3D GRMHD Jet Simulations

[and other stuff]

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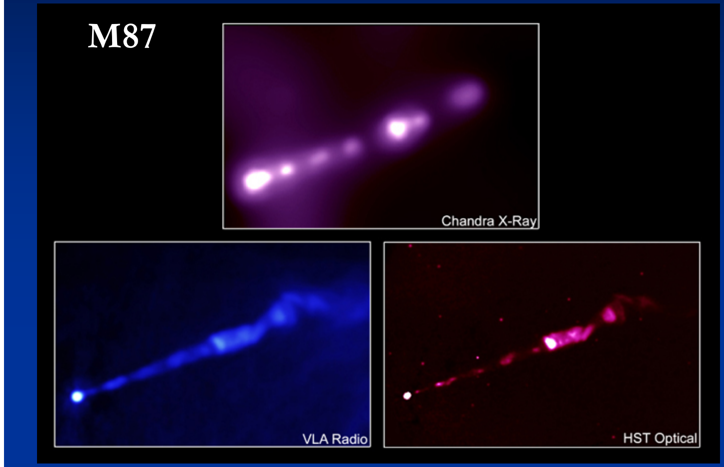
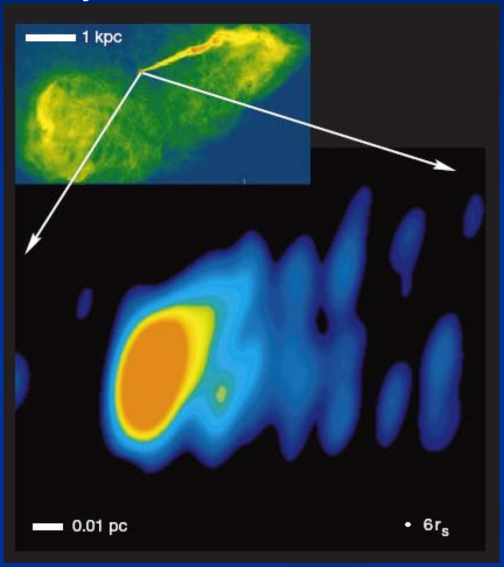
Issues Addressed

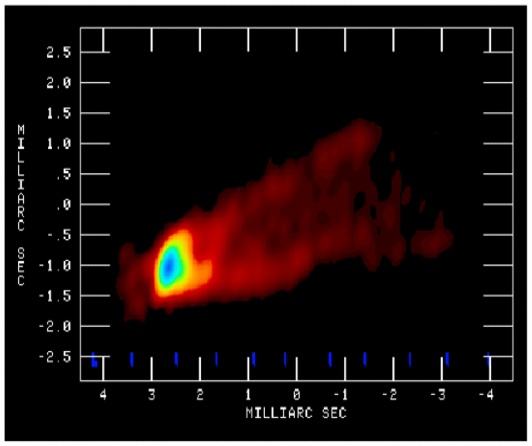
- Radio Loud/Quiet Dichotomy
  - Caused by Environment, Spin, Galaxy Evolution?
- Magnetosphere near BH
  - How different from NS?
- Jet Launching and Stability during Accretion
  - What is Dependence on Field and Turbulence?
  - What helps or hurts stability?

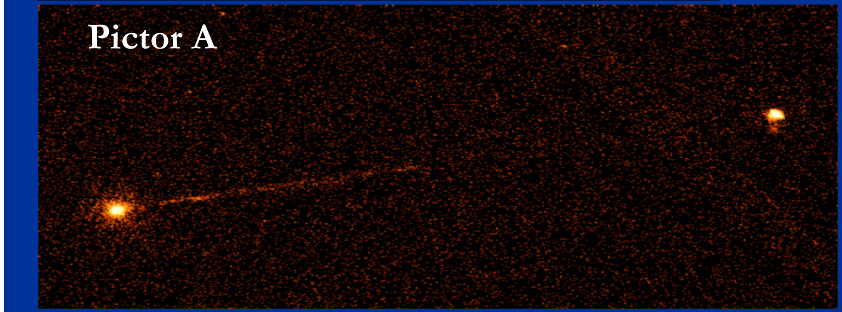
AGN Jets

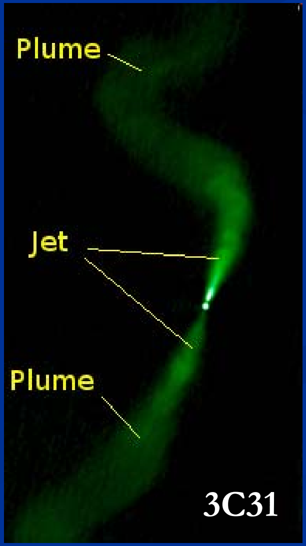


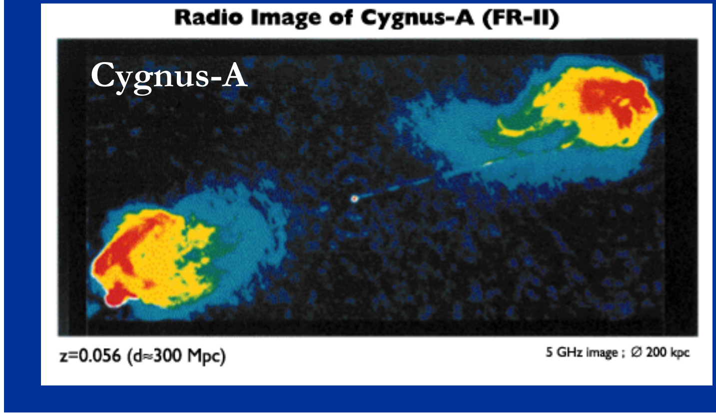
Junor/Biretta/Walker

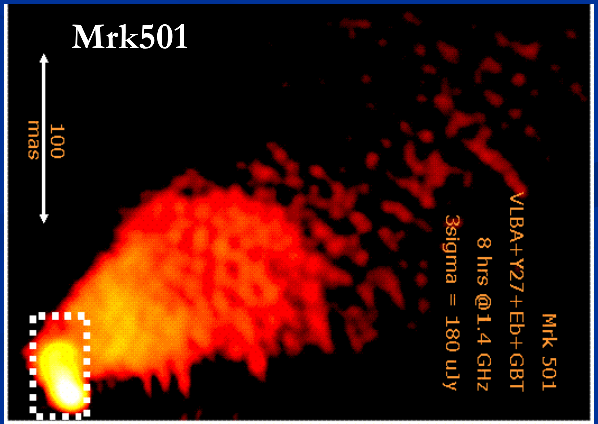












The Sample

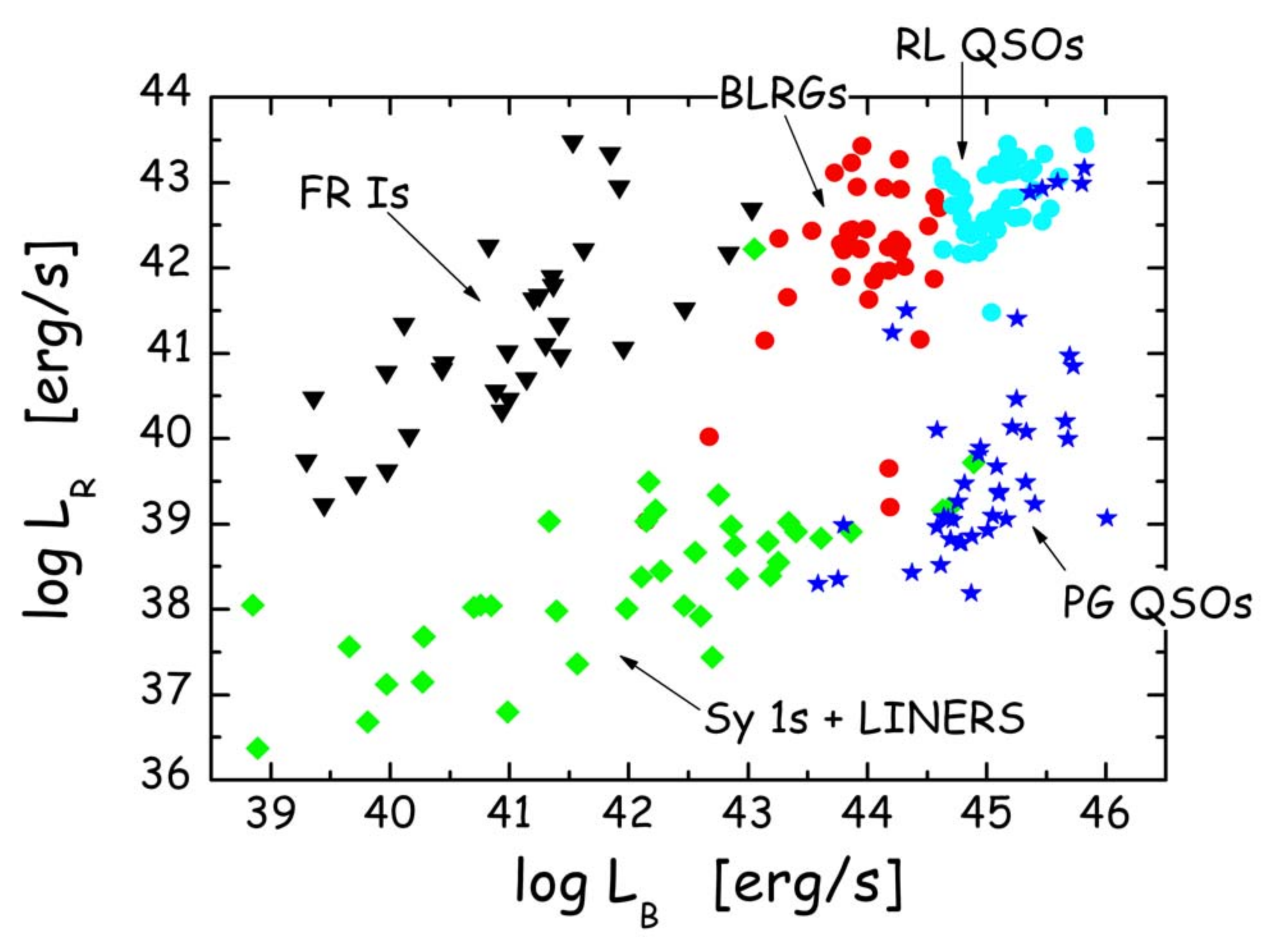
Want to camapare the main jet parameter, i.e. bulk kinetic power L_j, with the main parameters of the central engine, namely M_{BH} and L_{acc}, for AGNs covering many decades in radio and disk luminosities. Hence, our sample has to be by definition *heterogeneous and incomplete*.

Select sources (BLRGs, BLRQs, Sy1s, LINERs, FR Is, PG QSOs) for which:

(i) the optical flux of the unresolved nucleus is known;
(ii) the total radio flux is known (including extended emission);
(iii) the black hole mass can be estimated.

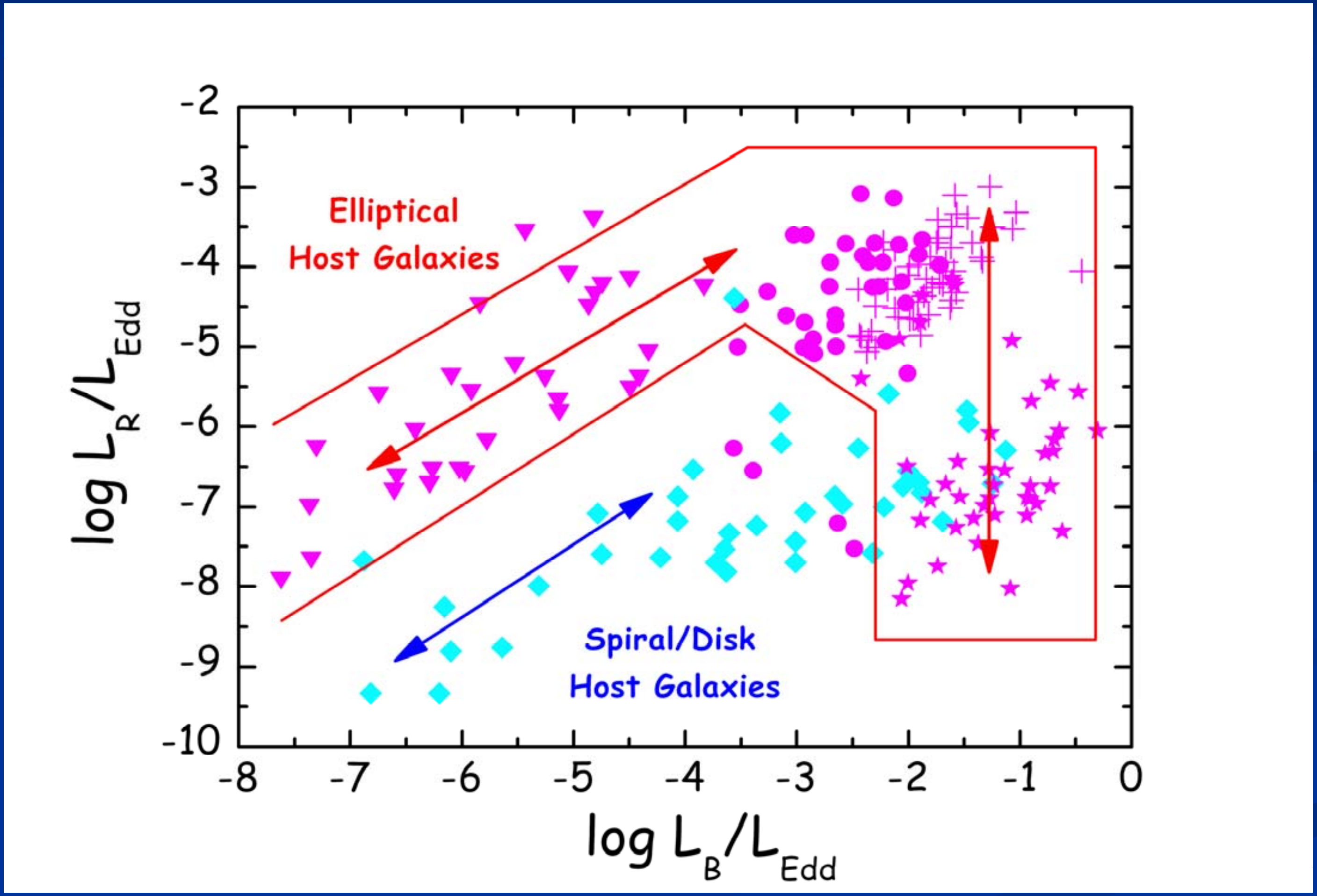
Want to avoid complications due to signifcant beaming and obscuration, and hence we exclude blazars (OVVQs, HPQs, FSRQs, BL Lacs) as well as type-2 AGNs (NLRGs, Sy2s).

Two sequences on L_B–L_R plane

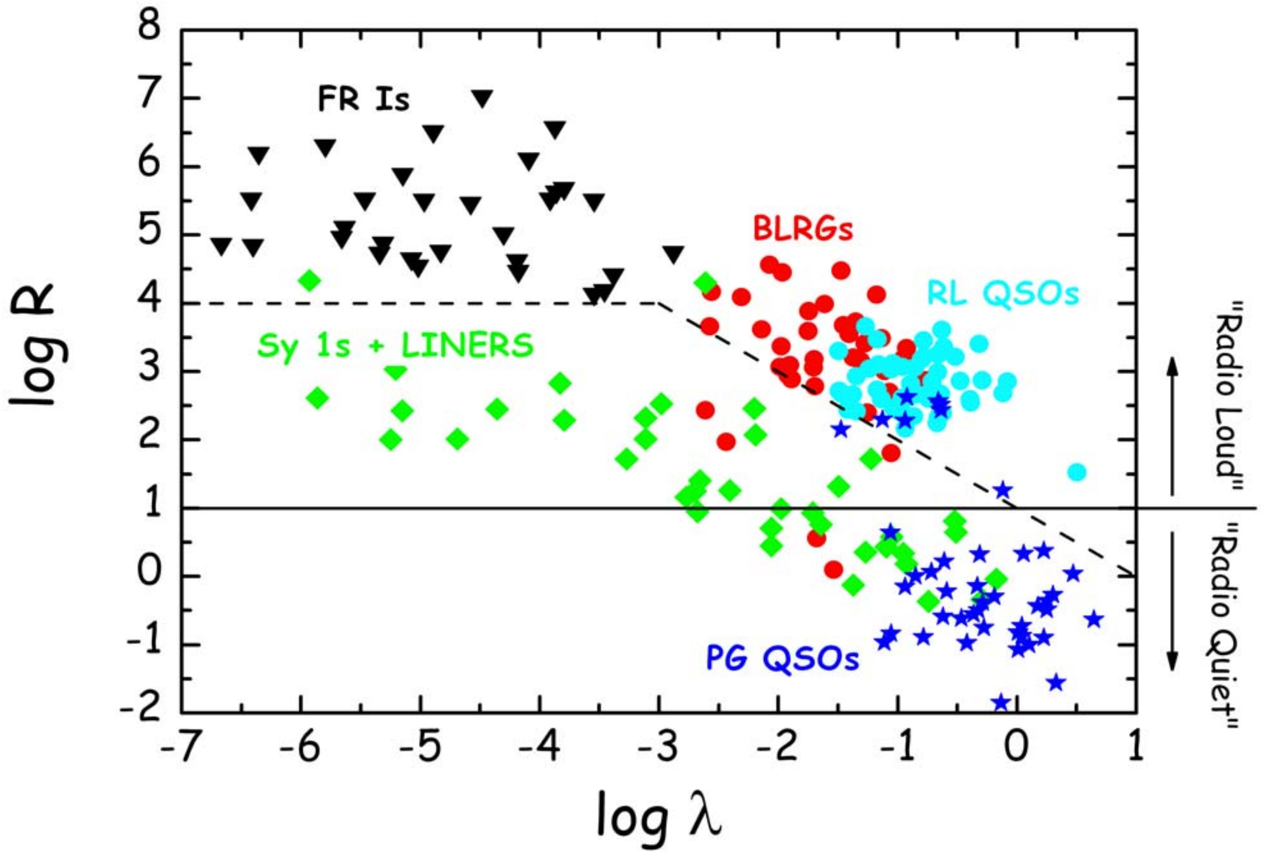


(Sikora, Stawarz, & Lasota 2007)

