

# Imaging Accretion Disk Evolutions

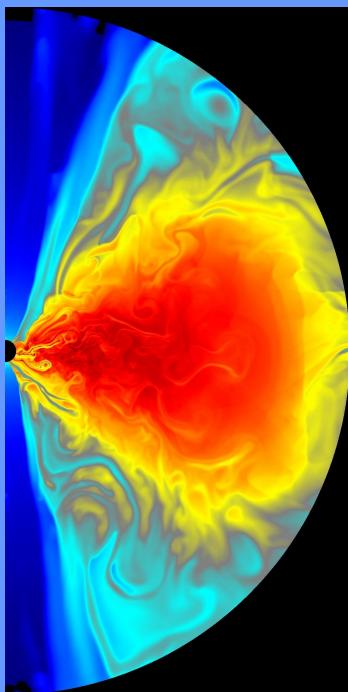
Scott C. Noble

UIUC

UIUC : Charles Gammie,  
Po Kin Leung,  
Laura Book

CfA : Jon McKinney

Firenze: Luca Del Zanna



# Outline

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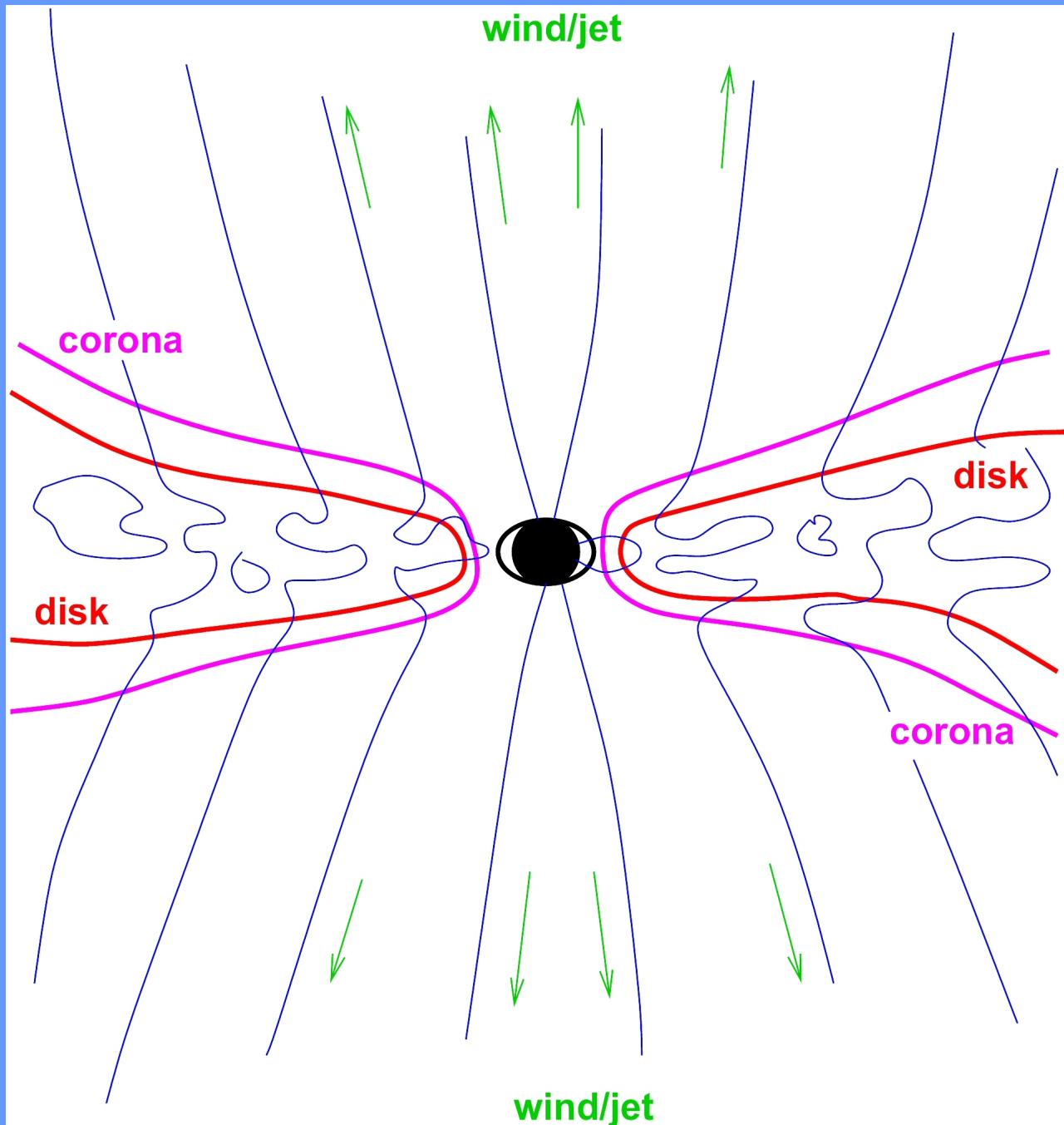
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- Intro. to accretion disks
- HARM
- New improvements to HARM
- Jet simulations
- Application: Sgr A\*
- Relativistic radiative transfer
- Models of Sgr A\* emission

# Astrophysical Disks

Disk Type	Gravity Model
Galaxies, Stellar Disks, Planetary Disks	Newtonian
X-ray binaries, AGN	Stationary metric
Collapsars, SN fall-back disks	Full GR

- MRI explains ang. mom. transfer whenever the disk is ionized!



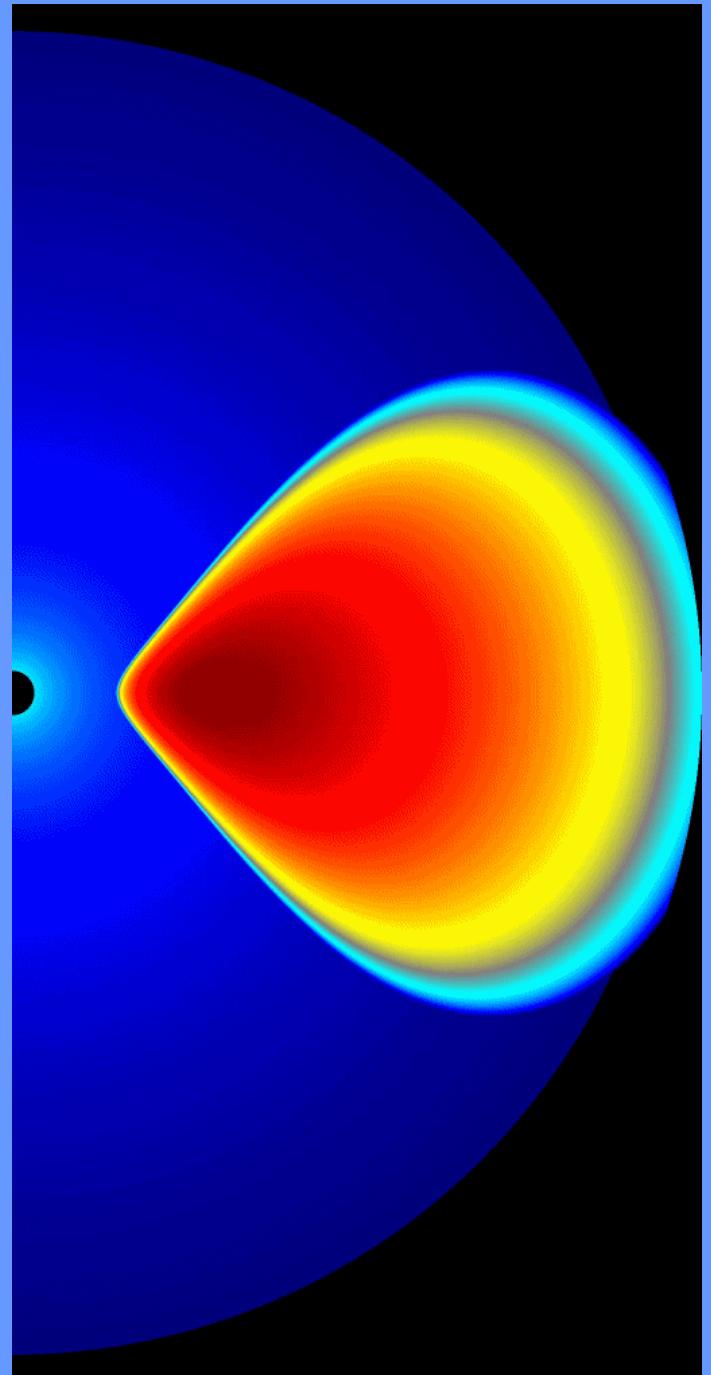
# HARM (Gammie, McKinney, Toth 2003)

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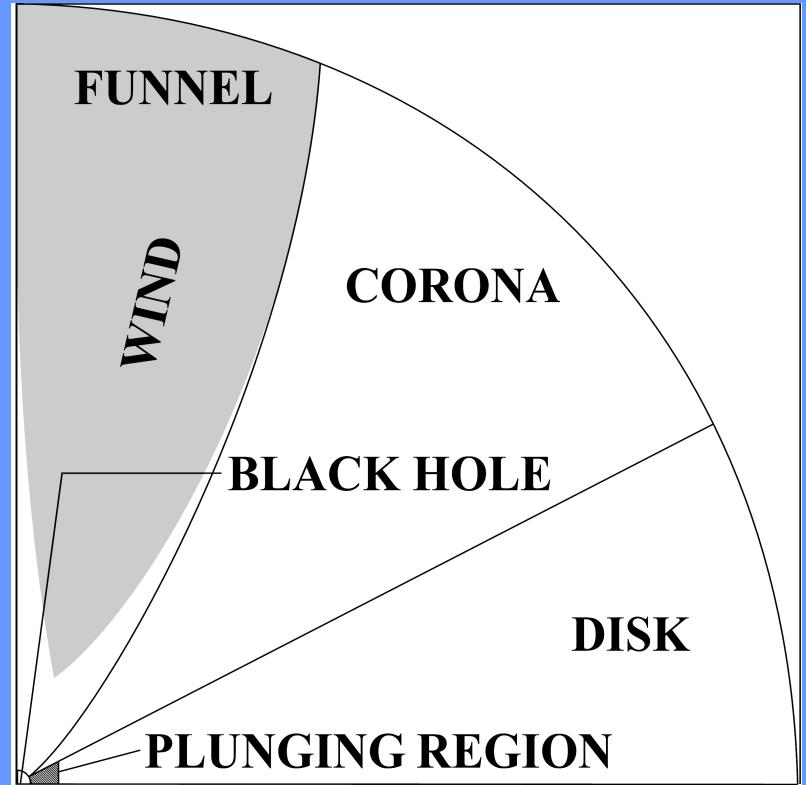
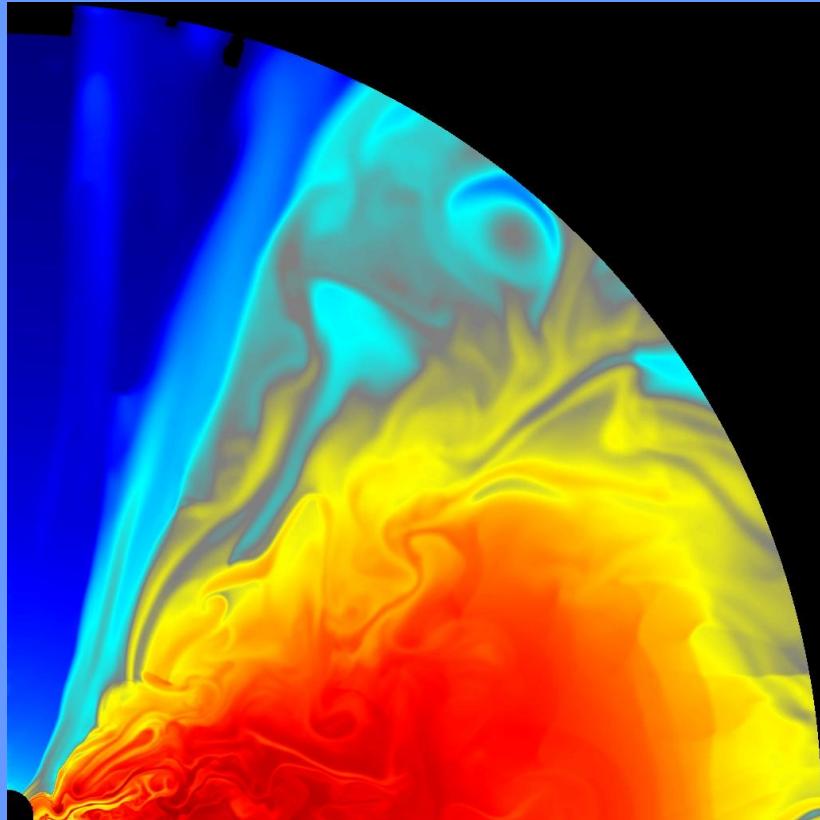
- Axi-sym. grMHD on Kerr-Schild
- HLL flux or Kurganov-Tadmor (LF-like) flux
- MC, minmod slope limiters
- Constrained Transport: flux-CT (Toth 2000)
- “5D” or full inversion for primitive variables
- Simple MPI domain decomposition
- Specialized coordinates focus cells near equator

