How to Form Ultrarelativistic Jets

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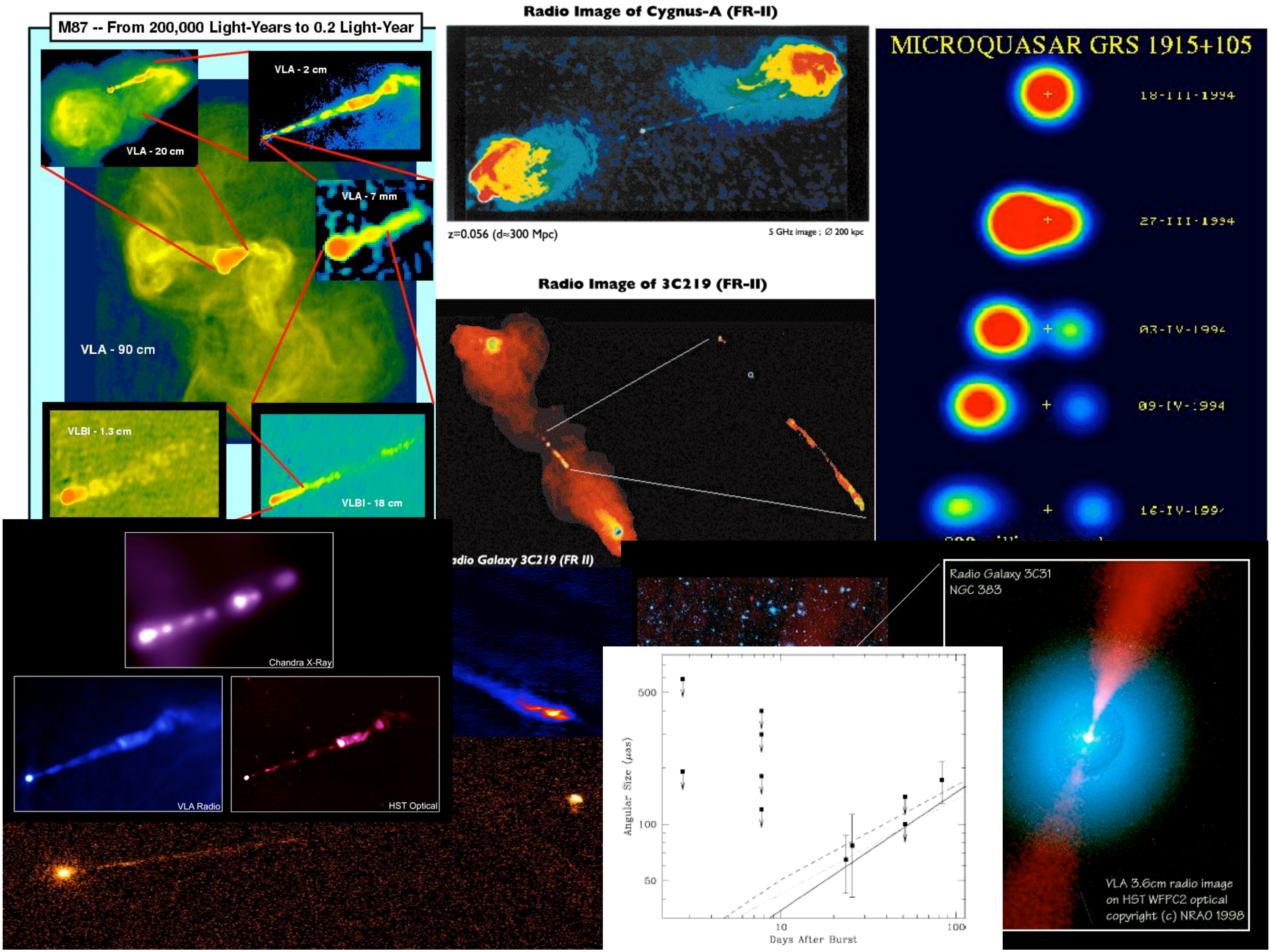
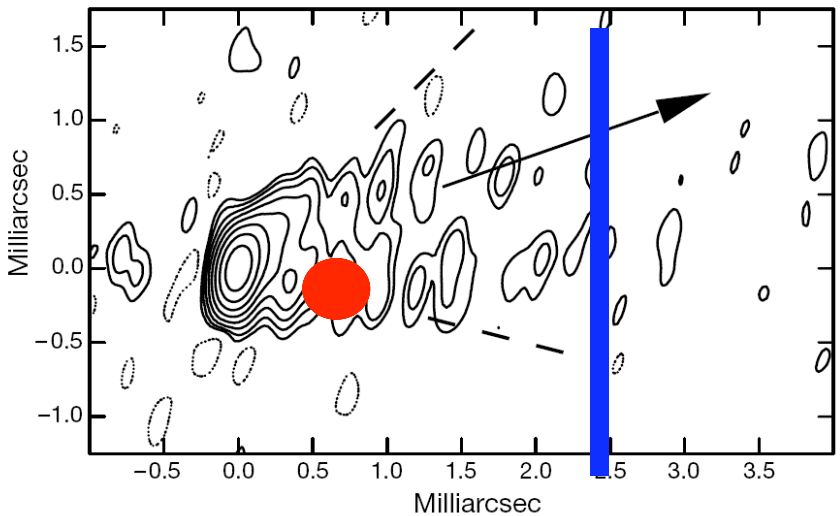
Oct 10, 2007

Chandra Symposium 2007


M87 -- From 200,000 Light-Years to 0.2 Light-Year
VLA - 2 cm
VLA - 20 cm
VLA - 7 mm
VLA - 90 cm
VLBI - 1.3 cm
VLBI - 18 cm
Radio Image of Cygnus-A (FR-II)
z=0.056 (d≈300 Mpc)
5 GHz image ; ∅ 200 kpc
Radio Image of 3C219 (FR-II)
MICROQUASAR GRS 1915+105
18-III-1994
27-III-1994
03-IV-1994
09-IV-1994
16-IV-1994
Chandra X-Ray
VLA Radio
HST Optical
adio Galaxy 3C219 (FR II)
Radio Galaxy 3C31
NGC 383
VLA 3.6cm radio image
on HST WFPC2 optical
copyright (c) NRAO 1998
Angular Size (μas)
Days After Burst
500
100
50
10
100

