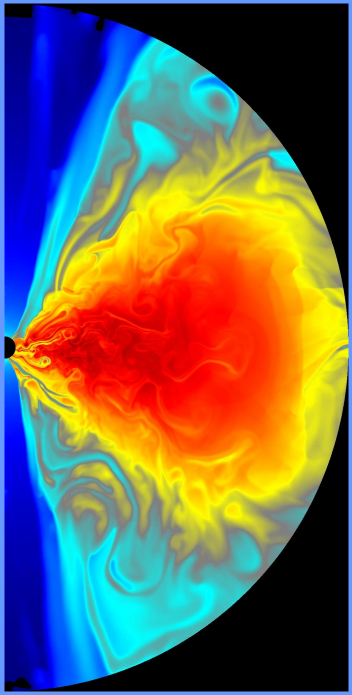
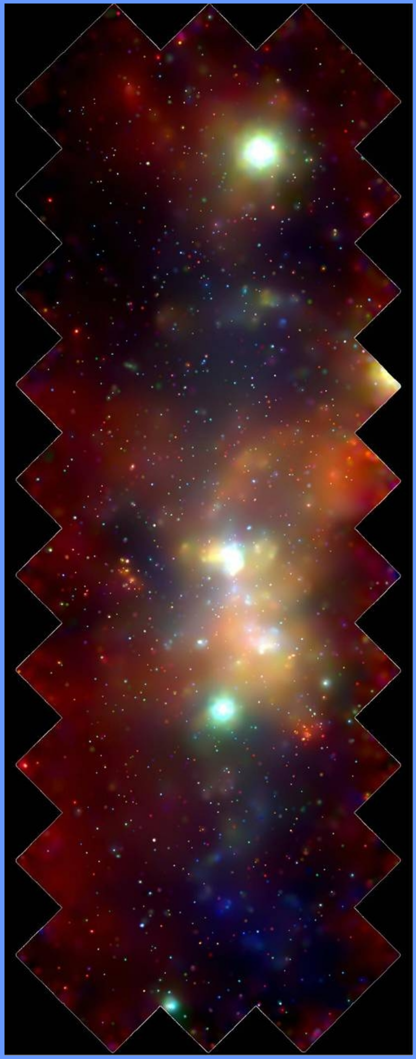
Simulating VLBI Images of Sgr A*



Scott C. Noble

UIUC

UIUC : Charles Gammie,
Po Kin Leung,
Laura Book
CfA : Jon McKinney
Firenze: Luca Del Zanna



MG11, Berlin, July 28, 2006

Outline

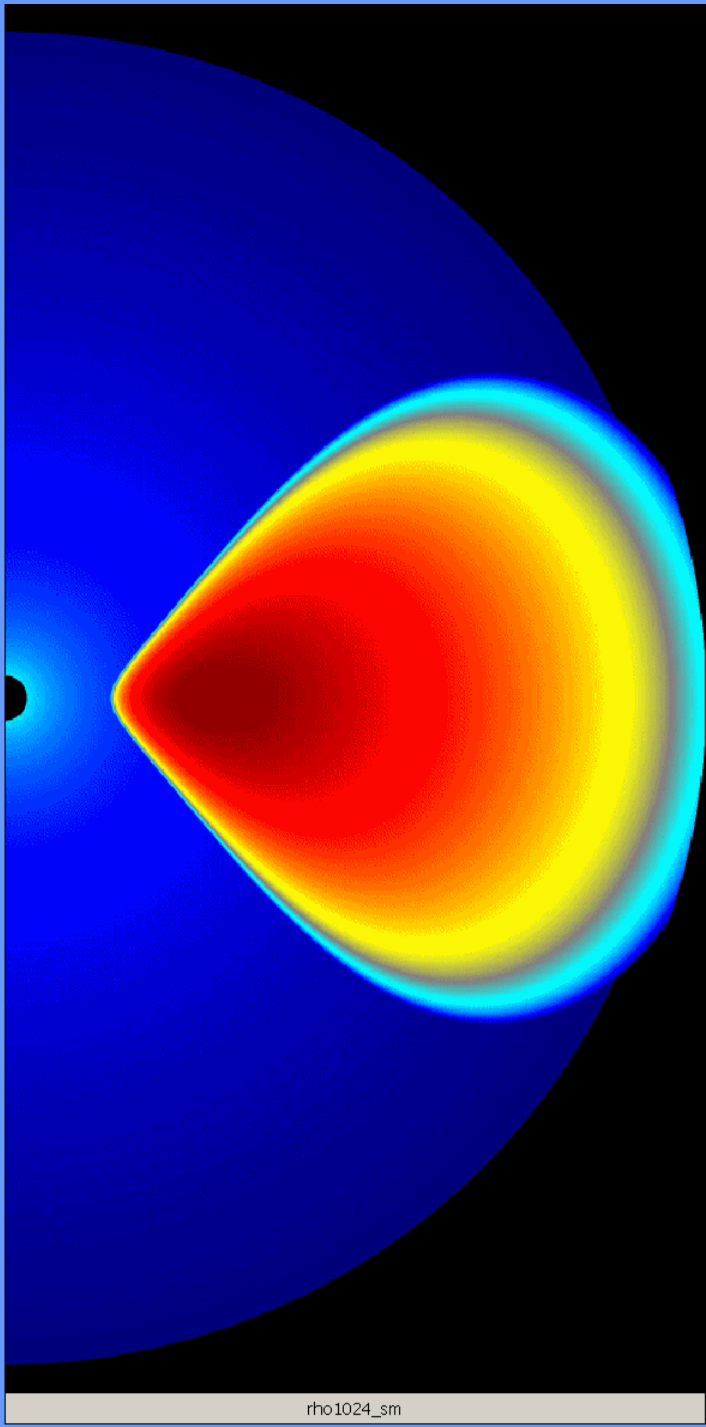
- HARM
- New improvements to HARM
- Jet simulations
- Application: Sgr A*
- Relativistic radiative transfer
- Models of Sgr A* emission

HARM (Gammie, McKinney, Toth 2003)

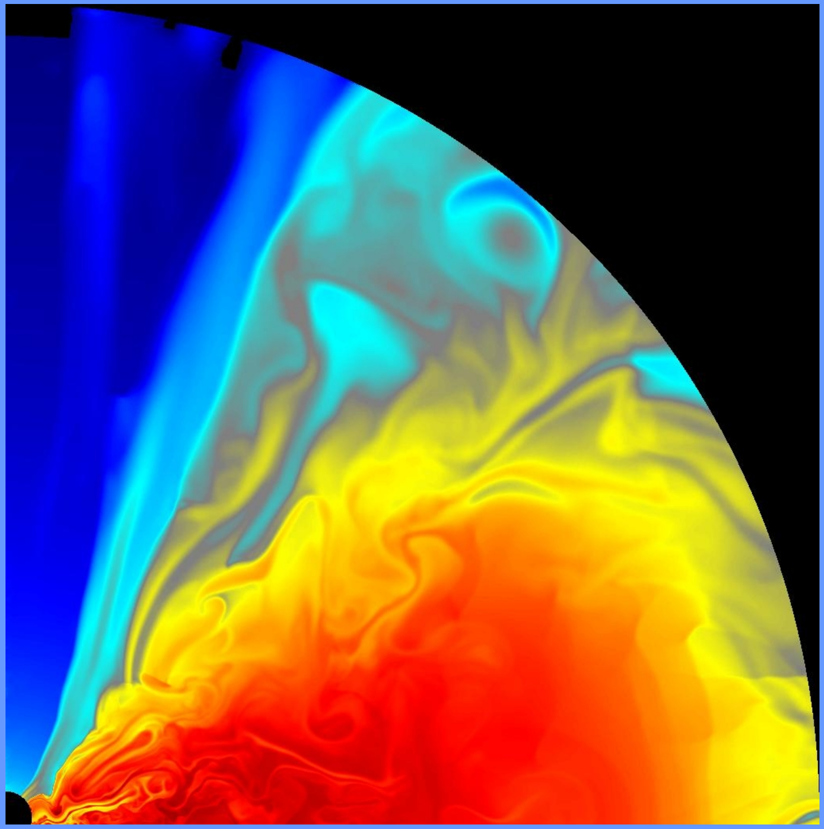
- Axi-sym. grMHD on Kerr-Schild
- HLL flux or Kurganov-Tadmor (LF-like) flux
- MC, minmod slope limiters
- Constrained Transport: flux-CT (Toth 2000)
- “5D” or full inversion for primitive variables
- Simple MPI domain decomposition
- Specialized coordinates focus cells near equator

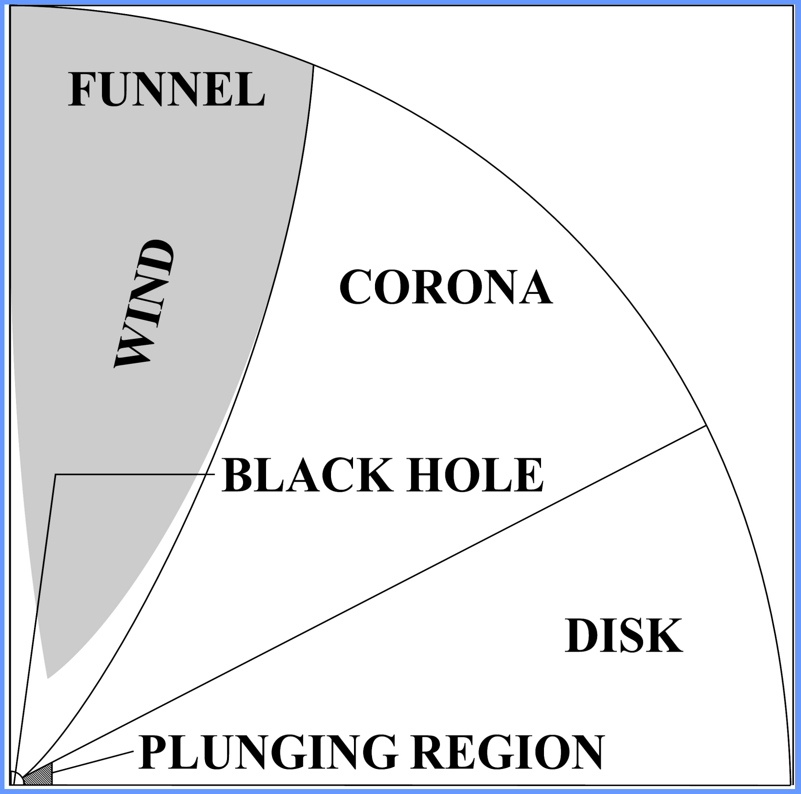
- Fishbone-Moncrief Torus
- Poloidal Init. B-Field follows density contours, Pgas / Pmag = 100
- a = 0.9375
- Rmax = 40 M
- 1024x1024 cells

