A general relativistic, multi-wavelength study of accretion flow and relativistic jet

Tomohisa KAWASHIMA
(ICRR, U. of Tokyo)

In collaboration with:
Ken. Ohsuga (U. Of Tsukuba)
Hiroyuki R. Takahashi (Komazawa U.)

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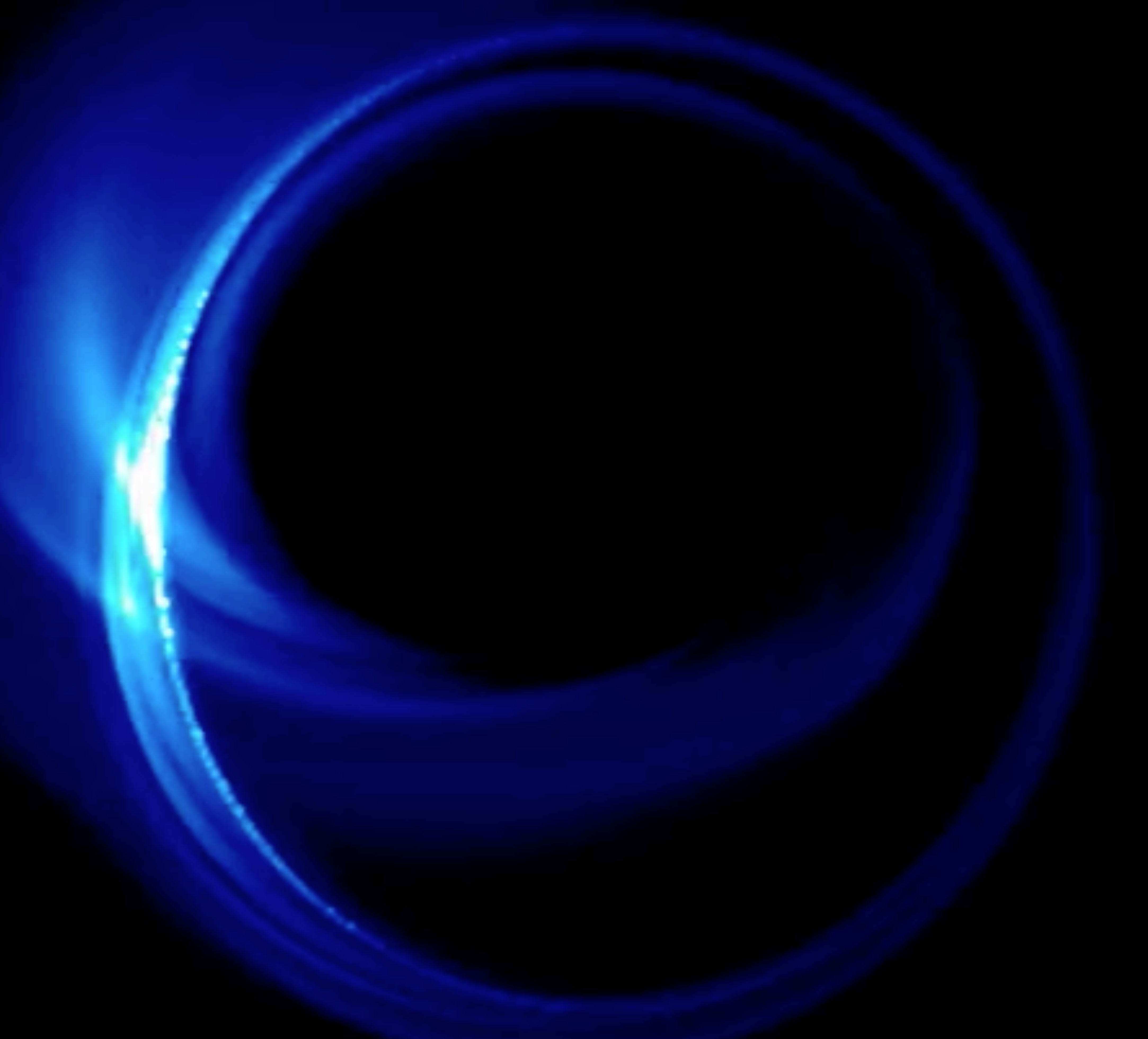
Cho Ilje (KASI), K. Hada(NAOJ), M. Nakamura (Hachinohe C),
K. Toma (Tohoku U), and EHT/EAVN Collaboration members



General Relativistic Magnetohydrodynamic simulation (UWABAMI code) +
<u>General Relativistic Radiative Transfer calculation (RAIKOU code)</u>

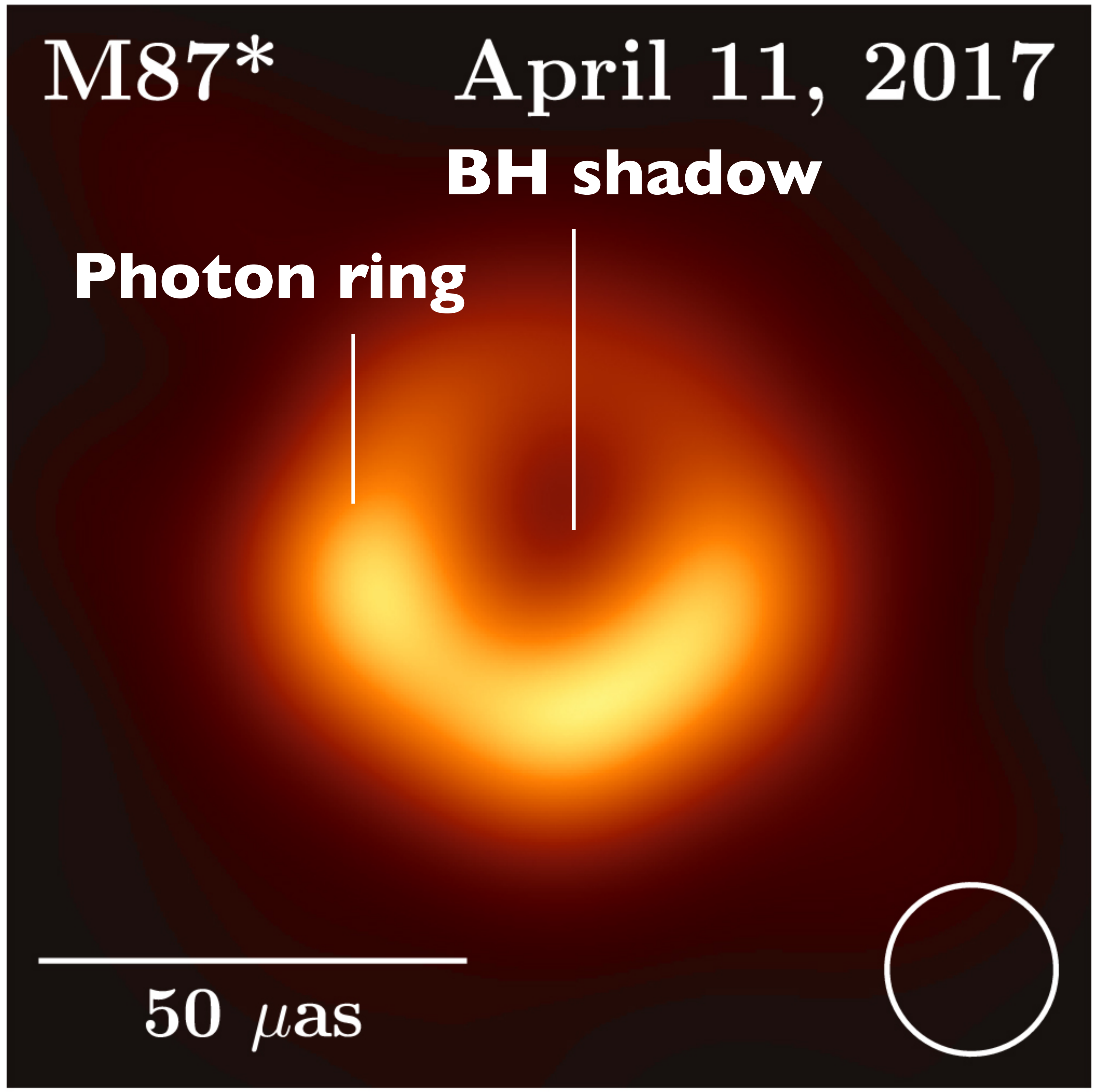
EHT2017 observation results and remaining important issues

- What we achieved：

✓ BH shadow has been detected.

✓ BH mass is constrained to be ~ 6.5x10^9 M_sun.

✓ Powerful evidence of the presence of supermassive BH



- **Remaining (important) works**

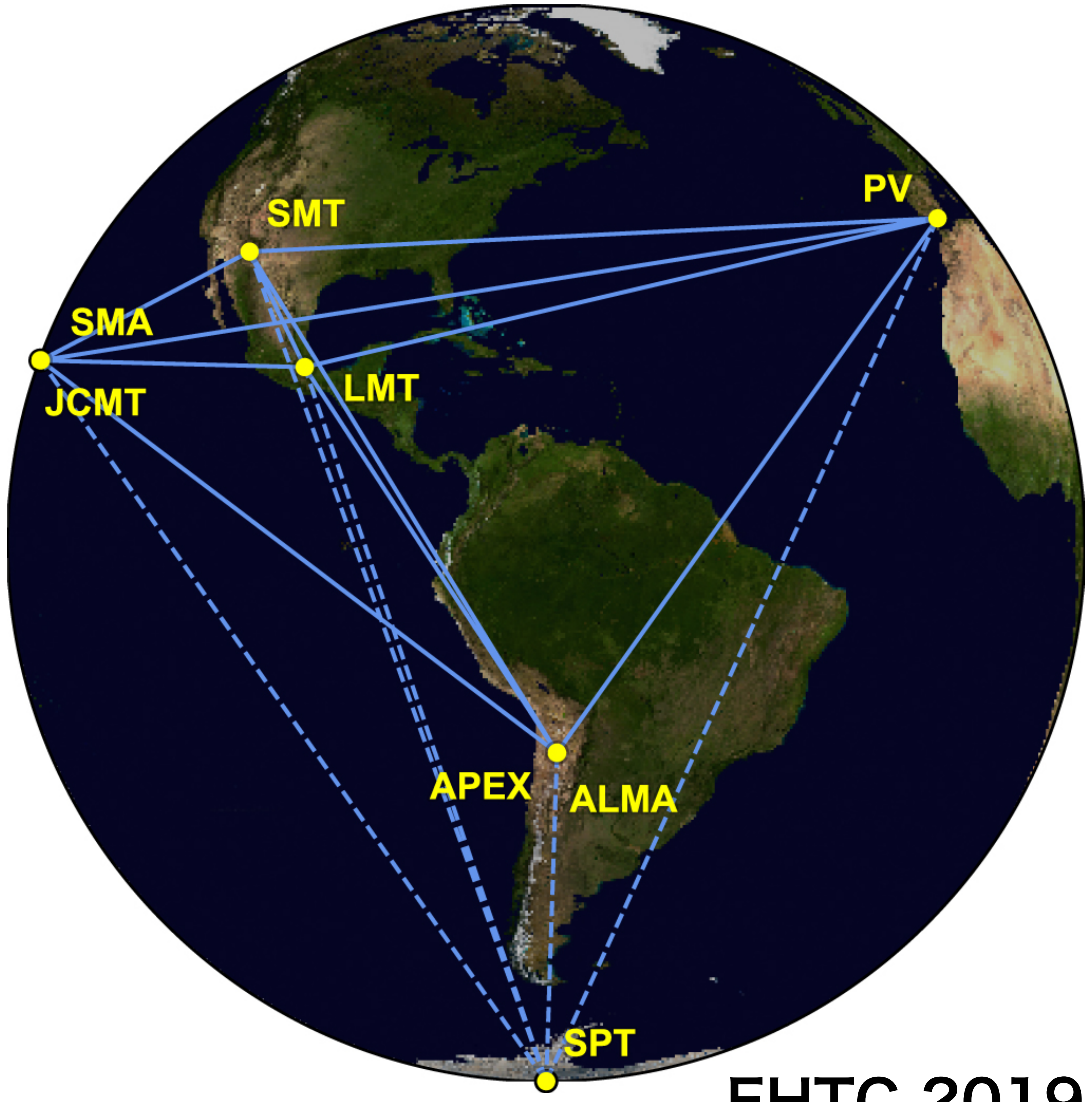
✓value of BH spin

✓Formation mechanism of jets

✓Dynamics of accretion flow

✓Emission region is jet or accretion flow?

