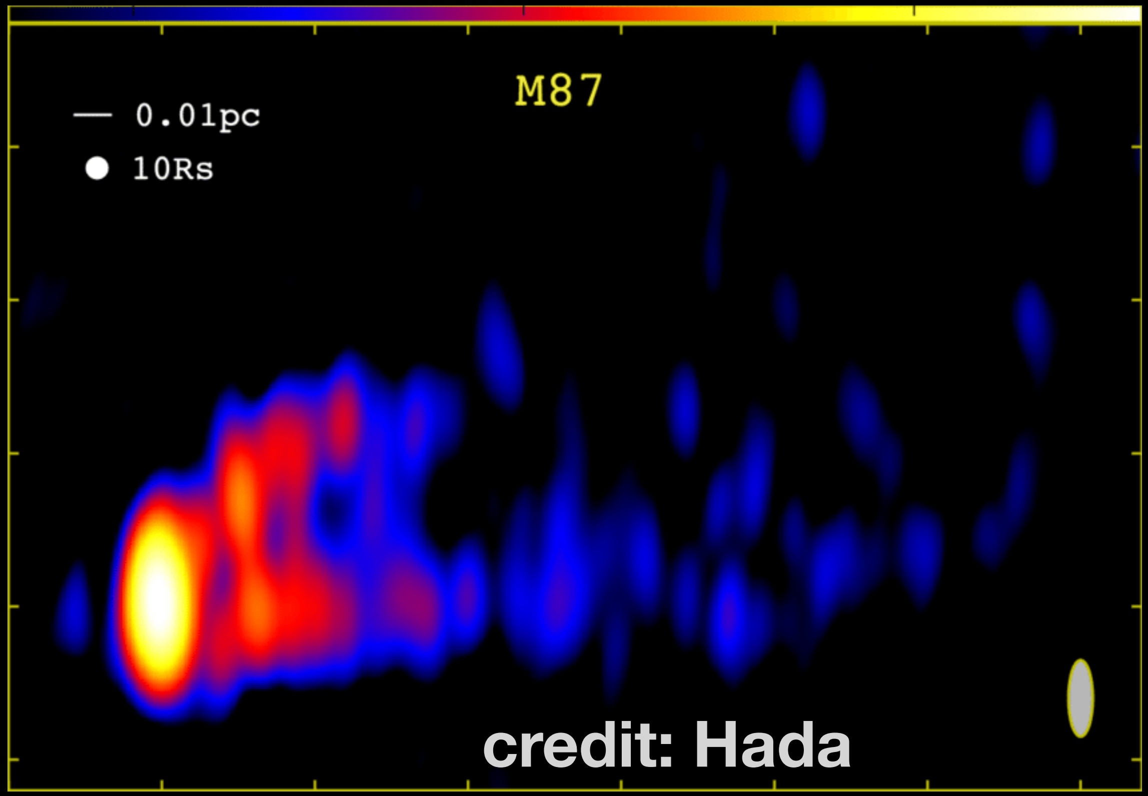
Linking VLBI observation with GRMHD theory at **all scales**:

Phenomenological models of black hole jets/accretion

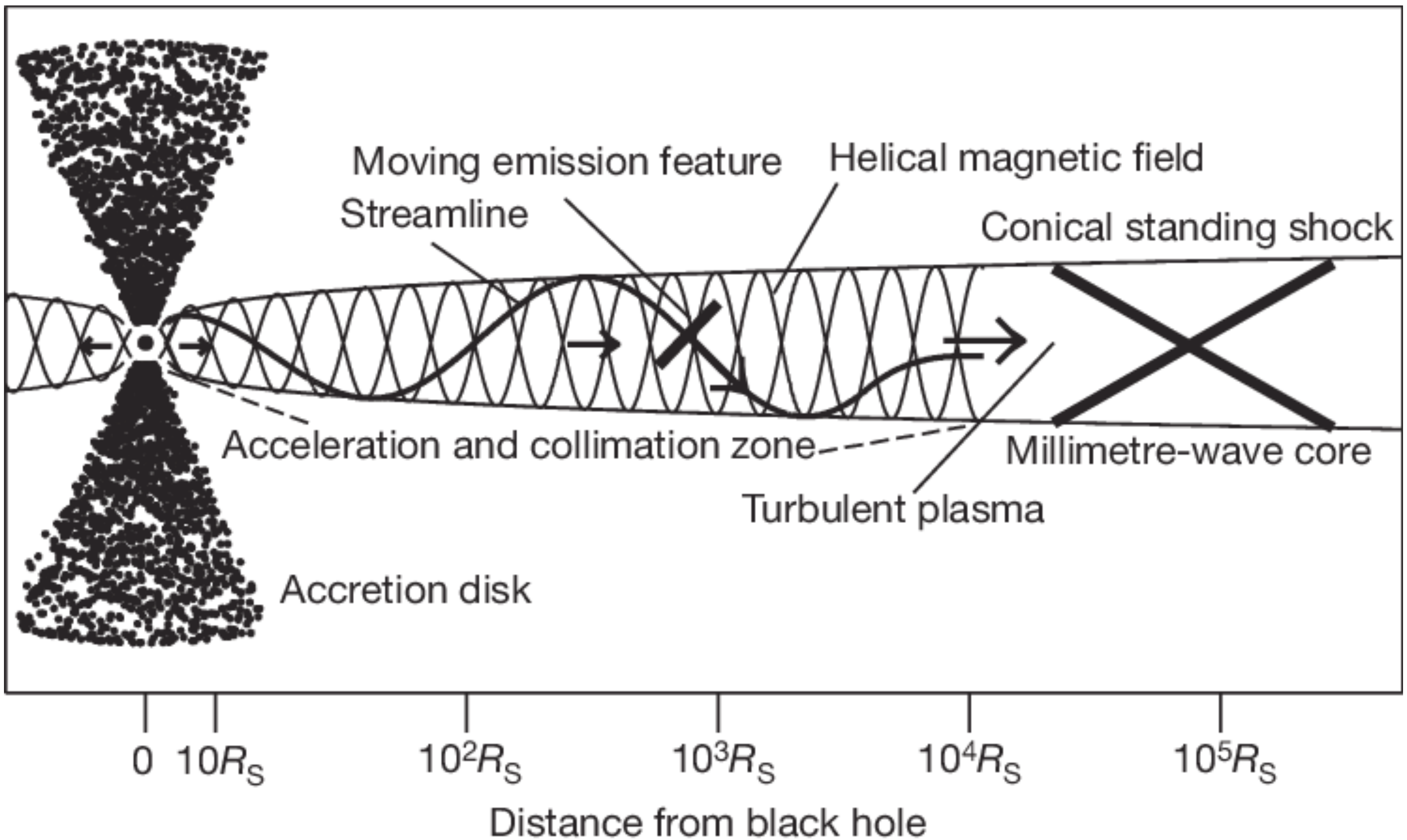


Hung-Yi Pu

BH astrophysics with VLBI workshop Jan 18th, 2021

國立臺灣師範大學
NATIONAL TAIWAN NORMAL UNIVERSITY
中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics
Event Horizon Telescope

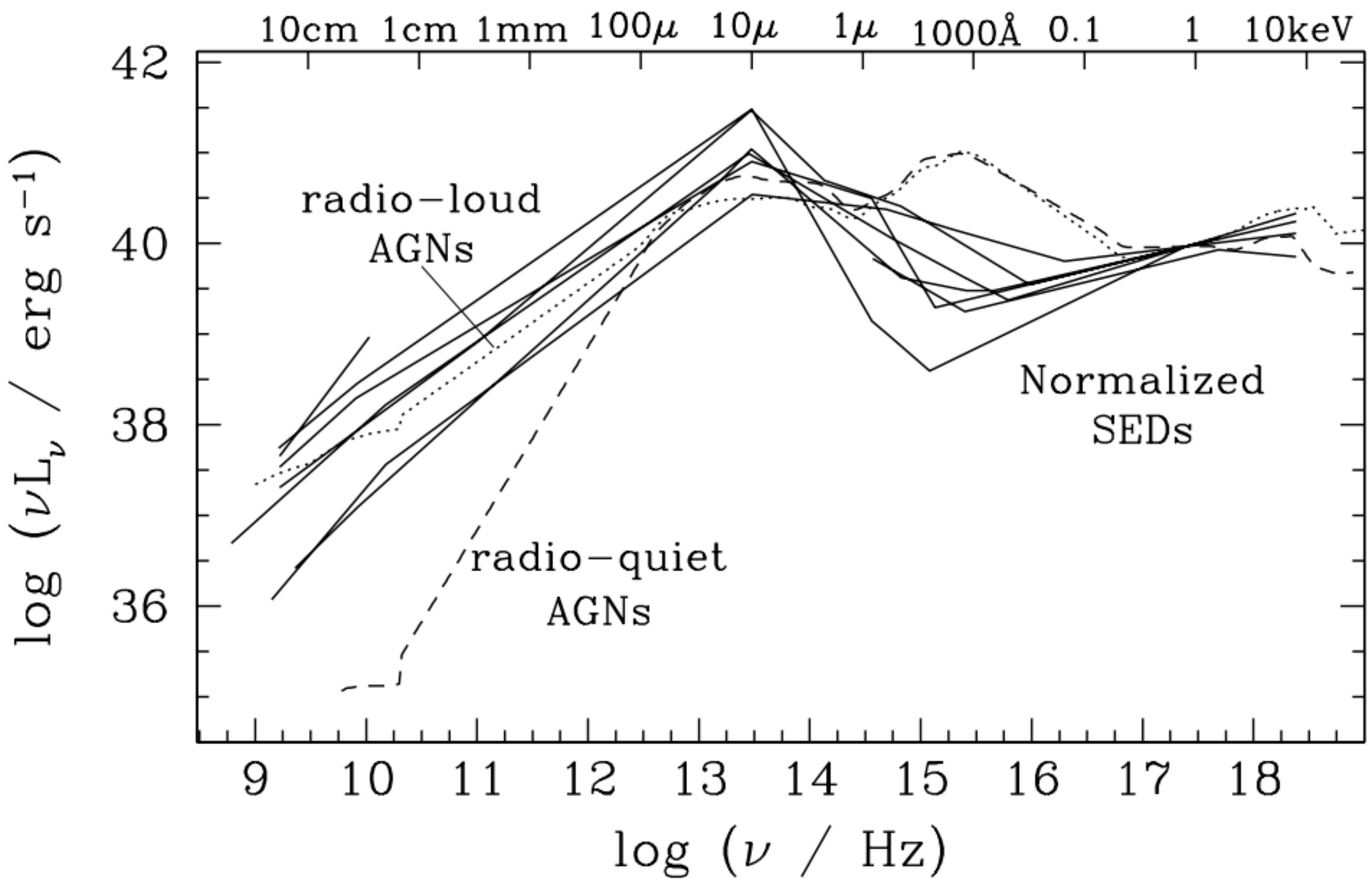
VLBI: story across many order of magnitude



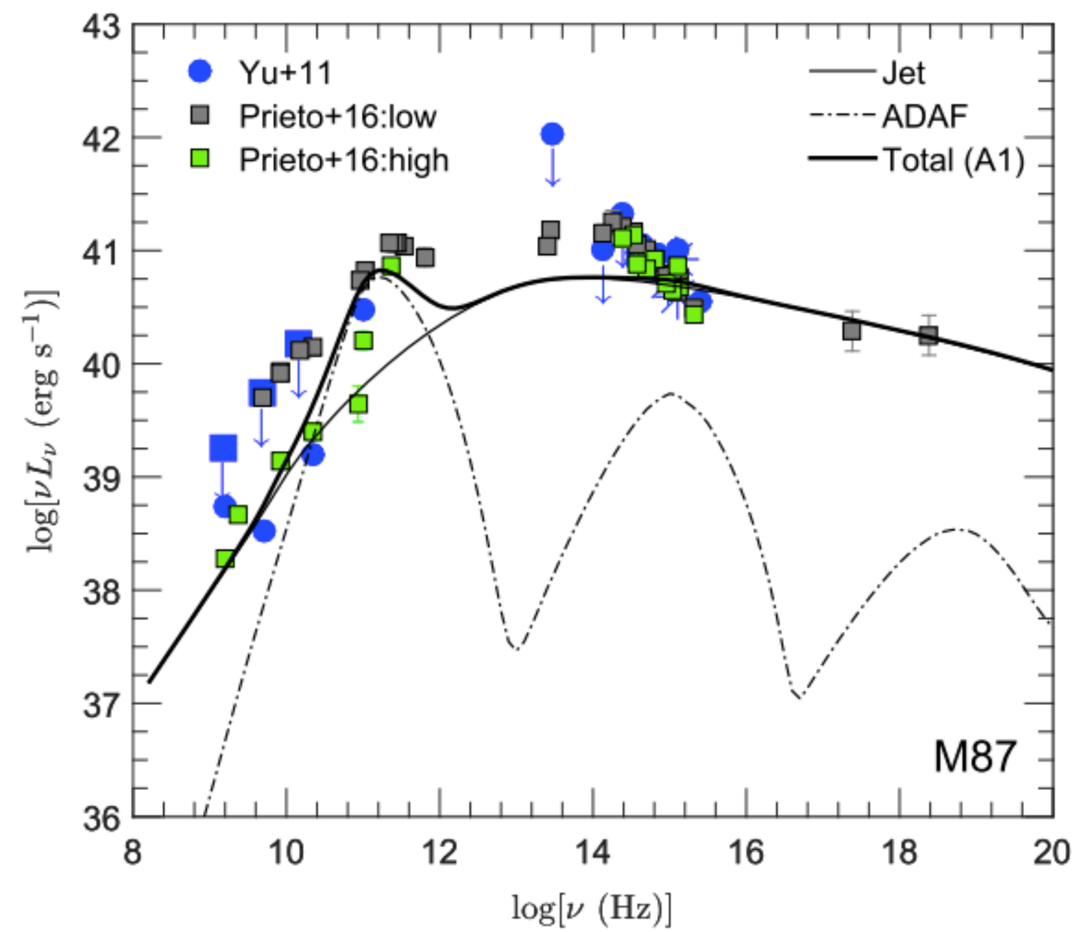
Marscher+ 2008

LLAGN

Ho 1999



Li, Yuan, & Xie 2016



RIAF (Radiatively Inefficient Accretion Flow):

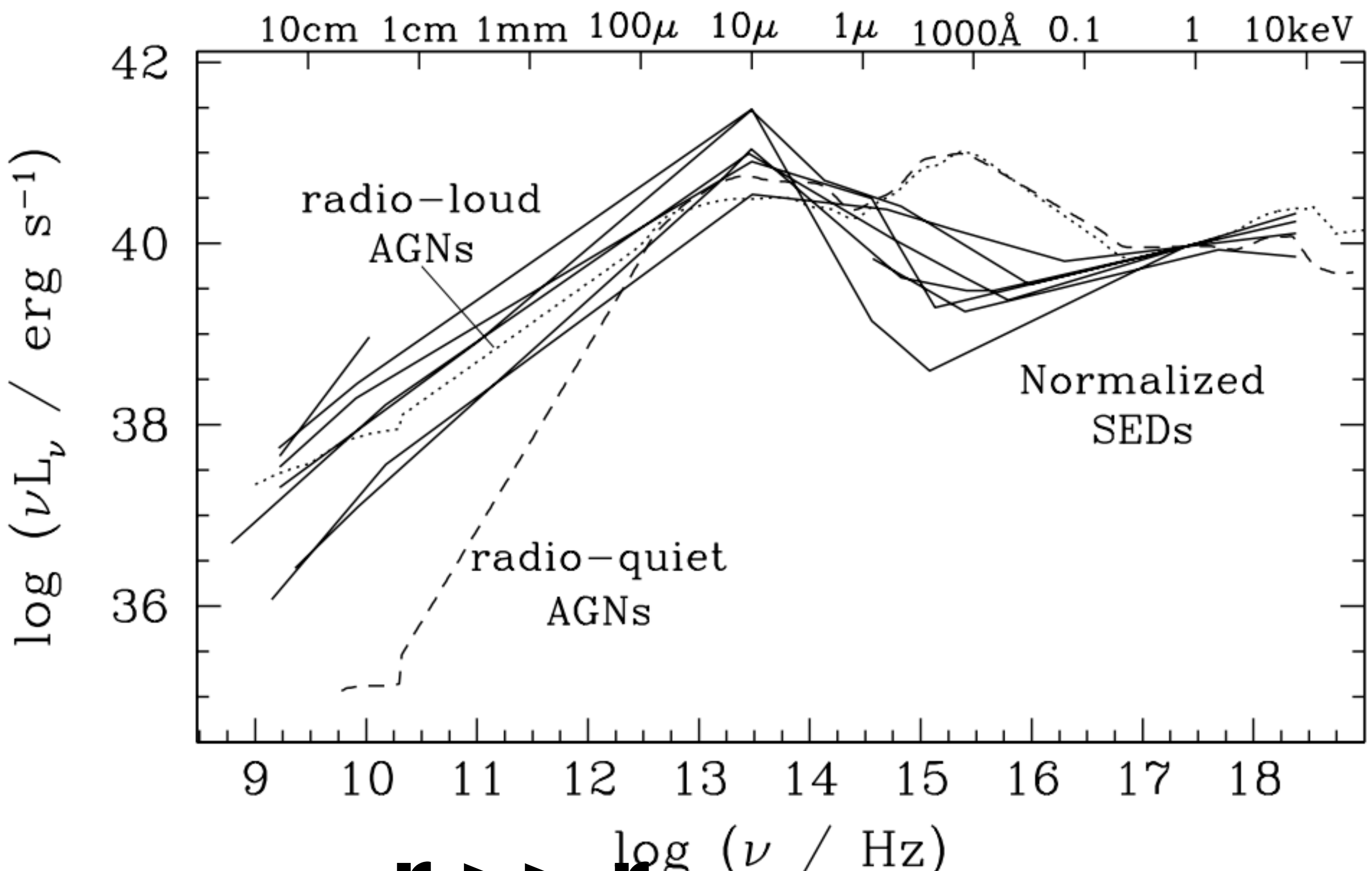
low accretion rate → *insufficient interaction bt. ion & e-*

→ (1) *geometrically thick accretion flow*

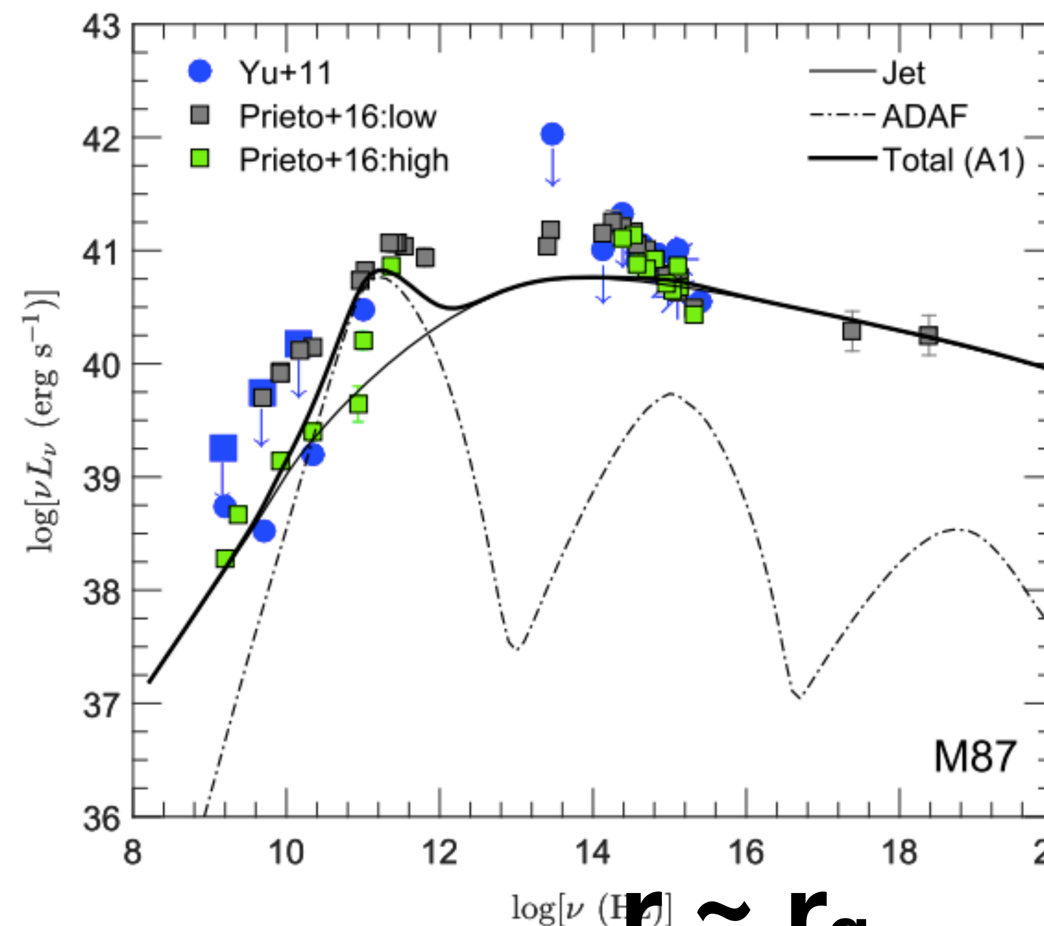
→ *(2) two temperature accretion flow*

LLAGN

Ho 1999



Li, Yuan, & Xie 2016



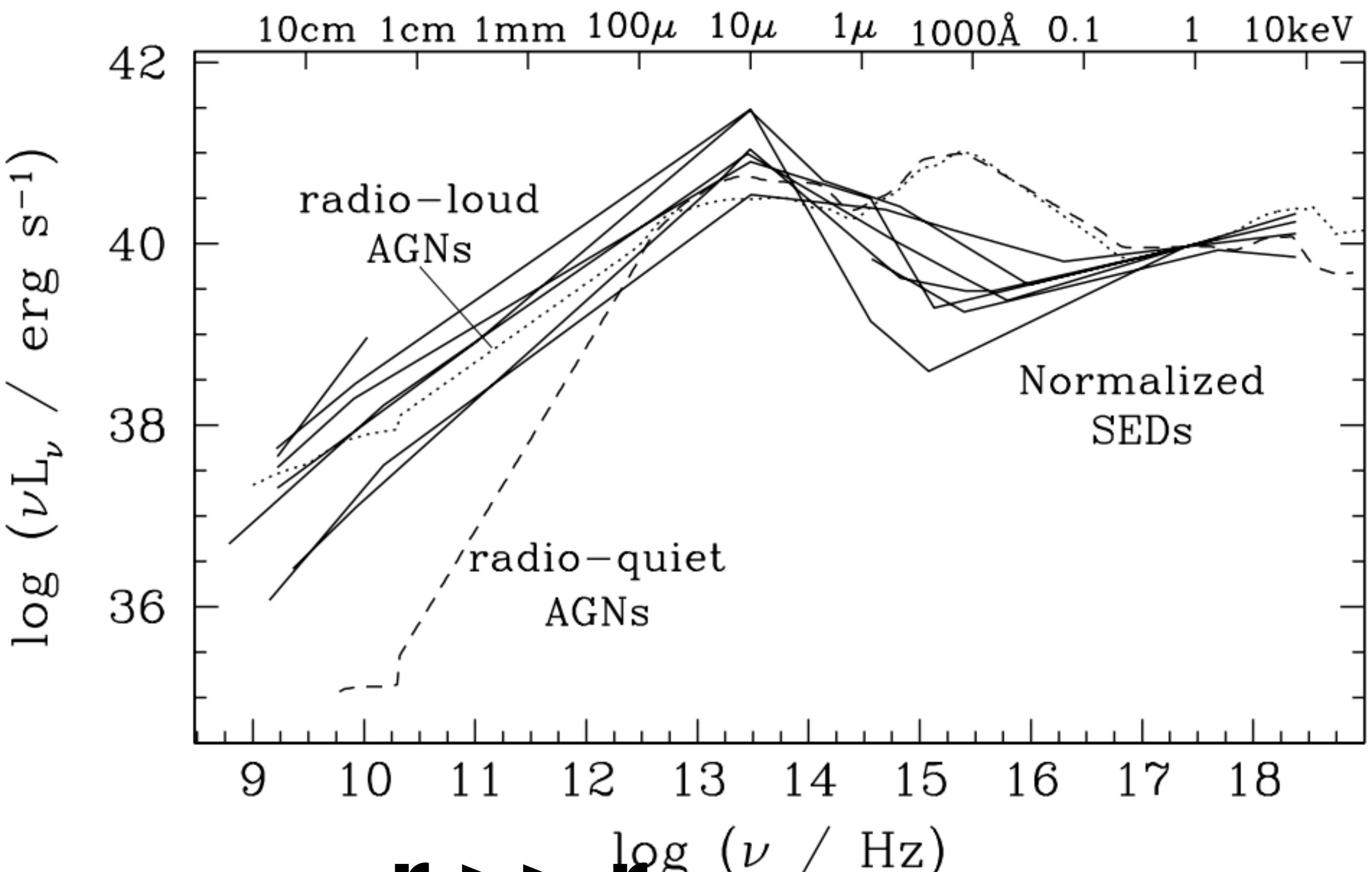
r >> r_g **r ~ r_g**

frequency ↗ photon sphere ↘ GR effect ↗

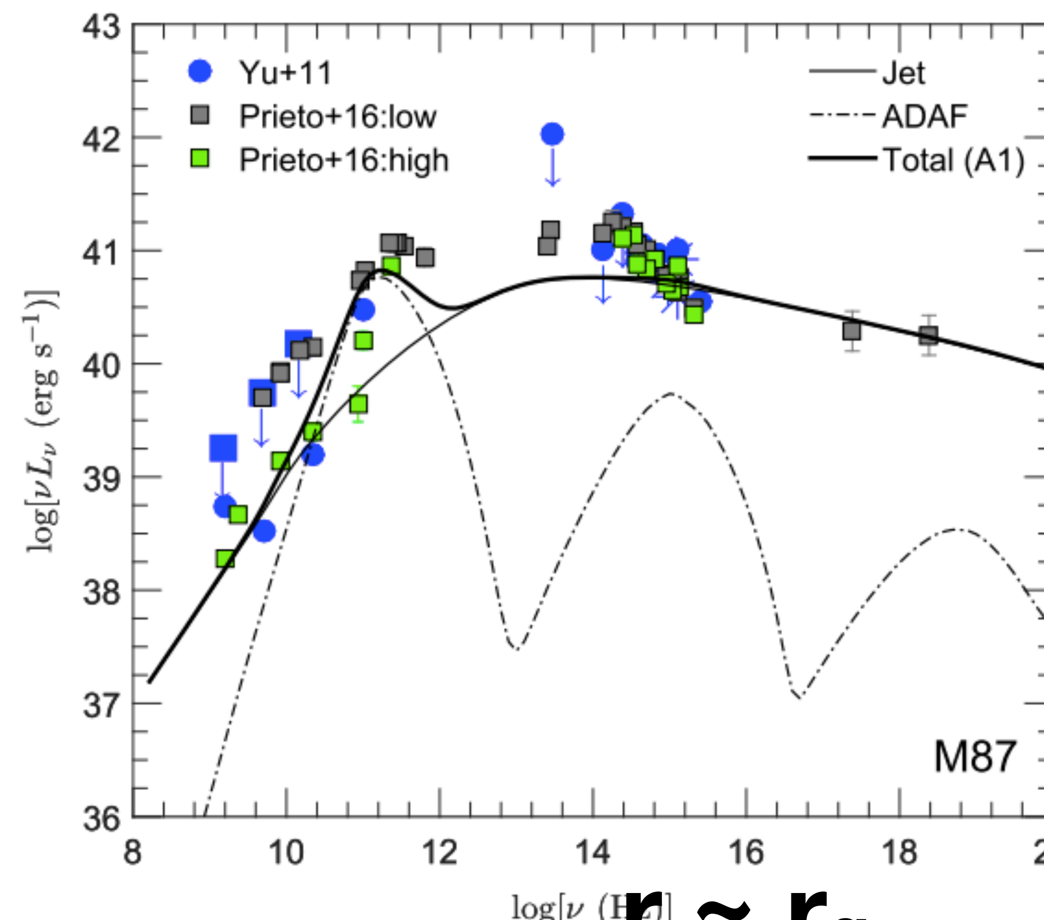
syn radiation from e- with thermal & non-thermal energy distribution!

