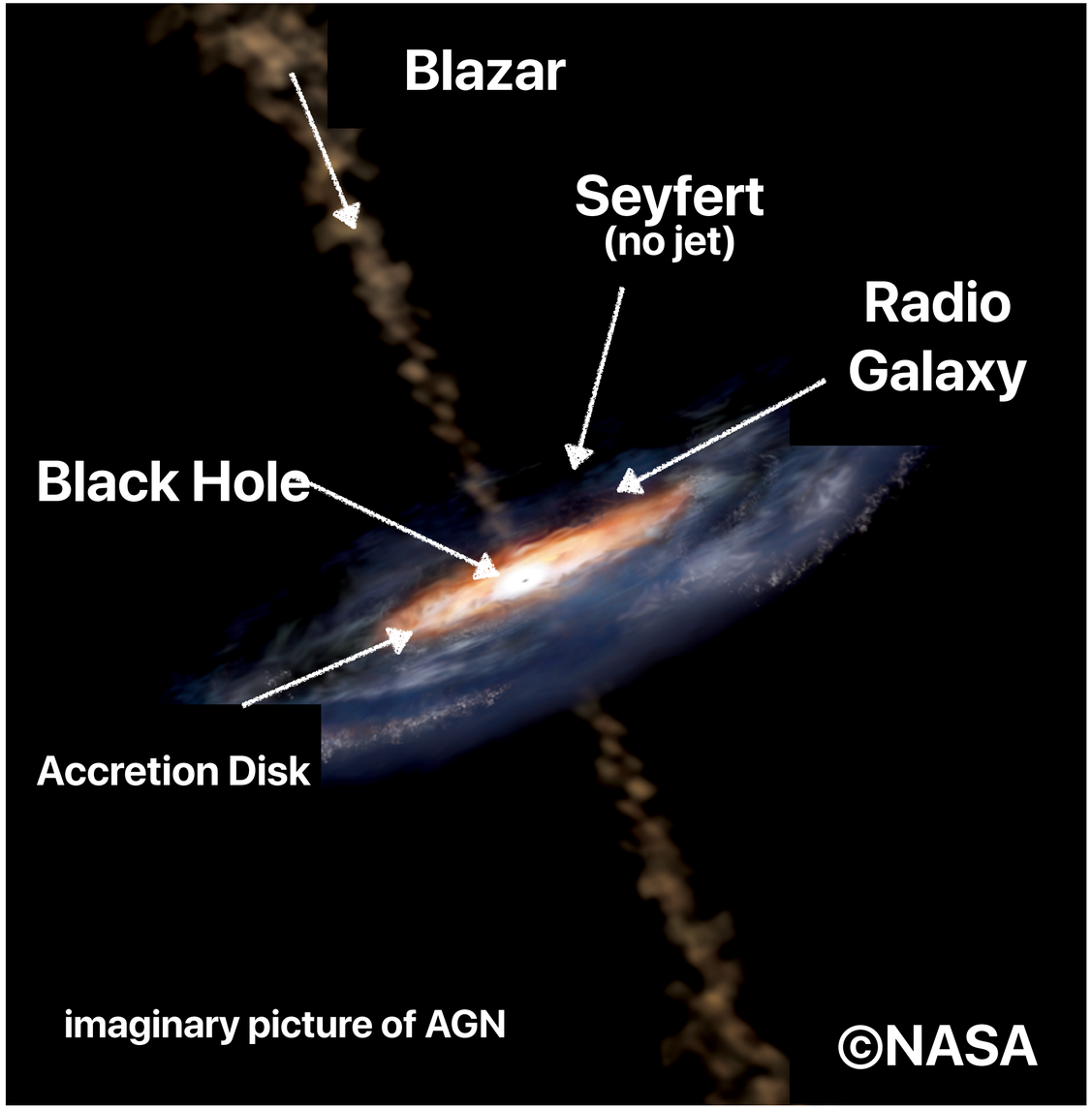
Unjetted AGNs as Neutrino Sources

Yoshiyuki Inoue

KM3NeT Meeting @ Online, 2022-09-20

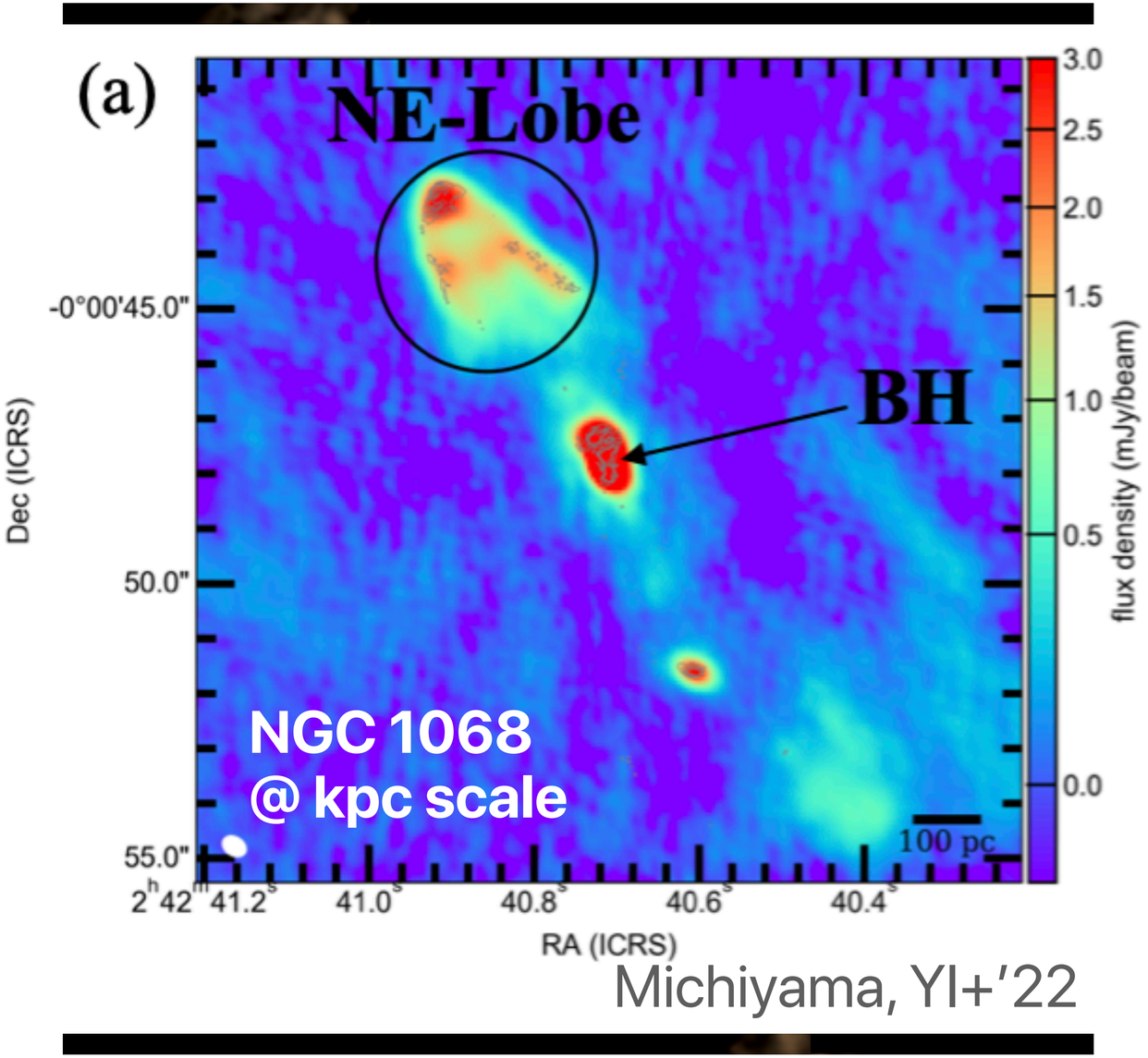
Unjetted AGNs ~ Radio-Quiet AGNs ~ Seyferts



- Active Galactic Nucleus = AGN
- 90% of AGNs are radio-quiet.
- Radio-quiet AGNs ~ Seyfert galaxies (or quasars, when luminous)
  - Also as unjetted AGNs.
  - unjetted ~ radio-quiet ~ Seyfert
- **Emission arises from disk**.

