Collimated Jet or Expanding Outflow : Possible Origin of GRBs and X-ray Flashes

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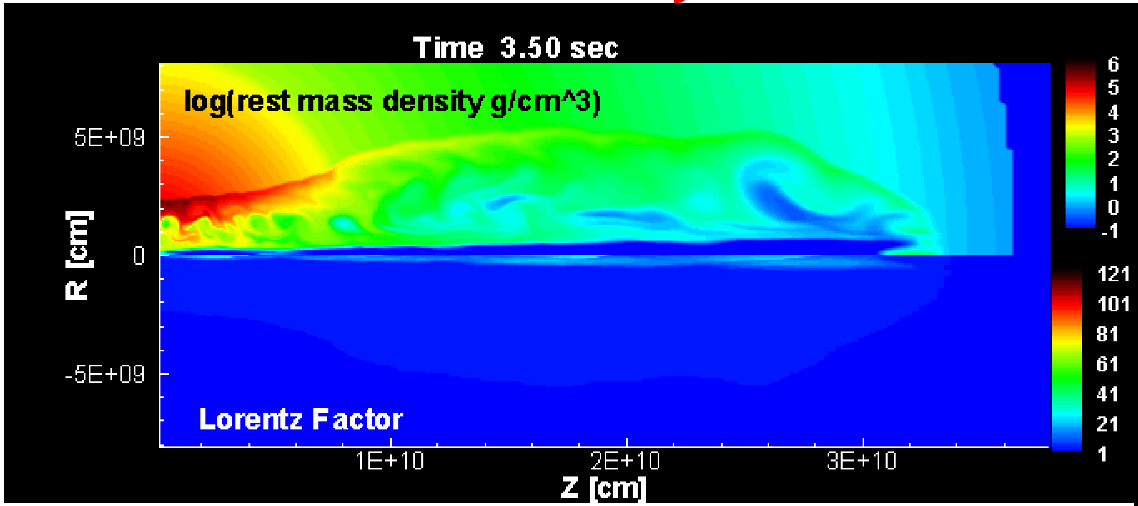
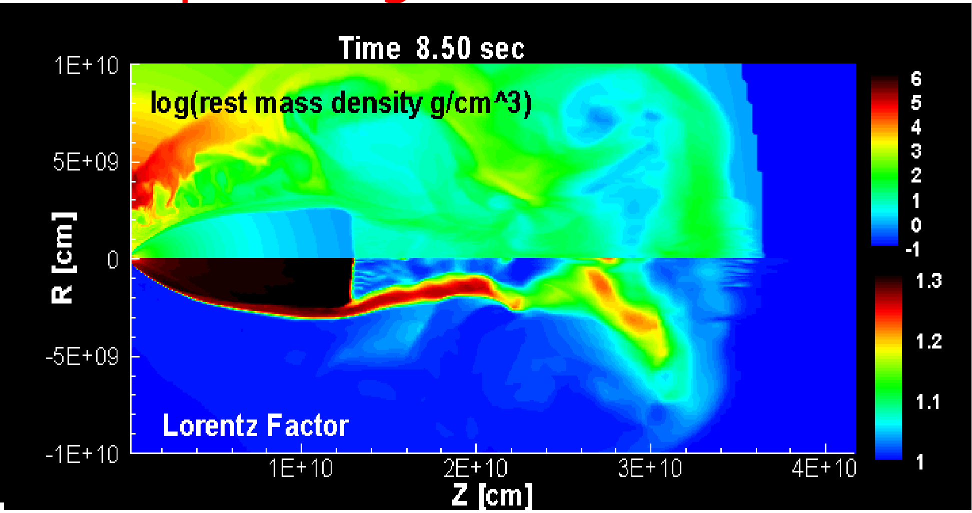
"Collimated Jet"



"Expanding Outflow"



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Challenges Relativistic Jets
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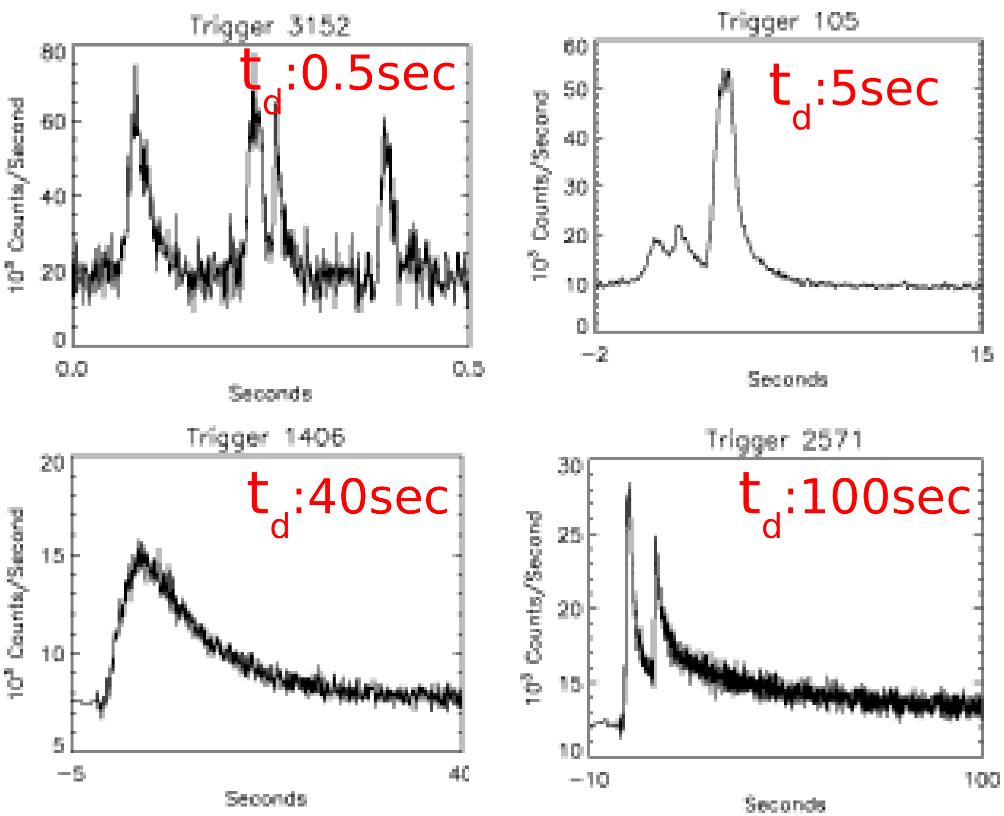
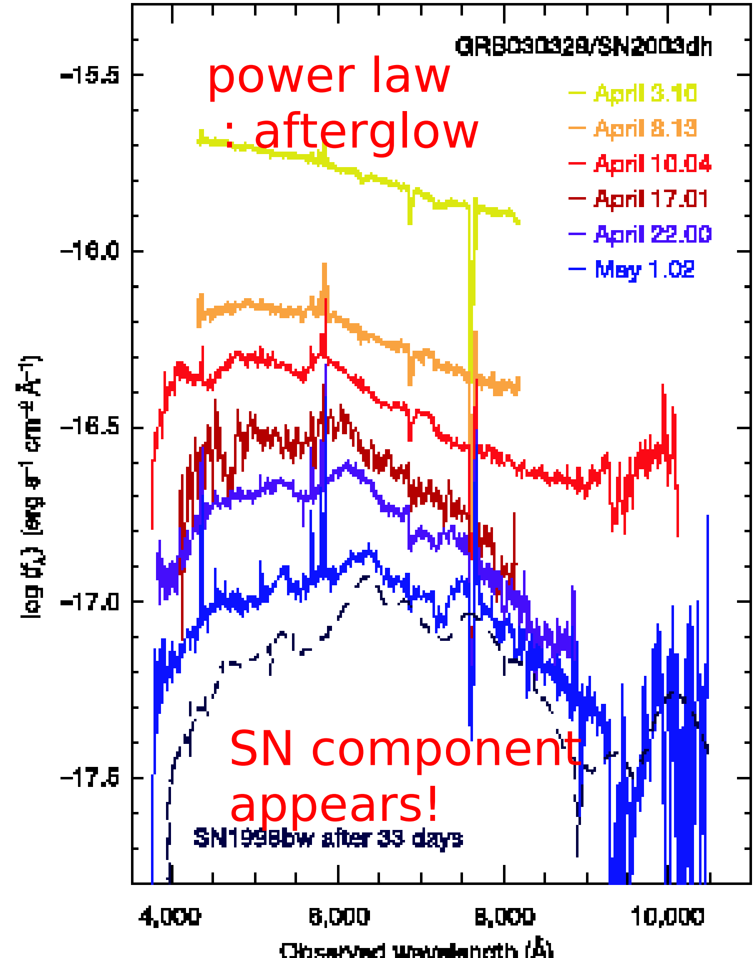
GRBs are the most energetic phenomena in the sky

