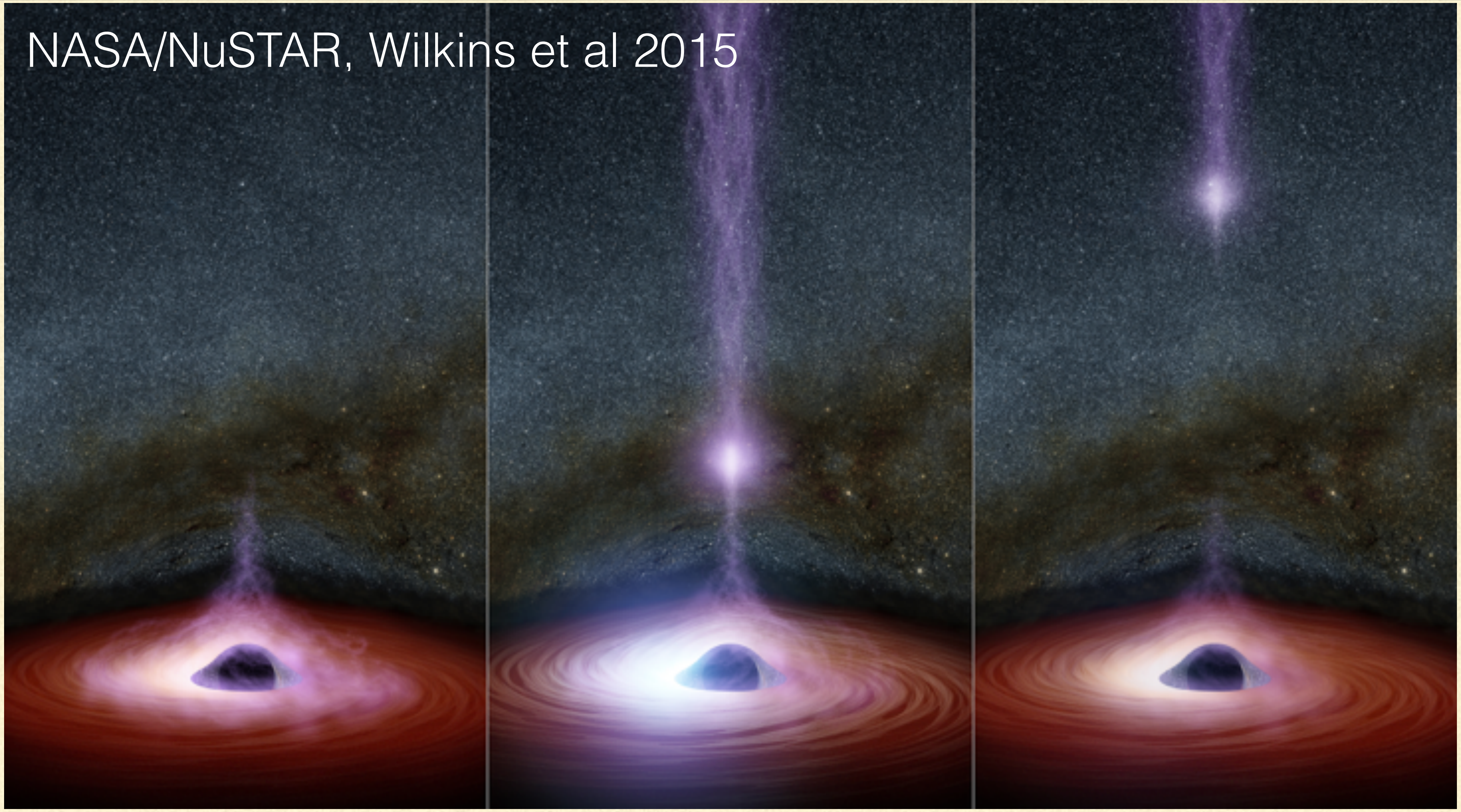


Formation of lamp-post coronae in Seyfert Galaxies and X-ray binaries

Yajie Yuan (Spitzer Fellow, Princeton)

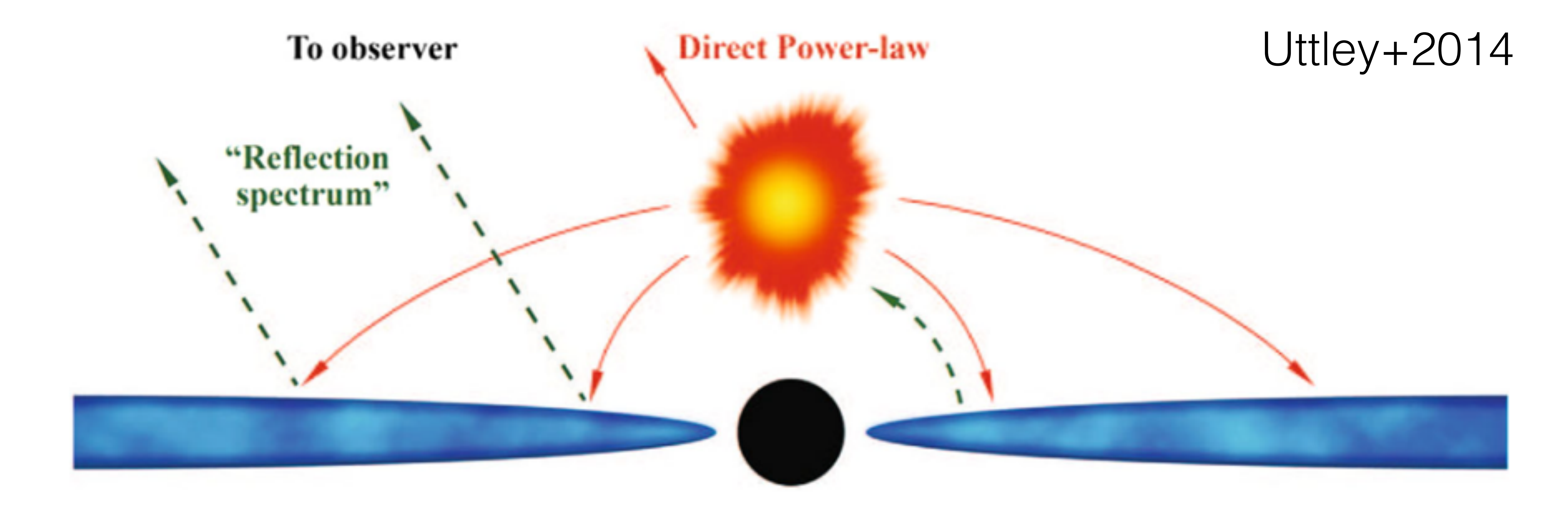
In collaboration with: Roger Blandford, Dan Wilkins (Stanford)
and Anatoly Spitkovsky, Alex Chen (Princeton)

Outline

- Observations and puzzles
- Possible scenarios for the compact X-ray corona:
  - Gap at the base of the jet (?)
  - Tangling of small scale flux tubes near the axis
- Summary and perspectives

X-ray coronae in Seyfert Galaxies

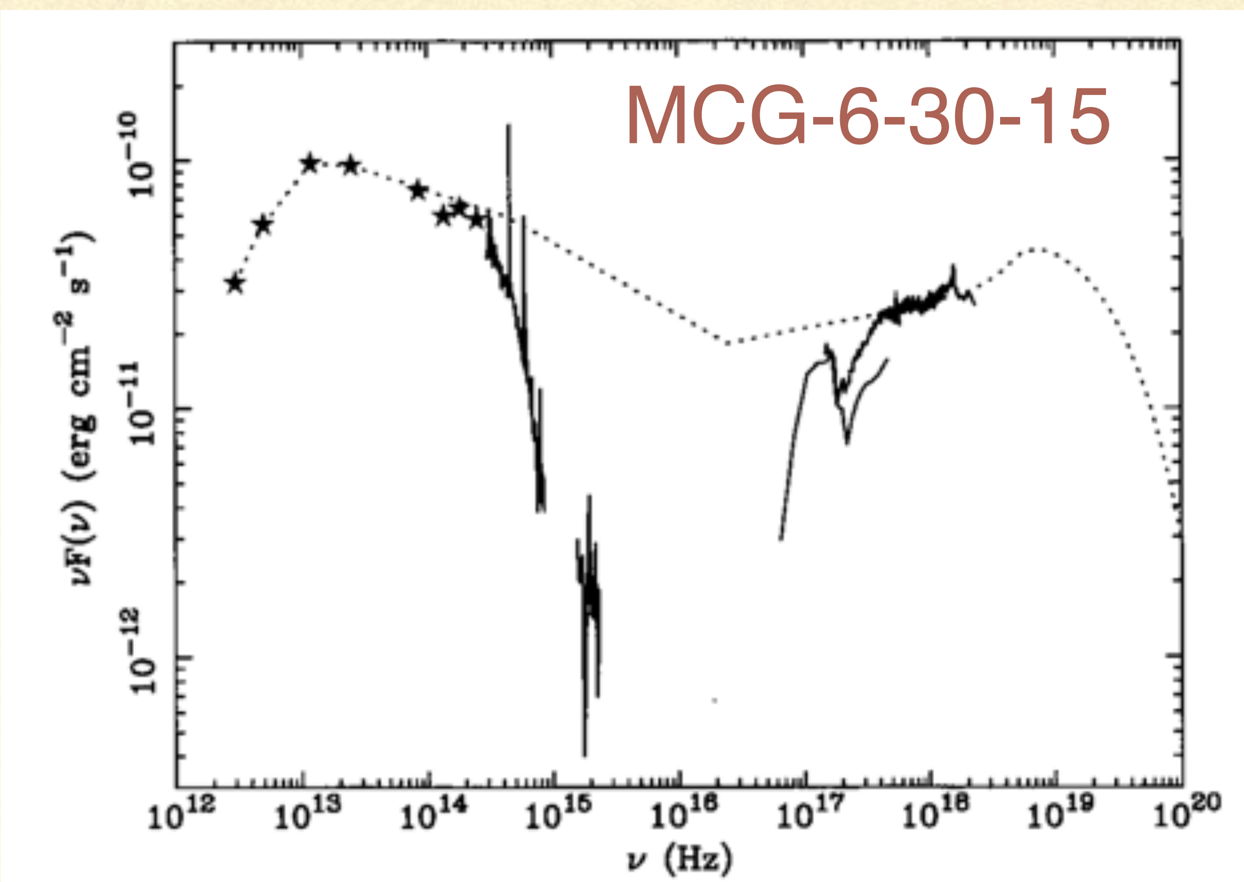
- Spiral galaxies, $M \sim 10^6$–$10^8\ M_\odot$, Radio quiet
- $L \sim 0.01 - 1\ L_{Edd}$
- $L_X \sim L_{O/UV}$



