Max-Planck-Institut
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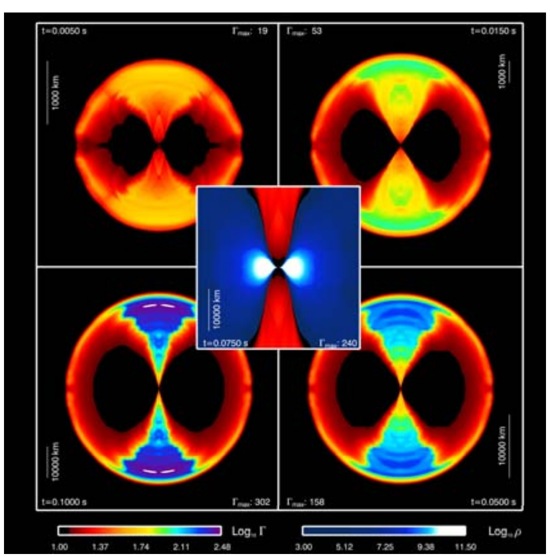
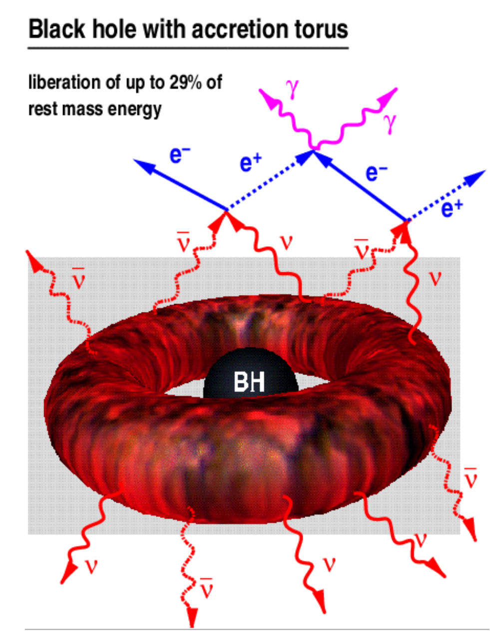
Relativistic outflows from remnants of compact object mergers and their viability for short GRBs



Miguel A. Aloy

In collaboration with:
T.-H Janka and E. Müller
(find out more @ **`astro-ph/0408291`**)



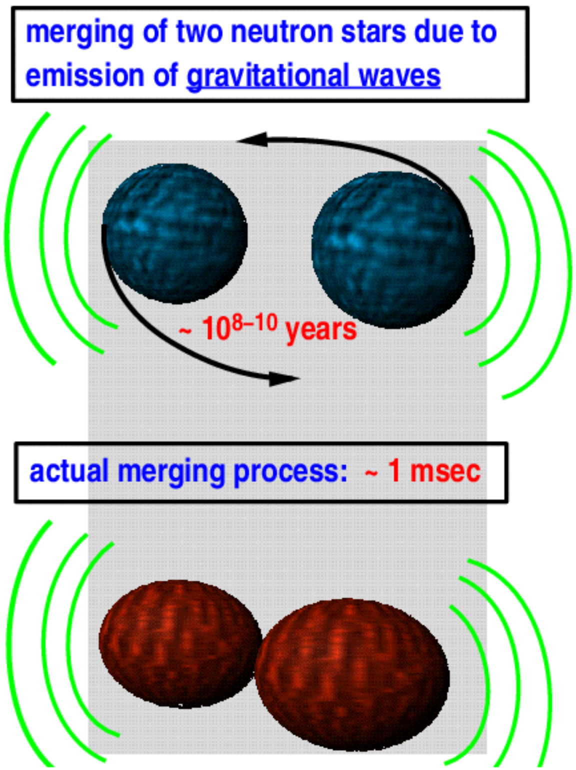
Progenitors of short GRBs: setting the stage

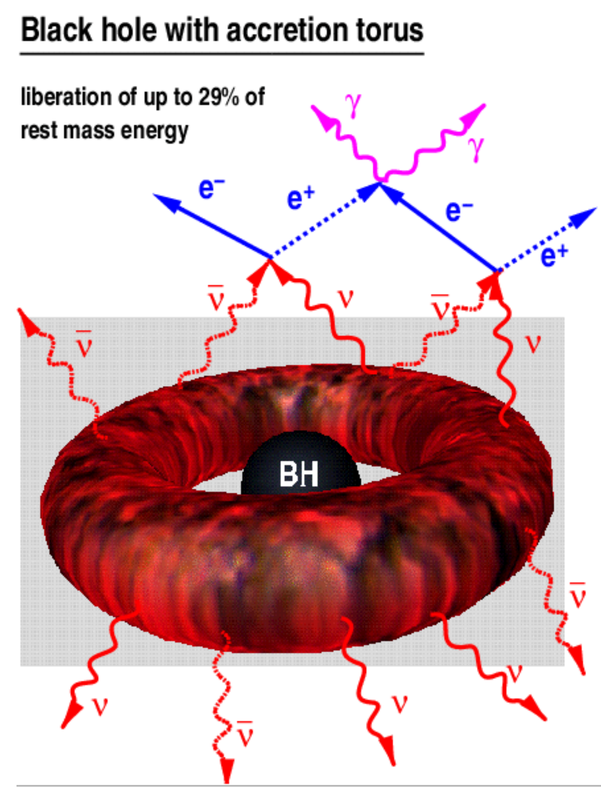
Merger of a system of compact binaries (SCBs):
(Pacynski, Goodman, Dar, Eichler et al., Mochkovitch et al., etc.)

- After the merger of a SCB a central BH (M_{BH} ~ 2-3M_{sol}) girded by a thick accretion torus (M_{torus}~ 0.05 – 0.3M_{sol}).

- Once the thick disk is formed, up to ~10^{51} ergs can be released above the poles of the BH in a region that contains <10^{-5} M_{sun} of baryonic matter due to $\nu\bar{\nu}$ annihilations preferentially near axis ⇒ acceleration to ultrarelativistic speeds.

- If the observed duration T_{obs} is related to the lifetime of the system T_a this kind of events can only belong to the class of short GRBs because T_{disk}~ 0.05 – 0.5 s.





Progenitors of short GRBs: our goals

1. The viability of the scenario of merging SCBs for producing ultrarelativistic outflows (winds, jets, radial outflows, canon balls?).
2. Mechanism of *collimation* (if any) of the outflowing plasma (typical opening angles and consequences on the observed rate of events).
3. Expected durations of the GRB events generated in this framework and their relation to the time during which the source of energy is active (T_a).

How to : GRHD simulations (astro-ph/0408291)

-Build up a *likely* initial model

Schwarzschild BH

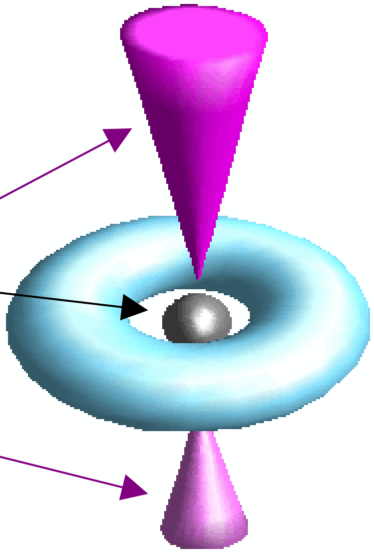
+

thick accretion torus

-Release energy in a baryon clean environment

-EoS: ideal gas of neutrons + e^+e^- + radiation

(Witti, Janka & Takahashi 1994)

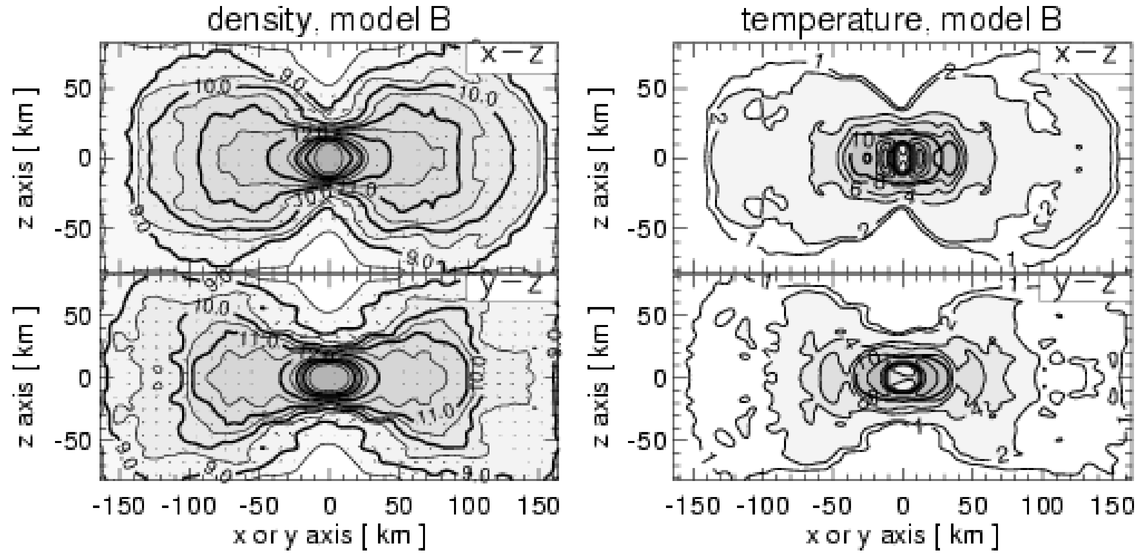


Initial model

Two approaches:

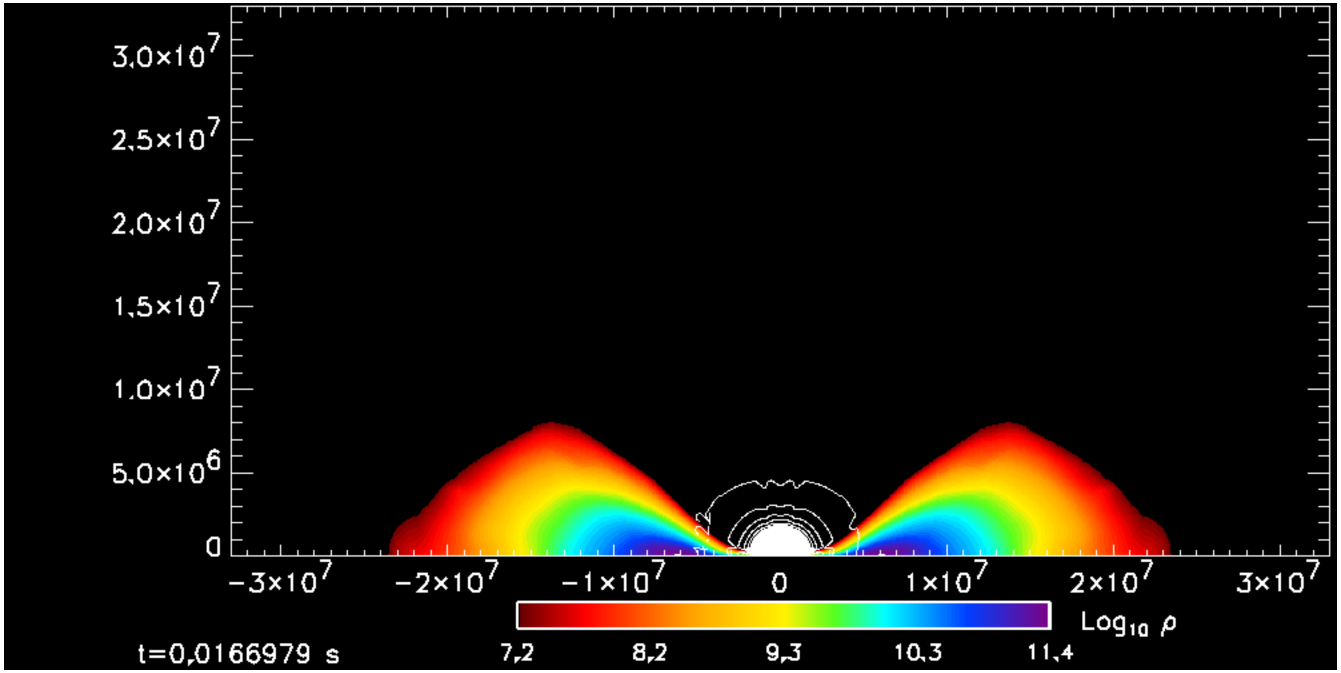
Type-A: Put a toroidal-like distribution of matter and angular momentum around a Schwarzschild BH (guided by the Newtonian simulations of Ruffert & Janka 2001) and let it relax to an equilibrium configuration.

M_{torus} ~ 0.17 M_{sun}
M_{BH} ~ 3 M_{sun}
M_{env} ~ 10^{-2} M_{sun}



Ruffert & Janka (2001), A&A, 380, 544

Relaxed initial model



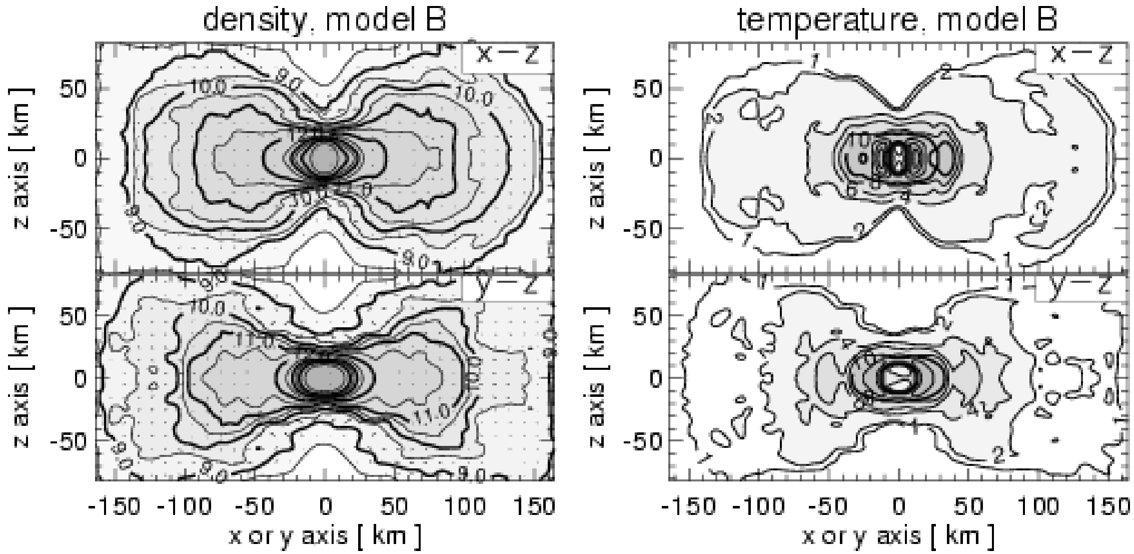
Aloy, Janka & Müller (2004), astro-ph/0408291

Initial model

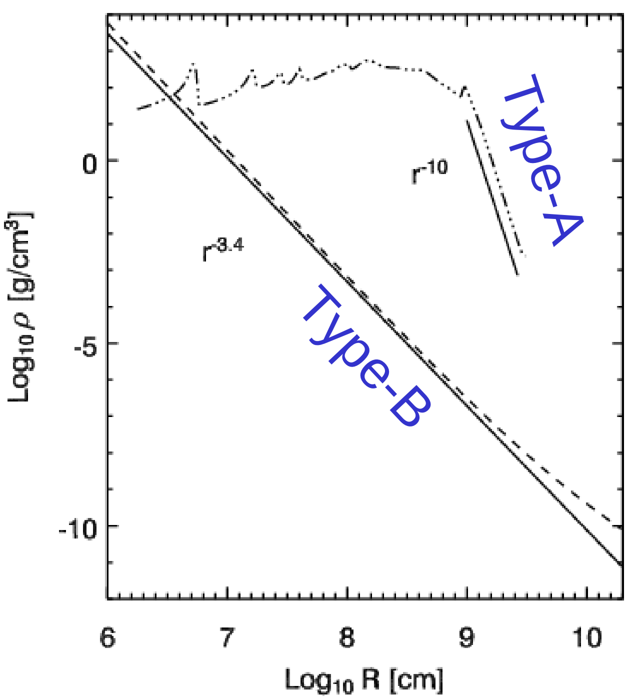
Two approaches:

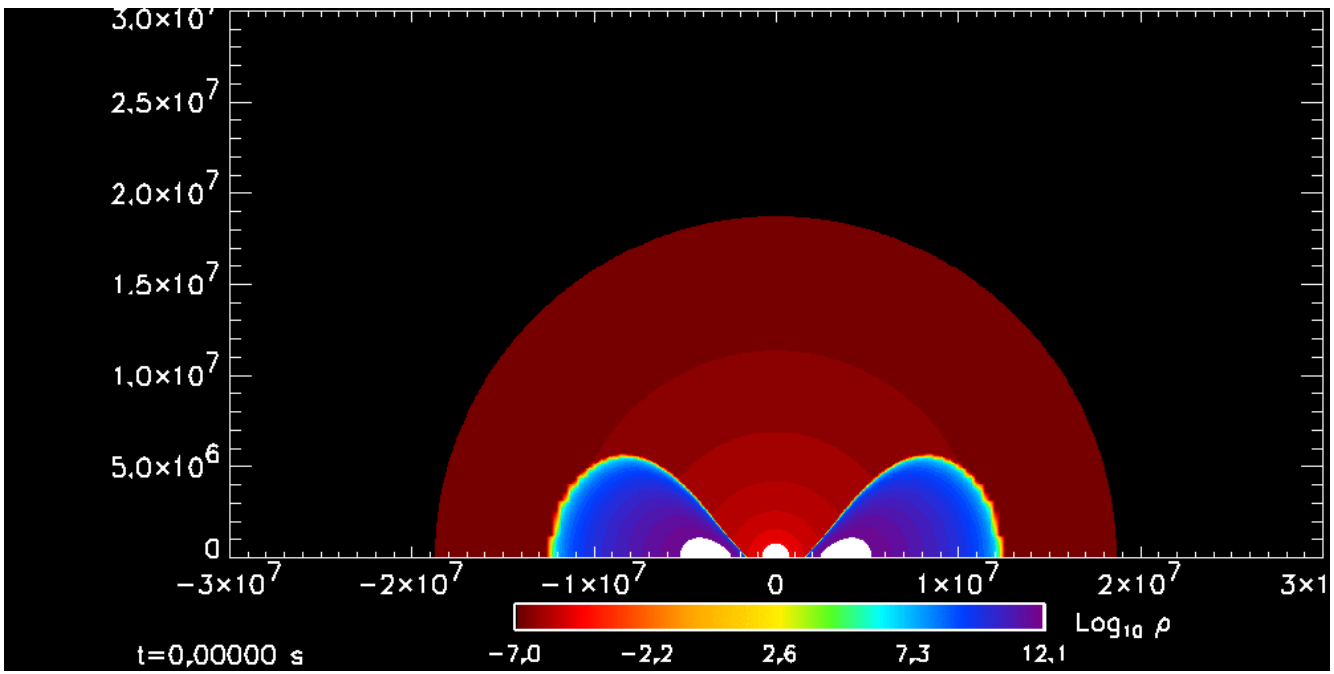
Type-B: Follow Font & Daigne (2003) prescription to build up equilibrium tori around a BH. Outside use Michel (1972) spherical accretion solution.

