Propagation and Hydrodynamic Instabilities in Relativistic GRB Jets from Collapsars

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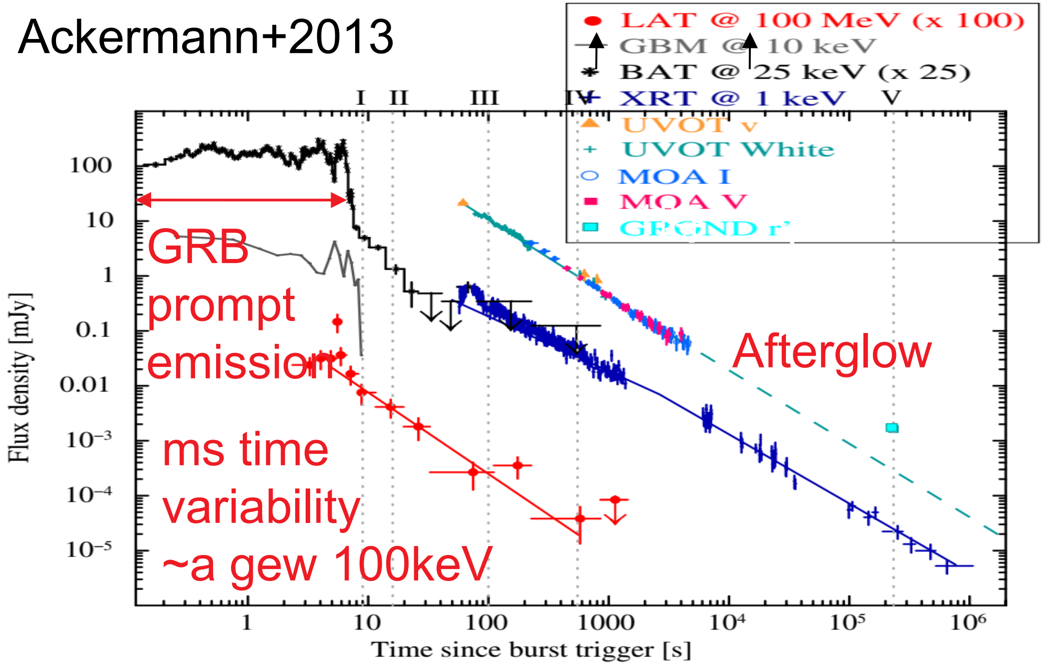
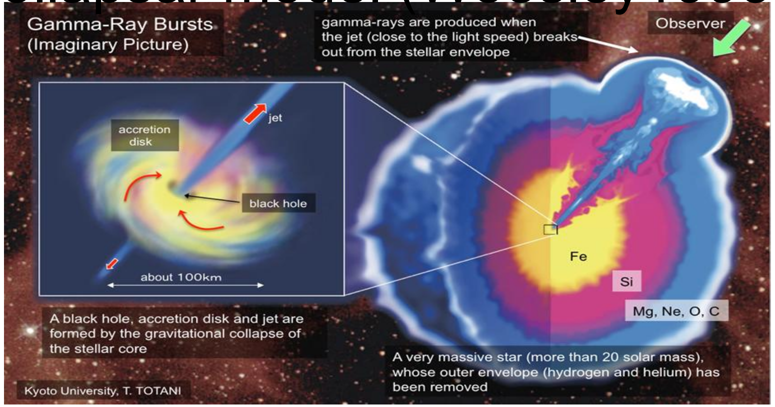
Multi-messenger Astrophysics in the Dynamic Universe
-- Frontier in computational relativistic astrophysics
and its applications (2nd week), 2026.2.5
AM, Ioka in prep.

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)

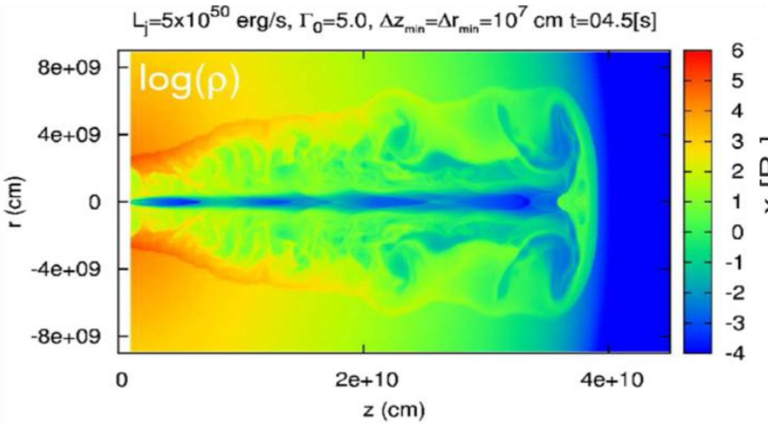
We need to understand formation of structures in the jet and cocoon. The structure formation directly affects breakout time and efficiency.

Jet propagation : Numerical relativistic HD / MHD

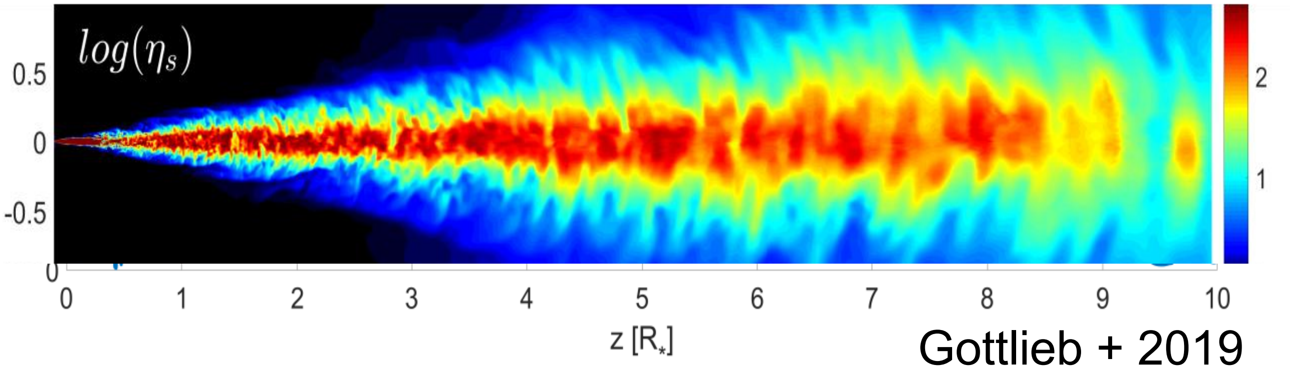
Numerical hydrodynamic/magneto-hydrodynamic simulations have been done