CAUTION: Unjetted does not mean no-jet

Unjetted AGNs ~ Radio-Quiet AGNs ~ Seyferts



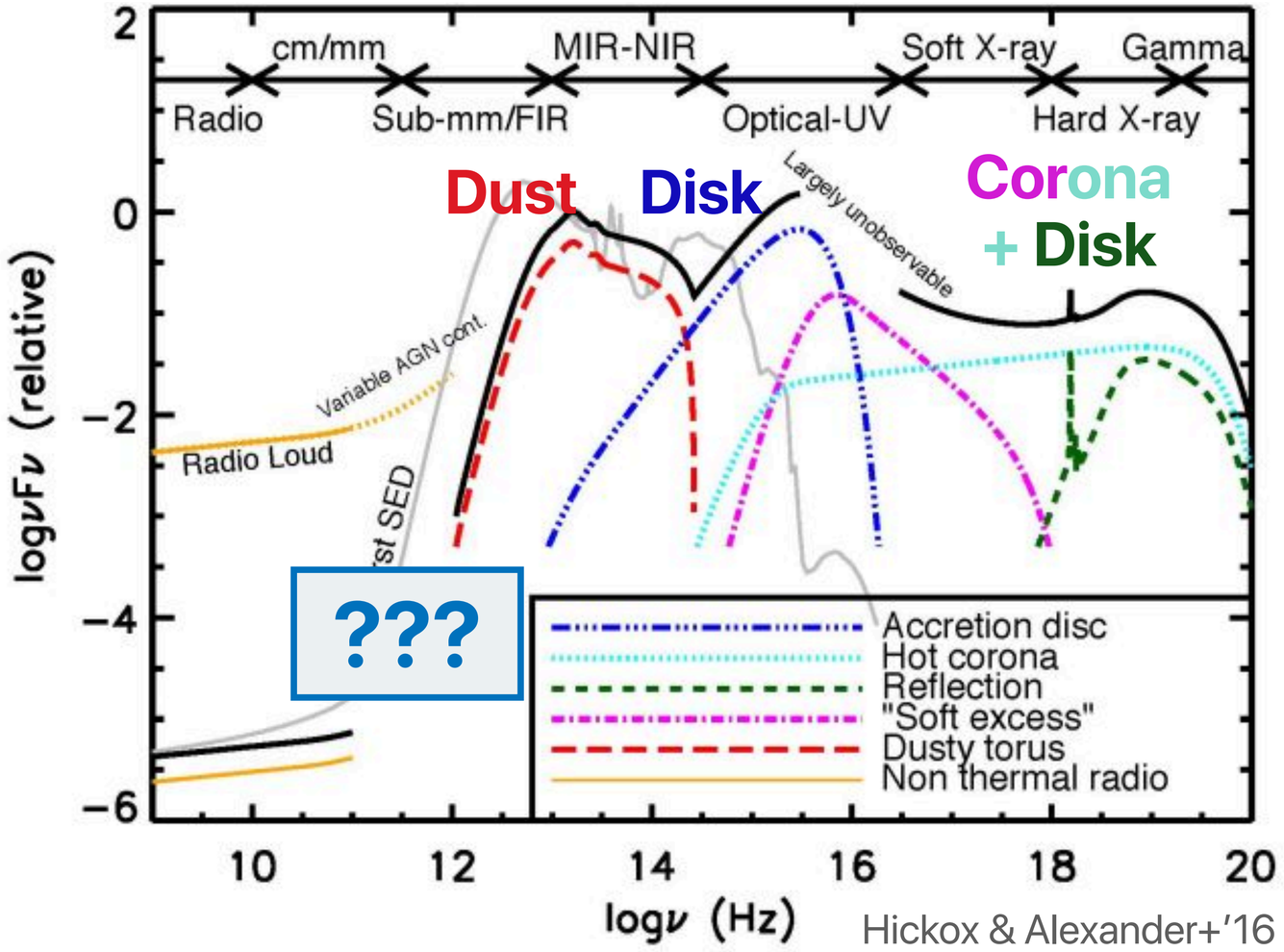
Michiyama, YI+'22

- Active Galactic Nucleus = AGN
- 90% of AGNs are radio-quiet.
- Radio-quiet AGNs ~ Seyfert galaxies (or quasars, when luminous)
  - Also as unjetted AGNs.
  - unjetted ~ radio-quiet ~ Seyfert
- **Emission arises from disk**.

CAUTION: Unjetted does not mean no-jet

Multi-wavelength spectrum of Unjetted AGNs

Thermal emission dominates.

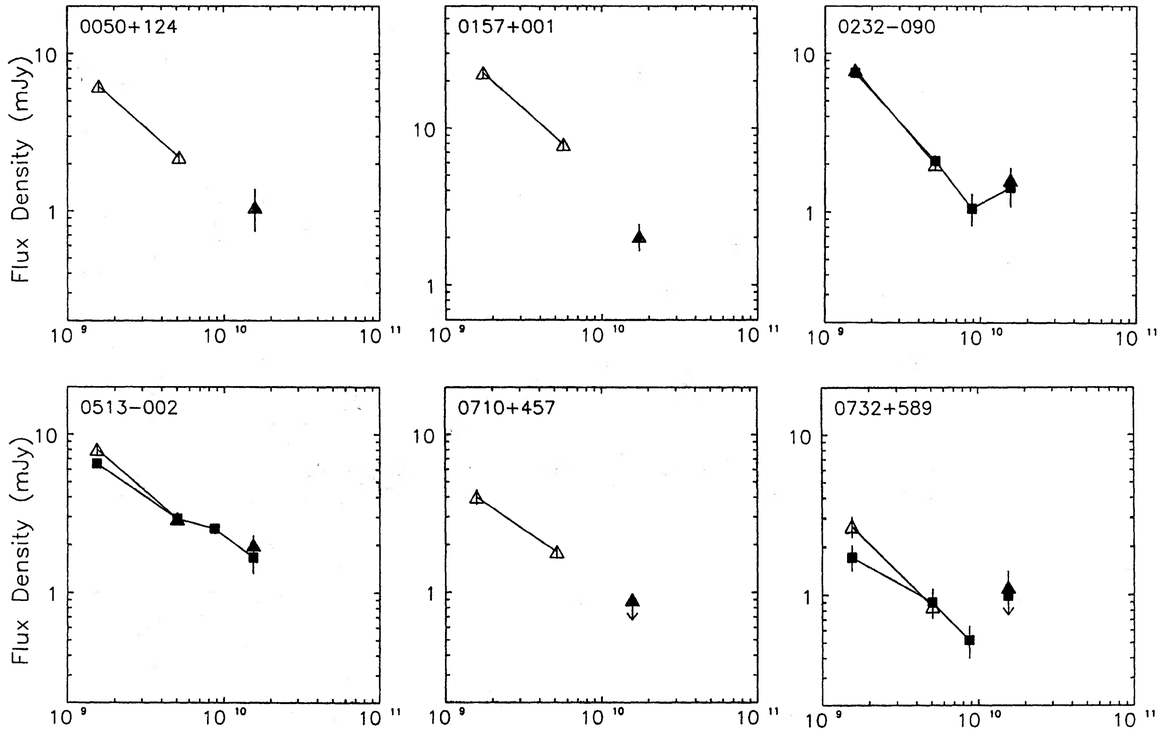


Hickox & Alexander+'16

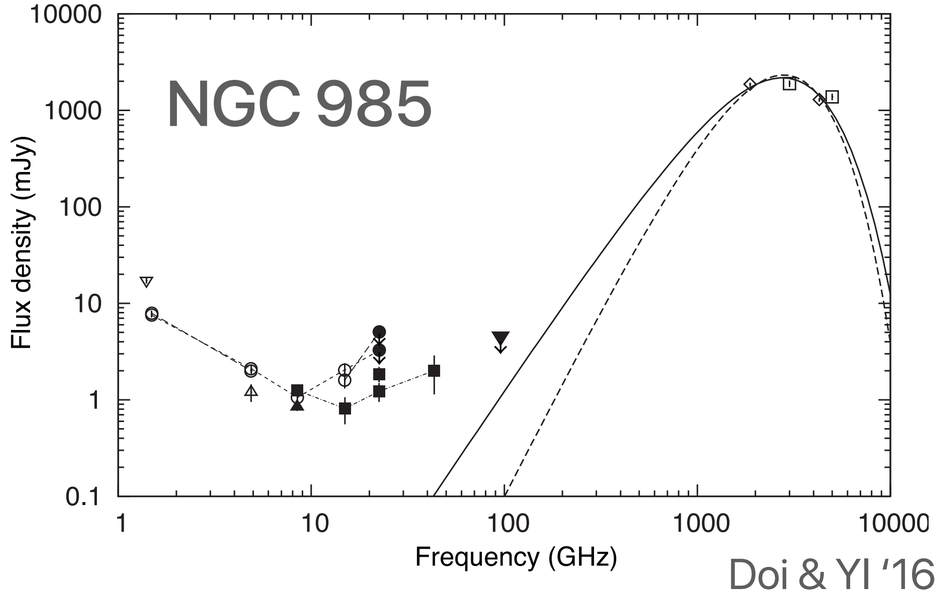
- If unjetted AGNs are neutrino sources,
  - we should see non-thermal EM emission.
- BUT, in unjetted AGNs,
  - thermal emission is everything "so far".
- **Where is non-thermal signature?**

Millimeter excess in nearby Seyferts

Unknown component in AGN SED?



