Making a GRB jet

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OUTLINE

- Introduction
- Models (previous and current)
- Results
- Conclusions
- Future Work

Introduction to GRBs

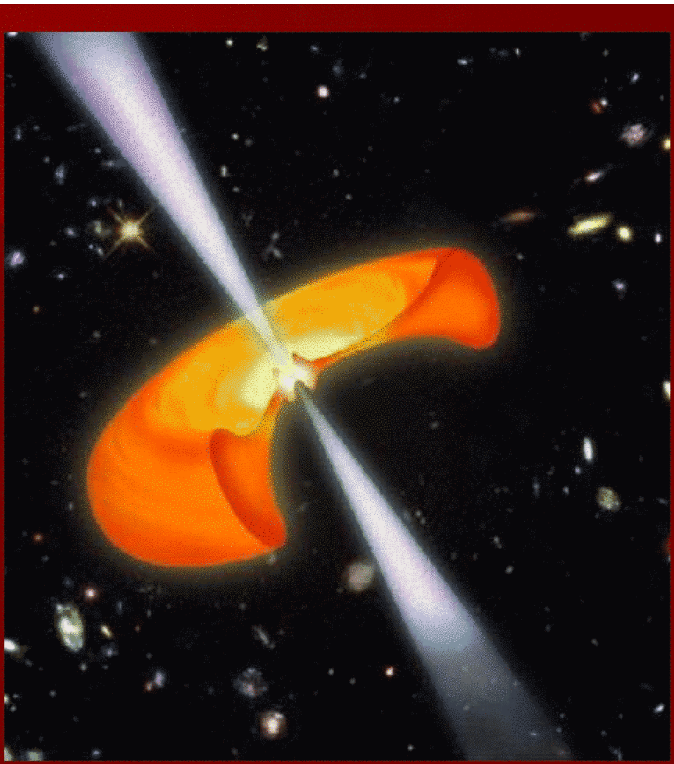
- Two populations of GRBs (i.e., short and long bursts).
- Two leading models: mergers and collapsars.
- GRBs vs. SN (can we apply models for SN to GRBs?)

Q: What Powers Most Energetic Sources ?
A: Accretion on Black Holes!

$$L = \eta c^2 \dot{M}_a$$

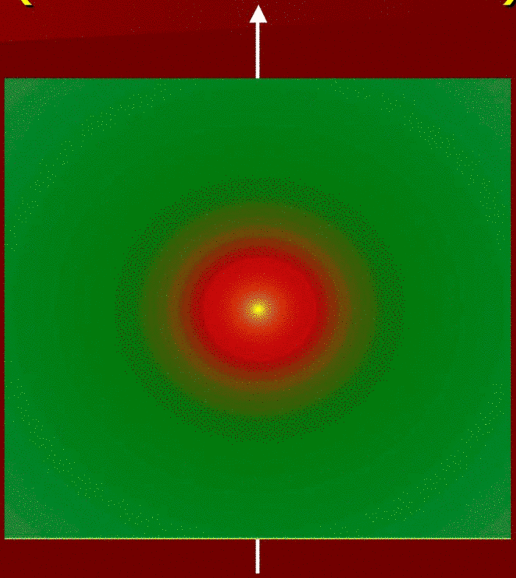
Introduction cont.

- The main challenge is not the ultimate energy source, but how to turn this energy into predominately gamma rays with the right nonthermal broken power low spectrum with the right temporal behavior.
- Relativistic fireball shock model deals with this challenge [Rees & Meszaros (1992, 1994) but see also pioneering earlier work by Cavallo & Rees (1978), Paczynski (1986, 1990), Goodman (1986) and Shemi & Piran (1990)].



Generic picture of an accreting system (pm,swift)

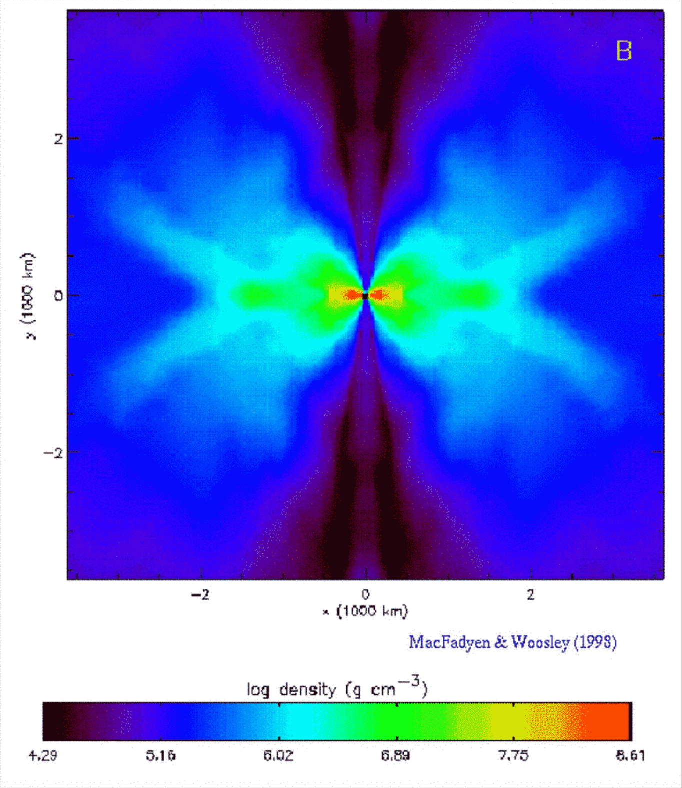
A collapse of a rotating envelope (HD inviscid case)

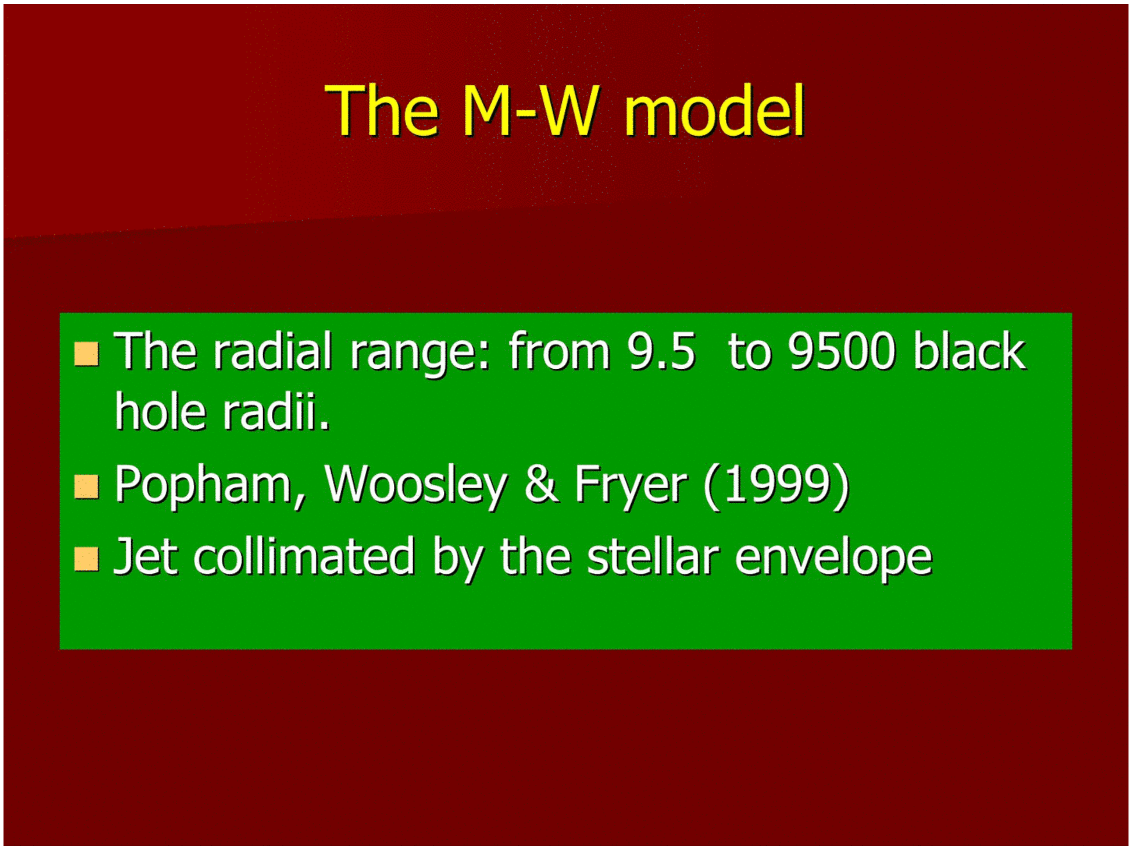


Proga & Begelman (2003a)

The key elements of previous simulations of the collapsar model (MacFadyen & Woosley 1999).

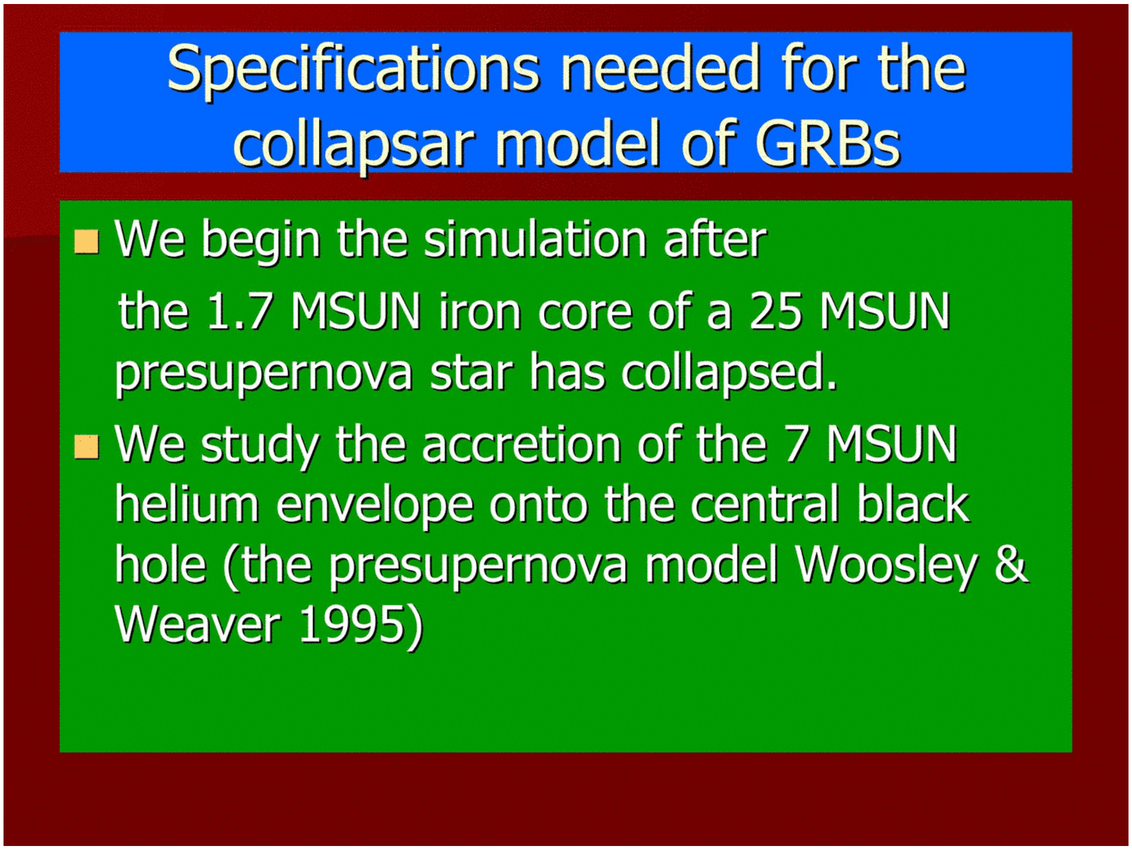
- Hydrodynamics (axisymmetry)
- Sophisticated equation of state
- Neutrino cooling
- Photodisintegration
- Energy dissipation and angular momentum transport modeled with ‘alpha’ viscosity (i.e., Shakura Sunyaev disk model)





The M-W model

- The radial range: from 9.5 to 9500 black hole radii.
- Popham, Woosley & Fryer (1999)
- Jet collimated by the stellar envelope



Specifications needed for the collapsar model of GRBs

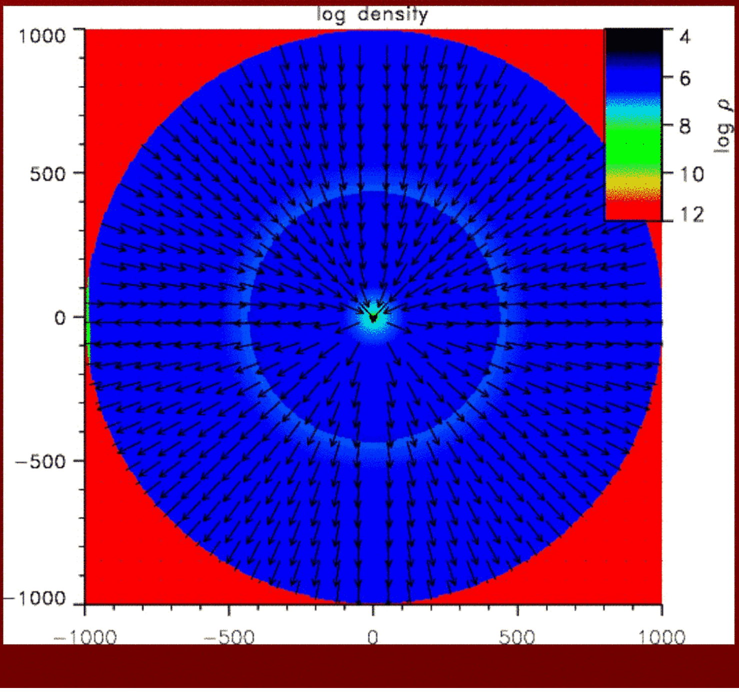
- We begin the simulation after

  the 1.7 MSUN iron core of a 25 MSUN presupernova star has collapsed.
- We study the accretion of the 7 MSUN helium envelope onto the central black hole (the presupernova model Woosley & Weaver 1995)

MHD collapsar models

- Theory of magnetic jets: Blandford, Konigl, Lyutikov, Spruit, Vlahakis …
- Simulations: Mizuno et al. 2004a and b; De Villiers, J.-P, Staff, J., & Ouyed R. 2005; and work of J. Hawley, C. Gammie, J. McKinney…

Our models



Our models

- Important elements:
  - axisymmetry,
  - sophisticated EOS,
  - neutrino cooling,
  - photodisintegration,
  - small latitude-dependent ang. momentum
  - MHD limit (weak radial magnetic field; weak means that fluid is super-Alfvenic),
  - gas can be heated by artificial resistivity (the magnetic field changes sign across the equator)

microphysics

Our models

- Forces:
  - gravity (Paczynski-Wiita potential),
  - gas pressure, and
  - centrifugal force
  - magnetic forces

Note that angular momentum can be transported by MRI or magnetic braking.

