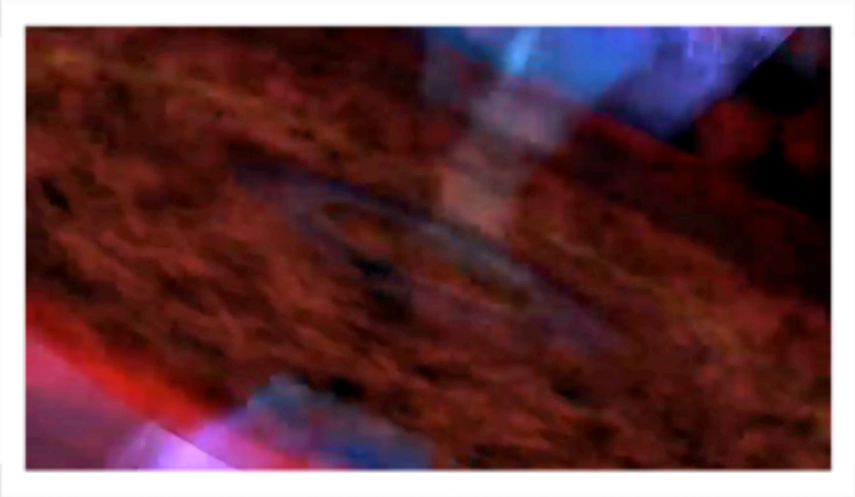
Theoretical Overview of Black Hole Accretion and Jet

a journey to the horizon scale

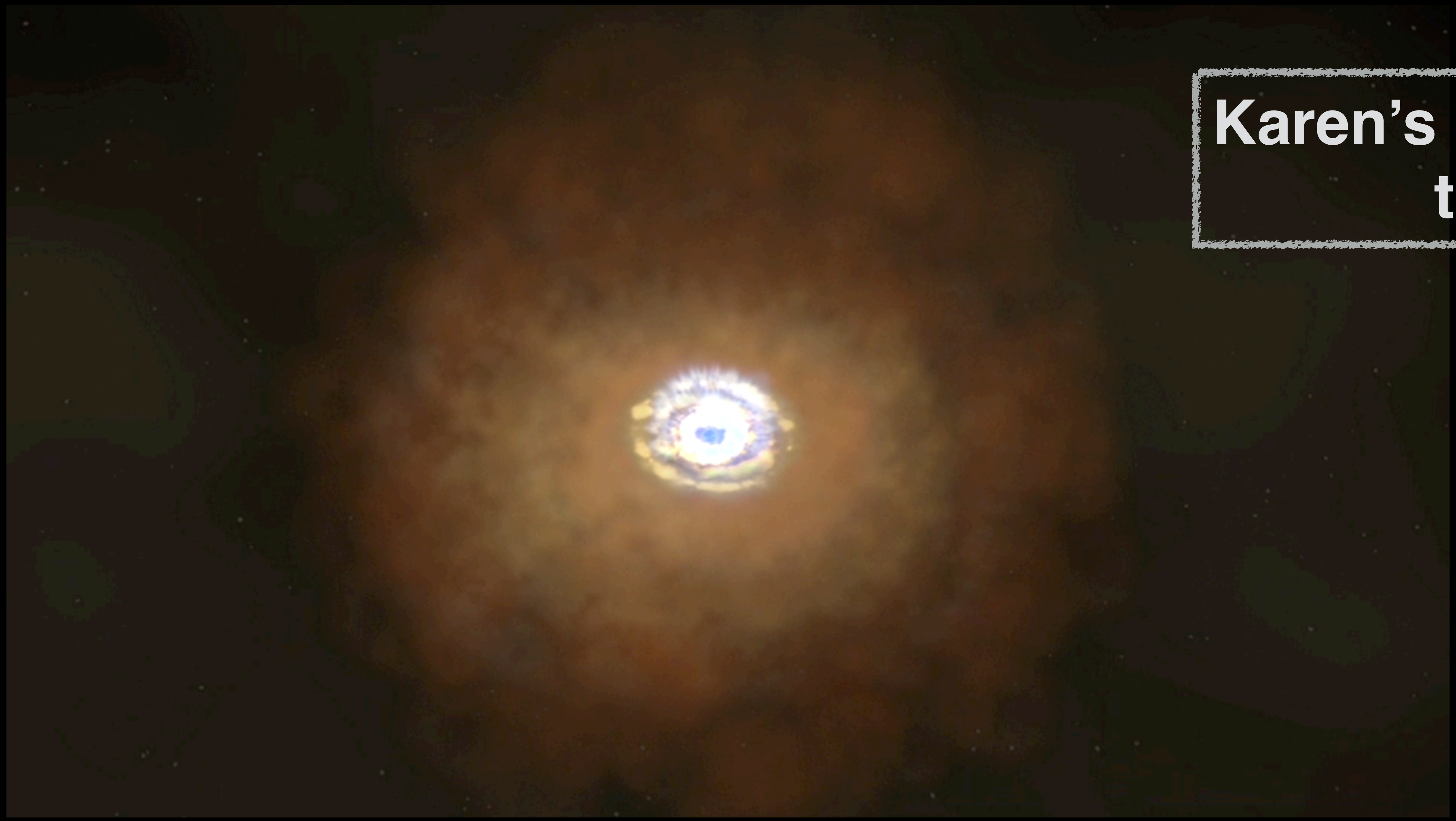


Hung-Yi Pu (卜宏毅)
Oct 22nd 2020
NCTS Workshop: Multiscale Feedback on Galaxy Evolution

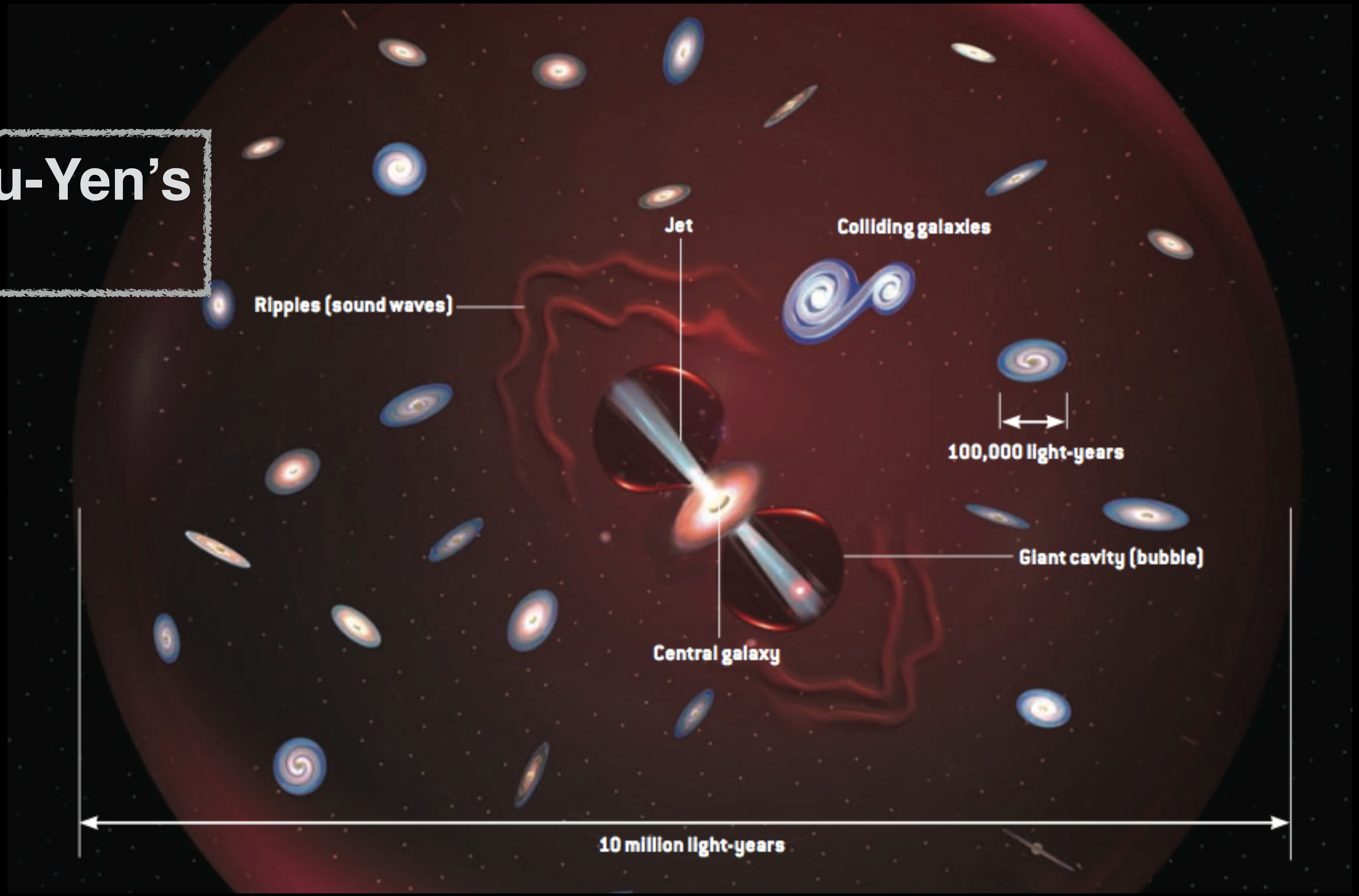
國立臺灣師範大學
NATIONAL TAIWAN NORMAL UNIVERSITY

black holes: compact, yet powerful

quasar/radiative mode



radio/kinetic mode



Karen's + Yu-Yen's talk

But…. how?

outline

- understanding the central engine: black hole (BH)
  - how gravity works in general relativity?
  - BH as spacetime structure
- BH accretion and jet physics:
  - theory
  - (selected) simulation
- final remarks

how gravity works? why spacetime?

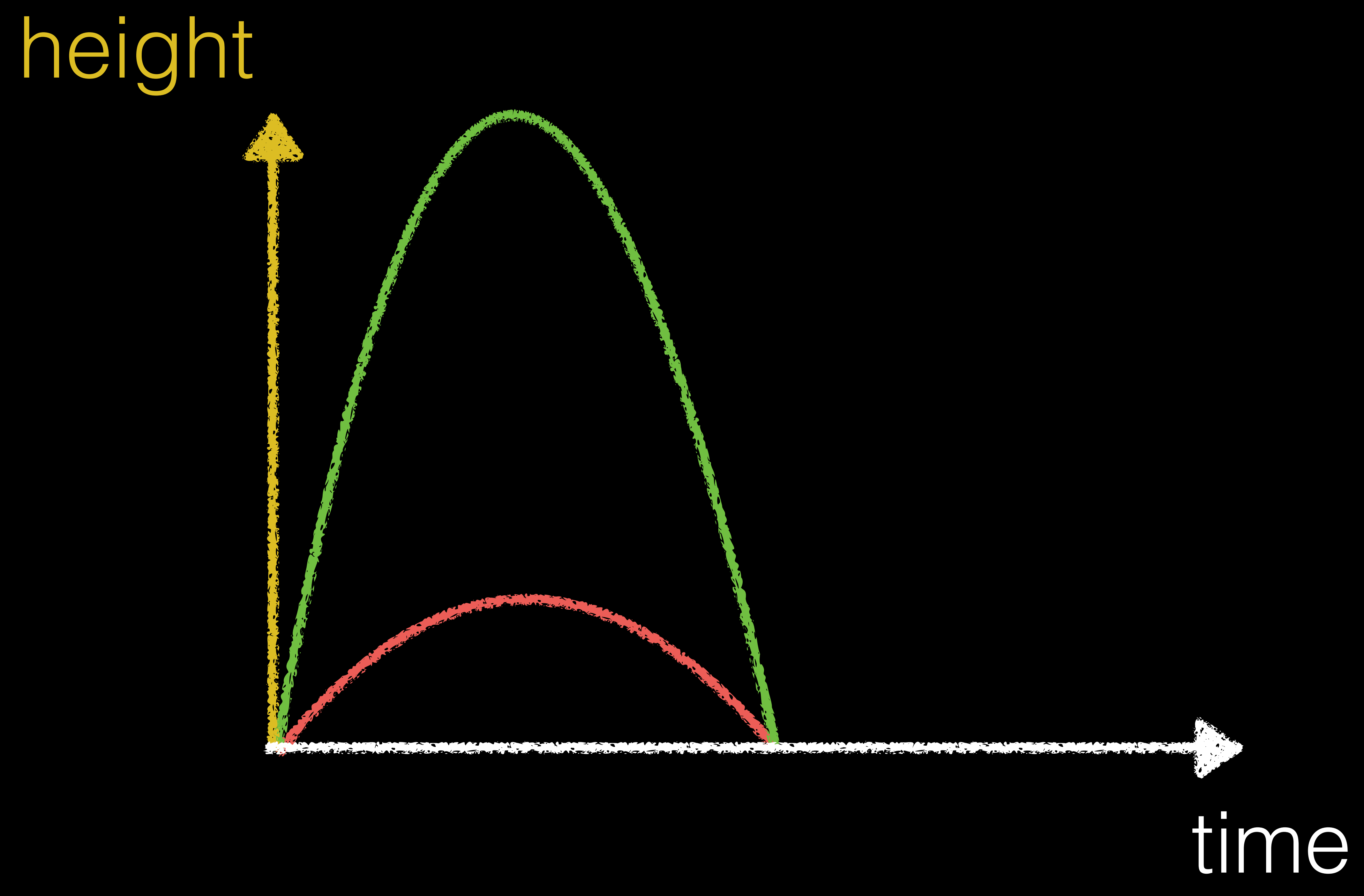
weak gravity

?

how gravity works? why spacetime?

strong gravity

weak gravity

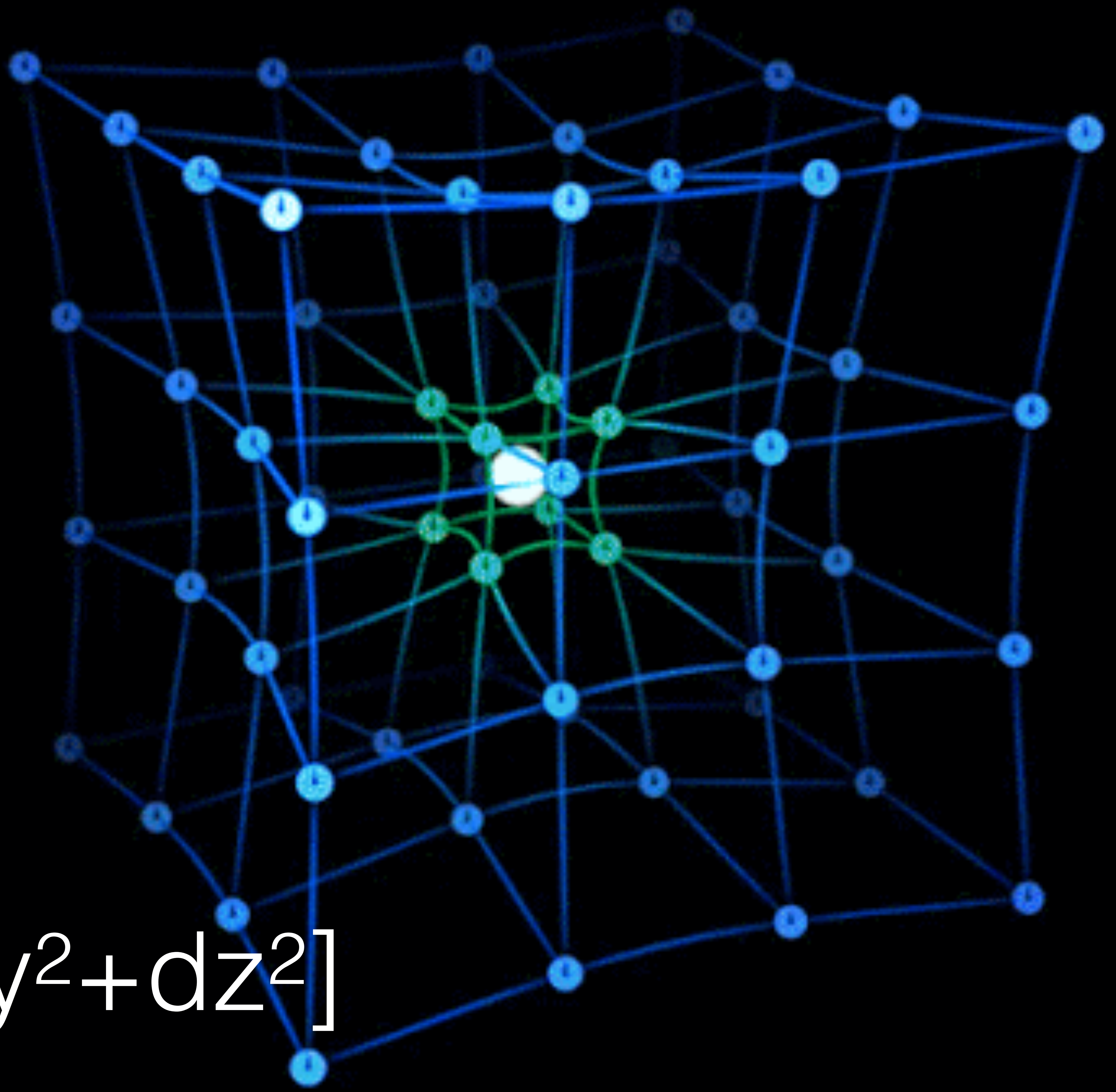



r1
r2
height
the same spacetime curvature
r1 = r2
time x
speed of light

Theory of General Relativity:

gravity
= curved **spacetime**

described as **geometry**



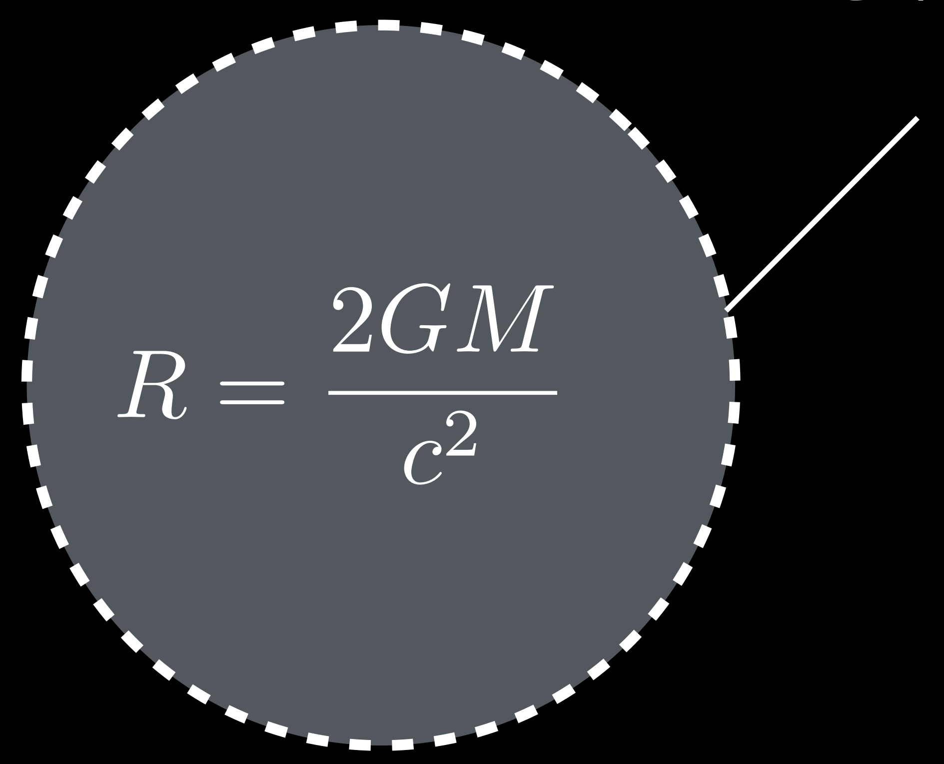
e.g. $ds^2 = -f(r)dt^2 + f'(r)[dx^2 + dy^2 + dz^2]$

(pseudo-Riemannian)

black hole: spacetime structure

Non-rotating BH:

described by Schwarzschild geometry (1916)

