# Relativistic Jets in Collapsars

Collapsing rotating presupernova star
⇒ accretion disk + black hole
⇒ relativistic jets
⇒ fire ball, GRBs, afterglows

- Initial model: helium star model from presupernova evolution and collapsing
- Not worrying about making jets. Assuming preformed jets
- Propagation of relativistic jets in collapsars
- Implications for observations

# Special Relativistic Hydrodynamics

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{F}^i(\mathrm{u})}{\partial x^i} = 0$$

$$\mathbf{u} = (D, S^1, S^2, S^3, \tau)^T$$

$$\mathbf{F}^i = (Dv^i, S^1 v^i + p\delta^{1i}, S^2 v^i + p\delta^{2i}, S^3 v^i + p\delta^{3i}, S^i - Dv^i$$

$D, S^1, S^2, S^3, \tau$: rest-mass density, momentum density and energy density in the laboratory frame

A Hyperbolic System of Conservation Laws

Godunov-Type High-Resolution Shock-Capturing Methods based on exact or approximate solutions of Riemann problems.

Calculation of fluxes ⇒ Time advance

- High order in space:
  PPM, reconstruction
  Besides $p, \rho, \ldots$ (cell average),
  $p_l, p_r, \rho_l, \rho_r, \ldots$ (edge of cell)
- High order in time:
  Instaneous flux (unlike PPM) ⇒ Low order
  Runga-Kutta ⇒ High order
  $t, t+\delta t, t+2\delta t, \ldots \Rightarrow t+\delta t$
- Conservation laws: lab frame
  Riemann problem: local frame
  Lab frame ⟺ Local frame
  Coupling of space and time (iteration)

## Initial Setup

- 15 $M_\odot$ rotating helium star, 0.1 solar composition
- evolved to iron core collapse (*Heger*)
- collapsing for 10 seconds (*MacFadyen*)

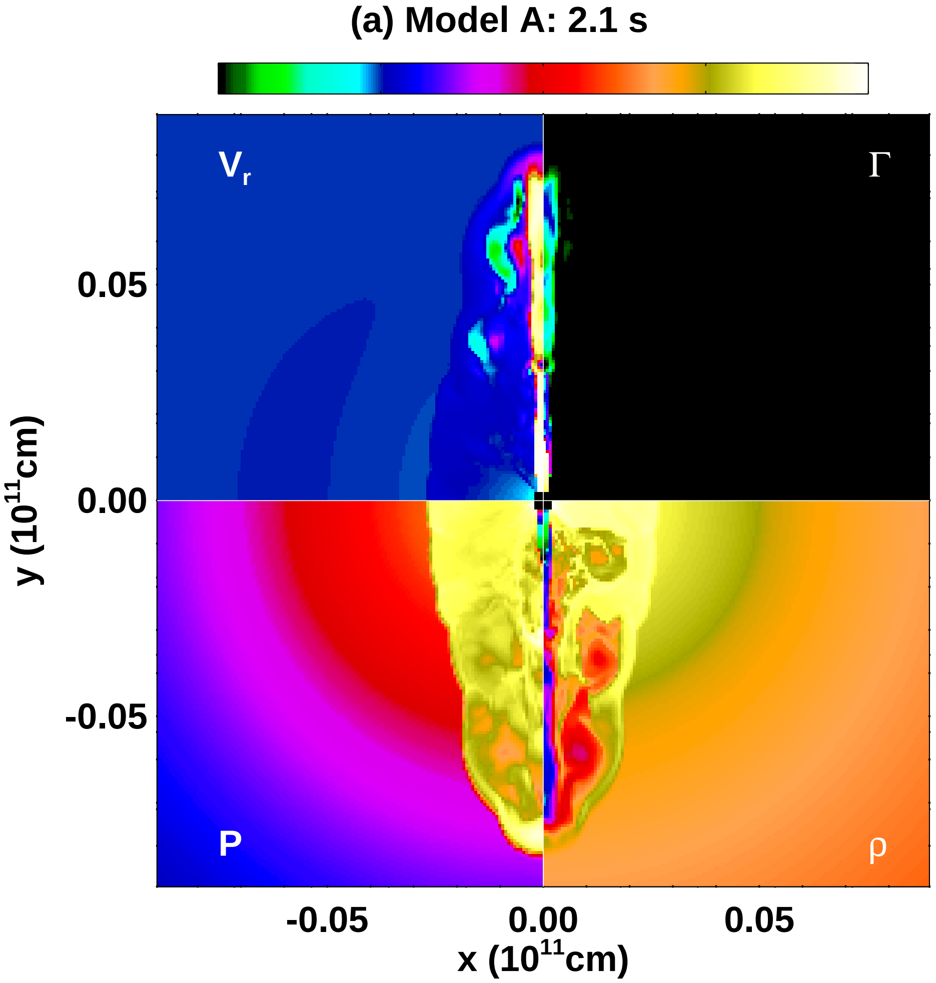
- $2 \times 10^8$ cm – $9 \times 10^{10}$ cm
- Comp. Grids: 2-D spherical grid $(r, \theta)$
  480 logarithmically spaced radial zones
  120 uniform angular zones in $0^o \leq \theta \leq 30^o$
  80 logarithmically spaced zones in
  $30^o \leq \theta \leq 90^o$