M87 Jet Formation/Interaction



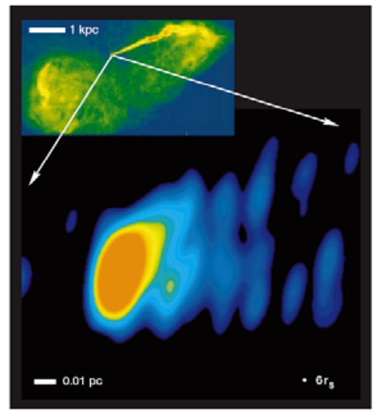
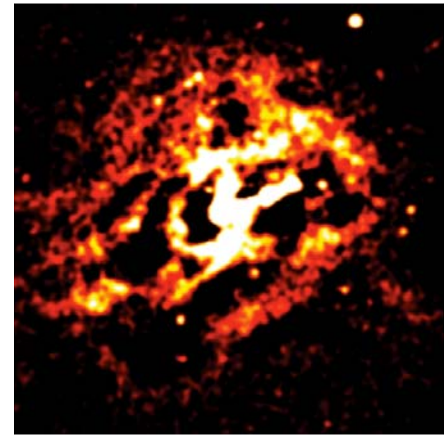
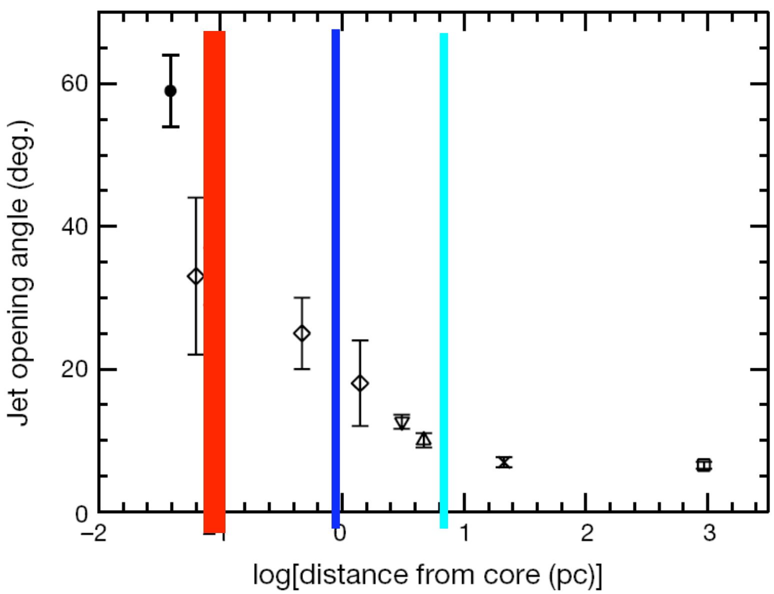


Figure 2 Pseudo-colour rendition of the nucleus of M87 at 43 GHz on 3 March 1999. See Fig. 1 for details. The filled white circle at lower right indicates $6r_s$, which is the diameter of the last stable orbit around a non-rotating black hole. The inset (top left) is a 15-GHz VLA image illustrating the large-scale jet.

Junor (1999) & Biretta (1999,2002)

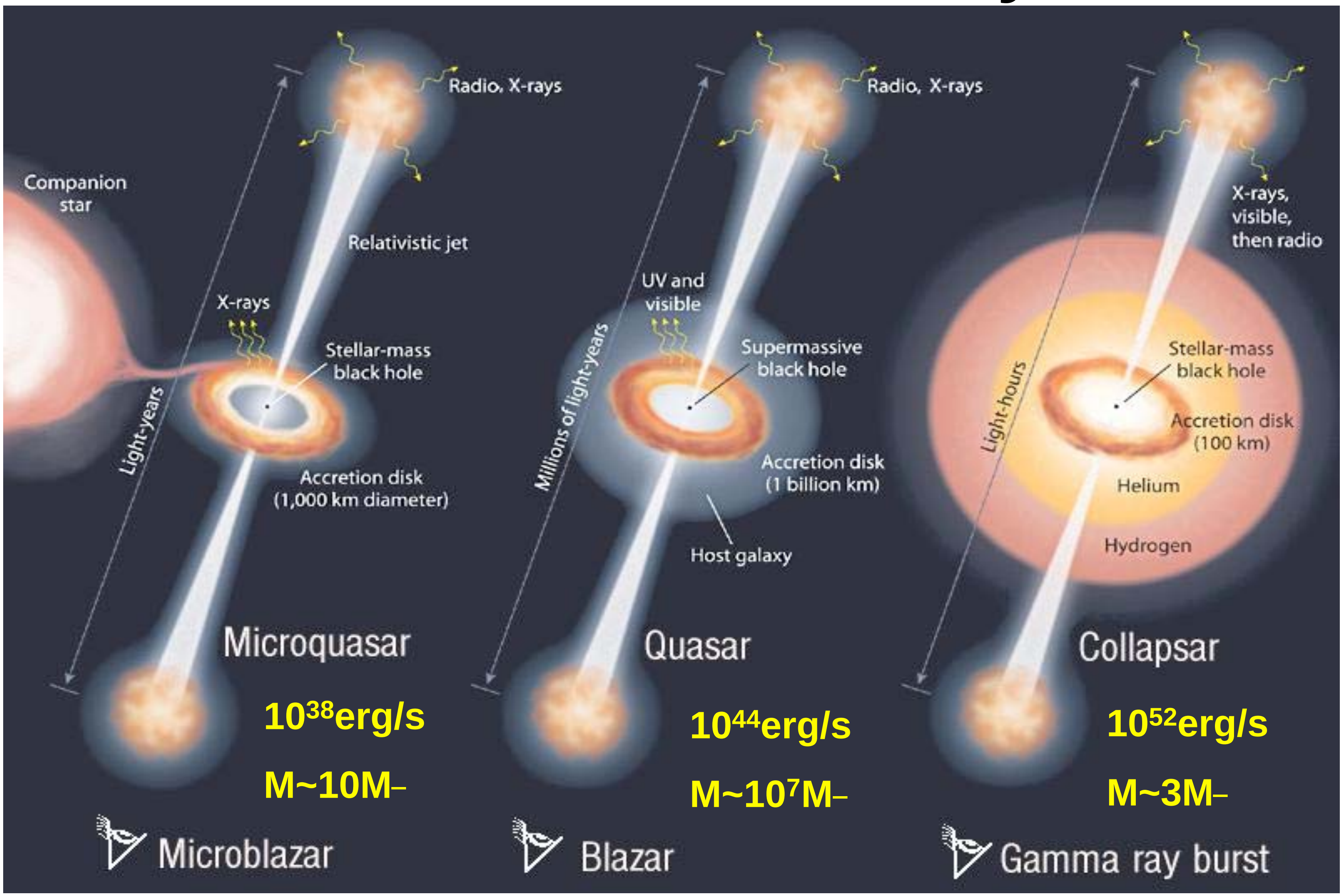


NASA/CXC/H.Feng et al.



