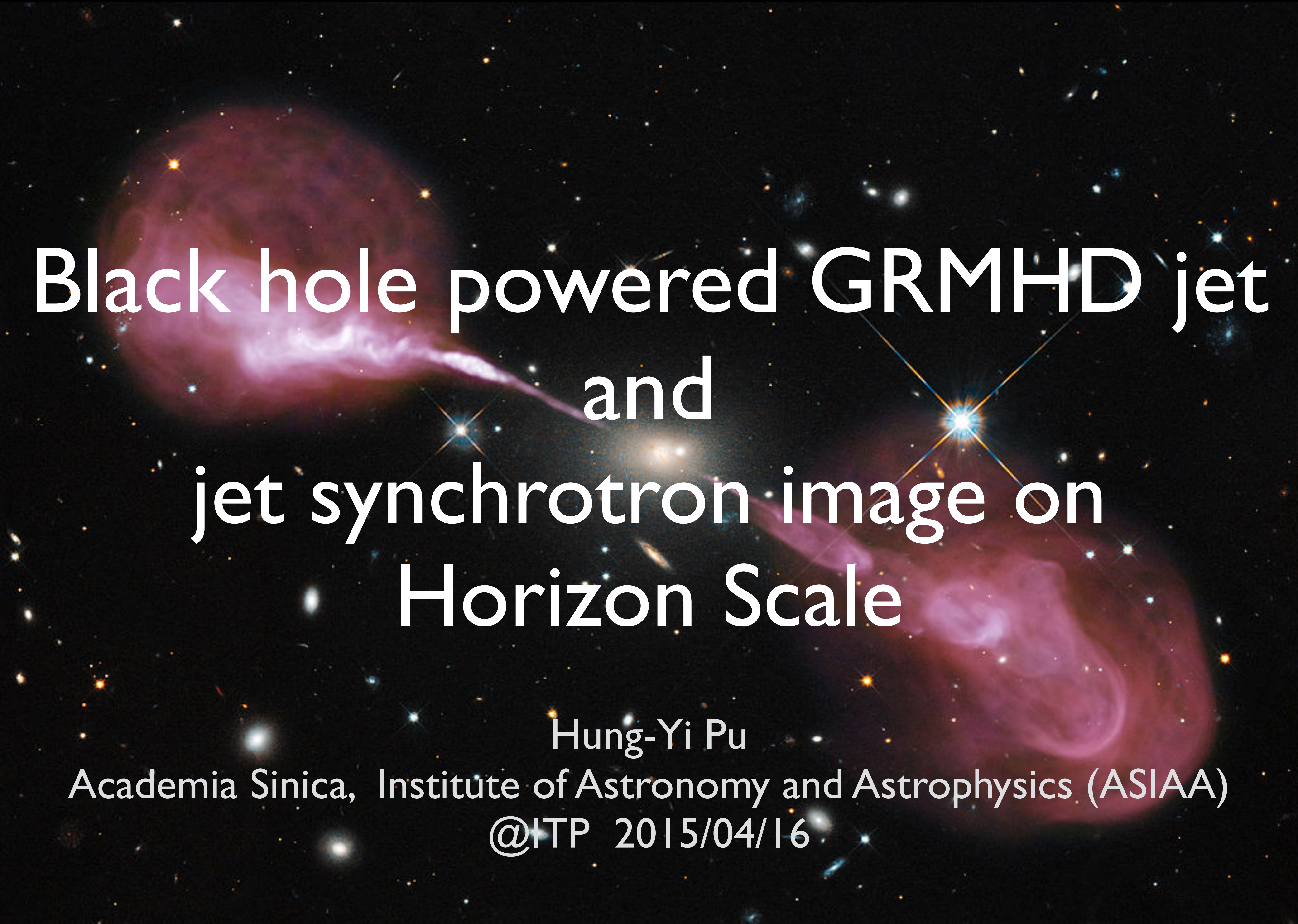

Black hole powered GRMHD jet and jet synchrotron image on Horizon Scale

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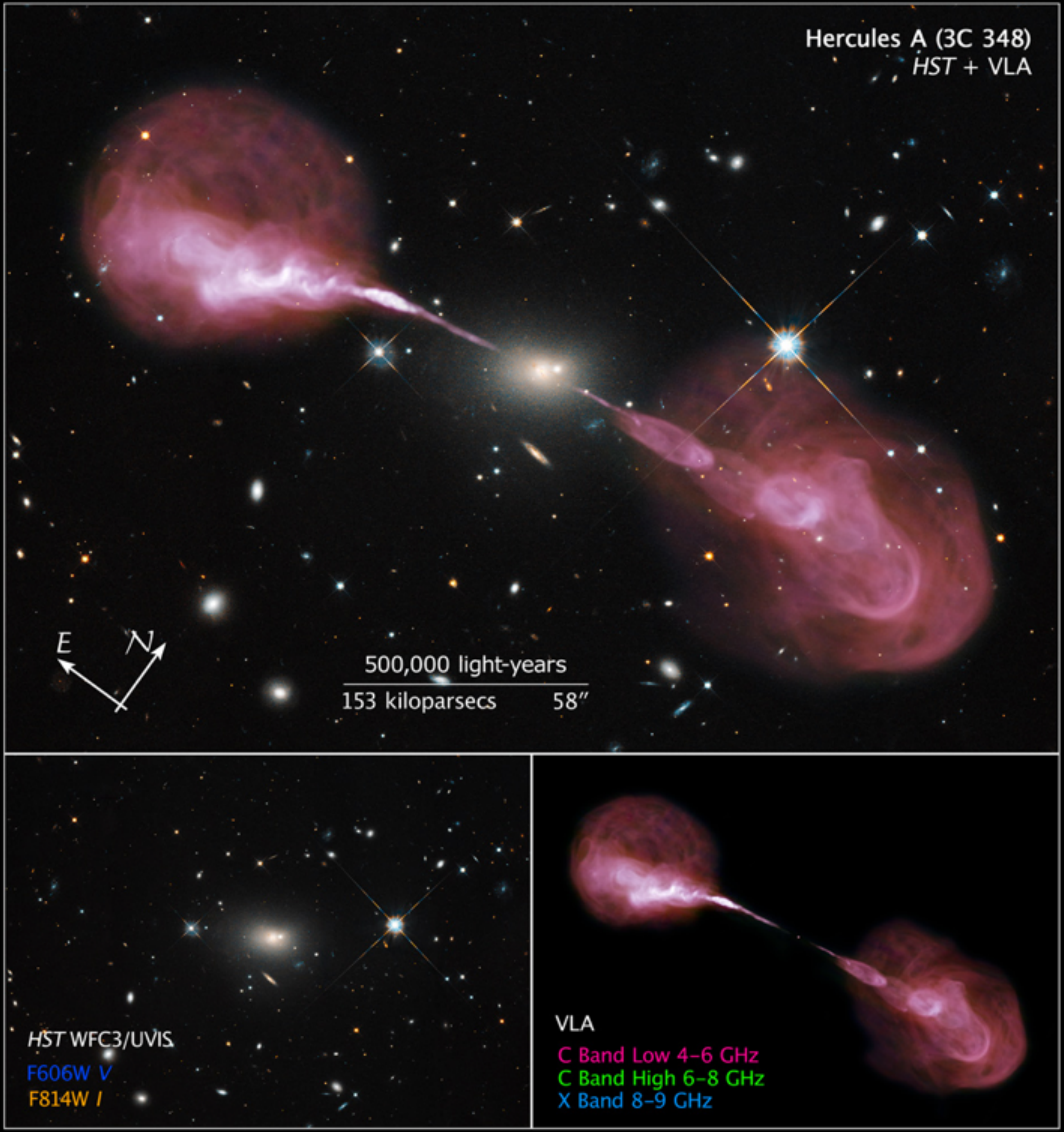
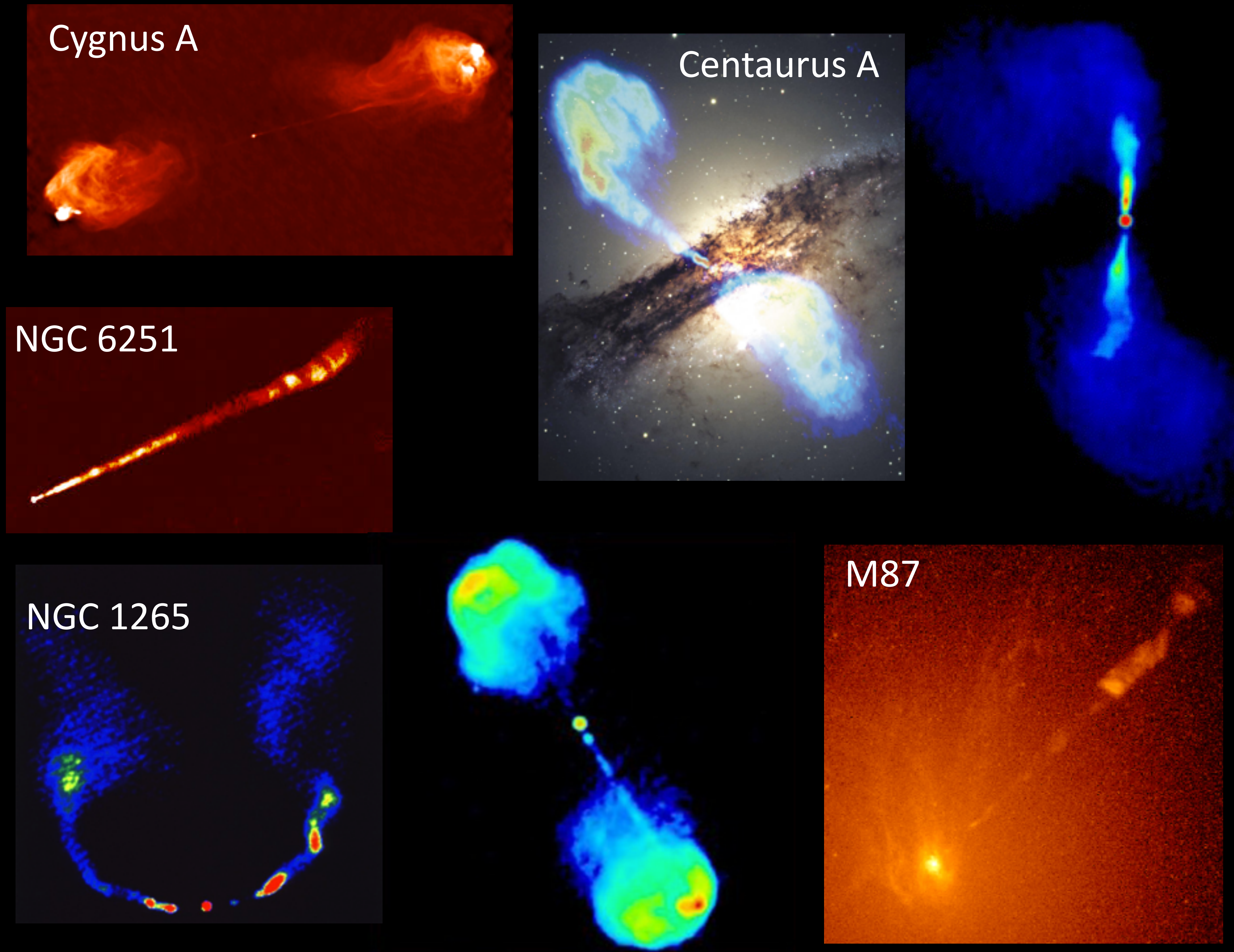
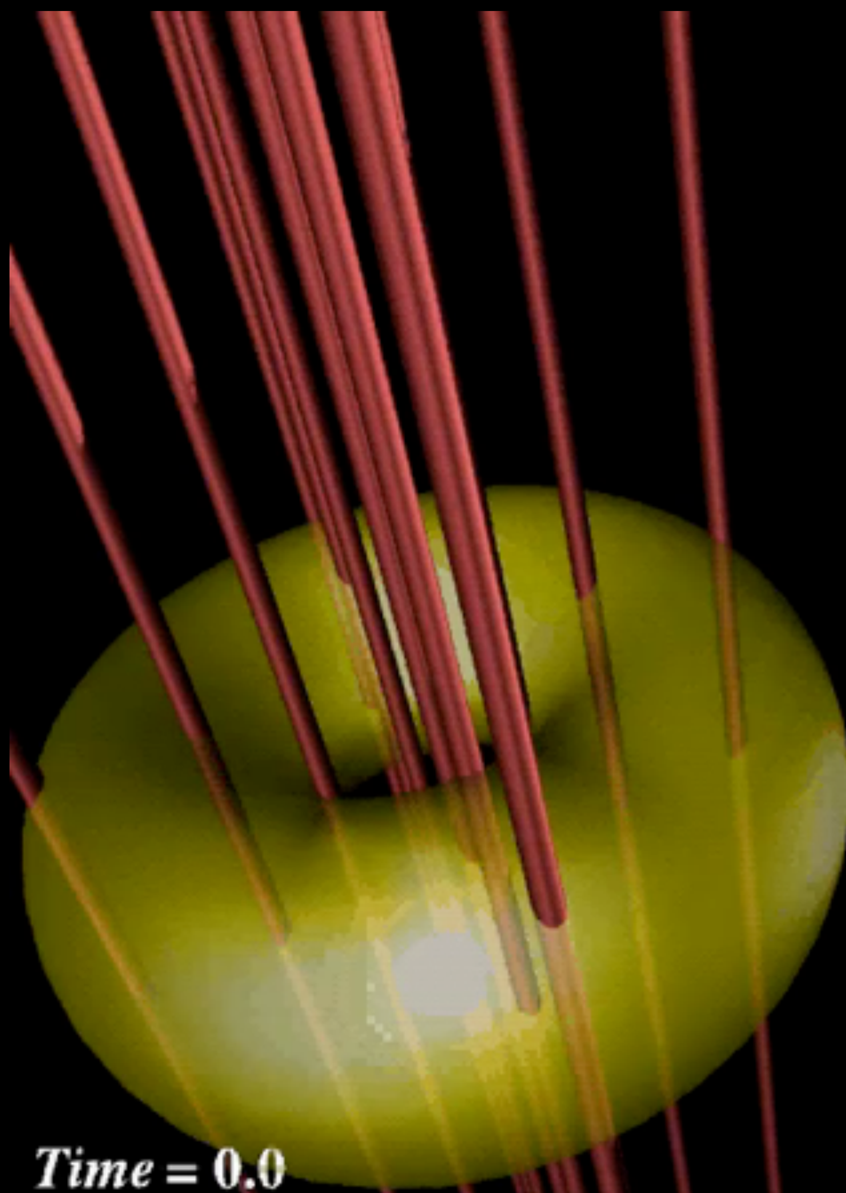
@ITP 2015/04/16


