Probing Black Hole Spacetime and Dynamics of Accretion Flow with Relativistic Jet via General Relativistic Multi-Wavelength Radiative Transfer

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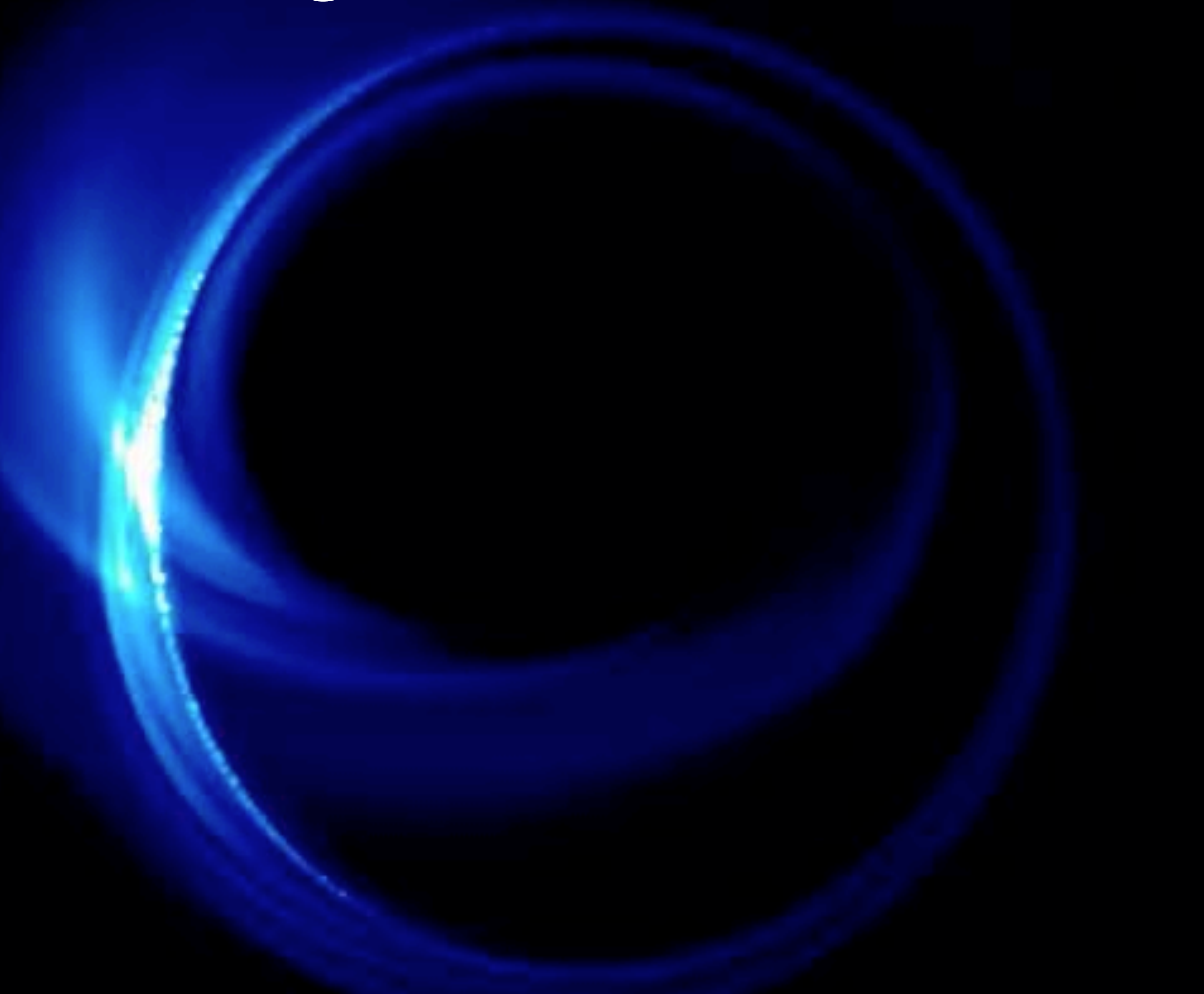


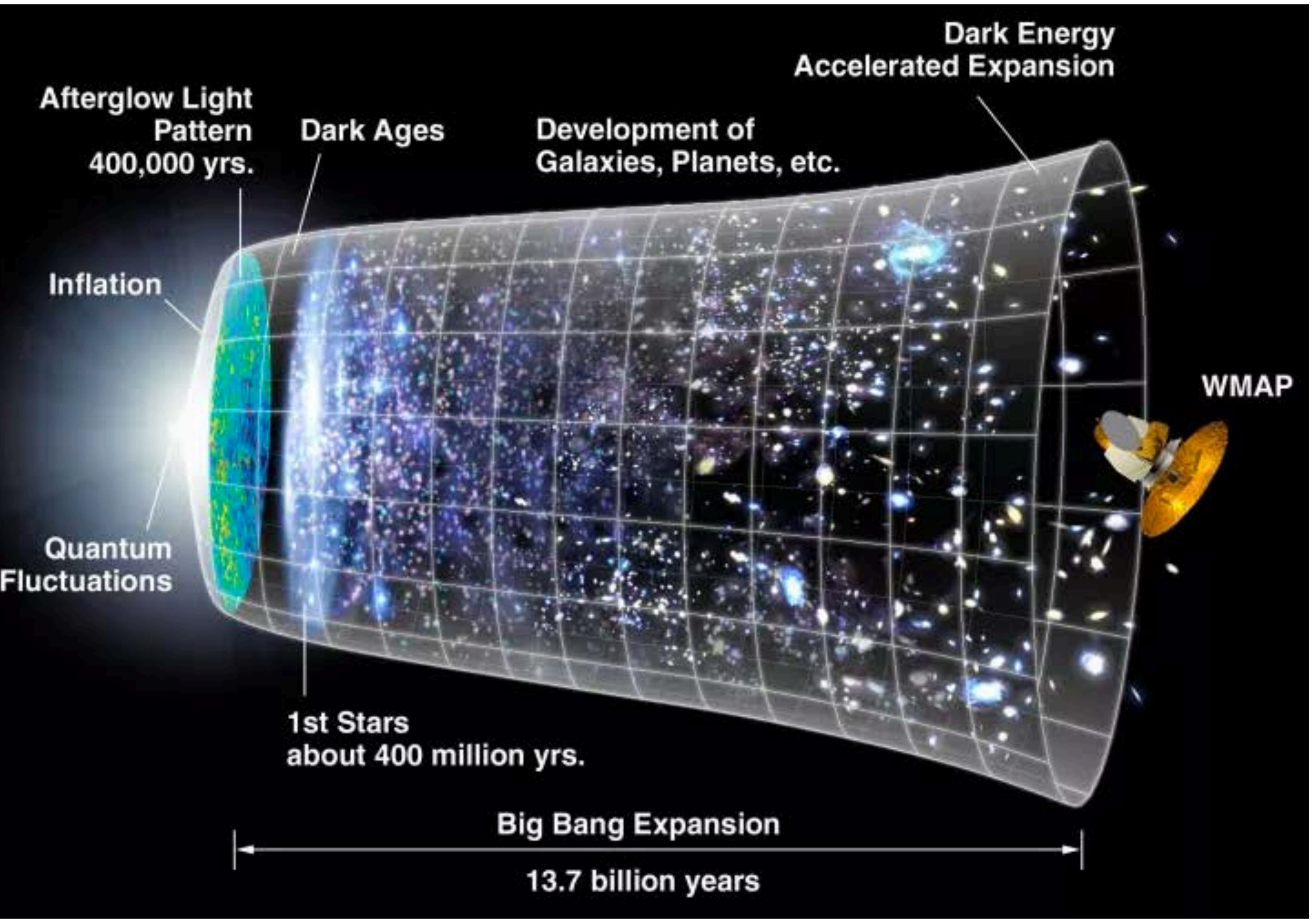
General Relativistic Magnetohydrodynamic simulation (UWABAMI code) +
General Relativistic Radiative Transfer calculation (RAIKOU code)

Accreting black holes (BHs) in astrophysics

mechanical/radiative feedback
→ co-evolution of BHs and host galaxies, cosmology

acceleration of cosmic rays
→ possible origin of UHECR, VHE gamma-ray, neutrino

analogy of physics of jets
→ gamma-ray burst as a EM counter part GW events



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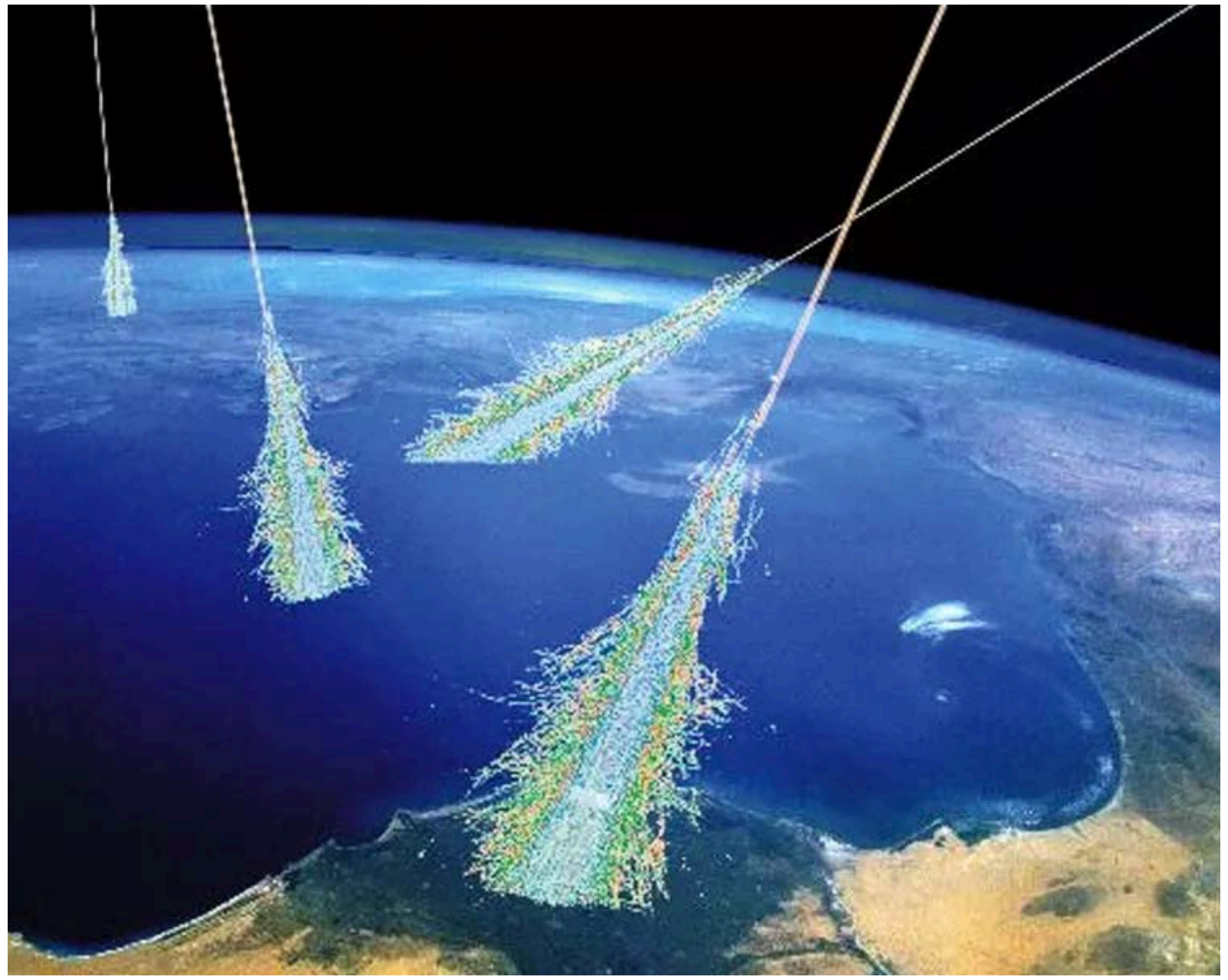

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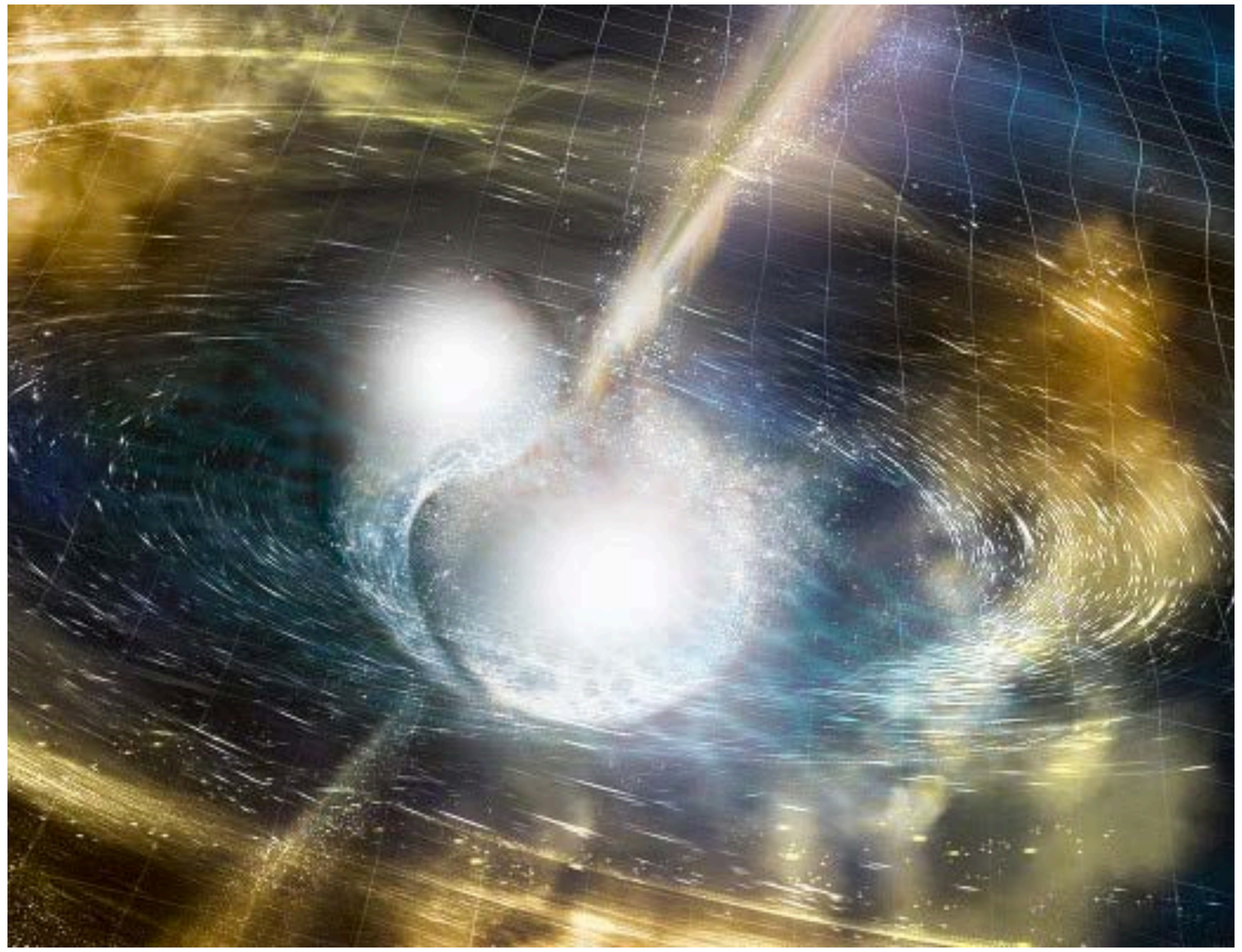

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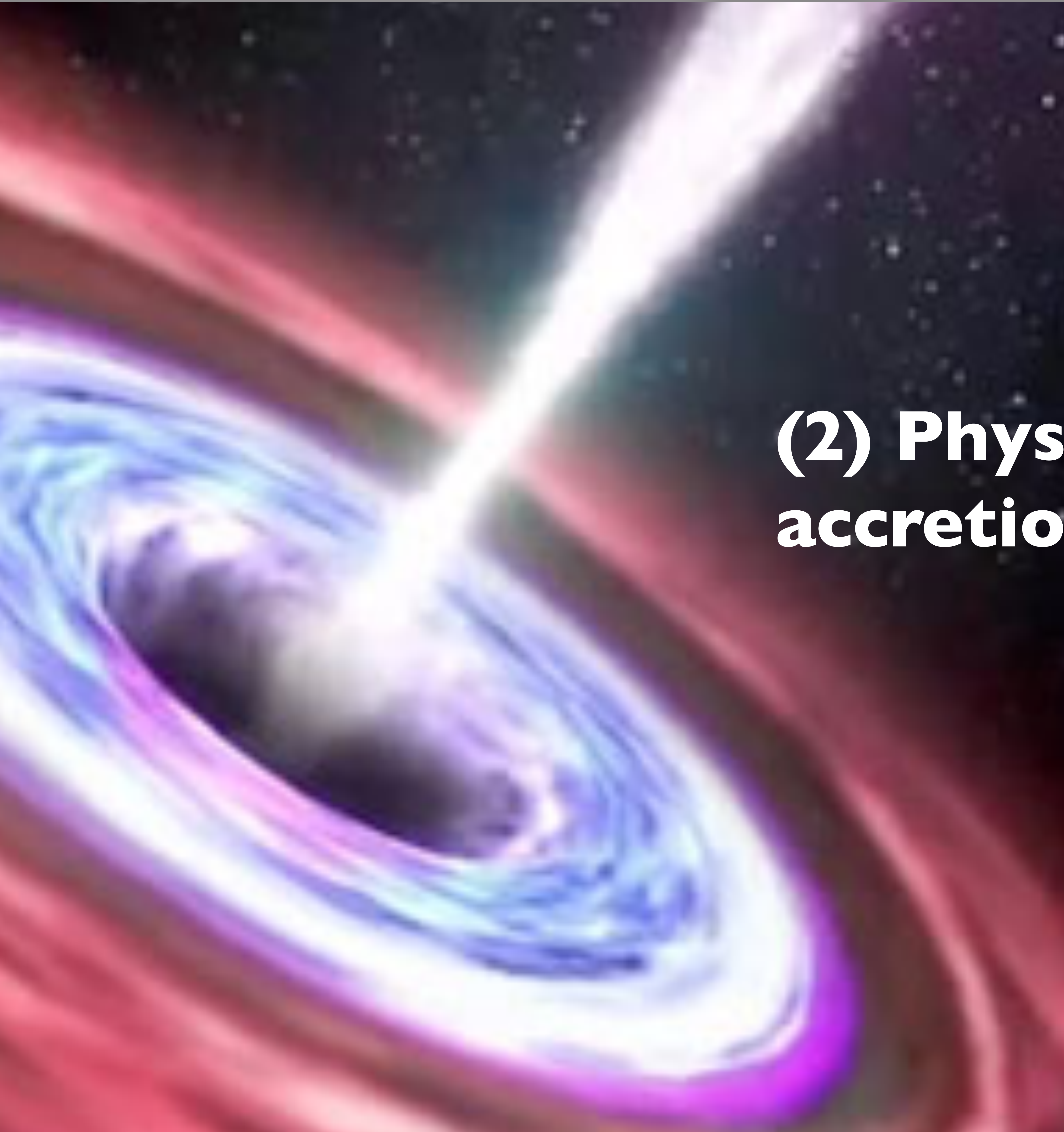
Key questions in black hole (BH) astrophysics



(1) BH spacetime?

