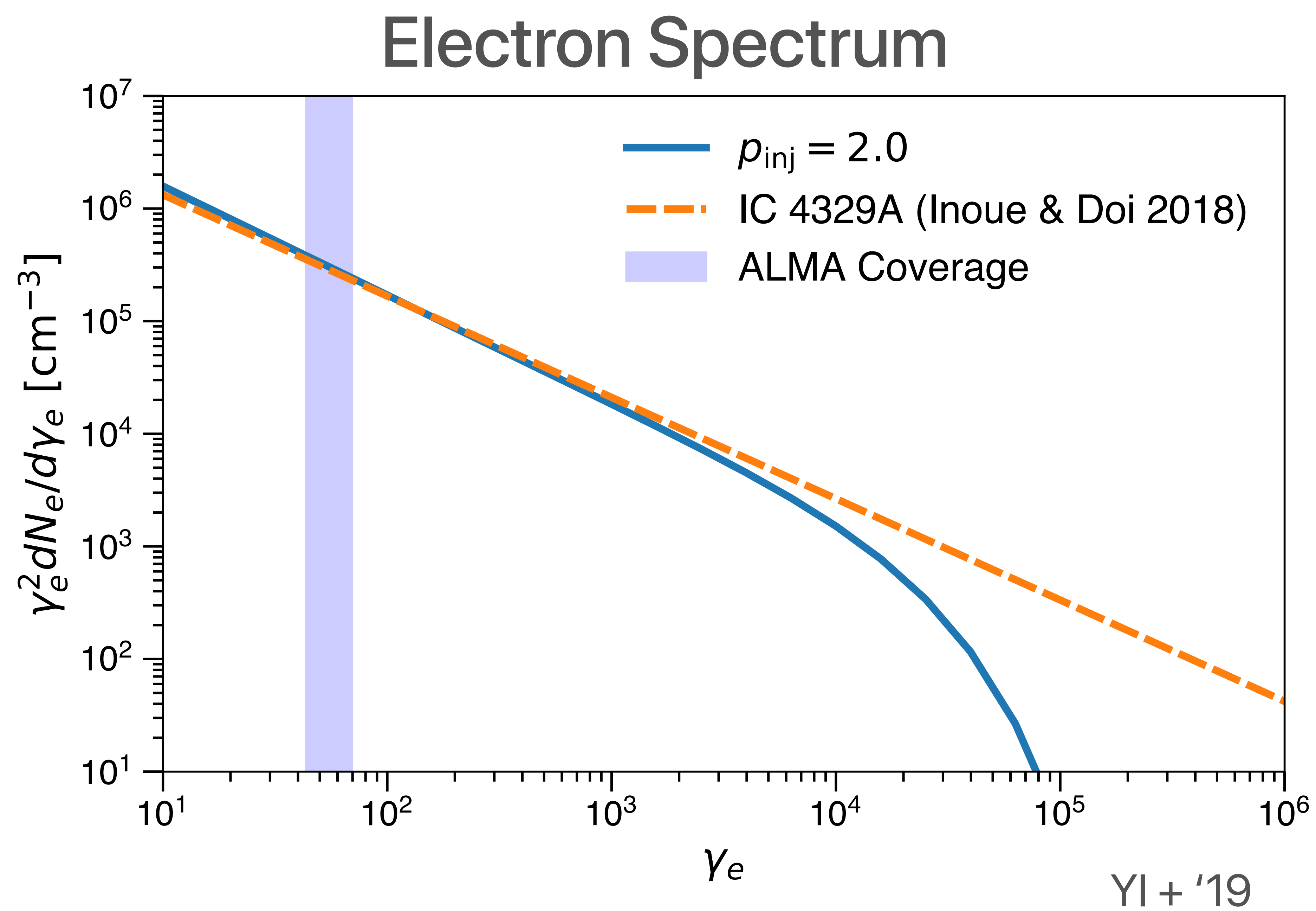


YI & Doi '18

Generation of Non-thermal Electrons in Coronae

- 1st-order Fermi acceleration can explain the observed electrons
  - Injection index of 2
  - Where is the acceleration site?
- Other mechanisms may be difficult.
  - Because of low magnetic field and accretion rate.