Hercules A (3C 348)
HST + VLA
E
N
500,000 light-years
153 kiloparsecs
58″
HST WFC3/UVIS
F606W V
F814W I
VLA
C Band Low 4-6 GHz
C Band High 6-8 GHz
X Band 8-9 GHz


Cygnus A
Centaurus A
NGC 6251
NGC 1265
M87

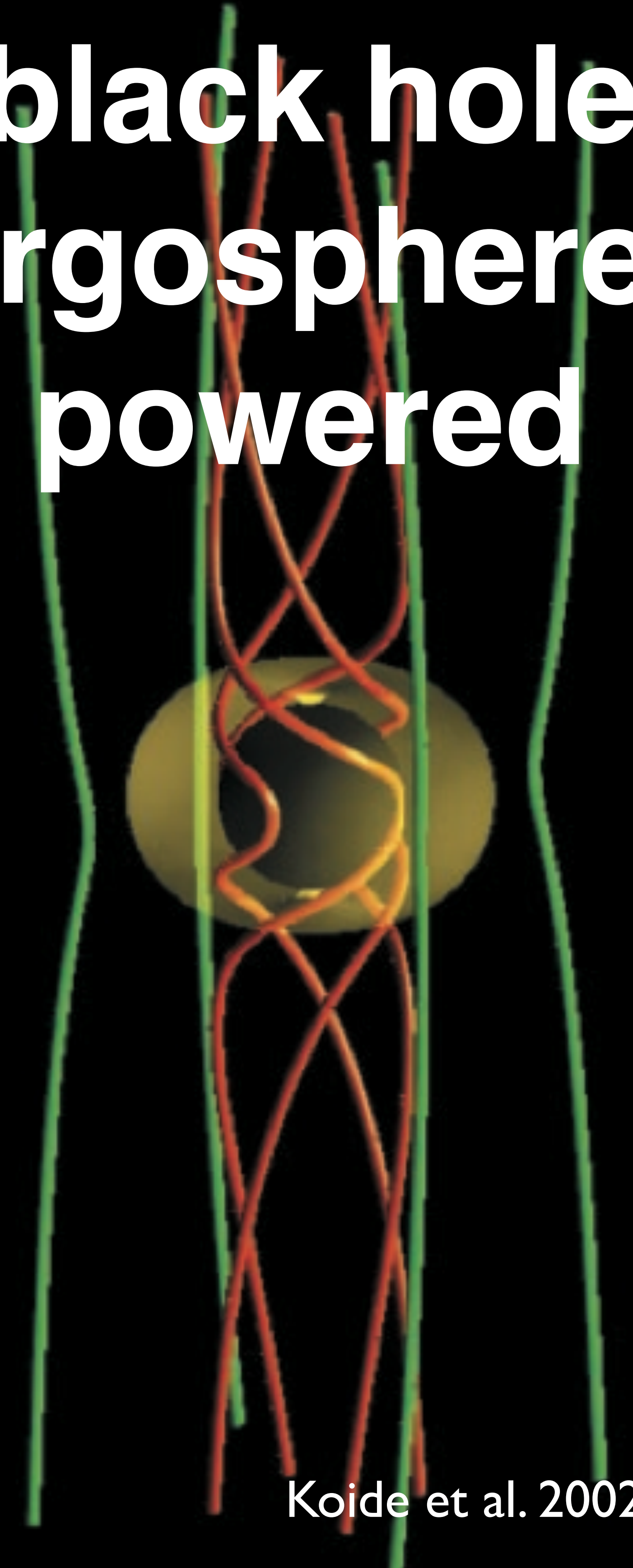
accretion-powered



movie by Nakamura

or

black hole (ergosphere)-powered



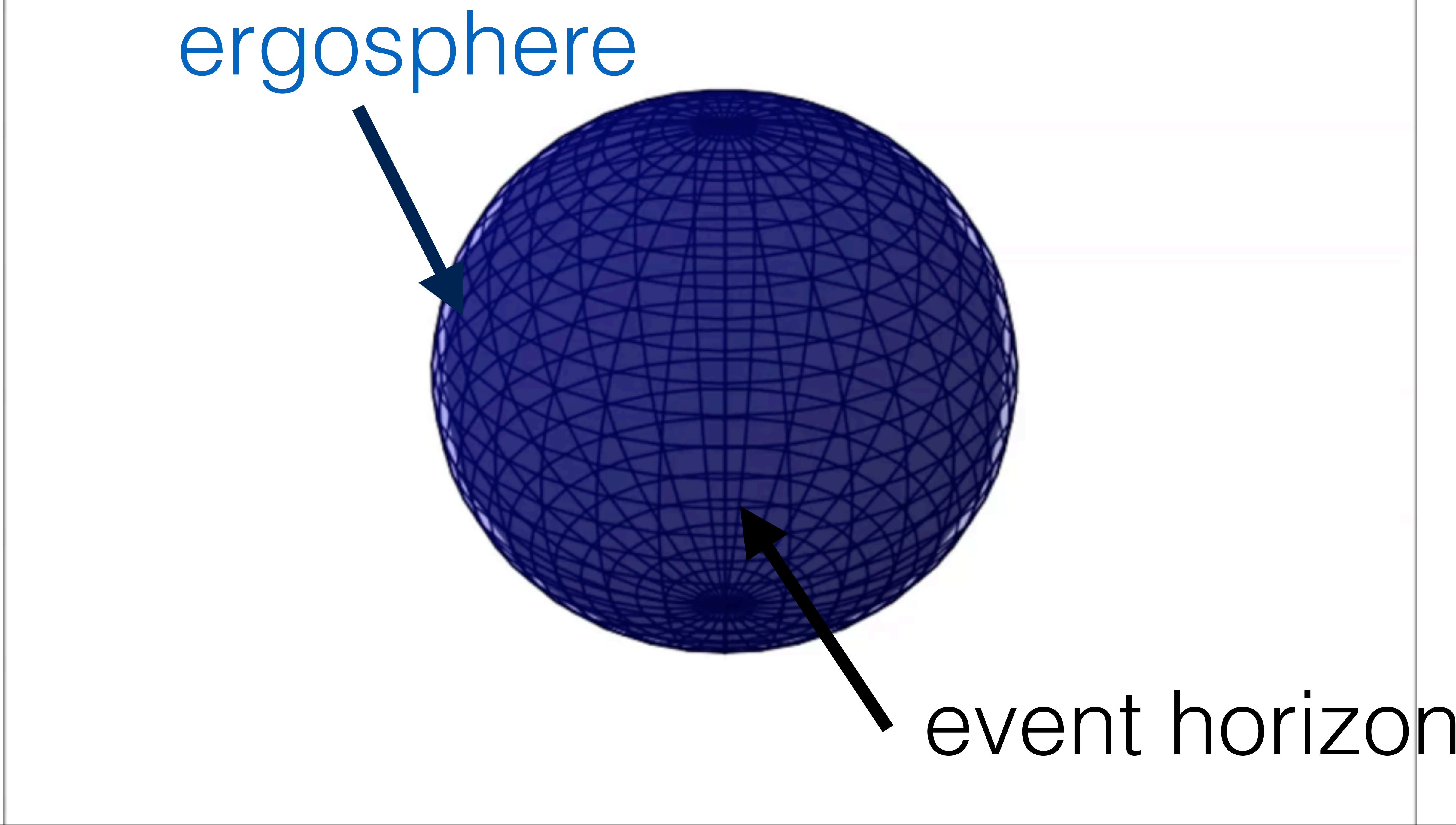
Koide et al. 2002

Outline

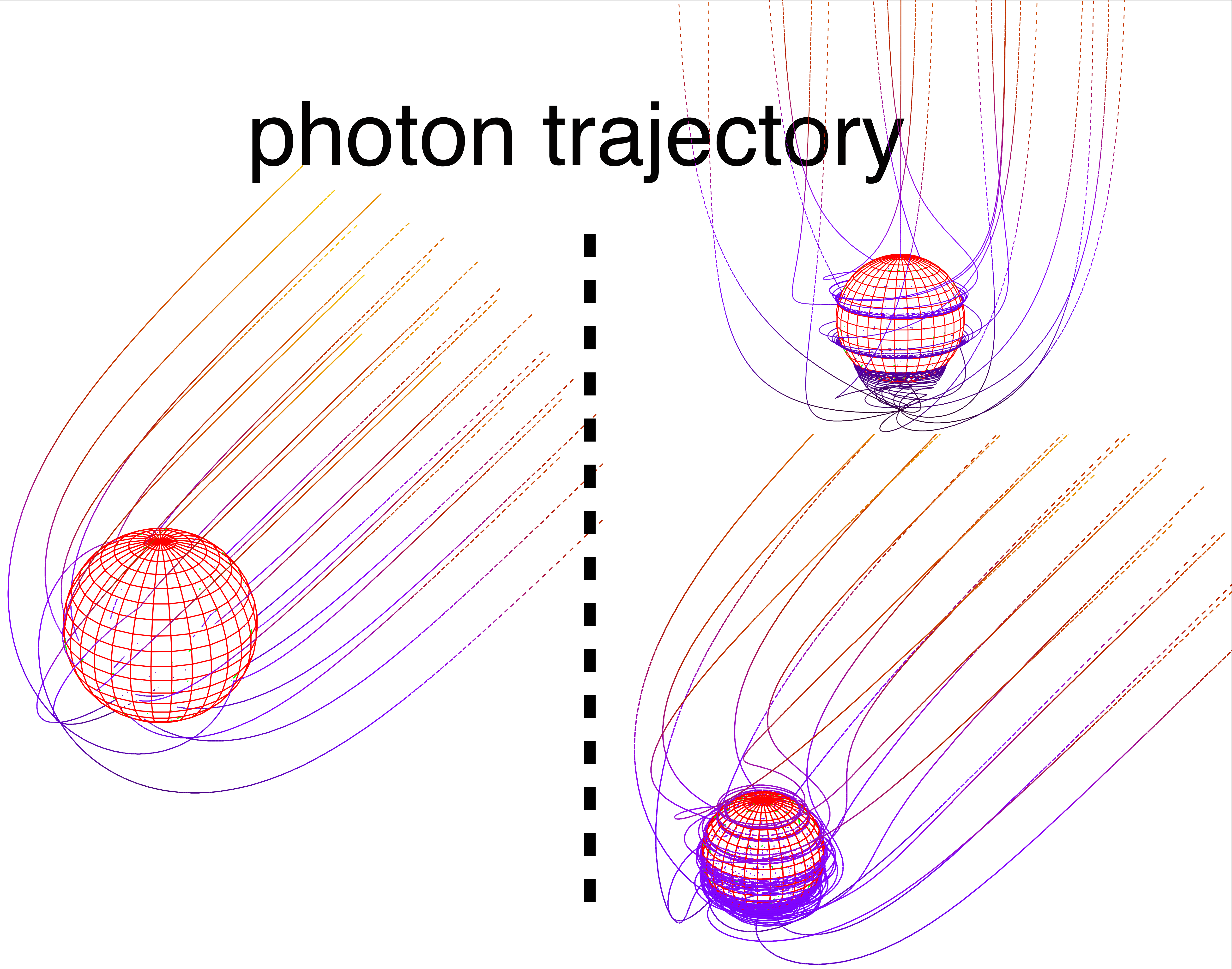
- black hole powered GRMHD jet model
  - jet launching at the expense of black hole rotational energy
  - semi-analytical approach
- Synchrotron Radiation Image
  - ray-tracing and GR relativistic transfer
  - challenge
- Summary

Frame Dragging Effect

around a rotating black hole

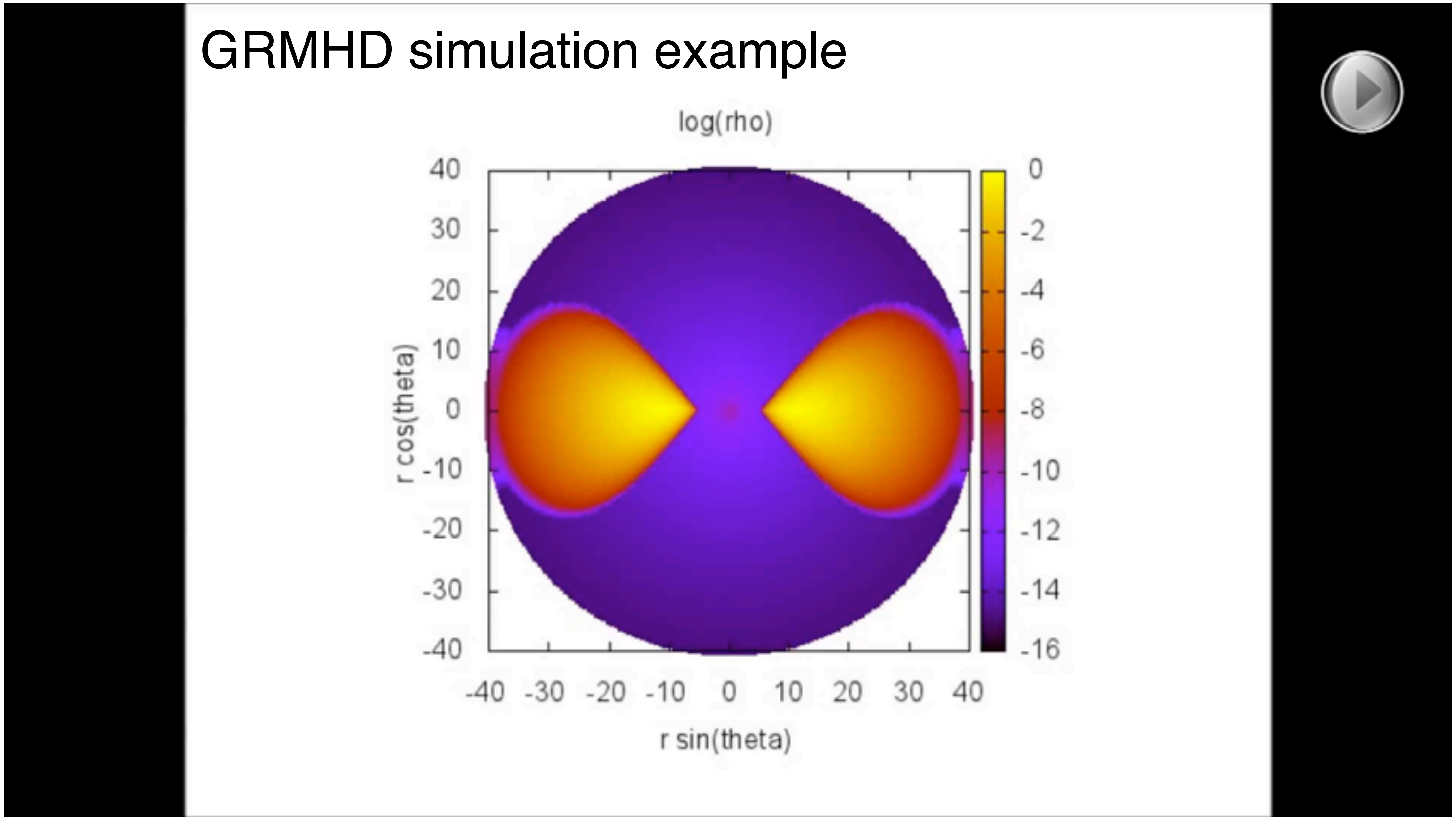


photon trajectory

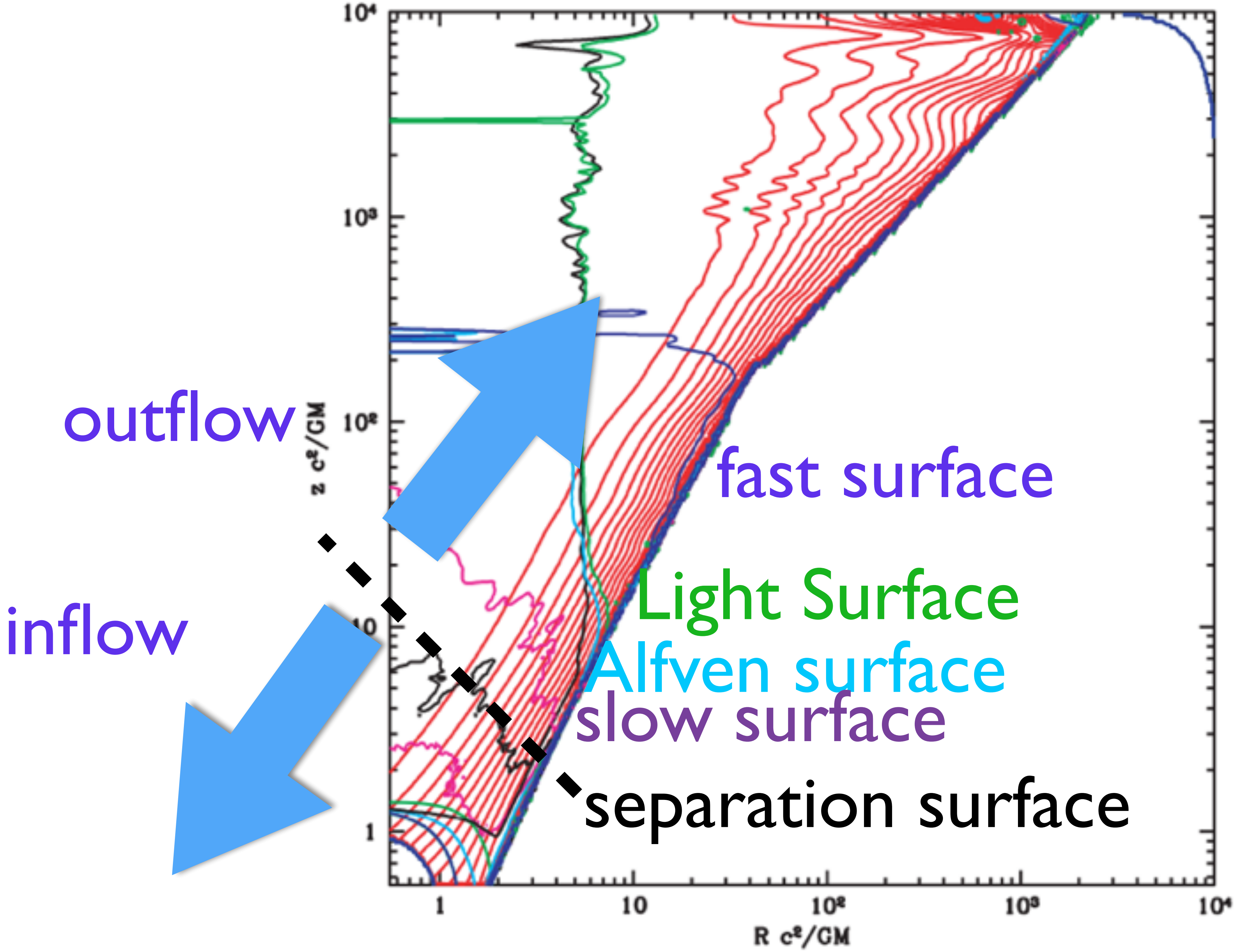


Extraction of Black hole Energy:

by large scale magnetic field (Blandford & Znajek 1977)
by GRMHD flow (Takahashi et al. 1990)