X-ray: NASA/CXC/CfA/W.Forman et al.; Optical: DSS

Black Hole Accretion Systems



Mirabel & Rodriguez (Sky & Telescope, 2002)

BH Accretion/Wind/Jet Issues

- Origin of **organized** field
- Poynting jet / disk wind / neutrino power
- Disk-wind-jet **coupling**
- Jet **collimation, acceleration, stability**
- Mass-**loading** and angular **structure** (GRB light curves)
- **Reconnection** paradigm vs. **shocks**
- AGN **feedback**

Blandford & Znajek

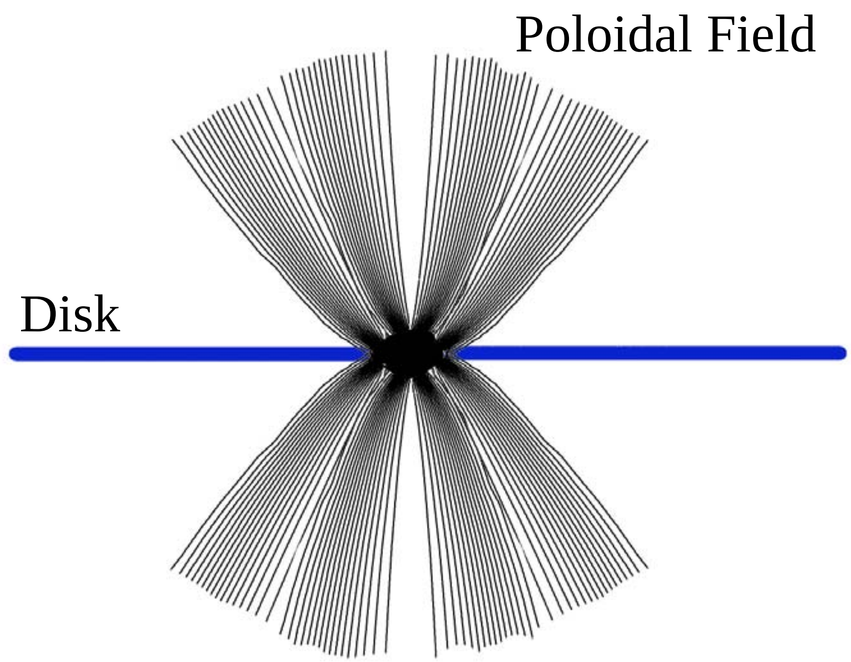
Assumptions:

•Kerr BH (slowly rotating)

•Force-free ED or EM>MA

•Axisymmetric

•Stationary



Solve:

•Maxwell's Equations

OR

•Conservation equations

Find:

•Outward Flux of Energy

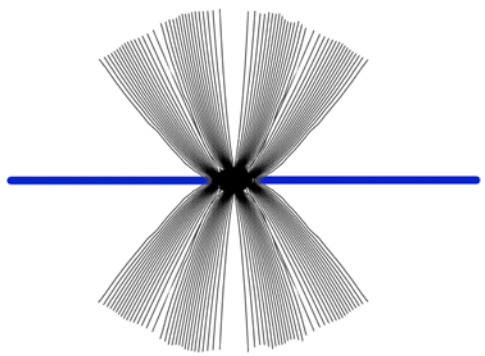
•Magnetic Field Structure

(monopole or parabolic)

Energy Extraction

- Dimensional Argument

$$\dot{E}^{(EM)} \sim B^2(\tfrac{4\pi}{3}L^3)T^{-1}$$



$L \equiv GM/c^2$
$T \equiv L/c$
$j \equiv J/M^2$
$r_+ \equiv L(1 + \sqrt{1 - j^2})$
$\Omega_H \equiv jc/2r_+$

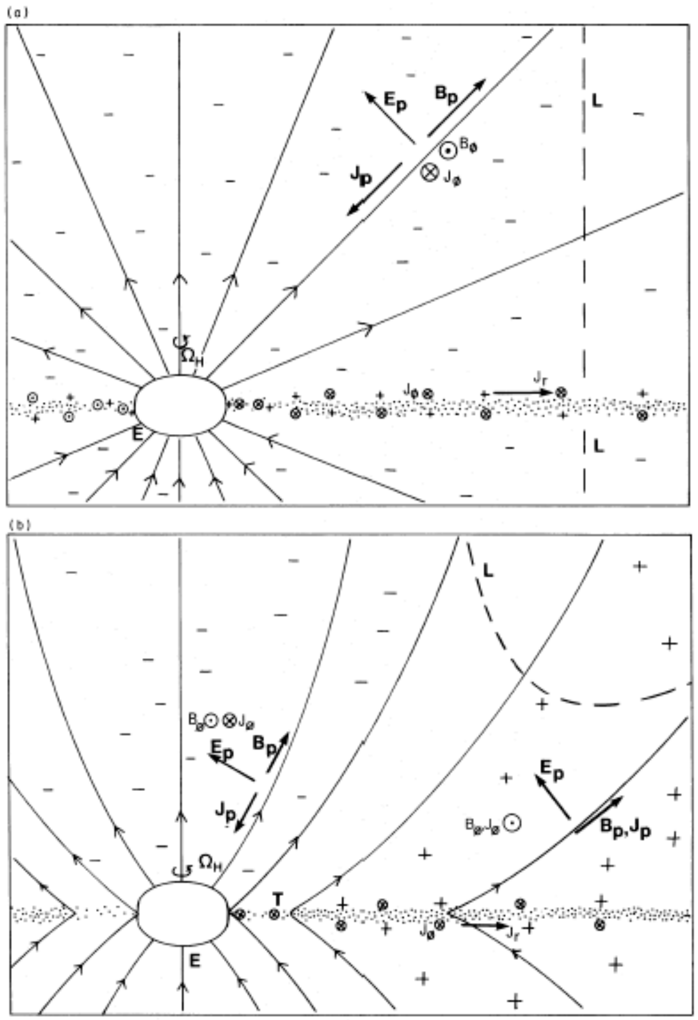
- BZ Solution for (split) monopole field

