GRB jet propagation in a circumstellar bubble. Dynamics and afterglow light curves

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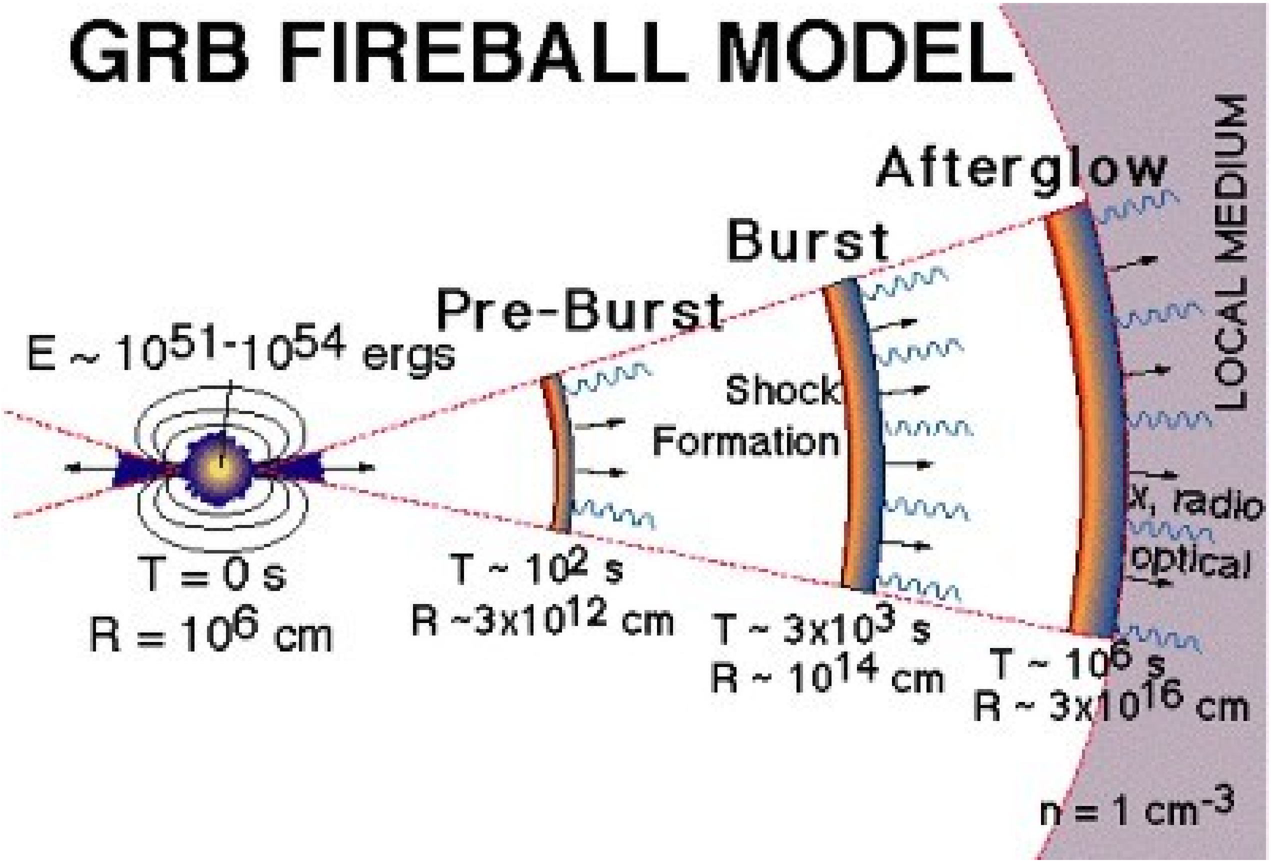
Brussels, 2013

Outline

- **Introduction and Motivation**
  GRBs, afterglows, shell collisions, flares
- **1D model of energy injection**
  Dynamical simulations and light curves
- **2D model of energy injection in a circumstellar bubble**
  Dynamical simulation of the evolution of the interstellar medium around a rotating massive star and two-shell structured jet propagation inside the resulting medium.

Introduction



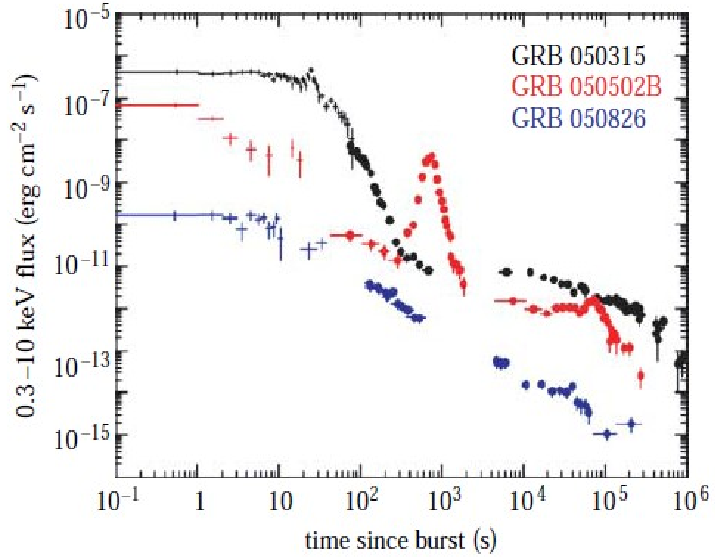
Artist's illustration of the GRB fireball model

Internal shock collisions produce the gamma-rays, while the afterglow is attributed to emission during the deceleration of then external shock in the ambient medium.

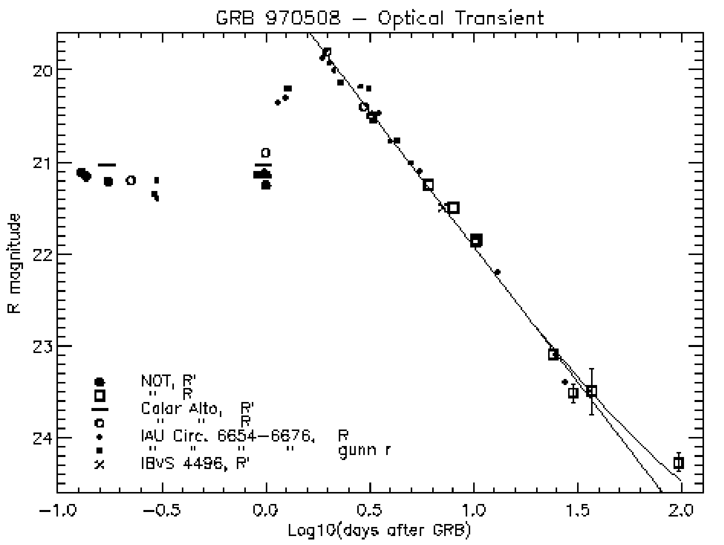
(Pazcynski 1986, Goodman 1986, Rees and Meszaros 1994)

