Non-thermal Coronal Activity in Seyfert Galaxies

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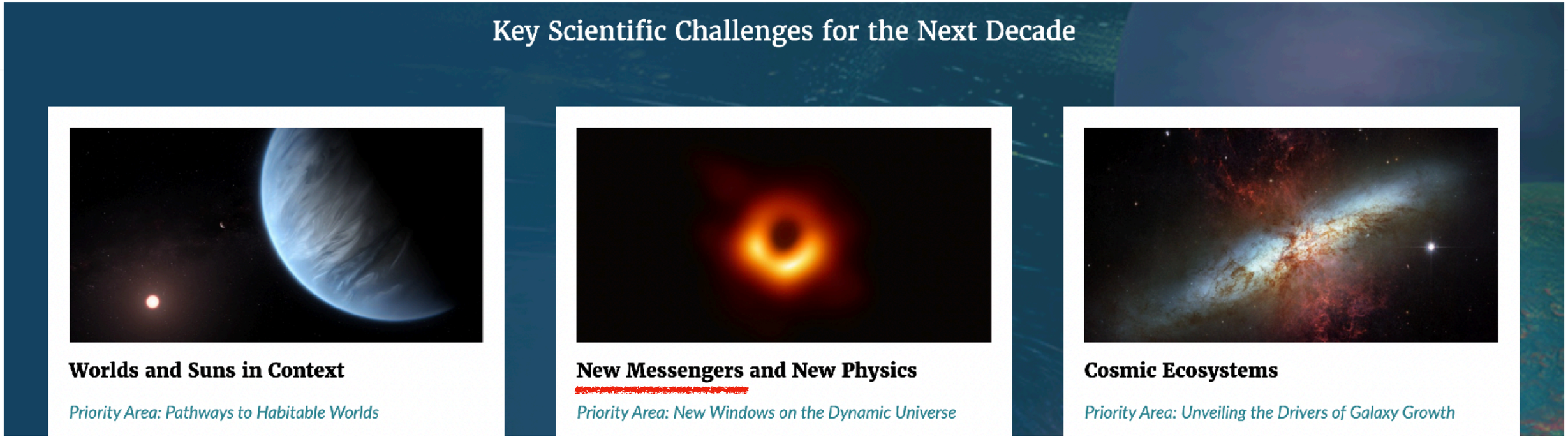
Introduction

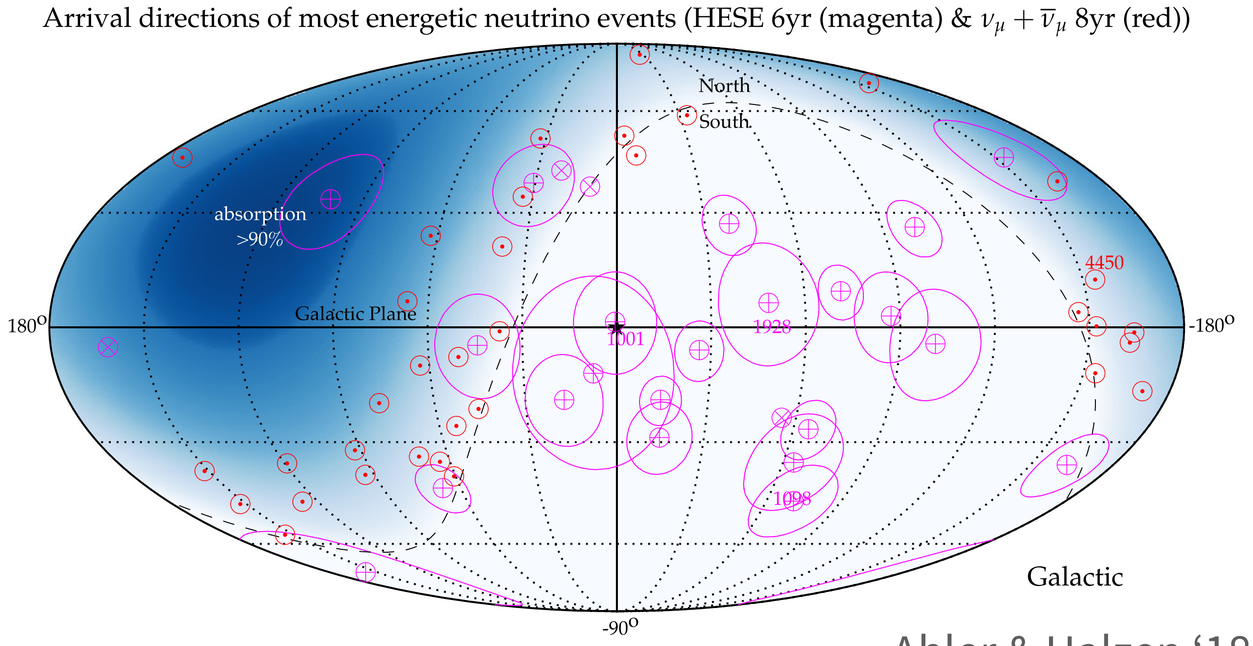
Pathways to Discovery in Astronomy and Astrophysics for the 2020s



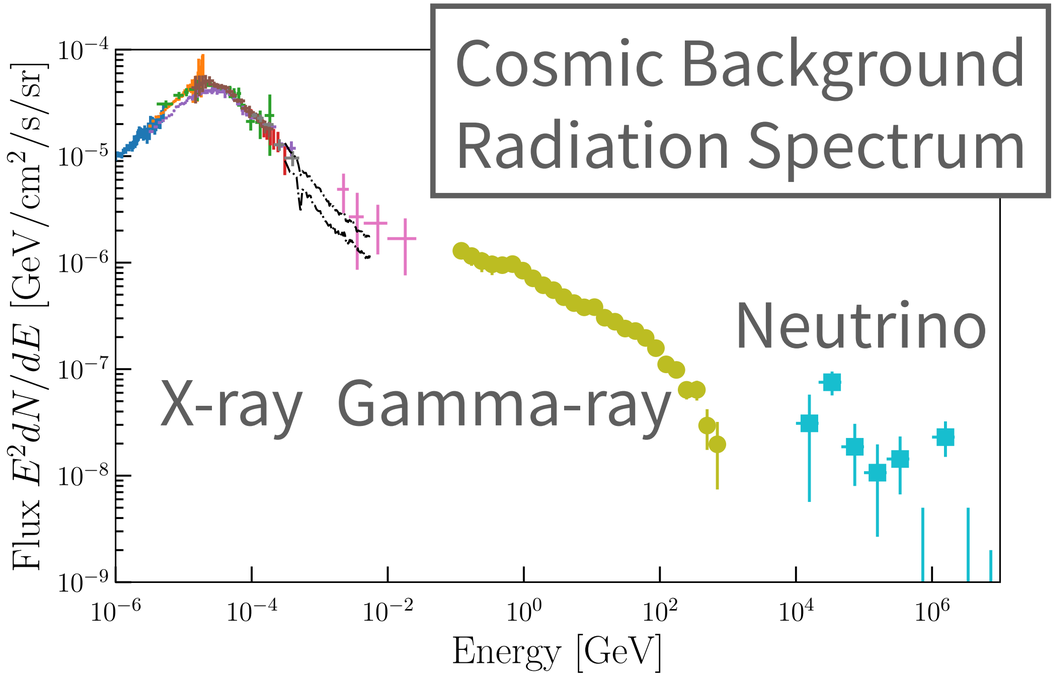
- Two frontiers in Multi-Messenger Astronomy:
  - Gravitational Waves
  - Neutrinos

What are the origins of high energy neutrinos?

$\gtrsim 100$ Neutrinos (TeV-PeV) from the sky



Ahler & Halzen '18

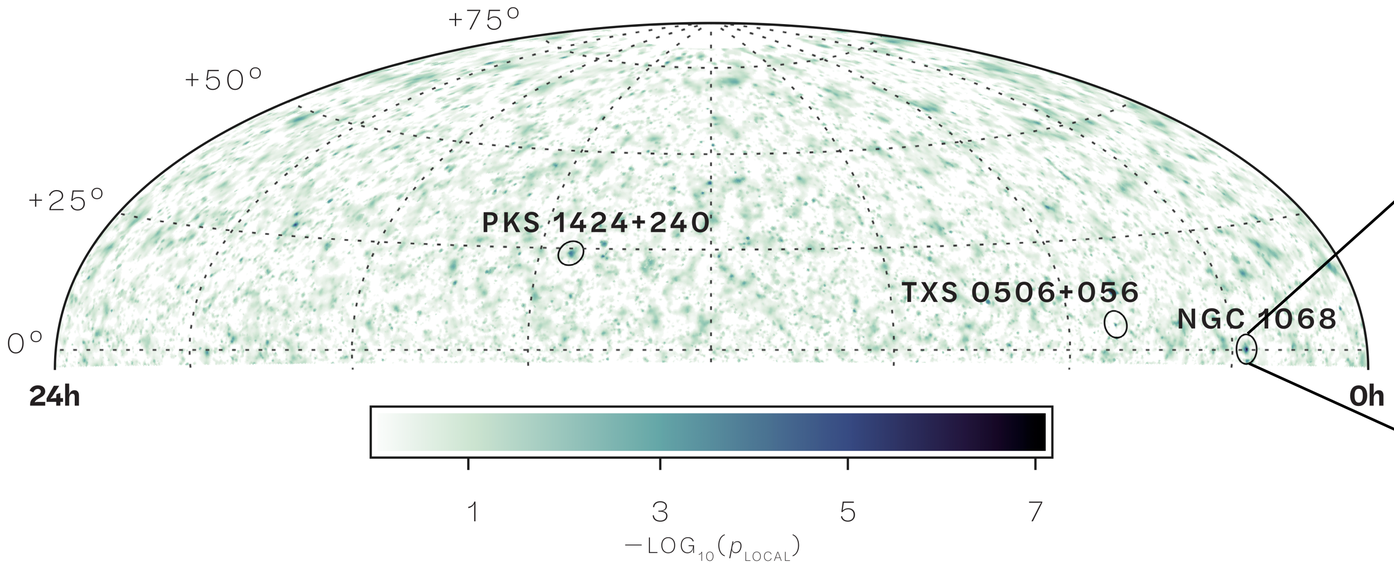


- Cosmic Neutrino Flux level = $0.1 \times$ Cosmic GeV Gamma-ray Background (CGB)
  $= 10^{-3} \times$ Cosmic X-ray Background (CXB)

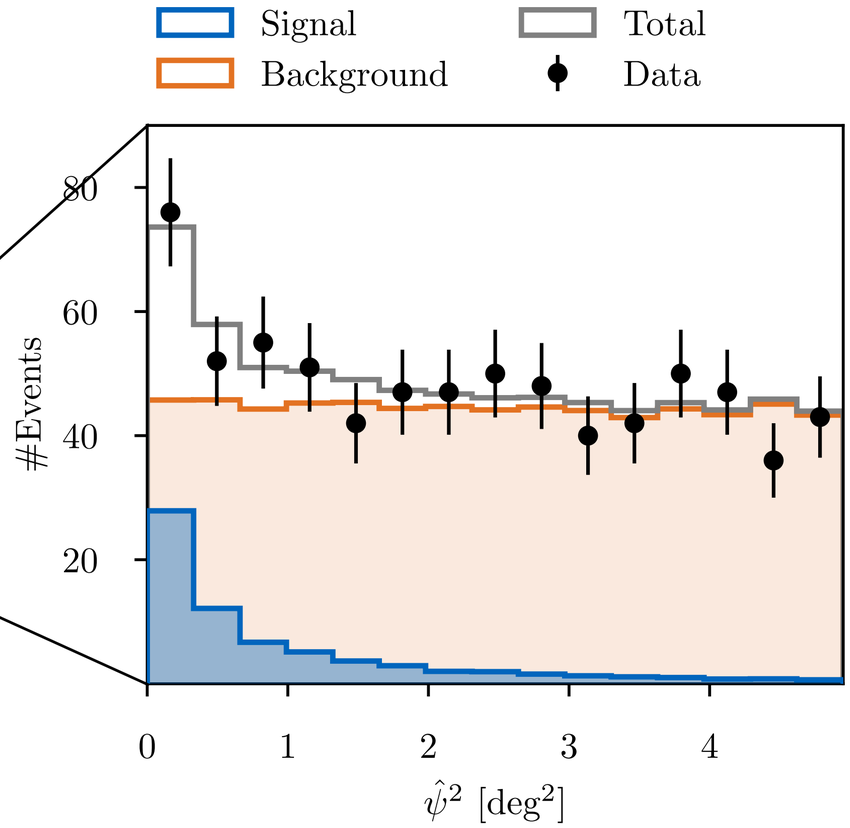
- CXB and CGB are dominated by **Active Galactic Nuclei (AGNs)**.

IceCube detection of TeV neutrinos from NGC 1068

Evidence of Non-thermal Activity in a Seyfert galaxy



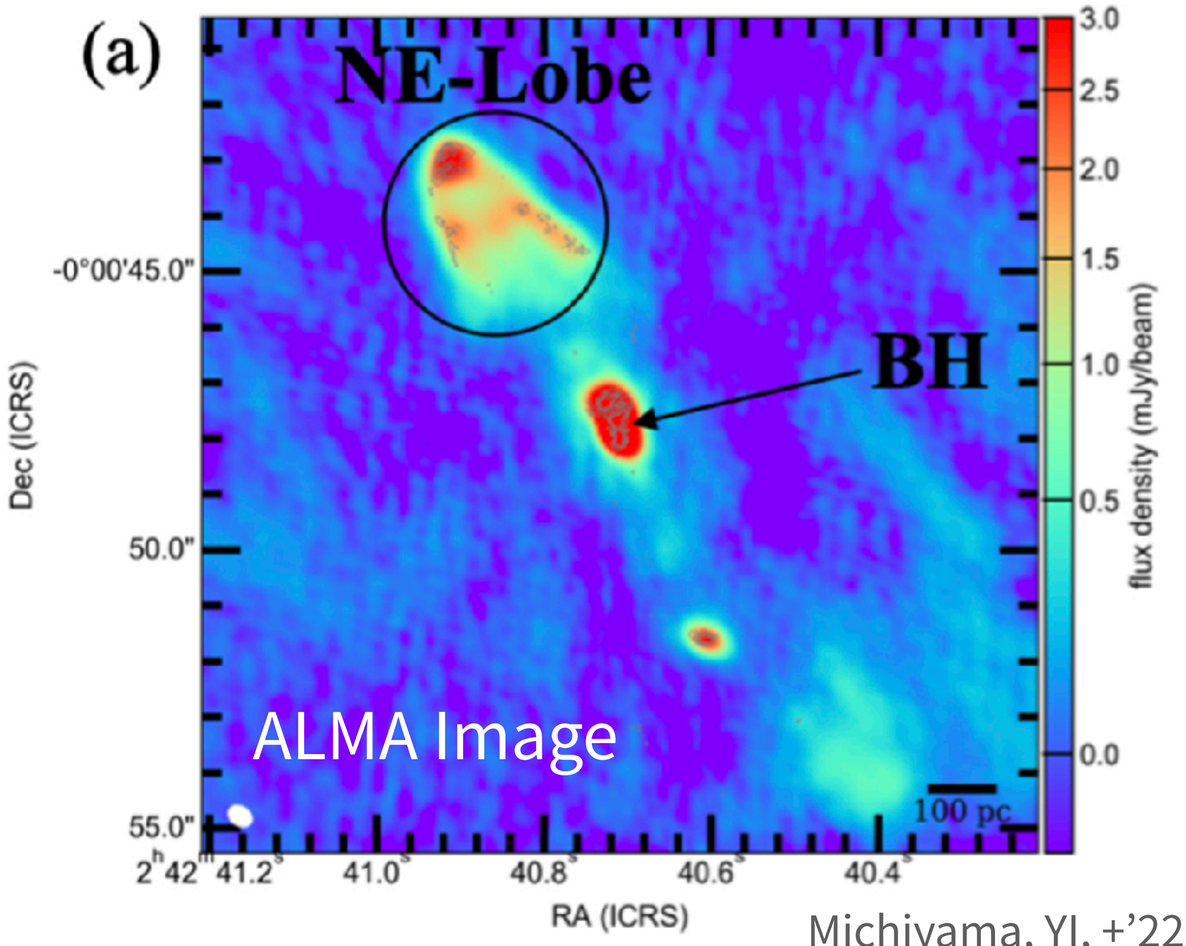
IceCube 2022



IceCube 2022

What is NGC 1068?