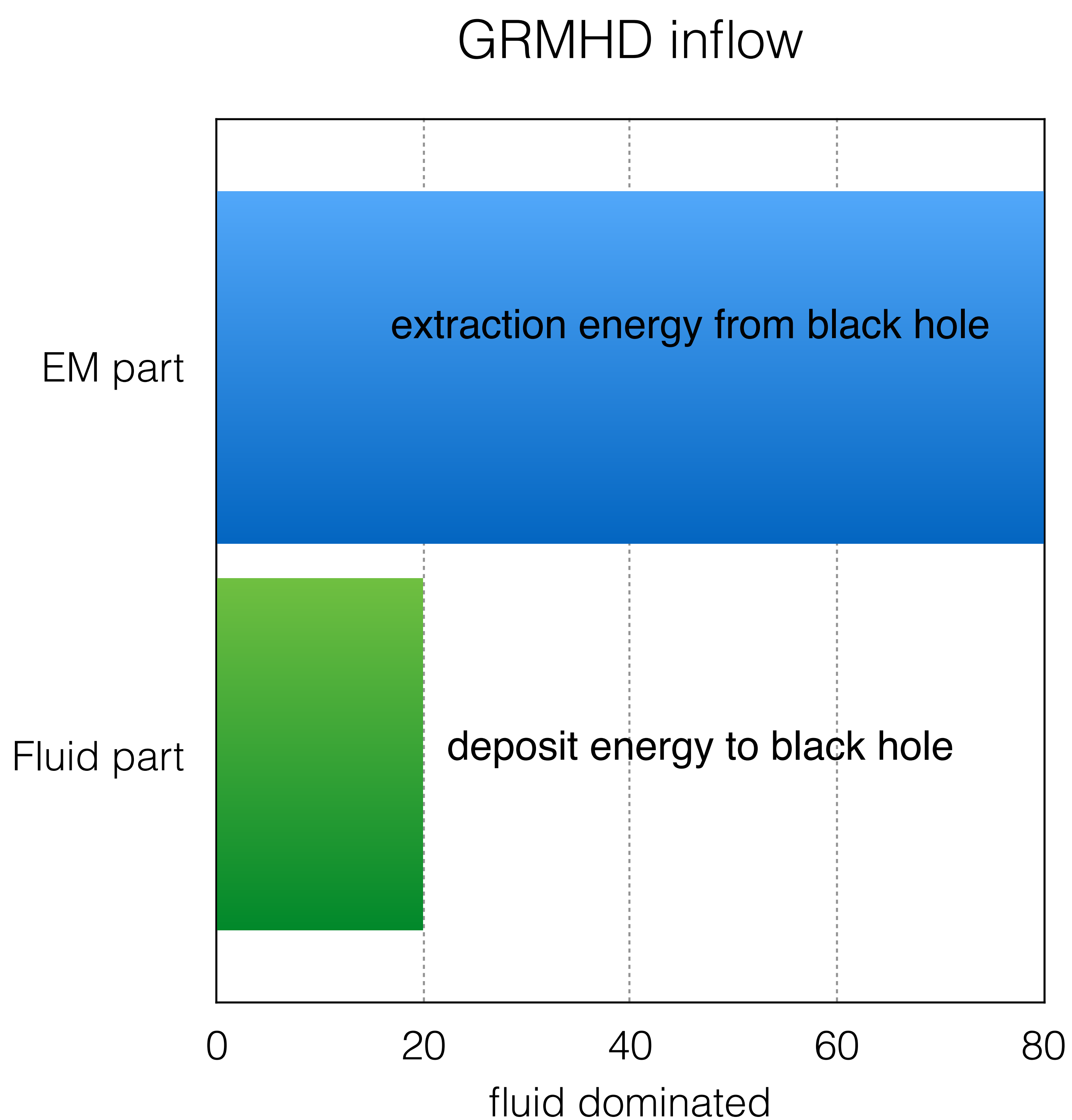


GRMHD flow structure



time-averaged GRMHD simulation result, McKinney 2006

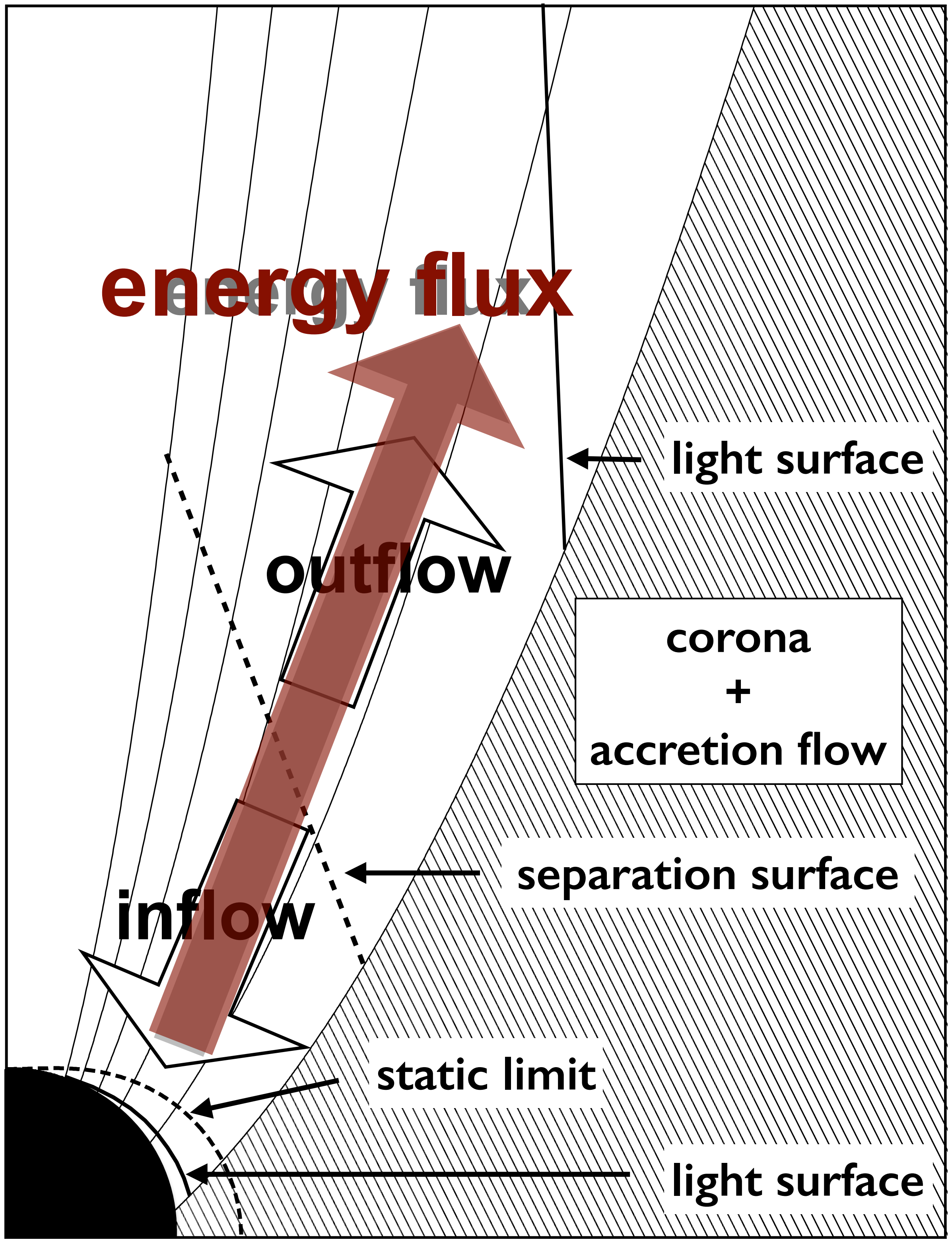
inflow



The black hole rotational energy is extracted outward when the flow become magnetically dominated

launching and quenching of relativistic jet can be related to the accretion state
(Pu et al. 2012, Globus & Levinson 2013)

