3D relativistic GRB jet propagation in collapsars

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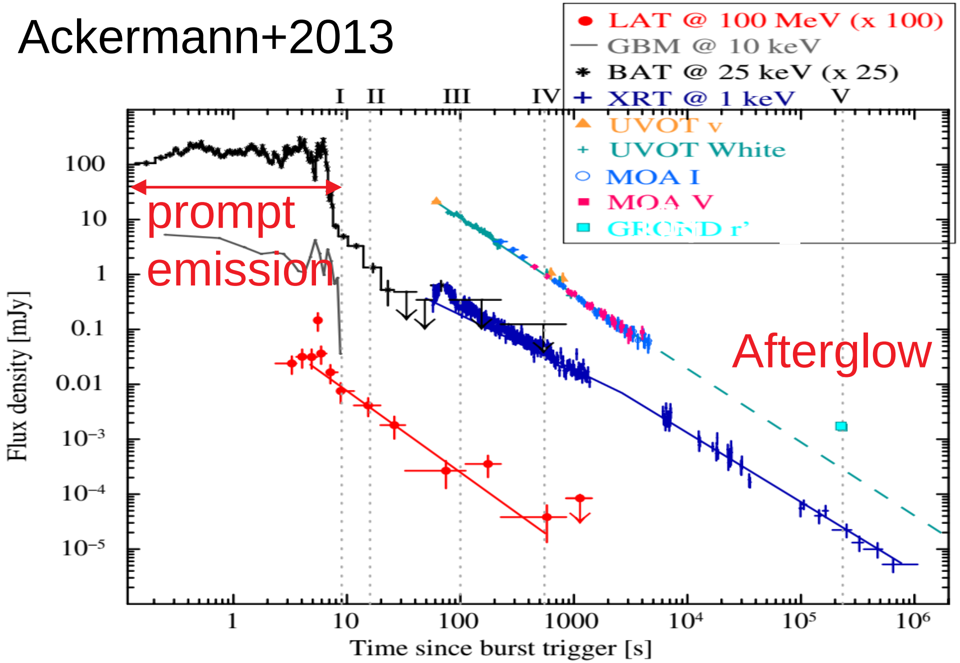
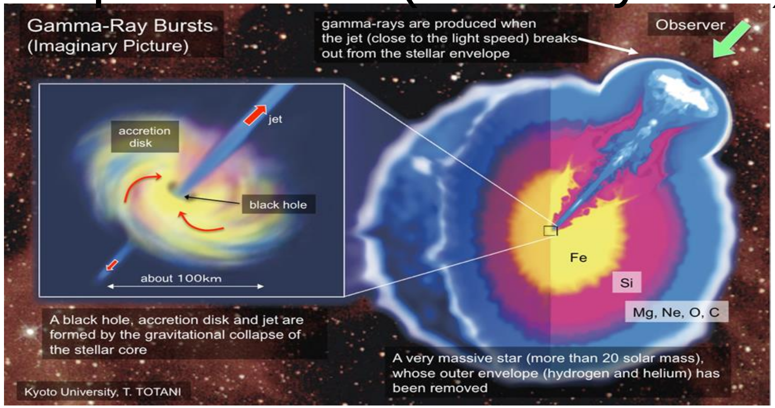
RIKEN, Wako
2025.2.18 Mizuta & Ioka in prep.

Long Gamma-ray burst

GRB110731A
Ackermann+2013



collapsar model (Woosley1993)



Gamma-ray burst associated with supernova

GRB 980425/SN1998bw(Galama+1998)
GRB 030329A /SN2003dh (Hjorth +2003)
GRB 060218/SN2006aj (Campana + 2006)
GRB 100316D/SN2010bh (Fan+2011)
GRB 171205A/SN2017iuk (Wang + 2018)

Long gamma-ray bust jets need to penetrate dense stellar envelopes. before shock breakout and gamma-ray emittions.

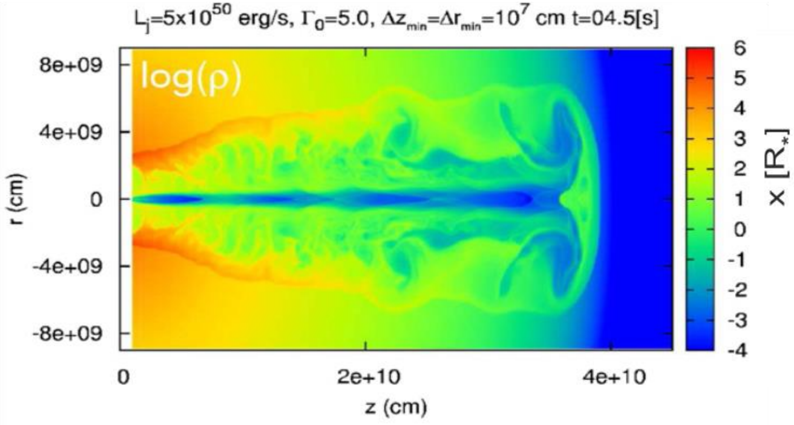
We need to understand formation of structures in the jet and cocoon.

Jet propagation : Numerical special relativistic hydrodynamics

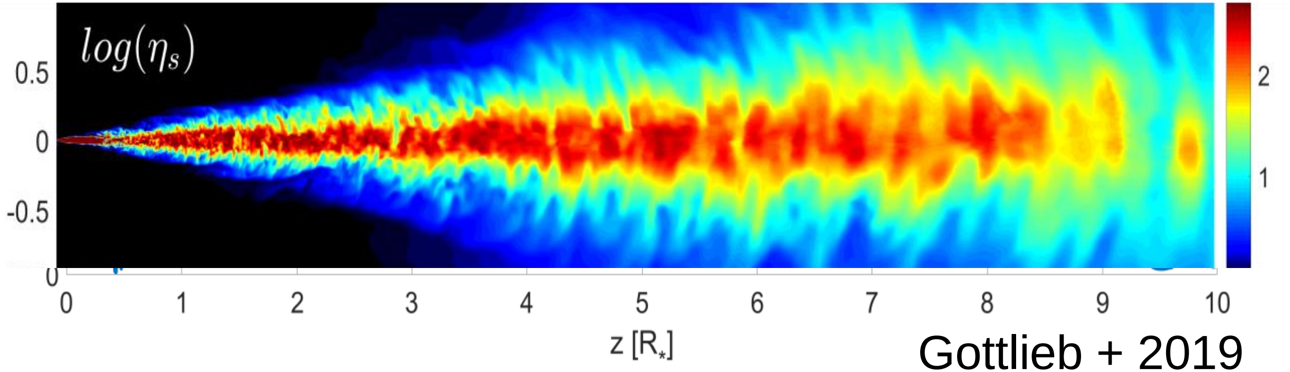
Numerical hydrodynamic/magneto-hydrodynamic simulations have been done

Collapsar : Aloy+00, Zhang+03,04, Mizuta+04,06,09,13, Morsony+ 07, 10
Lazzati+09,13, Nagakura+11,12, Hamidani +17
Lopez-Camana +13,16, Geng+16, Parsotan+18, Ito+19,
Gottlieb+20

Binary merger : Aloy+05, Nagakura+14, Lazzati+17, Gottlieb+18, 19, 21
Hamidani+20, Ito+21, Pavan+21, Gottlieb+23

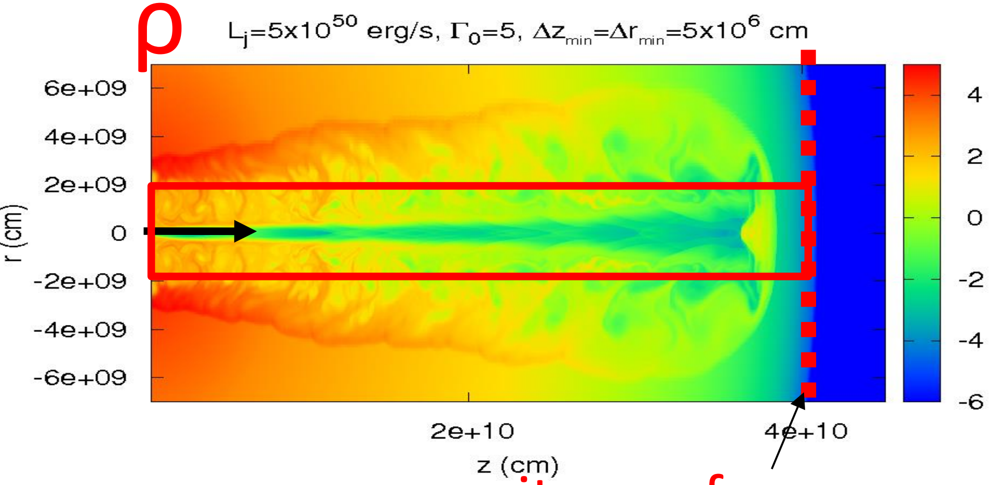


Mizuta & Ioka 2013
(2D axis-symmetric)



Gottlieb + 2019
3D

High resolution hydro. simulations(2D, axisymmetric AM+2013)



High resolution grid points are devoted
At least in the jet and cocoon.