Barvainis+'96



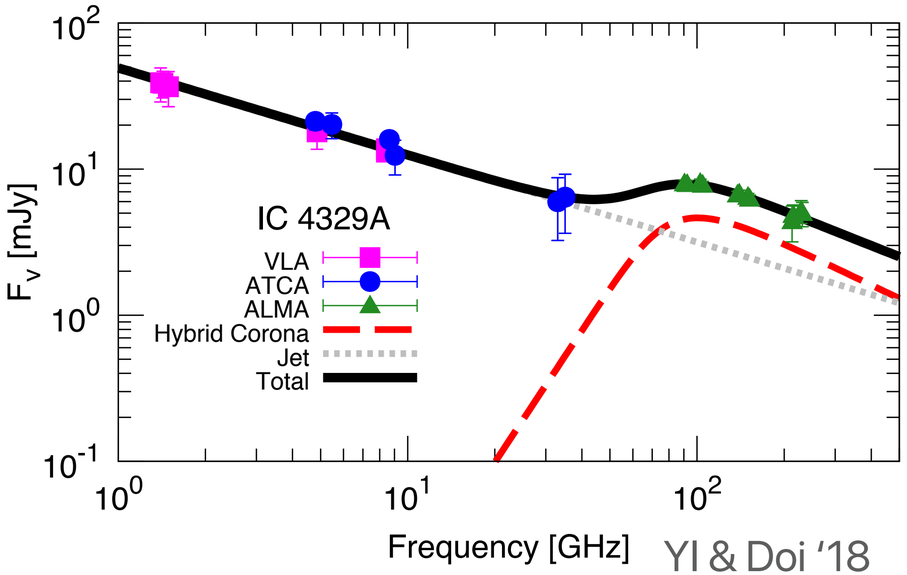
Doi & YI '16

- Spectral excess in the mm-band

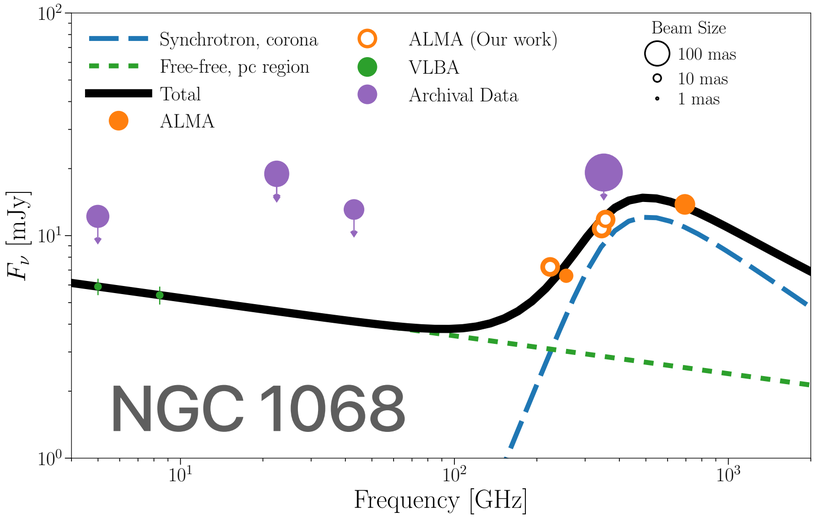
  (e.g., Antonucci & Barvainis'88; Barvainis+'96; Doi & Inoue '16; Behar+'18).

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

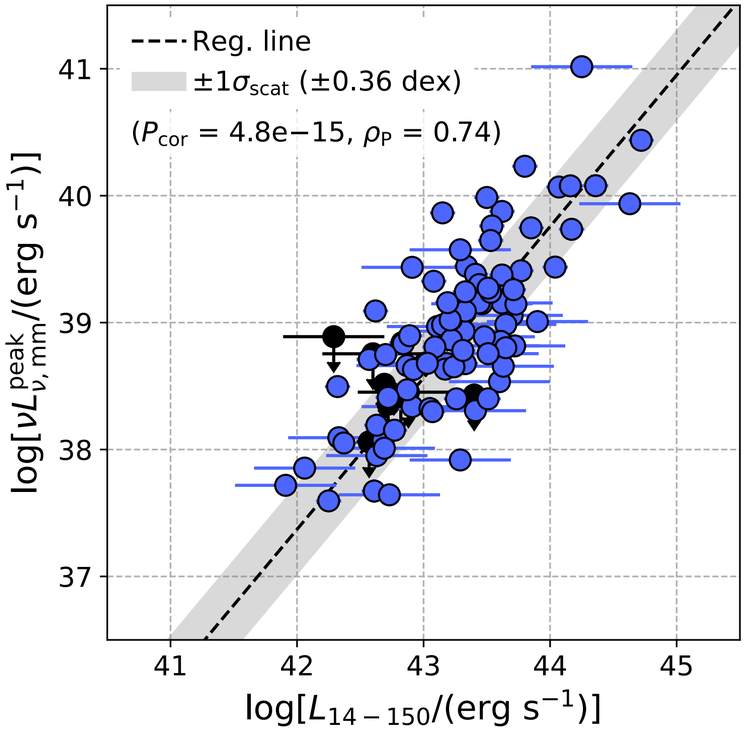
ALMA observations toward nearby Seyferts