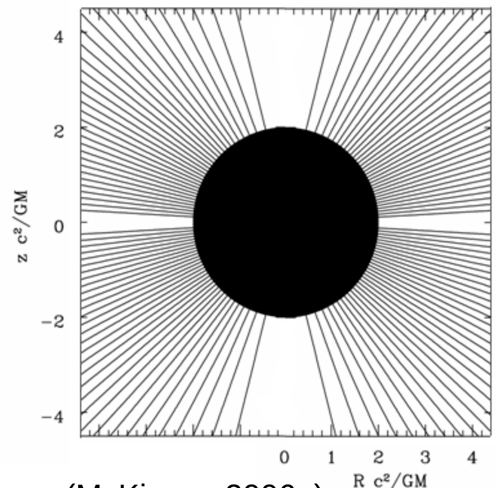
$$\dot{E}^{(EM)}(r_+) = 3\epsilon j^2 \left[(B^r)^2 \left(\frac{4\pi}{3}L^3\right) T^{-1}\right] + \mathcal{O}(j^4)$$

BZ Efficiency factor:

$$\epsilon \equiv \left[\left(\frac{2\omega}{\Omega_H}\right)\left(2 - \frac{2\omega}{\Omega_H}\right)\right] \approx 1$$

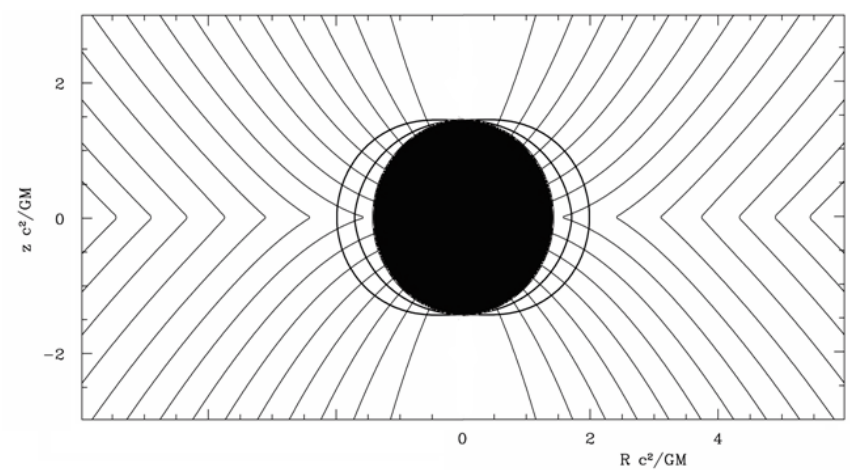
BZ vs. McKinney





(McKinney 2006a)

- Blandford's swindle
- Collimation: disk currents beat hoop-stresses
- Realistic disk field?



(McKinney & Narayan 2006b)

Next: 3D, Stability, Cold GRMHD (add mass, keep T=0)

GRMHD

Assumptions:

•Kerr BH (a/M~0.94~spin eq.)

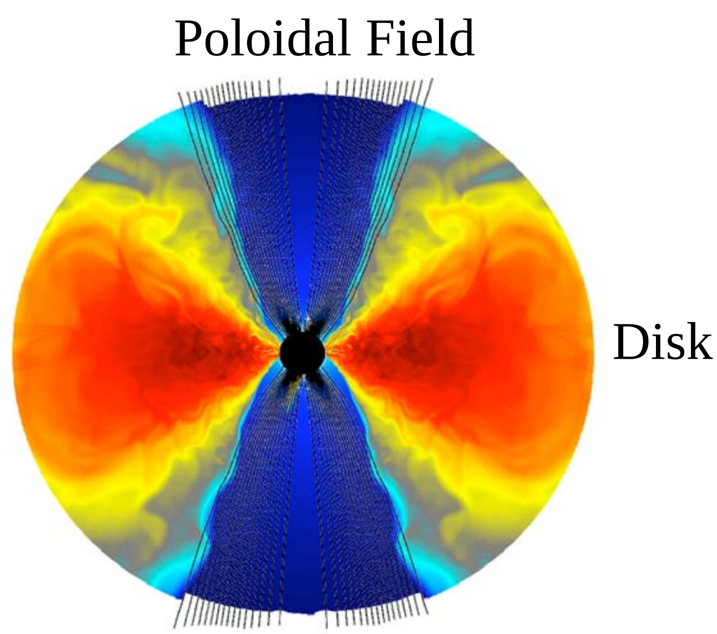
•Kerr-Schild coordinates

•Matter + fields (MA+EM)

•Ideal MHD, ideal (γ=4/3) gas

•Axisymmetric, nonradiative

•Initial hydro-eq.thick torus (H/R» 0.2)



Solve:

•Time-dependent conservation equations

•Induction equation with r¢B=0 constraint

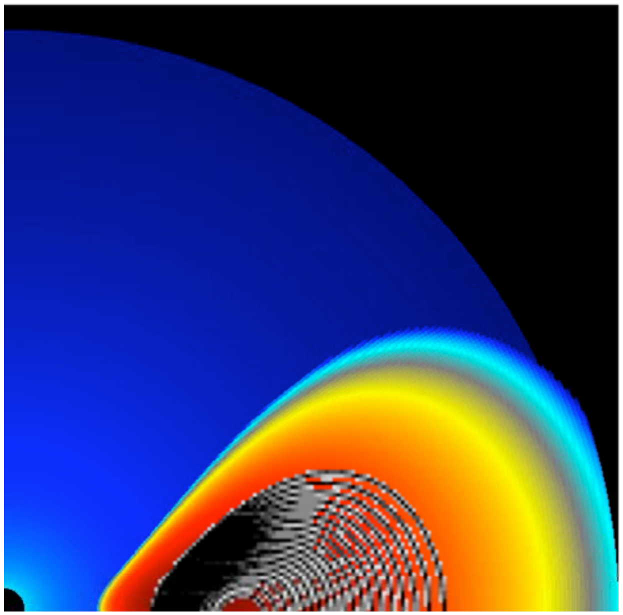
Gammie, McKinney, Toth (2003)

McKinney & Gammie (2004)

Gammie, Shapiro, McKinney (2004)

