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

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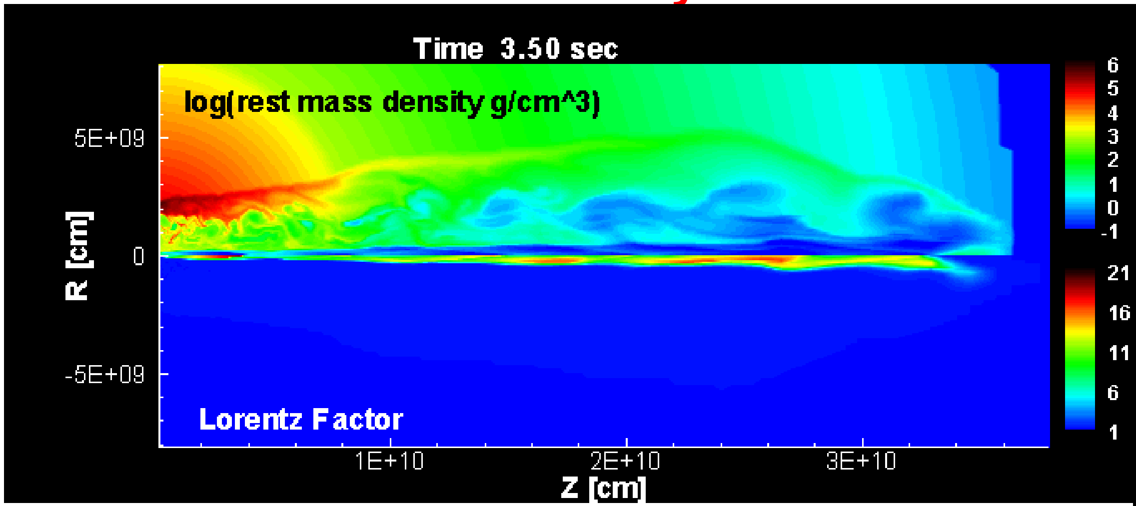
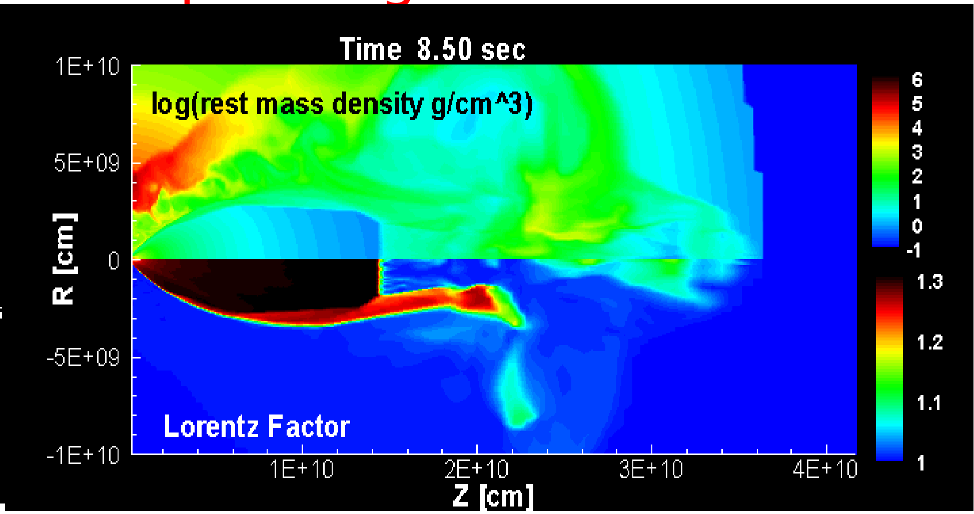
“Collimated Jet”



“Expanding Outflow”



Contents

1. GRBs, X-ray flashes, SNe
2. Our Model
3. Results & Discussions
4. Conclusion

submitted to ApJ
GRB-SN connection
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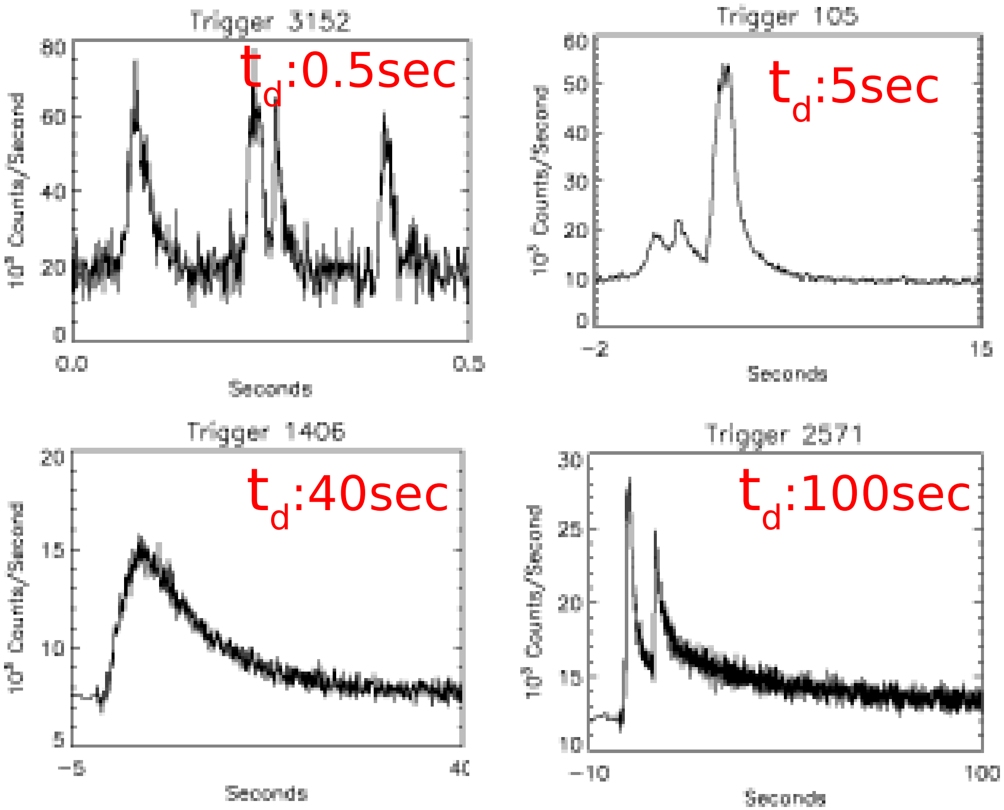
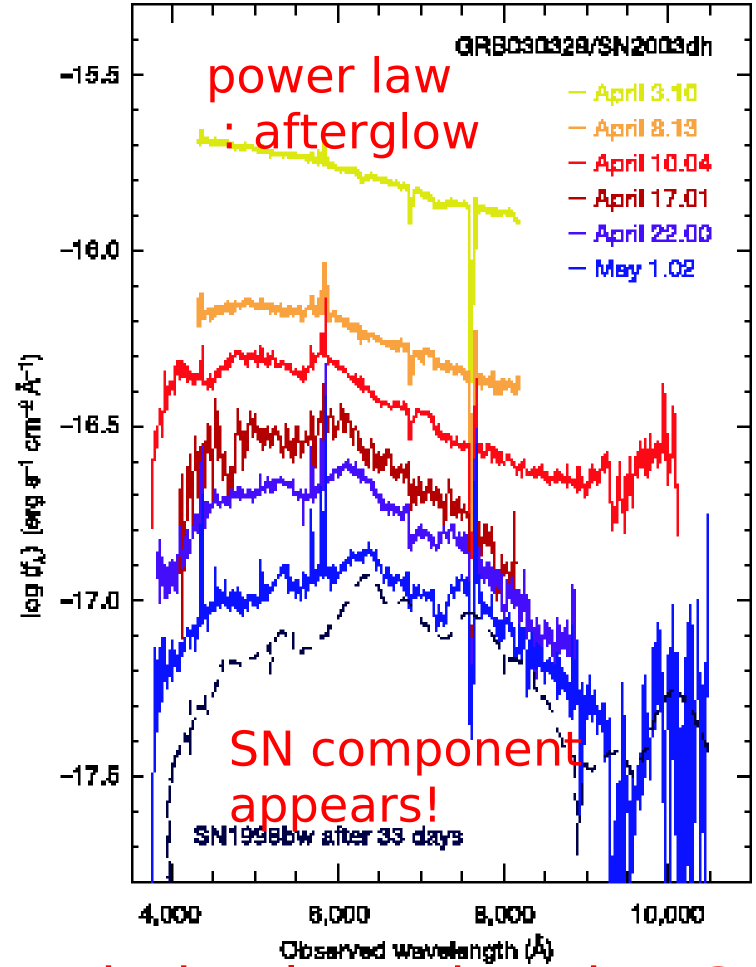
GRBs are the most energetic phenomena in the sky

$E \sim 10^{50\text{-}53}$ ergs. (isotropic)
About 1000 events / year are observe
Duration : $t_d \sim$ 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

