Thermal emission in black-body dominated GRBs

Miguel A. Aloy

ERC Fellow
Departamento de Astronomía y Astrofísica

collaborators
C. F. Cuesta-Martínez, M. Obergaulinger, P. Mimica

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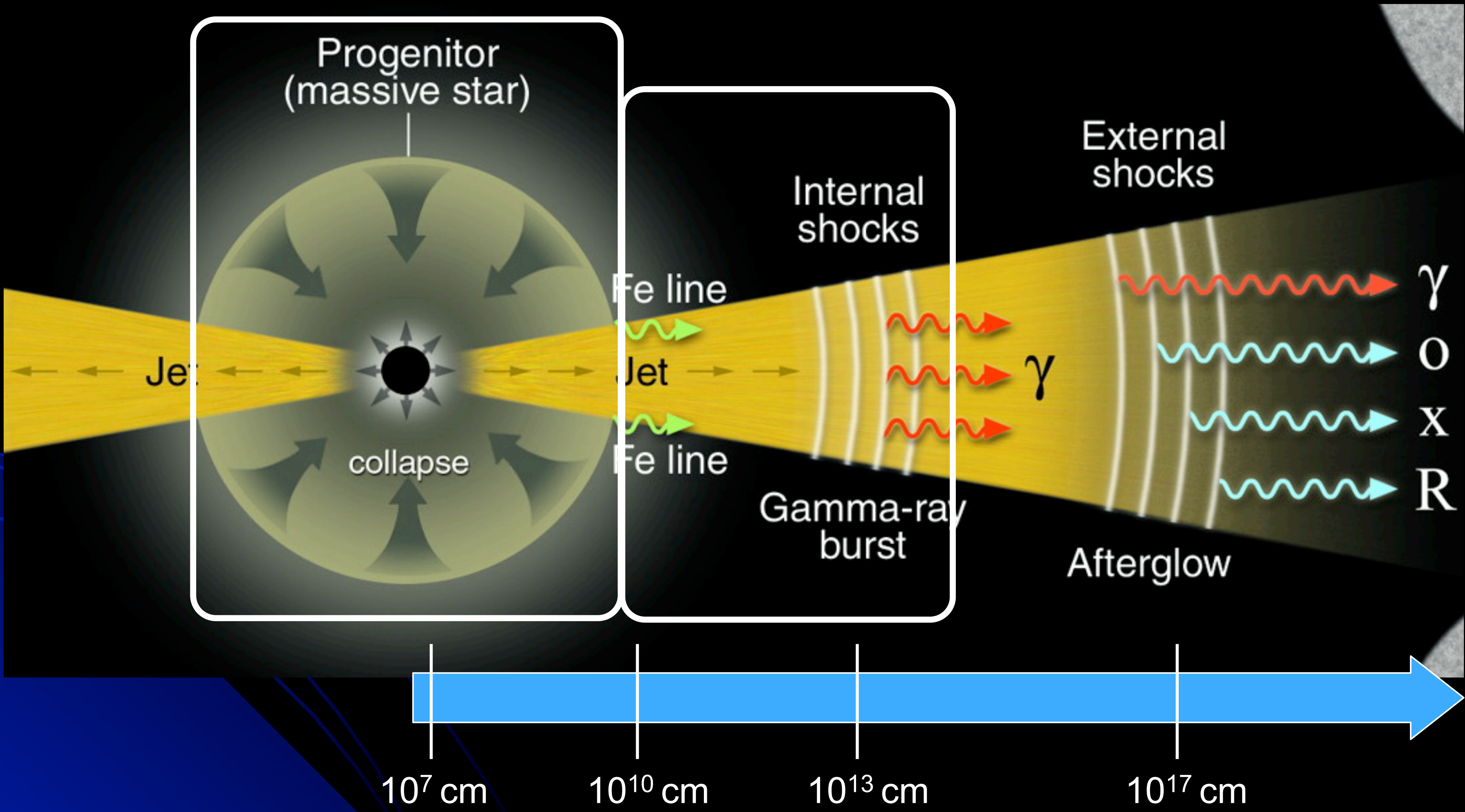
Meszaros (2002)



