Mutli-Scale Physics of Black Hole Phenomena

Jonathan C. McKinney
UMD

Talk Collaborators

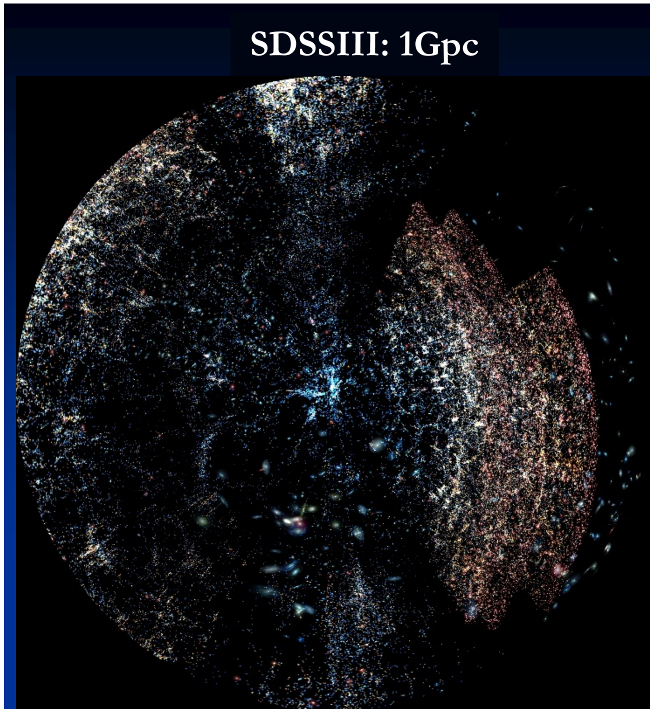
Magnetized Accretion/Jet: Mark Avara (UMD), Megan Marshall (UMD), Peter Polko (UMD) , Alexander Tchekhovskoy, Roger Blandford, Sam Gralla (Arizona)

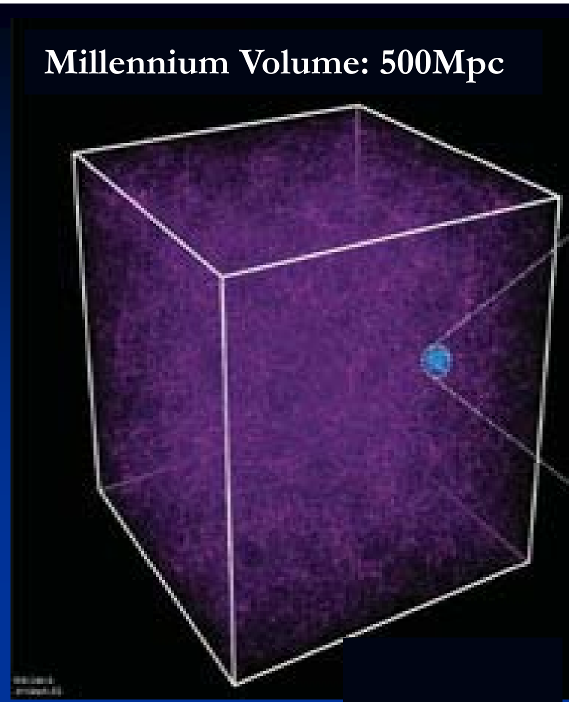
Quasar Growth / AGN Feedback: Ramesh Narayan (Harvard), Jane Dai (UMD), Aleksander Sadowski (MIT), Alexander Tchekhovskoy (Berkeley)

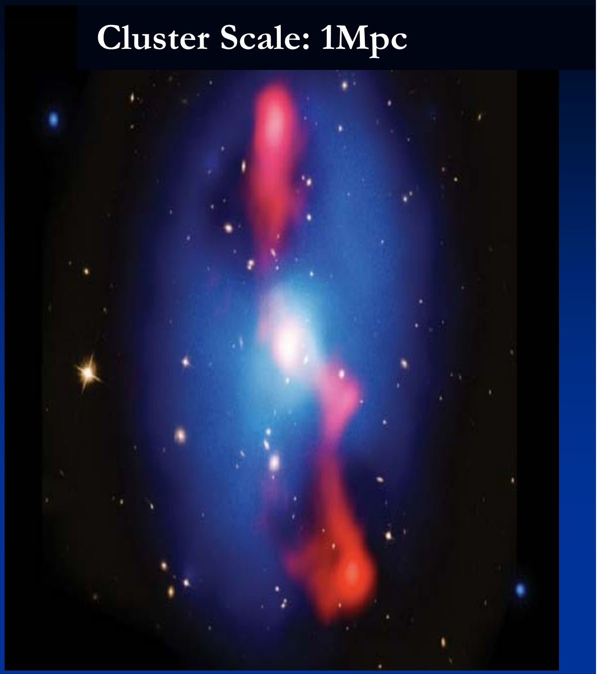
Horizon-Scale Emission: Roman Gold (UMD), Avery Broderick (Perimeter), Jason Dexter (MPE), Shep Doeleman (Haystack), Michael Johnson (Haystack), Charles Gammie (UIUC), Asaf Pe'er & Michael O`Rieden

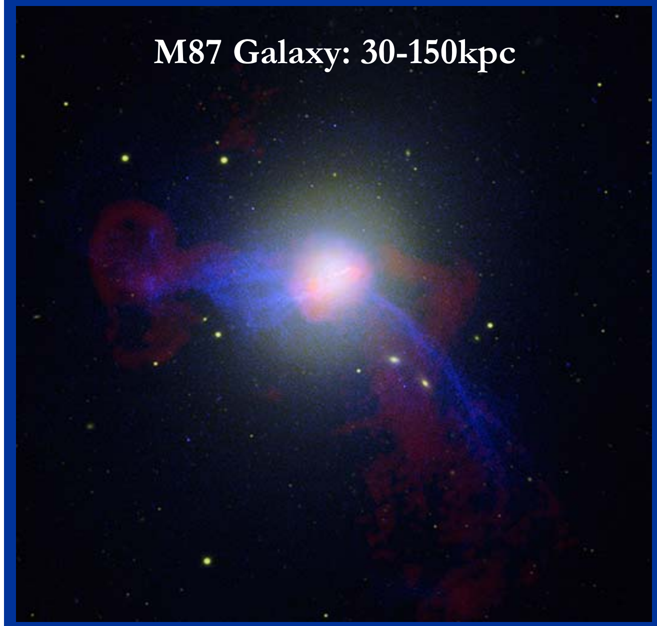
Outline

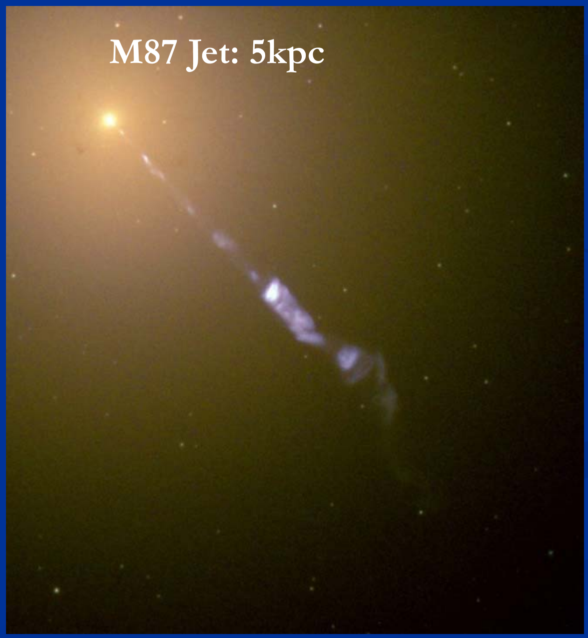
- Multi-Scale Physics of Black Hole Engines
- Quasar Growth and AGN Feedback
- Horizon-Scale Observations vs. Theory

