How can we find black holes?

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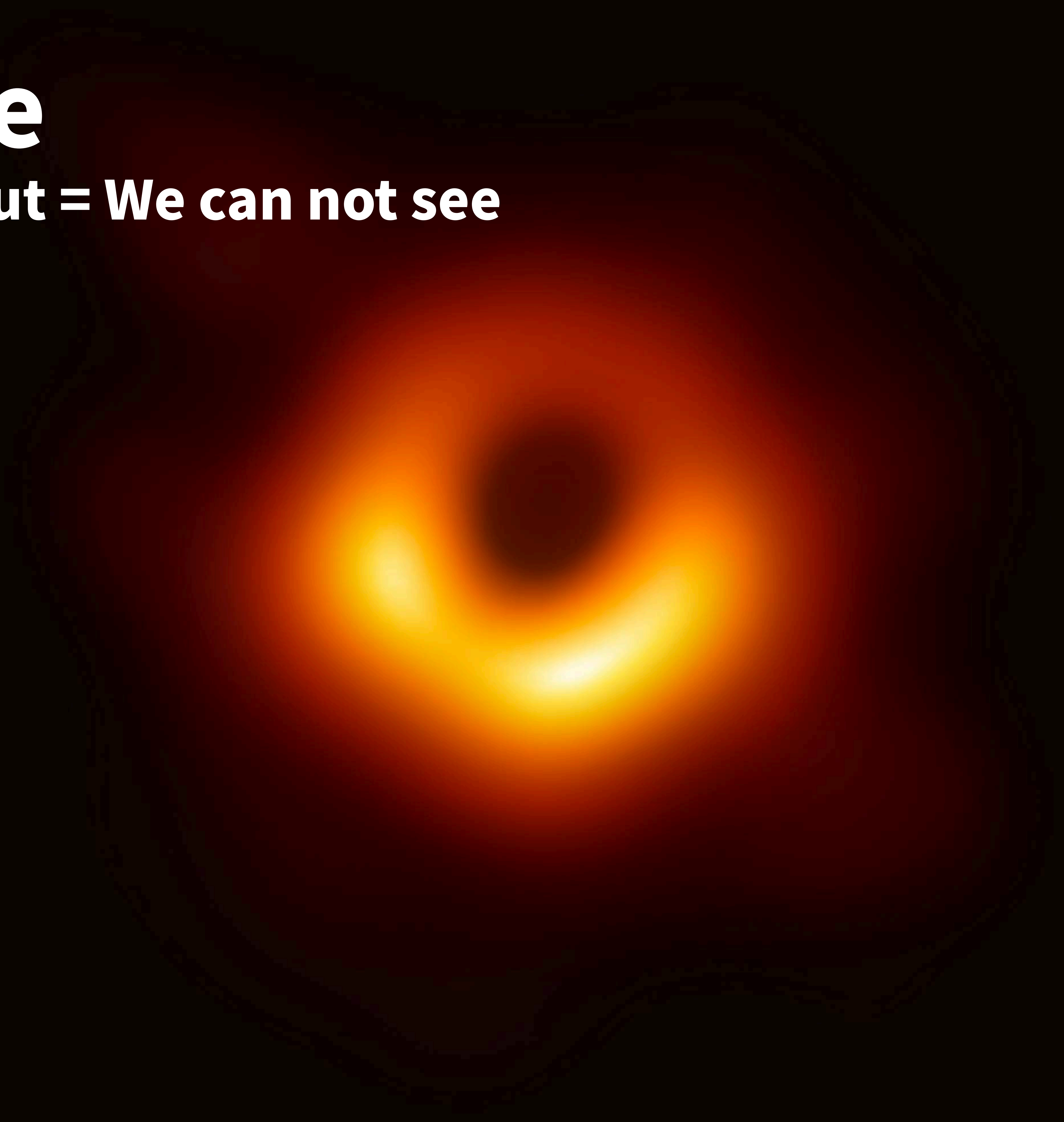
SciScis Workshop @ Osaka, 2021-03-15

大阪大学 OSAKA UNIVERSITY
OU TAP Osaka University Theoretical Astrophysics
RIKEN iTHEMS
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Black Hole

No light can get out = We can not see



We can see invisibles.

Guess from circumstantial evidence

How do we see the universe?

~13.8 Glyr

~10^{23} km

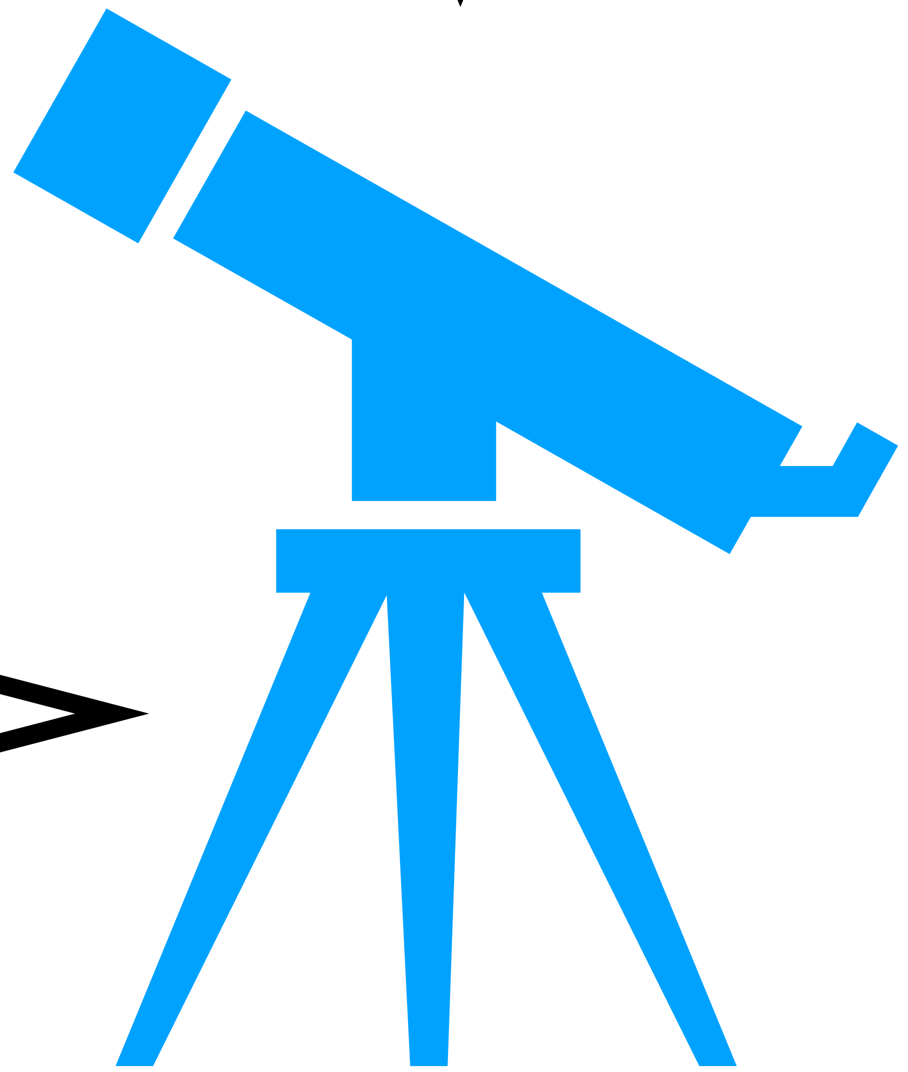
Very Very Far

Electromagnetic waves

Cosmic rays

Gravitational waves

Image
Position
Flux
Variability

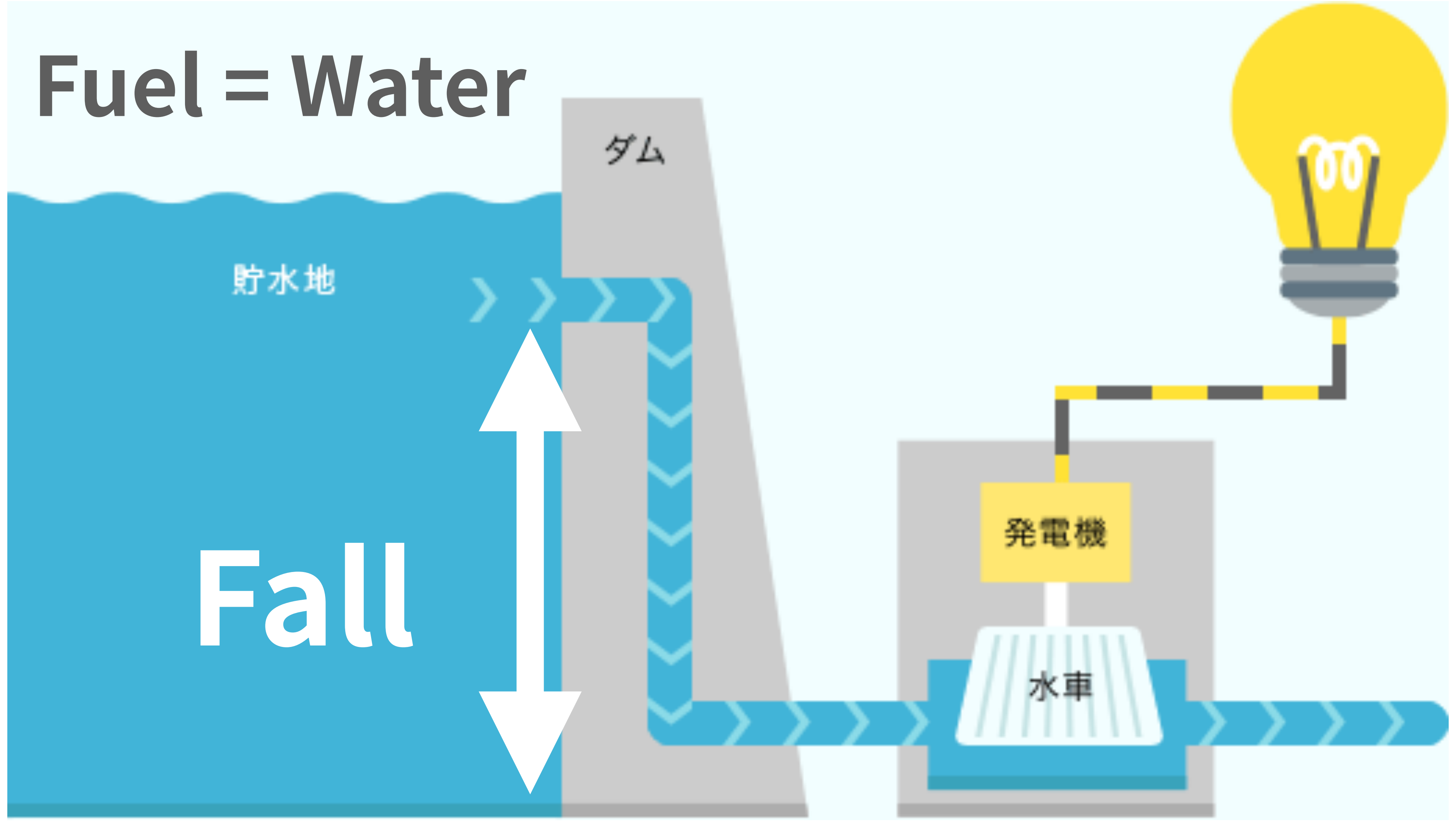


+ Physics =
Understand the universe
Prediction
New science

Finding black holes through light

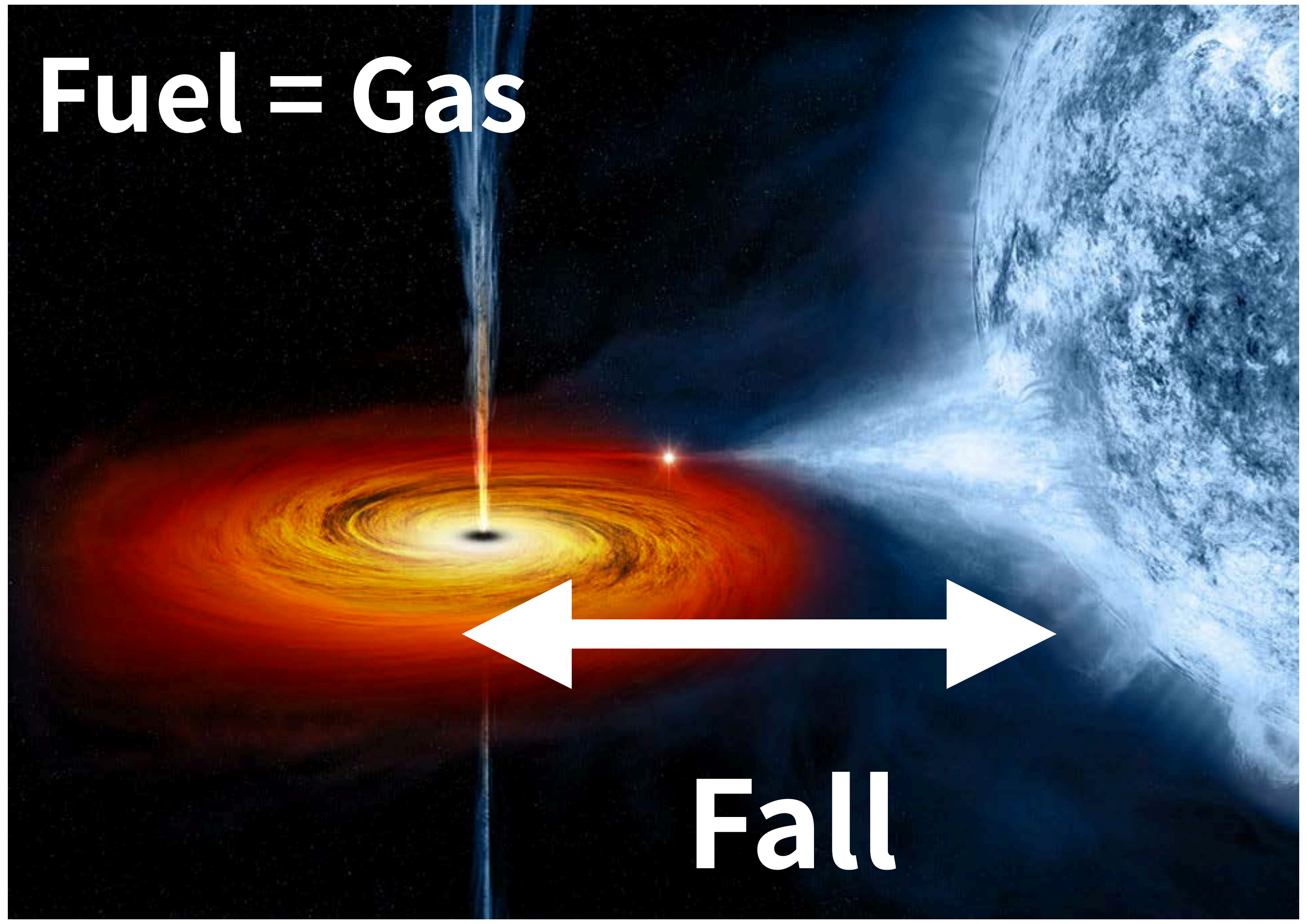
Do Black Holes Shine?

Water Power Plant



https://www.sbenergy.jp/study/illust/water/

Black Hole Power Plant



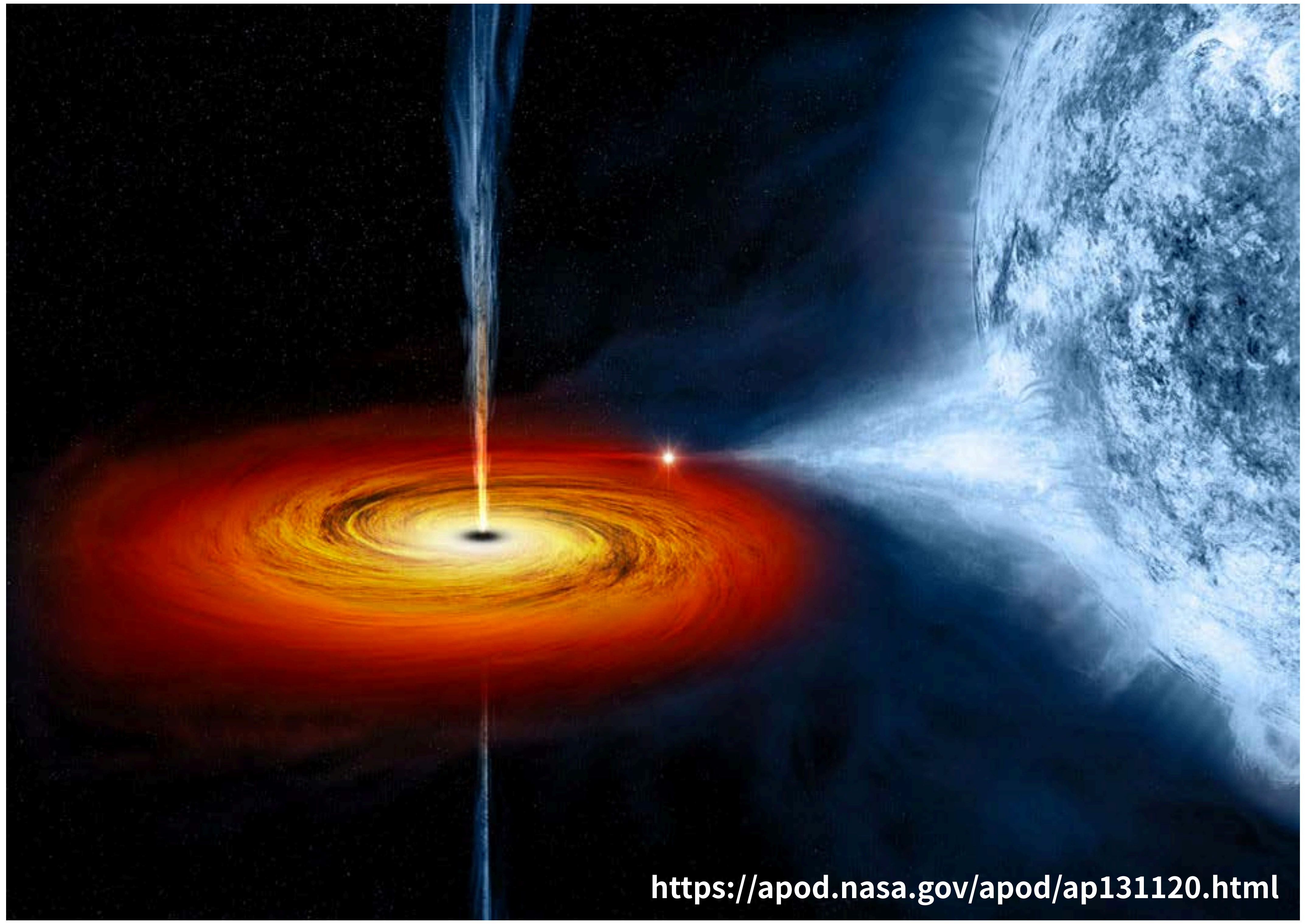
https://apod.nasa.gov/apod/ap131120.html

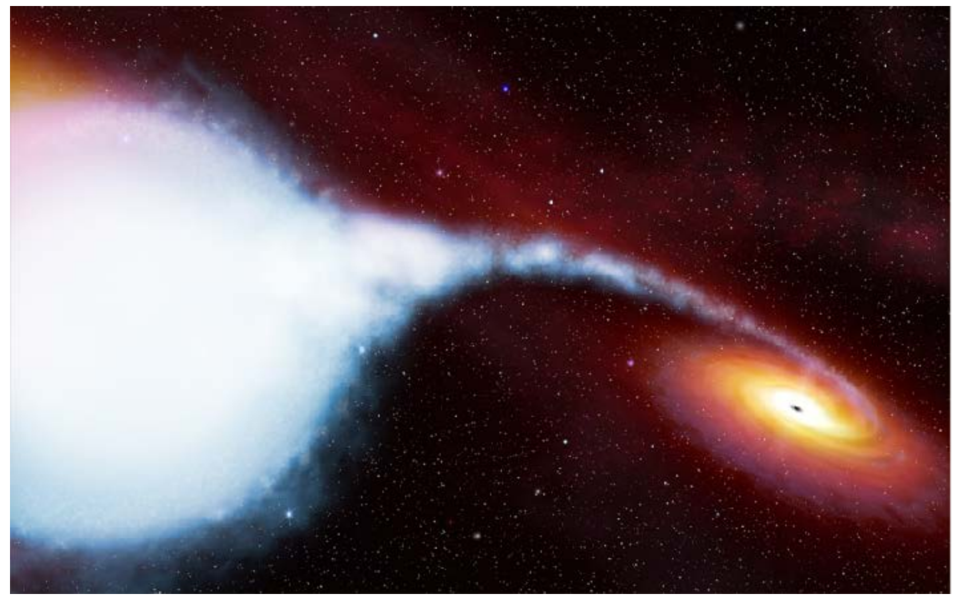
- Black hole itself does not shine. But, surrounding gas shines.
  - Release gravitational potential energy through gas fall (accretion).
- Gas fall → Gas friction → Frictional heat → Radiation

Which black hole can we see?

Example: Black Hole Binary System

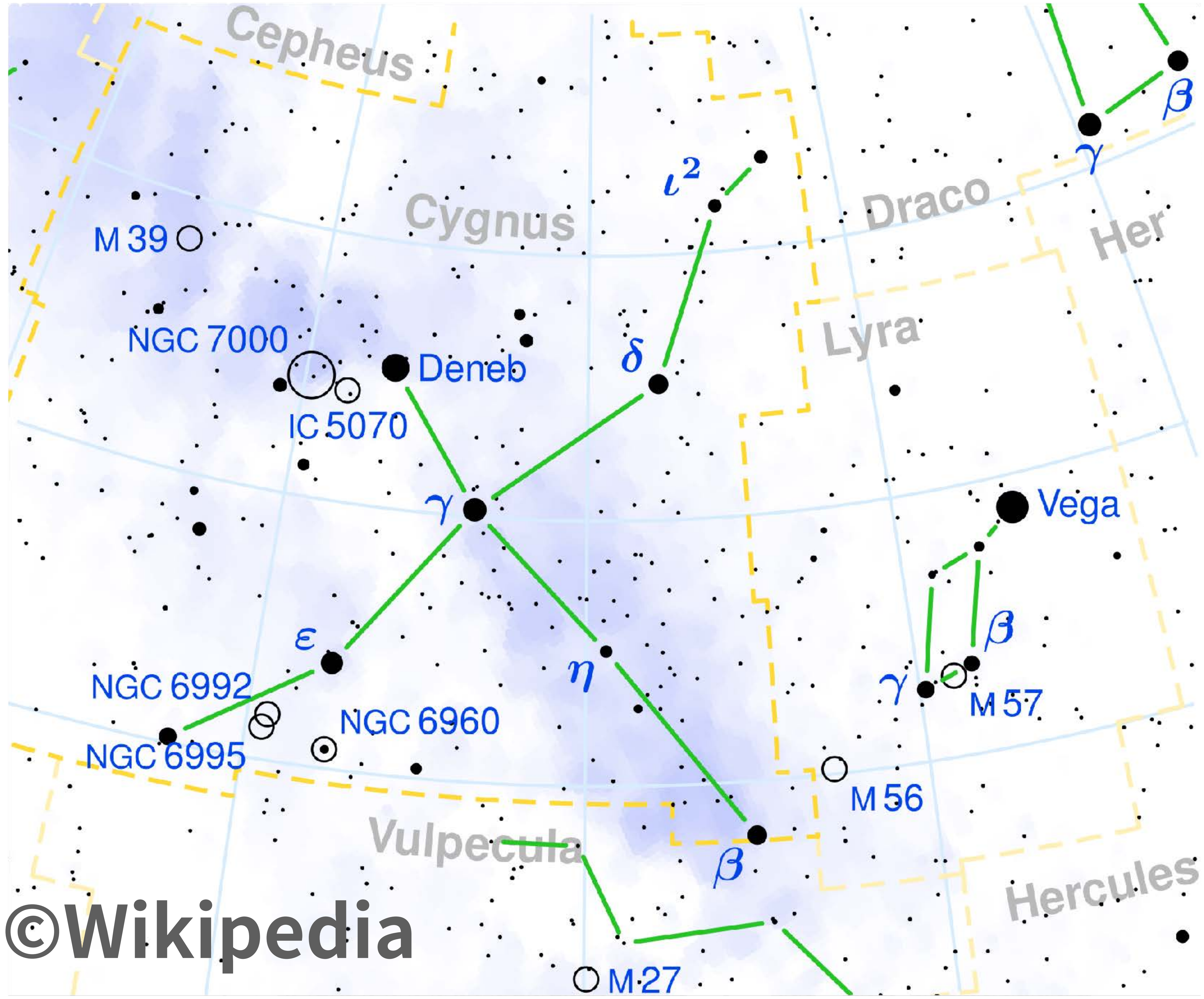
- A system consisting one black hole and one star
- Orbiting around each other.
    - like the Sun and the Earth
- Orbital period : ~1 day
- Separation :
  a few times solar radius

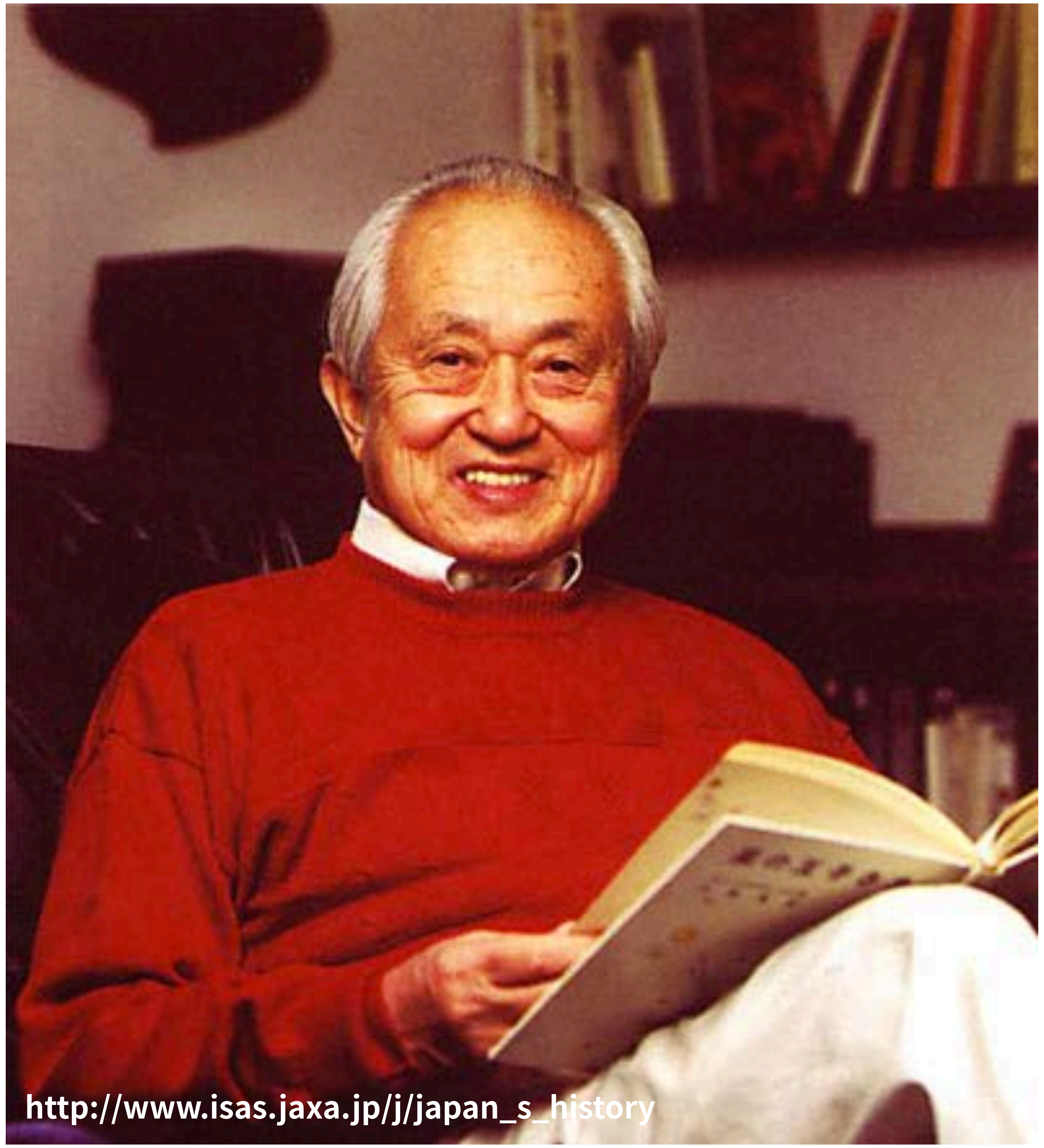




Cygnus X-1: First Black Hole Candidate

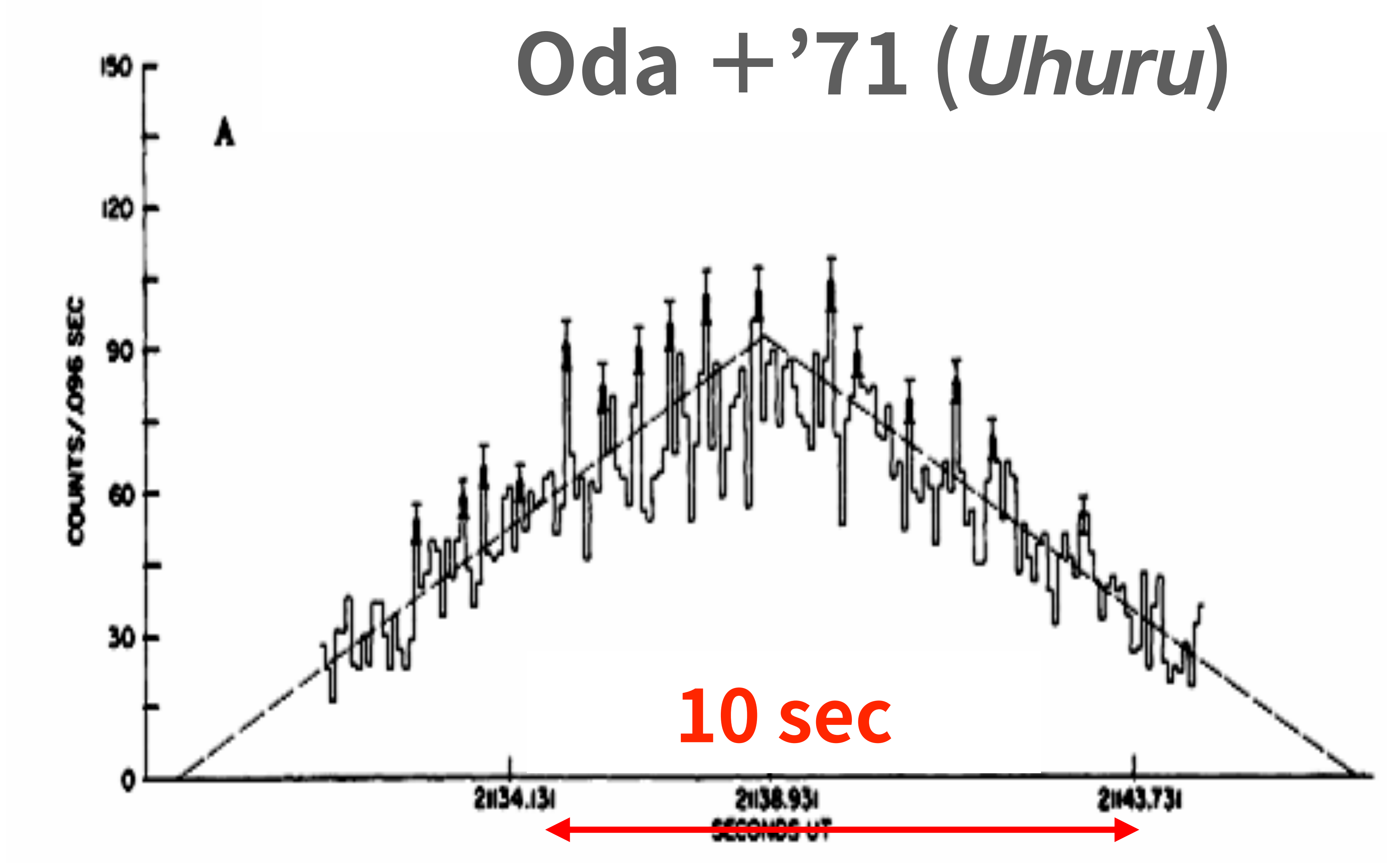
One of the most well studied black hole binary systems.



