

Simulations of dynamics and emission from magnetized GRB ejecta

Petar Mimica

Departament d'Astronomia i Astrofísica, Universitat de València

Miguel Angel Aloy

Departament d'Astronomia i Astrofísica, Universitat de València

Dimitrios Giannios

Department of Astrophysical Sciences, Peyton Hall, Princeton

Buenos Aires, 29 October 2009

Outline

- **Introduction**

- magnetization and ejecta-medium interaction

- **RMHD numerical simulations**

- dynamics of ejecta deceleration
 - observational effects?

- **Summary**

Afterglow

- **Early afterglow**

- initial interaction of GRB ejecta with the external medium
- probe into ejecta properties (reverse shock)

- **Late afterglow**

- probe total ejecta energy and external medium properties
- shock propagating into the external medium

Ejecta-medium interaction

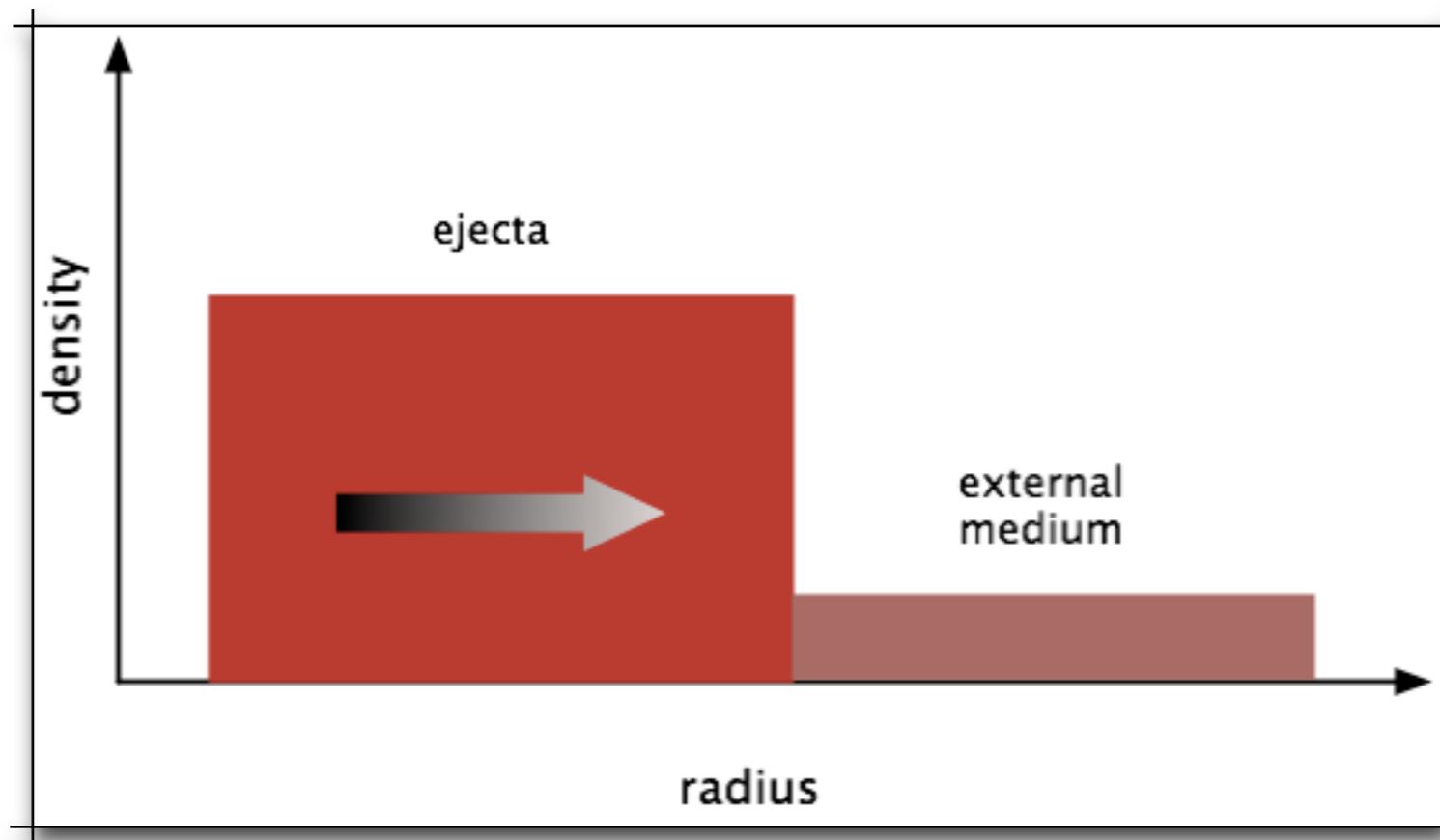
- ejecta at the onset of the afterglow:

- cold $P \ll \rho c^2$

- highly relativistic $\gamma \gg 1$

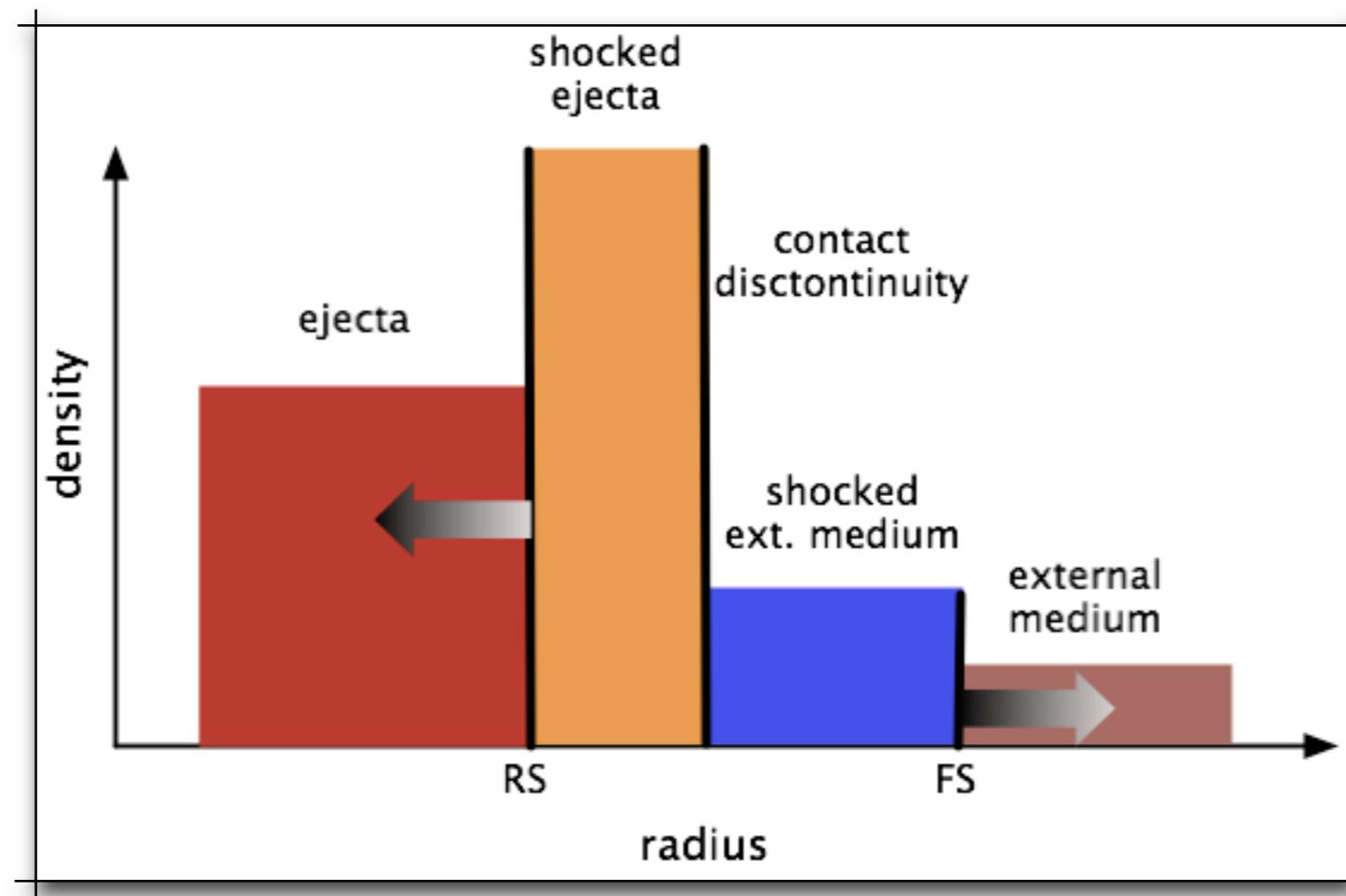
- total energy $E_K(1 + \sigma)$

- magnetization parameter $\sigma := \frac{B^2}{4\pi\gamma\rho c^2}$

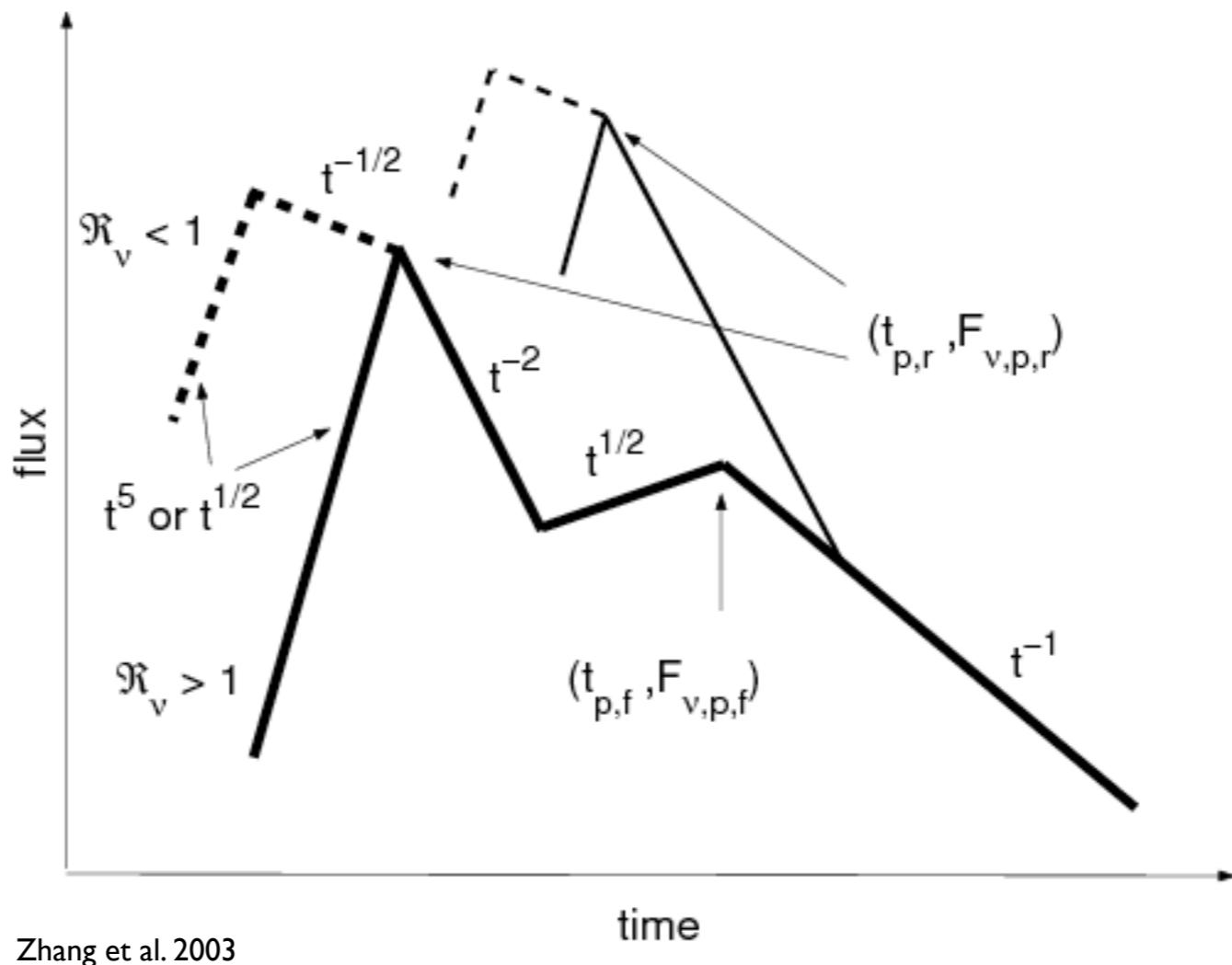


Initial deceleration

- forward-reverse shock structure forms (Sari & Piran 95)
- **reverse shock (RS):** decelerates and compresses ejecta
- **forward shock (FS):** propagates into the external medium

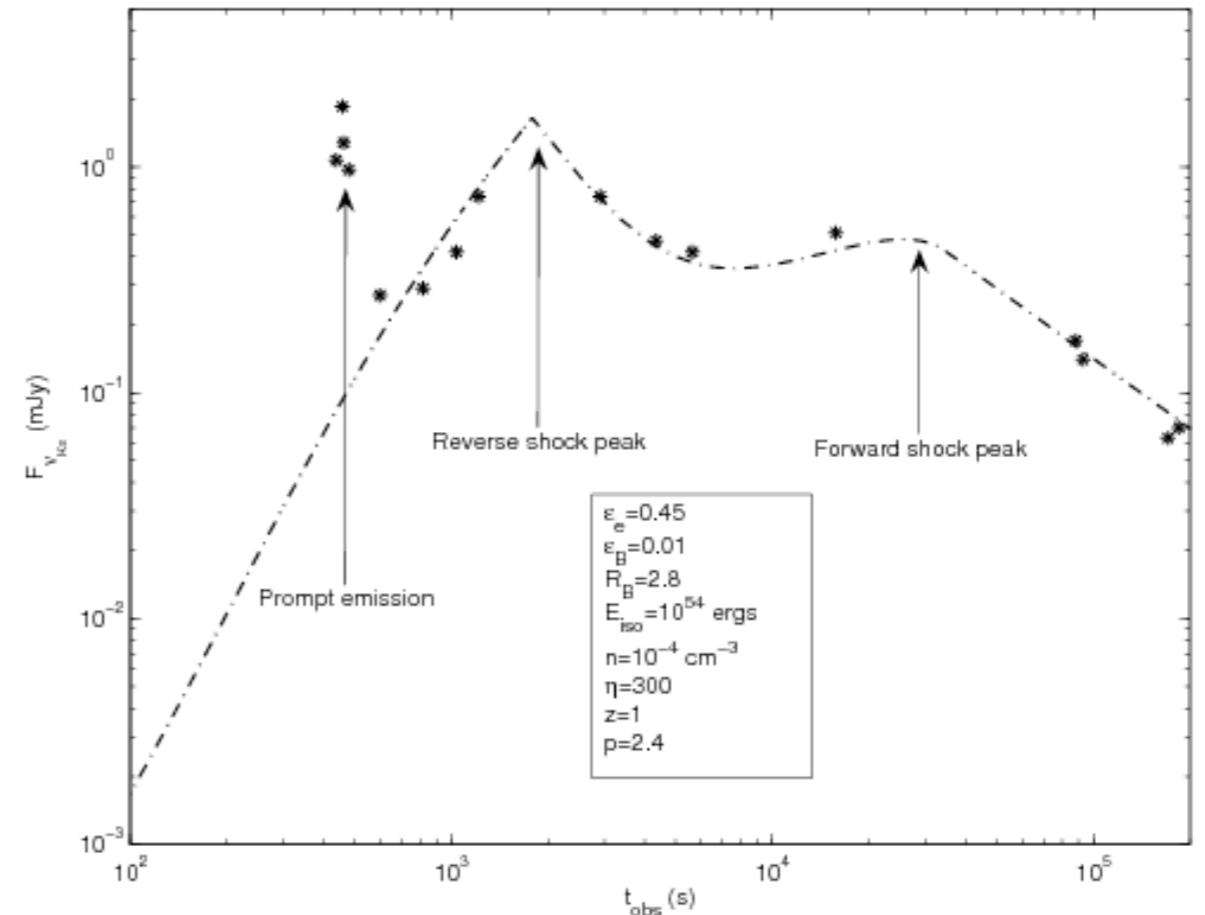
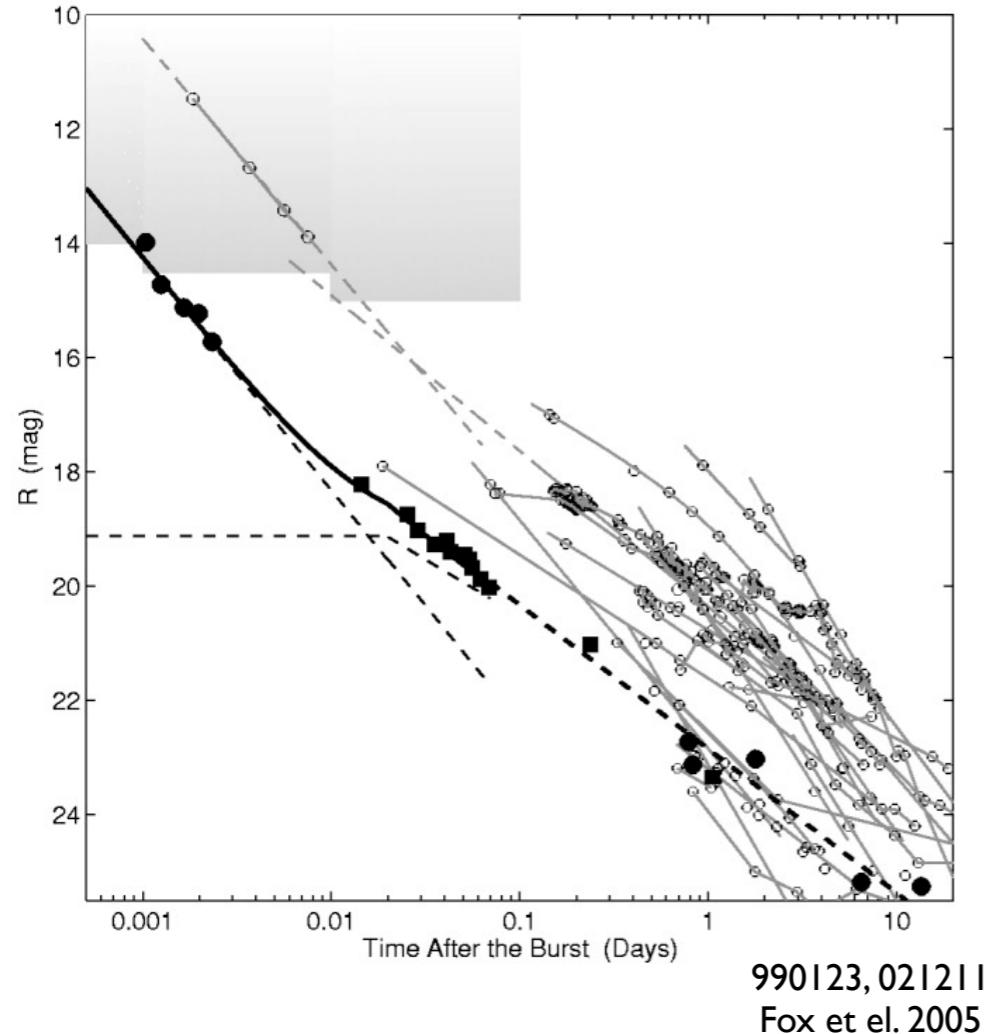


