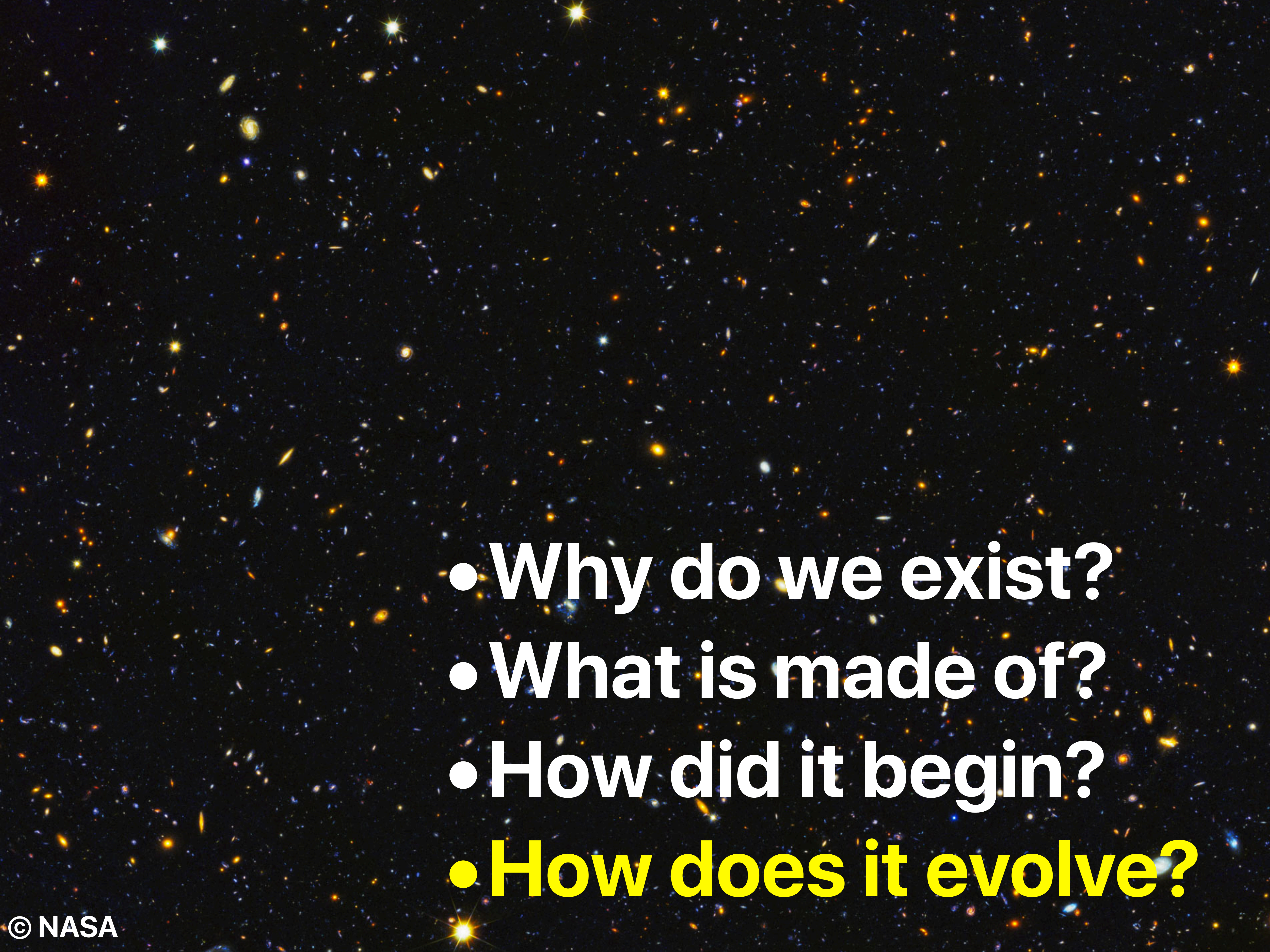
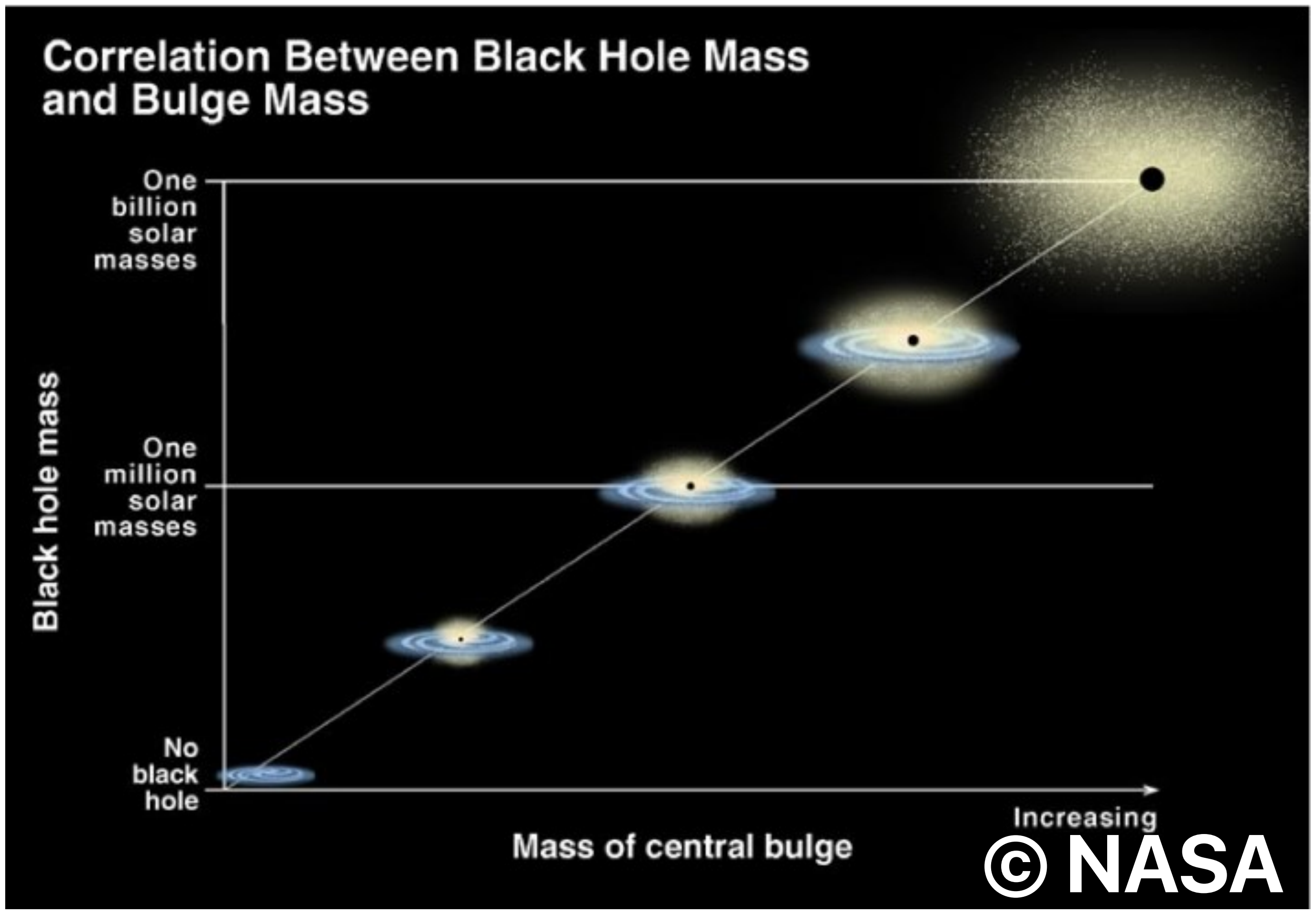
Detection of Coronal Magnetic Activity in Nearby Active Supermassive Black Holes

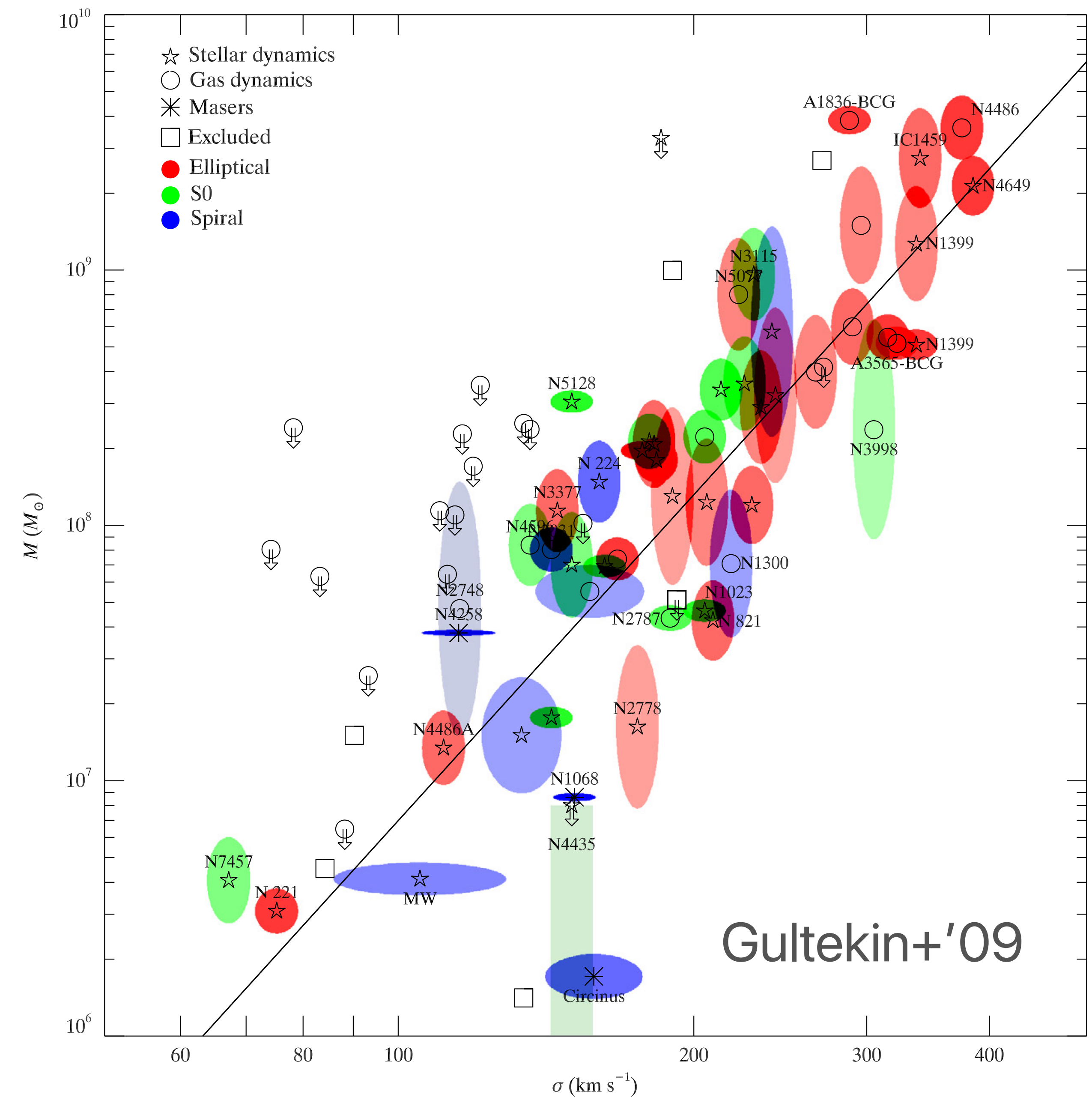
Yoshiyuki Inoue (RIKEN)

RIBF Seminar @ RIKEN, 2018-05-14


• Why do we exist?
• What is made of?
• How did it begin?
• How does it evolve?
© NASA

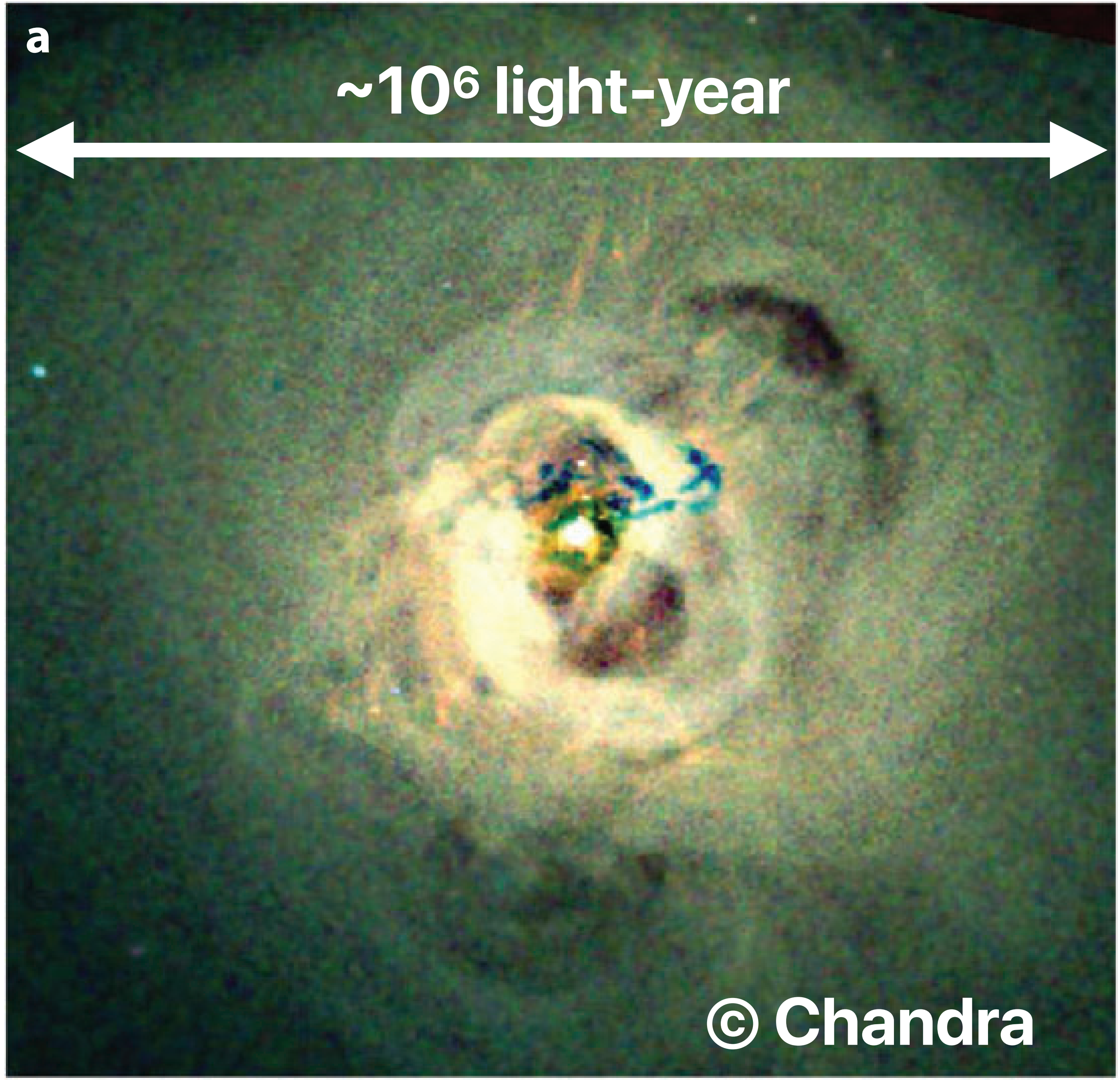
Black Holes Control Evolution of the Universe





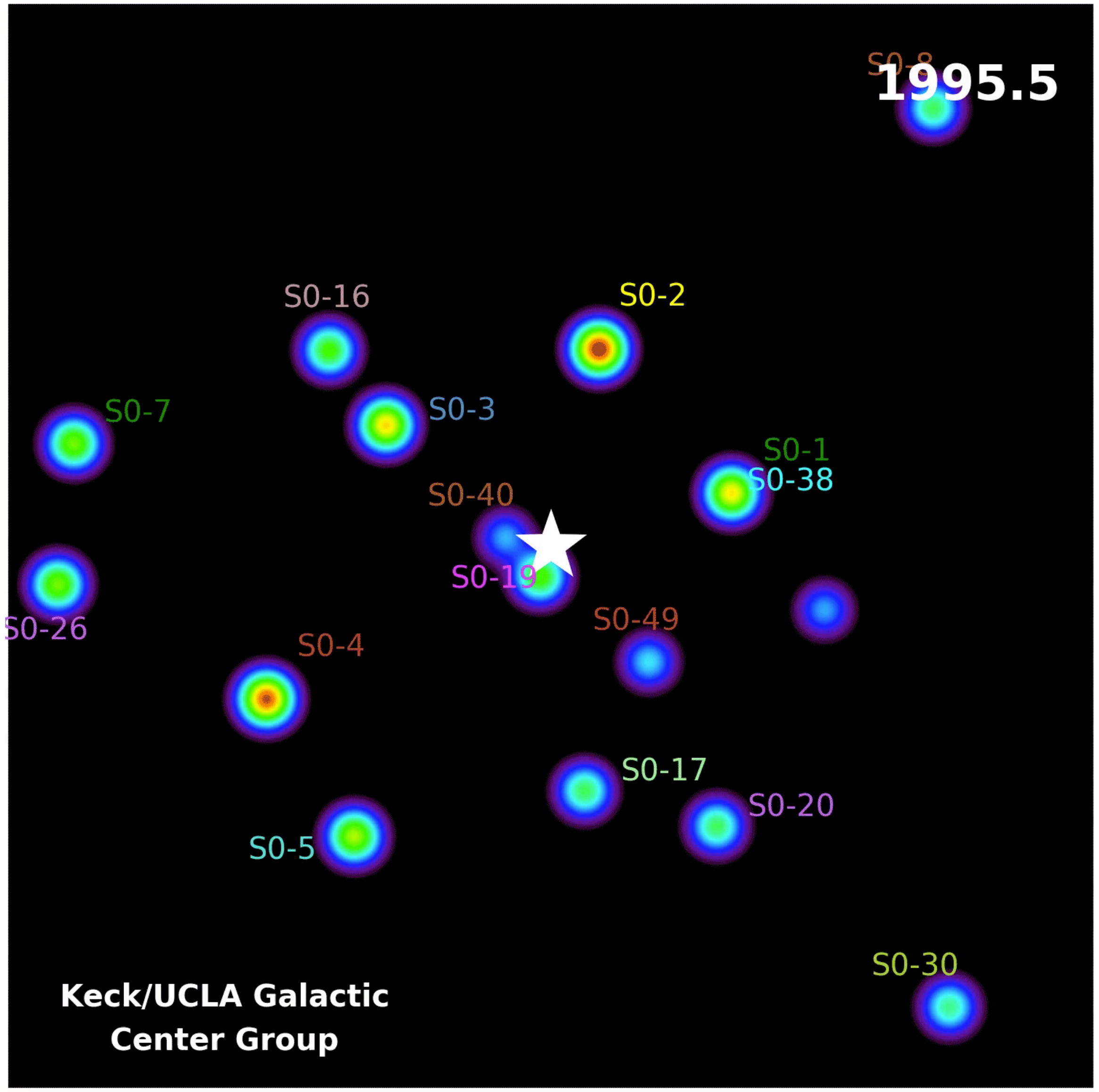
- Supermassive black holes
  - Evolve together with galaxies (e.g. Kormendy & Gebhardt 2001)