LLAGN

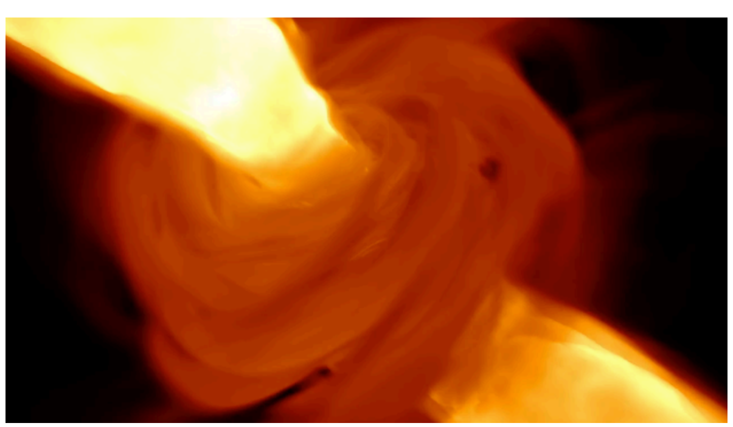
Ho 1999



Li, Yuan, & Xie 2016



$r \gg r_g$ → **$r \sim r_g$**



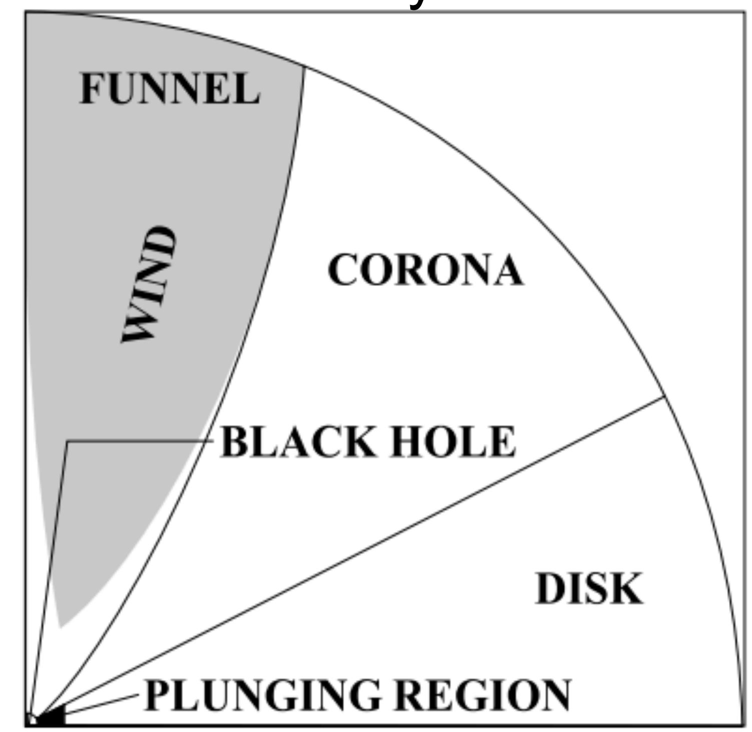
thanks to low accretion rate:
optically thin

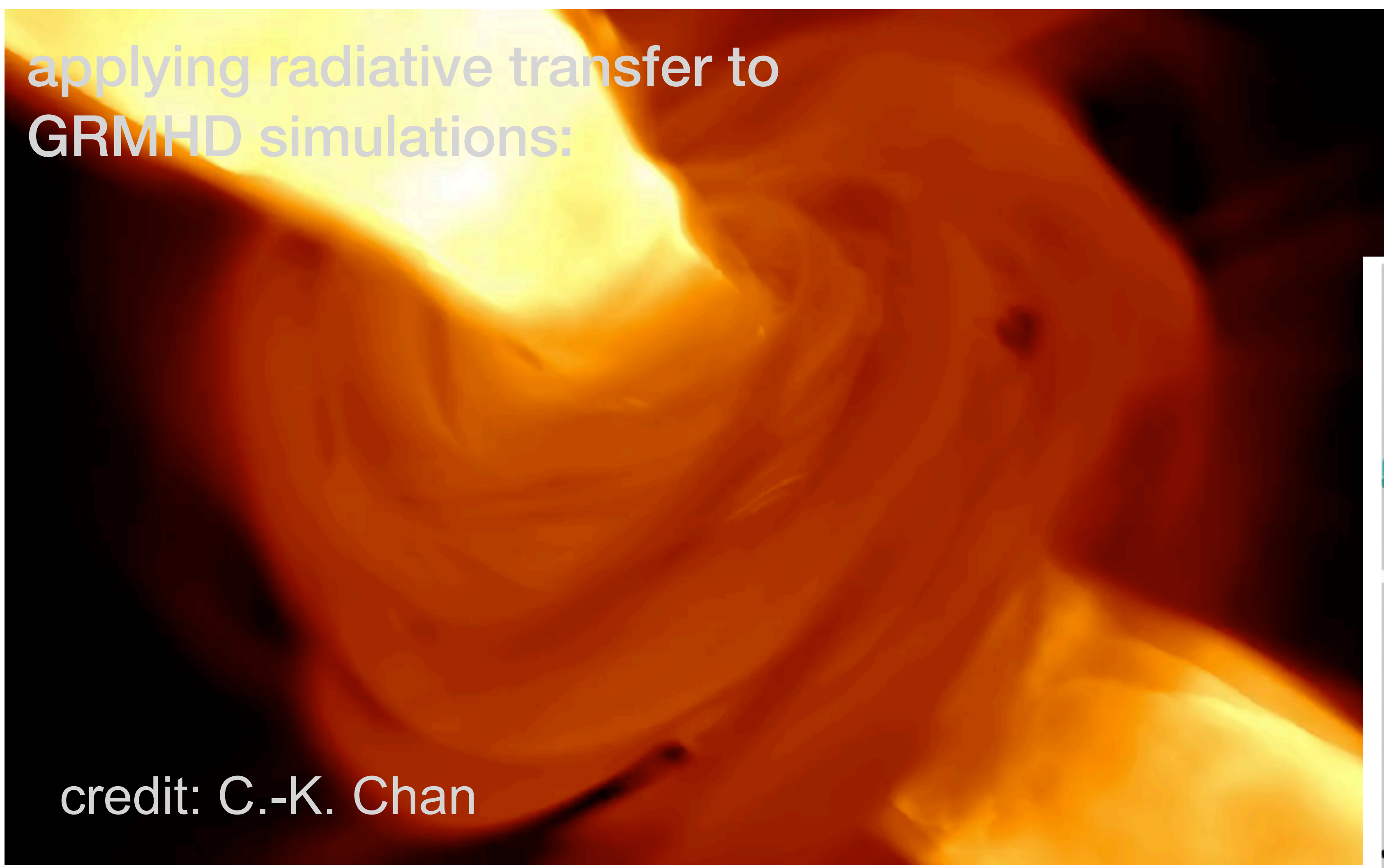
general relativistic magnetohydrodynamics

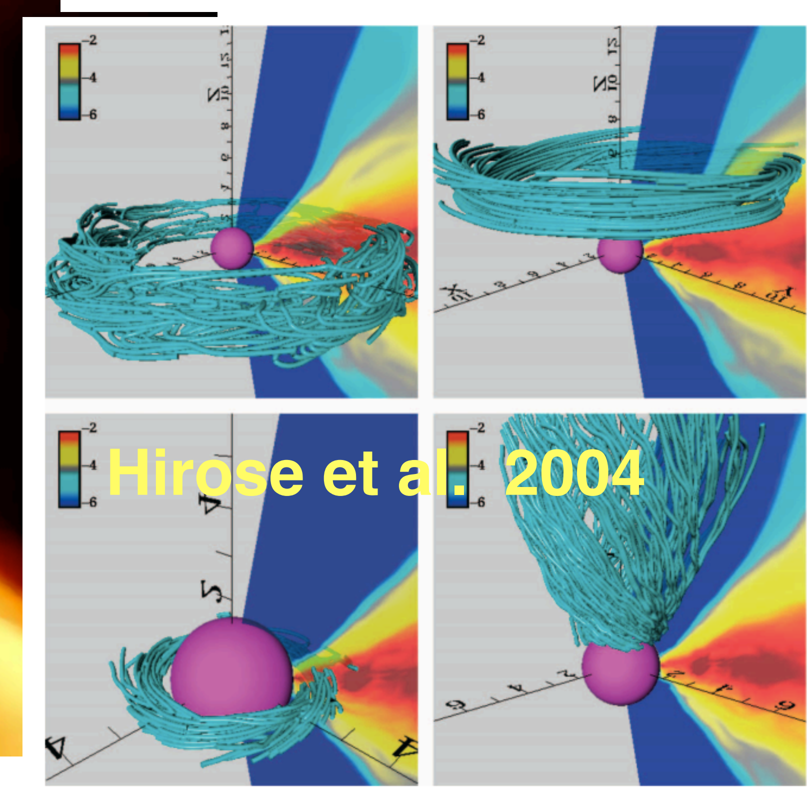
the need of GRMHD simulations

- to simulate 3D structure of jet
- to simulate dynamical feature

Mckineey & Gammie 04



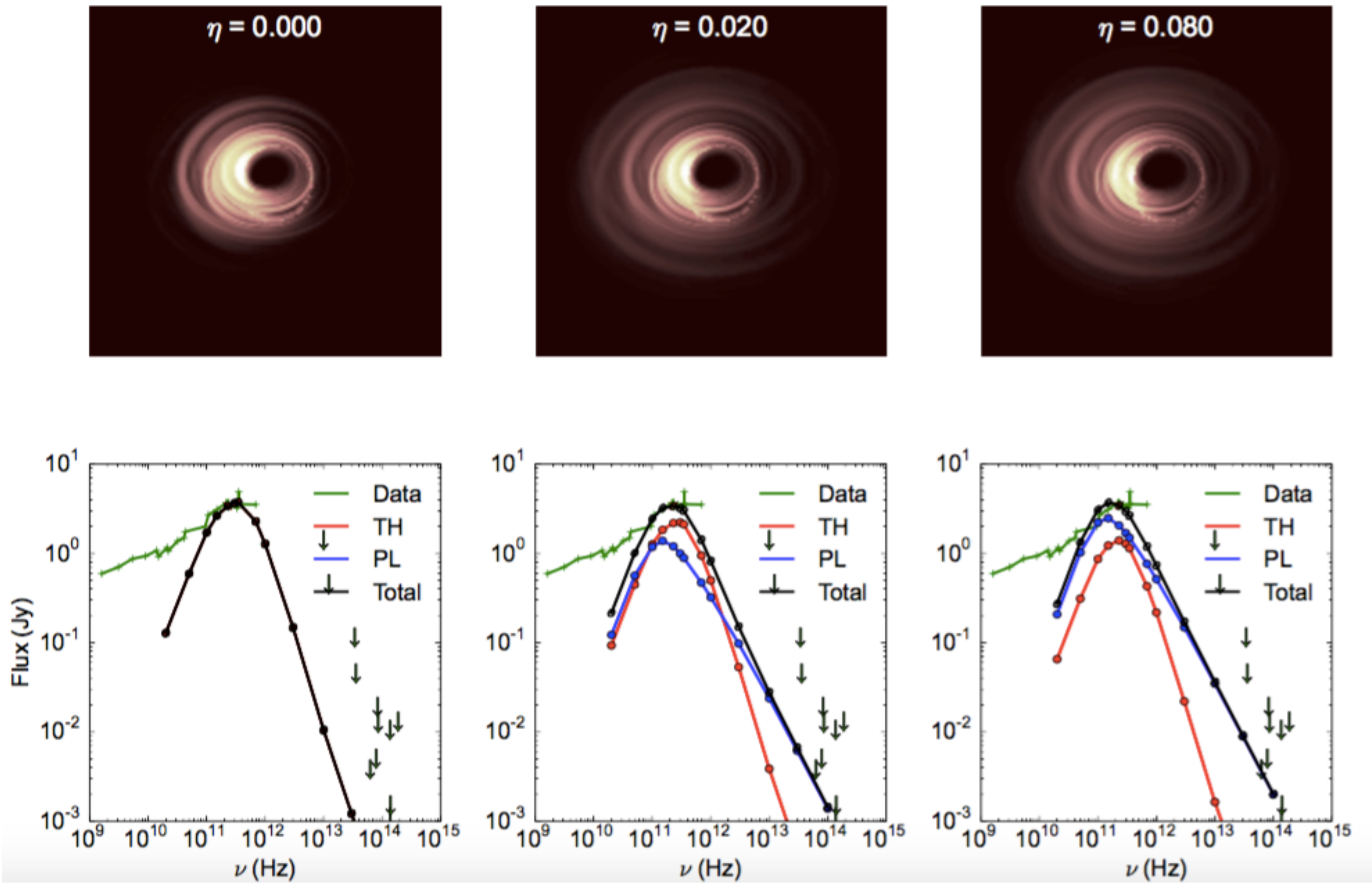




the need of GRMHD simulations

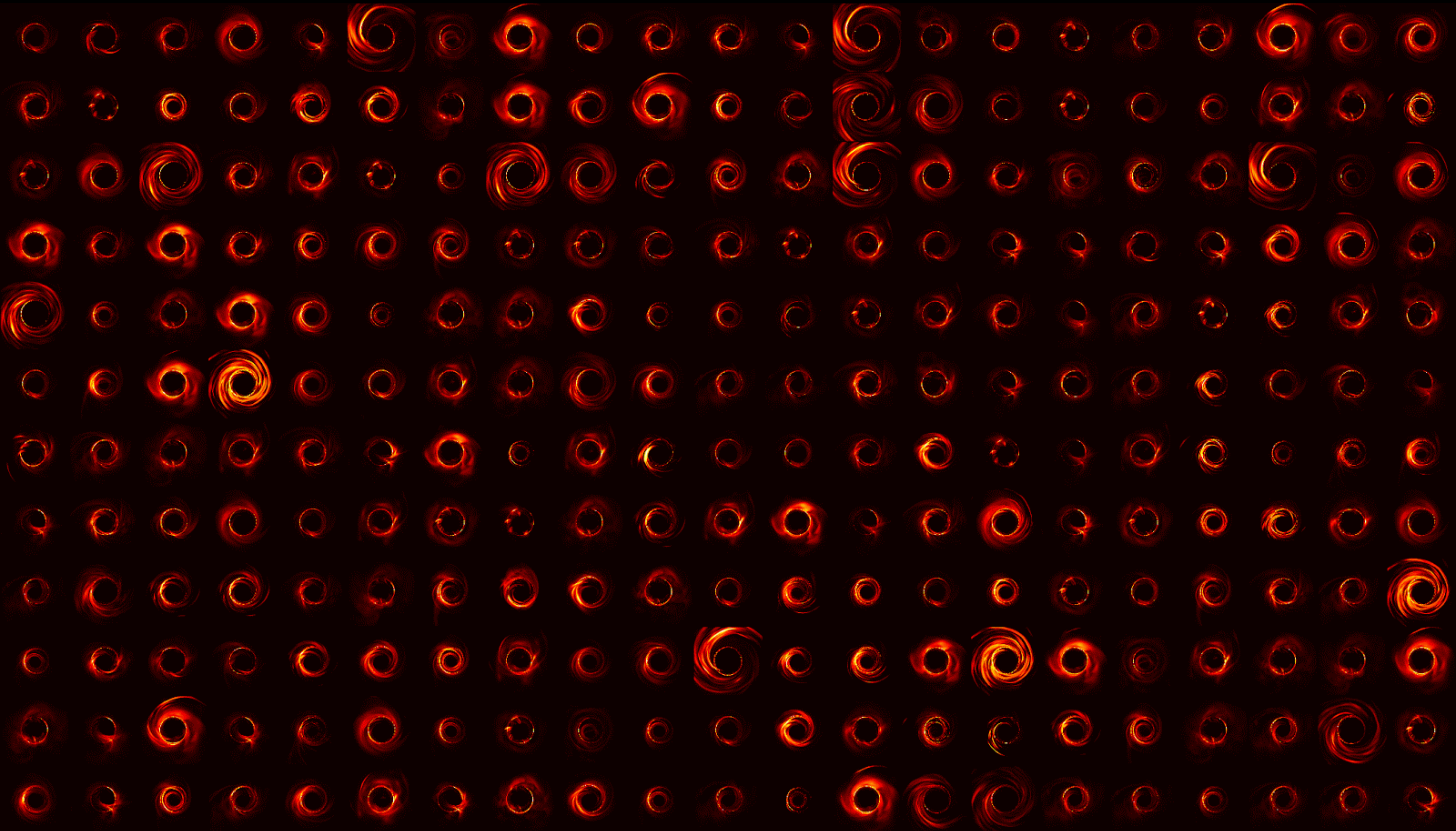
- to simulate 3D structure of jet
- to simulate dynamical feature
- for RIAF, radiation contribution to the **dynamics** can be ignored
- one-fluid simulation has been actively developed since ~2000
- uncertainty for simulating radiation feature of two temperature flow + non-thermal syn. jet

Mao et al. 2017

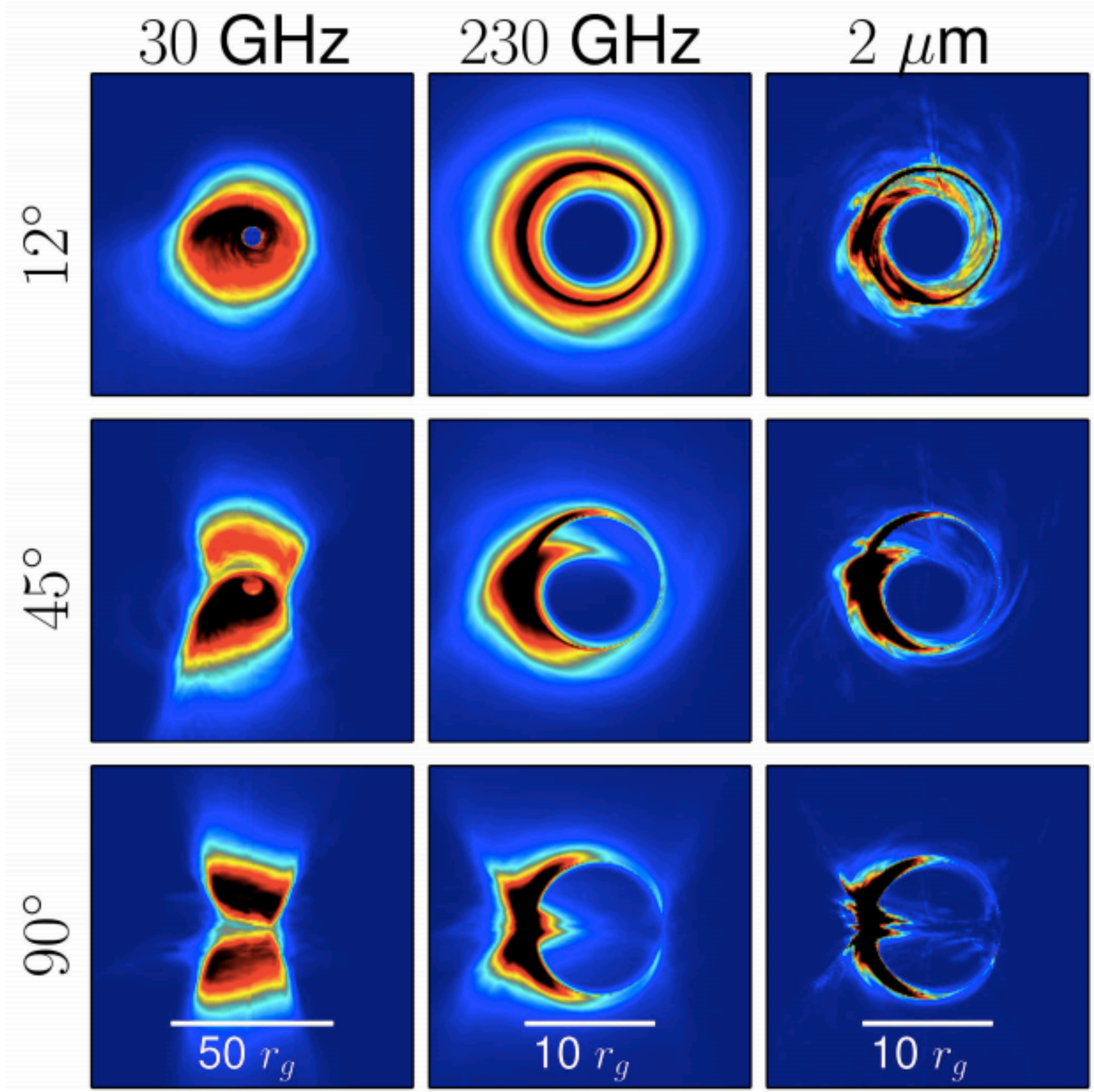


EHT image library

(Ti/Te parametrization according to plasma beta)



Ressler+ 2016
post-processing
“two-fluid” GRMHD
simulation of Sgr A*;
thermal synchrotron
images



how can phenomenological models help?

- usually **semi-analytical**: prompt, flexible, and heuristic (useful for demonstration and parameter search)
- a complementary way to study global properties of the jet (funnel) region
- wide applications: from **horizon to large scale**

why phenomenological models?

- Here we are talking about **GR**MHD models includes all GR features, model become **SR**MHD automatically far away from the source and gravity effect is negligible

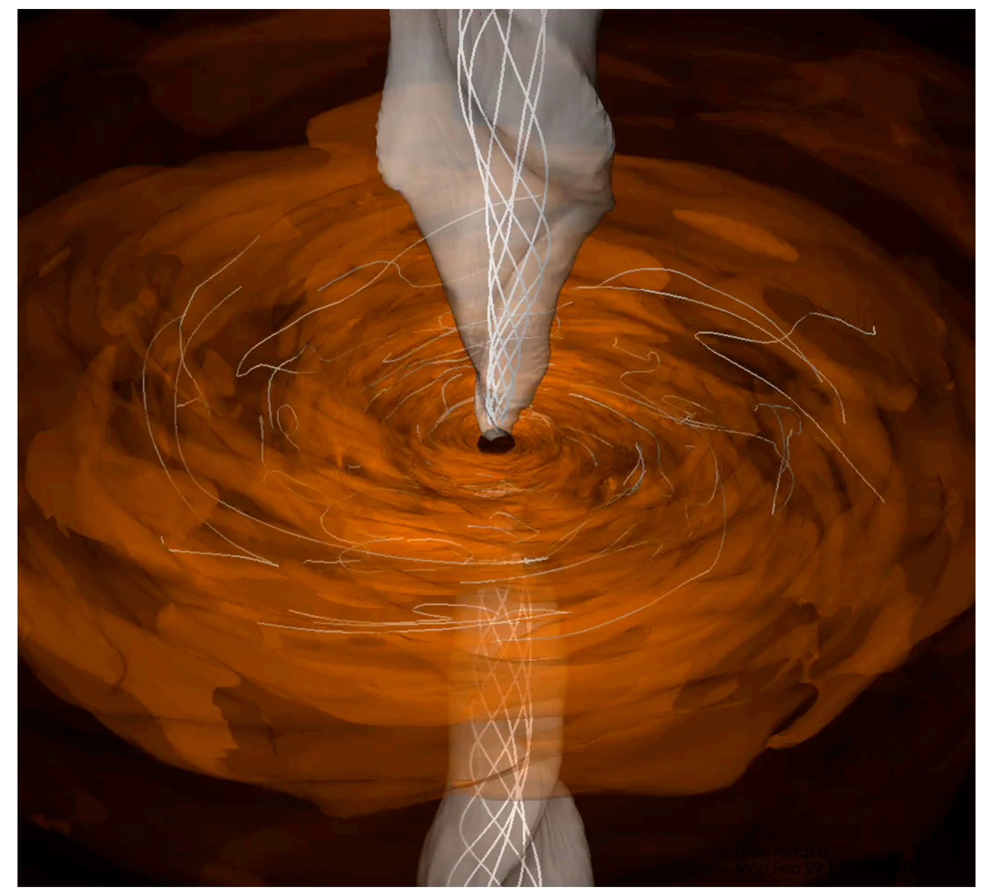
why phenomenological models?

- Here we are talking about **GR**MHD models includes all GR features, model become **SR**MHD automatically far away from the source and gravity effect is negligible

- Not necessary works well if **key features** in not included, or the simplicity does not exist.
- What are the **key feature** for BH accretion/ jet?

outline

- Black hole structure/magnetosphere with RIAF environment
- accretion
  - numerical simulation
  - semi-analytical model
- jet
  - numerical simulation
  - semi-analytical model

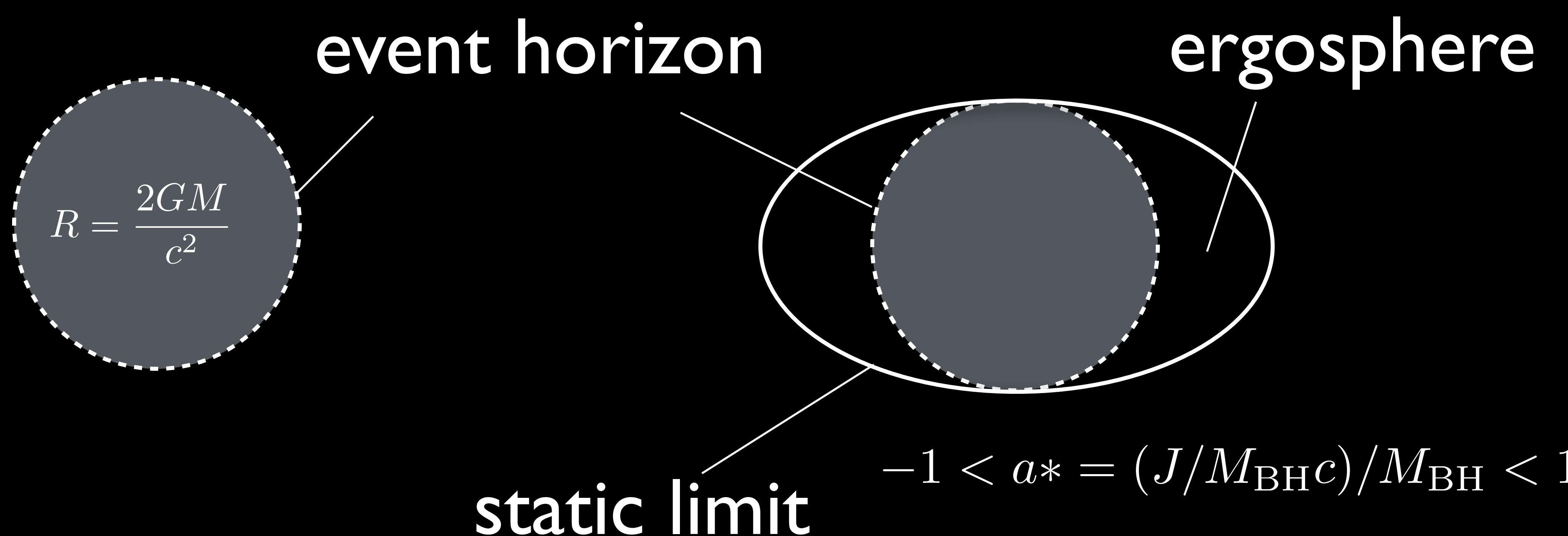


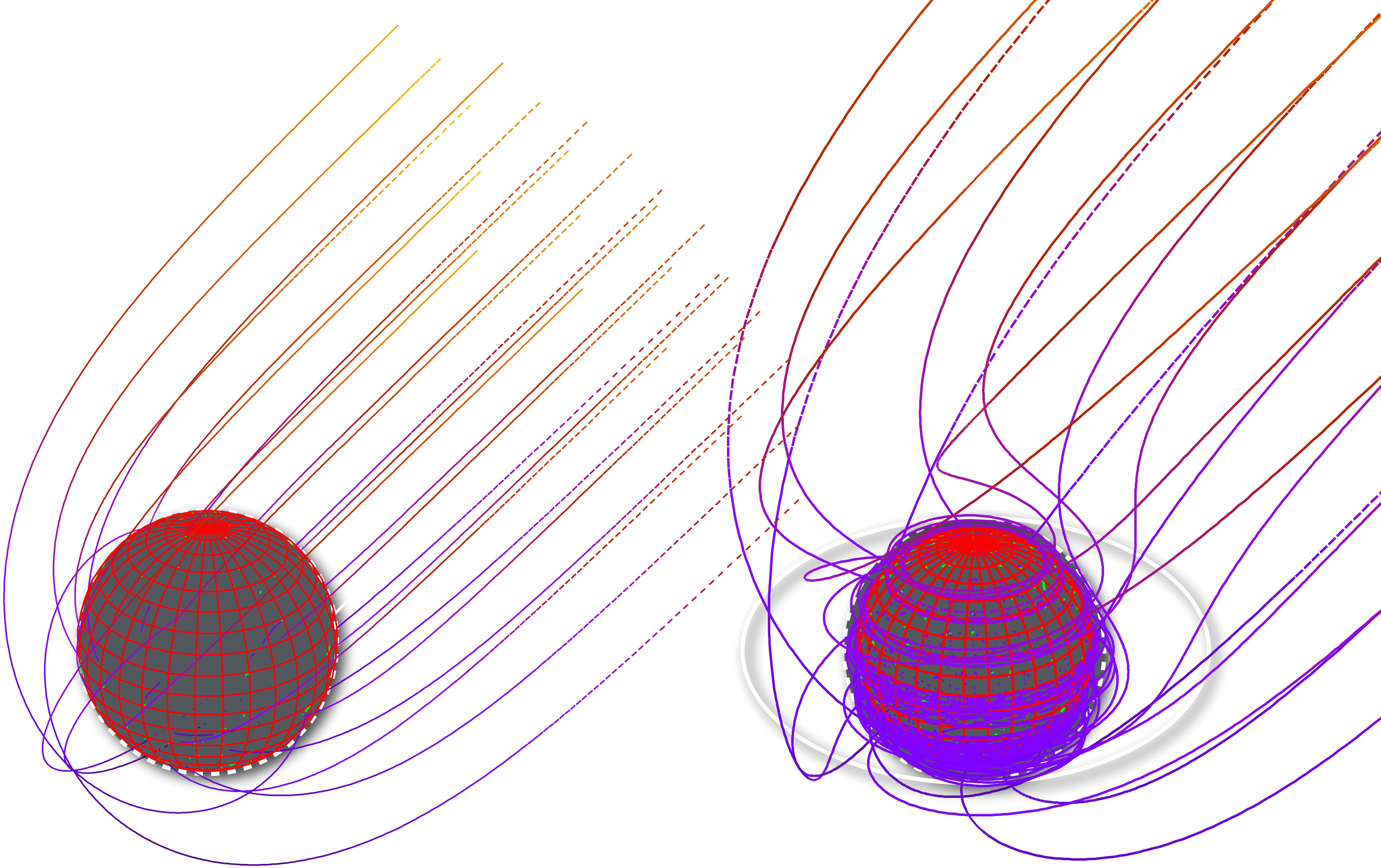
credit: Shiokawa

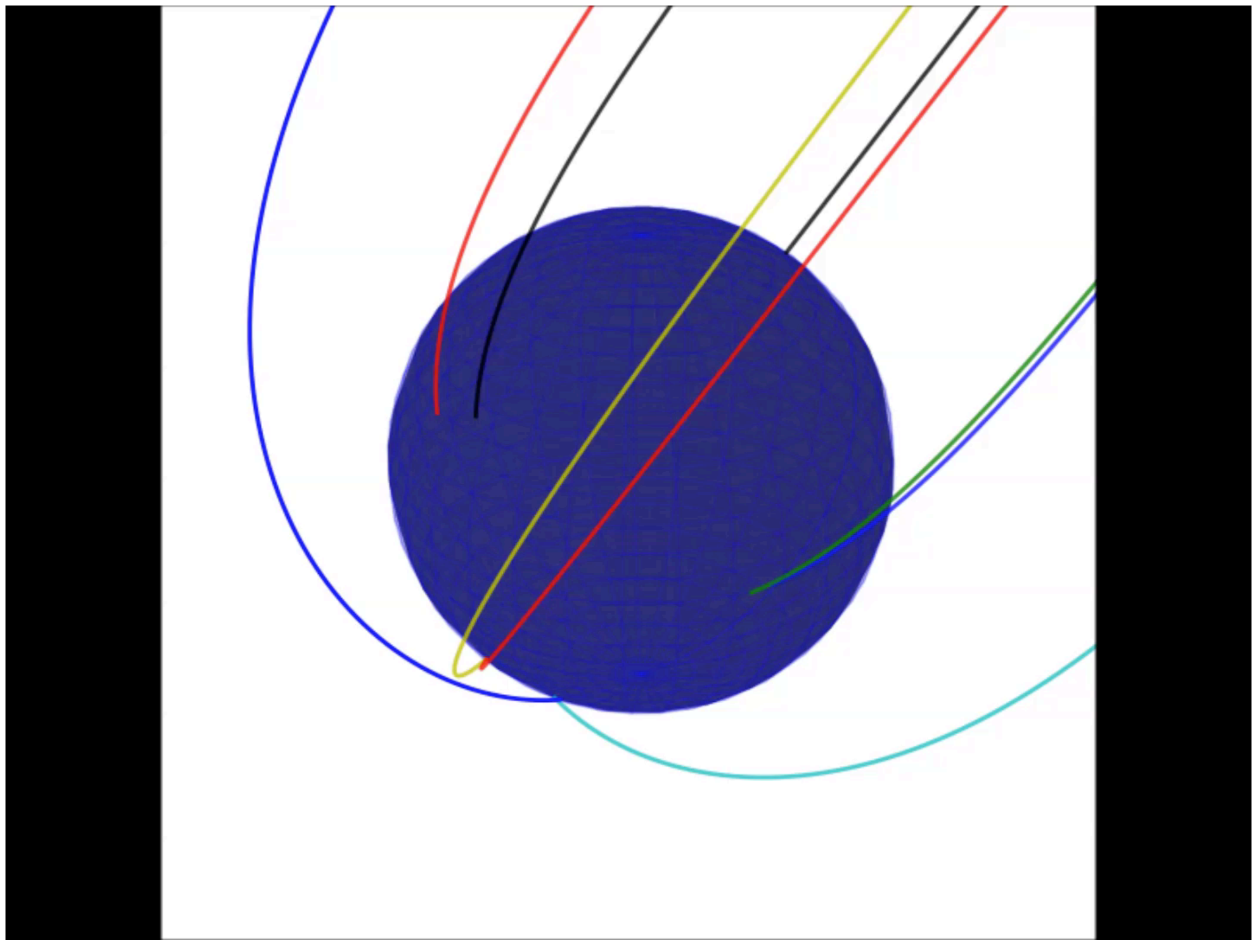
black hole: spacetime structure

Non-rotating BH:
described by Schwarzschild geometry (1916)

