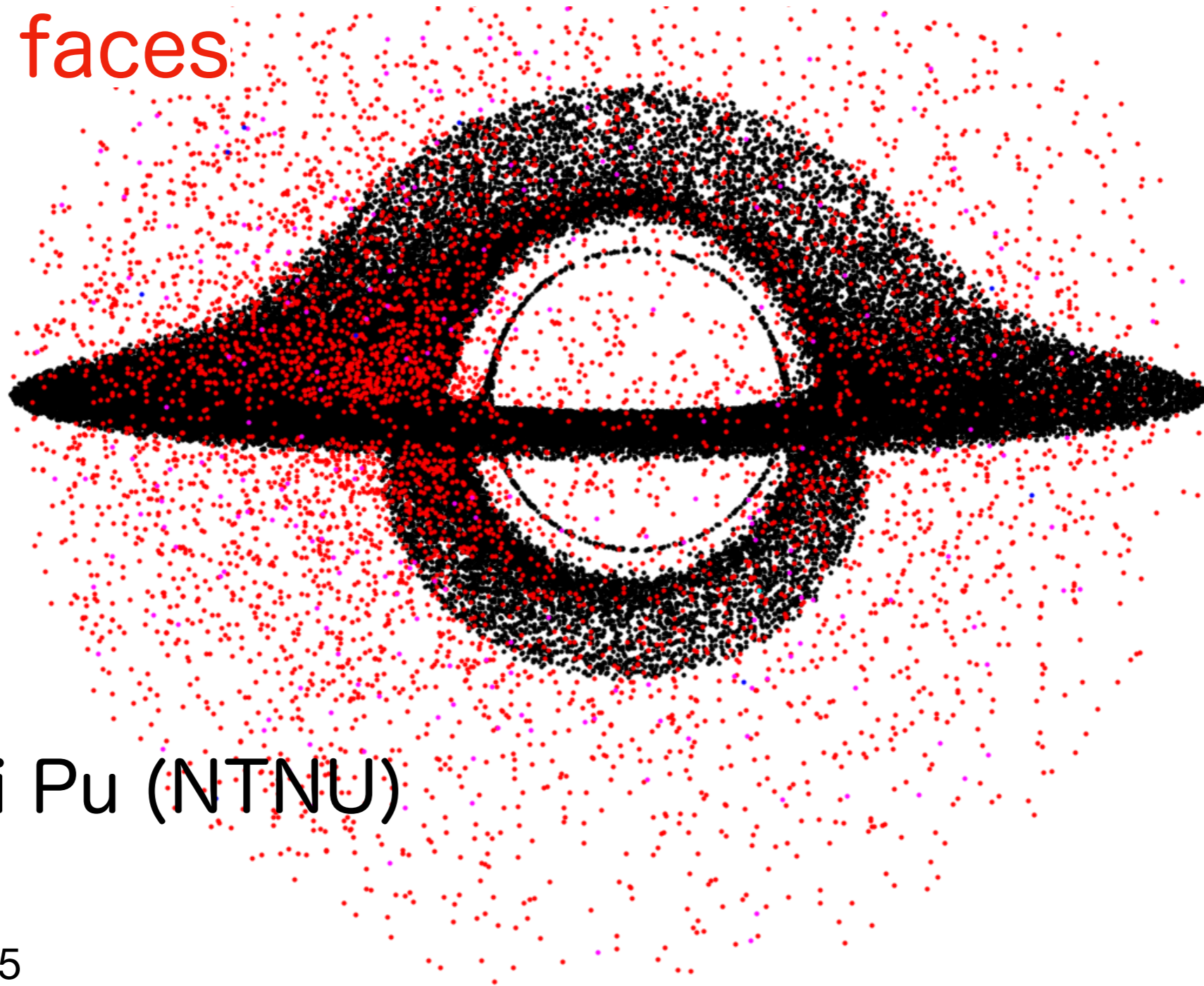


Seeing the Unseeable:

GPU-powered portraits of a black hole's many faces



Hung-Yi Pu (NTNU)

EANAM10

September 15

EHT 2019



Curved spacetime

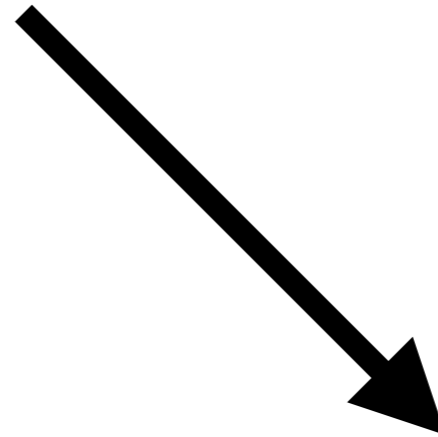
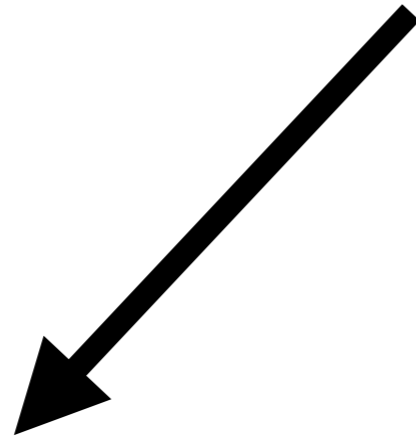
+

Radiative transfer

= GRRT

(General relativistic Radiative Transfer)

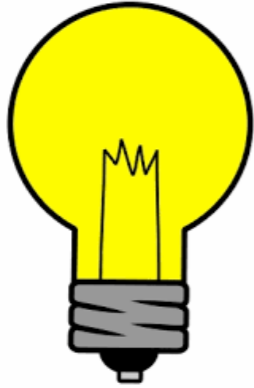
GRRT



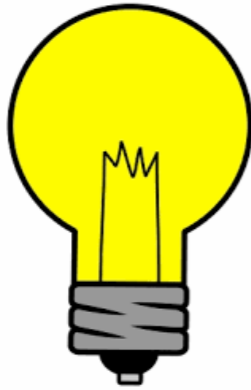
observer to source

source to observer

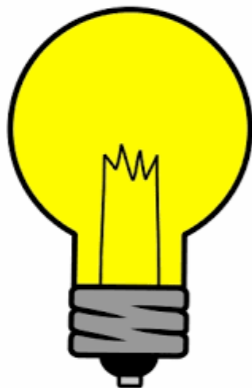
source to observer
(forward in time)



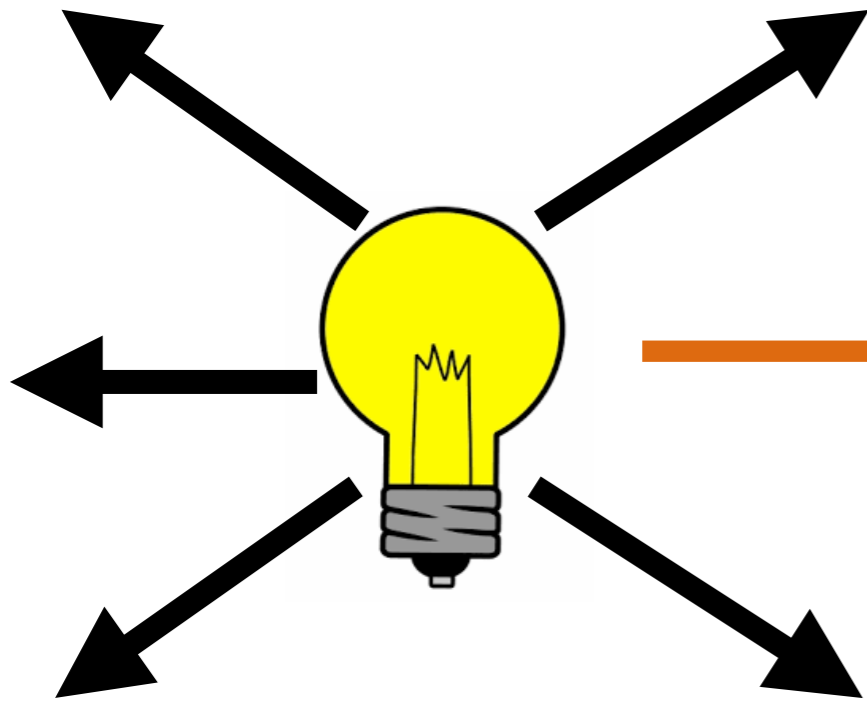
source to observer
(forward in time)



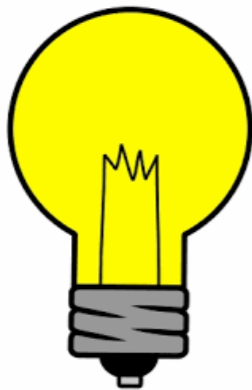
observer to source
(Backward in time)

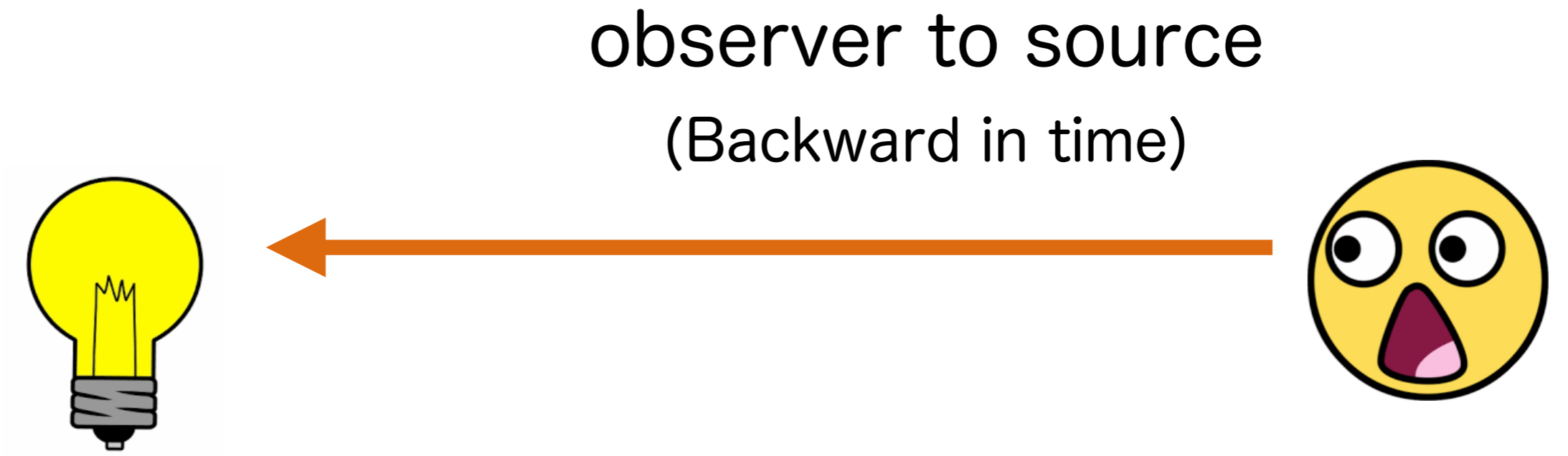
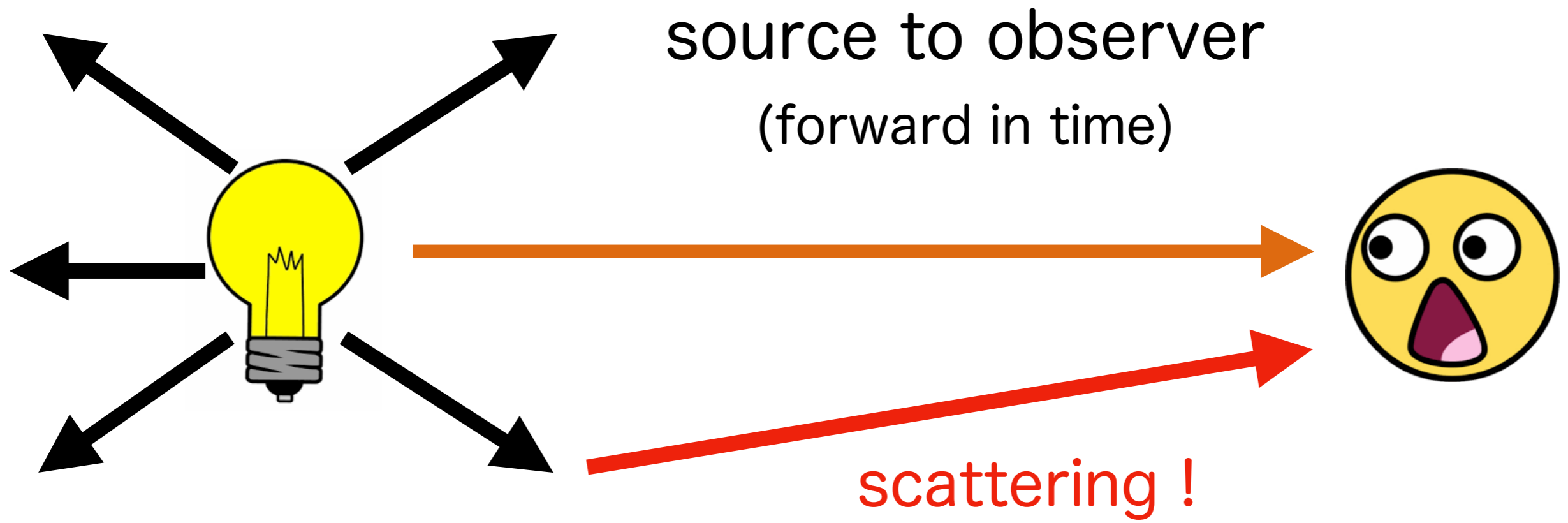


source to observer
(forward in time)

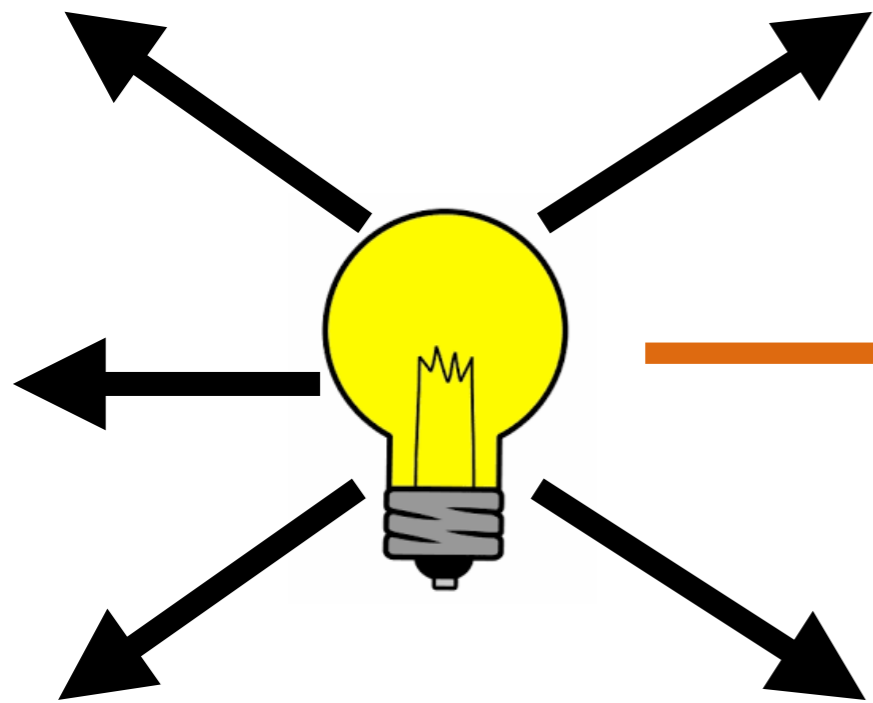


observer to source
(Backward in time)





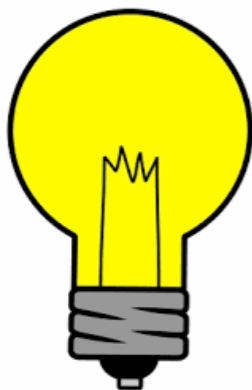
source to observer
(forward in time)



scattering !

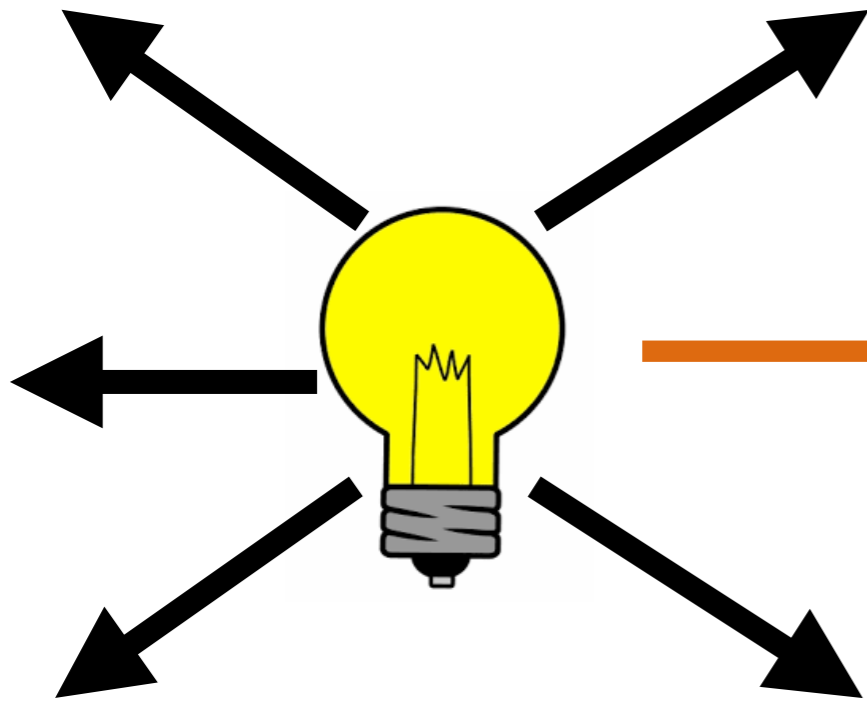
X-ray observation

observer to source
(Backward in time)

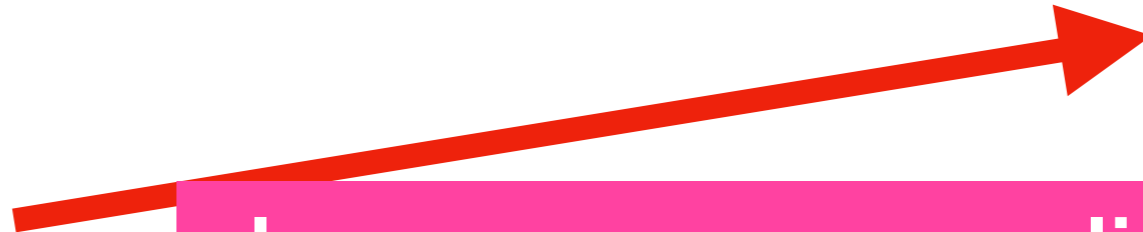


Radio observation

source to observer
(forward in time)



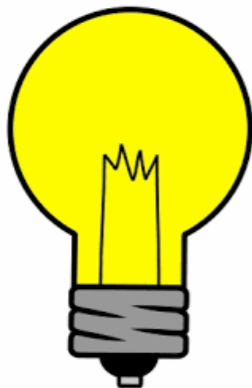
X-ray observation



slower, more complicated,
but powerful



observer to source
(Backward in time)



Radio observation



faster and "easy"



outline

GRRT



observer-to-source

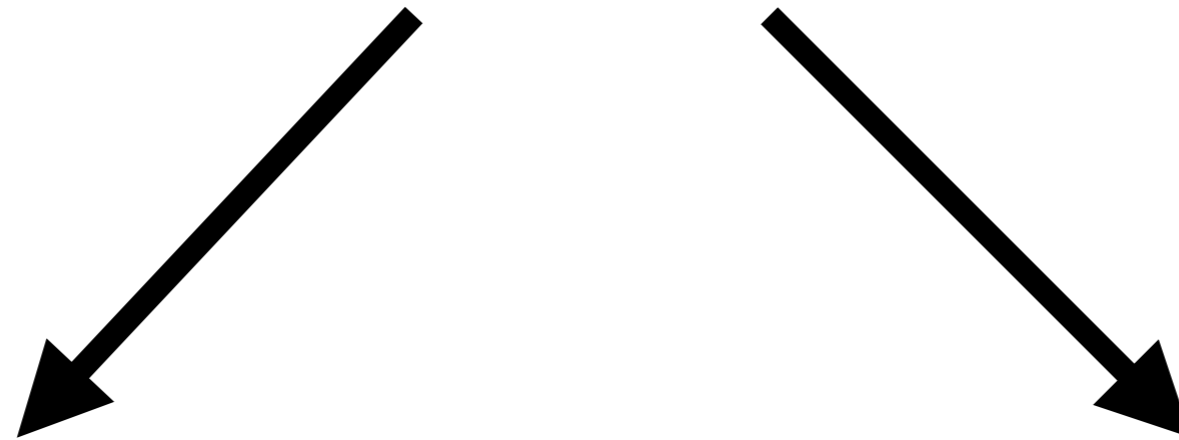
- How it works
- Odyssey example: Modeling EHT image with *Odyssey*

How GPU can help?

source-to-observer

- MCRT (Monte Carlo Radiative Transfer)
- How it works
- photon packet
- (inverse Compton) scattering physics
- *Iliad* example: Modeling stellar mass BH image and spectra

GRRT



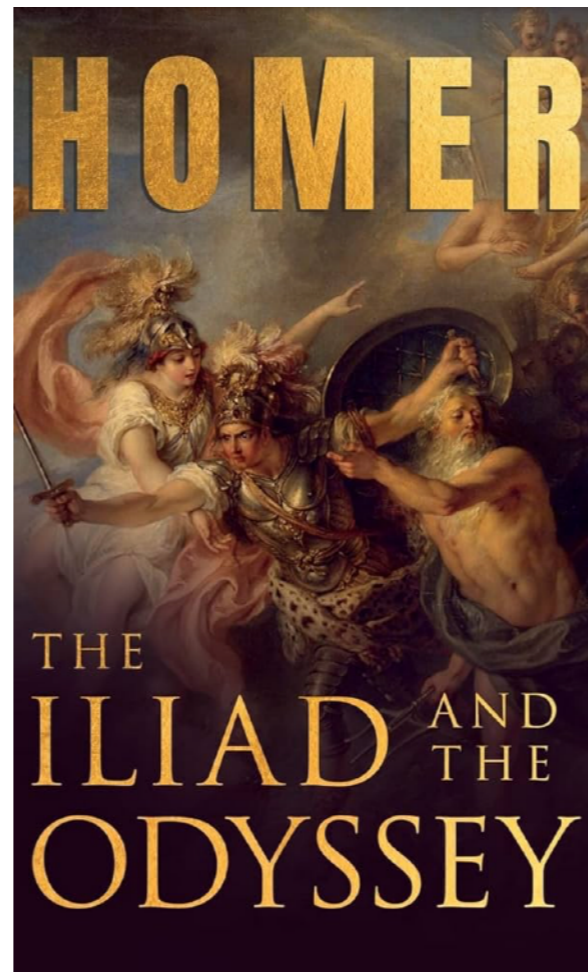
observer-to-source

source-to-observer

GPU code:
Odyssey
(Pu & Yun et al. 2016)

Other **GPU codes**:
GRay (Chan et al. 2013)

Other available **CPU codes**:
ipole (Moscibrodzka & Game 2018),
BHOSS (Yours stall. 2012, 2020),
grtrans (Dexter 2016),
Raptor (Bronzwaer 2018) etc.