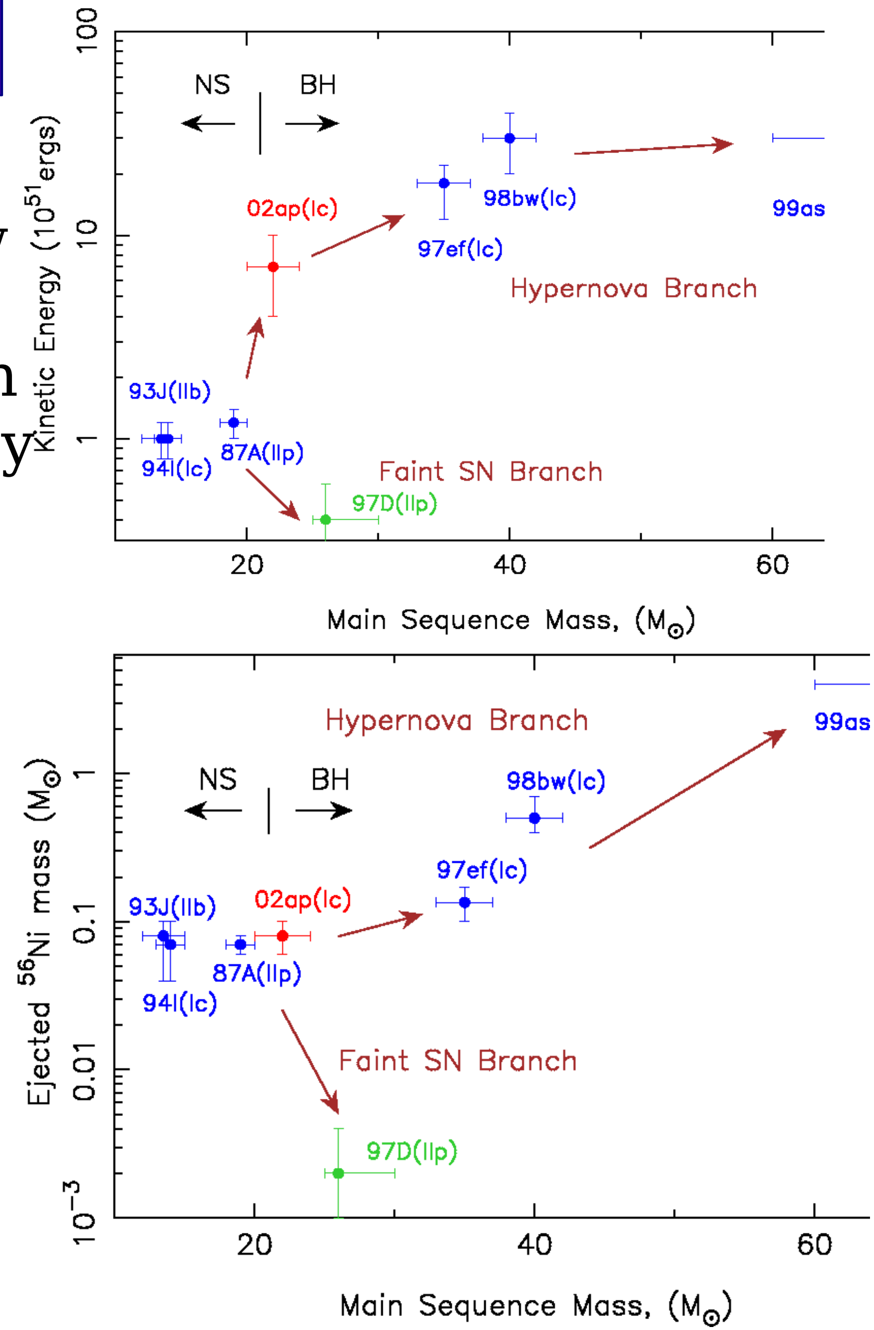


Association long duration GRB-SN is observed.
ex. GRB980425/SN1998bw,
GRB030329/SN2003dh,
GRB060218/SN2006aj.

SN1998bw(Hypernova)

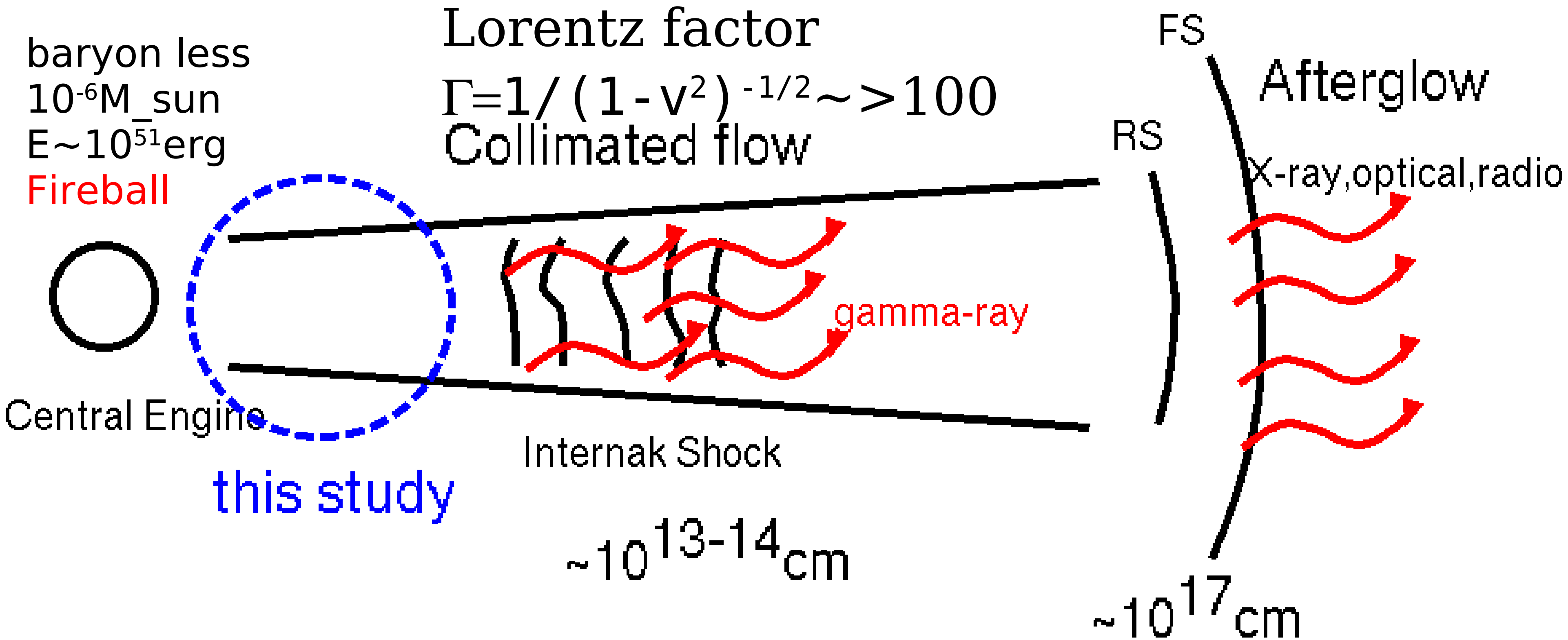
The explosion energy of SN1998bw is ~2 x 10^{52} erg (Iwamoto 1998) which is 10 time larger energy than that of normal explosion and usually categorized in hypernova.
This SN is also categorized in Type Ic SNe (massive star collapse).

This HN produces very rich Ni
~ 0.5 solar mass.



Nomoto et al.(2003)
astro-ph/0209064

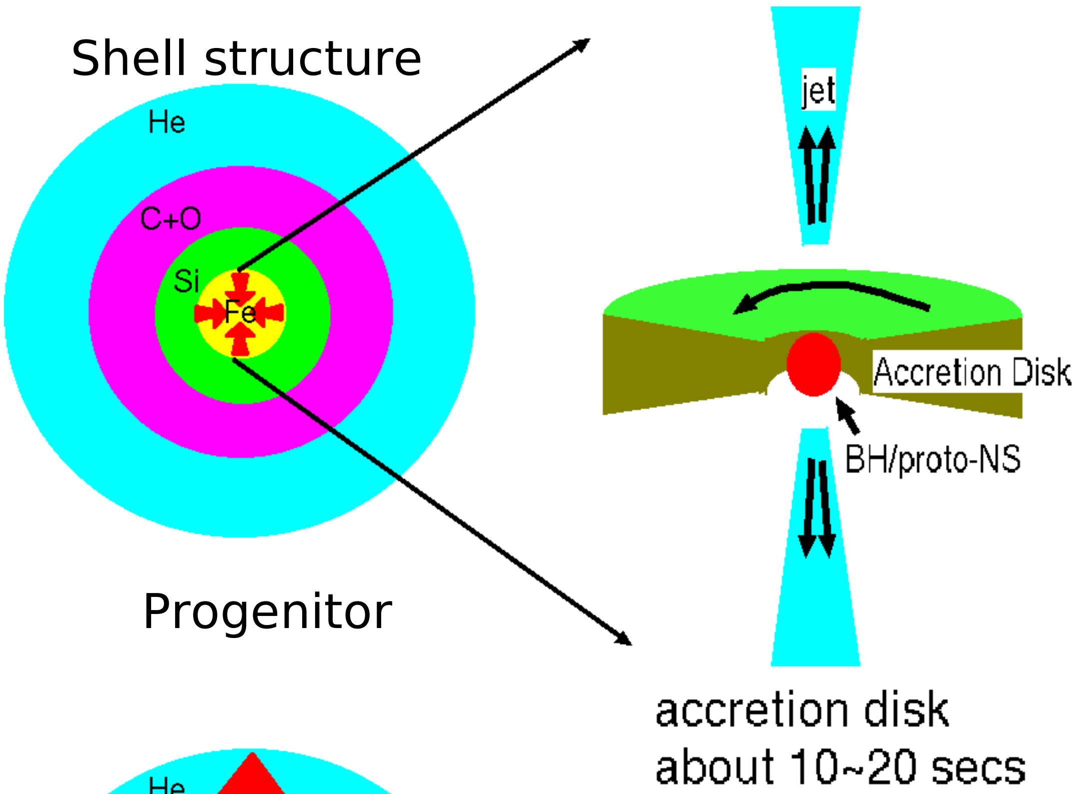
The theory predicts : GRB begins with highly thermal dominated plasma and expands as a relativistic jet : standard fireball & relativistic jet model (Rees & Meszaros (1992), Piran (1999))



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 !)

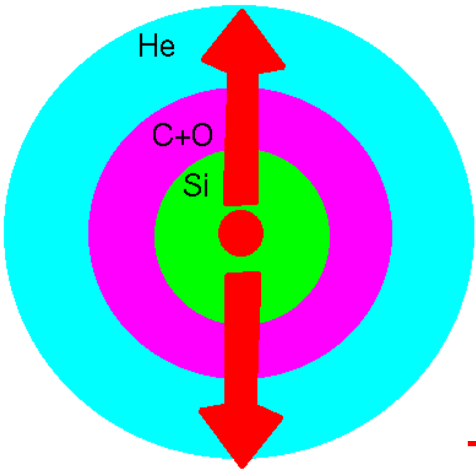
Collapsar model is a kind of core collapse SN and highly aspherical explosion. (Wooseley 1993, MacFadyen et al. 1999)



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

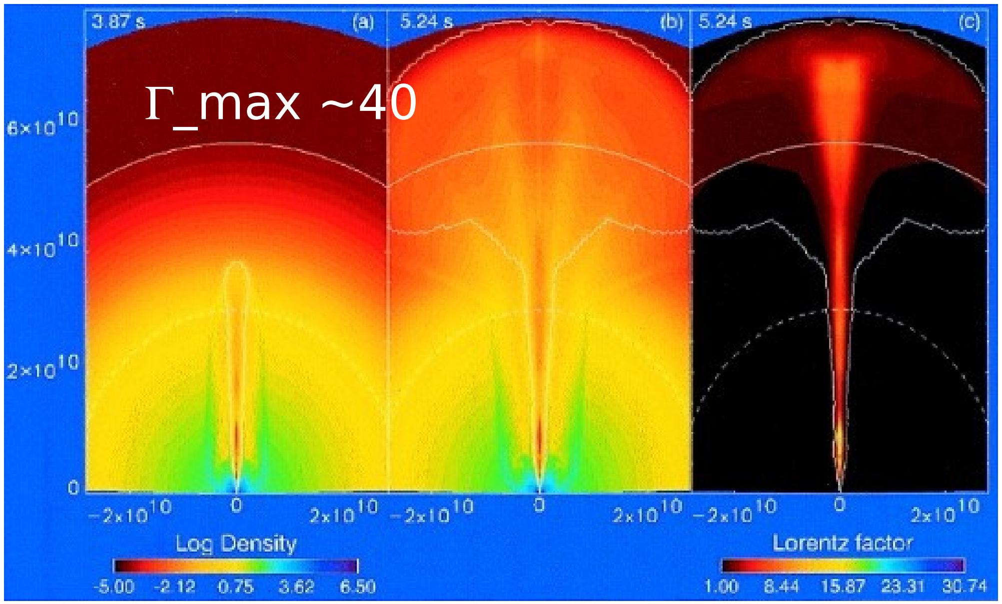
MHD and/or “neutrino annihilation” forms bipolar jets.