ρ



Disk Morphology





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

Primitive Variable Inversion

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

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

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

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

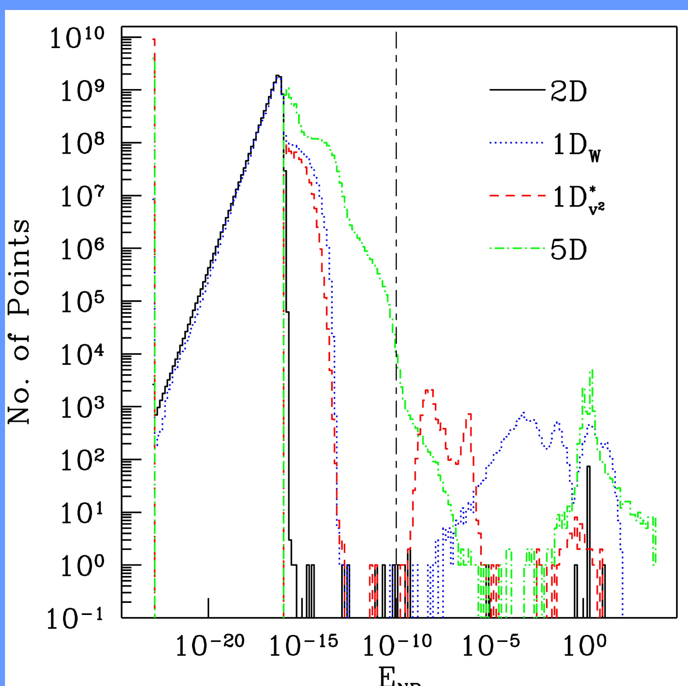
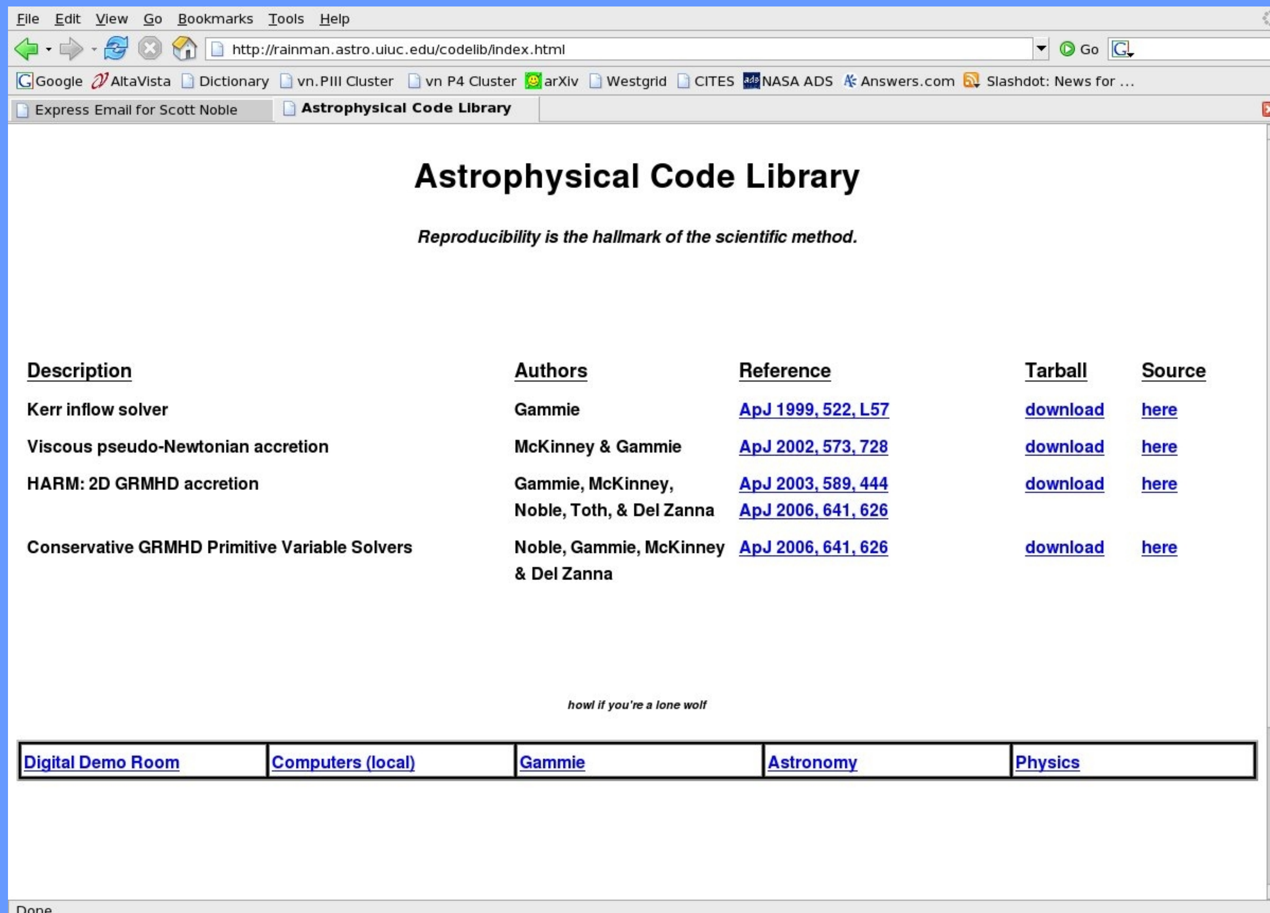


Table 6. Accretion Disk Efficiency Comparison

Method	NR steps per sol.	Zone-cycles/node/sec. [a]	Failure Rate
2D	4.19	24535	9.57×10^{-5}
$1D_W$	4.18	23860	9.33×10^{-5}
$1D^\star_{v^2}$	5.22	20585	9.46×10^{-5}
5D	4.52	14741	9.22×10^{-5}

Download the code!



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http://rainman.astro.uiuc.edu/codelib/index.html

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Express Email for Scott Noble | Astrophysical Code Library

Astrophysical Code Library

Reproducibility is the hallmark of the scientific method.