Black Holes Control Evolution of the Universe



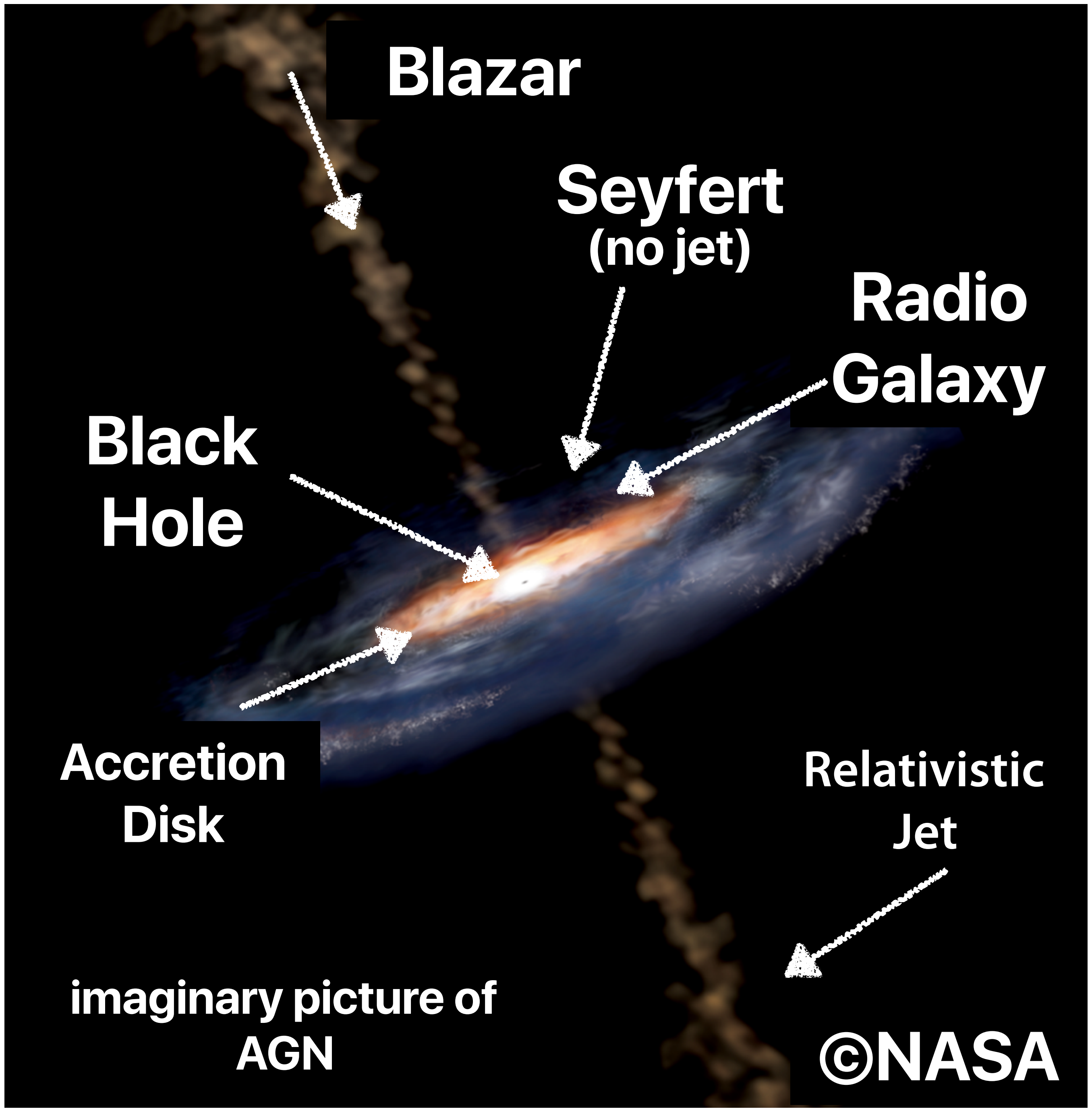
- Supermassive black holes
  - Affect surrounding gas from galactic scales to beyond (e.g. Fabian '12)

Supermassive Black Hole



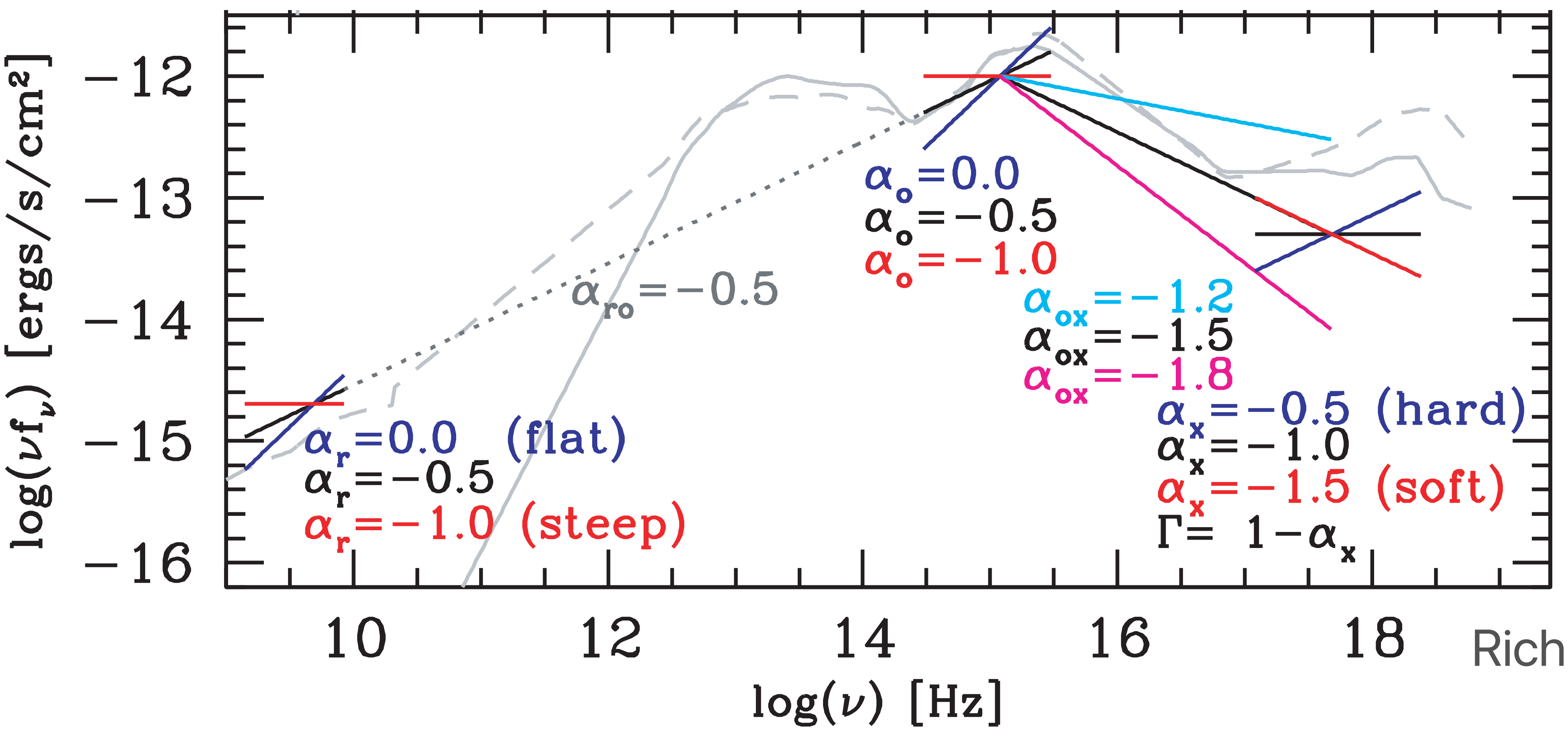
- Supermassive (>10^6 solar mass) black hole @ center of every galaxy
- 4×10^6 M_{sun} Black hole exists at the Galactic center of our Galaxy

Supermassive Black Holes are Active



- Active Galactic Nuclei (AGNs)
  - Gas accretion on to black holes
    - brighter than galaxies
  - Relativistic jets
  - Hot coronae

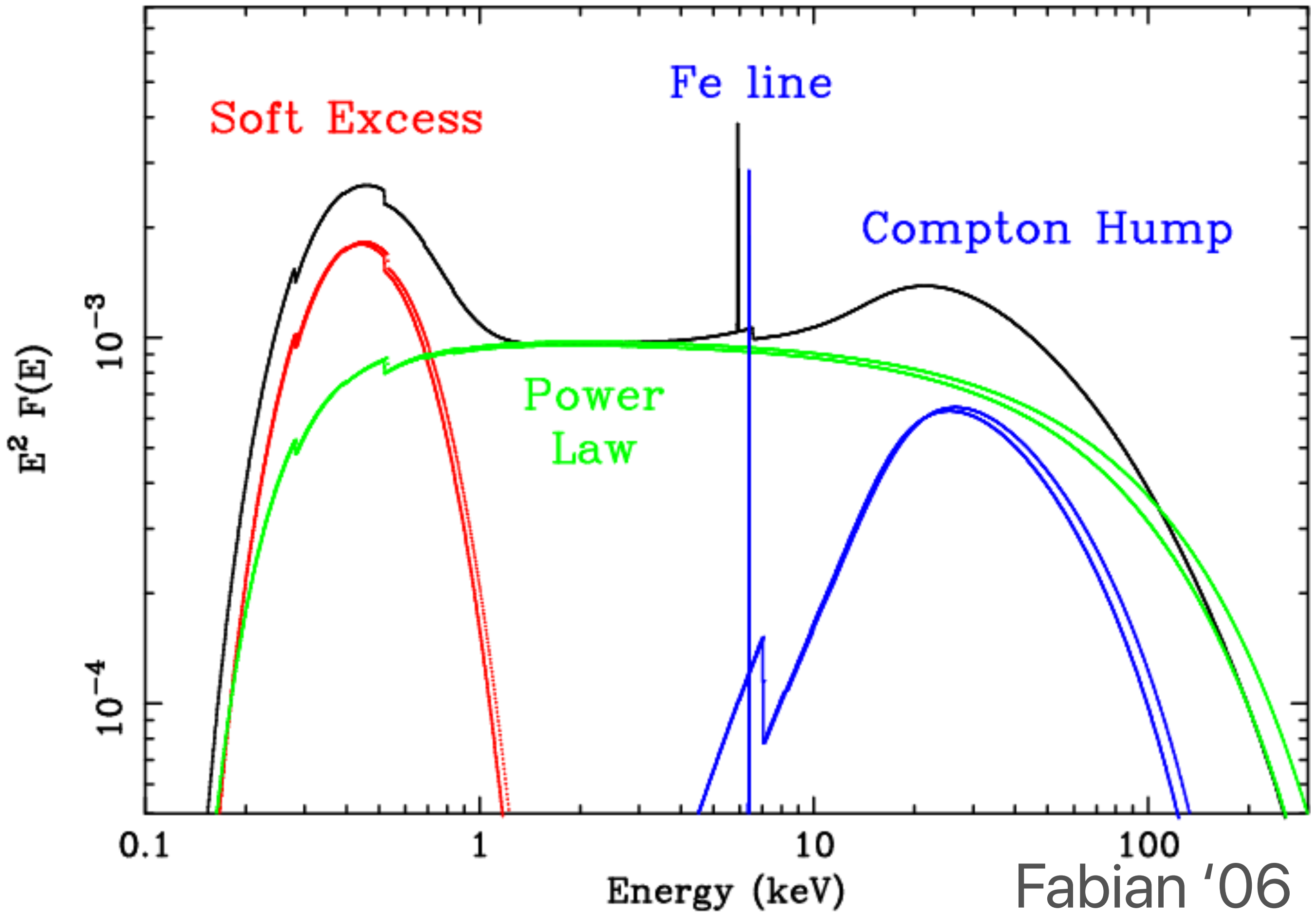
Emission from AGNs



Richards+’06

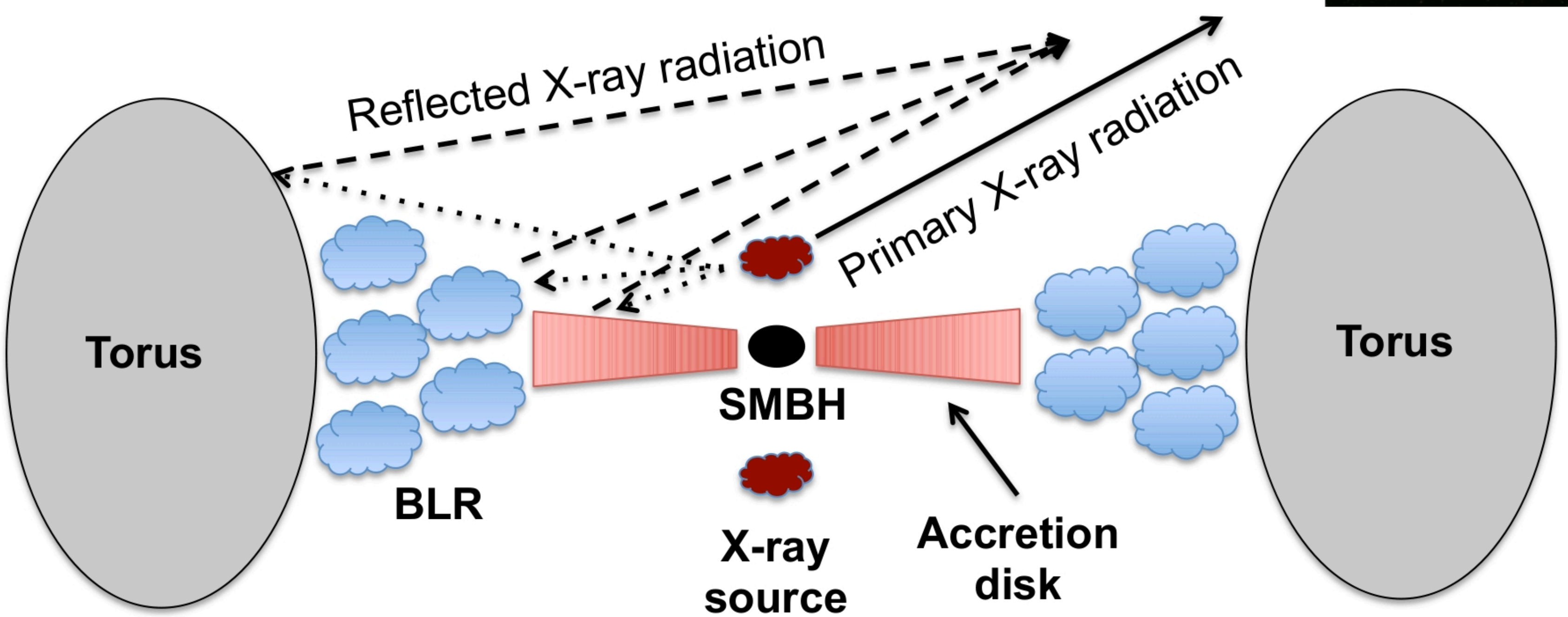
- radio: jet, galactic cosmic rays
- IR : dust (>~0.1 pc ~ 3e17 cm)
- opt: accretion disk (<~0.1 pc ~ 3e17 cm)
- X-ray: disk corona (~10 r_s ~3e14 cm for 10^8 M_{sun})

