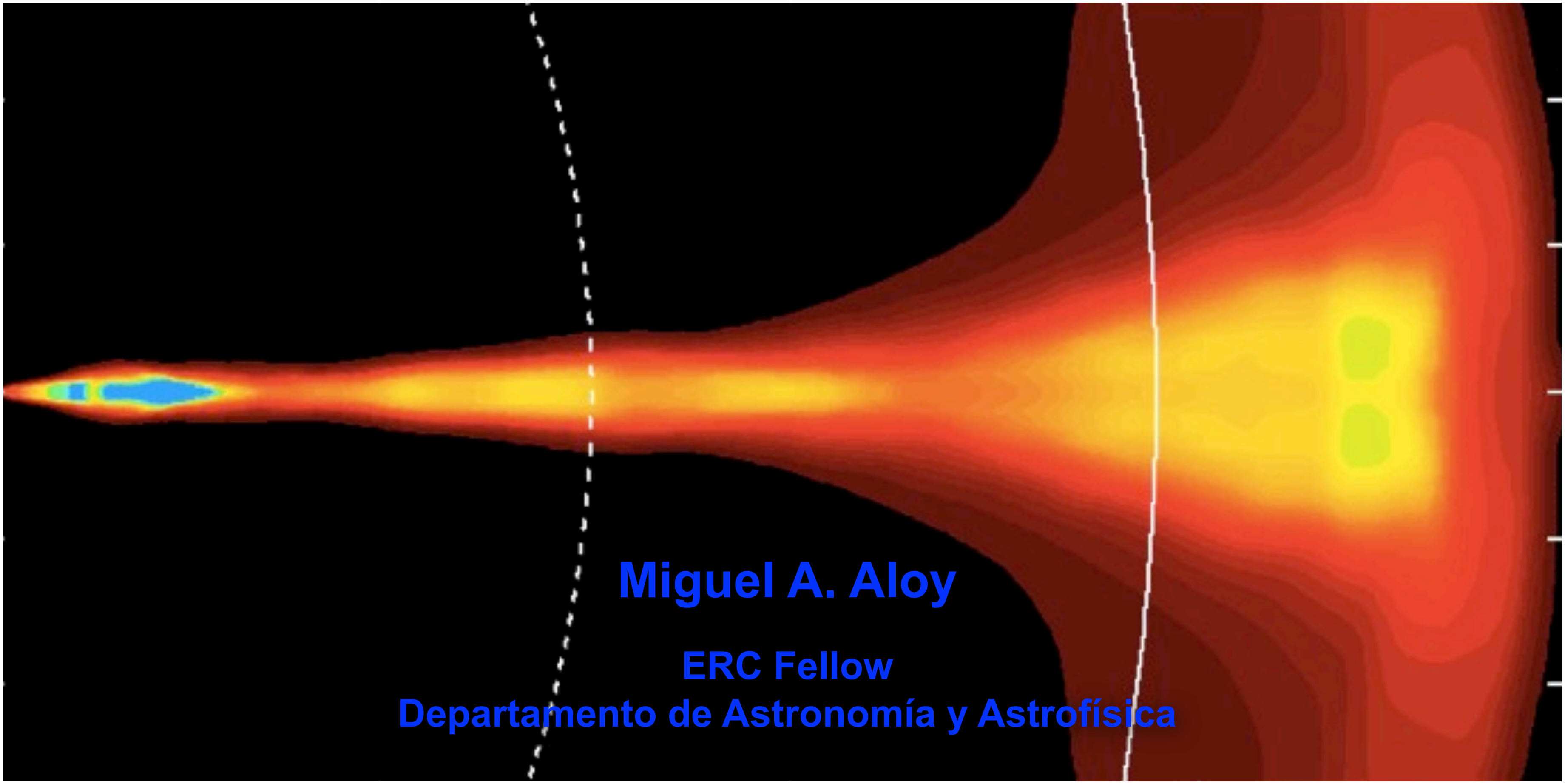
Gamma-ray burst jets



Miguel A. Aloy

ERC Fellow
Departamento de Astronomía y Astrofísica

collaborators
N. DeBrye, T. Rembiasz, M. Obergaulinger, P. Cerdá-Durán,
P. Mimica, E. Müller, A. Mizuta, etc.

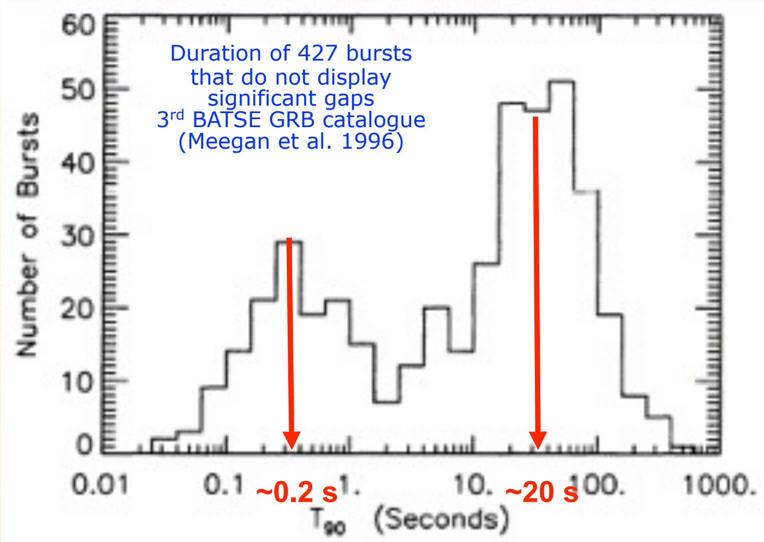
EANAM- 2012

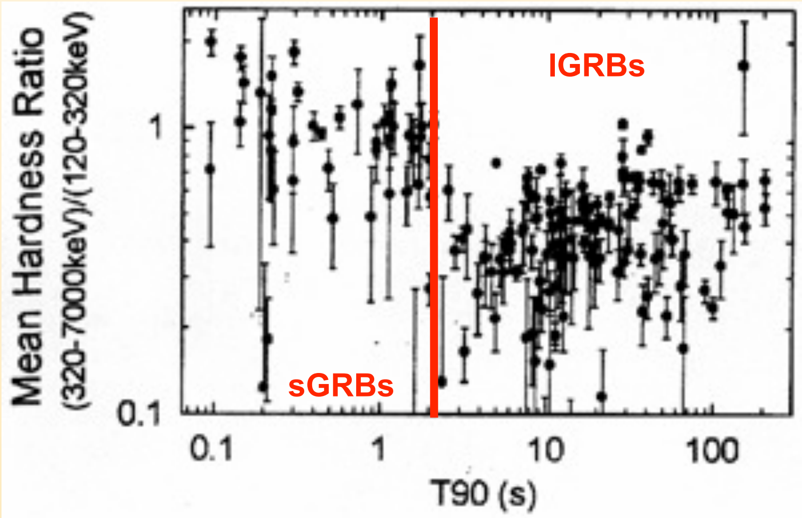
Kyoto, 30 – 10 - 2012

General Properties of (typical) GRBs

Observed:

- Duration: 0.01-1000 s.
  Two classes:
  - *Short:* T_{90} < 2s, harder
  - *Long:* T_{90} > 2s, softer





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  - *Short:* T_{90} < 2s, harder
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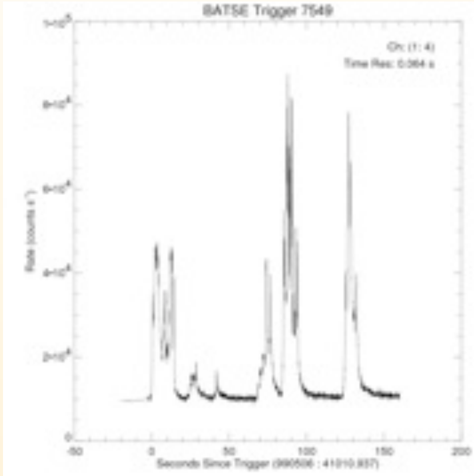
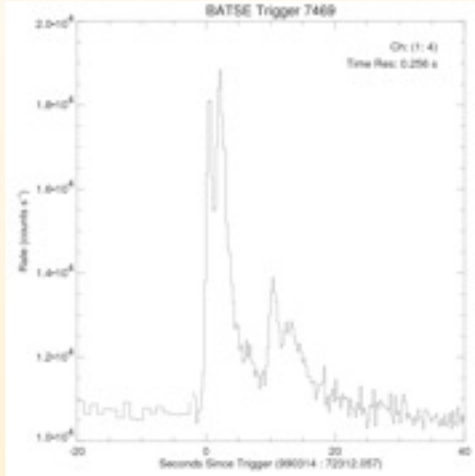
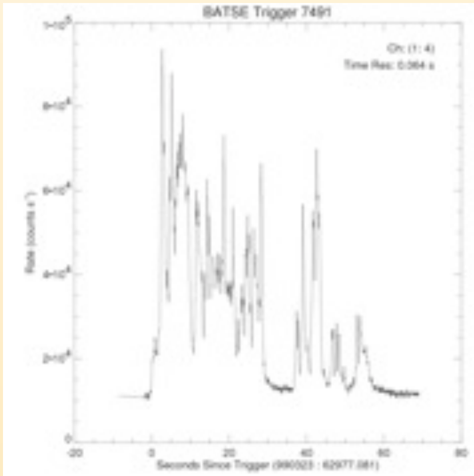
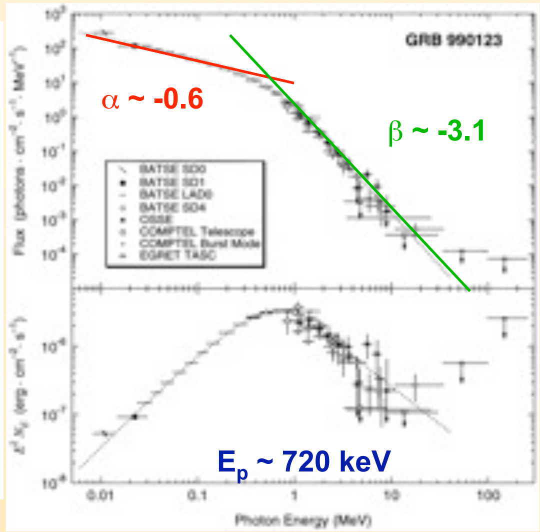
- Fluence: $S \sim 10^{-7}$-10^{-3} erg/cm^2
- Spectrum: non-thermal,
  0.1-100 MeV
- Variability: high, 1-10 ms
- Rate: 1/day **(lGRBs)**
  0.3/day **(sGRBs)**









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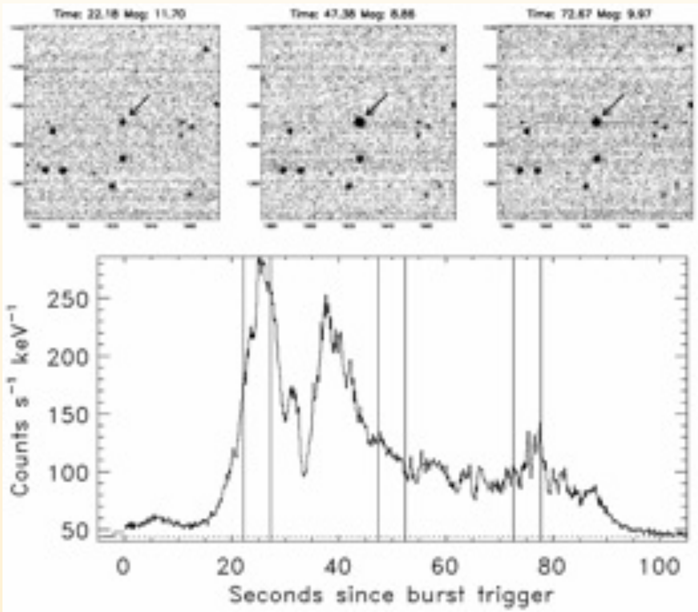
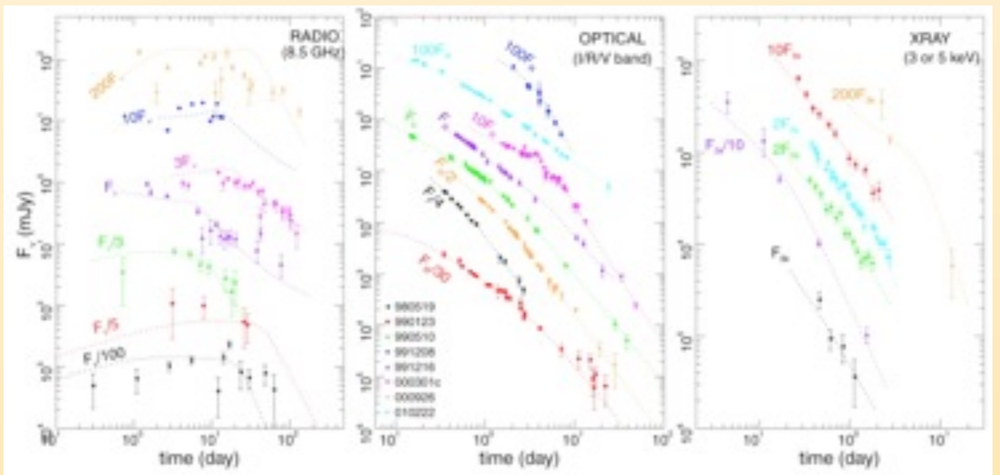
- Variability: high, 1-10 ms
- Rate: 1/day **(lGRBs)**
  0.3/day **(sGRBs)**
- Associated events: afterglows in X-rays (~100%), optical (~70%), radio (~50%)
  $F(t) \sim t^{-a}$ $a \sim 1 - 2$
- Host galaxies:
  lGRBs: starforming, dwarf, low-metallicity
  sGRBs: old elliptical + sligthtly star-forming
- Location:
  lGRBs: z=0.0085 - 8.2, <z>~1.3 - 2,
  sGRBs: z=0.16 - 6.7, <z>~0.3-0.5

3 ROTSE prompt optical images (Akerlof et al. 1999)

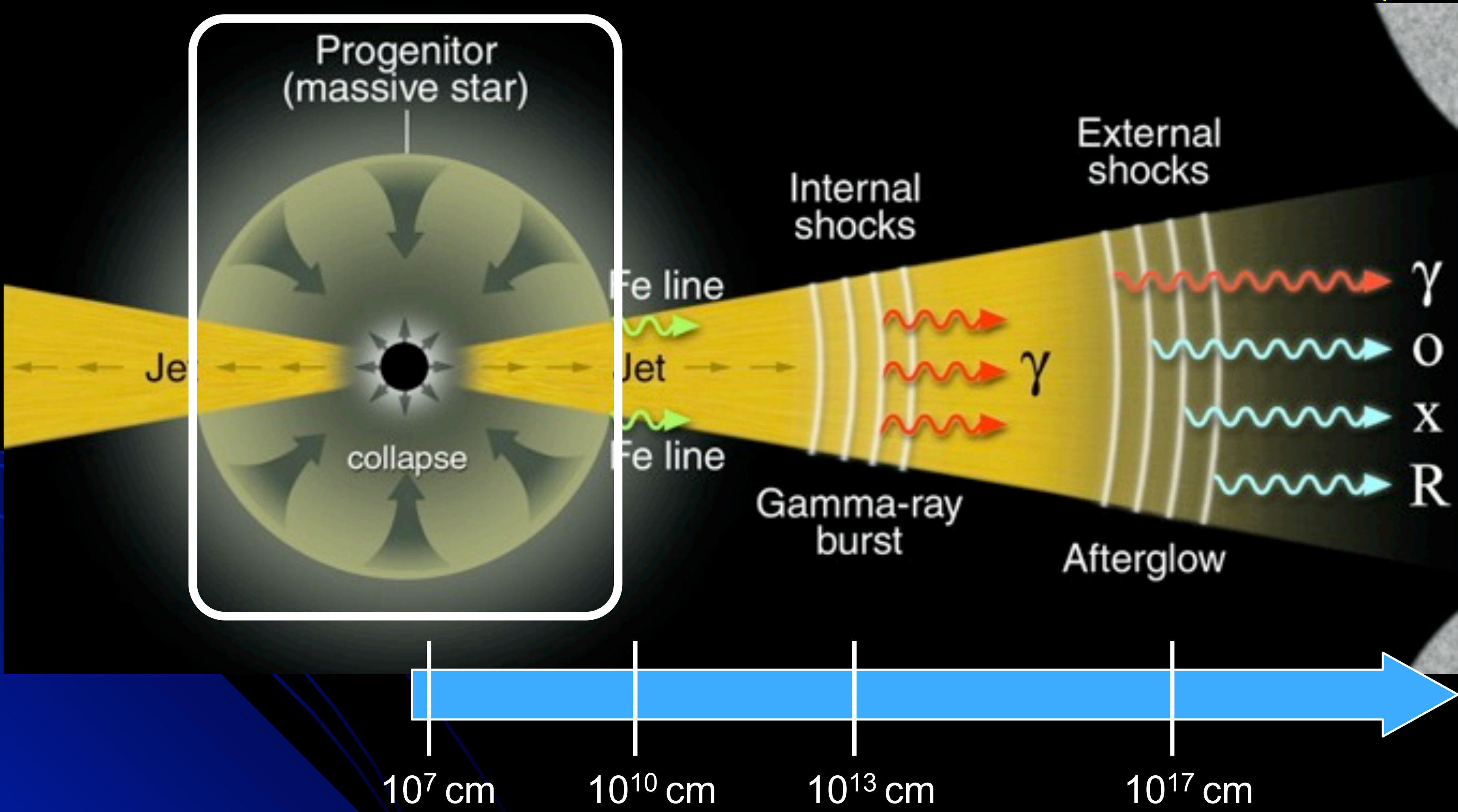


BATSE time profile. The intervals between vertical lines correspond to the 3 optical observations



GRB jets: a multiscale problem

Meszaros (2002)