$\Delta z_{min}=\Delta r_{min}=10^7$cm or $=5\times10^6$cm

$E_j=5\times10^{50}$erg/s, $r=8\times10^7$cm

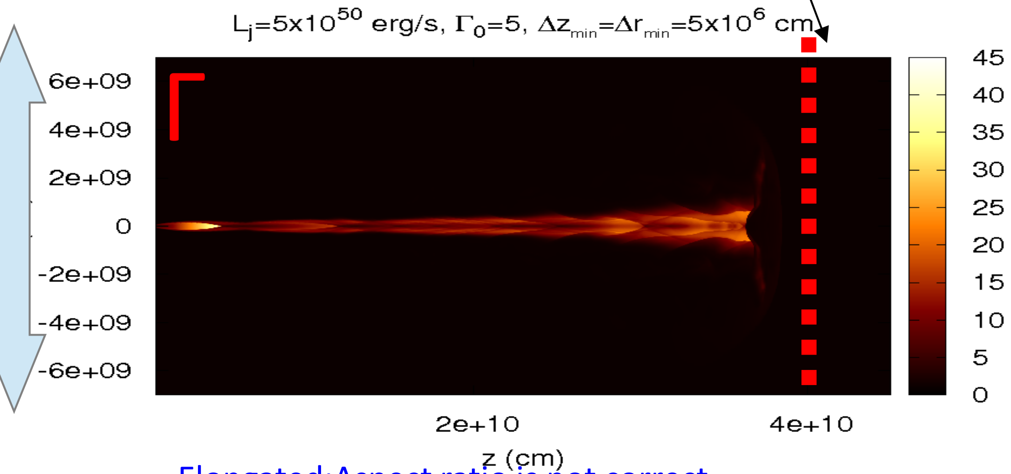
$\eta=h_0\Gamma_0=533$

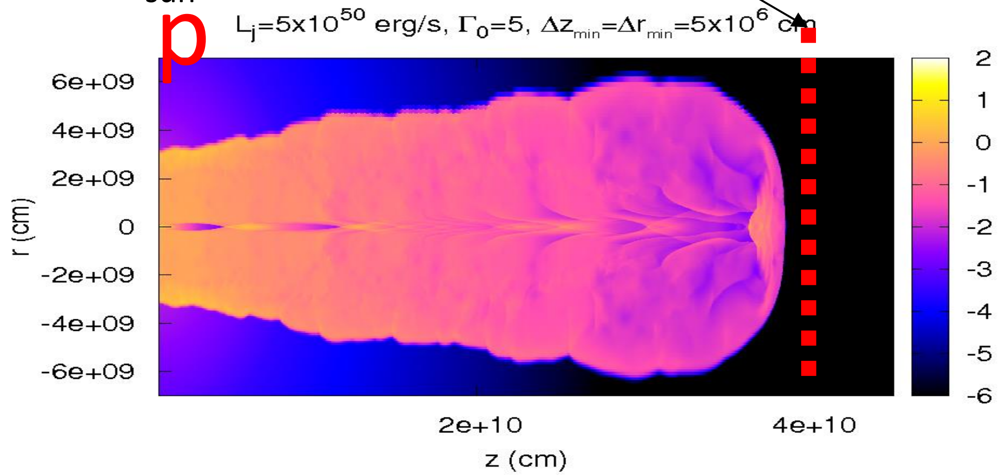
$\Gamma_0=2.5, 5, 10$

Progenitor : Woosley & Heger(2006)

$M\sim14M_{sun}$, $R^*=4\times10^{10}$cm

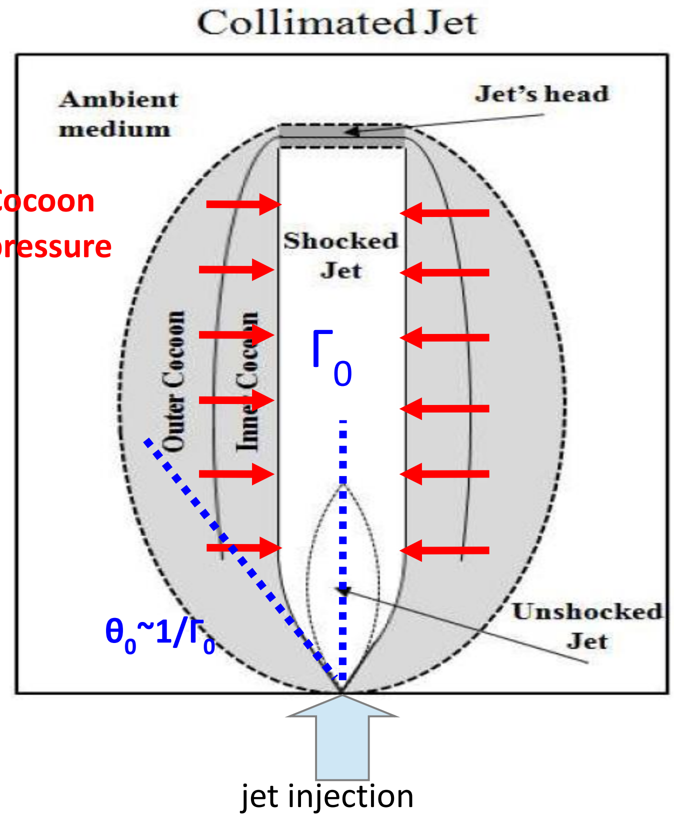
progenitor surface

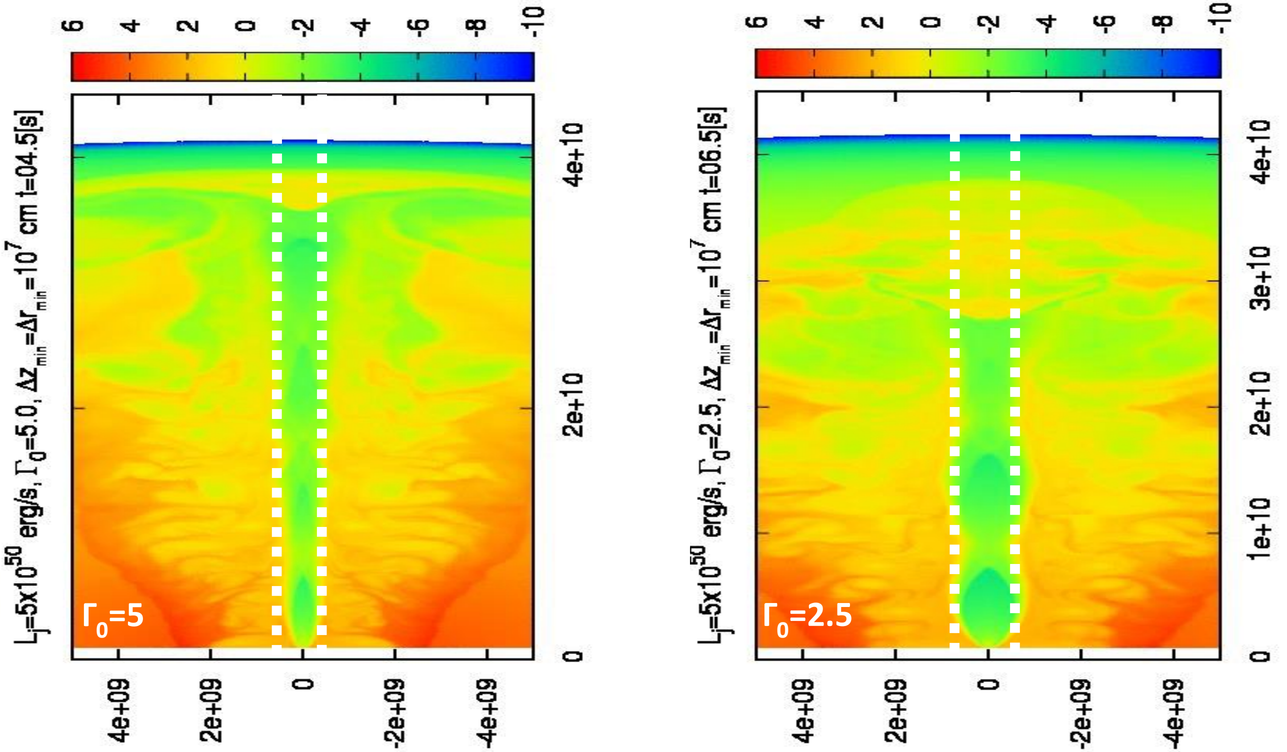




Elongated:Aspect ratio is not correct

Cocoon confinement (Before break)