✓Other sources (e.g., Sgr A*)

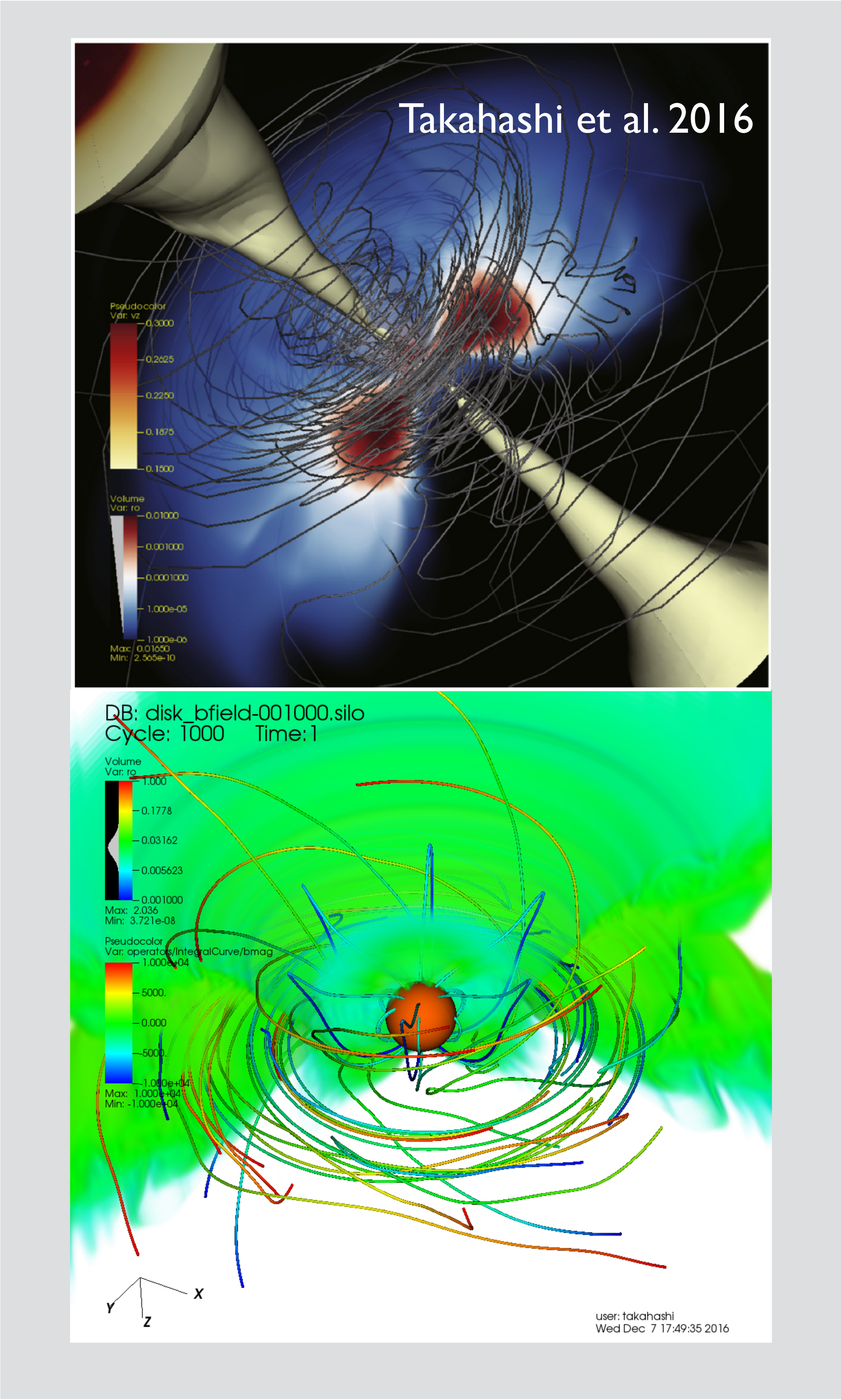


EHTC 2019 (incl. T. Kawashima)

Power of multi-wavelength radiative transfer

Theory/Simulation

what we know：fluid properties
(i.e, density, temperature, etc.)



Large gap!

We need radiative transfer calculations of

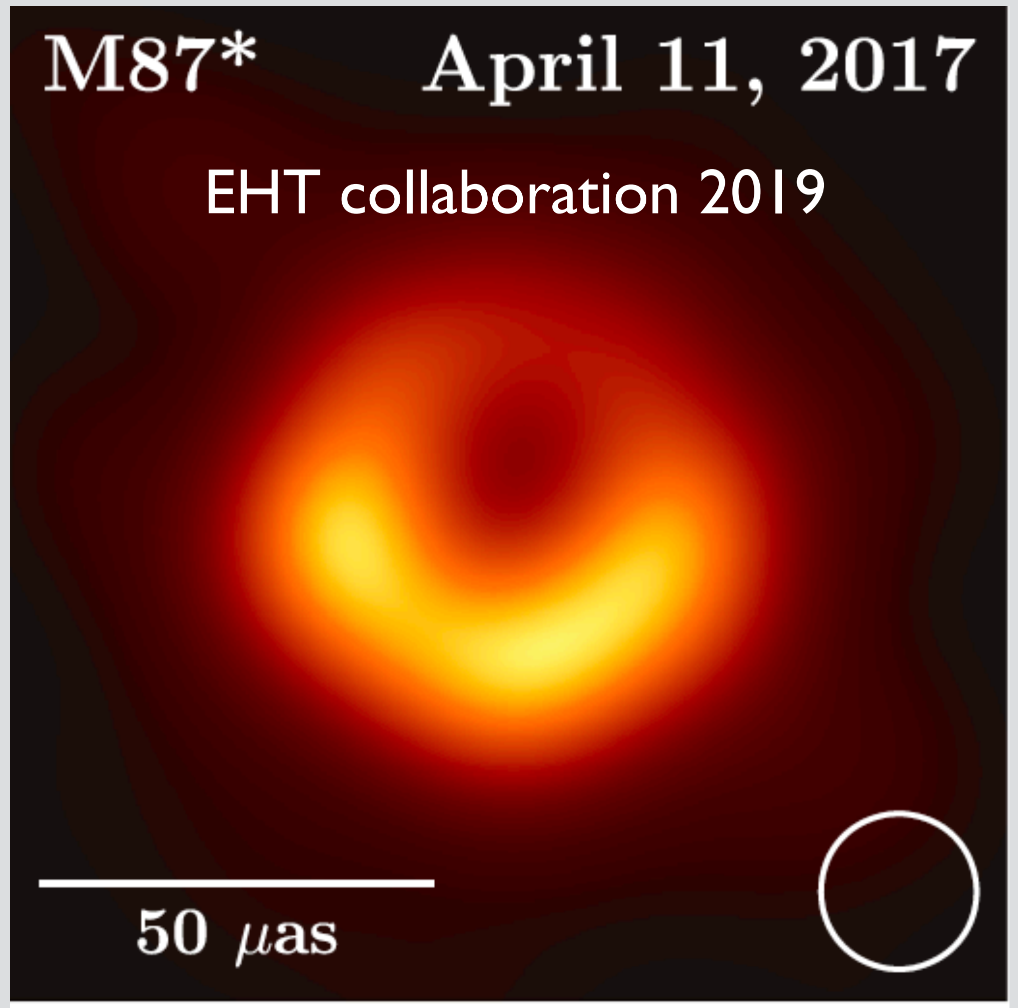
- Imaging
- Spectral Energy Distribution (SED)

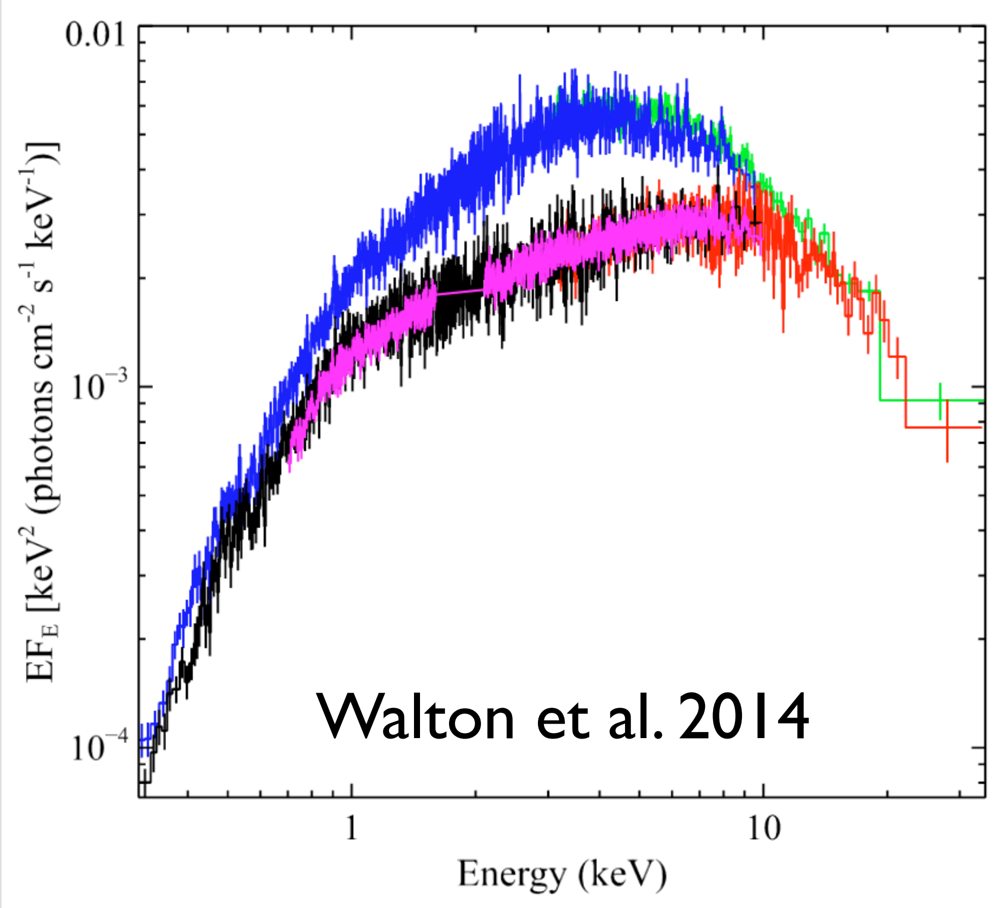
The detailed calculation of general relativistic radiative transfers will enable us to study