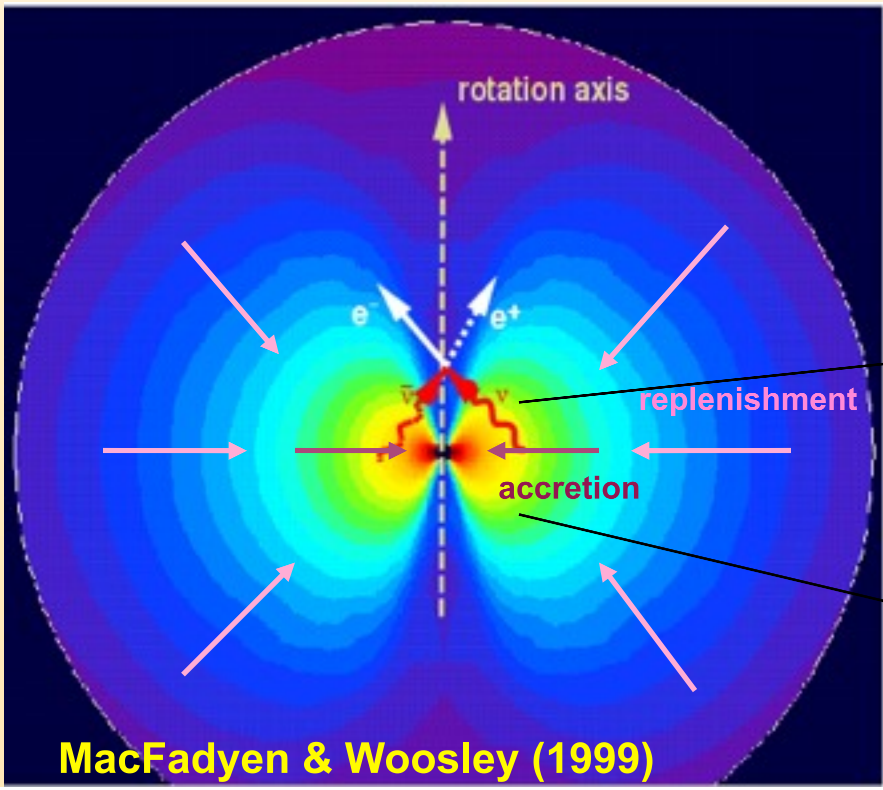


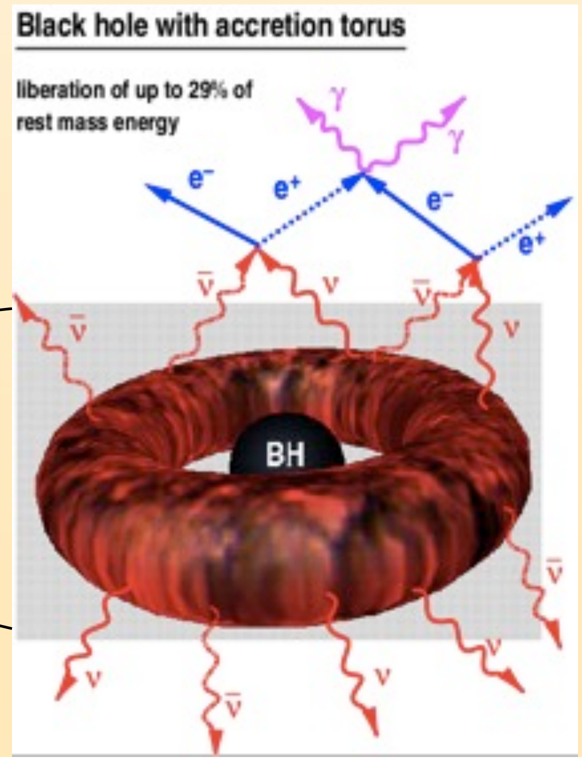
Progenitors lGRB: Collapsars

Woosley (1993)

Collapse of a massive ($M_* \sim 30M_\odot$, WR) rotating star that does not form a successful SN but collapses to a BH ($M_{BH} \sim 3M_\odot$) surrounded by a thick accretion disk. The hydrogen envelope is lost by stellar winds, interaction with a companion, etc.

- The viscous accretion onto the BH ⇒ strong heating ⇒ thermal νν-annihilating preferentially around the axis ⇒ formation of a relativistic jet (Γ>10)?.
- Alternative generation: hydromagnetic (Blandford-Payne mechanism) or electromagnetic (Blandford Znajek mechanism).





The formation of the central engine

DeBrye, Cerdá-Durán, Font, Aloy (2012), in prep.

GRHD simulations:

sufficiently massive stars collapse and form BHs

(e.g., O'Connor & Ott 2011, Dessart, O'Connor & Ott 2011)

↓

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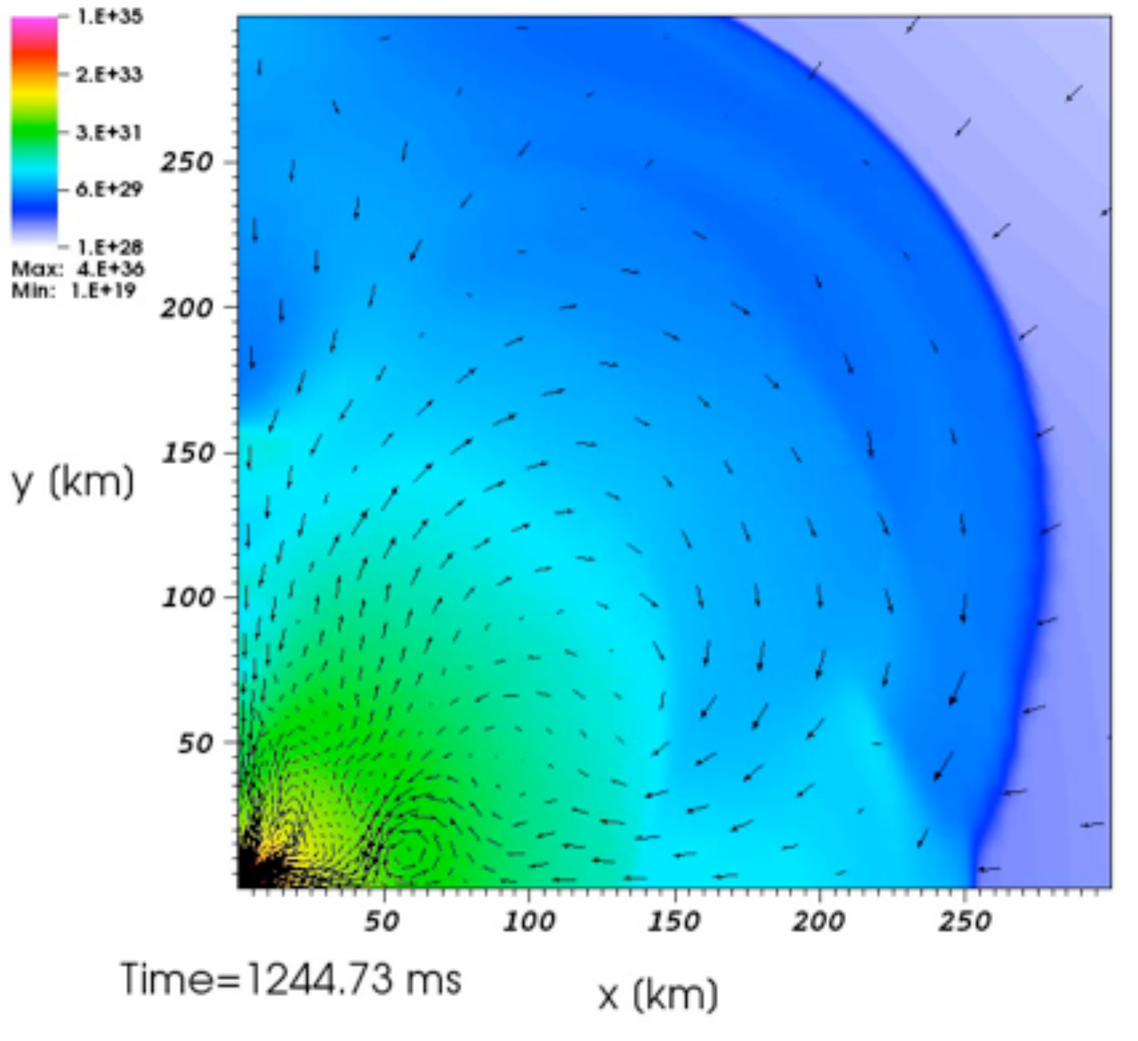
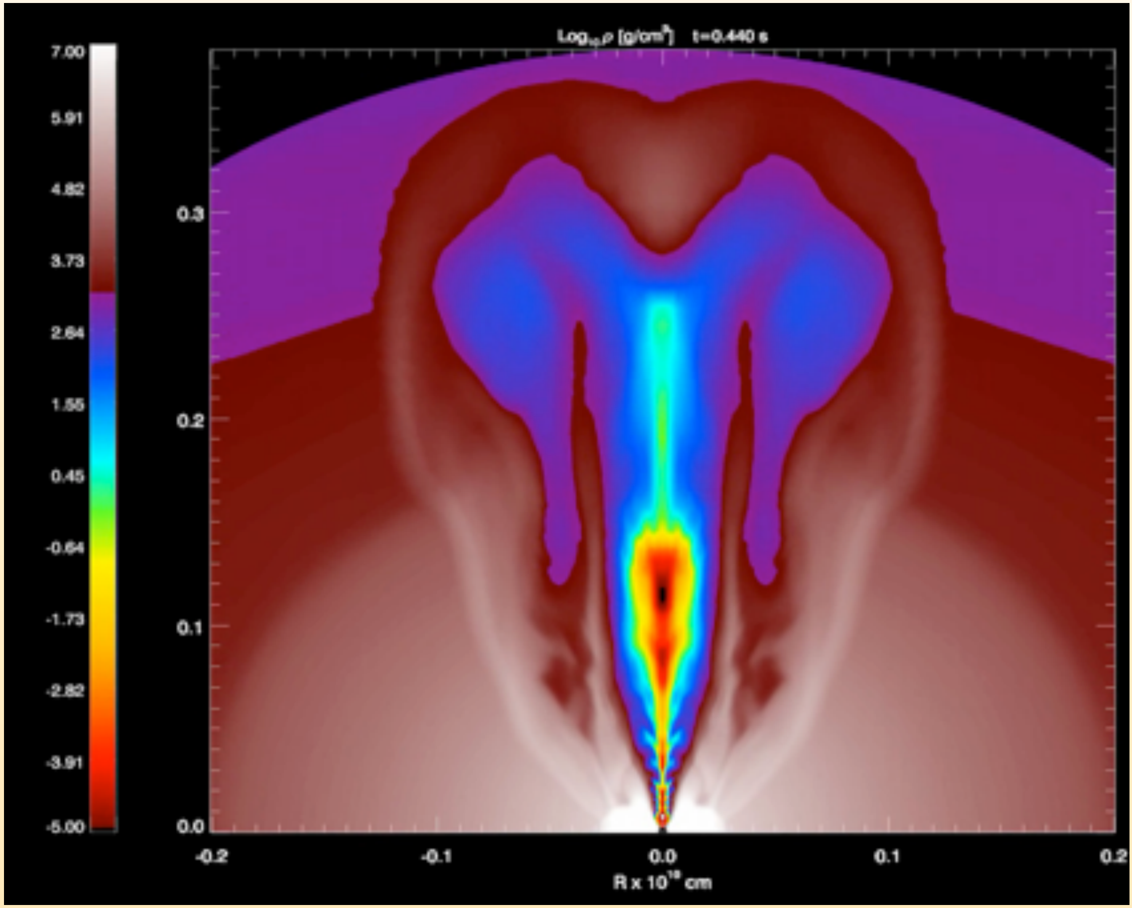


Generic features learned from numerical simulations of collapsars



Aloy et al (2000)

(see also Mizuta's talk)

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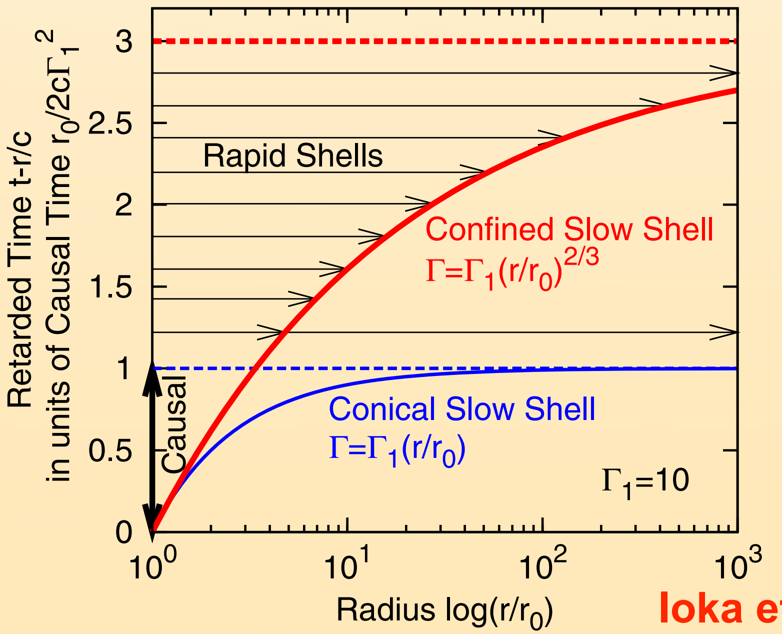
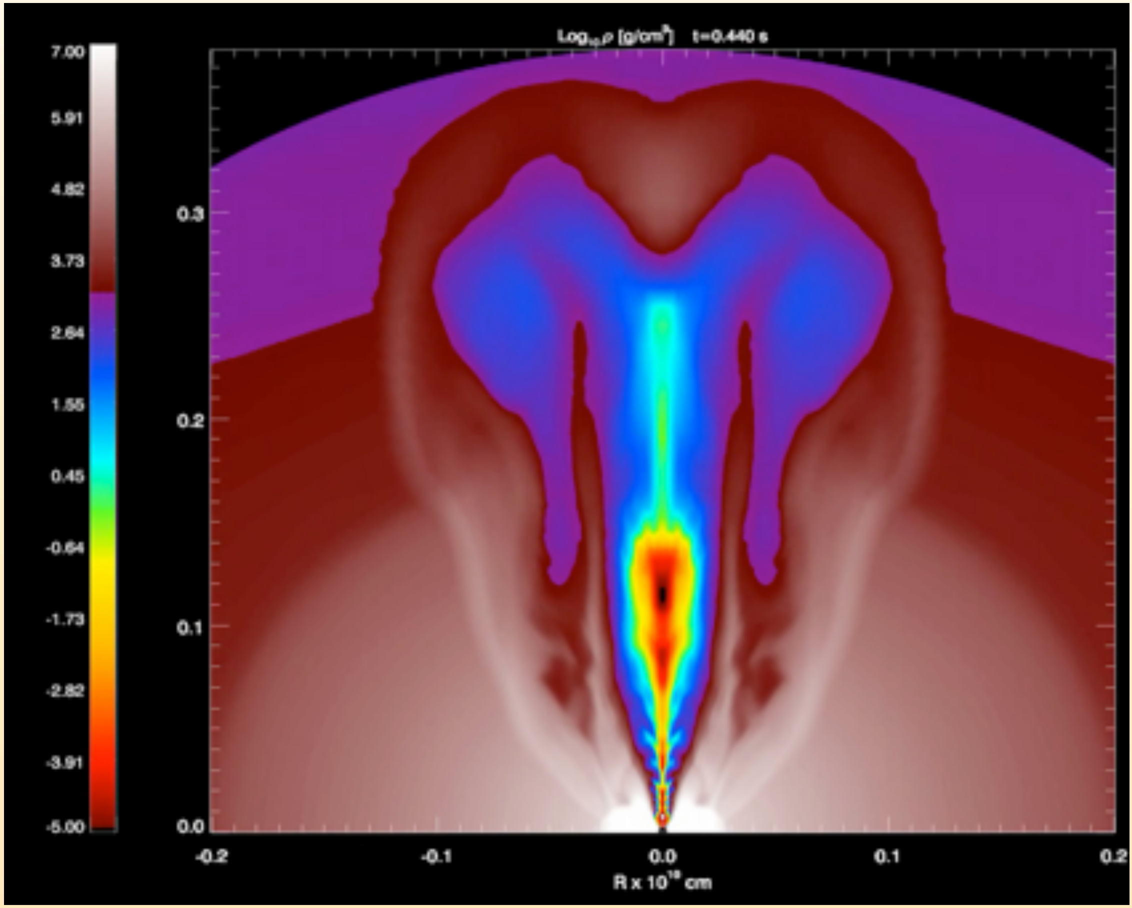
COLLIMATION:

– Jets are inertially (progenitor recollimation) or magnetically (self-collimation) confined with $\theta_{break}<5^o$ (even if $\theta_0=20^o$; Zhang et al 2003). Indeed, θ_{jet} decreases with distance, which is important for IS models (Ioka et al. 2011).