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, Urrutia+25, Shibata+25, Płonka+26

Binary merger : Aloy+05, Nagakura+14, Lazzati+17, Gottlieb+18, 19, 21
Hamidani+20, Ito+21, Pavan+21, 25, Urrutia+23, Mattia+24, Dreas+26

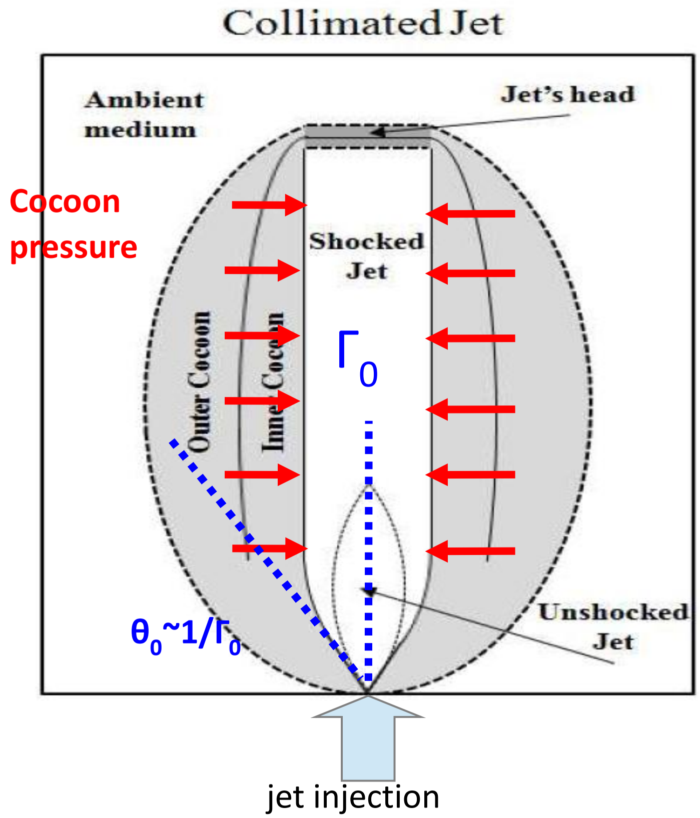


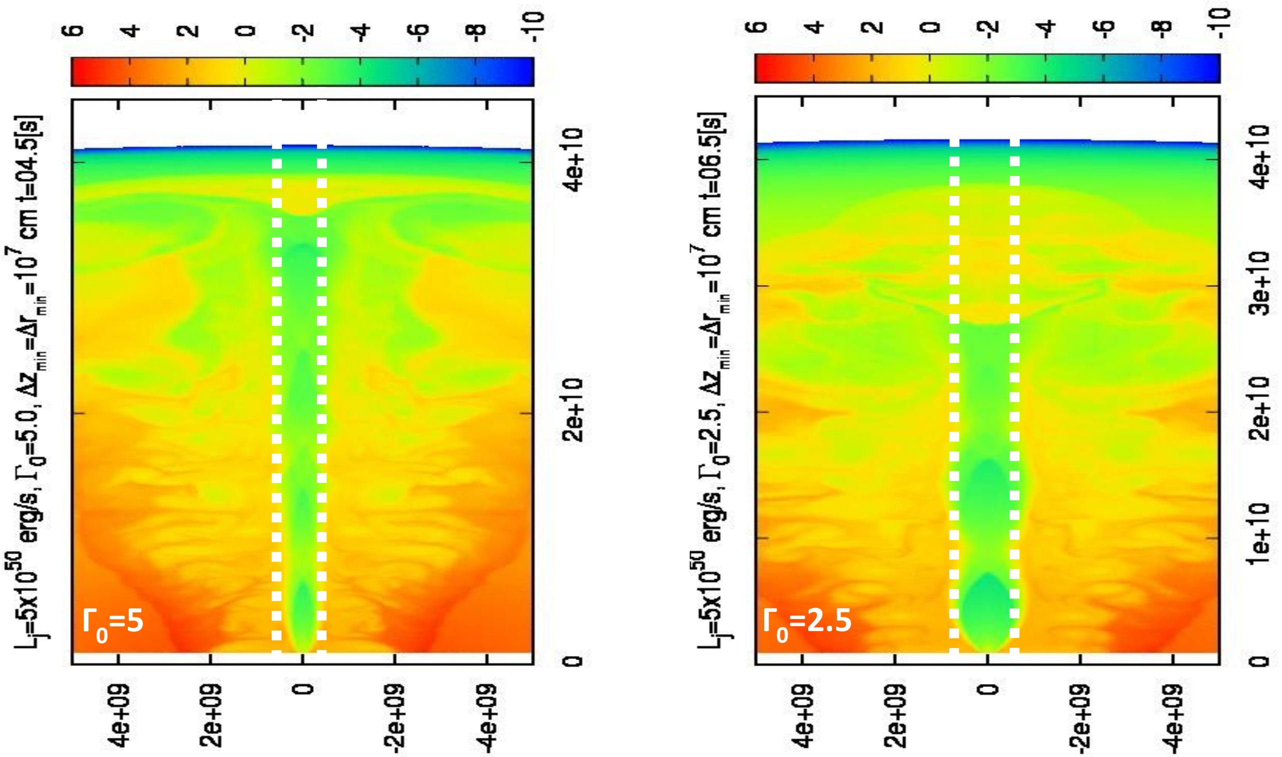
Mizuta & Ioka 2013
(2D axis-symmetric)



Gottlieb + 2019
3D

Cocoon confinement (Before break)