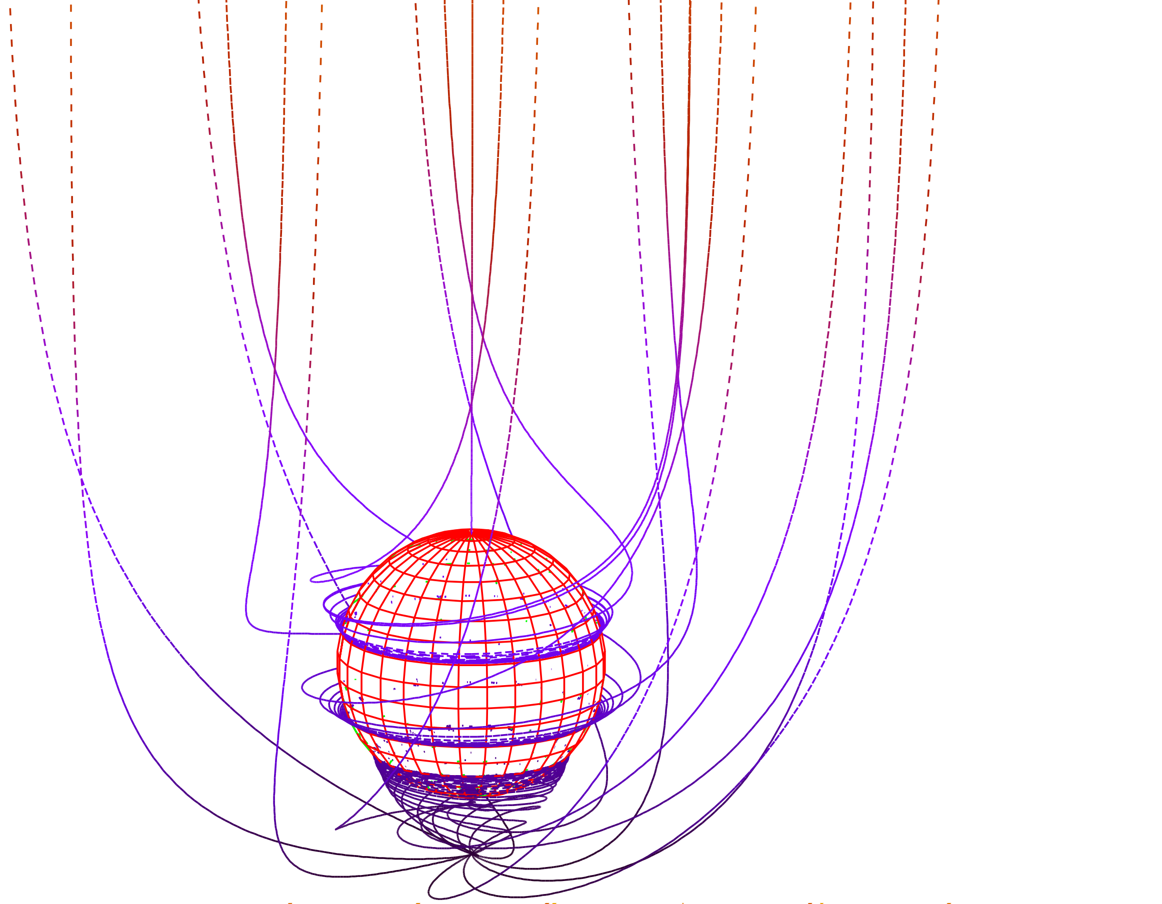
Rotating BH:
described by Kerr geometry (1963)

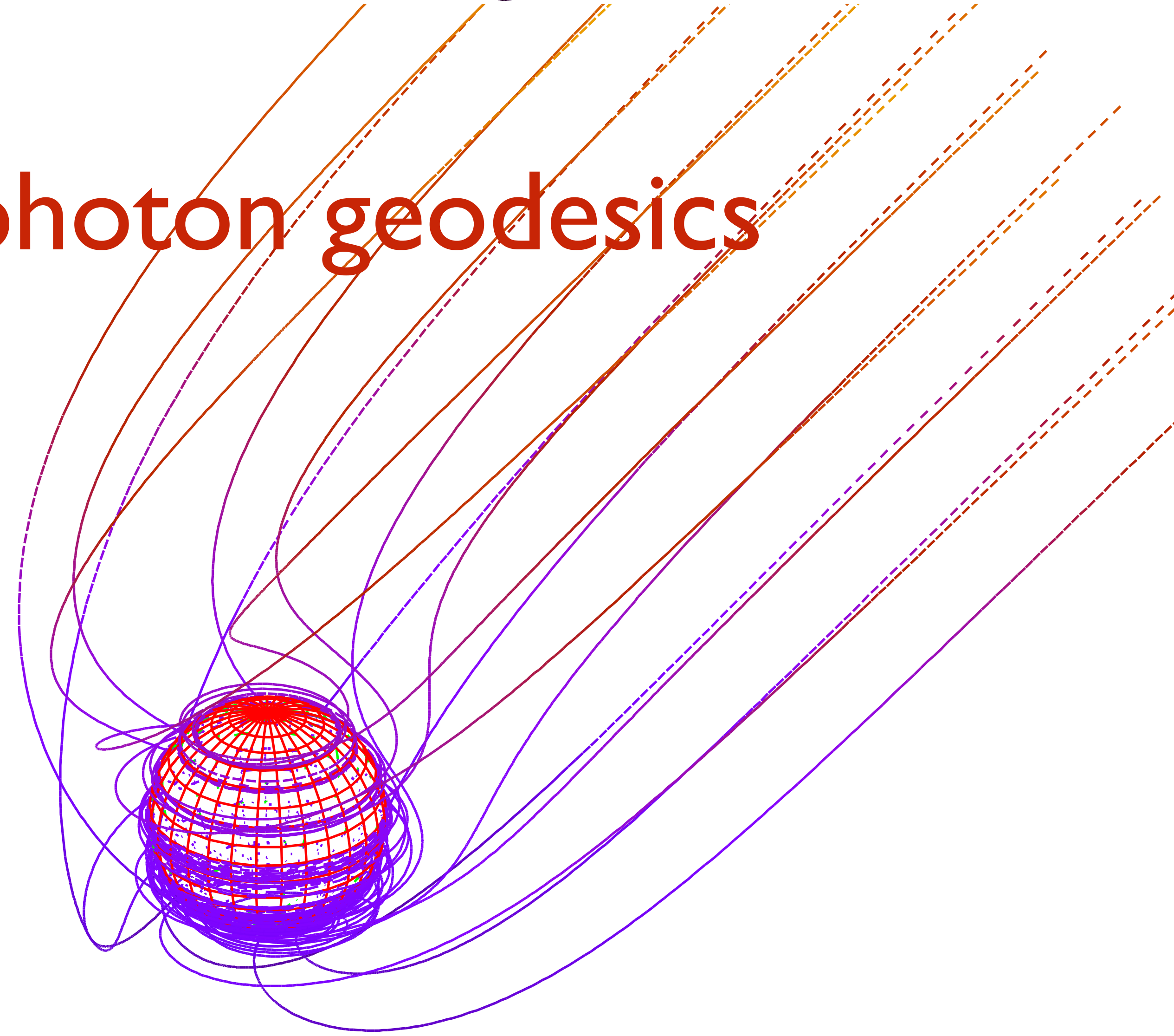






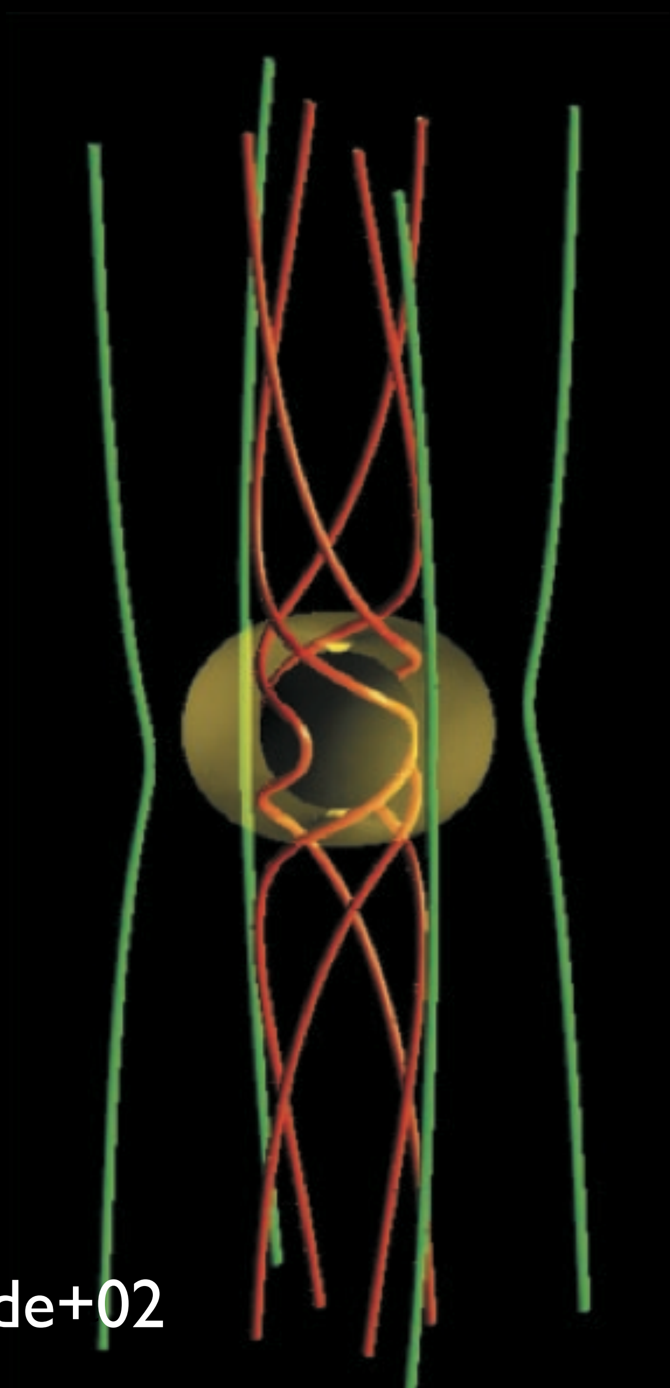
photon geodesics



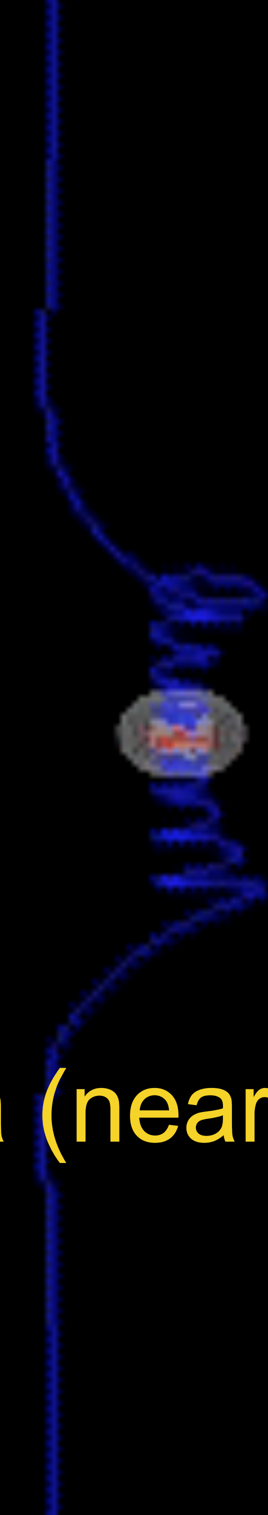


extraction of BH rotational energy by magnetic fields

Penrose&Ford 71,
Blanford&Znajeck 77,
Takahashi+90



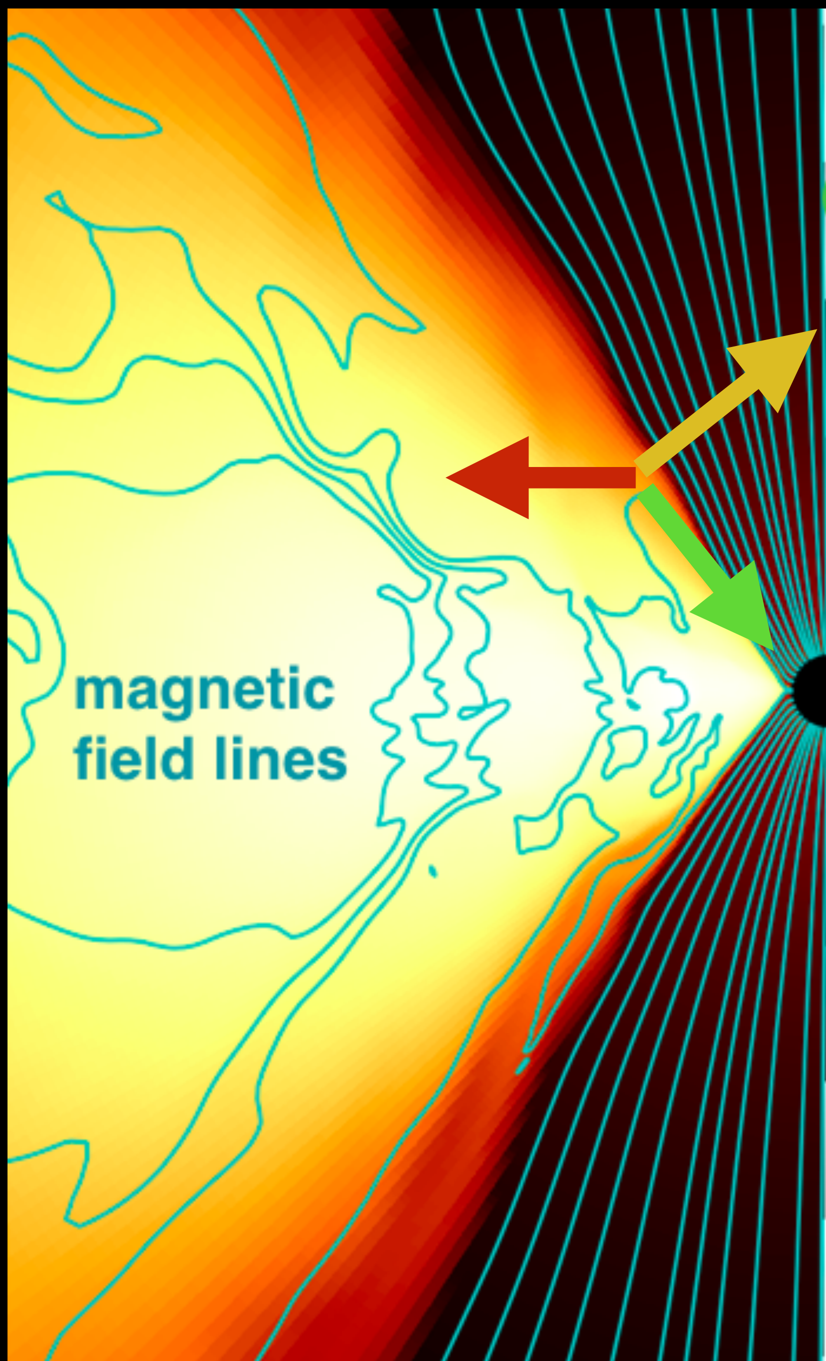
Koide+02



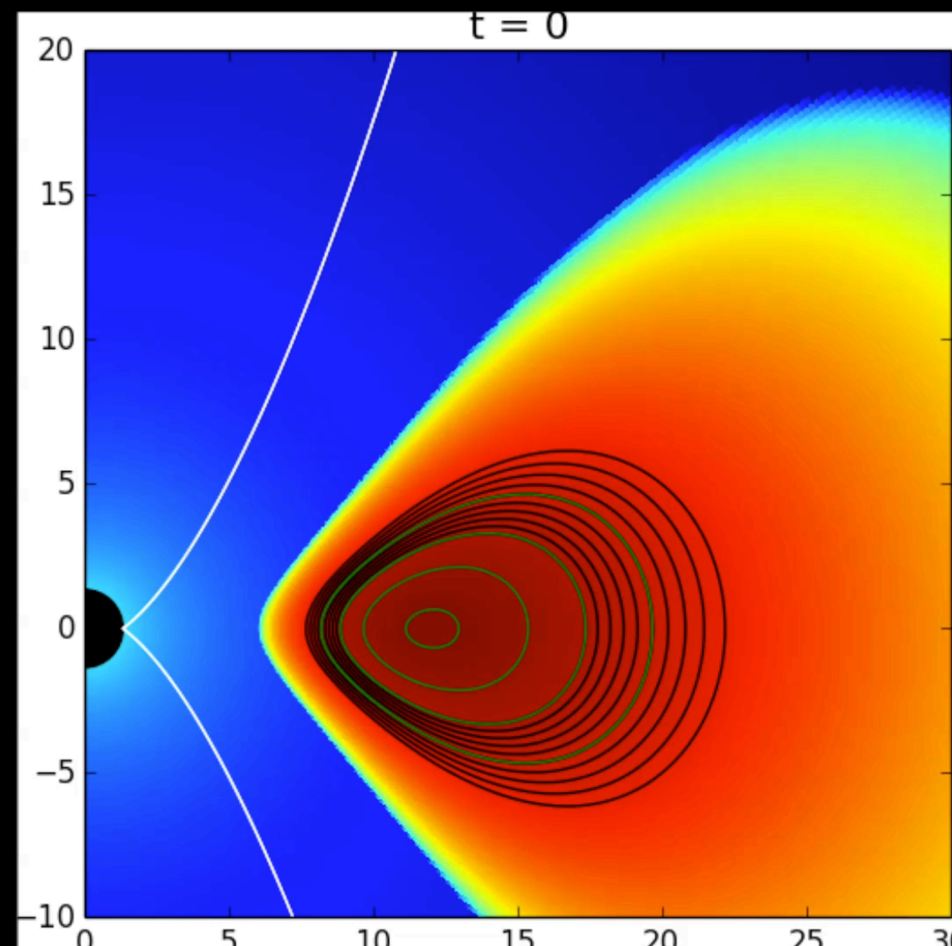
few plasma (nearly vacuum)

Semenov+04

“stationary state”



more plasma —> accretion flow



magnetic field

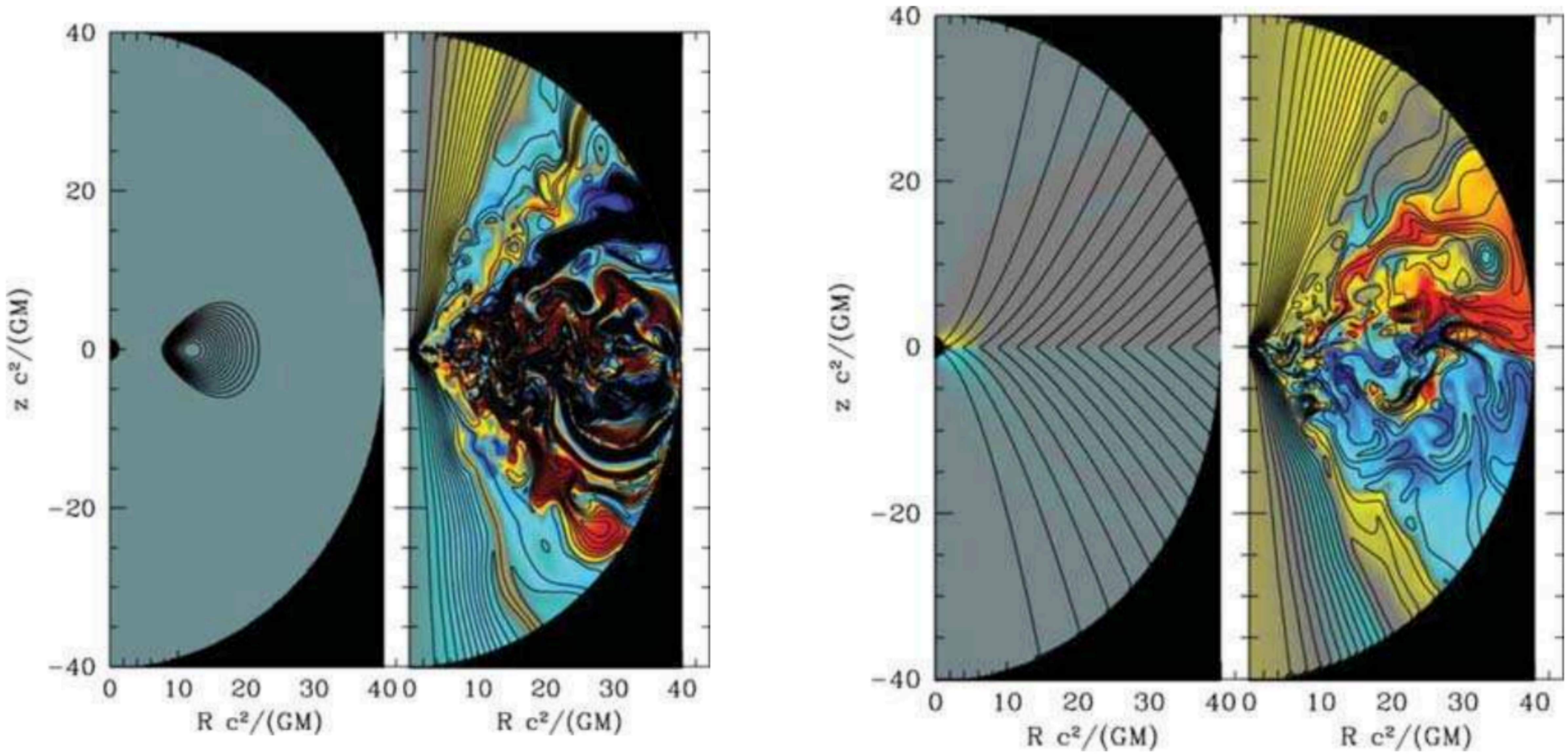
strong weak

braking

Magneto-
Rotational
Instability
(Bulbus & Hawley 91)