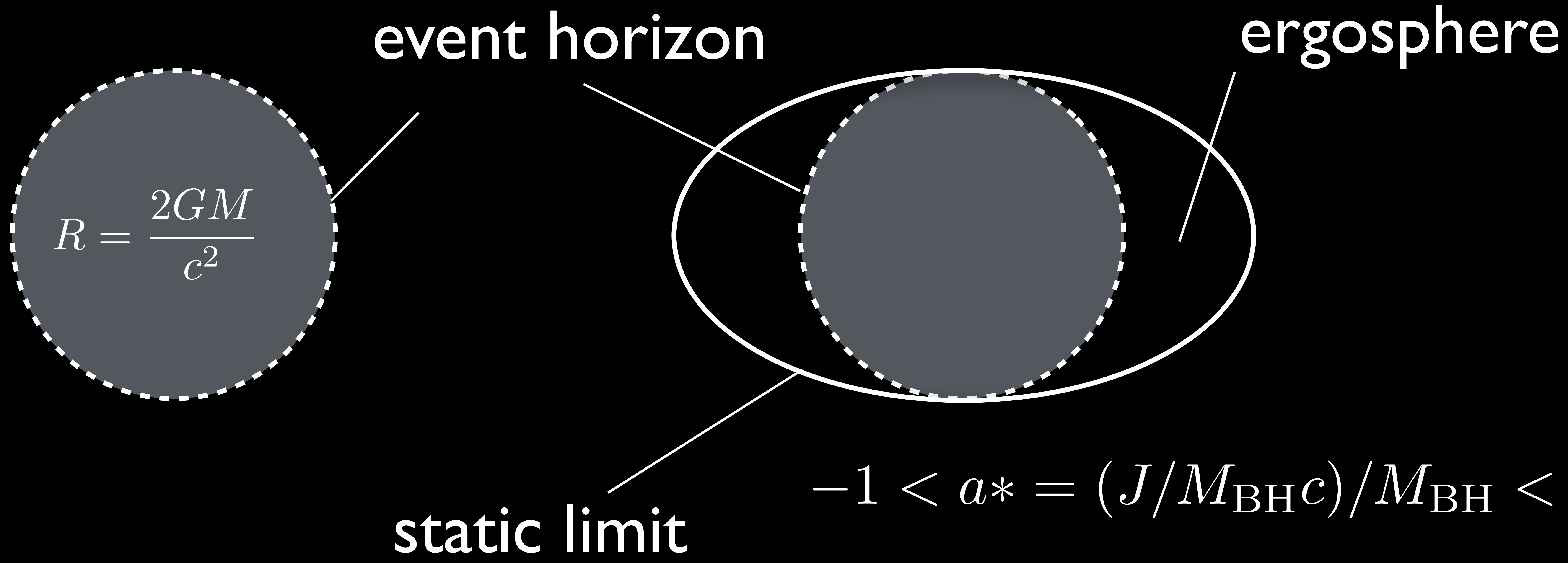


cosmic censorship: ”nature forbids naked singularity”

black hole: spacetime structure

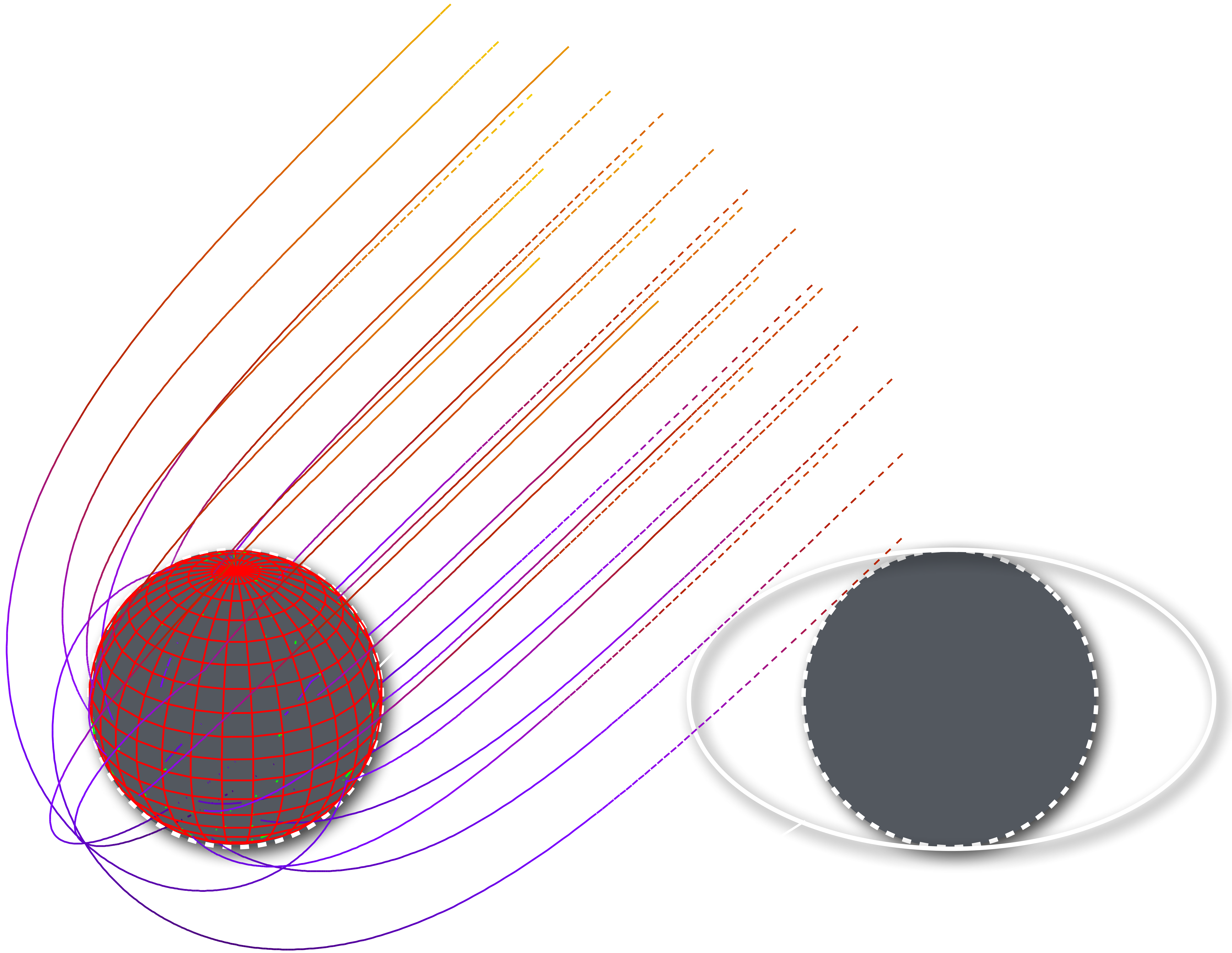
Non-rotating BH:
described by Schwarzschild geometry (1916)

Rotating BH:
described by Kerr geometry (1963)

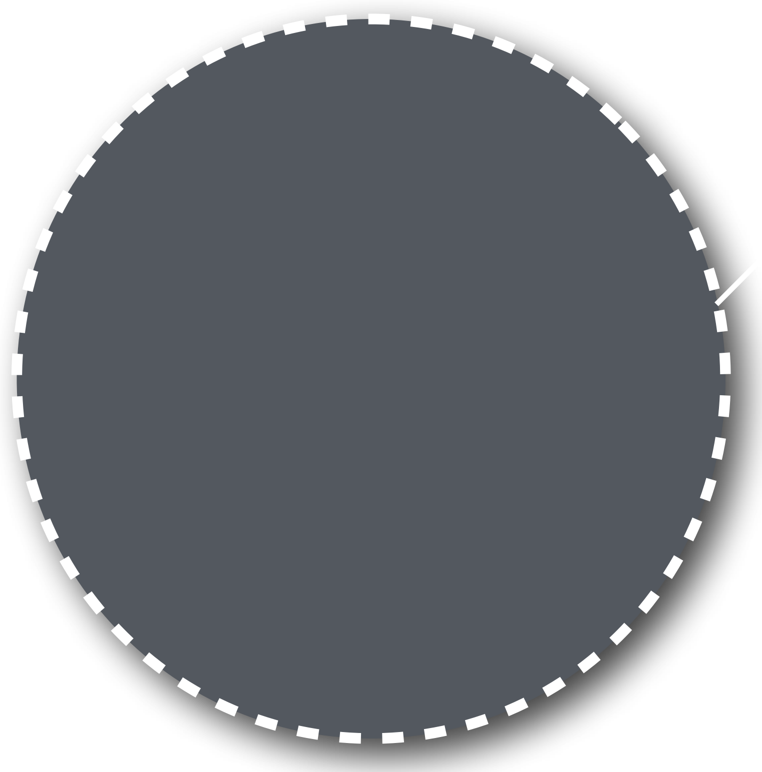
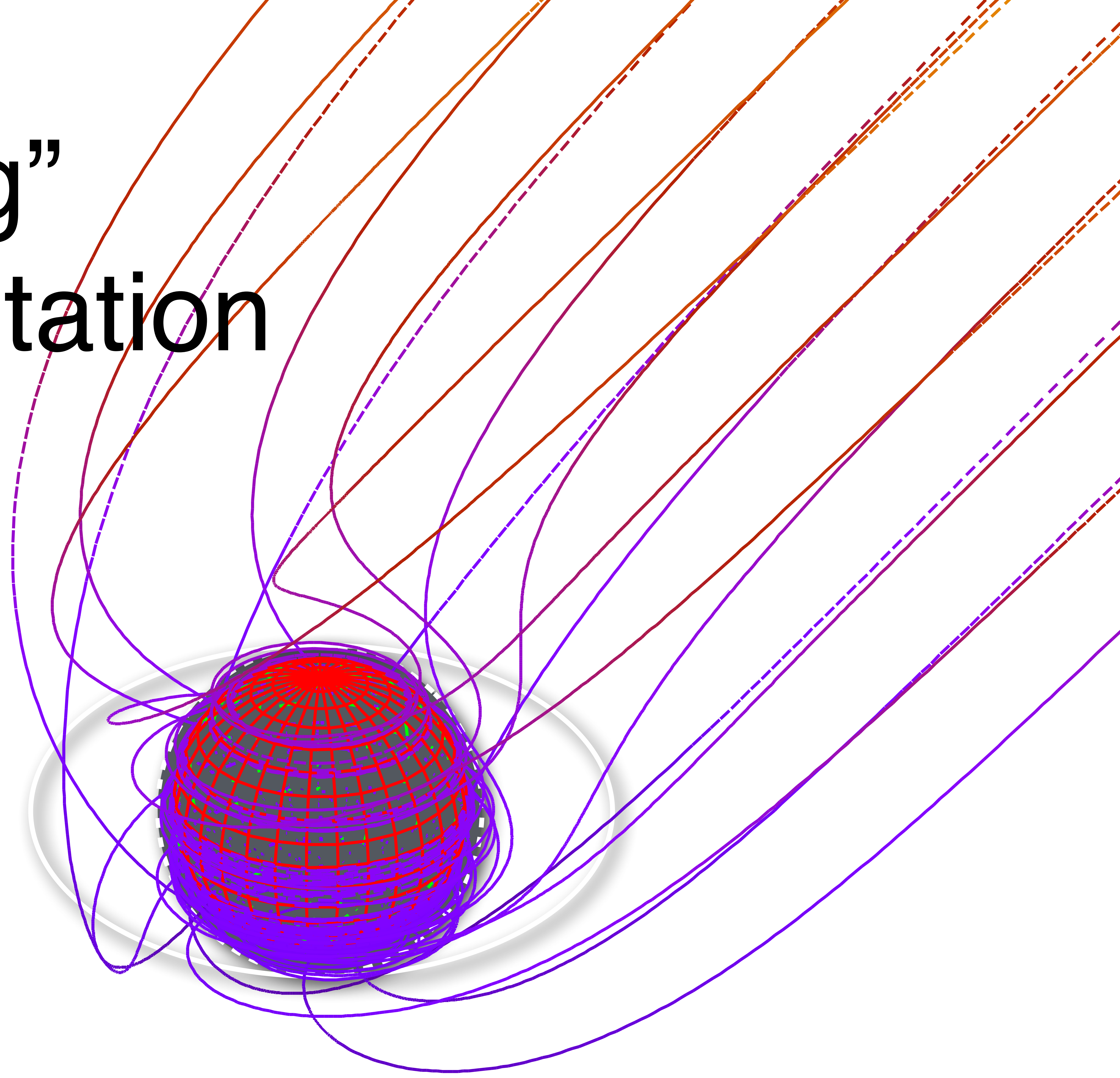


$$-1 < a* = (J/M_{\rm BH}c)/M_{\rm BH} < 1$$

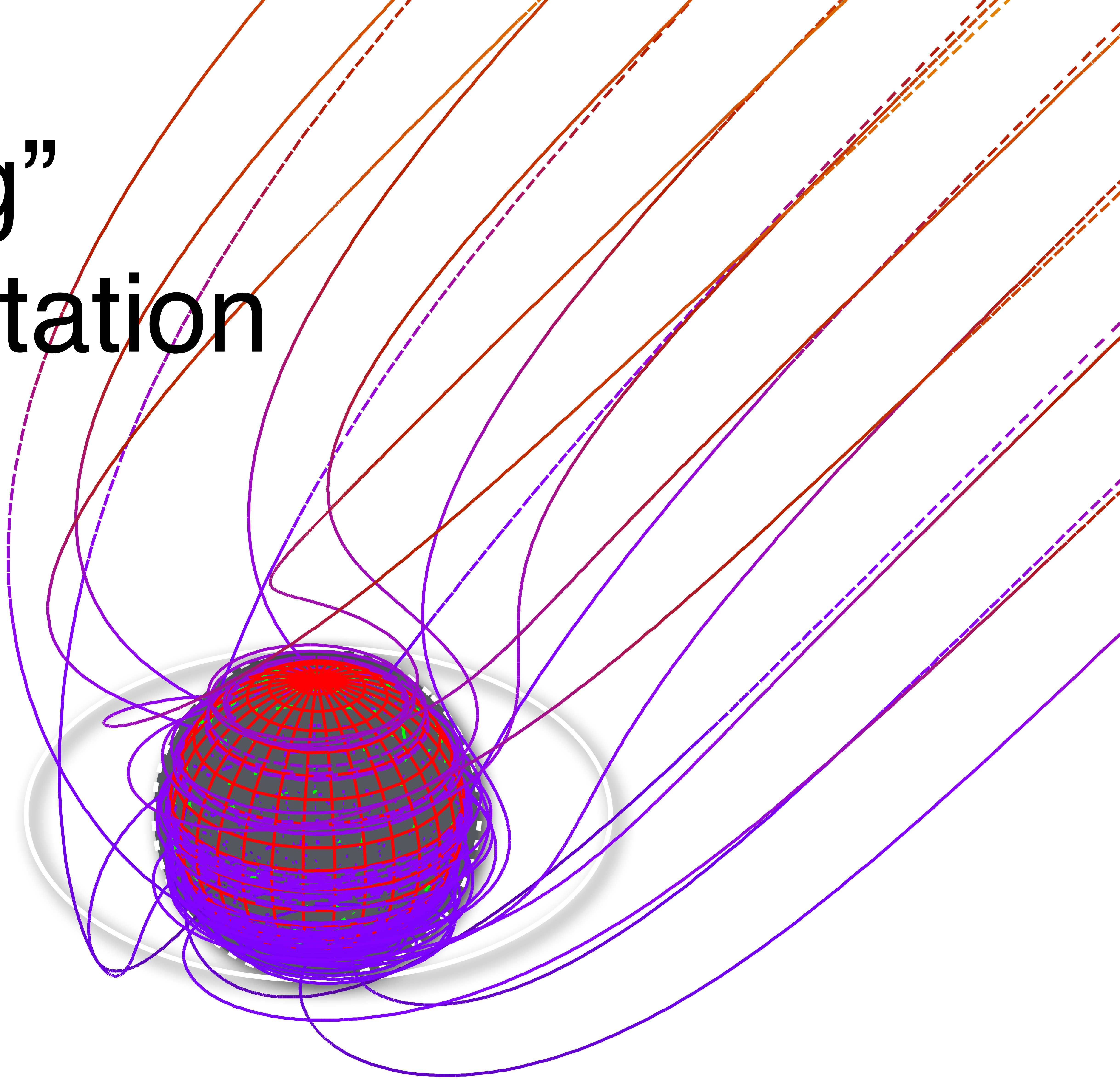
Kerr hypothesis: "astronomical black holes are described by the Kerr metric"



“frame dragging”
due to spacetime rotation

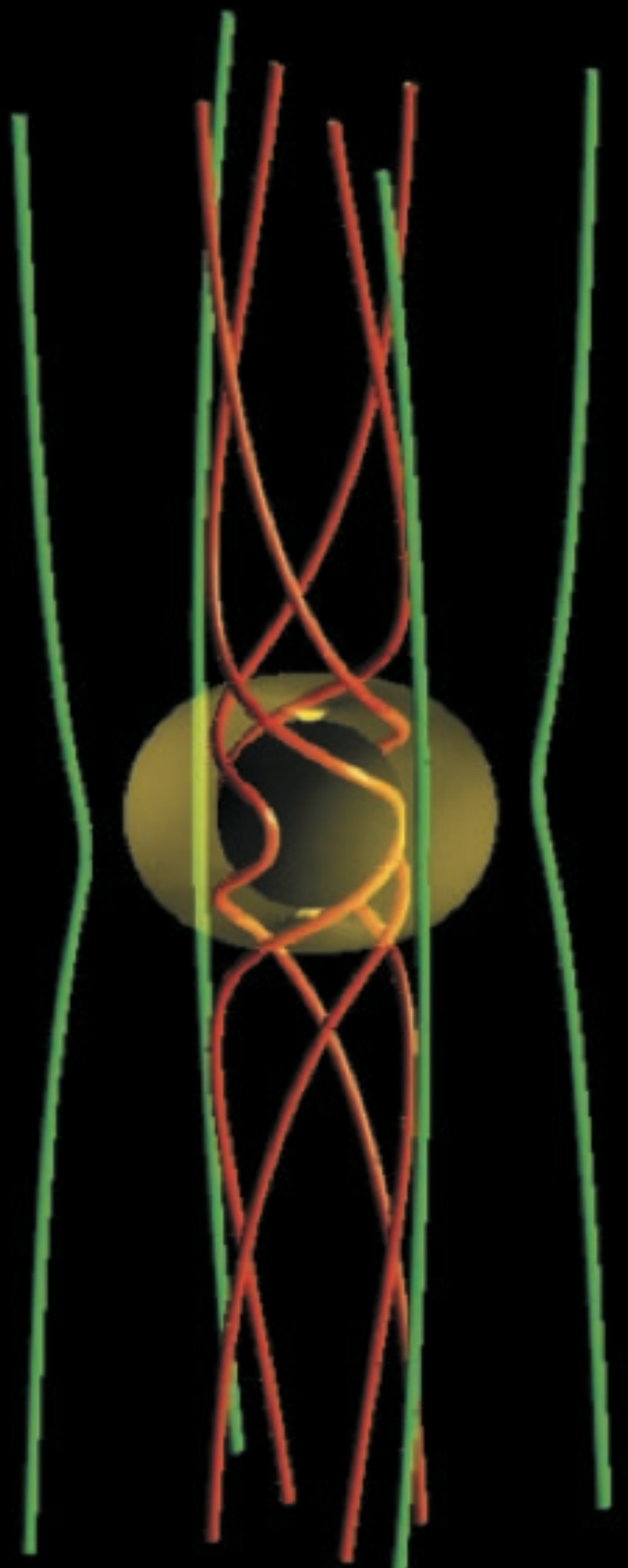



"frame dragging" due to spacetime rotation



extraction of BH rotational energy by magnetic fields

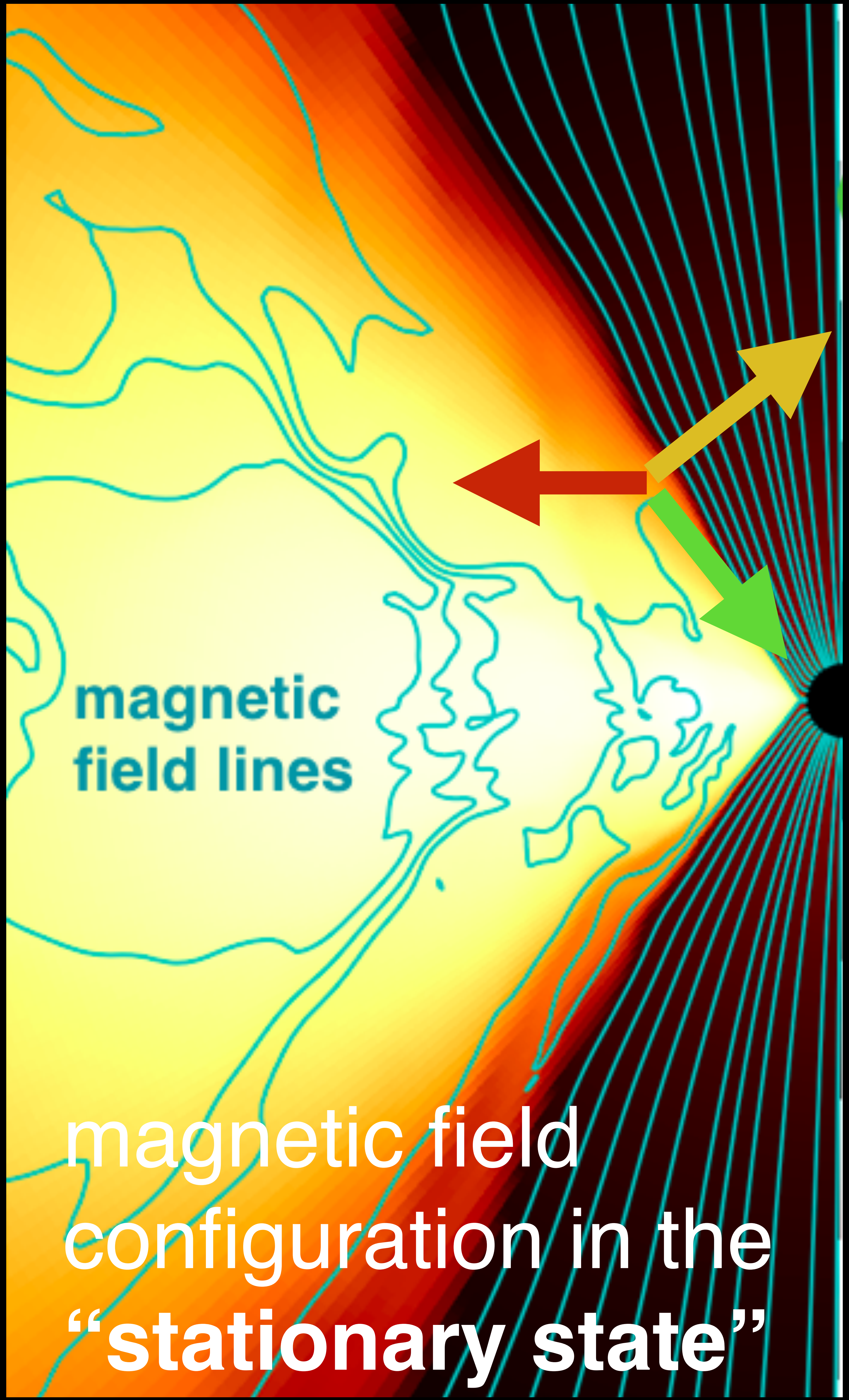
Penrose71,
Blanford&Znajeck+04,
Takahashi+90

