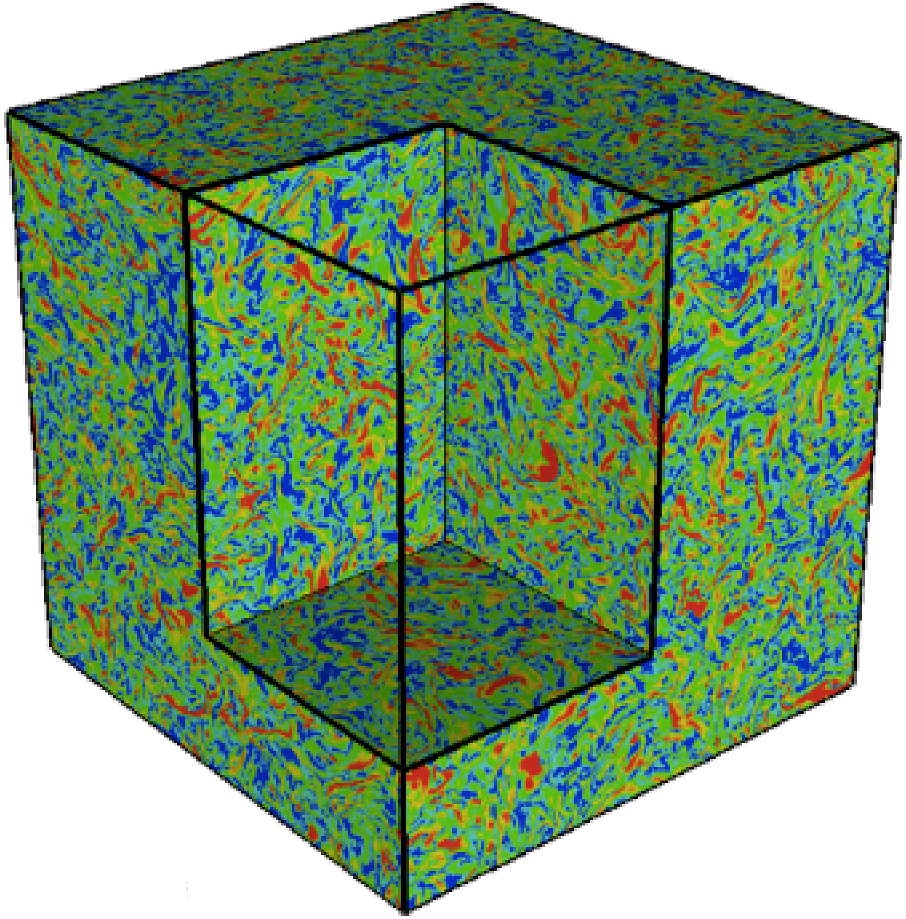
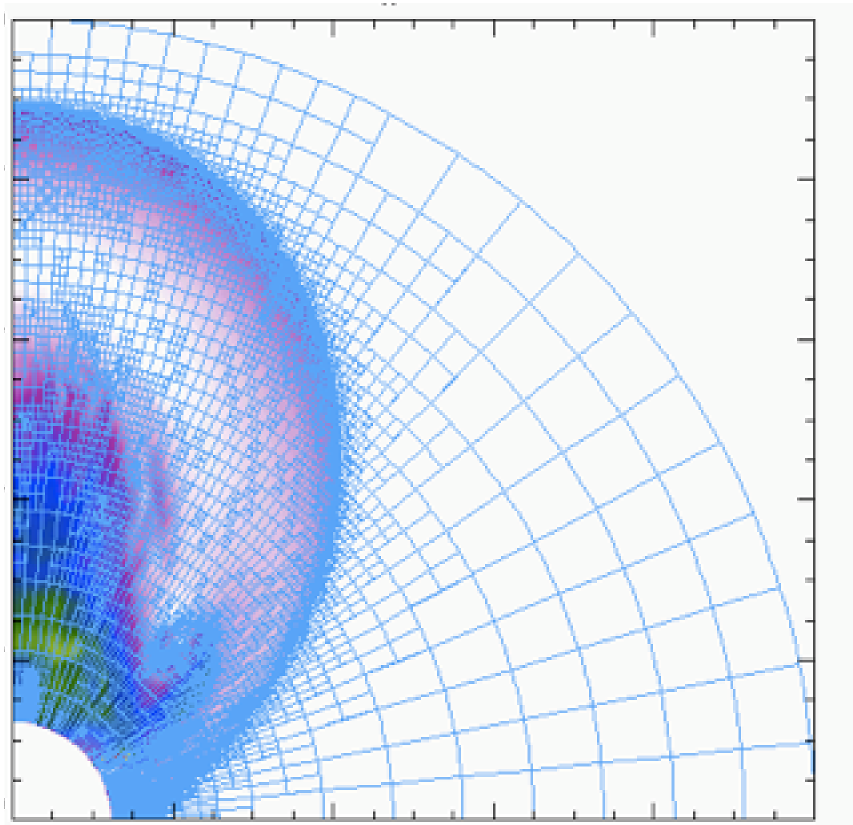
Collapsar Model

A MacFadyen (NYU)
w/ W. Zhang, P. Duffel, J. Zrake

(Magneto-) Hydrodynamics of GRB Outflows

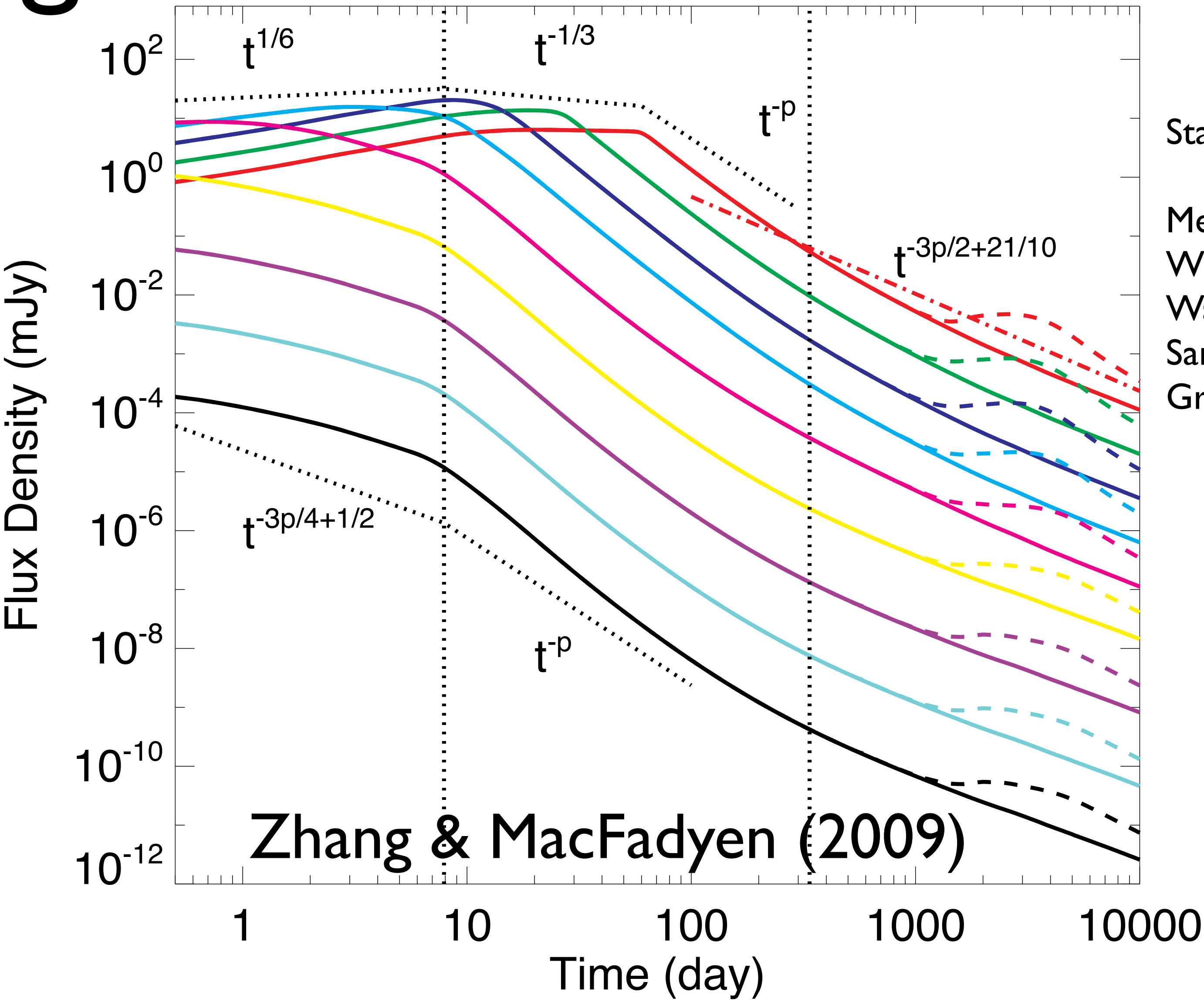


Zhang, AM&Wang, ApJL (2009)



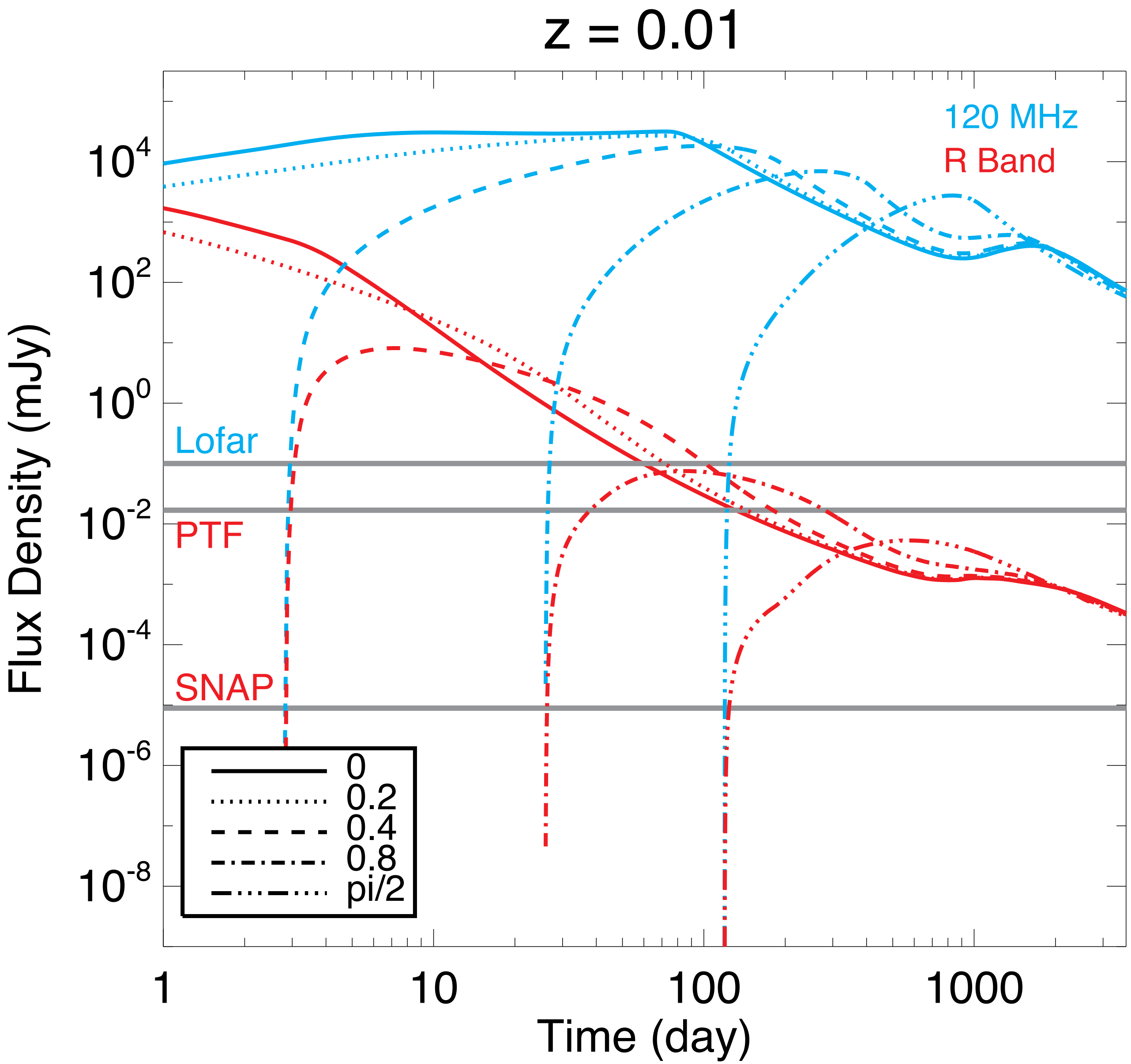
Zhang & AM ApJ (2009)

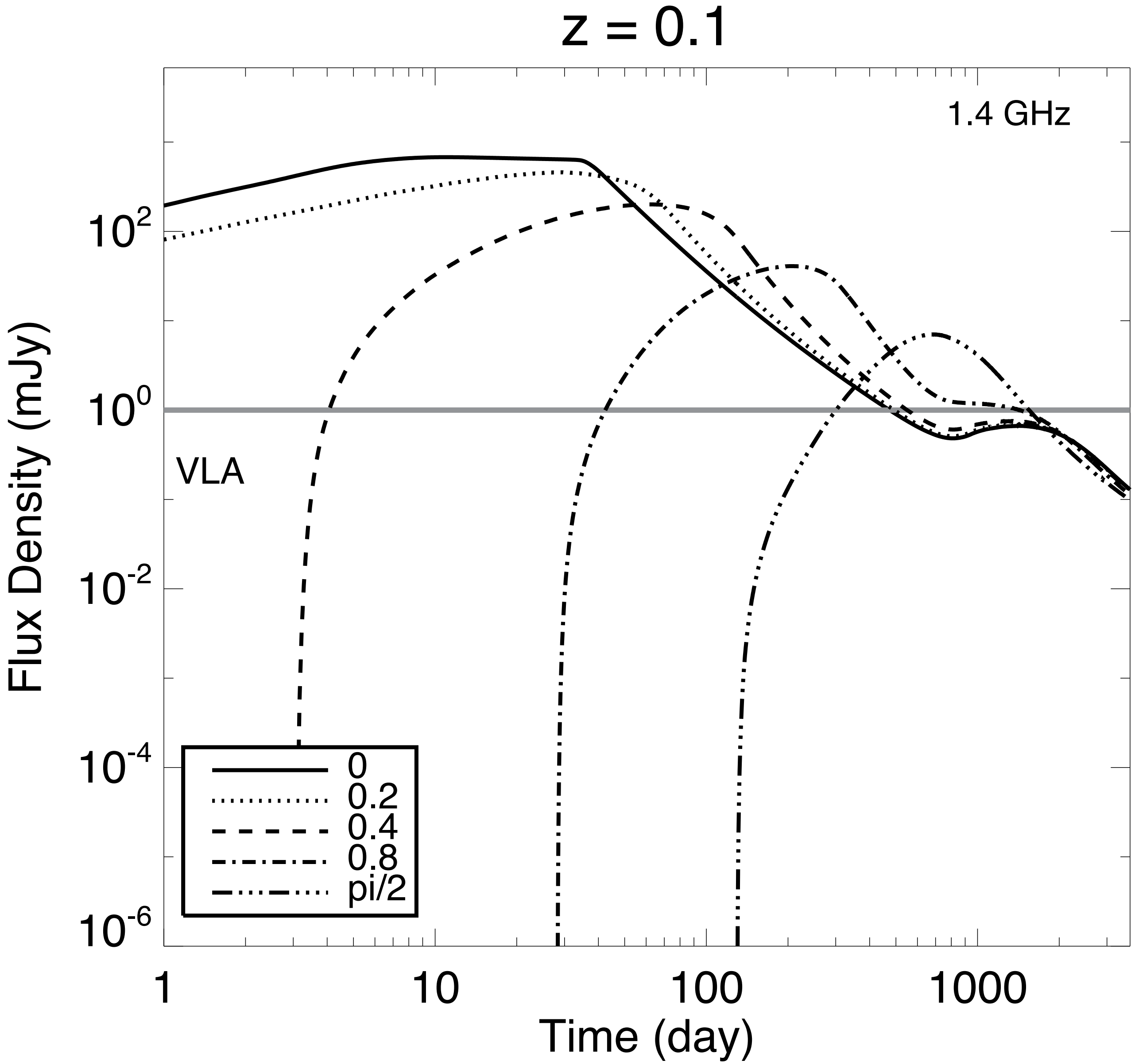
Light Curves Radio-X-Ray



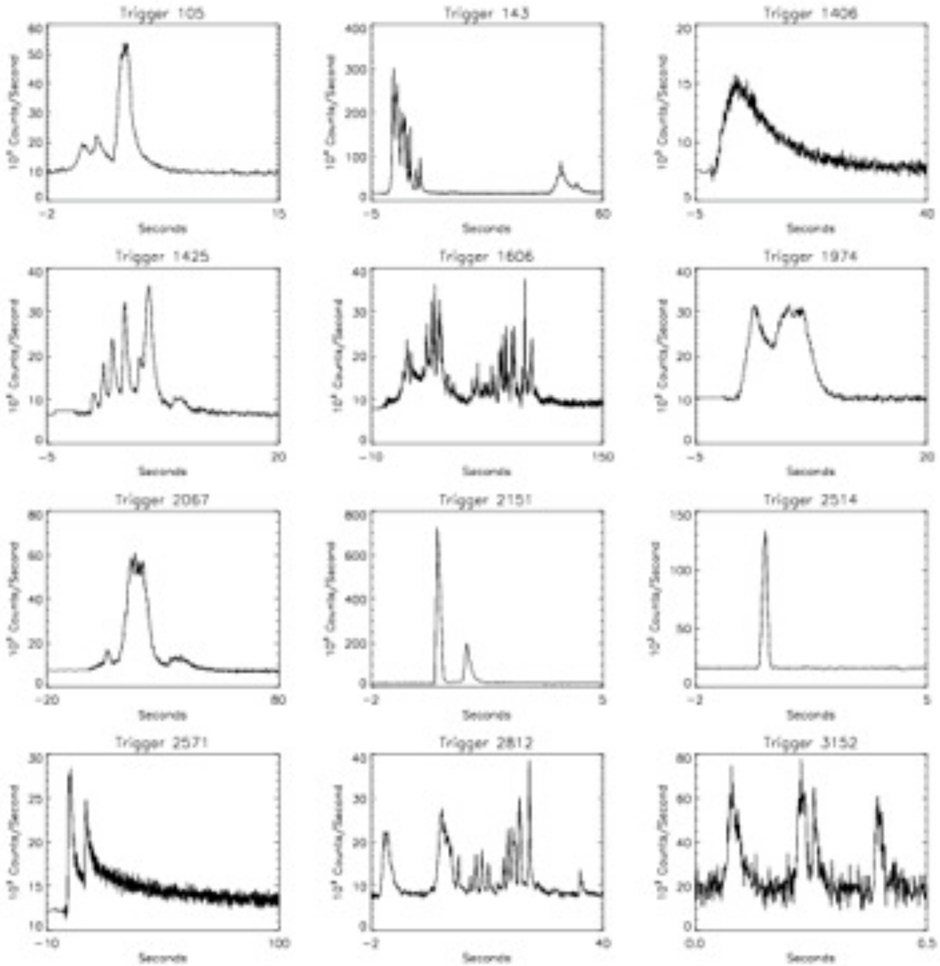
Standard AG model:

Meszaros & Rees(1997),
Wijers et al (1997),
Waxman(1997),
Sari et al(1998),
Granot et al (1999)

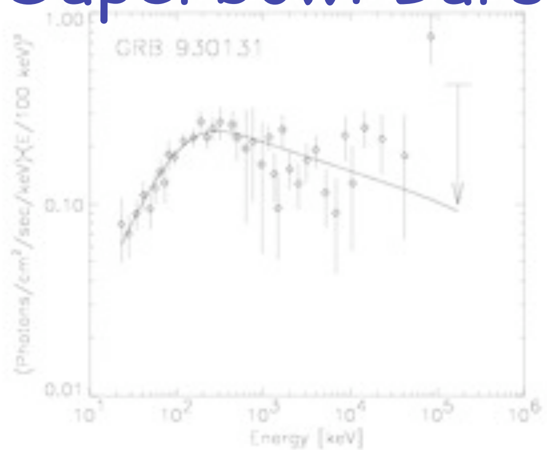

z = 0.01
120 MHz
R Band
Lofar
PTF
SNAP
Flux Density (mJy)
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
0.2
0.4
0.8
pi/2
1
10
100
1000
Time (day)


z = 0.1
1.4 GHz
VLA
Flux Density (mJy)
Time (day)
10^2
10^0
10^-2
10^-4
10^-6
1
10
100
1000
0
0.2
0.4
0.8
pi/2

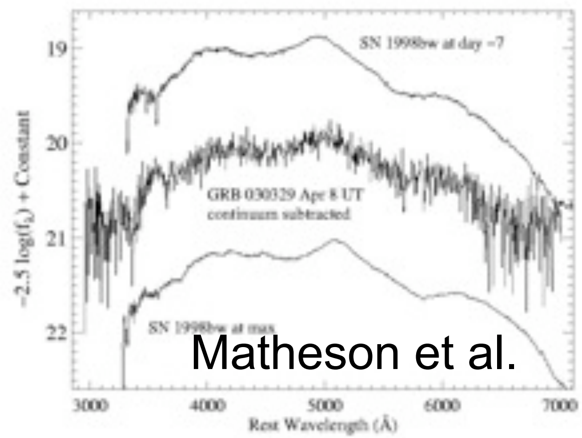
GRB Light Curves



Superbowl Burst



SN2003dh



~0.5 Msun

Ni56

ms variability + non-thermal spectrum

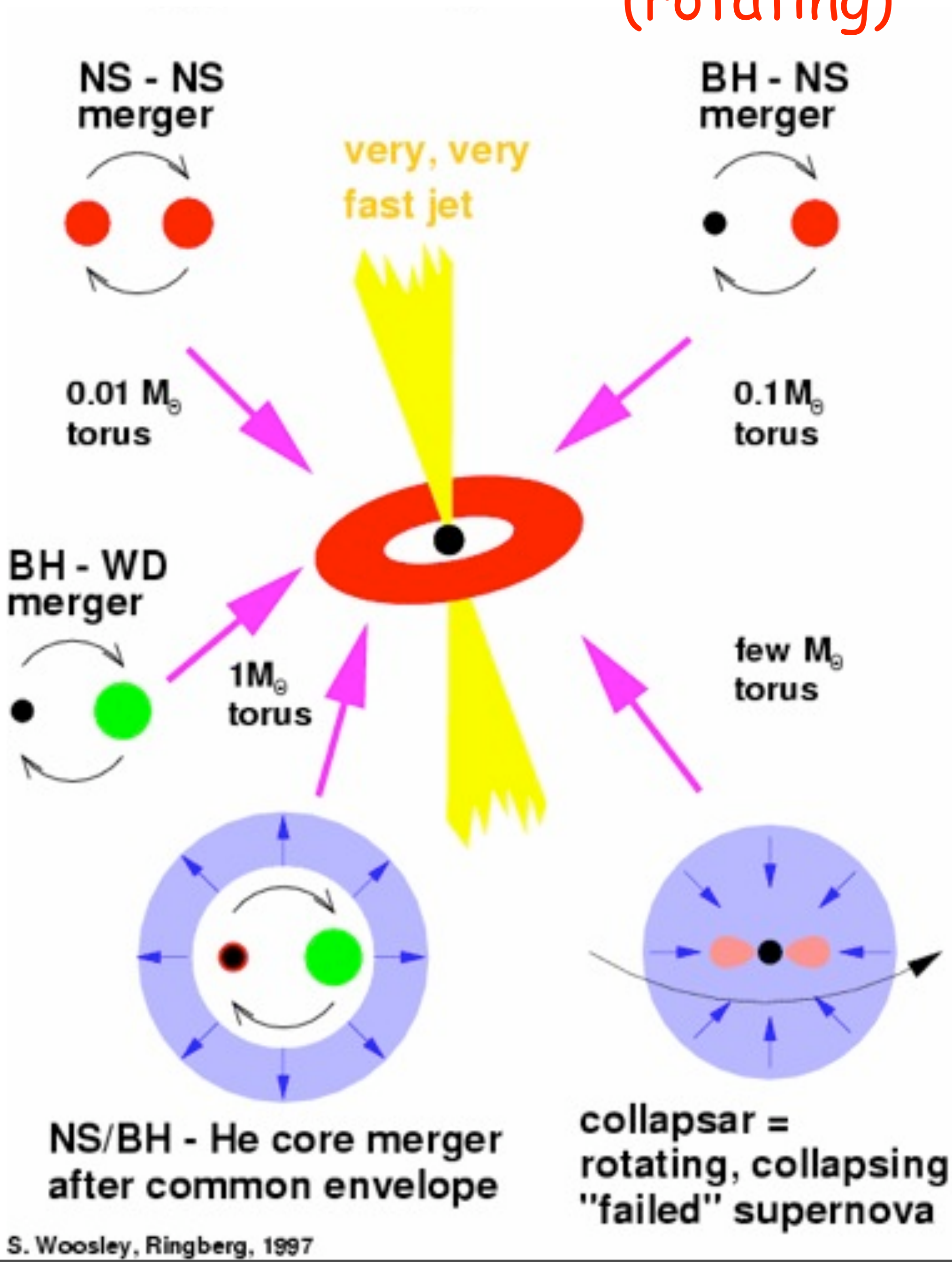
$M = E/ \Gamma c^2 \sim 10^{-6} M_{sun}$

Compactness -> $\Gamma \geq 100$

Ultra-relativistic

Ultra-clean

Hyper-accreting black hole or high field neutron star (rotating)



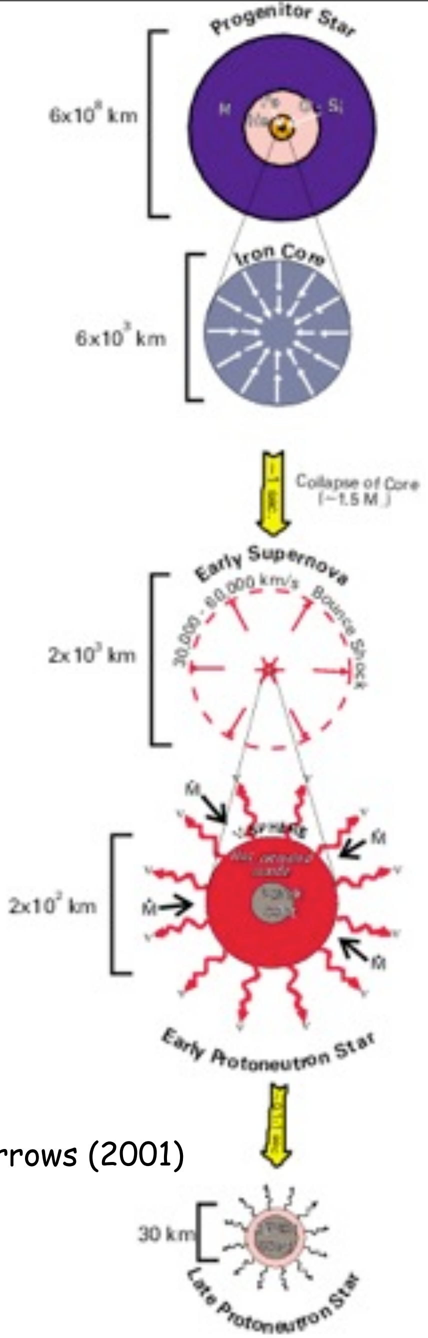
GRB photons are made far away from engine.

Can't observe engine directly with light. (neutrinos, gravitational waves?)

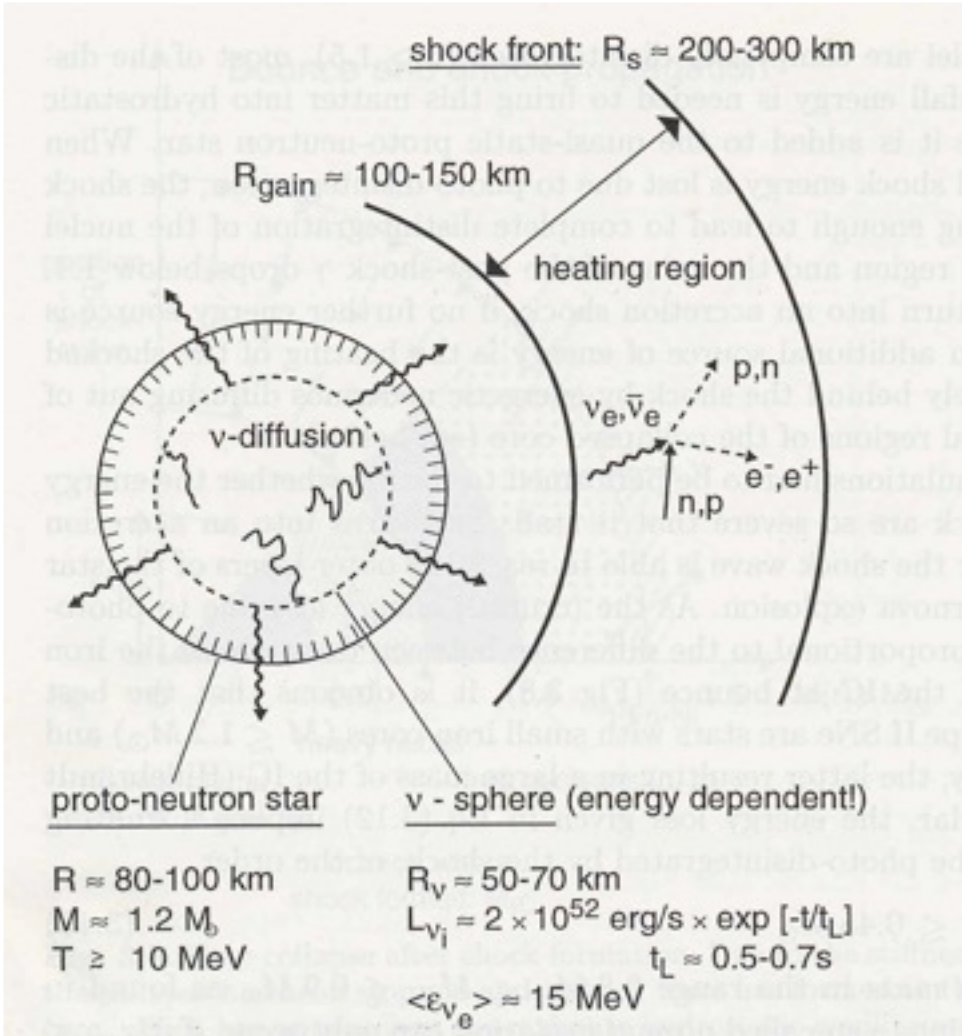
Electromagnetic process or neutrino annihilation to tap power of central compact object.

"Delayed" SN Explosion

Accretion vs. Neutrino heating



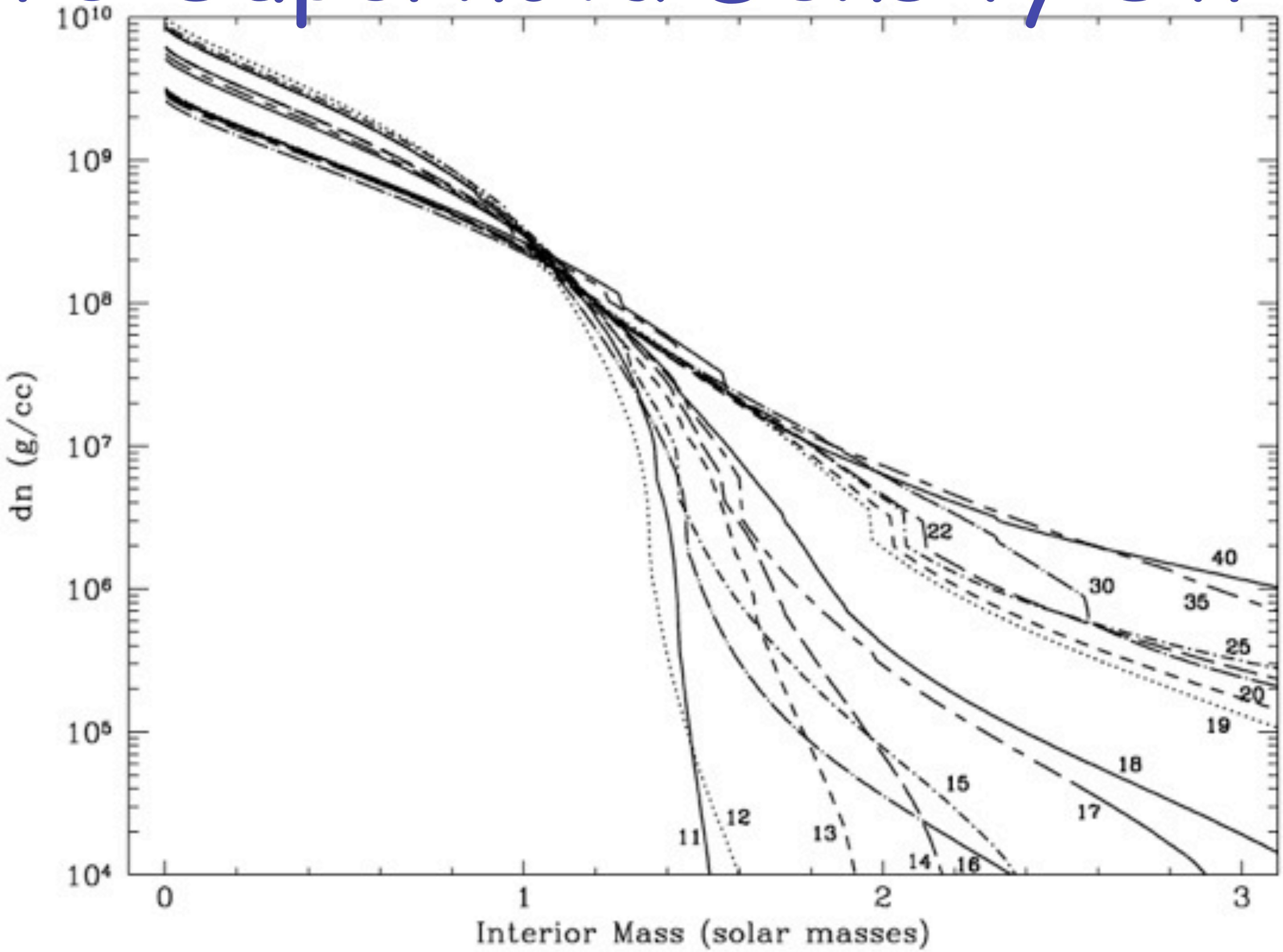
Burrows (2001)



Muller (1999)

Thursday, August 27, 2009

Pre-Supernova Density Structure



Bigger stars:

Higher entropy

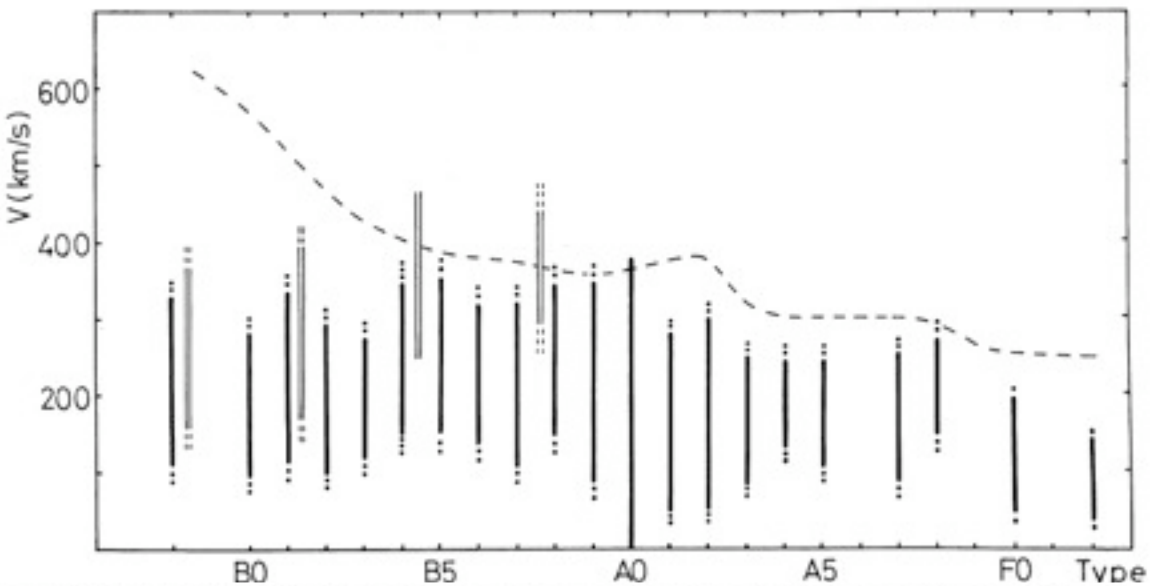
Shallower density gradients

Woosley & Weaver (1995)

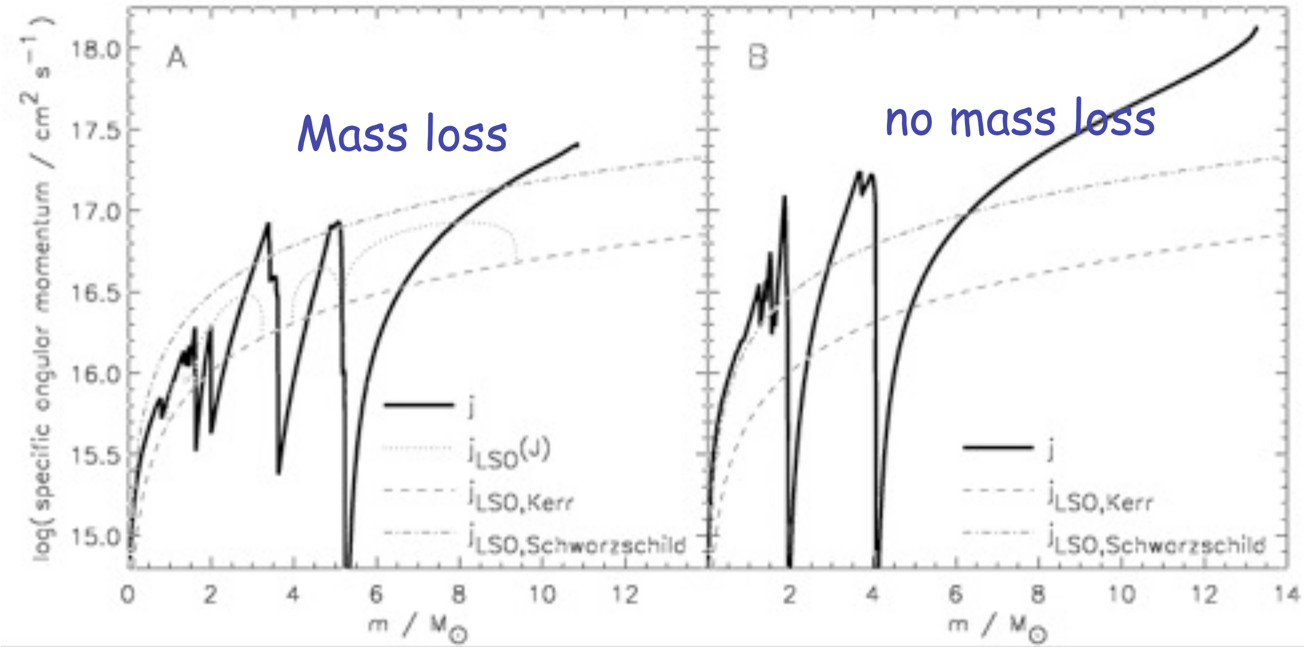
Stellar Rotation

Mass loss removes angular momentum

Low metallicity helps keep Ang. Mom.