- Fishbone-Moncrief Torus
- Poloidal Init. B-Field follows density contours,  
 $P_{\text{gas}} / P_{\text{mag}} = 100$
- $a = 0.9375$
- $R_{\text{max}} = 40 \text{ M}$
- $1024 \times 1024$  cells

$\rho$



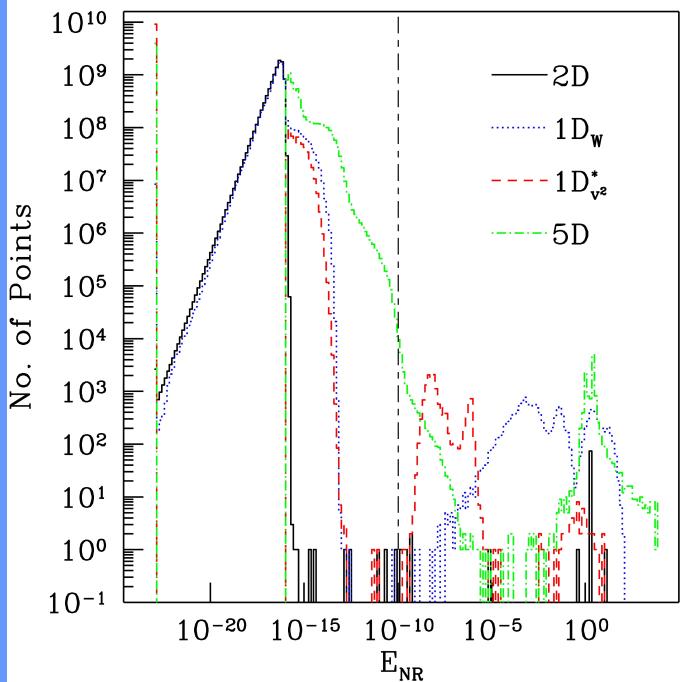
# Disk Morphology



McKinney & Gammie (2004)  
Hawley, De Villiers, Krolik, Hirose 2003+

# Primitive Variable Inversion

Noble, Gammie, McKinney,  
Del Zanna *ApJ* **641** 626  
(2006)



$$Q_\mu = -n_\nu T^\nu{}_\mu \quad \tilde{Q}_\mu = (g_{\mu\nu} + u_\mu u_\nu) Q^\nu$$

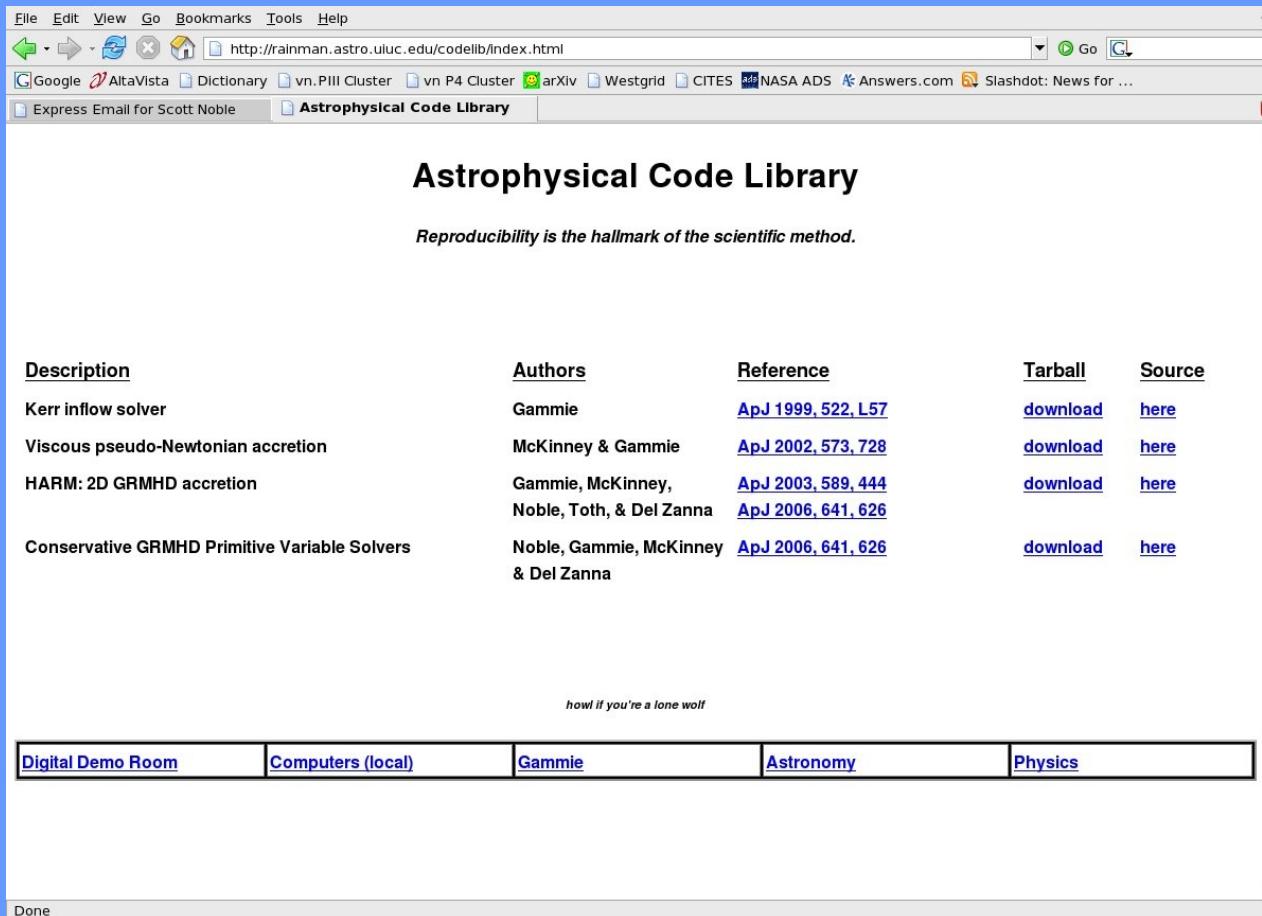
$$\tilde{Q}^2 = v^2 (B^2 + W)^2 - \frac{(Q \cdot B)^2 (B^2 + 2W)}{W^2}$$

$$\tilde{Q}^2 = v^2 (B^2 + W)^2 - \frac{(Q \cdot B)^2 (B^2 + 2W)}{W^2}$$

Table 6. Accretion Disk Efficiency Comparison

Method	NR steps per sol.	Zone-cycles/node/sec. <sup>a</sup>	Failure Rate
2D	4.19	24535	$9.57 \times 10^{-5}$
$1D_W$	4.18	23860	$9.33 \times 10^{-5}$
$1D_{v^2}^*$	5.22	20585	$9.46 \times 10^{-5}$
5D	4.52	14741	$9.22 \times 10^{-5}$

# Download the code!



A screenshot of a web browser window displaying the "Astrophysical Code Library" page. The browser's address bar shows the URL: <http://rainman.astro.uiuc.edu/codelib/index.html>. The page title is "Astrophysical Code Library". Below the title is a quote: "Reproducibility is the hallmark of the scientific method." A table lists five entries, each with a description, authors, reference, tarball download link, and source link. At the bottom of the page is a footer with navigation links and a "Done" button.

Description	Authors	Reference	Tarball	Source
Kerr inflow solver	Gammie	<a href="#">ApJ 1999, 522, L57</a>	<a href="#">download</a>	<a href="#">here</a>
Viscous pseudo-Newtonian accretion	McKinney & Gammie	<a href="#">ApJ 2002, 573, 728</a>	<a href="#">download</a>	<a href="#">here</a>
HARM: 2D GRMHD accretion	Gammie, McKinney, Noble, Toth, & Del Zanna	<a href="#">ApJ 2003, 589, 444</a> <a href="#">ApJ 2006, 641, 626</a>	<a href="#">download</a>	<a href="#">here</a>
Conservative GRMHD Primitive Variable Solvers	Noble, Gammie, McKinney & Del Zanna	<a href="#">ApJ 2006, 641, 626</a>	<a href="#">download</a>	<a href="#">here</a>