Optical FS+RS emission



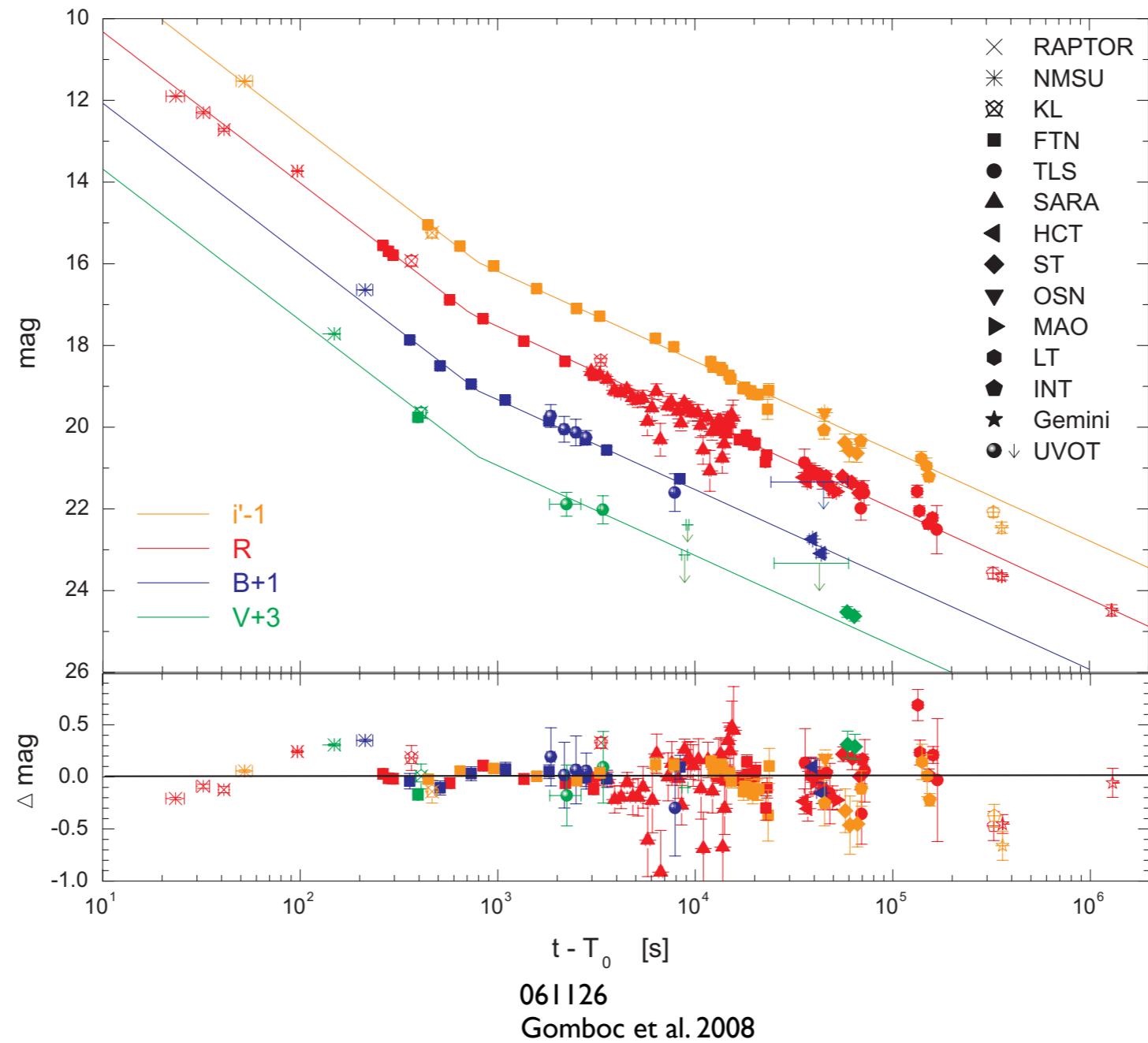
Zhang et al. 2003

Optical FS+RS emission



041219A
Blake et al. 2005, Fan et al. 2005

Optical FS+RS emission

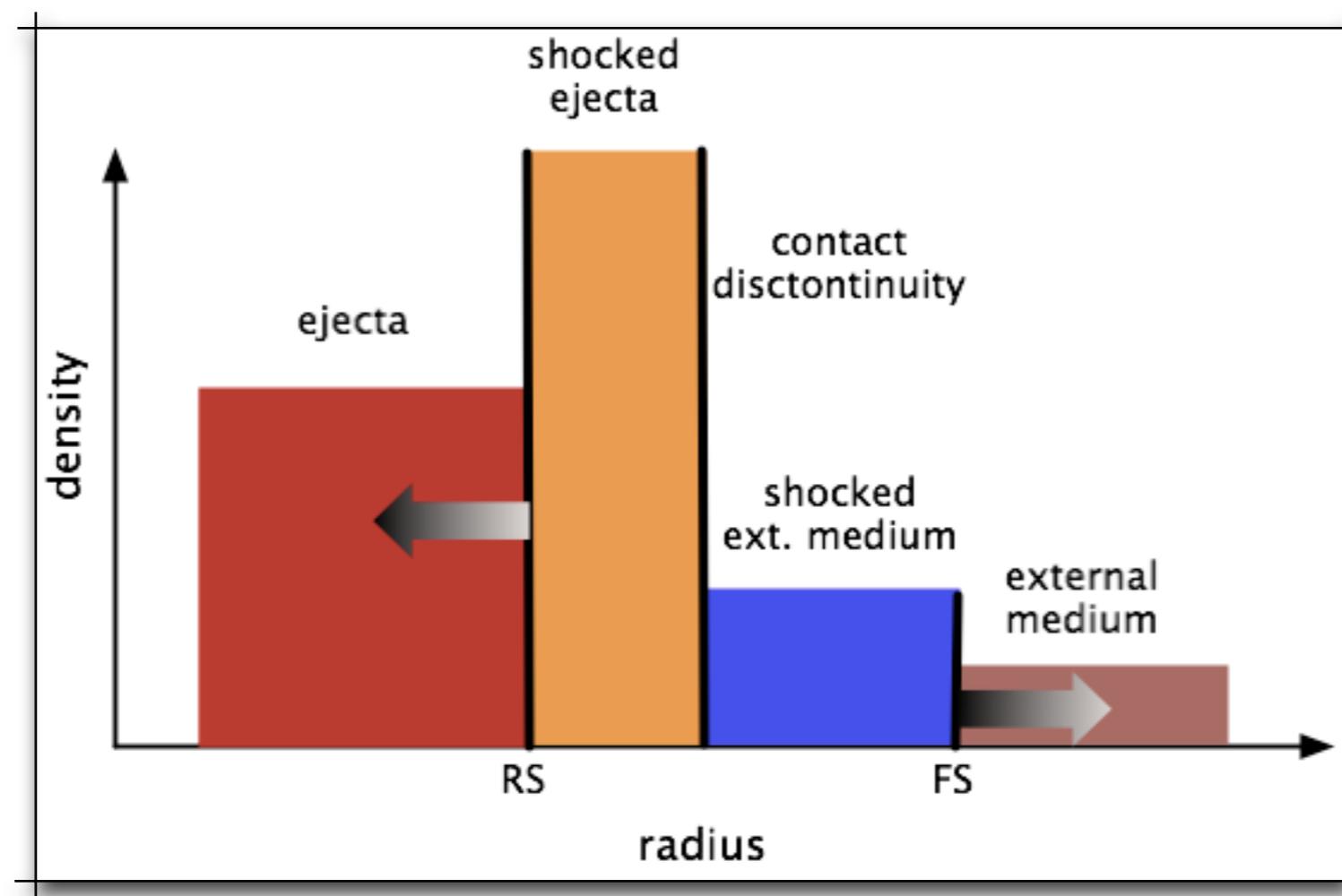


Optical RS emission

- (possible) RS detections in the *Swift* era (Gomboc et al. 2009)
041219A, 050525A, 050904, 060111B,
060117, 061126, 080319B
- no reverse shock optical component detected in most early afterglows** (Roming et al. 2006)

Initial deceleration: $\sigma=0$

- forward-reverse shock structure always forms (Sari & Piran 95)
- **reverse shock (RS):** decelerates and compresses ejecta
- **forward shock (FS):** propagates into the external medium



Initial deceleration: $\sigma=0$

- model: homogeneous spherical shell with parameters

- radial width Δ_0
- initial Lorentz factor γ_0
- energy E

- external medium density $n_e m_p$

- Sedov length $l = (3E/4\pi n_e m_p c^2)^{1/3}$

- Sari & Piran (1995): strength of the RS depends on

$$\xi := \sqrt{\frac{l}{\Delta_0}} \frac{1}{\gamma_0^{4/3}} \approx 0.73 E_{53}^{1/6} n_0^{-1/6} \Delta_{12}^{-1/2} \gamma_{2.5}^{-4/3}$$

$$E = 10^{53} E_{53} \text{erg} \quad \Delta = 10^{12} \Delta_{12} \text{cm}$$

$\xi \gg 1$ thin shell, Newtonian RS

$$\gamma = 10^{2.5} \gamma_{2.5} \quad n_e = 1 n_0 \text{cm}^{-3}$$

$\xi \ll 1$ thick shell, relativistic RS

Initial deceleration: $\sigma > 0$

- much less studied
- RS shock crossing radius (Zhang & Kobayashi 05)

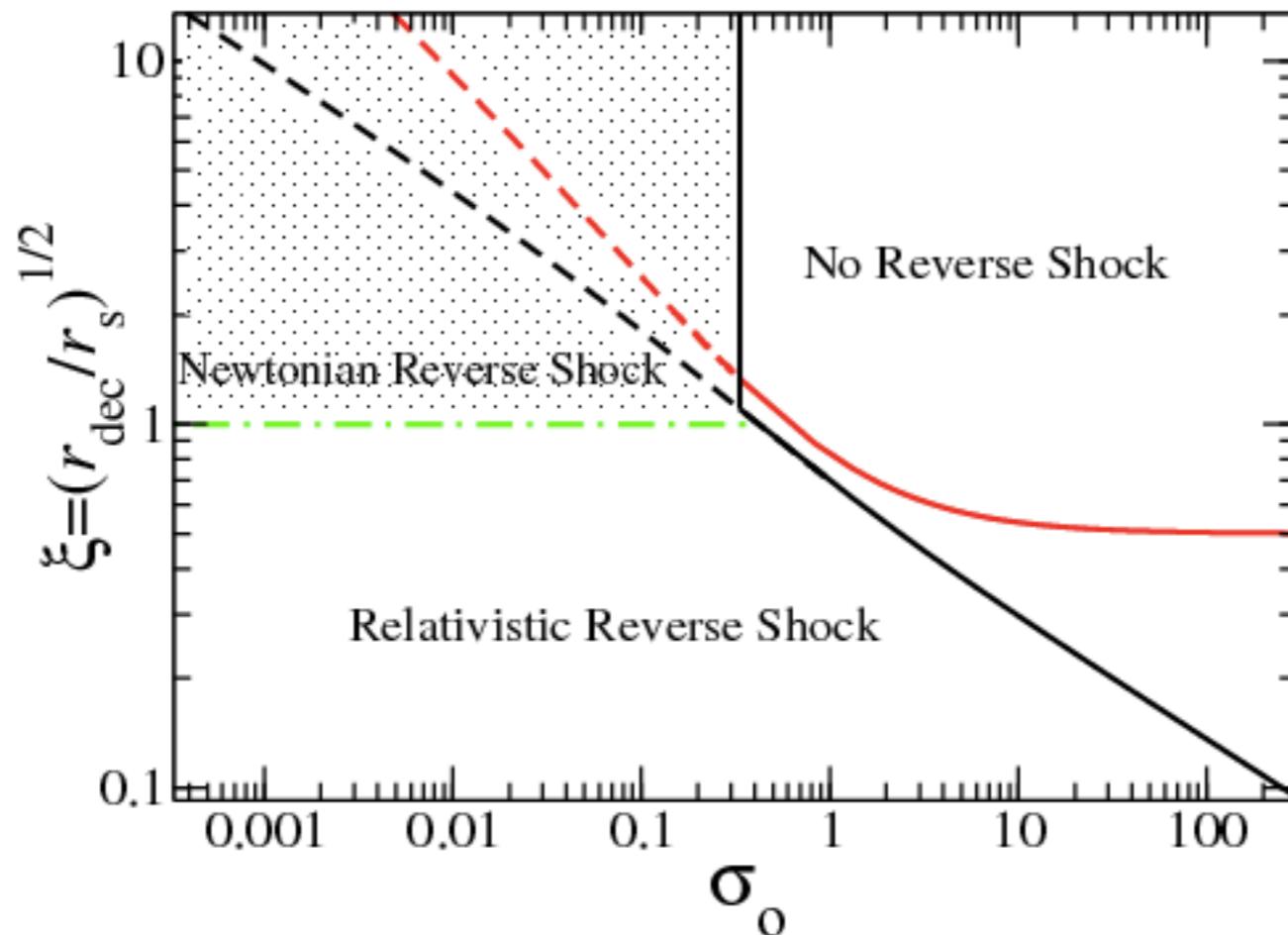
$$r_{rs} \approx \frac{r_{rs}^H}{\sqrt{1 + \sigma}} = \frac{l^{3/4} \Delta^{1/4}}{\sqrt{1 + \sigma}}$$