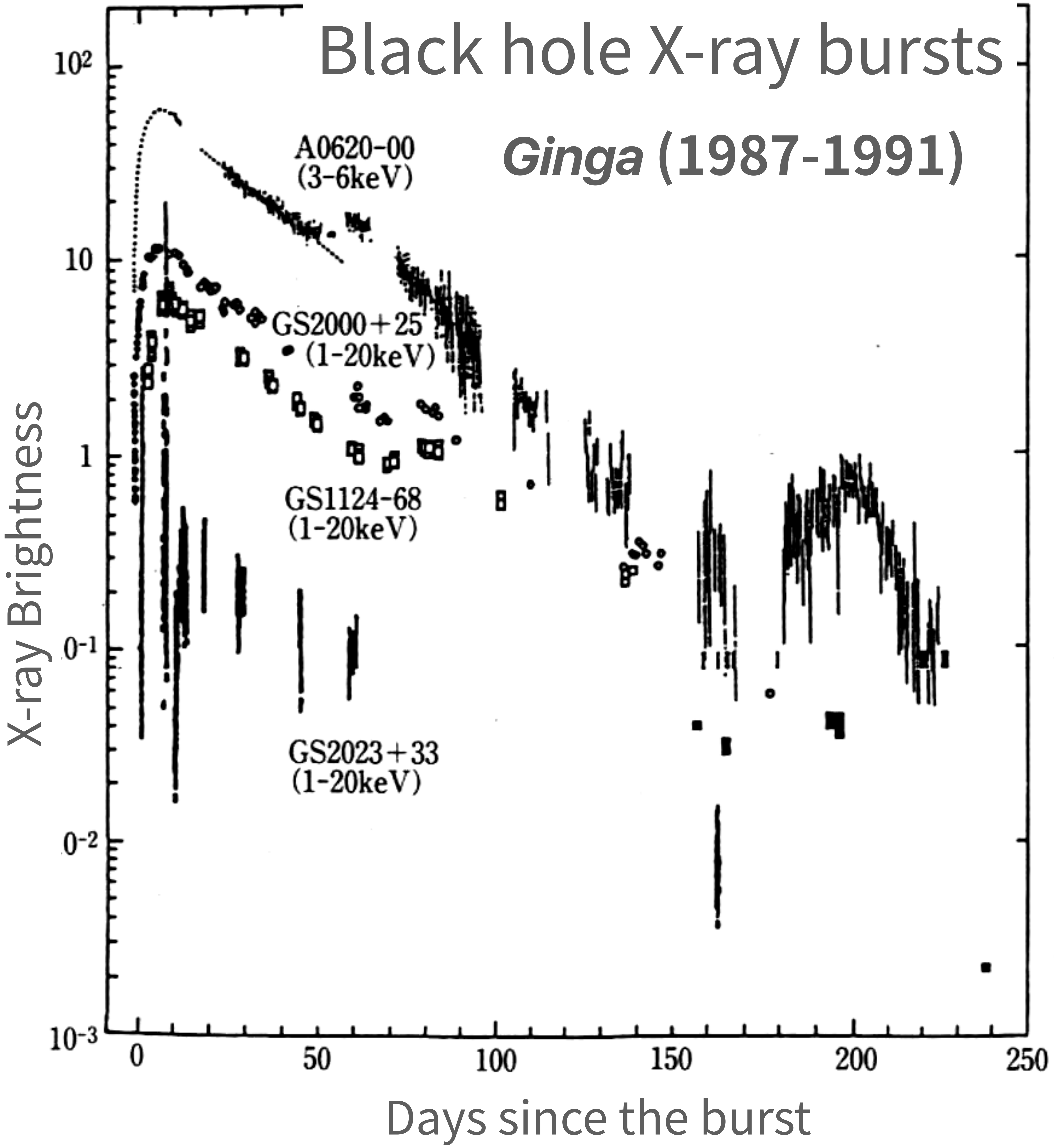


Minoru Oda

Time Variability



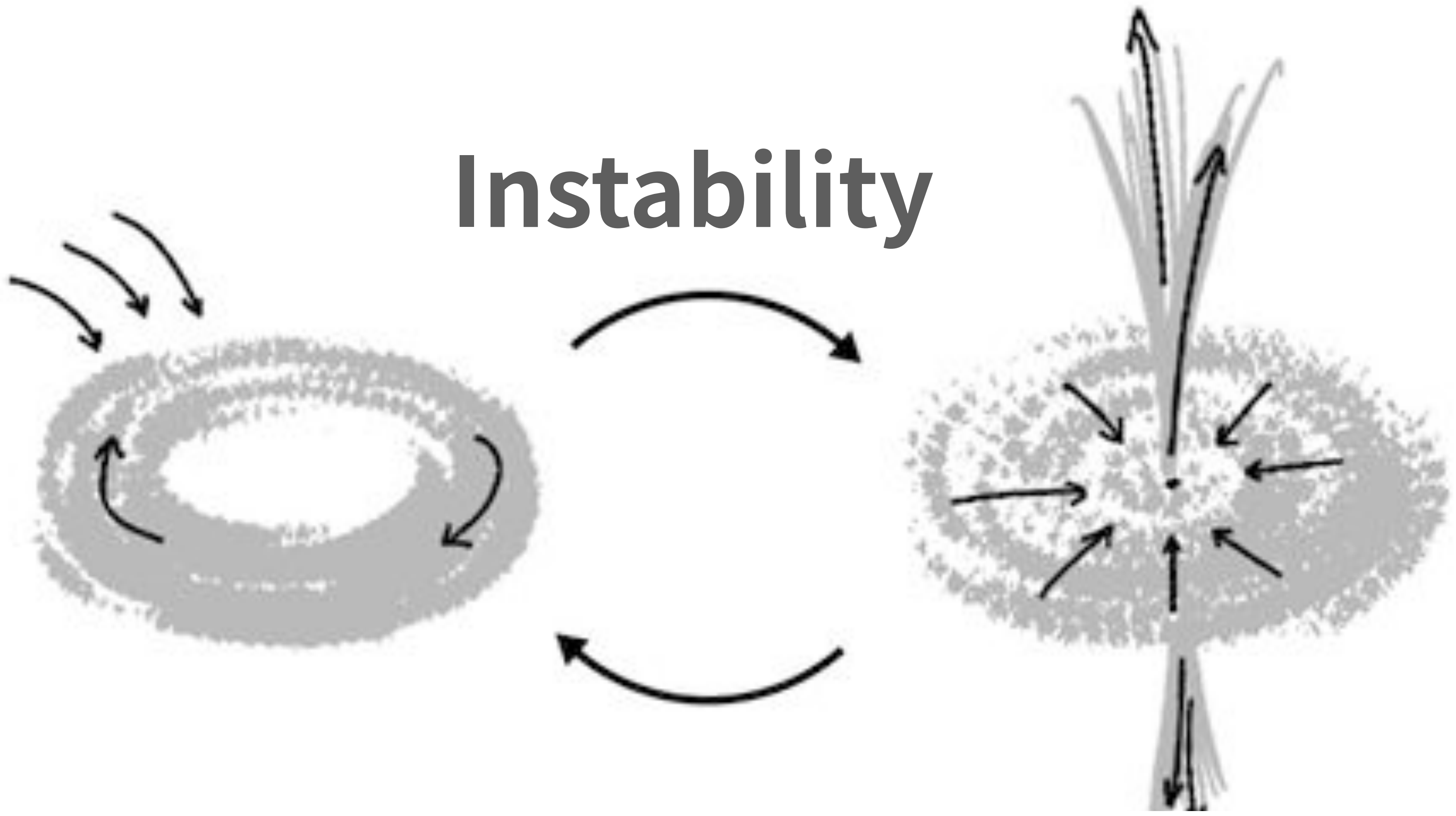
- Black holes show strong variability
  - = extreme environment.
- Every ~10 years, Galactic black holes unleashes extraordinarily bright X-Ray burst.
  - >100 times brighter in a few days.



Disk Instability Model

Why are X-raying black hole variable?

- Black hole accreting materials (disk) changes its states.

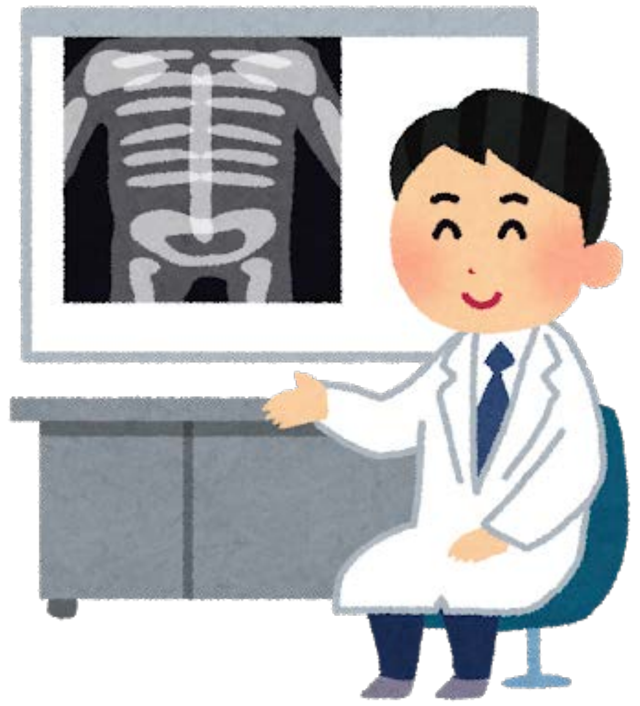


Store Gas (Quiet Phase)

Gas Fall (Flare Phase)

Sorry in Japanese. But, for students, you may want to read this book 嶺重慎 ブラックホール天文学入門

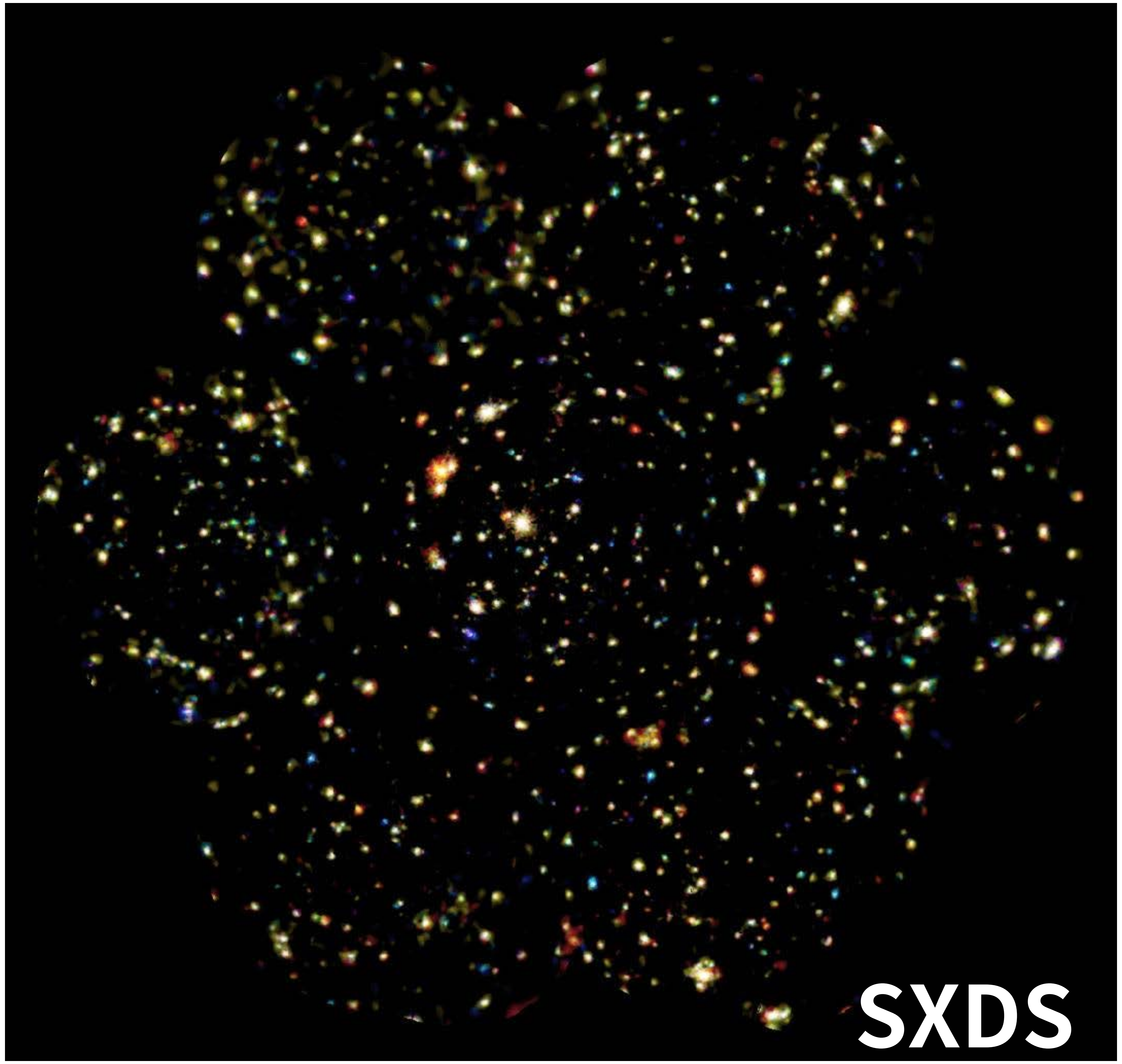
https://www.youtube.com/watch?v=qKq2OGG7m68



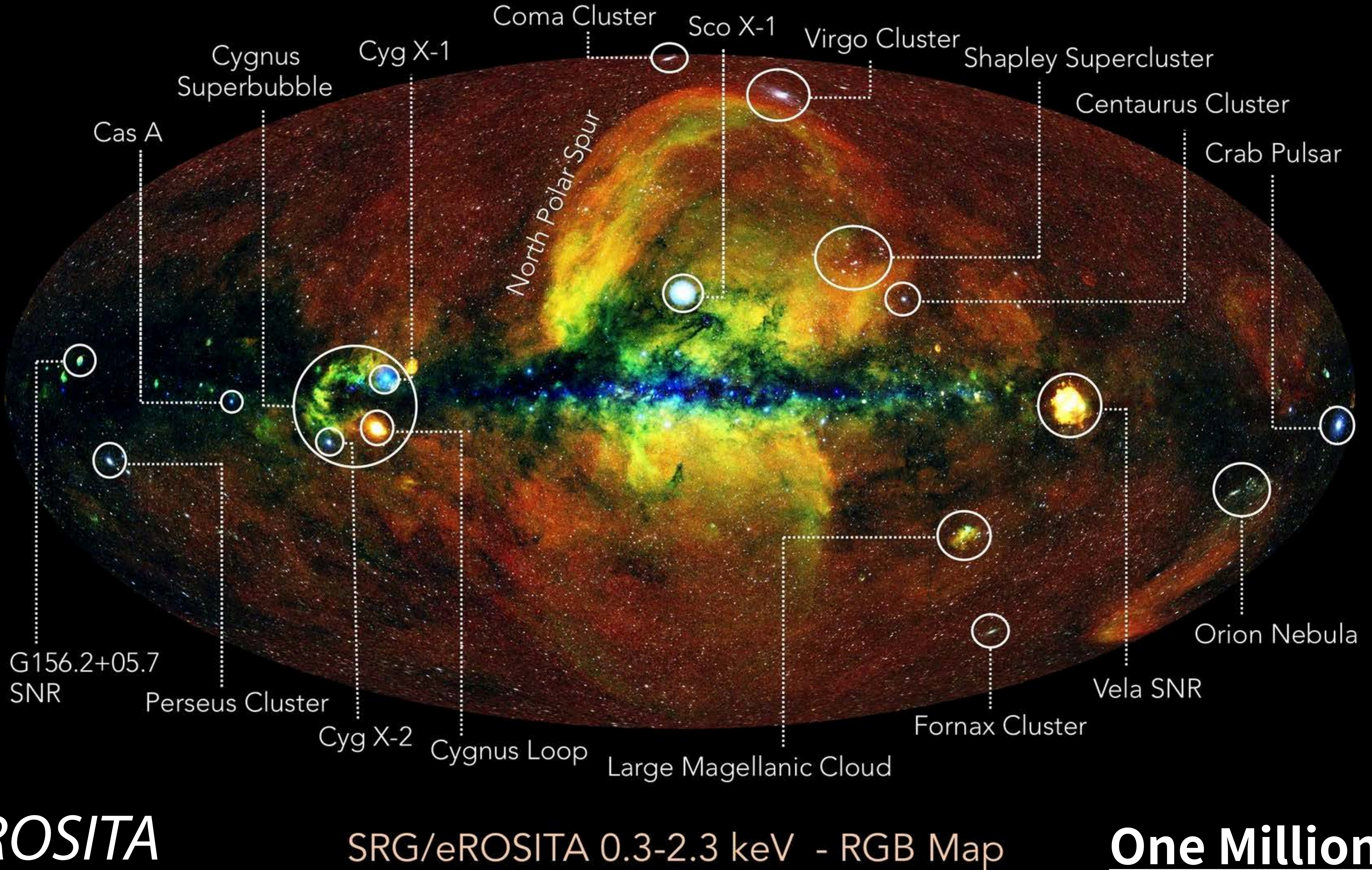
Let’s find black holes using X-ray

Take Roentgen photo of the sky

- These bright spots are X-rays from supermassive black holes.
  - one million to 10 billion solar mass.



The latest view of the X-ray sky

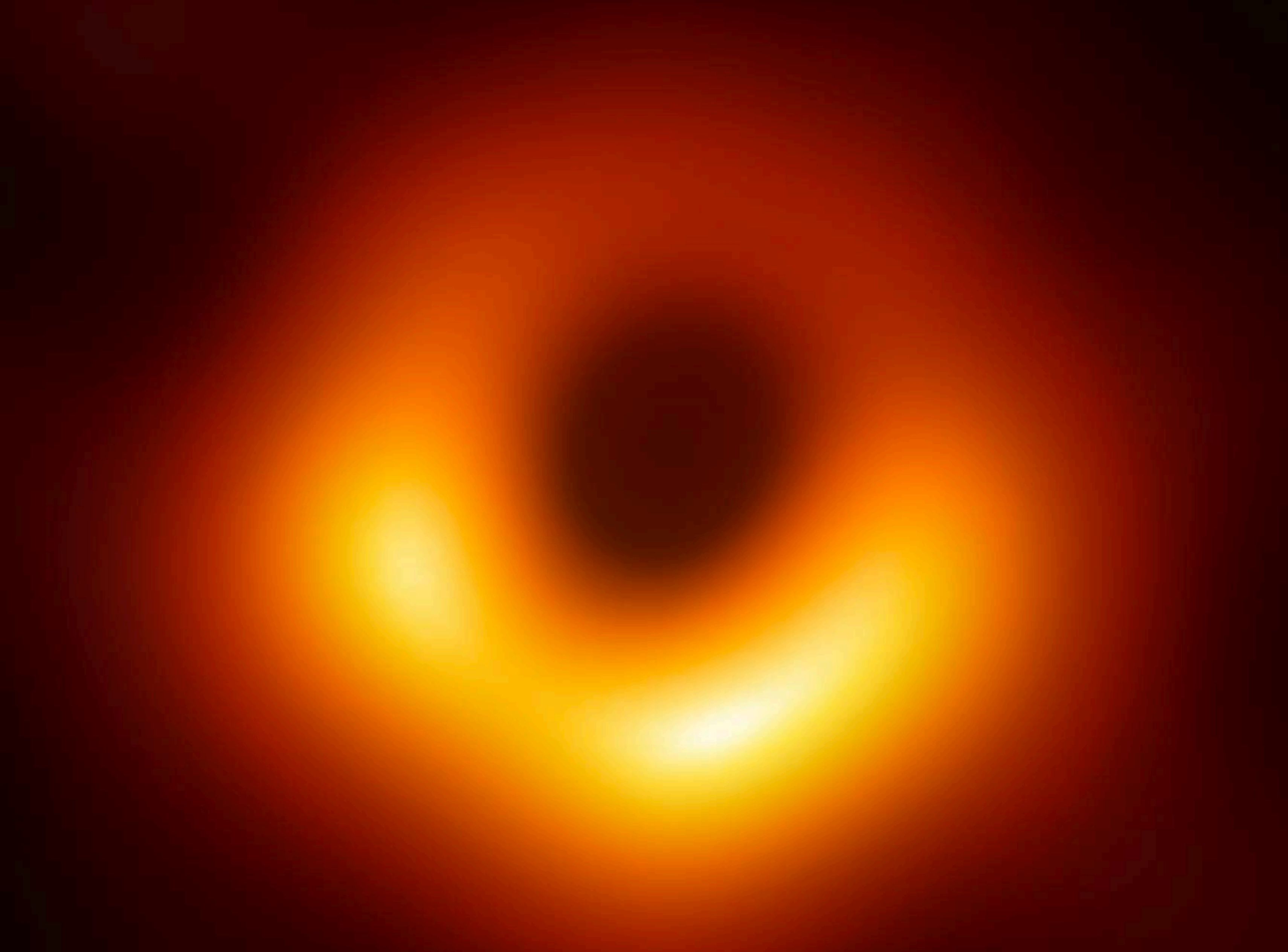


SRG/e-ROSITA

One Million Objects

Let’s take a photo of a Black Hole.

First Image of a black hole?



- M87 galaxy
- 55 million light year
- 6.5 billion solar mass

- Radio wave @ 1.3 mm
  - Smart phones use ~cm waves
- Resolution：20 μarcsec (???)

Finding black holes through motion

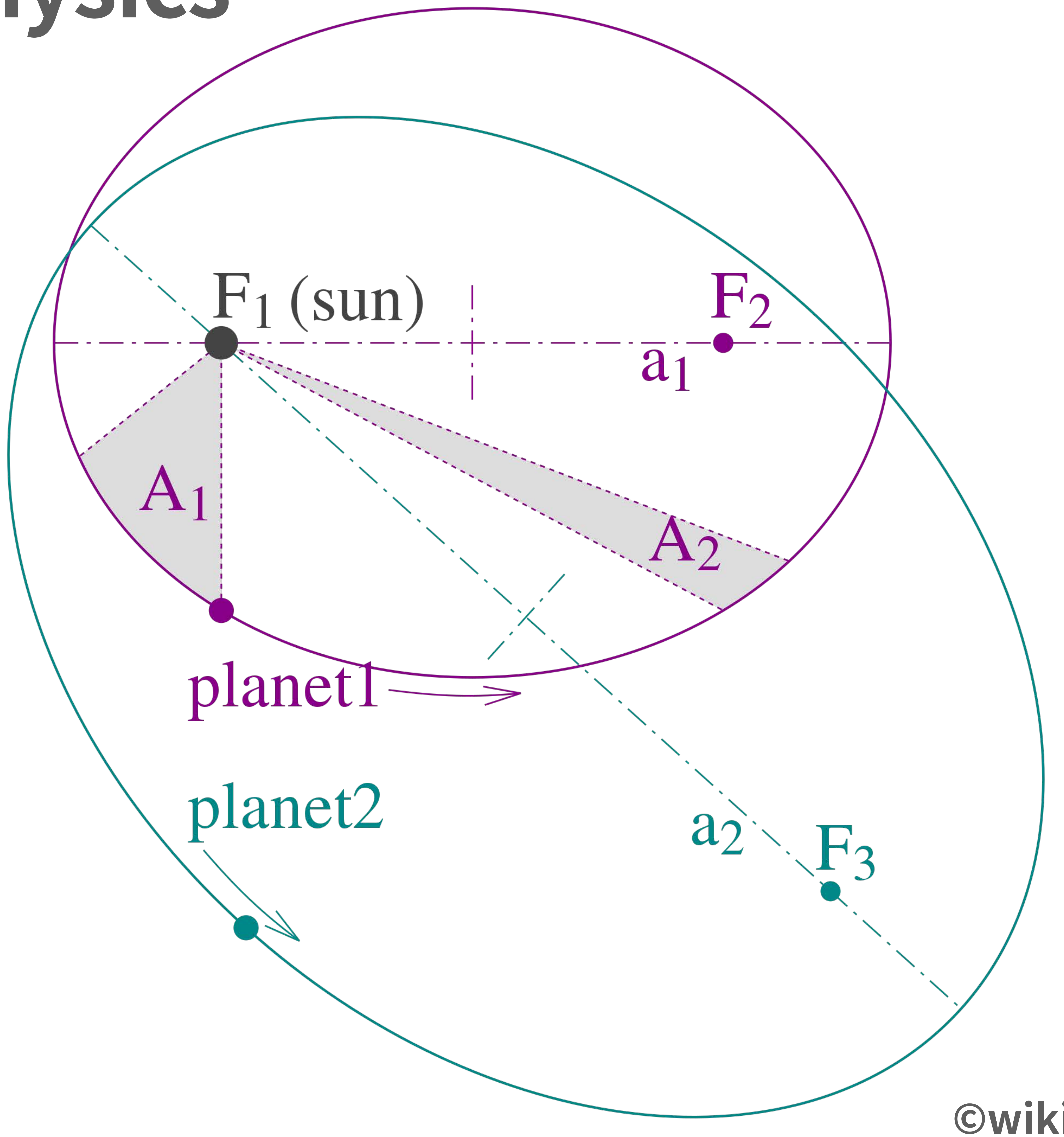
Nobel Prize in Physics 2020

Black holes and the Milky Way's darkest secret

Remember High School Physics

Kepler Motion

- Consider motion of point mass (**m**) orbiting around an object with a mass of **M** with a separation distance of **r**.
- Given the angular velocity ω:
  - $mr\omega^2 = G\frac{mM}{r^2}$
- Circular velocity $v_K = r\omega$, then
  - $v_K = \sqrt{\frac{GM}{r}}$

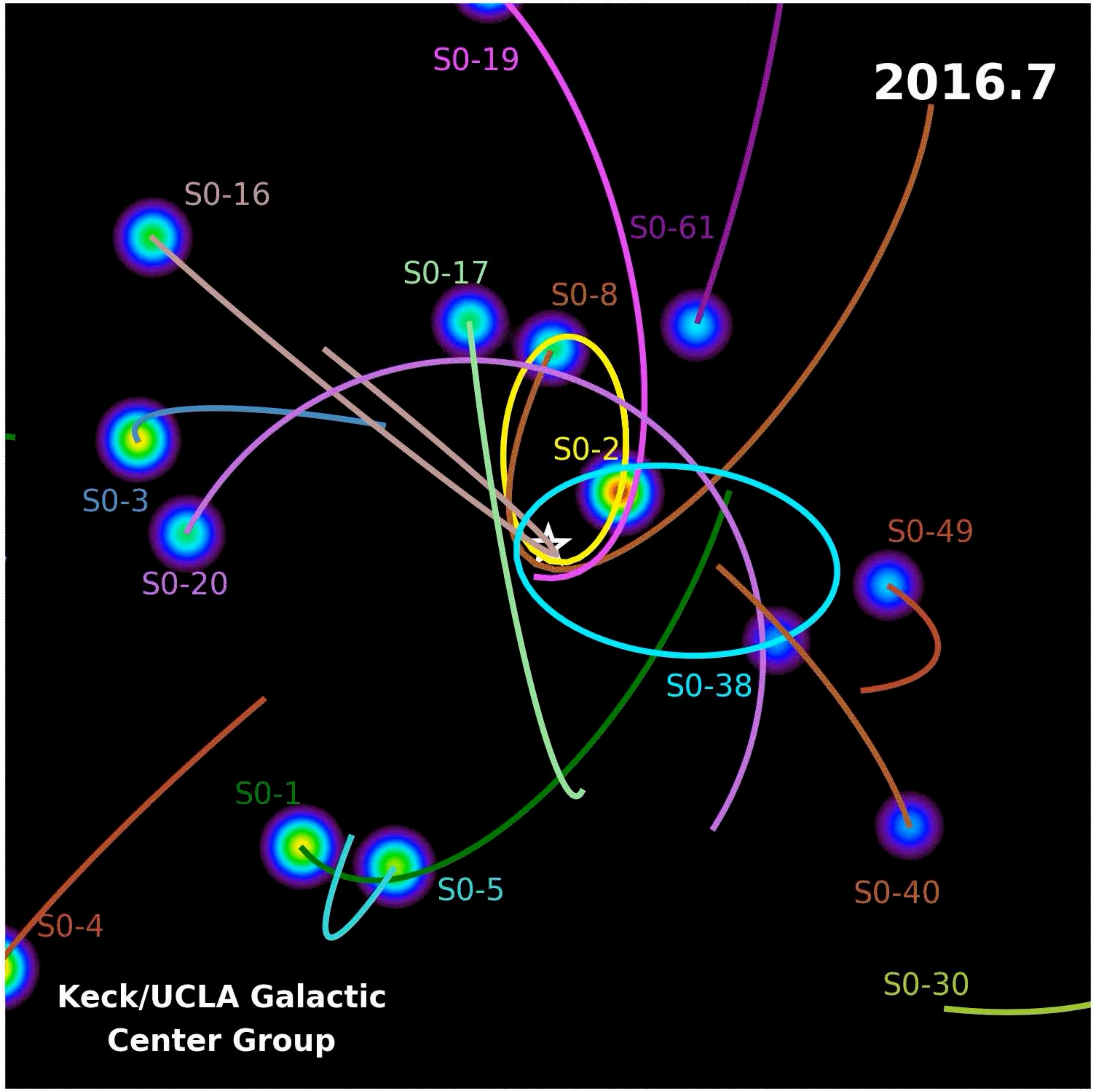


Supermassive Black Hole at the Center of the Galaxy

Physics is high school level. But, its importance is Nobel prize level.