An obscured Seyfert galaxy with a weak jet activity

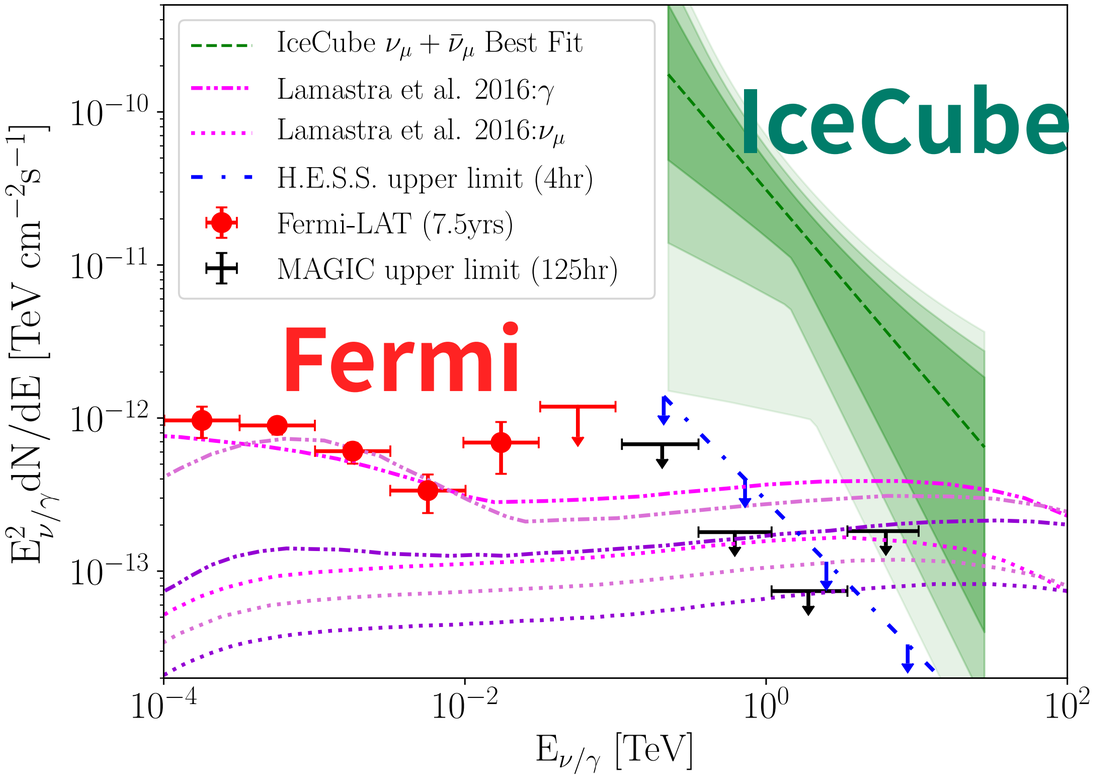


Michiyama, YI, +'22

Where is the neutrino production site?

"Neutrino flux > Gamma-ray flux" = Gamma-ray Optically-Thick 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**

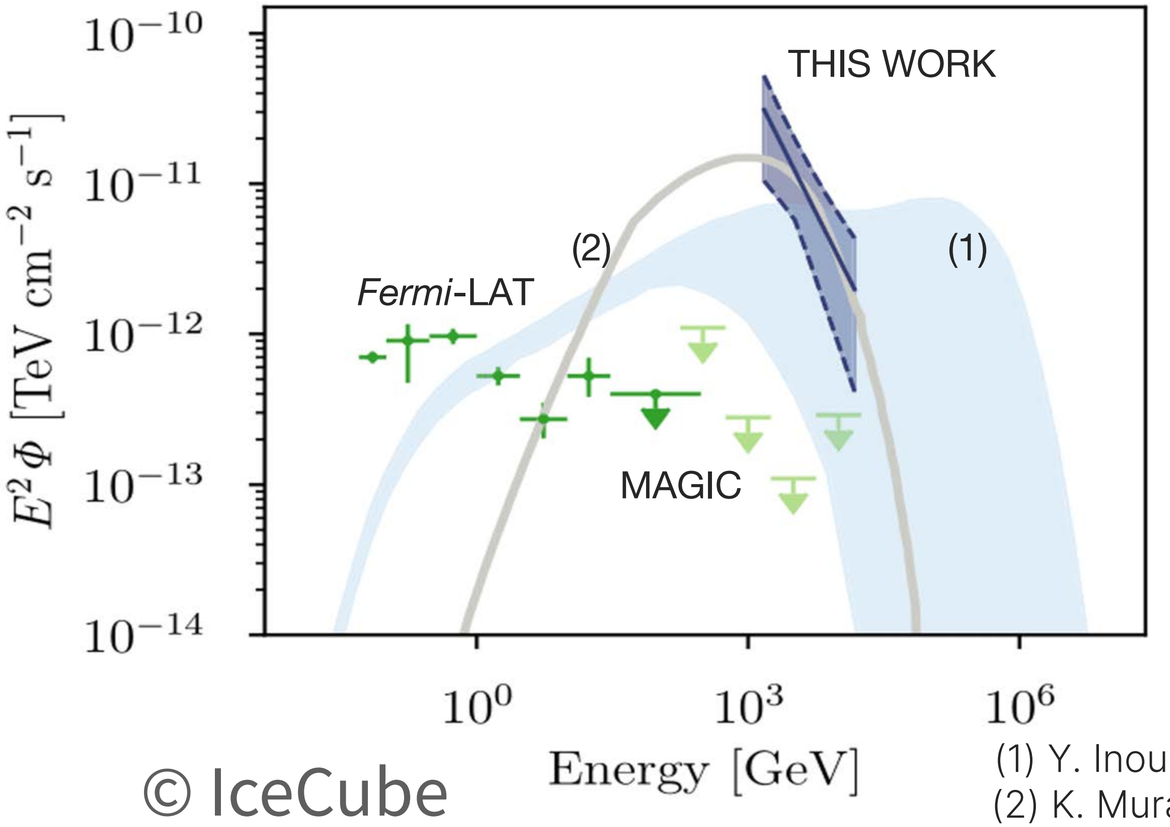


IceCube 2020

Neutrino Emission from Seyfert Corona

High energy particle acceleration in AGN corona region?

NGC 1068: a cosmic obscured accelerator



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

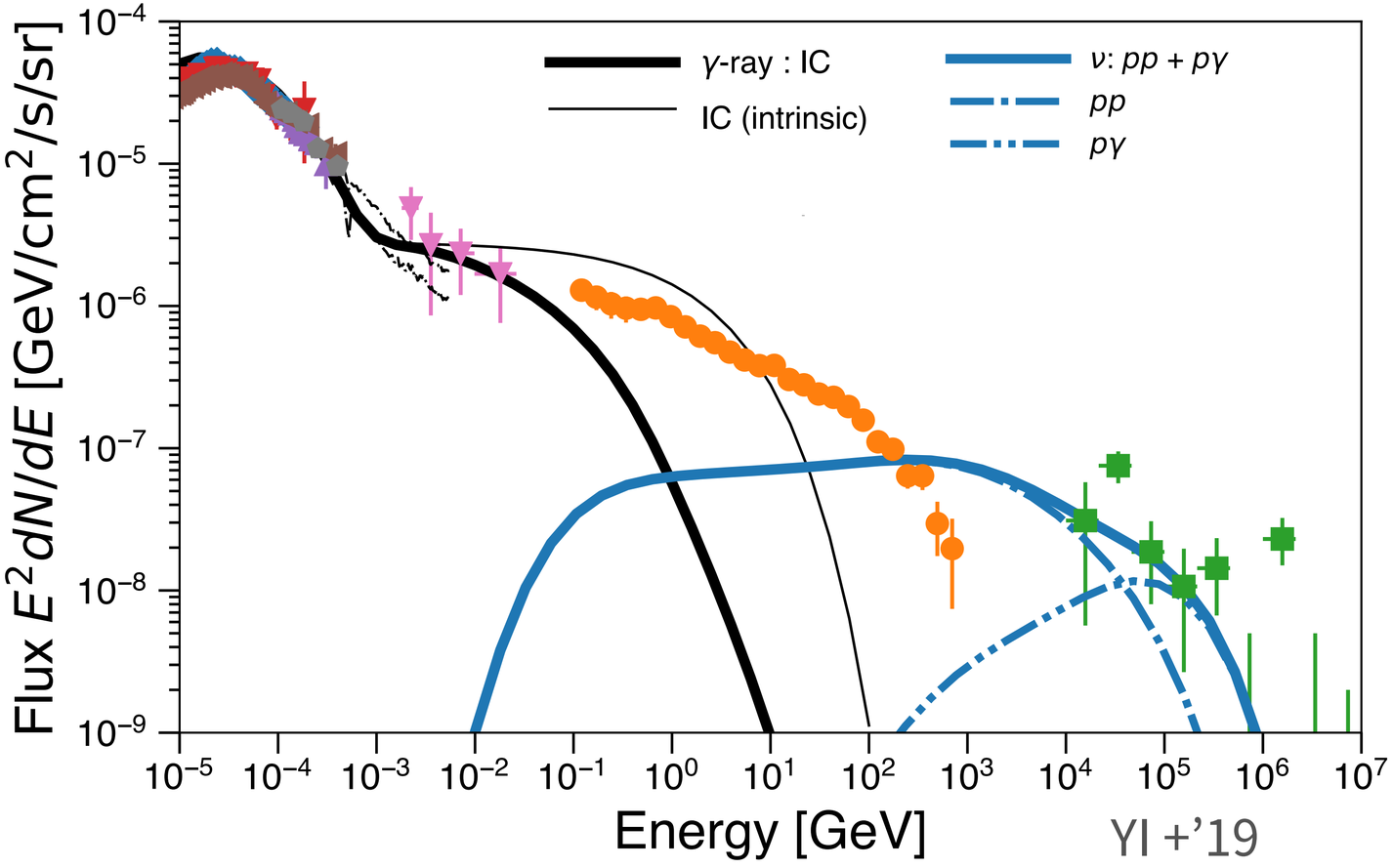
➡ $L_{\mathrm{CR}}(>10\ \mathrm{TeV}) \sim 10^{43}\ \mathrm{erg/s}$

  - Note: $L_X \sim 3-7\times10^{43}\ \mathrm{erg/s}$
- If cosmic rays exist in corona region,
  - pp and/or $p\gamma$ interactions can produce neutrino emission.

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

Cosmic High Energy Background Radiation

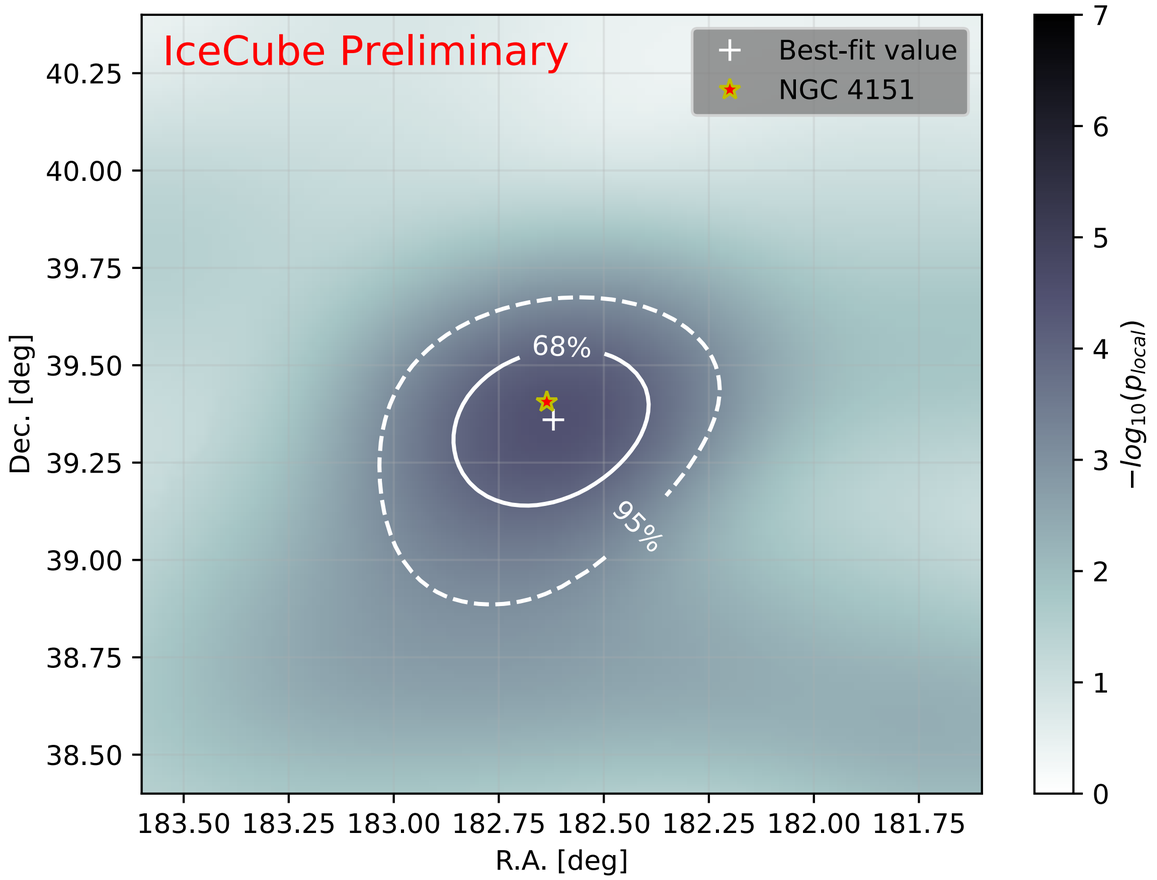
If Seyferts are neutrino sources,



- Seyferts can simultaneously explain
  - TeV neutrino background
    (see also Begelman+'90; Stecker+'92; Kalashev+'15; Murase+'20).
  - X-ray background
    (e.g., Ueda+'03, Ueda+'14).
  - MeV gamma-ray background
    (e.g., YI+'08, YI+'19, Murase+'20).

