Opening angle of GRB jet

$\theta_j \sim C x \Gamma_0^{-1}$ (C~1/5)

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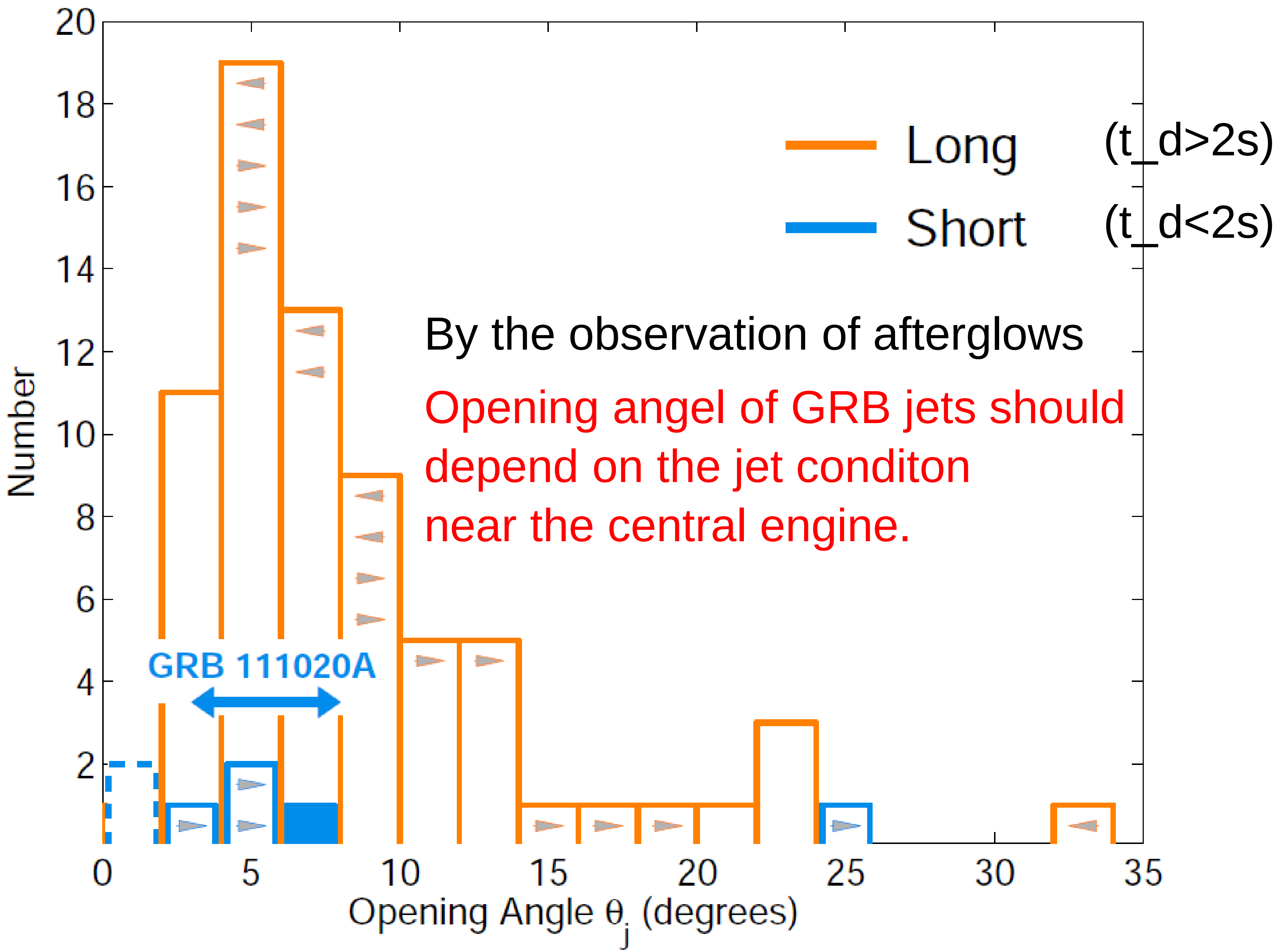
Distribution of opening angle of GRB jets

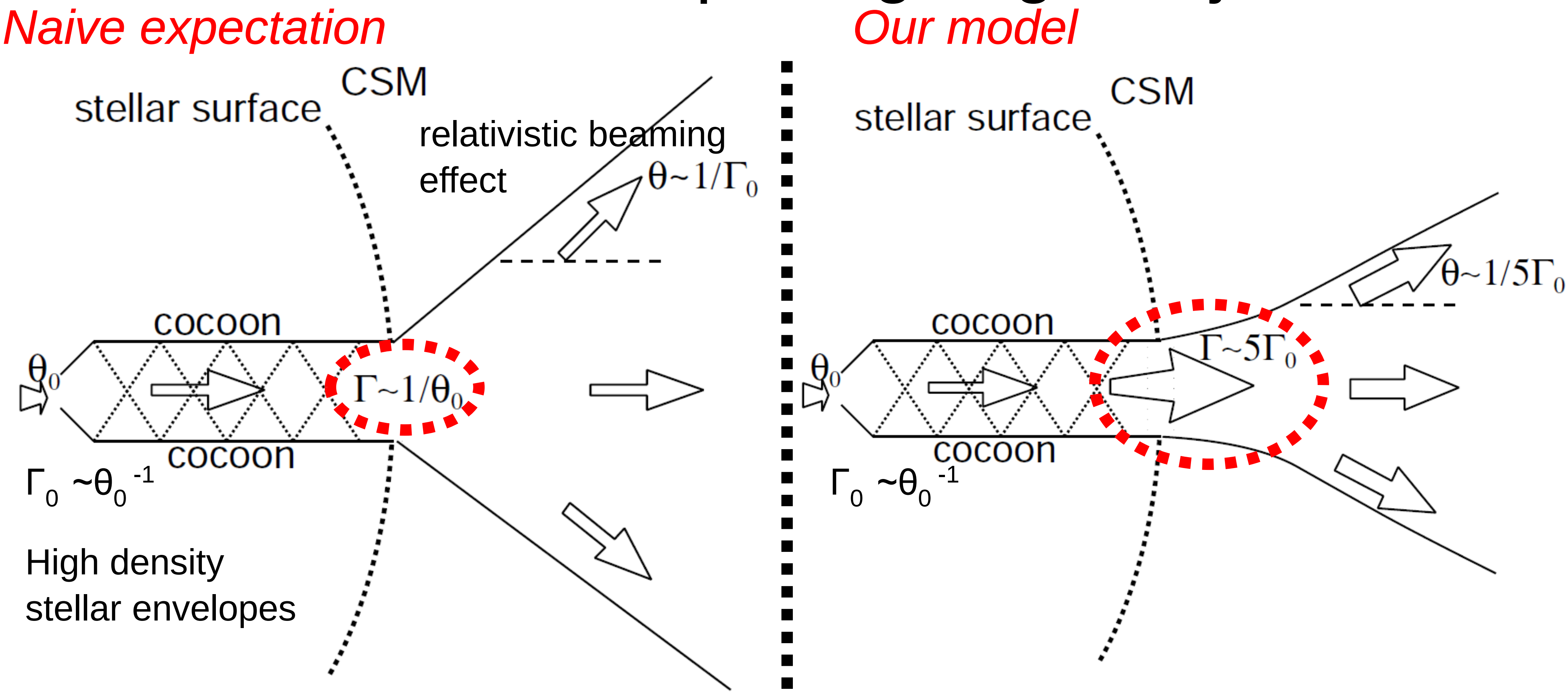


By the observation of afterglows

Opening angel of GRB jets should depend on the jet conditon near the central engine.

Fong et al. (2012)

What determines opening angel of jets ?



For the jet from collapsars, the jet is influenced by the interaction with stellar envelopes.

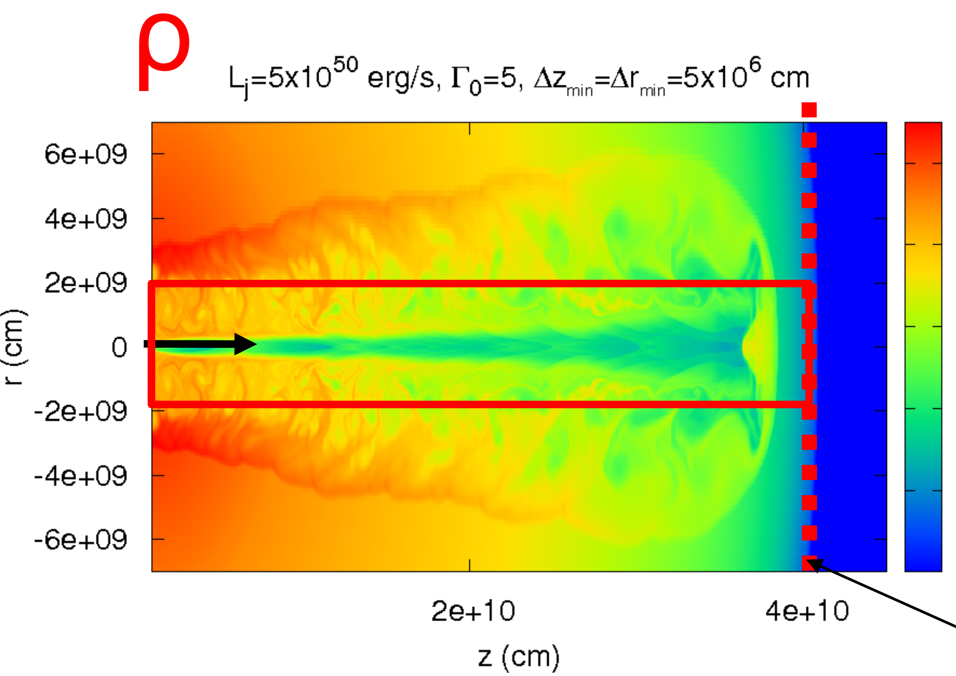
Before shock break , the jet is not well accelerated (Γ~O(10)).