X-ray Emission from AGN Disks



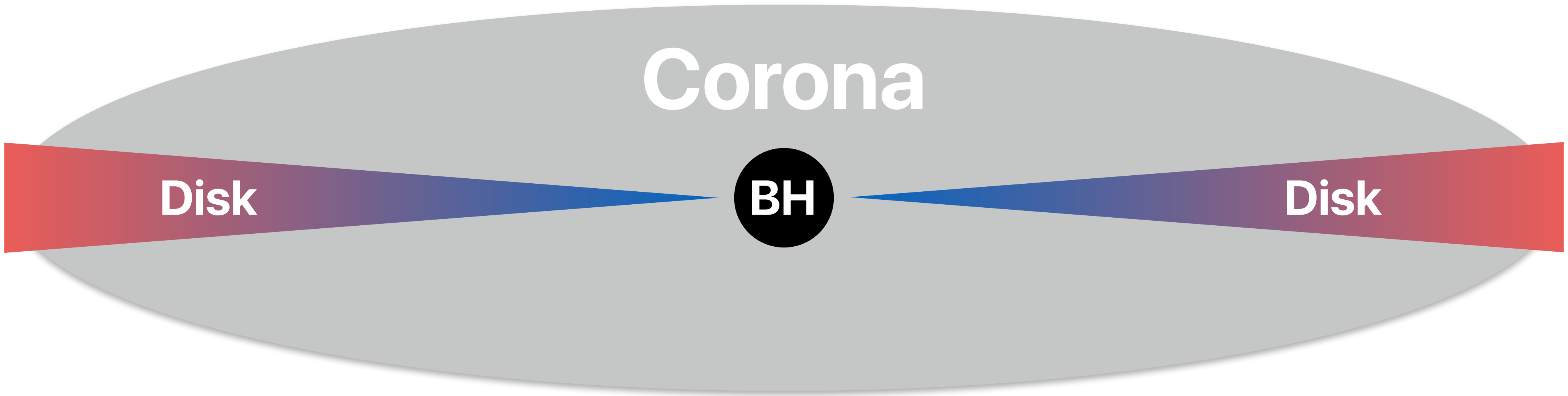
Fabian '06

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



©Ricci

Accretion Disk Corona



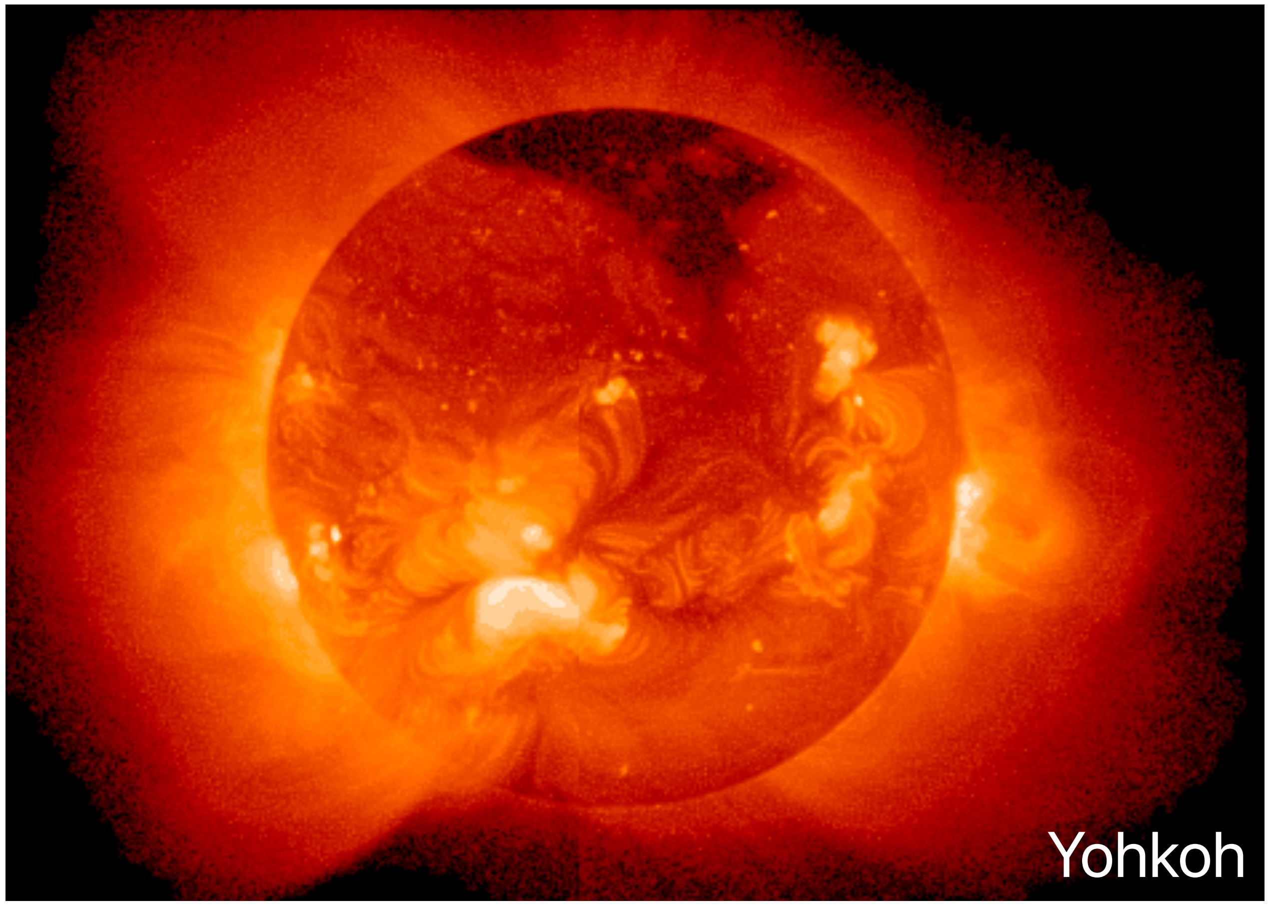
- Black hole accretion disks have hot coronae like the Sun ?
- High energy cutoff

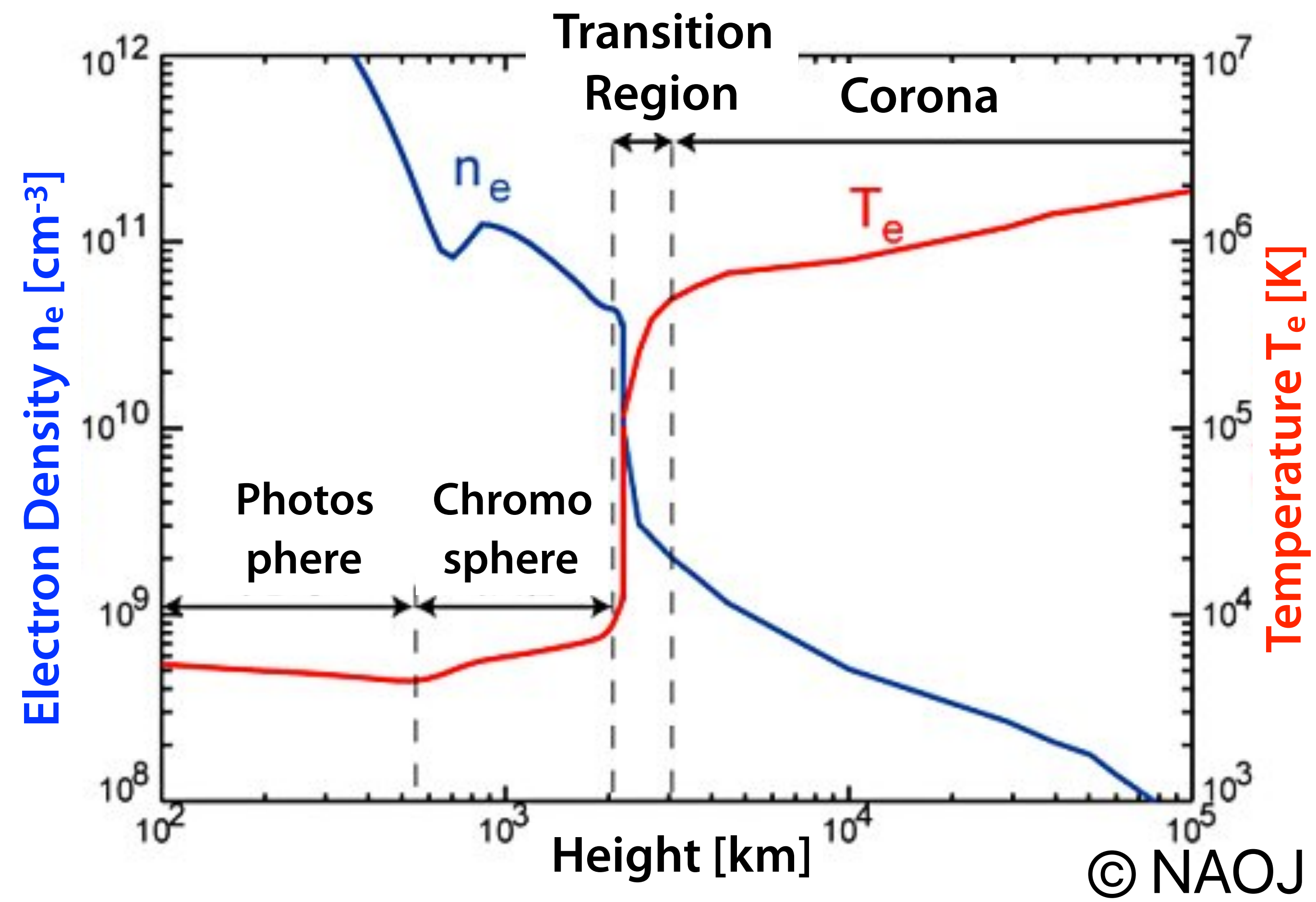
➡ $T_e \sim 10^9\ \mathrm{K}\ (k_B T_e \sim 10^2\ \mathrm{keV})$

- Power-law spectrum : Compton-y parameter

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

Solar Corona Heating





- 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

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

1. Reconnection heating = Compton Cooling in corona

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

2. Conduction heating = evaporation cooling in disk chromosphere

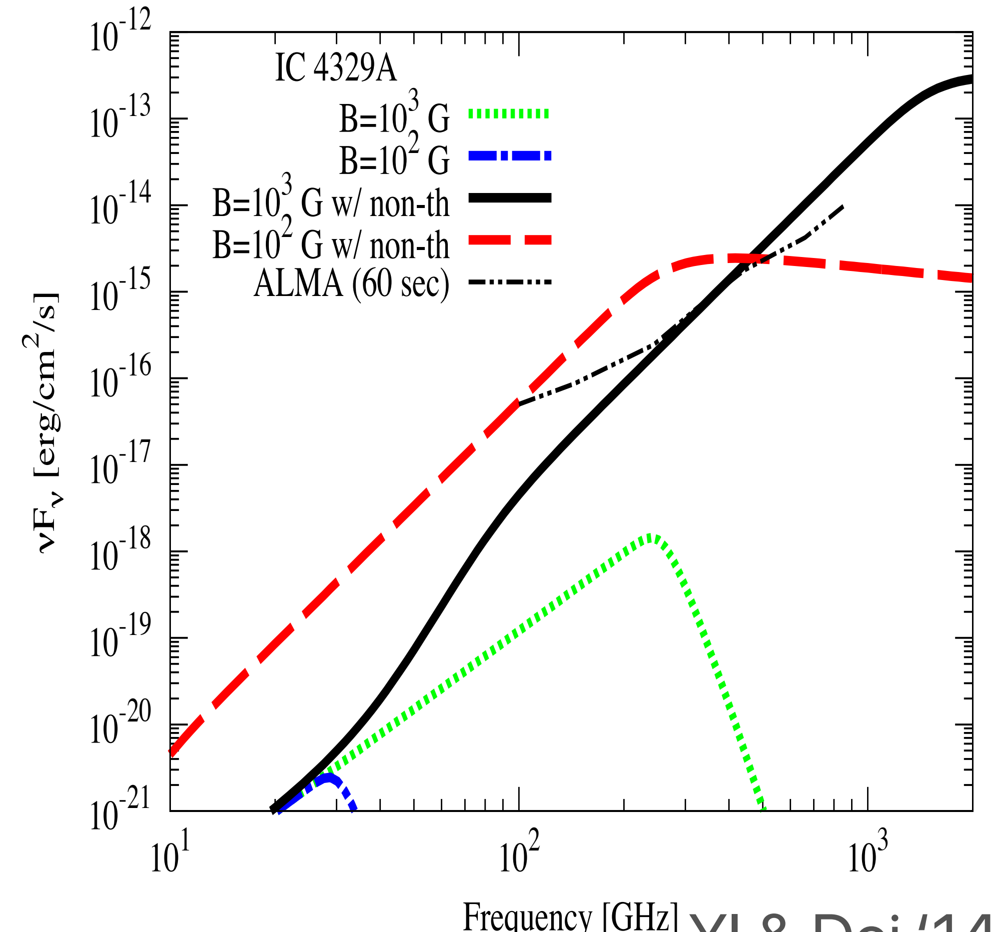
$$\frac{k_0 T^{7/2}}{l} \approx \frac{\gamma}{\gamma - 1} n_e k_B T_e \left(\frac{k_B T_e}{m_H}\right)^{1/2}$$

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

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

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 a AGN corona is magnetized, synchrotron radiation is expected
  (YI & Doi '14, Raginski & Laor '16)

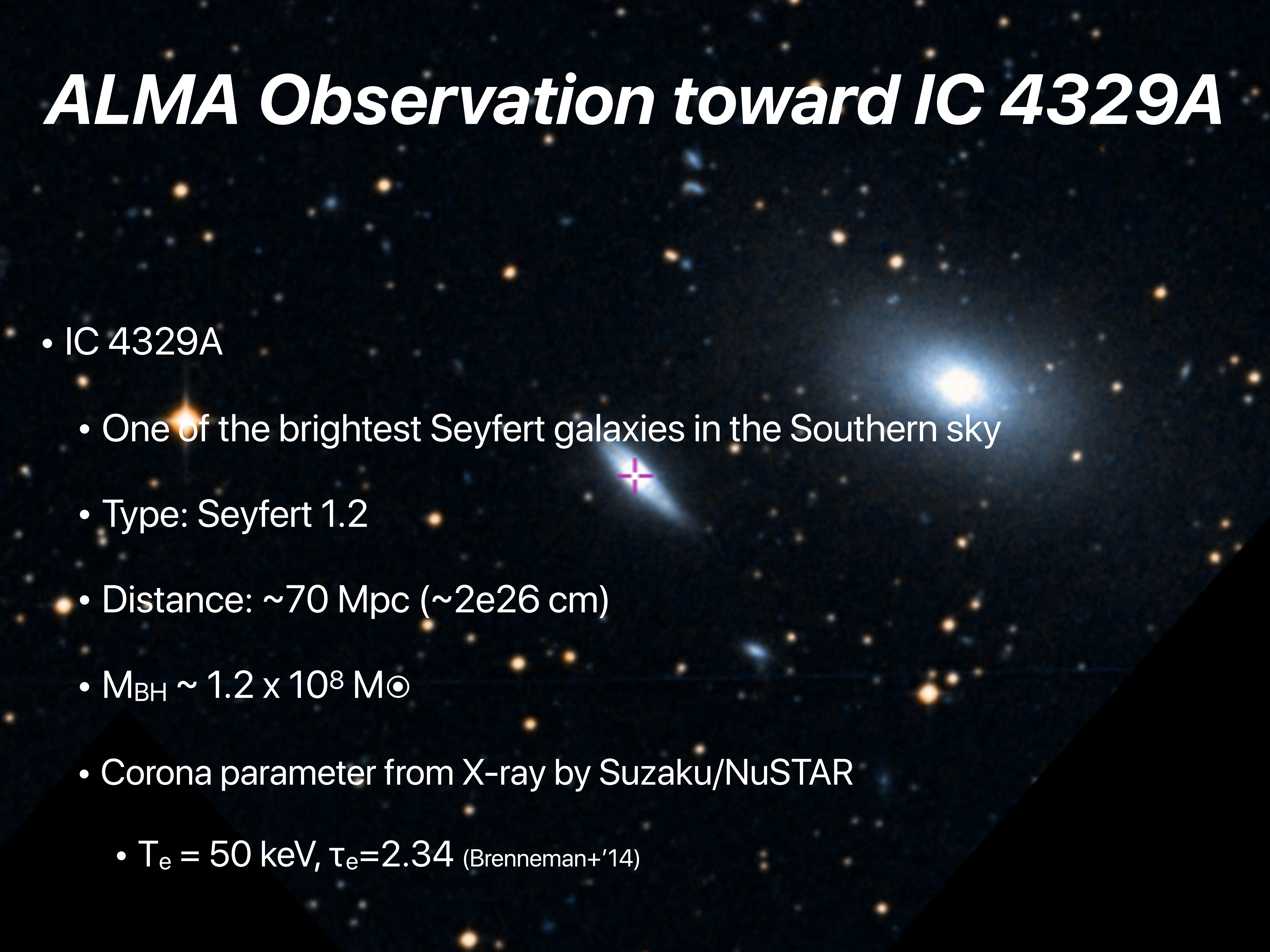


YI & Doi '14

Now we live in the ALMA era.

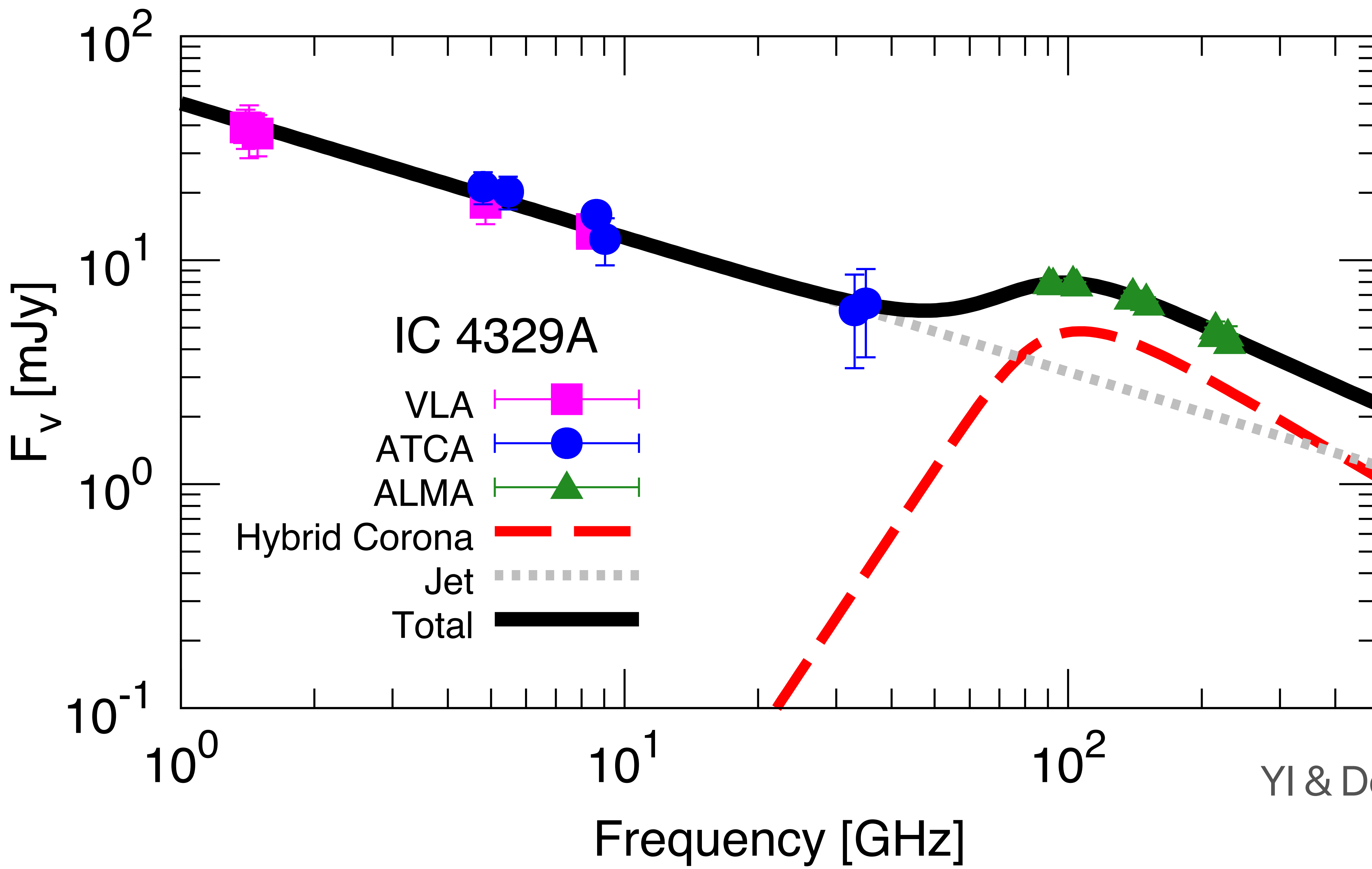
- The **Atacama Large Millimeter/submillimeter Array** (**ALMA**) is an astronomical interferometer of 66 radio telescopes in the Atacama Desert of northern Chile (from wikipedia).
- Covers millimeter and submillimeter bands.
- Has much higher sensitivity and higher resolution than before.