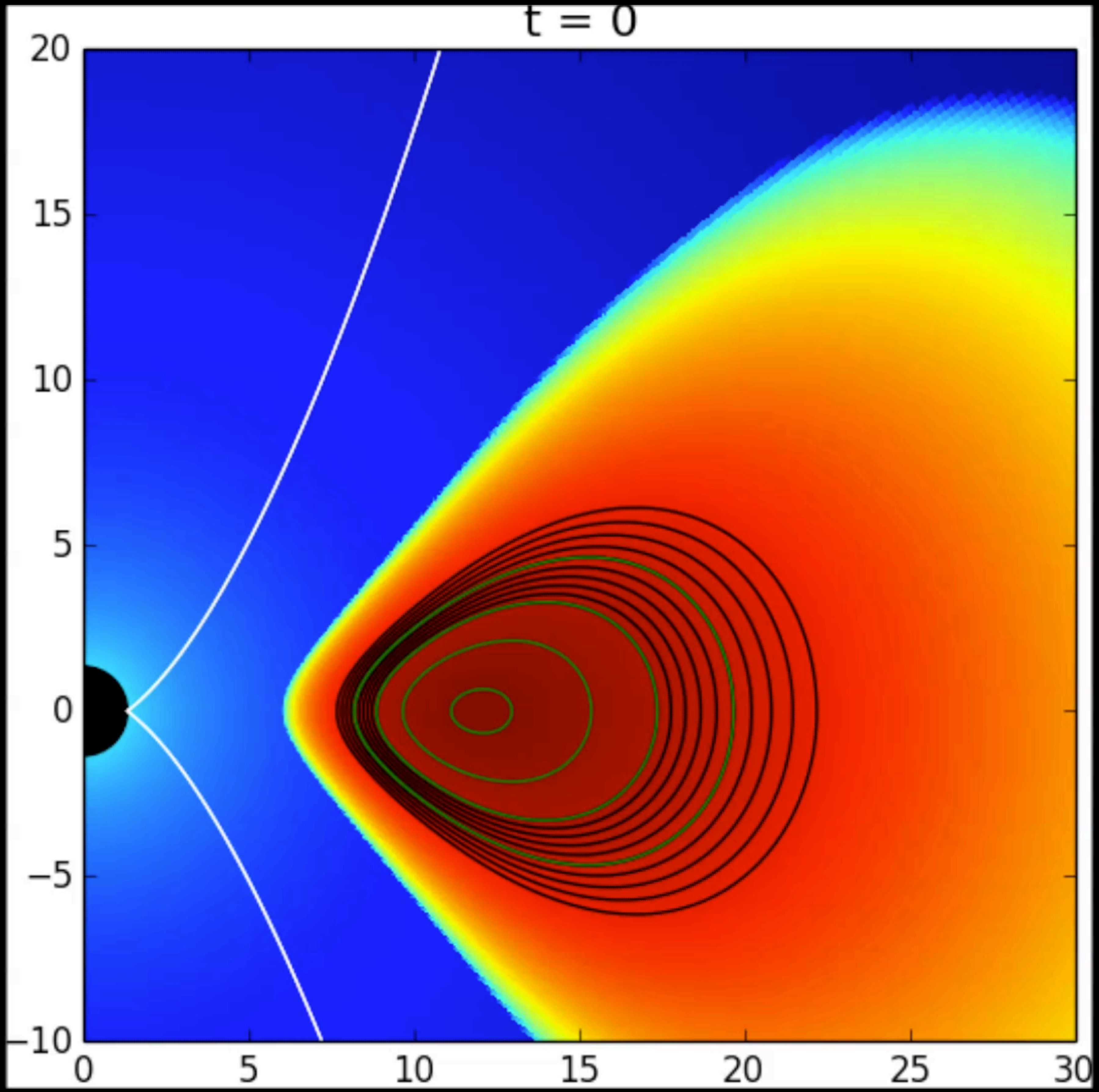


Semenov+04, Koide+02

few plasma (nearly vacuum)

General **R**elativistic **M**agneto**H**ydro**D**ynamics simulation





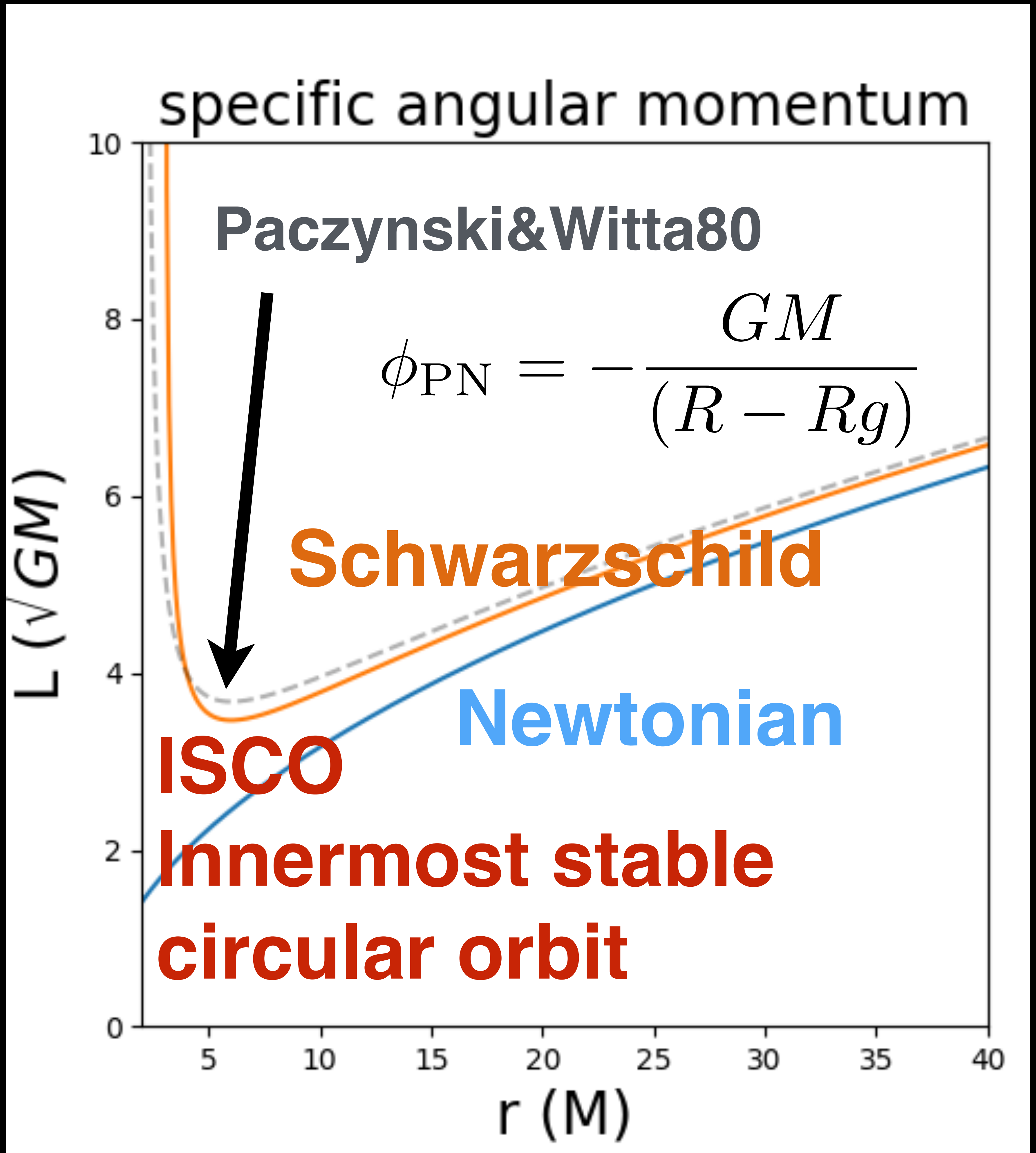
more plasma —> accretion flow

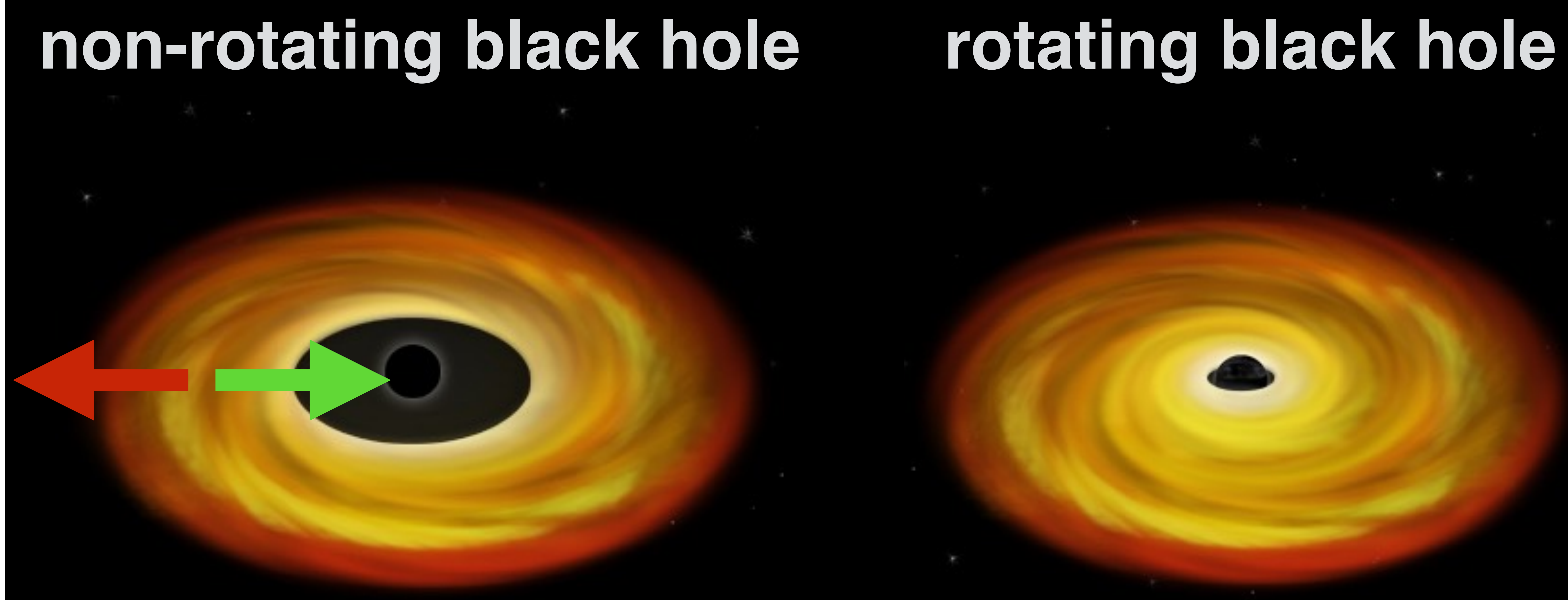
magnetic field

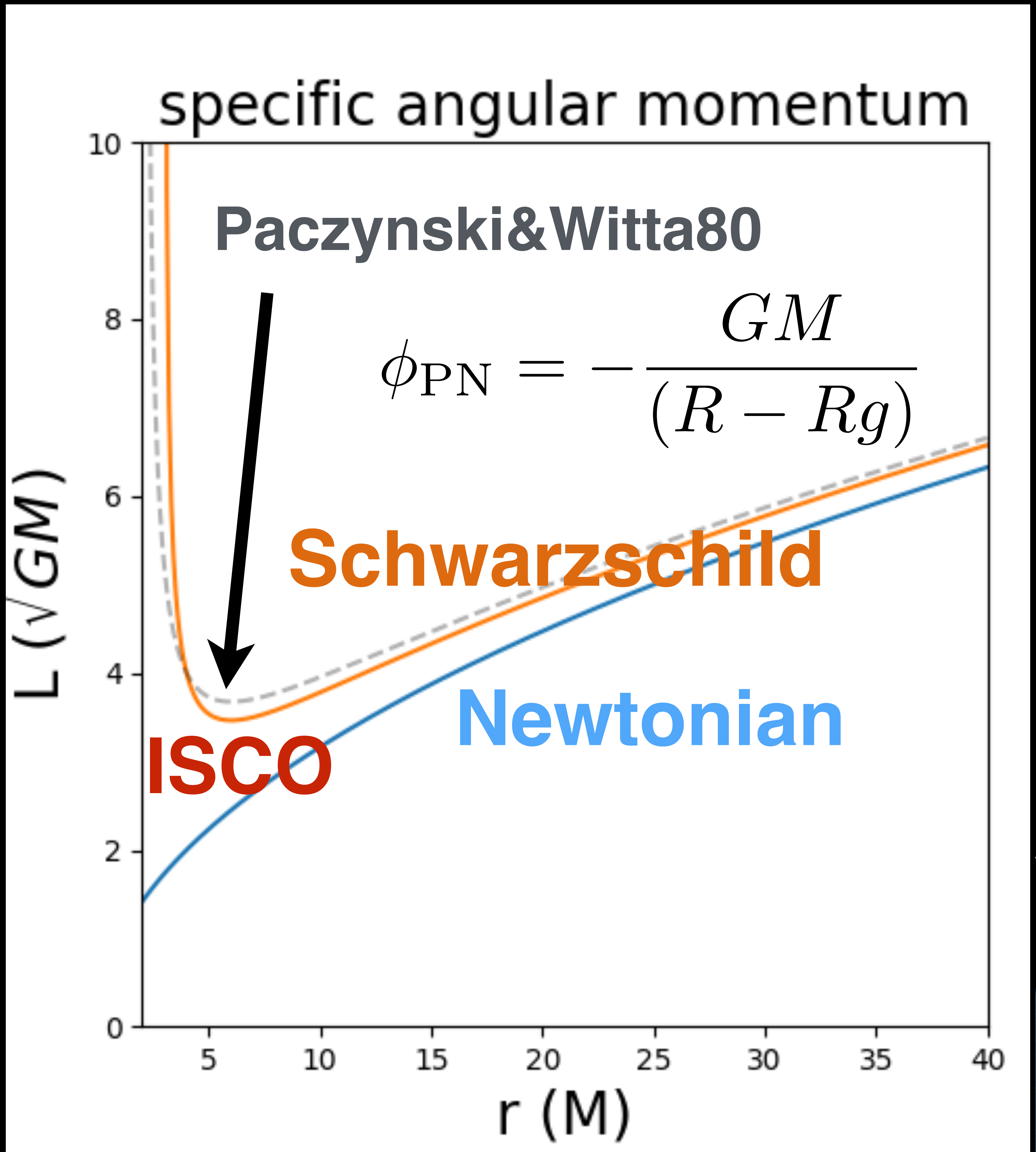
strong → braking

weak → Magneto-Rotational Instability (Bulbus & Hawley 91)

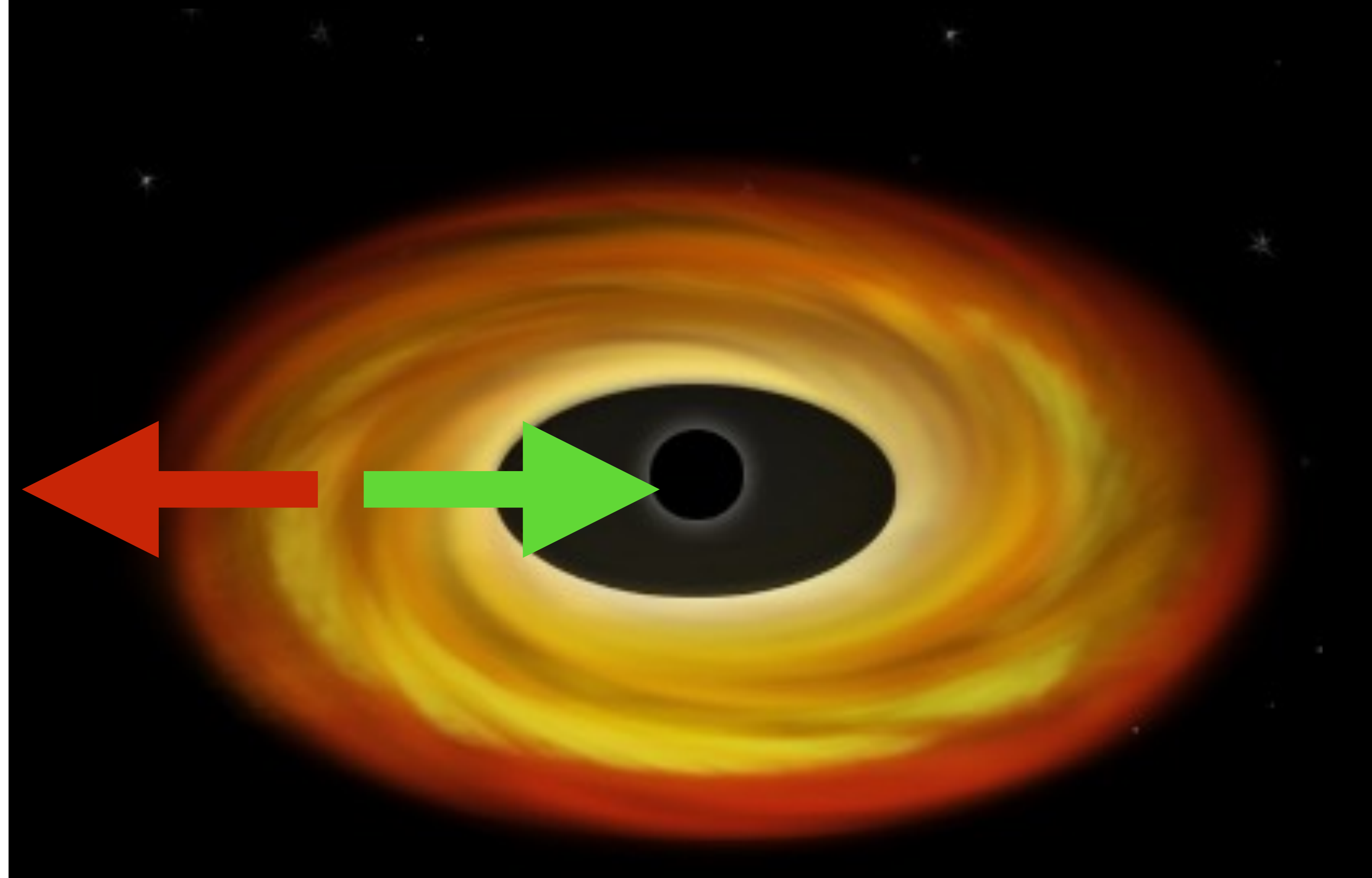
$$R = \frac{2GM}{c^2} \qquad \Delta E \approx \frac{GMm}{R} = 0.5mc^2$$