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

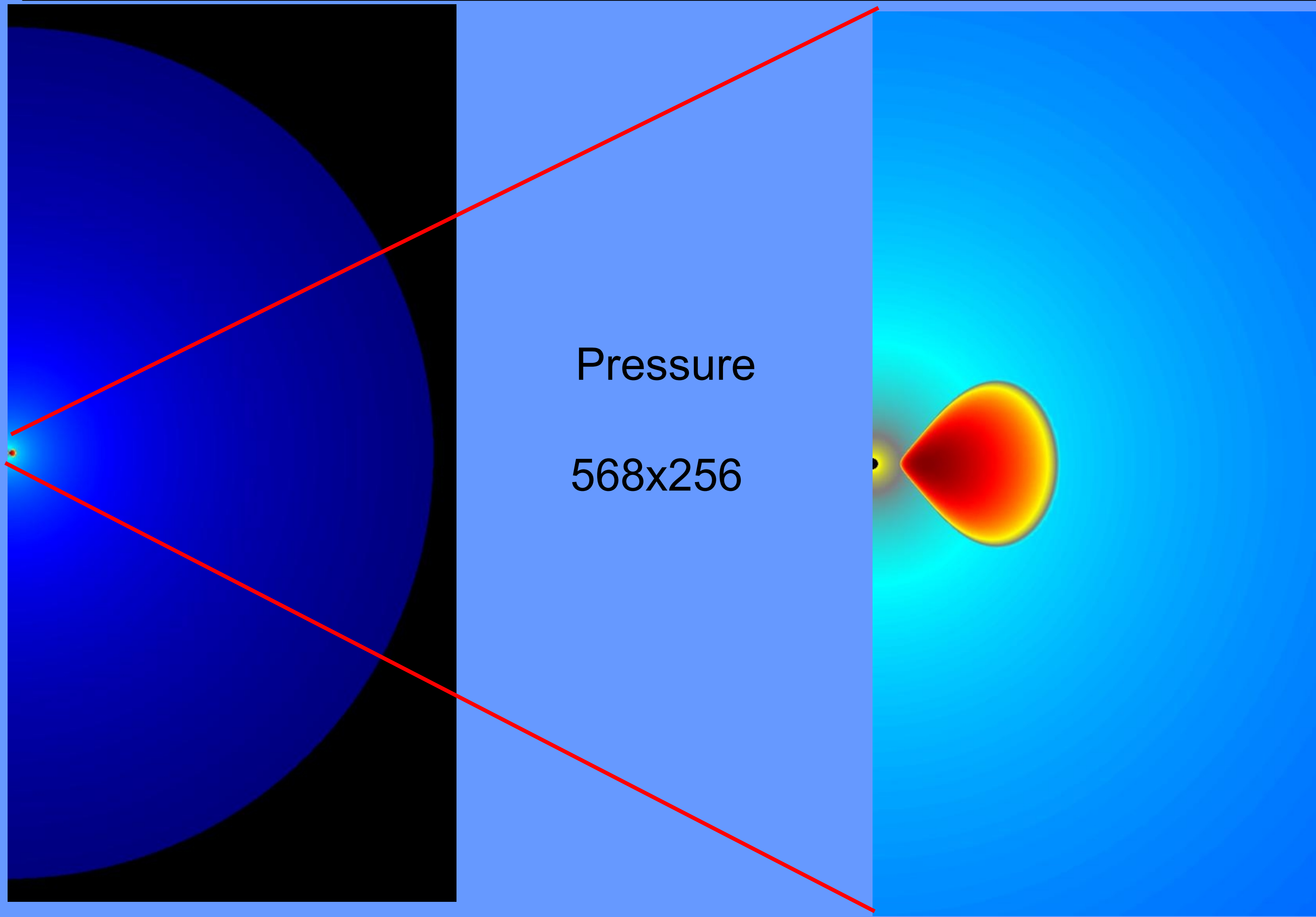
howl if you're a lone wolf

Digital Demo Room	Computers (local)	Gammie	Astronomy	Physics

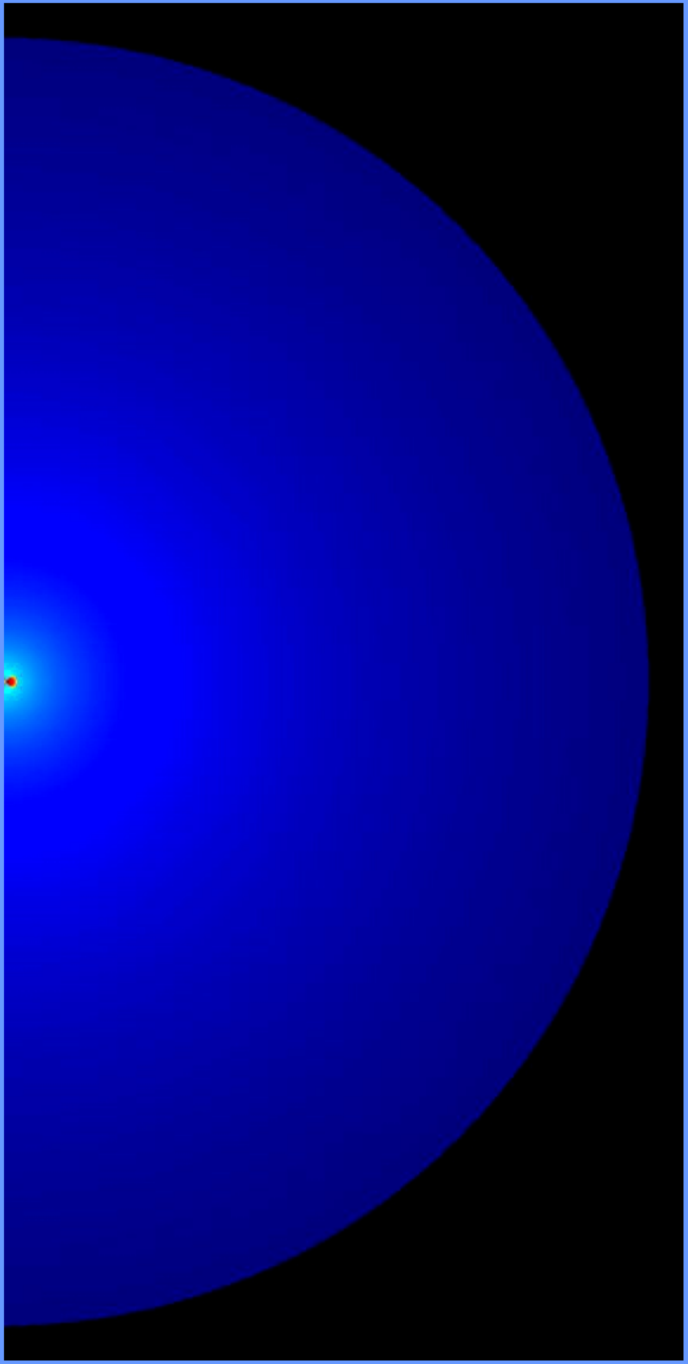
Done

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

Outflows

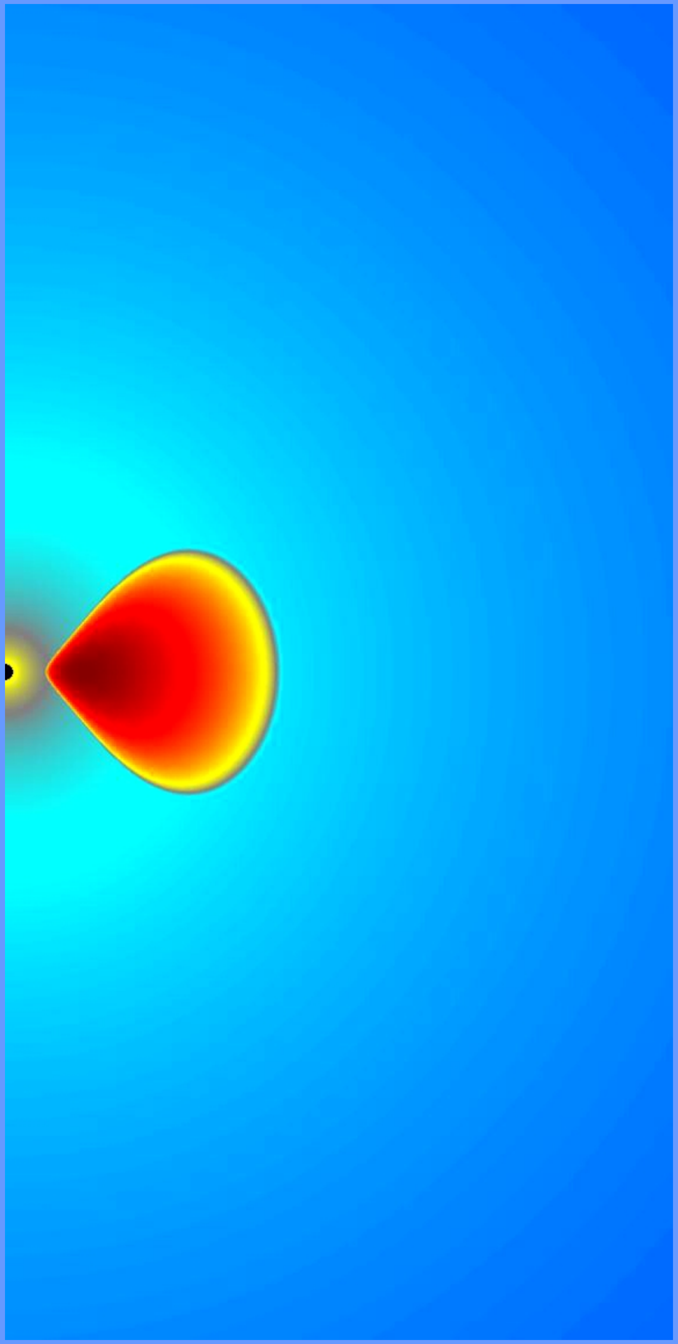


2100M 100M

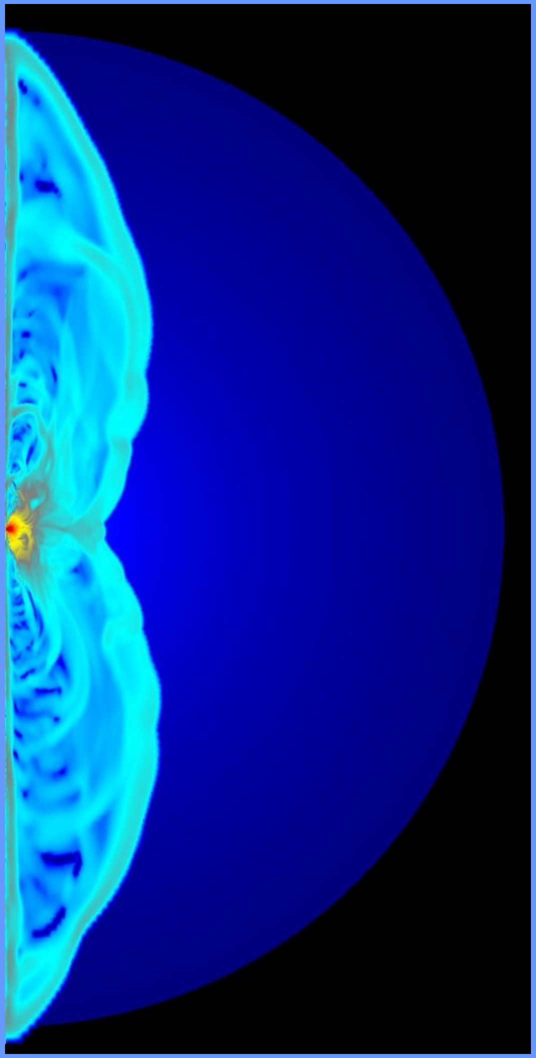


Pressure

568x256



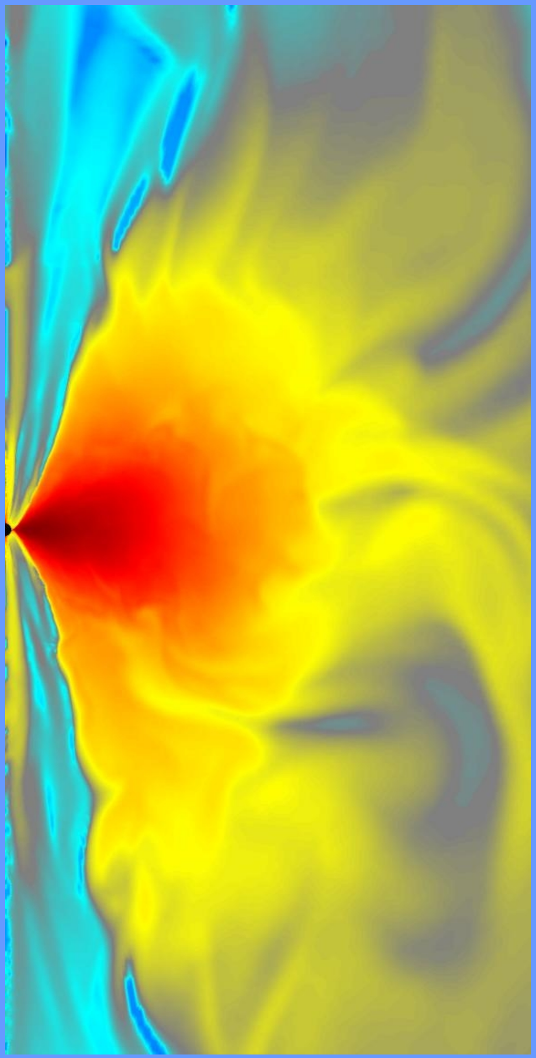
Outflows



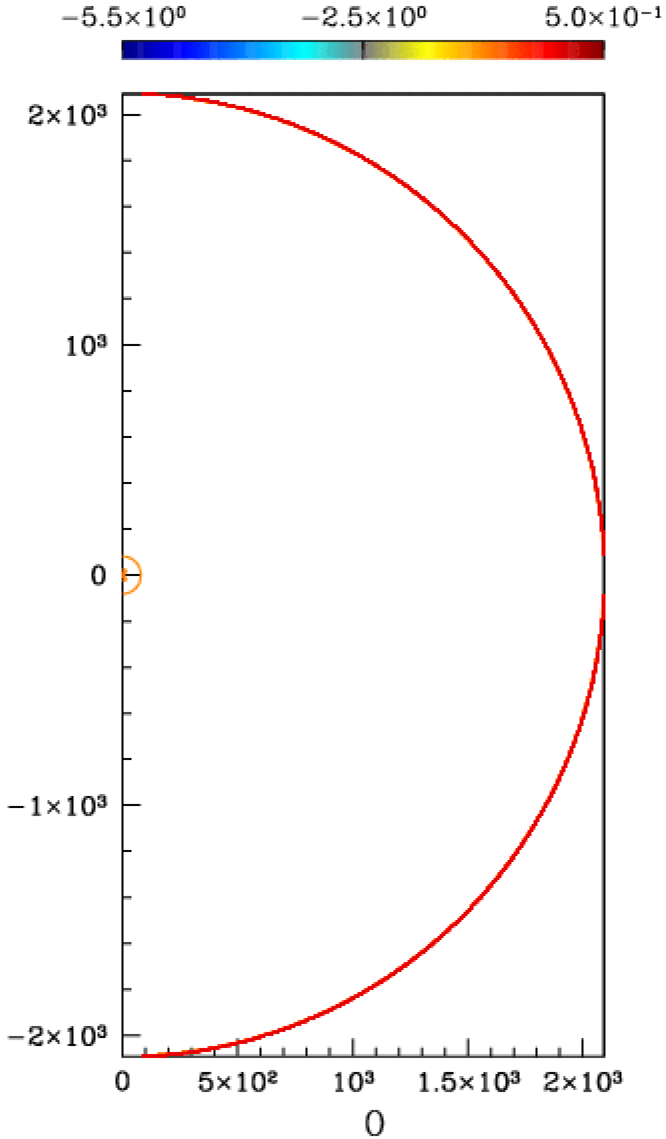
Pressure

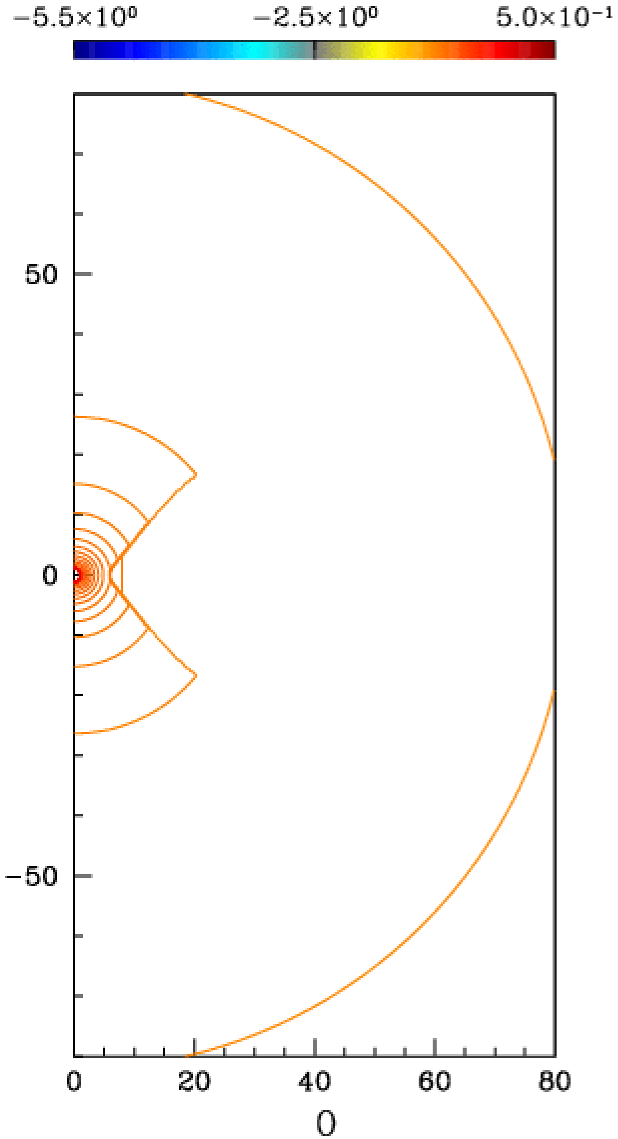
568x256

t=2900M

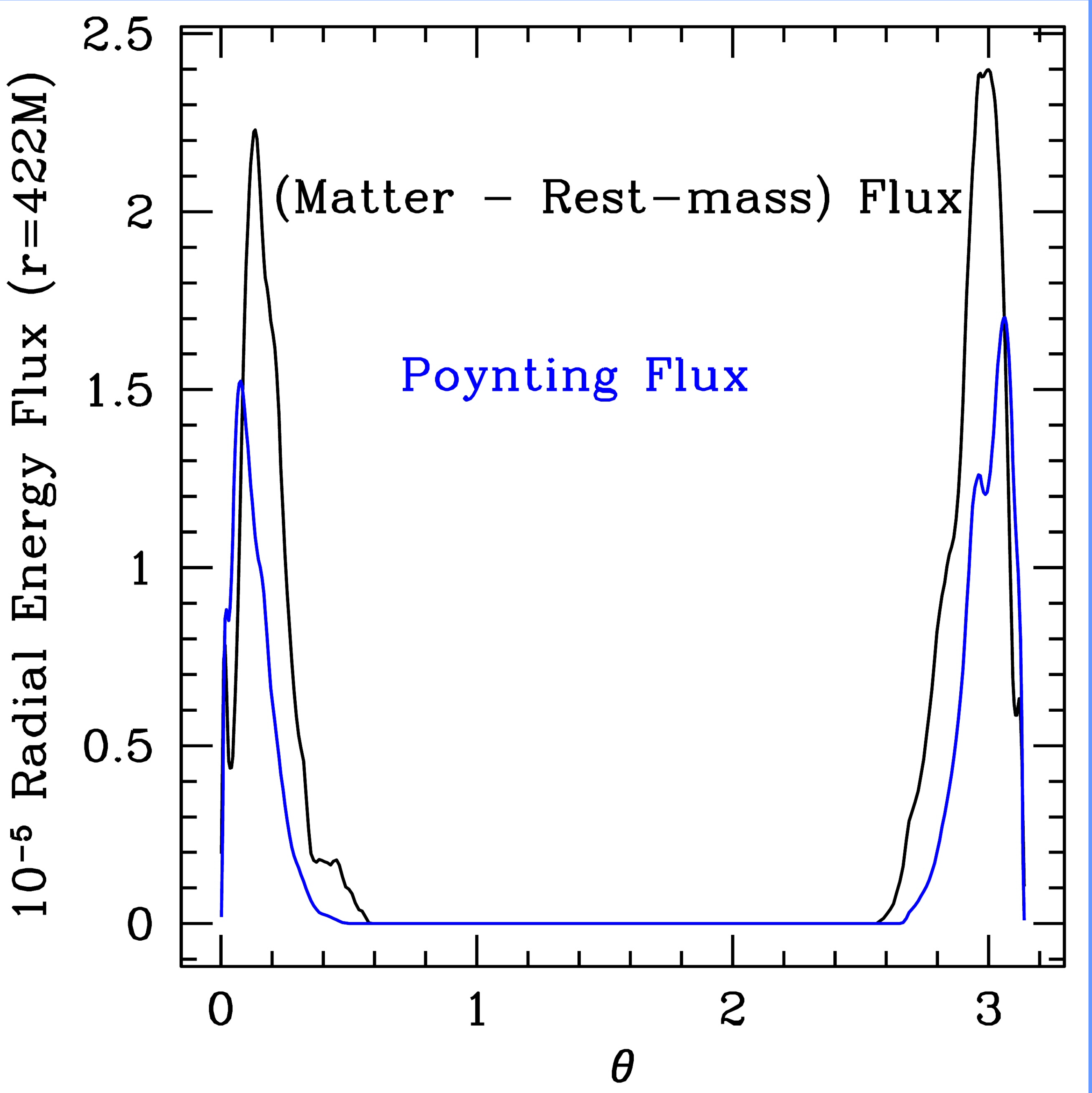


Relativistic Bernoulli Parameter: $h u_t$





t=1100M



(Matter − Rest−mass) Flux
Poynting Flux
10^{-5} Radial Energy Flux (r=422M)
θ
0
0.5
1
1.5
2
2.5
0
1
2
3

