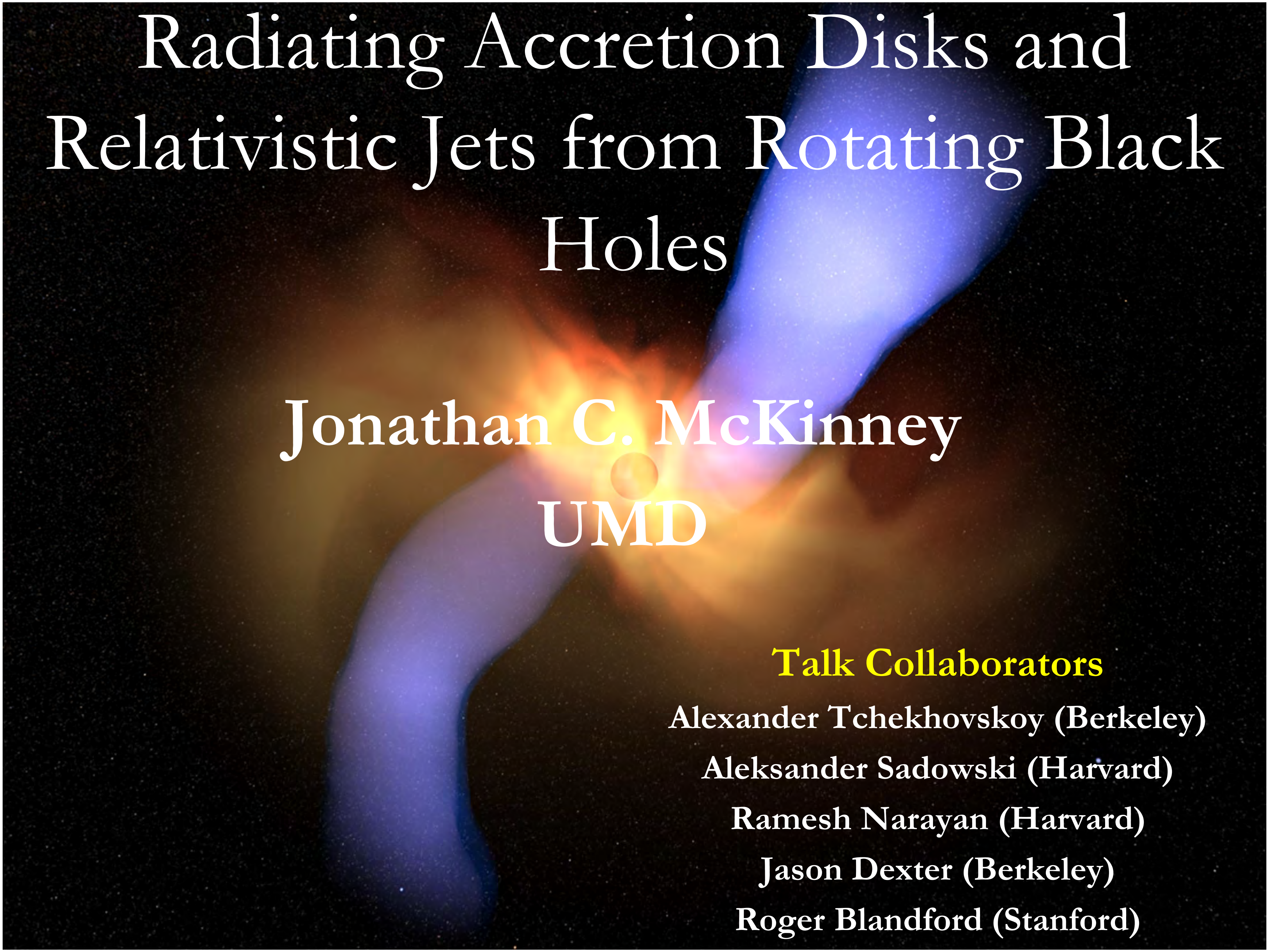

Radiating Accretion Disks and Relativistic Jets from Rotating Black Holes

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UMD

Talk Collaborators

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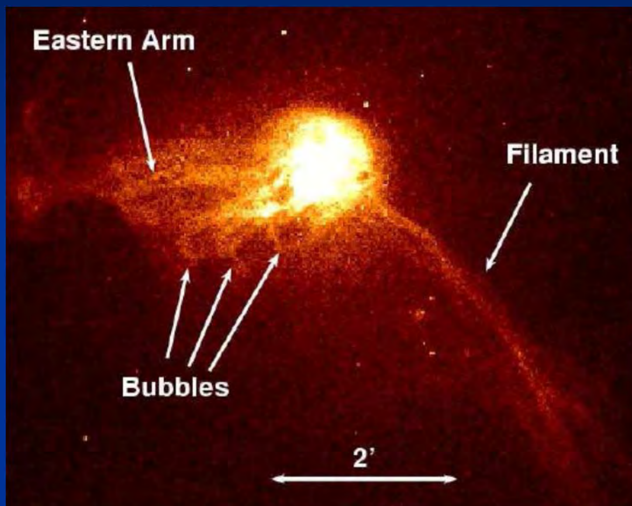
Aleksander Sadowski (Harvard)

Ramesh Narayan (Harvard)

Jason Dexter (Berkeley)

Roger Blandford (Stanford)

6§ 10^9M. BH in M87



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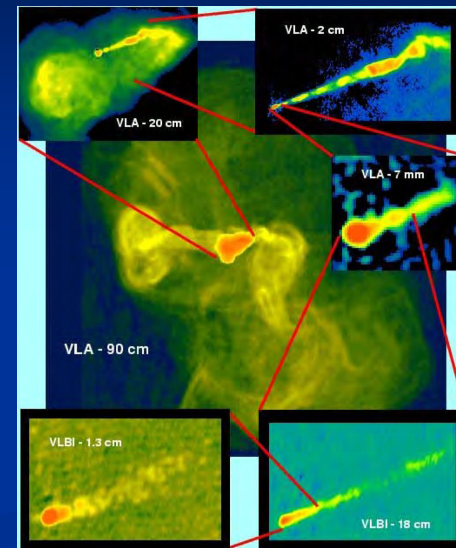
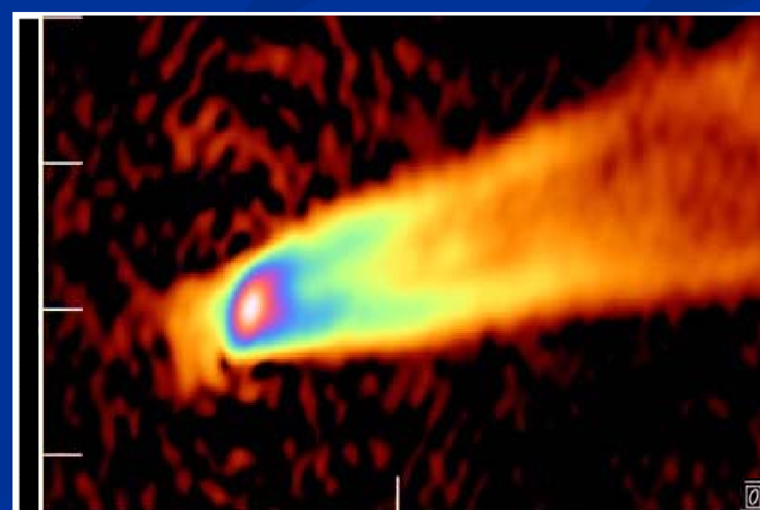


Y OE I#U dg lr#4nsf#- 3139sf

Mxqru +4<<<,

E lhwd#+4<<</5335,

- M~(6.6+-0.4)E9Msun
  (Gebhardt & Thomas 2009)
- D~16Mpc
- Lbol/Ledd~1E-6
- Lbol/(Mdot c^2)~1E-2



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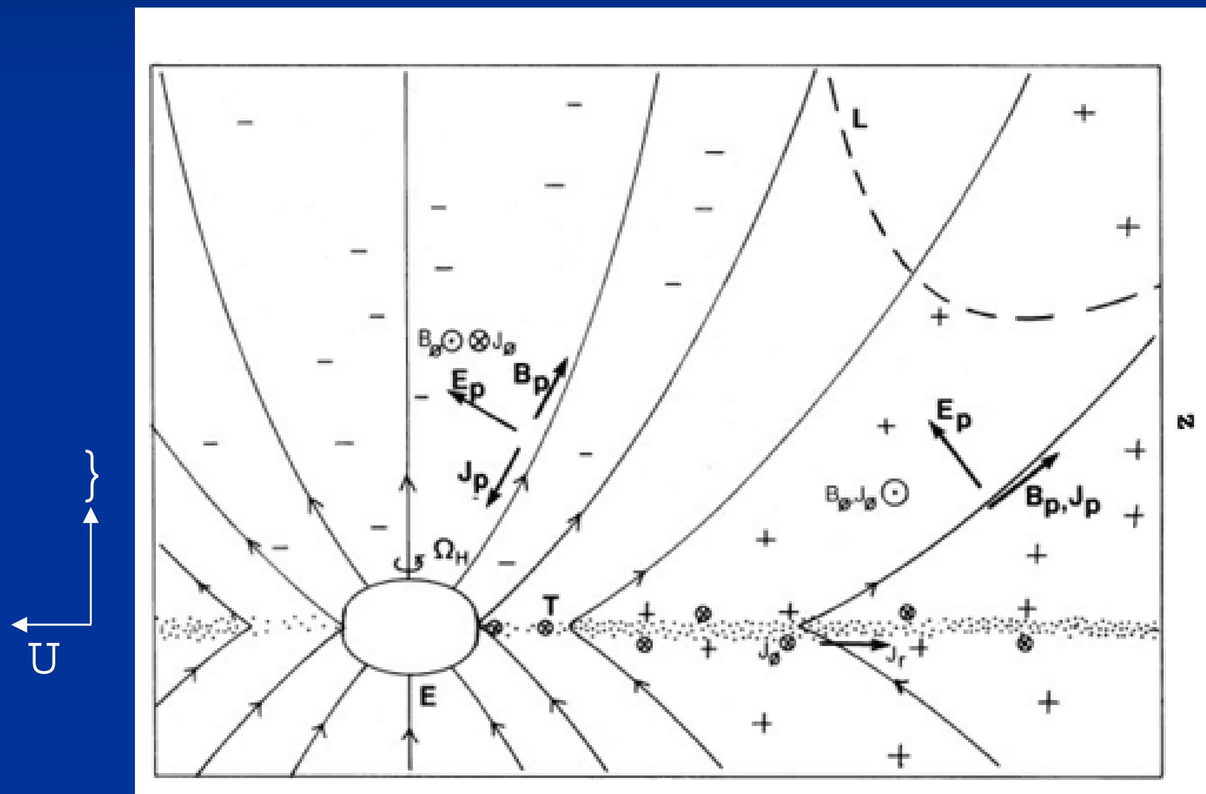
Role of Magnetic Field / Flux