Free-fall time scale
$\sim 1/\mathrm{sqrt}(\rho G) \sim 100\mathrm{sec}$
>> jet crossing time scale
$\sim 10\mathrm{sec}$

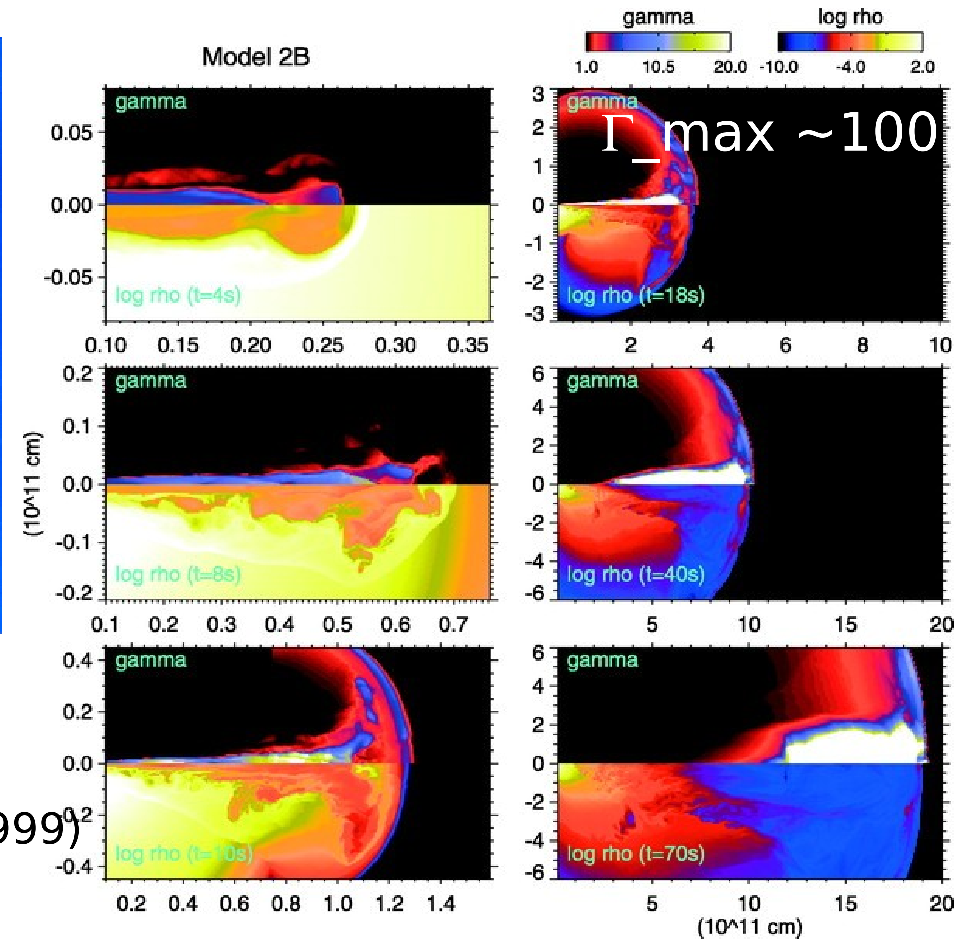
This formed jet should propagate in the progenitor !

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.



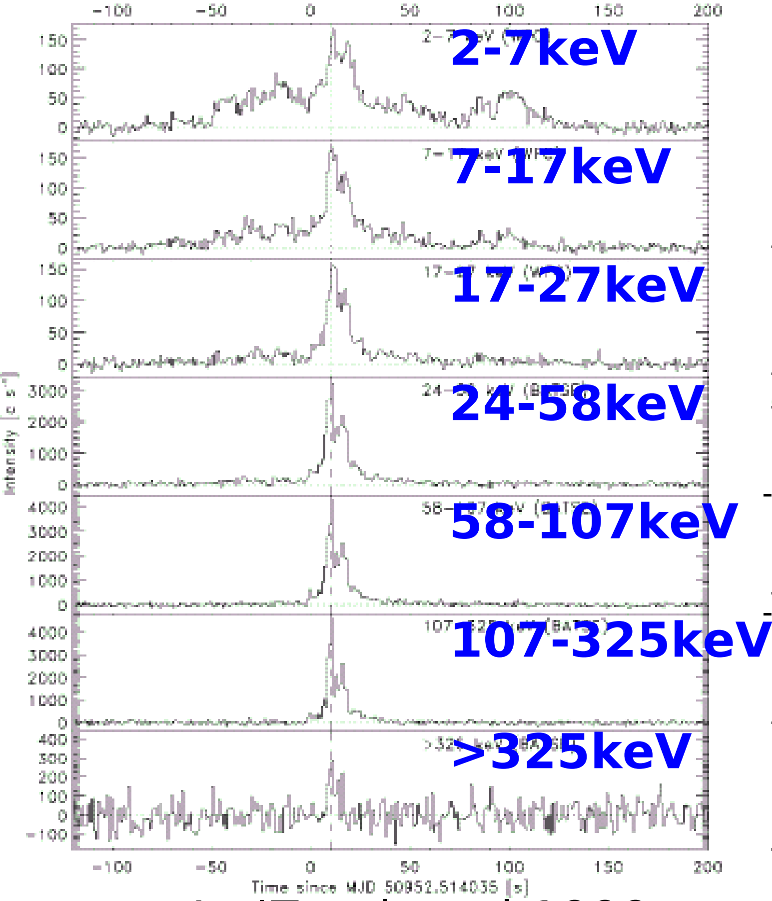
Zhang et al. (a jet injected)

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

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

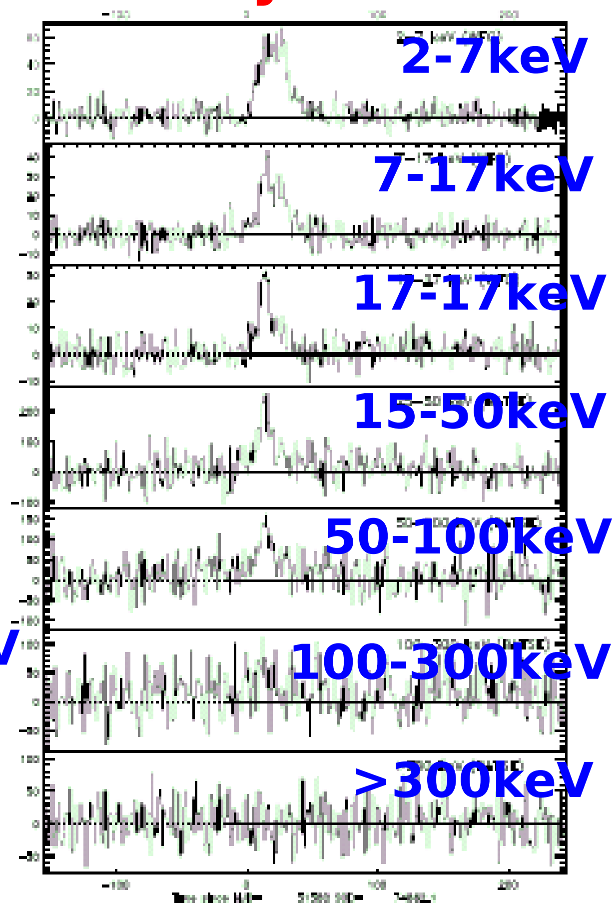
There are similar phenomena to GRBs
Those are X-ray Flashes(XRFs) and X-ray rich GRBs

Light curve
GRB980519



Int'Zand et al 1999

Light curve
X-ray Flash

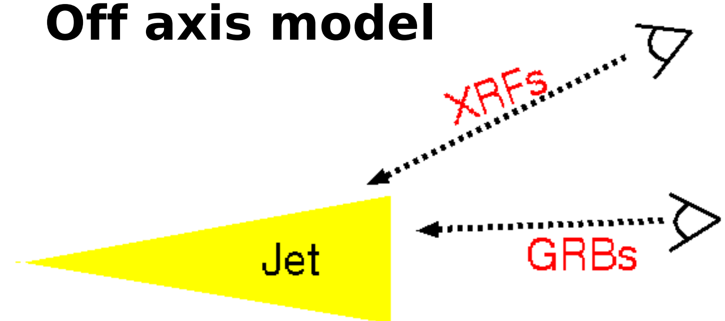


Heise et al. (2001)

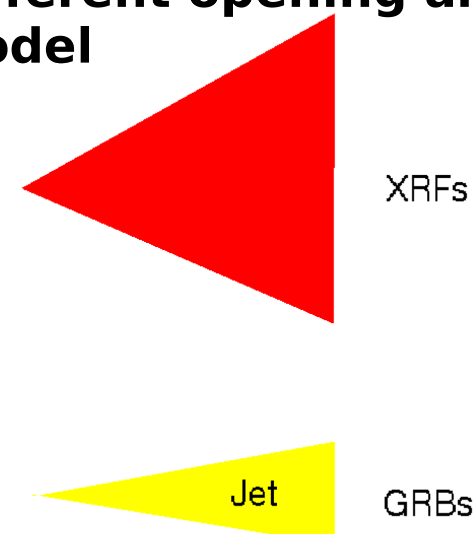
No remarkable signals in γ-ray range.