Jet Properties

- 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

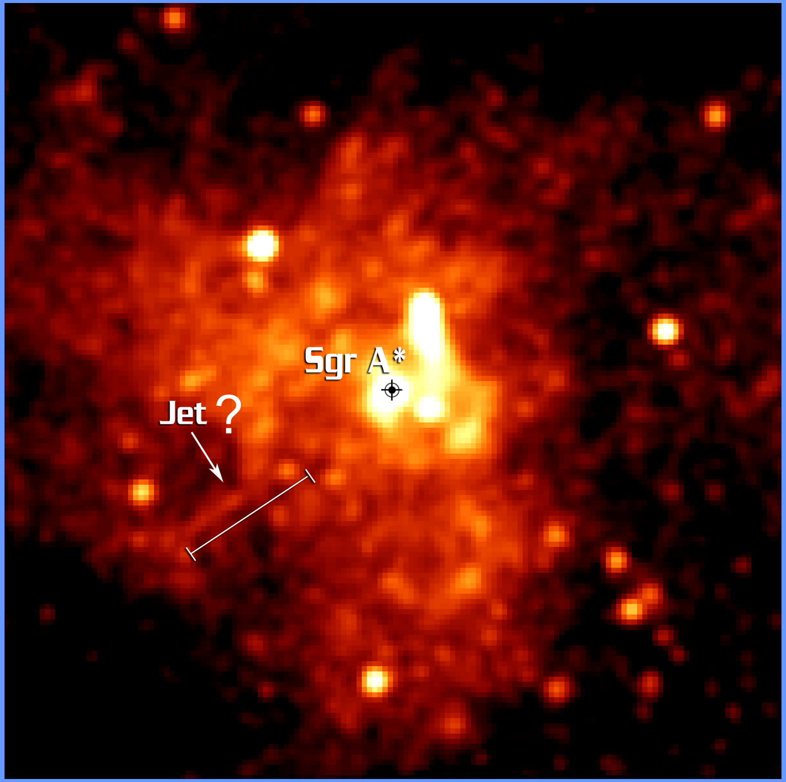
Why Sgr A* ?

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

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

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

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

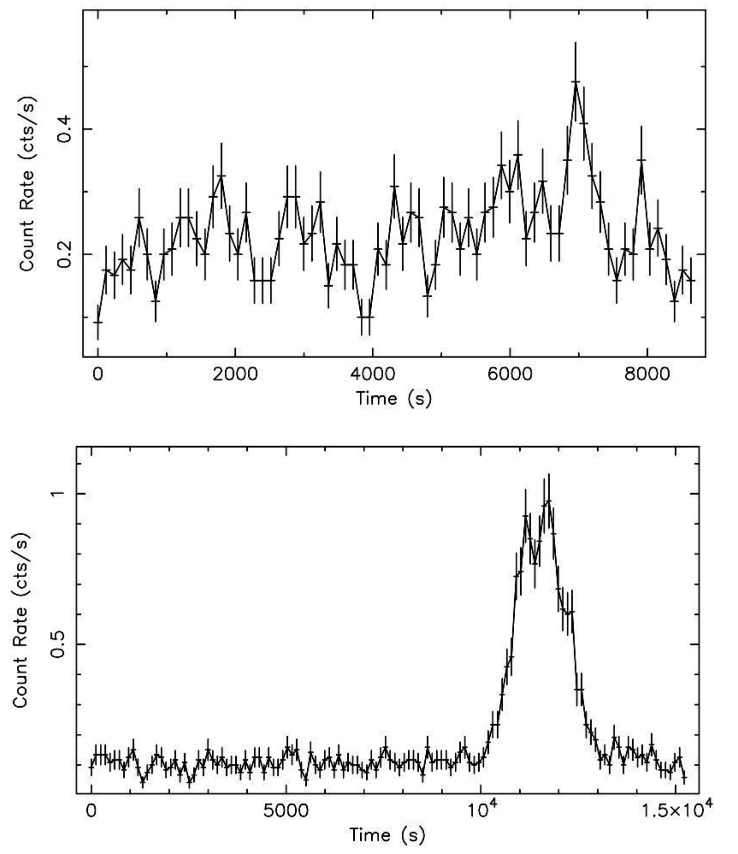


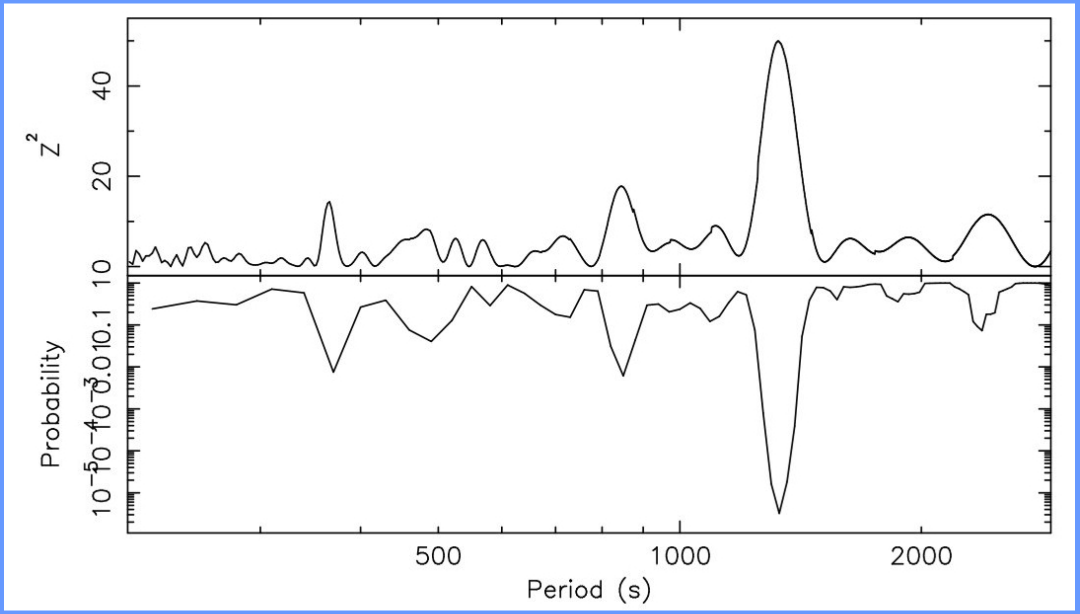
NASA/CXC/MIT Baganoff et al.
1.23 arcmin per side

Sgr A*'s Spin

Belanger et al. 2006

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



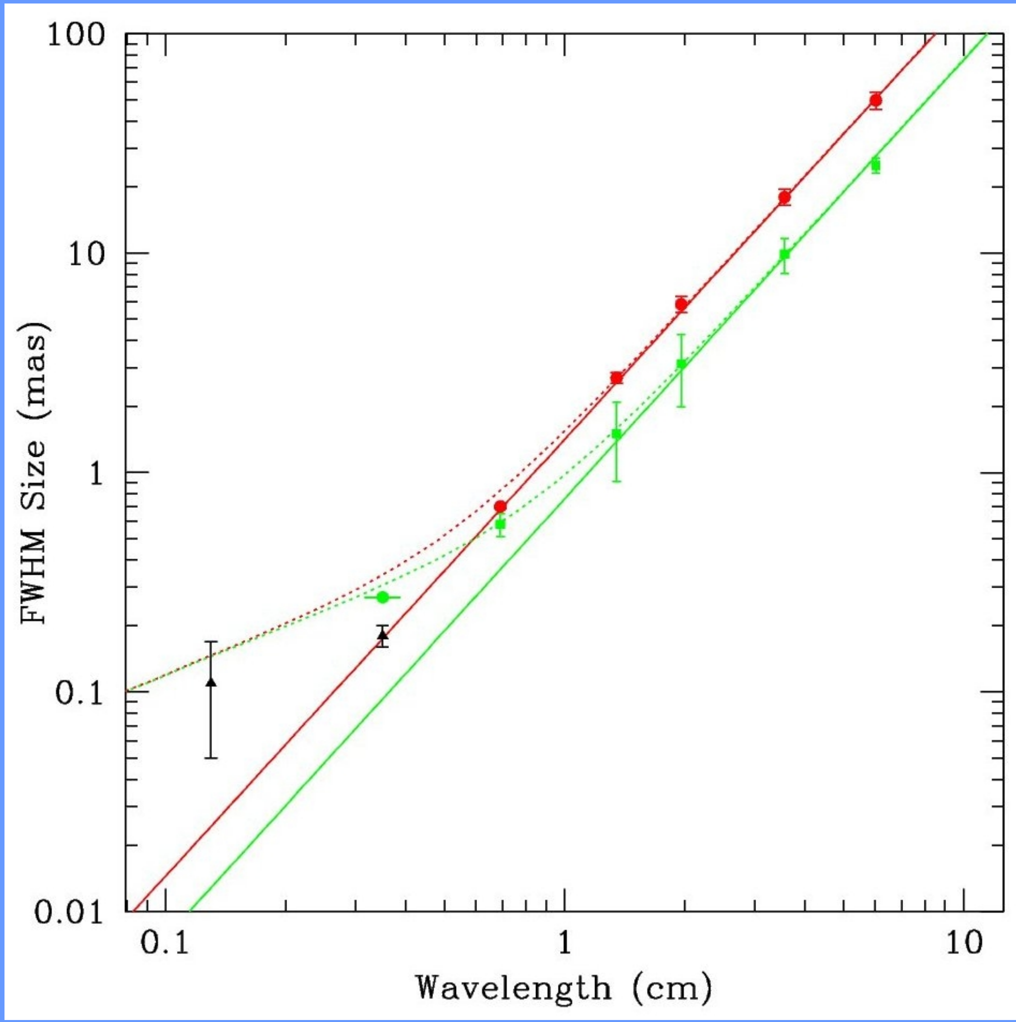


Sgr A* in the Radio

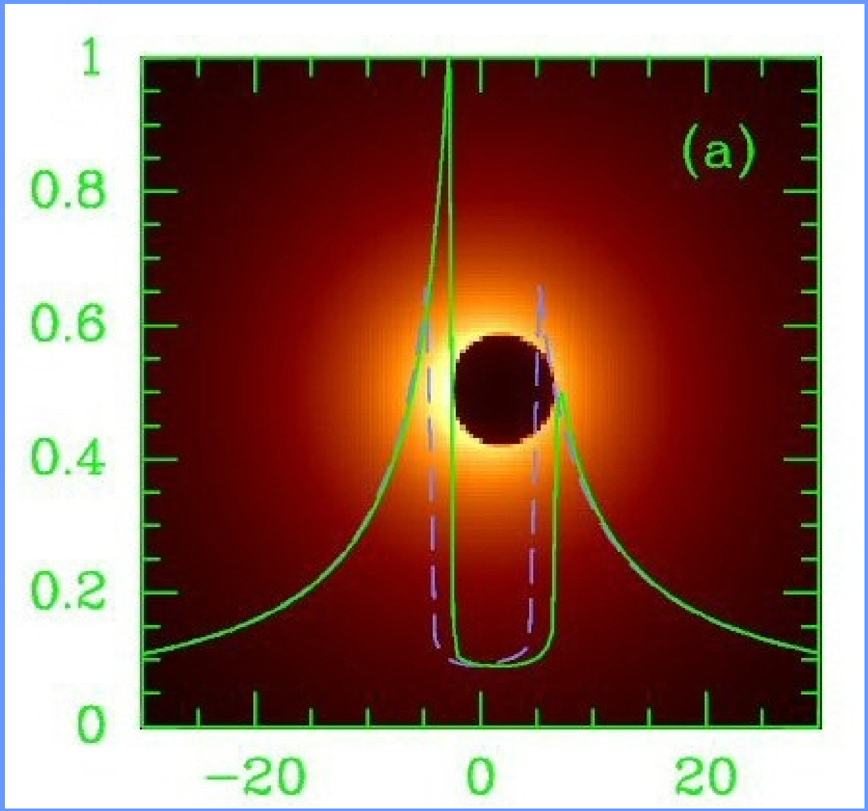
Shen et al. **Nature** (2005)
 < 25 M ~ 2 AU

- Shrinking with increasing frequency
- Power also increases with frequency to ~1mm
- 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!