$E \sim 10^{50\text{-}53}$ ergs. (isotropic)
About 1000 events / year are observe
Duration : t_d ~ a few ms up to
a few 1000 secs.
light curve and duration differ each other



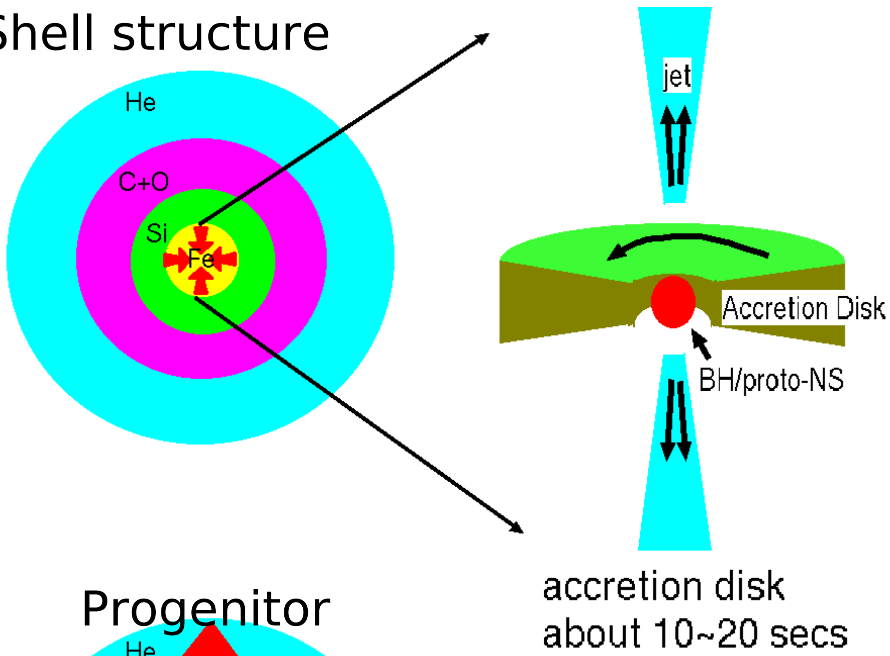
Spectrum :after a few days
~ after a month from the burst



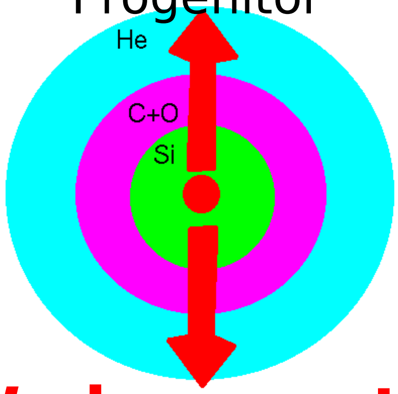
Association long duration GRB-SN is observed.
ex. GRB980425/SN1998bw,
GRB030329/SN2003dh,
GRB060218/SN2006aj.

Collapsar model is a kind of core collapse SN and highly aspherical explosion. (Wooseley 1993, MacFadyen et al. 1999)

Shell structure



Progenitor



1. Fe core collapses and becomes BH/proto-NS. Outer layers begin to free-fall.

2. Due to rotation of the progenitor, accretion gas is expected to form an accretion disk
MHD and/or “neutrino annihilation” forms bipolar jets.

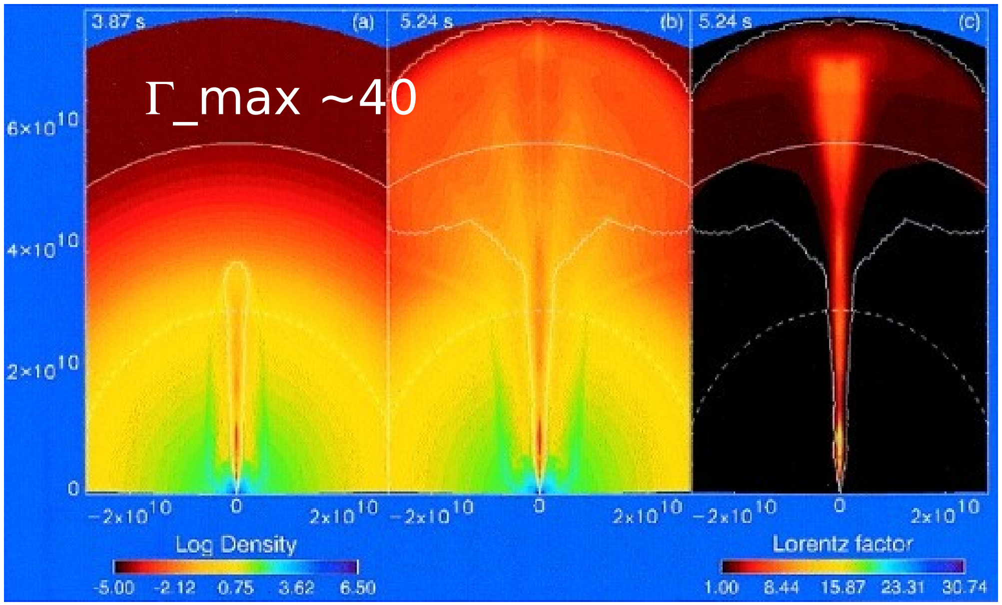
Free-fall time scale
~1/sqrt(ρG)~100sec
>> jet crossing time scale
~10sec

This formed jet should propagate in the progenitor !

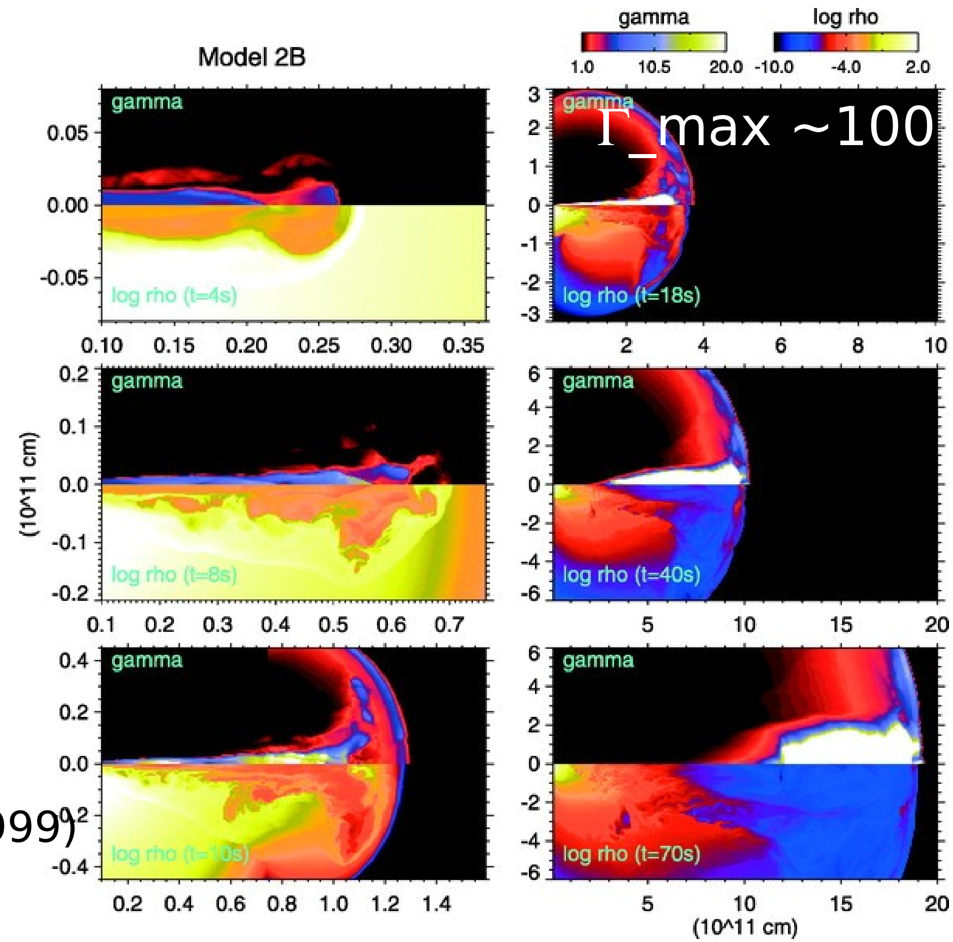
We have not fully understood what the central engine is.
How can we make highly relativistic collimated outflow ?