$M_{torus} \sim 0.17\ M_{sun}$
$M_{BH} \sim 2.44\ M_{sun}$
$M_{env} \sim 10^{-7}\ M_{sun}$



Ruffert & Janka (2001), A&A, 380, 544



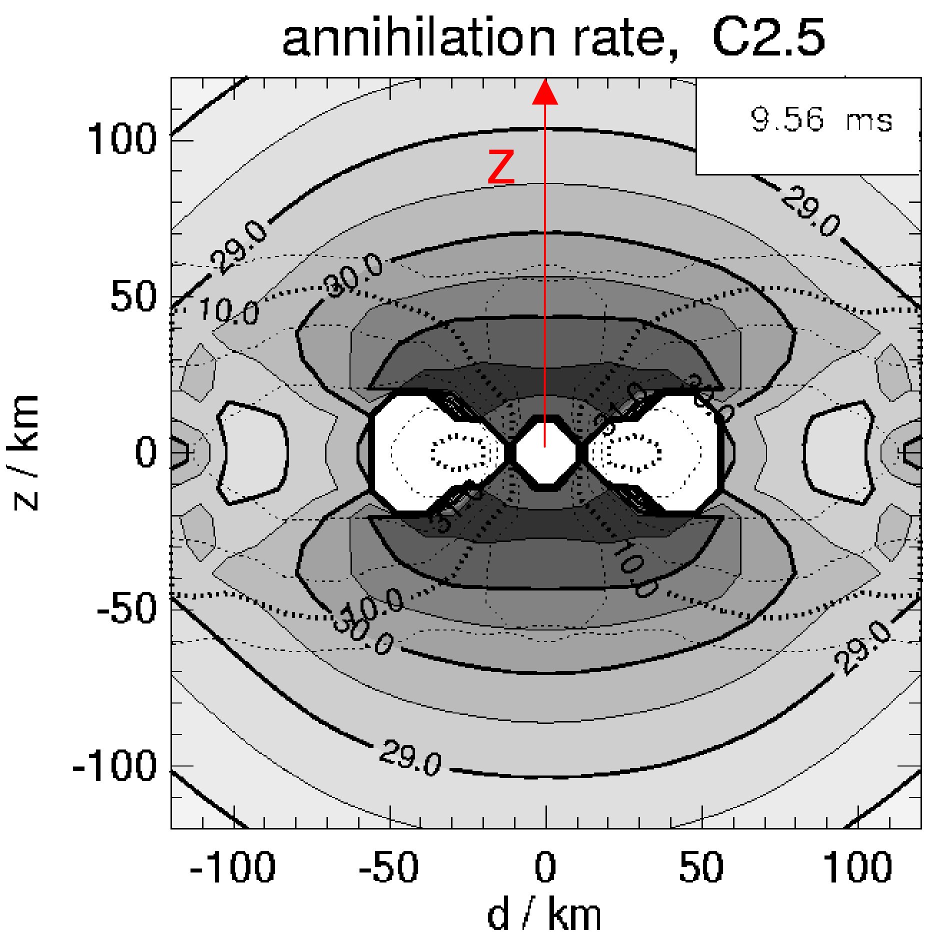


Aloy, Janka & Müller (2004), astro-ph/0408291

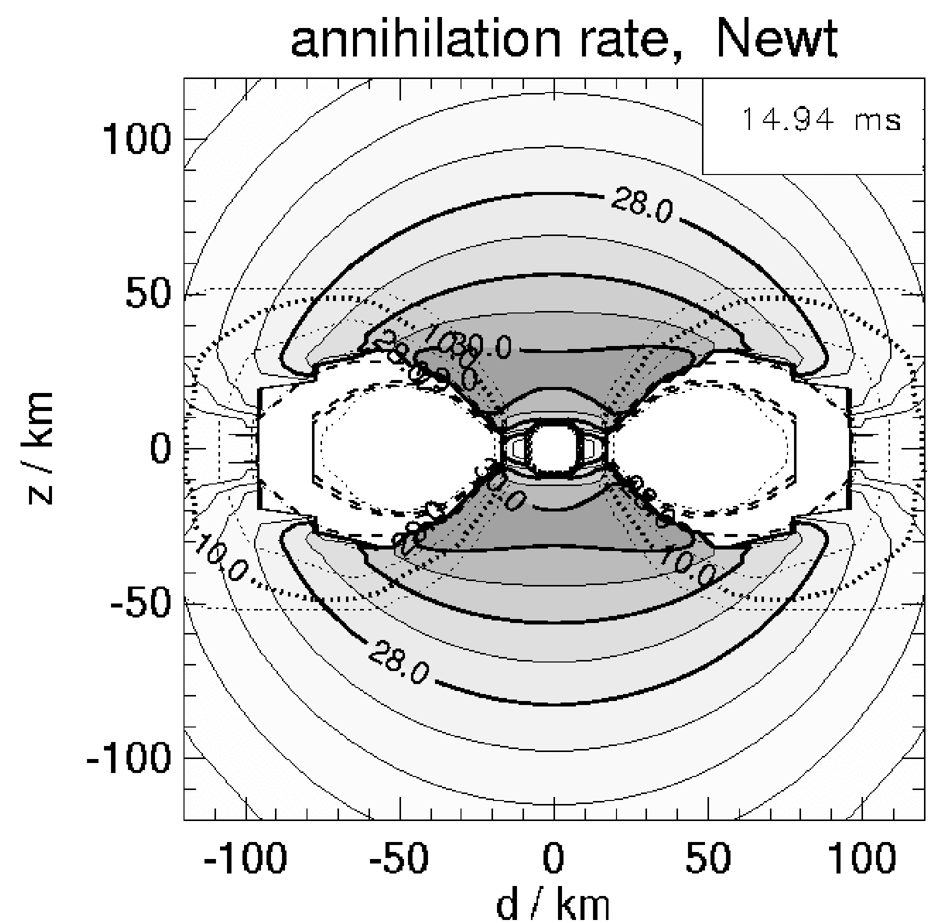
Modelling the energy release

Guided by previous results of Janka, Ruffert et al. showing that both in NS-NS mergers (Ruffert & Janka 1999) and in BH-NS mergers (Janka et al. 1999), can be released up to 10^{51} ergs above the poles of the black hole in a region that contains less than 10^{-5} M_{sun} of baryonic matter. The dependence in z-distance is:

$$q(z) = q_0 / z^n; \quad z = r \sin\theta; \quad n \sim 5; \quad \theta_0 \sim [30^o, 75^o]$$



Janka et al. (1999), ApJ, 527, L39



Ruffert & Janka (1999), A&A, 344, 573

Models explored up to now

- Energy deposition region:

Cone of 30º to 75º around the rotation axis that extends from R_{min}= 1.02 - 2.05 R_s (innermost boundary) to infinity

- Grids: r (log spaced) x (uniform)

Type A: 460 x 200 zones. R_{max} = 3 x 10^9 cm

Type B: 500 x 200 zones. R_{max} = 2 x 10^{10} cm (+resolution checks up to 2000x200 zones)

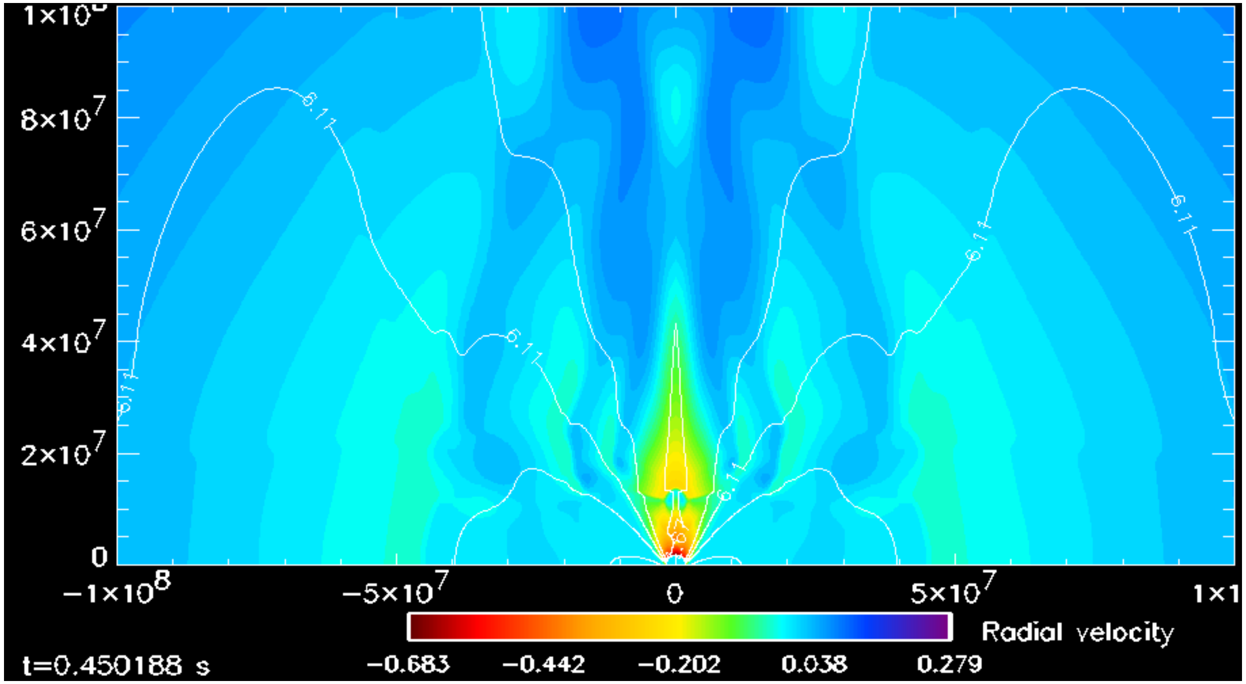
	Model	$\dot{E}$ [erg s^{-1}]	θ_0	v_p [c]		$\Gamma_{\max}$		θ_w		M_f [g]
				(10 ms)	(100 ms)	(10 ms)	(100 ms)	(10 ms)	(100 ms)	(100 ms)
Type-A	A01	10^{49}	30°	0.67	0.62	18	18	$< 1^\circ$	$< 1^\circ$	$4.0 \cdot 10^{15}$
	A02	$2 \cdot 10^{50}$	30°	0.63	0.63	81	232	11.3°	6°	$8.8 \cdot 10^{23}$
	A03	$2 \cdot 10^{50}$	45°	0.80	0.67	11	27	9.5°	3.9°	$4.5 \cdot 10^{24}$
	A04	$2 \cdot 10^{50}$	75°	0.67	-	7	-	8.5°	-	-
	A05	10^{51}	30°	0.99	0.82	84	562	15.0°	15°	$3.5 \cdot 10^{25}$
	A06	10^{51}	45°	0.97	-	80	-	15.8°	-	-
	A07	10^{51}	75°	0.90	0.60	13	37	12.5°	8.13°	$2.4 \cdot 10^{25}$
	A08	10^{50}	31.4°	0.83	0.70	20	20	3.8°	2.9°	$1.4 \cdot 10^{22}$
	A09	$5 \cdot 10^{51}$	30°	0.70	0.97	91	748	23°	26°	$3.3 \cdot 10^{26}$
Type-B	B01	$2 \cdot 10^{50}$	45°	0.995	0.99994	33	247	36°	30°	$5.4 \cdot 10^{24}$
	B02	$2 \cdot 10^{50}$	60°	0.999	0.99995	40	274	35°	21°	$5.0 \cdot 10^{24}$
	B03	$2 \cdot 10^{50}$	75°	0.97	0.998	17	17	9.4°	2.3°	$6.2 \cdot 10^{22}$
	B04	10^{49}	45°	0.96	0.99991	30	244	30°	18°	$3.2 \cdot 10^{23}$
	B05	10^{51}	45°	0.999	0.99997	33	232	34°	28°	$2.8 \cdot 10^{25}$
	B06	10^{50}	41.4°	0.9991	0.99992	40	238	30°	23°	$2.8 \cdot 10^{24}$
	B07	$2.35 \cdot 10^{50}$	45°	0.995	0.99996	34	238	35°	28°	$4.0 \cdot 10^{24}$
	B08	$2.35 \cdot 10^{50}$	45°	0.999	0.99996	34	253	33°	24°	$3.8 \cdot 10^{24}$

Results

- P_{thr} ~ $10^{48\text{-}49}$ erg/(s·sr):
  * in the initial model matter falls in through the axis of rotation (v_{in}~0.6c- 0.97c)

  * model dependent but the feature may be generic

  * our threshold is probably higher than in real mergers (type-A) or maybe irrelevant in type-B models.