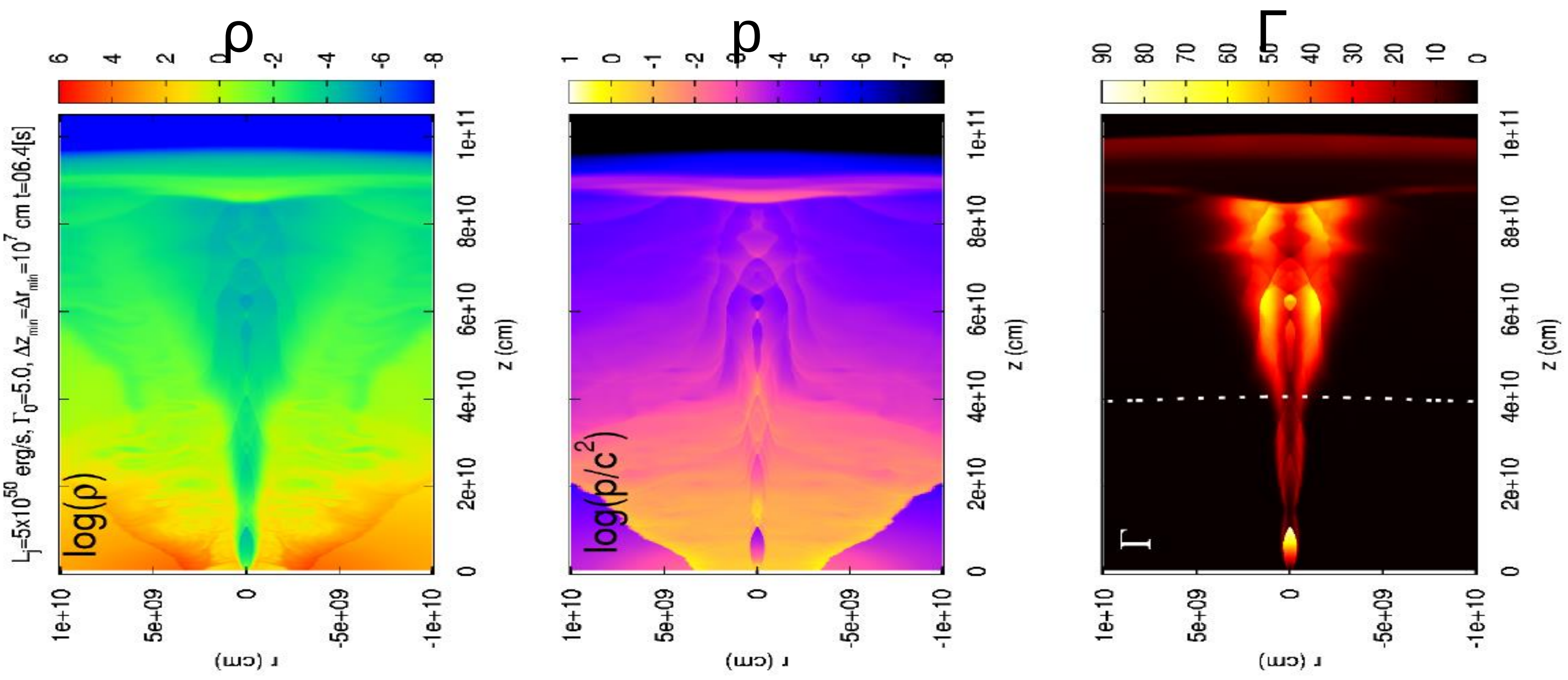
AM+2013)

Bromberg + (2011)
collimation shock
+
Cylindrical jet ($\Gamma \sim \Gamma_0$)

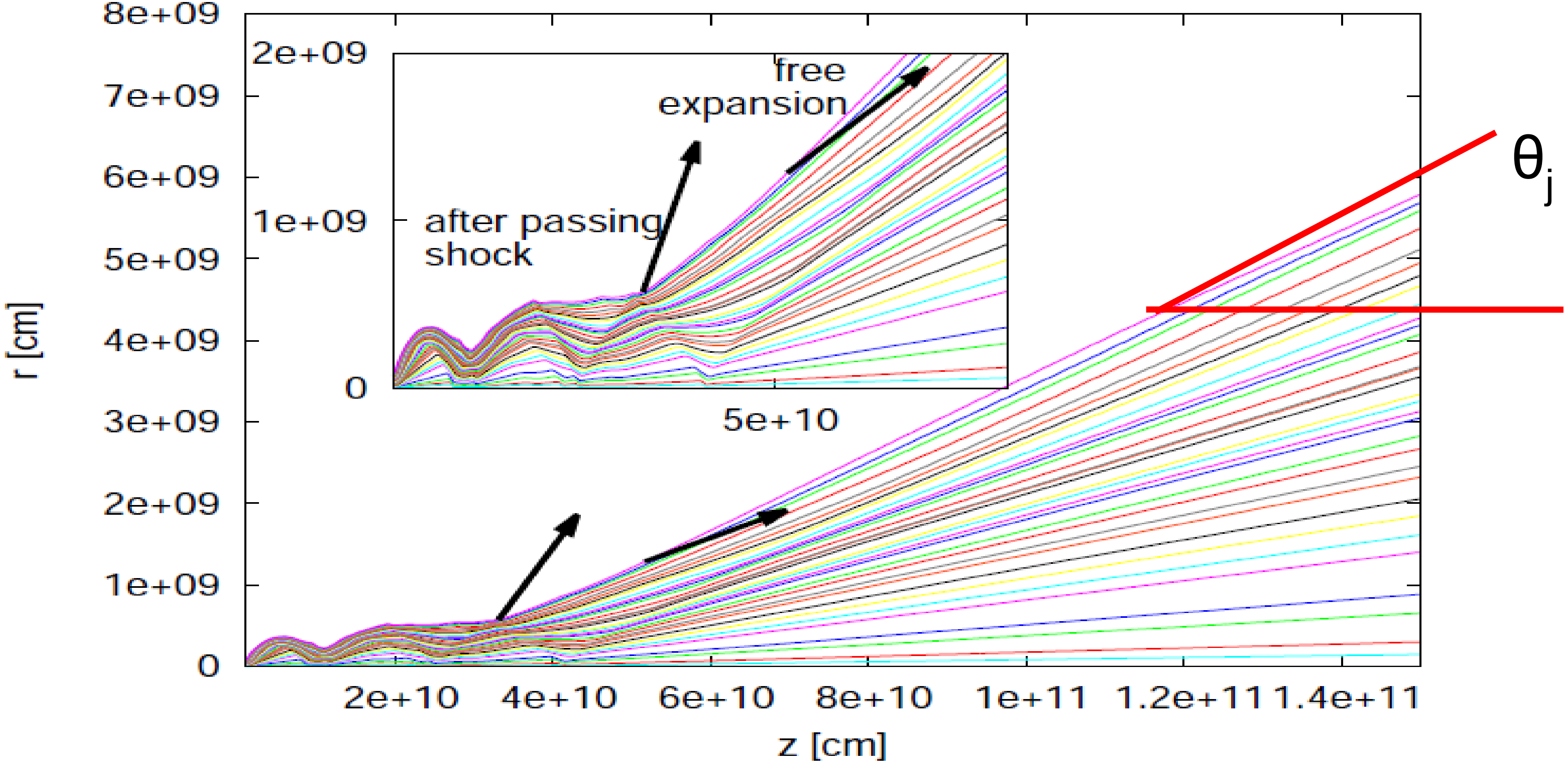
See also Komissarov & Falle 1998

After collimation shock, jet is almost cylindrical shape as Bromberg et al. predicted. Some oblique shocks can be seen inside the jet