Another Seyfert candidate: NGC 4151

"2.9-sigma"



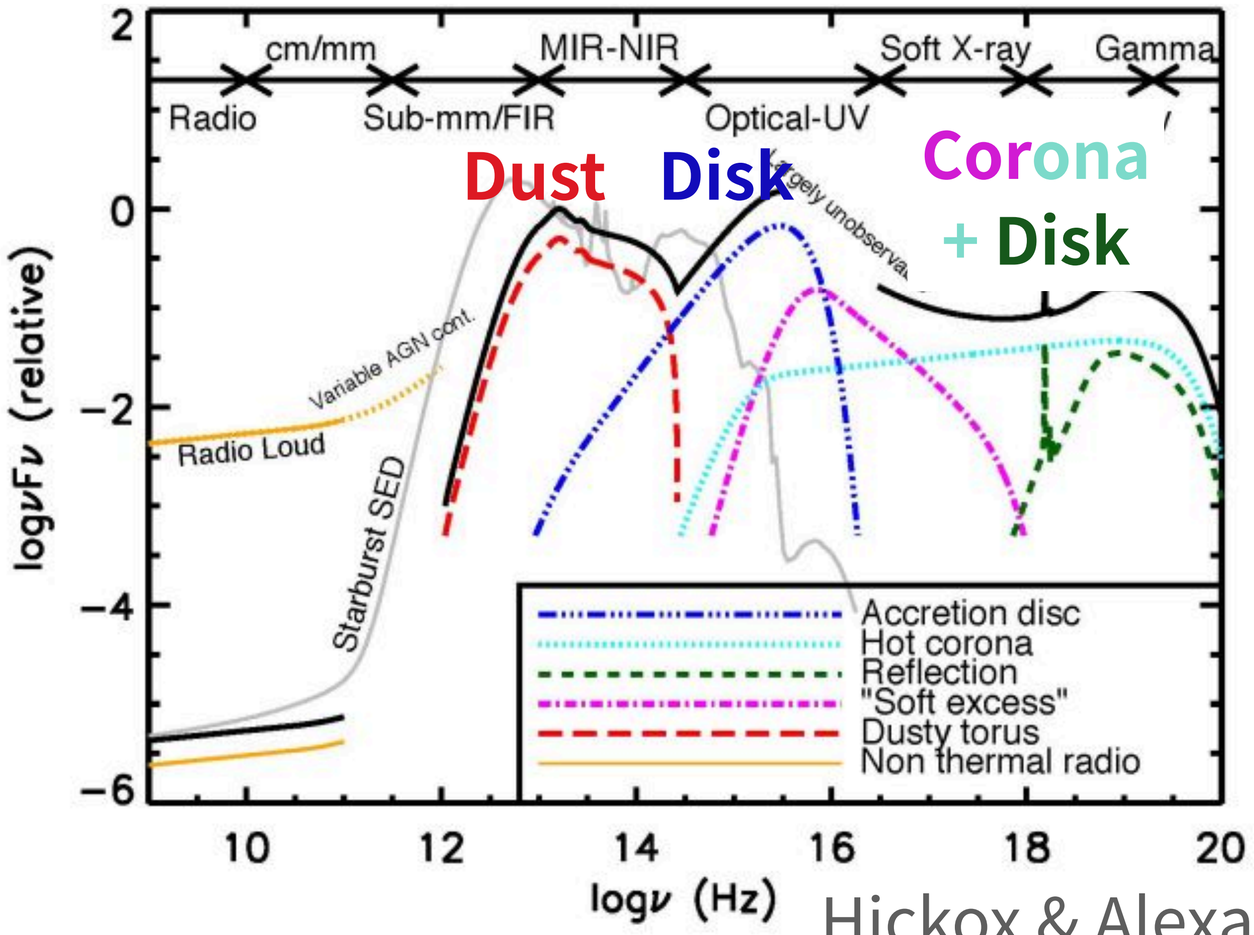
2307.15349

- At ICRC 2023, IceCube reported 2.9-sigma detections of NGC 4151 and CGCG 420-015.
- NGC 4151 is the apparently brightest Seyfert galaxy in X-ray band.
- **But, have we seen any evidence of non-thermal activity in Seyfert galaxies?**

Non-thermal Activity in Seyfert Galaxies

Do we see non-thermal activities in Seyferts?

No, we haven't! Thermal emission dominates everything.

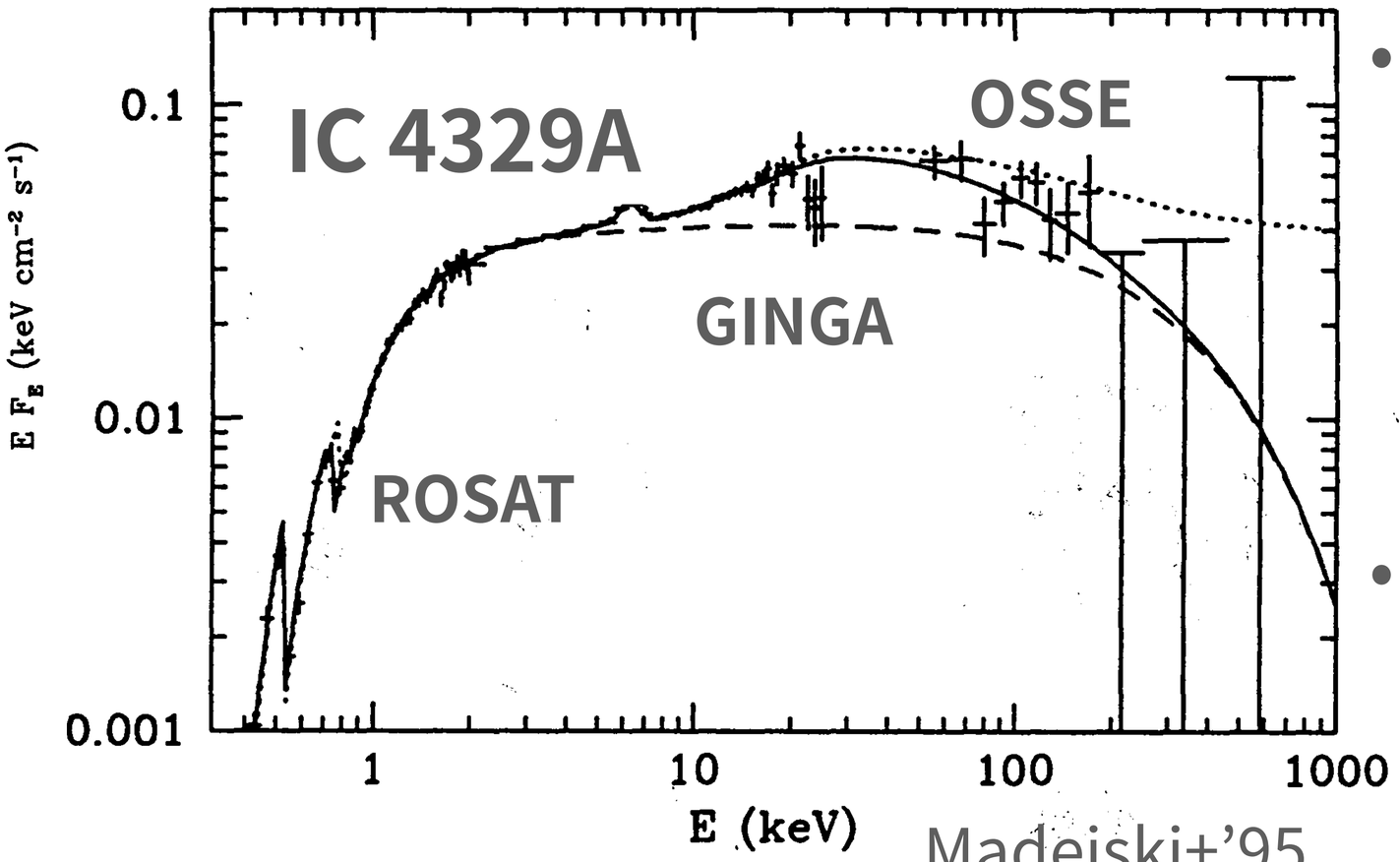


- If Seyferts are neutrino sources,
  - we should see non-thermal emission.
- BUT, thermal emission is everything.
- **Where is non-thermal signature?**

Hickox & Alexander+'16

Investigation of non-thermal activities in Seyferts

X-ray ? GeV ? MeV ?



Madejski+’95

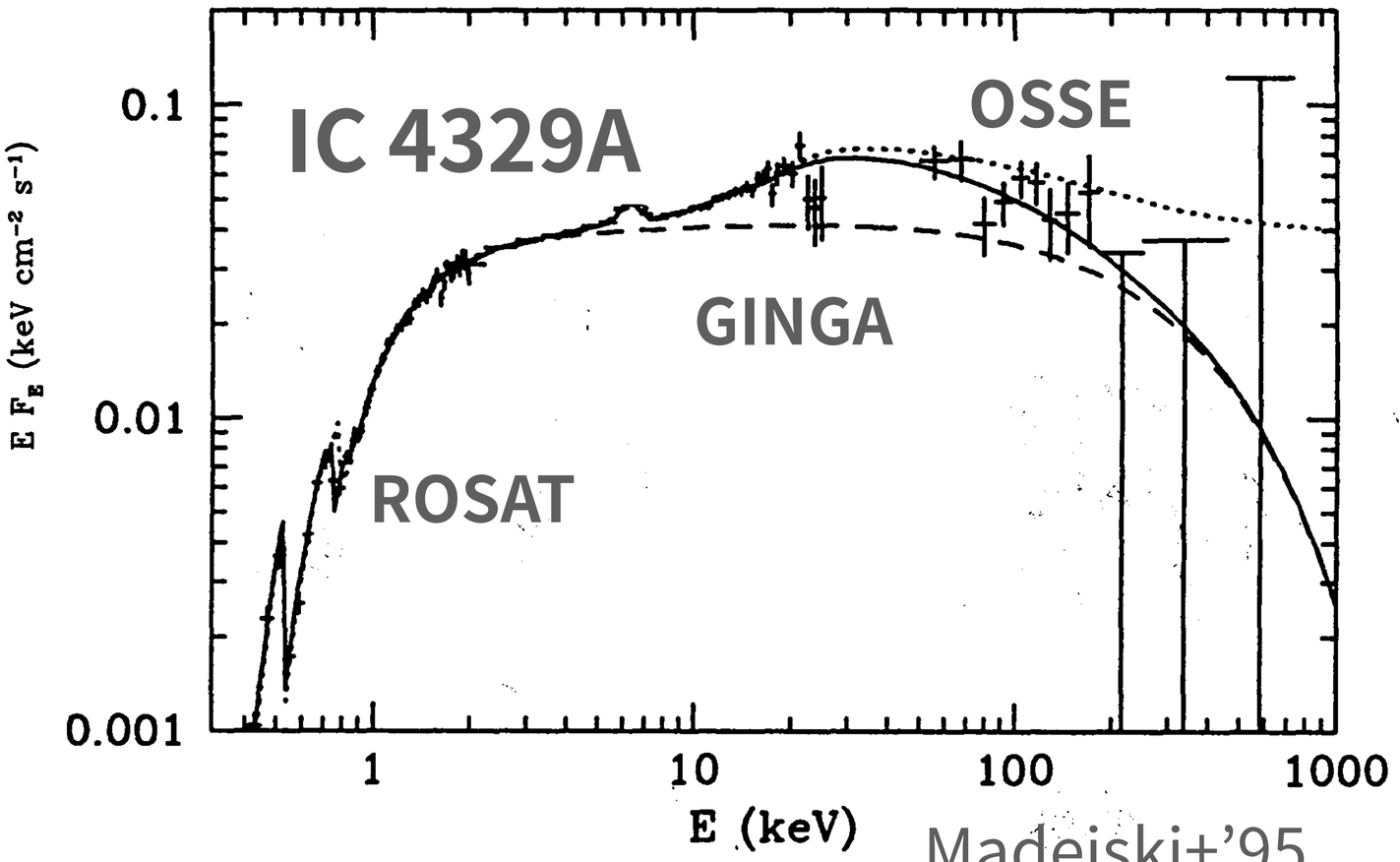
- Cascade or Synchrotron Self-Compton for X-ray continuum (e.g., Kazanas & Ellison ’86; Zdziarski ’86)

  ➡Neutrino emission (Stecker+’92)

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

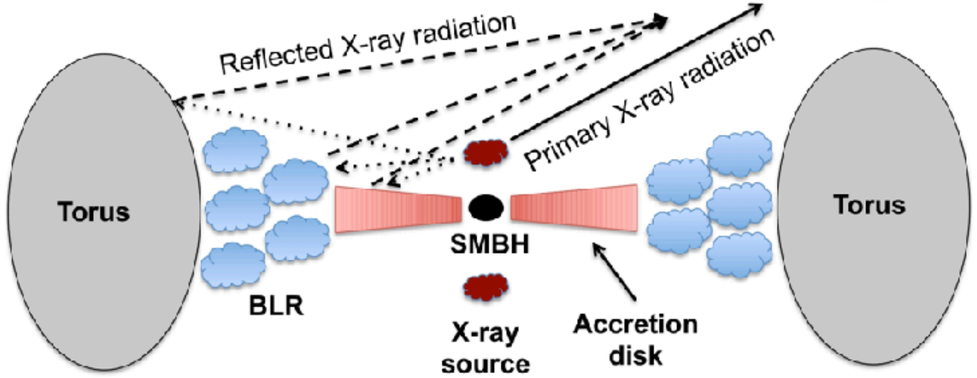
X-ray emission is from black hole corona

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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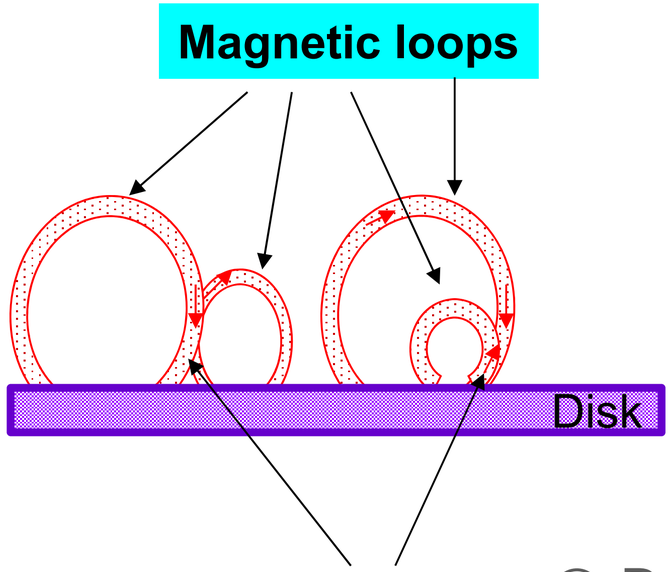
Coronal Synchrotron emission?

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)
  - Non-thermal electrons in corona?
    (YI, Totani, & Ueda ’08)
- **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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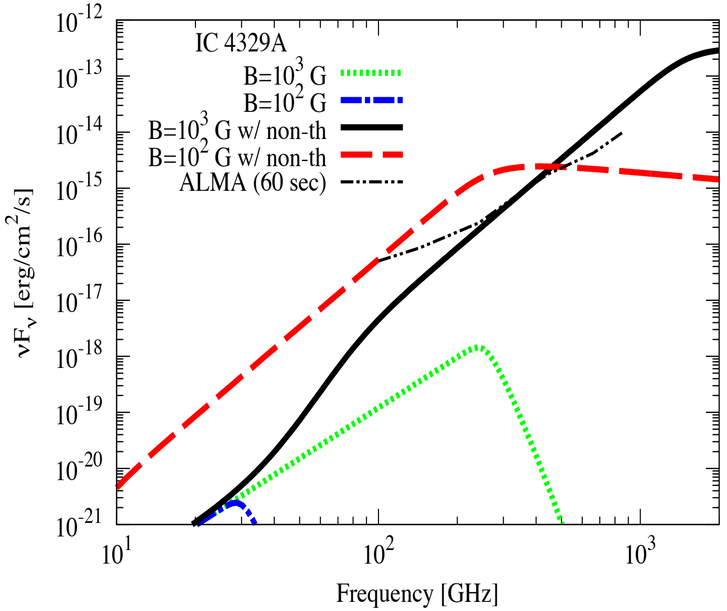
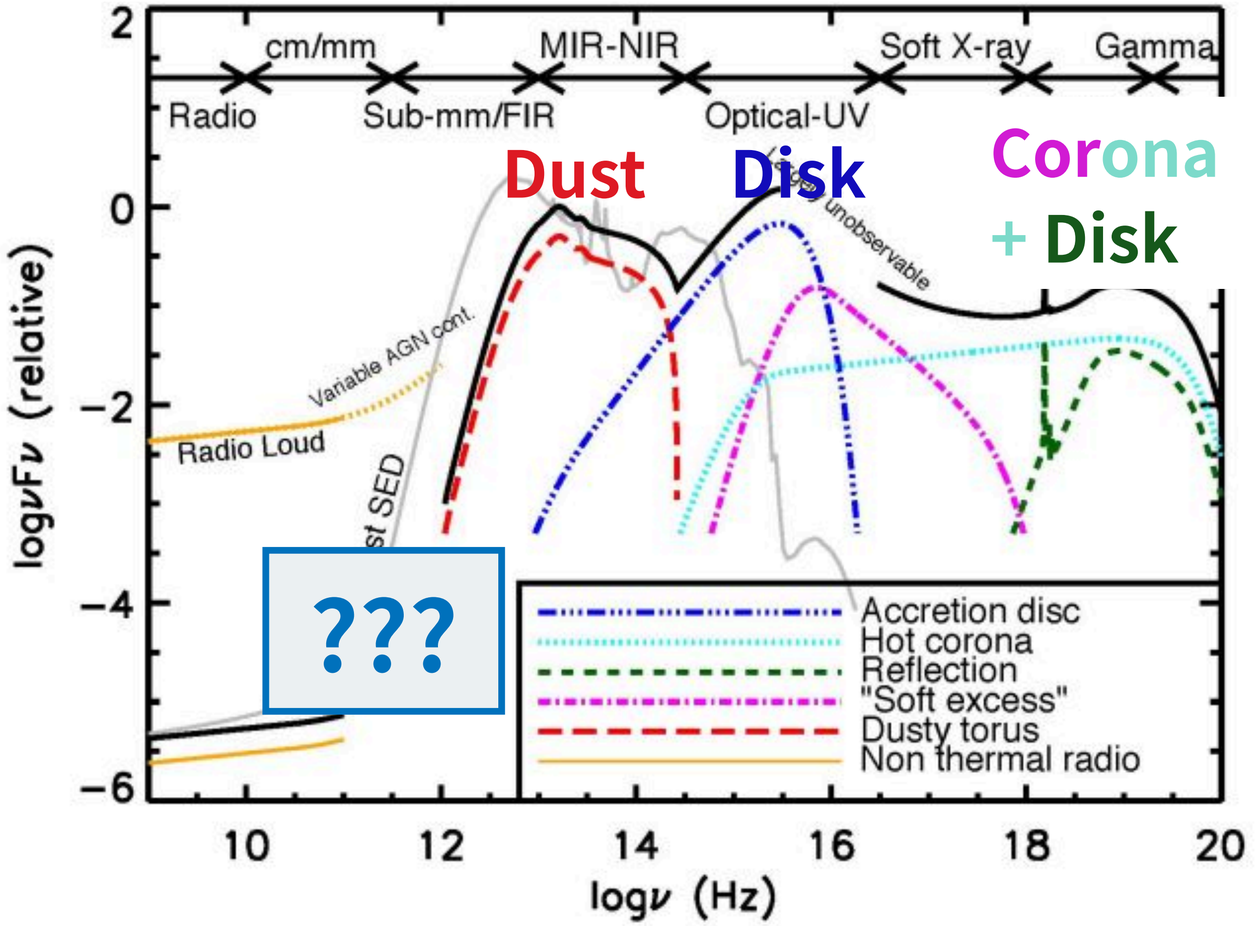


YI & Doi ‘14

Coronal Magnetic Activity in Seyfert Galaxies

Do we understand all the activities in Seyferts?