Fukuda (1982)



Heger, Woosley & Spruit (2000,205) ,Woosley& Heger (2006), LangerYoon (2006)

IF Two conditions occur (sometimes):

1. Failure of neutrino powered SN explosion
   - a. complete
   - b. partial (fallback)
2. Rotating stellar cores
   - $j > 3 \times 10^{16}$ cm^2/s

THEN

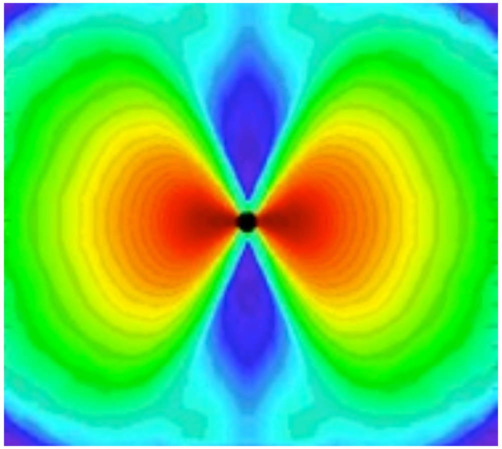
Rapidly accreting black hole, ($\dot{M} \sim 0.1\ M_\odot/s$)

fed by collapsing star ($t_{dyn} \sim 446\ s/\ \rho^{\frac{1}{2}} \sim 10\ s$)

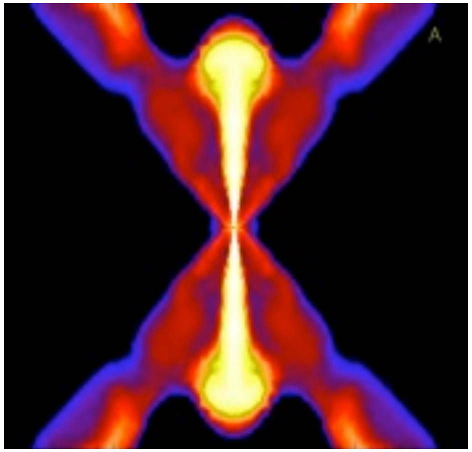
Disk formation

⇒ **COLLAPSAR**

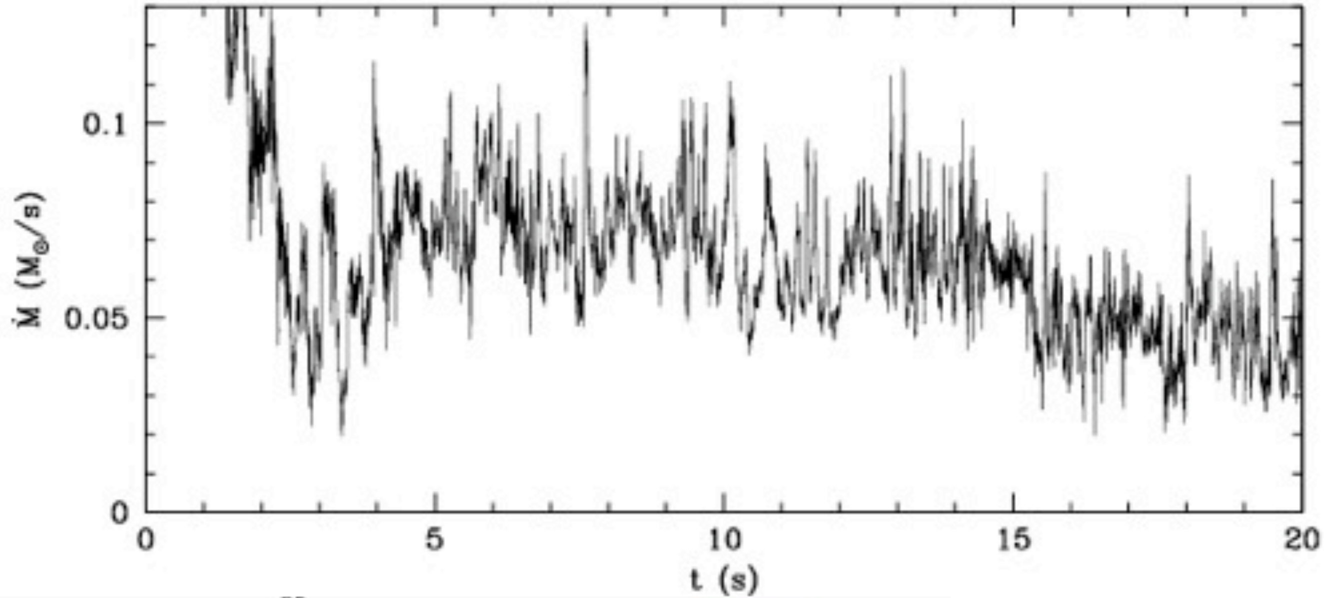
Collapsar - Disk and Jet

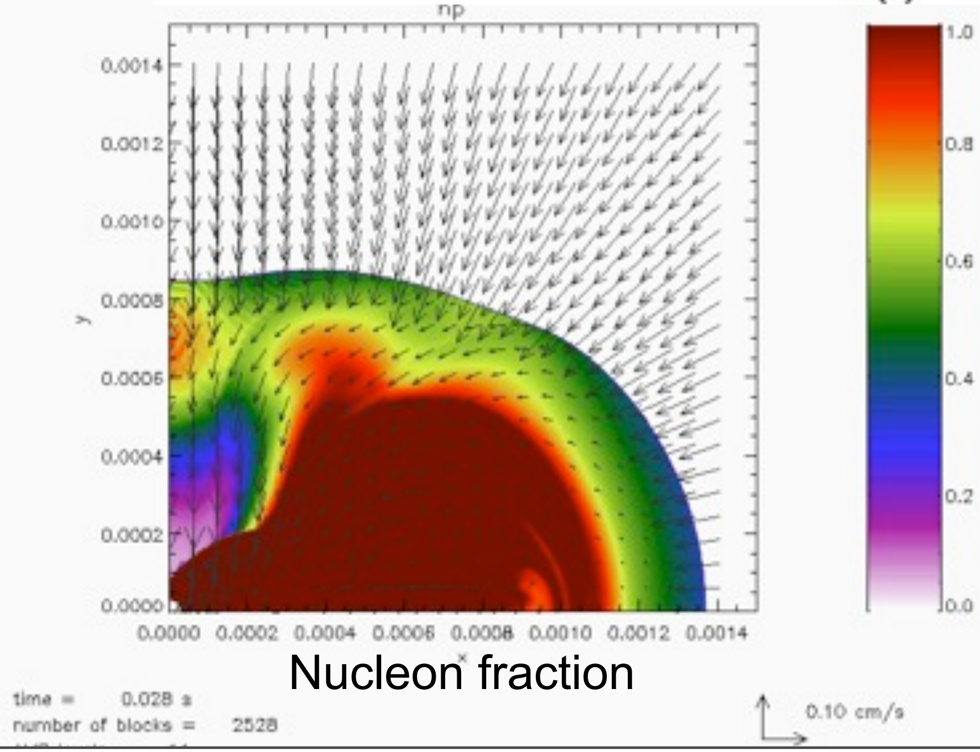


- pre-SN 15 Msun Helium star
- Newtonian Hydrodynamics (PPM)
- alpha viscosity
- rotation
- photodisintegration (NSE alpha, n, p)
- neutrino cooling, thermal + URCA optically thin
- Ideal nucleons, radiation, relativistic degenerate electrons, positions
- 2D axisymmetric, spherical grid
- self gravity
- $R_{in} = 9\ R_s\ R_{out} = 9000\ R_s$

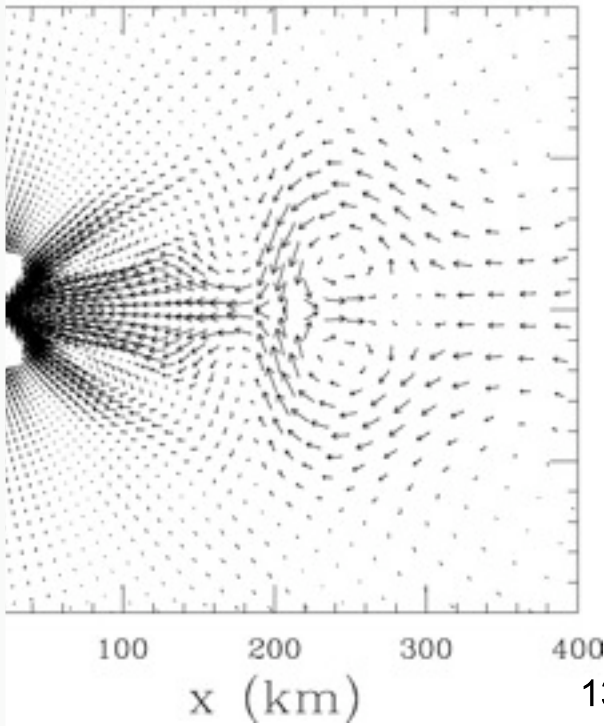


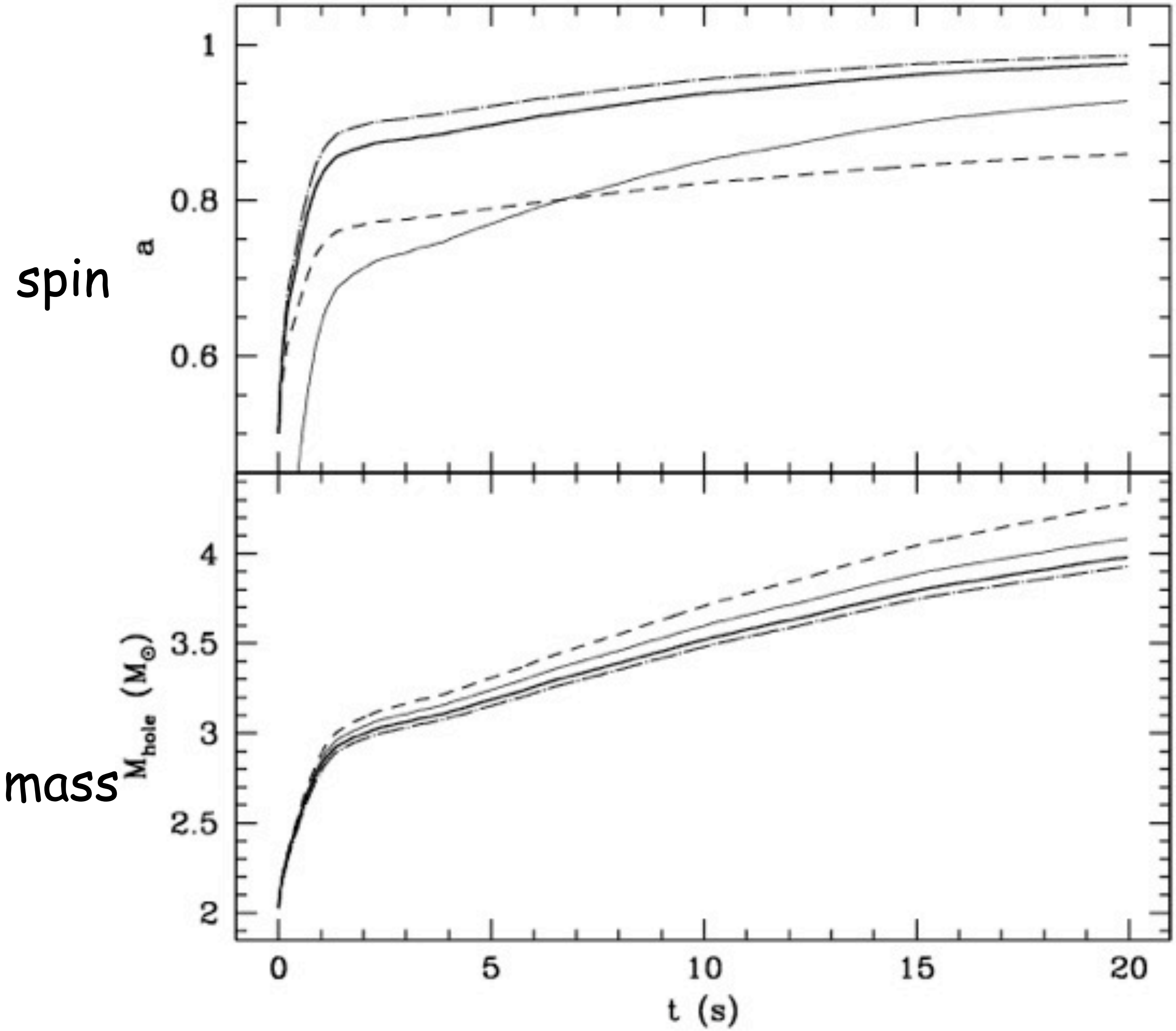
$\alpha = 0.1$ $\langle \dot{M} \rangle = 0.07\ M_{sun}/s = 1.3 \times 10^{53}$ erg/s





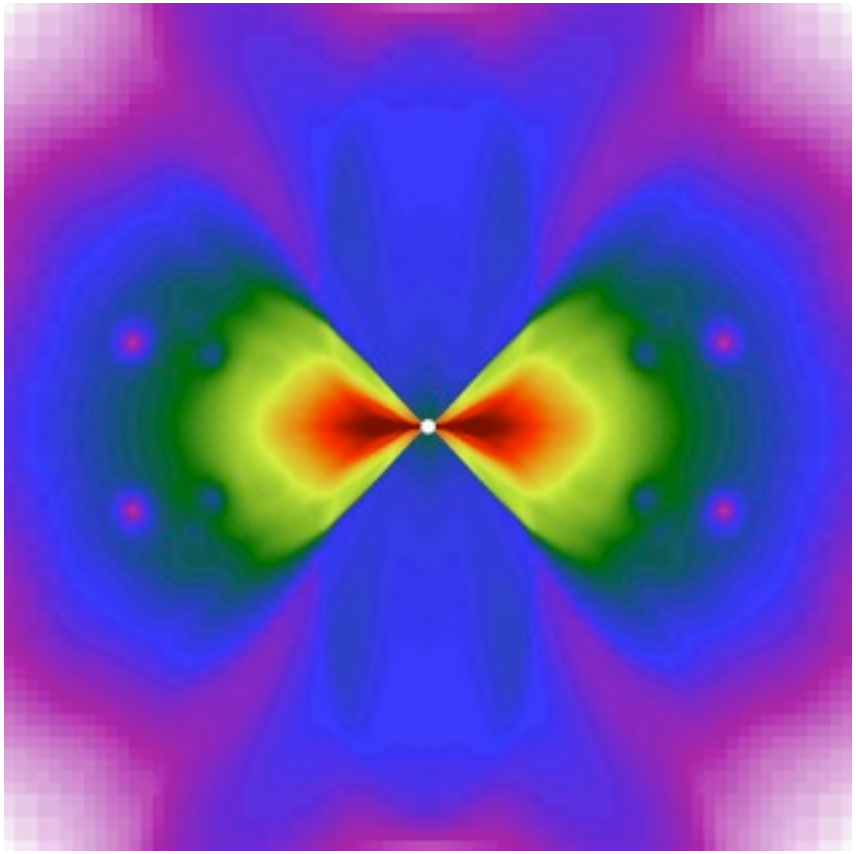
Nucleon fraction





Use 1D neutrino cooled "slim" GR disk models from Popham,Woosley & Fryer (1999).