- All the successful models produce relativistic *collimated* outflows:

⇒ initially the disk provides the collimation via cocoon/disk interaction, i.e., the opening angle of the beam is set by the torus inclination.

- pure hydrodynamic collimation (no need for B- fields).

* For low dE/dt ⇒ initial opening angle set after ~ 1-3 ms ($_j$ ~ 3-5), but modified later by the high density halo.
* For high dE/dt ⇒ initial opening angle set after a torus scale-height light-crossing time (~ 0.5-1 ms) with $_j$ ~ 3-5.

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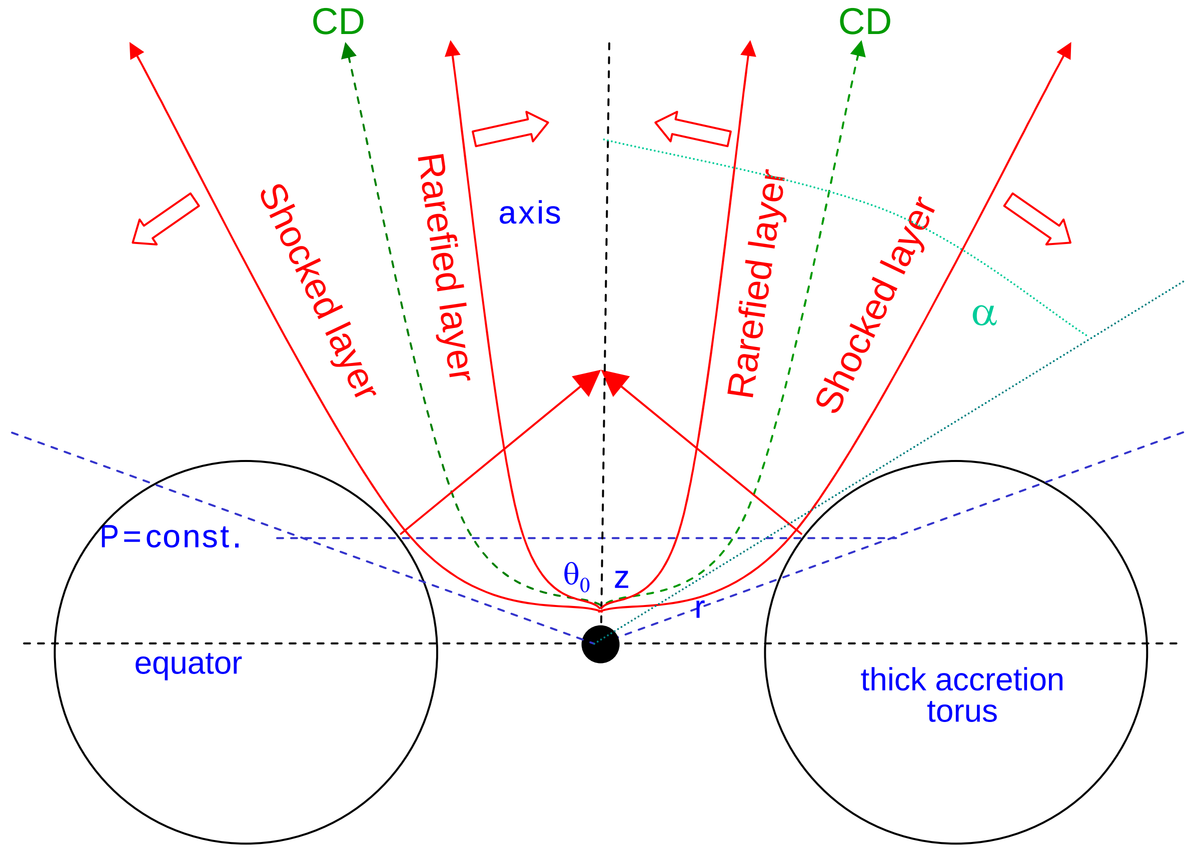

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Results (evolution up to 100 ms)

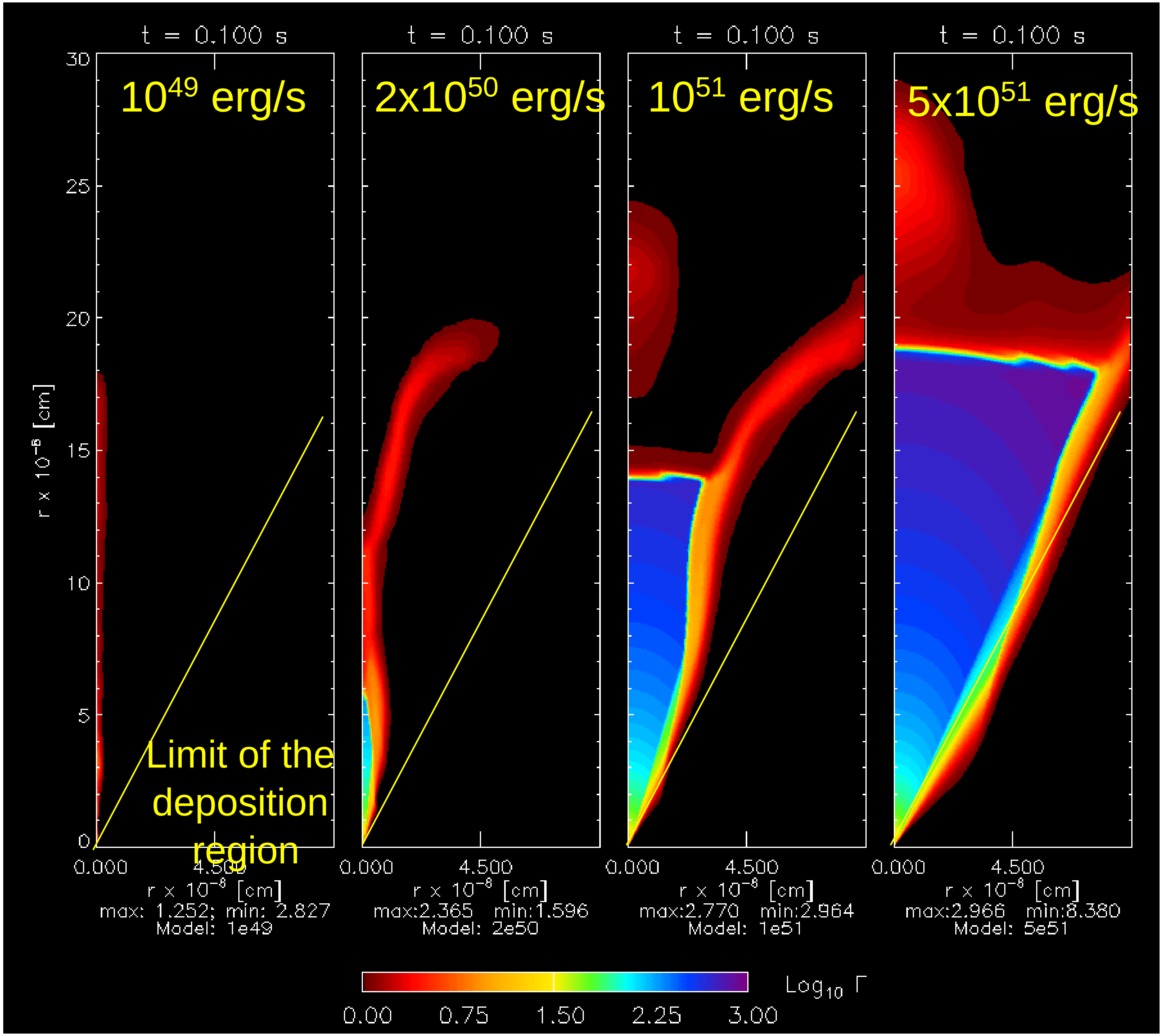
Type A

Morphology: For P> P_{thr} ~ 10^{49} erg/s the outflows are either knotty, narrow, relativistic jets (P < 10^{51} erg/s) or conical, smooth, wide angle, ultrarelativistic winds (P > 10^{51} erg/s).

Outflow open. half-angle: It is determined by the high density external medium (low P) or by the inclination angle of the side walls of the torus (large P).

Propagation speed: between ~ 0.6c (P < 10^{51} erg/s) and ~0.97c (P > 10^{51} erg/s).

Collimation: (dense) external medium (+ torus).