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

Off axis model



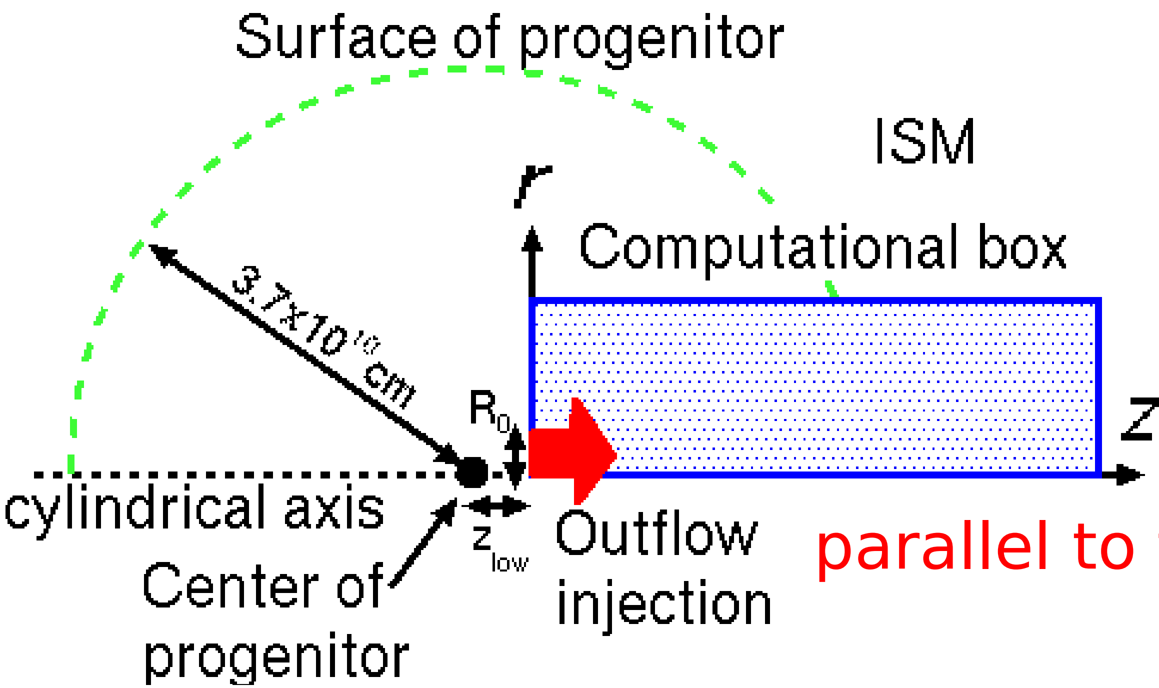
Different opening angle model



Numerical Models

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

Initially spherical, 2D axisymmetric geometry

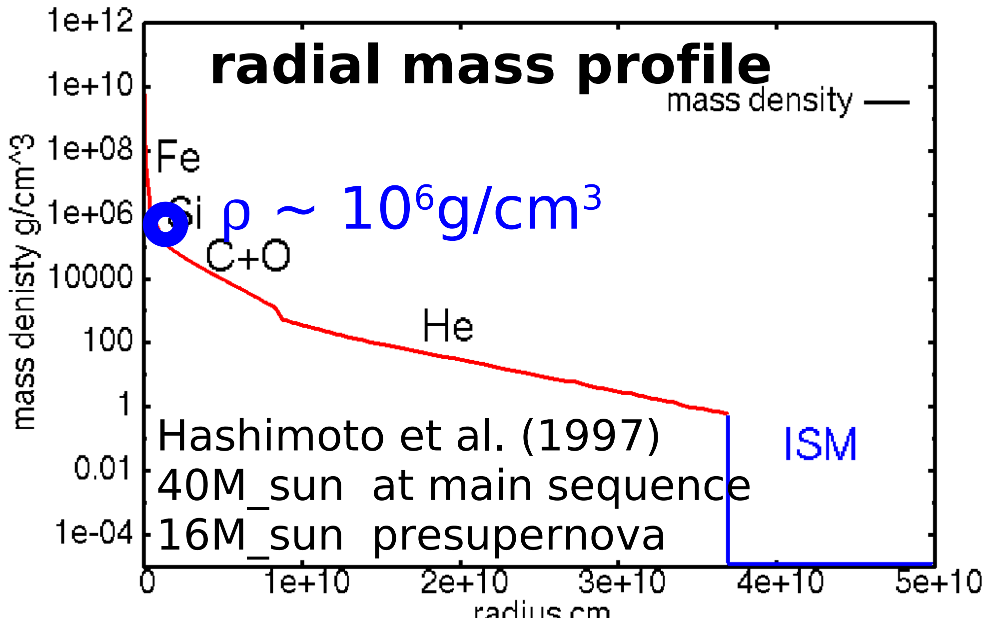


$R_0 = 7 \times 10^7$cm

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

cf. R_{BH}(1M_sun)~3×10^5cm

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

Maximum Lorentz factor can be derived from energy conservation law

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

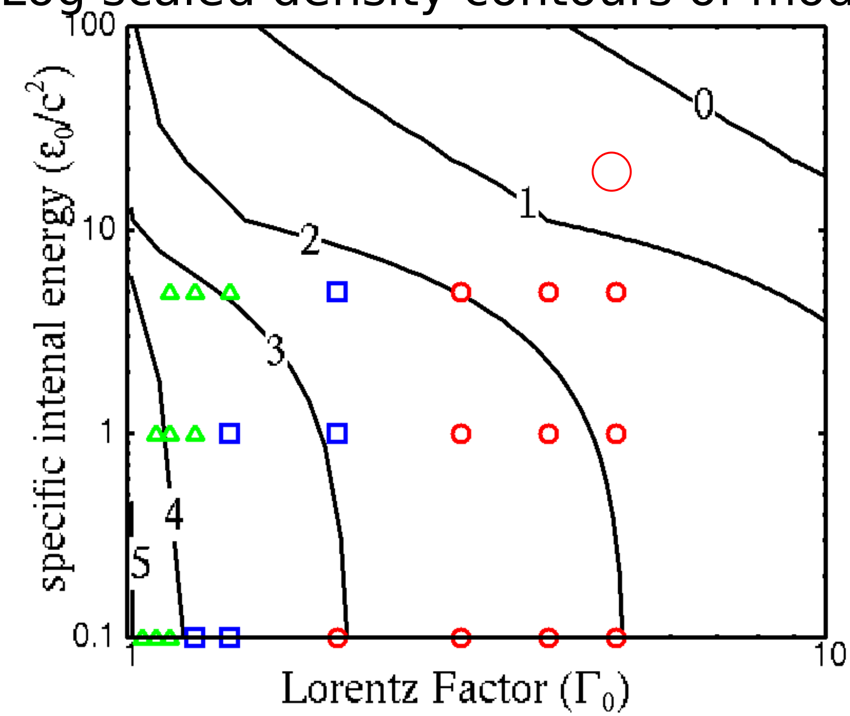
assuming free expansion

cf .SNe

v~sqrt(E / M),

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

Log scaled density contours of models



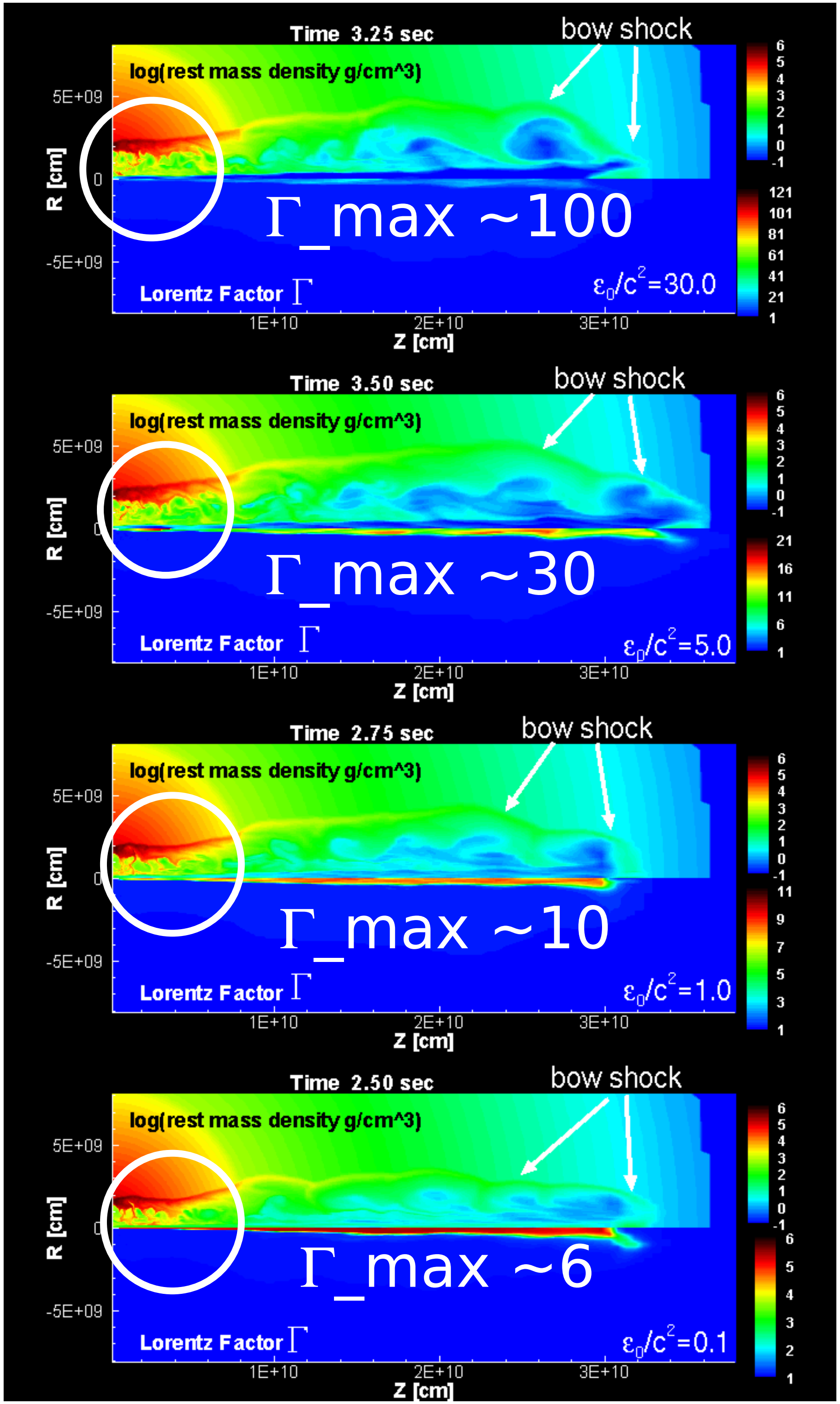
Γ_0 : bulk Lorentz factor

$\Gamma_0(v_0/c)$=1.05(0.3),1.15(0.5) 1.4(0.7),2(0.87),3(0.94) 4(0.97),5(0.98)