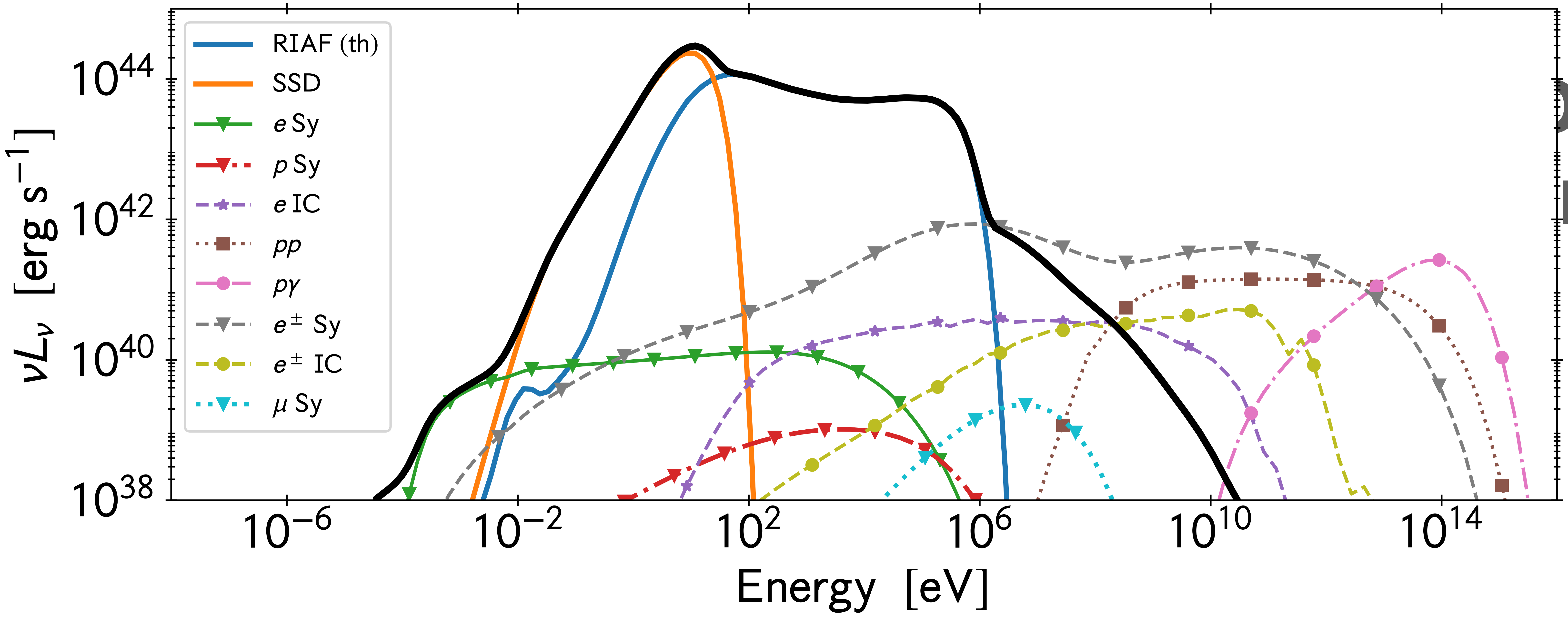


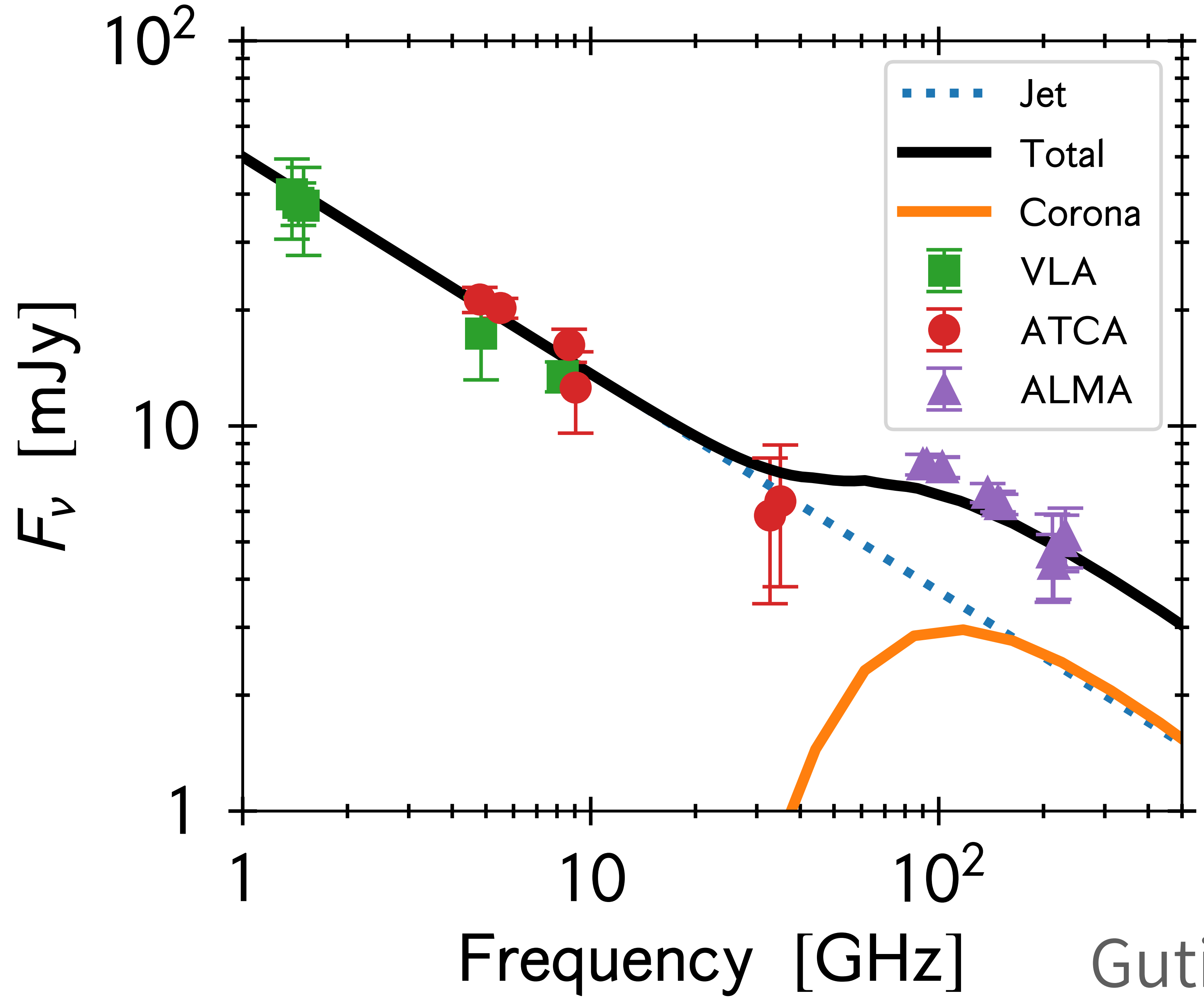


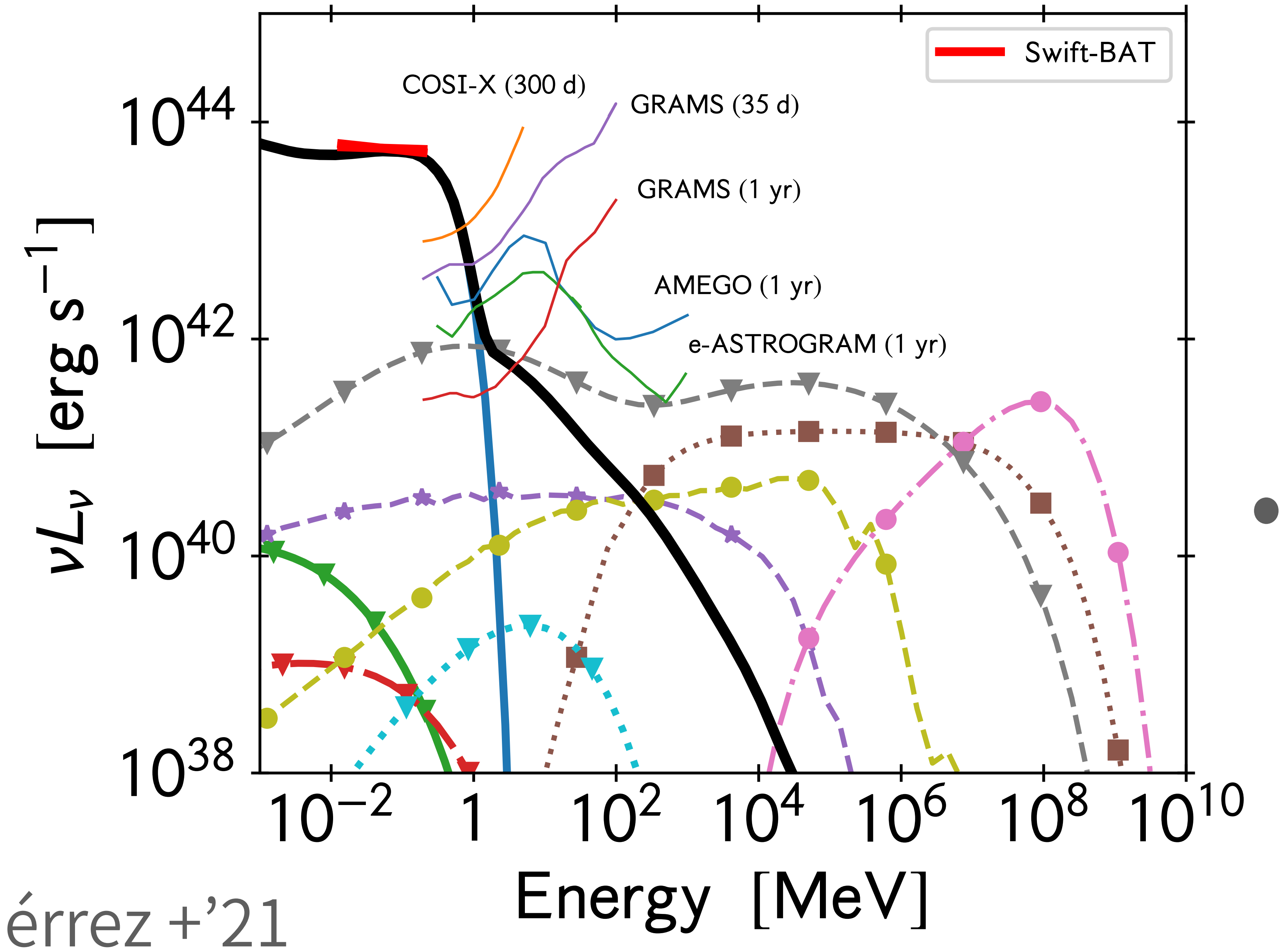
YI + '19

ronae

Neutrinos