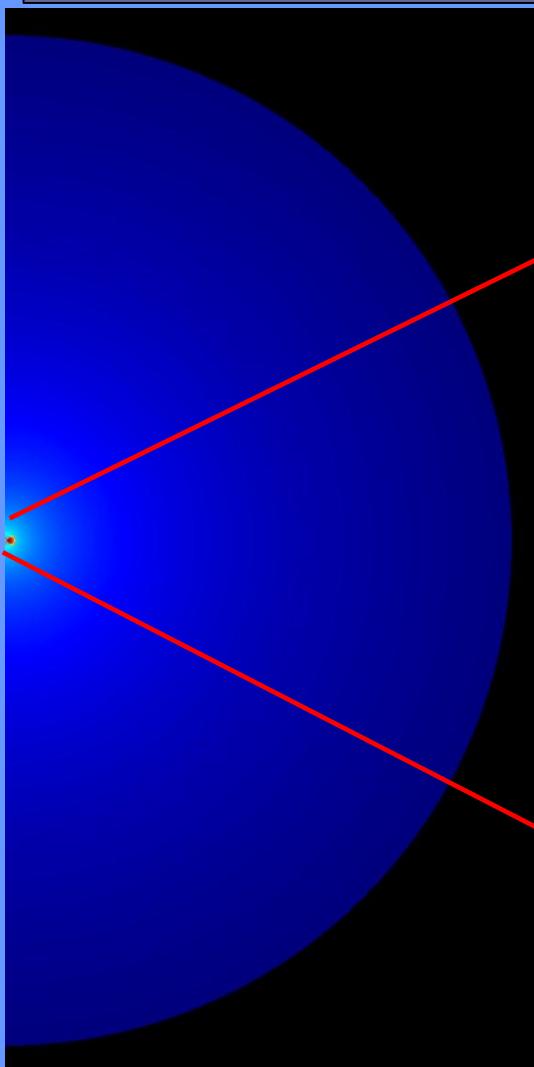
*howl if you're a lone wolf*

Digital Demo Room   Computers (local)   Gammie   Astronomy   Physics

Done

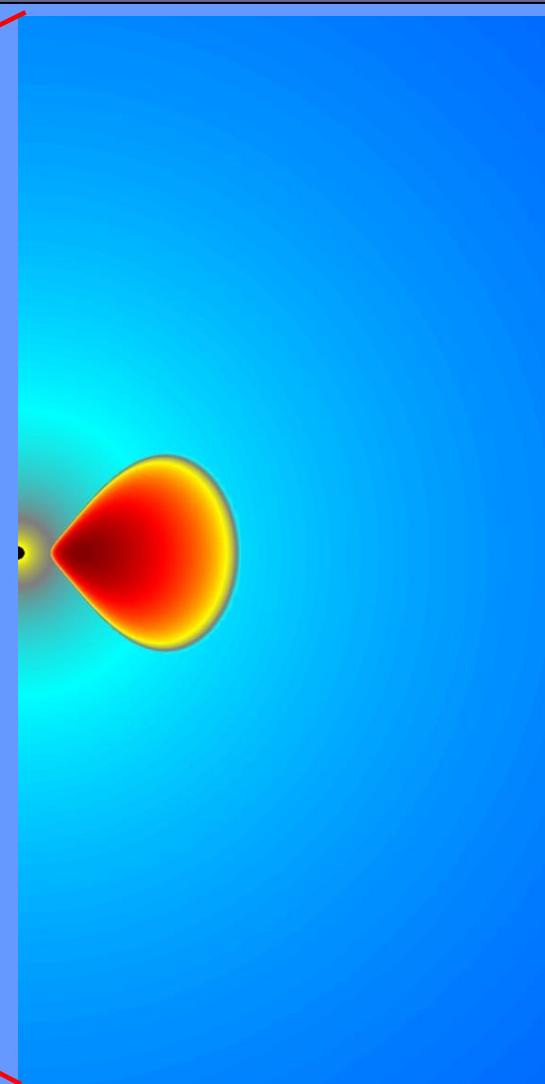
<http://rainman.astro.uiuc.edu/codelib/>

