

Coronal Magnetic Activity in nearby Active Supermassive Black Holes

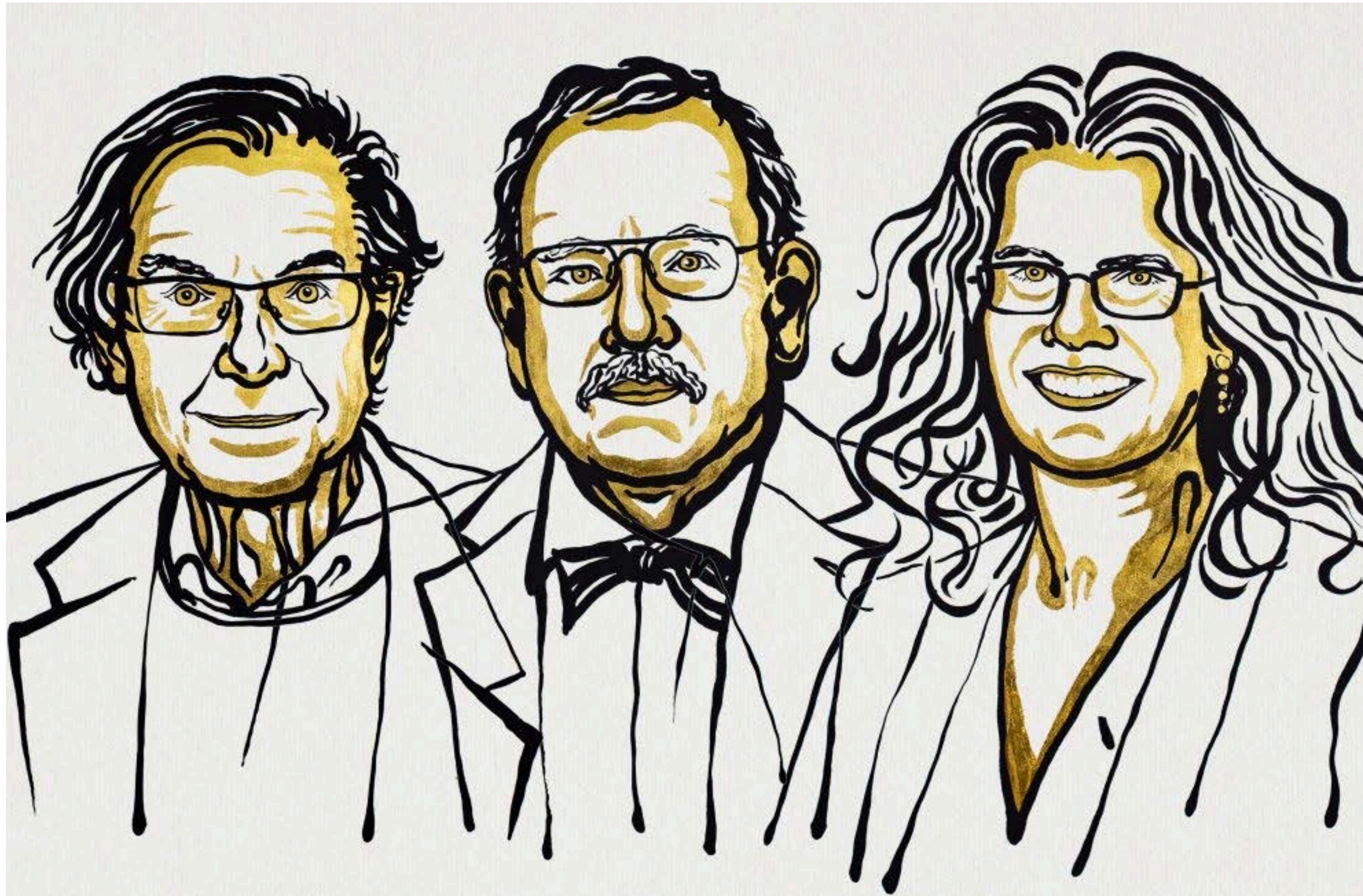
Yoshiyuki Inoue

CUHK Colloquium @ Online, 2020-10-23



Nobel Prize in Physics 2020

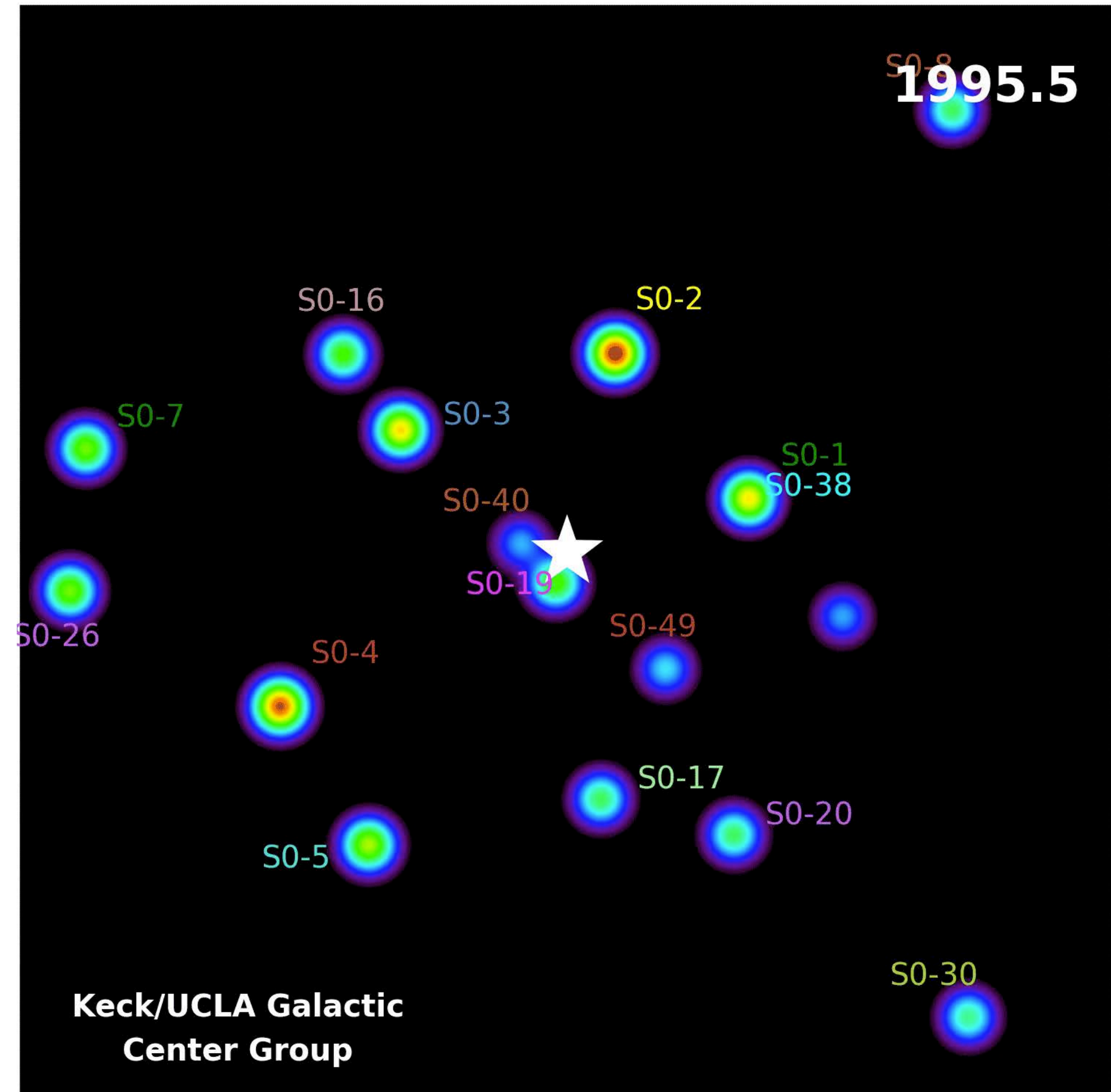
Black holes and the Milky Way's darkest secret



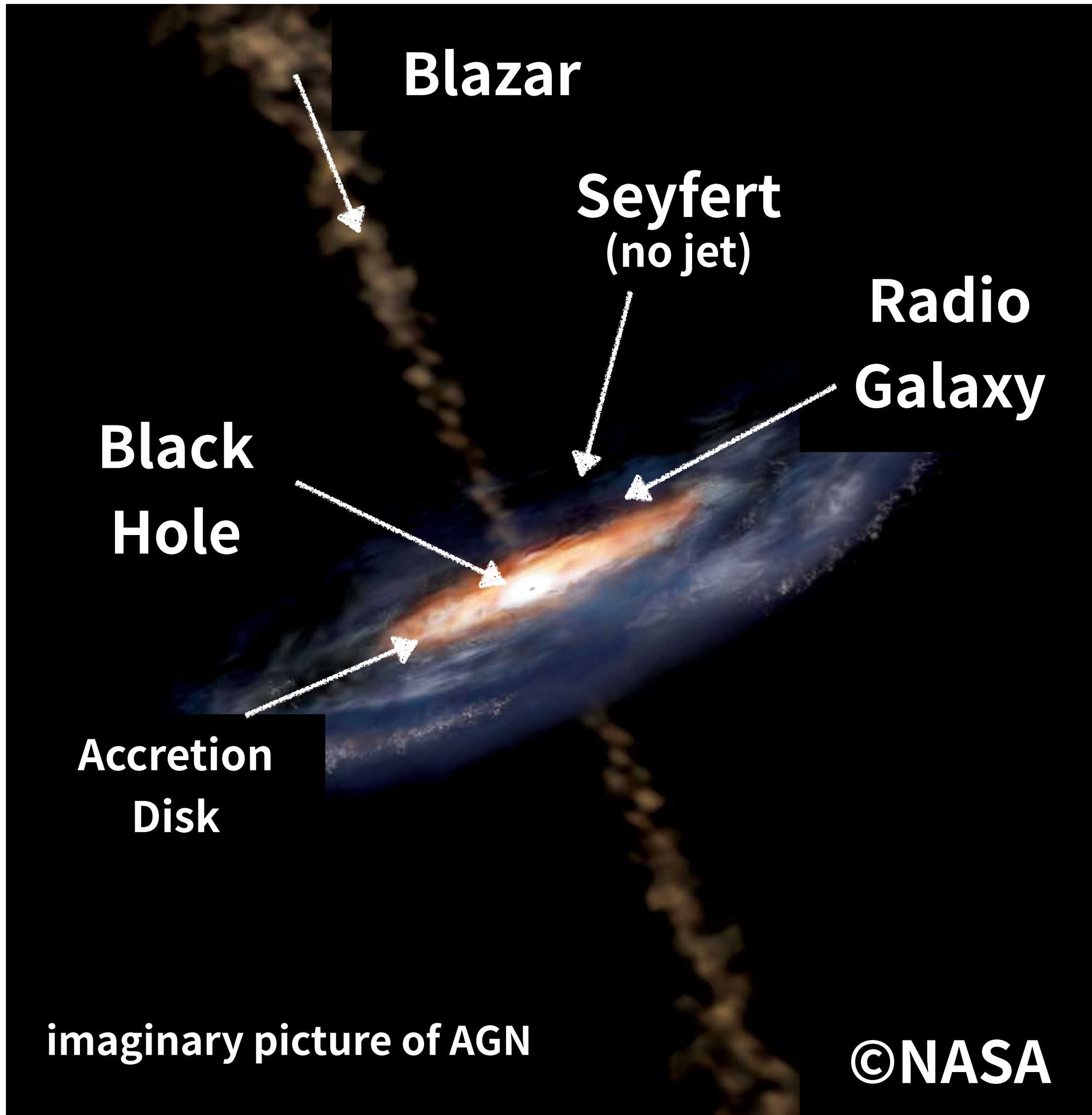
Supermassive Black Hole at the Center of the Galaxy

Motion of Stars at the Galactic center

- 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,
 - $M_{\text{BH}} \sim 4 \times 10^6 M_{\odot}$