Motivation

Different types of flares appear in the afterglow



N. Gehrels 2007

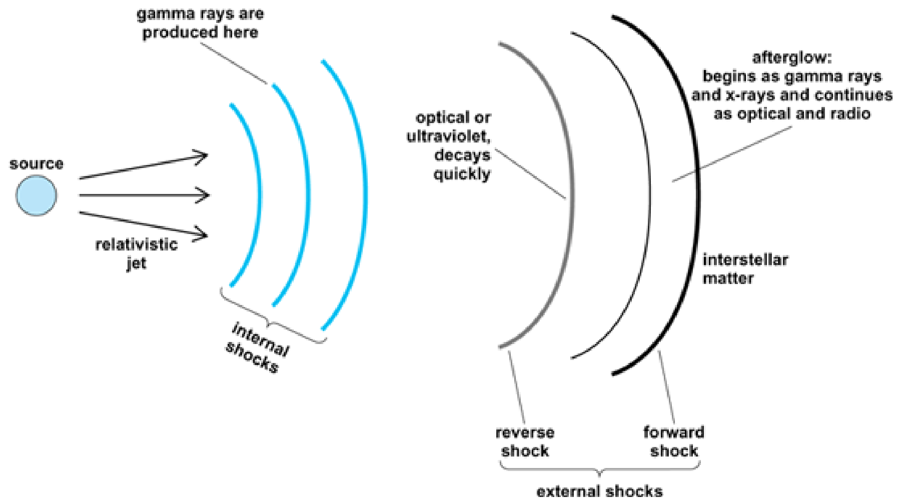


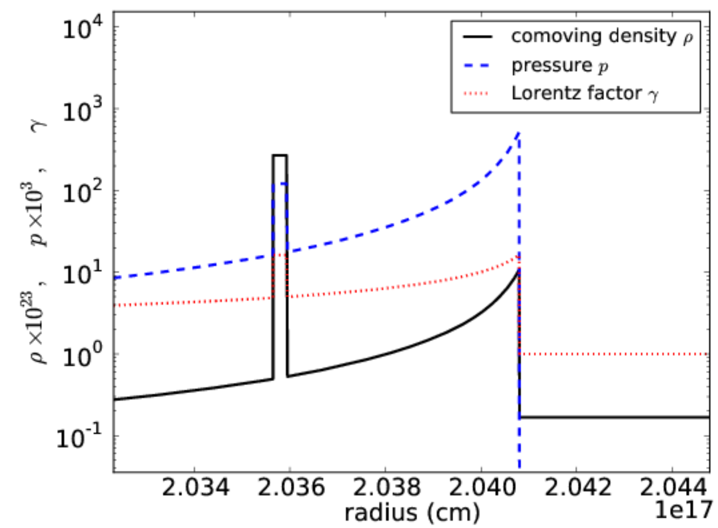
H. Pedersen 1997

- Flares in the afterglow indicate a late central engine activity.
- Different characteristics of the flares suggest that several mechanisms can produce flares.

1D model

Dynamical simulation



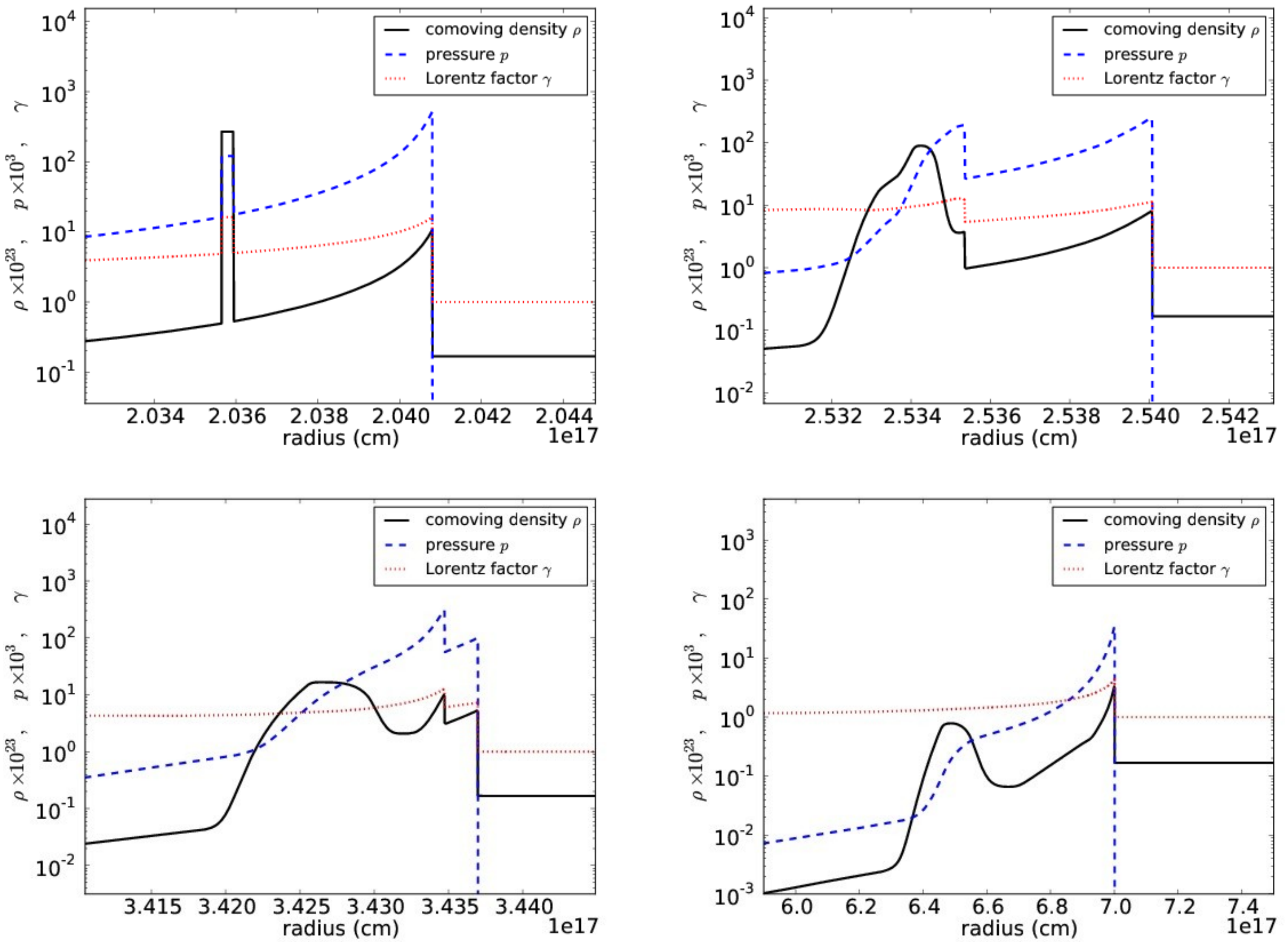


- External shock described by the BM self similar solution
- The second shell is chosen as cold and ultra-relativistic with $\Delta t=1000$ sec placed in distance $\Delta R=10^{14}$ cm behind the external shock.

- Size of the domain [0.01, 10] x 10^{18} cm
- 240 cells at the coarsest level of refinement

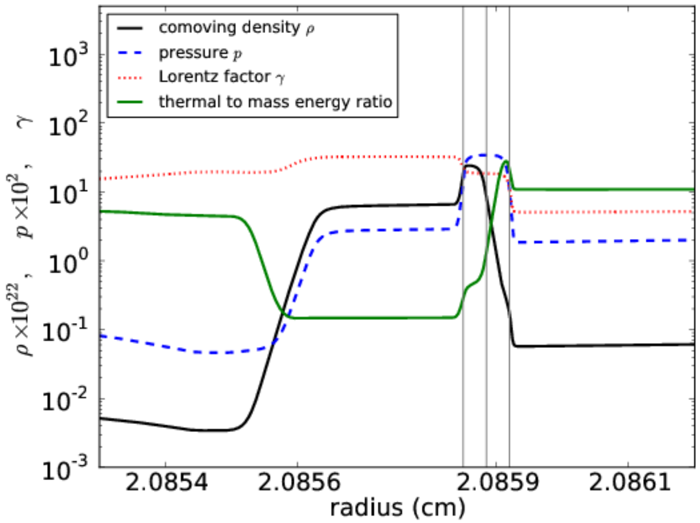
- We use 22 levels of refinement leading to an effective resolution of 5 x 10^{8} cells.