Numerical simulations by Aloy et al(‘00),Zhang et al.(‘03,’04), Mizuta et al.(‘06,’09), Lazzati et al. (‘09), Nagakura et al.(‘11)

Analytic work by Bromberg et al. (2011)

How about after shock break ?

High resolution 2D relativistic hydro. simulations



E_j=5x10^{50}erg/s, r=8x10^{7}cm

$\Gamma_\infty = h_0 \Gamma_0$ =533

Γ_0=2.5, 5, 10

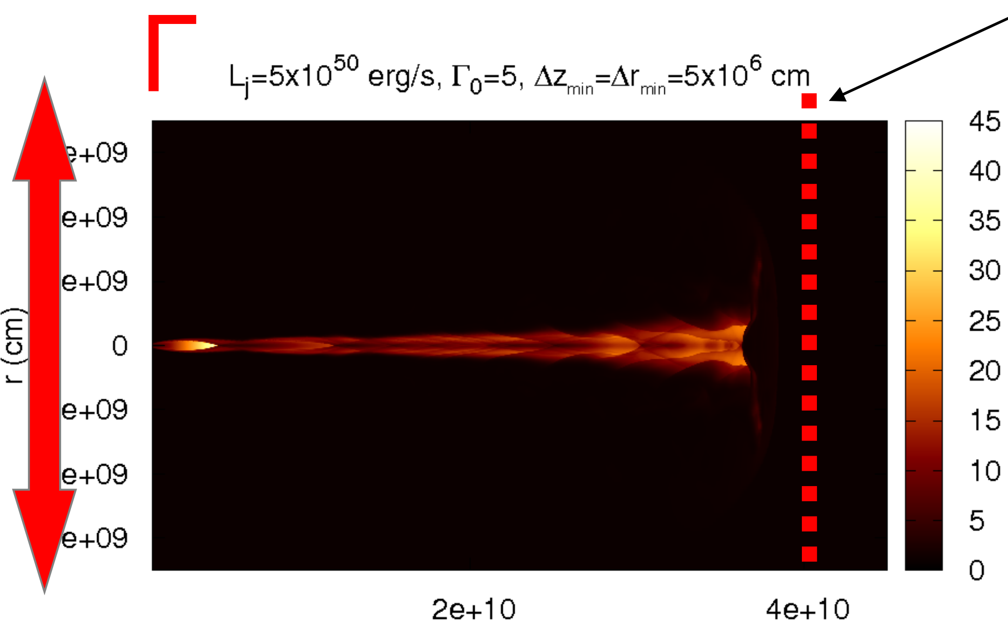
Progenitor : Woosley & Heger(2006)

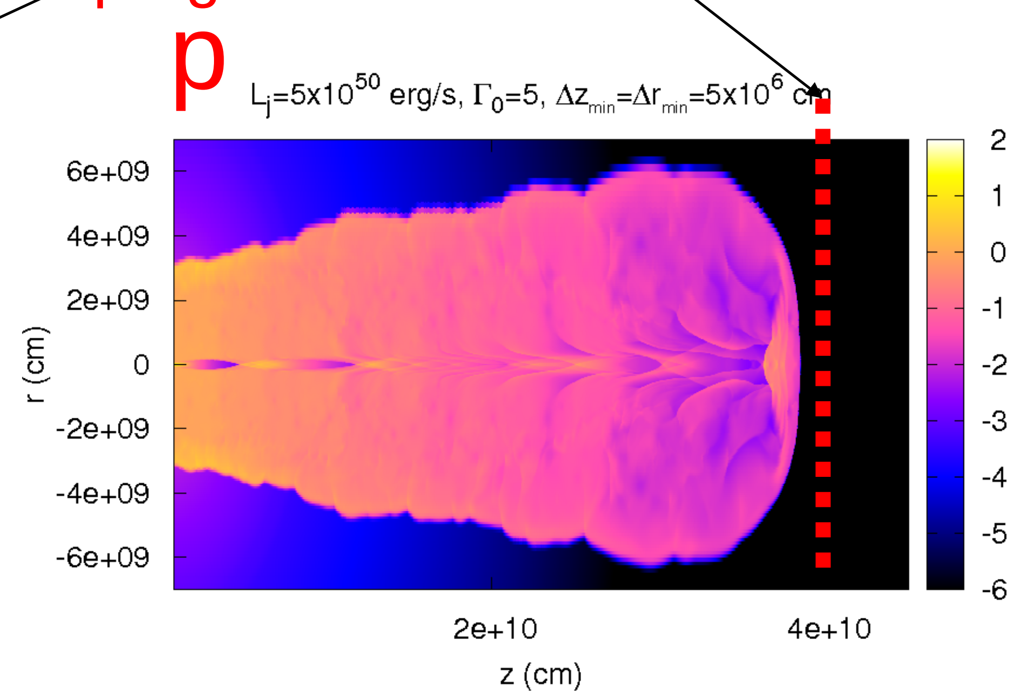
M~14M_{sun}, R*=4x10^{10}cm

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

(Δz_{min}=Δr_{min}=10^{7}cm / Δz_{min}=Δr_{min}=5x10^{6}cm)

progenitor surface



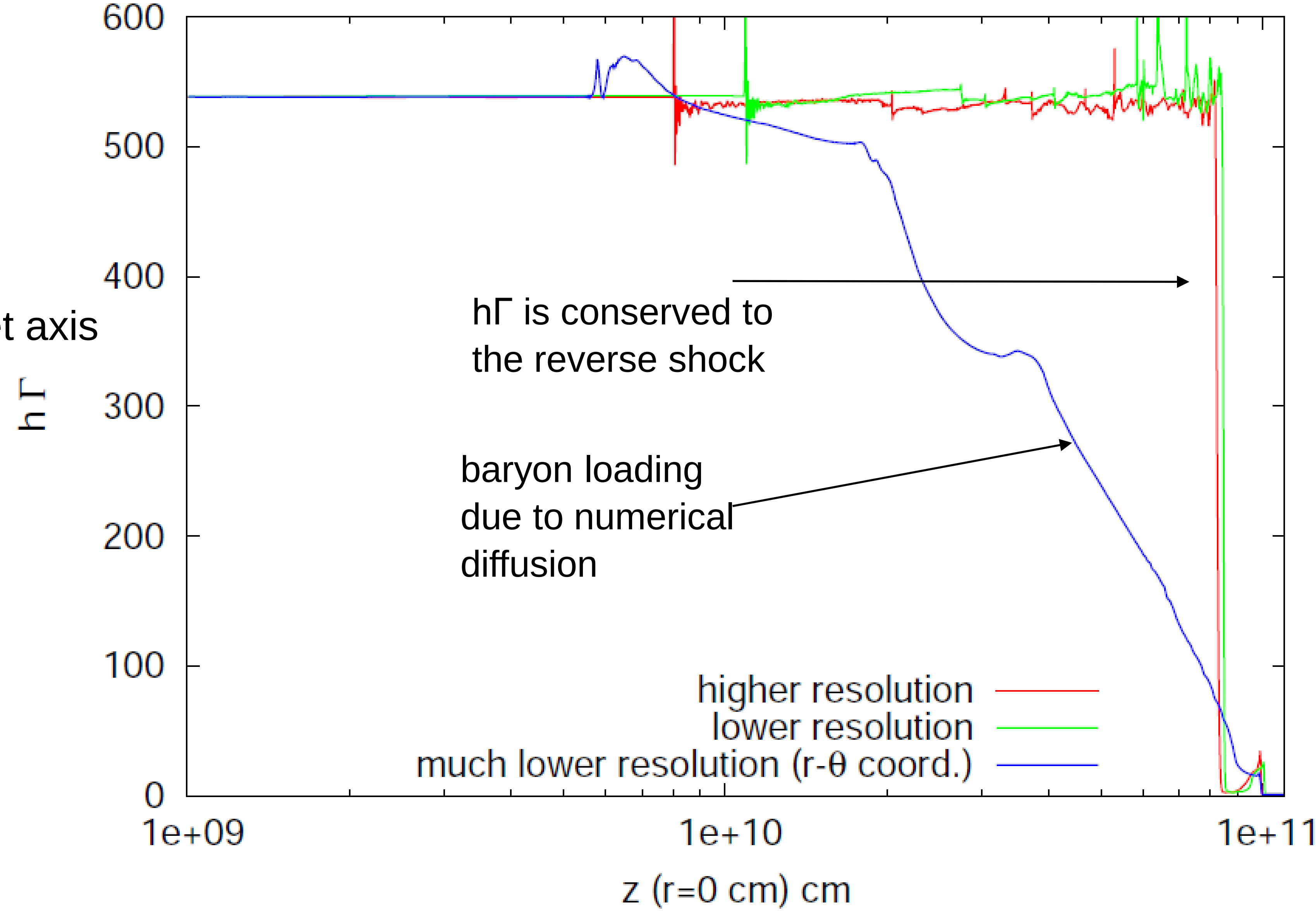


Elongated : Aspect ratio is not correct

Why is high resolution necessary ?