Blandford-Znajek 77 Jet



P 2 #Psi^2 Ω^2_H

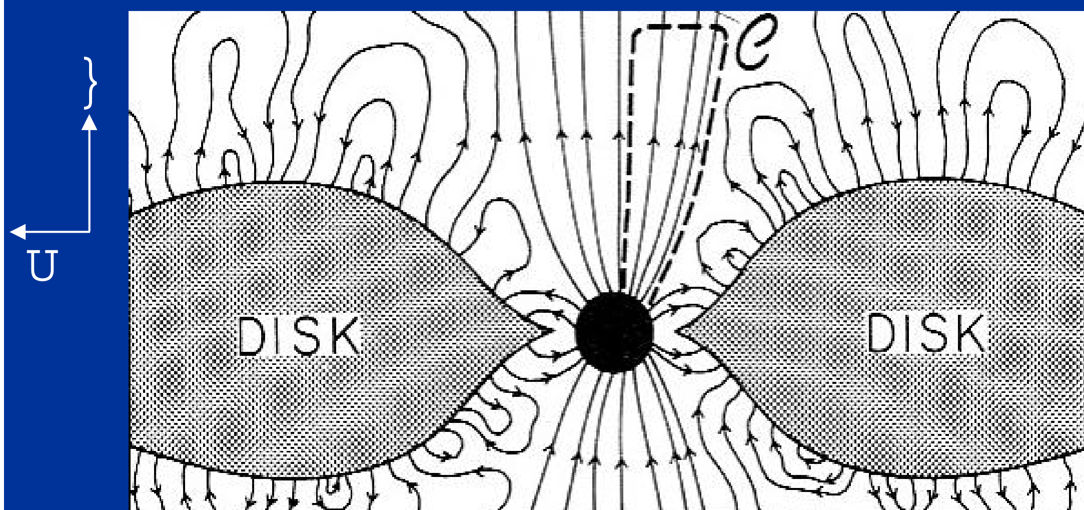
Role of Magnetic Field / Flux

Weak Field MRI Disk

+

Blandford-Znajek Jet

= Flux is Fine-Tuned



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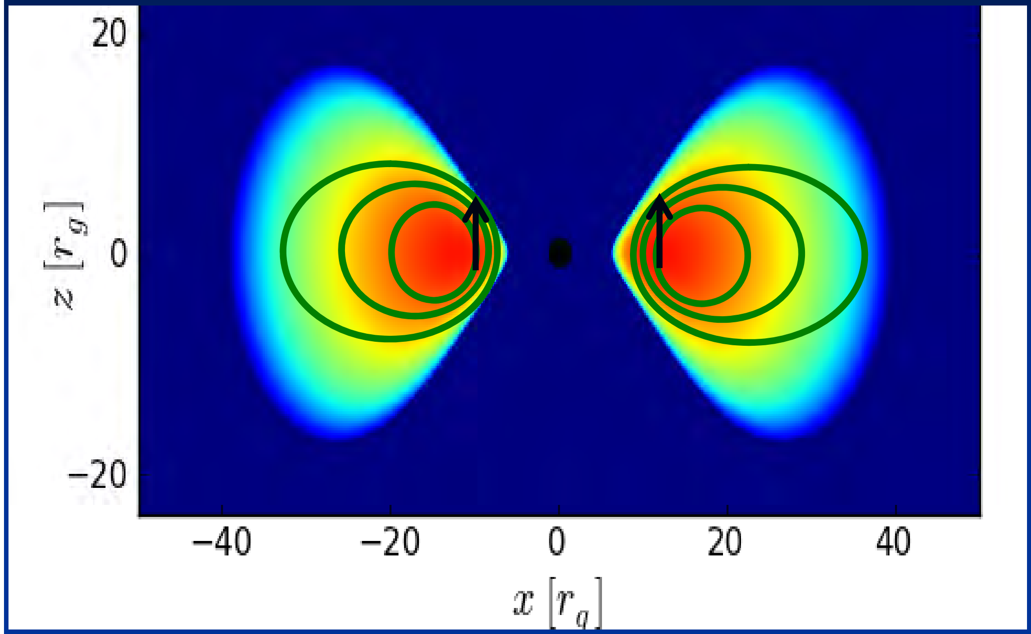
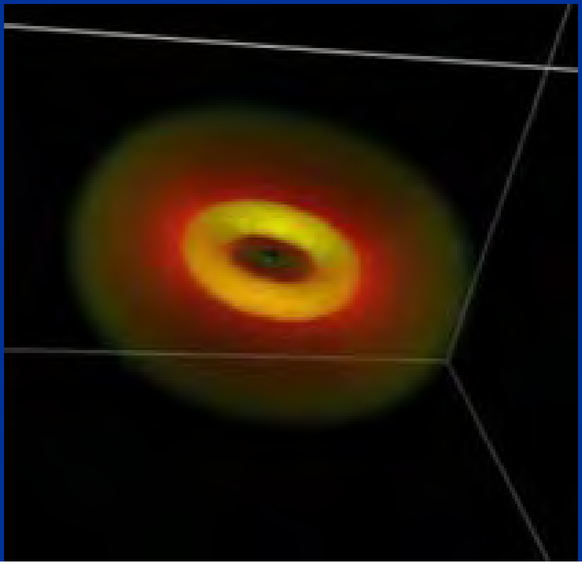
Classic GR-MHD Models

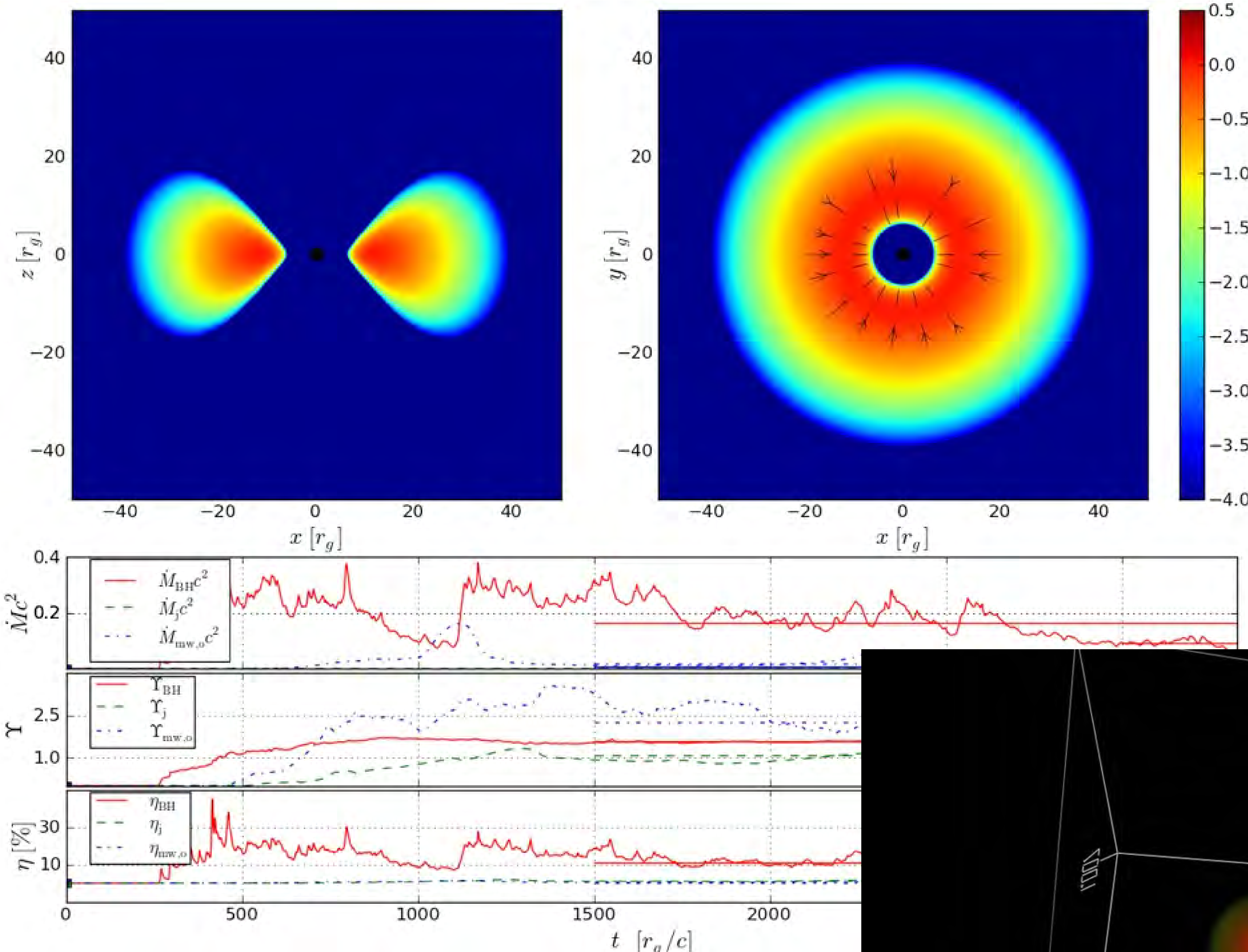




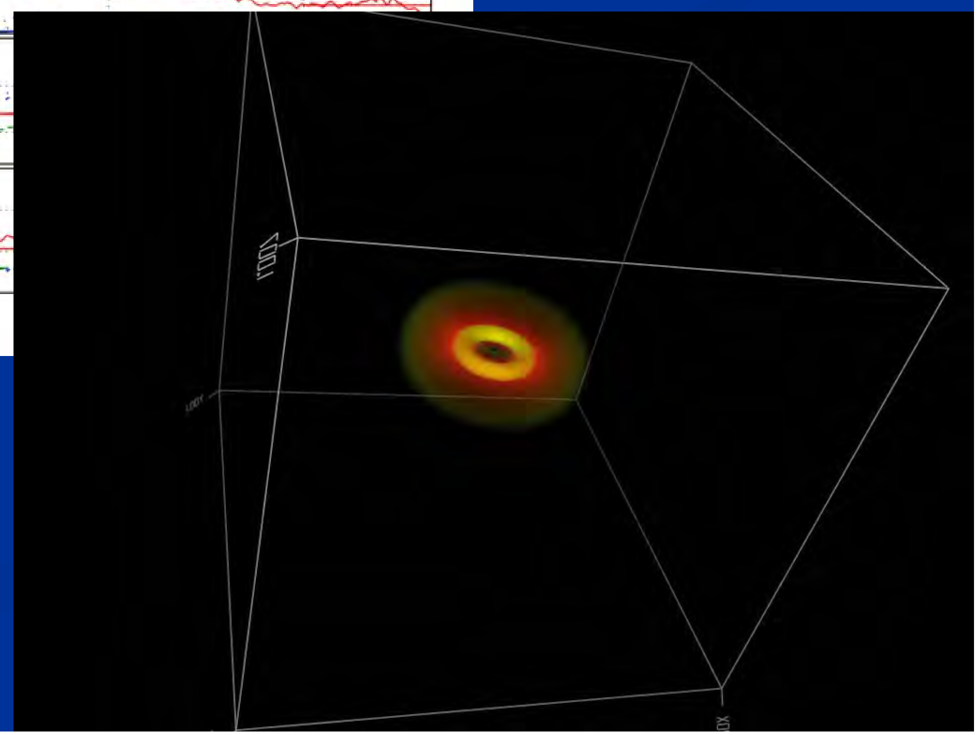
MHD (Fluid) Conservation:
Mass-Energy-Momentum-Flux

Physical Setup:
Spin: a=0.94
Disk: Radiatively Inefficient
Disk: Thick Short-R Disk
Field: Limited Magnetic Flux
Field: 1-loop dipole (and Quad)
Duration: ~5,000M

Numerical Setup:
Fully 3D (no syms.)
256x128x32 – 256x128x64
Kerr-Schild Coords.
Large outer box radius



McKinney & Blandford (2009)
Hawley et al.
Gammie et al.
Fragile et al.
Komissarov et al.