1D model



Snapshots of the simulation before and after the merger.

1D model



- At the position of the **forward shock**

$$n_2 / n_1 = 7.8$$
$$p_2 / p_1 = 10$$

- At the position of the **reverse shock**

$$n_3 / n_4 = 5.5$$
$$p_3 / p_4 = 12.3$$

The forward shock while propagating into the external shell matter increases its thermal energy while at the same time a reverse shock traverses the second shell.

We consider this energy injection into the second shell to produce the flares in the afterglow

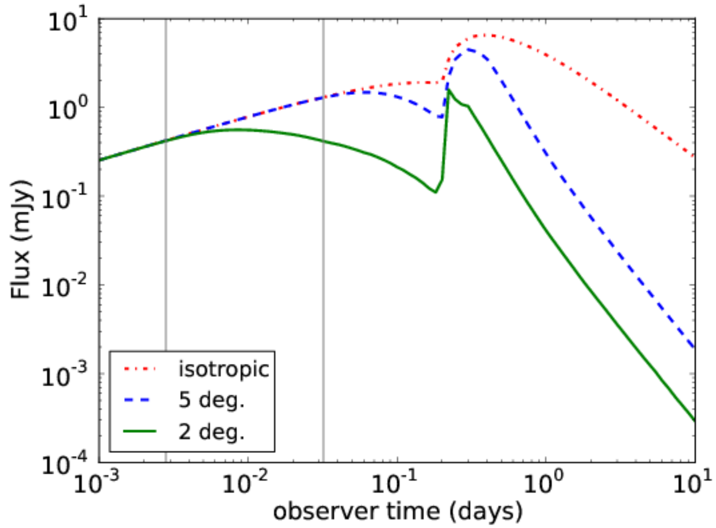
1D model

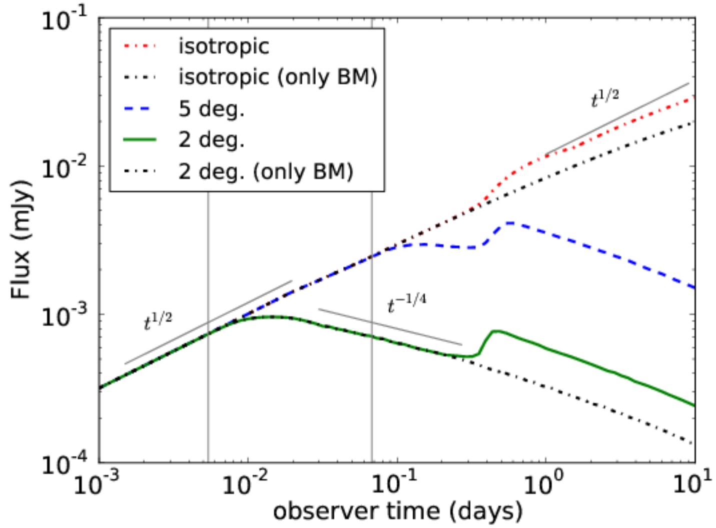
Optical and radio light curves

- A fraction of the total thermal energy behind the shock goes to particle acceleration and another one to the generation of the magnetic field.

$\varepsilon_E = 0.1$
$\varepsilon_B = 0.01$
$p = 2.5$

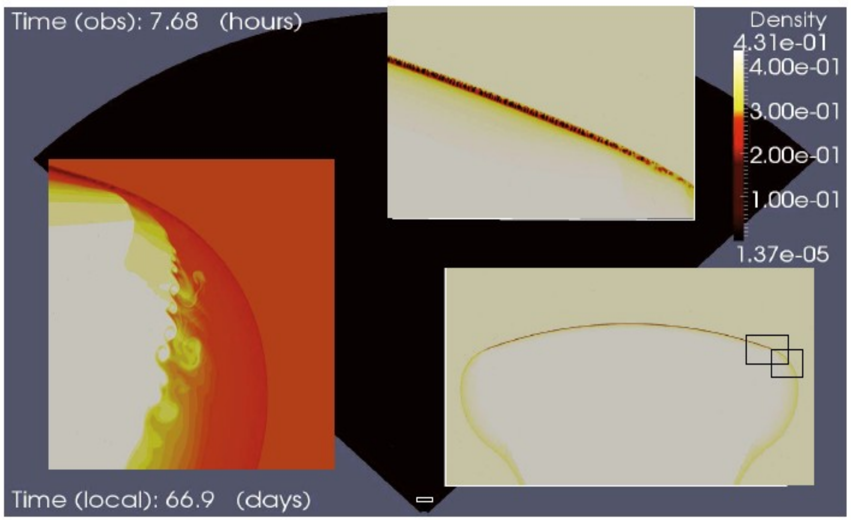
- We see a rebrightening for spherical explosion while for small a small opening angle jet a more flare-like behavior is observed.



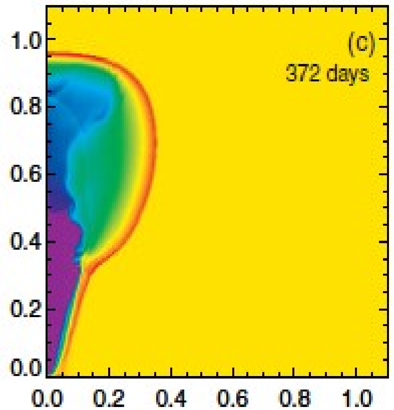


2D models

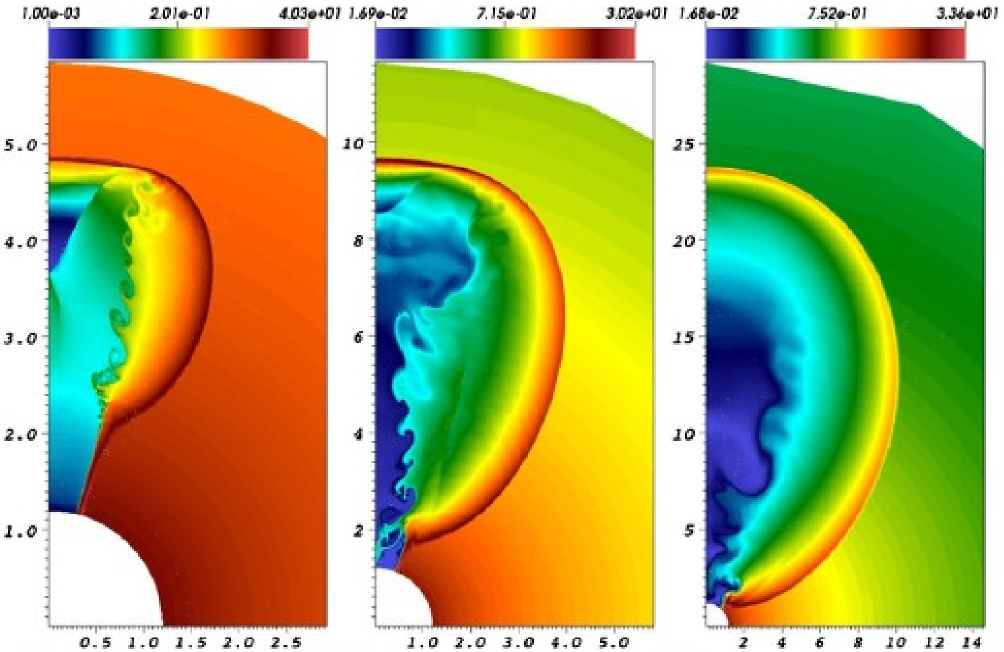
- Significant spreading is predicted from analytical models (Rhoads 1999, Sari et al. 1999) while numerical simulations show more modest expansion (Zhang & MacFadyen 2009, Meliani et al. 2010)