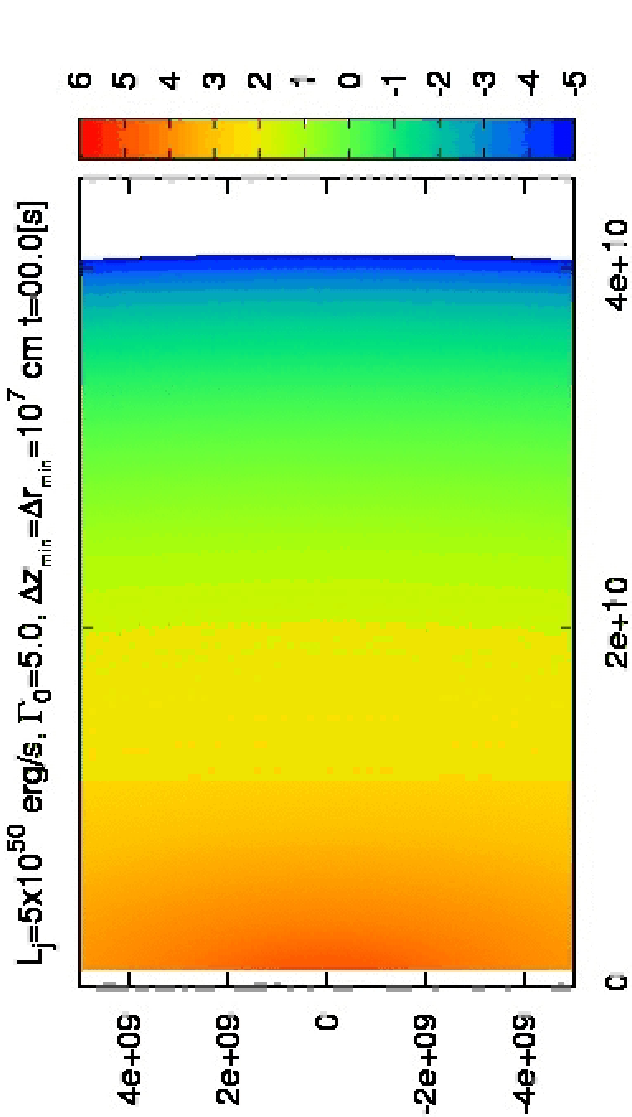
hΓ (=const along stream line, steady state :Bernoulli's principle)