GPU code:
Illiad
(coming soon)

Other available **CPU codes**:
grmonty (Dolence et al. 2009),
RAIKOU (Kawashima et a. 2023)

observer to source approach
&
Odyssey code

GR Radiative Transfer

* photon p_α *energy shift

* fluid u^α $\frac{E_{\text{comoving}}}{E_{\text{obs}}} = \frac{p_\alpha u^\alpha|_0}{p_\alpha u^\alpha|_\infty}$

*radiative transfer

$$\frac{d\mathcal{I}}{d\tau_\nu} = -\mathcal{I} + \frac{\eta}{\chi}$$

$\mathcal{I} = I_\nu/\nu^3 = \text{invariant}$

$\chi = \nu\alpha_\nu$
(invariant)

$\eta = j_\nu/\nu^2$
(invariant)

Modeling BH image: How it works

$$\gamma^{-1} \equiv \frac{E_{\text{comoving}}}{E_{\text{obs}}} = \frac{p_\alpha u^\alpha|_0}{p_\alpha u^\alpha|_\infty}$$

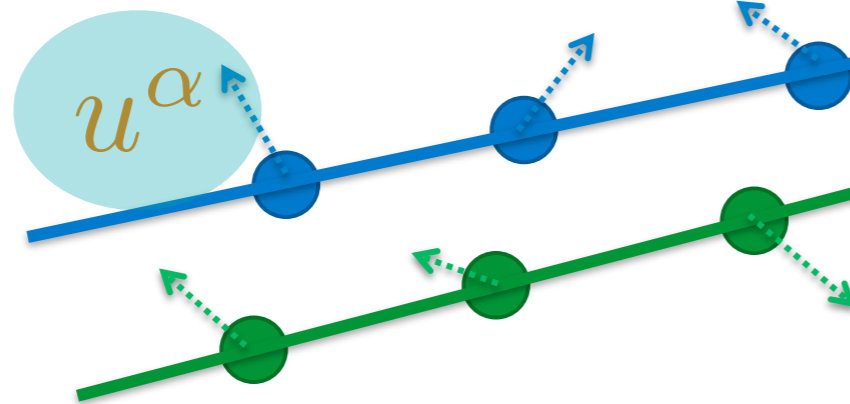
Fuerst & Wu 2004

$$\mathcal{I} = I_\nu / \nu^3 = \text{invariant}$$

$$p_t = -E$$

$$p_\phi = L_z$$

fluid's co-moving frame



observer's image frame

$$\left(\frac{dt}{d\lambda}, \frac{dr}{d\lambda}, \frac{d\theta}{d\lambda}, \frac{d\phi}{d\lambda}, \frac{dp_r}{d\lambda}, \frac{dp_\theta}{d\lambda} \right)$$

Fuerst & Wu 2004

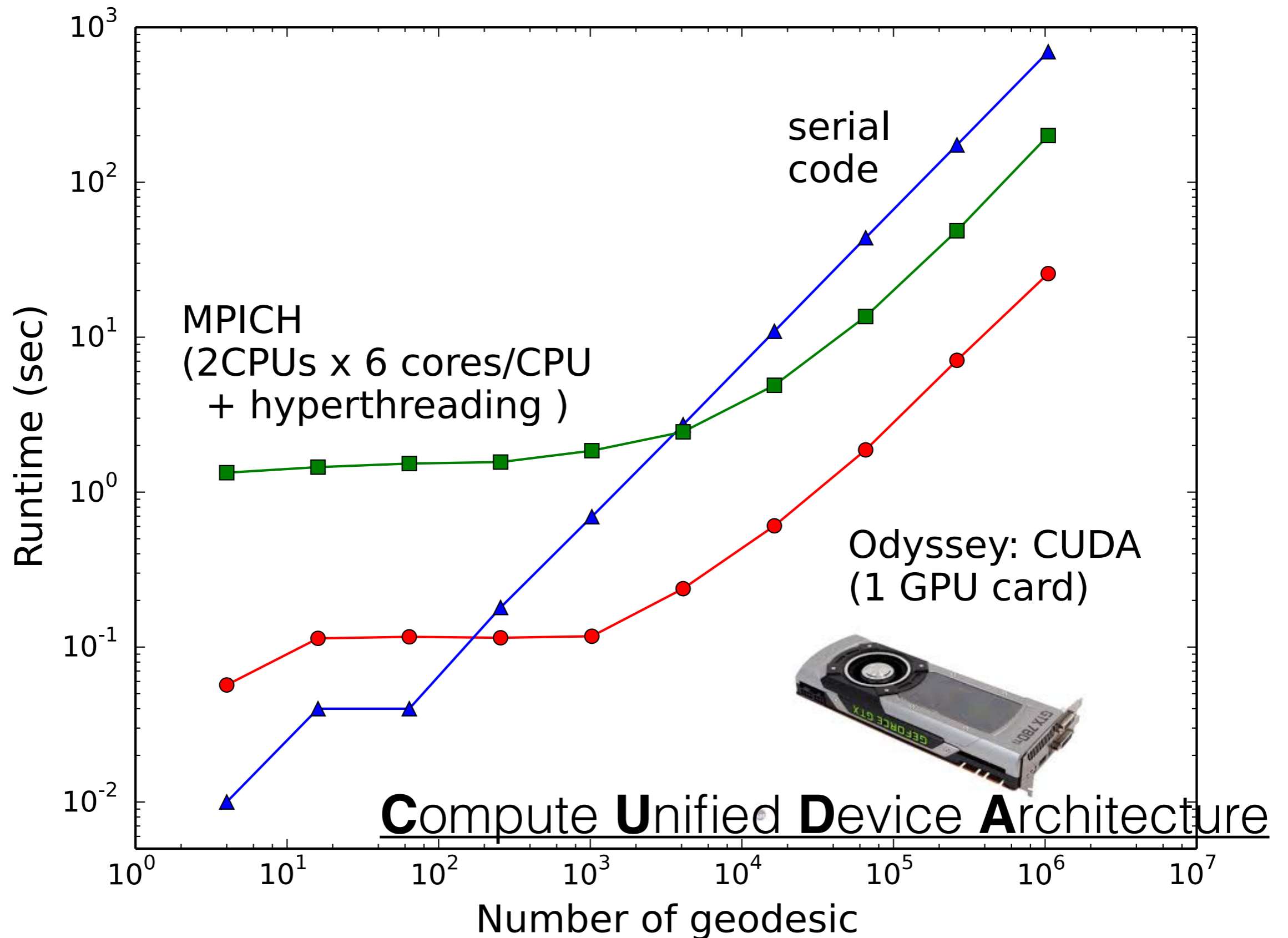
$$\frac{d\mathcal{I}}{d\tau_\nu} = -\mathcal{I} + \frac{\eta}{\chi}$$



$$\frac{d\tau}{d\lambda} = \gamma^{-1} \alpha_{0,\nu}$$

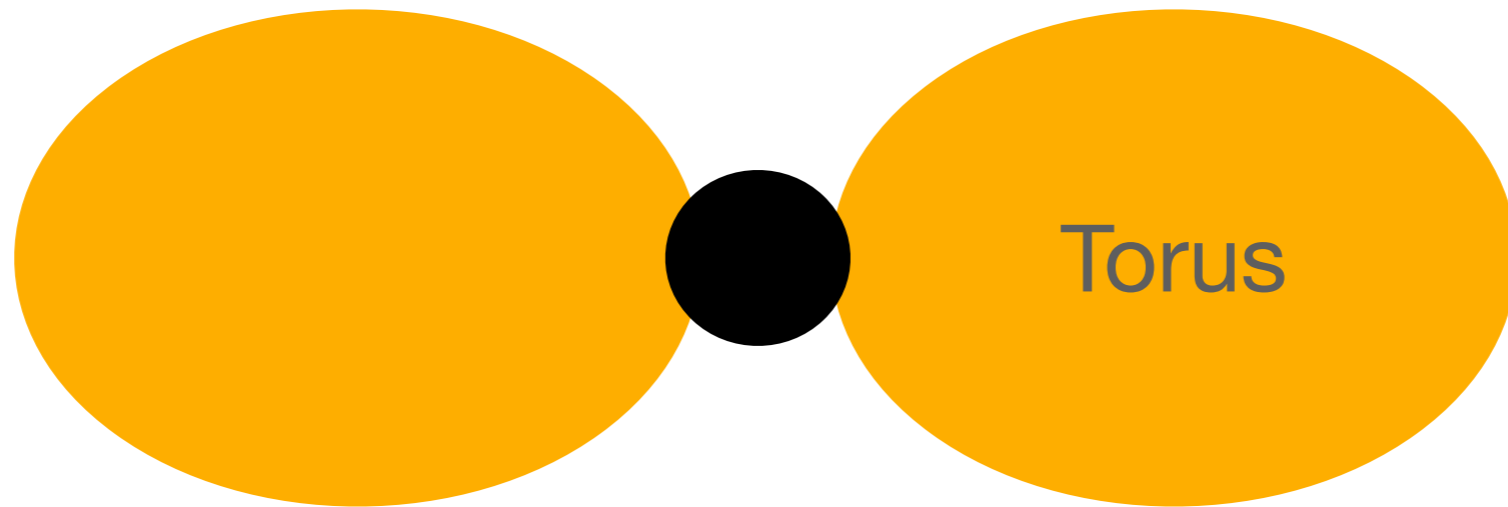
$$\frac{d\mathcal{I}}{d\lambda} = \gamma^{-1} \left(\frac{j_{0,\nu}}{\nu^3} \right)$$

Odyssey: a GPU based parallel code for GRRT

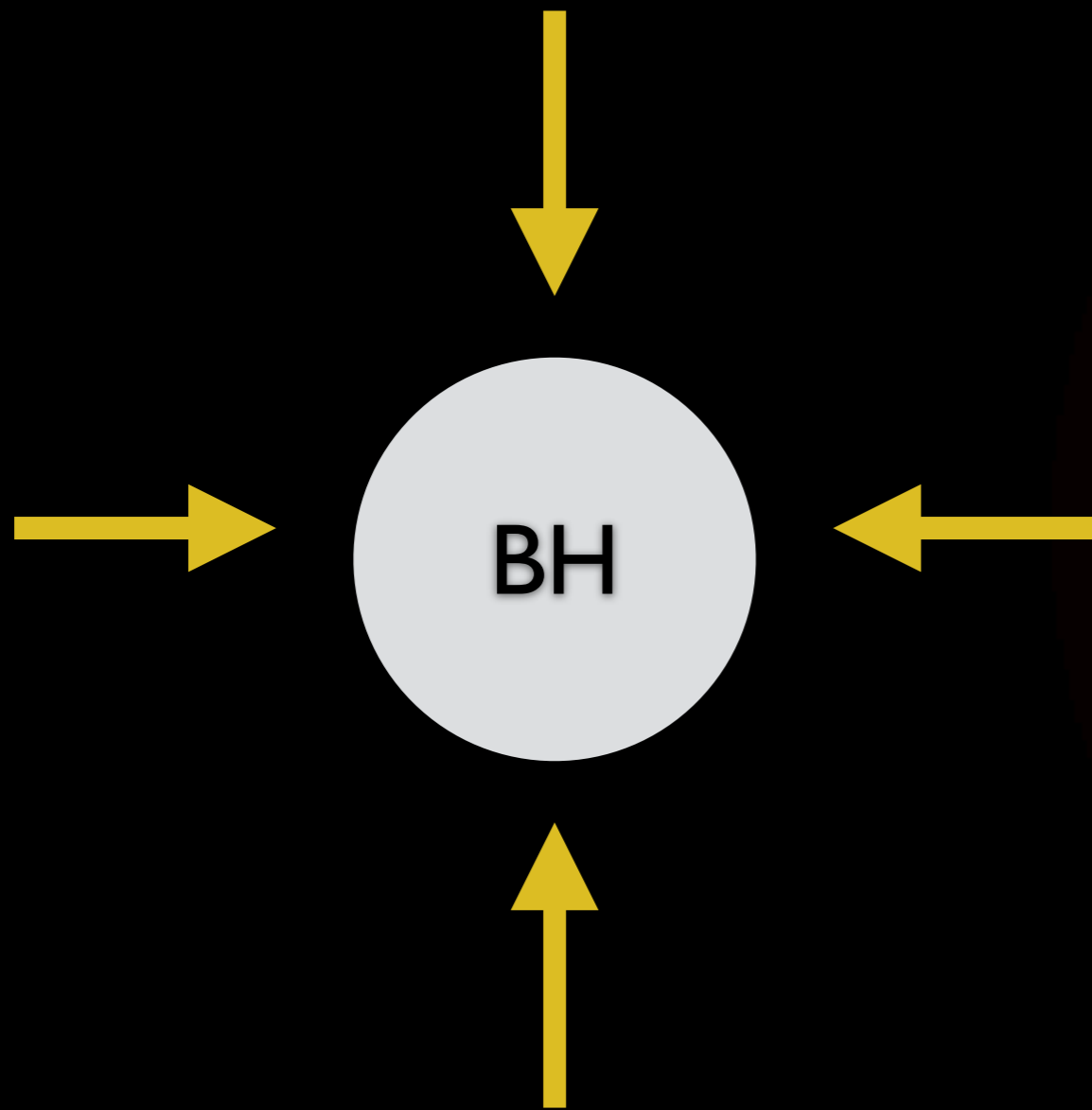


Odyssey example:

Non-rotating BH with a
geometrically thick accretion flow



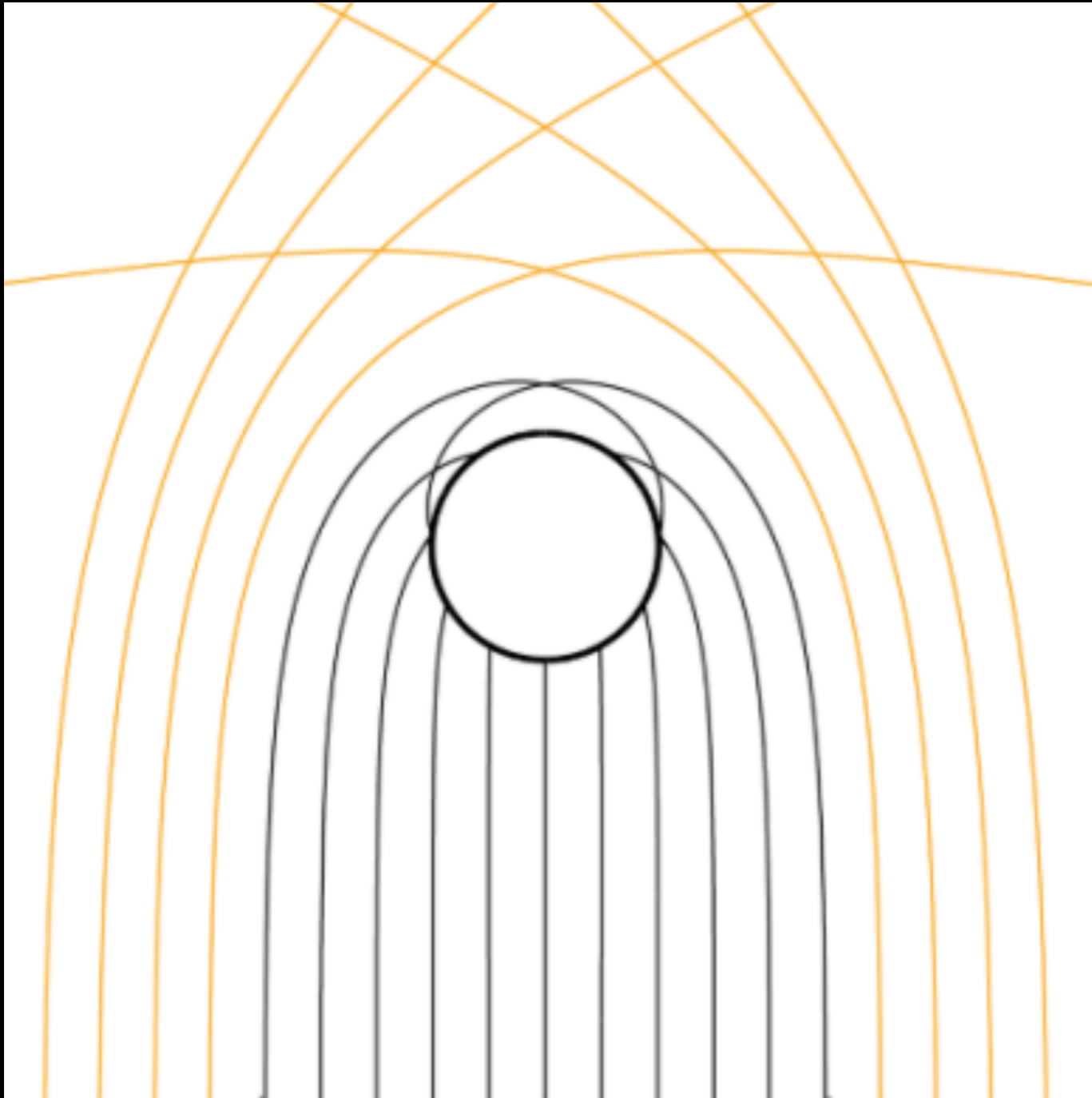
Black hole shadow size $\sim 10 GM/c^2$



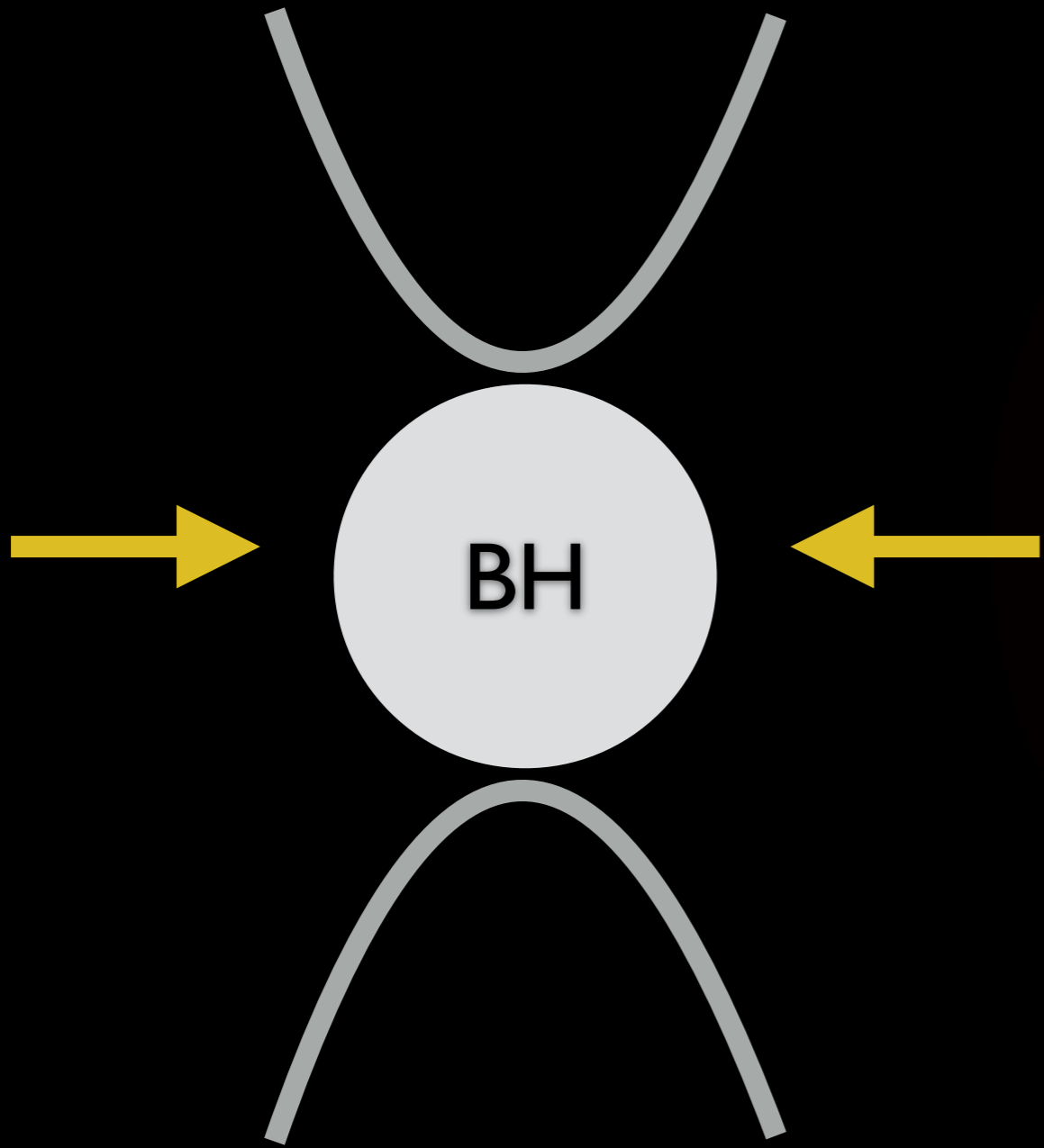
geometrically thick, optically thin accretion flow
(quasi-spherical flow)