- **BH spacetime (mass and spin)**
- **dynamics of accretion flow and jet**

Observation

What we know: radiation
(i.e., image, SEDs)





RAIKOU(来光): a general relativistic, multi-wavelength radiative transfer code

Kawashima, et al. (in prep.), EHT GRRT code comparison paper (2020)

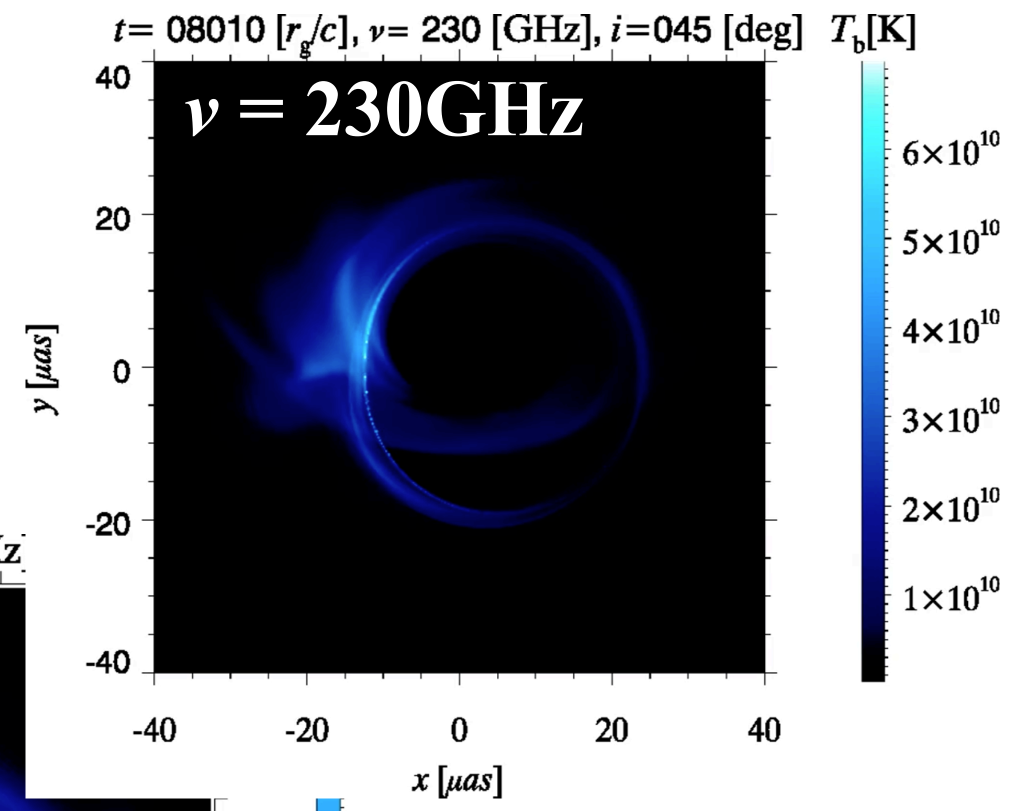
<u>RAIKOU:</u> Radiative trAnsfer In Kerr-spacetime for accretiOn and oUtflow

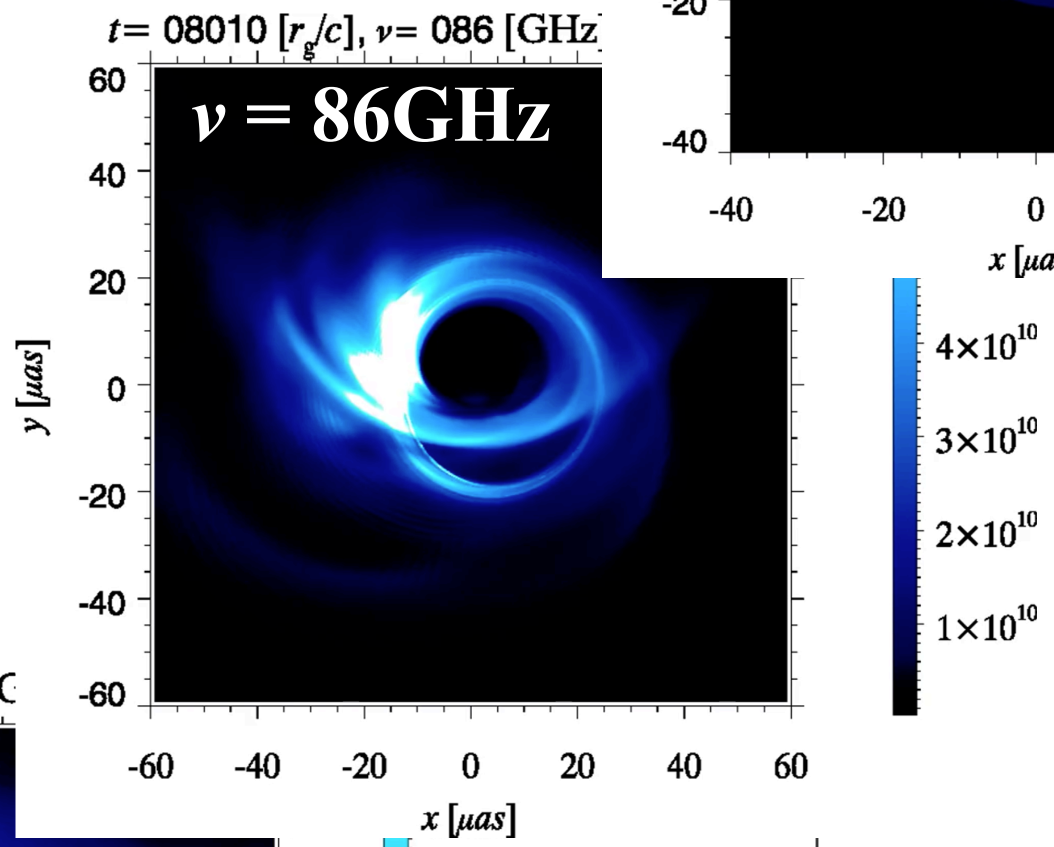
- **<u>Ray-tracing method:</u>**
  - ✓8th order embedded Runge-Kutta method w/ adoptive stepsize control
- **<u>Radiative processes:</u>**

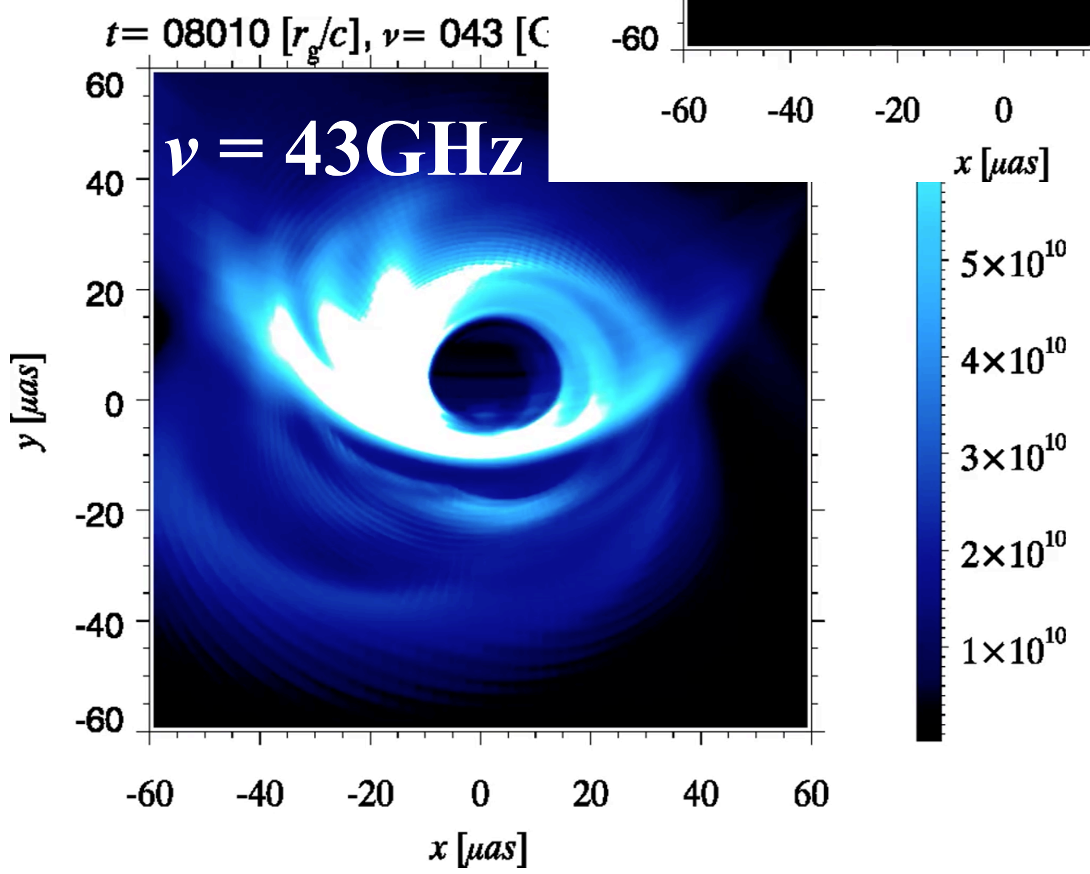
✓emission/absorption
- Cycle-synchrotron via thermal electrons
- Synchrotron via non-thermal electrons
- Bremsstrahlung via thermal electrons