Equations of MHD

$$\frac{D\rho}{Dt} + \rho\nabla\cdot v = 0$$

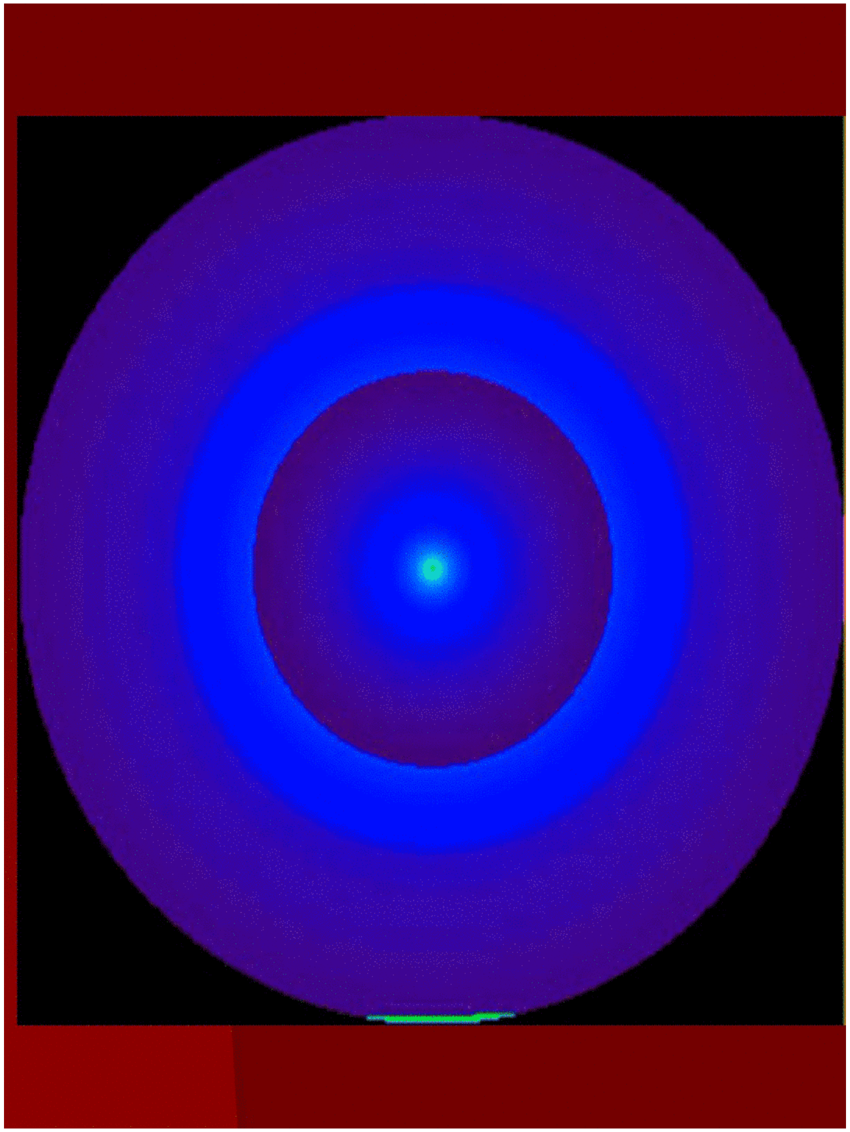
$$\rho\frac{Dv}{Dt} = -\nabla P + \rho\nabla\Phi + \frac{1}{4\pi}(\nabla\times B)\times B$$

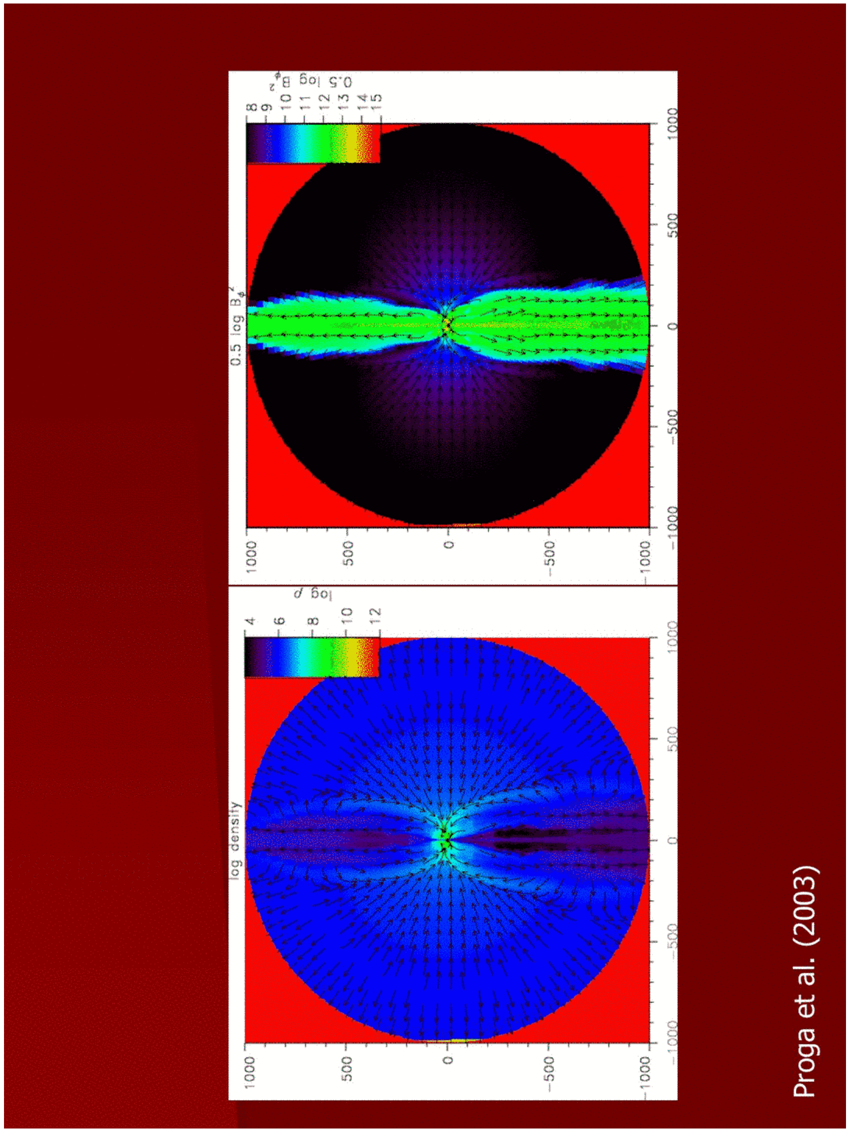
$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P\nabla\cdot v + \eta_r J^2 - L$$

$$\frac{\partial B}{\partial t} = \nabla\times\left(v\times B - \eta_r J\right)$$

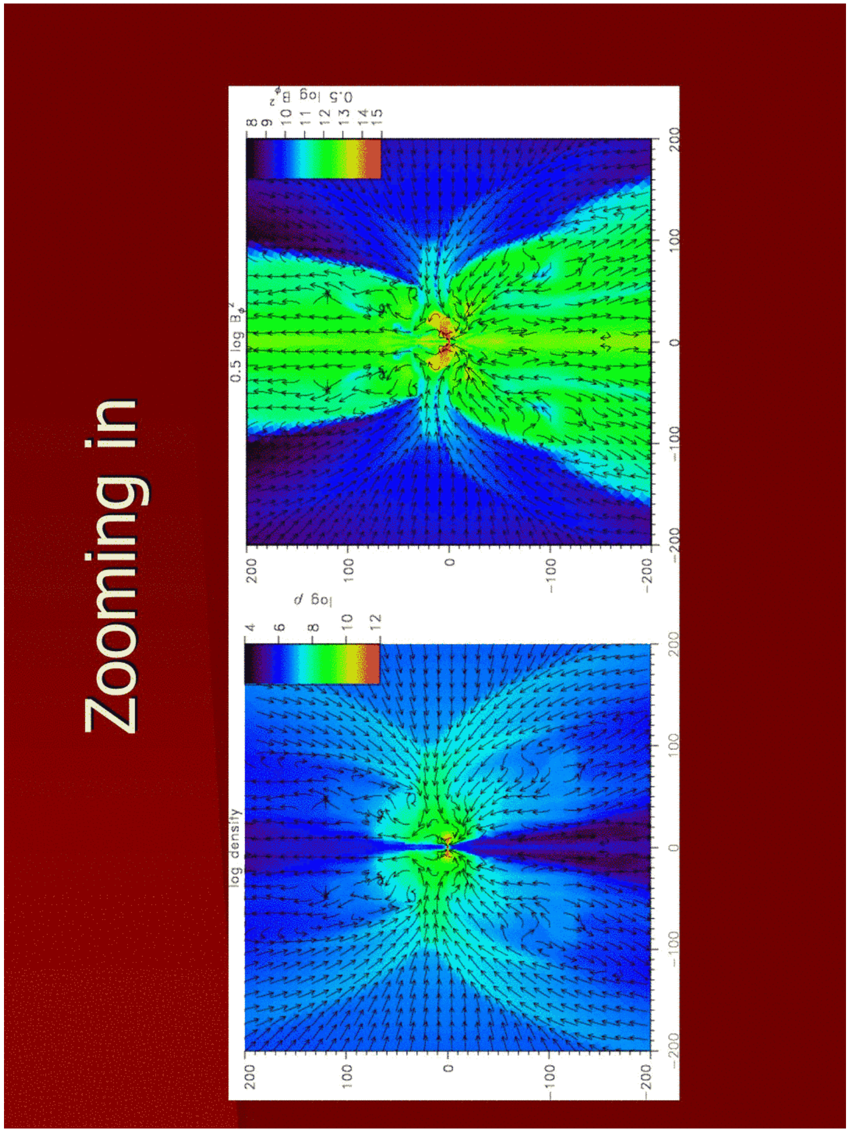
The equations are solved using the ZEUS-2D code (Stone & Norman 1992)