e.g., Falcke et al. 2000

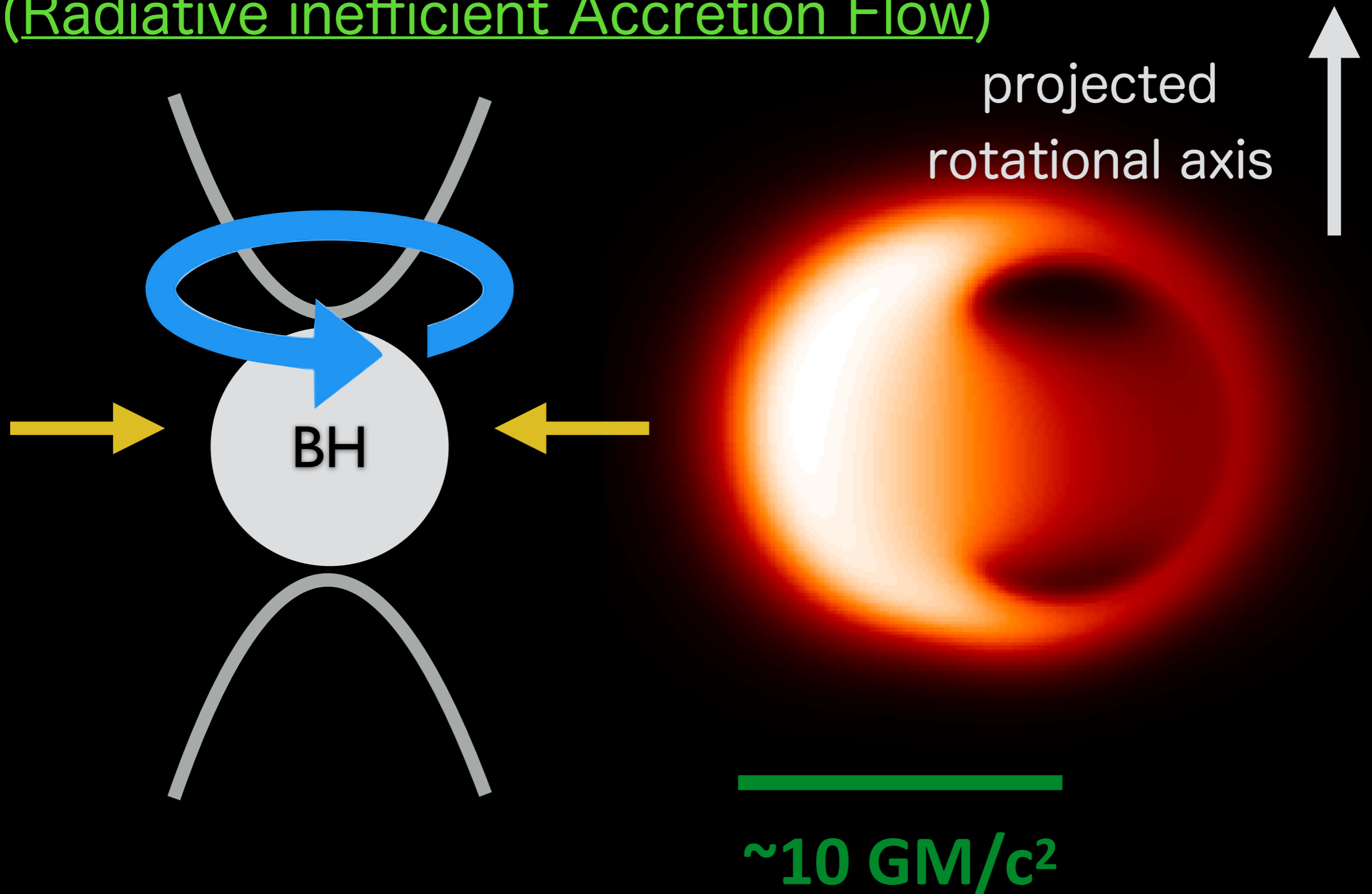
Black hole shadow size $\sim 10 GM/c^2$



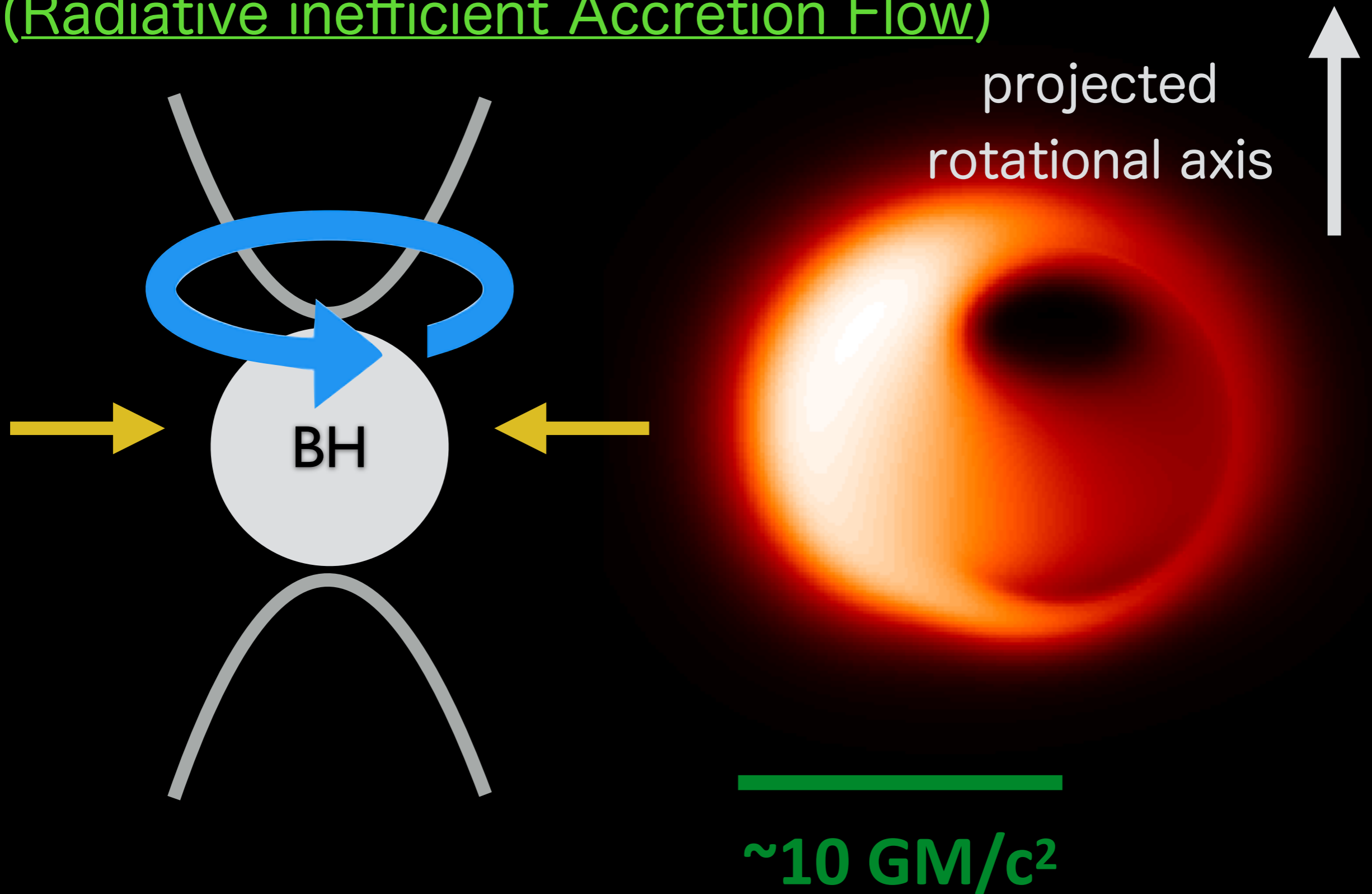
e.g., Falcke et al. 2000



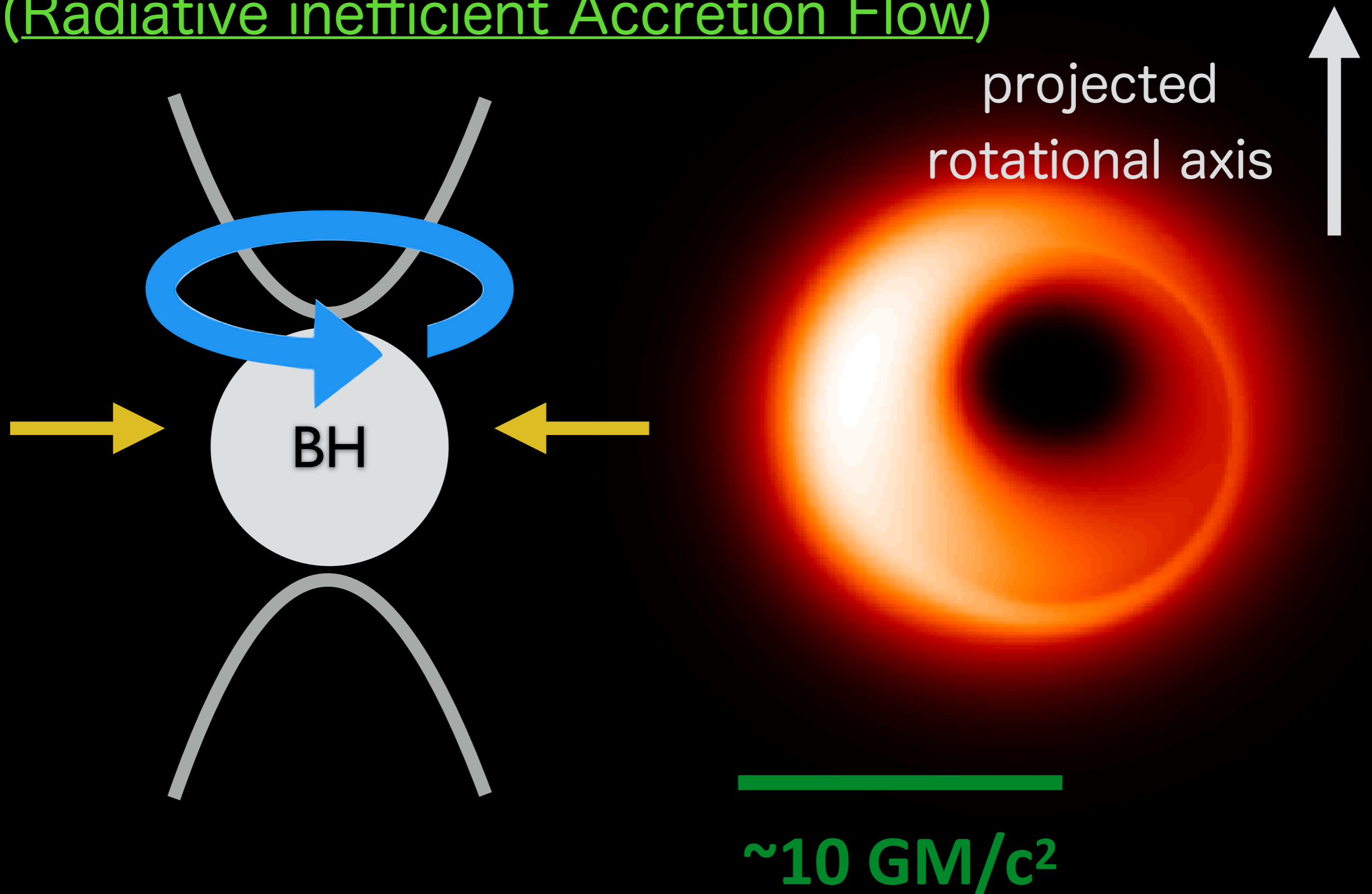
geometrically thick, optically thin accretion flow
(Radiative inefficient Accretion Flow)



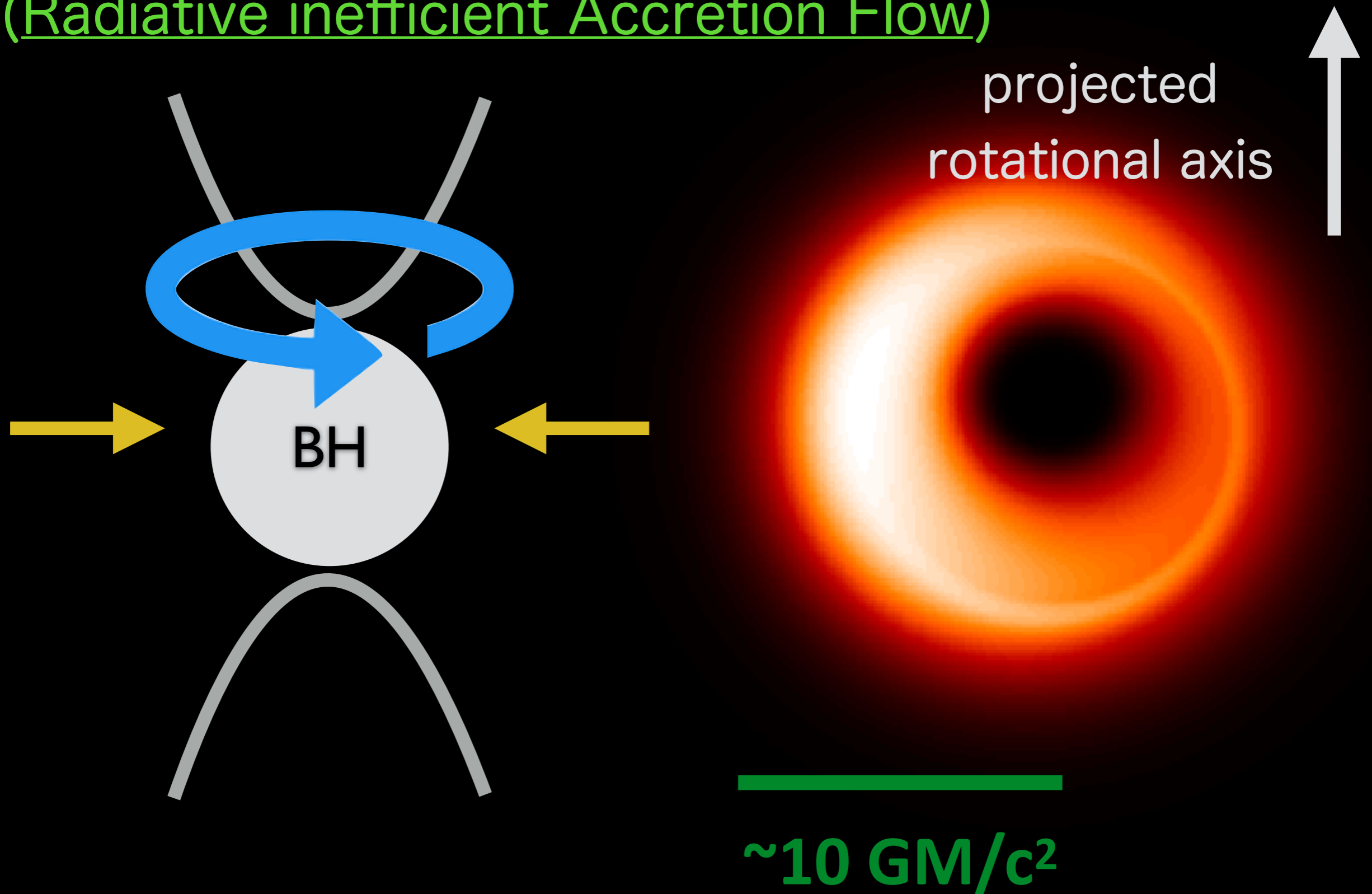
geometrically thick, optically thin accretion flow
(Radiative inefficient Accretion Flow)



geometrically thick, optically thin accretion flow
(Radiative inefficient Accretion Flow)

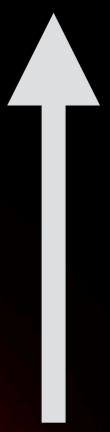


geometrically thick, optically thin accretion flow
(Radiative inefficient Accretion Flow)





projected
rotational axis



~10 GM/c²

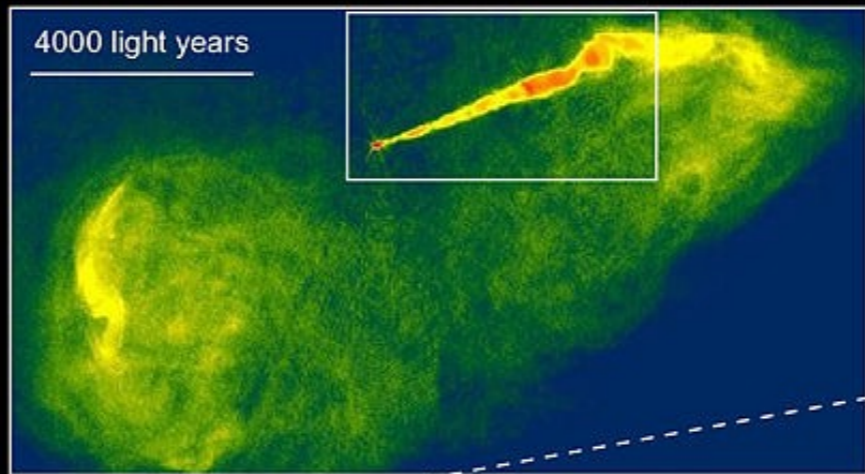
e.g., Broderick & Loeb 2006, HYP et al. 2014, HYP & Broderick 2018



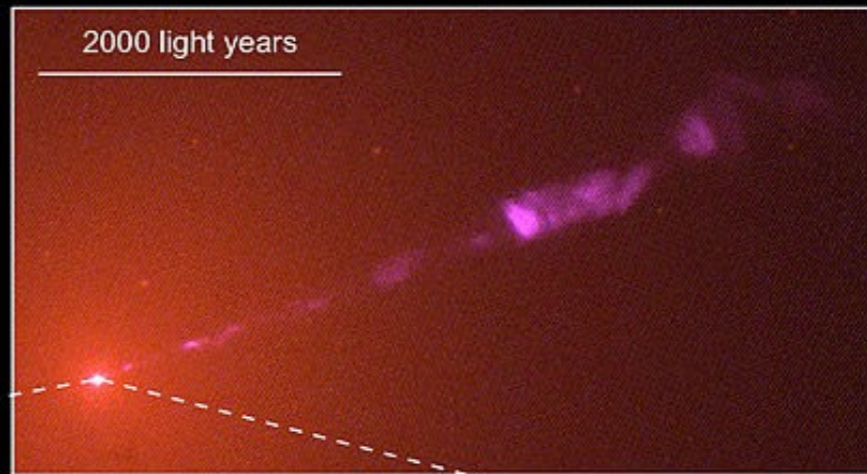
projected
rotational axis

BH rotational axis is pointing away from Earth

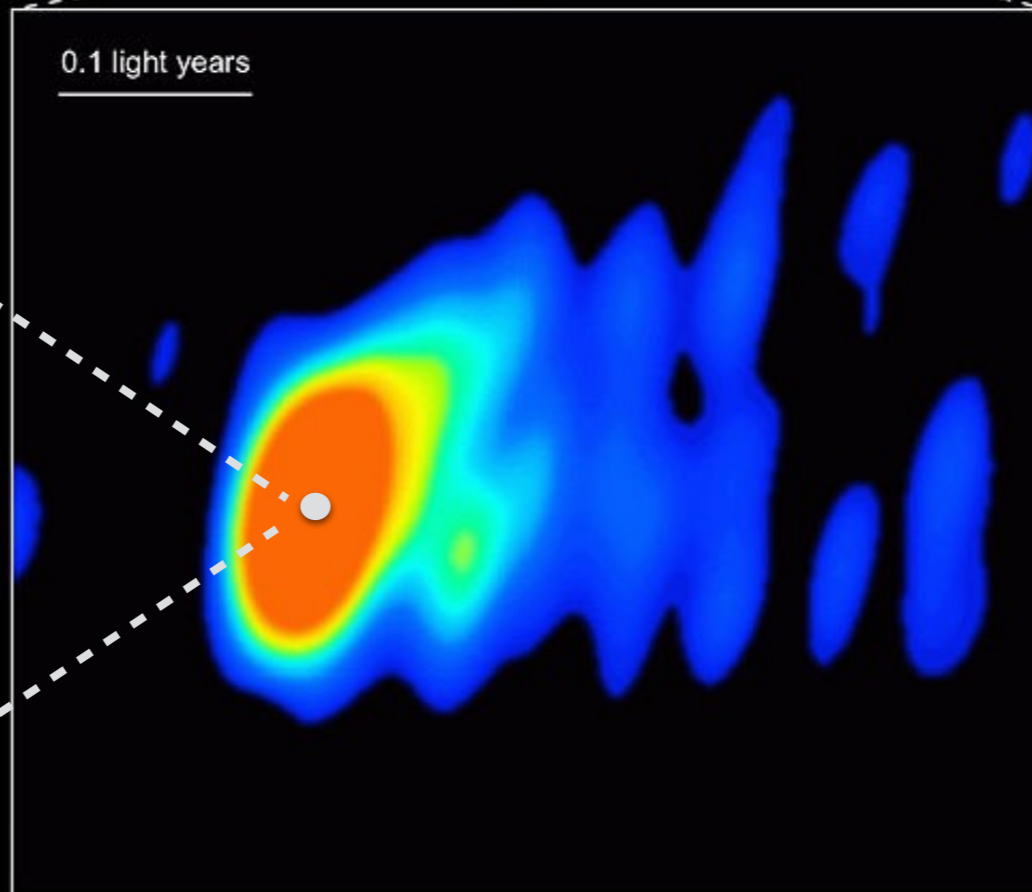
Galaxy M87



VLA
Radio



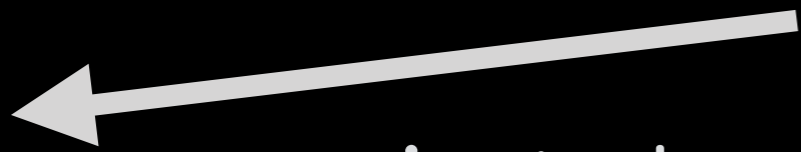
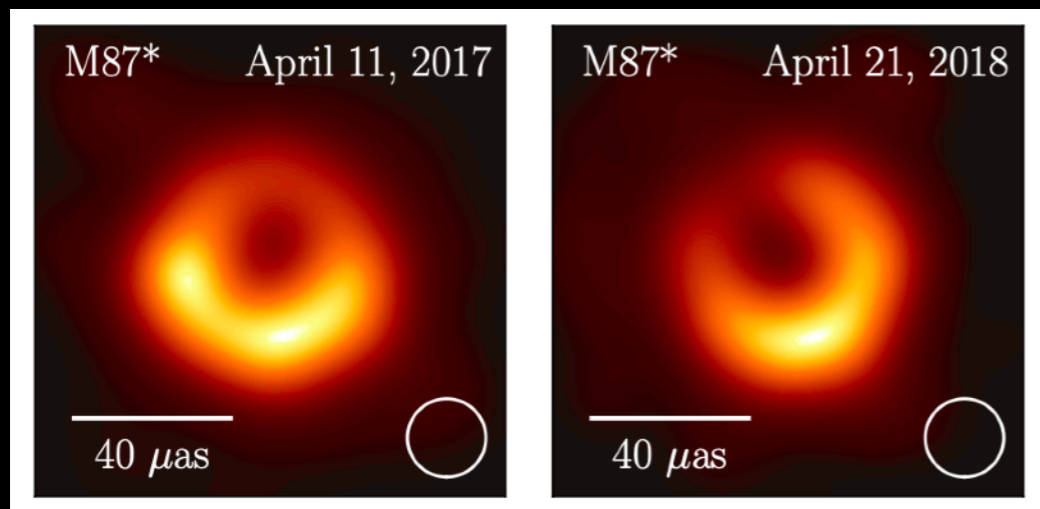
HST • WFPC2
Visible



VLBA
Radio

NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

EHT 230 GHz



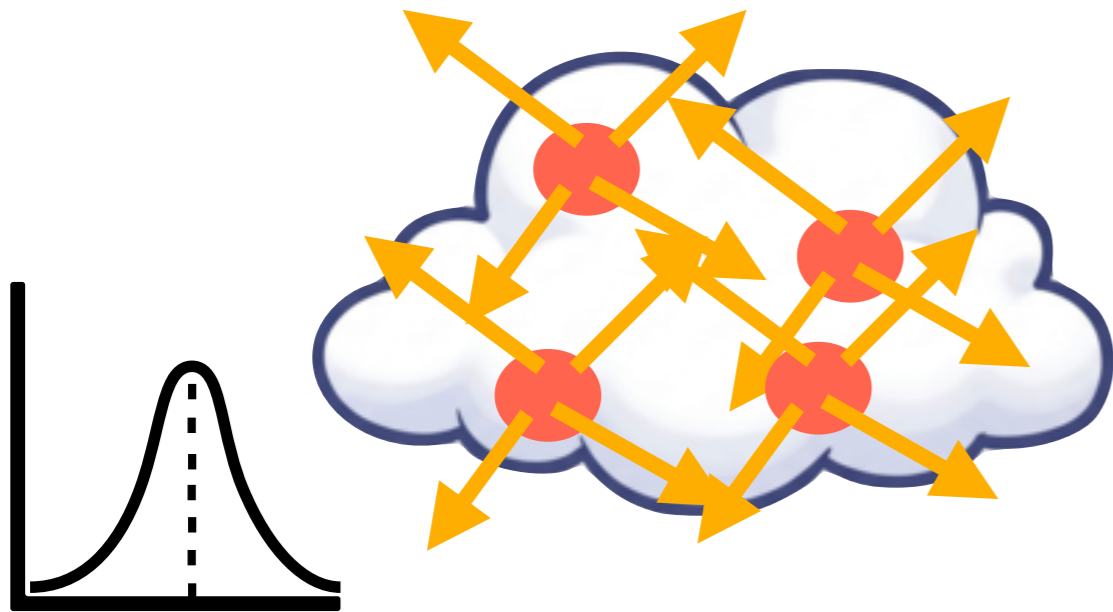
projected
rotational axis

Source to observer approach
&
Illiad code

Sampling in MCRT: photon packet

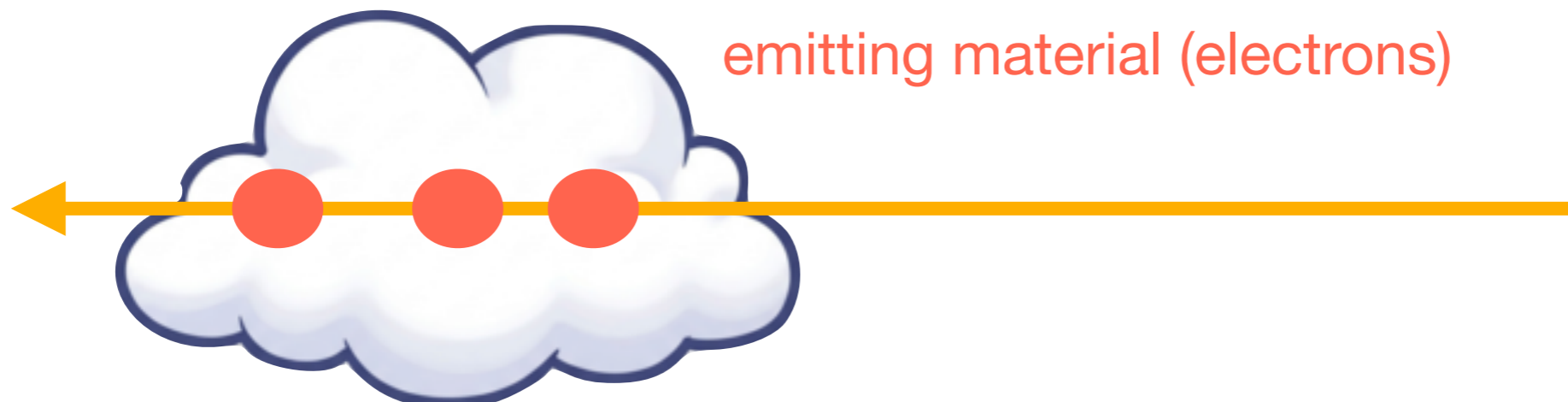
distribution of space, energy, photon packet direction

source-to-observer



$$W = \frac{N_{\text{realphotons}} (\sim 10^{\leq 50})}{N_{\text{photon packets}} (\sim 10^{7-9})}$$

observer-to-source



Inverse Compton Scattering

Changing direction and energy of photon



bat: electron
baseball: photon

*Photon gain most energy for a head-on collision

Inverse Compton Scattering

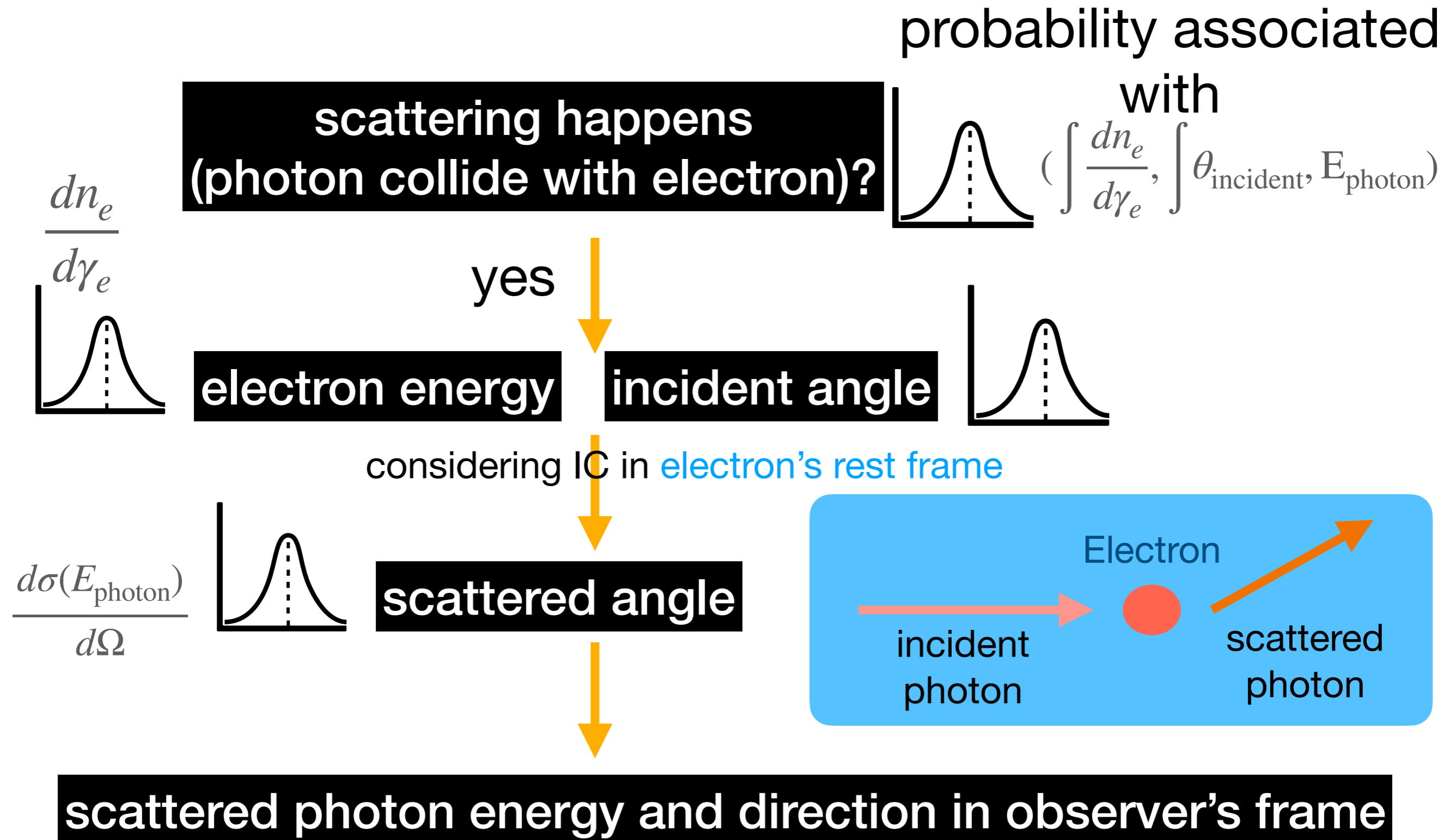
Changing direction and energy of photon



bat: electron
baseball: photon

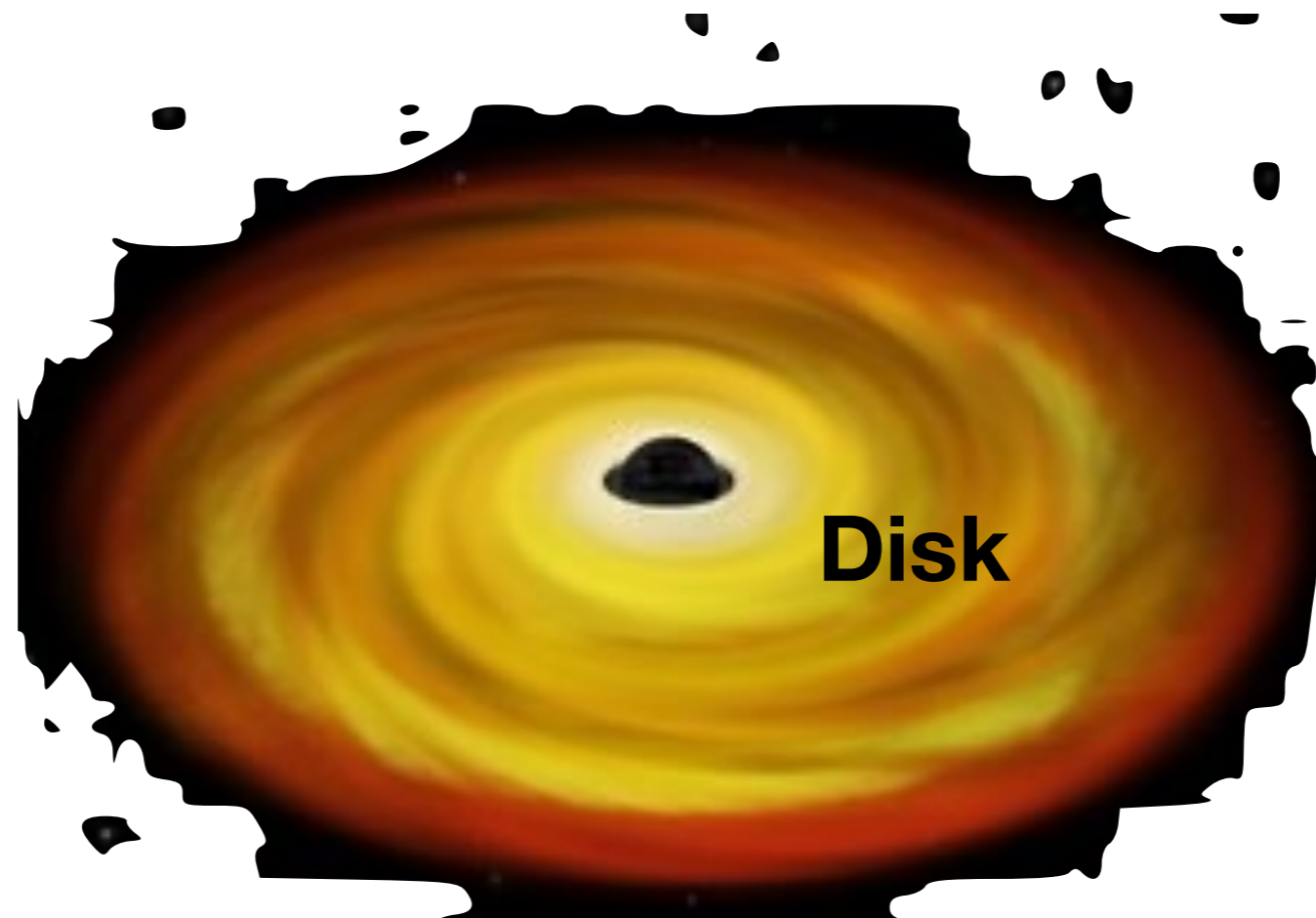
*Photon gain most energy for a head-on collision