Collapsar is a strong candidate of the central engine of long duration GRBs (observationally supported !)

Two types of approaches by Relativistic HD: thermal energy deposition & injected jet



Aloy et al. (ApJL 2000)
(thermal energy deposition)
Relativistic version of MacFadyen et al. (1999)



An emerging jet from the center should propagate in the progenitor and erupt to ISM.

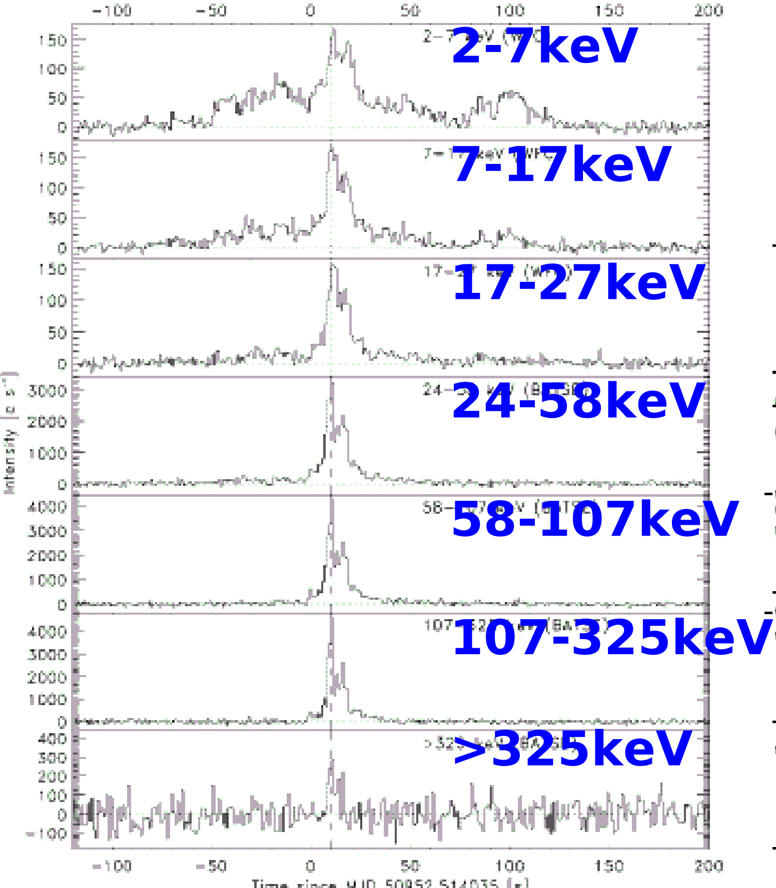
Zhang et al. (a jet injected)

These calculations show successful eruption of relativistic jets from the progenitor.

But there still remains some issues.......

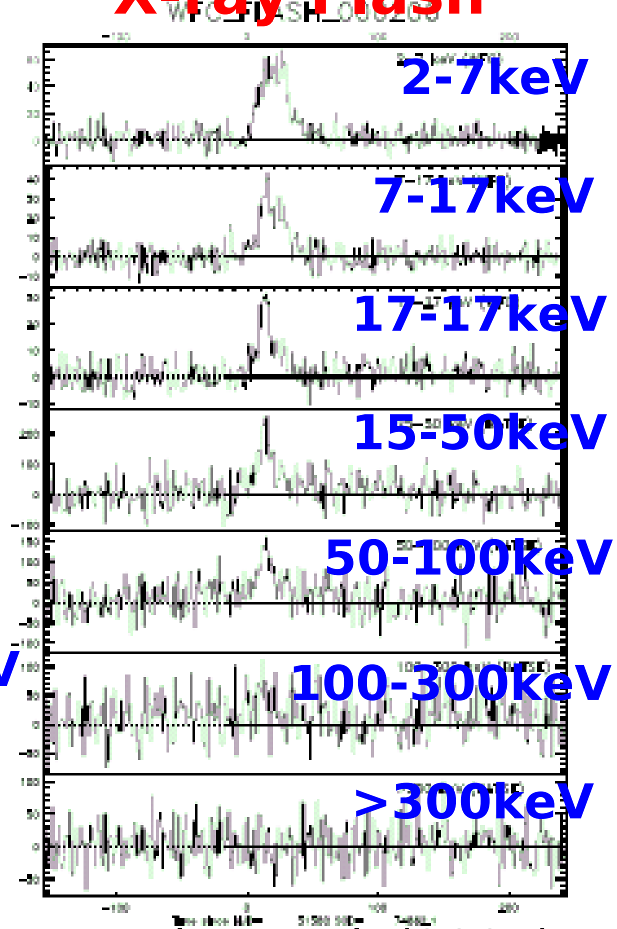
There are similar phenomena to GRBs
Those are X-ray Flashes(XRFs) and X-ray rich GRBs

Light curve
GRB980519



Int'Zand et al 1999

Light curve
X-ray Flash

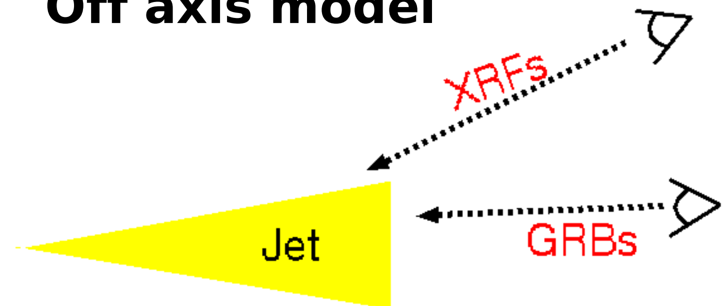


Heise et al. (2001)

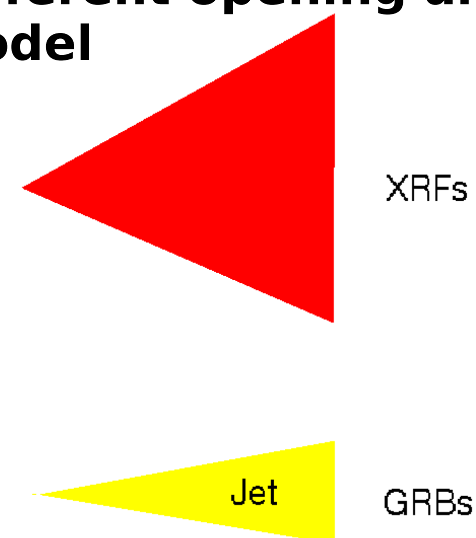
No remarkable signals in γ-ray range.