Accretion Disk Structure

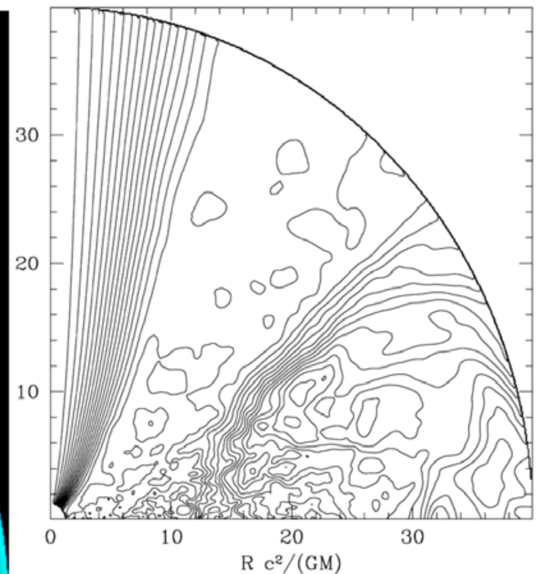
Log of mass density



•Evacuated at poles

•Turbulent in equator

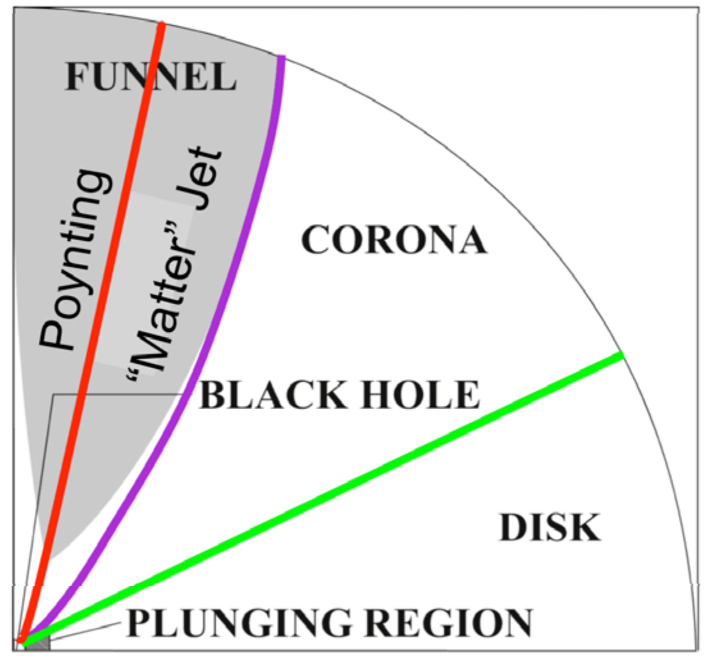
Poloidal Field



•Ordered at poles

•Random in equator

Flow Structure



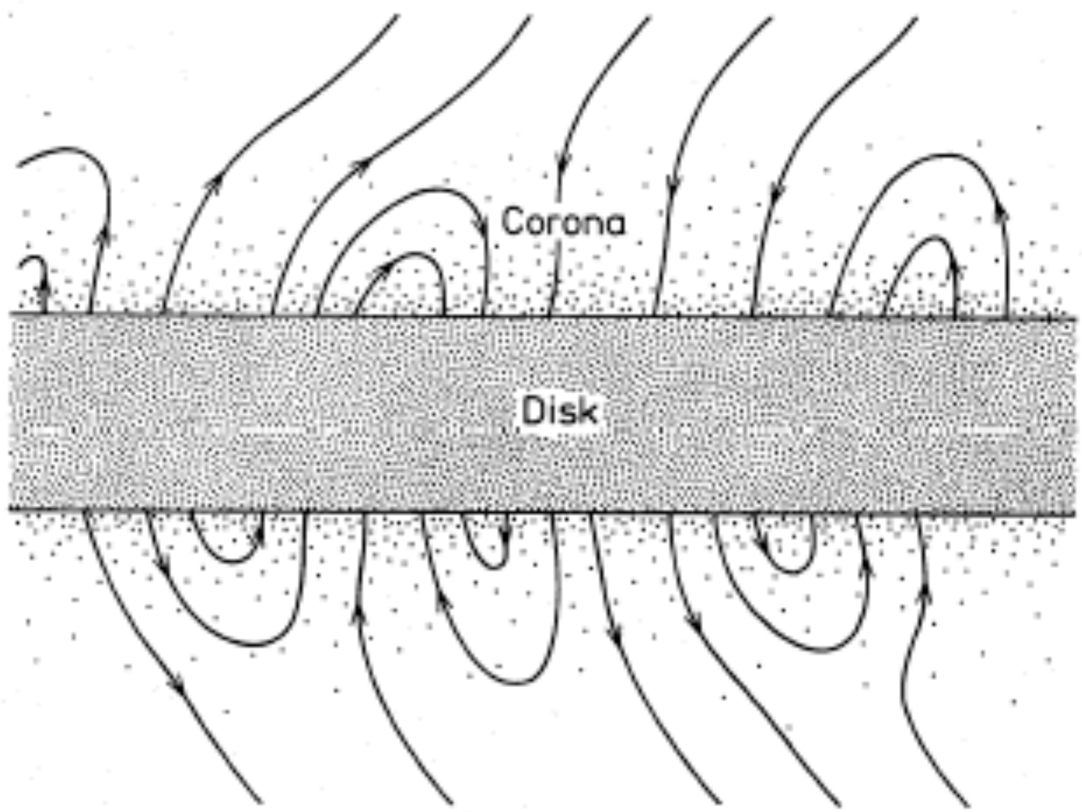
CORONA: MA~EM

FUNNEL: EM dominated

JETS: Unbound, outbound flow

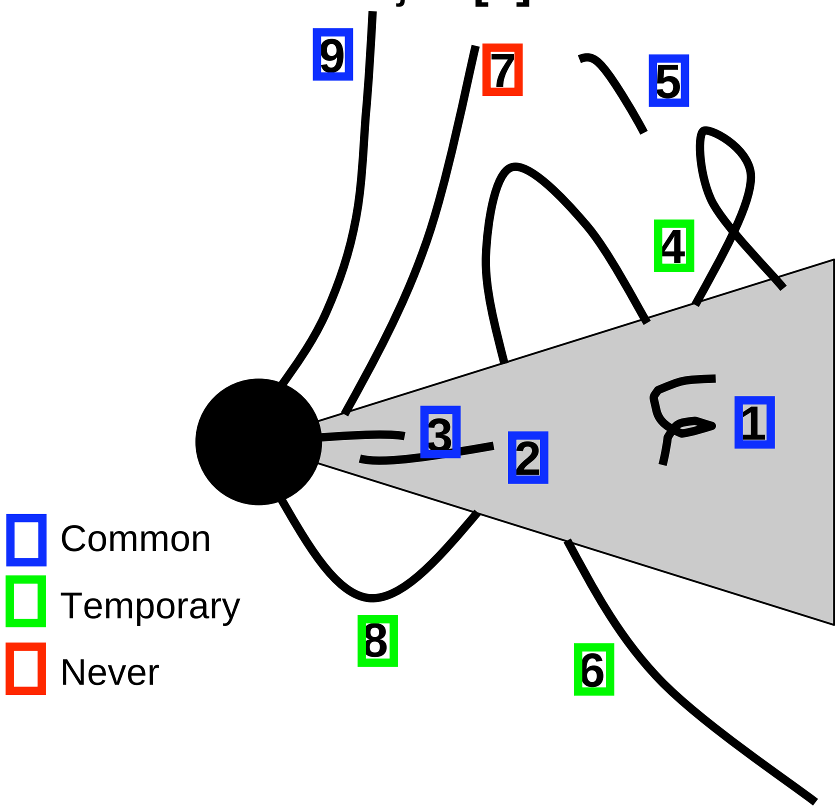
McKinney & Gammie (2004)