(2) Physics of accretion flow?

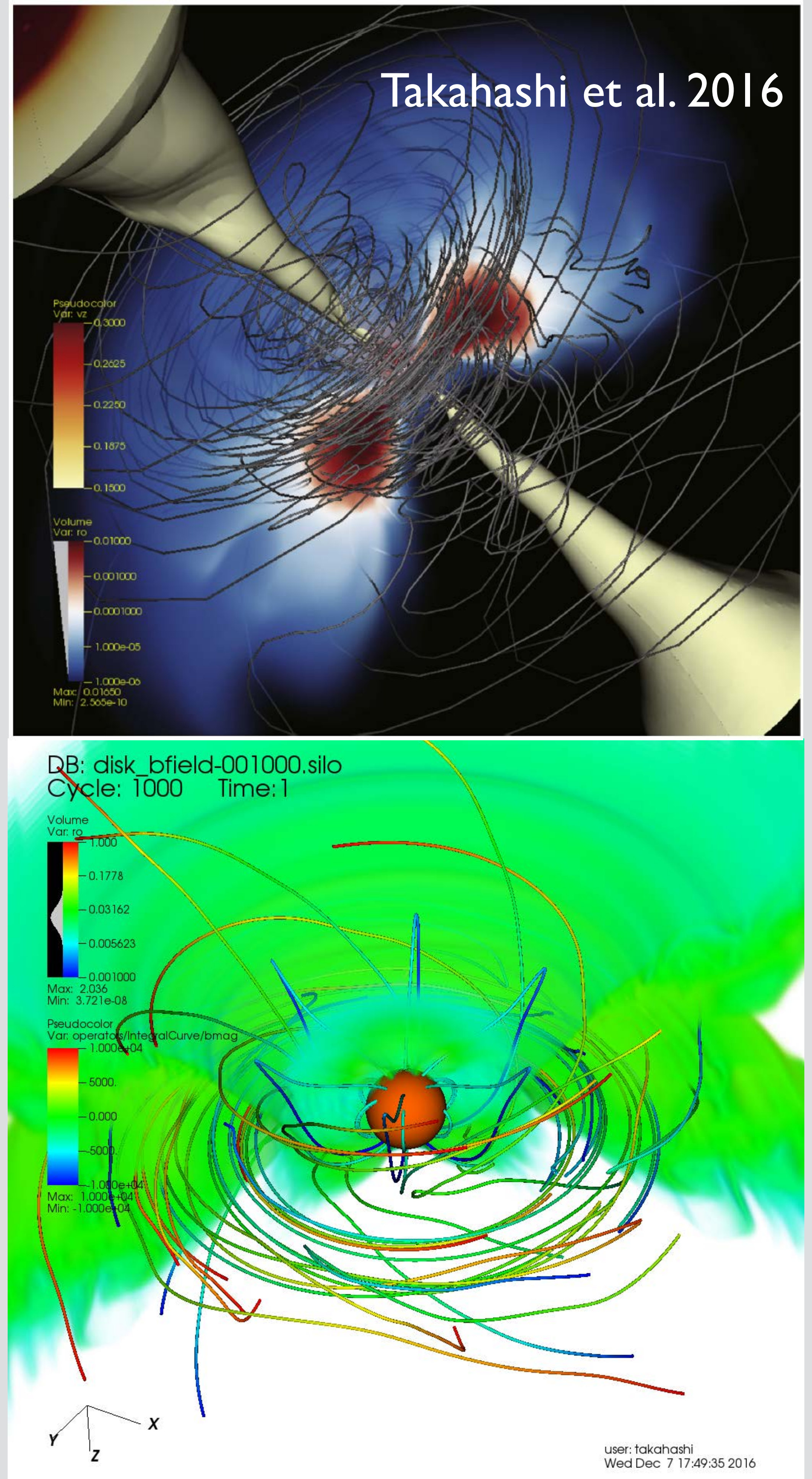
(3) Formation and acceleration of relativistic jets?

(1) - (3) are related each other.
general relativity, magnetohydrodynamics (kinetics of plasma), and <u>Radiative Transfer</u> are needed.

Power of radiative transfer

Theory/Simulation

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



Large gap!

We need radiative transfer calculations of

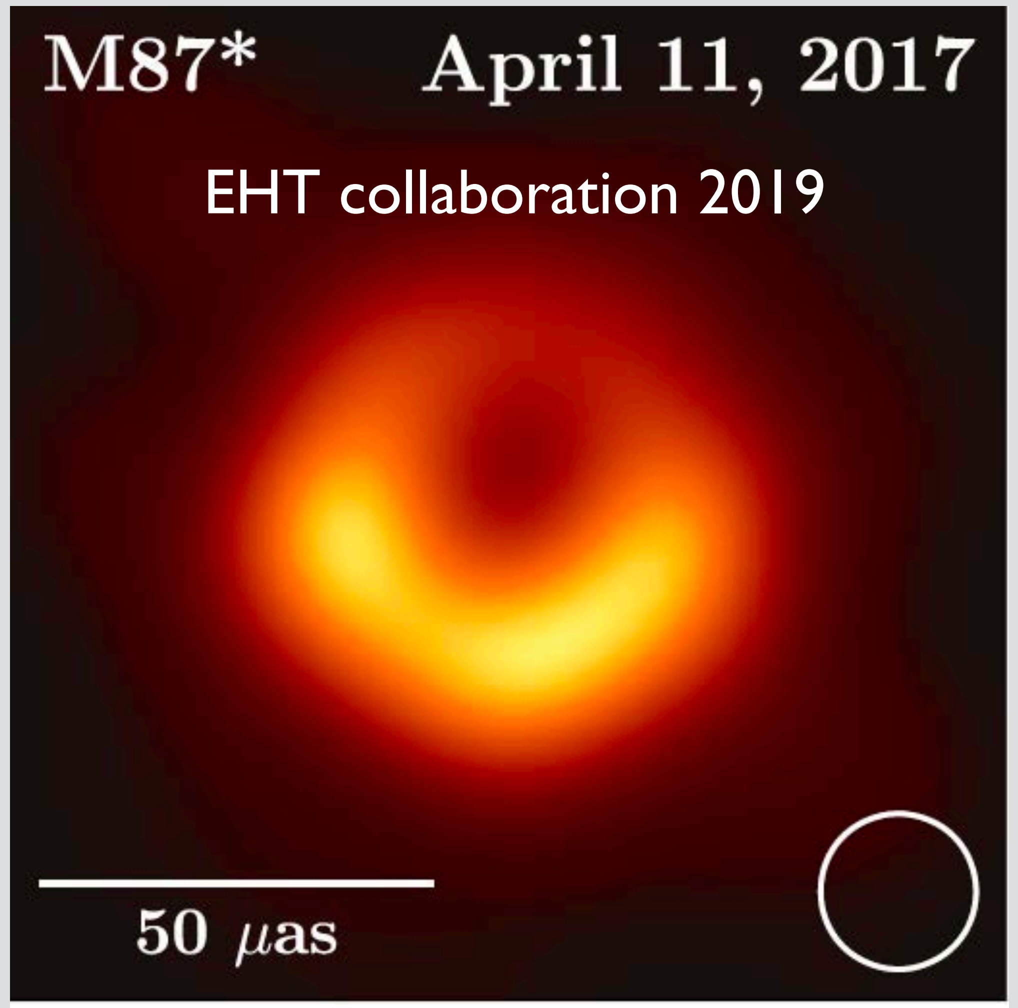
- Imaging
- Spectral Energy Distribution (SED)

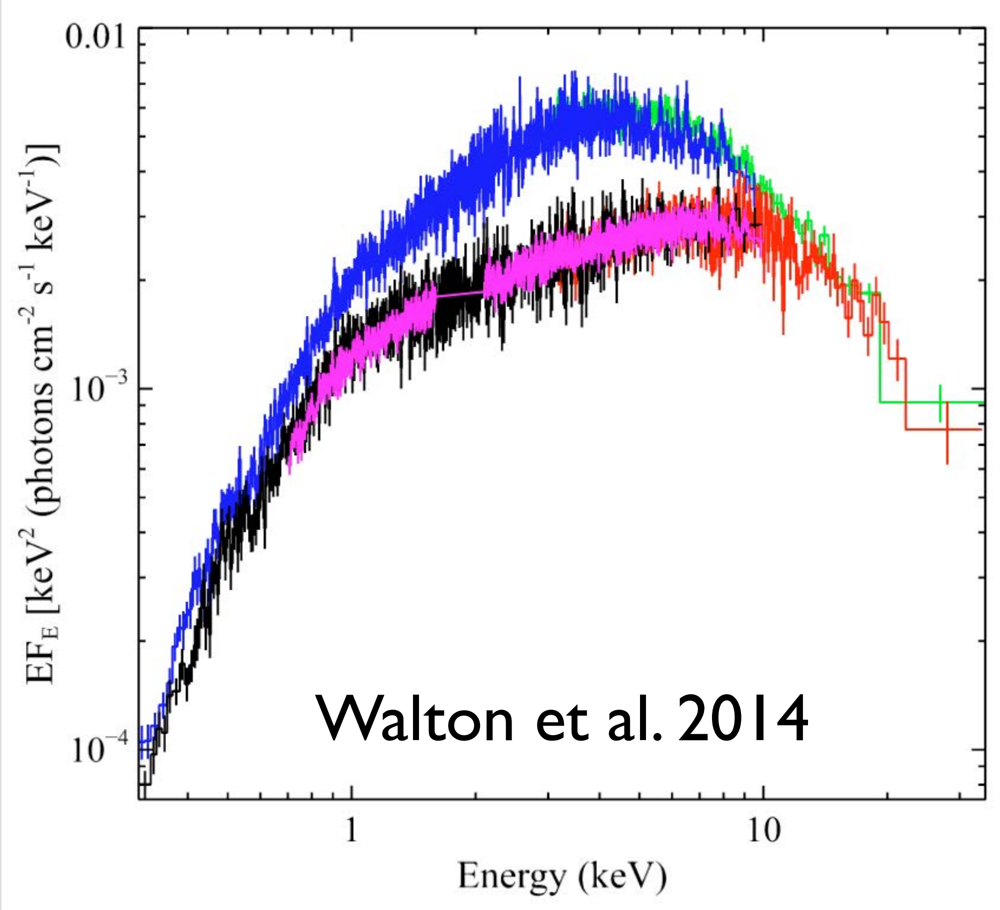
The detailed calculation of general relativistic radiative transfers will enable us to study

- **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)

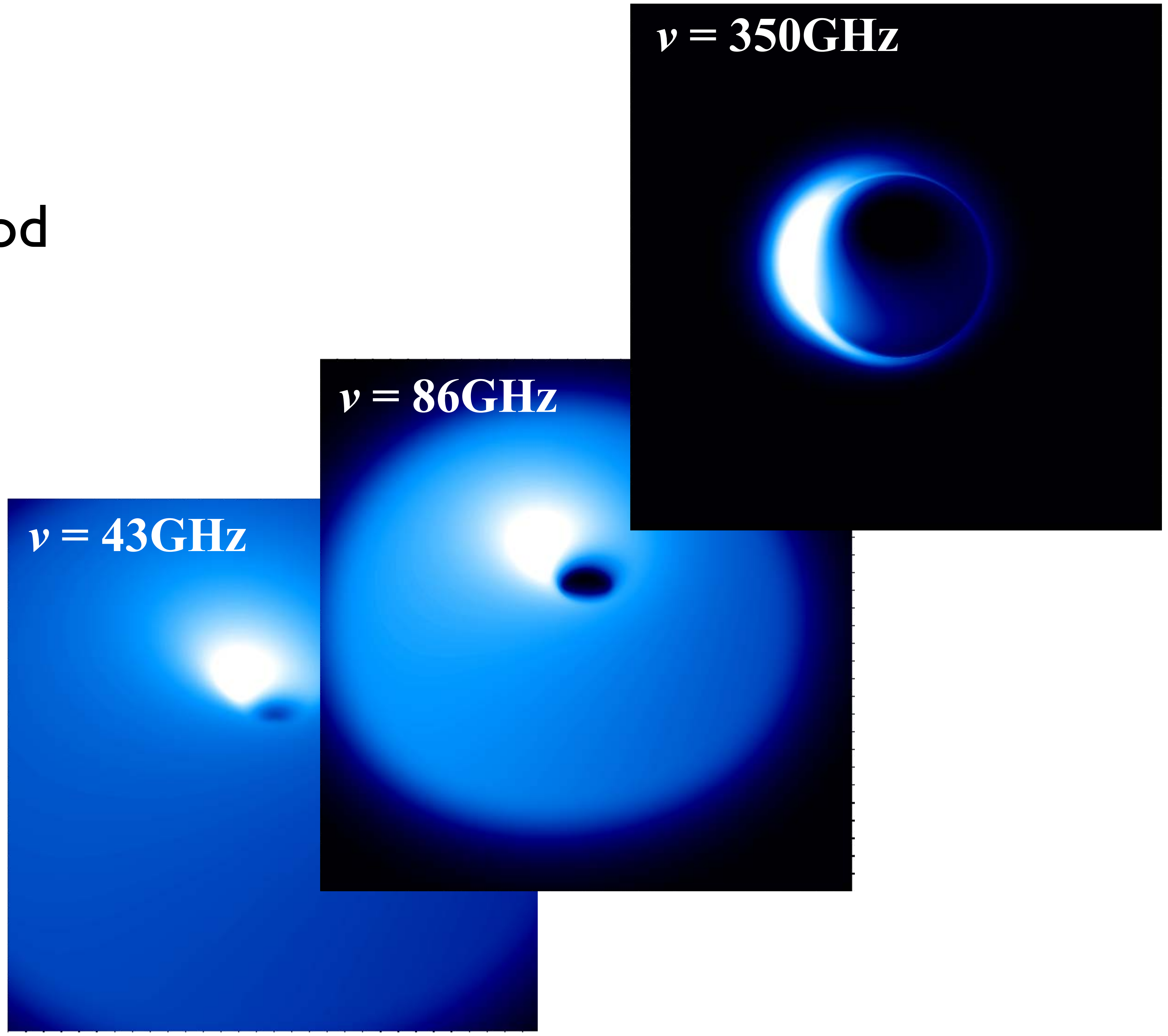
RAIKOU: Radiative trAnsfer In Kerr-spacetime for accretiOn and oUtflow

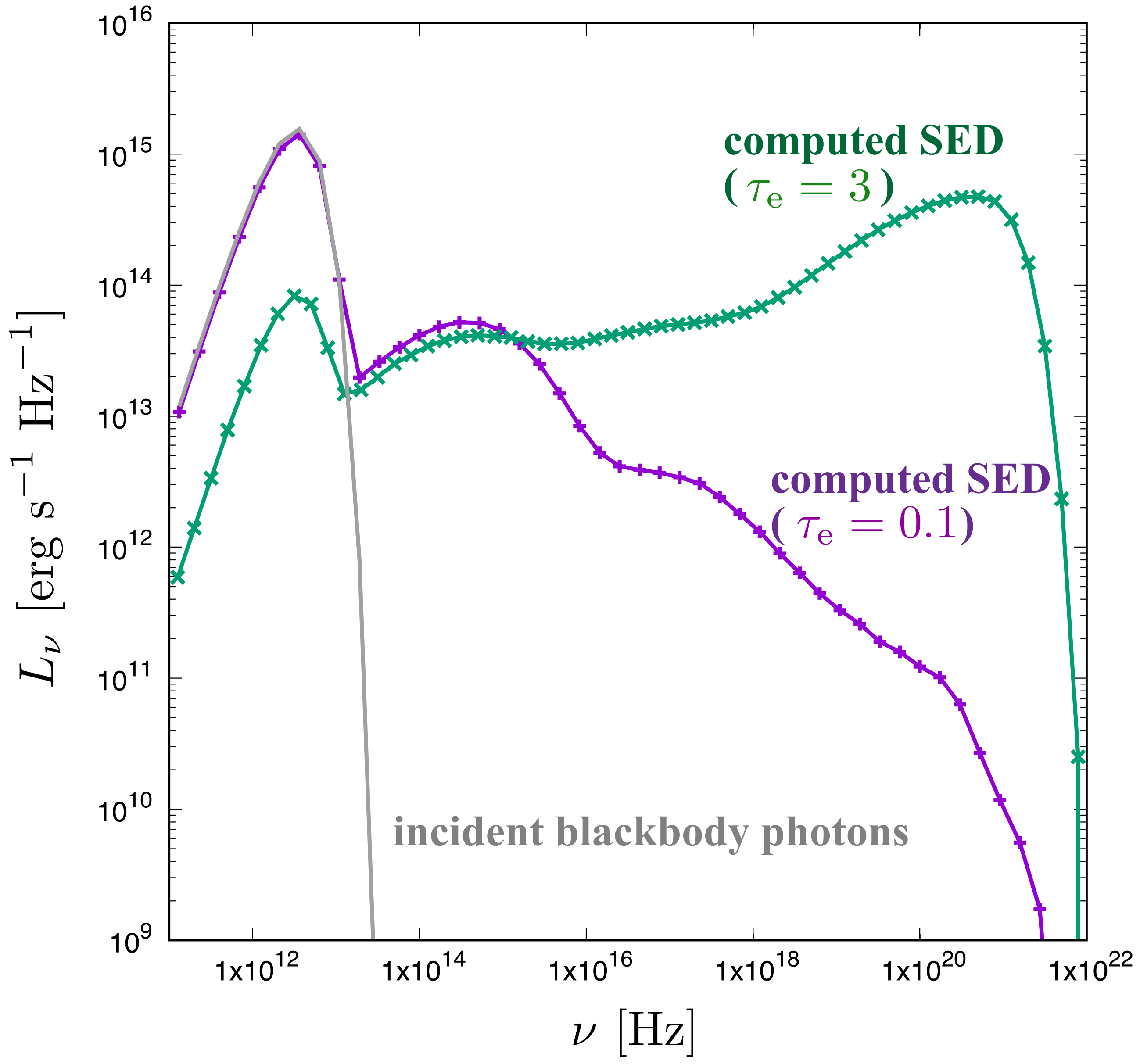
- **Ray-tracing法:**
  - ✓8th order embedded Runge-Kutta method w/ adoptive stepsize control
- **Radiative processes:**