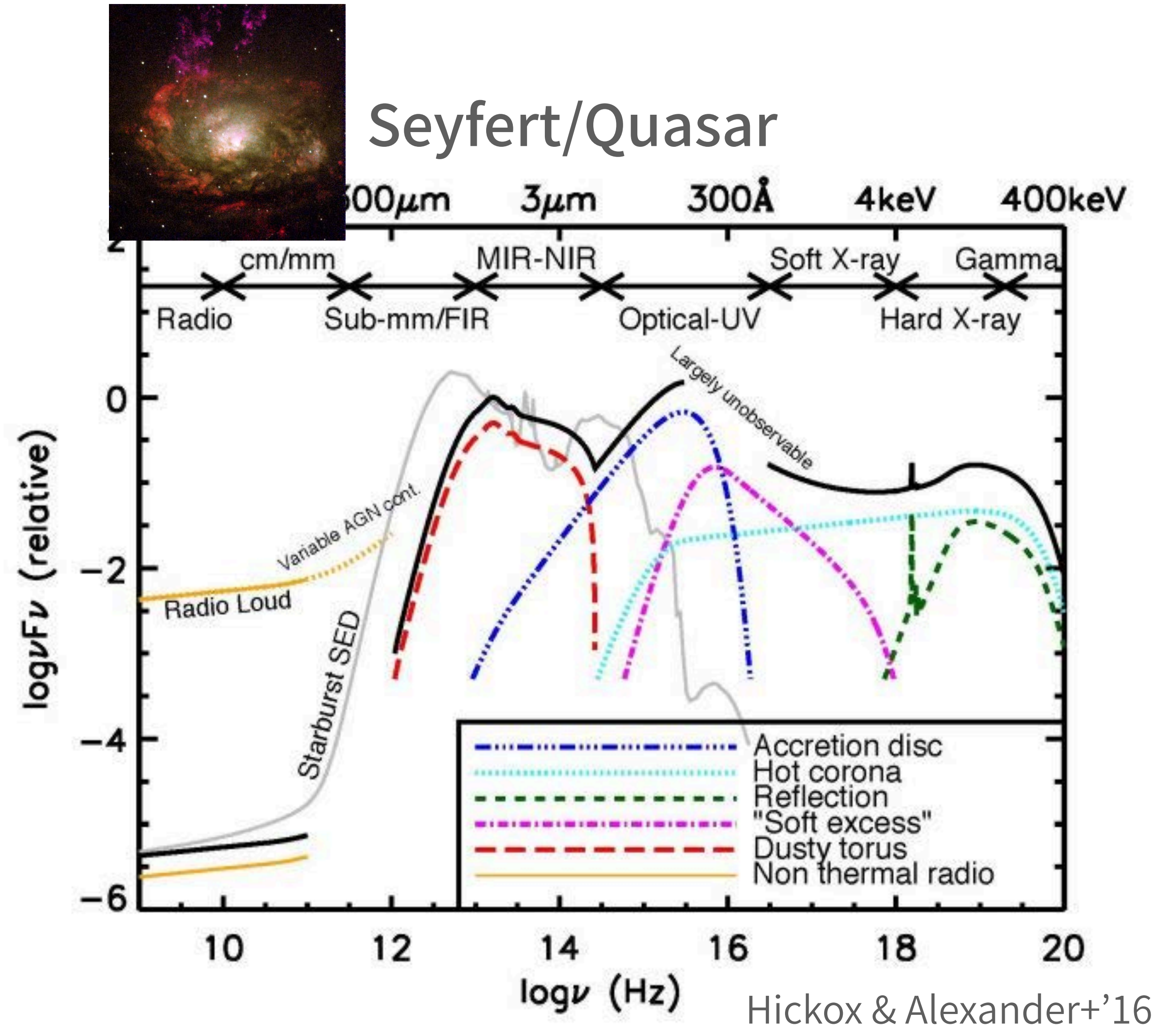
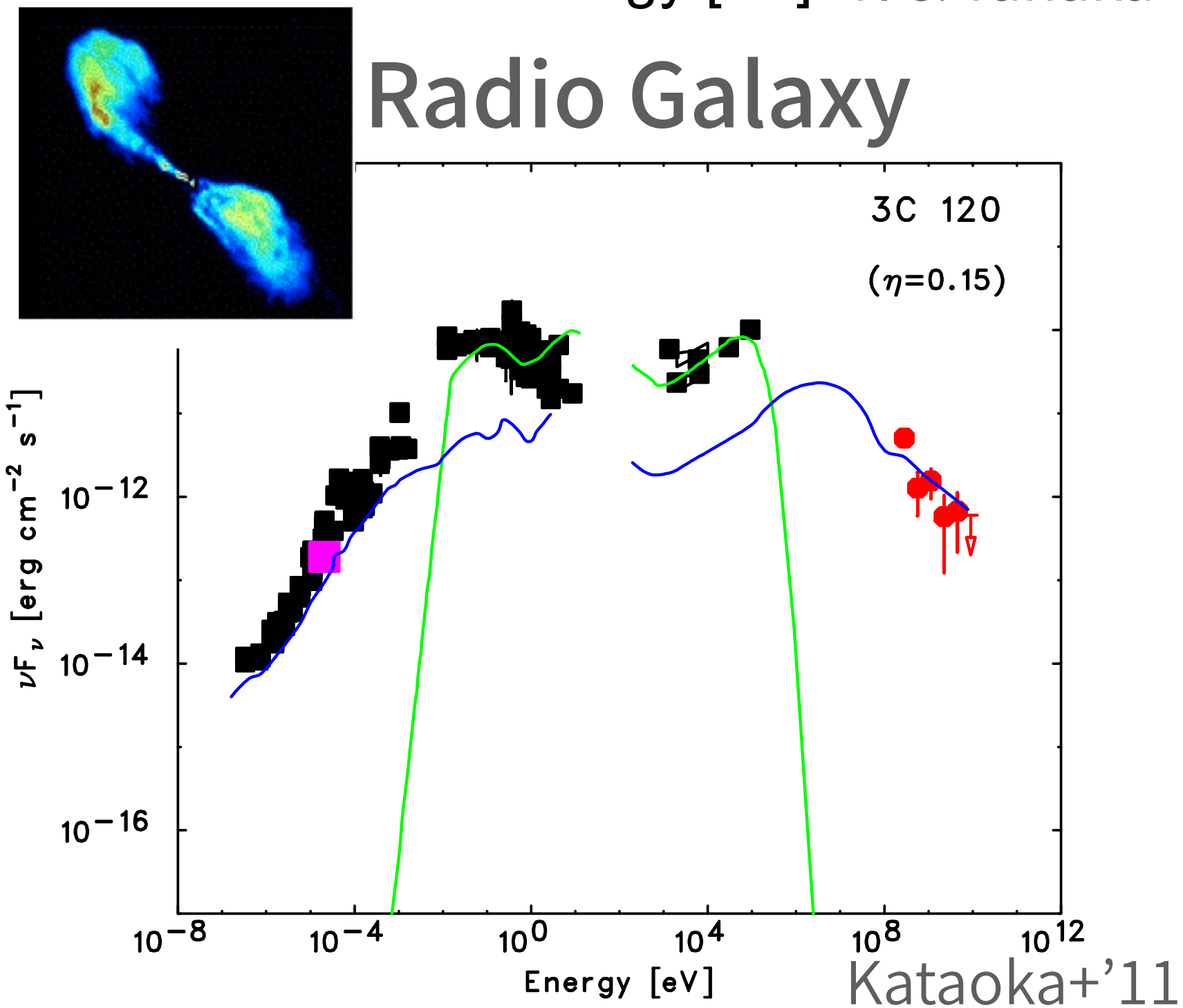
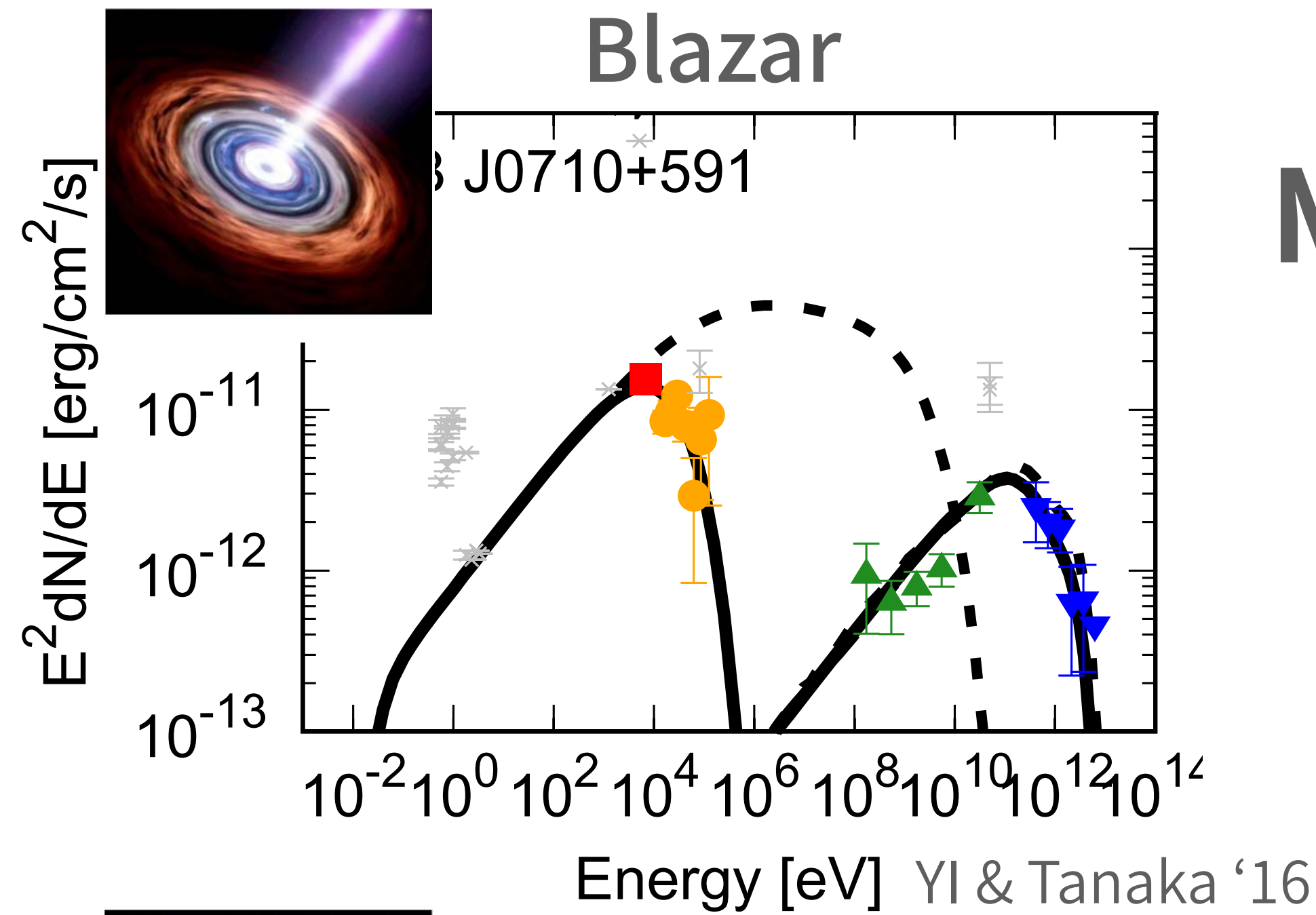
Supermassive Black Holes are Active



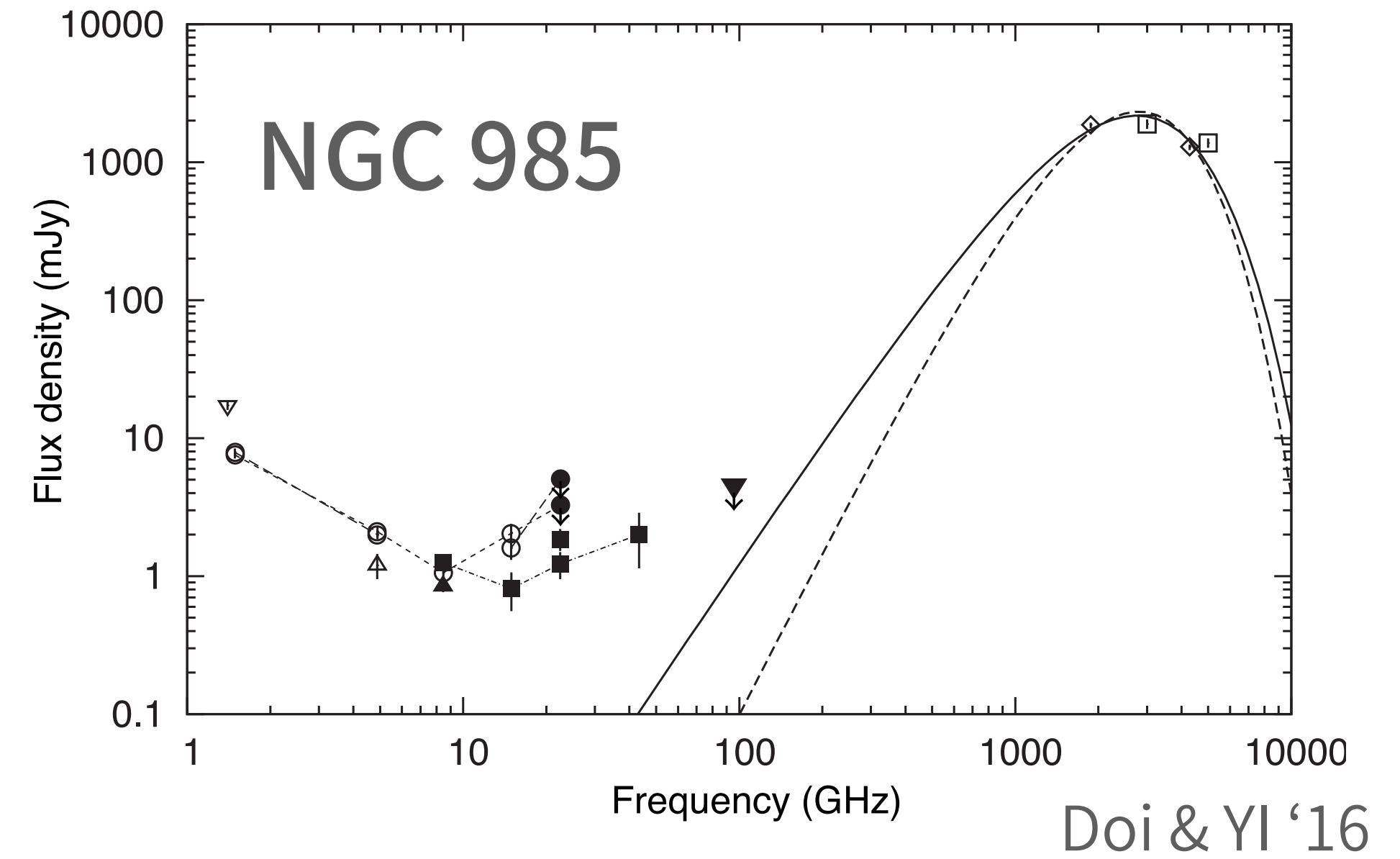
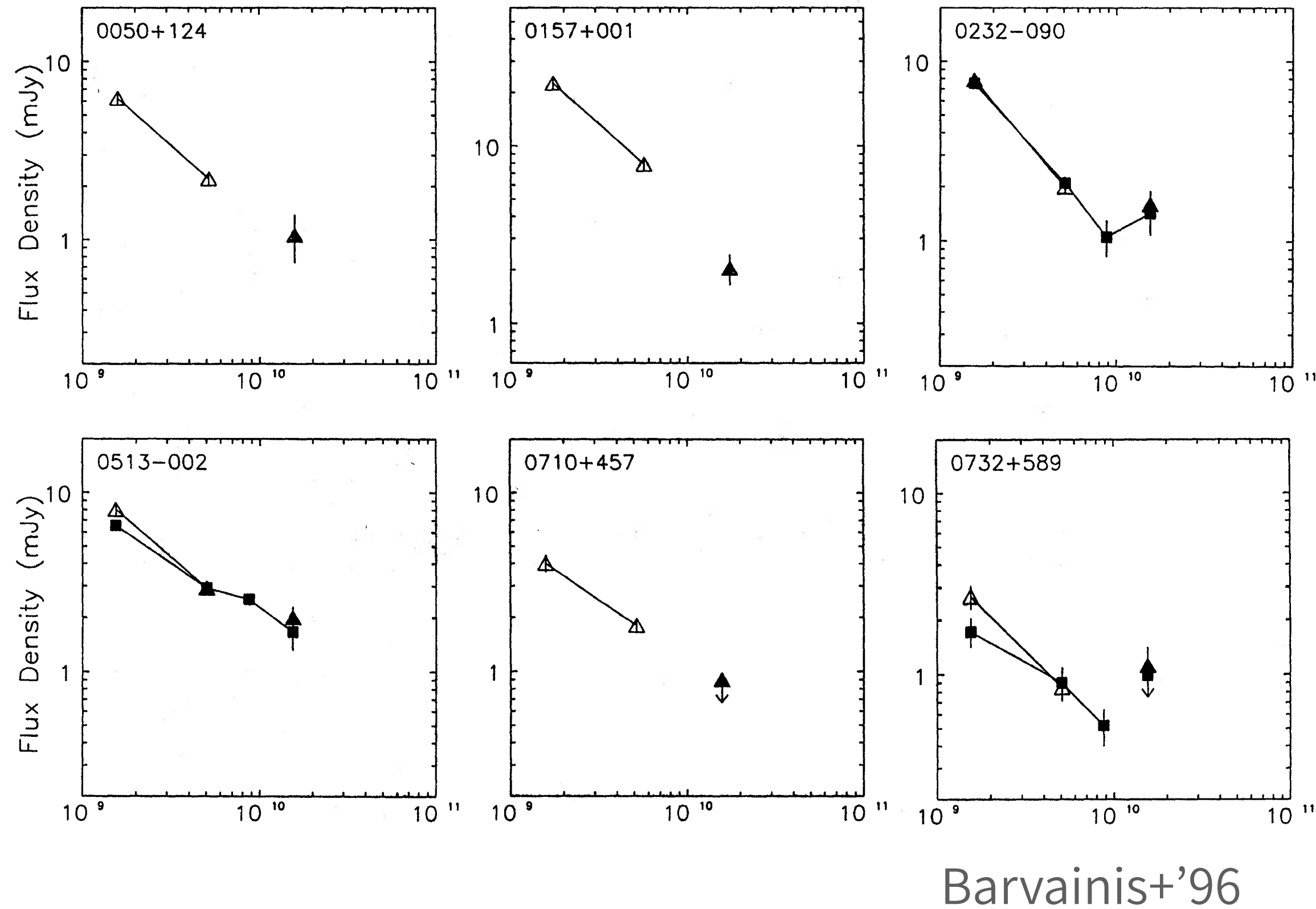
- Gas accretion
➔ brighter than galaxy
- Active Galactic Nuclei (AGNs)
- Various populations
 - Blazar, Radio galaxy, Seyfert
- Unsolved mysteries of AGNs
 - Evolution? Power? Jet? Corona?,,,,