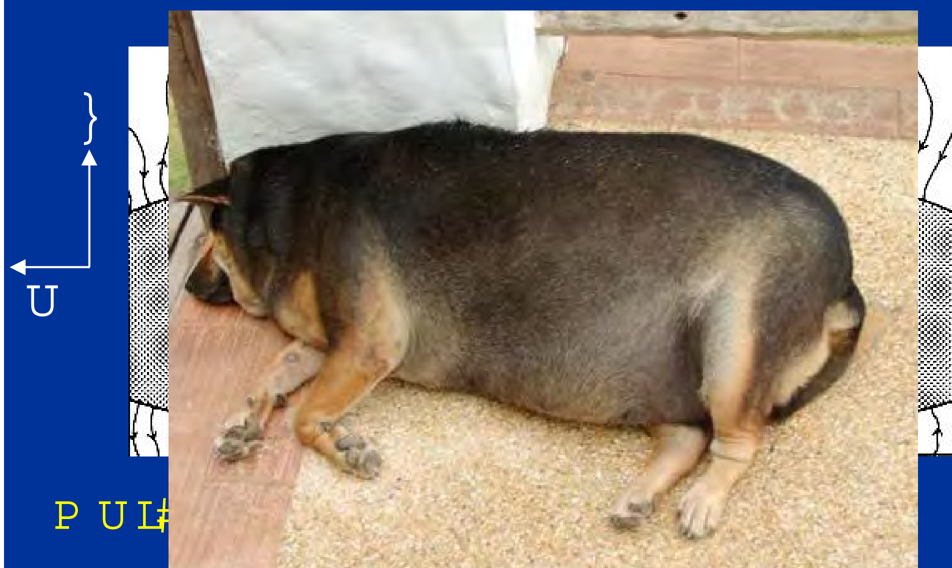
Results:

Magneto-rotational instability
Exponential amplification
Arbitrarily Weakly Powered Jet

Role of Magnetic Field / Flux

Weak Field MRI Disk
+
Blandford-Znajek Jet
= Flux is Fine-Tuned

Saturated Field MAD Disk
+
Blandford-Znajek Jet
= Flux in Force Balance



P U L#

E odqggirug) #] qdmhn +::,#P dfG rqdog#) #W kruqh#
+;5,/#E doexv) #K dz dh|#+4<<4/4<;;,

P D G #@ #P djqhwlfdoo|#D uuhvwhg#G lvn

] qdmhn#+:9,/#E lvqrydw|l0N rjdq#) #U x}p dlnlq#
+:7/:9,/#Q dud|dq hw#do1#+36,/#U h|qrogv#hw#do1#+39,/#
Ljxp hqvkfkhy hw#do1#+36,/#£N rp lvdury +3<,

How much Magnetic Flux?

- Coherent Flux near Galactic Nucleus:
  - $\Phi \sim 0.1\ \mathrm{pc^2G}$ or greater Lang, C. C., Morris, M., & Echevarria, L. 1999, ApJ, 526, 727
- Magnetospheric Radius (McKinney, Tchekhovskoy, Blandford 2012):

1) Mass Flux: $\Sigma = \dot{M}/(2\pi r \epsilon v_{\mathrm{ff}})$ $\dot{M} = \dot{M}_{\mathrm{H}}\ (r/r_g)^n$

2) Gravity Balancing Field: $GM\Sigma/R^2 \sim 2B_R B_z/4\pi \sim B_z^2/2\pi$

3) Solve for Bz: $B_z \sim 10^5 \epsilon_{-1}^{-1/2} m_8^{-1/2} \dot{m}^{1/2} (r/r_g)^{-5/4+n/2}$ G

4) Integrate Bz within r_m to get magnetic flux (›) within r_m .

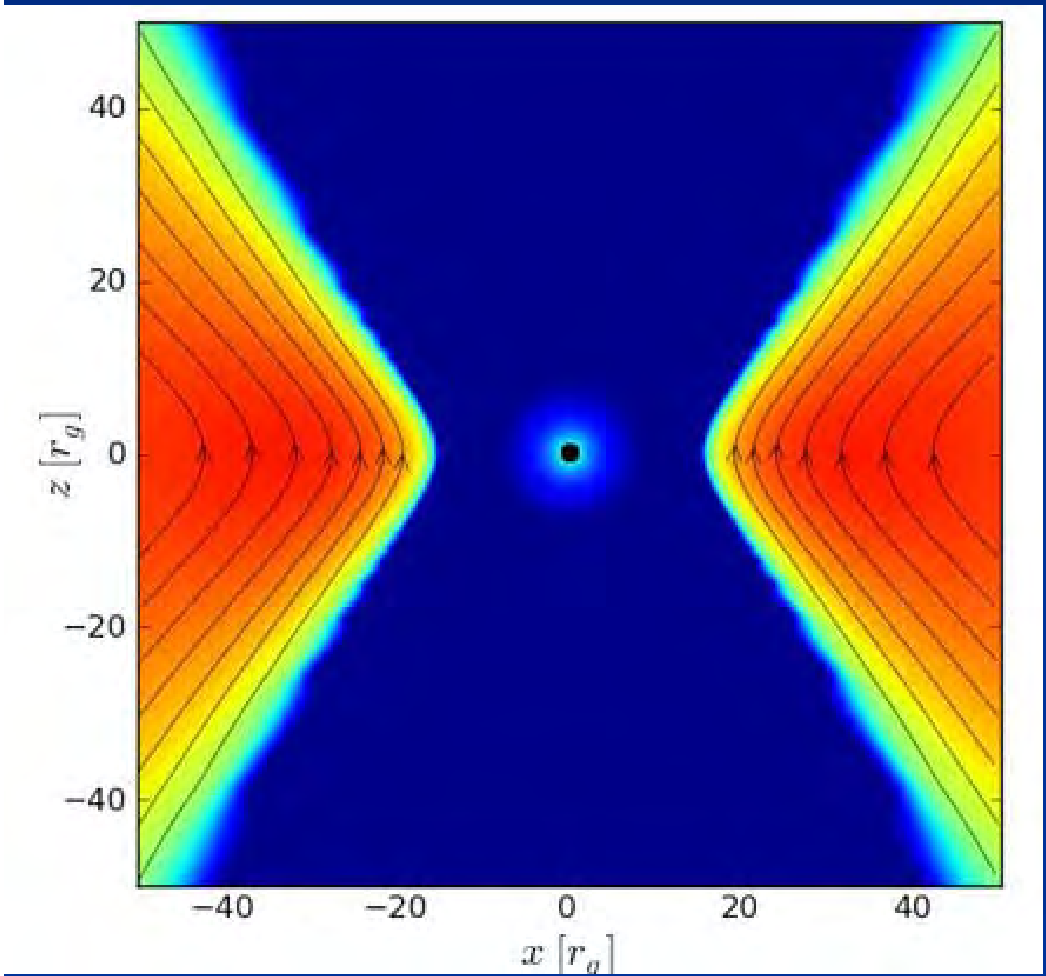
5) Solve for r_m : $r_m \sim r_g \left(12000\left(\frac{3}{4}+\frac{n}{2}\right)\right)^{\frac{4}{3+2n}} \epsilon_{-1}^{\frac{2}{3+2n}} m_8^{-\frac{6}{3+2n}} \dot{m}_{\mathrm{H}}^{-\frac{2}{3+2n}} \left(\frac{\Phi}{0.1\mathrm{pc^2G}}\right)^{\frac{4}{3+2n}}$

SgrA* : $r_m \sim 10^7\ r_g$ (n=1)

M87 : $r_m \sim 10^2\ r_g$ (n=1)

Role of Magnetic Flux Accumulation

Dim.less Flux: Psi/Mdot^{1/2}



Physical Setup:

GRMHD + rho,u floor

Spin: a=0.99 (+-0.9,0.5,0.2,0.1,0)

Radiatively Inefficient

Thick Extended-R Disk

Run: ~30,000M to ~100kM

Numerical Setup:

Fully 3D (no syms), large Rout

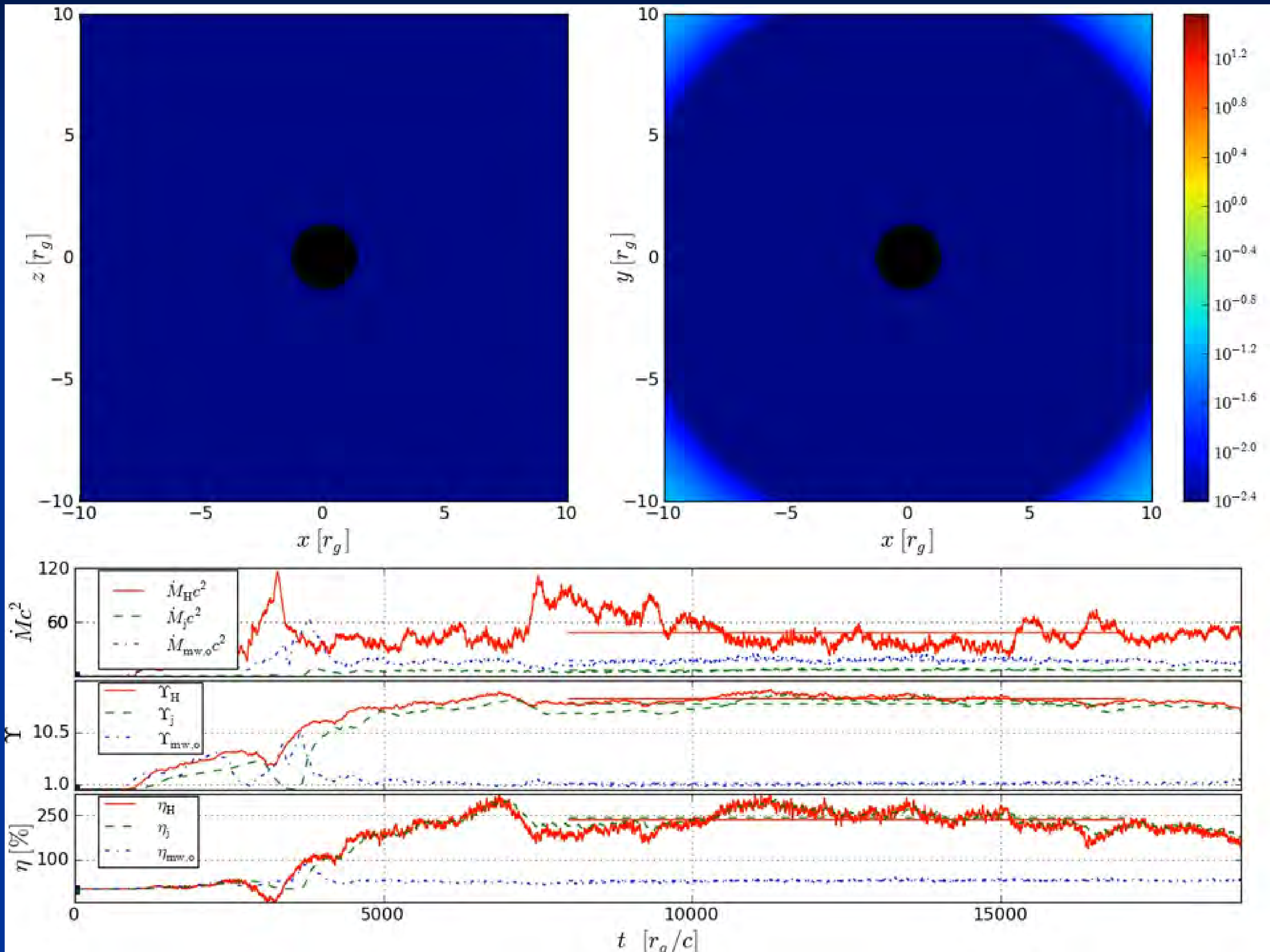
Kerr-Schild Coords

288x128x128 – 272x128x256

Explicit Res+Conv Tests

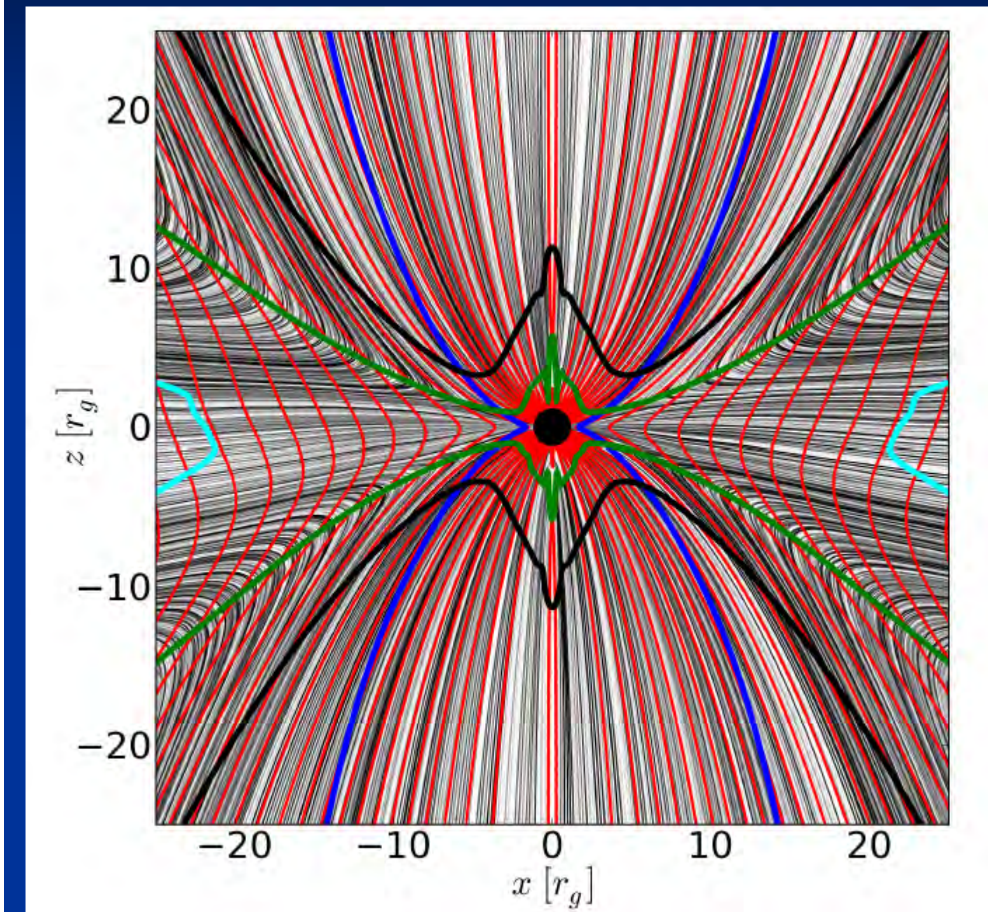
Tchekhovskoy, Narayan, McKinney (2011)
McKinney, Tchekhovskoy, Blandford (2012)
Narayan et al. (2012)

Going MAD



$z\ [r_g]$
$x\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
$10^{1.2}$
$10^{0.8}$
$10^{0.4}$
$10^{0.0}$
$10^{-0.4}$
$10^{-0.8}$
$10^{-1.2}$
$10^{-1.6}$
$10^{-2.0}$
$10^{-2.4}$
$\dot{M}c^2$
$\dot{M}_{\rm H}c^2$
$\dot{M}_{\rm j}c^2$
$\dot{M}_{\rm mw,o}c^2$
Υ
$\Upsilon_{\rm H}$
$\Upsilon_{\rm j}$
$\Upsilon_{\rm mw,o}$
$\eta\ [\%]$
$\eta_{\rm H}$
$\eta_{\rm j}$
$\eta_{\rm mw,o}$
$t\ \ [r_g/c]$

MAD Structure



Time-Azimuthal Average:

Red: Magnetic Field Lines
Gray: Velocity Stream Lines

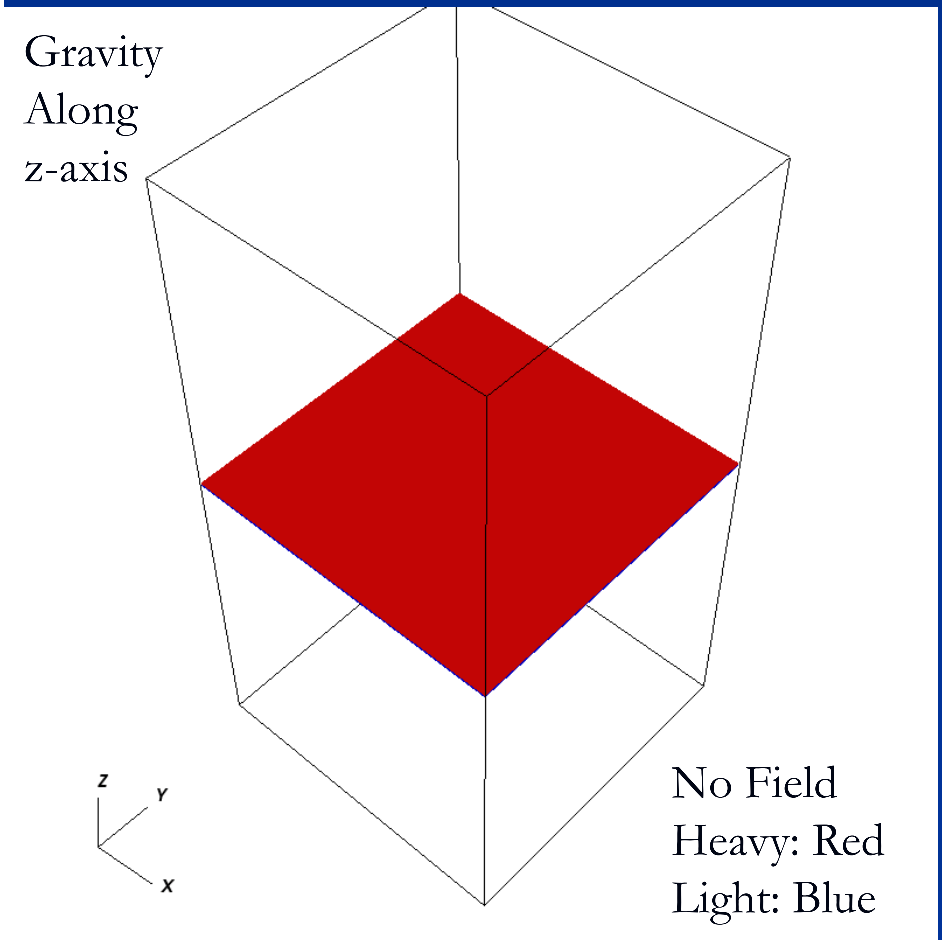
Blue: Disk-Jet Boundary
Green: Outflow
Black: Unbound Outflow

- **Magnetic Flux Accumulates up to Natural Limit**
- **Greater than 100% BH and jet efficiencies!**
- **MRI (magneto-rotational/Balbus-Hawley instability) suppressed!**

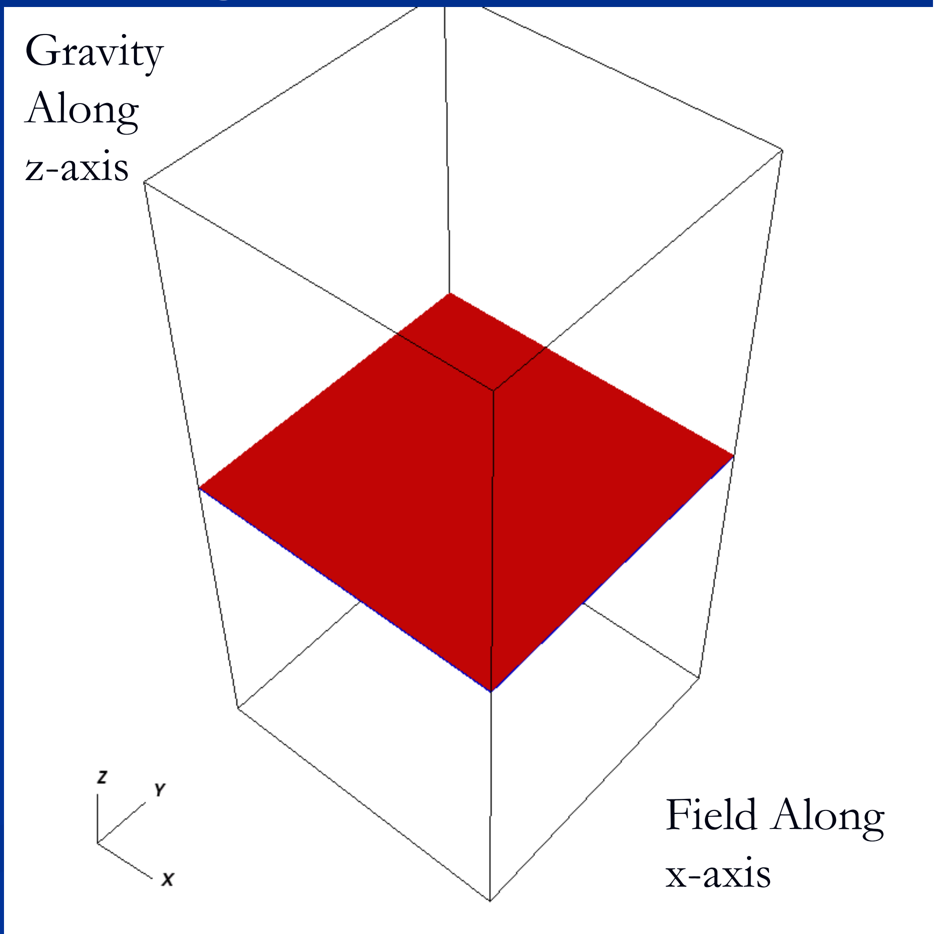
Ljxp hqvkfkhy hw#do1#+3;/3<,/#W fkhnkryvnr| hw#do1#+44/45,/#P fN lqqh|#hw#do1#+45,