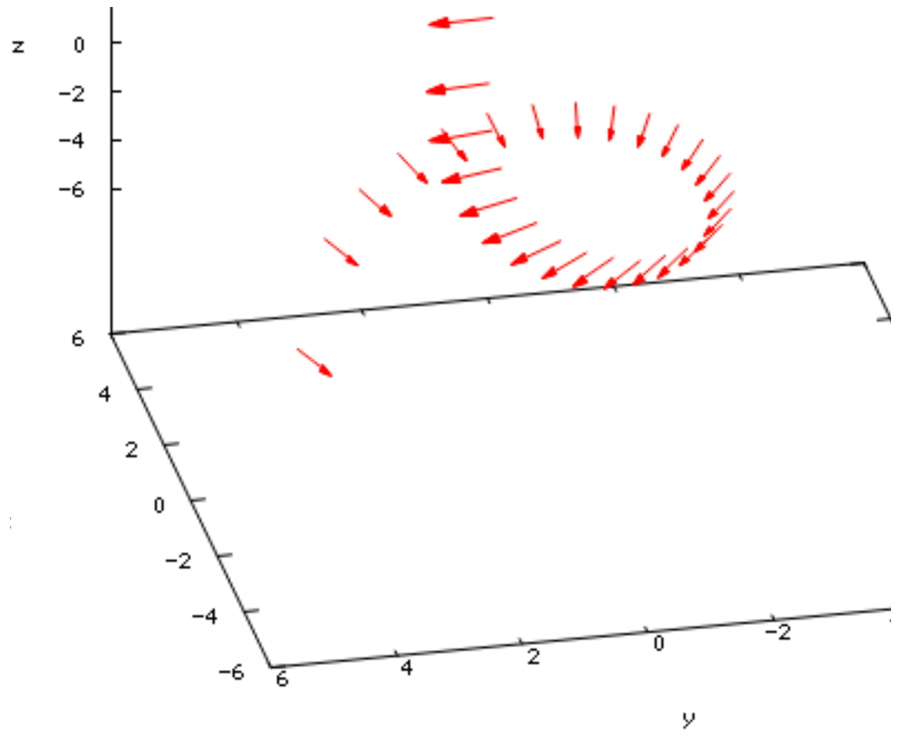
✓ scattering (Monte-Carlo method)
- Compton/inverse-Compton scattering via thermal and non-thermal electrons

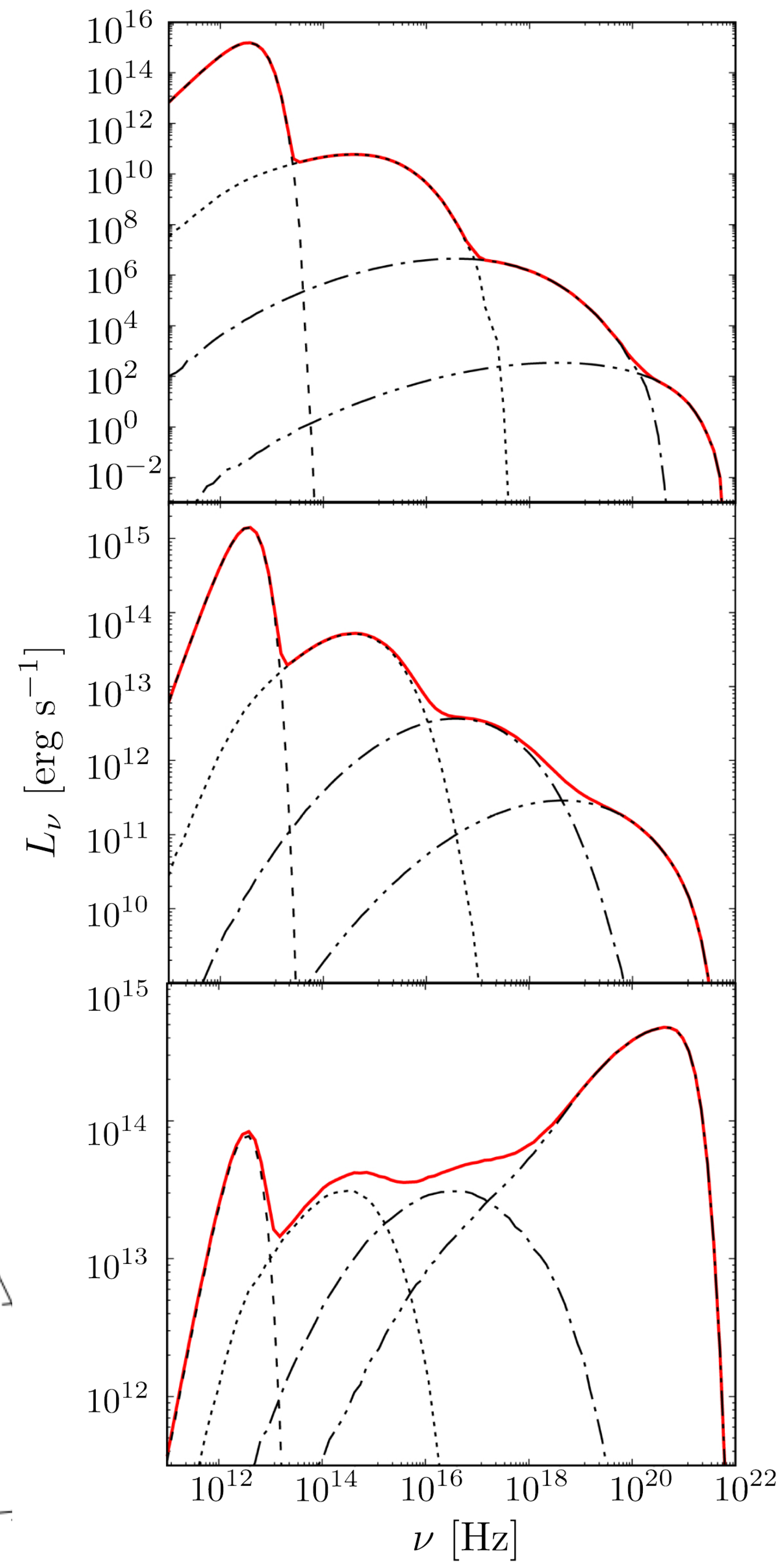
✓ Polarization (now implementing)