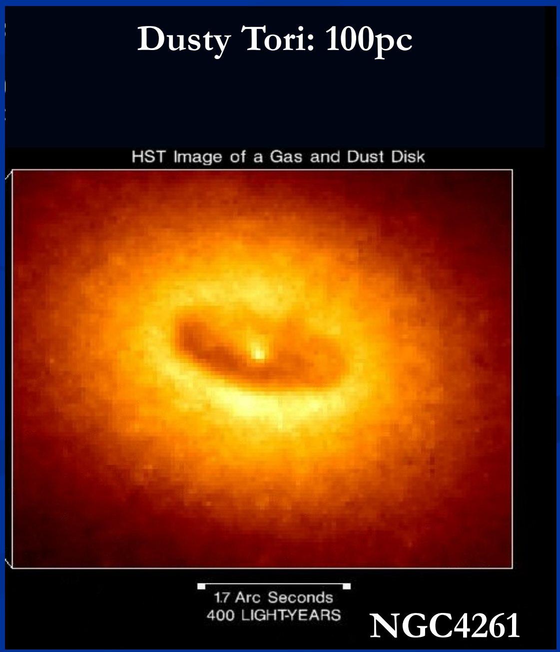

SDSSIII: 1Gpc

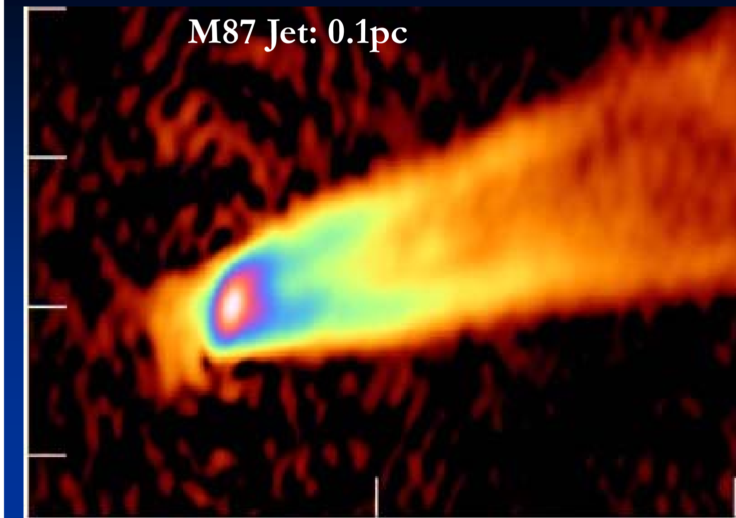

Millennium Volume: 500Mpc

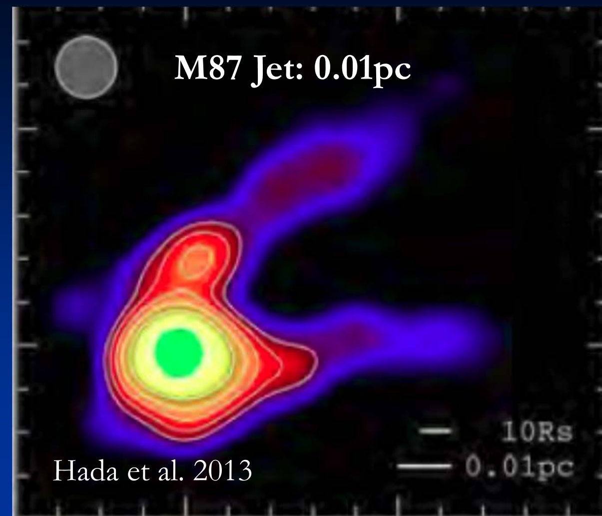

Cluster Scale: 1Mpc

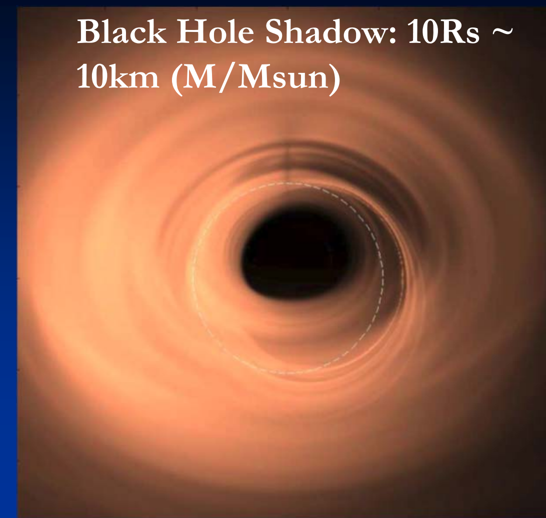

M87 Galaxy: 30-150kpc


M87 Jet: 5kpc

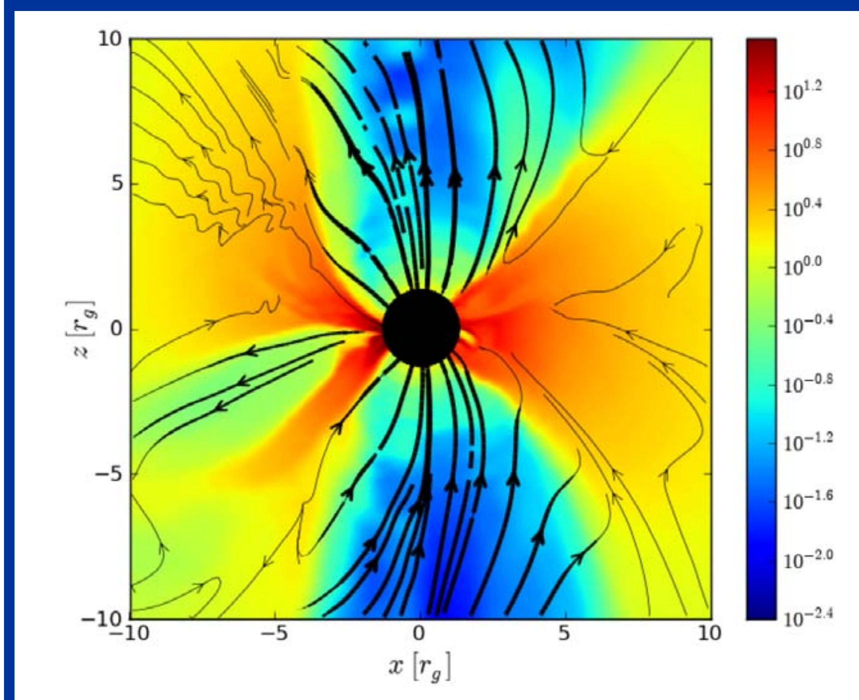

Dusty Tori: 100pc
HST Image of a Gas and Dust Disk
17 Arc Seconds
400 LIGHT-YEARS
NGC4261



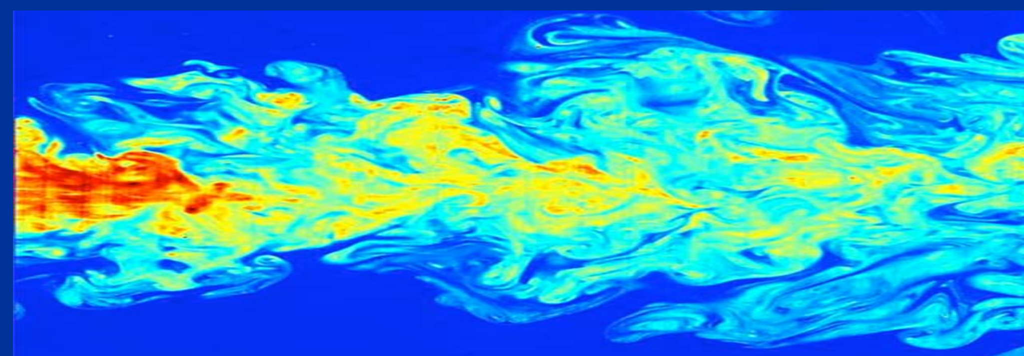


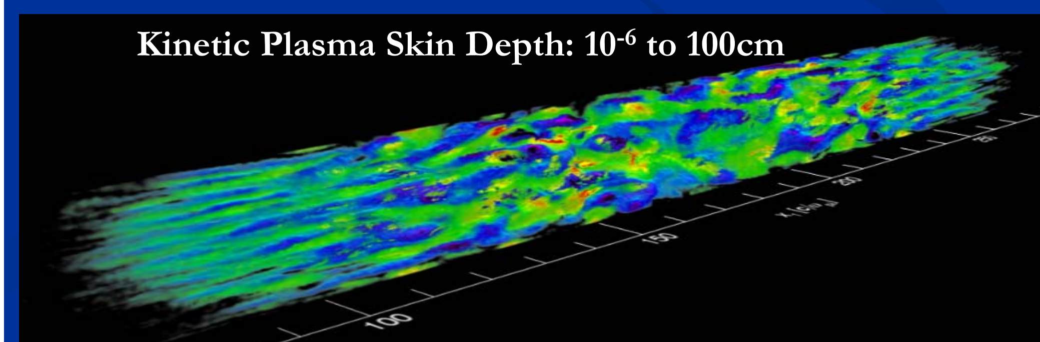


Magnetized Accretion and Jet: 0.1Rs

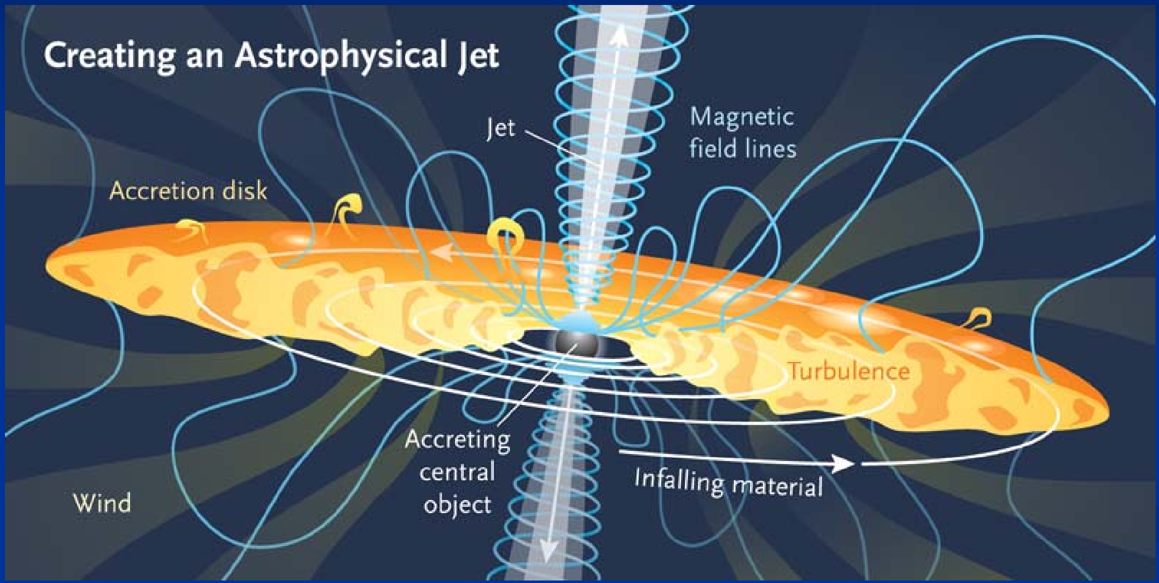


Magnetized Turbulence: ~1cm





Accreting Black Holes



Sky & Telescope (Apr 2010)

Properties of Accreting BHs:
Magneto-Turbulent Disk
Relativistic Jet and Wind
Thermal Plasma
Collisionless Effects
Non-Thermal Plasma

Non-Thermal Plasma:
Shocks (e.g. Fermi Acceleration)
Magnetic Reconnection

Pair Processes:

$\gamma\,\gamma \rightarrow e^+\,e^-$
$\gamma e \rightarrow e\,e^+\,e^-$
$\gamma p \rightarrow p\,e^+\,e^-$

$ee \rightarrow ee\,e^+\,e^-$
$ep \rightarrow ep\,e^+\,e^-$
$ep\,e^{+-} \rightarrow ep\,e^{+-}$

BZ77: $E + e^+\,e^- \rightarrow N\,e^+\,e^- + M\,\gamma$
Schwinger: $E \rightarrow e^+\,e^-$

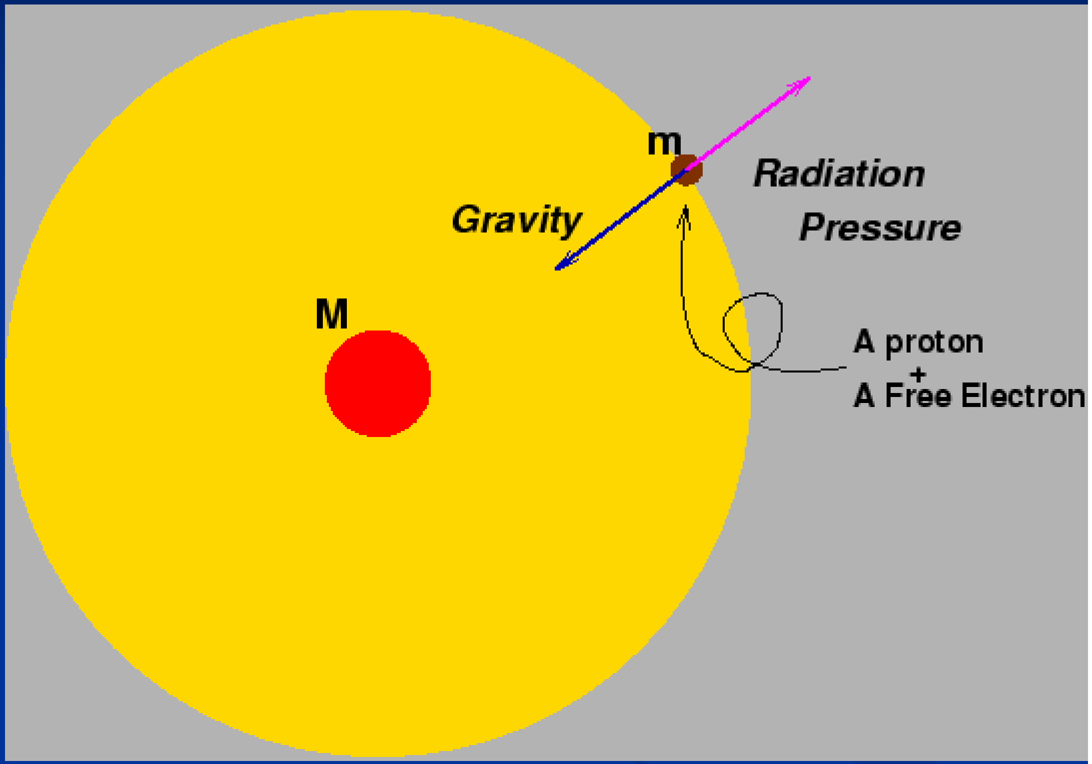
Photon Radiation Processes:
Cyclo-Synchrotron
Comptonization (Scattering)
Bremsstrahlung (free-free, etc.)
Pair Annihilation

Eddington Rate of Accretion

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

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

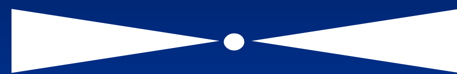
$$(m_p >> m_e)$$



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

Disk States (Mdot, M, B?)