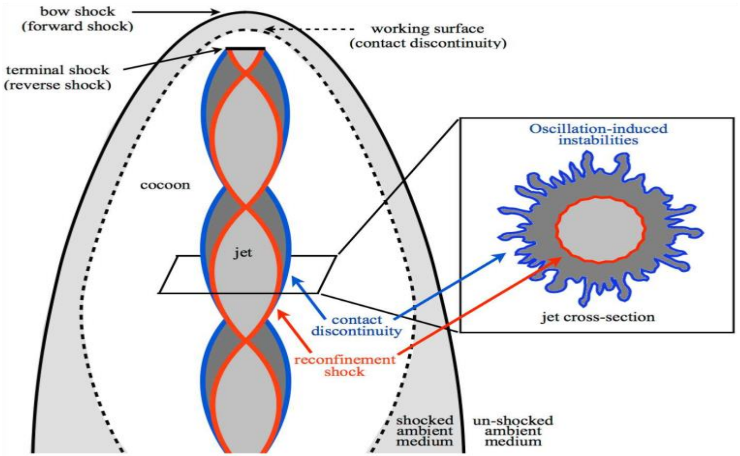
Jet is still confinced by the cocon, even after the jet breakout

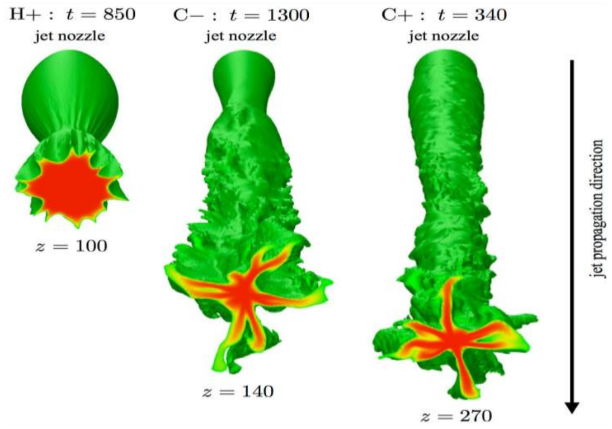


Particle traces injected at t=5 s



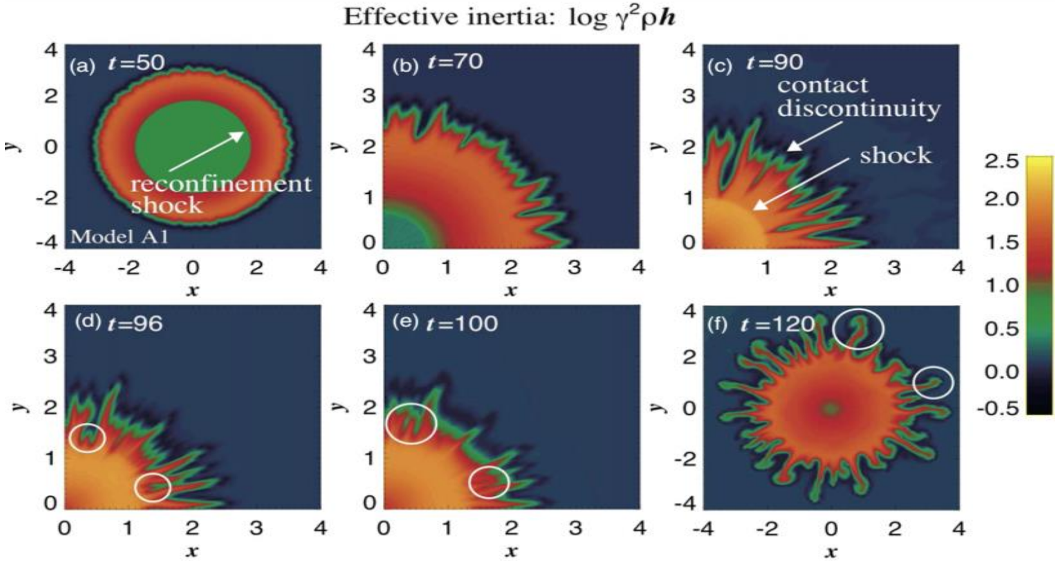
Jets in 3D : Recollimation shock instability





Mastumoto + 2019

Rayleigh–Taylor Instability + Richtmyer–Meshkov instability
Matsumoto +(2013, 2017, 2019)
Toma+(2017)



centrifugal instability (CFI)
Gourgouliatos & Komissarov (2017, 2018)

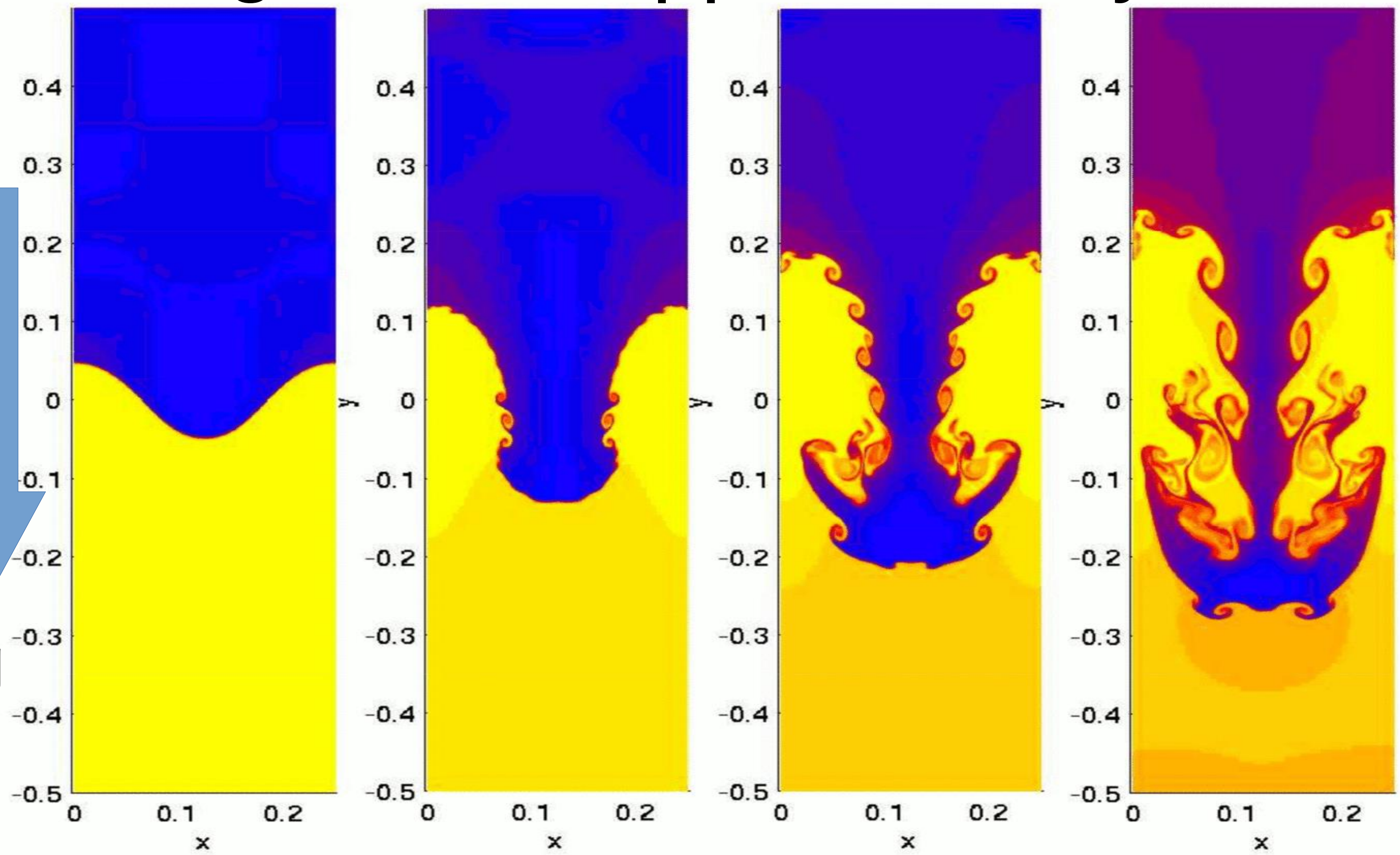
Rayleigh-Taylor instability occurs, when light fluid supports heavy fluid