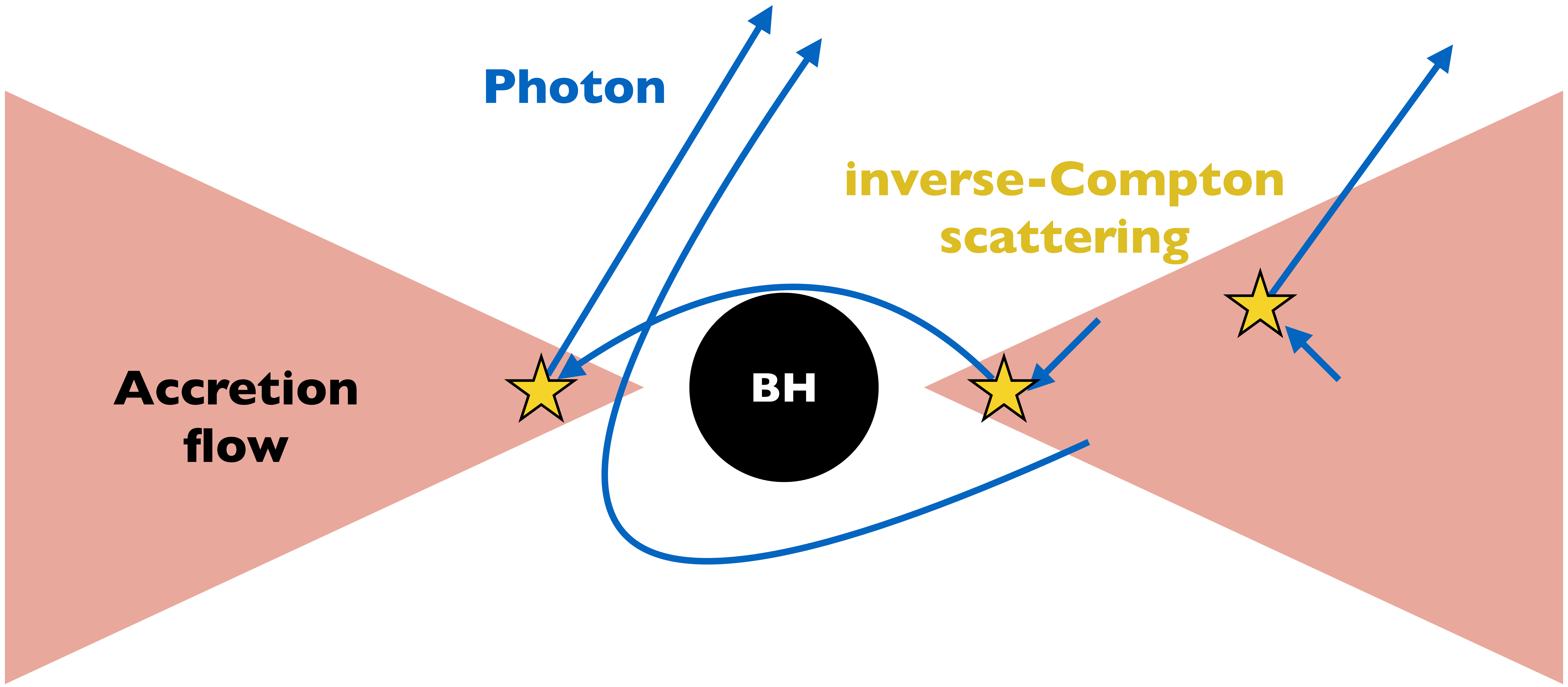






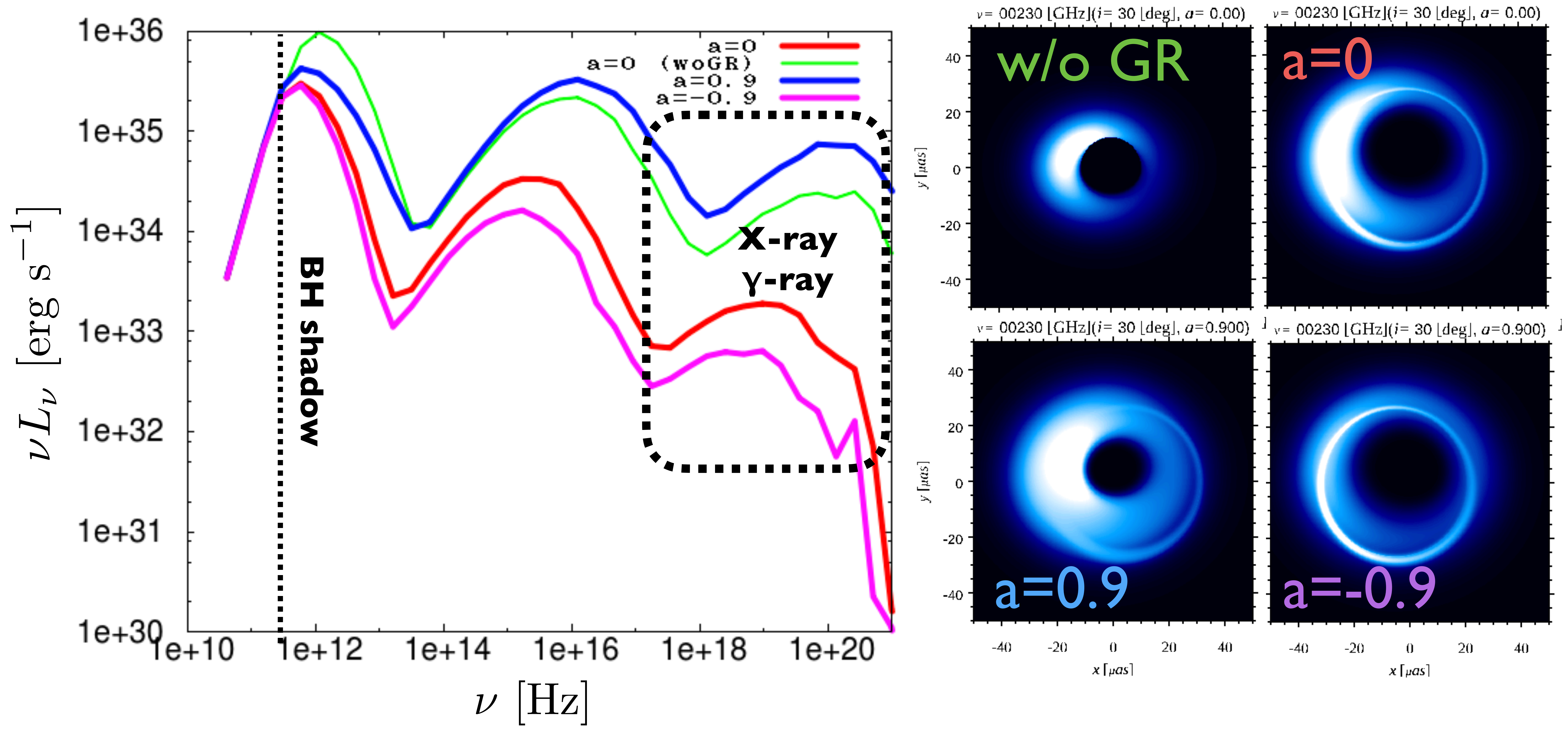


Exploring a possible to determine the BH spin with X-ray and γ-ray?
Model setup



- Keplearian shell model (Falcke + 2000, Broderick & Loeb 2006, Pu + 2016)
- cyclo-synchrotron emission/absorption + Compton/inverse-Compton scatteing, calculated by MC transport solver implemented to RAIKOU
- BH mass 4.3 x 106 M_sun
- BH spin a = -0.9, 0, 0.9
- viewing angle i = 30 degree

BH shadow + Multiwavelength SED (Kawashima + in prap.)

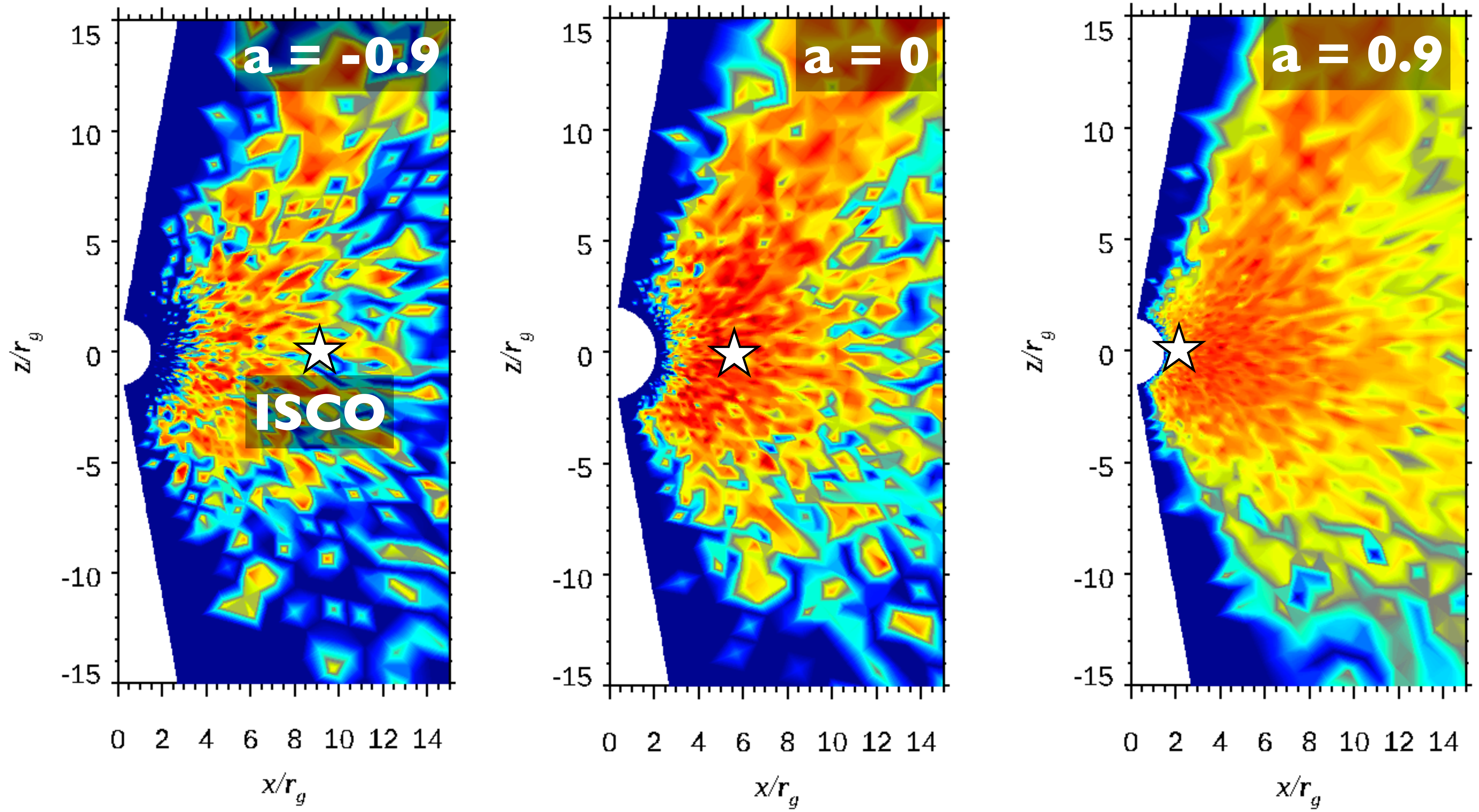


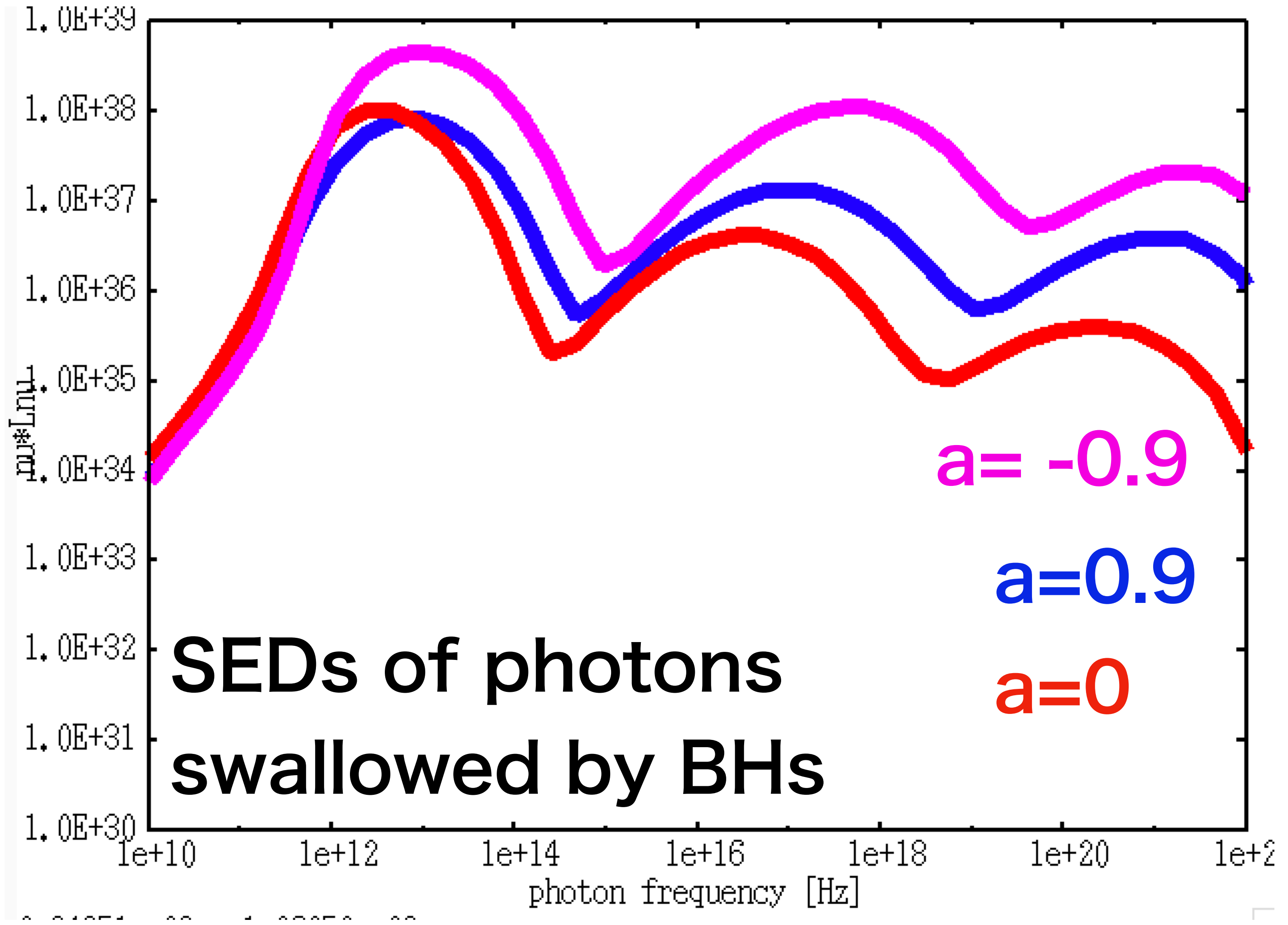
- BH spin significantly affects the SEDs, especially in X-ray and γ-ray
  → Even if the BH-shadow morphology is difficult to distinguish the BH spin, it may be possible to constrain the BH spin.

Where does the inverse-Compton scattering take place ?