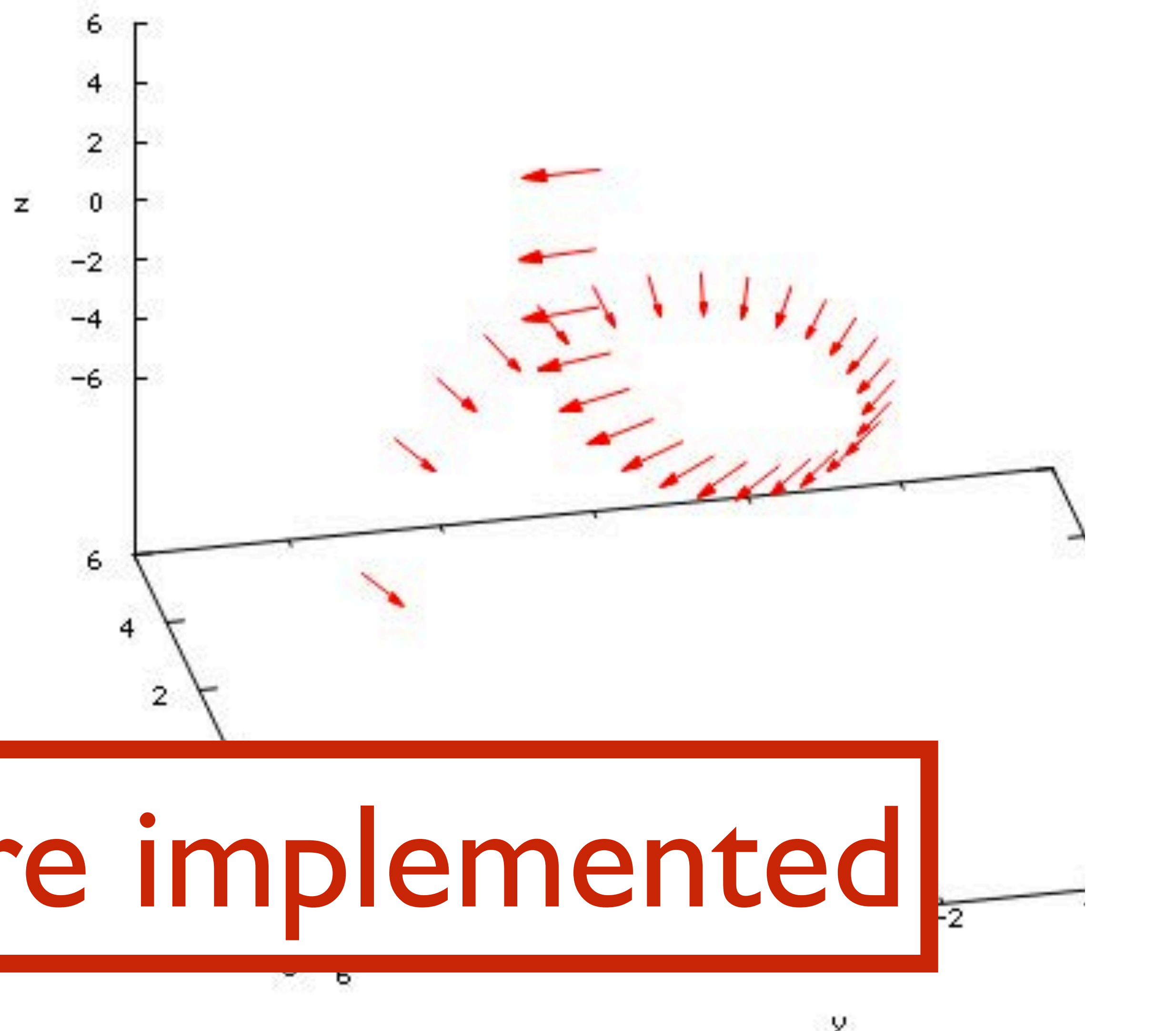
✓emission/absorption
- Cycle-synchrotron via thermal electrons
- Synchrotron via non-thermal electrons
- Bremsstrahlung via thermal electrons

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

✓ Polarization (now implementing)

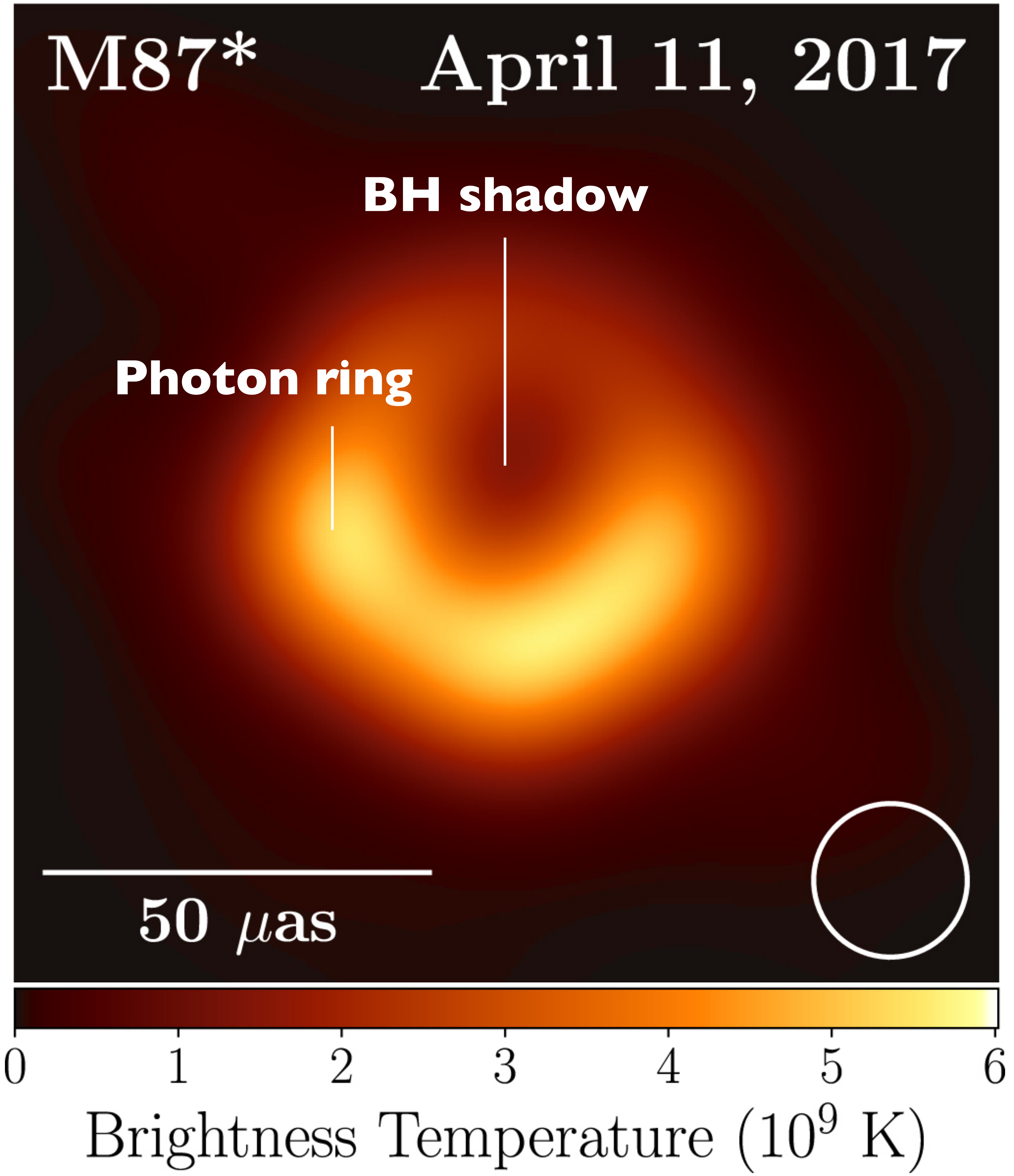


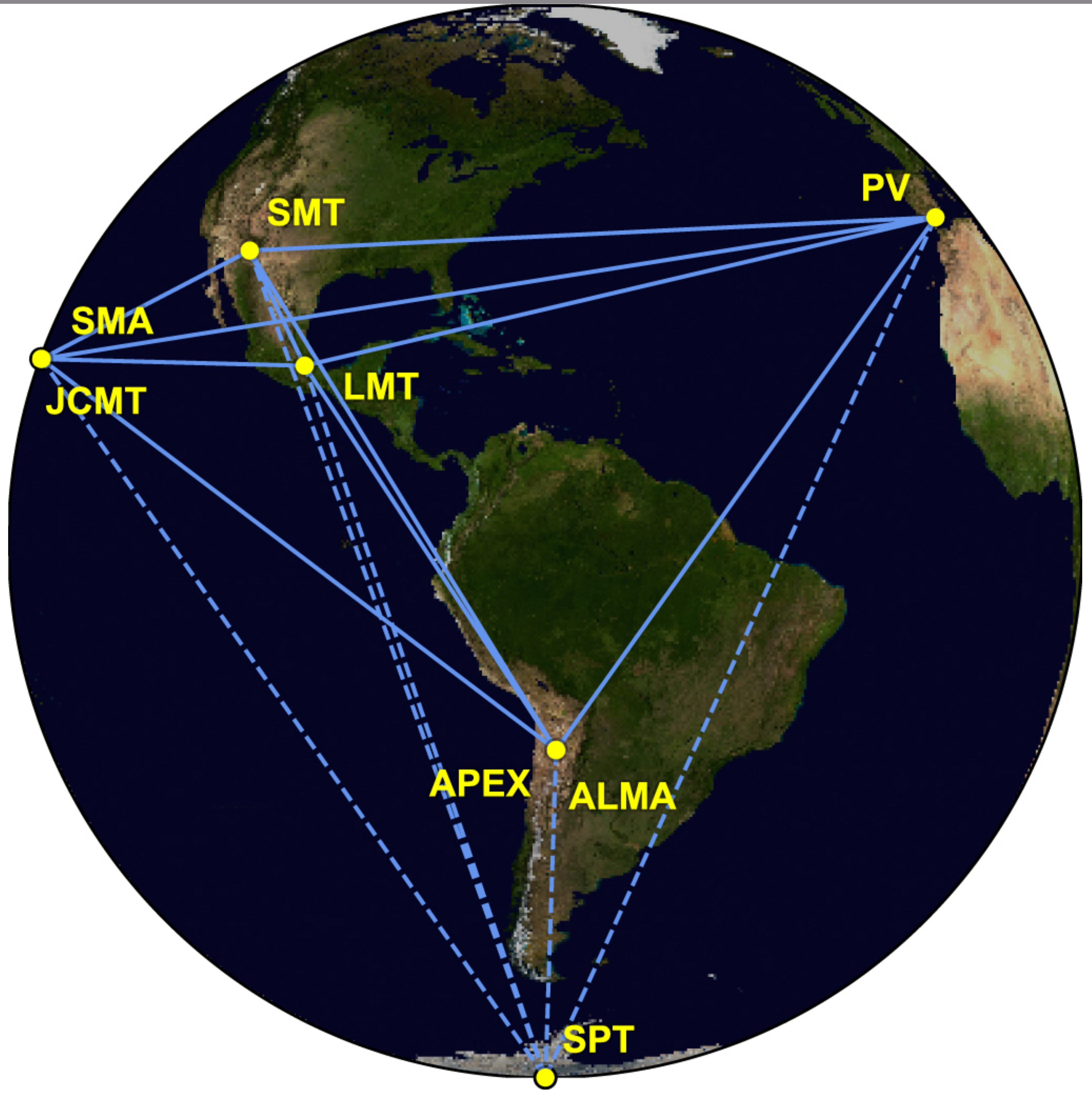




(Almost) all the important continuum processes near BHs are implemented

First detection of BH shadow in M87
(EHT Collaboration 2019 incl. T Kawashima)

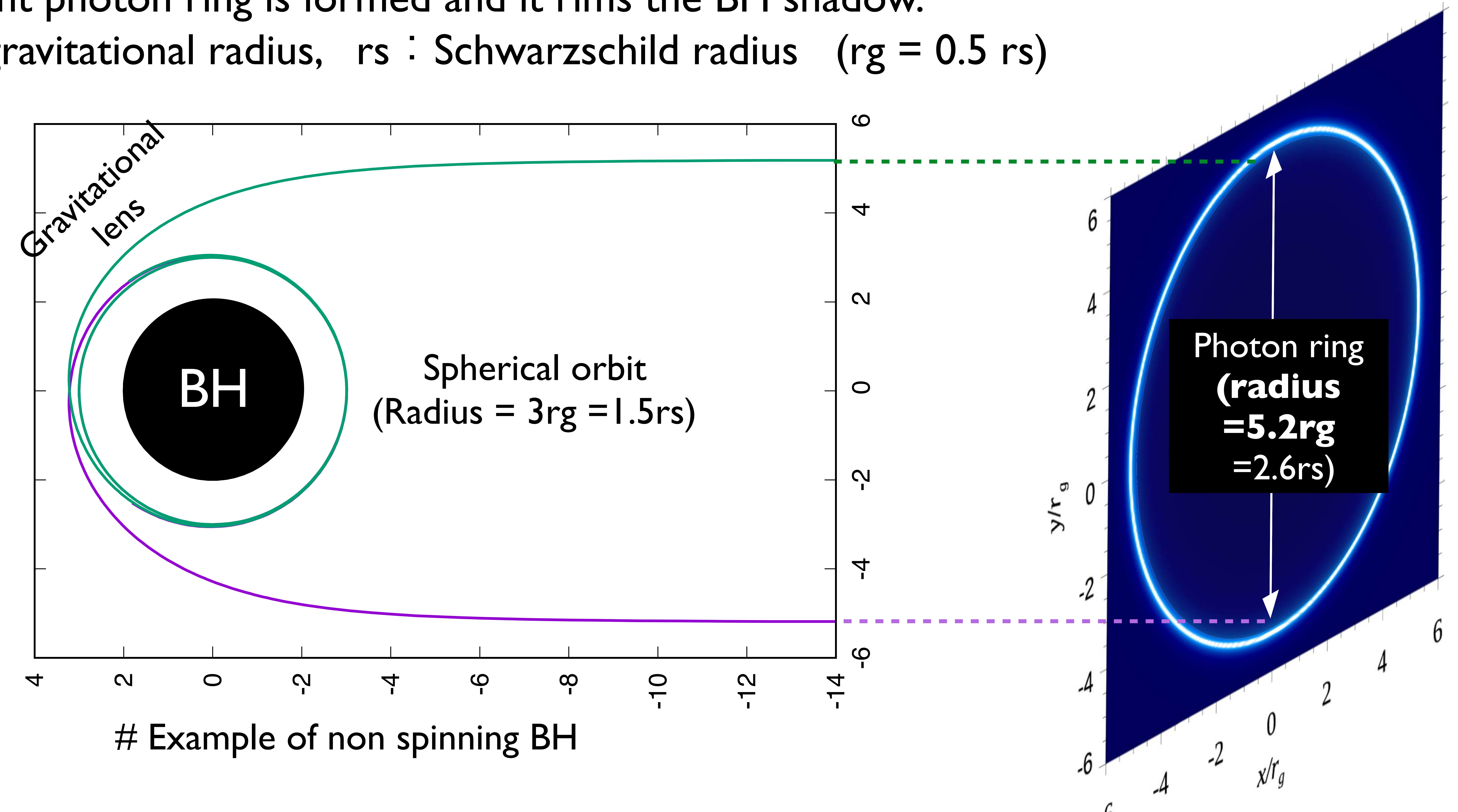




Event Horizon Telescope (EHT) has successfully detected the BH shadow in M87, which is one of the most famous relativistic jet source!

Formation of photon ring and BH shadow

- Photon ring：gravitationally lensed image of (unstable) spherical orbit of photons
- Photons passing through near the spherical orbit gain the intensity via "emissivity x length", then, the bright photon ring is formed and it rims the BH shadow.
  ※ rg：gravitational radius, rs：Schwarzschild radius (rg = 0.5 rs)



Example of non spinning BH

Calculation of photon ring in M87 EHT Collaboration (inc. Kawashima T.) 2019

General Relativistic MagnetoHydroDynamic (GRMHD) simulation +
General Relativistic Radiative Transfer (GRRT) calclualtion

- **The mass of M87 BH has 6.5x109 M_sun.**
- **Powerful evidence of the presence of supermassive BH**

What we achieved and remaining works

- What we achieved：

  ✓ BH has 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

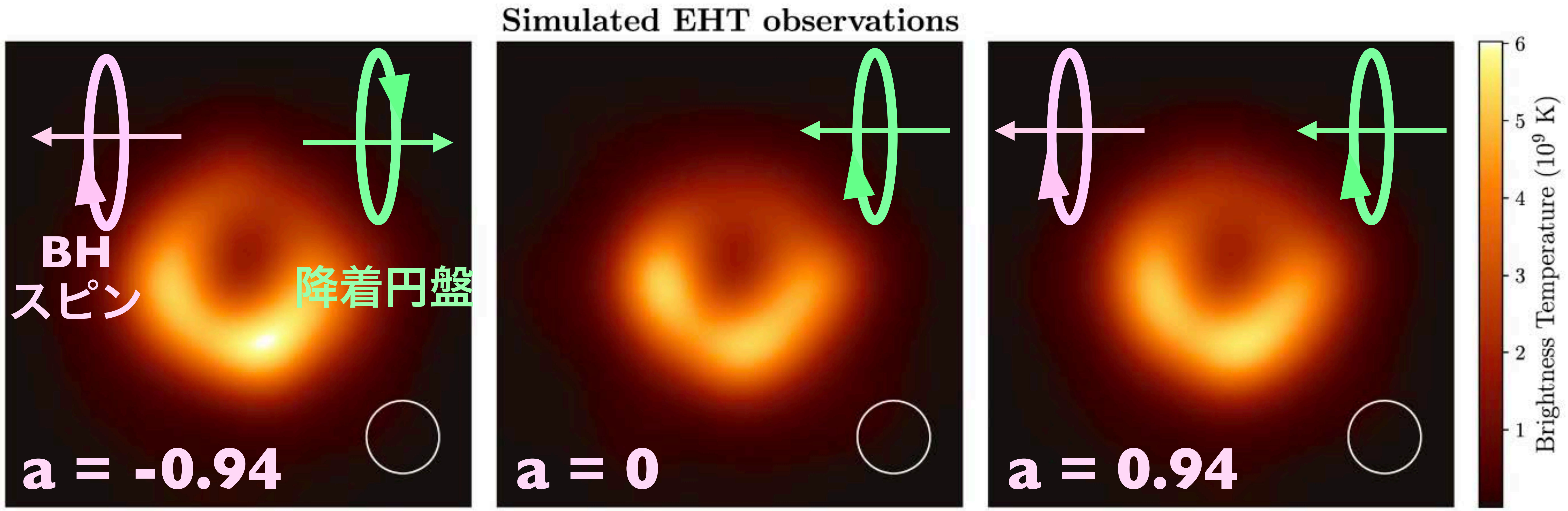
  ✓Formation mechanism of jets

  ✓Dynamics of accretion flow

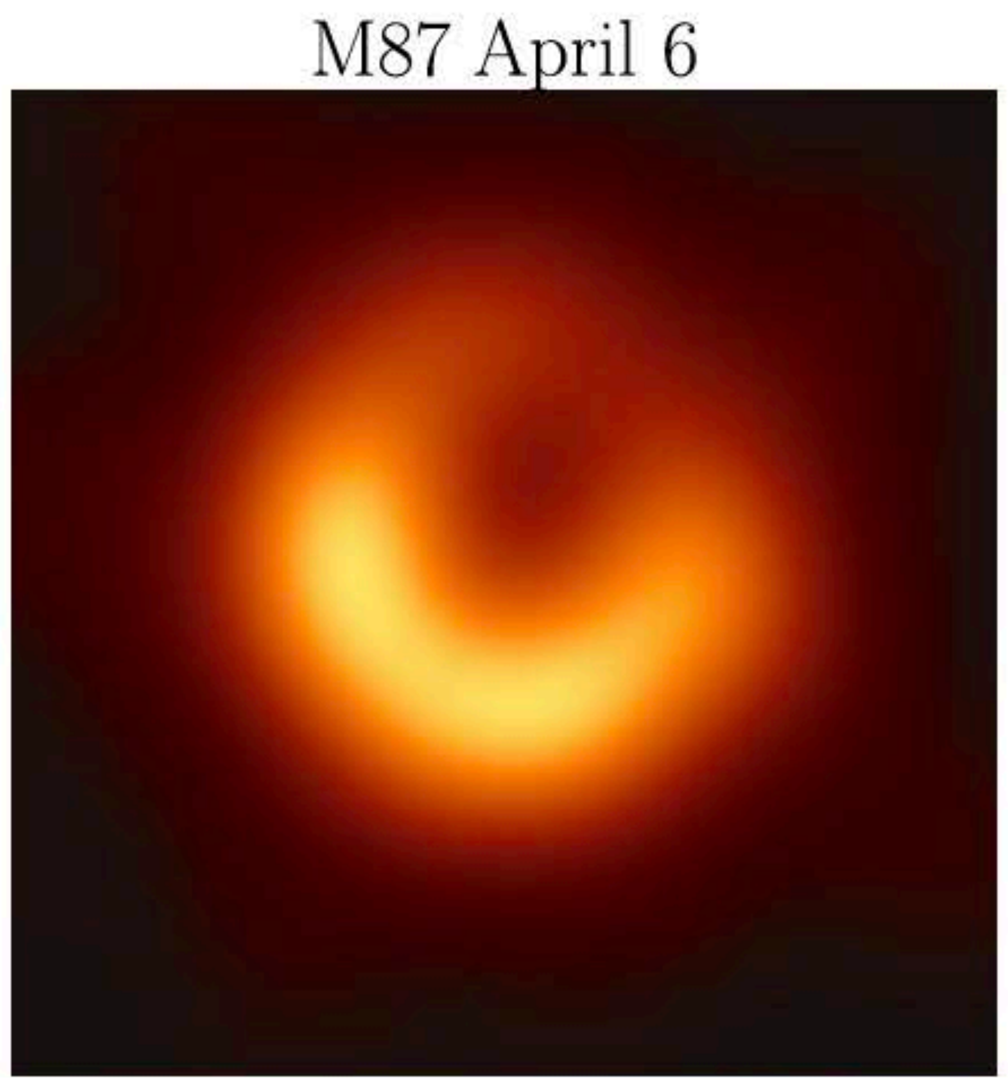
  ✓Emission region is jet or accretion flow?