The same two sequences emerge on (L_B/L_{Edd})-(L_R/L_{Edd}) plane



Radio-Loud / Radio-Quiet



Main parameters

$$L_B \equiv \nu_B \times L_{\nu B} \quad , \quad \lambda_B \equiv 4400\ \text{Å}$$

nuclear B-band luminosity

by assumption $L_{acc} = 10 \times L_B$

$$L_R \equiv \nu_R \times L_{\nu R} \quad , \quad \nu_R \equiv 5\ \text{GHz}$$

total jet radio luminosity

by assumption $L_j \propto L_R$

$$R \equiv L_{\nu R}/L_{\nu B} \approx 10^5 \times (L_R/L_B)$$

radio-loudness parameter

$$L_{Edd} = 4\pi G M_{BH} m_p c/\sigma_T \approx 10^{38} \times (M_{BH}/M_\odot)\ \text{erg/s}$$

Eddington luminosity

$$\lambda \equiv L_{acc}/L_{Edd} = 10 \times (L_B/L_{Edd})$$

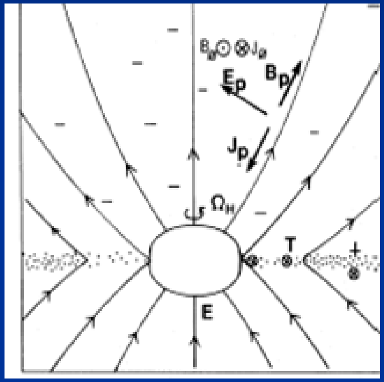
accretion rate

Possible Solutions to Dichotomy

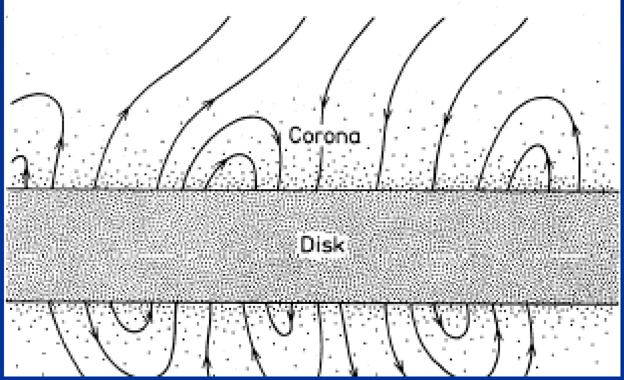
- Changes in Field Geometry or Confinement
- Mass-loading (Meier et al. 97: Magnetic Switch)
- Variation in amount of BH/Disk Magnetic Flux
  - Flux trapping (Reynolds 06, Garafalo 09)
  - Difference in Disk Thickness (Meier 01)
- Non-Dipolar Fields (Beckwith/McKinney)
- Radio power may not map to jet power:
  - ISM interaction and radio generation

Disk-BH-Jet Connection

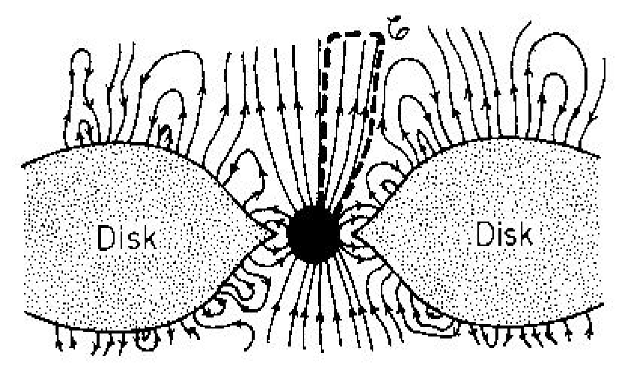
BZ77



Blandford & Payne ‘82

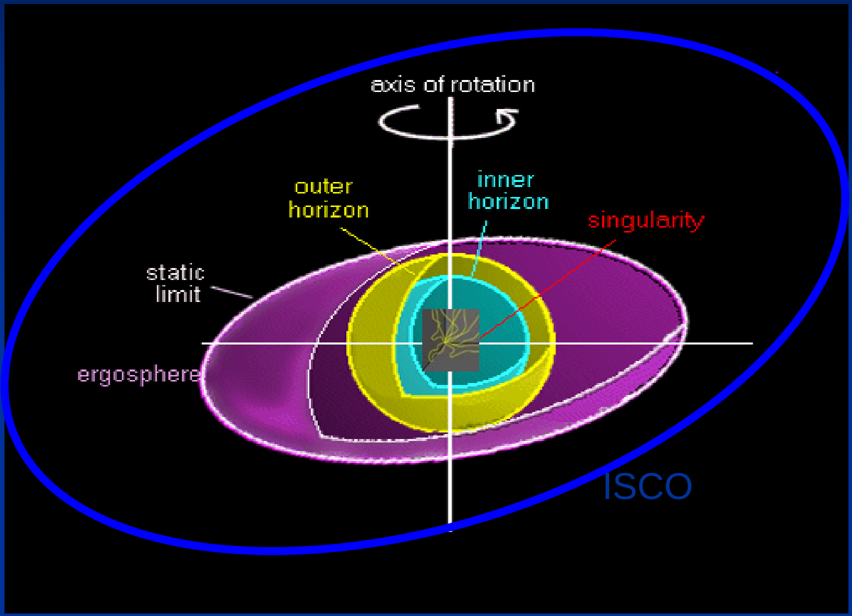


MacDonald & Thorne ‘82



- What is the structure of the electro-magnetosphere?
  - vs. spin? (Meissner Effect)
  - vs. jet mass-loading? (σ)
  - vs. accreted field geometry? (dipolar vs. quadrupolar, etc.)
  - in presence of non-axisymmetric turbulence?

Black Holes



Michell 1783 Escape velocity:

$$mv^2/2 = GMm/r \rightarrow v = \sqrt{2GM/r}$$

$$v = c \rightarrow r = 2GM/c^2$$

No-Hair Theorem:

Mass: M, Spin: J, Charge: $\xcancel{Q}$

Horizon: $r_H = M \pm \sqrt{M^2 - a^2}$

Static Limit: $r_S = M \pm \sqrt{M^2 - a^2 \cos^2\theta}$

Inner-most stable circular orbit (ISCO): $3r_H$ for a=0 , $1r_H$ for a=M

Photon Sphere: Inside, objects cannot orbit at all (~$3/2r_H$ for a=0)

Static Limit: Varies from $1r_H$ to $2r_H$ for a=M (ergosphere inside)

Horizon: Inside, objects must fall

Singularity: Reached in finite time (superstring theory?)

Equations of Motion

- Mass Conservation (ρ_0)
- Maxwell's Equations (E, B, ρ, J)
- Energy-Momentum Conservation (u, p, and v)

Closure:

- EOS: p(u)
- Ohm's law: J(E, B,η_i) : e.g. $J_{co}=\sigma E_{co}$ & $E_{co}=0$
- Viscosity + Resistivity

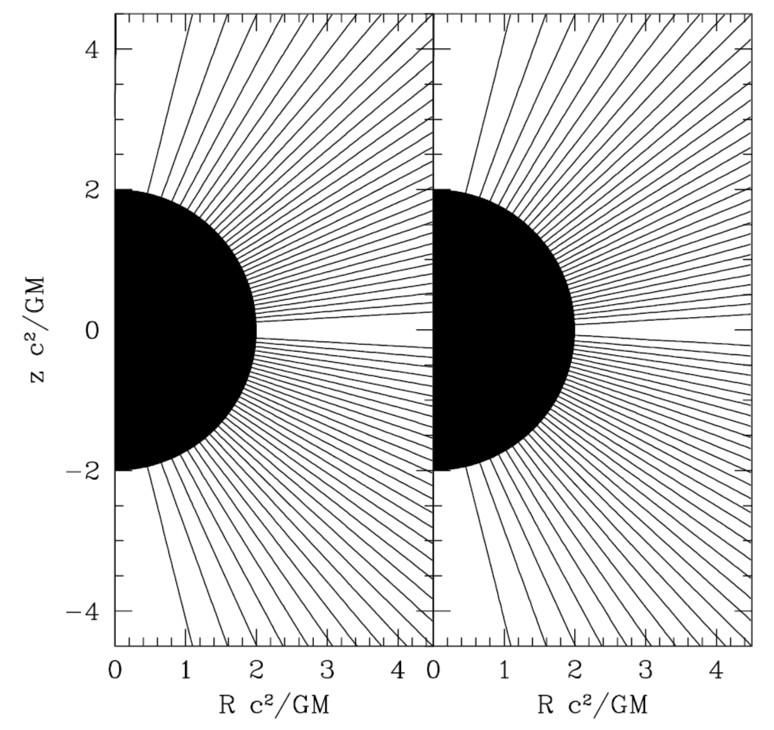
... in GR

BH Magnetospheres 101

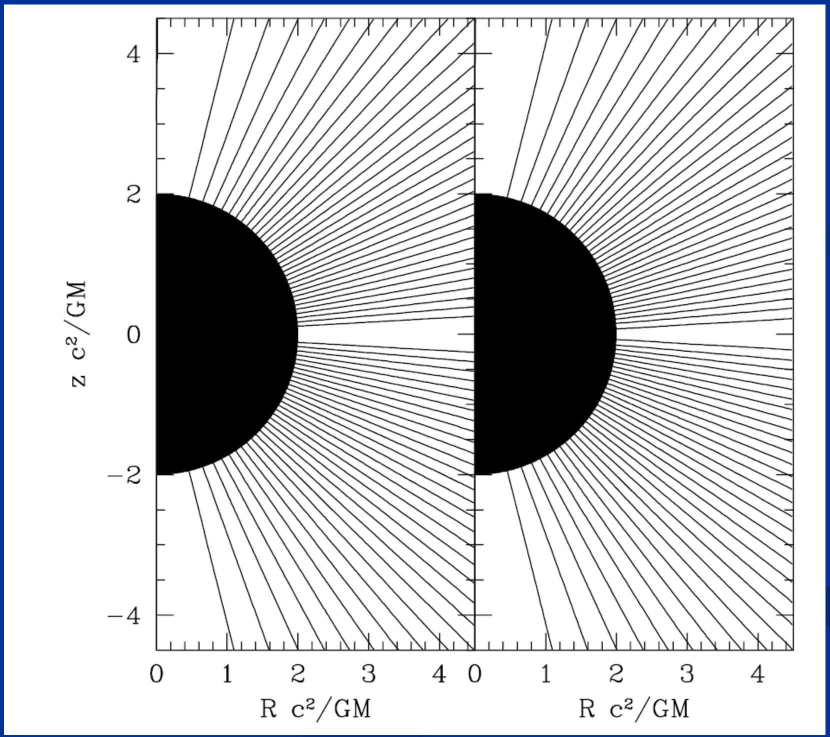
$$F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}$$

$$A_\phi - A_\phi^0 = \int_s B \cdot ds = \int_\theta \sqrt{-g} B^r - \int_r \sqrt{-g} B^\theta$$