Retrograde BH ⟷ Prograde BH

Viewing angel is 30 degree

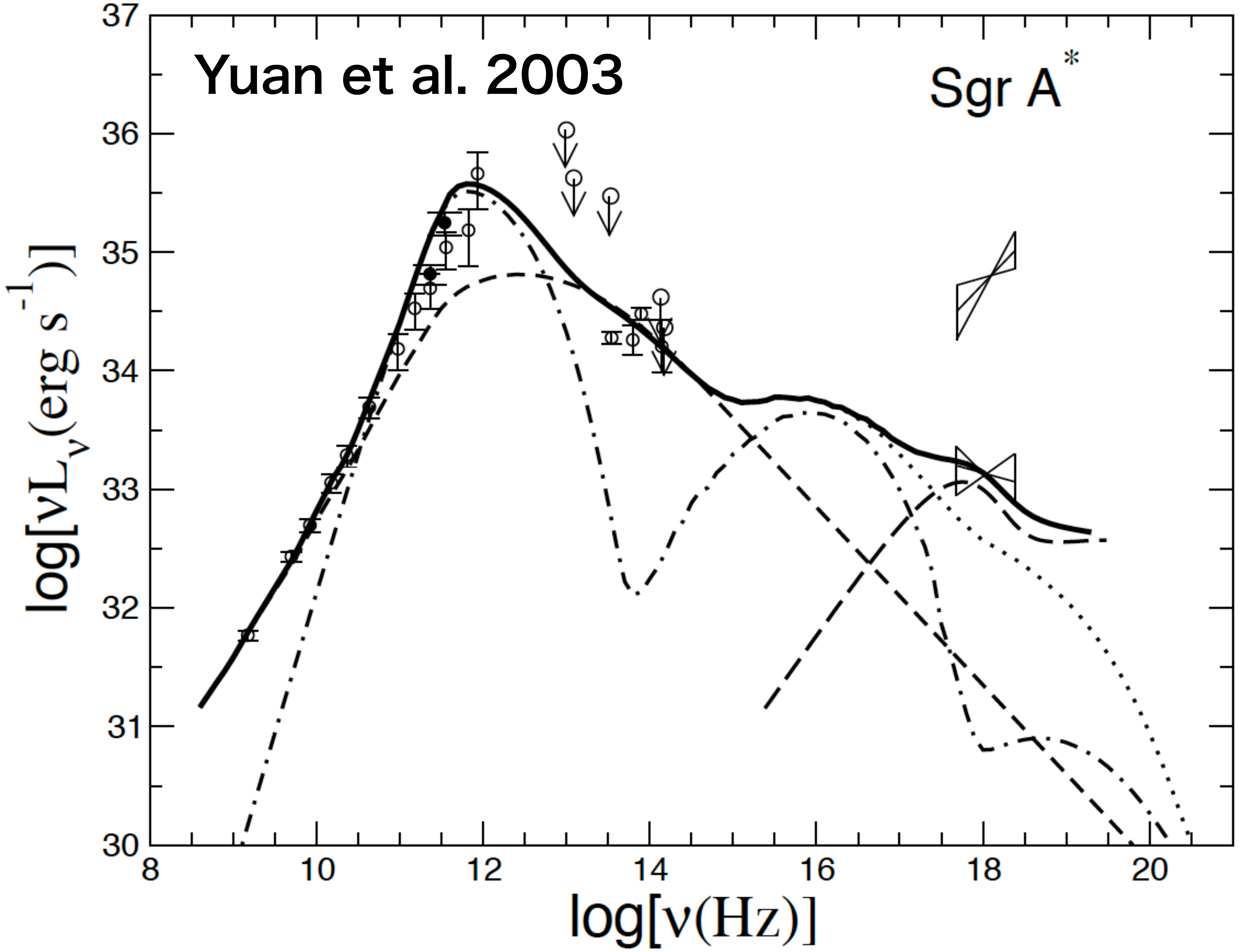


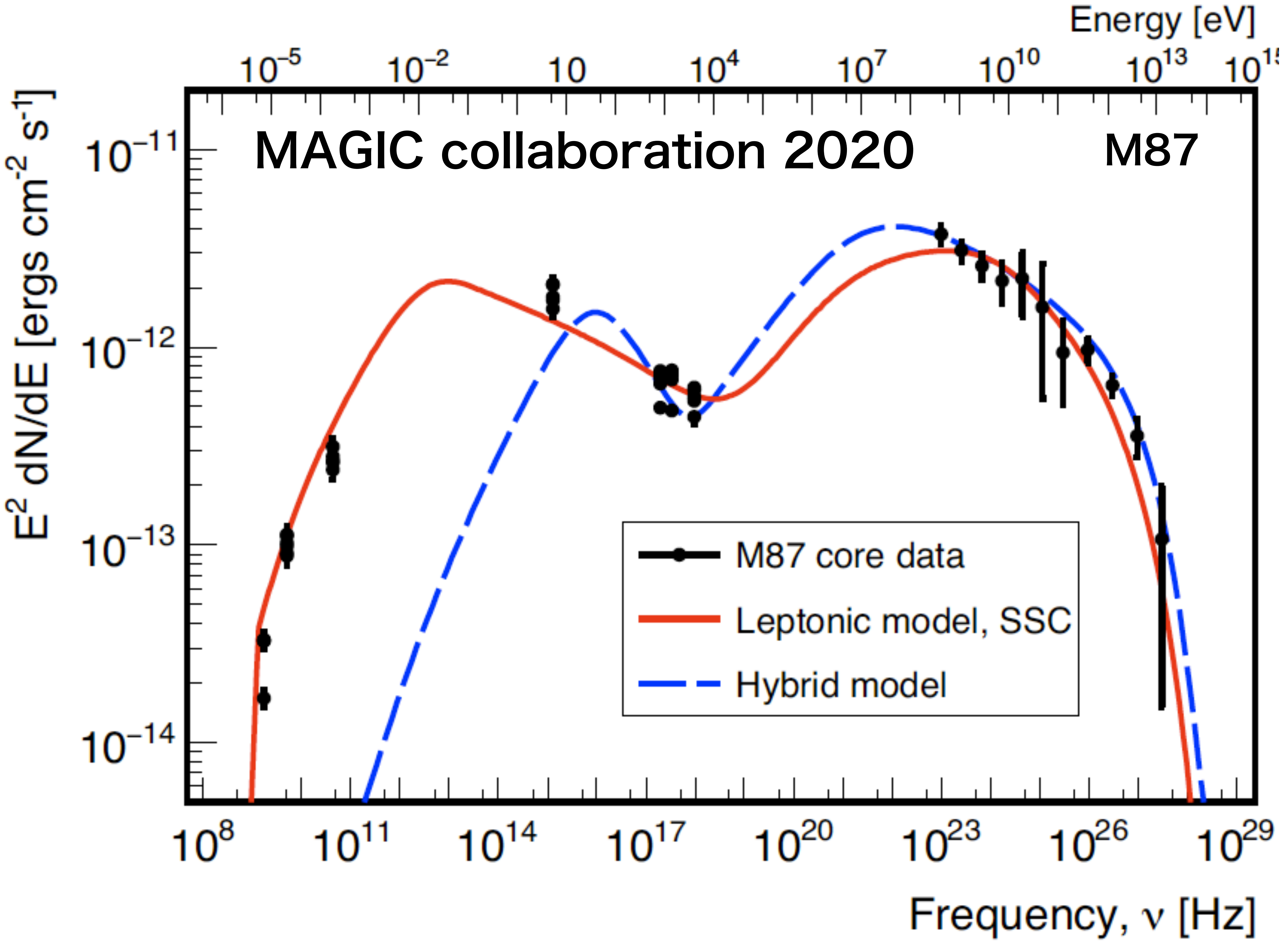


- Color displays where the how many photons are upscattered with recording the highest frequency and escape to the observer at 30deg (red/bule: large/small amount)
- We interpret that retrgrade BH →outer location of ISCO →significant inflow motion → scattered photons are beamed into the BH → less X-ray emission (For a=0, the radius of the event horizon is larger, i.e., the potential is less deep, so that the SED is soft.)

Importance of nonthermal electrons

- In low-frequency radio-band, the nonthermal electrons may be required to fit the SEDs in Sgr A*
- The VHE gamma-ray emission in M87 will also require nonthermal electrons.
- The nonthermal-electron studies are important.