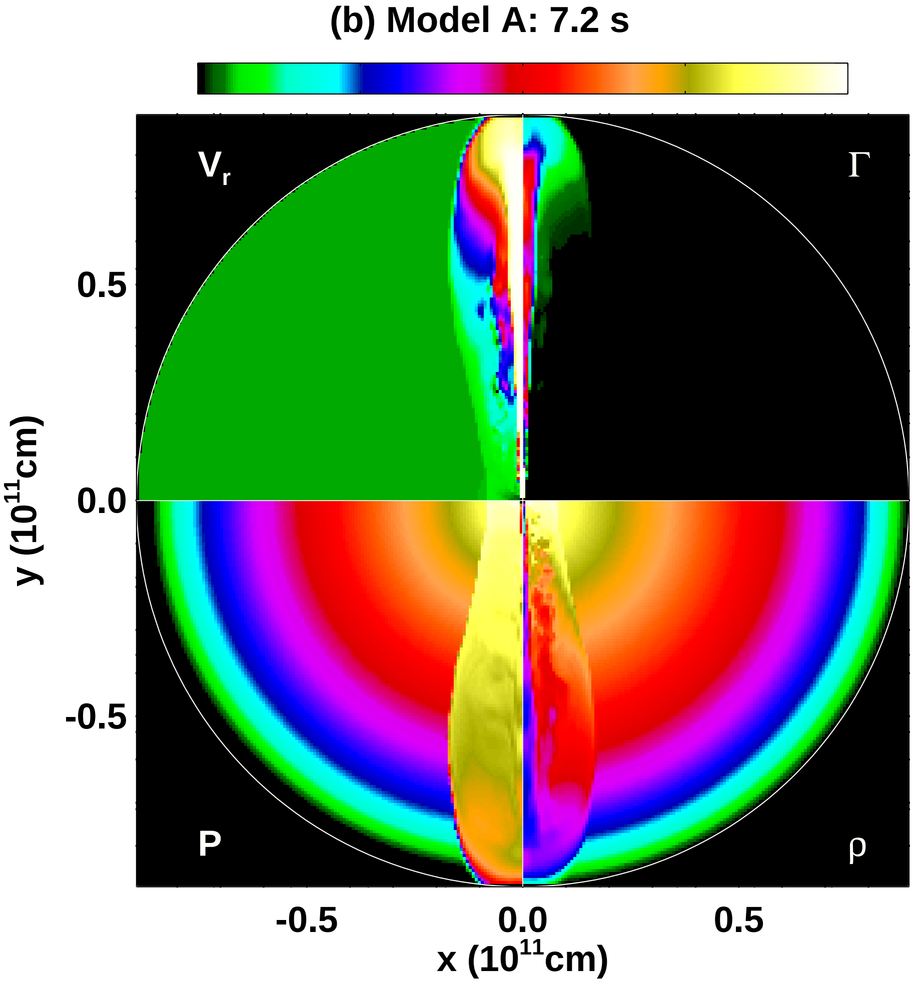
- Newtonian gravity of BH
- Real EOS

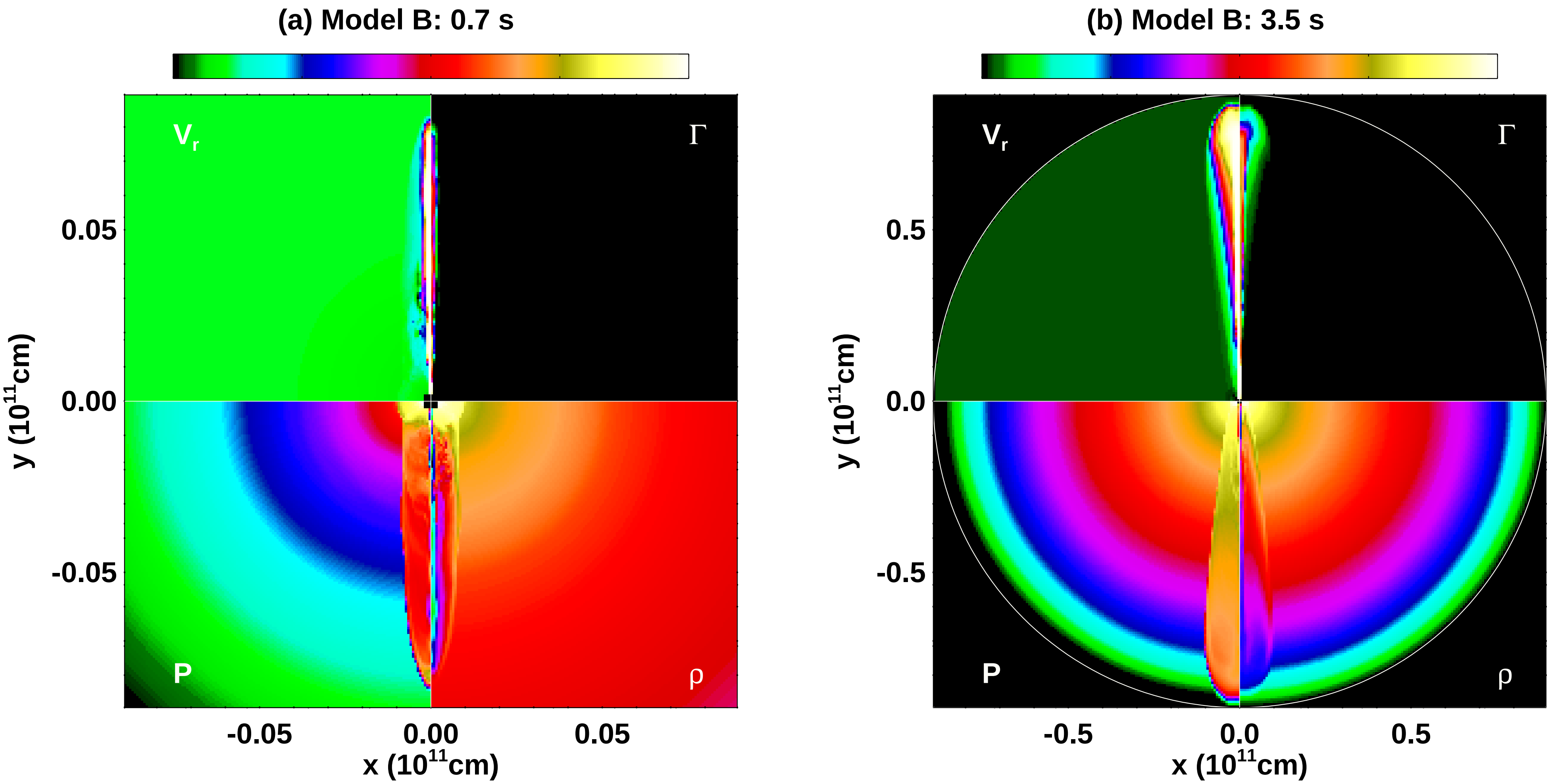