# Outflows

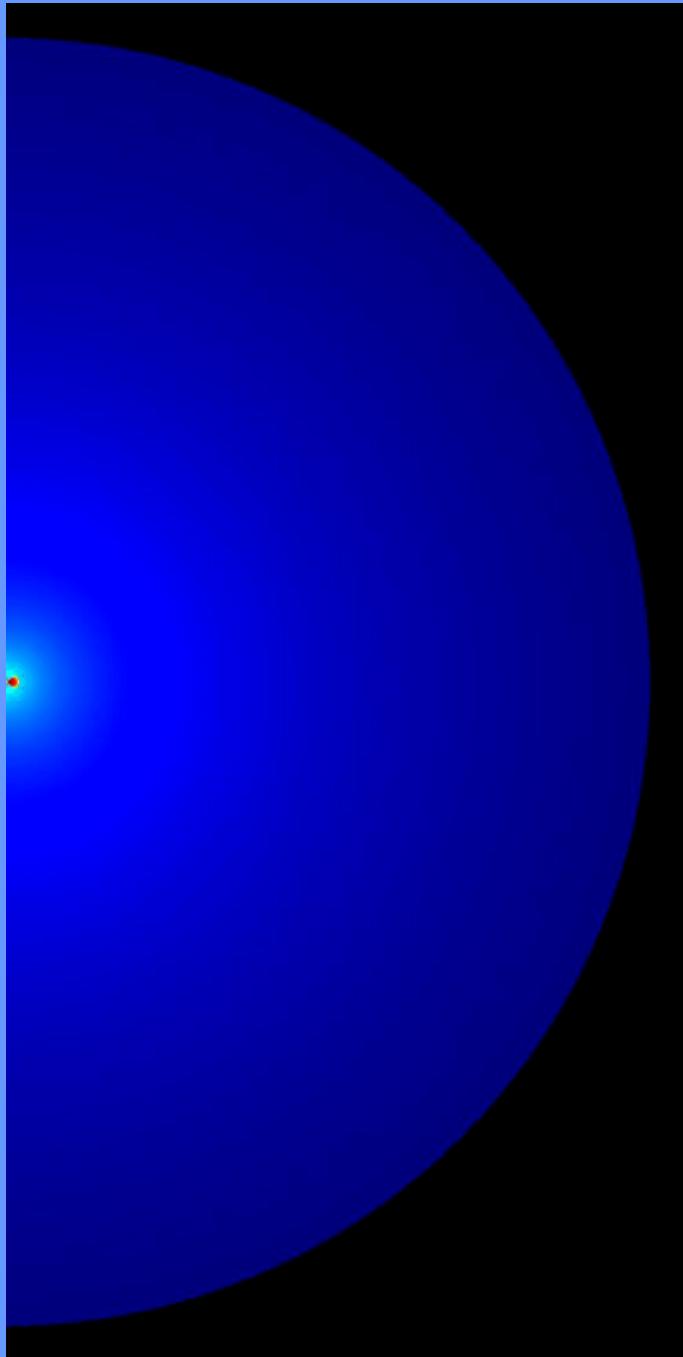


2100M

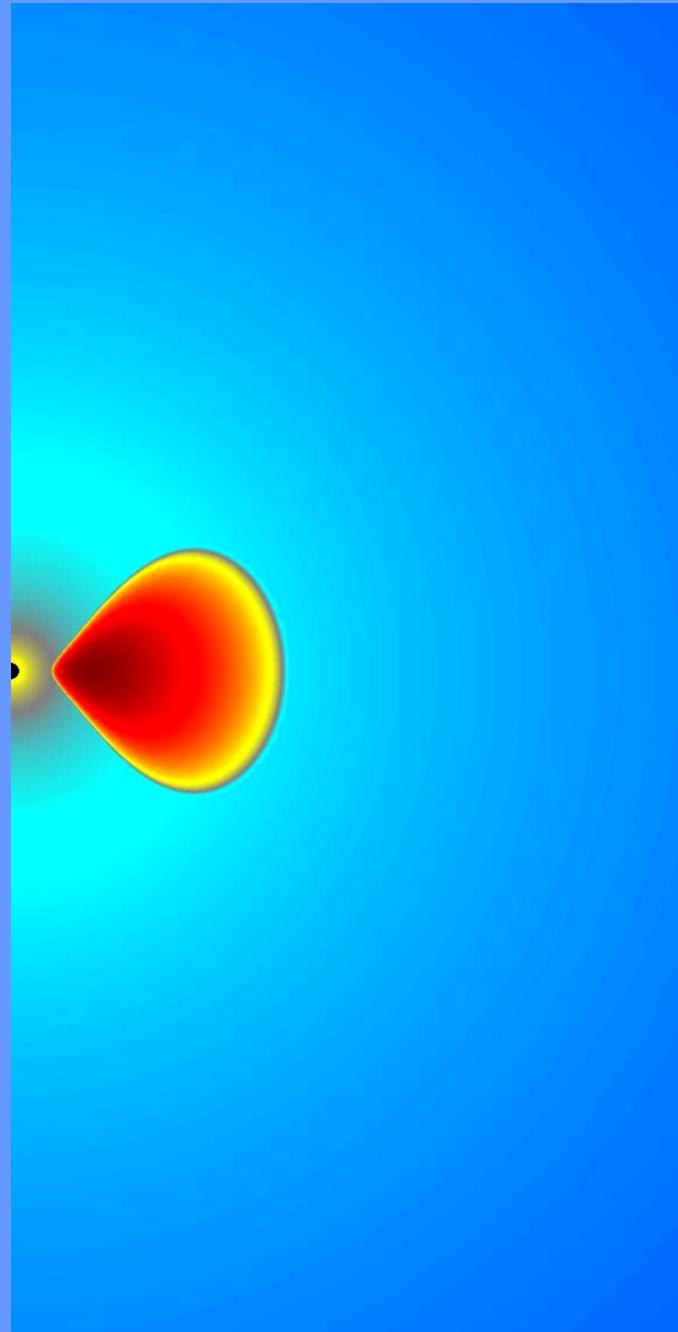
Pressure  
568x256



100M

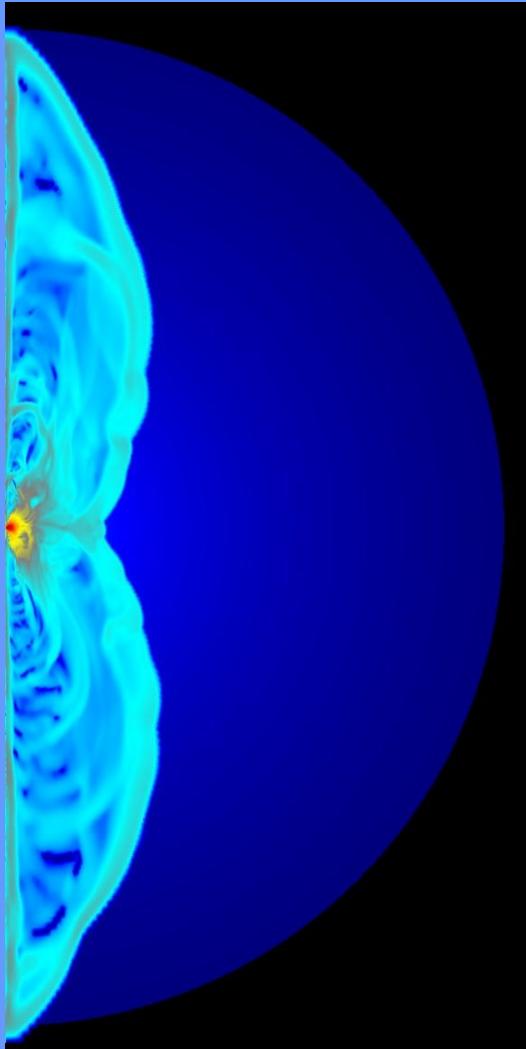


Pressure  
568x256



# Outflows

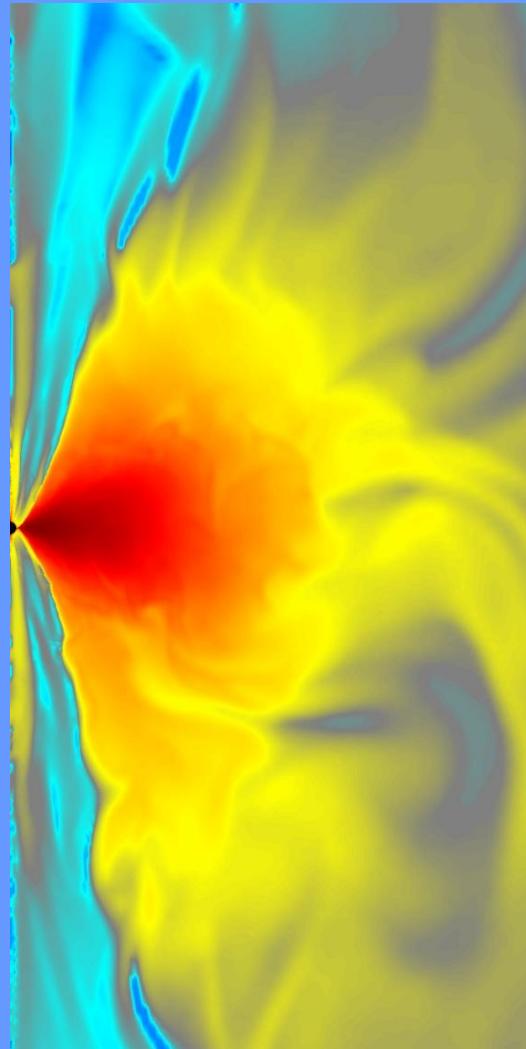
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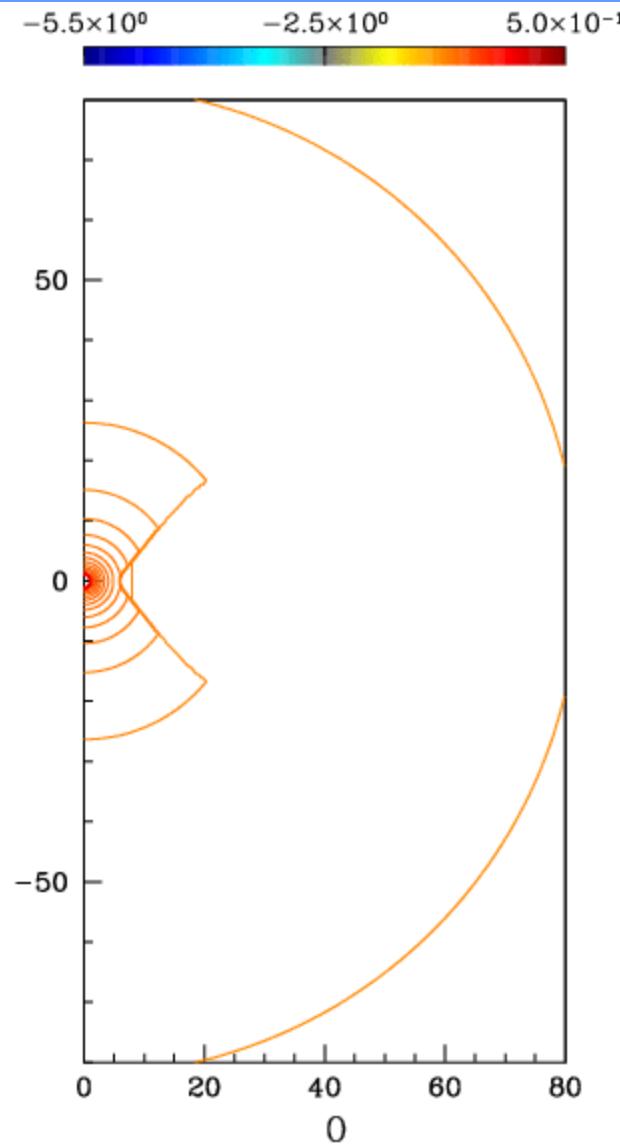
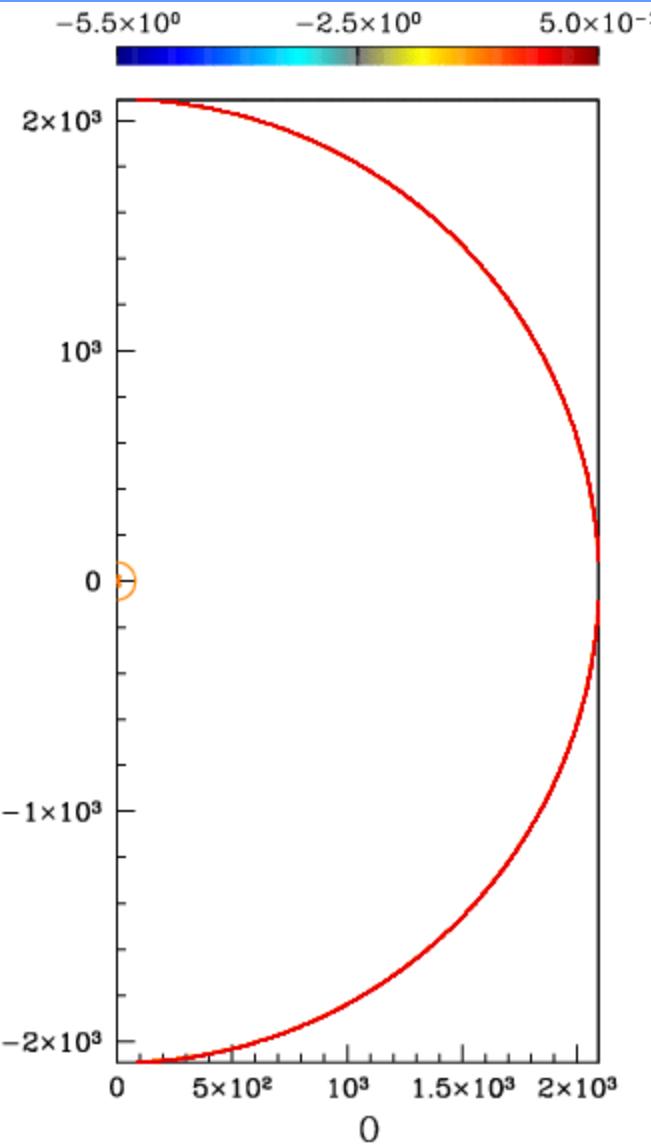
Pressure

568x256

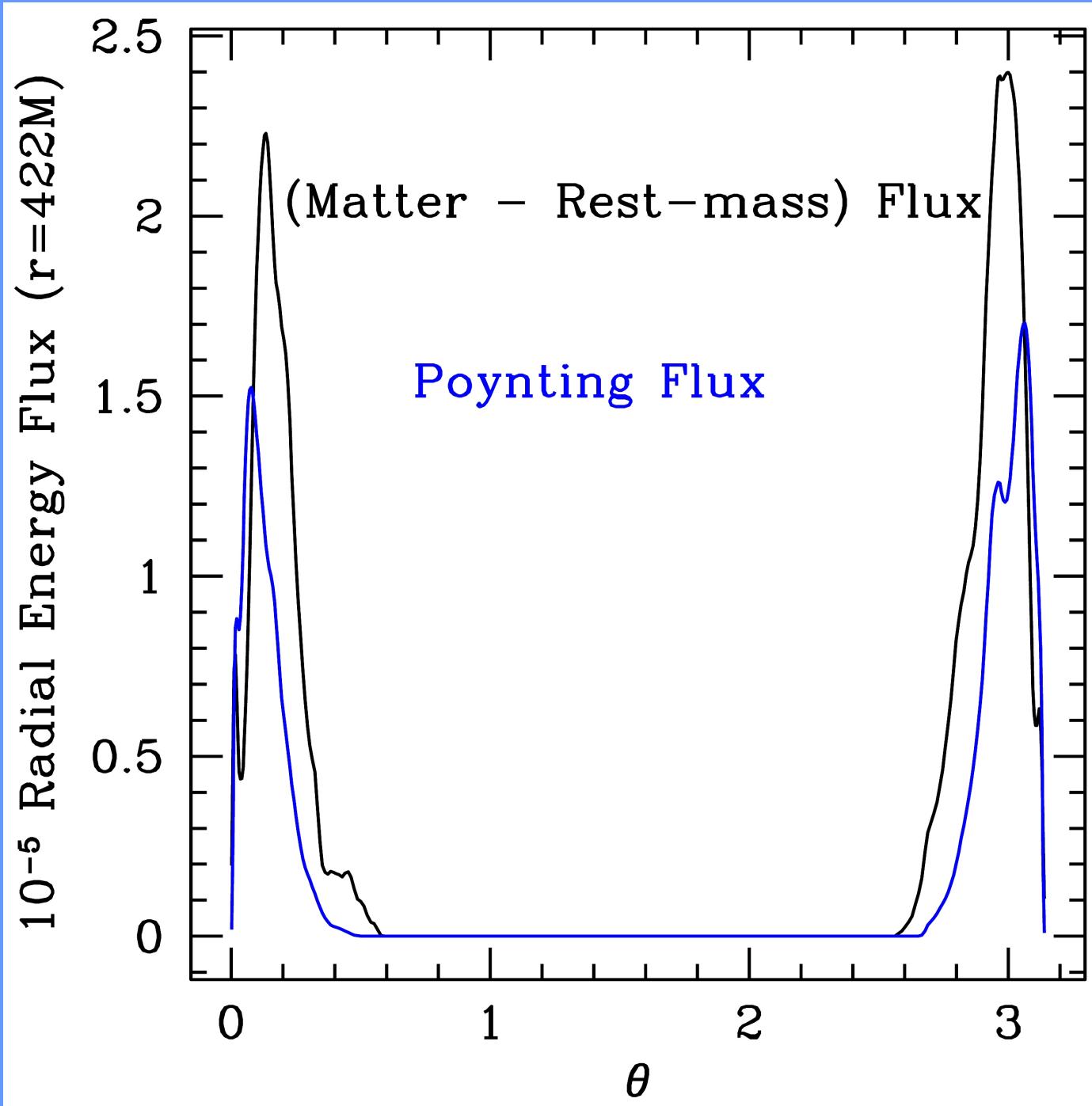
t=2900M



# Relativistic Bernoulli Parameter: $h u_t$



$t=1100M$



# Jet Properties

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- Relativistic:  $\Gamma \sim 3 - 10$
- Similar Hydro. & EM radial fluxes at large  $r$
- Collimation from centrifugal wind and toroidal fields
- Generic problem with jet simulations:

**floor dependent!!**  $\rho_{flr} = 10^{-4} \rho_{max} r^{-2}$        $u_{flr} = 0.01 \rho_{flr} r^{-1}$

- Consistent with:
  - McKinney 2006
  - Krolik & Hawley 2006

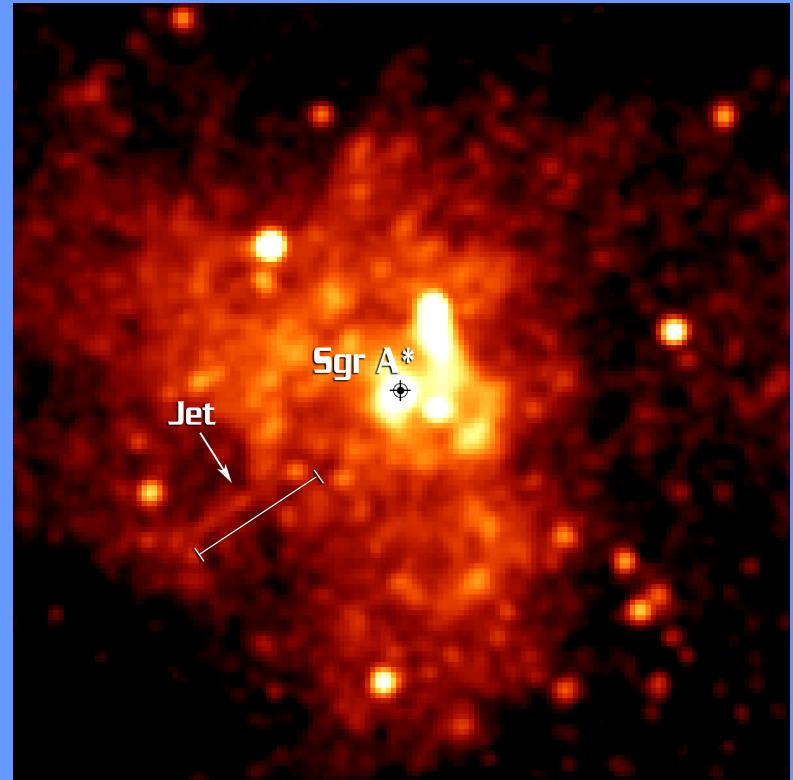
# Why Sgr A\* ?