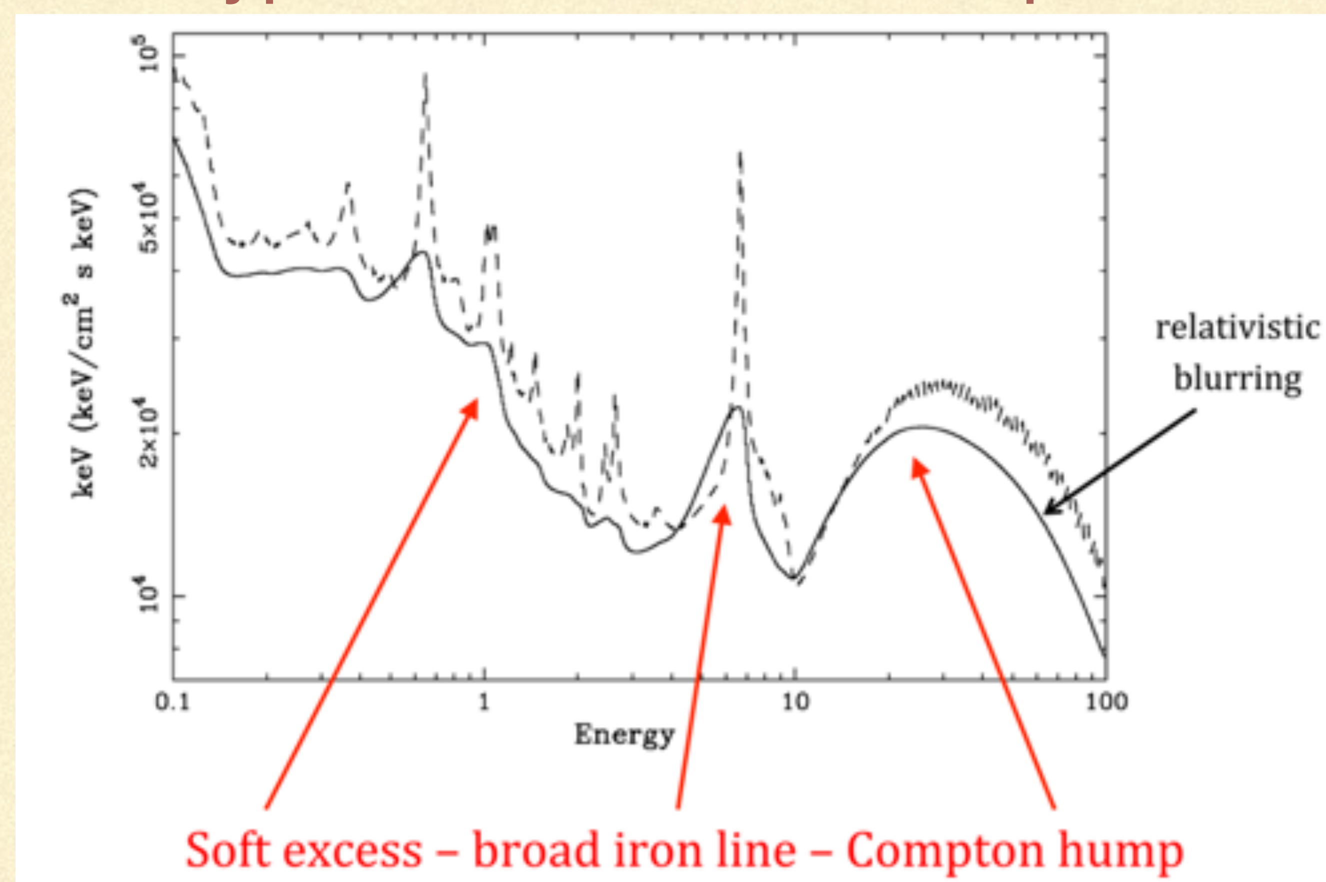
X-ray coronae in Seyfert Galaxies

- Spiral galaxies, M ~ 10^6–10^8 $M_\odot$, Radio quiet
- L ~ 0.01 — 1 L_{Edd}
- L_X ~ $L_{O/UV}$

typical local reflection spectrum



Reynolds+1997



Uttley+2014

Lamppost coronae?

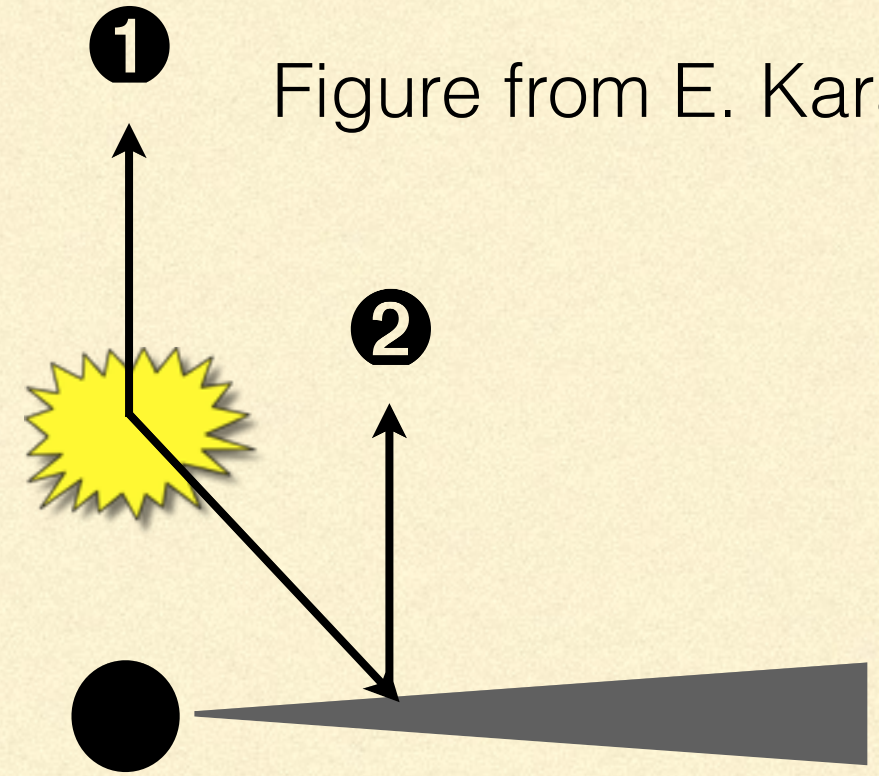
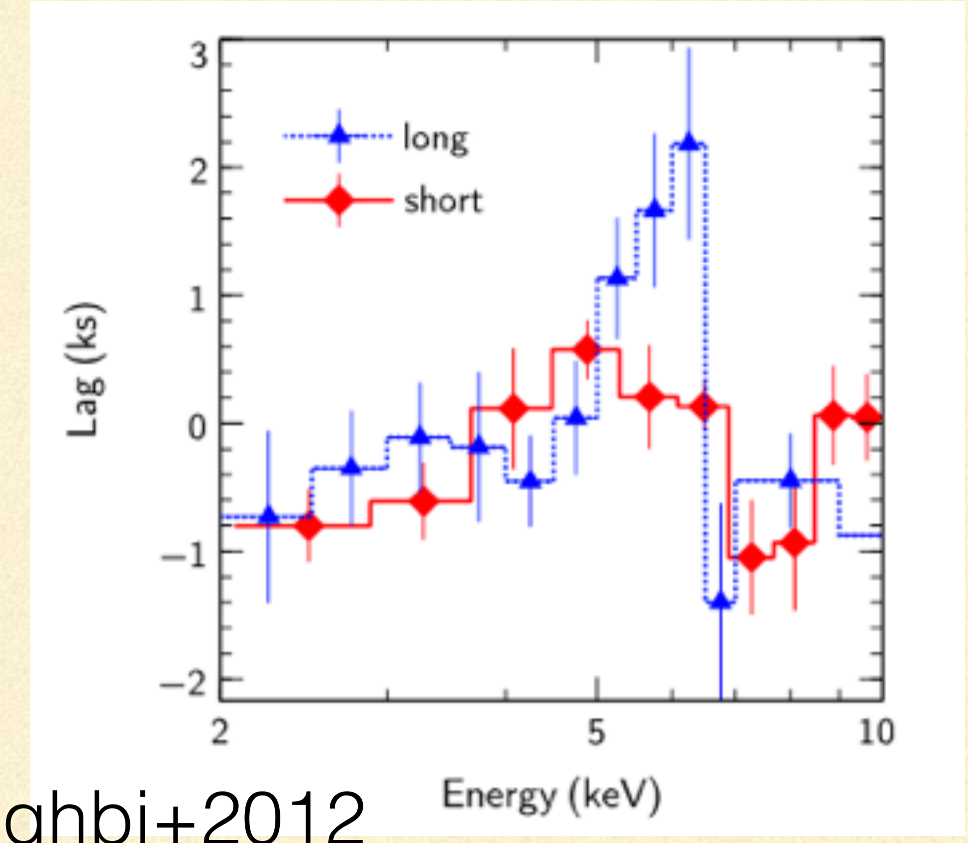