Millimeter Excess in Nearby Seyferts

Multi-wavelength spectrum of AGNs



Millimeter excess in nearby Seyferts



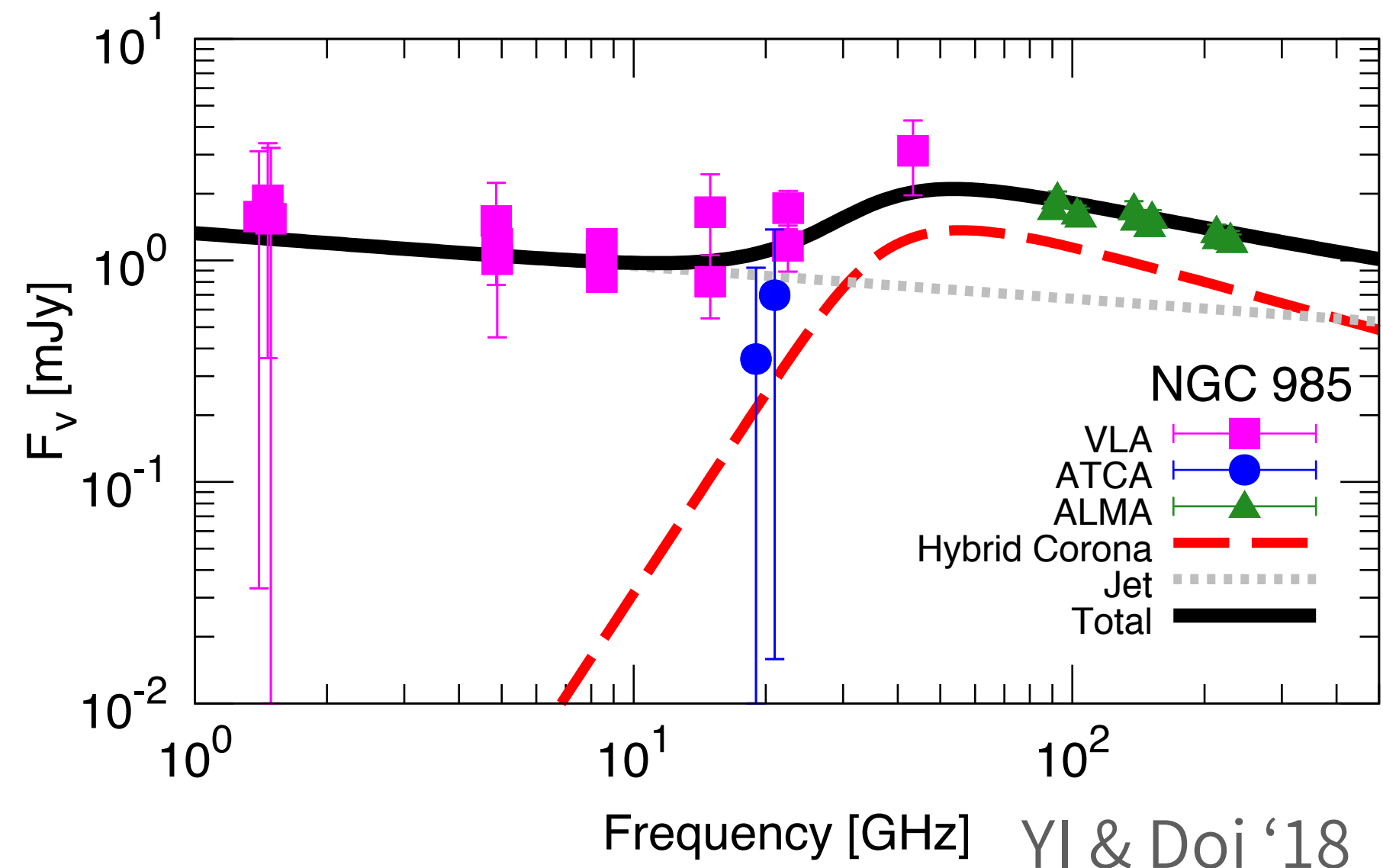
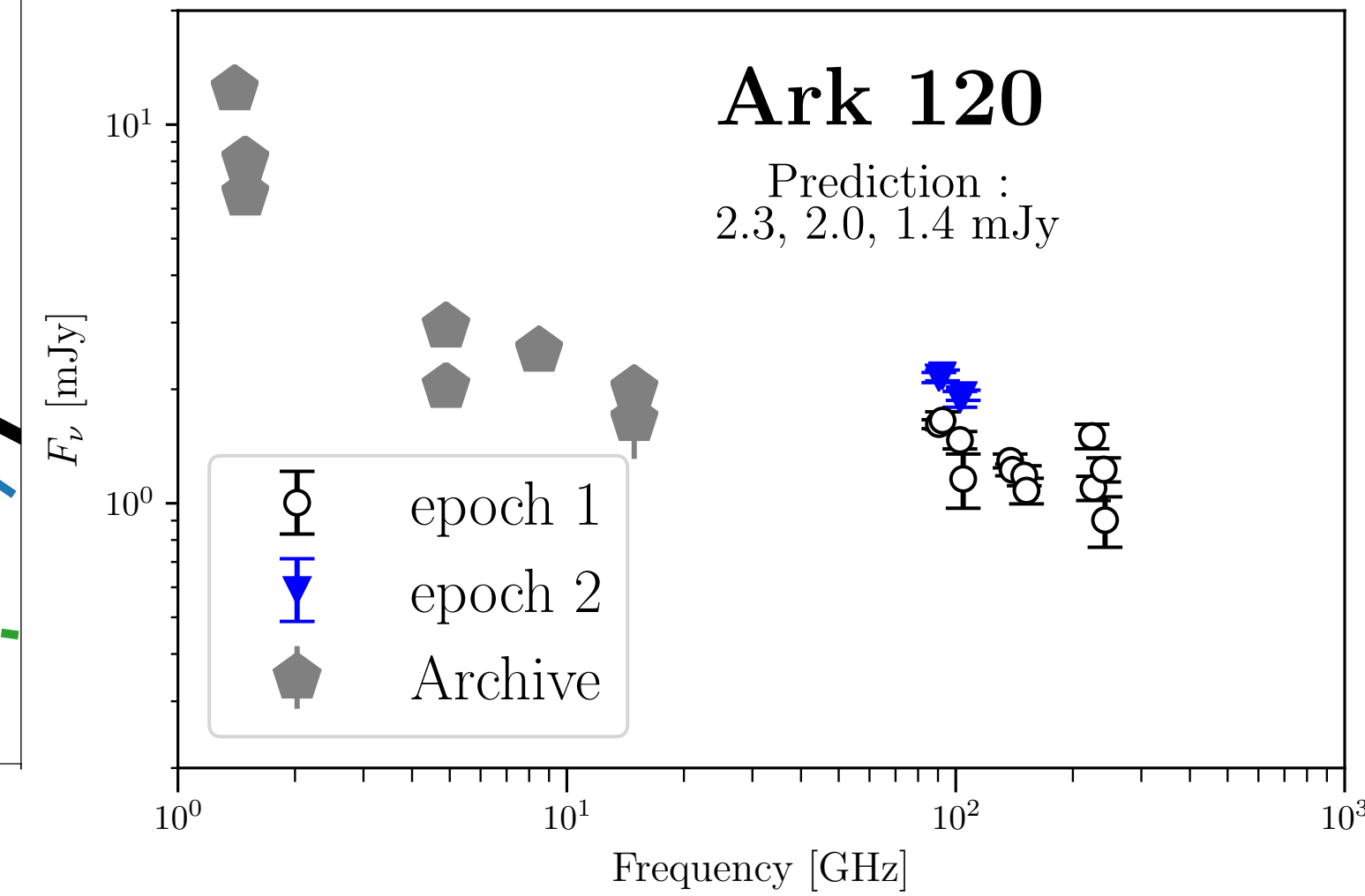
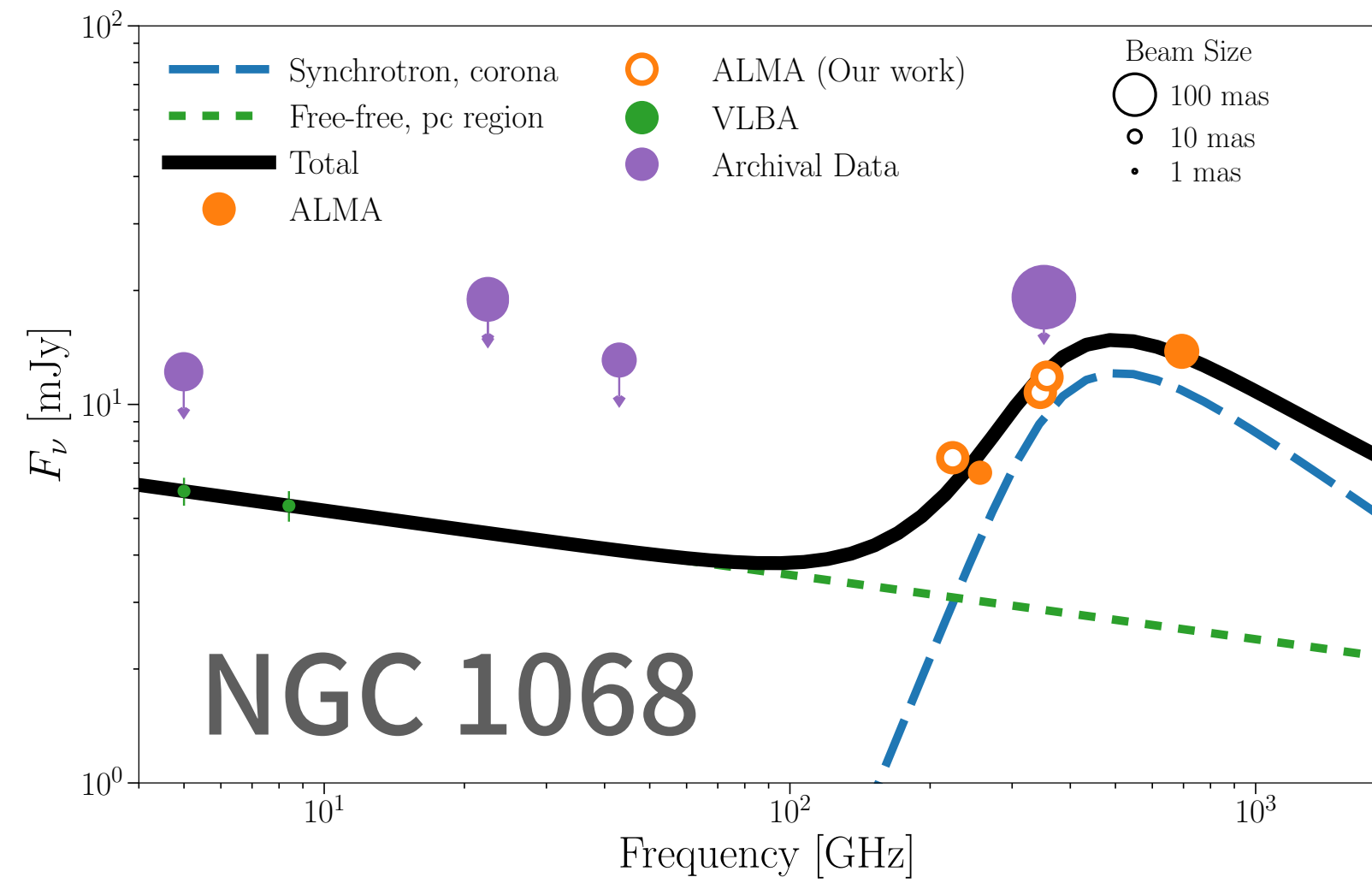
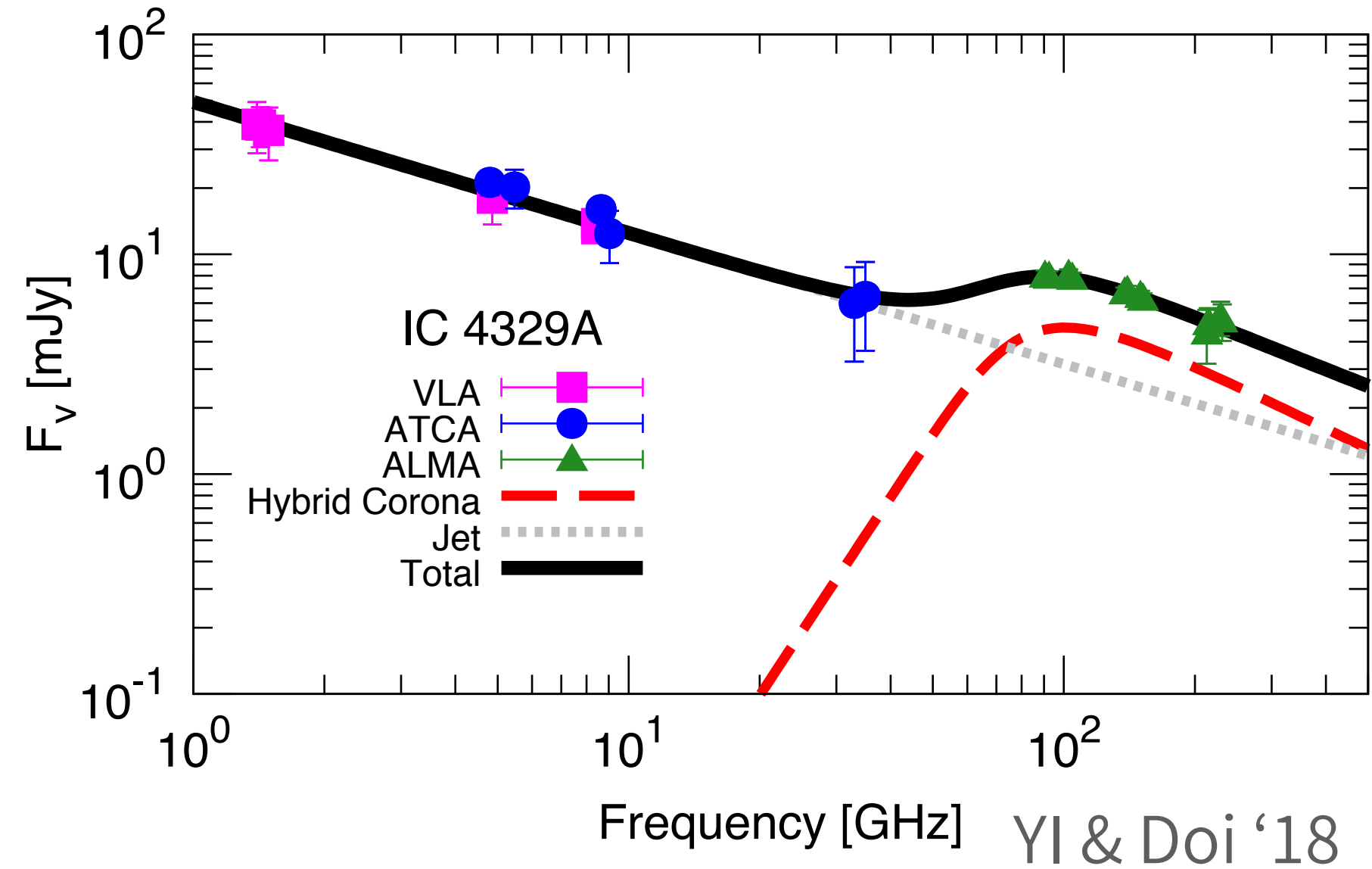
- Spectral excess in the mm-band
(e.g., Antonucci & Barvainis'88; Barvainis+'96; Doi & Inoue '16; Behar+'18).
- Contamination of extended components?
- Multi-frequency property?

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.