$$A_\phi = (1 - \cos\theta)$$

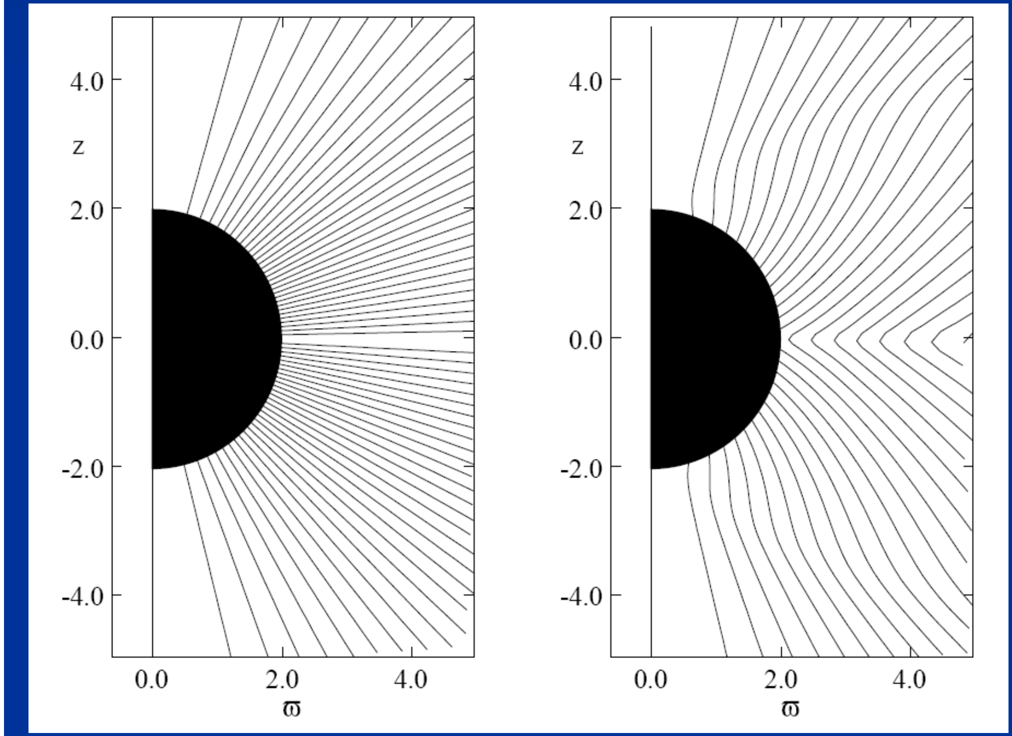


Pure Monopole a=0

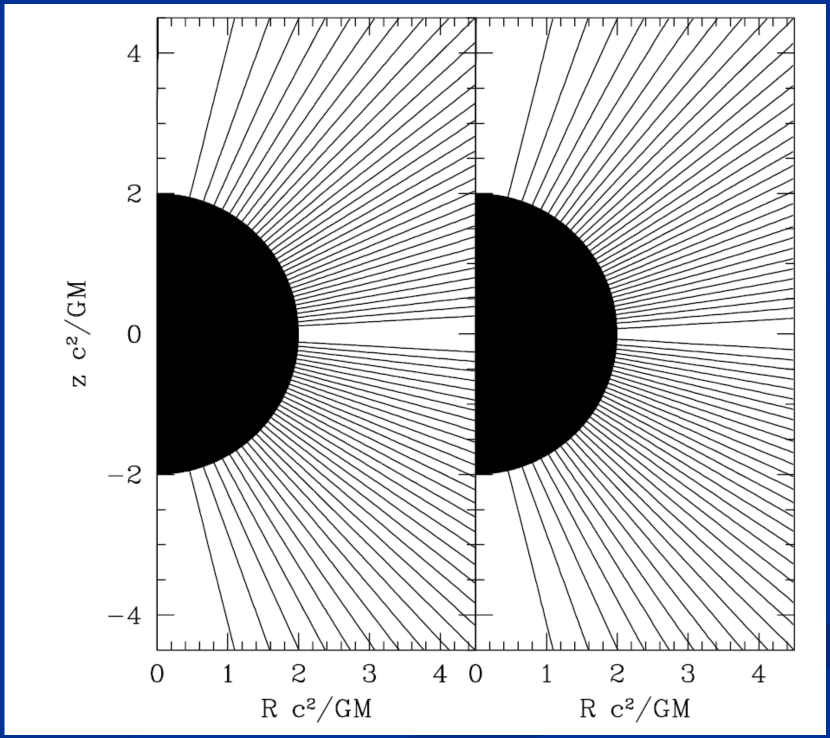


Split-Monopole a=0

Split-Monopole a=0 or small a



Komissarov 04 – 5GM/c^3

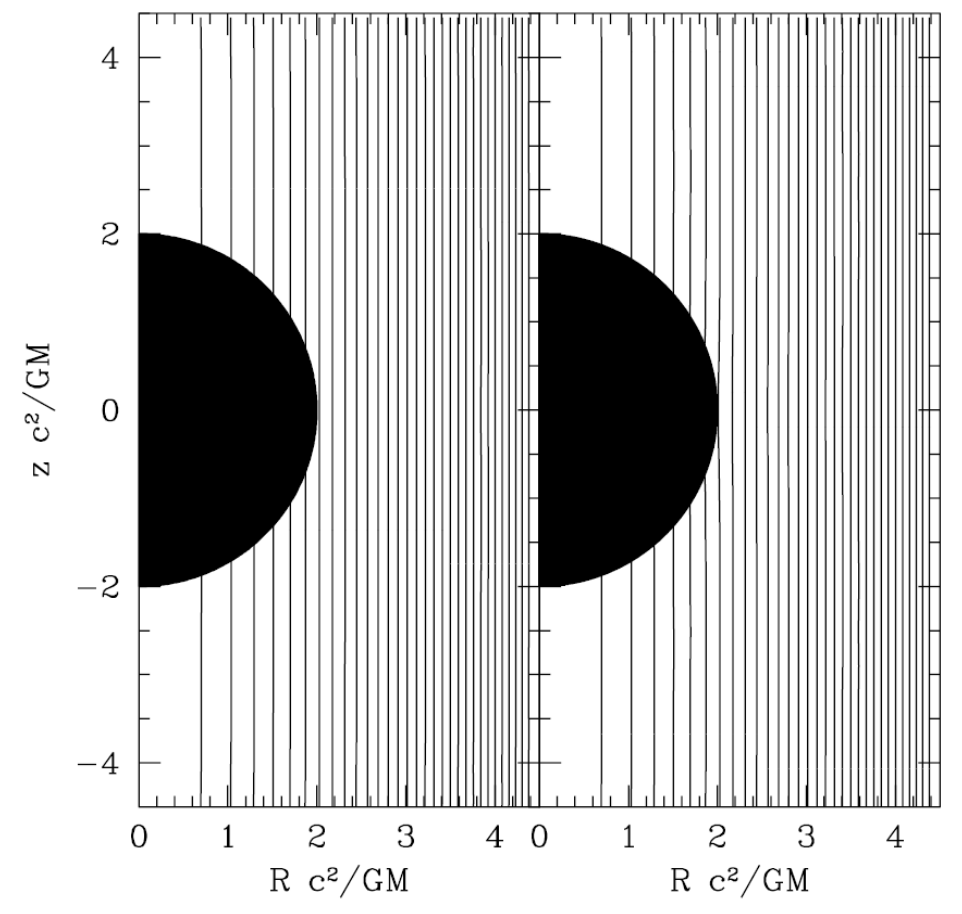


McKinney 06 – 10^{4}GM/c^3

Wald Solution: a=0 or small a

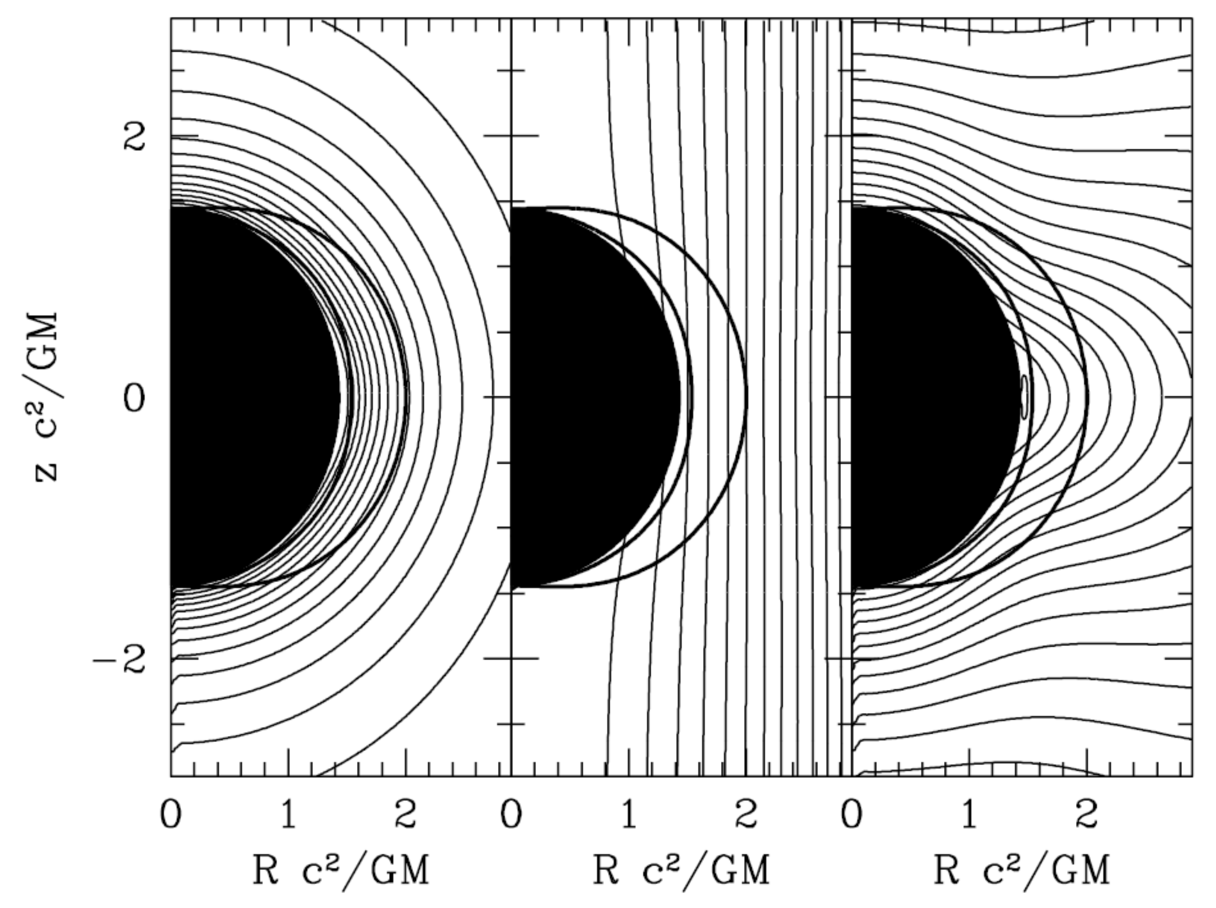
$$A_\mu = B_0(2at_\mu + \phi_\mu)$$

$$J^\mu = F^{\mu\nu}_{;\nu} = 0$$



McKinney 06 – 10^4GM/c^3

Wald a=0.9



Light Surface:

$u \cdot u = -1$

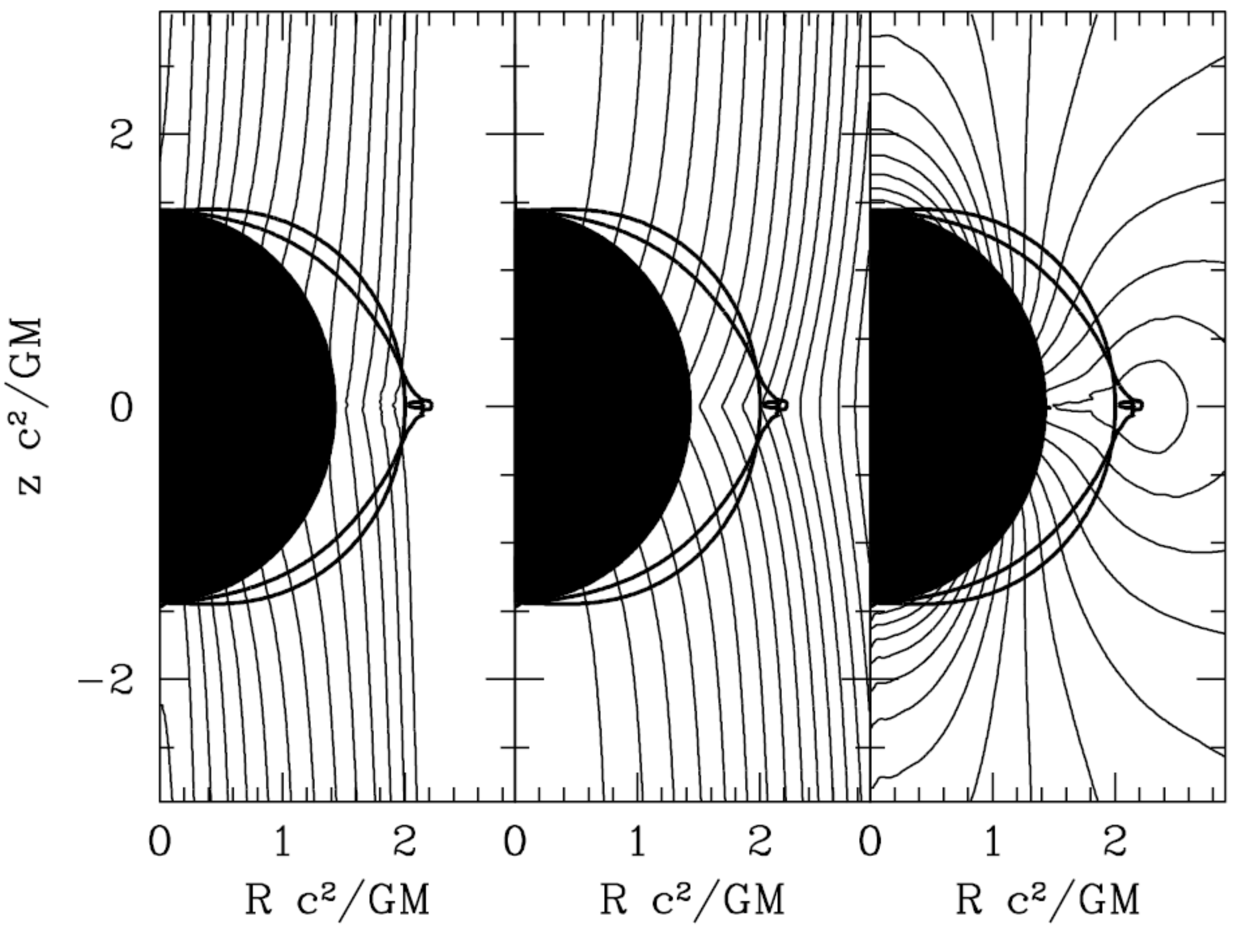
$u^t \rightarrow \infty$

$g_{tt} + 2\Omega g_{\phi t} + \Omega^2 g_{\phi\phi} = 0$

$\Omega = E_\theta / B^r = -E_r / B^\theta$

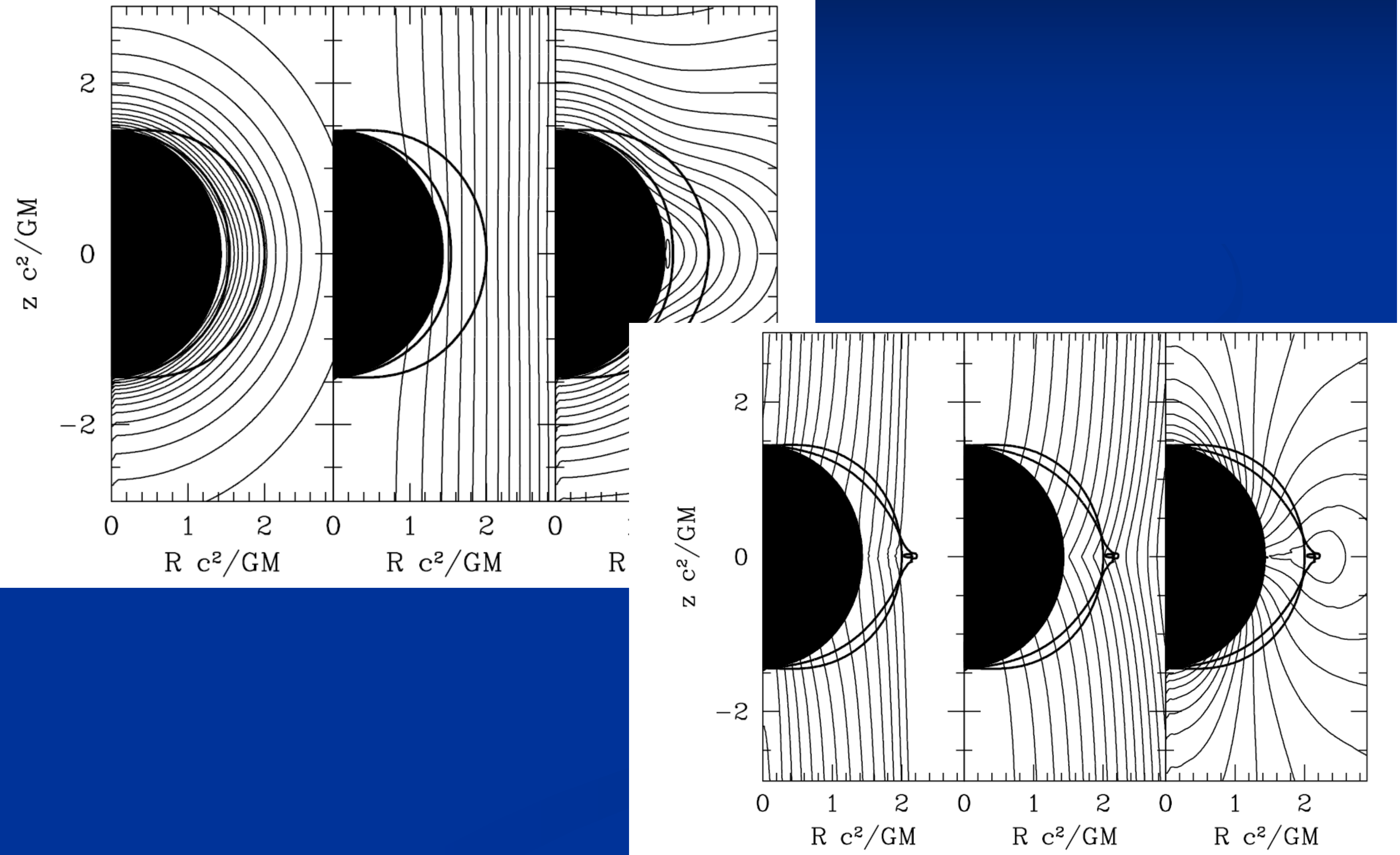
Ω/Ω_H: **0-0.67 , A_ϕ** , b^2

Conductive* Wald a=0.9

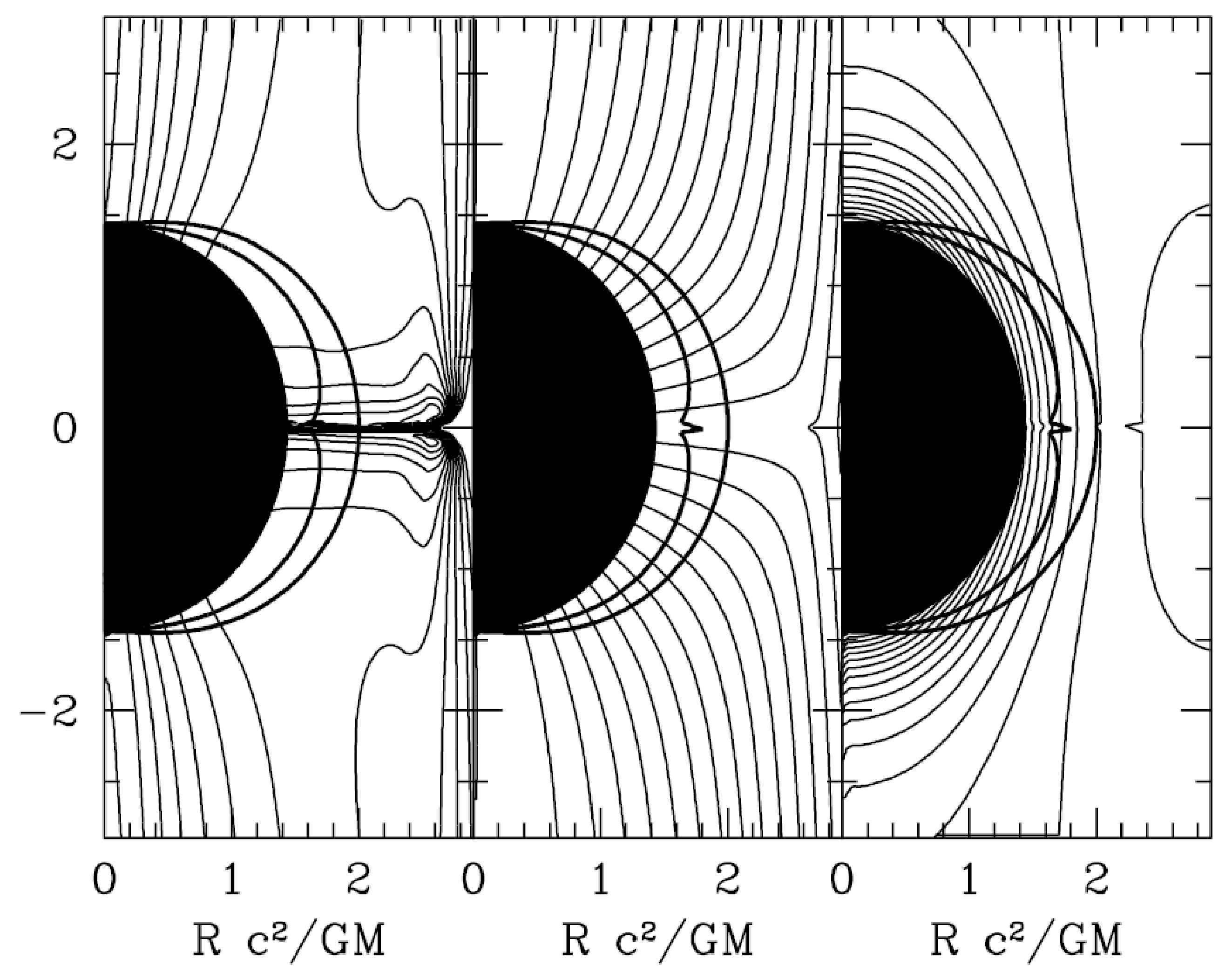


Ω_F: **0-0.67** , $\mathbf{A_\phi}$, b^2

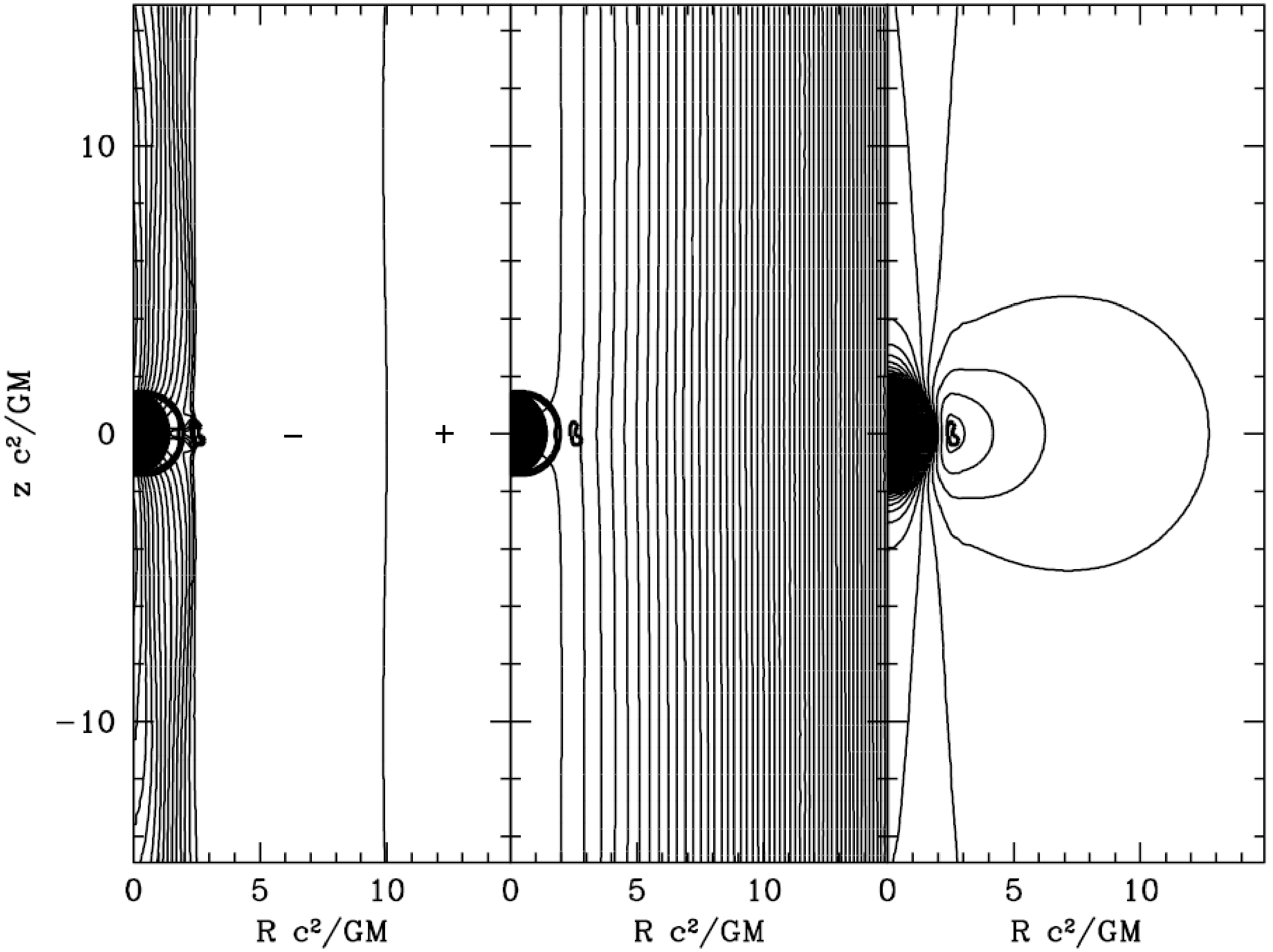
Vacuum vs. Conductive* Wald



Conductive** Wald a=0.9

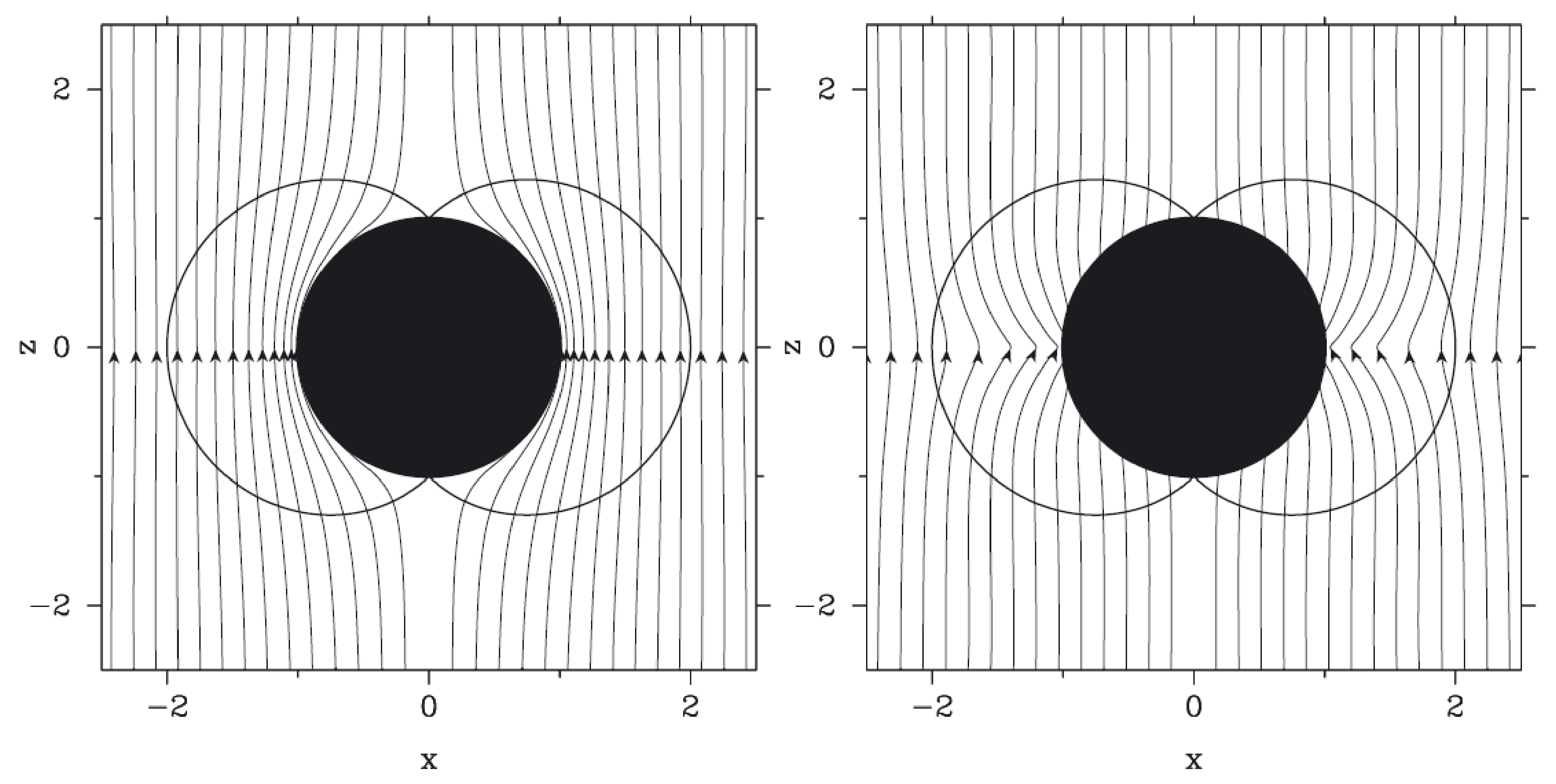


Conductive** Wald a=0.9



a=0.999 Force-Free GRMHD

Komissarov & McKinney 07 vs. King, Lasota, Kundt 75, et al.