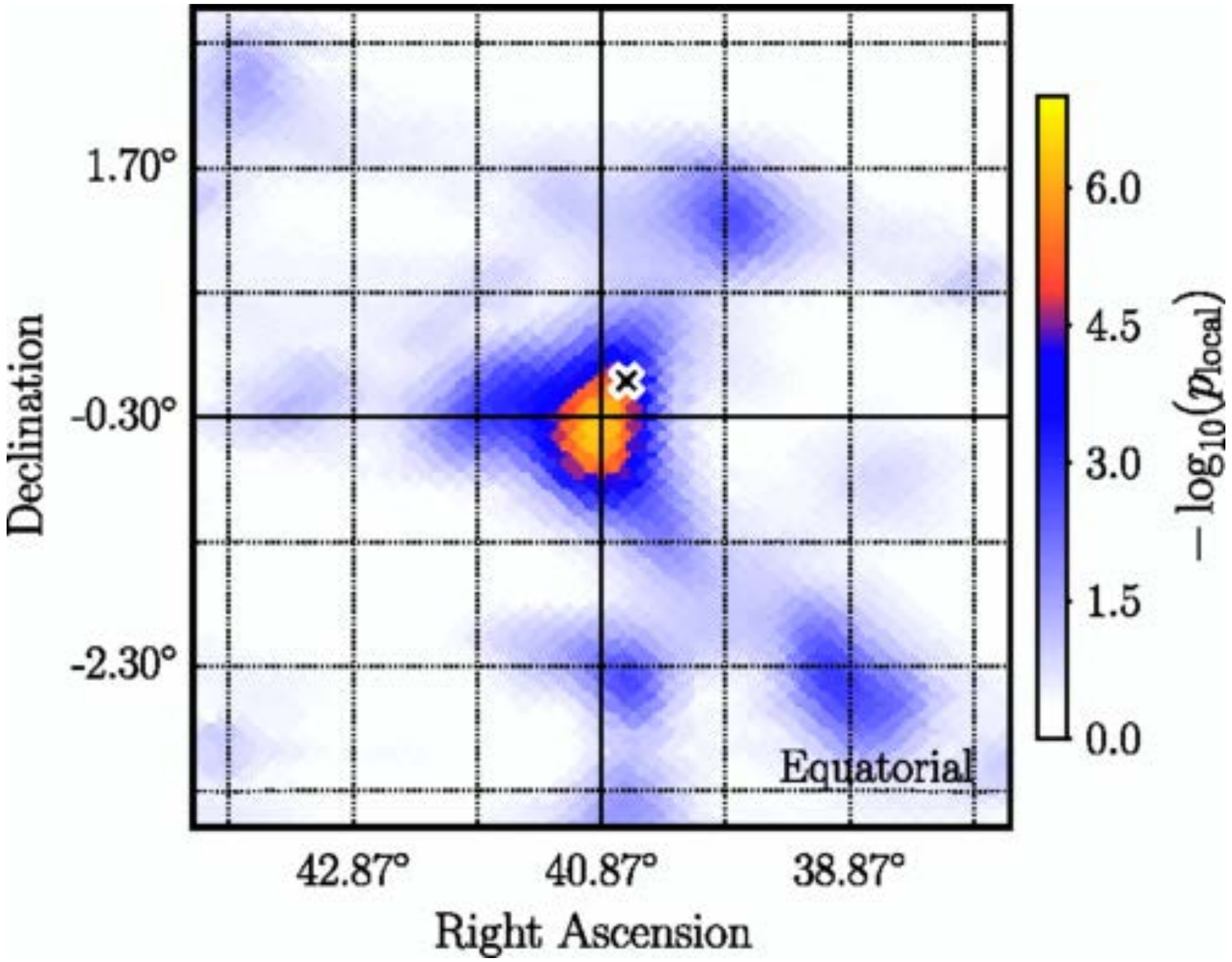


Gutiérrez +'21

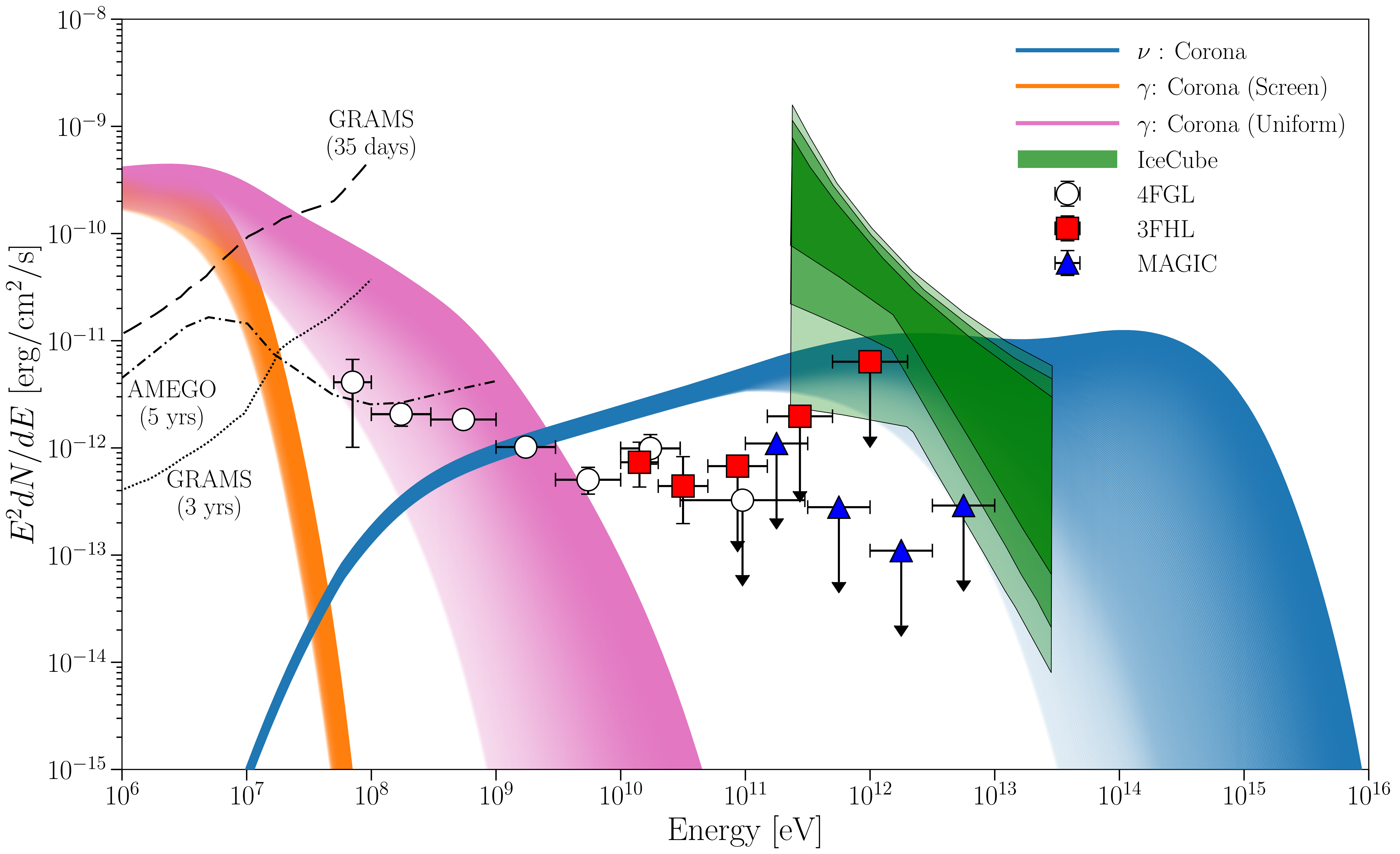
- MeV emission
  - but, no GeV emission
- Protons would be accelerated simultaneously
  - Generation of high energy neutrinos
- See also Stecker+'91, '92, '05, '13; Kalashev+'15; Murase+'20; Gutiérrez +'21; Kheirandish+'21

IceCube Hottest Spot

NGC 1068 (no strong jet)