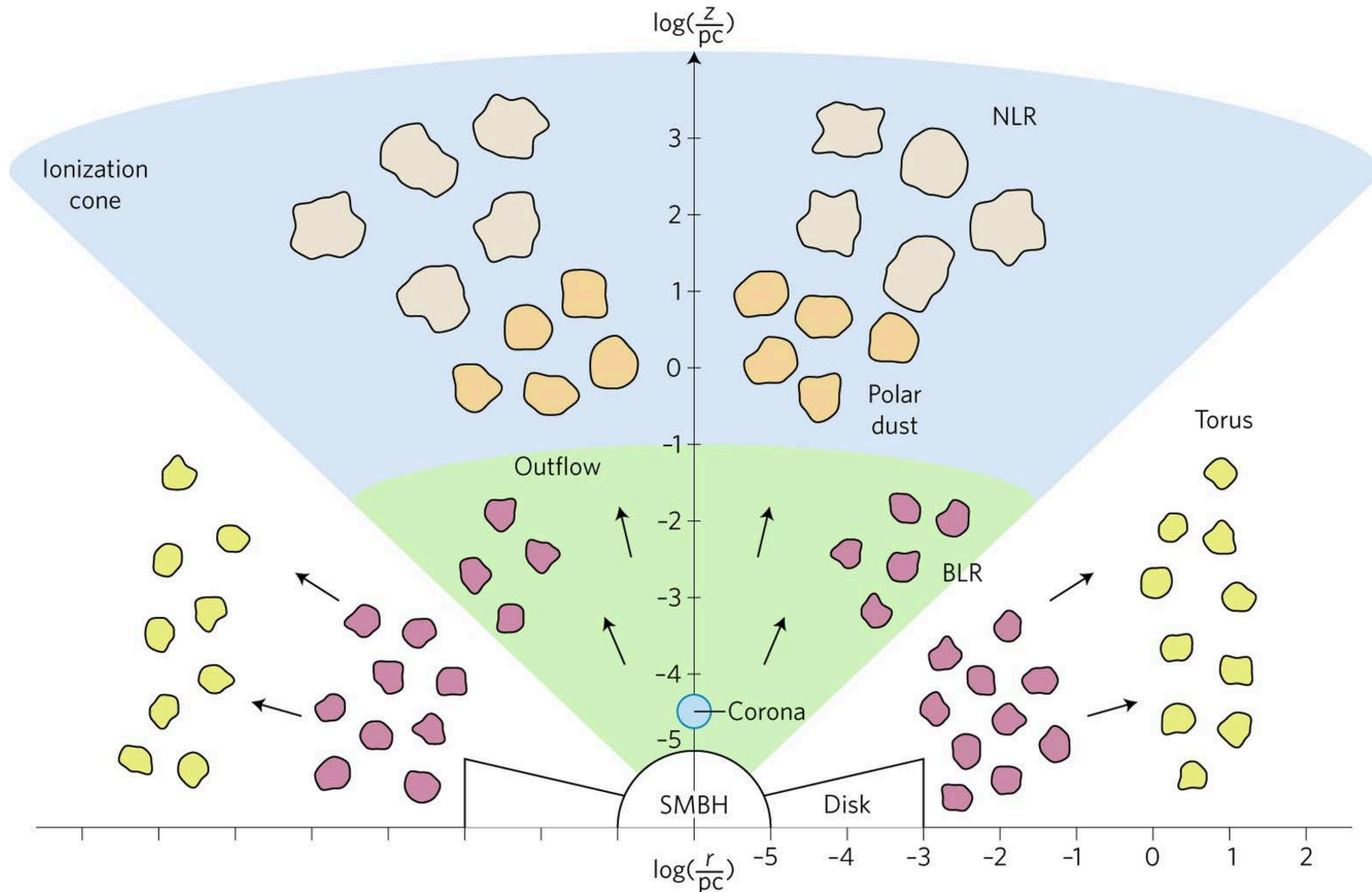
ALMA observations toward nearby Seyferts



- 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

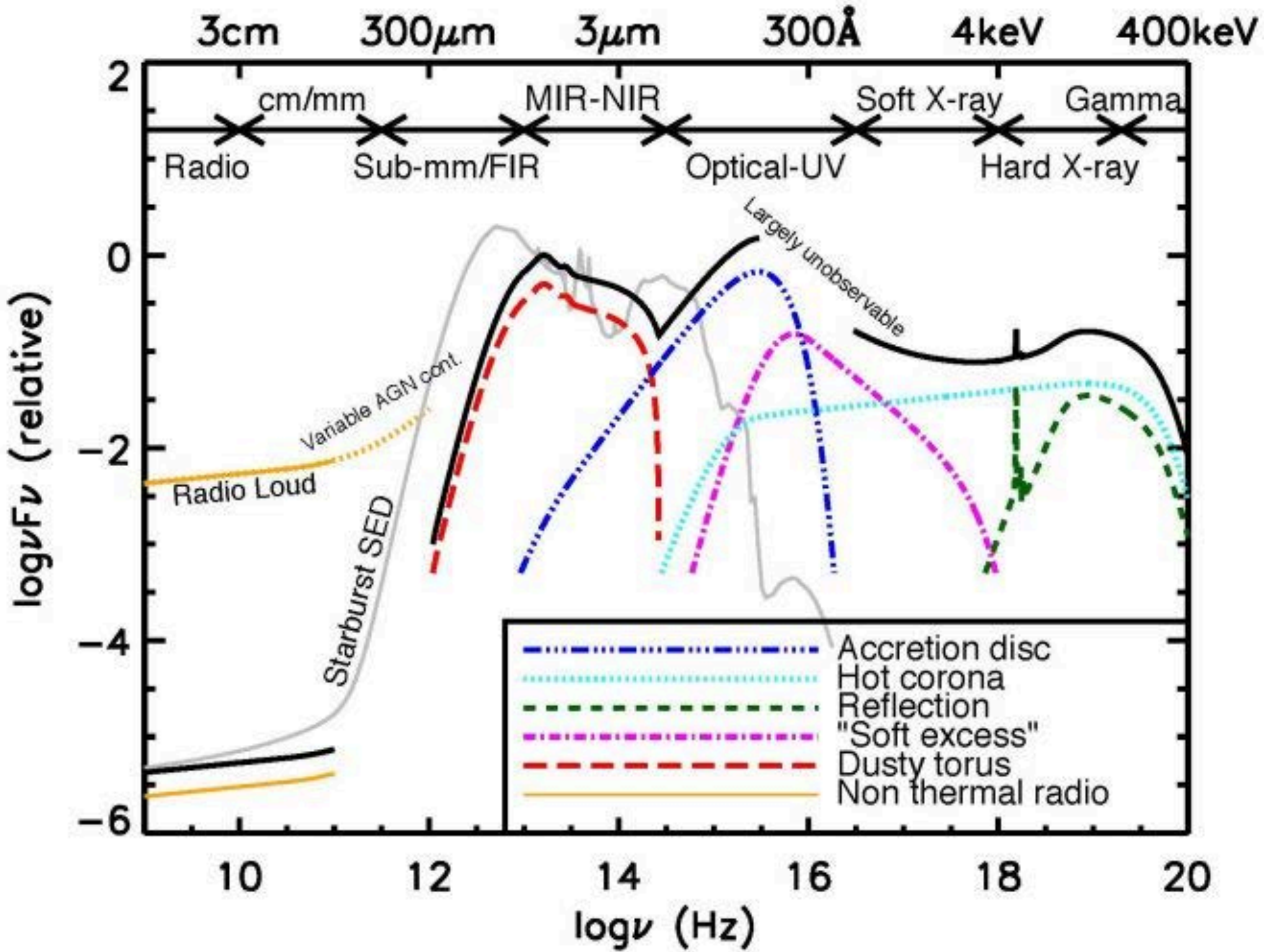
Where is the origin of the mm excess?



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

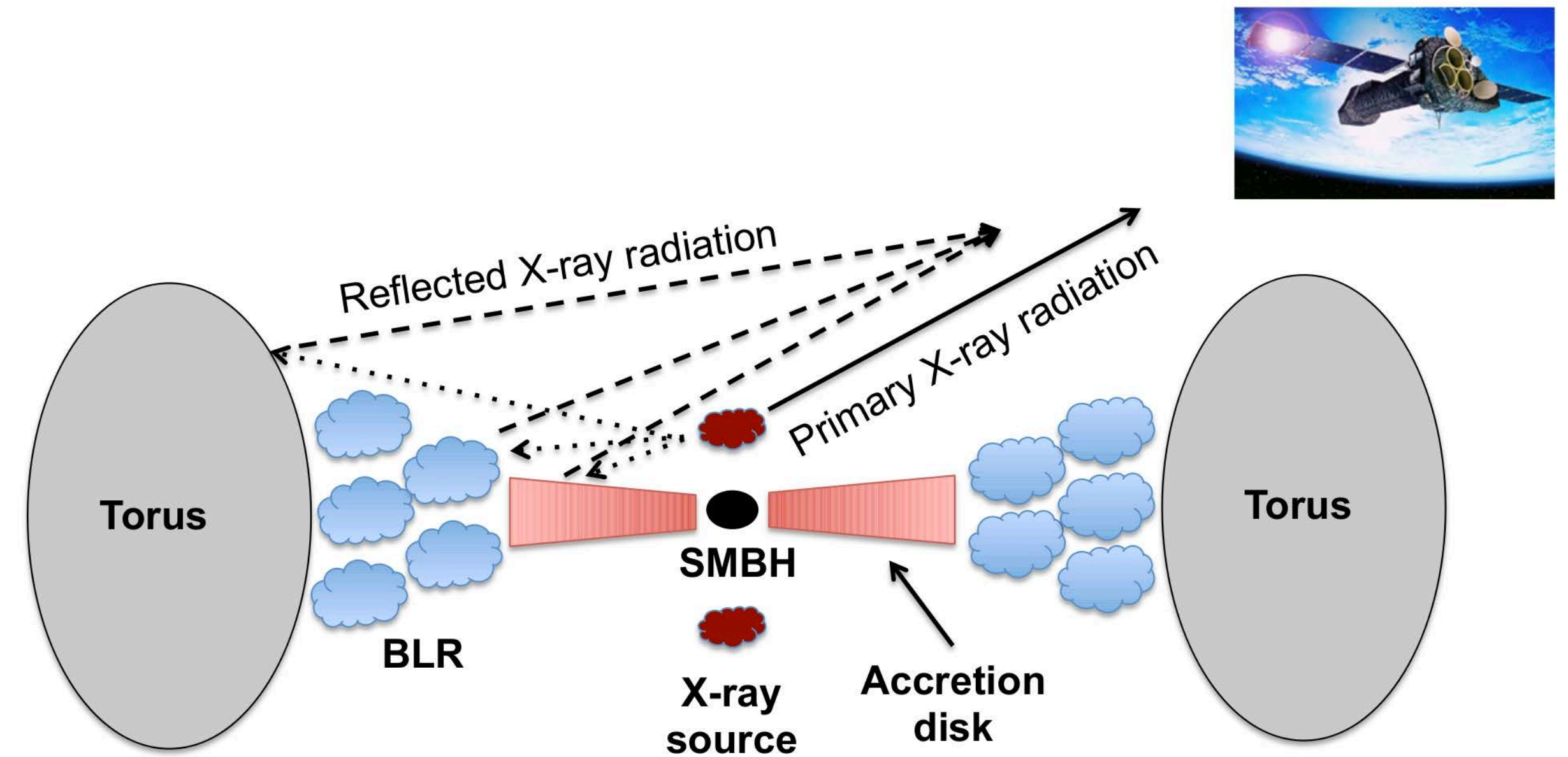
Coronal Synchrotron Emission

X-ray emission from black hole corona



Hickox & Alexander+'16

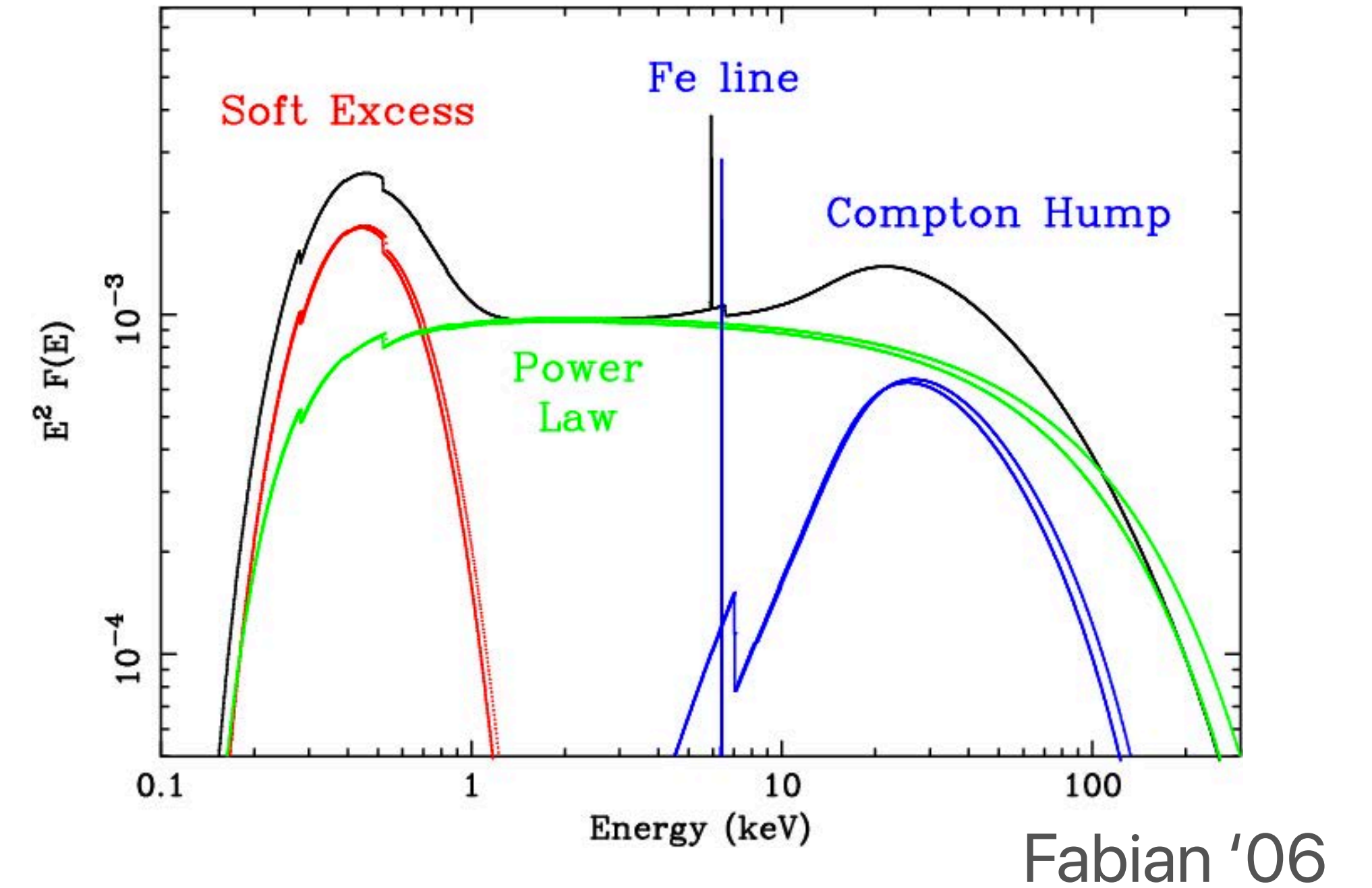
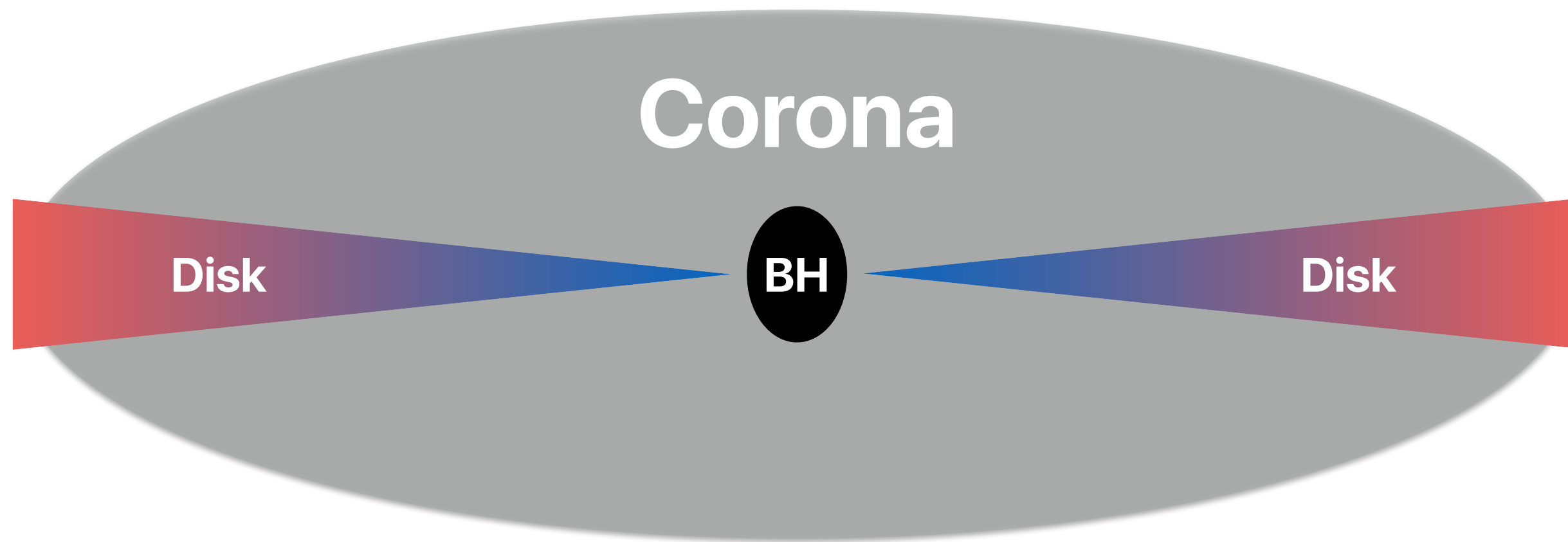
- Power-law continuum is generated by Comptonization of disk photons in the **corona**.