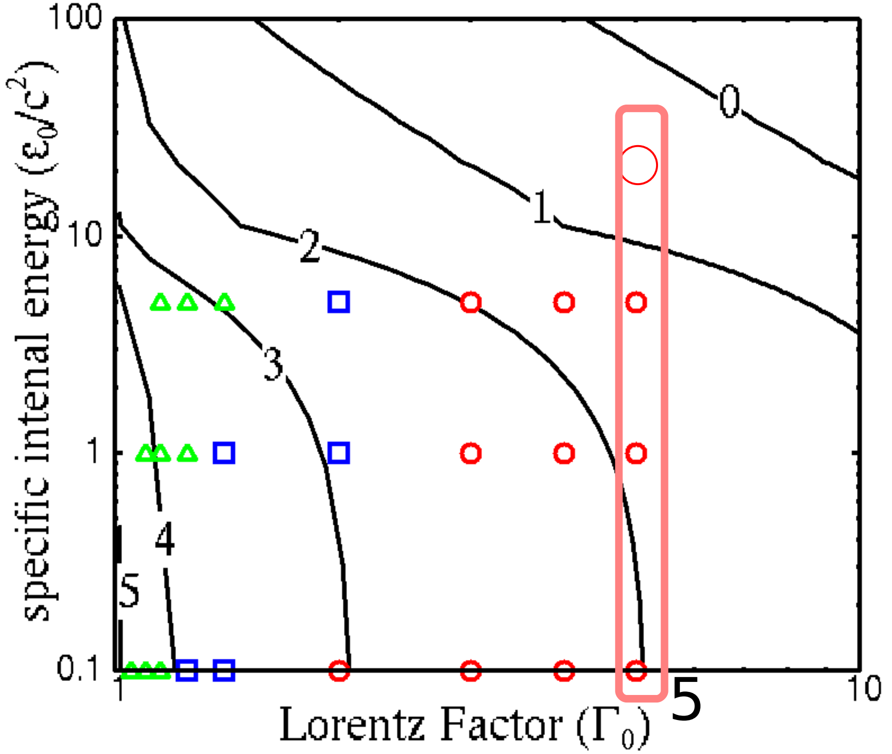
ε_0 : specific internal energy

ε_0/c^2=0.1,1.0,5.0

Results and Discussions

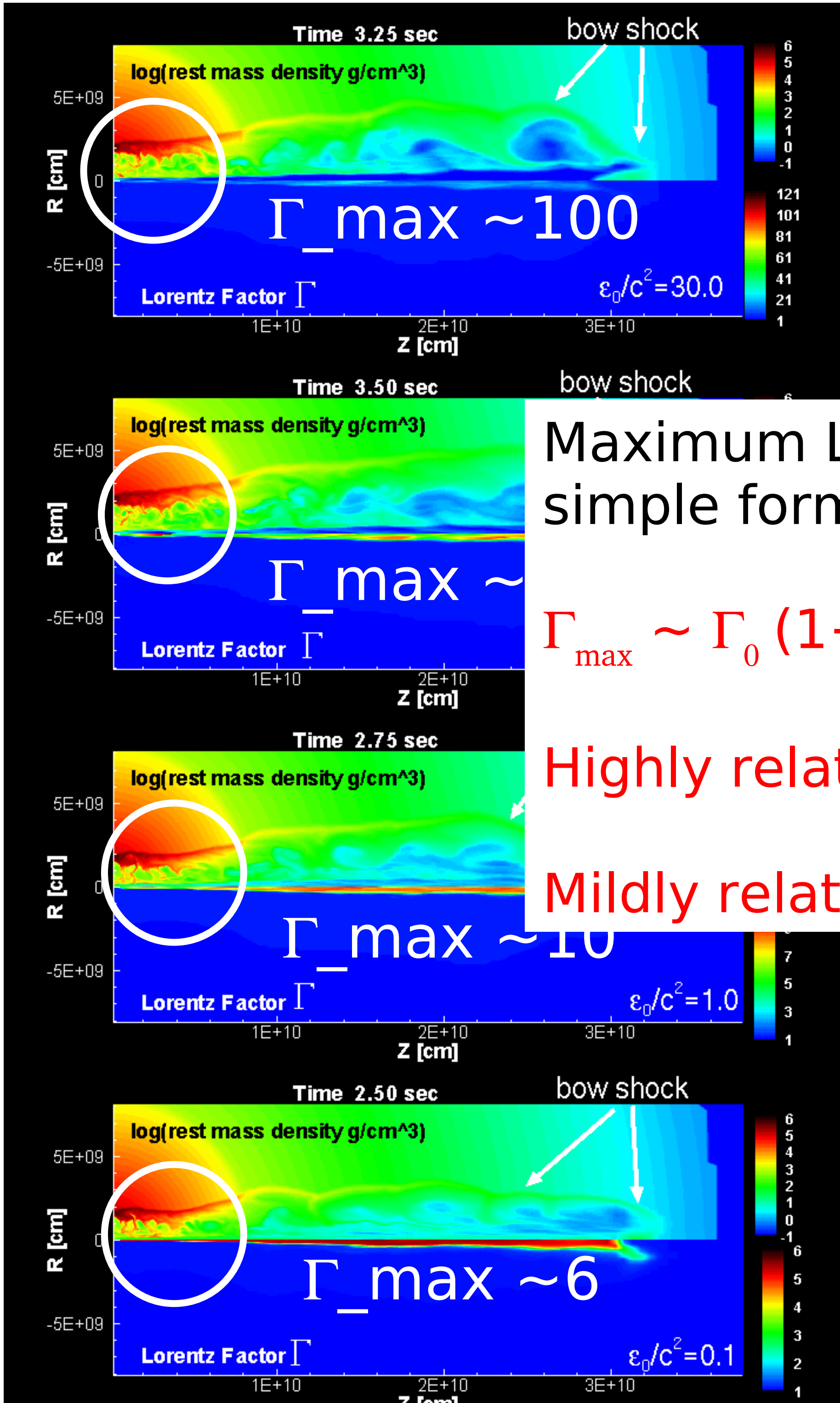


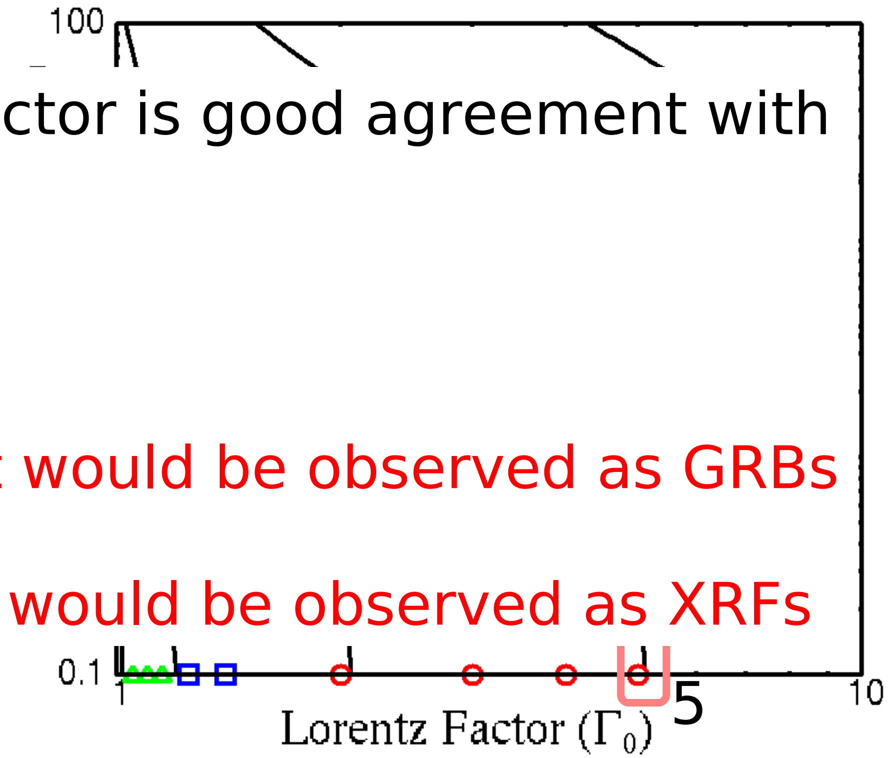
Results (1) Cases Γ_0=5 "Collimated jet"



The outflow can keep the collimated structure and show successful eruption from the progenitor

Results (1) Cases $\Gamma_0=5$ "Collimated jet"