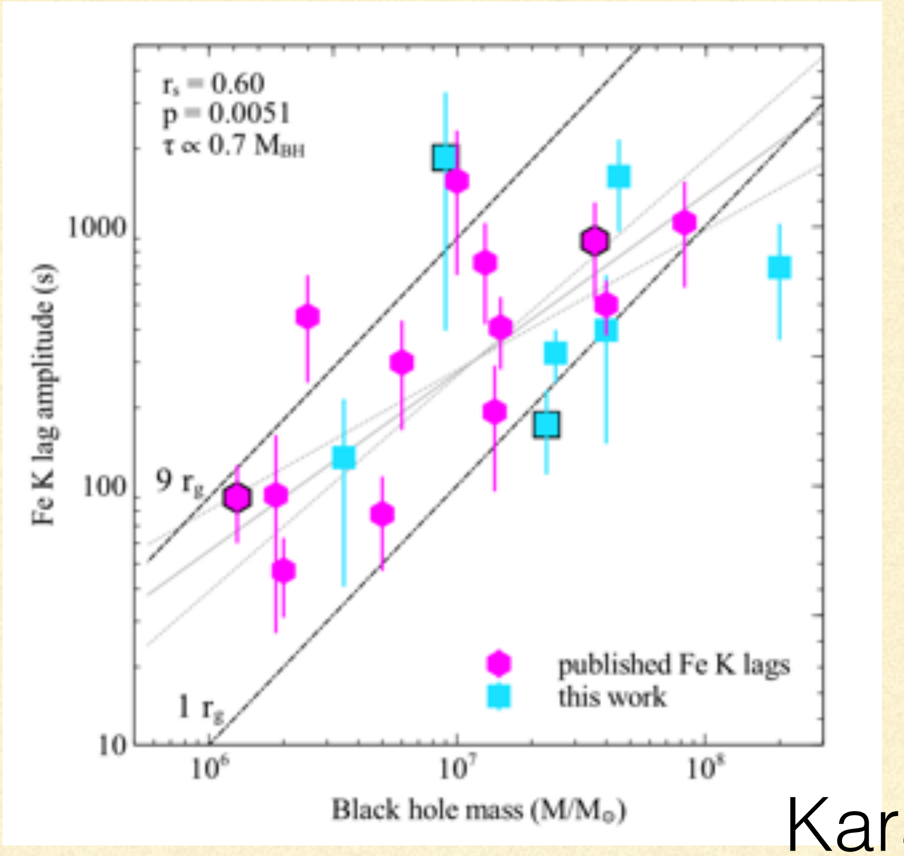
Figure from E. Kara

- Reverberation mapping
- emissivity profile modeling
- Microlensing

Iron K lag in NGC 4151



Zoghbi+2012

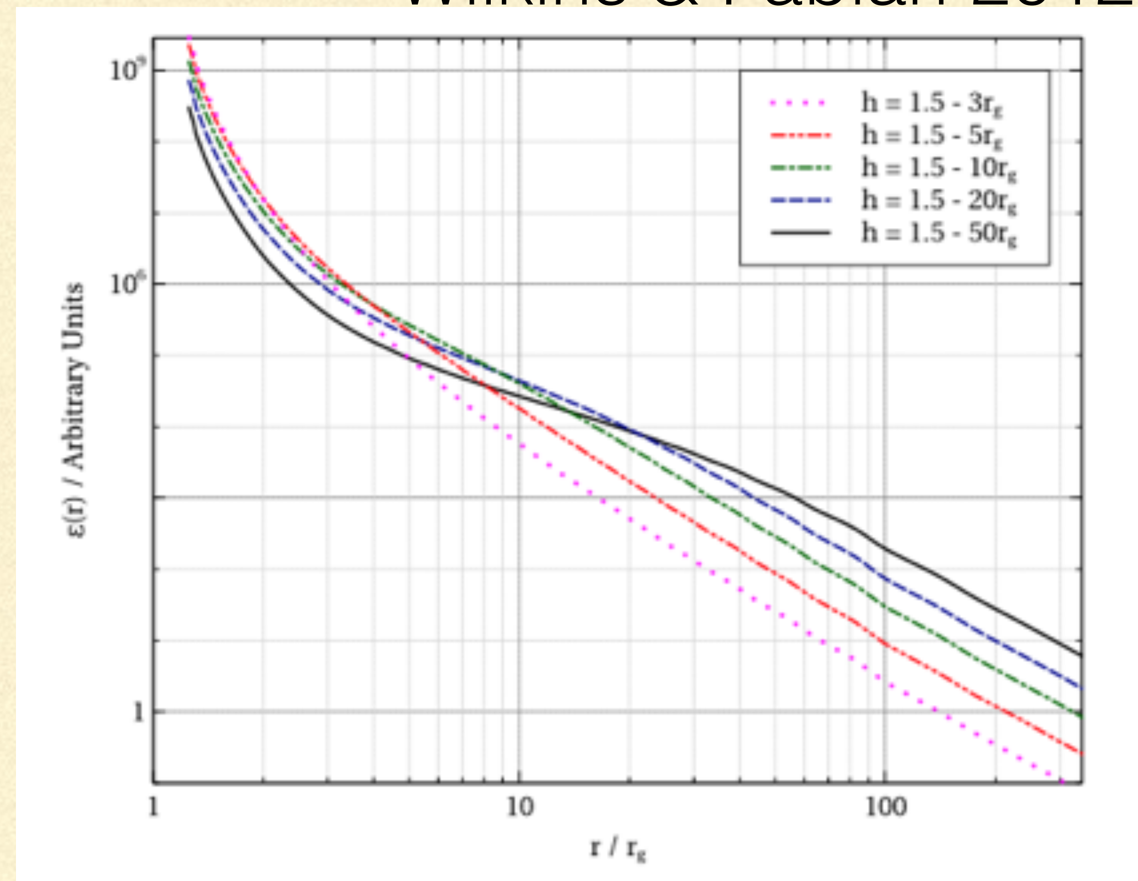


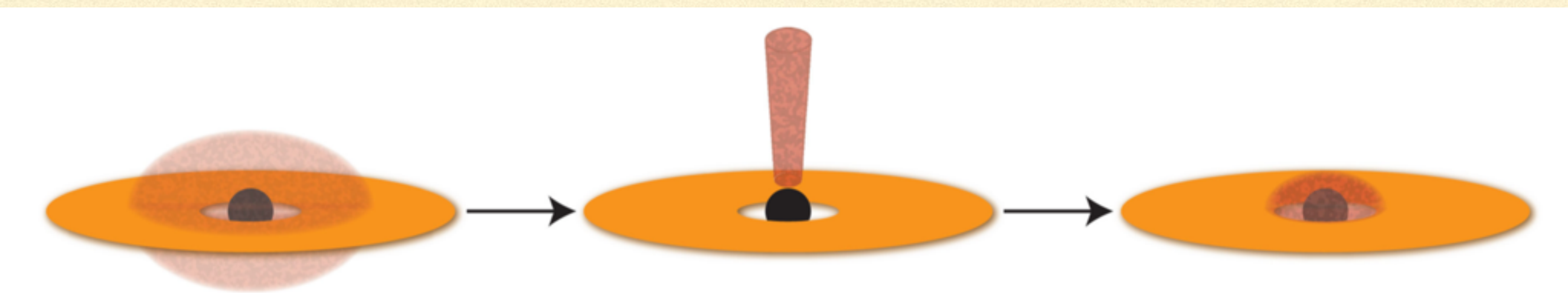
Kara+2016

Lamppost coronae?

- Reverberation mapping
- emissivity profile modeling
- Microlensing

Wilkins & Fabian 2012





Mrk 335, Wilkins & Gallo 2015

Lamppost coronae?

- Reverberation mapping
- emissivity profile modeling
- Microlensing

Object (1)	$\log(M_{BH}/M_\odot)$ (2)	L/L_{Edd} (3)	Log(Size/cm) (4)	$\langle S \rangle$ (r_g) (5)
Q 2237+0305	8.68 ± 0.36	0.44	$15.46^{+0.34}_{-0.29}$	41^{+28}_{-17}
RX J1131−1231	8.32 ± 0.62	0.03	14.04–14.68	$7.4^{+7.6}_{-3.8}$
Q J0158−4325	8.2 ± 0.2	0.4	$14.3^{+0.4}_{-0.5}$	$8.5^{+6.1}_{-3.5}$
HE 1104−1805	9.37 ± 0.33	0.36	14.2–15.0	$1.1^{+0.7}_{-0.4}$
HE 0435−1223	8.76 ± 0.44	0.11	<15.07	$13.8^{+8.6}_{-5.3}$
PG 1115+080	9.1 ± 0.2	0.37	$15.6^{+0.6}_{-0.9}$	21^{+29}_{-12}

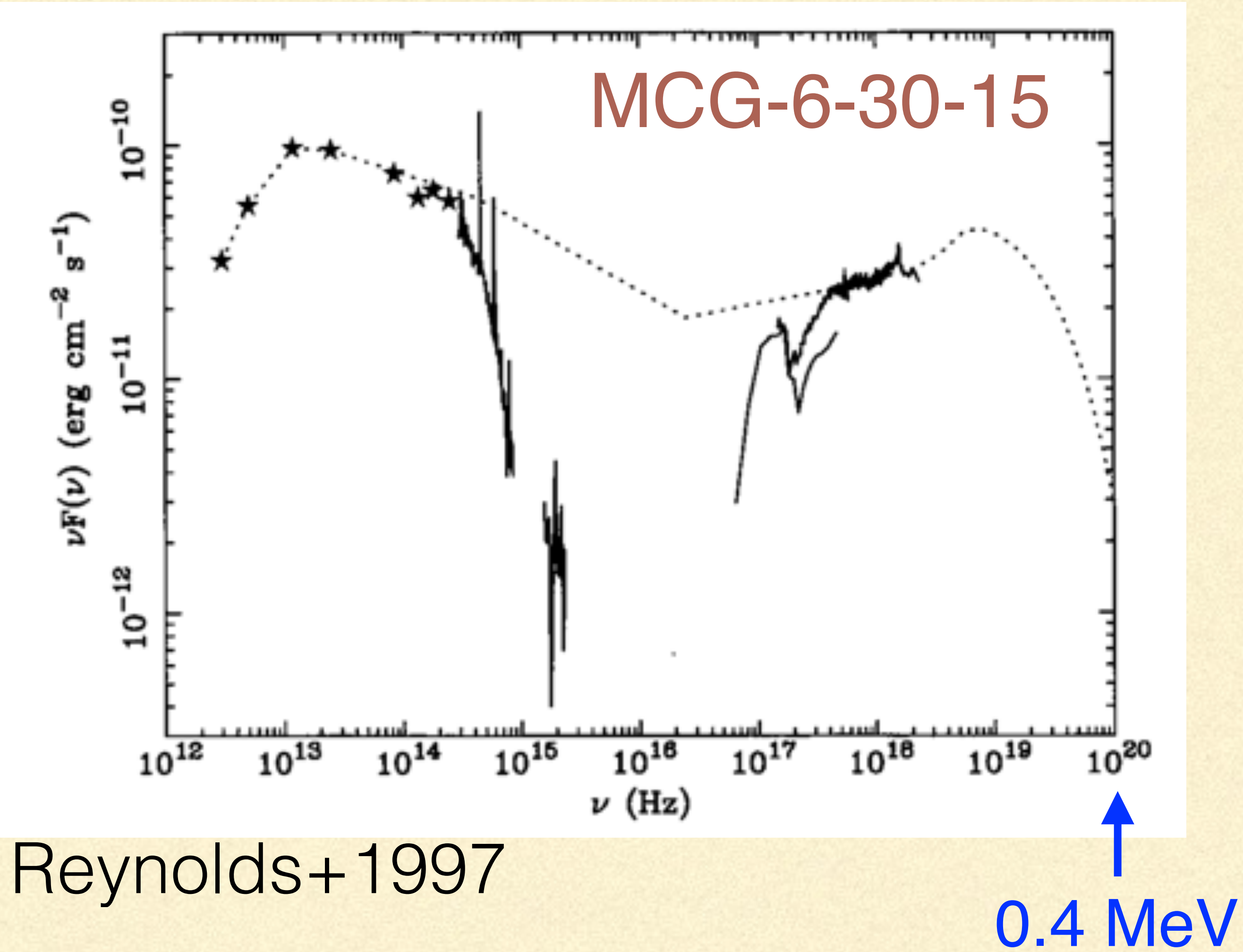
Morgan+2008; Chartas+2009; Mosquera+2013; Reis&Miller2013

Questions to answer

- Why is the corona so compact, and located at such a special place (a few gravitational radii above the BH)?
- Why is the X-ray luminosity so high?
- Is this relevant to the radio loud/quiet dichotomy?

Scenario 1: gap at the jet base

Scenario 1: gap at the jet base



Reynolds+1997

- If there are already plenty of MeV photons, gaps may not need to form
- What if gap is the sole source for X-rays and MeV emission?
  - Does the strong radiative drag on particles help enhancing the dissipation?

$$L_{\rm O/UV} \sim 0.1 L_{\rm Edd} \sim 10^{43} \text{erg s}^{-1}$$

$$u_s \sim 10^8 \text{erg cm}^{-3}$$

$$\epsilon_{s,\max} \sim 100\,\text{eV}$$

$$\gamma_{\rm thr} \sim m_e c^2/\epsilon_{s,\max} \sim 10^4$$

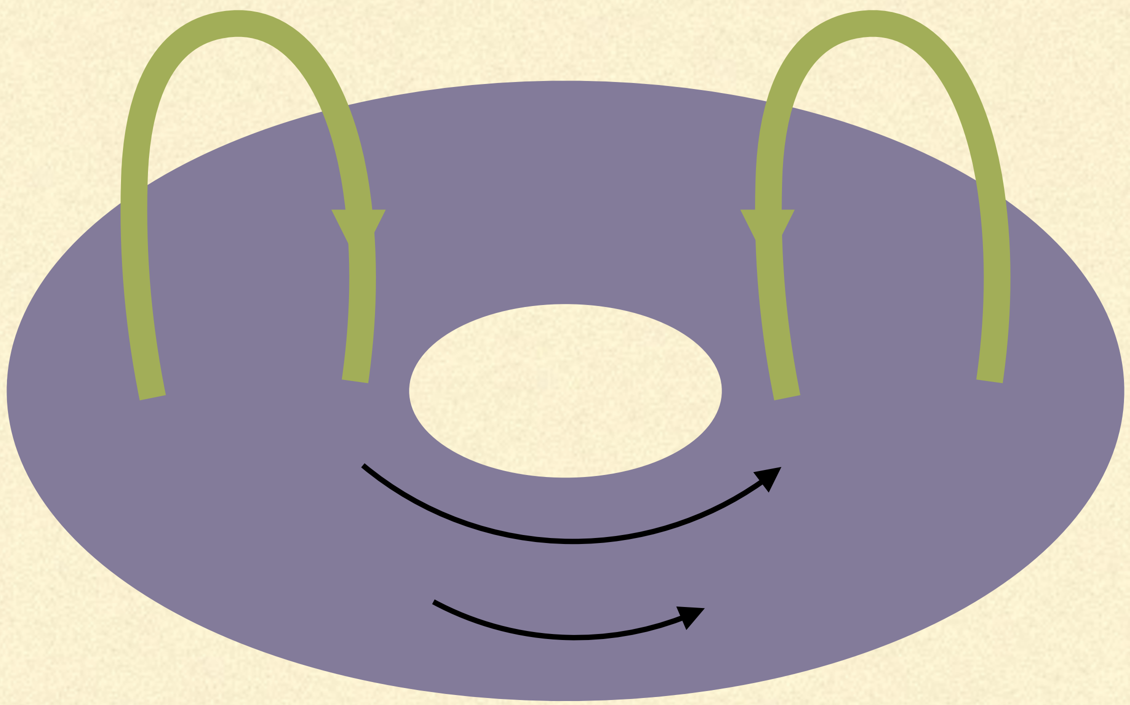
$$B \sim B_{\rm Edd} \sim 10^5\ \text{G}$$