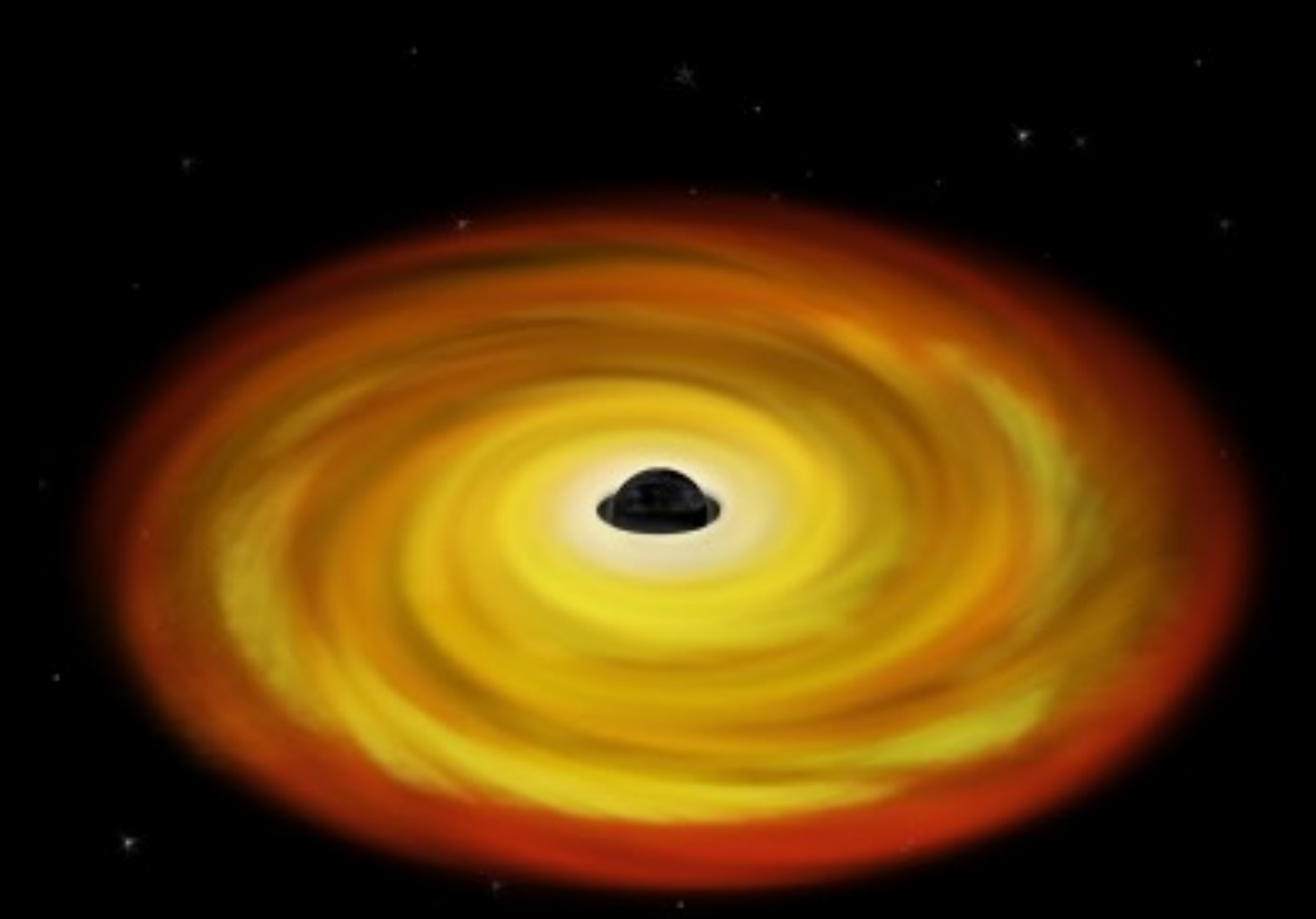




non-rotating black hole



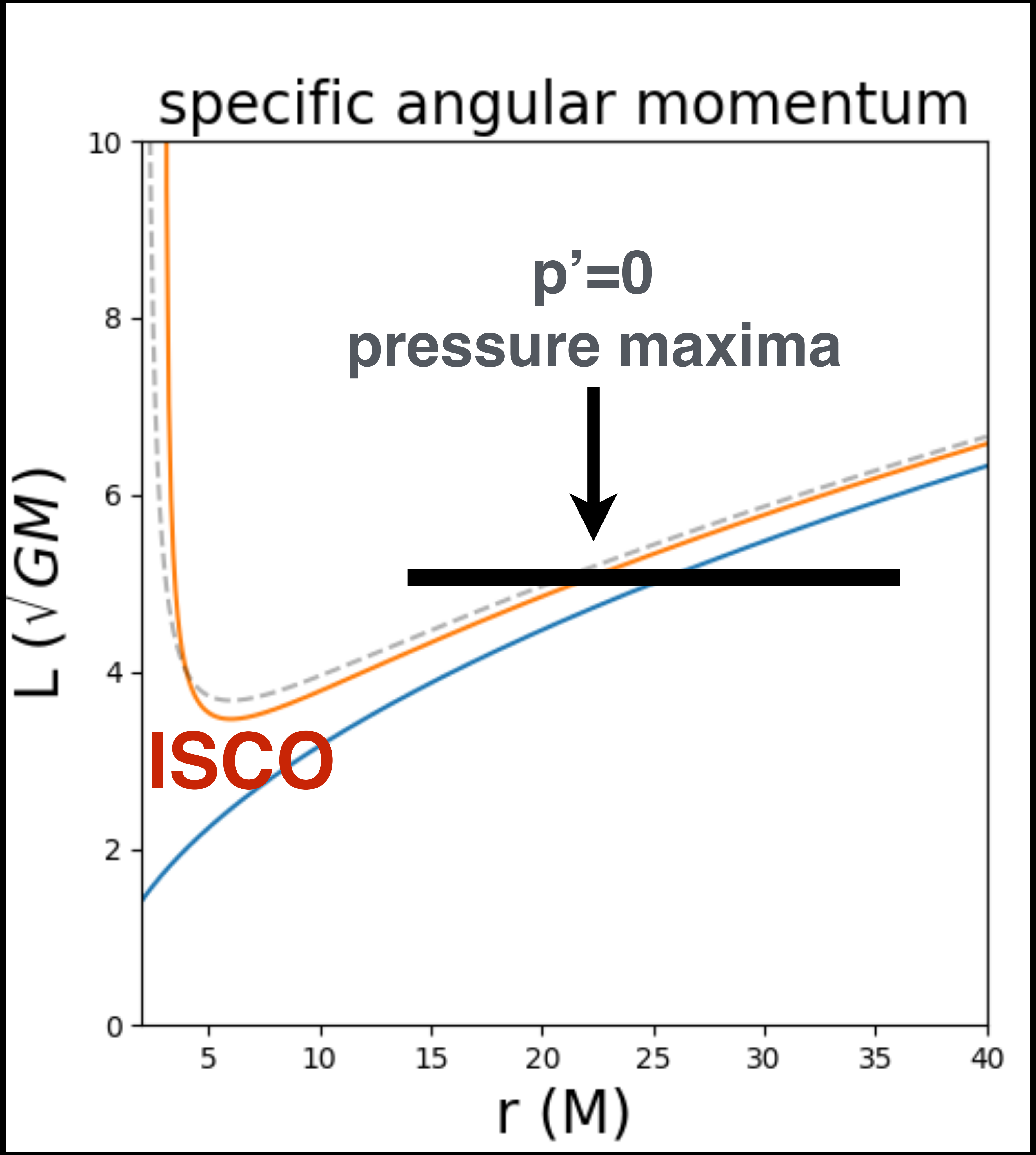
rotating black hole

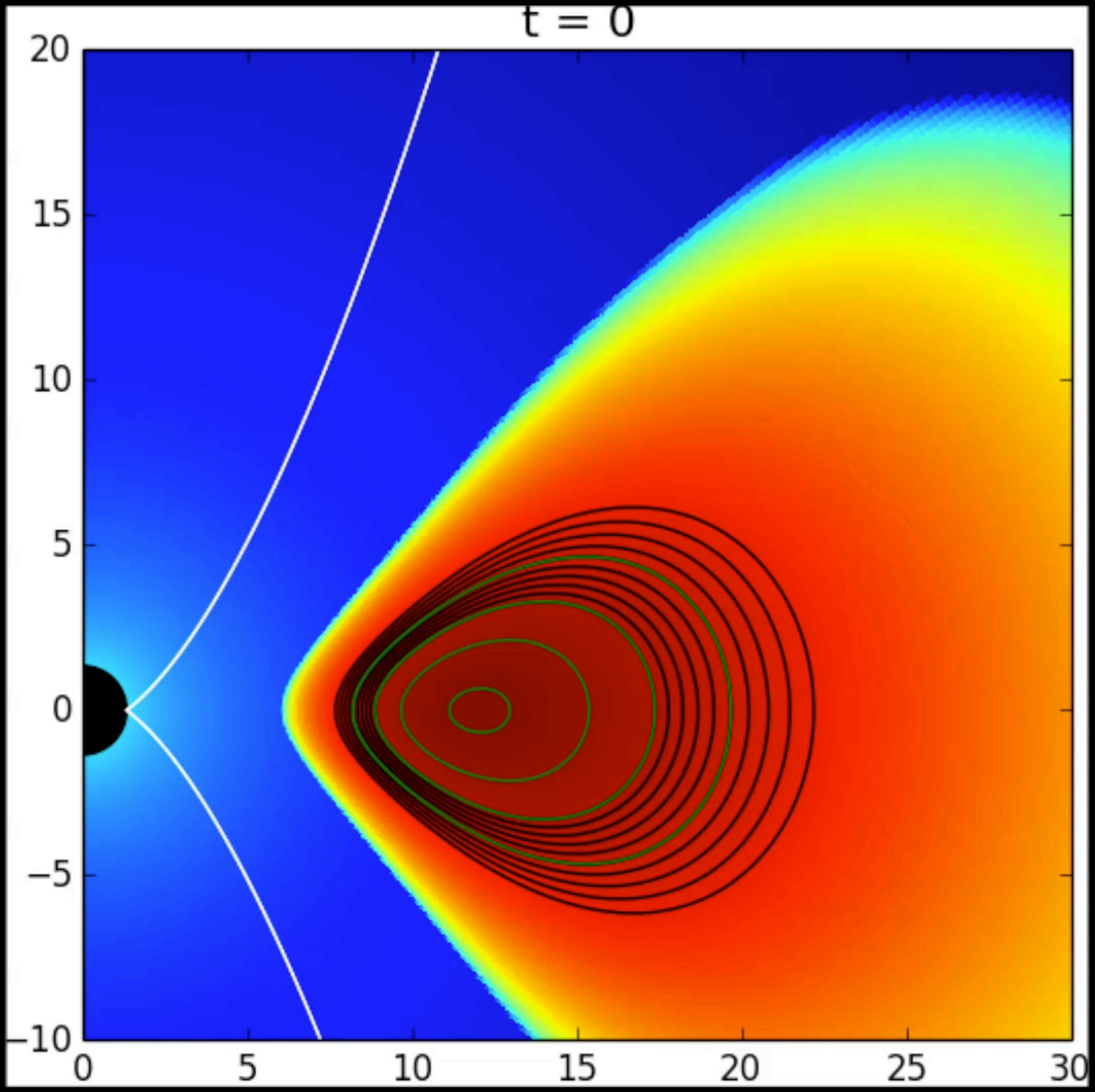


$$E|_\infty - E|_{\rm ISCO} = 0.06 \ \ \dot{m}c^2$$

$$E|_\infty - E|_{\rm ISCO} = 0.42 \ \ \dot{m}c^2$$

BH accretion:
most powerful stable power factory in the Universe


specific angular momentum
p'=0
pressure maxima
ISCO
L (√GM)
r (M)
10
8
6
4
2
0
5
10
15
20
25
30
35
40


t = 0
20
15
10
5
0
−5
−10
0
5
10
15
20
25
30

$$\frac{l^2}{r^3} = \frac{GM}{r^2} \rightarrow$$

centrifugal force

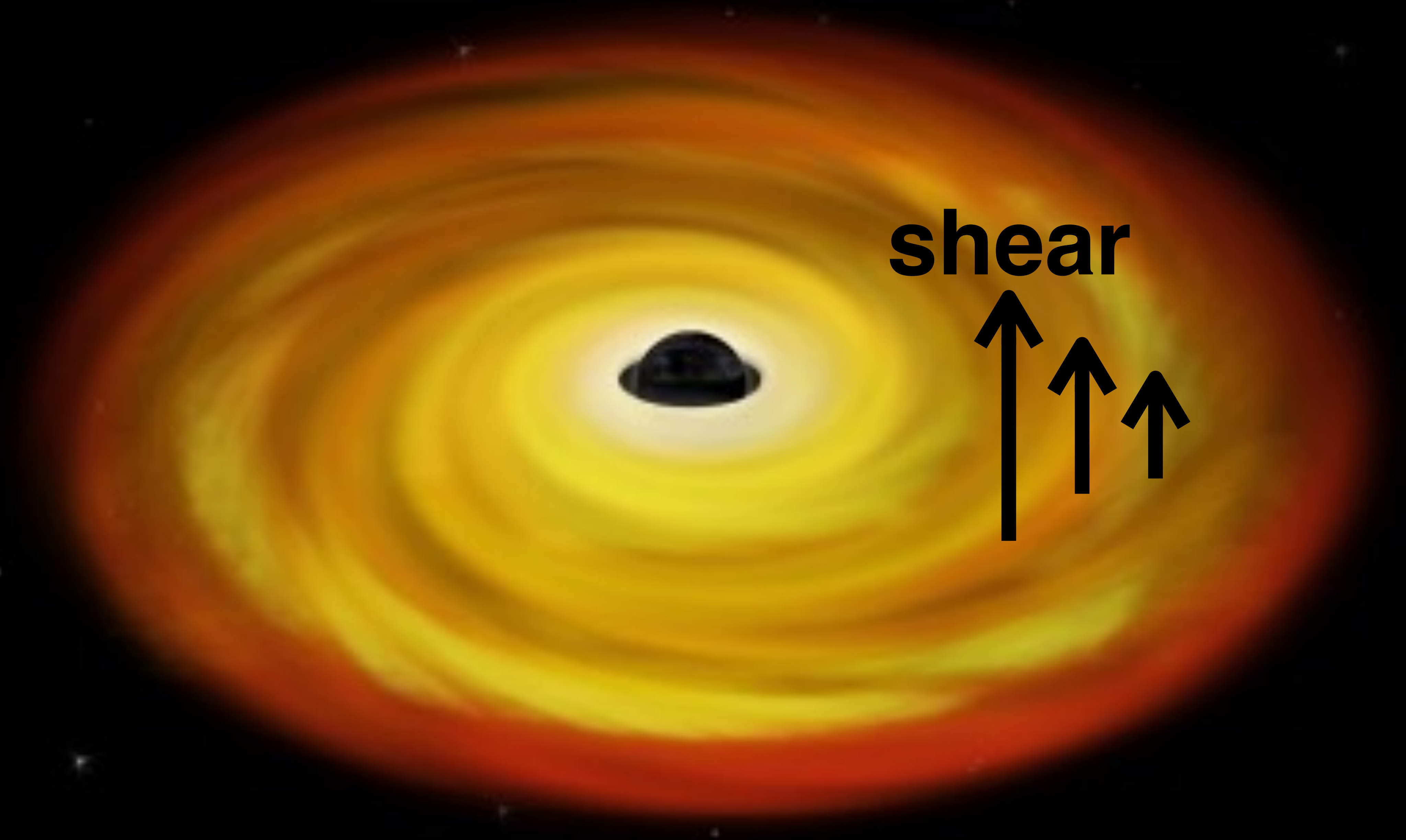
gravity force

centrifugal force barrier:

$$r_{\mathrm{barrier}} = \frac{l^2}{GM}$$

angular momentum problem for object with R > r_{barrier}

ways to accretion: (1) get rid of angular momentum (2) shock



inevitable plasma heating
=> where does those energy go?

$$v_r \rho T \frac{ds}{dr} = q^+ - q^- = q^{\mathrm{adv}}$$

$$v_r \rho T \frac{ds}{dr} = q^+ - q^- = q^{\mathrm{adv}}$$

viscous heating — radiative cooling — advection cooling

thin disk (Shakura-Sunyaev 1973, Novikov-Throne 1973)

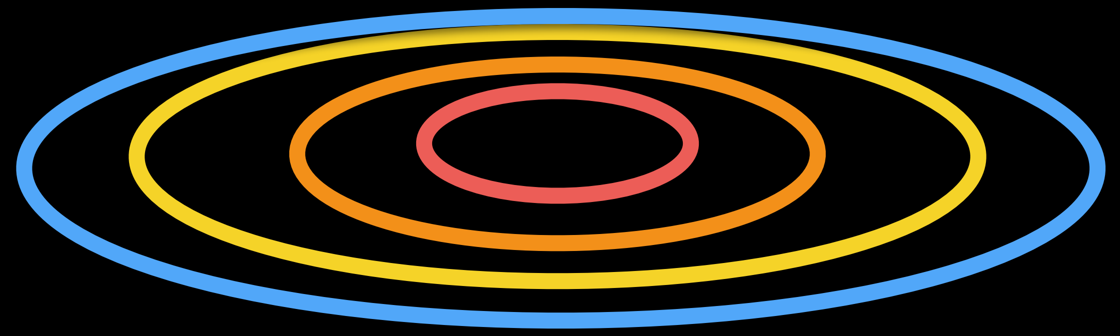
Yu-Yen's talk

radiative cooling dominated:

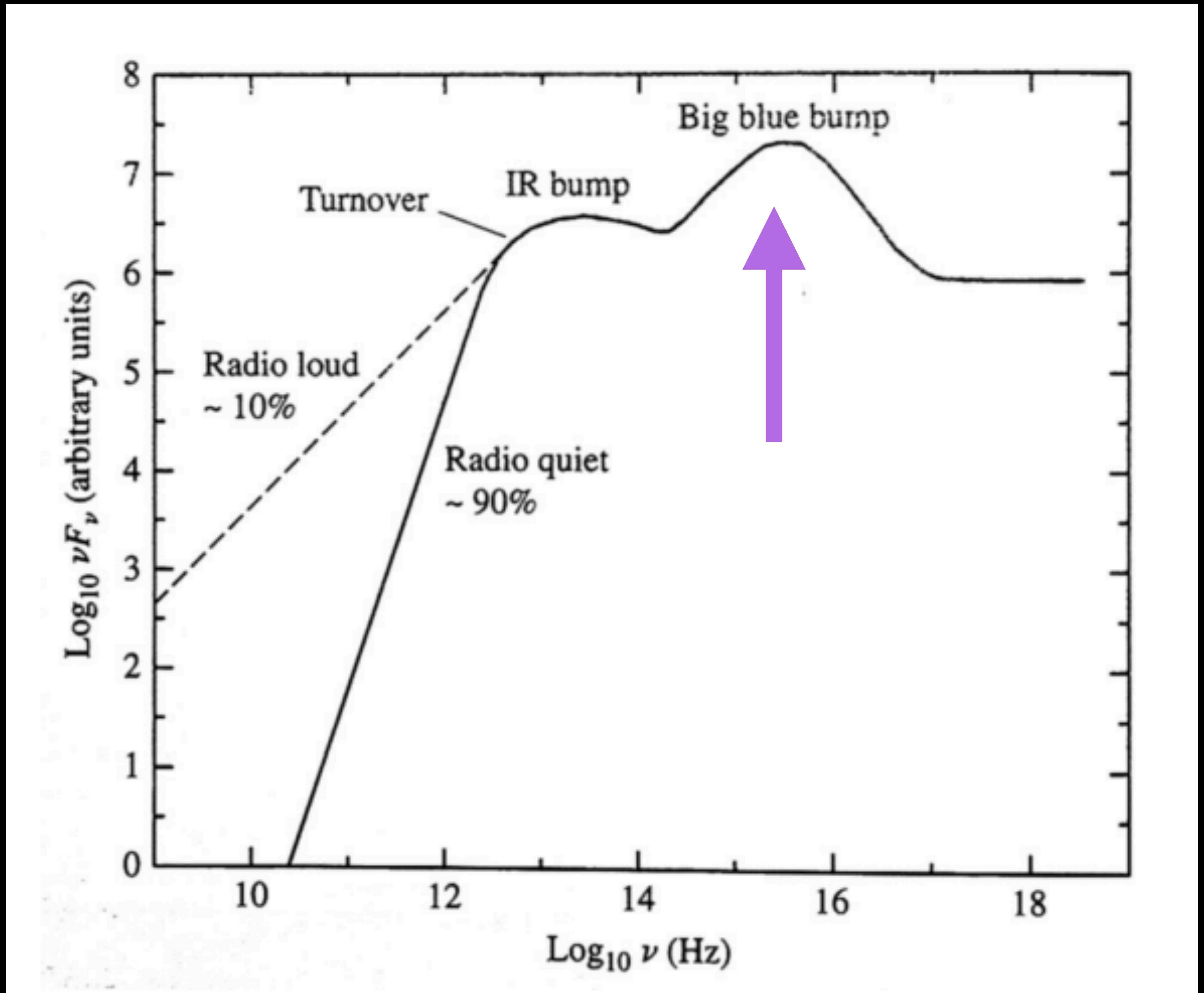
$$q^+ \approx q^- (\gg q^{adv})$$

Teff(r): multi-color

T~ $10^{5\text{-}7}$ K



luminous quasar, Seyferts, BHXB in thermal high/soft state



$$v_r \rho T \frac{ds}{dr} = q^+ - q^- = q^{\rm adv}$$

viscous heating

radiative cooling

advection cooling

ADAF

advection cooling dominated:

$$q^+ \approx q^{adv} (\gg q^-)$$

(radiatively inefficient accreting flow)

heat are stored inside the flow due to:

(Ichimaru77;Narayan & Yi 94, 95; Abramowicz+95, Yuan & Narayan 14)

optically thin

low density, collisionless ($T_i \sim T_{virial} \gg T_e$)

LLAGN, BHXB in thermal low/hard state

(Begelman78;Abramowicz+89;Sadowski+14)

optically thick

high density, photon trapping

Tidal disruption events, Ultra Luminous X-ray binaries

$$v_r \rho T \frac{ds}{dr} = q^+ - q^- = q^{\rm adv}$$

viscous heating | radiative cooling | advection cooling

ADAF

advection cooling dominated:

$$q^+ \approx q^{adv} (\gg q^-)$$

(radiatively inefficient accreting flow)

★another choice: outflow

ADIOS (advection-dominated inflow-outflow solutions; Blandfor & Begelman 99)

(Ichimaru77;Narayan & Yi 94, 95; Abramowicz+95, Yuan & Narayan 14)

optically thin

low density, collisionless ($T_i \sim T_{virial} >> T_e$)

LLAGN, BHXB in thermal low/hard state

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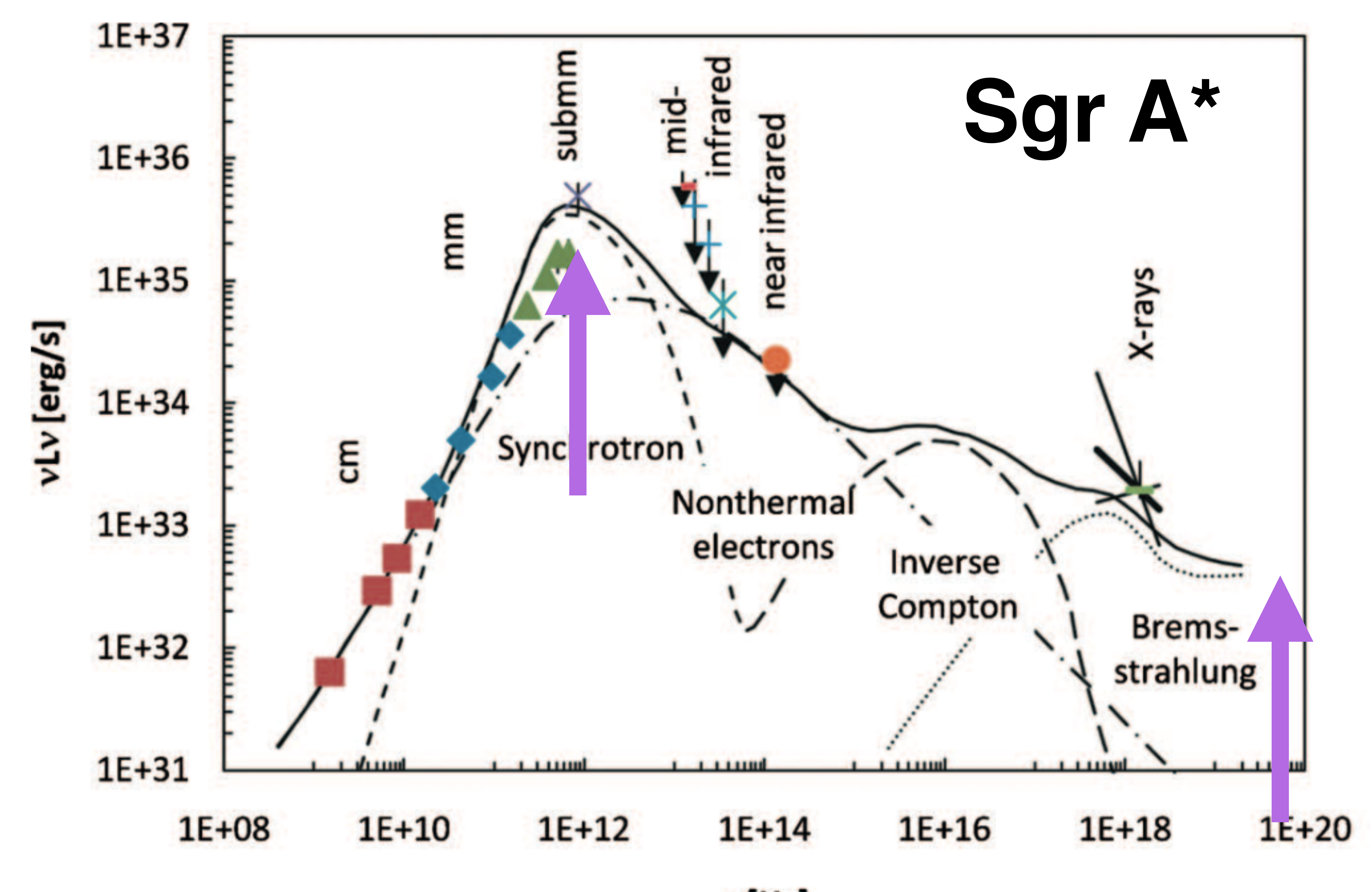
Tidal disruption events, Ultra Luminous X-ray binaries