Along jet axis

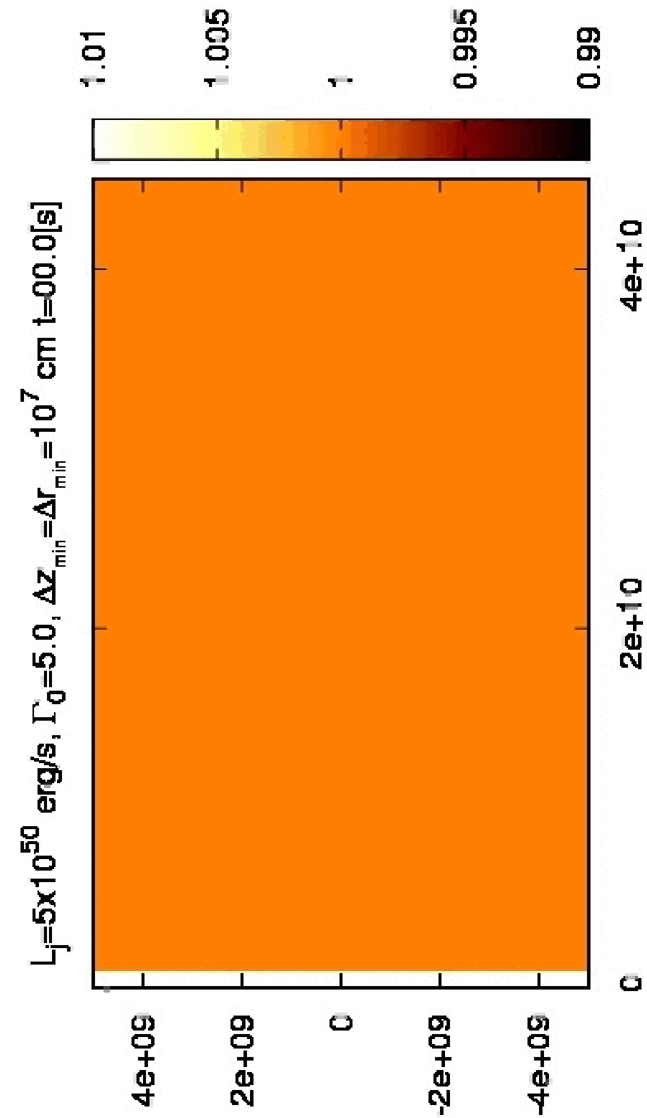


Γ_0=5

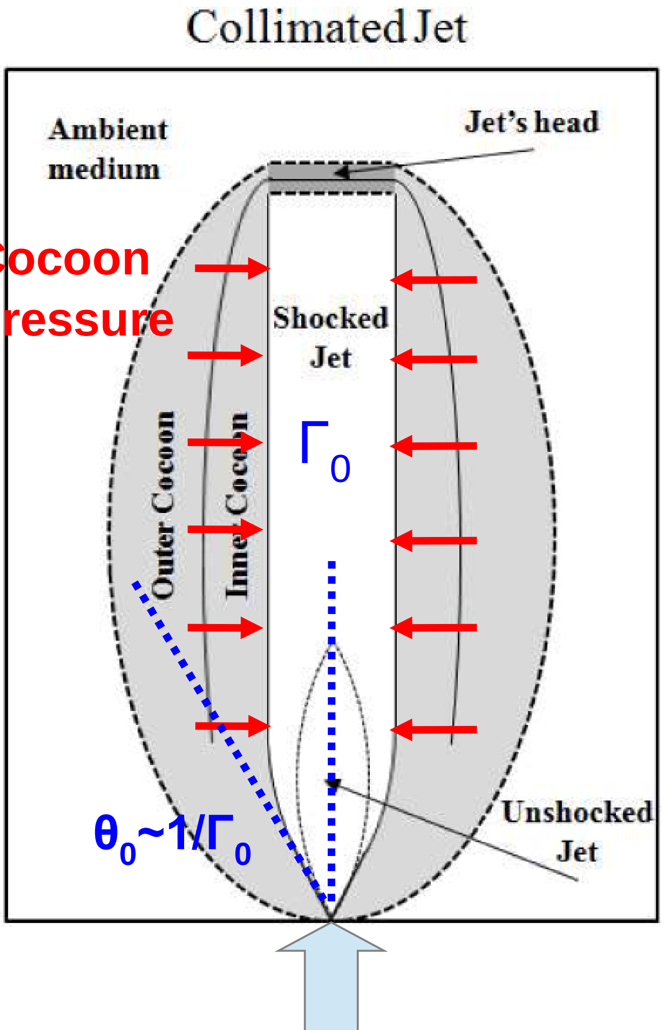
mass density



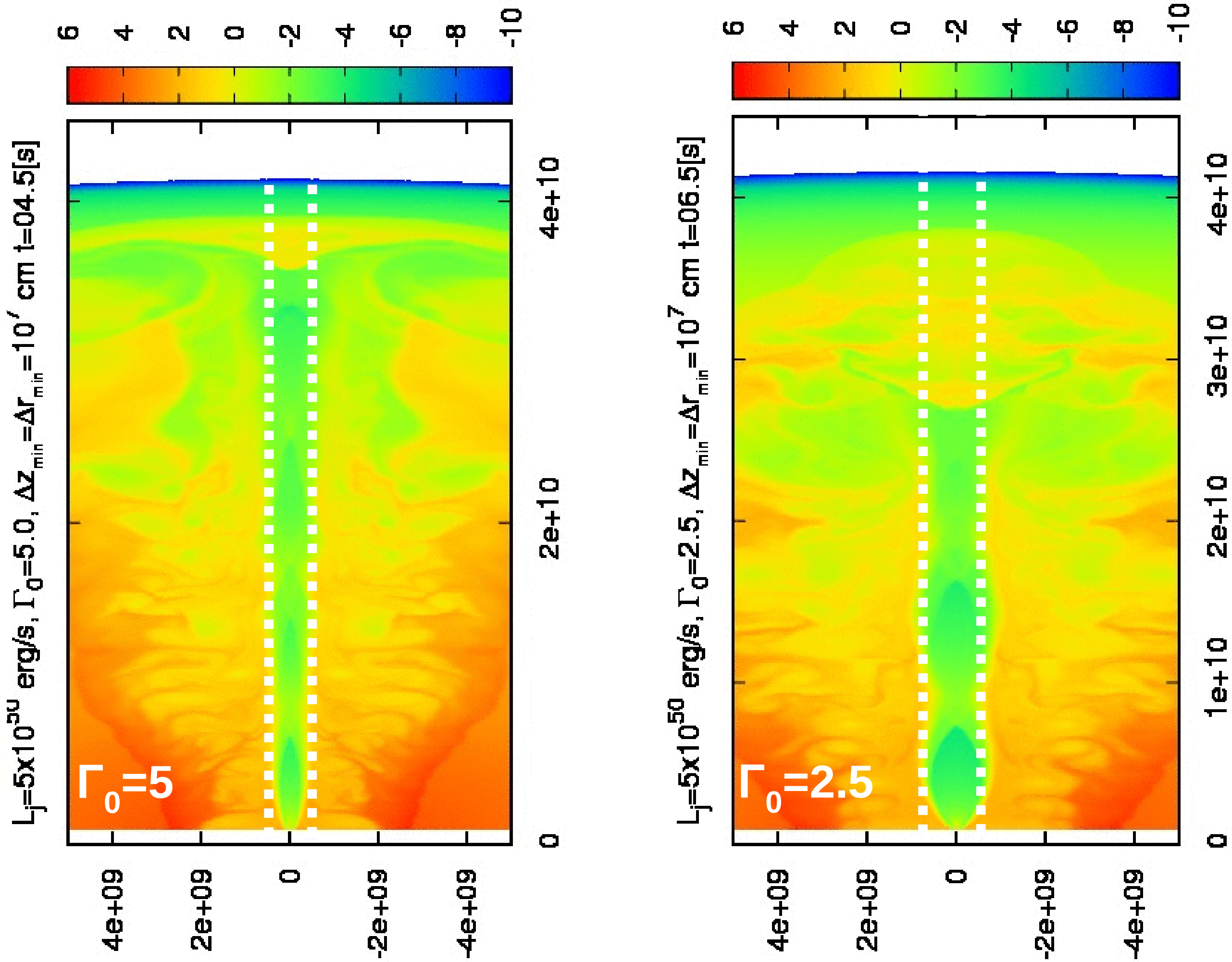
Lorentz factor



Cocoon confinement (Before break)



jet injection

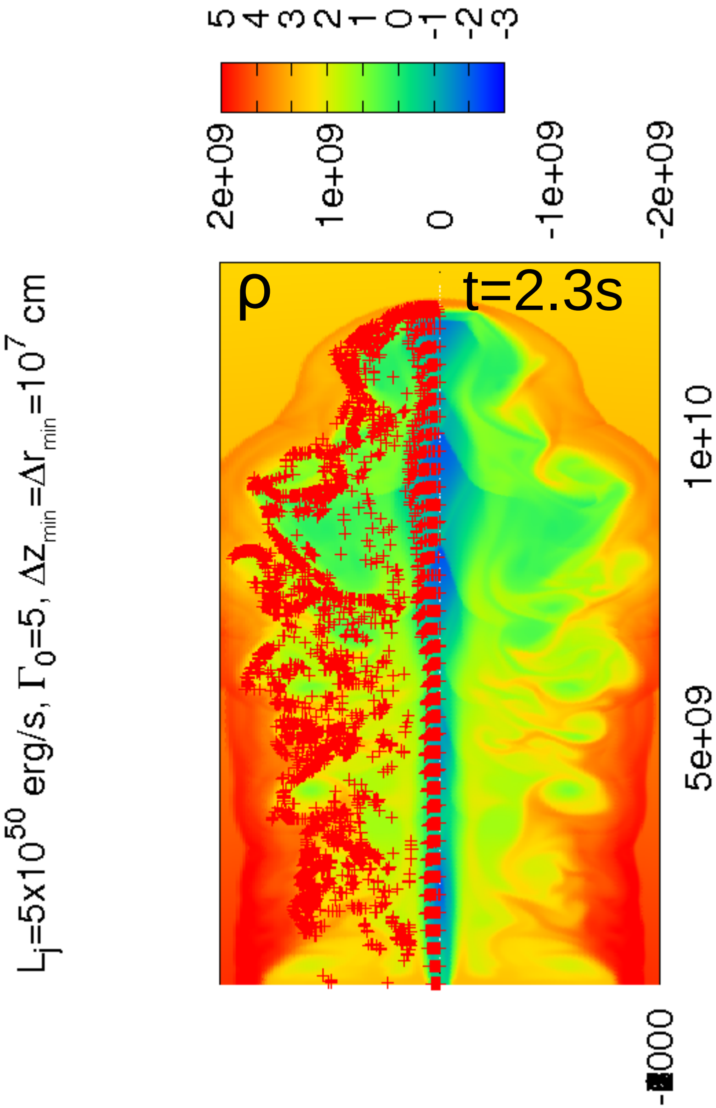


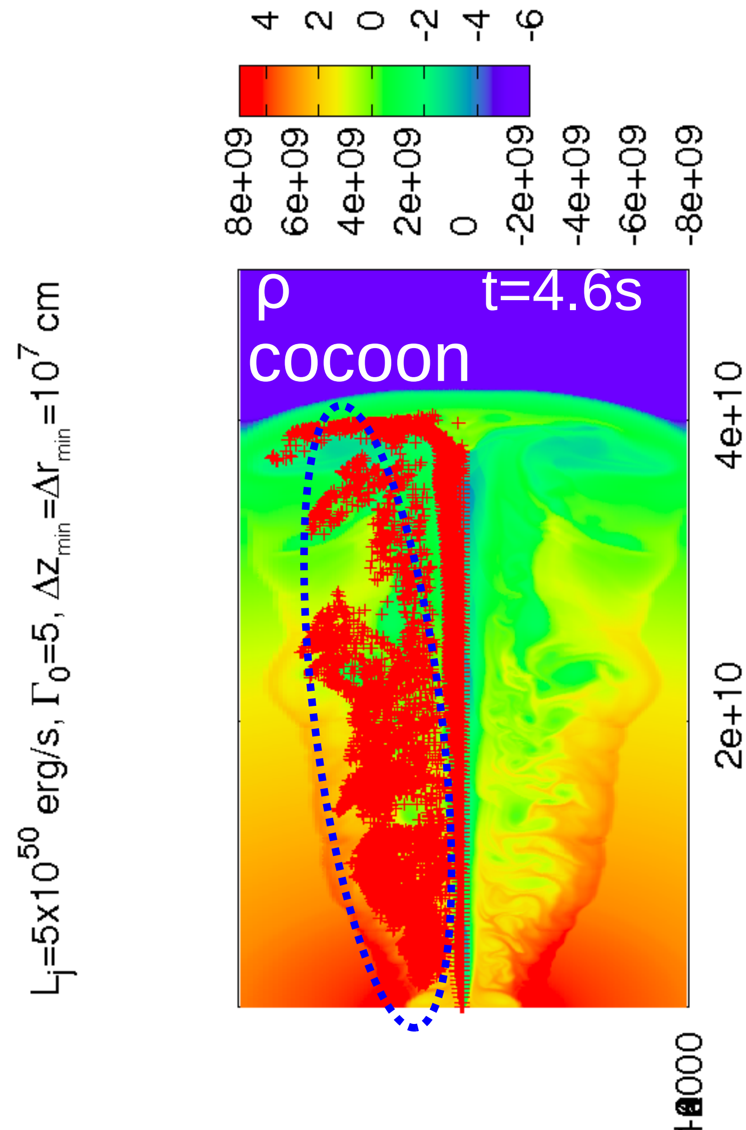
Bromberg + (2011)
collimation shock
+
Cylindrical jet ($\Gamma \sim \Gamma_0$)