Mostly yes. But, mm-wave is still an open and accessible window!

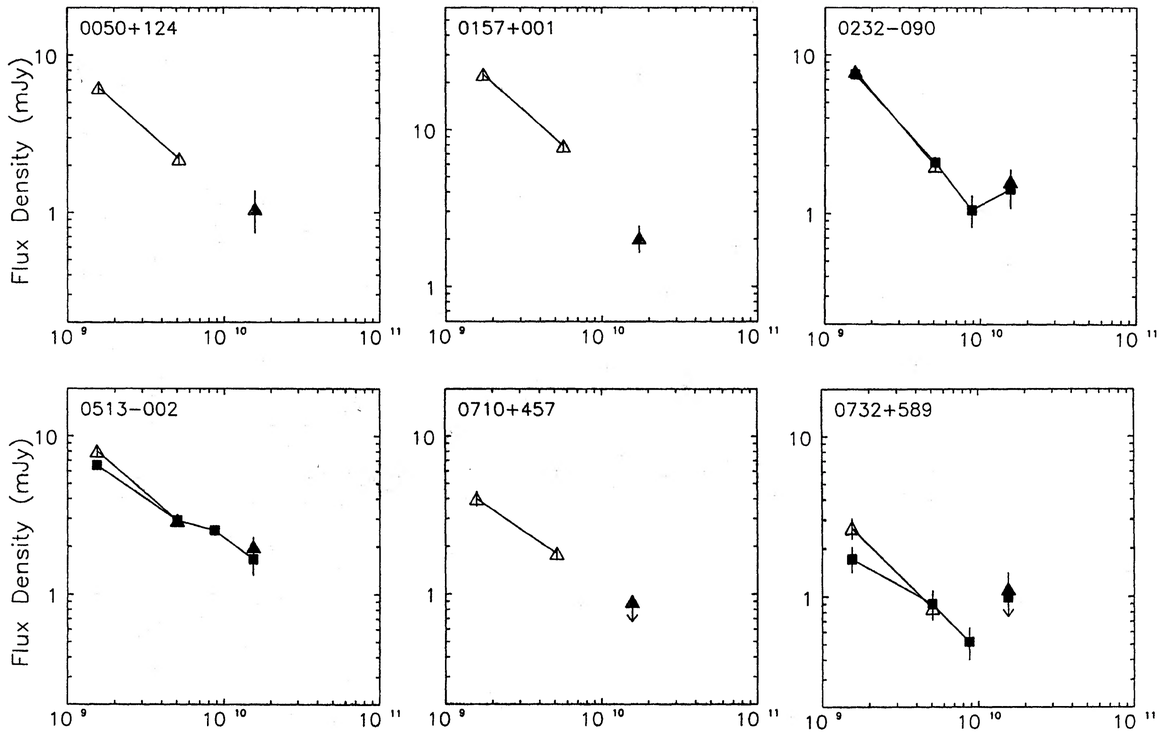


- millimeter-wave band is not well investigated.
  - Why? Because of dust
- Dust emission would be much brighter than coronal synchrotron signals.

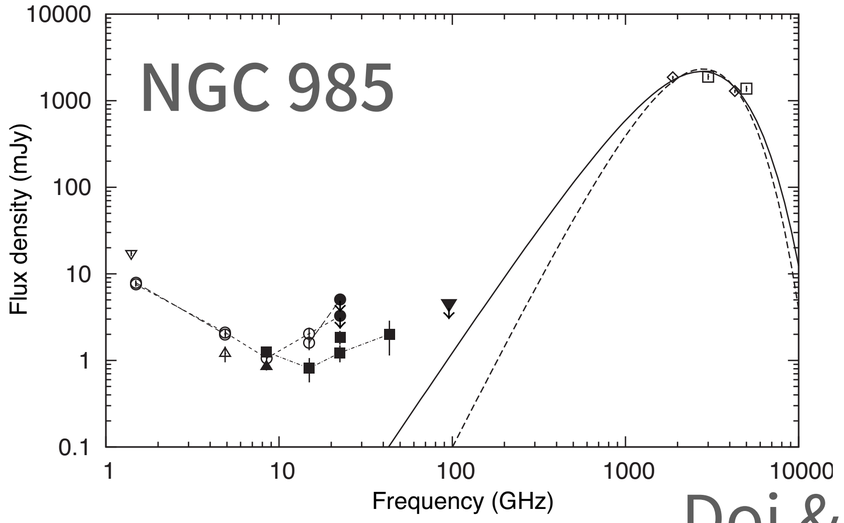
Hickox & Alexander+'16

Hints of millimeter excess in nearby Seyferts

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



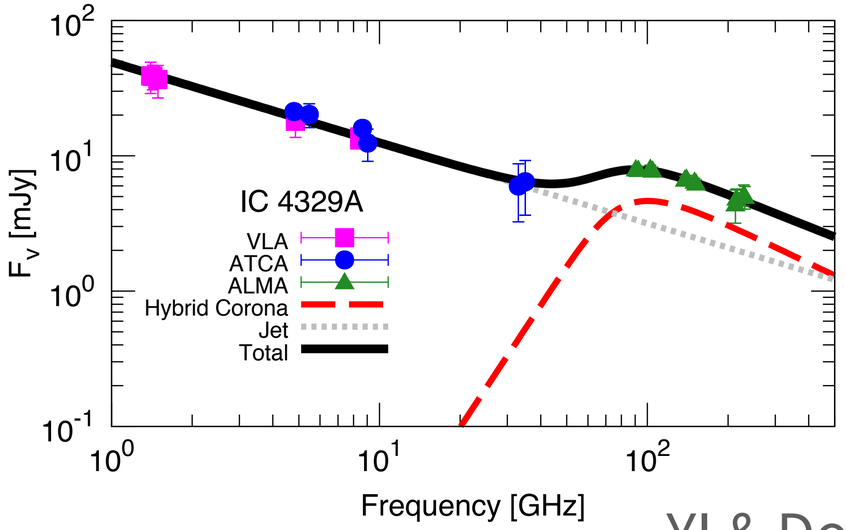
Barvainis+'96



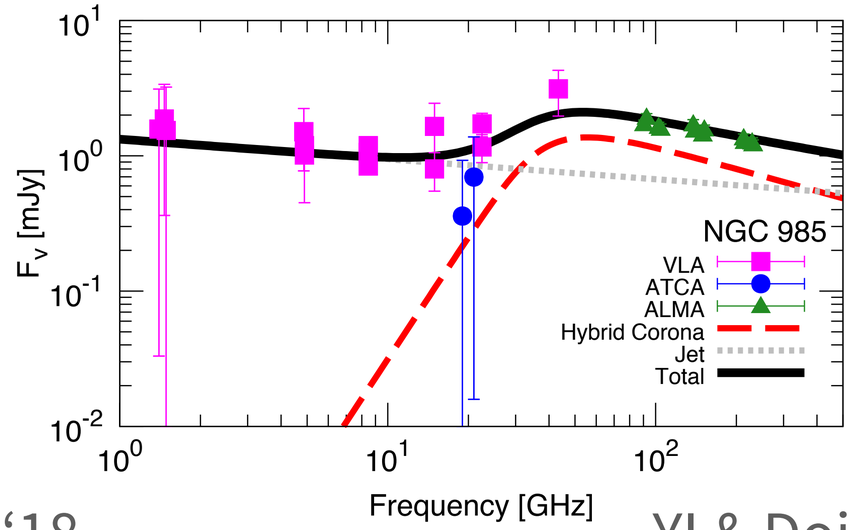
Doi & YI '16

- 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?

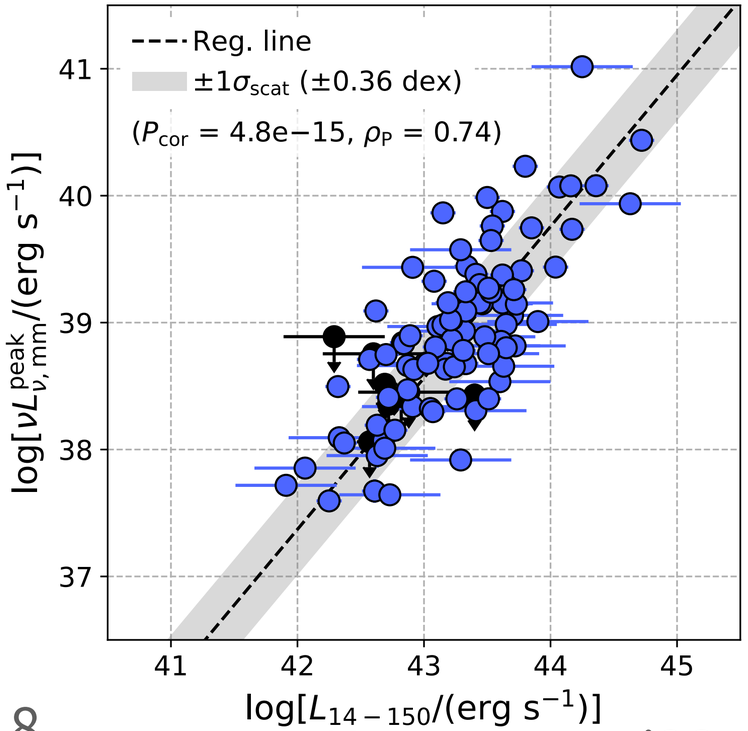
ALMA observations toward nearby Seyferts



YI & Doi ‘18



YI & Doi ‘18



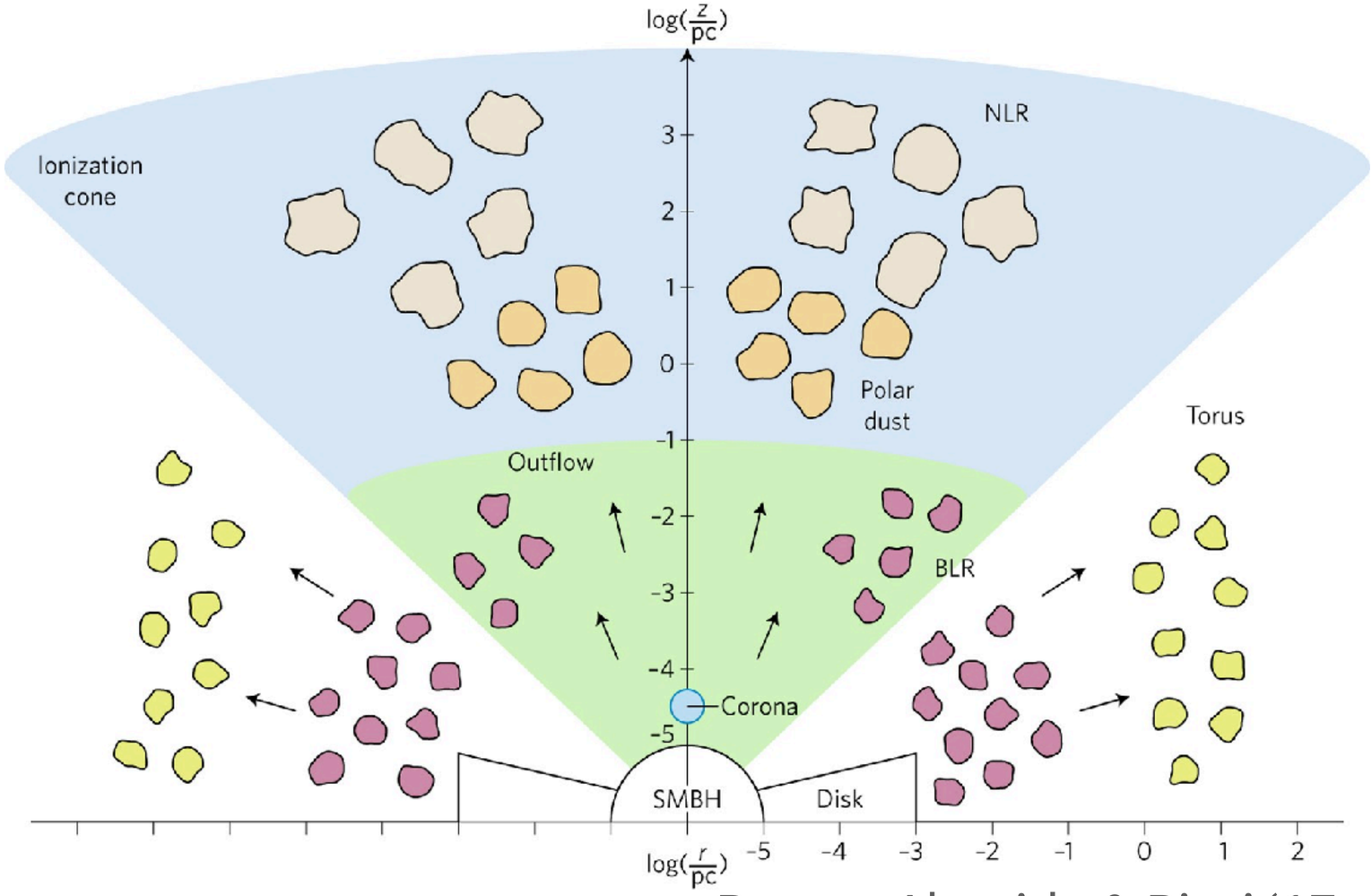
Kawamuro+’22

Michiyama, YI, + submitted

- **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+ submitted; Barnier, YI +in prep.)
- Correlation b/w mm and X-ray luminosities (Kawamuro+’22, Ricci+’23)
- Size : < 10 pc → Nucleus

Structure of AGN core in the <10 pc scale

Where is the origin of the mm excess?