$$v_r \rho T \frac{ds}{dr} = q^{+} - q^{-} = q^{\mathrm{adv}}$$

viscous heating — radiative cooling — advection cooling

ADAF



Yuan et al. 2003; Genzel 2010

optically thin

$T_i \sim 10^{11\text{-}12}$ K

$T_e < 10^{9\text{-}11}$ K

including primary EHT tagets: Sgr A*, M87

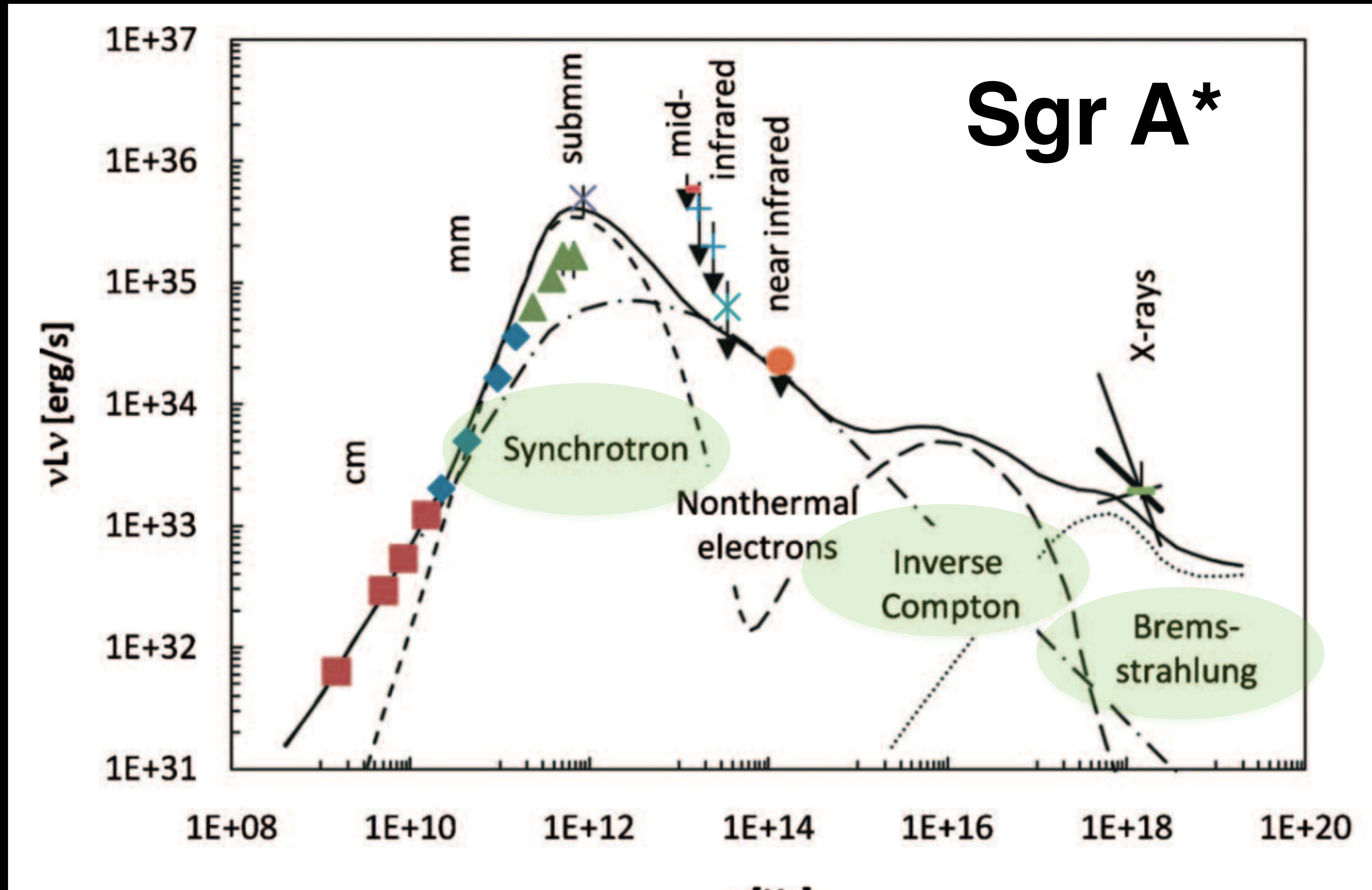
we can see BH shadow!

mm/sub-mm observation for M87 (from syn. emission)

$$v_r \rho T \frac{ds}{dr} = q^+ - q^- = q^{\mathrm{adv}}$$

viscous heating | radiative cooling | advection cooling

ADAF



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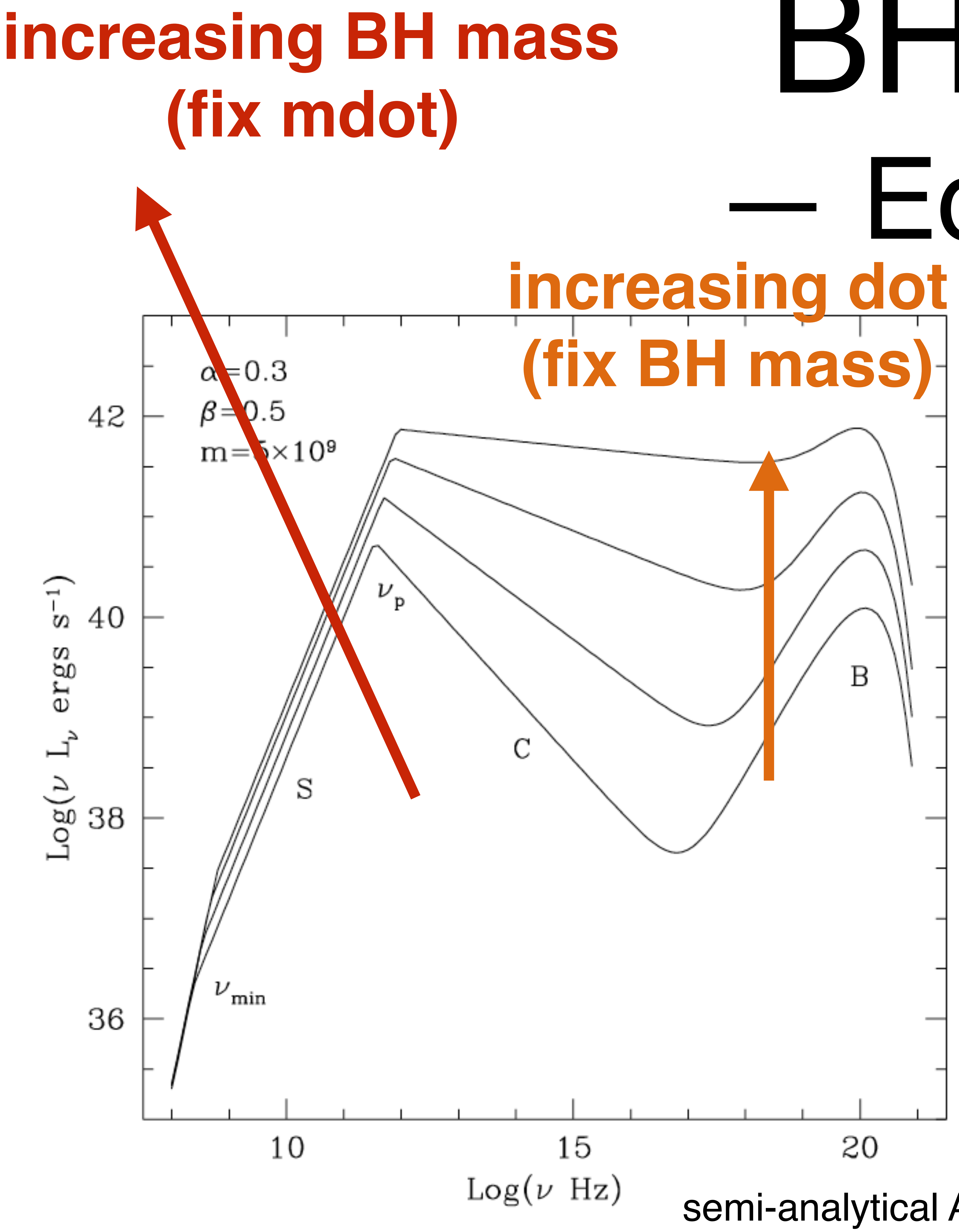
BHs: big and small
— Eddington accretion rate



$$L_{\rm Edd} = 1.26 \times 10^{38} \frac{M_{\rm BH}}{M_\odot} \; erg/sec$$

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta_{\rm eff} c^2} = 2 \times 10^{-8} \frac{M_{\rm BH}}{M_\odot} \; M_\odot/yr$$

$$\dot{M}_{\rm BH} = \dot{m} \dot{M}_{\rm Edd}$$

semi-analytical ADAF spec by Mahadevan97

$\dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$

cf. Ken's talk

accretion rate

optically-thick ADAF: slim disk

(advection cooling)

due to photon trapping

1

thin disk

(radiation cooling)

0.01

optically-thin ADAF, hot accretion flow

(advection cooling)

due to hot ions

$\dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$

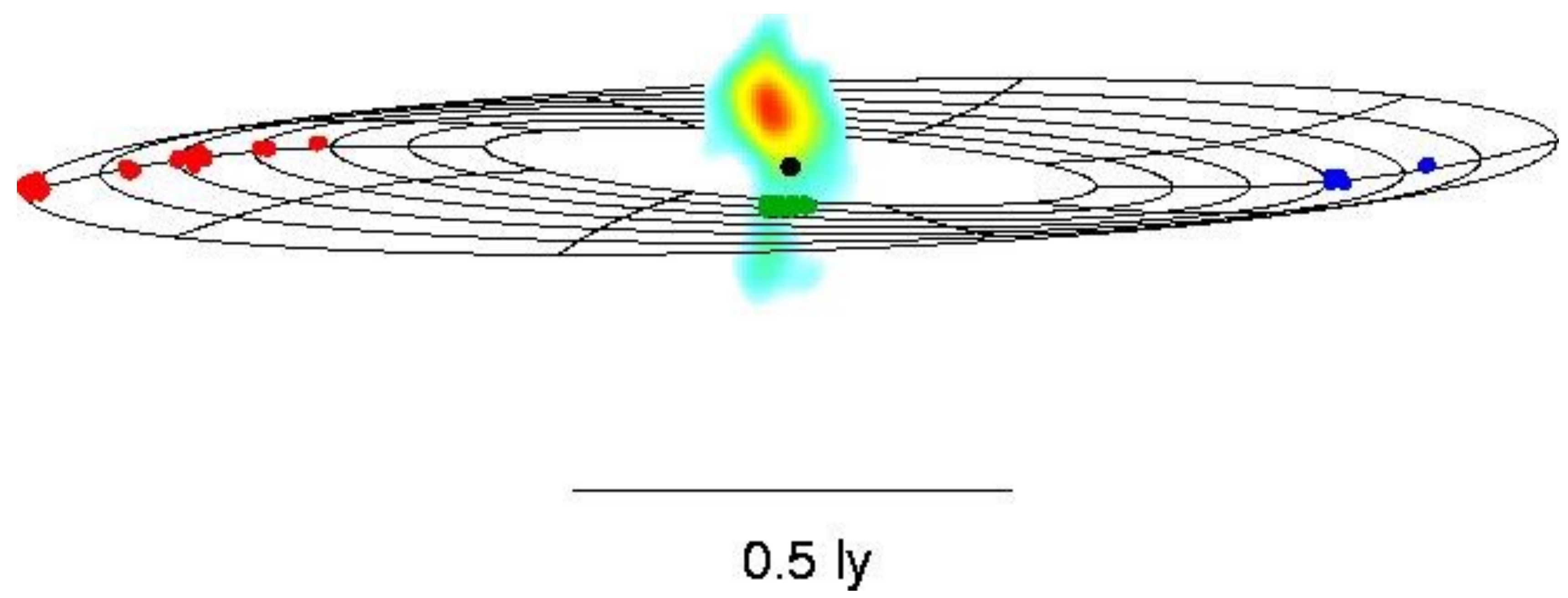
accretion rate

Cheng-Yu's talk

optically-thick ADAF: slim disk

(advection cooling)

due to photon trapping



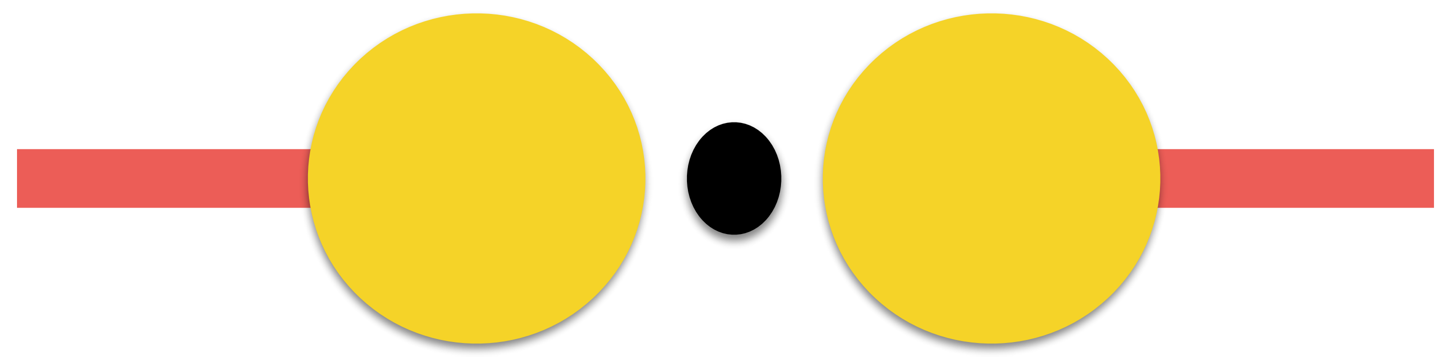
1

thin disk

(radiation cooling)

e.g. NGC 4258; maser measurement confirms the thin disk part

0.01



optically-thin ADAF, hot accretion flow

(advection cooling)

due to hot ions

$\dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$

accretion rate

optically-thick ADAF: slim disk

(advection cooling)

due to photon trapping

1

thin disk

(radiation cooling)

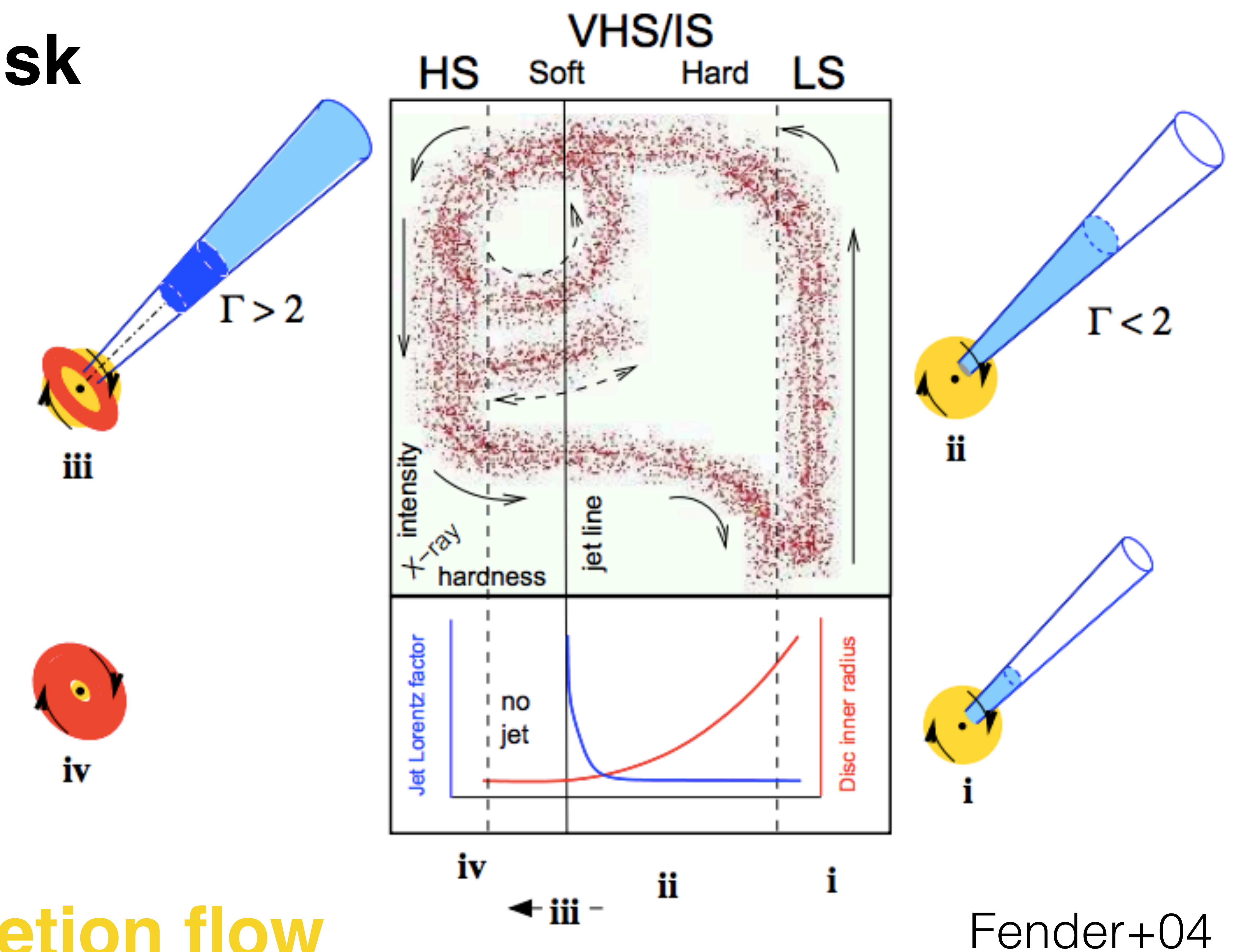
0.01

optically-thin ADAF, hot accretion flow

(advection cooling)