Results

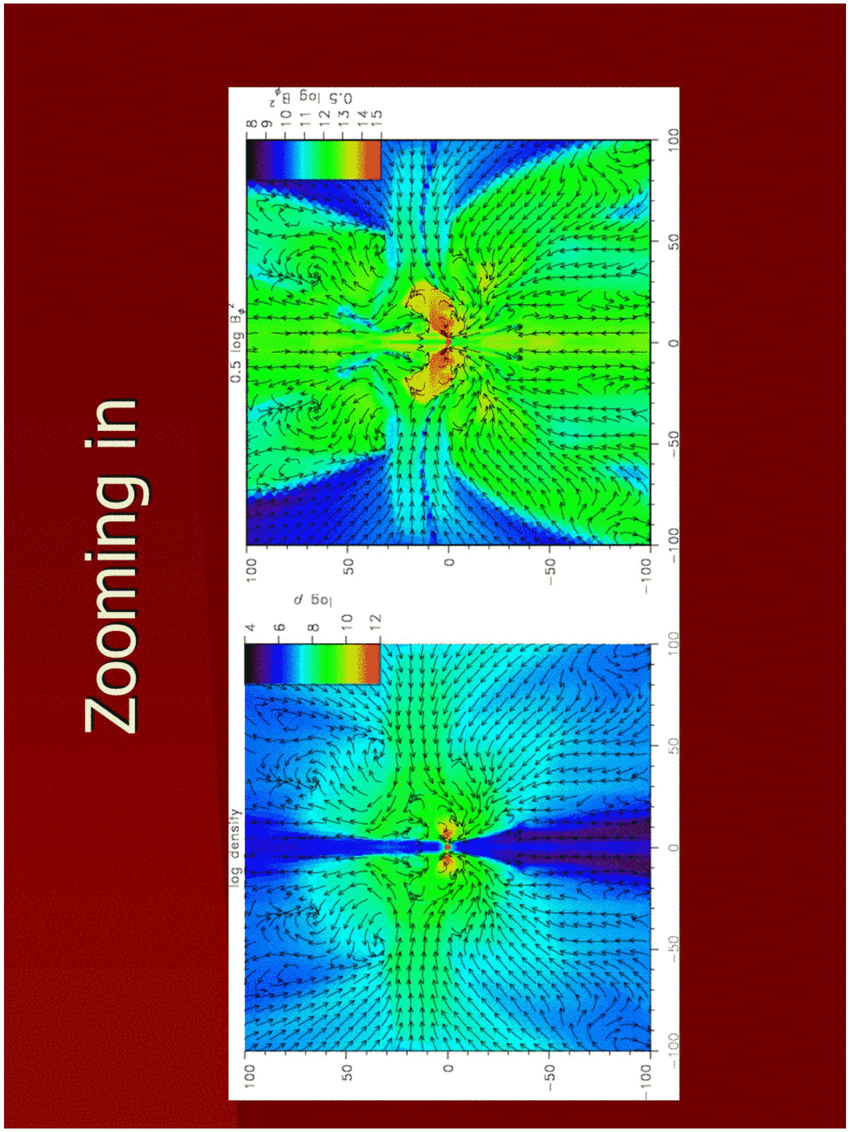




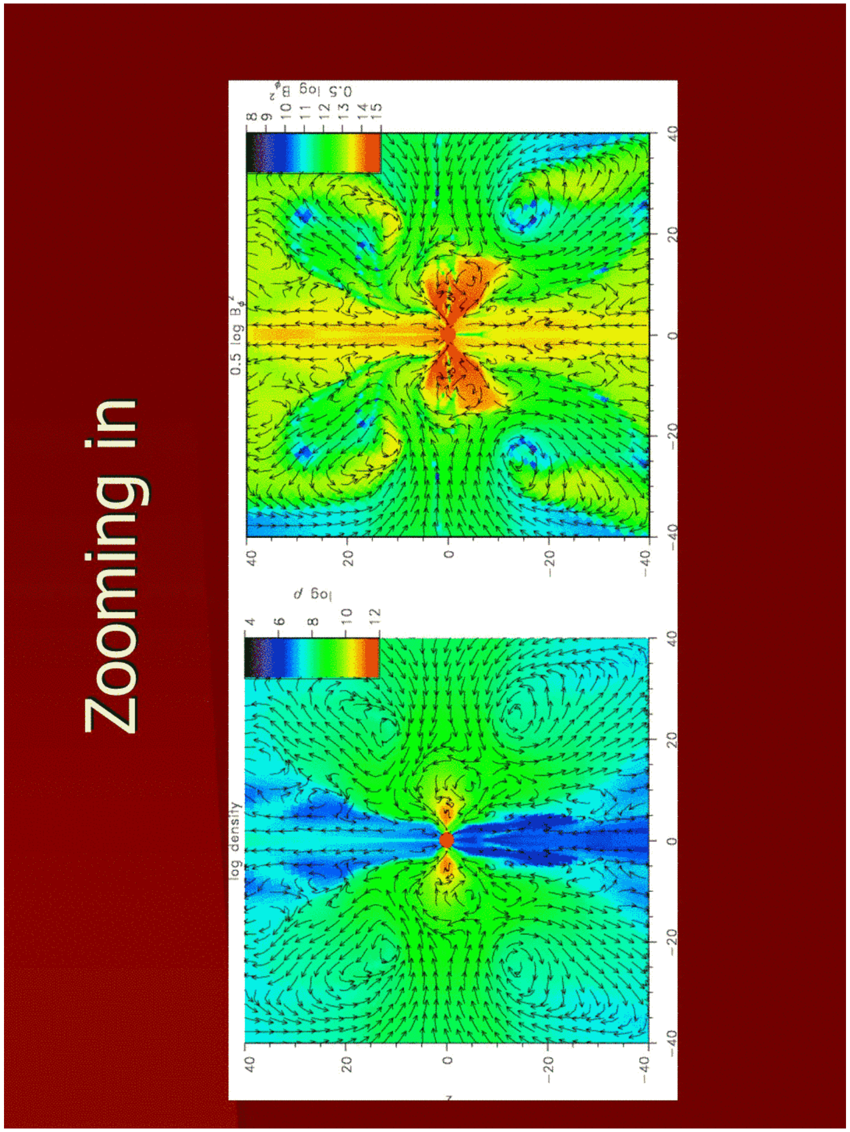
Proga et al. (2003)



Zooming in

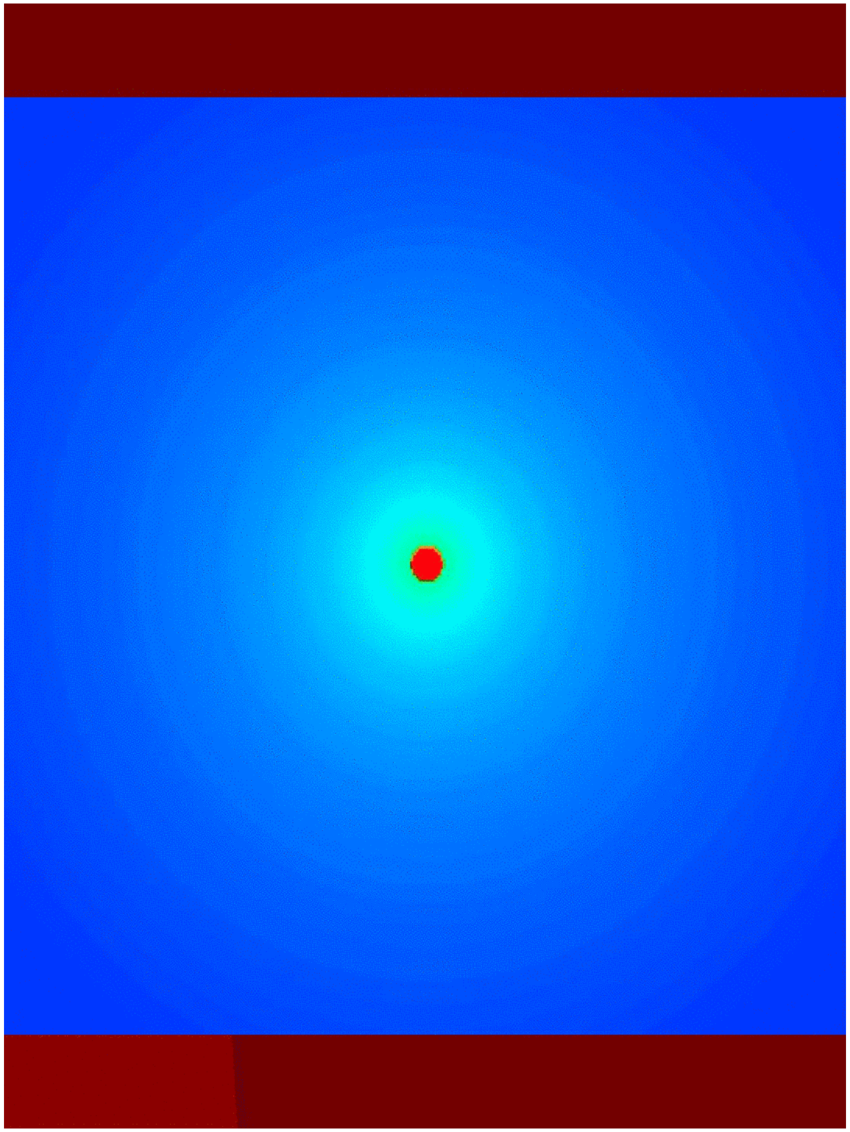


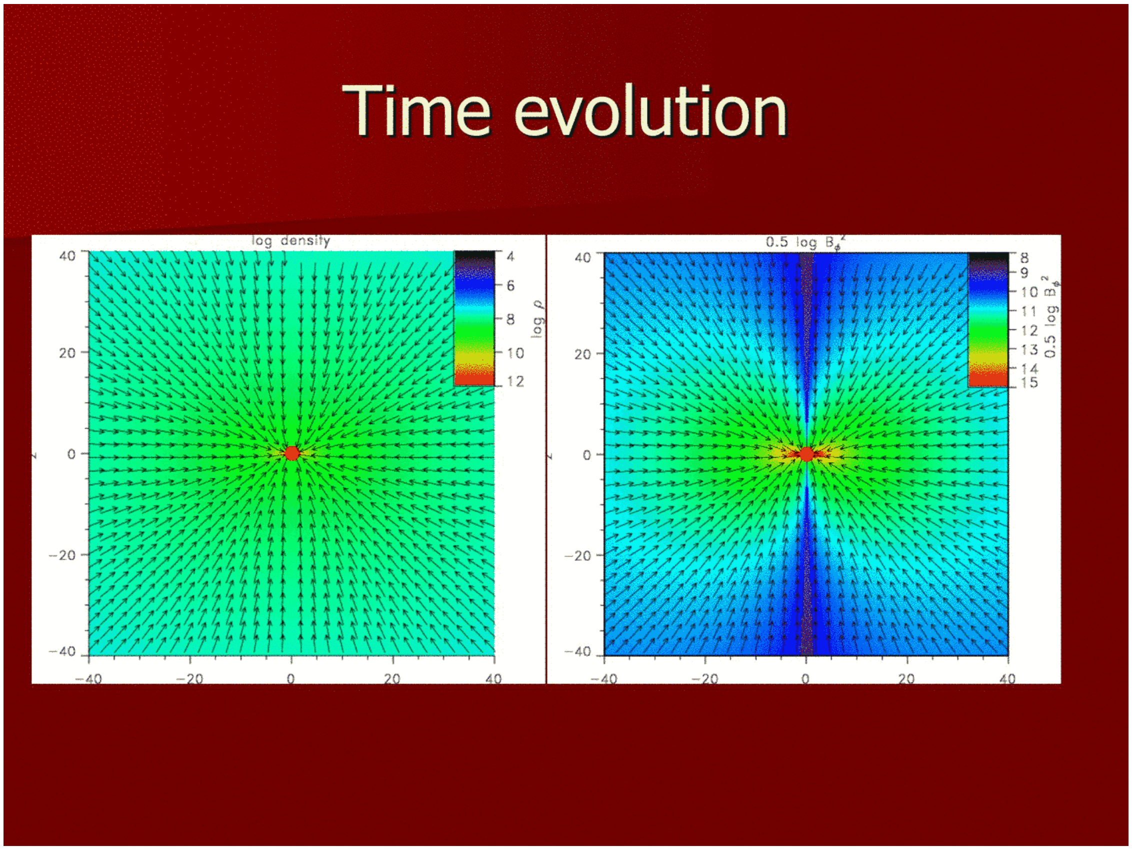
Zooming in



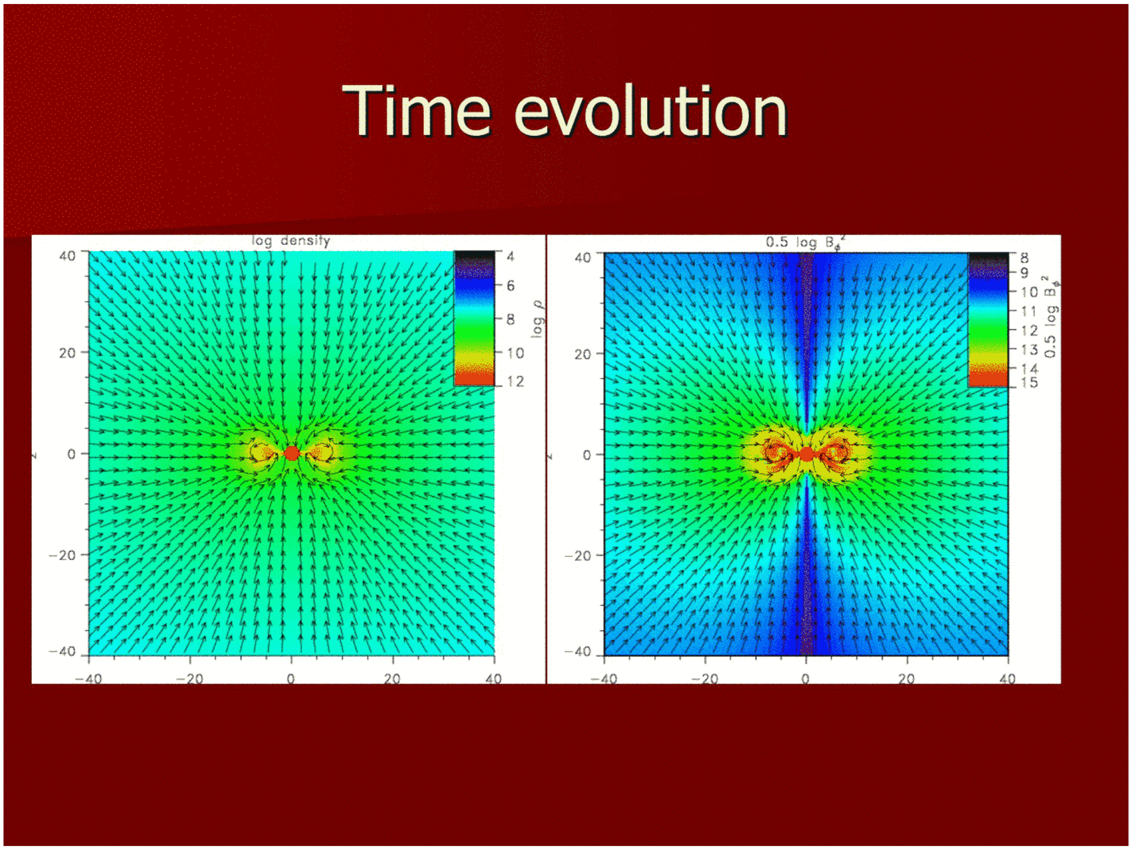
Zooming in

log density
log ρ
4
6
8
10
12
0.5 log B$_\phi^2$
8
9
10
11
12
13
14
15
40
20
0
−20
−40
z