Collapsar – General Relativistic AMR (2009) GRAM code

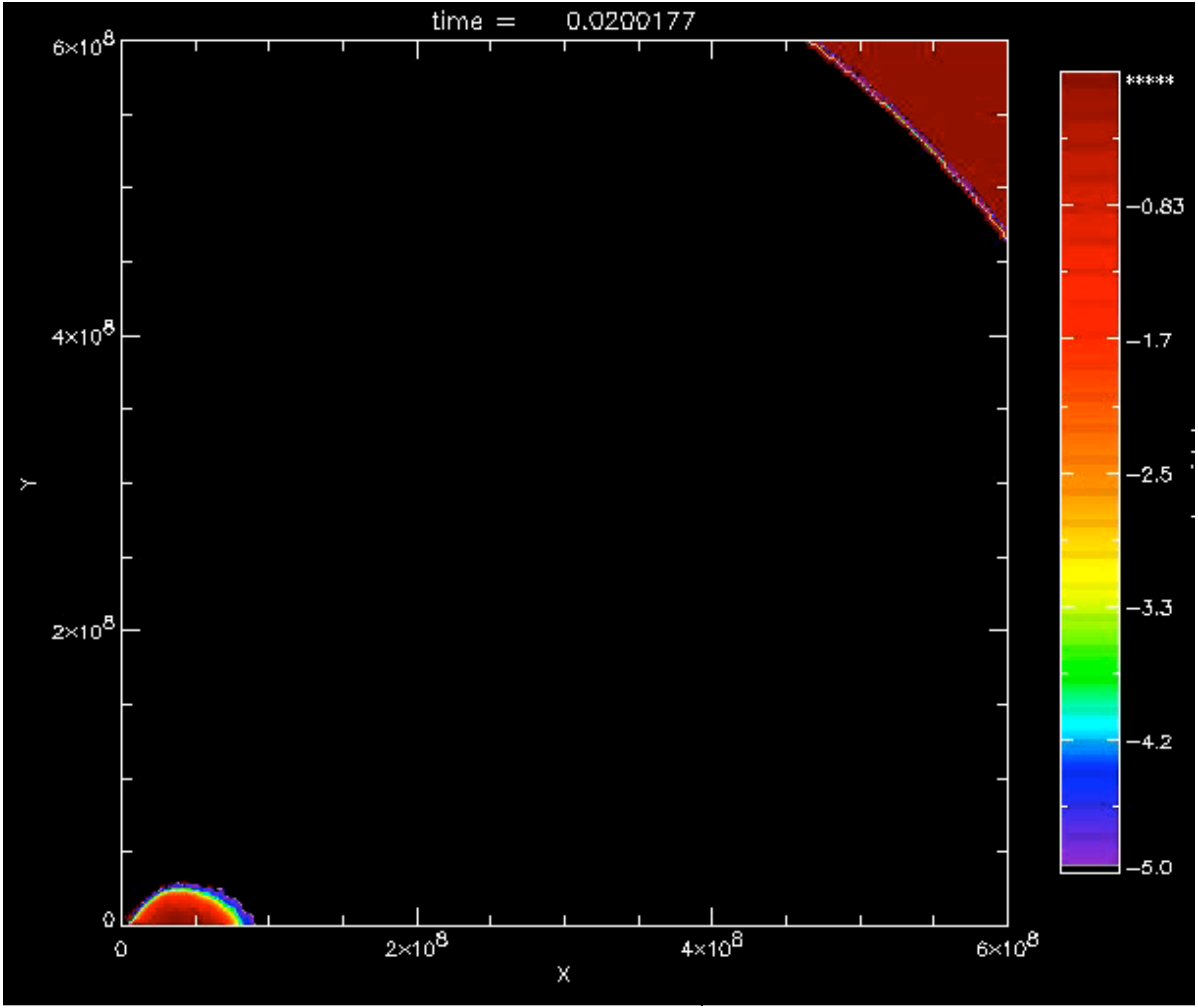


- rho ~ 10^9 g/cm^3
- T ~ 10^10 K
- M_dot ~ 0.1 M_sun/s
- t_acc ~ 20 s
- R_in ~ 2 R_g

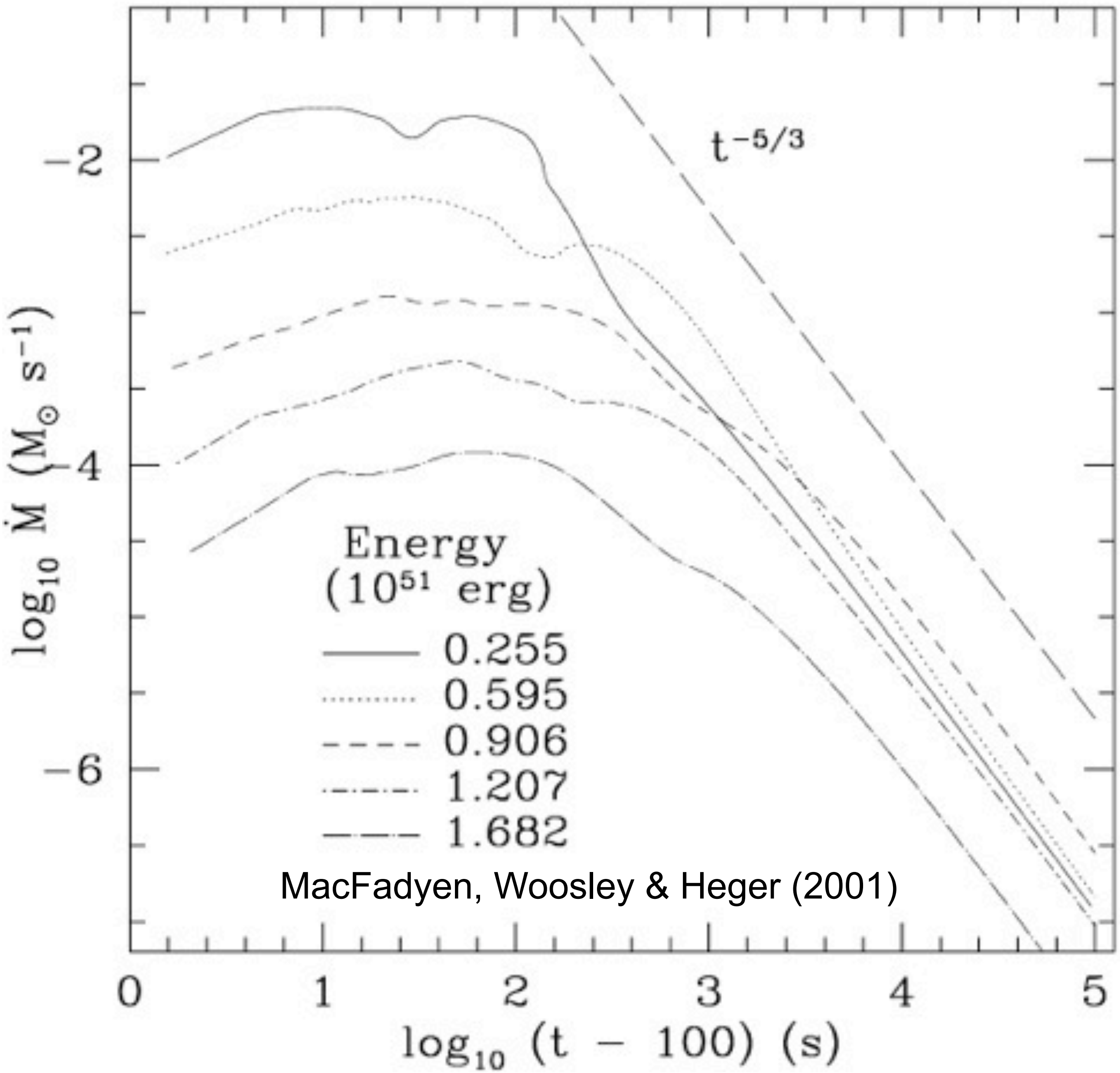
“Nickel Wind”

Nickel Wind Movie

$T > 5 \times 10^9$ K

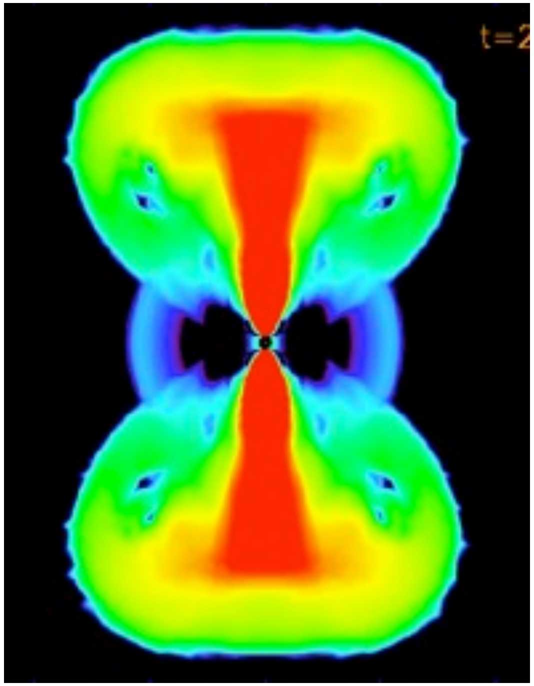

time = 0.0200177
6×10^8
4×10^8
2×10^8
0
Y
X
*****
−0.83
−1.7
−2.5
−3.3
−4.2
−5.0

Late accretion

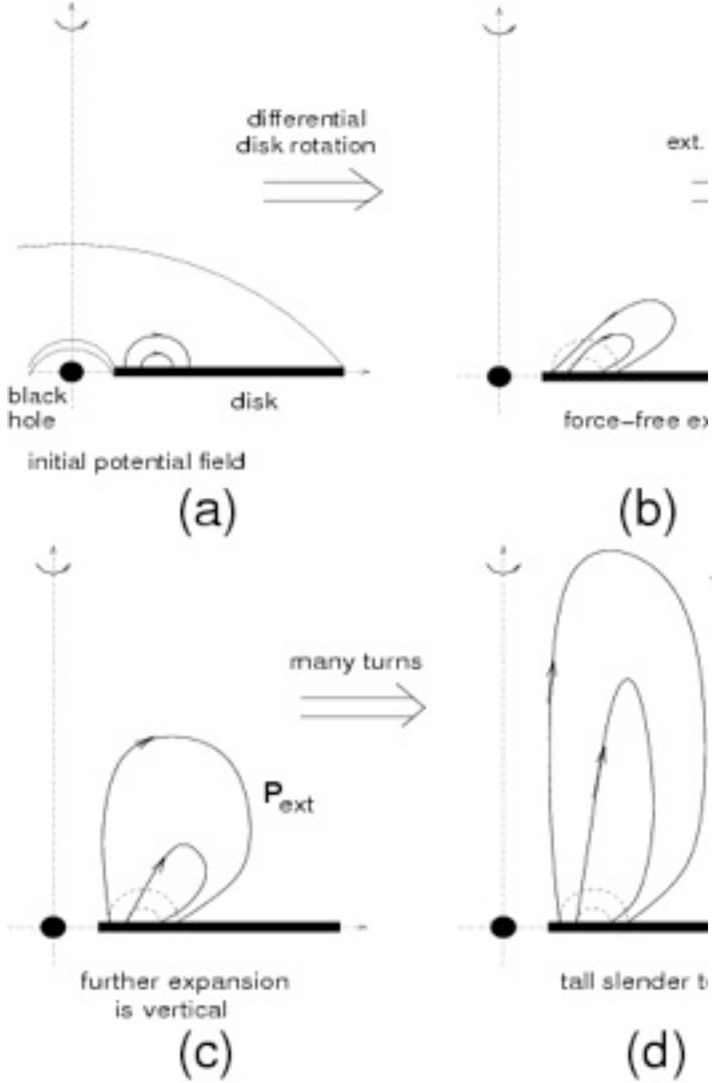


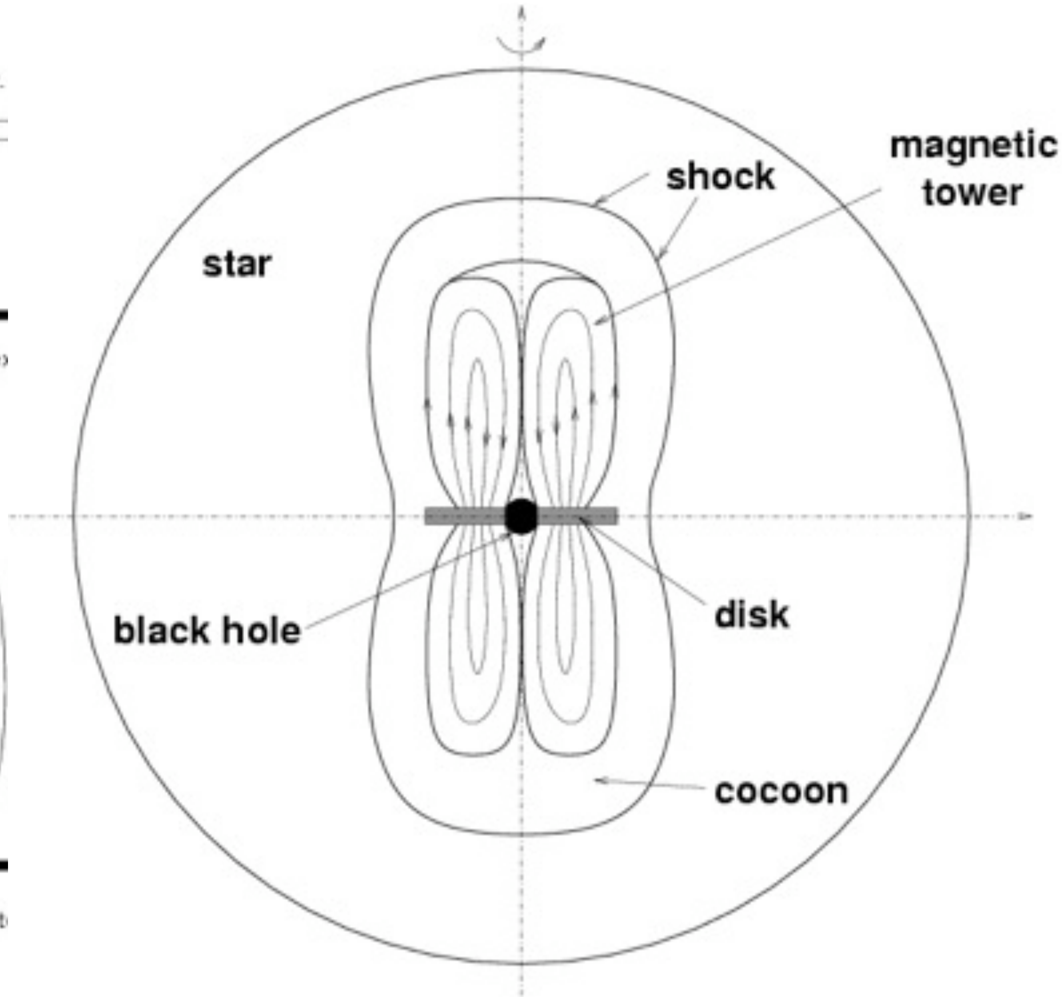
Same star exploded with a range of explosion energies.

Significant accretion for thousands of seconds to days.



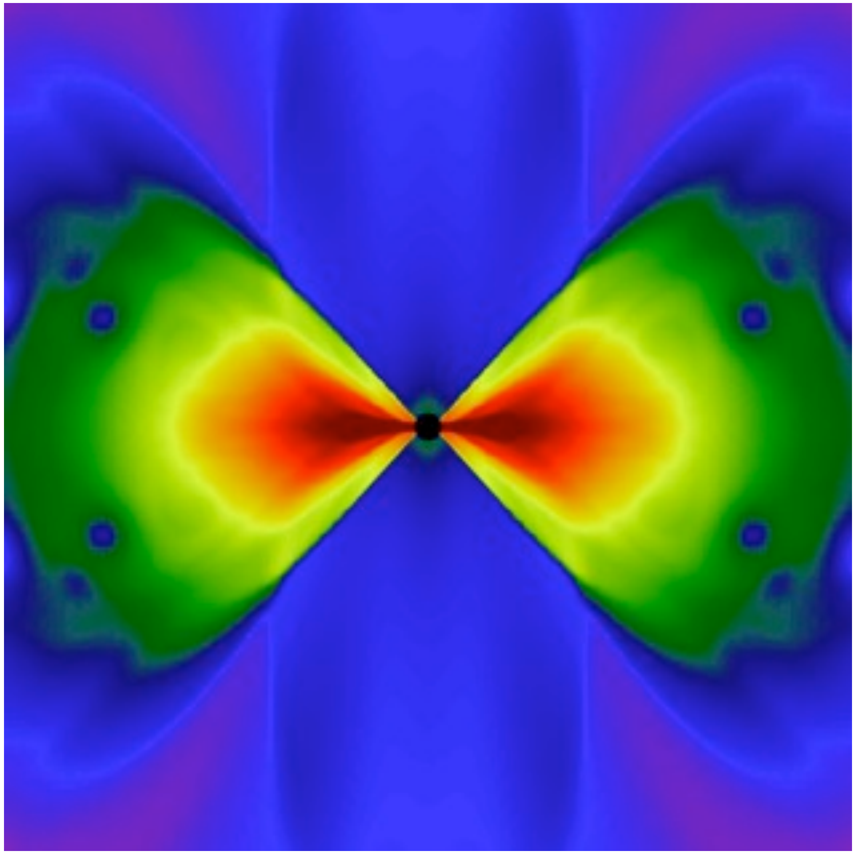
Magnetic Tower

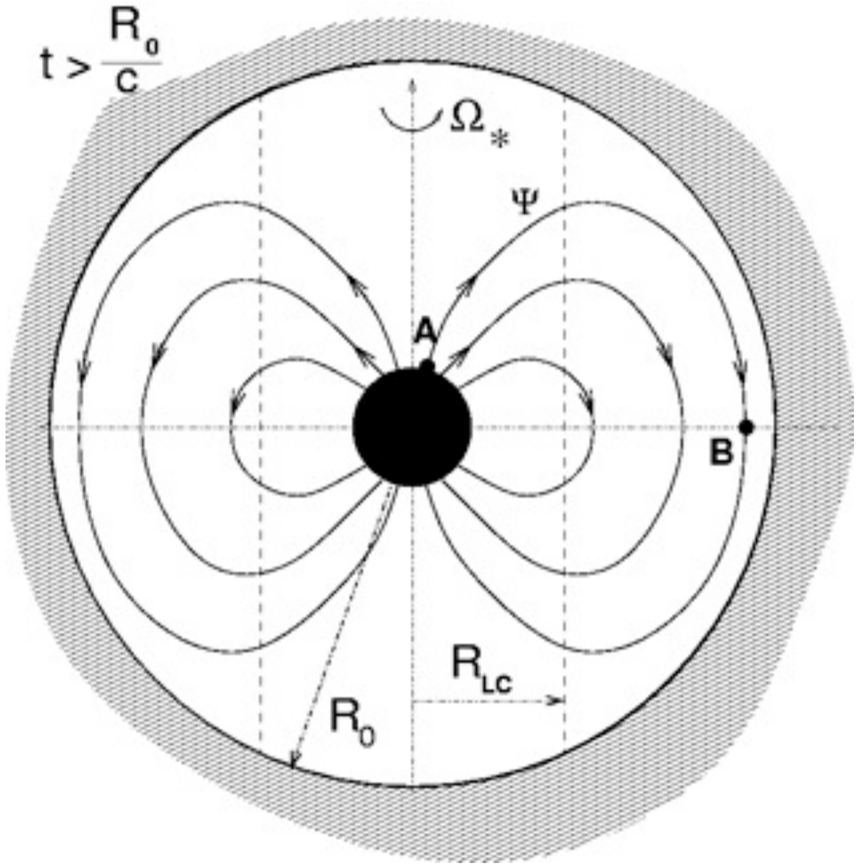




Uzdensky & AM (2006,2007), Kommisarov et al (2007), Bucciantini et al (2007), Dessart et al (2007)

Collapsar vs. Magnetar





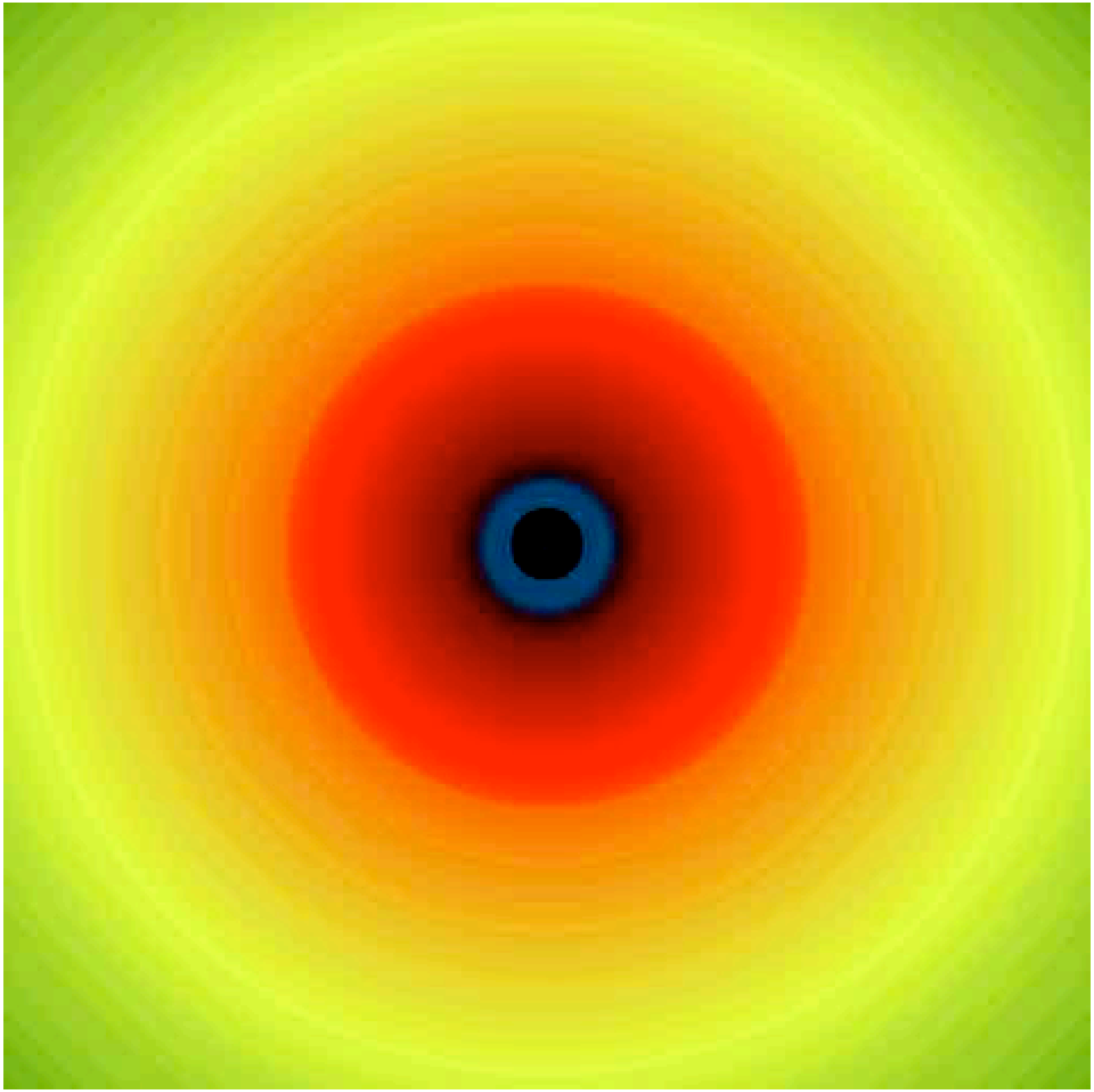
Uzdensky & AM (2006,2007)