Meliani 2010



Zhang and MacFadyen 2009

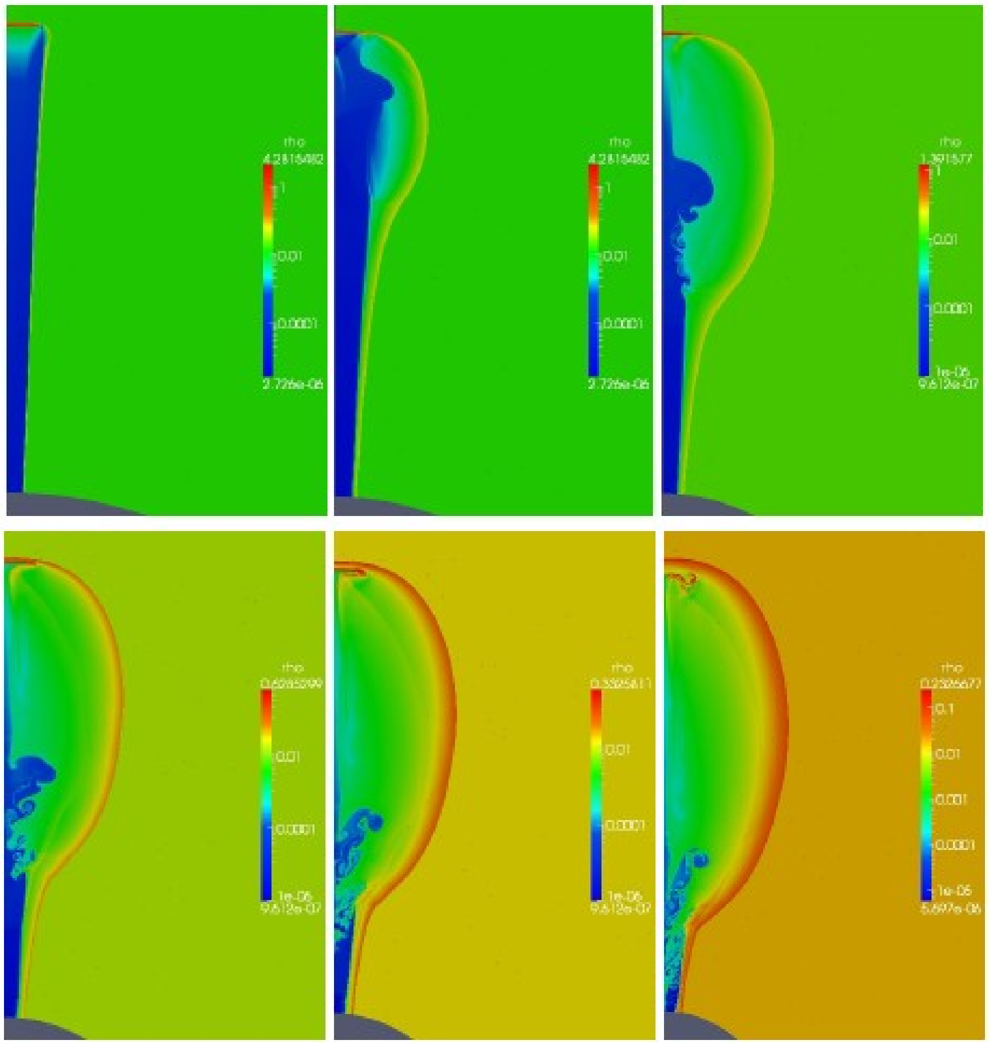


De Colle et al. 2012

2D model

Global evolution of the jet covering a time period between t_e= 79 days and t_e= 200 days.

- **Forward** and **reverse** shock form at the region of the second shell in a fashion similar to the one observed in the 1D case.
- **Small expansion** of the jet in the sideways direction is observed.
- **KH instabilities** develop at the contact discontinuity which at later stages occupy the base of the jet.
- ***Egg-shaped*** formation of the external shock.



GRB jet propagation in a circumstellar bubble

- The majority of long duration GRBs come from the death of massive stars, therefore the propagation of a GRB jet inside such a medium should be investigated.

- Evidence suggest that afterglow light curves are strongly affected by the circumburst medium

- The strong time variability can not be explained by means of a constant medium

=> **More realistic models required**

Structure of our model

- A stellar evolution model is used as an input for the evolution of the circumstellar medium

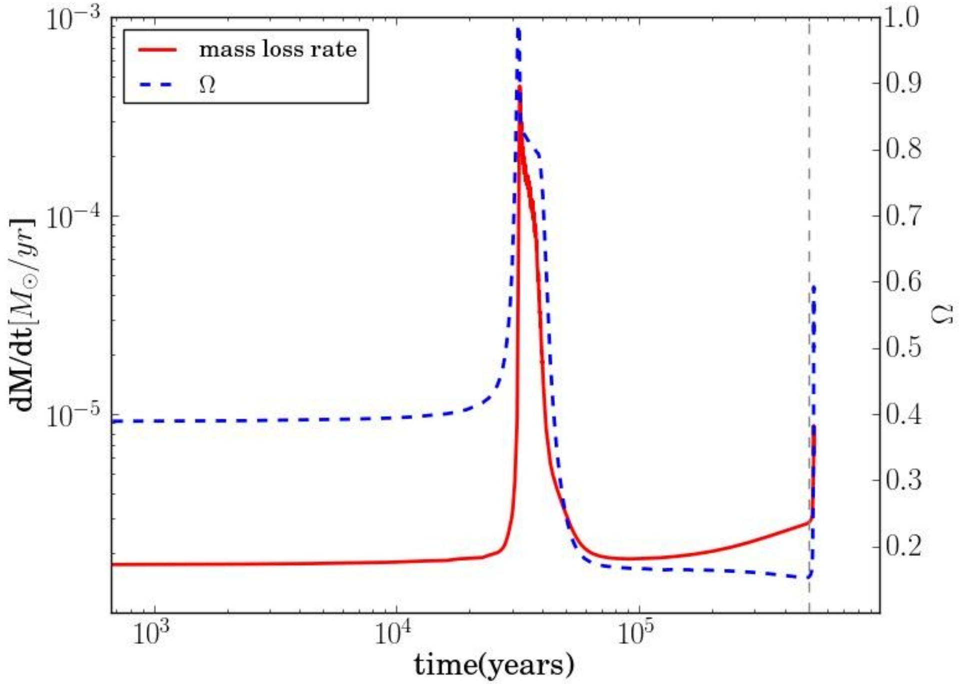
- We perform high resolution 1D simulation at the initial stage of the evolution of the medium for accuracy reasons.