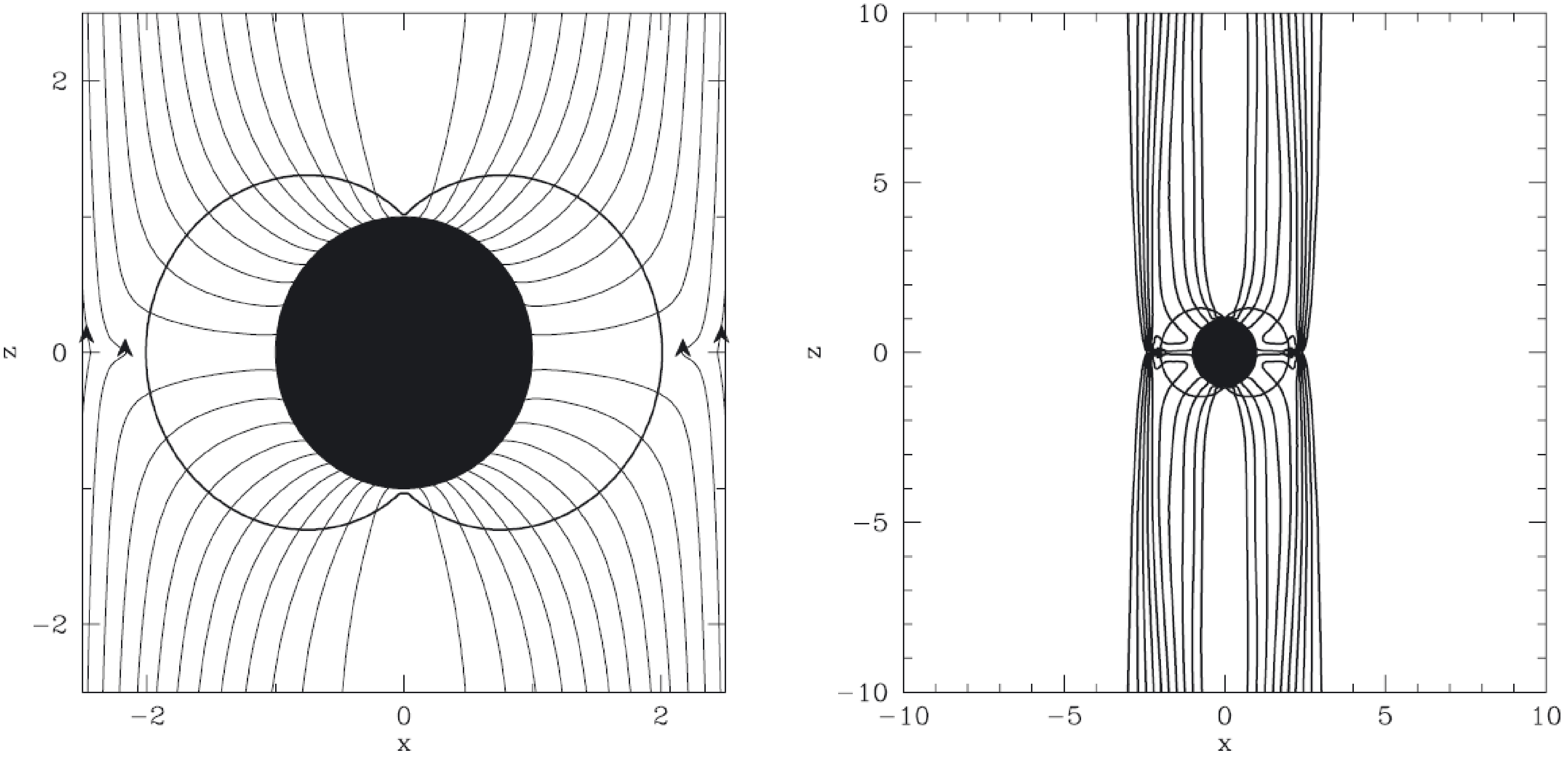


Vacuum

Conducting*

a=0.999 Force-Free GRMHD

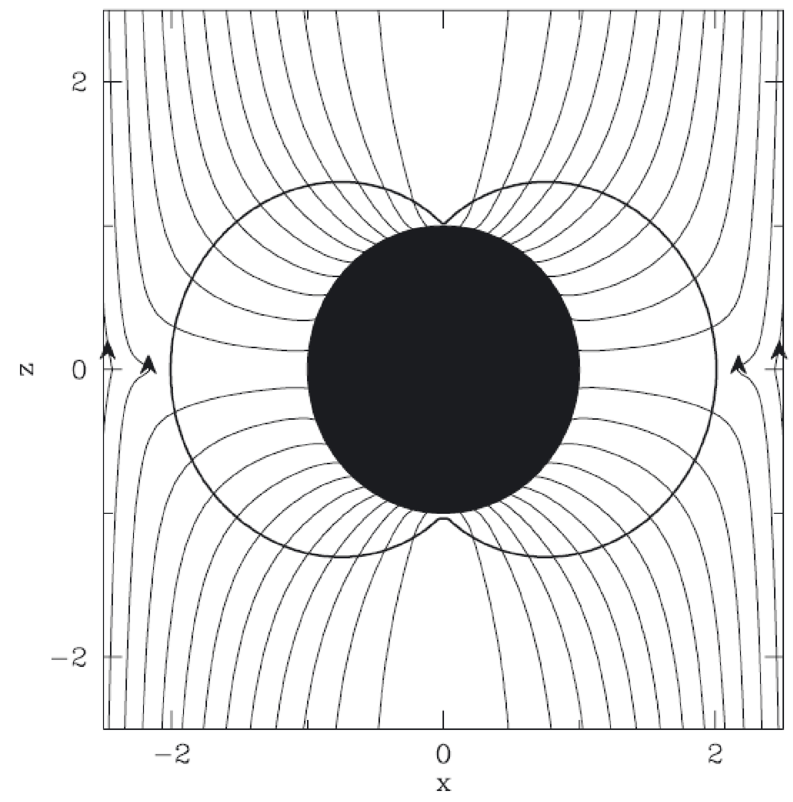
Komissarov & McKinney 07

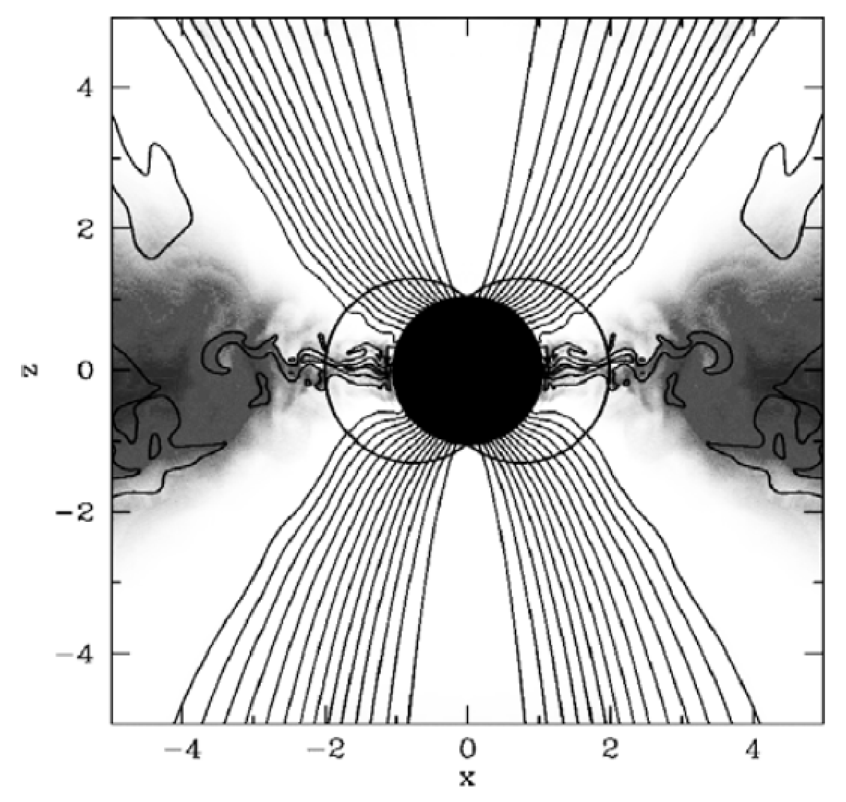


Conducting**

Ω_F Jet

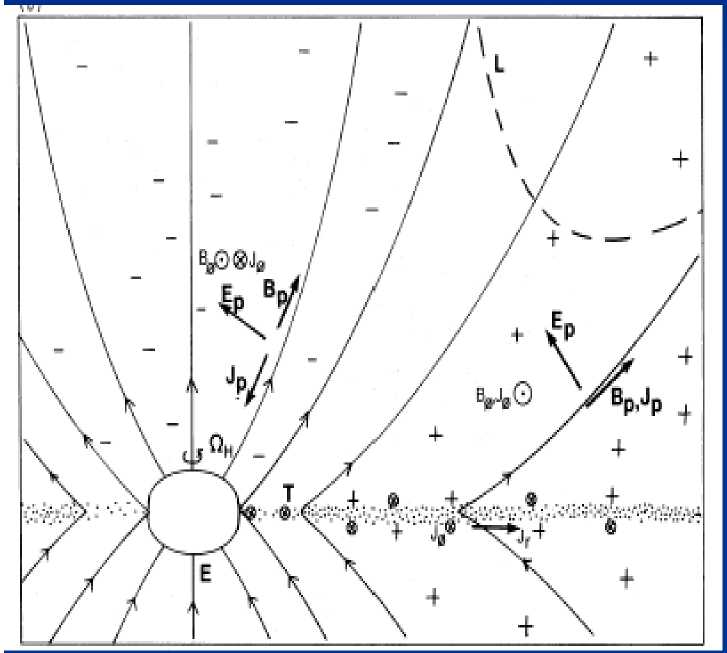
2D GRMHD Disk a=0.999





Komissarov & McKinney 07

Disks w/ Paraboloidal Fields



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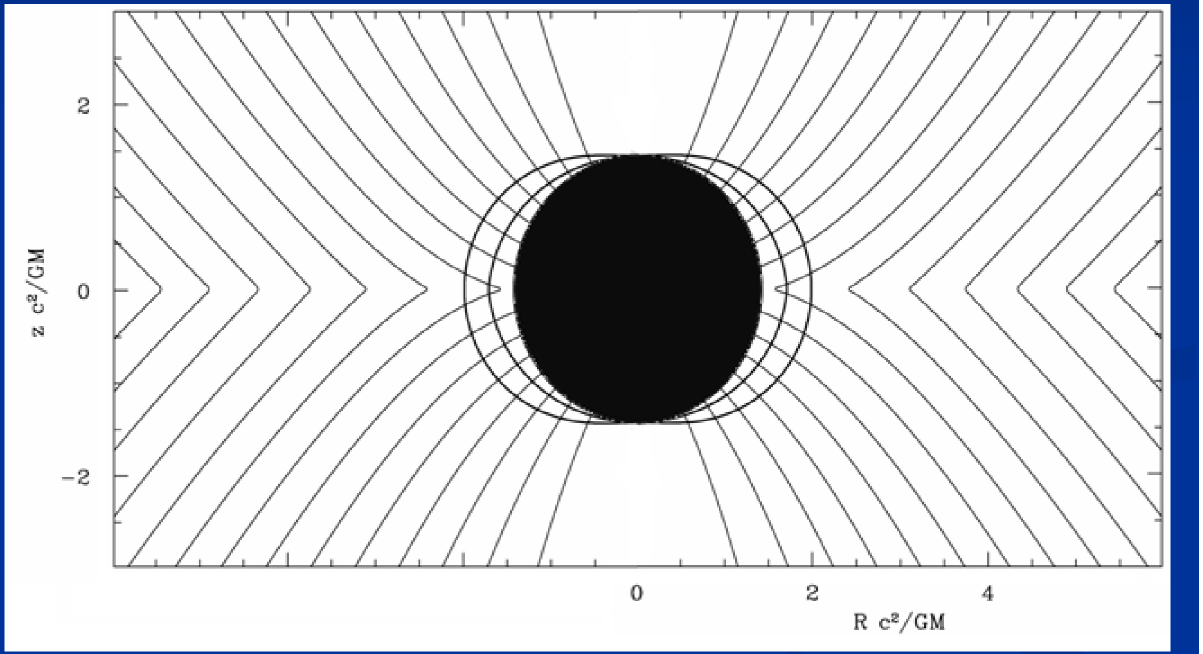
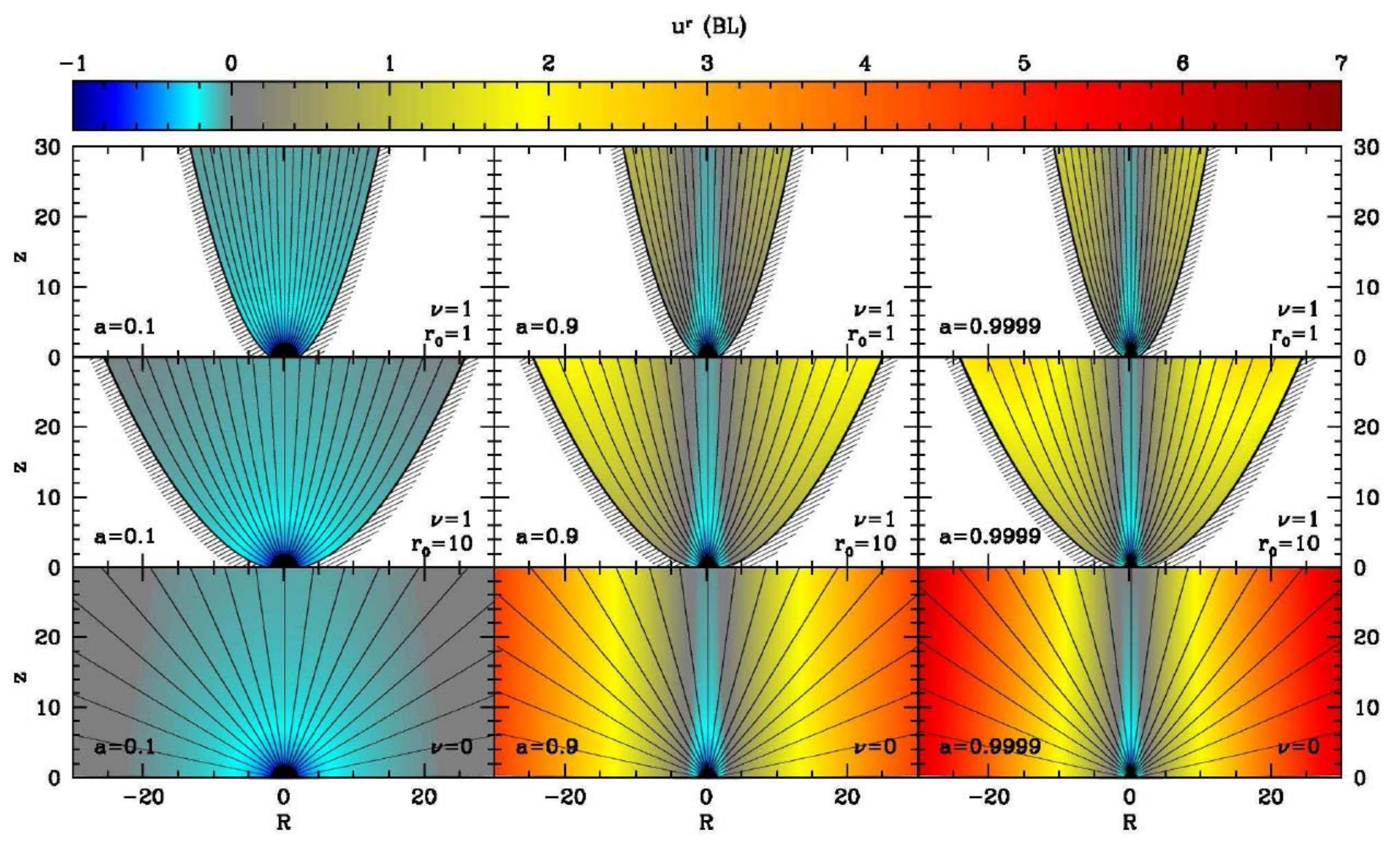


McKinney & Narayan 2007

$$A_\phi \propto [(r+r_0)/(r_H+r_0)]^\nu(1-\cos\theta)$$

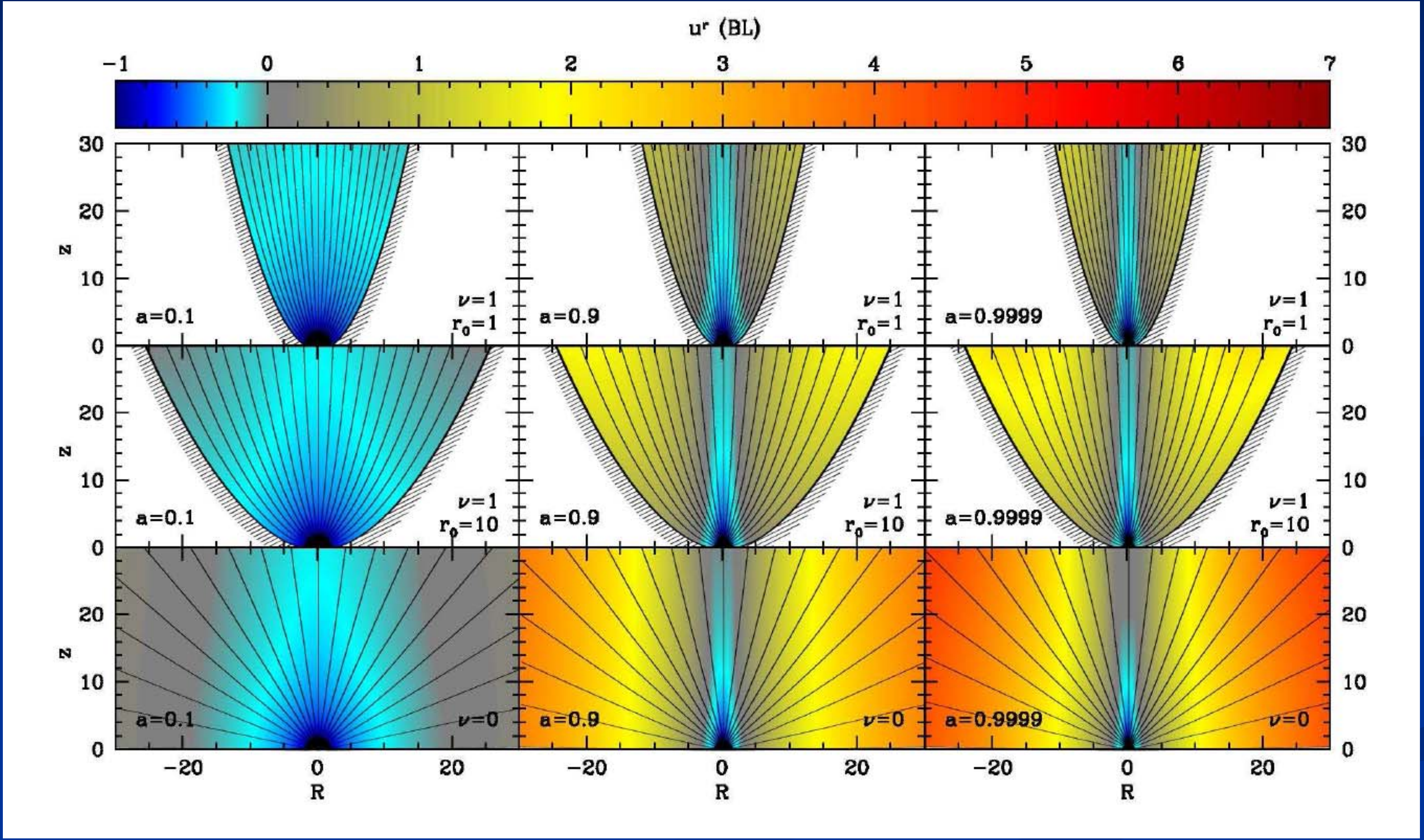
Force-Free GRMHD



Tchekhovskoy, Narayan, McKinney 09

$$A_\phi \propto [(r+r_0)/(r_H+r_0)]^\nu(1-\cos\theta)$$

GRMHD - walls



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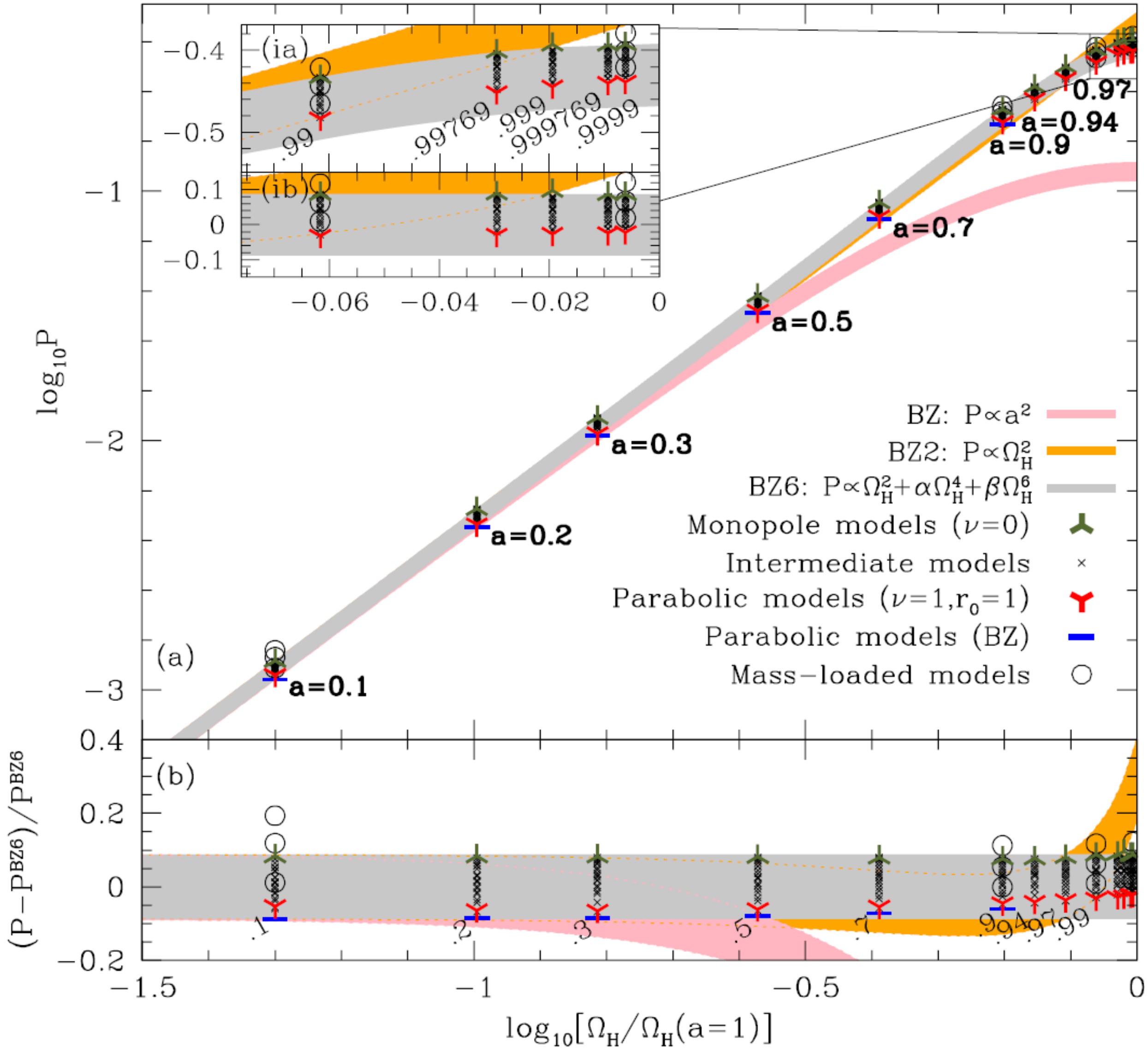
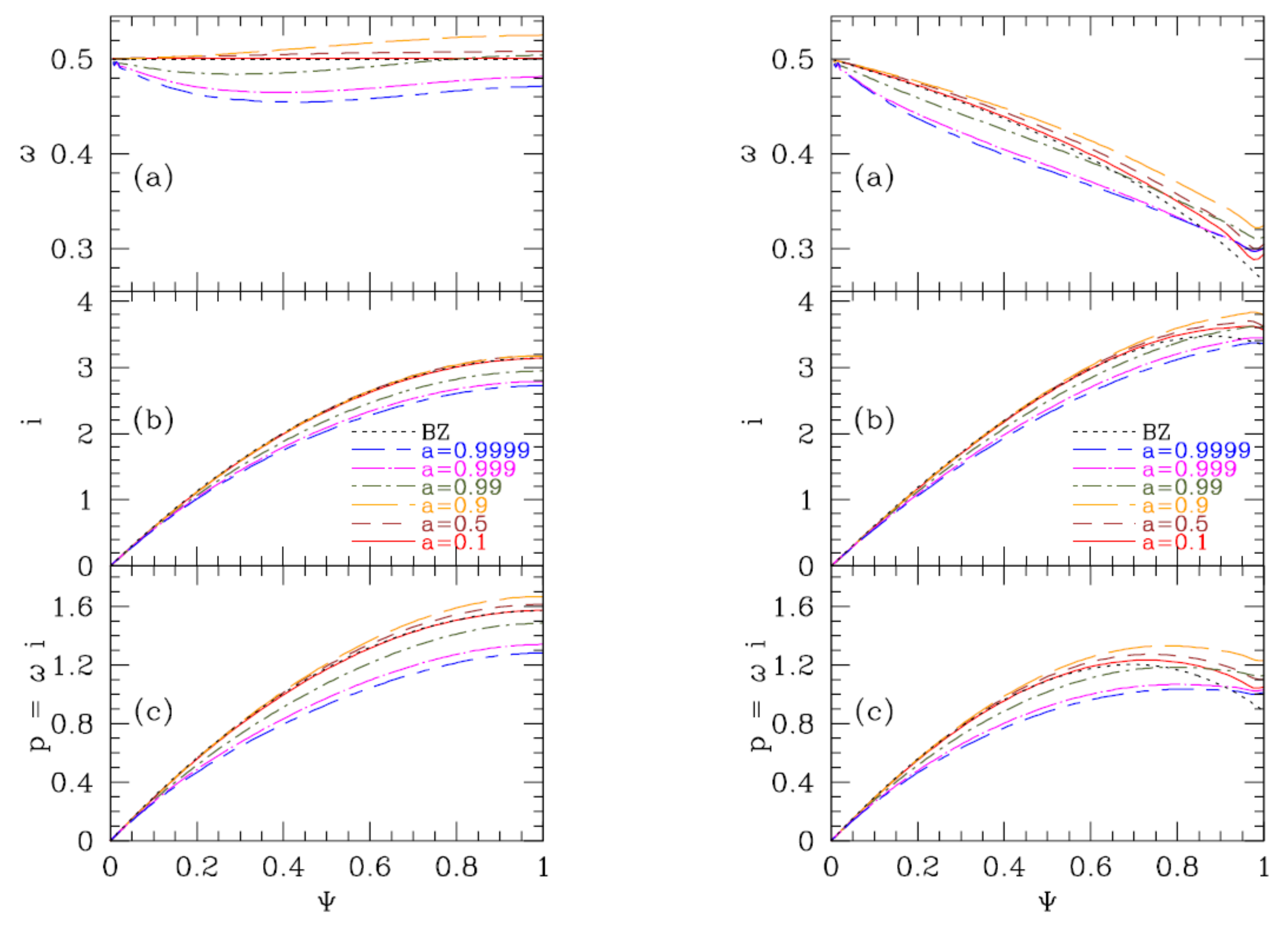
Power vs. Spin