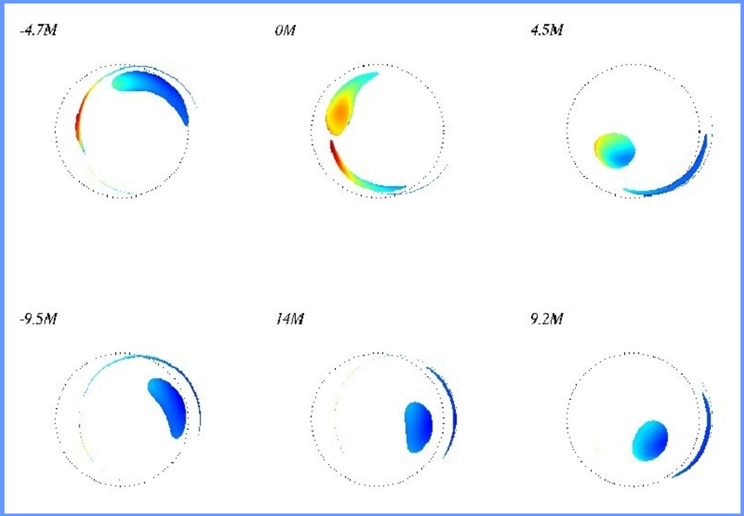
Other RT Calculations

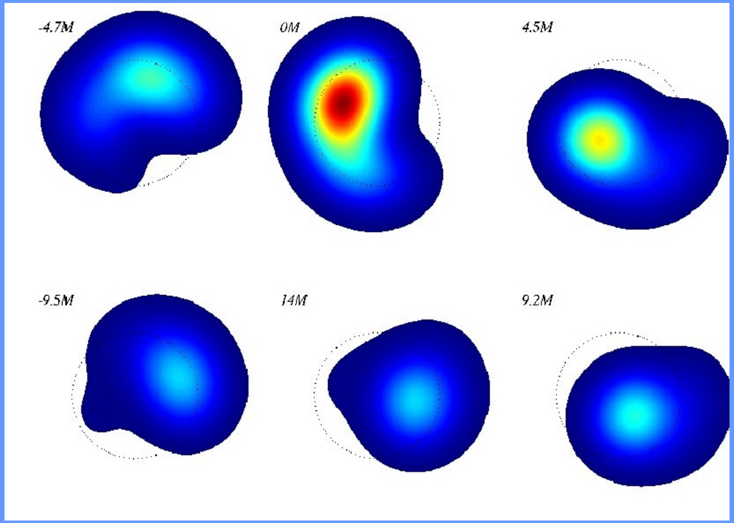


Falcke, Melia, Agol (2000)

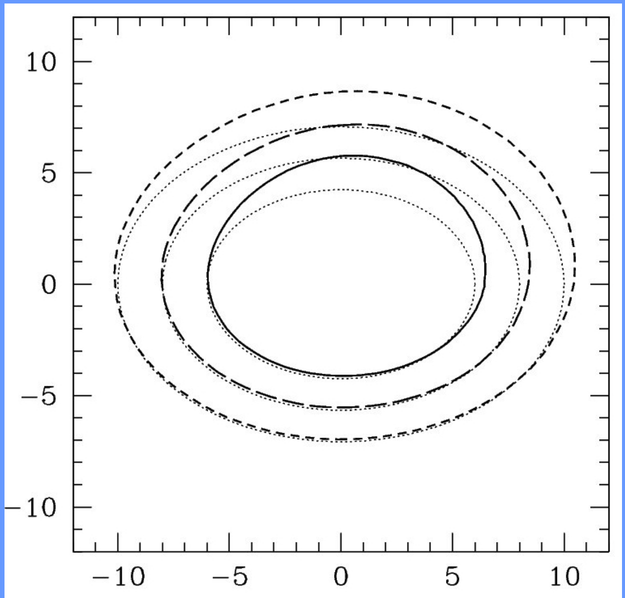
- Free-falling gas
- Black hole spin a=0.998
- $j_\nu = \nu_0 / r^2$
- i = 45 deg.
- $\lambda = 0.6\, mm$

Other RT Calculations

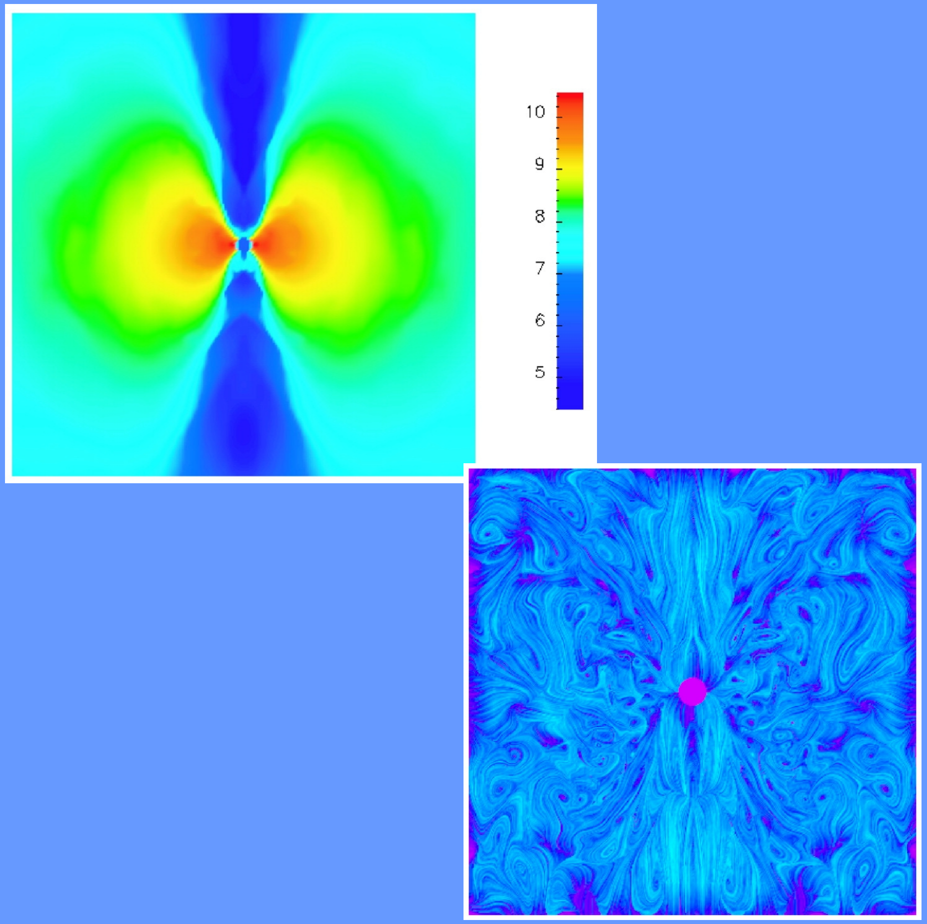




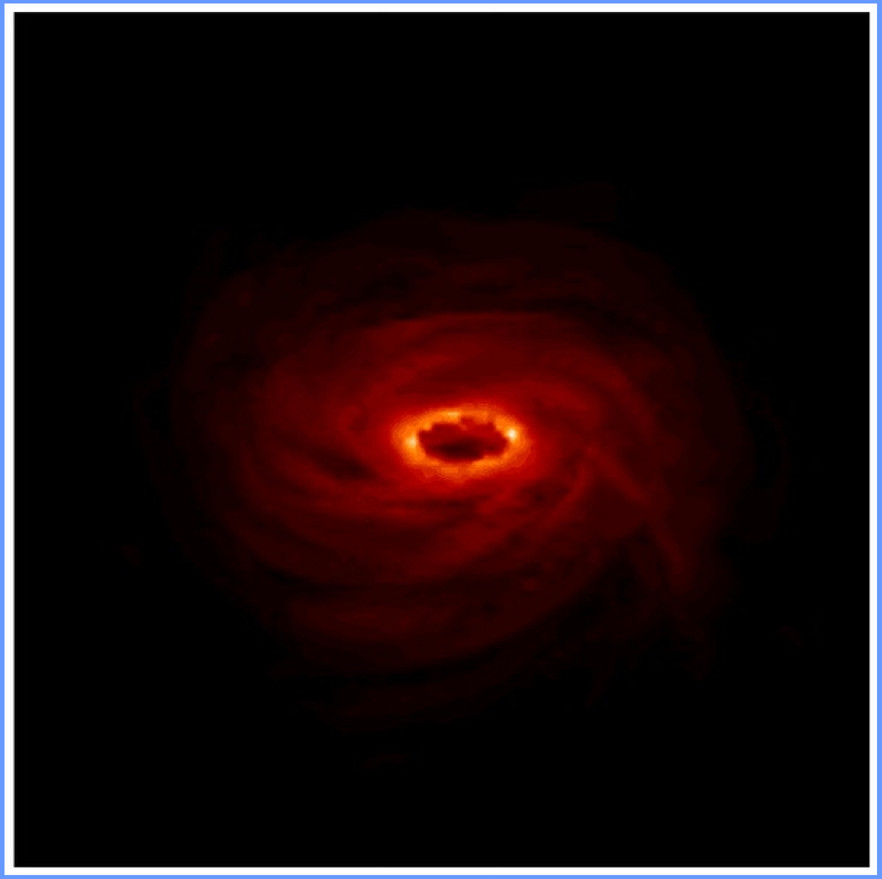
Broderick and Loeb (2005)



Other RT Calculations

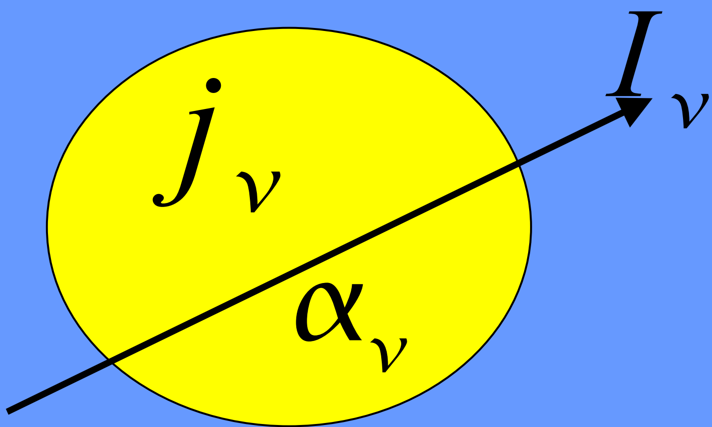


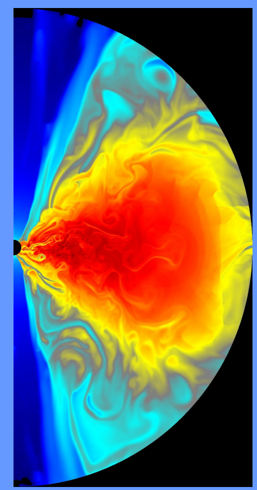
Igumenshchev, Narayan, Abramowicz (2003)



Goldston, Quataert, Igumenshchev (2005)

Relativistic Radiative Transfer





$$\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu$$

$$j = j_\nu / \nu^2$$

$$\alpha = \alpha_\nu$$

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

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

- 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^-'s
  Te = Tp
- Use Wardzinski & Zdziarski (2000) for synch. emissivity
- Bremsstrahlung, too
- Accretion rate sets energy scale of emission

Disk Properties

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

$$n_e, T_e, B^2 \propto \dot{M}$$

$$\dot{M} = 5.15\,x\,10^{-9}\,M_{sun}/\,yr$$

$$Te = 10^{10} - 10^{12}\,K$$

$$n_e = 10^{8} - 10^{10}\,cm^{-3}$$

$$B = 1 - 6000\,G$$

RIAF Disk Properties (Yuan et al. 2003)

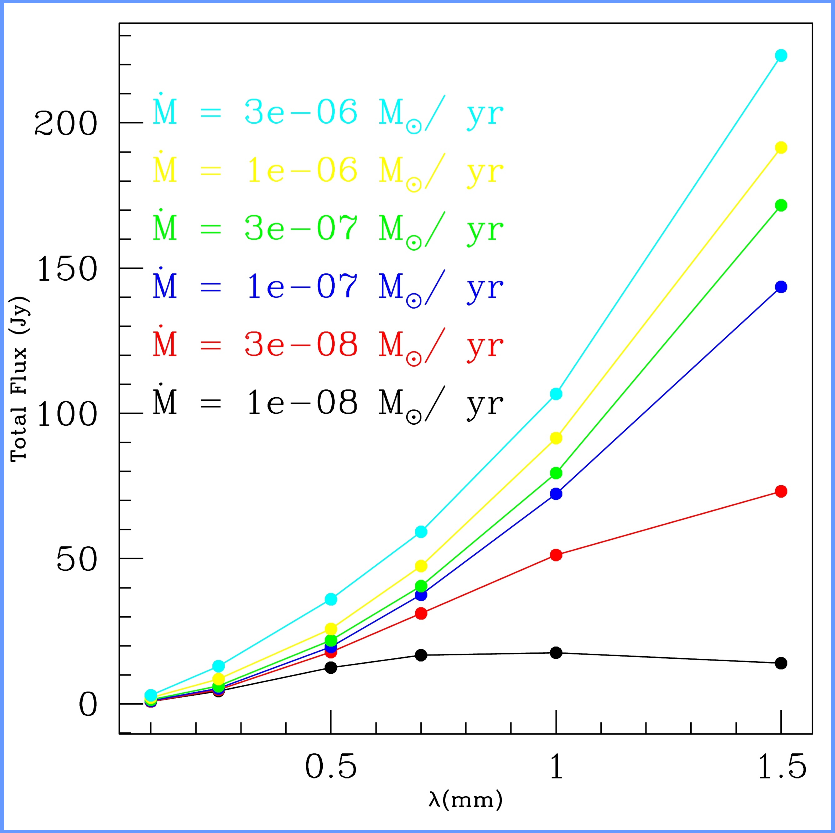
$$\dot{M} = 4.8\,x\,10^{-8}\,M_{sun}/\,yr$$