GRBs from Stars

- Need ejecta to escape star before engine dies. T_engine > T_escape
- T_escape ~ 2 x T_light (~3 s = 10^11 cm)
- T_engine >> T_dyn for BH or NS
- T_ACCRETE ~ 20-100s s for massive star
- Need angular momentum (not too much)
- Need to lose H envelope -> WR progenitor and Type Ibc supernova (if Ni56)

AMR
jet+wind

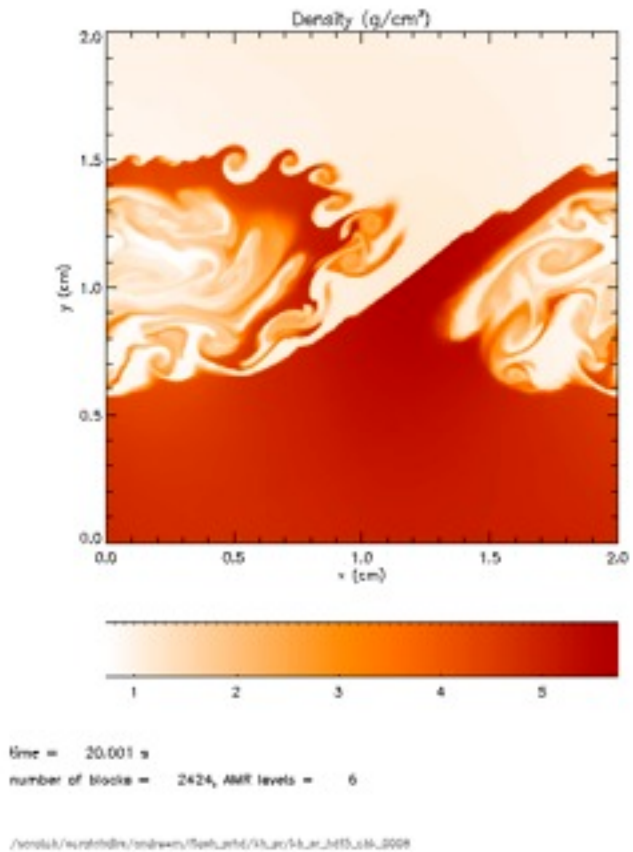
AM&Zhang
(2009)

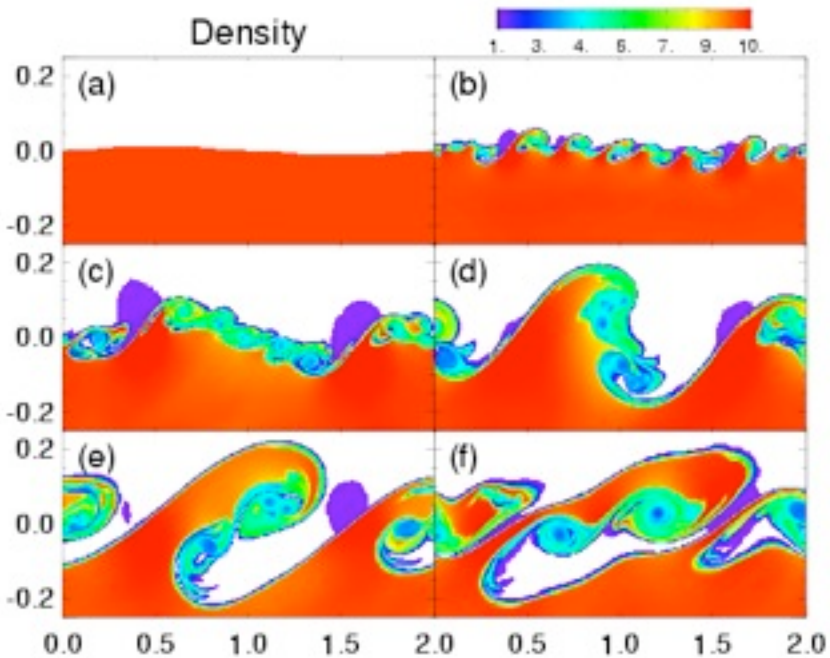


AMR
jet+wind

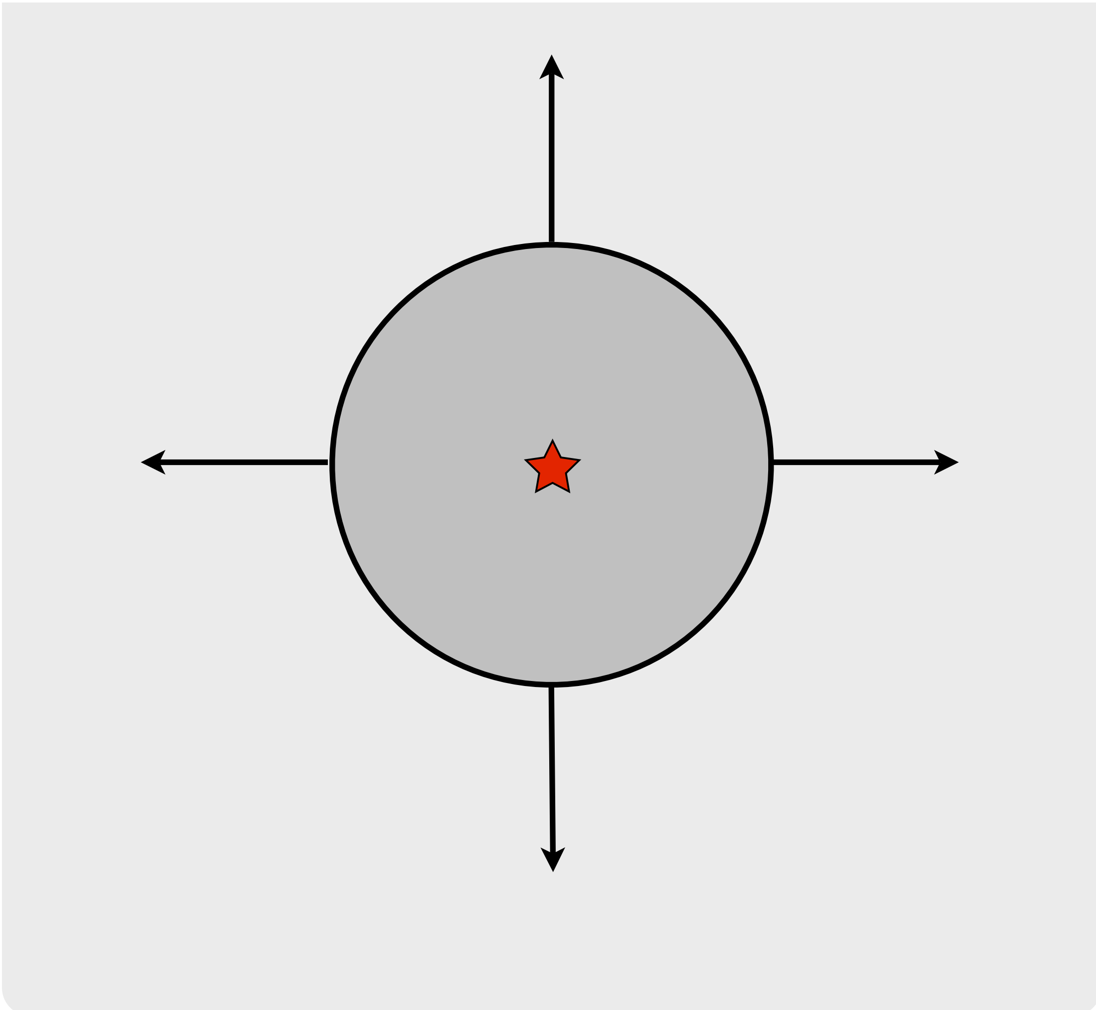
AM&Zhang
(2009)