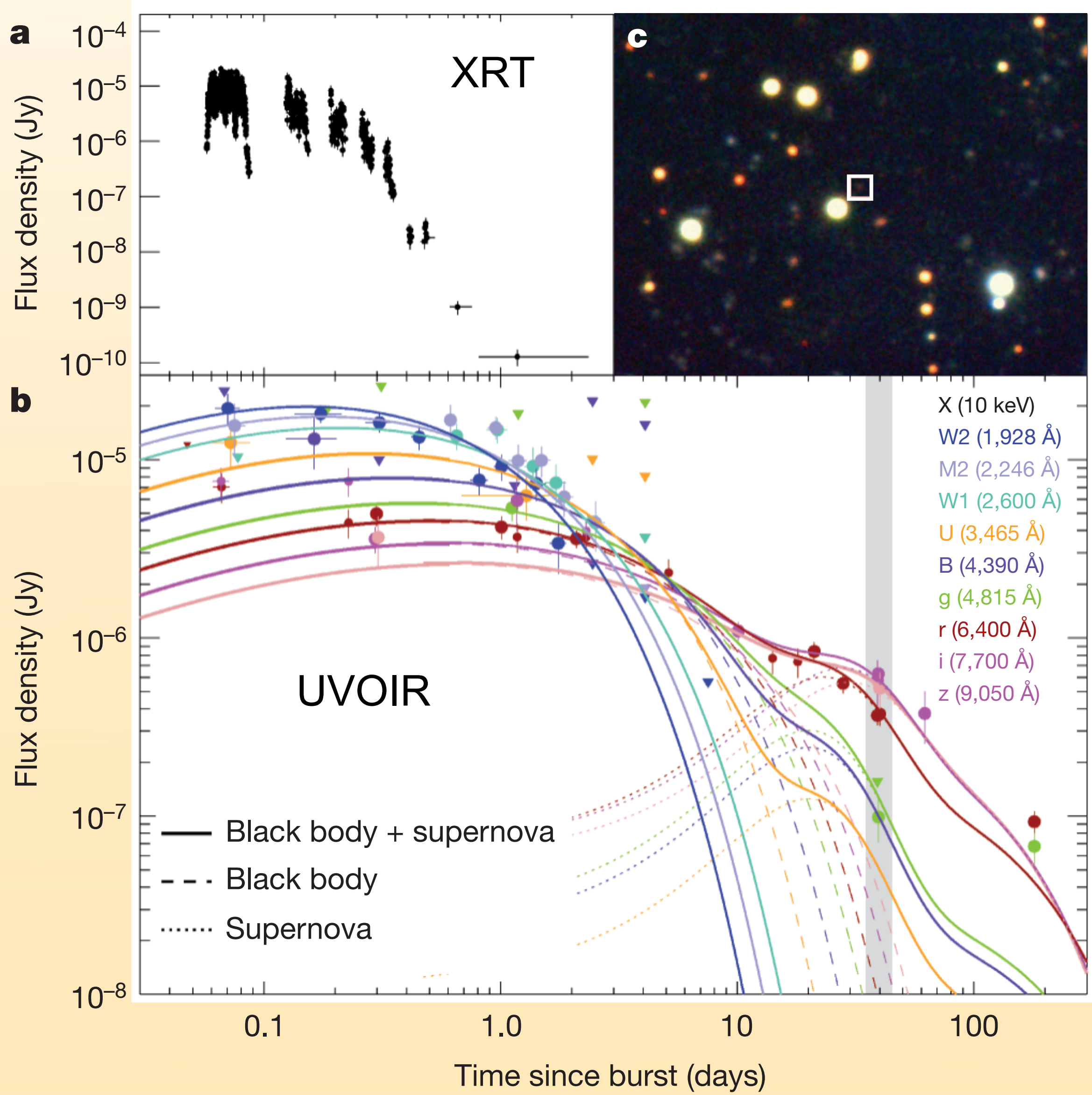
GRB 101225A: A Christmas puzzle

Why is it *unusual*?

- Its γ-ray emission was exceptionally long-lived (T_{90} > 2.000 s).
- It has no classical afterglow: the X-ray emission following the GRB (0.38 h < t < 18 days) is best fitted with BB + PL.
- During the first 2 h, there is a persistent X-ray source, seemingly different from the "afterglow" emission.
- After 10 days there is a flattening of the LC, *suggestive* of an associated SN.
- Prototype of a class? Among nearby GRB-SNe without a classical afterglow, there is a class (*BB-dominated*) of very long GRBs with very low E_{peak}, all of them showing a thermal component in X-rays.

Thöne+ (2011)

OSIRIS/GTC



Forensic analysis

"When all possibilities have been eliminated, whatever remains, however improbable, must be the truth."
(Sir Arthur Conan Doyle)

What ***is*** GRB 101225A?

- *A stellar murder* on Christmas day (Thöne, et al. 2011, *Nat*, **480**, 72):
  A neutron star (likely material author of this crime) in a binary system undergoes a common envelope phase (the system must survive the SN explosion giving birth to the main suspect) with a massive He-star companion. The NS merges with the core of the He-star and induces its dead as a *faint* SN. Just a bit before the murder, a central compact object is born, probably a massive/hypermassive NS, which eventually collapses to a BH, producing a collapsar-like jet, whose propagation through the previously ejected hydrogen mantle of the secondary gives rise to the observed phenomenology.