The phenomena look like quite similar. The event rate of XRFs is similar to those of GRBs

Off axis model

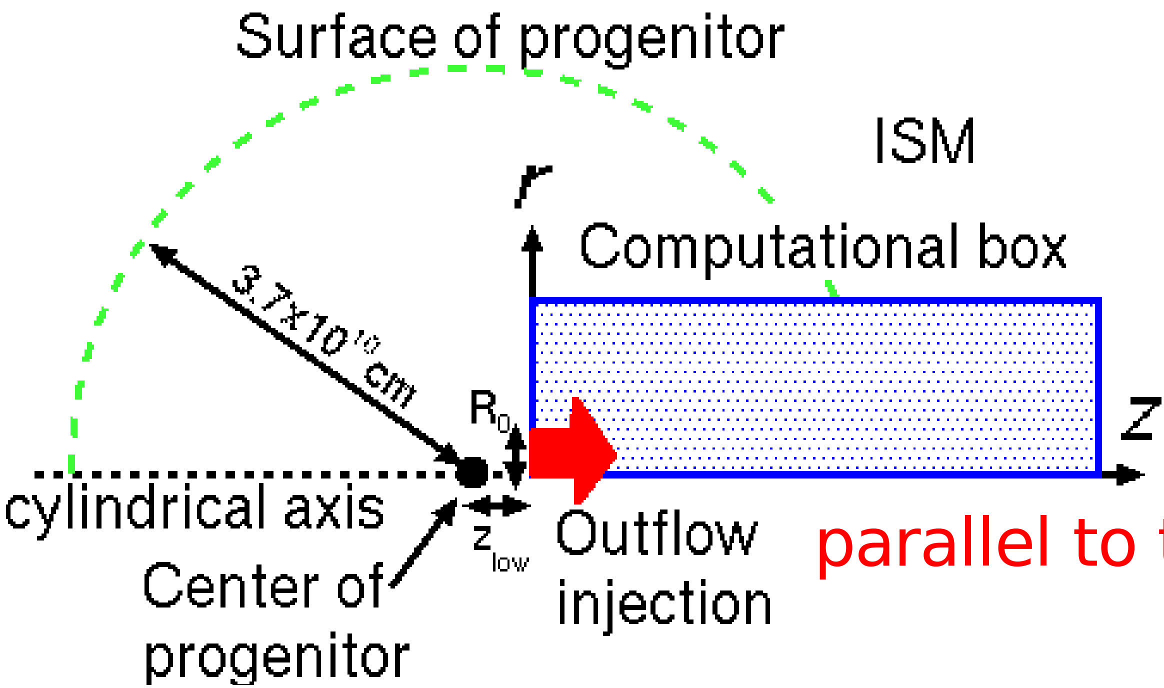


Different opening angle model



We have studied jet propagation by outflow injection. Numerical set up of our model

Initially spherical, 2D axisymmetric geometry

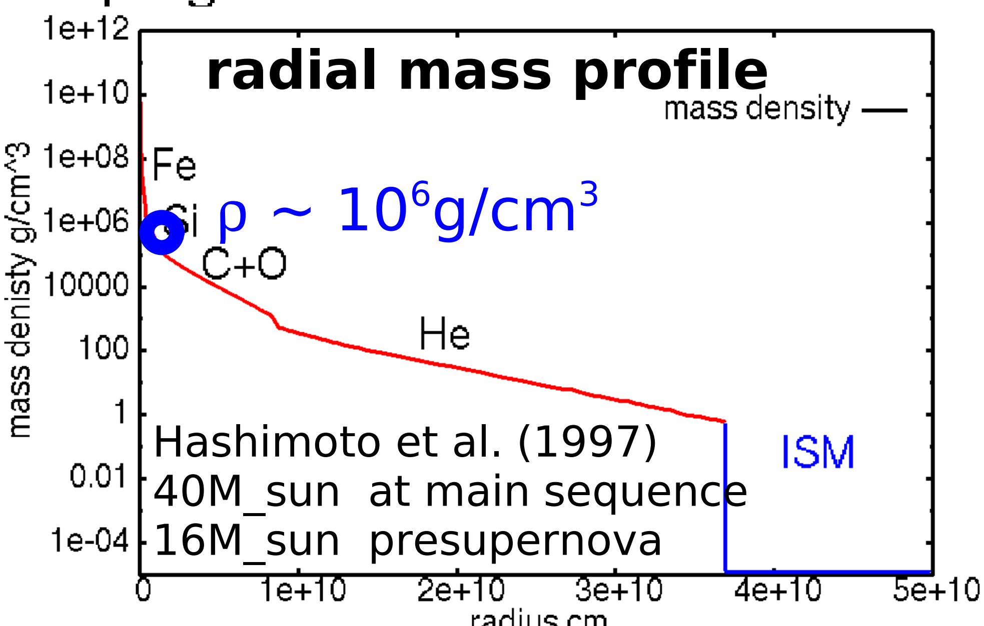


$R_0 = 7 \times 10^7$ cm

$z_{low} = 2 \times 10^8$ cm

cf. R_{BH}(1M_sun)~3×10^5 cm

parallel to the axis, no opening angle



2D Relativistic hydrodynamic Eq. are solved.

$p = (\gamma - 1) \rho \varepsilon \quad \gamma = 4/3$ (const)

Mizuta et al. '04,'06

We have done parametric study on injected outflow condition, varying kinetic and thermal energy of injected outflow

Four parameters are necessary to define the outflow

We fixed two of them.

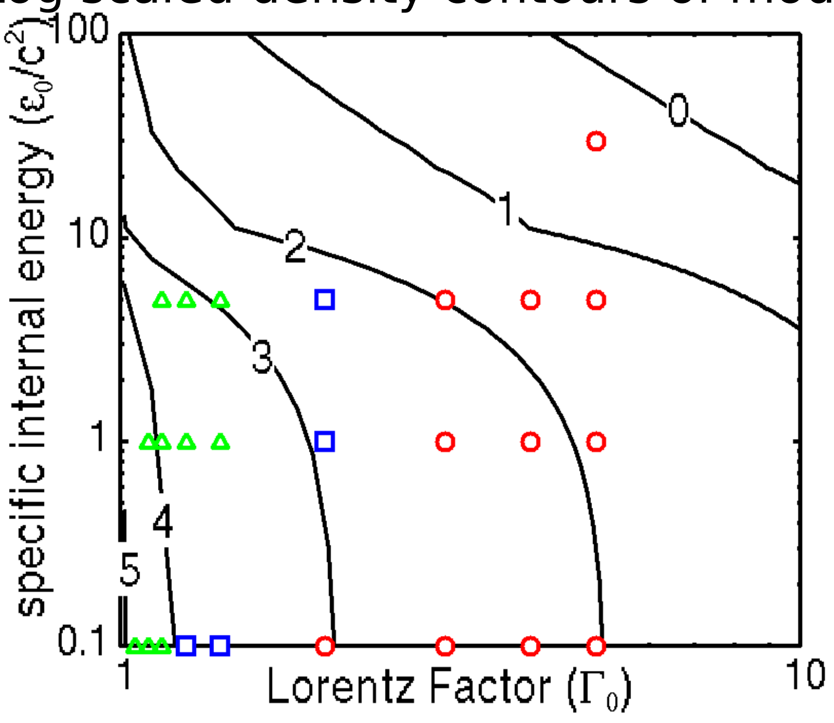
- $R_0 = 7.0 \times 10^7$ cm
- $dE/dt = 1.0 \times 10^{51}$ erg / sec

where $E = E_{kin} + E_{th}$ follow up to 10secs

E_tot=1.0×10^{52} erg

We vary Γ_0, and ε_0 / c^2 of the outflow

Log scaled density contours of models



Maximum Lorentz factor can be derived from energy conservation law

$\Gamma_{max} \sim \Gamma_0 (1+\varepsilon_0/c^2)$

assuming free expansion

cf .SNe

v~sqrt(E / M),

where $E = E_{kin} + E_{th}$

Γ_0 : bulk Lorentz factor

$\Gamma_0(v_0/c)$=1.05(0.3),1.15(0.5)