Ioka et al (2011)



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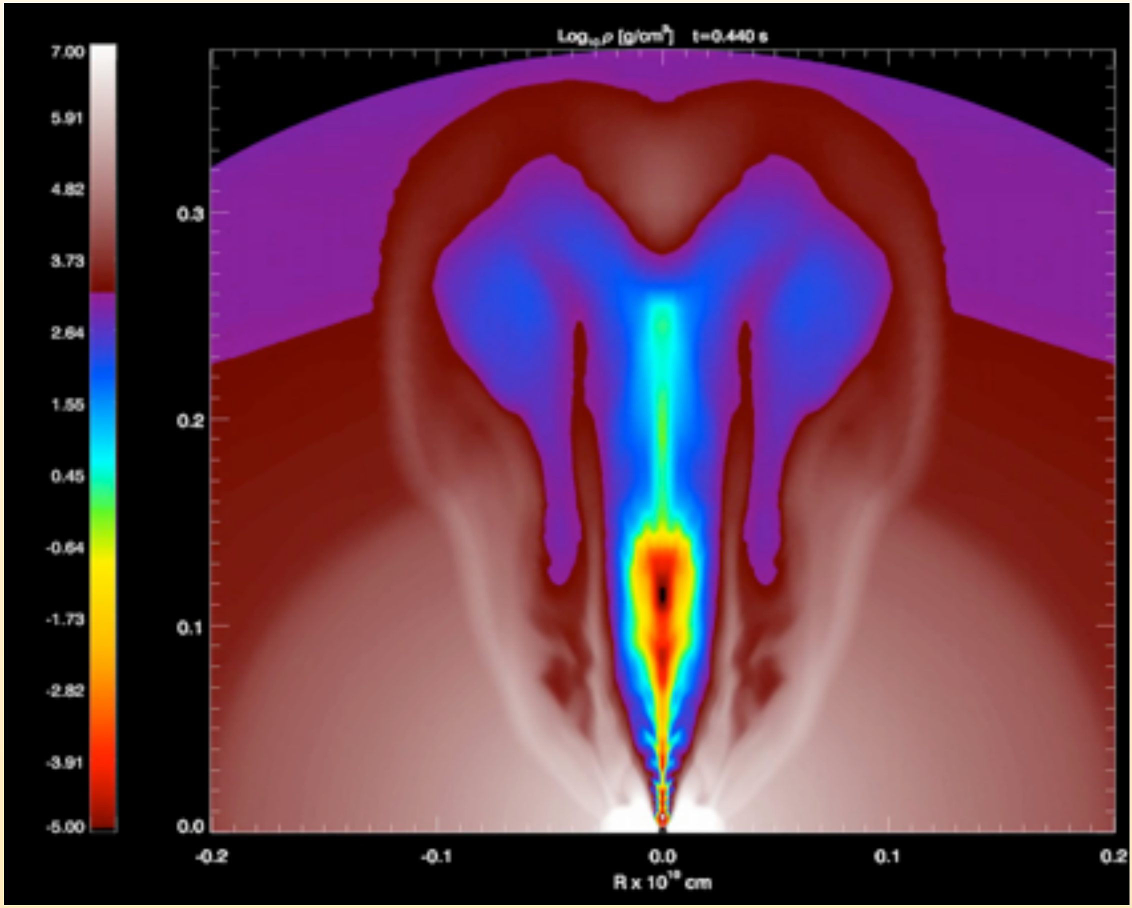
– Jets show transverse structure: ultrarelativistic spine ($\Gamma\sim50$) of $\theta_{core}<5^o$ + moderately relativistic, hot shear layer ($\Gamma\sim5\text{-}10$) extending up to $\theta_{shl}<30^o$ (Aloy et al. 2000, 2002)



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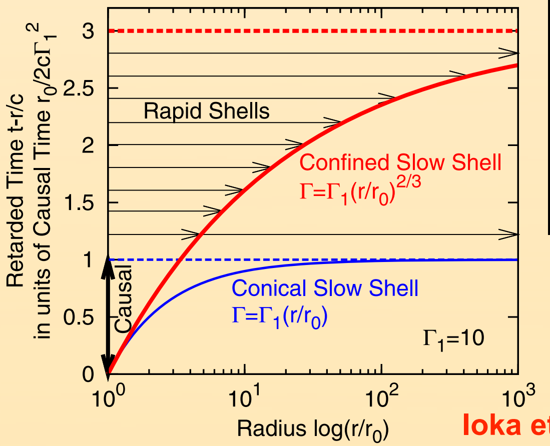

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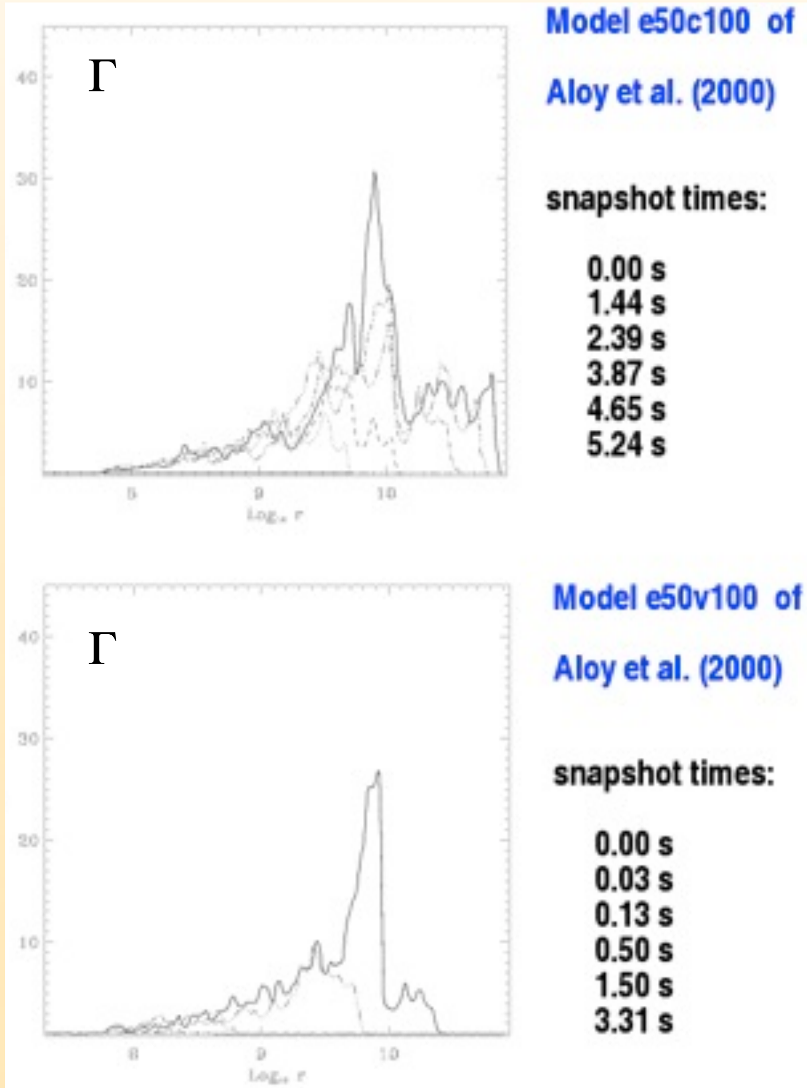

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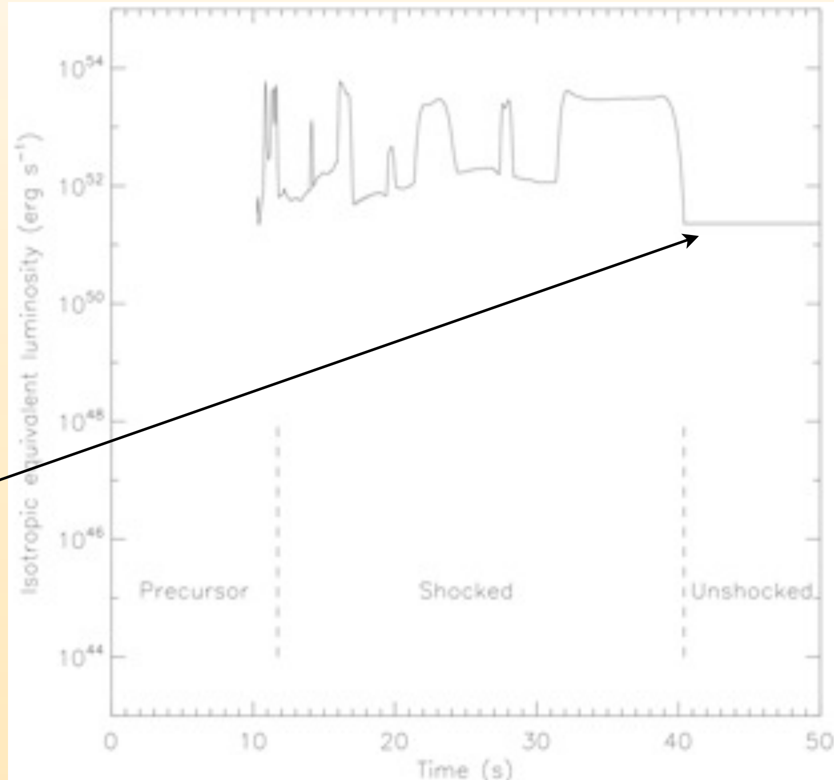
3. Morsony et al. (2007) speculate that intrinsic source variability might be observed in the tail of the GRB emission (unfortunately, the faintest!).



Morsony et al. 2007

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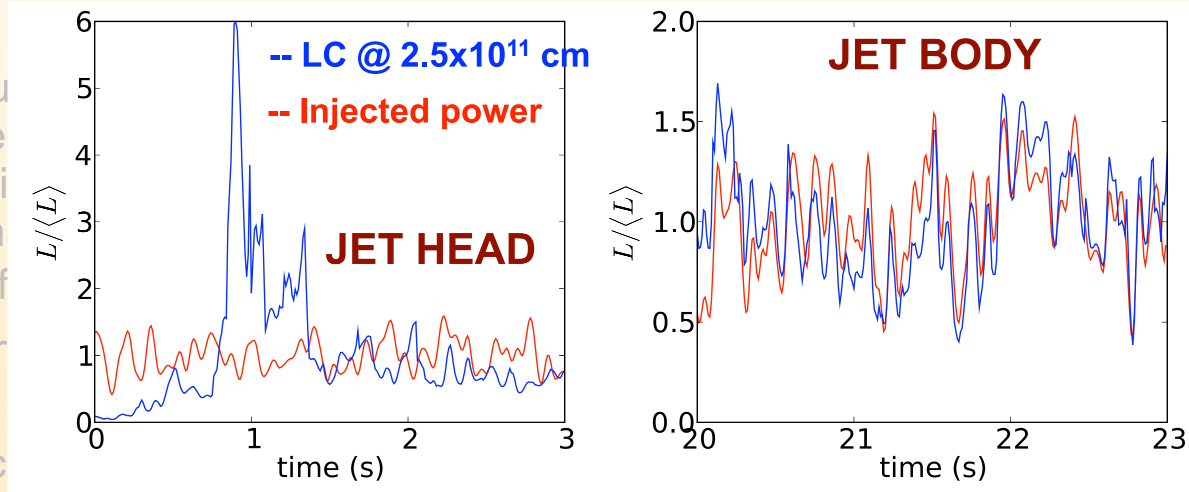

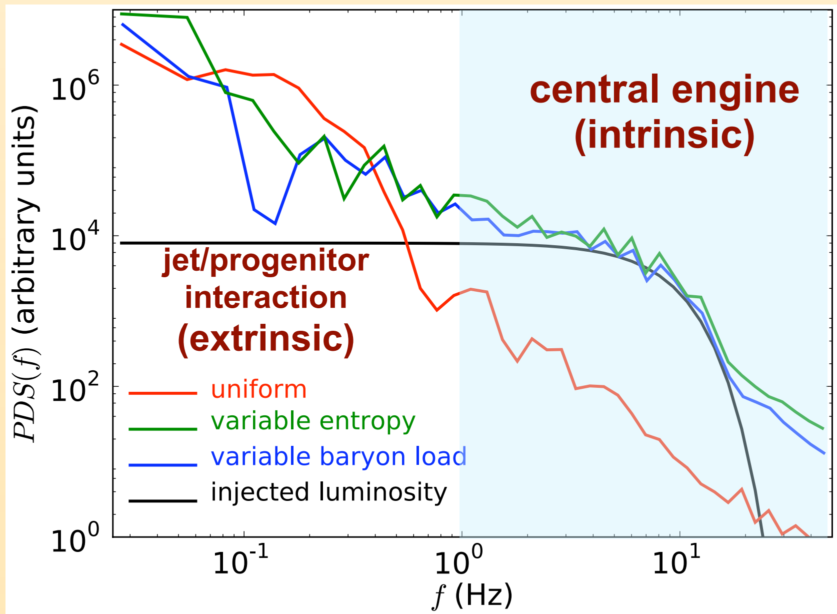

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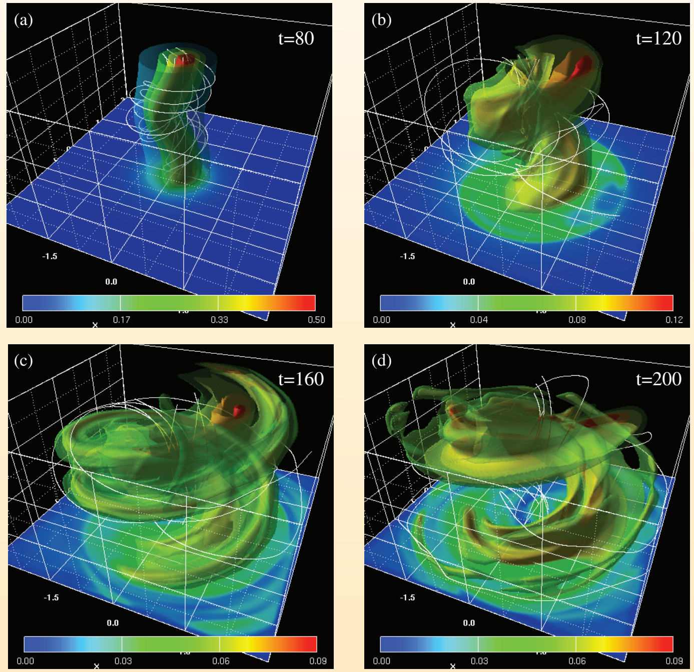
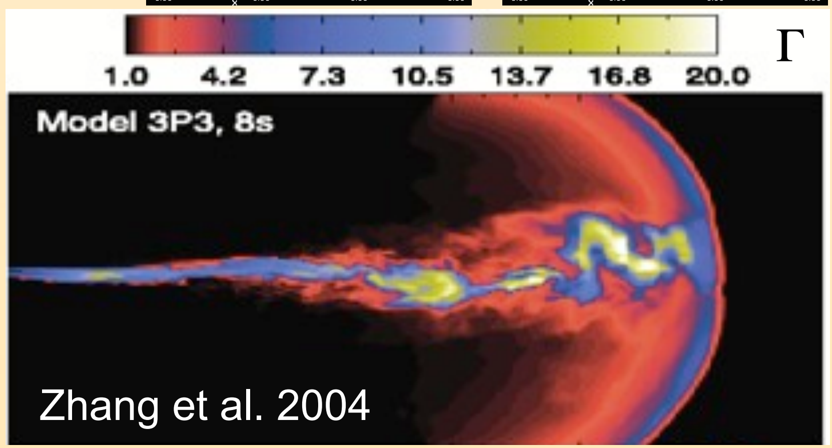
5. Jets are also stable in 3D RHD (Zhang et al. 2004) but still unclear whether 3D RMHD collapsar-jets will be stable (Mizuno+ 2012).



Mizuno et al. 2012

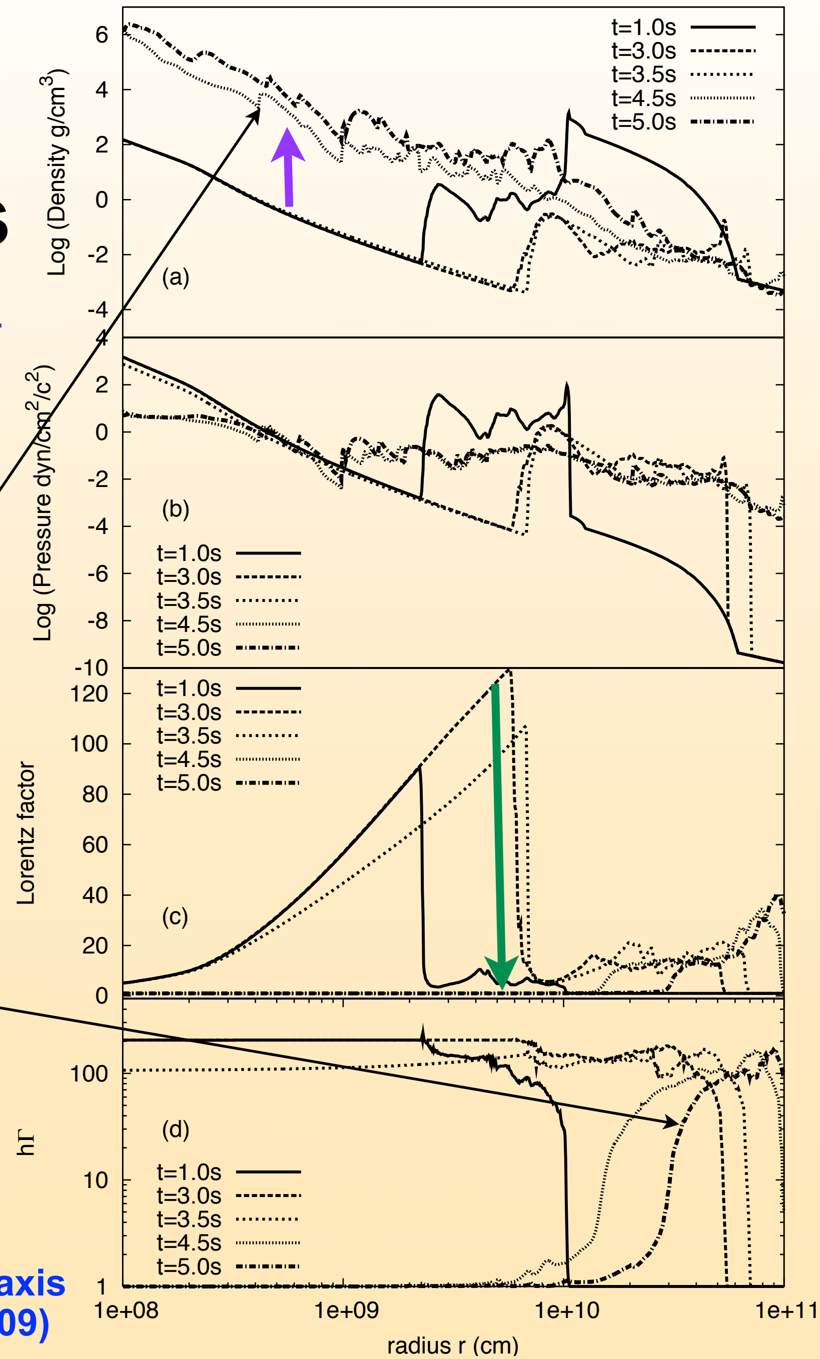


R~10^{11} cm

Generic features learned from numerical simulations of collapsars

DYNAMICS AFTER THE ENGINE TURNS OFF

- Engine is switched gradually off after t_{inj}=3 s.
- The unshocked region is lost
  - The unshocked region is refilled from the sides: ρ grows yielding a decrease of Γ.
  - To see any effect of the engine variability (as suggested by Morsony et al. 2007) the injection must be rather long $t_{inj} \gtrsim 20$ s.
  - *Short* ($t_{inj} \lesssim 5$ - 10 s) long GRBs will show only extrinsic variability (not from the engine).
  - The shocked region accelerates by conversion of thermal-to-kinetic energy, being possible to reach Γ_∞ ~200



Model HE16, profiles along the axis Mizuta & Aloy (2009)

Why do we need magnetic fields to grow?