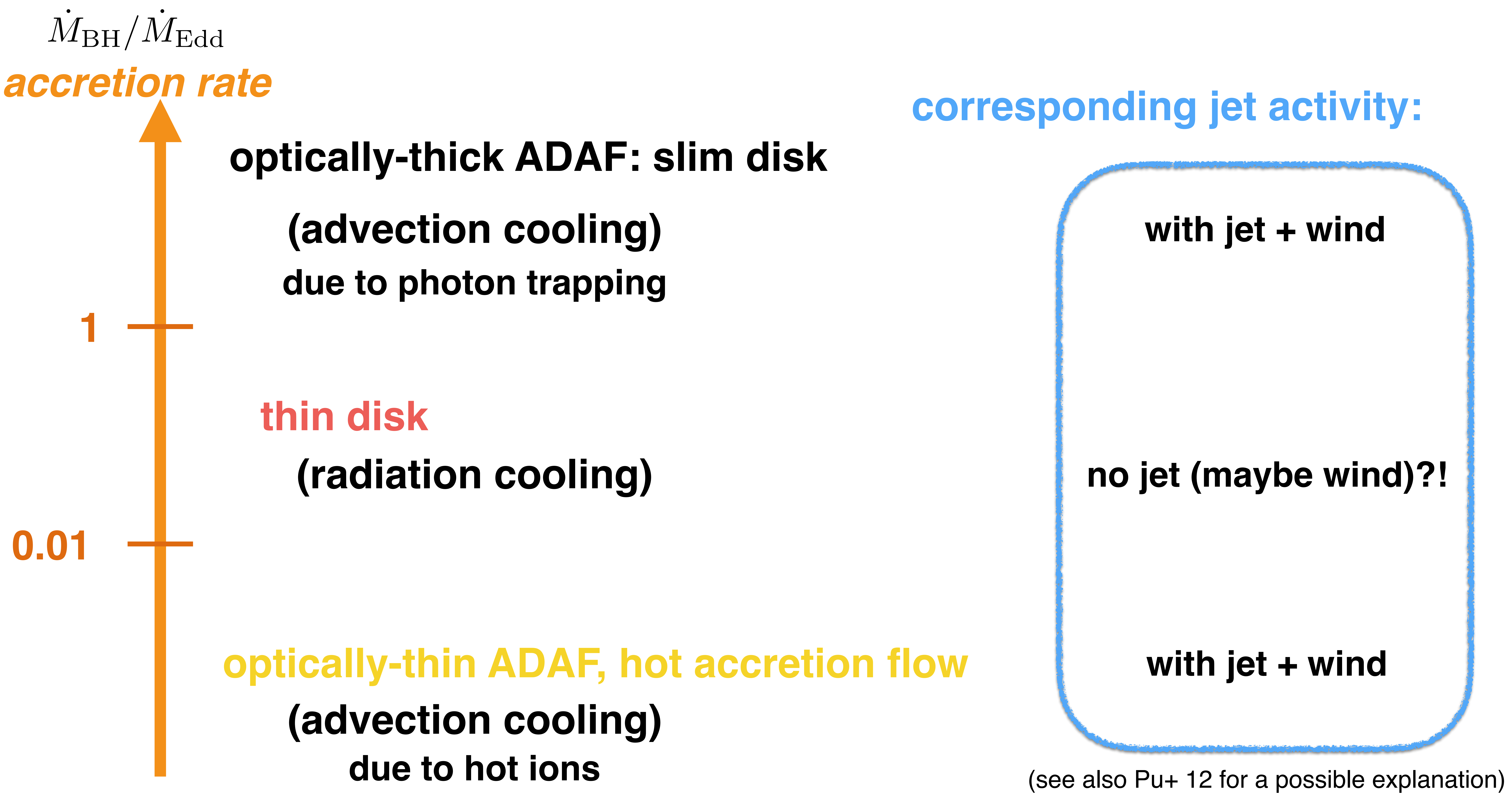
due to hot ions

a “unified model” from BHXB suggests disk-jet coping

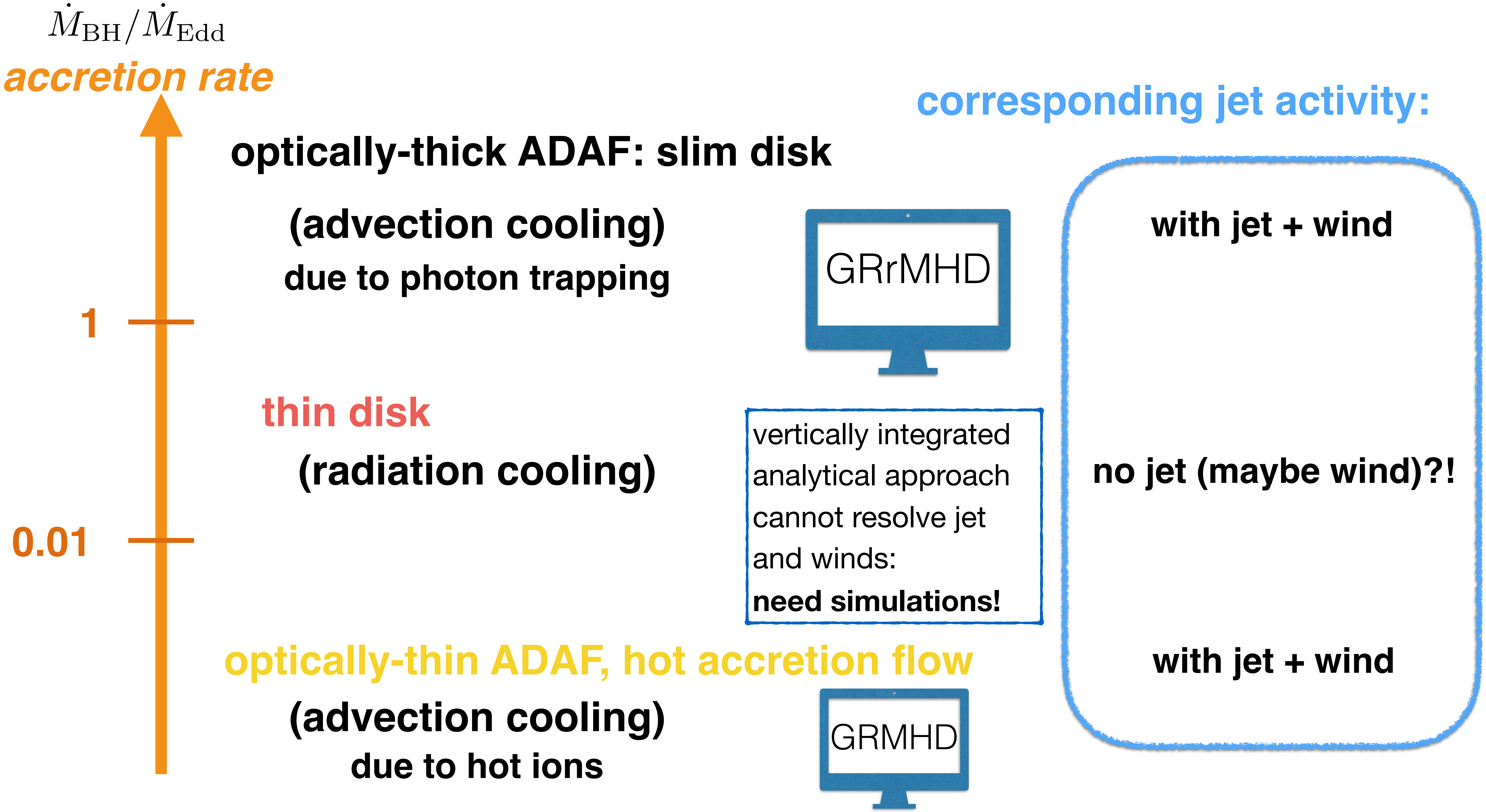


Fender+04

Holger’s talk



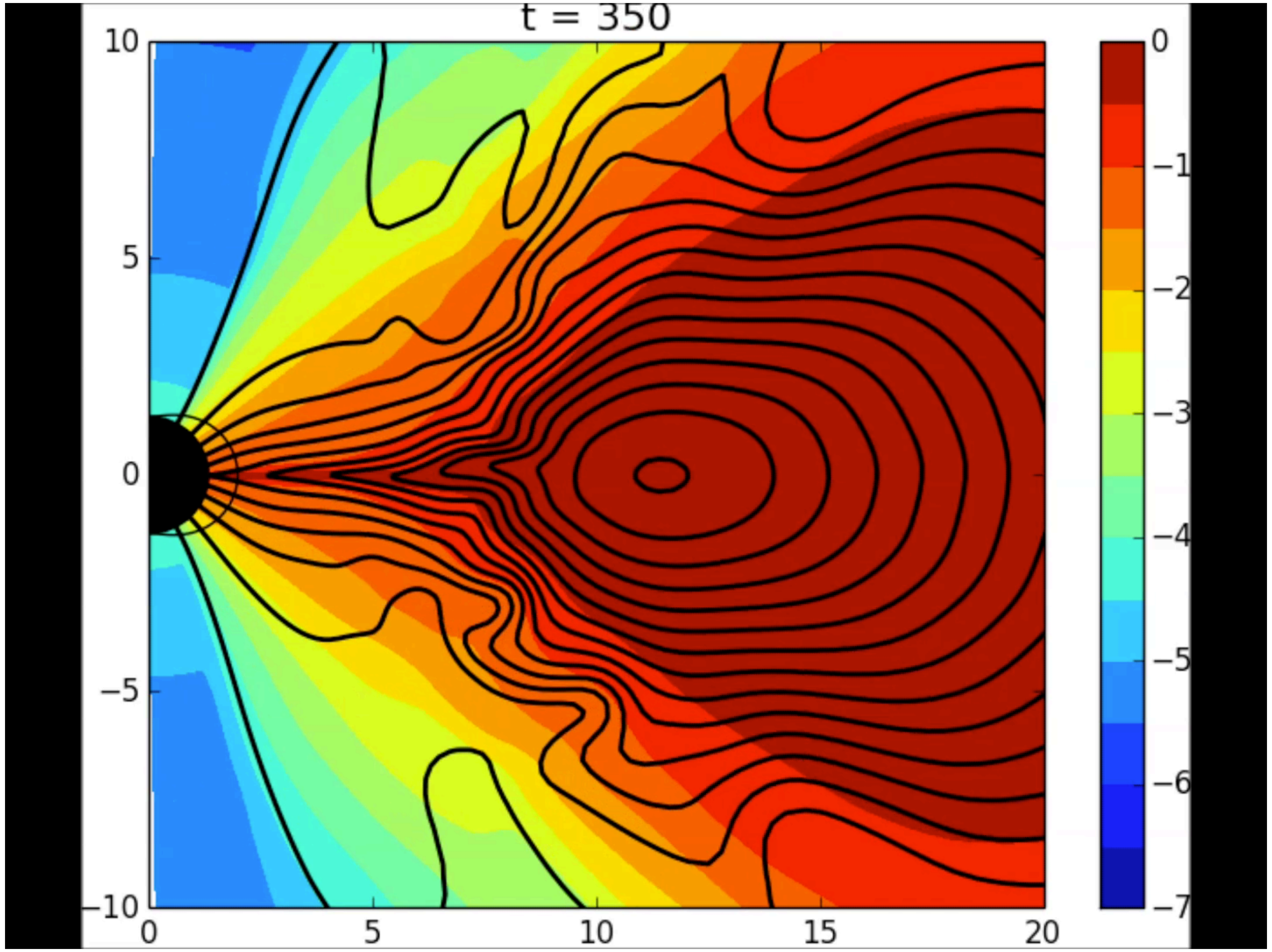
$\dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$
accretion rate
corresponding jet activity:
optically-thick ADAF: slim disk
(advection cooling)
due to photon trapping
with jet + wind
1
thin disk
(radiation cooling)
no jet (maybe wind)?!
0.01
optically-thin ADAF, hot accretion flow
(advection cooling)
due to hot ions
with jet + wind
(see also Pu+ 12 for a possible explanation)



$\dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$
accretion rate
1
0.01
optically-thick ADAF: slim disk
(advection cooling)
due to photon trapping
GRrMHD
thin disk
(radiation cooling)
vertically integrated analytical approach cannot resolve jet and winds:
need simulations!
optically-thin ADAF, hot accretion flow
(advection cooling)
due to hot ions
GRMHD
corresponding jet activity:
with jet + wind
no jet (maybe wind)?!
with jet + wind

GRMHD numerical simulation for RIAF

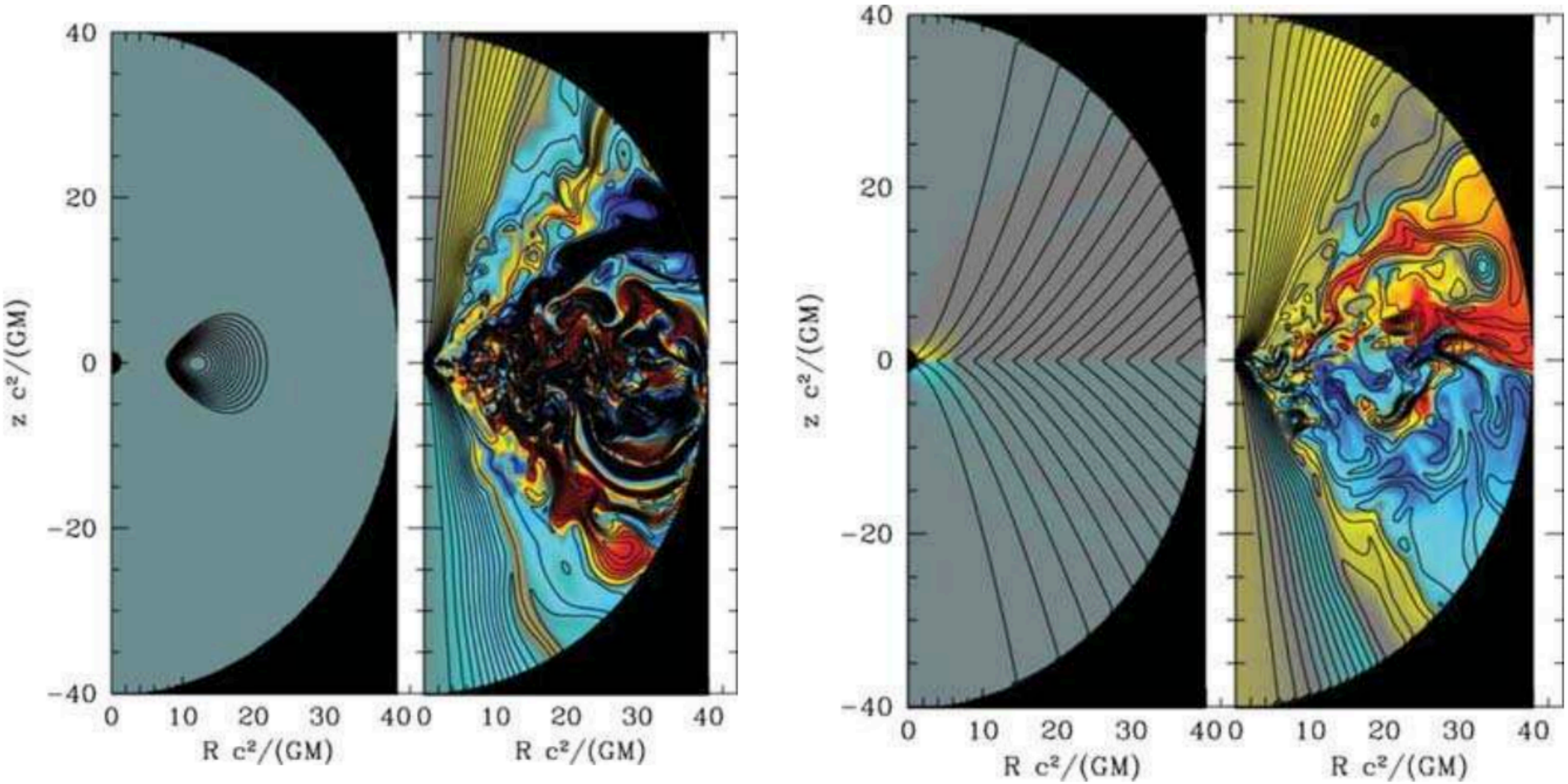
(time unit: GM/c^3)



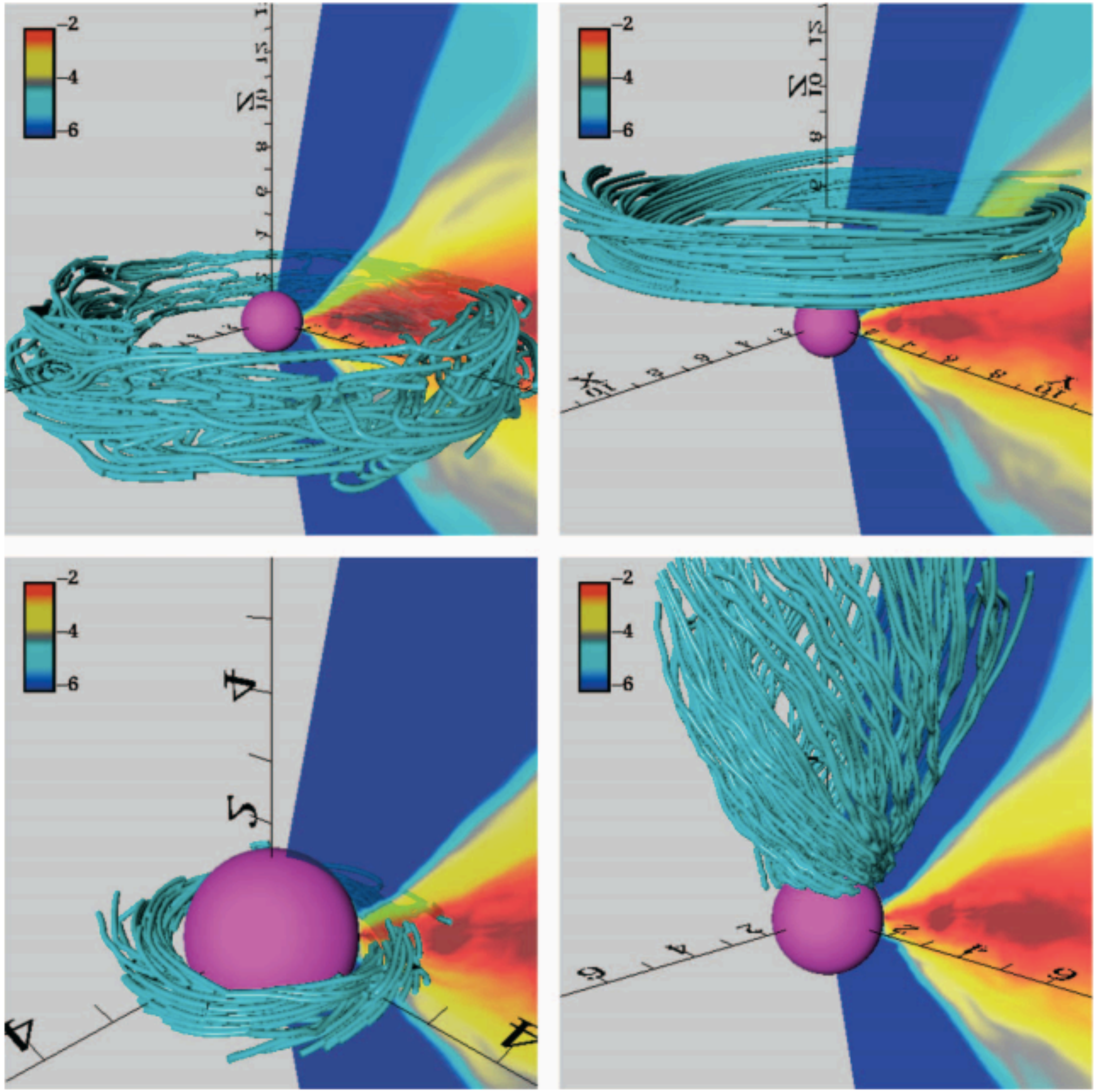
(scale unit: GM/c^2)

- approximation: just **ignore radiation**!
- **black hole mass** and **accretion rate** (or, alternatively, density unit) can be specified AFTER the simulation
- actively developed since ~2000
- starting from **one-fluid** simulation

initial magnetic field does matter



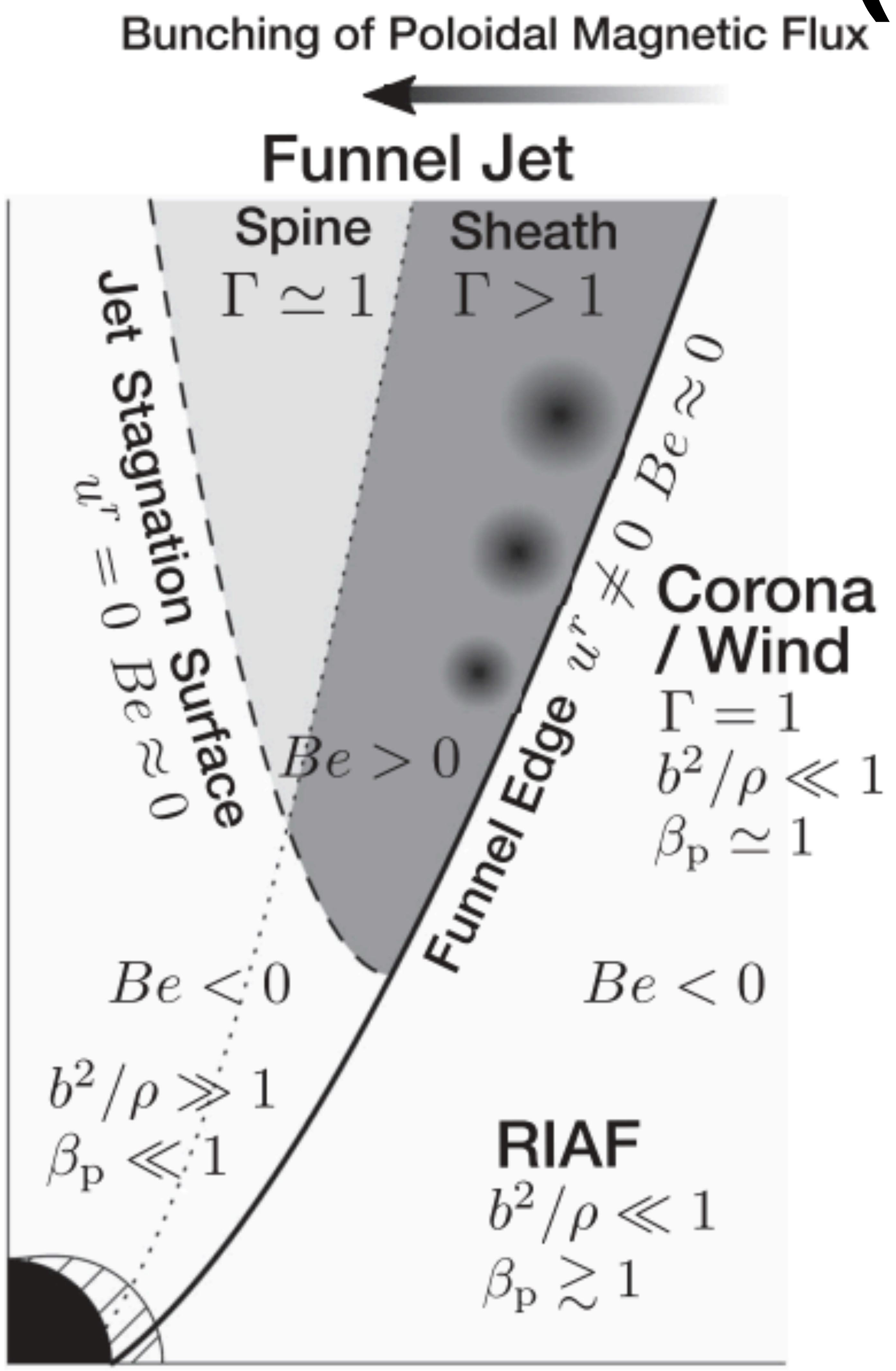
McKinney & Narayan 07



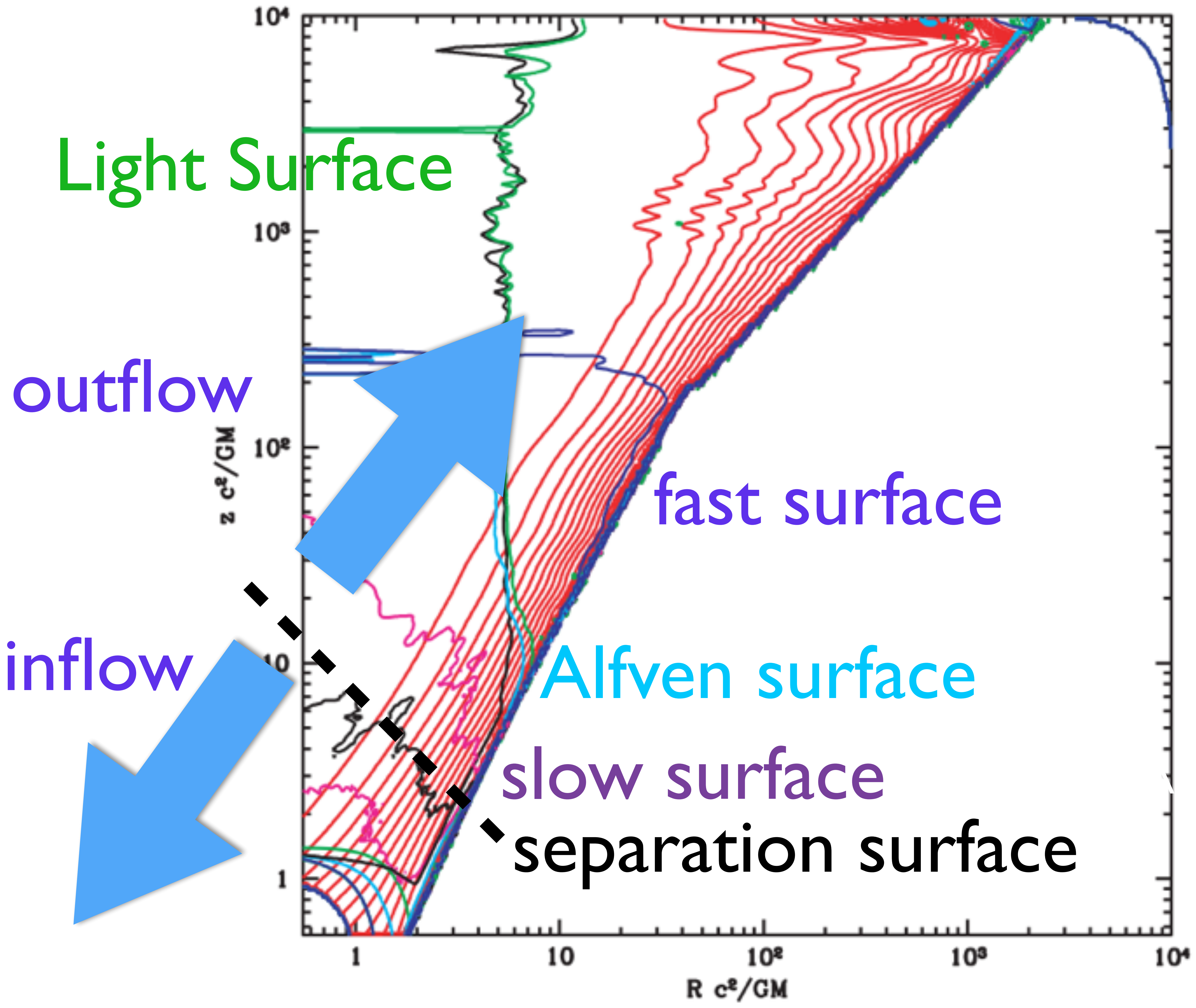
Hirose & Krolik
2003, 2004,
2005a, 2005b

inflow and outflow share the same (large-scale) field line!

