Coronal Magnetic Activity in Nearby Seyferts

Yoshiyuki Inoue

In collaboration with: Akihiro Doi, Dmitry Khangulyan, Samuel Barnier, Nhat-Minh Ly, Tomonari Michiyama, Takayoshi Sano, Shinsuke Takasao

MeV–PeV Frontiers: New Perspectives in Gamma-Ray Astronomy and Particle Acceleration @ Kashiwa, 2025-12-17

大阪大学 OSAKA UNIVERSITY

宇宙物理 OU TAP Osaka University Theoretical Astrophysics

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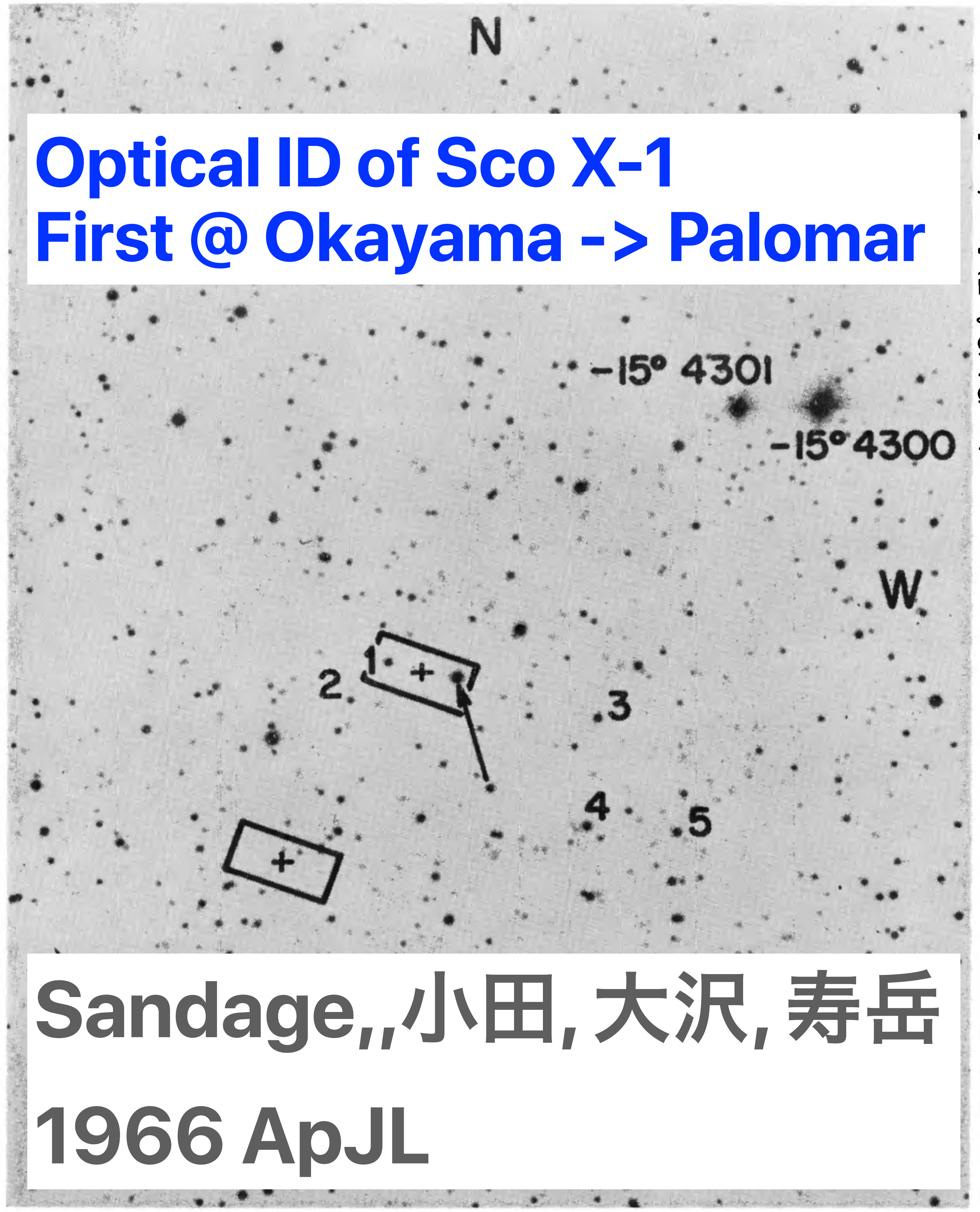
Multi-wavelength/Multi-messenger Astronomy

Long History,,,

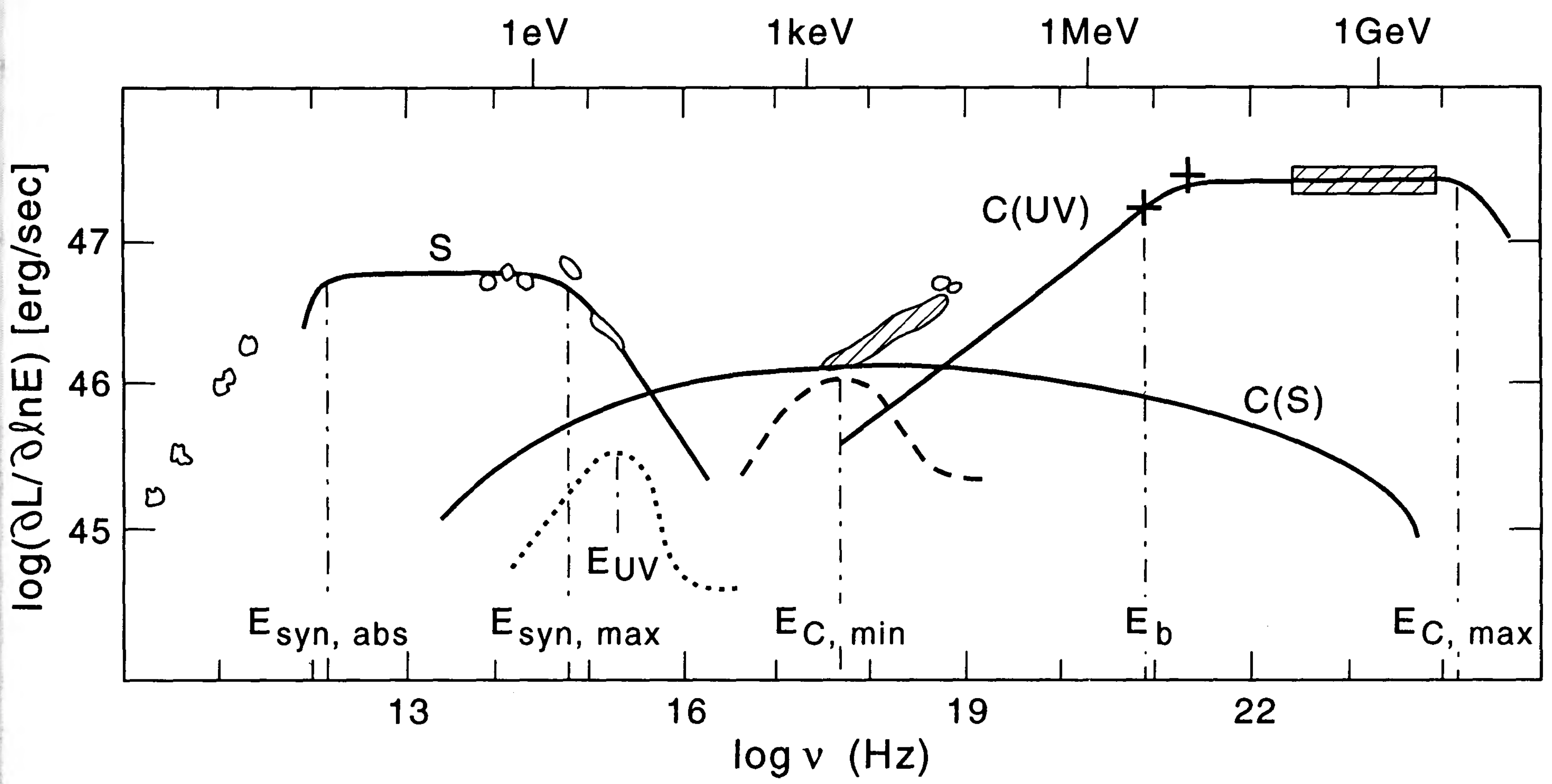


Optical ID of Sco X-1
First @ Okayama -> Palomar

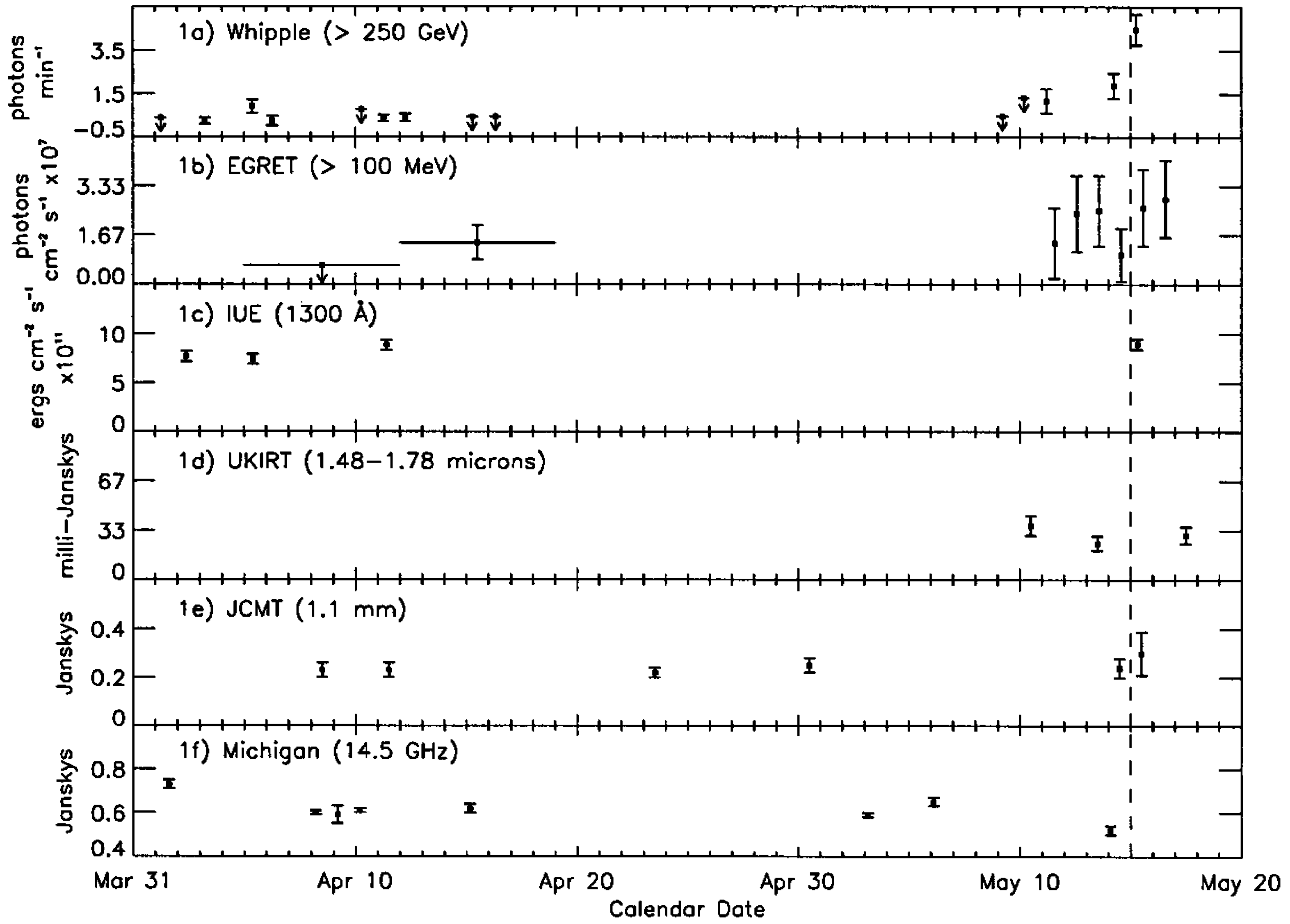
Sandage,,小田,大沢,寿岳

1966 ApJL

FIG. 1.—Photograph of the region containing the new X-ray position of Sco X-1, reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are marked by crosses surrounded by a rectangle of 1 by 2 arc min. The object described in the text is marked with an arrow. The identifications of other stars for which photoelectric photometry exists are also marked.



Sikora, Begelman, & Rees 1994 ApJ;
See also Dermer & Schlickeiser 1993 ApJ



Macomb,,, 近藤, 窪, 牧野, 牧島, 高橋, 田代 1995 ApJL;
See also Makino+'1987 ApJ ; Takahashi+'1996;

- Multi-wavelength astronomy has already started in 1990s (or 1960s).
- What innovation will we make in 2030s?

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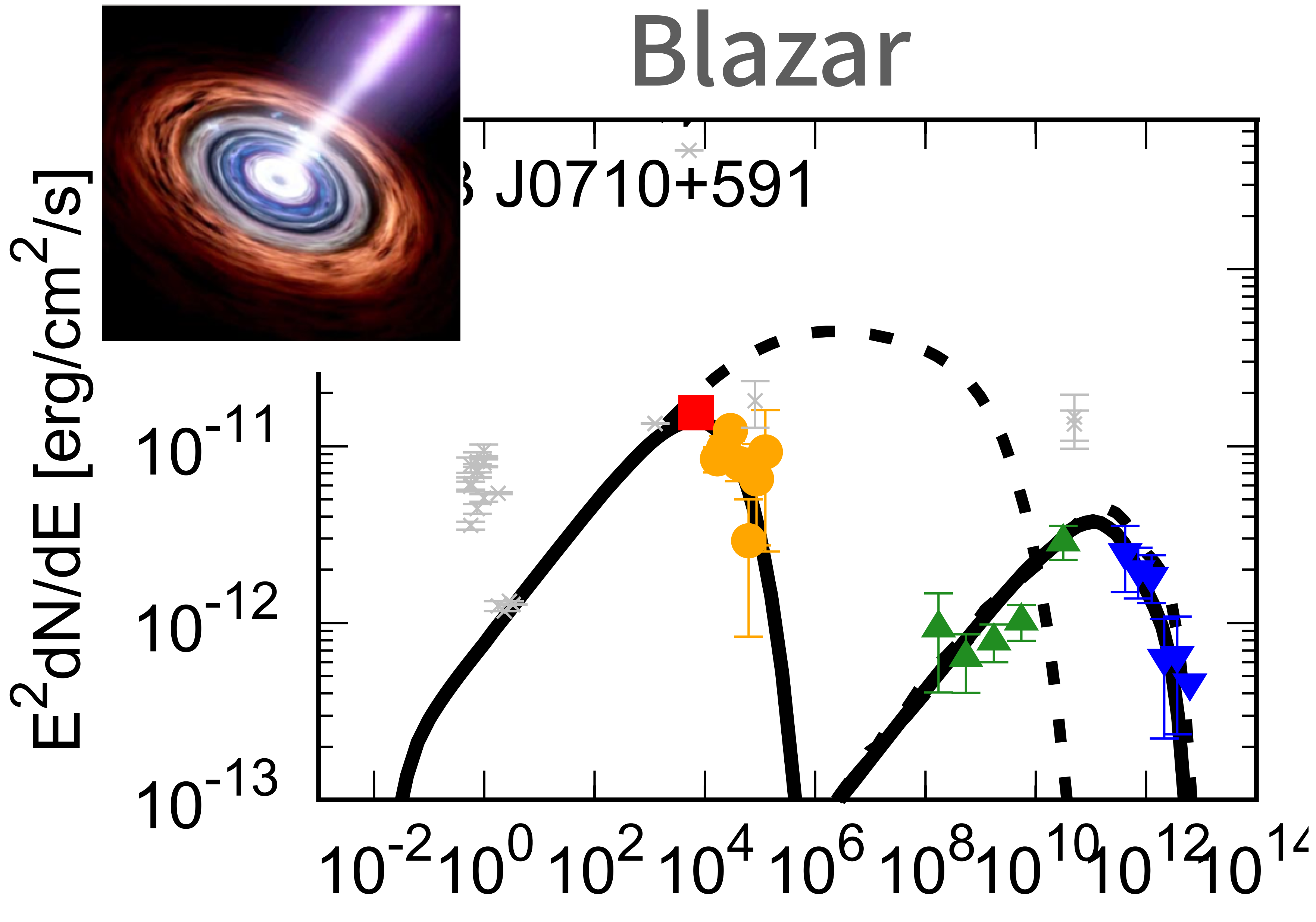
Outline

- Hot Coronae in Seyfert Galaxies
- Coronal Magnetic Activity in Seyfert Galaxies
- Coronal Magnetic Field?
- Non-thermal Coronal Magnetic Activity
  in Seyfert Galaxies