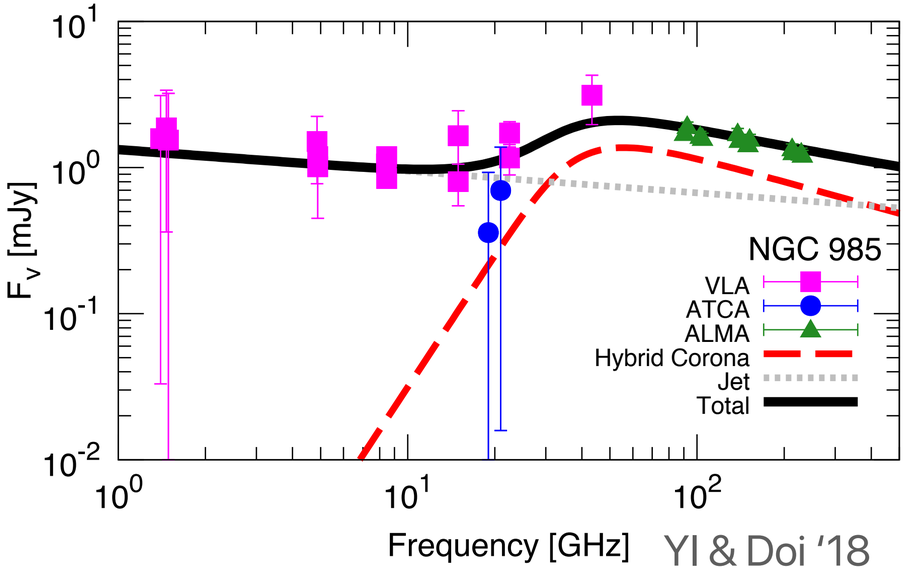
YI & Doi '18



YI, Khangulyan, & Doi '20



Kawamuro+'22

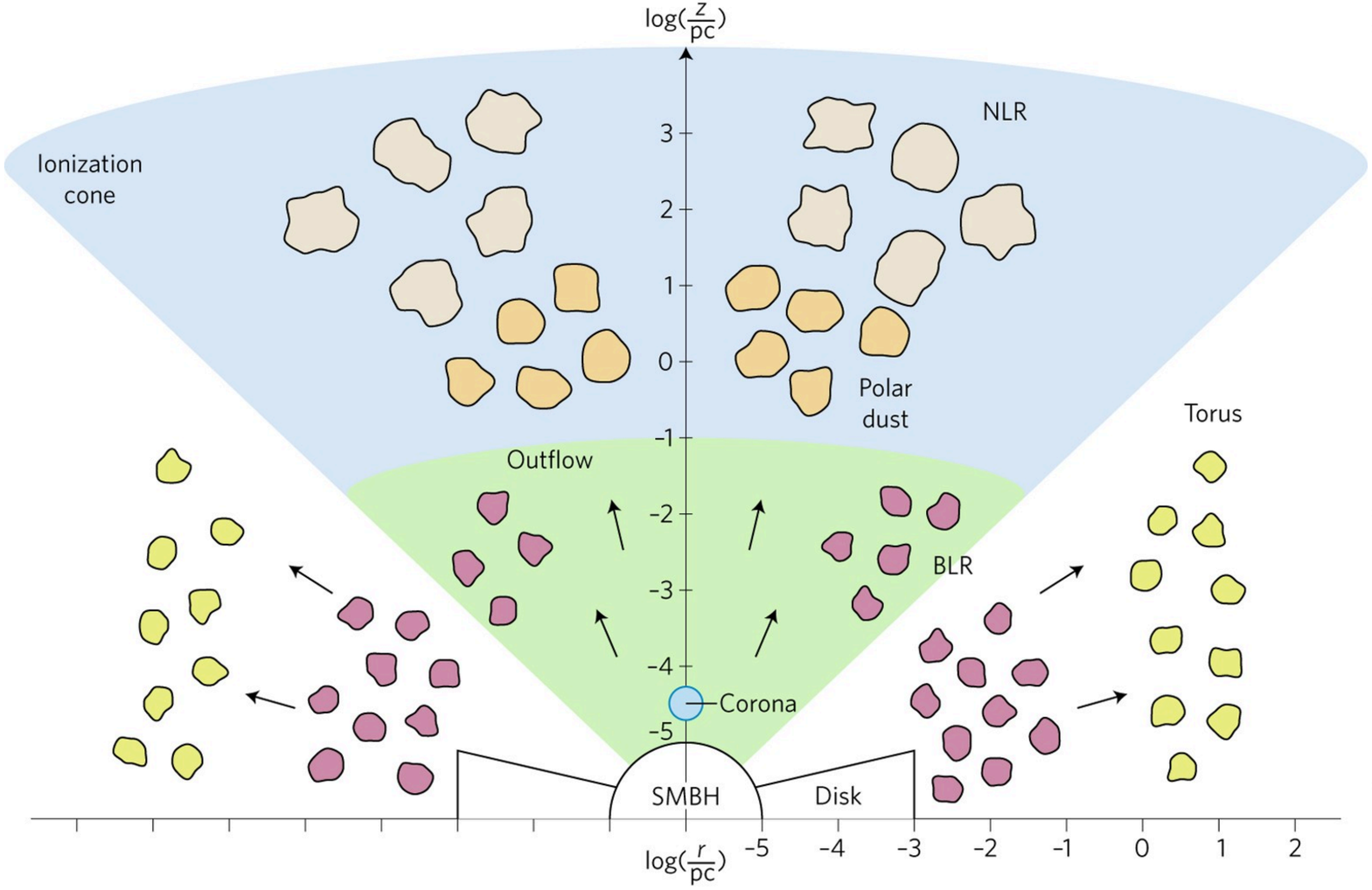


YI & Doi '18

- 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 month (see also Behar+'20)
- Correlation b/w mm and X-ray luminosities (Kawamuro+'22)
- Size : < 10 pc → Nucleus

Structure of AGN core in the <10 pc scale

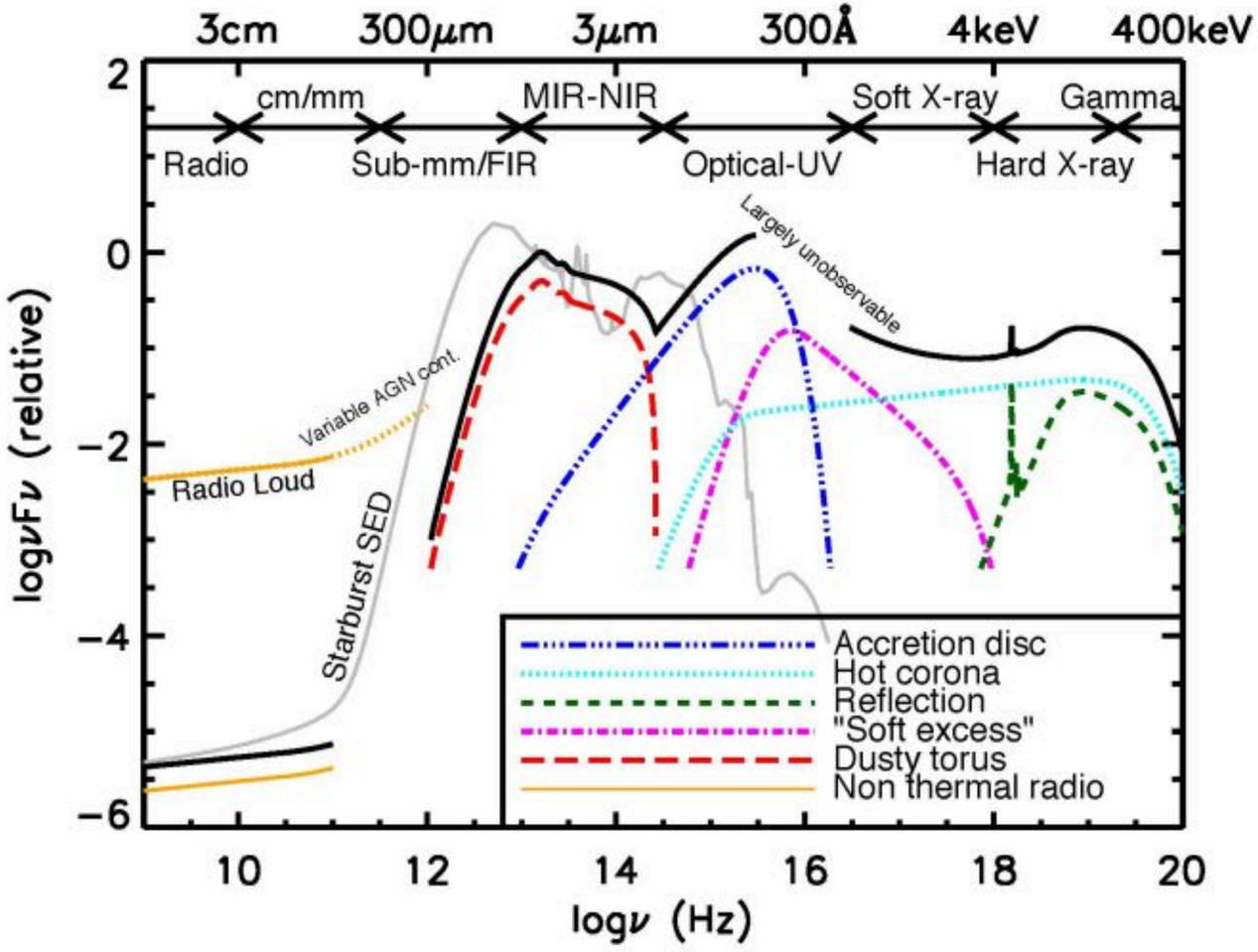
Where is the origin of the mm excess?