$$B = 1 - 6000\,G$$

$$T_e = 10^{10} - 10^{12}\,K$$

$$n_e = 10^{6} - 10^{8}\,cm^{-3}$$

Accretion Rate Study



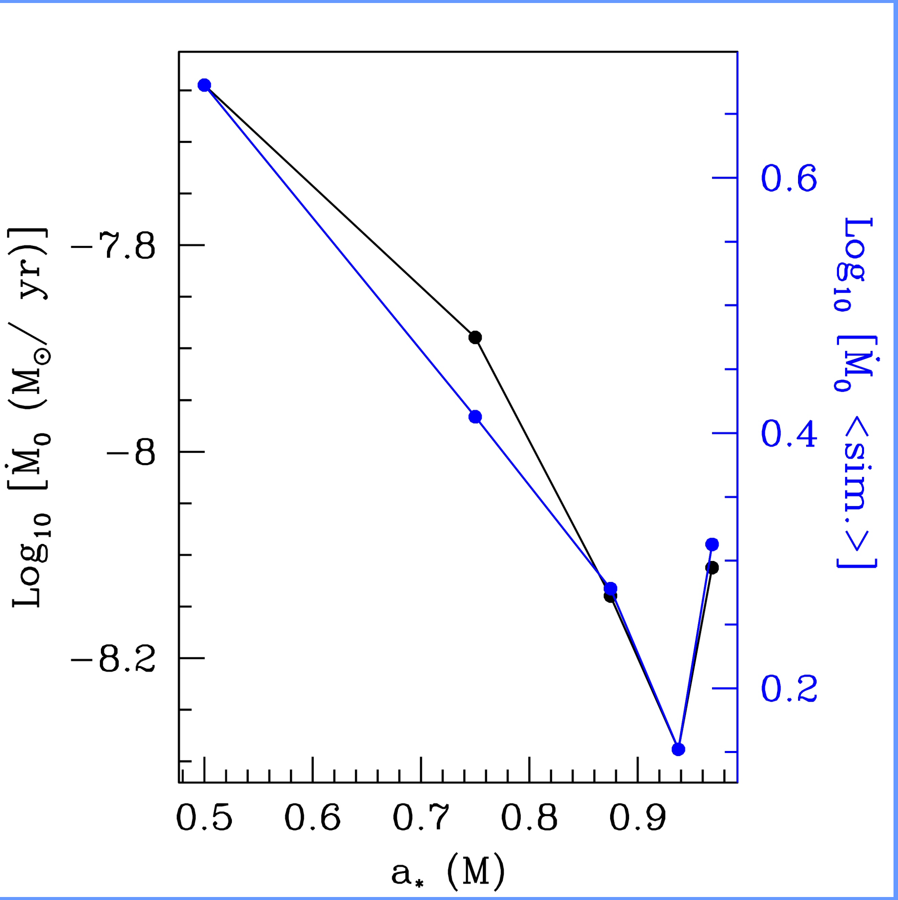
$$Flux = 4\,Jy$$

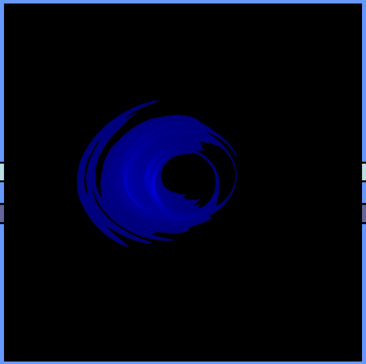
$$\dot{M} = 5.15\,x\,10^{-9}\,M_{sun}/\,yr$$

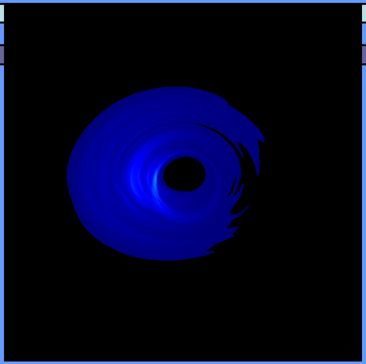
- Consistent with values from Rotation Measures by
  - Macquart et al.(2006): 0.2 – 4 x 10^{-8}
  - Marrone et al.(2006): <10^{-6} -10^{-7}

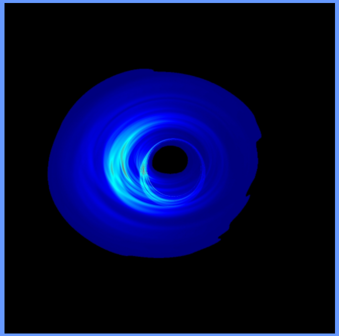
Need to calculate it ourselves!!