Hot Coronae
in Seyfert Galaxies

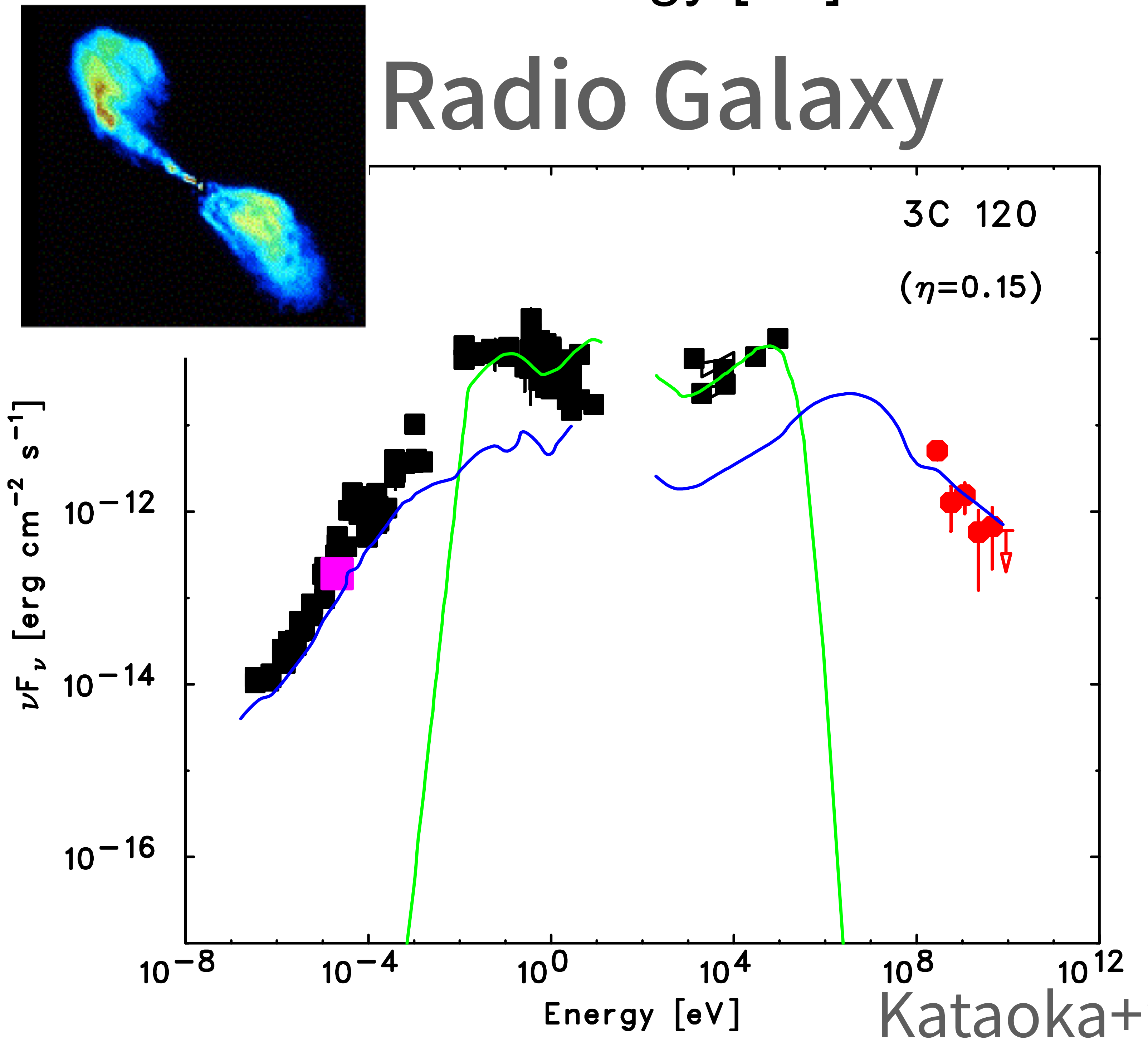
Multi-wavelength spectrum of AGNs

Blazar



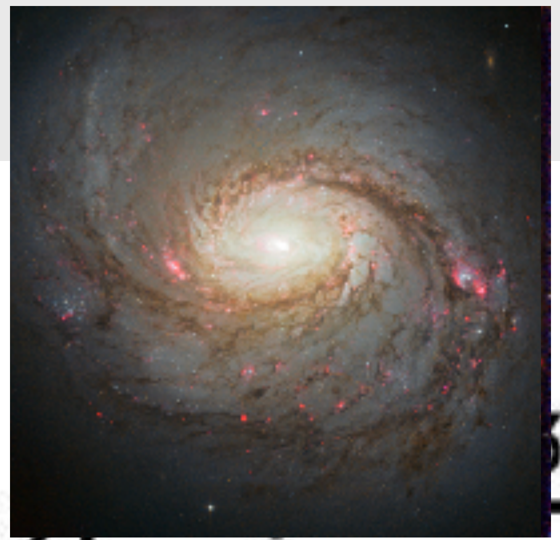
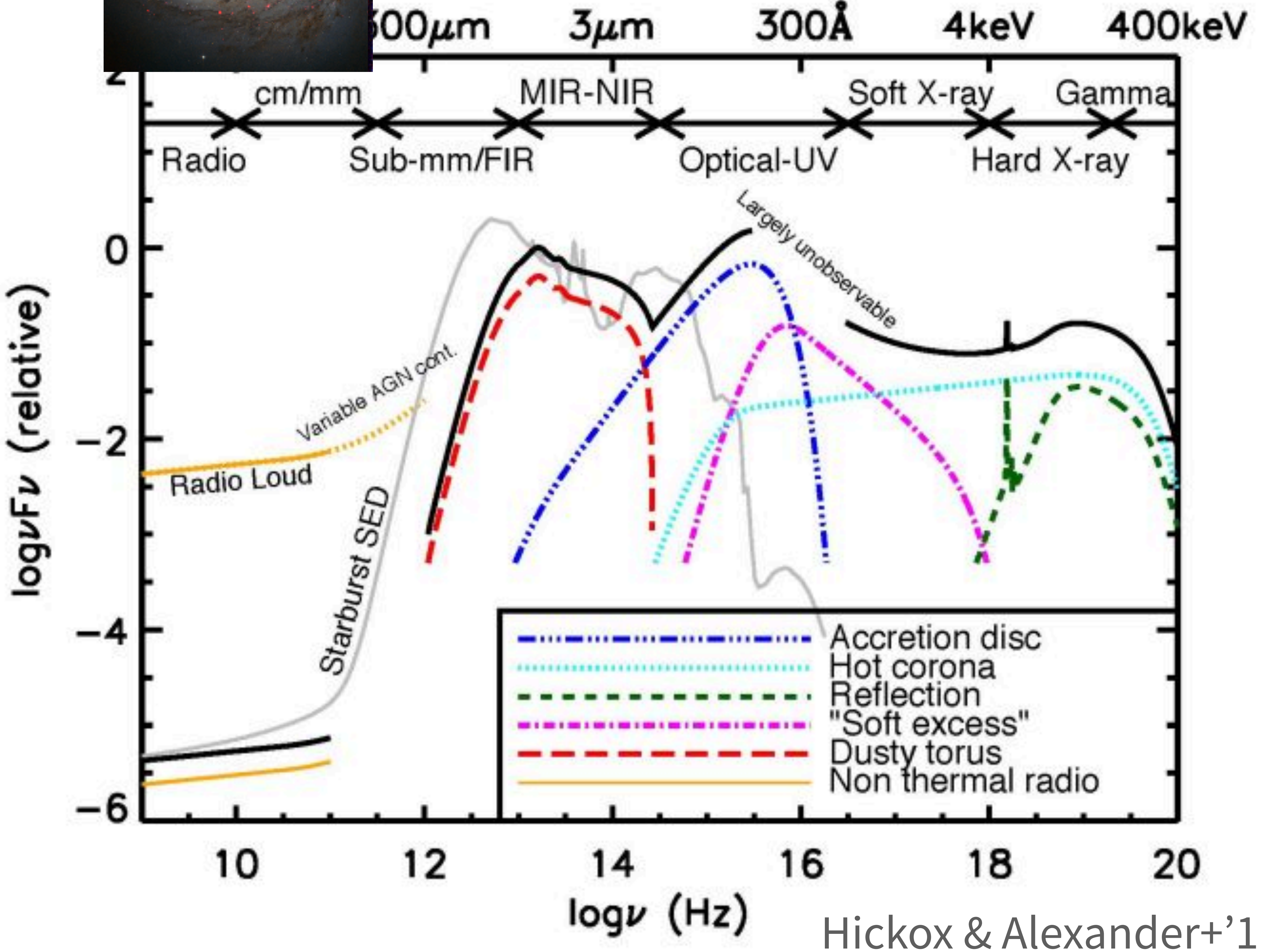
YI & Tanaka '16

Radio Galaxy



Kataoka+'11

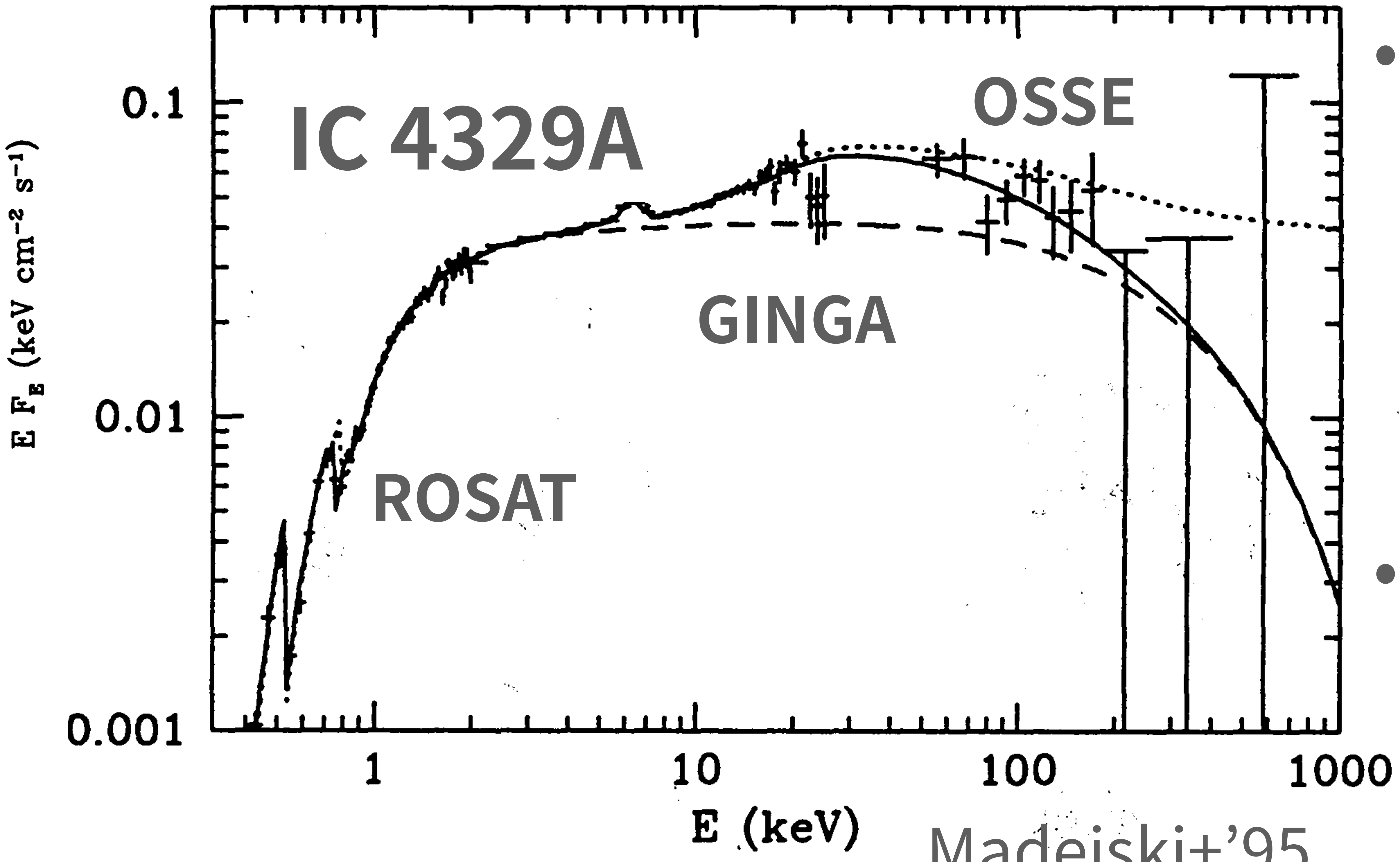
Seyfert/Quasar

Hickox & Alexander+'16

What is the origin of Seyfert X-ray emission?

High-energy non-thermal particles?



Madejski+’95

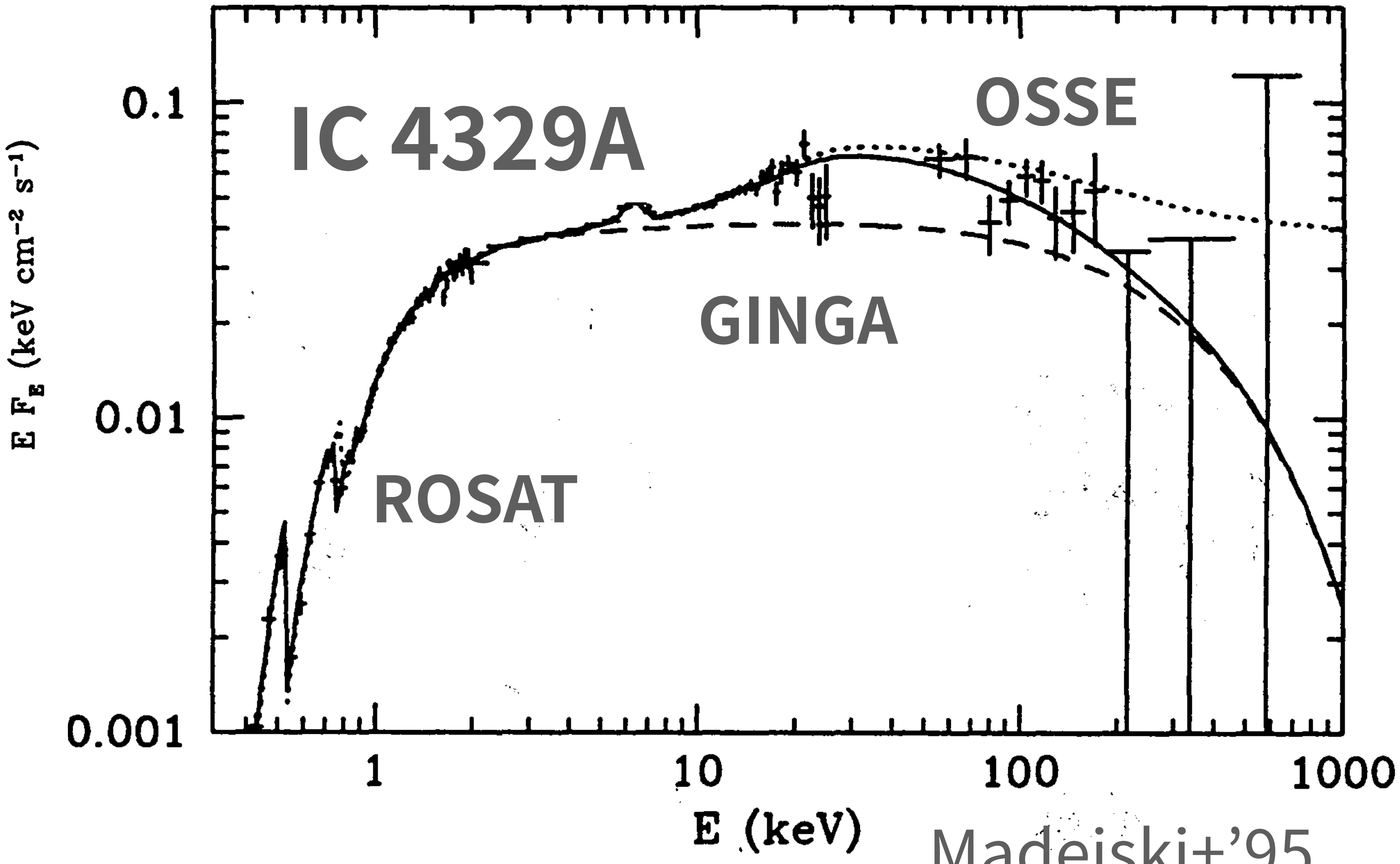
- Gamma-ray cascade for X-ray continuum (e.g., Kazanas & Ellison ’86; Zdziarski ’86)

  ➡Neutrino emission (Stecker+’92)

- But,
  - non-detection of power-law tail (e.g., Madejski+’95; Lin+’93)

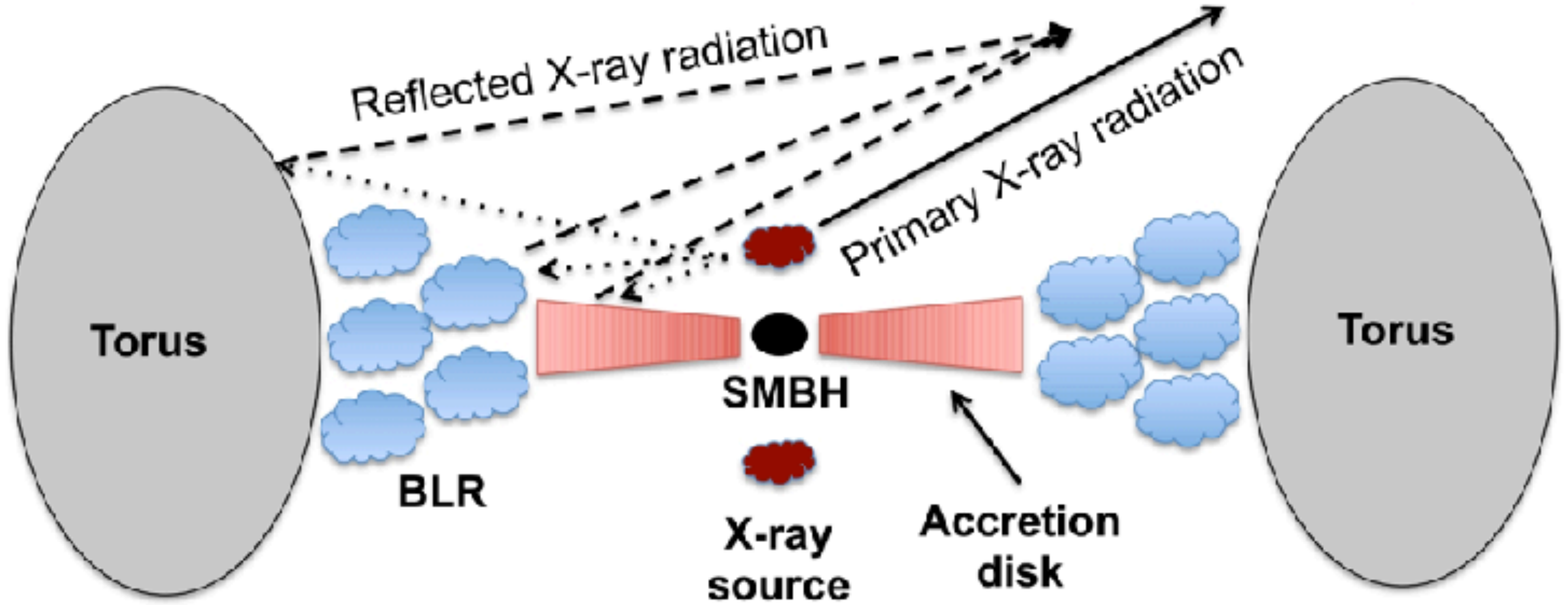
X-ray emission is from black hole corona

100 keV hot plasma above/below accretion disks



Madejski+'95

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



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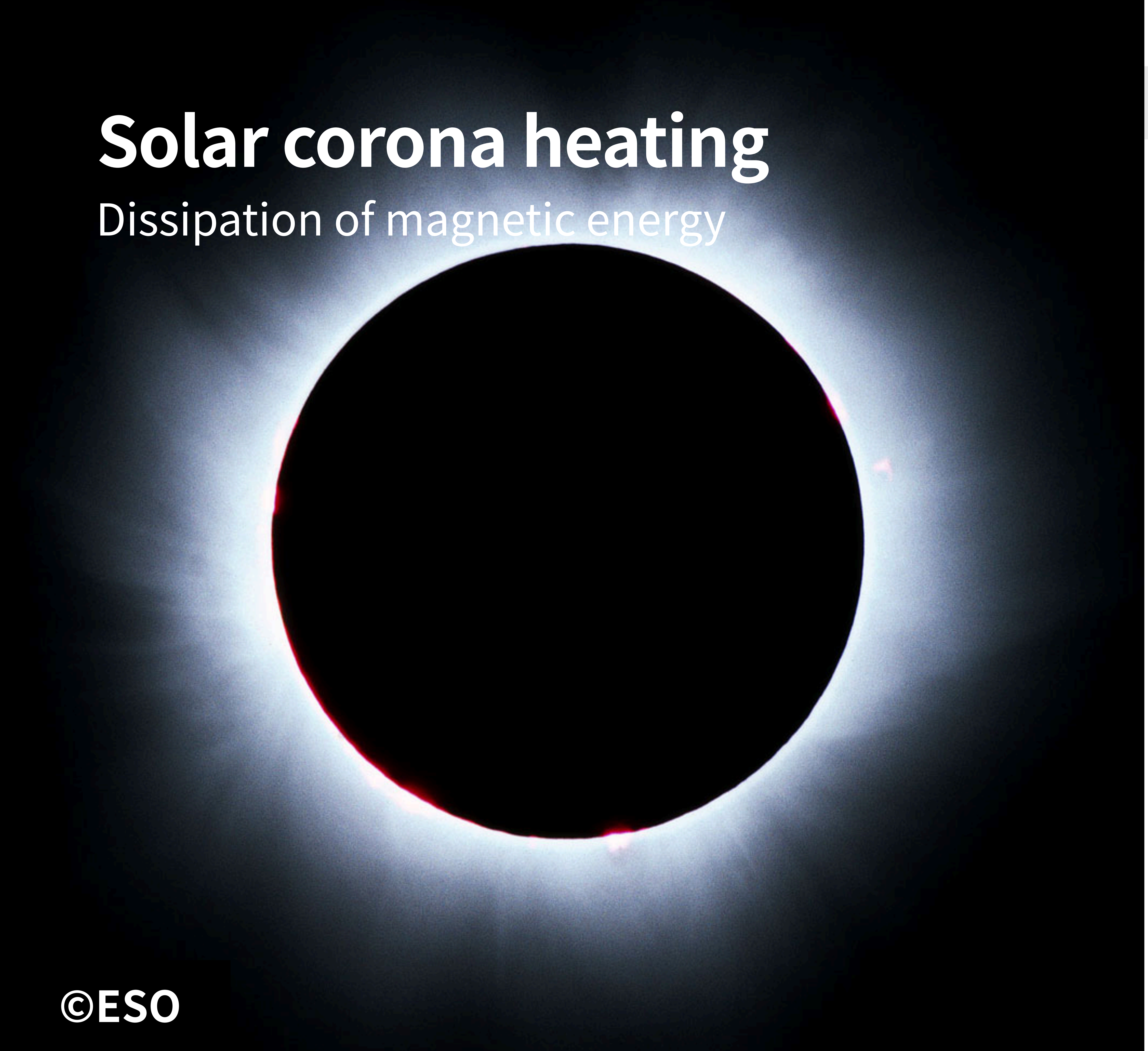
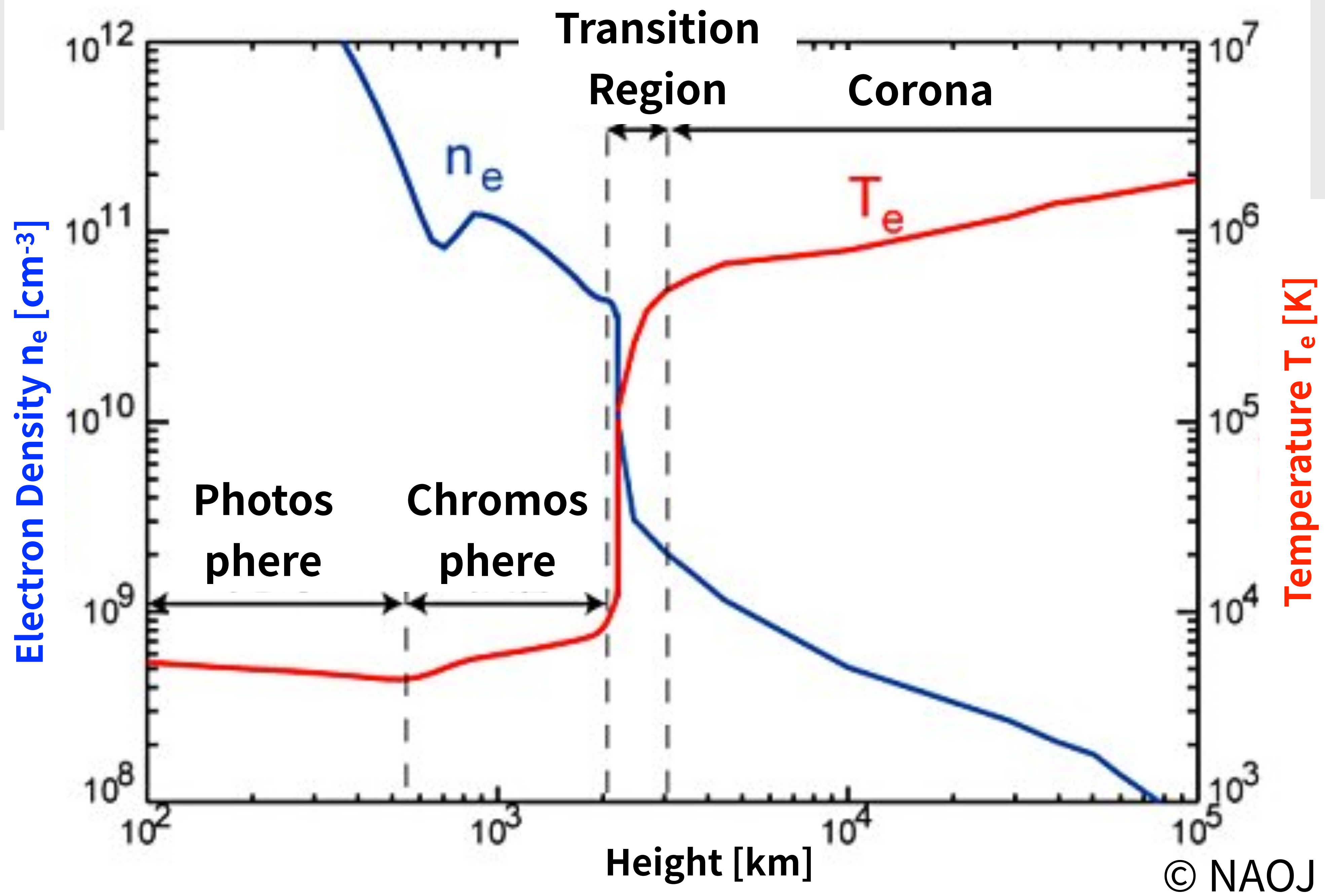
Solar corona heating