Super-Eddington state
(radiation dominated)



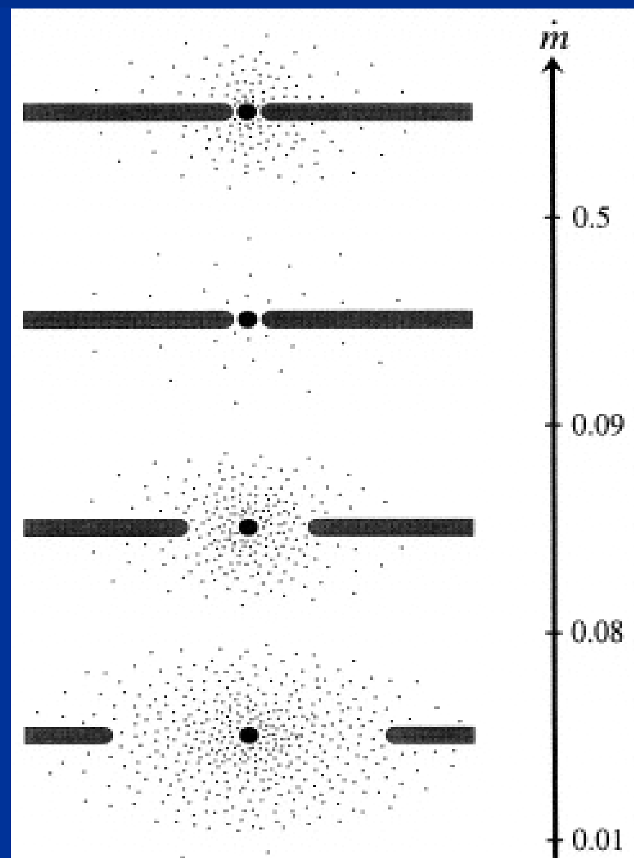
$\dot{m}>1$ $\dot{m}=Ledd/(c^2\eta)$

Very high state
(disk+corona)

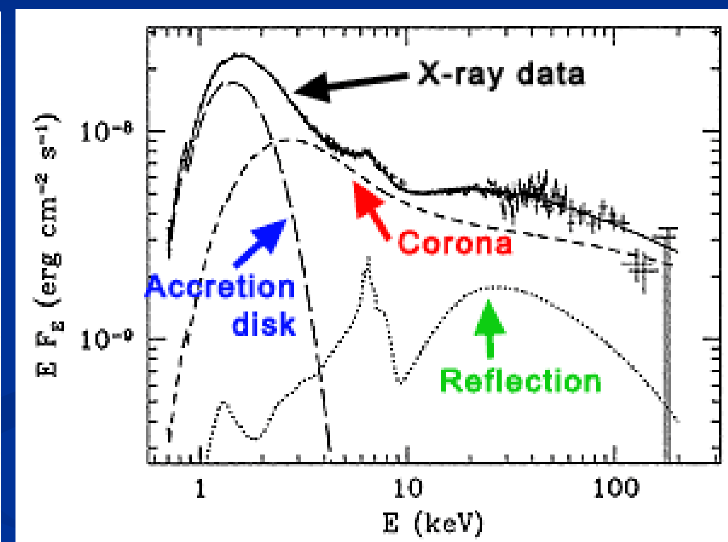
High/soft state
(standard disk)

Intermediate state

Low/hard state
(RIAF/ADAF)



Esin et al. (1997)



Cosmological Evolution of BH Mass

$\dot{M}$ 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
$$t_{Edd} = \frac{\kappa c}{4\pi G} = 4.5\times 10^{8}\, yr$$

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

Final mass exponentially sensitive to 1/efficiency

So exponentially sensitive to BH spin!

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

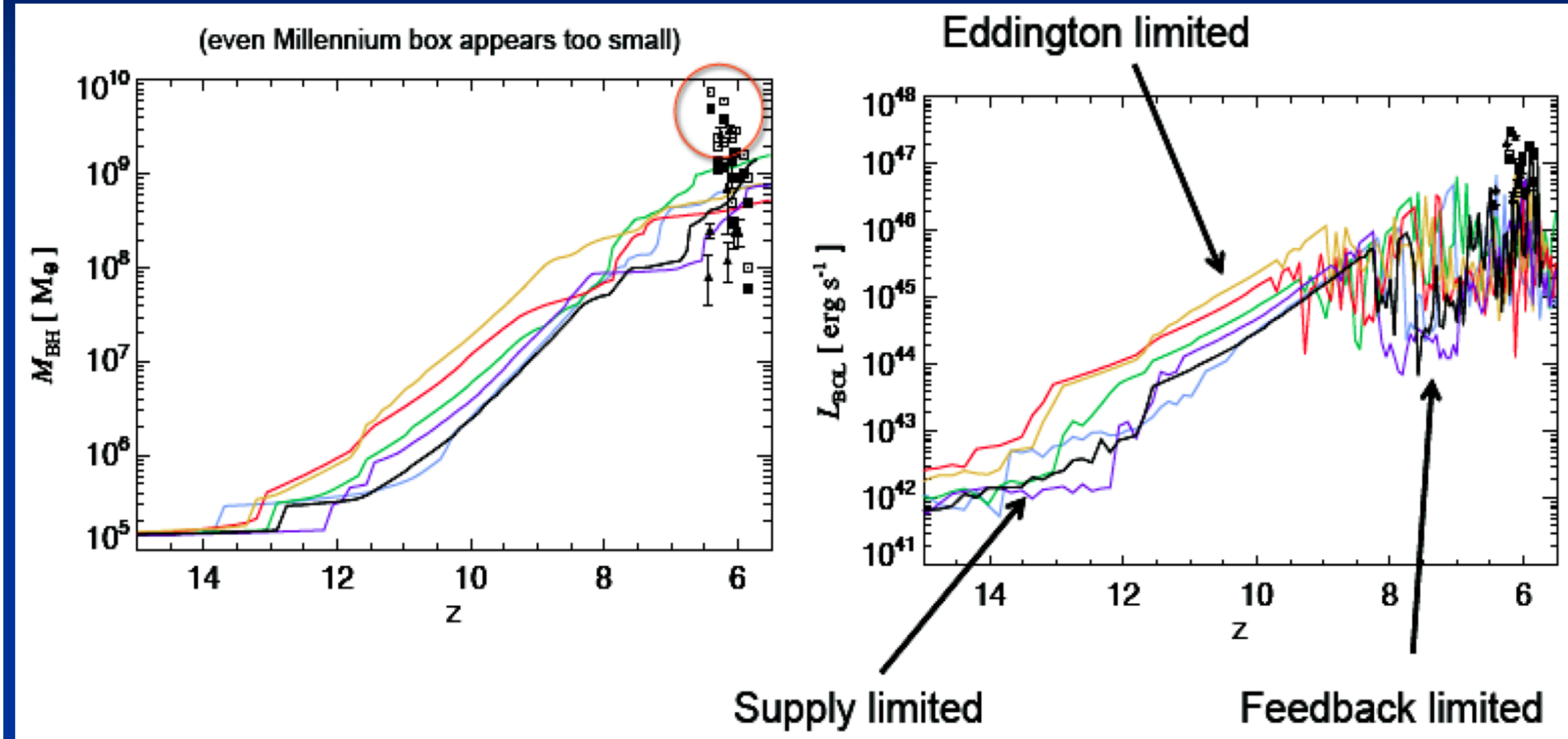
$$\varepsilon_{\min} < 0.08$$

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**

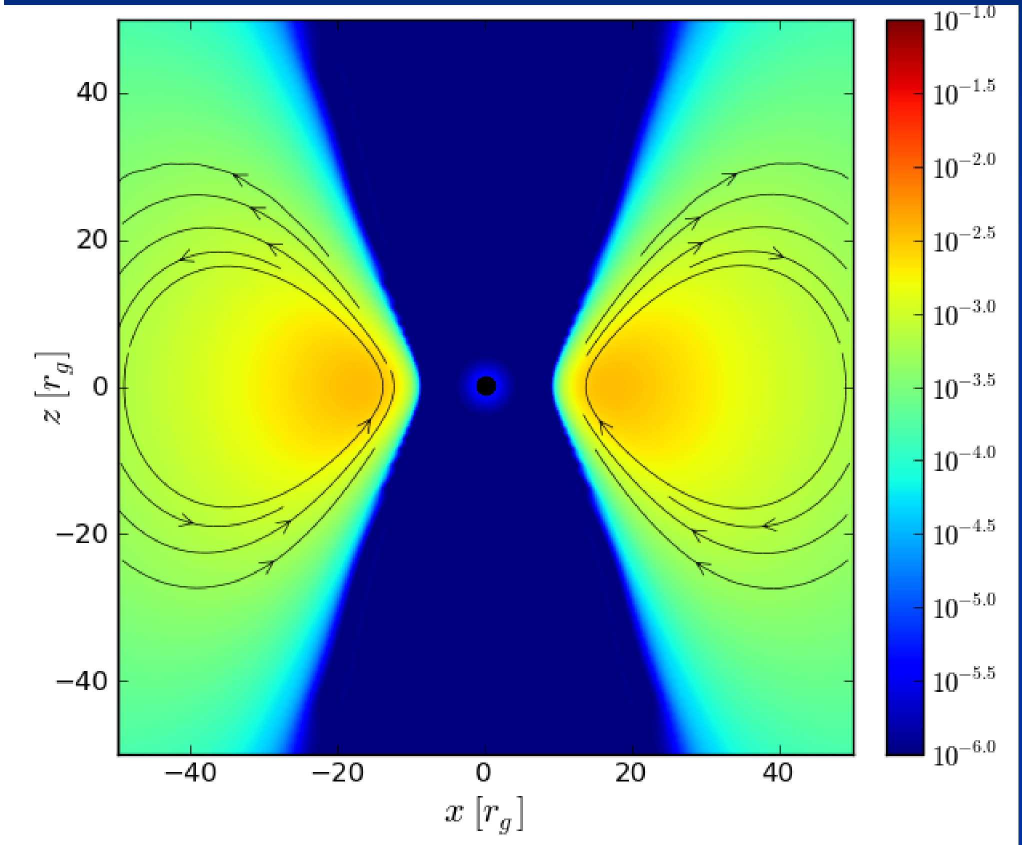
Eddington Limited



Costa et al. (2014)

Sijacki et al.

Super-Eddington Accretion



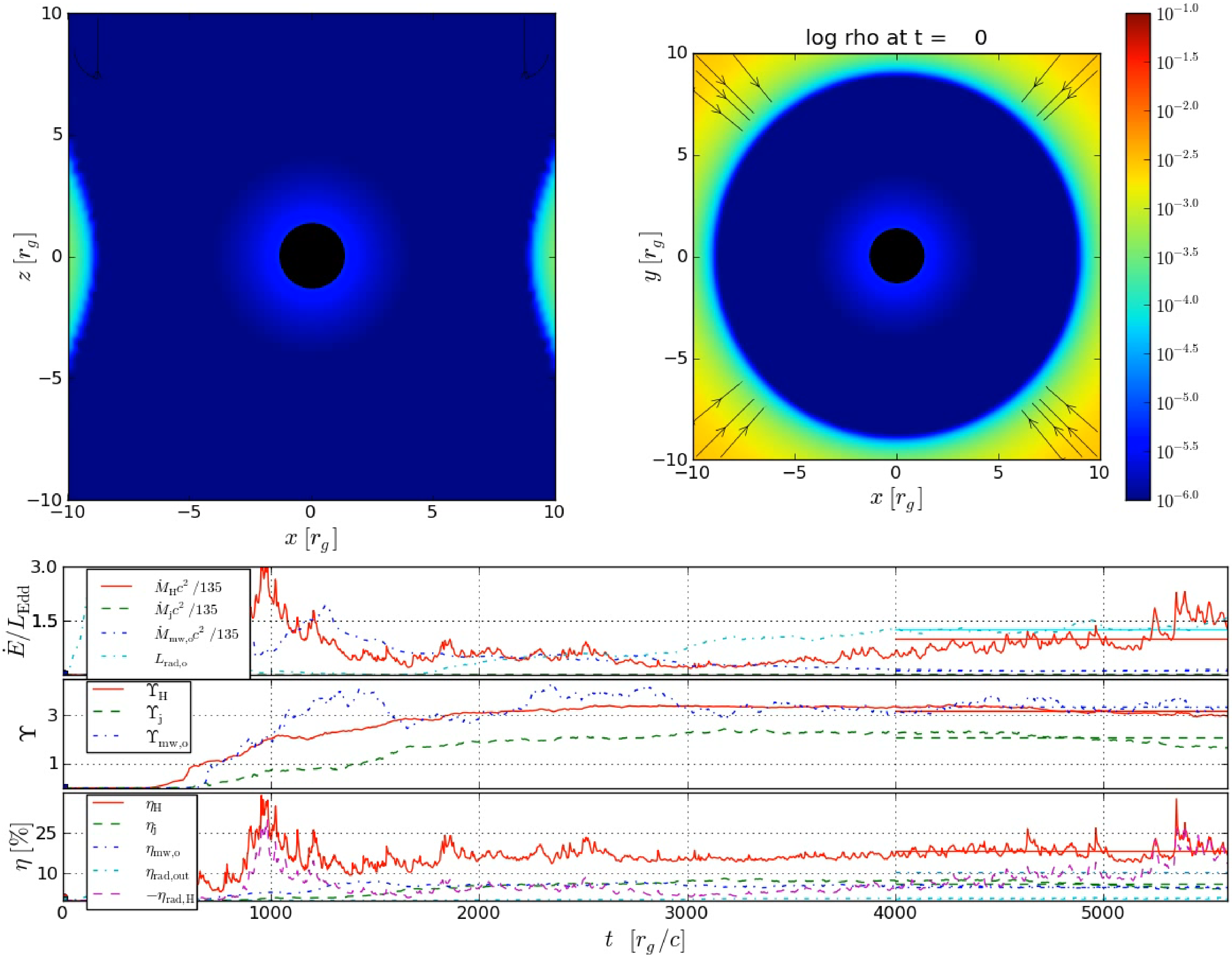
Physical Setup:

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

Numerical Setup:

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

Sadowski, Narayan, McKinney, Tchekhovskoy (2014)
McKinney, Tchekhovskoy, Sadowski, Narayan (2014)

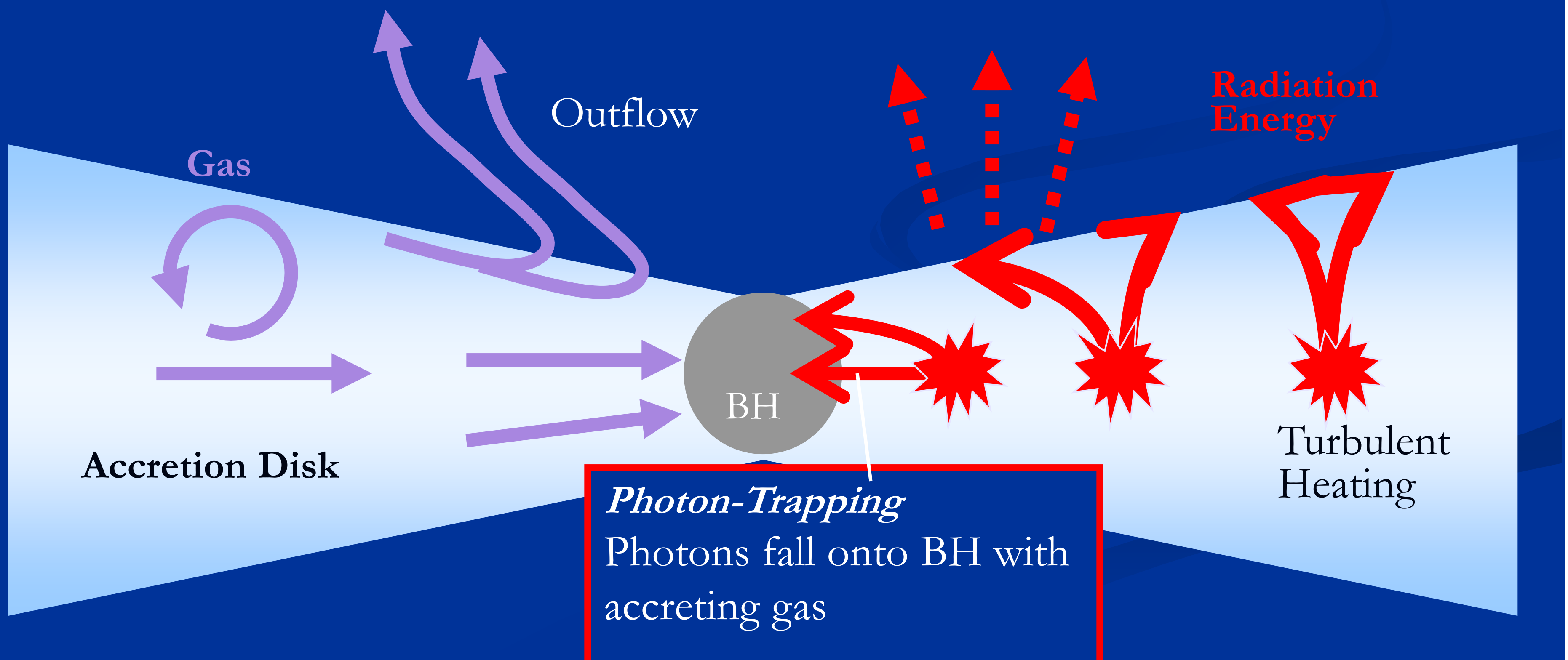

log rho at t = 0
$x\ [r_g]$
$z\ [r_g]$
$y\ [r_g]$
$10^{-1.0}$
$10^{-1.5}$
$10^{-2.0}$
$10^{-2.5}$
$10^{-3.0}$
$10^{-3.5}$
$10^{-4.0}$
$10^{-4.5}$
$10^{-5.0}$
$10^{-5.5}$
$10^{-6.0}$
$\dot{E}/L_{\rm Edd}$
$\dot{M}_{\rm H}c^2\ /135$
$\dot{M}_{\rm j}c^2\ /135$
$\dot{M}_{\rm mw,o}c^2\ /135$
$L_{\rm rad,o}$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

No Limits on accretion

1) High Opacity: $E_0 > \sim 10^2 L_E / 4\pi r^2 c$ but $F_0 \sim c E_0 / \tau$

2) Trapping: $v E_0 < 0$ & L regulated to $< \sim L_E$

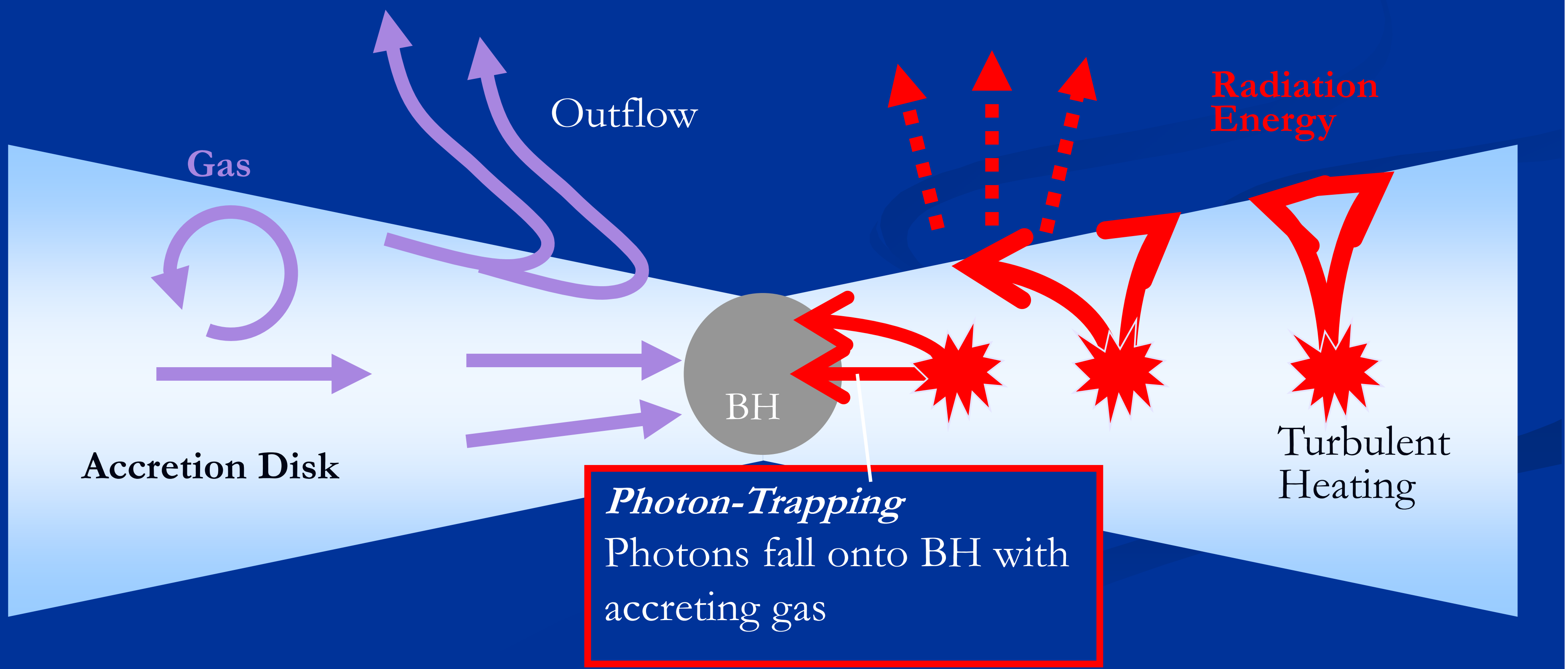
3) Geometry -> Anisotropic Radiation



AGN Feedback

1) Radiation and Wind each: 0.1% to 1%

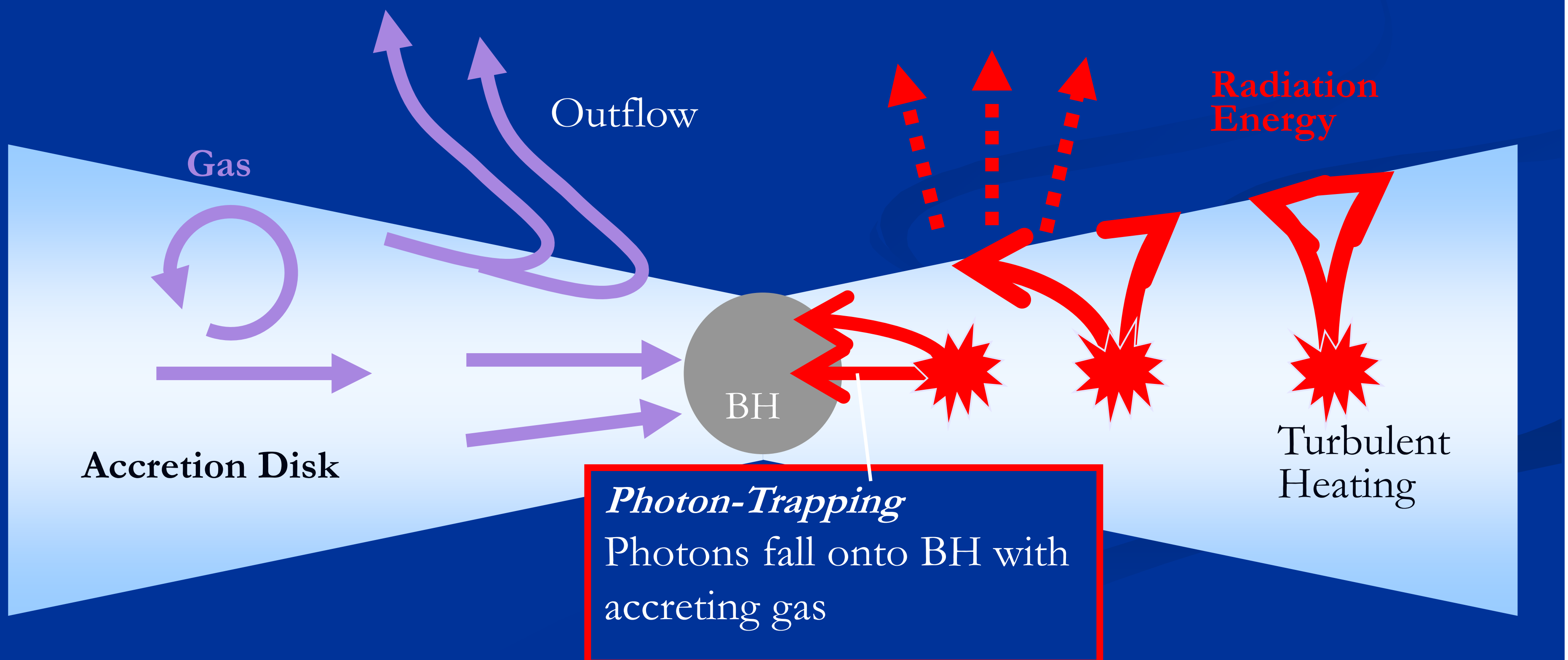
2) Normally AGN Feedback Eff = 5% * 5% ~ 0.25%



Improving our Models

1) Compton Scattering: Taps grav. energy for Radiation
2) Double Compton: Soft photons (rad. dominated)

These might affect Outflows, Radiative Efficiency, etc.