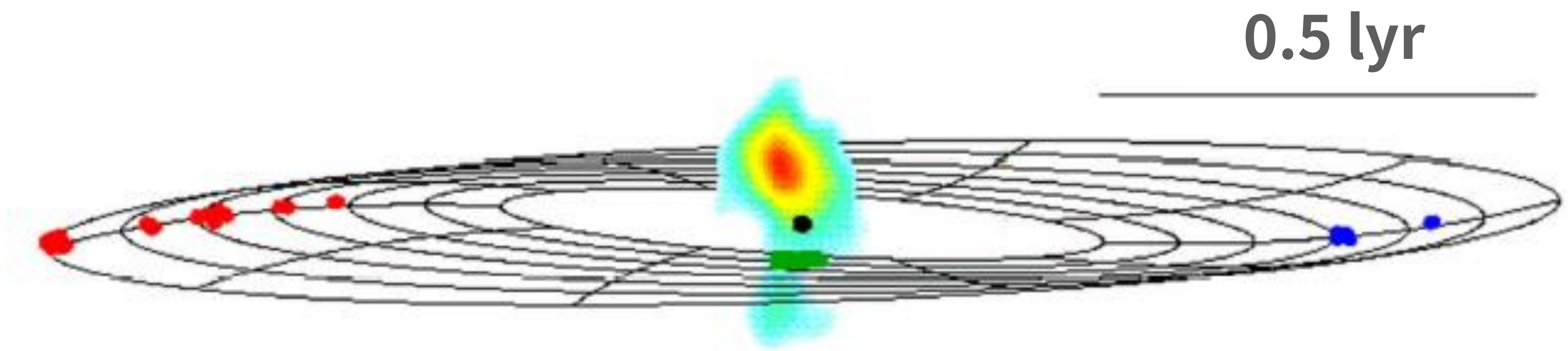
- Kepler motion of stars by the gravity of the central black hole
- Supermassive (>10^6 solar mass) black holes @ galactic center
  - In the Milky way,
    - $M_{\rm BH} \sim 4 \times 10^6 M_\odot$

Motion of Stars at the Galactic center

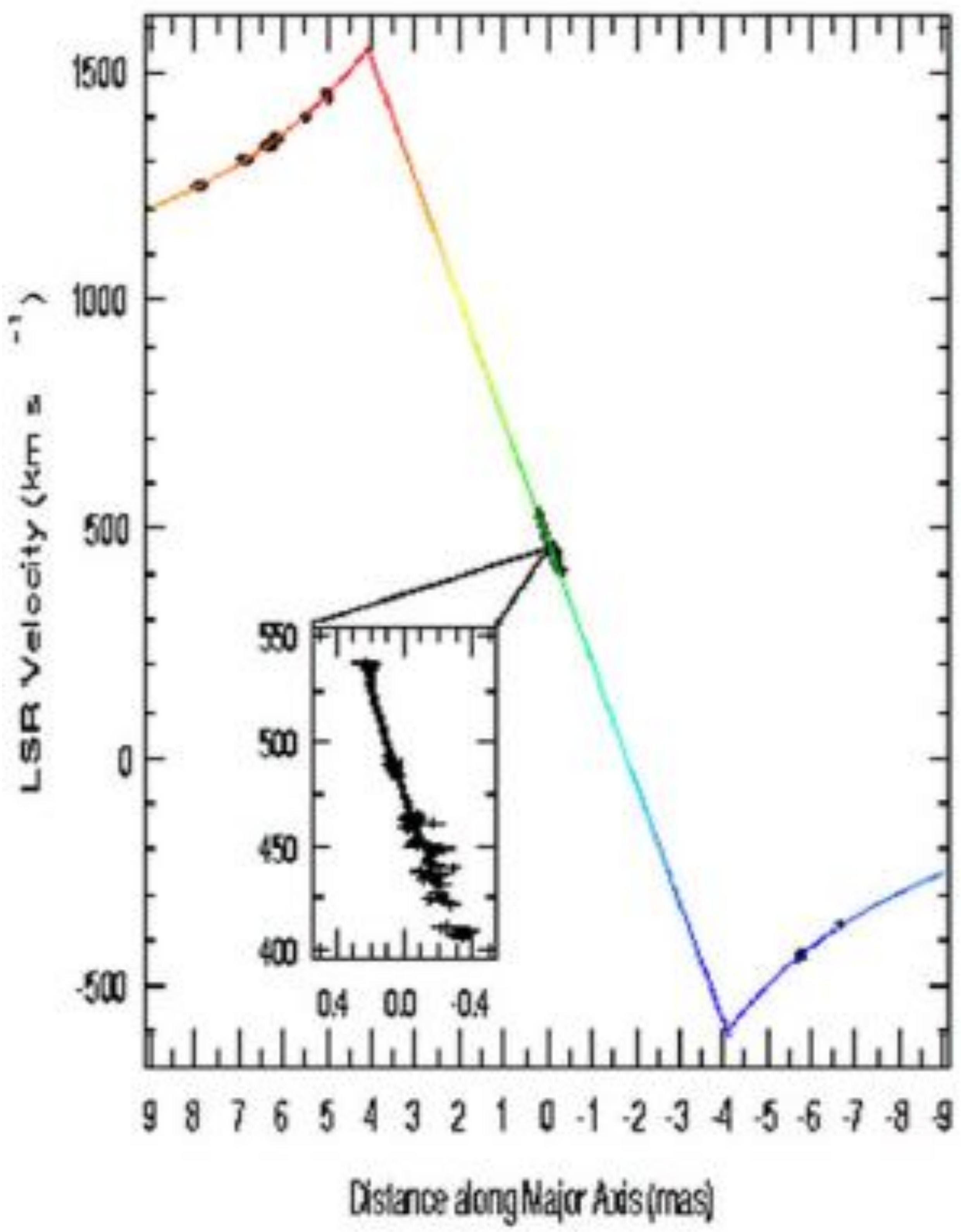


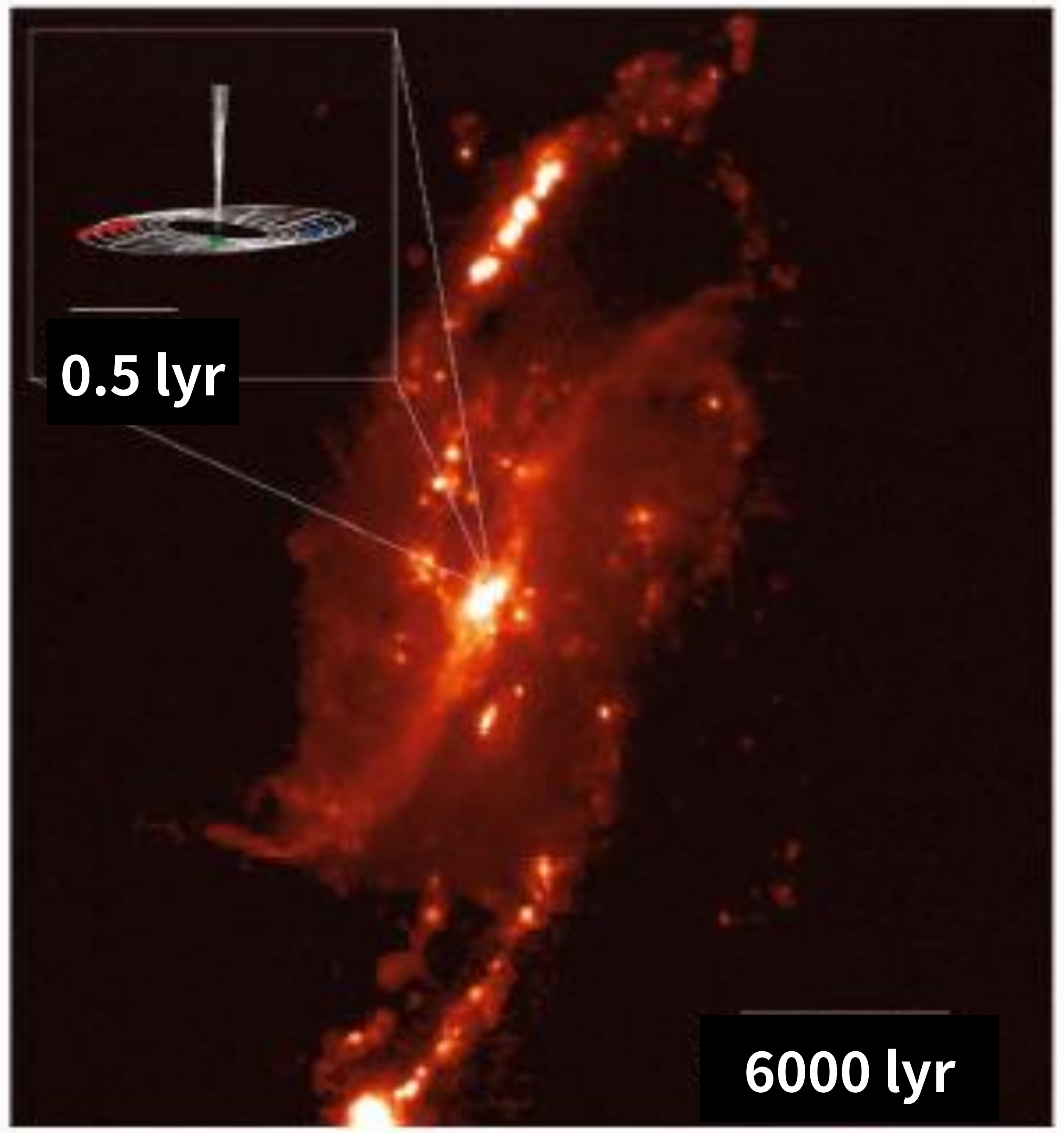
Finding black holes through gas motion

Radio



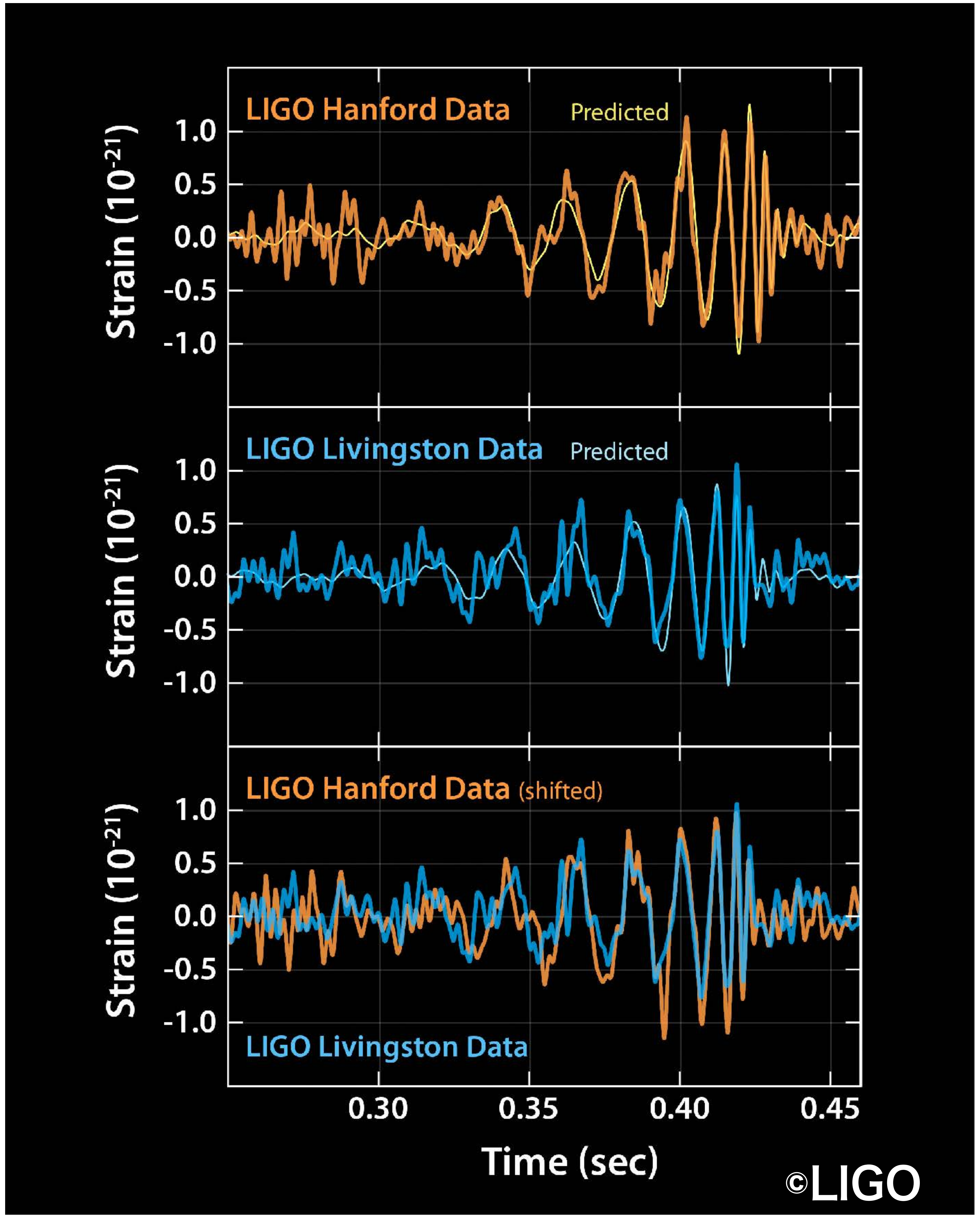
- Accreting gas emit radio emission
- First discovery of Kepler motion around a supermassive black hole



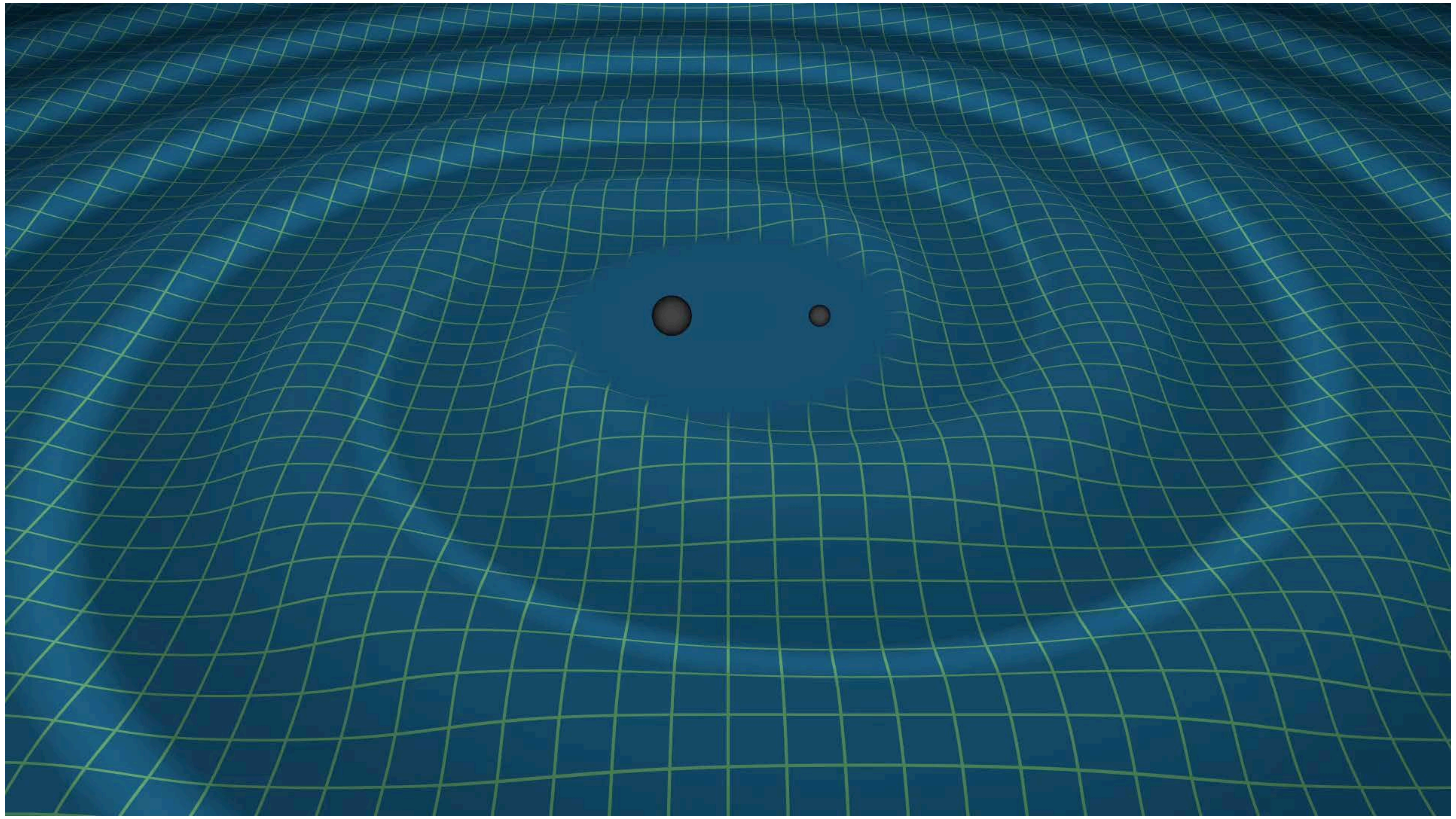


Nakai+'93; Miyoshi+'95

Find Black Holes through Gravitational Waves



xxx black holes are found



Black holes in the Universe

Many Black Holes?

Milky Way

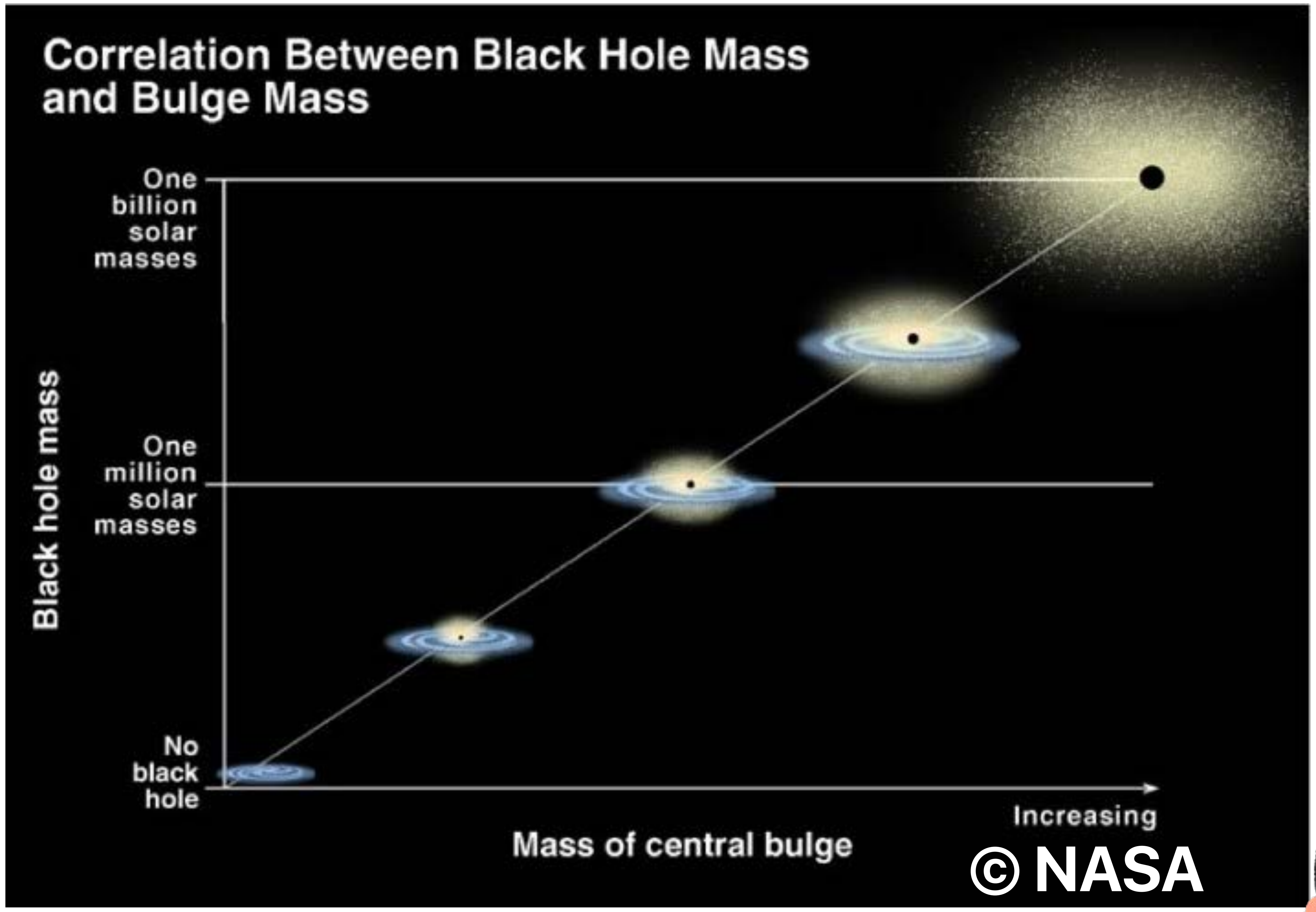
- $>10^{11}$ stars in our Galaxy
- $>10^{7}$ black holes are expected!
- Observed black holes: a few tens only.

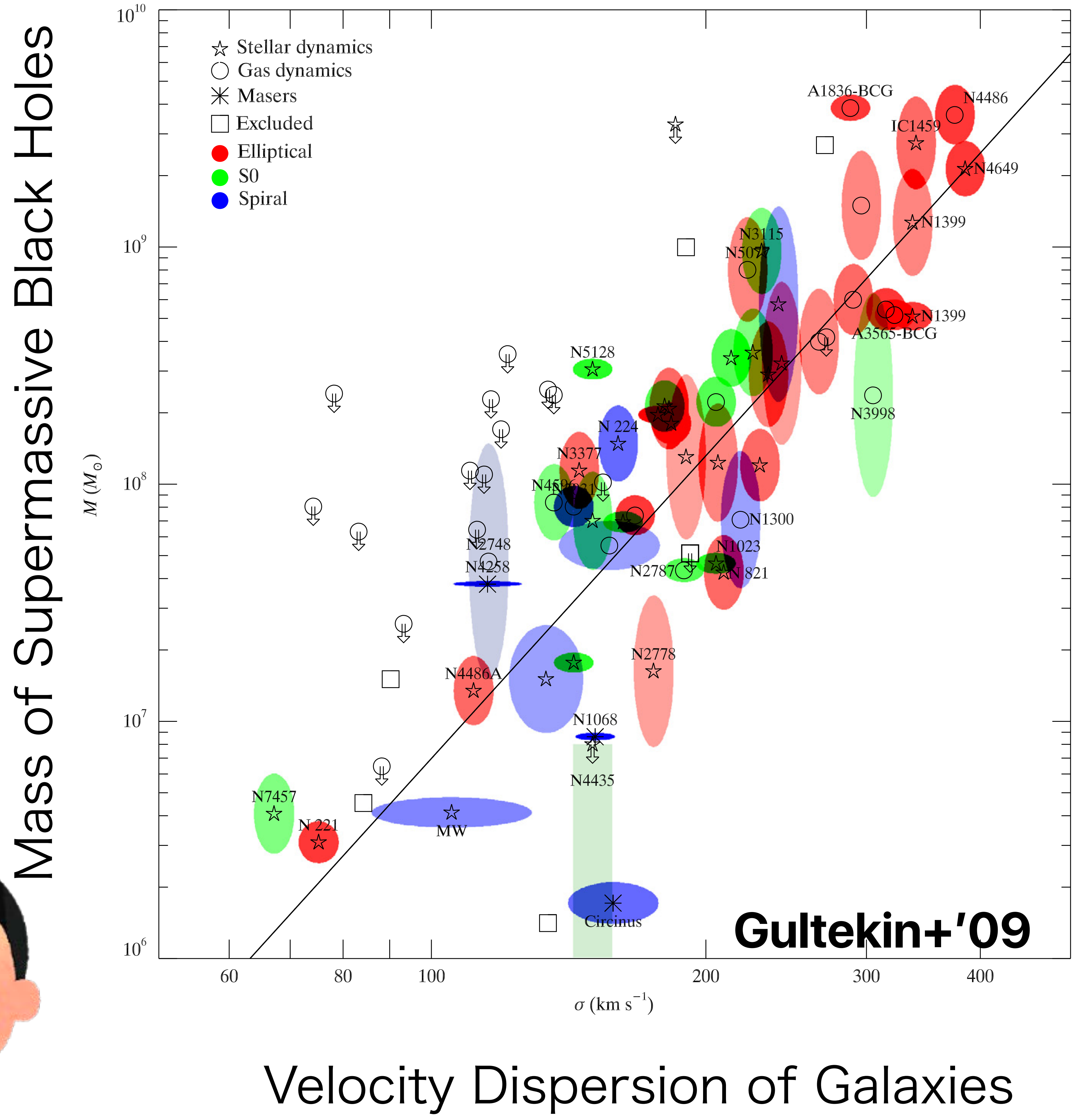
Many Black Holes?

Universe

- $>10^{11}$ galaxies
  - in the Milky way, $>10^{7}$ black holes.
- Then, $>10^{18}$ black holes in the sky!

Supermassive Black Holes and Galaxies



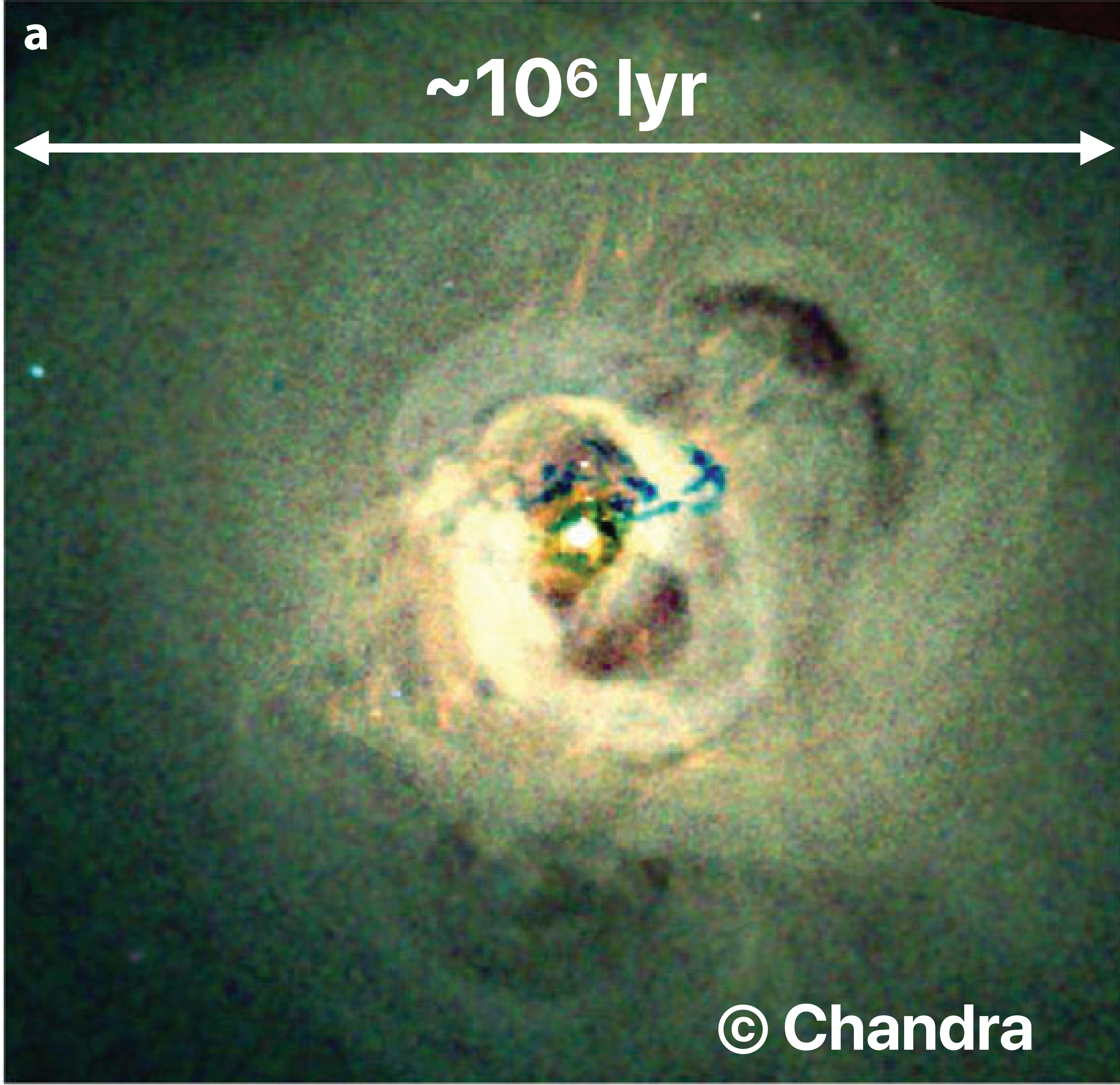


- Massive galaxies harbors more massive black holes.

Supermassive Black Holes and the Universe

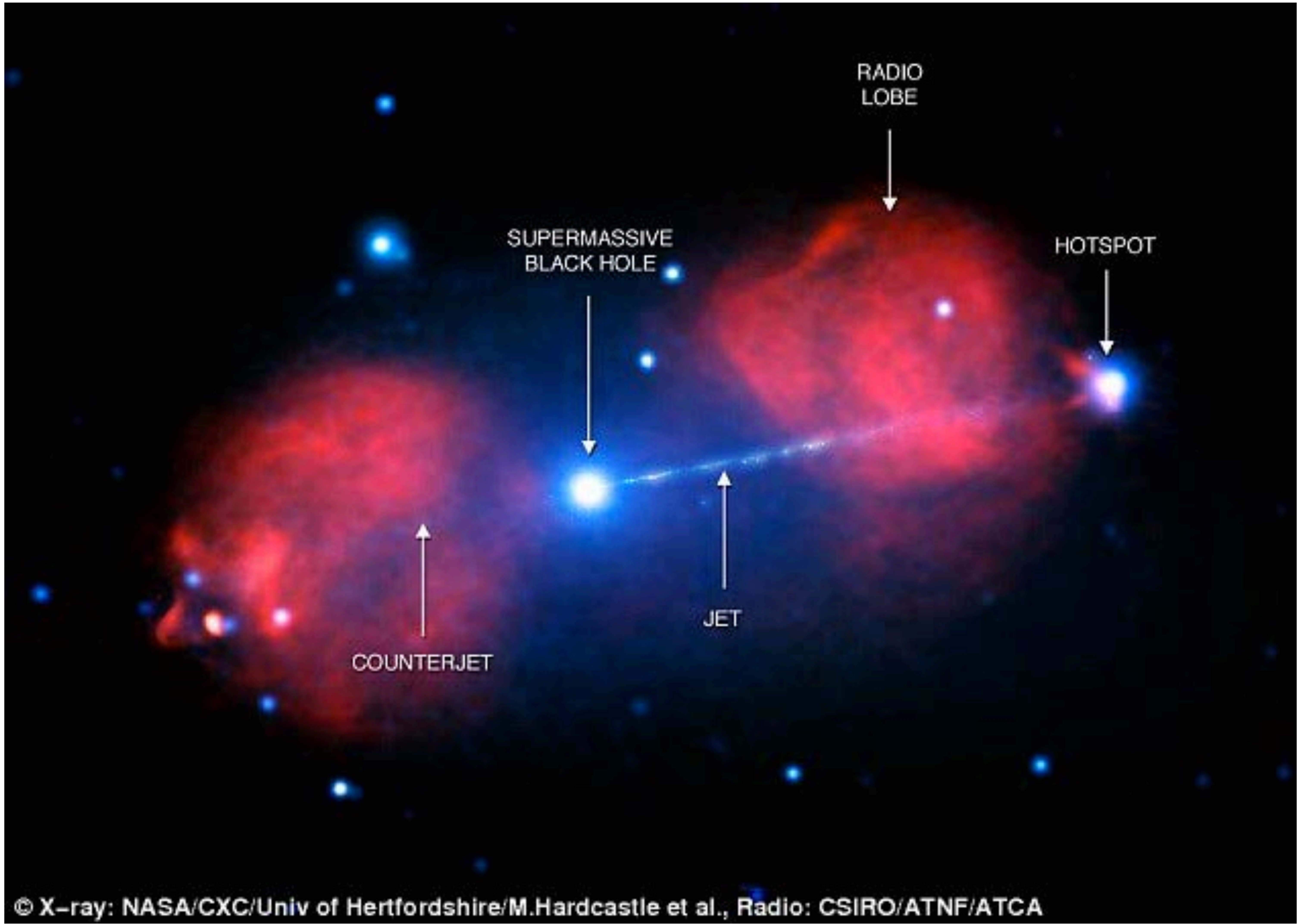
- Black hole activity pushes gas away at large scale.

Please ask Abed (Our moderator), why and how.