IceCube 2020

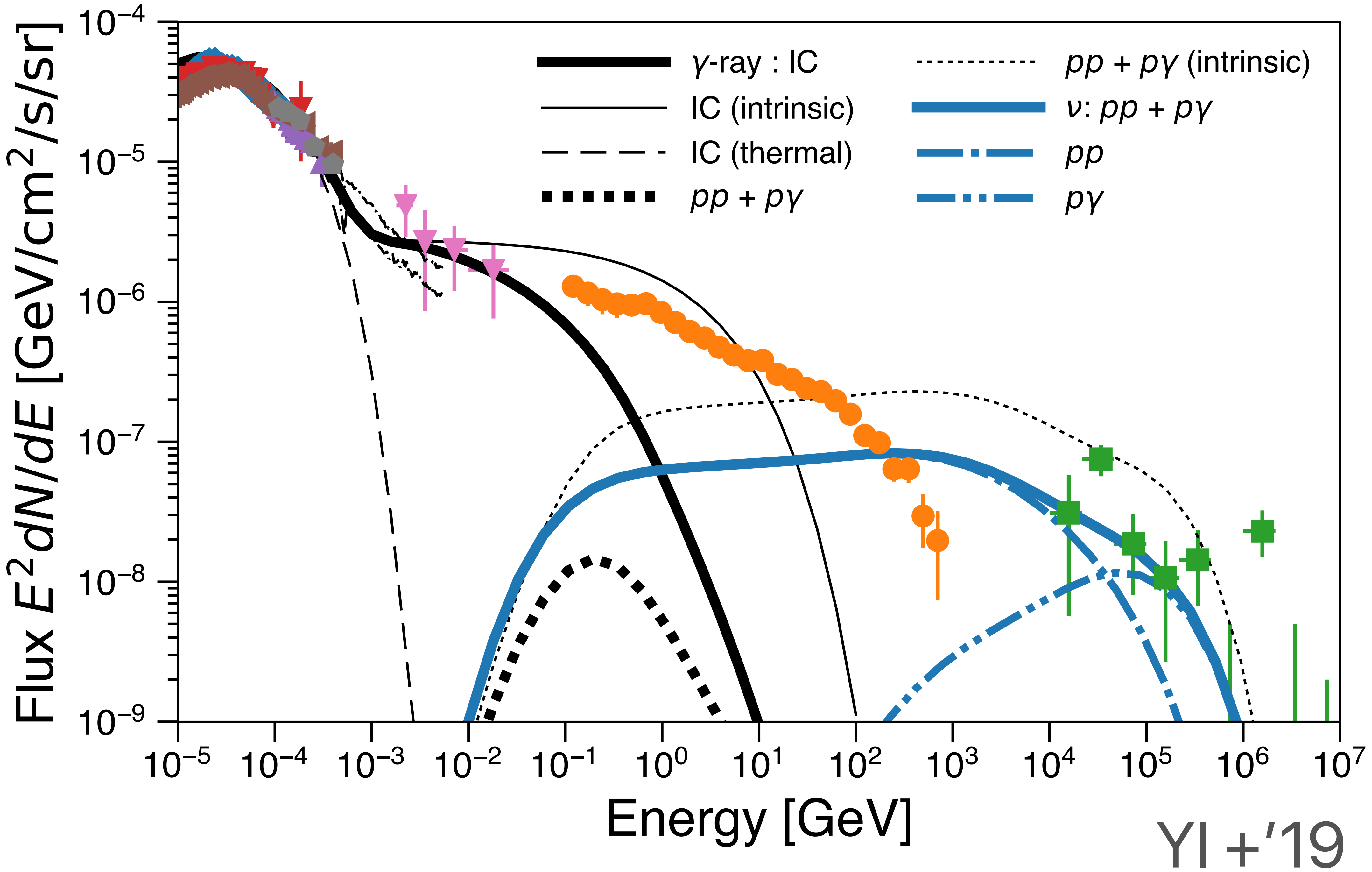


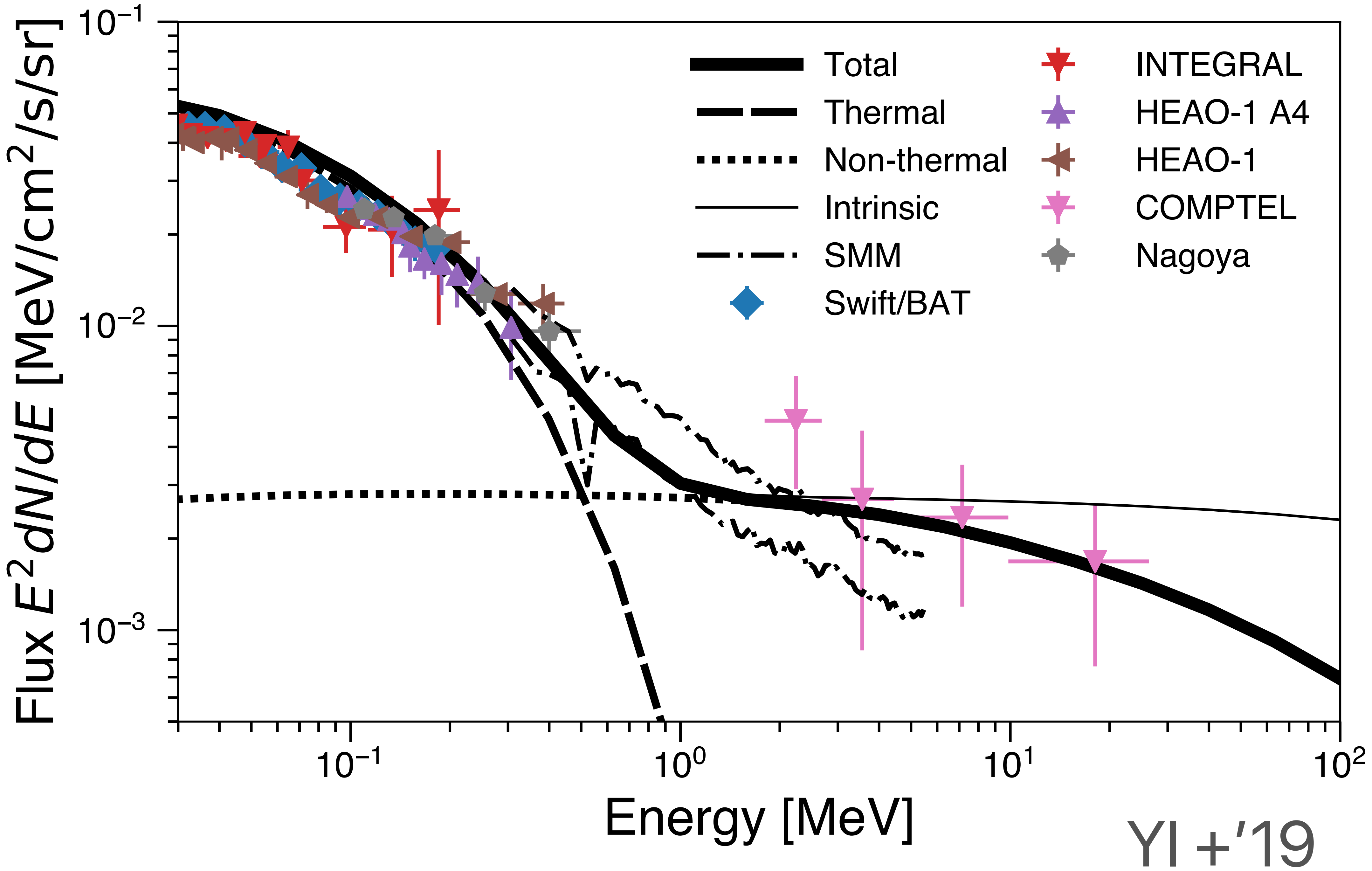
YI, Khangulyan, & Doi, '20

- Type-2 Seyfert NGC 1068 is reported at **2.9-σ**.
- If the signal is real, corona can be a plausible neutrino production site (see also Müller & Romero '20, Murase+'20).

Cosmic High Energy Background Radiation

Integrated history of the Universe