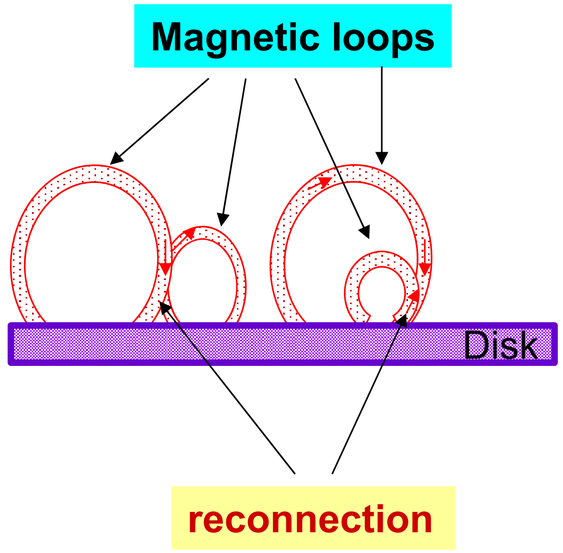
Ramos-Almeida & Ricci '17

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

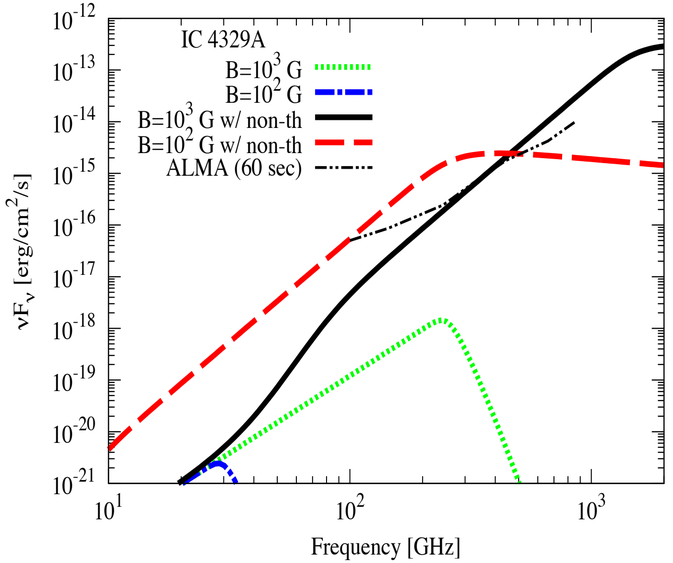
X-ray photons are from *hot corona*



Hickox & Alexander+'16



© B. Liu

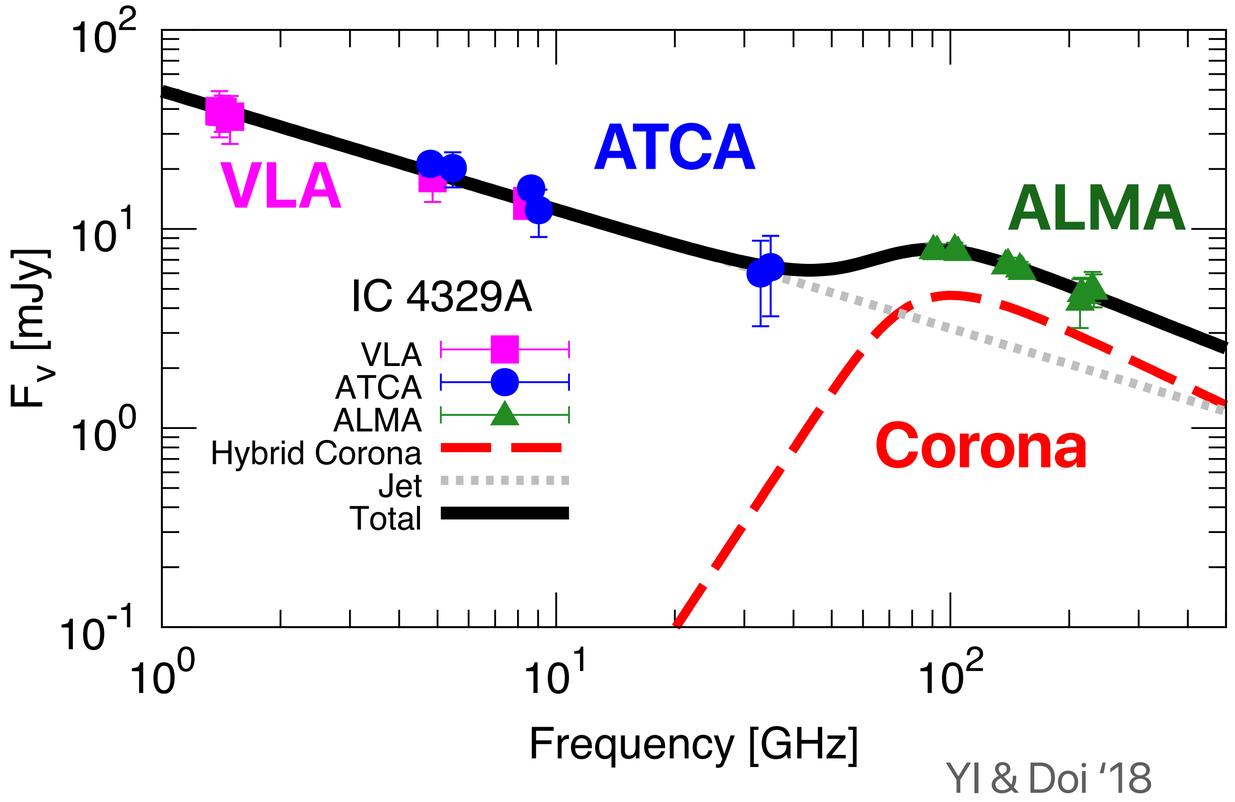


YI & Doi '14

- Hot corona ~ 100 keV
- Heated by magnetic activity ?
  (e.g., Haardt & Maraschi '91; Liu, Mineshige, & Shibata '02)
- If so, **<u>coronal synchrotron radiation</u>** is expected
  (Di Matteo+'97; YI & Doi '14; Raginski & Laor '16)

cm-mm spectrum of AGN core

A case of IC 4329A

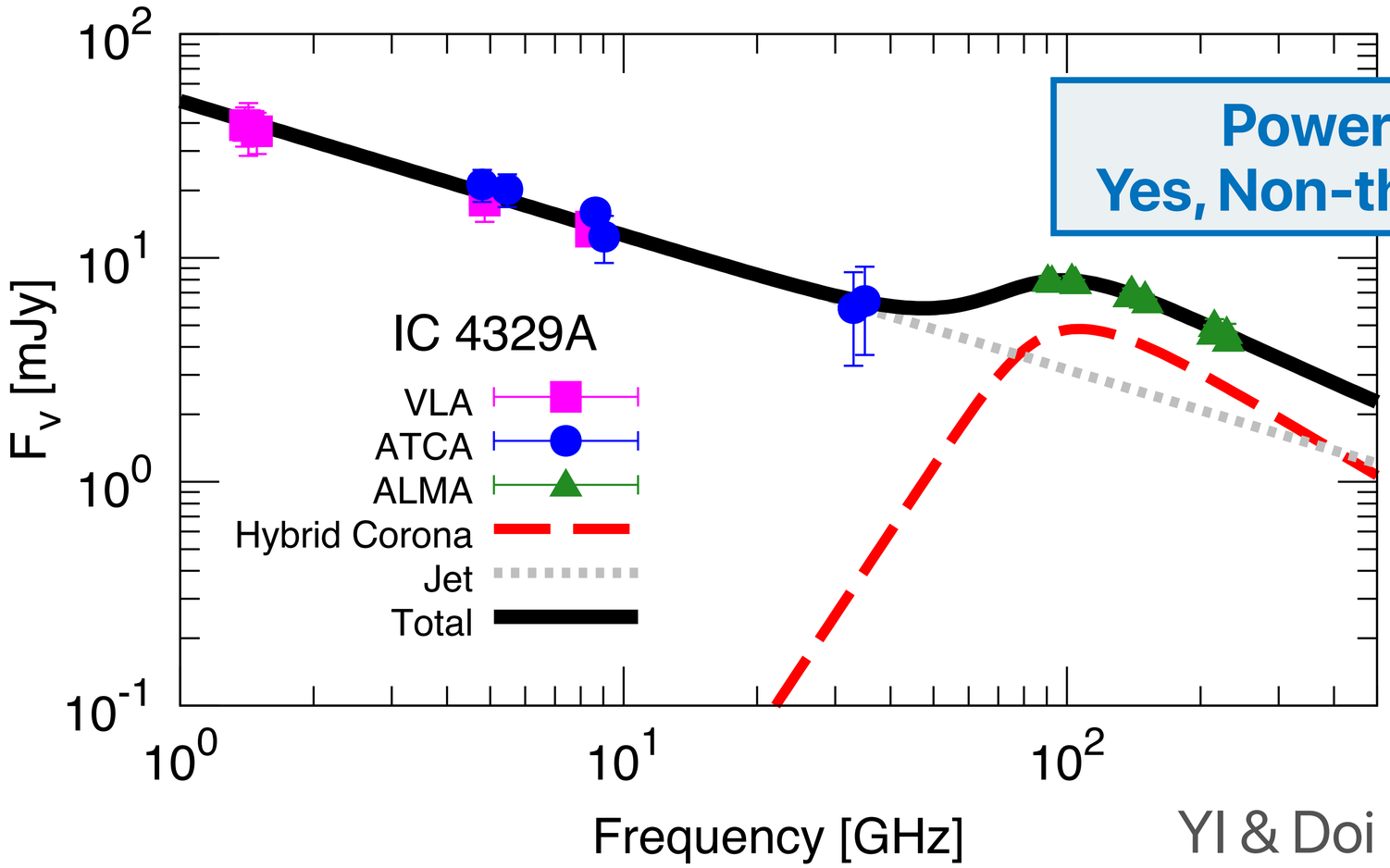


YI & Doi '18

- 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

Radio Spectrum of AGN Core

Non-thermal tail in the mm spectrum



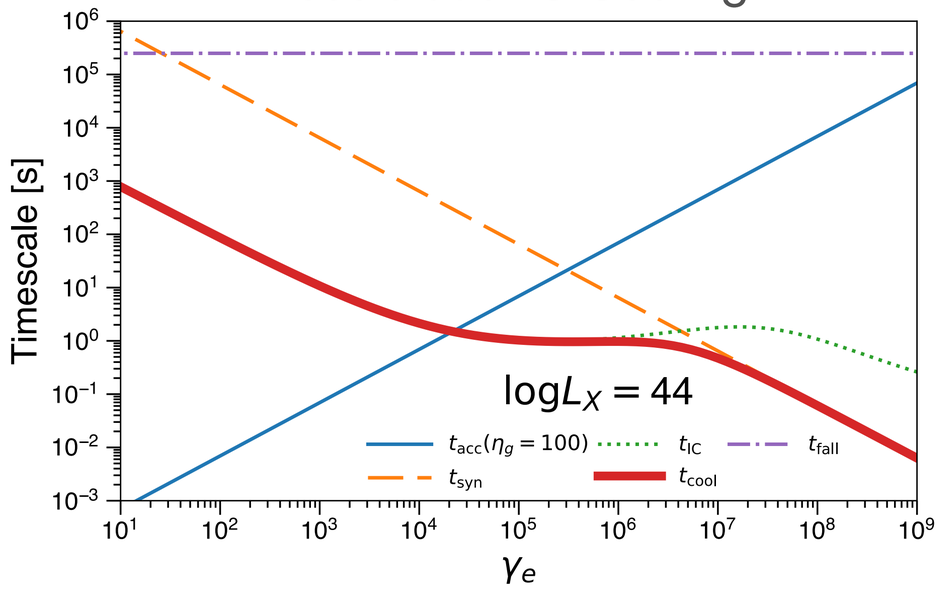
Power-law Tail ?
Yes, Non-thermal Activity