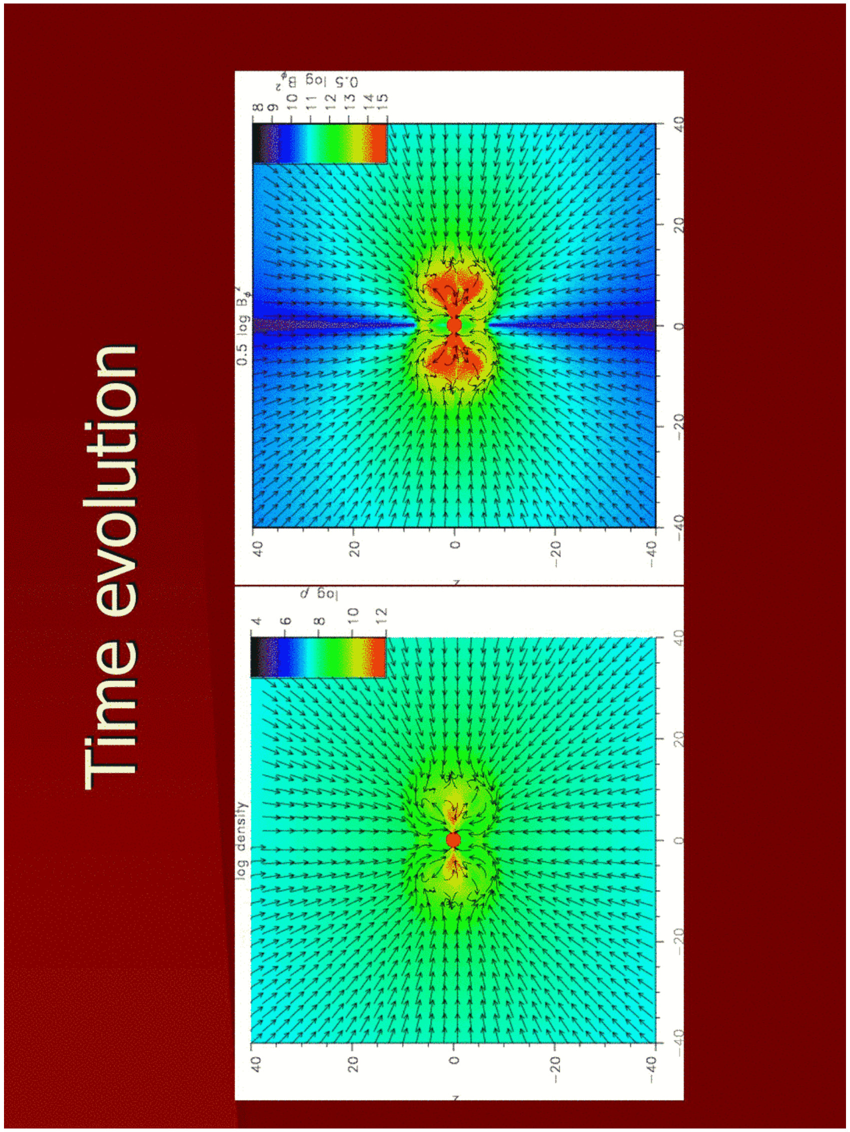




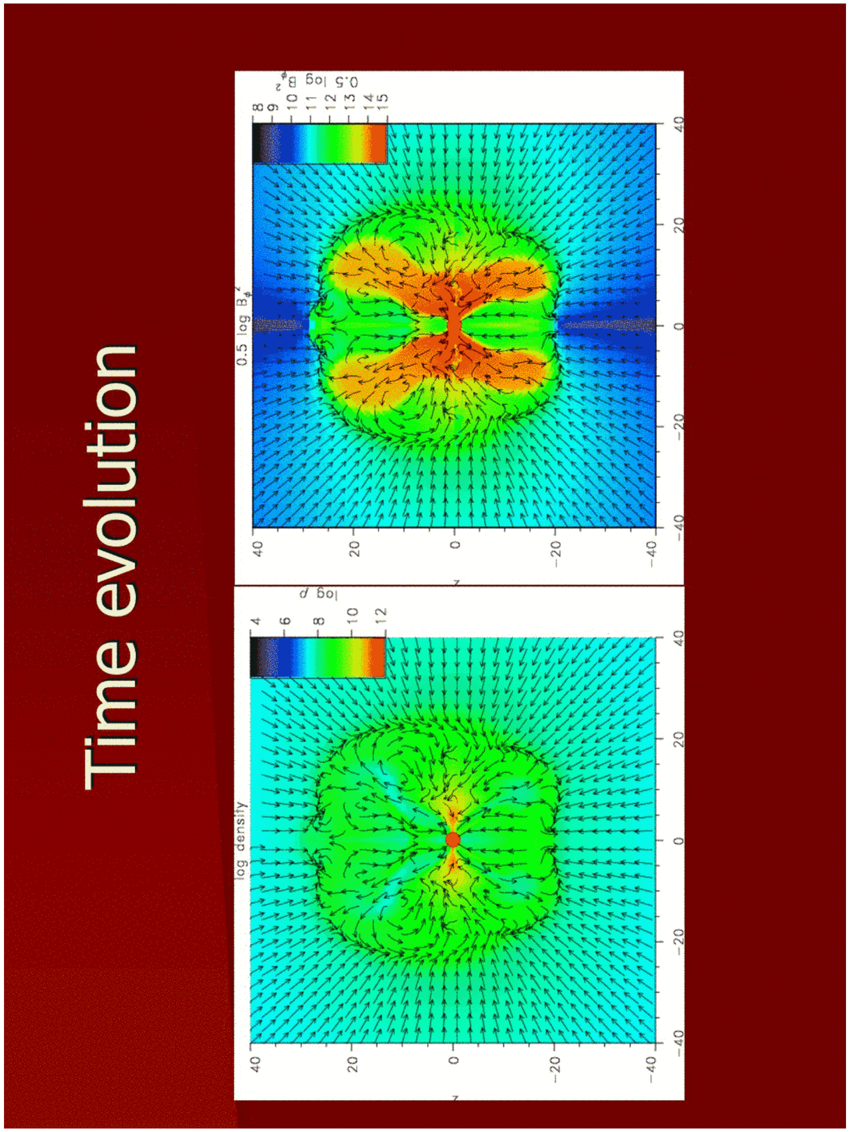
Time evolution



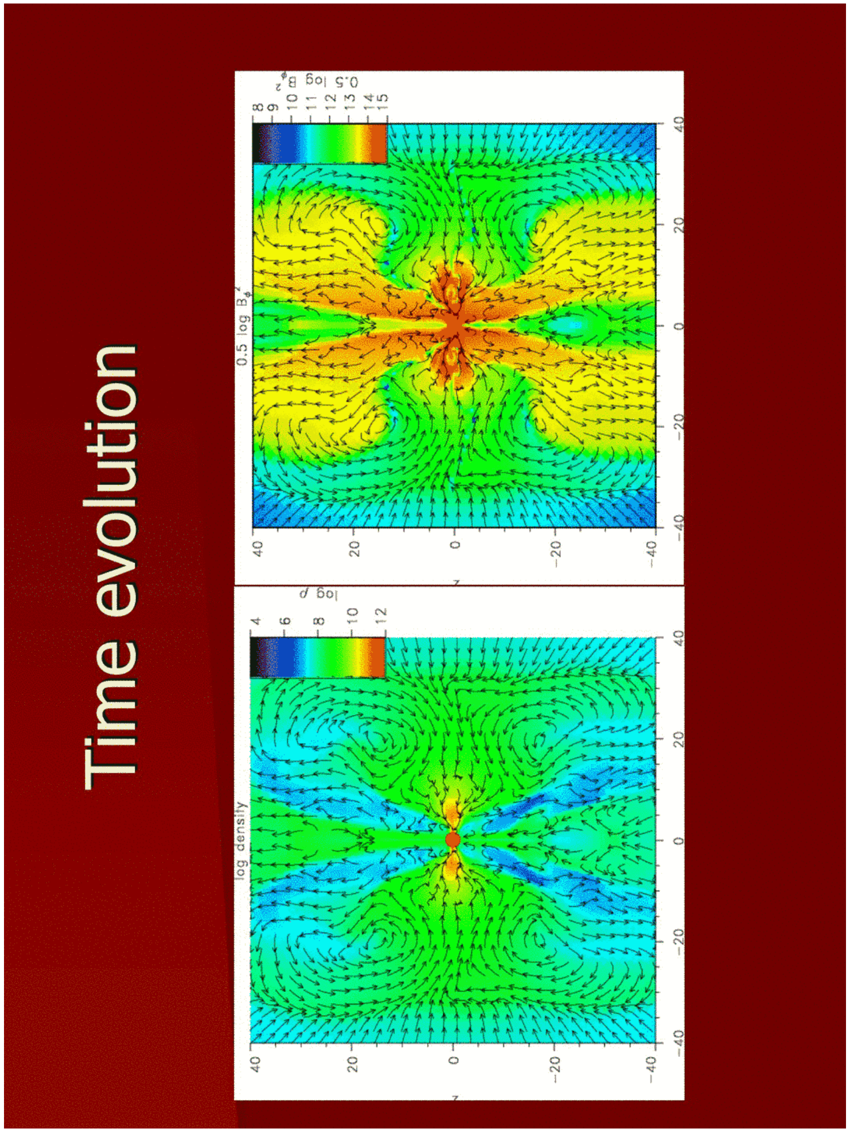
Time evolution



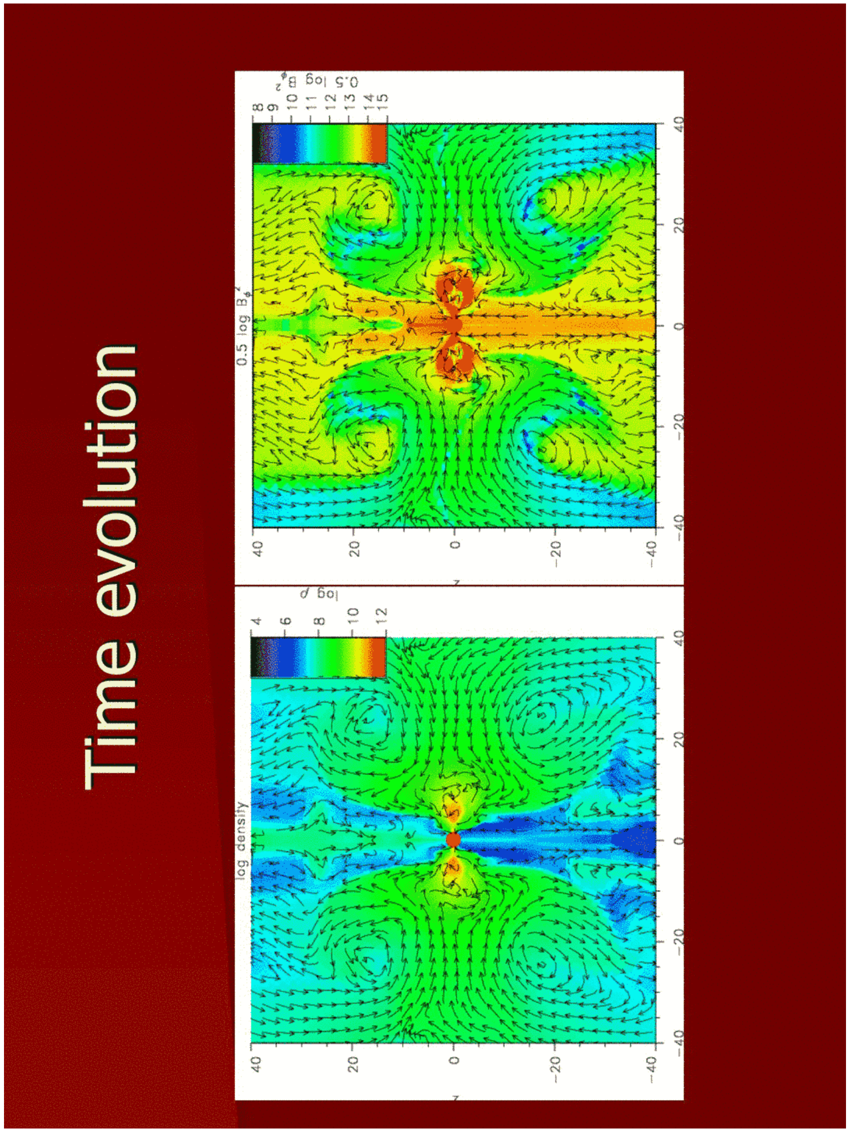
Time evolution



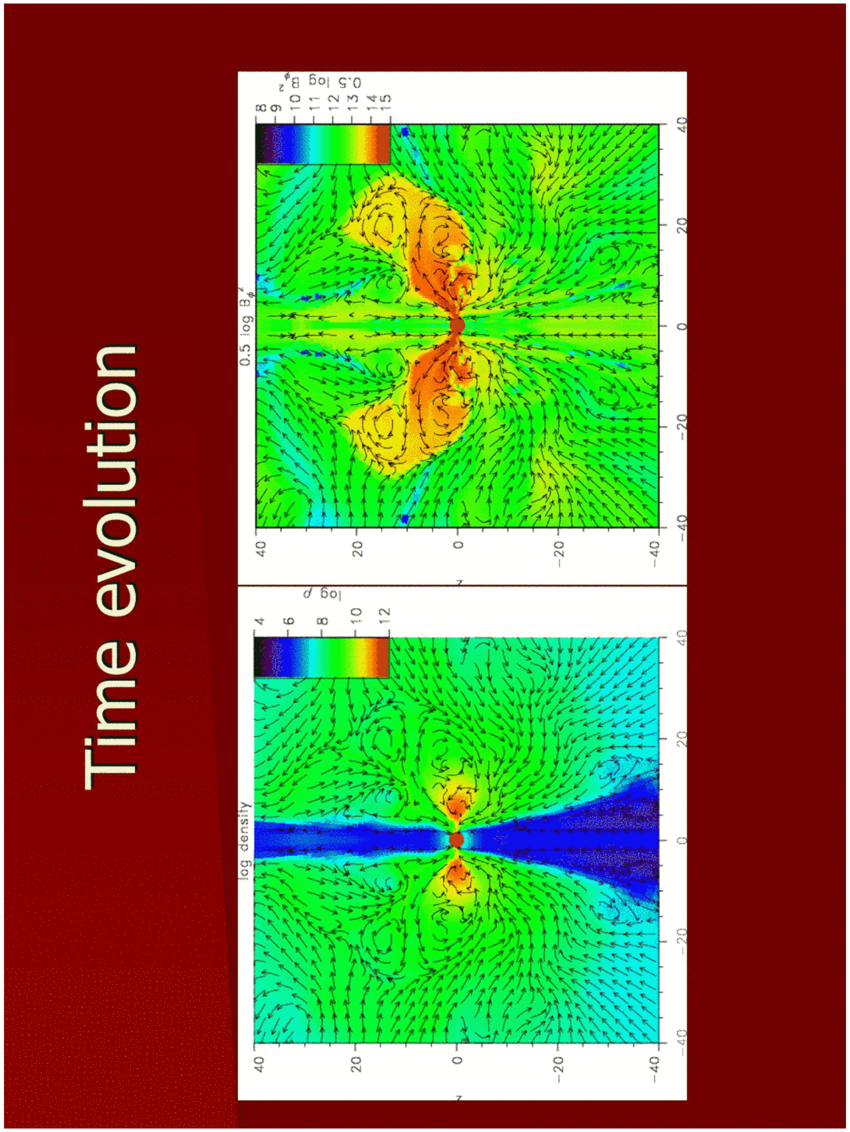
Time evolution



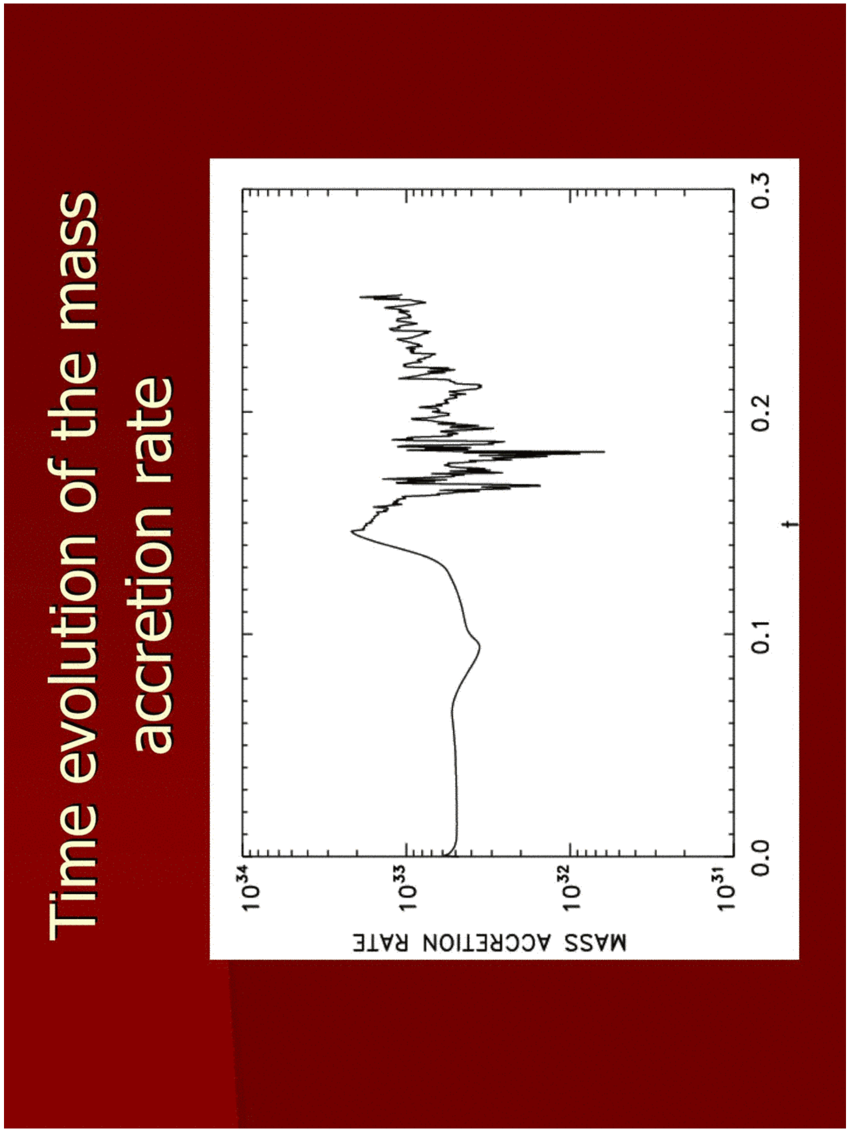
Time evolution



Time evolution

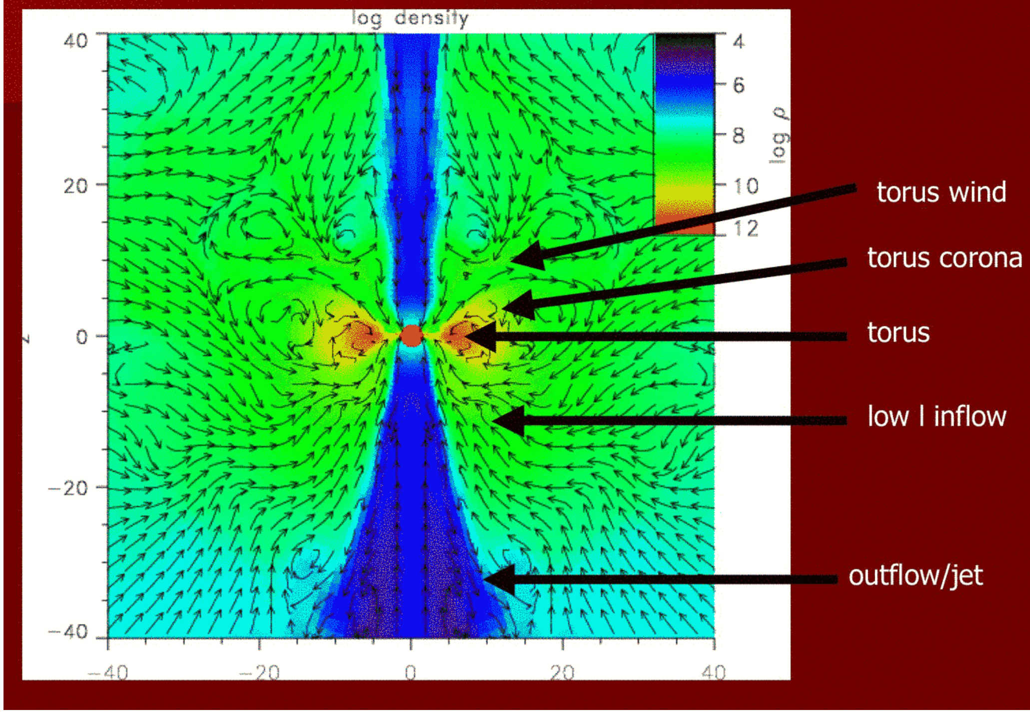


Time evolution



Time evolution of the mass accretion rate