- In 2D we simulate the formation of the circumstellar bubble.

- We initiate a 2D simulation of a GRB jet propagating inside the circumstellar bubble

GRB jet propagation in a circumstellar bubble

1. Stellar evolution model

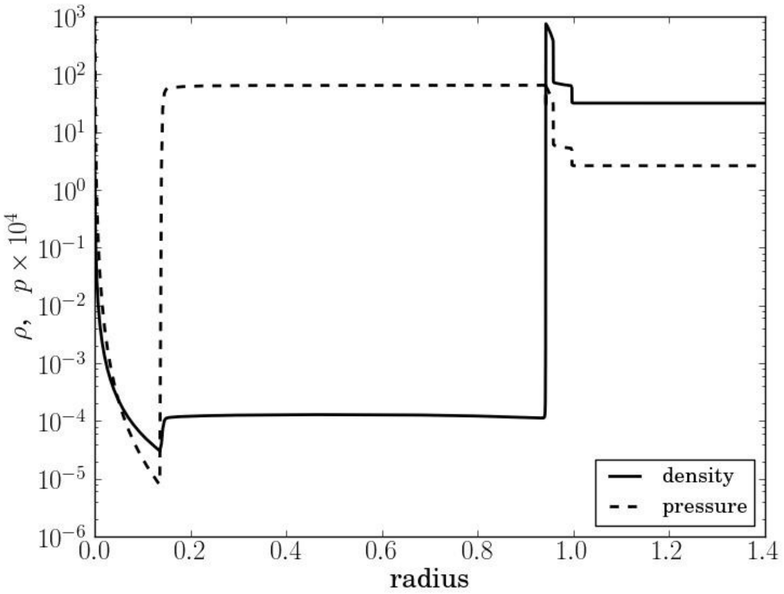


Yoon et al. 2006 evolution model for a low metallicity (Z=0.001) massive star ($M=16M_\odot$)

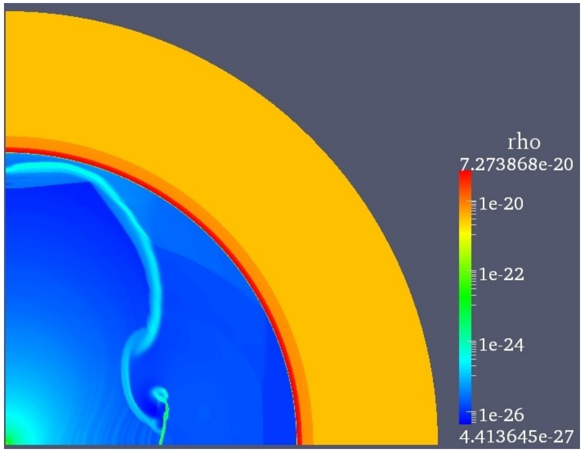
- The initially constant **angular rotation** and moderate **mass loss rate** is followed by a sudden increase when the star reaches the phase of critical rotation.
- The mass loss rate and rotational velocity of the star are used as an input for our dynamical simulation of the circumstellar medium.

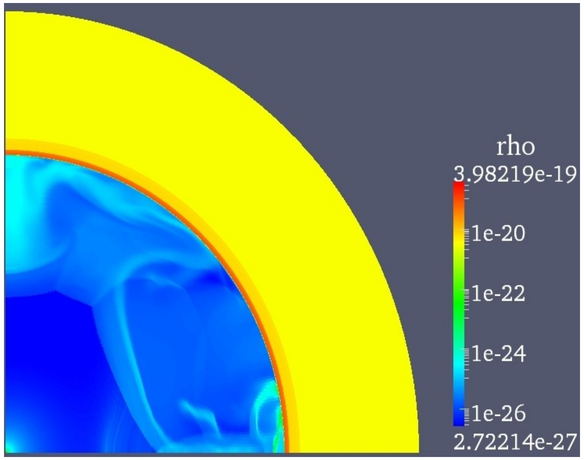
GRB jet propagation in a circumstellar bubble