But if there is:

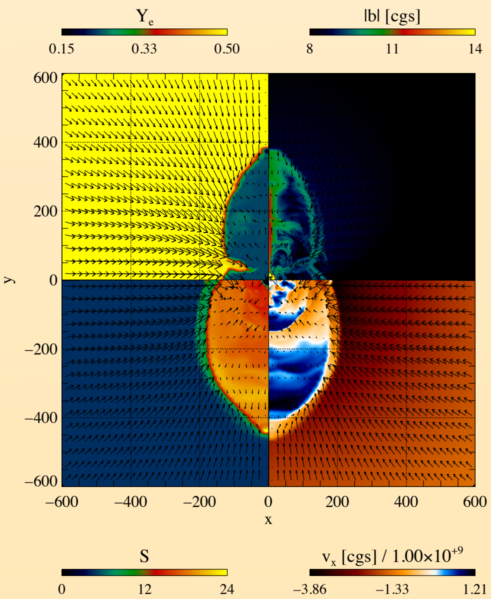
rotation, and **seed magnetic fields**

(working out time-scales and different amplificat. mechanisms)

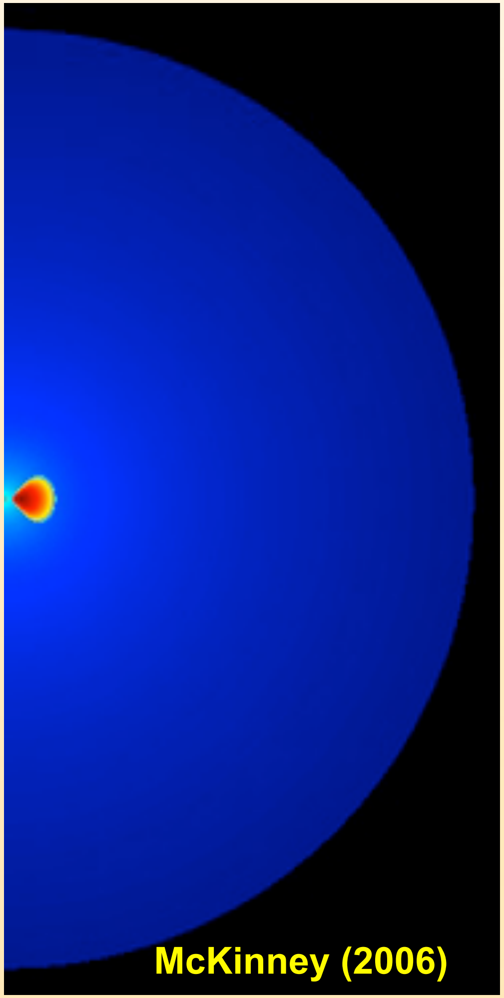
→ **magnetic fields can be terribly amplified!**

↓

Jet production



Obergaulinger, Aloy & Müller (2006); see also Takiwaki, Kotake & Sato (2009); Nagataki (2009)



Why do we need magnetic fields to grow?

— The B-fields in presupernova models are too small.

But if there is:

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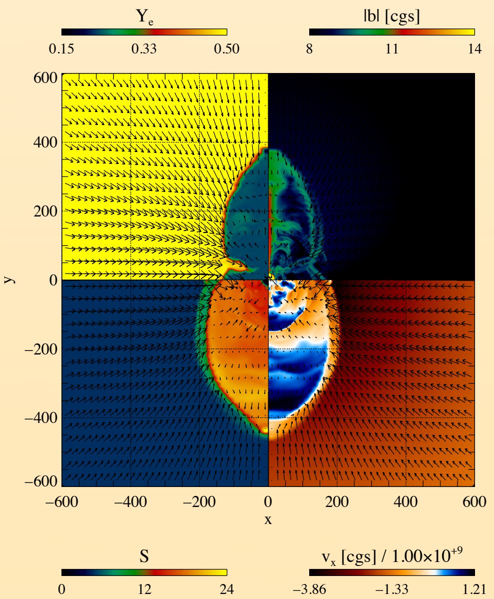

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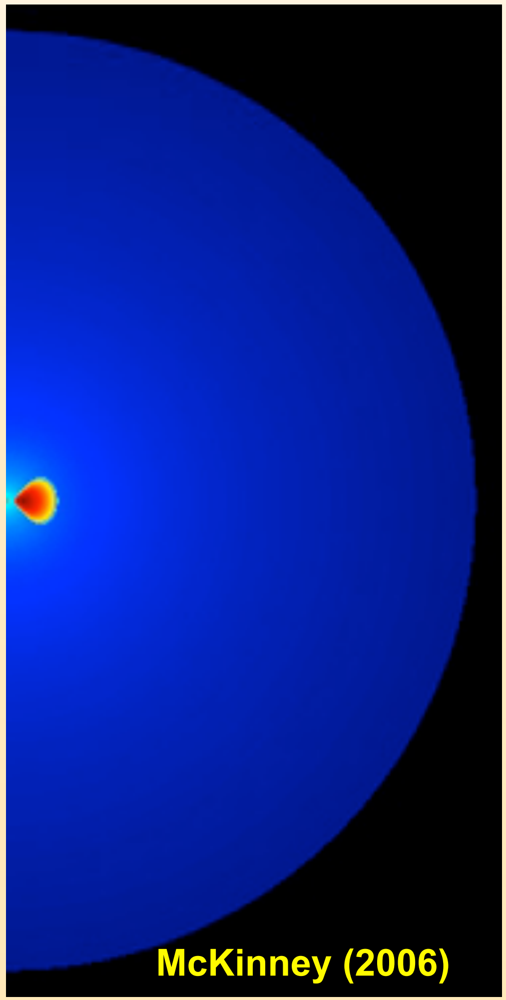
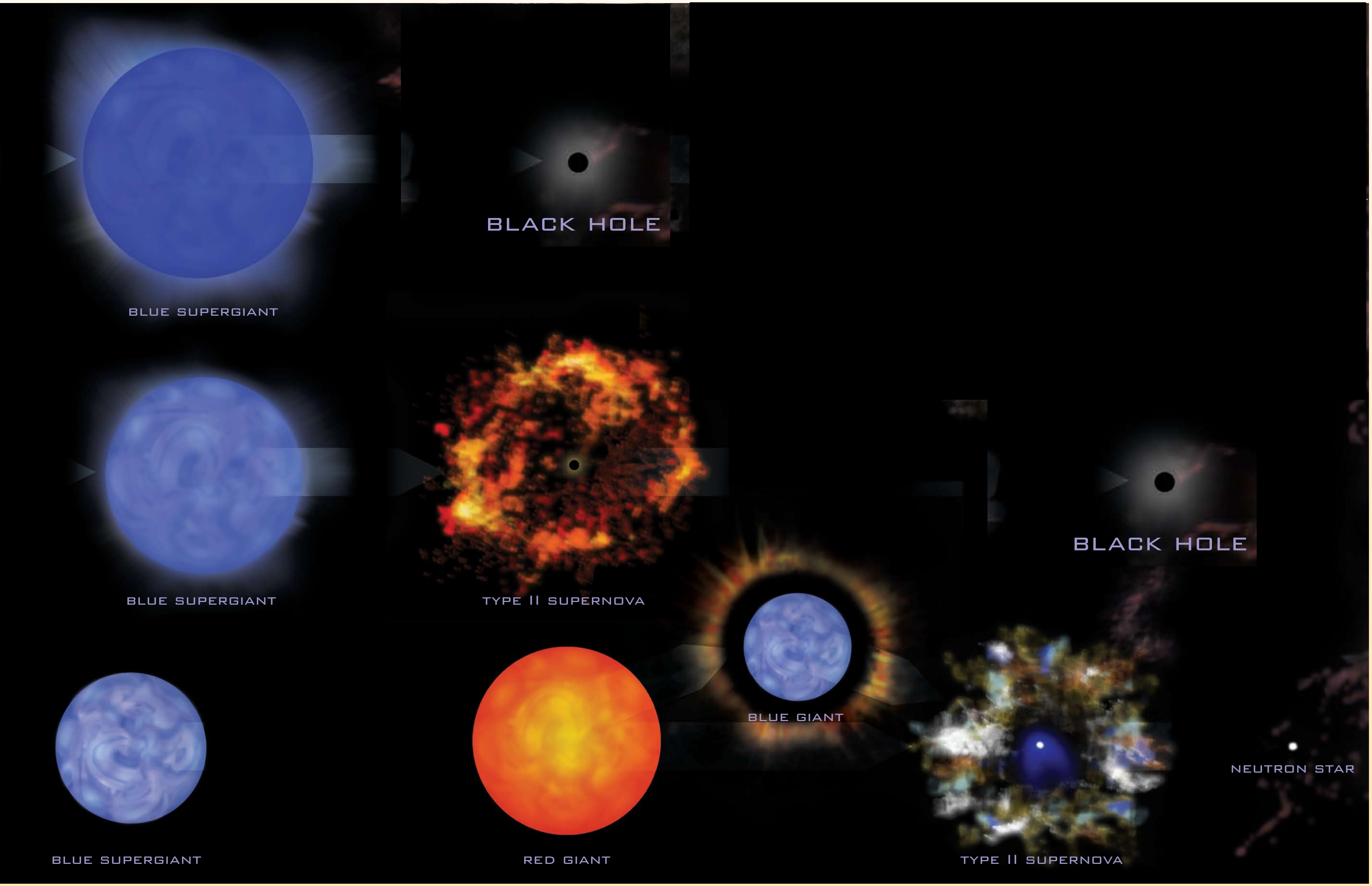


(see Moiseenko's talk)

B-field growth in PNS and CC-SNe



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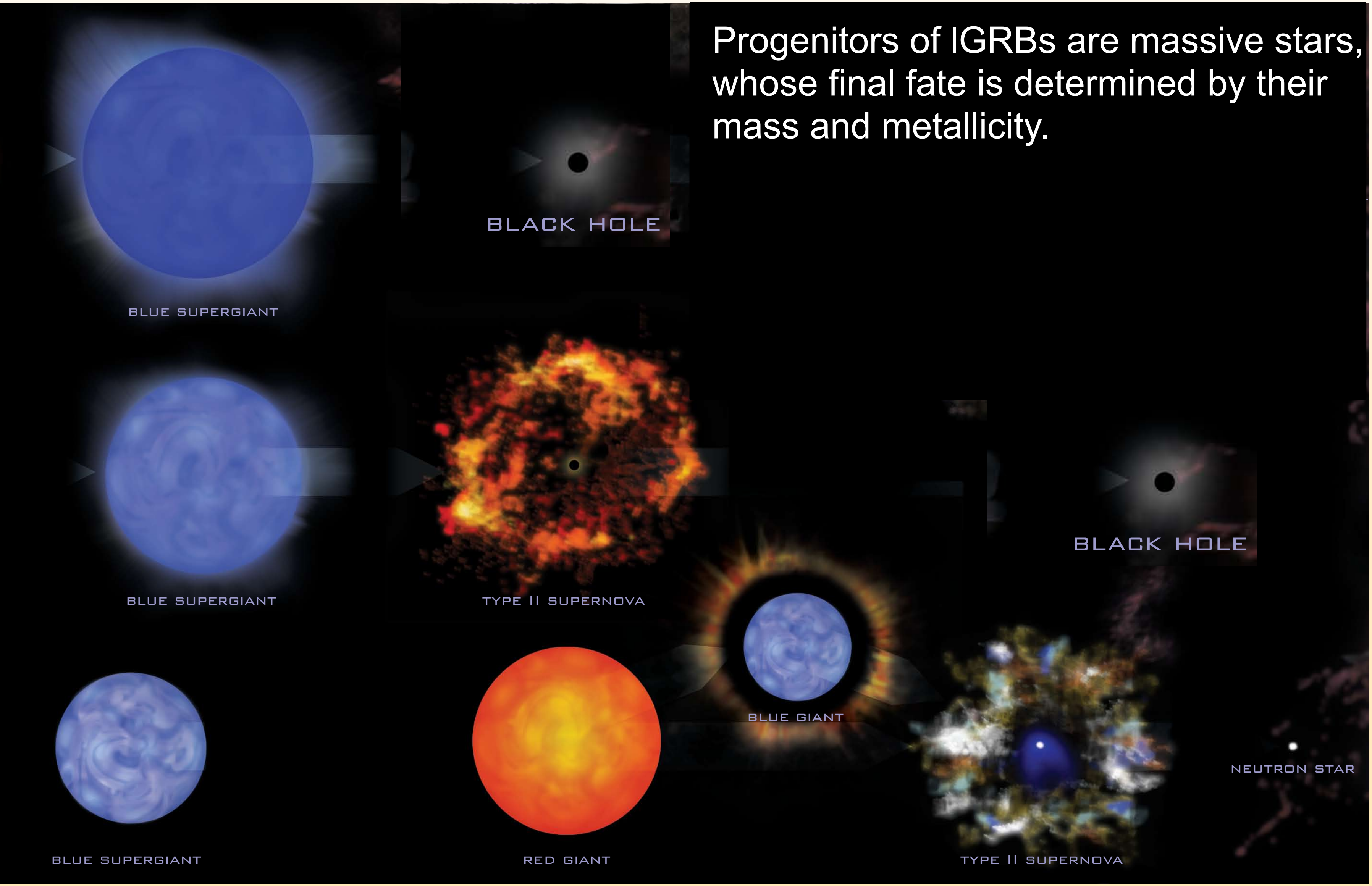
Progenitors of lGRBs are massive stars, whose final fate is determined by their mass and metallicity.



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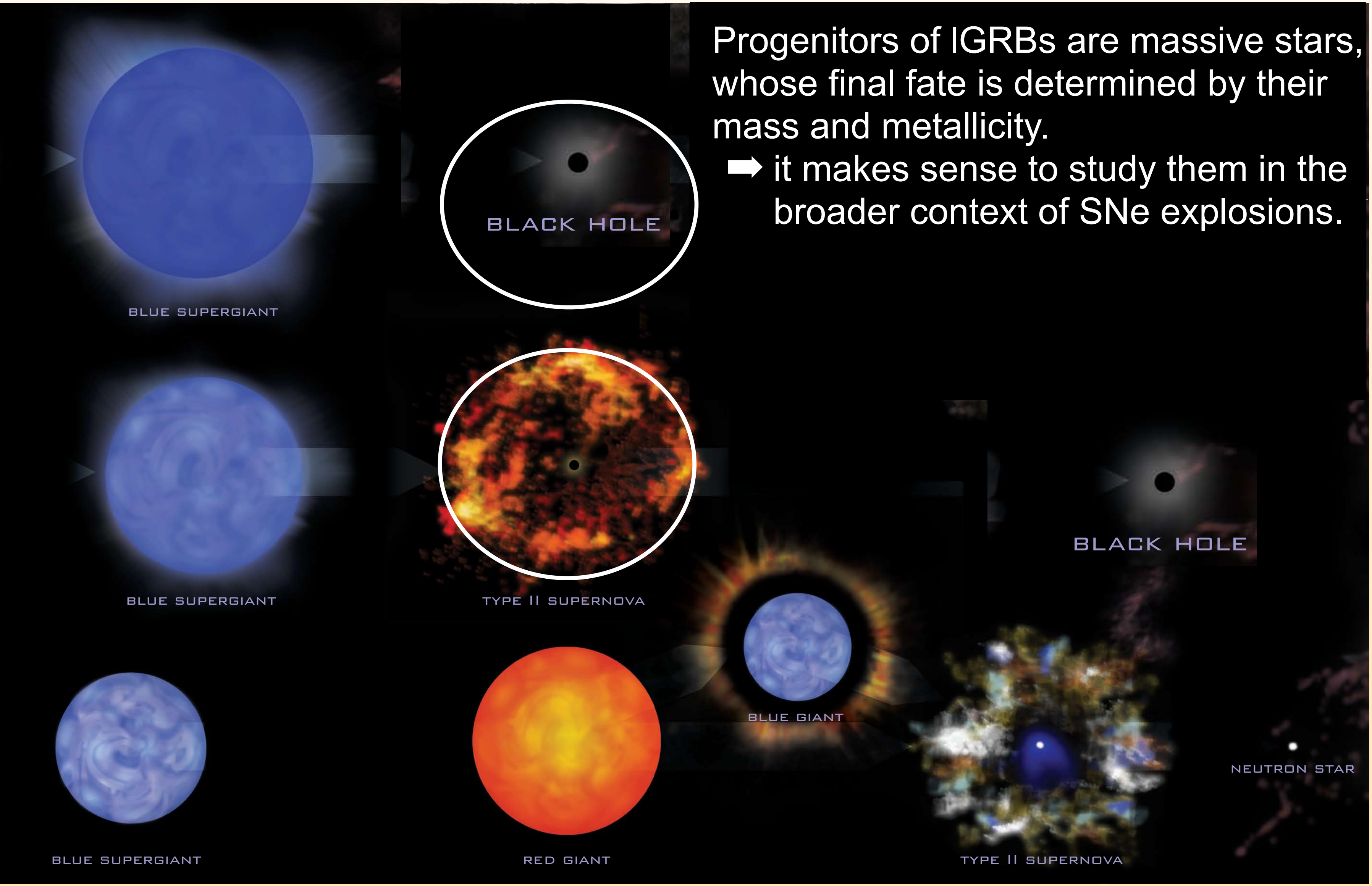
➡ it makes sense to study them in the broader context of SNe explosions.