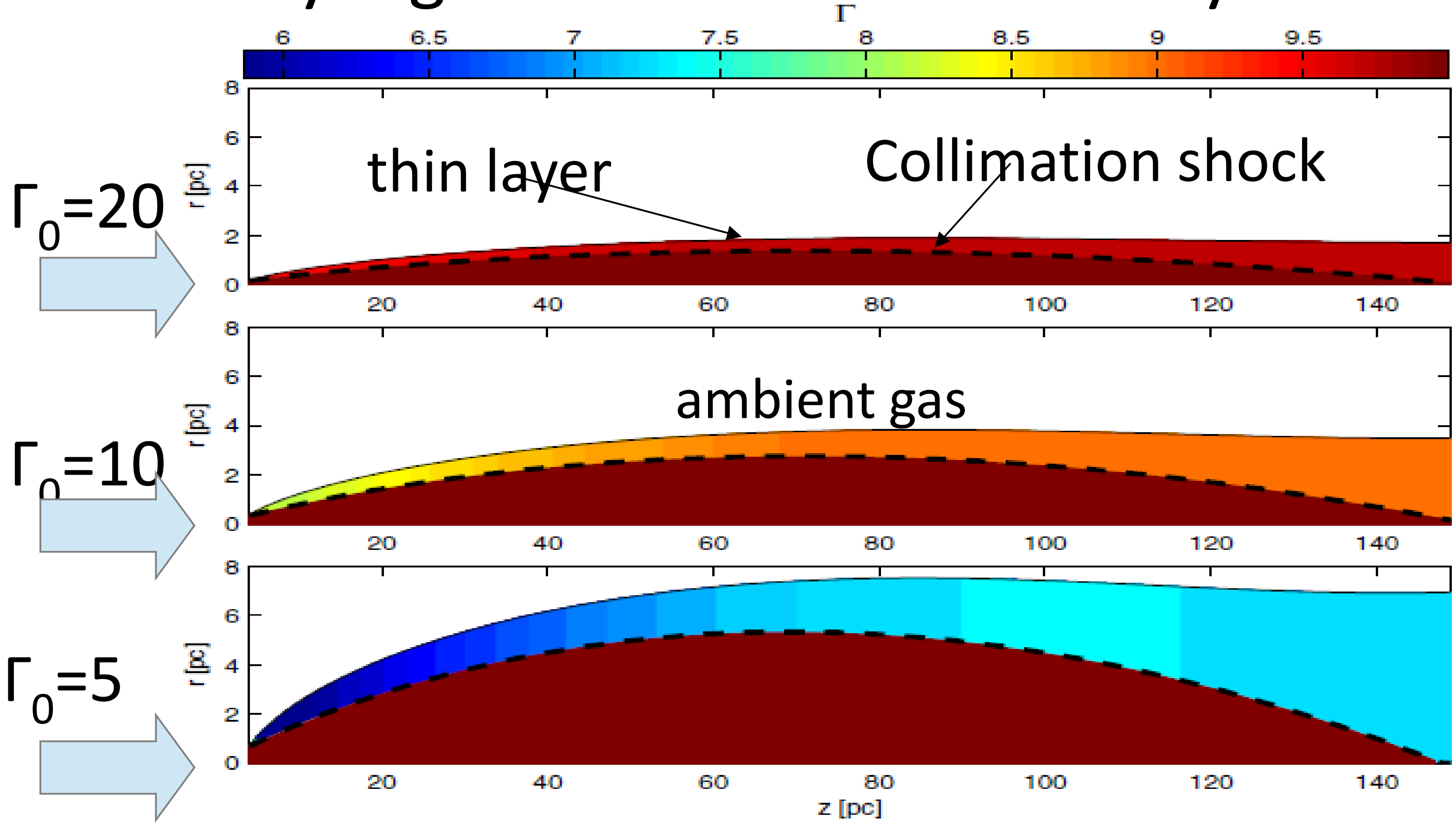
Mizuta & Ioka 2013 ApJ

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

See also Komissarov & Falle 1998

Resolution at least around jet axis is important to resolve the structures inside the jets

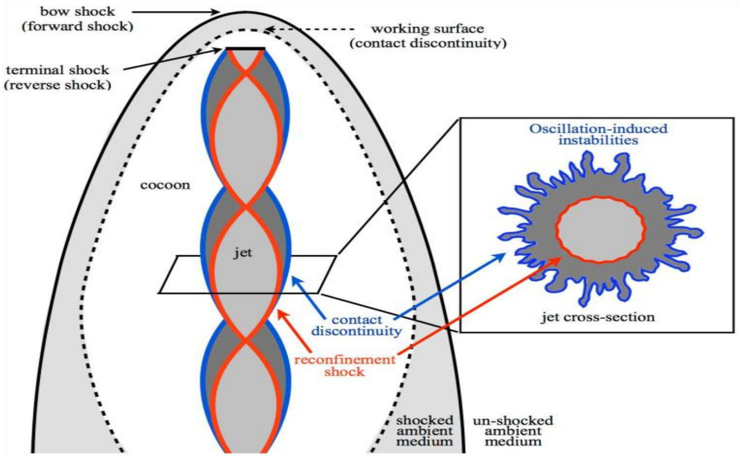
Why high resolution is necessary ?

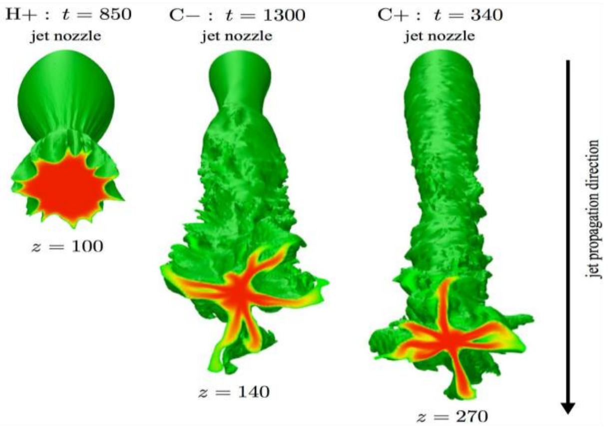


$\theta_0 = 1/\Gamma_0$

Bromberg, Levinson (2009)