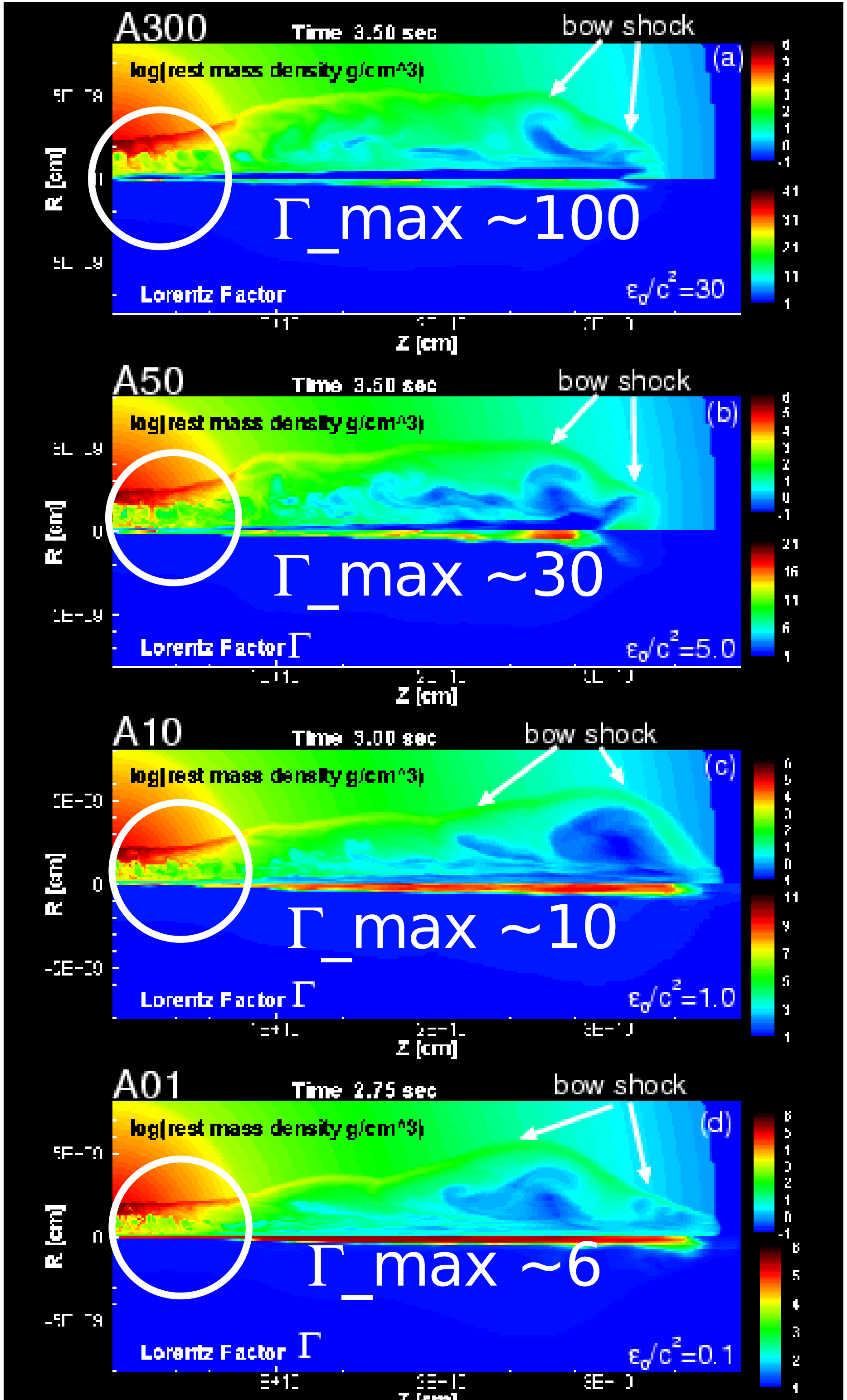
1.4(0.7),2(0.87),3(0.94)

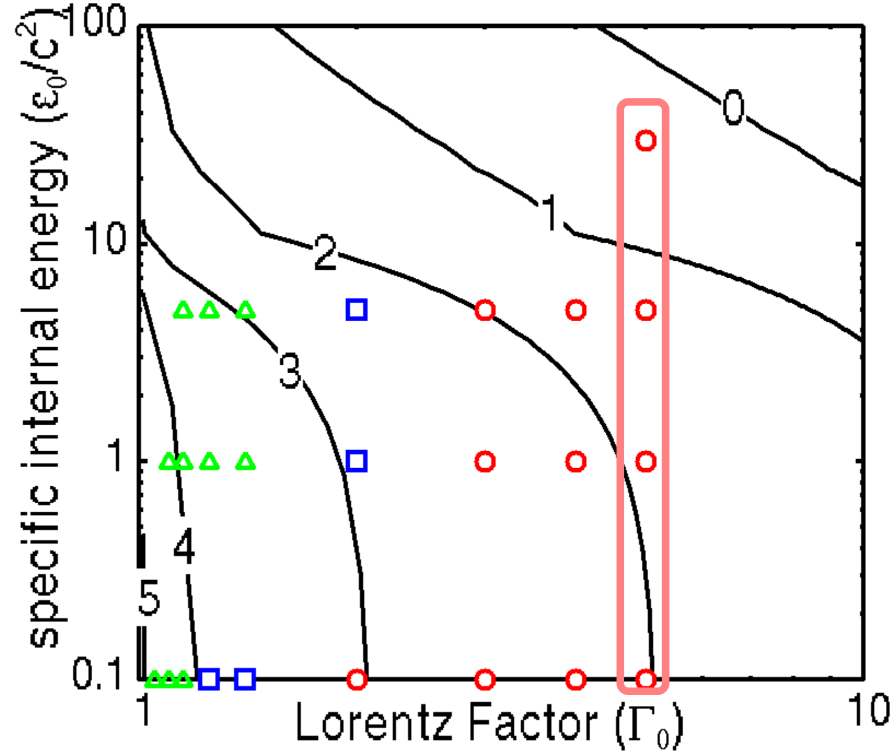
4(0.97),5(0.98)

ε_0 : specific internal energy

ε_0/c^2=0.1,1.0,5.0

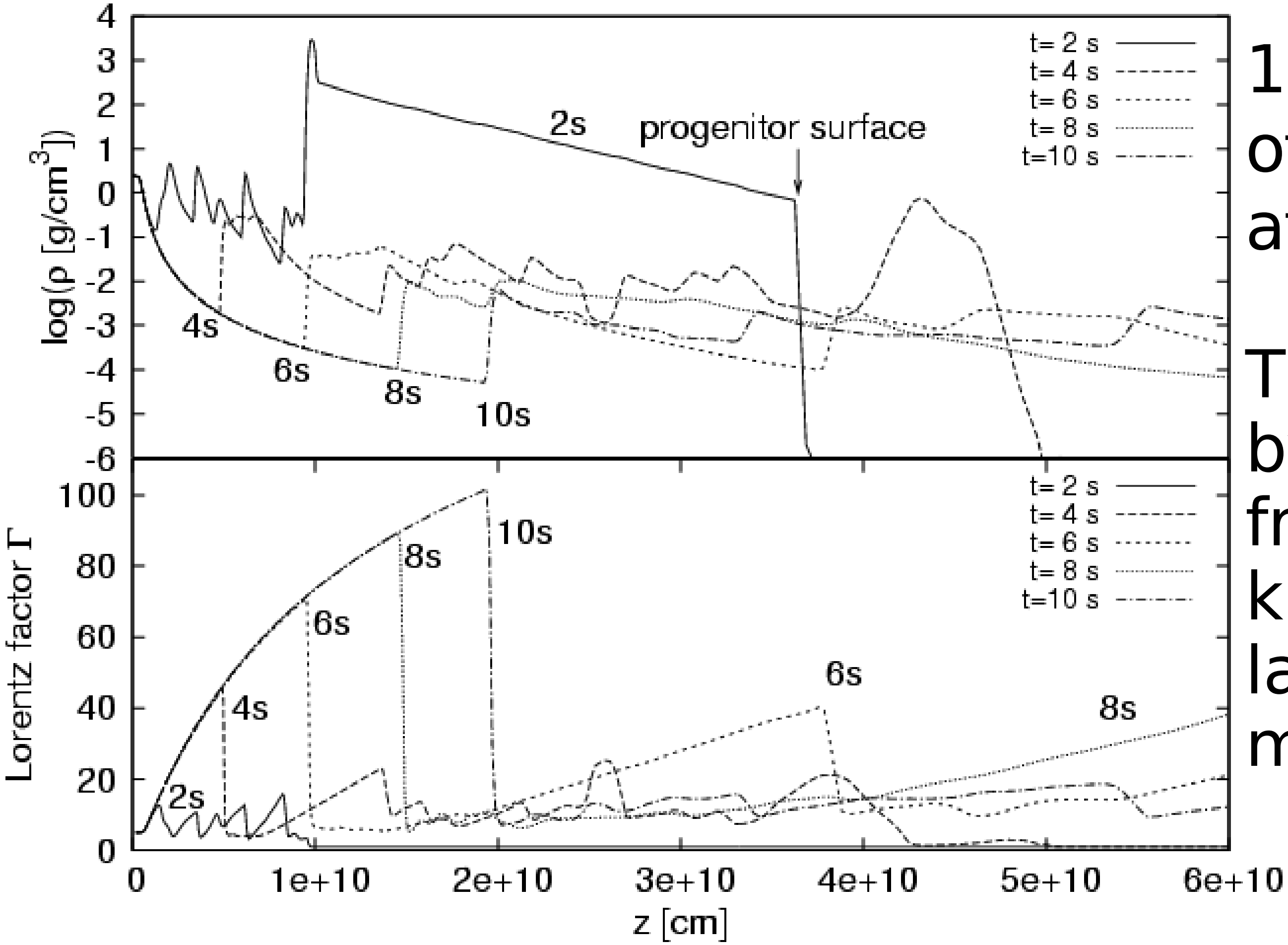
Results (1) Cases Γ_0=5 "Collimated jet"