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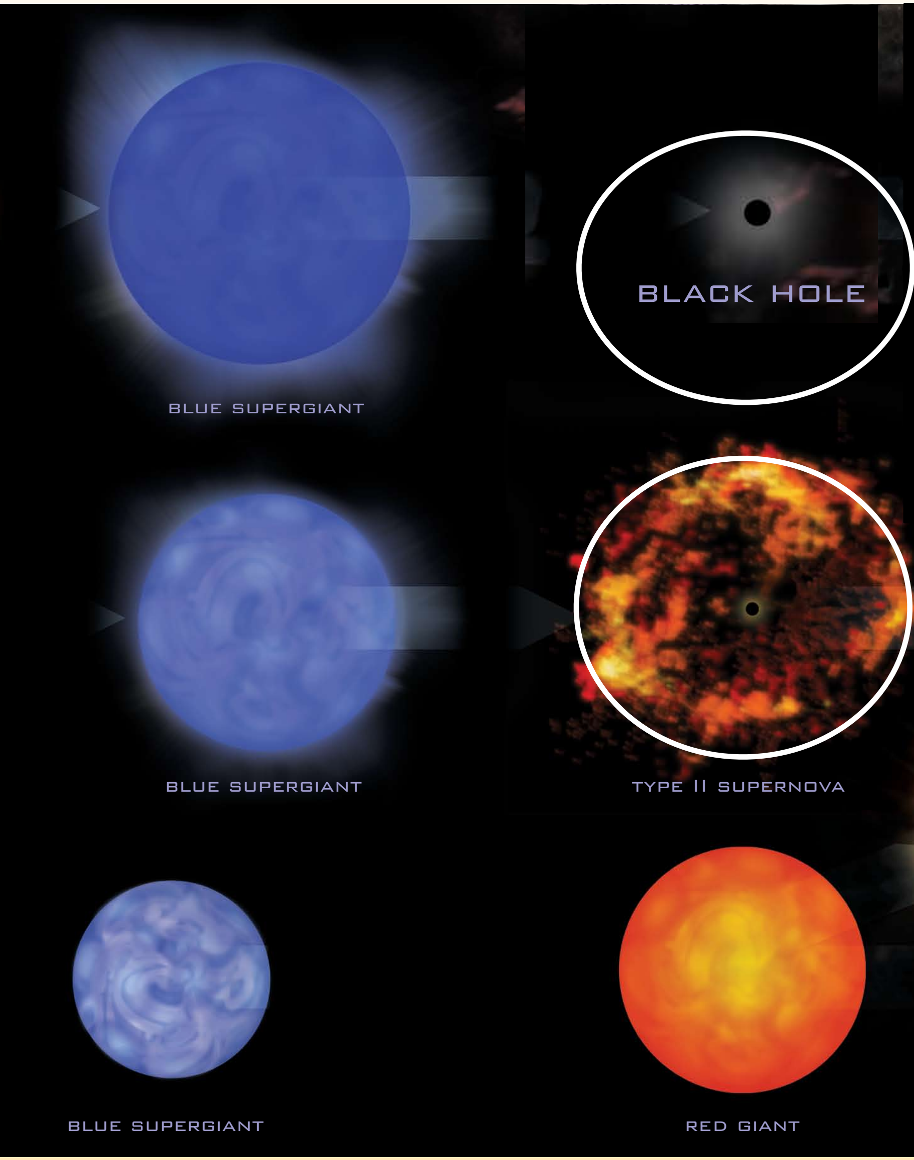

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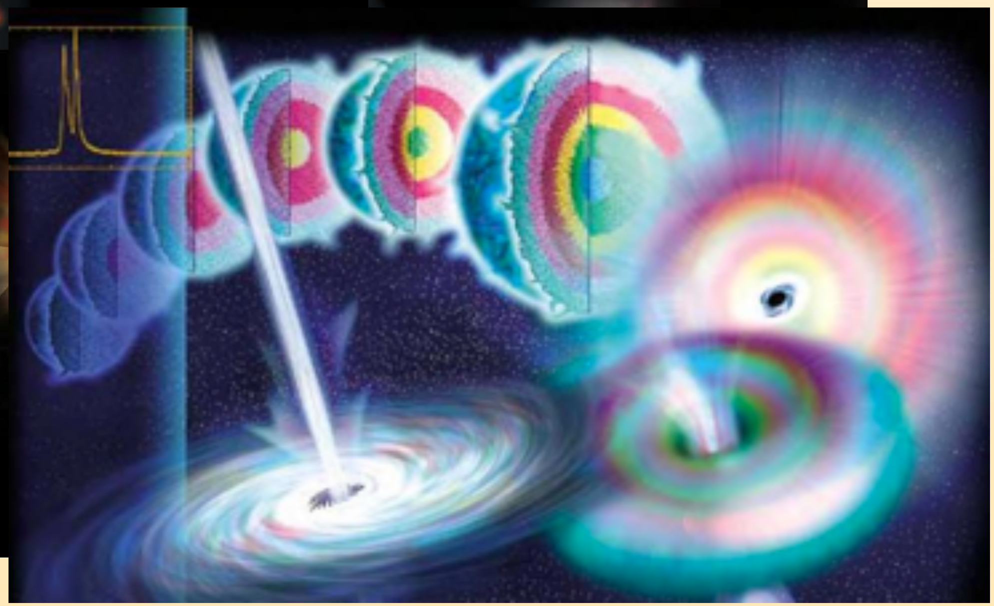
➡ understanding the B-field growth in SNe progenitors is key to understand the B-field growth in lGRB progenitors.



B-field growth in PNS and CC-SNe

- field amplification by
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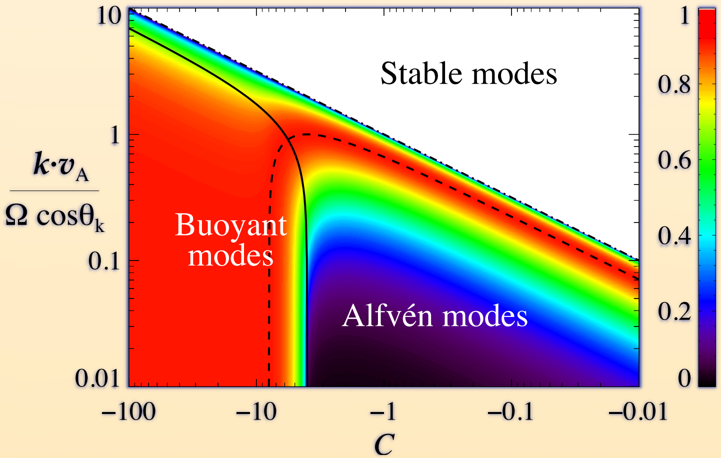
(Obergaulinger, Cerdá-Durán, Müller, Aloy 2009)



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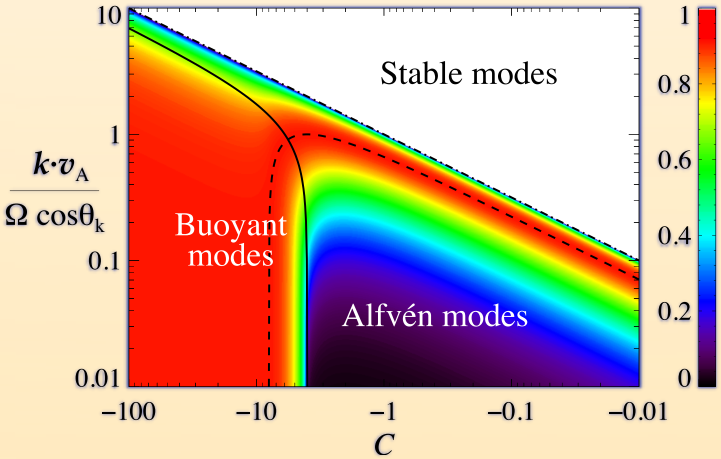

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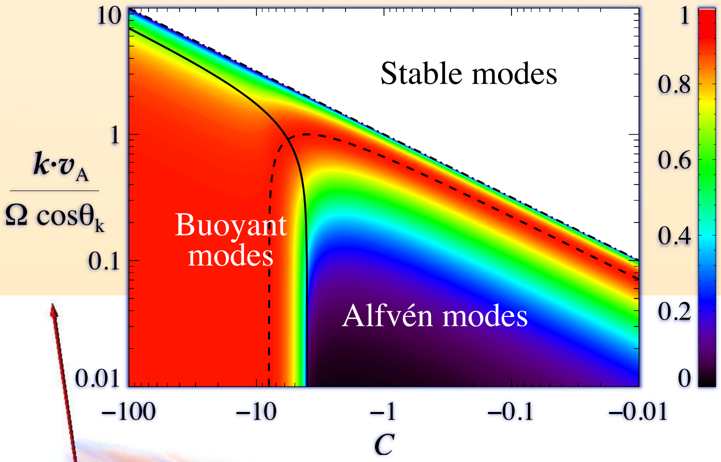

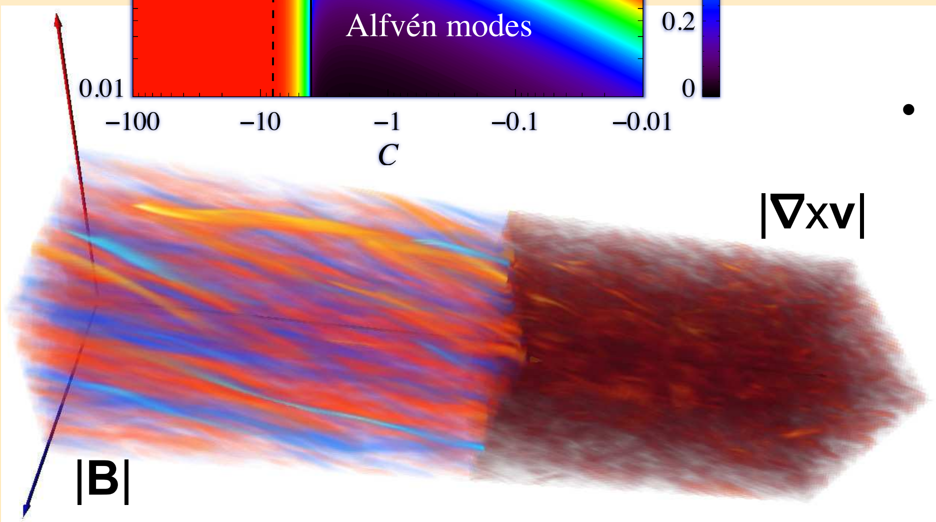

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    - $|B|^{max} \sim 10^{15}$ G if secondary growth of channel flows
    - Otherwise, $|B|^{max} \sim 10^{14}$ G, when LOCALLY $e_{mag} \sim 0.1 \times e_{kin}^{\phi}$. (Obergaulinger, et al. 2009)

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closure relations

$$\partial_t e_{MRI} + \vec{\nabla} e_{MRI} \vec{v} = \Gamma_{MRI} e_{MRI} - \Gamma_{par} e_{par}$$
$$\partial_t e_{par} + \vec{\nabla} e_{par} \vec{v} = \Gamma_{par} e_{par} - \varepsilon_{dis}$$

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  - apropriate closure modelling of turbulence
- approach: combine local and global modelling, using numerical techniques of a very high order of accuracy

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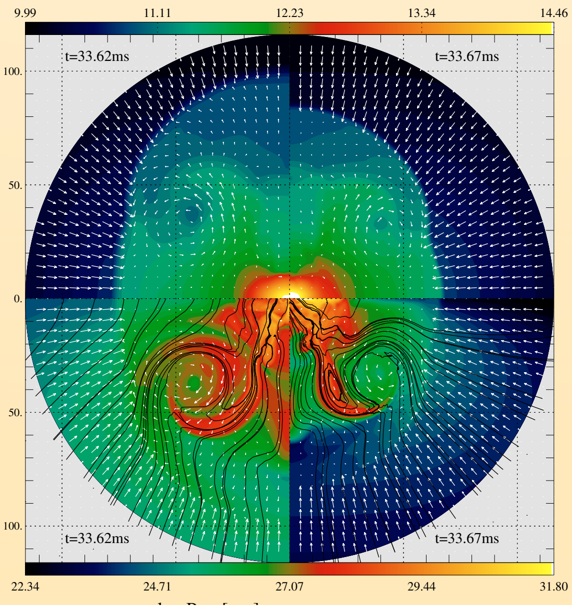
↓

global modelling
(up to 9th order)



Obergaulinger, Aloy & Müller (2006)

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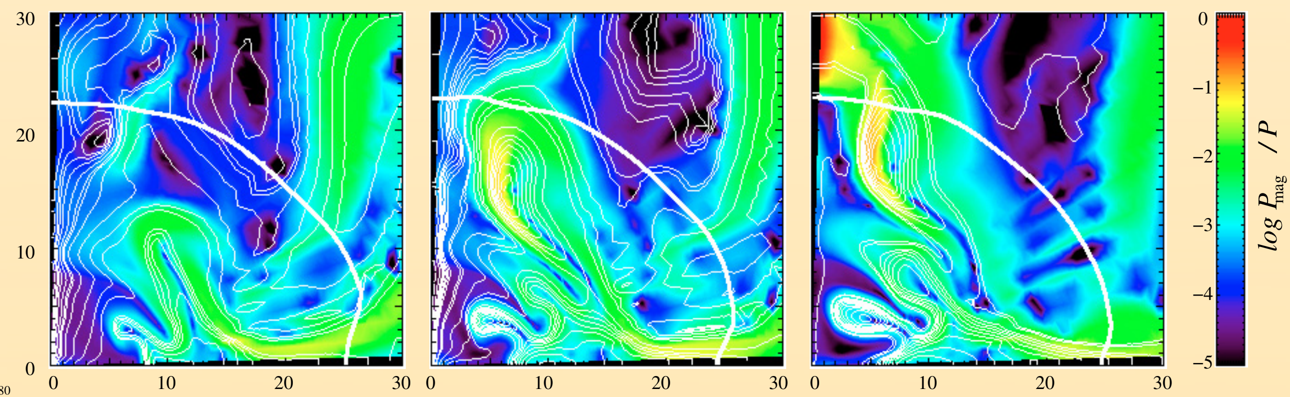
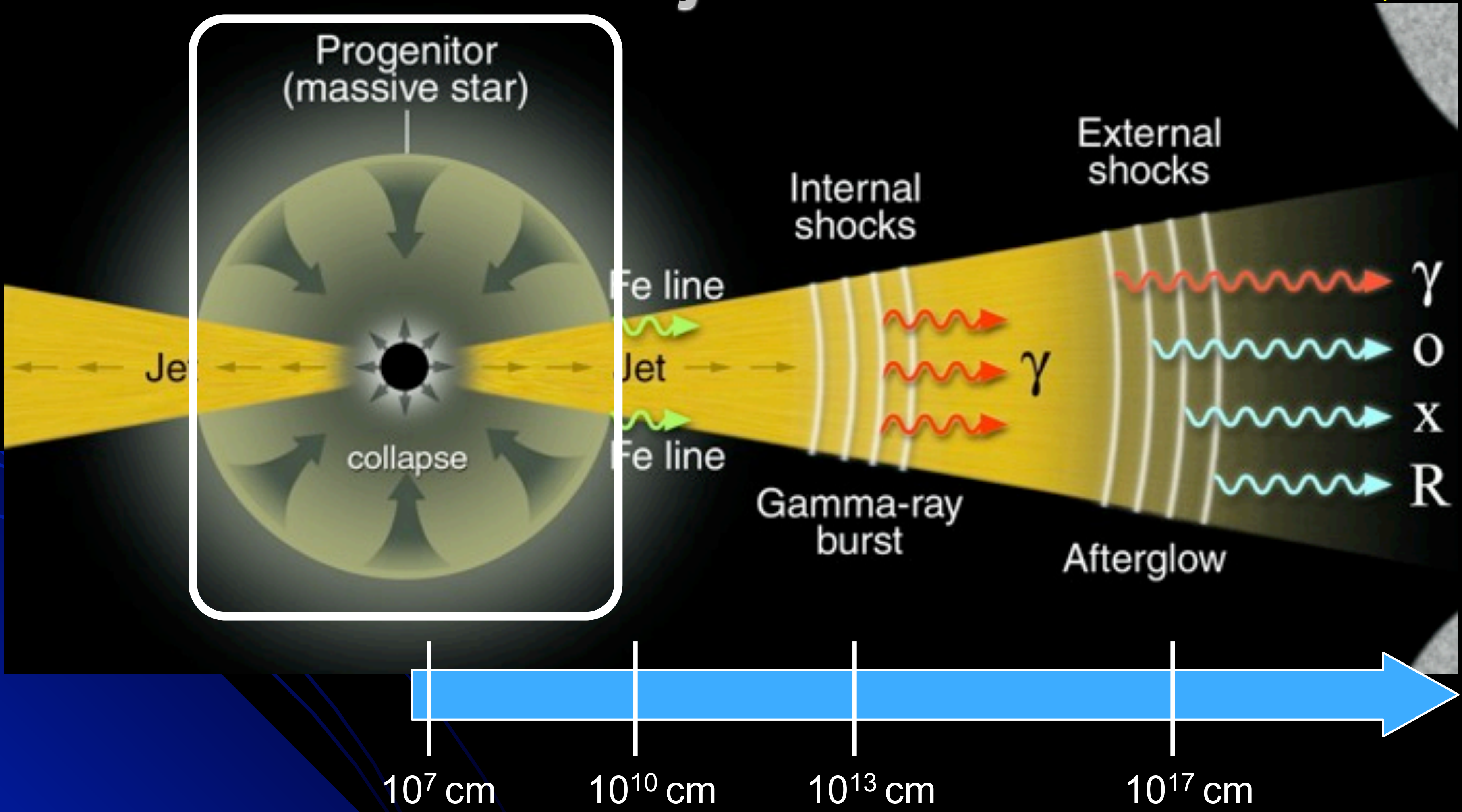
  - apropriate closure modelling of turbulence
- approach: combine local and global modelling, using numerical techniques of a very high order of accuracy
- goal: a simple description of the saturation of the MRI as a sub-grid model in global simulation

Cerdá-Durán et al. (2008)



Observational signature of GRB jets

Meszaros (2002)