$$E \sim \frac{4\gamma^2 \sigma_T u_s}{3e}, \quad \frac{E}{B} \sim 10^{-4}$$

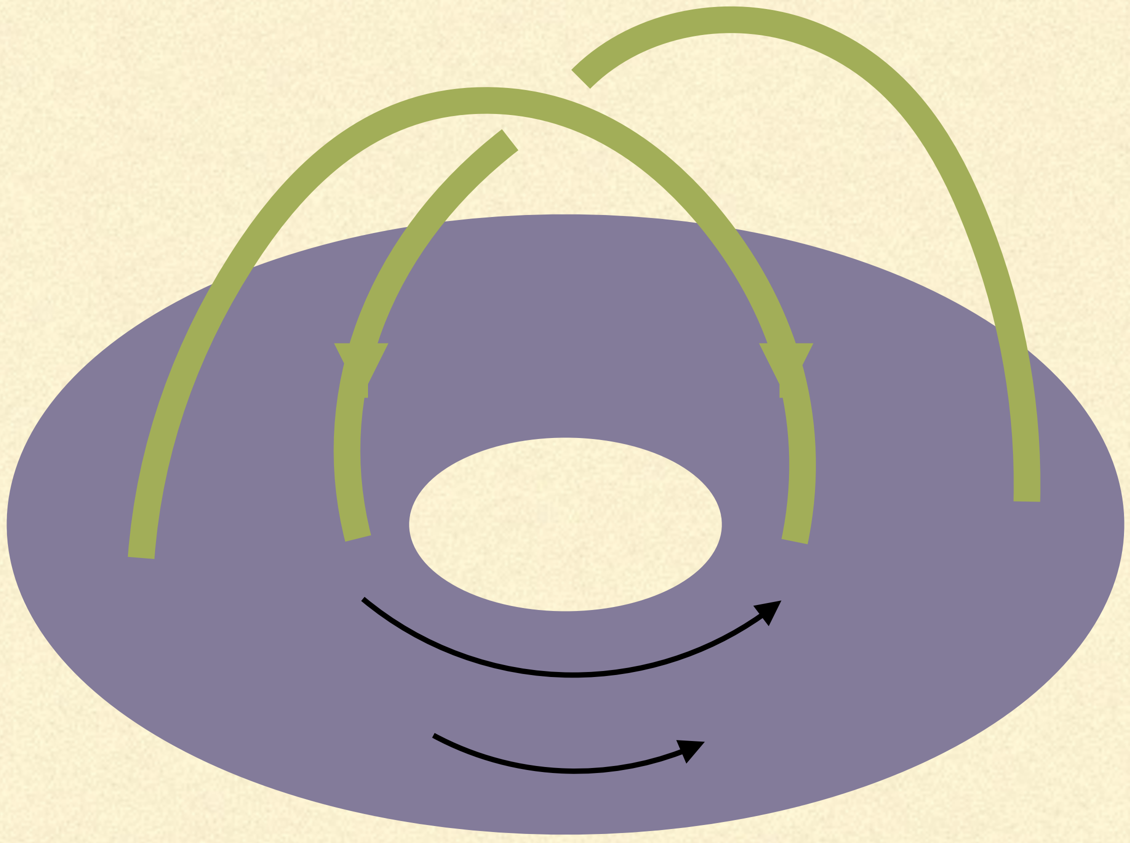
$$\frac{P_{\rm diss}}{L_{\rm jet}} \sim \frac{E j r_g^3}{B^2 r_g^2 c} \sim \frac{E}{B} \sim 10^{-4}$$

Too small!

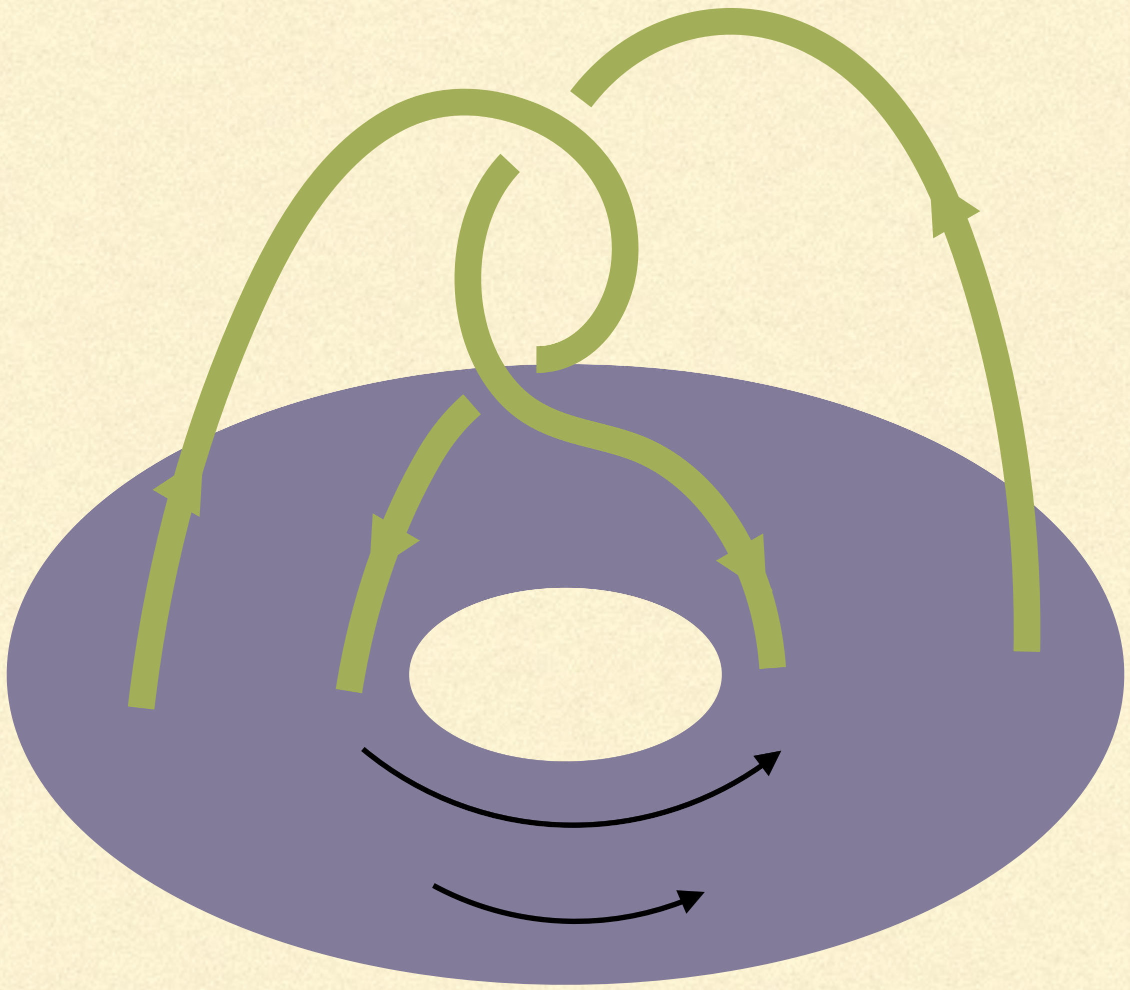
Scenario 2: tangling of small scale flux tubes near the axis



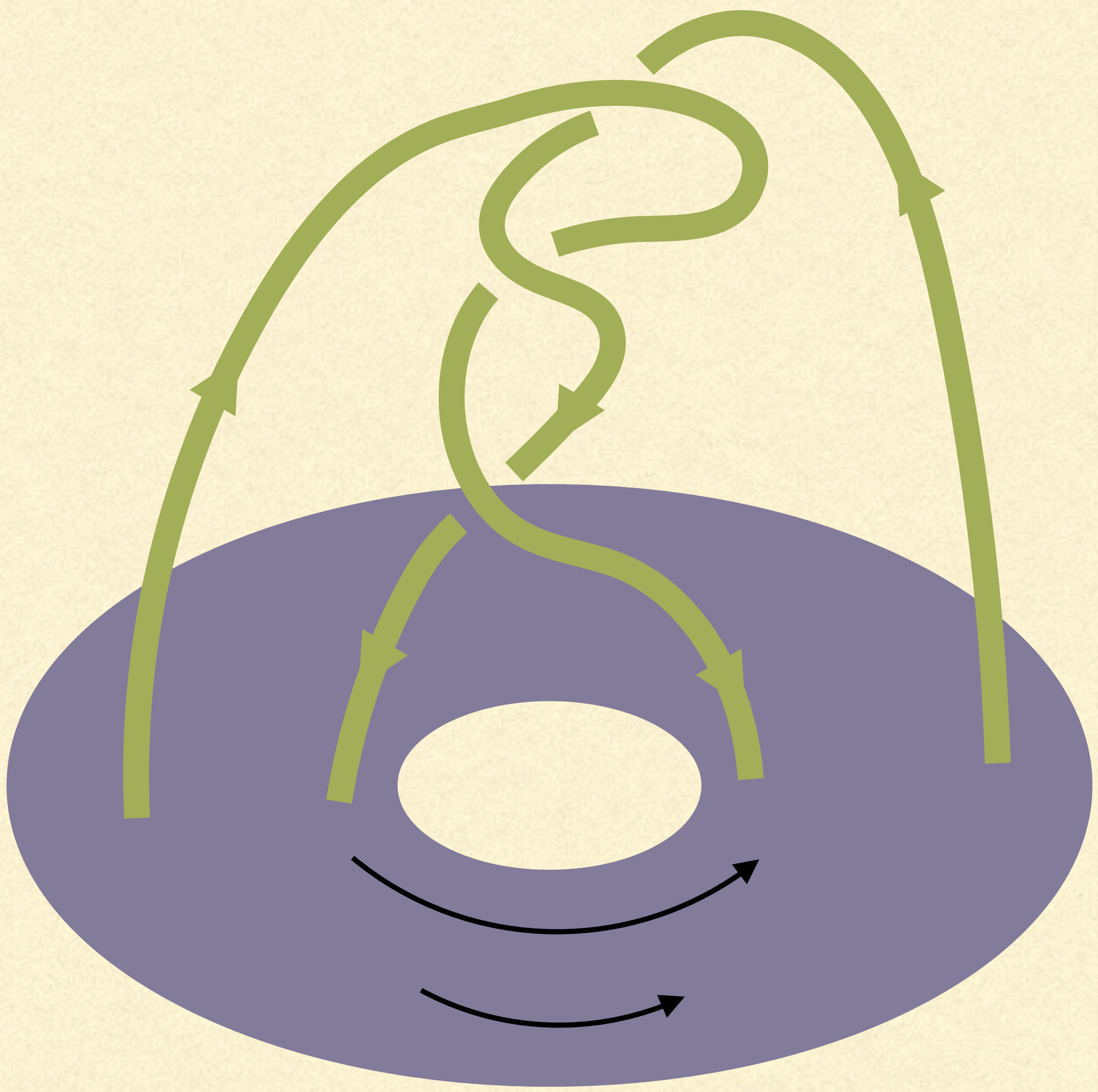
Scenario 2: tangling of small scale flux tubes near the axis