accretion

initial magnetic field configuration does matter



McKinney & Narayan 07

magnetic energy
= mass energy

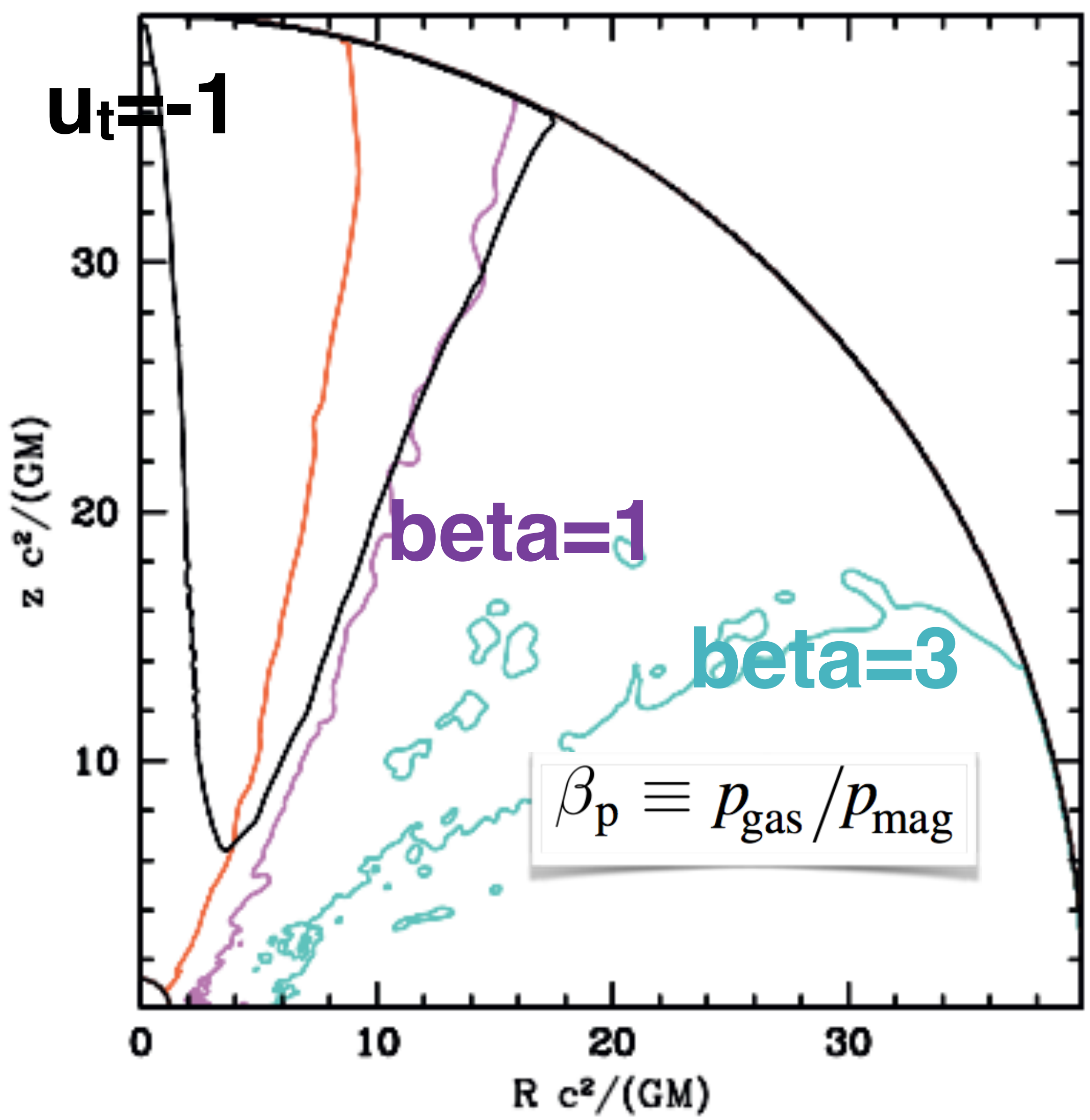


Fig. 2a

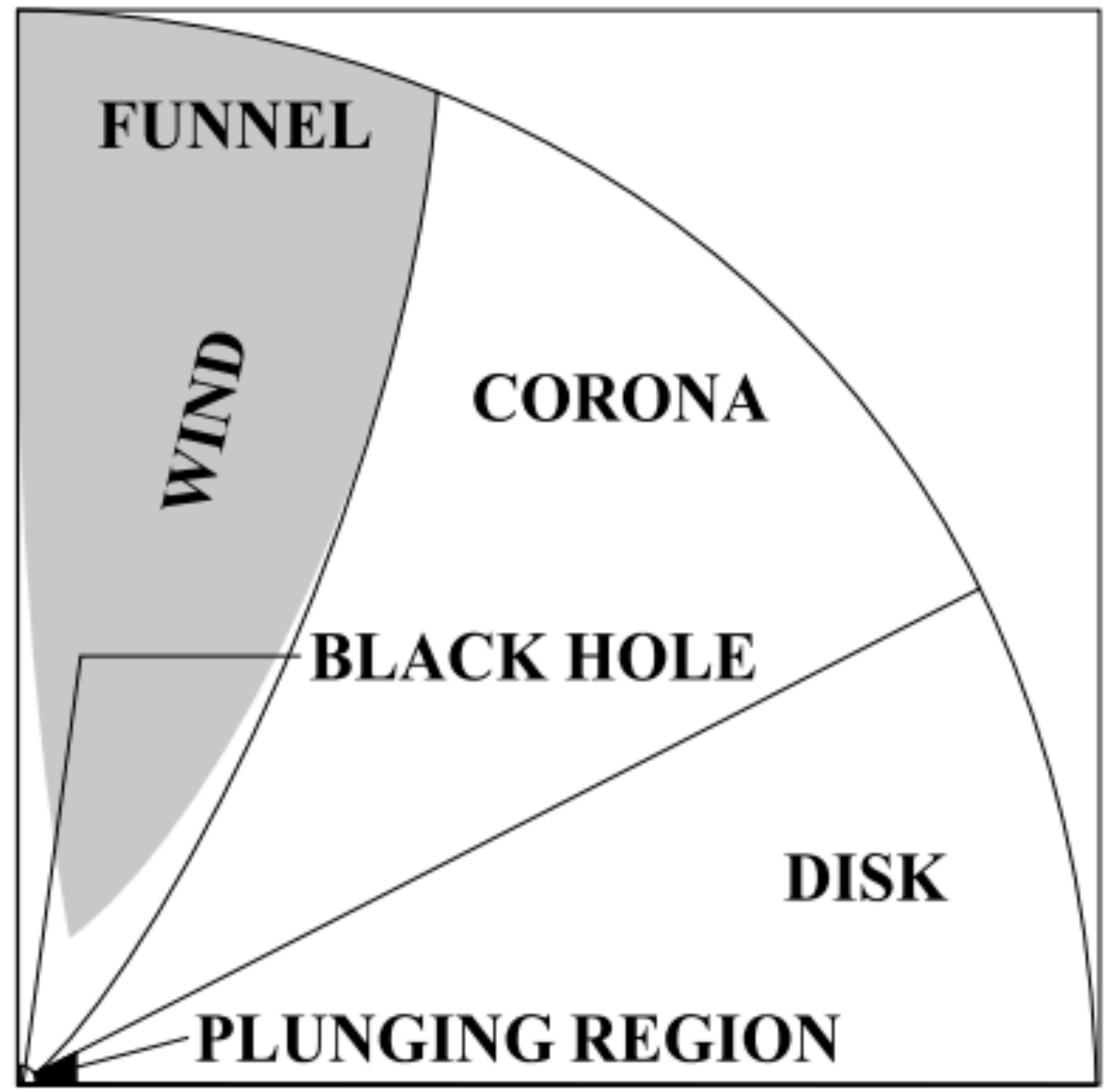
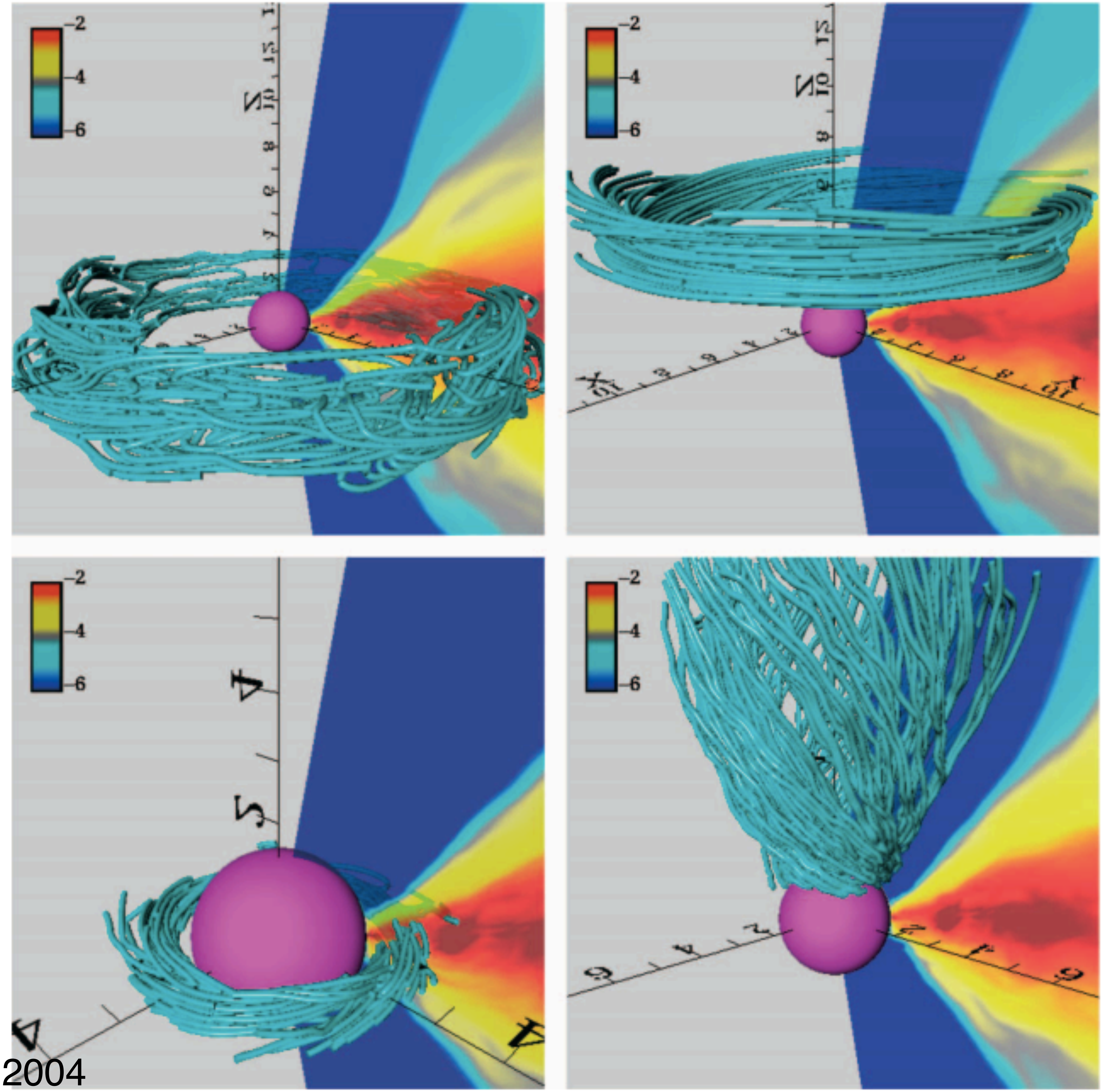


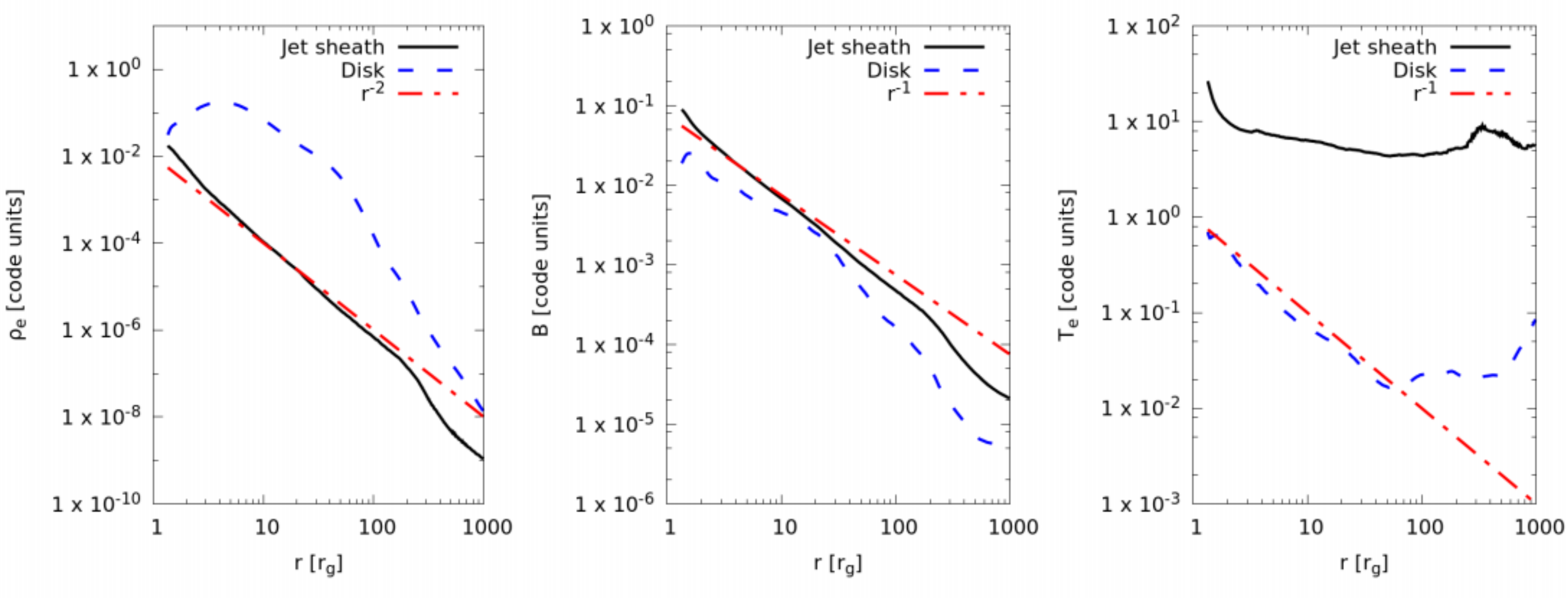
Fig. 2b

Mckineey &Gammie 04



Hirose et al. 2004

Davelaar+ 2020(see, e.g. Moscibrodzka+2013,2014)



GR Radiative Transfer

*Photon p_α

*GR + HD/ MHD u^α

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

*energy shift $\dfrac{E_{\rm comoving}}{E_{\rm obs}} = \dfrac{p_\alpha u^\alpha|_0}{p_\alpha u^\alpha|_\infty}$

*radiative transfer $\dfrac{\mathrm{d}\mathcal{I}}{\mathrm{d}\tau_\nu} = -\mathcal{I} + \dfrac{\eta}{\chi}$

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

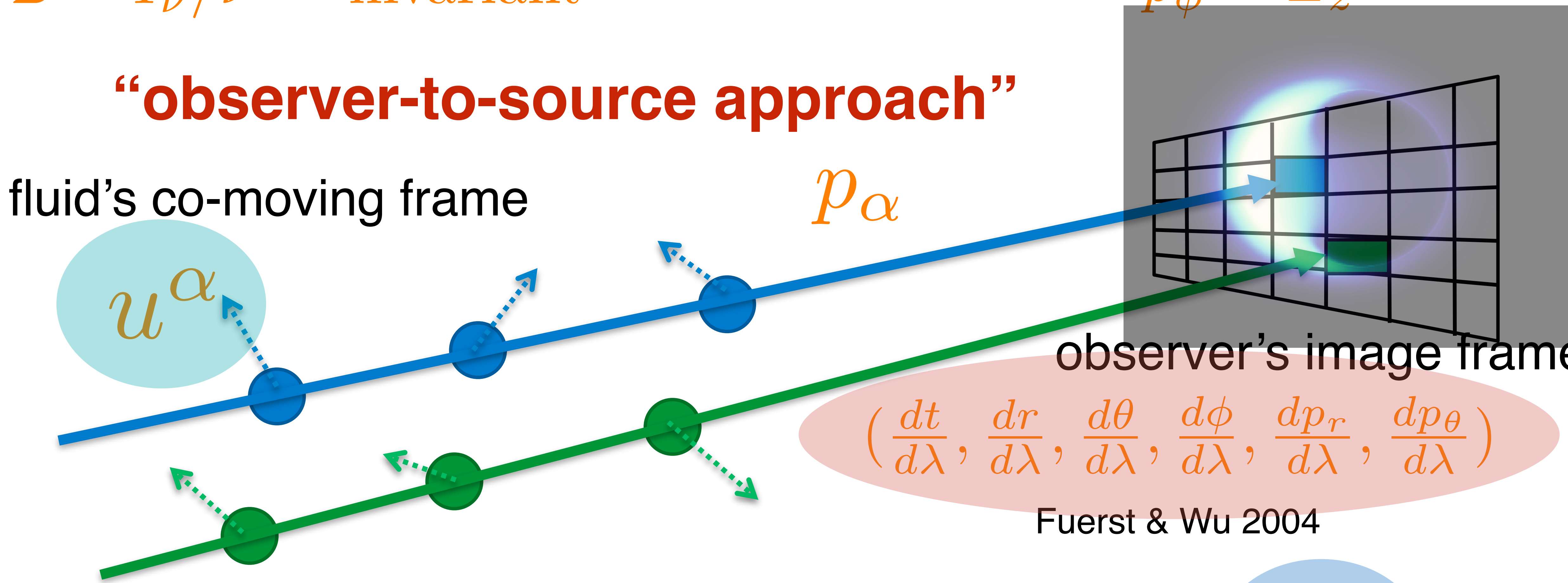
$$\gamma^{-1} \equiv \frac{E_{\mathrm{comoving}}}{E_{\mathrm{obs}}} = \frac{p_\alpha u^\alpha|_0}{p_\alpha u^\alpha|_\infty}$$

$$p_t = -E$$

$$p_\phi = L_z$$

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

“observer-to-source approach”

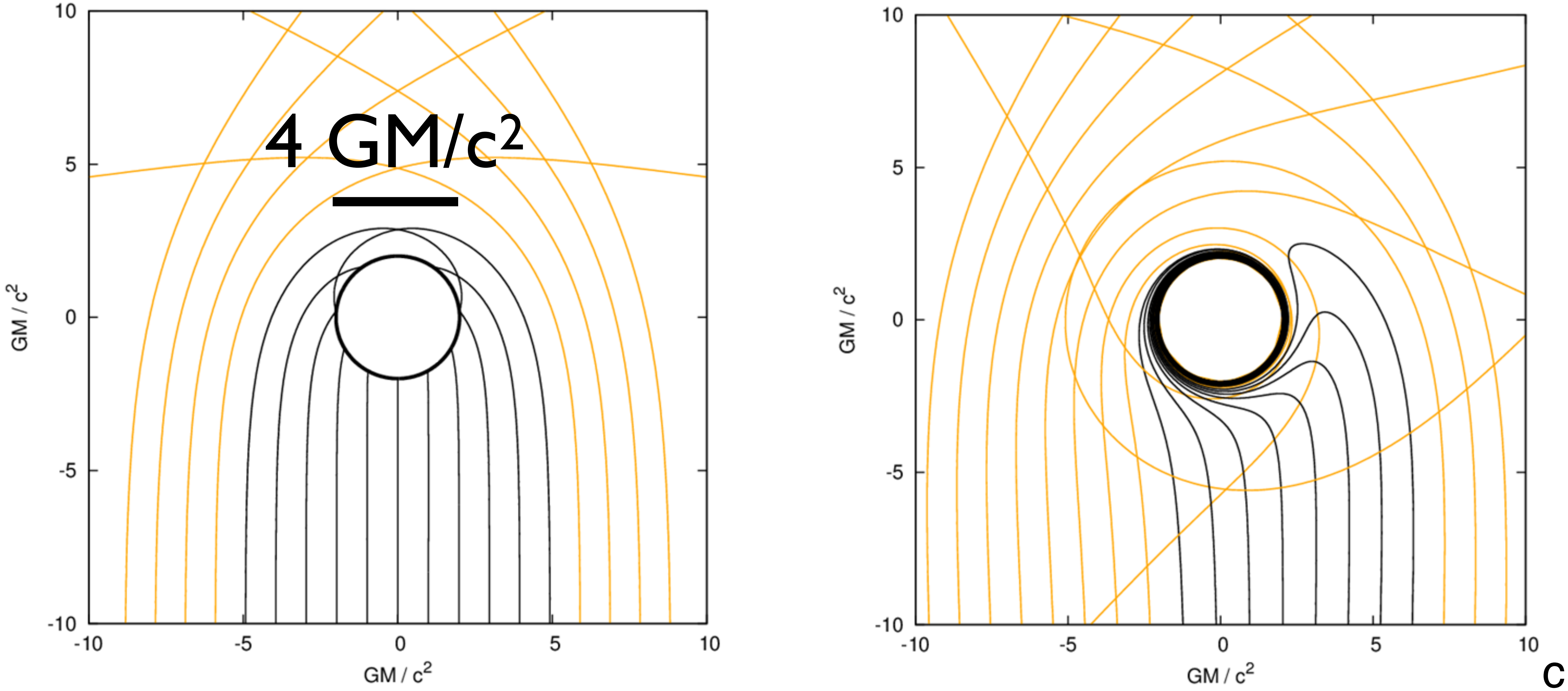


$$\frac{\mathrm{d}\mathcal{I}}{\mathrm{d}\tau_\nu} = -\mathcal{I} + \frac{\eta}{\chi}$$

Younsi et al. 2012

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

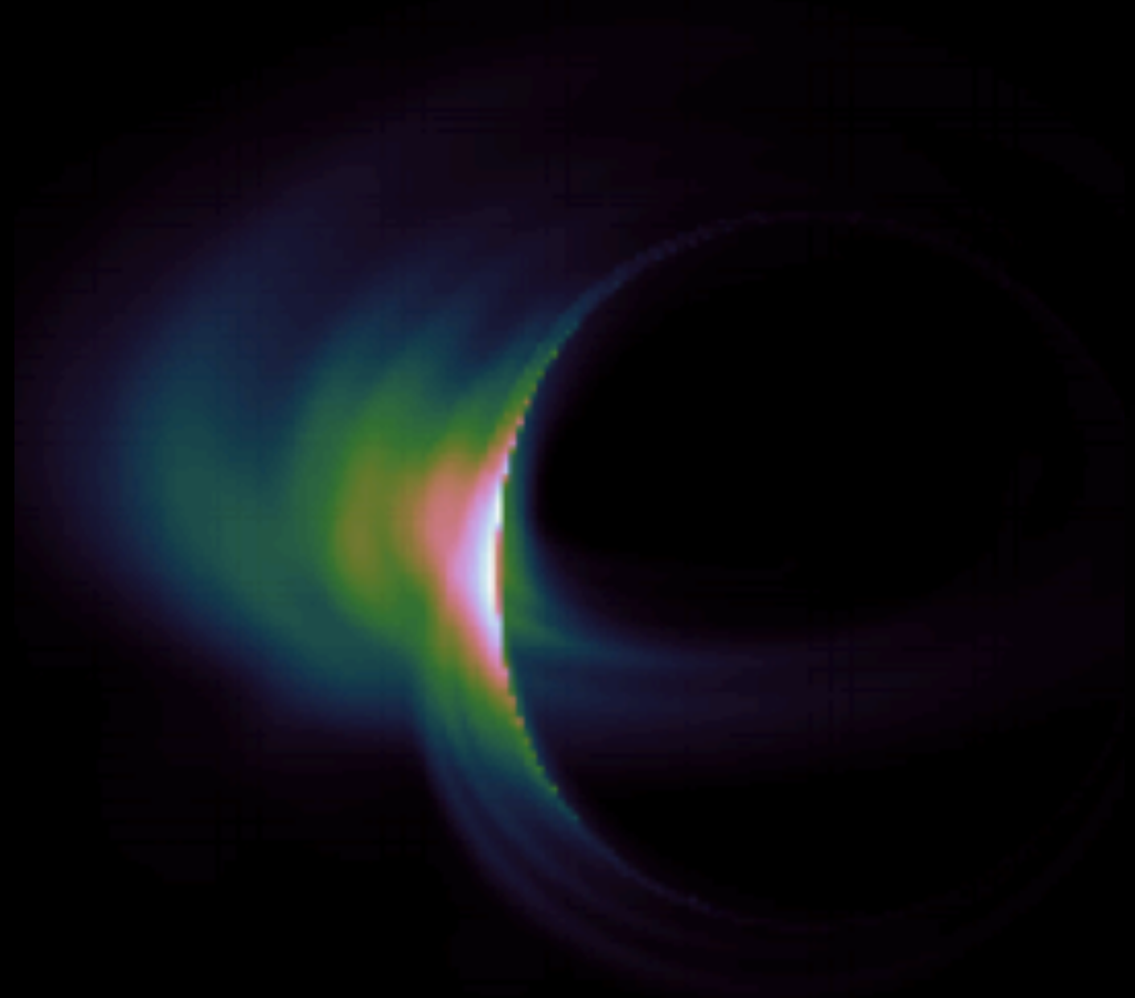
$$\frac{\mathrm{d}\mathcal{I}}{\mathrm{d}\lambda} = \gamma^{-1}\left(\frac{j_{0,\nu}}{\nu^3}\right)$$