Disk States (Mdot, M, B?)

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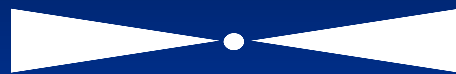
(radiation dominated)



$\dot{m}>1$ $\dot{m}=L_{edd}/(c^2\eta)$

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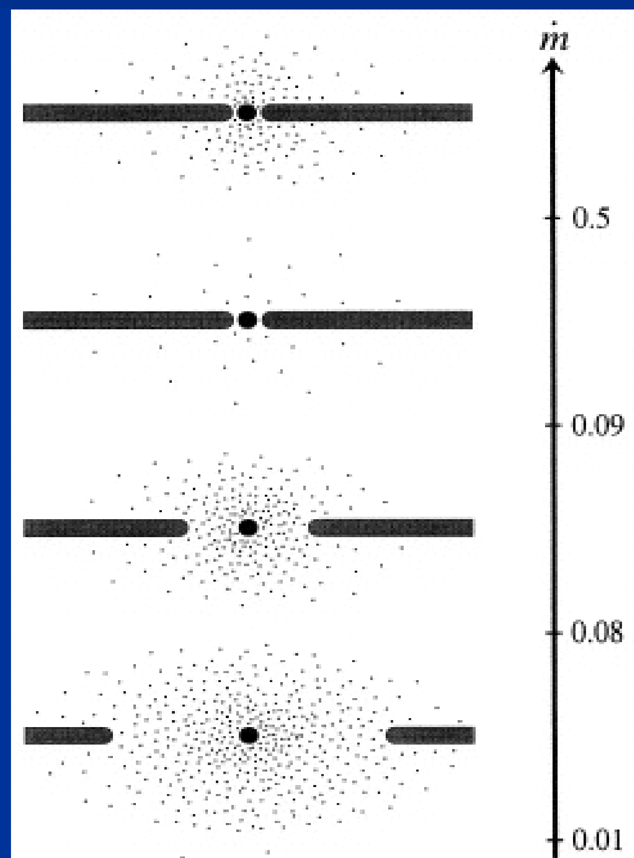
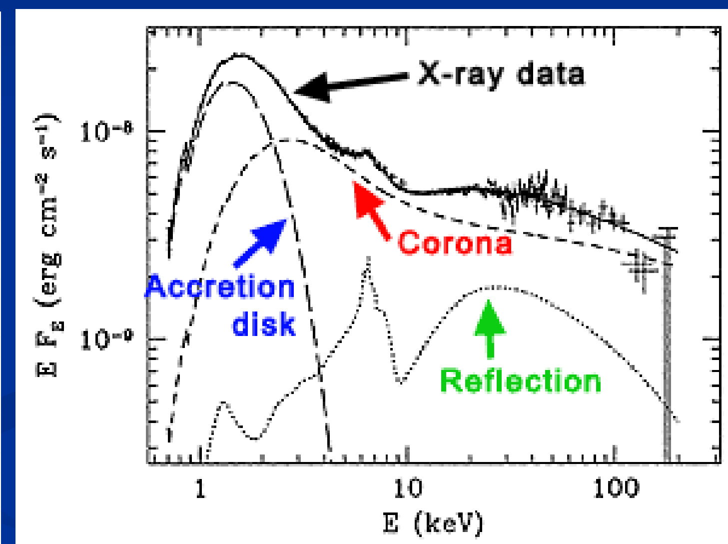
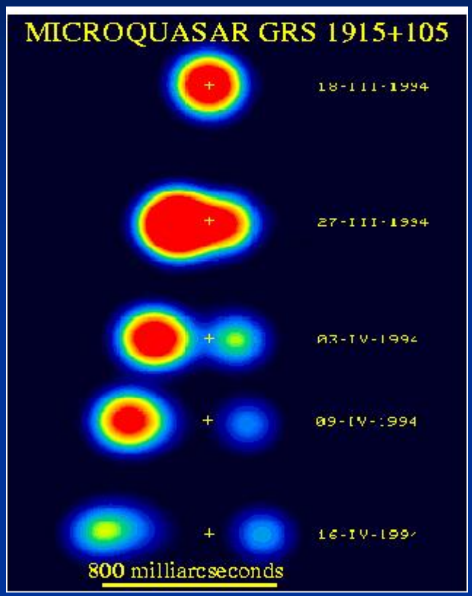


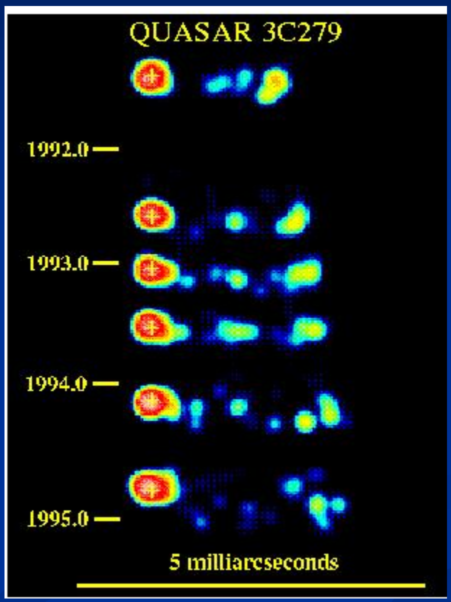
Esin et al. (1997)



Relativistic Jets



Mirabel & Rodriguez (1994,1999)



Wehrle et al (2001)

GRS1915+105:

v~6c (obs.)

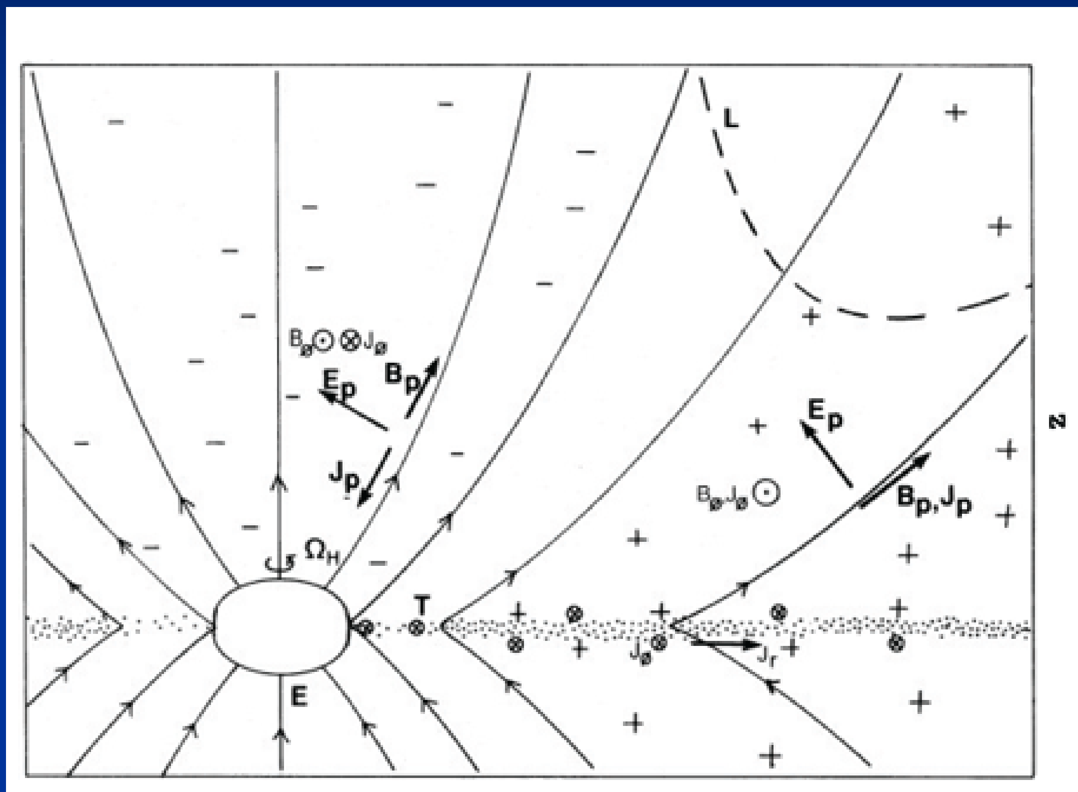
v~0.92c (actual)

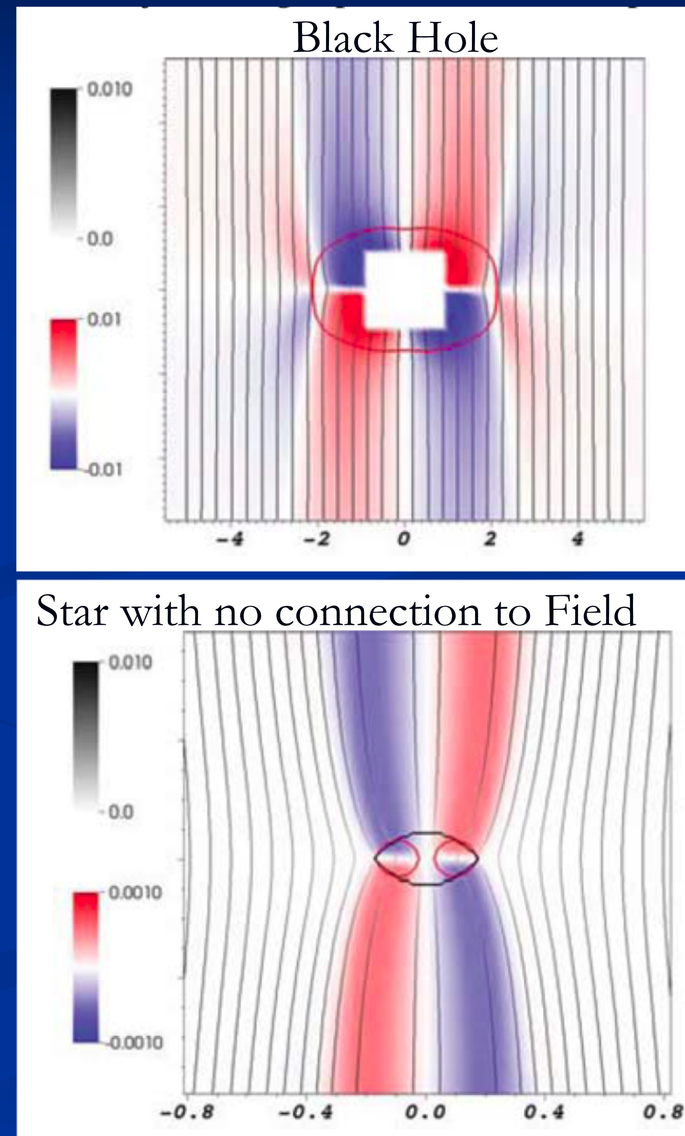
3C279:

v~4.8-7.5c (obs.)