Scenario 2: tangling of small scale flux tubes near the axis

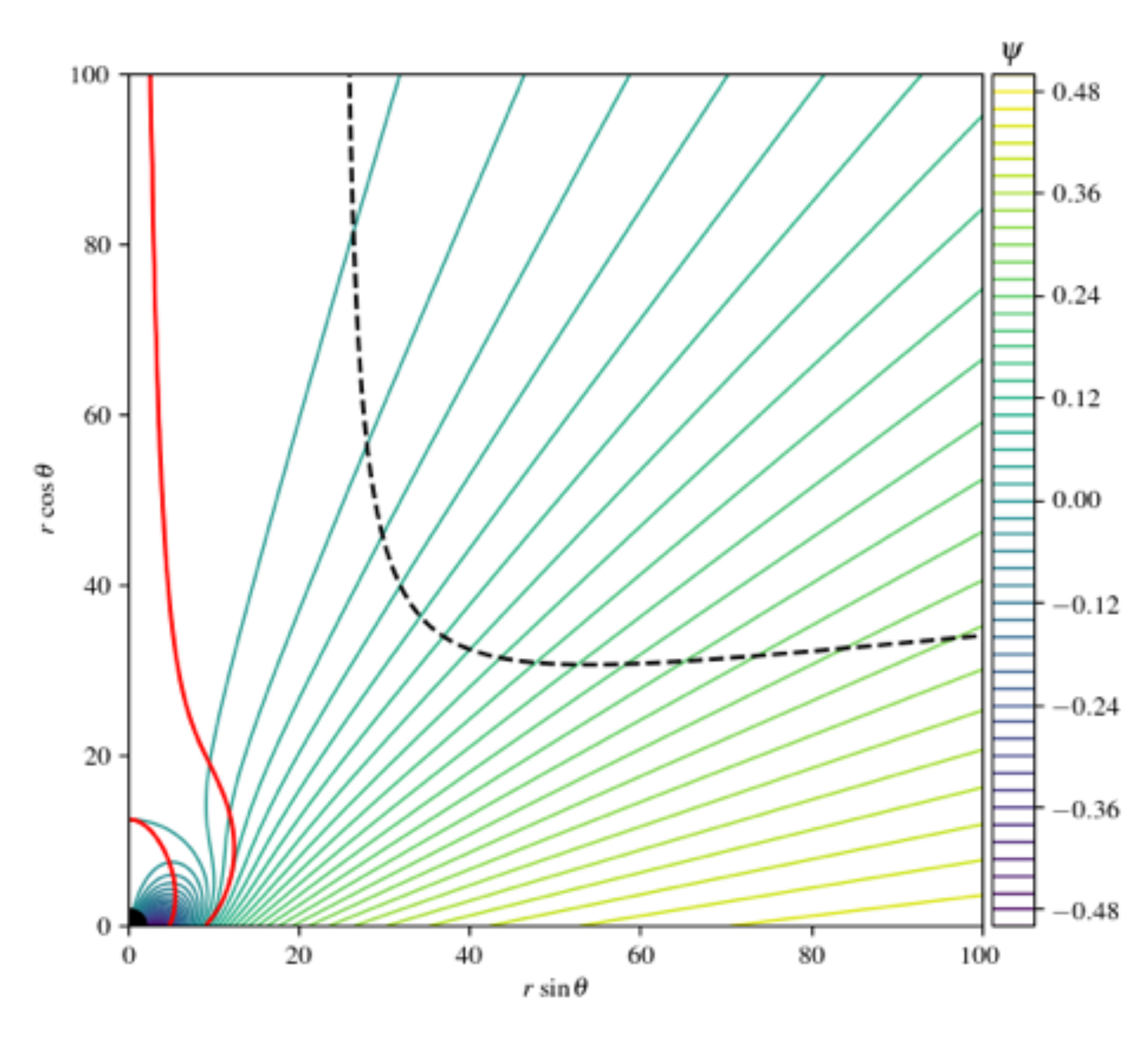


Scenario 2: tangling of small scale flux tubes near the axis



Force-free configuration in Kerr spacetime

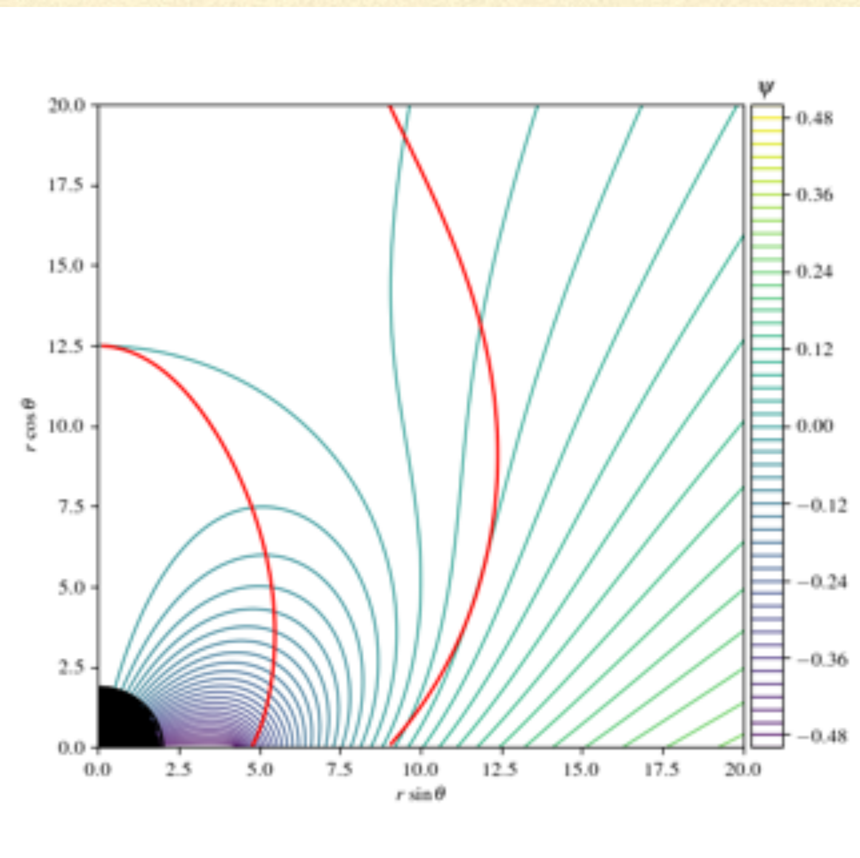
- Force-free, axisymmetric, steady state: Grad-Shafranov equation
- Earlier works: Uzdensky 2004, 2005, low spin regimes
- My new relaxation method, can also handle outer light surfaces for favorable configurations



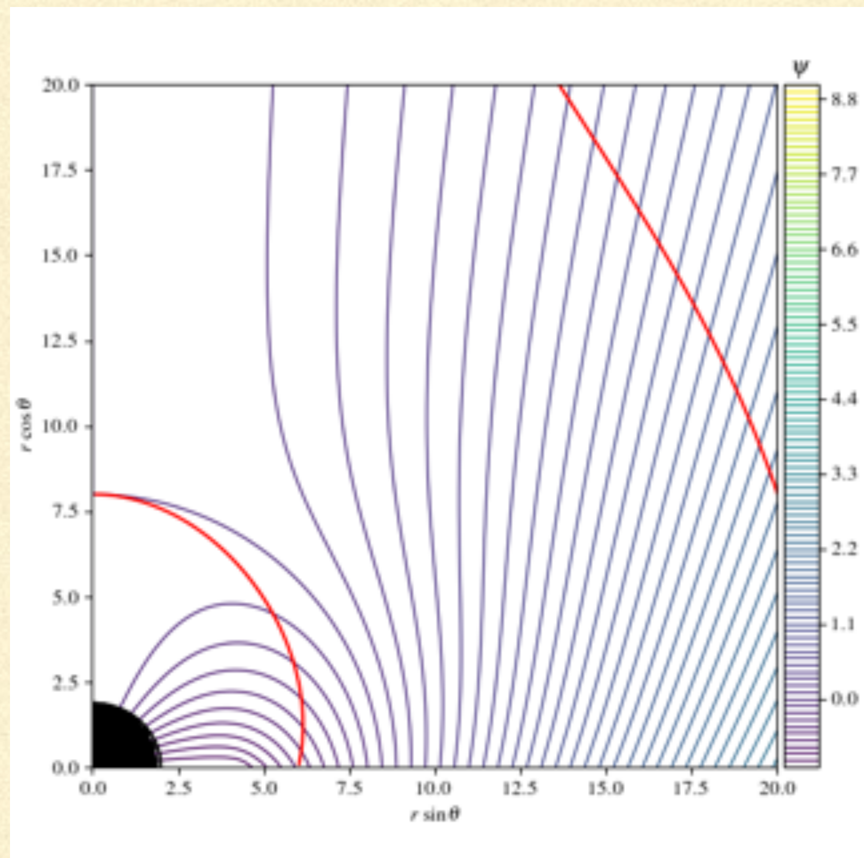
As field lines can slip on the BH, closed field lines linking the hole and the disk can exist in steady state!

What determines the extent of the closed zone?

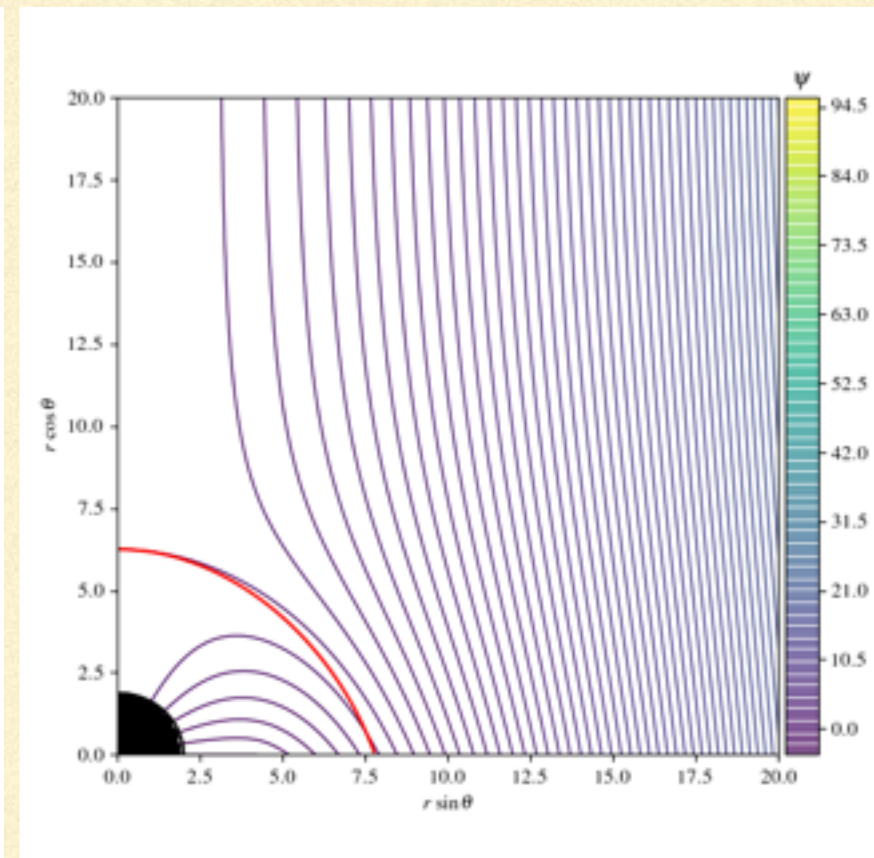
Effect of “external pressure”