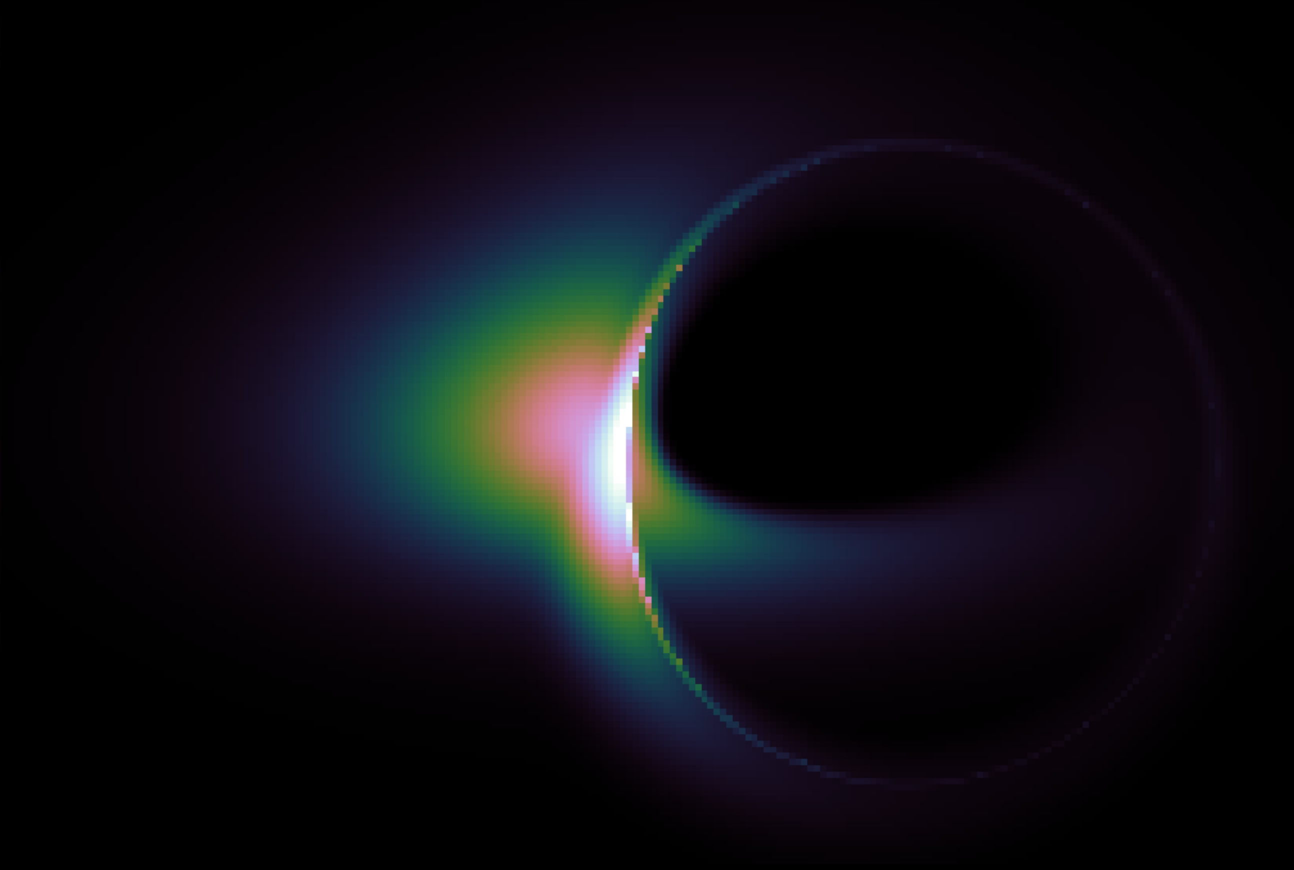


credit: Pu

~40μas for M87; ~50μas for Sgr A*

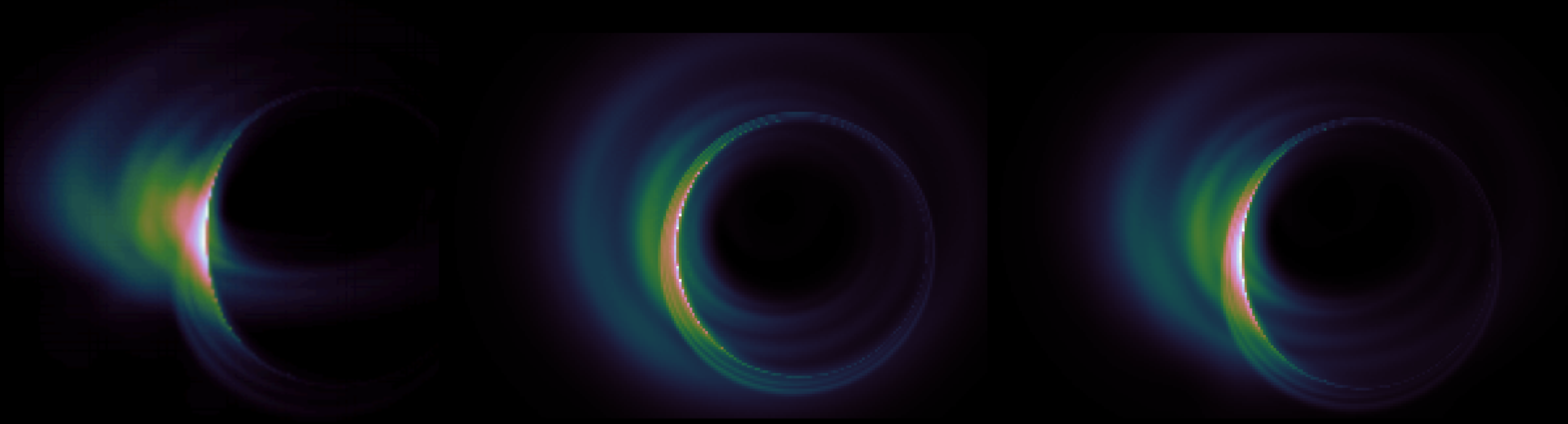
GRMHD numerical simulation + GRRT



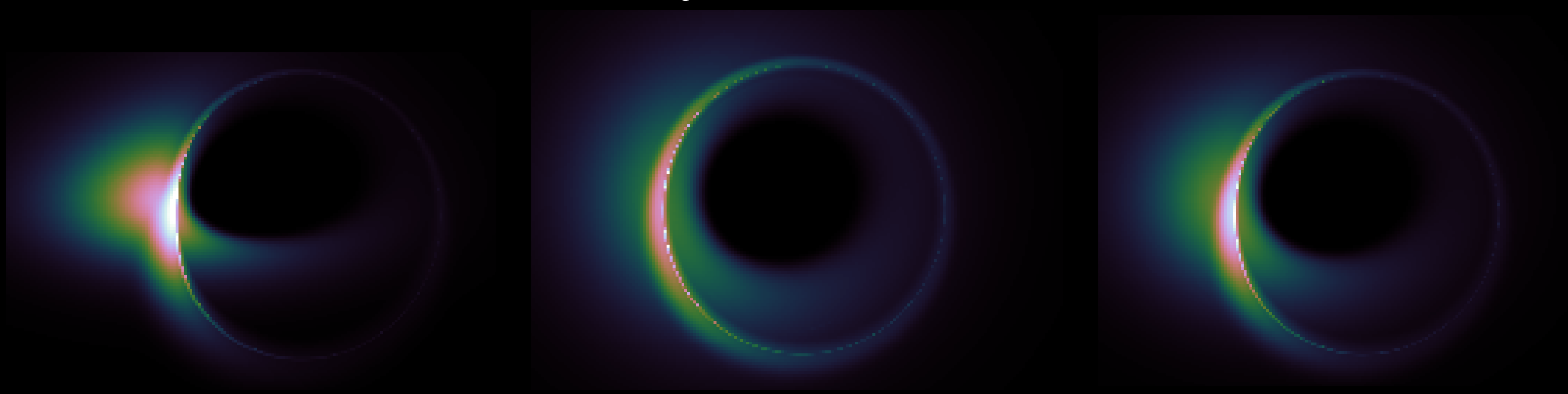


phenomenological model + GRRT

GRMHD numerical simulation + GRRT



phenomenological model + GRRT



$$Z = r\cos\theta$$

$$R = r\sin\theta$$

$$n_e = n_e^0 \exp\left(\frac{Z^2}{2(HR)^2}\right) r^{-1.1}$$

$$T_e = T_e^0 r^{-0.84}$$

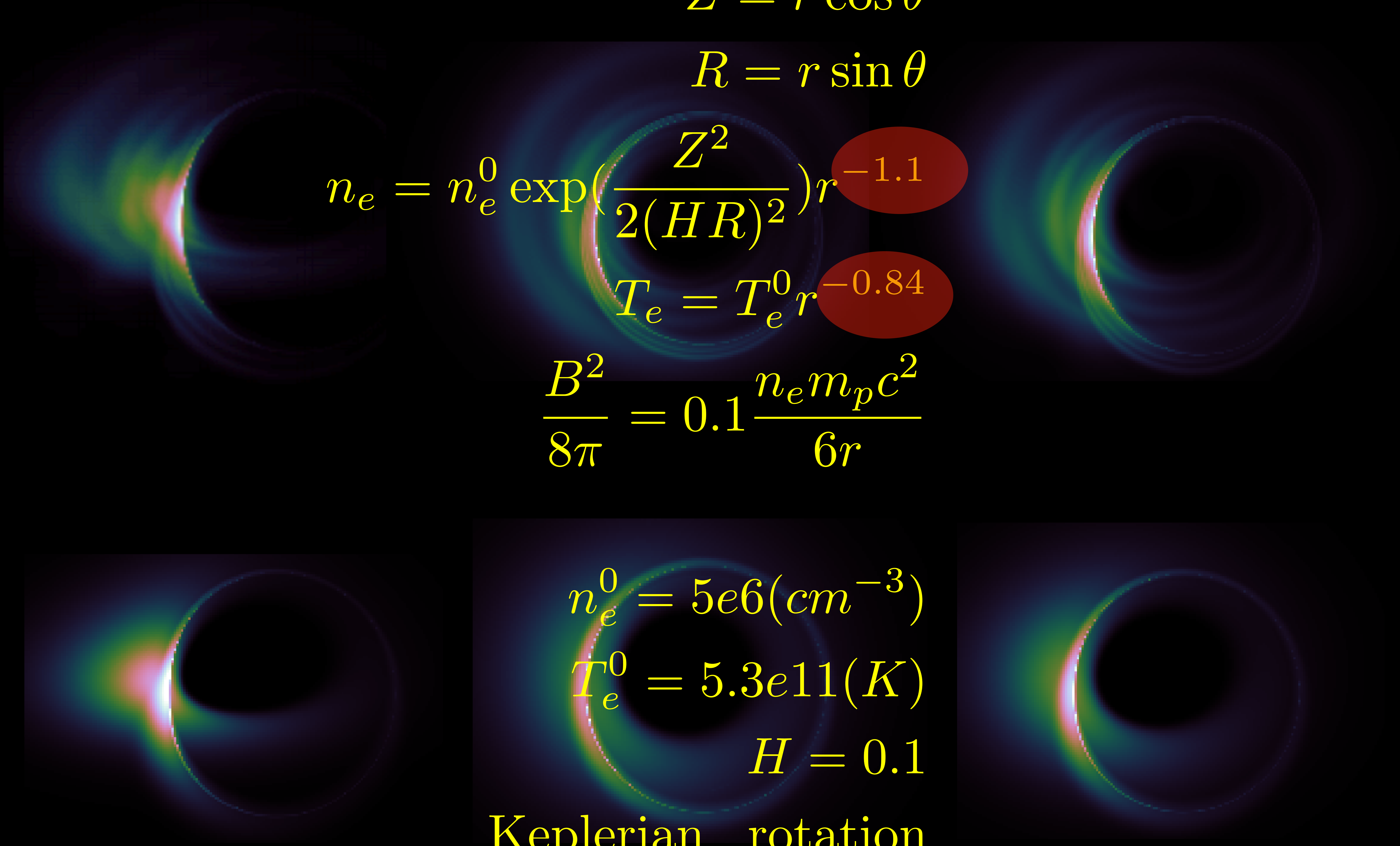
$$\frac{B^2}{8\pi} = 0.1\frac{n_e m_p c^2}{6r}$$

$$n_e^0 = 5e6(cm^{-3})$$

$$T_e^0 = 5.3e11(K)$$

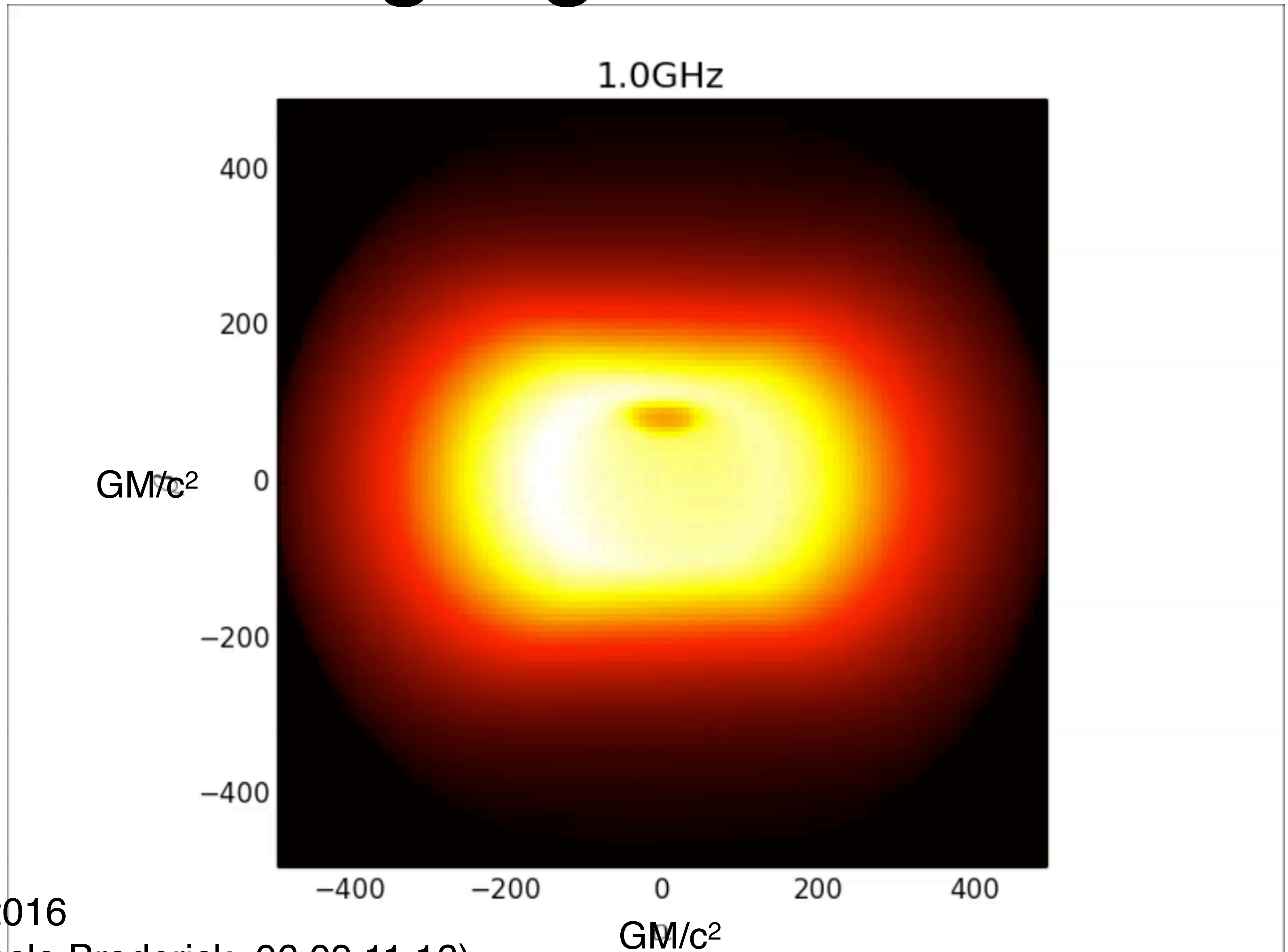
$$H = 0.1$$

Keplerian rotation



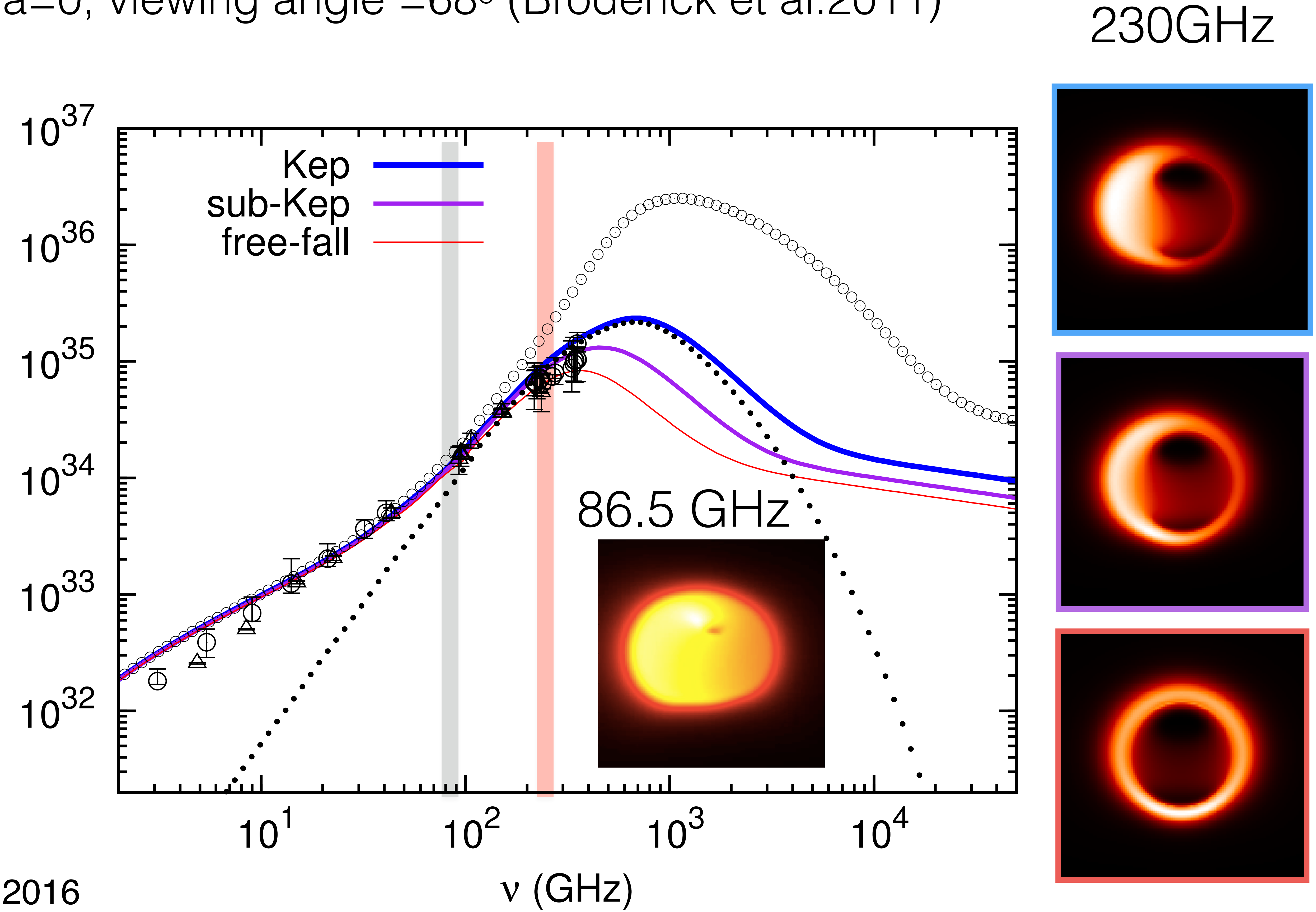
Broderick+ 2006, Pu+ 2016, 2018

Modeling Sgr A*



Pu+ 2016
(see aslo Broderick+06,09,11,16)

*a=0, viewing angle =68o (Broderick et al.2011)



Pu+ 2016

Dynamical dependency

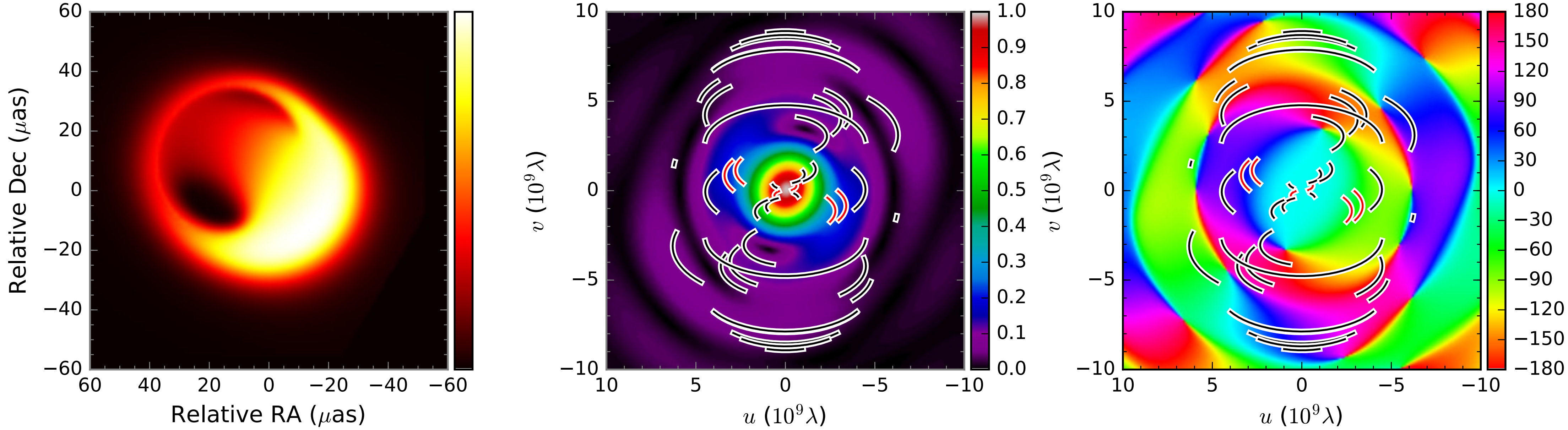
*effect of flow dynamics **only**

rotation

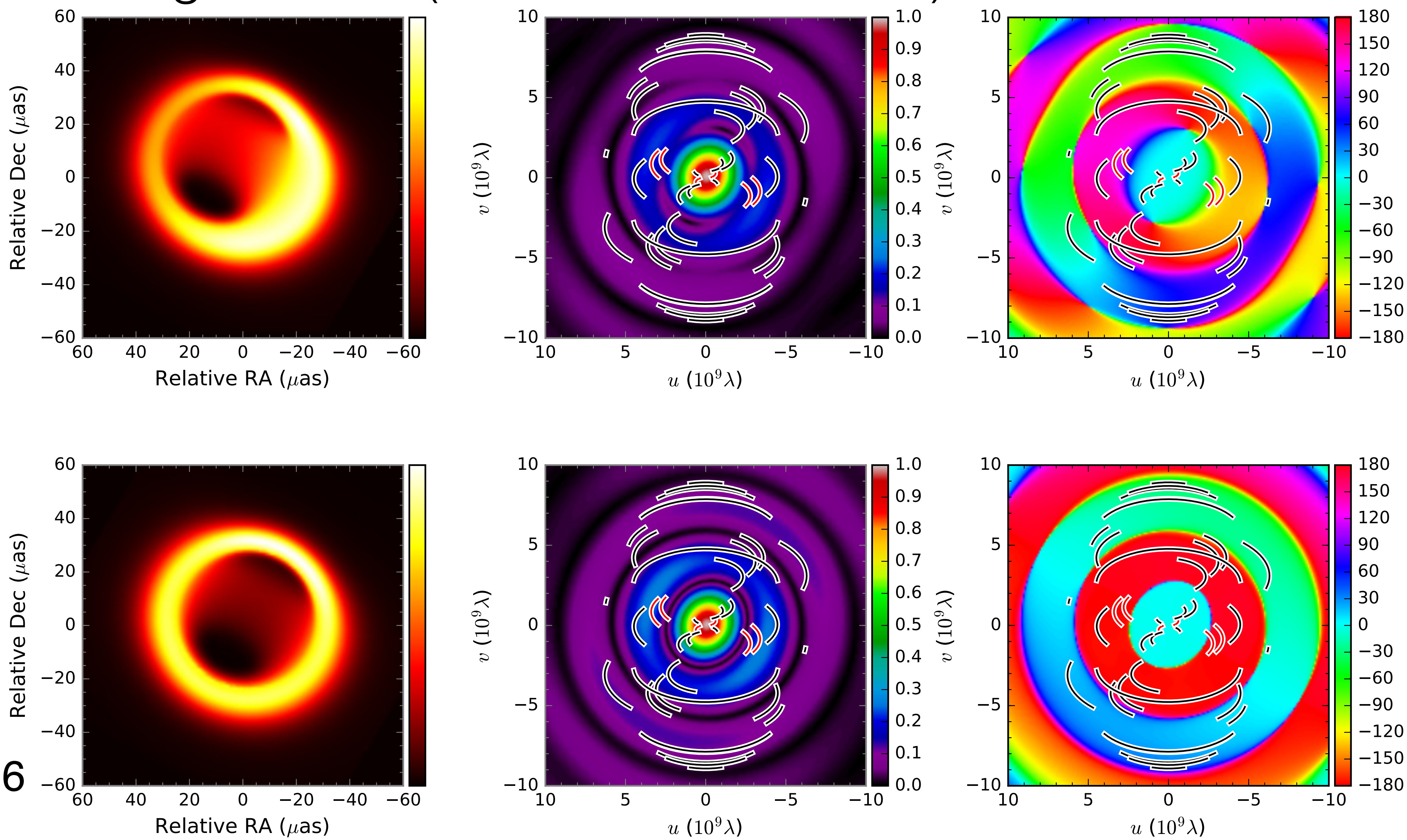
free-fall

sub-Keplerian

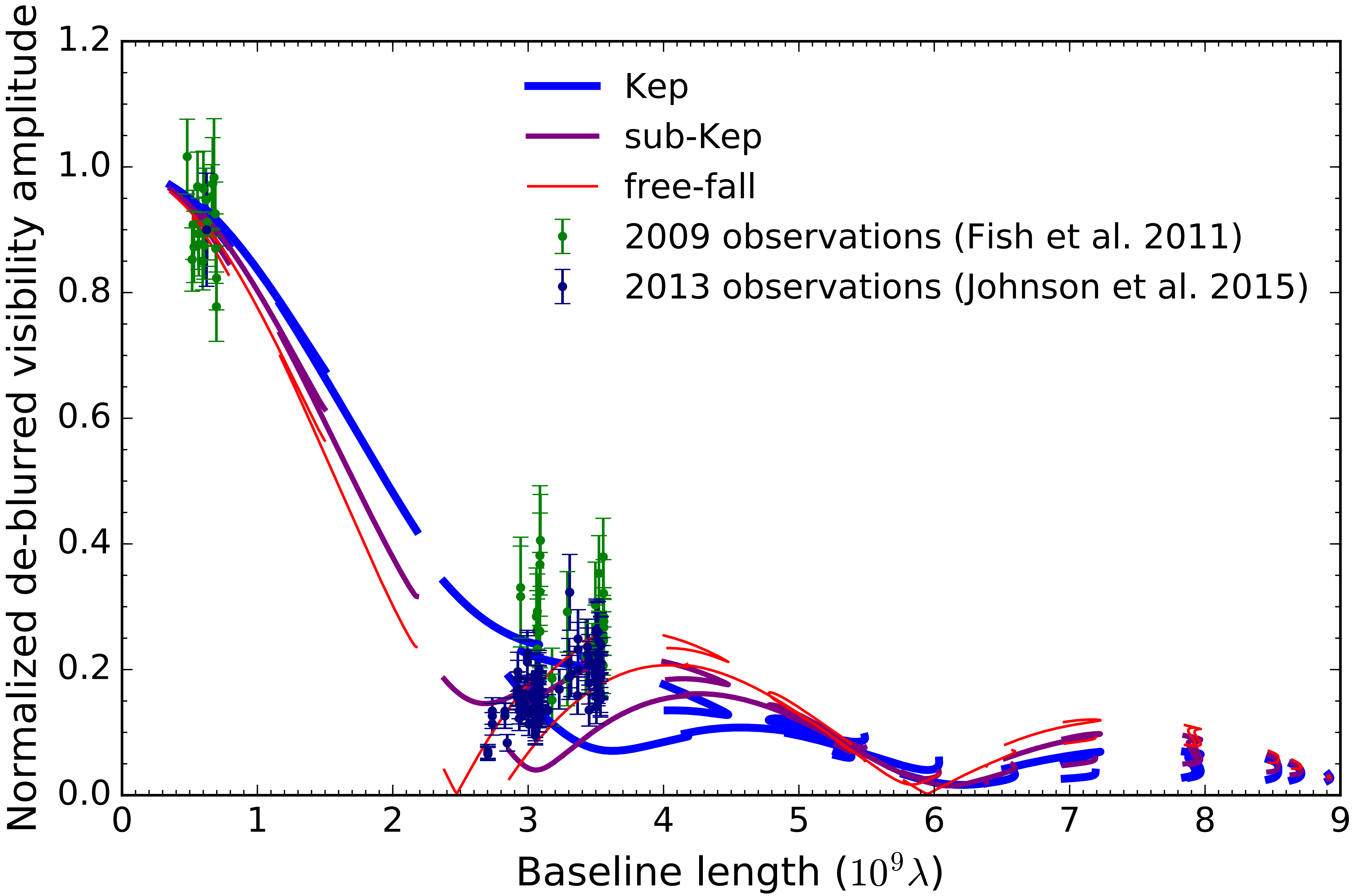
Keplerian rotating



*position angle =150° (Broderick et al.2016)



Pu+ 2016



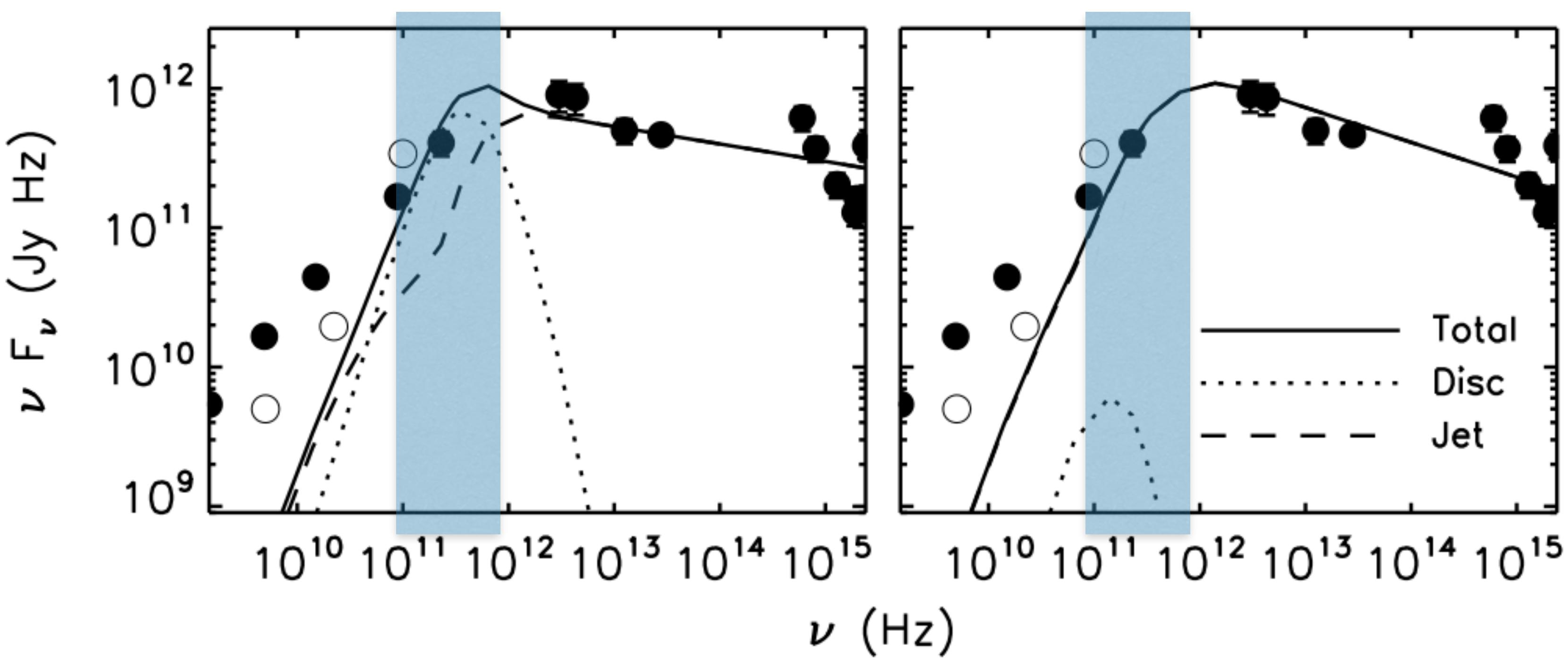
Kep
sub-Kep
free-fall
2009 observations (Fish et al. 2011)
2013 observations (Johnson et al. 2015)
Normalized de-blurred visibility amplitude
Baseline length ($10^9\lambda$)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
1
2
3
4
5
6
7
8
9

Pu+ 2016

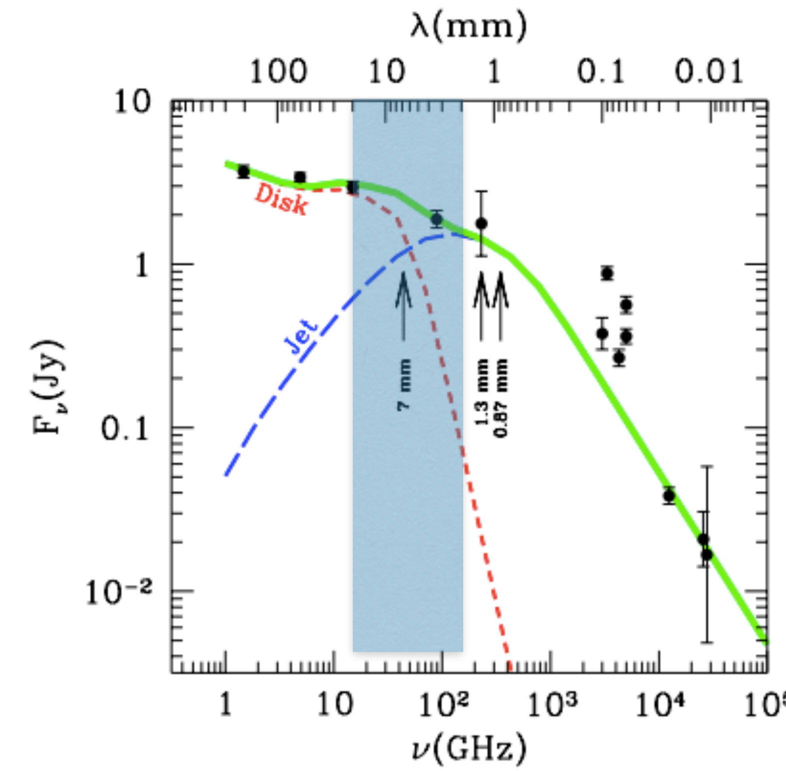
Jet

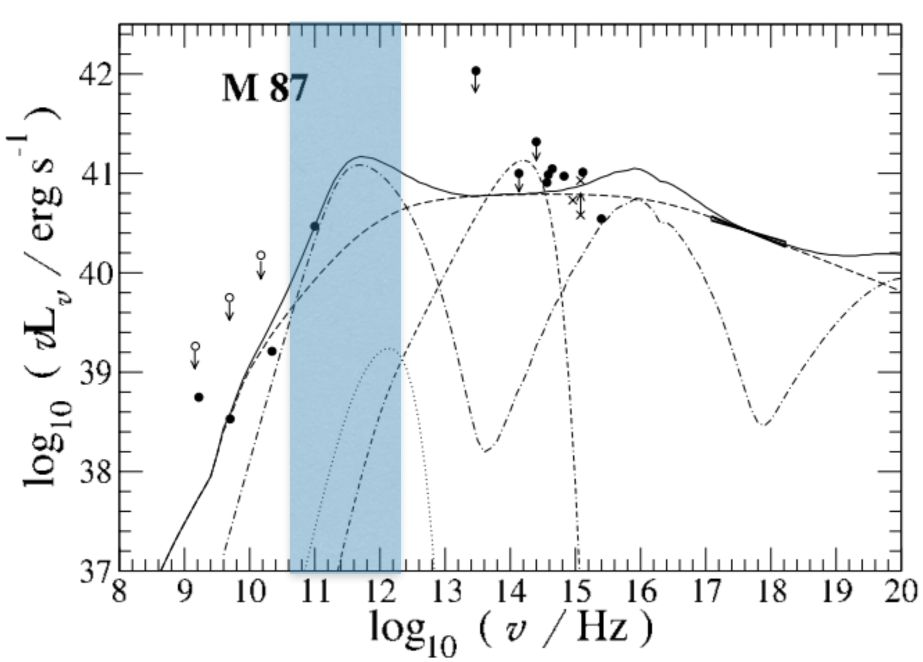
accretion or jet ? compact or extended?