Accretion Occurs through Magnetic Rayleigh-Taylor Modes

Hydrodynamics



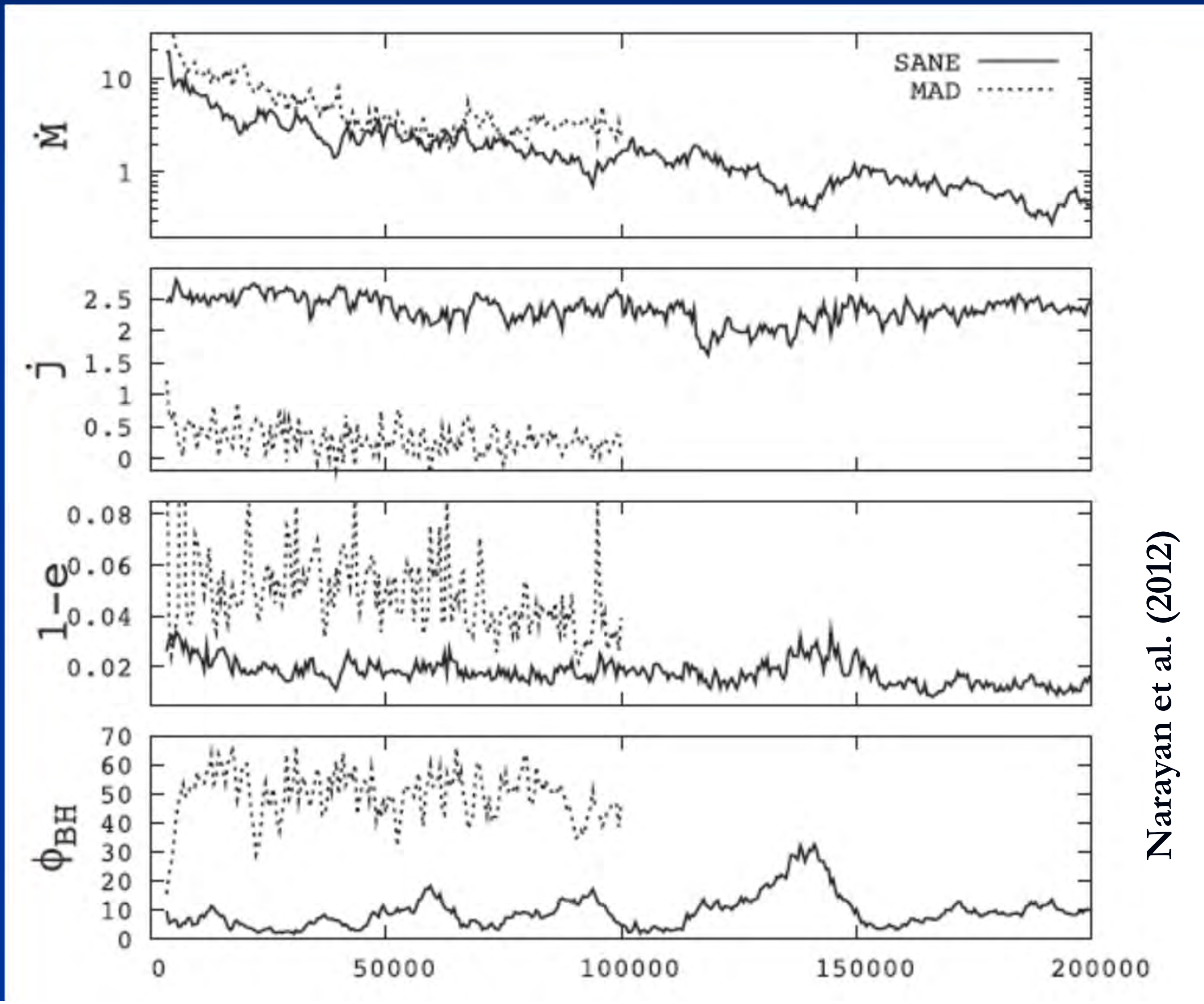
MagnetoHydrodynamics



Athena, Stone et al.

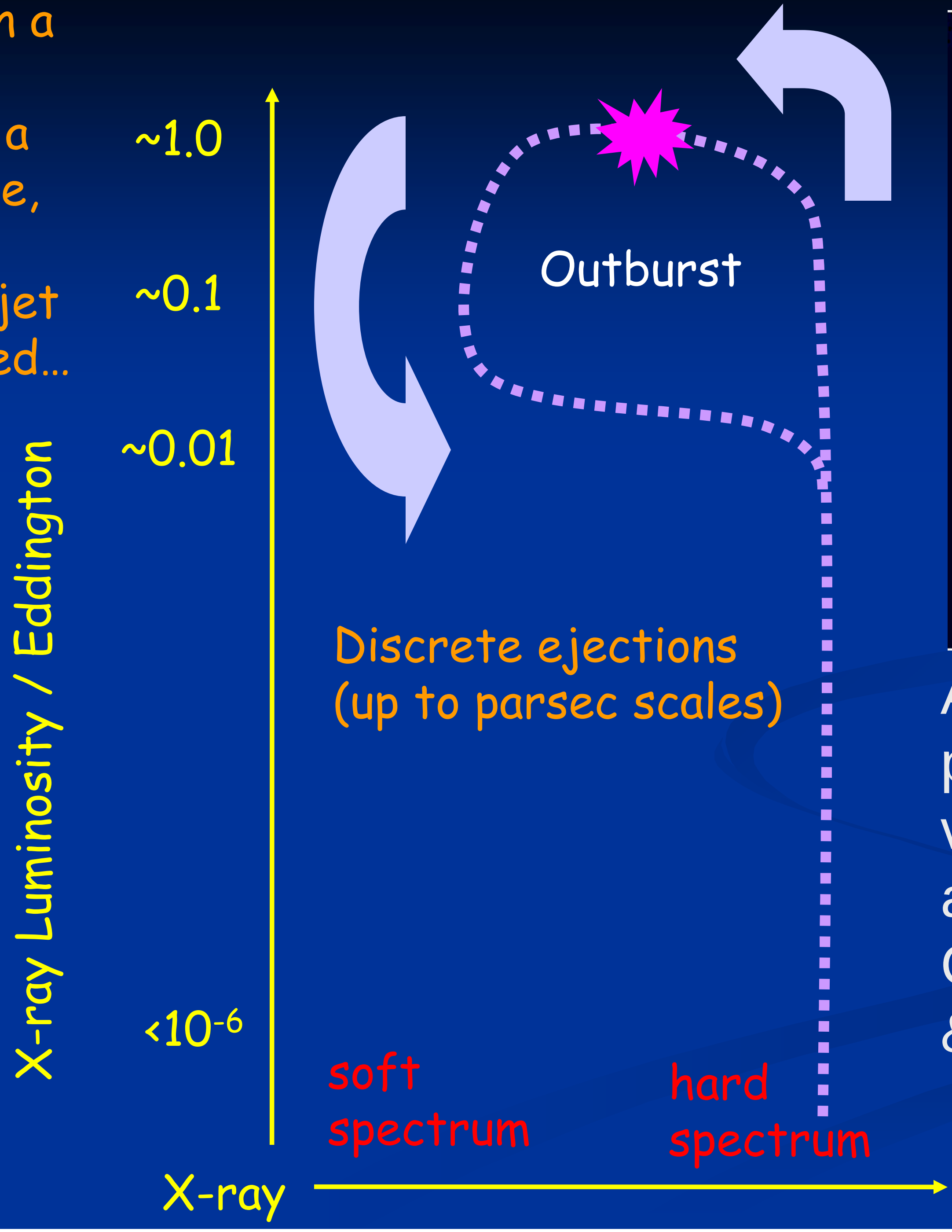
Advection vs. Diffusion of Magnetic Flux

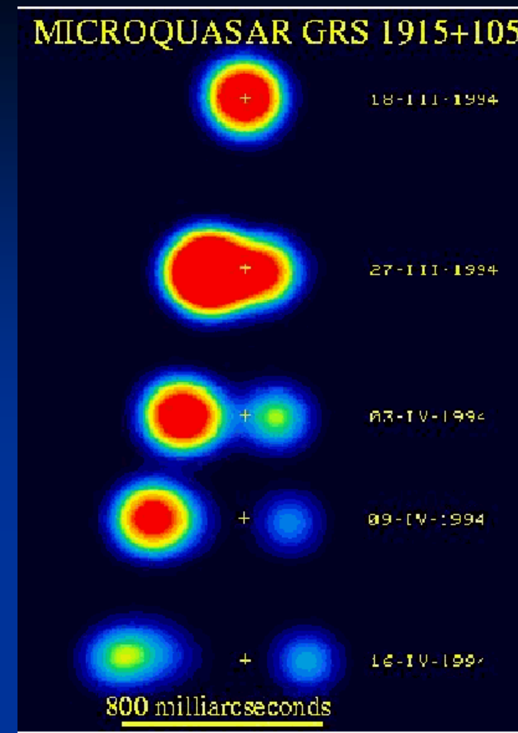
(Van Ballegooijen 89 , Pringle 93, Lubow et al. 94 _VS_ Rothstein & Lovelace or Beckwith 09 or Guan & Gammie 09)



Narayan et al. (2012)