2. Dynamical simulation of the evolution of the circumstellar medium



A.J. van Marle 2012

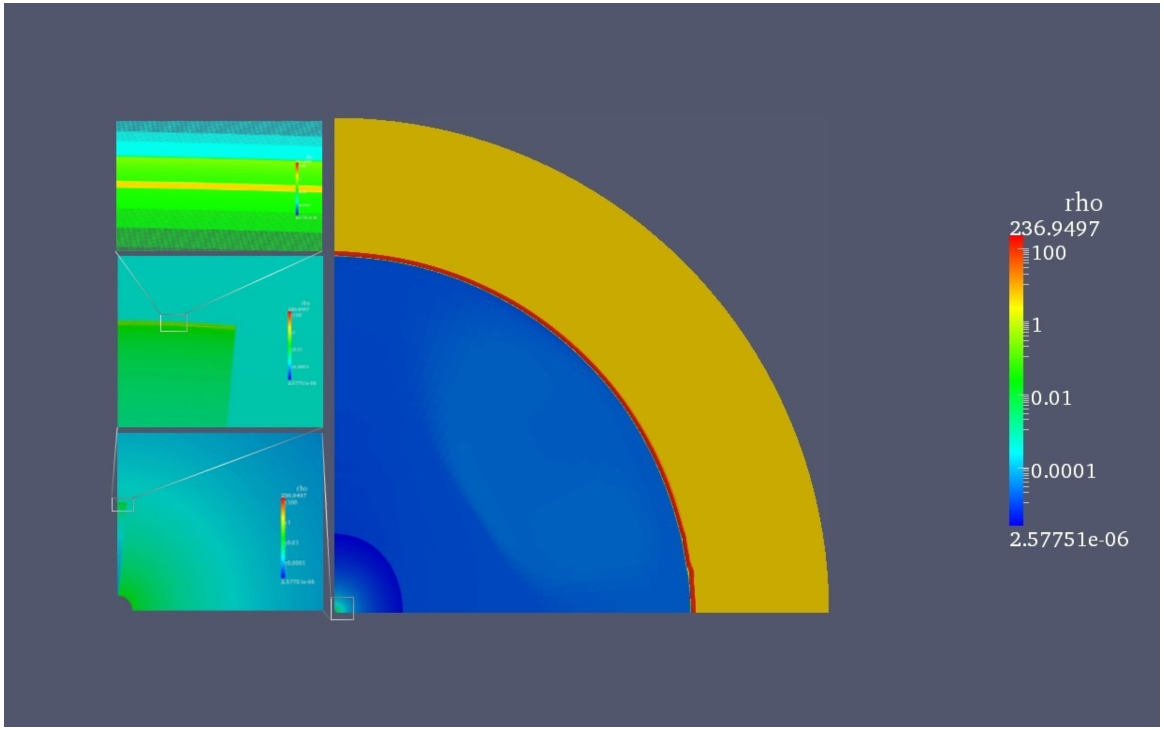




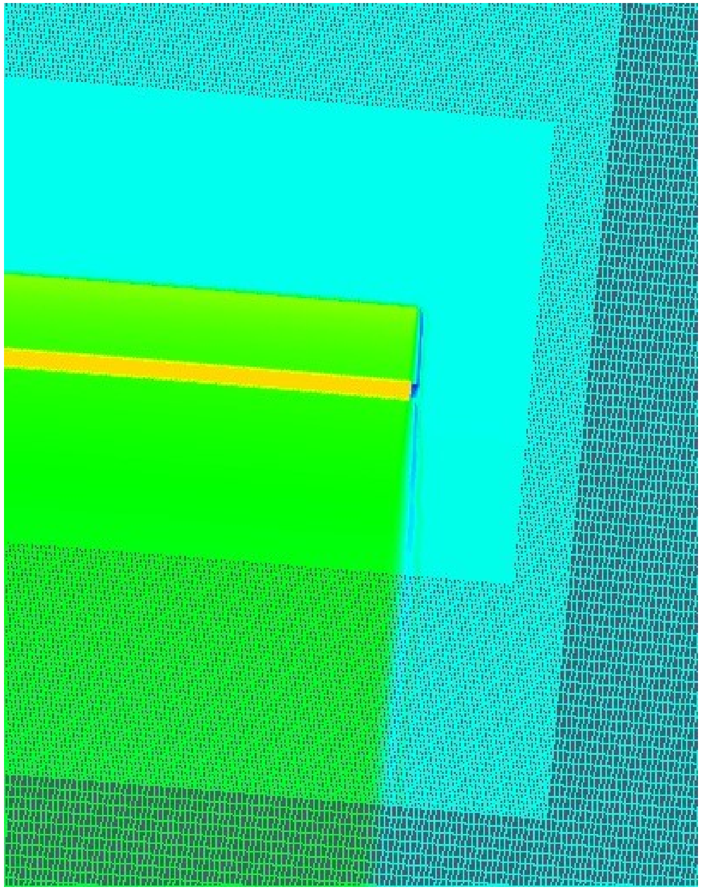
$$\frac{\dot{m}(\theta)}{\dot{m}(0)} = \frac{F(\theta)}{F(0)} = 1 - \Omega^2 \sin^2 \theta$$

Dynamical simulation of the evolution of the circumstellar medium around a fastly rotating massive star.

GRB jet propagation in a circumstellar bubble



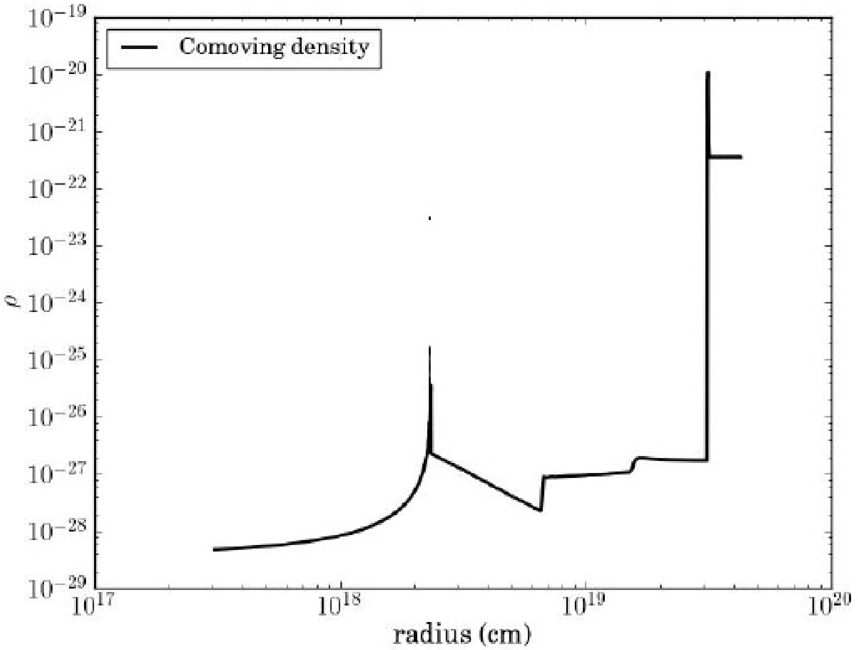
Circumstellar bubble and jet initiation

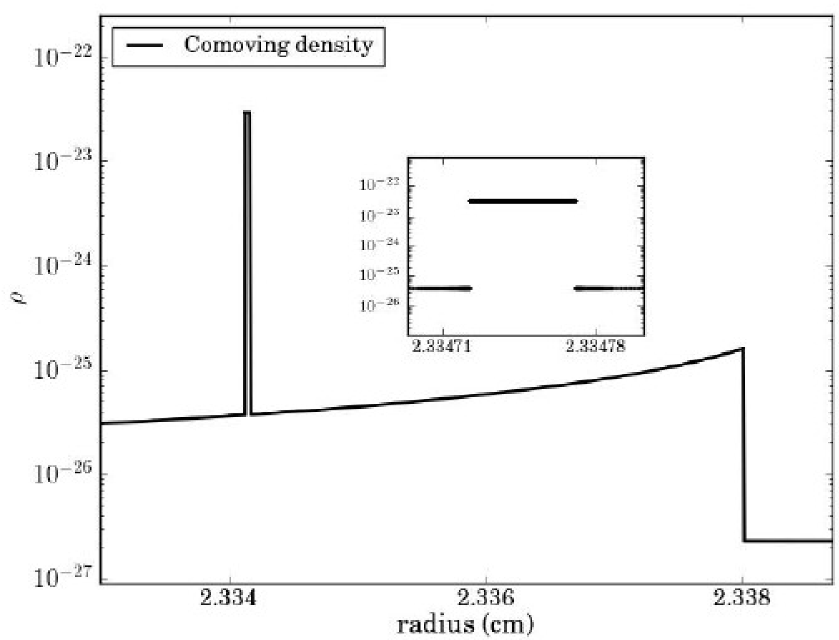


Zoom-in at the GRB jet

Jet initiation inside the circumstellar bubble. The highest resolution is enforced in the vicinity of the two shells (15 refinement levels).

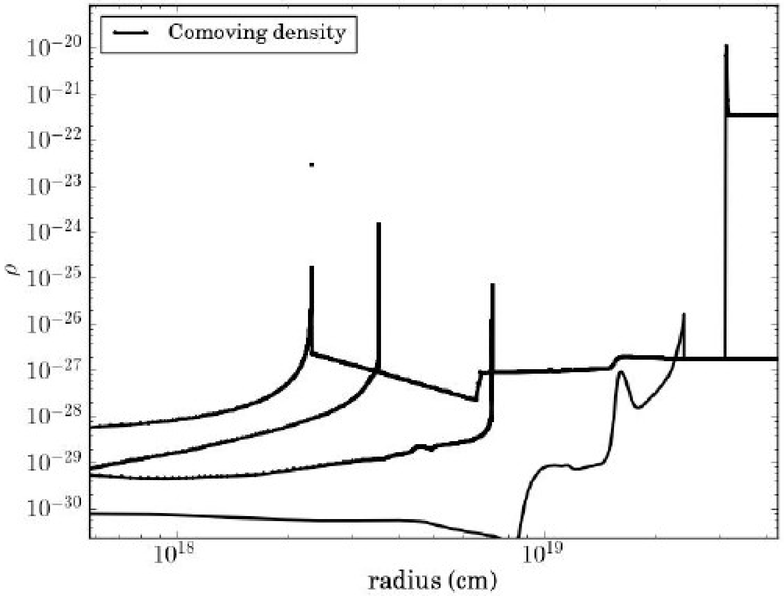
GRB jet propagation in a circumstellar bubble