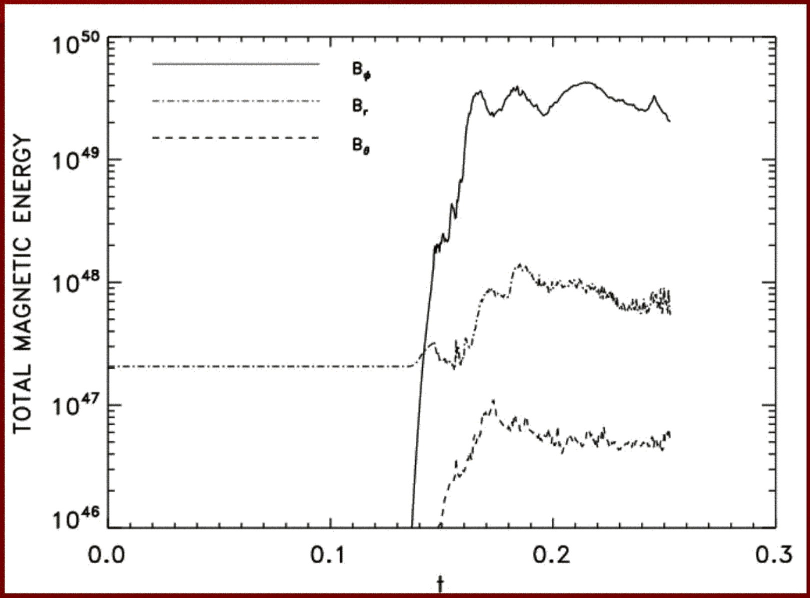
Multi-component flow.



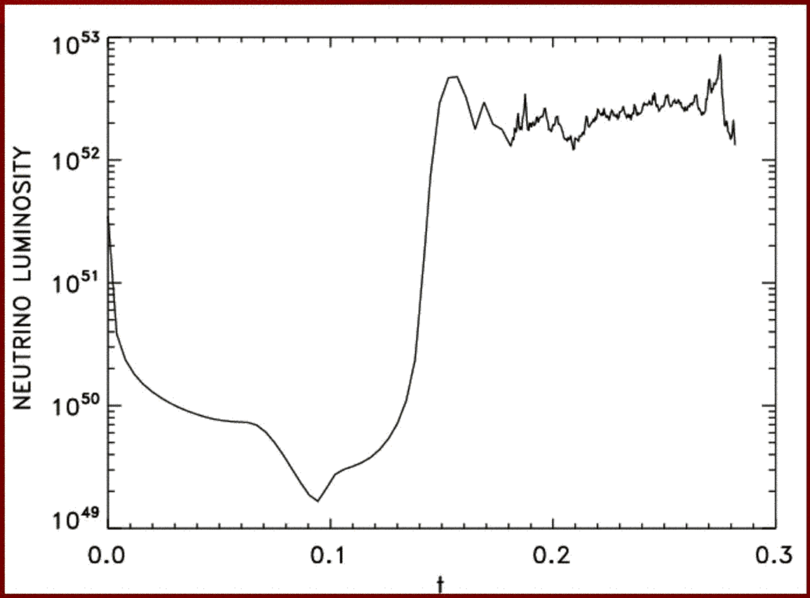
Implications of variable accretion flows:

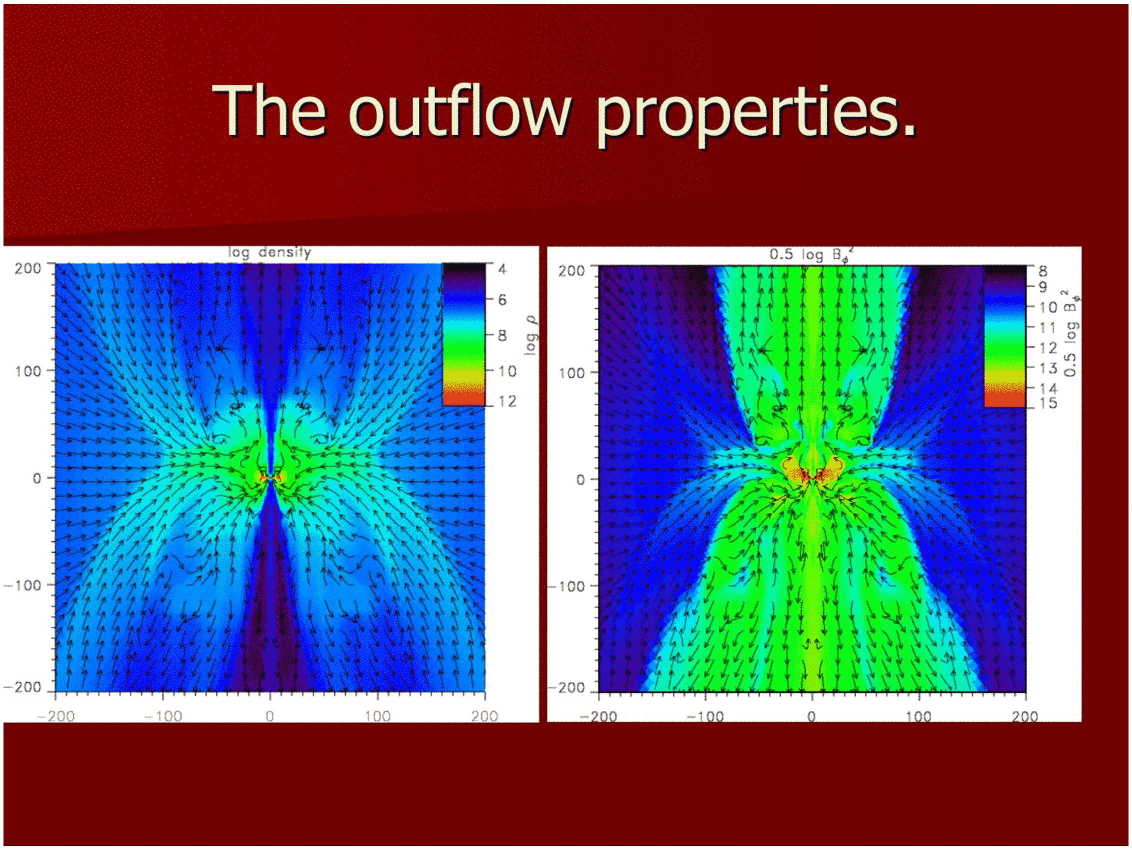
- Energy dissipation
- Light curves
  - direct
  - indirect: triggering internal shocks or causing variable external shock or both.

Time evolution of total magnetic energy.

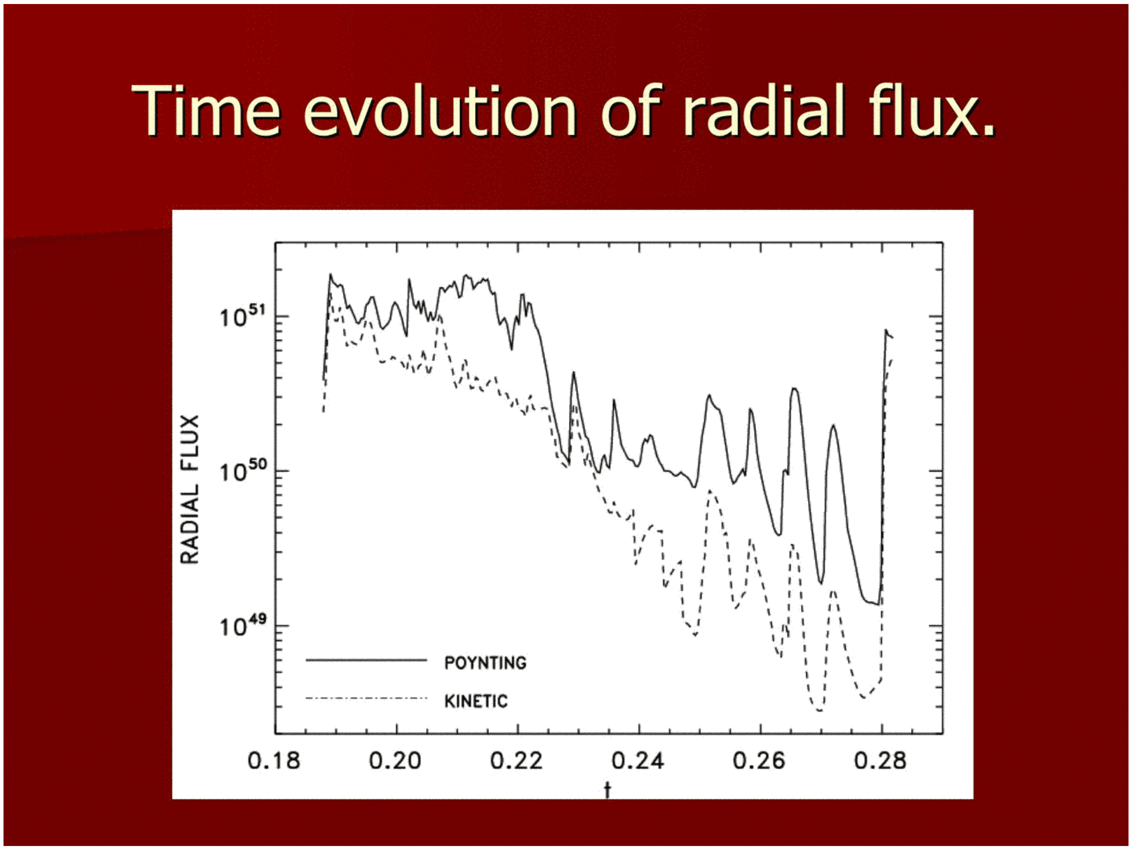


Time evolution of the neutrino luminosity.