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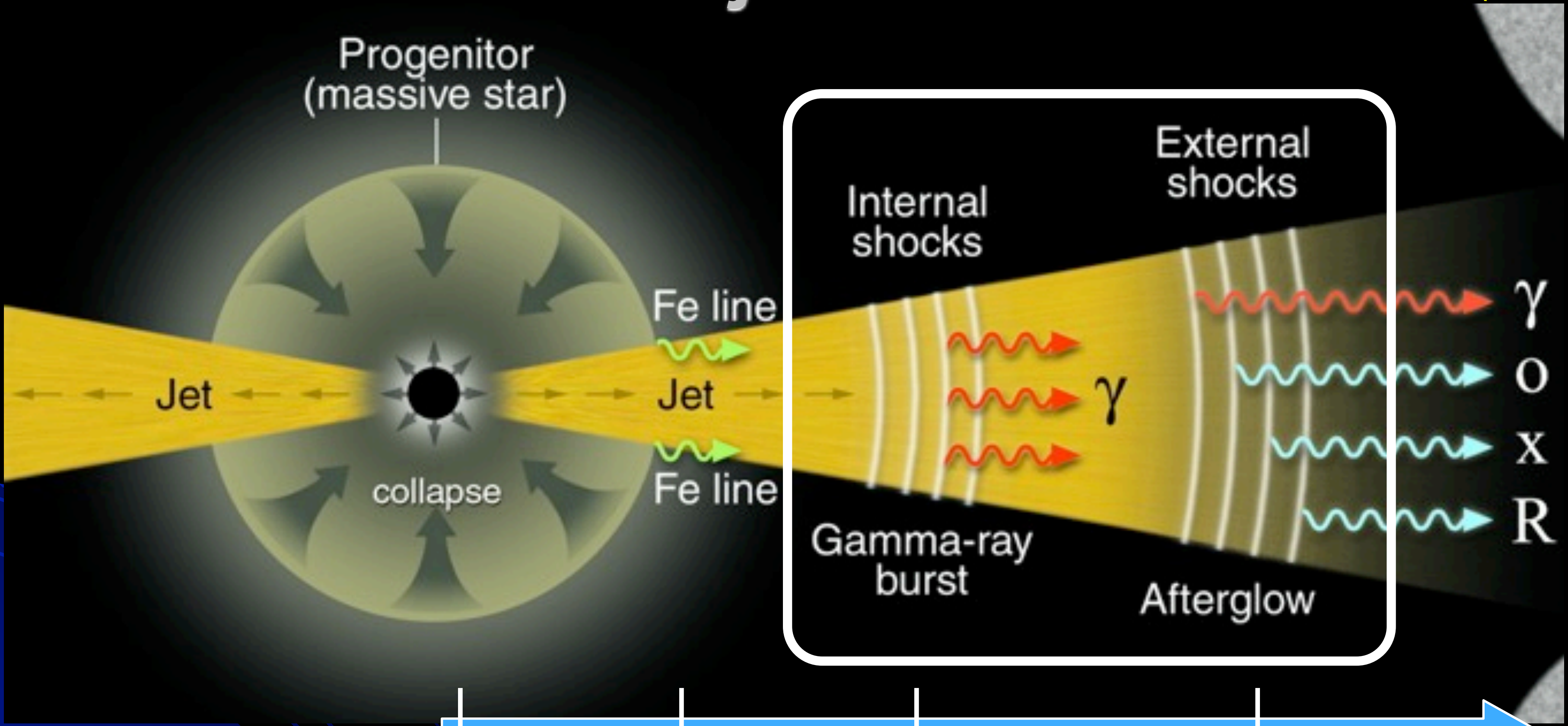
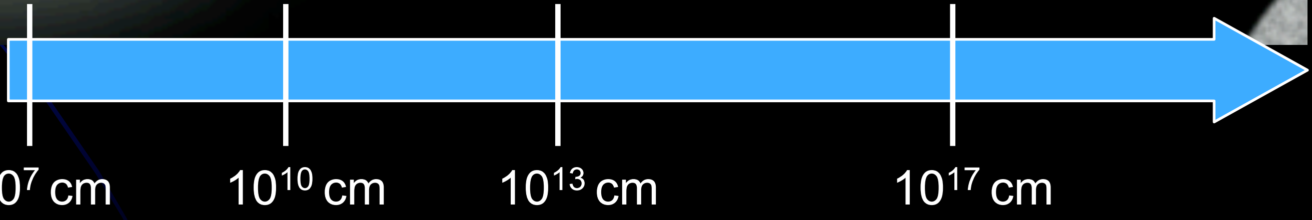
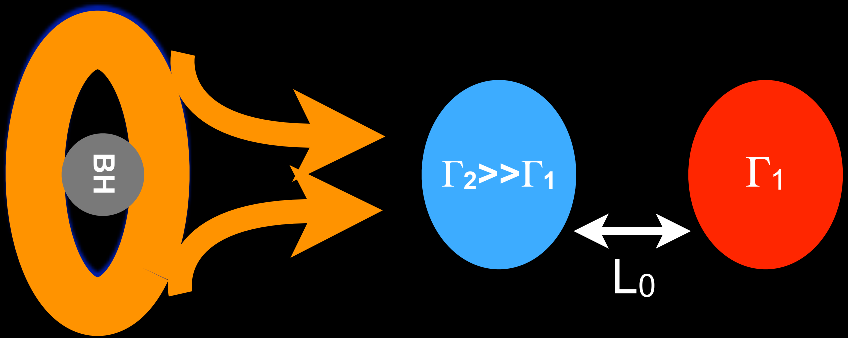


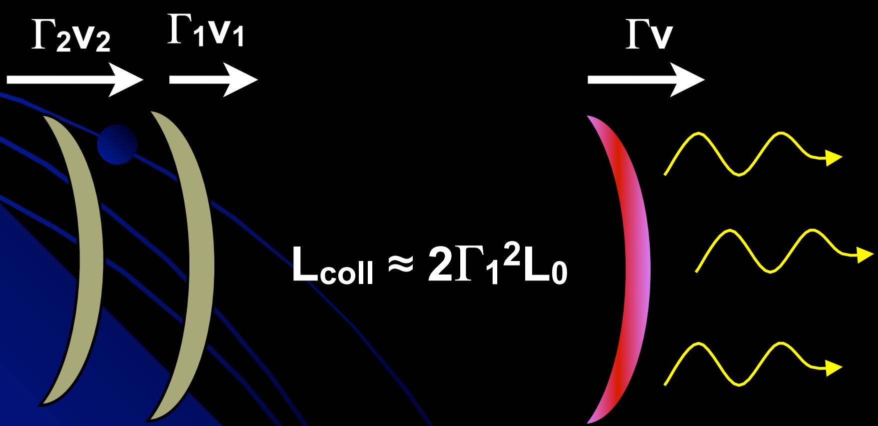


How are ISs produced?

The internal shock scenario (Rees & Mészáros 1994, Spada et al. 2001) is used to explain both blazars and the GRB prompt phase.



1. An intermittently working central engine ejects shells with different velocity



2. faster shells collide with the slower ones (L_{coll}) and produce ***internal shocks***

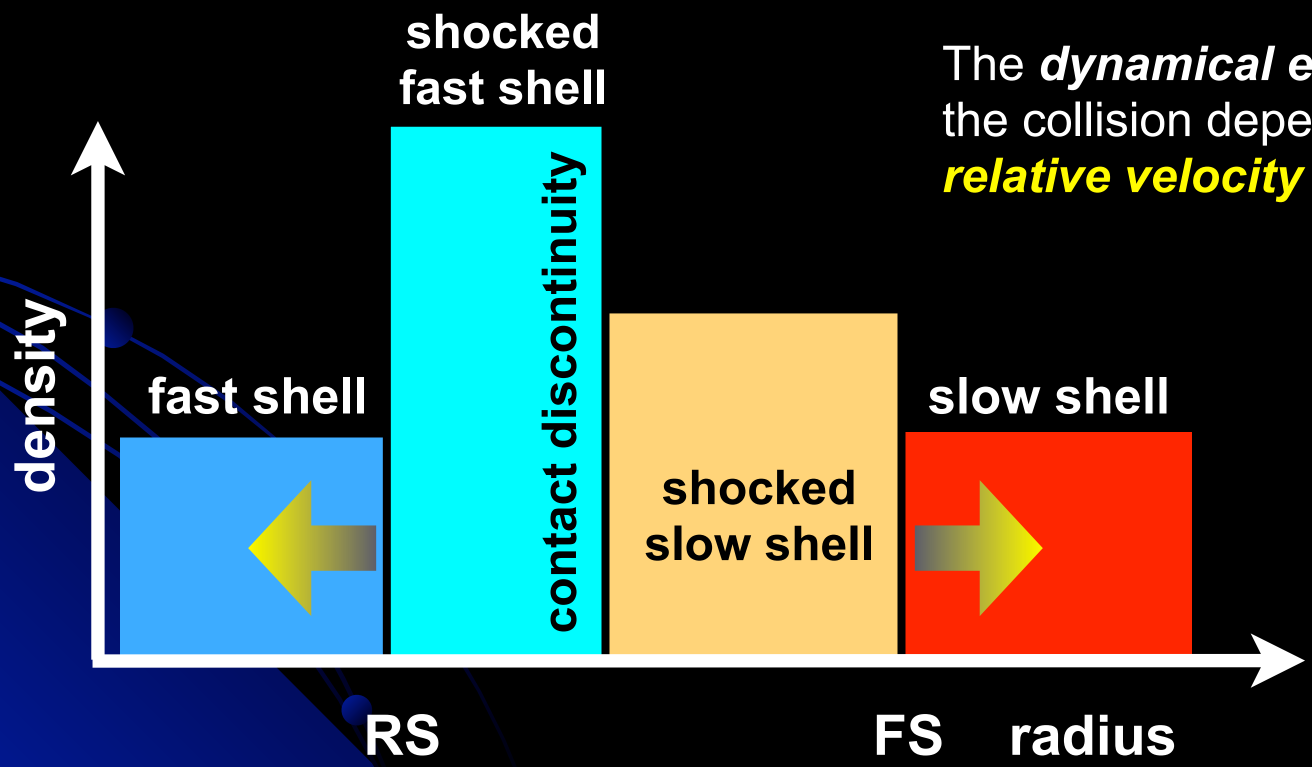
3. particles are accelerated at relativistic shocks and produce the non-thermal radiation (dissipate the relative kinetic energy)

Magnetic dissipation has been typically ignored as source of energy see, however, Romanova & Lovelace 1992; Sikora et al. 2005; McKiney & Uzdensky 2012

Internal shocks (I): cold shells

A forward and a reverse shock form always (Sari & Piran 1995).

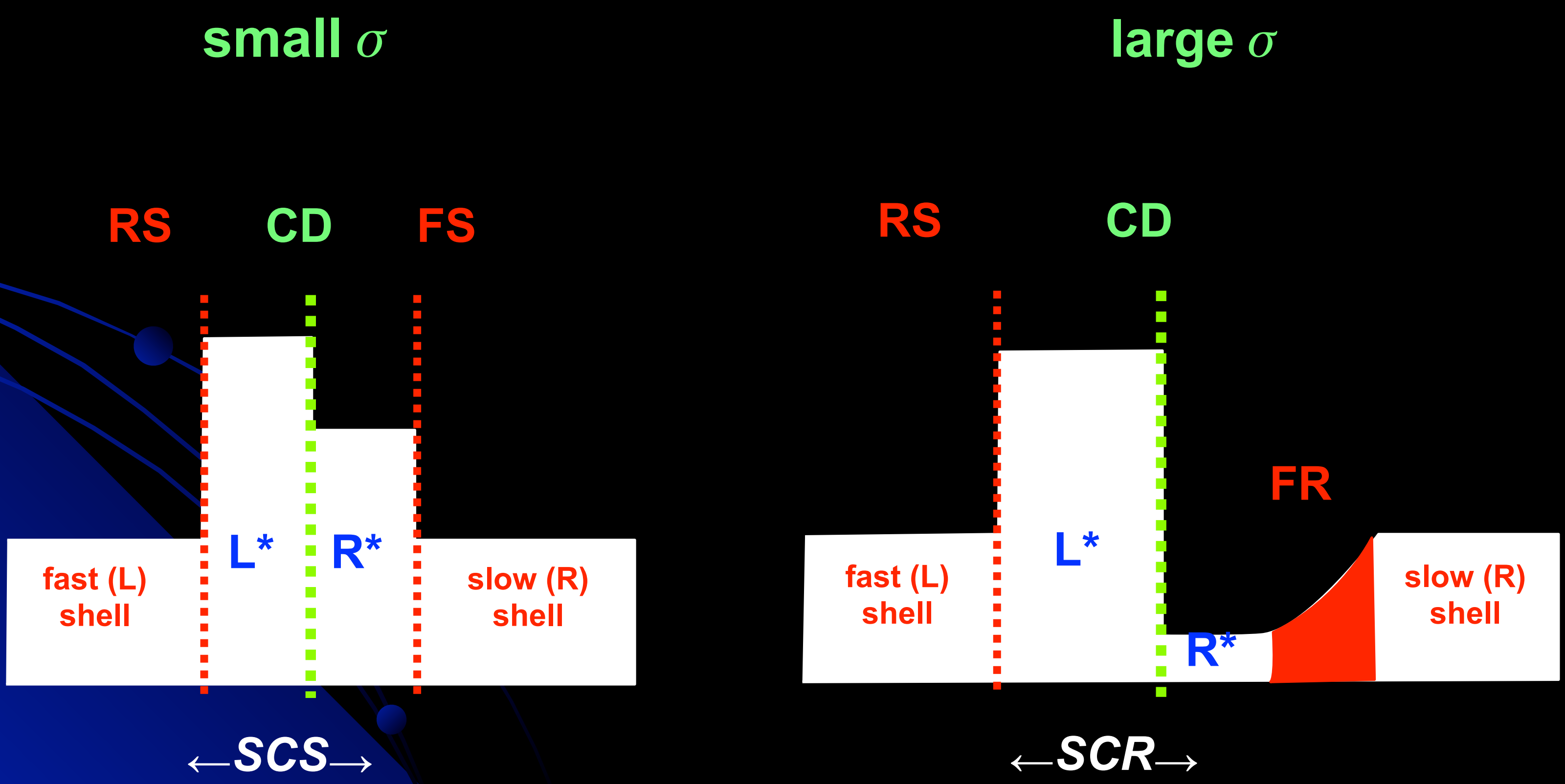
- Reverse shock (RS): compresses the faster shell and decelerates it.
- Forward shock (FS): compresses and sweeps the slower shell.



The ***dynamical efficiency*** of the collision depends on the ***relative velocity*** of the shells.

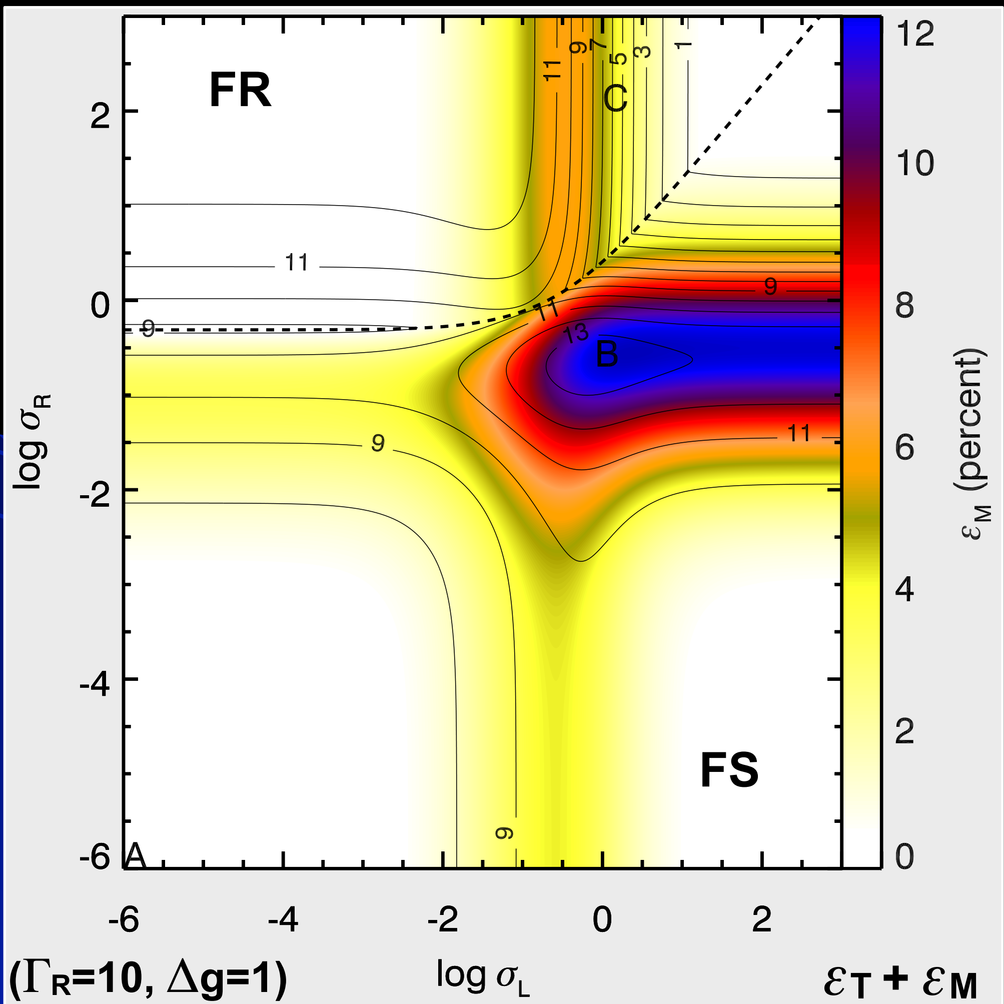
Internal shocks (II): magnetized shells

Differently from non-magnetized shells, if the magnetization is large enough, a forward rarefaction (FR) rather than a FS forms (Mimica, Aloy & Müller 2007).



Internal shocks (III): magnetized shells

The dynamical efficiency in collisions of strongly magnetized shells has been assessed by Mimica & Aloy (2010). They can induce reconnection & turbulence (Zhang & Yan 2011)



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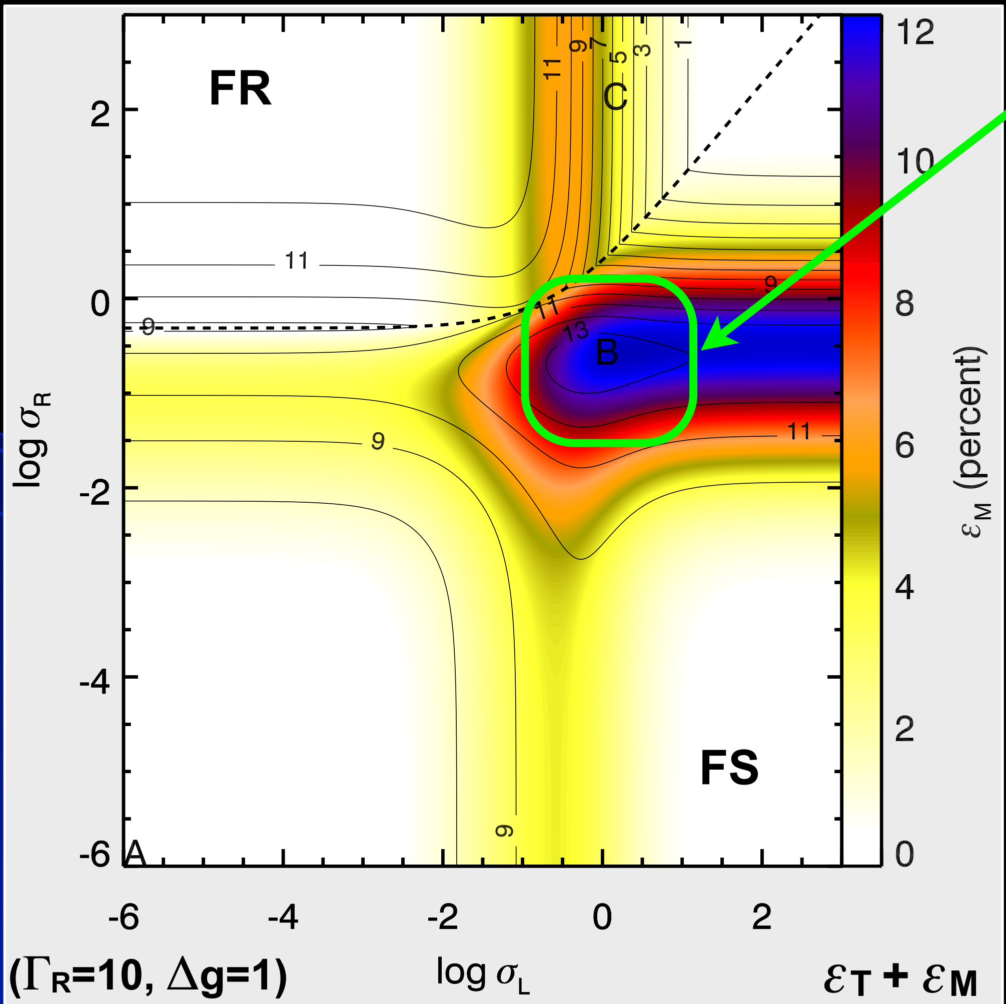