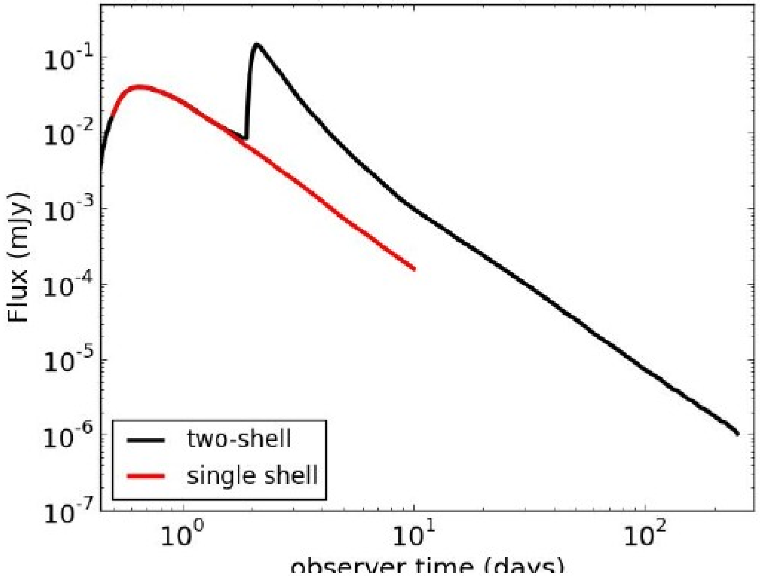




- 1D simulation with 24 levels of refinememt. Two-shell structured jet propagating into the circumstellar bubble.

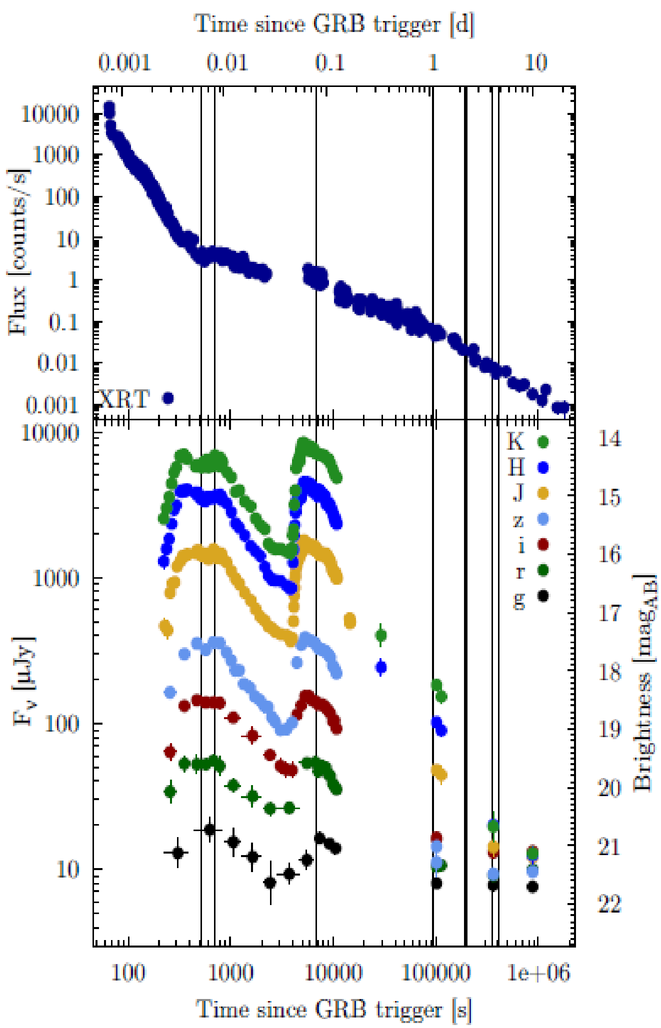
GRB jet propagation in a circumstellar bubble



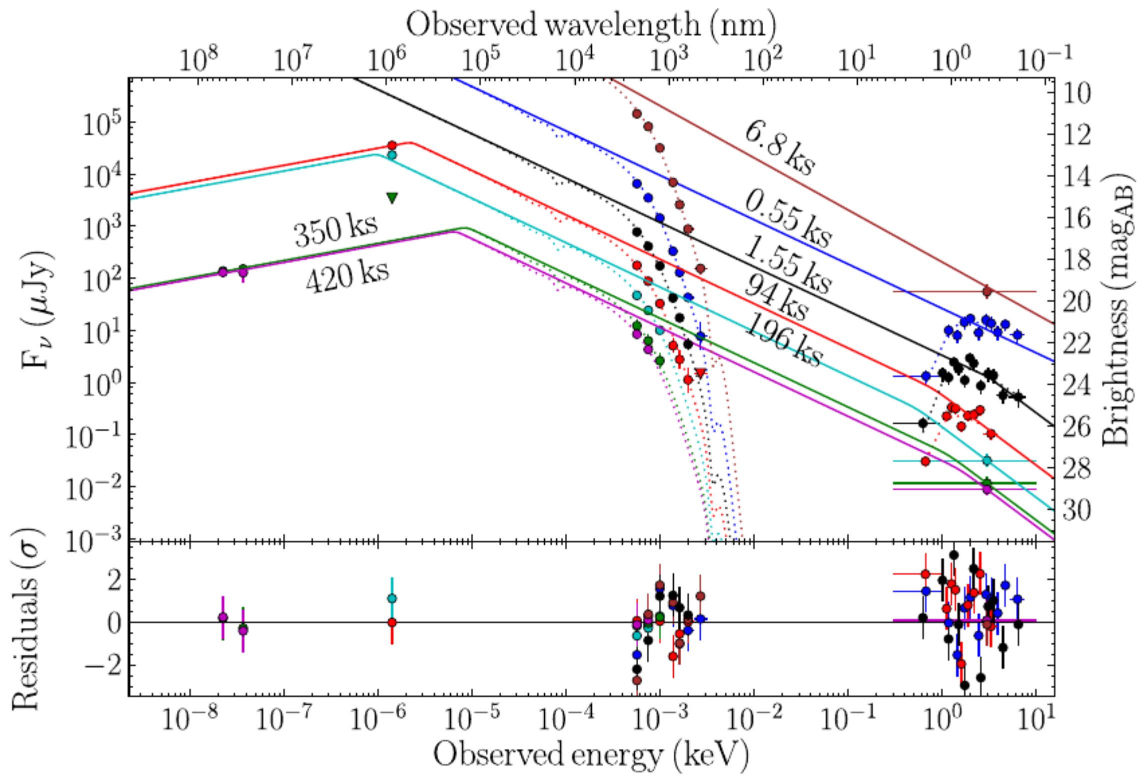


- We notice a flaring behavior due to the collision between the two shells
- The crossing from the terminal shock does not result in any significant alteration on the light curves.
- Effects arising from the crossing of the jet from the external shock are yet to be seen (simulation in progress...)