- Closest supermassive black hole
  - Genzel et al. 2003
  - Ghez et al. 2005

$$M_{SgrA} = 3.76 \times 10^6 M_{sun}$$

$$d \sim 8\text{kpc} \quad 1 \text{arcsecond} = 10^5 R_s$$

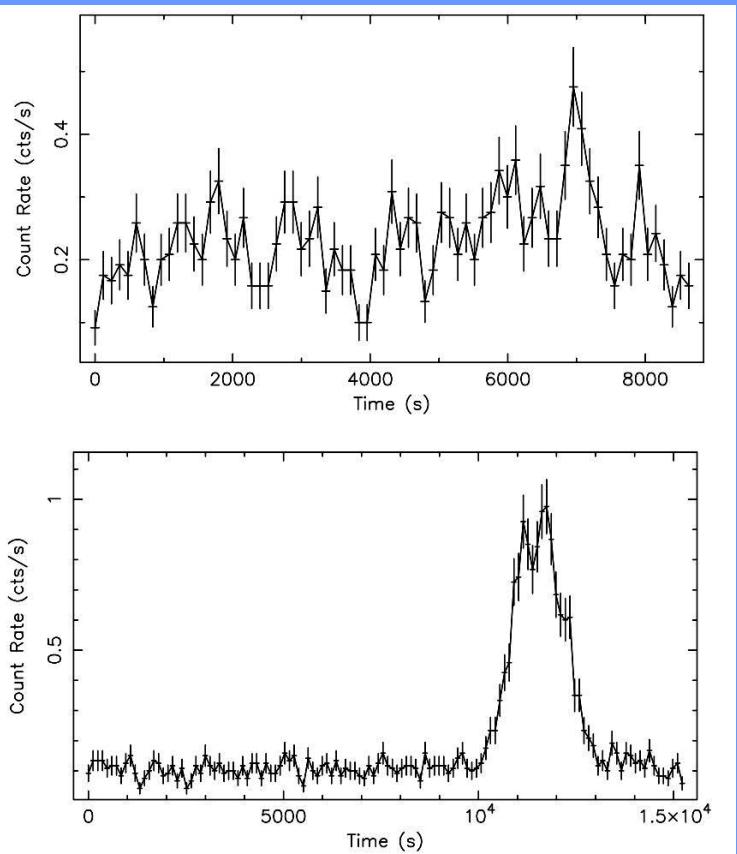
- Best chance at observing shadow cast by an event horizon
- Fits well with our simulations (opt. thin)



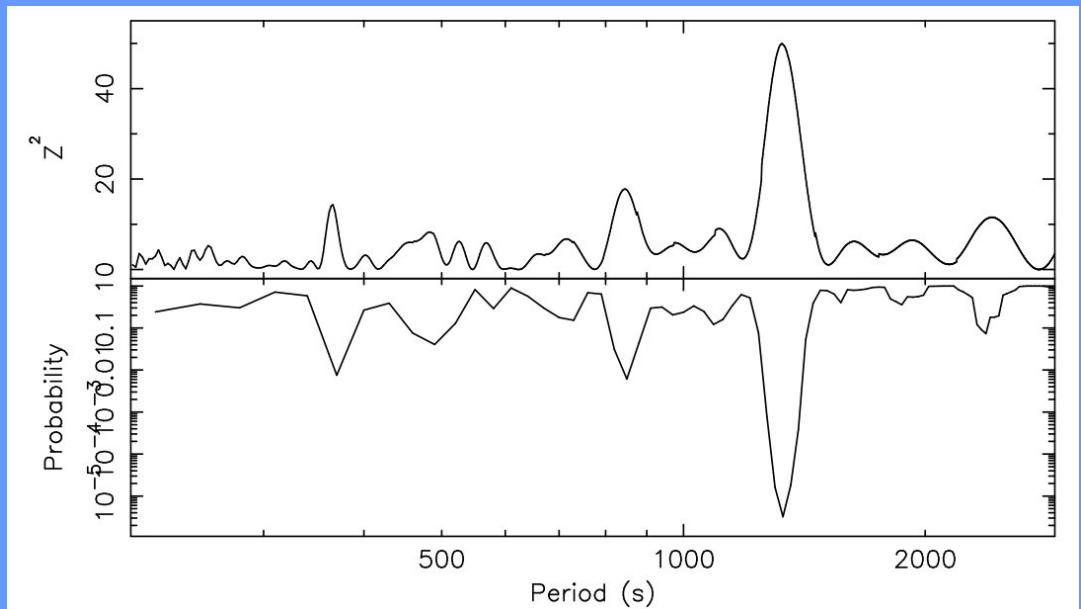
NASA/CXC/MIT Baganoff et al.  
1.23 arcmin per side

# Sgr A\*'s Spin

Belanger et al. 2006



- 22min periodicity (X-ray)
- 1 in 3 million chance of being random
- $\rightarrow a > 0.22$



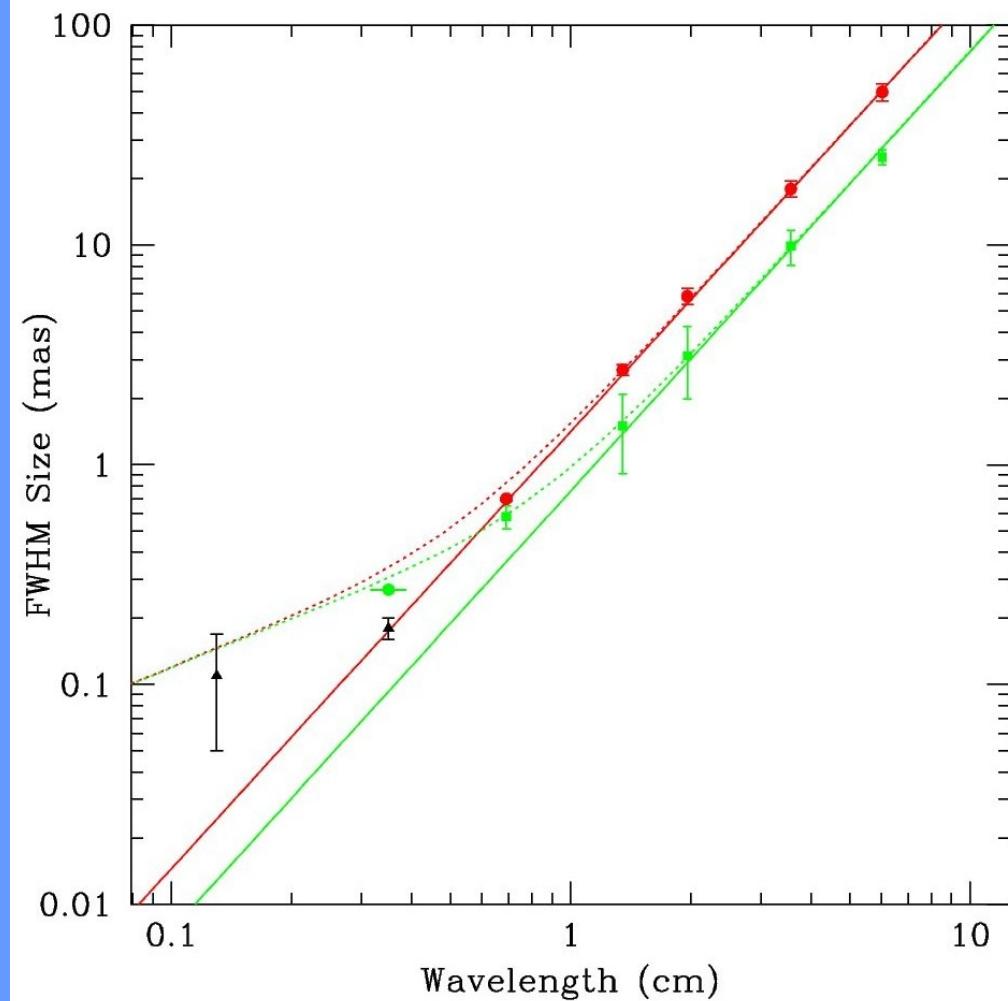
# Sgr A\* in the Radio

Shen et al. **Nature** (2005)

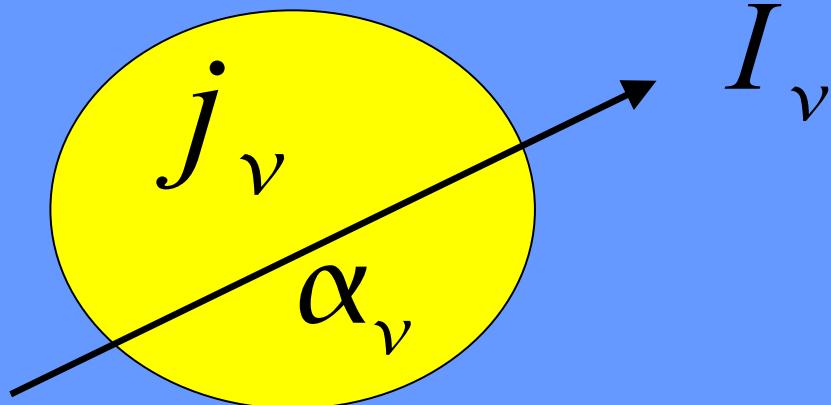
$< 25 \text{ M} \sim 2 \text{ AU}$

- Shrinking with increasing frequency
- Power also increases with frequency to  $\sim 1\text{mm}$
- Suggests disk may be becoming optically thin with freq.
- At limit of VLBI radio, working on mm VLBI