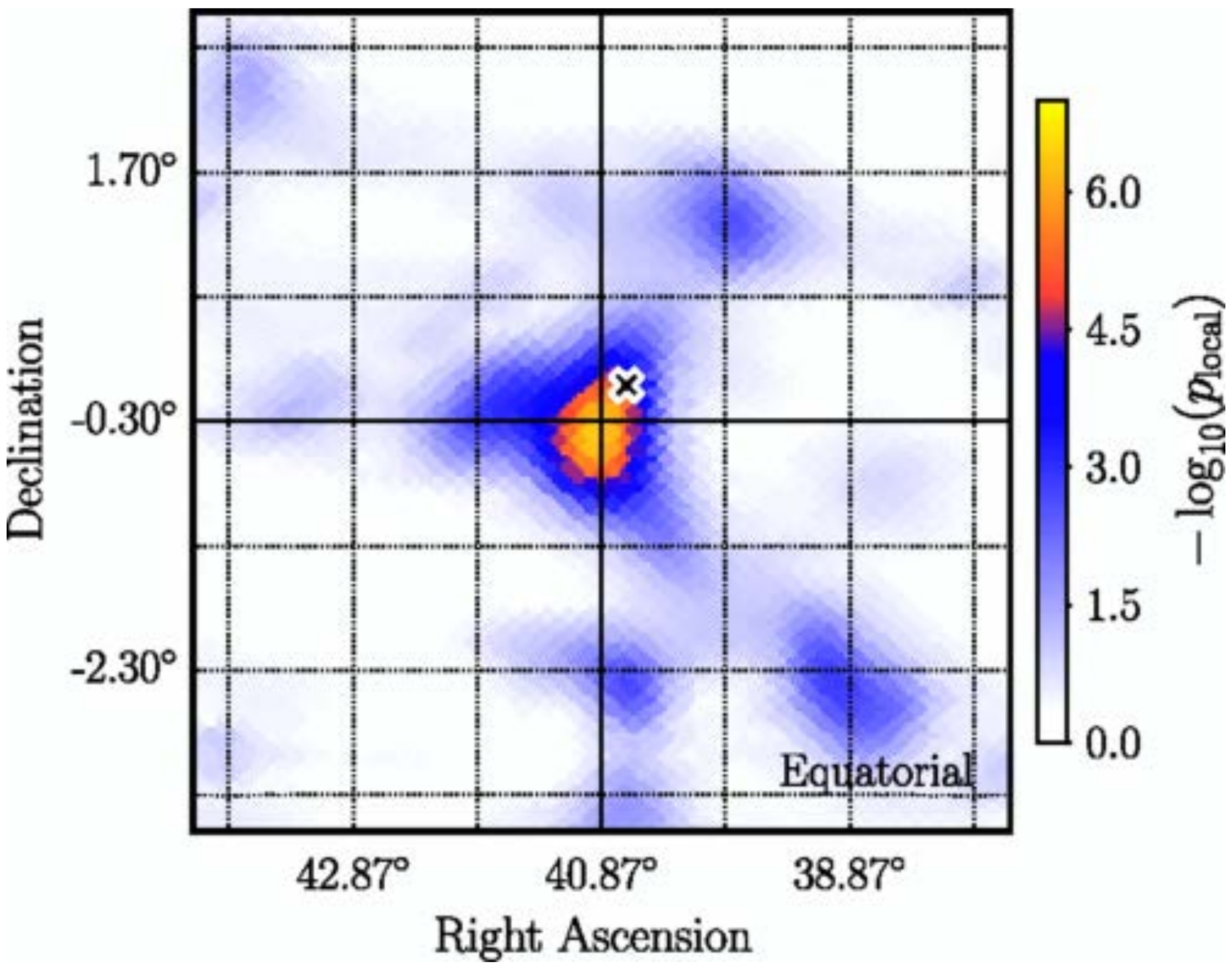


Extreme Phenomena around Black Holes

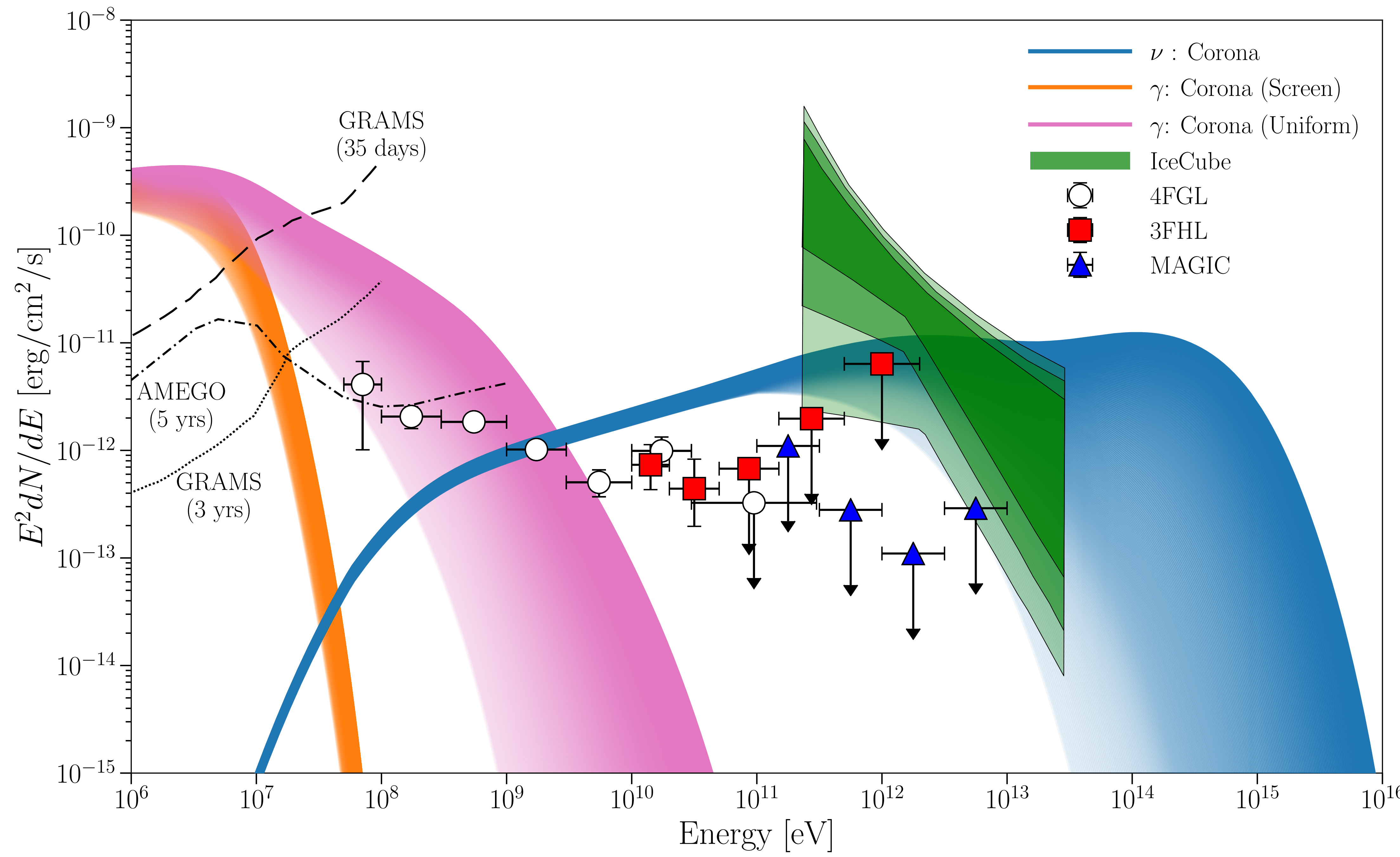
Hot plasma & High Energy Particles → X-ray, Gamma-ray, Cosmic-ray, Neutrino



Neutrinos from a Nearby Supermassive Black Hole?



IceCube 2020



YI, Khangulyan, & Doi, '20

- TeV neutrinos are reported from a nearby supermassive black hole.
- How generated? Black hole corona?

Mystery of Black Holes

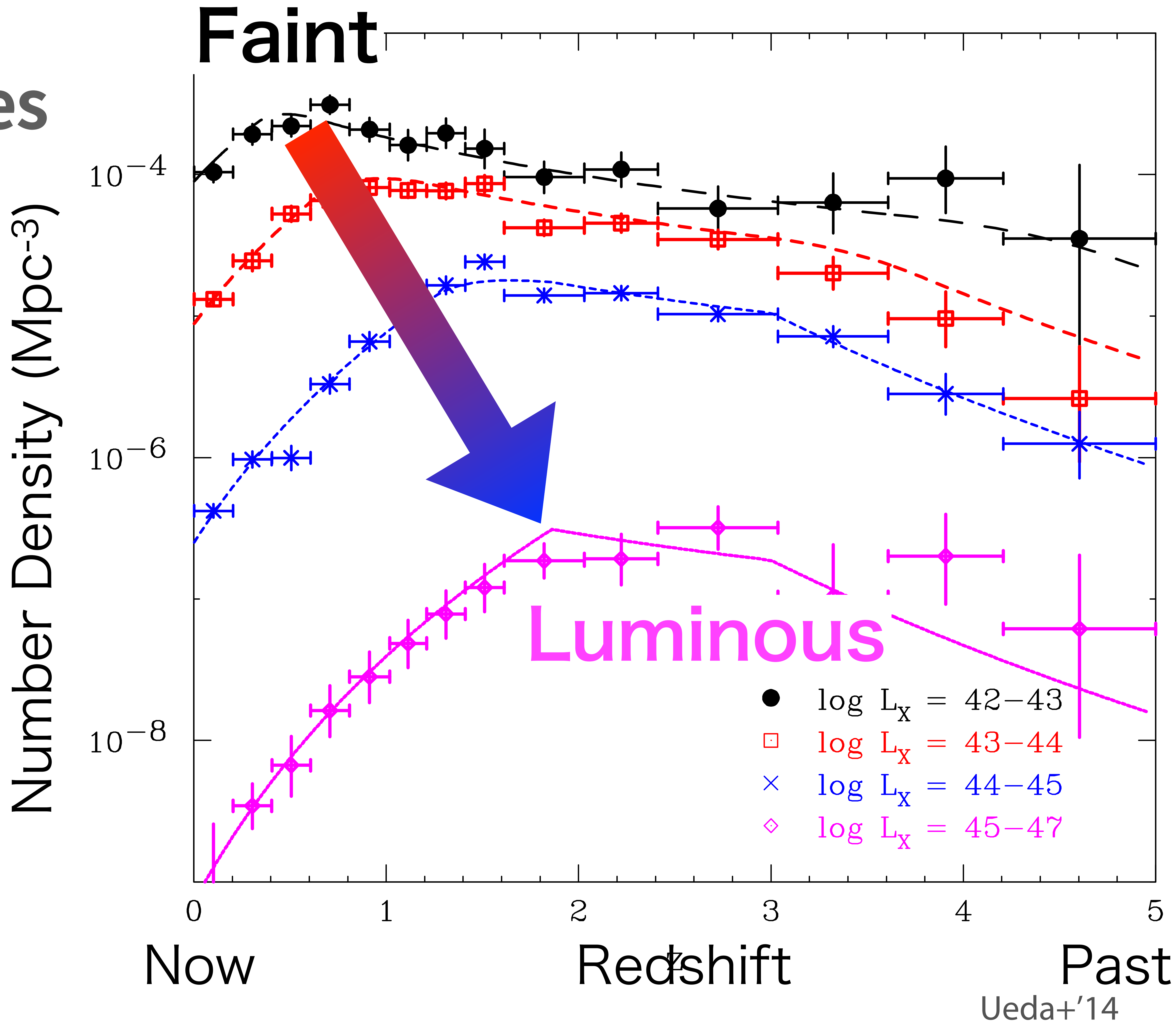
- Black hole information?
- Are there primordial black holes?
- How can black holes are formed?
- How many black holes in the universe?
- How can supermassive black hole be formed?
- How does gas fall into black holes?
- Relativistic jet formation, correlation, and acceleration?
- How do they evolve together with galaxies?
- What do they do for galaxies?
- Can they make ultra-high-energy cosmic rays?
- and more…

Summary

Using physics,
we can find “Black Holes”.

Evolution of Supermassive Black Holes

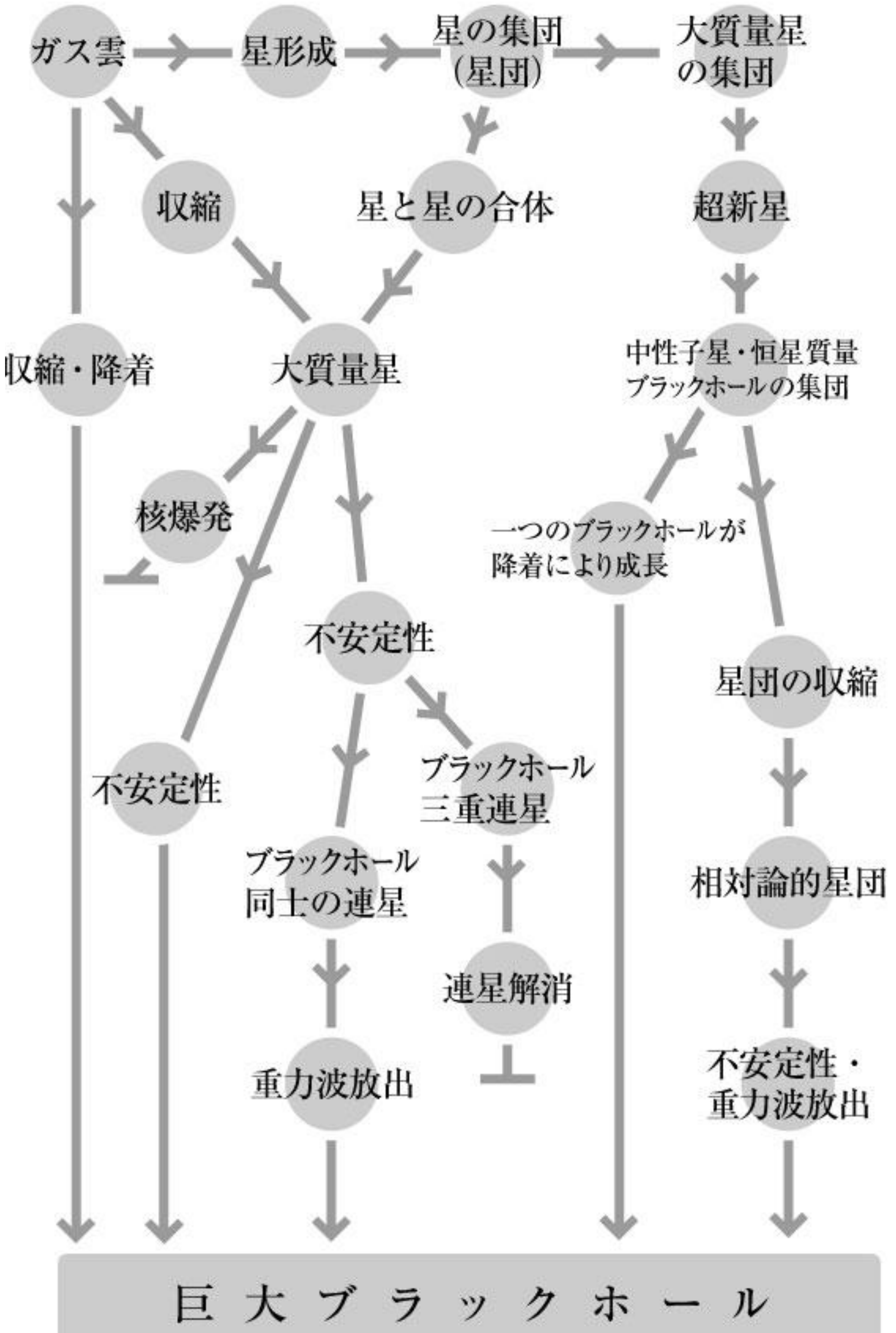
- Luminous (~Massive) black holes were more actively formed in the past.