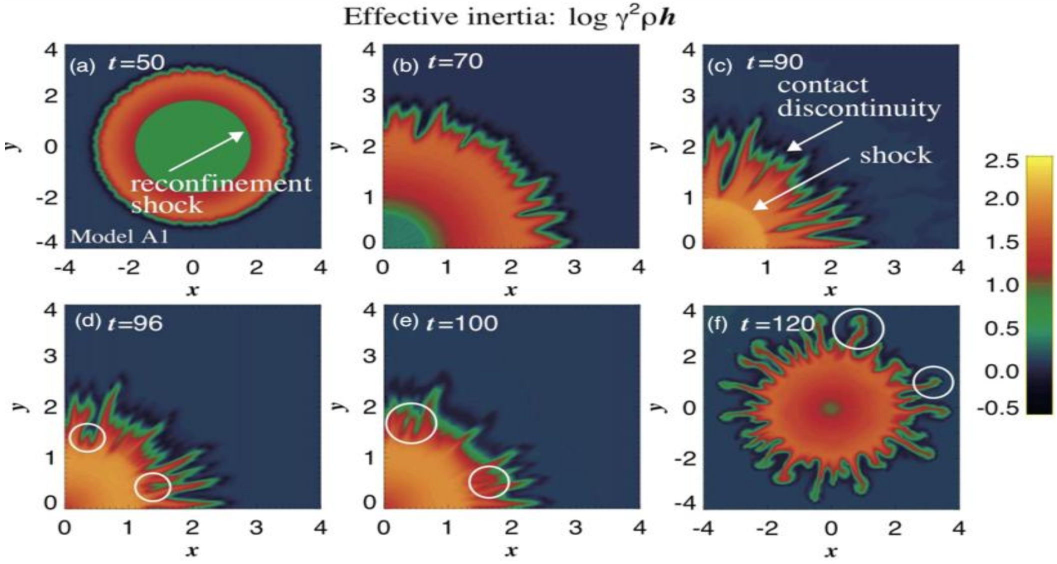
Jets in 3D : Recollimation shock instability





Mastumoto + 2019

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



Growth of RTI is very sensitive to the resolution, because the shorter wavelength mode can grow up faster.

New 3D SRHD code (--*SkyMirror* (3D SRHD))

Based on our well tested 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)