ALMA Observation toward IC 4329A



- IC 4329A
  - One of the brightest Seyfert galaxies in the Southern sky
  - Type: Seyfert 1.2
  - Distance: ~70 Mpc (~2e26 cm)
  - $M_{BH} \sim 1.2 \times 10^8 M_\odot$
  - Corona parameter from X-ray by Suzaku/NuSTAR
    - T_e = 50 keV, τ_e=2.34 (Brenneman+’14)

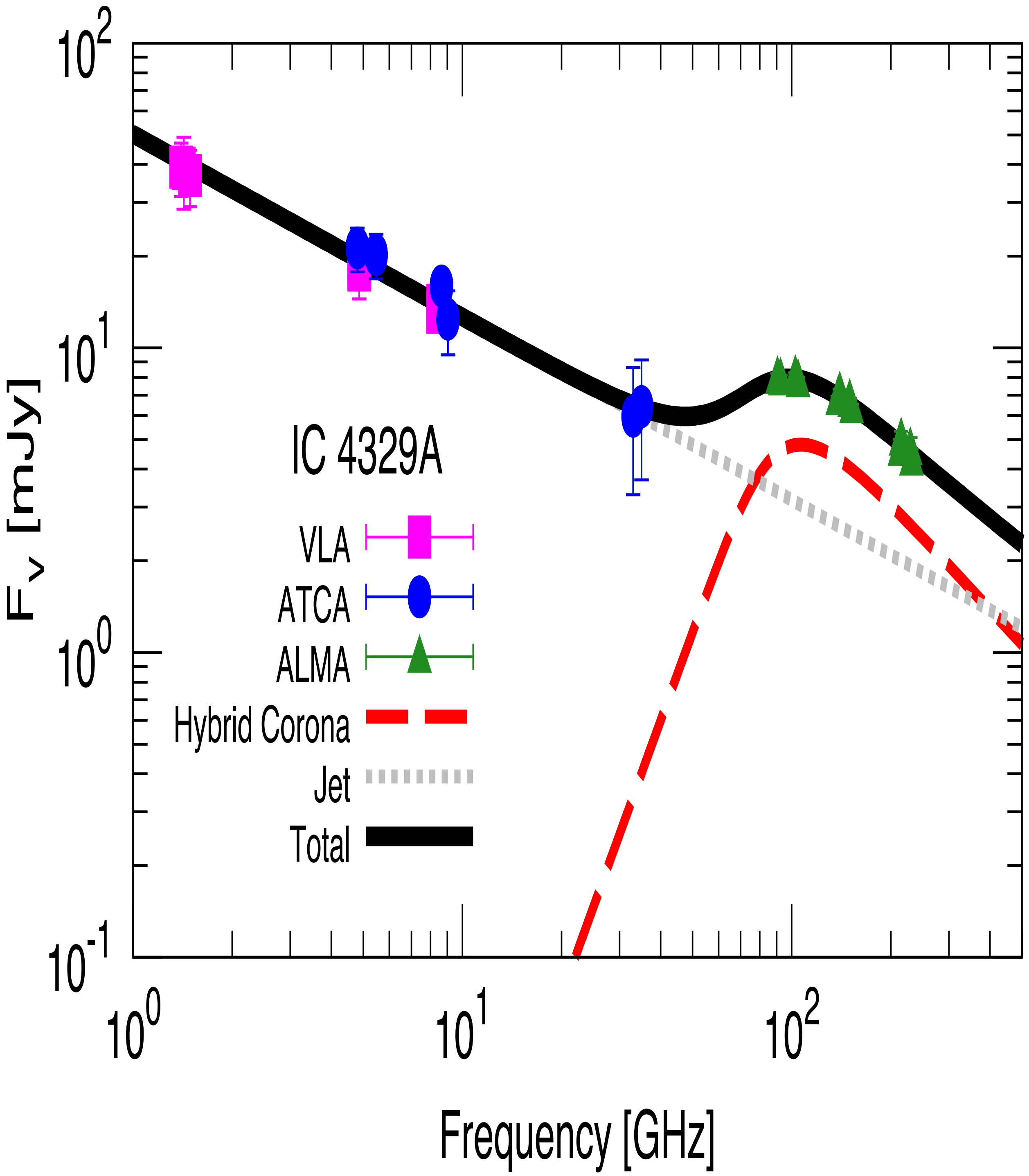
cm-mm spectrum of IC 4329A Core



YI & Doi '18

- Clear mm excess from cm spectrum

Coronal parameters



YI & Doi 2018

- Hybrid corona model (YI & Doi '14)
- Non-thermal electron fraction : $\eta = 0.04$ (fixed)
- Non-thermal spectral index $p = 2.9$
- Size: 40 r_s
- B-field strength : 10 G
- We also see the coronal synchrotron emission from NGC 985.

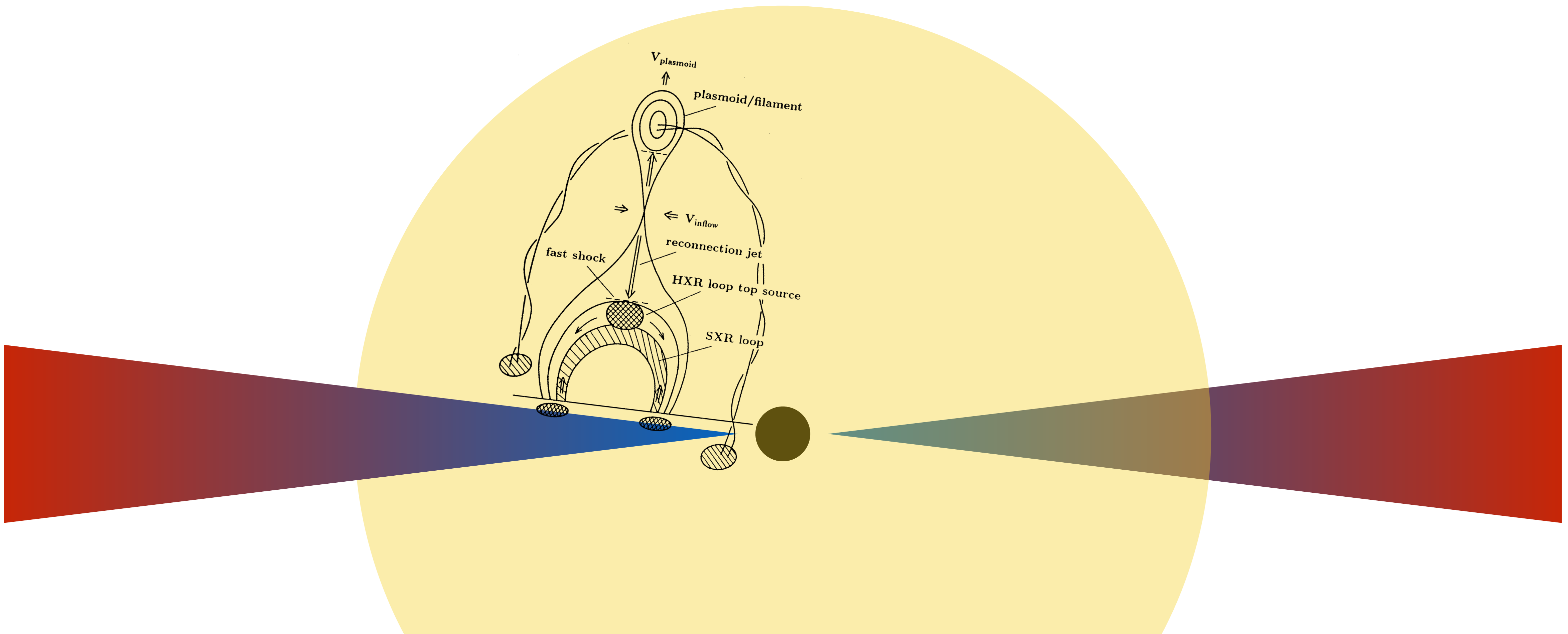
Reconnection Corona

$$\frac{B^2}{4\pi} V_A \approx \frac{4kT}{m_e c^2} n\sigma_T c U_{\rm rad} l, \ \textbf{?}$$

- Magnetic Heating Rate
  - $Q_{B,\,heat} \sim 10^{10}$ erg/cm^2/s
- Compton Cooling Rate
  - $Q_{IC,\,cool} \sim 10^{13}$ erg/cm^2/s (w/ $L = 0.1\ L_{Edd}$)
- Magnetic field energy is **NOT** sufficient to keep coronae hot.

Previous view of corona

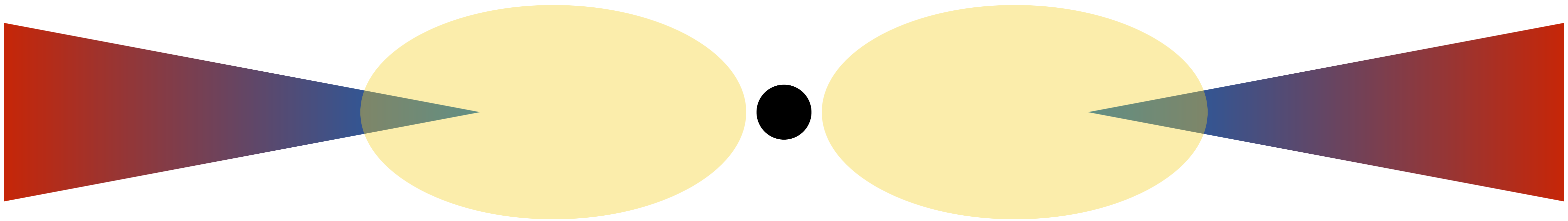
- A standard accretion disk goes close to the BH.
- Reconnection-heated hot coronae above/below the disk.
  - But, not enough magnetic energy from our ALMA obs.

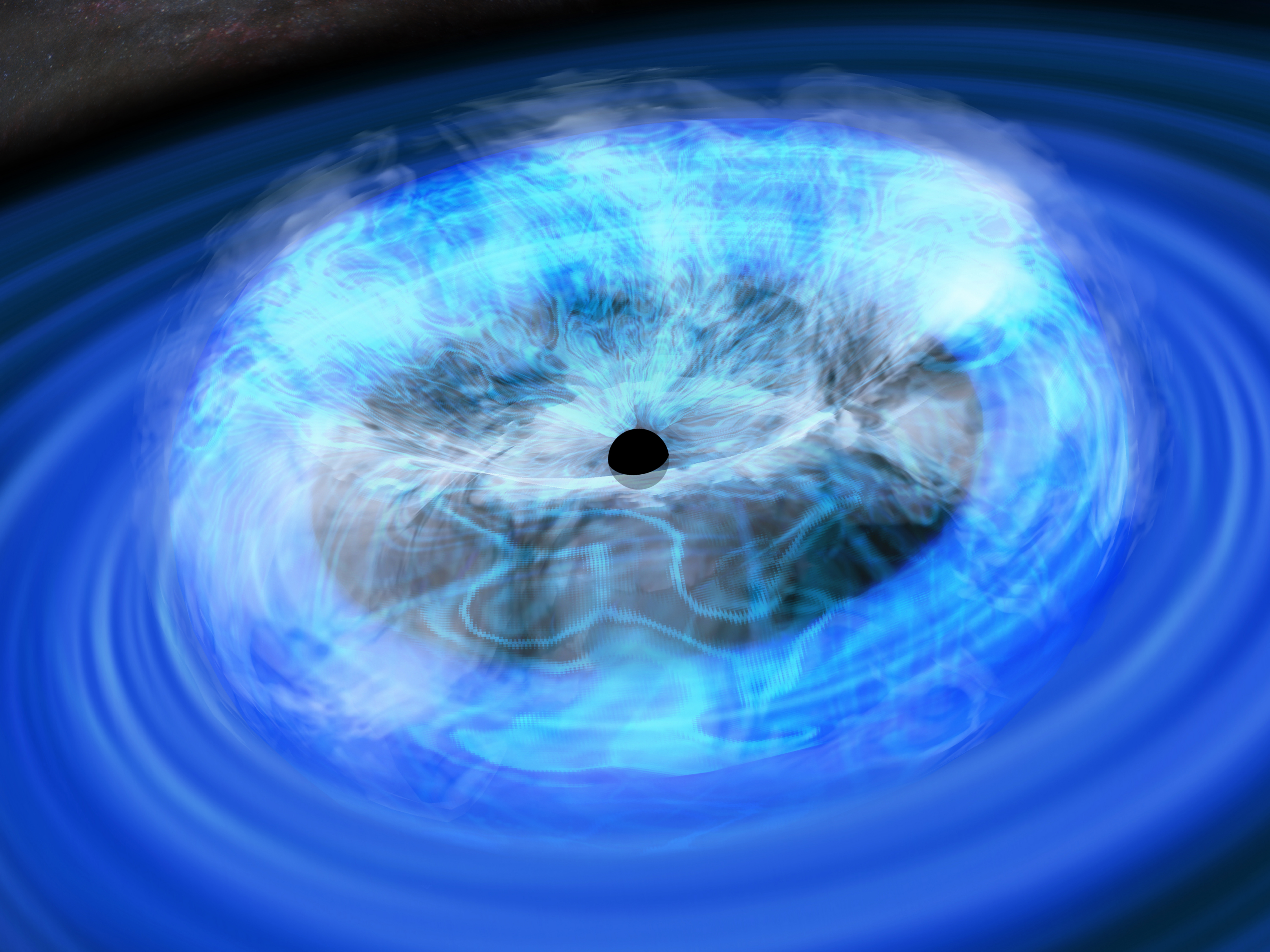


A possible interpretation: Truncated disk

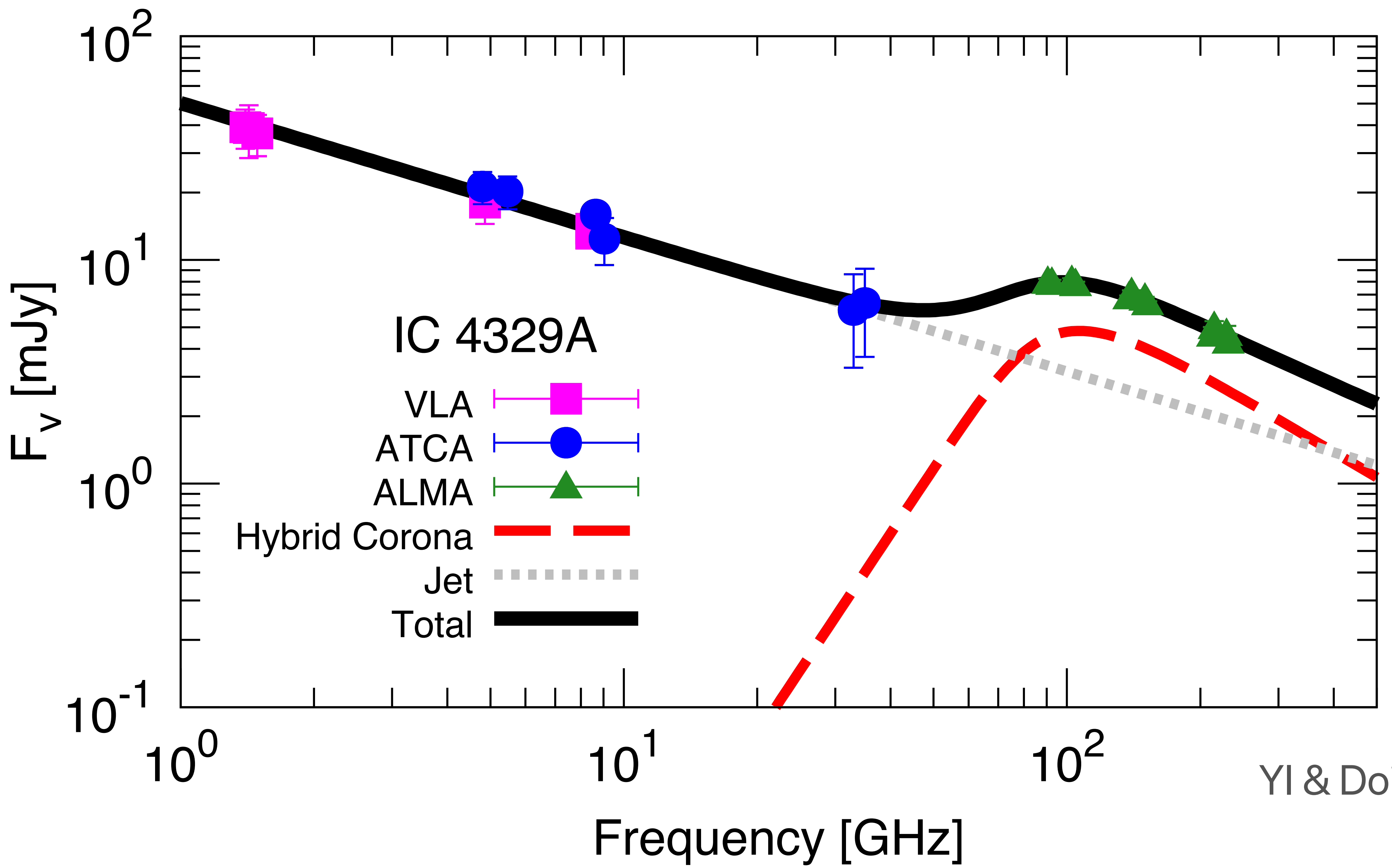
- Standard disk is truncated at some radii (e.g. ~40 r_S)
  - The inner part becomes hot accretion flow (Ichimaru '77, Narayan & Yi '94, '95).
    - Heated by advection.
  - Suggested for Galactic X-ray binary obs.