Dissipation of magnetic energy



©ESO



- 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

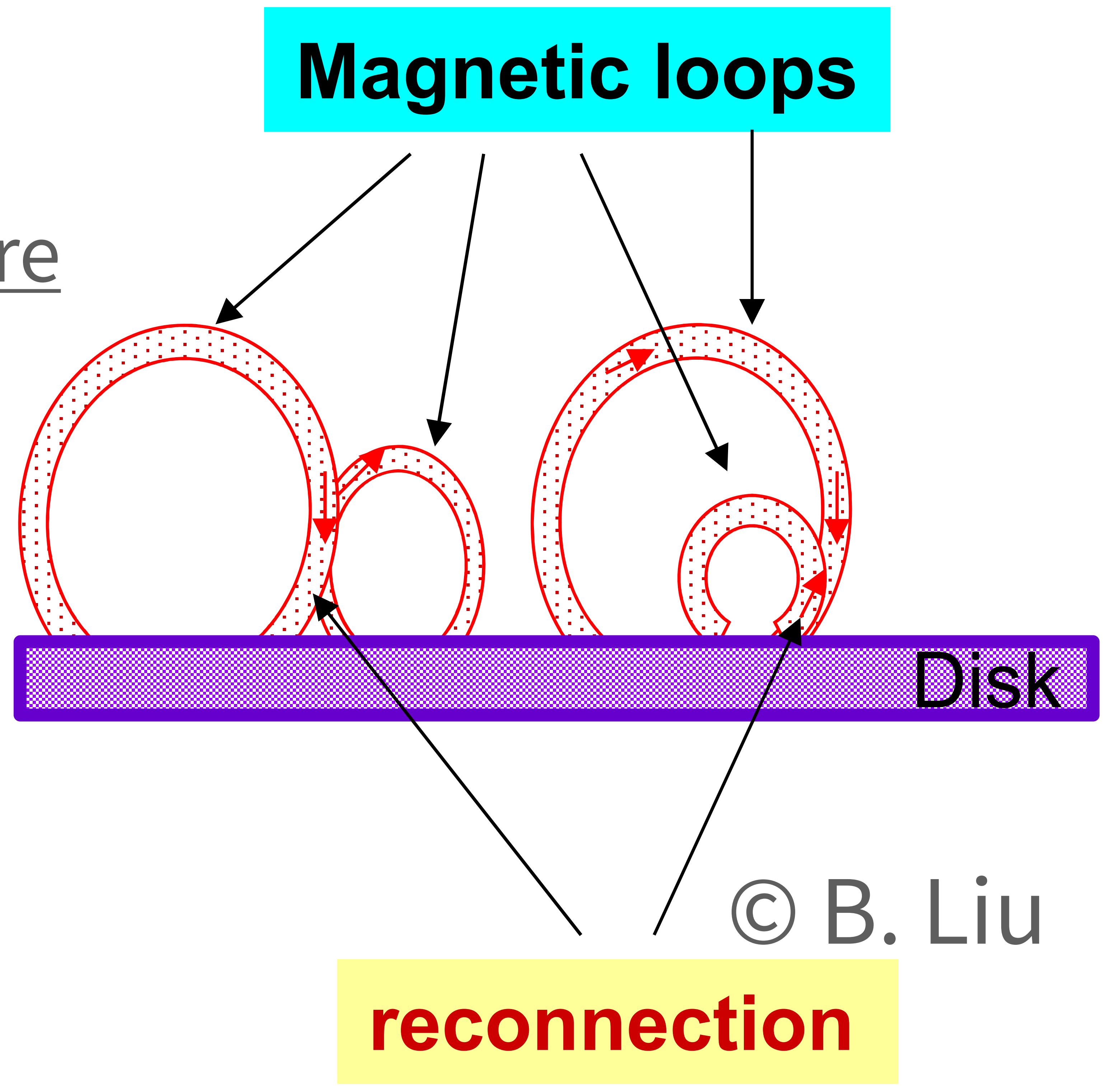
1. Reconnection heating = Compton cooling <u>in corona</u>

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

2. Conduction heating = Evaporation cooling <u>in disk chromosphere</u>

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

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

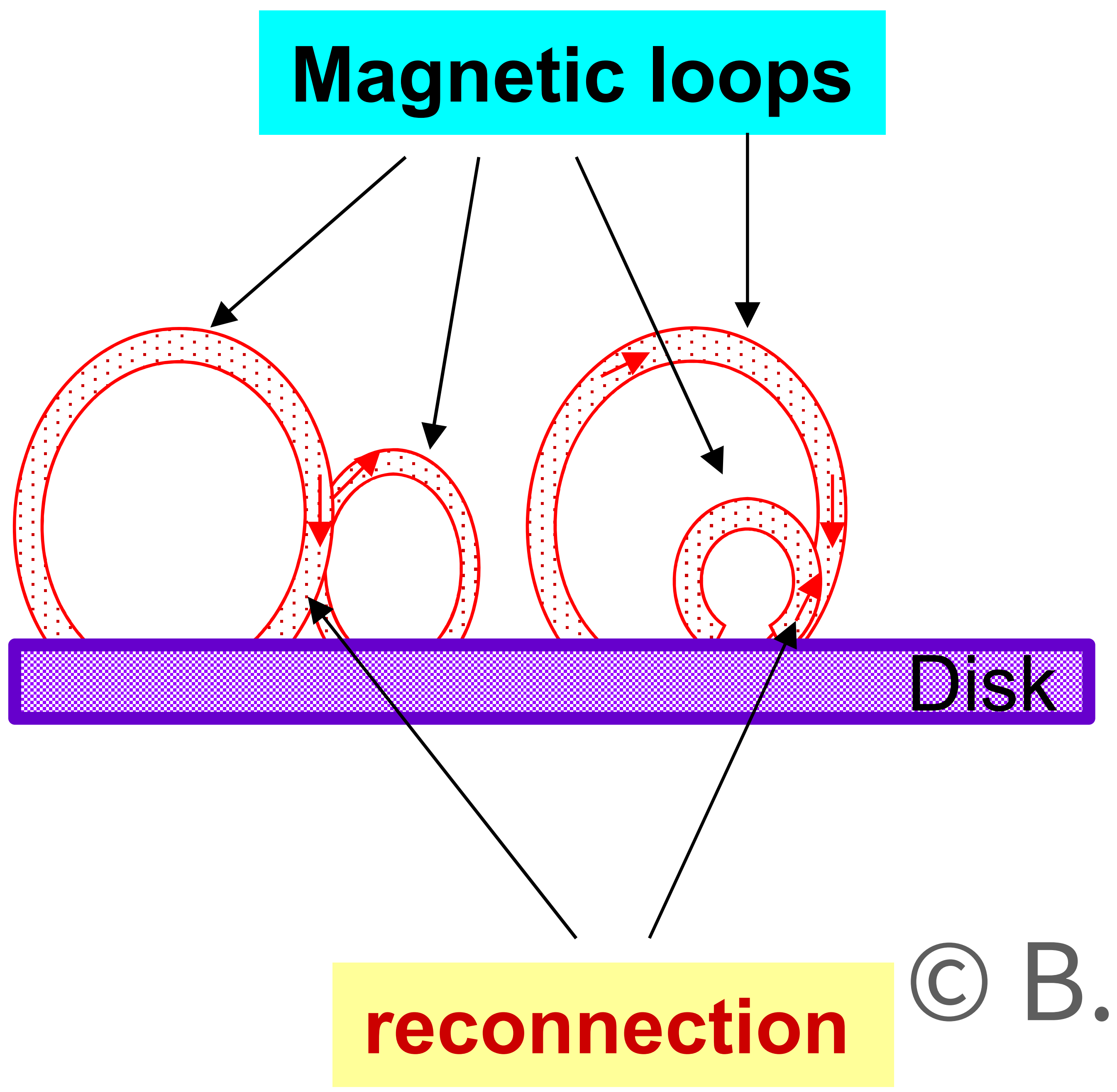


Coronal Magnetic Activity in Seyfert Galaxies

Coronal Synchrotron emission?

Magnetized corona can generate Syn emission

- Hot corona ~ 100 keV
  - Heated by magnetic activity ?
    (e.g., Haardt & Maraschi '91; Liu, Mineshige, & Shibata '02; Beloborodov '17)
- **Millimeter Coronal Synchrotron Emission**
  (Di Matteo+'97; YI & Doi '14; Raginski & Laor '16)
  - Due to Synchrotron self-absorption, we expect a spectral break at 10-1000 GHz (mm-wave).



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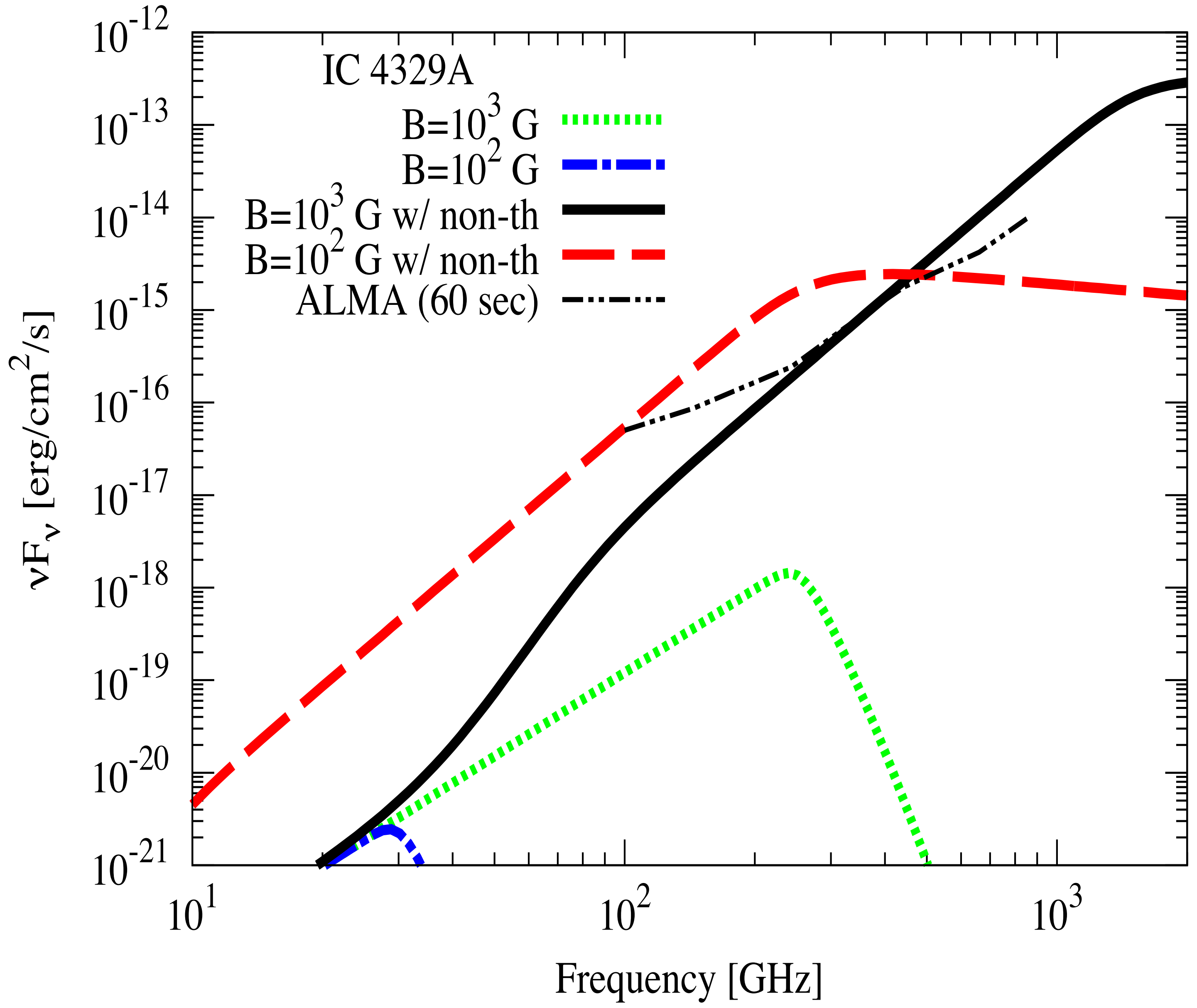
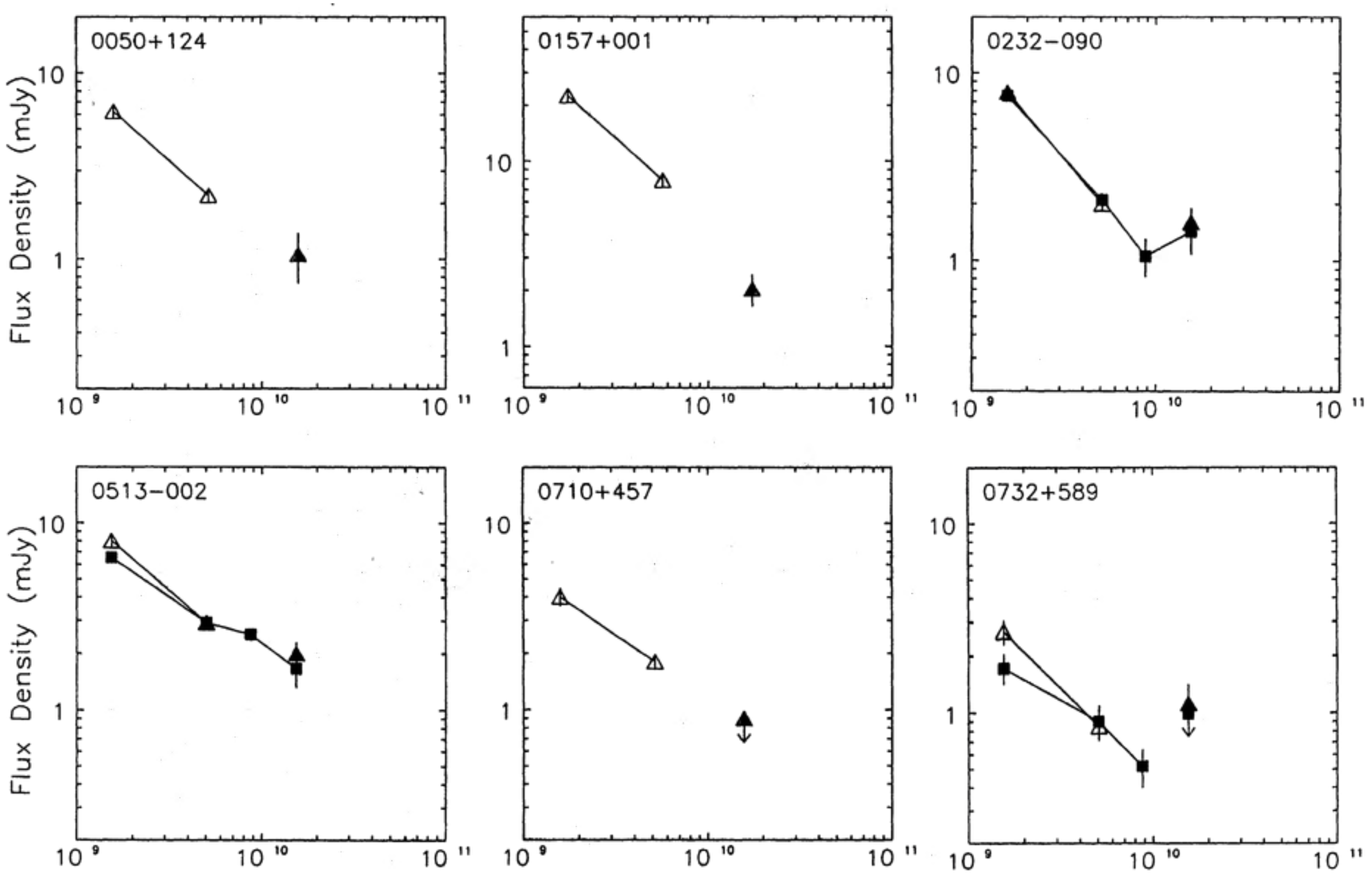


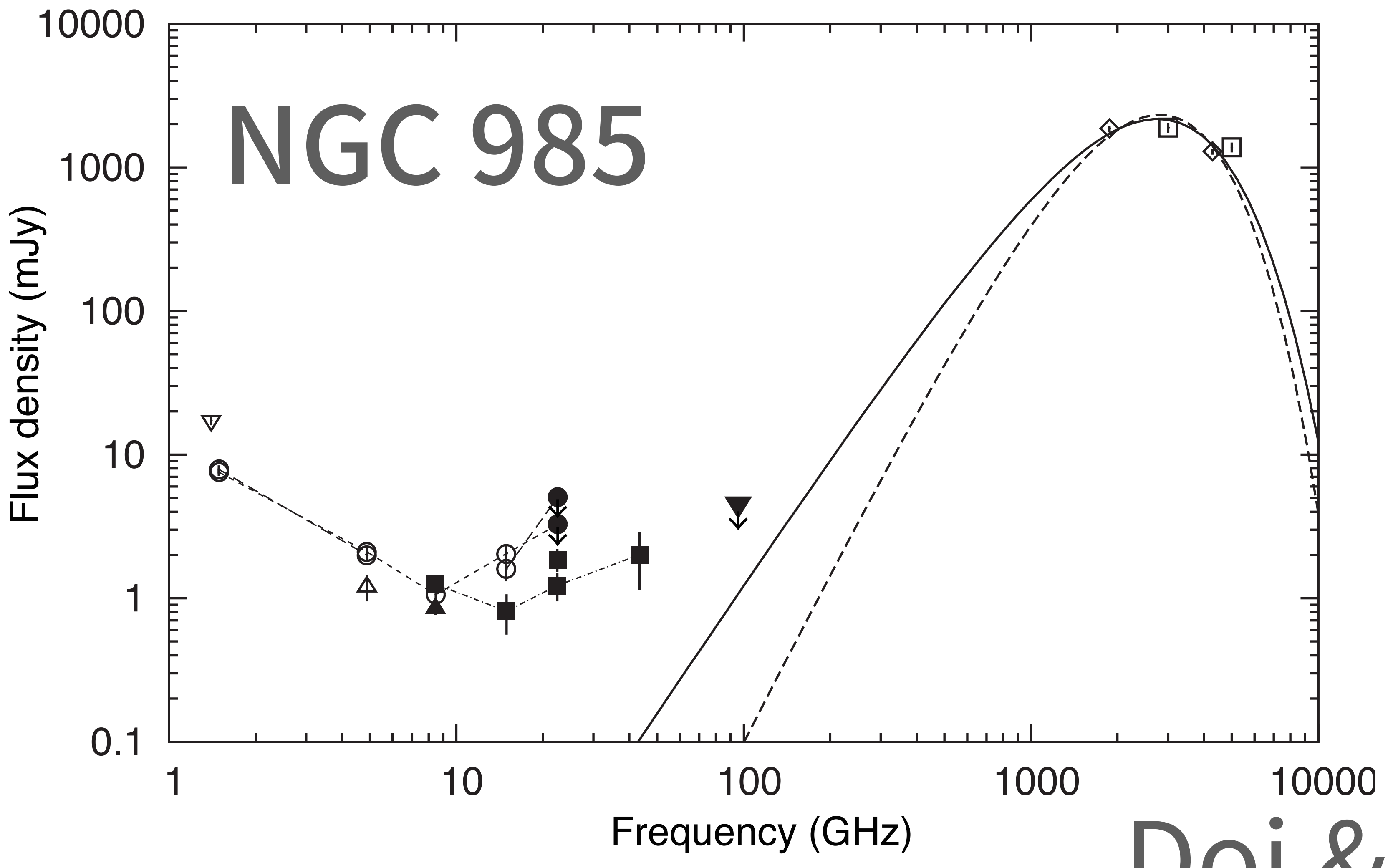
YI & Doi '14

Hints of millimeter excess in nearby Seyferts

A new component in AGN SED? Non-thermal coronal Synchrotron?