- contact radius: fast magnetosonic waves cross the ejecta (Giannios, Mimica & Aloy 08)

$$r_c \approx \Delta \gamma^2 \left(\sqrt{\frac{1 + \sigma}{\sigma}} - 1 \right)$$

Existence of a reverse shock

- for typical GRB parameters the condition for the existence of a reverse shock is (Giannios, Mimica & Aloy 08) $\sigma < 0.6 n_0^{1/2} \Delta_{12}^{3/2} \gamma_{2.5}^4 E_{53}^{-1/2}$



$$\xi \approx 0.73 E_{53}^{1/6} n_0^{-1/6} \Delta_{12}^{-1/2} \gamma_{2.5}^{-4/3}$$

- even if RS forms for high magnetization it can only dissipate kinetic energy, a **small fraction** of the total (Zhang & Kobayashi 05)

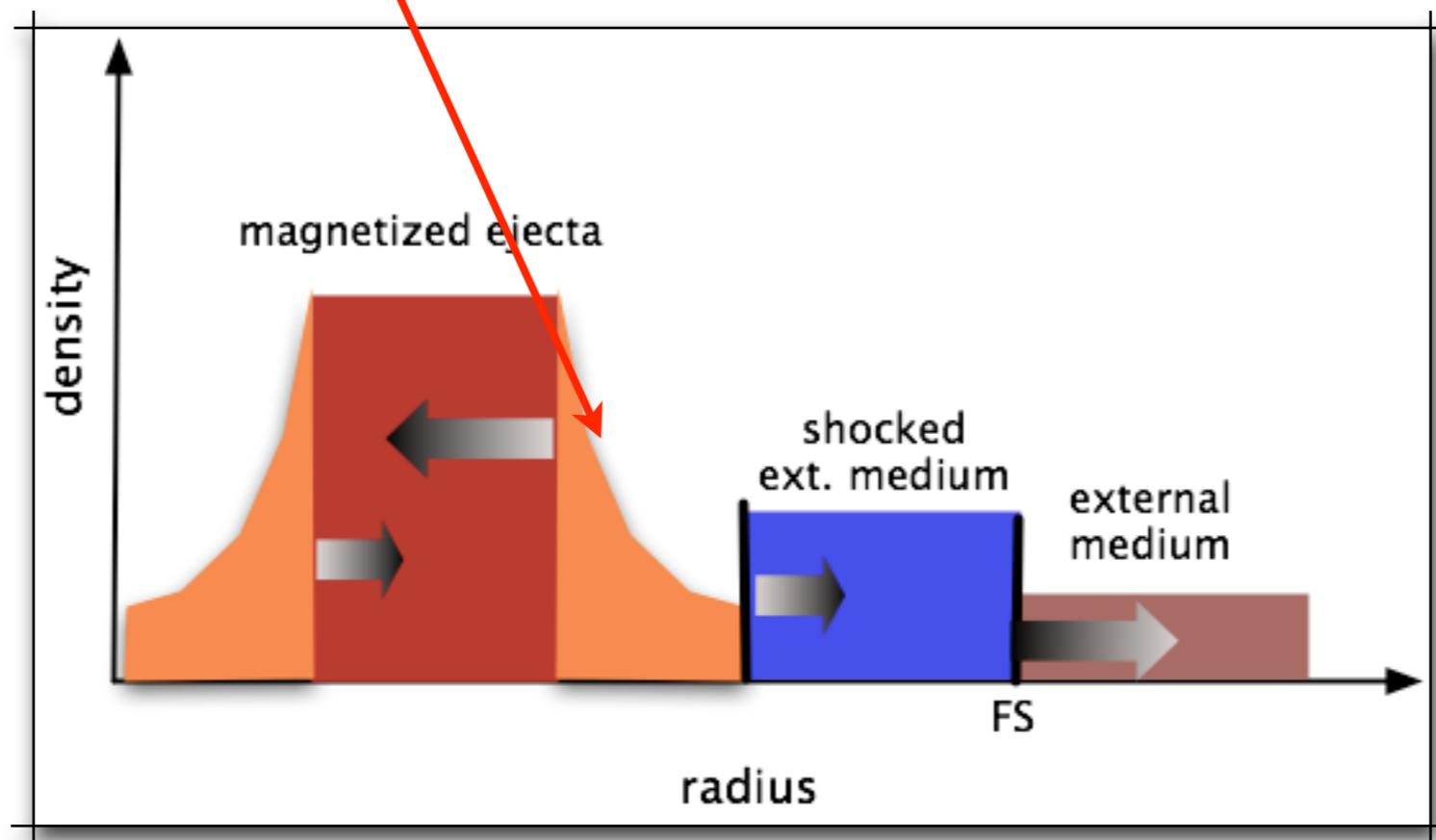
Strongly magnetized ejecta

- "**reverse rarefaction**": accelerates and rarefies ejecta
- **forward shock**: propagates into the external medium

(talk by Mizuno)

Mizuno et al. 09

Mimica, Giannios & Aloy 09

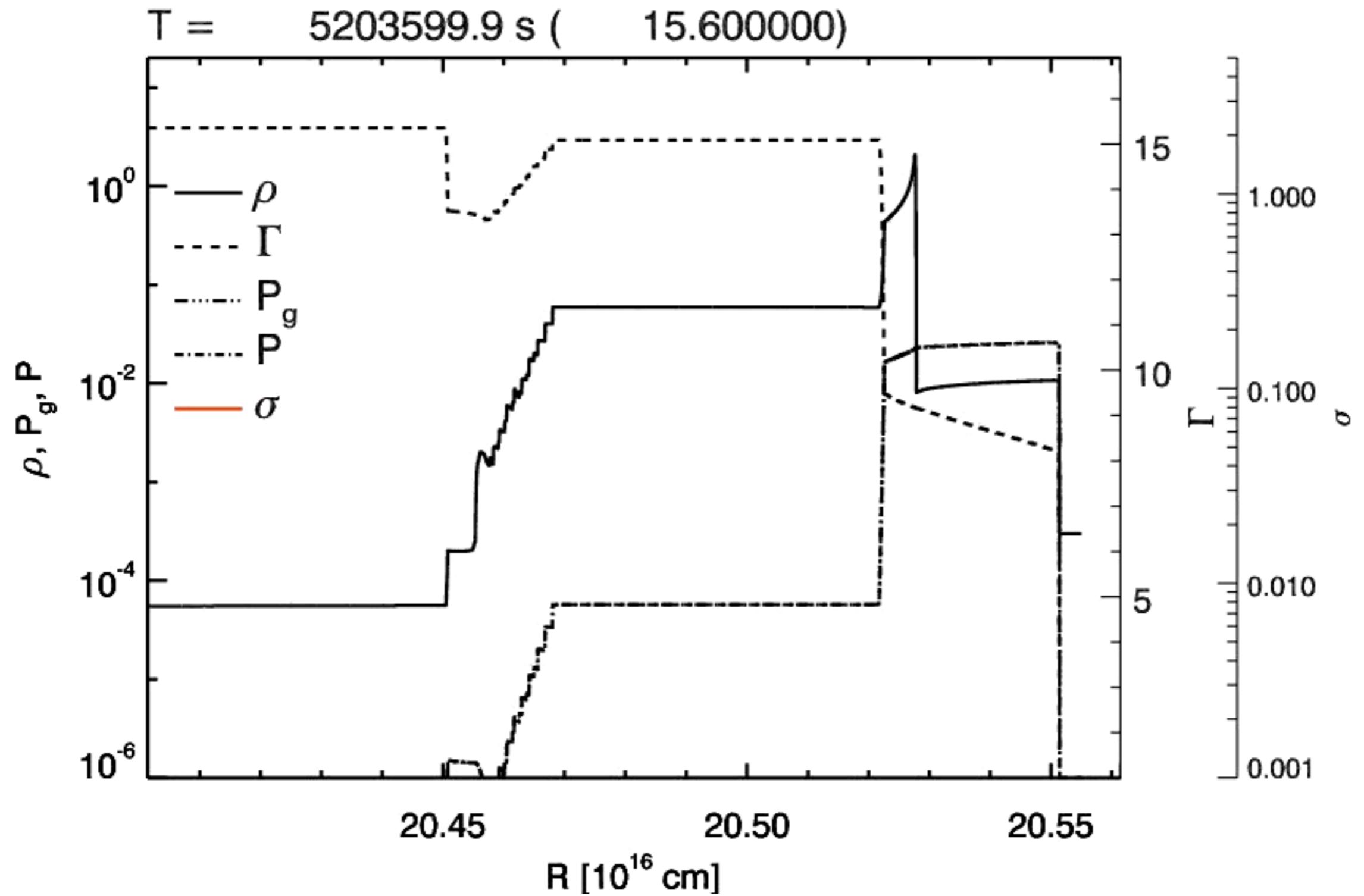


Numerical simulations

- we want to:
 - 1.study ejecta internal evolution
 - 2.check the analytical conditions for RS existence
 - 3.study the energy transfer from ejecta to external medium
 - 4.compute the light curves
- *MRGENESIS* extension of the *GENESIS* code is used to perform simulations (RMHD, shock capturing, PPM, HLLC solver) (Aloy et al. 99; Leismann et al. 05; Mimica, Aloy & Müller 07)
- focus on **hydro** and **strongly magnetized**, thin and thick shells
- 1D simulation, 100K numerical cells, 100M iterations, 128-1024 CPUs
- ref.: Mimica, Giannios & Aloy (2009;A&A **494**, 879)