YI & Doi ‘18

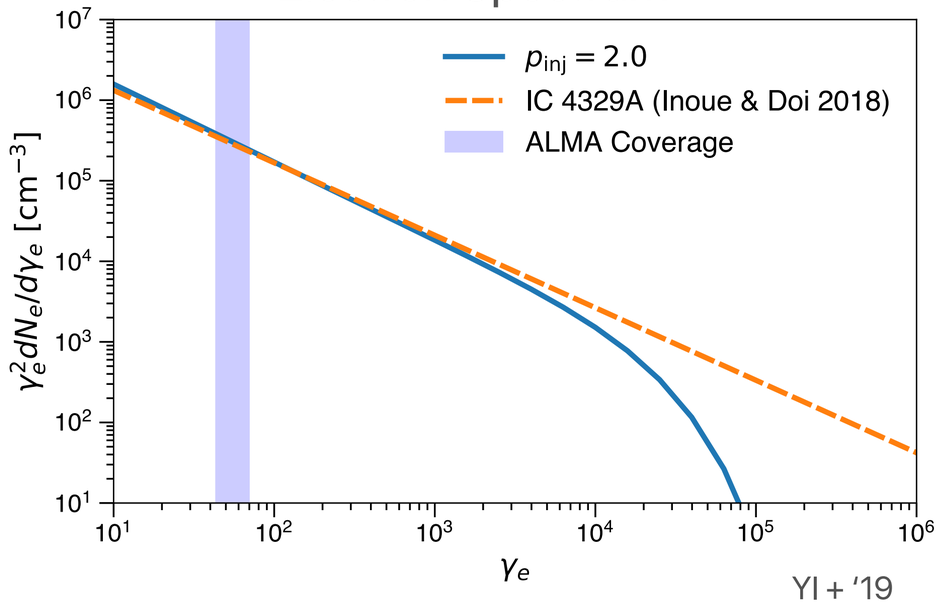
Generation of Non-thermal Electrons in Coronae

- 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.

Acceleration & Cooling



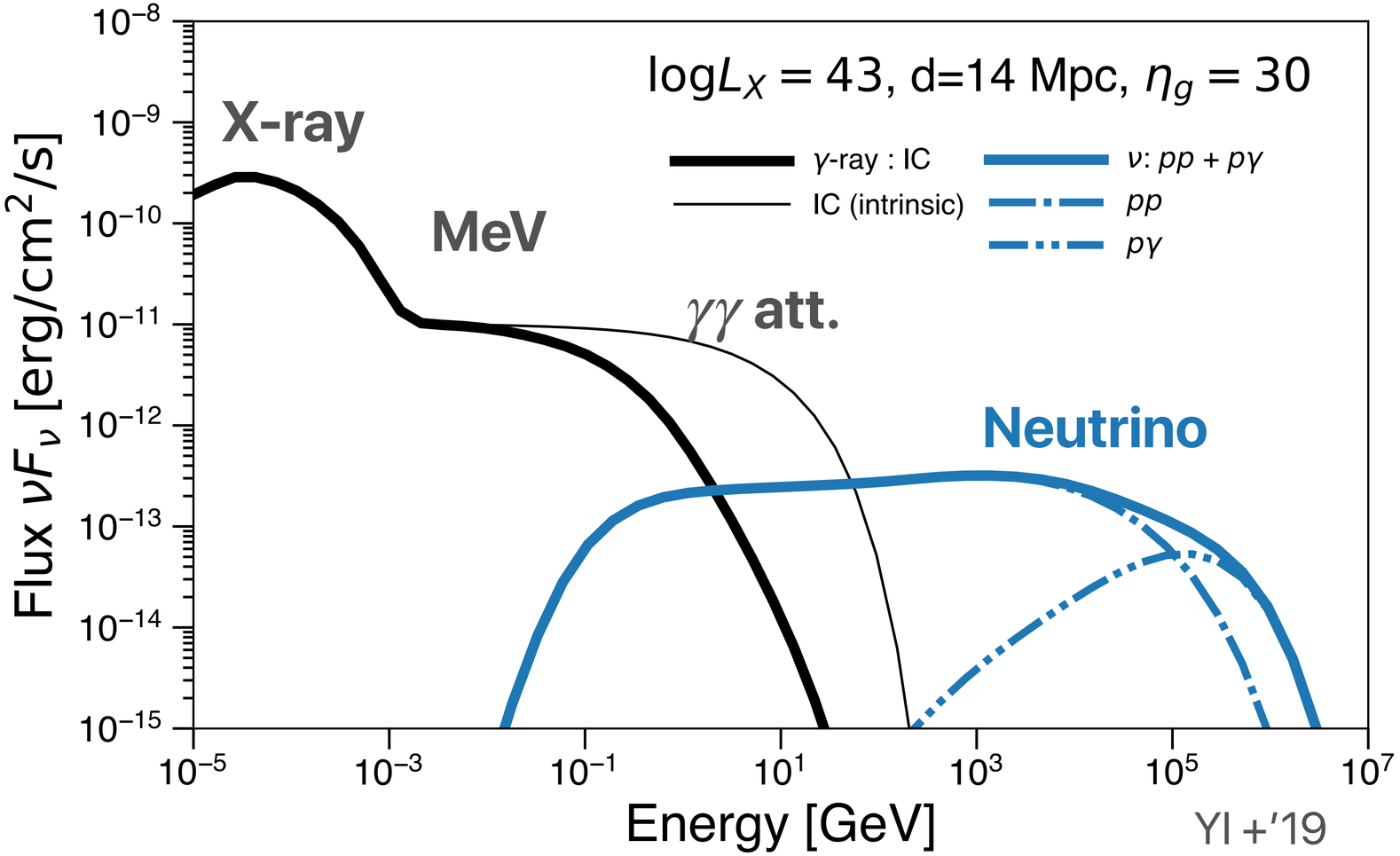
Electron Spectrum



YI + '19

High energy emission from AGN coronae

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

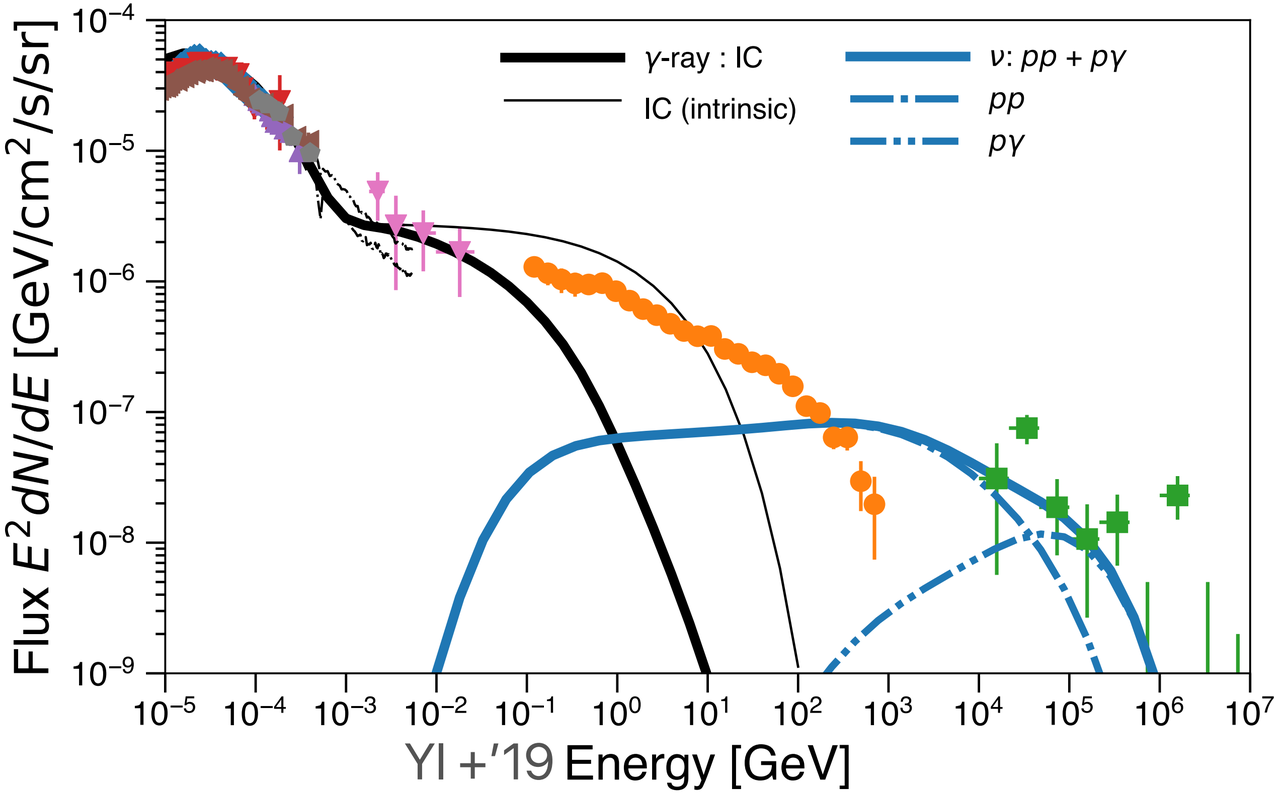


YI +'19

- MeV emission
  - but, no GeV emission
- 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