## Jet Parameters

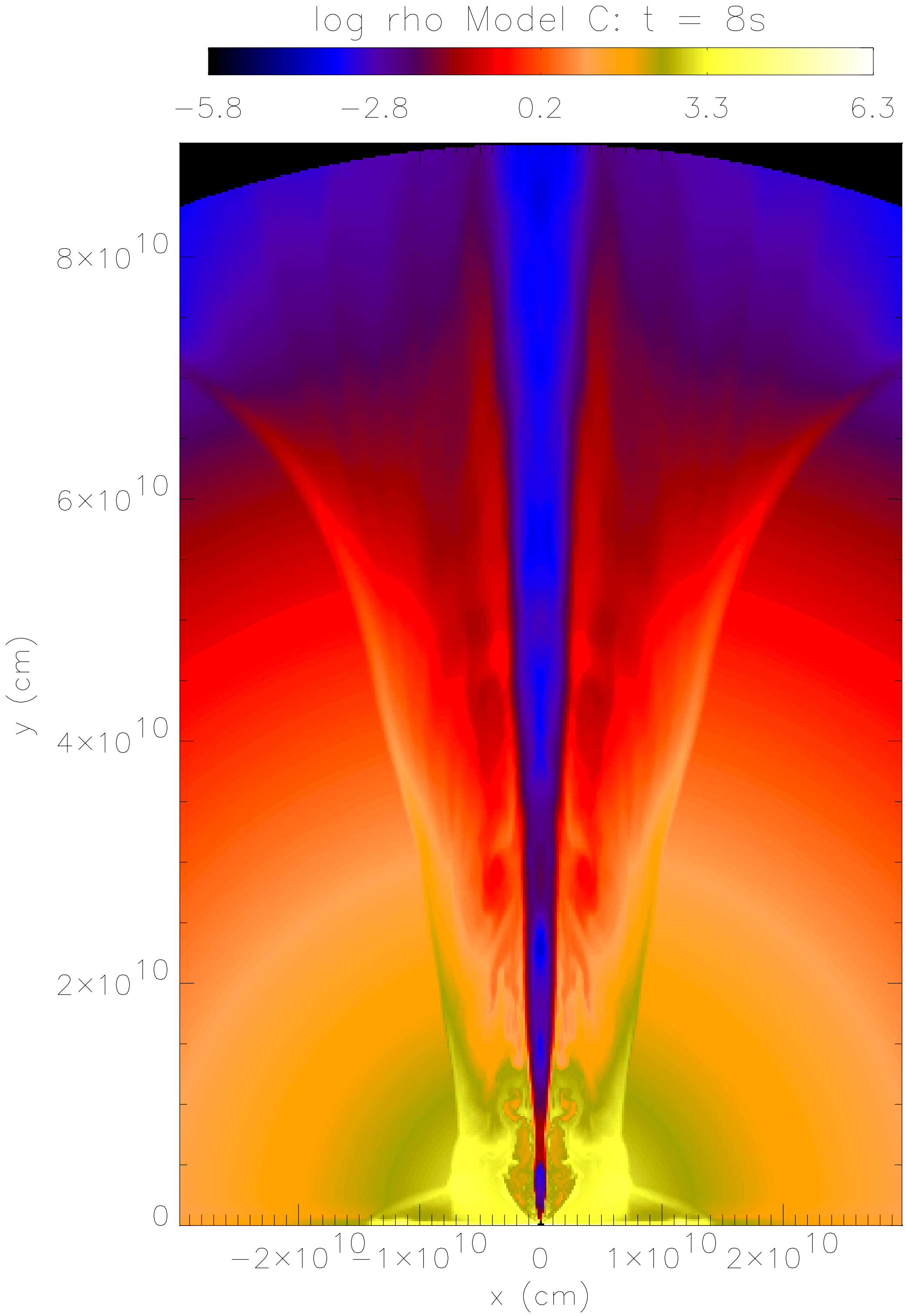
- Energy deposition rate: $\dot{E}$
- Initial opening angle: $\theta_0$
- Initial Lorentz factor: $\Gamma_0$
- Ratio of kinetic energy to total energy: $f_0$