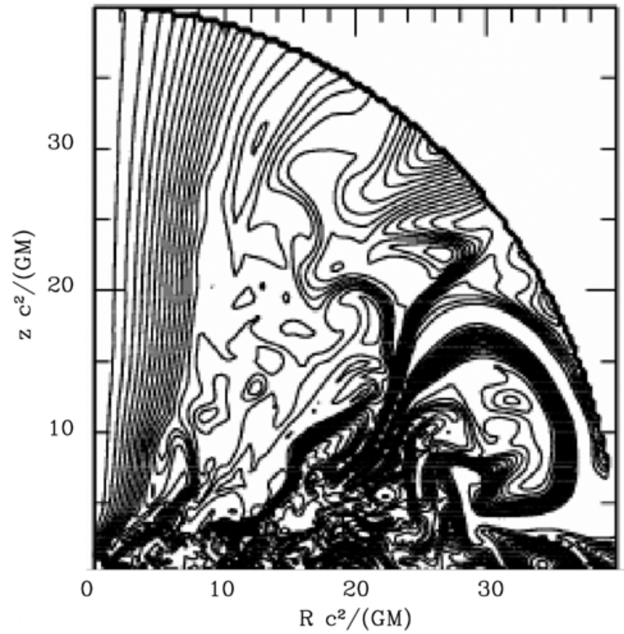
Blandford-Payne Disk Field Geometry



Common Field Lines

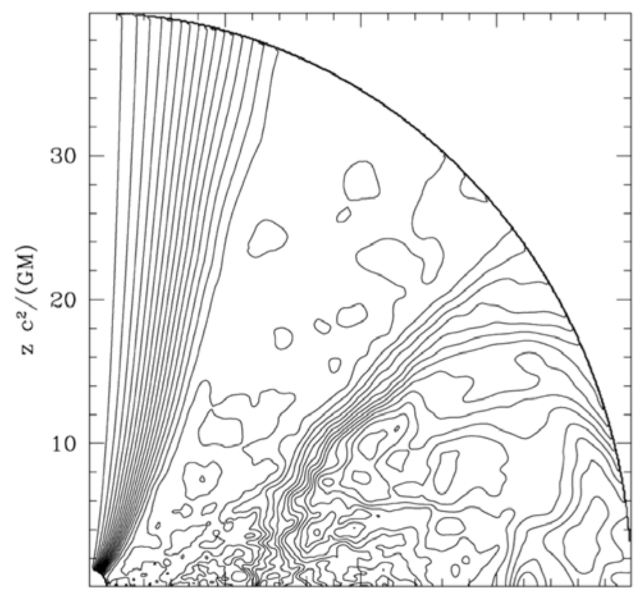
Balbus & Hawley (MRI) **[1]**
Gammie & Krolik **[2,3]**
Effect of reconnections **[4,5]**
Lovelace or Blandford-Payne **[6,7]**
Konigl & Vlahakis **[6,7,~9]**
Uzdensky, Matsumoto **[8]**
Blandford & Znajek **[9]**





Final

State



Time

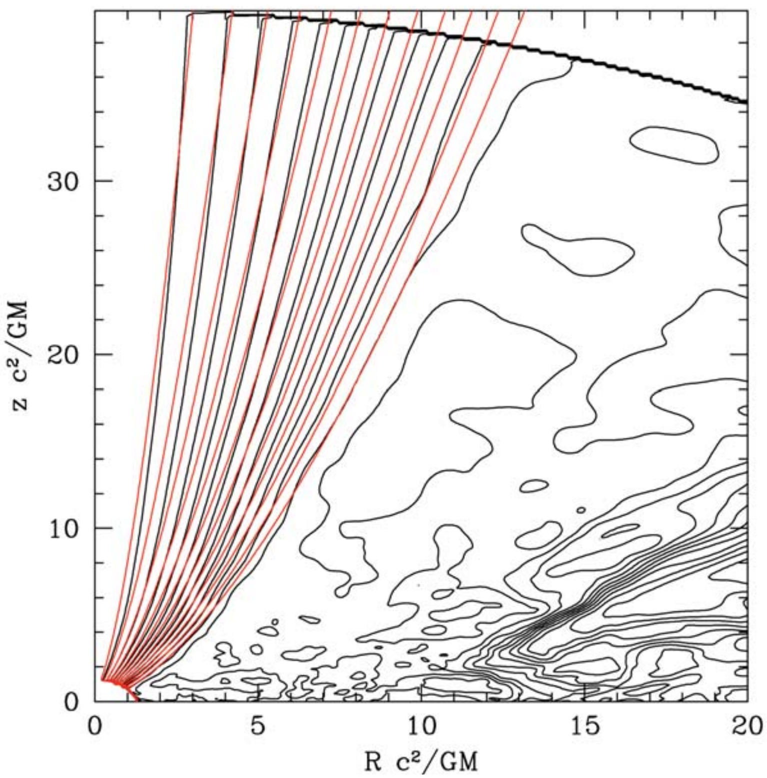
Avg.