ρ_u

v

ρ_d

g



Li & Li @Los Alamos

New 3D special relativistic hydrodynamic code

(similar with our 2D version (Mizuta + 2004,2006))

・Numerical flux : Approximate Riemann solver

- Marquina flux (3 waves, Donat & Marquina (1996))
- HLL (2 waves Schneider et al. (1993), Duncan & Hughes (1994))
- **HLLC (3 waves Toro 1994, Mignone and Bodo (2005))**

・Cell reconstruction (interpolation funtion＋limiter against numerical oscillation)

MUSCL + minmod limiter (2nd or 3rd order)

MUSCL + superbee limiter (2nd or 3rd order)

PPM (3rd order)

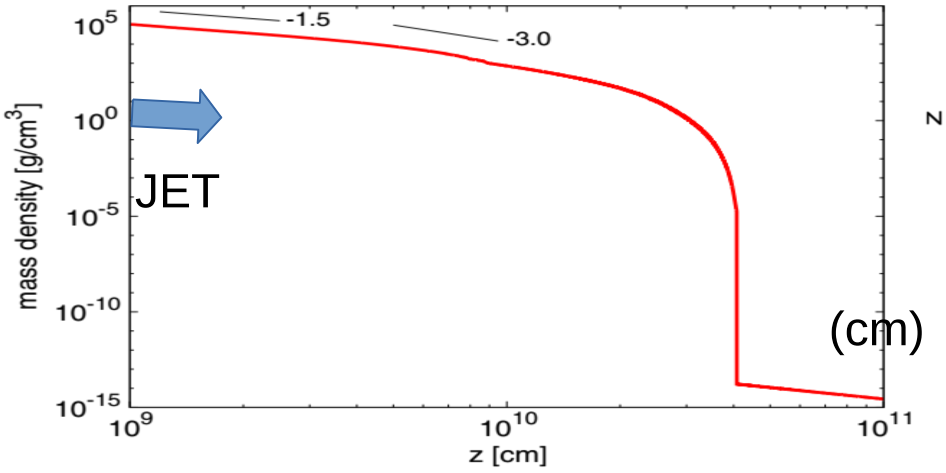
・Time integration

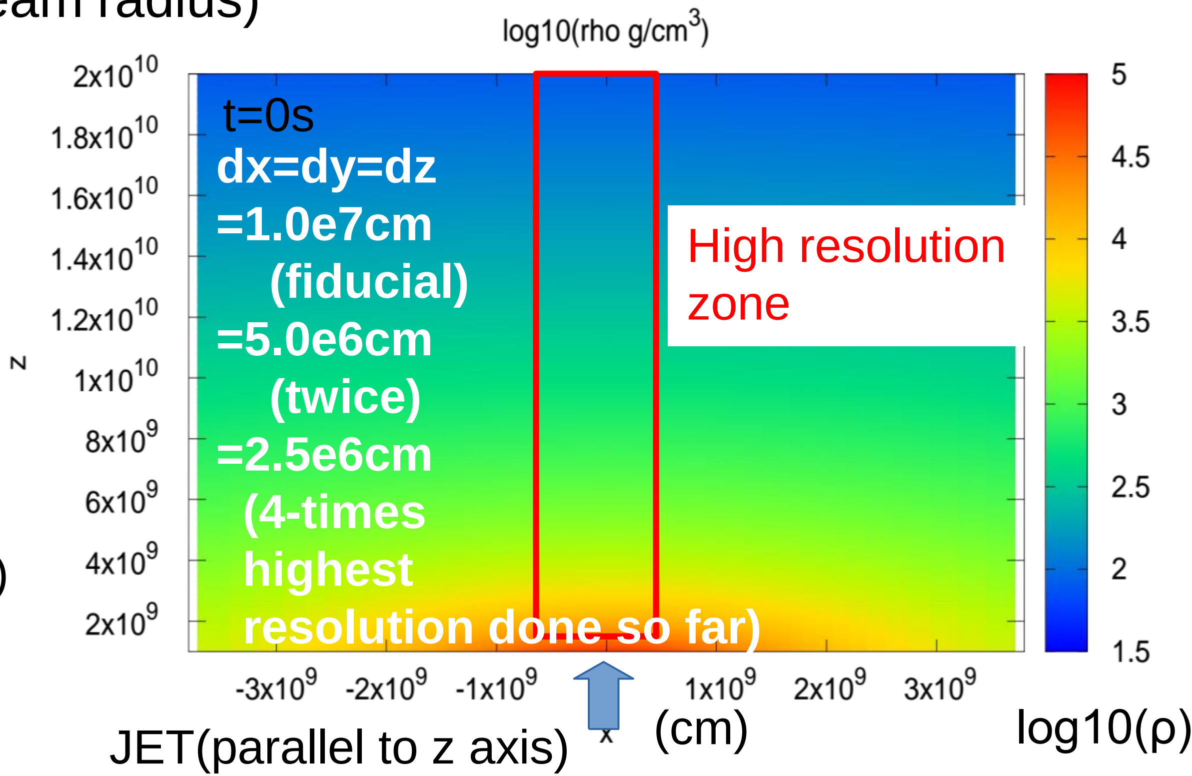
TVD Runge-Kutta method (**2nd** or 3rd , Shu & Osher 1988)

Numerical condition

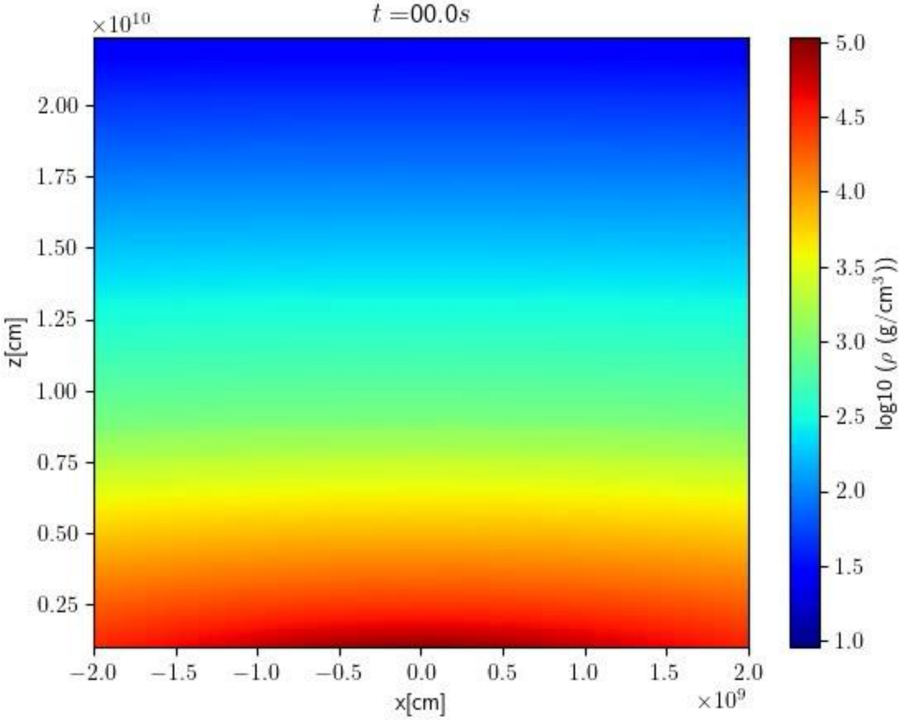
- Almost same as Mizuta & Ioka 2013 (MI13, collapsar jet assuming 2D axisymmetric) .
- Progenitor model : 16TI, 14M_sun @ pre-SN (Woosley & Heger 2006)
- Jet inlet : @ z=1.e9, radius 8.e7cm
  $h_0\Gamma_0$=538, vz=0.98c(Γ=5), Lj= 5.e50 erg/s
- resolution study (**8, 16, 32** grids/beam radius)