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

See also Komissarov & Falle 1998

Probe particles

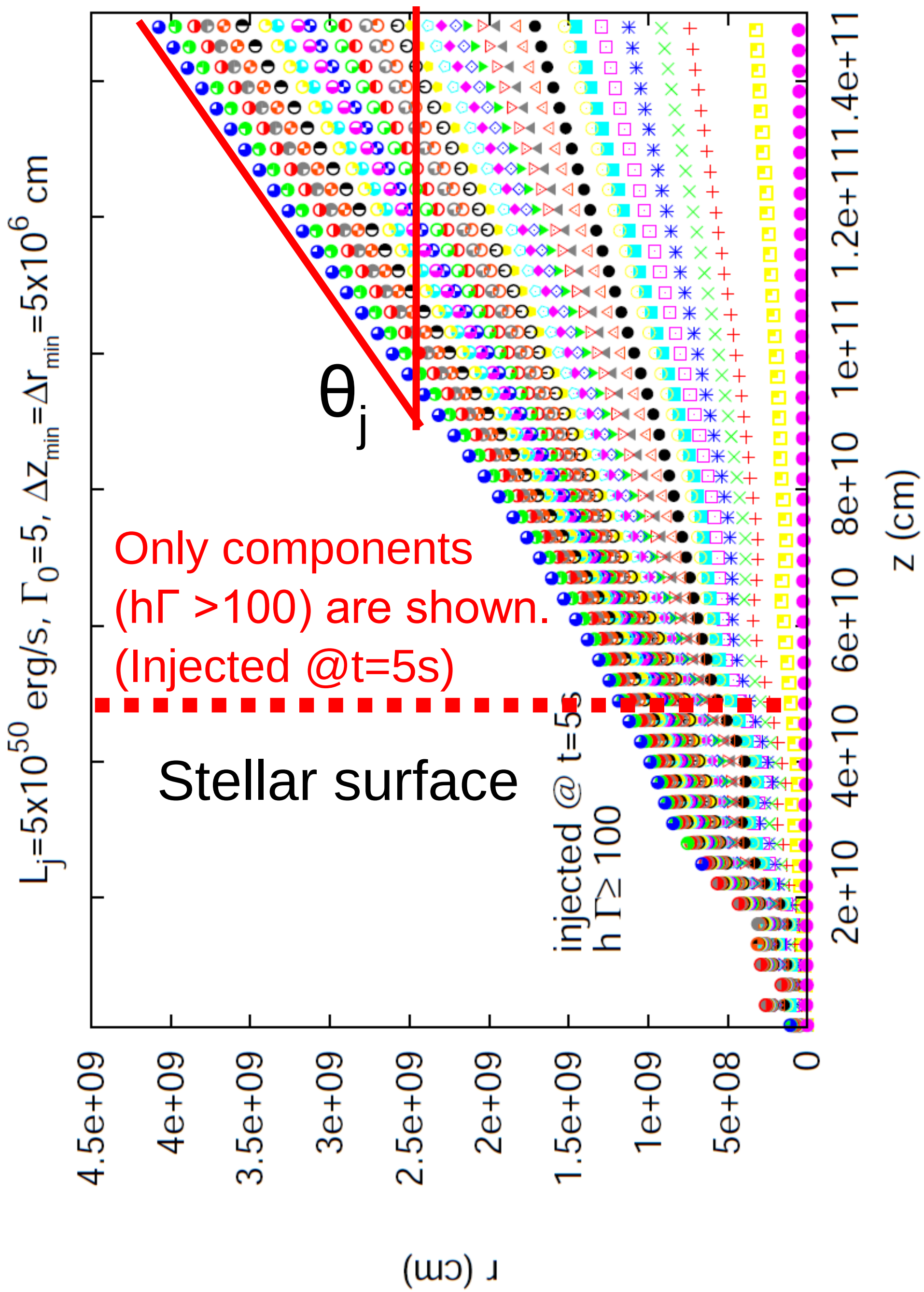




Every 0.01s, 32 particles are injected with the jet

particle trace $\boldsymbol{x}_{new}=\boldsymbol{x}_{old}+\boldsymbol{v}_{r,z}\times\Delta t$

Particle traces (injected at t=5 s together but different r)



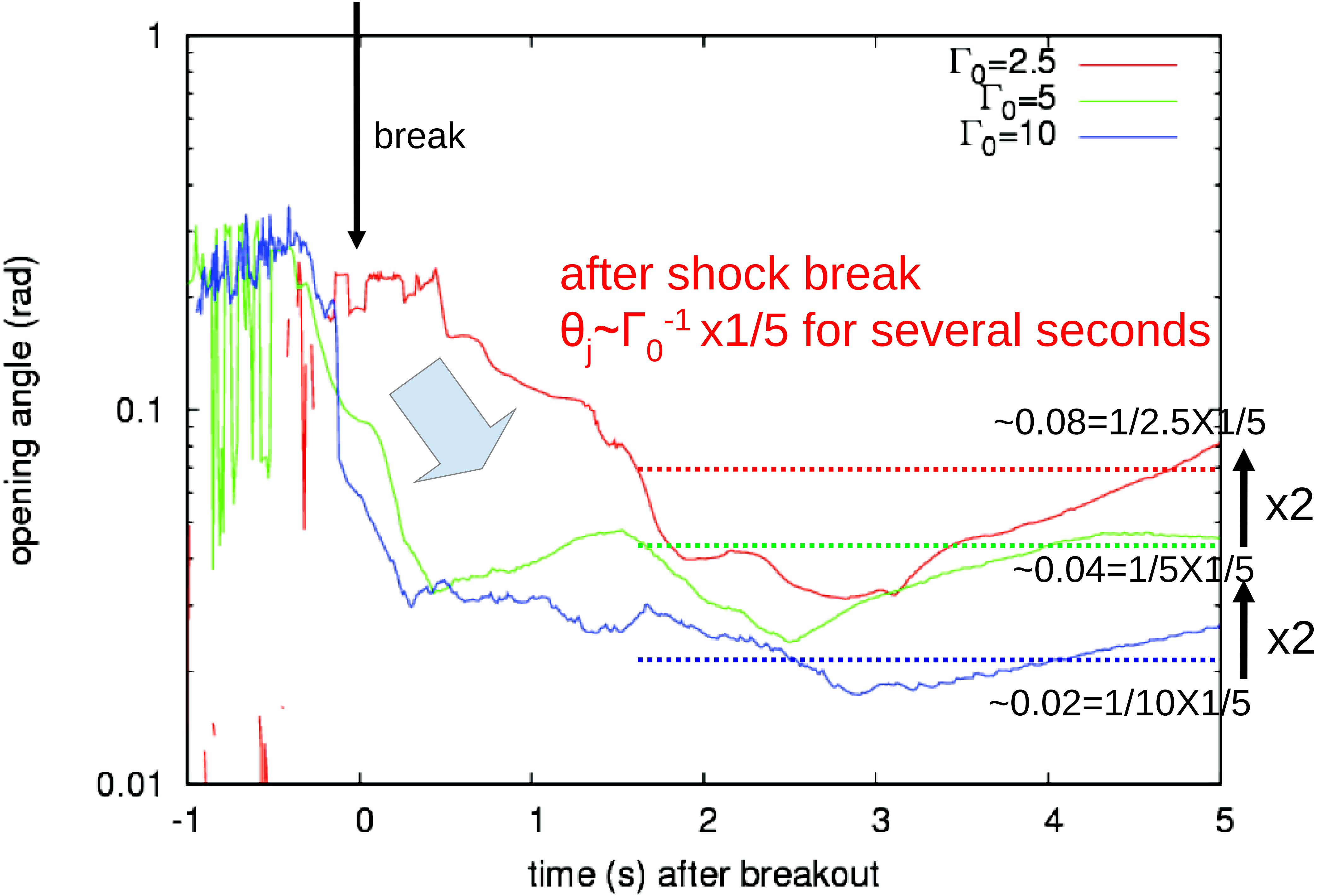
Probe particles allow us to follow Lagrange motion of the gas.

Particle path is bent, when particle crosses the shock.