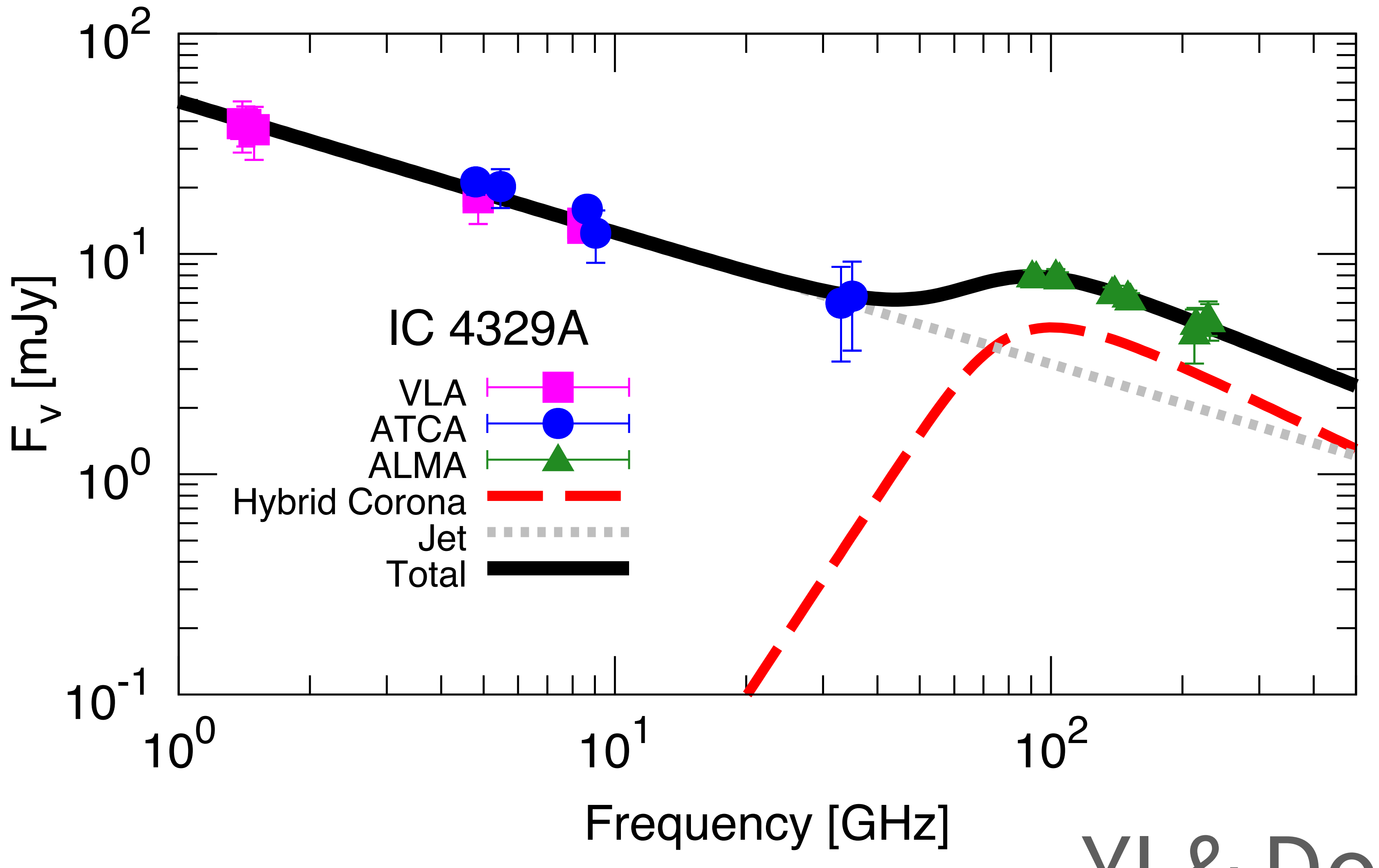
Barvainis+'96



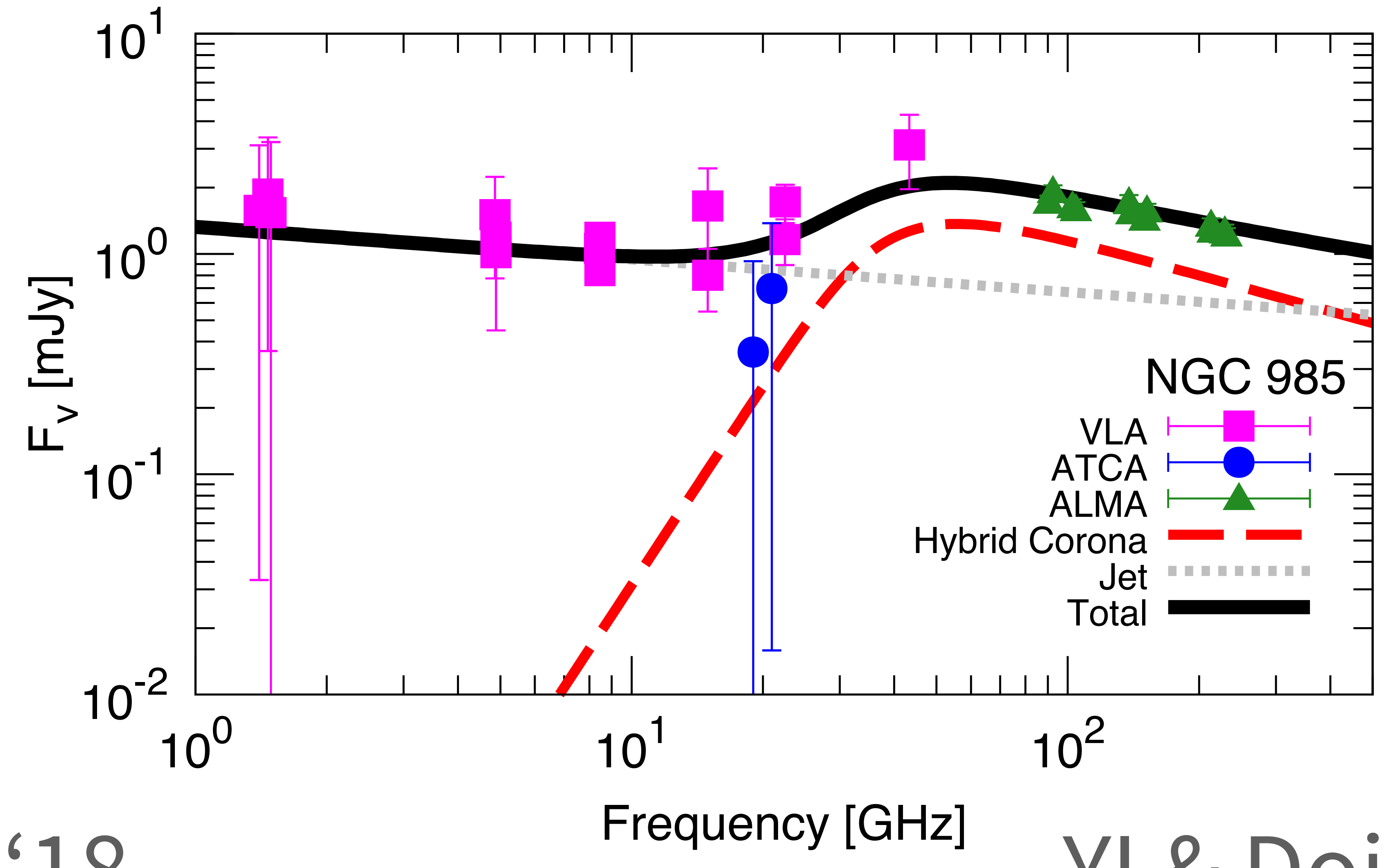
Doi & YI '16

- 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?

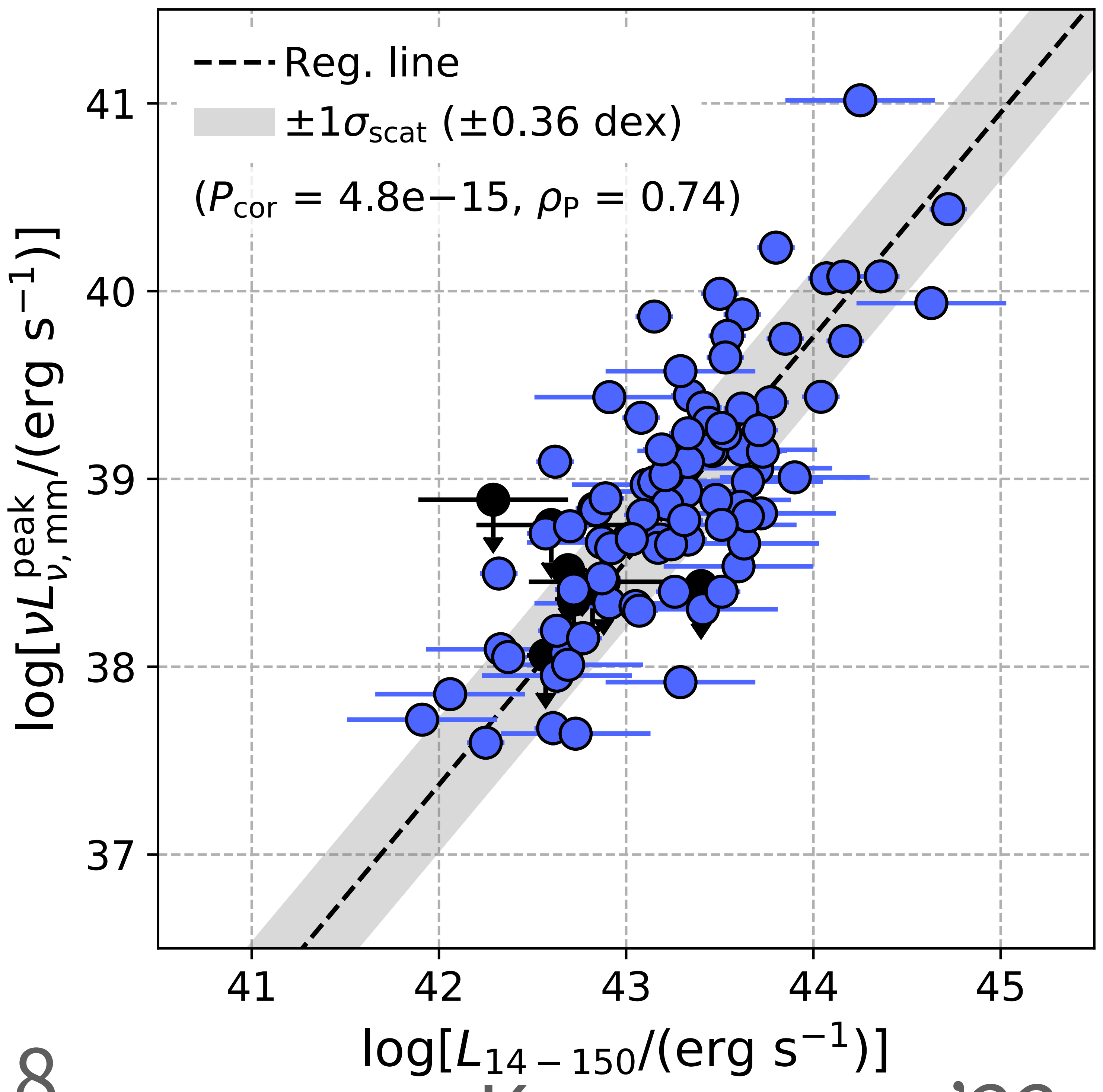
ALMA observations toward nearby Seyferts



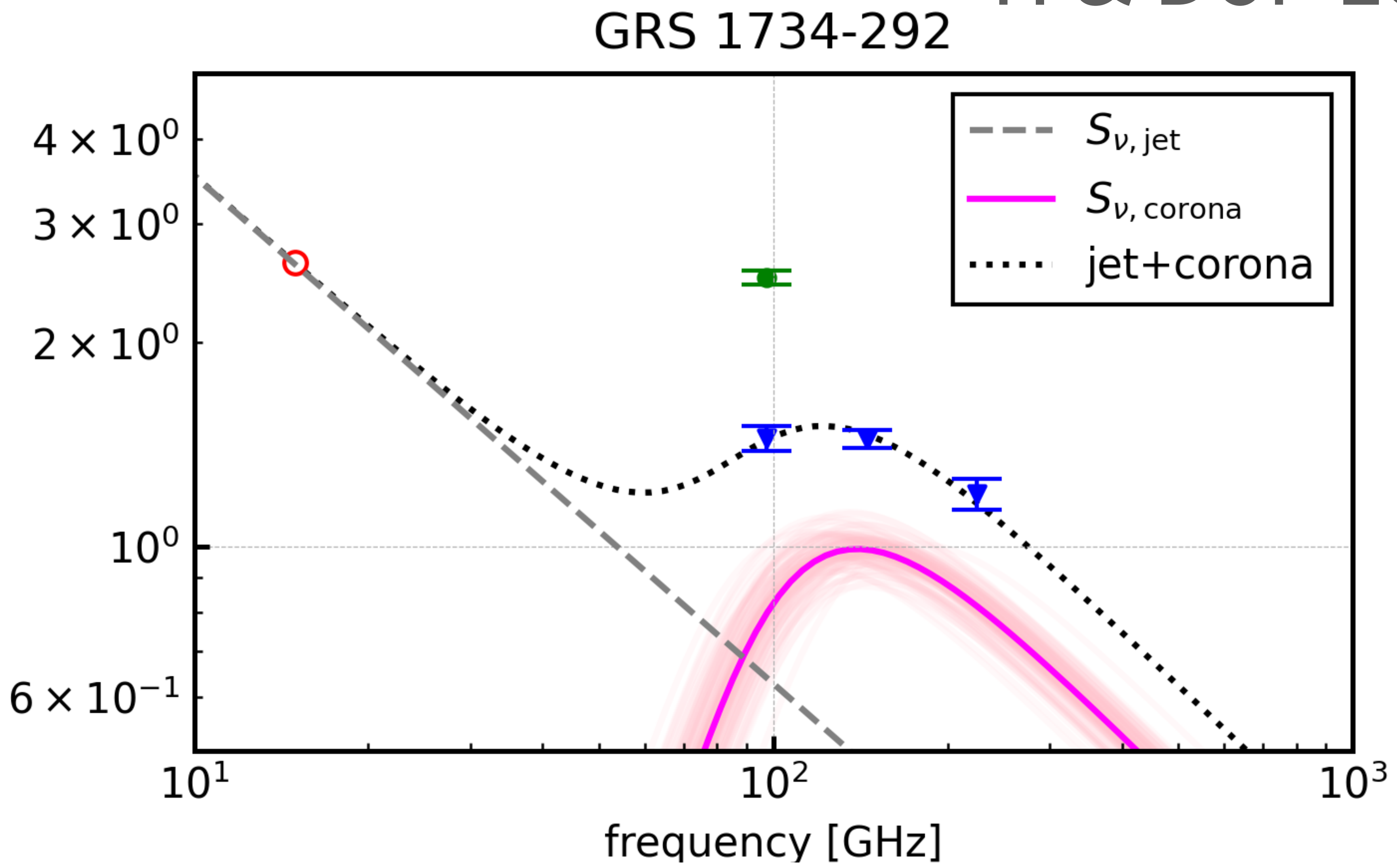
YI & Doi '18



YI & Doi '18



Kawamuro+'22



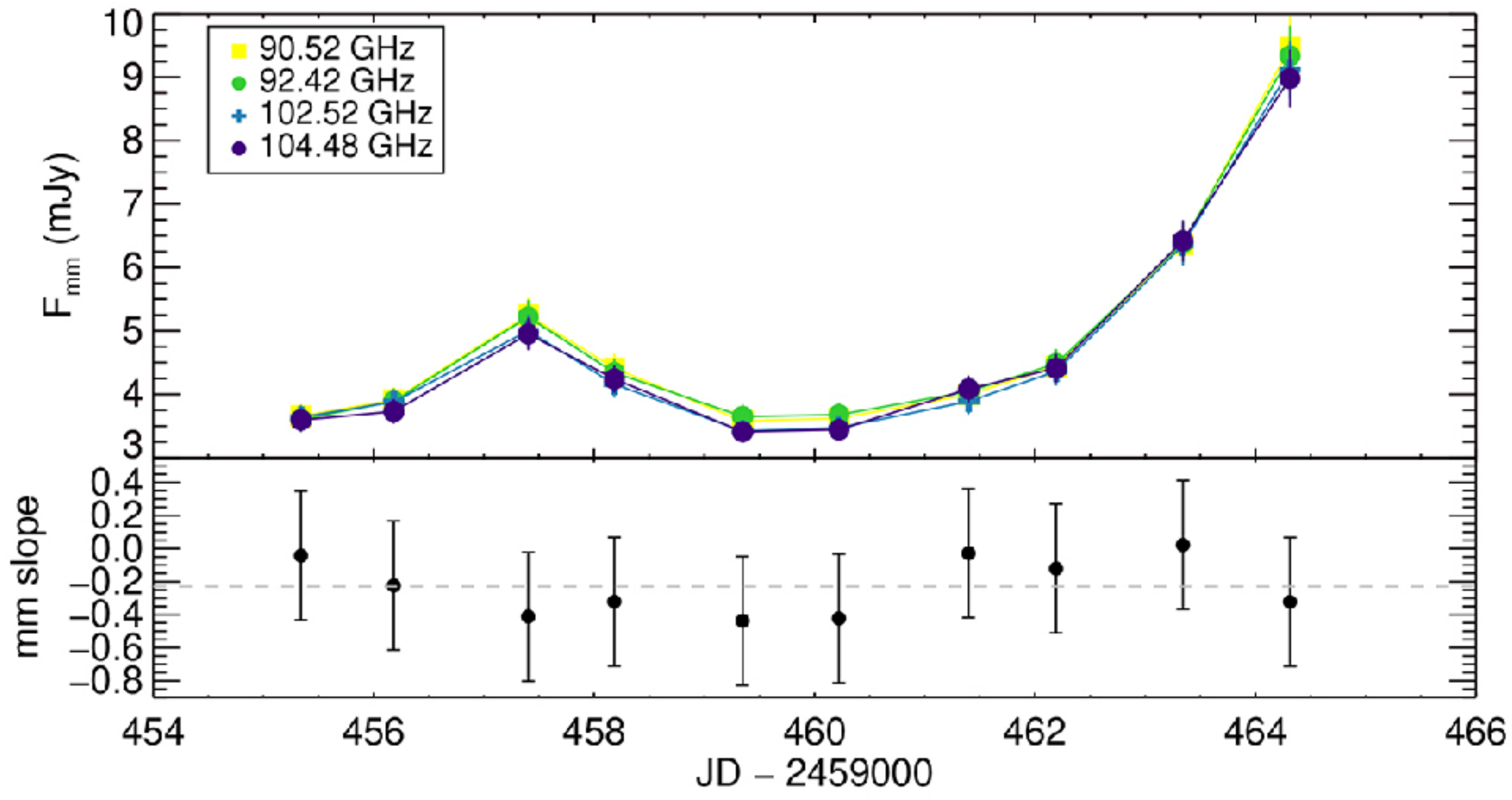
Michiyama, YI, '24

- **Clear excess w/ PL tail in nearby Seyferts**
  (YI & Doi '18; YI, Khangulyan, & Doi '20; Kawamuro+'22; Michiyama, YI, +'23)
- Flux ~ 1-10 mJy peaking @ a few tens GHz
- Time variability <4 days
  (Michiyama, YI '24; Shablovinskaia+'24; Jana, YI '25; Barnier, YI +in prep.)
- Correlation b/w mm and X-ray luminosities (Kawamuro+'22; Ricci+'23)
- Unresolved by ALMA → Size : < 10 pc → Nucleus