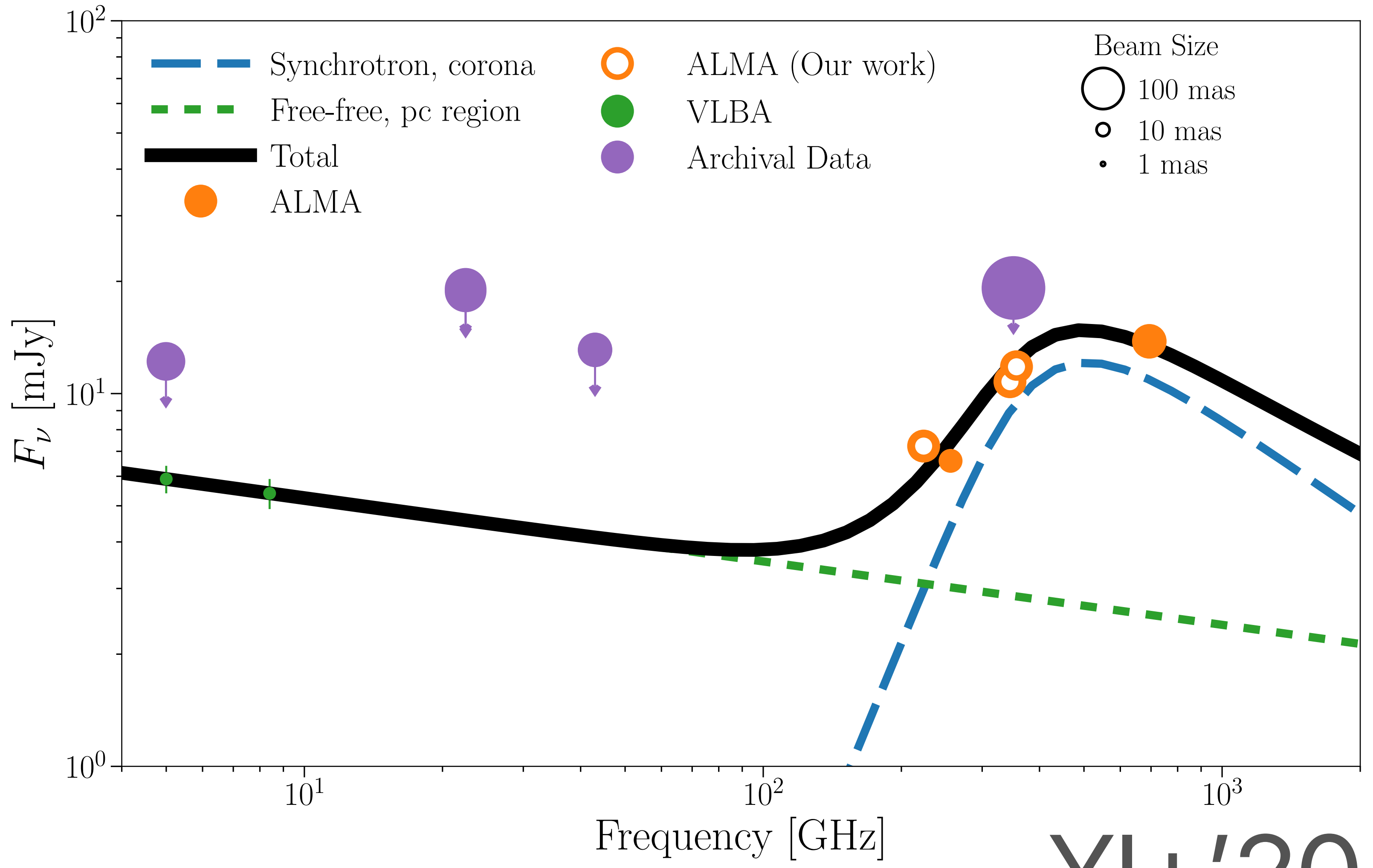


- Seyferts can explain TeV neutrino background (see also Begelman+'90; Stecker+'92; Kalashev+'15; Murase+'20).
- Seyferts can explain X-ray & MeV gamma-ray background (YI+'08, YI+'19, Murase+'20).
  - **BUT**, if both protons and electrons carry ~5% of the shock energy and gyrofactor is 30.

How can we test the model?