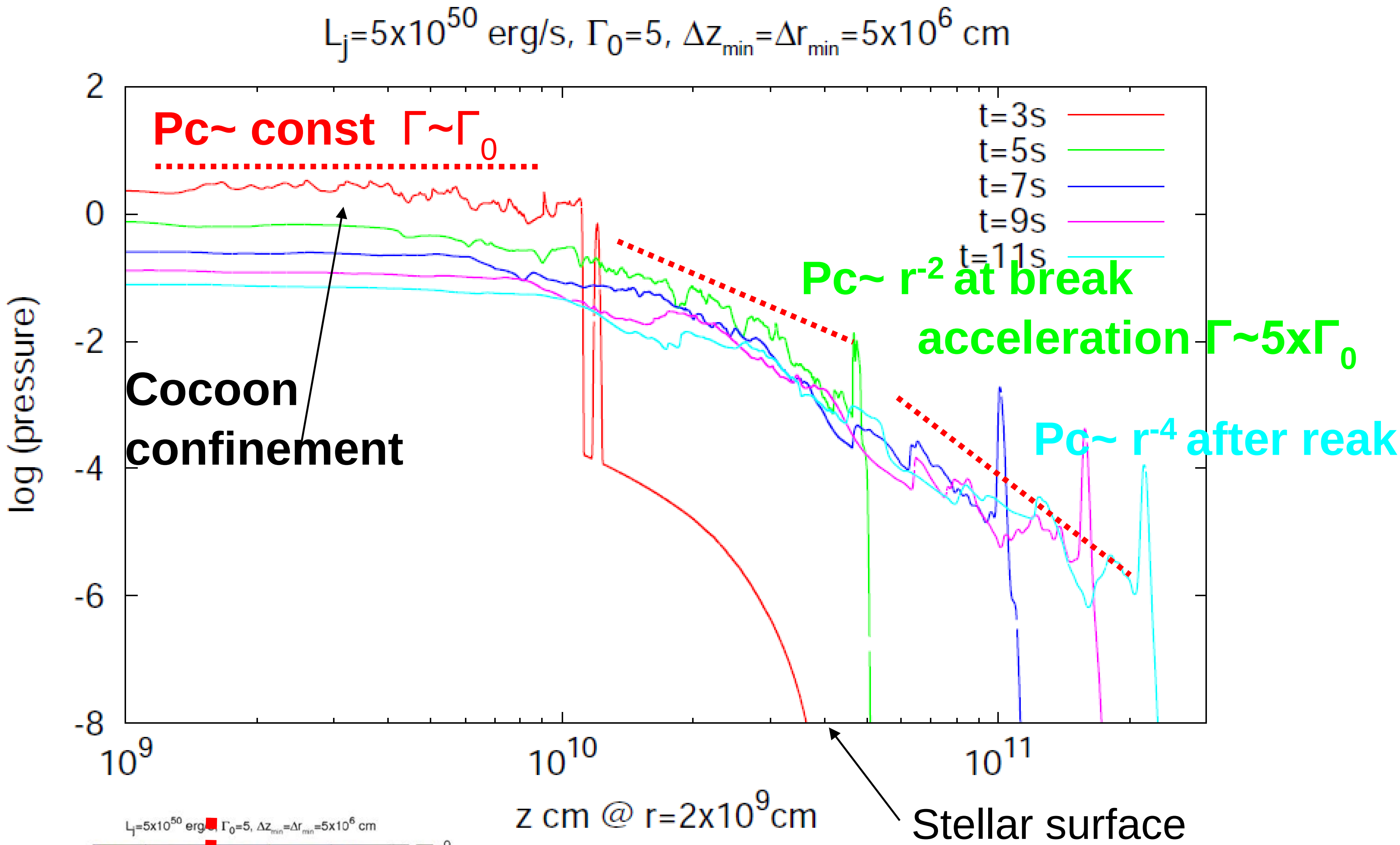
Each particle path is straight line at z>8e10cm.

Opening angle of the jet is defined as the most outer particle path.

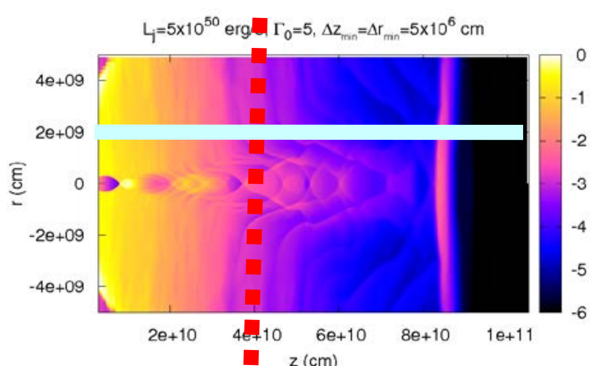
Time evolution of jet opening angles



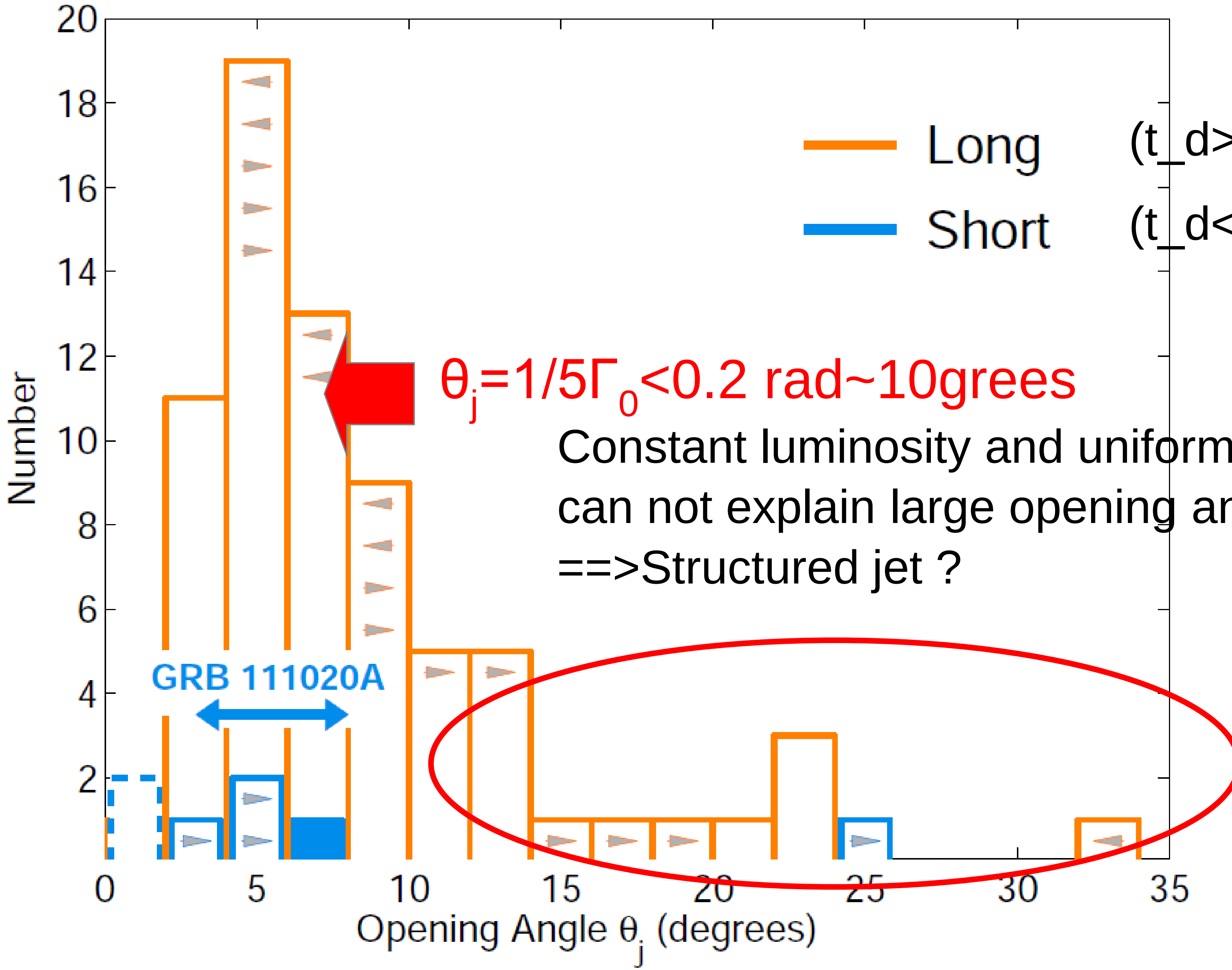
1D Pressure profile in the cocoon



p



Distribution of opening angle of GRB jets



$\theta_j = 1/5\Gamma_0 < 0.2$ rad~10grees

Constant luminosity and uniform jet
can not explain large opening angle jets
==>Structured jet ?

Fong et al. (2012)

Conclusion

- High resolution calculation of jet from collapsars have been done to avoid numerical baryon loading