Maximum Lorentz factor is good agreement with simple formula

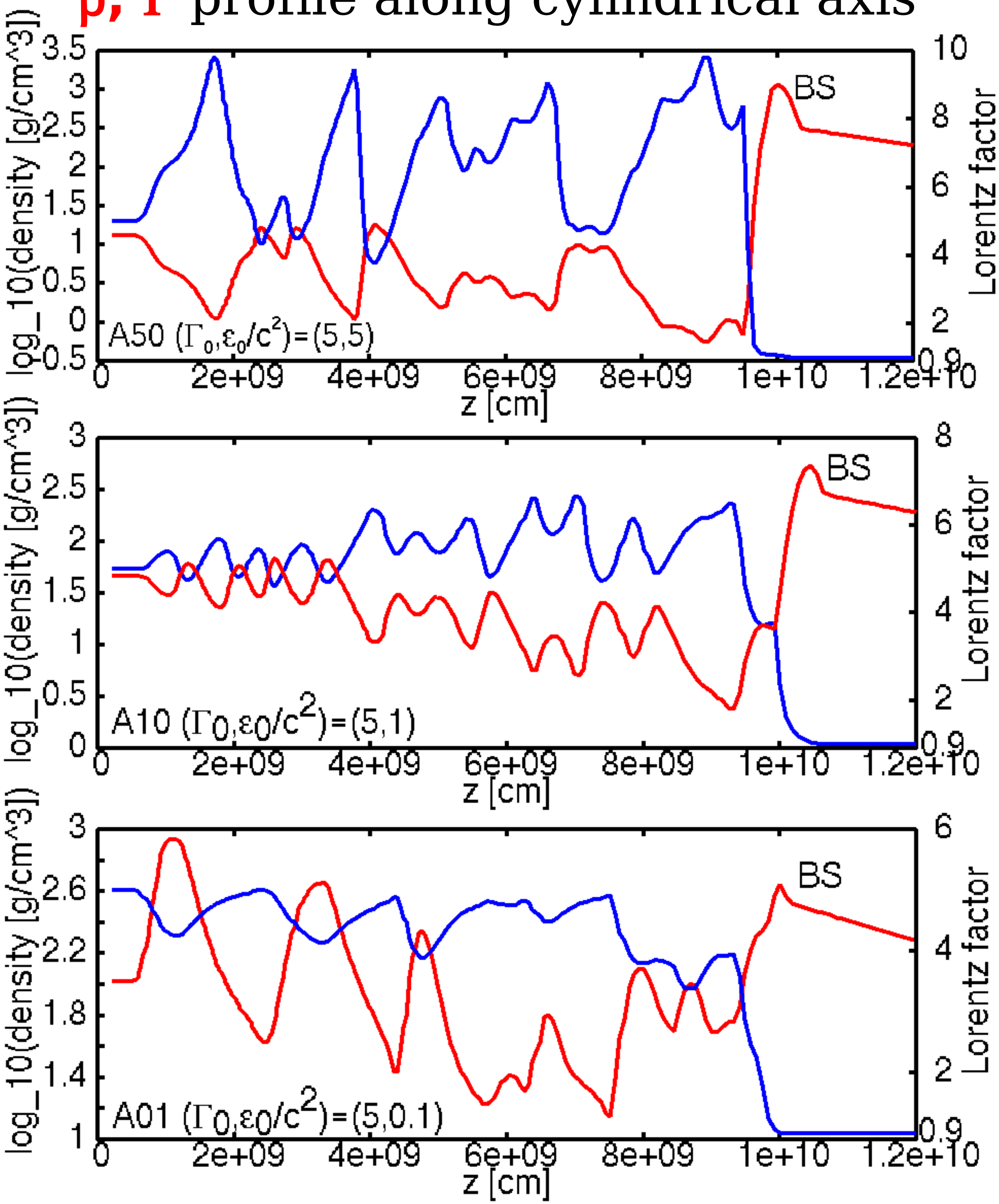
$$\Gamma_{max} \sim \Gamma_0 (1+\varepsilon_0/c^2)$$

Highly relativistic jet would be observed as GRBs

Mildly relativistic jet would be observed as XRFs

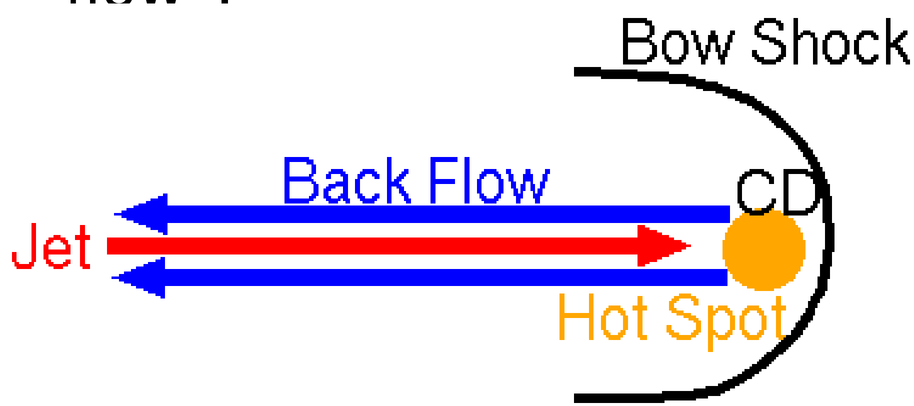
The outflow can keep the collimated structure and show successful eruption from the progenitor

ρ, Γ profile along cylindrical axis



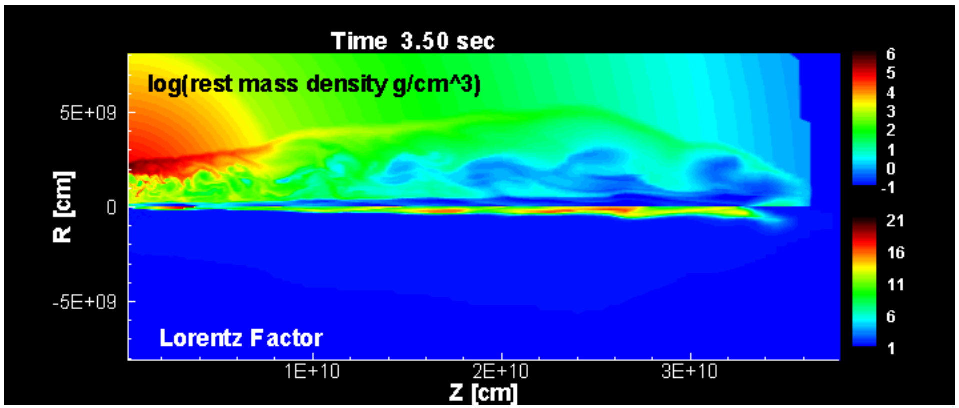
In the collimated outflows (jets) internal structures can be seen

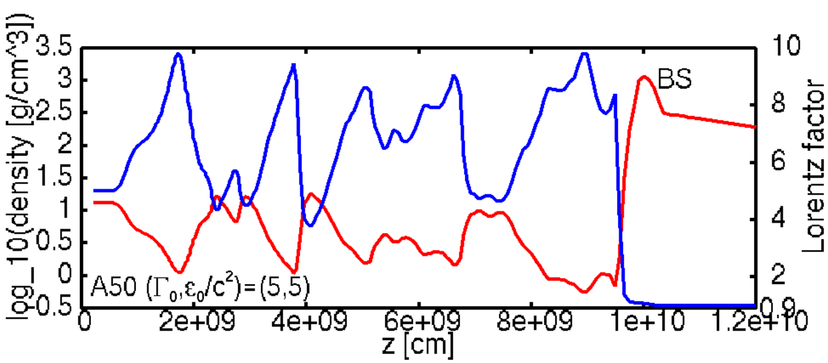
When the gas expands, the Lorentz factor increases (rarefaction).
The discontinuities correspond to the internal shocks.
Those are trigged by the “shear flow instability” in the jet or the “interaction between the jet and back flow”.



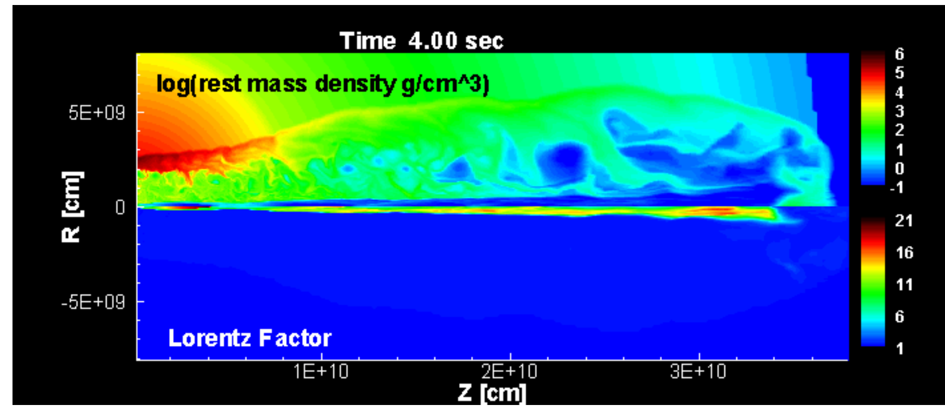
Higher resolution calculation show similar property of the dynamics, but finer structure appears.