©Ricci

Black Hole Accretion disk corona

Hot plasma around BH



- High energy cutoff

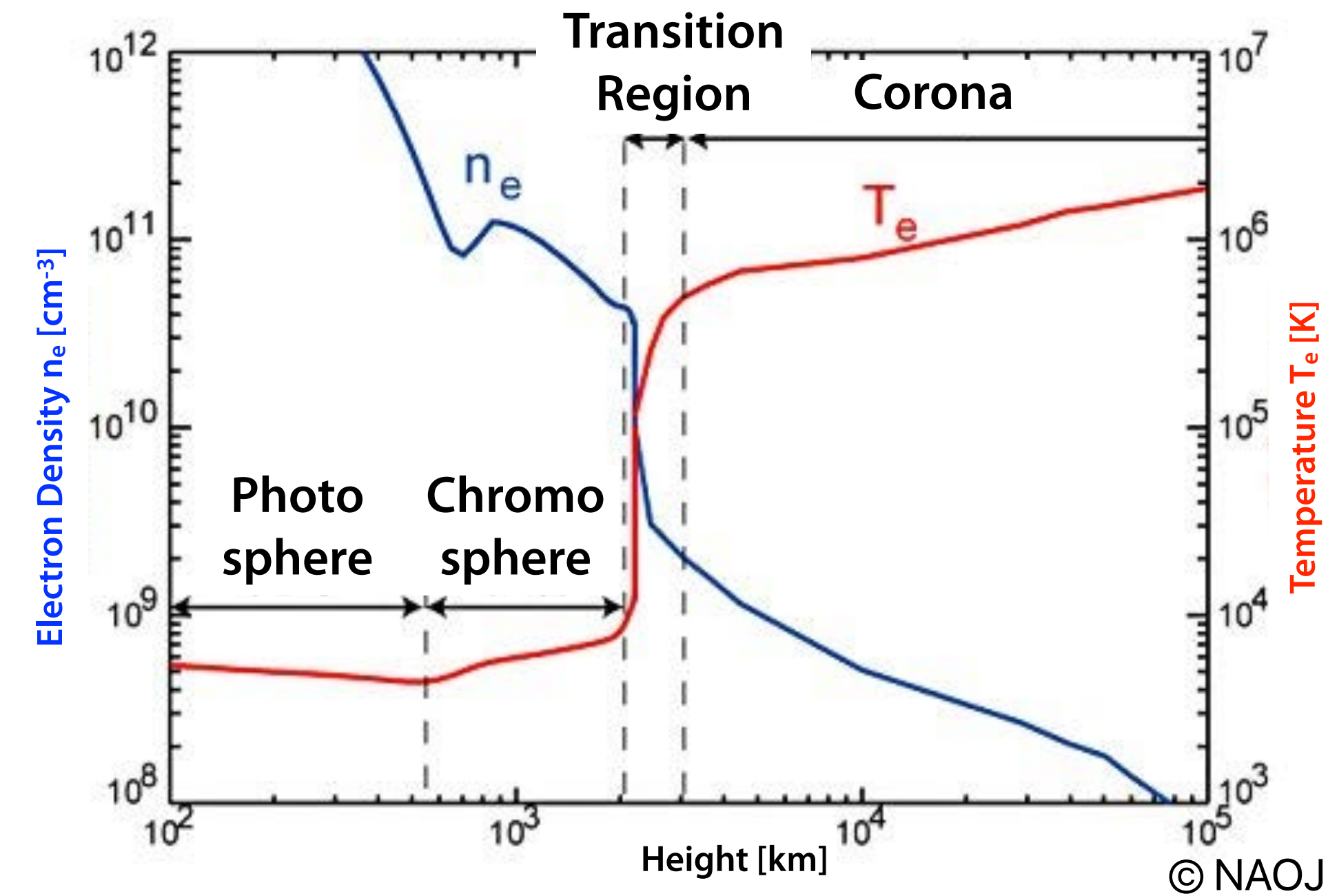
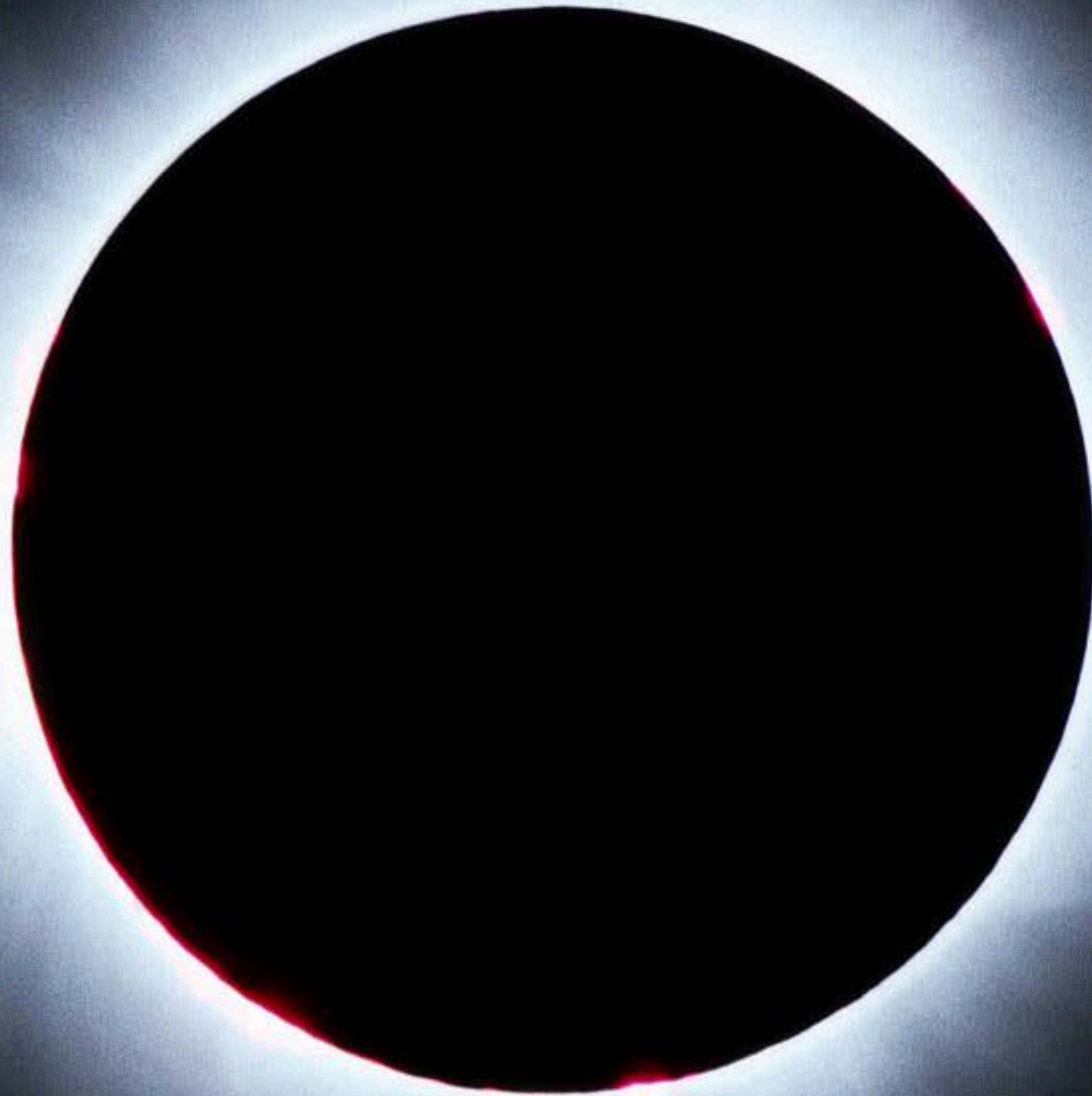
$$\sqrt{k_B T_e} \sim 10^9 \text{ K} \sim 100 \text{ keV}$$

- Power-law spectrum:
Compton y -parameter

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

Solar corona heating

Dissipation of magnetic energy



- Magnetic activity heats the solar corona to $\sim 10^6$ 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

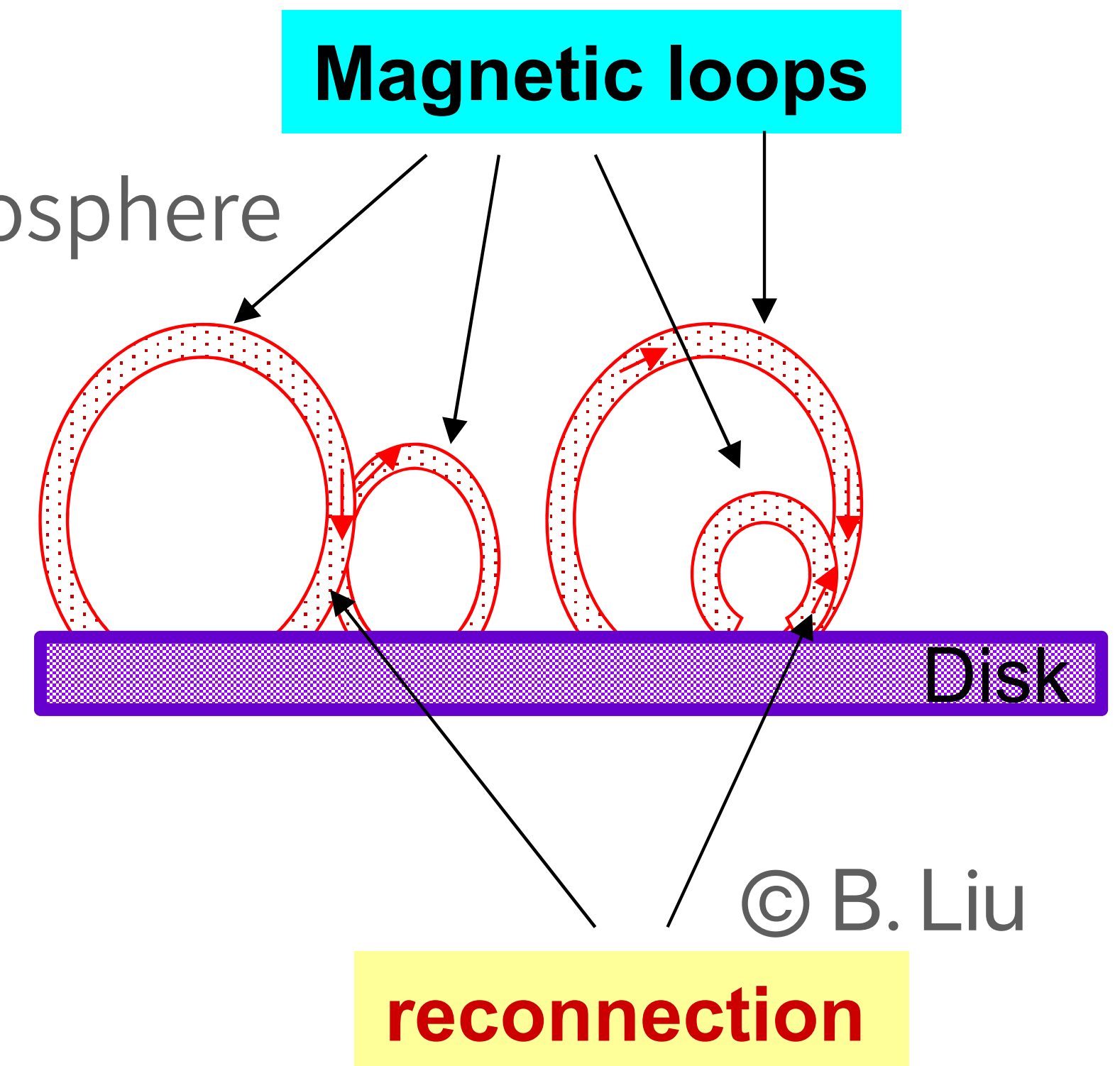
1. Reconnection heating = Compton cooling in corona

$$\checkmark \quad \frac{B^2}{4\pi} V_A \approx \frac{4k_B T_e}{m_e c^2} n_e \sigma_T c U_{\text{seed}} l \sim y c U_{\text{seed}}$$