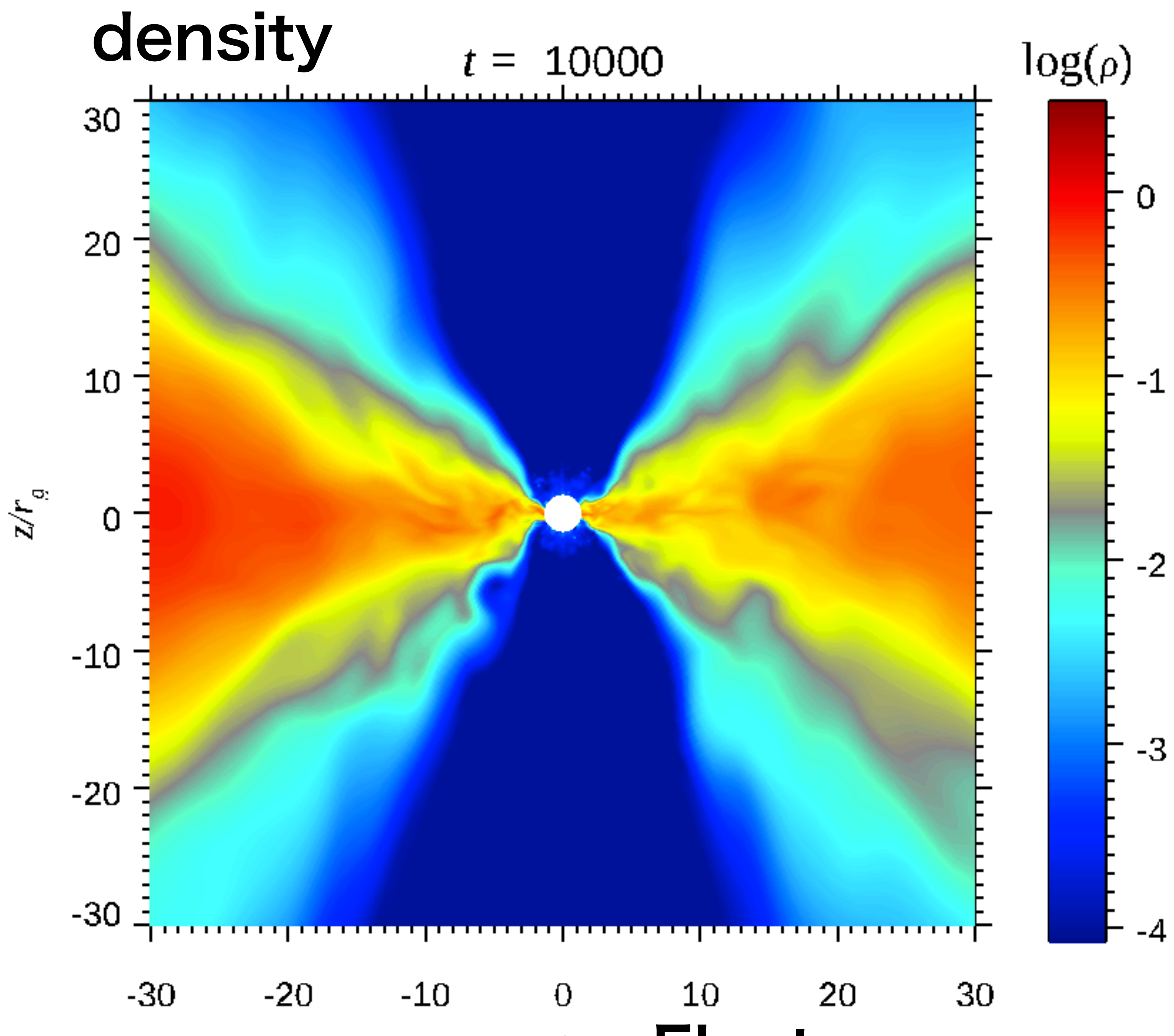


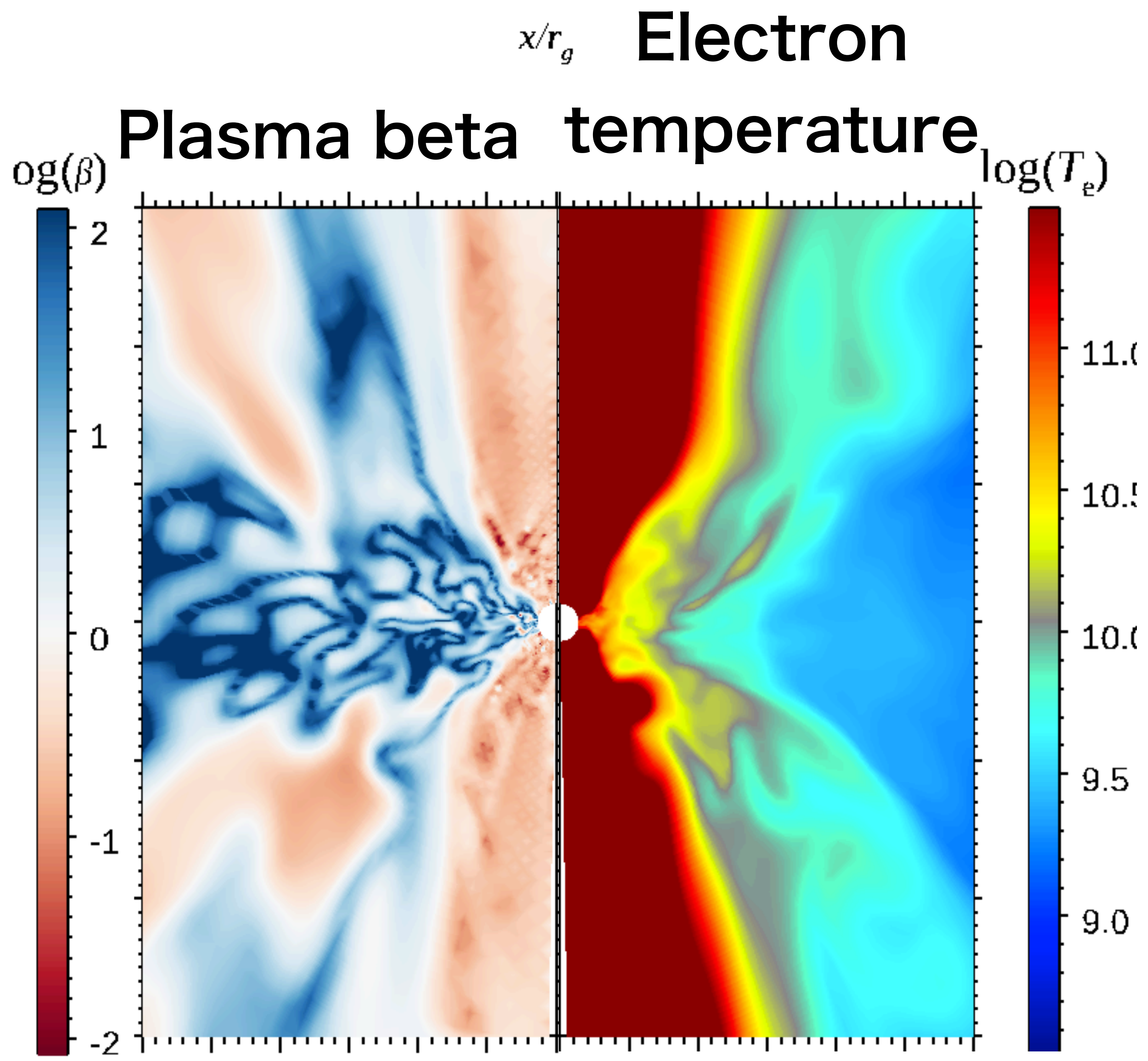


Towards GRMHD + GRRT w/ nonthermal electrons

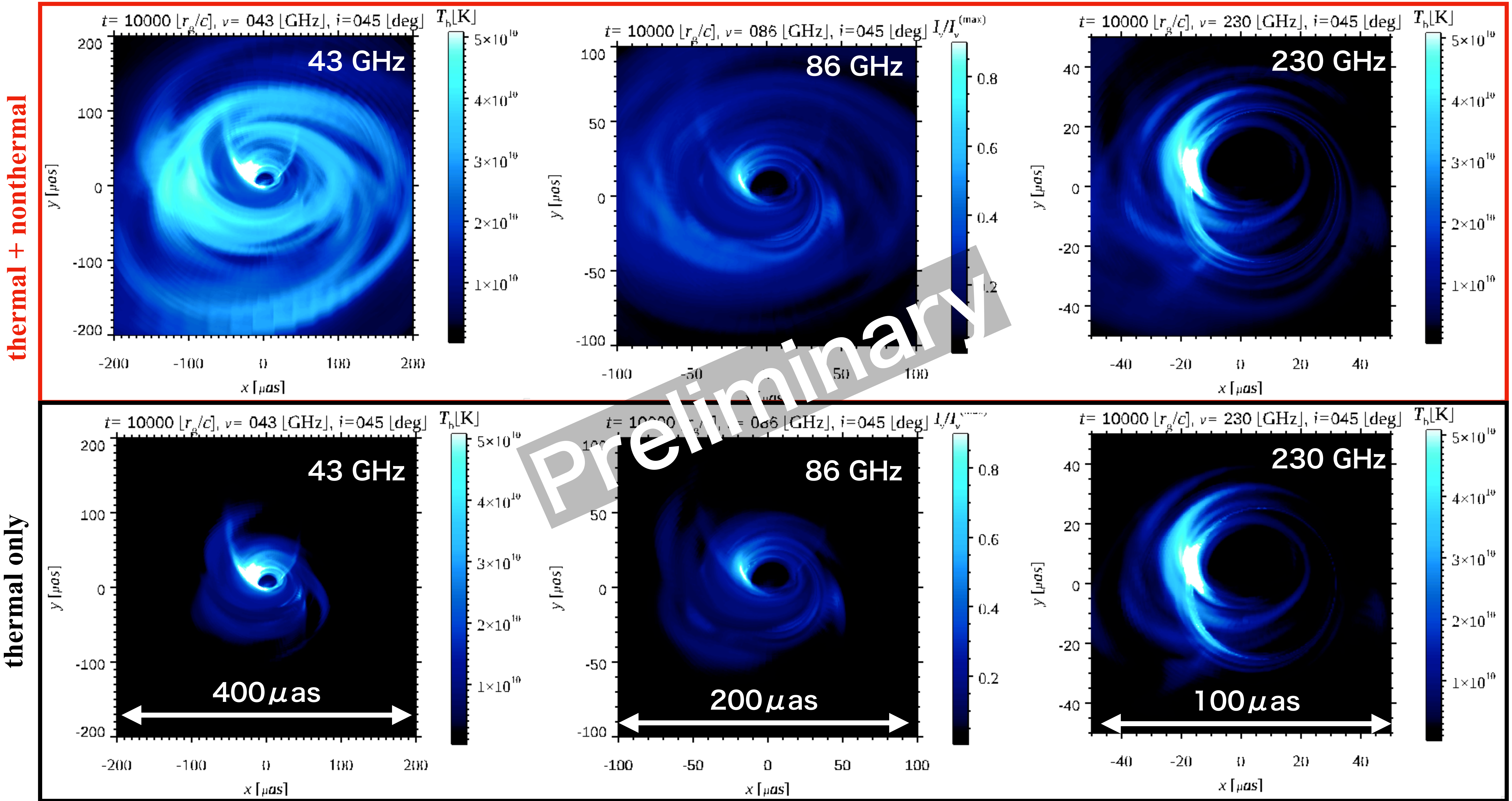
- GRMHD: simulated by UWABAMI code (GRRMHD code in Takahashi + 2016)
- GRRT: RAIKOU code
- Target : Sgr A*
- Inclination angle: 45 degree
- BH spin a = 0.9375
- Thermal Electron: $\frac{T_\mathrm{p}}{T_\mathrm{e}} = R_\mathrm{high}\frac{\beta^2}{1+\beta^2} + R_\mathrm{low}\frac{1}{1+\beta^2}$

  Rhigh = 5, Rlow = 1
- Nonthermal electron
  - Single power law with gamma_min = 30, gamma_max = 10^6, PL index = 3.5 (similar to the other work, e.g., Chael + 2017)
  - Energy density is 1 % of that of magnetic energy at each position in the region magnetization sigma < 1 (see e.g., Dexter+ 2012).