**Want to predict what they'll see!**



# Relativistic Radiative Transfer



$$j = j_\nu / \nu^2 \quad \frac{d I_\nu}{d s} = j_\nu - \alpha_\nu I_\nu$$

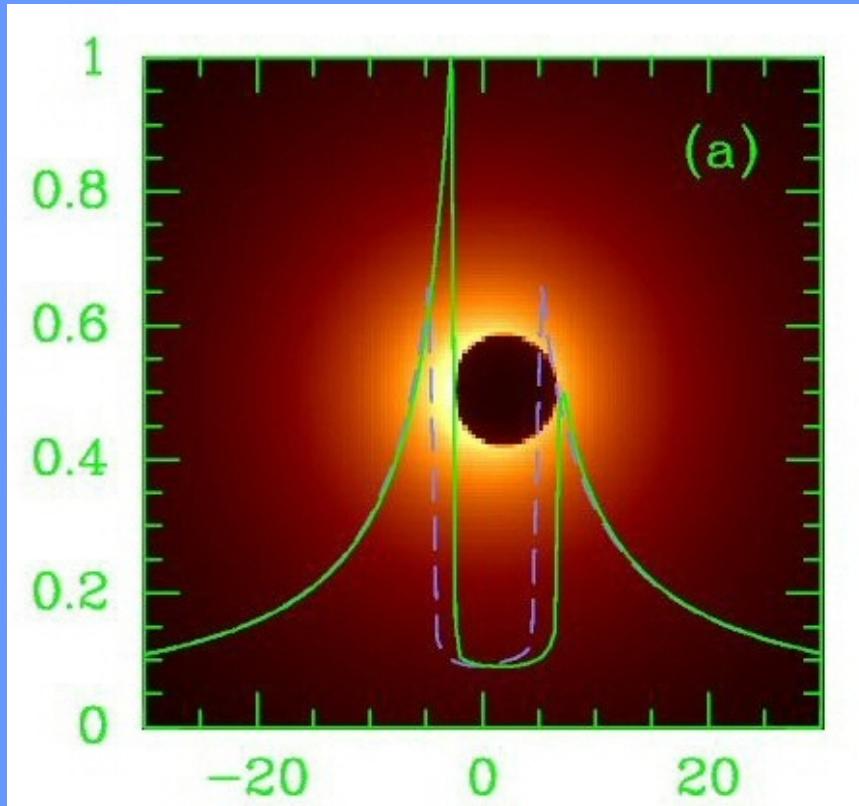
$$\alpha = \alpha_\nu$$

$$I = I_\nu / \nu^3$$

$$\frac{d I}{d \lambda} = j - \alpha I$$

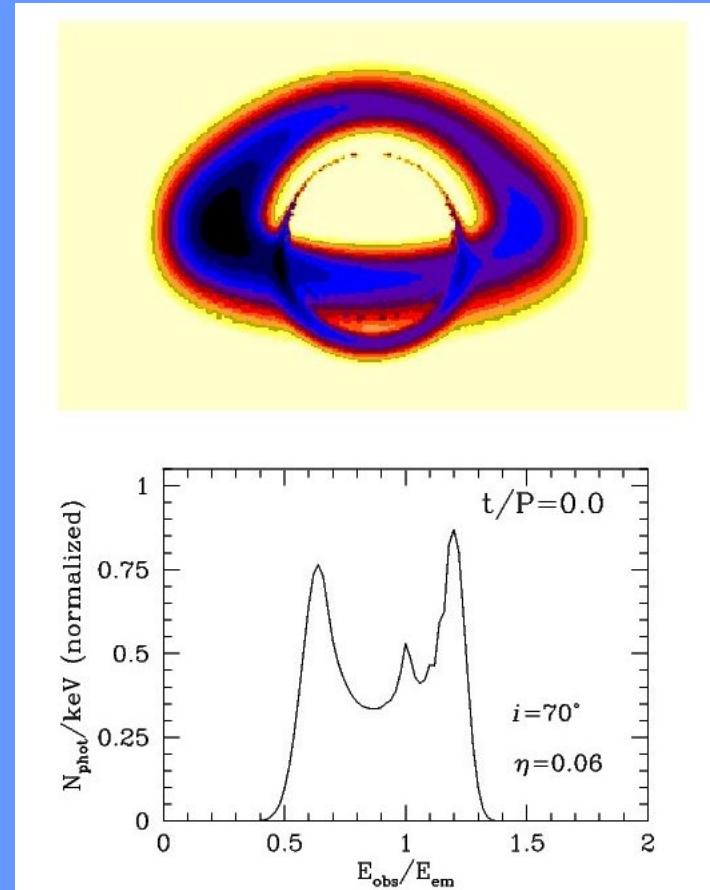
- Integrate geodesics in Kerr-Schild
- Interpolate time-slice of HARM data to geodesic path
- Calculate RT functions and solve RT eq.
- Assume thermal dist. of e<sup>-</sup>'s  
 $T_e = T_p$
- Use Wardzinski & Zdziarski (2000) for synch. emissivity
- Bremsstrahlung, too
- Accretion rate sets energy scale of emission

# Example RT Calculations



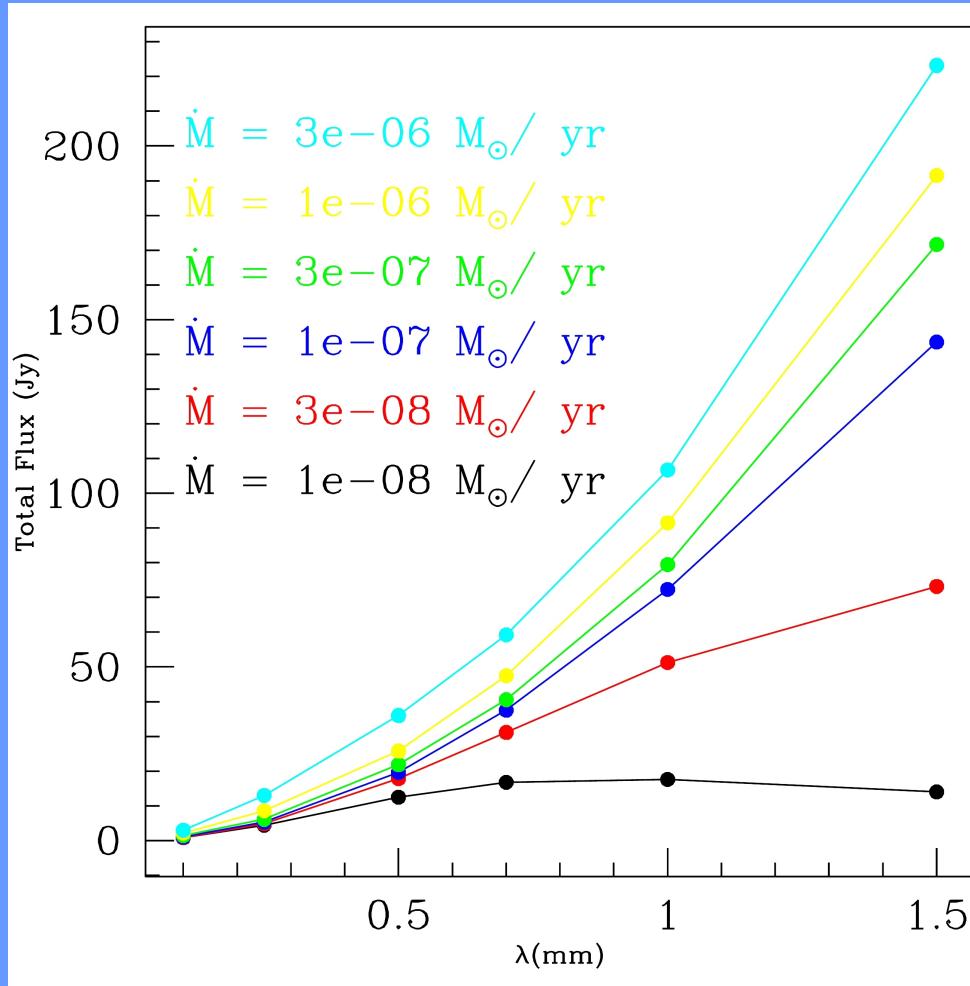
Falcke, Melia, Agol (2000)

-- Also see Kris Beckwith's Poster!!

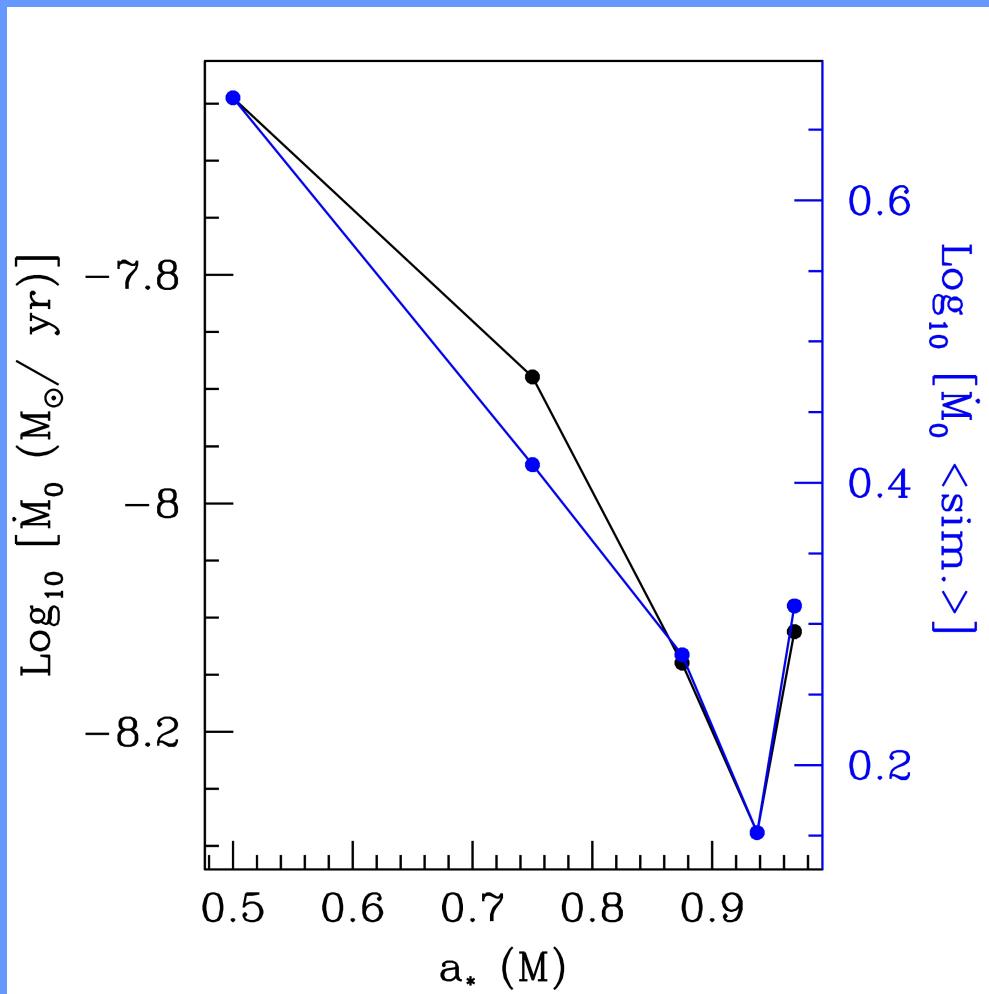


Schnittman & Rezzolla (2005)