Radial mass density profile

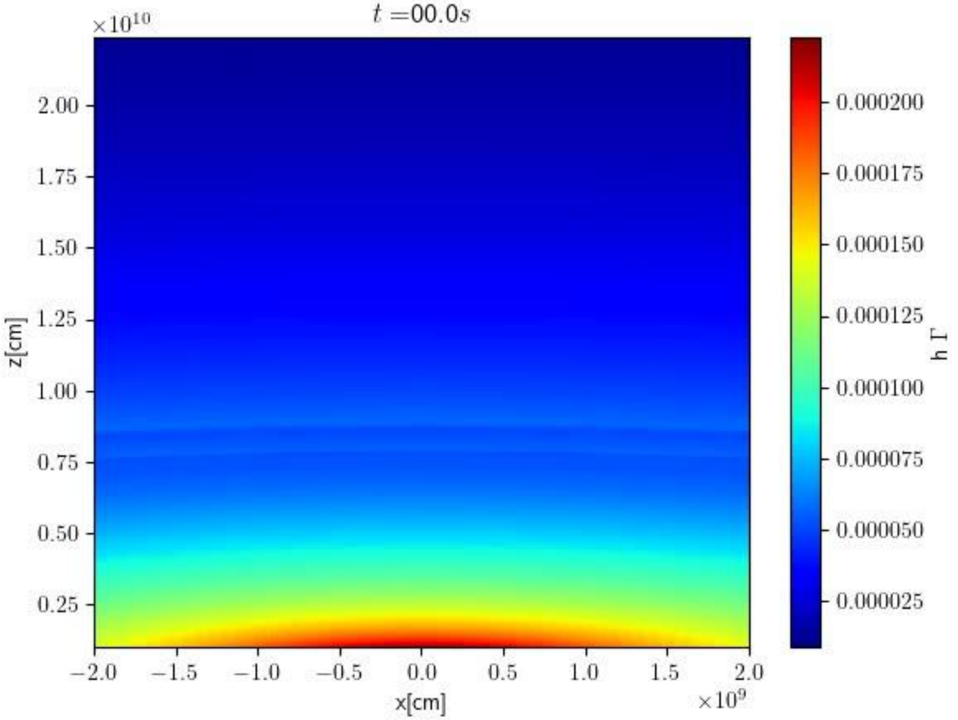




Log10(Mass density)

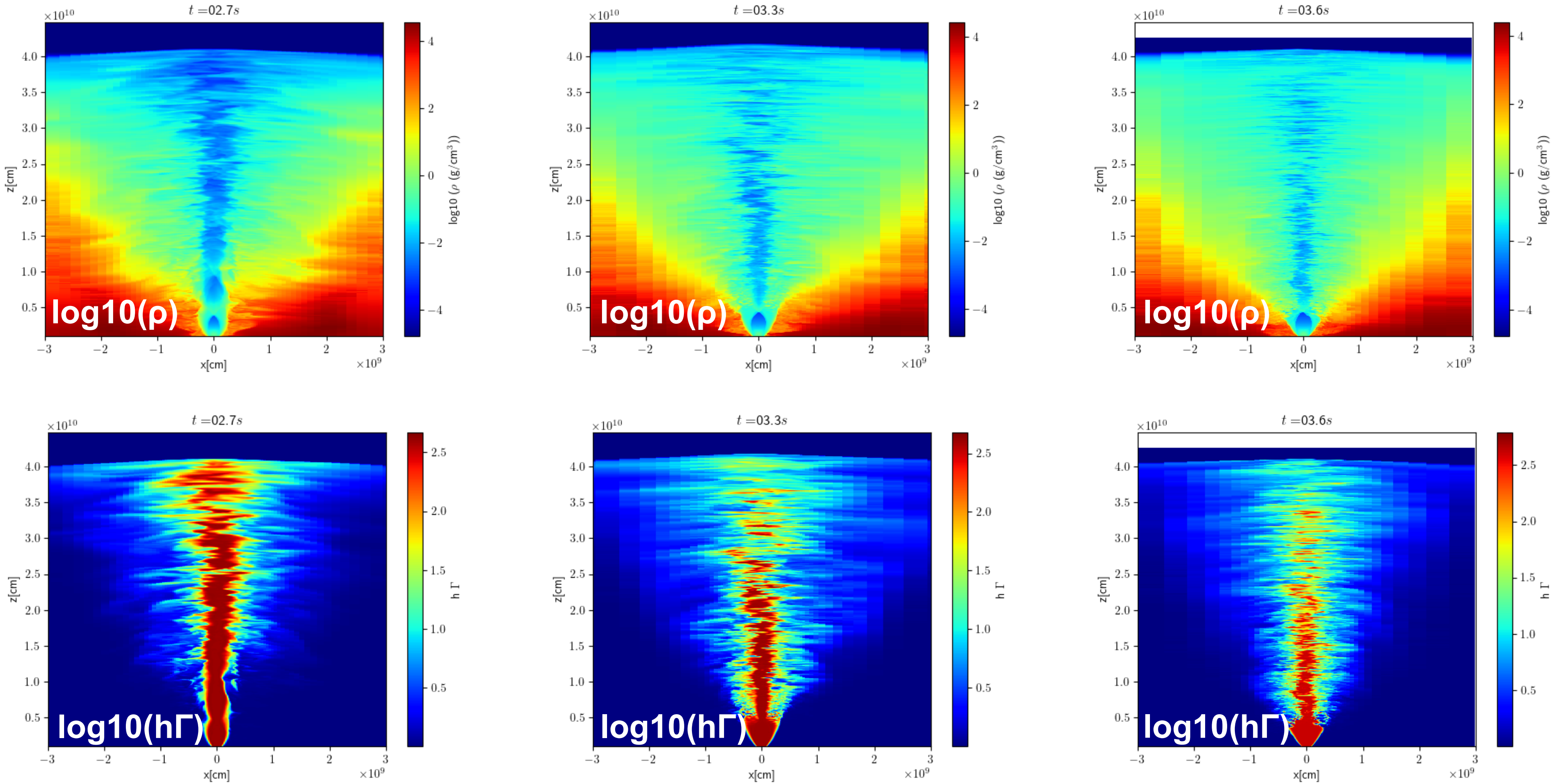


Log10(h Γ)