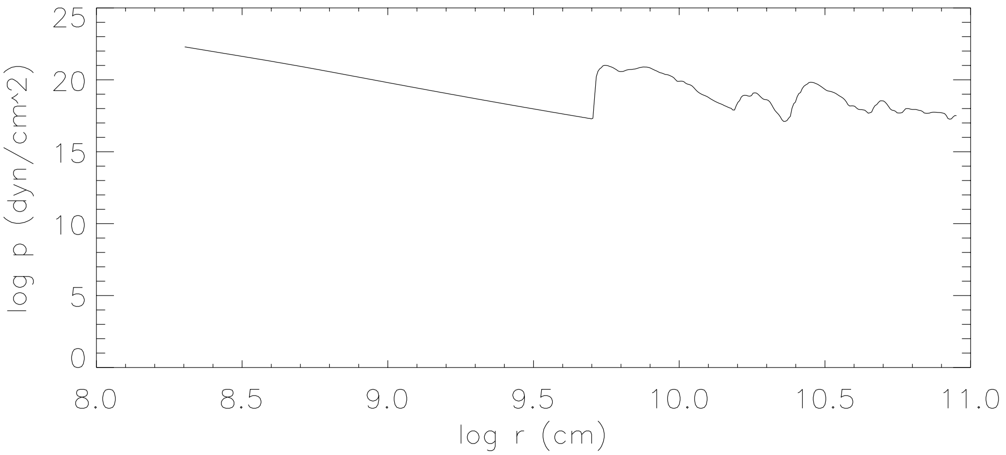
| | $\dot{E}(\mathrm{ergs\,s^{-1}})$ | $\theta_0$ | $\Gamma_0$ | $f_0$ |
|---|---|---|---|---|
| Model A | $10^{51}$ | $20^0$ | 50 | 0.33 |
| Model B | $10^{51}$ | $5^0$ | 50 | 0.33 |
| Model C | $3 \times 10^{50}$ | $10^0$ | 5 | 0.025 |

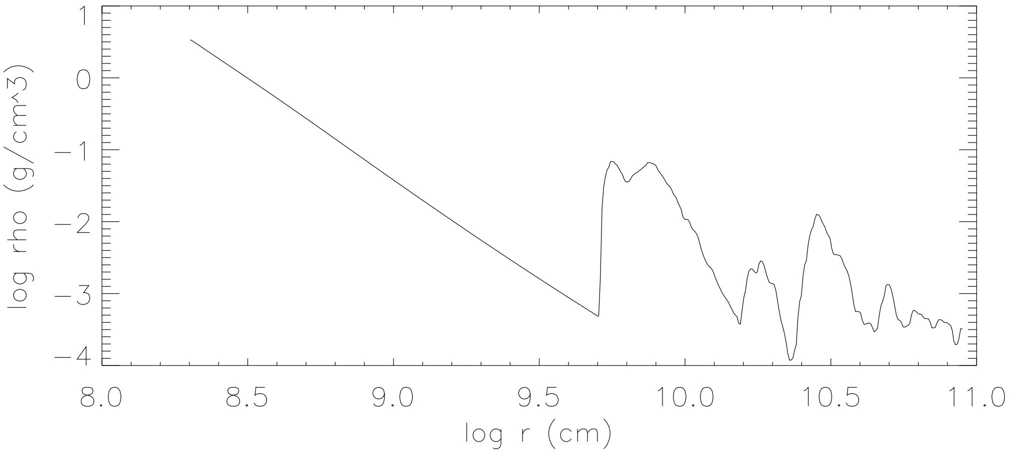

(a) Model A: 2.1 s
V$_r$
Γ
P
ρ
0.05
0.00
-0.05
y ($10^{11}$cm)
-0.05
0.00
0.05
x ($10^{11}$cm)