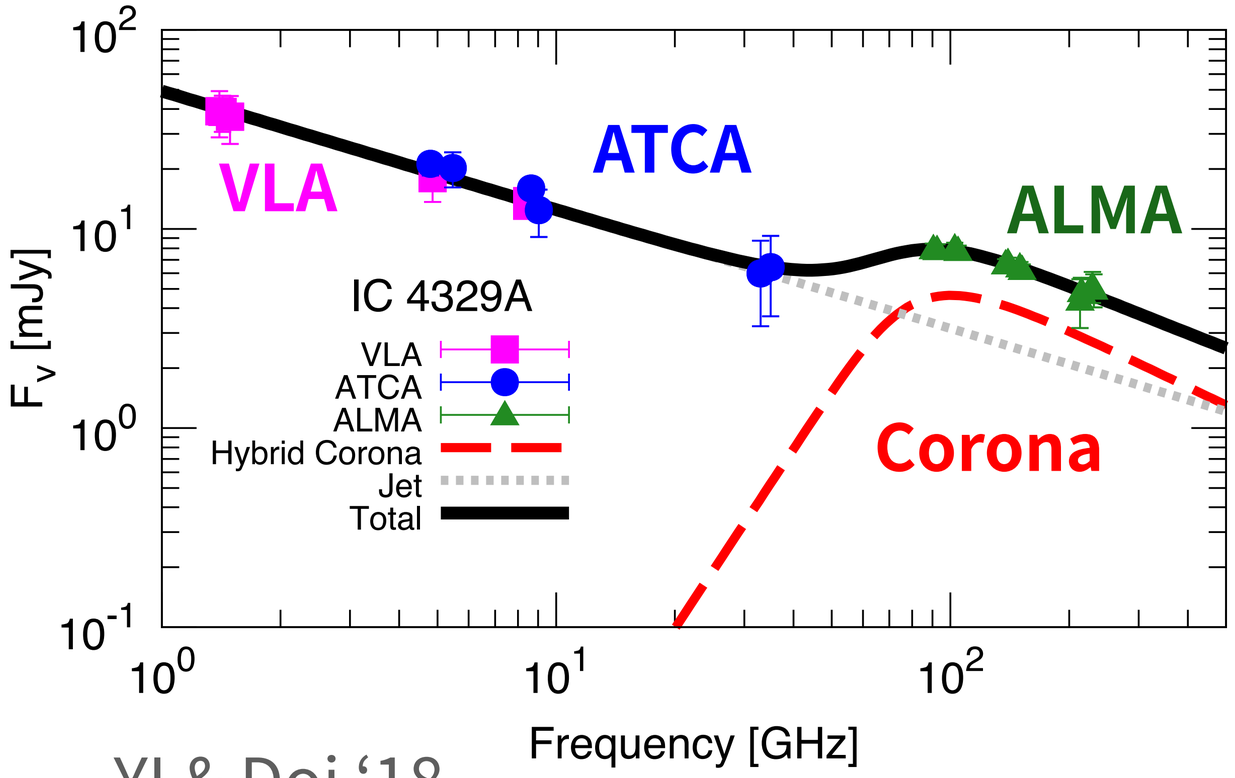


Ramos-Almeida & Ricci ‘17

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

cm-mm spectrum of AGN core

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



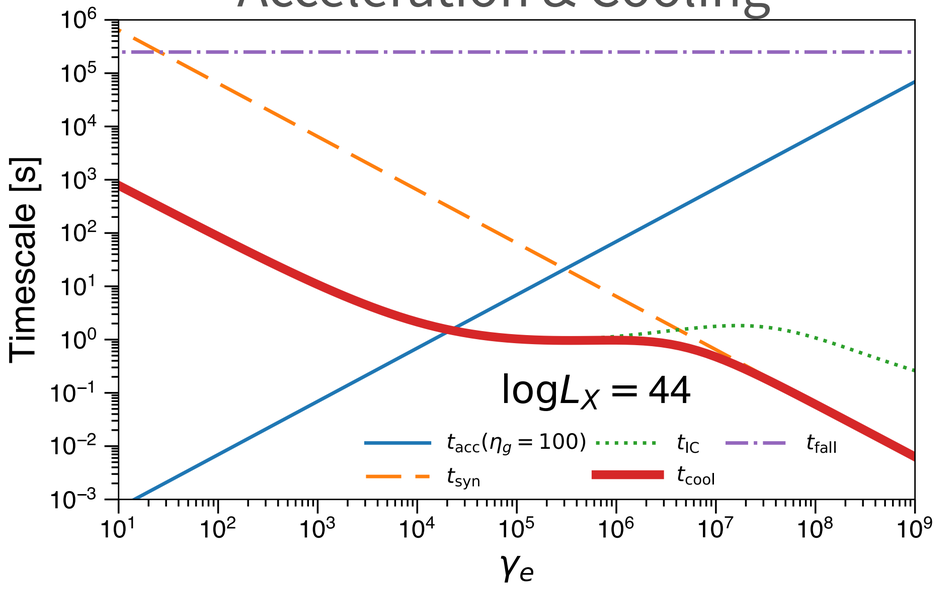
YI & Doi ‘18

- 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

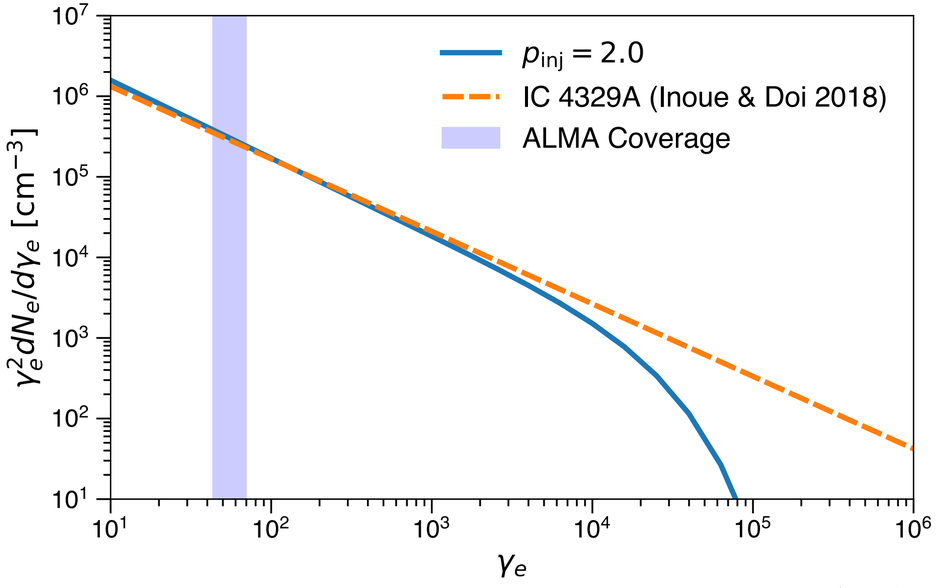
Generation of non-thermal electrons in coronae

- 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?**
  - Time variability is a key to answer this question.
- Note: more ALMA samples are needed.

Acceleration & Cooling



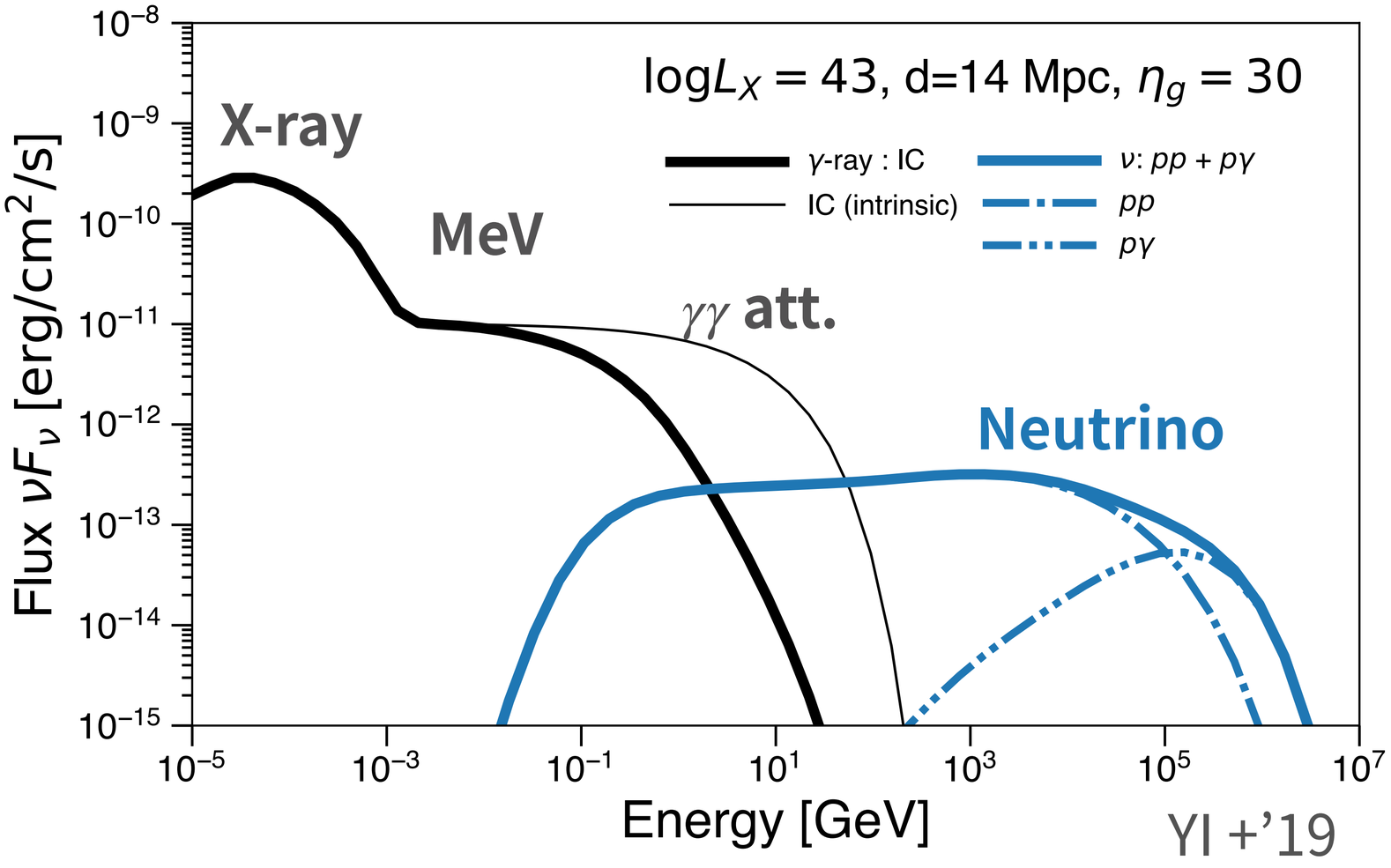
Electron Spectrum



YI + '19

High energy emission from AGN coronae

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



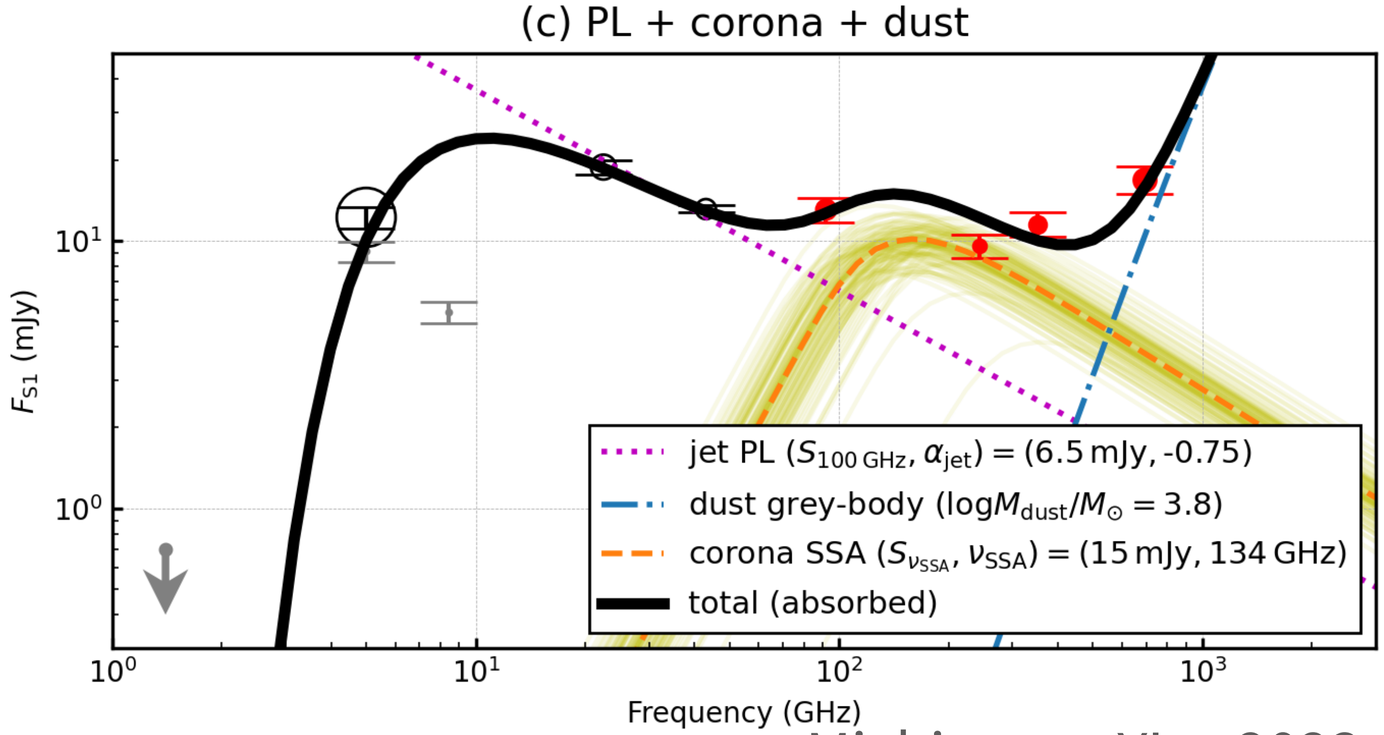
YI +'19

- MeV emission
  - but, no GeV emission
- Protons would be accelerated

  ➡high energy neutrinos
- **Proton power is determined to reproduce the data**
- See also Stecker+'91, '92, '05, '13; Kalashev+'15; Murase+'20; Gutiérrez +'21; Kheirandish+'21