Relativistic Mixing

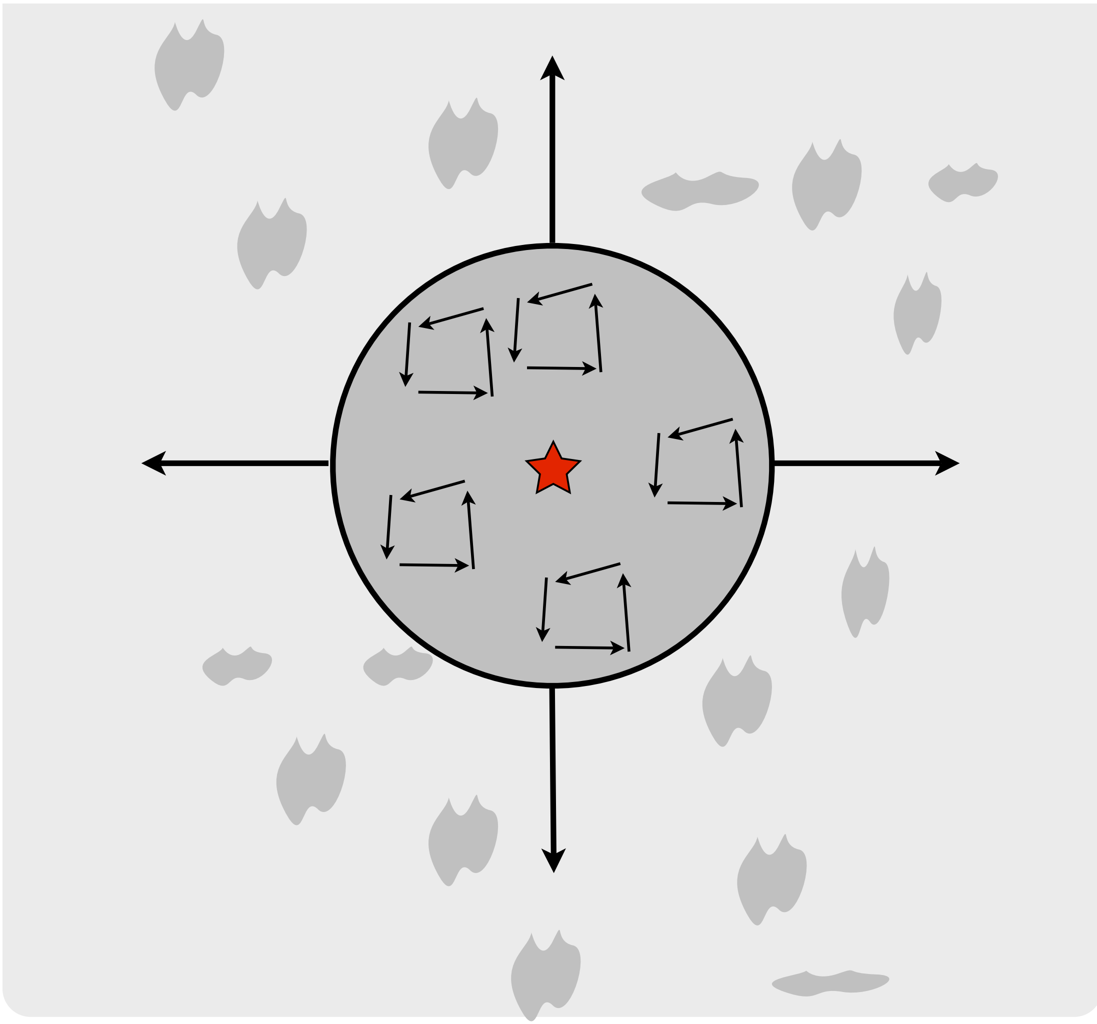




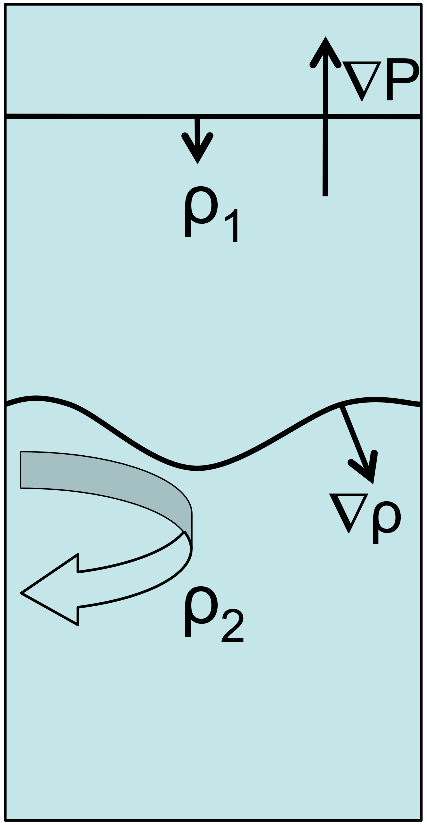
Smooth & Spherical



Clumpy & Spherical



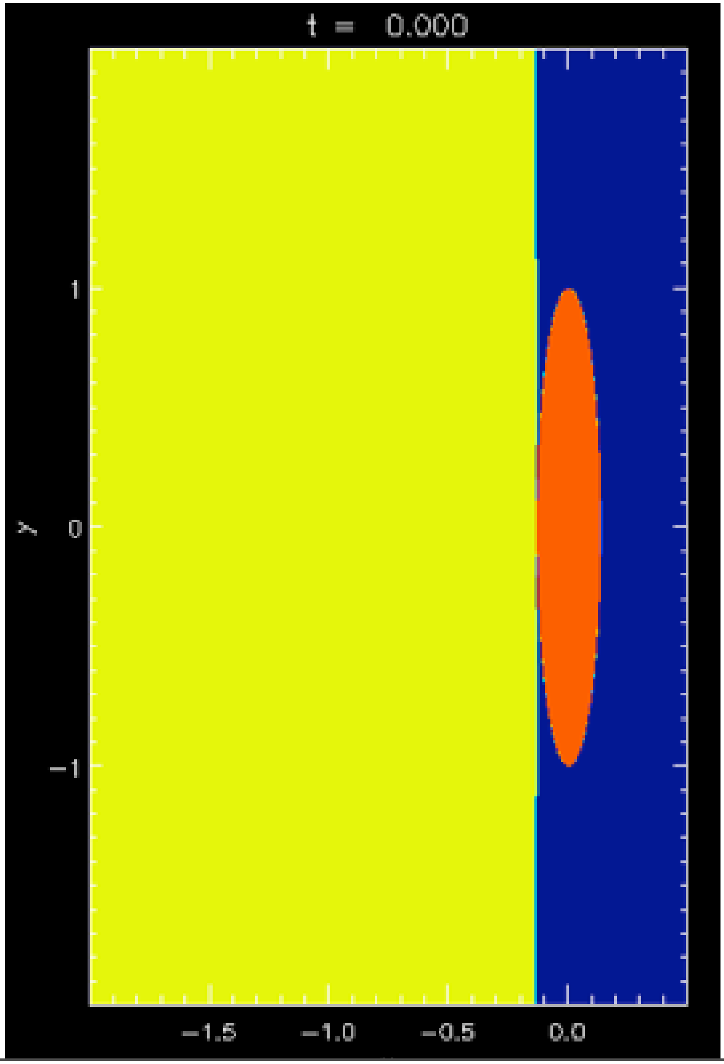
Vorticity Generation

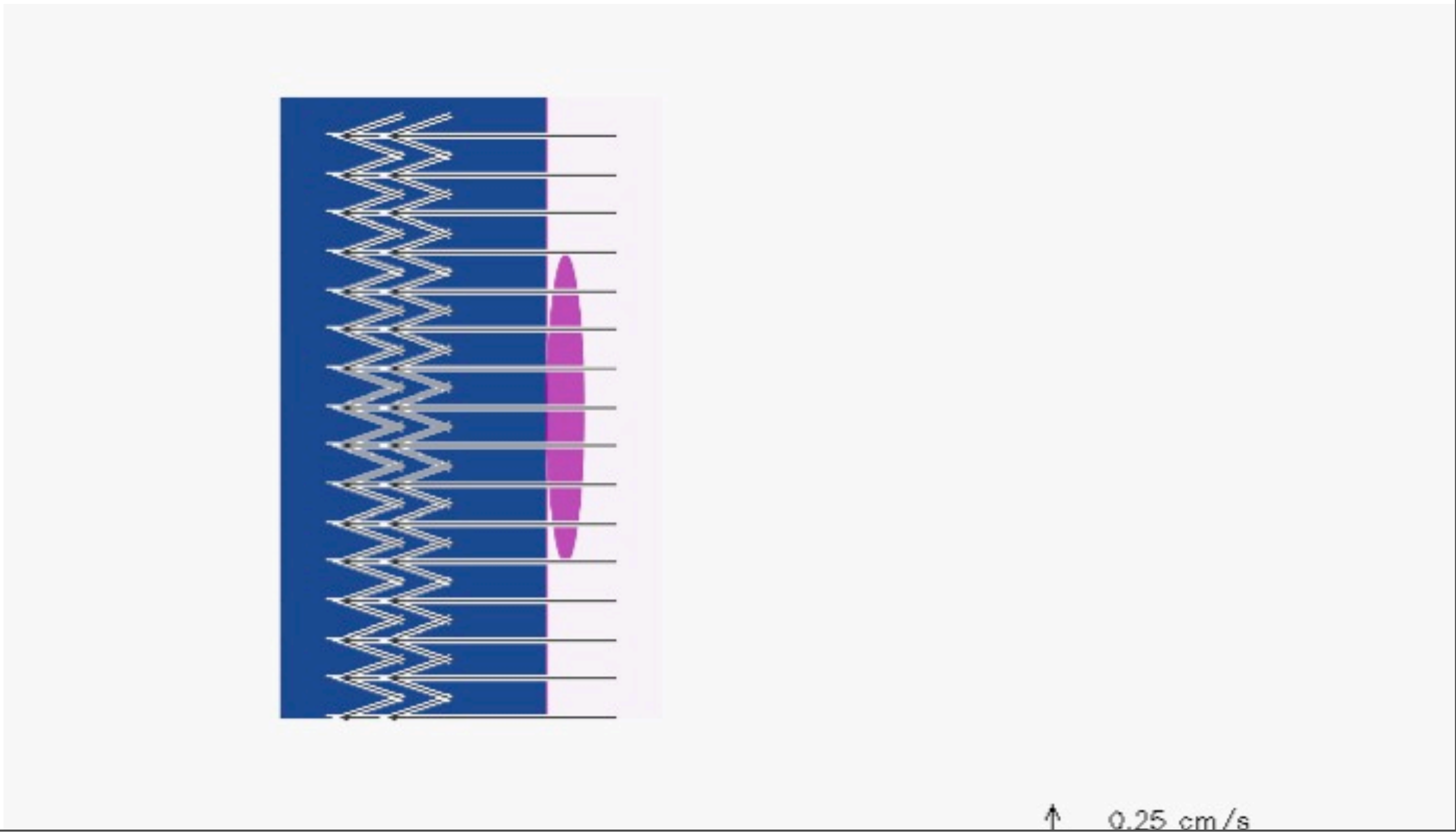


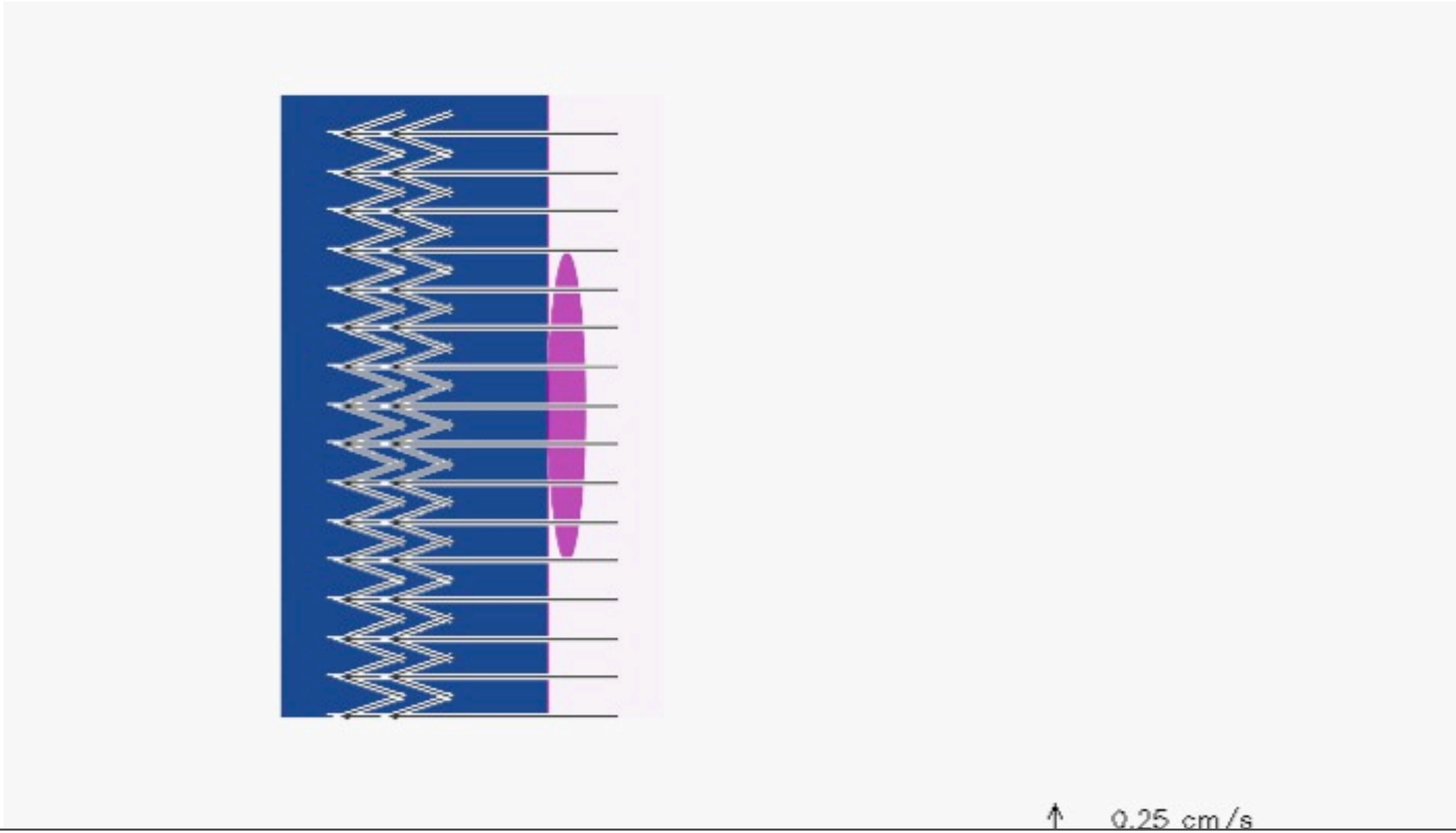
$\eta_t = k[u]A\eta$ $\quad A \equiv (\rho_1-\rho_2)/(\rho_1+\rho_2)$

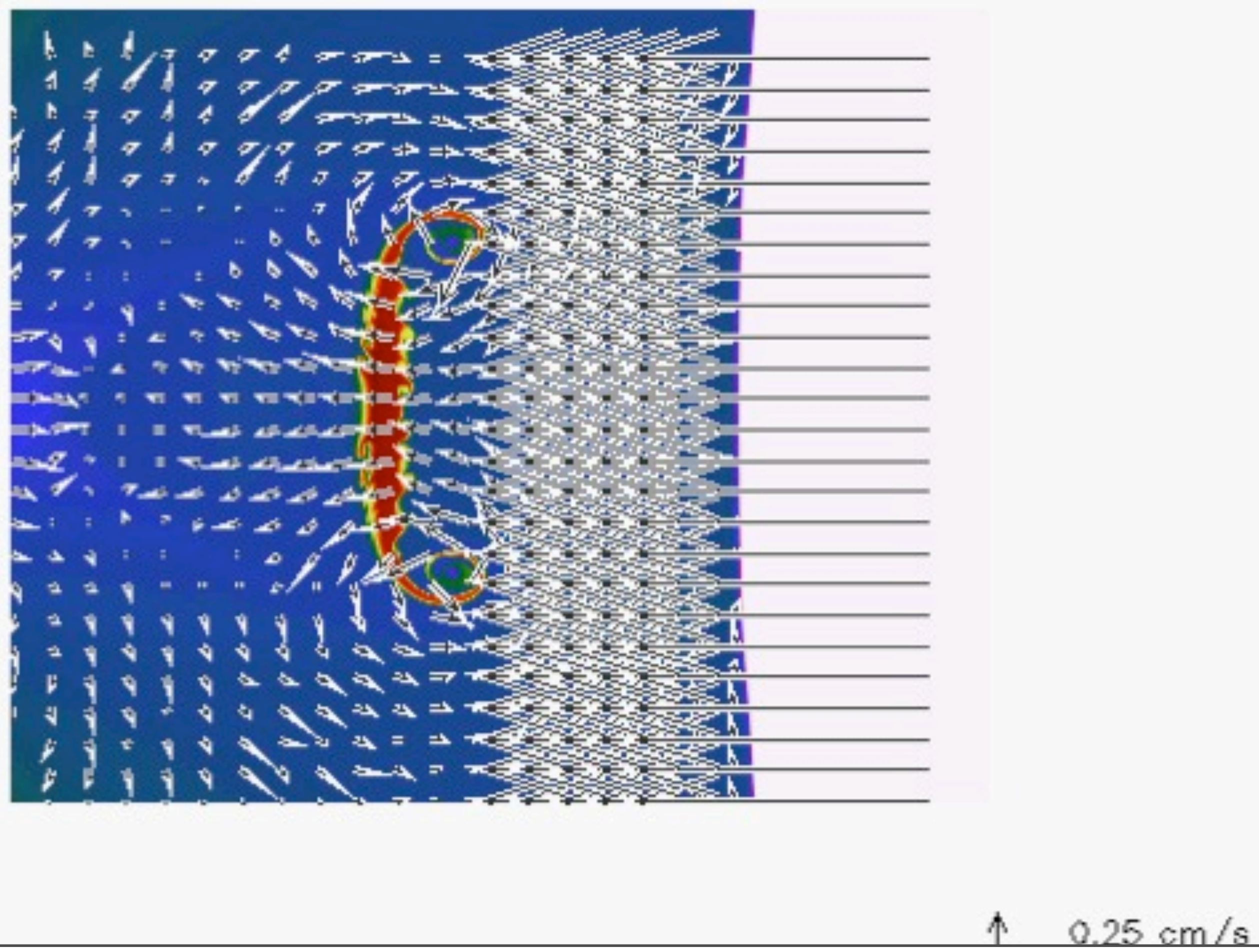
Ultra-relativistic Vorticity and Shock Dynamics

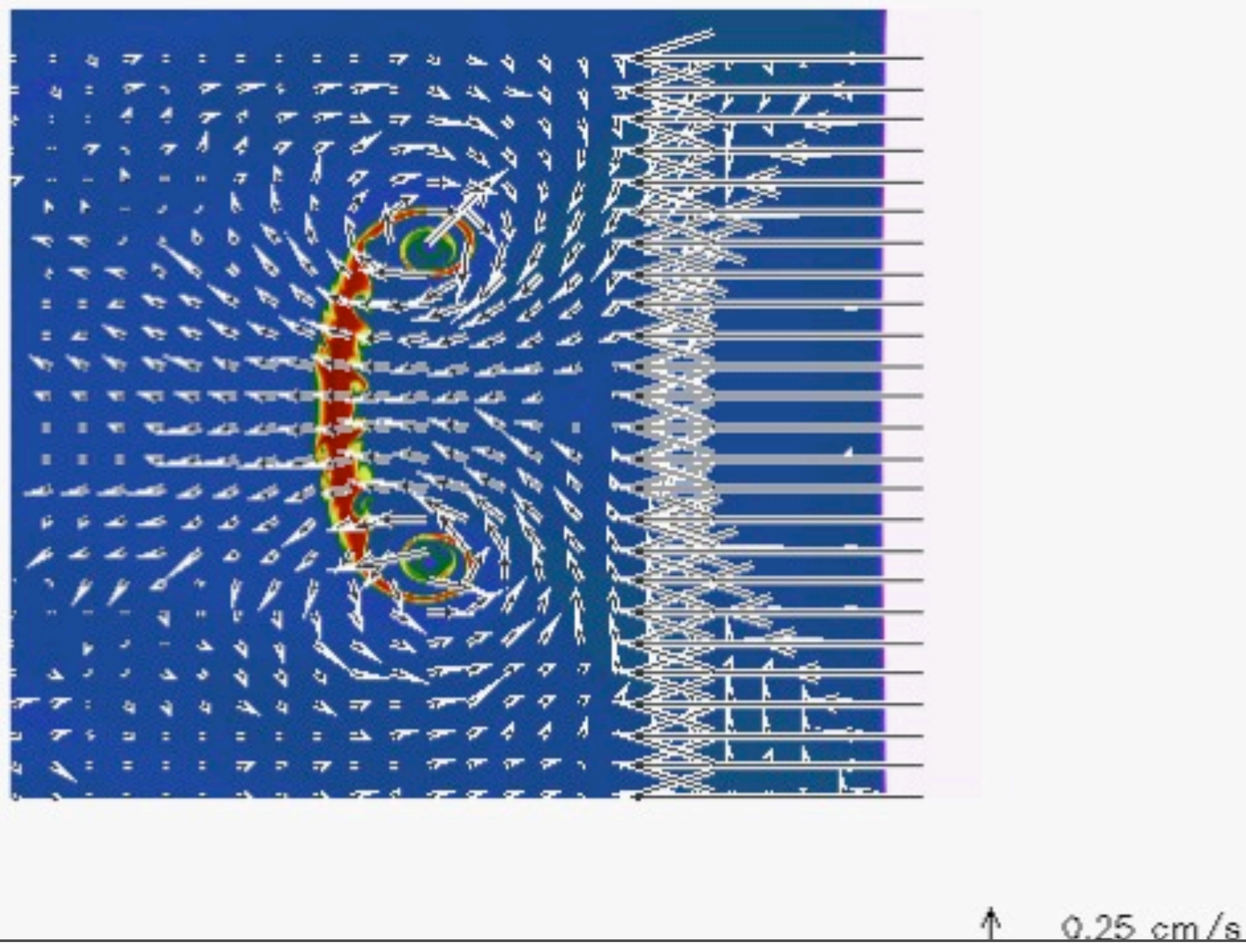
Goodman & MacFadyen (2008)