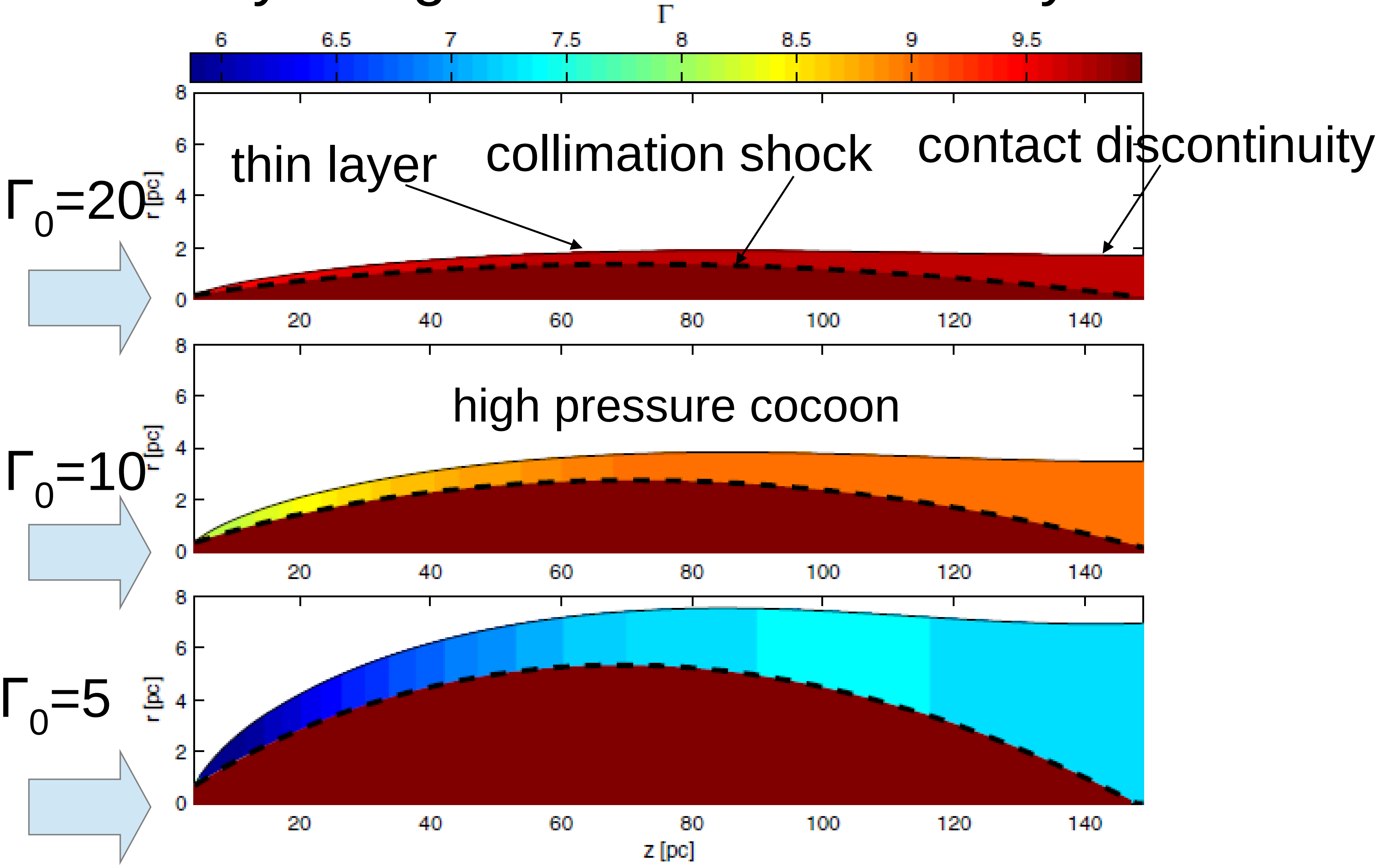
- Pressure drops in the cocoon just before the break due to exponential drop of the progenitor's mass density profile. Lorentz factor increases to about $5\times\Gamma_0$ at the break.

- The opening angle after the break for first several seconds

$$\theta_j \sim C \times \Gamma_0^{-1} \quad (C \sim 1/5)$$

- Structured jet is preferred for large opening angle jets. (ex. GRB120422A short duration, low luminosity)

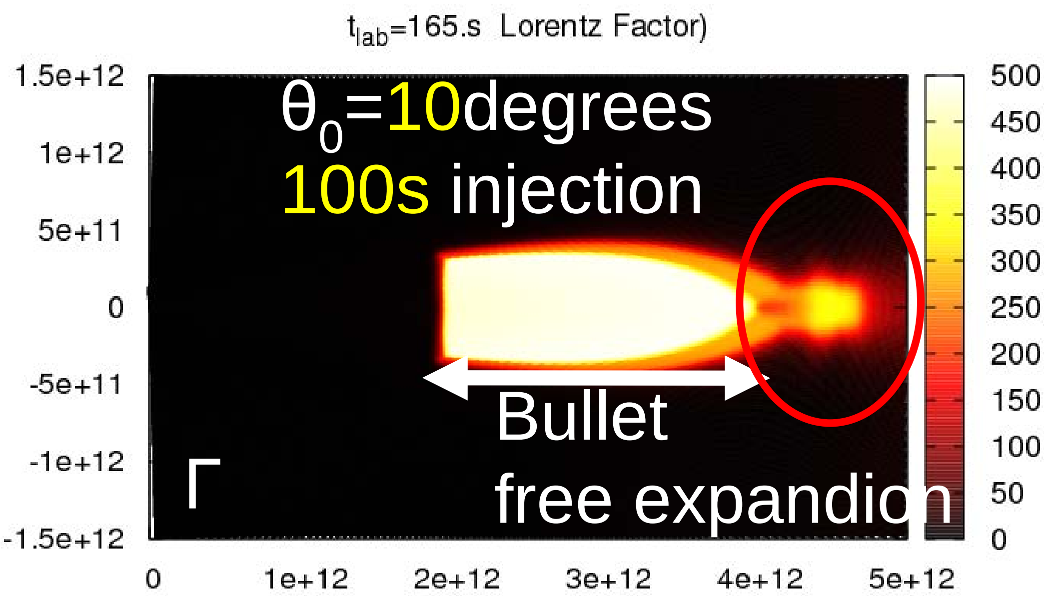
Why is high resolution necessary ?

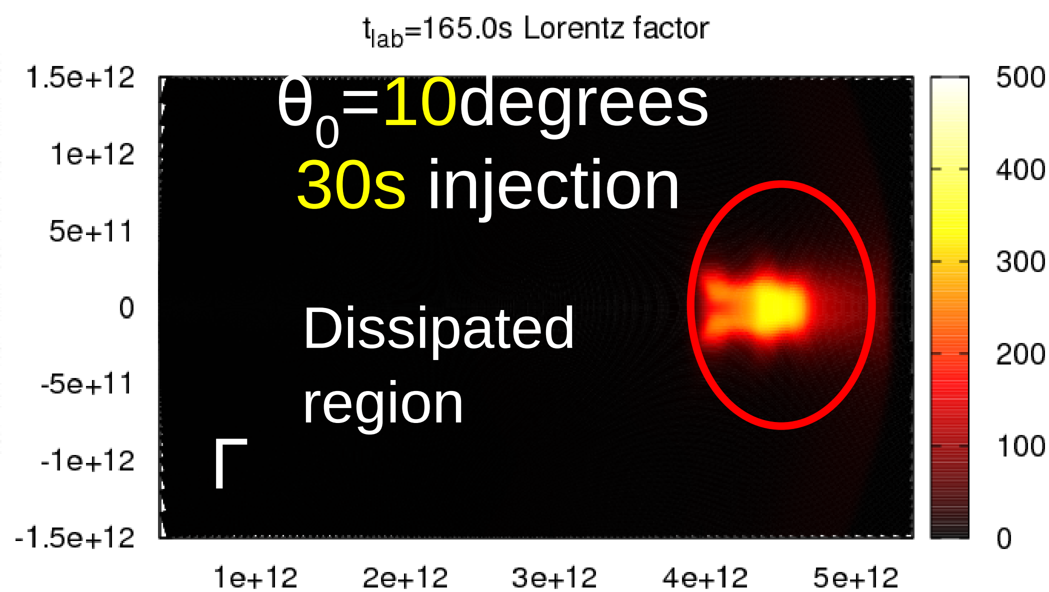


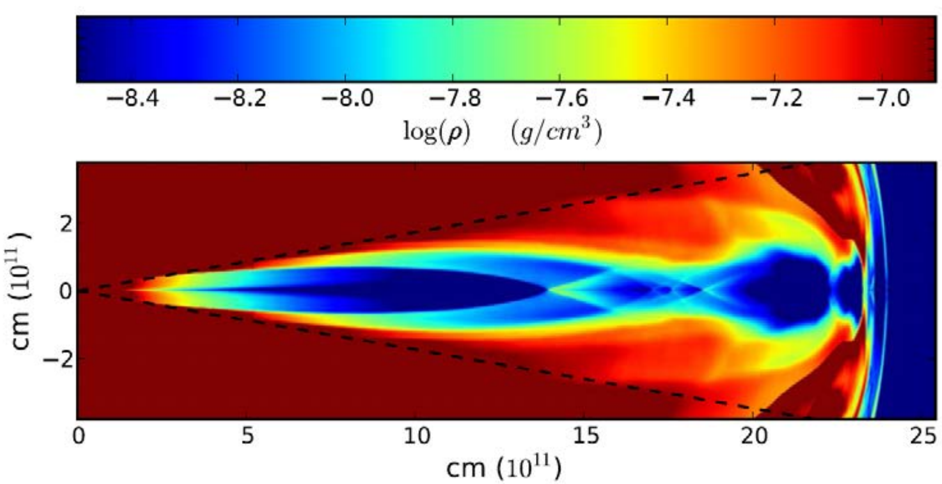
$\theta_0=1/\Gamma_0$

Bromberg, Levinson (2009)

Numerical simulations of GRB jet from Collapsar







Lazzati et al. (2009)

Collapsar からのGRB Jet のシミュレーション

複雑な構造をしたジェット先端

＋

自由膨張をする部分

解析解 Bromberg 2011との比較 (4)

周りの密度ρ$_a$が z の関数の場合数値的に求める $\rho_a = \rho_0 (z_h/z_0)^{-\alpha}$

ジェット先端の位置

$$z_h \approx \xi_h \beta_h c t \simeq \left(\frac{t^3 L_j}{\rho_a \theta_0^4} \right)^{1/5} \left(\frac{16}{3\pi} \frac{\eta \xi_a \xi_h^4}{\xi_c^2} \right)^{1/5}$$

Collimation shock が閉じる位置

$$\hat{z} \simeq \left(\frac{t^4 L_j^3}{c^5 \rho_a^3 \theta_0^2} \right)^{1/10} \left(\frac{6}{\pi^{3/2}} \frac{\xi_h \xi_c^2}{\eta \xi_a} \right)^{1/5}$$