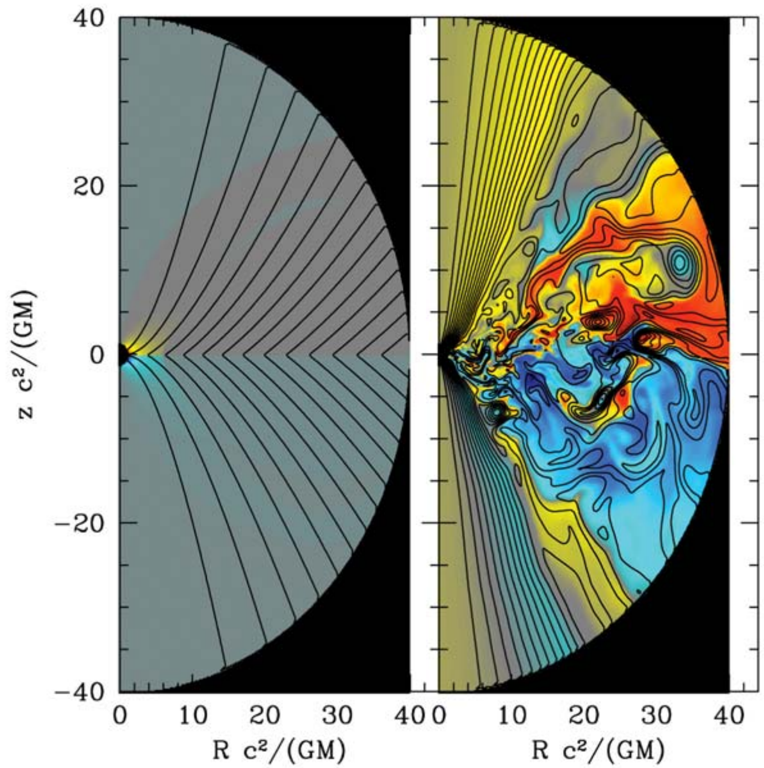
State

McKinney (2005)

Disk-Jet Coupling

- Nearly stationary force-free jet with BP-like scaling
- MRI drives disk+corona to support funnel field
- No Blandford-Payne field from disk





McKinney & Narayan (2006a)

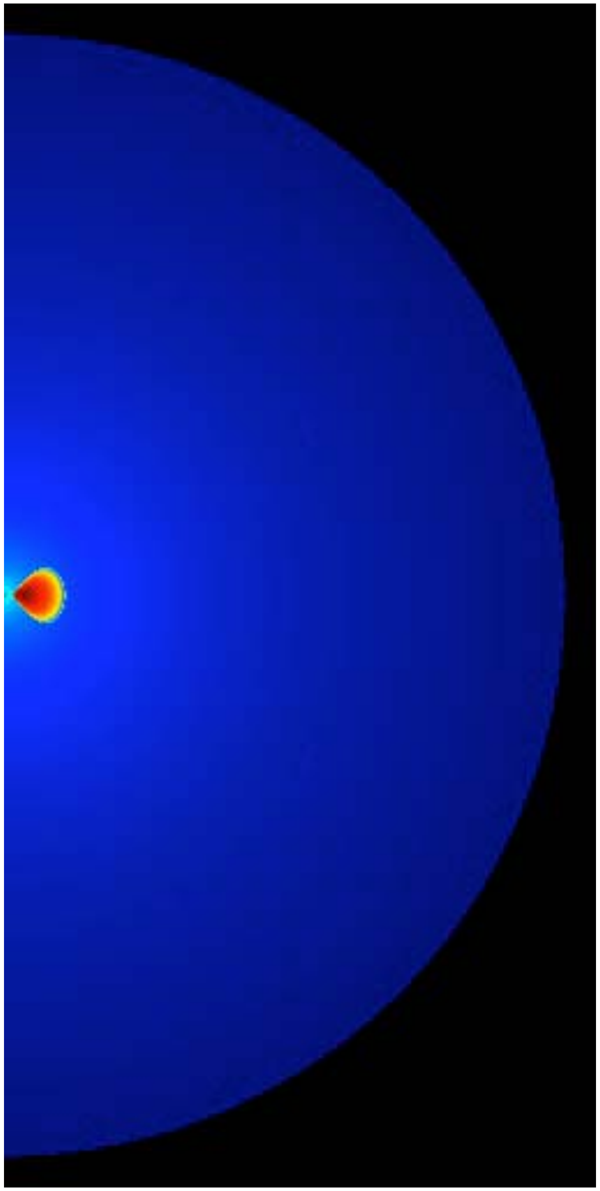
Large Scale Jet

$r \gg 10^4\ GM/c^2$

10^{10}cm

$t \gg 10^4\ GM/c^3$

0.1s



Magnetic Domain:

r<~1000M

$$\Gamma \propto (r/5)^{1/2}$$

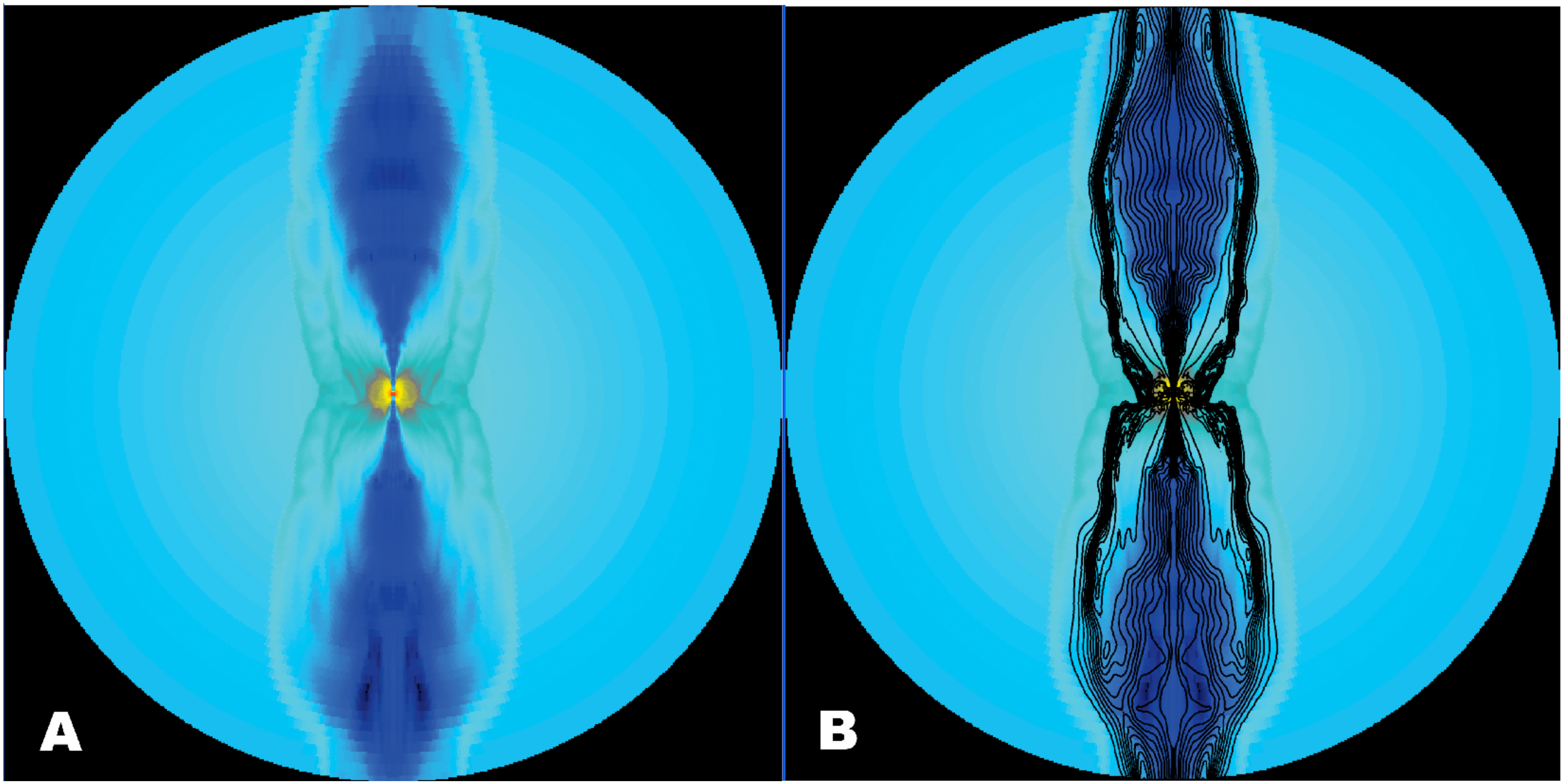
$$\theta_j \propto r^{-1/3}$$

Thermal Domain:
r>~1000M

Adiabatic expansion of shocked material

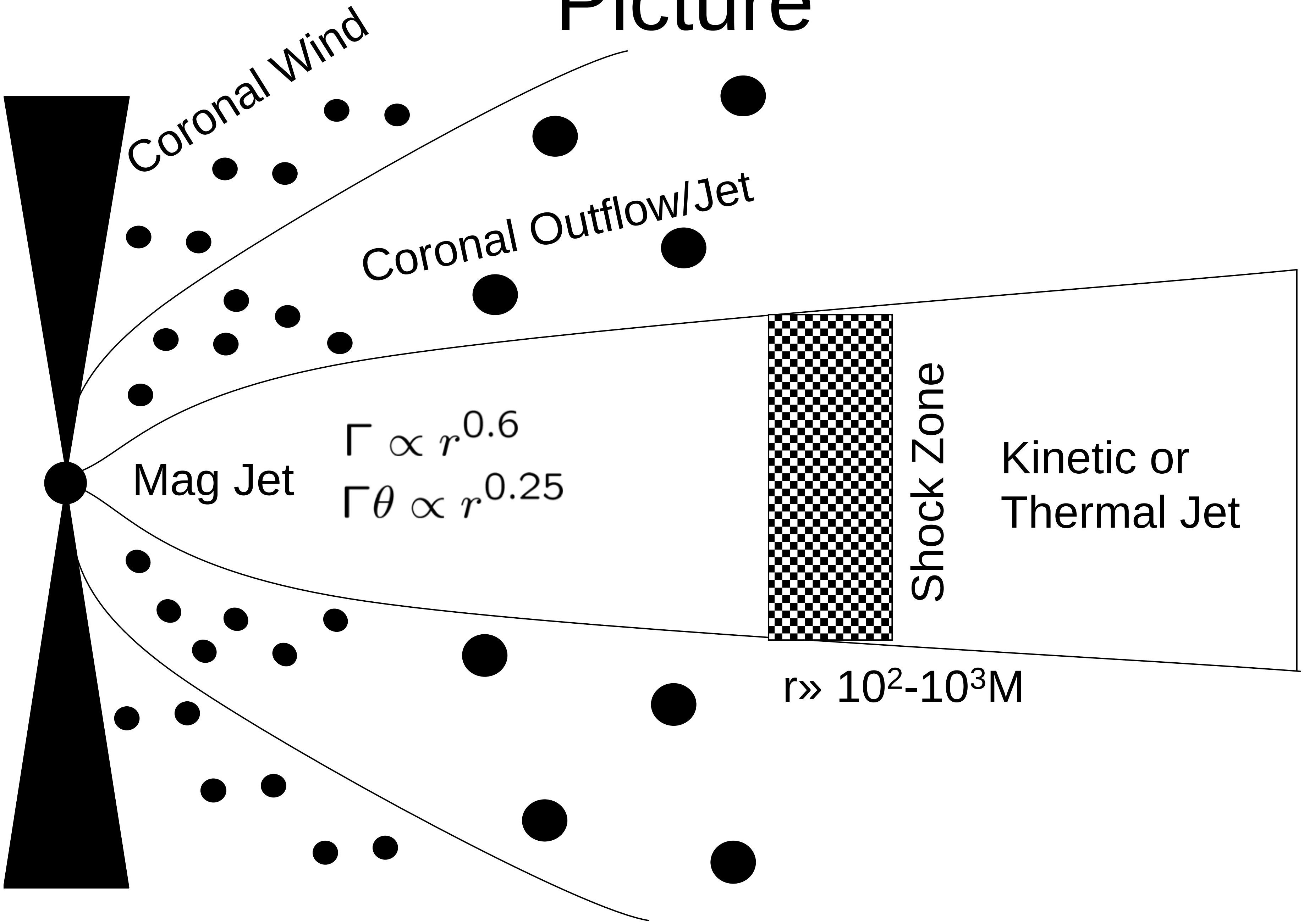
McKinney (2006c)

Density and Field: Large scales



McKinney (2006c)

Picture



Coronal Wind
Coronal Outflow/Jet
Mag Jet
$\Gamma \propto r^{0.6}$
$\Gamma\theta \propto r^{0.25}$
Shock Zone
Kinetic or
Thermal Jet
r» 10^2-10^3M

Summary of Science Learned

- Jets driven by BH are clean and so fast
- Winds driven by disk are dirty and slow
- Jet collimated by corona/wind
  - not by internal rotation (i.e. hoop stresses)
- Kink instability probably not effective
- Reconnection not necessary for dissipation of magnetic energy