  ✓Other sources (e.g., Sgr A*)

Theoretical images w/ various BH spin

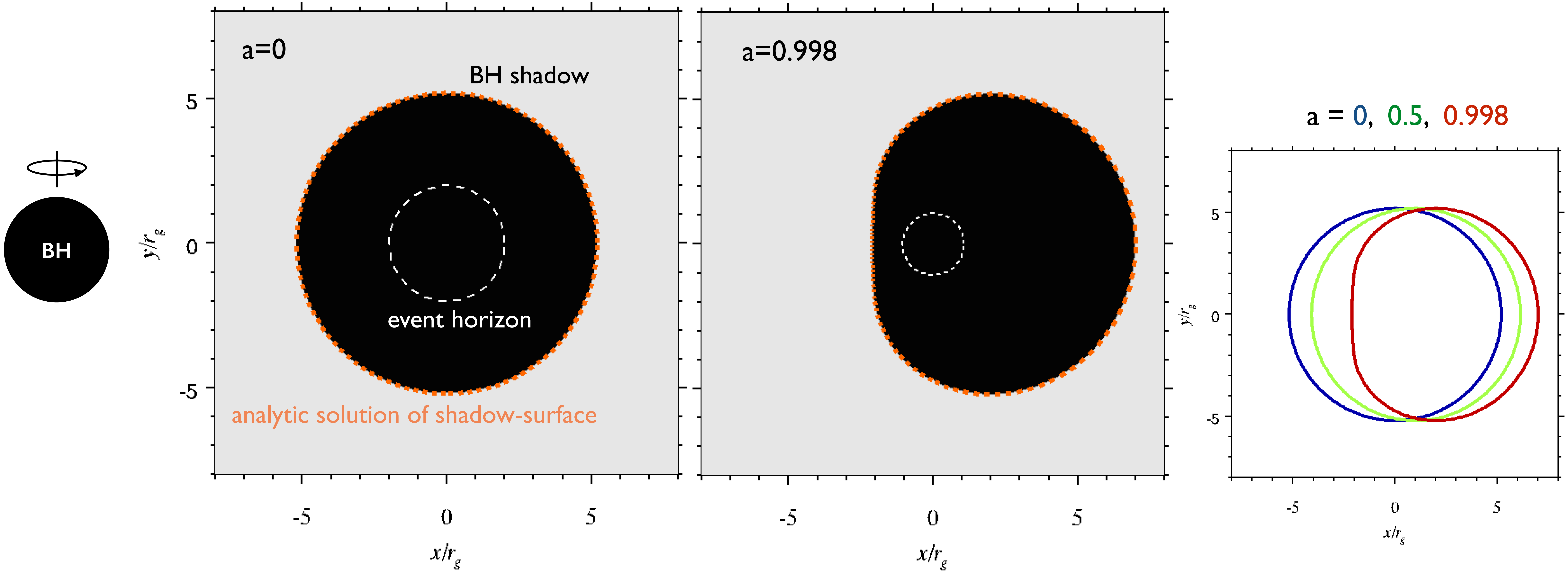


EHT2017 observation



Towards future EHT:
Exploring BH spin and launching of relativistic jets

Dependence of BH shadow (photon ring) on BH spin



- Dependence of size of photon ring on BH's
  - mass : STRONG (it is proportional to BH mass)
  - spin : WEAK (the difference is within only ±5%)

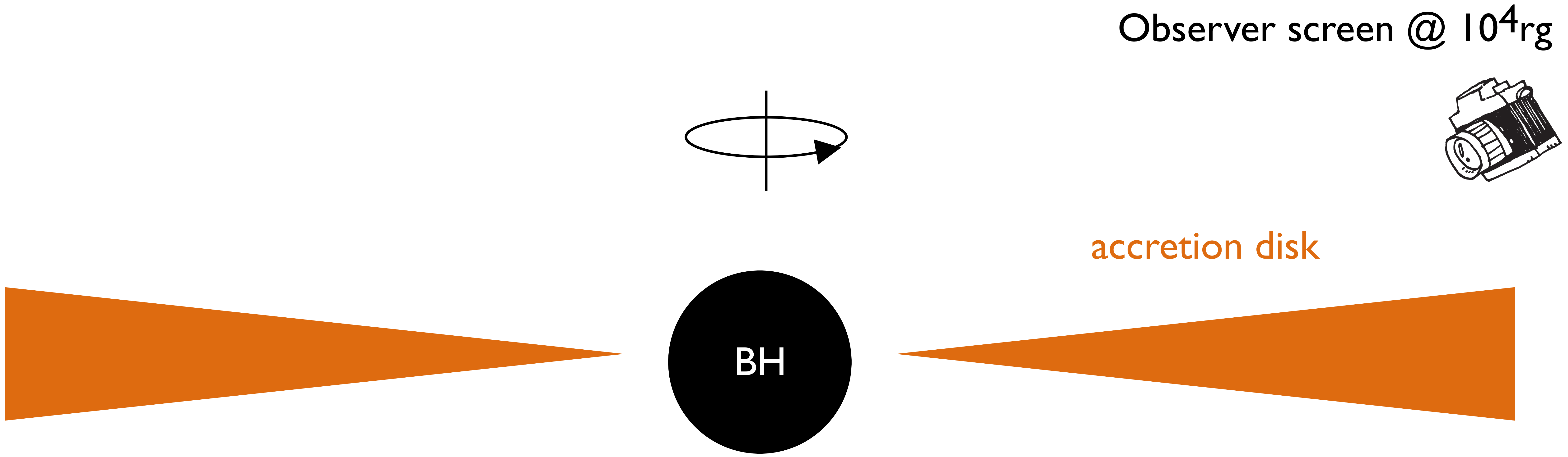
<u>The center of the photon ring just slide to the direction perpendicular to the BH-spin axis.</u>

- Good for evaluating BH mass, but not good for estimating BH spin.

A new method constraining the BH spin

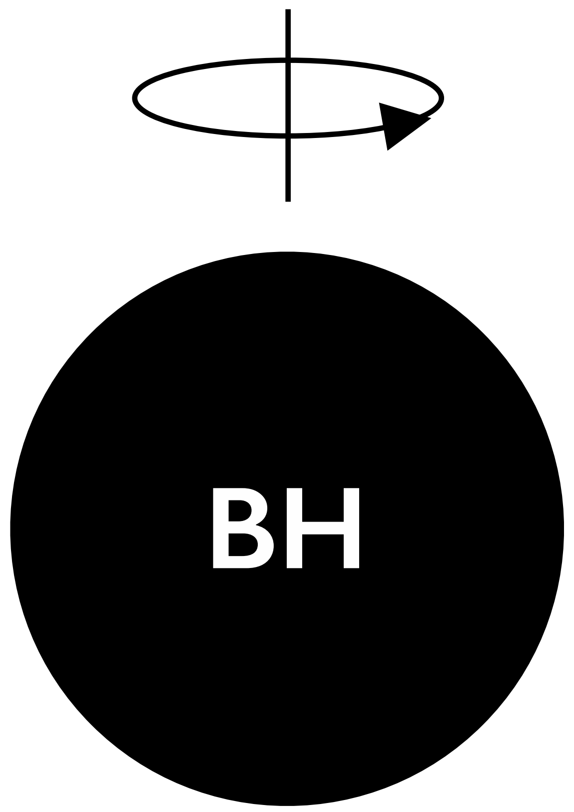
Kawashima Kino, & Akiyama 2019

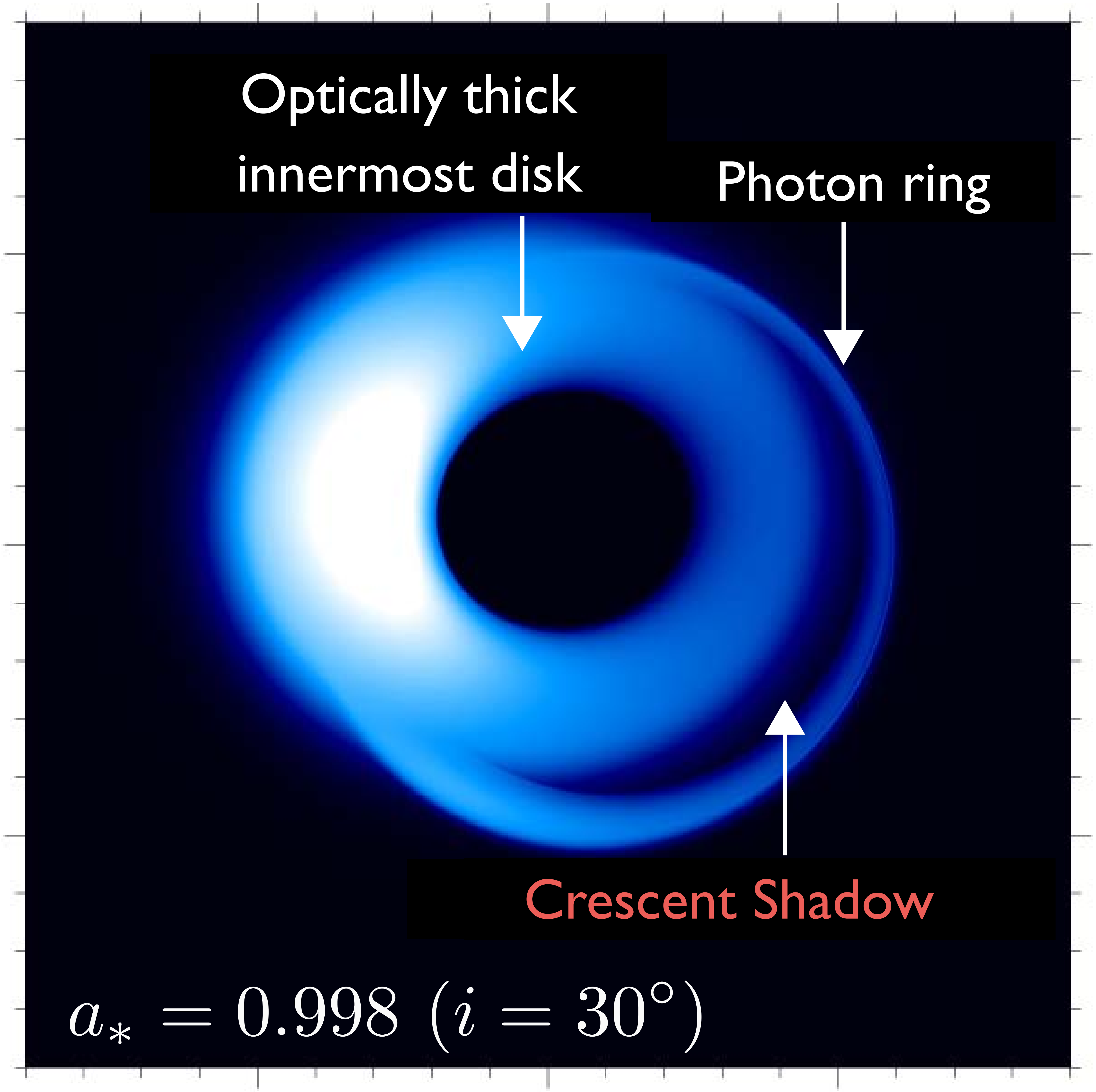
We calculate the BH shadow in a flaring state, in which the mass accretion rate is moderately higher than that observed by EHT2017, to explore a new signature of the BH spin



- For simplicity, we consider accretion flow only as in some previous works (Keplearian shell model: Broderick & Loeb 2006)
- Cyclo-synchrotron emission/absorption
- BH mass: 6.2 x 10^9 solar mass
- BH spin: a = 0.5, 0.75, 0.998,   viewing angle i = 15, 30 degree
- Relatively higher mass accretion rate $\gtrsim 10^{-3} M_{\odot}\ \mathrm{yr}^{-1}$

BH shadow in flaring state (a=0.998)



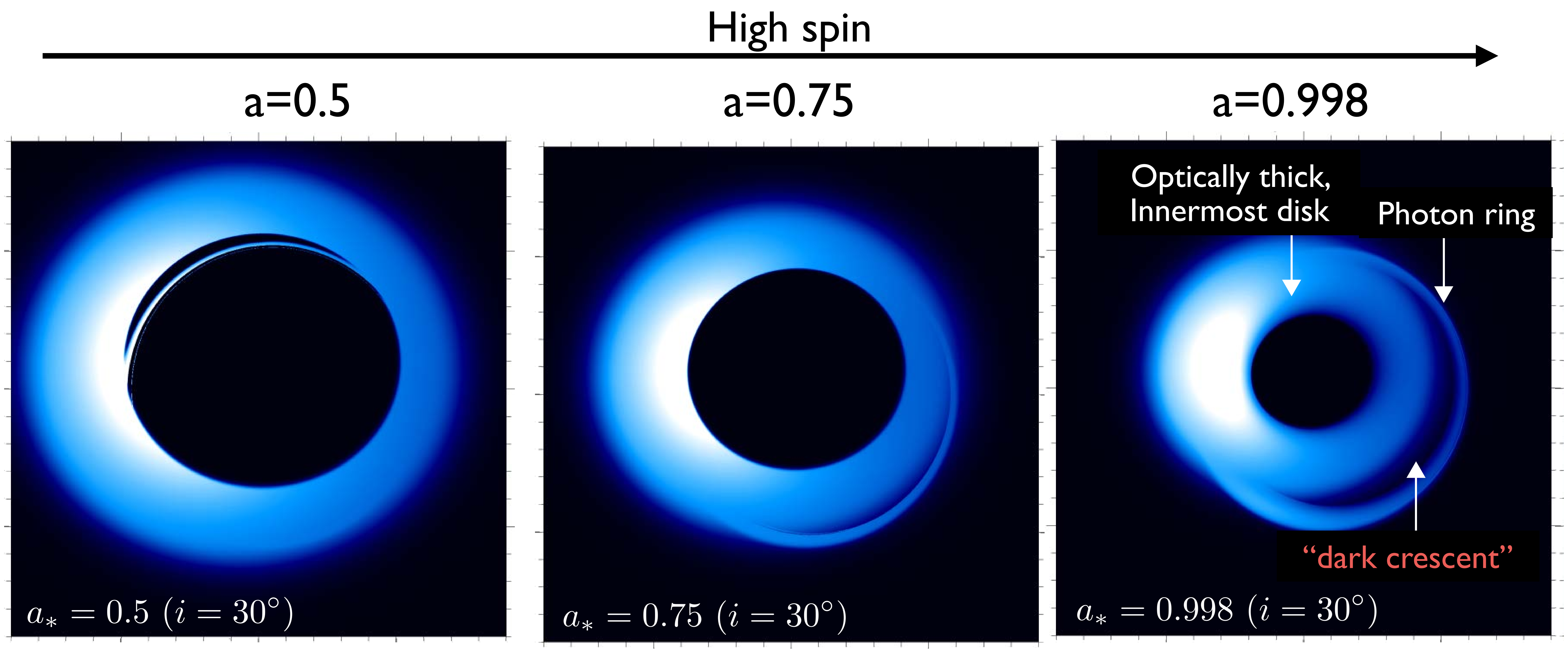


Optically thick ring image appears when the mass accretion rate is a bit higher.

Photon ring also appears because the plasma is optically thin outside the inner region of accretion flow.