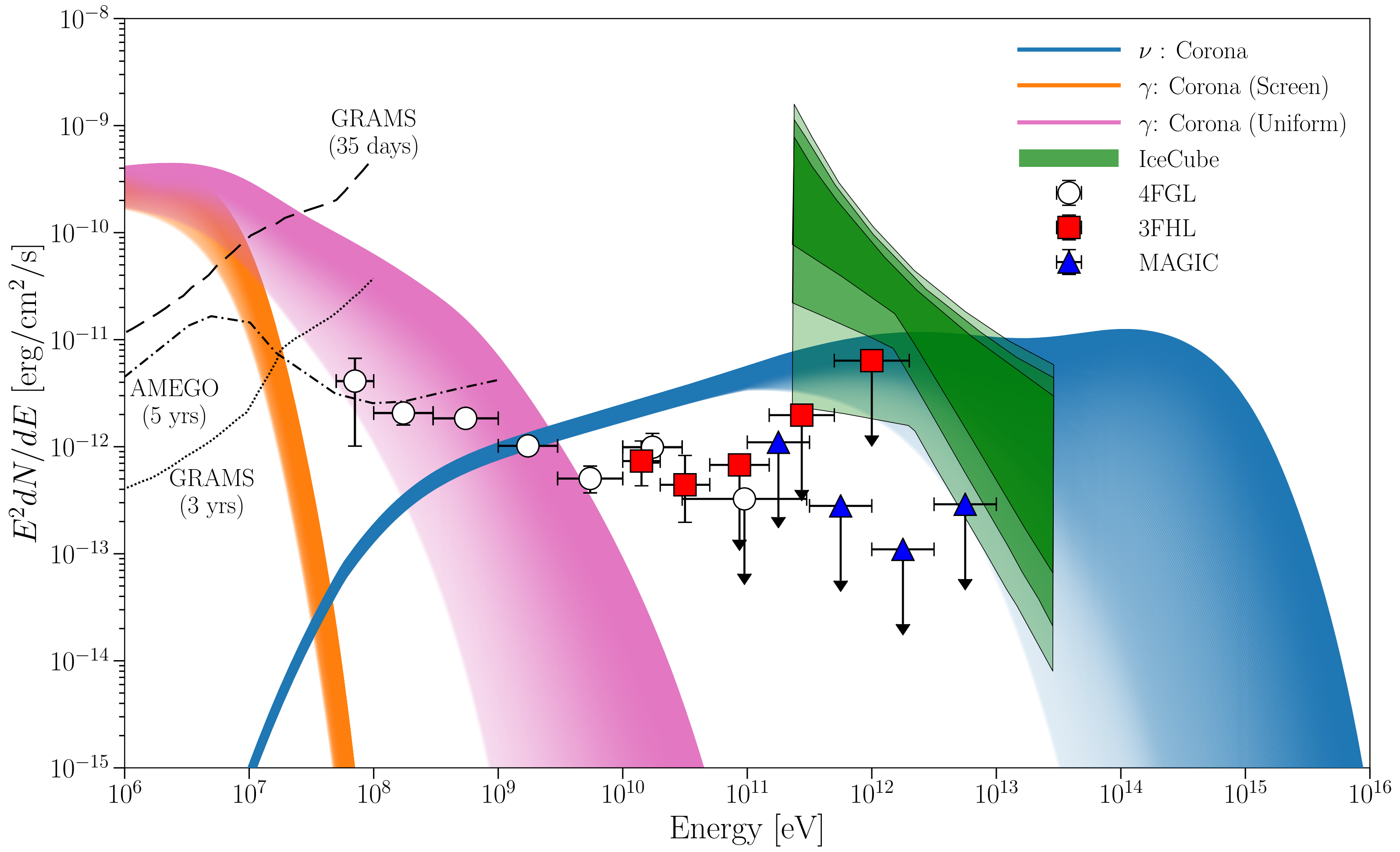
ALMA? GRAMS? AMEGO? IceCube? XRISM?