ALMA Observations toward the NGC 1068 Core

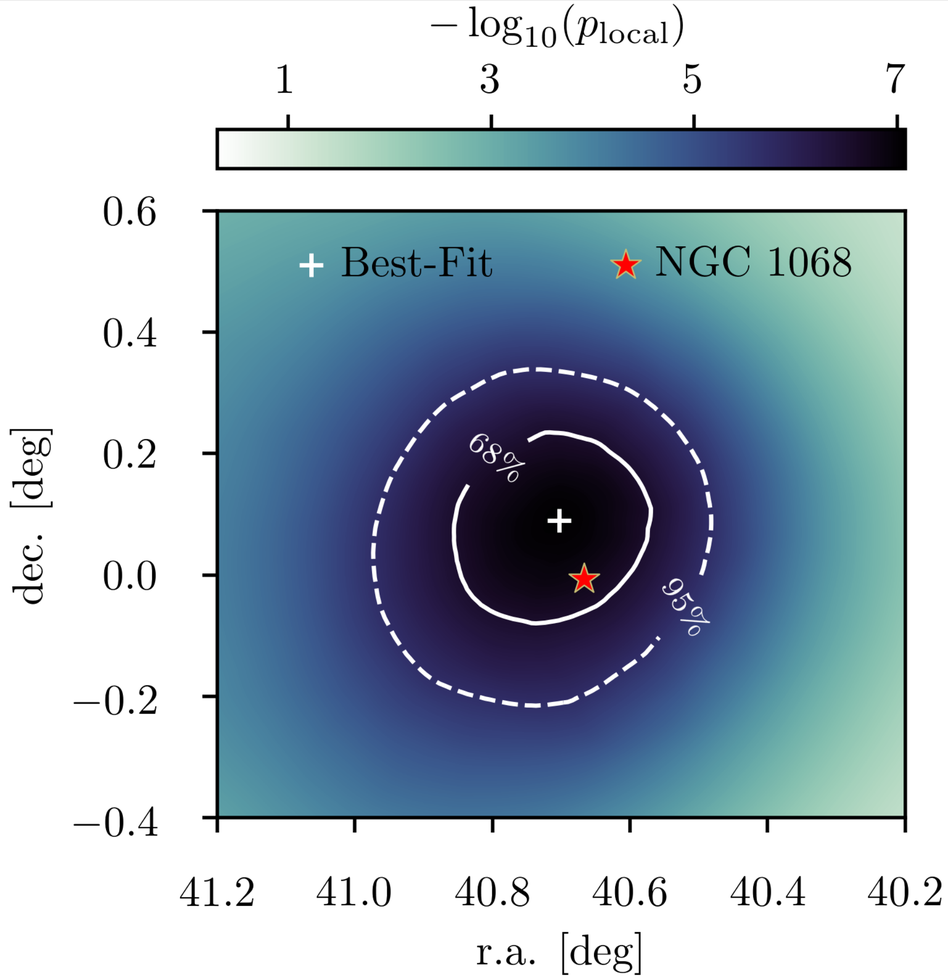
mm excess is there



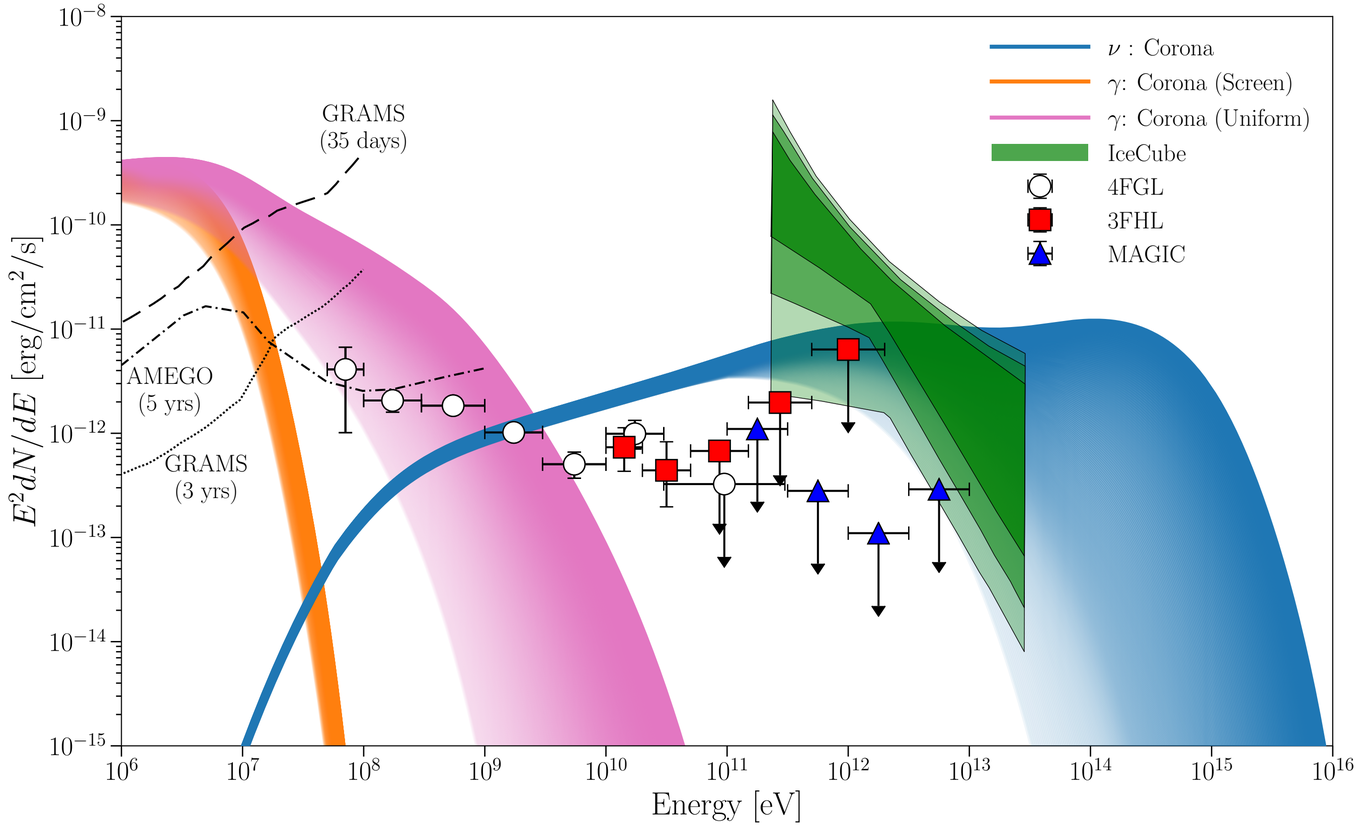
Michiyama, YI, + 2023

- Based on our analysis (YI+'20; Michiyama, YI+2023.)
- 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



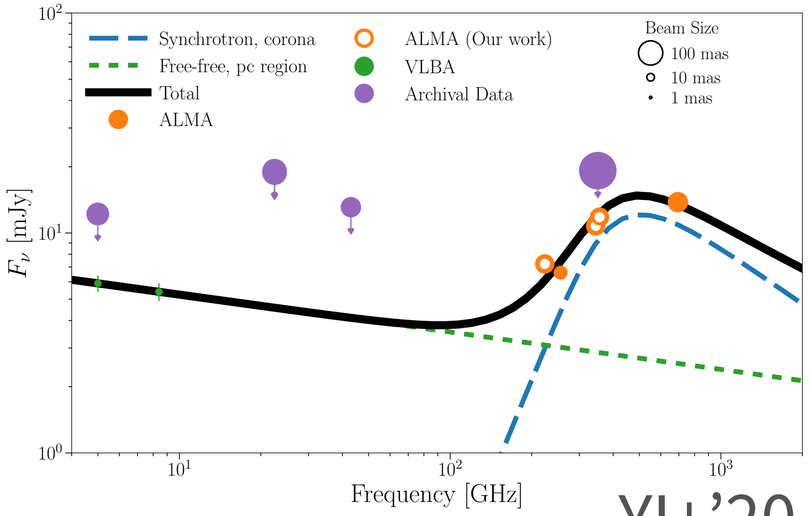
YI, Khangulyan, & Doi, ’20

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

How can we test the corona model?

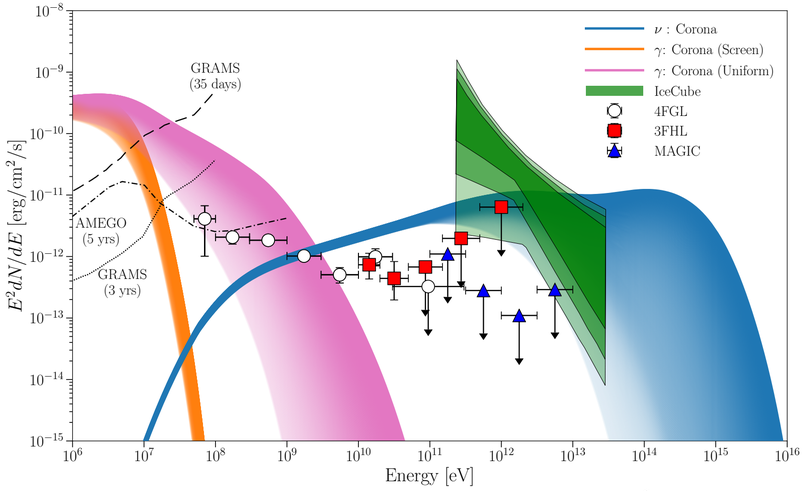
ALMA? ngVLA? JEDI? COSI-X? GRAMS? AMEGO? IceCube-Gen2? KM3Net? XRISM?

mm-band



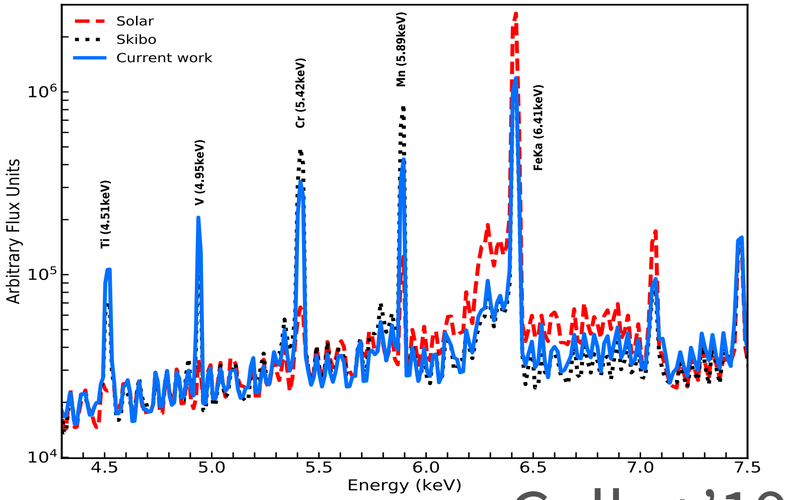
YI+'20

MeV & TeV ν



YI+'20

X-ray

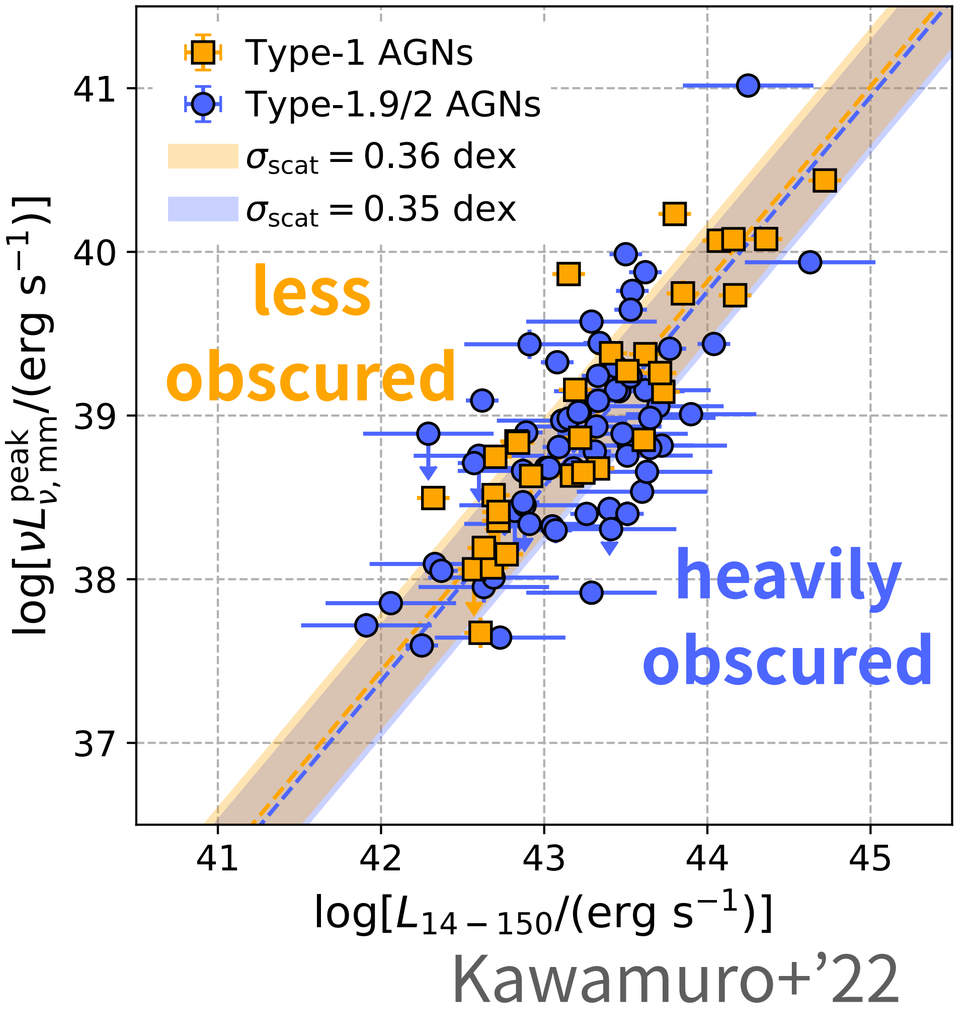


Gallo+'19

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

Finding Neutrino-Loud Seyferts?

A synergy among neutrinos, Hard X-ray, and mm is important



Kawamuro+'22

- Dust torus attenuates Optical/X-ray emission.

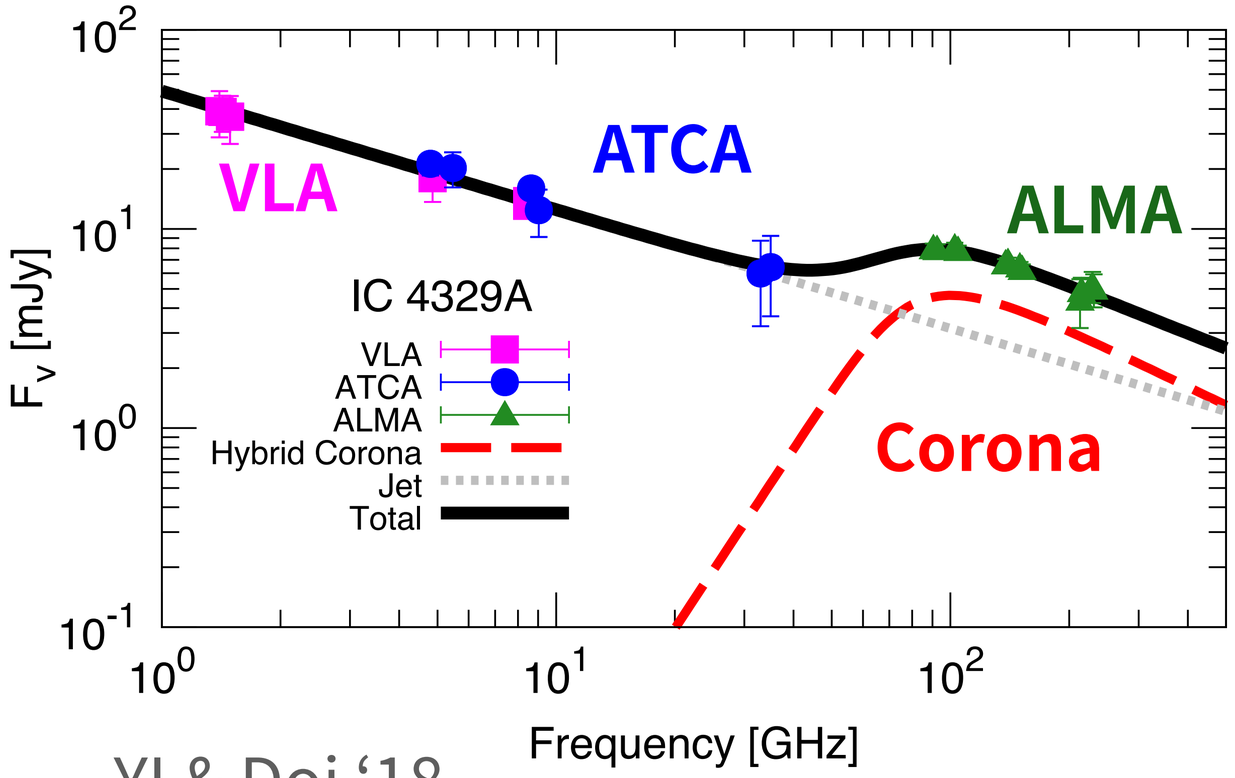
  ➡ Hard X-ray survey (e.g., BAT catalog)

- 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, ngVLA) will not be attenuated.
- BAT survey + follow-up by (ALMA + IceCube/KM3NeT/TRIDENT?) is the best solution.