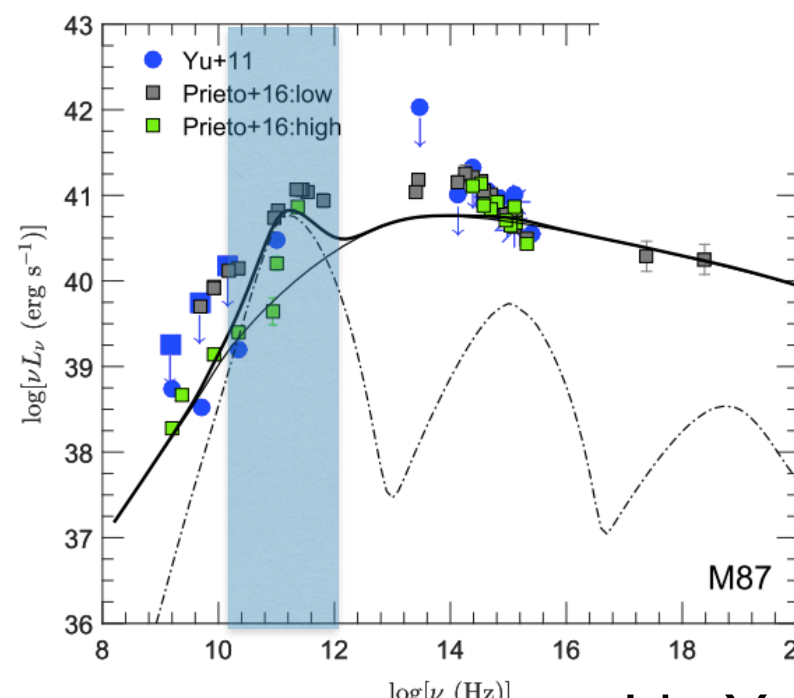
Dexter, McKinney, & Agol 2012



Broderick & Loeb 2009



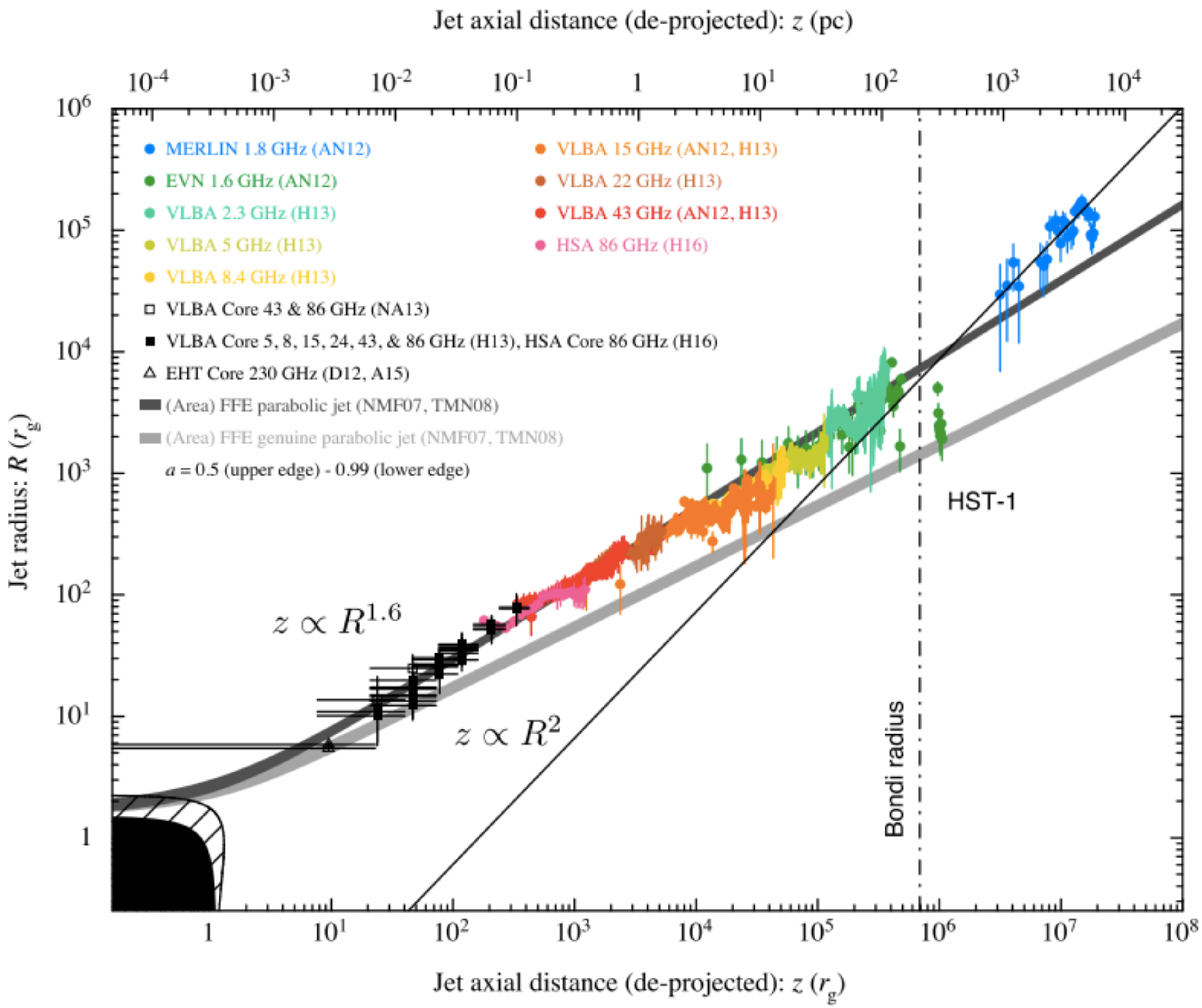




M 87

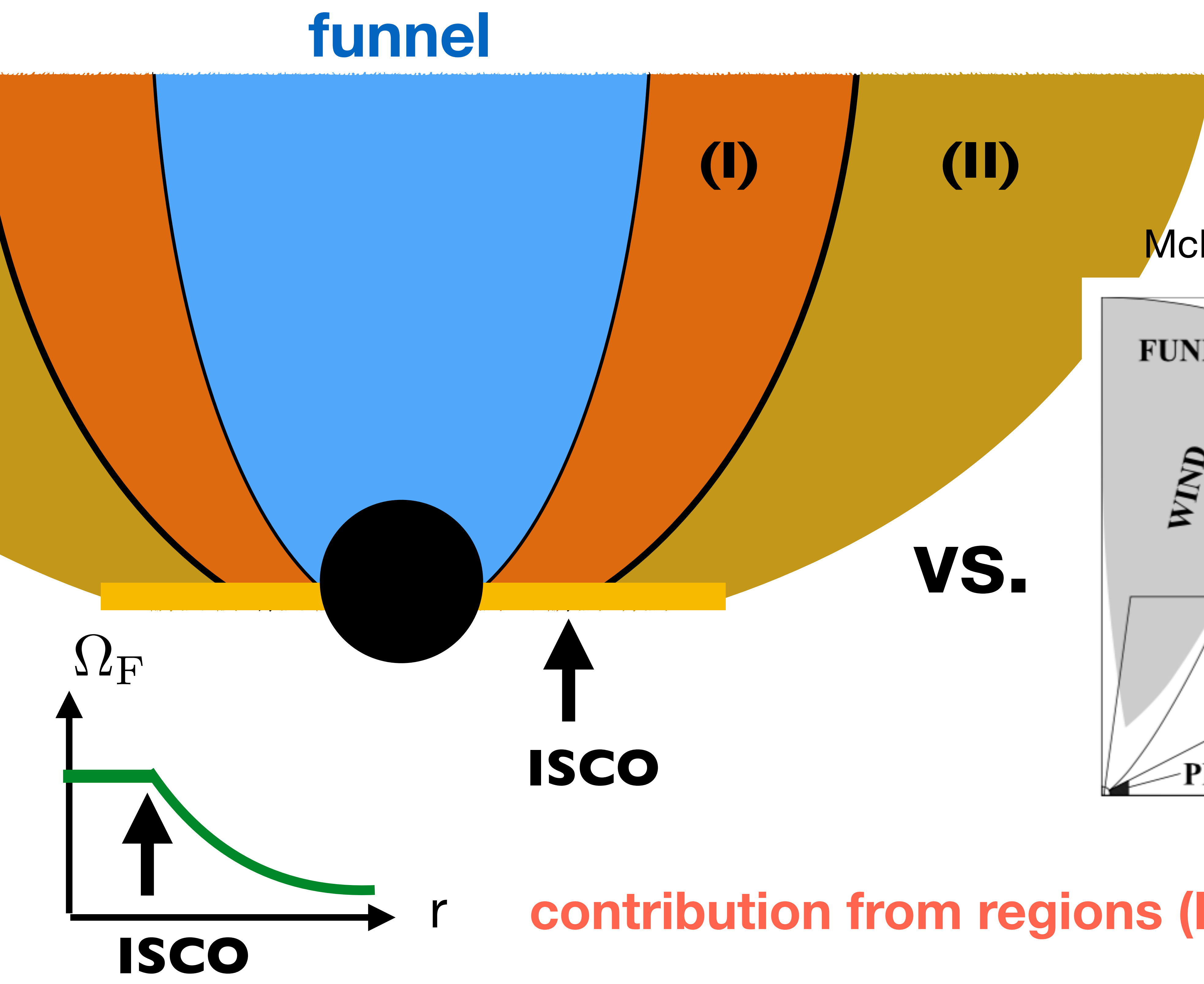
Yu, Yuan, & Ho 2016

Li, Yuan, & Xie 2016


Jet axial distance (de-projected): z (pc)
10-4
10-3
10-2
10-1
1
101
102
103
104
106
105
104
103
102
101
1
MERLIN 1.8 GHz (AN12)
EVN 1.6 GHz (AN12)
VLBA 2.3 GHz (H13)
VLBA 5 GHz (H13)
VLBA 8.4 GHz (H13)
VLBA Core 43 & 86 GHz (NA13)
VLBA Core 5, 8, 15, 24, 43, & 86 GHz (H13), HSA Core 86 GHz (H16)
EHT Core 230 GHz (D12, A15)
(Area) FFE parabolic jet (NMF07, TMN08)
(Area) FFE genuine parabolic jet (NMF07, TMN08)
a = 0.5 (upper edge) - 0.99 (lower edge)
VLBA 15 GHz (AN12, H13)
VLBA 22 GHz (H13)
VLBA 43 GHz (AN12, H13)
HSA 86 GHz (H16)
HST-1
z ∝ R1.6
z ∝ R2
Bondi radius
Jet radius: R (rg)
1
101
102
103
104
105
106
107
108
Jet axial distance (de-projected): z (rg)

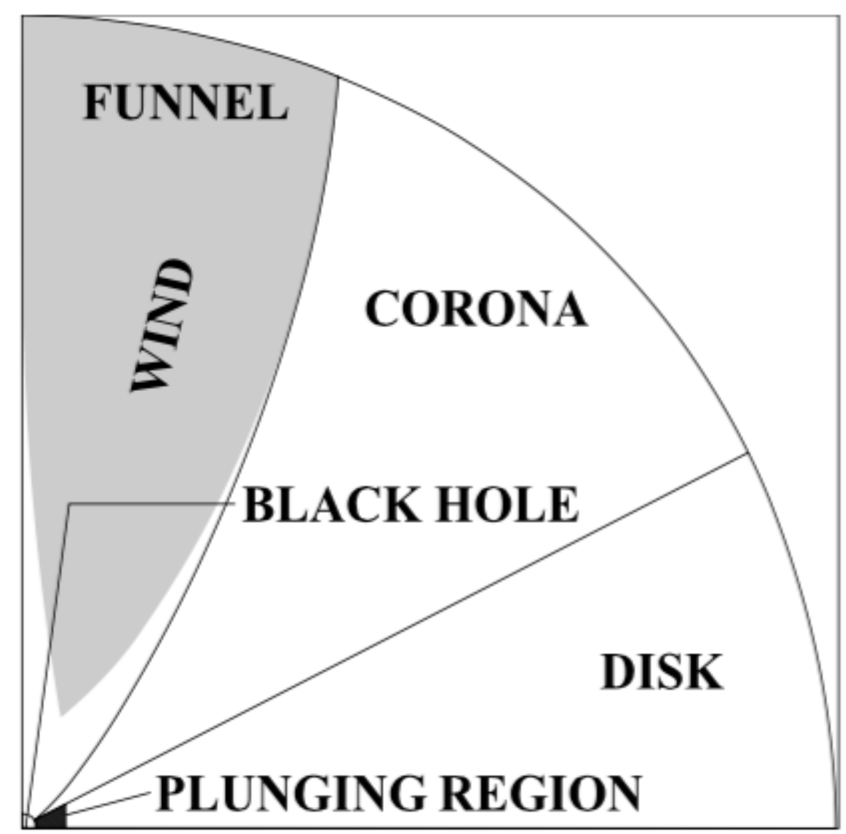
Nakamura+18

Notes on the jet region

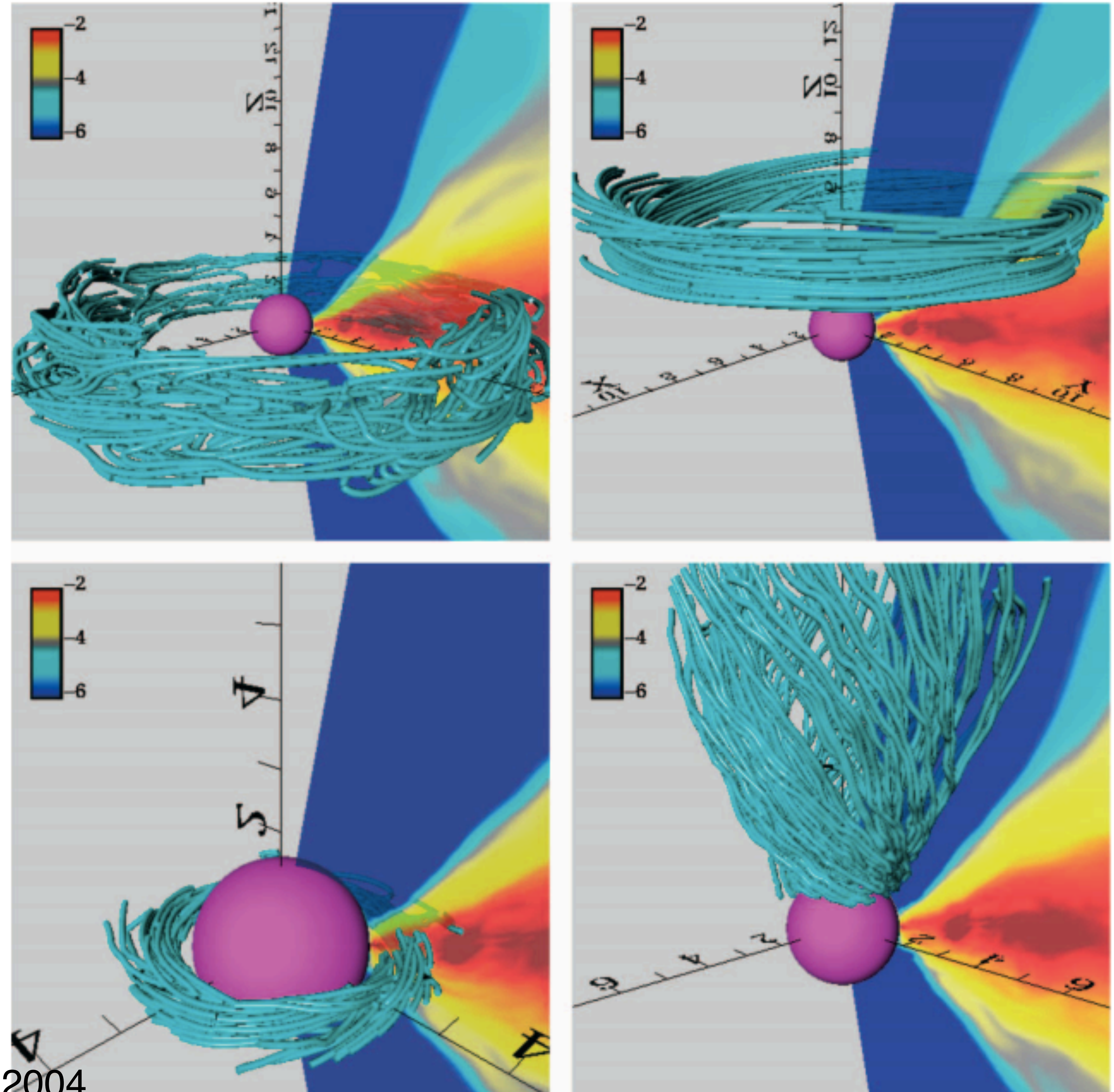


vs.

McKinney & Gammie (2004)



contribution from regions (I) (II) for LLAGN?



Hirose et al. 2004

Flow acceleration (I)

Hydrodynamics:

Flow acceleration (II)

A = Alfven
SM = slow magnetosonic
FM = fast magnetosonic

Hydrodynamics:

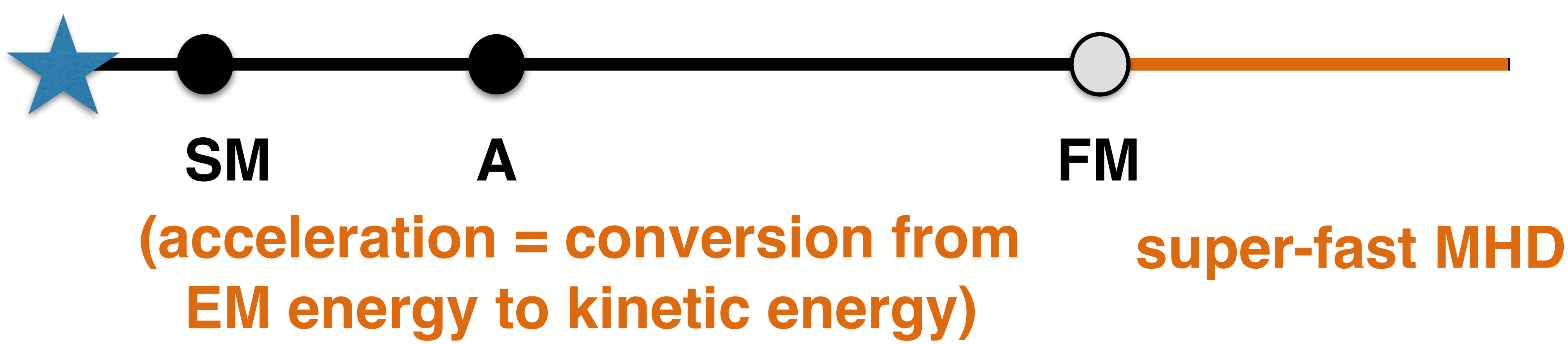
MagnetoHydrodynamics (MHD)

Flow acceleration (II)

A = Alfven
SM = slow magnetosonic
FM = fast magnetosonic

Hydrodynamics:

MagnetoHydrodynamics (MHD)



Flow acceleration (III)

A = Alfven
SM = slow magnetosonic
FM = fast magnetosonic

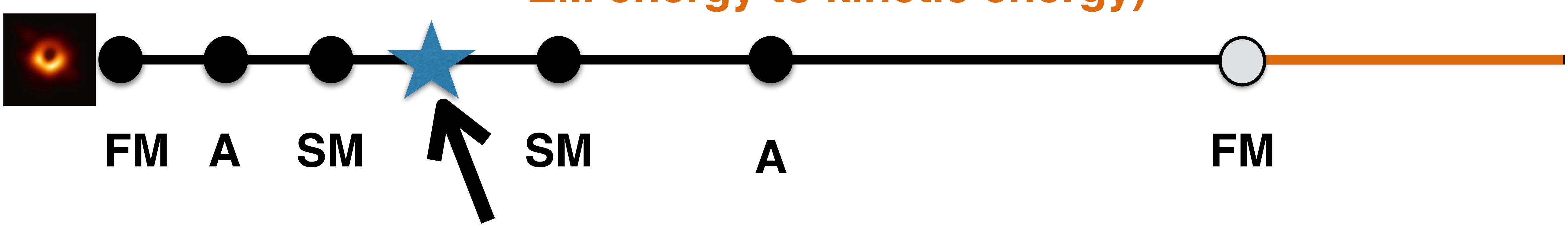
Hydrodynamics:

MagnetoHydrodynamics (MHD)

(acceleration = conversion from EM energy to kinetic energy)

super-fast MHD

GRMHD

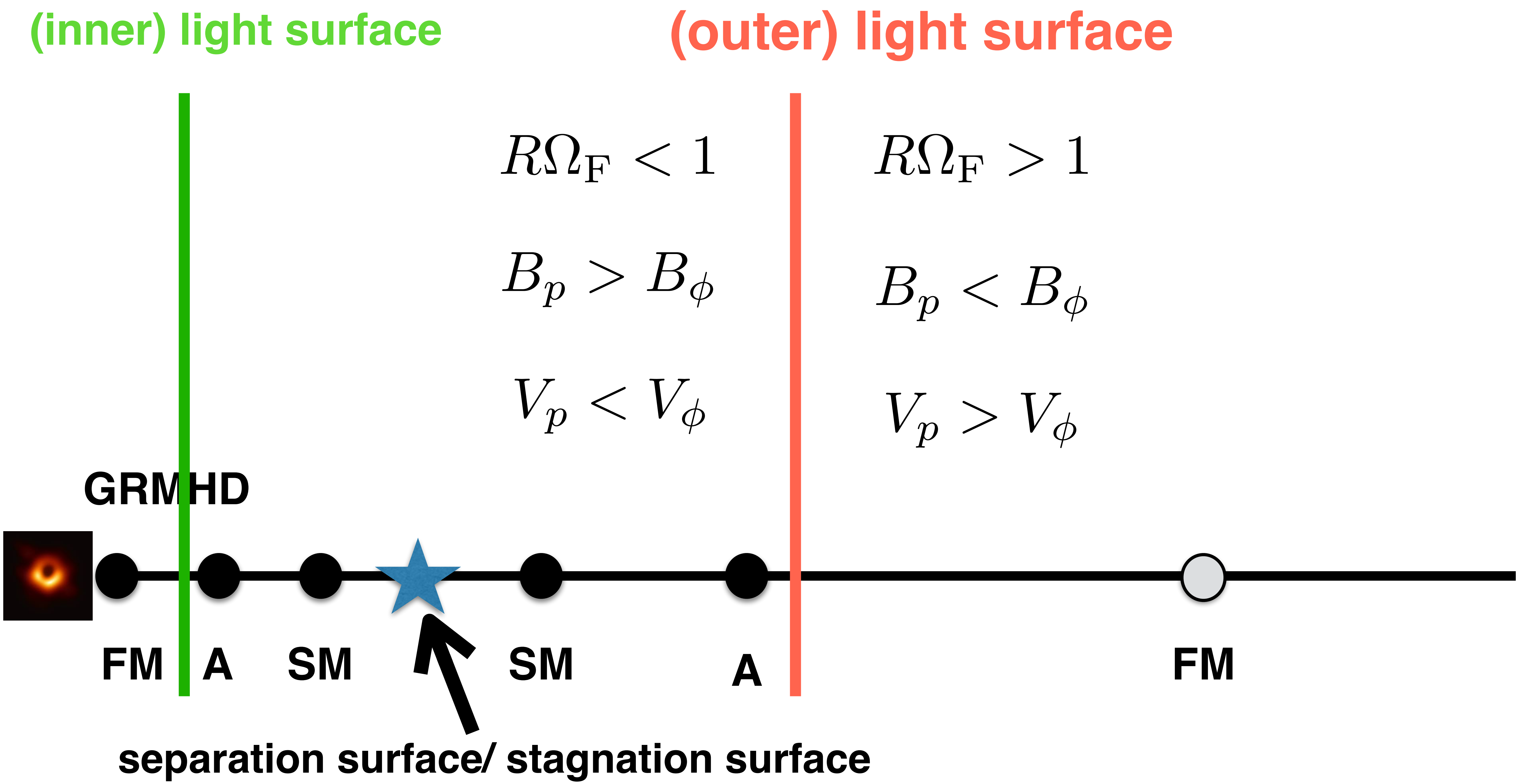


separation surface/ stagnation surface

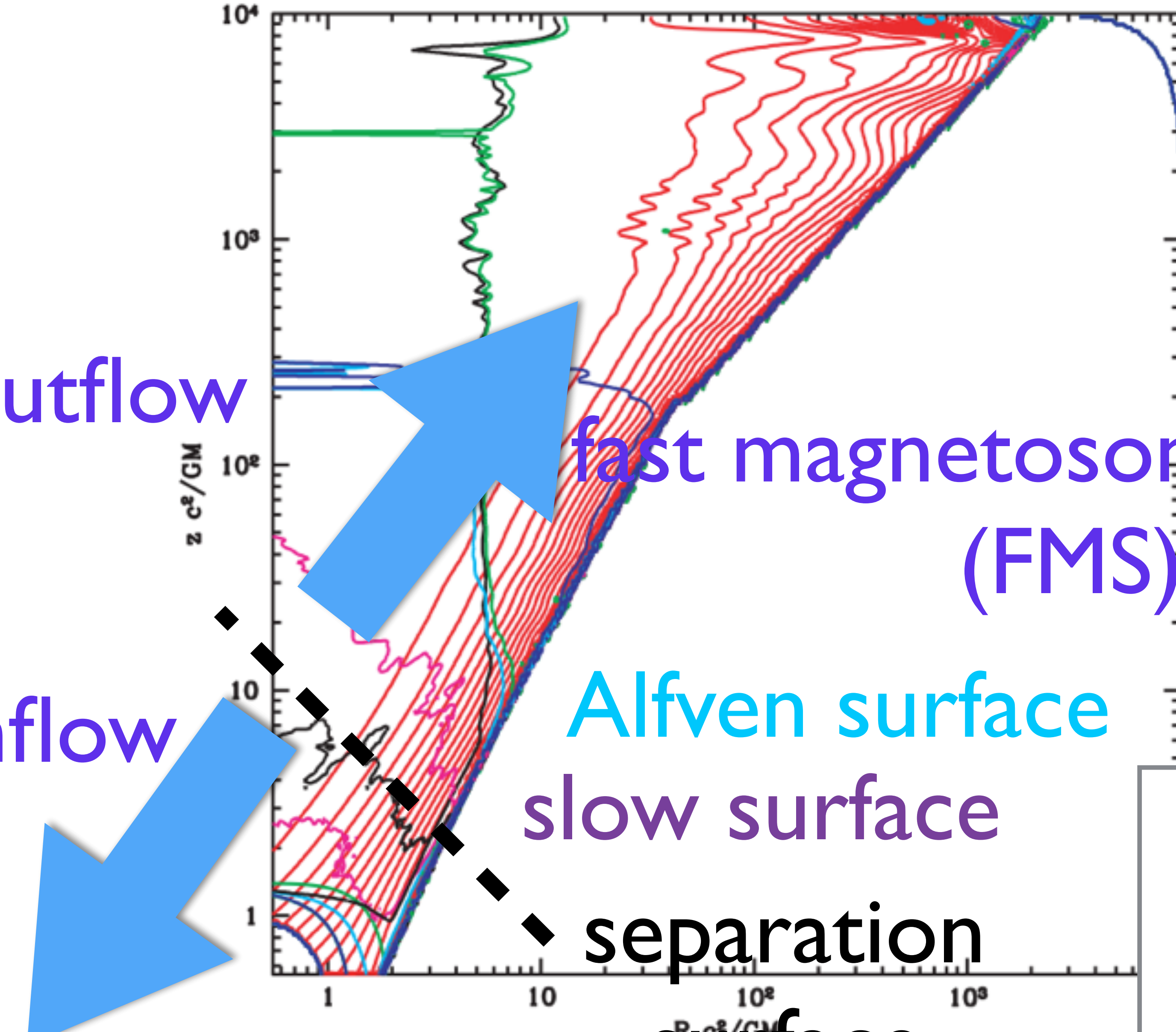
Flow acceleration (III)