$$\beta_p \equiv p_{gas}/p_{mag}$$

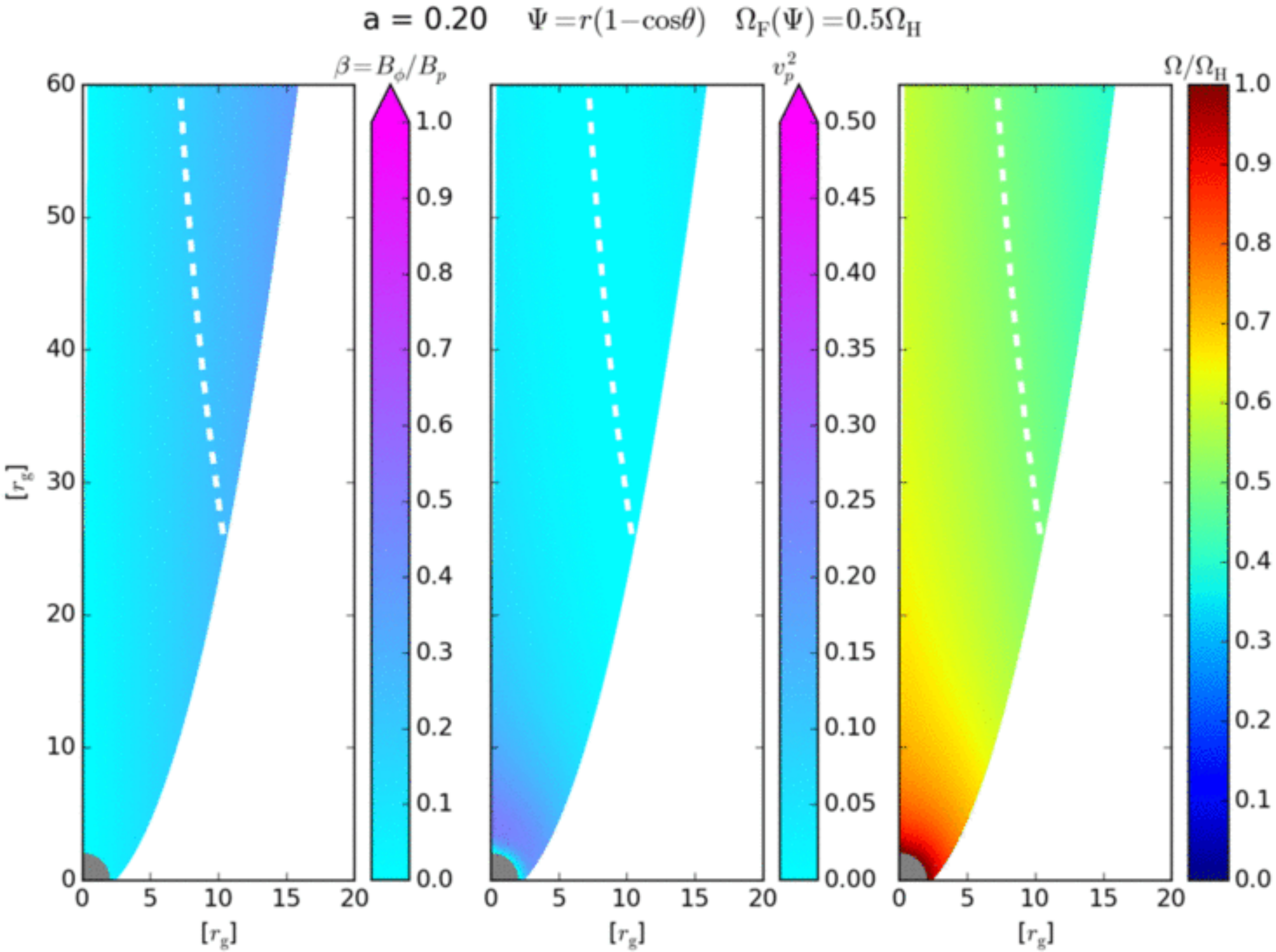


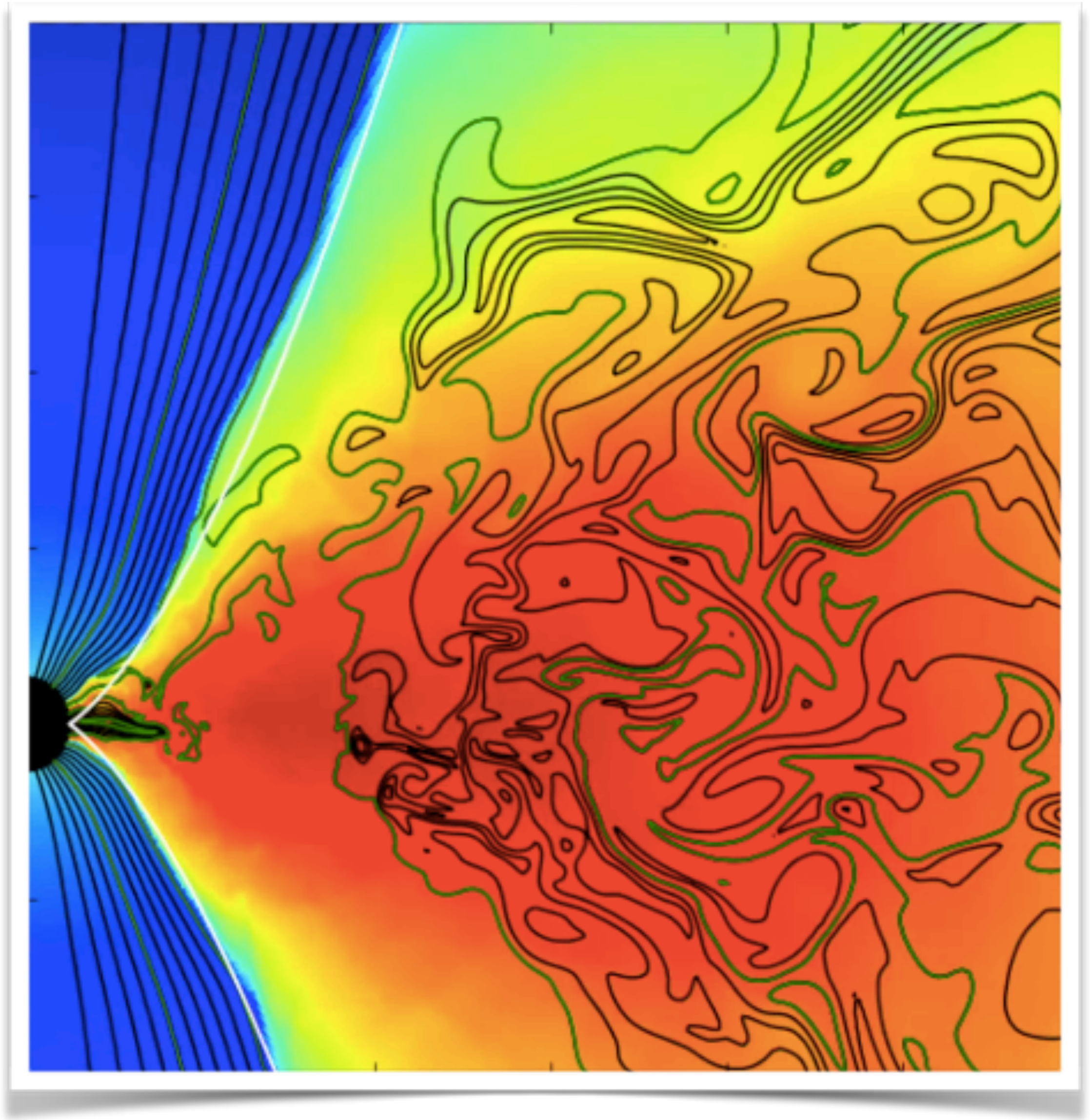
Nakamura+18 (see also Pu+ 15,20 for analytical approaches)



time-averaged GRMHD simulation result
McKinney06

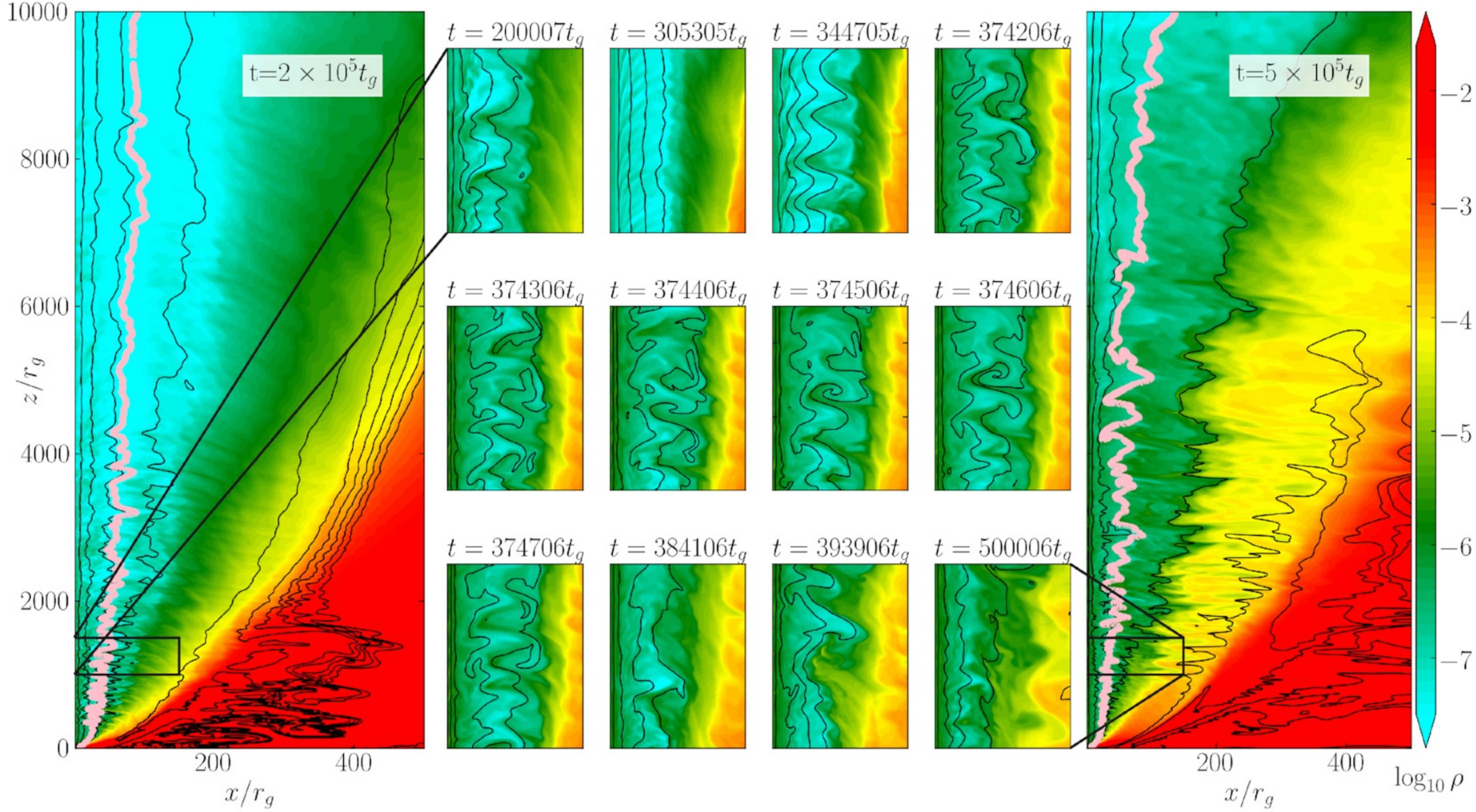
stagnation as function of BH spin





semi-analytical GRMHD jet model
by Pu & Takahashi 20

Mixing between the jet and the disc wind leads to mass loading of the jet



Chatterjee+ 19, by using GPU-accelerated GRMHD code H-AMR (Liska +18)

wind properties

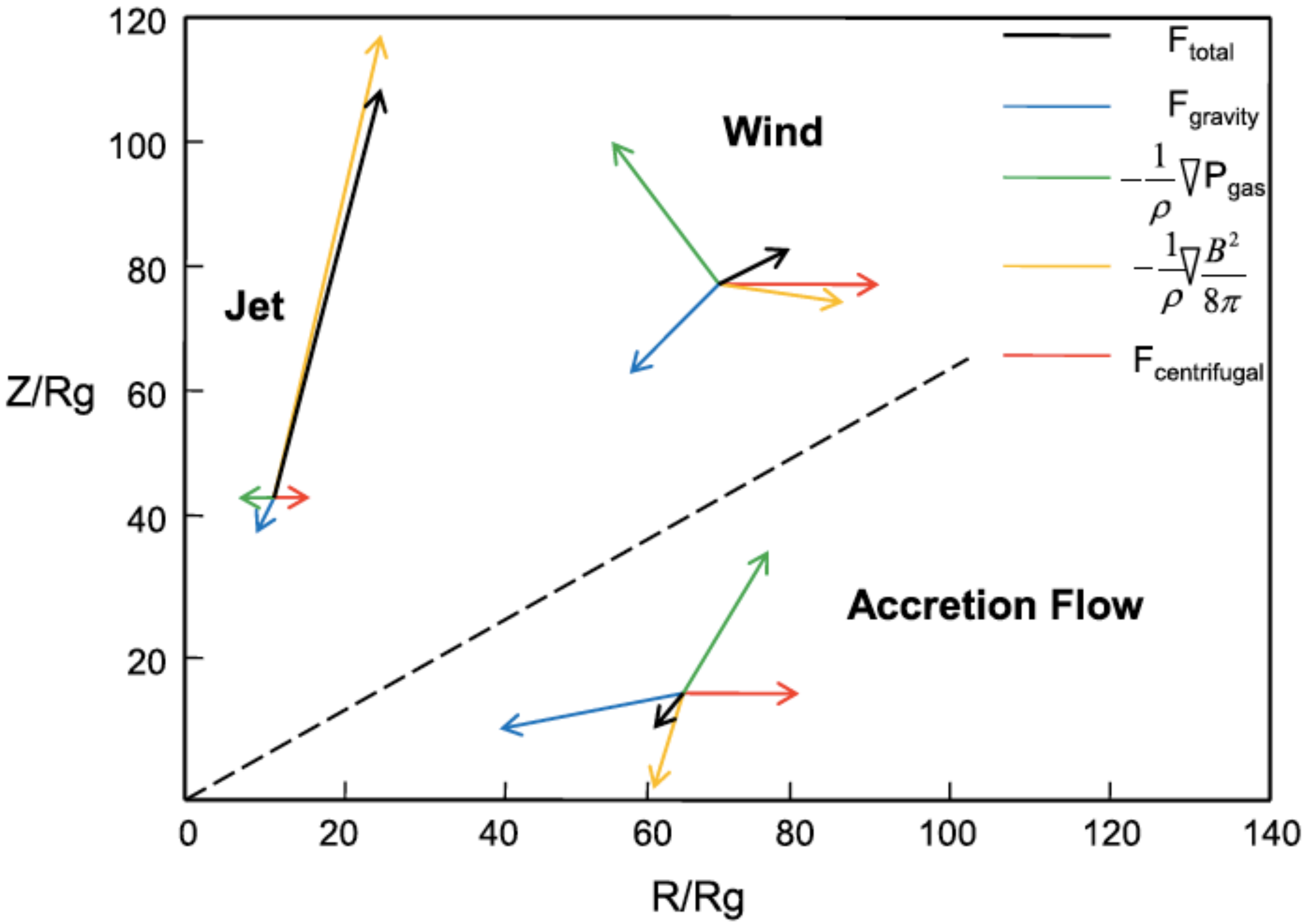
wind from hot accretion:

$$\dot{M}_{\rm wind} \propto \dot{M}_{\rm BH} \times r^s$$

$$s \approx 1$$

Cheng-Yu's talk

Holger's talk

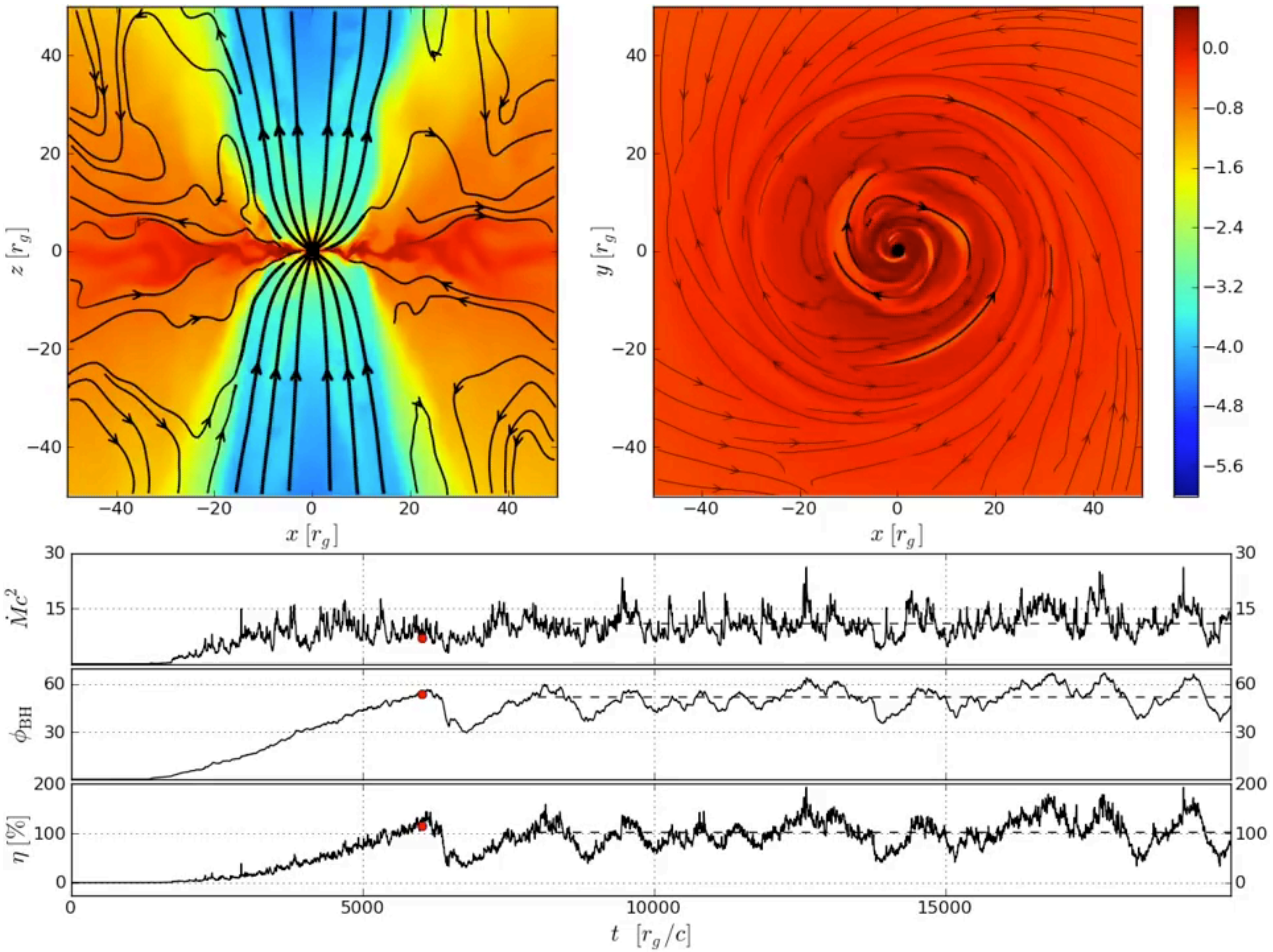


Yuan+15: 3D GRMHD simulation, a=0

$P_{jet} > P_{acc}$ for a fast-spinning black hole?