Sampling in MCRT: scattering physics



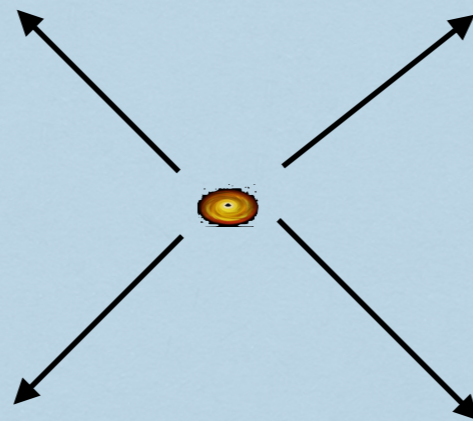
Iliad example:

Rotating stellar mass BH
(Novikov-Thorne) accretion disk



source-to-observer

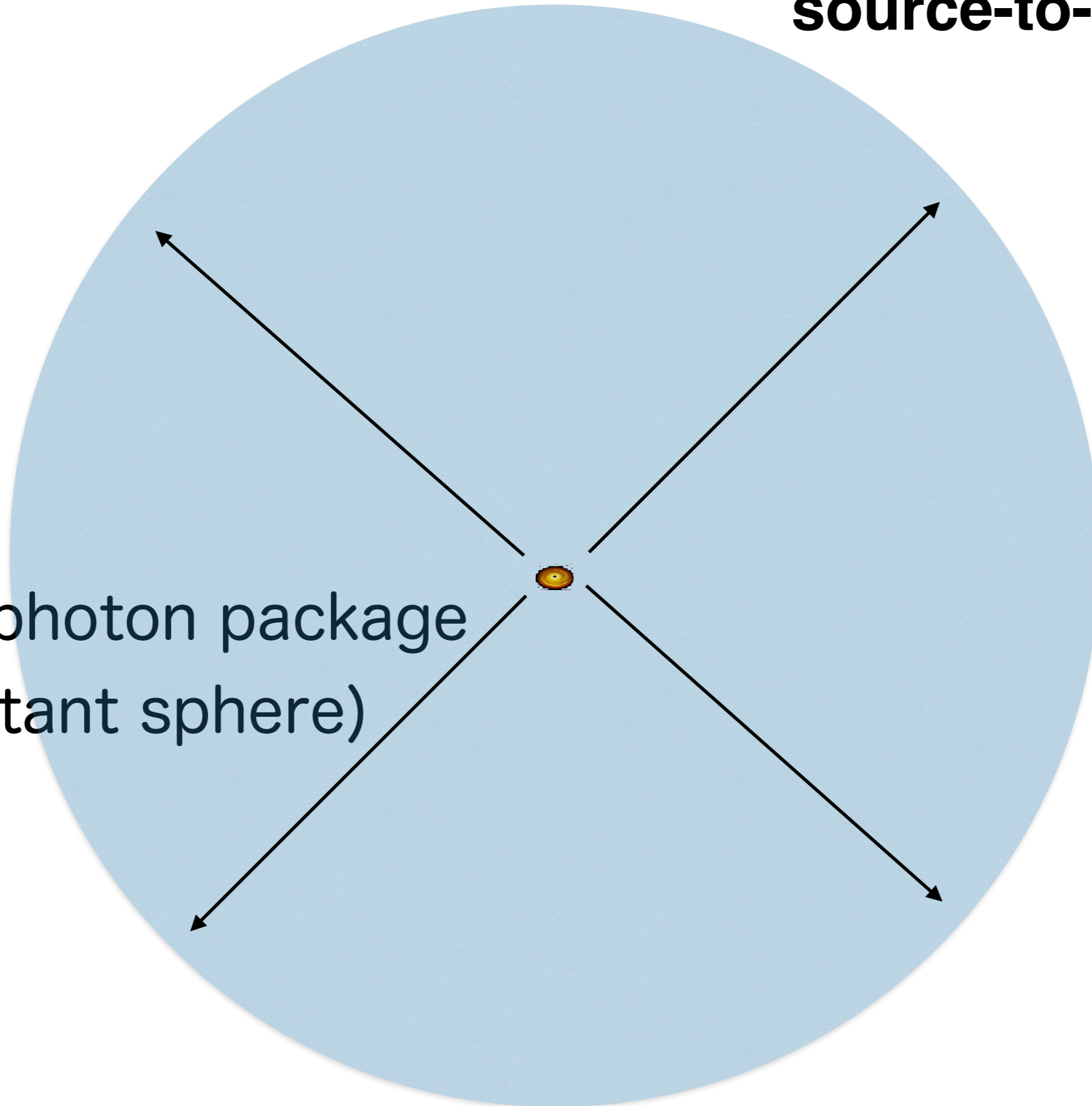
fire photon package



source-to-observer



recycle photon package
(at a distant sphere)

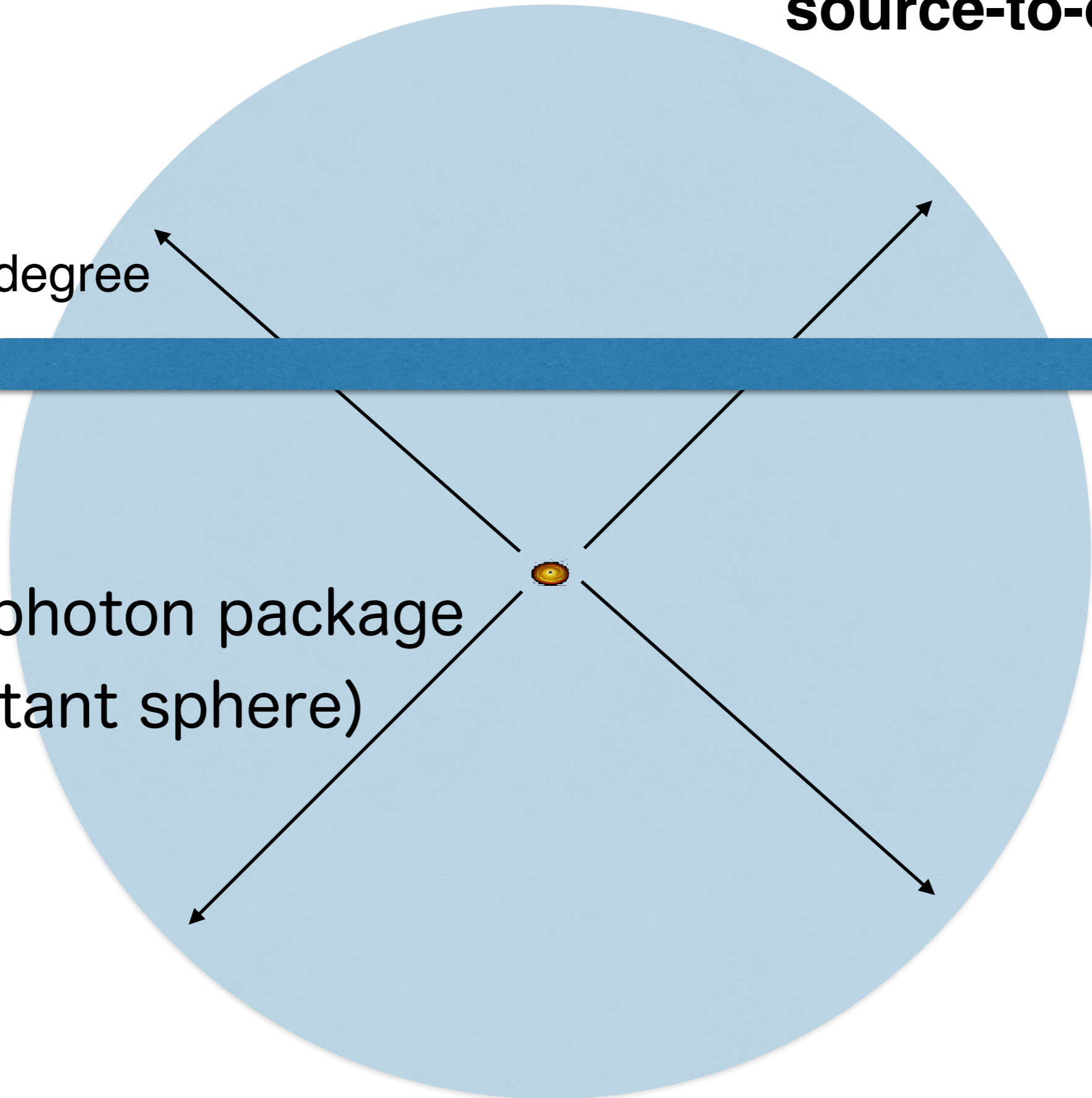


source-to-observer

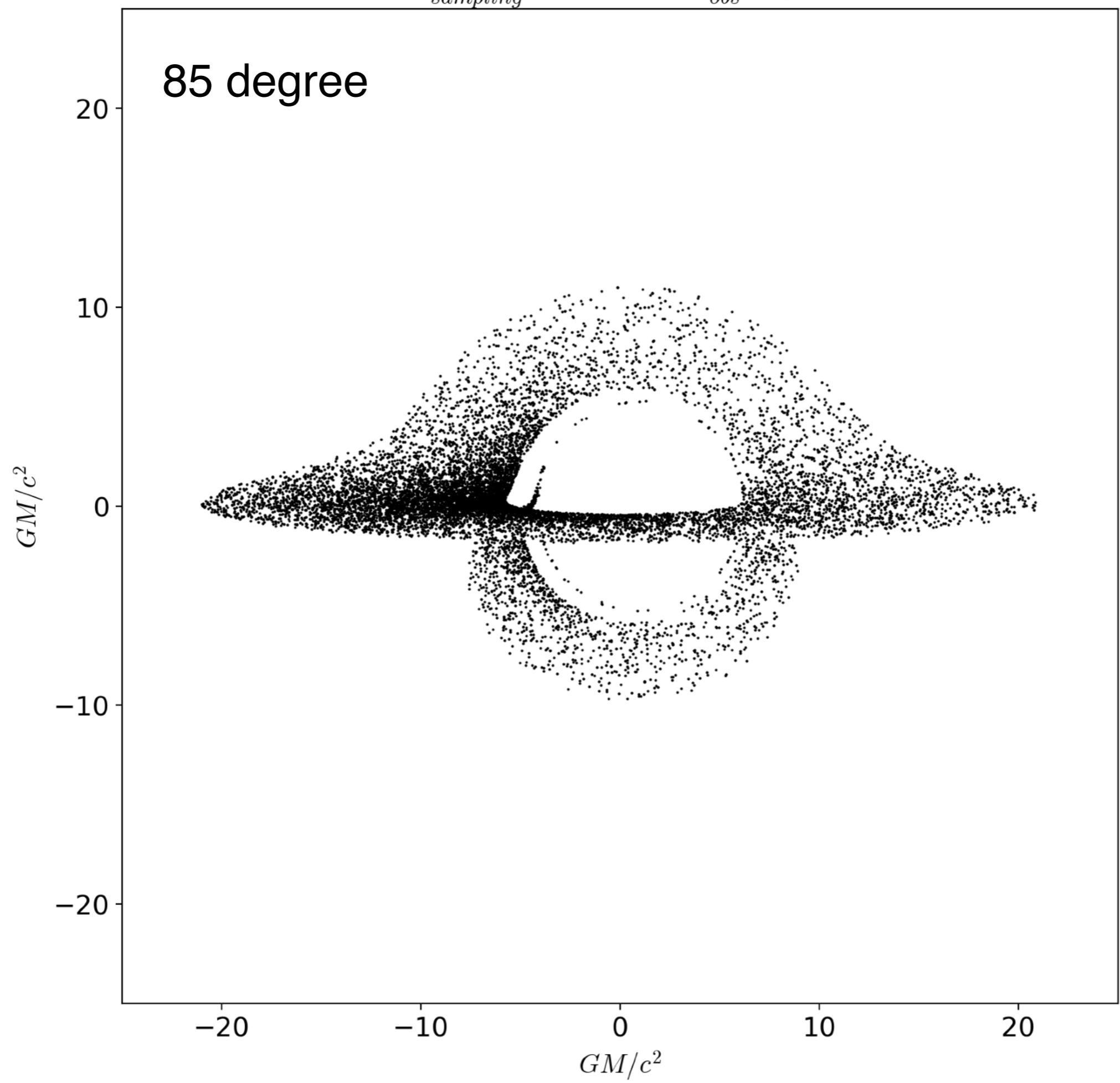
85 degree



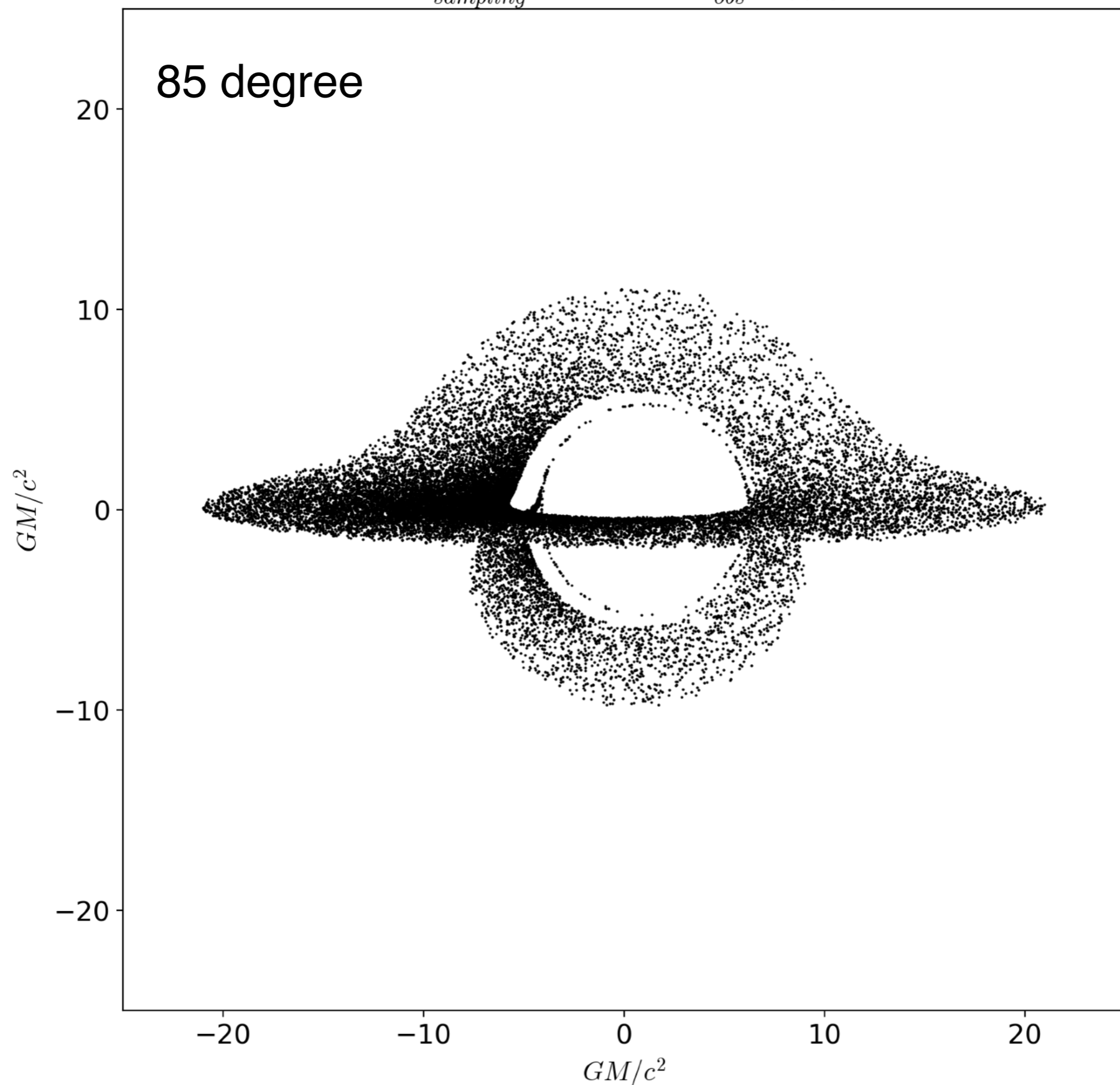
recycle photon package
(at a distant sphere)



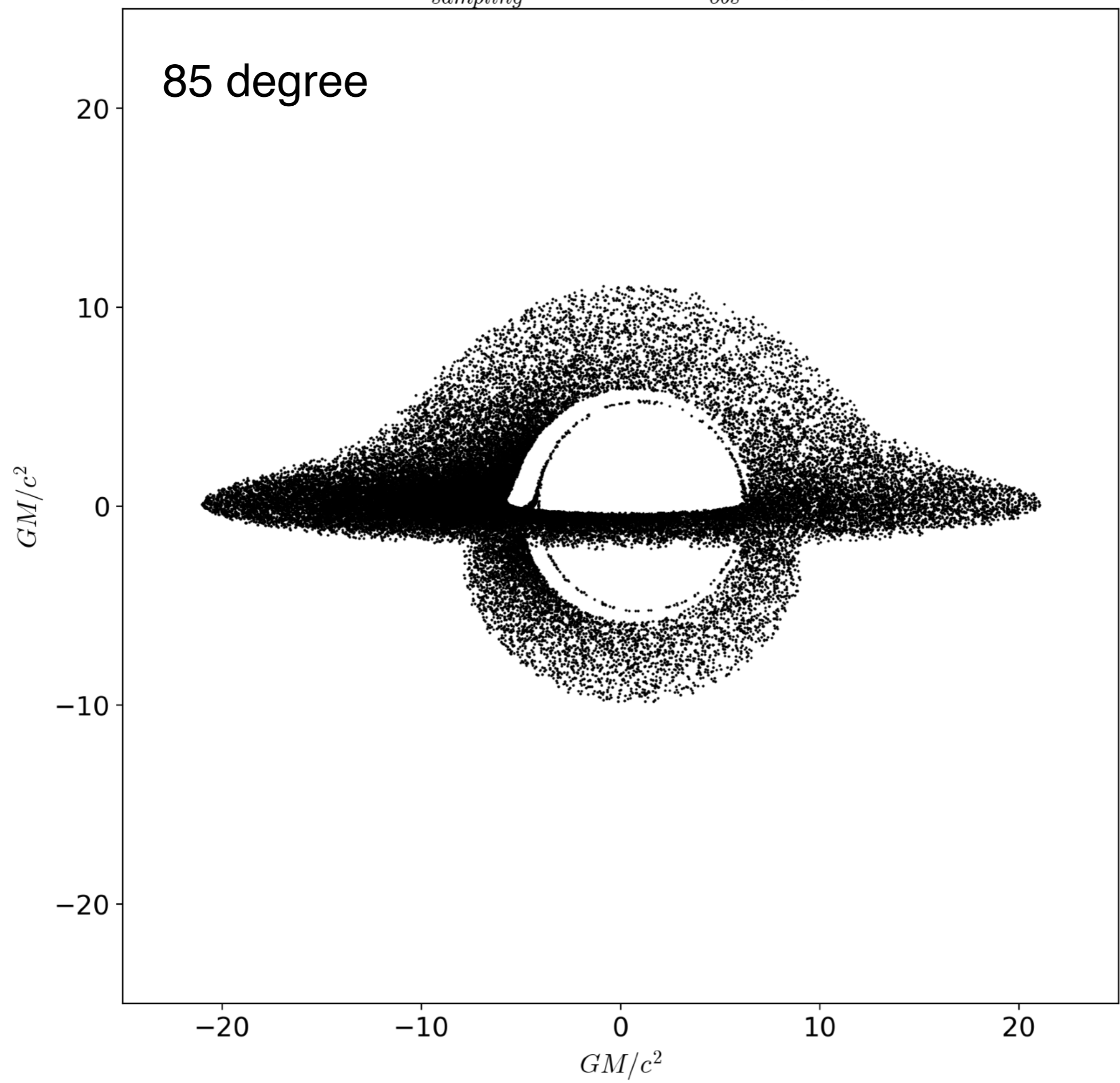
$N_{sampling} = 11761$ $\theta_{obs} = 85.0$

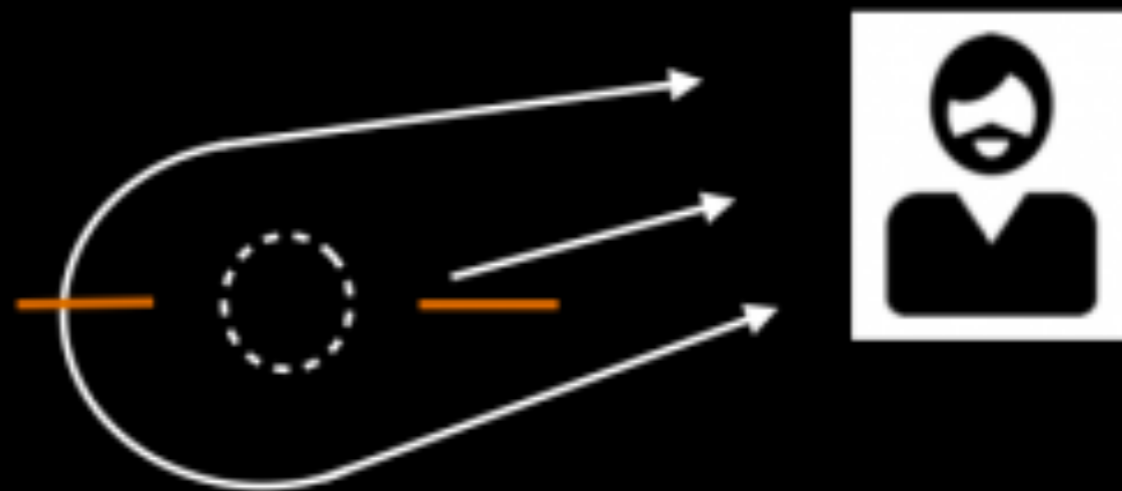
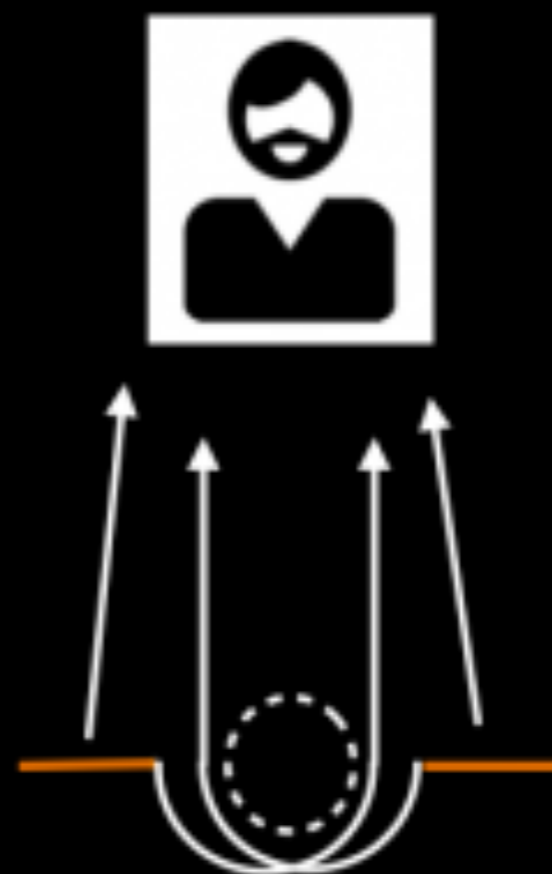