Crescent shadow appears between the optically thick innermost disk and photon ring

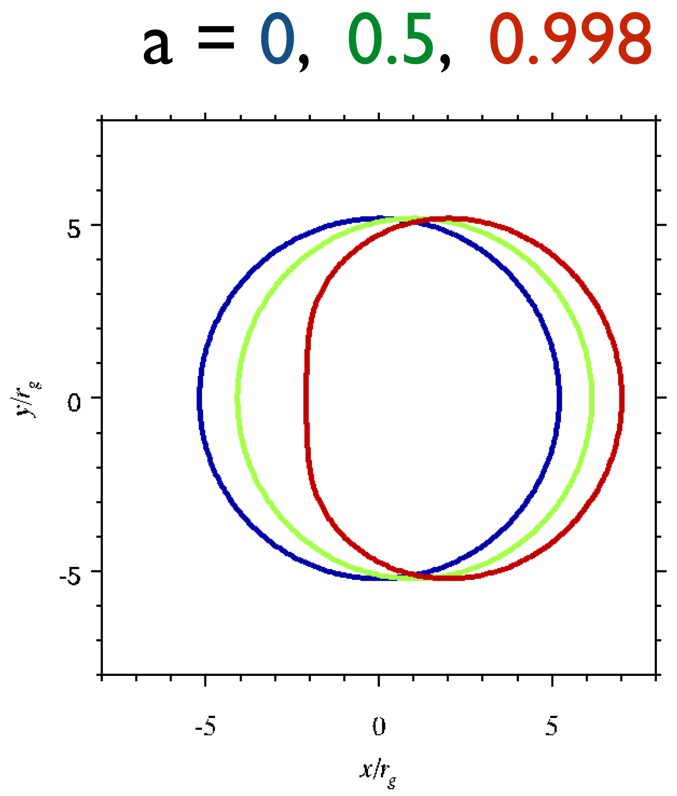
Dependence of BH shadow images on BH spin



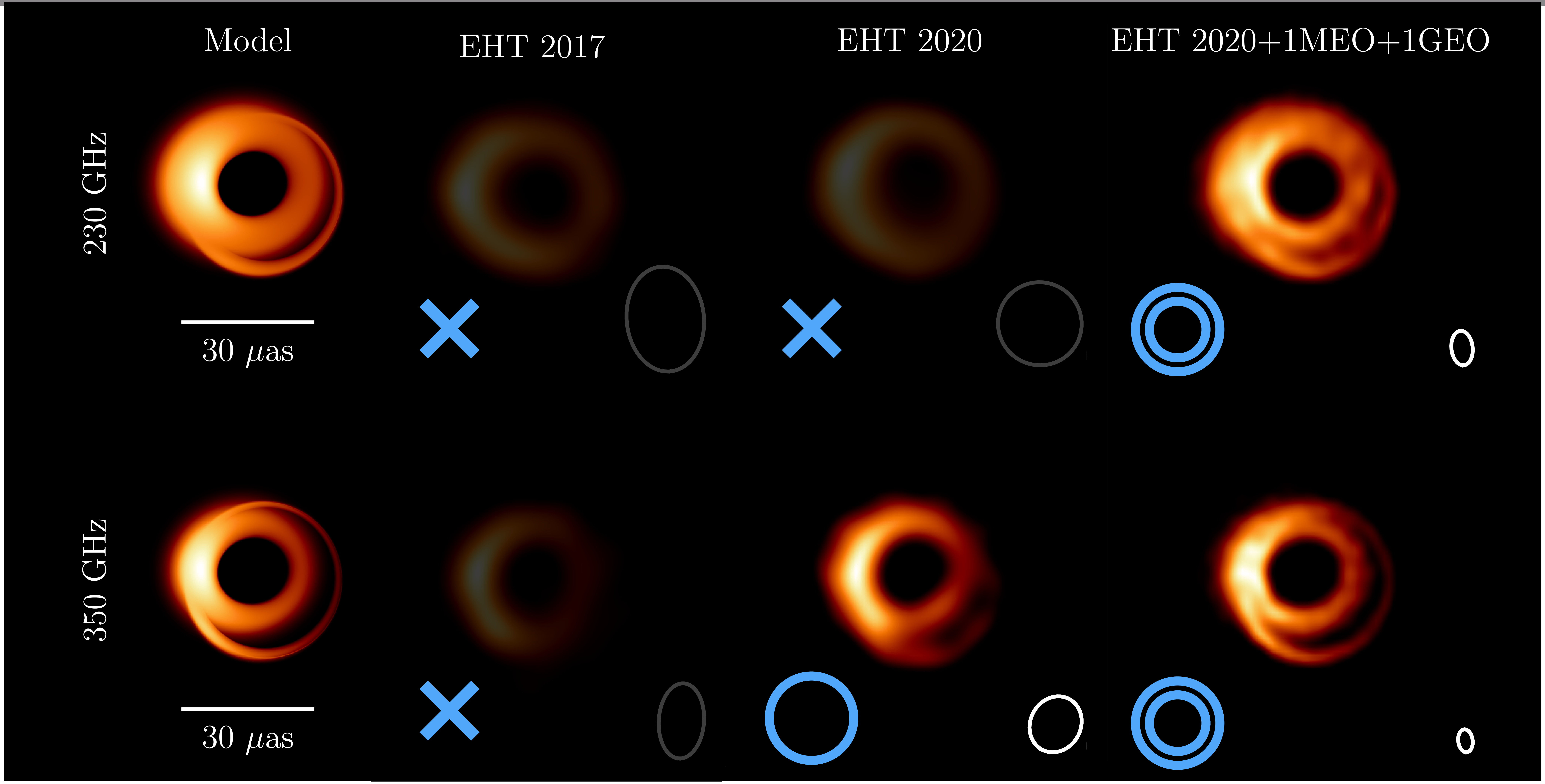
- When the BH spin is high, the center of photon ring shifts.

  → **The dark crescent appears.**

This feature can be a new method constraining the BH spin.

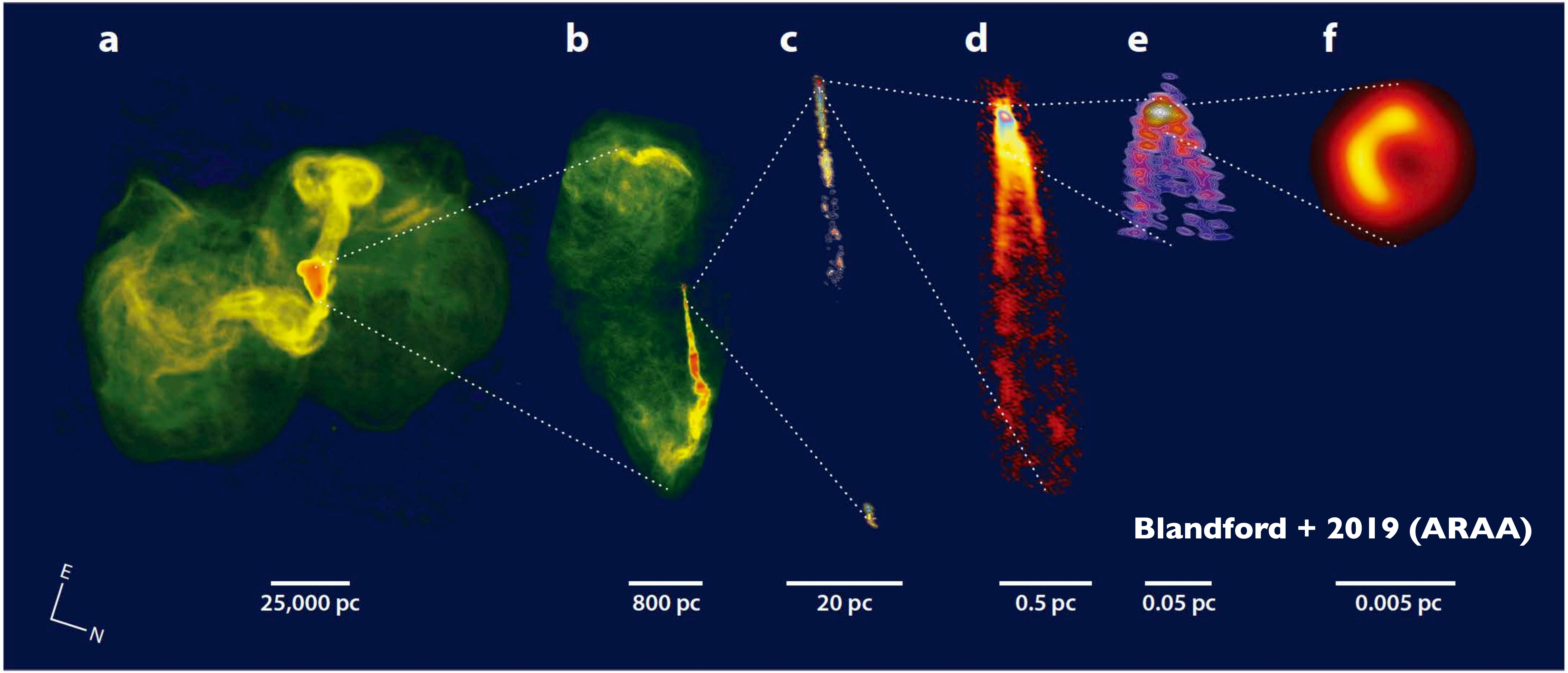


Synthetic Images of dark crescent, assuming current and future EHT array



- **It can be detected by using extend EHT with space VLBI after 2020s! (2030s?)**
- **Both of 230GHz and 350GHz observations are important.**

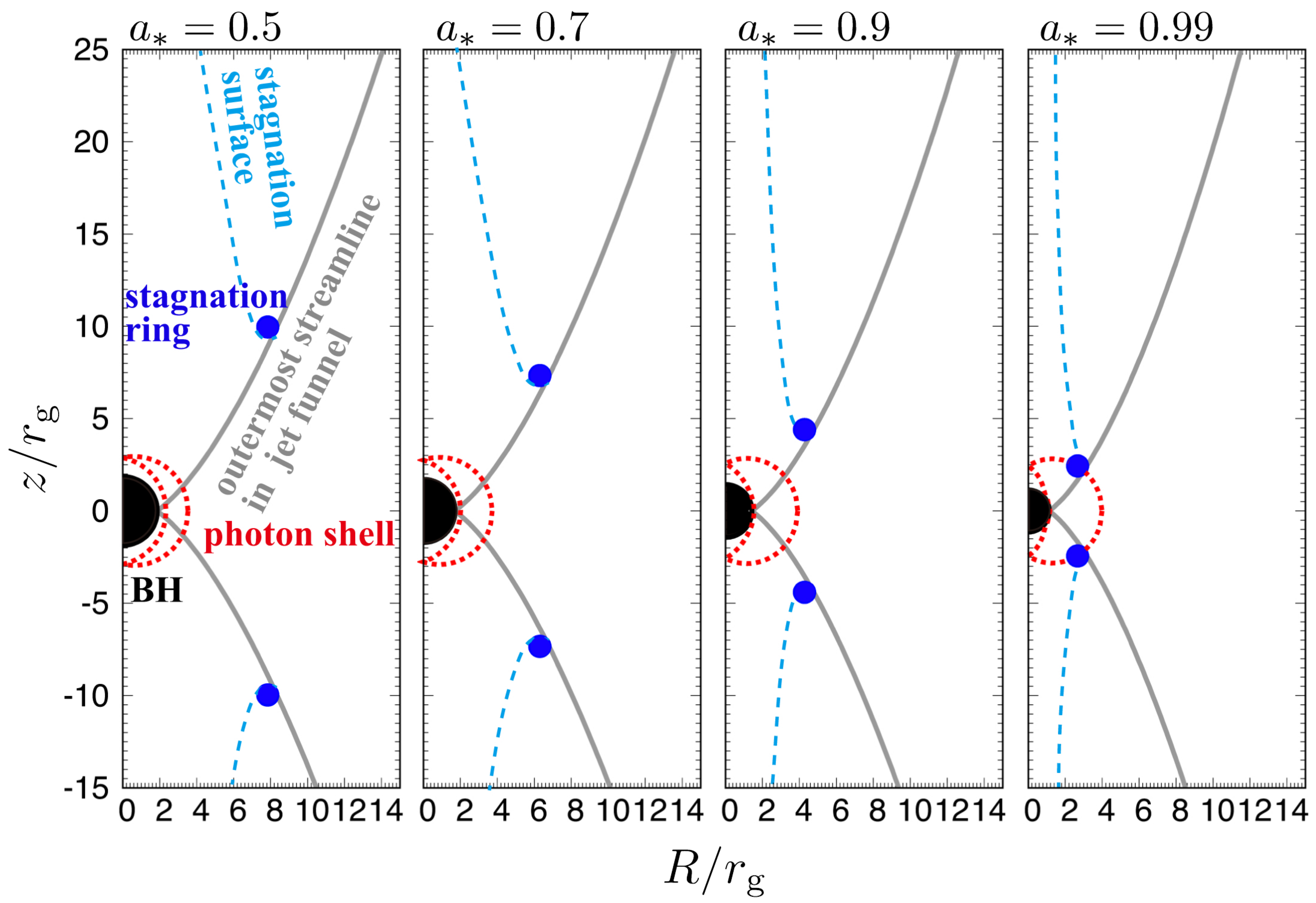
Is the jet-base emission important for ring image?



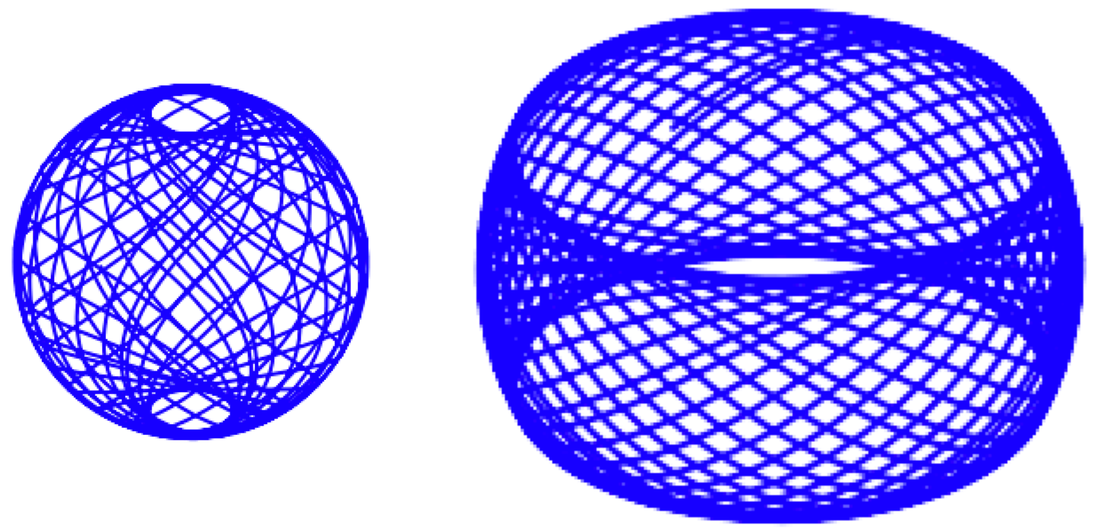
- The emission at the jet base would be important for formation of the ring-like image?

Overview of the model

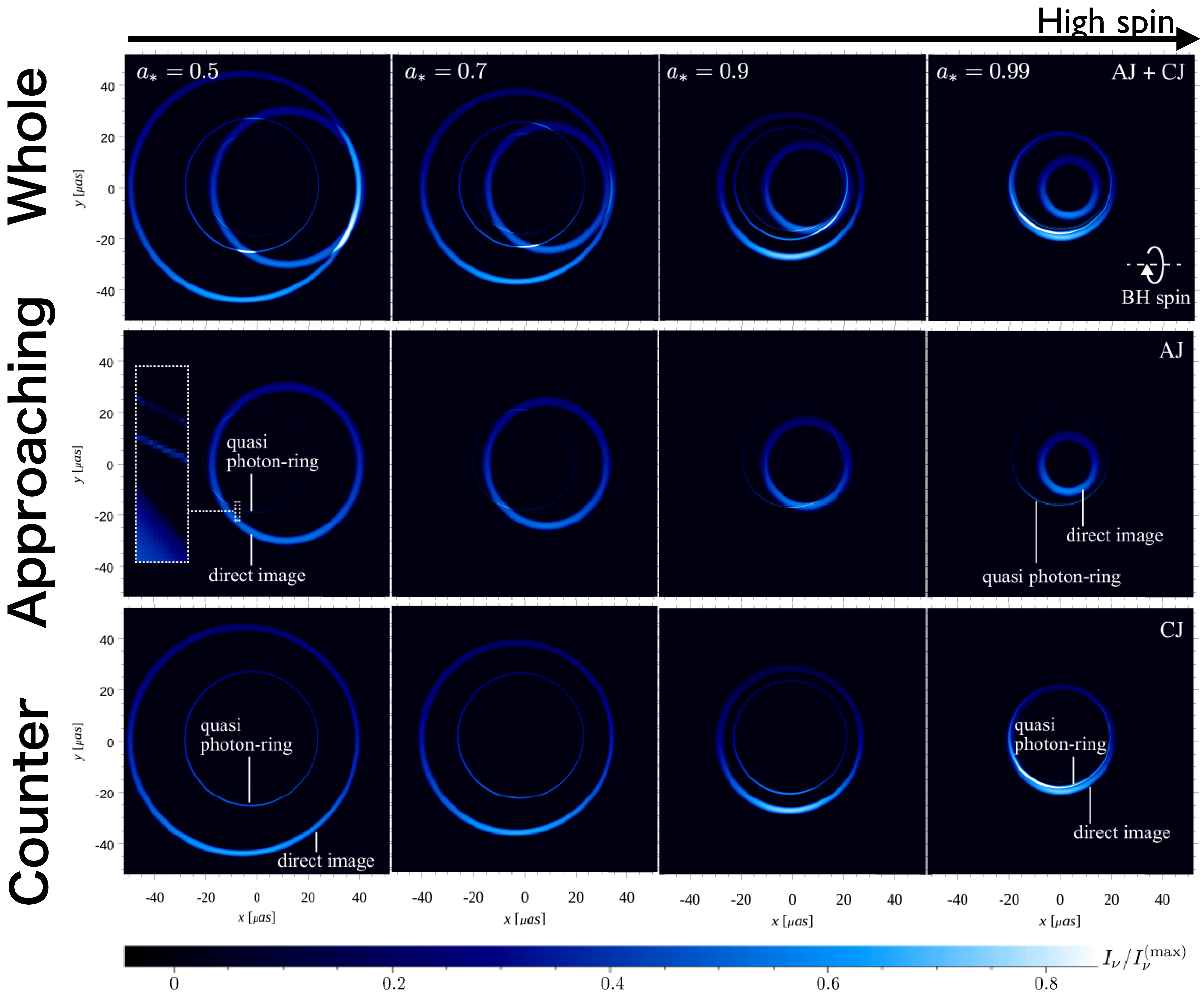
- Electron-positron plasma may be injected near the stagnation surface inside the jet funnel.(Broderick & Tchekhovskoy 2015)
- We explore the importance of the emission from the electron-positron plasma at the jet-base for the formation of the ring-like image at 230GHz in M87!