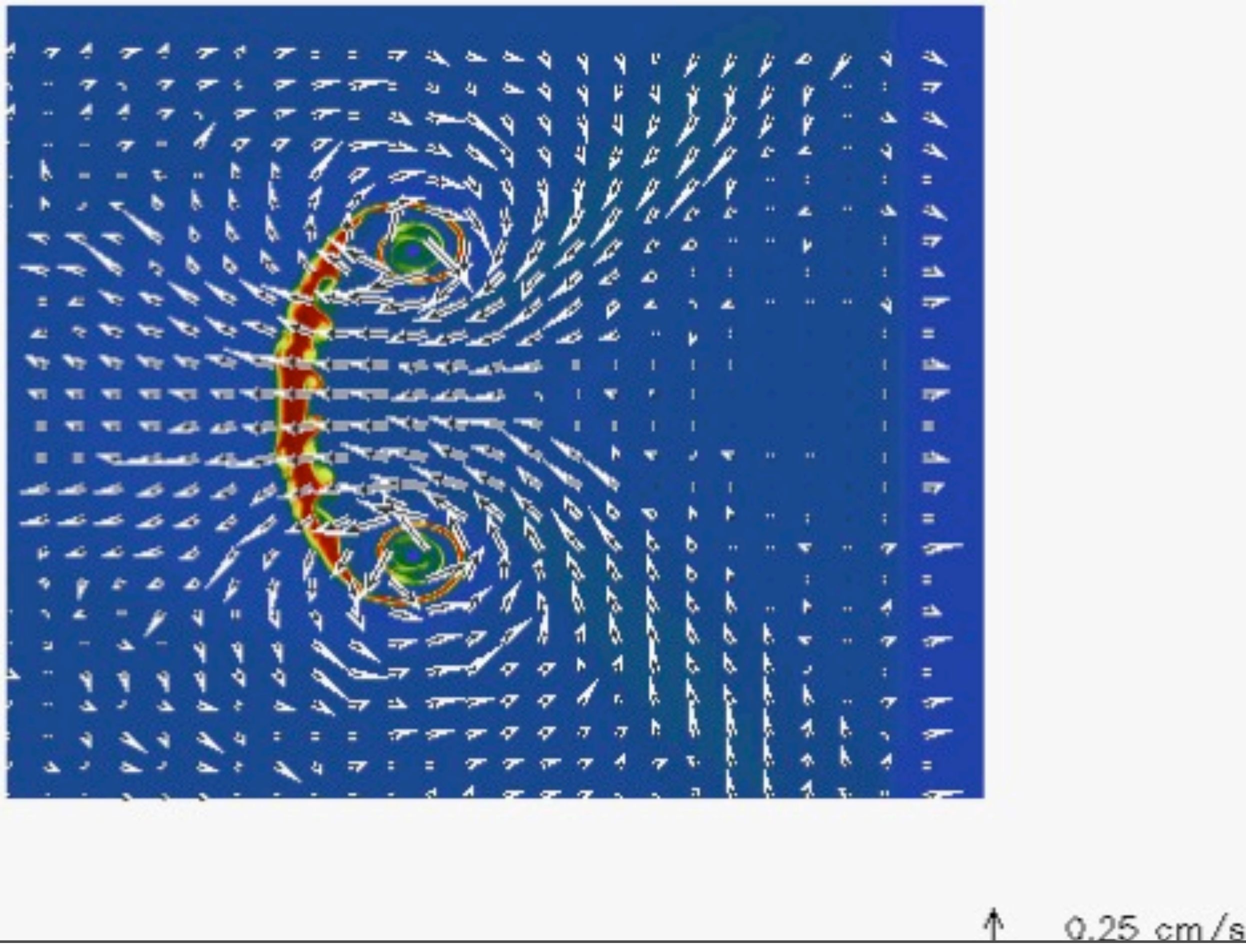

t = 0.000
1
0
−1
y
−1.5
−1.0
−0.5
0.0

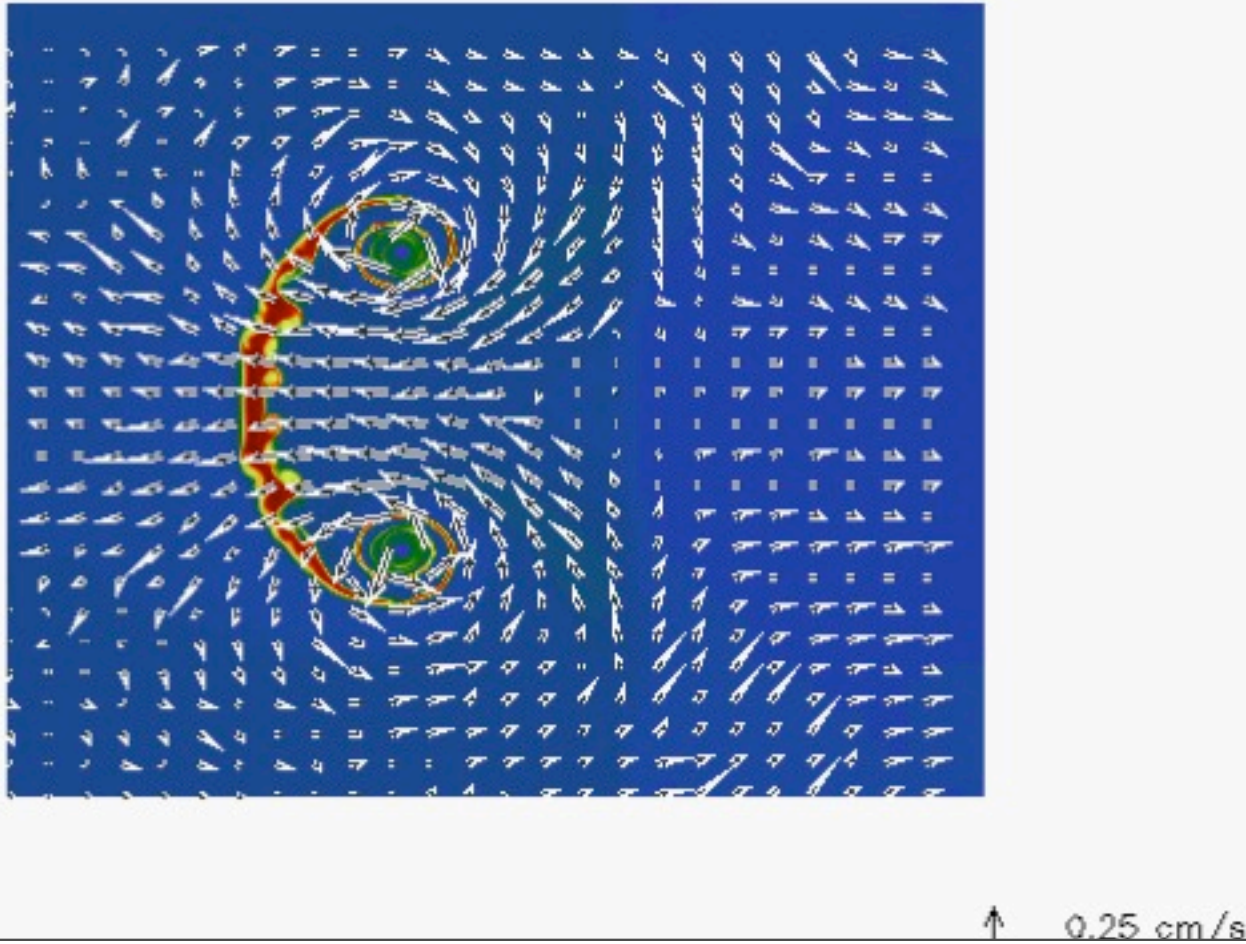

0.25 cm/s


0.25 cm/s

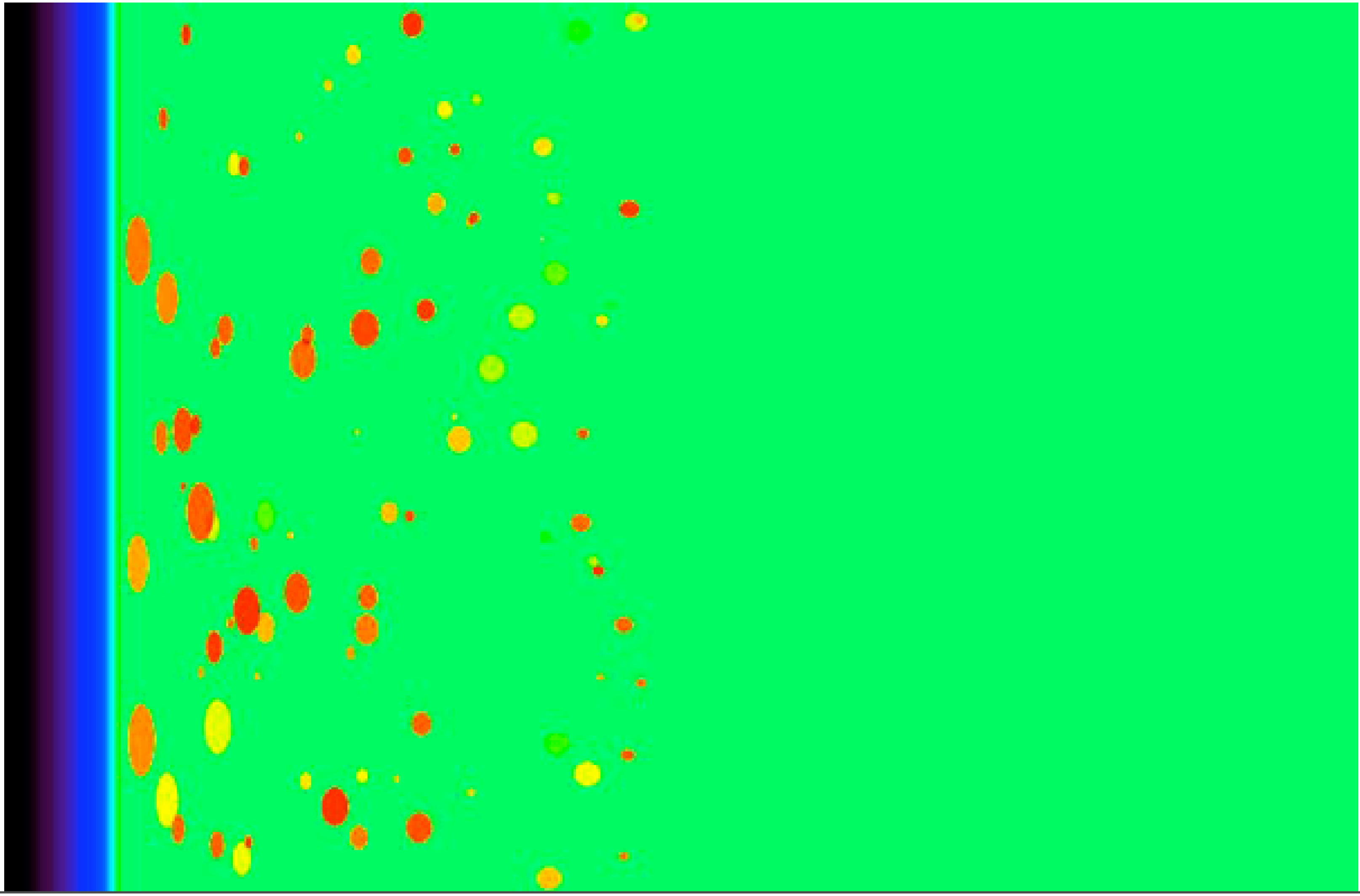

0.25 cm/s


0.25 cm/s

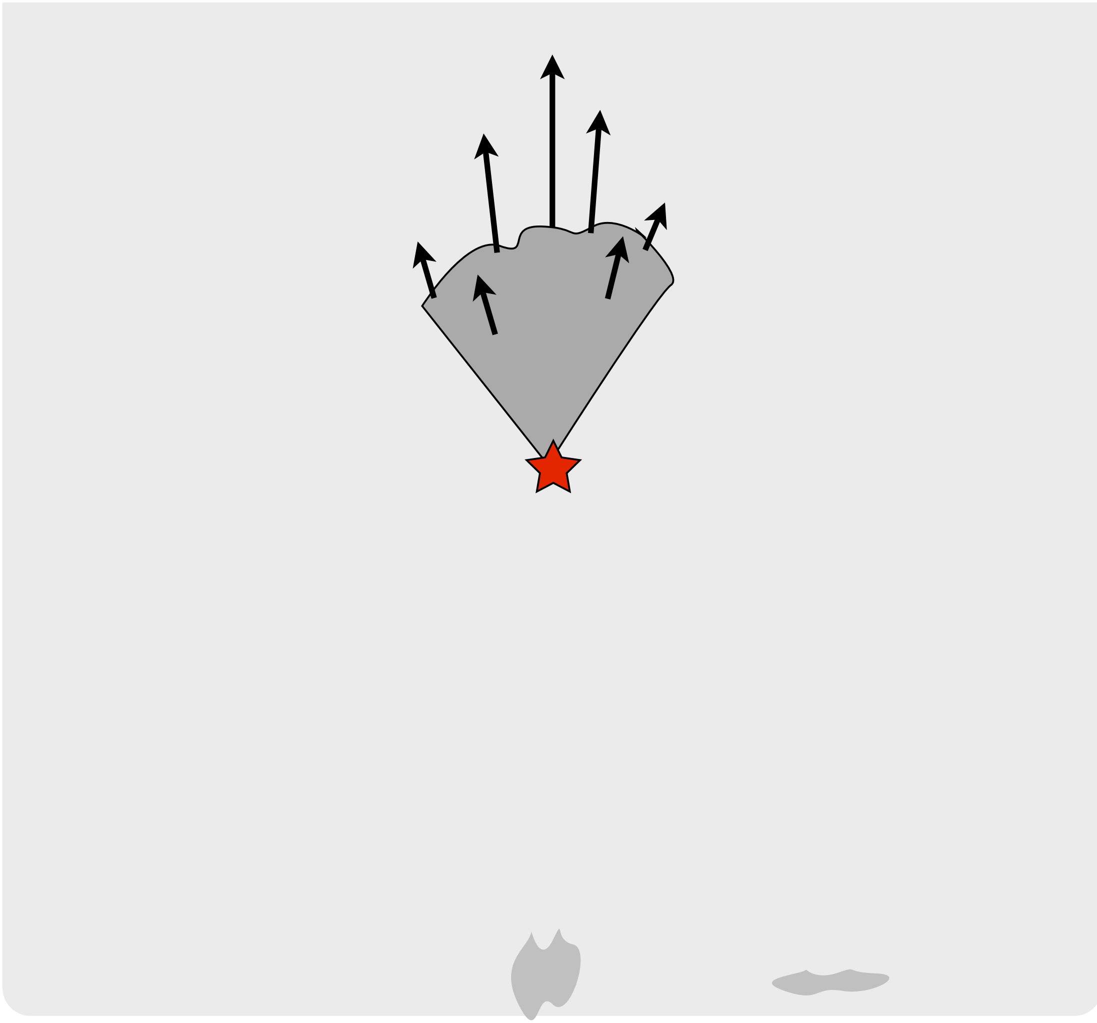

0.25 cm/s


0.25 cm/s

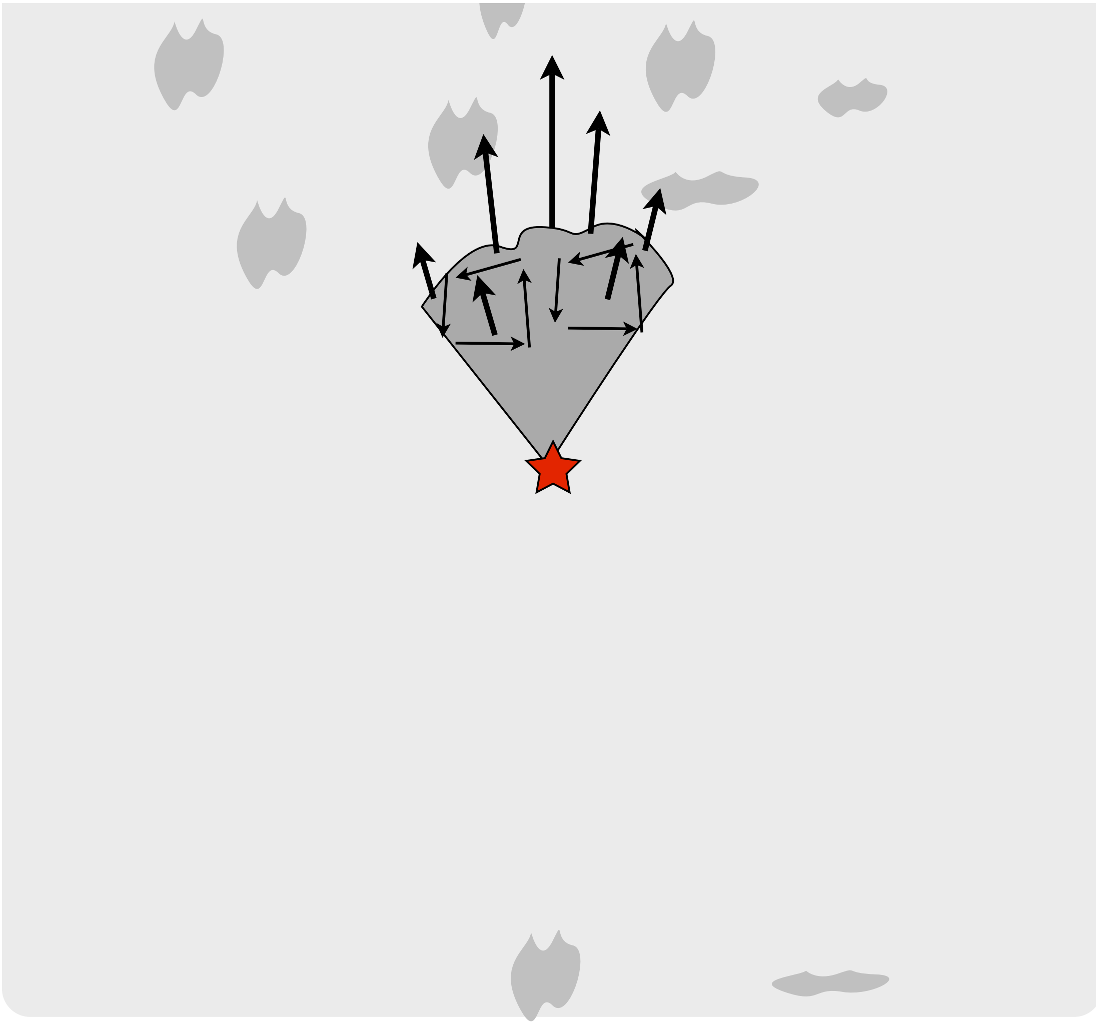
Clumpy Medium



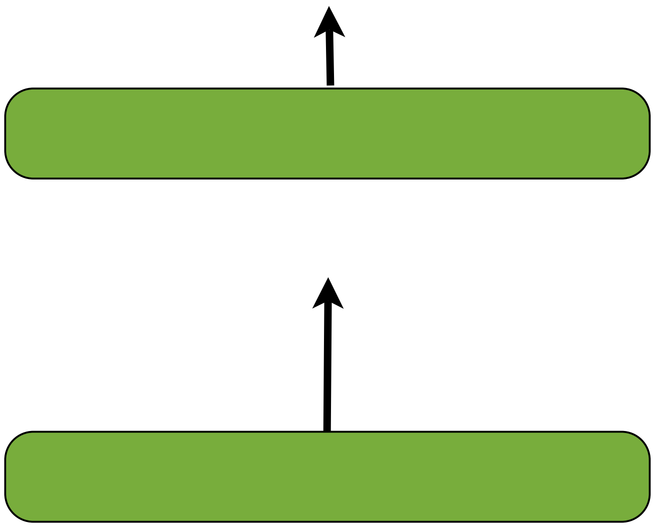
Jet & Shear



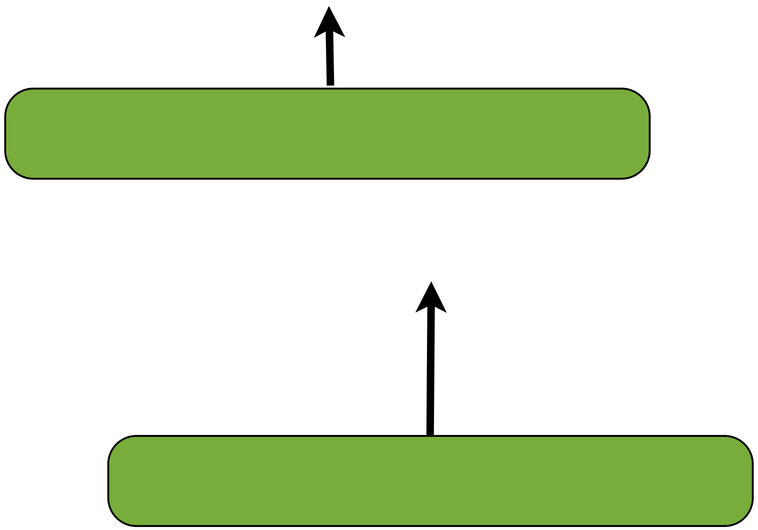
Jet & Clumps



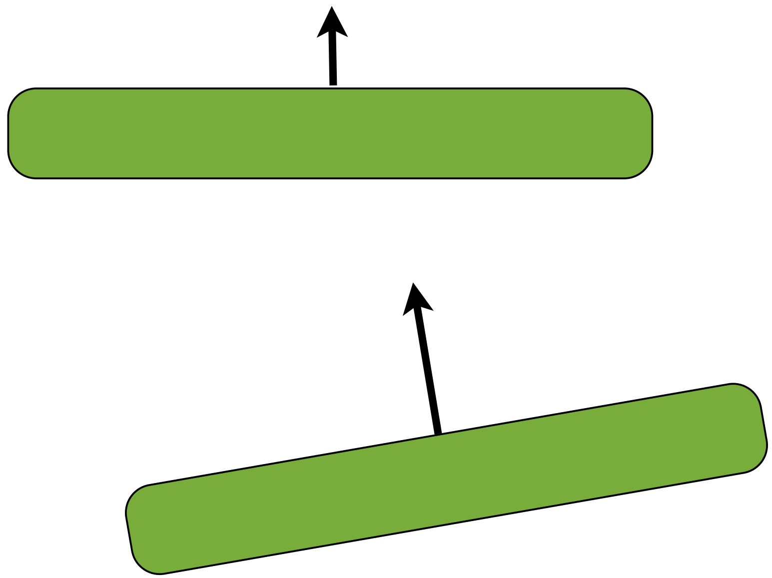
Flying Pancakes



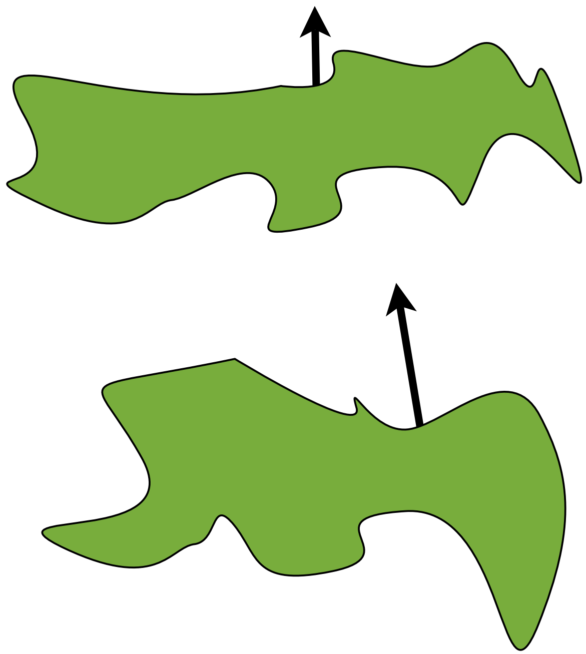
Misaligned



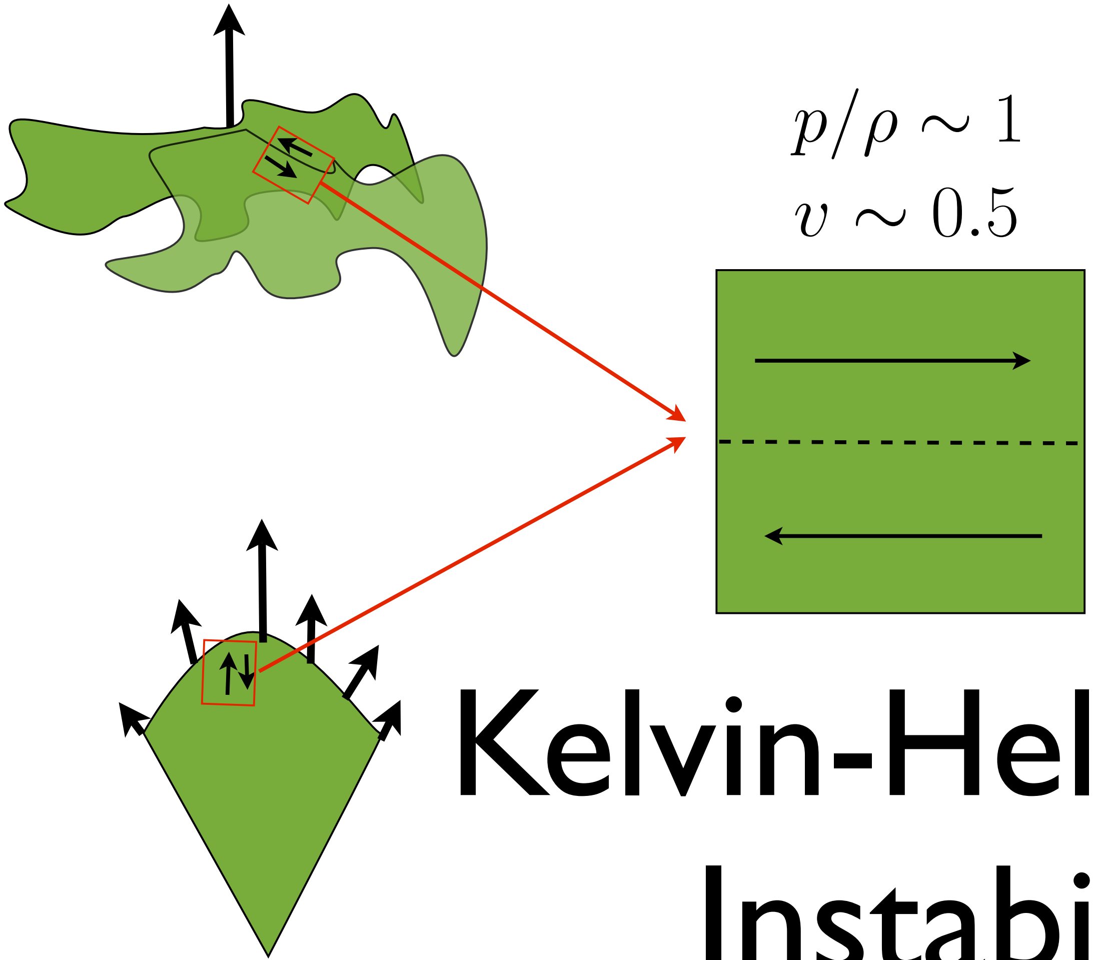
Oblique



Colliding Clumps



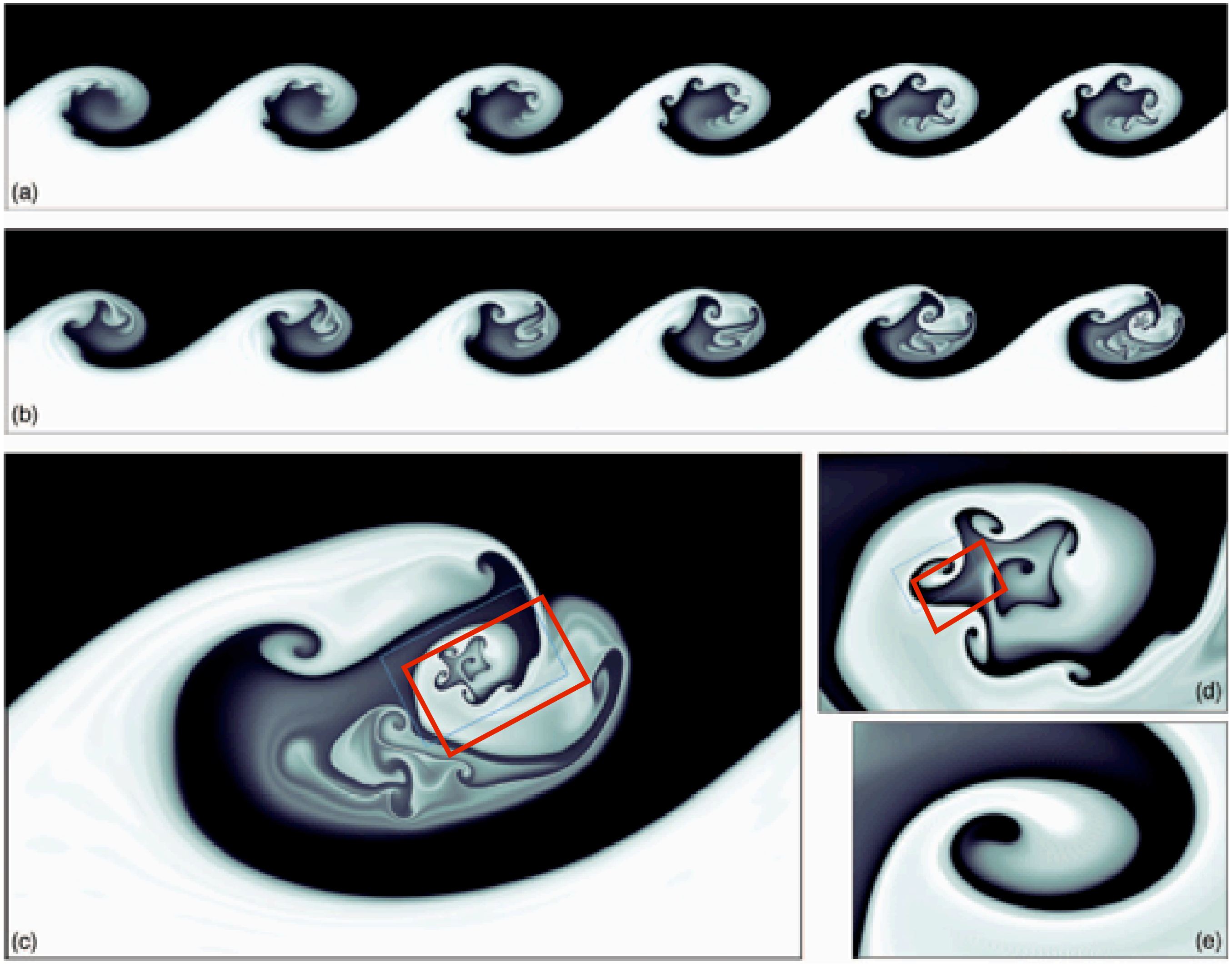
Shear Patches



Kelvin-Helmholtz Instability

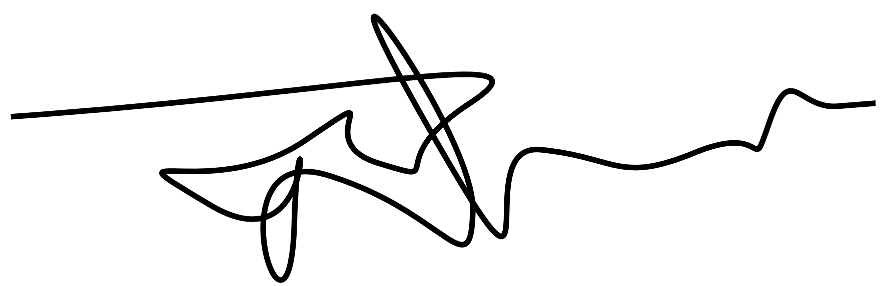
Kelvin Helmholtz Clouds

Big Whirls Have Little Whirls

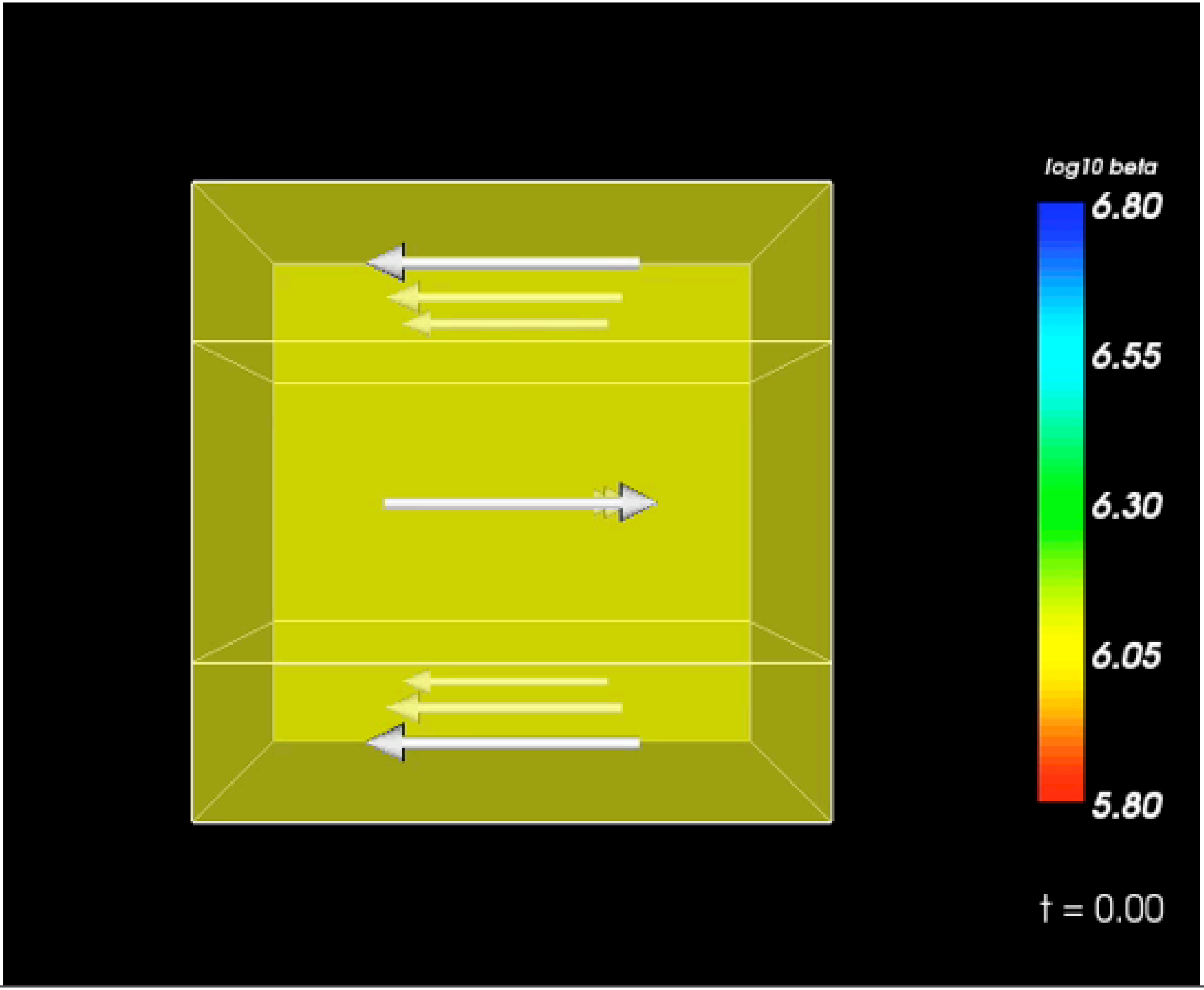