See also Kohta Murase's talk

Cosmic High Energy Background Radiation

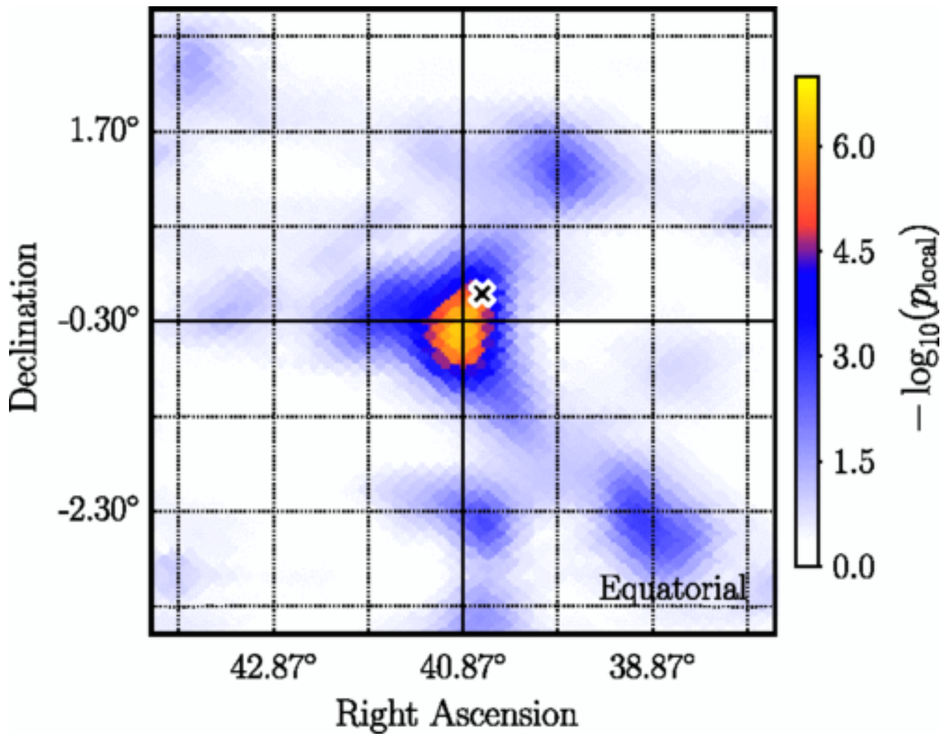


- Seyferts can explain TeV neutrino background
  (see also Begelman+'90; Stecker+'92; Kalashev+'15; Murase+'20).

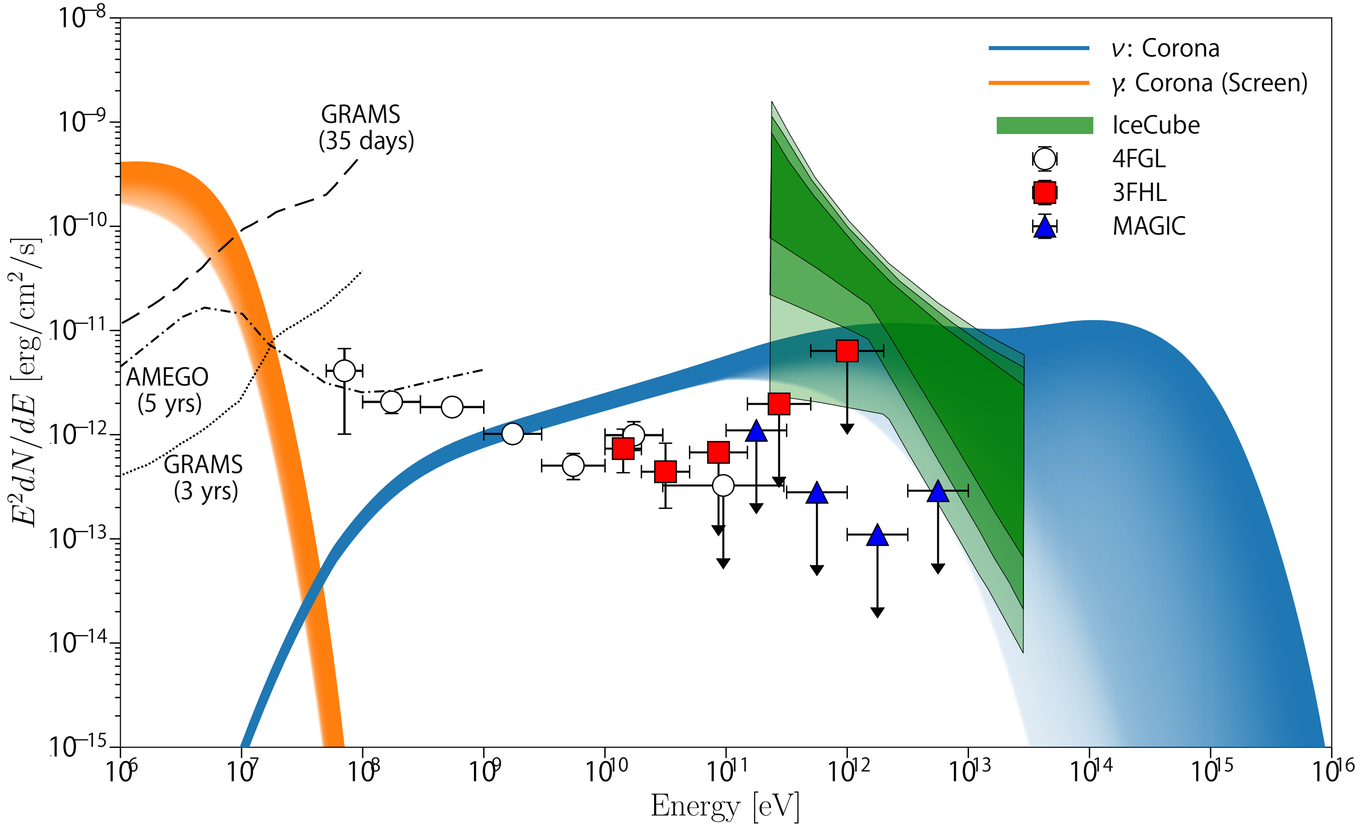
- Seyferts can explain X-ray & MeV gamma-ray background
  (YI+'08, YI+'19, Murase+'20).

IceCube Hottest Spot ?

NGC 1068 (no strong jet)



IceCube 2020



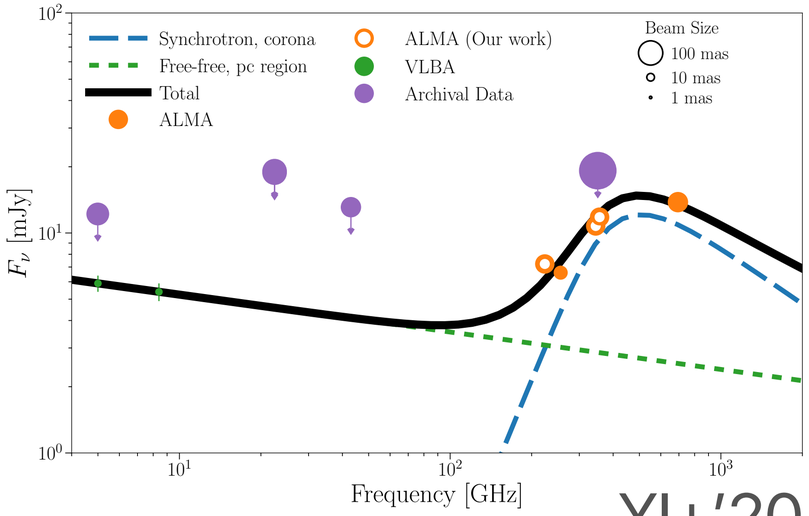
YI, Khangulyan, & Doi, '20

- 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).