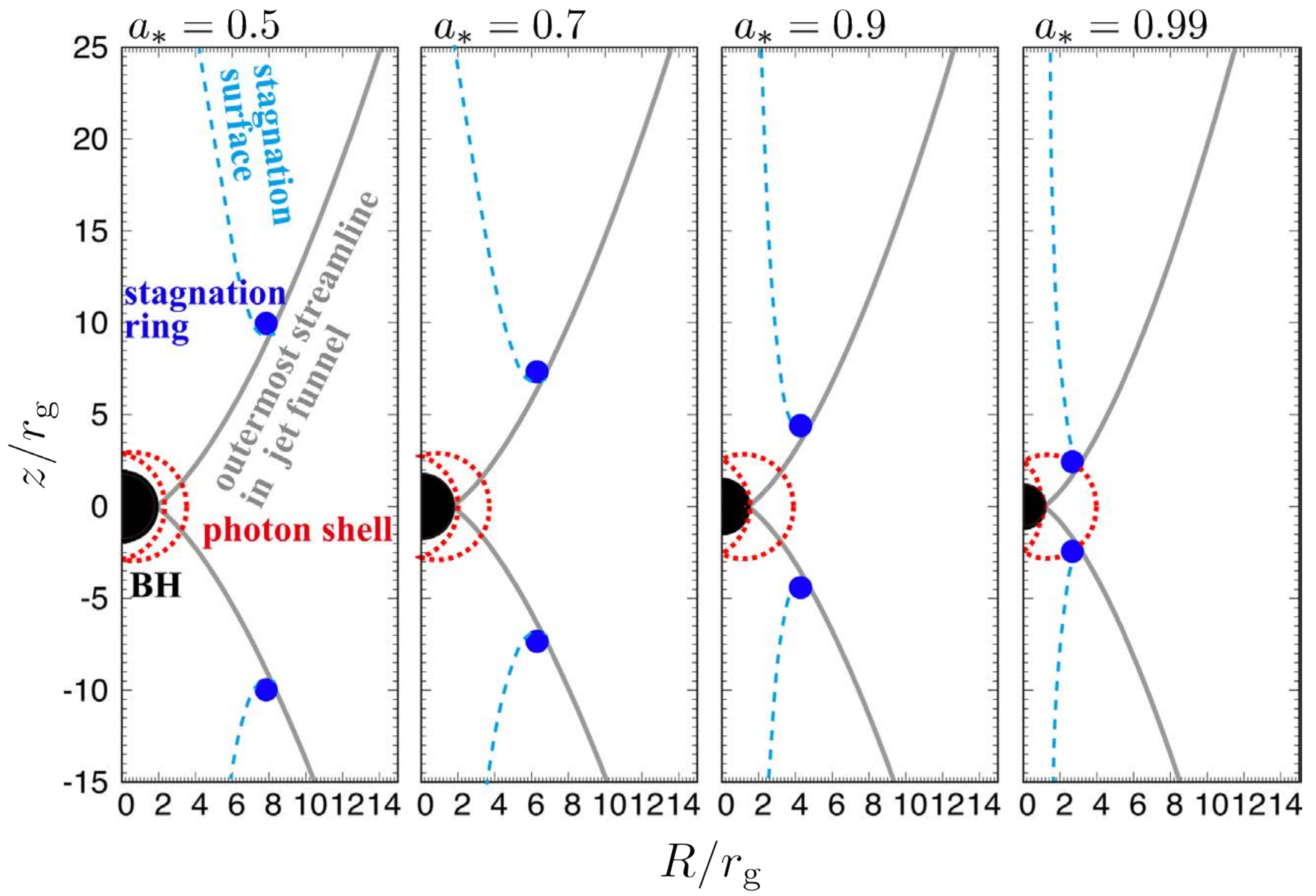


Photon sphere of highly spinning BH



Appearance of jet injection point

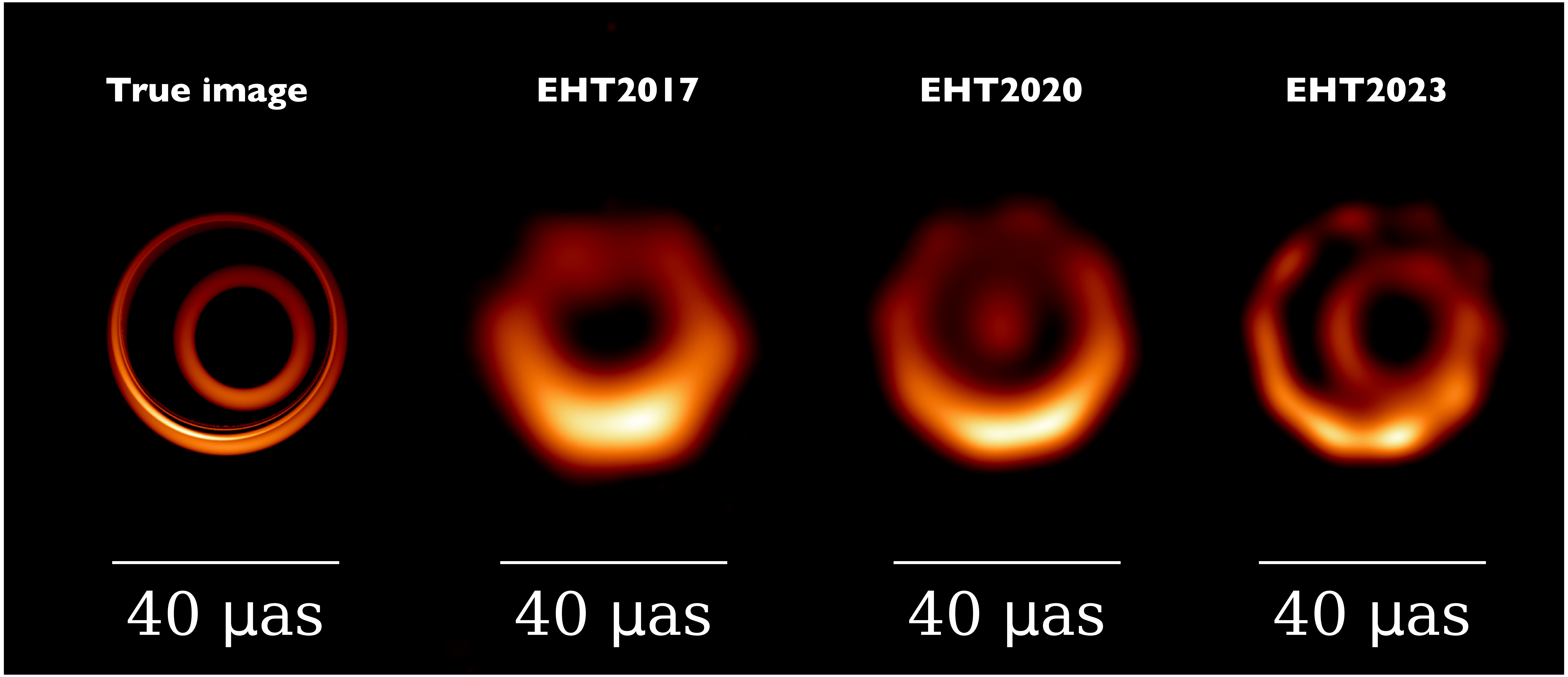




- Large BH spin→Direct image of jet tends to overlap to the photon ring
- For a=0.99, diirect image of counter jet overlaps to the photon ring, but inner ring due to approaching jet still appears.

→ Conflict with EHT 2017? Let us examine assuming the array of EHT

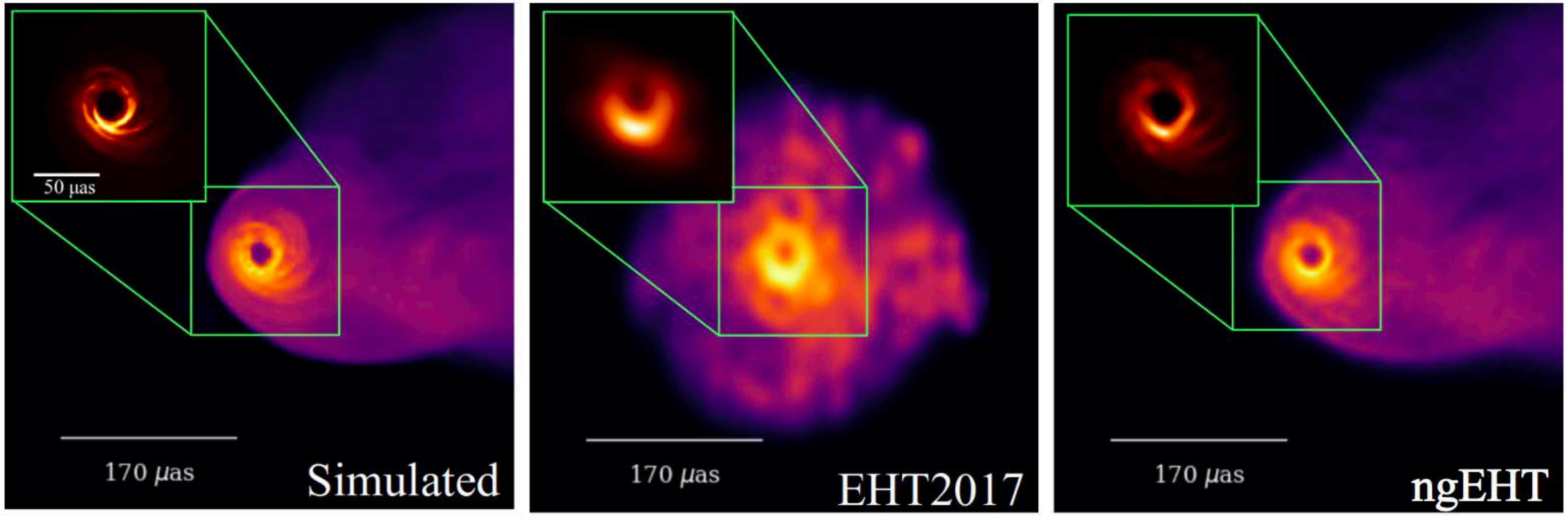
Synthetic image of jet-base emission



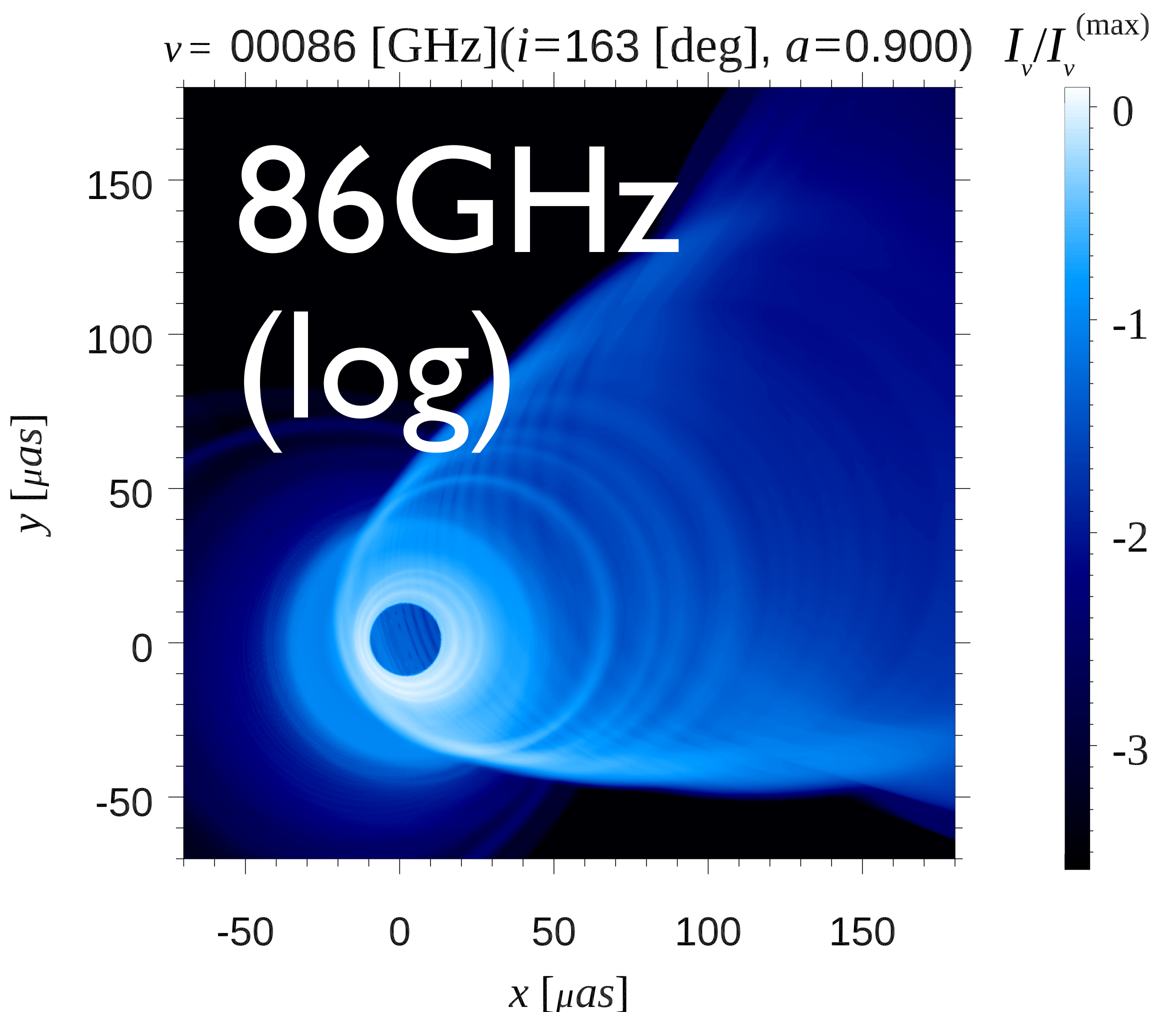
- "Photon ring + jet-base image" can reproduce the observed image with EHT2017 (It should be emphasized that this a fine tuning model).
- This means that the observed image may include the important information of the jet base.
- We can examine our models using forthcoming EHT!

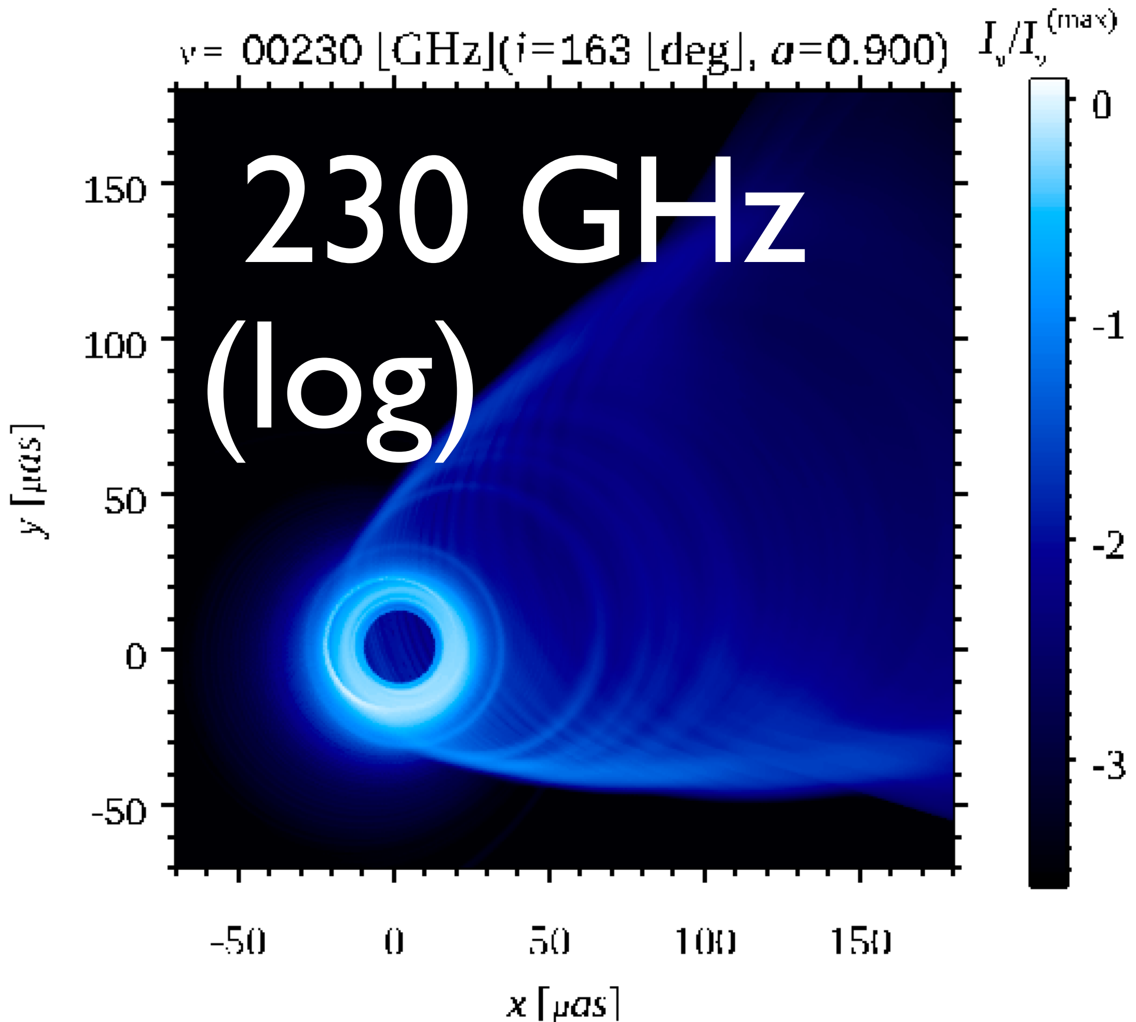
Explore the global jet structure

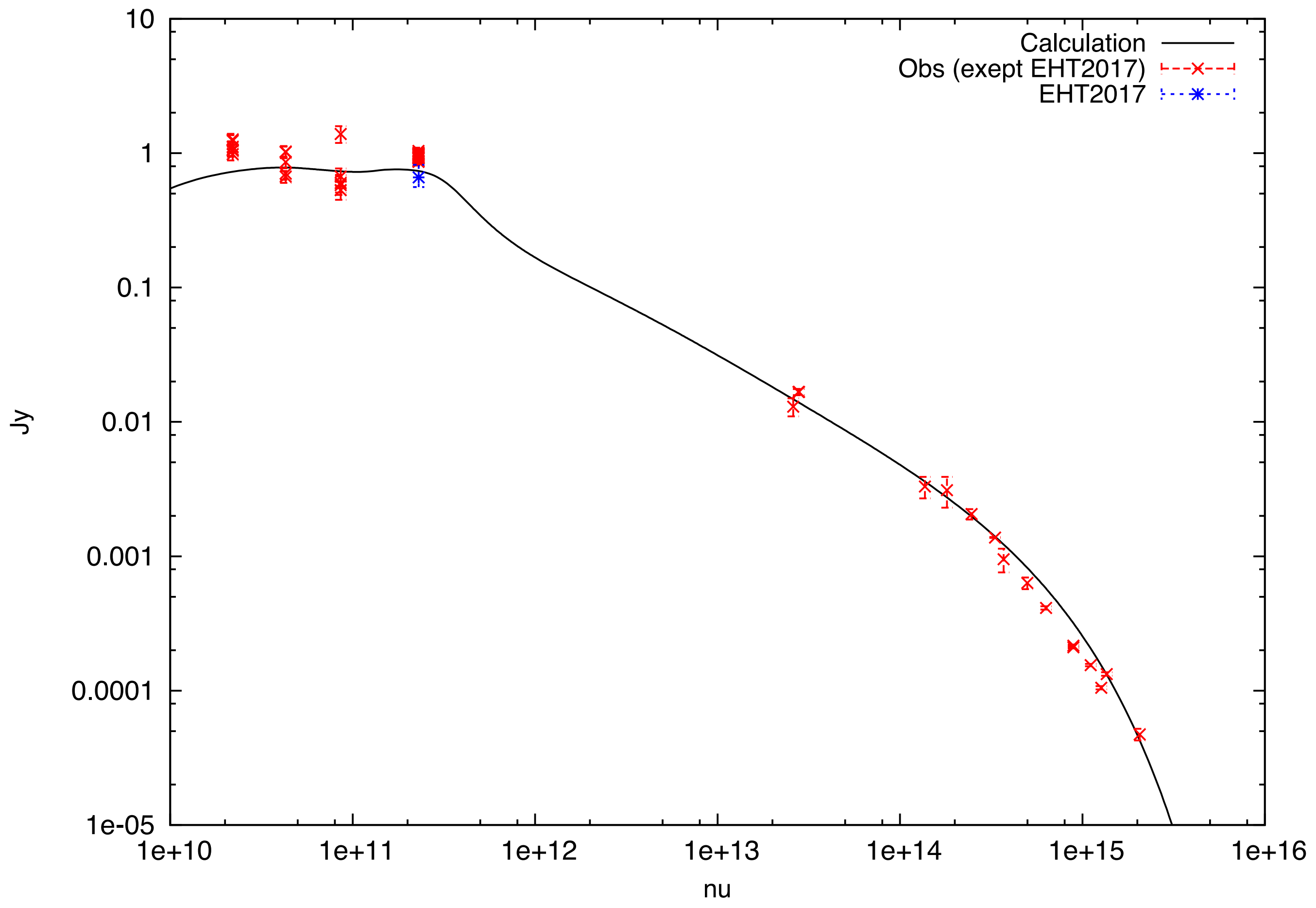
(Blackburn et al. 2019, astro2020 white paper GRRMHD simulation Chael + 2019)



We are performing multi-wavelength simulations including non-thermal electrons! (Kawashima + in prep.)