Day to Year time variability in the mm excess

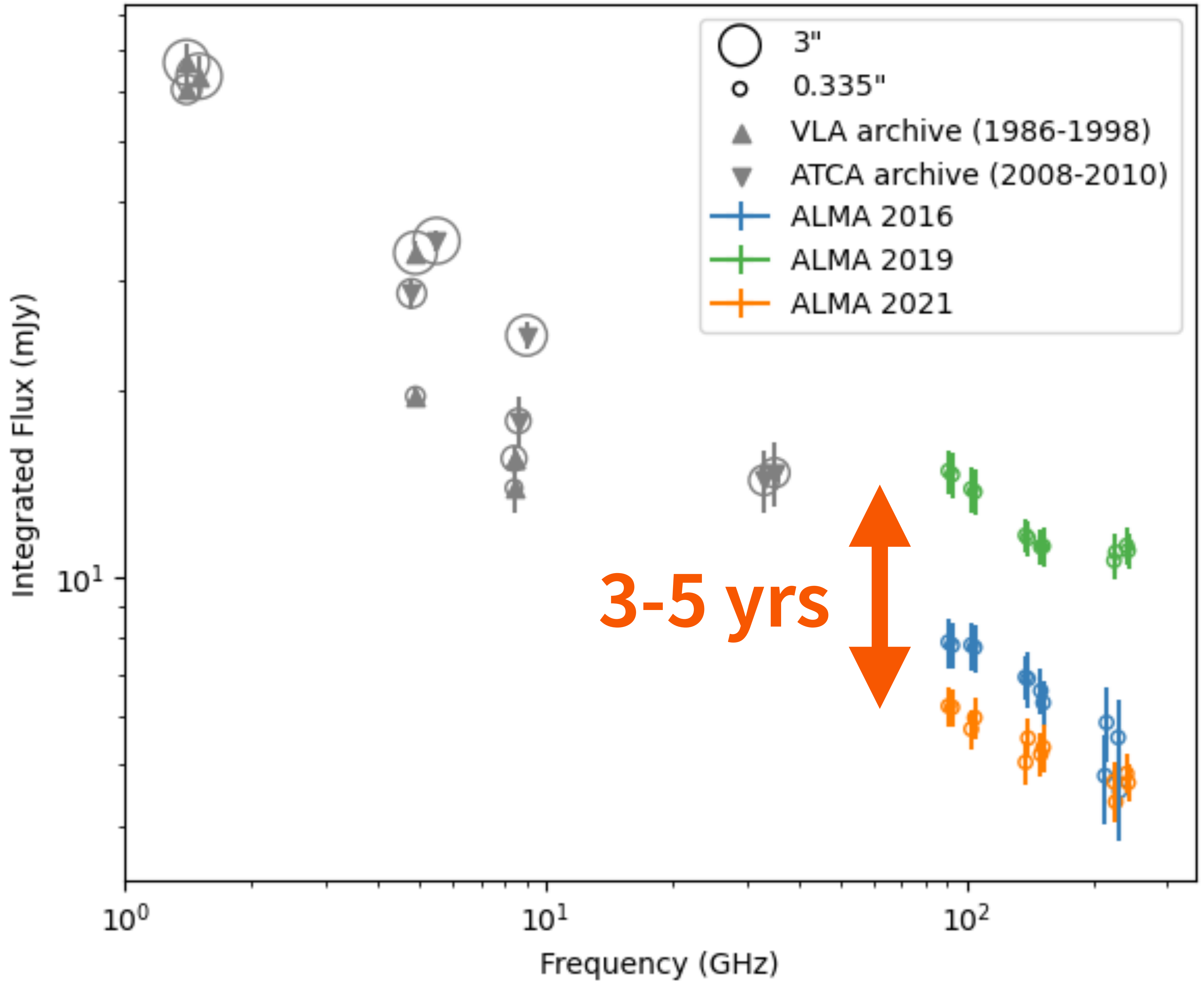
Origin should be small regions

IC 4329A



Shablovinskaia+'24

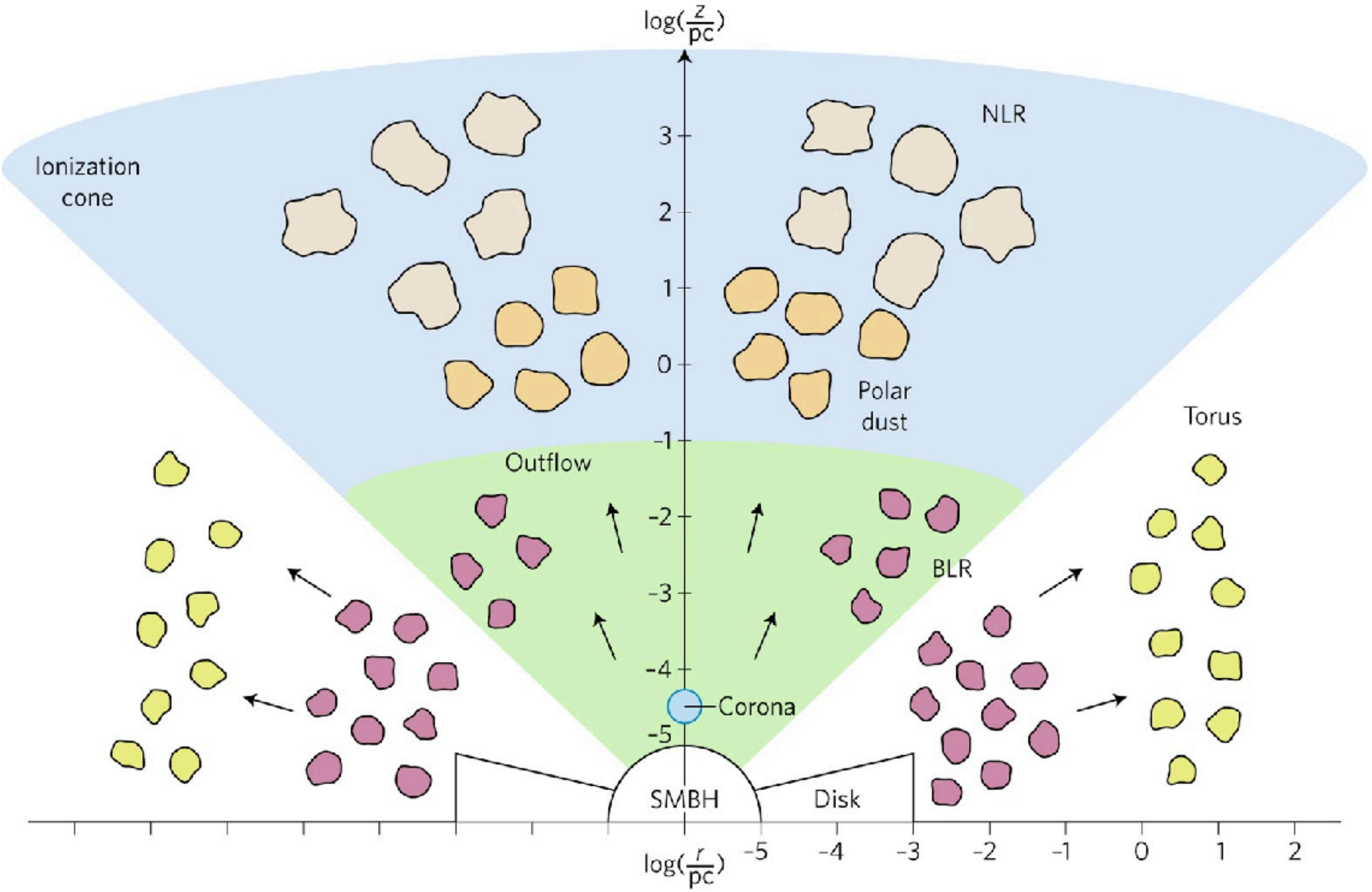
IC 4329A



Barnier, YI, + in prep.

Where is the origin of the mm excess?

Structure of AGN core in the <10 pc scale

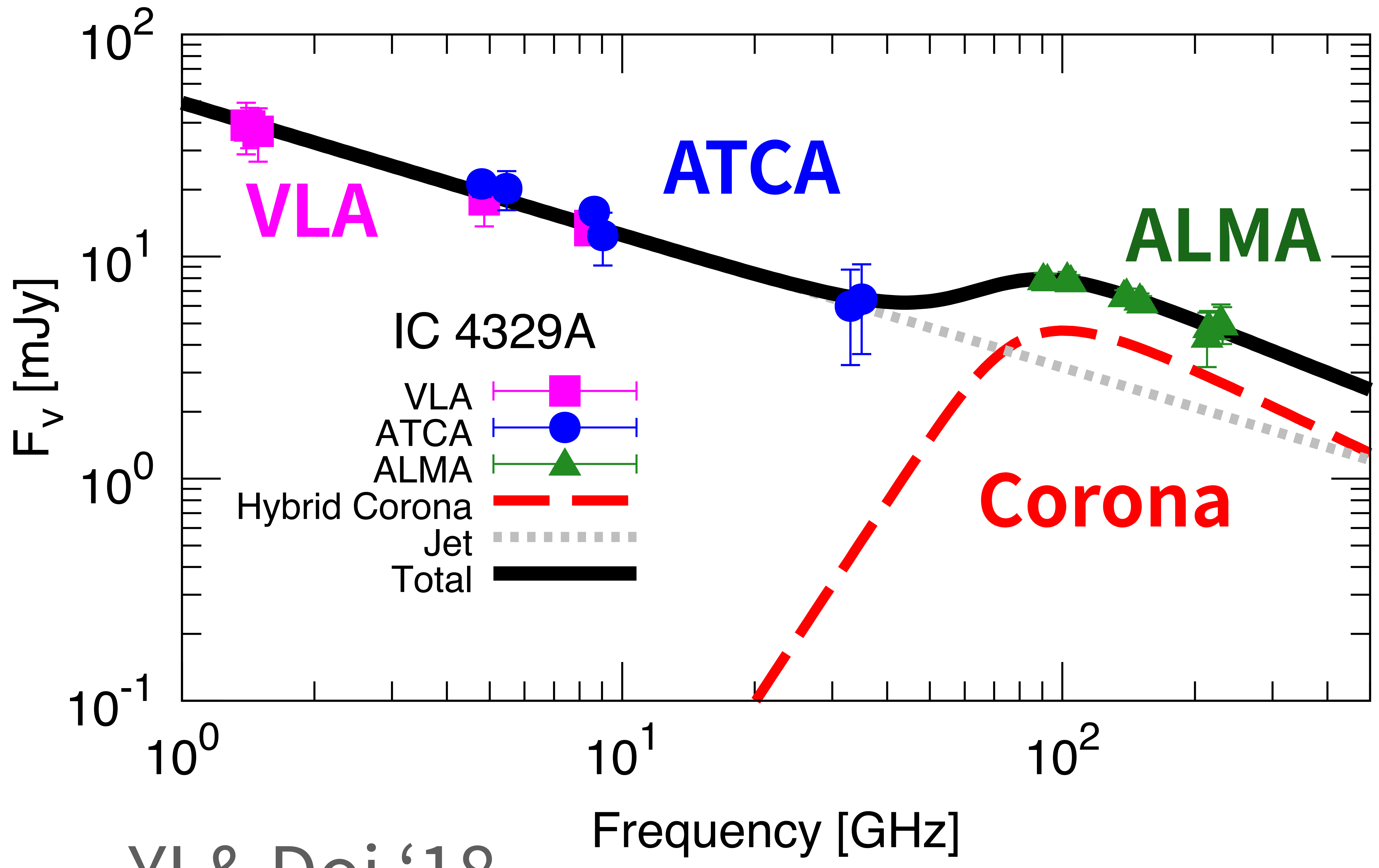


Ramos-Almeida & Ricci ‘17

- Dust torus?
  - spectral shape, not enough, variability
- Free-free?
  - spectral shape, not enough
- Jet?
  - radio-quiet
- Wind (Henkla+'25)?
  - day-scale or shorter variability probably difficult (see also Yamada, Sakai, YI, & Michiyama '24)
- **Corona**

cm-mm spectrum of AGN core

Corona can explain the mm excess



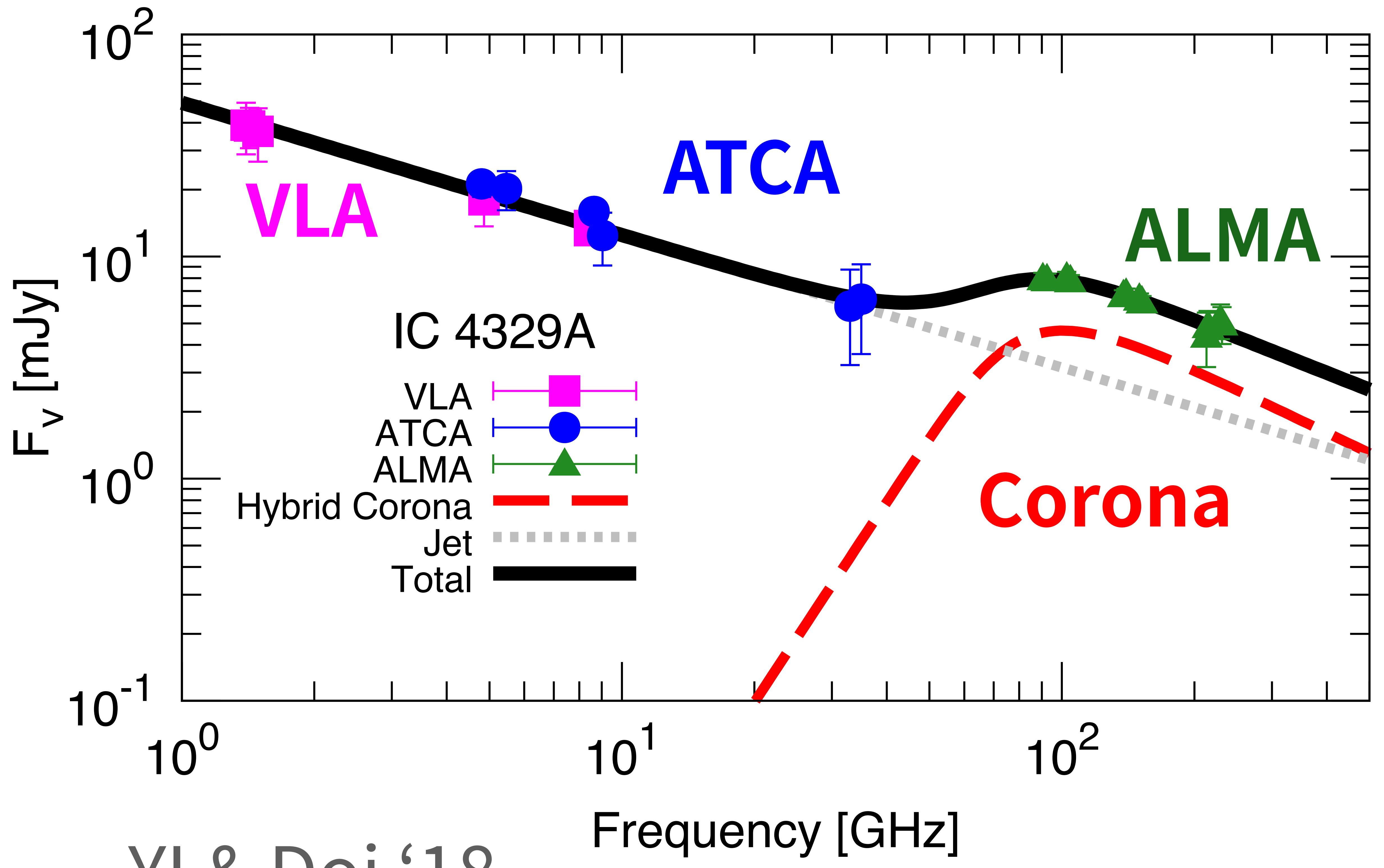
YI & Doi ‘18

- 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 electron index: 2.9
- Size: 40 r_s
- B-field strength : 10 G

Coronal Magnetic Field?

cm-mm spectrum of AGN core

Weak Magnetic Field



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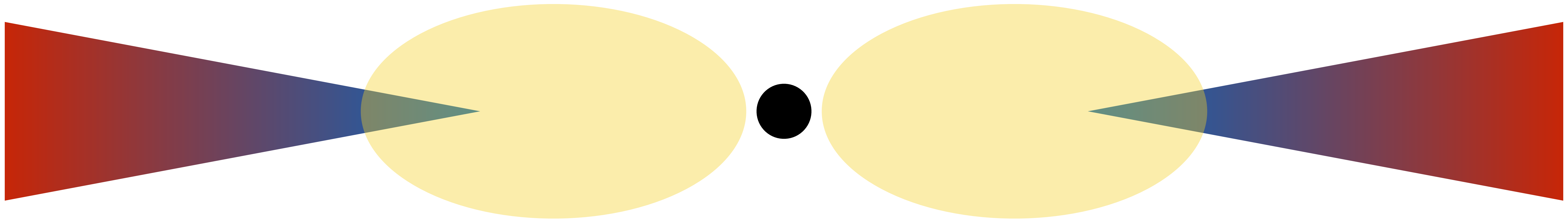
- Non-thermal electron index: 2.9
- Size: 40 r_s
- **B-field strength : 10 G** (see also Shablovinskaya+'24)

Can we heat up corona by magnetic activity?

Implication for the truncated accretion disk structure

- Heating vs Cooling
  - Magnetic Heating: $B^2 V_A / 4\pi$
    - $Q_{B,\text{ heat}} \sim 10^{10}$ erg/cm^2/s
  - Compton Cooling: $4kTn_e\sigma_T c U_{\text{rad}} l / m_e c^2$
    - $Q_{IC,\text{ cool}} \sim 10^{13}$ erg/cm^2/s
  - **Magnetic field energy is NOT sufficient to keep coronae hot.**

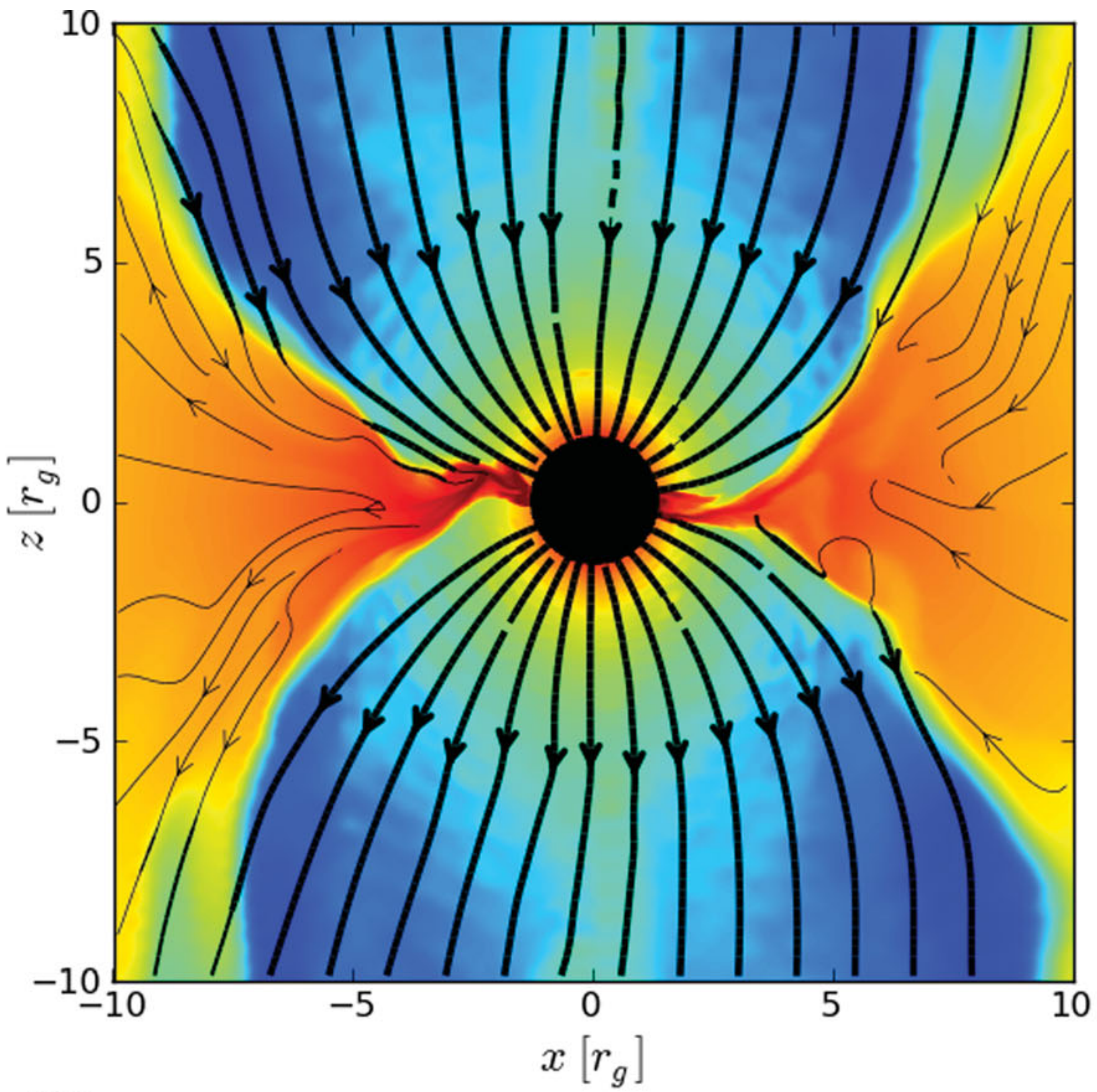
- Disk truncation at some radii (e.g. ~40 r_s)
  - The inner part = hot accretion flow (Ichimaru '77, Narayan & Yi '94, '95).
    - **Advection Dominated Corona?**
    - We can expect $kT_e \sim 86\ \text{keV}\ (\tau_T/1.1)^{2/5}$ (YI+'19)
  - Suggested for Galactic X-ray binaries. (e.g. Poutanen+'97; Kawabata+'10; Yamada+'13).



Plasma beta is too high? (too low magnetic field?)

Are weak-jet AGNs MAD or not MAD?

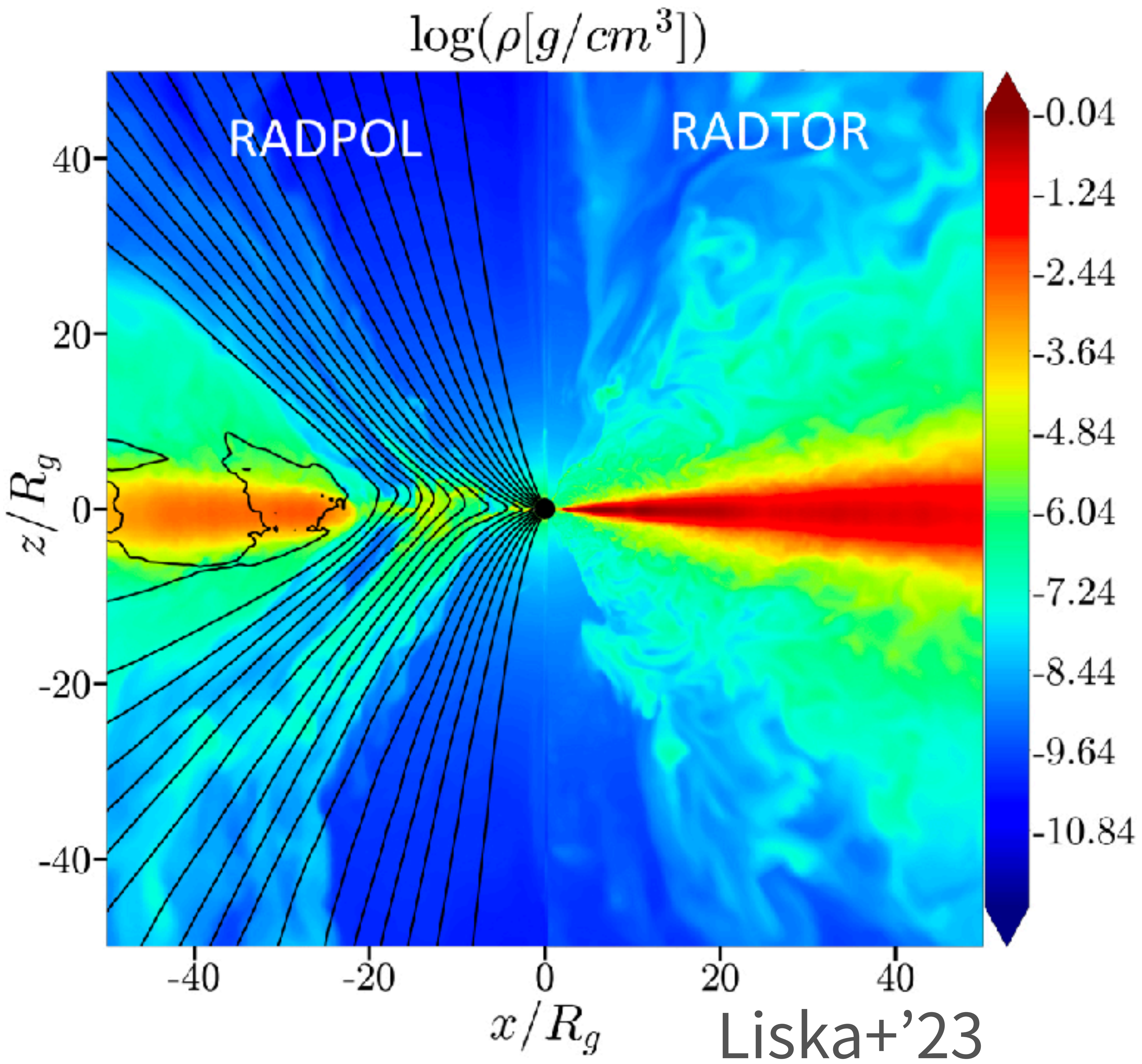
- Our ALMA analysis suggests
  - coronal B-field is ~10-30 G at 30 r_S.
  - **In terms of plasma beta ($\beta \equiv p_{\rm gas}/p_{\rm mag}$), we have $\beta \sim 100$.**
  - Gas pressure dominates the accretion dynamics.
- However, GRMHD simulations suggest $\beta \ll 1$ for some cases (e.g., McKinney+'12; Tchekhovskoy+'11; Liska+'23)
  - so-called magnetically arrested disk (MAD; Narayan'03)