2. Conduction heating = Evaporation cooling in disk chromosphere

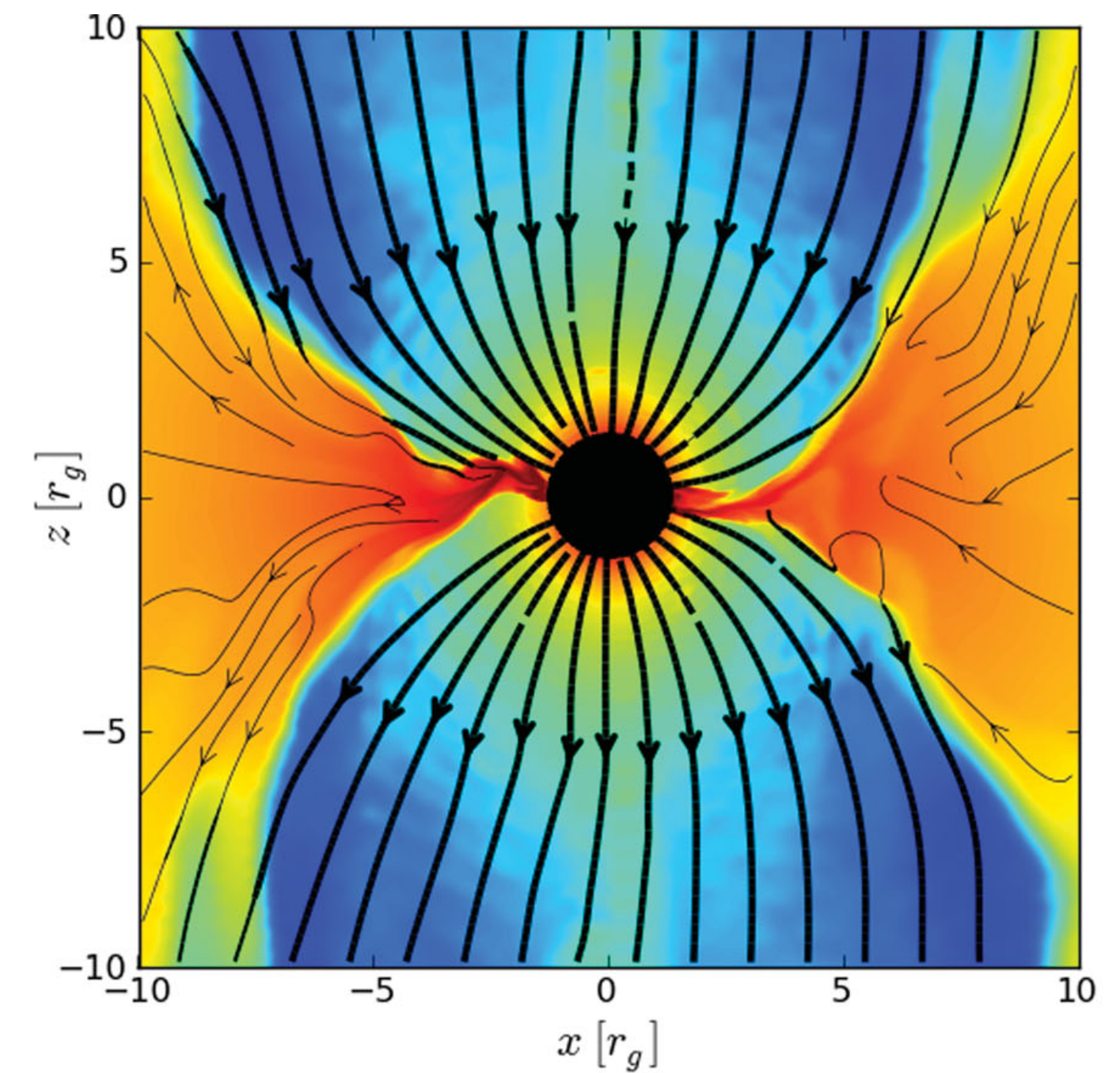
$$\checkmark \quad \frac{k_0 T^{7/2}}{l} \approx \frac{\gamma}{\gamma - 1} n_e k_B T_e \left(\frac{k_B T_e}{m_H} \right)^{1/2}$$

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

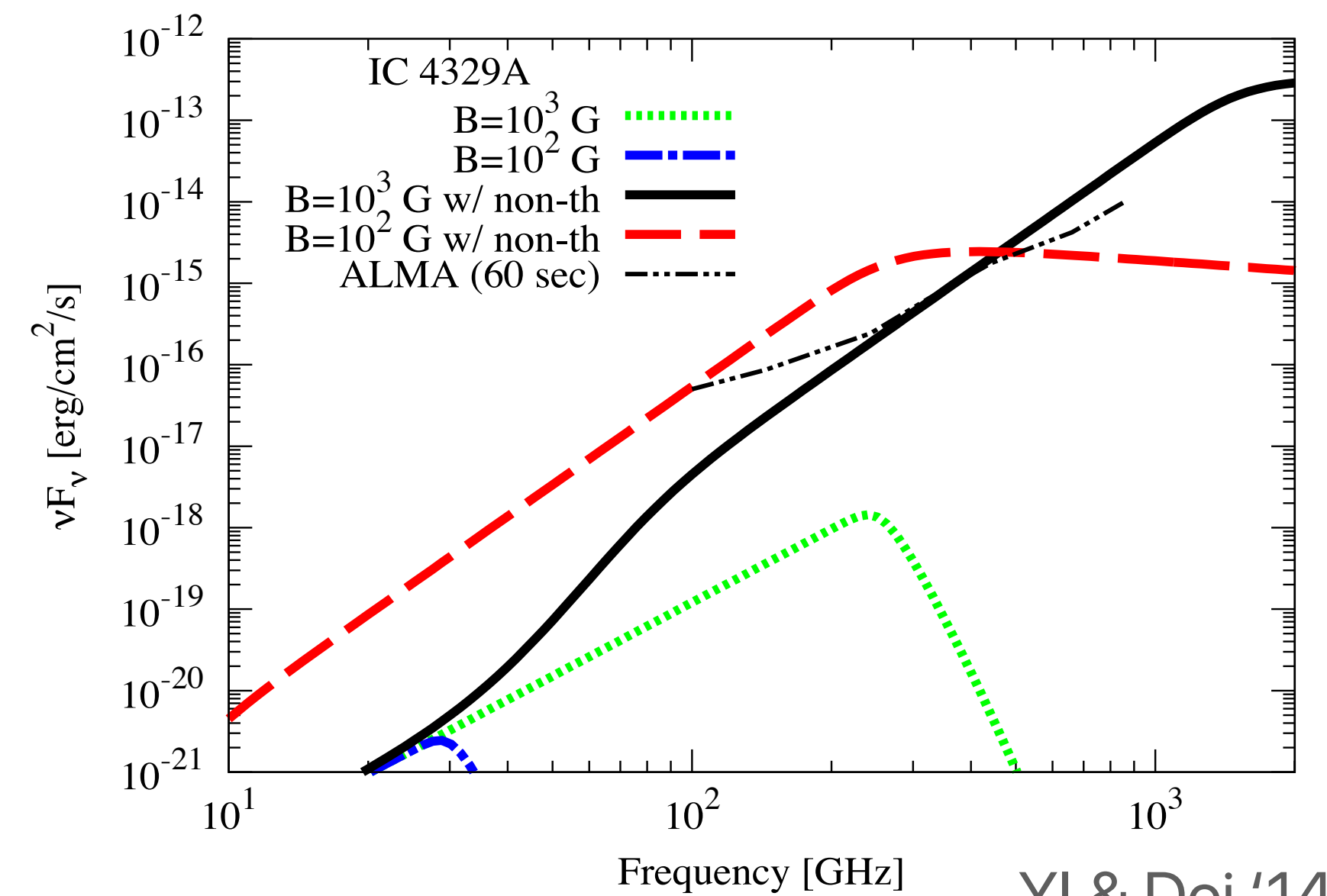


Magnetic Fields around SMBHs

- Never measured. But important 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



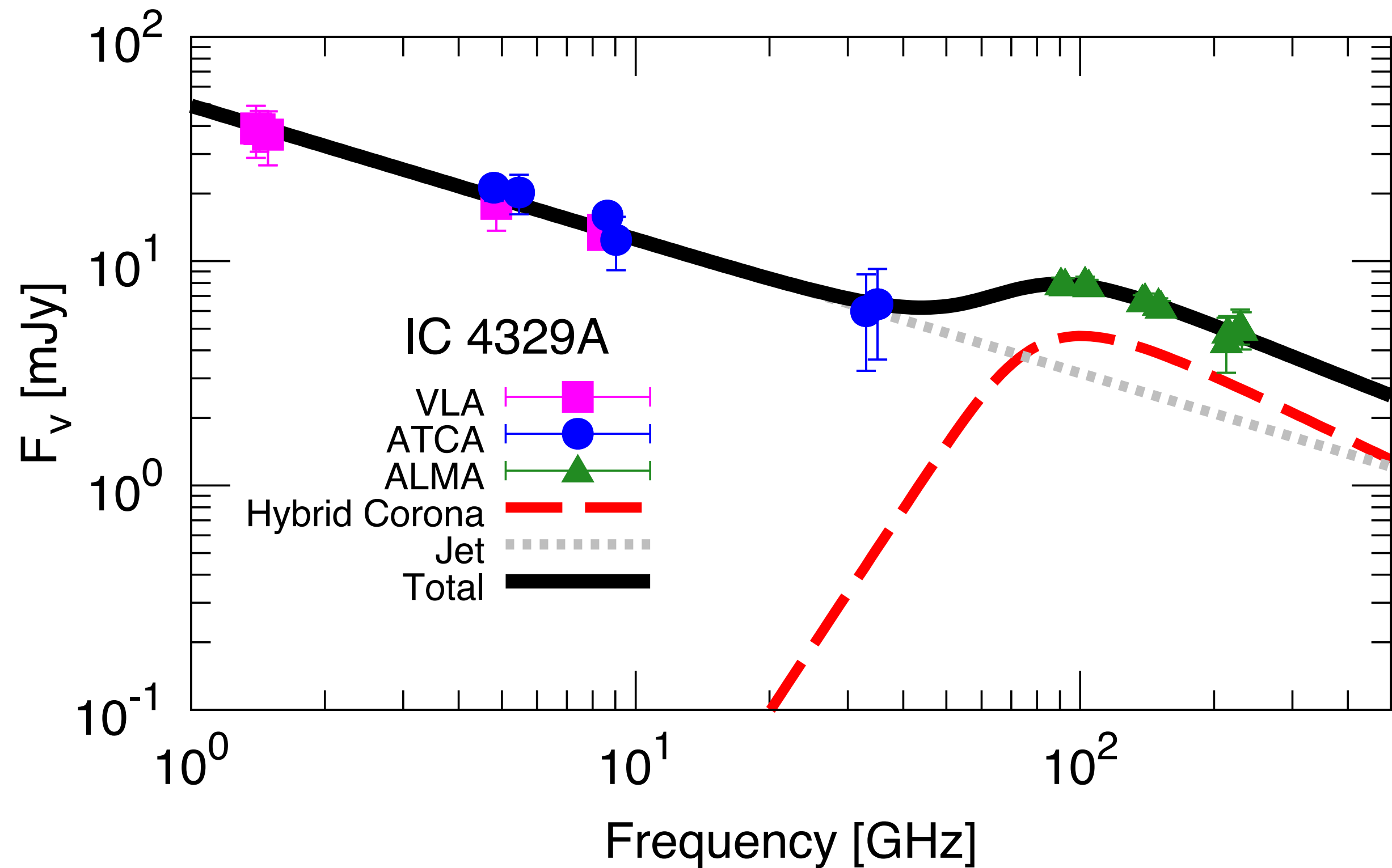
McKinney et al. '12



Yi & Doi '14

cm-mm spectrum of AGN core

A case of IC 4329A



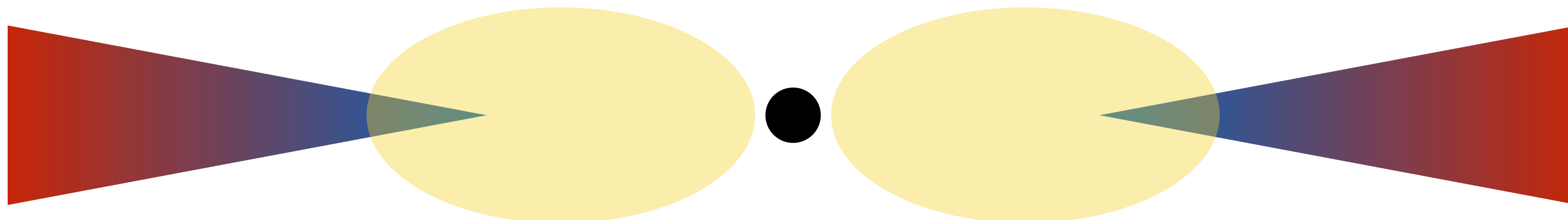
YI & Doi '18

- Hybrid corona model (YI & Doi '14)
- Non-thermal electron fraction : $\eta = 0.03$ (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.

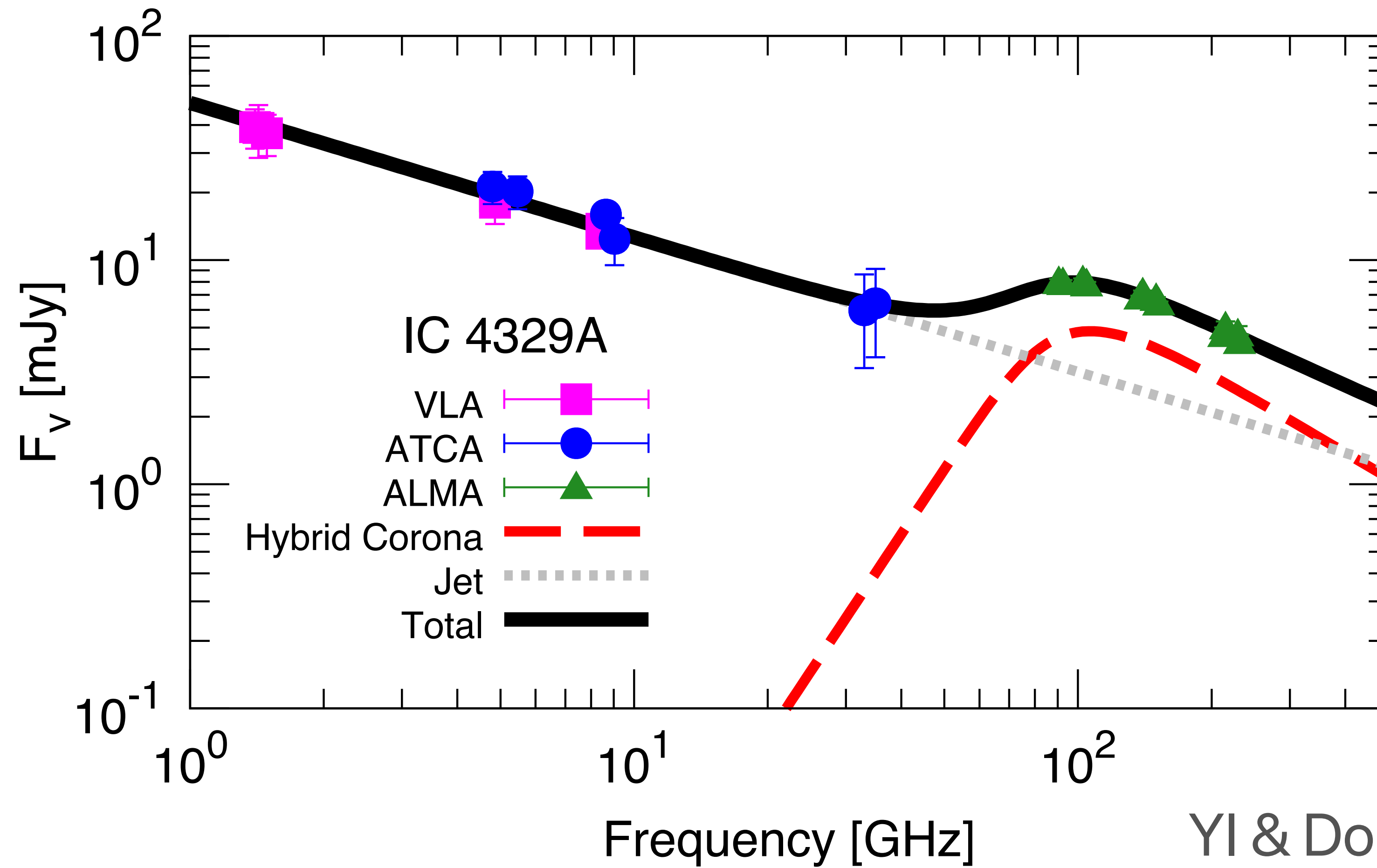
- Heating and Cooling
 - Magnetic Heating: $B^2 V_A / 4\pi$
 - $Q_{B, \text{heat}} \sim 10^{10} \text{ erg/cm}^2/\text{s}$
 - Compton Cooling: $4kTn_e\sigma_T c U_{\text{rad}} l / m_e c^2$
 - $Q_{\text{IC, cool}} \sim 10^{13} \text{ erg/cm}^2/\text{s}$
 - Magnetic field energy is **NOT** sufficient to keep coronae hot.
- Disk truncation at some radii (e.g. $\sim 40 r_s$)
 - 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.