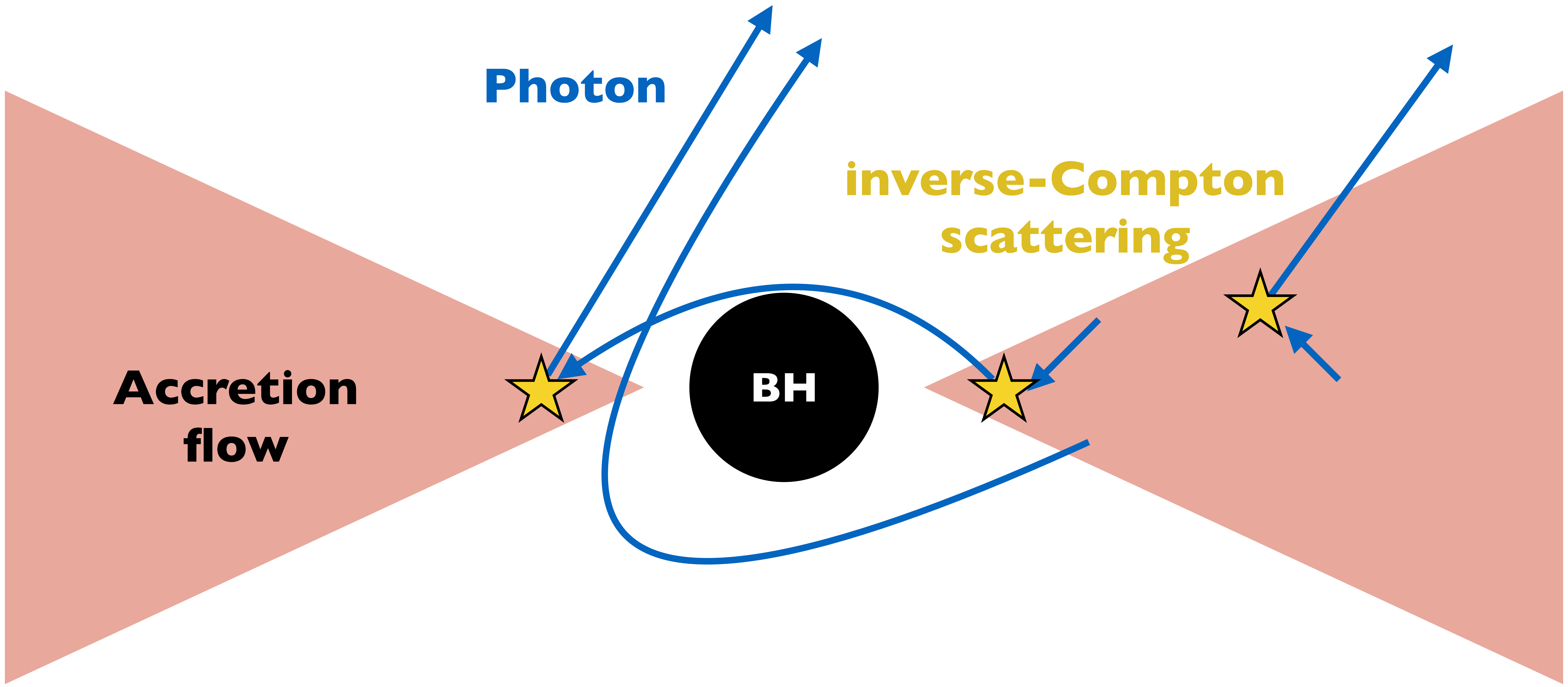






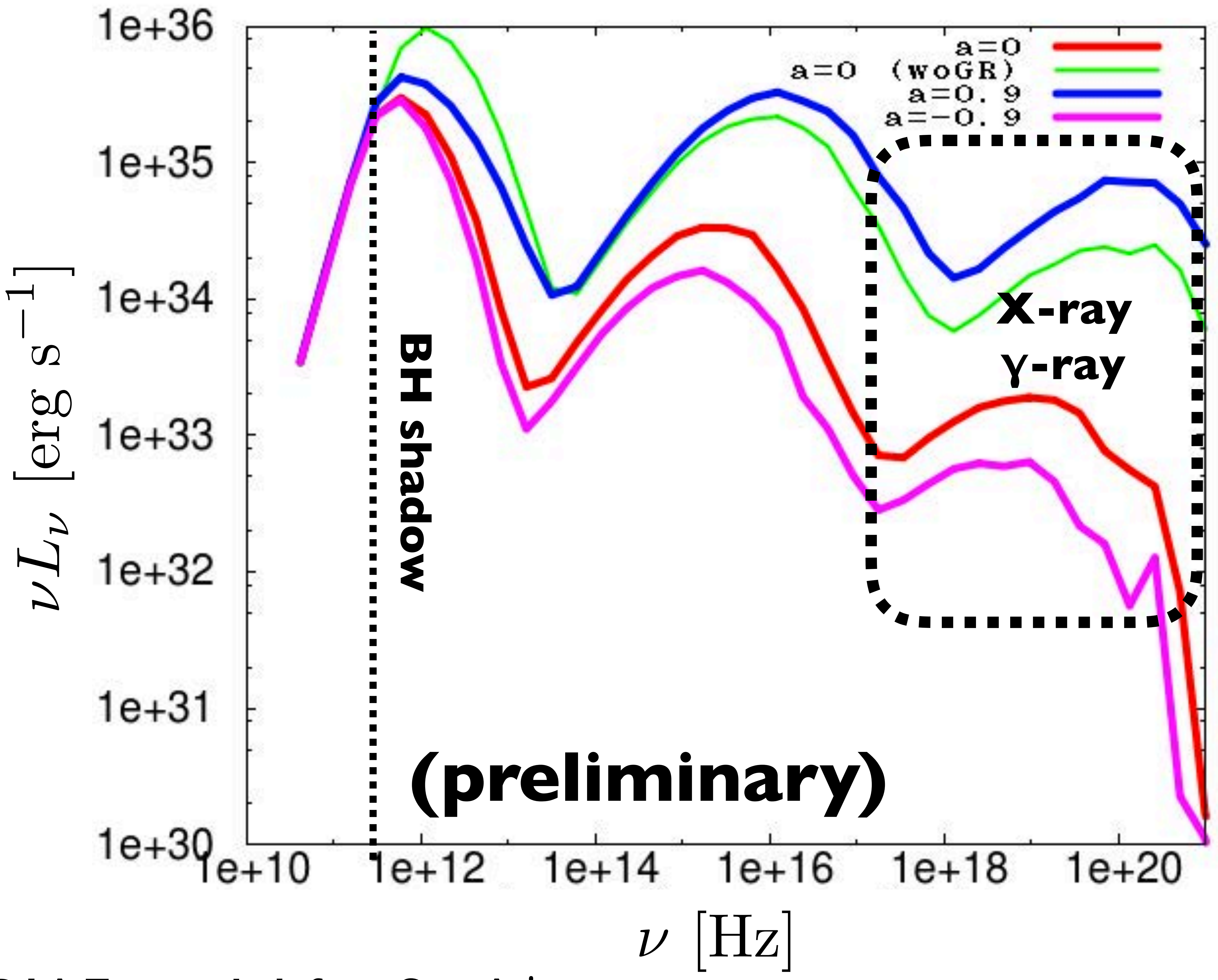
Towards multi-wavelength study from radio to gamma-ray

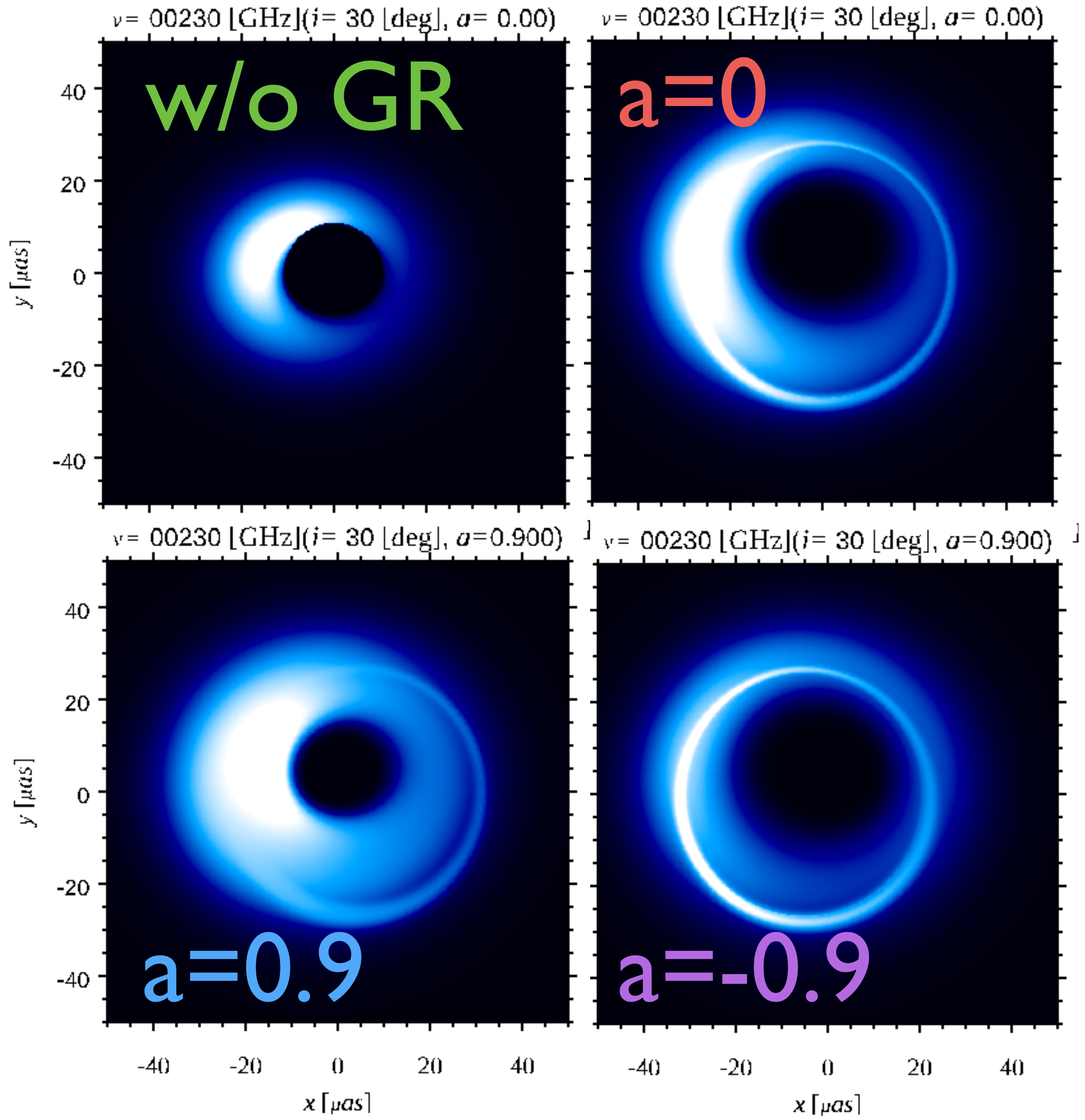
Is it possible to determine the spin using X-ray, γ-ray?
Model setup



- 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 (来光)
- BH mass 4.3 x 106 M_sun
- BH spin a = -0.9, 0, 0.9
- viewing angle i = 30 degree

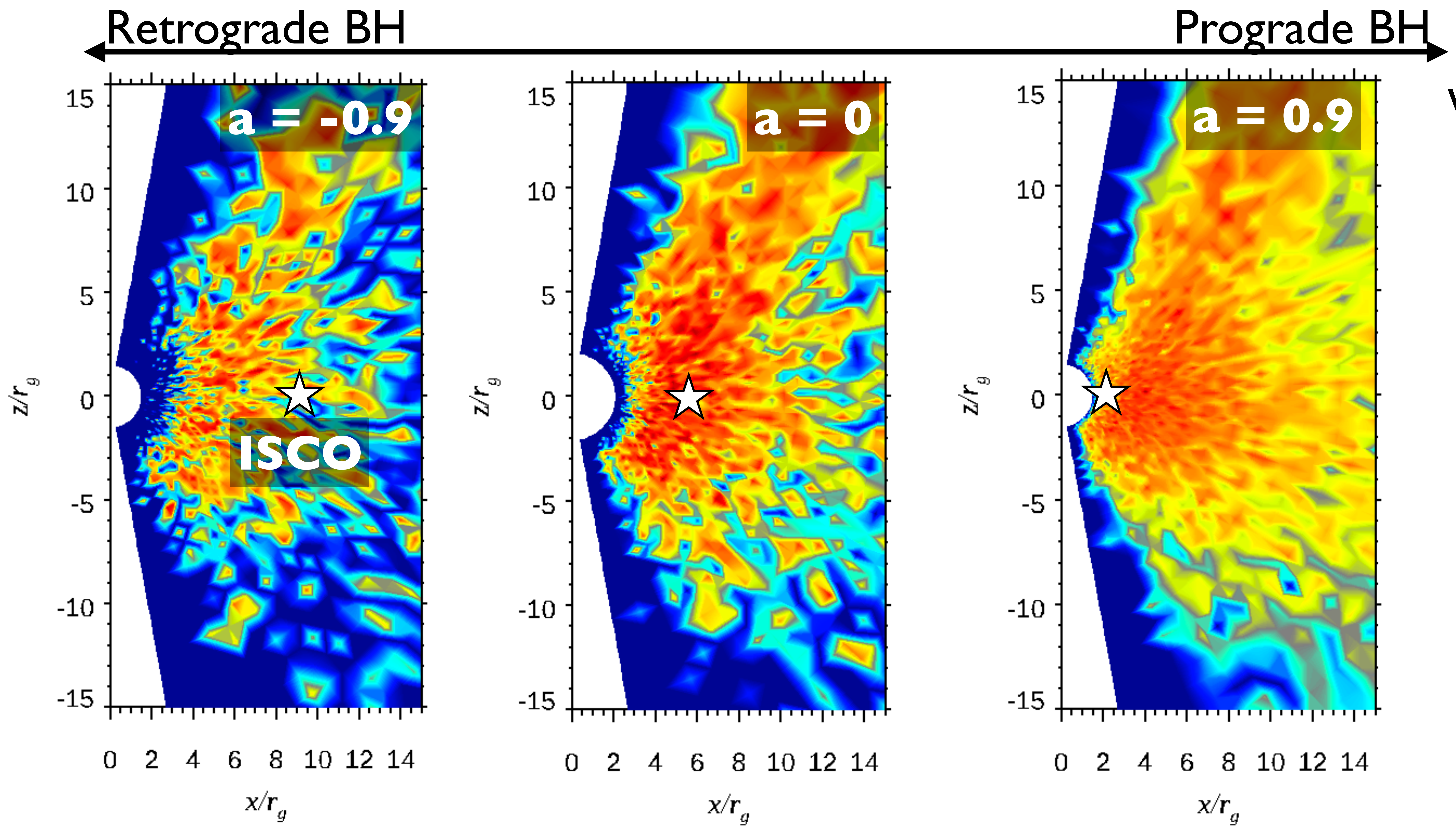
BH shadow + Multiwavelength SED





- Simple RIAF model for SgrA*
- BH spin signifiantly affect 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.

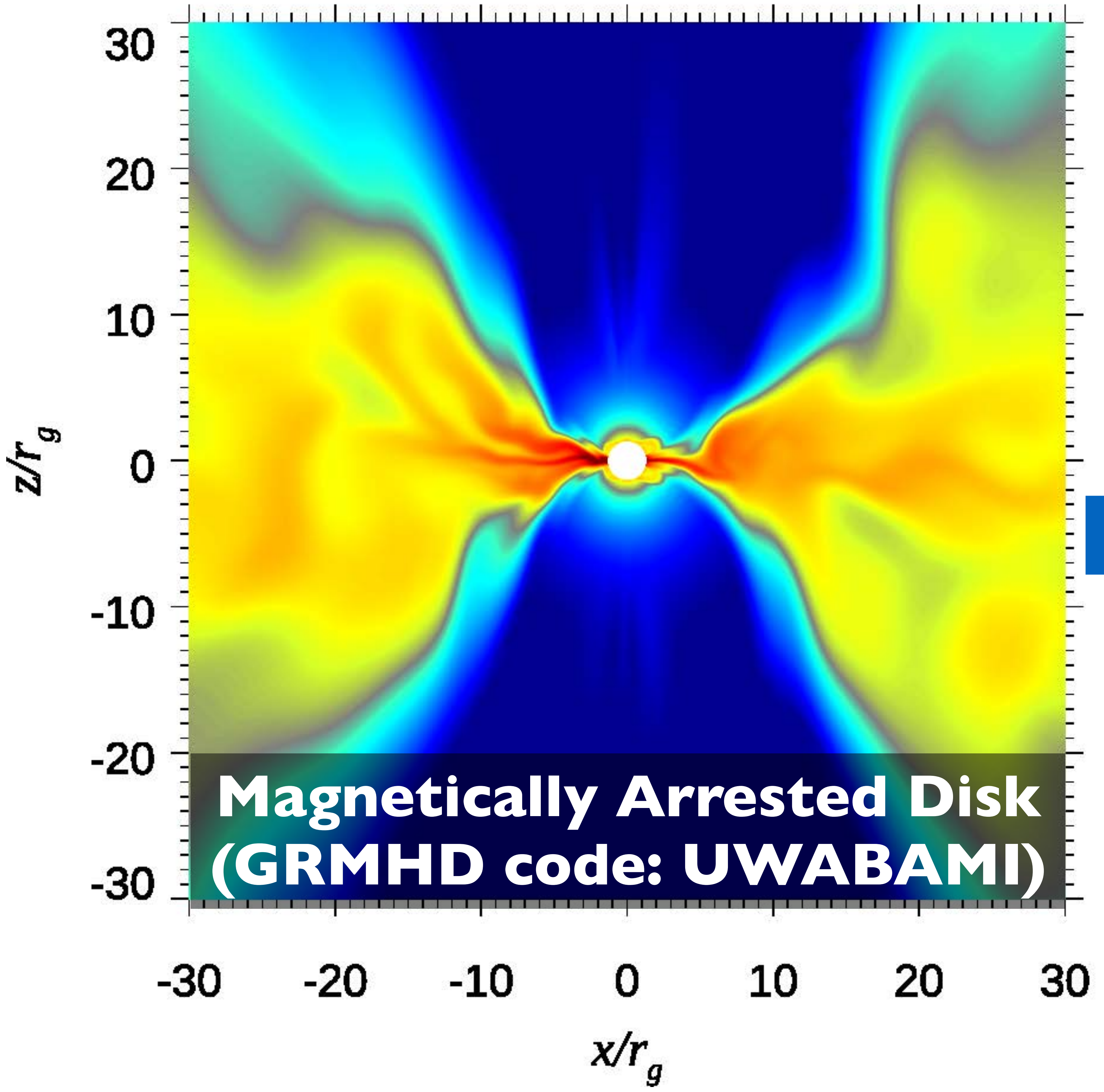
Where does the inverse-Compton scattering take place ?