$\psi_d = r_{\rm ISCO}(1/r_0 - 1/r)$



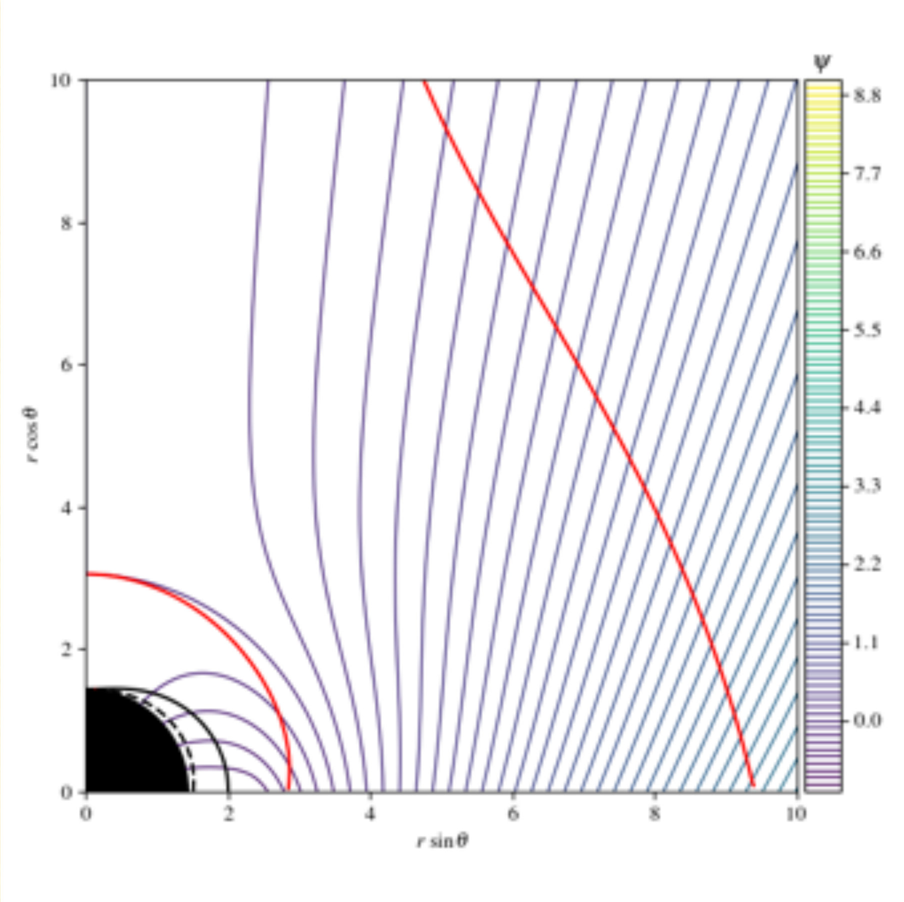
$\psi_d = (r - r_0)/r_{\rm ISCO}$



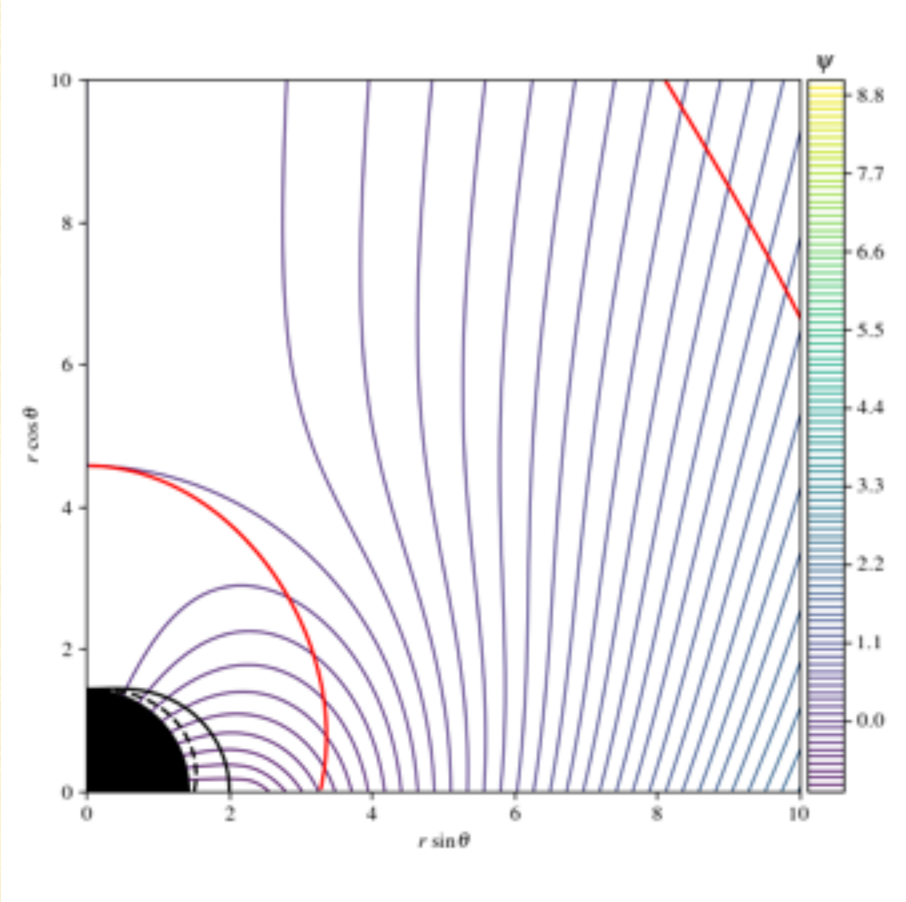
$\psi_d = (r^2 - r_0^2)/r_{\rm ISCO}^2$

Foot point on the disk

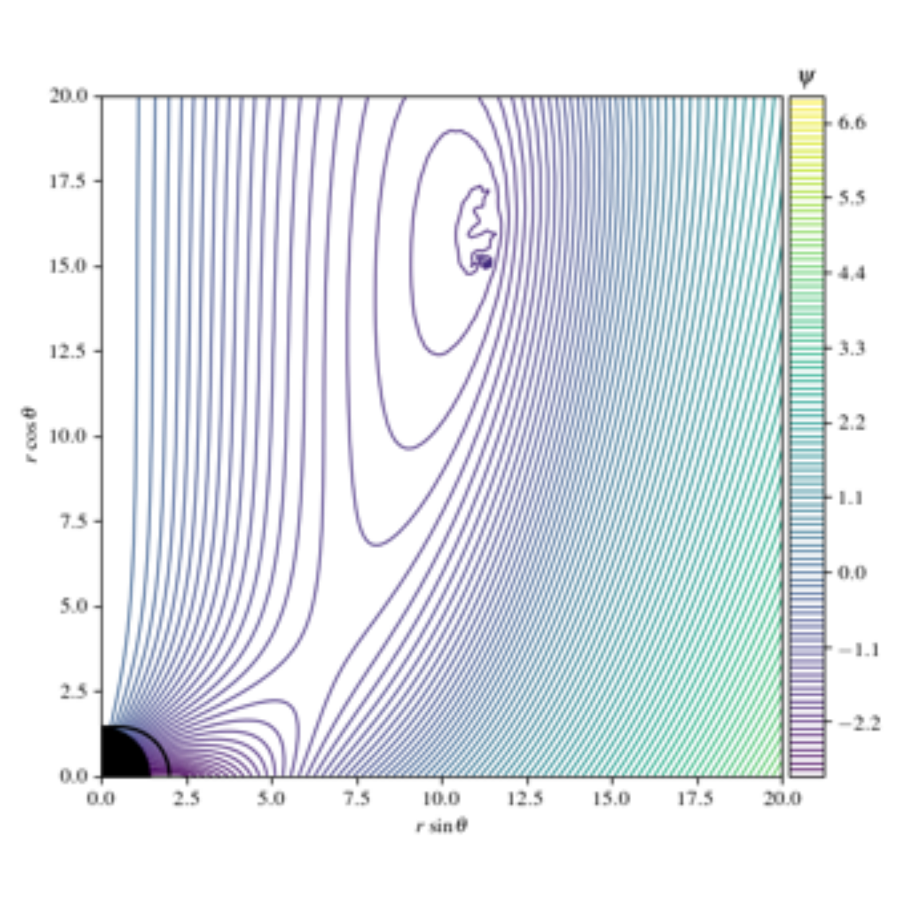
$$\psi_d = (r - r_0)/r_{\rm ISCO}$$



$r_0 = 1.5 r_{\rm ISCO}$



$r_0 = 2 r_{\rm ISCO}$

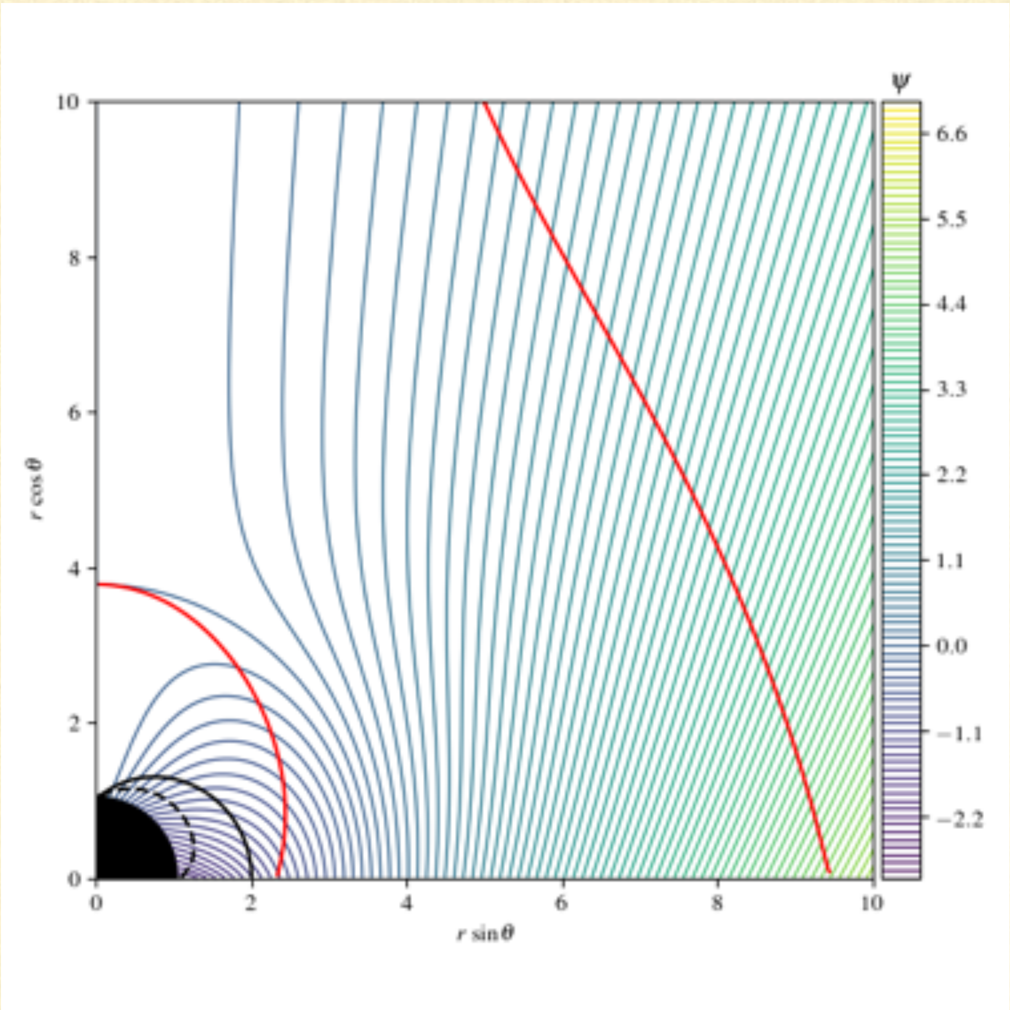


$r_0 = 4 r_{\rm ISCO}$

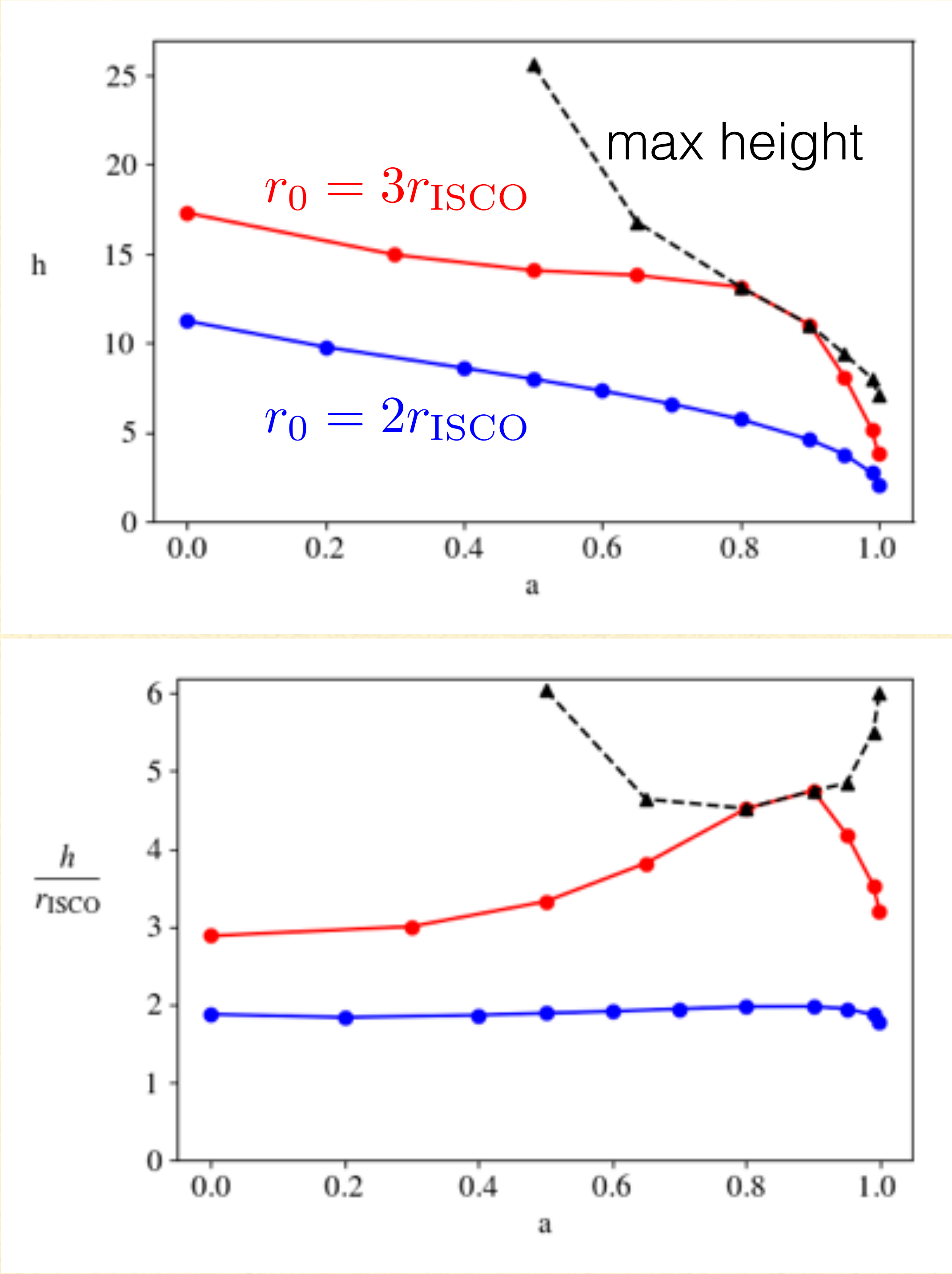
Consistent with Uzdensky 2005

Effect of BH spin

$$\psi_d = (r - r_0)/r_{\rm ISCO}$$



$$a = 0.999,\ r_0 = 3r_{\rm ISCO}$$



Steady state approach is missing a few important things:

- Stability
- Possible non-axisymmetric modes
- Time evolution and dissipation

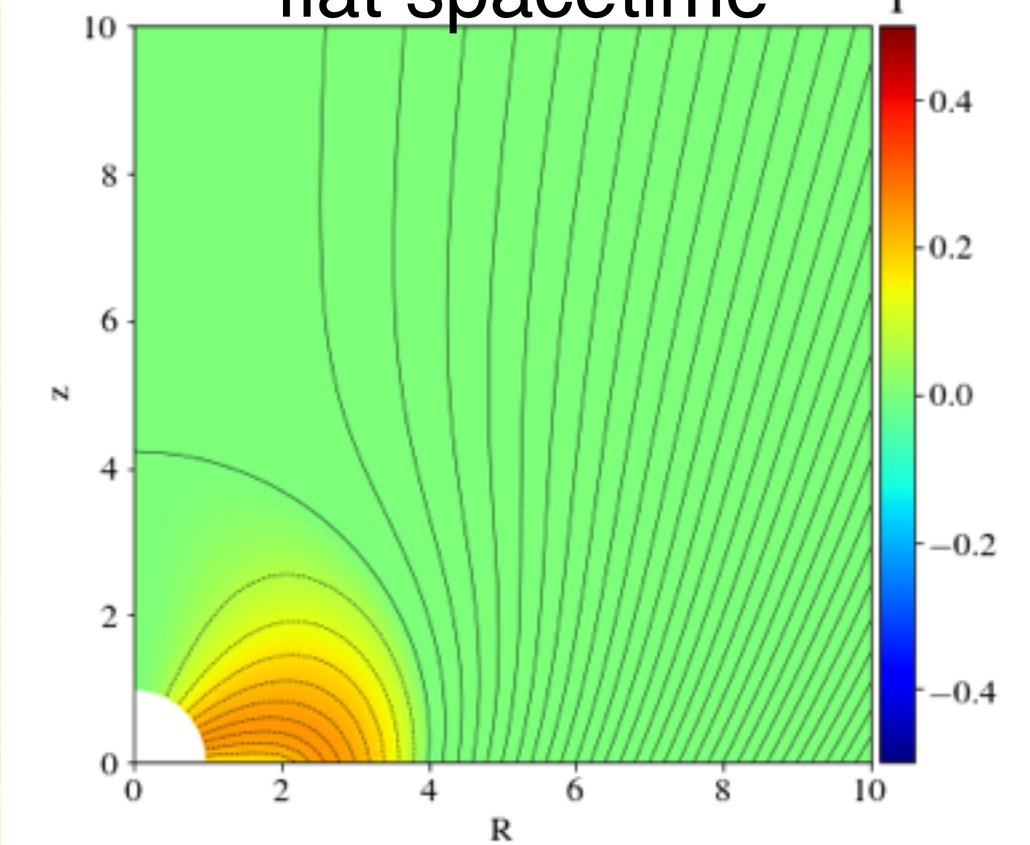
Need 3D time-dependent simulations!

cf. Parfrey+2015

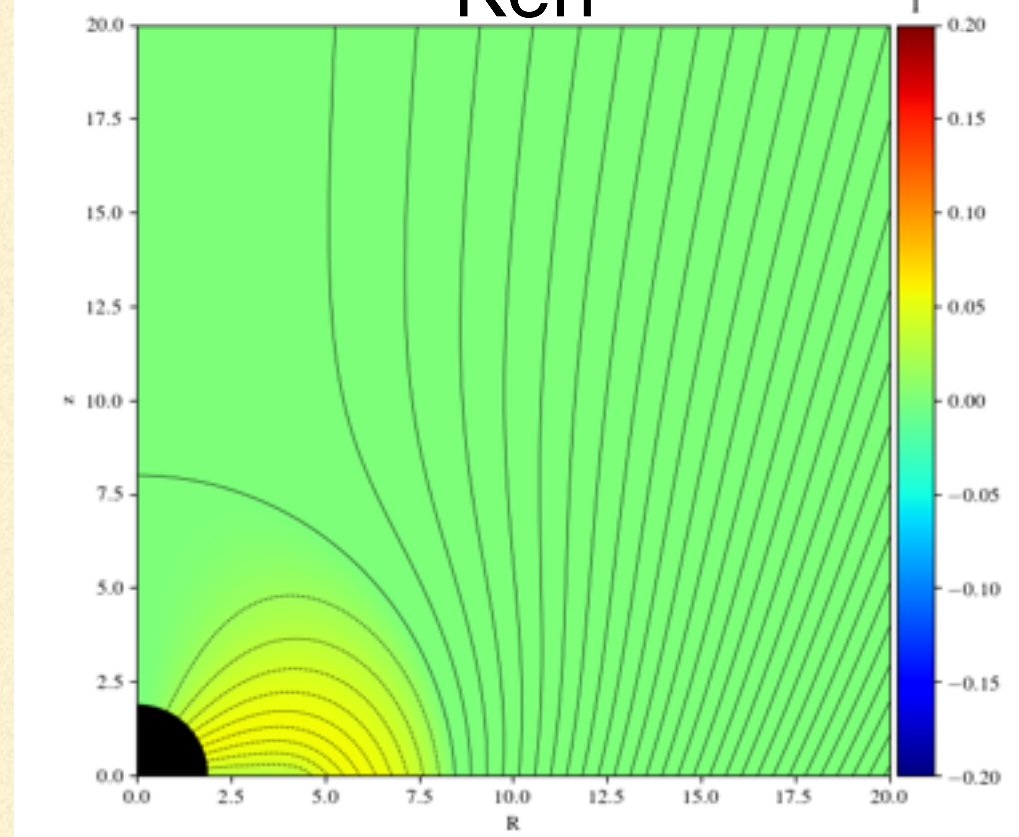
A test case

- We use the time-dependent, relativistic force-free code originally developed by Anatoly Spitkovsky (2006)
- Mimicking the electromagnetic effect of the black hole using a rotating, resistive membrane in flat spacetime
  - On the membrane, $B_{\parallel}'=4\pi K$, $E_{\parallel}'=RK=4\pi K=B_{\parallel}'$, where K is the surface current, R is the surface resistivity