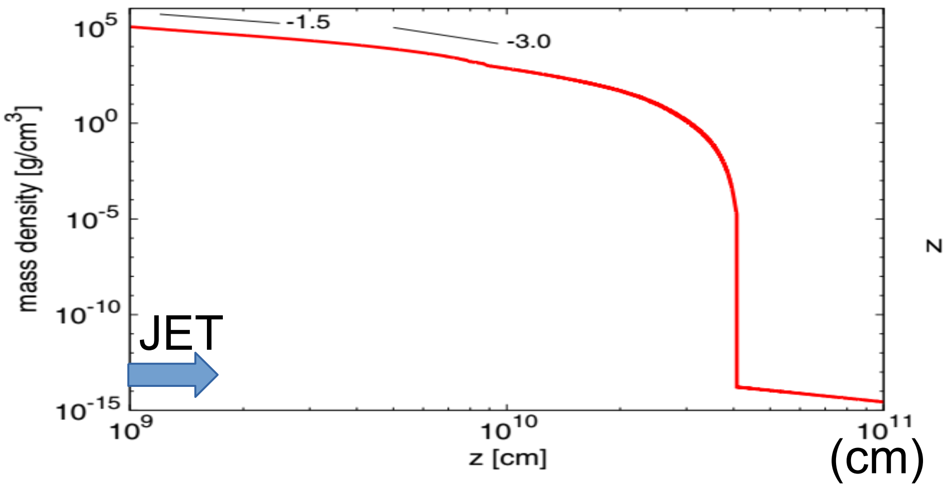
・Time integration

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

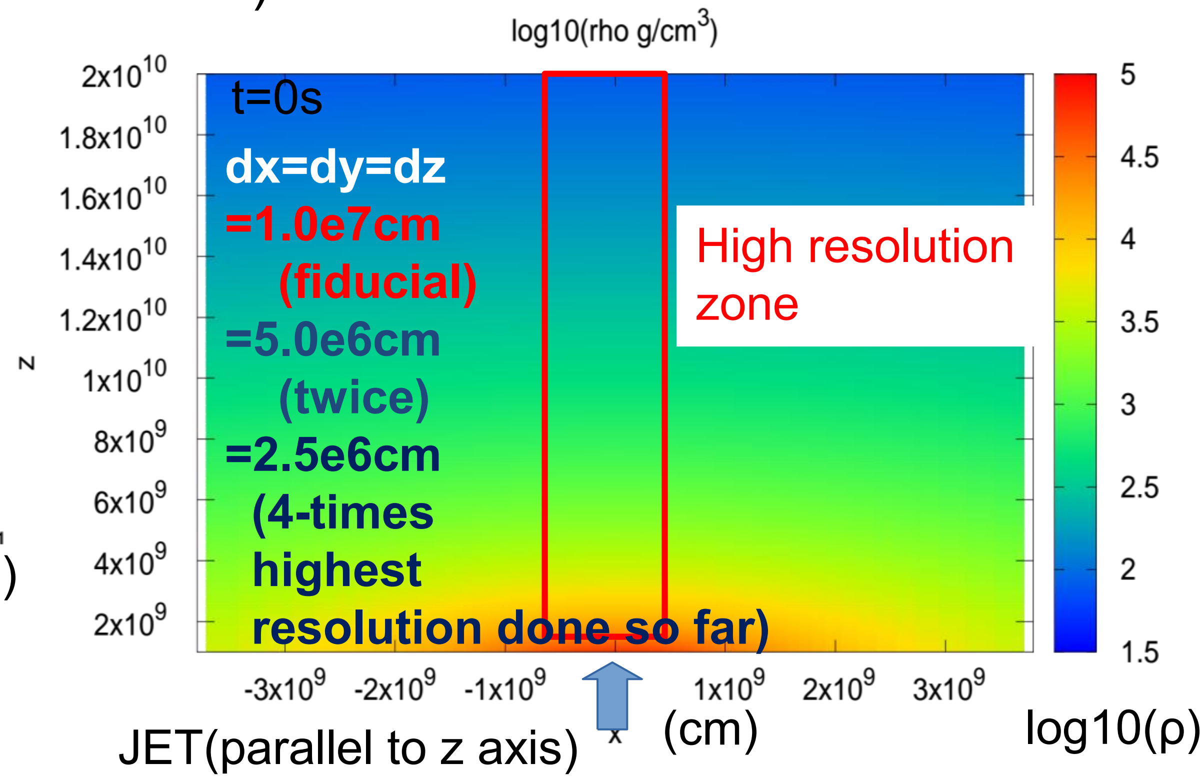
Numerical condition

- 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

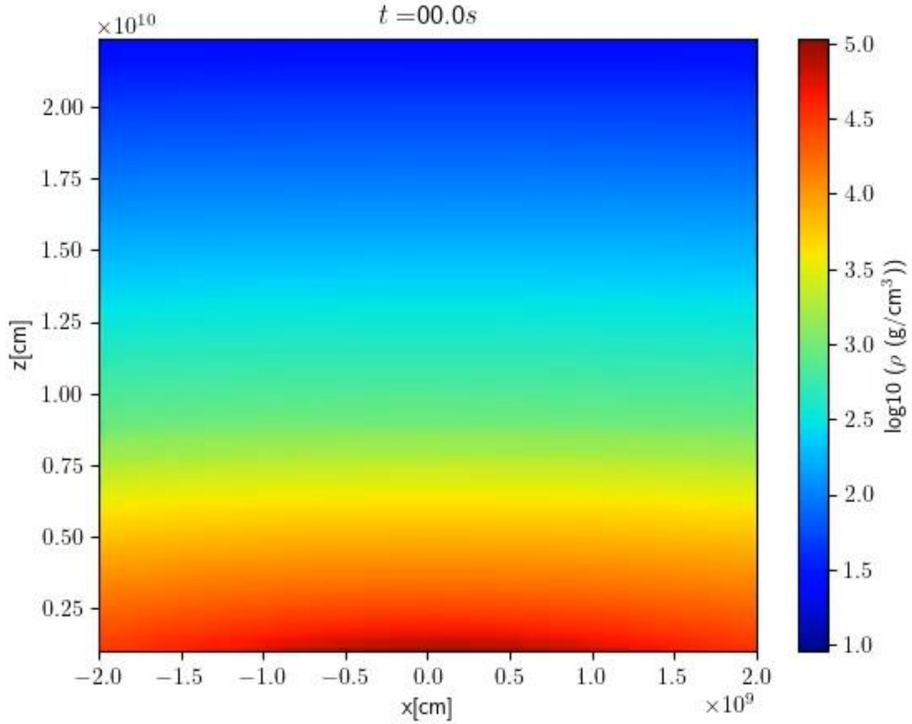


pre-SN model (Woosley & Heger 2006)

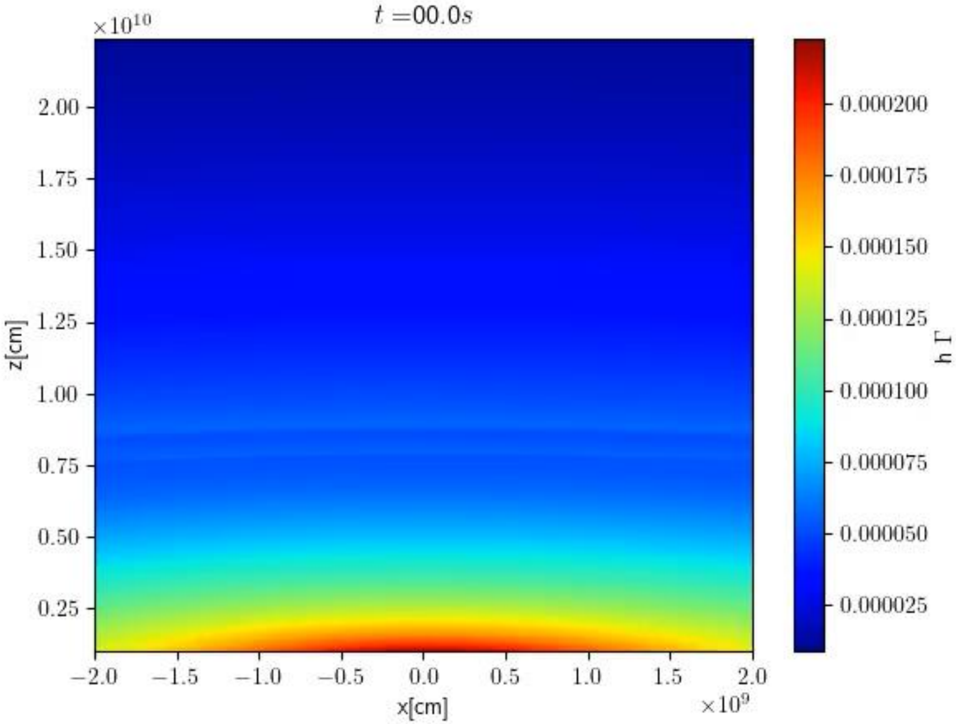


Fiducial model

log10(ρ)