Results (evolution up to 100 ms)

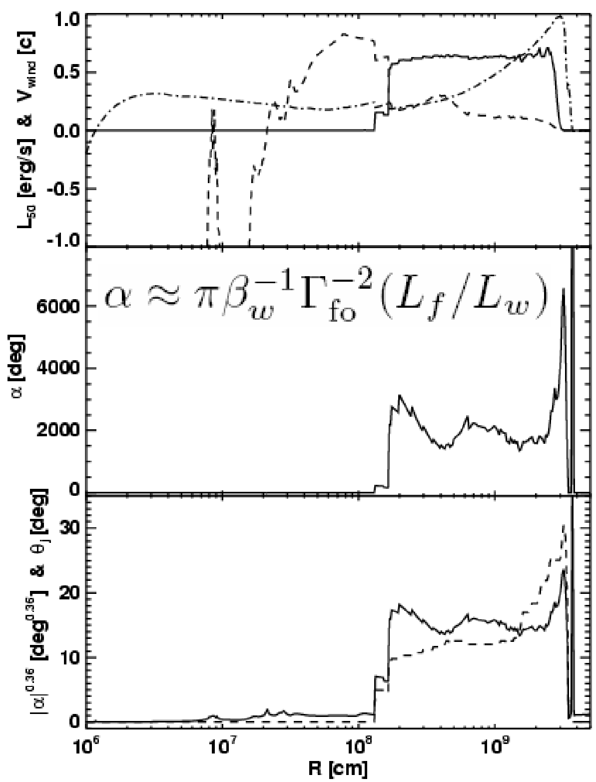
Type B

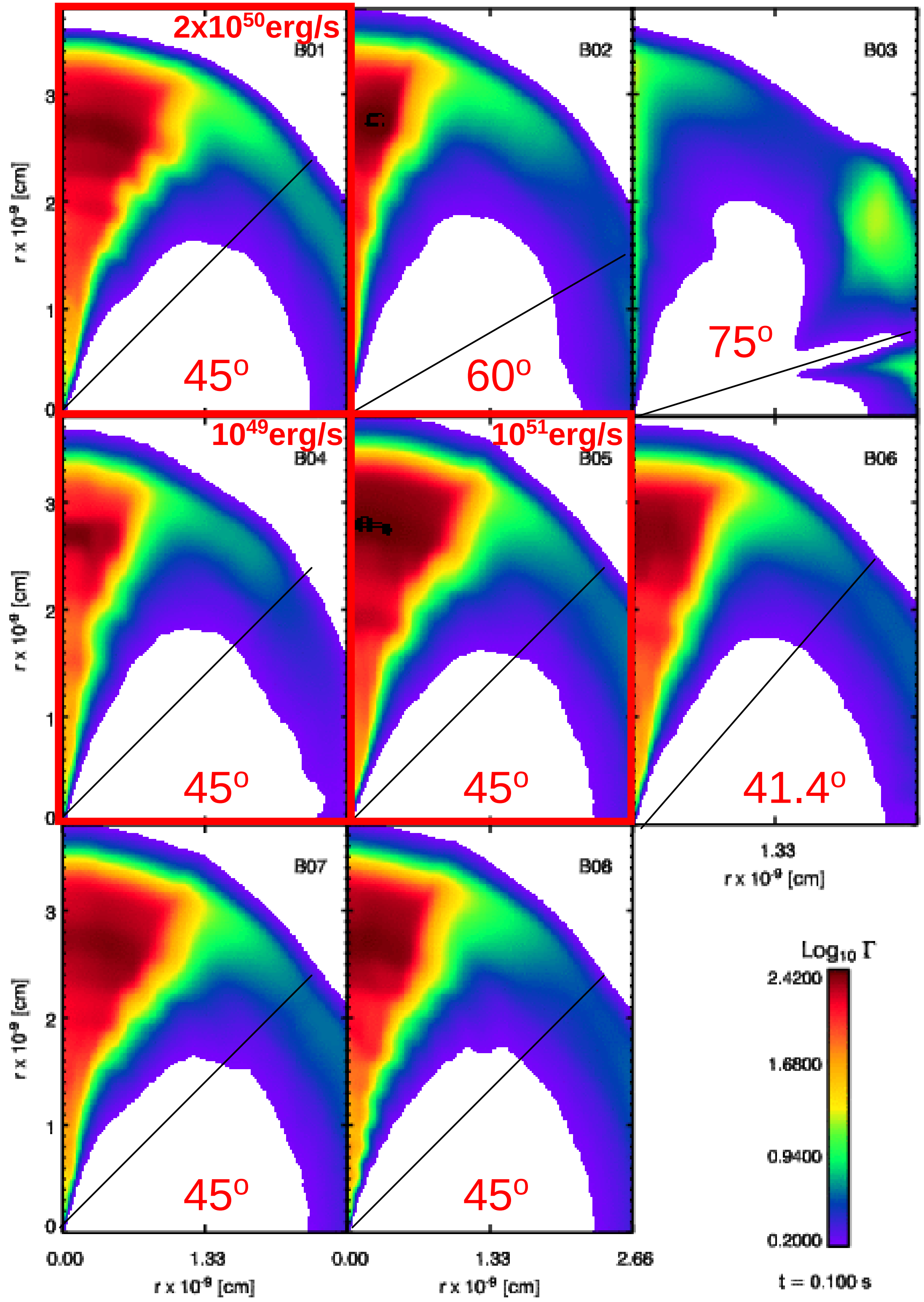
Morphology: For P> P_{thr} ~ 10^{48} erg/(s·sr) the outflows are always conical, wide angle, ultrarelativistic jets.

Outflow opening half-angle: ~ 20° to 30°. It is determined by the inclination angle of the side walls of the torus (large P/V).

Propagation speed: larger than ~0.9999c.

Collimation:
torus
(no LE00)





Post-switch-off evolution

The typical time scale in which the merging of SCBs may release energy is of some fractions of a second.

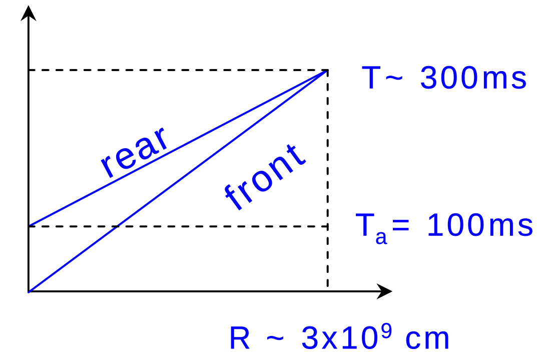
We have switched off the energy deposition after T_a=0.1s and followed the subsequent evolution of two models: one of type-A (P =5x10^{51} erg/s in ${}_0=30^{o}$) and another of type-B (P =2x10^{50} erg/s in ${}_0=45^{o}$).

A condition to produce a successful GRB is:

$$\Gamma_{front} \text{ ultrarelativistic} \Leftrightarrow V_{rear} \leq V_{front} \quad \text{(a)}$$

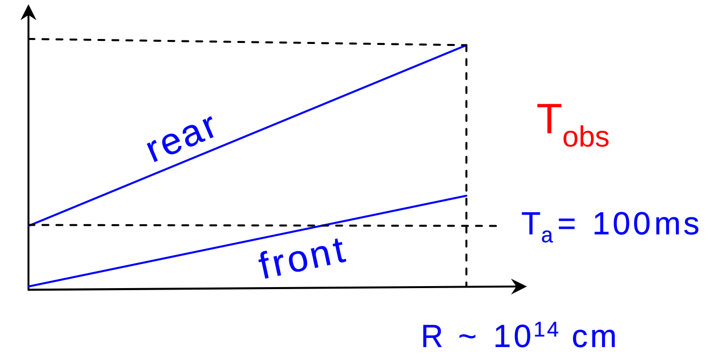
Type A

Unsuccessful GRB: Condition (a) does not hold because the environment is too dense and the front shock of the fireball decelerates.

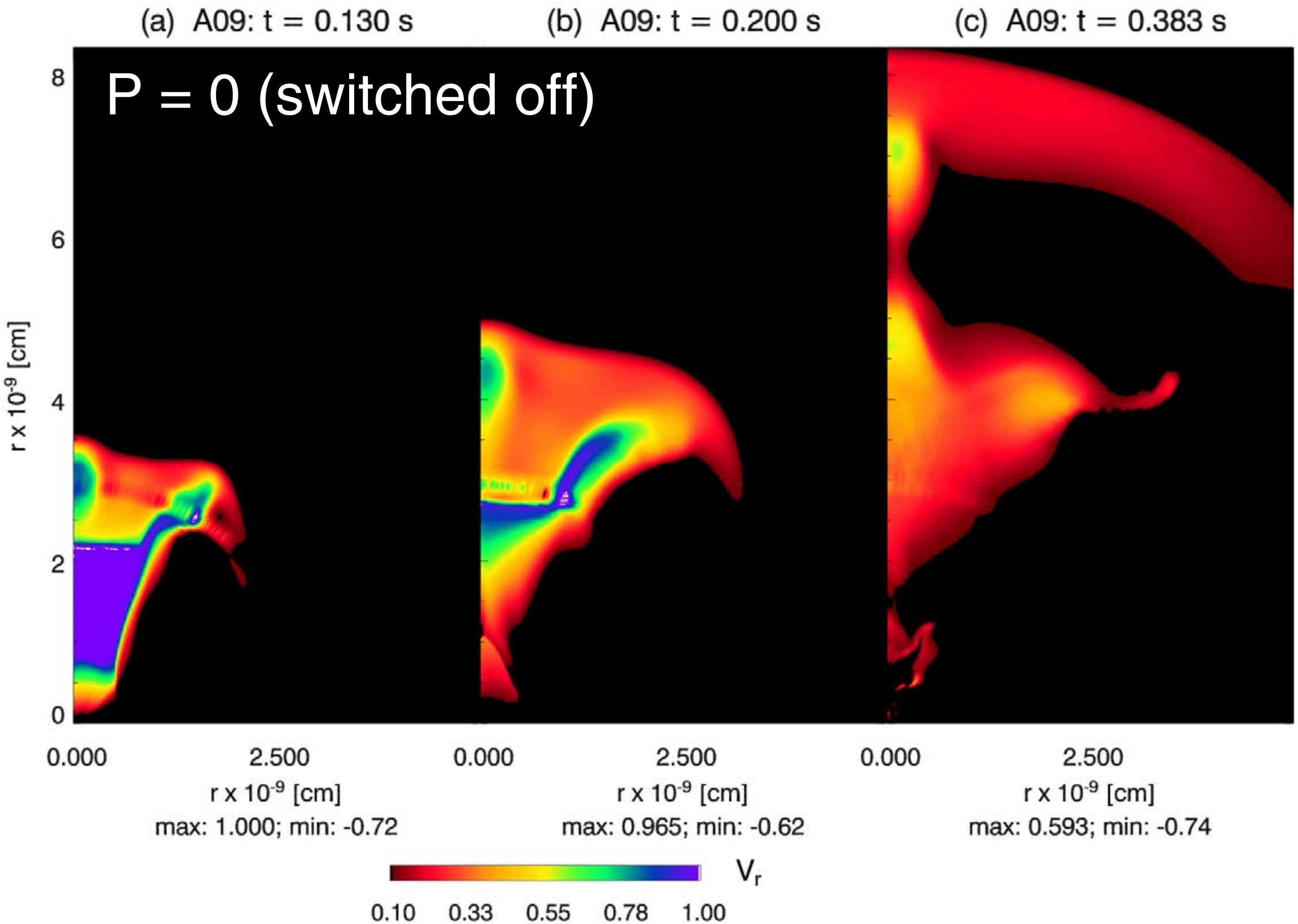


Type B

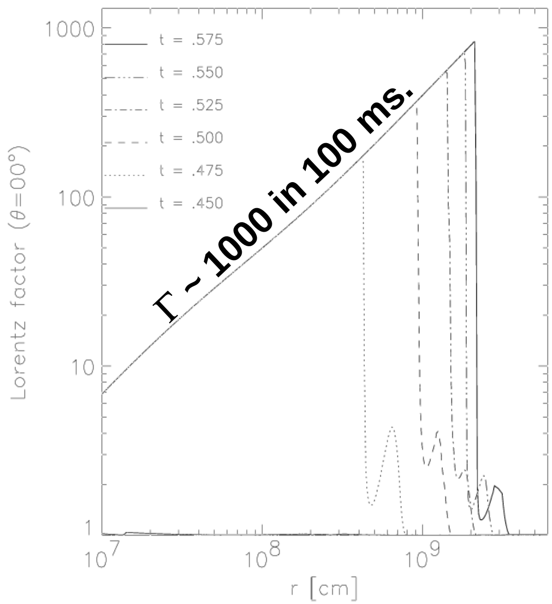
May produce a successful GRB: Condition (a) is $V_{rear} < V_{front}$ in this case. Thus, the fireball stretches radially and, it can produce events with durations of several seconds, i.e., $T_a \ll T_{obs}$.