High Energy Emission From Coronae

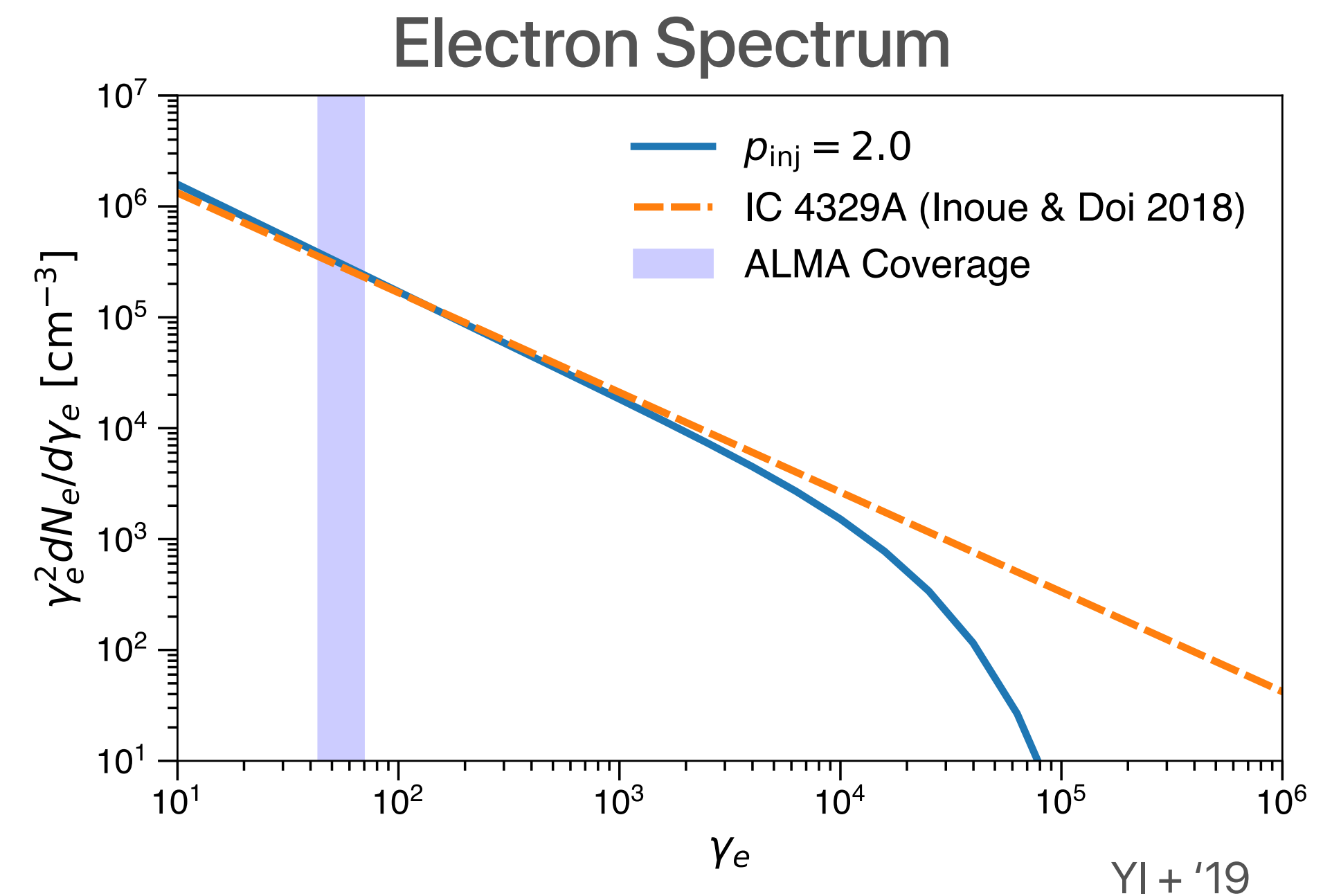
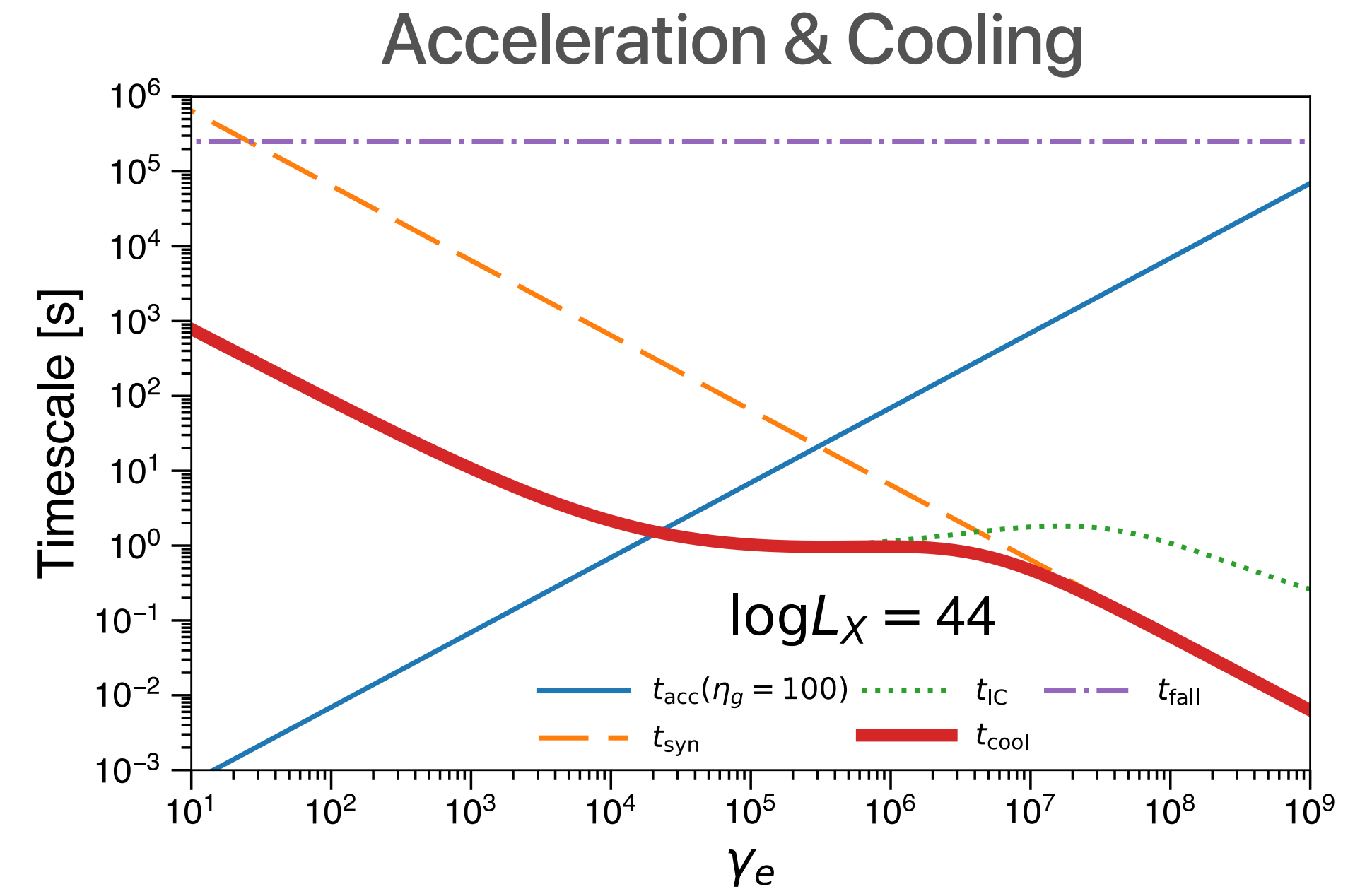
Radio Spectrum of AGN Core

Non-thermal tail in the mm spectrum



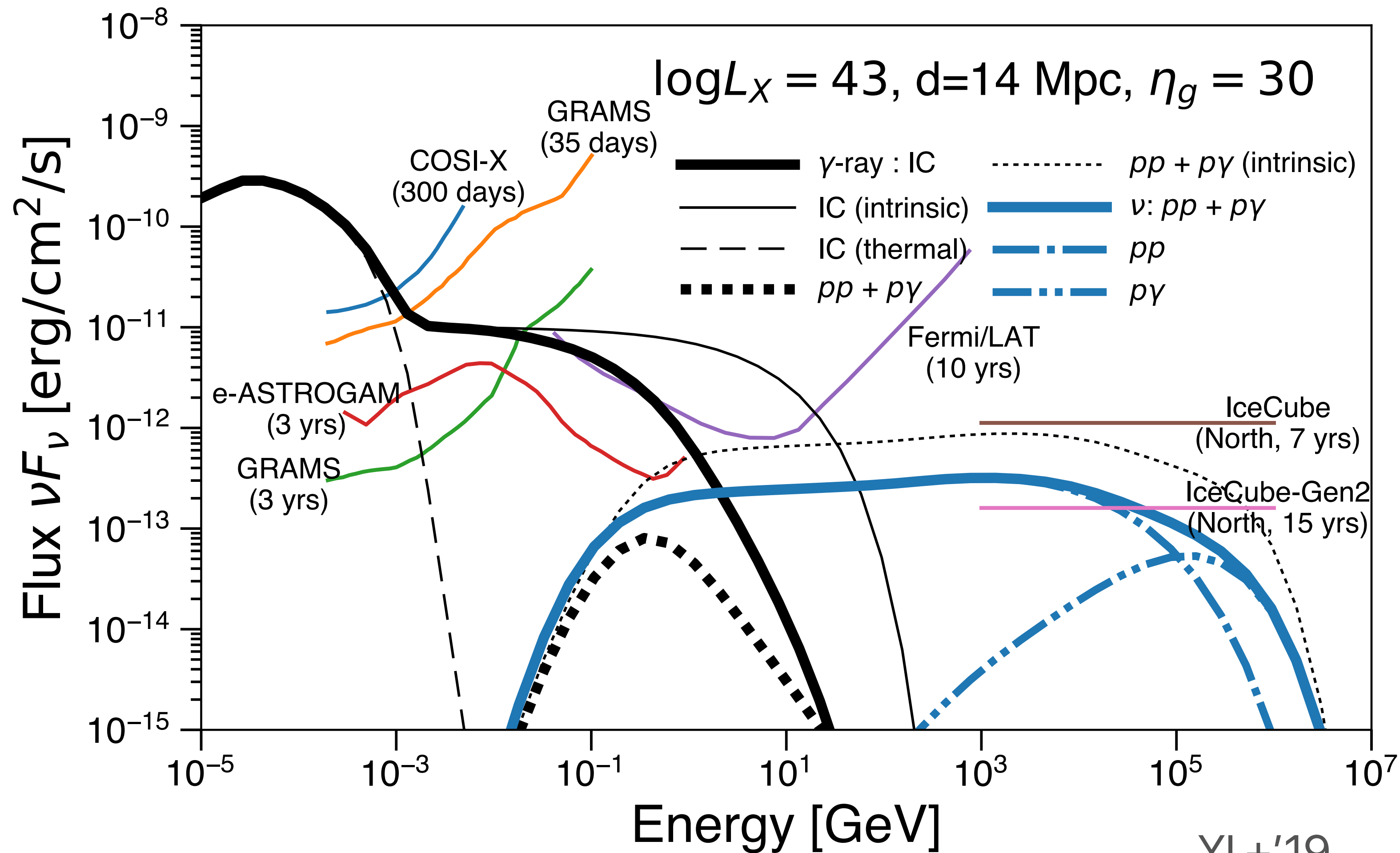
Generation of Non-thermal Electrons in Coronae

- 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.



High energy emission from AGN coronae

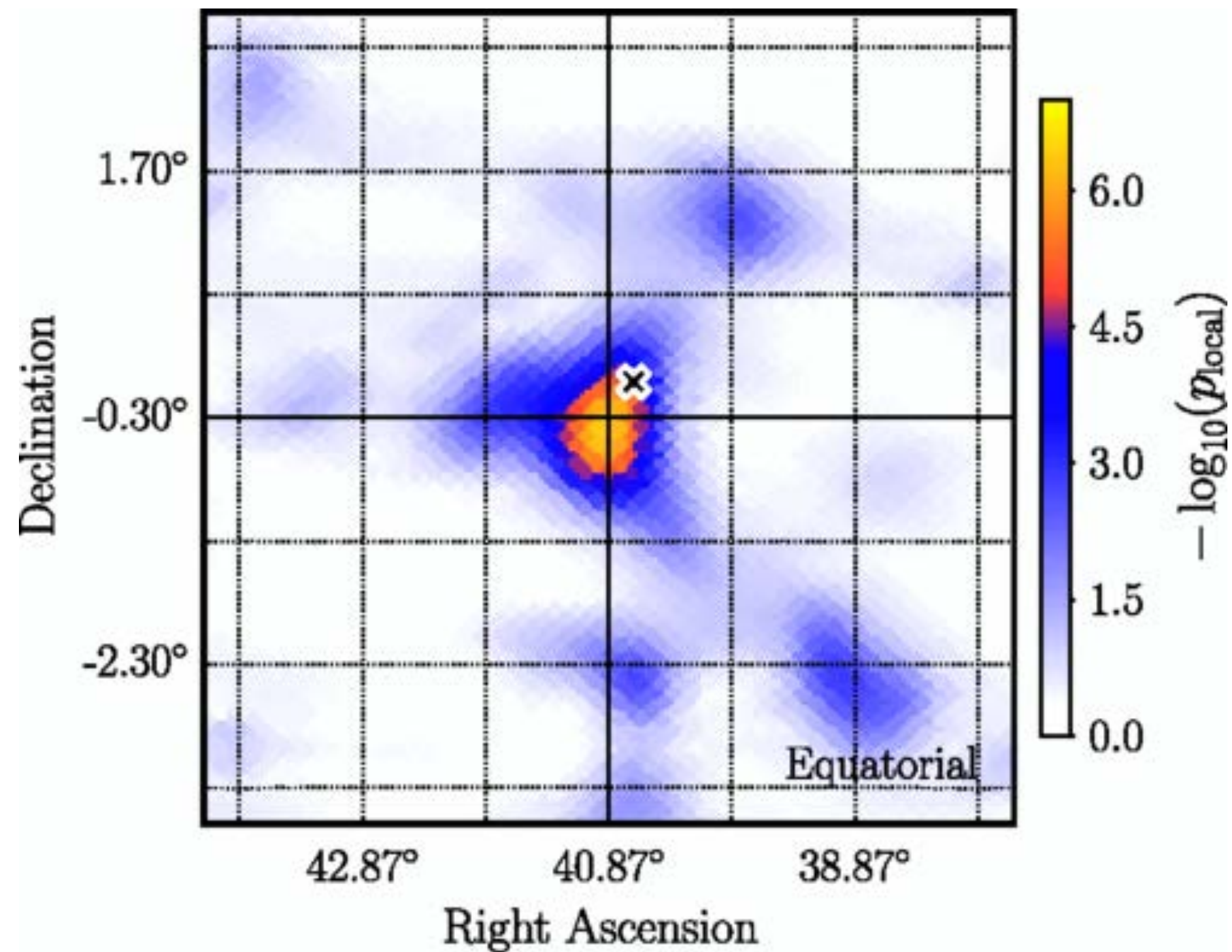
Multi-messenger Signature: MeV Gamma-ray & TeV Neutrinos