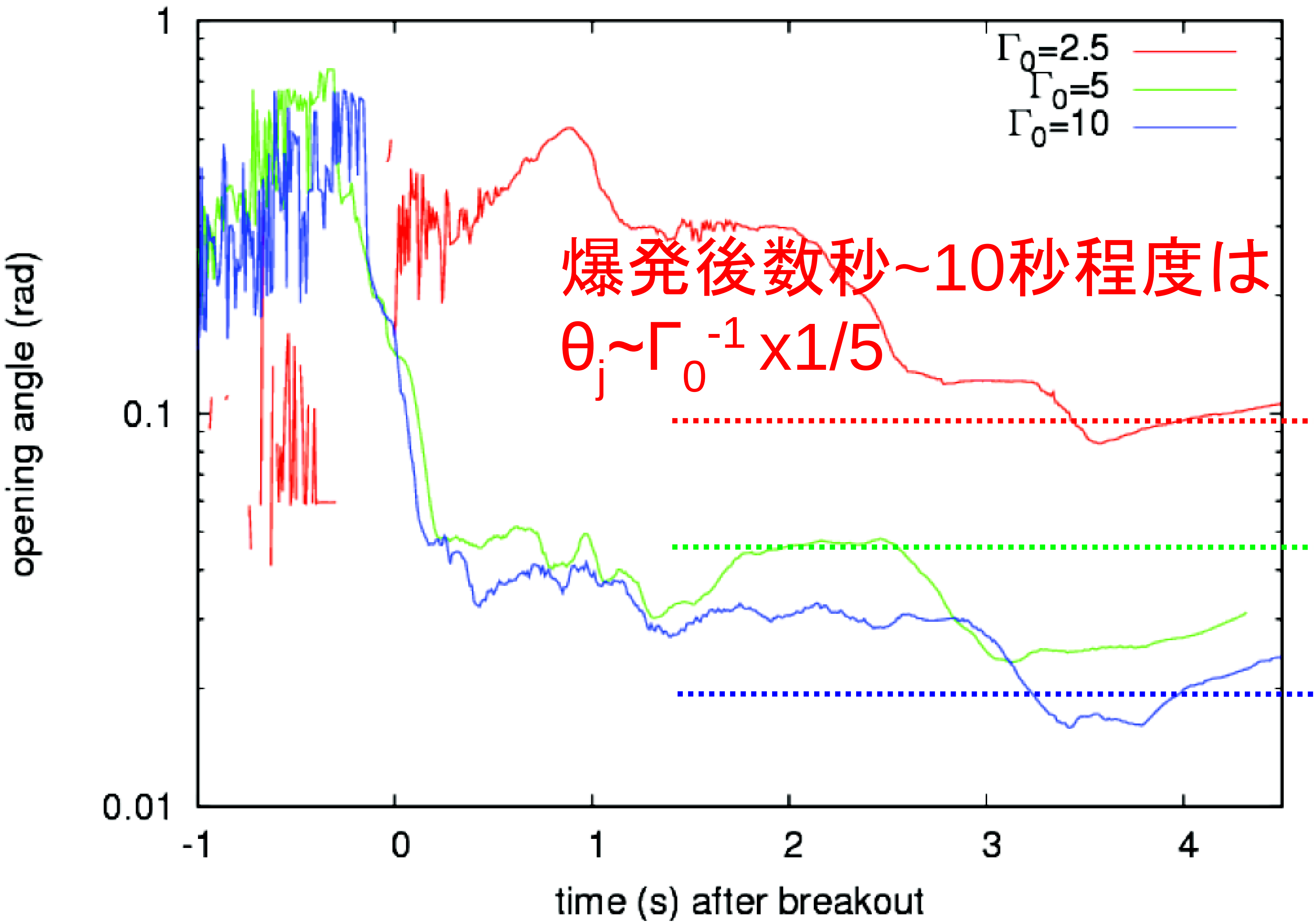
Collimation shock の最大の半径
〜 collimation shock 後のジェット半径

$$r_j \equiv \left(\frac{\Sigma_j}{\pi} \right)^{1/2} \simeq \left(\frac{t^4 L_j^3 \theta_0^8}{c^5 \rho_a^3} \right)^{1/10} \left(\frac{3}{16\pi^{3/2}} \frac{\xi_h \xi_c^2}{\eta \xi_a} \right)^{1/5}$$

$$\xi_h = \xi_c = \frac{5-\alpha}{3}, \; \xi_a = \frac{3}{3-\alpha}$$

$$\rho_a = \rho_0 (z_h/z_0)^{-\alpha}$$

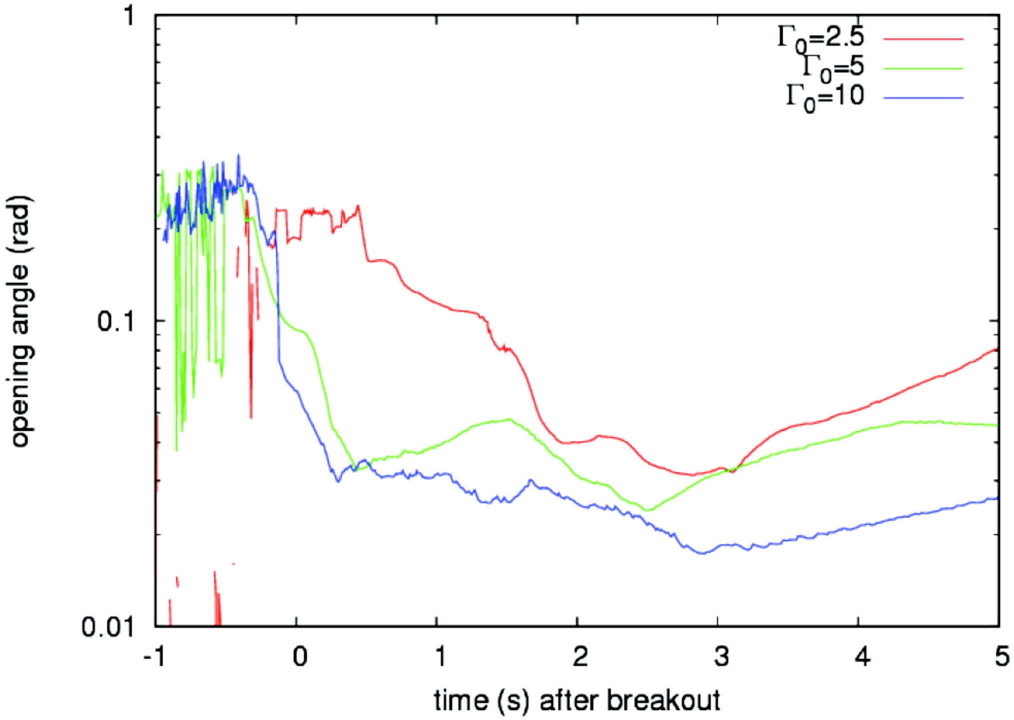
ジェットの開き角(高解像度)



GRB 120422A/SN 2012bz(Ic型)

(Zhang+, Melandri+2012,Levesque+2012)

z=0.283, E_iso~4.5x10^{49}erg, T90~5s



Wide jet==>

Short ,low-luminosity GRB associate with supernova ?

$$\Gamma \leqslant 6.5 \left(\frac{\epsilon_e}{0.01}\right)^{-0.21} \left(\frac{\epsilon_B}{0.01}\right)^{0.18}$$

Zhang+2012

$$r_s = \theta_0 z\,(1 + A z_*) - A\theta_0 z^2, \quad A \equiv \sqrt{\frac{\pi c P_c}{L_j \beta_{j0}}}$$

内部衝撃波が再び軸にぶつかる z は rs=0 を解いて

$$\hat{z} = A^{-1} + z_*$$

$r_s = zq_0$ とすると、z=z* : ジェットとコクーンの相互作用が始まり、Collimation shock が初めて生じる z

$$z_* = \max\{R_*, z(P_{j0} = P_c)\}$$

R*: injection 半径

$$z_* < A^{-1} \qquad L_j \geq 4\pi P_{j0}\Gamma_{j0}^2\beta_{j0} z_*^2\theta_0^2 c$$ を課すと

$$\Gamma_{j0}(z_*)\beta_{j0}(z_*) \gtrsim \theta_0^{-1}.$$

ジェット自身の横方向の膨張が無視できる条件: “sufficiently fast jet”

$z^* \ll A^{-1}$, $R^* \ll A^{-1}$ ならば $$\hat{z} = A^{-1}$$

z= $\hat{z}/2$ でrs はピークを持ち、それ以降は shocked gas は軸に平行流に

$$\Sigma_j(z > \hat{z}) \simeq \frac{1}{4}\pi\hat{z}^2\theta_0^2 \simeq \frac{L_j\theta_0^2}{4cP_c}. \qquad L_j \simeq 4P_c\Gamma_{j1}^2\Sigma_j c. \qquad \Gamma_{j1}(z > \hat{z}) = \frac{1}{\theta_0}$$