McKinney et al. '12

We are observing AGNs without powerful jets

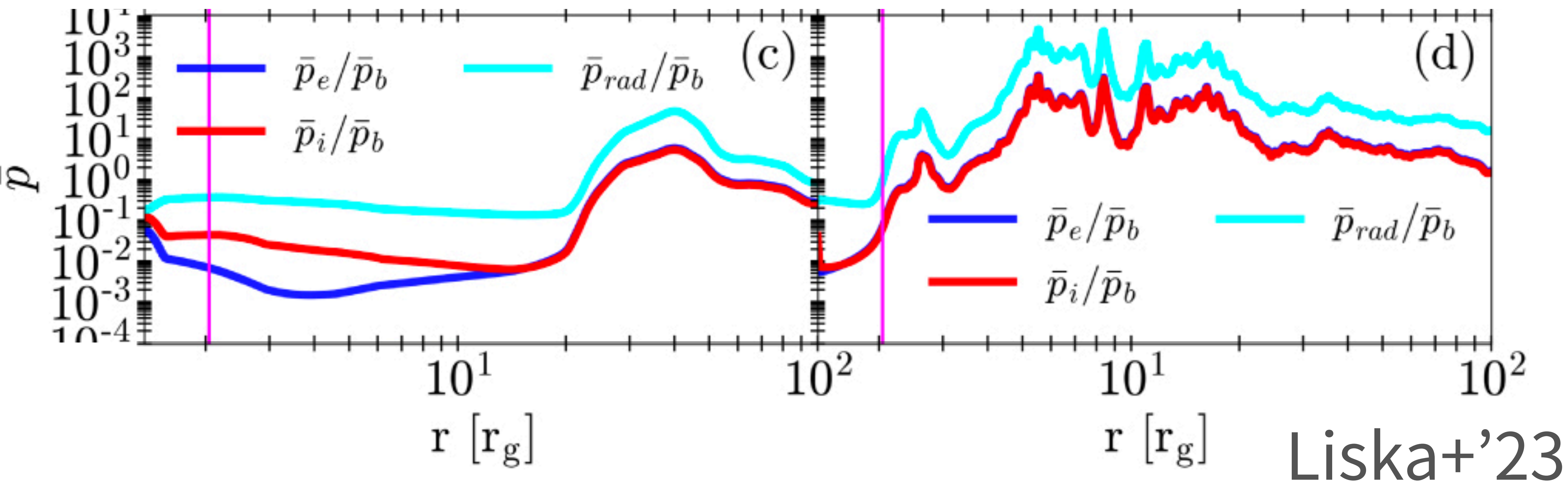
MAD is needed for powerful jet production



Liska+'23

Poloidal

Toroidal



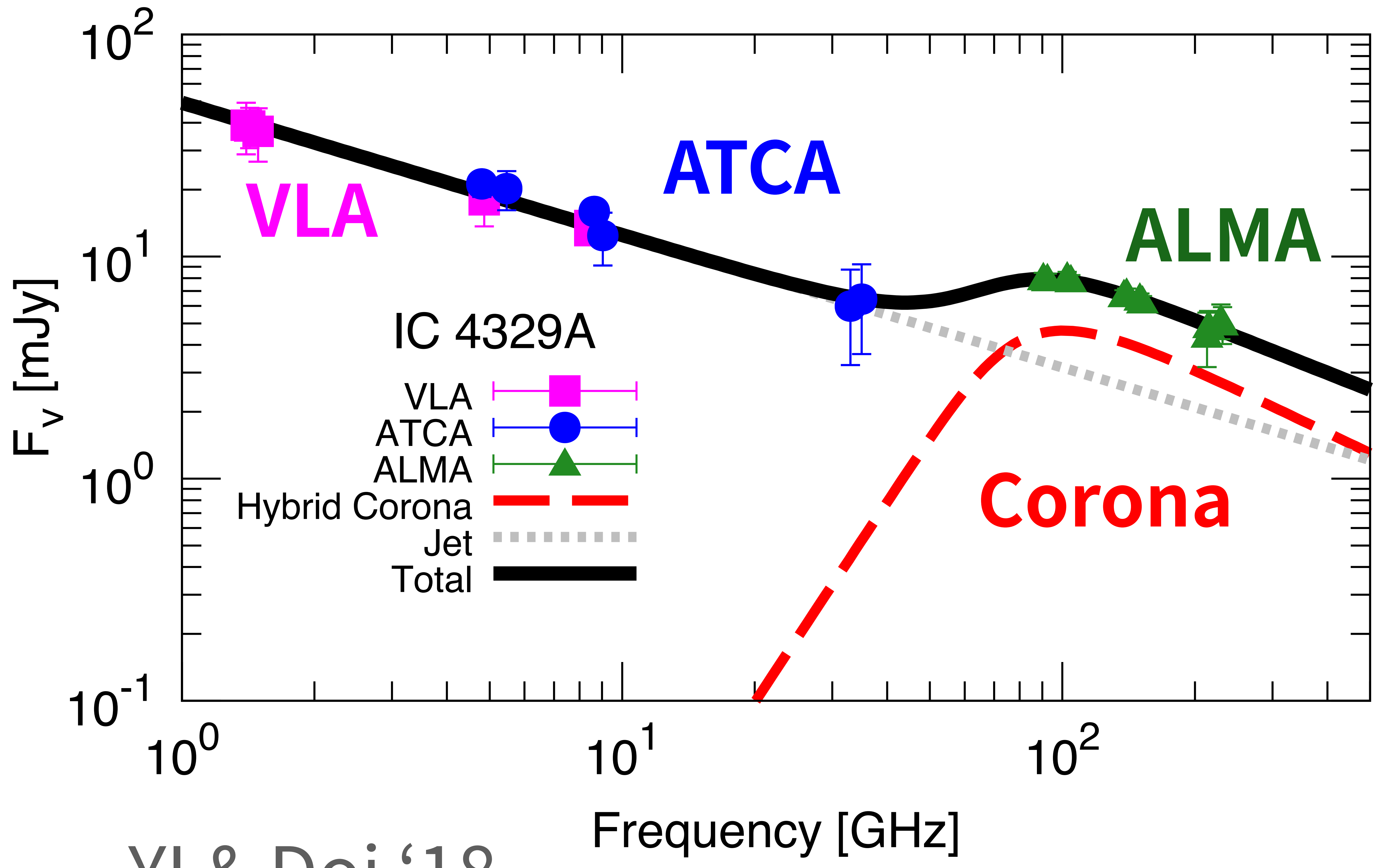
Liska+'23

- MAD is achieved when strong large-scale poloidal magnetic field exists.
  - Otherwise, Parker instability would regulate $\beta \sim 10 - 100$ (e.g., Takasao+'18; Liska+'23)
  - **Coronal magnetic field may strongly depend on initial magnetic field configuration.**

Non-thermal Coronal Magnetic Activity in Seyfert Galaxies

cm-mm spectrum of AGN core

Power-law mm spectrum : Evidence of non-thermal coronal activity



YI & Doi '18

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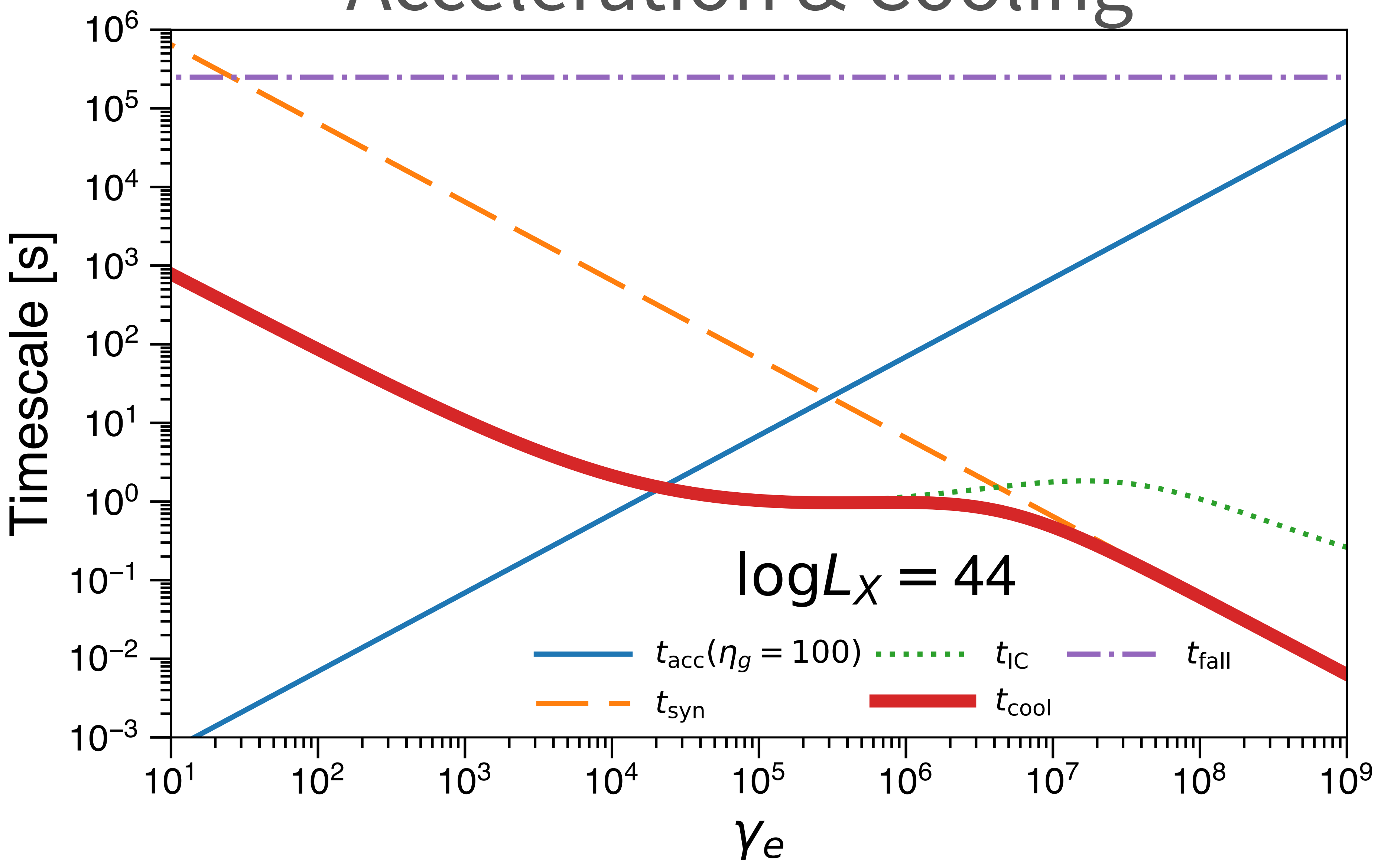
  (YI & Doi '14)
- Non-thermal electron fraction: 0.03 (fixed)
  - Consistent with the MeV gamma-ray background spectrum
    (YI, Totani, & Ueda '08; YI+'19)
- **Non-thermal electron index: 2.9**
- Size: 40 r_s
- B-field strength : 10 G

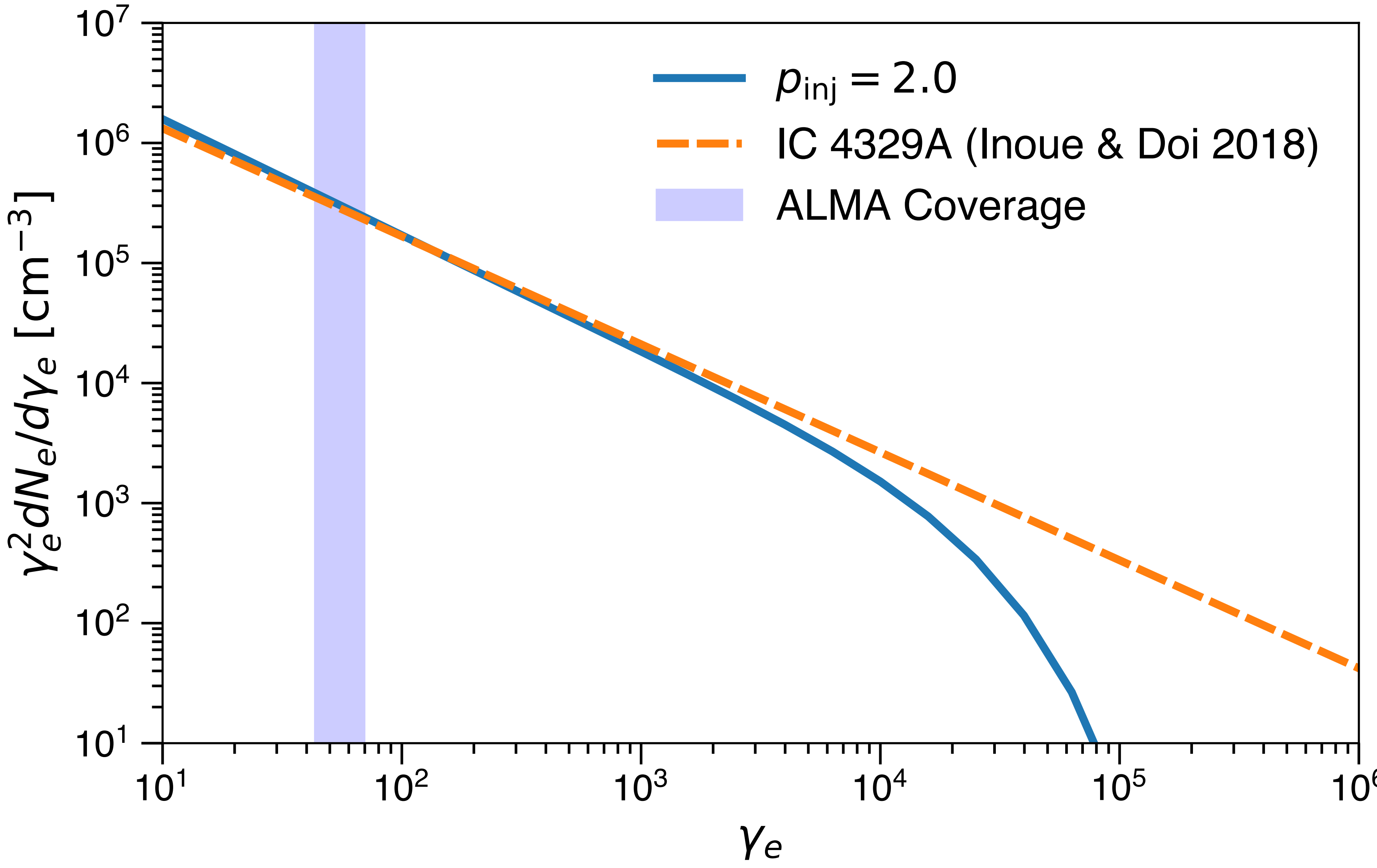
Generation of non-thermal electrons in coronae

- Required CR injection index : ~2
  - 1st-order Fermi acceleration would explain the observed electrons
  - Other mechanisms may be difficult.
    - Because of low magnetic field.
- What is the acceleration mechanism?

Acceleration & Cooling



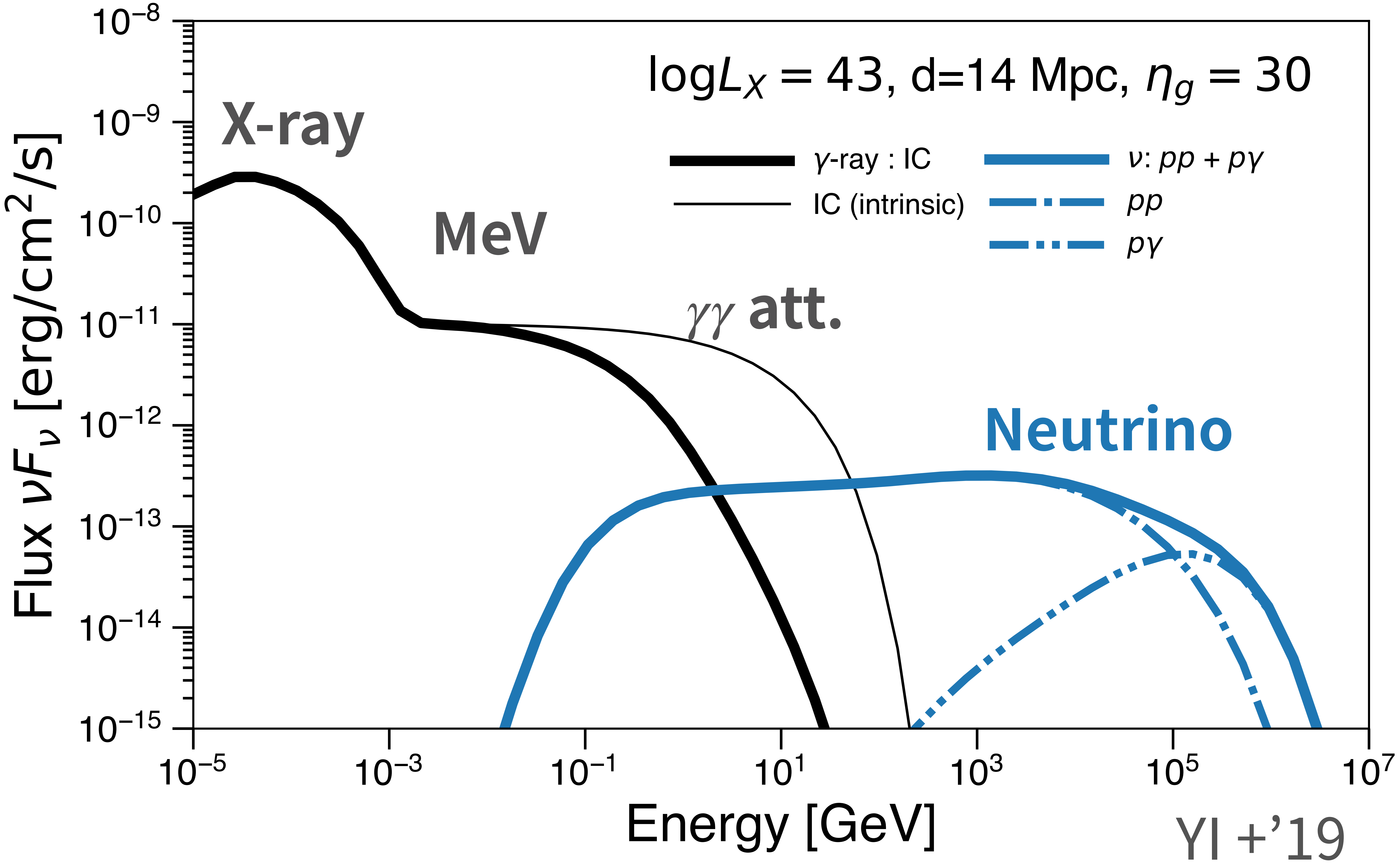
Electron Spectrum



YI + '19

High energy emission from AGN coronae

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



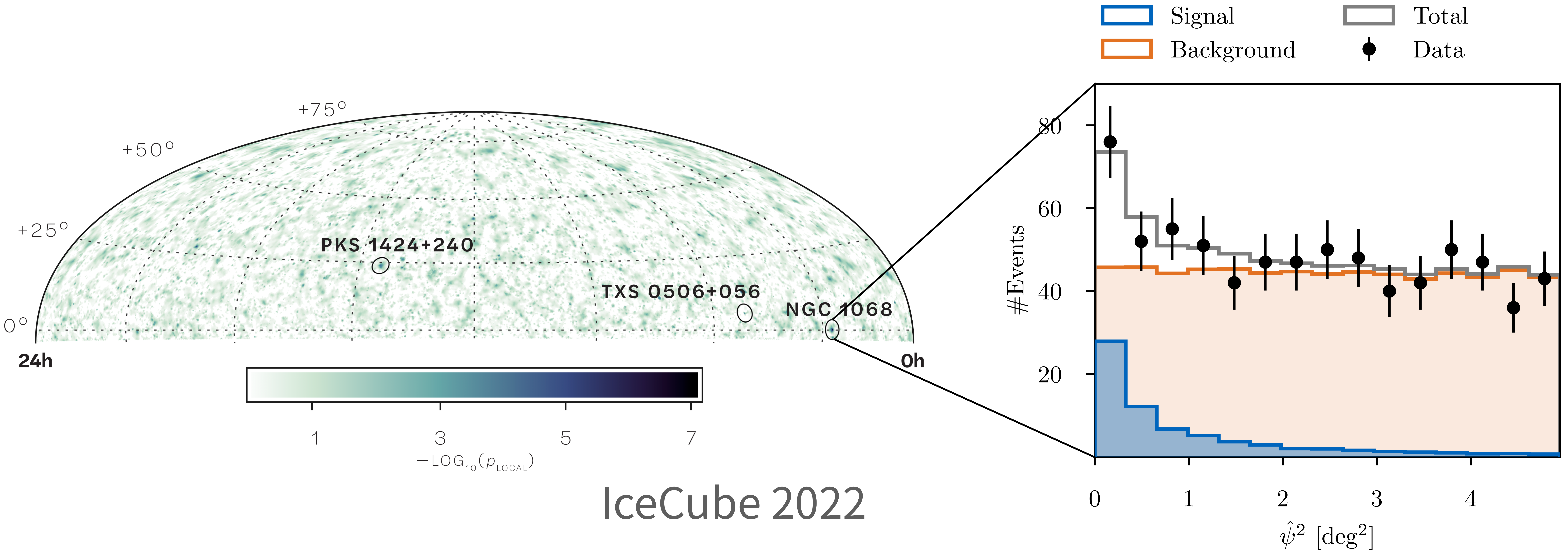
YI +'19

- MeV emission
  - but, no GeV emission
  - **Key for disentangling the degeneracy of non-thermal electron fraction**
- Protons would be accelerated