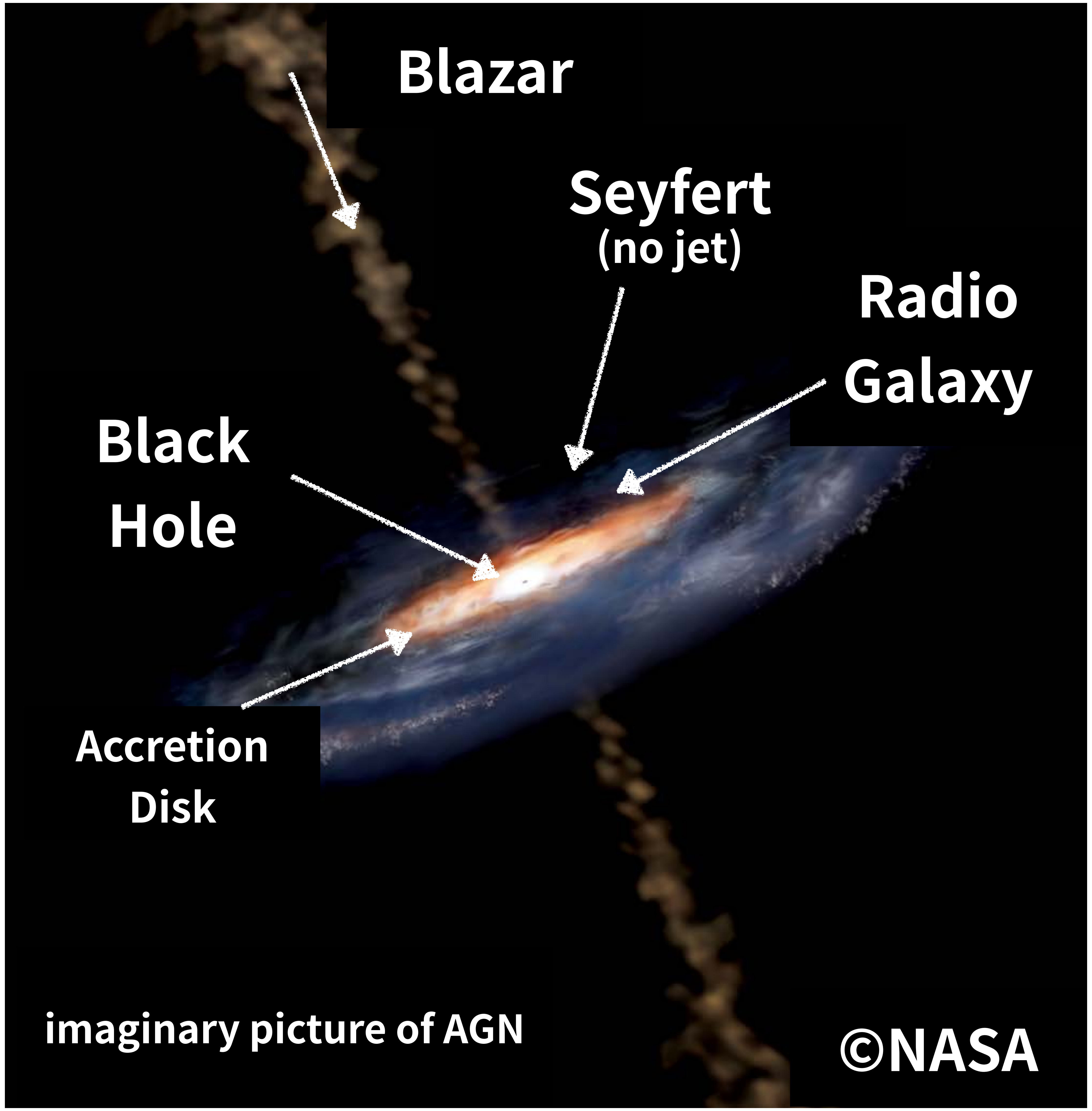
巨大ブラックホールの作り方

リース・ダイアグラム

- でかい星をつくる
- 星団を作ってから合体合成



Supermassive Black Holes are Active



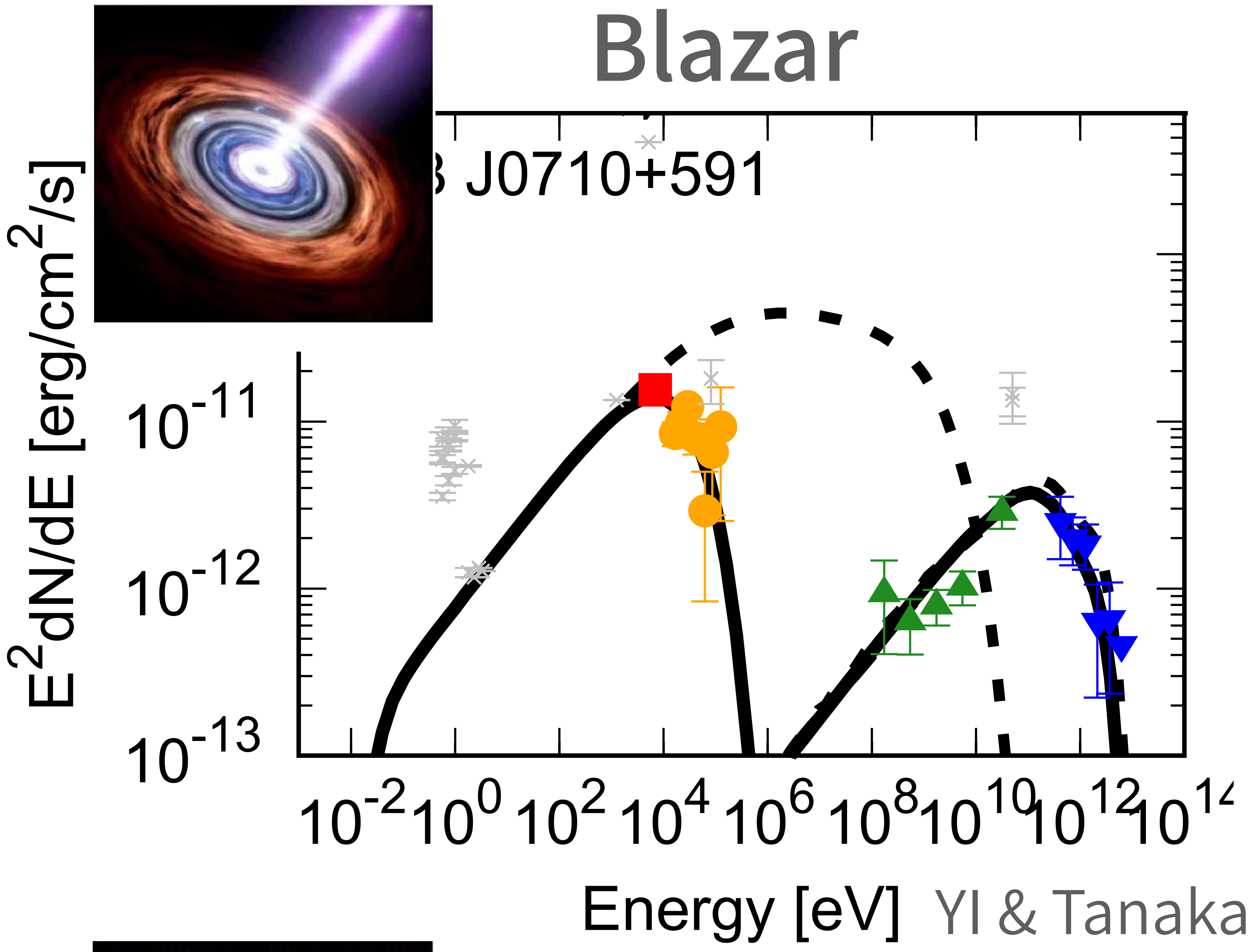
- Gas accretion

  ➡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

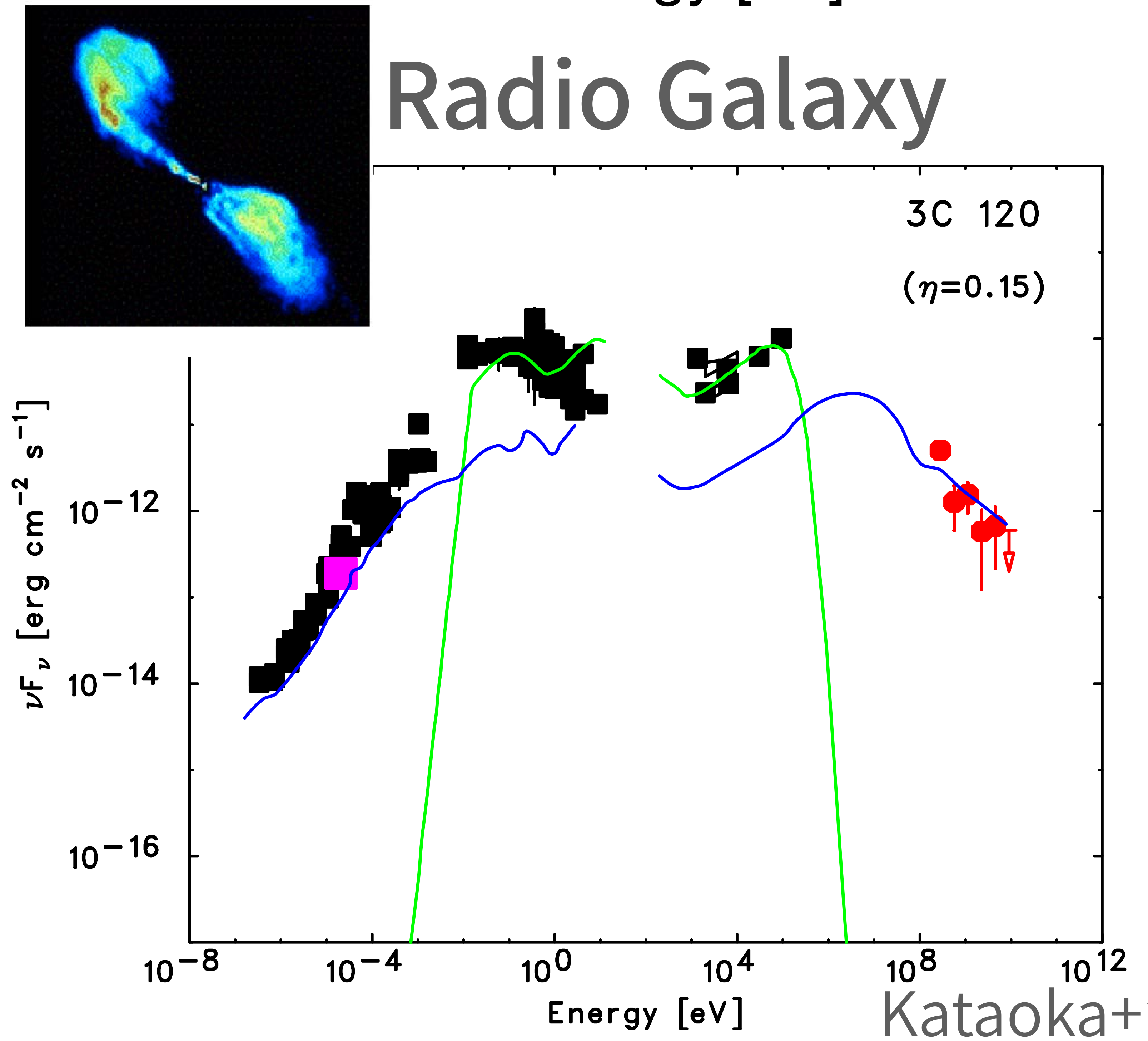
Multi-wavelength spectrum of AGNs

Blazar



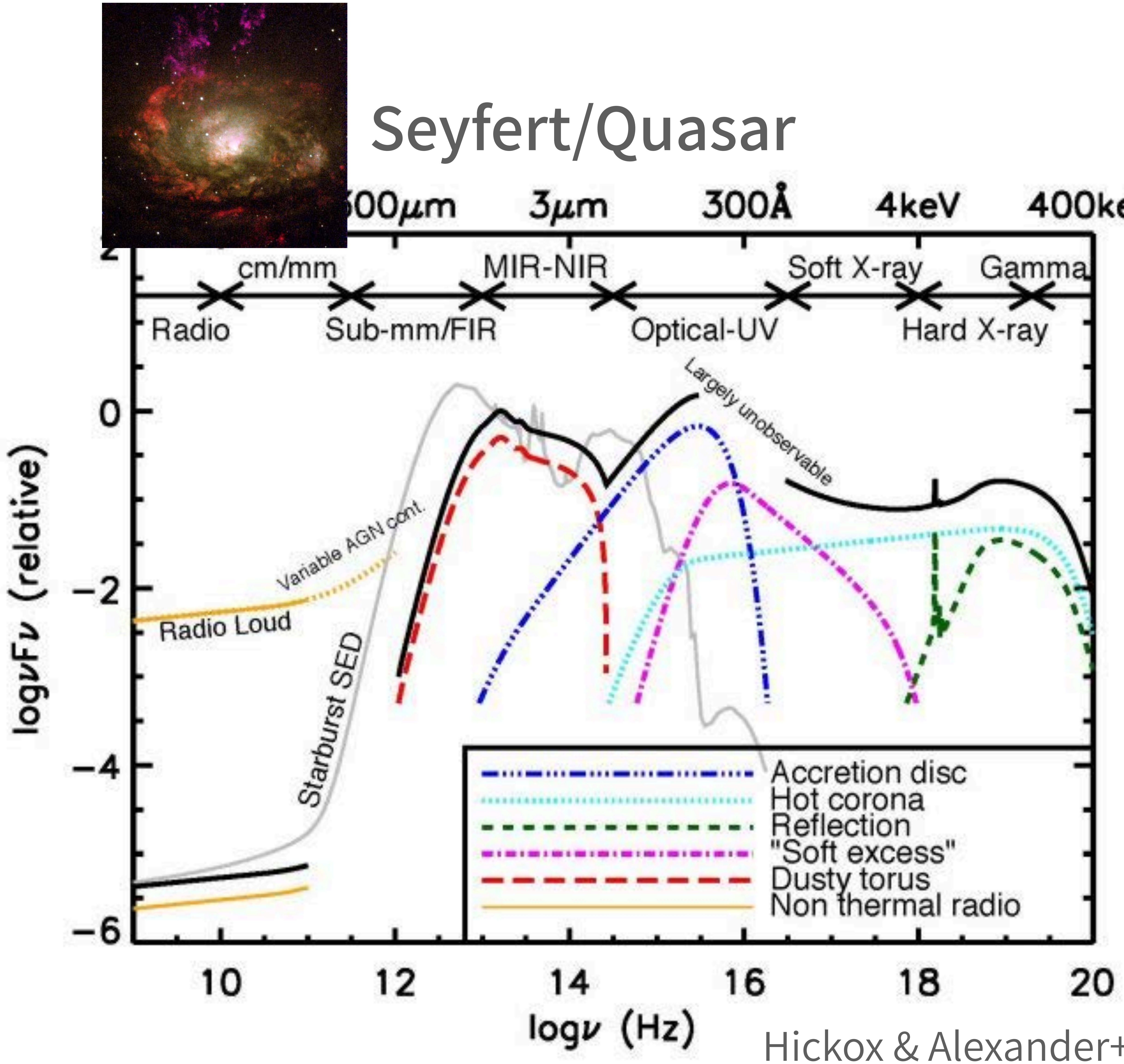
YI & Tanaka '16

Radio Galaxy



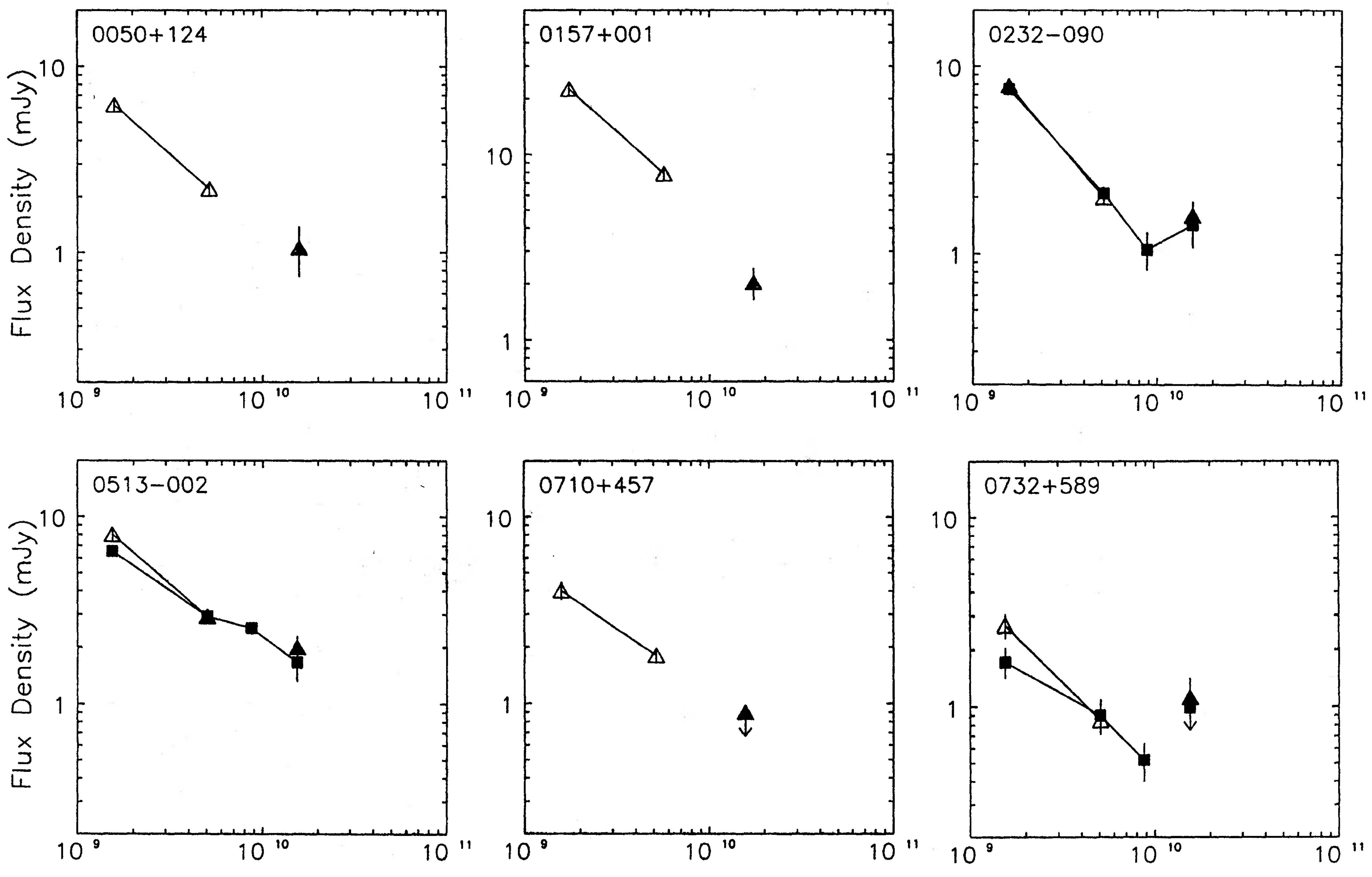
Kataoka+'11

Seyfert/Quasar

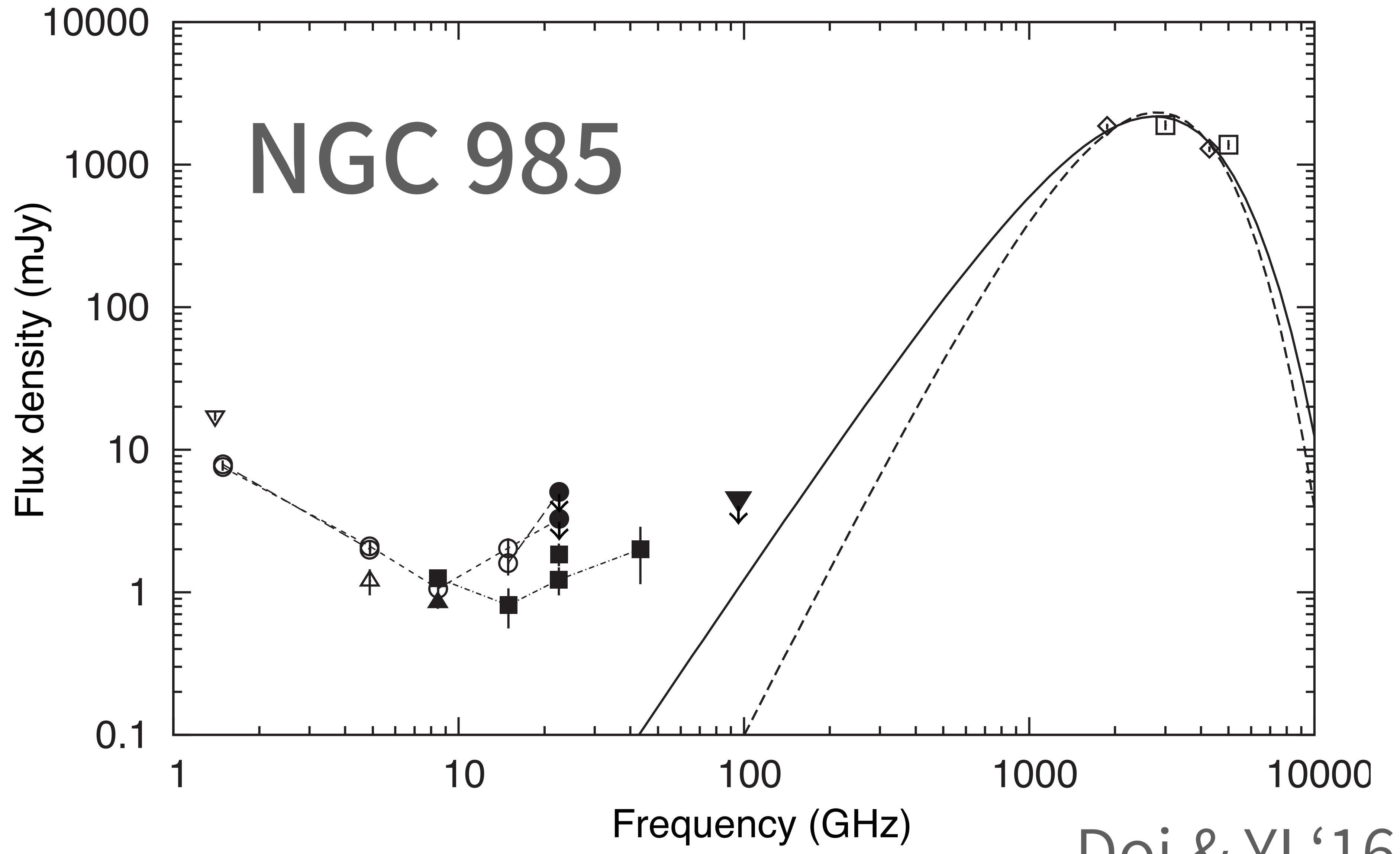


Hickox & Alexander+'16

Millimeter excess in nearby Seyferts



Barvainis+'96



Doi & YI '16

- Spectral excess in the mm-band

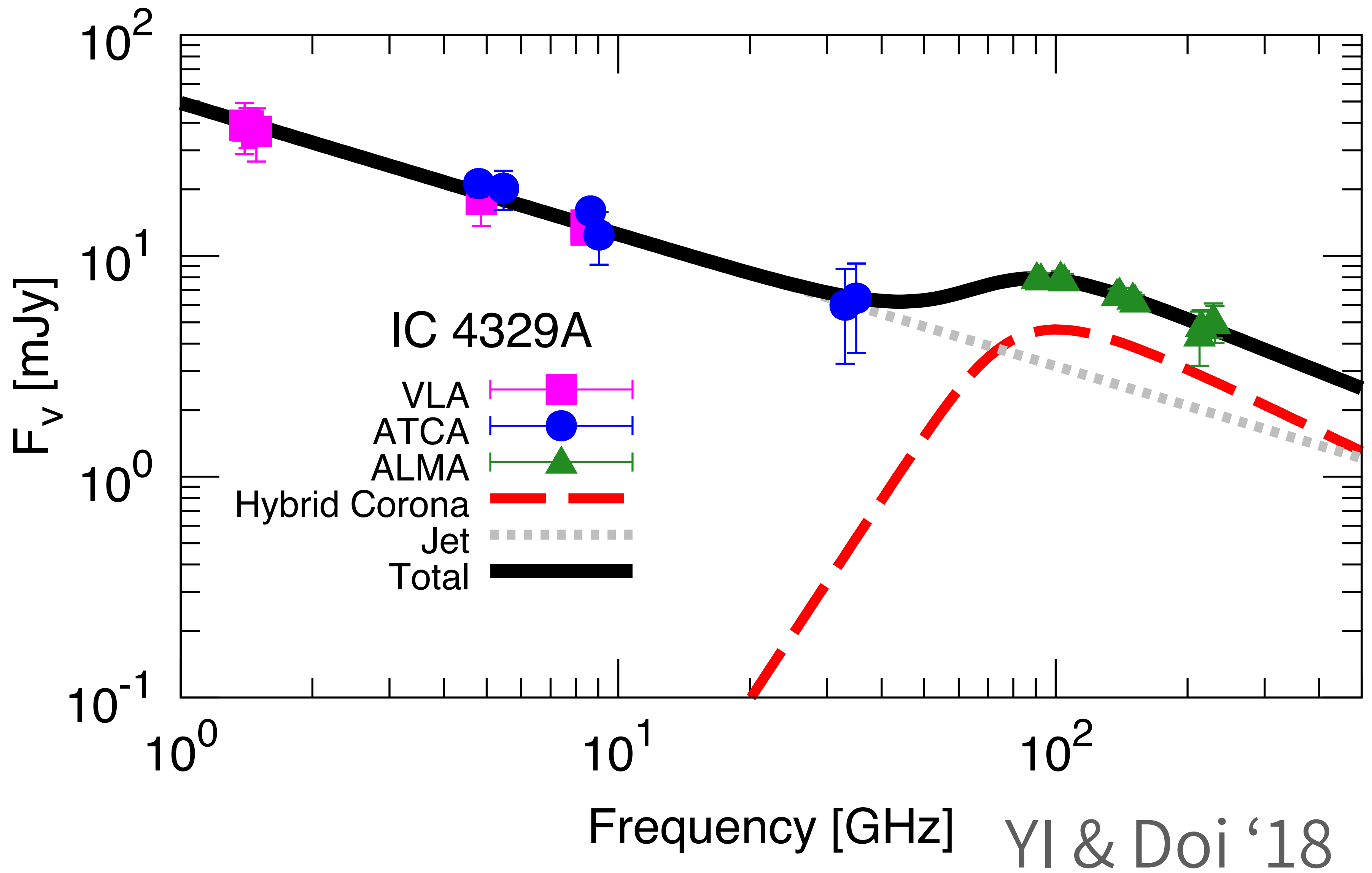
  (e.g., Antonucci & Barvainis'88; Barvainis+'96; Doi & Inoue '16; Behar+'18).

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

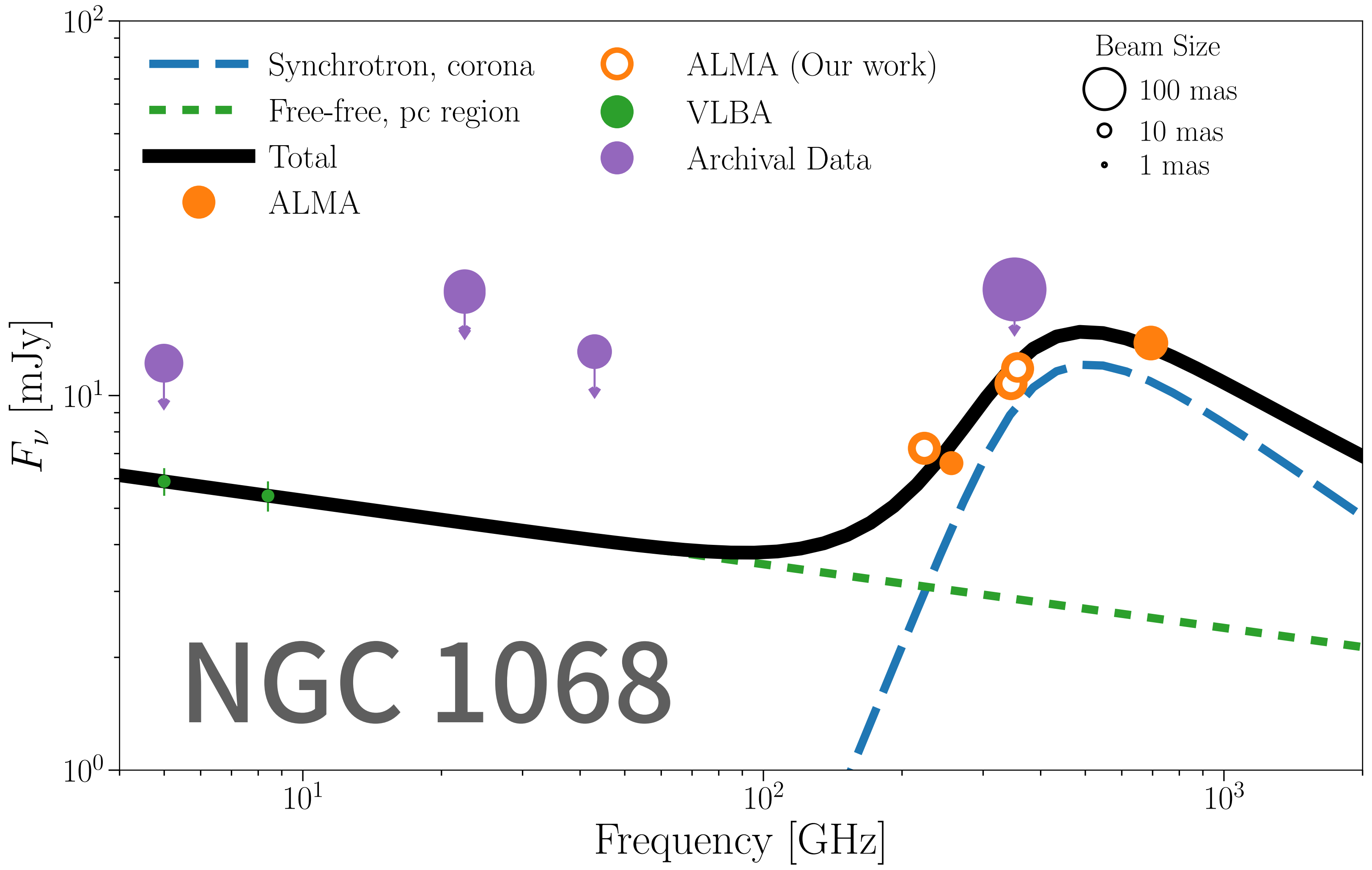
Now we live in the ALMA era.

- 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.

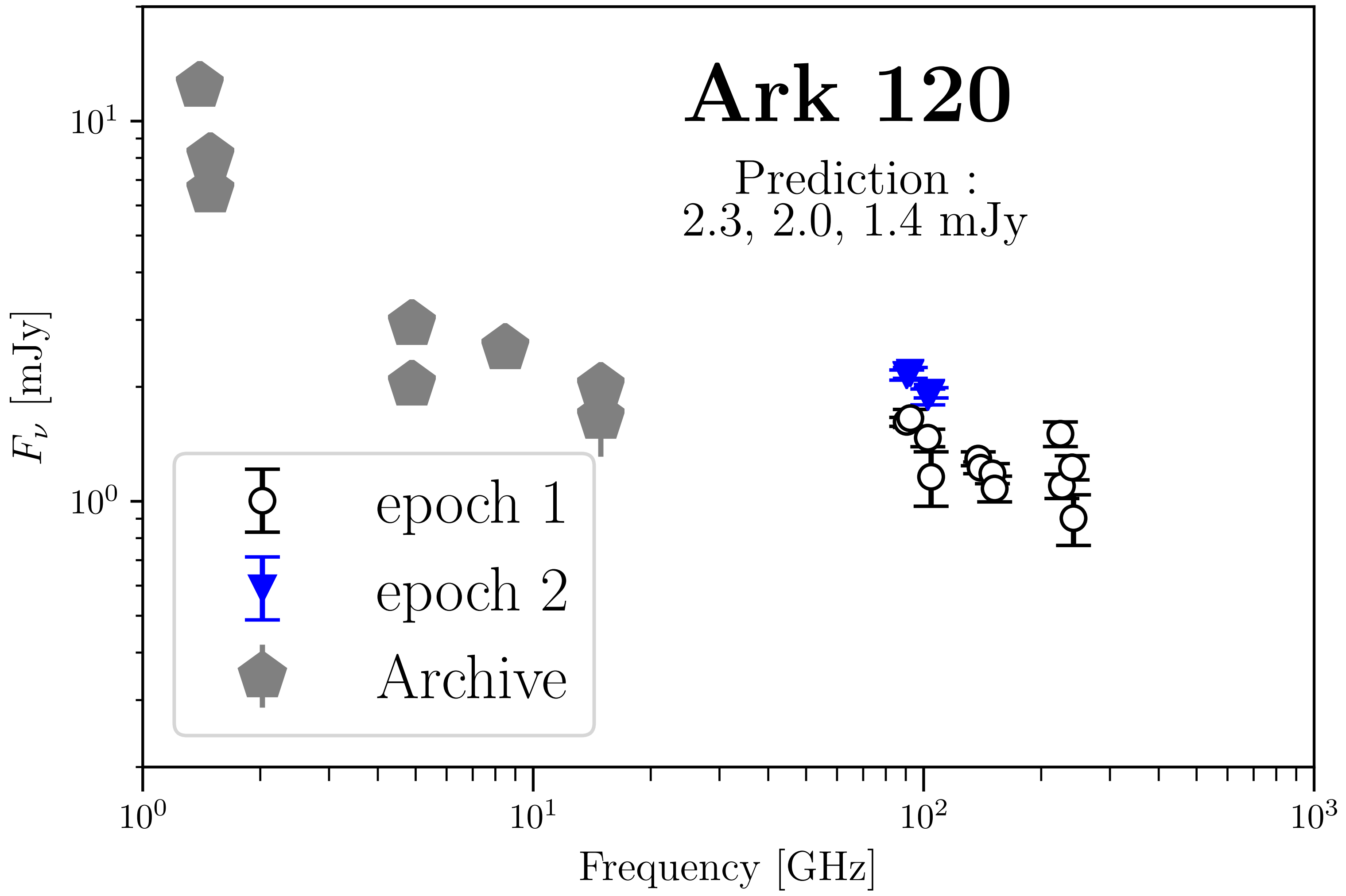
ALMA observations toward nearby Seyferts



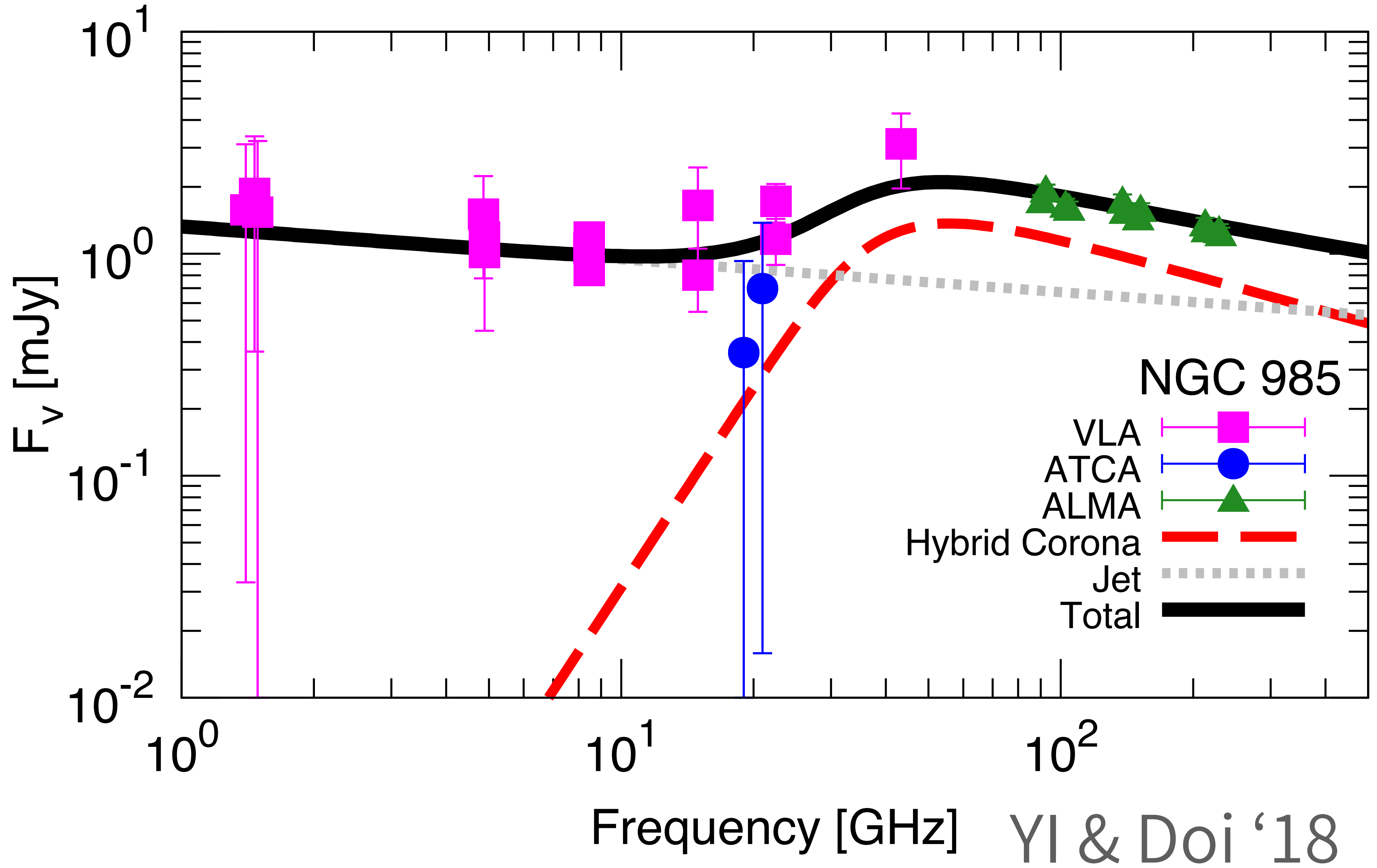
YI & Doi '18



YI, Khangulyan, & Doi '20



YI+'in prep.

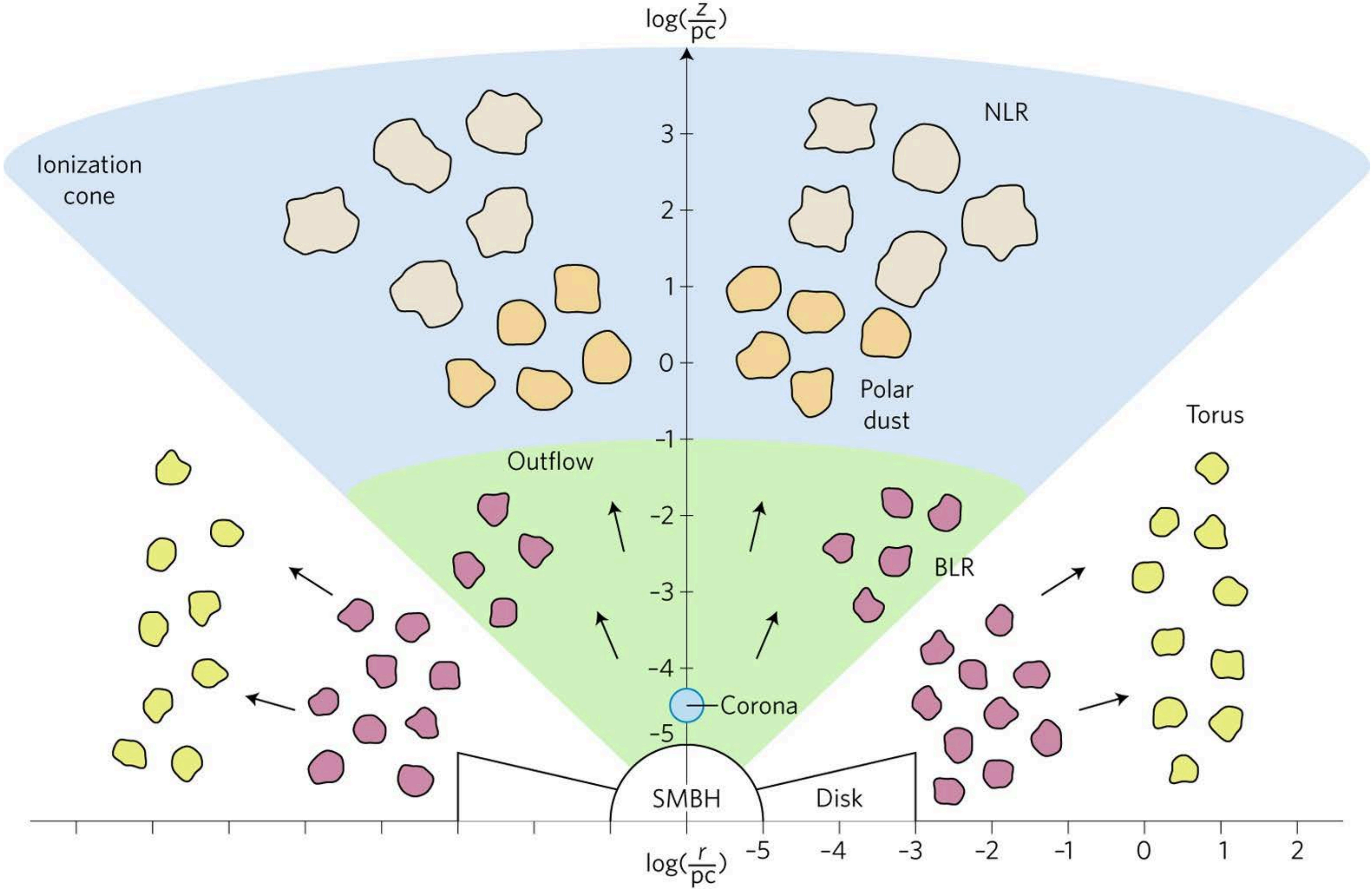


YI & Doi '18

- 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?

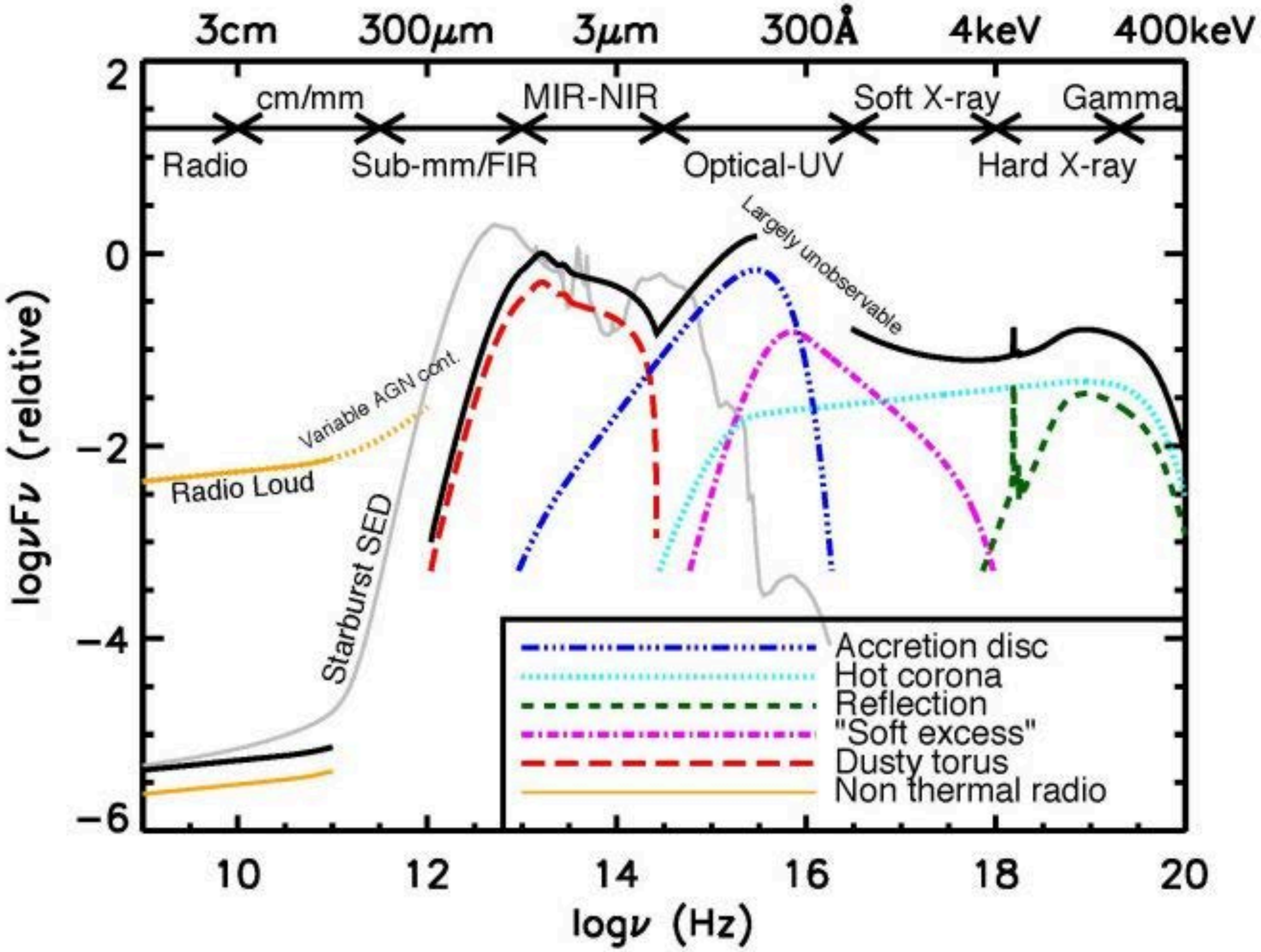


Ramos-Almeida & Ricci '17

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

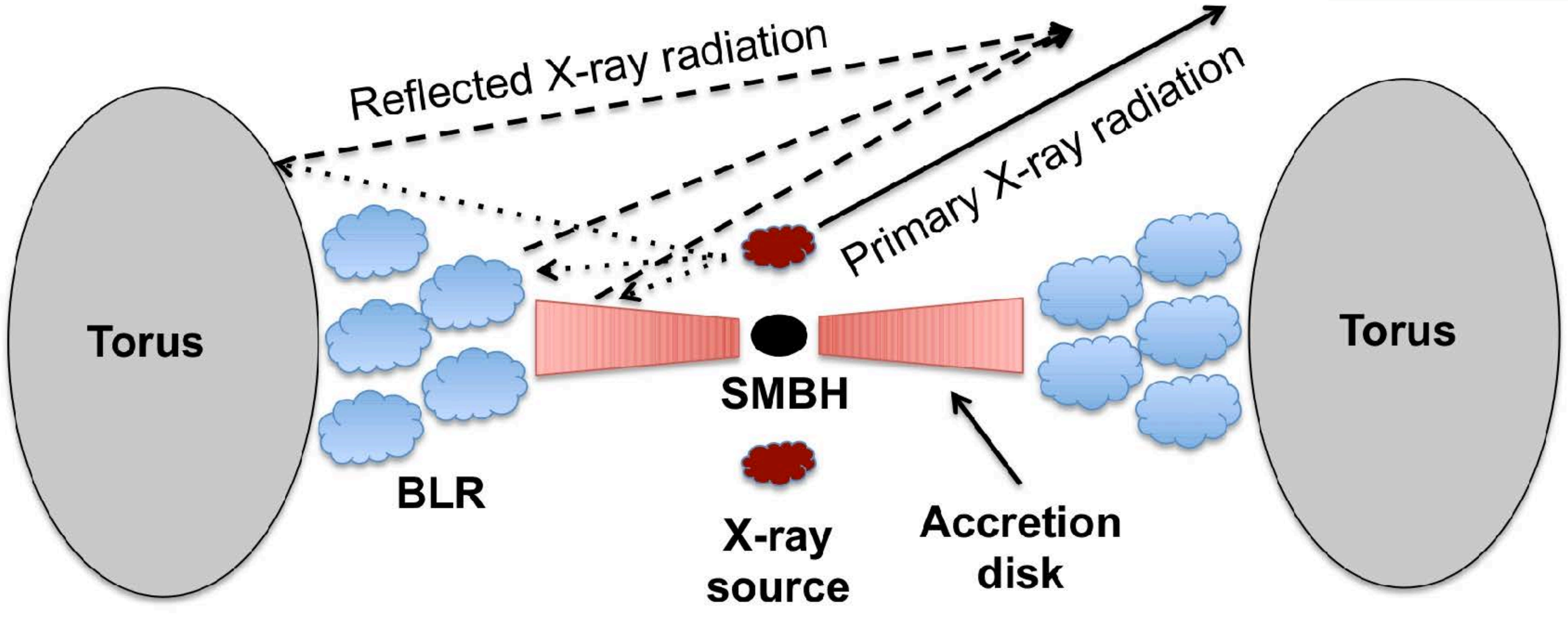
Coronal Synchrotron Emission

X-ray emission from black hole corona



Hickox & Alexander+'16

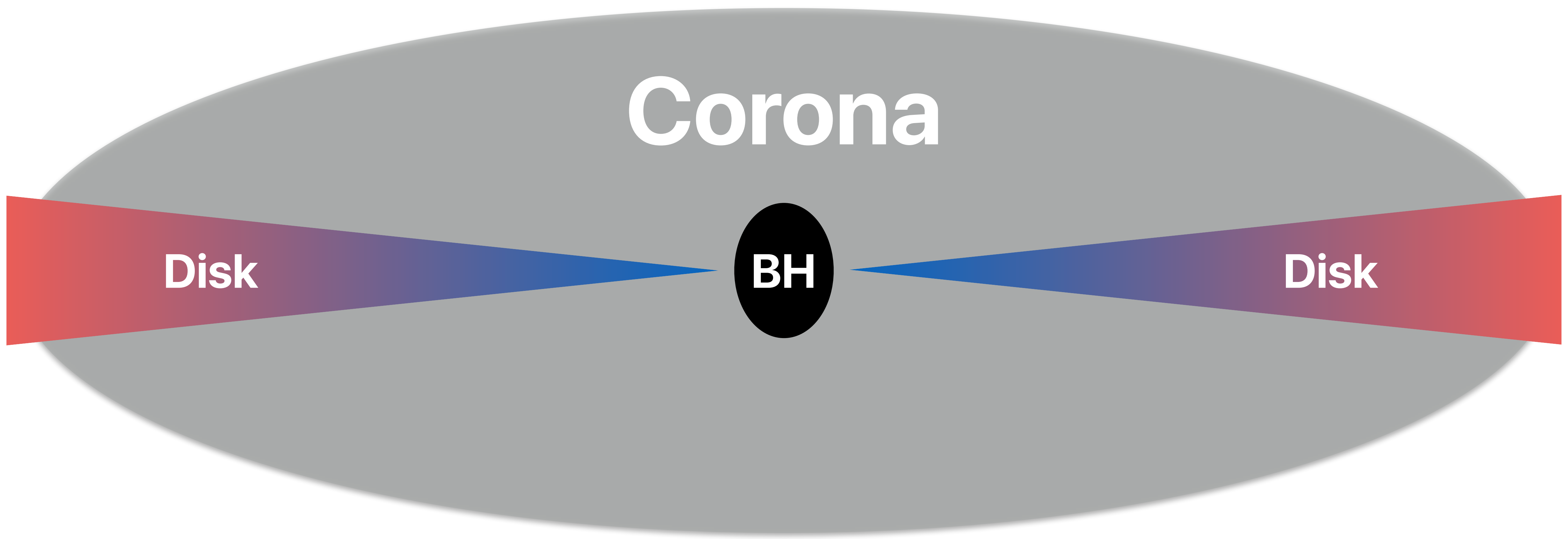
- Power-law continuum is generated by Comptonization of disk photons in the **corona**.