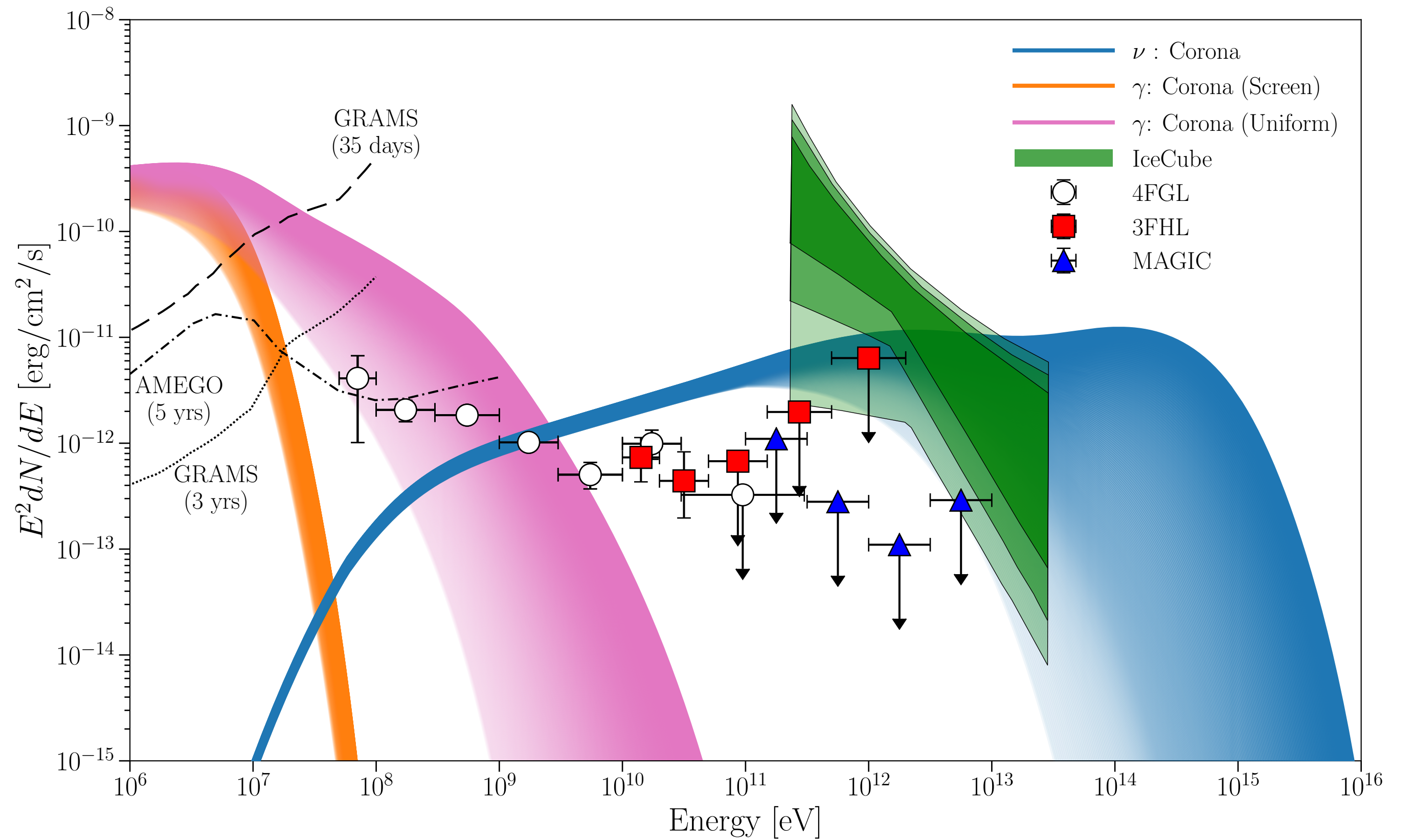
- MeV emission
- but, no GeV emission
- Protons would be accelerated simultaneously
- Generation of high energy neutrinos

IceCube Hottest Spot

NGC 1068 (no jet)



IceCube 2020

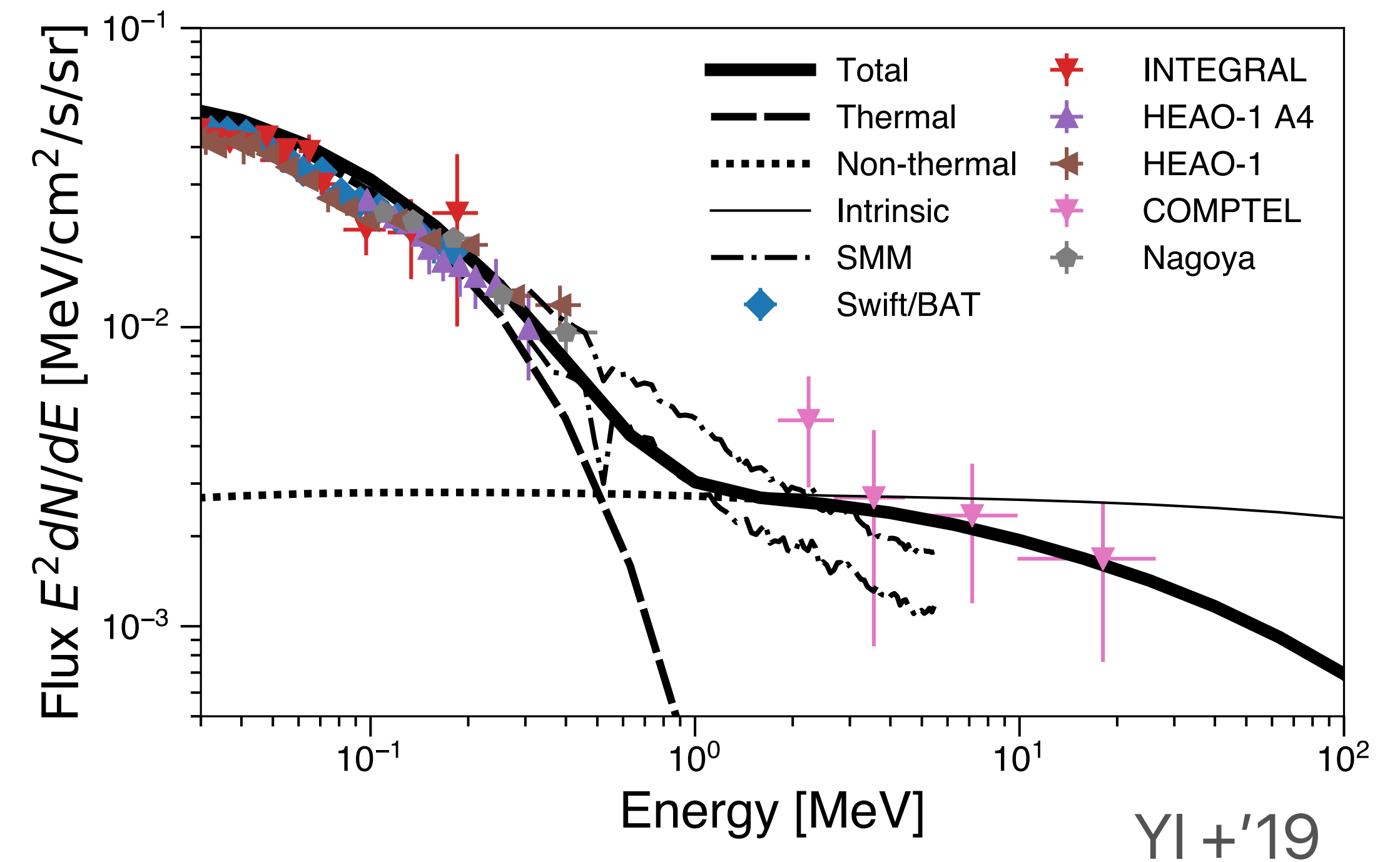
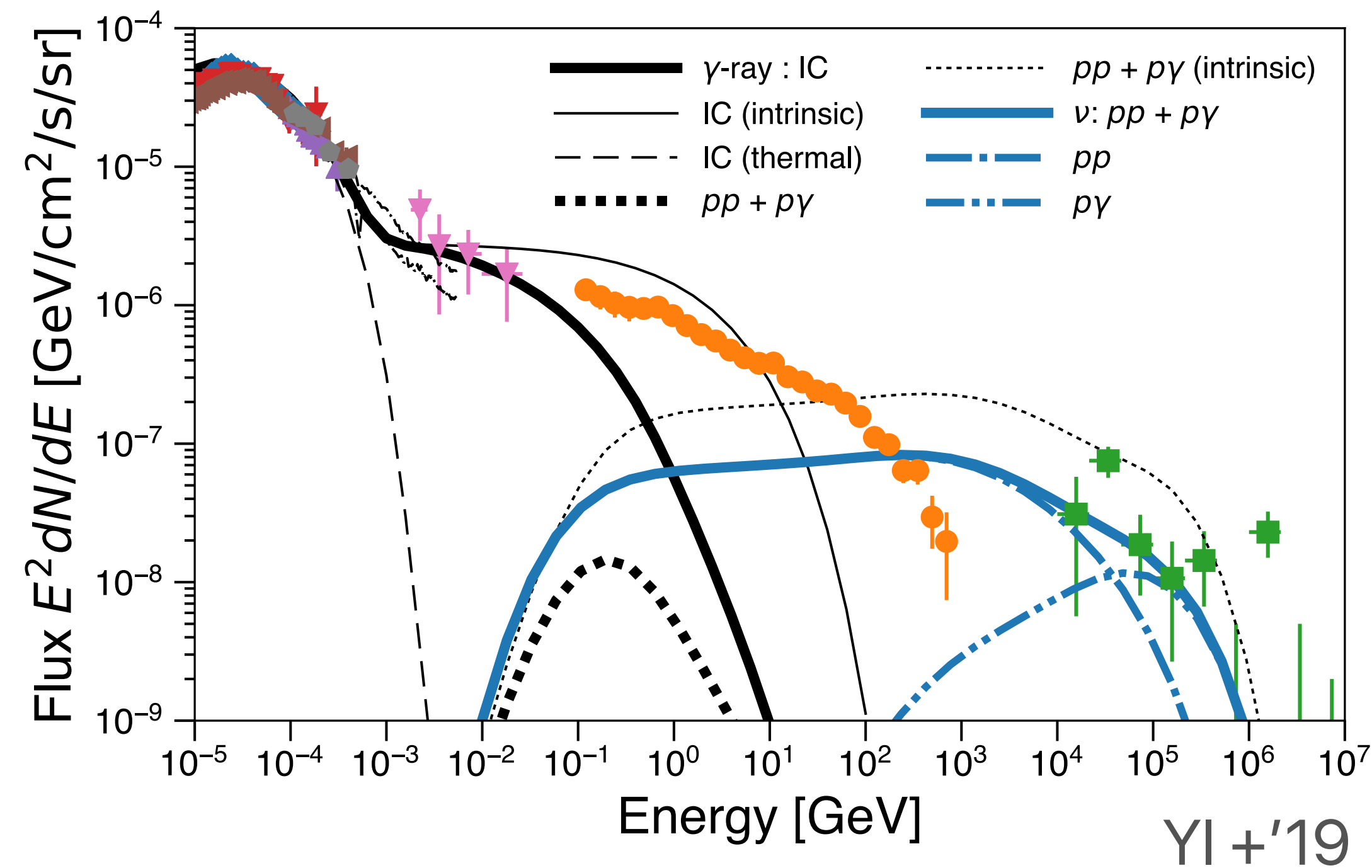


YI, Khangulyan, & Doi, '20

- Type-2 Seyfert NGC 1068 is reported at 2.9- σ .
- If the signal is real, corona can be a plausible neutrino production site.

Cosmic High Energy Background Radiation

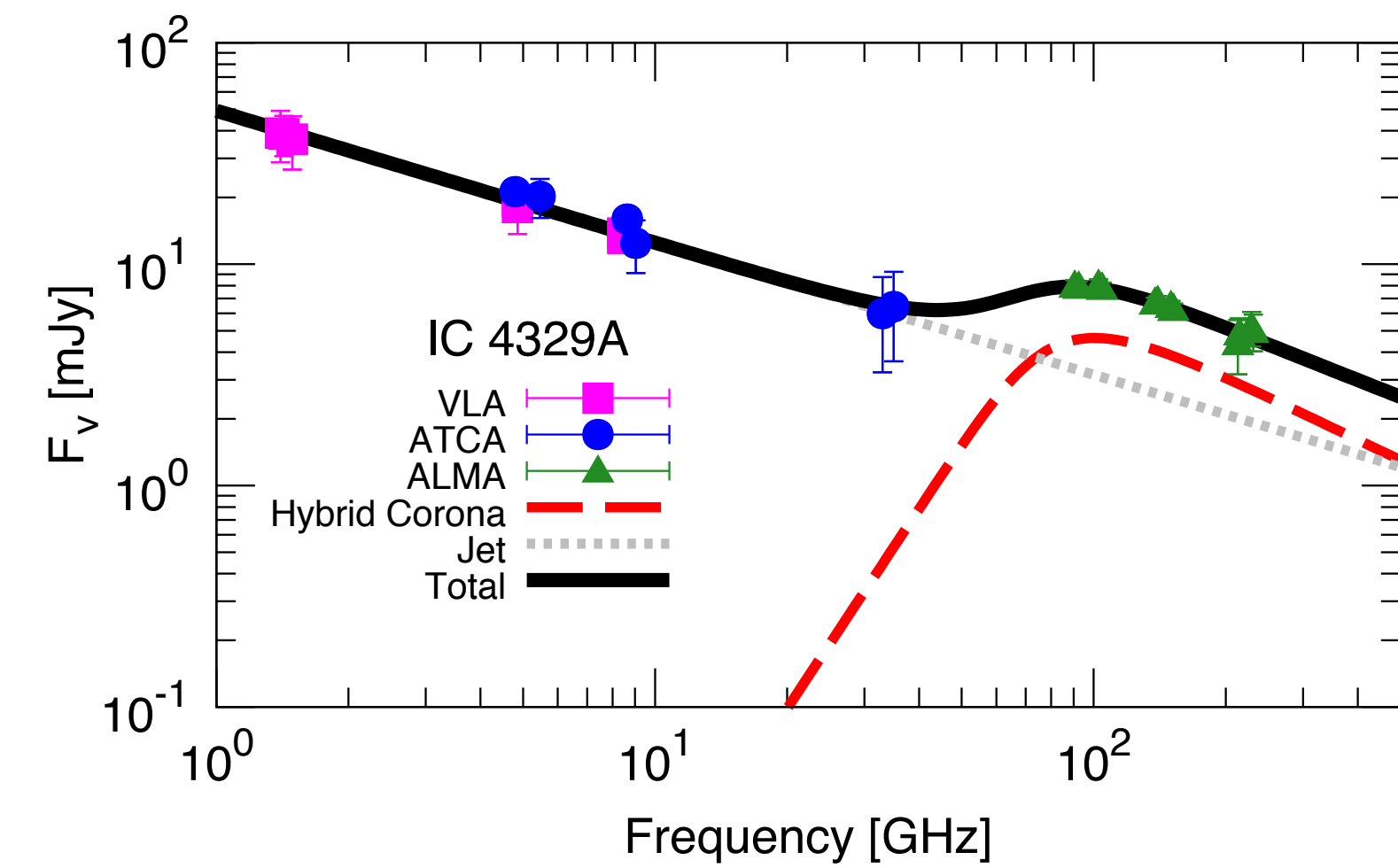
Integrated history of the Universe



- 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).
 - But, if both protons and electrons carry $\sim 5\%$ of the shock energy and gyrofactor is 30.

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