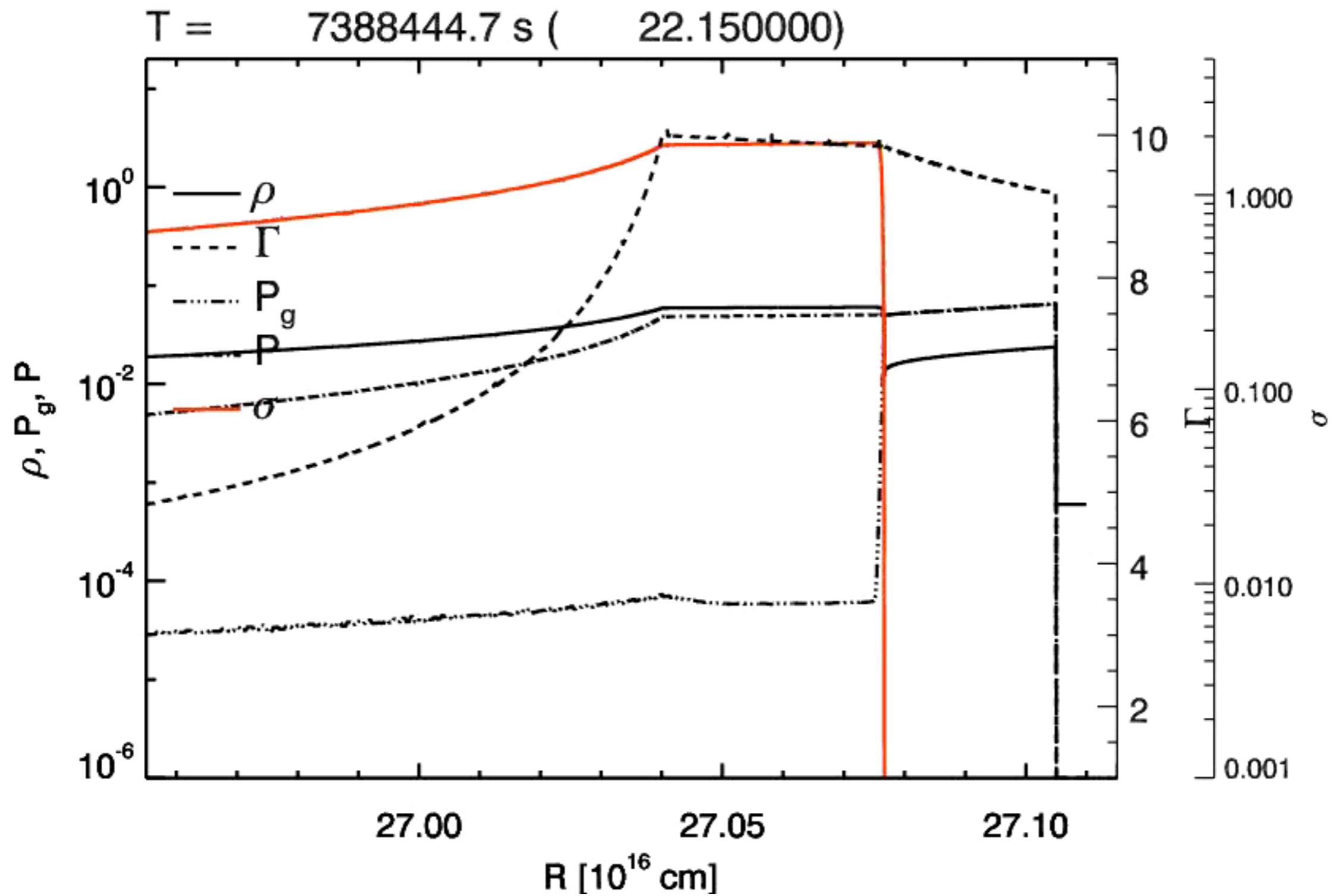
$\sigma=0$ model

$\sigma=0$ model

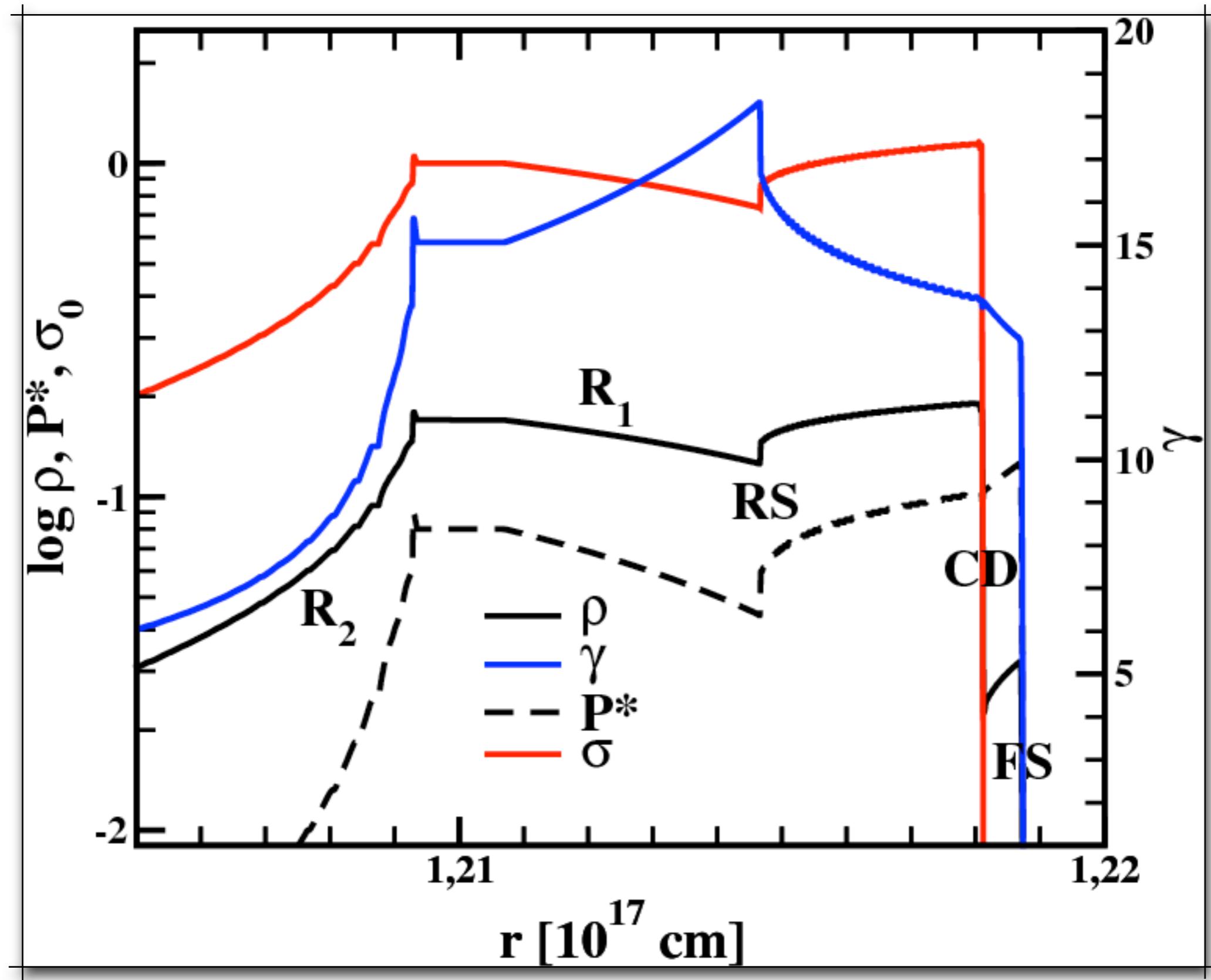


$\sigma=1$ model

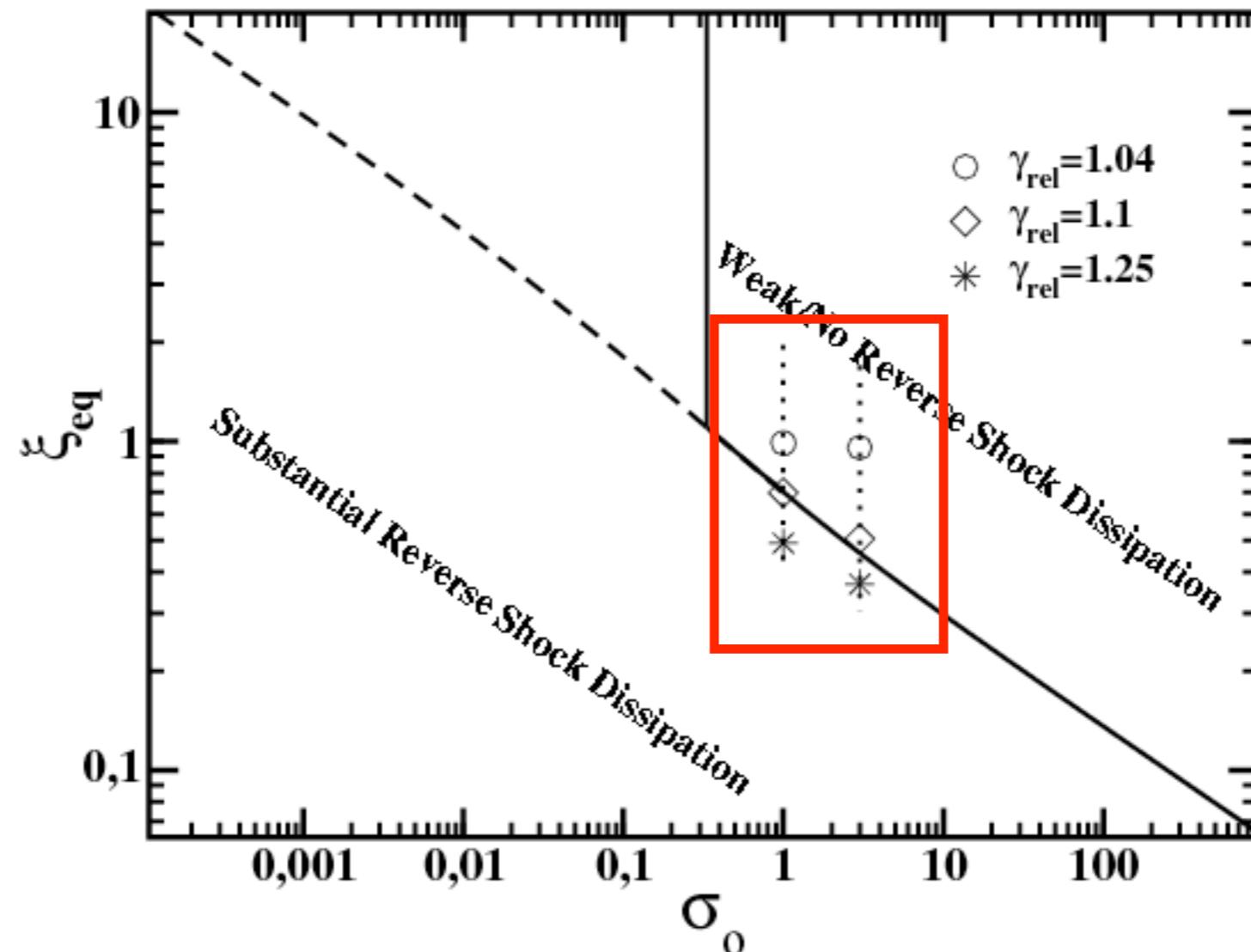
$\sigma=1$ model



Flow structure ($\sigma=1$)