$$p^{BZ} \approx \Phi^2 a_*^2$$

$$\Phi \propto BM^2$$



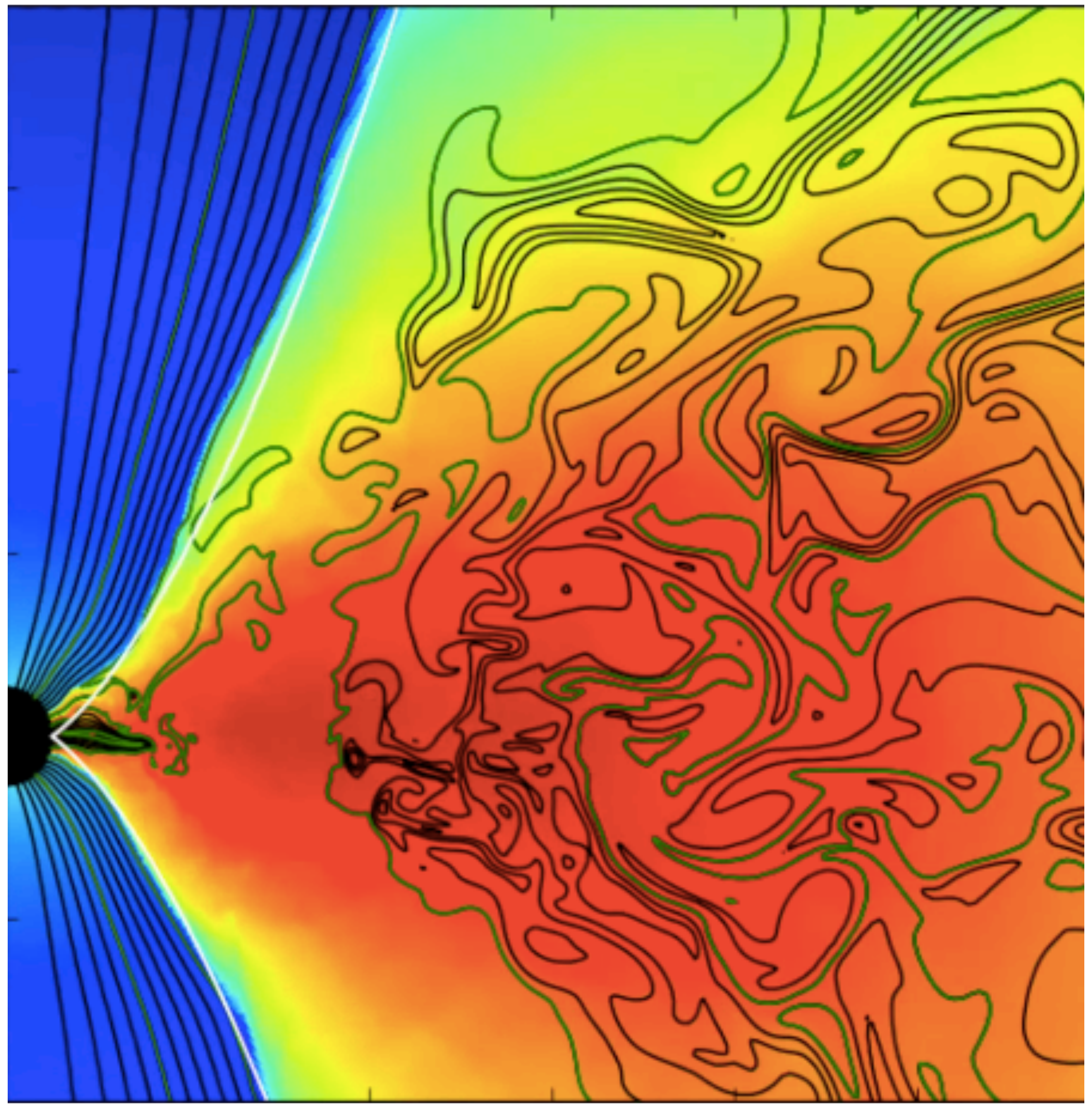
Tchekhovskoy+11

more magnetic flux on black hole → **upper limit**

$$\phi \equiv \Phi_{\rm BH}(\dot{M} R_g^2 c)^{-1/2}$$

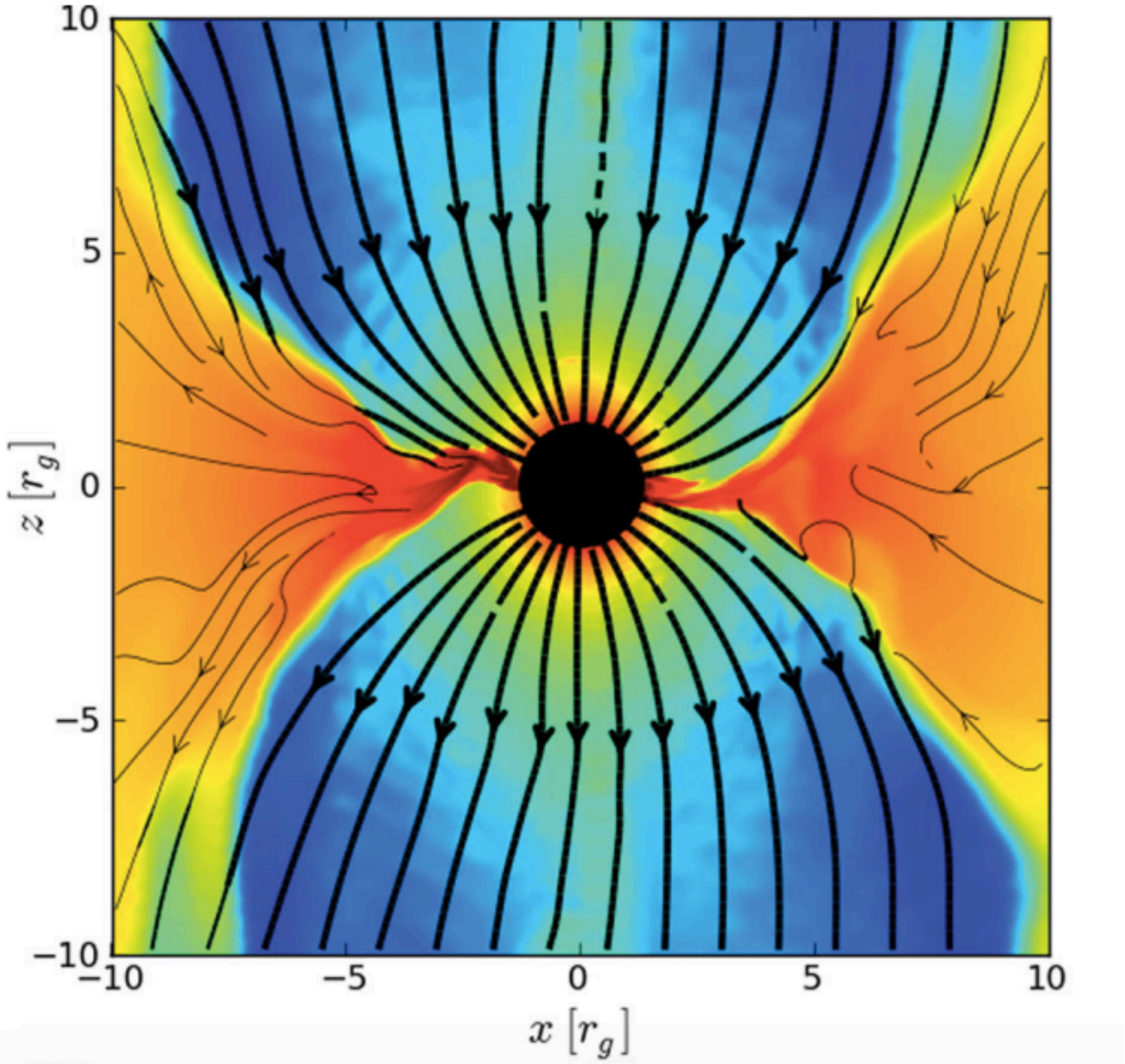
$\phi \sim 1$ $\phi \sim 50$

SANE
(Standard And Normal Evolution)

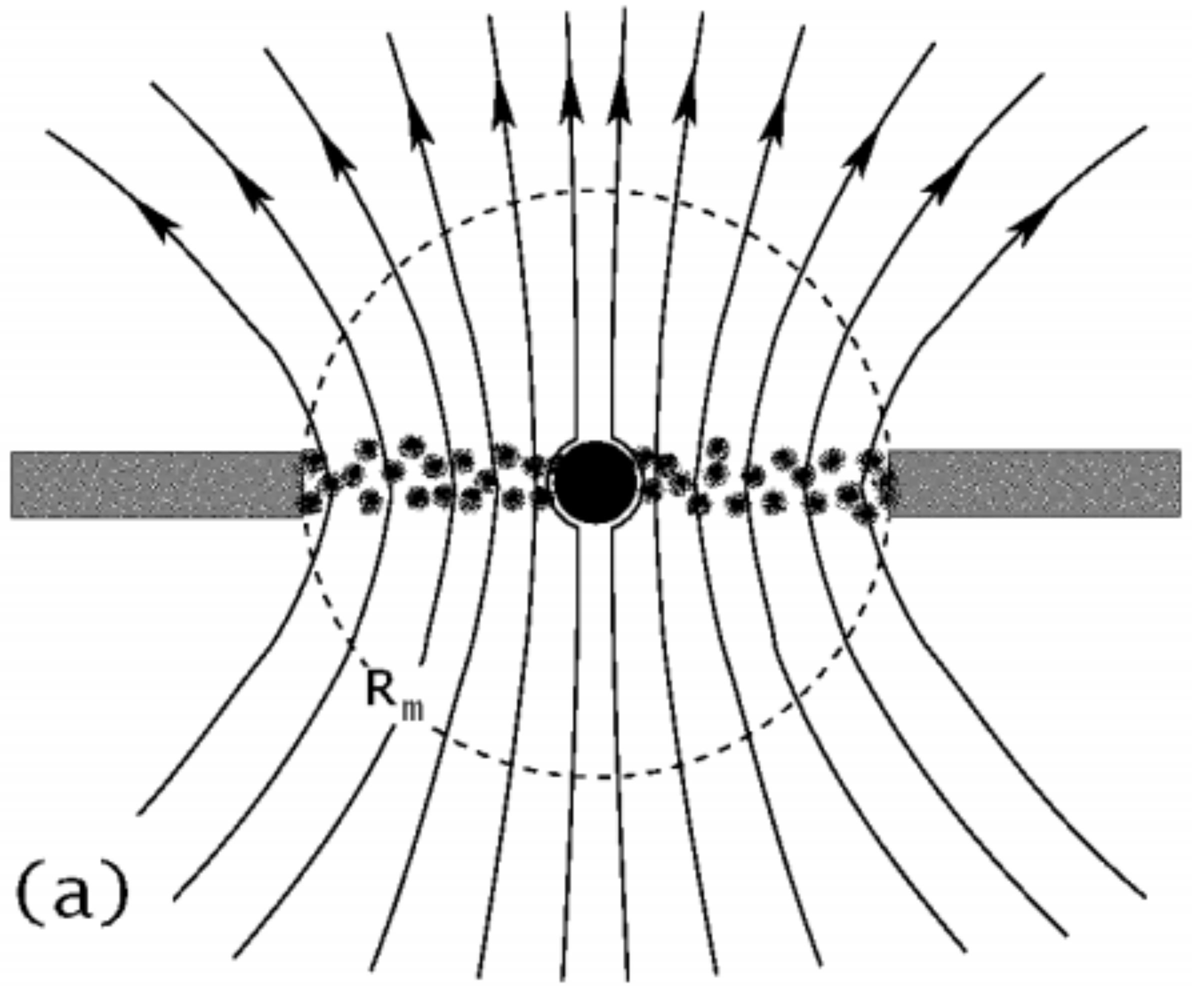


e.g. Narayan+12

MAD
(Magnetically Arrested Disk)



Narayan+03, Tchekhovskoy+11; McKinney+12



Narayan+03

linking simulations to **EHT observations** with known unknowns

parameterize the thermodynamics/electron heating:

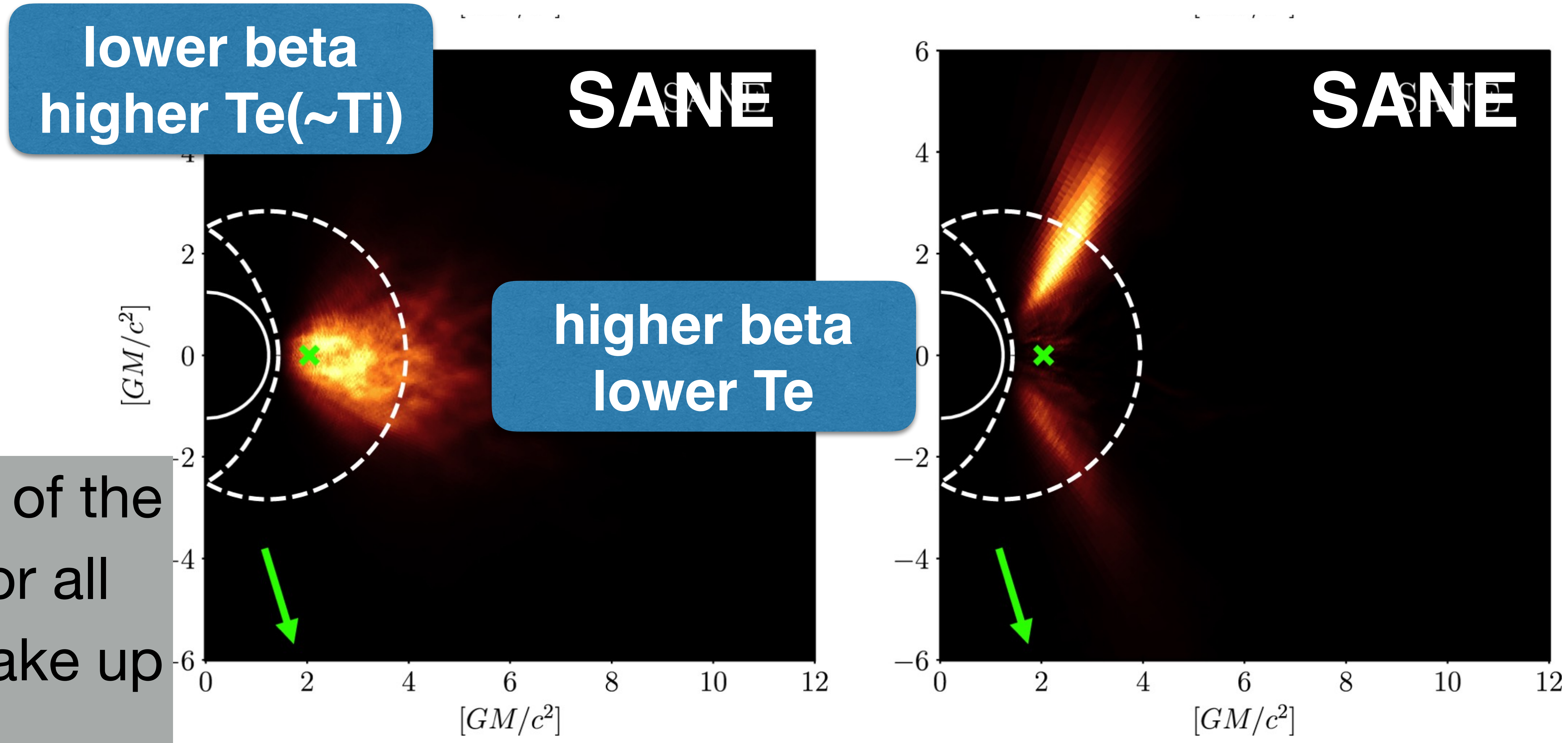
$$T_i/T_e = R_{\rm high}\frac{\beta_{\rm p}^2}{1+\beta_{\rm p}^2} + \frac{1}{1+\beta_{\rm p}^2}$$

$$\beta_{\rm p} \equiv p_{\rm gas}/p_{\rm mag}$$

Mościbrodzka et al (2016)

Rhigh=1, 10, 20, 40, 80, 160

lower the Te near the equatorial region



Binned location of the point of origin for all photons that make up an image

EHT paper V

ps. non-thermal electrons is also important but ignored

beyond one-fluid approximation

two fluid
(ions + thermal electrons)

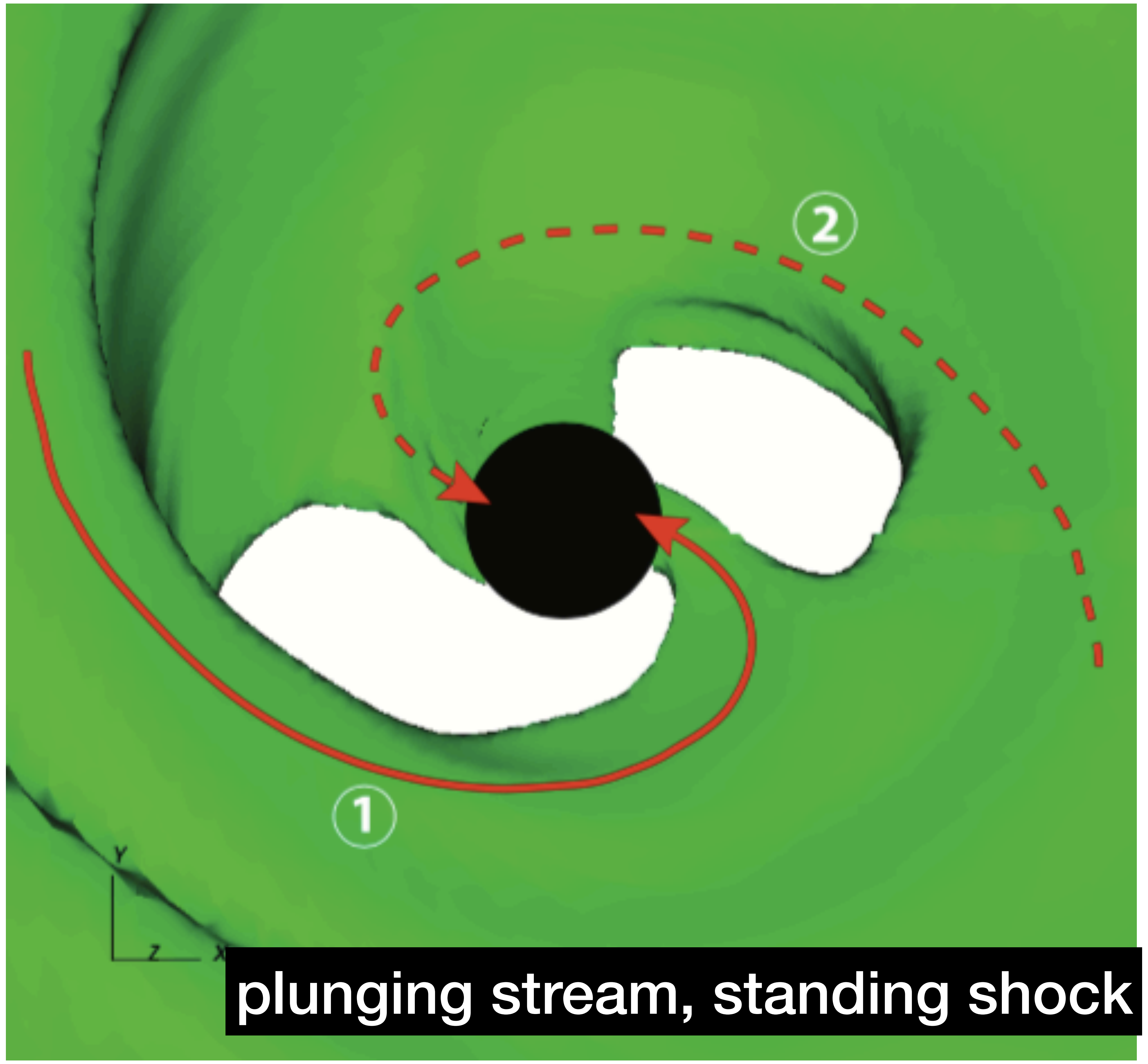
based on single-T flow via post-processing steps
(Ressler et al. 2015, 2017)
(Ryan et al. 2017 GRRMHD:ebhlight)

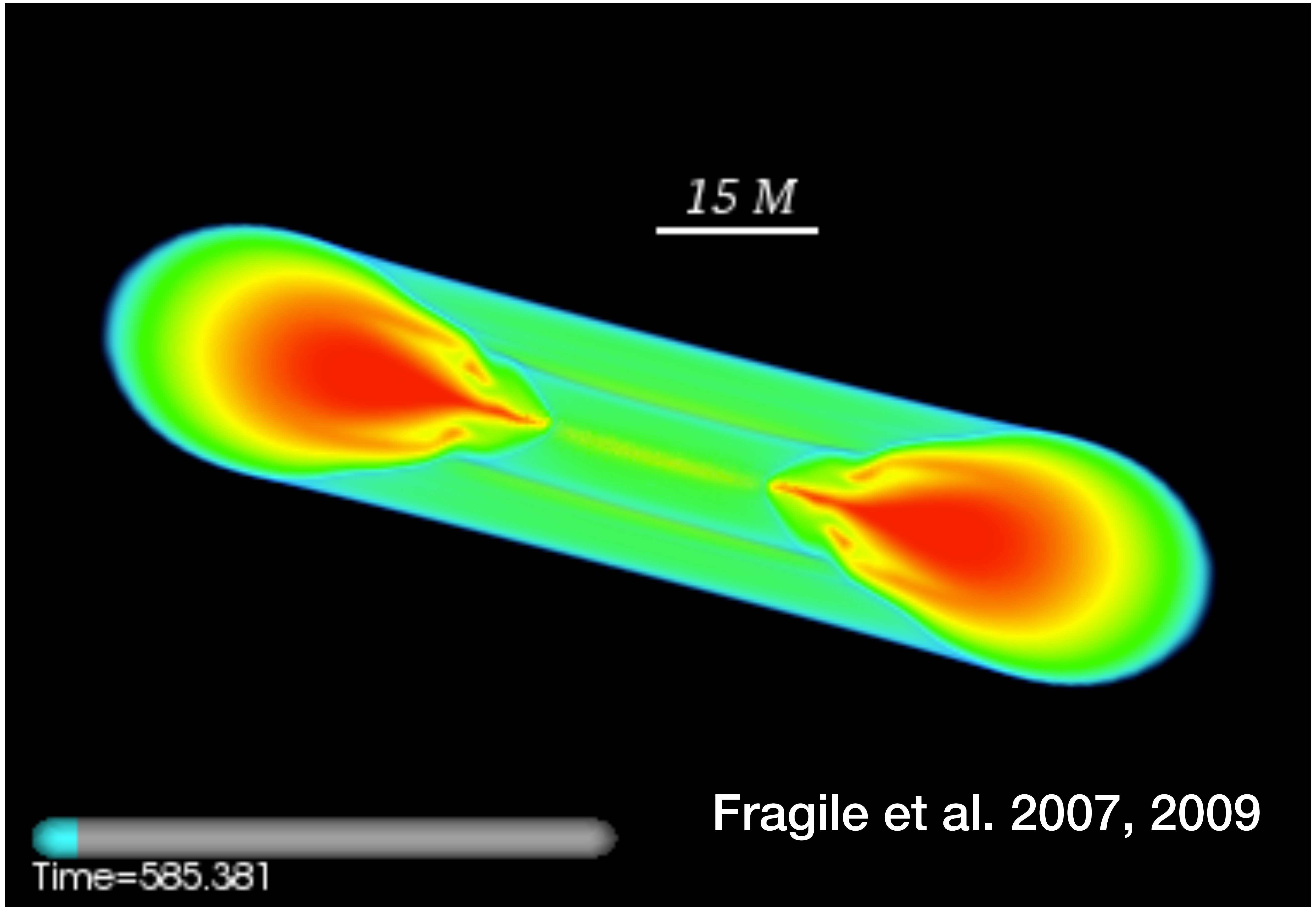
independent two fluid
Sadowski et al. 2017 GRrMHD:KORAL

three fluid
(ions + thermal electrons +
non thermal electrons)

independent three fluid
Chael et al. 2017; GRrMHD:KORAL

Tilted disk





(see also Chatterjee+ 20)

Final Remarks

- what's interesting about BH accretion (on horizon-scale)?
  - (1) accretion type as function of accretion rate (related to plasma physics, energy equation)
  - (2) relativistic jet, winds (disk-jet coupling)
  - (1)+(2): physical origins of AGN feedback (if exist)
  - black hole spin, magnetic field matters: **simulation** brings surprises, **analytical model** brings insights; input from *microphysics (sub-grid physics)* needed **cf. Karen's talk**
  - other physics beyond horizon-scale: feedback, jet acceleration etc.
- with EHT (and LIGO/VIRGO/KAGRA), we are heading the **golden age of Black Hole Astrophysics** (in strong gravity regime!) **cf. Yen-Chen's talk**

★ Opportunities for all students in Taiwan!