A = Alfven
SM = slow magnetosonic
FM = fast magnetosonic

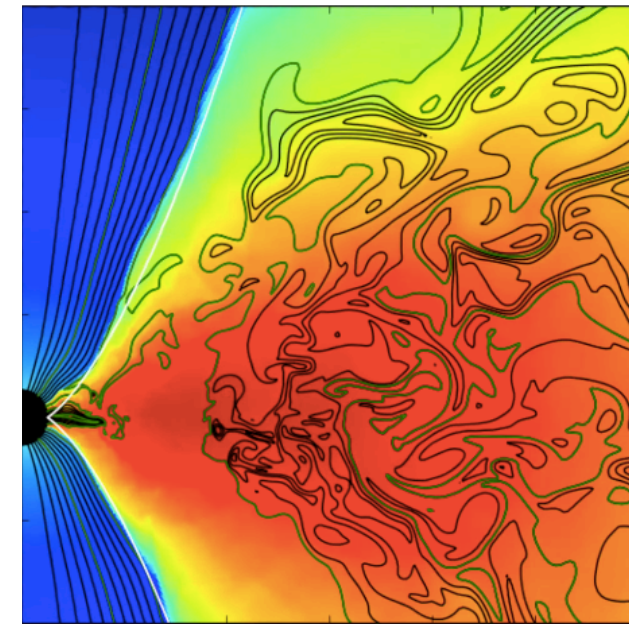
$$R\Omega_{\mathrm{F}} \approx 1$$



form MHD jet to GRMHD jet



time-averaged GRMHD simulation result
McKinney 2006



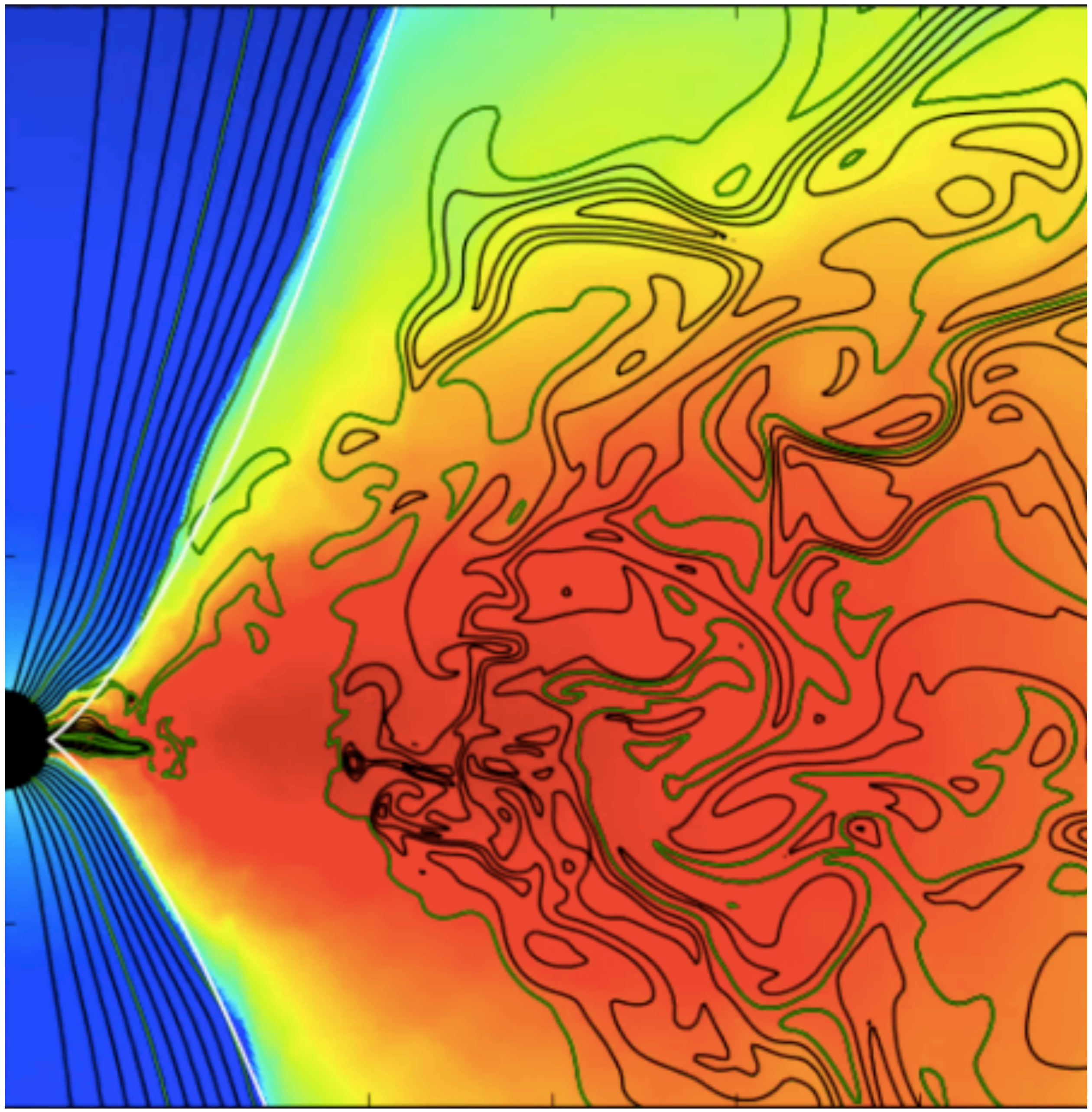
$$T^{\mu\nu}_{;\nu} = 0$$

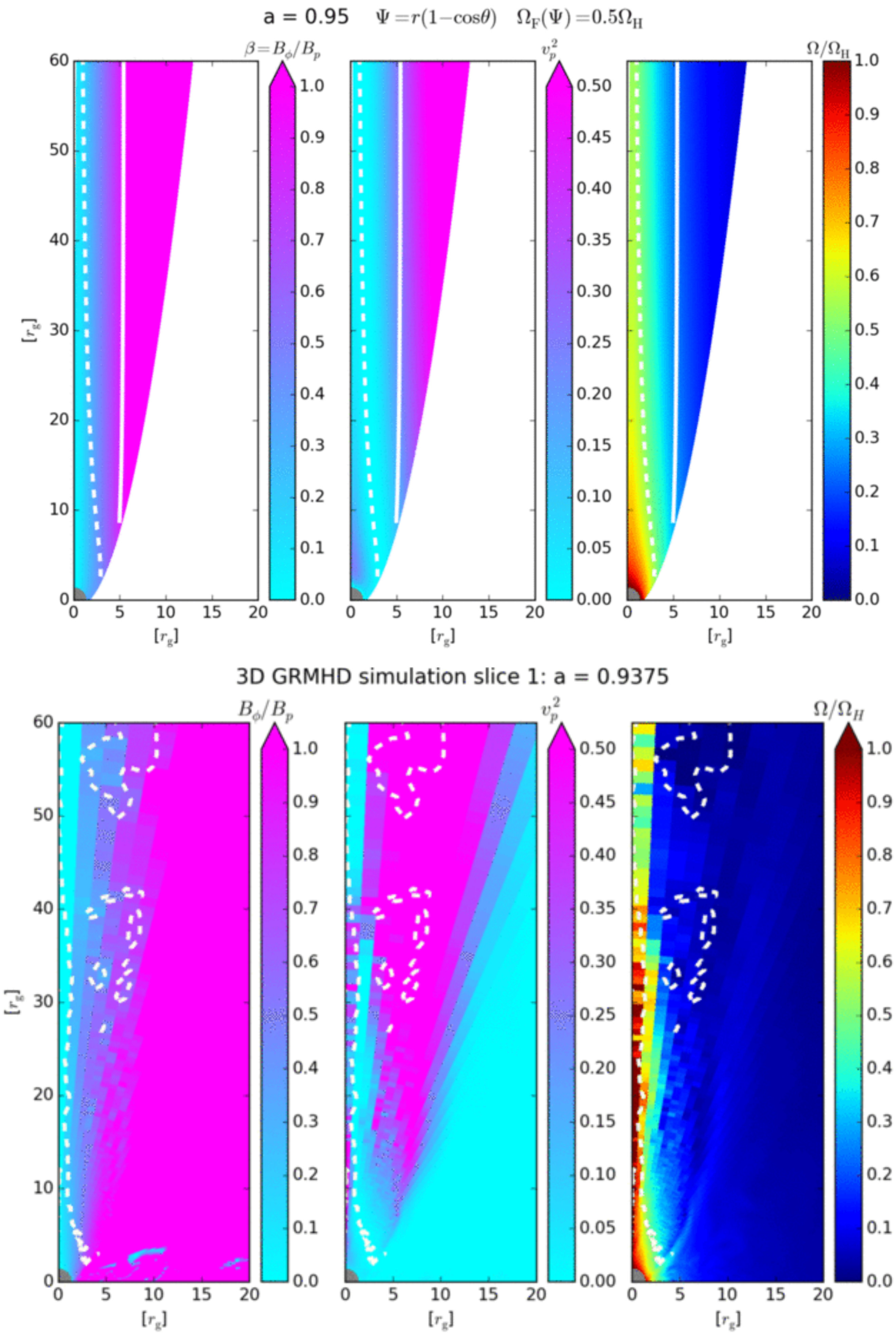
$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{EM}} + T^{\mu\nu}_{\mathrm{Plasma}}$$

trans-field:
Grad-Shafrnov (GS) eqn.

parallel-field:
wind (Bernoulli) eqn.

Q: Is it possible to quickly approximate GRMHD flow structure in the funnel region?





semi-analytical model

Yes!

phi-slides of 3D GRMHD simulation (one snapshot)

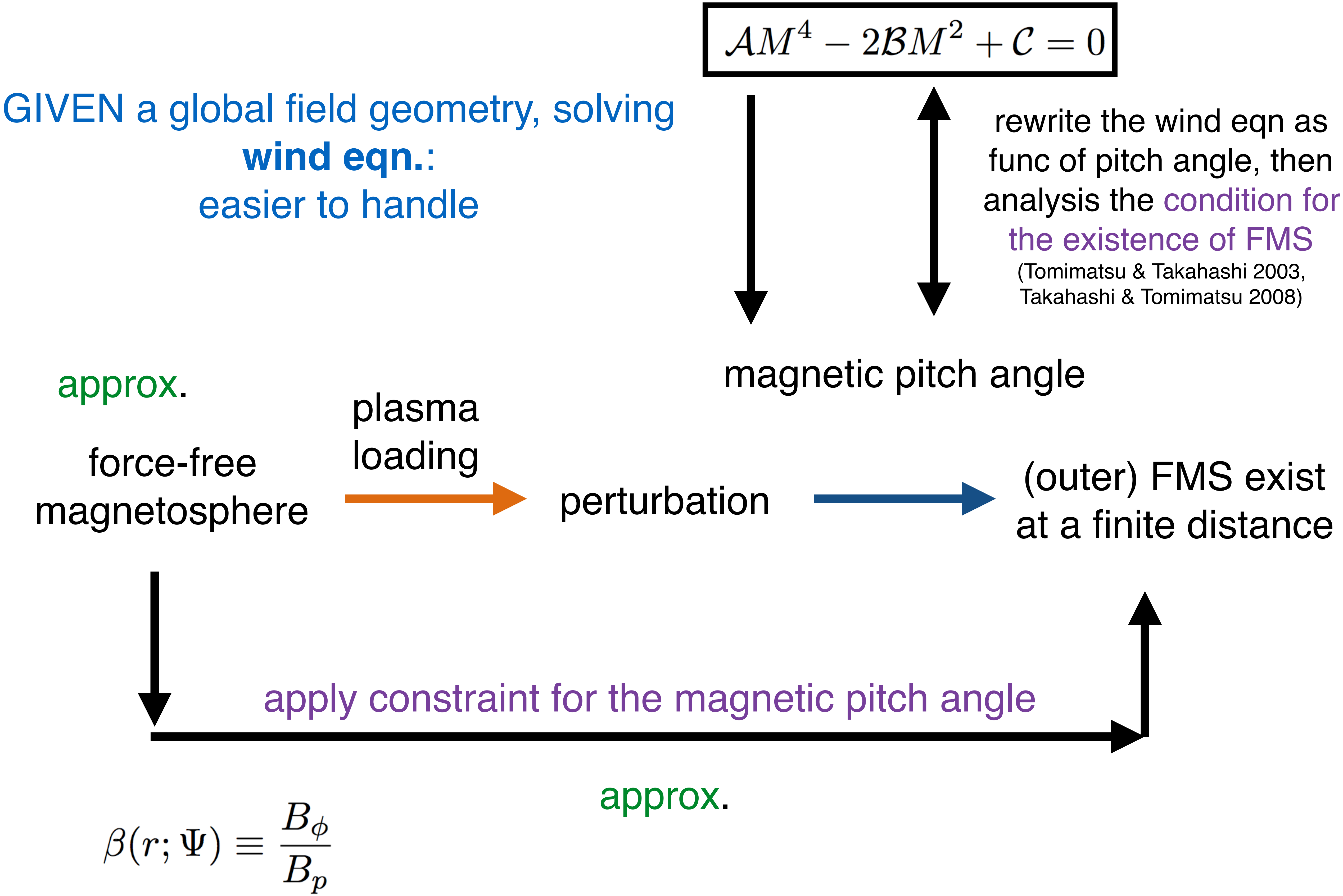
Known MHD features

- fast-magnetosonic (FMS) point exist only when the magnetic flux decreases with distance (Takahashi & Shibata 1998, Tchekhovskoy et al. 2009)
- mass loading + force-free field = FMS surface exist and efficient MHD flow acceleration take place (Beskin et al. 1998, Beskin & Nokhrina 2006)
- collimation ⟷ acceleration ⟷ FMS

solving
Grad-Shafrnov (GS) eqn.:
tough or time-consuming

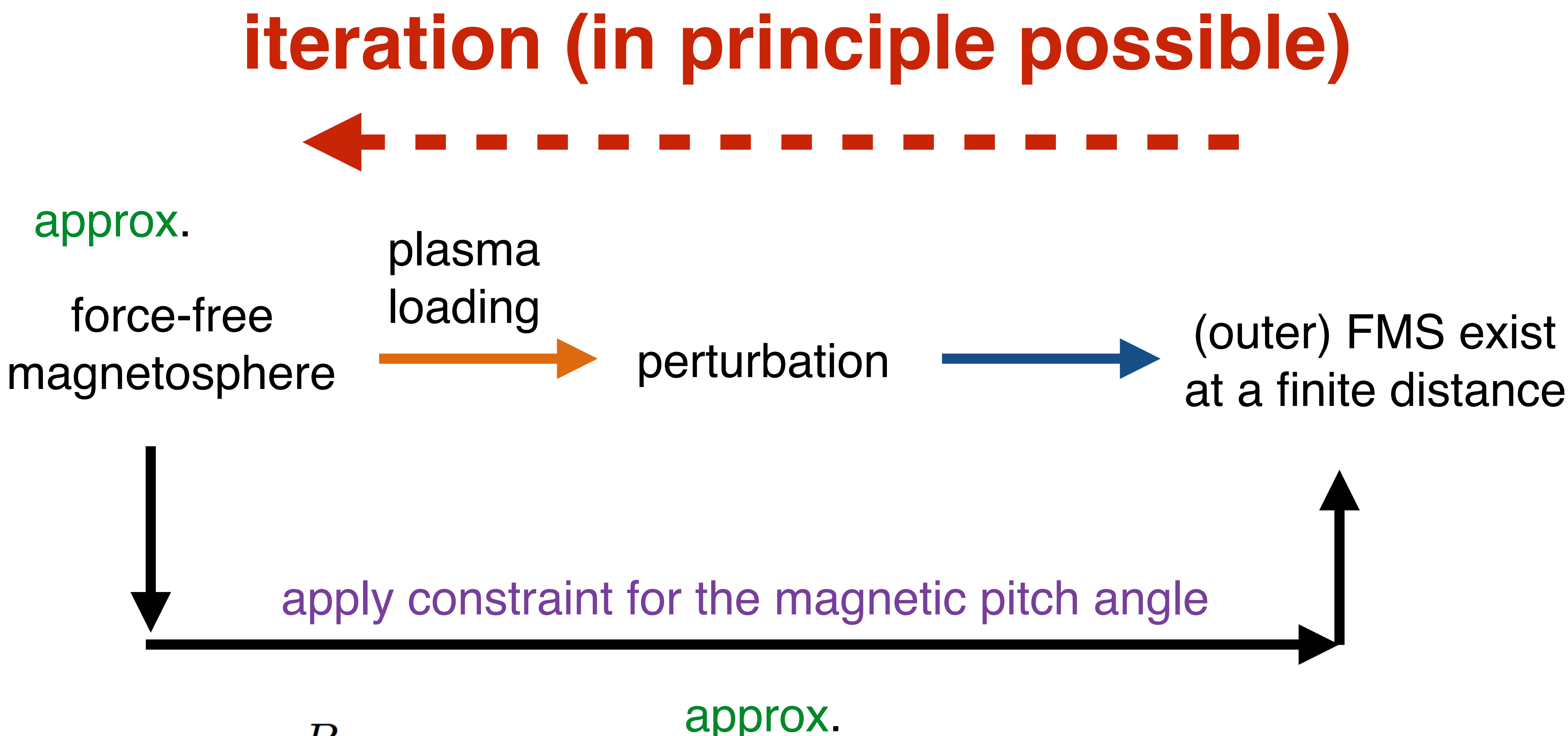
GIVEN a global field geometry, solving
wind eqn.:
easier to handle

force-free magnetosphere → (plasma loading) → perturbation → (outer) FMS exist at a finite distance



$\mathcal{A}M^4 - 2\mathcal{B}M^2 + \mathcal{C} = 0$
GIVEN a global field geometry, solving **wind eqn.**: easier to handle
rewrite the wind eqn as func of pitch angle, then analysis the condition for the existence of FMS
(Tomimatsu & Takahashi 2003, Takahashi & Tomimatsu 2008)
magnetic pitch angle
approx.
force-free magnetosphere
plasma loading
perturbation
(outer) FMS exist at a finite distance
apply constraint for the magnetic pitch angle
approx.
$\beta(r;\Psi) \equiv \frac{B_\phi}{B_p}$

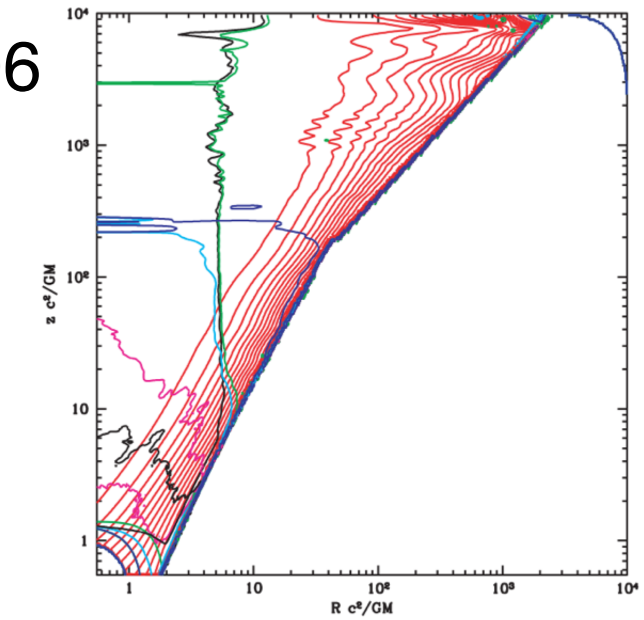
Pu & Takahashi 20:
even without iteration, the approximation is good enough



$$\beta(r;\Psi) \equiv \frac{B_\phi}{B_p}$$

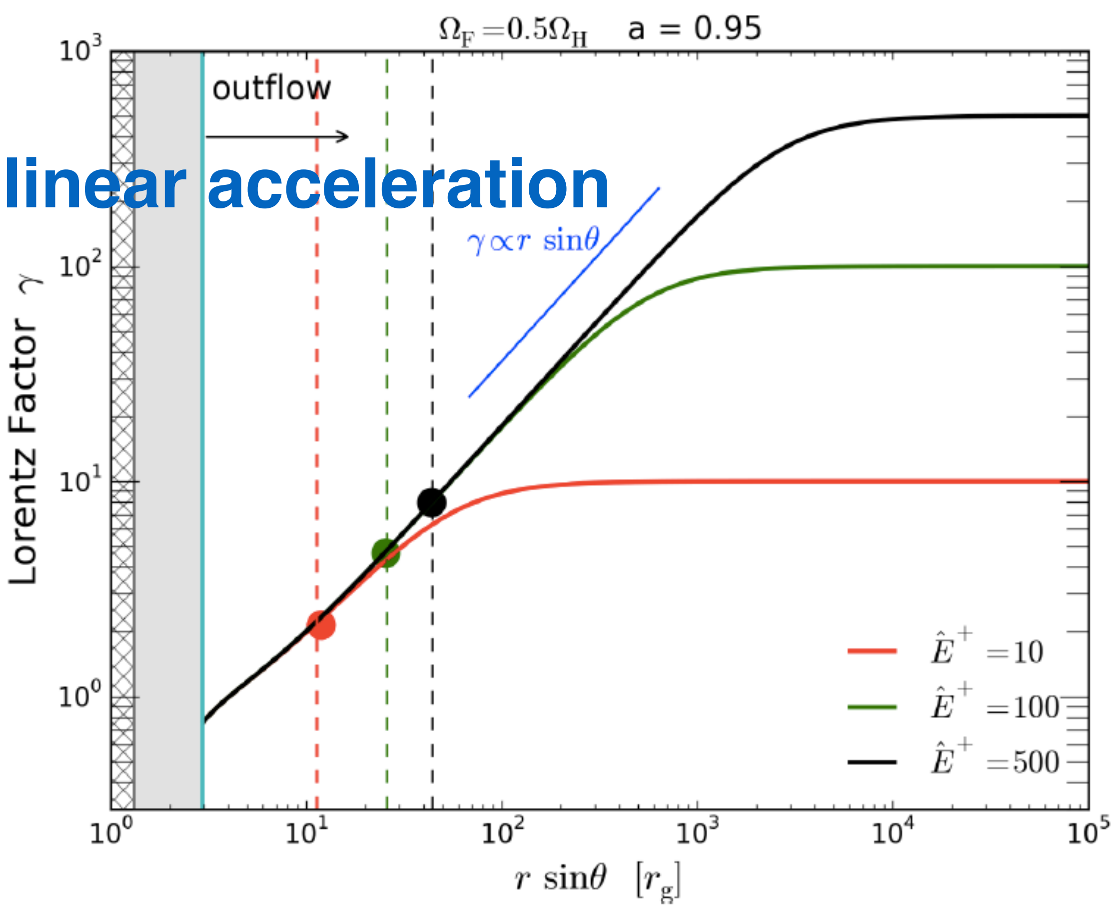
McKinney 06

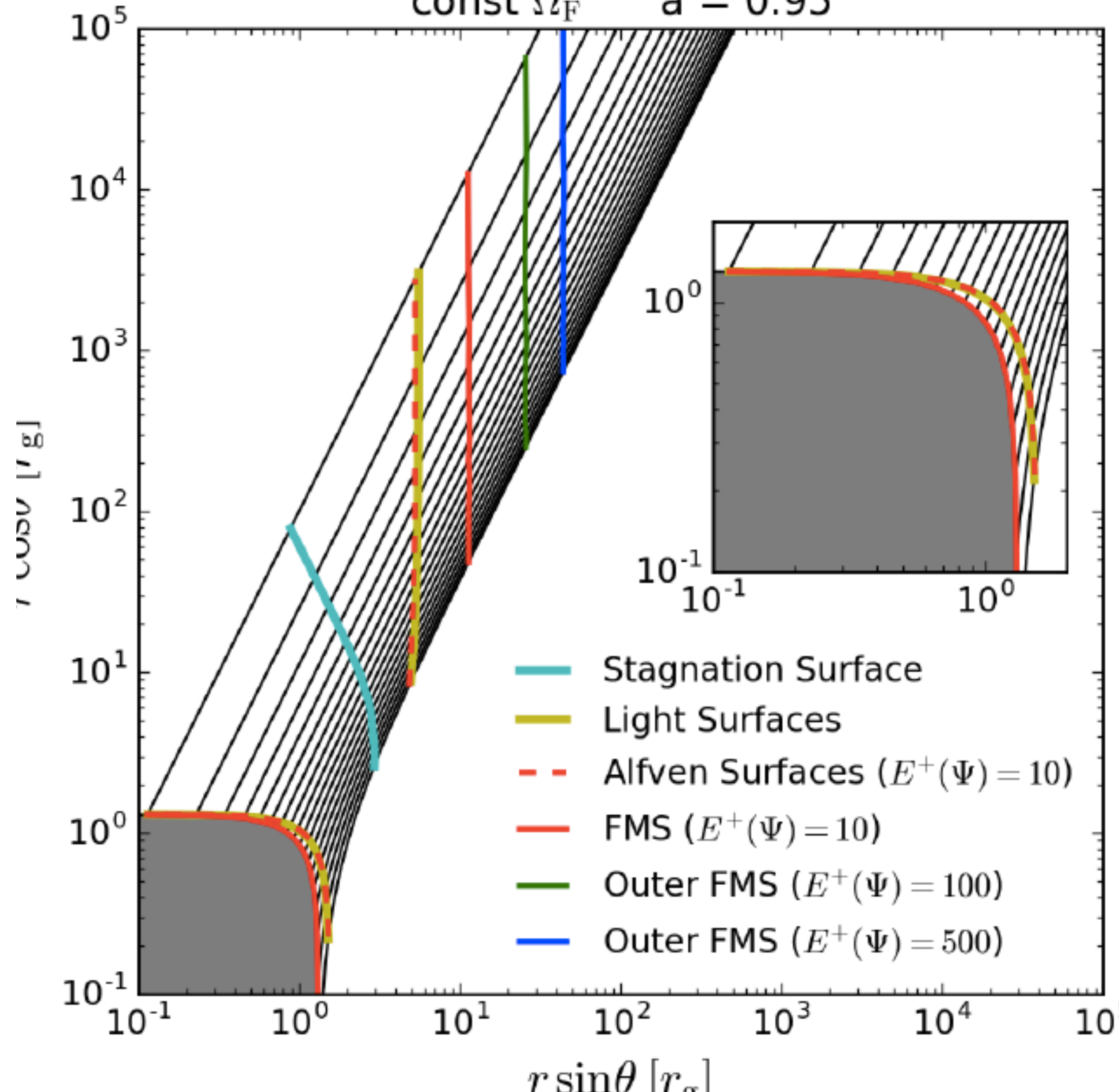
model includes:
extract BH energy by the inflow—> outward Poynting flux is smoothly propagate to outflow region—> jet acceleration



varying jet energy

linear acceleration



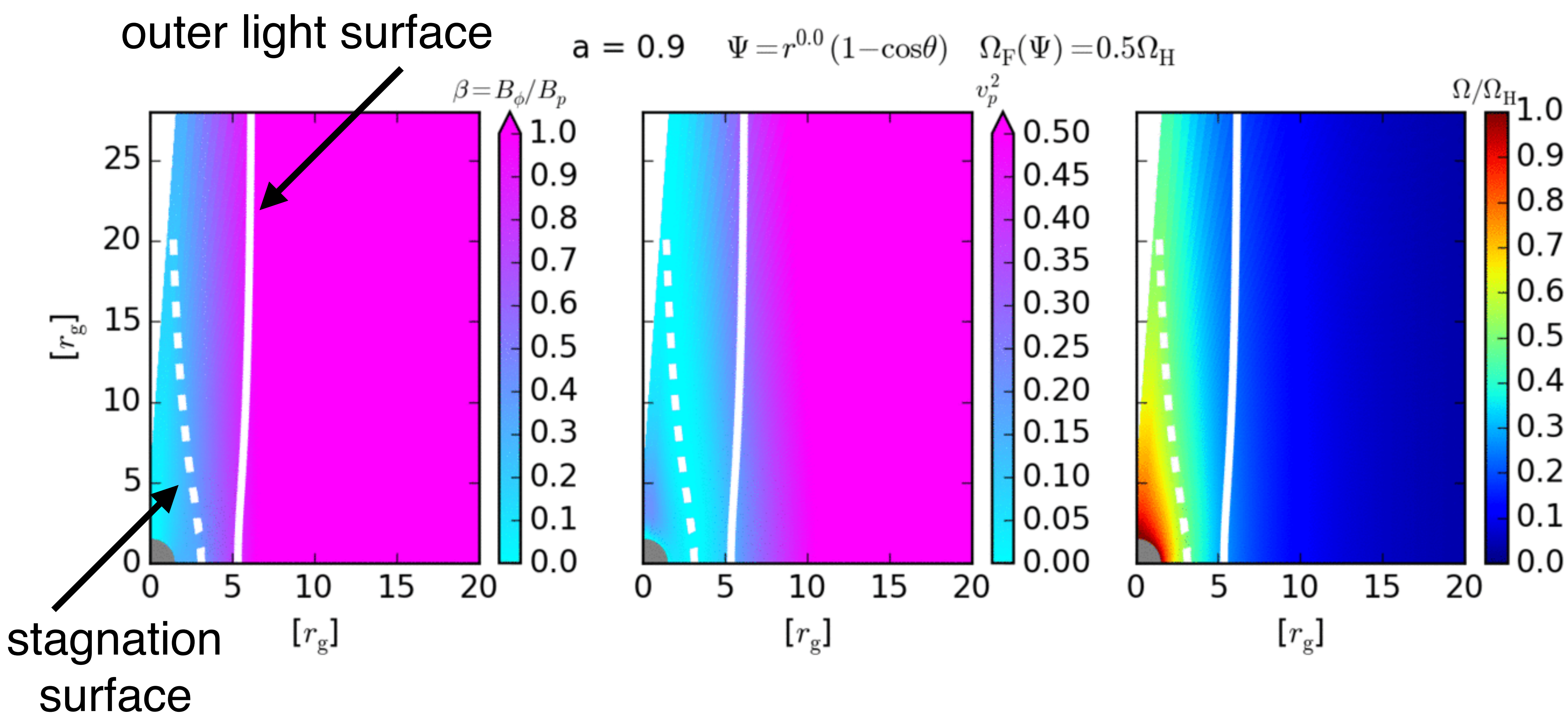


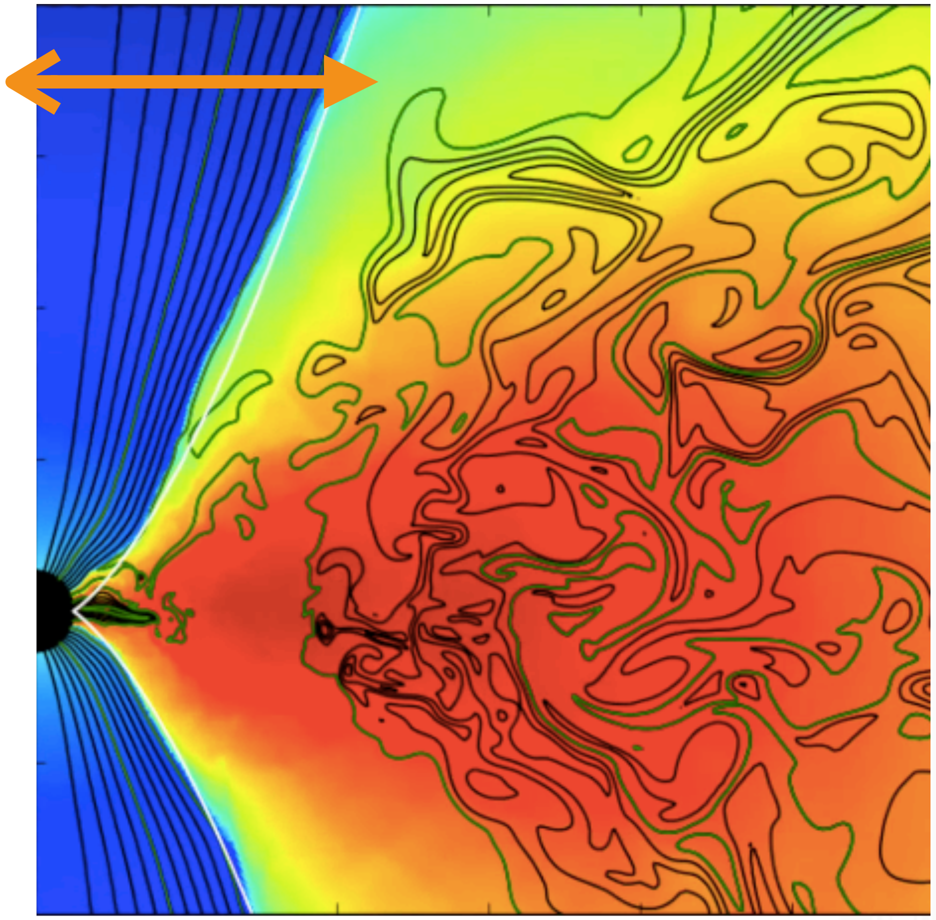
Pu & Takahashi 20
(see also Pu+ 13, 15)