The outflow can keep the collimated structure and show successful break from the progenitor.
Highly relativistic jet would be observed as GRBs
Mildly relativistic jet would be observed as XRFs

Highly Lorentz factor component (more than 100) appears in late phase of the injection in one model



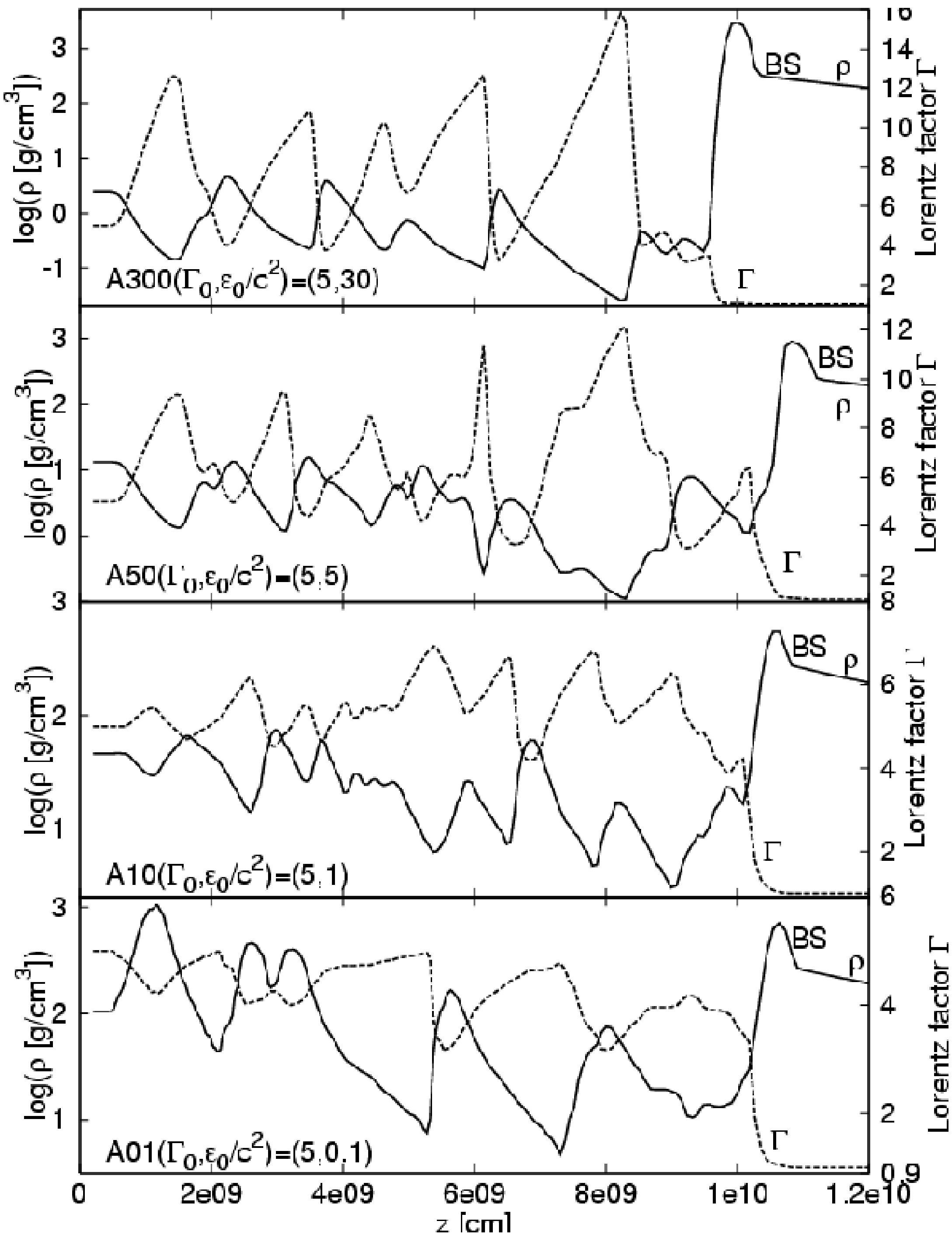
1D profiles along z axis of model ($\Gamma 0, \varepsilon 0$)=(5,30) at different times.

The acceleration caused by energy conversion from thermal energy to kinetic energy produces large Lorentz factor more than 100.

Maximum Lorentz factor is good agreement with simple formula

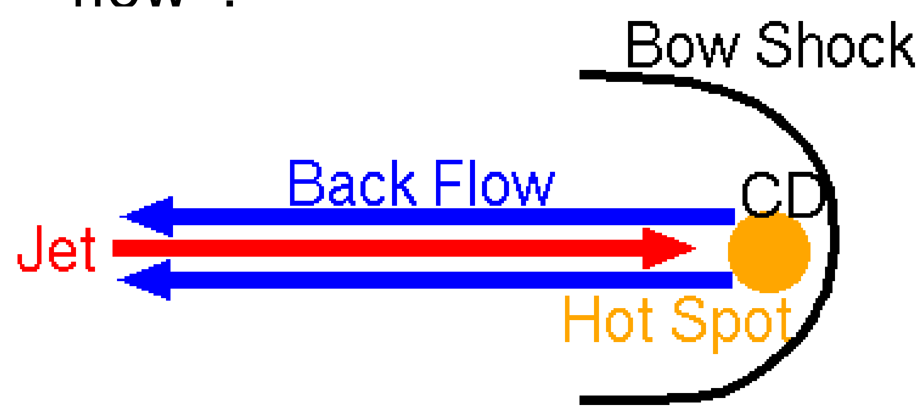
$\Gamma_{max} \sim \Gamma_0 (1+\varepsilon_0/c^2)$