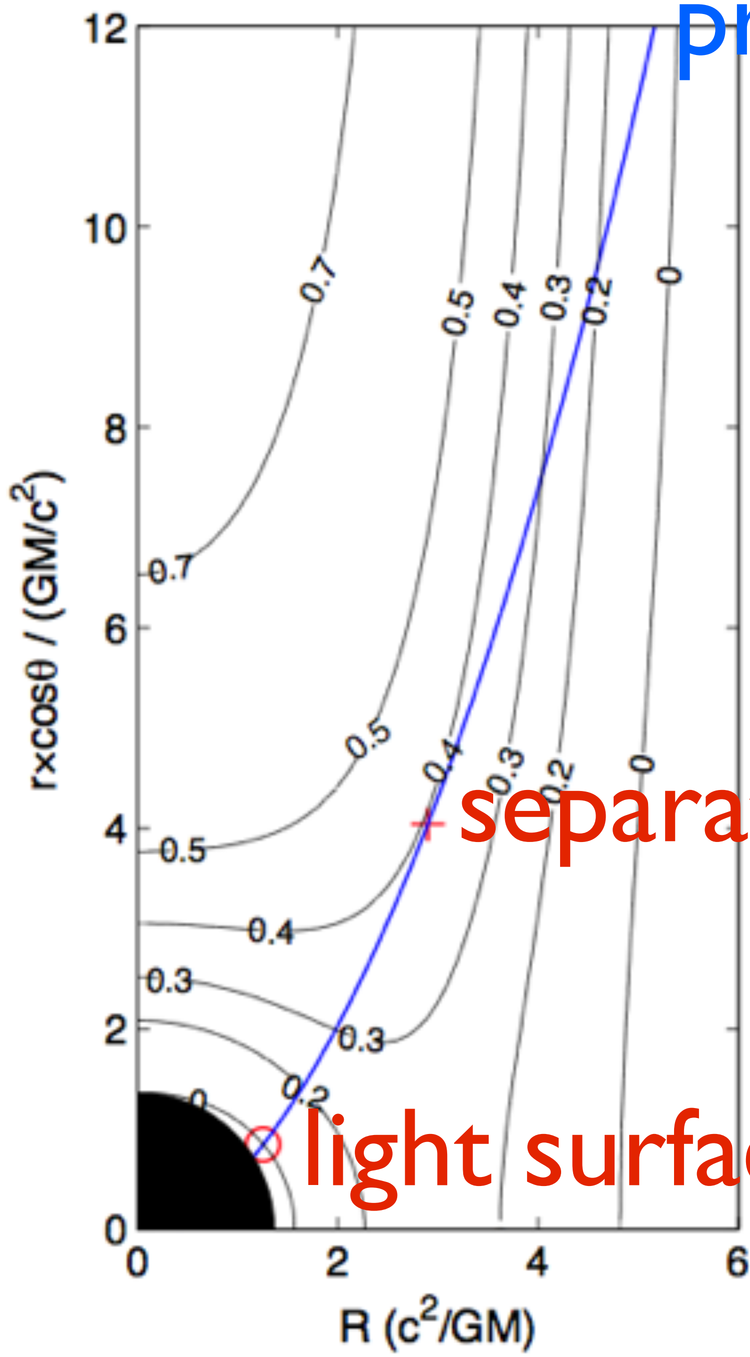
from inflow to outflow

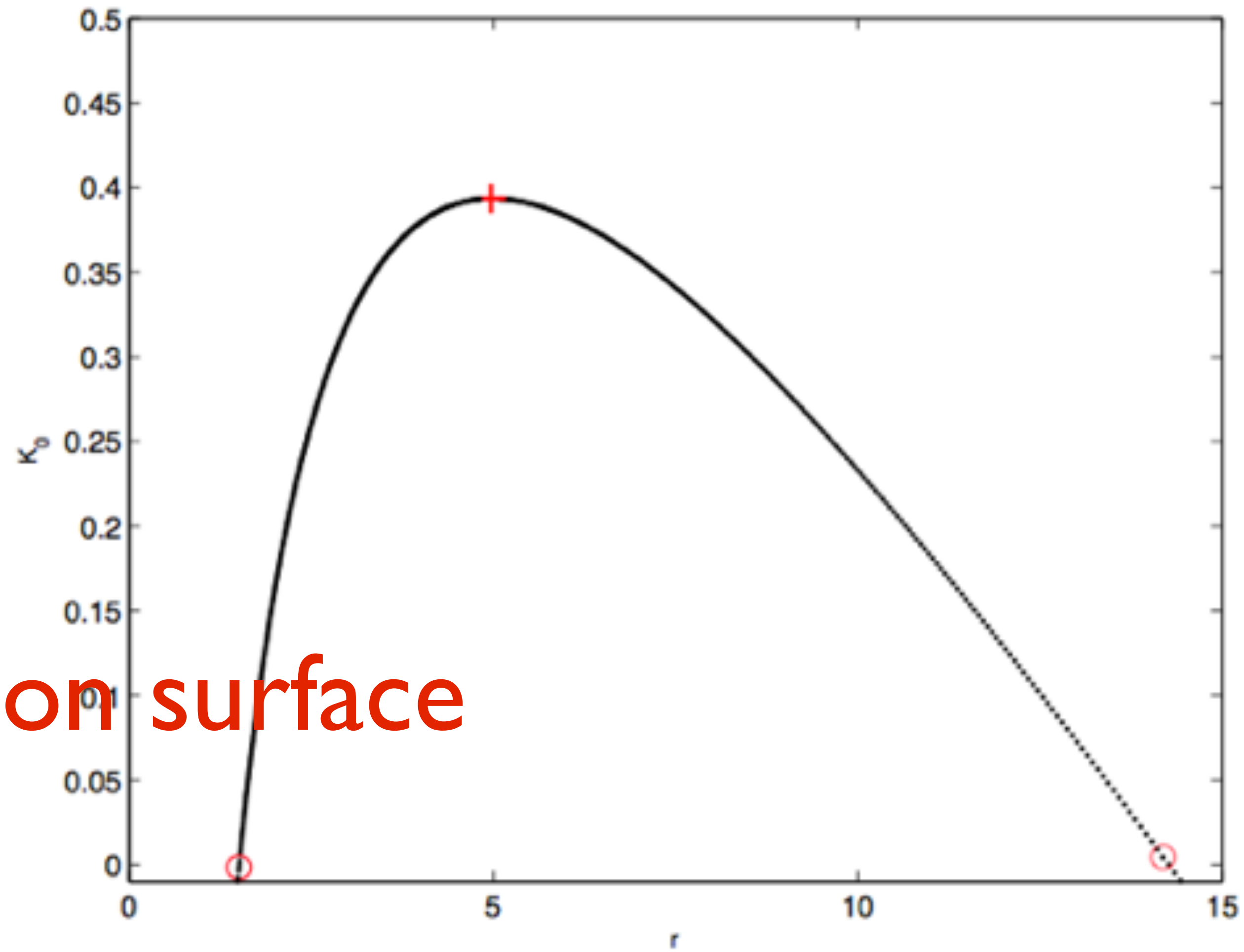


H.-Y. Pu et al. 2015

- focus on magnetically dominated case
- the develop of the outflow is constraint by the inflow, assuming Poynting energy flux is continuously propagate outward

how to distinguish inflow/outflow?





$$K_0 = -\Big(g_{\phi\phi}\Omega_F^2 + 2g_{t\phi}\Omega_F + g_{tt}\Big)$$

conserved quantities along field line

$$\left(nu^{\mu}\right)_{;\mu} = 0,$$

$$F_{\mu\nu} u^{\mu} = 0.$$

$$\left(\xi_{\mu} T^{\mu\nu}\right)_{;\nu} = 0,$$

$$\left(\eta_{\mu} T^{\mu\nu}\right)_{;\nu} = 0,$$

$$\Omega_F(\Psi) = \frac{F_{tr}}{F_{r\phi}} = \frac{F_{t\theta}}{F_{\theta\phi}},$$

$$\eta(\Psi) = \frac{\sqrt{-g}\, nu^r}{F_{\theta\phi}} = -\frac{\sqrt{-g}\, nu^{\theta}}{F_{r\phi}}$$

$$= \frac{\sqrt{-g}\, nu^t (\Omega - \Omega_F)}{F_{r\theta}},$$

$$E(\Psi) = E_{\mathrm{FL}} + E_{\mathrm{EM}}$$

$$= -\mu u_t - \frac{\Omega_F}{4\pi\eta} \sqrt{-g}\, F^{r\theta}$$

$$= -\mu u_t - \frac{\Omega_F}{4\pi\eta} B_{\phi},$$

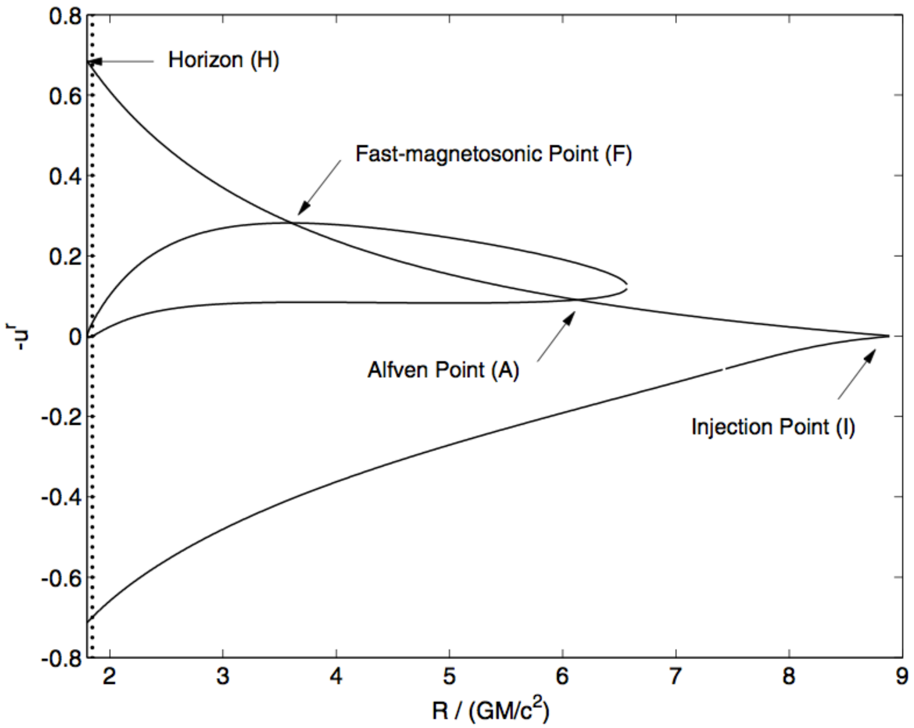
$$L(\Psi) = L_{\mathrm{FL}} + L_{\mathrm{EM}}$$

$$= \mu u_{\phi} - \frac{1}{4\pi\eta} \sqrt{-g}\, F^{r\theta}$$

$$= \mu u_{\phi} - \frac{B_{\phi}}{4\pi\eta},$$

mathematical settings

- magnetic dominated flow
- cold flow; velocity=0 at separation surface
- four conserved quantities along field line: (E, L, mass loading, field velocity) = (rs, rA, mass loading, field velocity)
- remaining two condition: passing fast surface + matching condition



inflow v.s. outflow

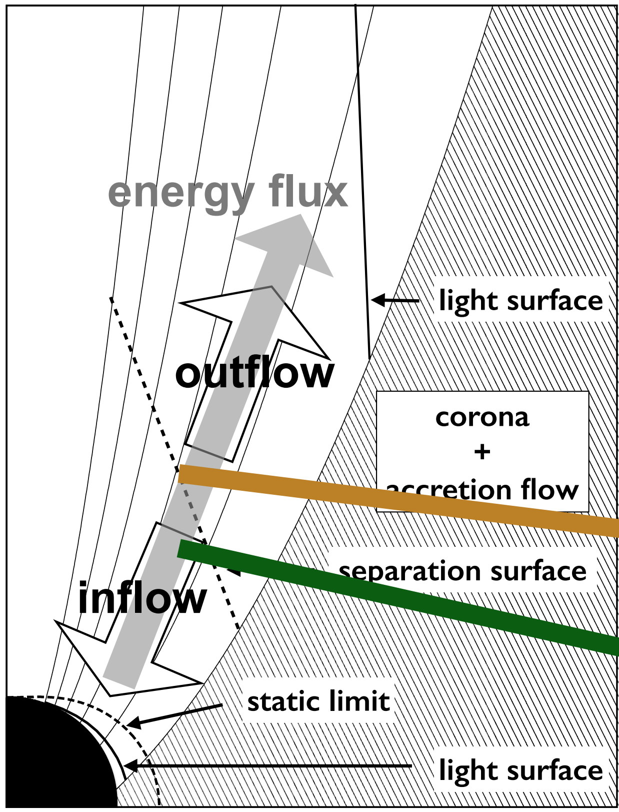
- for all kinds of magnetic field, the inflow pass fast surface automatically, as required by causality
- the outflow pass the fast surface ONLY when a non force-free field line is considered, we therefore consider the MHD perturbed parabolic field considered in Beskin+ 06

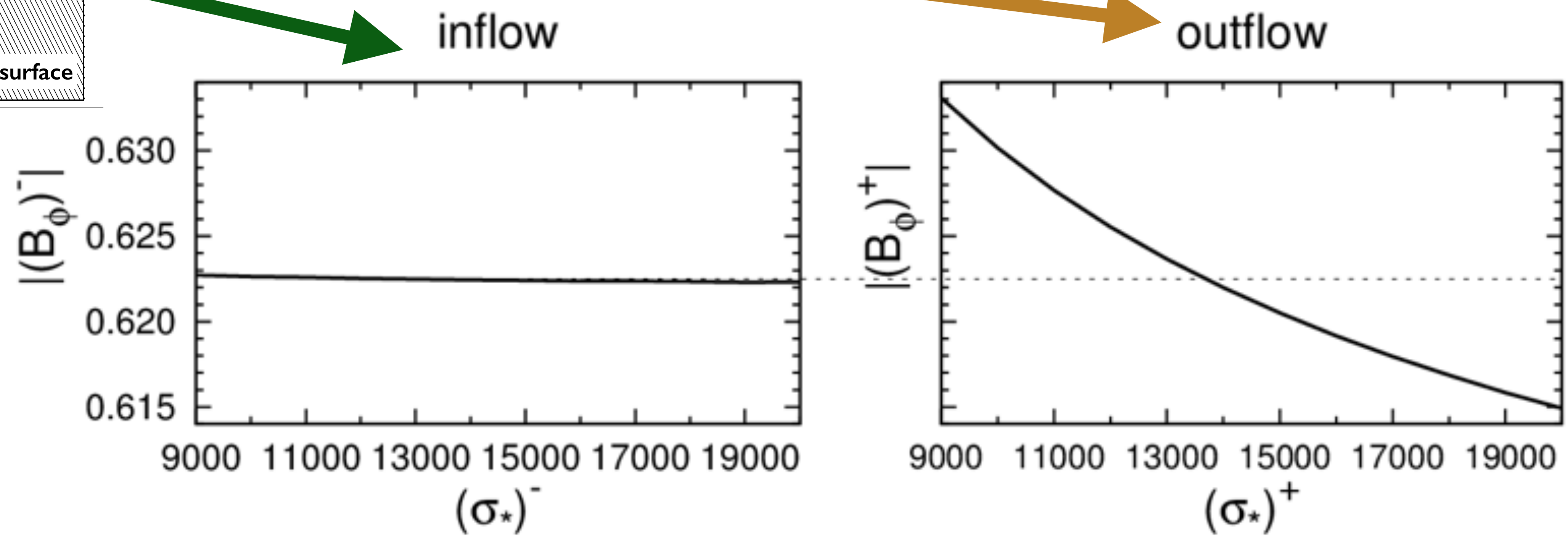
Table 2

Properties of PFD GRMHD Flow Along the Same Hole-Threading Field Line

	Inflow Solution	Outflow Solution
u^r	<0	>0
u^θ	>0	<0
u^ϕ	>0	>0
u^t	>0	>0
$E = E_{\rm FL} + {\rm E}_{\rm EM}$	<0	>0
$E_{\rm FL}$	>0	>0
$E_{\rm EM}$	<0	>0
$L = L_{\rm FL} + {\rm L}_{\rm EM}$	<0	>0
$L_{\rm FL}$	>0	>0
$L_{\rm EM}$	<0	>0
$\mathcal{E}^r = \mathcal{E}^r_{\rm FL} + \mathcal{E}^r_{\rm EM}$	>0	>0
[a]$\mathcal{E}^r_{\rm FL}$	<0	>0
$\mathcal{E}^r_{\rm EM}$	>0	>0

how to match inflow and outflow solution?