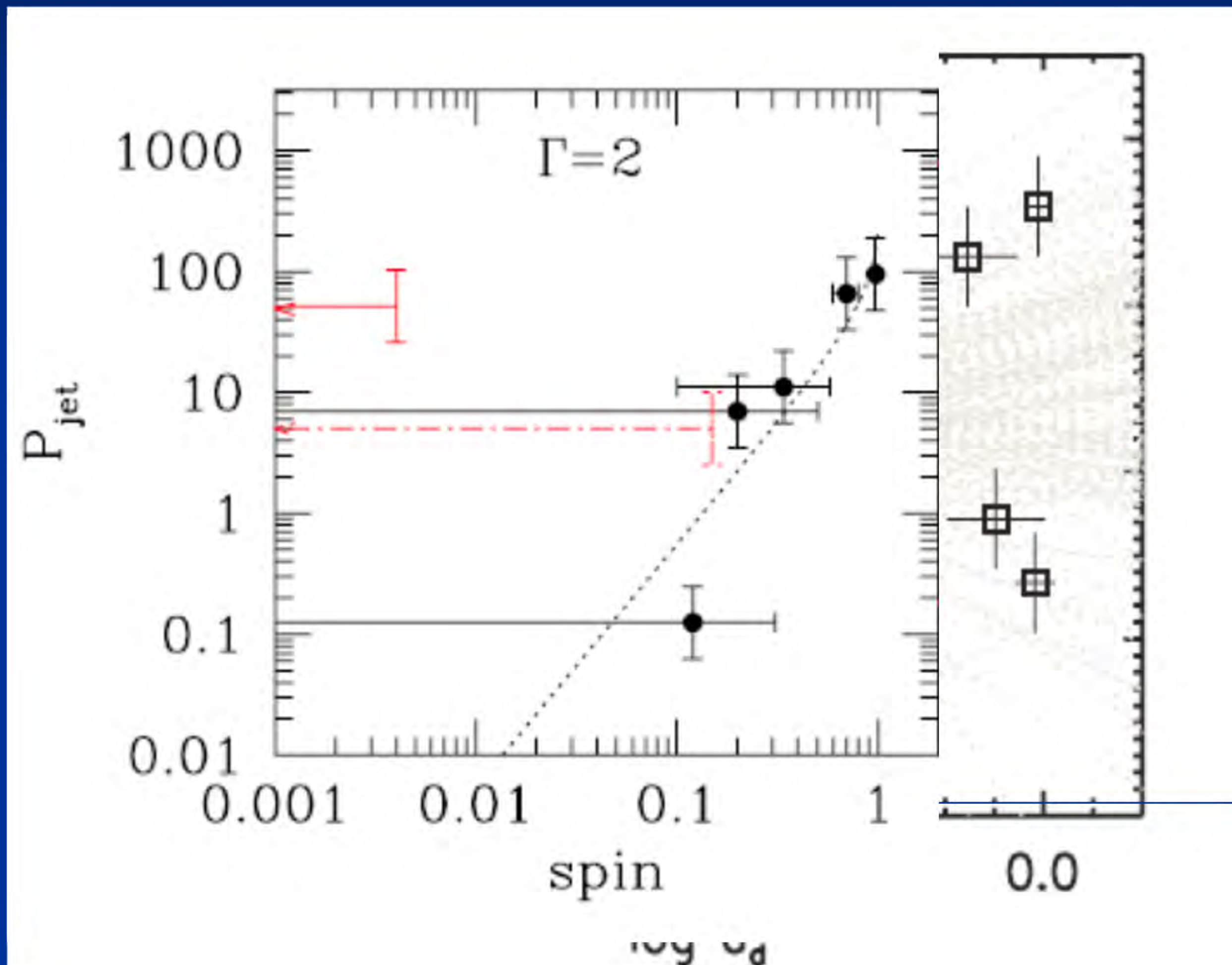
Early on in a major outburst, a large-scale, very powerful jet is produced…



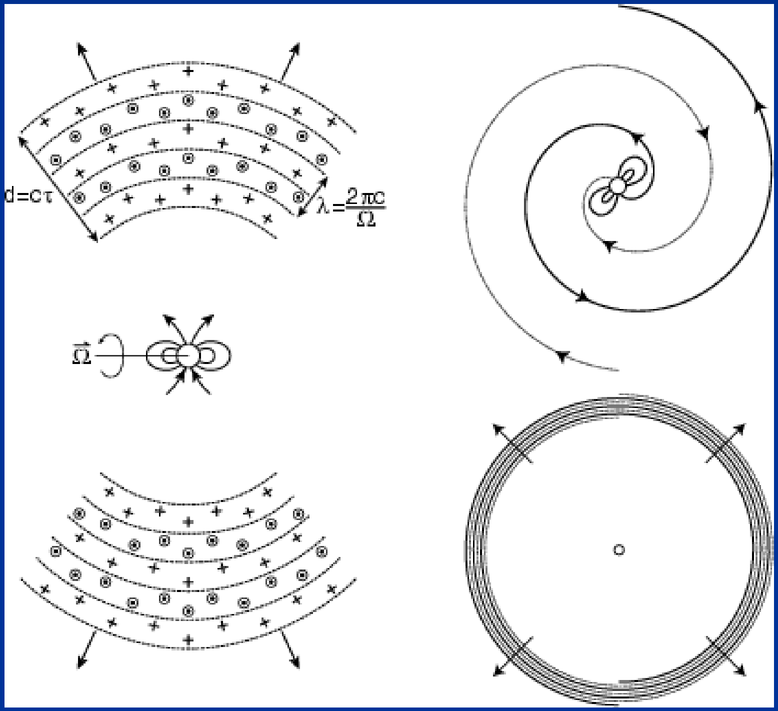


Around this point strong and variable QPOs appear (e.g. Casello, Belloni & Stella 2005)

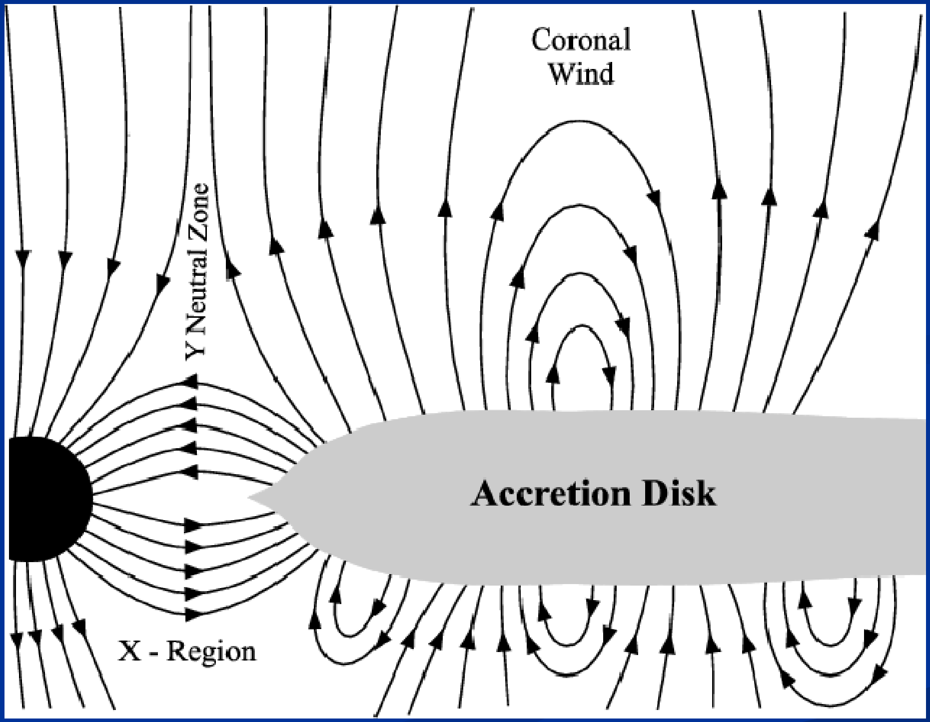
Transient Jets Spin Powered?



Striped Winds/Jets
Vs.
Magnetospheric Reconnection

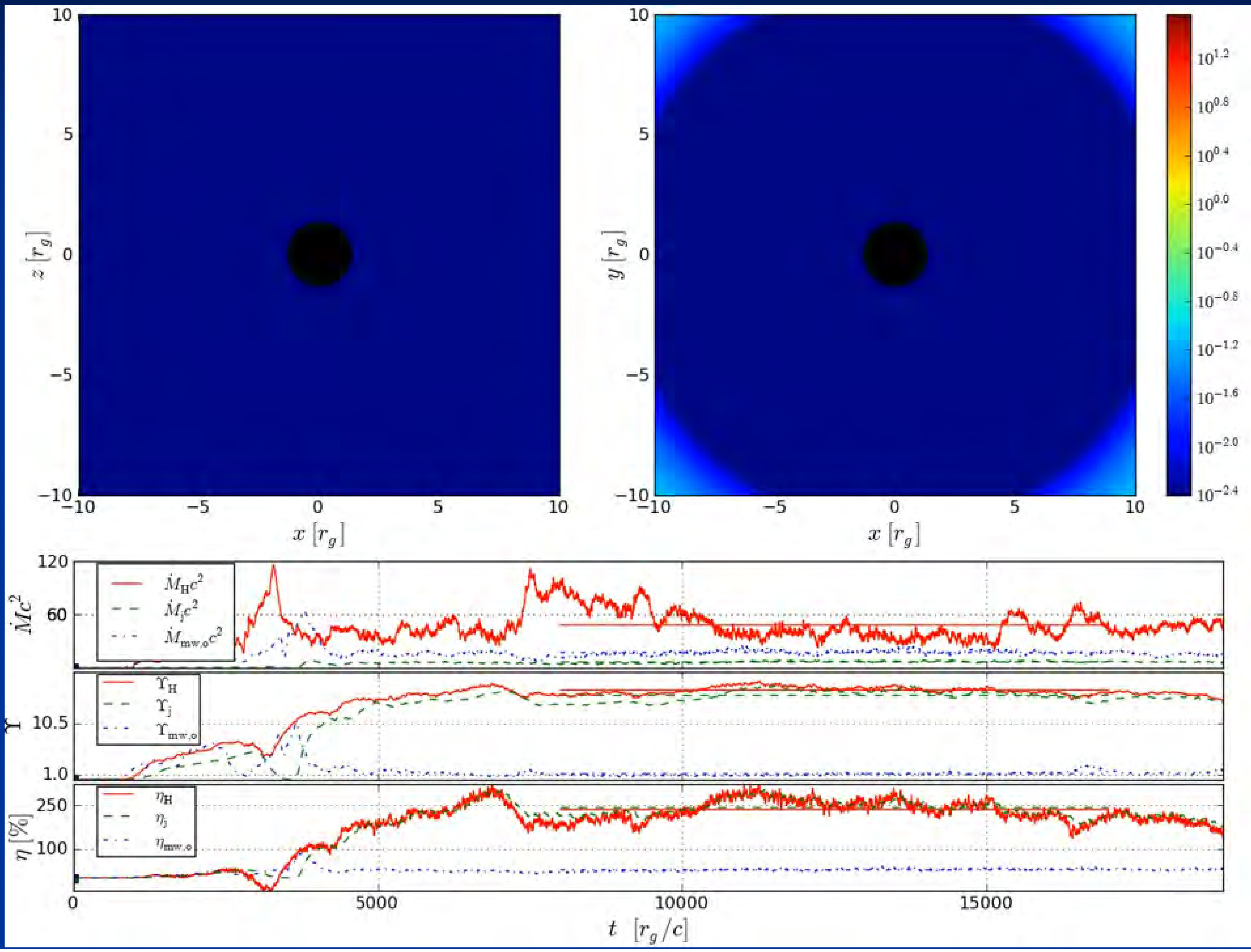


Coroniti (90)
Begelman (98)
Spruit, Daigne, & Drenkhahn (2001)
Giannios et al. , McKinney & Uzdensky (2012)