$N_{sampling} = 23544$ $\theta_{obs} = 85.0$



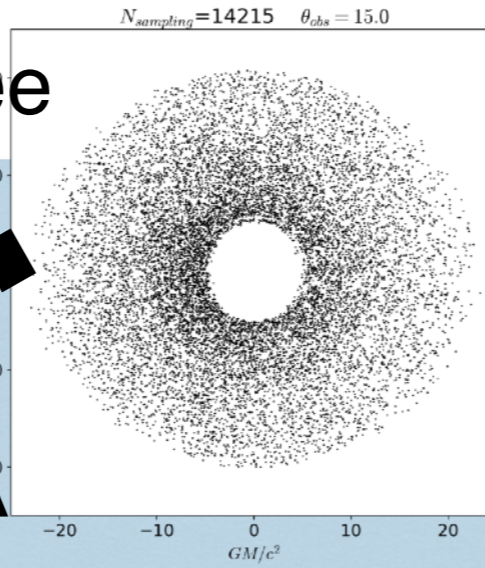
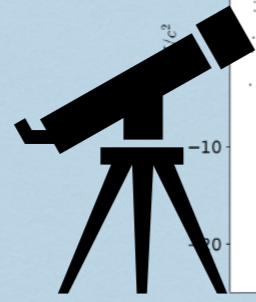
$N_{sampling} = 46926$ $\theta_{obs} = 85.0$



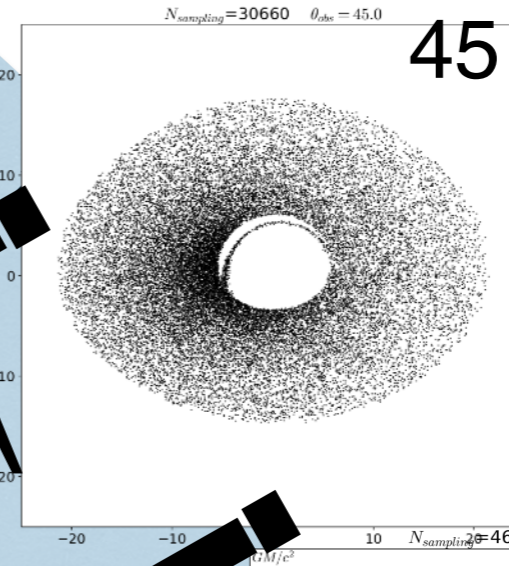


source-to-observer

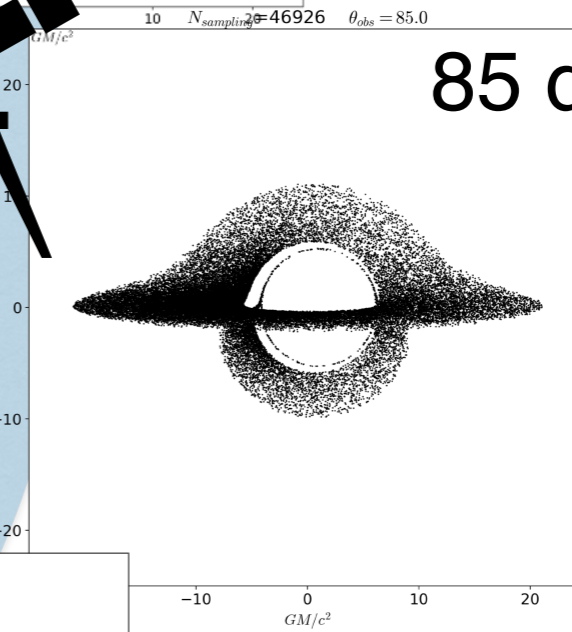
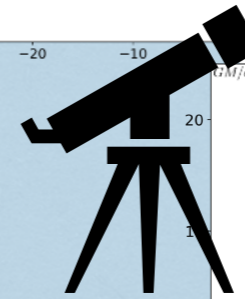
15 degree



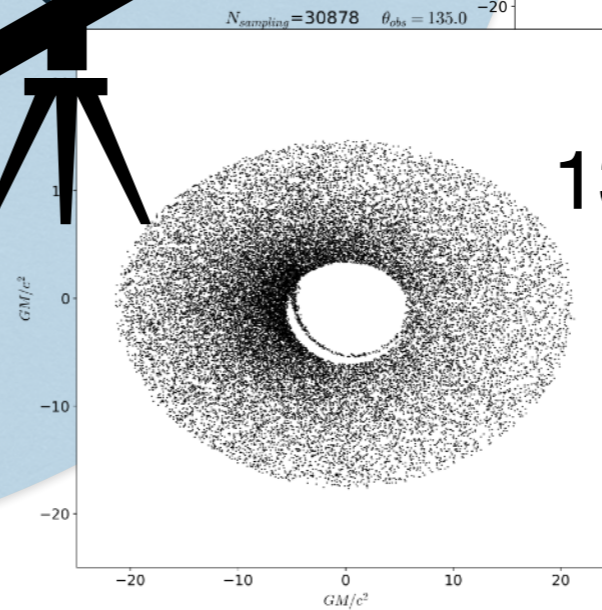
45 degree



85 degree



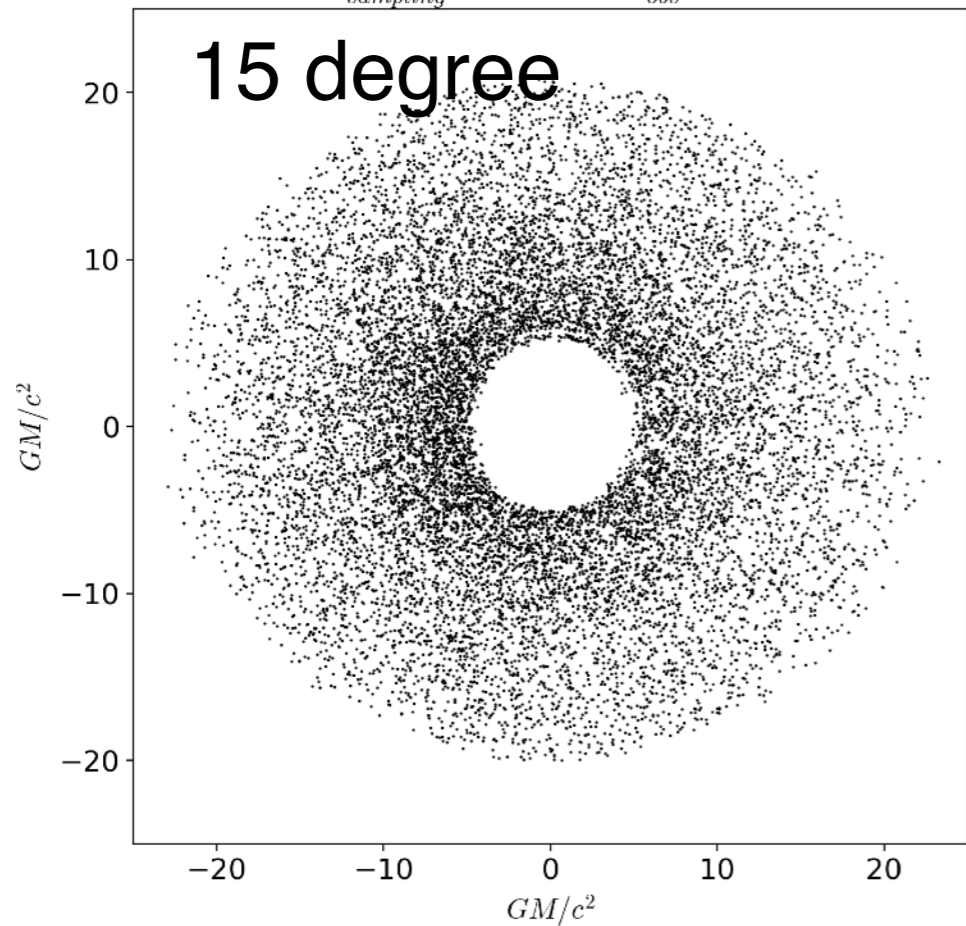
135 degree



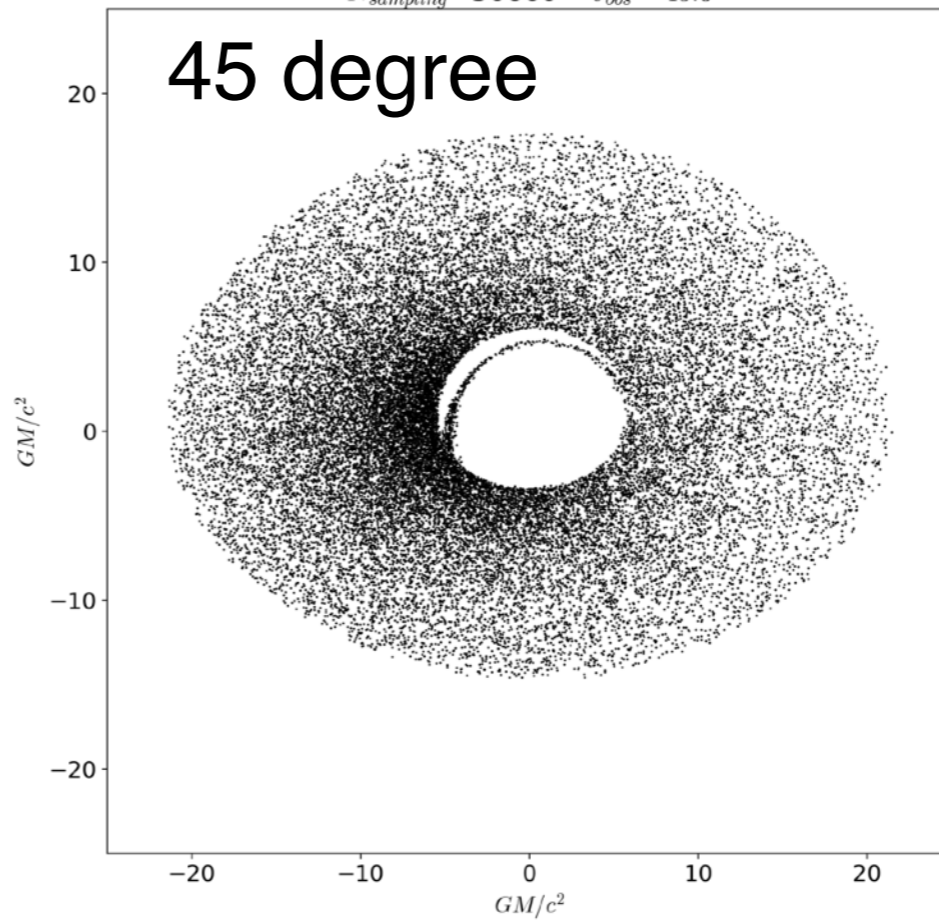
$\sim 10^6$ photon packet



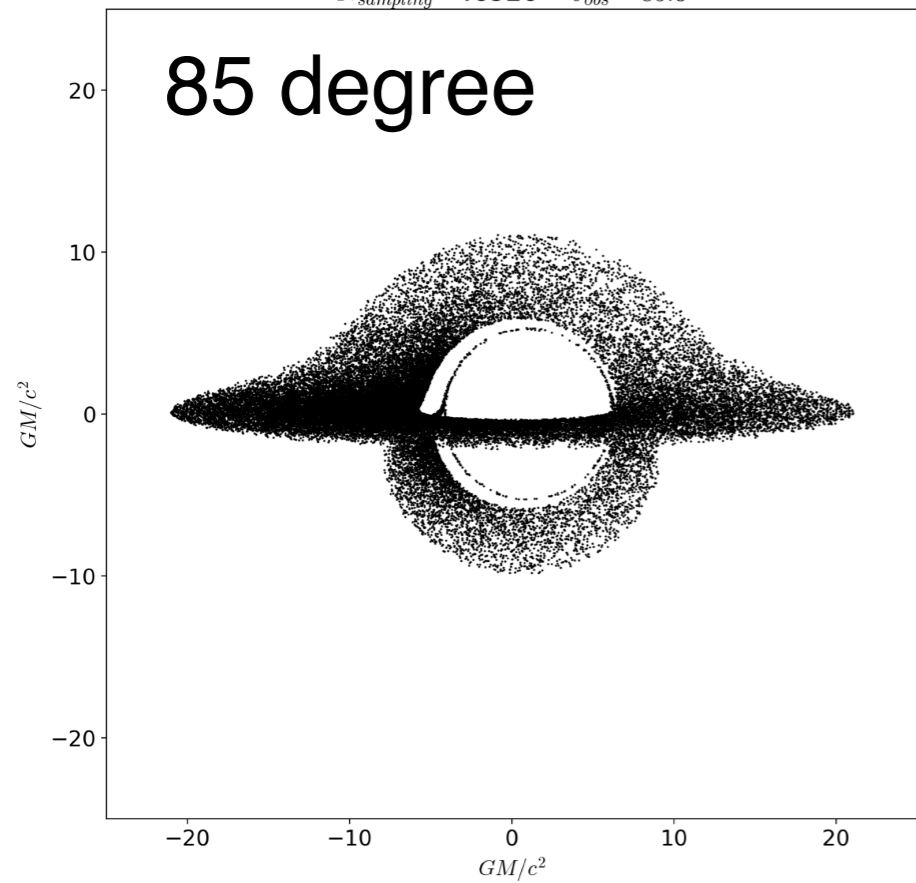
$N_{\text{sampling}}=14215$ $\theta_{\text{obs}}=15.0$



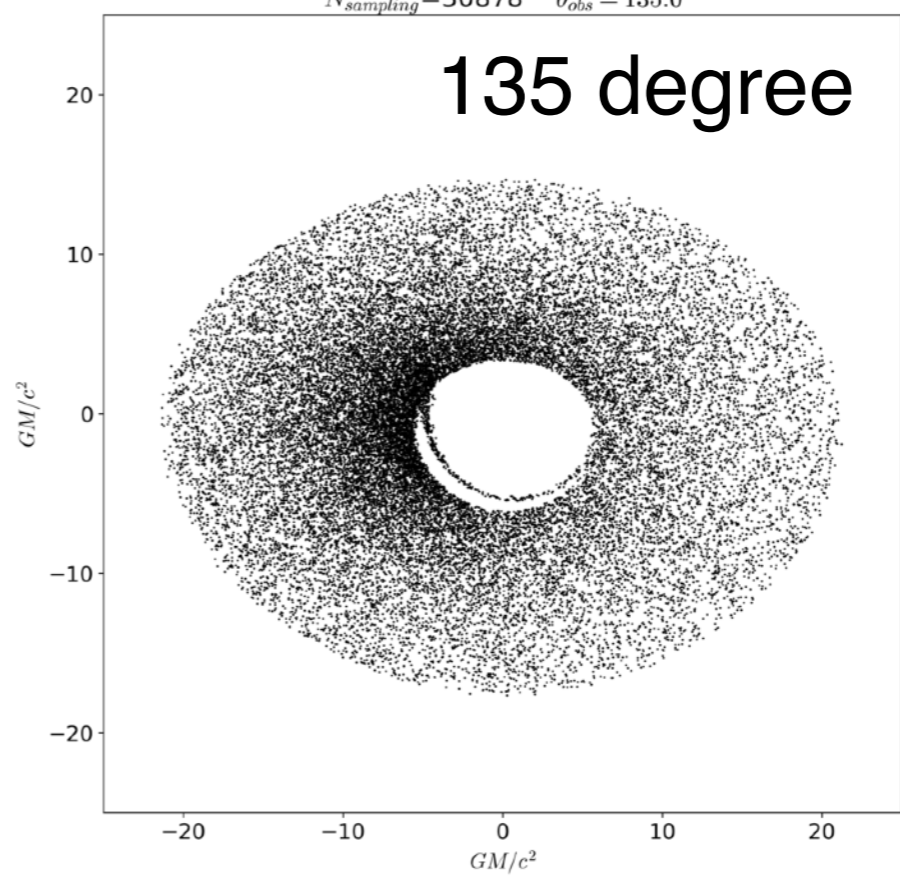
$N_{\text{sampling}}=30660$ $\theta_{\text{obs}}=45.0$

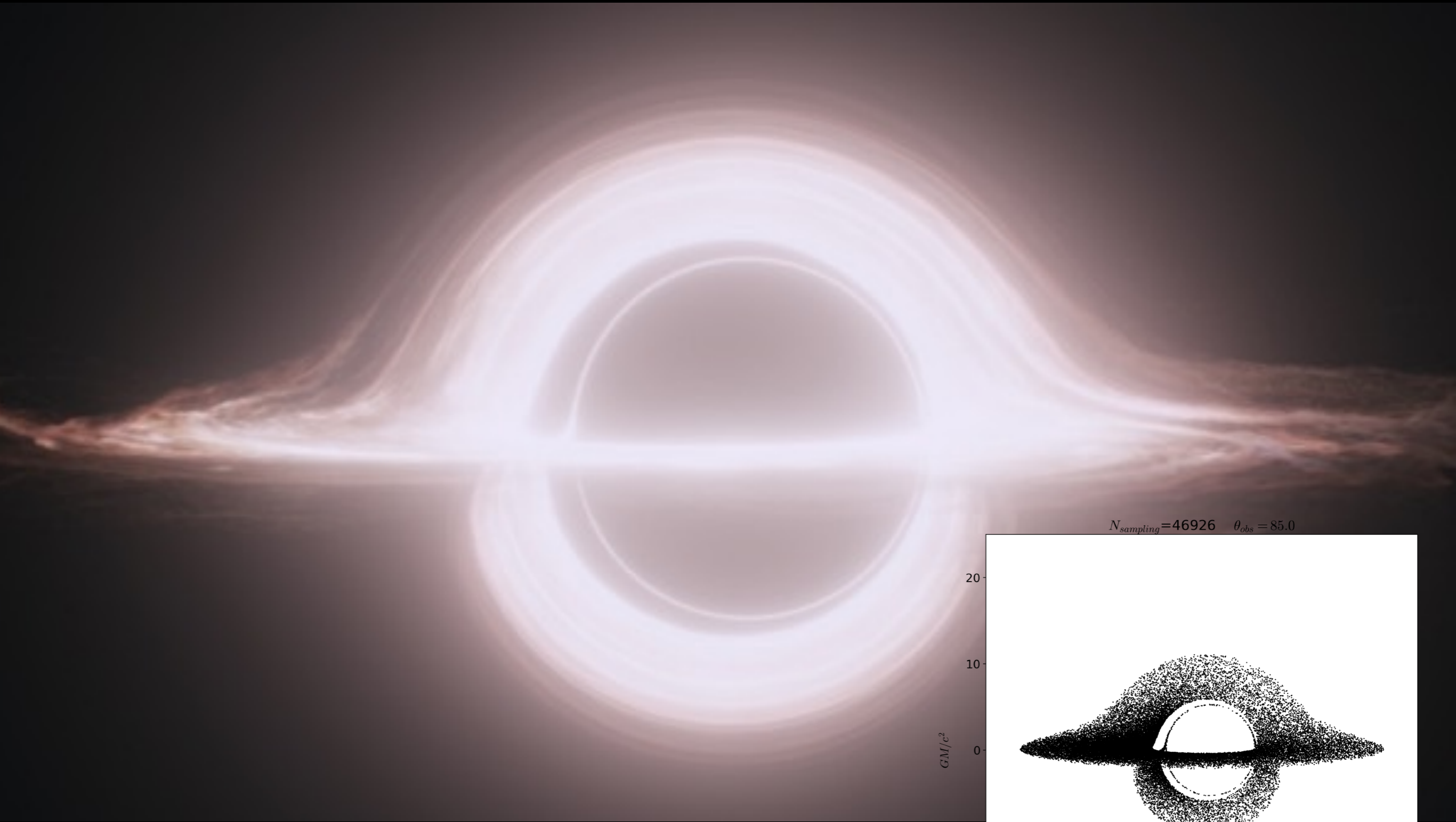


$N_{\text{sampling}}=46926$ $\theta_{\text{obs}}=85.0$



$N_{\text{sampling}}=30878$ $\theta_{\text{obs}}=135.0$

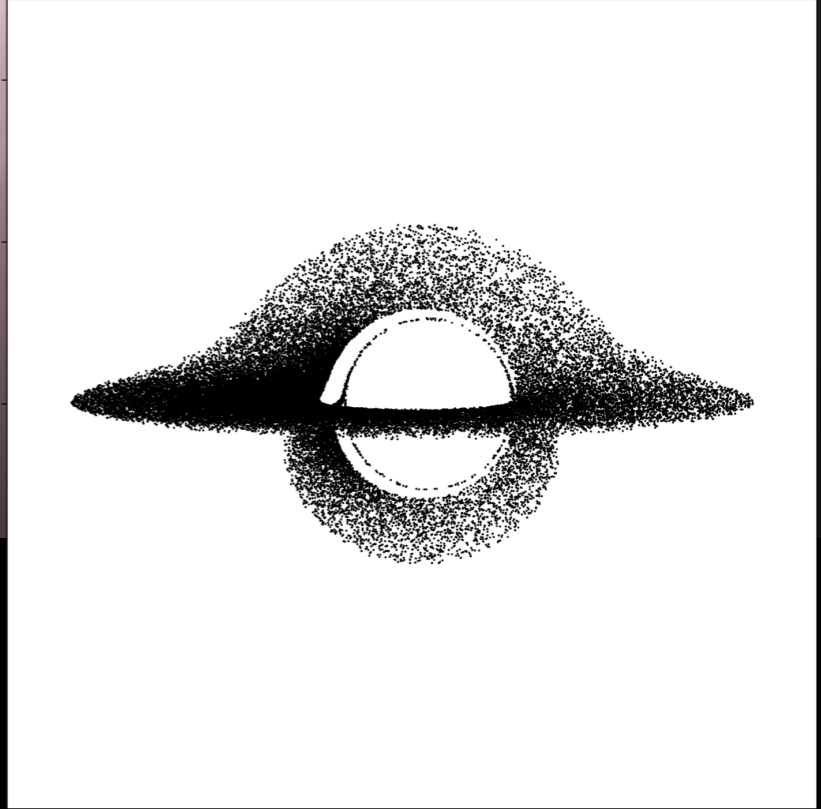




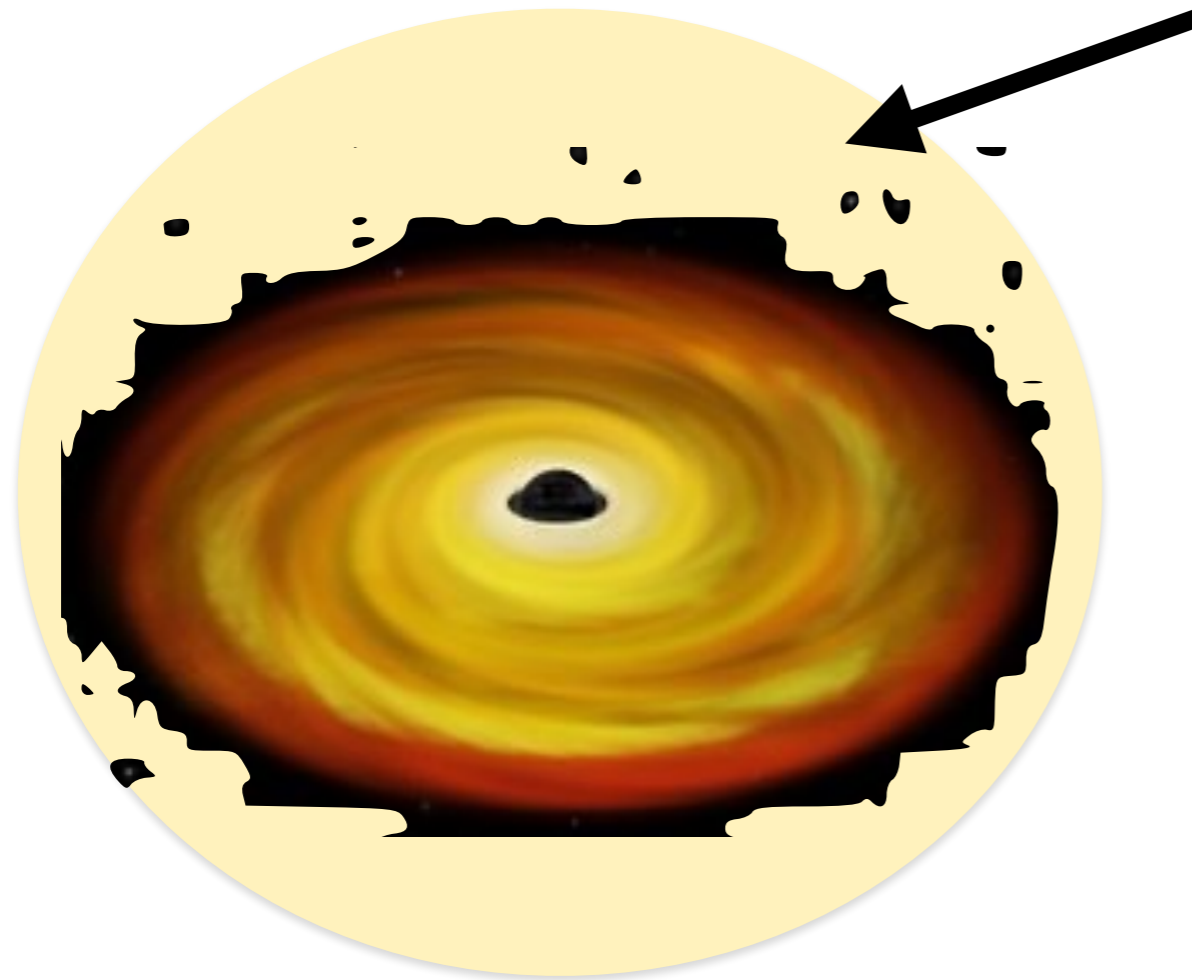
$N_{\text{sampling}}=46926$ $\theta_{\text{obs}}=85.0$

GM/c^2

20
10
0



Hot corona (relativistic electrons)