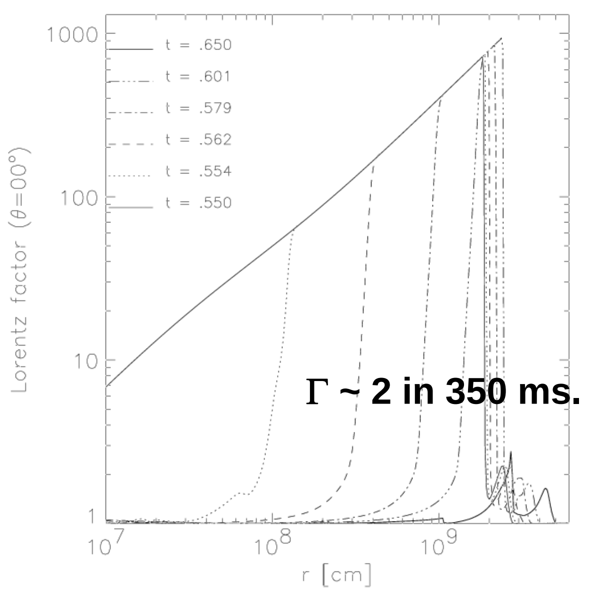


Post-switch-off evolution. Type-A (merger in high density environment)



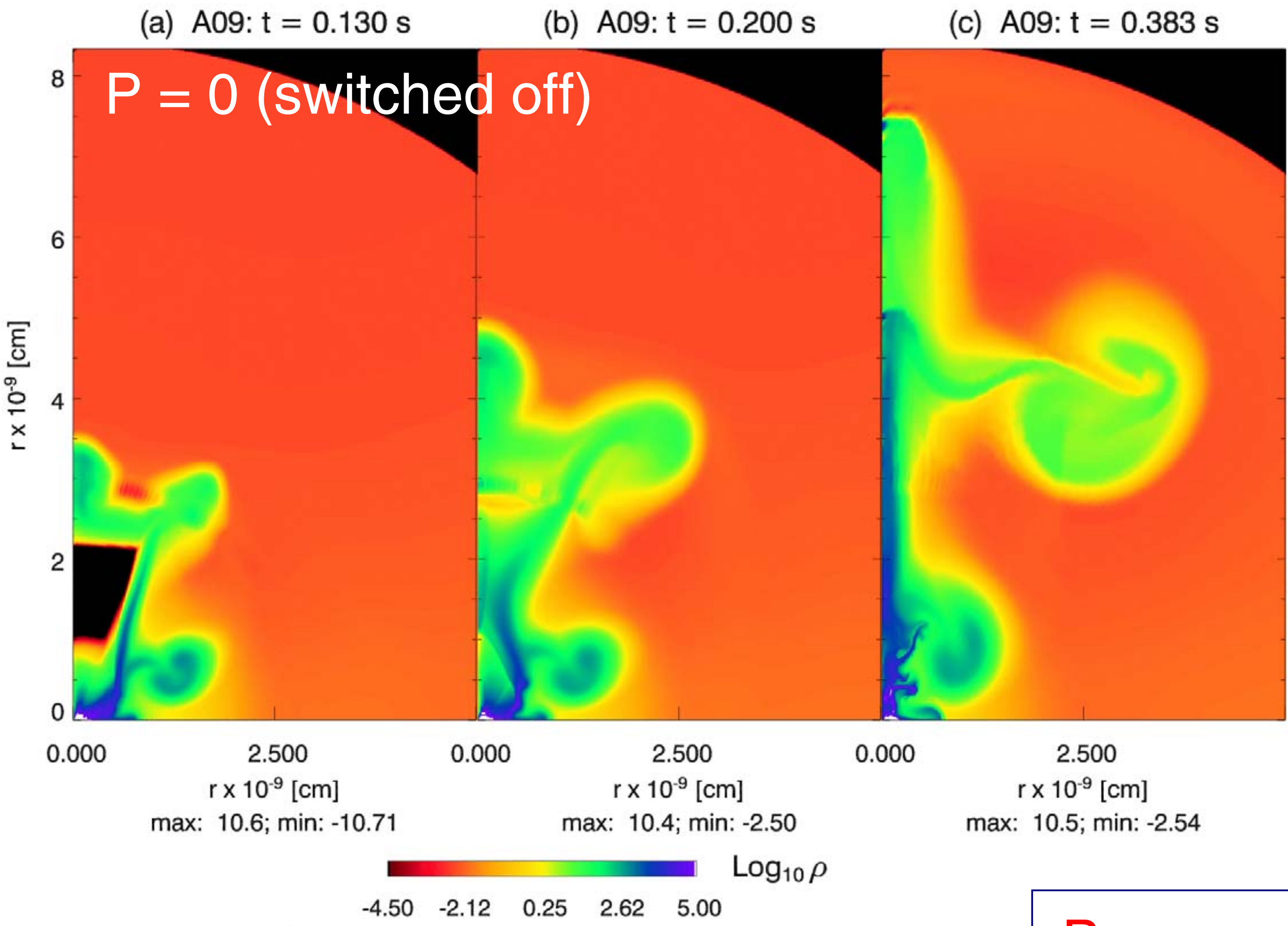
No GRB!!!





$P_{A09} = 5 \times 10^{51}$erg/s

Post-switch-off evolution. Type-A (merger with high density halo)



No GRB, instead: UV-flash.

Assuming adiabatic evolution of the cloud:

$$R_t \approx 3\cdot 10^{13}\ \mathrm{cm}\left(\frac{\kappa}{\kappa_e}\right)^{1/2}\left(\frac{M}{10^{-5}\ \mathrm{M}_\odot}\right)^{1/2}$$

$$t_t \approx R_t/c \approx 10^3\ \mathrm{s}\left(\frac{\kappa}{\kappa_e}\right)^{1/2}\left(\frac{M}{10^{-5}\ \mathrm{M}_\odot}\right)^{1/2}$$

P_{A09} = 5x10^{51}erg/s

$$T_t \approx 5\cdot 10^4\ \mathrm{K}\left(\frac{T_0}{1.5\cdot 10^9\ \mathrm{K}}\right)\left(\frac{\kappa}{\kappa_e}\right)^{-1/2}\times\left(\frac{M}{10^{-5}\ \mathrm{M}_\odot}\right)^{-1/2}\left(\frac{R_0}{10^9\ \mathrm{cm}}\right)$$

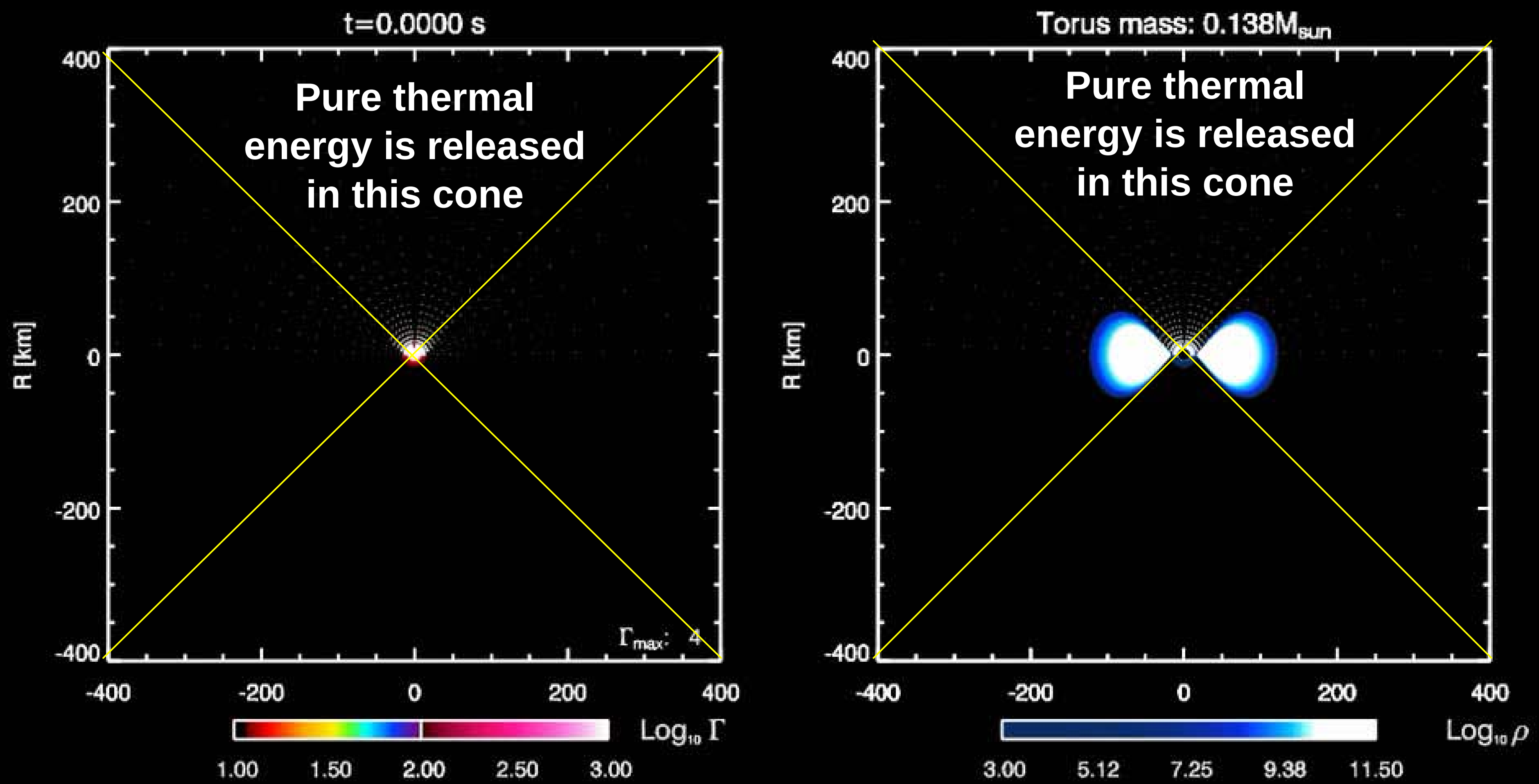
Because of the small L_m, only closeby events will be visible

$$L_m \approx 7\cdot 10^{42}\ \mathrm{erg\,s^{-1}}\left(\frac{T_0}{1.5\cdot 10^9\ \mathrm{K}}\right)^4\left(\frac{\kappa}{\kappa_e}\right)^{-1}\times\left(\frac{M}{10^{-5}\ \mathrm{M}_\odot}\right)^{-1}\left(\frac{R_0}{10^9\ \mathrm{cm}}\right)^4$$

Post-switch-off evolution. Type-B (merger with low density halo)

- For P = 2×10^{50} erg/s the Lorentz factor grows up to ~ 1000 in 500 ms.
- Switching off the energy release leads to an almost selfsimilar growth

  $\Rightarrow$ it is possible to produce a successful GRB!