  ➡high energy neutrinos
- See also Stecker+'91, '92, '05, '13; Kalashev+'15; Murase+'20; Gutiérrez +'21; Kheirandish+'21

IceCube detection of TeV neutrinos from NGC 1068

Evidence of Non-thermal Activity in a **Seyfert** galaxy

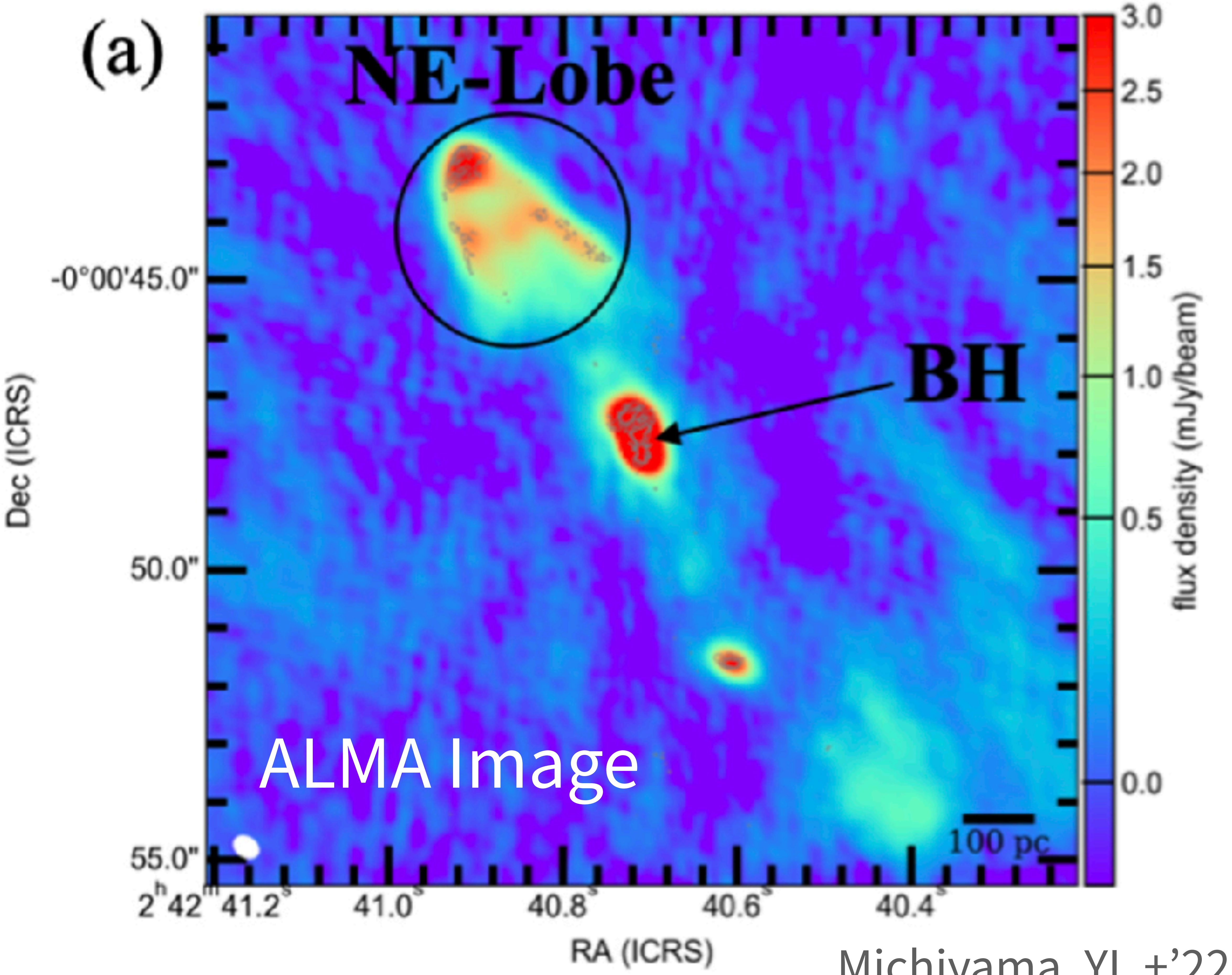


IceCube 2022

IceCube 2022

What is NGC 1068?

An obscured Seyfert galaxy with a weak jet activity

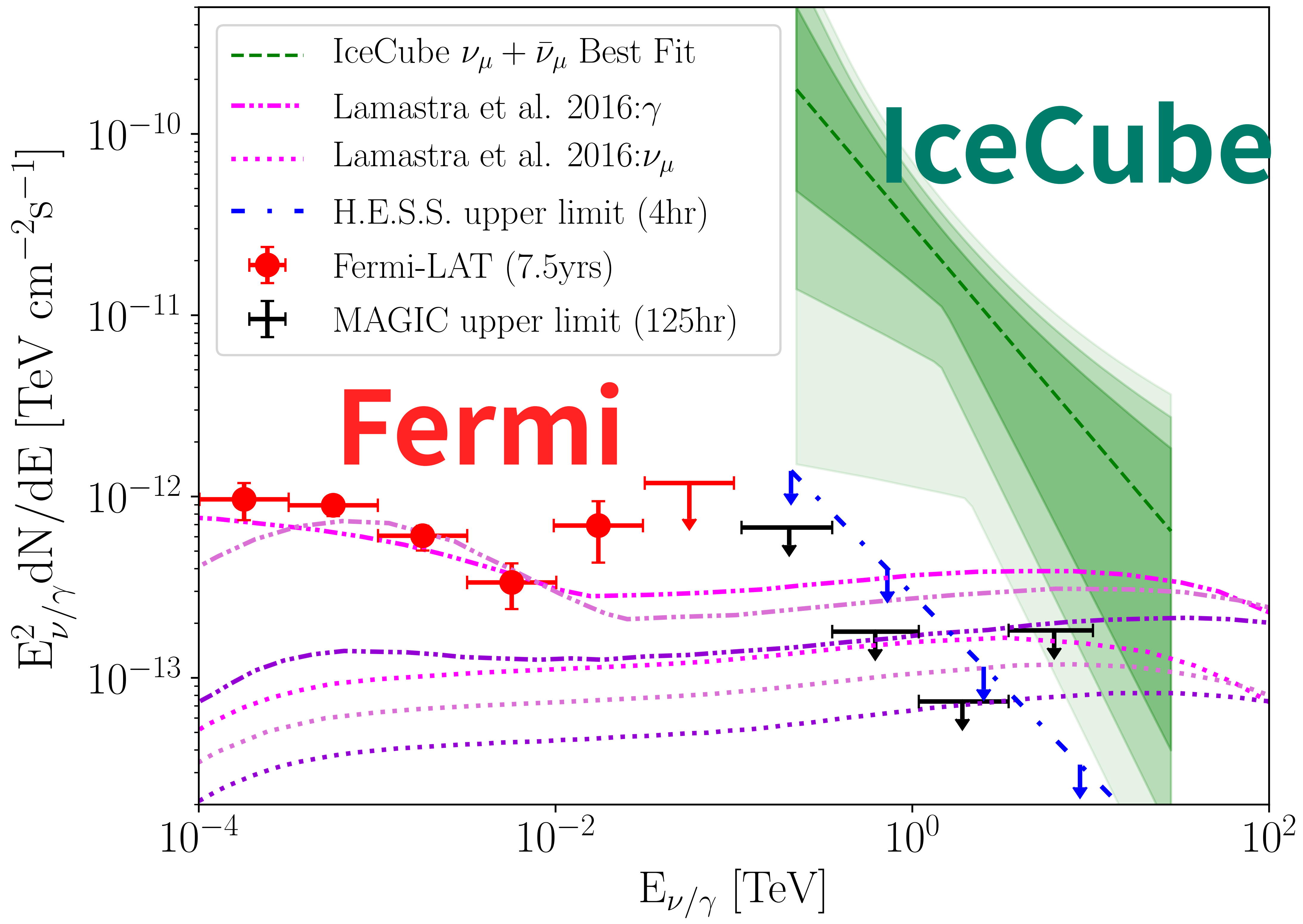


Michiyama, YI, +'22

Where is the neutrino production site?

"Neutrino flux > Gamma-ray flux" = Gamma-ray Opaque Region

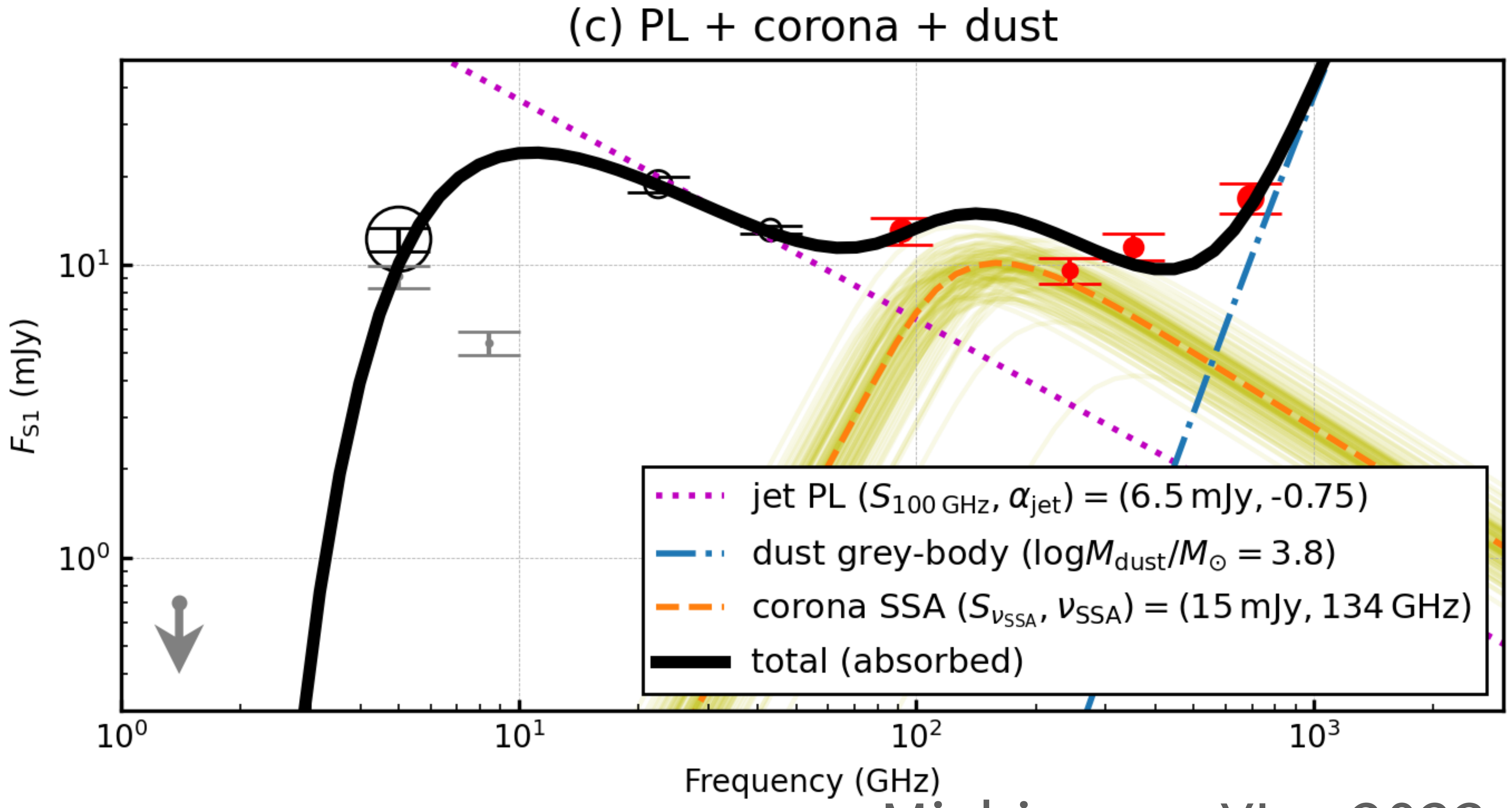
- Target photons : X-ray (~ 1 keV)
  - $\tau_{\gamma\gamma} \approx \frac{\sigma_{\gamma\gamma}}{4\pi c}\epsilon_X^{-1} L_X R^{-1} \simeq 10^5 \left(\frac{\epsilon_X}{1\ \mathrm{keV}}\right)^{-1} \frac{L_X}{L_{\mathrm{Edd}}} \frac{R_s}{R}$
- Host galaxy : Unlikely
- X-ray binaries : Not enough
  (see Swartz+'11, YI+'21)
- **Seyfert Corona (~10-100 R_s) : Most Likely**



IceCube 2020

ALMA Observations toward the NGC 1068 core

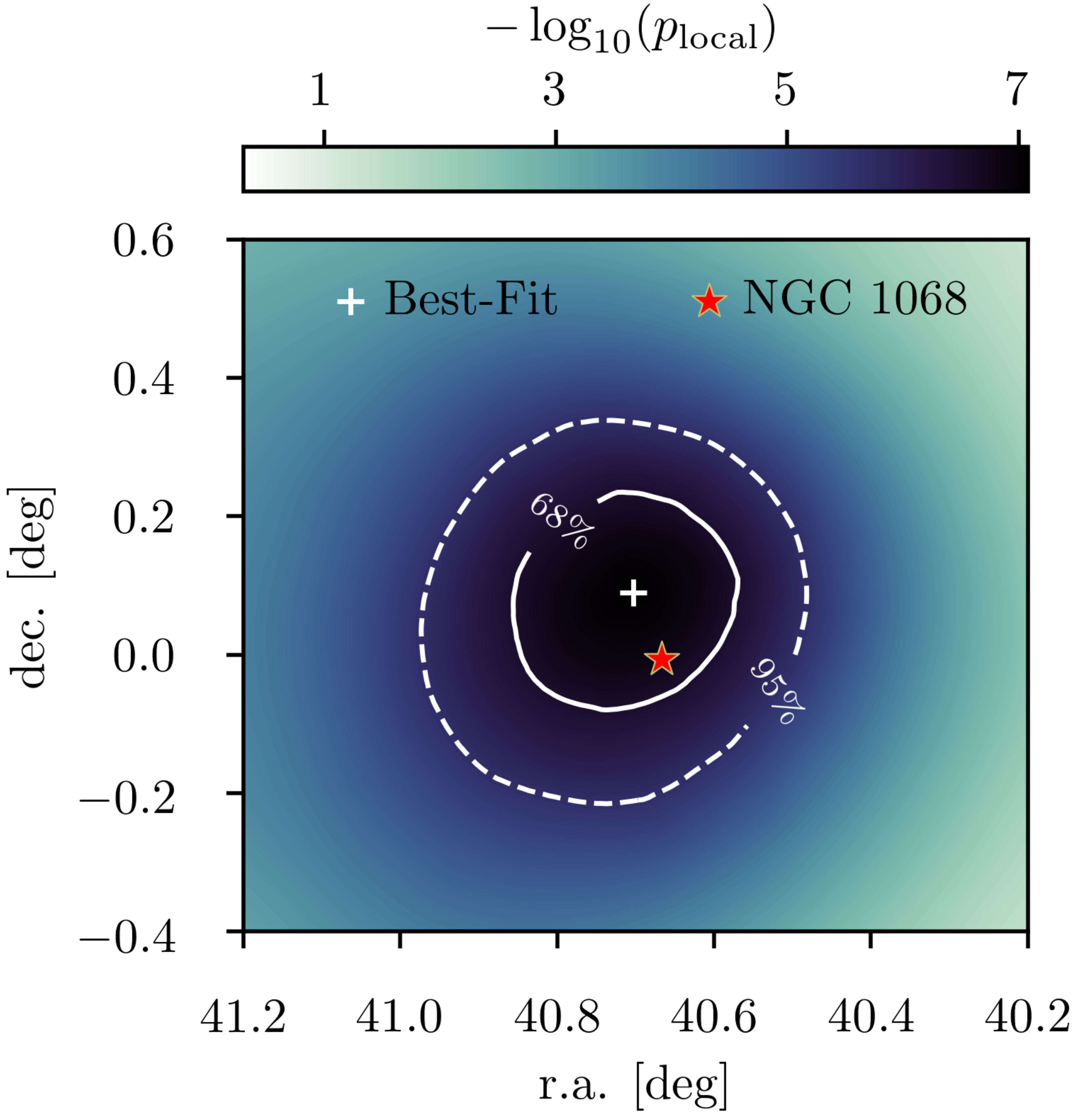
mm excess is there



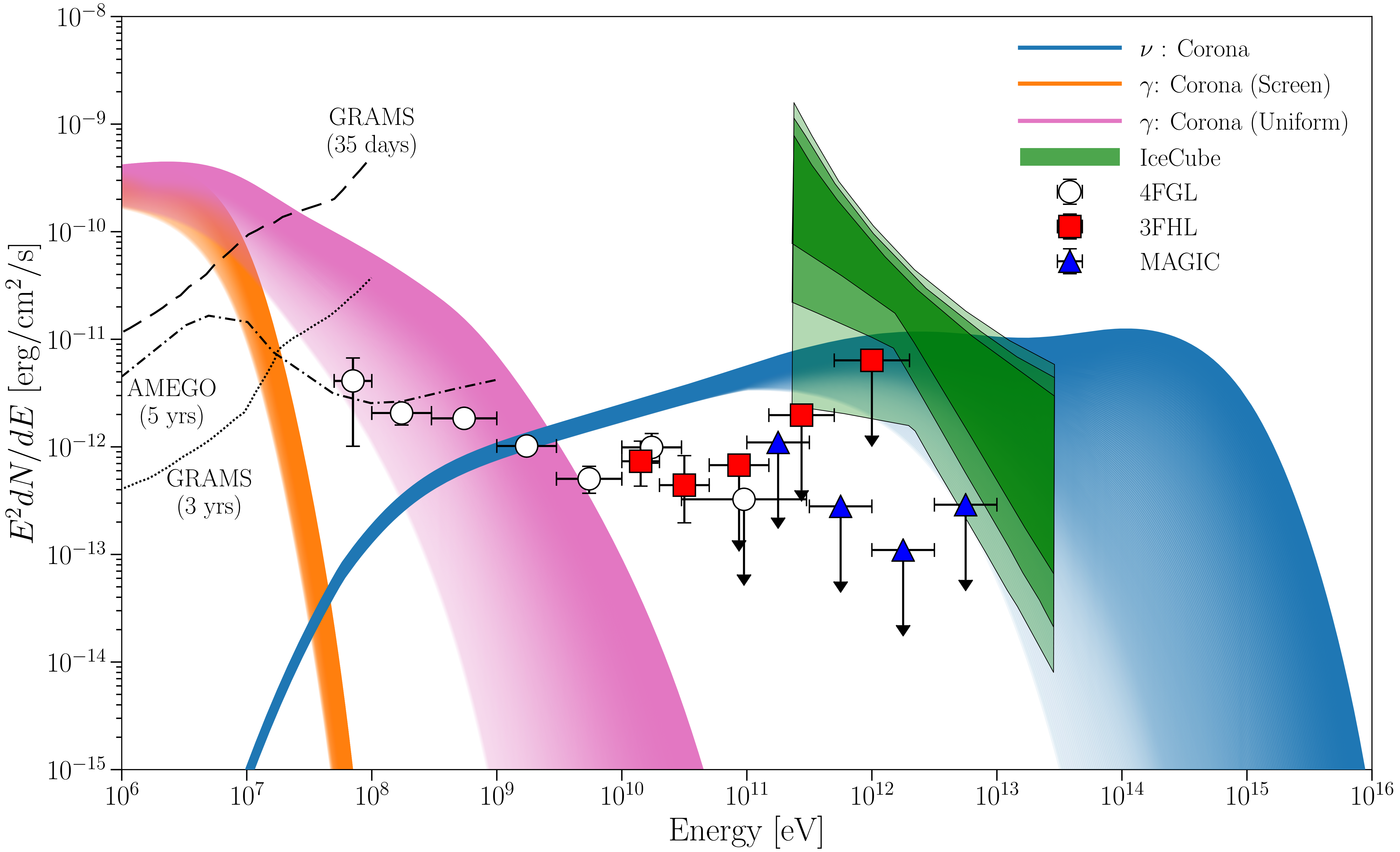
Michiyama, YI, + 2023

- Based on our analysis (YI+'20; Michiyama, YI+2023; See also Mutie+'25)
- Corona Size: ~10-30 r_s
- Coronal B-field: ~20-100 G
- More ALMA data would be necessary to clarify coronal property.