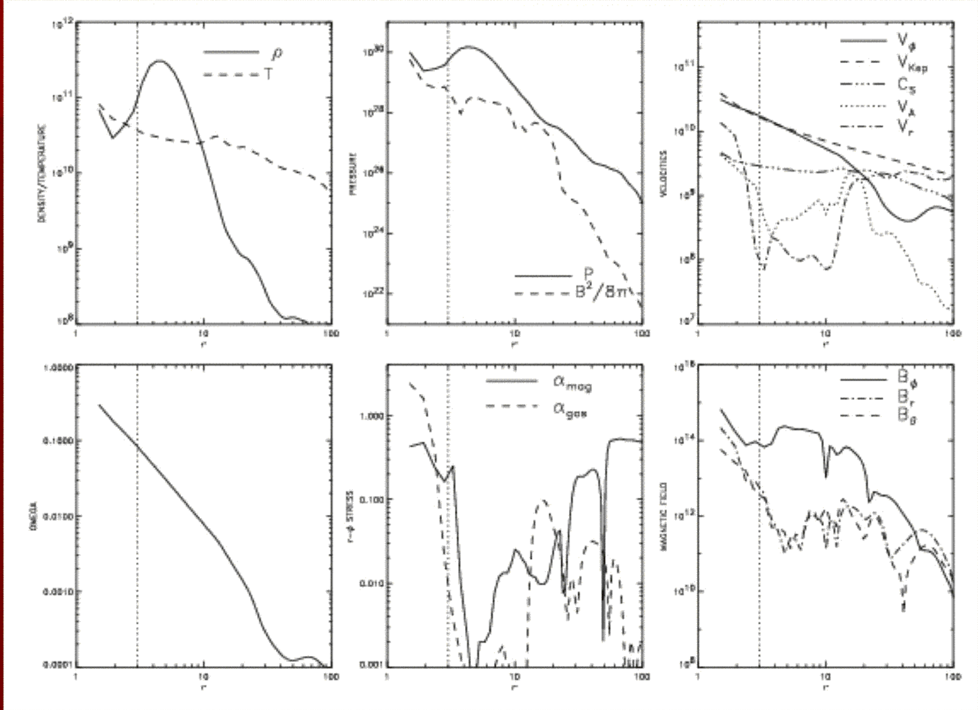


The outflow properties.

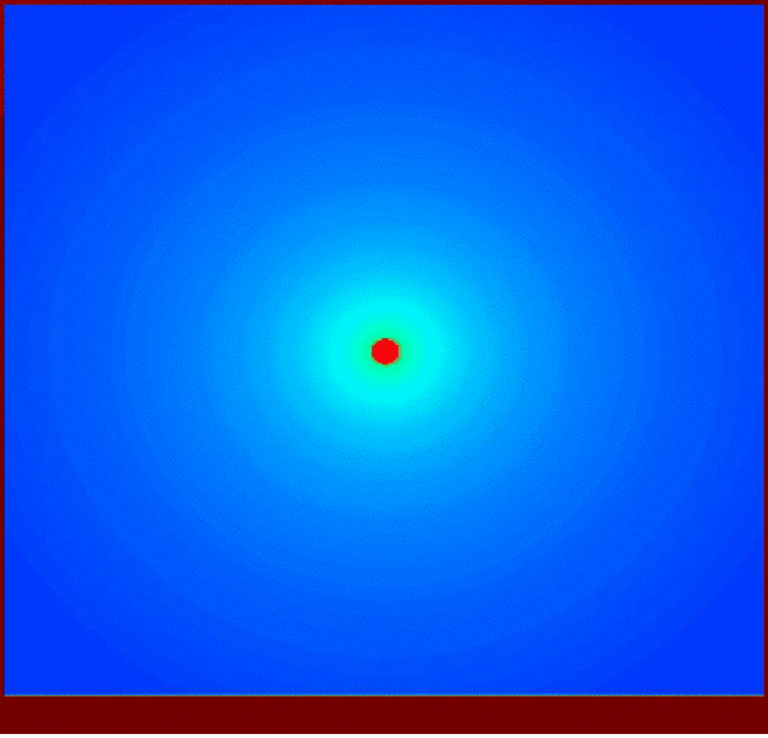


Time evolution of radial flux.

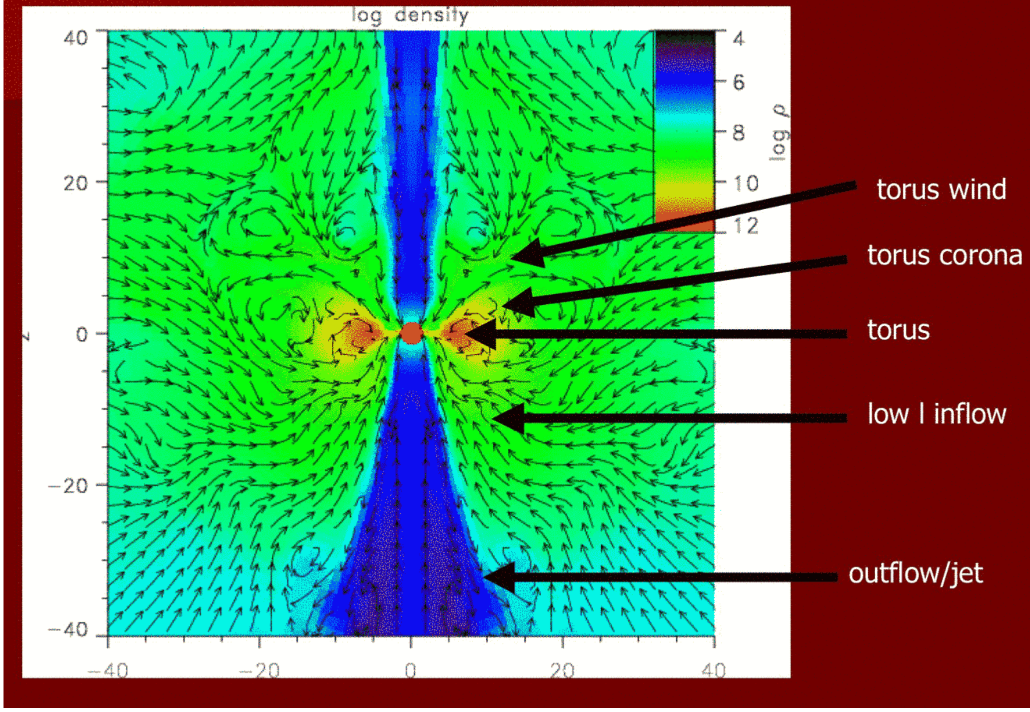
Radial profiles



How weak the initial magnetic field can be?



Multi-component flow.