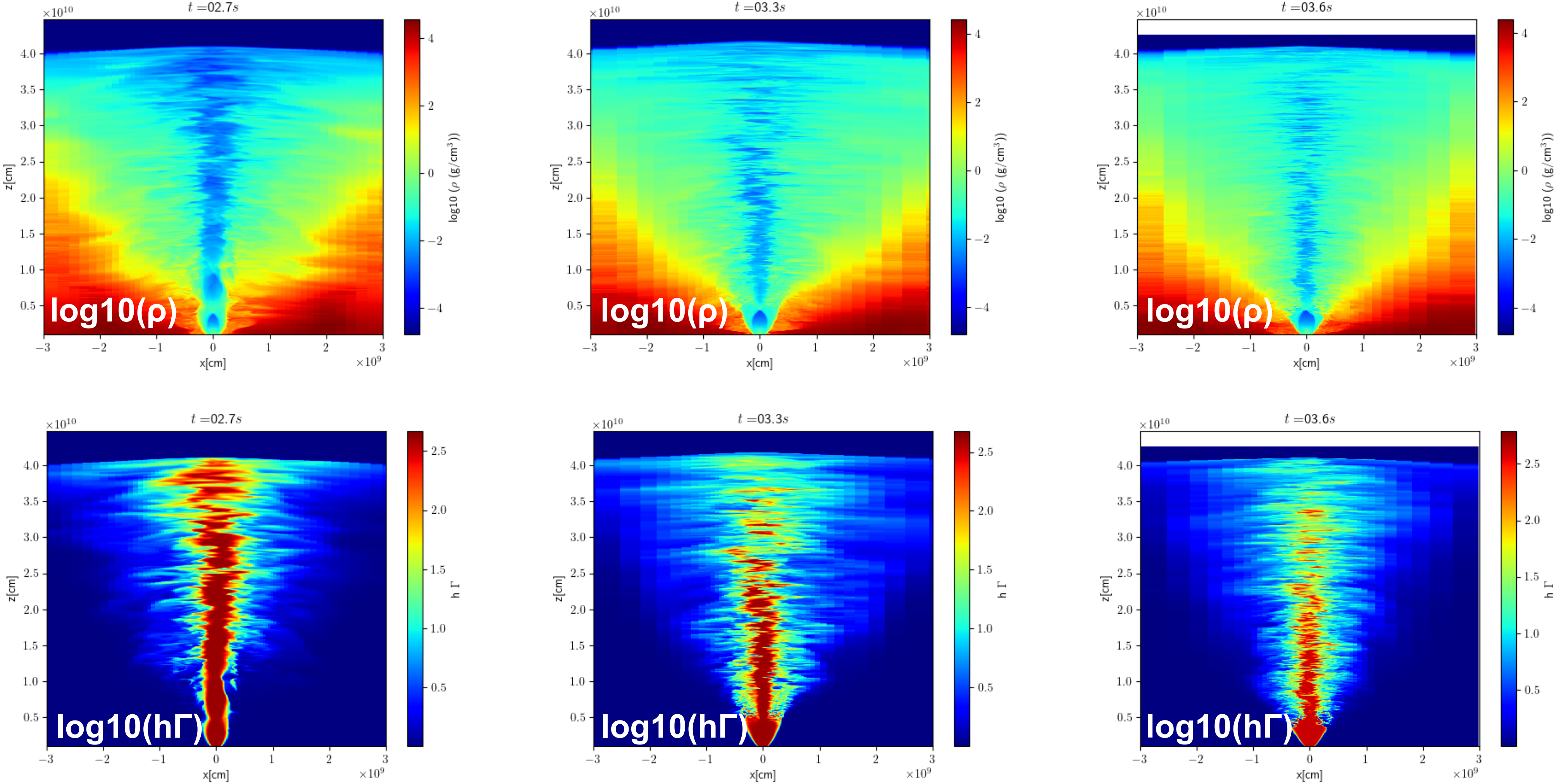


log10(hΓ)



XZ slices@shock breakout :Resolution effect

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



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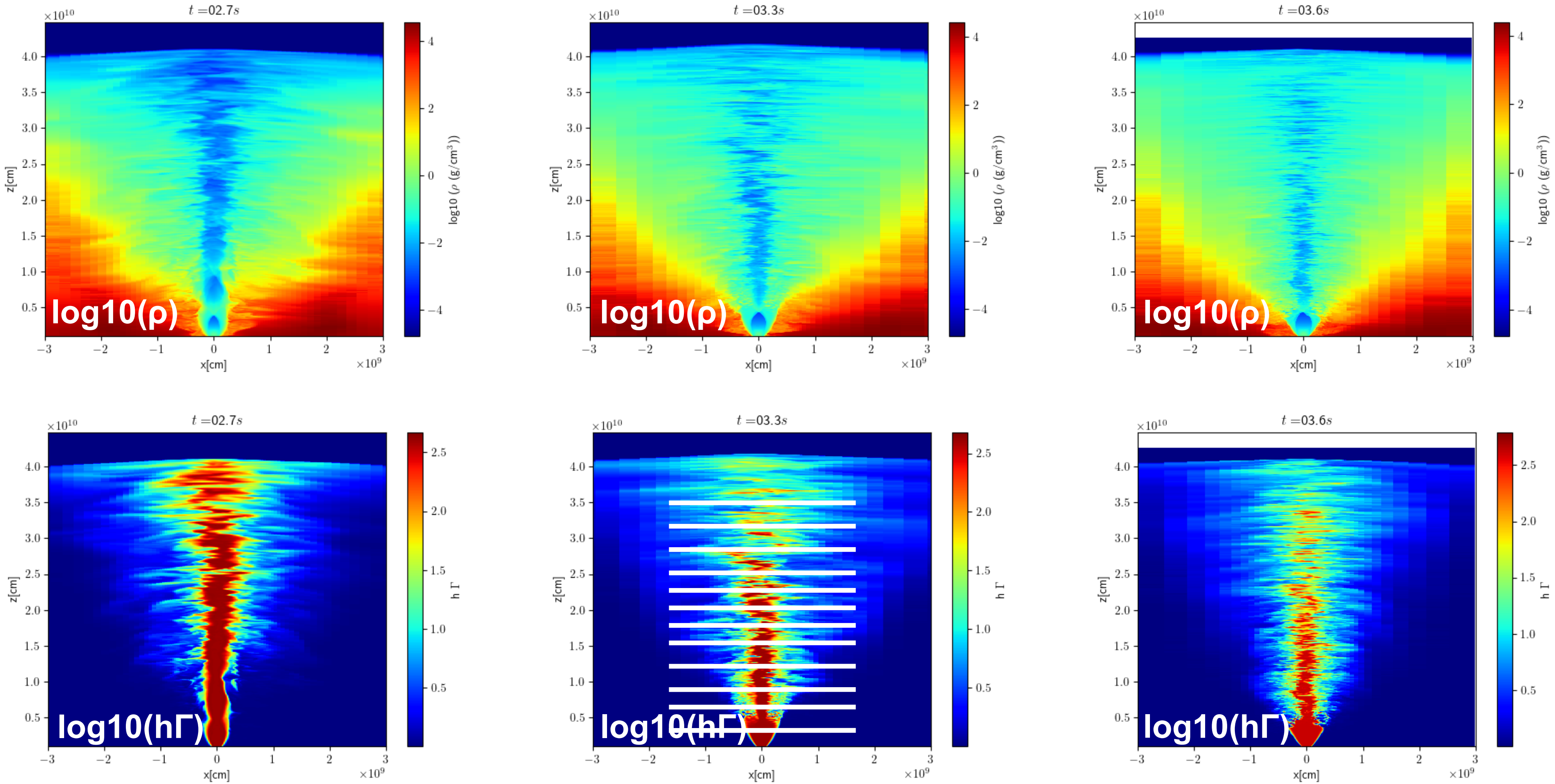
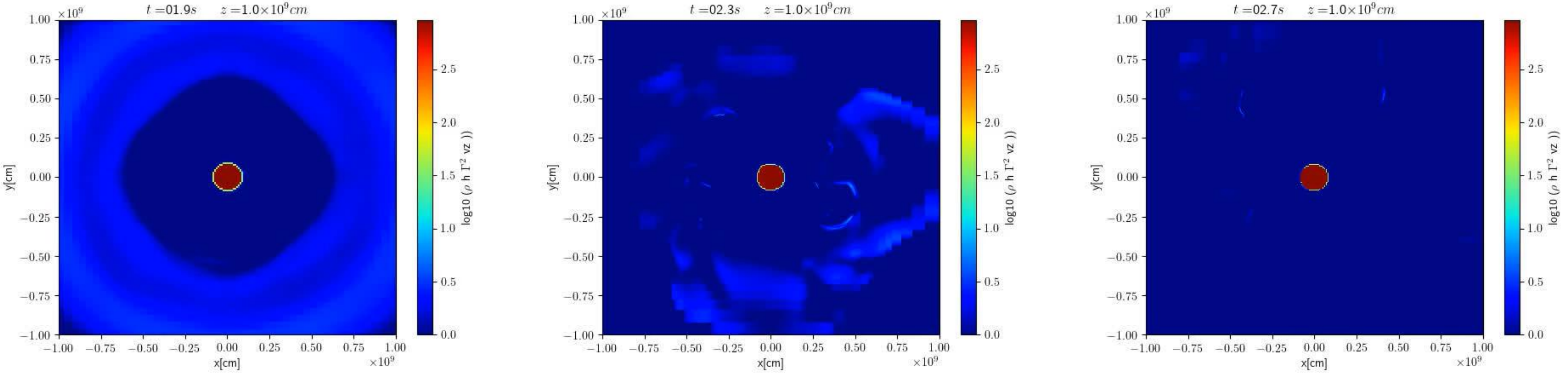