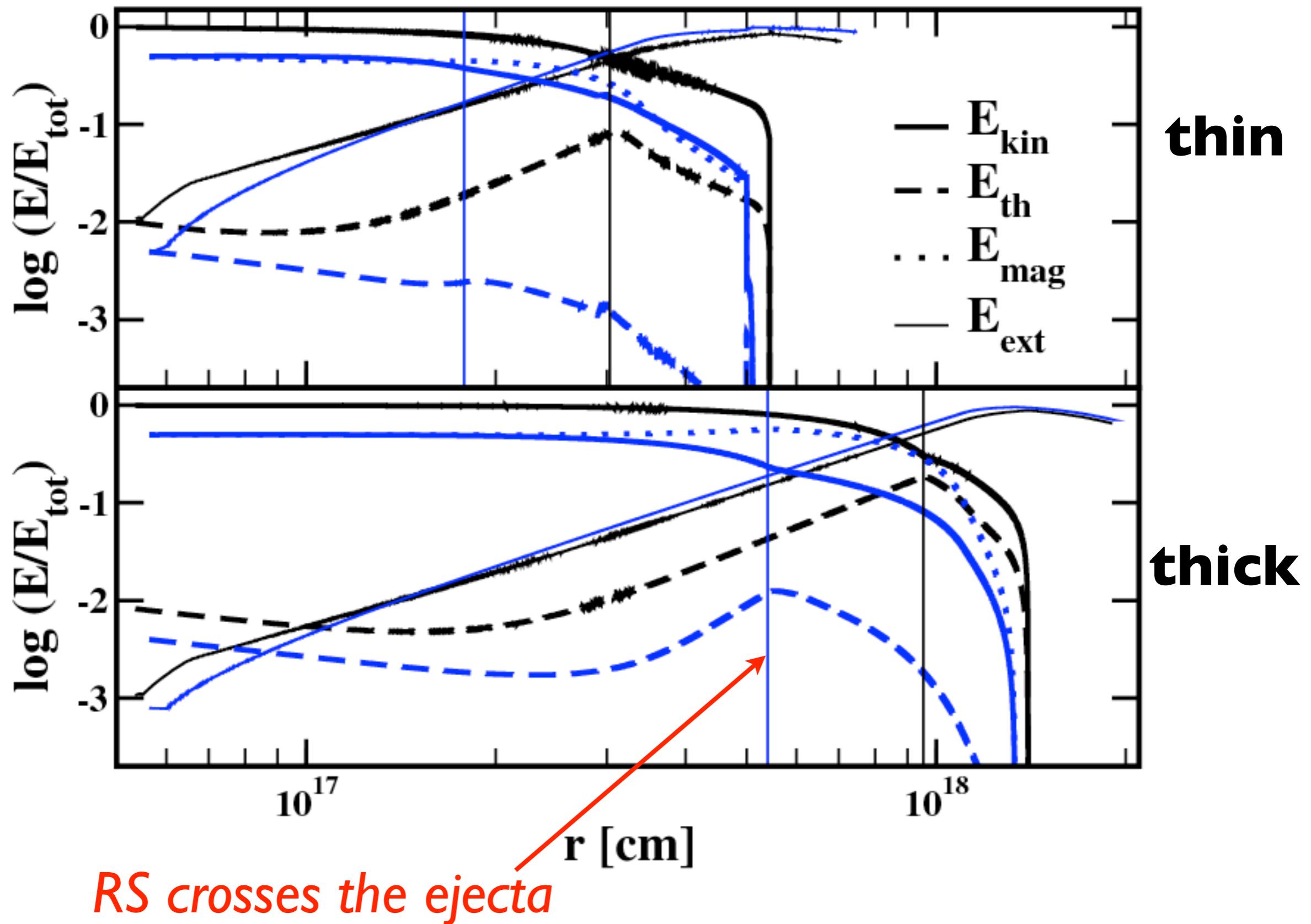


Reverse shock dissipation

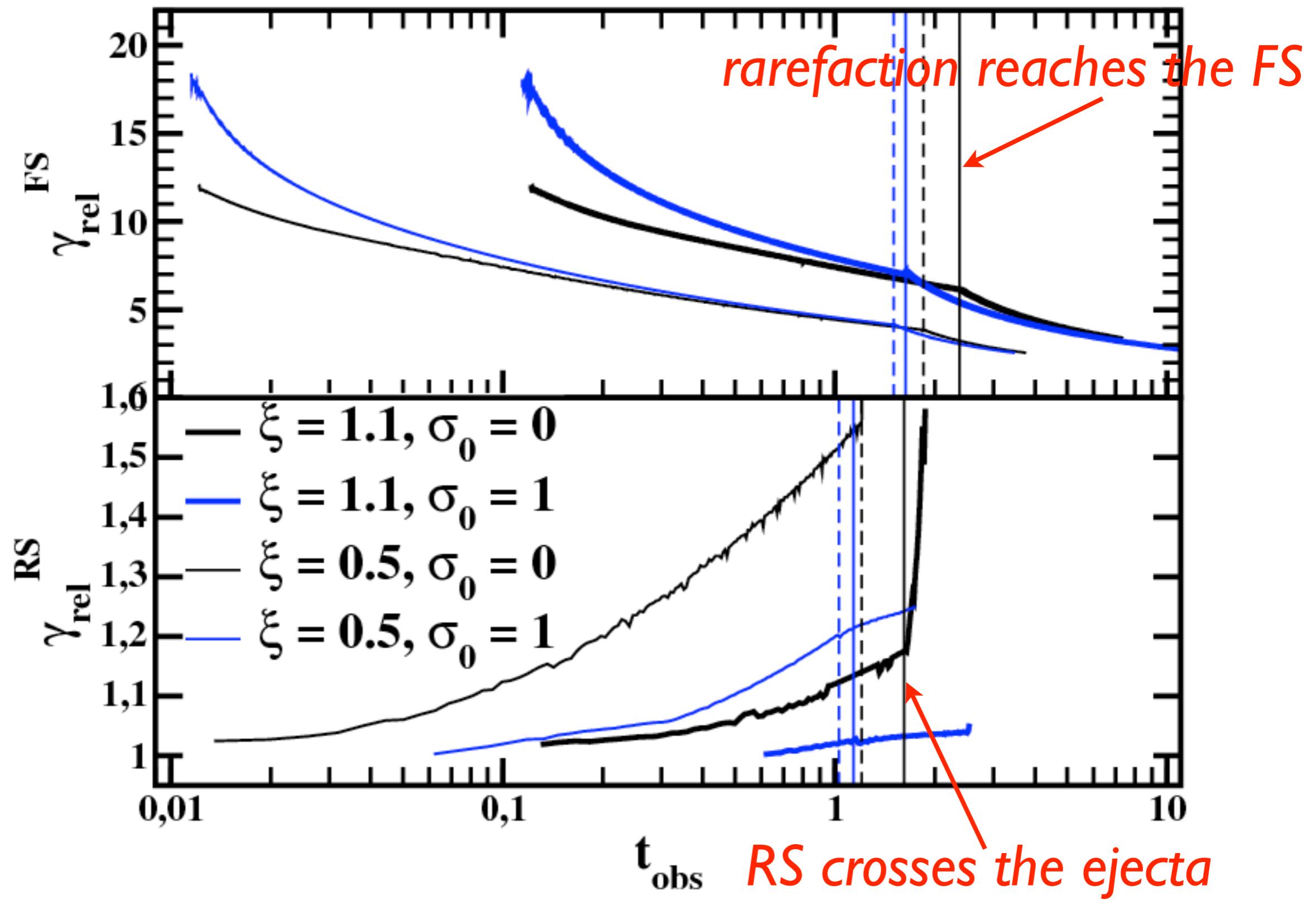


- for fixed σ , RS γ_{rel} drops below 1.1 at an analytically predicted ξ

Transfer of energy



Shock Lorentz factor



Rescaling to higher γ

$$\gamma_2 = f\gamma_1$$

$$t_2 = f^{-2/3}t_1$$

$$r_2 = f^{-2/3}r_{FS,1} + f^{-8/3}(r_1 - r_{FS,1})$$

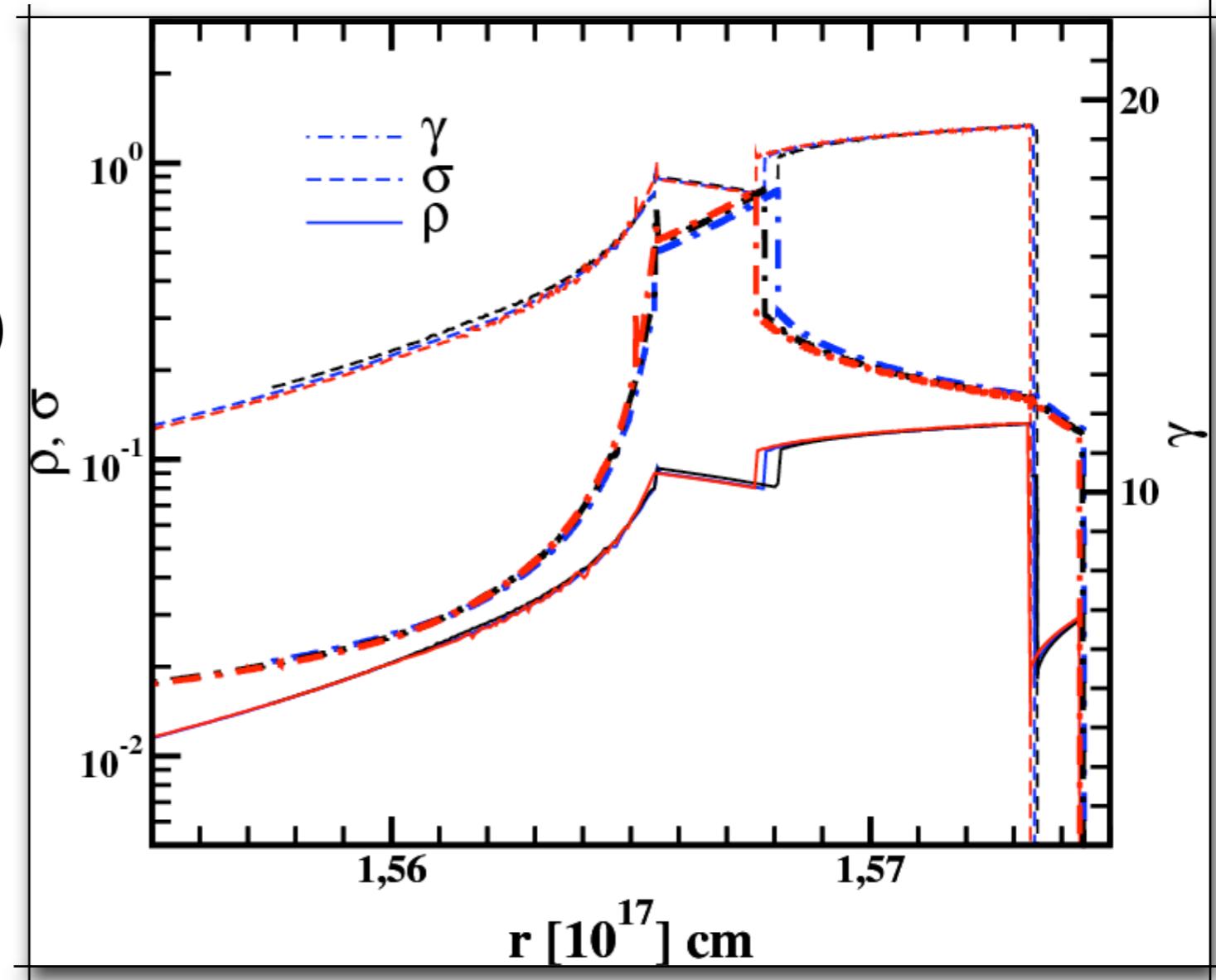
$$P_2(r_2, t_2) = f^2 P_1(r_1, t_1)$$

$$\rho_{\text{shell},2}(r_2, t_2) = f^2 \rho_{\text{shell},1}(r_1, t_1)$$