ρ, Γ profile along cylindrical axis

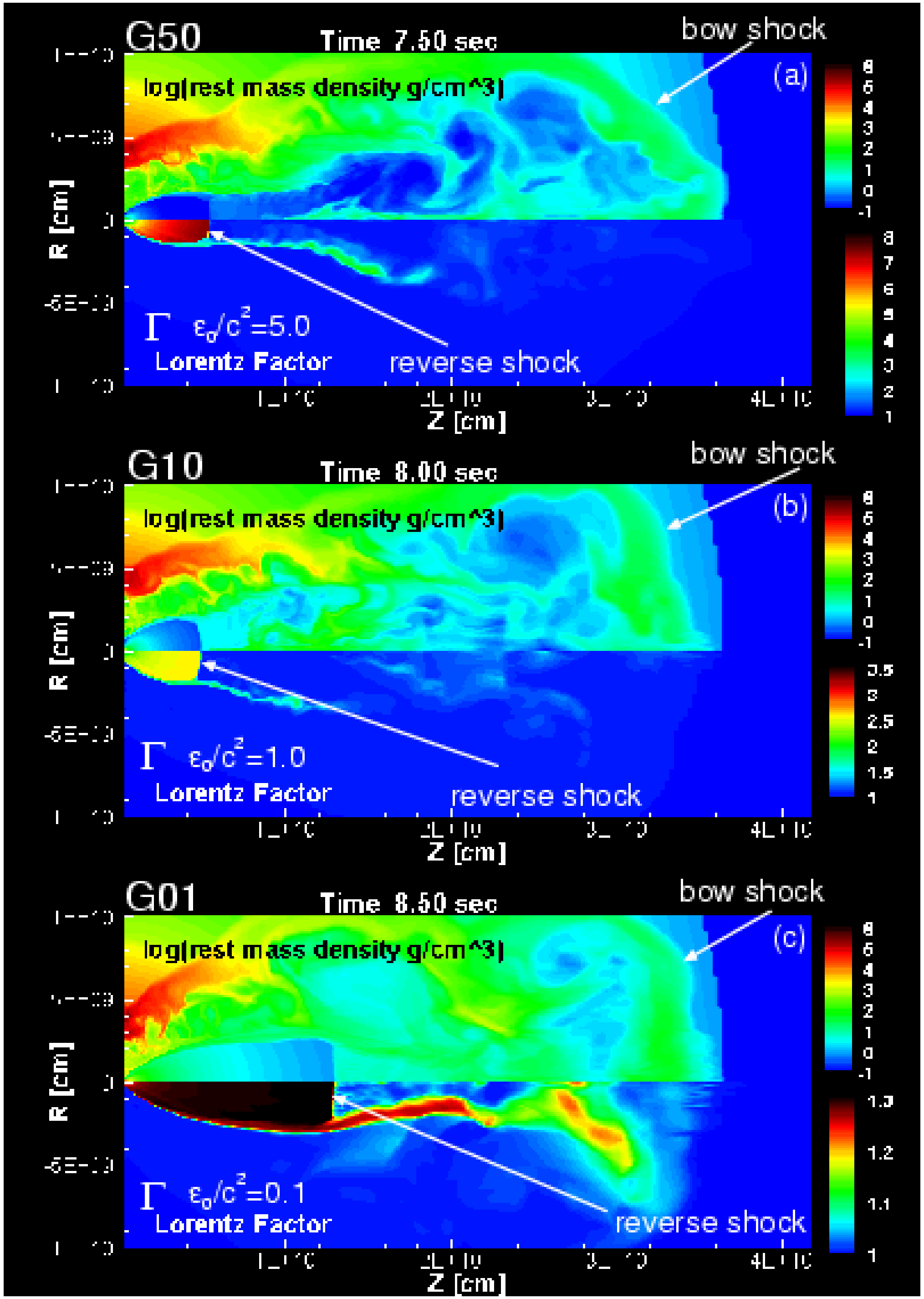


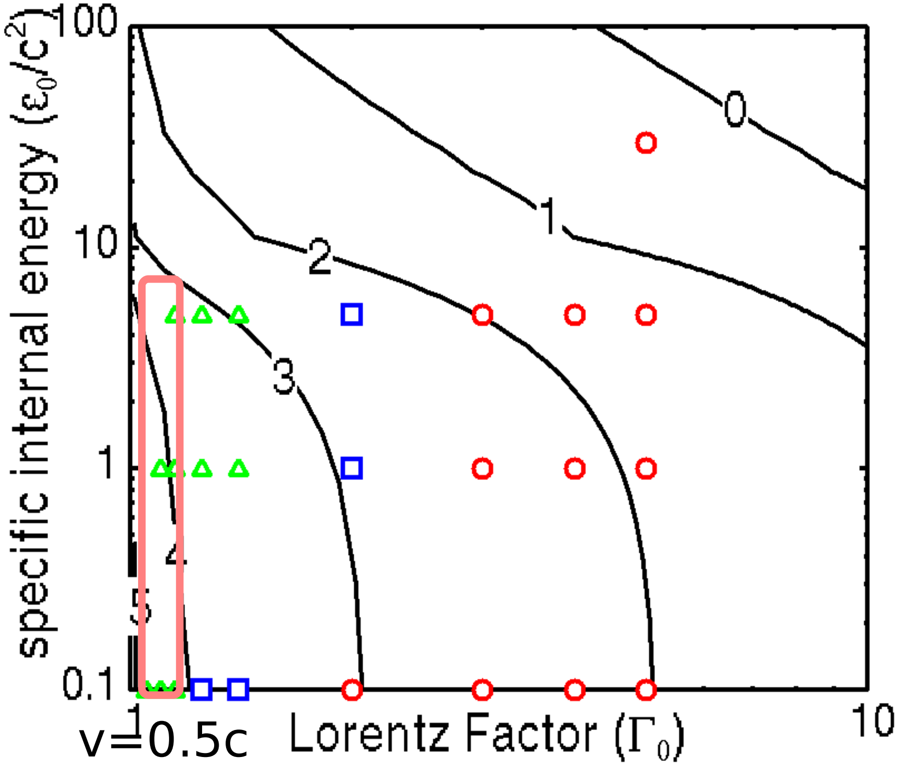
In the collimated outflows (jets) internal structures can be seen

When the gas expands, the Lorentz factor increases (rarefaction).
The discontinuities correspond to the internal shocks.
Those are trigged by the “shear flow instability” in the jet or the “interaction between the jet and back flow”.



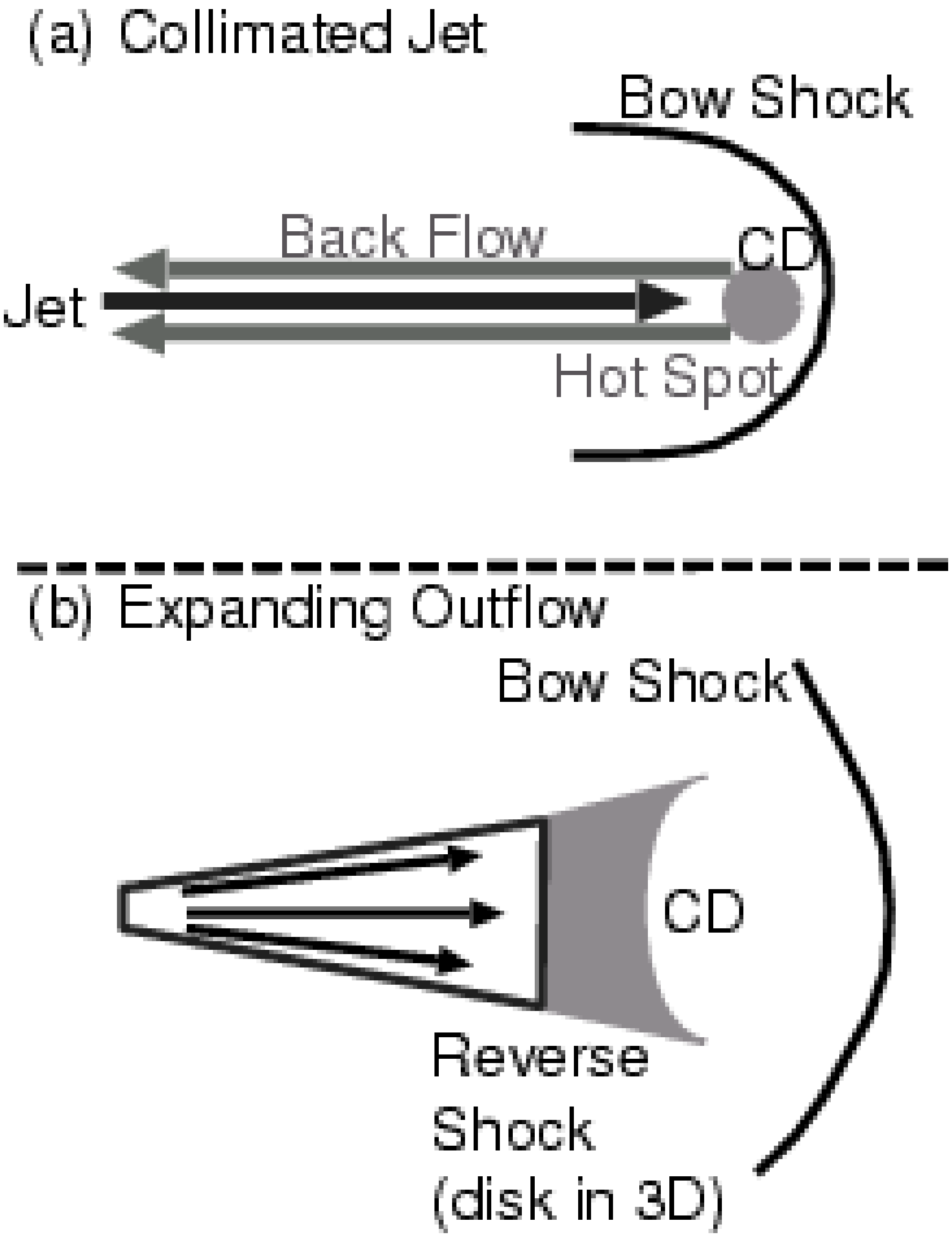
Results (2): Cases v_0=0.5c "expanding outflow"