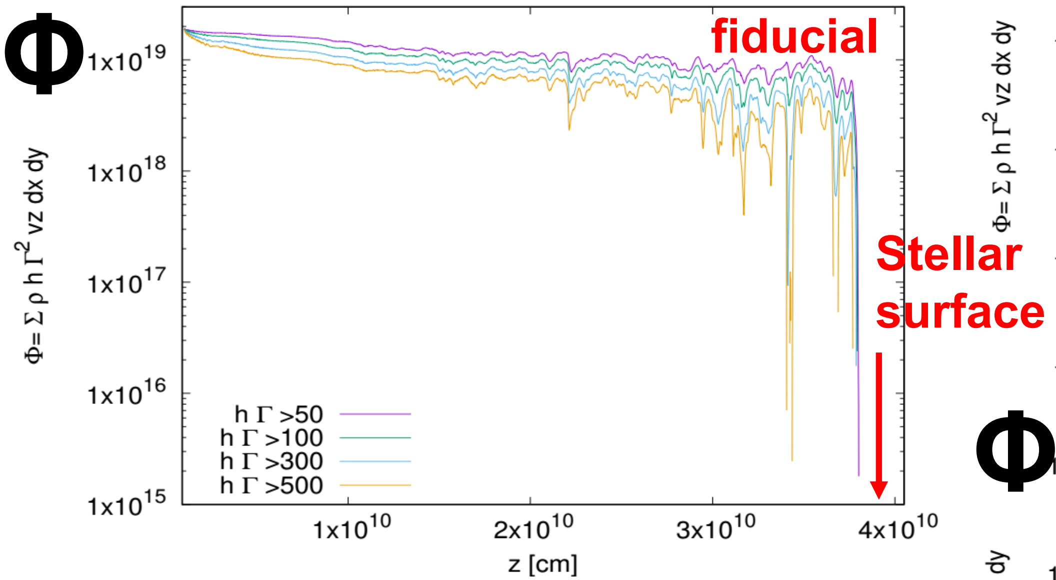
Growth of Hydrodynamic instability & Resolution effect