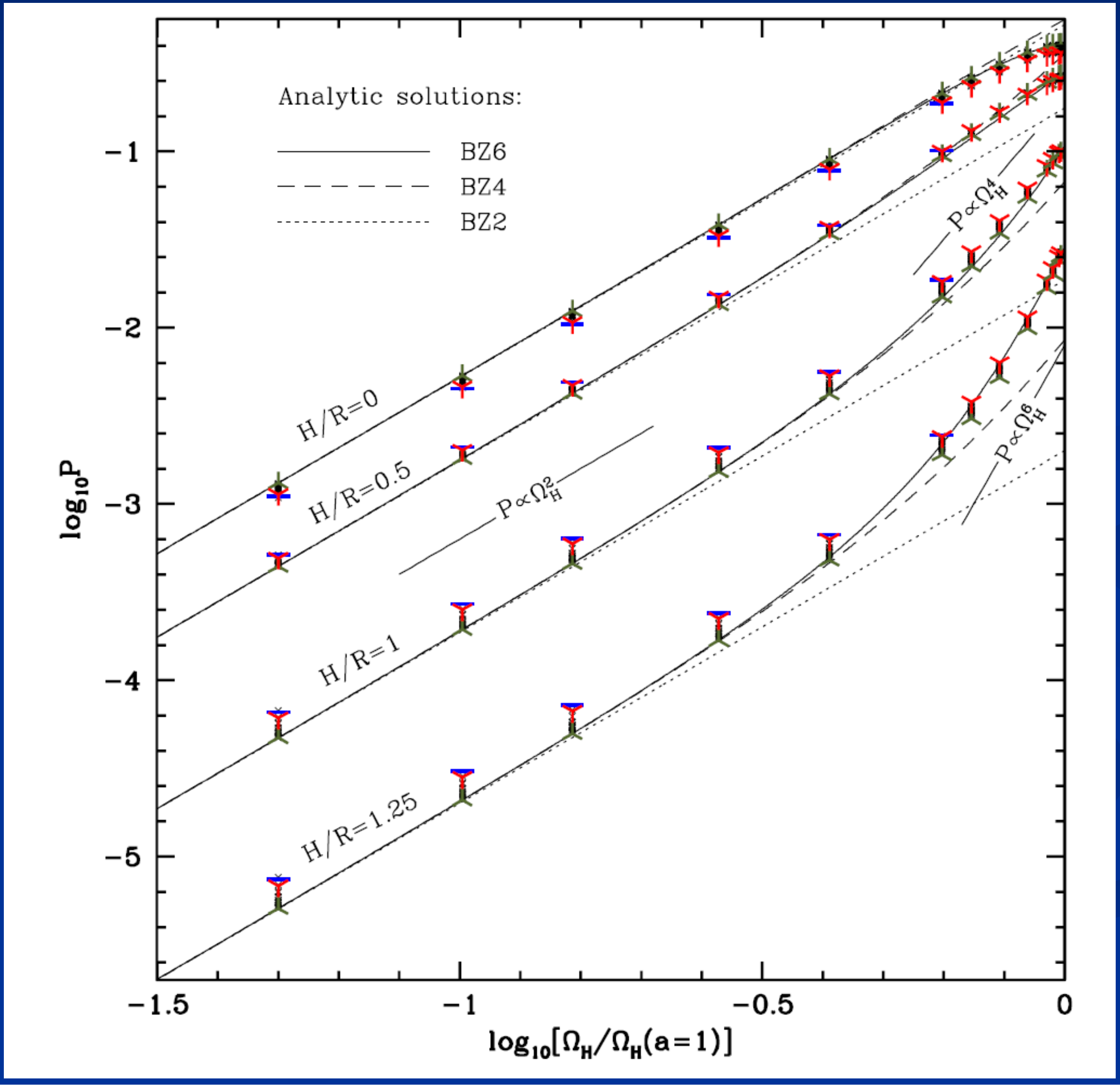
BH Angular
Rotation Rate

$$\Omega_H = ac/(2Mr_H)$$

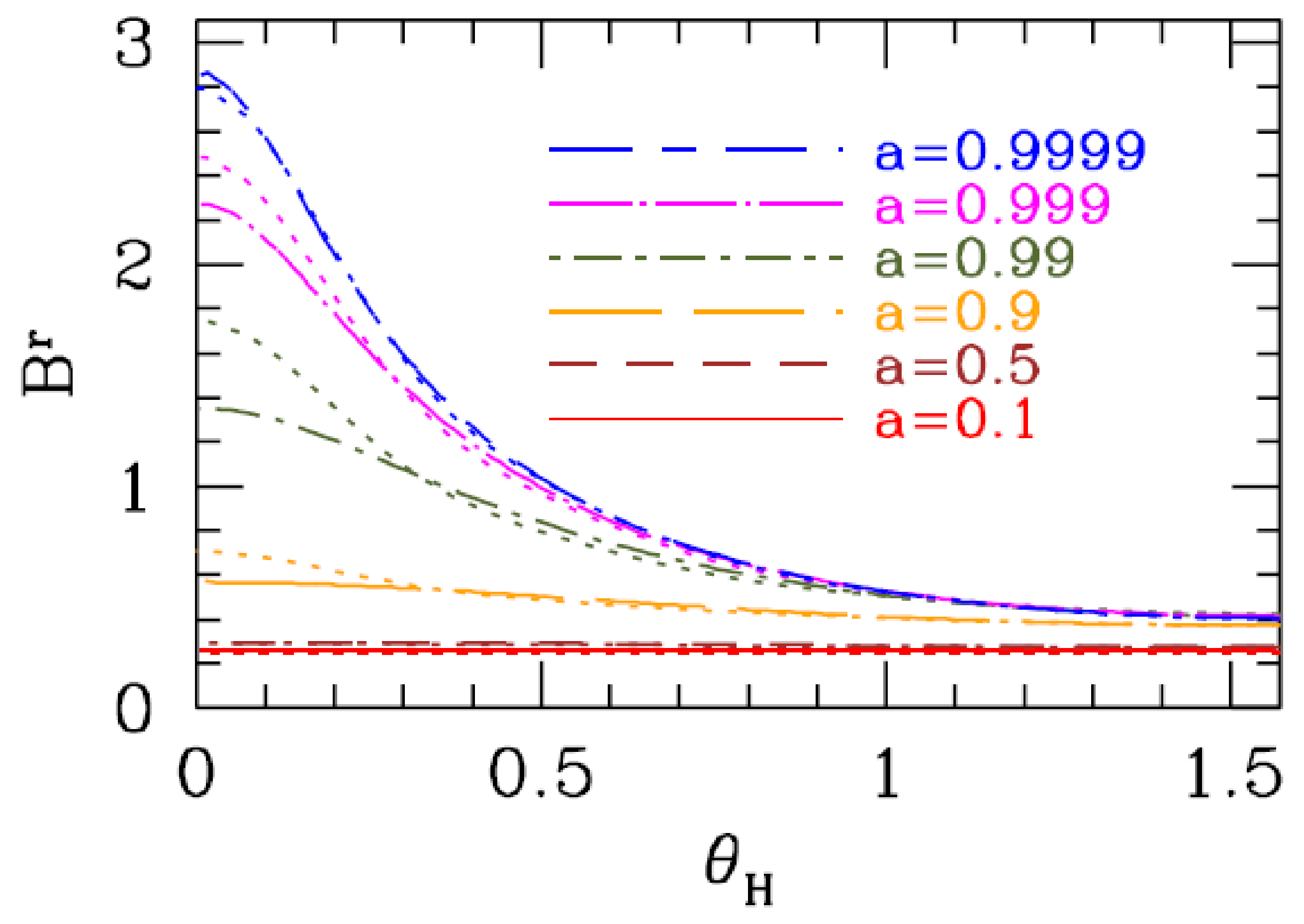
Conserved Quantities



Power vs. Angle vs. Spin



Field Strength vs. Angle vs. Spin



Derive Power vs. Spin vs. Angle

(1) $F_{\mathrm{E}}(\theta) = \left[2(B^r)^2\Omega(\Omega_{\mathrm{H}} - \Omega) r M \sin^2\theta\right]\Big|_{r=r_{\mathrm{H}}}$ $\sqrt{-g}B^r = A_{\phi,\theta}$

(2) Use $\Omega \approx \Omega_H/2$ -> F_E to a^2

(3) Derive Monopole A_ϕ to a^2 -> F_E to a^4

$\Psi = \Psi_0 + 16\Omega_{\mathrm{H}}^2\Psi_2 + \Omega_{\mathrm{H}}^4\Psi_4$ $\Psi_0(\theta) = 1 - \cos\theta$

$\Psi_2(r,\theta) = f(r)\sin^2\theta\cos\theta$

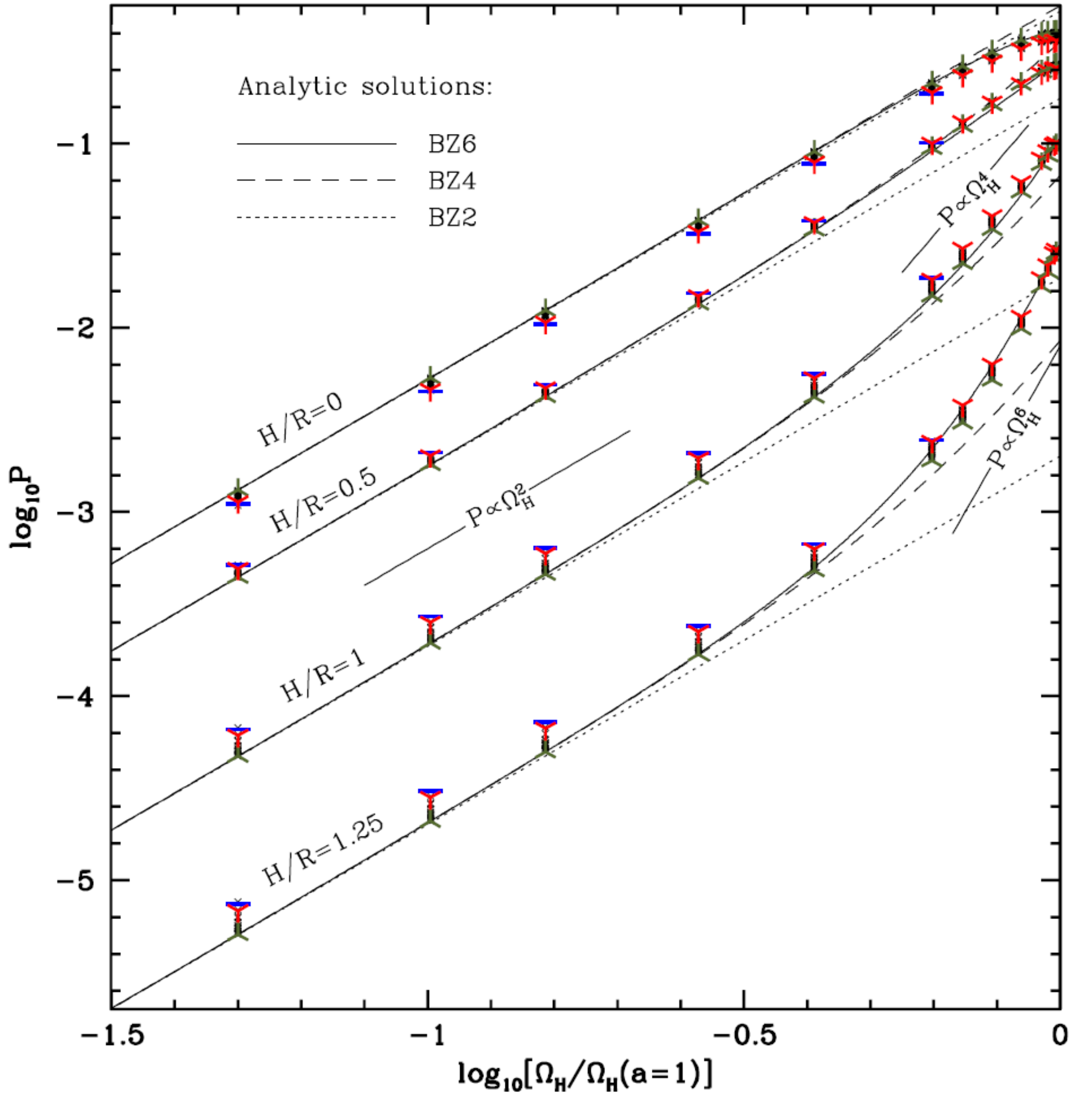
(4) Numerically Motivate A_ϕ to a^4 -> F_E to a^6

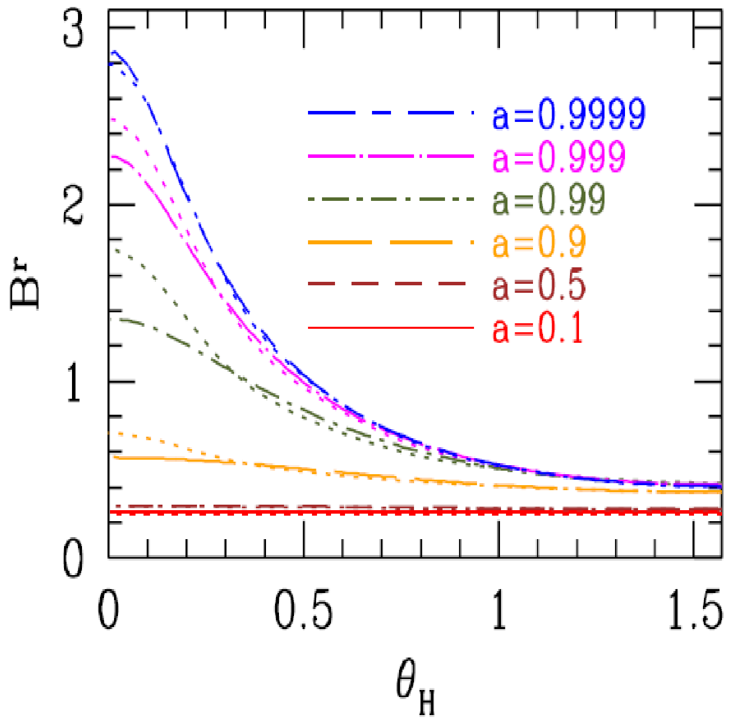
$\Psi_4(\theta) = \sin^2(\theta)\left[c_1\cos^{\alpha_1}\theta + c_2\cos^{\alpha_2}\theta + c_3\cos^{\alpha_3}\theta + c_4\cos^{\alpha_4}\theta\right]$

Result 1: P vs. Ω_F accurately fits all simulations

Result 2: Power subtended by smaller angles has steeper dependence on Ω_F: $P \propto \Omega_F^{(2n)}$

Power Results Reviewed





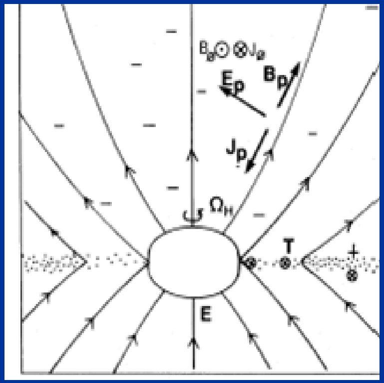
Review: Radio Dichotomy

- Total BH Power Depends upon Ω_F^2
  - Assumes fixed magnetic flux – may even be steeper
- Steeper Dependence at small solid angles (jet)
  - H/R~1 : $P \propto \Omega_F^4$: (consistent with McKinney 05)
  - H/R~1.25 : $P \propto \Omega_F^6$
  - (?) H/R~1.4 : $P \propto \Omega_F^8$
- Can BH Evolution Work? YES!
  - H/R\sim 1-1.4 (ADAF for high radio to optical)
  - a~0.2 for radio quiet, a~1 for radio loud
  - Consistent with spin evolution for elliptical vs. spirals (Volonteri 07)

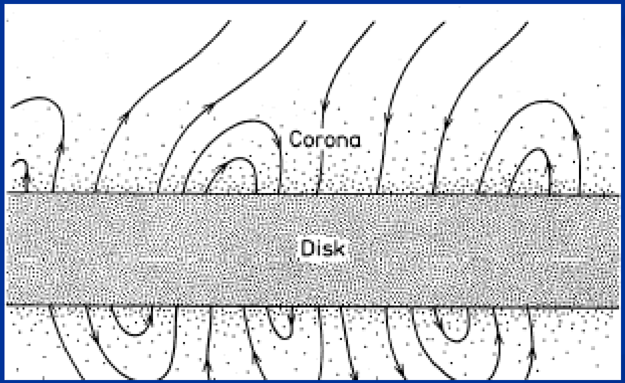
Disk-Jet Coupling Effects

- Old ideas: (Ghosh & Abramowicz 1997;Livio, Ogilvie, Pringle 1999)
  - $\alpha \sim 0.01 - 0.1$ in shearing box, predicts weak field near BH.
  - Sub-equipartition fields assumed near BH
  - Disk more powerful at producing EM jets

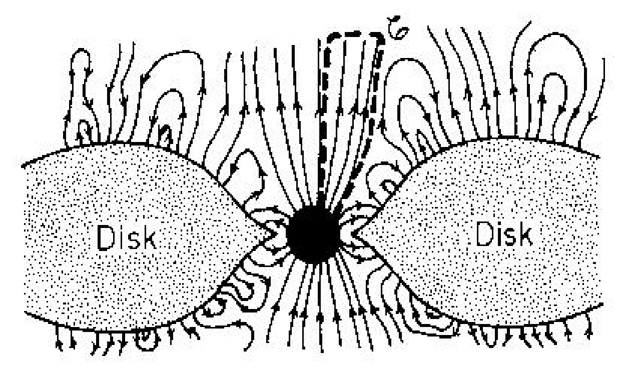
BZ77



Blandford & Payne ‘82

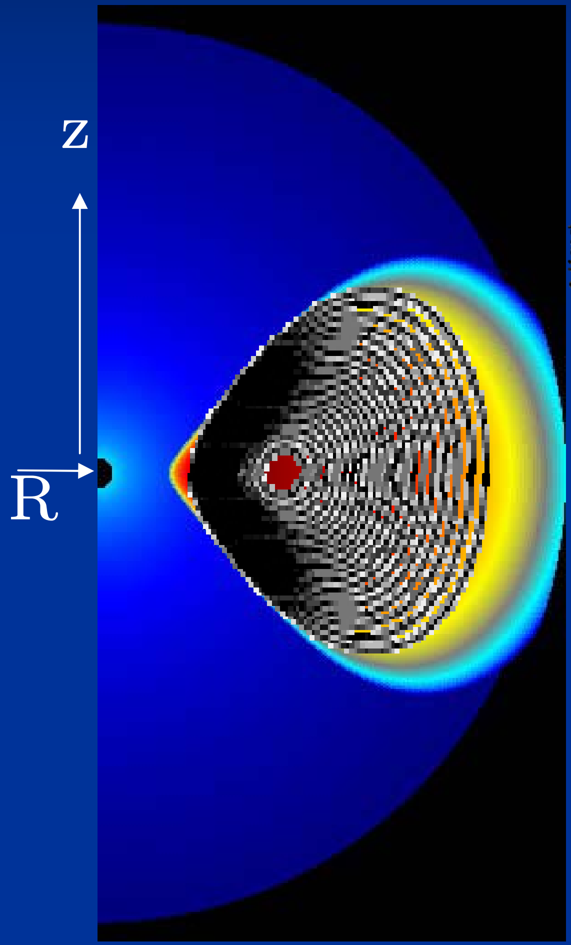


MacDonald & Thorne ‘82



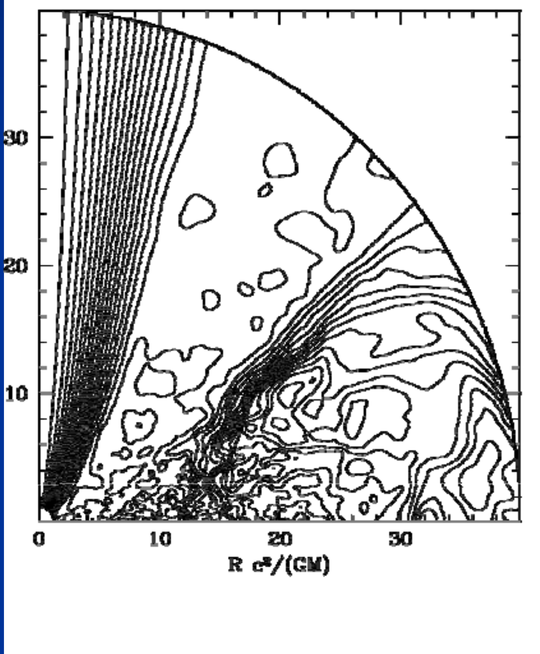
GRMHD Simulations

Log of mass density



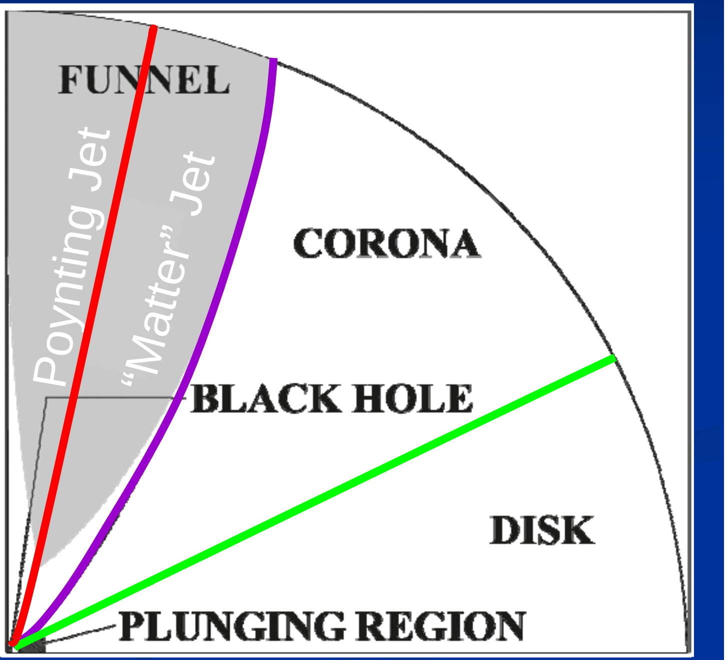
- Evacuated at poles
- Turbulent in equator