XZ slices@shock breakout :Resolution effect

fiducial t=2.7s | **Twice t=3.3s** | **4 times t=3.6s**



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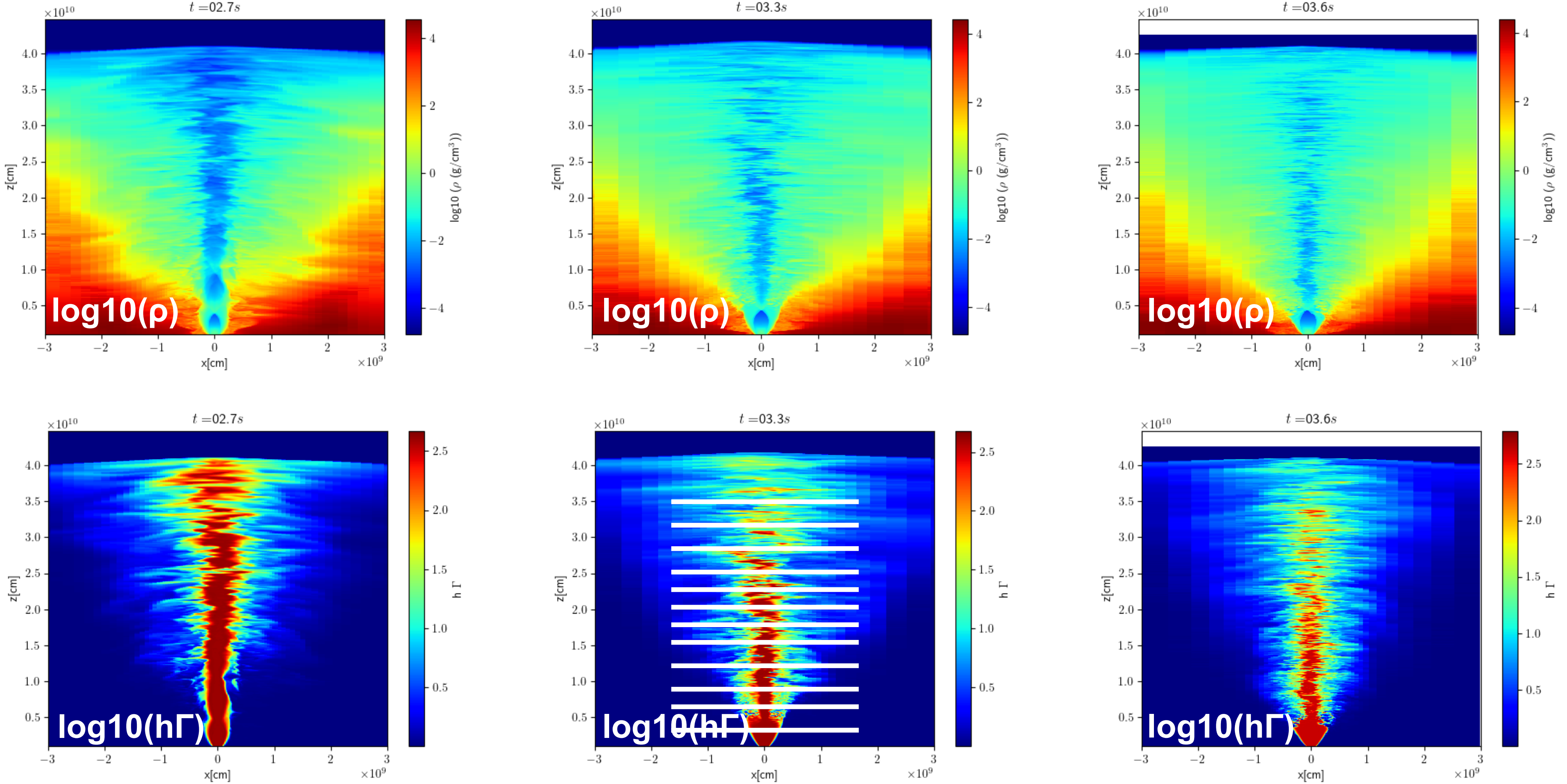
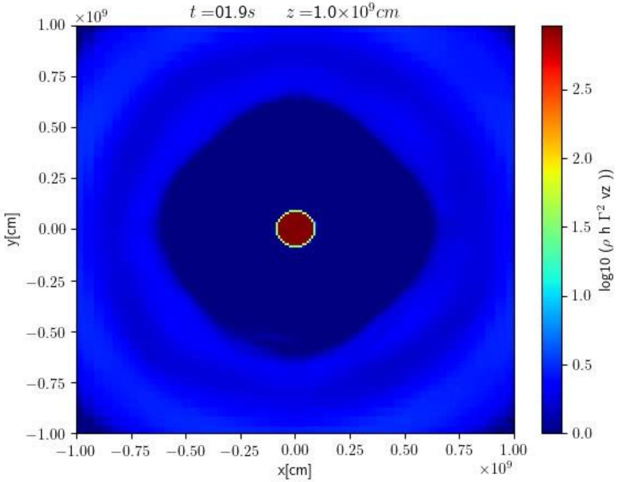
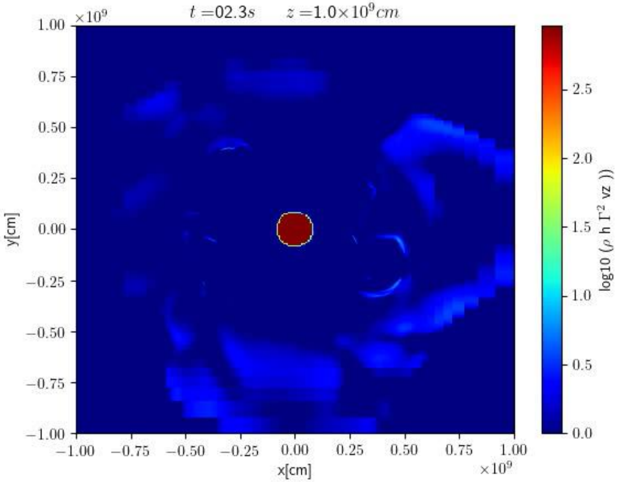
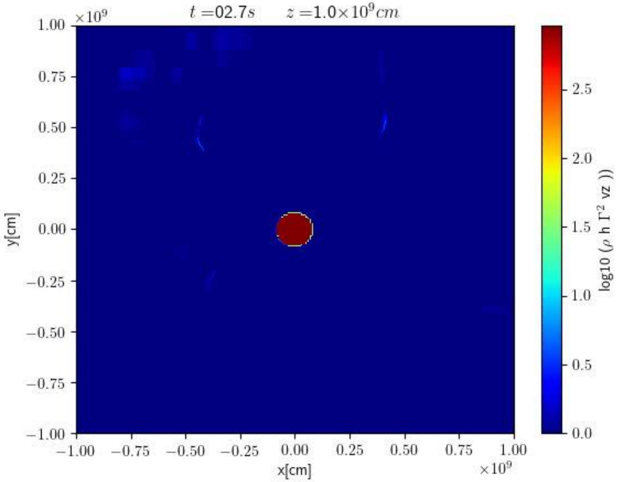


Cross sectional area map (kinetic luminosity) @ jet head = R*/2

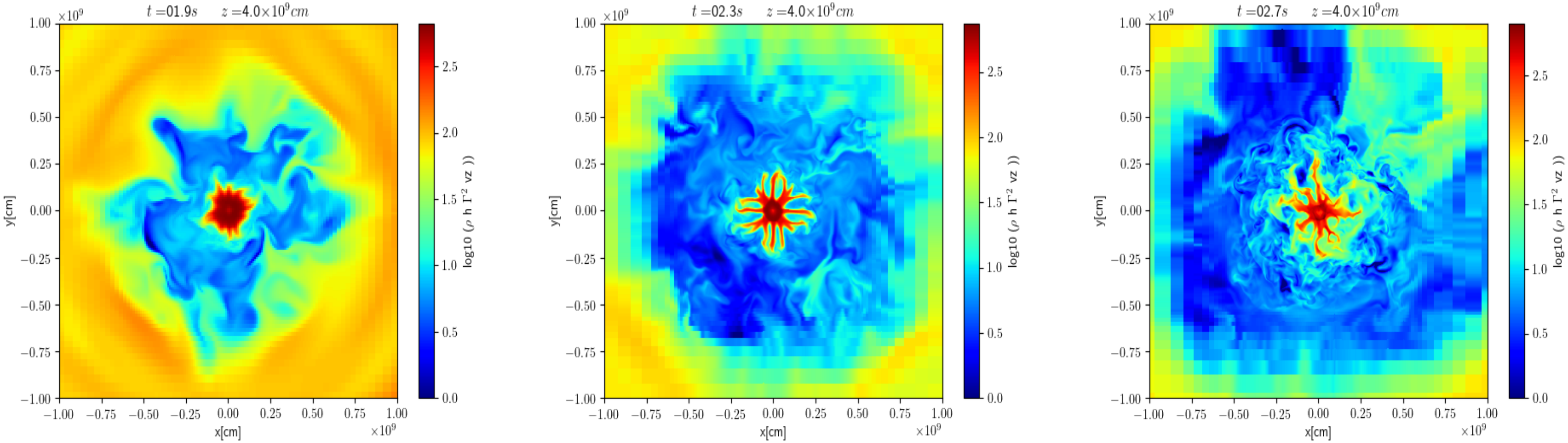






Growth of Hydrodynamic instability & Resolution effect

fiducial | **twice** | **4-times**



- Hydrodynamic instabilities grow up in all models.
  – Higher order modes are resolved in higher resolution models.
  – Higher order mode (short wave length perturbation) of Rayleigh-Taylor instability can grow up faster than lower mode.
  – Nonlinear evolution of the growth of instabilities are observed enhancement of mixing.
- The high-resolution calculations allow us to resolve finer structures not only in contact discontinuities of the jet but also in the cocoon.