Emission



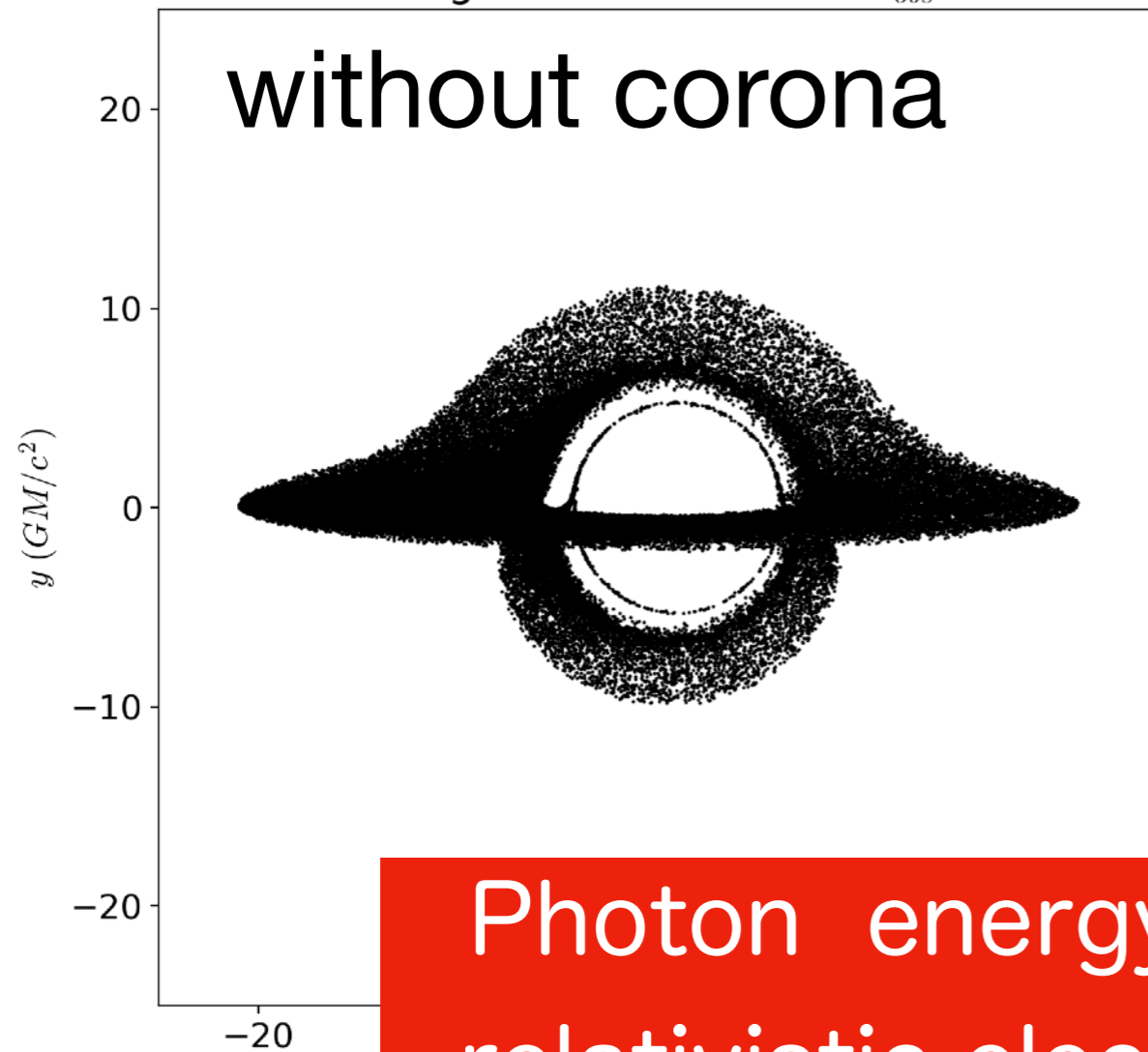
Absorption



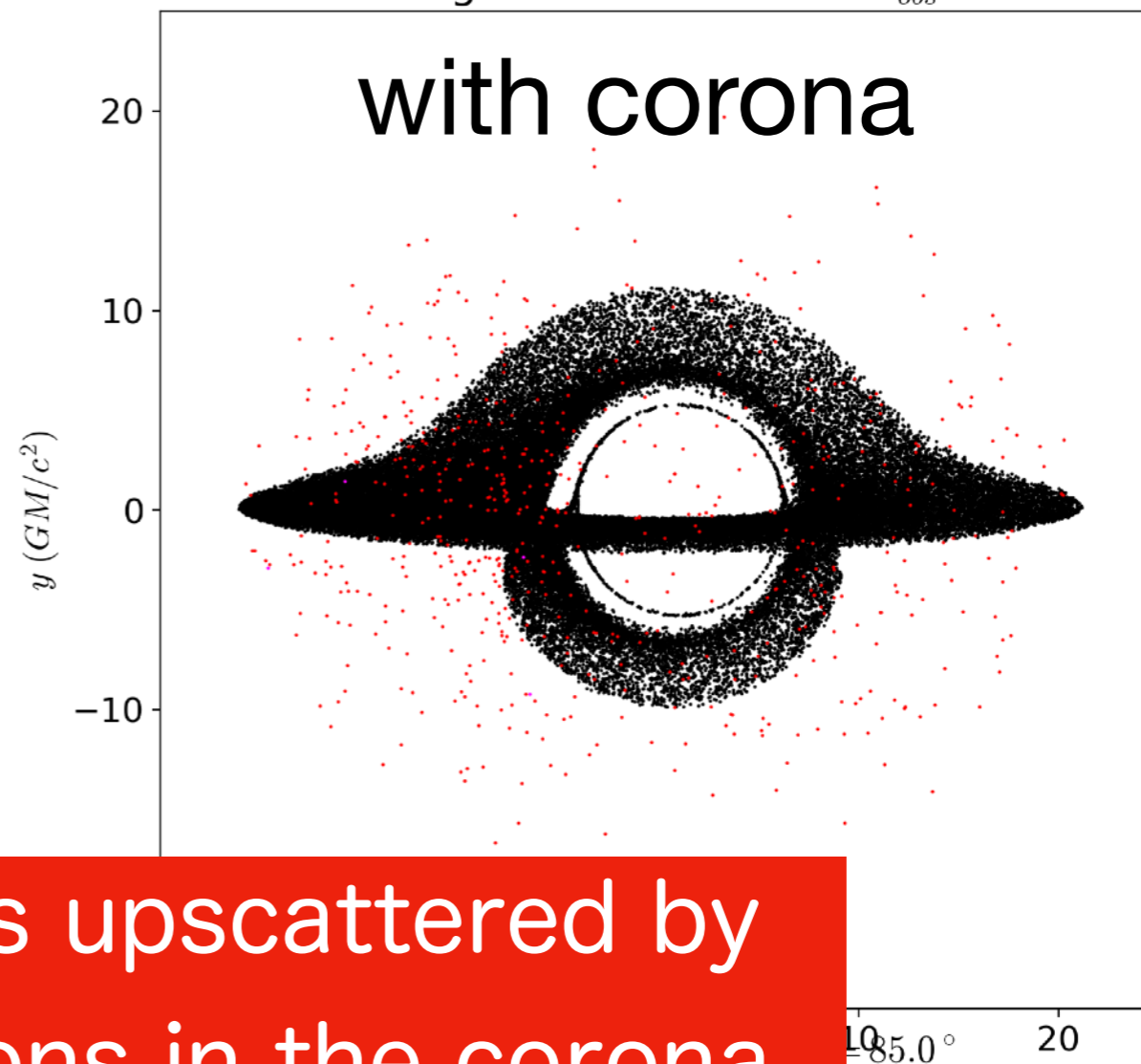
Scattering



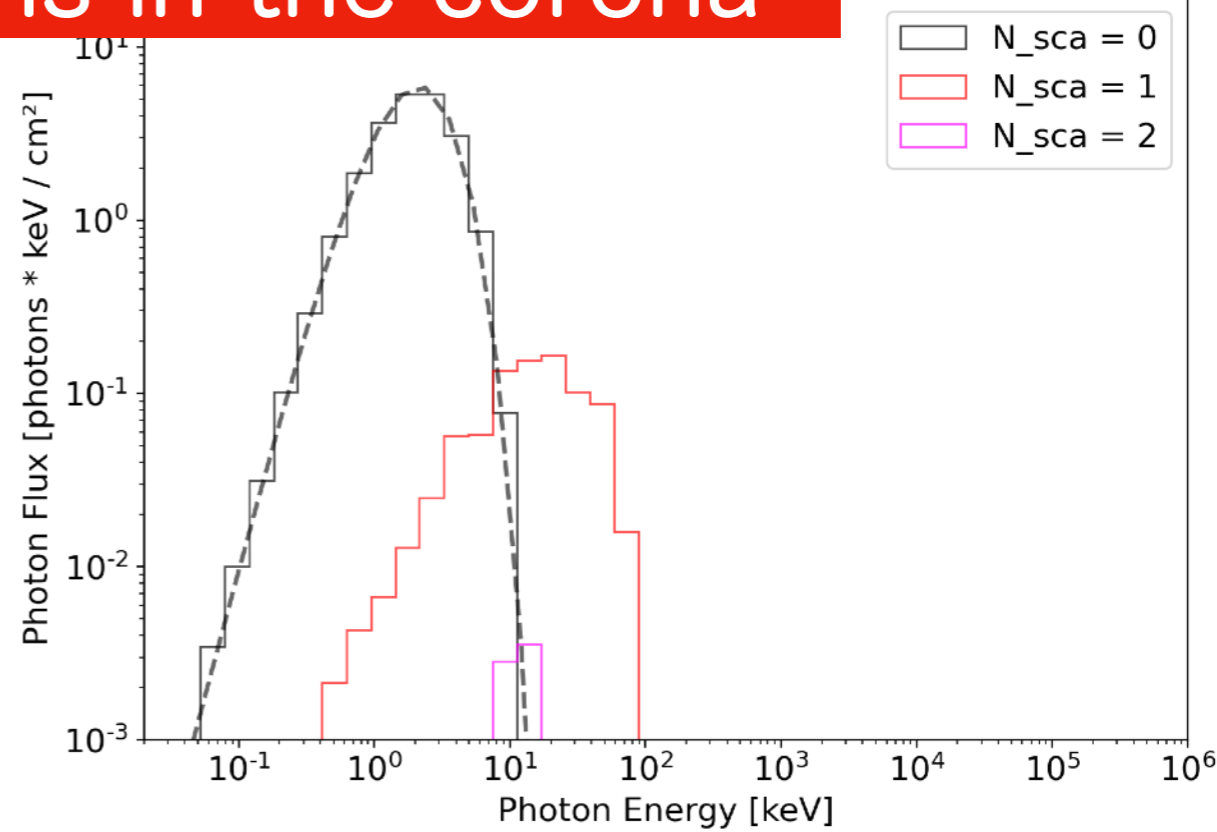
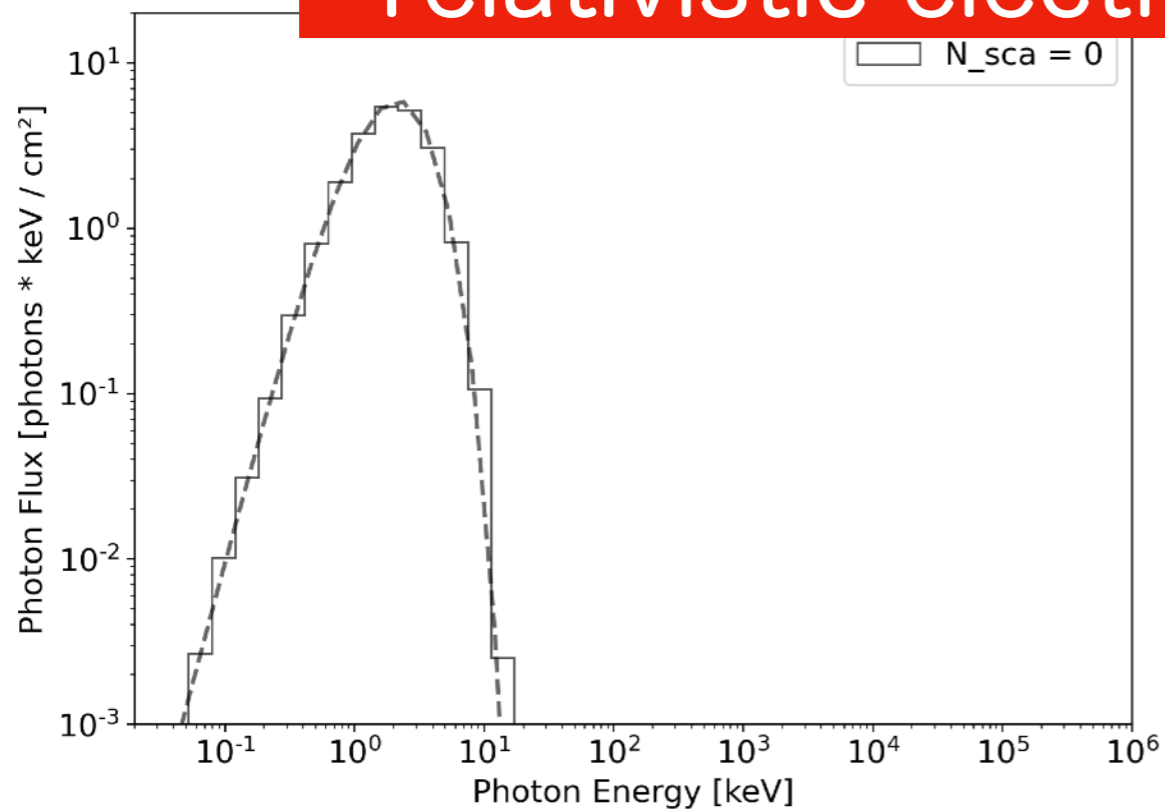
Photon Angular Distribution at $\theta_{obs} = 85.0^\circ$



Photon Angular Distribution at $\theta_{obs} = 85.0^\circ$

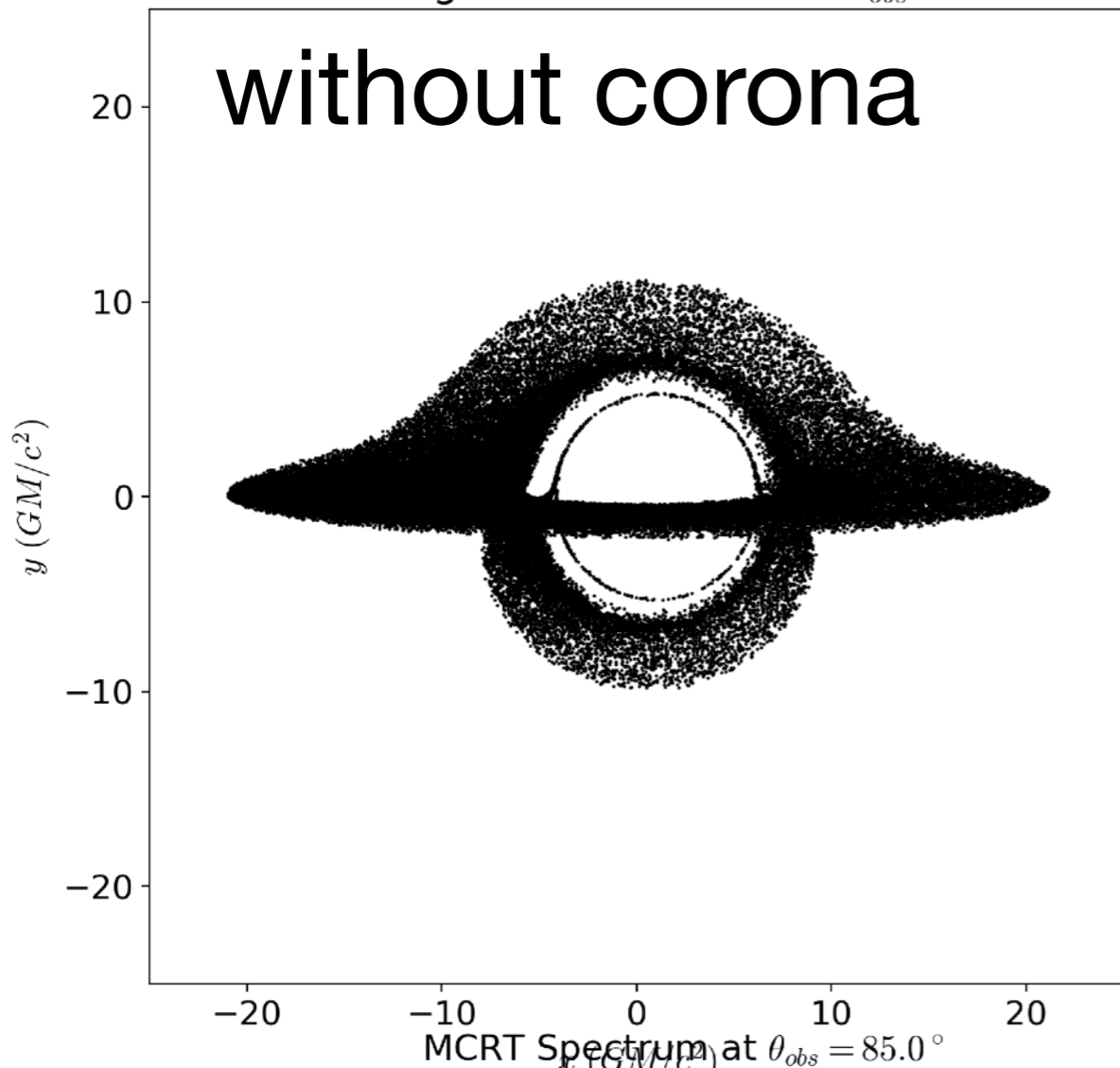


Photon energy is upscattered by relativistic electrons in the corona



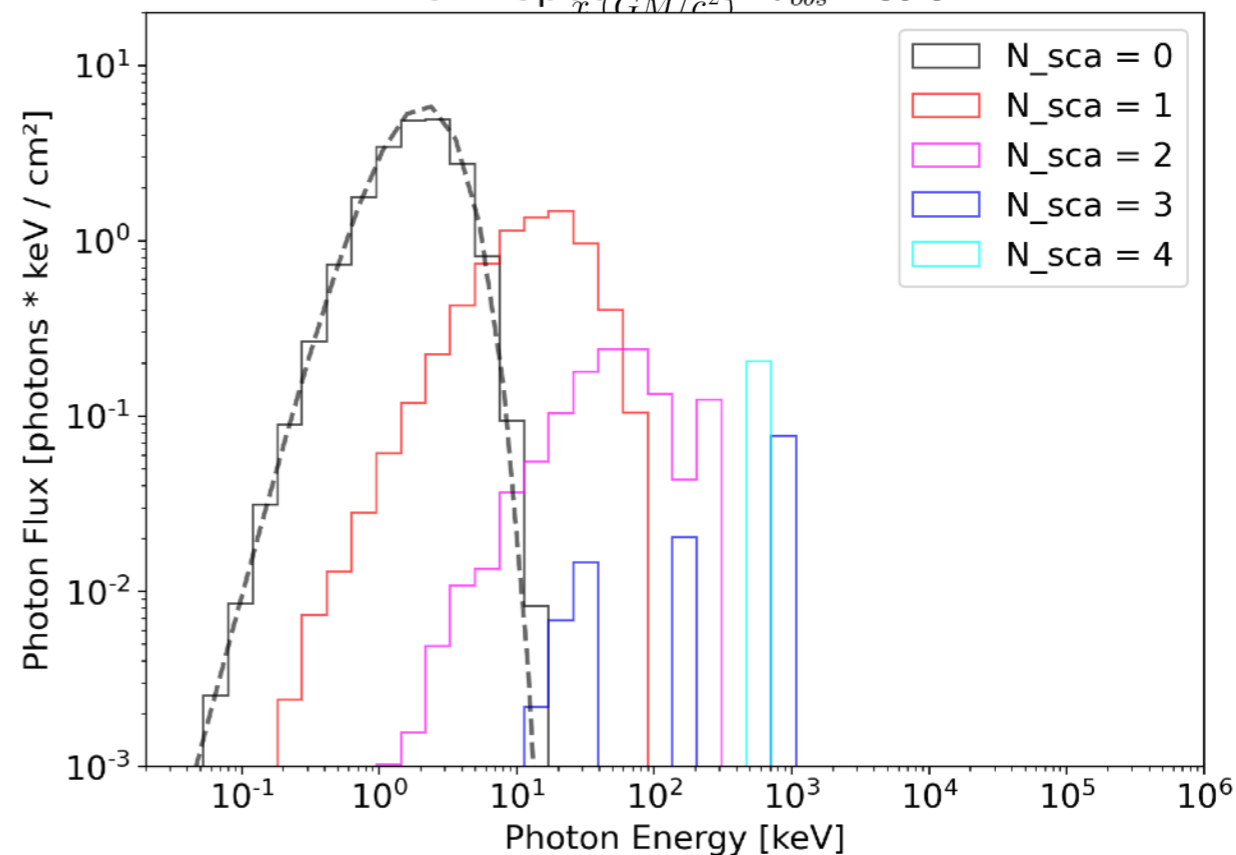
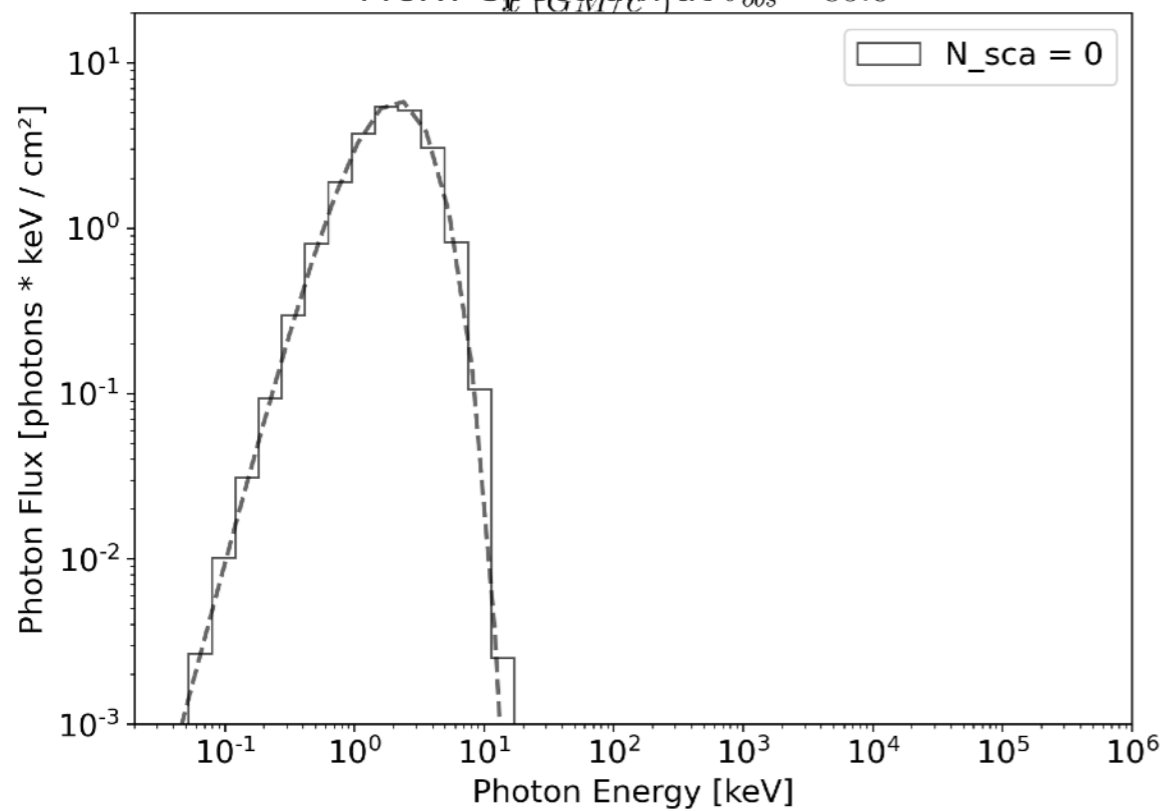
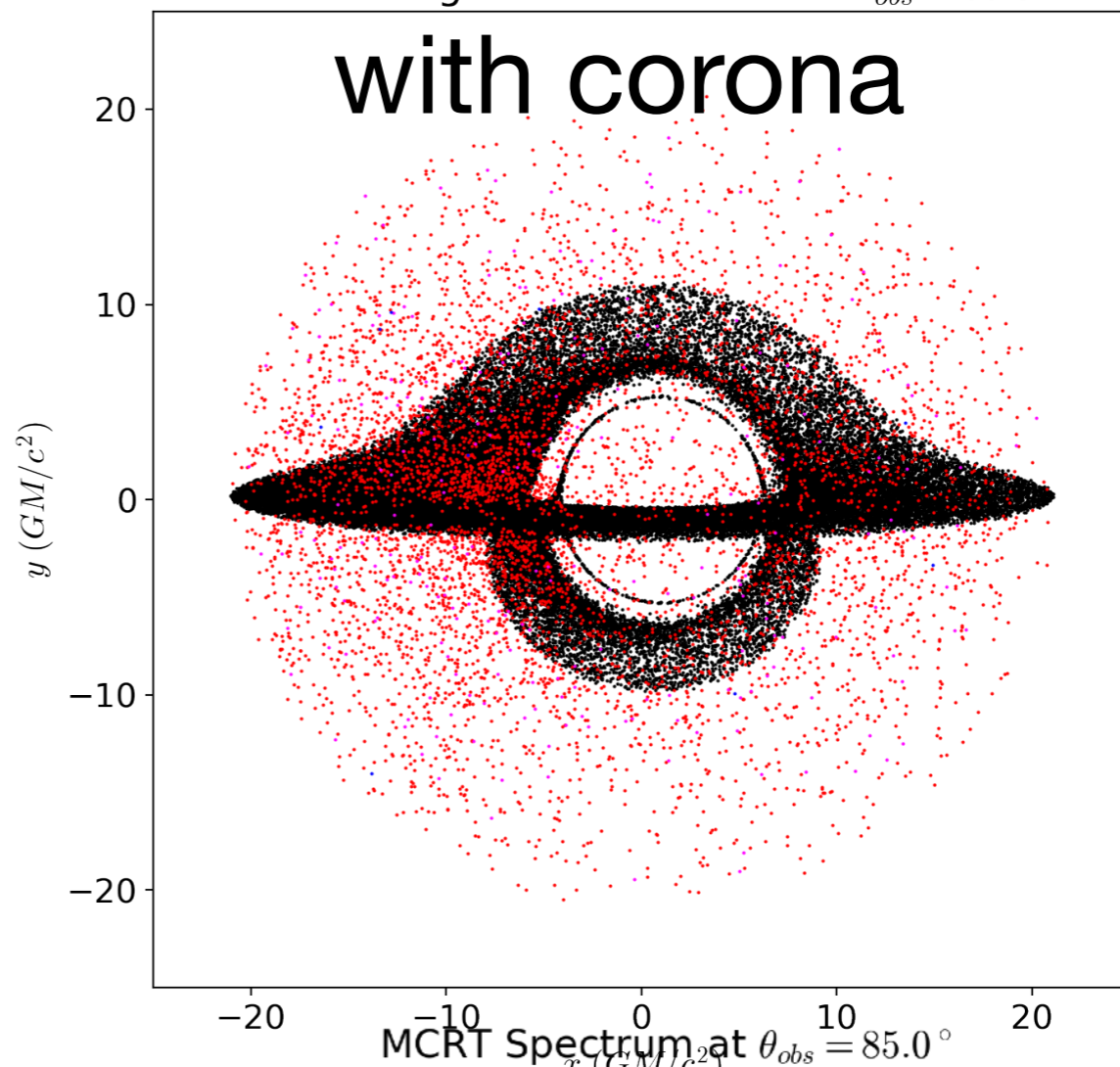
Photon Angular Distribution at $\theta_{obs} = 85.0^\circ$