Poloidal Field



- Ordered at poles
- Random in equator

Flow Structure



CORONA: MA~EM

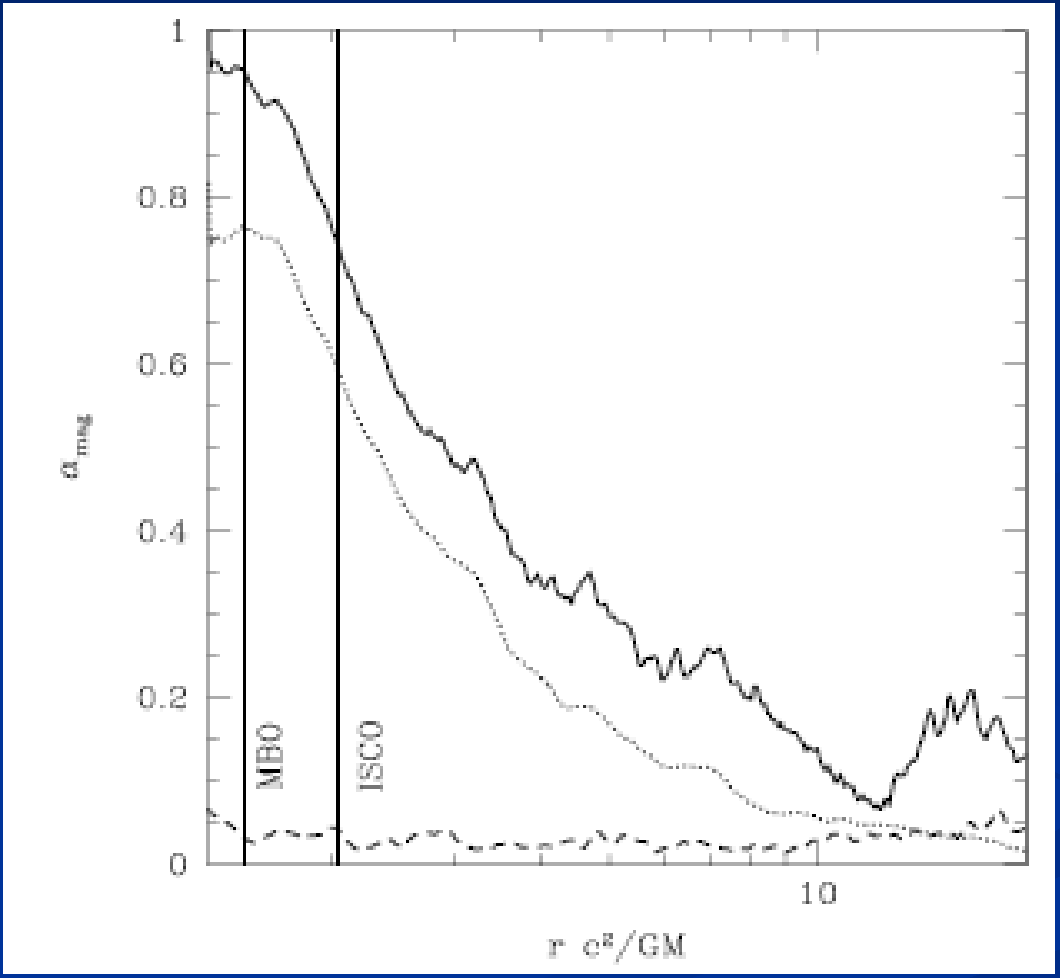
FUNNEL: EM dominated

JETS: Unbound, outbound flow

McKinney & Gammie (2004)

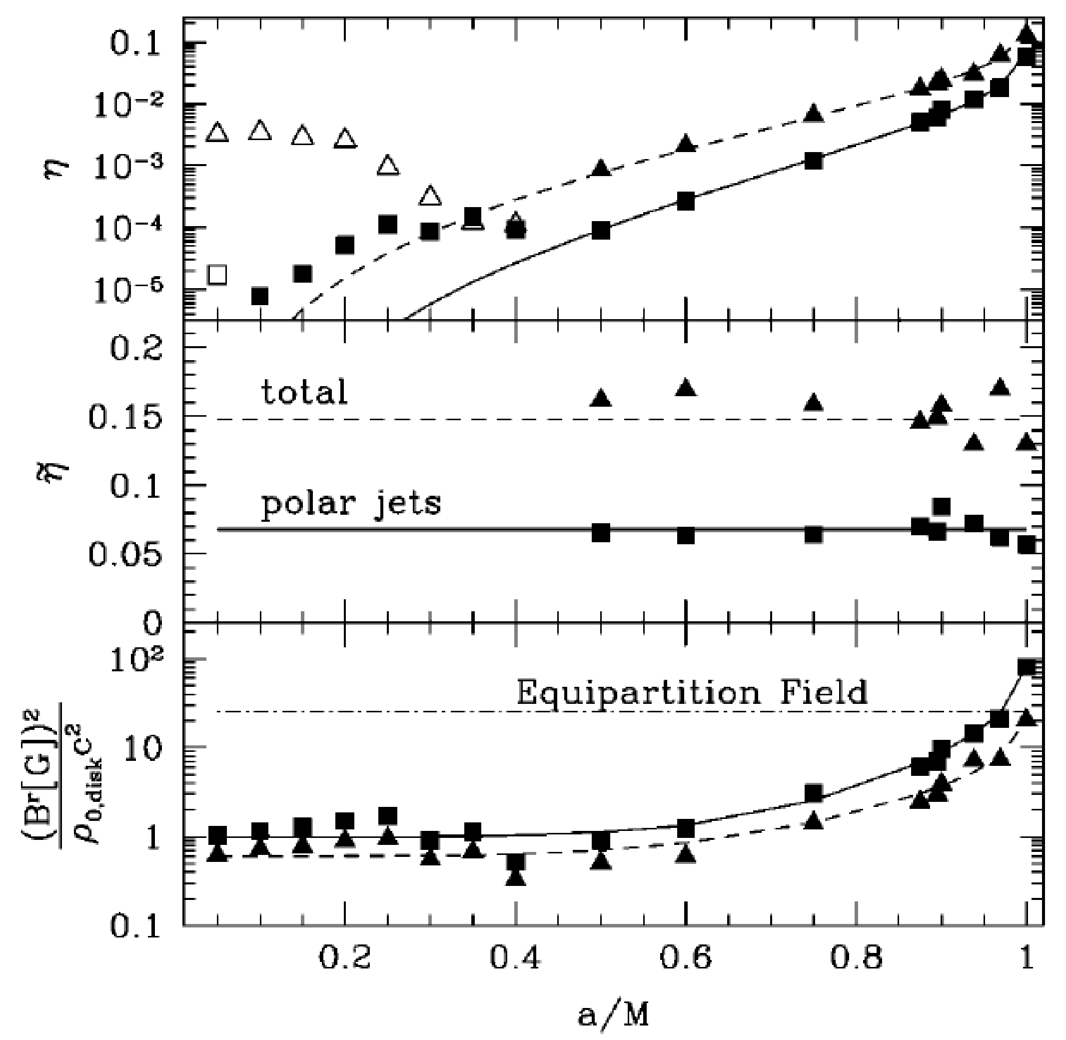
DeVilliers, Hawley, Krolik (2003-2004)

α~ 1 in plunging region

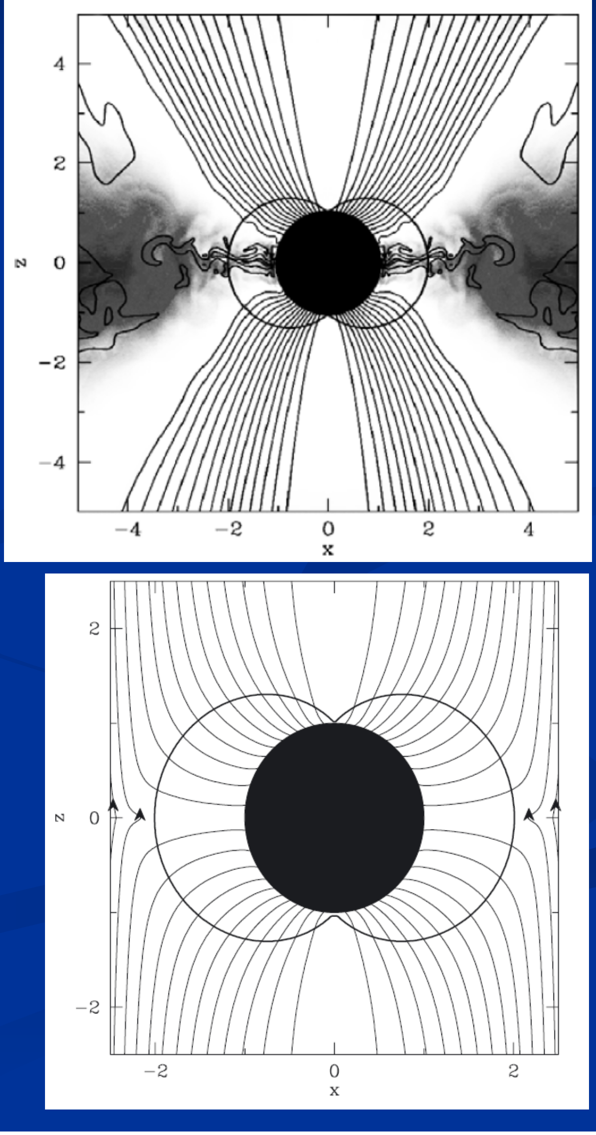


McKinney & Narayan (2007)

Field becomes super-equipartition for high spin

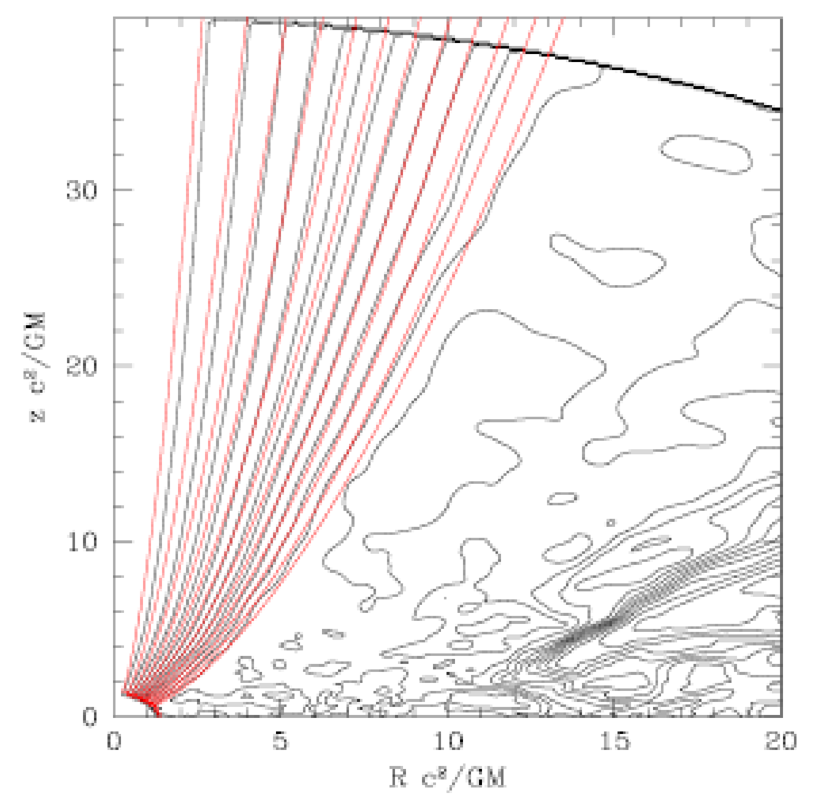


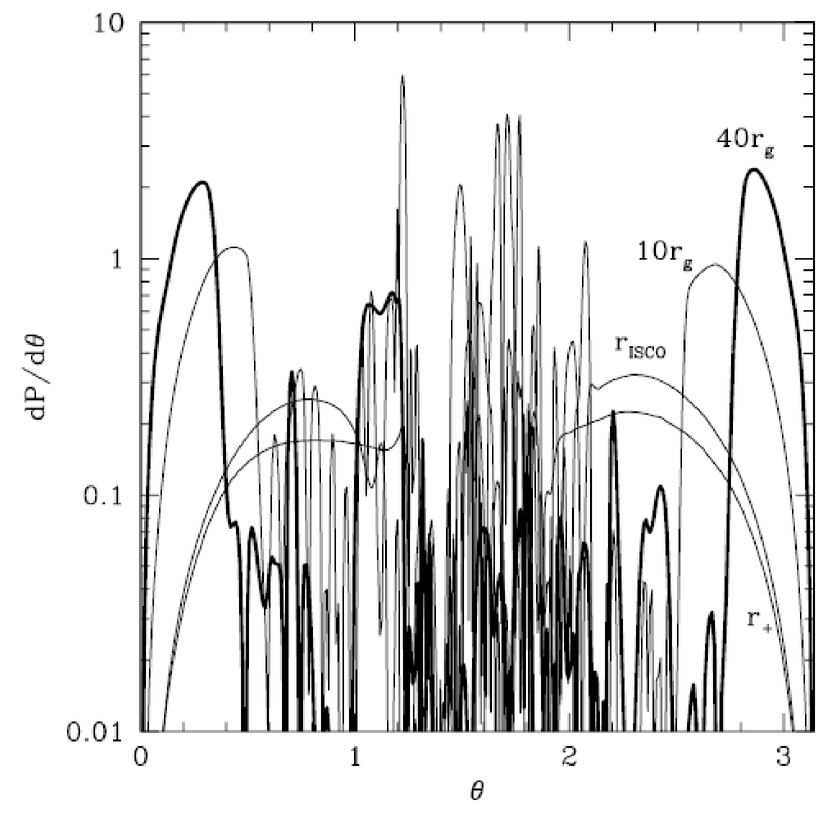
McKinney (2005)



Komissarov & McKinney (2007)