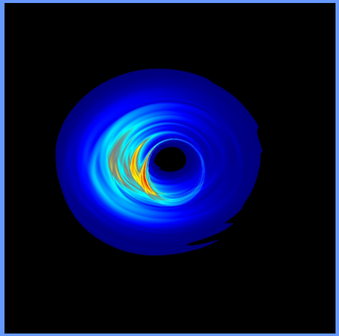
BH Spin Study

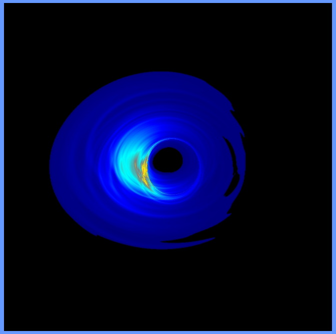




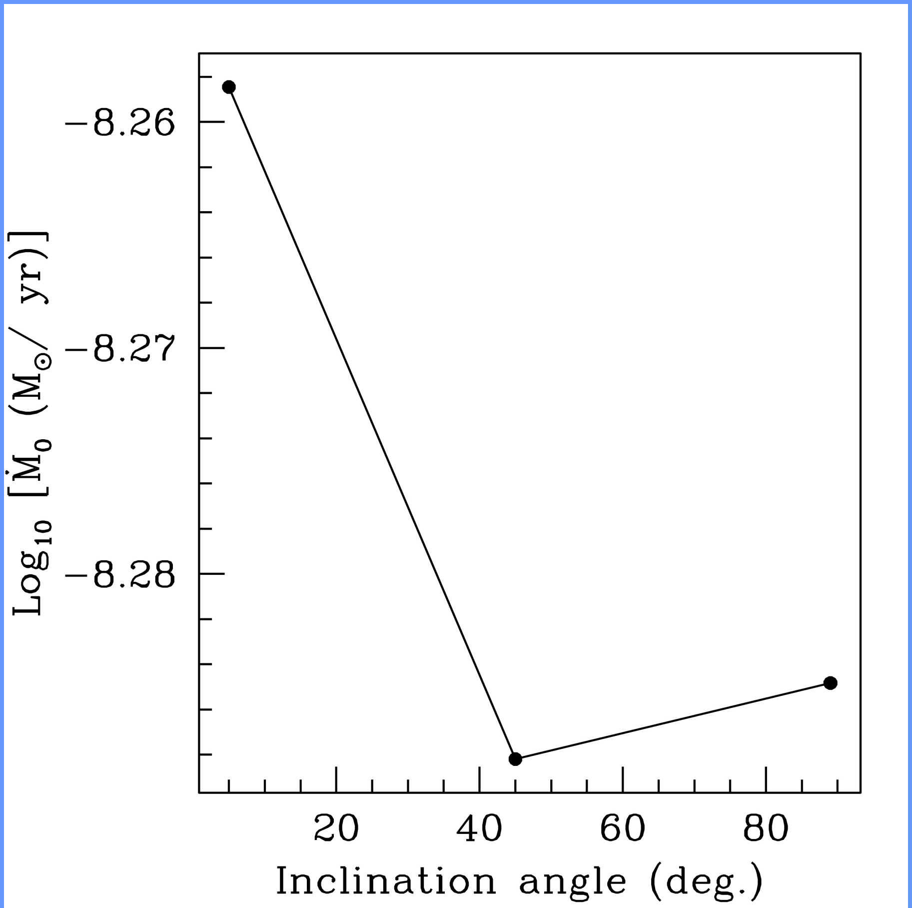


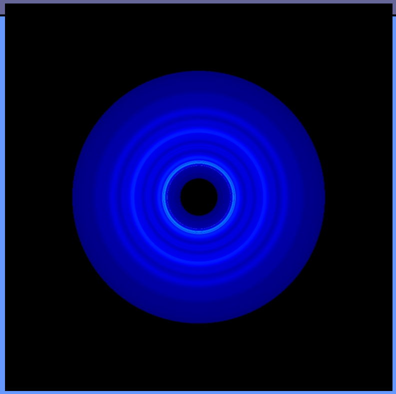


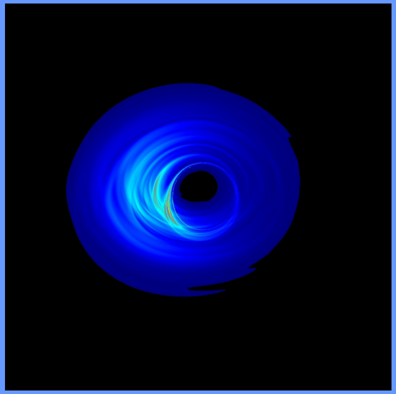


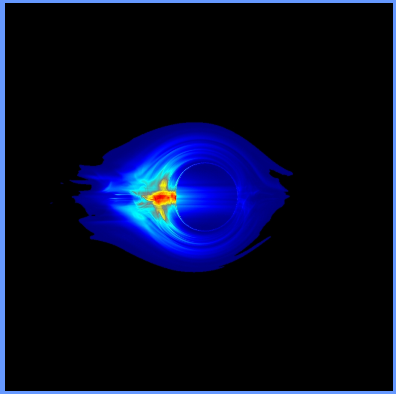


Camera Inclination Study



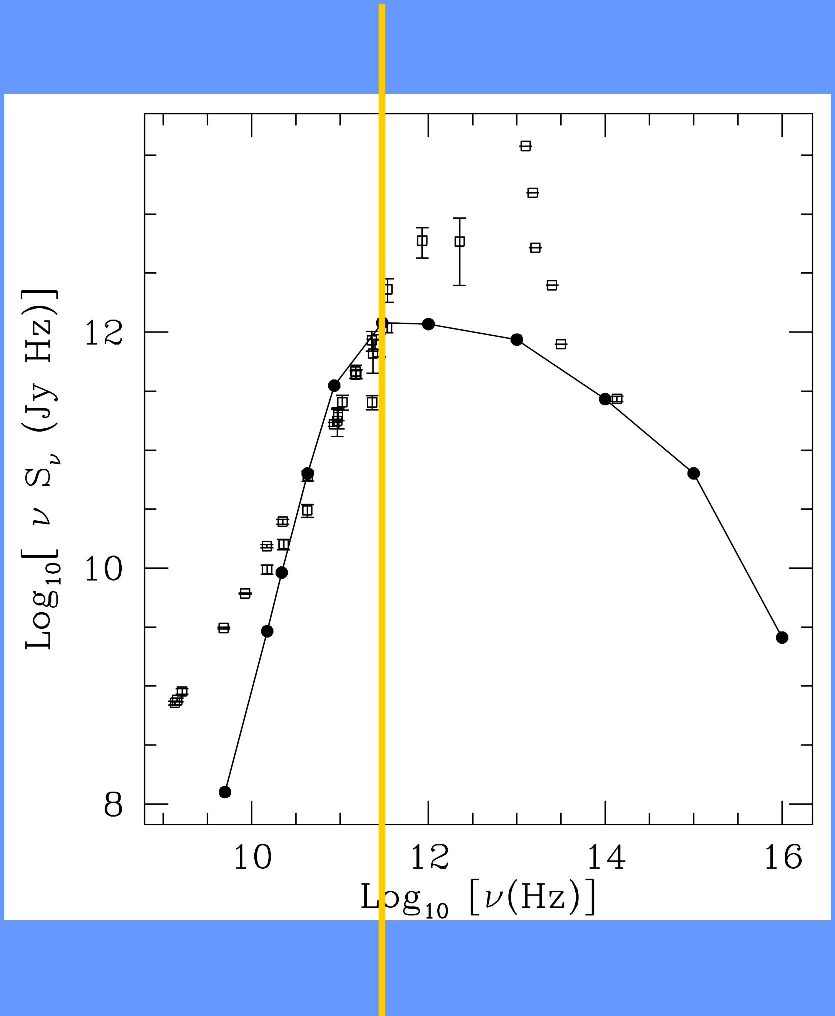


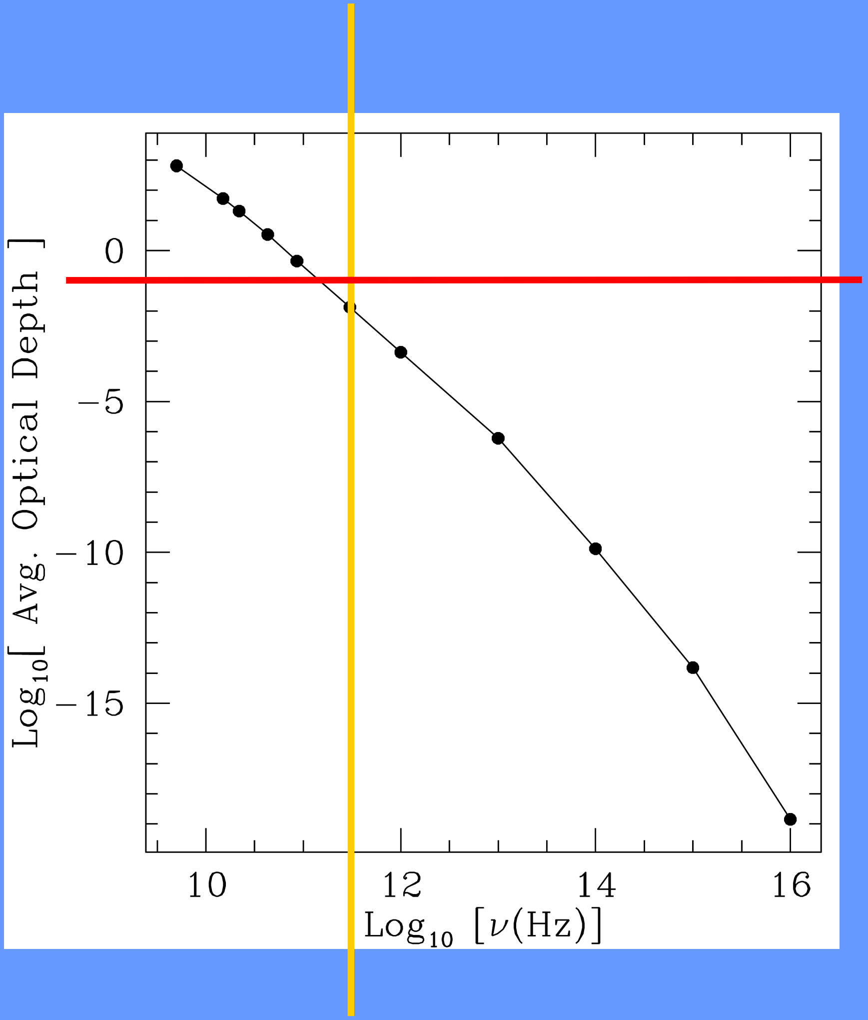




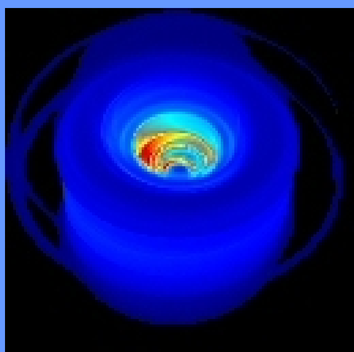
Spectrum

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

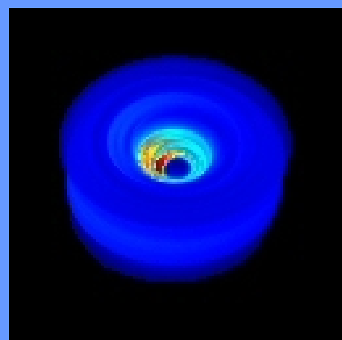




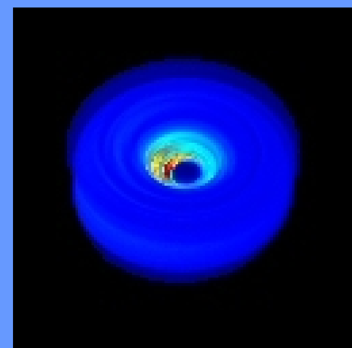
Angular Size with Frequency



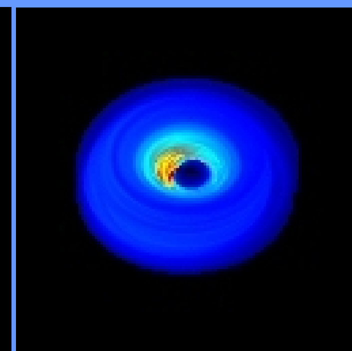
5 GHz



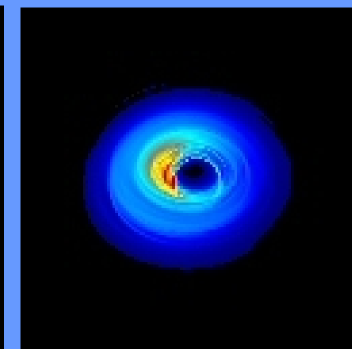
15 GHz



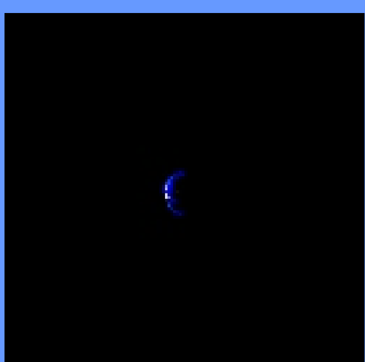
22 GHz



43 GHz



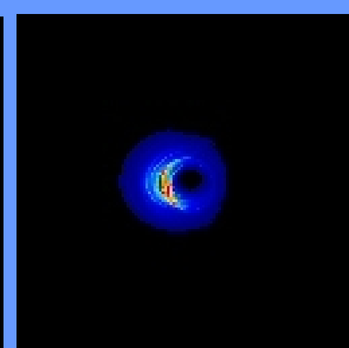
86 GHz



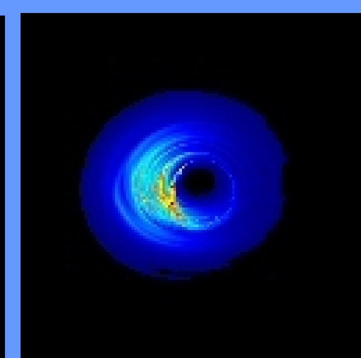
10^{15} Hz

10^{14} Hz

10^{13} Hz



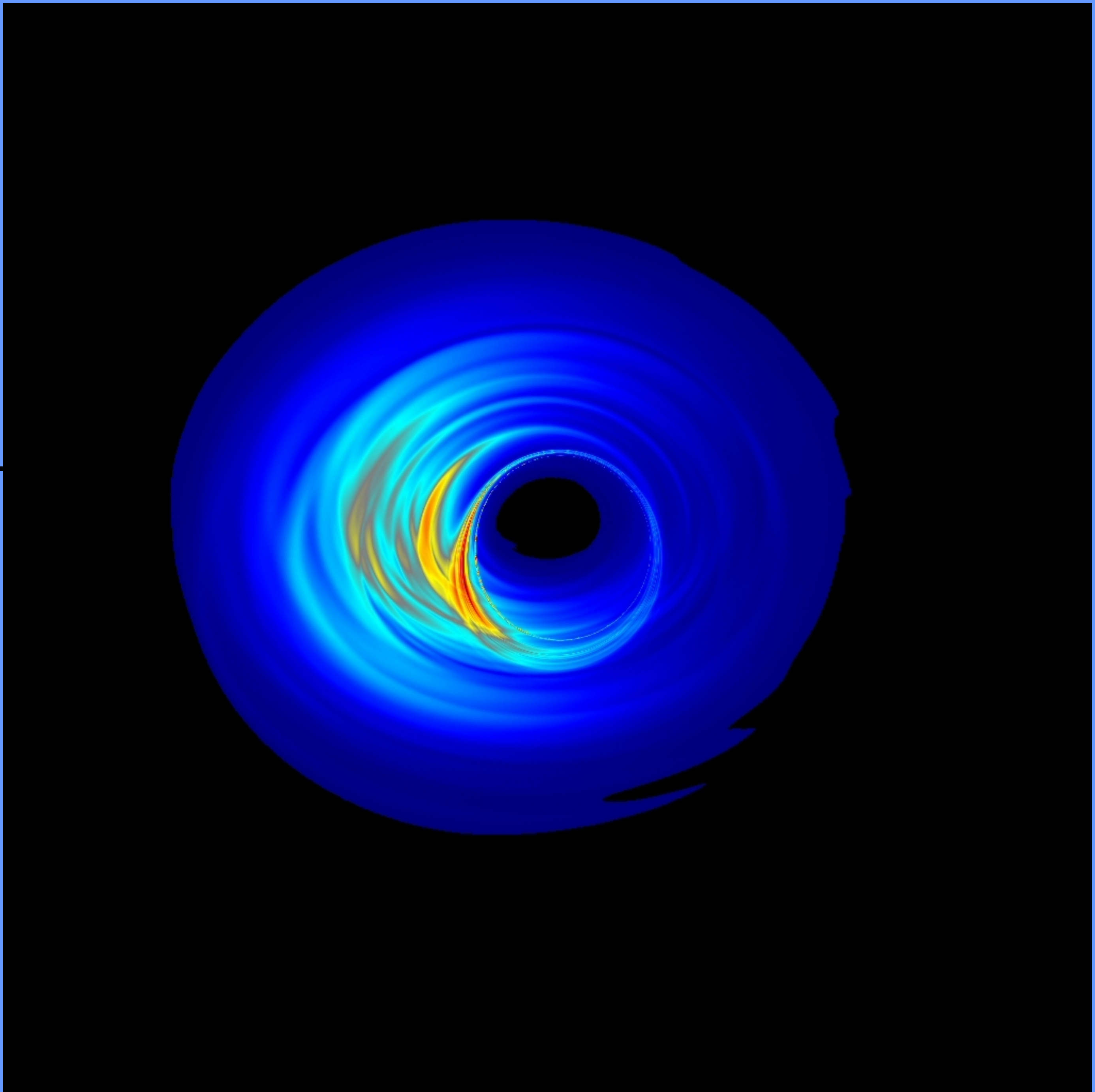
10^{12} Hz



300 GHz

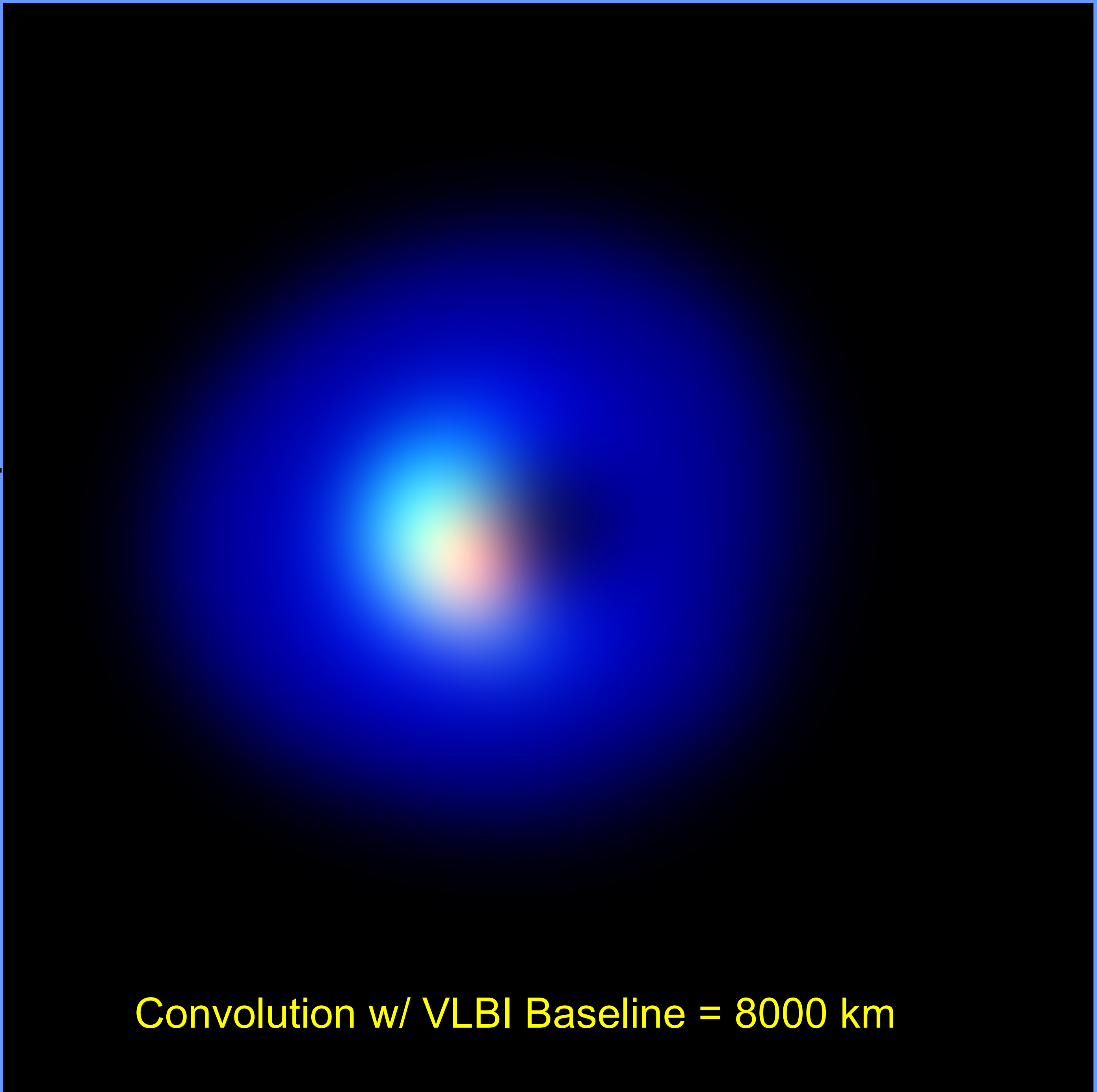
$$I_\nu$$

I = 45 deg.