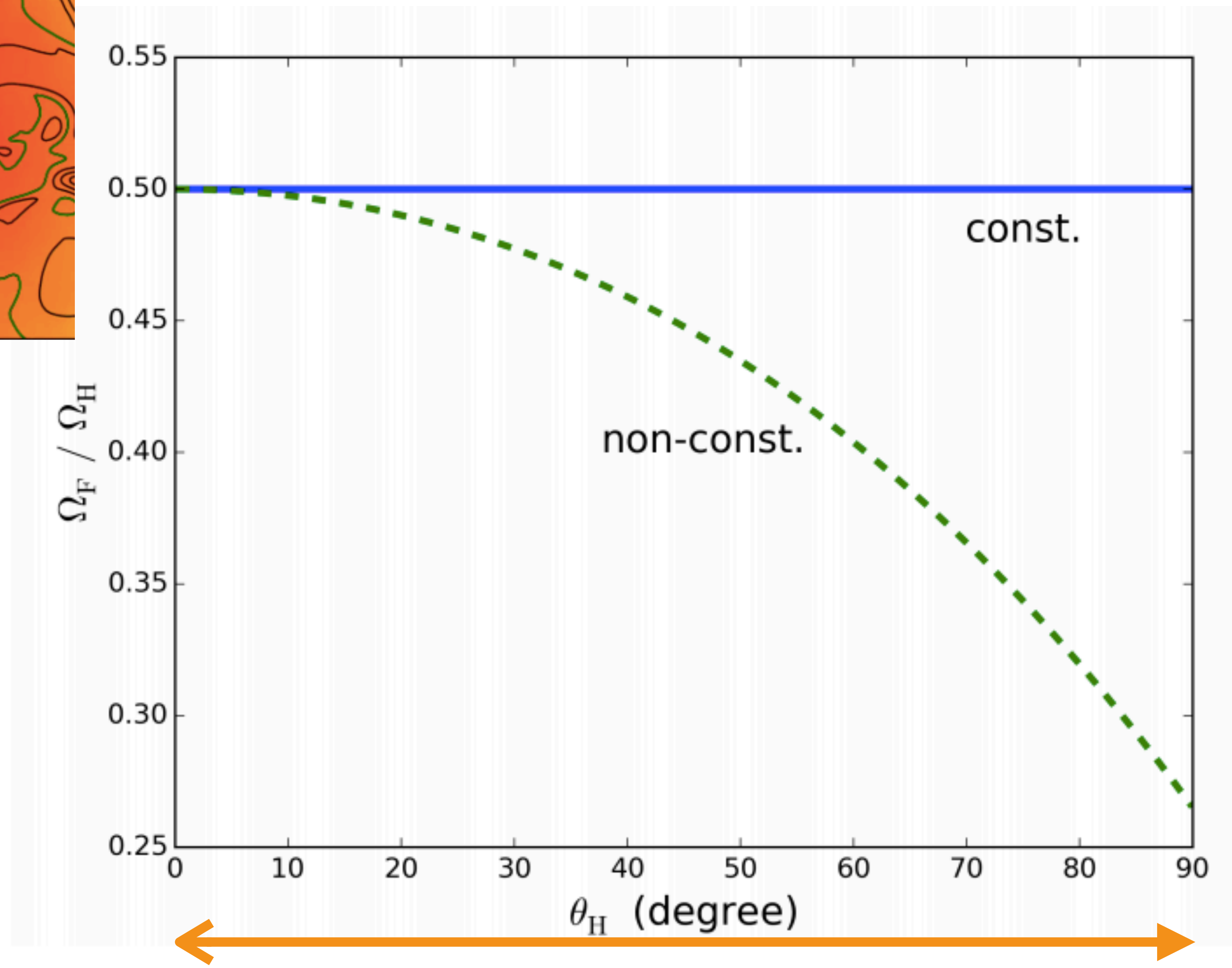
a good approximation of the force-free field (Tchekhovskoy et al. 2008)

$$\Psi(r, \theta; p) = r^p (1 - \cos\theta)$$

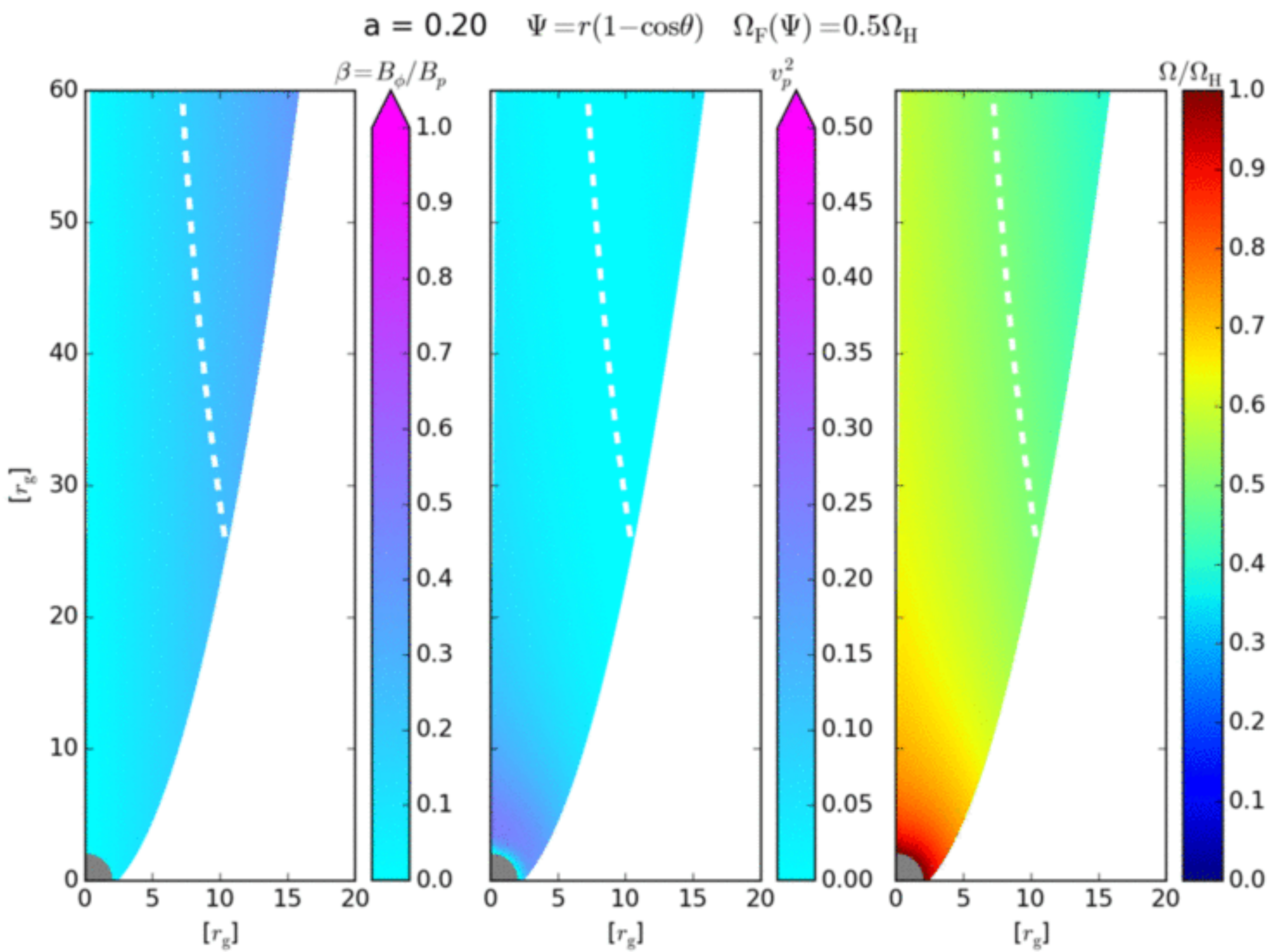
varying field line configuration



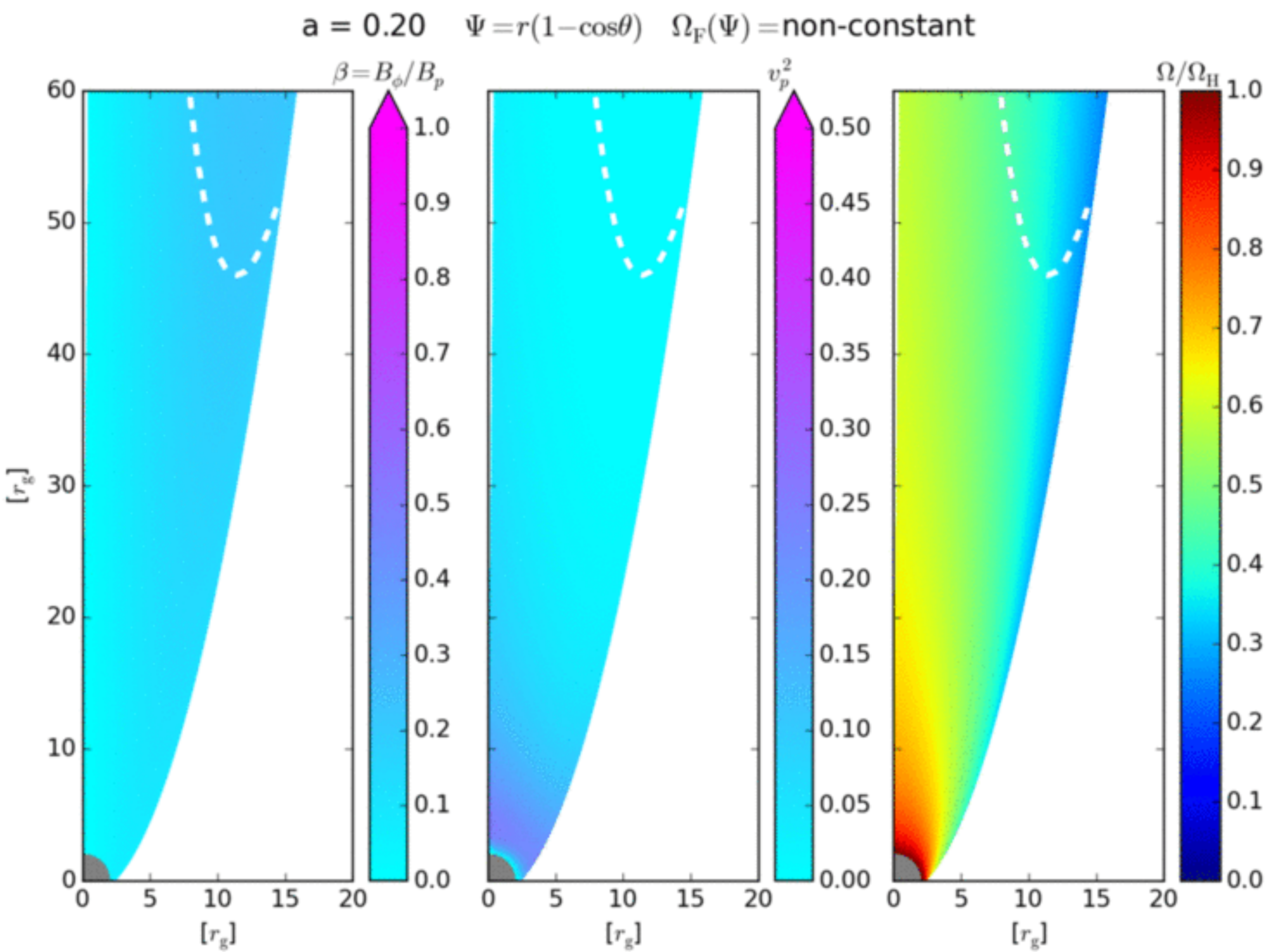



0.55
0.50
0.45
0.40
0.35
0.30
0.25
0
10
20
30
40
50
60
70
80
90
Ω_F / Ω_H
θ_H (degree)
const.
non-const.

varying BH spin



varying BH spin



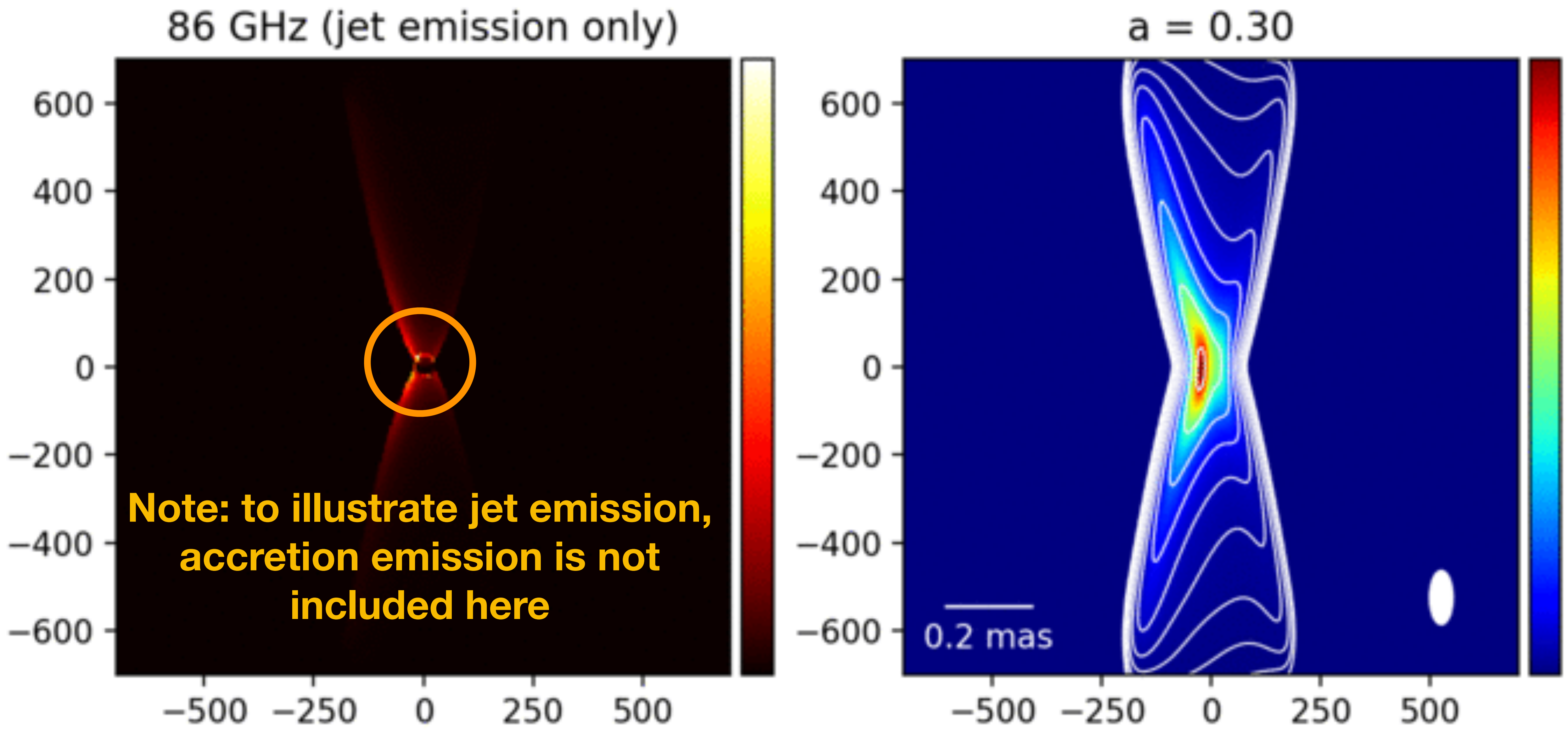
applying to VLBI observations

- **dynamics** vs. **mass-loading**; the later is treated as free parameter, as the injection of non-thermal electrons are unknown (see also **Ogihara's talk**)
- Could the stagnation surface be a possible injection site? (Pu+2018, Kawashima+2020)

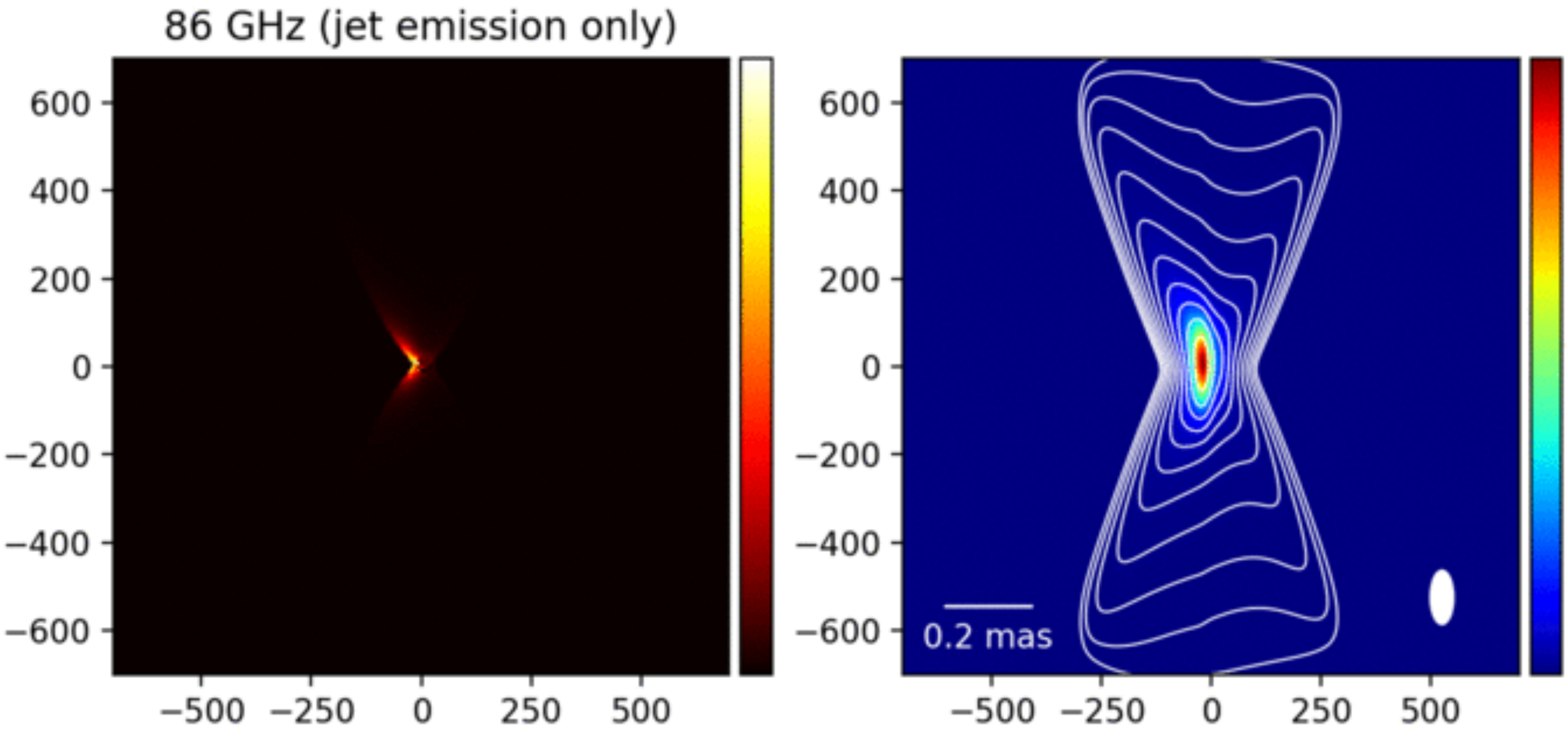
applying to VLBI observations

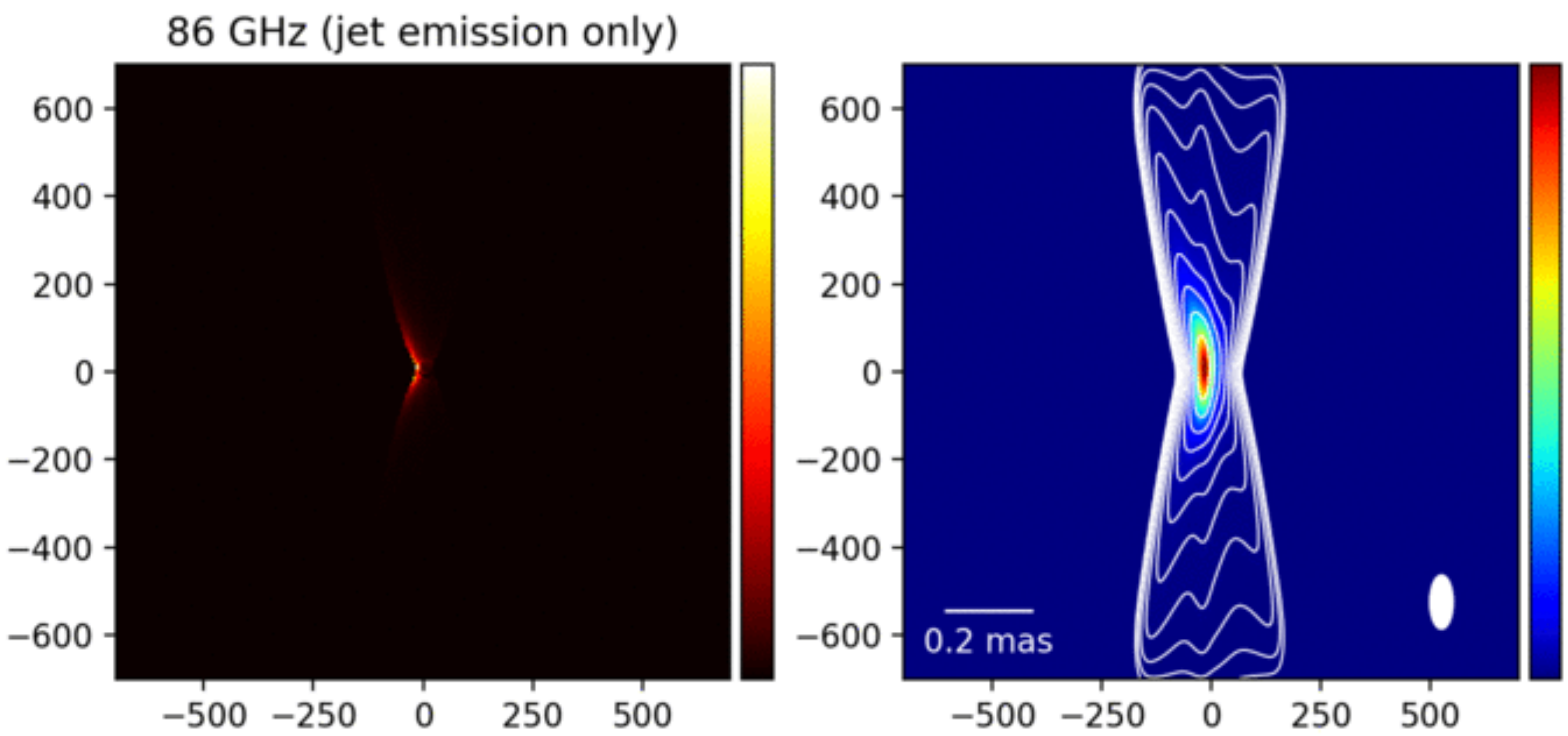
- fiducial parameters for the following movies:
  - adopt similar mass and distance as M87 for LLAGN parameters, i=60 degree, beam size: 50x120 uas (GMVA observation for M87, Kim+18)
  - non-thermal electron with a distribution follows
    1. electron number follows power-law decay with distance
    2. more mass loading near the jet edges
    3. emission contributed only from black hole threading field lines

varying black hole spin



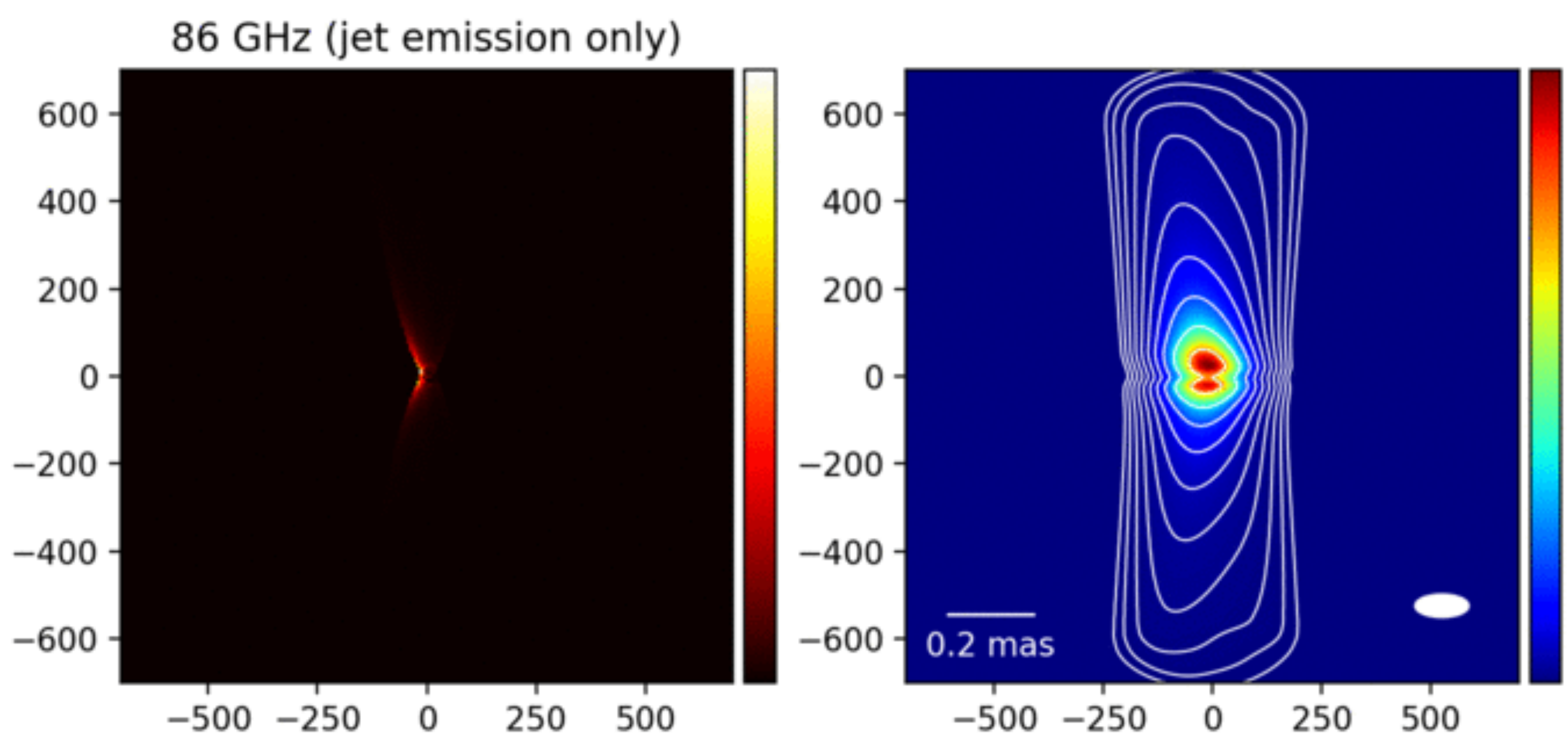
varying jet opening angle





varying mass loading

beam direction matters!



summary

- key direction in VLBI: connecting **horizon-scale to large scale** accretion/ jet physics
- **challenge**: origin of non-thermal electrons, subsequent cooling, parameter space survey, shock, entrained and other physics beyond horizon scale
- Phenomenological models (with possible implement of new physics) for BH accretion and jet are **ready for help**!

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