    (e.g. Poutanen+'97; Kawabata+'10; Yamada+'13).





cm-mm spectrum of IC 4329A Core

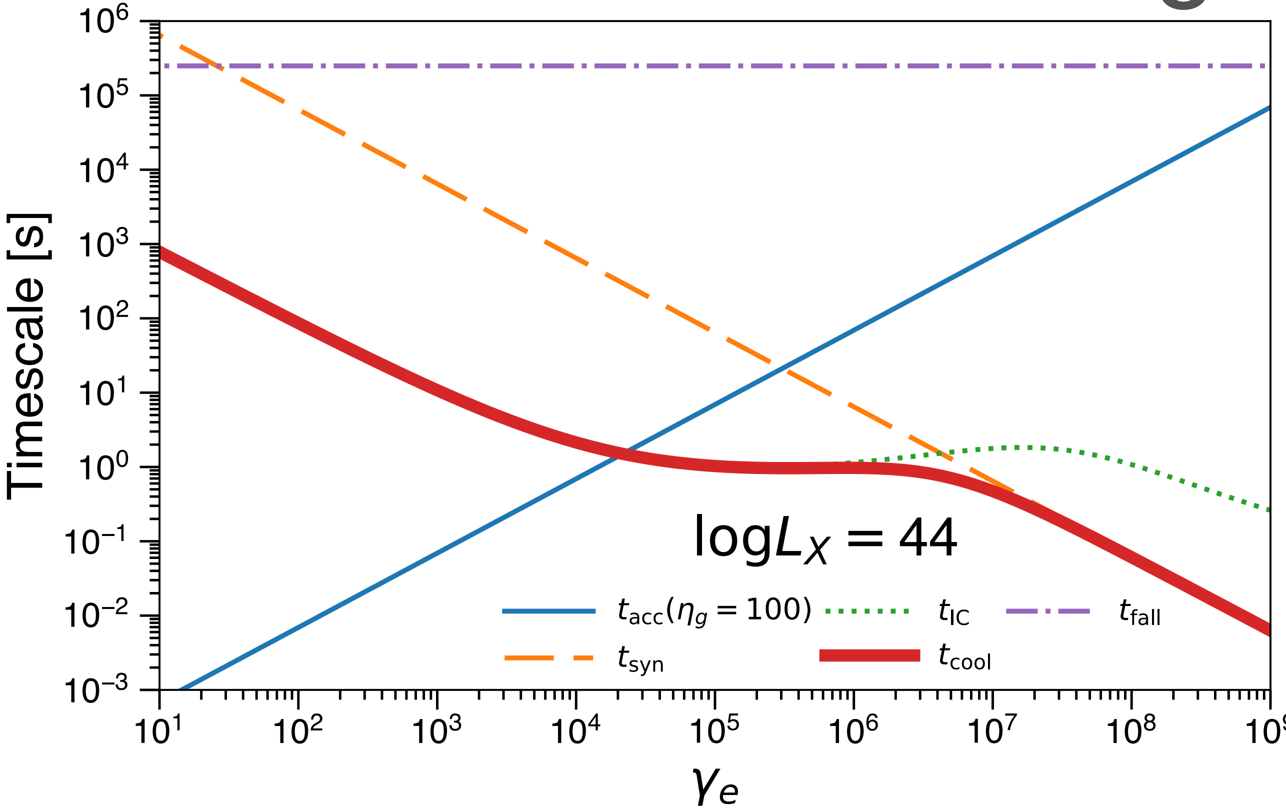


YI & Doi '18

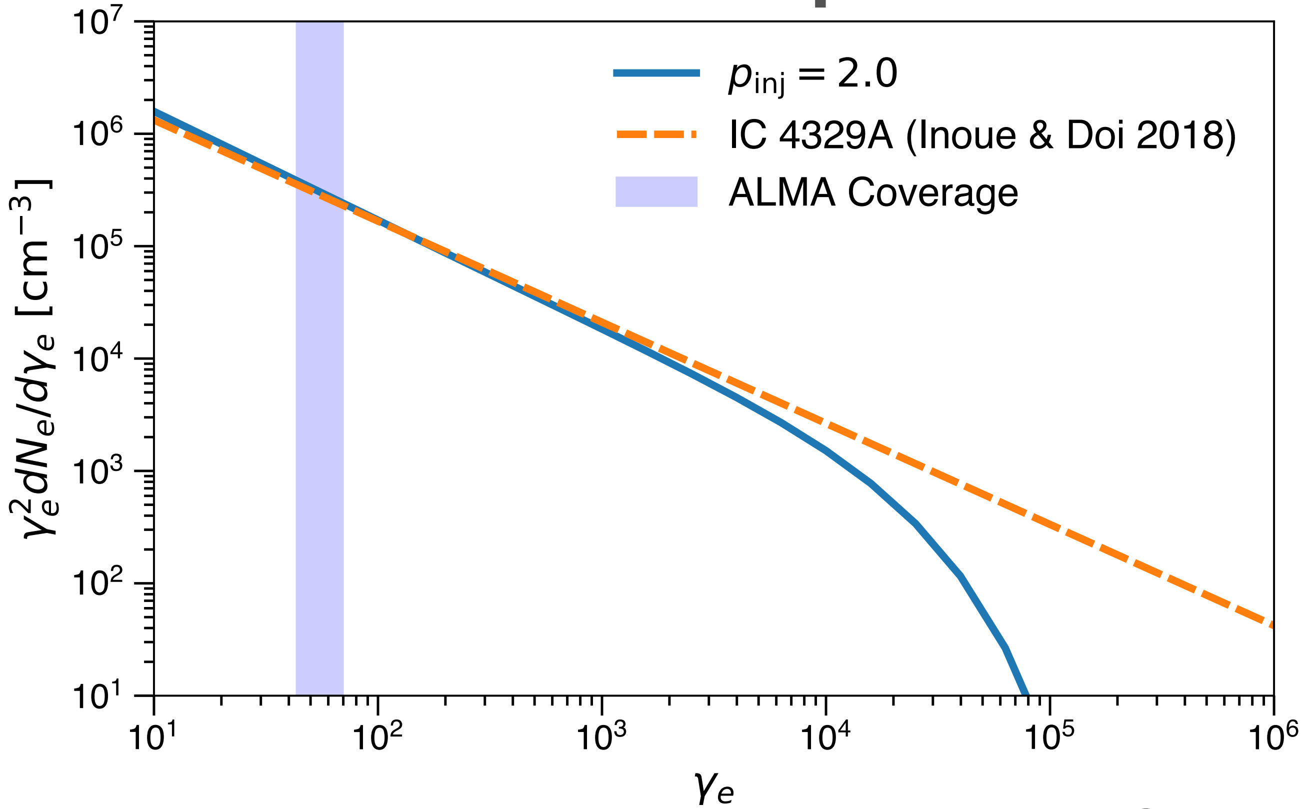
- Non-thermal electrons should exist in the coronae

Generation of High Energy Electrons in Coronae

Acceleration & Cooling



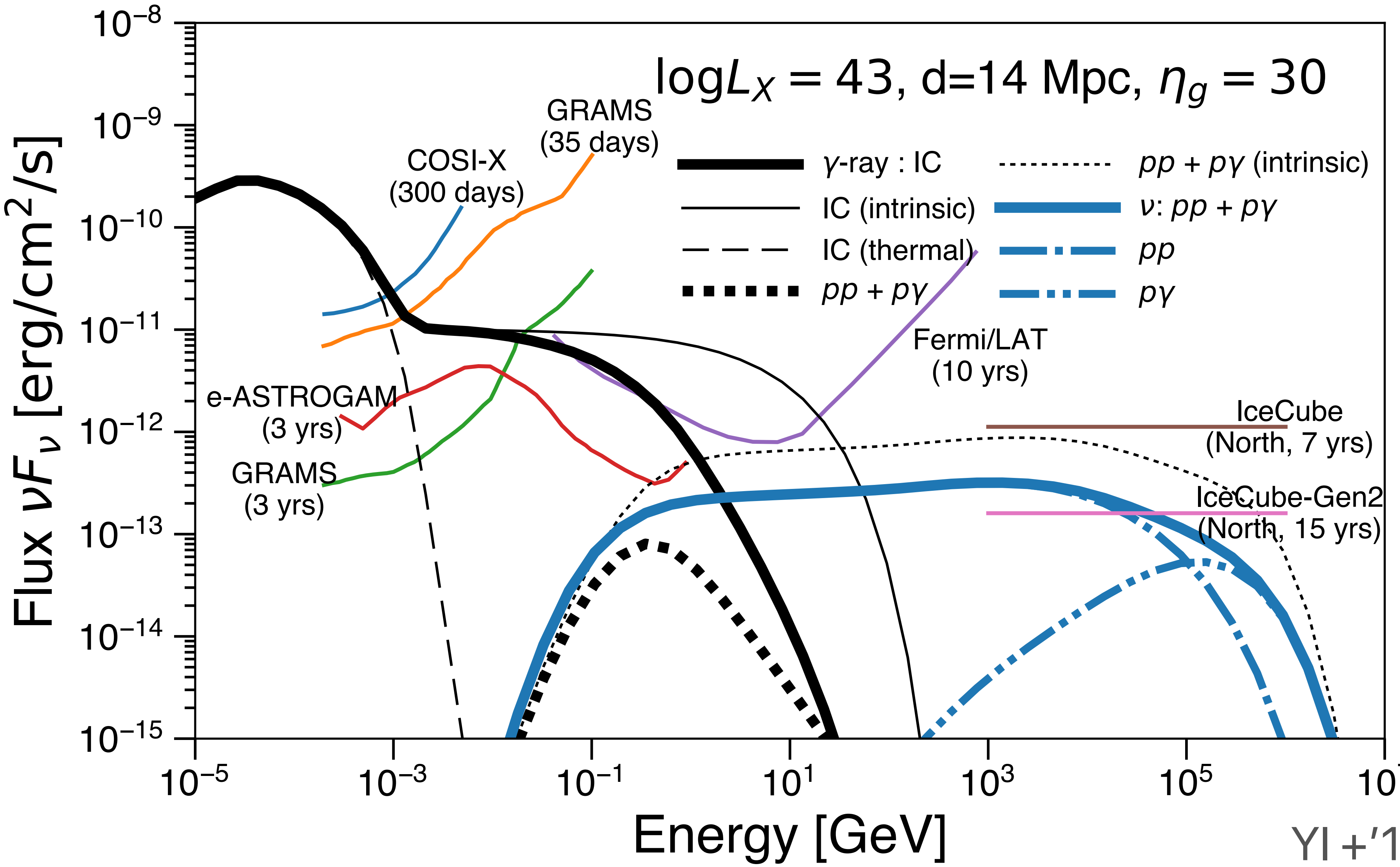
Electron Spectrum



YI + '19

- 1st-order Fermi acceleration can produce the observed electrons with an injection index of 2
- Other mechanisms may be difficult.
  - Because of low magnetic field and accretion rate.

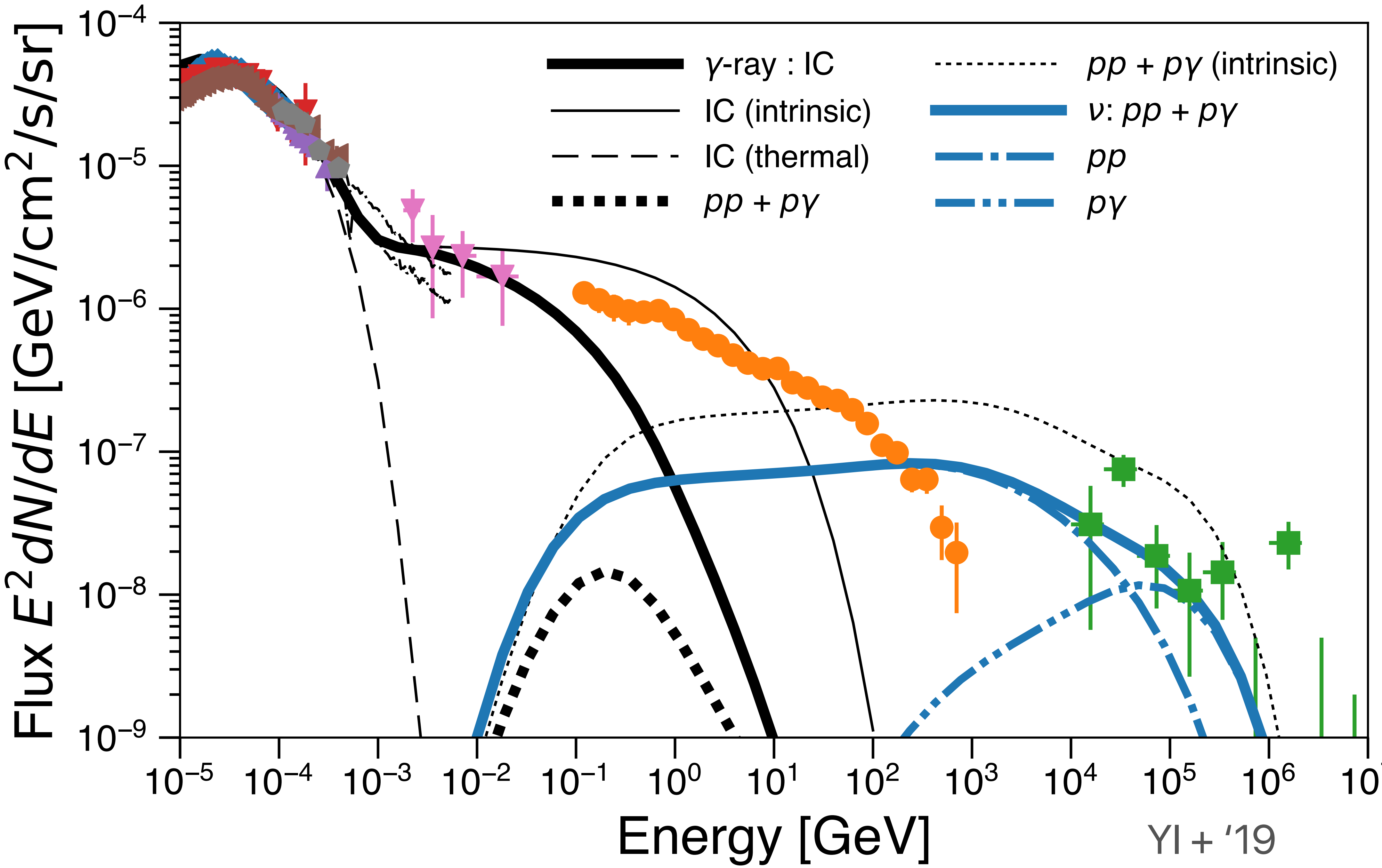
High energy emission from AGN coronae



YI +'19

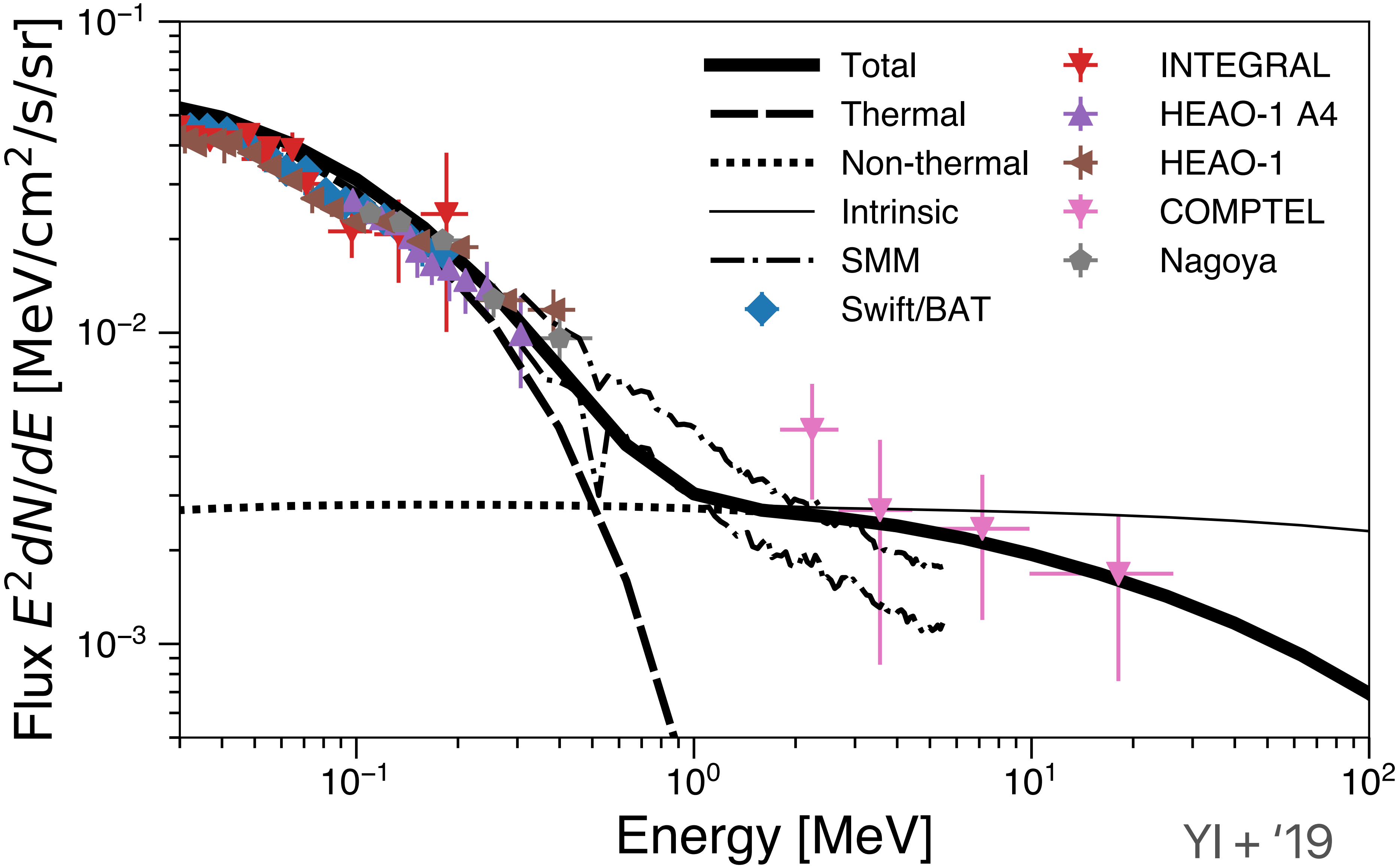
- MeV emission is expected, but no GeV emission due to pair creation
- Protons would also be simultaneously accelerated.
    - generation of neutrinos

Cosmic High Energy Background



- Seyferts can explain X-ray, MeV gamma-ray, & TeV neutrino background.
    - But, if both protons and electrons carry ~5% of the shock energy and gyrofactor is 30.