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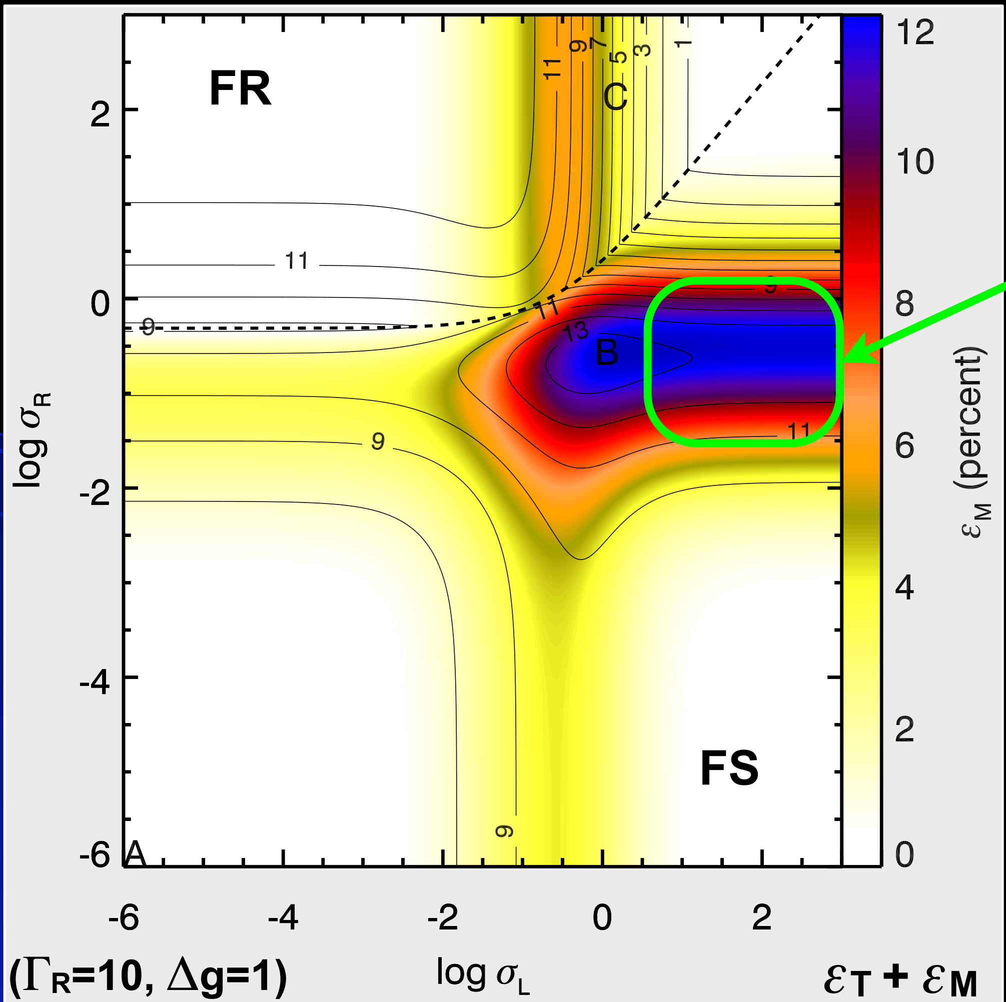

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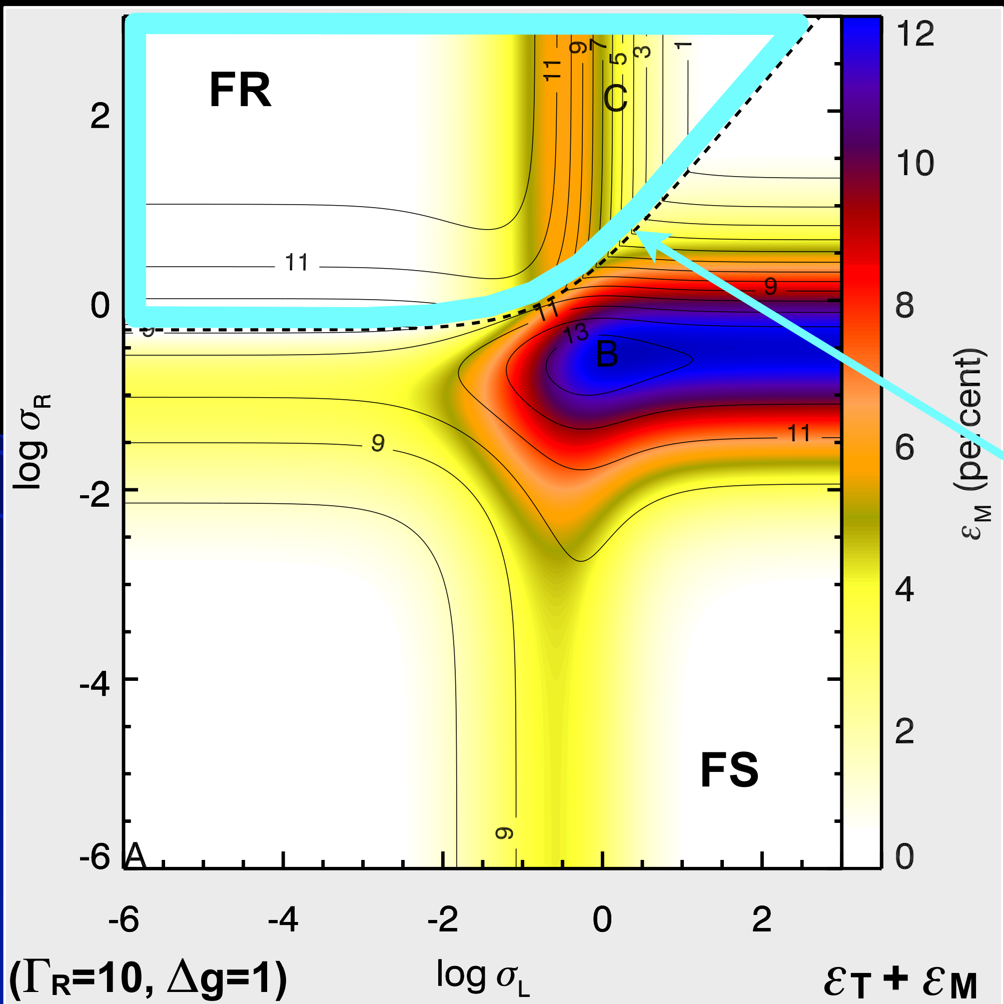

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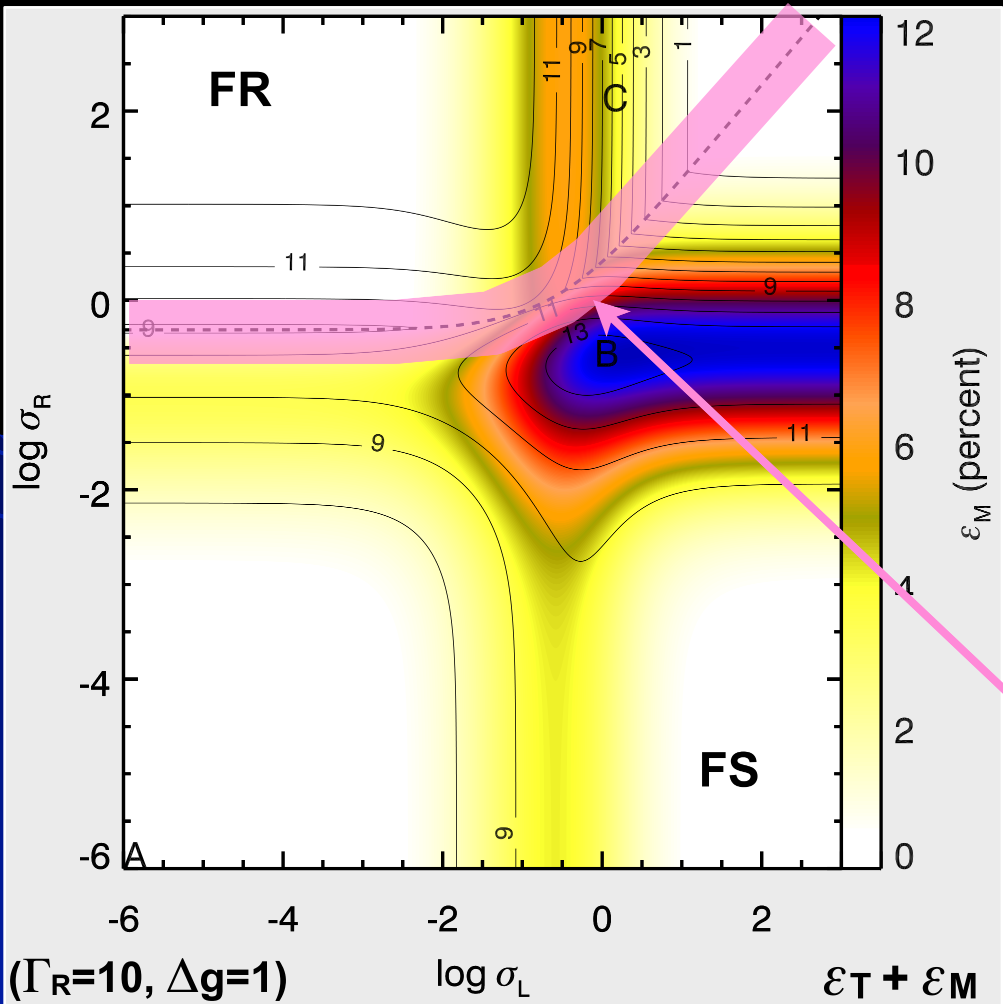

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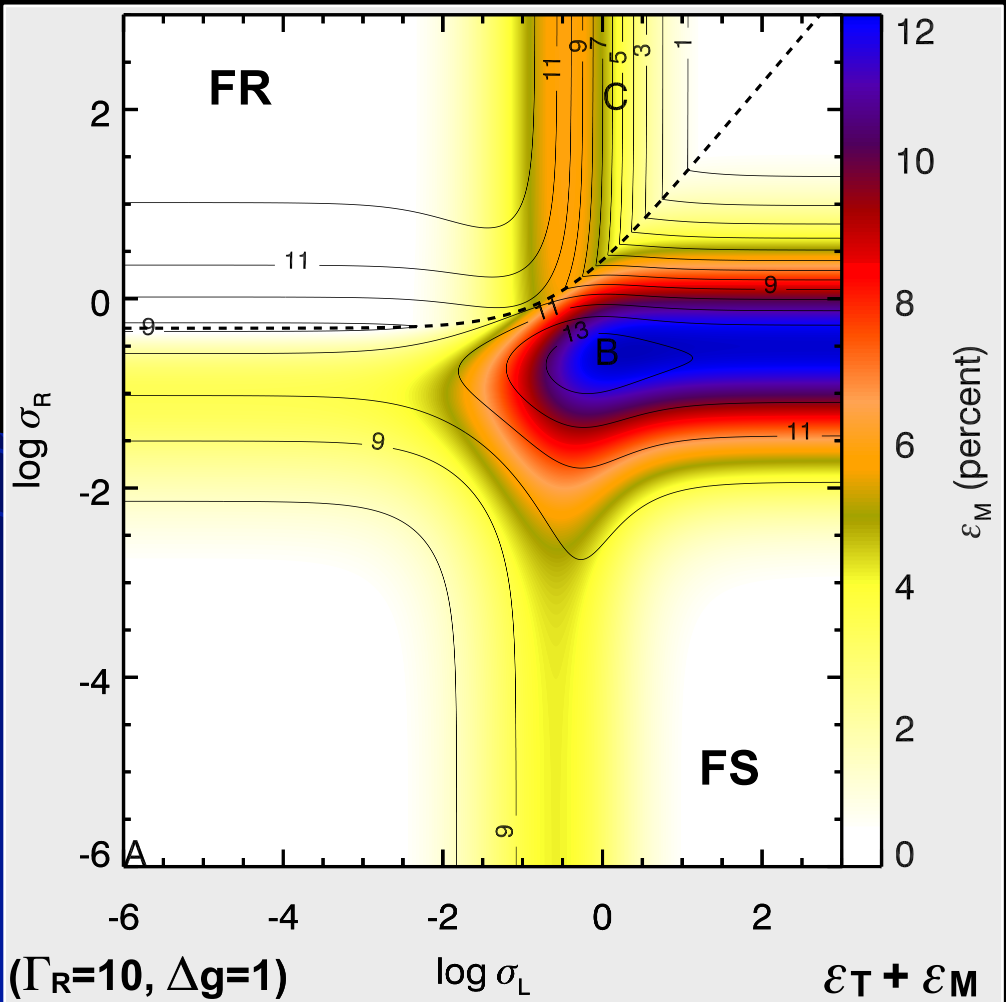

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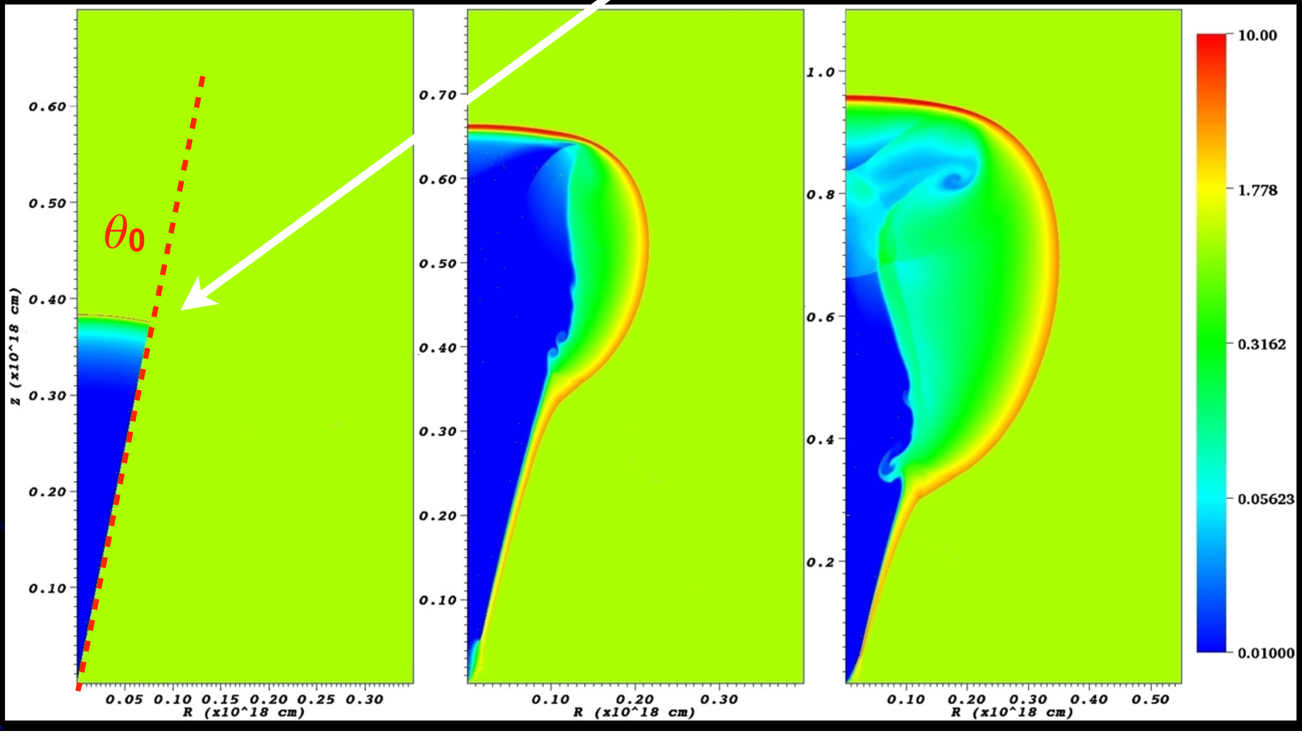

De Cole et al. (2012)

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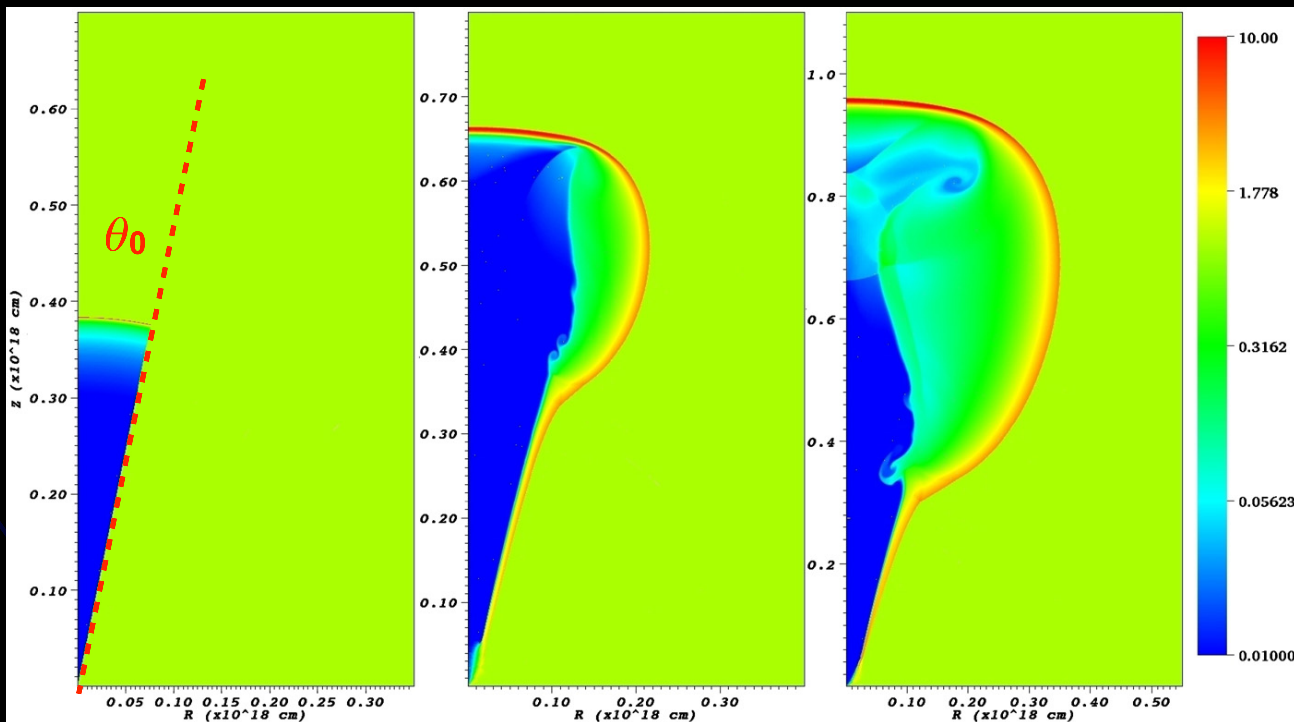