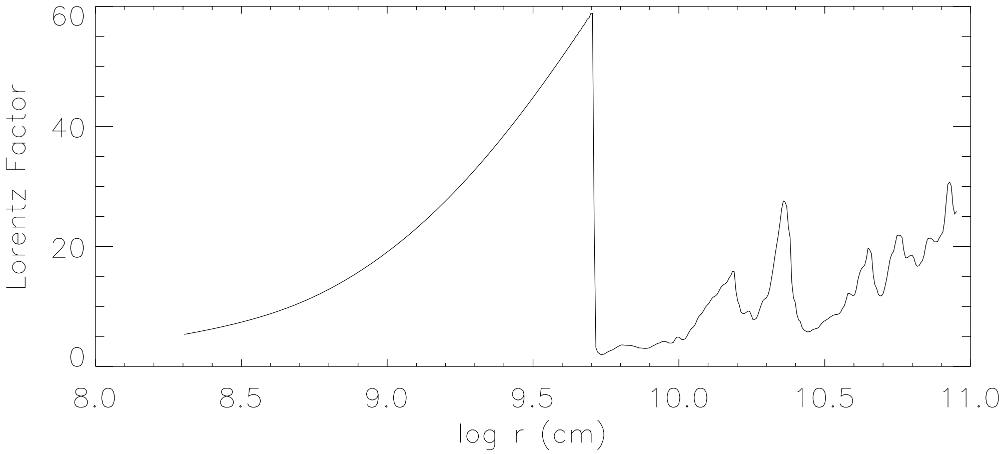

(b) Model A: 7.2 s
V$_r$
Γ
P
ρ
0.5
0.0
-0.5
y ($10^{11}$cm)
-0.5
0.0
0.5
x ($10^{11}$cm)


(a) Model B: 0.7 s
(b) Model B: 3.5 s
$V_r$
Γ
P
ρ
$V_r$
Γ
P
ρ
0.05
0.00
-0.05
-0.05
0.00
0.05
y ($10^{11}$cm)
x ($10^{11}$cm)
0.5
0.0
-0.5
-0.5
0.0
0.5
y ($10^{11}$cm)
x ($10^{11}$cm)


log rho Model C: t = 8s
−5.8
−2.8
0.2
3.3
6.3
8×10^10
6×10^10
4×10^10
2×10^10
0
y (cm)
−2×10^10
−1×10^10
0
1×10^10
2×10^10
x (cm)


log p (dyn/cm^2)
25
20
15
10
5
0
8.0
8.5
9.0
9.5
10.0
10.5
11.0
log r (cm)


log rho (g/cm^3)
1
0
−1
−2
−3
−4
8.0
8.5
9.0
9.5
10.0
10.5
11.0
log r (cm)