Spin Power

Blandford-Znajek 77 Jet





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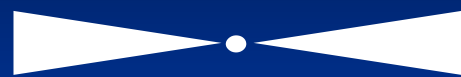
BZ Power P 2 #B^2 a^2

P 2 #Mdot ϕ^2 a^2

Ruiz et al. 2014

Disk States (Mdot, M, B?)

Super-Eddington state
(radiation dominated)



$\dot{m}>1$ $\quad$ $\dot{m}=L_{edd}/(c^2\eta)$

Very high state
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High/soft state
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Low/hard state
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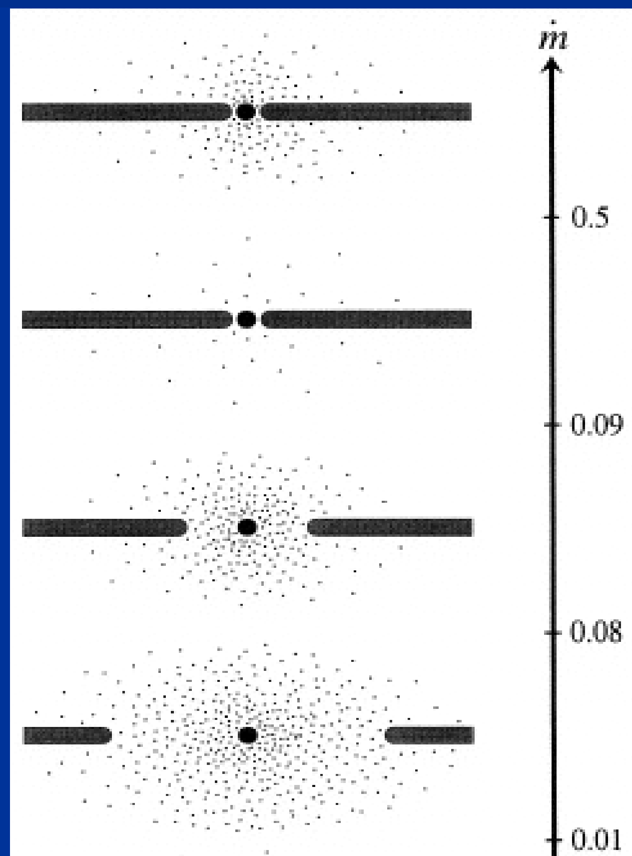
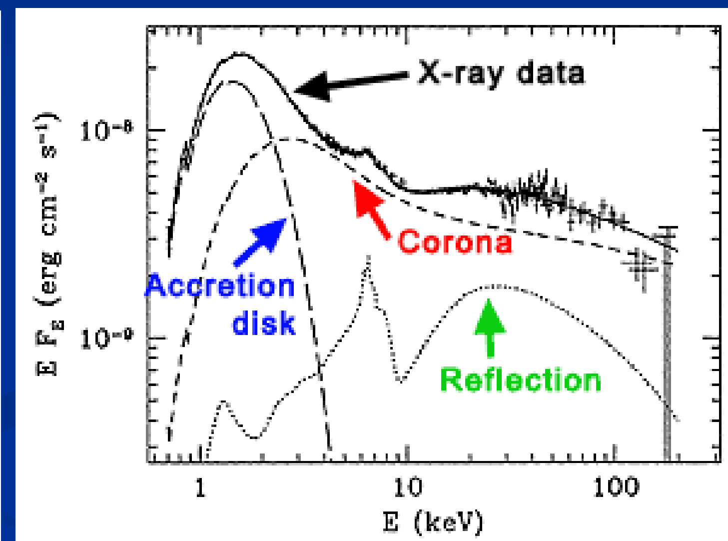
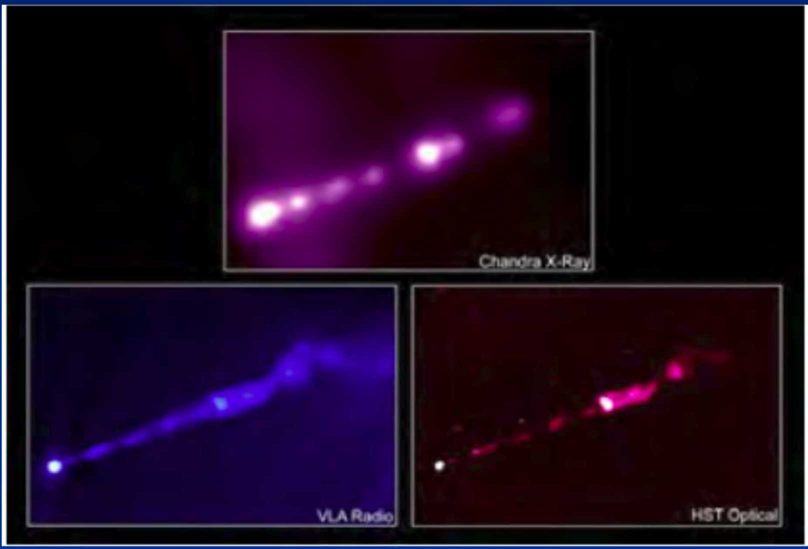


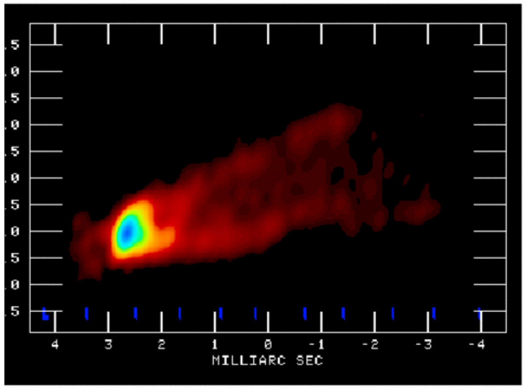
Esin et al. (1997)