Coronal Magnetic Field?

cm-mm spectrum of AGN core

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



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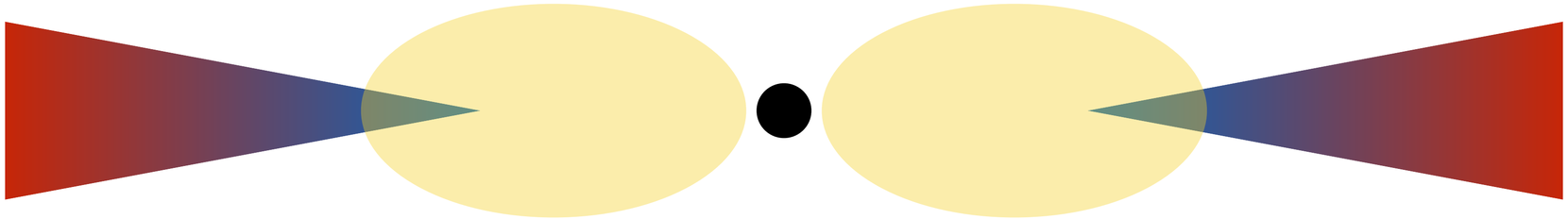
- Non-thermal electron index: 2.9
- Size: 40 r_s
- **B-field strength : 10 G**

How can we heat up corona?

Implication for the truncated accretion disk structure

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

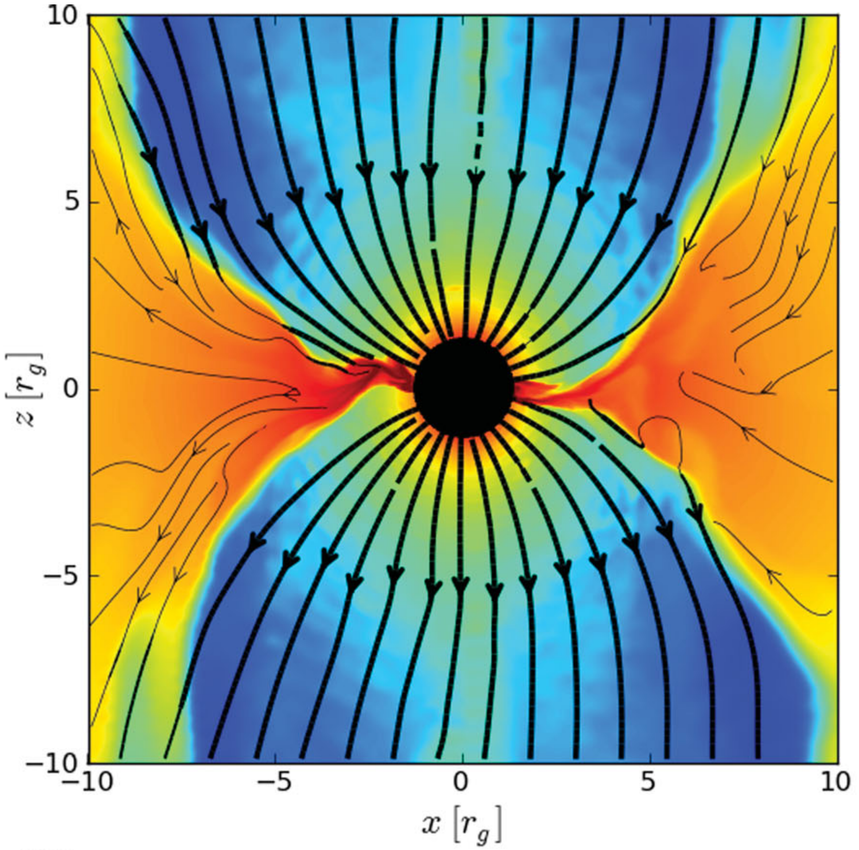
- Disk truncation at some radii (e.g. ~40 r_s)
  - The inner part = hot accretion flow (Ichimaru '77, Narayan & Yi '94, '95).
    - **Heated by advection.**
    - We can expect $kT_e \sim 86\ \mathrm{keV}\ (\tau_T/1.1)^{2/5}$ (YI+'19)
  - Suggested for Galactic X-ray binaries. (e.g. Poutanen+'97; Kawabata+'10;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



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

Are weak-jet AGNs MAD or not MAD?

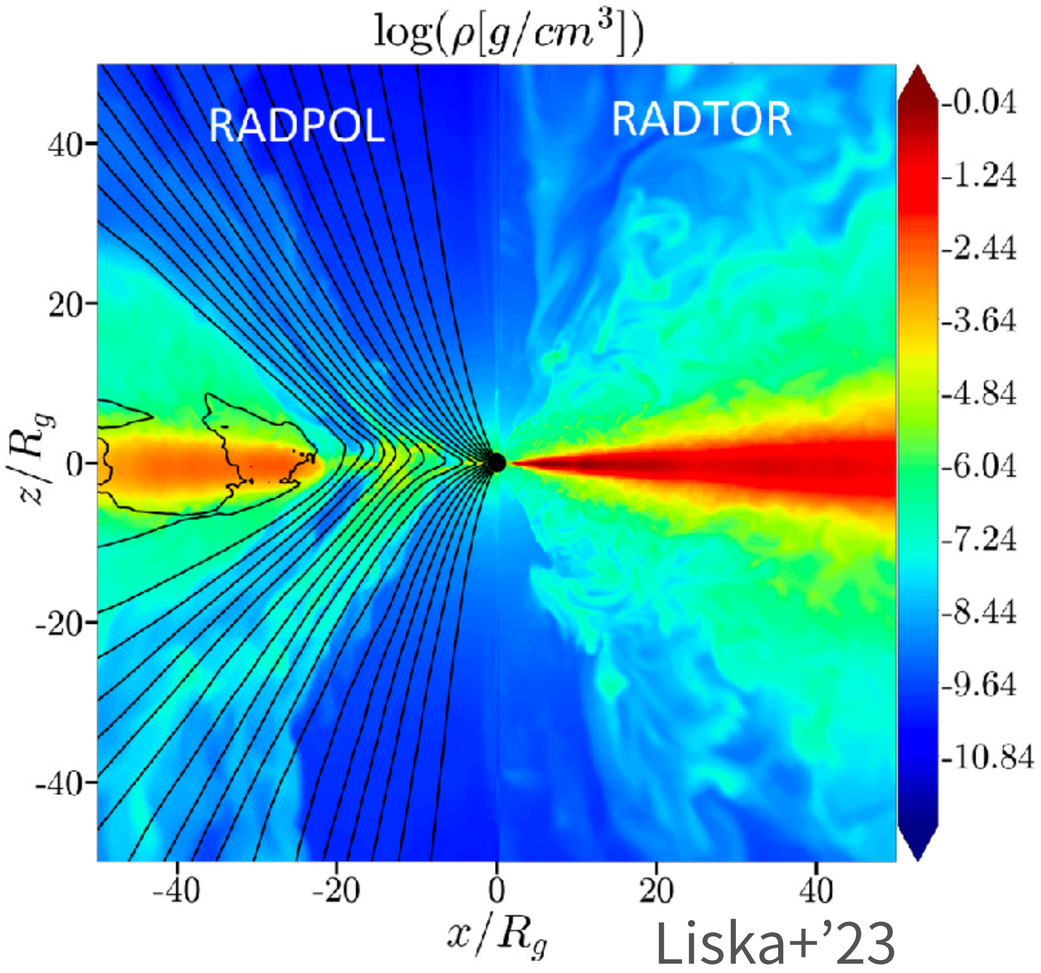
- Our ALMA analysis suggests
  - coronal B-field is ~10-30 G at 30 r_s.
  - **In terms of plasma beta ($\beta \equiv p_{\rm gas}/p_{\rm mag}$), we have $\beta \sim 10 - 100$.**
  - Gas pressure dominates the accretion dynamics.
- However, recent numerical simulations suggest $\beta \ll 1$ for some cases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



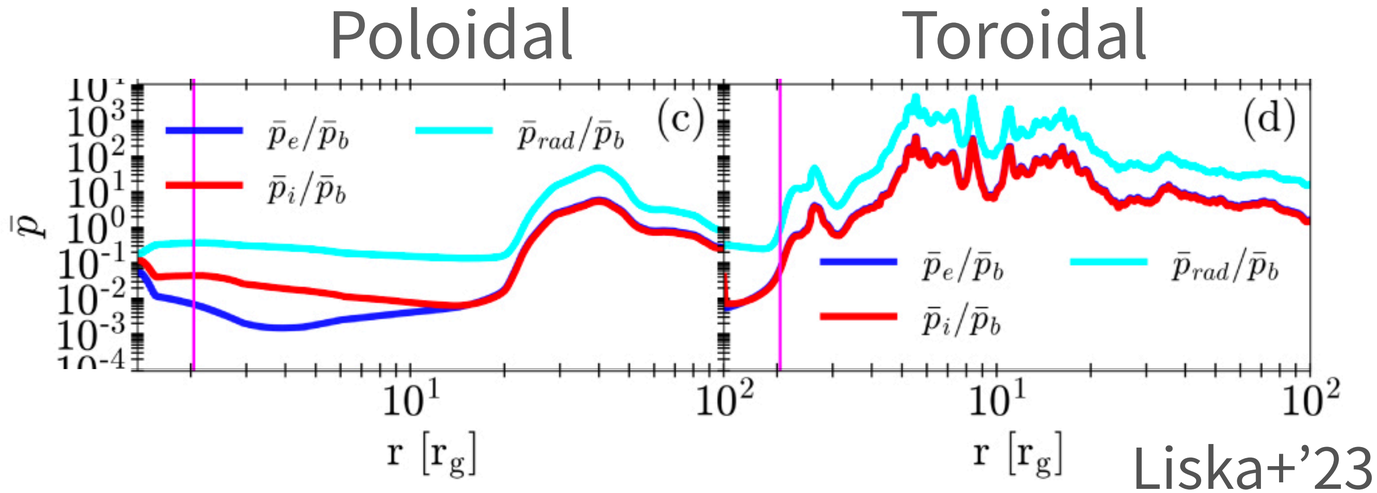
McKinney et al. '12

We are observing AGNs without powerful jets

MAD is needed for powerful jet production



Liska+'23



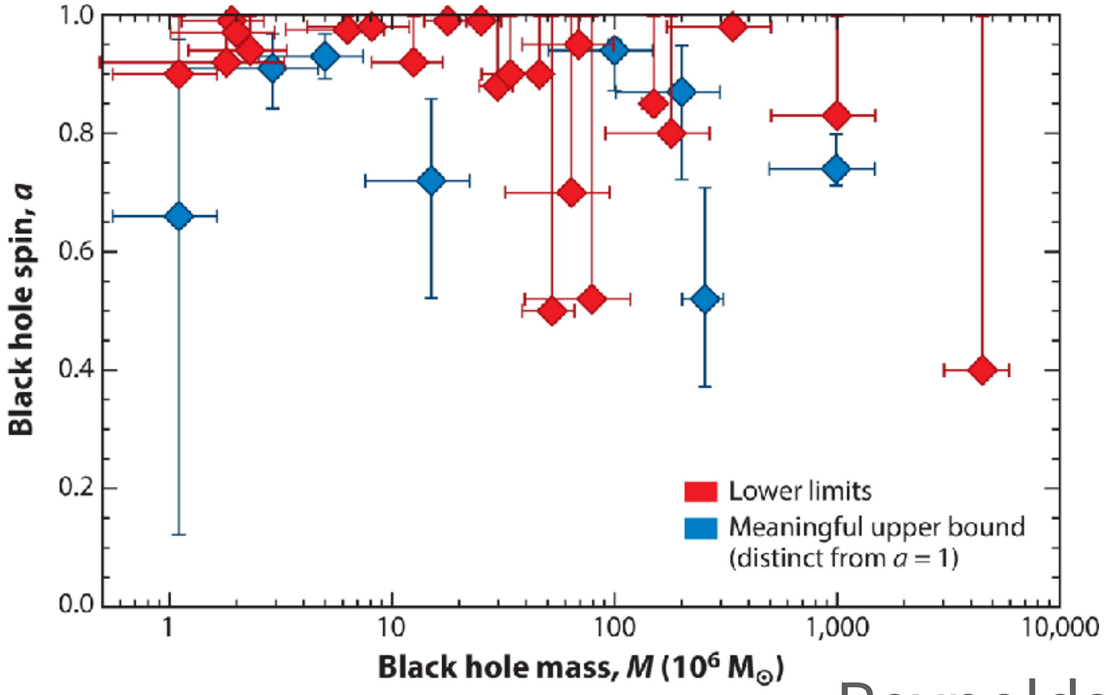
Liska+'23

- 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 strongly depends on initial magnetic field configuration.**

SMBH Spins and Dichotomy of AGNs

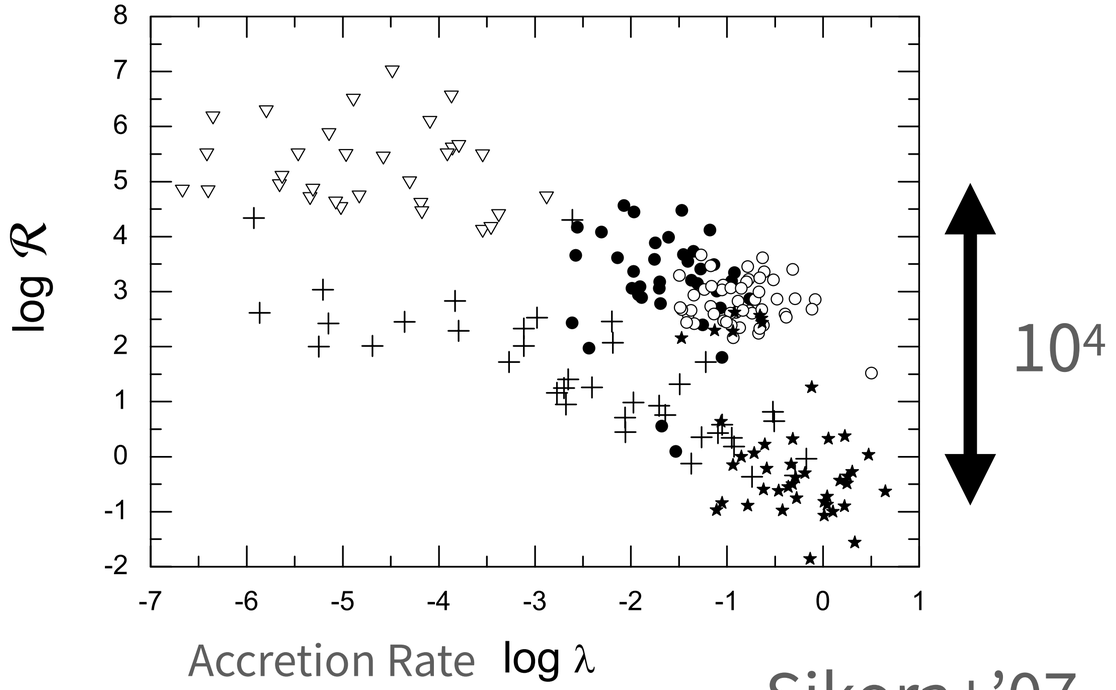
B of RL and RQ AGNs should be different because $P_{\rm jet} \approx P_{\rm BZ} \propto x_a^2 f(x_a) \phi_{\rm BH}{}^2 \dot{M}_{\rm in} c^2 \approx a^2 B^2$