Seyferts and Cosmic MeV Gamma-ray Background

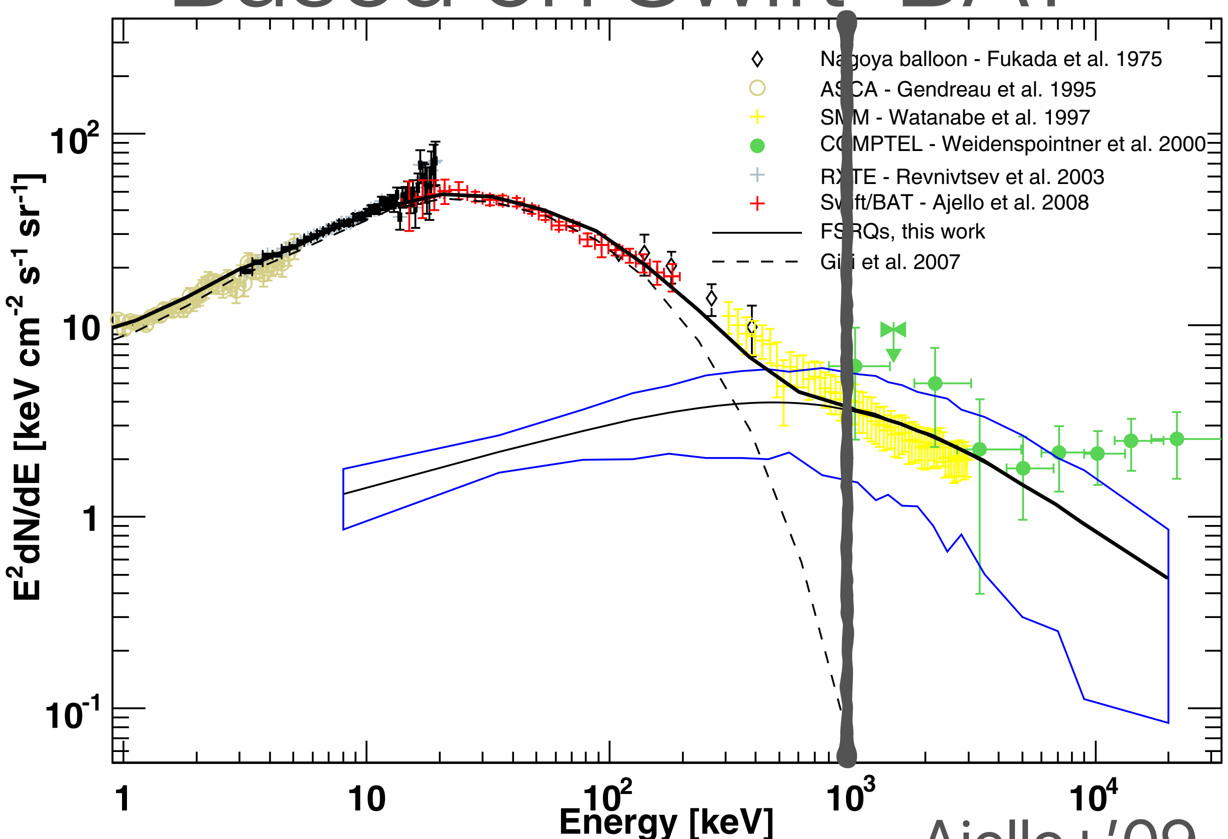


YI + '19

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

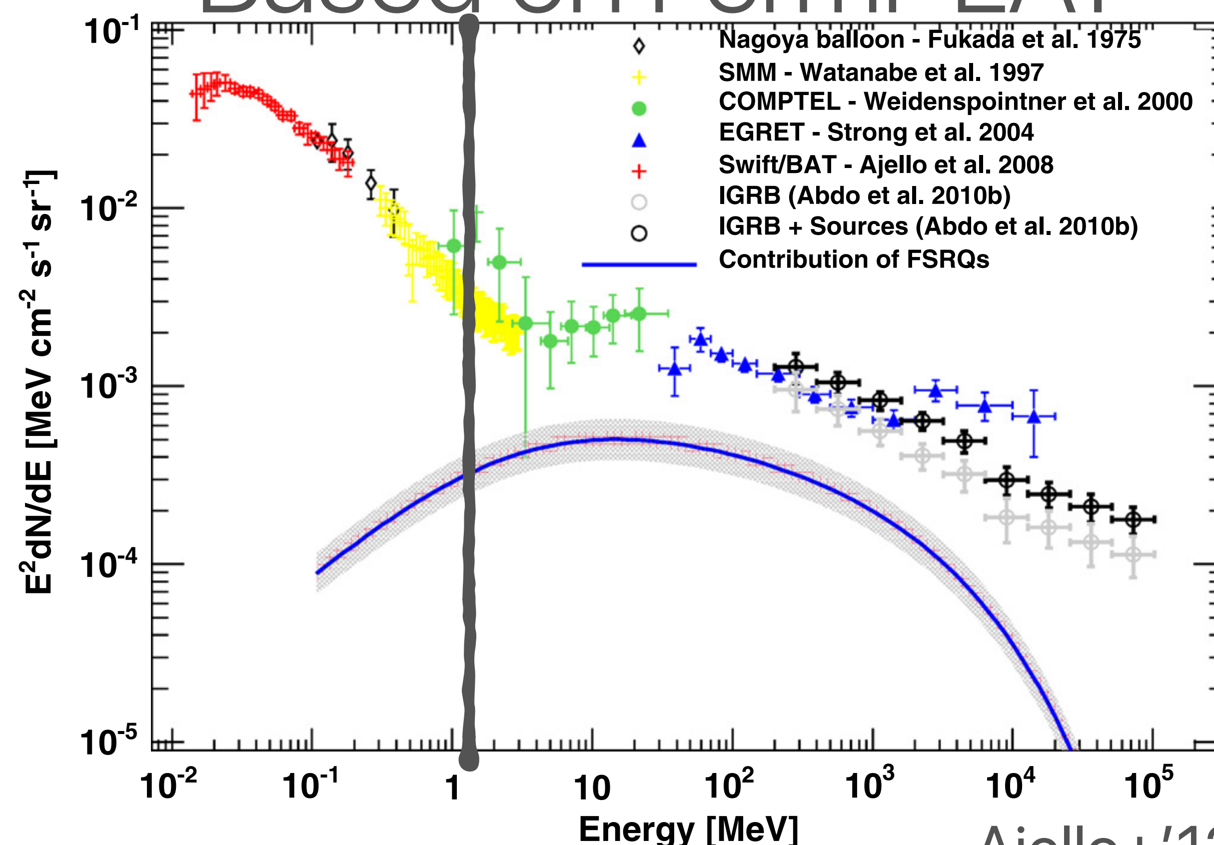
Blazars and Cosmic MeV Gamma-ray Background

Based on Swift-BAT



Ajello+'09

Based on Fermi-LAT

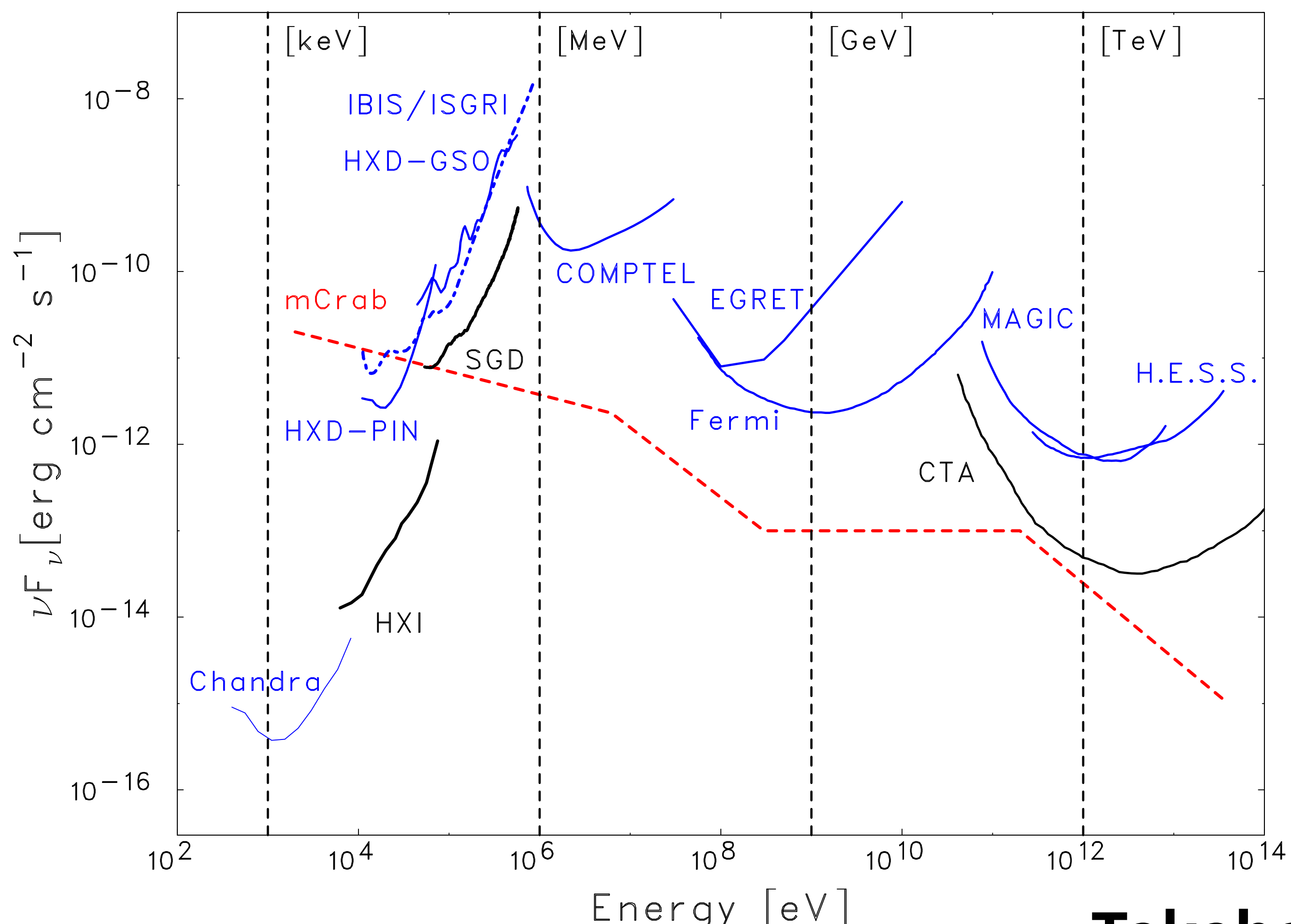


Ajello+'12

- Blazars contribute to the GeV gamma-ray background with a peak at ~100 MeV (e.g. YI & Totani '09, Ajello +'12)

➡Two components in gamma-ray spectra or two populations?

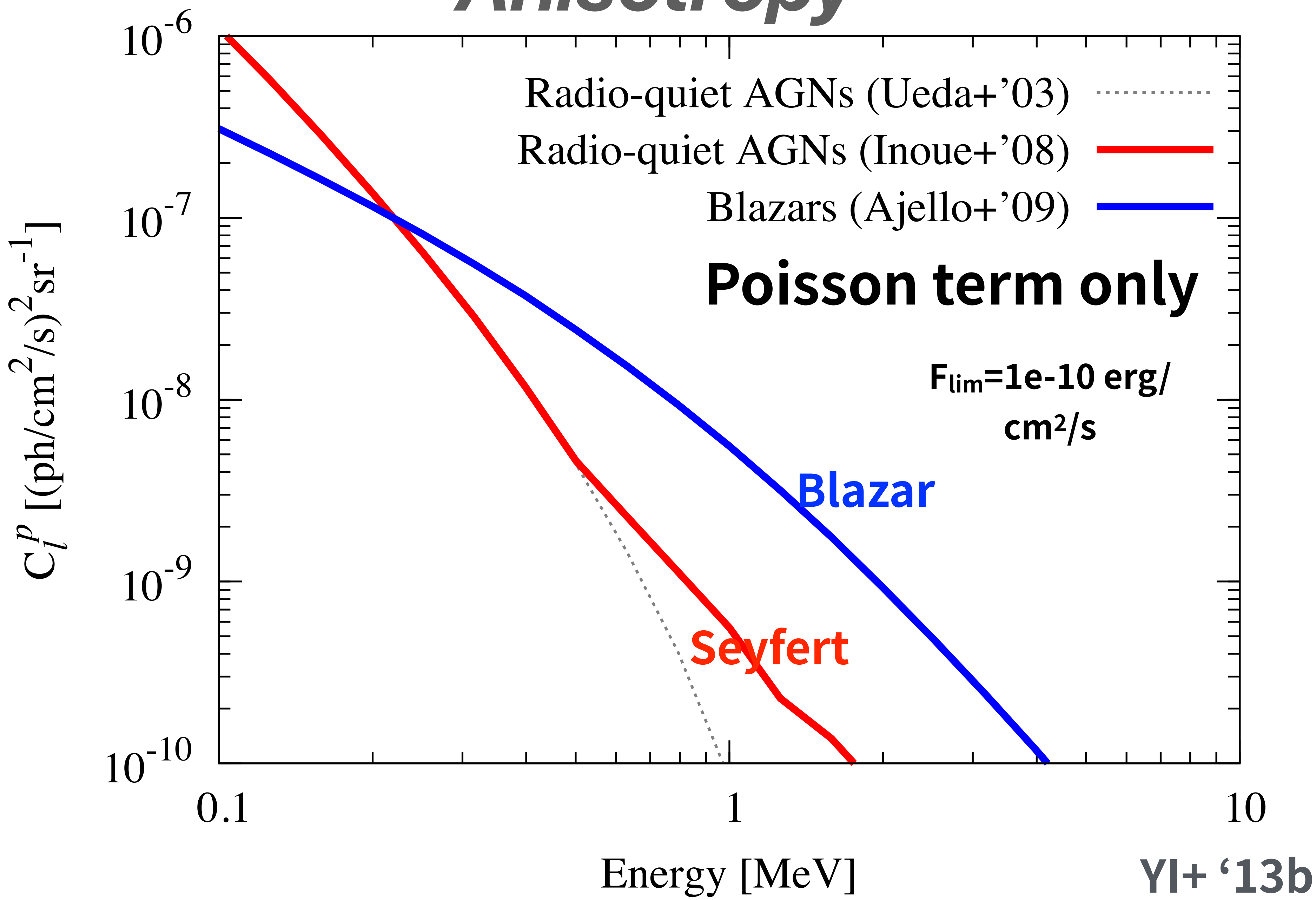
Not easy to resolve the MeV sky.



Takahashi+'13

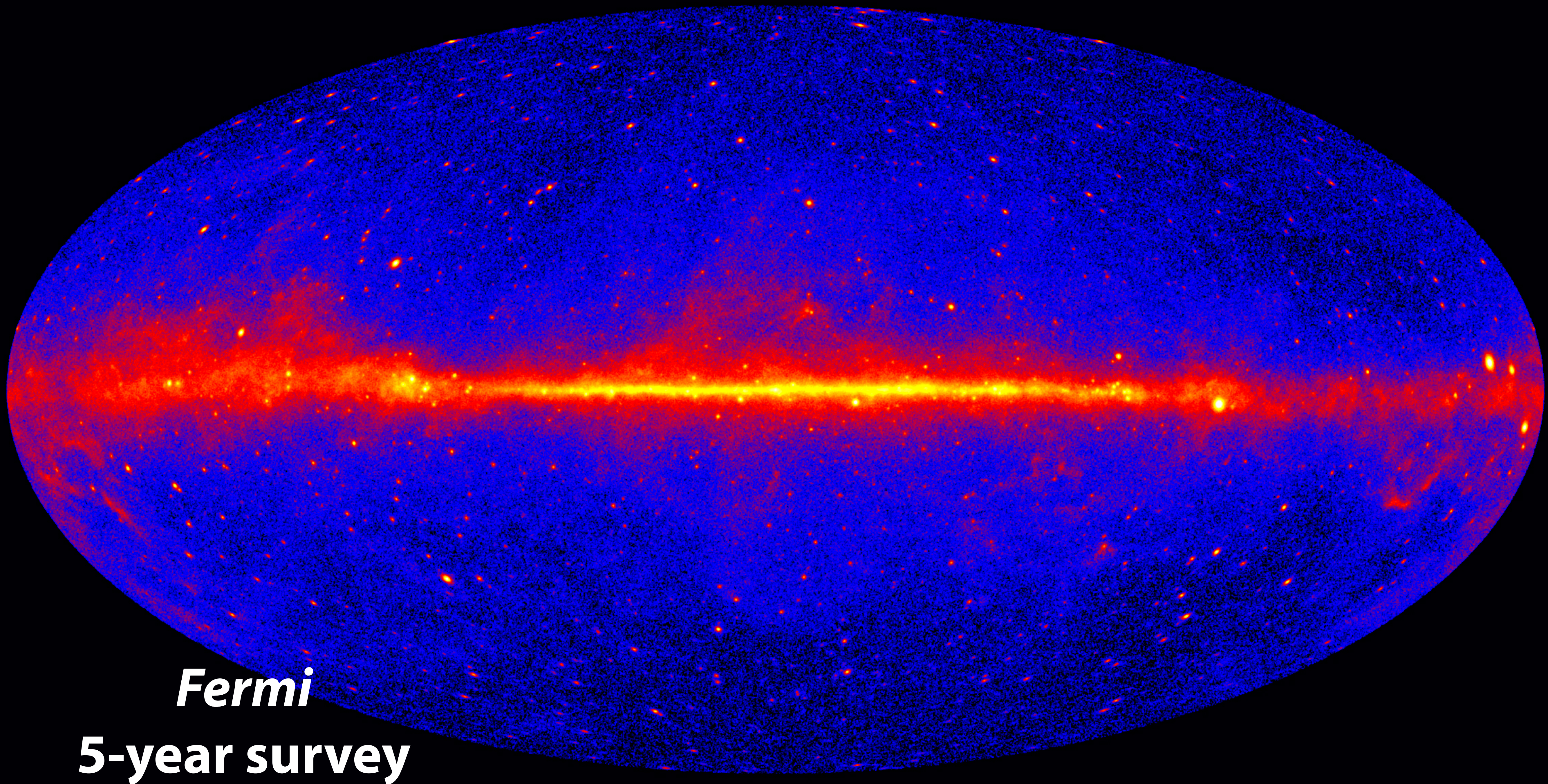
- Even achieving the sensitivity of 10^{-11} erg/cm^2/s, it is hard to resolve the MeV sky (*YI+'15*).
- Answers are in "***Anisotropy***".
  - Cosmic background radiation is not isotropic.
  - There is anisotropy due to the sky distribution of its origins.