torus wind

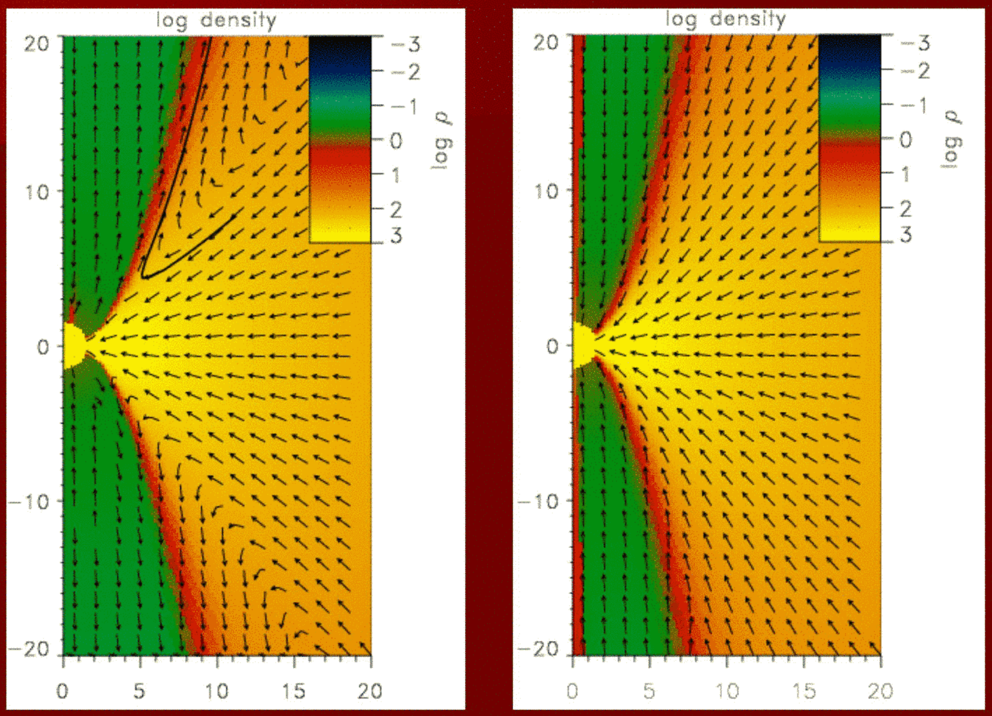
torus corona

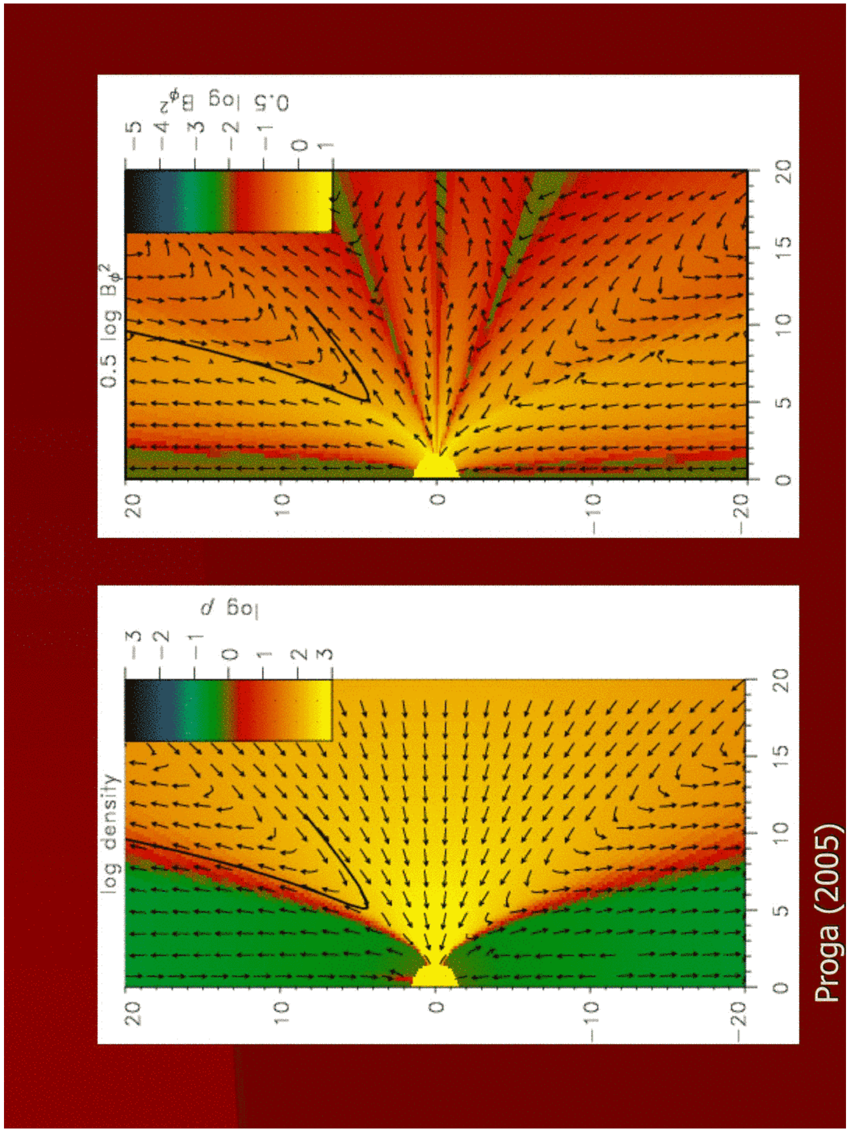
torus

low l inflow

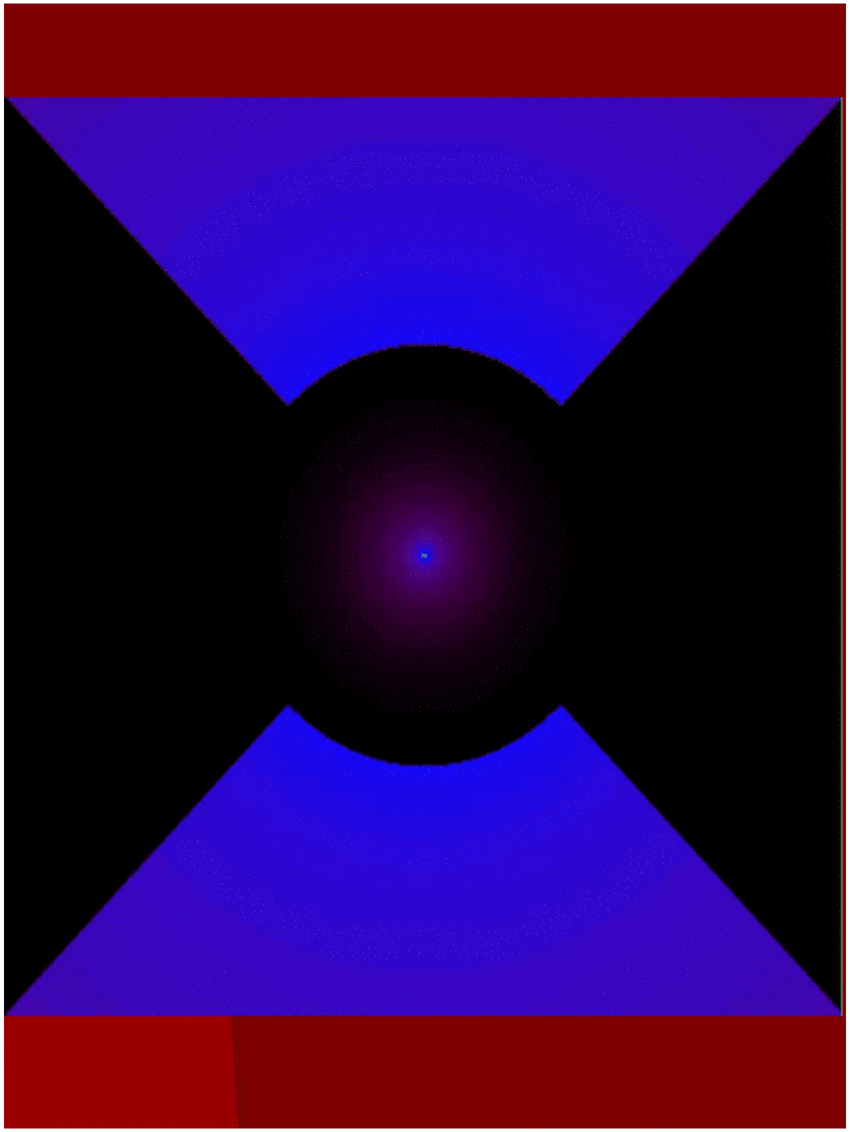
outflow/jet

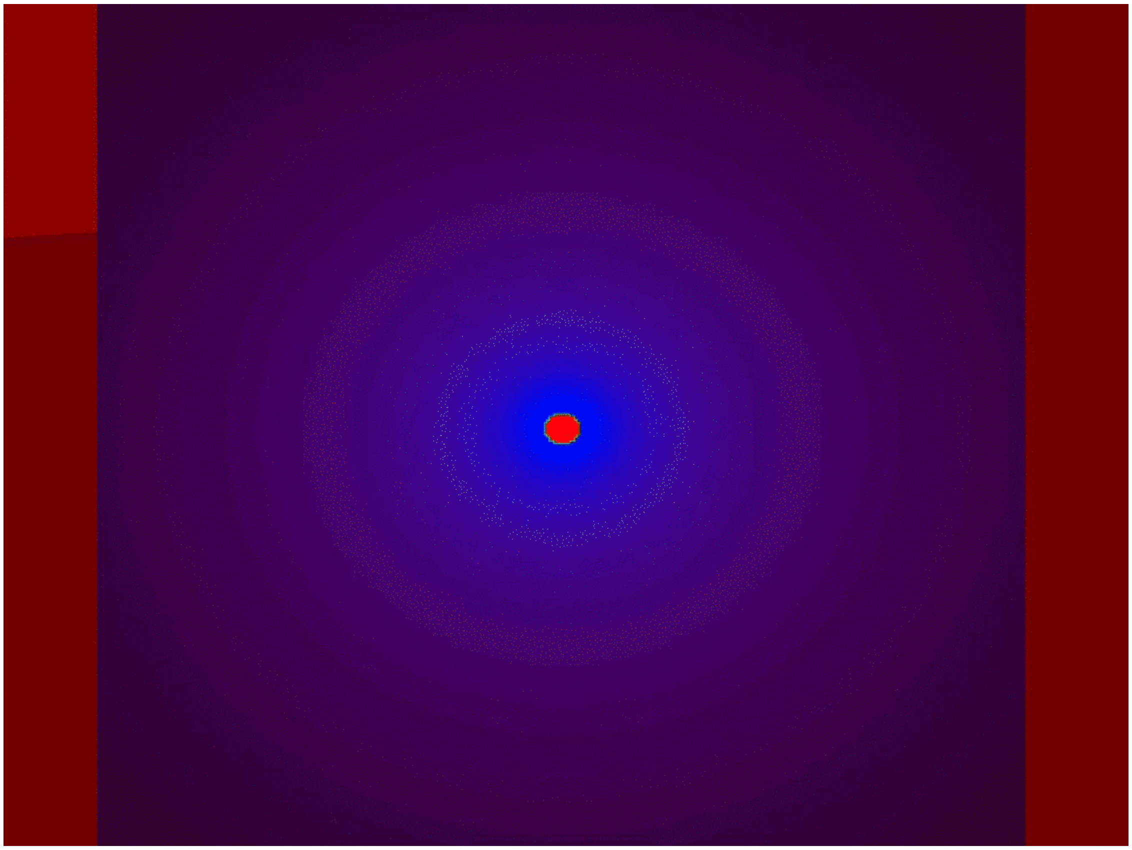
Does it have to be so complex?




0.5 log B$_\phi^2$
−5 −4 −3 −2 −1 0 1
0.5 log B$_\phi^2$
log density
−3 −2 −1 0 1 2 3
log ρ
20 10 0 −10 −20
0 5 10 15 20

Proga (2005)



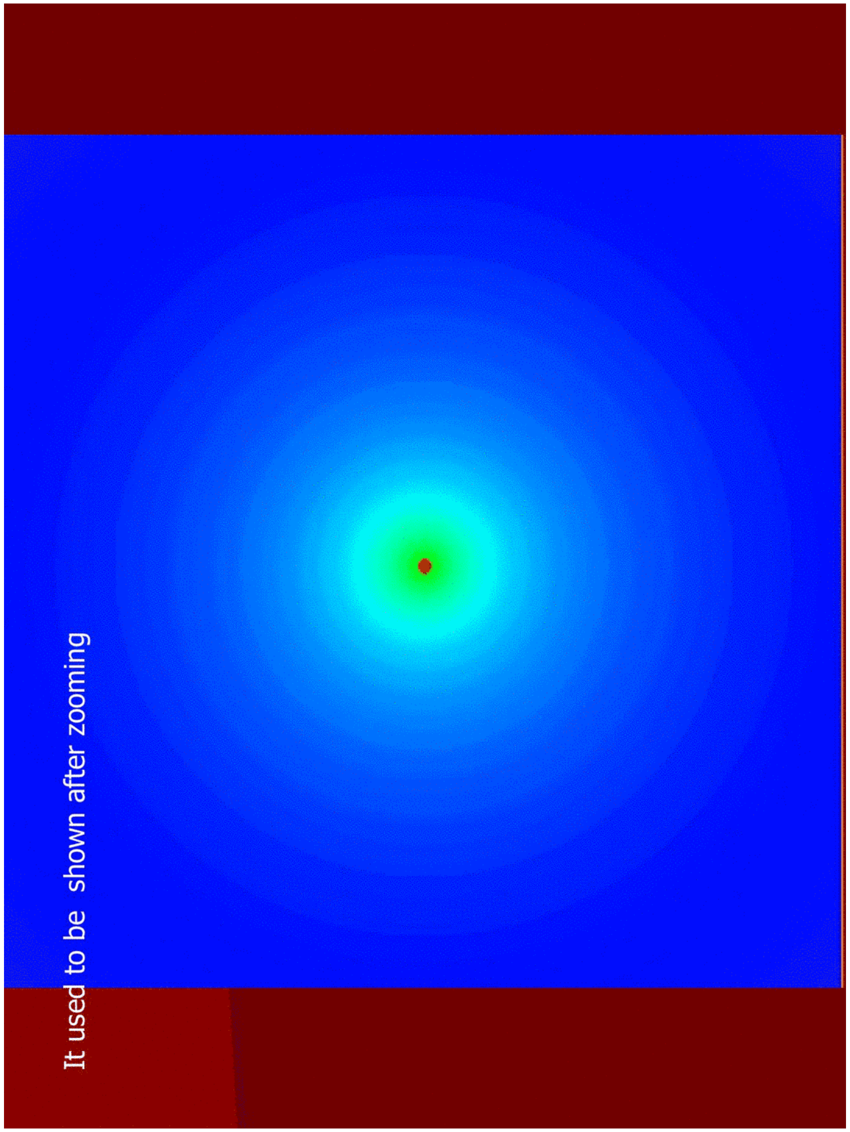


Conclusions

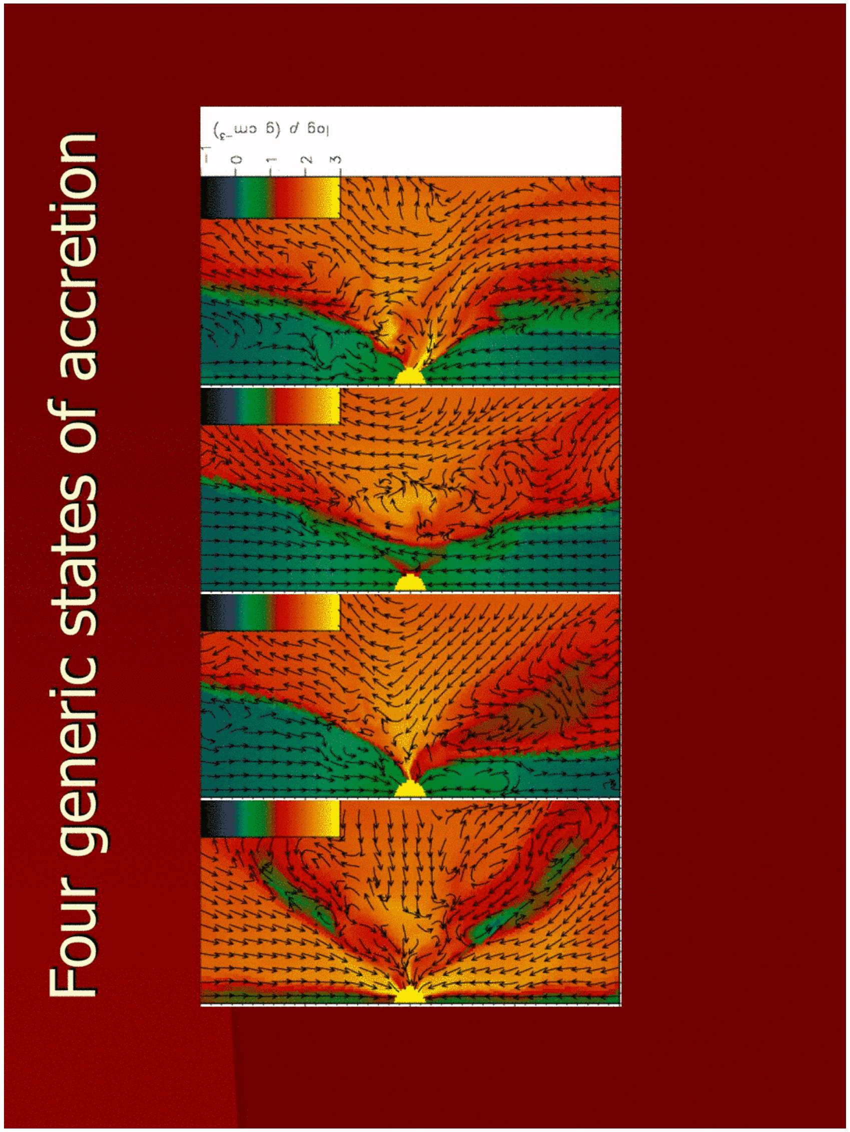
- Accretion can be via the torus due to MRI and via the polar funnel where material has zero or low l.
- MHD effects launch, accelerate and sustain a polar outflow (even for very low 'l' and very weak initial magnetic fields).
- The outflow can be Poynting flux-dominated.
- The torus, its corona and outflow can shut off the polar accretion.
- The MHD collapsar model is in many ways consistent with the HD model but the MHD model offers 'far more for far less' and shows more insights into the physics of the central engine of GBRs.
- Simulations of the MHD flows in the collapsar model are consistent with other simulations of MHD accretion flows onto SMHB (RIAF, GRMHD).

Future Work

- Cover larger radial domain (five or so orders of magnitude). Need AMR!?
- Explore various geometries of the initial magnetic field.
- Add more physics (e.g., neutrino driving)
- 3D MHD simulations.
- Relativistic/GR MHD simulations.
- Check observational consequences (e.g., burst duration, light curves, GRBs vs SN). Timing is good as SWIFT is to be launched soon.



It used to be shown after zooming



Four generic states of accretion

$l = l_0 f(\theta)$

$f_1(\theta) = 1 - |\cos(\theta)|$

$f_2(\theta) = 1 - \cos^{10}(\theta)$

l is in units of $2R_S c$

$\theta_1 = f^{-1}[\min(1, \frac{1}{l_0})]$

Some facts:

Energy Release from
Astronomical Objects

10^33 ergs/s = Sun

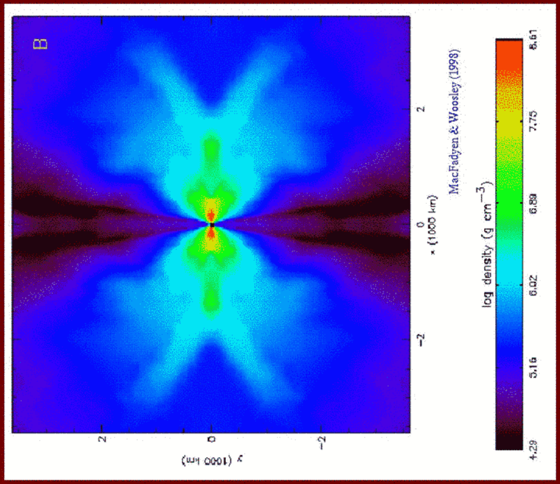
10^39 ergs/s = nova

10^41 ergs/s = SN

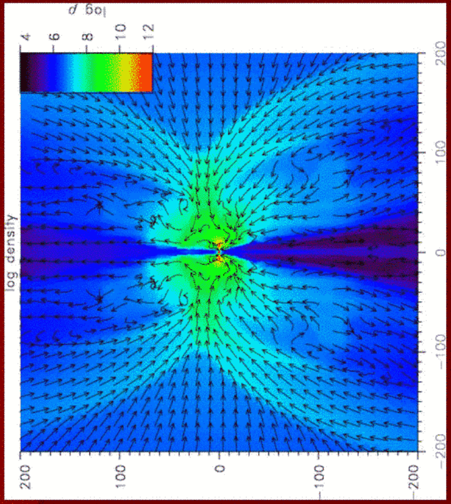
10^45 ergs/s = galaxy

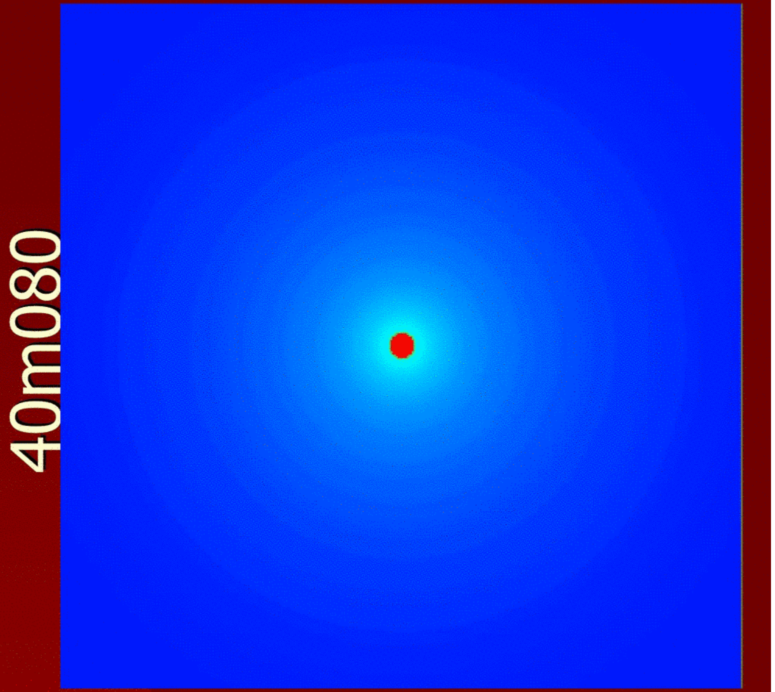
(in some cases just from the nuclei – AGN)