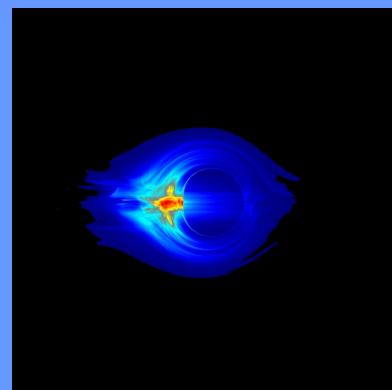
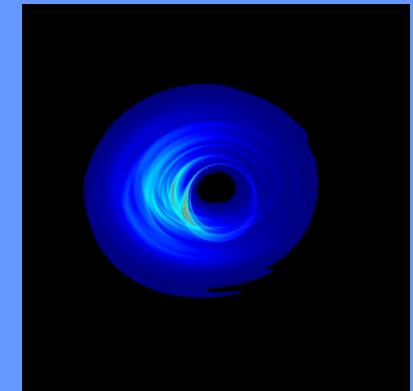
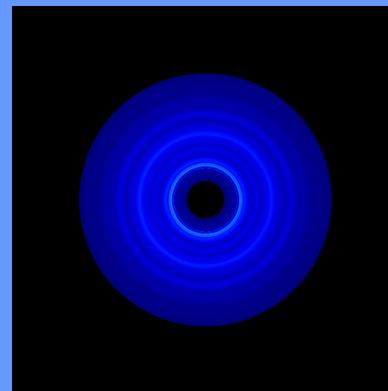
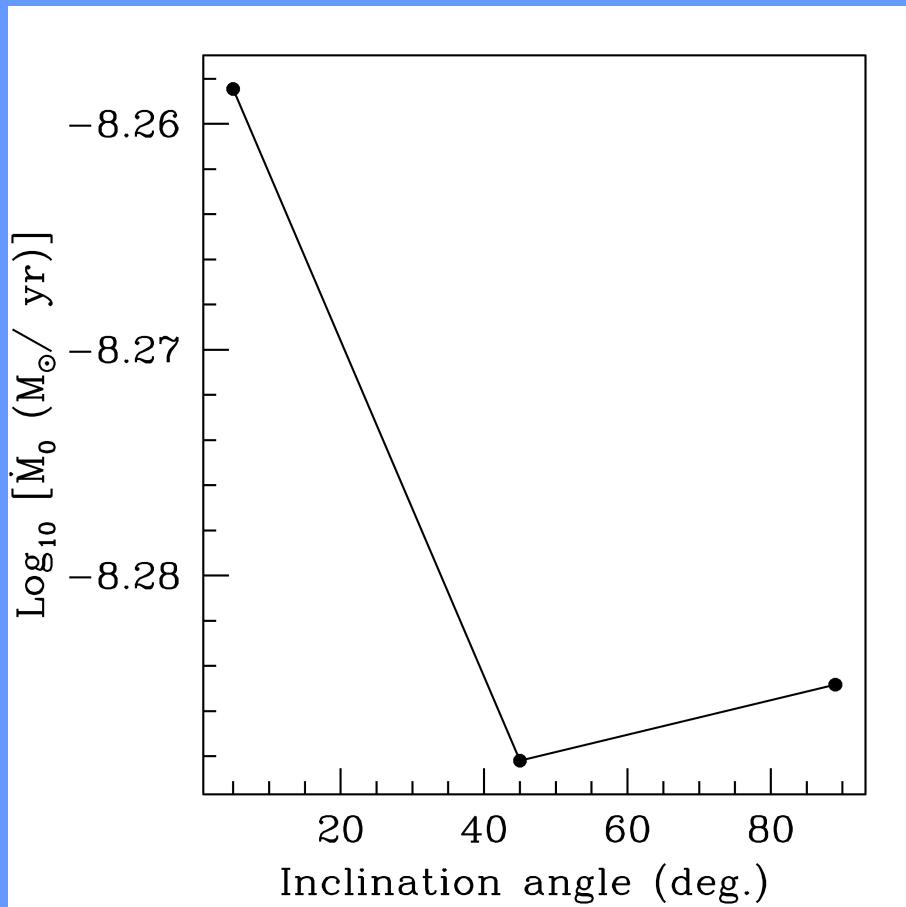
# Accretion Rate Study



# BH Spin Study

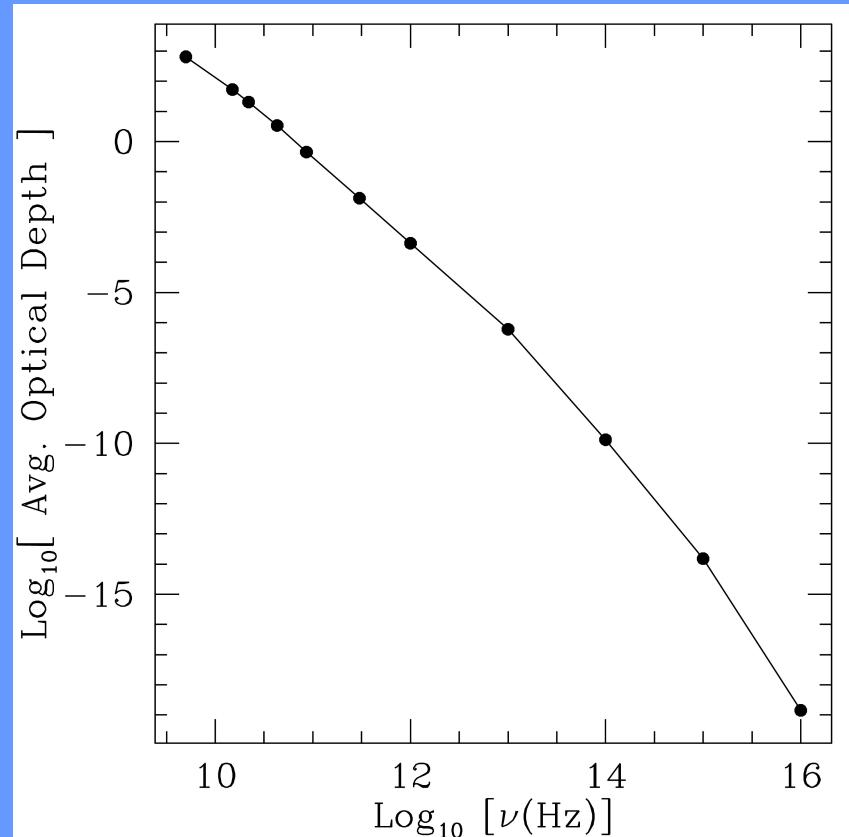
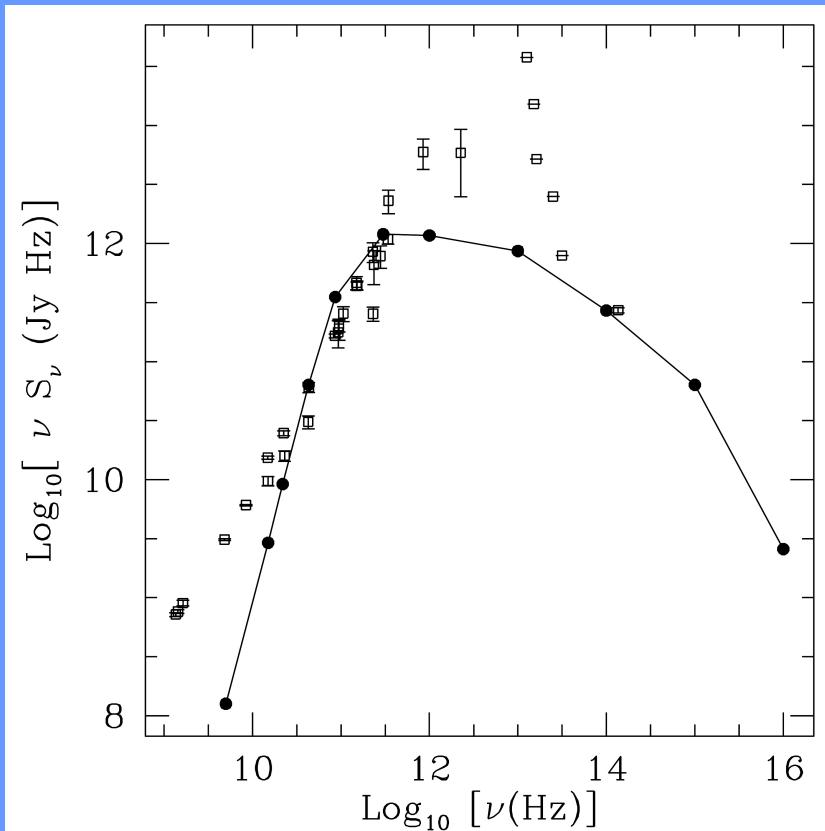


# Camera Inclination Study



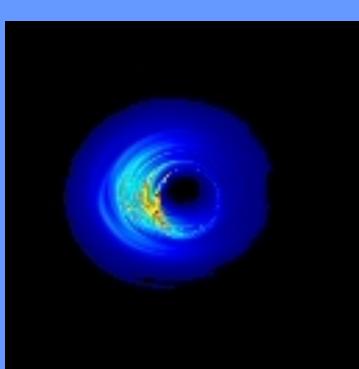
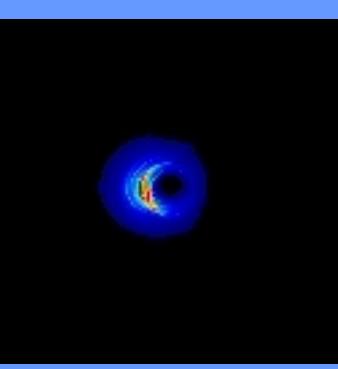
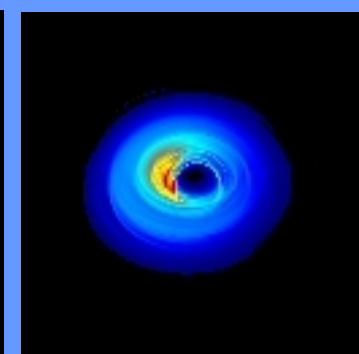
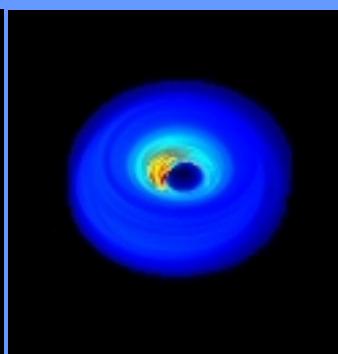
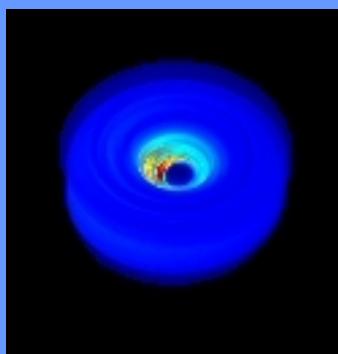
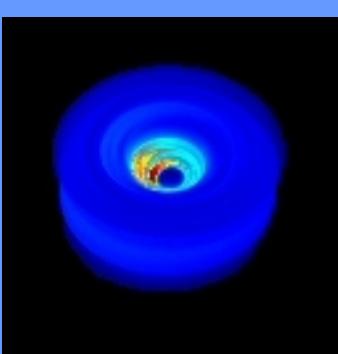
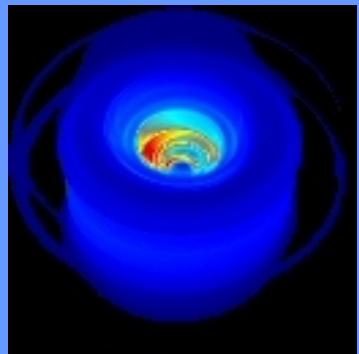
# Spectrum