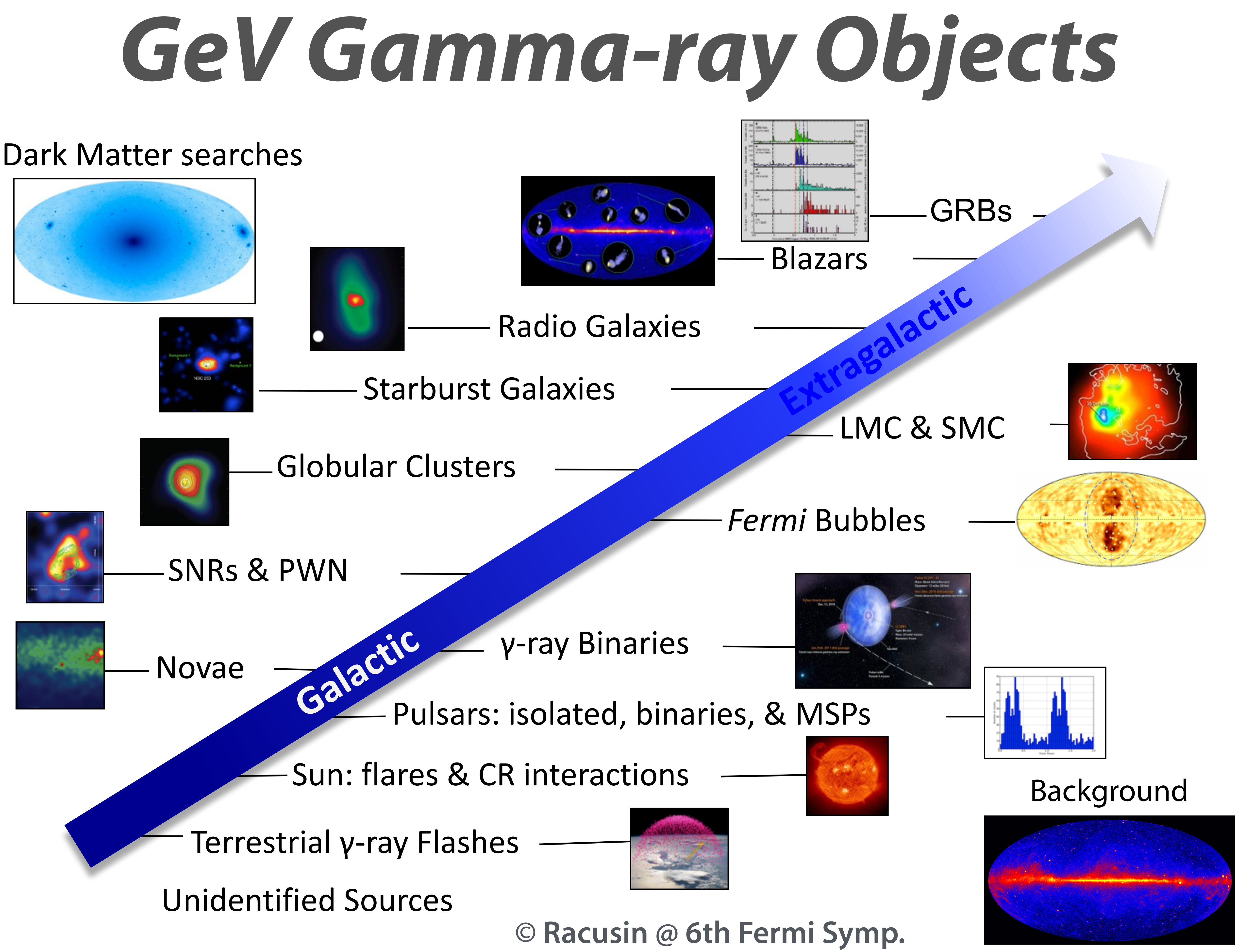
Cosmic MeV Gamma-ray Background "Anisotropy"



- Future MeV satellites will distinguish Seyfert & blazar scenarios through anisotropy in the sky.

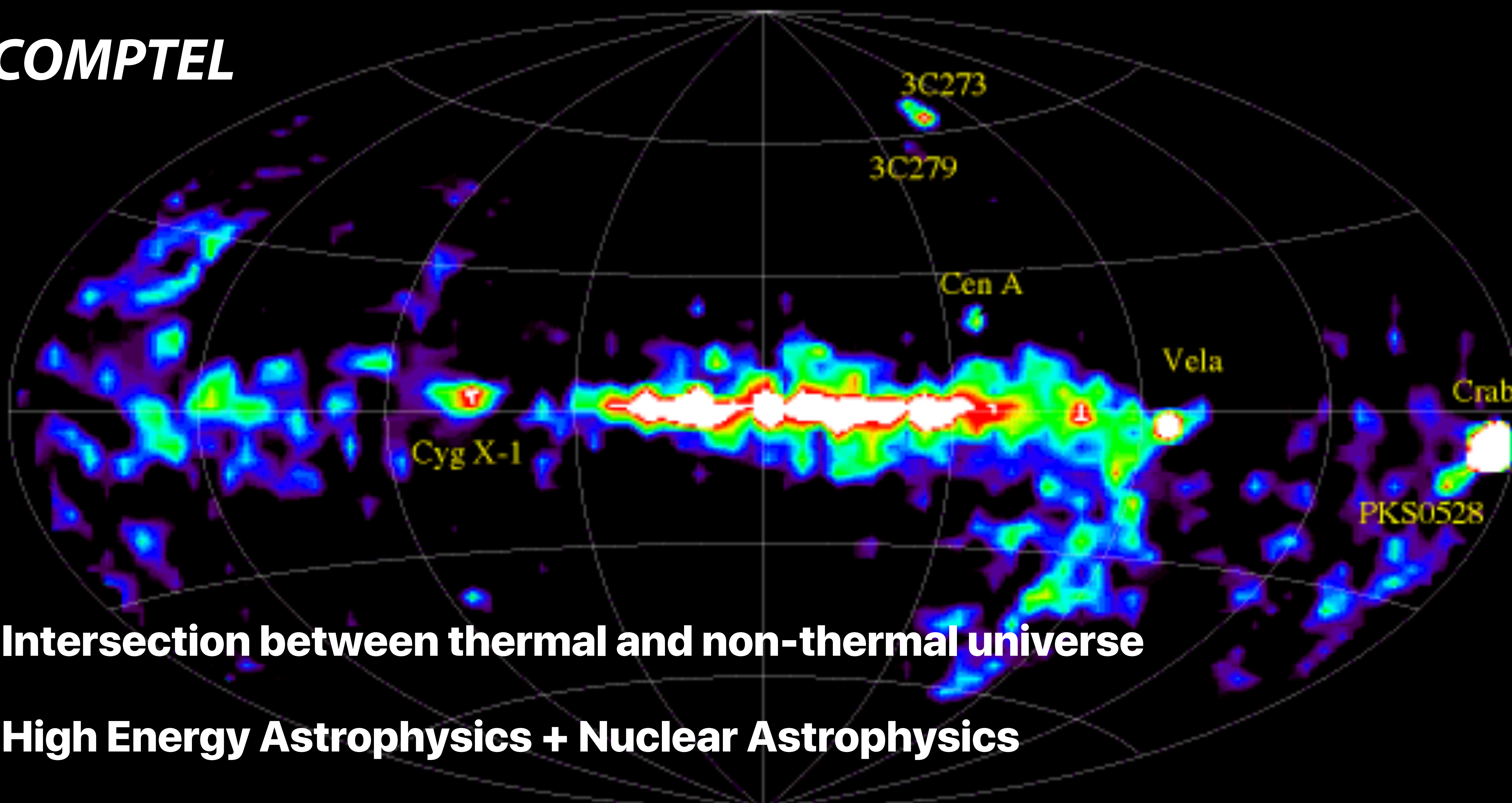
GeV Gamma-ray Sky




GeV Gamma-ray Objects
Dark Matter searches
GRBs
Blazars
Radio Galaxies
Starburst Galaxies
Extragalactic
LMC & SMC
Globular Clusters
Fermi Bubbles
SNRs & PWN
γ-ray Binaries
Novae
Galactic
Pulsars: isolated, binaries, & MSPs
Sun: flares & CR interactions
Background
Terrestrial γ-ray Flashes
Unidentified Sources
© Racusin @ 6th Fermi Symp.

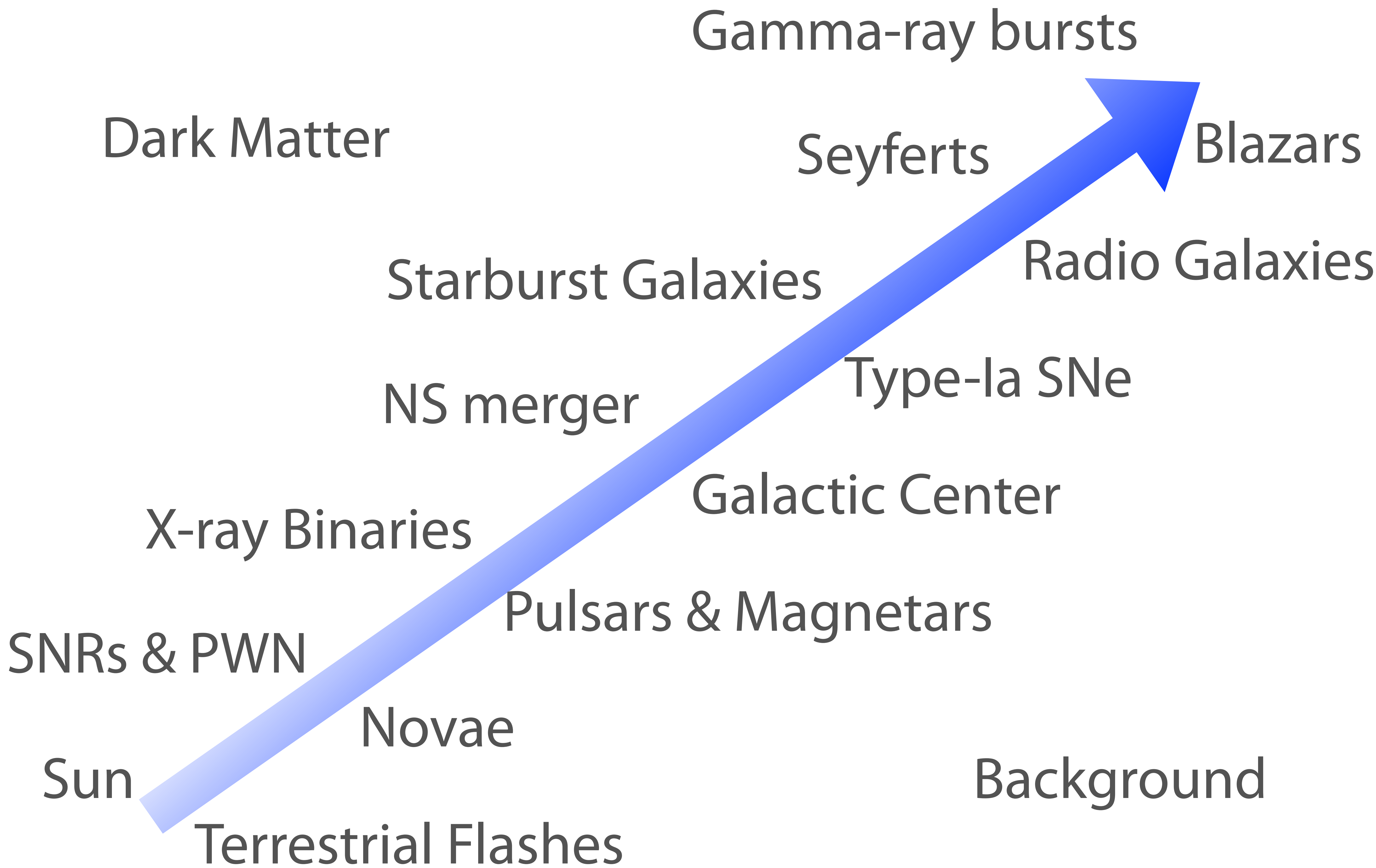
MeV Gamma-ray Sky

COMPTEL



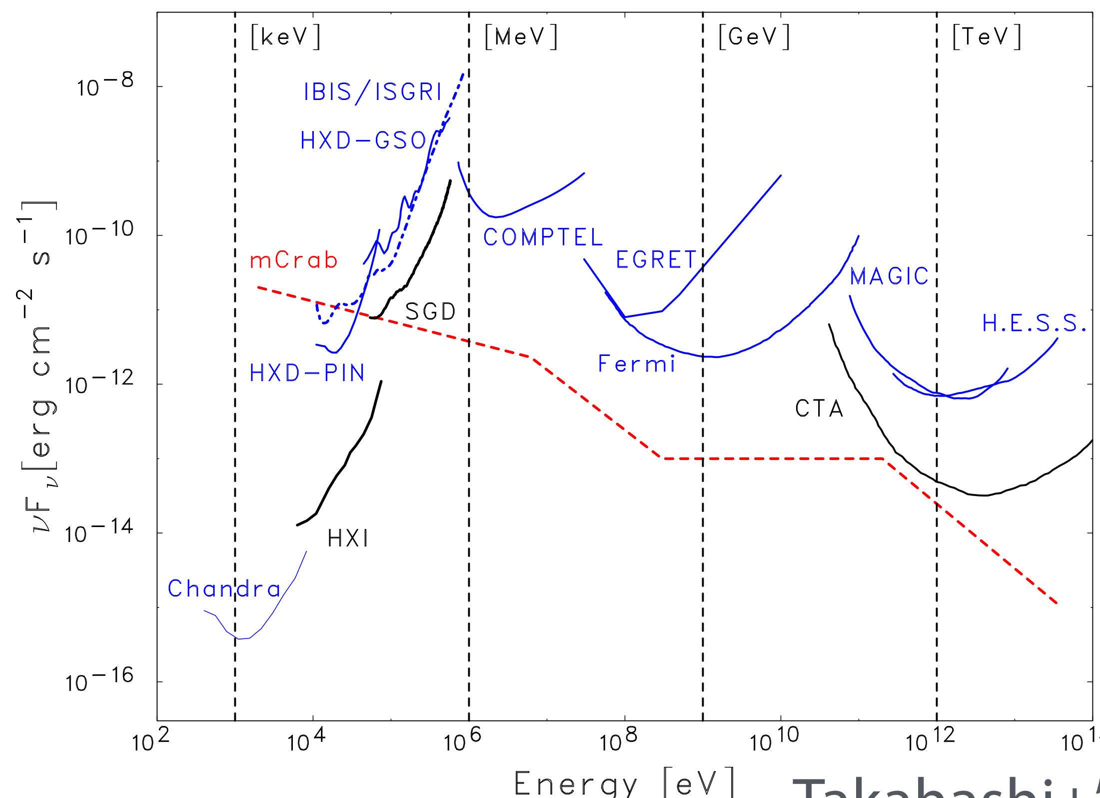
- Intersection between thermal and non-thermal universe
- High Energy Astrophysics + Nuclear Astrophysics
  - Many supermassive black holes are expected to be bright in MeV (YI+'15)
- We should open the MeV window in the sky.

MeV Gamma-ray Science

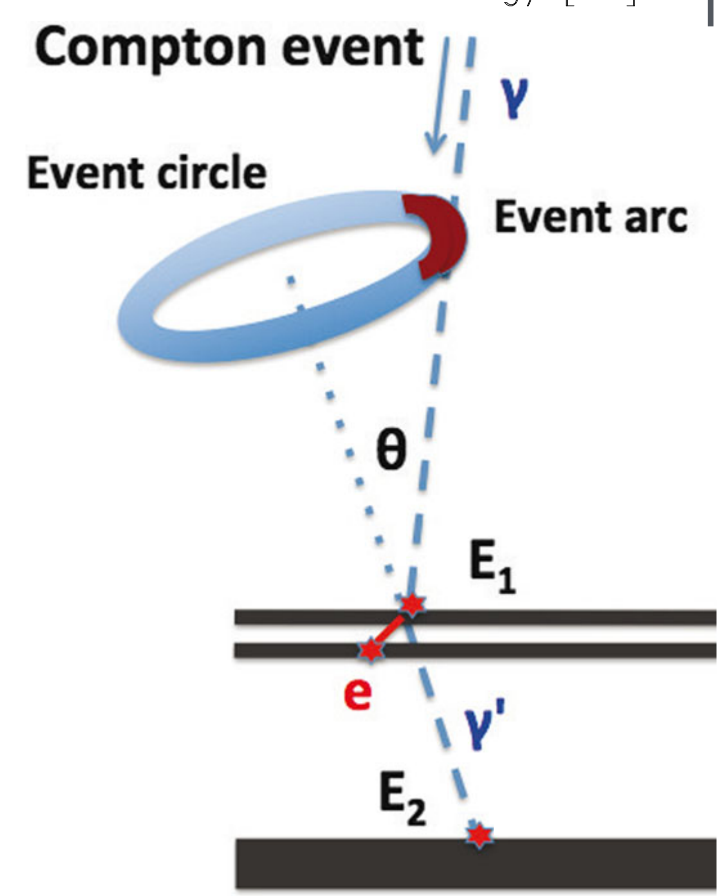


MeV Gamma-ray Observations

- ***Poor sensitivity***
  - 32 srcs in MeV
  - 1.25M srcs in X-ray, 3000 srcs in GeV, ~150 srcs in TeV
- Compton Camera
  - Detect Compton scattering events