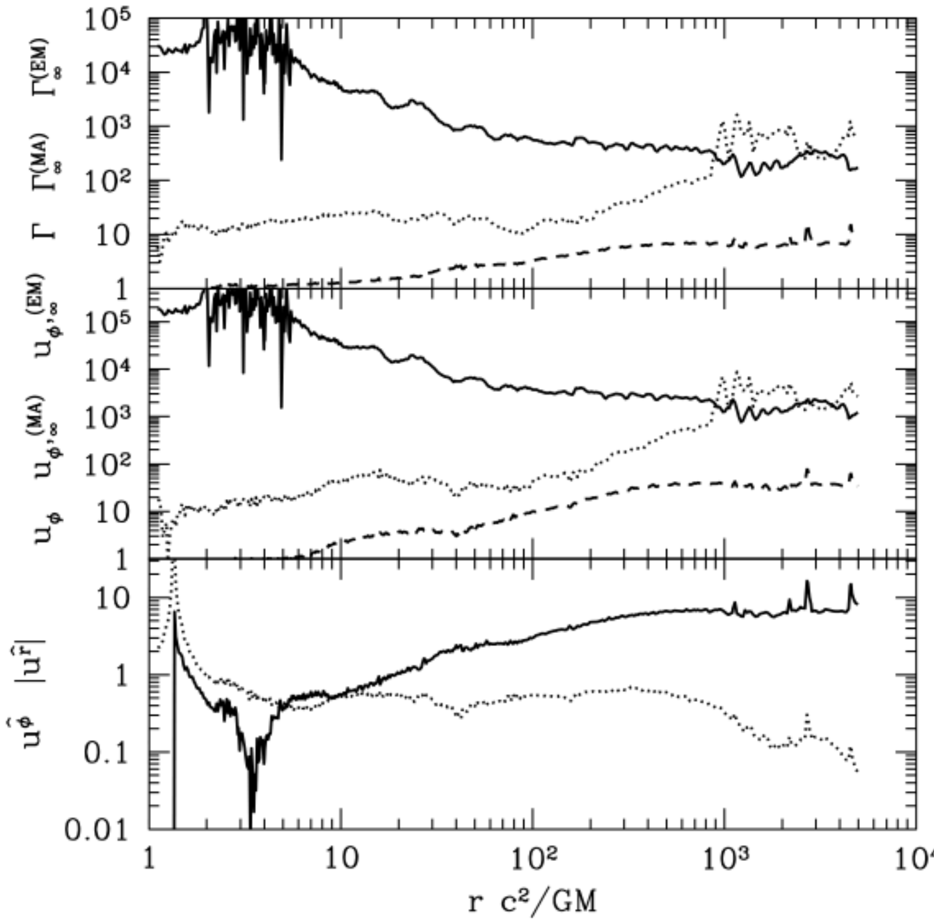


$$\begin{aligned}
\mathcal{E}^r &= \mathcal{E}^r_{\rm FL} + \mathcal{E}^r_{\rm EM} \\
&= nE_{\rm FL}u^r + nE_{\rm EM}u^r \\
&= -n\mu u_t u^r - \frac{\Omega_F}{4\pi}\frac{B_\phi}{\Sigma\sin\theta}A_{\phi,\theta}
\end{aligned}$$

$$\left(\mathcal{E}^r_{\rm EM}\right)^- = \left(\mathcal{E}^r_{\rm EM}\right)^+$$

$$\frac{\Omega_F}{4\pi}\left(B_\phi\right)^- = \frac{\Omega_F}{4\pi}\left(B_\phi\right)^+$$

semi-analytical jet model



McKinney 2006 (GRMHD simulation)