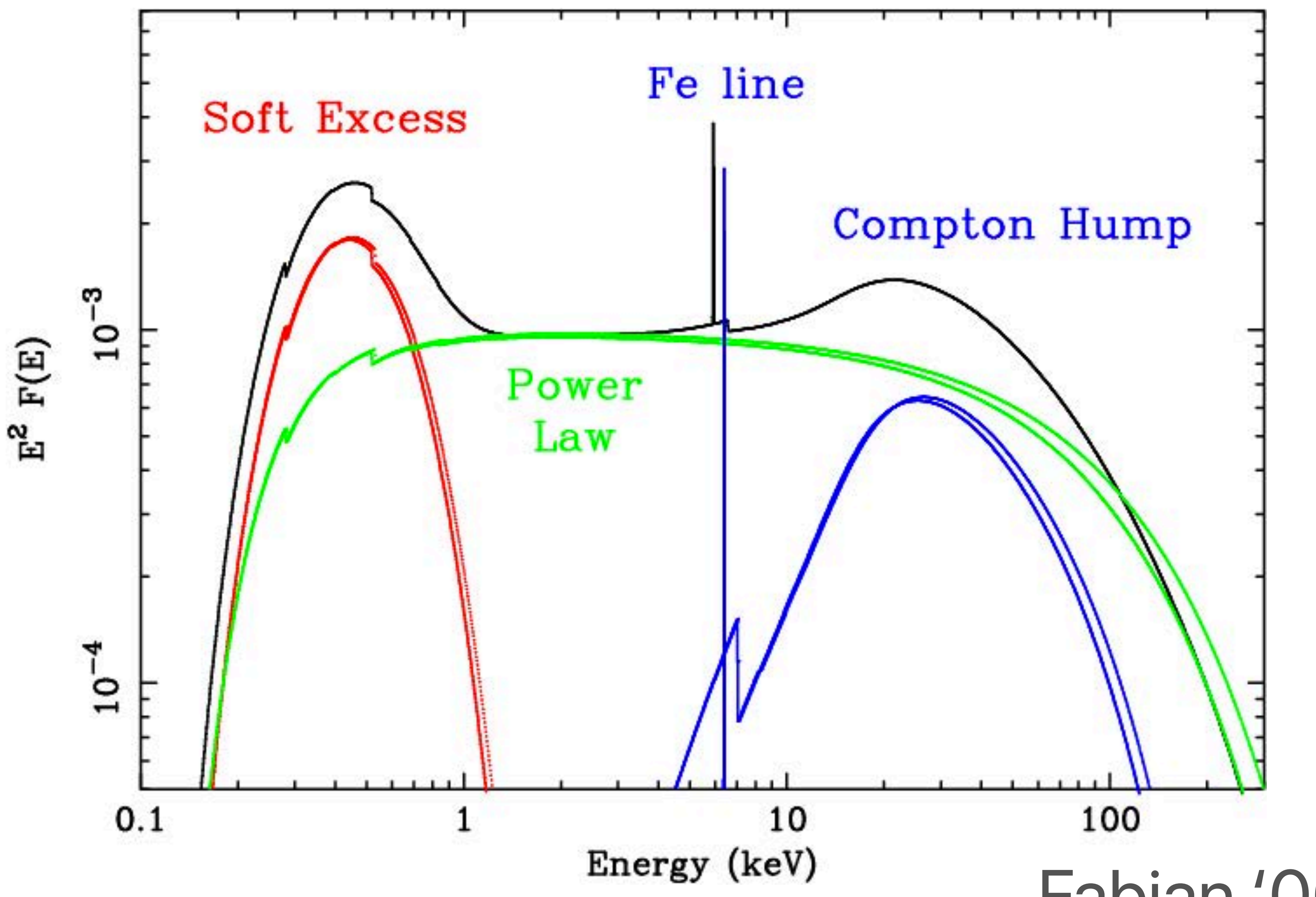


©Ricci

Black Hole Accretion disk corona

Hot plasma around BH





Fabian '06

- High energy cutoff

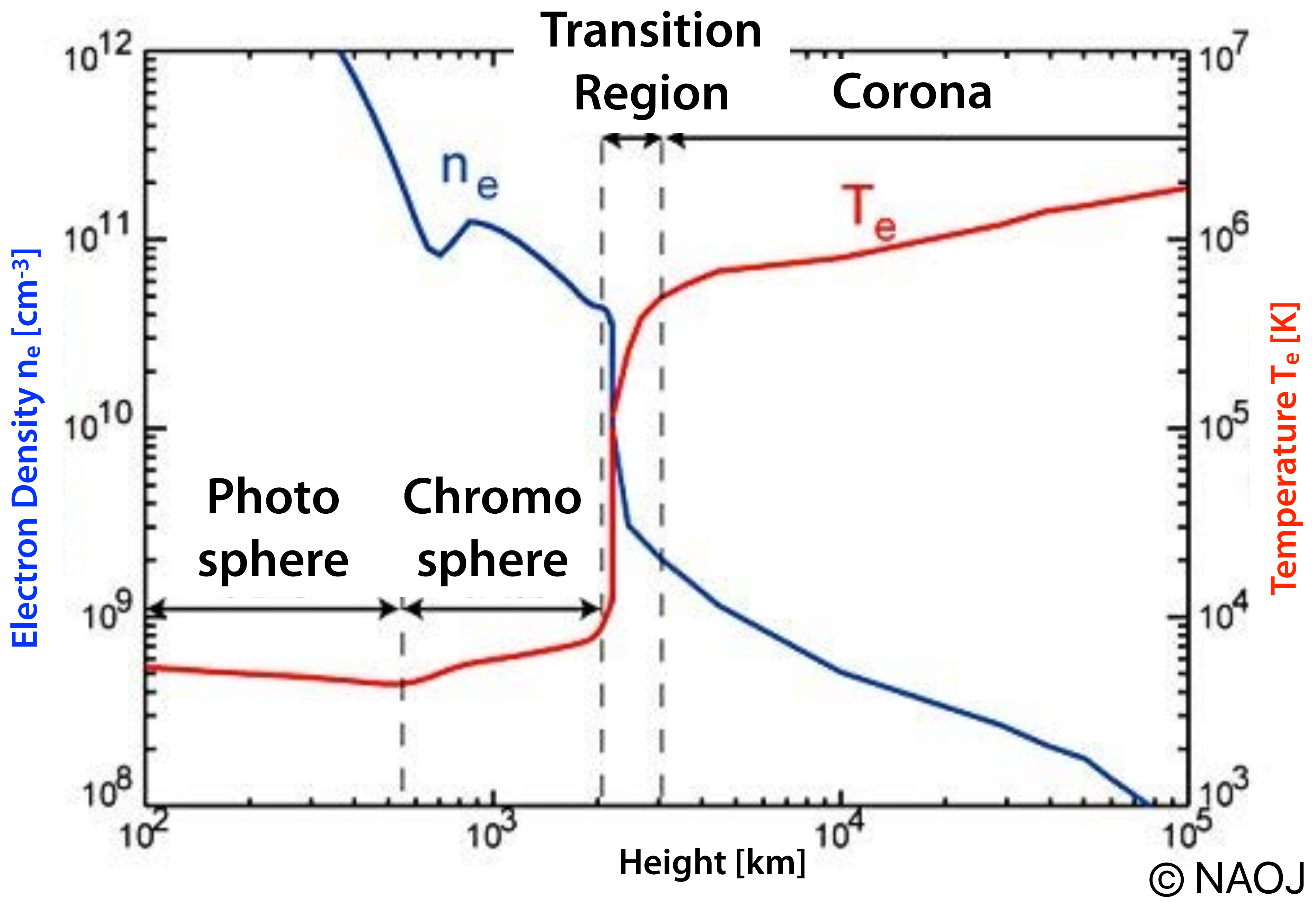
  ✓ $k_B T_e \sim 10^9$ K ~ 100 keV

- 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

Dissipation of magnetic energy



- 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

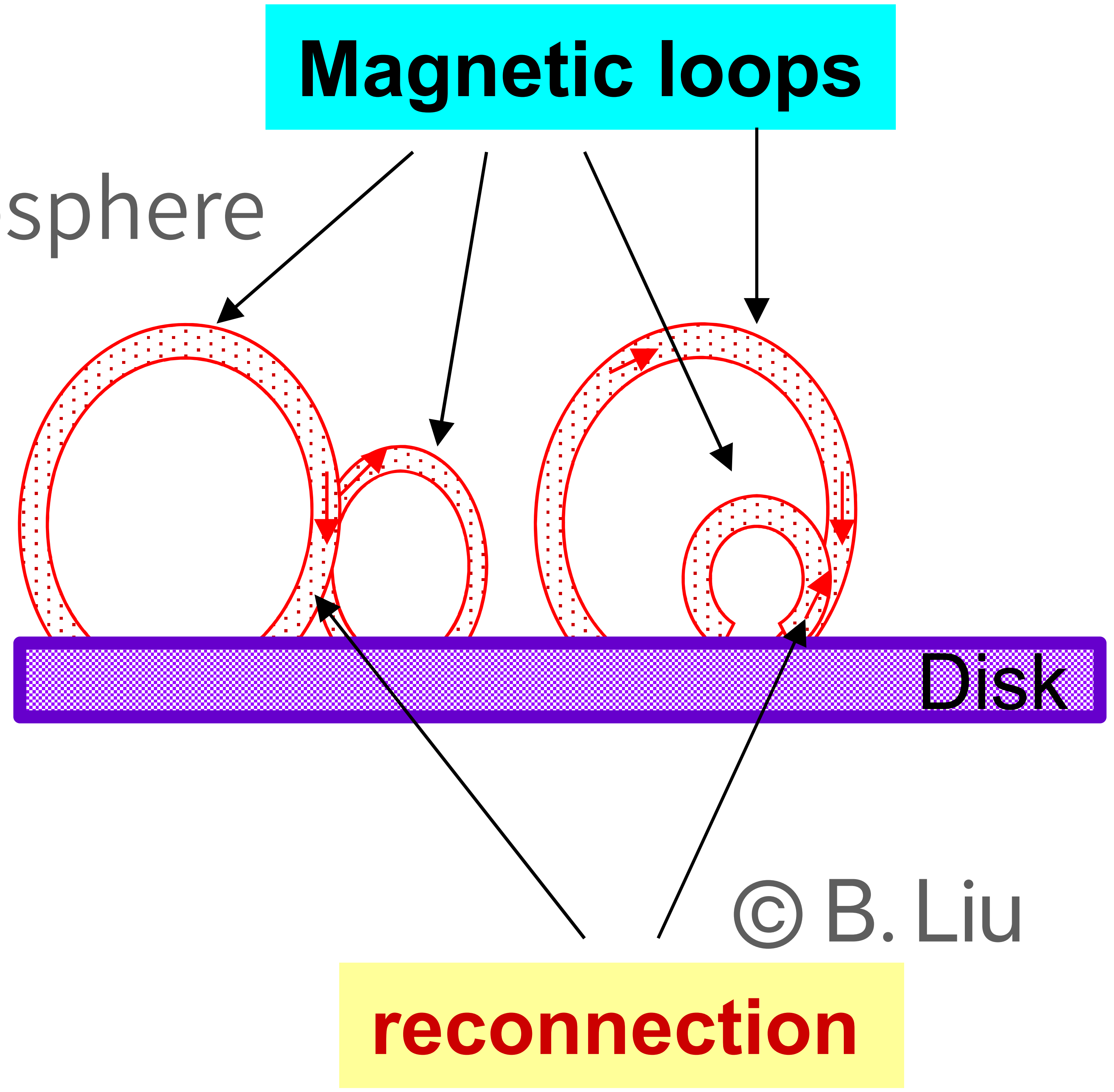
1. Reconnection heating = Compton cooling in corona

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

2. Conduction heating = Evaporation cooling in disk chromosphere

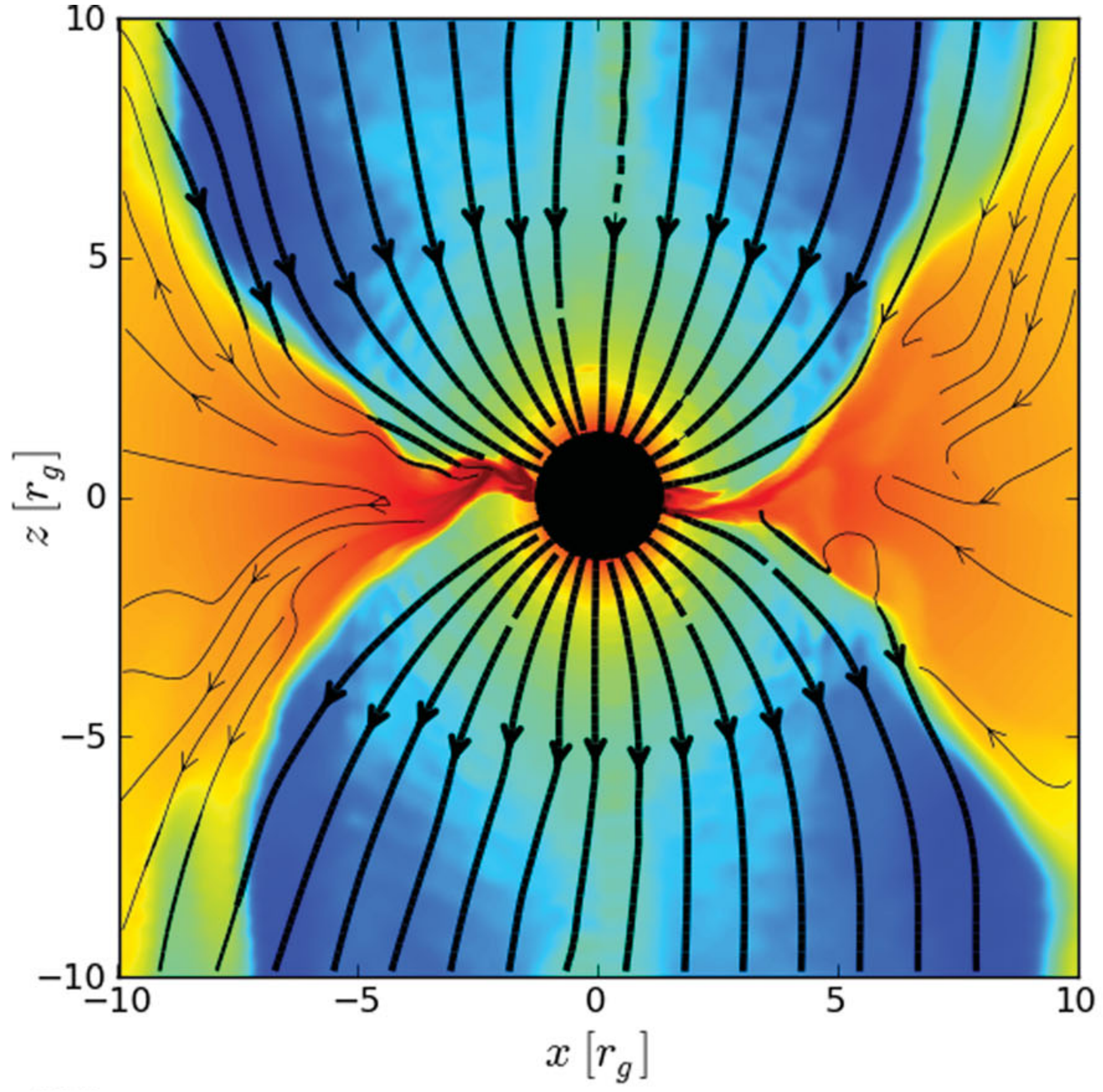
$$\checkmark \quad \frac{k_0 T^{7/2}}{l} \approx \frac{\gamma}{\gamma - 1} n_e k_B T_e \left(\frac{k_B T_e}{m_H}\right)^{1/2}$$

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

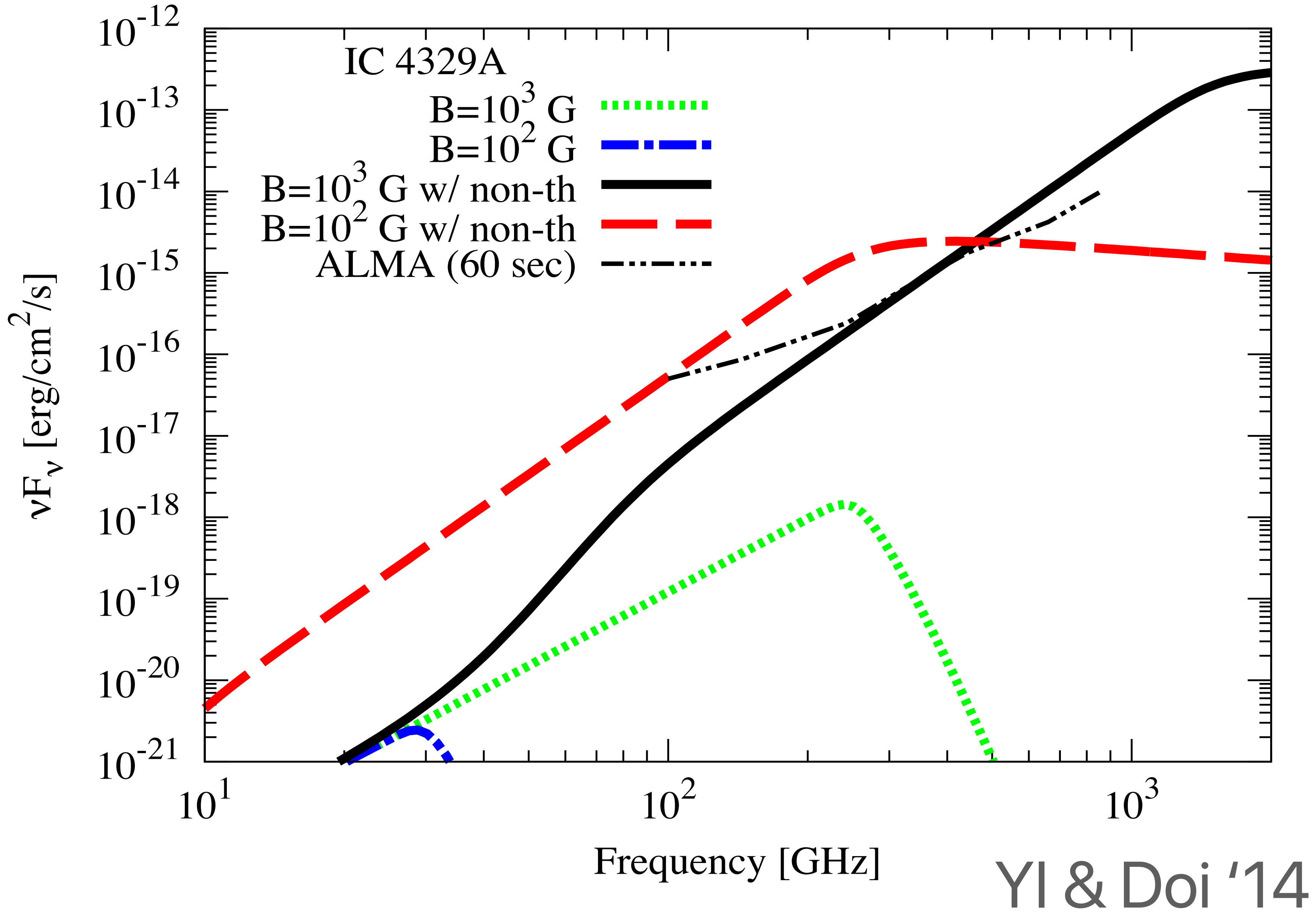


Magnetic Fields around SMBHs

- 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
  - **<u>coronal synchrotron radiation</u>** is expected
    (Di Matteo+’97; YI & Doi ’14; Raginski & Laor ’16)
  - Spectral excess appears in the mm band



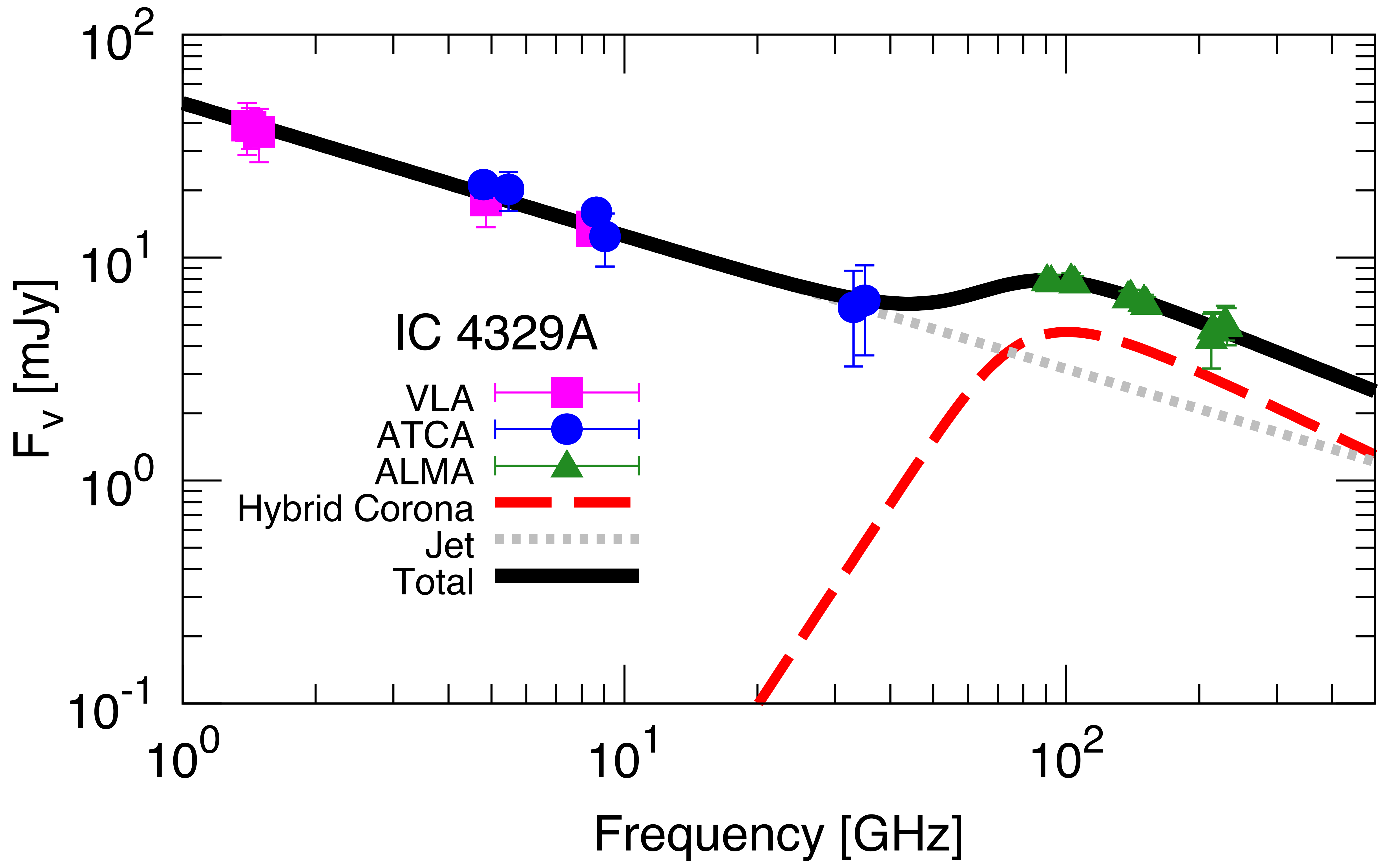
McKinney et al. ‘12



YI & Doi ‘14

cm-mm spectrum of AGN core

A case of IC 4329A



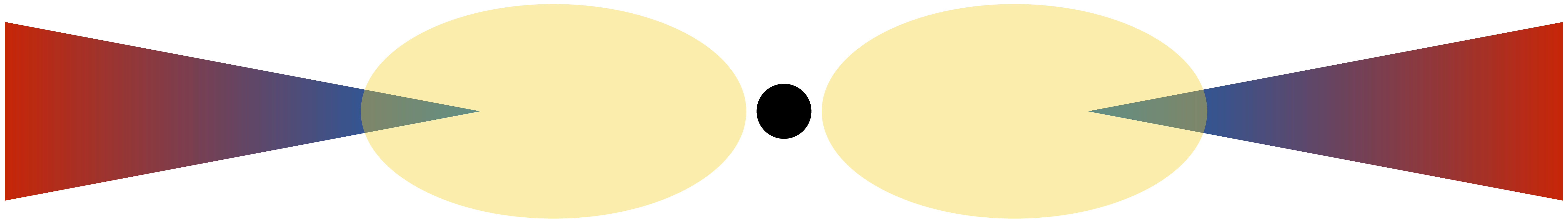
YI & Doi '18

- 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.

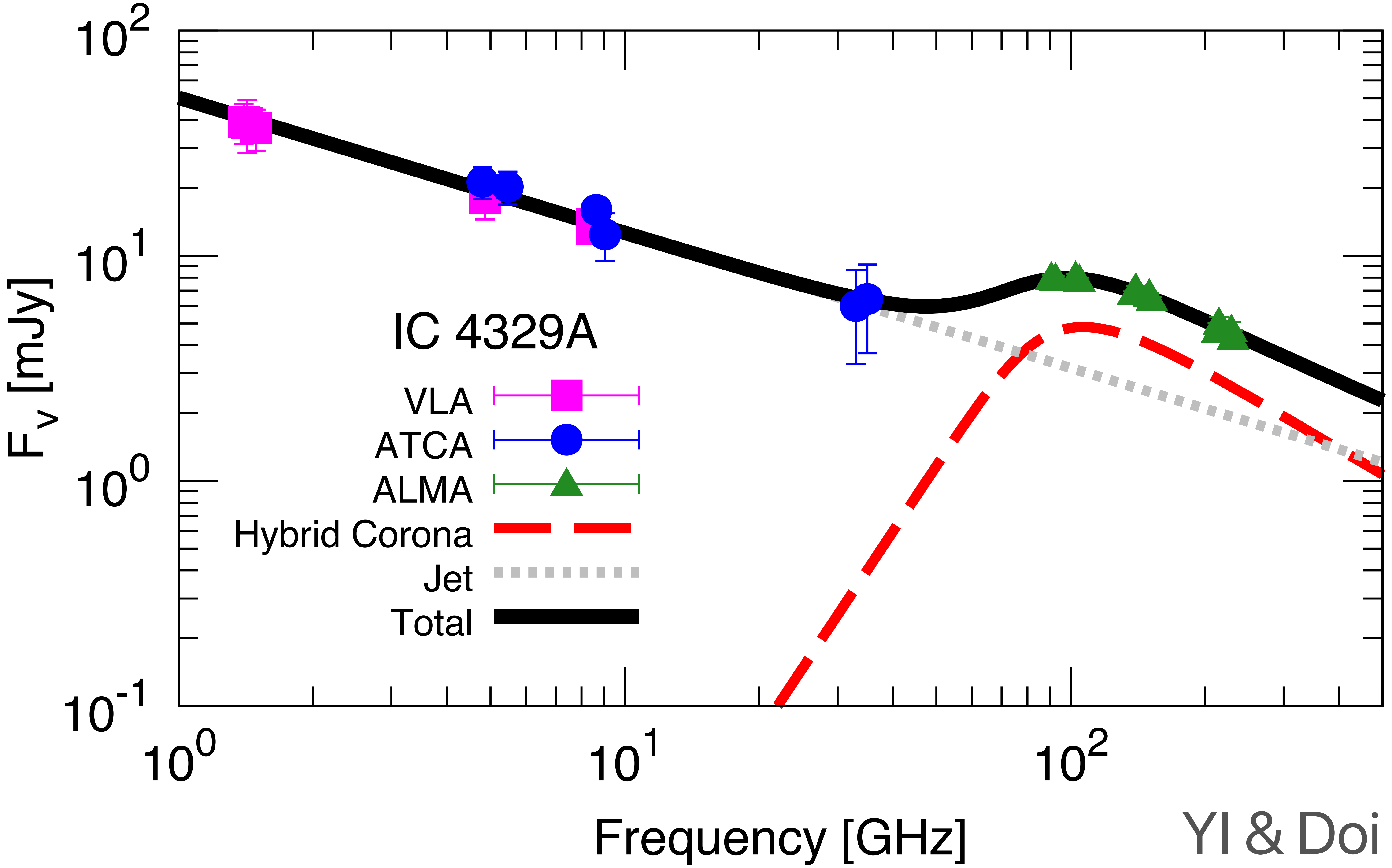
- Heating and Cooling
  - Magnetic Heating: $B^2 V_A / 4\pi$
    - $Q_{B,\,heat} \sim 10^{10}$ erg/cm^2/s
  - Compton Cooling: $4kTn_e\sigma_T c U_{rad} l / m_e c^2$
    - $Q_{IC,\,cool} \sim 10^{13}$ erg/cm^2/s
  - Magnetic field energy is **NOT** sufficient to keep coronae hot.
- Disk truncation at some radii (e.g. ~40 r_s)
  - The inner part = hot accretion flow (Ichimaru '77, Narayan & Yi '94, '95).
    - Heated by advection.
  - 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

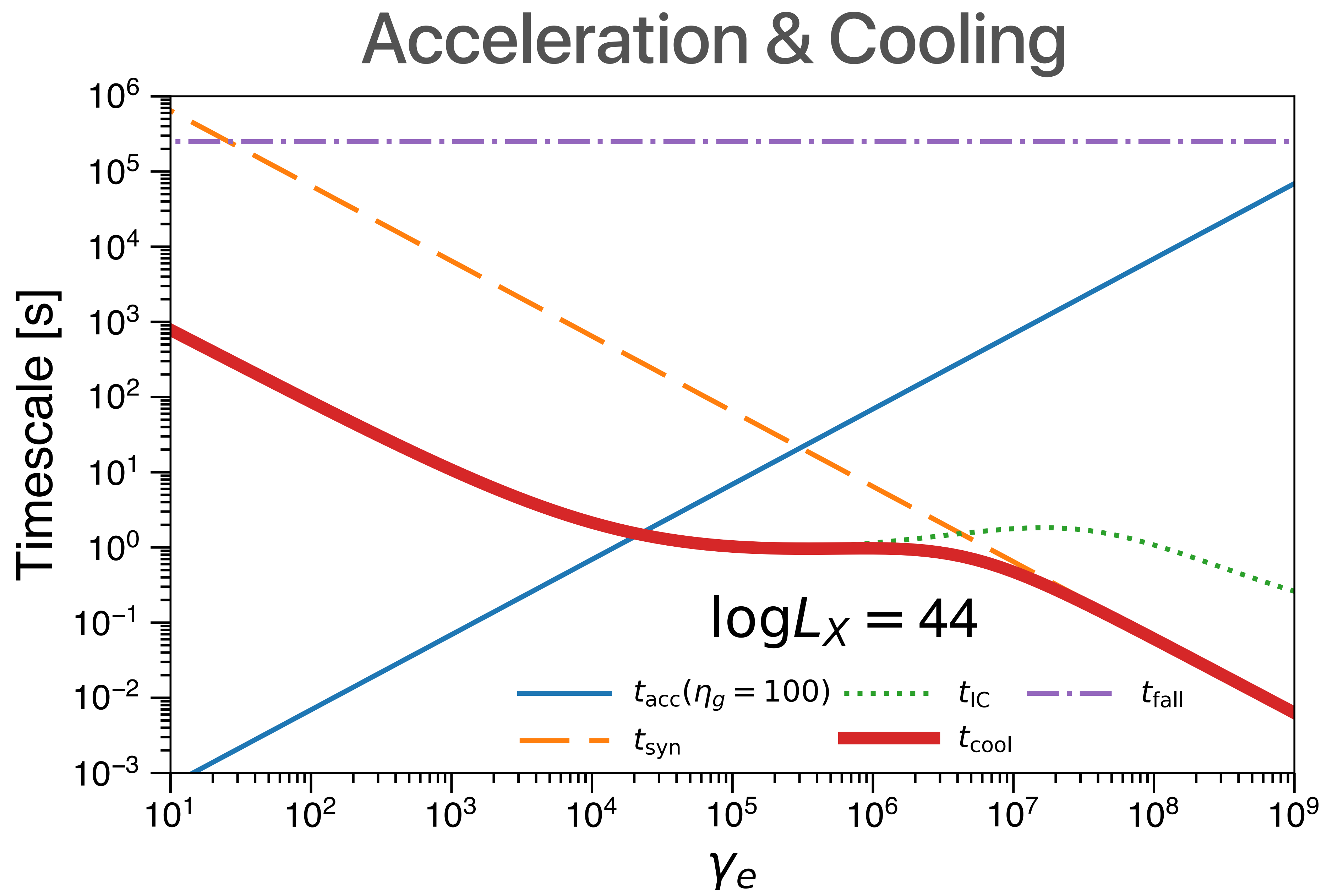
Non-thermal tail in the mm spectrum

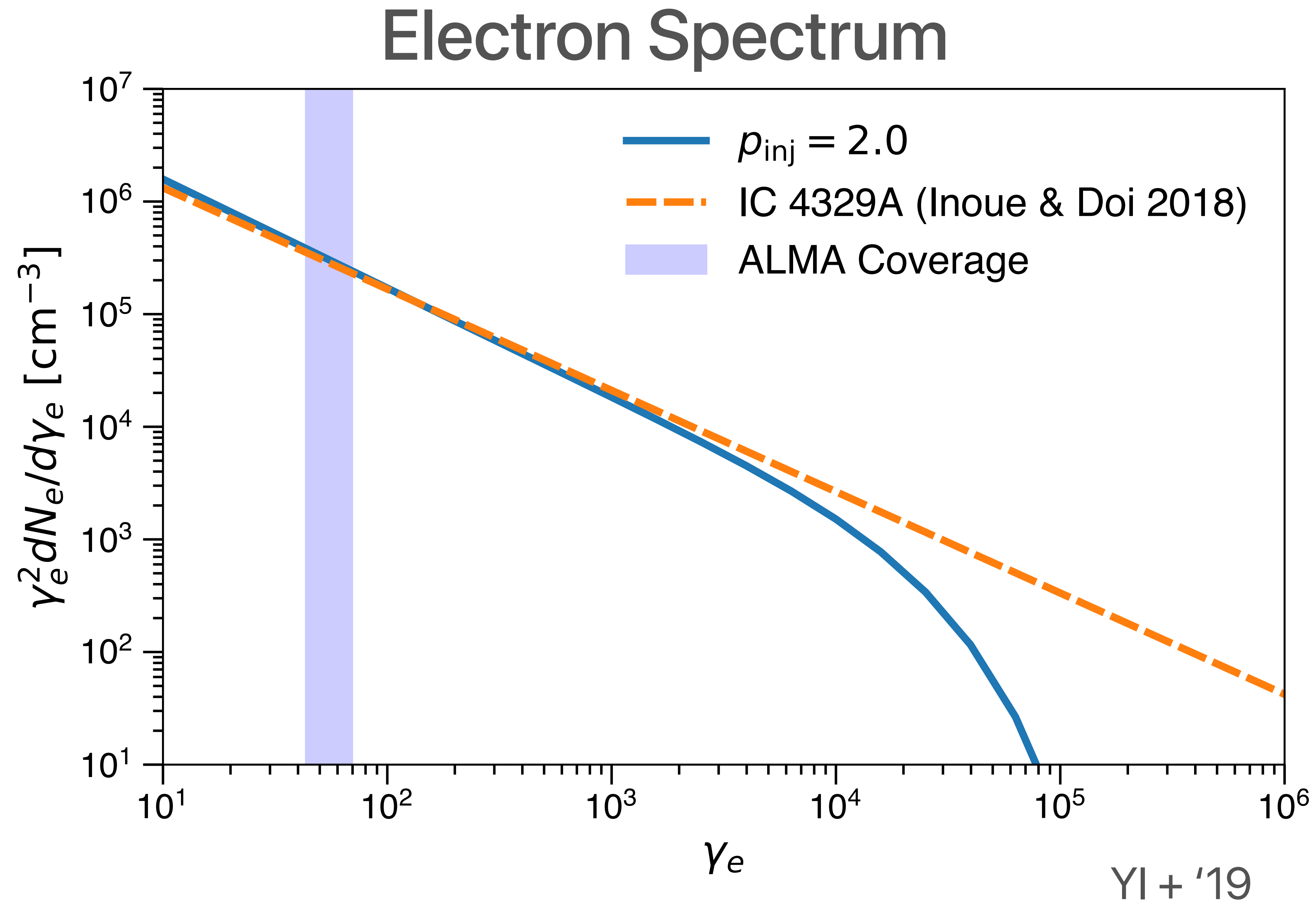


YI & Doi '18

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.