without corona



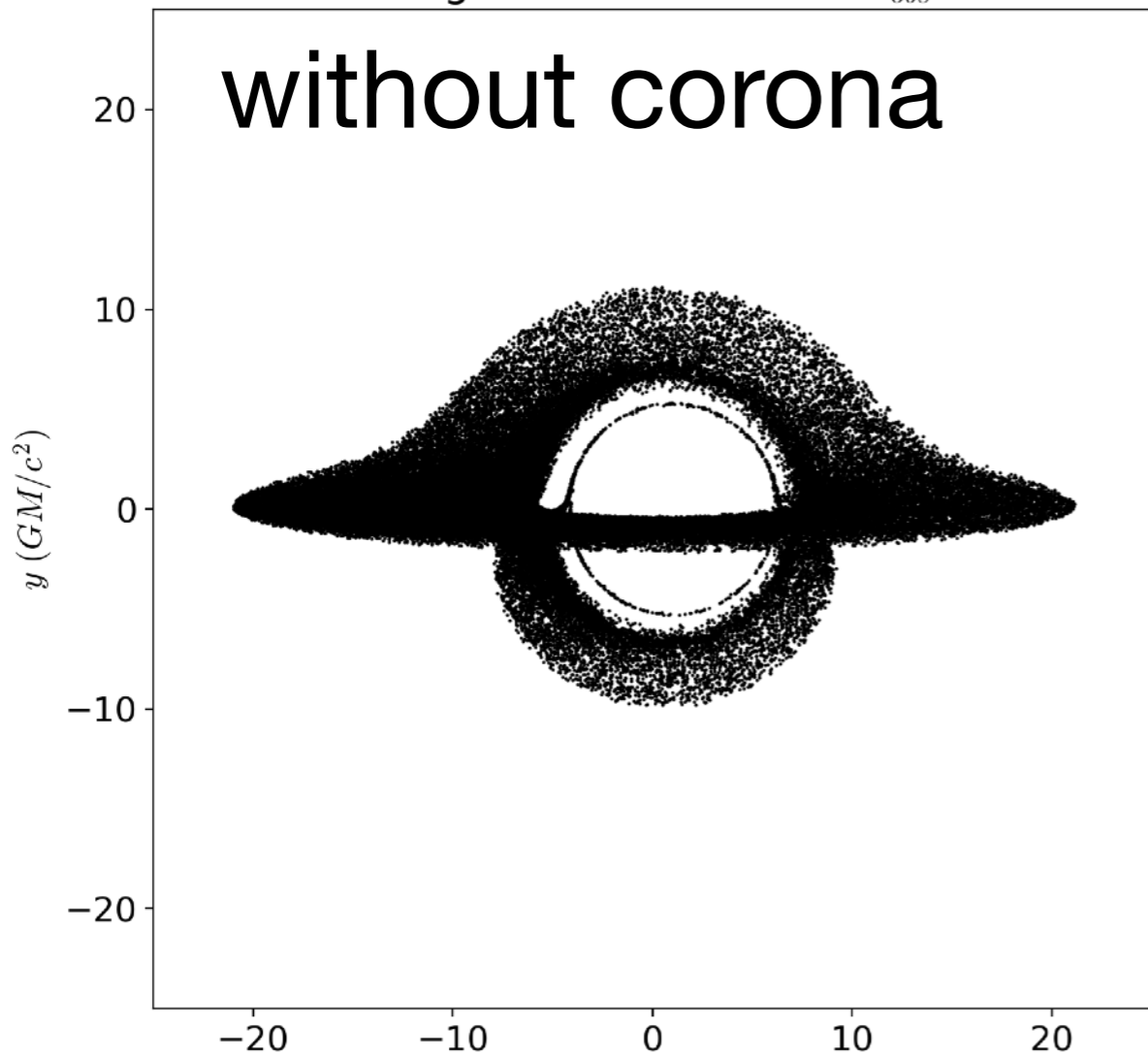
Photon Angular Distribution at $\theta_{obs} = 85.0^\circ$

with corona



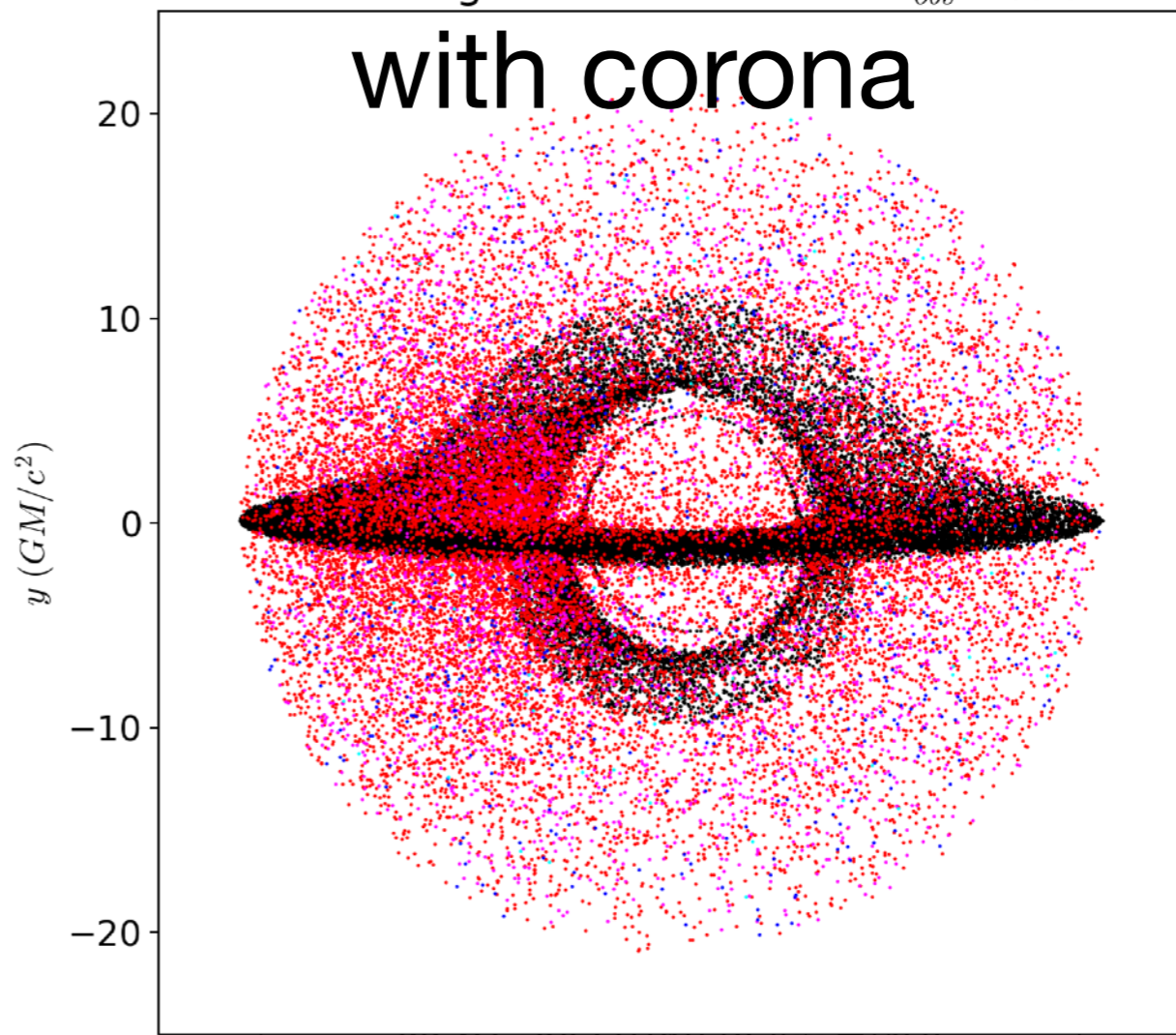
Photon Angular Distribution at $\theta_{obs} = 85.0^\circ$

without corona

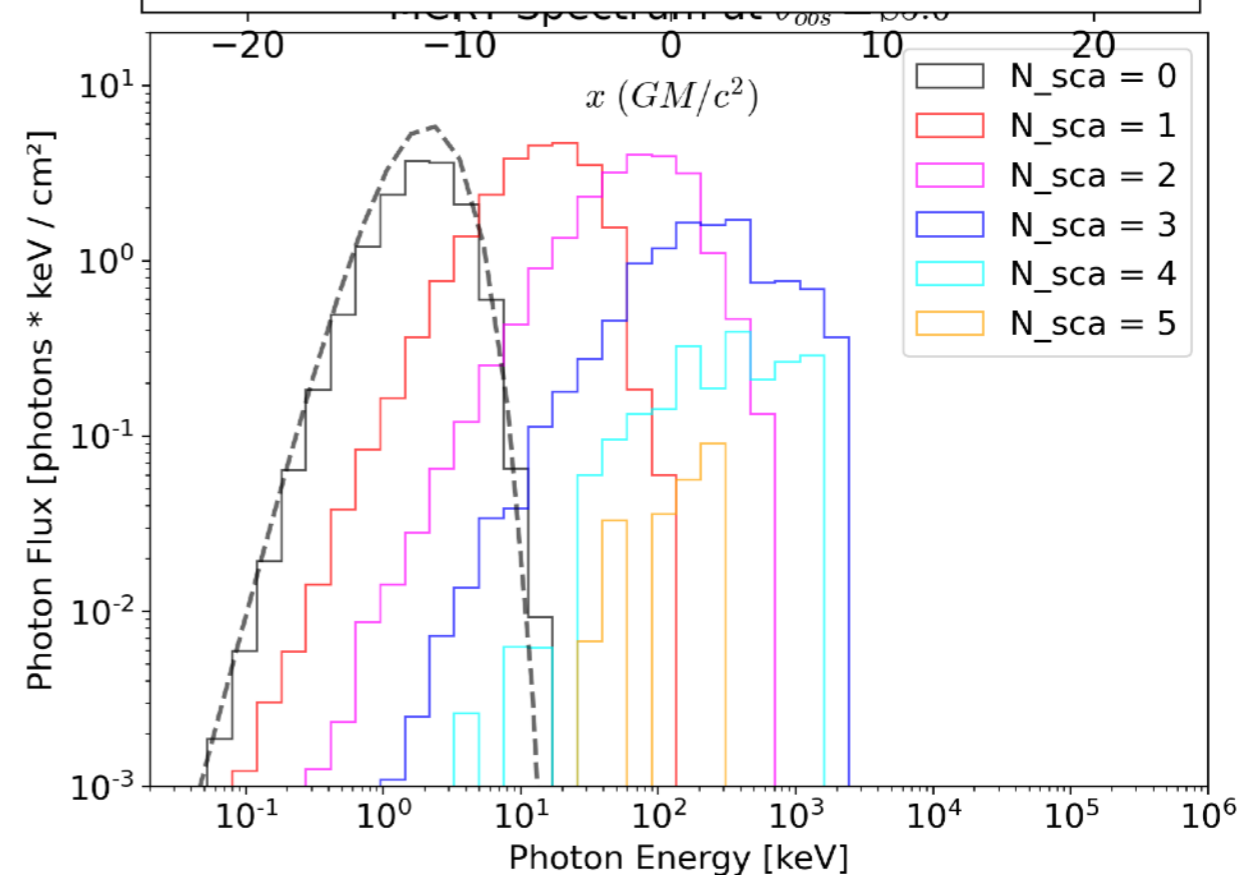
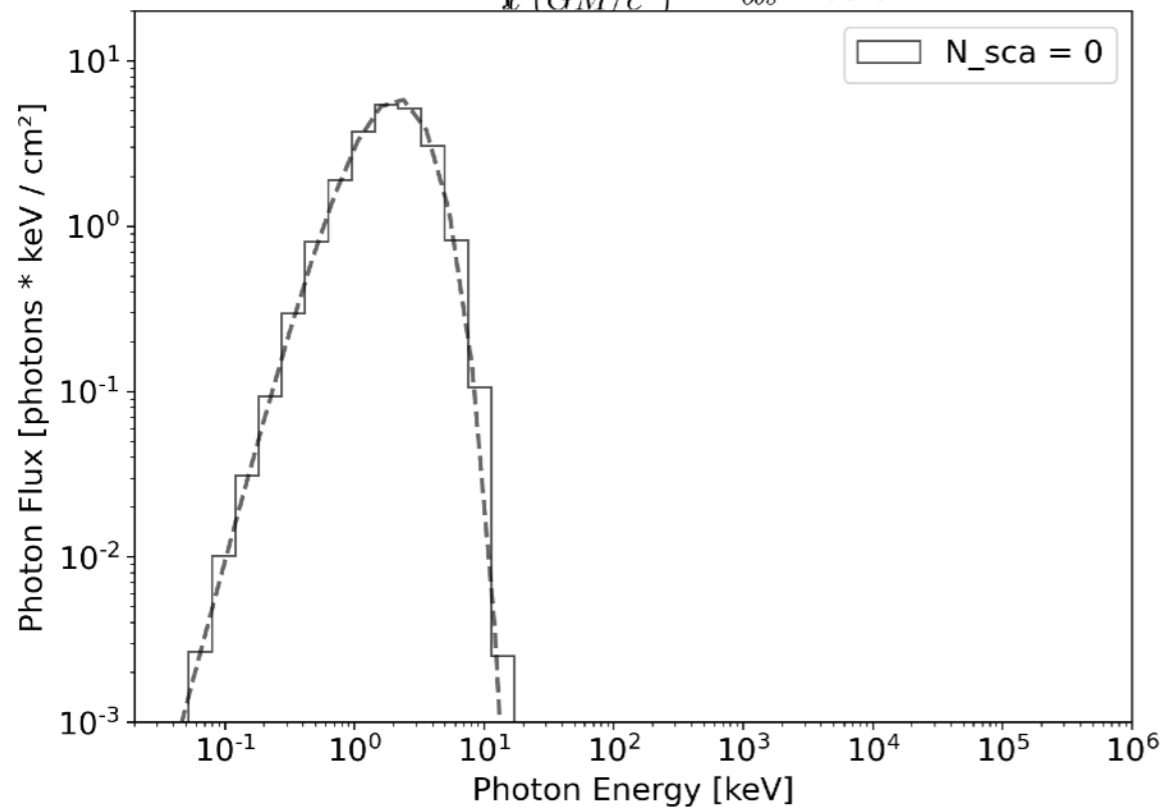


Photon Angular Distribution at $\theta_{obs} = 85.0^\circ$

with corona

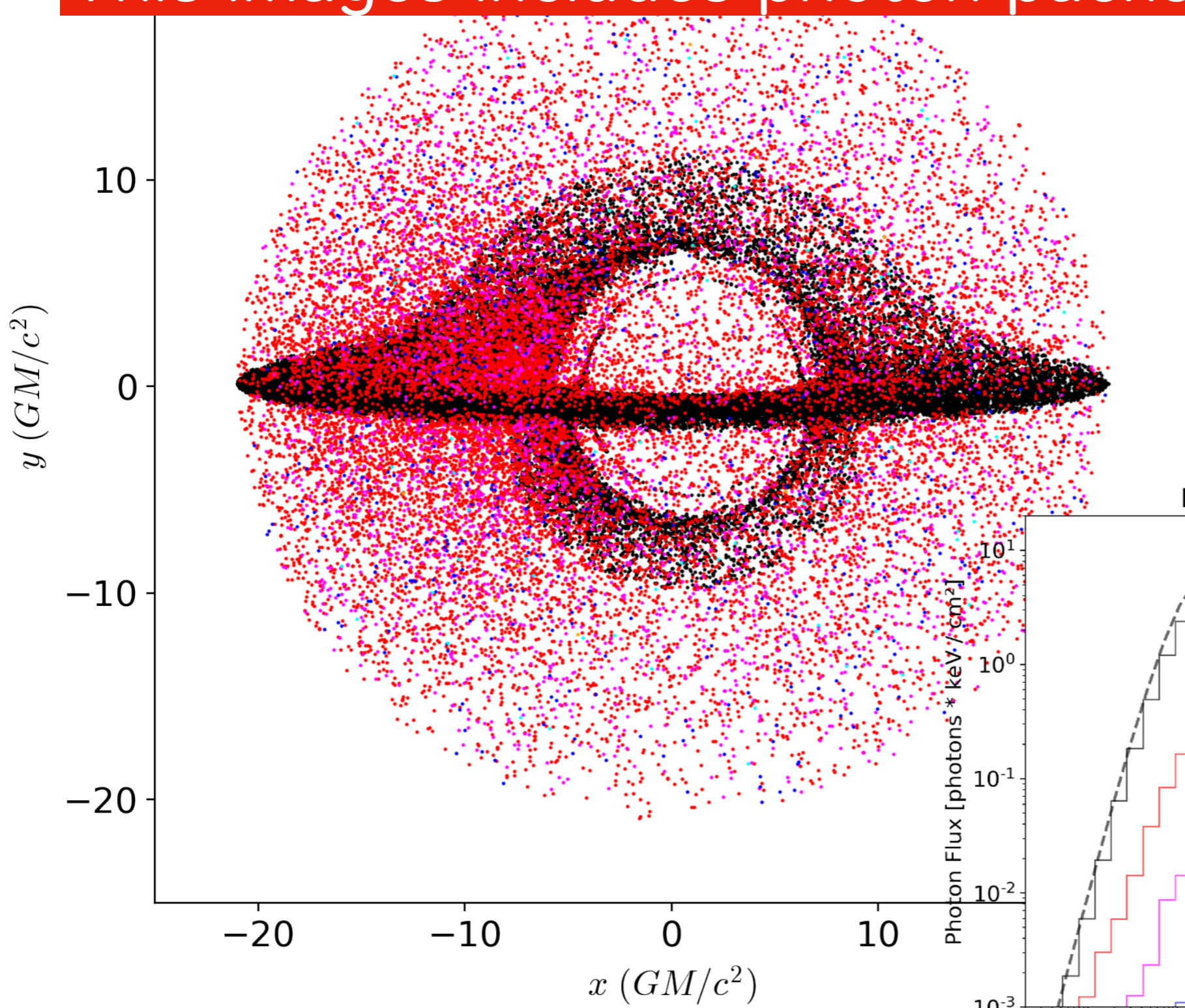


MCRT Spectrum at $\theta_{obs} = 85.0^\circ$

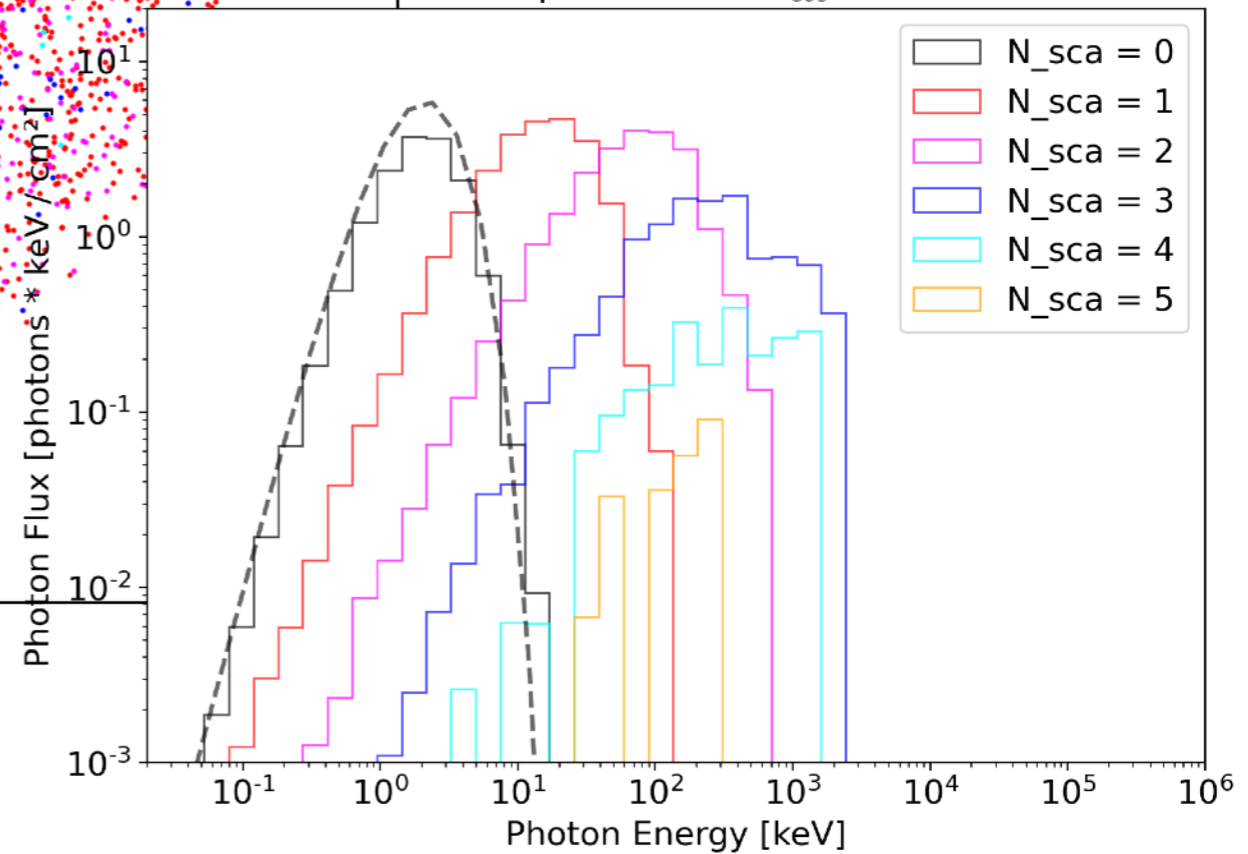


Photon Angular Distribution at $\theta_{obs} = 85.0^\circ$

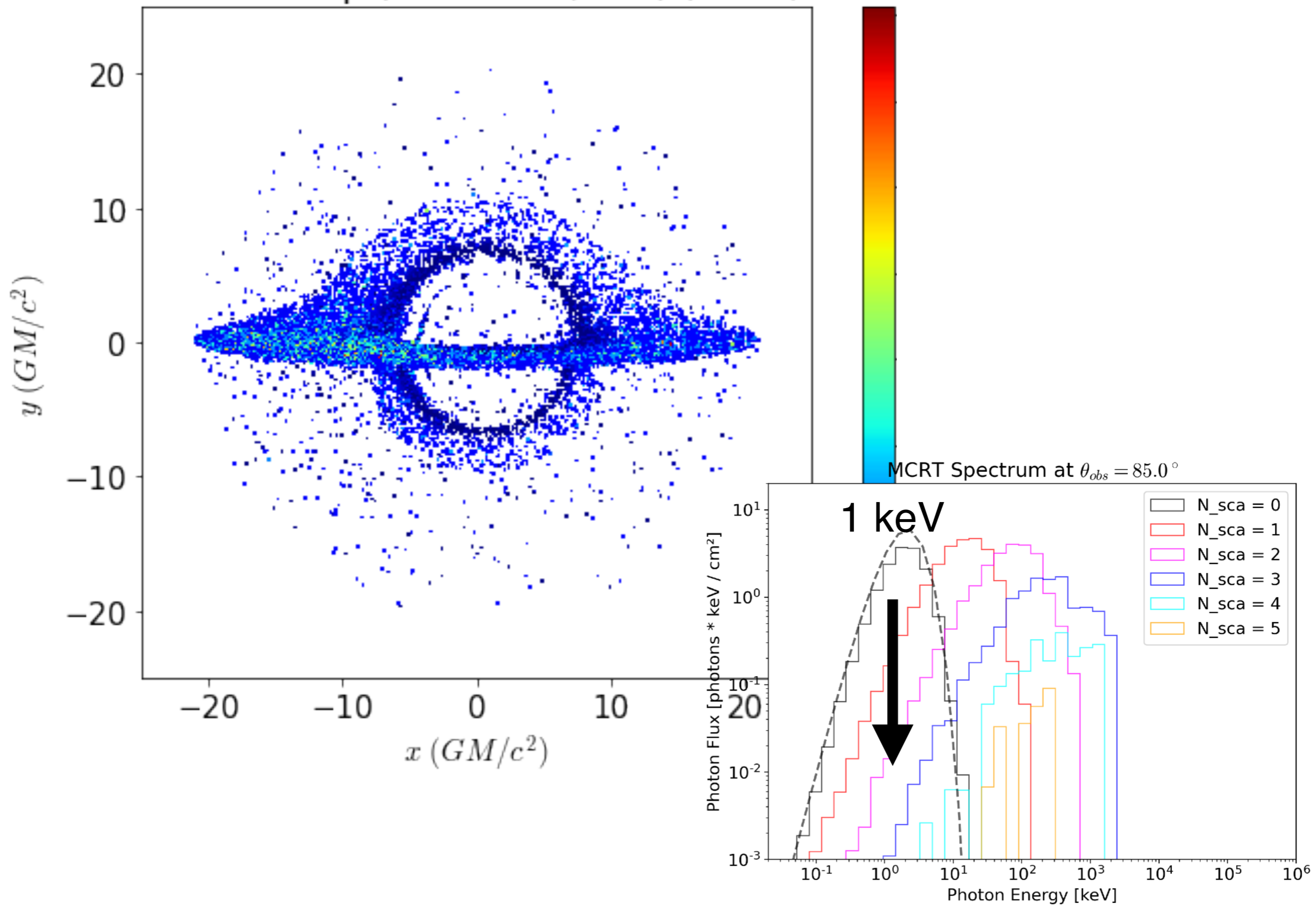
This images includes photon packets of all energy