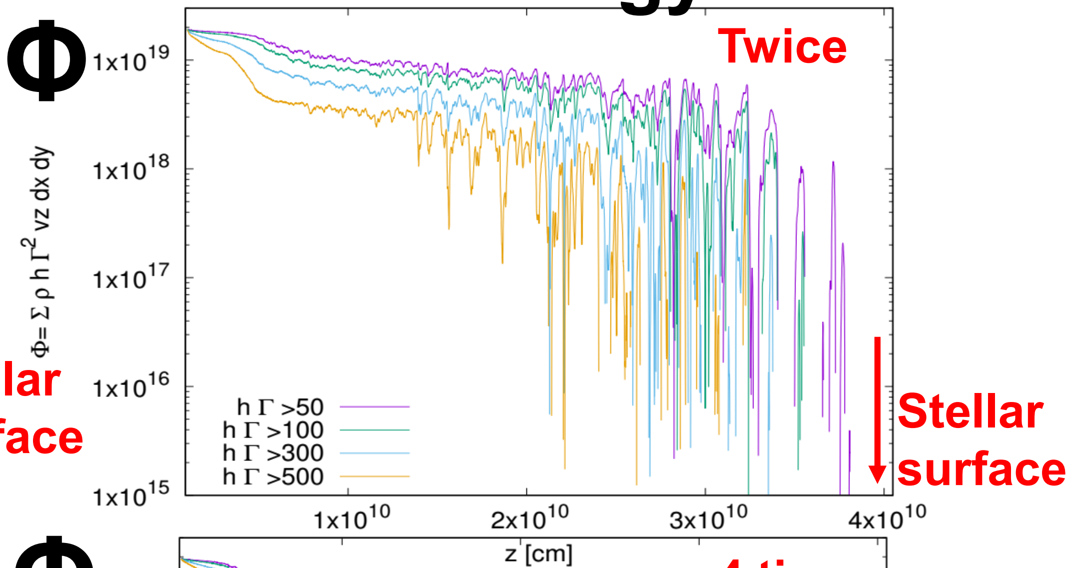
fiducial **twice** **4-times**

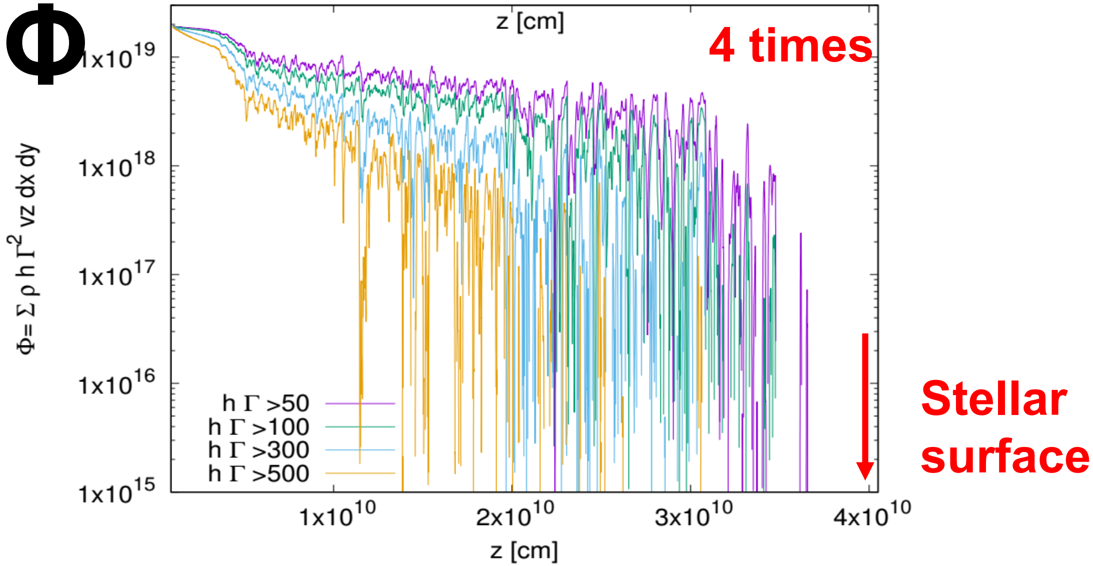


- Hydrodynamic instabilities grow up in all models.
  - Higher order modes are resolved in higher resolution models.
  - Higher order mode (short wave length perturbation) of Rayleigh-Taylor instability can grow up faster than lower mode.
  - Nonlinear evolution of the growth of instabilities are observed 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.

Resolution affects how much kinetic energy reaches the jet head







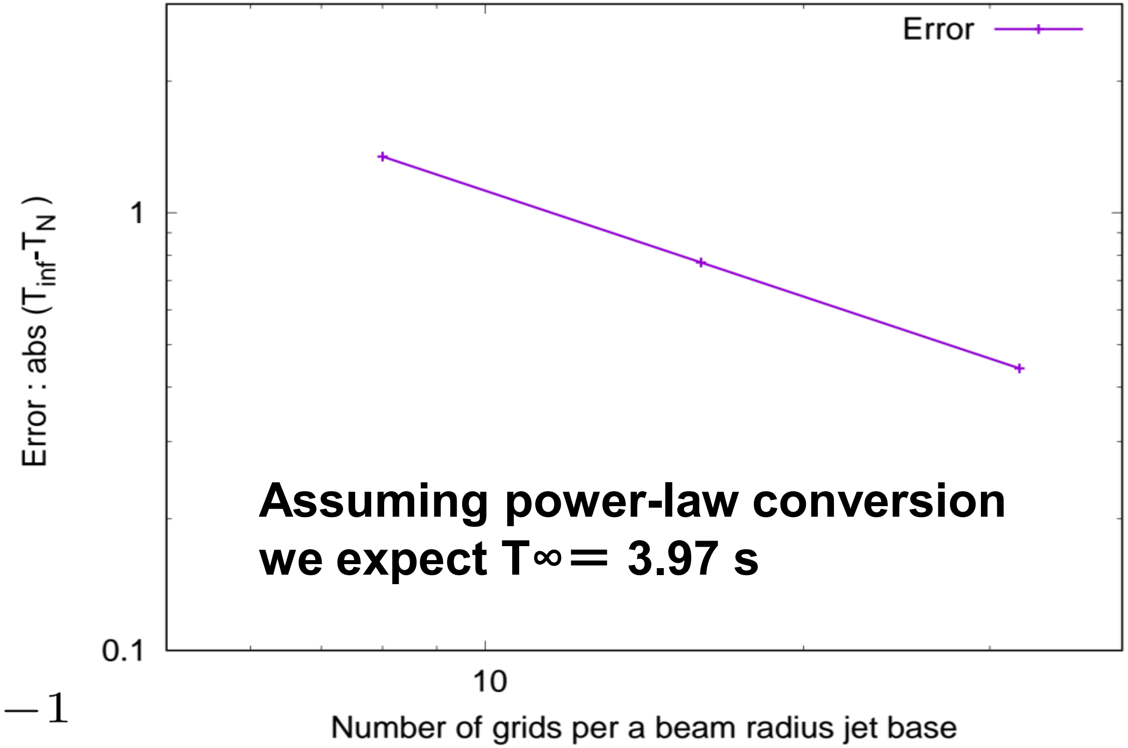
$$\Phi(z;A) = \int_{v_z>0,\, h\Gamma>A} \rho h \Gamma^2 v_z \, dx\, dy$$

More fluctuation → stronger mixing

Higher resolution → less energy reaches the head

Dicussion：Can real hydro jet penetorate the progenitor star ?

・Time for shock breakout
Fiducial model : t_br =2.7s
Twice model : t_br =3.3s
4 times model : t_br =3.6s
. : .
. : .
N(inf) : t= ?



We assume this relation holds

$$t_{\rm br}(N) = t_{\rm br,\infty} + C\,N^{-1}$$

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

Conclusion

- We developed a new 3D SRHD code, *SkyMirror*, and performed high-resolution 3D jet simulations.
- Higher resolution resolves short-wavelength hydrodynamic instabilities, leading to nonlinear mixing in the cocoon.
- Enhanced mixing reduces the efficiency of jet propagation and delays shock breakout.
- Even without strict convergence, realistic breakout times (~4 s) are expected.