Dicussion：Can real hydro jet penetorate the progenitor star ?

- Time for shock breakout

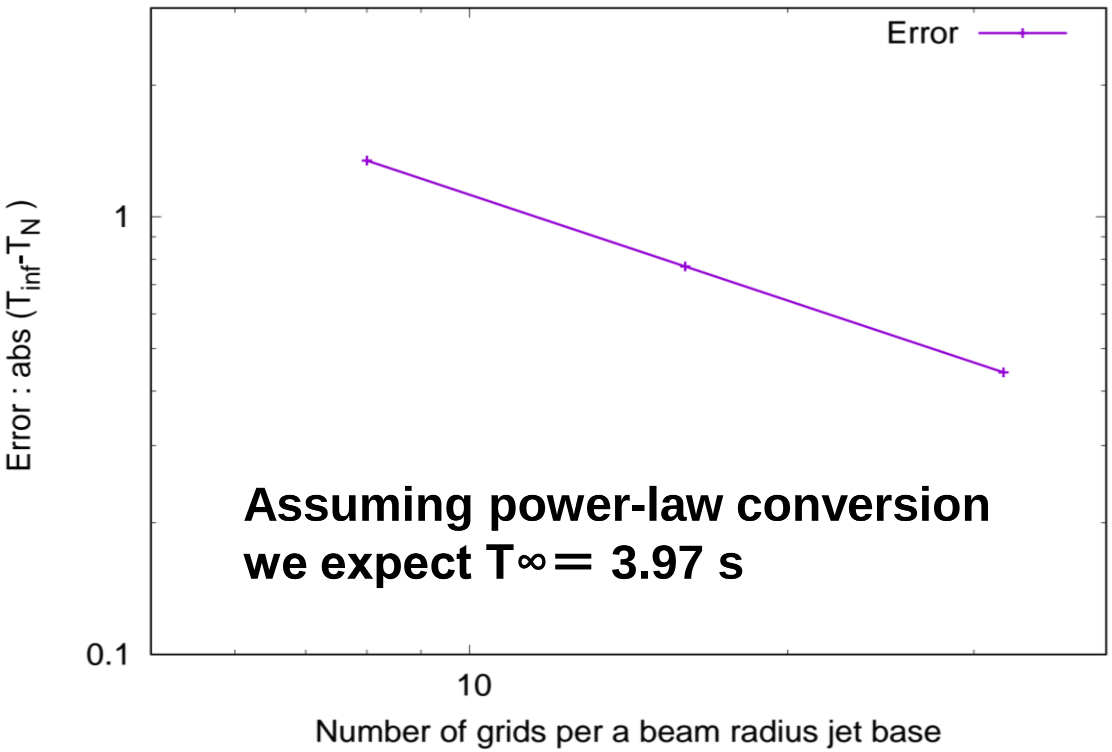
  Fiducial model : t=2.7s

  Twice model : t=3.3s

  4 times model : t=3.6s

  ⋮ ⋮ ⋮

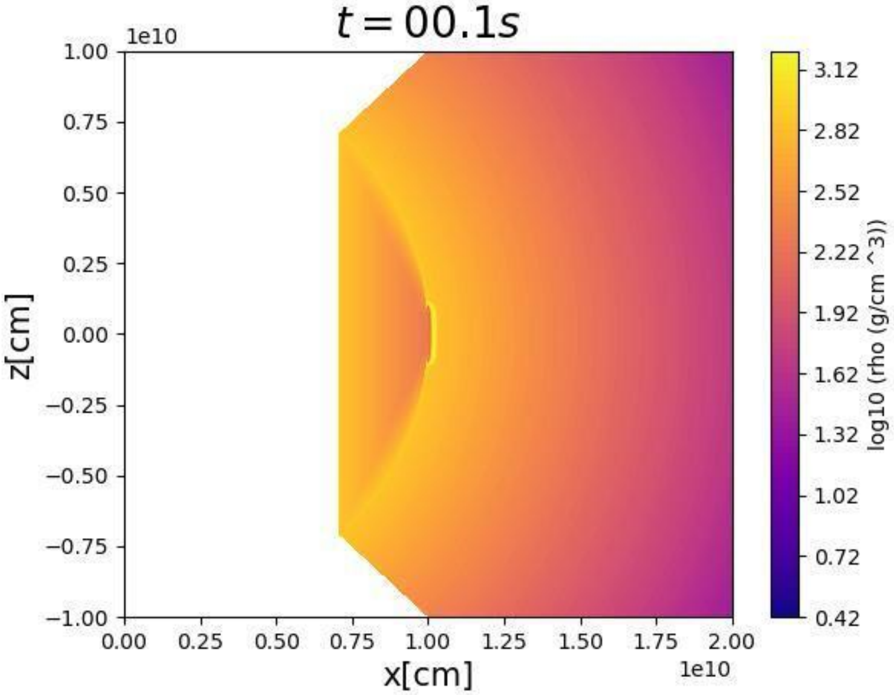
  N(inf) : t= ?

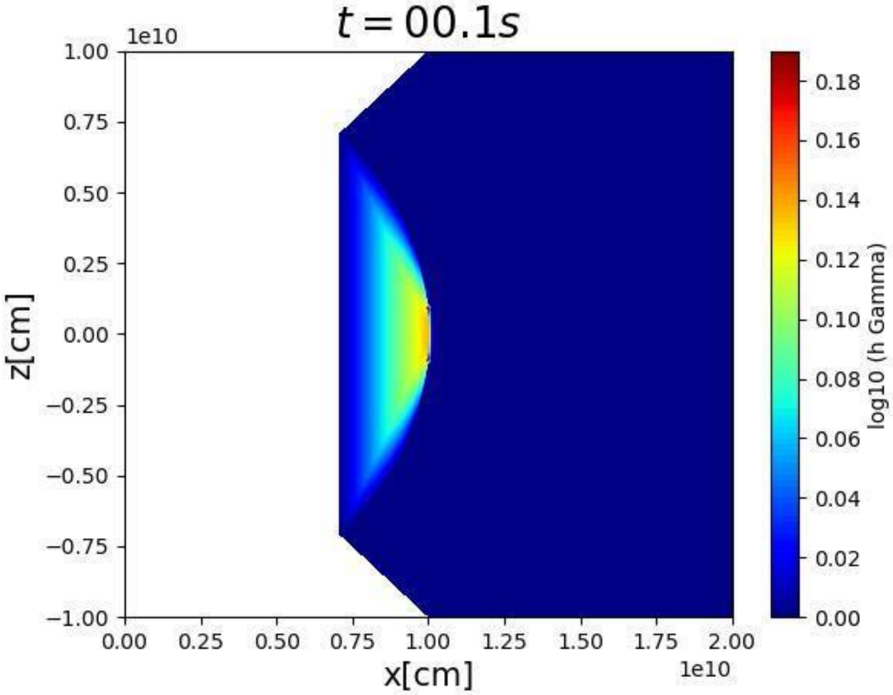


Assuming power-law conversion, we expect T∞＝ 3.97 s which is realistic time scale of central engine activity.

High resolution long term evolution of lGRB jets

Preliminary





Similar parameter setting with Ito+2019 but about 1.5 times higher resolution.
Dependence of injection radius. (1.e10cm v.s. 1.e9cm)
Raidative properties from these GRB jet will be studied by Ito-san.

Conclusion

- To simulate gamma-ray burst jet propagation based on the collapsar model, we developed a **3D SR-HD code** and performed 3D jet propagation simulations.
- The **growth of fluid instabilities** due to effective acceleration acting on the jet interface caused by lateral expansion and contraction of the jet, as pointed out in previous studies, was observed.
- **Resolution studies**
  - -- Higher resolution resulted in the growth of short-wavelength modes of fluid instabilities, leading to a **nonlinear stage and more complex turbulence** inside the cocoon.
  - -- The nonlinear growth of instabilities caused an increase in the jet component mixing into the cocoon before reaching the jet head, **reducing propagation efficiency** as resolution increased.
  - -- Although convergence as suggested in previous studies was not achieved, realistic shock breakout timing can still be expected at even higher resolutions.