$$\bar{B}^r = \sqrt{g_{rr}}\, B^r,$$

$$\bar{B}^\phi = \sqrt{g_{\phi\phi}}\, B^\phi.$$

Location of characteristic surfaces

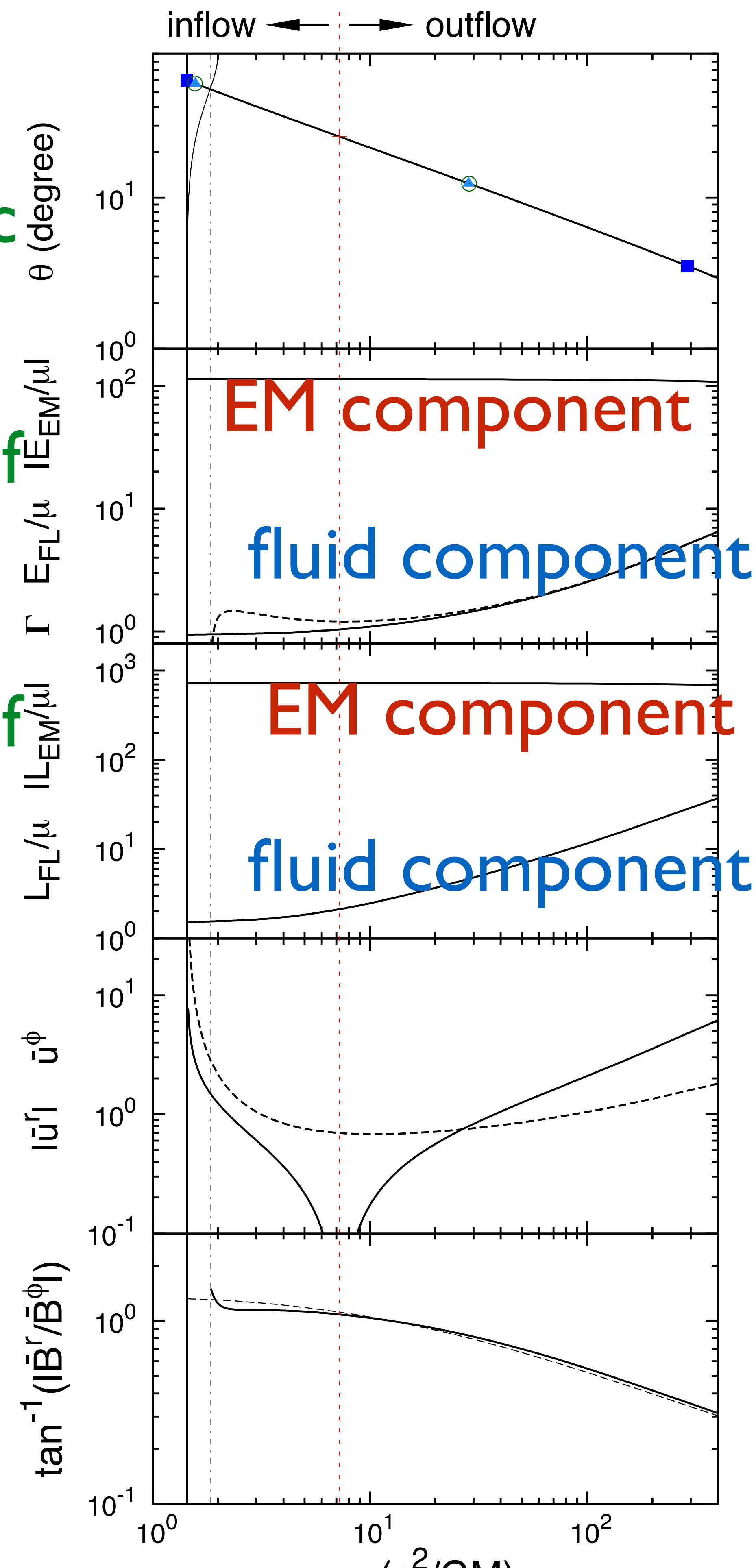
conversion of energy

$$\Gamma = \sqrt{-g_{tt}}\, u^t$$

conversion of angular momentum

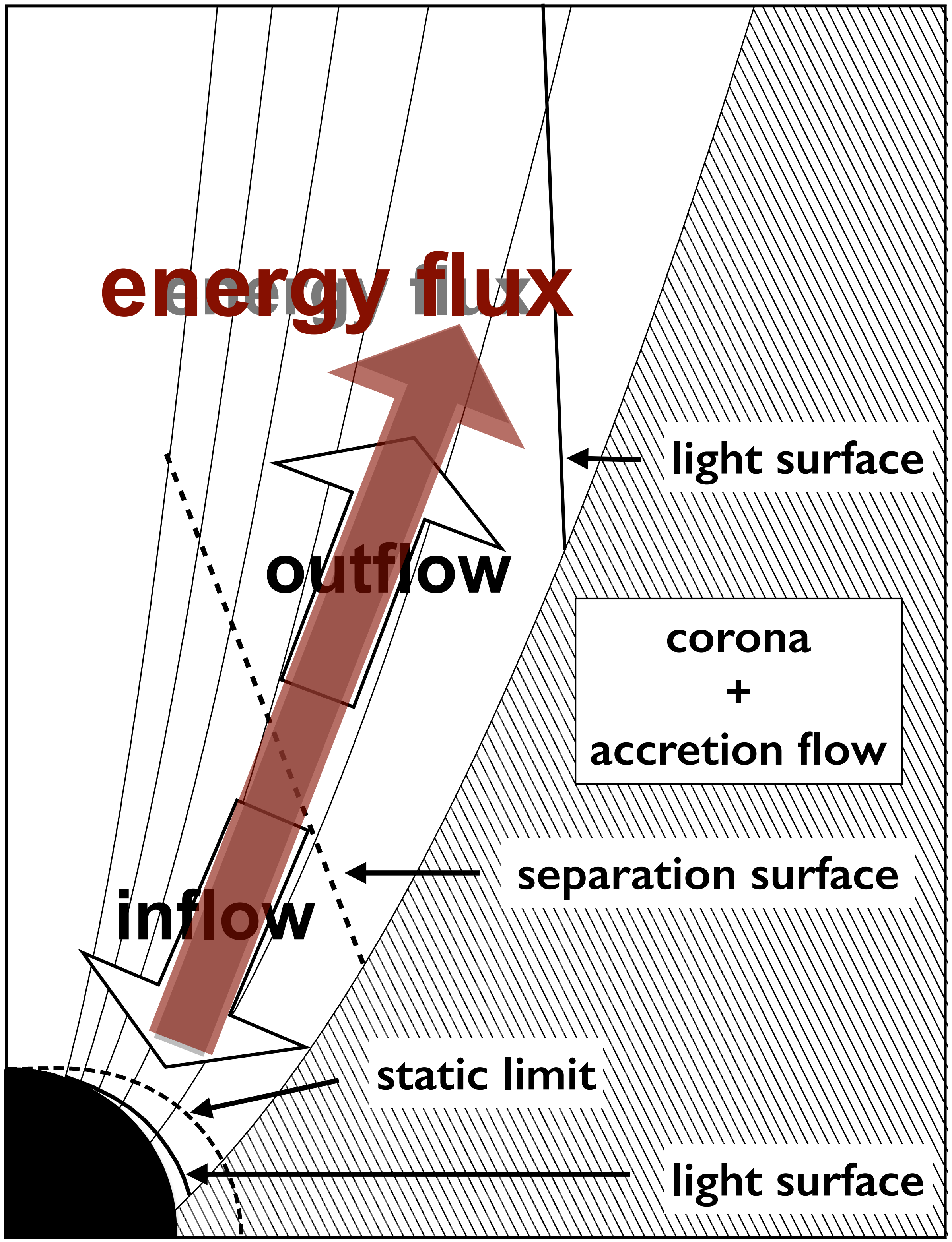
dynamical structure

pitch angle

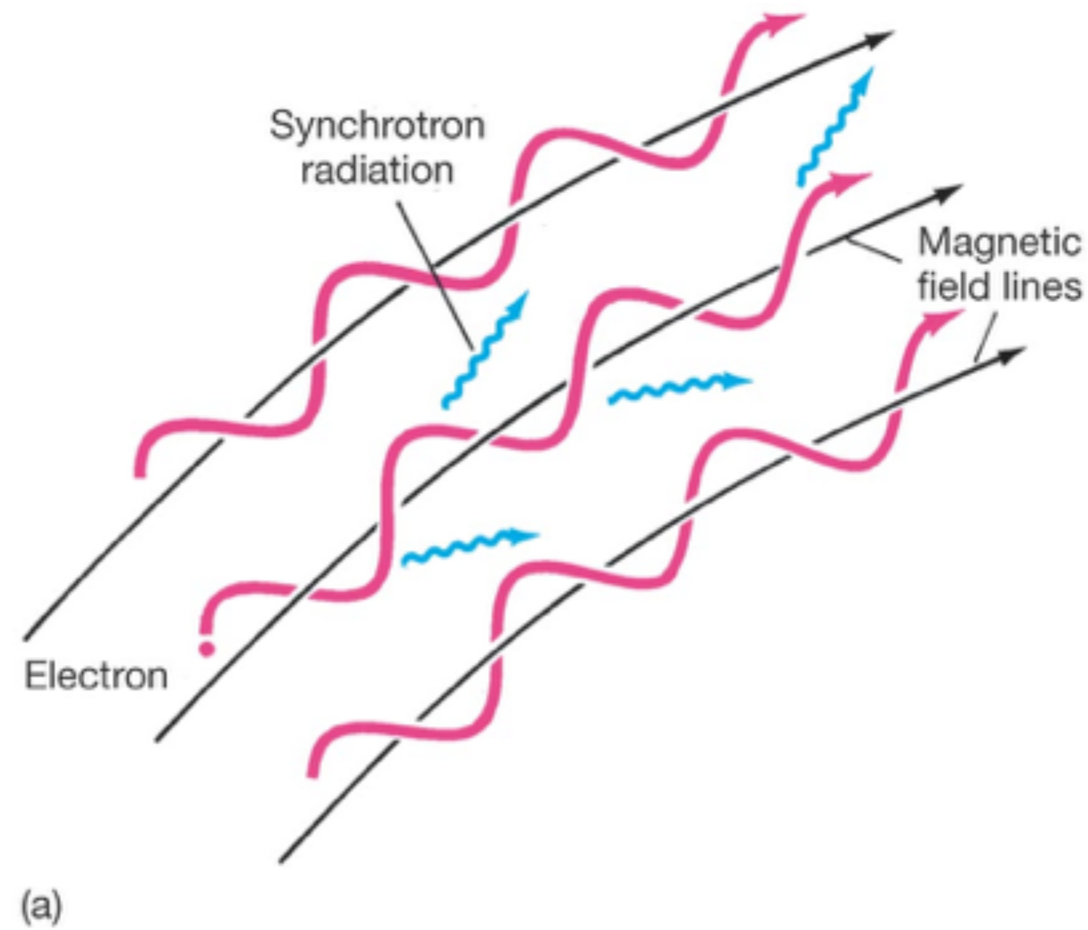


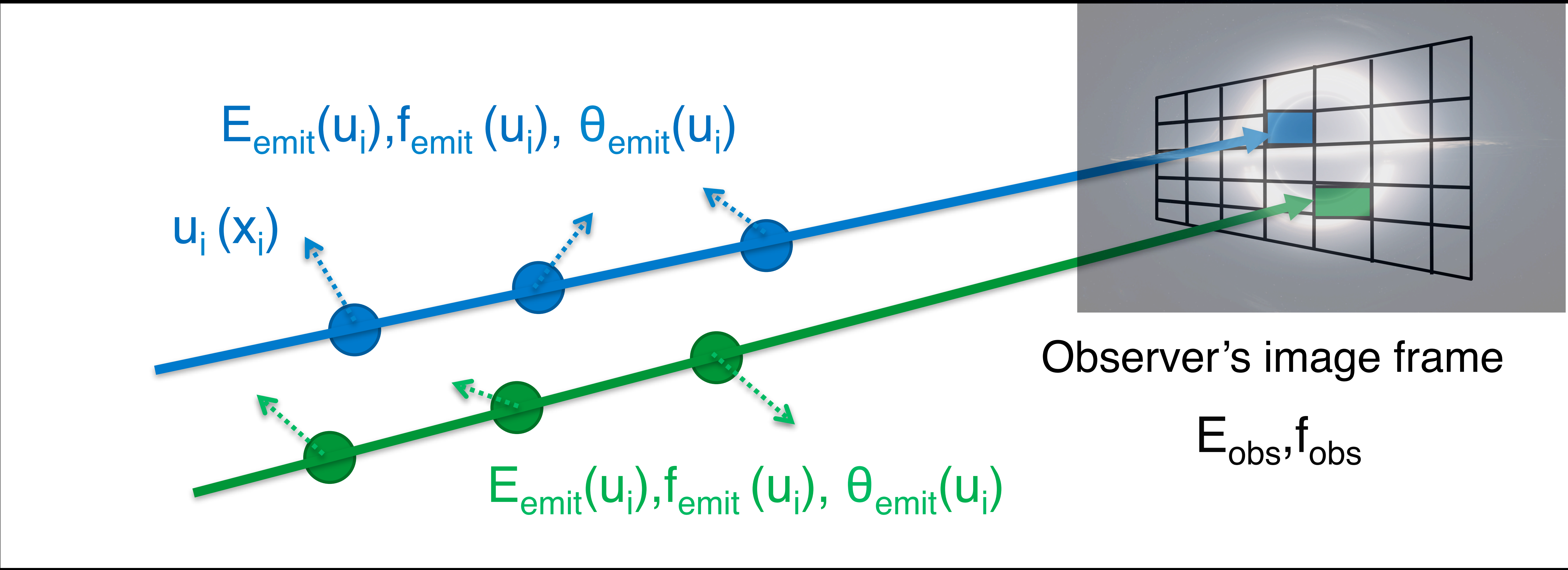
Pu et al. 2015 (semi-analytical solution)

Radiation!



jet emission at sub-mm is mainly contributed by Synchrotron radiation





- ray tracing (photon tracjectry backward in time)
- dynamics/distribution of surrounding materials
  (correction of energy/ frequency/ angle)