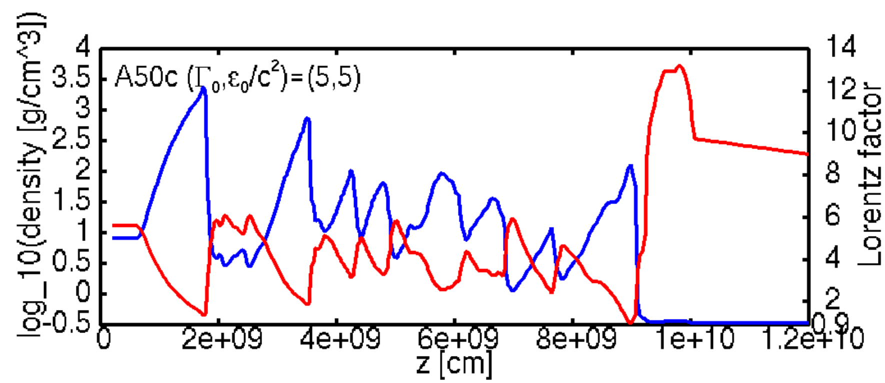
Normal resolution





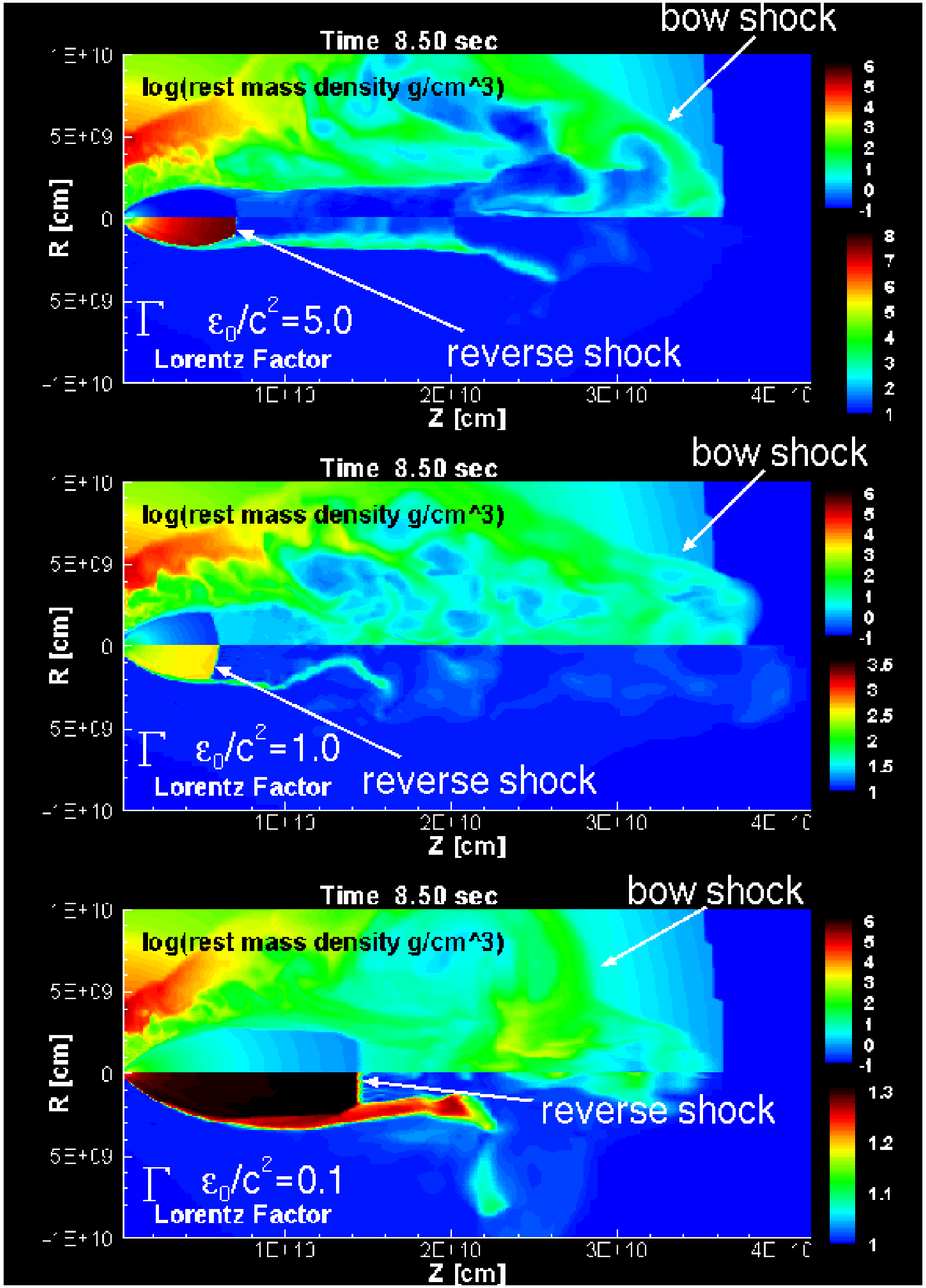
Higher (twice) resolution

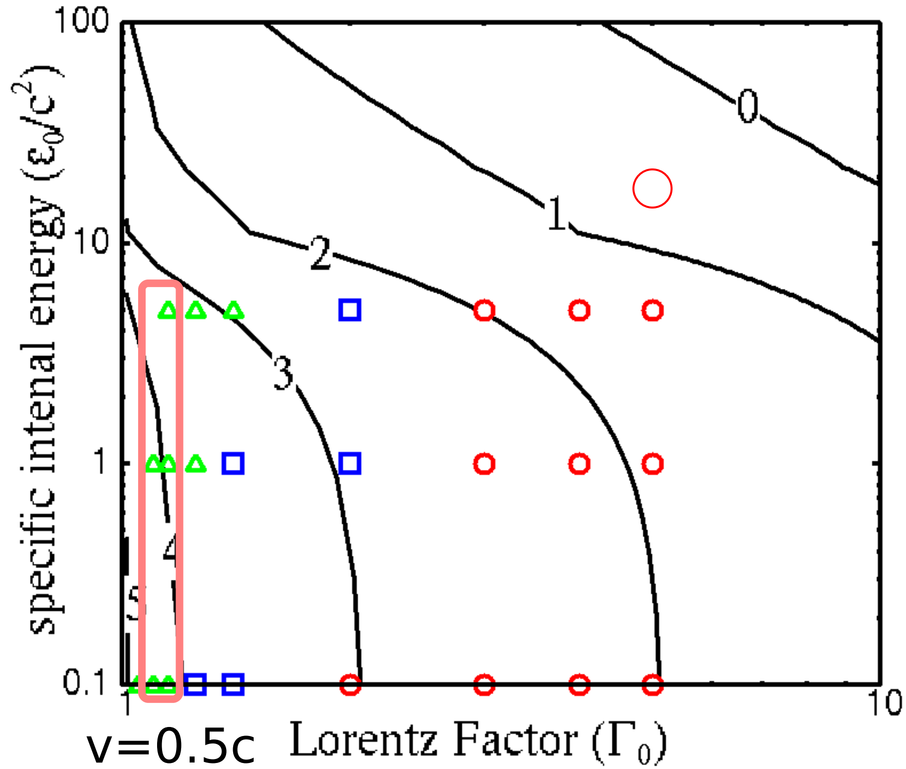




Fine structure in the cocoon in higher resolution calculation causes the drugging power in the early phase.
It also prevents side way expansion.
Unfortunately, we can not identify which mechanism mainly causes the growth of the internal structures in the jets

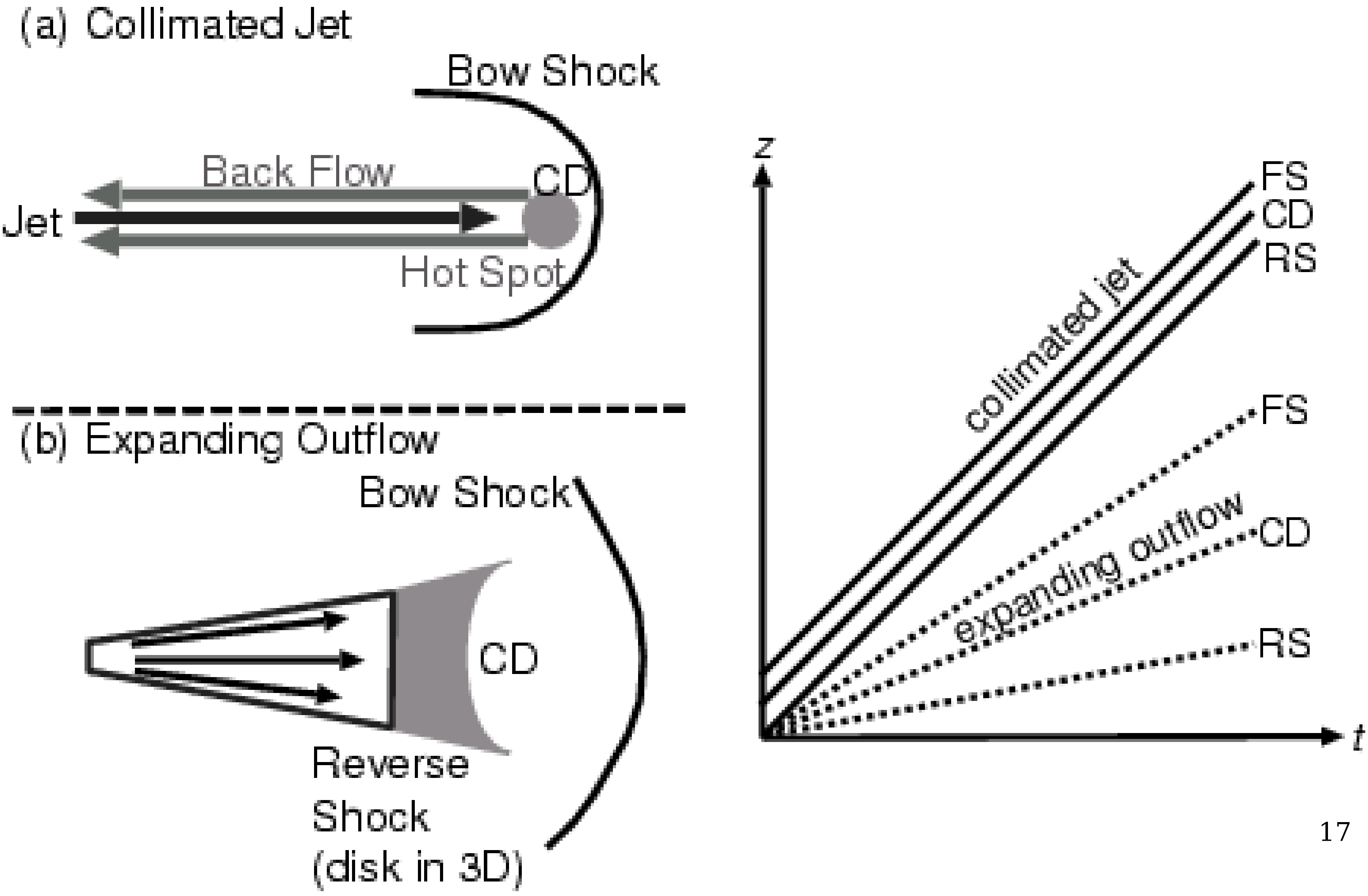
Results (2): Cases $v_0=0.5c$ "expanding outflow"