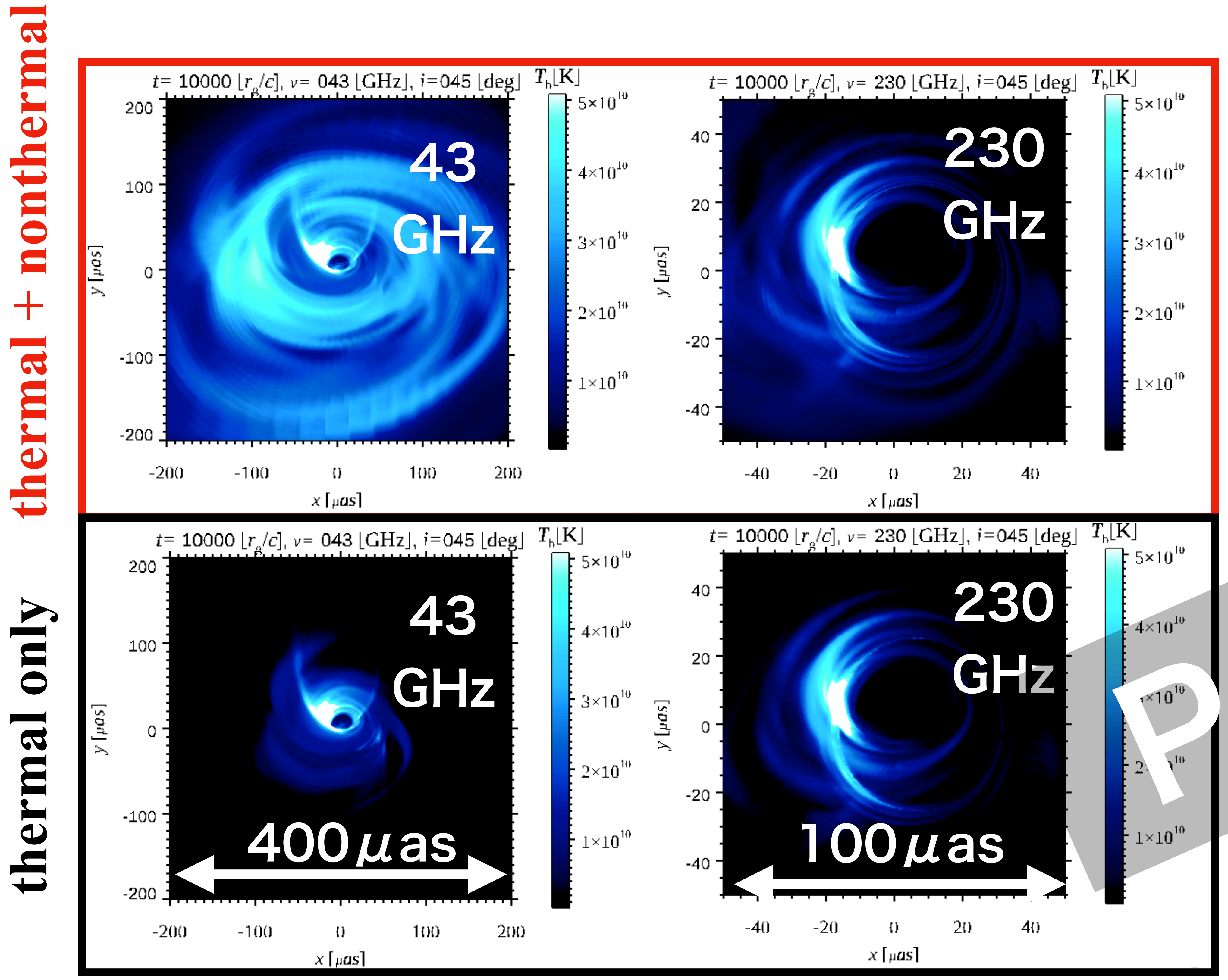




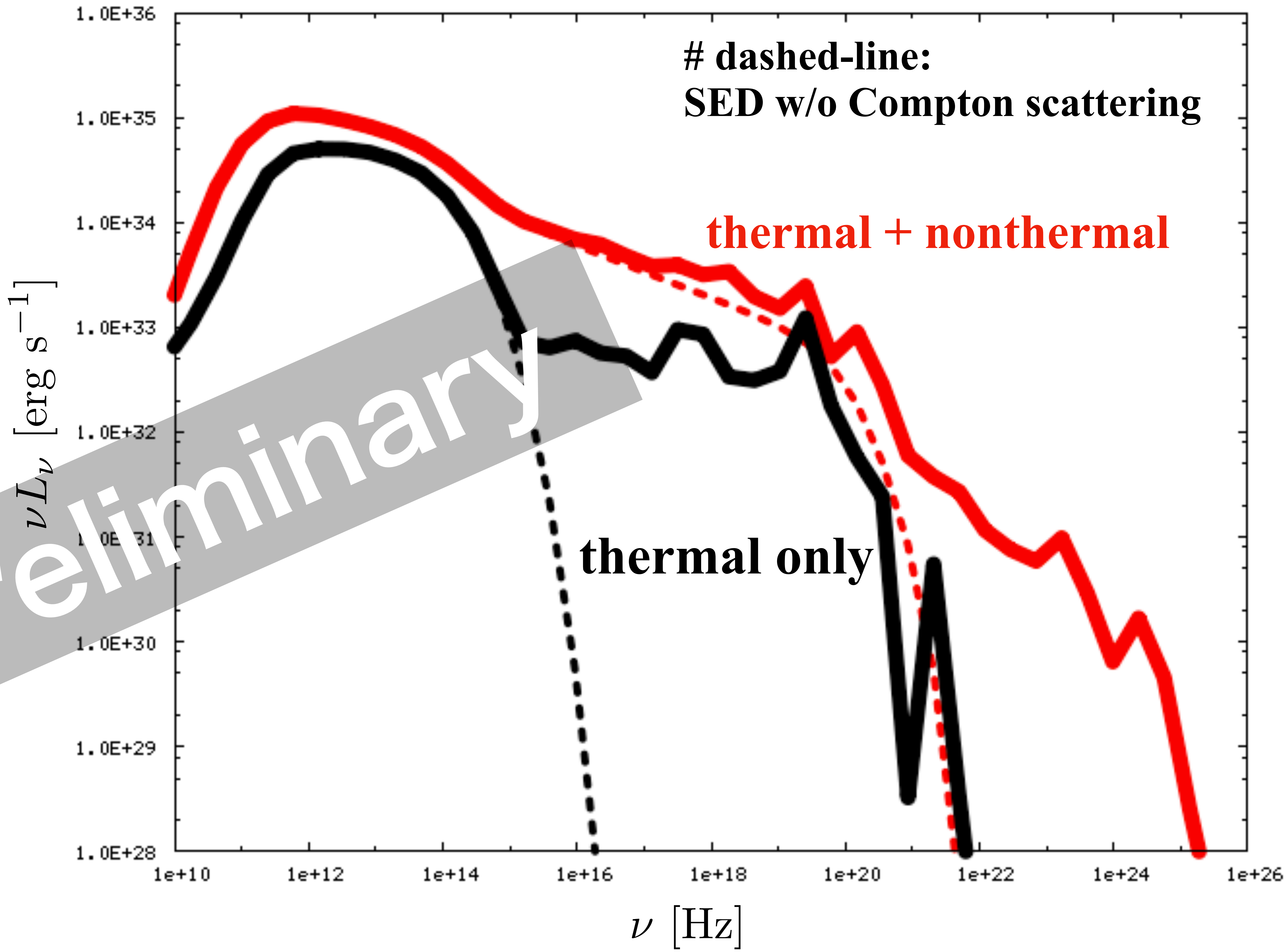
Result of GRMHD+GRRT calculation (I)



Result of GRMHD+GRRT calculation (2)



See, also EAVN observation results of Sgr A in low frequency band (Ilje's Talk in the next Morning!)*

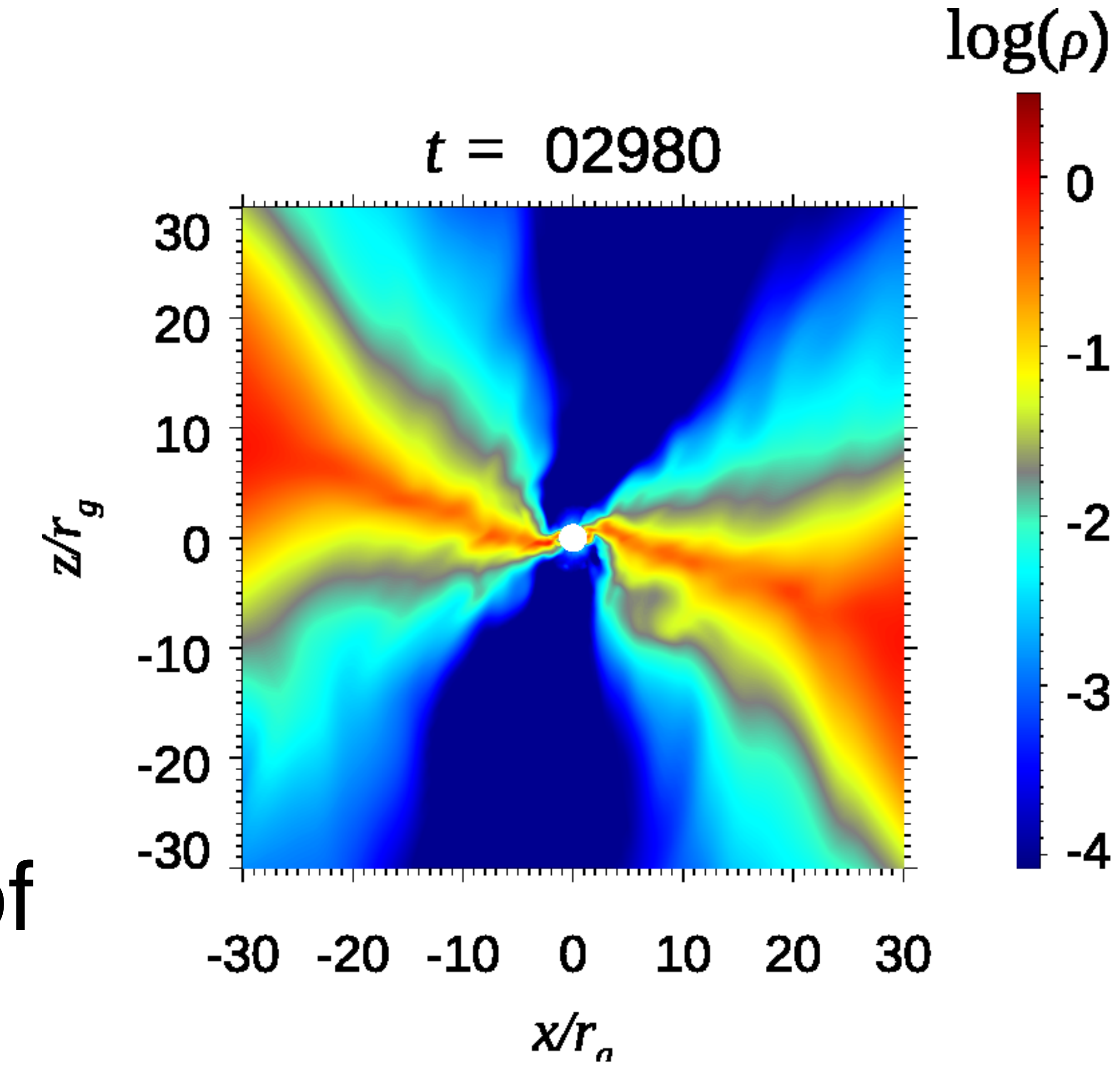


- synchrotron emission via nonthermal electrons enlarges the image in lower frequency band.
- The Synchrotron-self-Compton via non-thermal electrons significantly hardens the SED in X-ray and gamma-ray.

Summary

- We have calculated general relativistic, multi-wavelength radiative transfer calculation of accretion flow and outflow (jet + wind) in Sgr A*
- Simple RIAF models show the imprint of BH spin via the radius of the ISCO.
- Models based on GRMHD show that synchrotron emission via nonthermal electrons enlarges the image in lower frequency band. The Synchrotron-self-Compton via non-thermal electrons significantly hardens the SED in X-ray and gamma-ray. It may help us to understand the acceleration of electrons in the vicinity of the black hole!

Multi-wavelength study inc. X/γ-ray may enable us to understand the physics near event horizon.



(We hopefully think the results of GRRT images and SEDs of tilted accretion flow w/ LT precession will coming soon.)