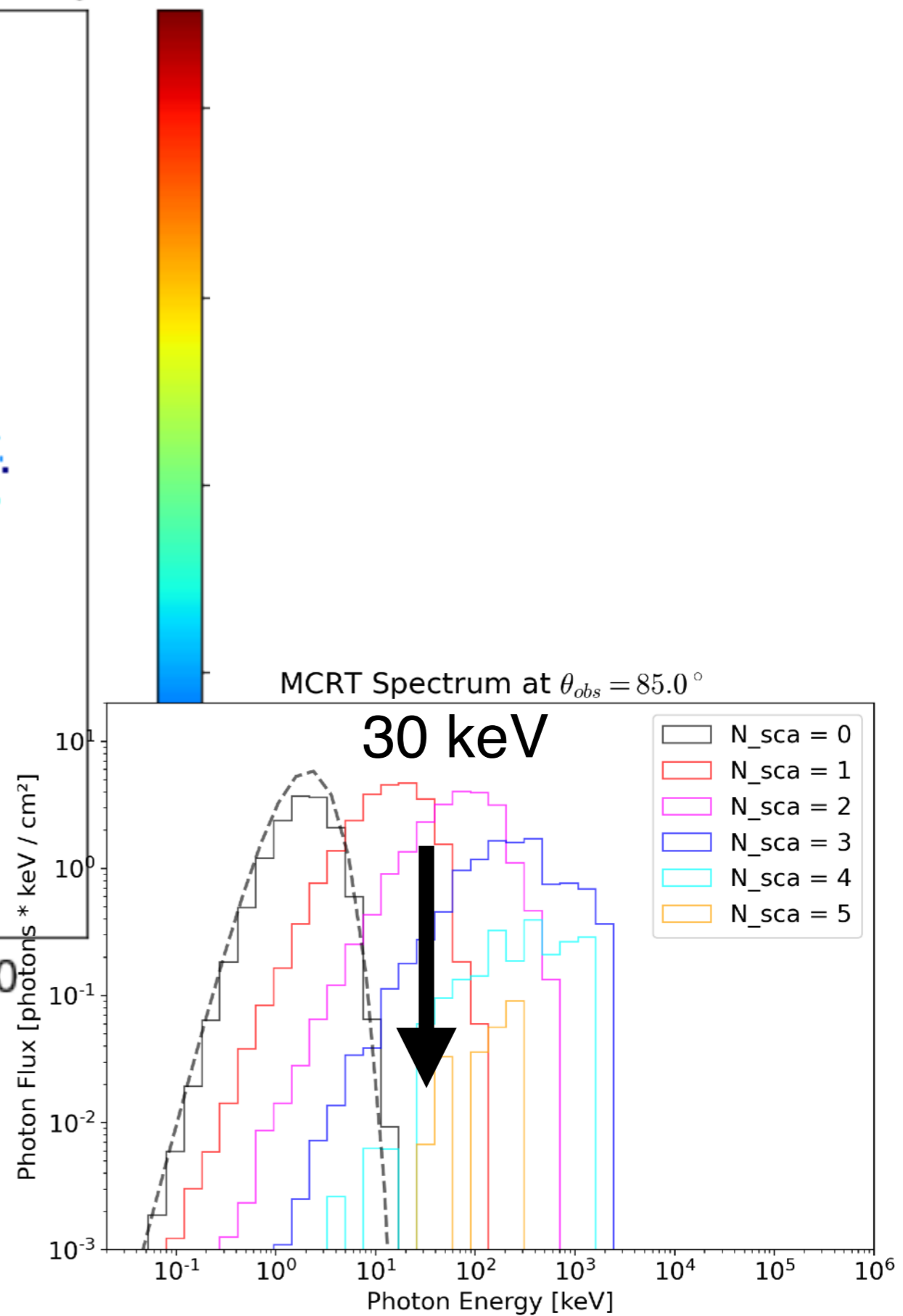
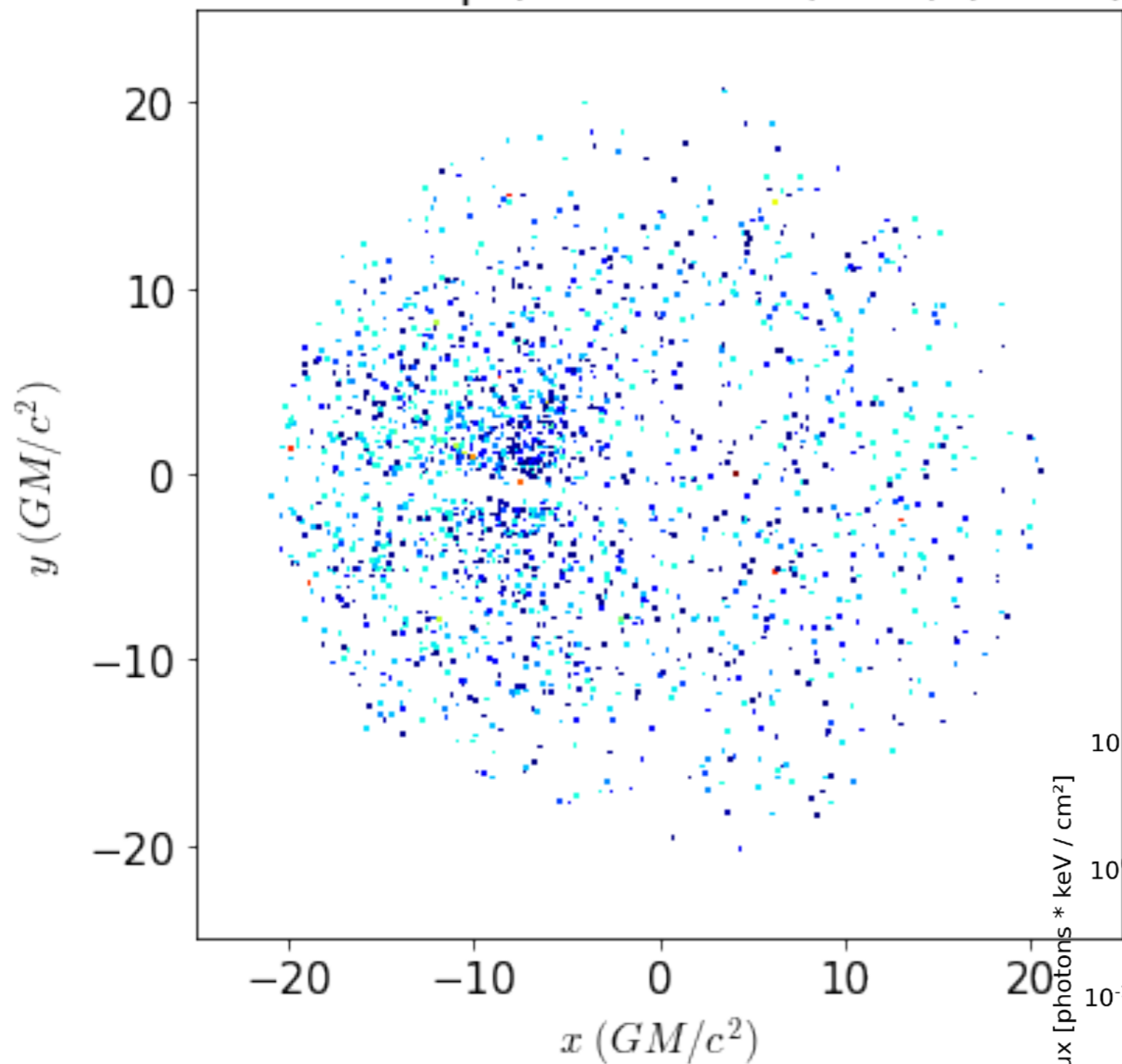
MCRT Spectrum at $\theta_{obs} = 85.0^\circ$



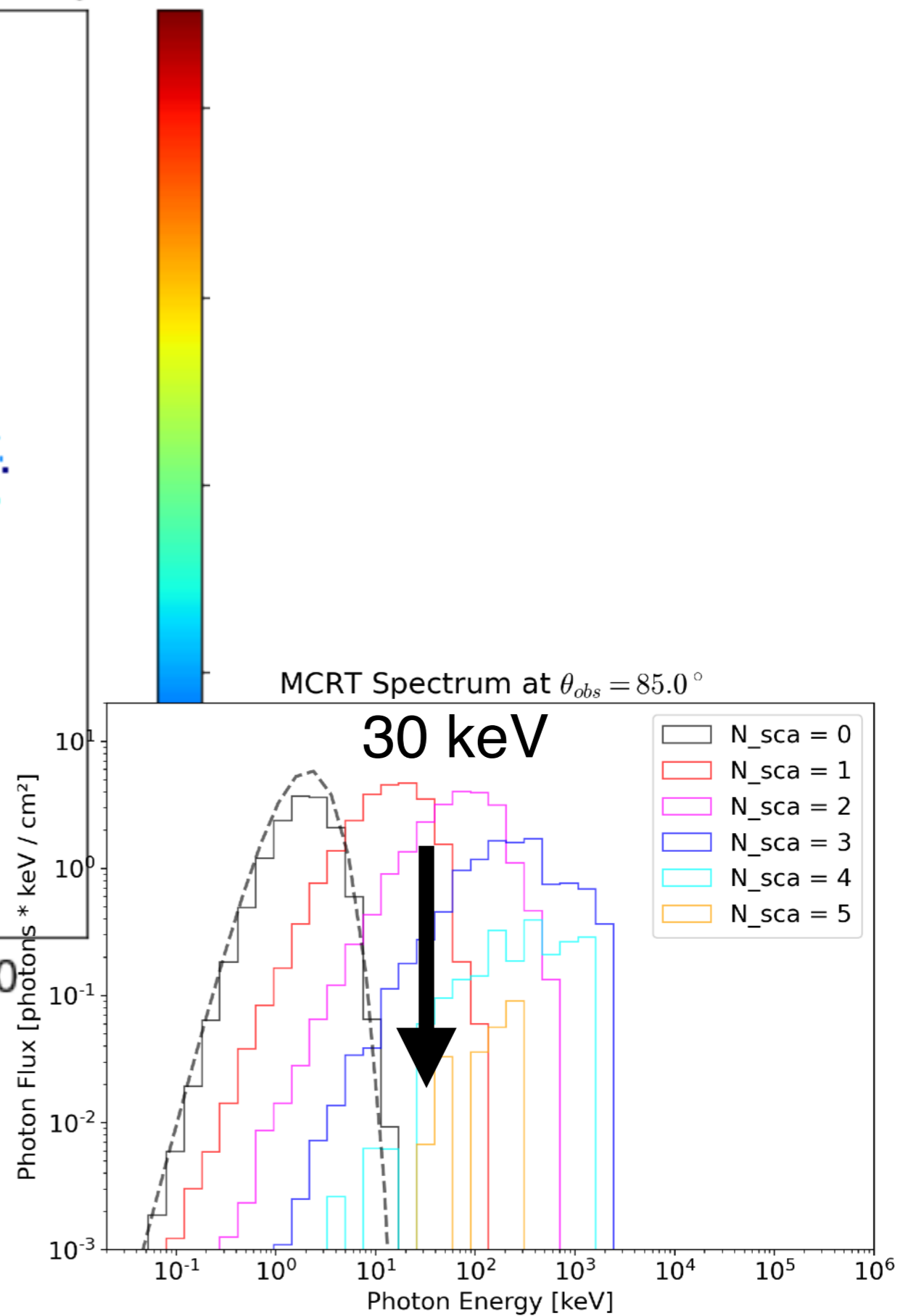
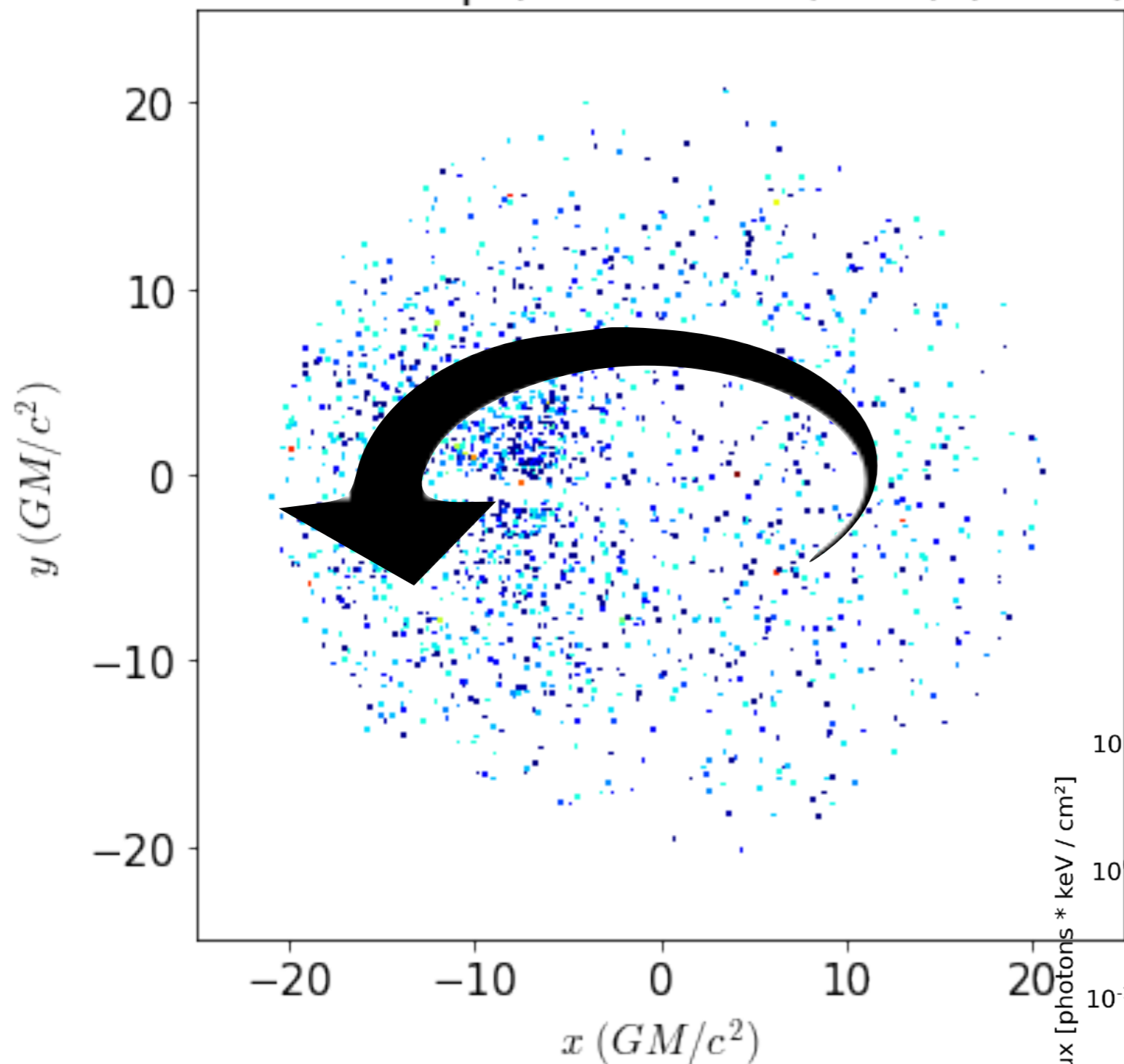
Photon Map ($E \sim 1$ keV, $\Delta \ln(\nu) = 0.6$)



Photon Map ($E \sim 30$ keV, $\Delta \ln(\nu) = 0.6$)

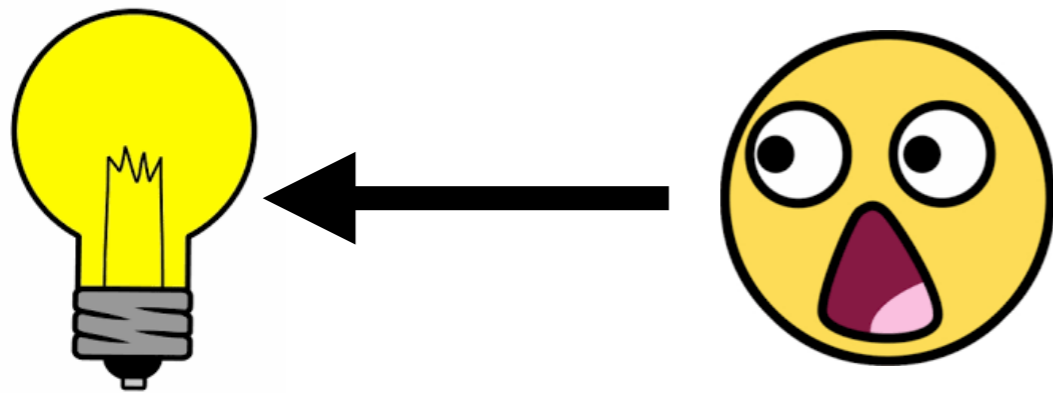


Photon Map ($E \sim 30$ keV, $\Delta \ln(\nu) = 0.6$)



Summary

GPU-based RT code is ready for ongoing and future horizon-scale black hole astrophysics!

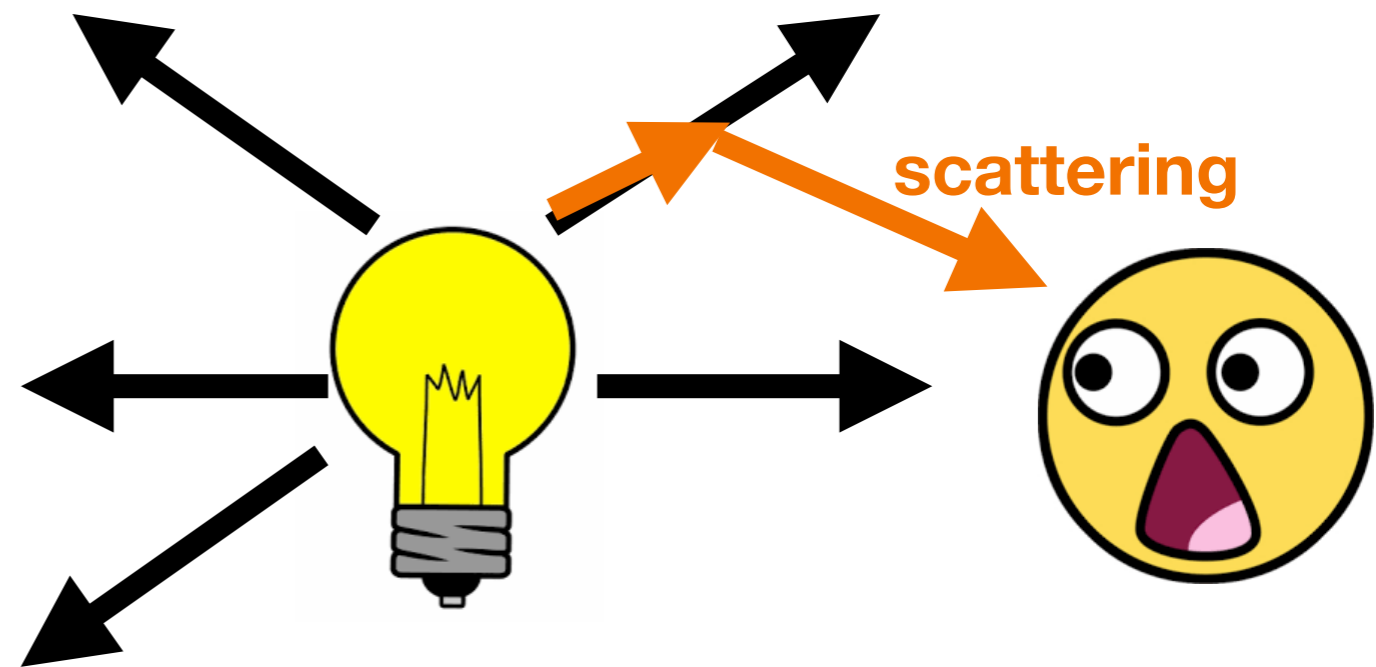


observer-to-source

faster and “easy”

Odyssey

Radio



source-to-observer

slower but powerful

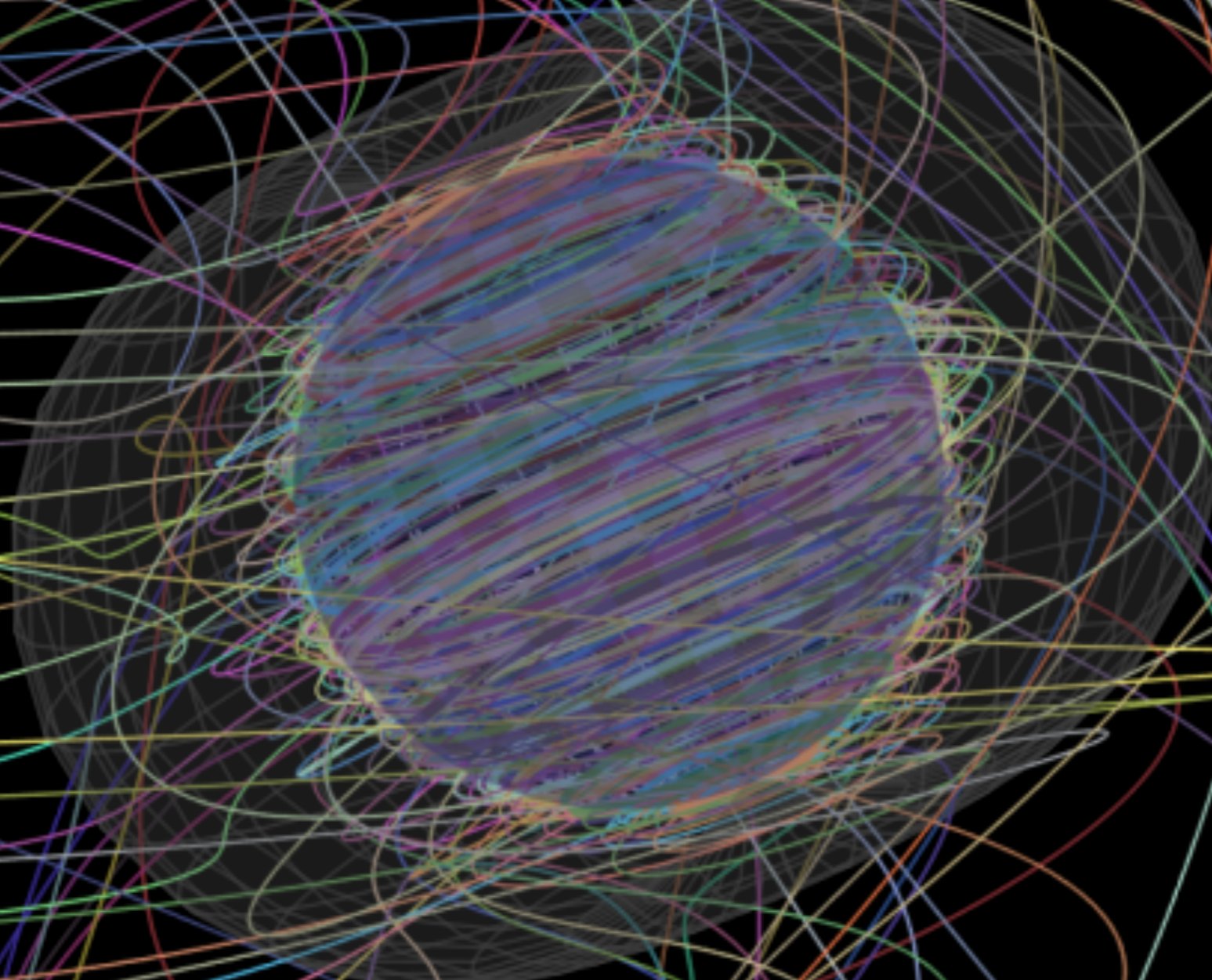
Illiad

X-ray

* in this talk we focus on intensity-only images and spectra, ignoring the polarization

Backup slides

Photon travel in a curved spacetime



computed by the public education software: Odyssey_Edu



Intensity-only radiative transfer:

$$\frac{d}{ds} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{pmatrix} - \begin{pmatrix} \alpha_I & \alpha_Q & \alpha_U & \alpha_V \\ \alpha_Q & \alpha_I & \rho_V & \rho_U \\ \alpha_U & -\rho_V & \alpha_I & \rho_Q \\ \alpha_V & -\rho_U & -\rho_Q & \alpha_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \quad (\geq 0)$$

pol. radiative transfer:

Faraday rotation

| 100% Q | 100% U | 100% V |
|--|--|--|
| <p>+Q Q > 0; U = 0; V = 0 (a)</p> | <p>+U Q = 0; U > 0; V = 0 (c)</p> | <p>+V Q = 0; U = 0; V > 0 (e)</p> |
| <p>-Q Q < 0; U = 0; V = 0 (b)</p> | <p>-U Q = 0; U < 0; V = 0 (d)</p> | <p>-V Q = 0; U = 0; V < 0 (f)</p> |

$$\frac{d}{ds} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{pmatrix} - \begin{pmatrix} \alpha_I & \alpha_Q & \alpha_U & \alpha_V \\ \alpha_Q & \alpha_I & \rho_V & \rho_U \\ \alpha_U & -\rho_V & \alpha_I & \rho_Q \\ \alpha_V & -\rho_U & -\rho_Q & \alpha_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Faraday conversion