- general relativistic radiative transfer
  (physical process take place locally)

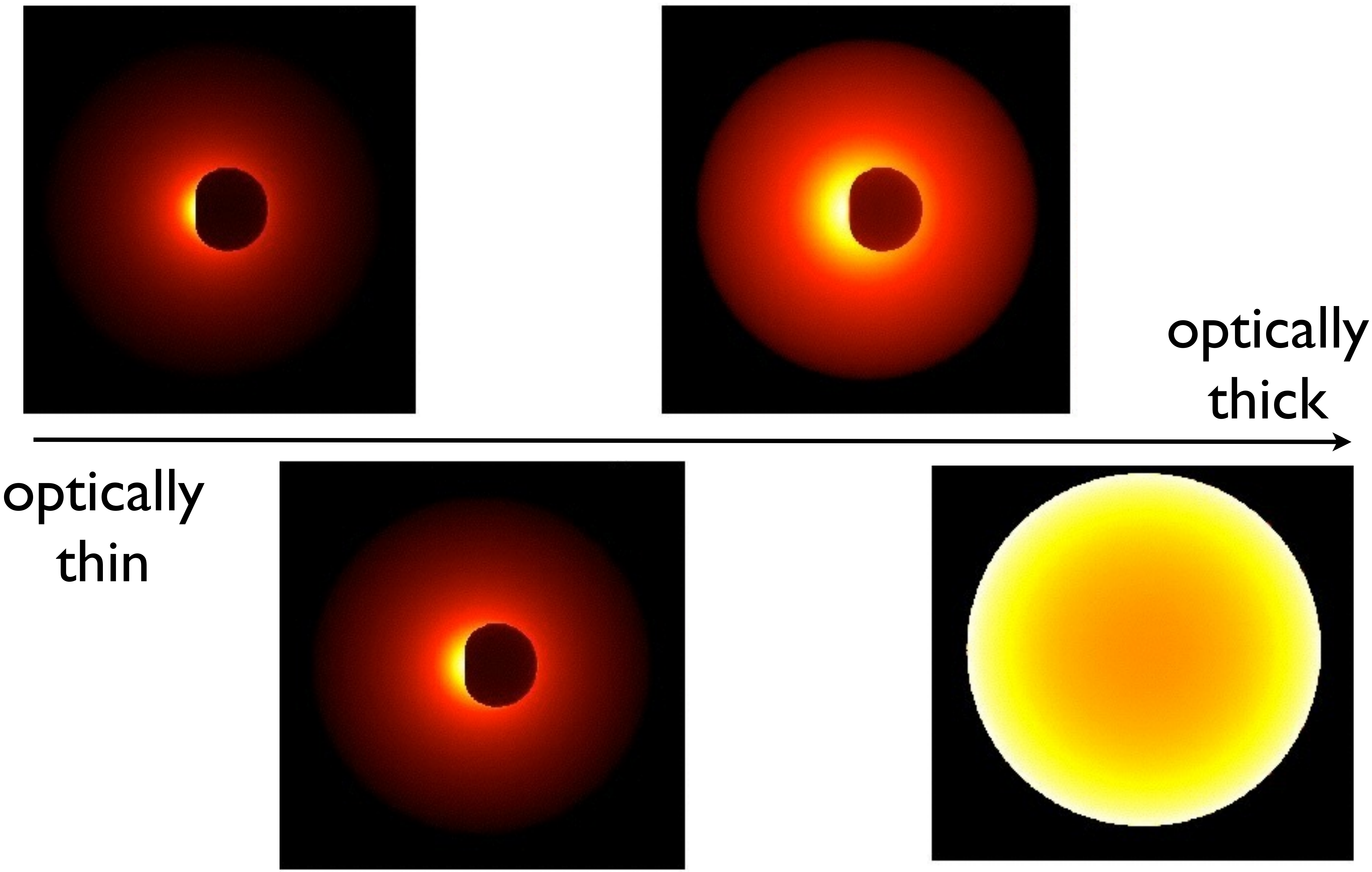
Shift of the Shadow

H.-Y. Pu (ASIAA)

H.-Y. Pu (ASIAA)

GRRT

General Relativistic Radiative Transfer



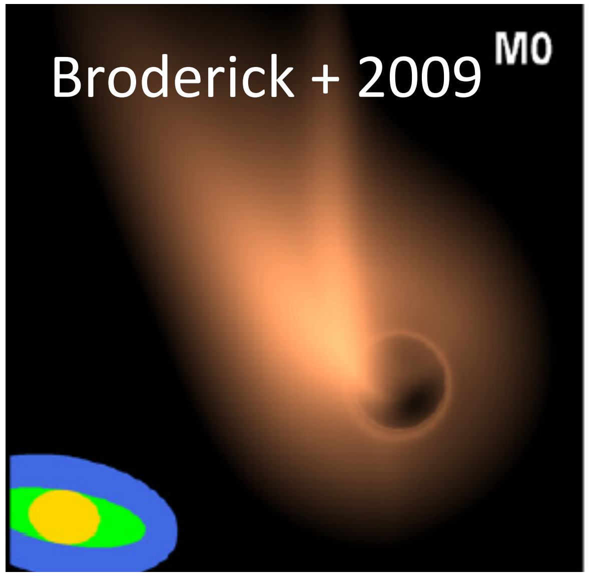
Synchrotron emission

- thermal (relativistic Maxwellian) energy distribution of electrons
- function of
  1. electron temperature
  2. magnetic field
  3. electron number density

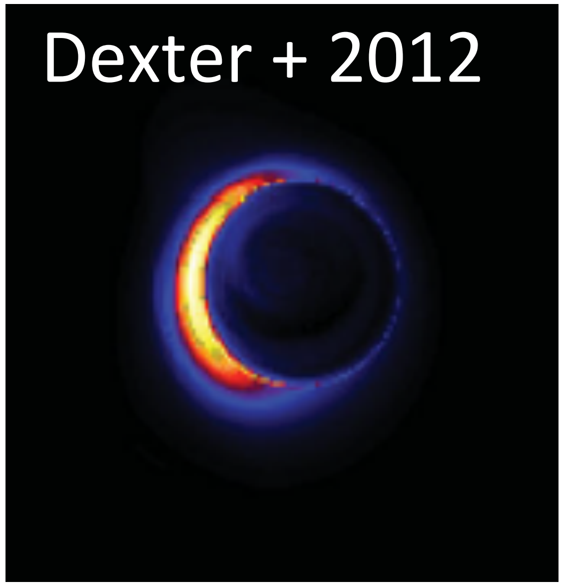
- power-law energy distribution of electrons
- function of:
  1. energy cut off
  2. power-law index
  3. magnetic field
  4. electron number

uncertainties!