GRB 100621A



Greiner et al. 2013



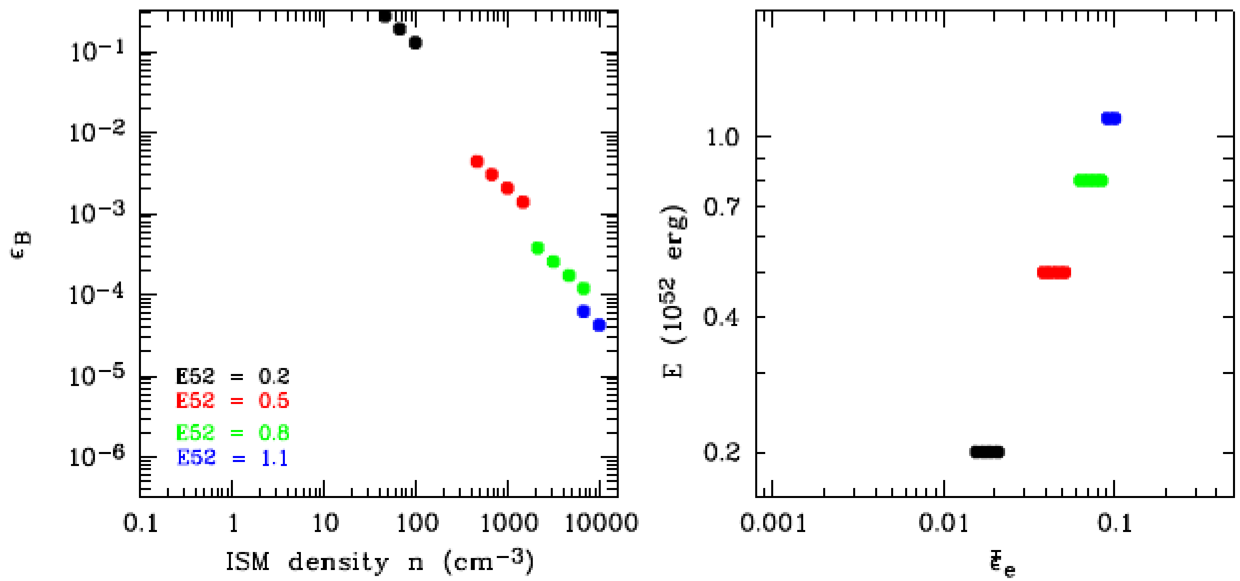
- Epoch 1
  optical/NIR and X-Rays dominated by canonical afterglow
- Epoch 2
  optical/NIR dominated by flares X-rays are superposition with canonical afterglow
- Epoch 3
  optical/NIR dominated by jump component X-rays by canonical afterglow and flares
- Epoch 4/5
  optical/NIR dominated by jump component X-rays by canonical afterglow
- Epoch 6/7
  optical/NIR dominated by jump component X-rays by canonical afterglow

GRB 100621A

- The circumburst environment is **ISM** like
- Given a steep spectral index **p=3.2**

$$\bar{\epsilon}_e^{2} \cdot \epsilon_B^{1/2} \cdot E_{52}^{1/2} = 7.0 \times 10^{-5}$$
$$\epsilon_B^{1/2} \cdot n^{1/2} \cdot E_{52} = 0.716$$

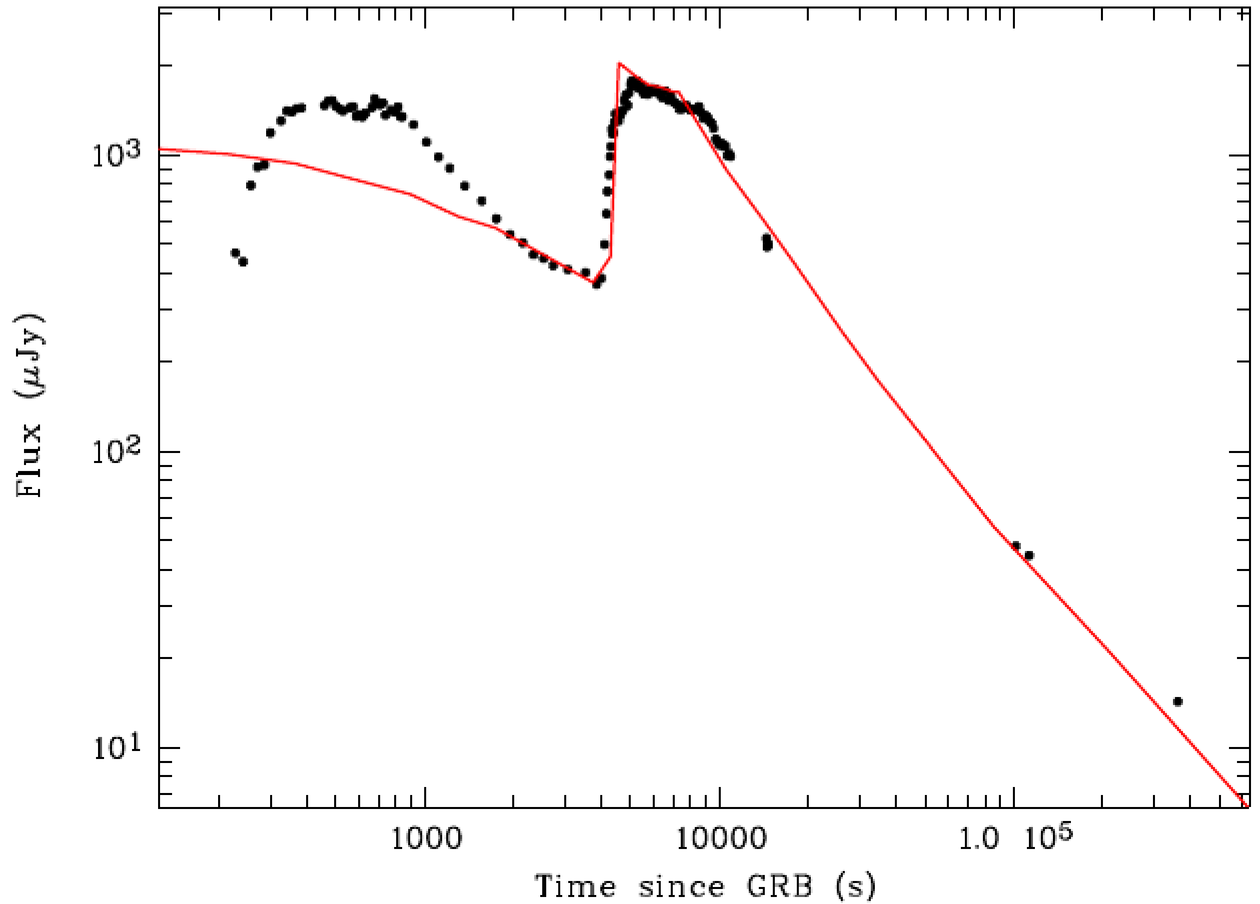
$$\bar{\epsilon}_e^{\,-1} \cdot \epsilon_B^{1/5} \cdot n^{3/5} \cdot E_{52}^{1/5} = 538$$
$$\bar{\epsilon}_e^{\,-1} \cdot \epsilon_B^{2/5} \cdot n^{7/10} \cdot E_{52}^{9/10} > 123$$



Greiner et al. 2013

GRB 100621A

$\epsilon_E = 0.1$
$\epsilon_B = 0.01$
$p = 2.5$
$\gamma = 23$
$n = 1$



Conclusions

- Strong flares appear in the afterglow due to collisions of ultra-relativistic shells. The shape of the flare depends on the physical parameters of the underlying jet
- Higher Lorentz factor and energy of the second shell translate into a significant change of the flare.
- The crossing of the jet from the terminal shock of a circumstellar bubble doesn't influence significantly the shape of the light curve.
  Possible influence of the crossing from the external shock should be anticipated.
- GRB 100621A is a strong candidate for the validation of the shock-refreshement scenario. Most likely this event is taking place in an ISM like environment.