How can we test the model?

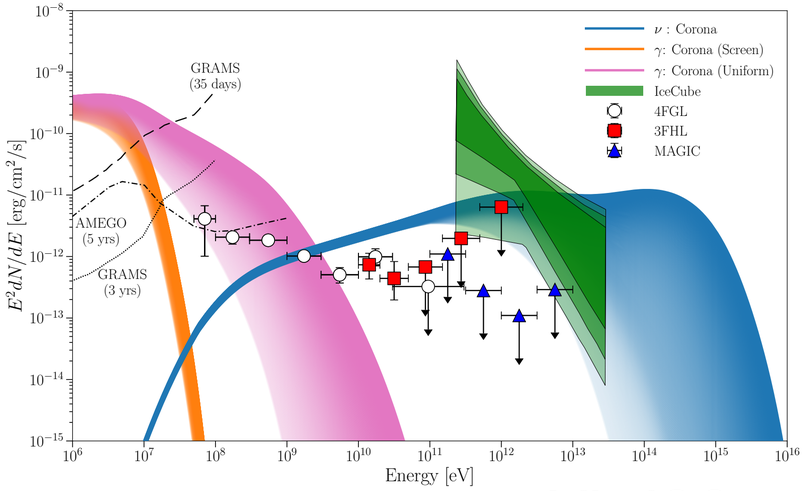
ALMA? ngVLA? FORCE? COSI-X? GRAMS? AMEGO? IceCube-Gen2? KM3Net? XRISM?

mm-band



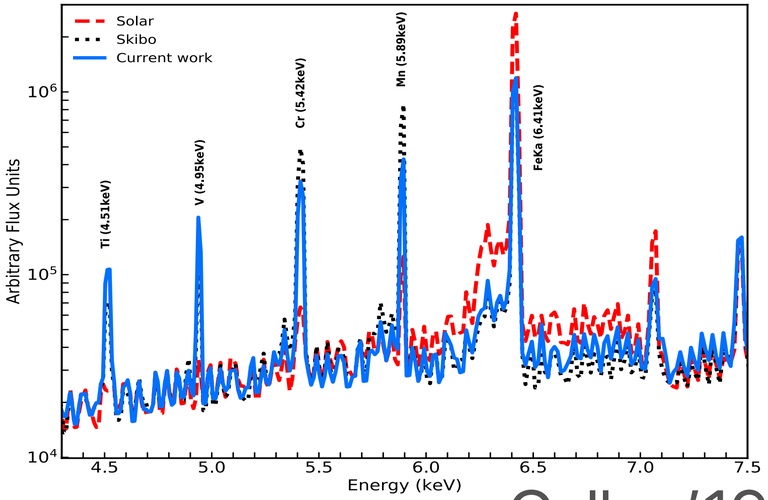
YI+'20

MeV & TeV ν



YI+'20

X-ray



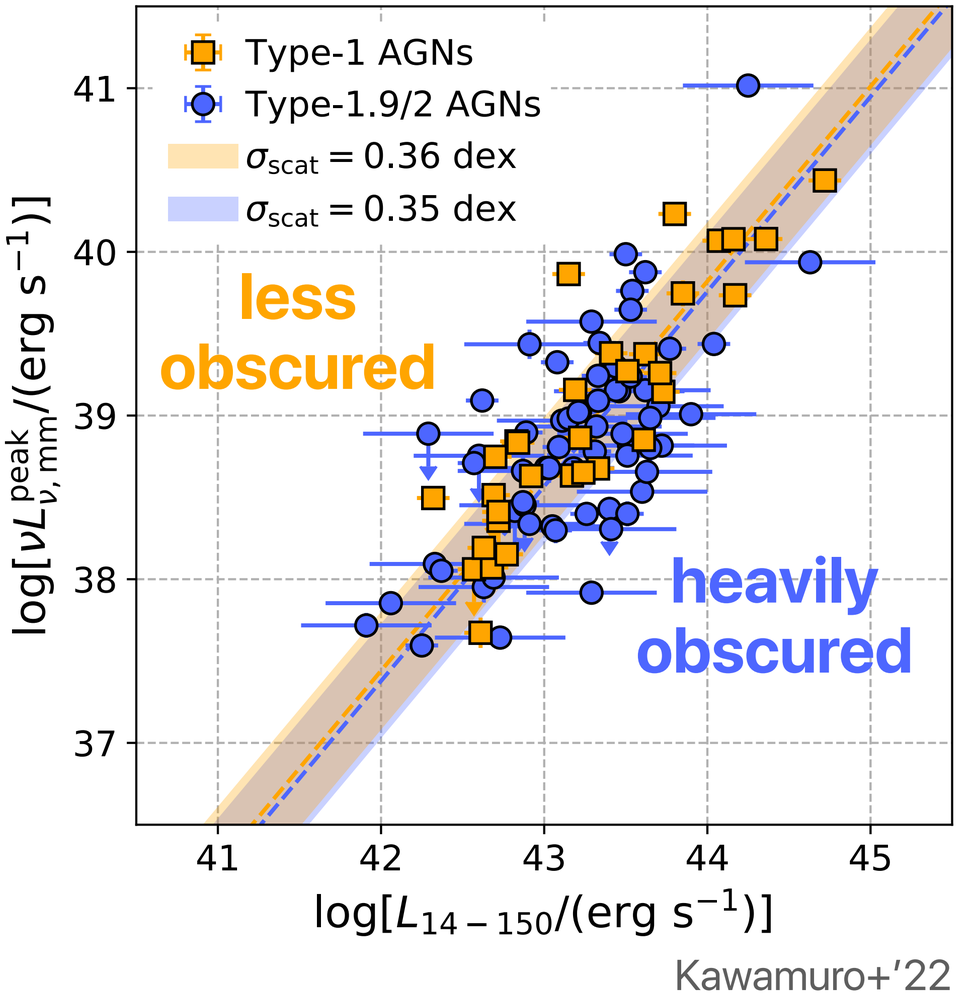
Gallo+'19

- mm-excess
- MeV PL tail

- **<u>TeV ν without GeV-TeV γ</u>**
- Nuclear spallation in X-ray

How to find Neutrino-Loud Seyferts?

Southern Sky is the best for a synergy with ALMA



Kawamuro+'22

- Dust torus attenuates Optical/X-ray emission.

  ➡ Hard X-ray survey (e.g., BAT catalog)

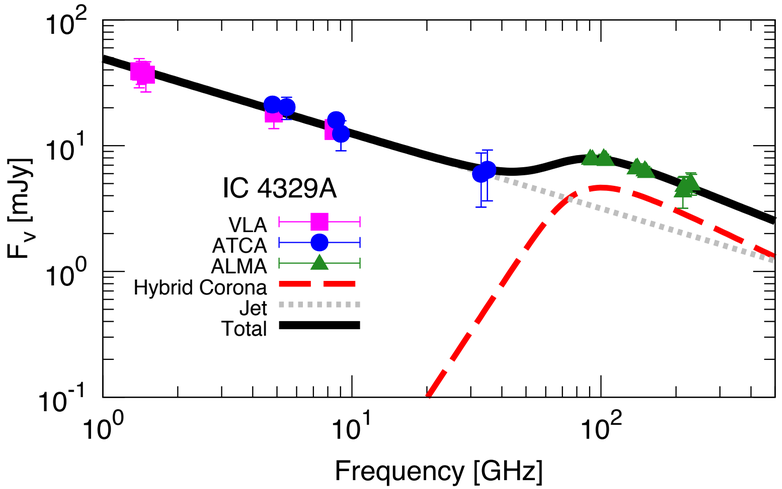
- BUT, if Compton-thick, even hard X-ray can be absorbed
  - Column density : $N_{\rm H} > 1.5 \times 10^{24}\ \rm cm^{-2}$
  - NGC 1068 is a Compton-thick AGN

- mm-wave (ALMA) will not.

- BAT survey + follow-up by (ALMA + KM3NeT) is the best solution.

Summary

- Unjetted AGNs ~ Radio-quiet AGNs ~ Seyferts
- Non-thermal radio emission in Seyfert SED is now seen by ALMA.
  - Originated in AGN corona
- AGN Corona is a production site of high energy particles.
  - Faint but Many in the sky
  - Can explain IceCube neutrino events (NGC 1068)
- BAT survey + follow-up by (ALMA + KM3NeT) will be the best to find neutrino-loud Seyferts



YI & Doi '18

Reconnection Corona Heating?

Implication for the truncated accretion disk structure.

- Heating vs Cooling
  - Magnetic Heating: $B^2 V_A / 4\pi$
    - $Q_{B,\,heat}$ ~ **10^{10}** erg/cm^2/s
  - Compton Cooling: $4kTn_e\sigma_T c U_{\rm rad} l / m_e c^2$
    - $Q_{IC,\,cool}$ ~ **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).