flat spacetime

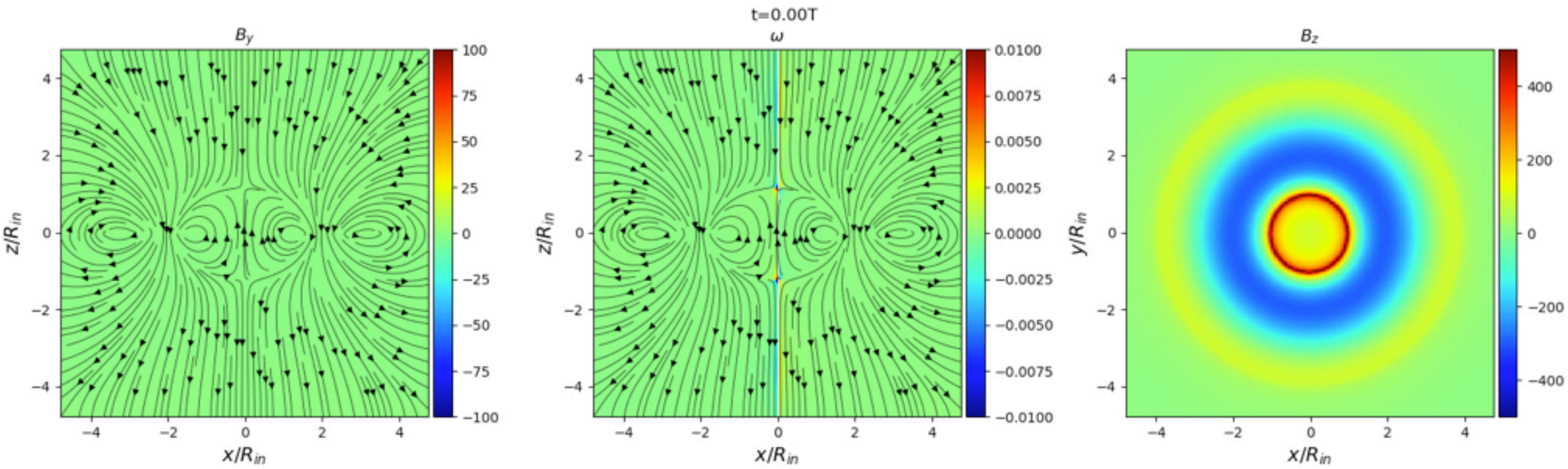


Kerr



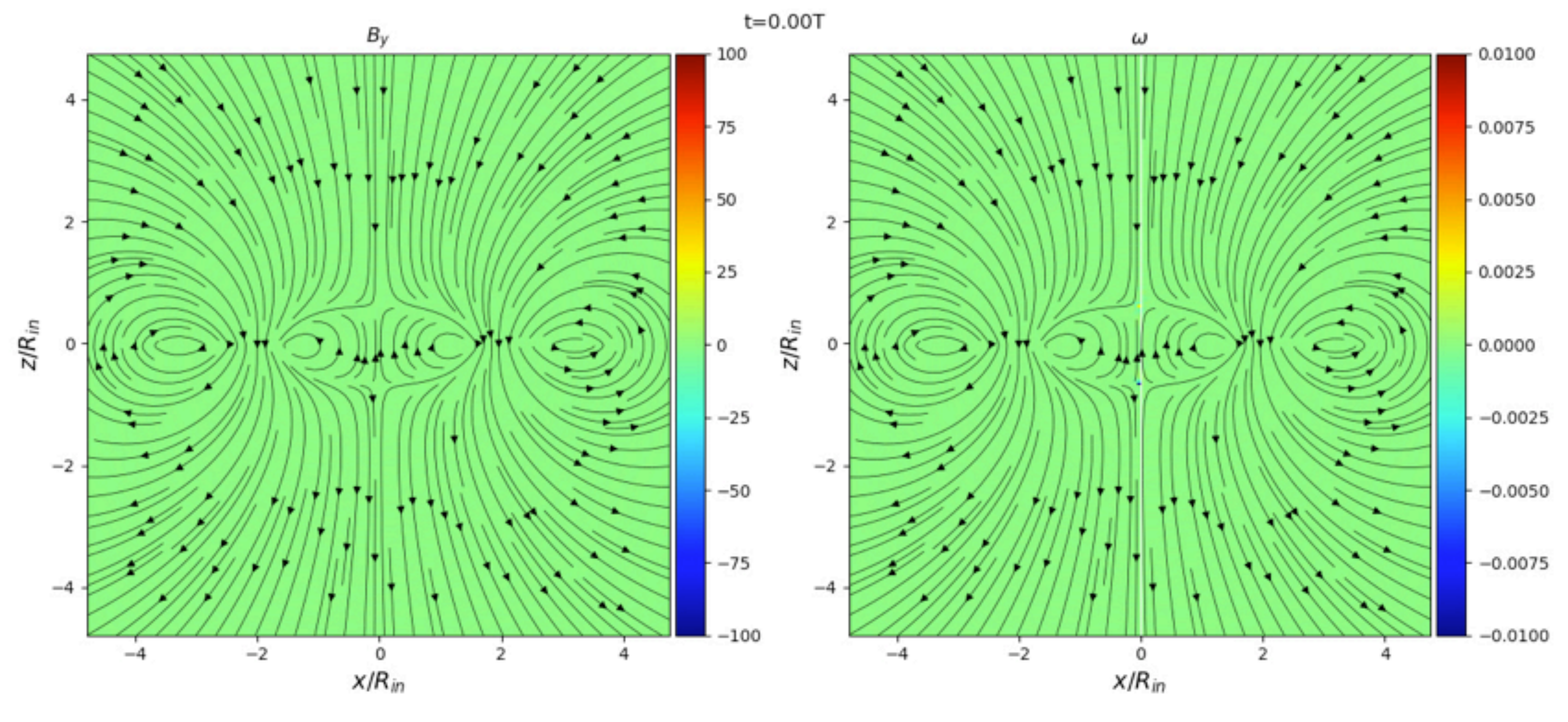
A test case

- A rotating resistive membrane disk (“BH”) surrounded by a perfectly conducting, non-rotating disk (“accretion disk”)
- Marginal confinement case: m=1 instability



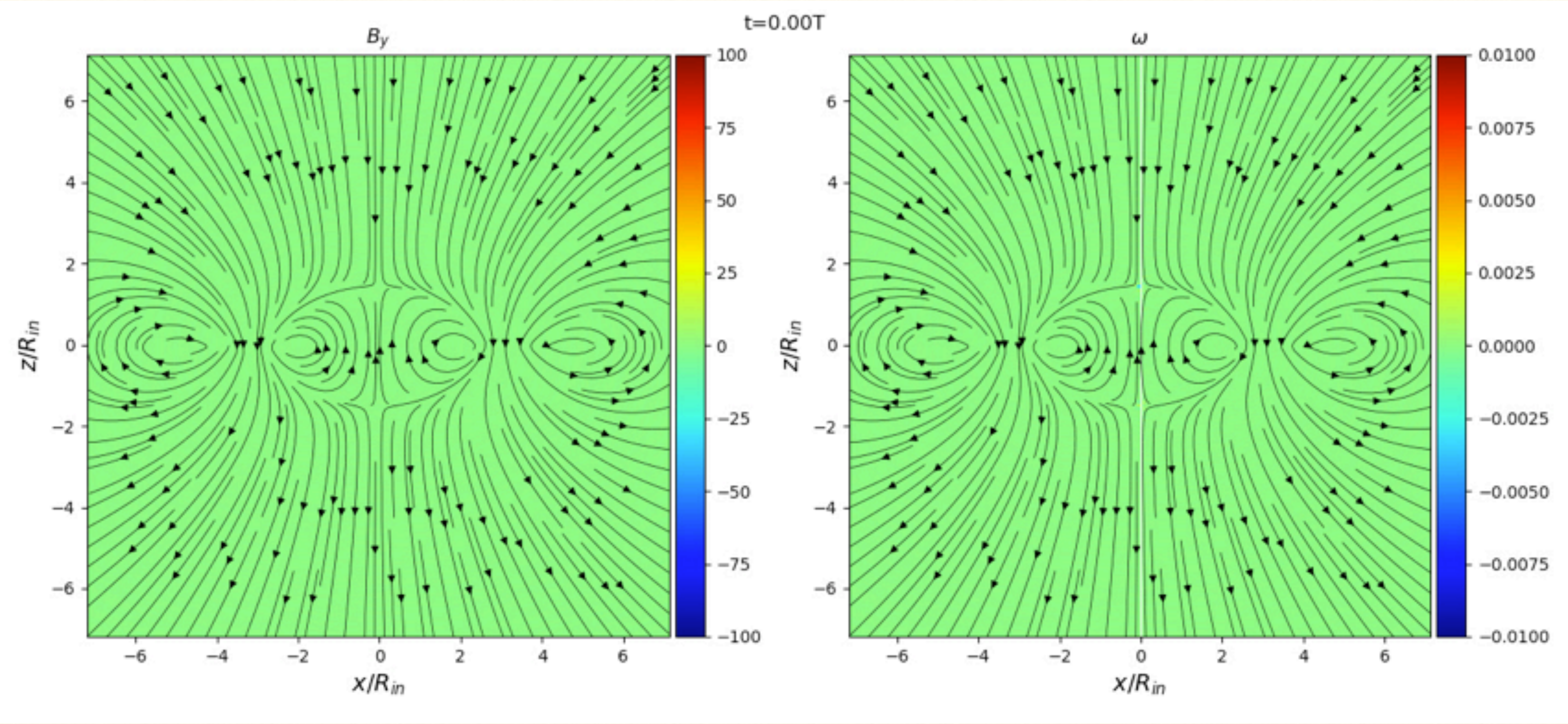
A test case

- Confined situation



A test case

- Unconfined situation



Energetics estimation

- Typical magnetic field strength:

$$B_{\rm Edd} = \sqrt{8\pi p_{\rm Edd}} = \sqrt{\frac{2L_{\rm Edd}}{3cr_g^2}} = \sqrt{\frac{m_p c^2}{r_e^2 r_g}} = 3.6\times 10^5 M_6^{-1/2}{\rm G}$$

- Power extraction from the black hole:
  - Voltage: $V \sim \omega\Phi \sim \epsilon_1 \Phi a c/r_g \sim 1.6\times 10^{19}\epsilon_1 a (B/B_{\rm Edd}) M_6 \ {\rm V}$
  - Power: $P \sim V^2/Z_0 \sim \epsilon_2 \Phi^2 a^2 c^2/(r_g^2 Z_0) \sim 6.8\times 10^{42}\epsilon_2 a^2 (B/B_{\rm Edd})^2 M_6^2 \ {\rm erg\ s^{-1}}$
  - Angular momentum flux: $\tau \sim P/\omega \sim \epsilon_3 \Phi^2 a c/(r_g Z_0)$
- Dissipation due to reconnection: $P_{\rm diss} \sim B^2 r^2 v_{\rm rec}/8\pi$

$$\frac{P_{\rm diss}}{L_{\rm Edd}} \sim \frac{1}{12\pi}\left(\frac{v_{\rm rec}}{c}\right)\left(\frac{r}{r_g}\right)^2\left(\frac{B}{B_{\rm Edd}}\right)^2$$

Summary

- Compact, Lamppost-like coronae seem typical from observations
- Possible dissipation mechanisms:
  - Electrostatic gap at the jet base is not favored based on energetics
  - Reconnection due to tangled small scale flux tubes near the axis may be a viable mechanism
  - This can be tested using relativistic force-free simulations, and maybe MHD simulations in the future.

A comment on mass loading

- Highly magnetized situation: particles behave like beads on a wire
- Lagrangian

$$L = \frac{1}{2}(g_{tt} + 2\Omega g_{t\phi} + \Omega^2 g_{\phi\phi})\left(\frac{dt}{d\tau}\right)^2 + (g_{0\phi} + \Omega g_{\phi\phi}) b^\phi \frac{dt}{d\tau}\frac{ds}{d\tau} + \frac{1}{2} b^2 \left(\frac{ds}{d\tau}\right)^2$$

$$\equiv \frac{1}{2} K \left(\frac{dt}{d\tau}\right)^2 + D \frac{dt}{d\tau}\frac{ds}{d\tau} + \frac{1}{2} b^2 \left(\frac{ds}{d\tau}\right)^2$$

- $\pi_t = u_0 + \Omega u_\phi$ is conserved
- (Super-)Hamiltonian $H = -\frac{K\left(\pi_s - \frac{D}{K}\pi_t\right)^2}{2(D^2 - Kb^2)} + \frac{\pi_t^2}{2K}$
- Inside the light surfaces, effective potential is $V_{\rm eff} = \frac{\pi_t^2}{2K}$

A comment on mass loading