Model B01:

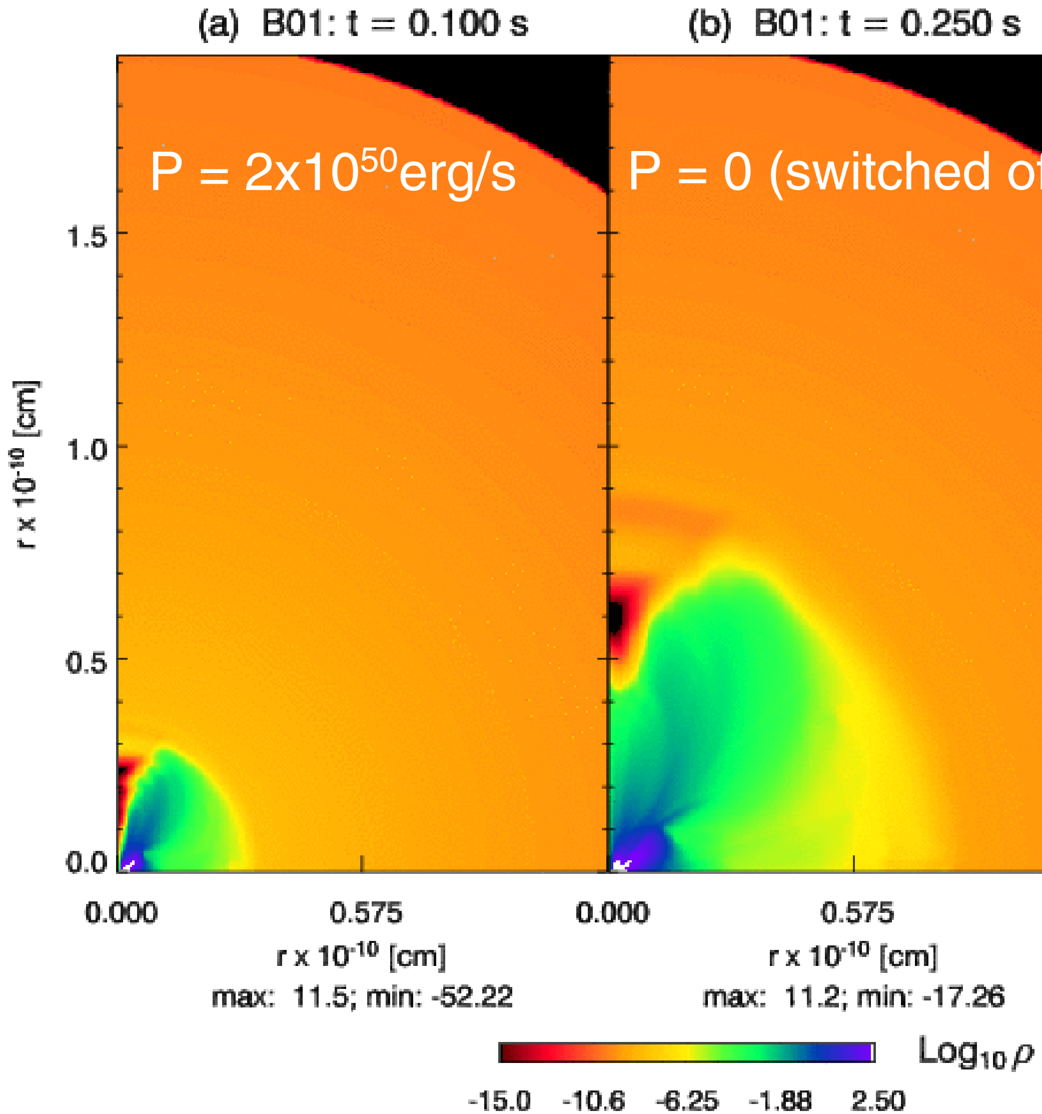
P = 2×10^{50} erg/s, $E_{dep} = 2\times10^{49}$ erg, $E_{\Gamma>100} \sim 6\times10^{48}$ erg, $E_{\Gamma>10} \sim 1.2\times10^{49}$ erg

$_{0} = 45^{o}$, $_{w} = 24^{o}$, $M_f = 7.4\times10^{24}$ g

Post-switch-off evolution. Type-B (merger with low density halo)

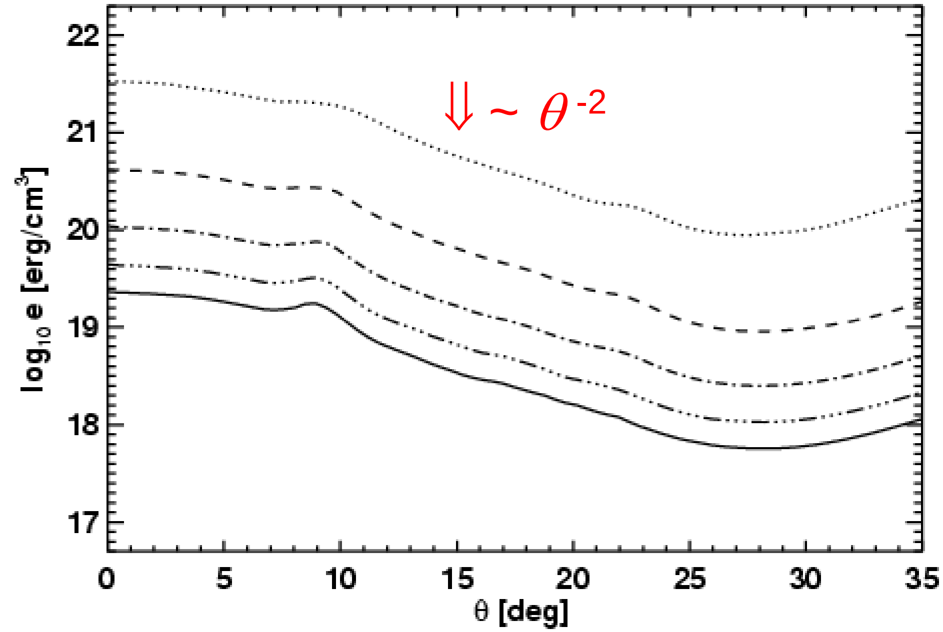
The fireball has a large internal energy reservoir even after ~ $5T_a$

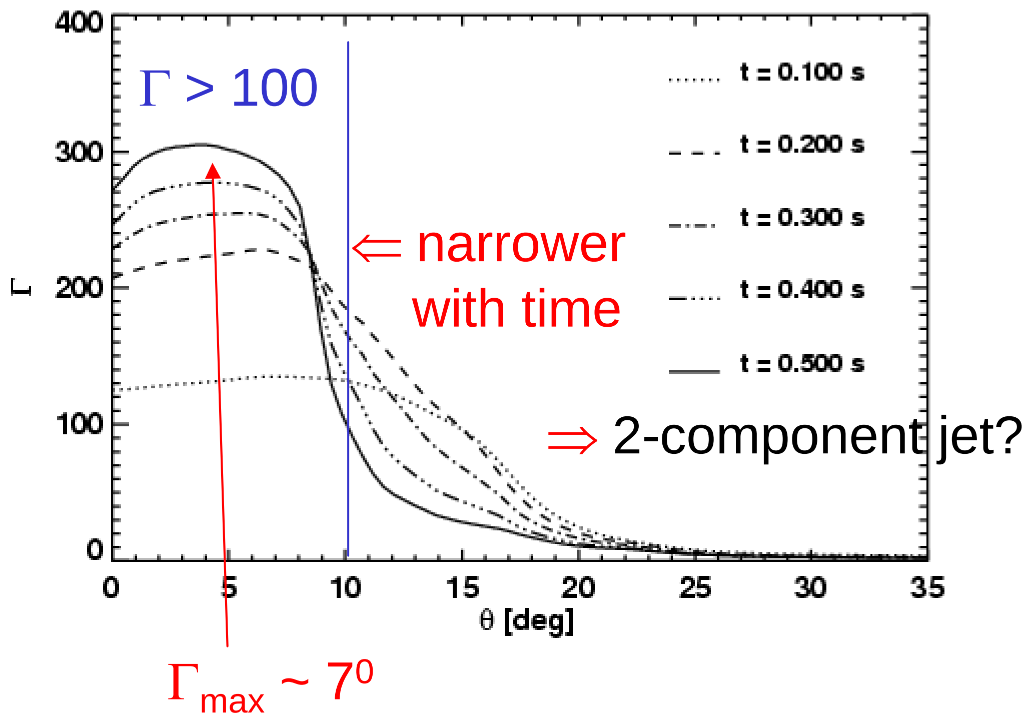
- ⇒ there is still room for further acceleration
- ⇒ no sign of saturation
  - ⇒ internal shocks develope although the resolution at $R>10^{10}$ cm is not good enough and a part of the structure created is erased.