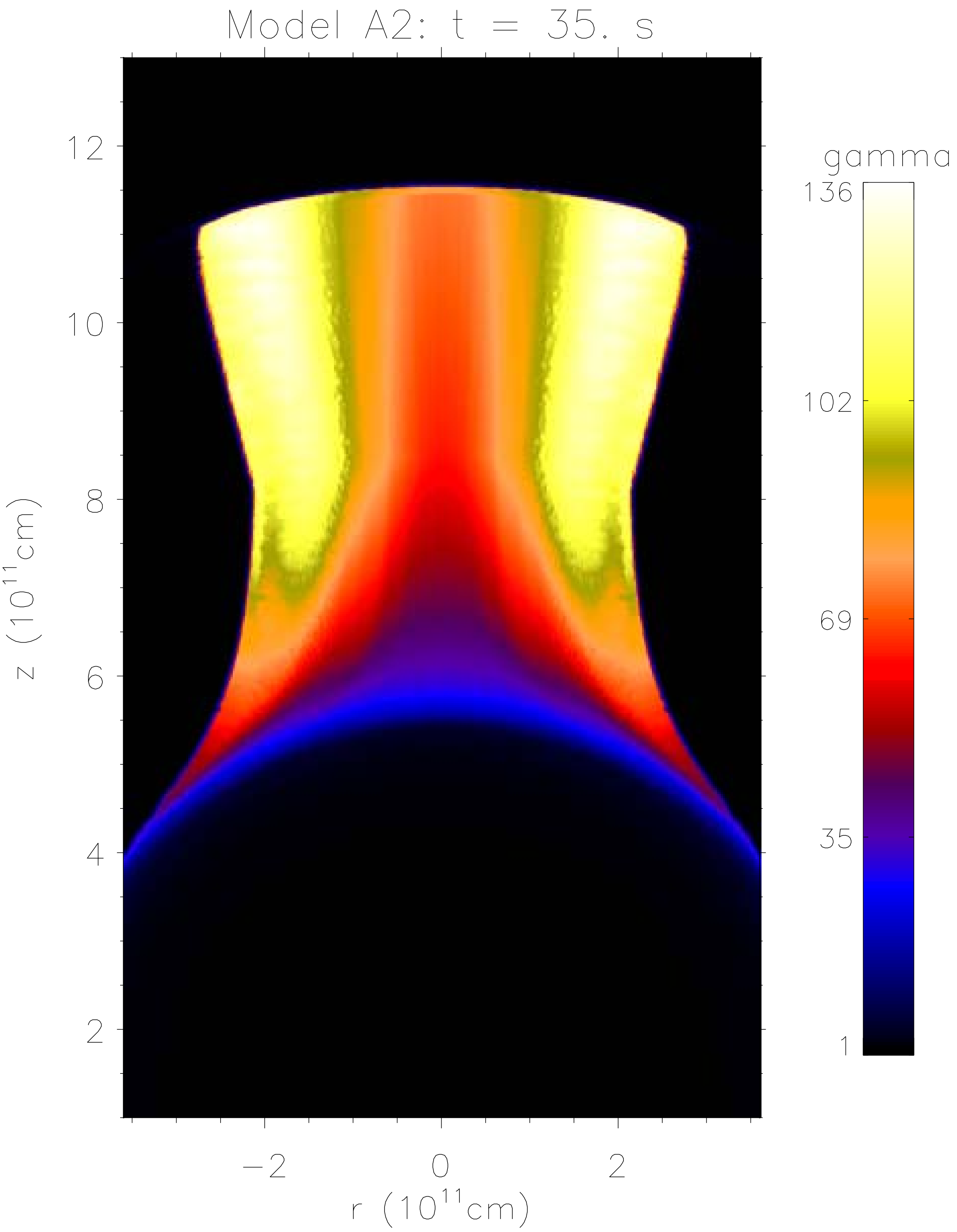

Lorentz Factor
60
40
20
0
8.0
8.5
9.0
9.5
10.0
10.5
11.0
log r (cm)