X-raying SMBH Spin Distribution



Reynolds+'21

Radio Loudness Distribution



Sikora+'07

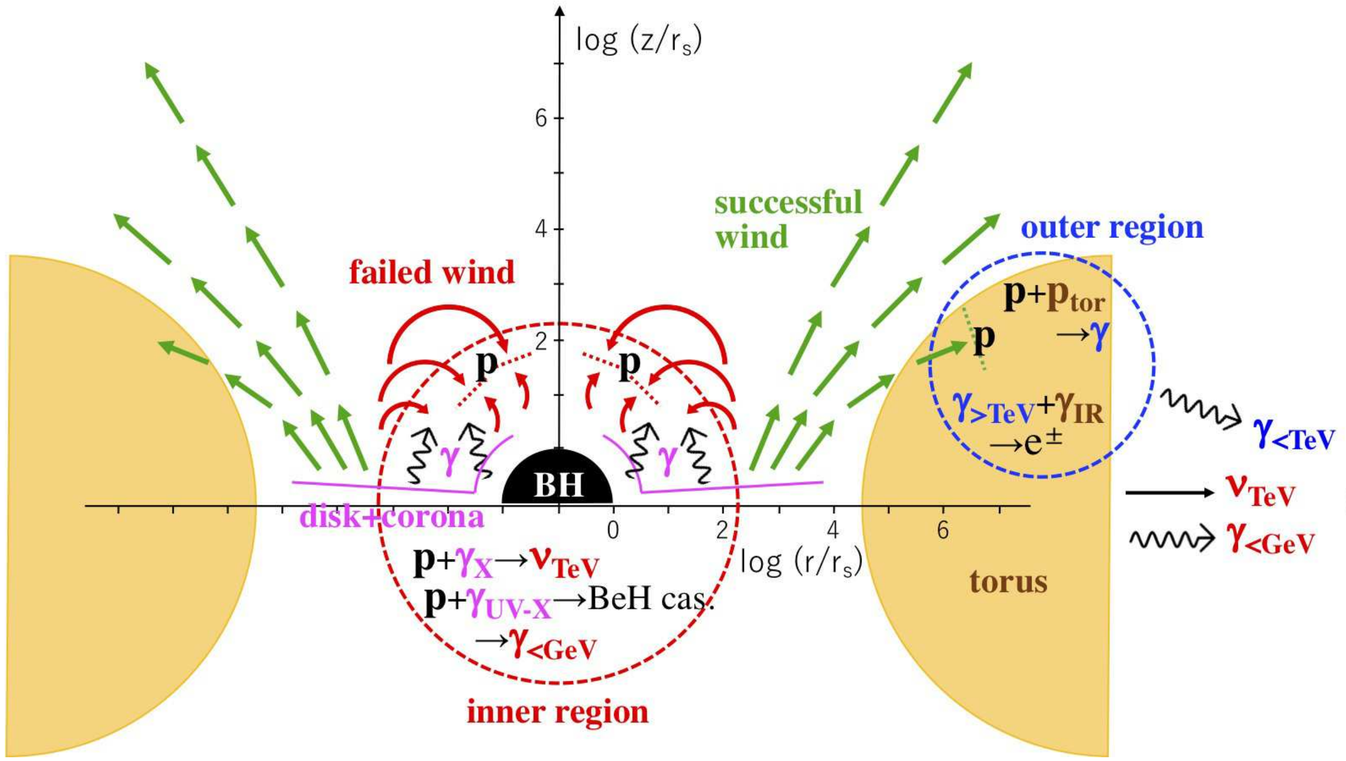
- Same spins a for all AGNs
- $\mathscr{R}$ differs for 4 orders of magnitude

Summary

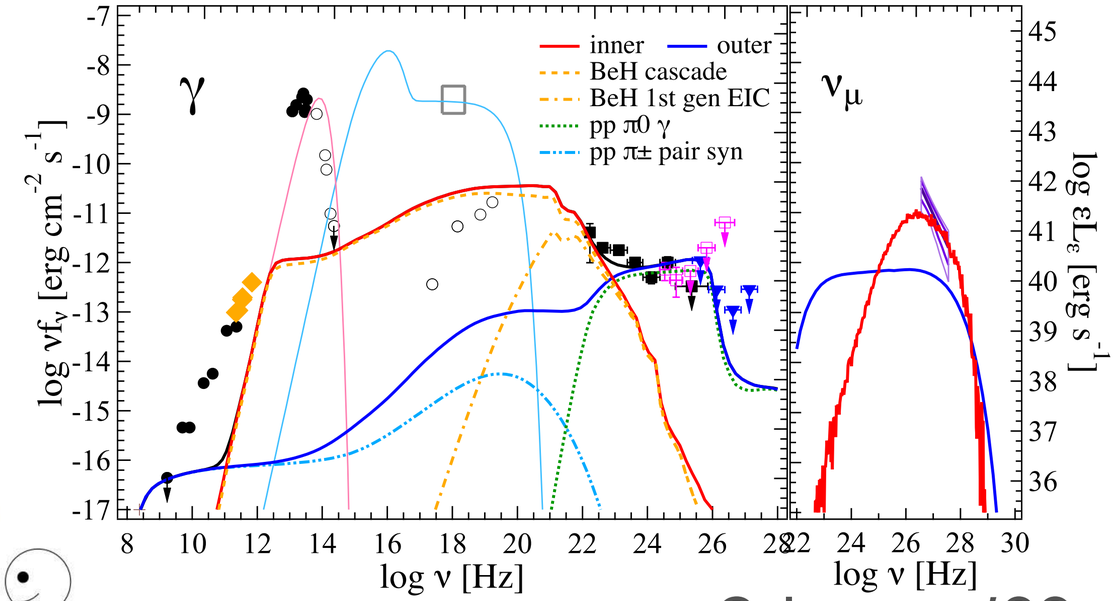
- Seyferts will be a dominant population in the neutrino sky
  - AGN corona would be a high-energy particle production site
  - ALMA/X-ray + IceCube observations would be important
- Are AGN corona in low-plasma beta? or high-plasma beta?

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

Interaction between Accretion Flows and Disk Winds

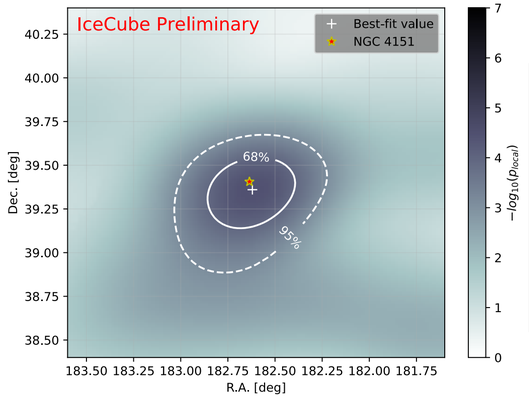


S. Inoue +'22



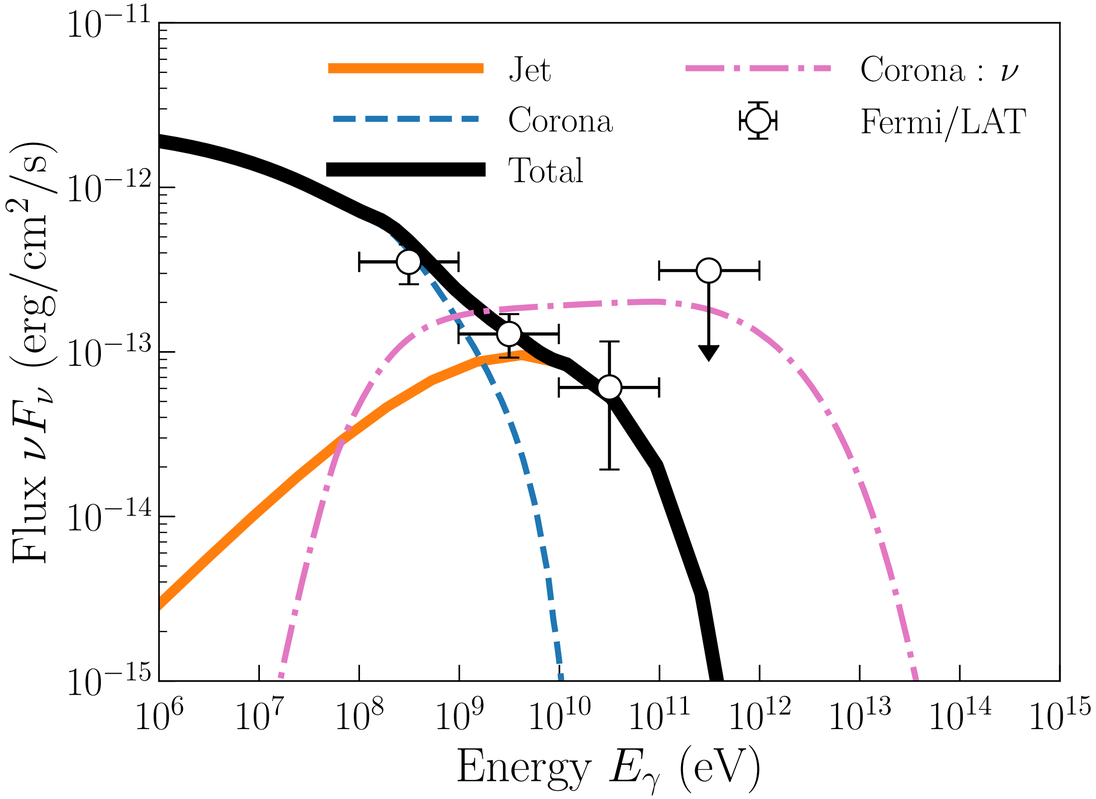
S. Inoue +'22

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

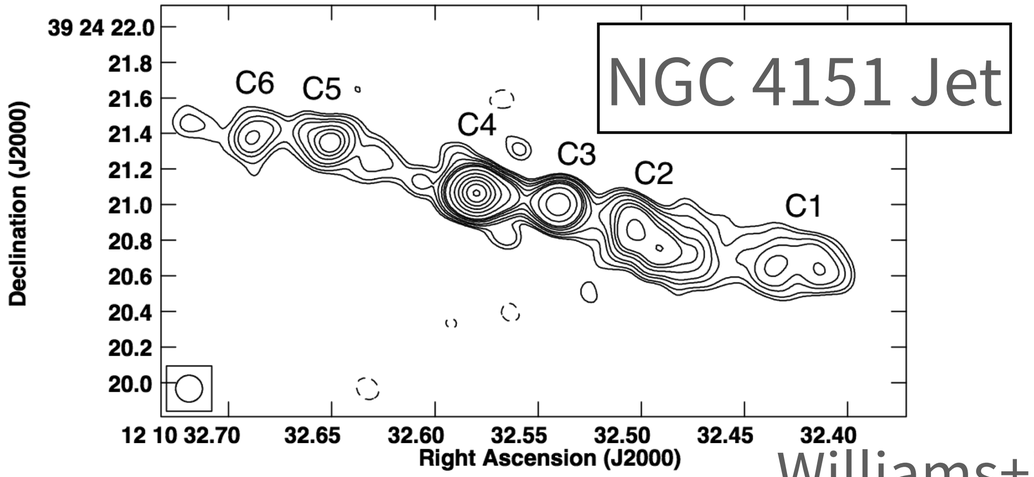


On the possible detection of NGC 4151

Corona model may be difficult to explain



YI & Khangulyan ‘23



Williams+’14

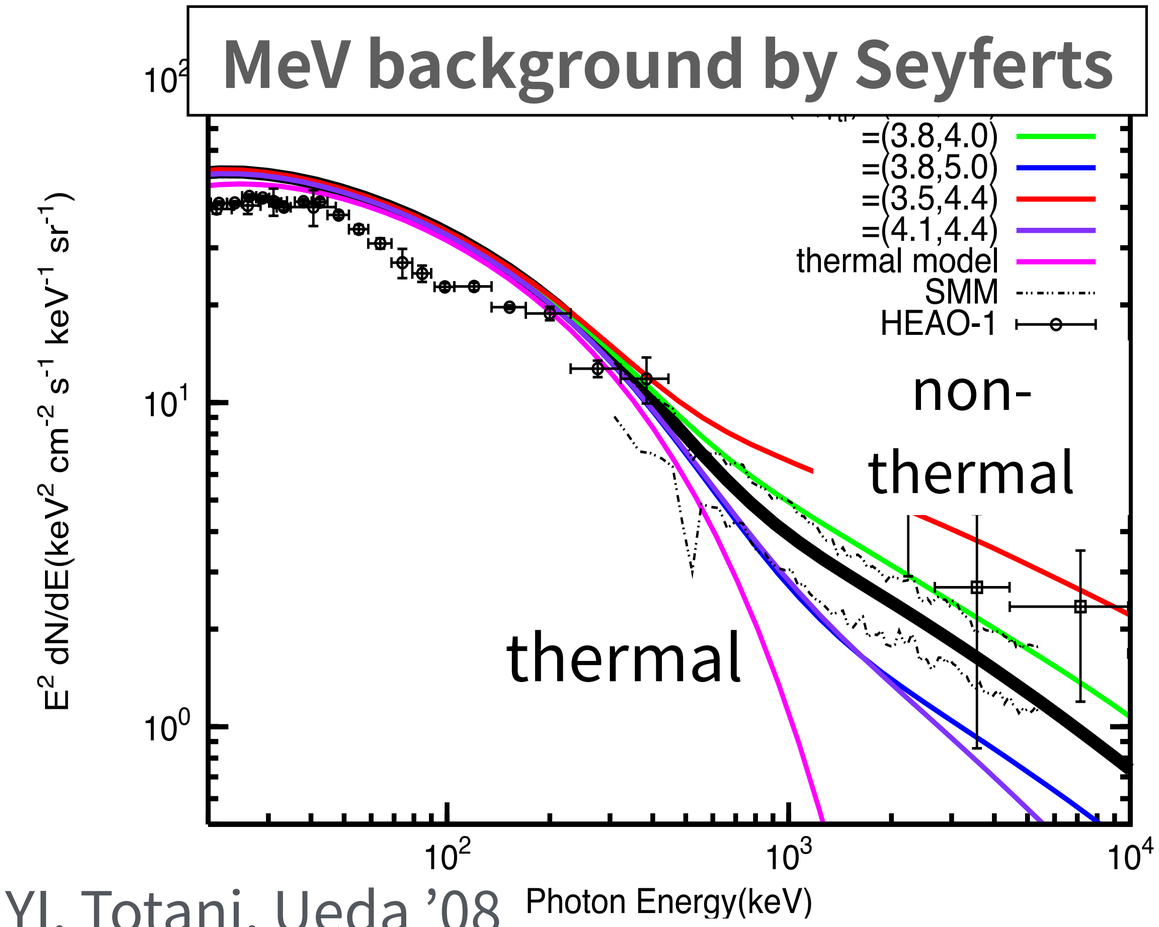
- Gamma-ray detected by Fermi (4FGL-DR2; Perretti+’23)
- Corona + Weak Jet model can explain the Fermi data
  - But, the expected neutrino flux is an order of magnitude below the IceCube threshold
- A nearby blazar exists (~1 deg away from NGC 4151)...

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.

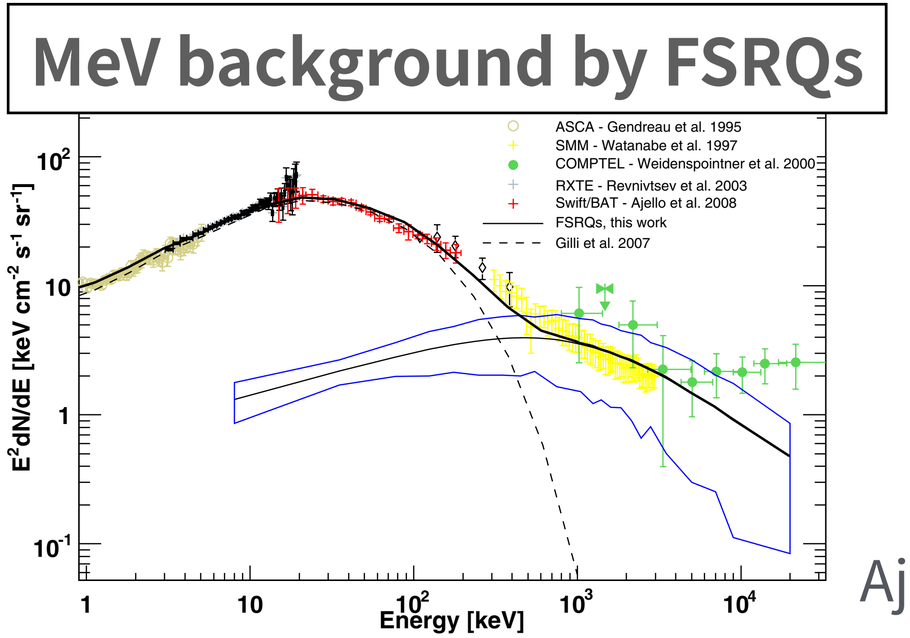
Investigation of non-thermal activities in Seyferts

X-ray ? GeV ? MeV ?



YI, Totani, Ueda ’08

- MeV background by hybrid corona in Seyferts?
  (YI, Totani, & Ueda ‘08)
- FSRQs can also explain the MeV background
  (Ajello+’09, but see also Toda, YI, + ‘21)



Ajello+’09