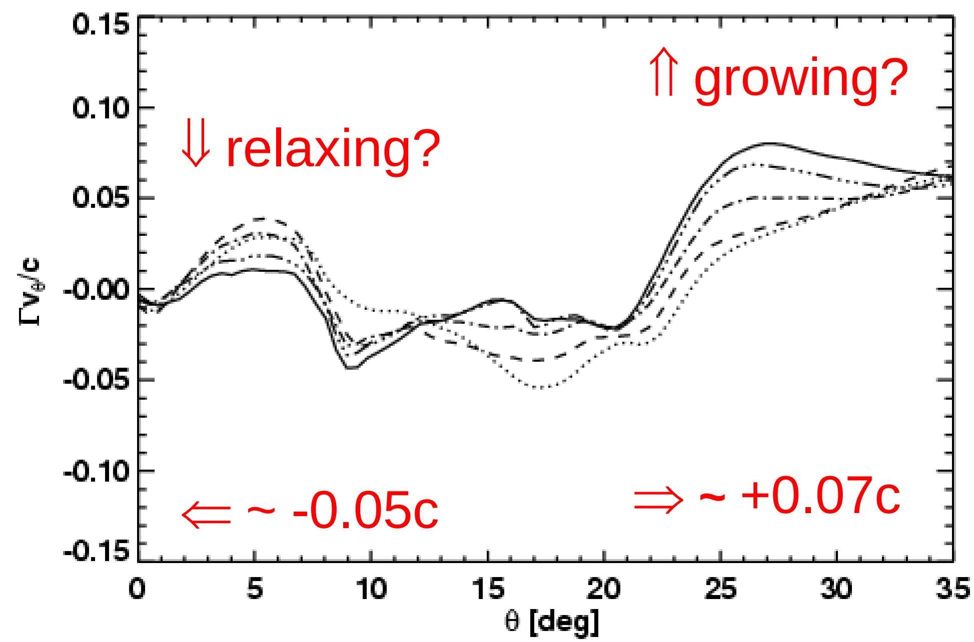


Post-switch-off evolution. Type-B

- ⇒ The radially averaged variables display a *non-monotonic* shape as a function of .
- ⇒ The internal energy as a function of the solid angle is *not constant*.
- ⇒ The sideways expansion in the comoving frame is subsonic.
- ⇒ A part of the fireball is *contracting!*.
- ⇒ $\theta_{\Gamma>100} \sim 5^{o} – 10^{o} \Rightarrow E_{iso} \leq 10^{51}$ erg.







Post-switch-off evolution. Type-B

⇒ $\theta_{\Gamma>100}$ ~ 5º – 10º ⇒ f_Ω ~ 0.4 – 1.5% of the hemisphere ⇒ $10^{50} \leq E_{iso} \leq 10^{51}$ erg.

⇒ 100 times more short GRBs than observed

(assuming isotropic detectability in all directions within the opening angle)

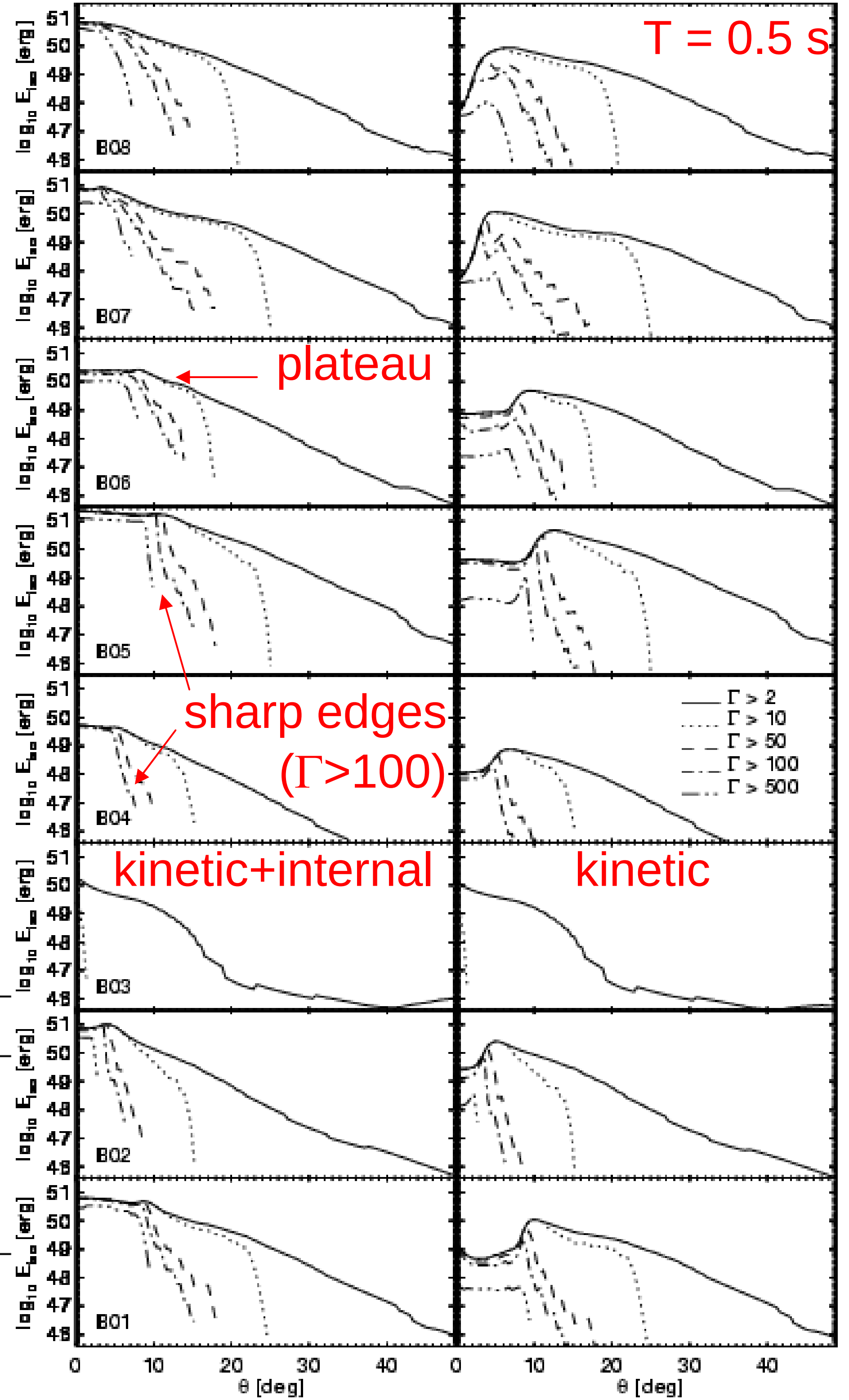
⇒ $\theta_{\Gamma>10}$ ~ 15º – 25º ⇒ f_Ω ~ 7 – 18% of the hemisphere ⇒ $10^{49} \leq E_{iso} \leq 10^{51}$ erg.

⇒ 10 times more short GRBs than observed

⇒ A rate of 100 y^{-1} observed short GRBs yields 10^{-5} $(f_\Omega / 0.01)^{-1}(Ng/10^9)^{-1}$galaxy^{-1} y^{-1} events, consistent with estimated NS+NS & NS+BH merger rates ~ 10^{-5} (e.g., Kalogera 2004; Fryer et al. 1999; Ghetta & Piran 2004)

Model	E_d [erg]	$\frac{E_{\Gamma>100}}{E_d}$	$\frac{E_{\Gamma>50}}{E_d}$	$\frac{E_{\Gamma>10}}{E_d}$	$\frac{E_{\Gamma>2}}{E_d}$	$\frac{E_{k,\Gamma>100}}{E_d}$	Γ_{max}	θ_w	M_f [g]	Γ_∞
B01	$2 \cdot 10^{49}$	0.29	0.36	0.59	0.70	$4.4 \cdot 10^{-3}$	859	24°	$7.4 \cdot 10^{24}$	1765
B02	$2 \cdot 10^{49}$	0.09	0.15	0.35	0.48	$4.8 \cdot 10^{-3}$	687	15°	$6.4 \cdot 10^{24}$	1217
B03	$2 \cdot 10^{49}$	0.00	0.00	$1.2 \cdot 10^{-4}$	0.04	0.00	16	3°	$1.9 \cdot 10^{22}$	142
B04	10^{48}	0.17	0.26	0.52	0.65	$5.1 \cdot 10^{-3}$	492	15°	$3.6 \cdot 10^{23}$	1601
B05	10^{50}	0.30	0.37	0.60	0.71	$8.3 \cdot 10^{-3}$	979	25°	$3.6 \cdot 10^{25}$	1848
B06	10^{49}	0.19	0.29	0.54	0.66	$3.7 \cdot 10^{-3}$	717	18°	$3.4 \cdot 10^{24}$	1761
B07	$1.65 \cdot 10^{49}$	0.14	0.25	0.59	0.72	$3.4 \cdot 10^{-3}$	839	25°	$7.6 \cdot 10^{24}$	1429
B08	$1.67 \cdot 10^{49}$	0.18	0.25	0.49	0.60	$4.5 \cdot 10^{-3}$	789	21°	$5.6 \cdot 10^{24}$	1607

⇒ 10% - 30% of E_{dep} within θ ~ 5º – 10º



Concluding remarks:

Releasing energy over the poles at rates above our P_{thr} and with a functional depencence suggested by Janka et al (1999) relativistic (Γ_{max} ~ 1000), collimated conical/jet-like, outflows are produced.

Collimation: via interaction with the external medium and/or the accretion torus. Aplication of the analytic Levinson & Eichler's collimation mechanism yields wrong results. Typical opening angles: $\theta_{\Gamma>100} \sim 5^o - 10^o$ ($\theta_{\Gamma>10} \sim 20^o - 30^o$).

$\therefore$ An observed rate of 100 y^{-1} short GRBs needs of 10^{-5} galaxy^{-1} y^{-1} merger events, which is consistent with estimated NS+NS & NS+BH merger rates.

While mergers in low-density environments successful GRBs can be produced, in high-density media the observational signature may be a thermal UV-flash ($T \sim 5 \times 10^4$ K) with very low luminosity ($L \sim 10^{43}$ erg/s) and durations of ~1000 s.

$\Rightarrow$ continuous transition between UV-flashes and GRBs??

The fireball stretches radially and, it can produce events with durations of few seconds (*although the central engine may survive only for a few 0.1 s*).

Our results are consitent with the fluence-duration proportionallity (short vs long GRBs; e.g., Balazs et al 2003): $E_{iso} \sim 10^{51}$ erg while $E_{dep} = 10^{49}$ erg (in 0.1 s).

The fireball structure is inhomogeneous both in radial and angular directions (KH-instab.) and has a contractive, ultrarelativistic core + relativistic, expanding layer