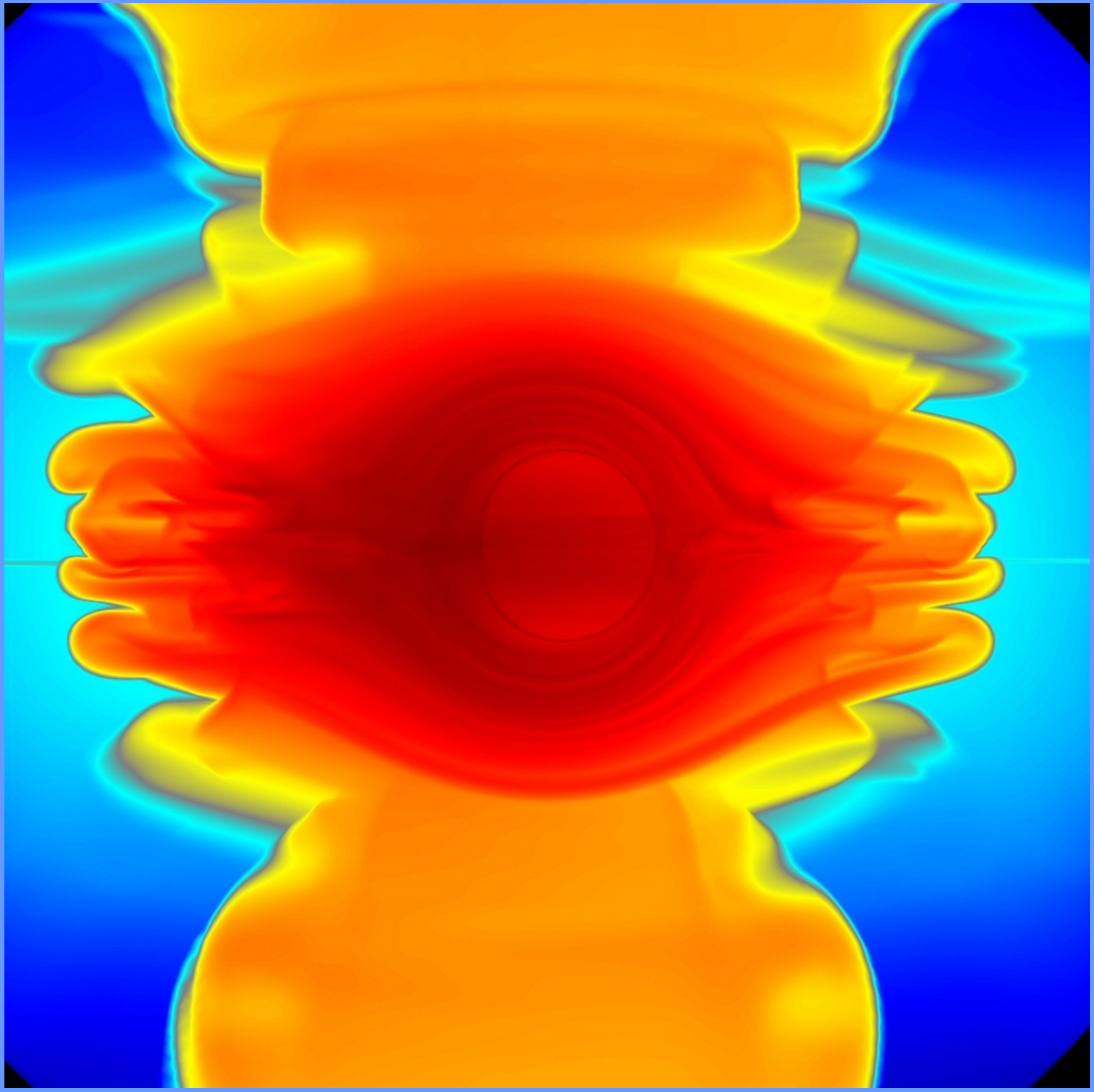
I_ν

I = 45 deg.



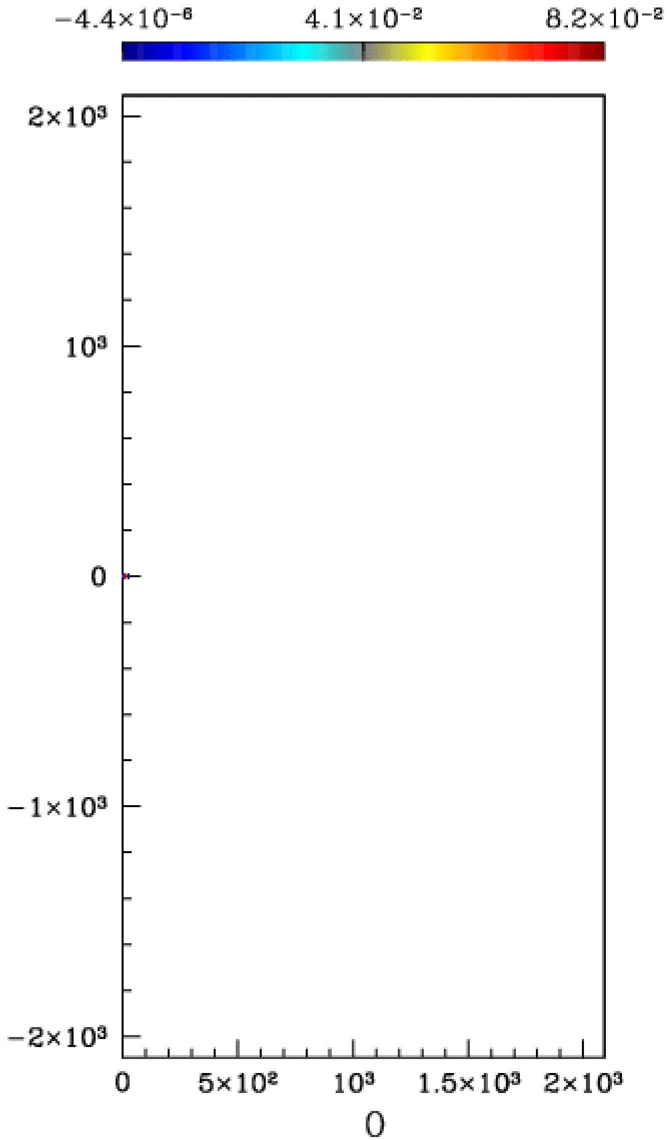
$\log I_\nu$

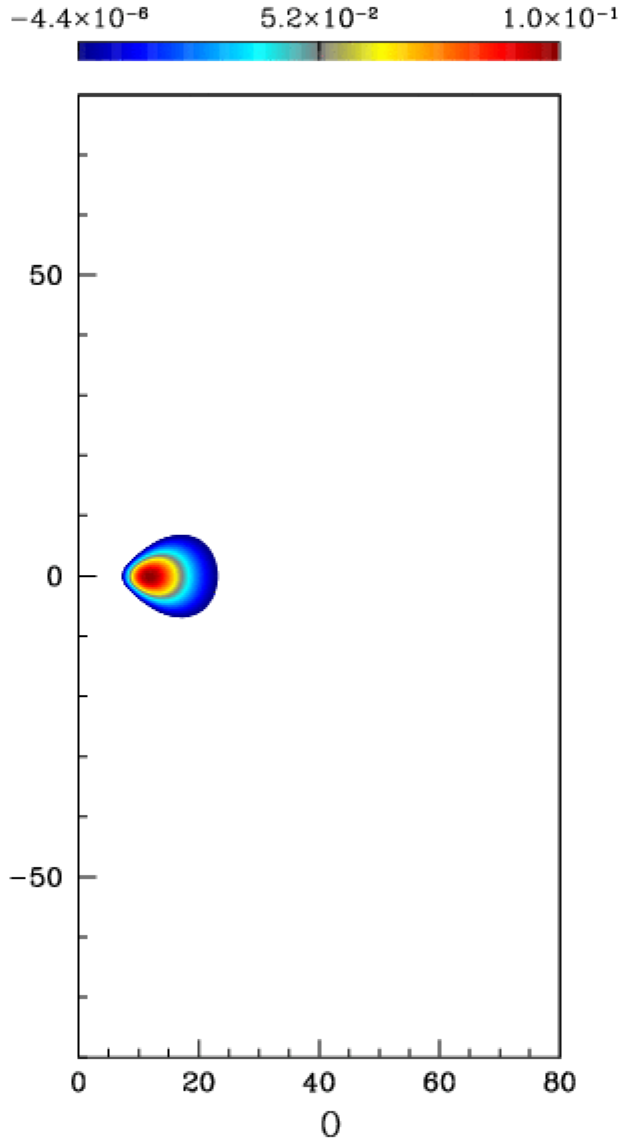
I = 90 deg.



The End

Poloidal Magnetic Field Lines





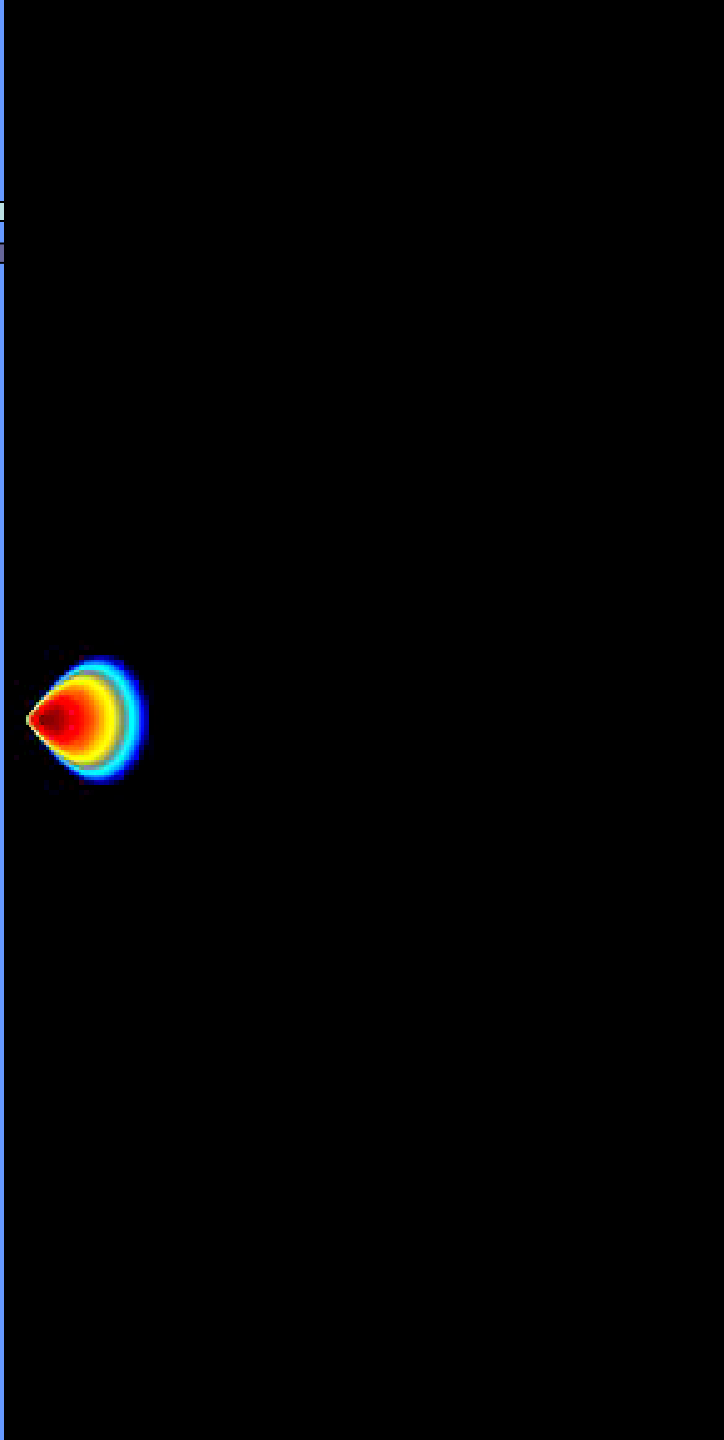
Jet through Molasses

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

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

t = 0 – 4000M

288x128



Jet through Molasses