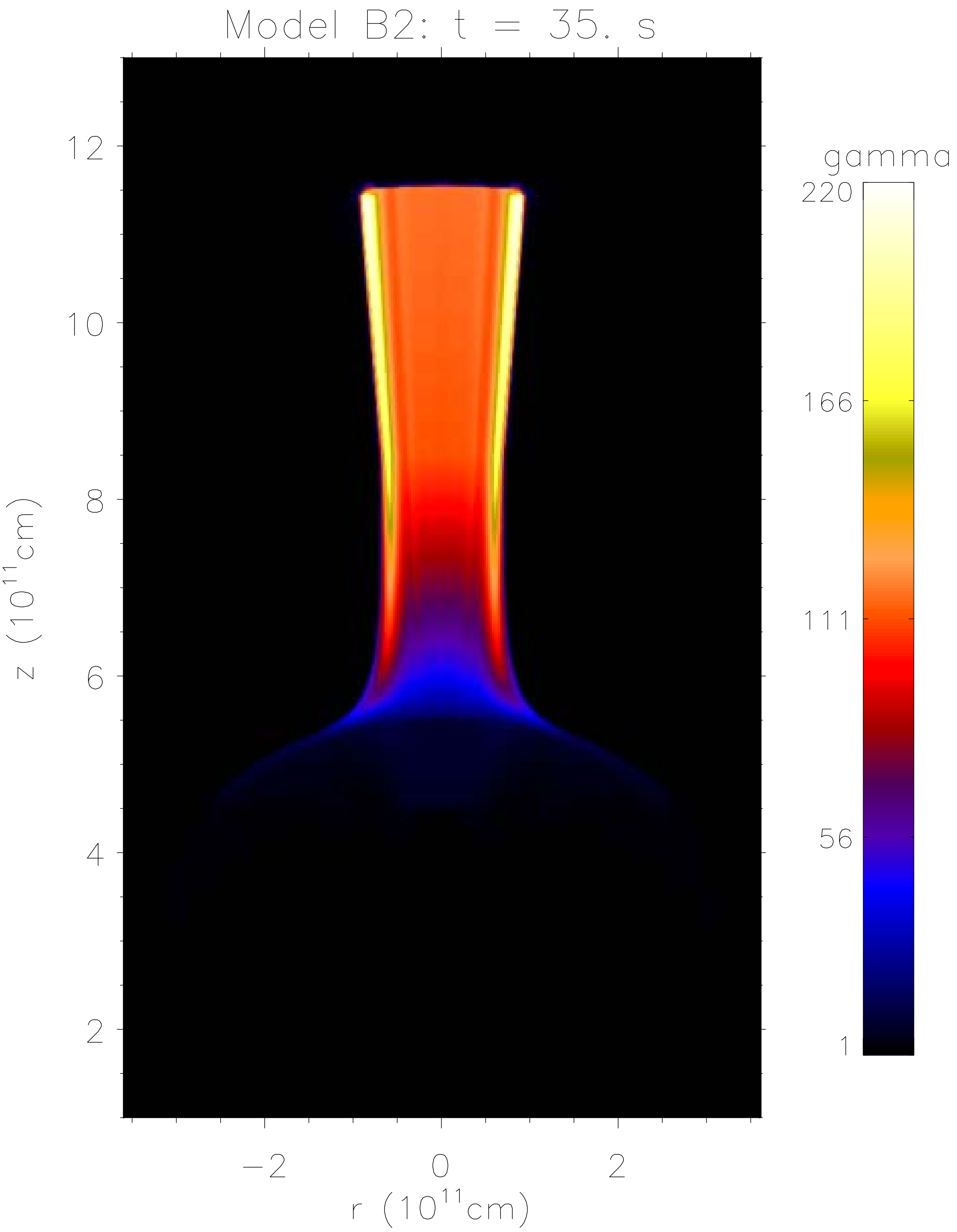
# Jets in Stellar Wind

- After breakout, the jet expands laterally because of high internal energy. Still small opening angle? Lorentz factor?

## *Second Series of Calculations*

- 2-D cylindrical
  r: (0, $3.6 \times 10^{11}$ cm), 720 zones
  z: ($1.0 \times 10^{11}$, $1.3 \times 10^{12}$ cm), 2400 zones
- $\rho \sim R^{-2}$
- $z = 1.0 \times 10^{11}$: jet injected, $\leq 5^o$, radially $10^{51}\,\mathrm{ergs\,s^{-1}}$ for 10 s, then gradually die in 10 s.
  Model A2: $\Gamma = 10, E_{tot}/E_k = 15$
  Model B2: $\Gamma = 50, E_{tot}/E_k = 3$


Model A2: t = 35. s
z (10^11 cm)
12
10
8
6
4
2
−2
0
2
r (10^11 cm)
gamma
136
102
69
35
1


Model B2: t = 35. s
gamma
220
166
111
56
1
z ($10^{11}$cm)
12
10
8
6
4
2
r ($10^{11}$cm)
−2
0
2

## Discussions

- Insensitive to initial parameters
  $\Rightarrow 5^o$ at edge of star
- Instability (not the central engine)
  $\Rightarrow$ time structure, light curve
- Luminosity – Variability
  (narrower jet $\Rightarrow$ more instabilities
  $\Rightarrow$ more variabilities
  narrower jet $\Rightarrow$ more luminous)
- GRB 980425: weak burst viewed from large angle
  Many 980425-type GRBs

# Future Work

- Small inner boundary ($5 \times 10^7$ cm
  Dumping energy and/or injecting jet
  (currently working)
- Can we see variations of engine? (Not)
- 3-D: unstable? time structure?
  non-axisymmetric effects?
  A more powerful code: putting AMR into the code
- More Physics: neutrino, $\alpha$-viscosity, magnetic field, ...
- Analytic work on instability