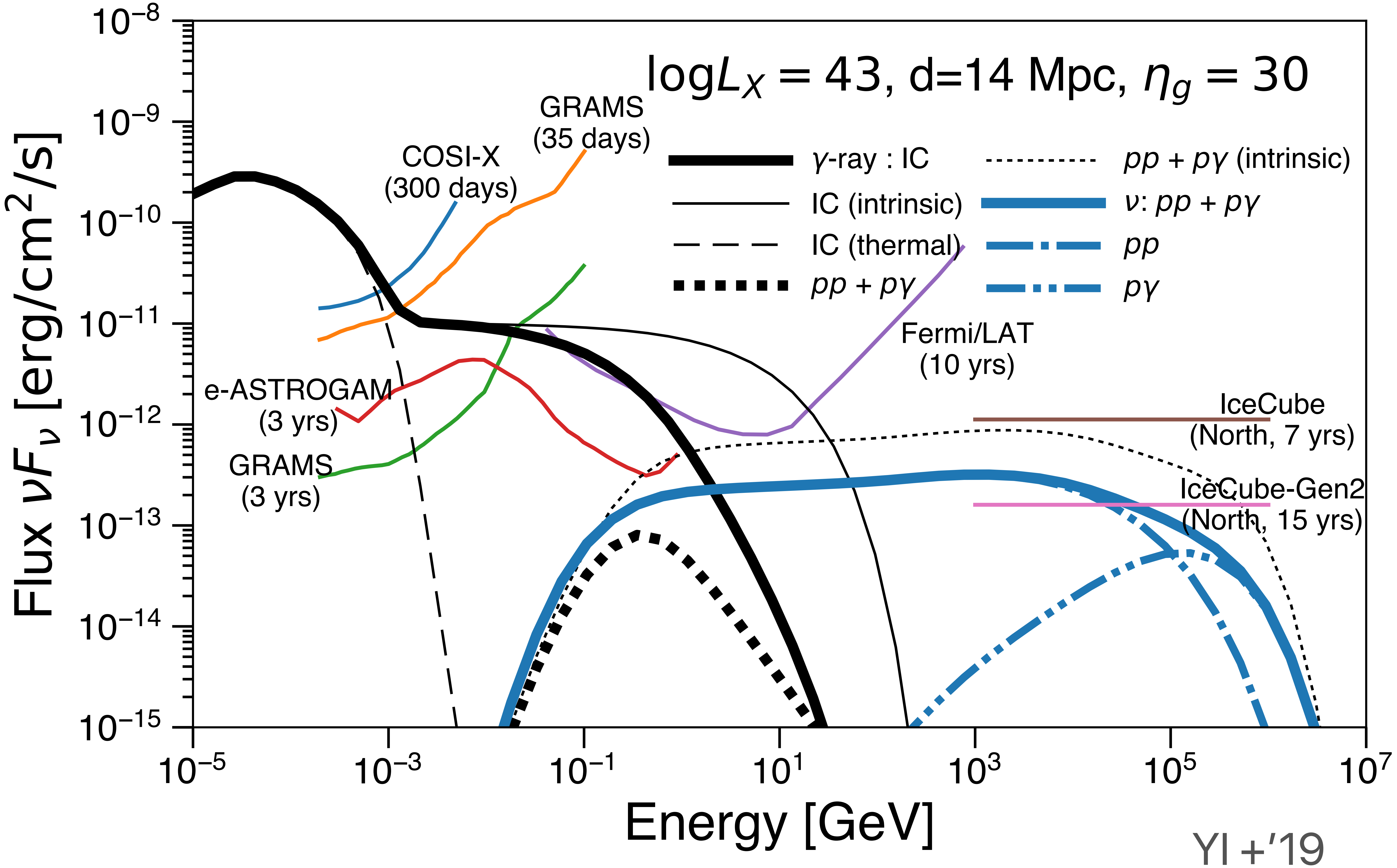




YI + '19

High energy emission from AGN coronae

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

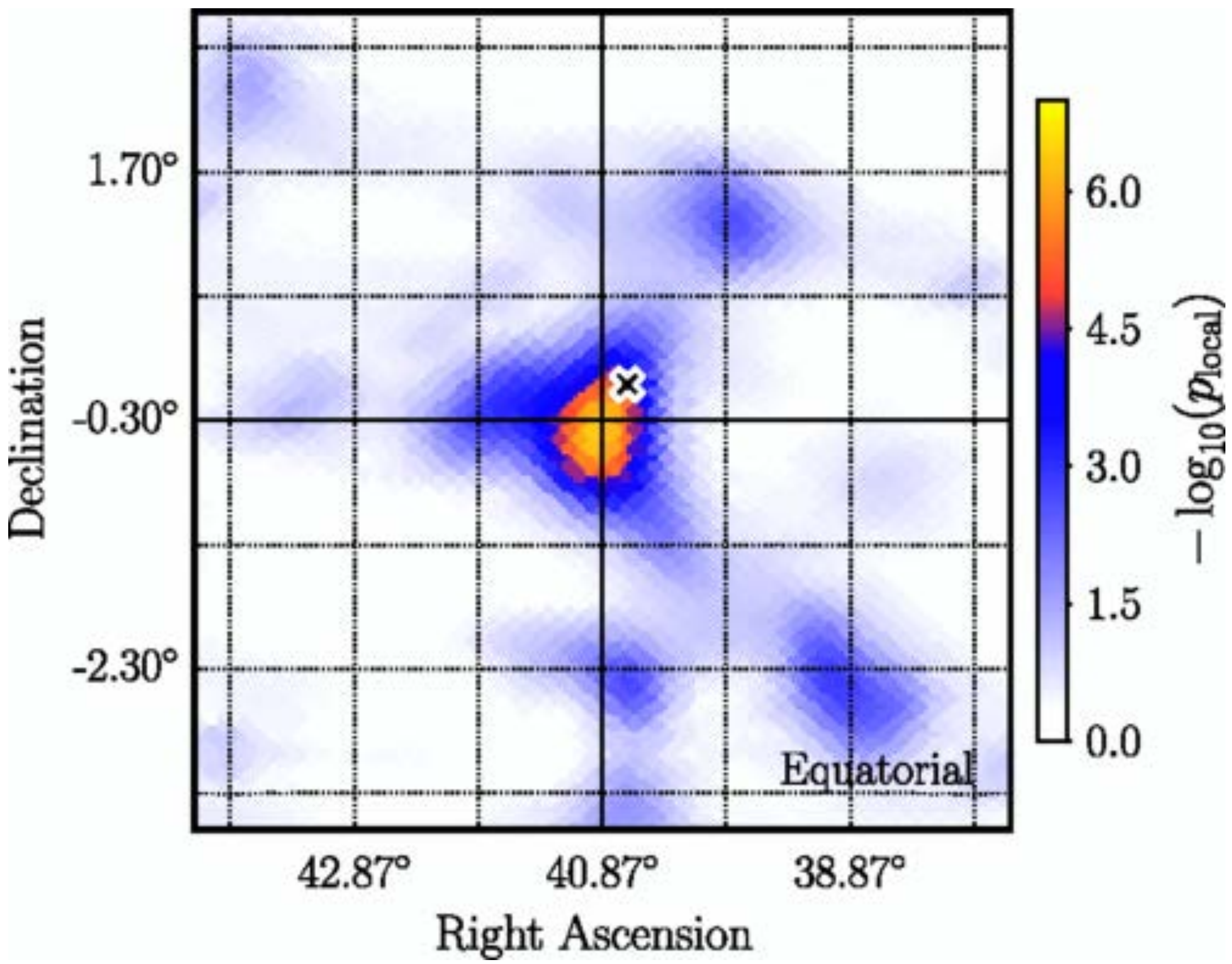


YI +'19

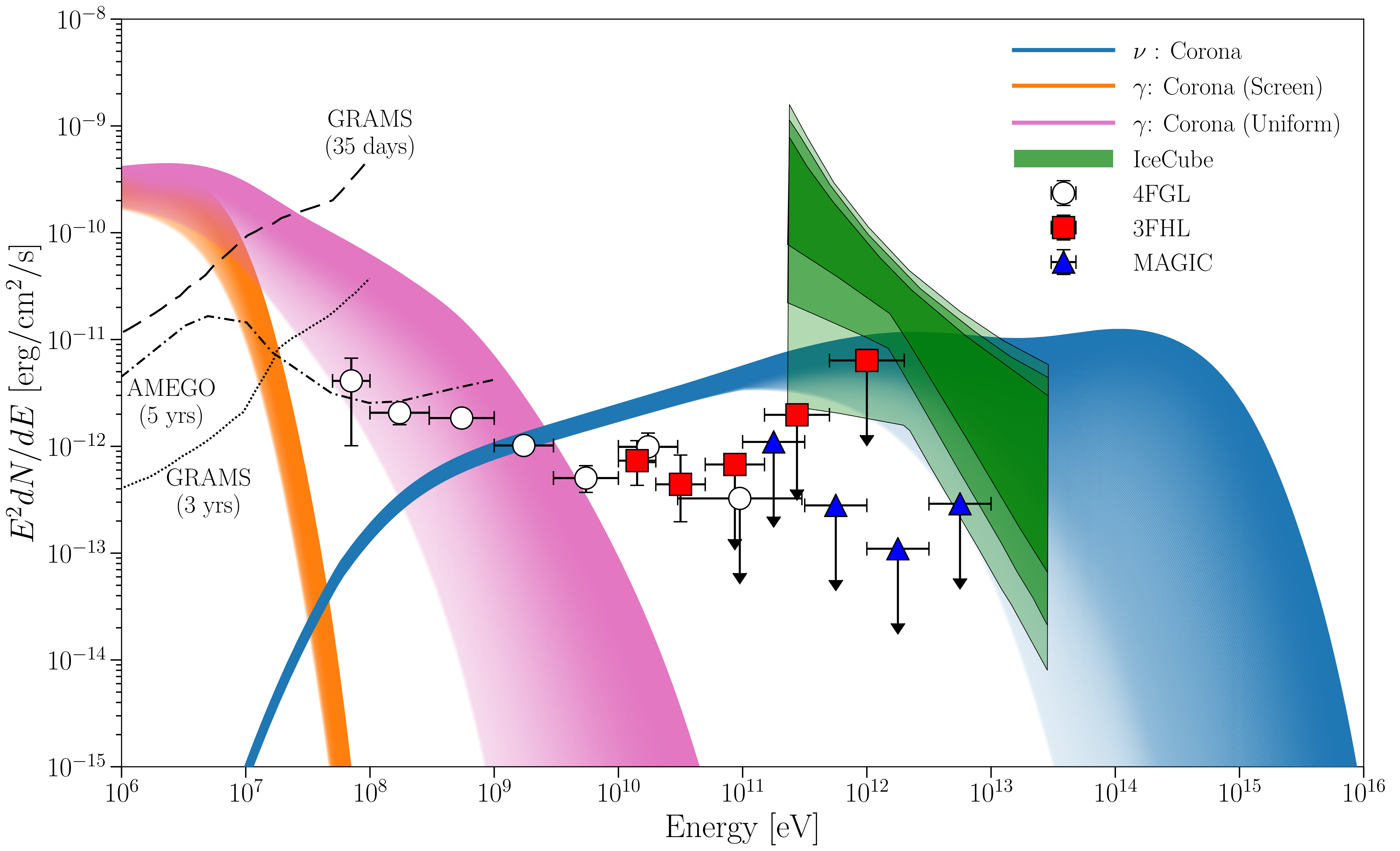
- MeV emission
  - but, no GeV emission
- Protons would be accelerated simultaneously
  - Generation of high energy neutrinos

IceCube Hottest Spot

NGC 1068 (no strong jet)



IceCube 2020

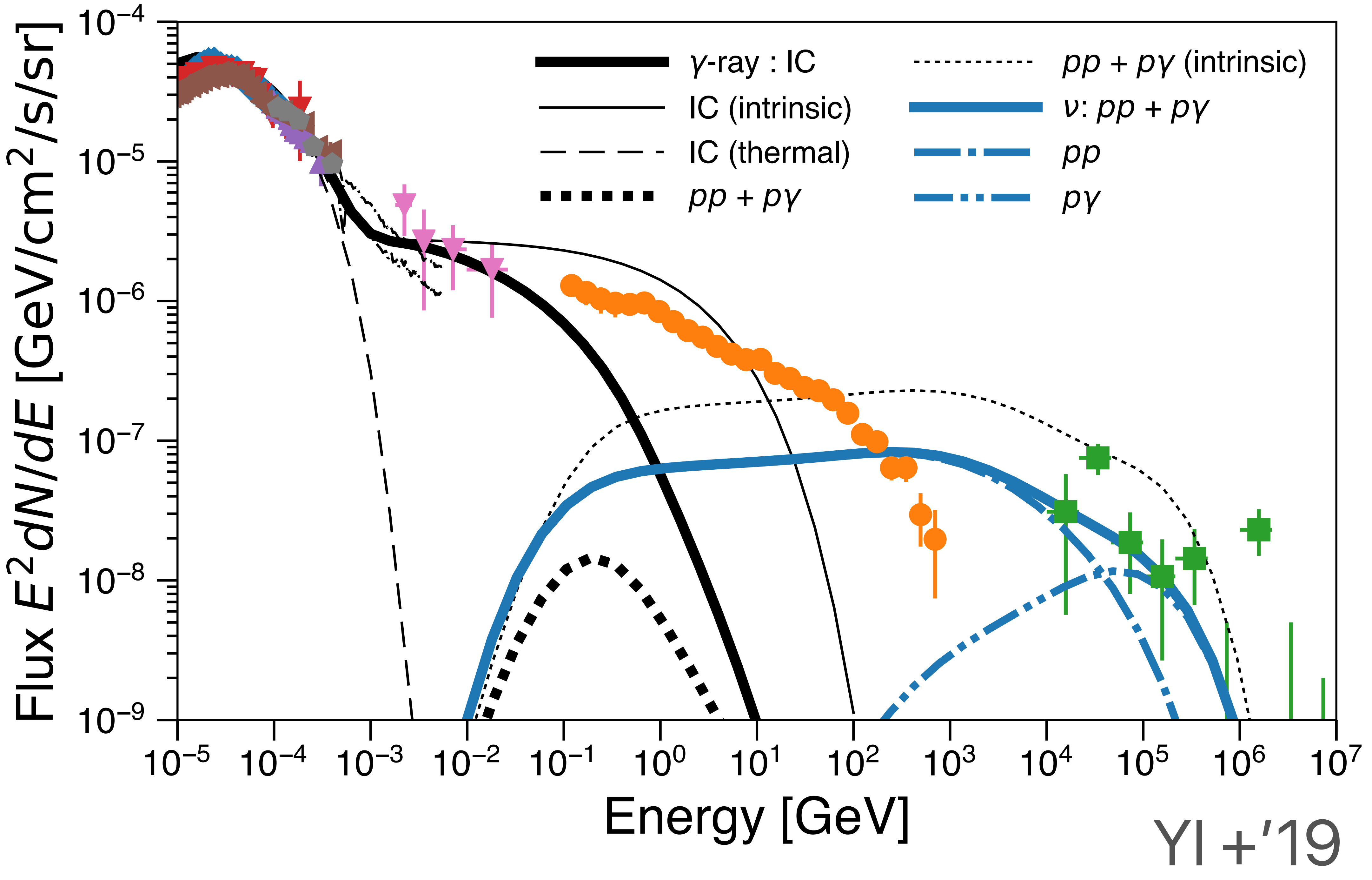


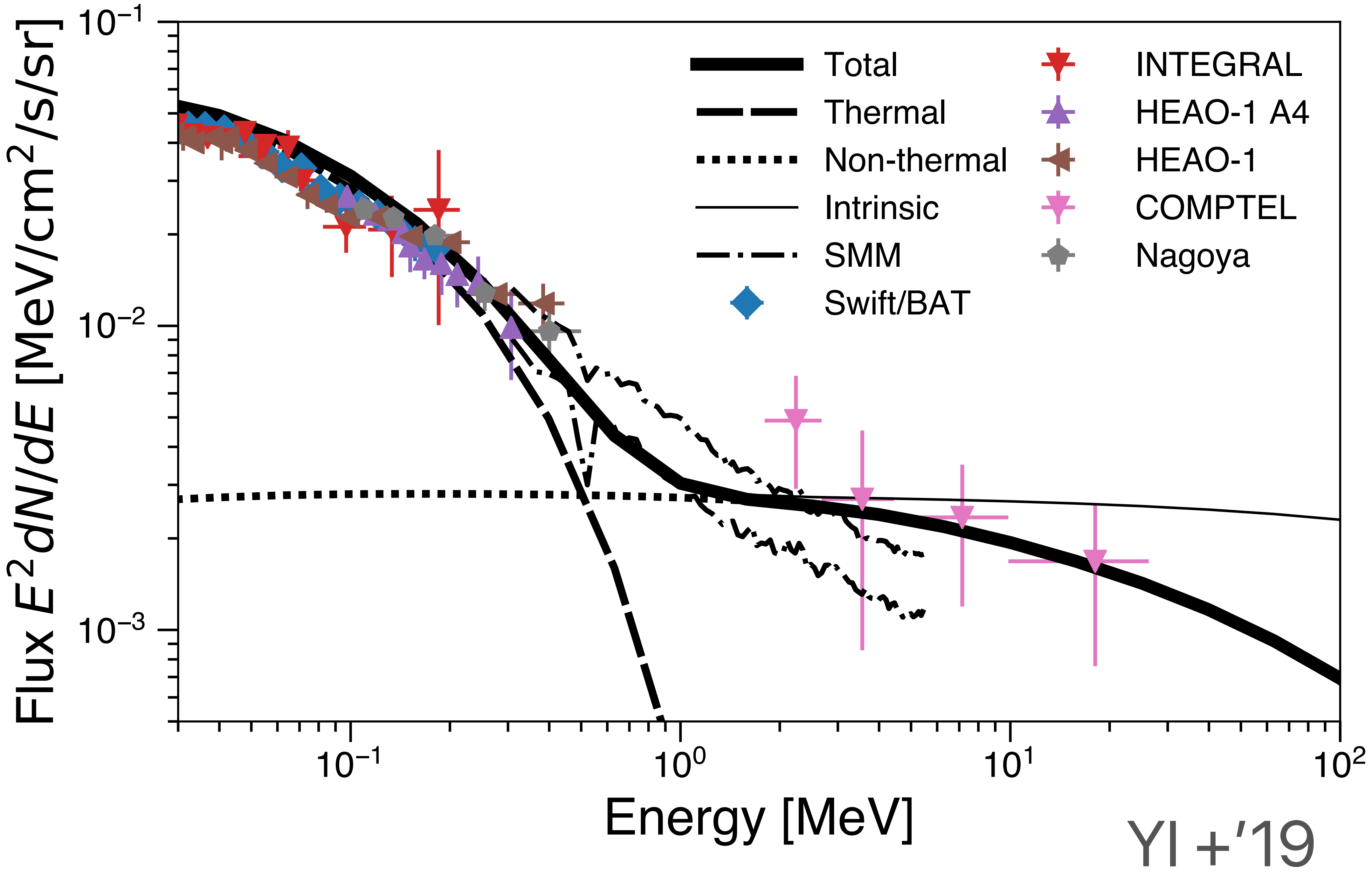
YI, Khangulyan, & Doi, '20

- 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).

Cosmic High Energy Background Radiation

Integrated history of the Universe



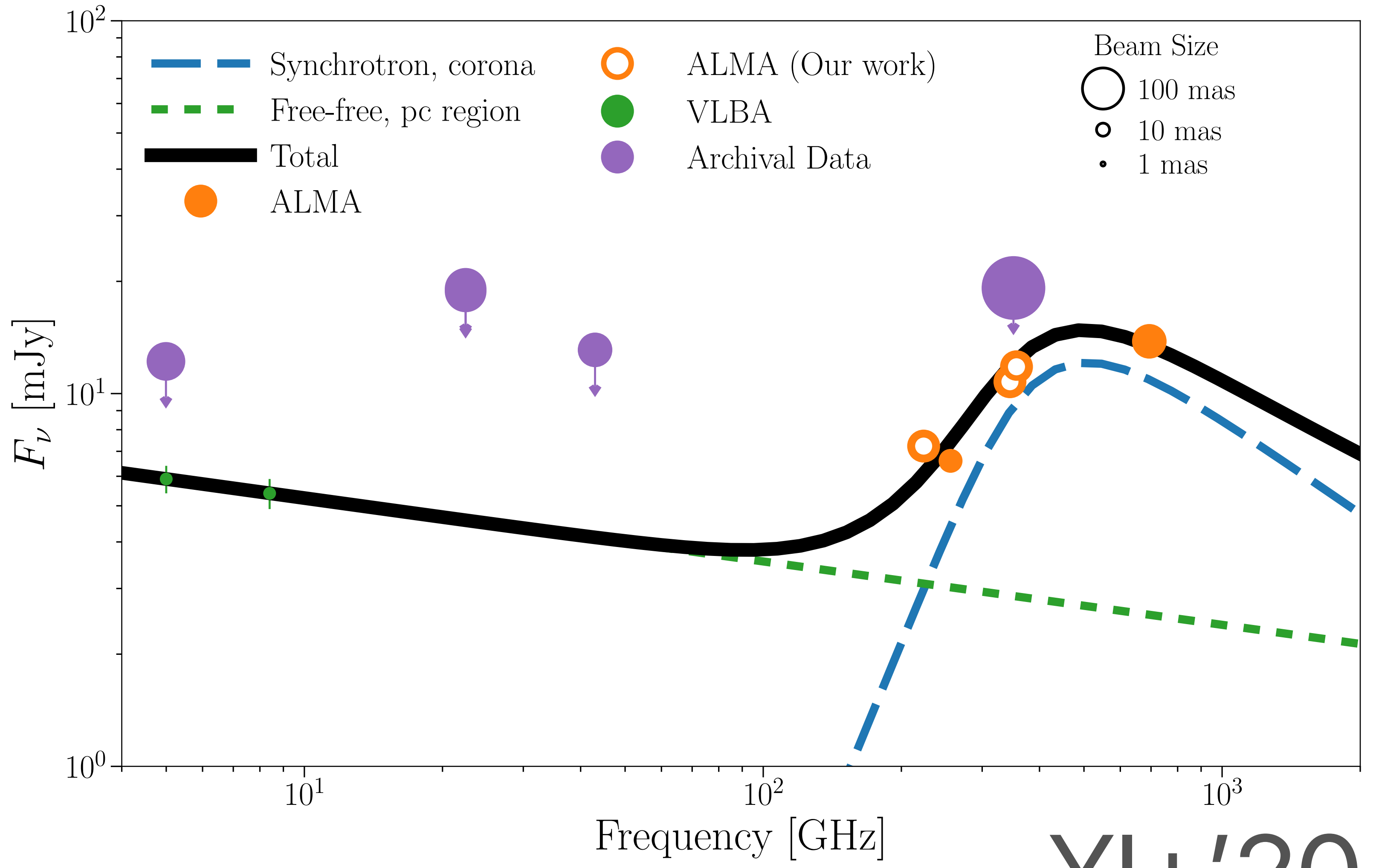


- Seyferts can explain TeV neutrino background (see also Begelman+'90; Stecker+'92; Kalashev+'15; Murase+'20).
- Seyferts can explain X-ray & MeV gamma-ray background (YI+'08, YI+'19).
  - But, if both protons and electrons carry ~5% of the shock energy and gyrofactor is 30.

How can we test the model?

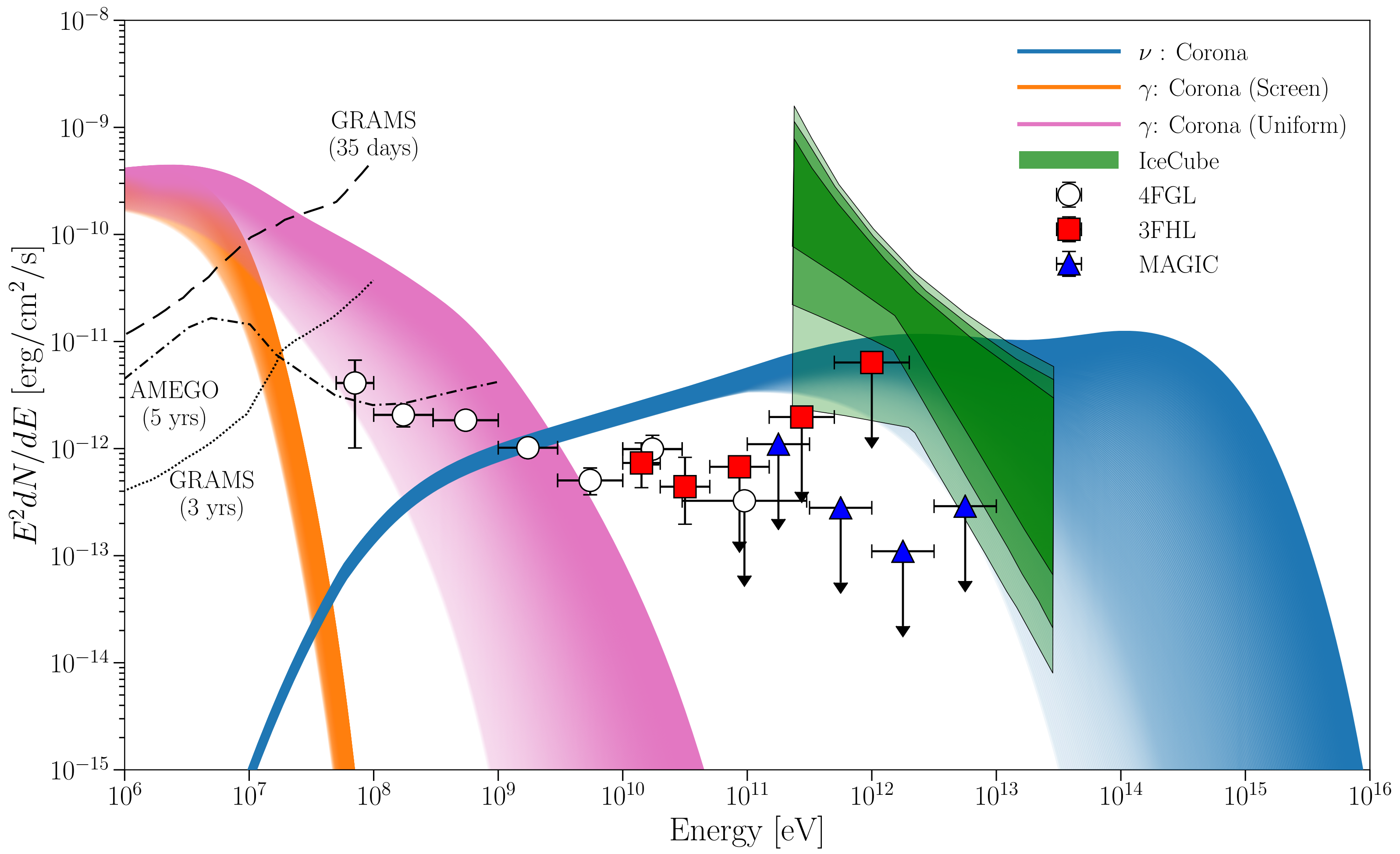
ALMA? GRAMS? AMEGO? IceCube? XRISM?