$$\rho_{\text{ext},2}(r_2, t_2) = f \rho_{\text{ext},1}(r_1, t_1)$$

Rescaling to higher γ

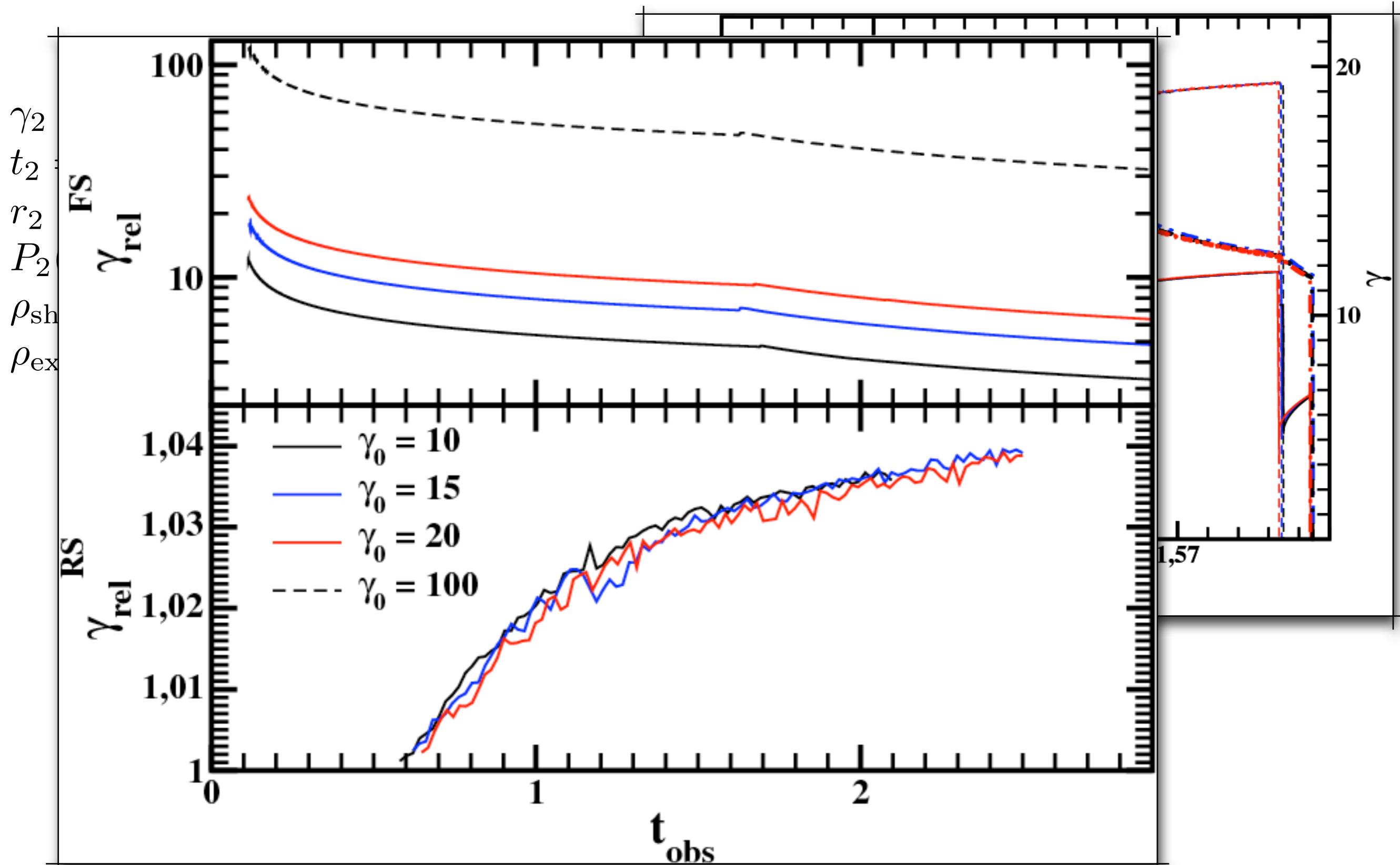
$$\begin{aligned}\gamma_2 &= f\gamma_1 \\ t_2 &= f^{-2/3}t_1 \\ r_2 &= f^{-2/3}r_{FS,1} + f^{-8/3}(r_1 - r_{FS,1}) \\ P_2(r_2, t_2) &= f^2 P_1(r_1, t_1) \\ \rho_{\text{shell},2}(r_2, t_2) &= f^2 \rho_{\text{shell},1}(r_1, t_1) \\ \rho_{\text{ext},2}(r_2, t_2) &= f \rho_{\text{ext},1}(r_1, t_1)\end{aligned}$$



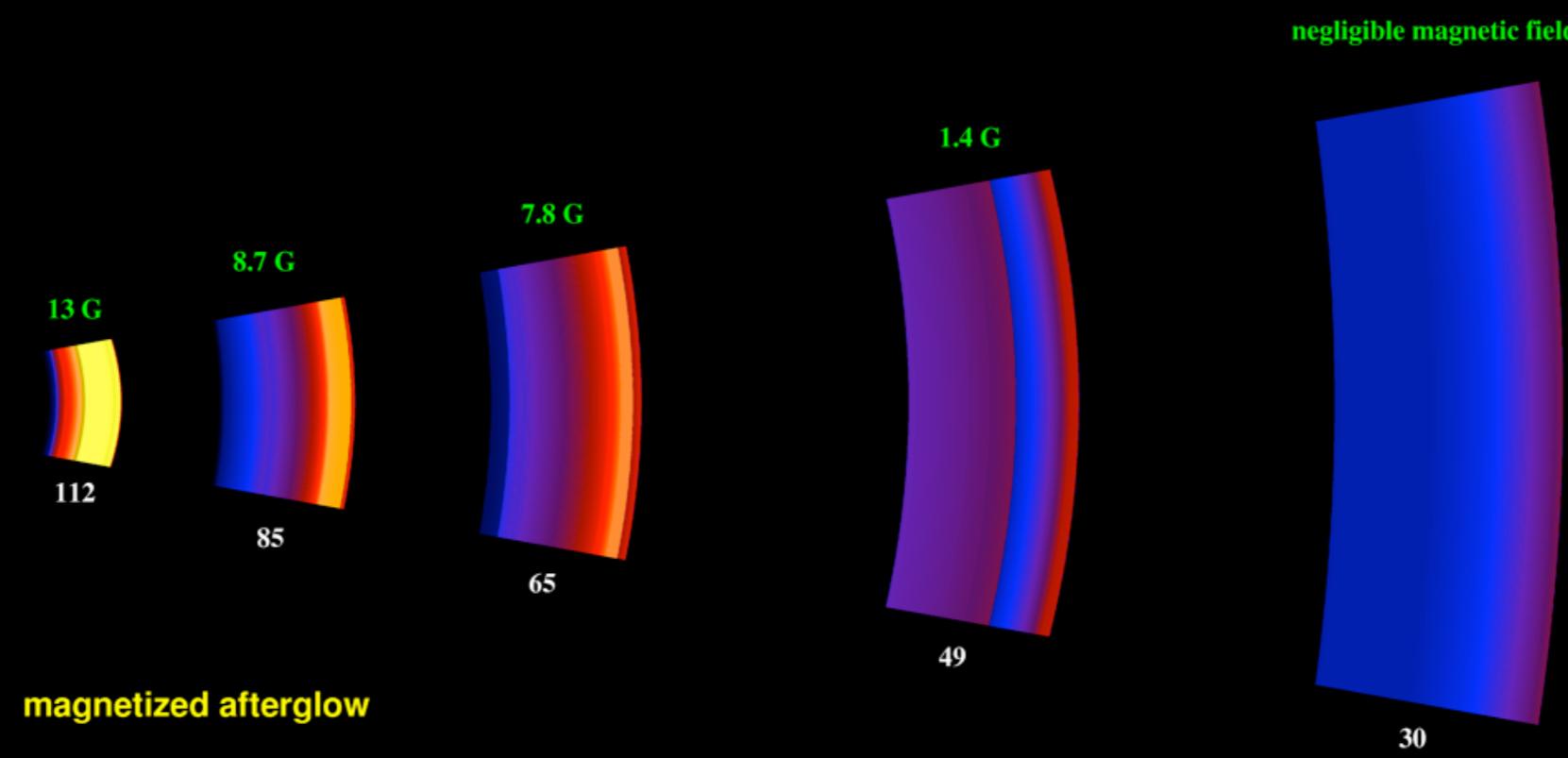
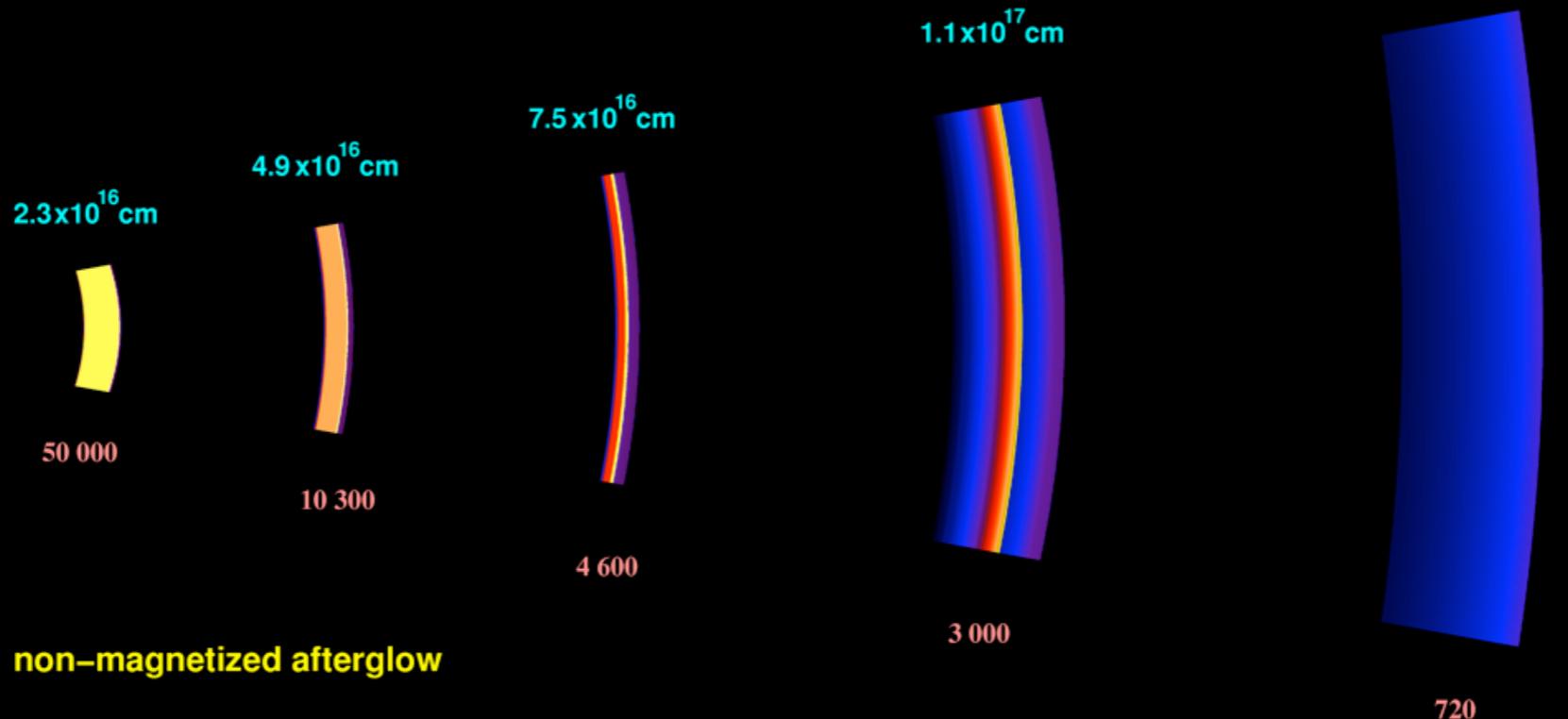
(invariant) normalized observer time