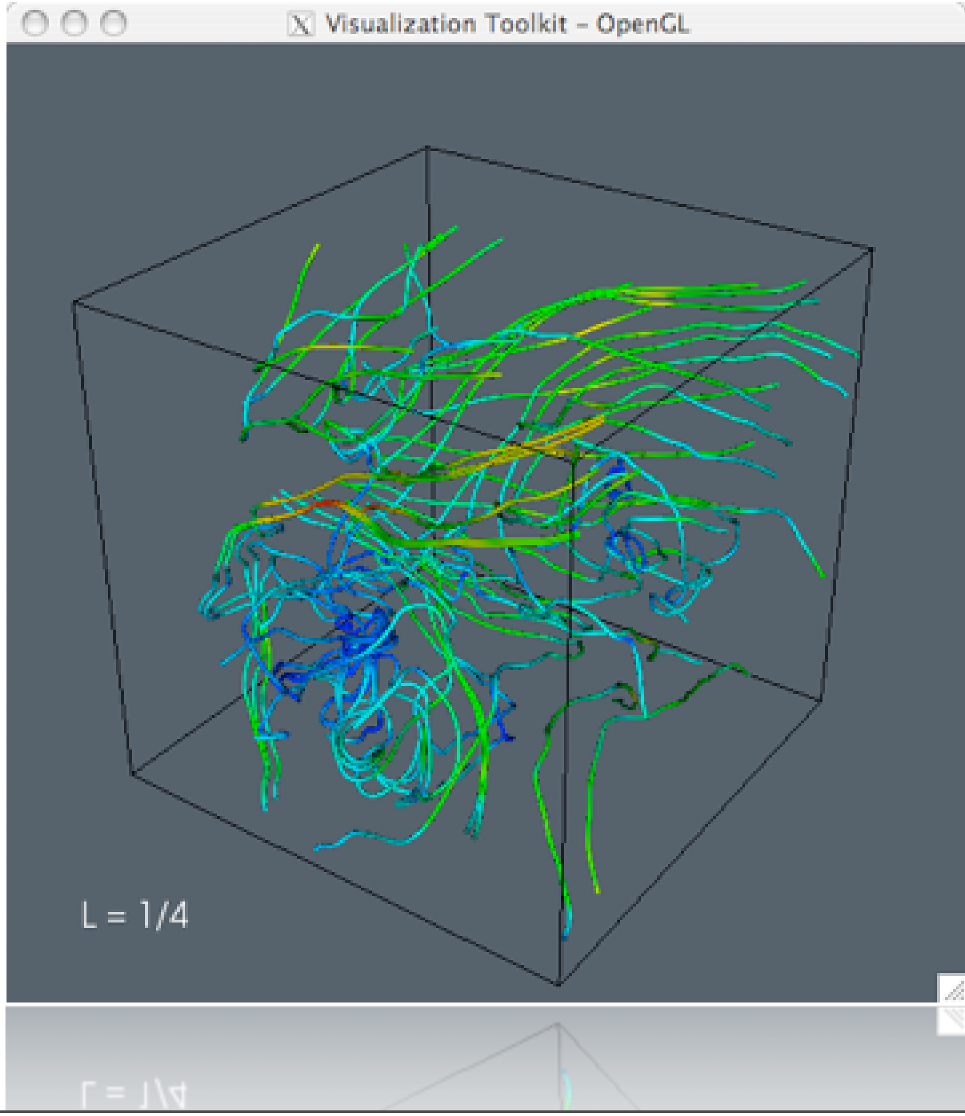
Joly et al (2008)

Twisting and Folding

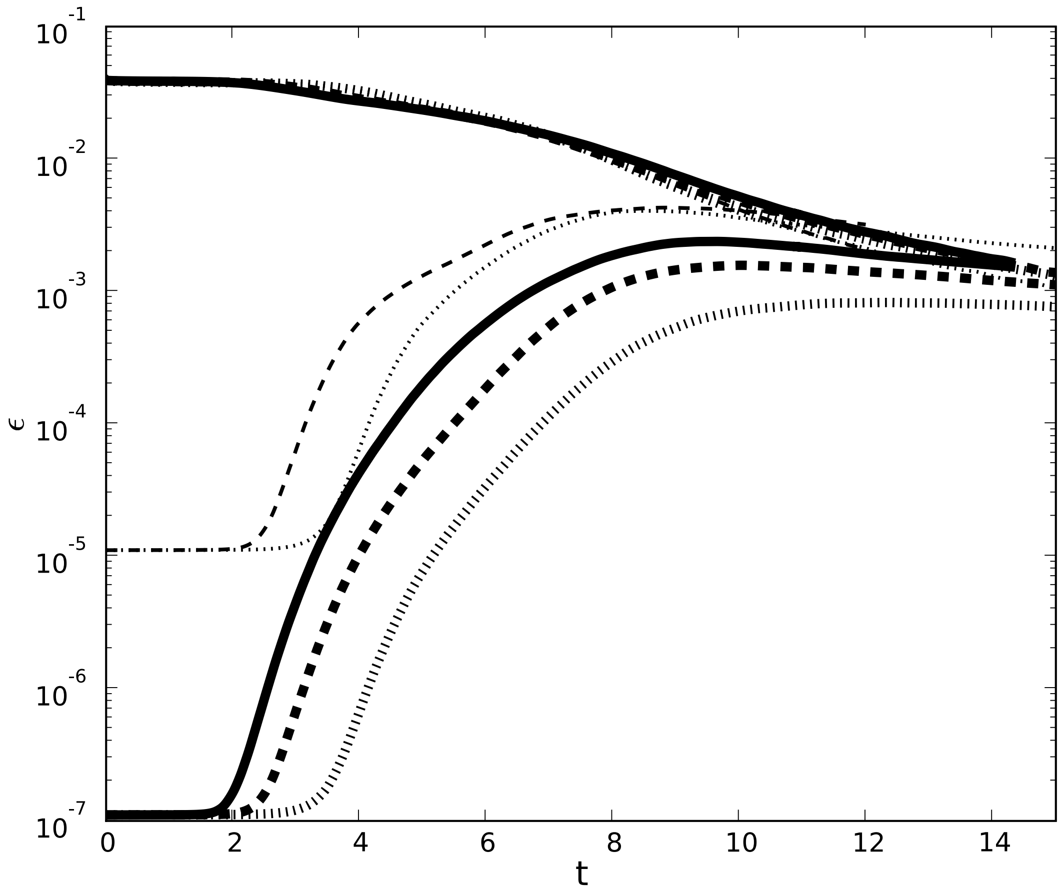


KH: 1024^3 Rel. MHD

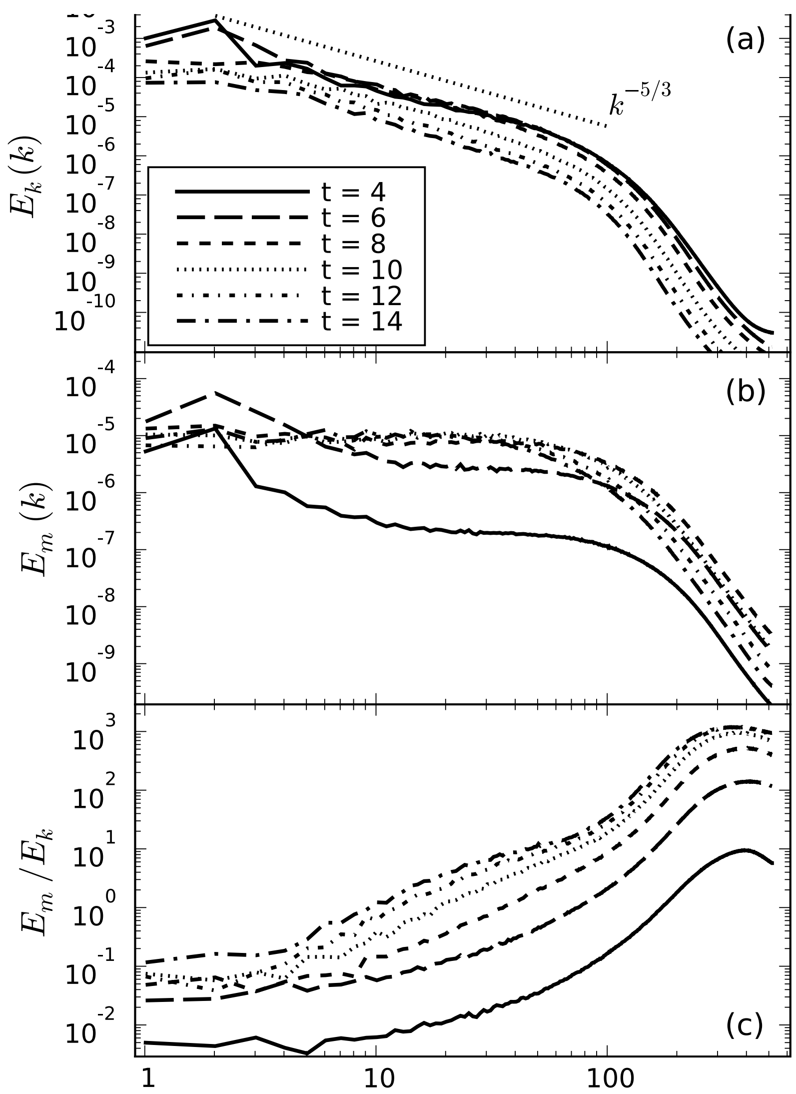



Visualization Toolkit - OpenGL
L = 1/4

Mag. & Kin. Energy



Power Spectra



Conclusions

- Light Curves from Hi-res 2D sims
- GRB AG Jets take > 10 years to isotropize
- $\epsilon_B = 5 \times 10^{-3}$
- $E_k \sim k^{-5/3}$ (Mild) RMHD Turbulence has Kolmogorov-like spectrum

Conclusions

- Long GRBs from massive rotating stars
- Need t_engine > t_escape
- Collapsars : t_accrete ~ 20 s
- Relativistic Jets escape compact stars (10^11 cm ~ few light seconds)
- WR wind important – clumpiness -> vorticity

->B field

* Computed 2D afterglow jet w/ AMR - slow spreading

* Synchrotron light curves- wind, off axis -> less jet break