NGC 1068 in neutrinos



IceCube 2022

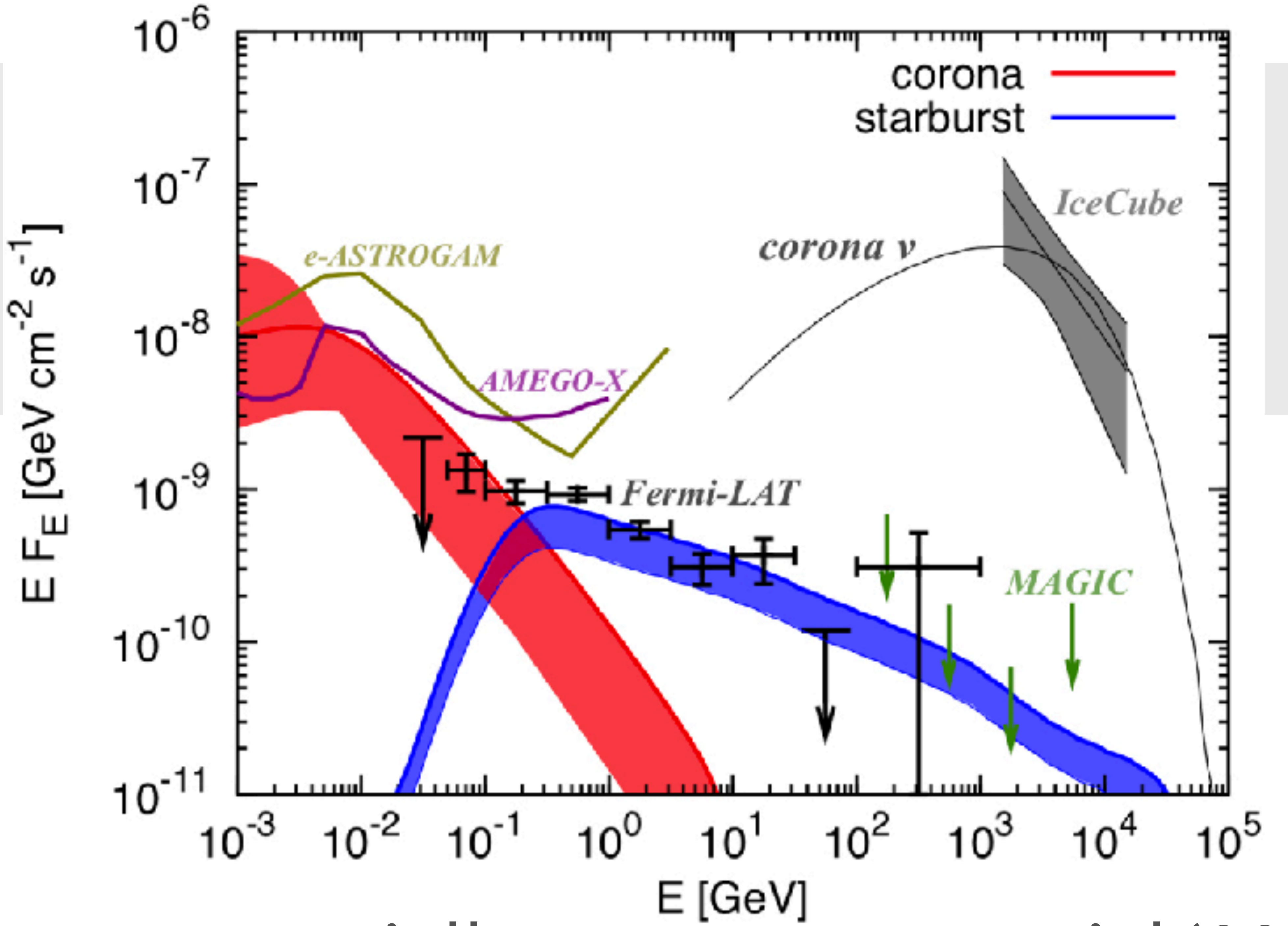


YI, Khangulyan, & Doi, ’20

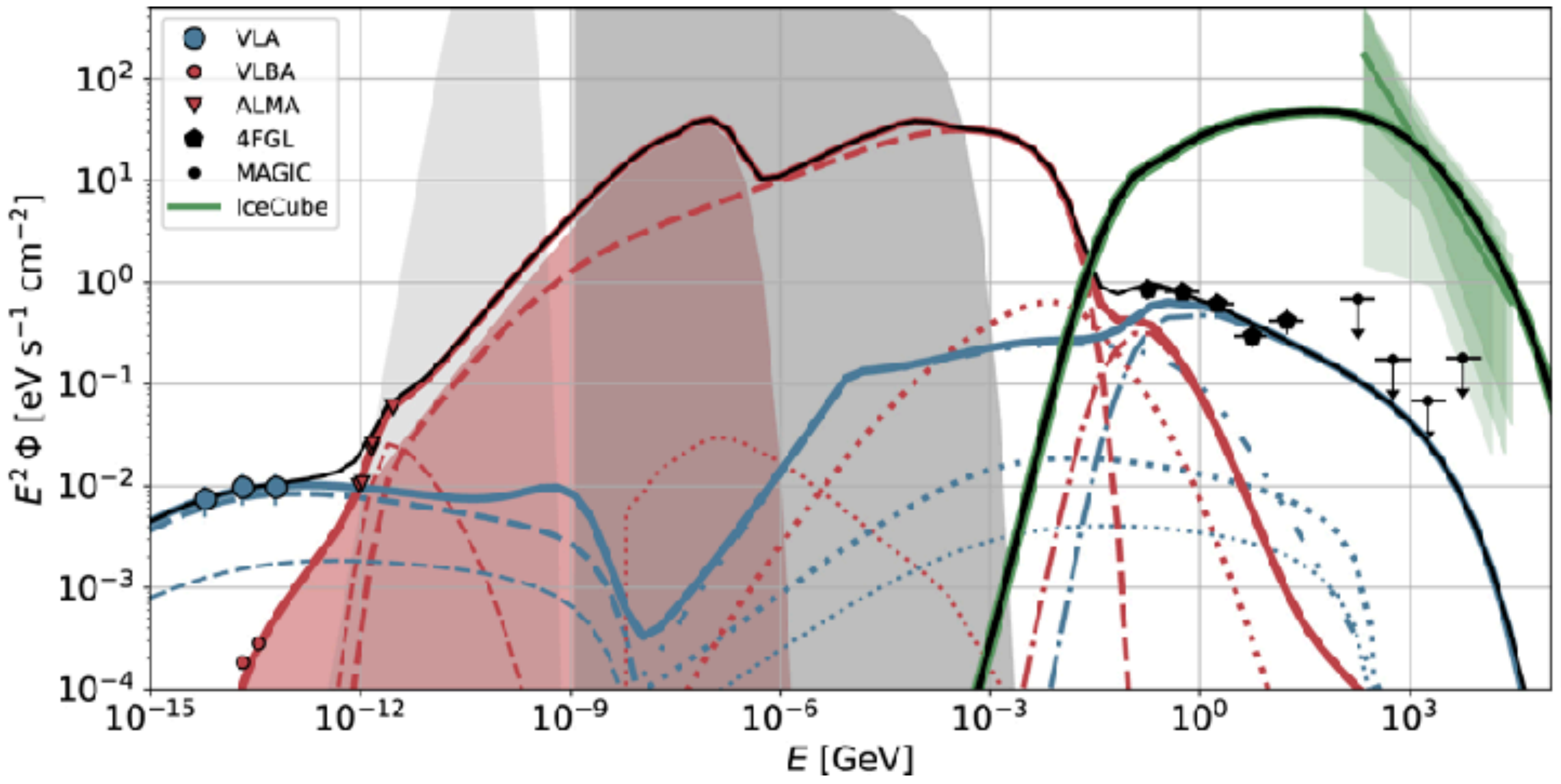
- Type-2 Seyfert NGC 1068 is reported at 4.2-σ.
- If the signal is real, corona may be a plausible neutrino production site
(Murase+’20; Kheirandish+’21; Anchordoqui+’22; Eichmann+’22; Fang+’23; Hooper+’23; Ajello+’23).

Coronal cosmic-ray power?

- Many models are proposed for Seyfert neutrinos (specifically NGC 1068).
  - YI+’20; Murase+’20; Kheirandish+’21; Anchordoqui+’22; Eichmann+’22; Fang+’23; Hooper+’23; Ajello+’23
- **We assume the cosmic-ray power.**
  - Neutrino flux ~ 0.1 cosmic-ray power.



Ajello, Murase, McDaniel ‘23

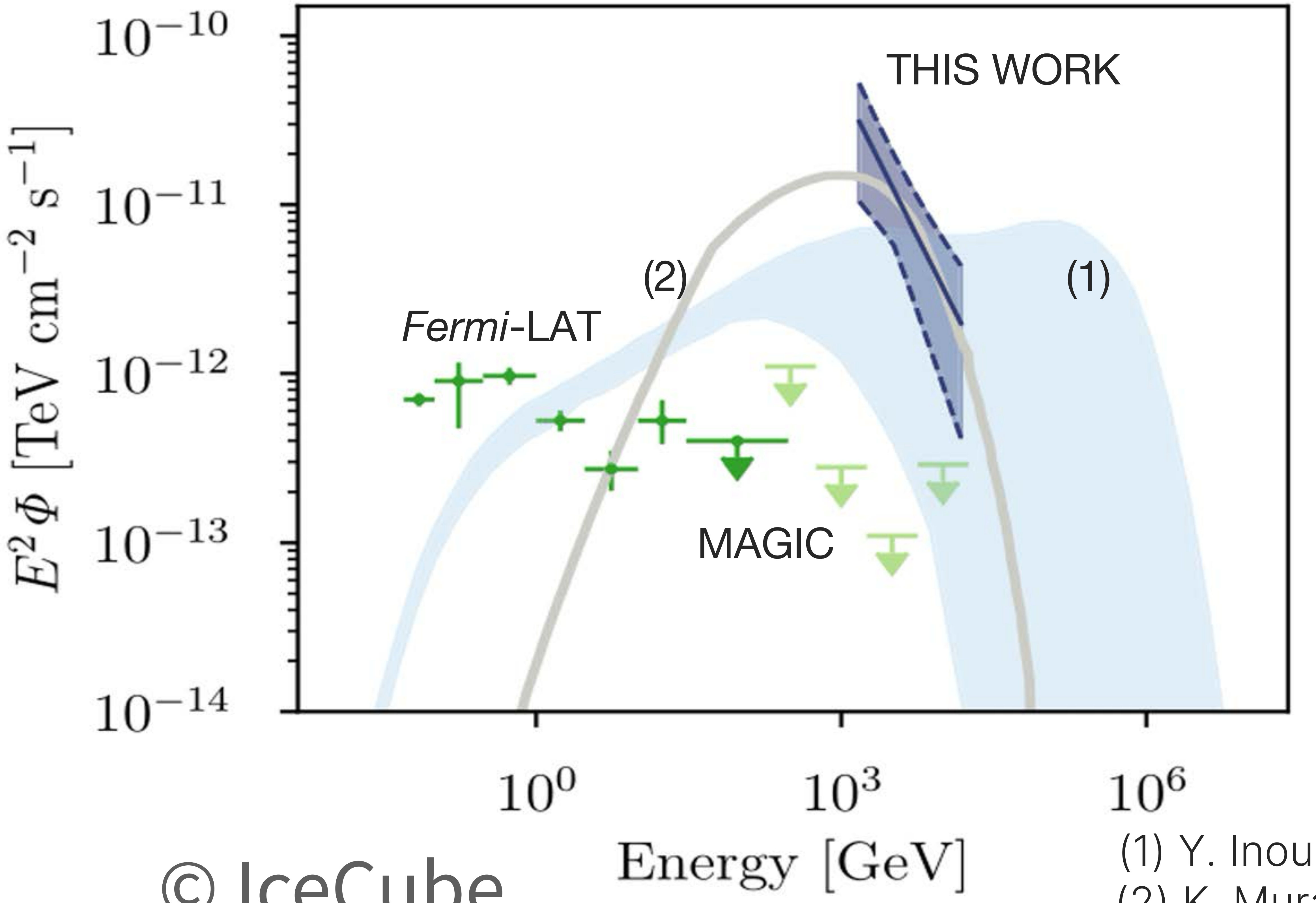


Eichmann+’22

How high CR power is required?

Efficient particle acceleration in AGN corona region?

NGC 1068: a cosmic obscured accelerator



- $\phi_{\nu_\mu+\bar{\nu}_\mu}(1.5-15\ \mathrm{TeV}) \sim 4\times10^{-11}\ \mathrm{erg/cm^2/s}$
- $L_{\nu_\mu+\bar{\nu}_\mu}(1.5-15\ \mathrm{TeV}) \sim 10^{42}\ \mathrm{erg/s}$

➡ $L_{\mathrm{CR}}(>10\ \mathrm{TeV}) \sim 10^{43}\ \mathrm{erg/s}$

- Note: $L_X \sim 3-7\times10^{43}\ \mathrm{erg/s}$

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

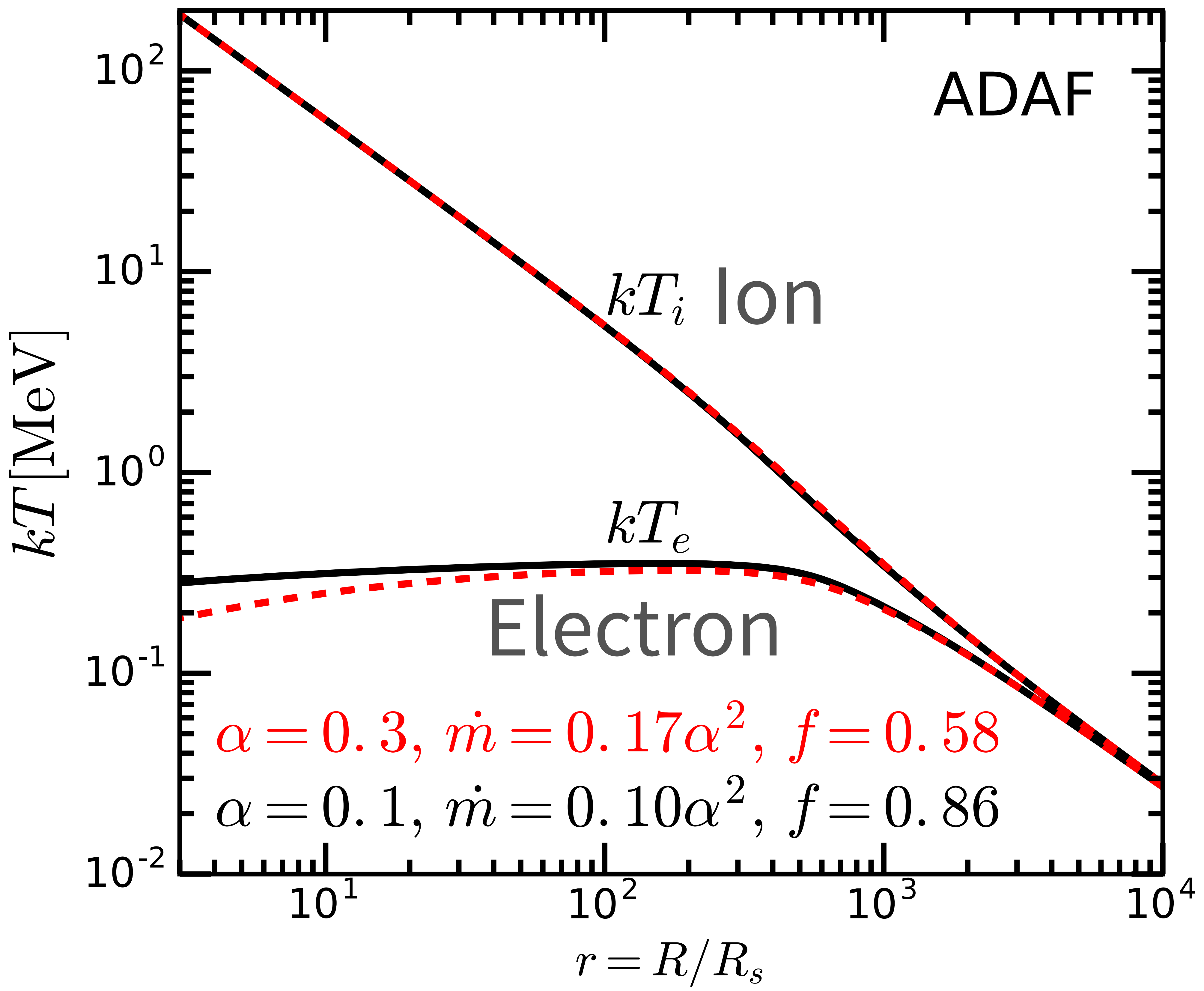
Upper limit on cosmic-ray power in AGN coronae

Accretion dynamics constrains the coronal CR power (YI, Takasao, Khangulyan '24)

- CR pressure can be expressed by Gas pressure
  $p_{\rm CR} = \delta\, \beta^{-1}\, p_{\rm gas}$
  - CR vs magnetic pressure ratio: $\delta \equiv p_{\rm CR}/p_{\rm mag} < 1$
  - Plasma beta: $\beta \equiv p_{\rm gas}/p_{\rm mag}$
- Coronal Gas Pressure?
  - Hot accretion flow → Two-temperature plasma
  - $p_{\rm gas} \approx n_i k_B T_i \approx \tau_X k_B T_i / R_c \sigma_T$

➡ $p_{\rm CR} \approx \dfrac{\delta}{\beta} \dfrac{\tau_X}{R_c \sigma_T} k_B T_i$

Hot Accretion Flow Temperature Profile



Kafexhiu + '19

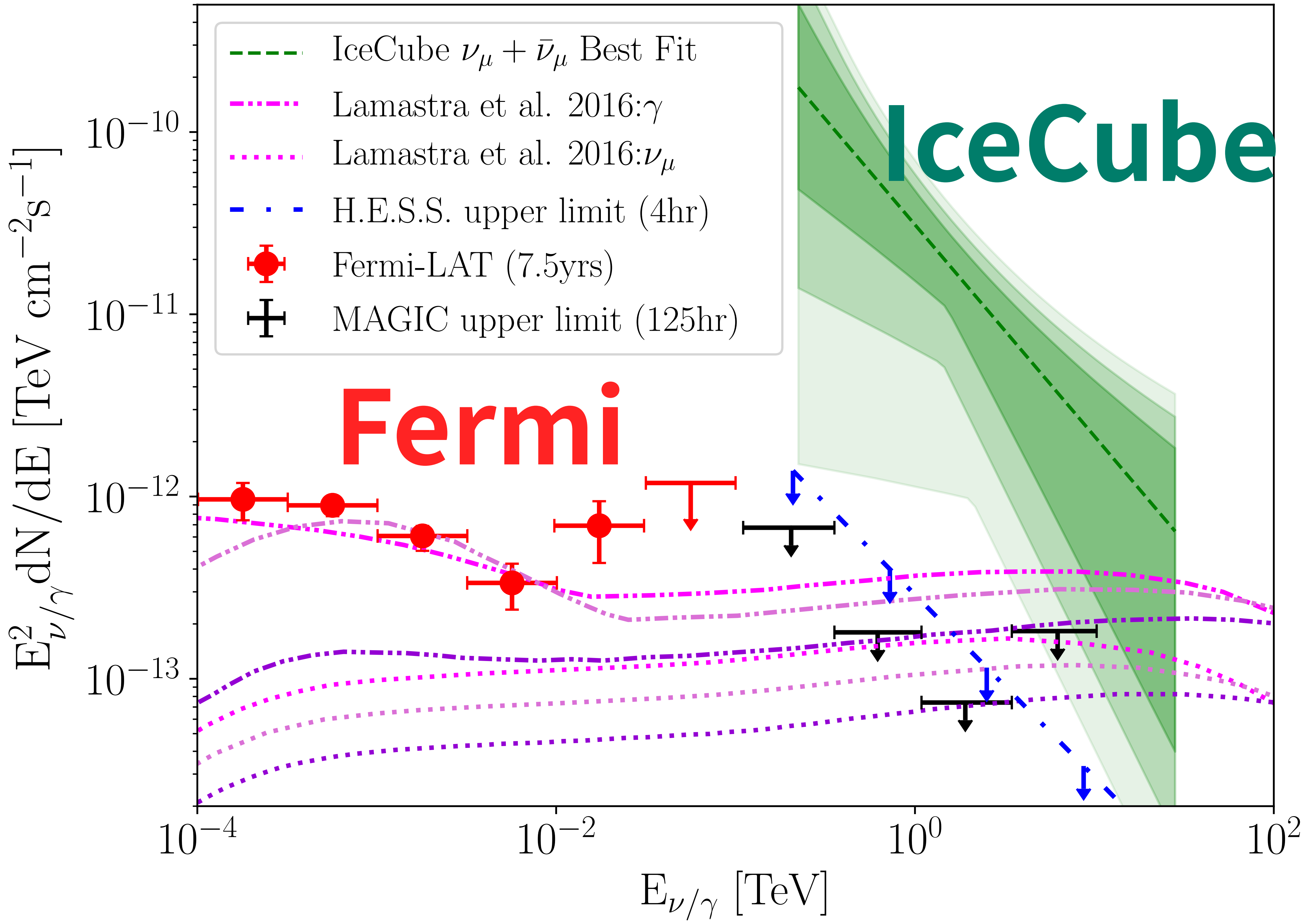
Upper limit on cosmic-ray power in AGN coronae

YI, Takasao, Khangulyan '24

- Energy density and pressure
  - $p_{\rm CR} = \frac{1}{3}\int dp 4\pi p^3 v(p) f(p) = \frac{1}{3} u_{\rm CR}$
- CR Luminosity is then

$$L_{\rm CR} \lesssim 7.3 \times 10^{41}\ \mathrm{erg\ s^{-1}} \left(\frac{\alpha}{0.1}\right)\left(\frac{\beta}{10}\right)^{-1} \times \left(\frac{\delta}{1}\right)\left(\frac{M_{\rm BH}}{10^7 M_\odot}\right)\left(\frac{r_c}{10}\right)^{-1/2}\left(\frac{\tau_X}{1}\right)$$

Requirement: $L_{\rm CR} > 10^{43}$ erg/s



IceCube 2020

Summary

- Coronal magnetic activity in Seyfert galaxies have been now observed by ALMA
    - Coronal magnetic field is ~10 G at ~30 R_S
    - Non-thermal particles exist in the BH corona
- Corona could explain the neutrino signals
    - But, IceCube flux of NGC 1068 would be too high for corona models, IF corona is high-β plasma.