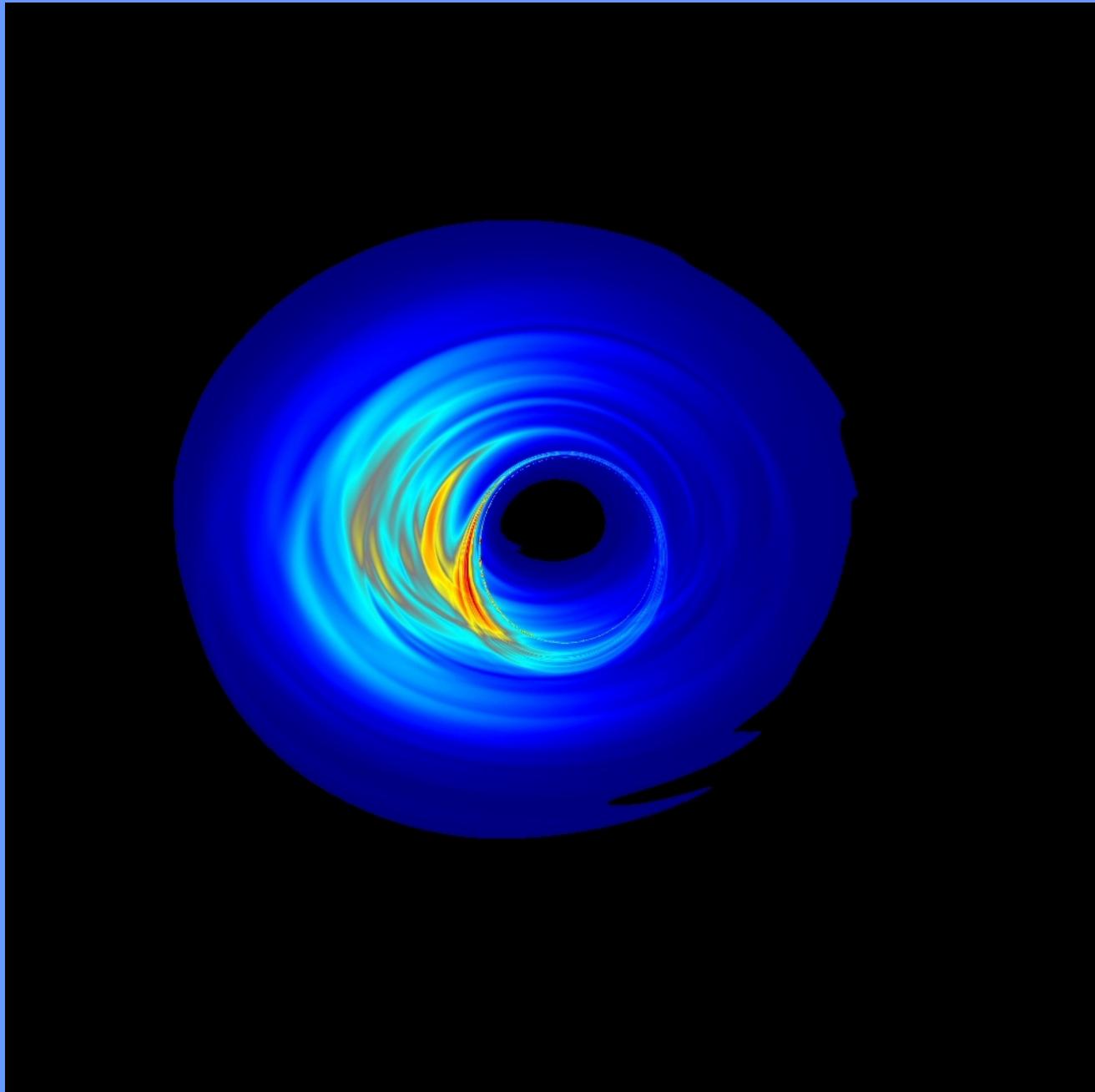
Set Flux at 1mm to 4 Jy to match expected peak emission

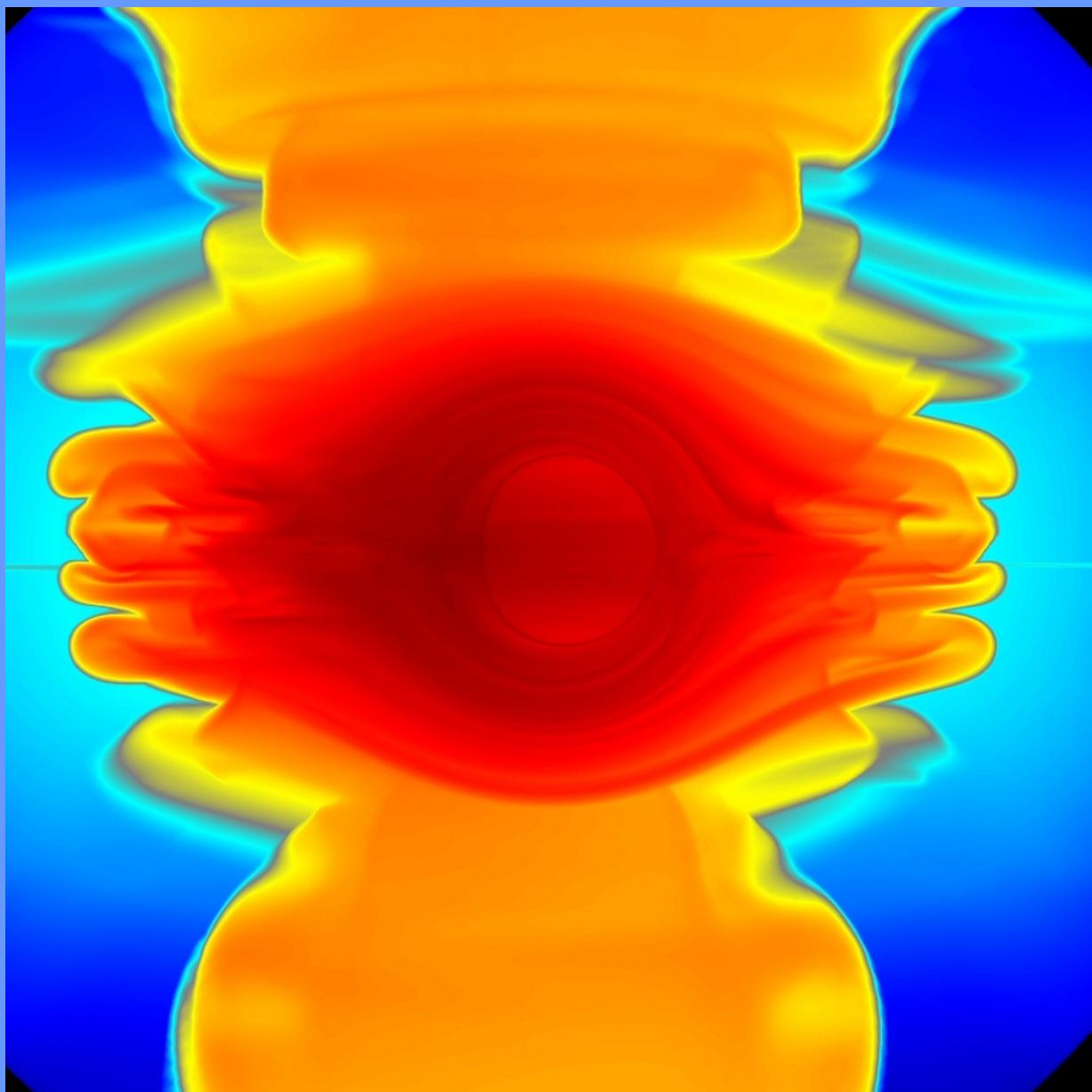


# Angular Size with Frequency

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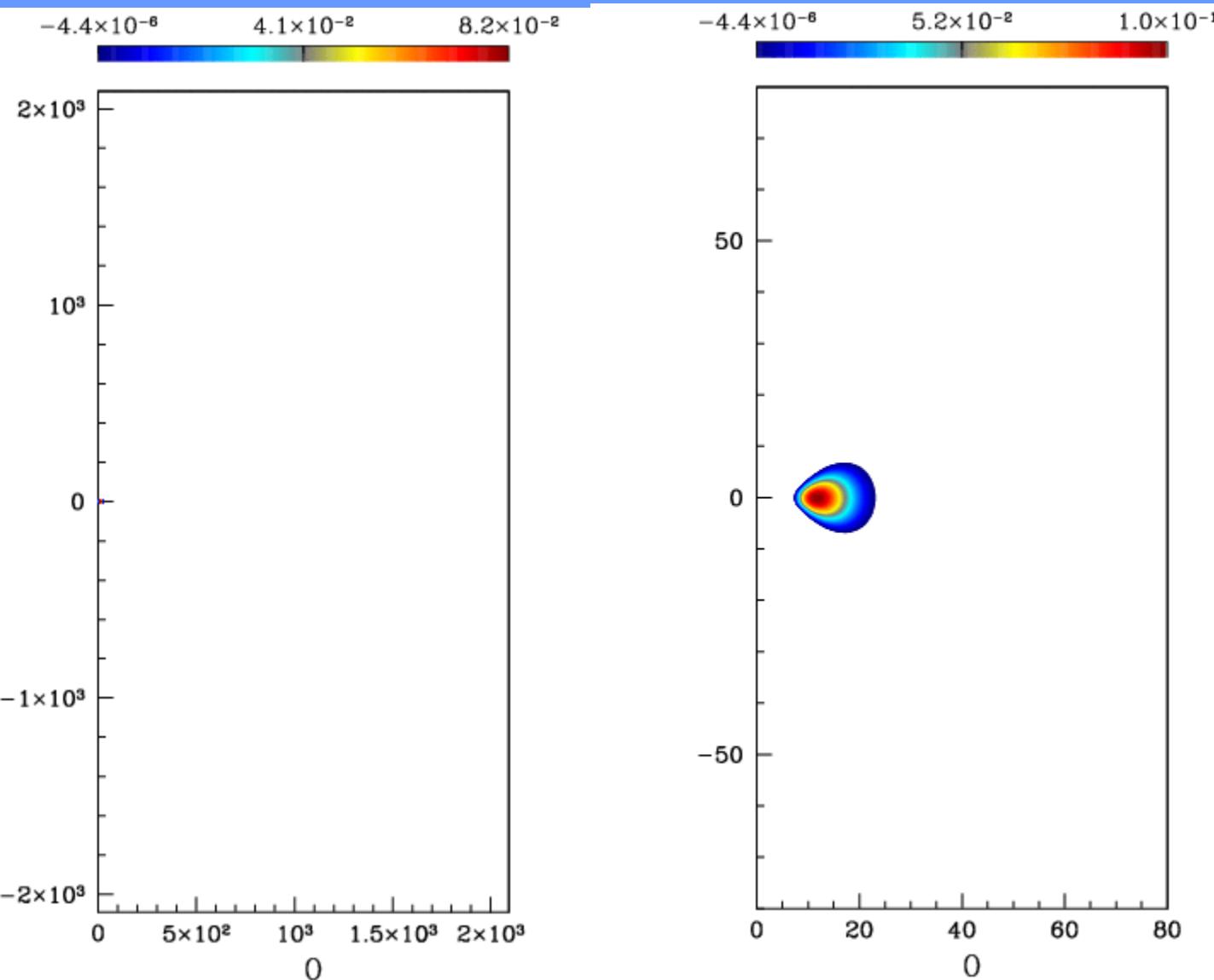






## Extra Slides

# Poloidal Magnetic Field Lines



# Jet through Molasses

$$u_{flr} = 0.01 \rho_{flr}$$

$$\rho_{flr} = 10^{-4}$$

$t = 0 - 4000M$

288x128



# Jet through Molasses