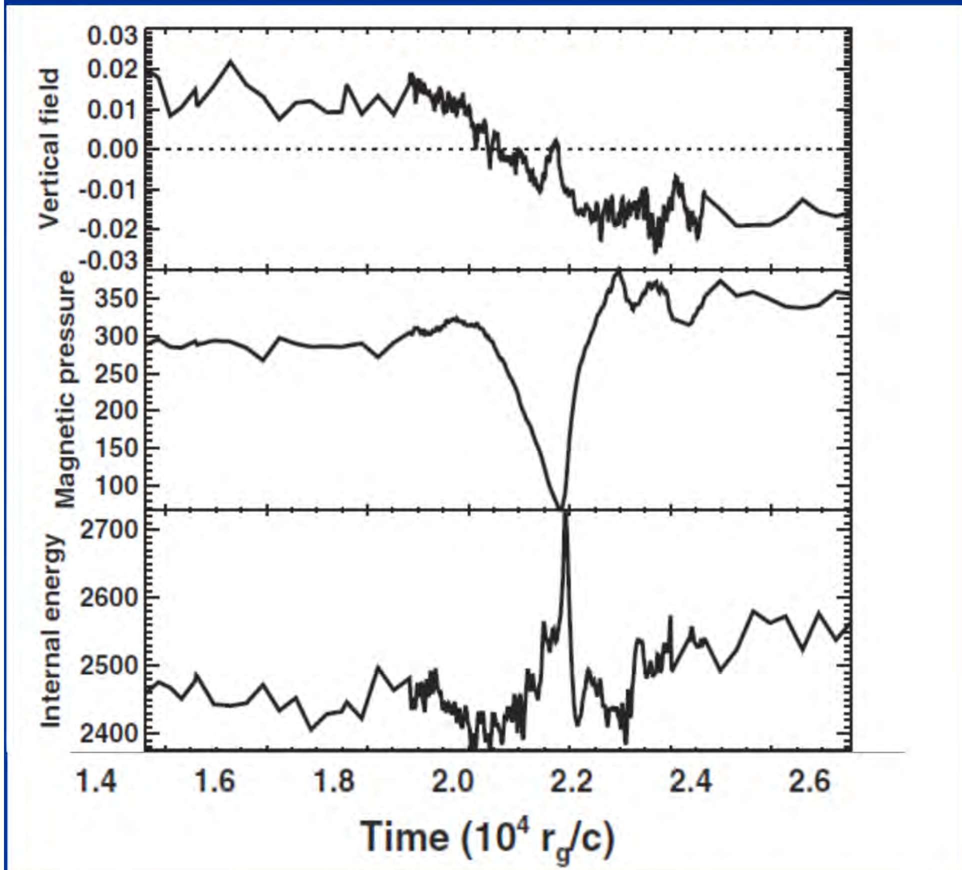


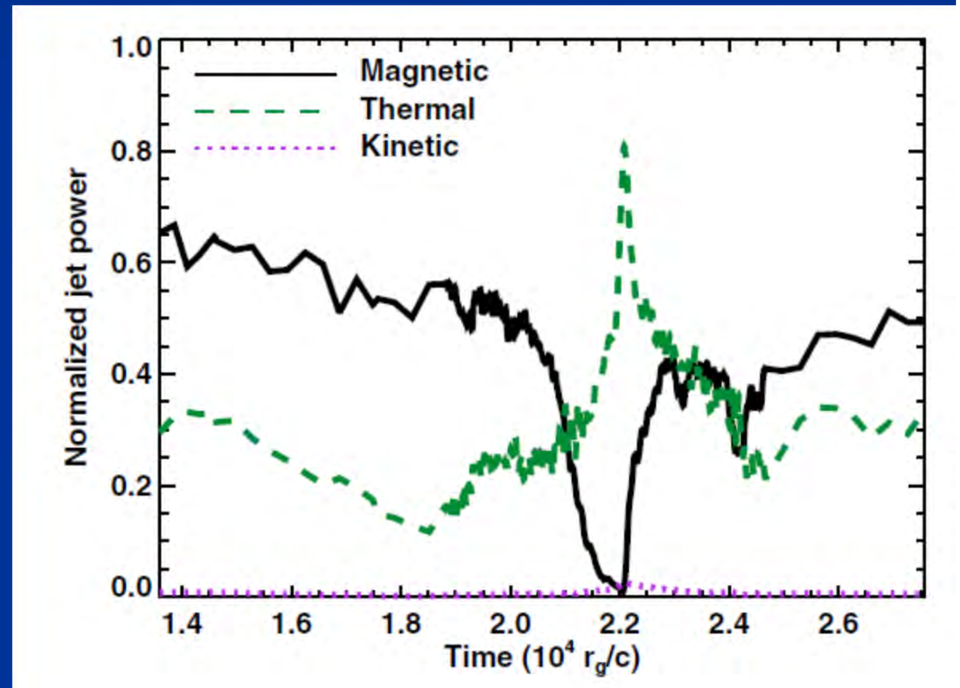
de Gouveia dal Pino, Lazarian (2005,2010)
Igumenshchev (2009)
Dexter, McKinney, Markoff, Tchekhovskoy (2014)
Tagger & Pellat (99), Livio et al. (03), King et al. (04), Begelman & Armitage (14)

Flipping MAD



BH Transient Jets
Flux vs. Spin/Rotation





BZ: Pjet\propto Psi^2 \Omega_H^2

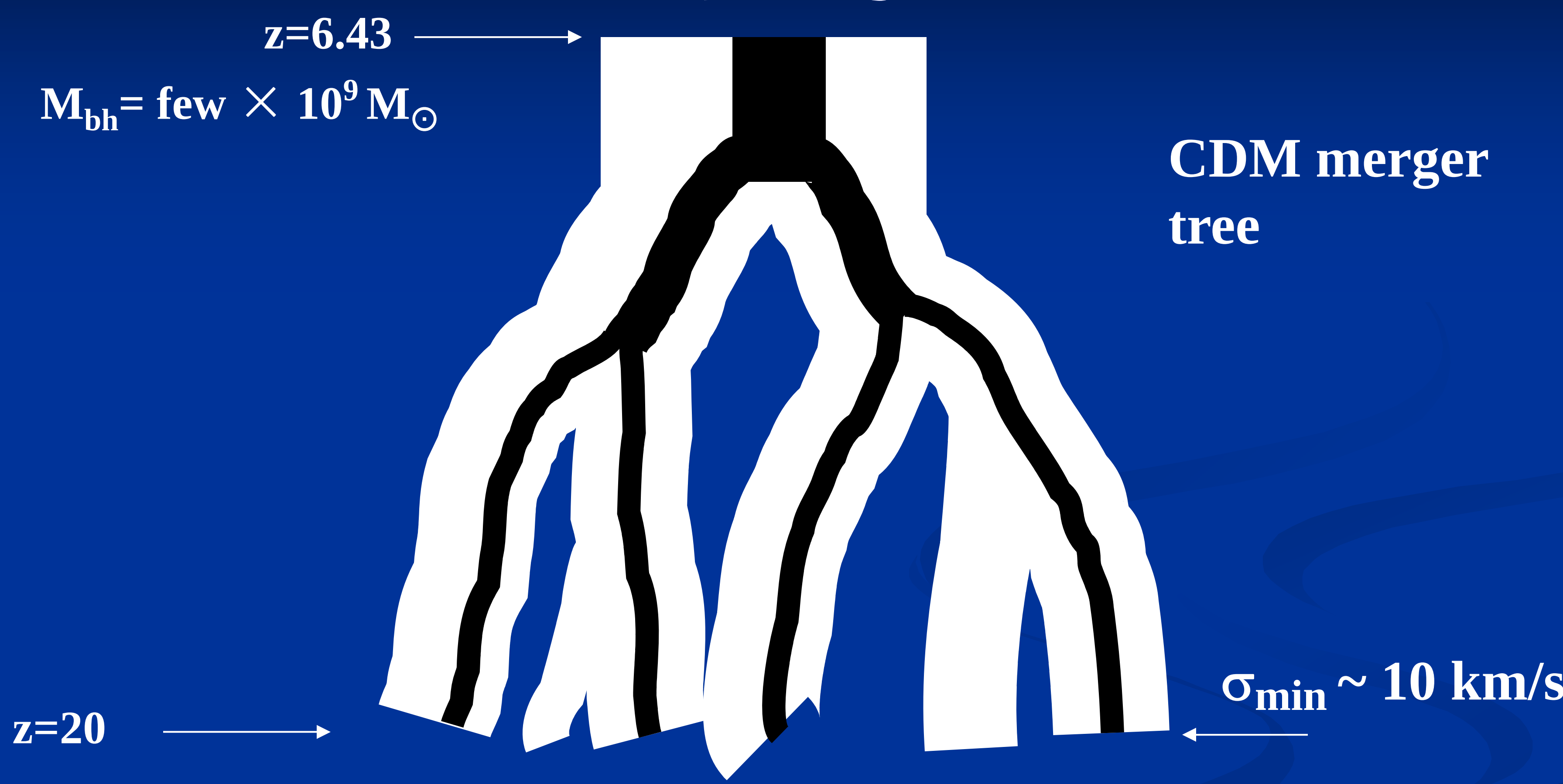
MR: Pjet\propto Psi^2 v_r

G h{whu/#P fN lqqh|/#P dunrii/#W fkhnkryvnr| +5347,

Eddington-Level Accretion

- Accretion exceed Eddington? (quasars, TDEs)
- Luminosity exceed Eddington? (ULXs)
- Inflows, Outflows, M-sigma (AGN, galaxies)
- $>10^9 M_\odot$ holes already by z~6 (seeds by z>10)

Growth of High-z Supermassive BHs



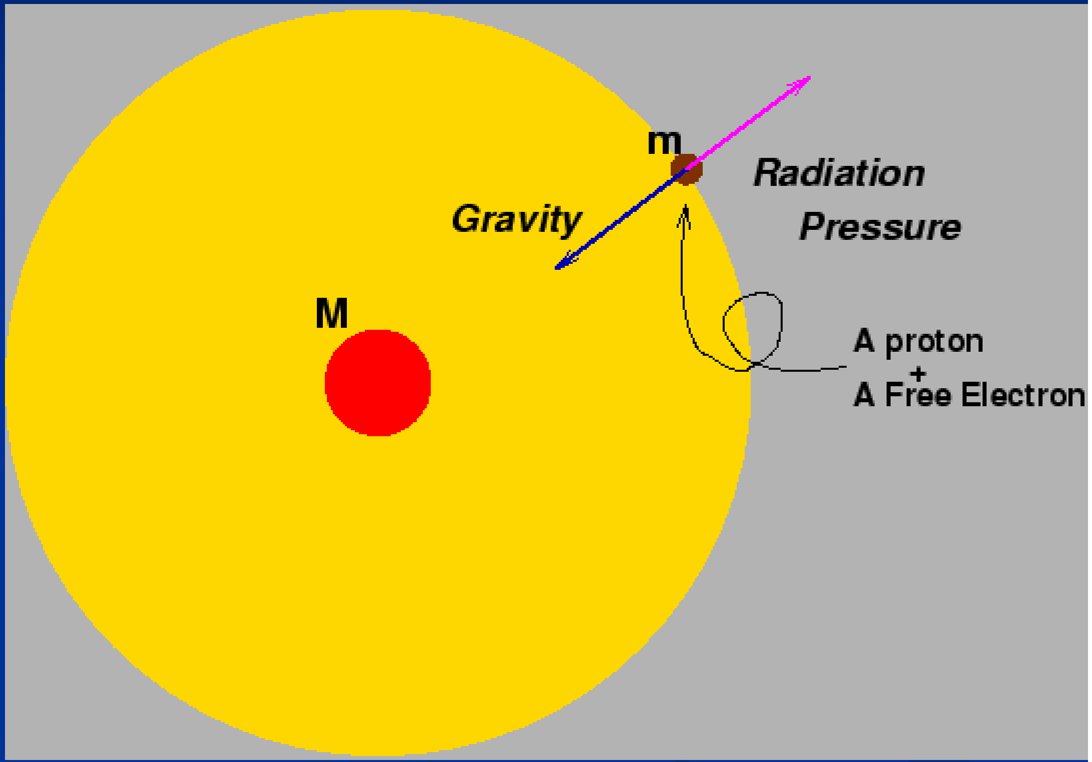
1. Can growing BHs contribute significantly to reionization?
2. How are the z~6 SMBHs with M_{bh} = few $\times$ $10^9 M_\odot$ assembled?
3. Issue: Maybe works at Edd, but then overproduce other BHs