mm-band



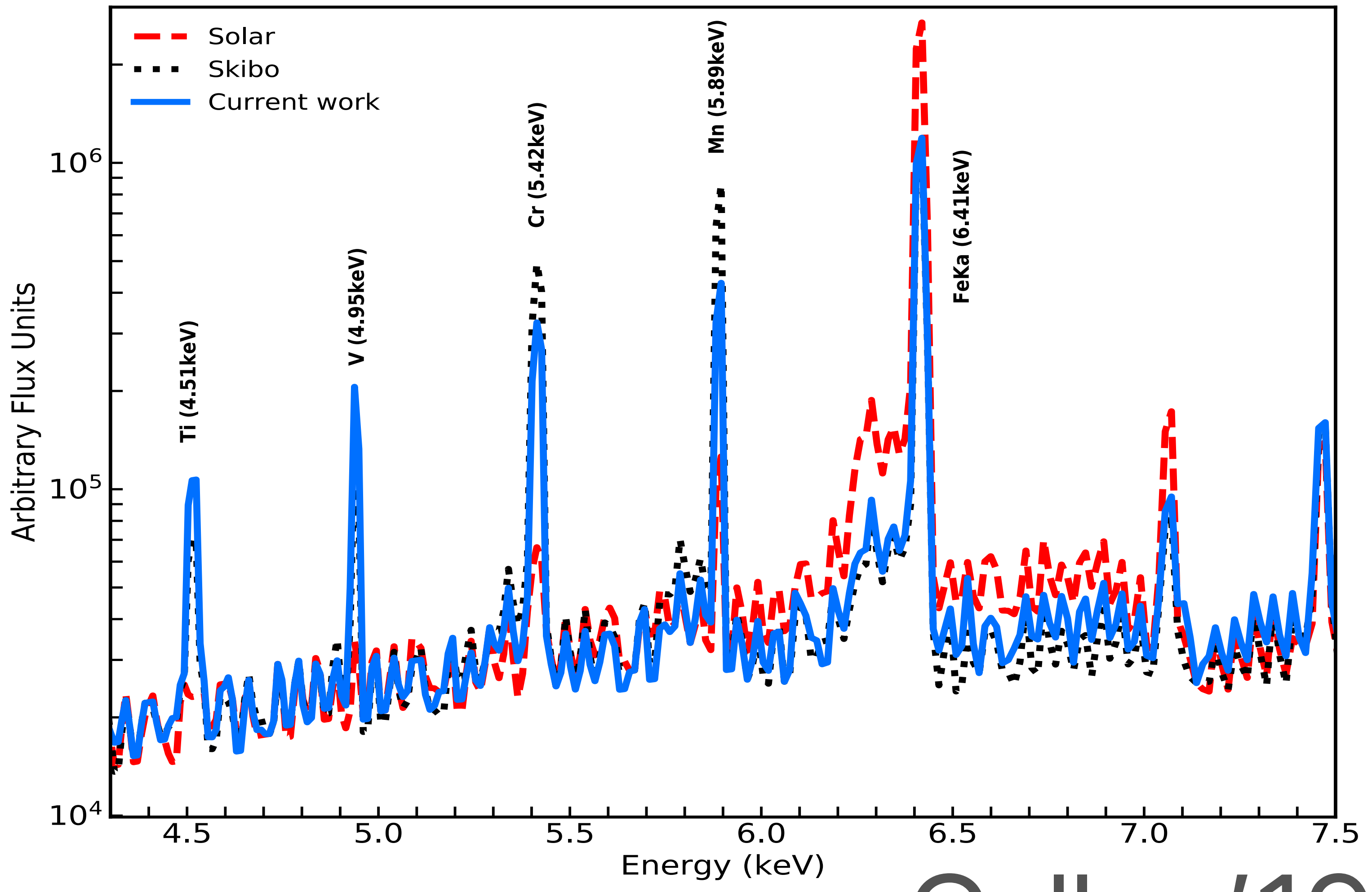
Yl+'20

MeV & TeV ν



Yl+'20

X-ray

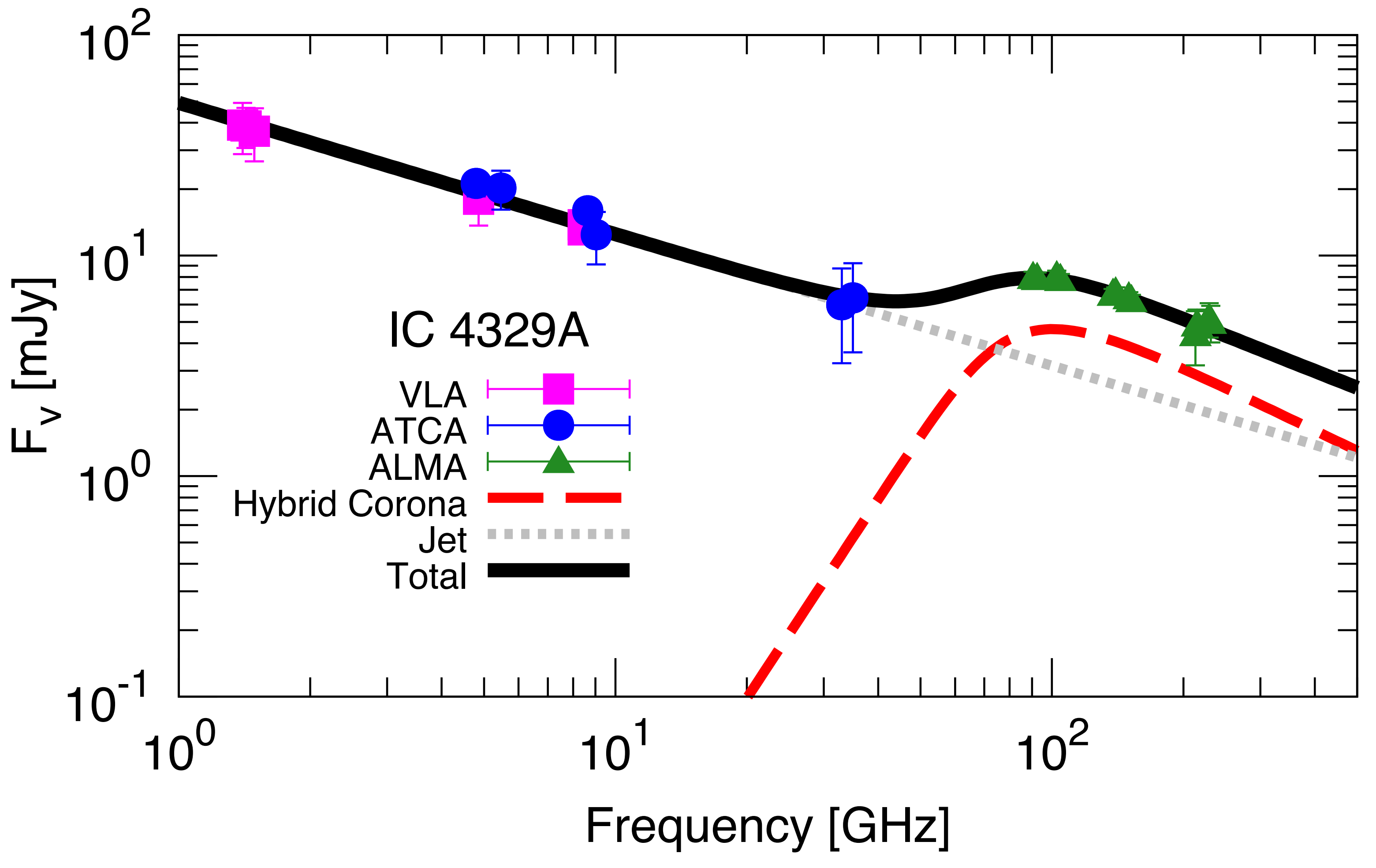


Gallo+'19

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

Summary

- Radio spectra (mm-band) of Seyferts are still not well understood.
- The mm-excess seems exist ubiquitously in nearby Seyferts.
  - ~1-10 mJy
  - Probably, originated from coronal synchrotron emission.
- Magnetic field are not strong enough to keep coronae hot.
- AGN Corona is a production site of high energy particles.
  - Can explain IceCube neutrino events (background & NGC 1068)



YI & Doi '18