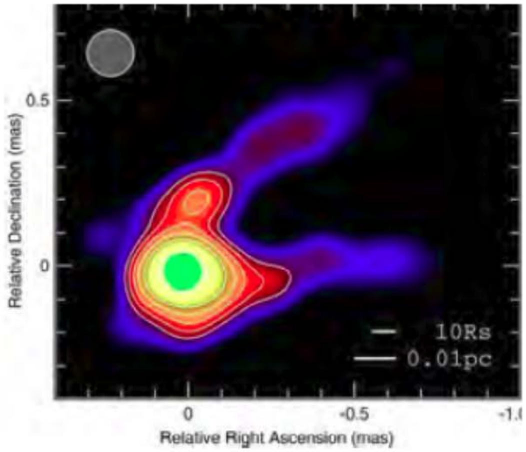
M87 Jet



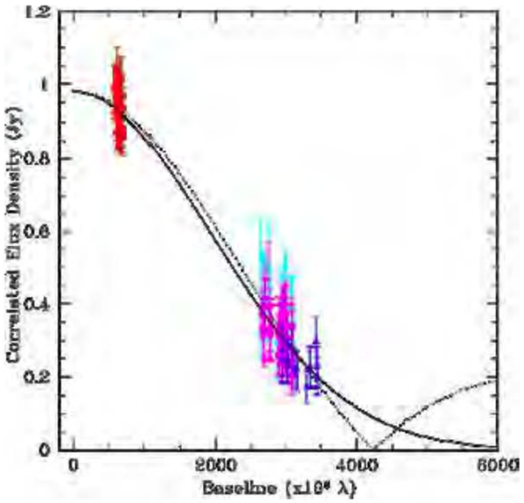
Walker et al. 2013

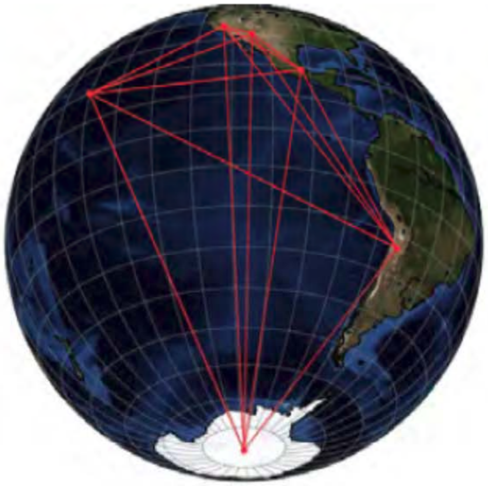


Hada et al. 2013



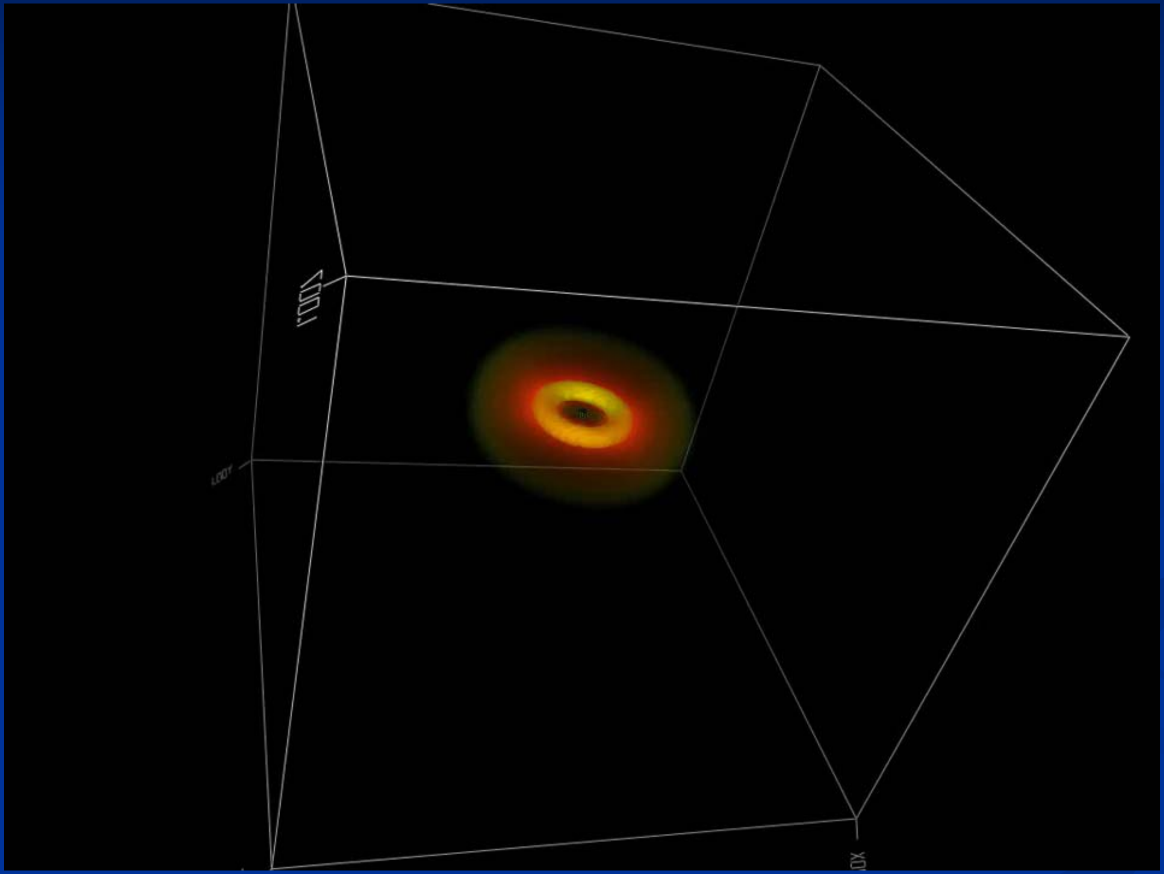
Doeleman et al. 2013





Event Horizon Telescope

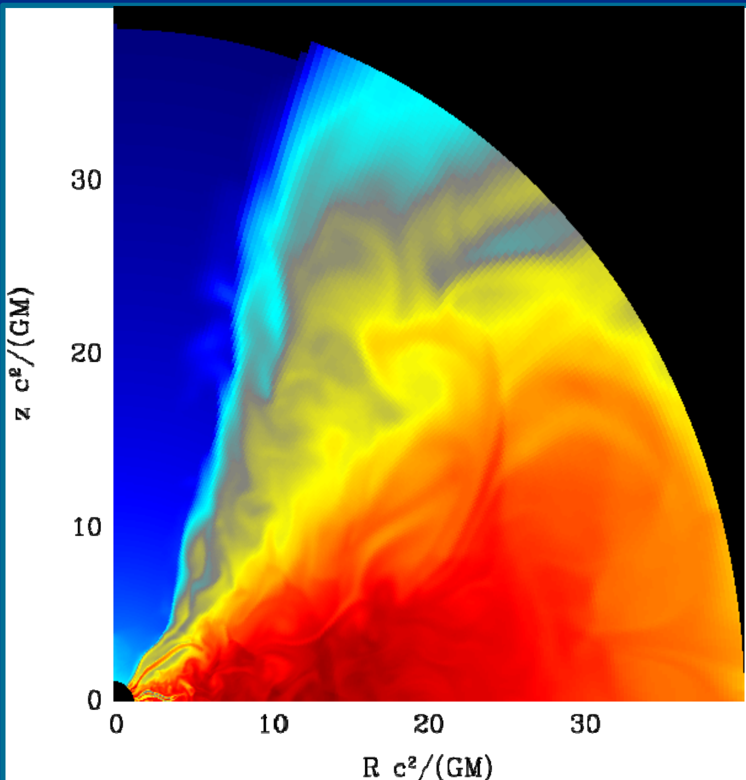
GRMHD Sim. Of RIAF Jet



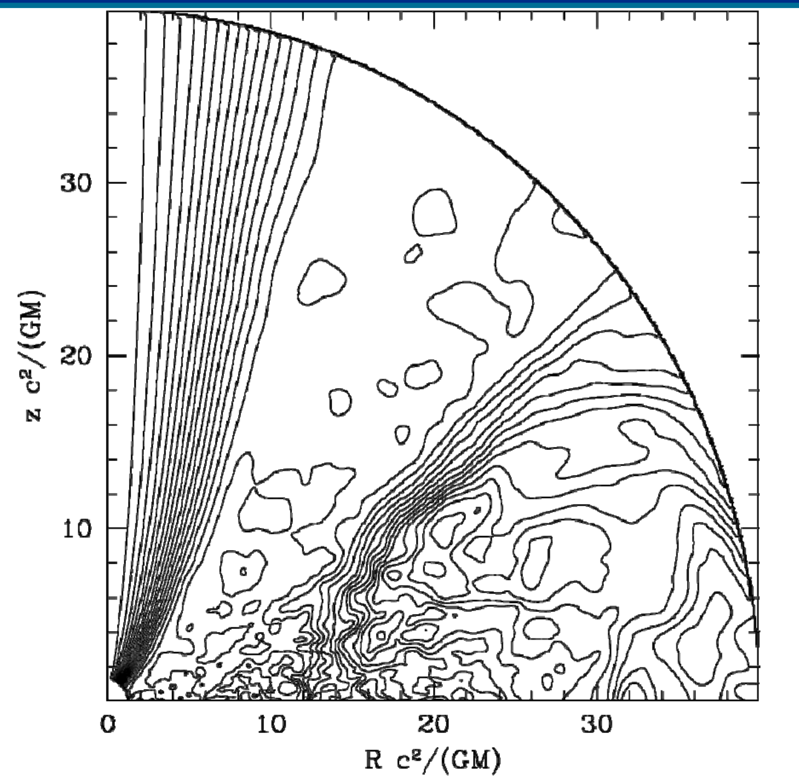
McKinney & Blandford (2009)
Hawley et al.
Gammie et al.
Fragile et al.
Komissarov et al.

Mass and Field Structure

Log of mass density



Poloidal Field

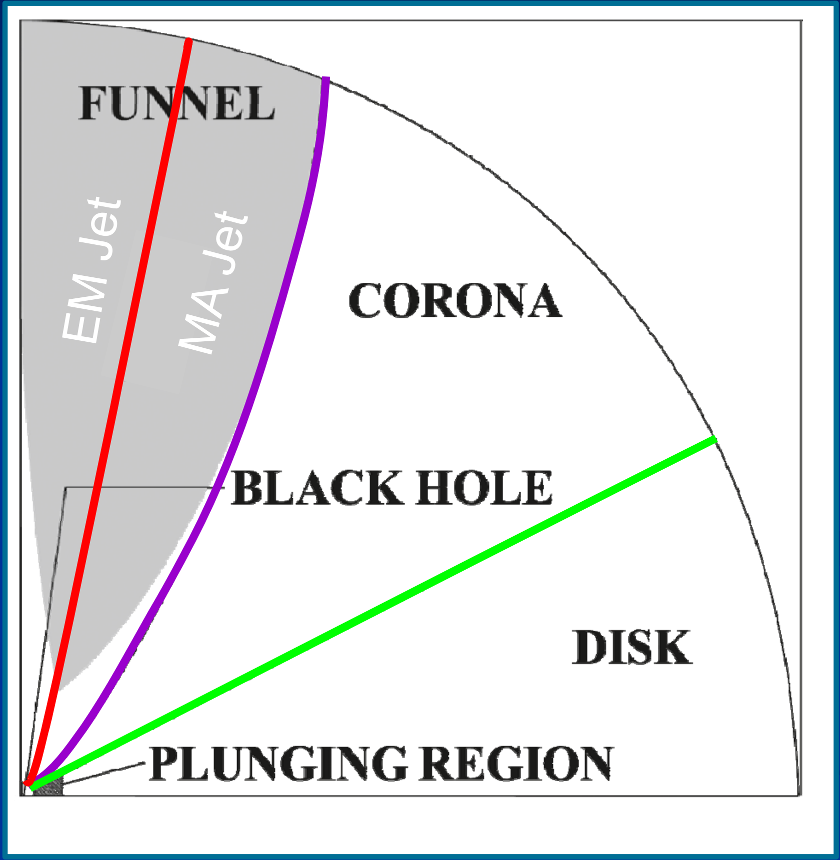


- Evacuated polar region
- Turbulent equatorial region

- Ordered polar field
- Random equatorial field

Flow Structure

$$\frac{B^2}{\rho c^2} >> 1$$



$$\beta = \frac{P_g}{P_b = B^2/(8\pi)} \sim 1$$

$\beta \sim 10$

CORONA: MA~EM

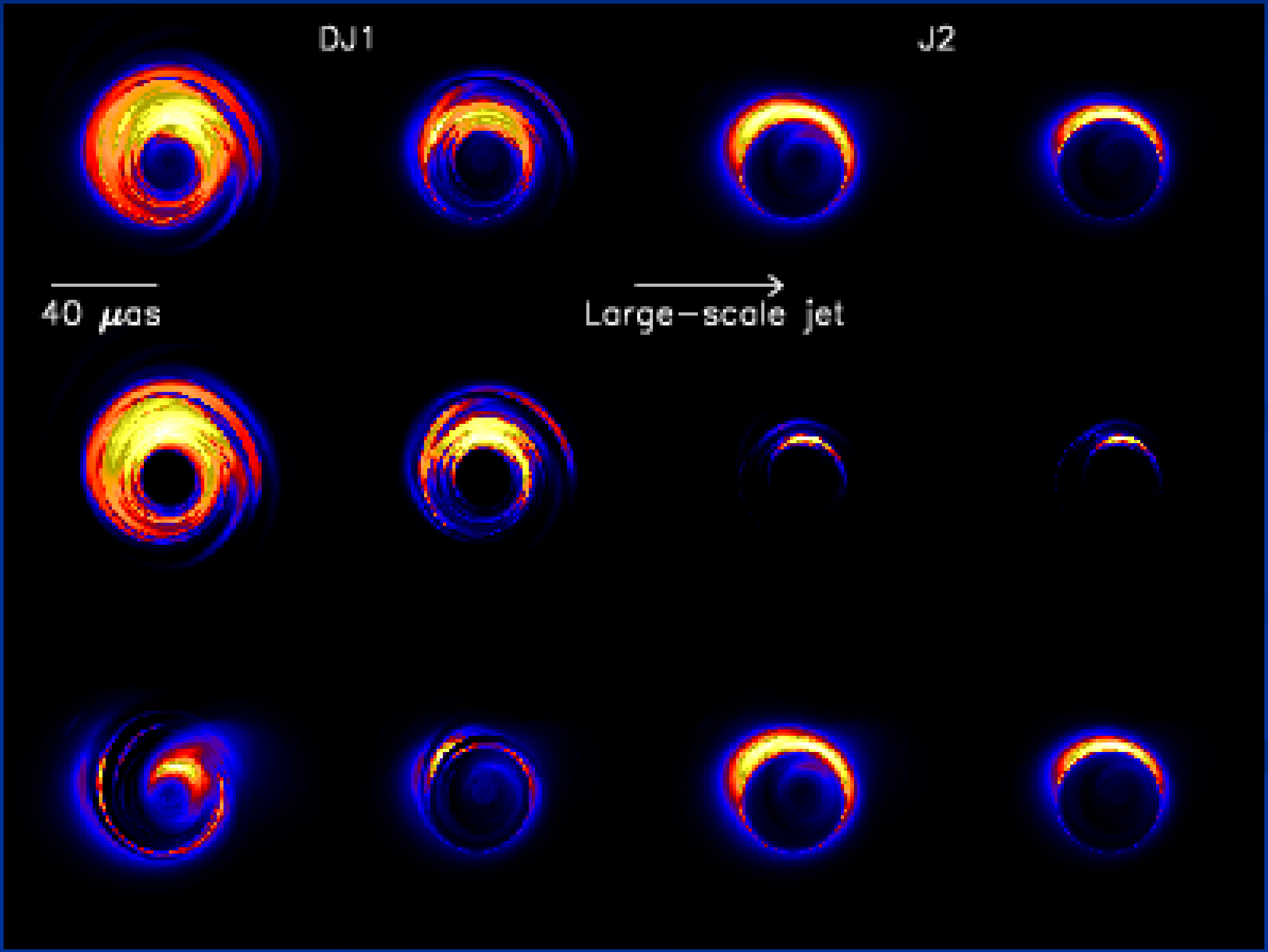
FUNNEL: EM dominated

JETS: Unbound, outbound flow

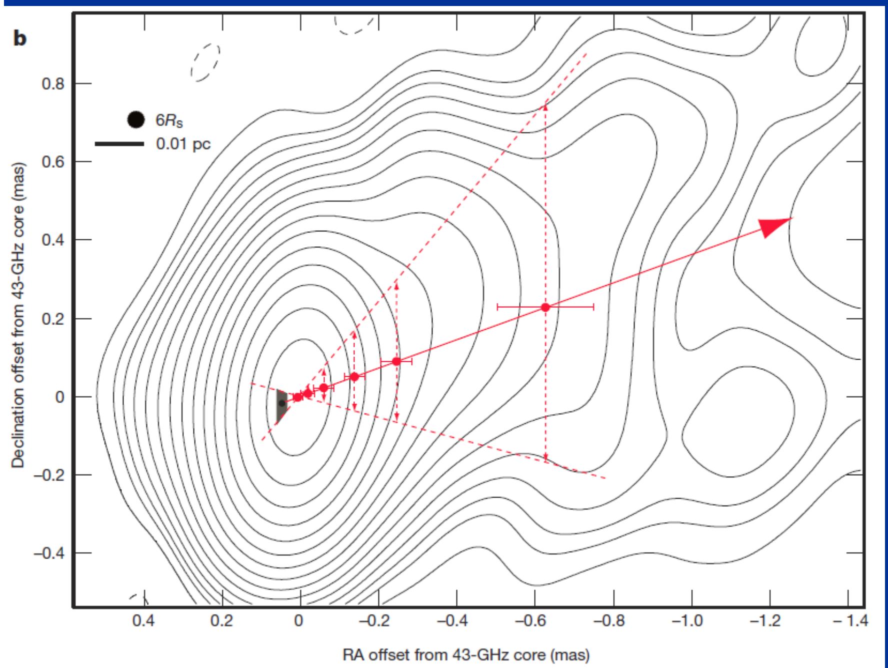
McKinney & Gammie (2004)