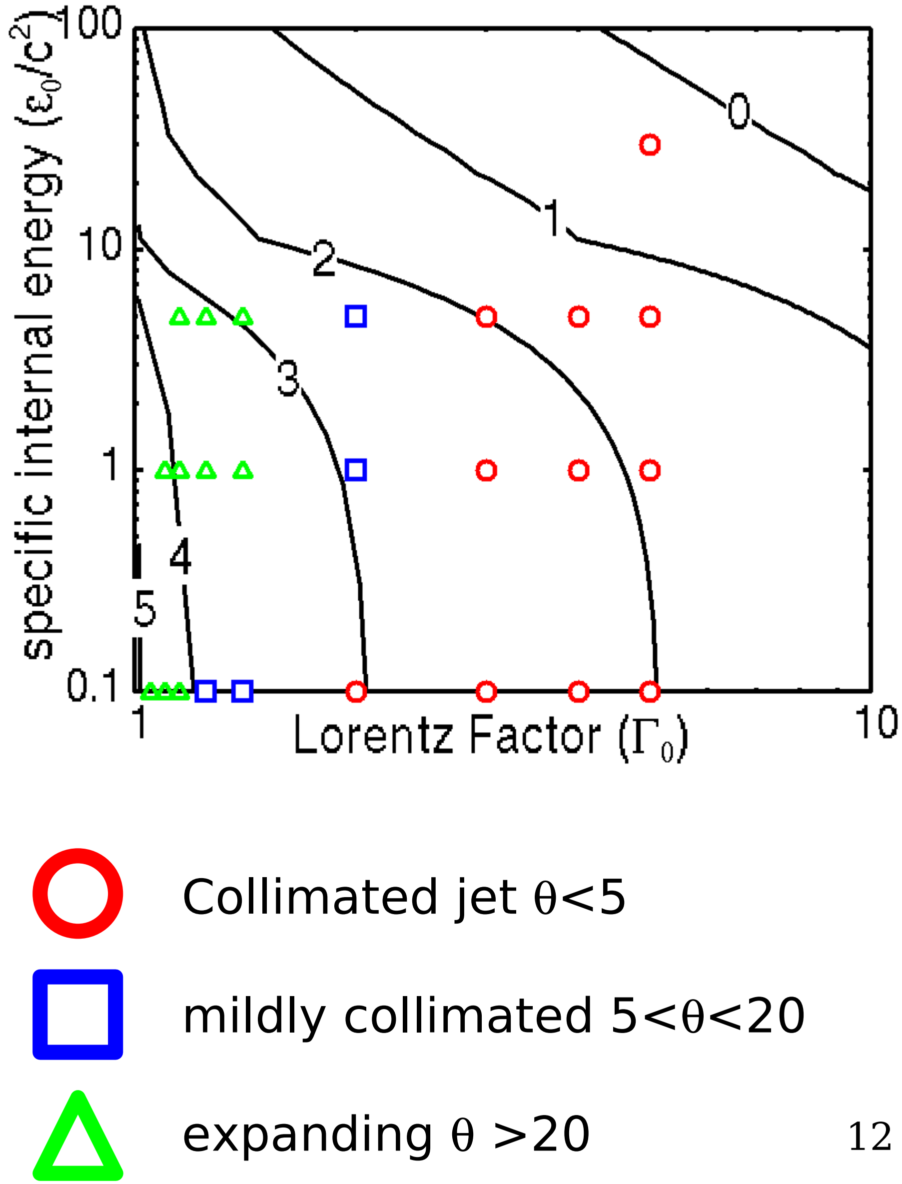




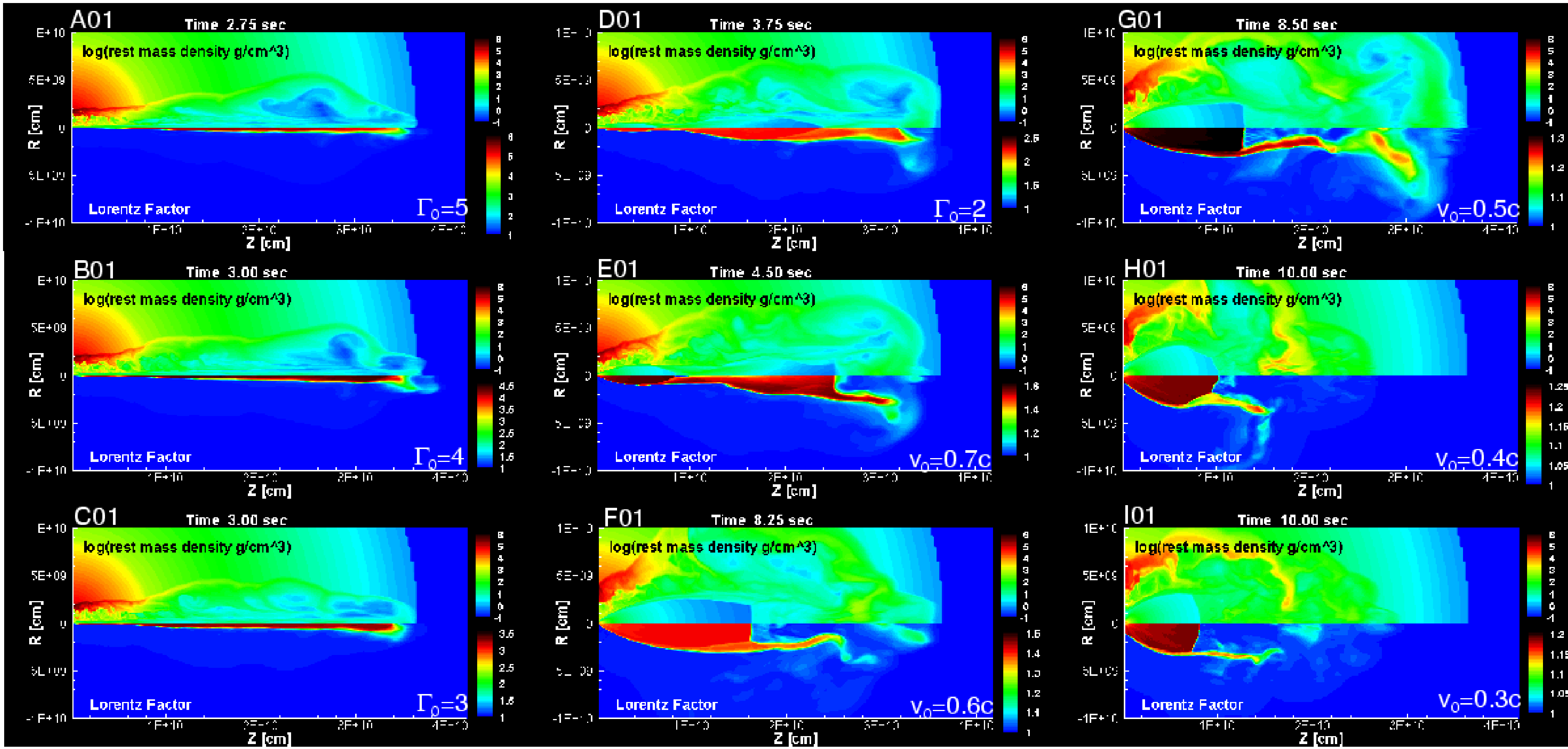
The expanding outflow looks like aspherical supernova explosion

The collimated jet has a back flow which enhances the collimation of the jet.





A continuous transition from collimated jet to expanding jet is observed ($\varepsilon_0/c^2 = 0.1$).



The other series ($\varepsilon_0/c^2 = 1.0, 5.0$) also show the same transition.

Summary

The feature of the outflow varies from collimated jet to expanding outflow by changing the injected outflow velocity.

The highly relativistic and collimated jet : GRBs

The mildly relativistic and collimated jet or expanding outflow
: X-ray Flashes

The non-relativistic expanding outflow
: aspherical SN (no GRB or X-ray Flash)

The achieved maximum Lorentz factor depends on the Lorentz factor and internal energy of the injected outflow.

Fine structures along the jet are observed.

Two possibilities
shear flow instability in the jet
nonlinear K-H instability (jet and back flow)