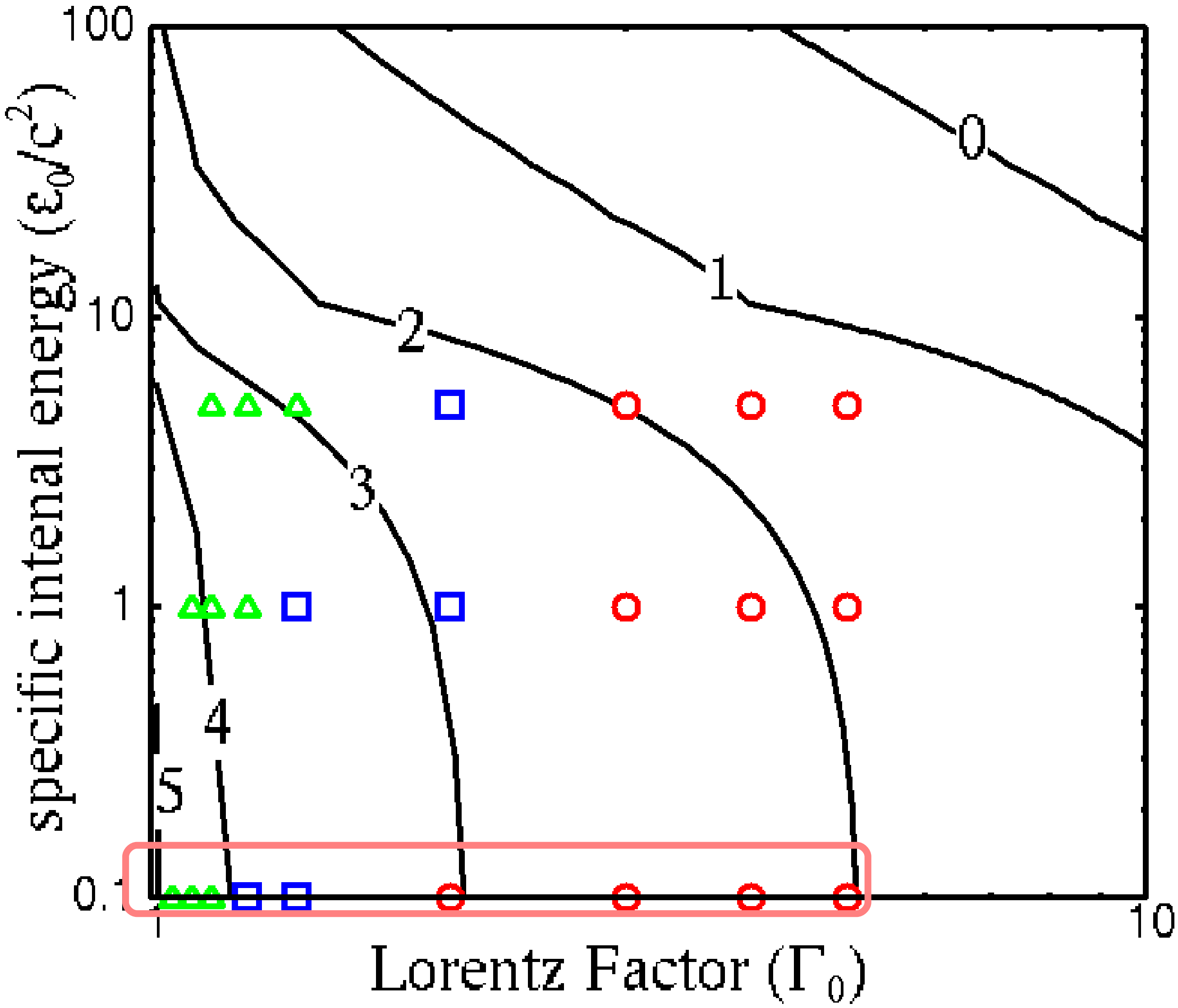


The expanding outflow looks like aspherical supernova explosion

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.



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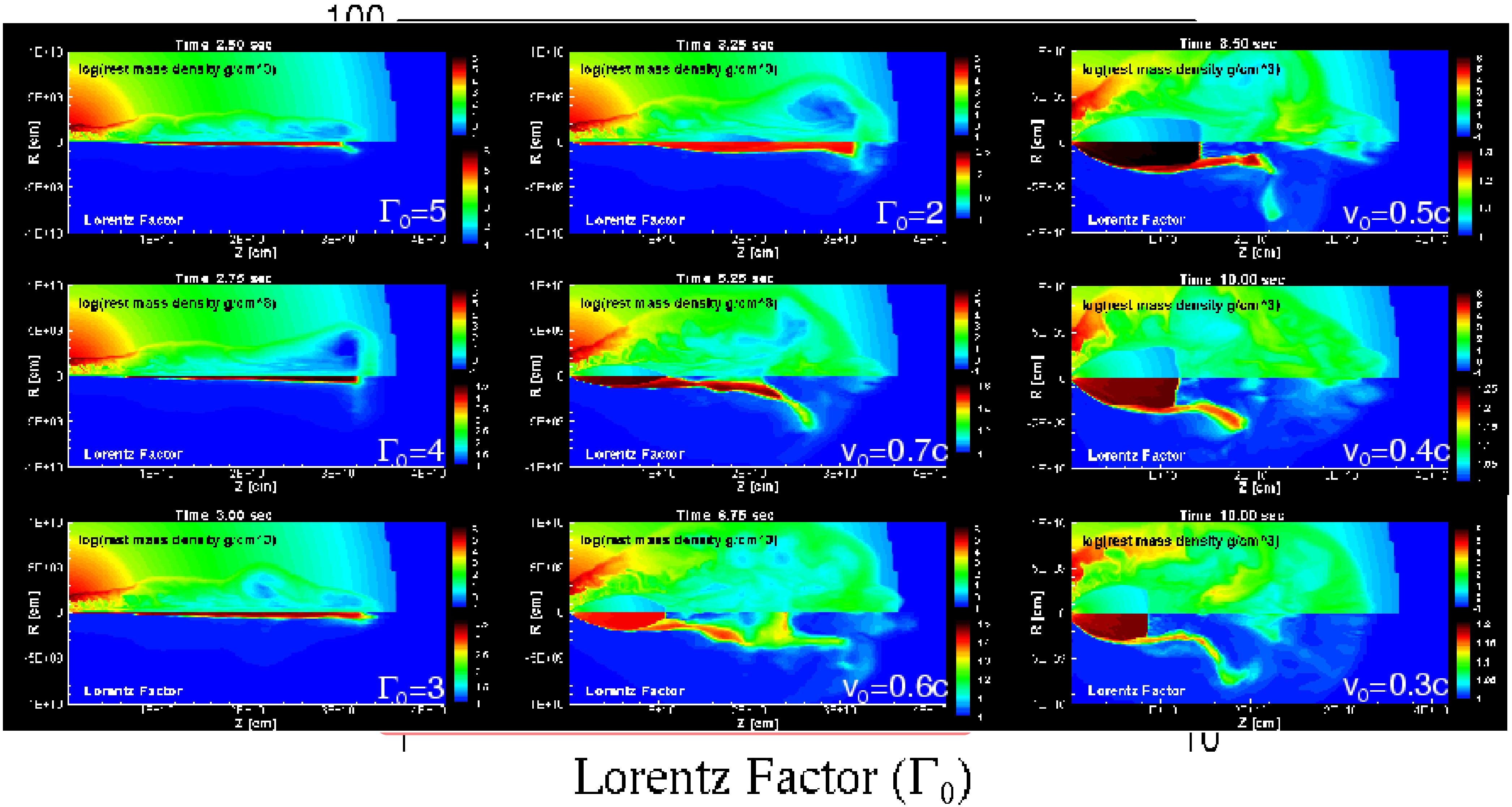

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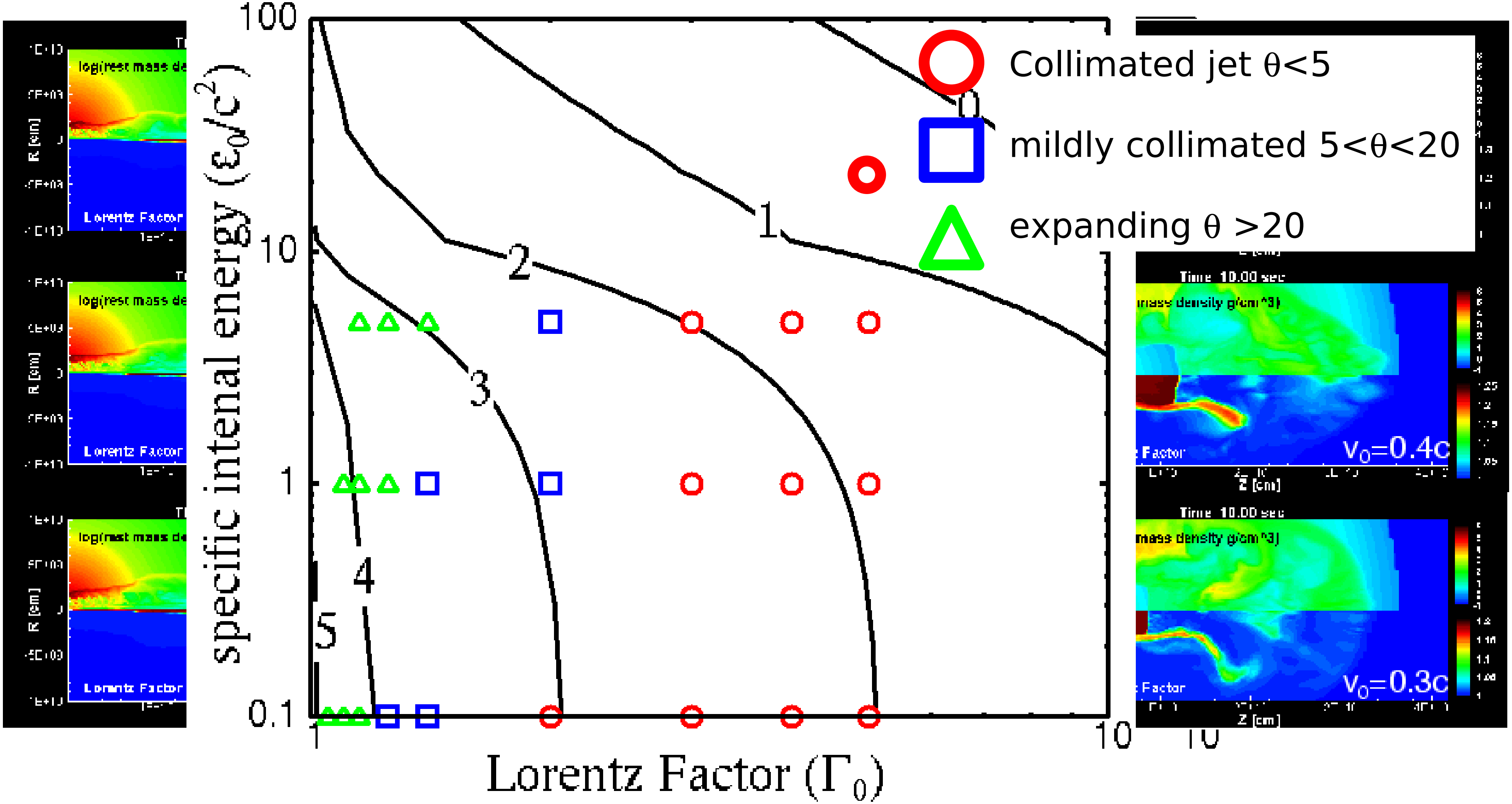

The other series (ϵ_0/c^2 =1.0, 5.0) also show the same transition.

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)

Future work

- Formation mechanism of outflow from the center of the progenitor

  - including neutrino physics (transport, cooling)
  - MHD

- Nucleosynthesis of the explosion

- After Eruption of the progenitor

  How the jet expands
  Radiative process
  Magnetic field generation
  Afterglow phase