Limits on accretion

$$F_{rad} = \frac{L\sigma_T}{4\pi c r^2}$$

$$F_{grav} = \frac{GM(m_p + m_e)}{r^2}$$

$$(m_p >> m_e)$$



$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} = 10^{46} \frac{M}{10^8 M_{sun}} erg/s$$

$\dot{M}$ is limited by Eddington, i.e.

$$L = \varepsilon c^2 \dot{M}_{acc} \le L_{Edd} = \frac{4\pi GMc}{\kappa}$$

($\kappa = \sigma_T / m_p =$ `opacity')

and some of rest mass energy turned into radiation, i.e.

$$\dot{M} = (1-\varepsilon)\dot{M}_{acc}$$

Eddington limited accretion:

$$\dot{M} < \frac{1-\varepsilon}{\varepsilon}\frac{M}{t_{Edd}}$$

With
$$t_{Edd} = \frac{\kappa c}{4\pi G} = 4.5\times10^{8}\,yr$$

Thus
$$\boxed{\frac{M}{M_0} < \exp\left(\left[\frac{1}{\varepsilon_{\min}} - 1\right]\frac{t}{t_{Edd}}\right)}$$

Final mass exponentially sensitive to 1/efficiency

Thus ε = 0.43 (maximal a = 1) restricts growth to only

$$M / M_0 < 20$$

Growing from $10M_{sun}$ to $M > 5\times10^9 M_{sun}$ by z = 6 requires

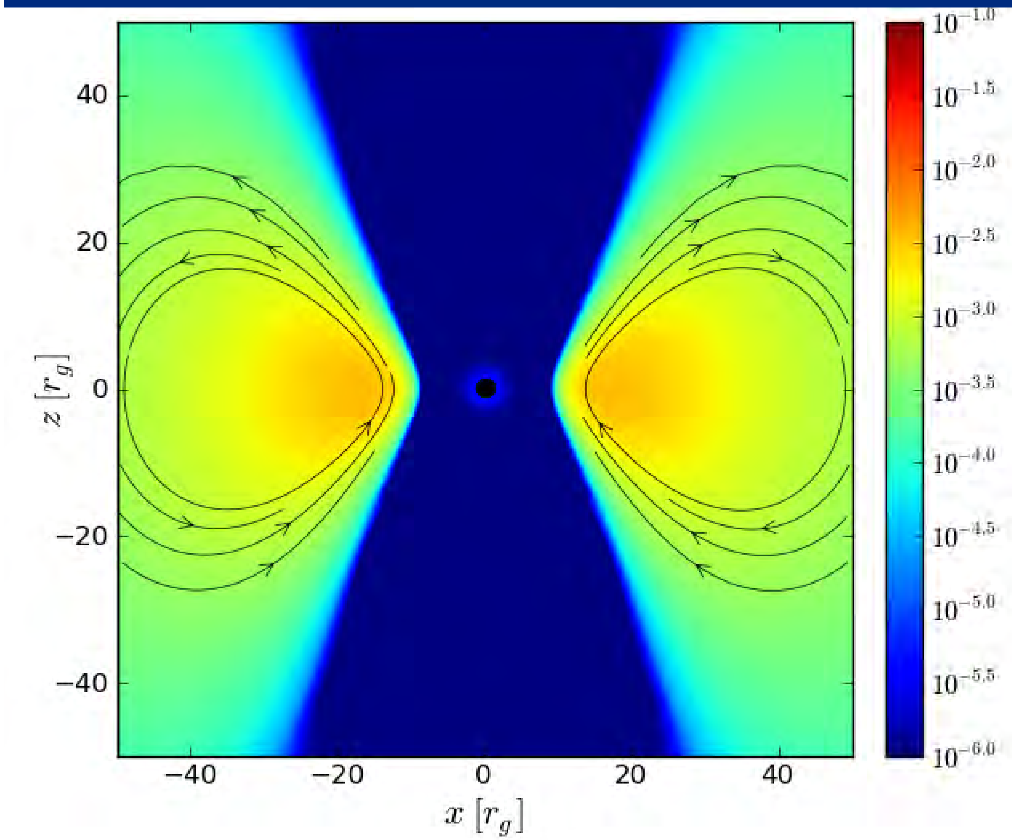
$$\varepsilon_{\min} < 0.08$$

i.e. a < 0.5 . Even lower spin if sub-Eddington in moments. Even smaller spin for UDFy-38135539 at z=8.6.

Rapid BH growth requires:

- **Quite low spin [King et al. , but overproduces int. BHs:** Tanaka & Haiman (2009)**]**
- **Or super-Eddington Accretion**

Super-Eddington Accretion



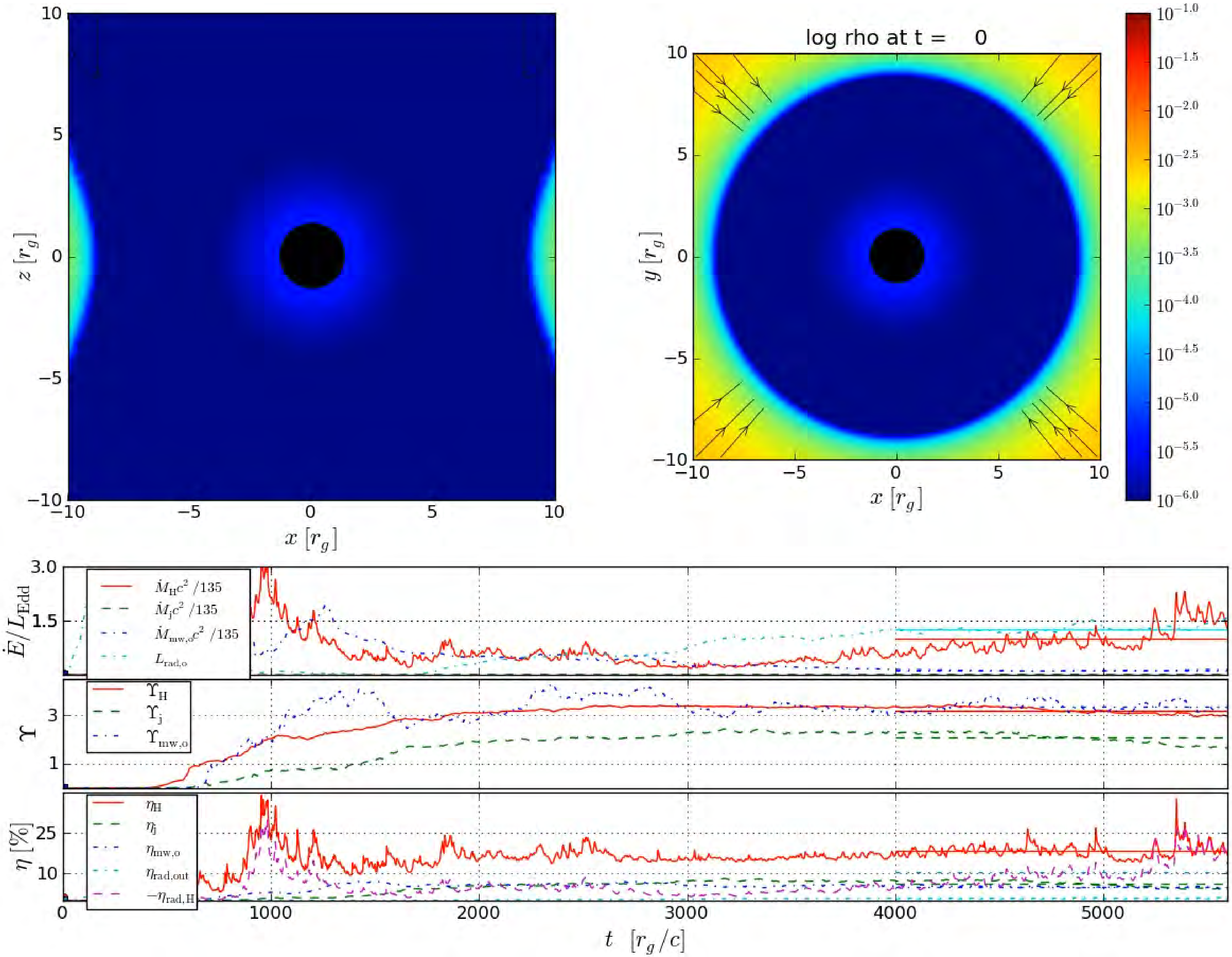
Physical Setup:

GRRMHD w/M1 (not FLD)
M1 Closure = Rad. Fluid
e-Scattering, FF+BF Abs
Spin: a=0.9375 (0,0.8)
Weak Mag. Field (not MAD)
Marg. Bound Torus
Run: ~5,000M – 20,000M

Numerical Setup:

Fully 3D Kerr-Schild Coords:
256x128x64
Implicit Covariant Rad. 4-force

Sadowski, Narayan, McKinney, Tchekhovskoy (2013)
McKinney, Tchekhovskoy, Sadowski, Narayan (2013)



log rho at t = 0
$z\ [r_g]$
$x\ [r_g]$
$y\ [r_g]$
$10^{-1.0}$
$10^{-1.5}$
$10^{-2.0}$
$10^{-2.5}$
$10^{-3.0}$
$10^{-3.5}$
$10^{-4.0}$
$10^{-4.5}$
$10^{-5.0}$
$10^{-5.5}$
$10^{-6.0}$
$\dot{E}/L_{\rm Edd}$
$\dot{M}_{\rm H}c^2\ /135$
$\dot{M}_{\rm j}c^2\ /135$
$\dot{M}_{\rm mw,o}c^2\ /135$
$L_{\rm rad,o}$
Υ
$\Upsilon_{\rm H}$
$\Upsilon_{\rm j}$
$\Upsilon_{\rm mw,o}$
$\eta\ [\%]$
$\eta_{\rm H}$
$\eta_{\rm j}$
$\eta_{\rm mw,o}$
$\eta_{\rm rad,out}$
$-\eta_{\rm rad,H}$
$t\quad [r_g/c]$

Super-Eddington Accretion

- Mass accretion rate can arbitrarily exceed Eddington rate
- Luminosity near Eddington, so Rad. Eff. very low!
- BH can rapidly grow even for large spin
- Isotropic Equivalent luminosity >10x Eddington for face-on view (ULXs?)
- Blandford-Znajek jet power scales with Mdot, so exceeds Lrad. May have implication to AGN Feedback

Classic Disk-Jet Theory

- Disk with weak Jet

(Fat Dog with tiny Tail)

- Weak Magnetic Fields Amplified by the MRI
- Invisible Jets
- Accretion Eddington Limited

Disk & Jet Theory

- Jet can dominate Disk (Dog Chasing Tail)
- Ordered Mag. Flux Piles-up
- Flipping MAD Hot Outbursts
- Super-Eddington Mdot and geom. beamed Lrad and Pjet