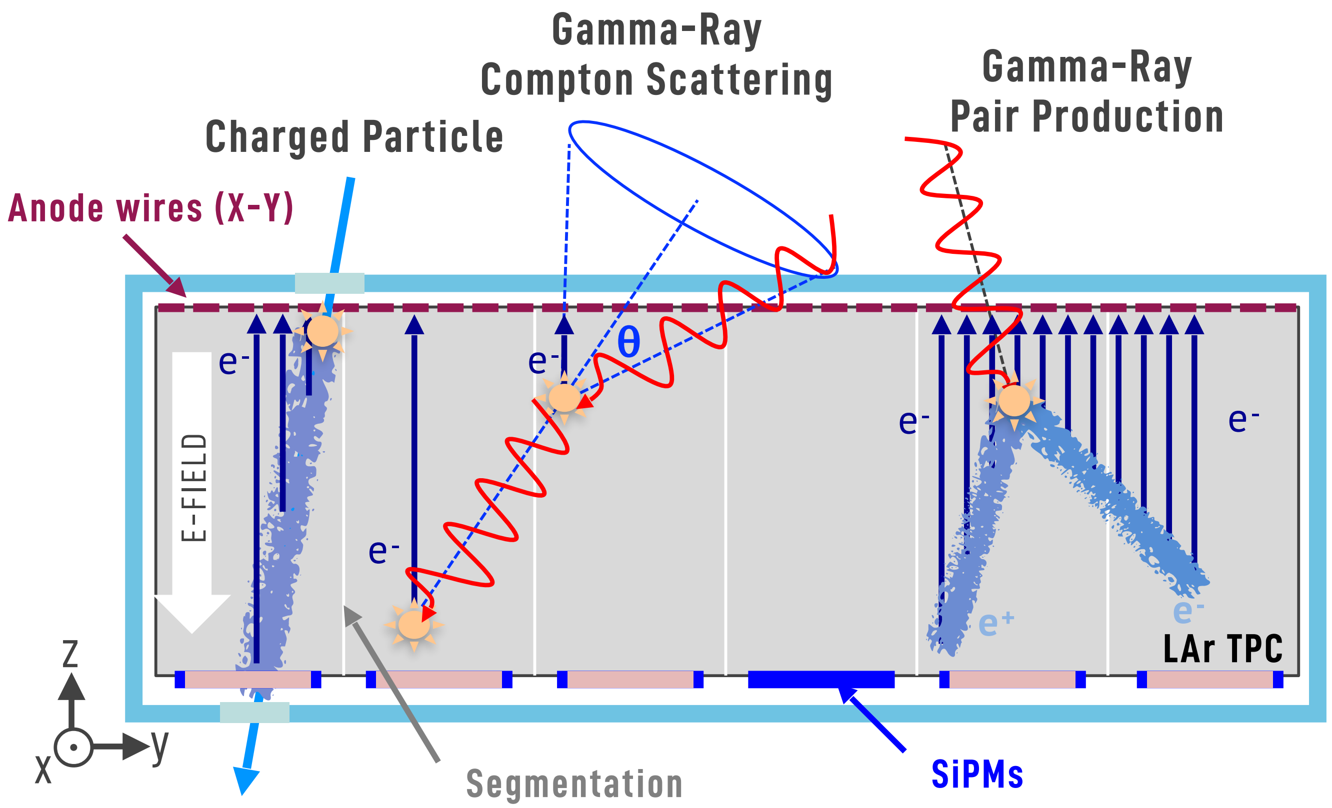


Takahashi+’13

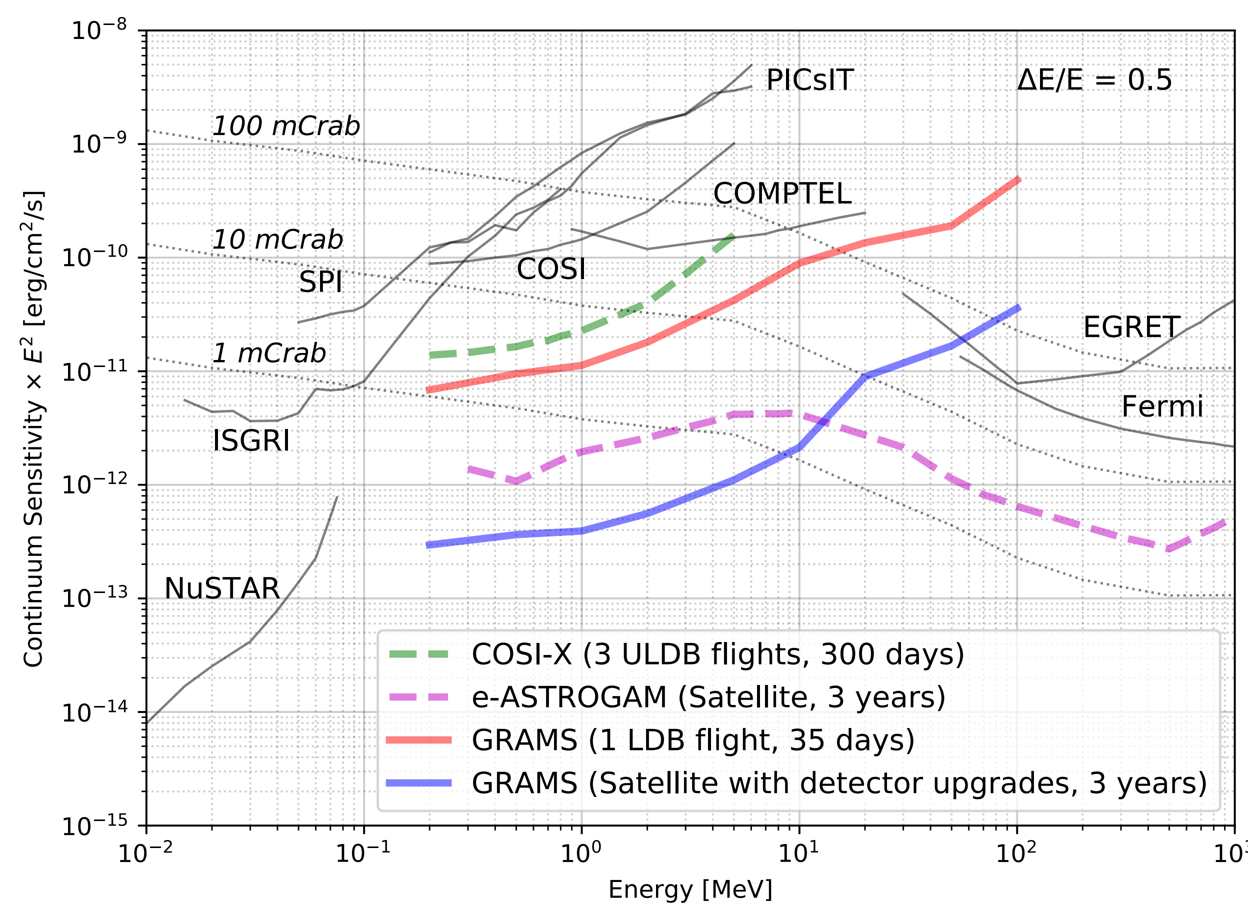


©e-ASTROGAM

Gamma-Ray and AntiMatter Survey (GRAMS; Aramaki+'19)

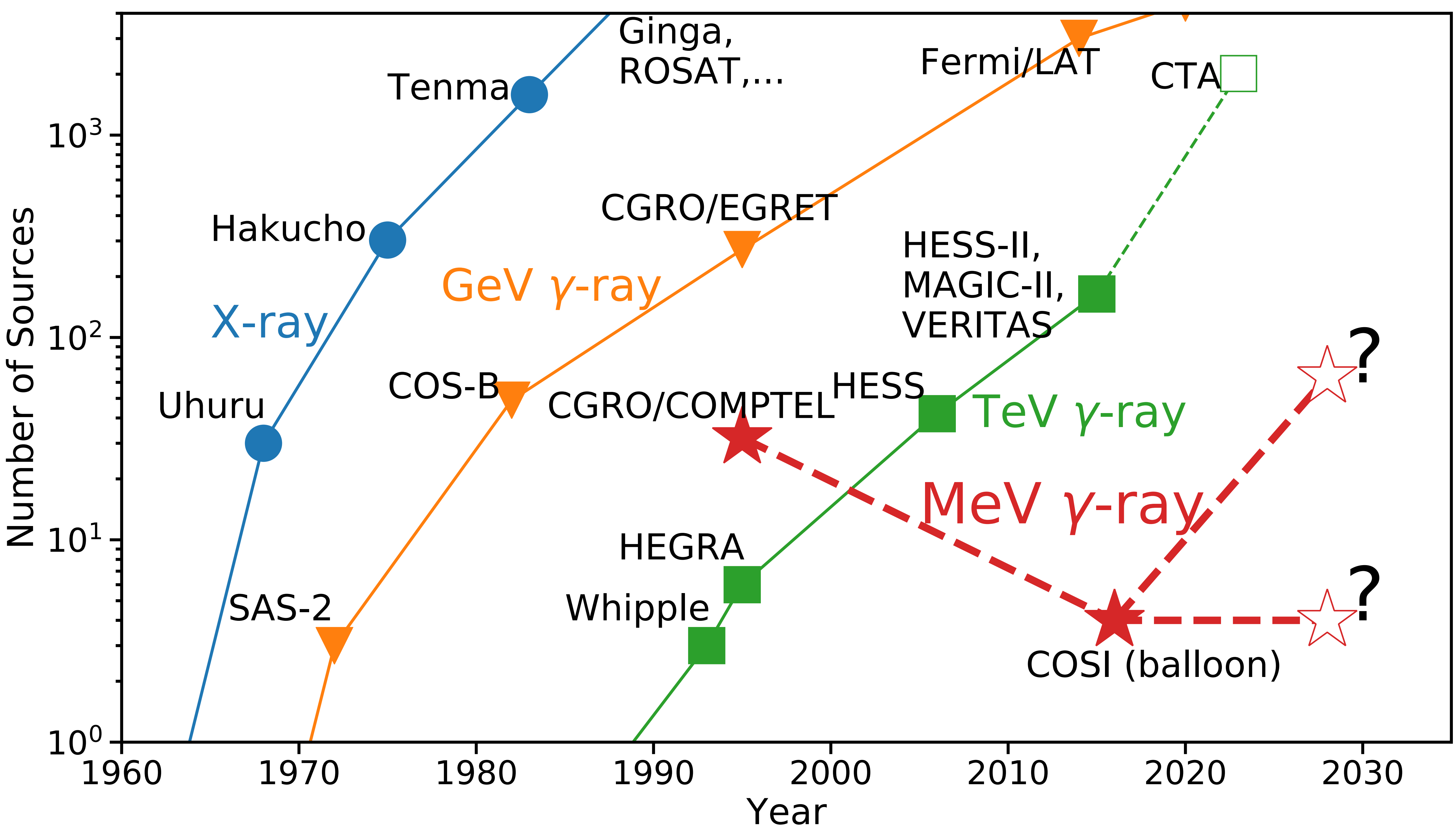


- Concept for future
  - MeV gamma-ray observation
  - Antimatter-based dark matter search
- Super-pressure ballon



- ***Liquid*** Argon time projection chamber
- Led by Colombia University and SLAC

Number of Astrophysical Objects

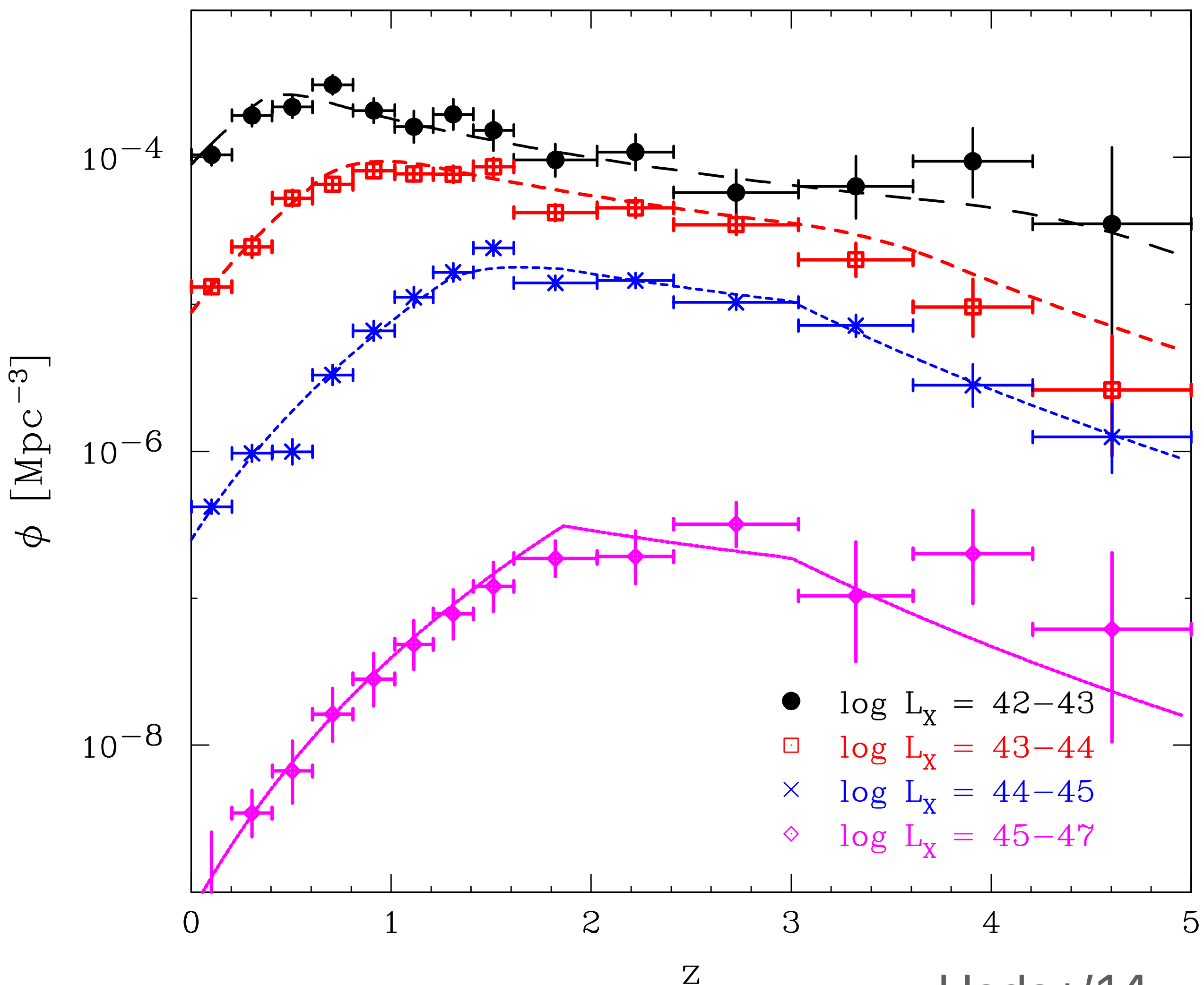


Kifune plot (modified by YI)

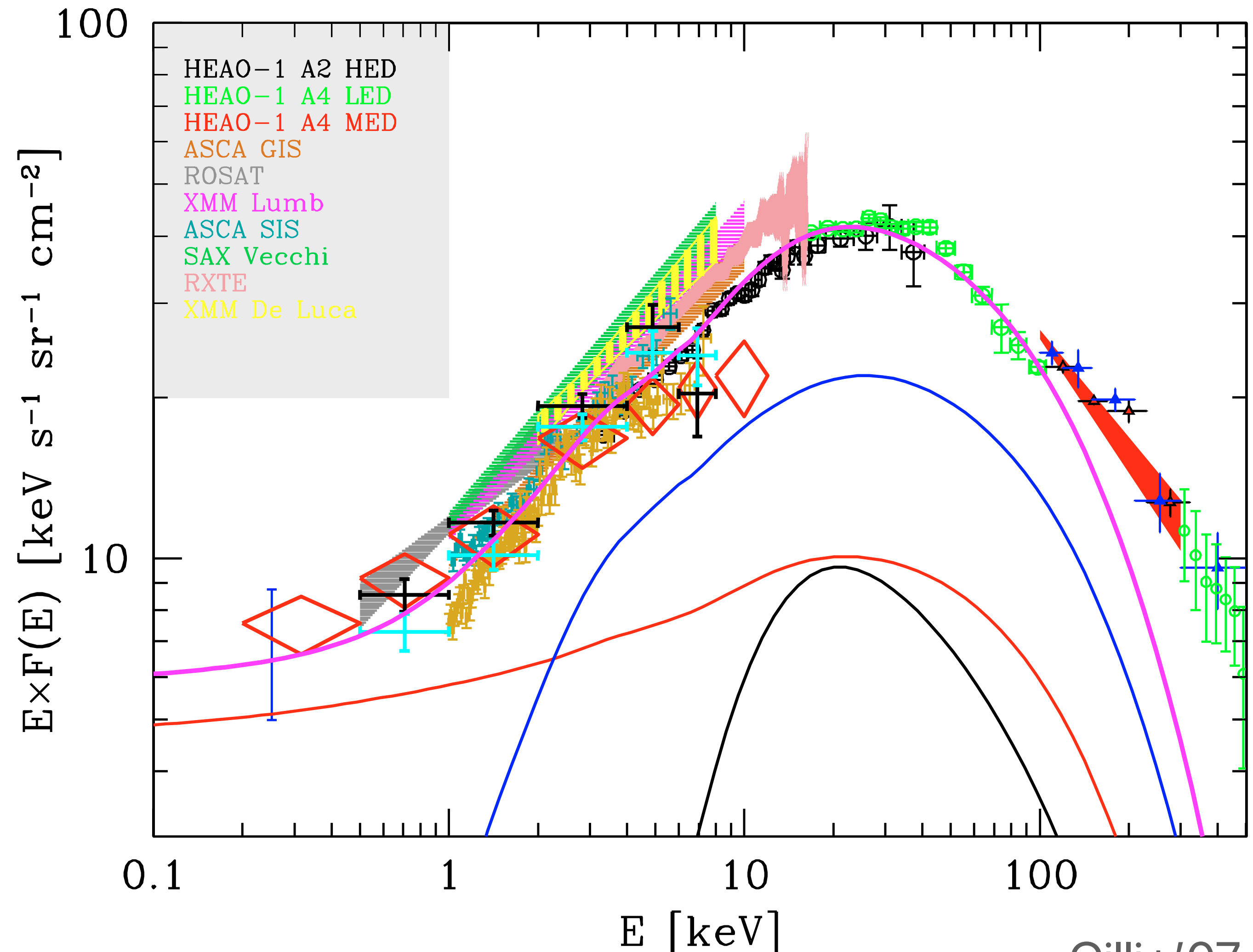
Summary

- Activity of supermassive black holes is a key for understanding the cosmic history
- Coronal synchrotron emission tells magnetic fields near SMBHs.
- ALMA has detected coronal synchrotron emission.
  - weak magnetic field
  - non-thermal electrons in coronae
- Seyferts may be responsible for cosmic X-ray, MeV gamma-ray, and TeV neutrino background fluxes.
- Future MeV gamma-ray mission is important.

Cosmic X-ray Background Radiation



Ueda+'14



Gilli+'07

- The origin of CXB is Seyferts.
  - >90 % of CXB at 0.5-10 keV has been resolved to individual AGNs.