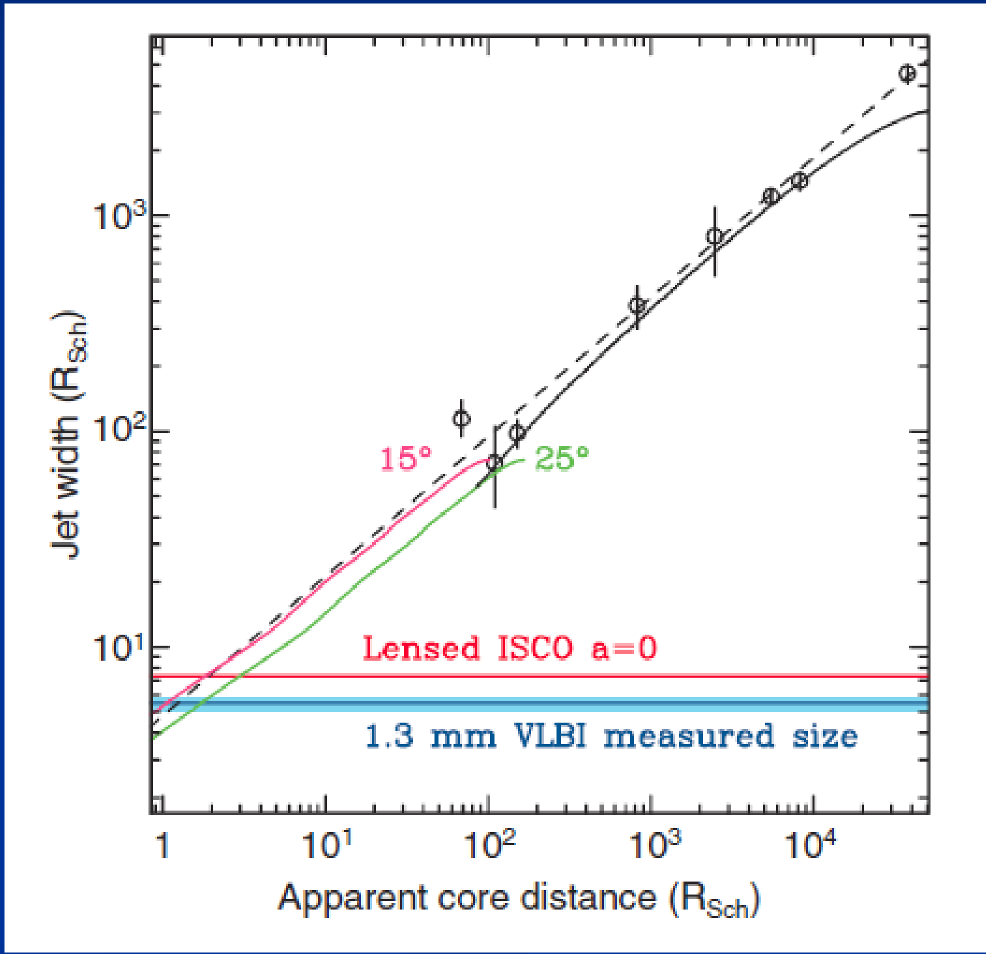
McKinney et al. (2014)

GR Radiative Transfer Sims. Predict Jet Base of size ~5rs



VLBI (EHT) has resolved size ~ 5rs!

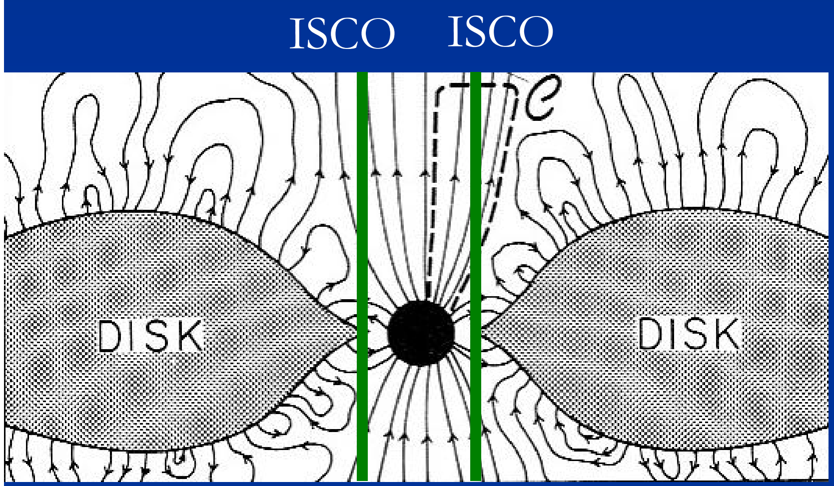


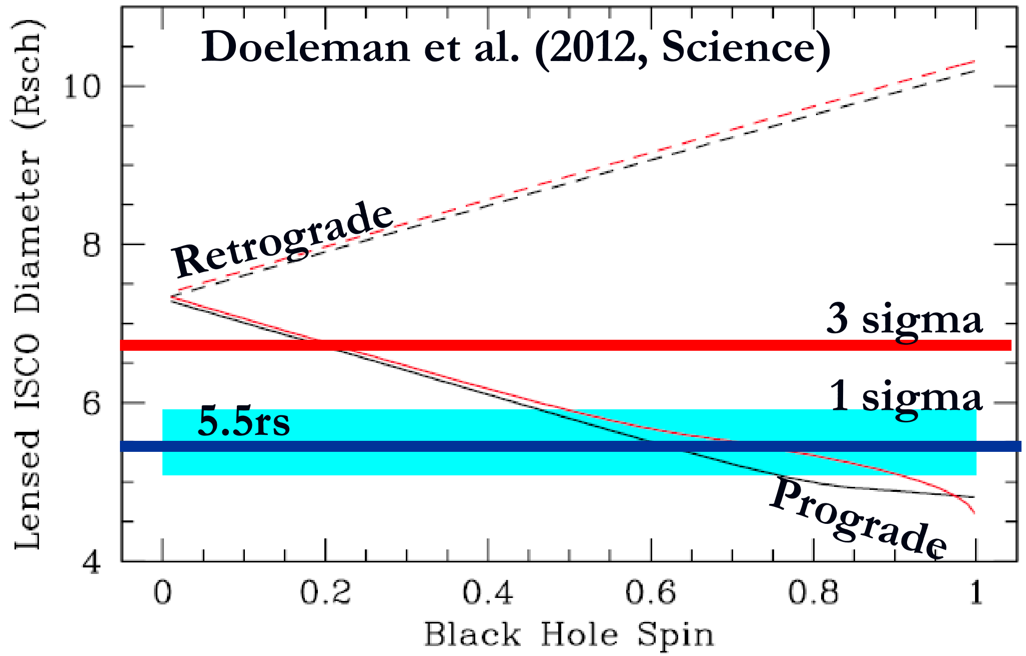


Hada et al. (2011, Nature)

Doeleman et al. (2012, Science)

Constraint of Spin in M87?



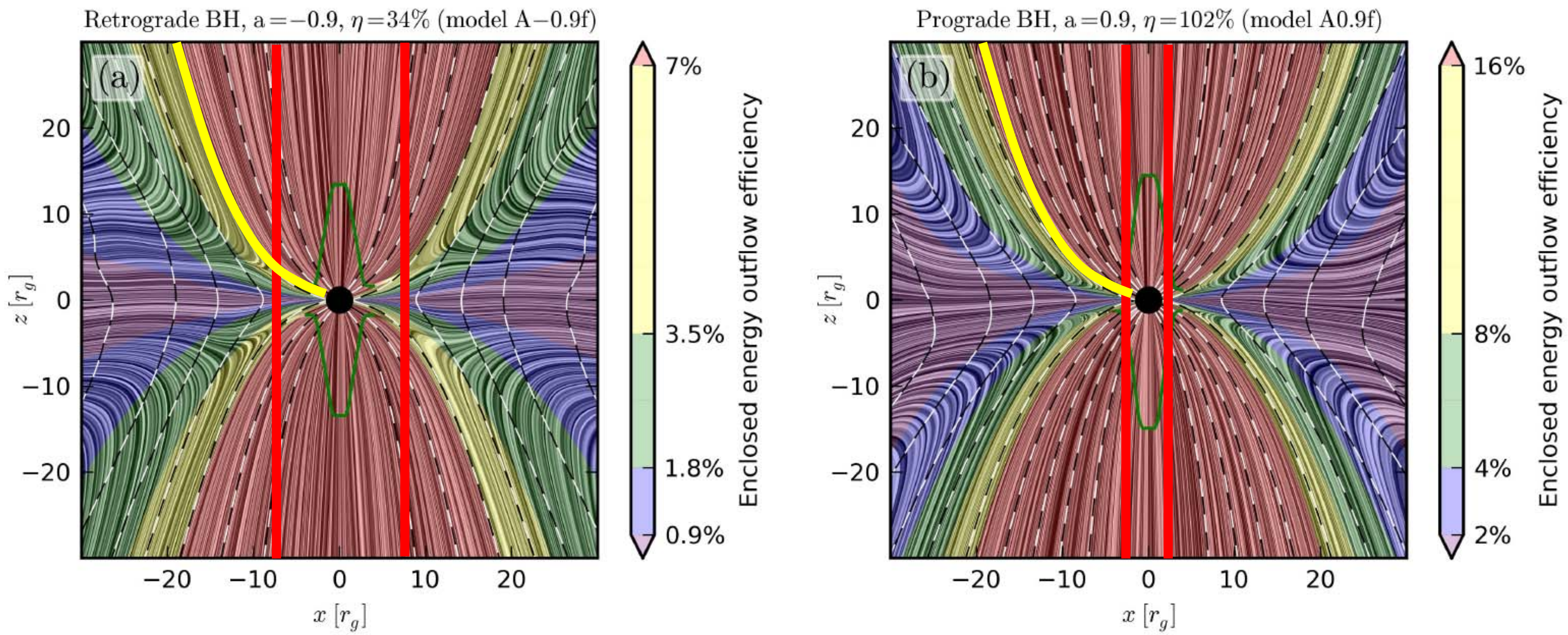


ISCO = Inner-Most Stable Circular Orbit

But …

- ISCO important for thin Keplerian disks but not for thick radiatively inefficient flows (RIAFs) as in M87

a = -0.9 and a = +0.9 Jets are similar size!



a= -0.9 : eff~35% ISCO=8.7M

a=+0.9 : eff~100% ISCO=2.3M

GRMHD Simulations (Jet = where most power is)

So, ISCO might not work as jet base size for M87

(Tchekhovskoy & McKinney 2012)

Summary

- Super-Eddington Accretion:
  - Mdot and Lum. are not limited to Eddington (quasars)
  - Face On Isotropic Equiv. Lum >10x Eddington (ULXs)
  - AGN Feedback from winds/radiation
  - Need Compton (maybe multi-frequency transfer)

- Horizon-Scale Emission:
  - Probe Jet Launching
  - Probe strong Gravity (e.g. shadow)
  - Polarization adds new constraints on disk vs. jet
  - Need: Collisionless effects, Pairs in Jet, Non-Thermal ele.