Zoology of Jet Images of M87

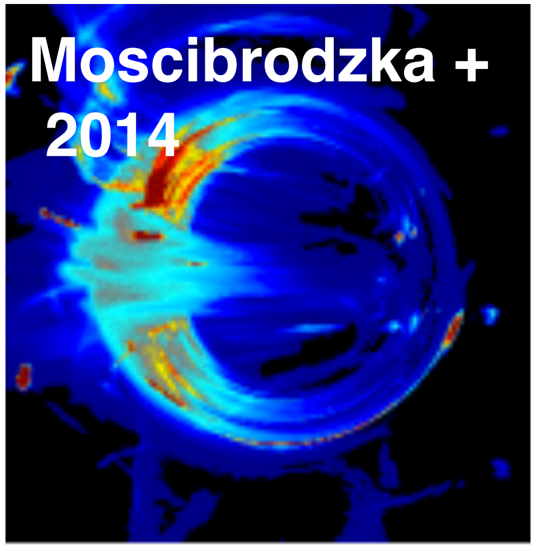


- thermal + non-thermal synchrotron (disk)
- non-thermal synchrotron (jet)
- semi-analytical force-free jet model



- thermal synchrotron (disk)
- non-thermal synchrotron (jet)
- post processing of GRMHD simulation results

- thermal synchrotron (disk+jet)
- isothermal jet
- post processing of GRMHD simulation results



Synchrotron image of Semi-analytical jet

Model Setup

◎ a/M (dimensionless black hole spin parameter): 0.9
◎ Inclination angle: 20 degree
◎ Field angular velocity: half of angular velocity of the event horizon
◎ Jet dynamics: the four momentum of the GRMHD flow is obtained by solving the wind equation along Blandford-Znajek parabolic field lines, by assuming the outward energy flux is continuous through the inflow and outflow region (right figure); since the outflow has no fast surface, we pick the outflow which has minimum energy to extend to 100 GM/c^2
◎ Magnetic field: scaled from the solution of the wind equation, with a typical strength ~5 Gauss
◎ Thermal electrons properties: (non-thermal electrons follow relativistic Maxwellian distribution and contribute to thermal synchrotron emission)

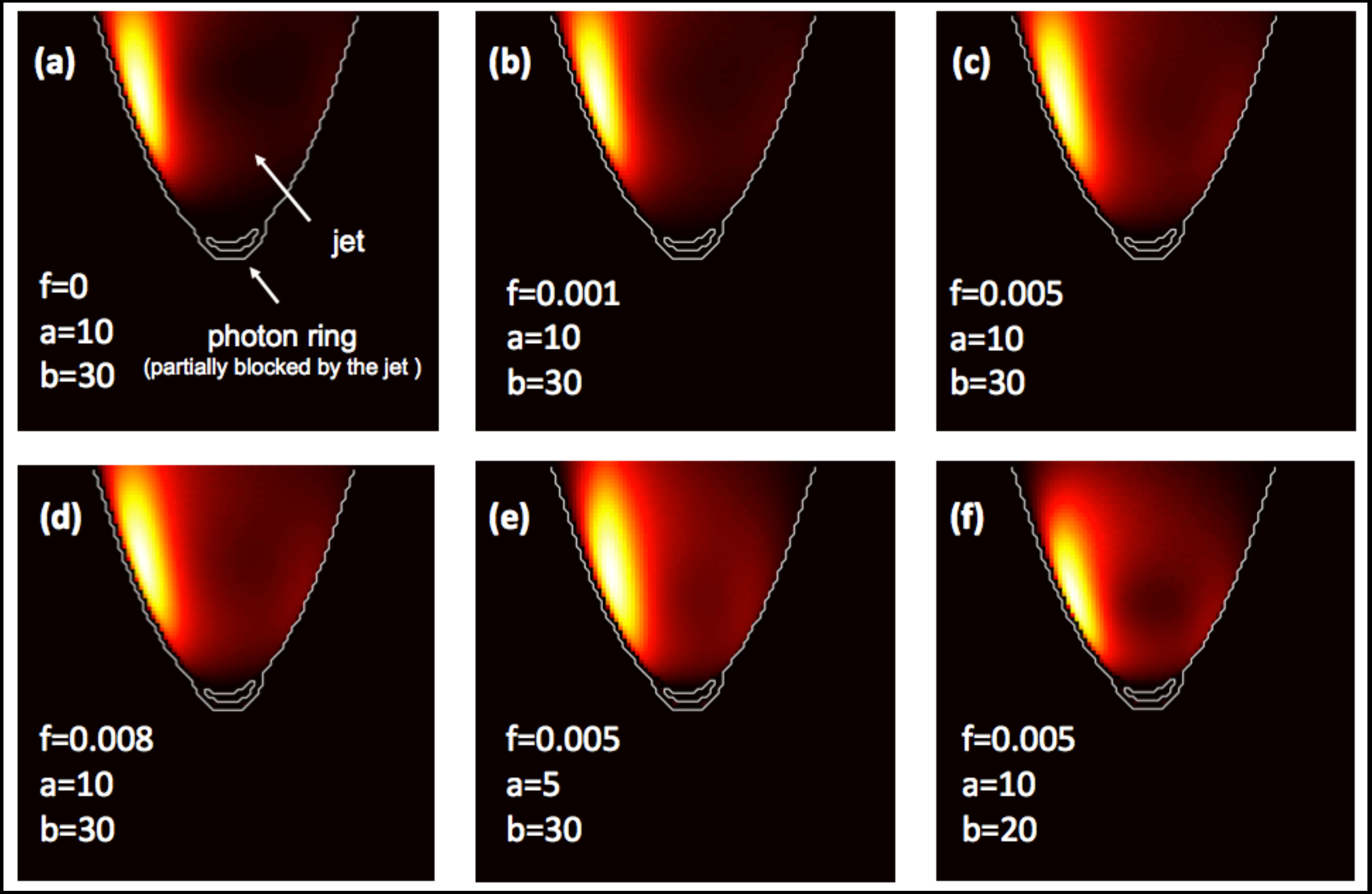
★ temperature: $kT_e/m_ec^2=2$
★ spatial distribution: $\mathbf{n_{th}= n_0 \exp[-r_c^2/(2a^2)] \exp[-r^2/(2b^2)]}$, where $n_0=10^7$, r_c is the cylindrical radius

◎ Non-thermal electrons properties : (non-thermal electrons follow power-law energy distribution and contribute to non-thermal synchrotron emission)

★minimum Lorentz factor: 50
★ maximum Lorentz factor: 10^5
★ power-law index: -3.5
★ spatial distribution: $\mathbf{n_{nth} = f\, n_{th}}$

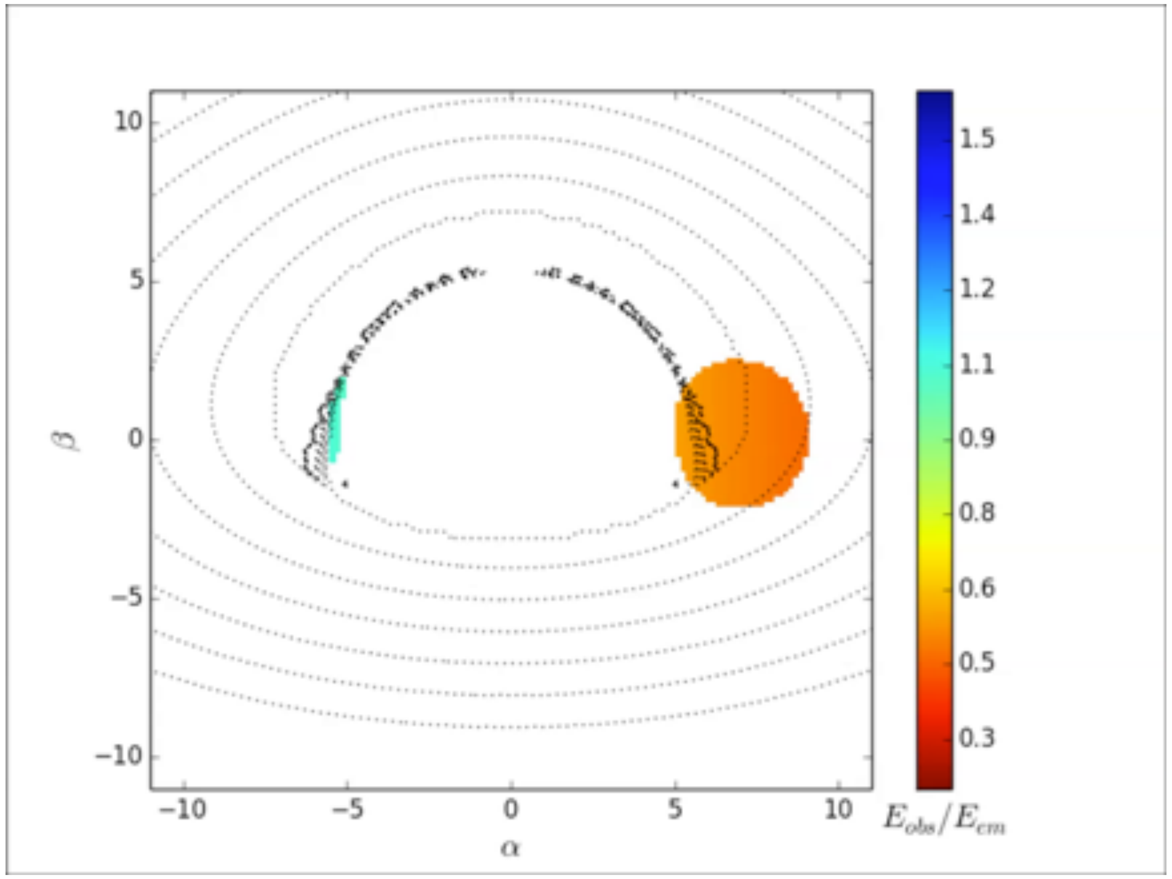
Finally, we fix the jet dynamics, and computed the jet synchrotron image with varied (f, a, b):

f: related to the mixture of thermal and non-thermal electrons
a: related to the electron distribution in r_c(cylindrical radius)-direction
b: related to the electron distribution in r-direction



preliminary results

- time-dependent feature (need to consider light-crossing time)
- evolution of electron energy distribution



- non equal-partition between the field and non-thermal electrons
- pair-production?

Summary

- GRMHD jet model
  - due to frame-dragging effect, jet can be powered by the rotating black hole
  - semi-analytical approach provide a complementary understanding of the relativistic jets, compared to GRMHD numerical simulations (e.x. free from numerical disspation)
  - next step: field configuration
- Synchrotron Radiation Image
  - important for upcoming sub-mm VLBI observation will reach micro-arcsec resolution
  - next step: uncertainty of electron properties