mm-band



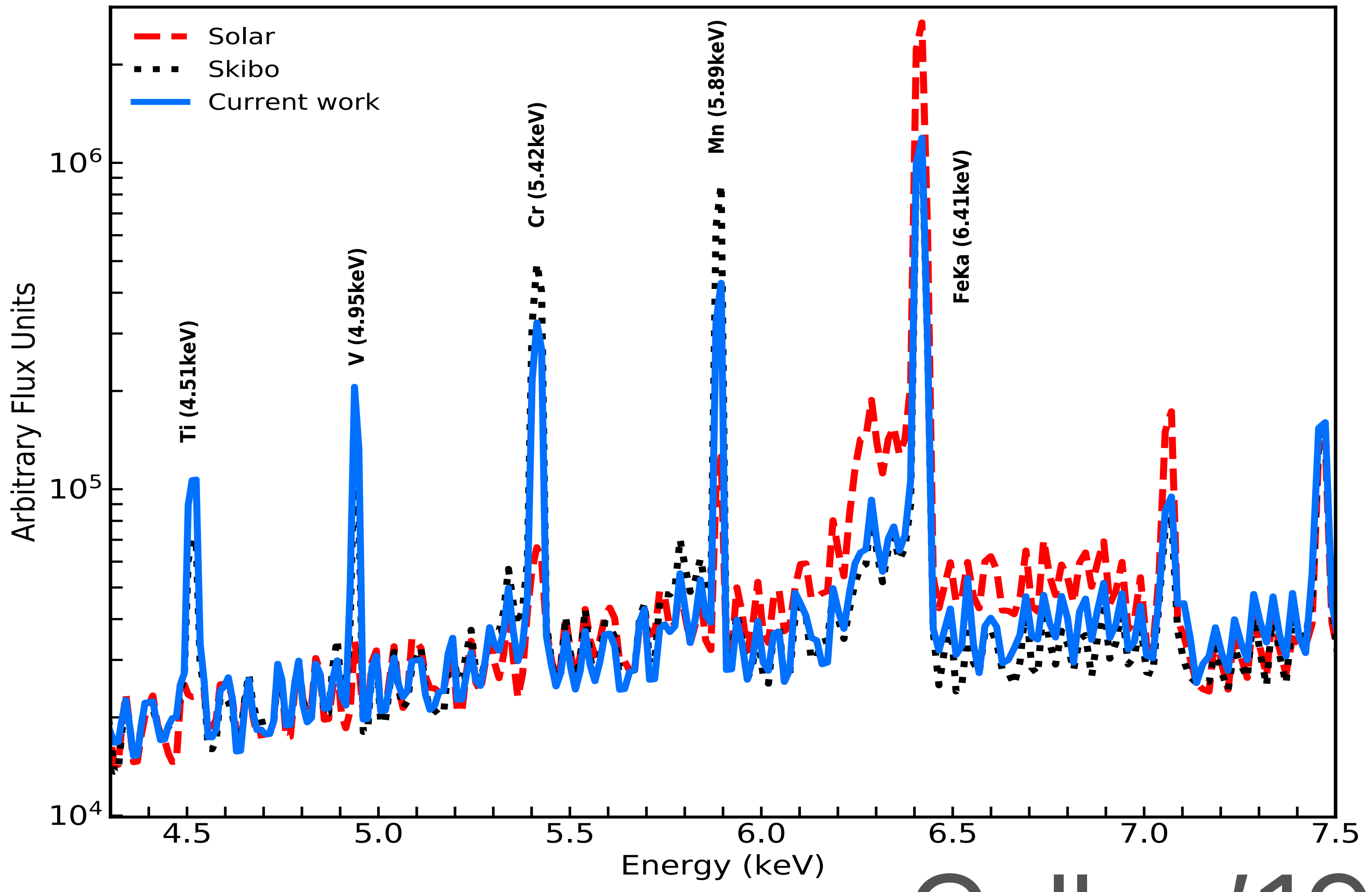
YI+'20

MeV & TeV ν



YI+'20

X-ray

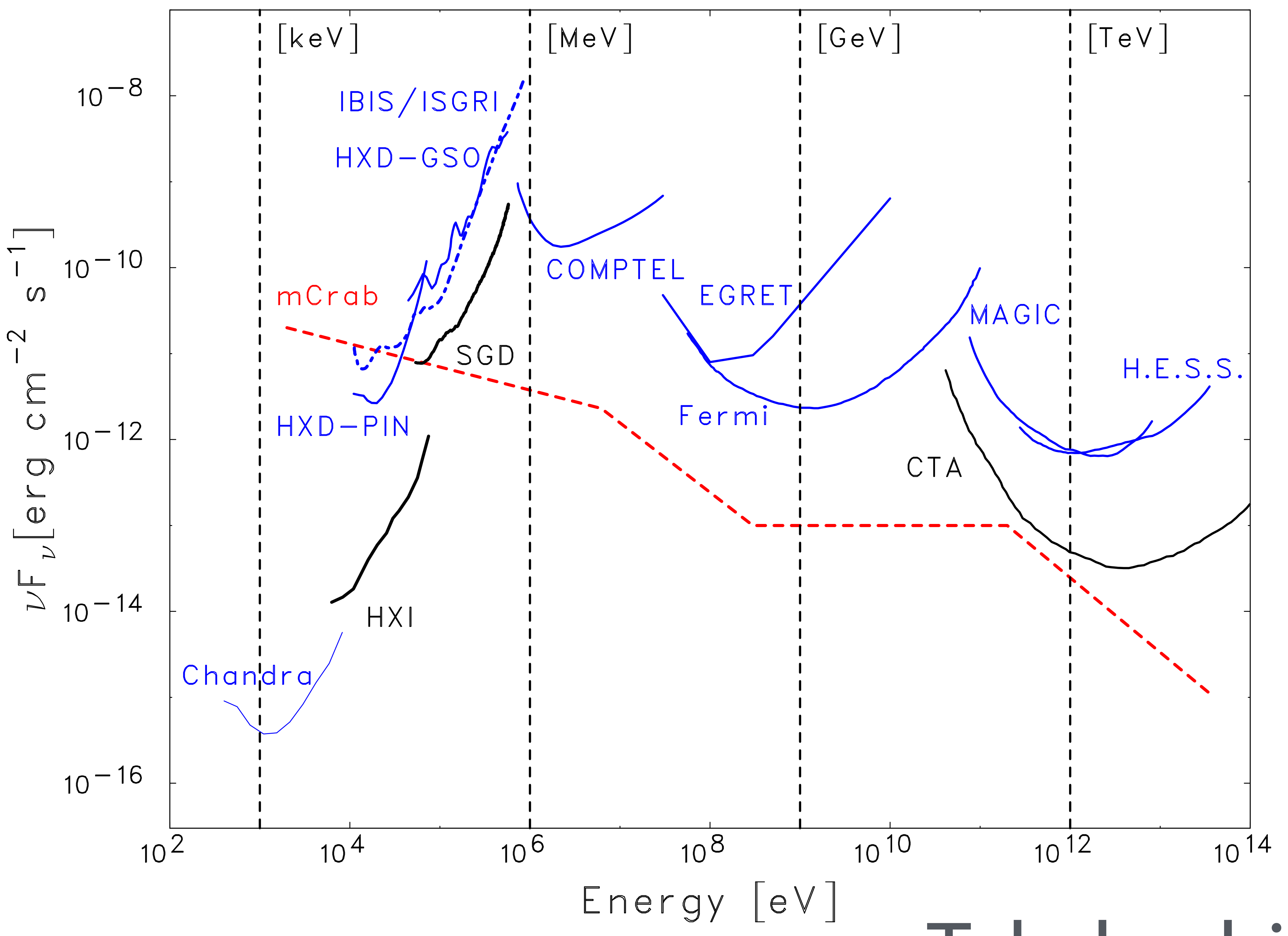


Gallo+'19

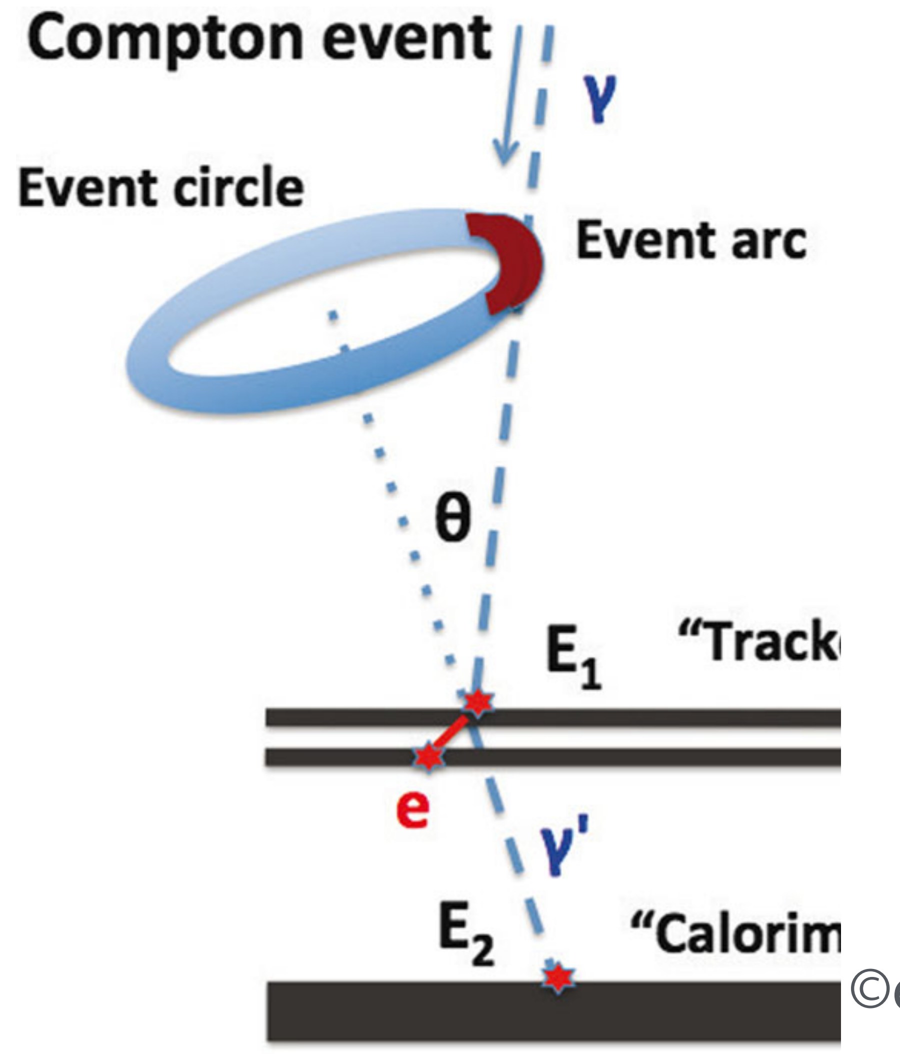
- mm-excess
- MeV PL tail
- TeV ν without GeV-TeV γ
- Nuclear spallation in X-ray

Future MeV Observations

Open the MeV Gamma-ray Astronomy



Takahashi+'13



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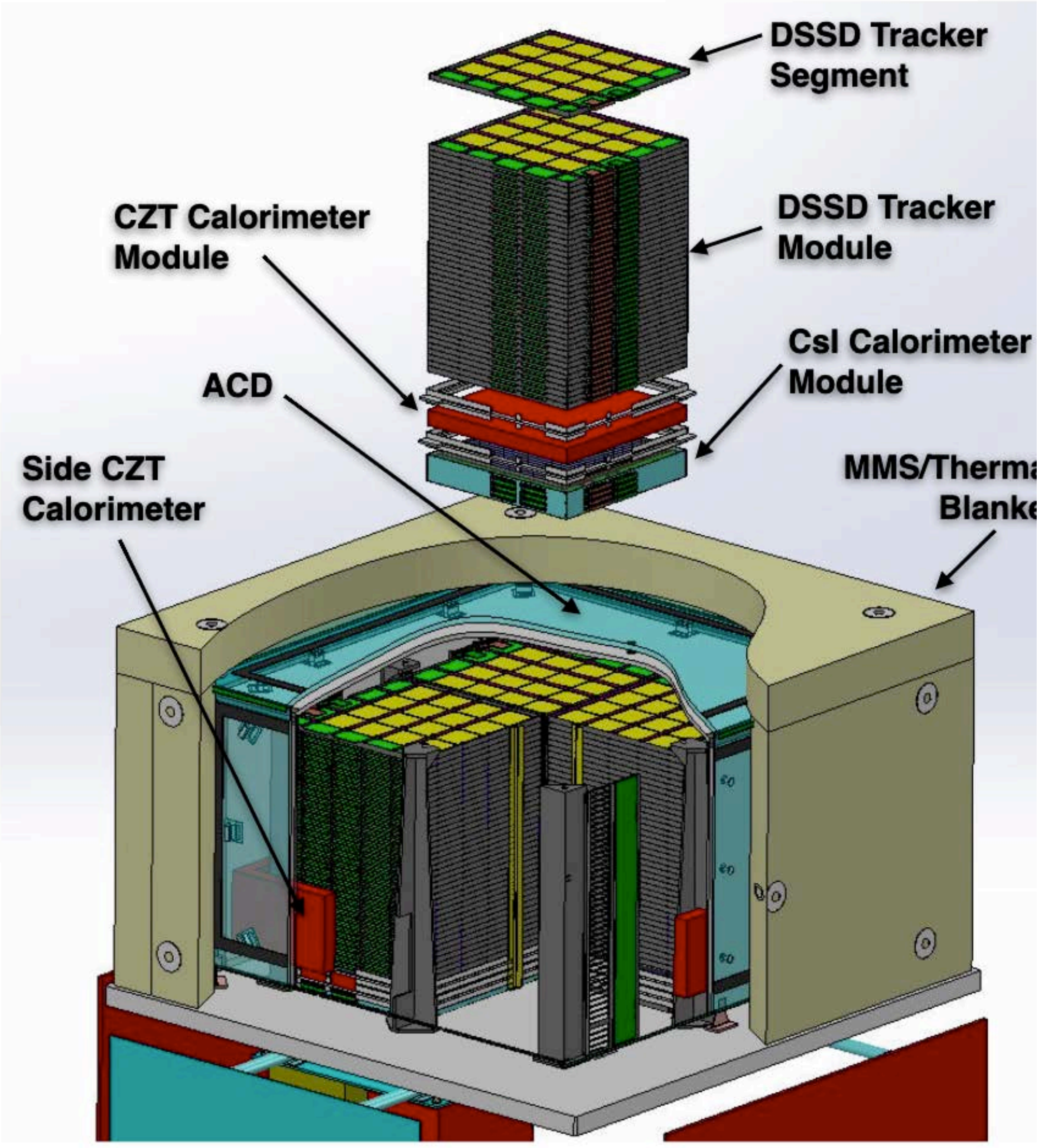
- **<u>MeV is still Challenging & Exploratory Research</u>**
- Various proposals: AMEGO, COSI-X, GRAINE, SGD, SMILE,,,

➡ Our plan: First, go to balloon missions. Then, to the space.

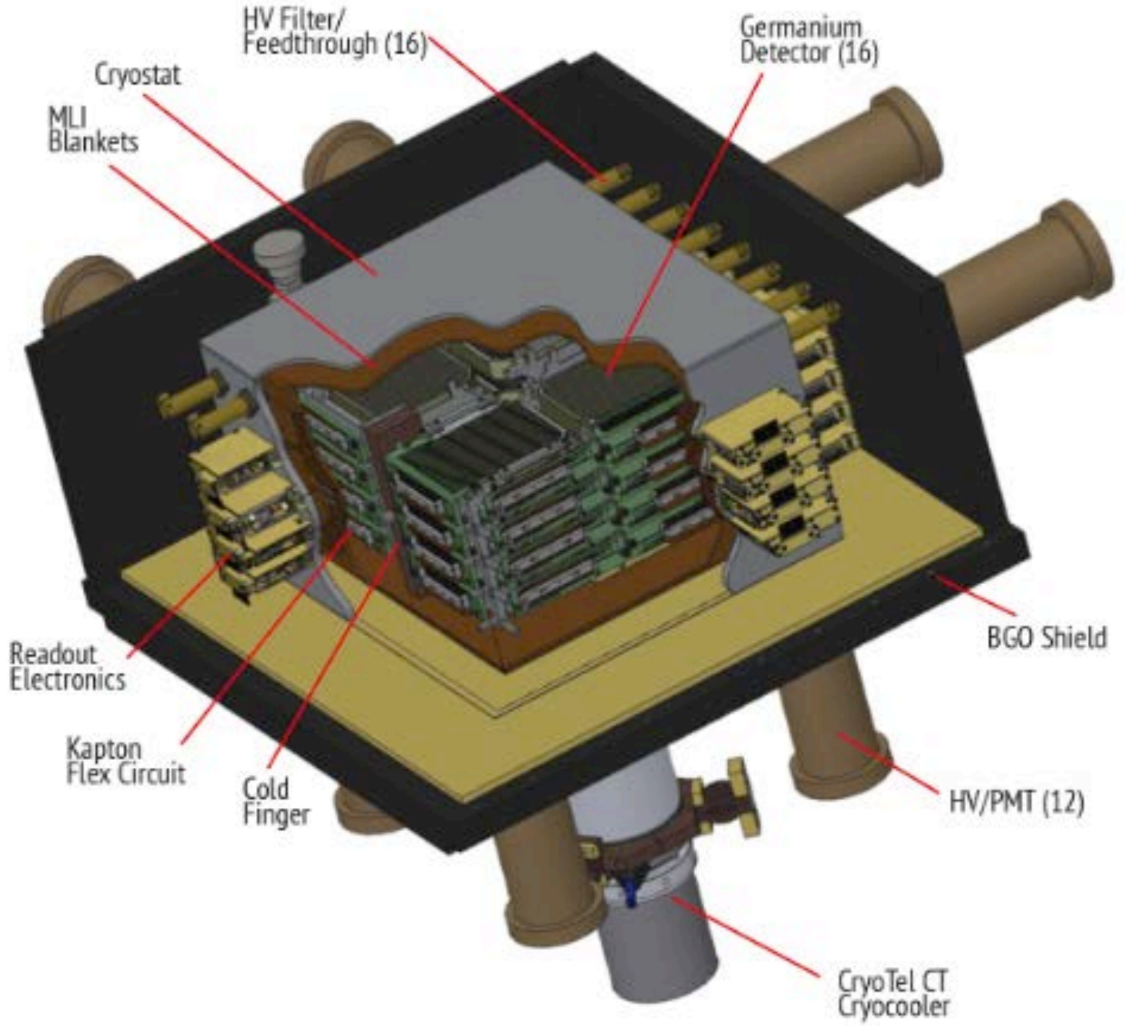
Proposed MeV Gamma-ray Missions

Not complete,,,,

Solid

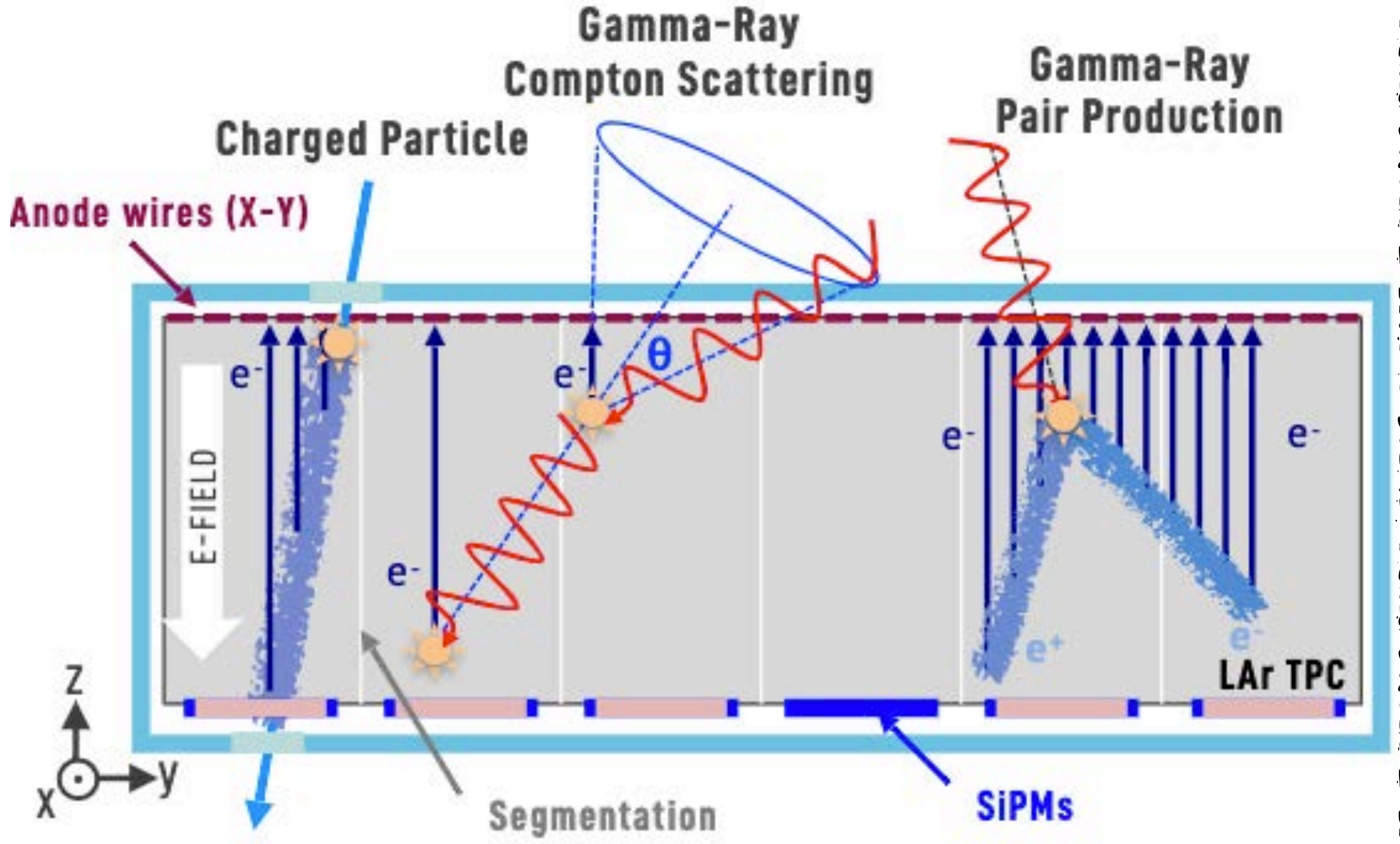


AMEGO



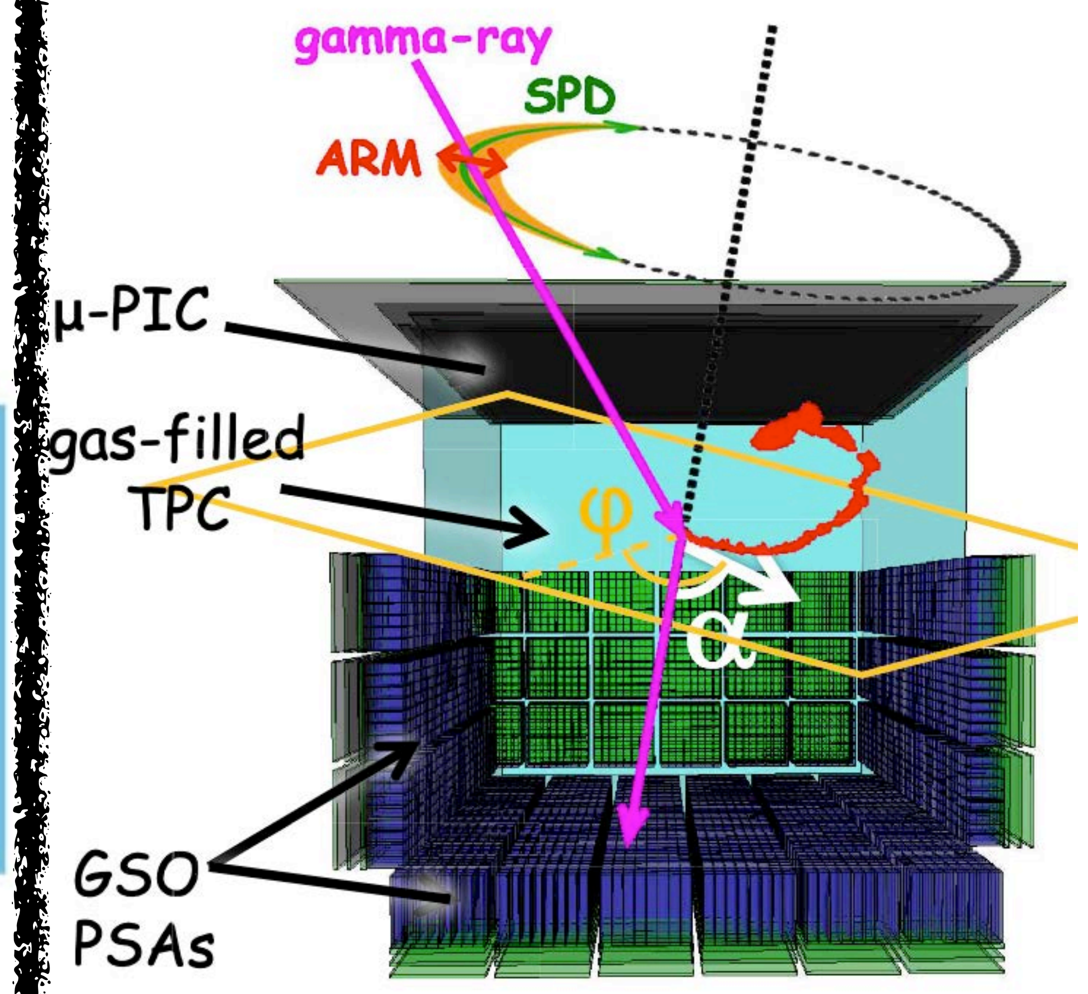
COSI

Liquid



GRAMS

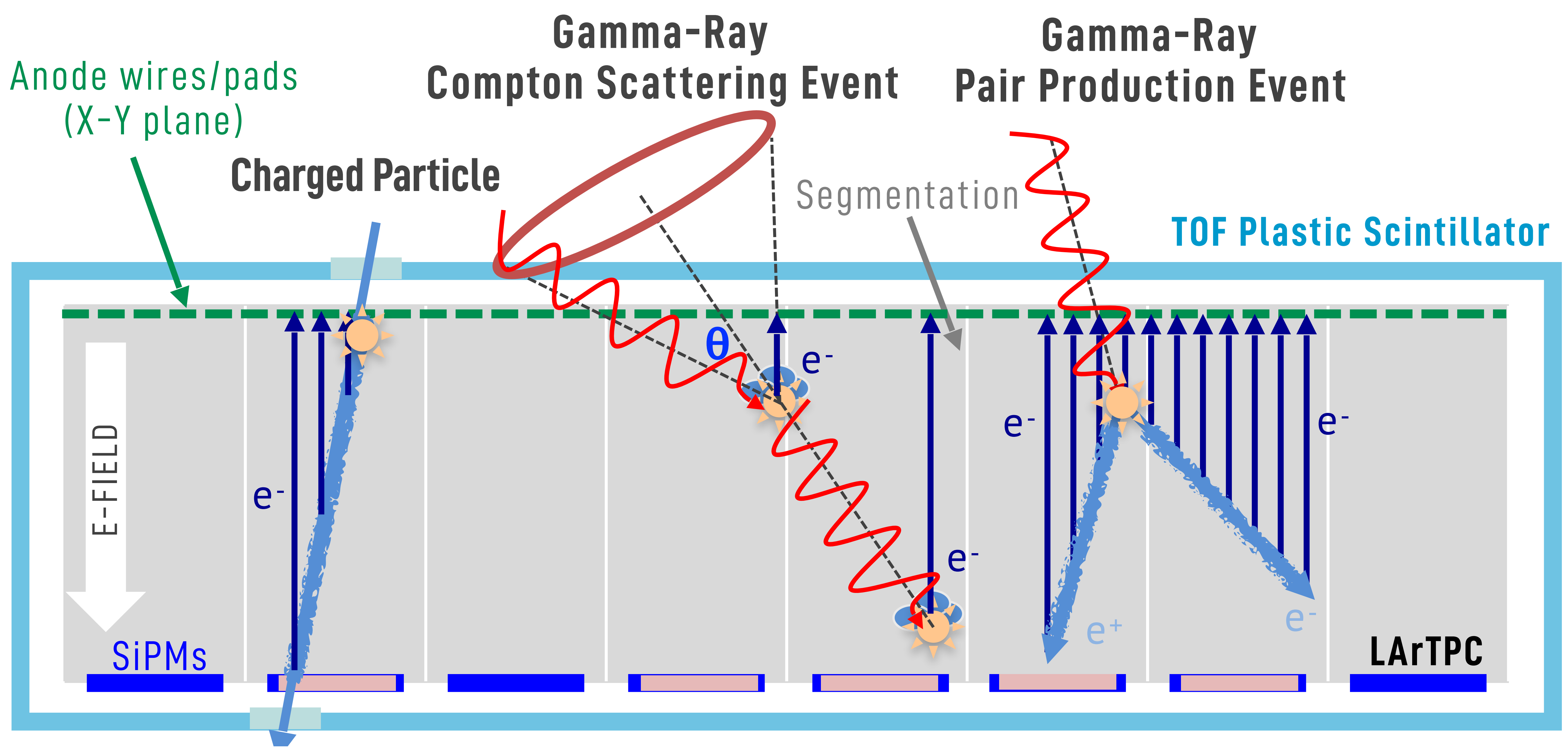
Gas

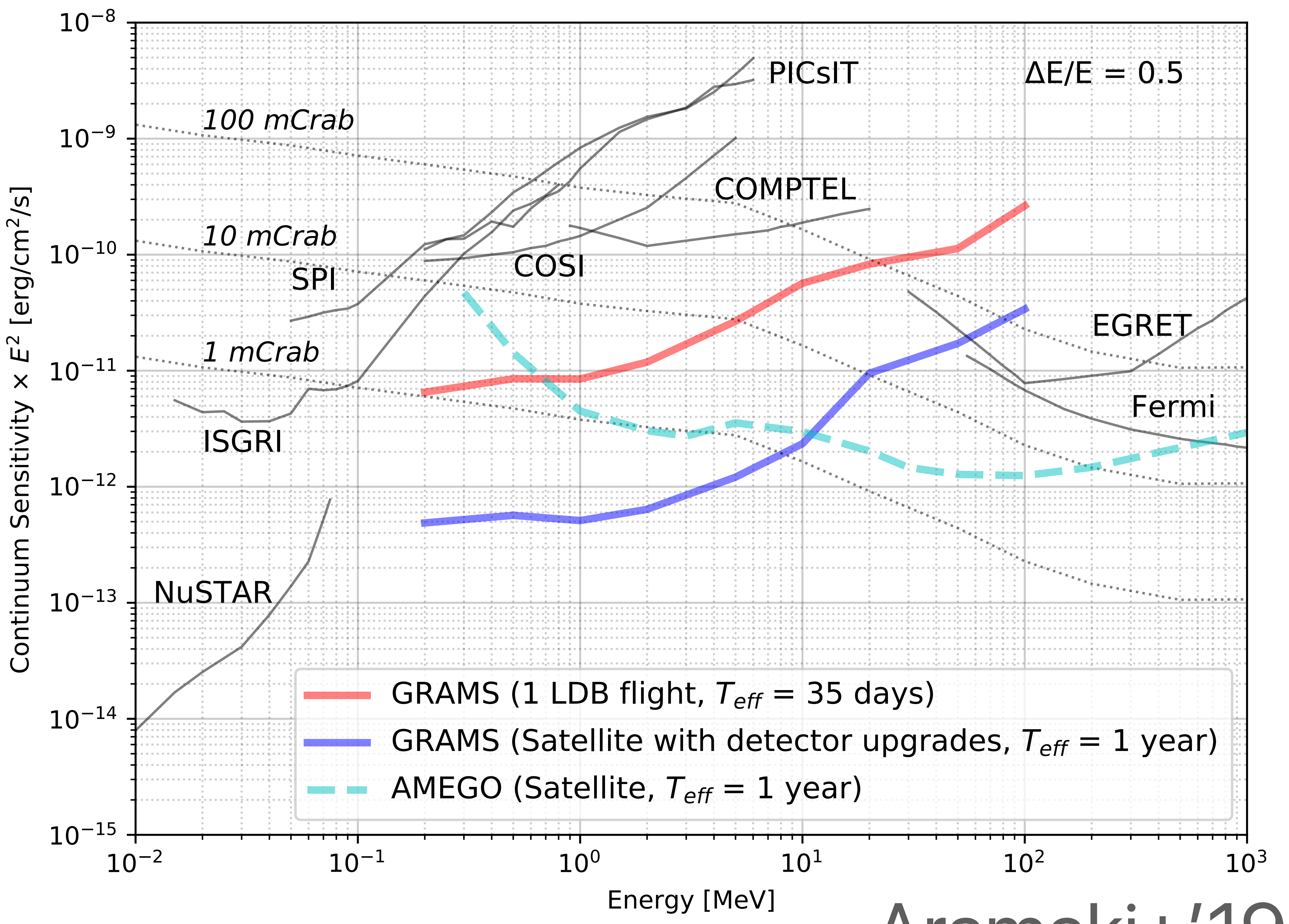


SMILE

Gamma-Ray and AntiMatter Survey (GRAMS)

Liquid Argon Time Projection Chamber (LArTPC) surrounded by Plastic scintillators





Aramaki+'19

- Plastic Scintillators: Veto
- LArTPC: Compton camera and calorimeter
- LArTPC is more cost-effective and more easily expandable, much less channels/ electronics required, almost no dead volume

まとめ

ブラックホールは「見える」