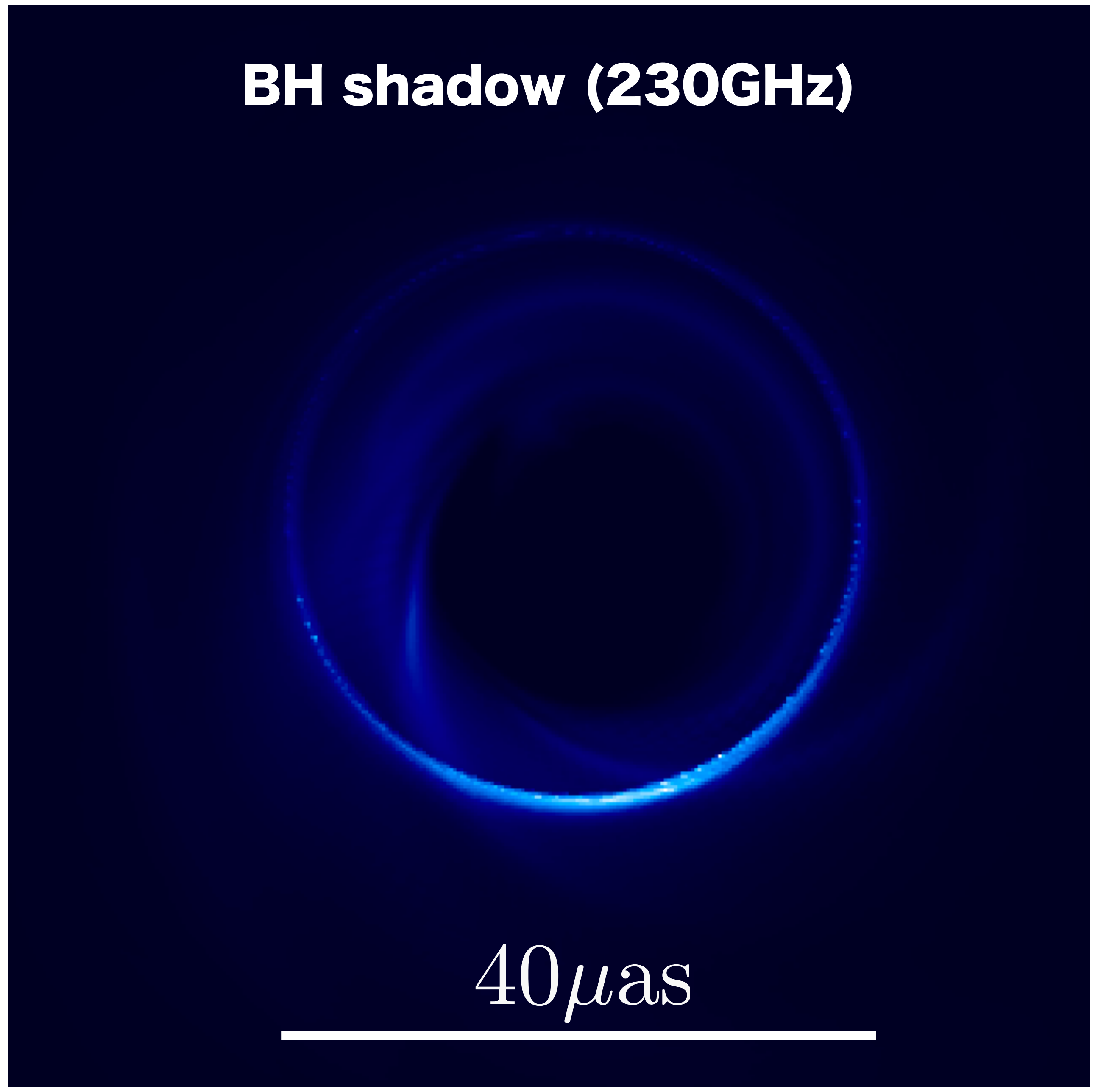
Viewing angel is 30 degree

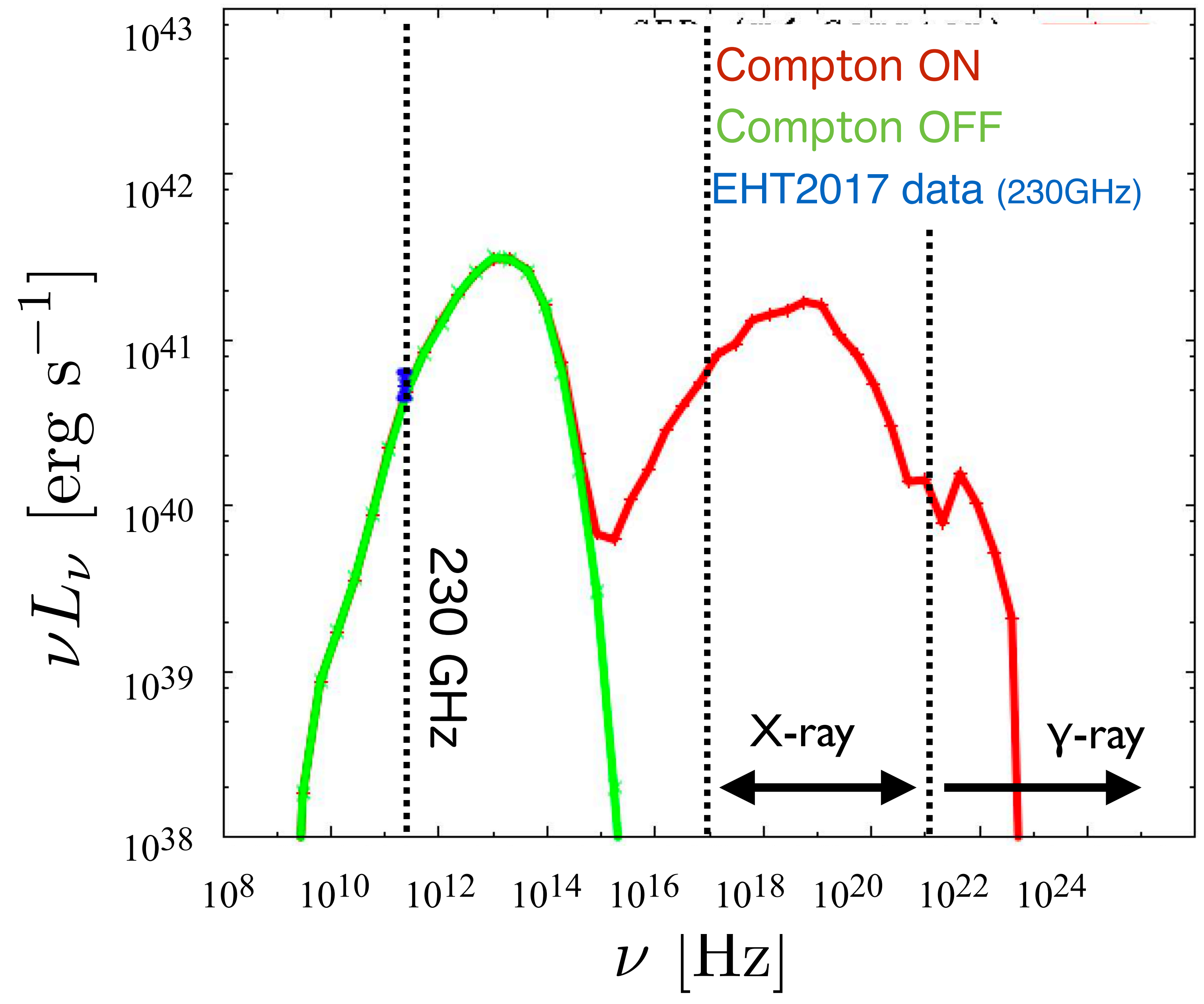
- Color displays where the how many photons are upscattered with recording the highest frequency and escape to the observer at 30deg (red/bule: large/small amount)
- We speculate that retrgrad BH →outer location of ISCO →significant inflow motion → scattered photons are beamed into the BH → less X-ray emission

Towards GRMHD simulation study



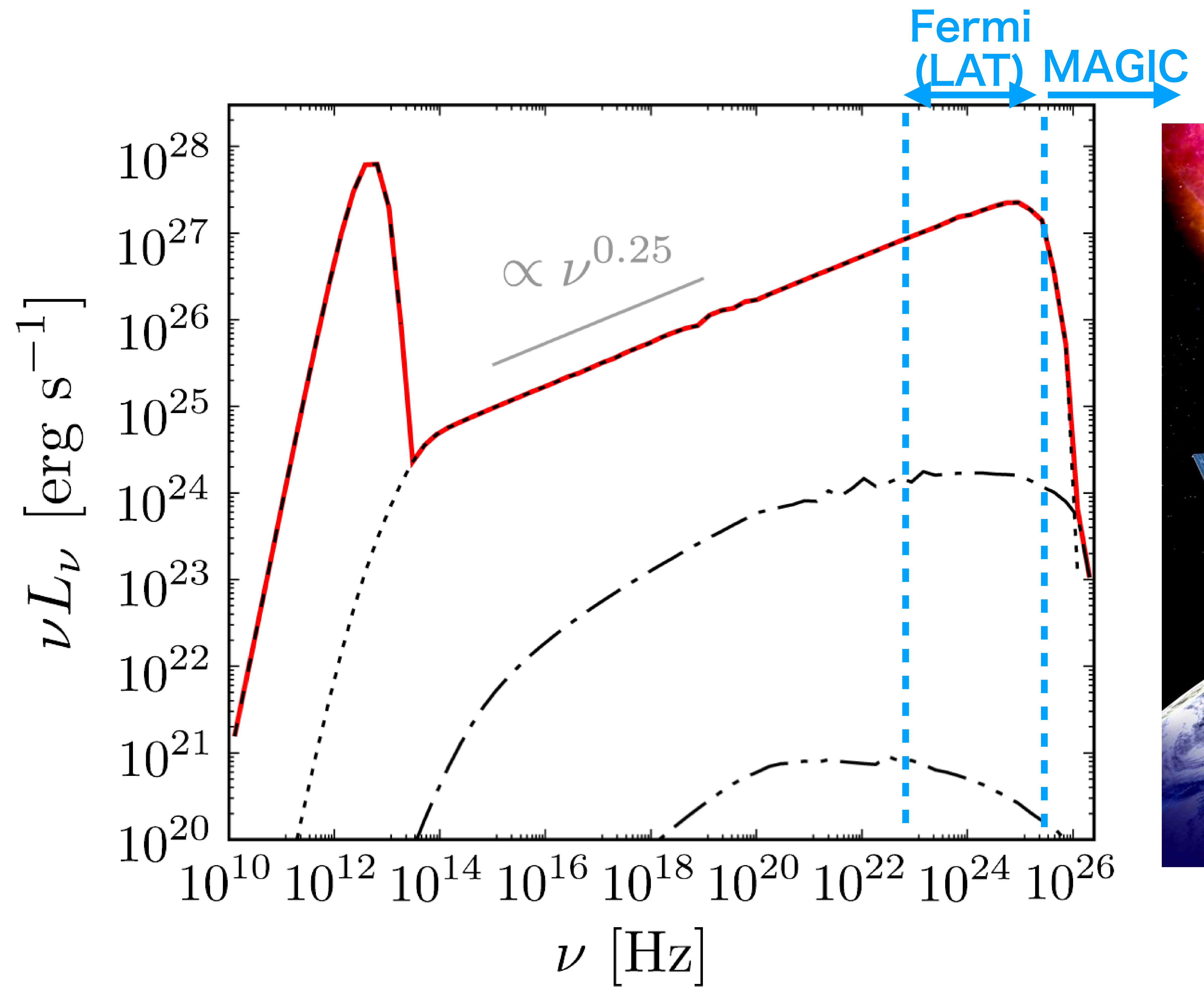
BH shadow + MWL SED





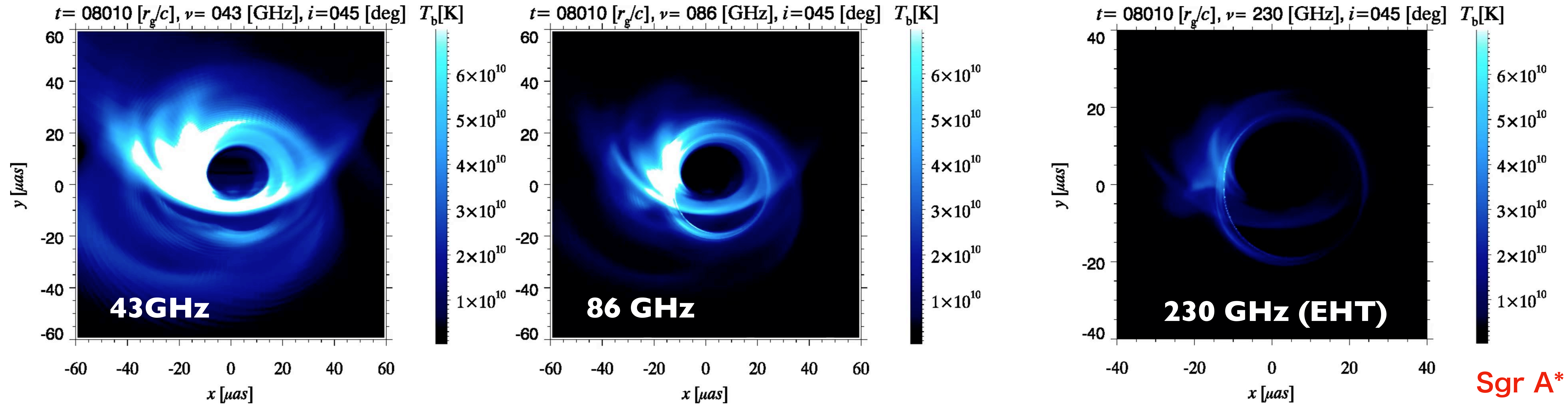
- Using GRMHD simulation (using UWABAMI code), we have started the calculation of BH shadow + MWL SEDs.
- Using the MWL SEDs, we are planning to explore the possibility of feature extraction.

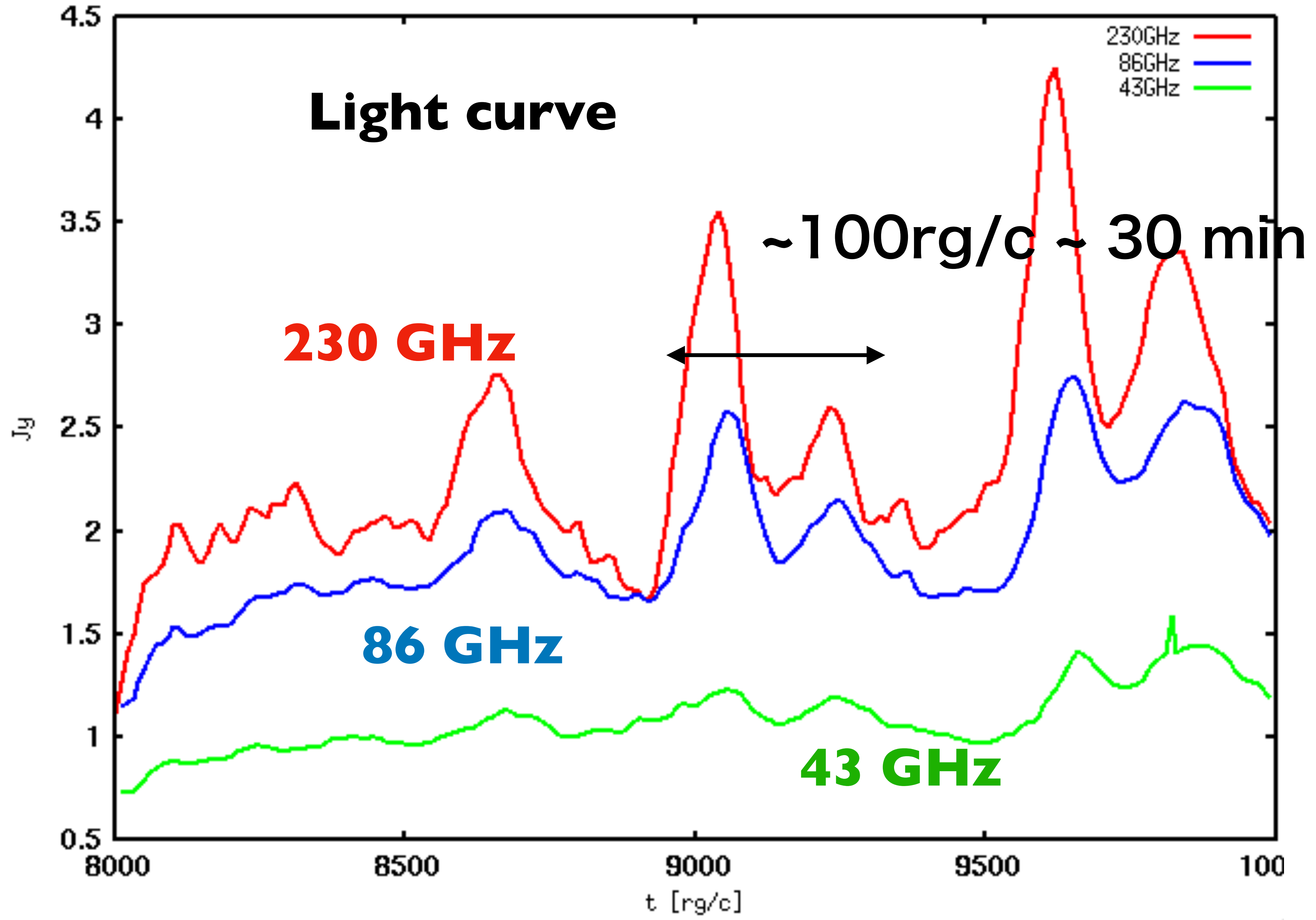
Towards (Very High Energy) gamma-ray



- The calculation module for Compton scattering w/ non thermal electrons have been implemented!
- We are planning to study the origin of jets and the physics of accretion flow in future work.

Towards lower photon frequency (preliminary)





- Time variation w/ ~100rg/c ~ 30 min have been observed in GRMHD simulation.
- What is the origin? It would be the imprint of important physics of accretion flow.

Summary

- EHT 2017 successfully observed BH shadow in M87*, and the BH mass is determined to be ~6 billion solar mass.
- Big issues still remain, e.g., BH spin, jet and accretion physics.
- Using multiwavelength, general relativistic radiative transfer code RAIOKOU, we are studying these issues.
  - ✓ Suggestion of a new method to constrain the BH spin with crescent-shadow in luminous state of M87. (future space-VLBI can detect).
  - ✓ Jet emission may be included in the ring-like image of EHT 2017 (ngEHT can identify our model)

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