Disk Jet degraded by mass-loading
BH cleans field of mass





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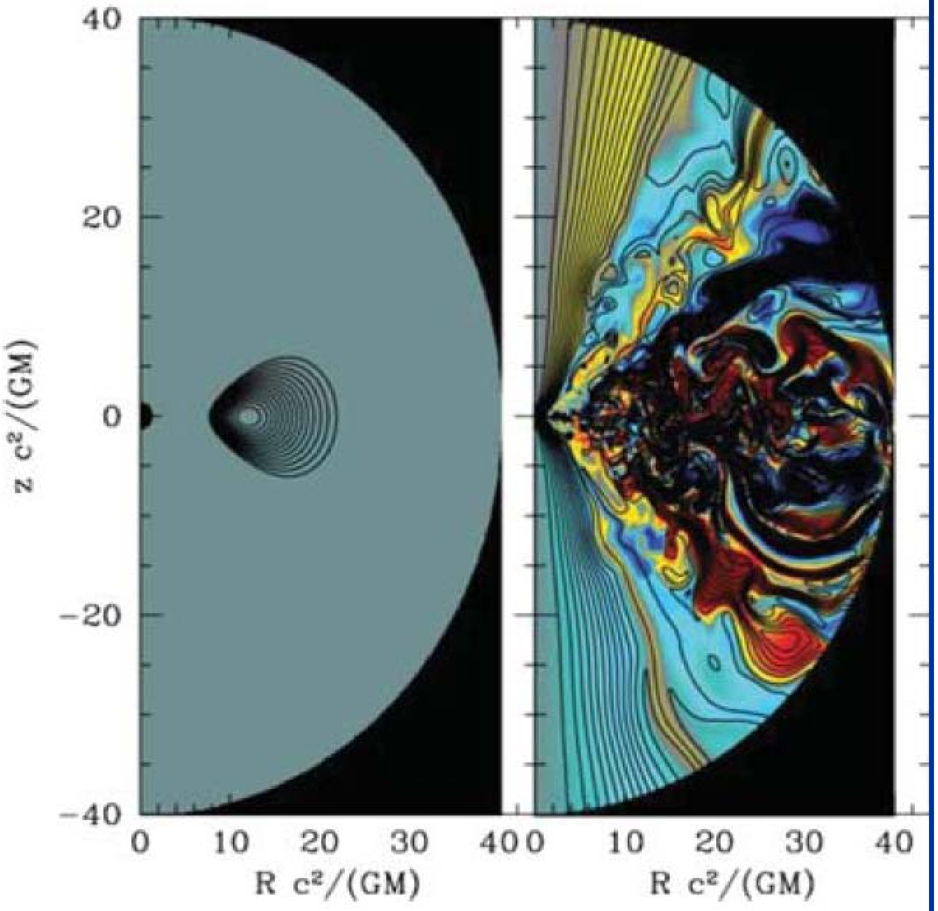
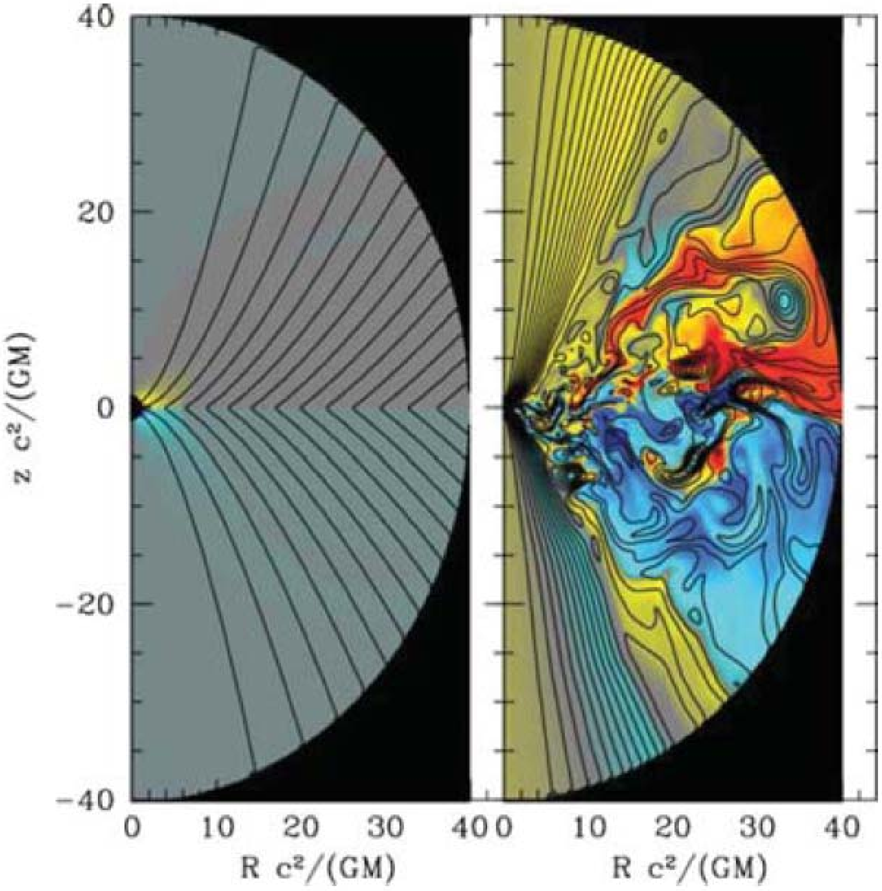
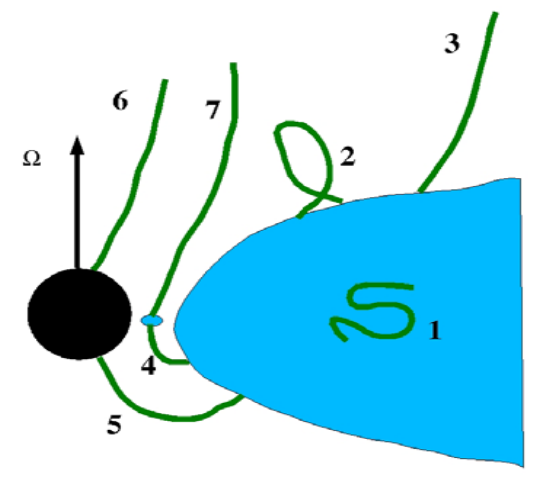
Disk Jet degraded by mass-loading BH cleans field of mass



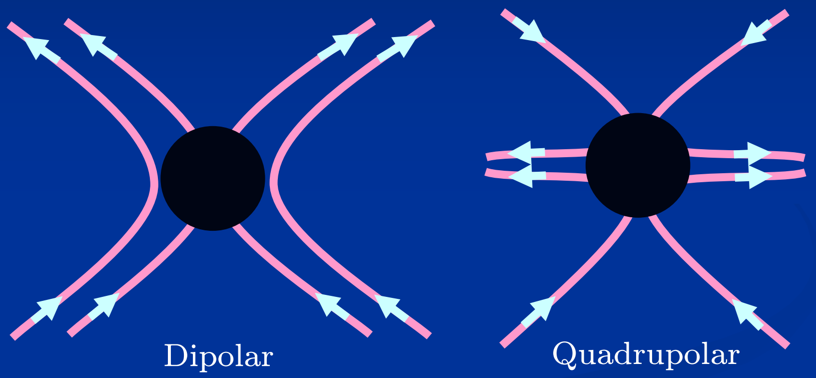


McKinney & Narayan (2007)

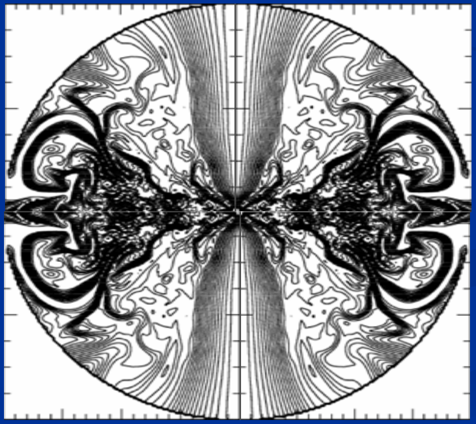
Emergent Magnetic Field Geometry



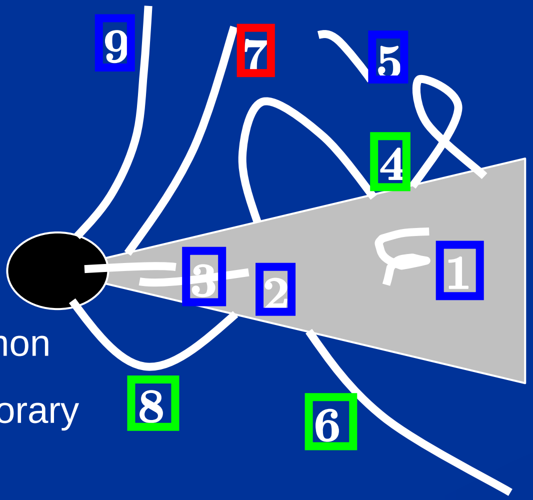
Blandford '02



Hirose/McKinney '05



- Balbus & Hawley (MRI) **[1]**
- Gammie & Krolik **[2,3]**
- Effect of reconnections **[4,5]**
- Lovelace or Blandford-Payne **[6,7]**
- Konigl & Vlahakis **[6,7,~9]**
- Uzdensky, Matsumoto **[8]**
- Blandford & Znajek **[9]**

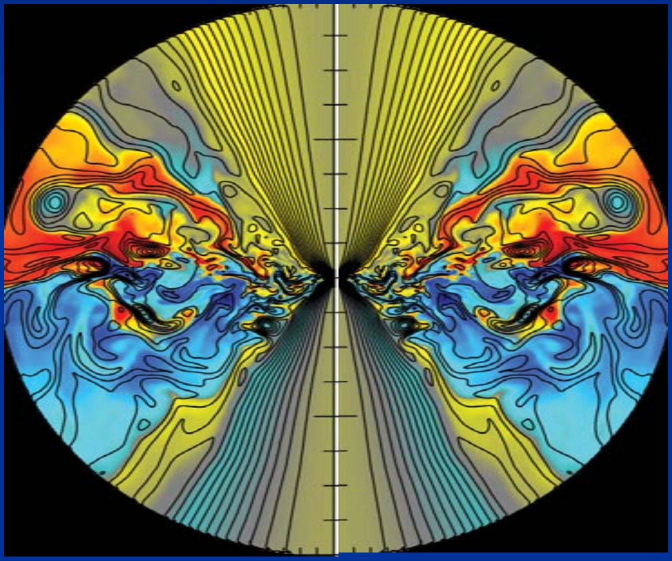


🟦 Common

🟩 Temporary

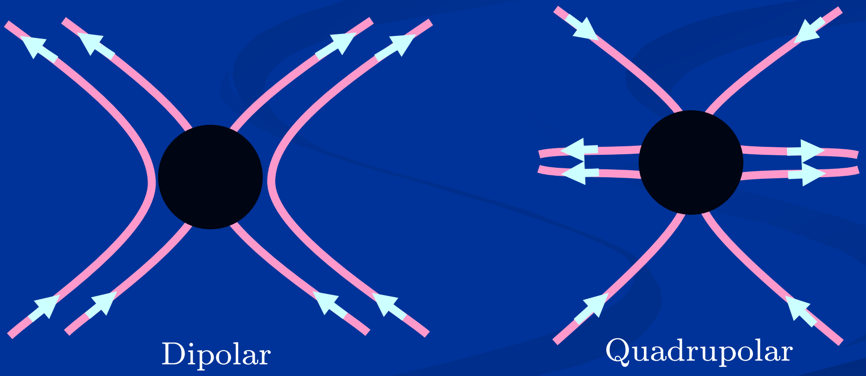
🟥 Never

Jet Formation Stability



Issues:

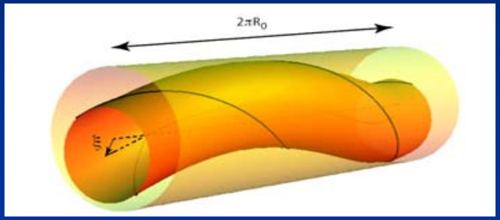
- Jet from Disk or BH?
- Unstable to Turbulence in Disk?
- Unstable to Accreting Disordered Field?



Jet Propagation Stability: Kink

- |m|=1 most dangerous: Center-of-mass shifted

$$e^{i(kz+lR+m\phi-\omega t)}$$



- Kruskal-Shafranov non-rel. criterion

$$\frac{|B^{\phi}|}{|B^{z}|} > \frac{2\pi R}{L}$$

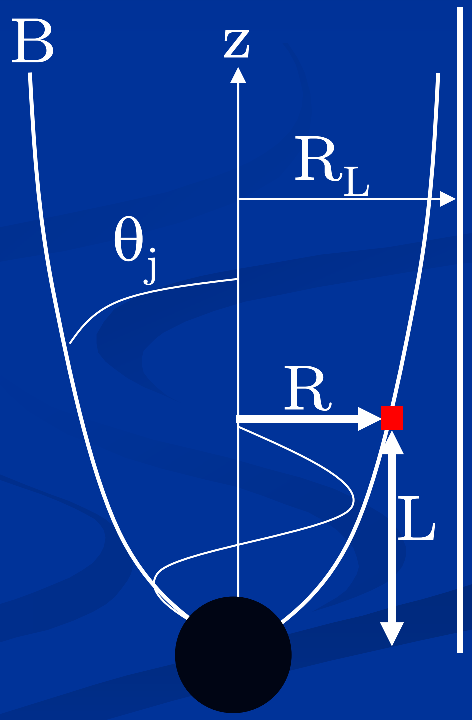
- Tomimatsu (2001) ~rel. criterion

$$\frac{|B^{\phi}|}{|B^{z}|} > \frac{R|\Omega_F|}{c} = \frac{R}{R_L}$$

- Narayan et al. (2009) rel. criterion

$$\frac{|B^{\phi}_{\text{co}}|}{|B^{z}_{\text{co}}|} > \text{few}$$

- Expansion & Finite Mass-loading: Jet goes out of causal contact



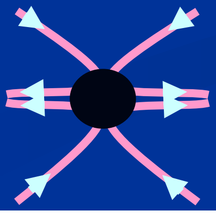
McKinney (2006)
Narayan et al. (2009)

Fully 3D GRMHD Sims

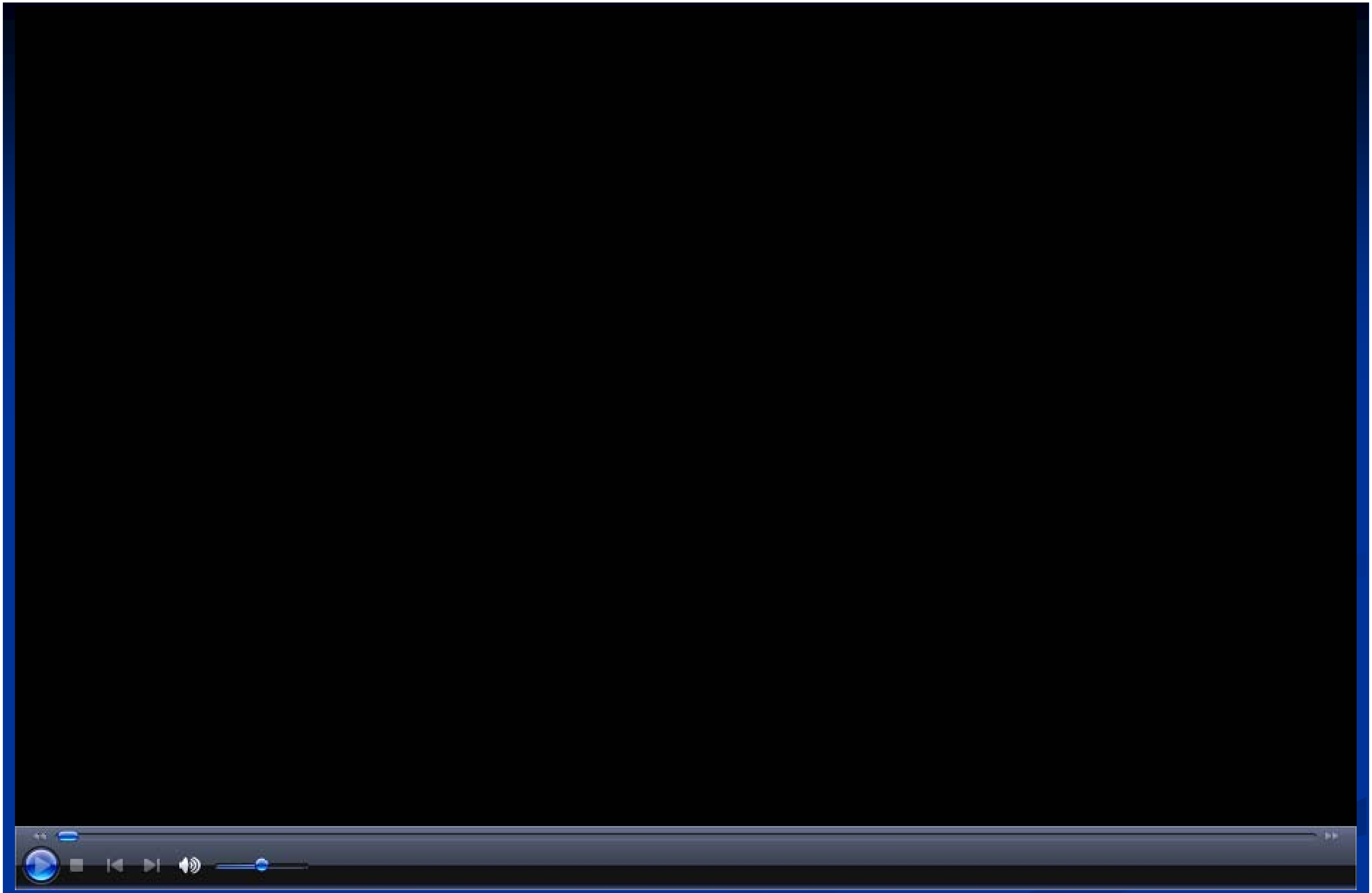
- Initial HD Eq. Thick Torus, a=0.93
- Field: Dipolar loop, Quadrupole loops, and large-scale versions
- No symmetries (in \theta or \phi)
    - Required to resolve the dangerous m=1 mode
- Conservative HARM 3D w/ Staggered Field
- PPM's base interpolation: 3rd order polynomial fit around flux positions attempted
- 128x64x32, 64x128x64,256x128x32,512x256x64
- Grid resolves disk near BH and jet far from BH

Fully 3D GRMHD Jet Simulations

McKinney & Blandford (2008)

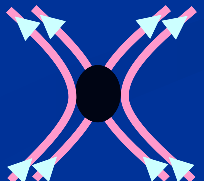


- Quadrupolar Field Jet Fails
- Magnetic field Crucial to explain x-ray binary states: i.e. for Jet or NOT



Fully 3D GRMHD Jet Simulations

McKinney & Blandford (2008)



- Dipolar Field Jet Succeeds: Relativistic Rotation, Expansion, Non-linear Saturation

Review:

- Magnetosphere of BH vs. NS
  - No surface, so flux can be pinched and slip around
  - Stagnation Point: Inflow and Outflow, particle creation
- Black Hole Driven Jet can become Relativistic
  - Requires Organized [mostly dipolar] Field
- Disk Driven Wind-Jet Weakly Relativistic
  - Mass-Loaded by Disk Turbulence
- Stability Maintained by ...
  - Relativistic Rotation of Field Lines
  - Expansion of Jet [and so Causal Disconnection]
  - Finite Mass-Loading [and so Causal Disconnection]
  - Non-linear Saturation [even Non-Rel. Jets can avoid Diss.]