$$t_{\text{obs},2} := \frac{ct_2 - r_2}{\Delta_2} = \frac{ct_1 - r_1}{\Delta_1} = t_{\text{obs},1}$$

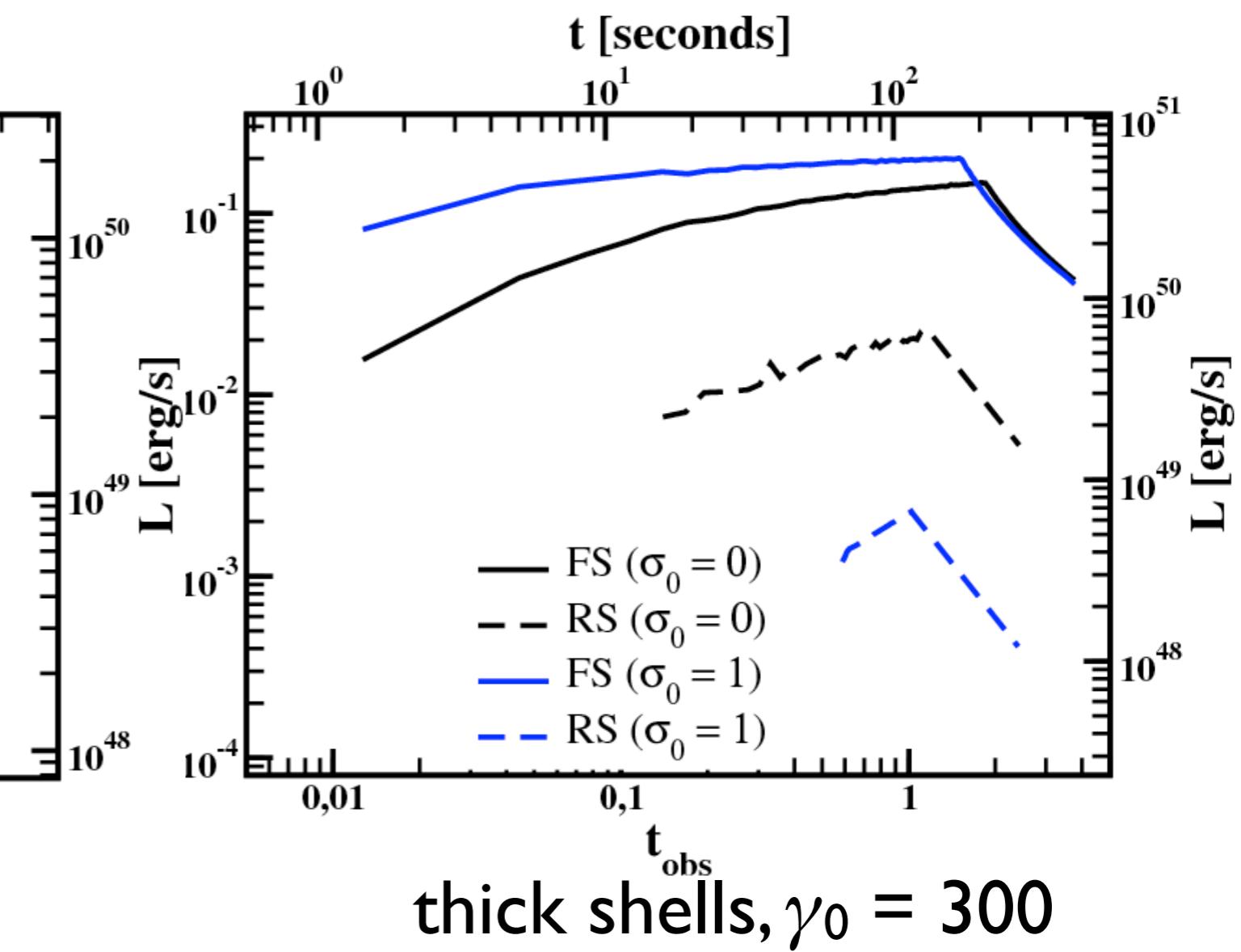
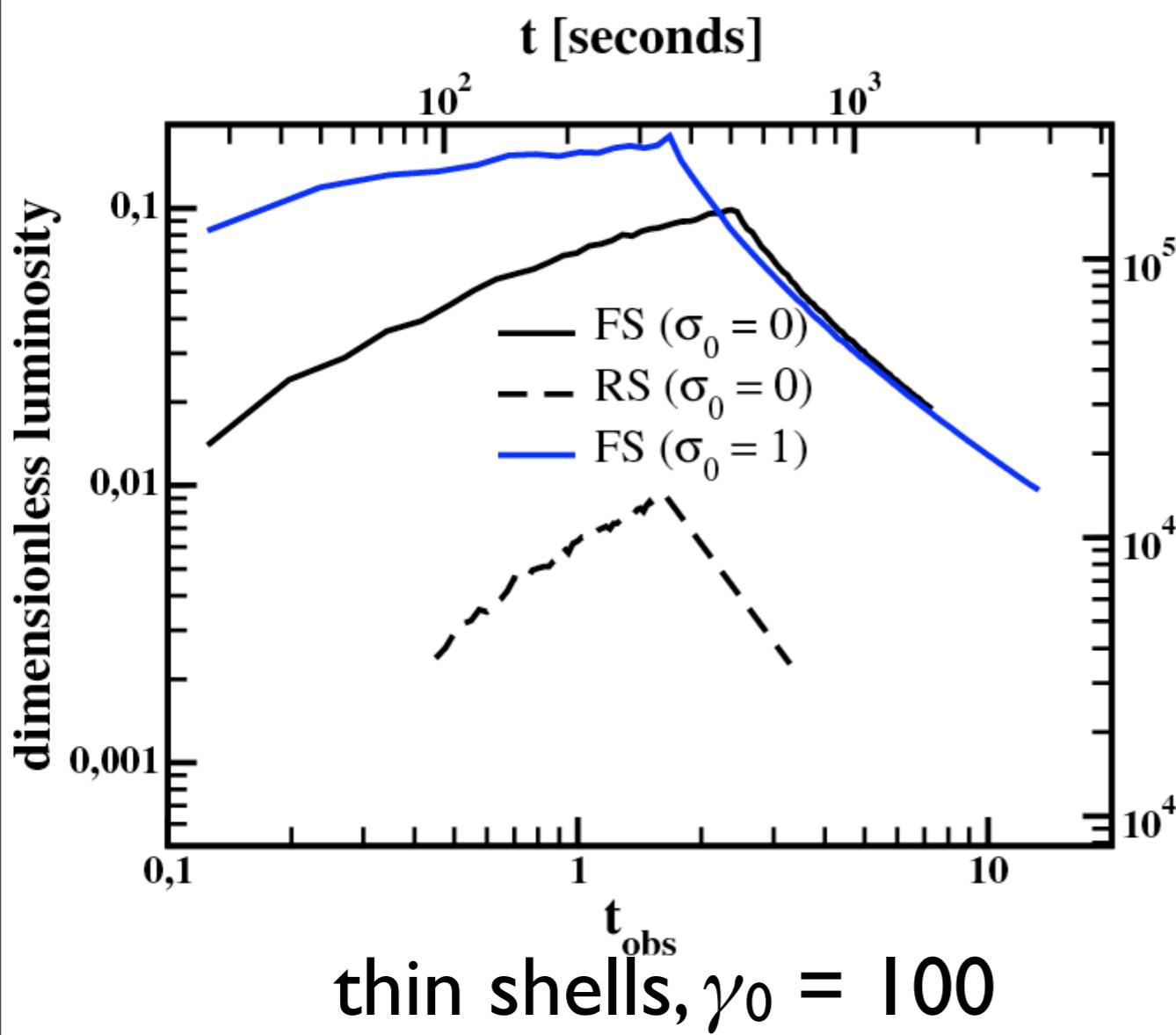
Rescaling to higher γ



Rescaled dynamics



"Bolometric" light curves



Summary

- magnetization strongly influences initial ejecta-medium interaction
- using RMHD simulations we studied the complete ejecta evolution
 - evolution controlled by just two parameters, ξ and σ
 - energy dissipated by the RS strongly depends on magnetization
 - bulk of the magnetic energy transferred into the external medium on a short time scale
 - rescaling relations enable computation of dynamics and light curves for realistic GRB parameters
- next steps: intermediate magnetization, multiwavelength light curves, wind-profile for external medium, ...