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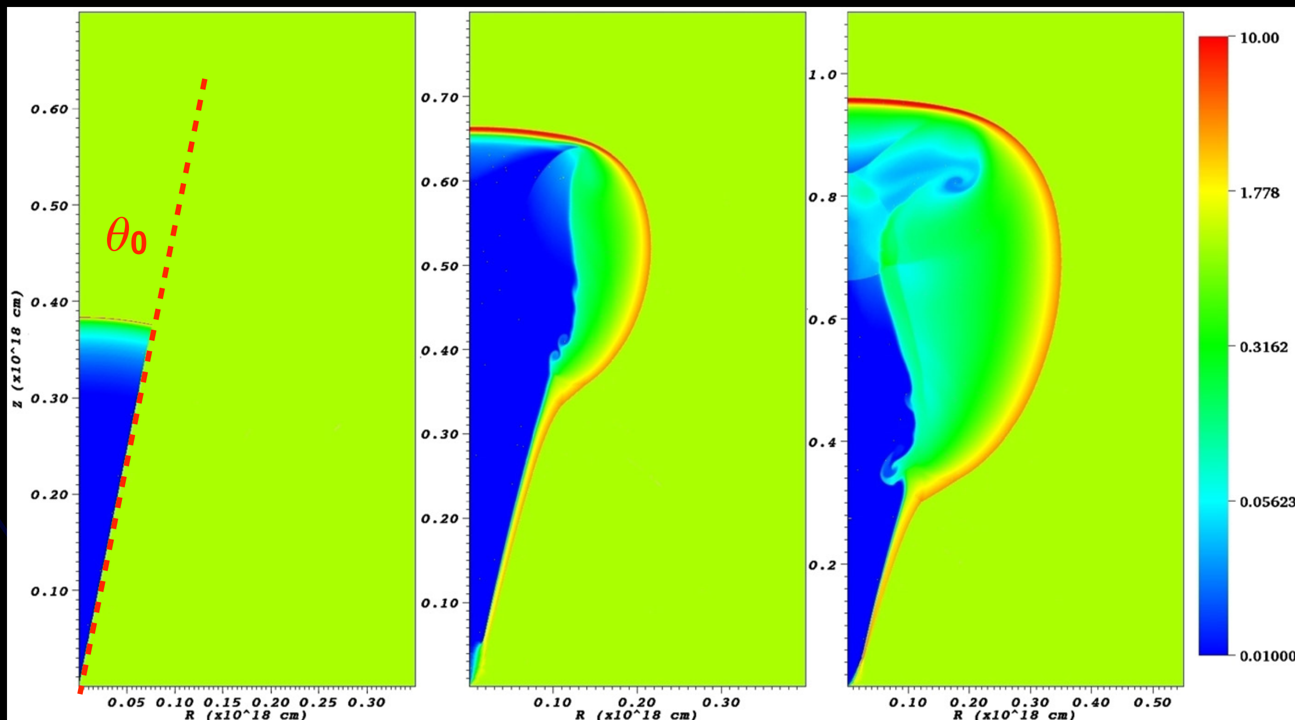
- Jet simulations of the AG emission (Granot et al. 2001) have been extended to well within the non-relativistic stage using AMR (e.g., Zhang & MacFadyen 2009; van Eerten et al. 2010; Wygoda et al. 2011; van Eerten & MacFadyen 2011; De Colle et al. 2012).



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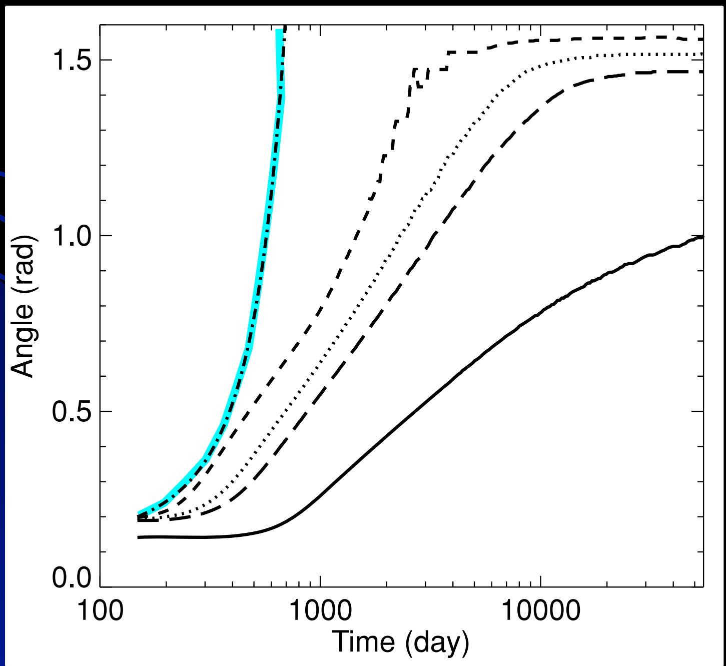
Main results:

- Lateral expansion: slower than expected analytically.

analytic: $\theta=\theta_0 \exp[(t-t_0)/t_{SNT}]$



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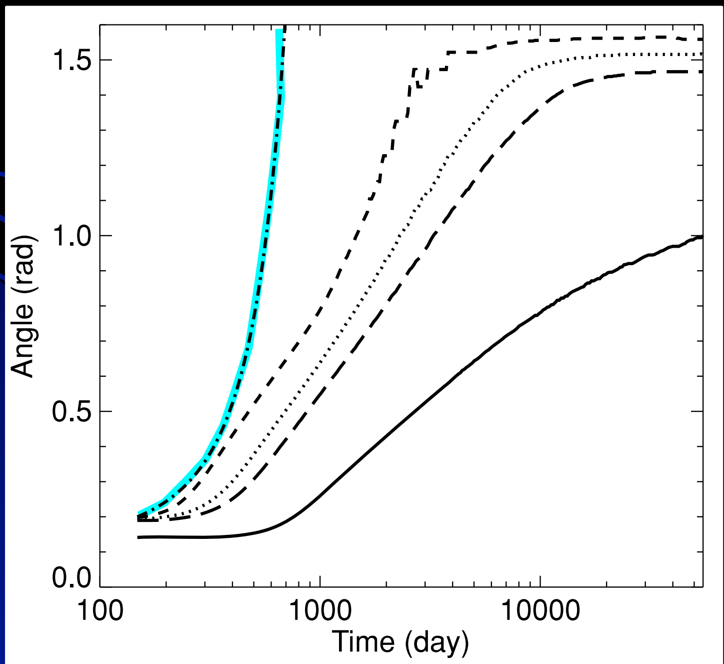

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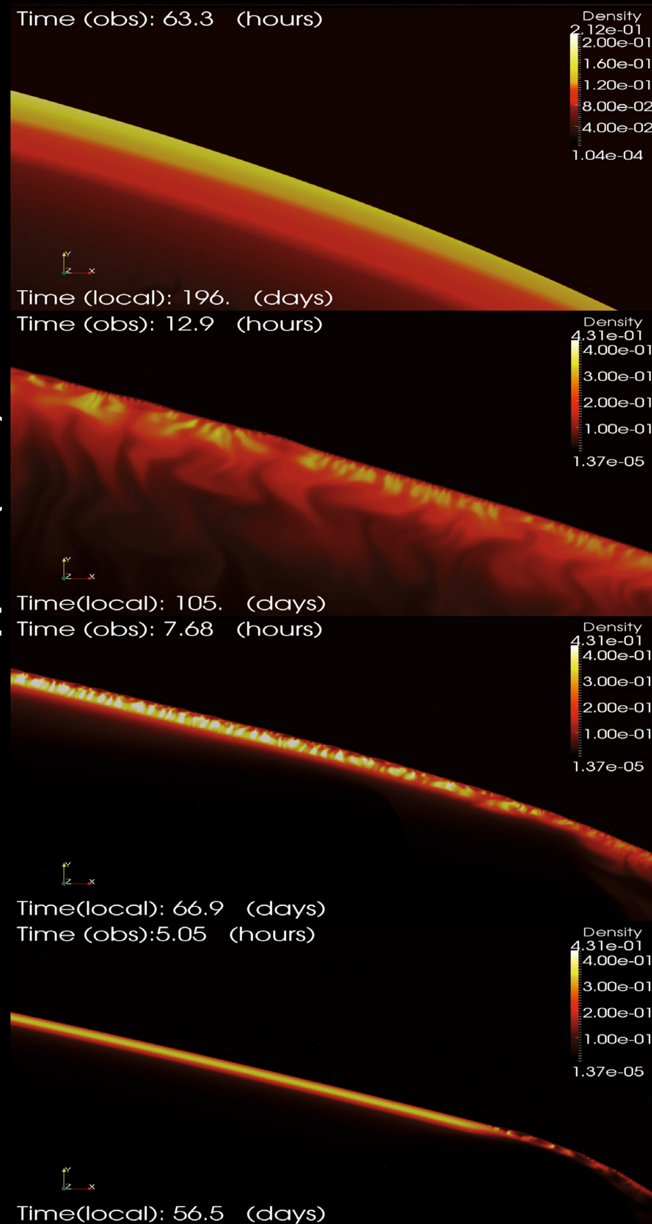

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Main results:

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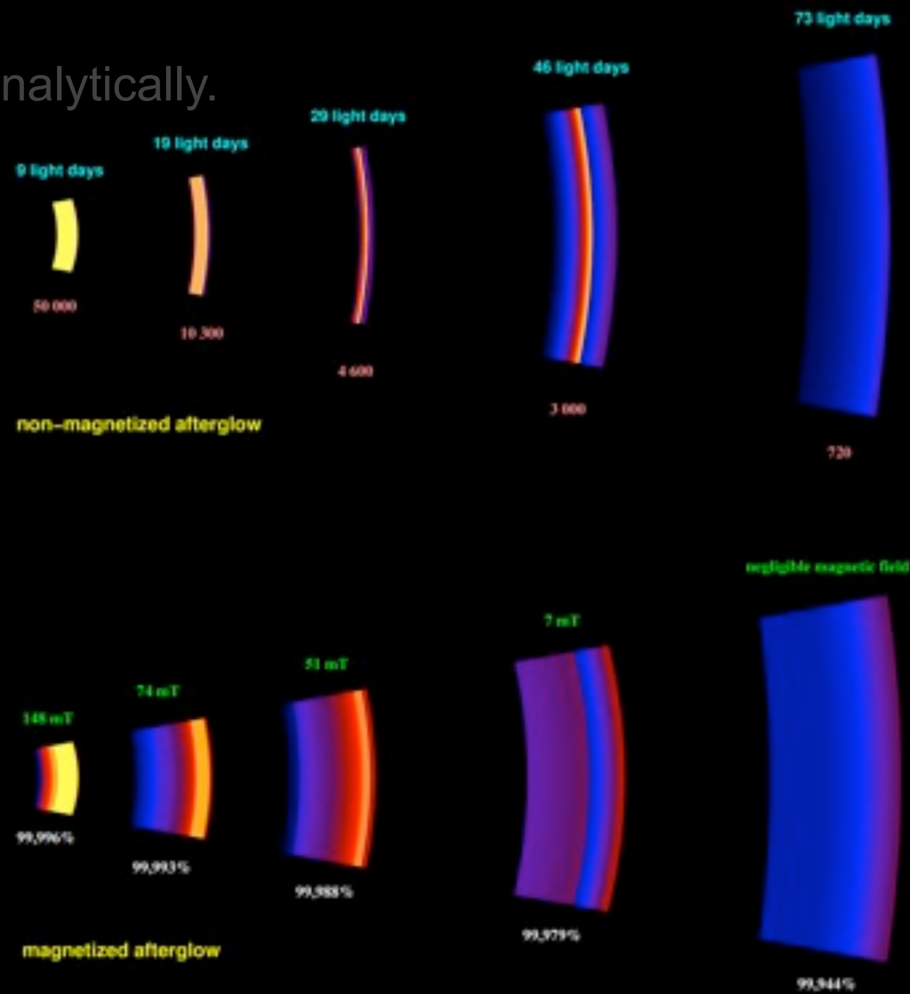
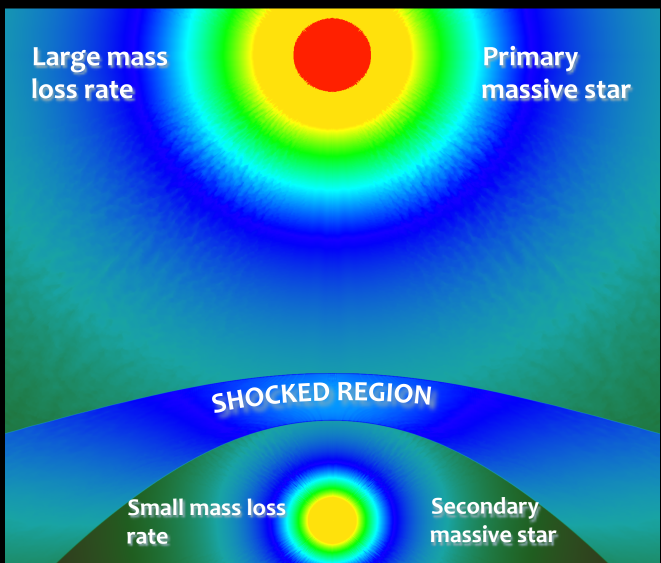
- Instability of the shock front for $\Gamma>15$.
- Magnetic fields affect the jet dynamics (deceleration) and (synch.) emission.
  - From 1D models we get:
    - the late evolution of strongly RMHD shells resembles that of HD shells
    - the magnetization is key in the onset of the FS emission.



Mimica et al. (2009, 2010)
uniform CBM



Mimica & Giannios (2011)
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Early afterglow

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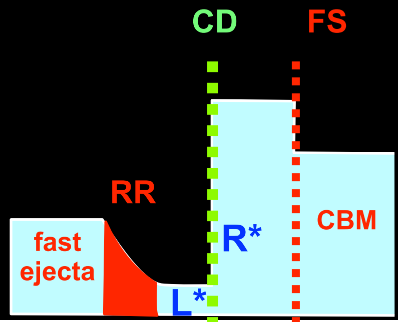
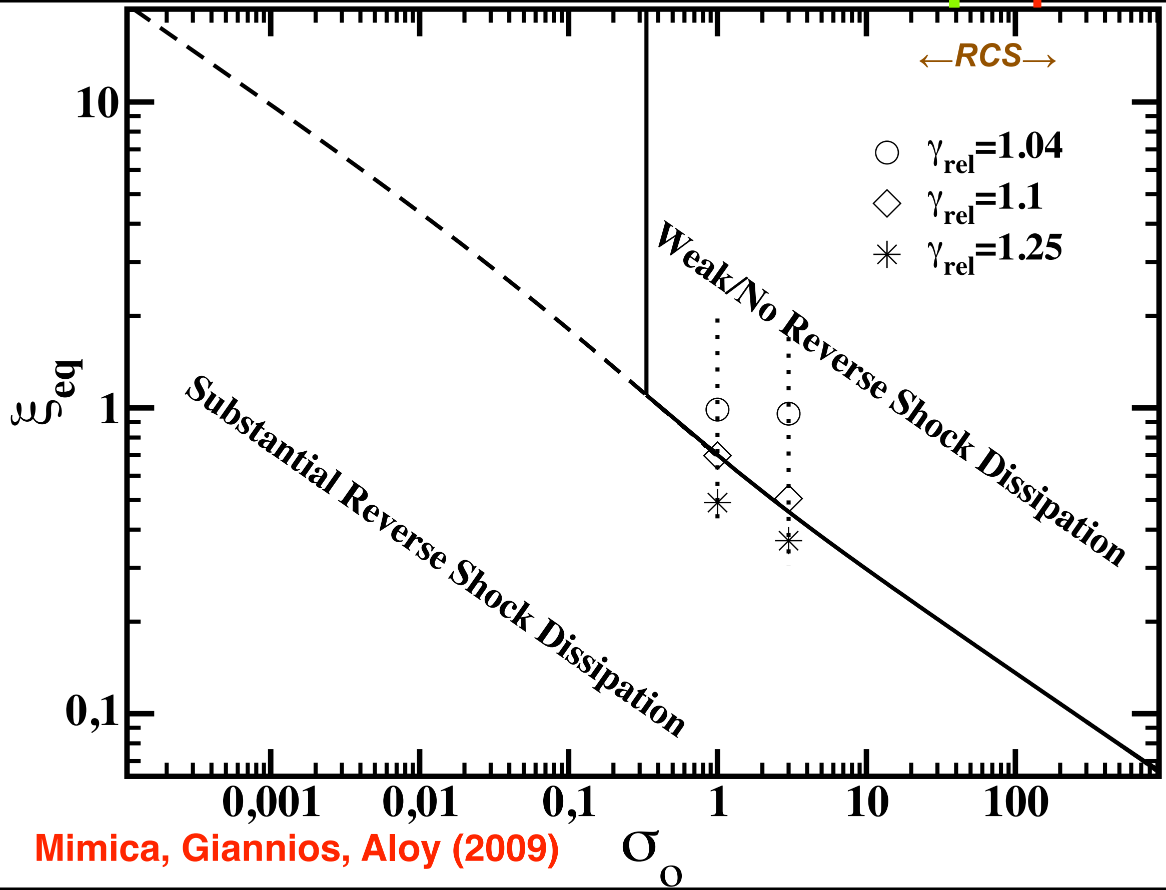


Our simulations have quantified which is the approximate magnetization of the ejecta (σ_o) to allow for the production of a reverse shock, which may accelerate particles, whose optical emission (***optical flash***) is envisioned to be the signature of such shock.

$$\sigma_0 := \frac{B_0^2}{4\pi\gamma_0\rho_0 c^2}$$

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



Mimica, Giannios, Aloy (2009)

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  - challenging (***multiscale* + *multiphysics* problem**).
  - validate our theoretical models of the foremost pieces of the GRB puzzle: central engine, ultrarelativistic flow, and ejecta long term evolution.
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  - Given the high resolution imposed by weak initial fields, a careful treatment should go beyond the limit of ideal MHD, involving, e.g., the formulation of a turbulence model for the unresolved magnetic fields + resistive processes.