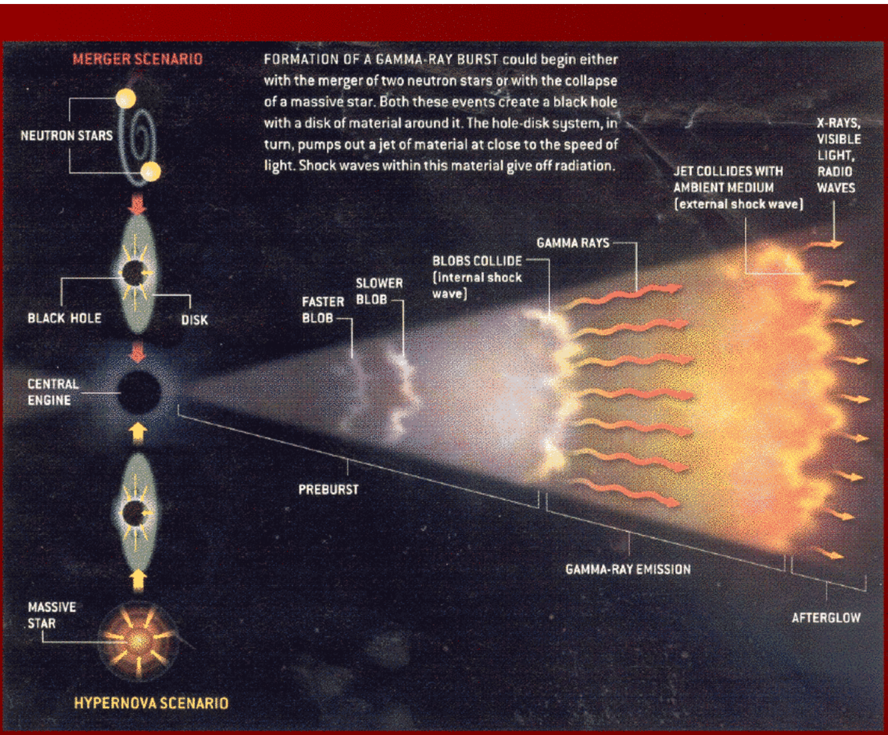
10^52 ergs/s = GRB



MacFadyen & Woosley (1998)





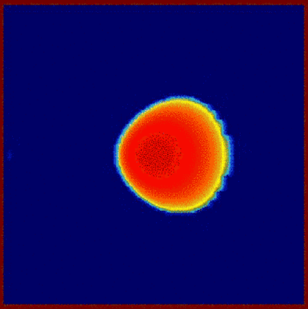


FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

- http://zebu.uoregon.edu/~js/lectures/gamma_ray_bursts.html

The Dynamical Structure of Nonradiative Black Hole Accretion Flows – to model LL AGN

[Hawley & Balbus (2002)]



3D simulations:Colors show log of azimuthally-averaged density.

$l = l_0 f(\theta)$

e.g.,

$f_1(\theta) = 1 - |\cos(\theta)|$

$f_2(\theta) = 1 - \cos^{10}(\theta)$

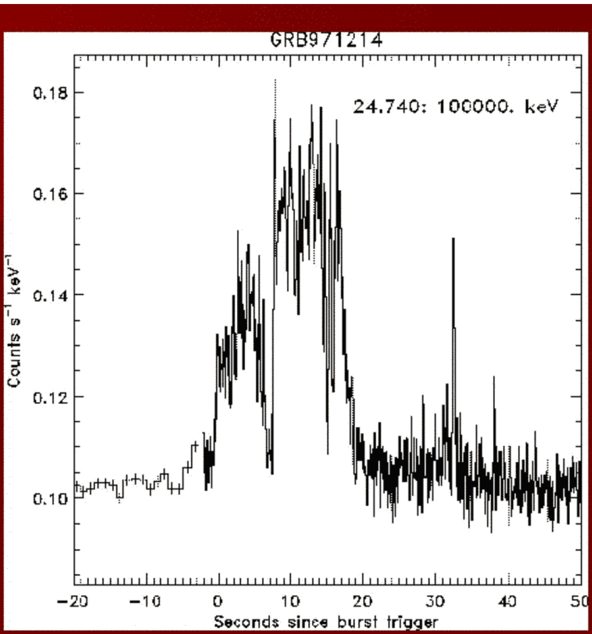
l is in units of $2R_S c$

$\theta_1 \equiv f^{-1}[\min(1, \frac{1}{l_0})]$

Energy Release with
Astronomical
Experience

10^33 ergs/s = Sun
10^39 ergs/s = nova
10^41 ergs/s = SN
10^45 ergs/s = galaxy

10^52 ergs/s = GRB



The gamma-ray intensity of GRB971214 evolving with time, as observed with the BATSE detectors onboard NASA's Compton Gamma-Ray Observatory.

GRB 990123

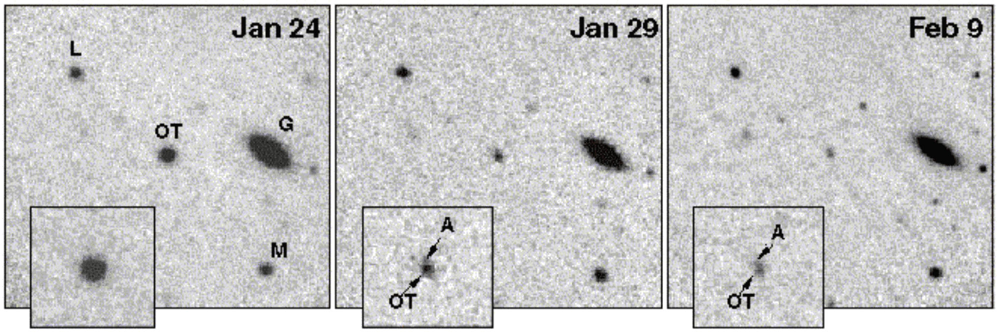
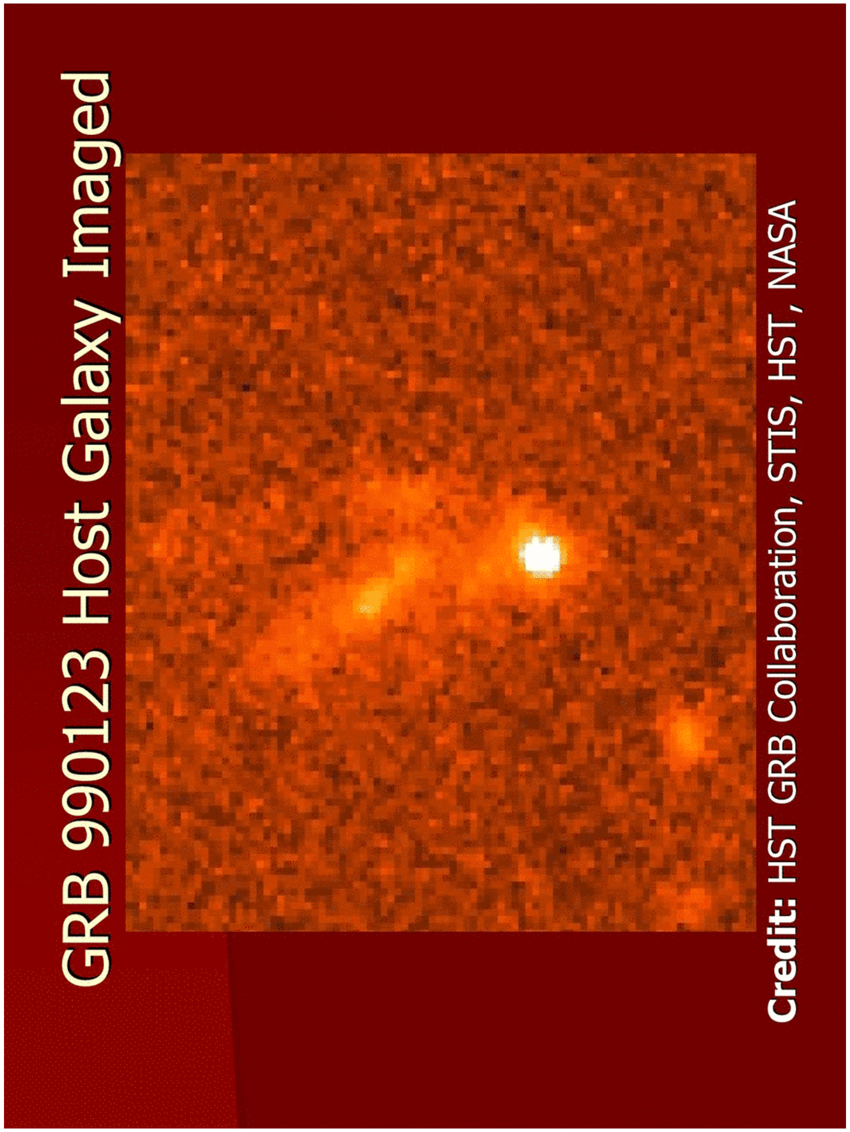
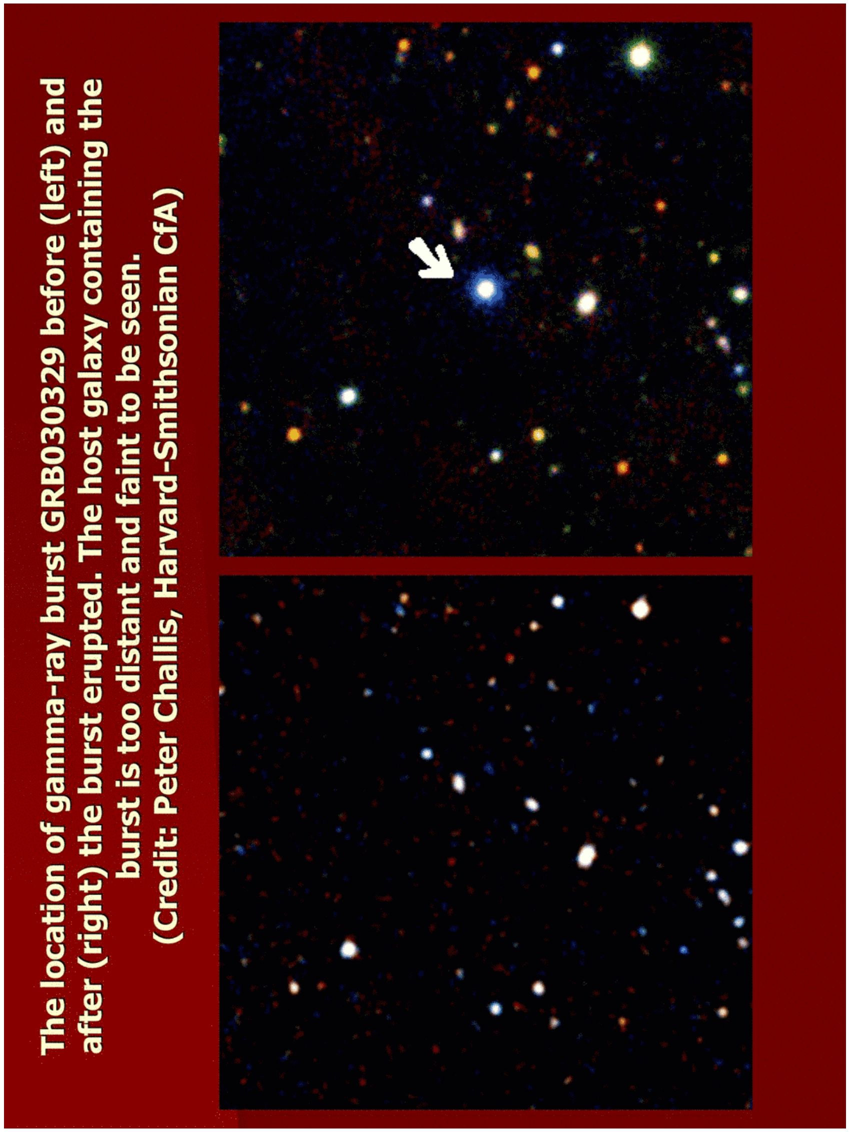


Fig. 1.— Three epochs of Keck I K-band imaging of the field of GRB 990123 (24 January 1999 UT, 29 January 1999, and 9 February 1999 UT). The field shown is 32 arcsec × 32 arcsec, corresponding to about 270 physical kpc (710 comoving kpc) in projection at $z = 1.6004$ (for $H_0 = 65$ km s^{-1} Mpc^{-1} and $\Omega_0 = 0.2$). The image is rotated to the standard orientation, so that the east is to the left and north is up. In the 24 Jan image, the OT dominates the host galaxy flux, but by 29 Jan the galaxy is resolved (see inset) from the OT.



GRB 990123 Host Galaxy Imaged

Credit: HST GRB Collaboration, STIS, HST, NASA



The location of gamma-ray burst GRB030329 before (left) and after (right) the burst erupted. The host galaxy containing the burst is too distant and faint to be seen.

(Credit: Peter Challis, Harvard-Smithsonian CfA)