- *An induced cometary suicide* on Christmas day (Campana, et al. 2011, *Nat*, **480**, 70):
  A wandering neutron star (again, likely inductor of this event) captures a minor body (a comet) and disrupts it because of the tidal forces. If the comet has a relatively small tensile strength, the captured body breaks down into gas, and forms a relatively thin annulus around the NS. The process can be chaotic and eventually the annulus turns into an extended accretion disk with flares coincident with the periastron passages, and the bolometric light curve is expected to decay, in the long term, as $t^{-5/3}$.

Unveiling the murder

"Get your facts first, and then you can distort them as much as you please." (Mark Twain)

In order to reconstruct the crime scene, we have to pay attention to the following elements:

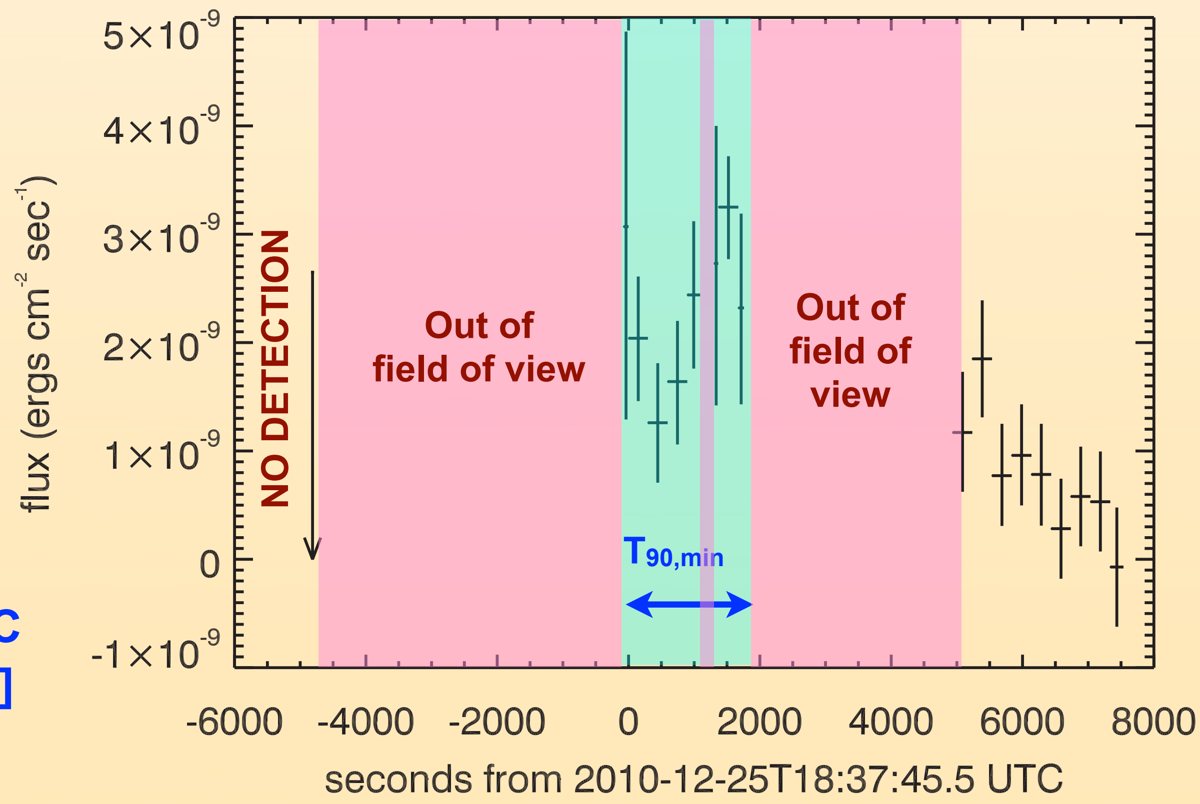
- Prompt GRB emission.
- Early X-ray signature (unusual because of the BB component and the standing X-ray source).
- Late UVOIR signature (also unusual because of the BB and the LC flattening).
- Do we see a SN?
- Do we see the host galaxy? (key to estimate the distance to the event, and settle whether it is local or cosmological).
- Do we see a *periodic behavior*? (important element to give credit to the cometary suicide interpretation).

Spectral fit of the BAT dataset

- The burst started before the beginning of the BAT data at ~ $T - T_0 = -100$ s and probably continued while the source was not in the BAT field of view in $T - T_0 \in$ [+1091 s, +1372 s].

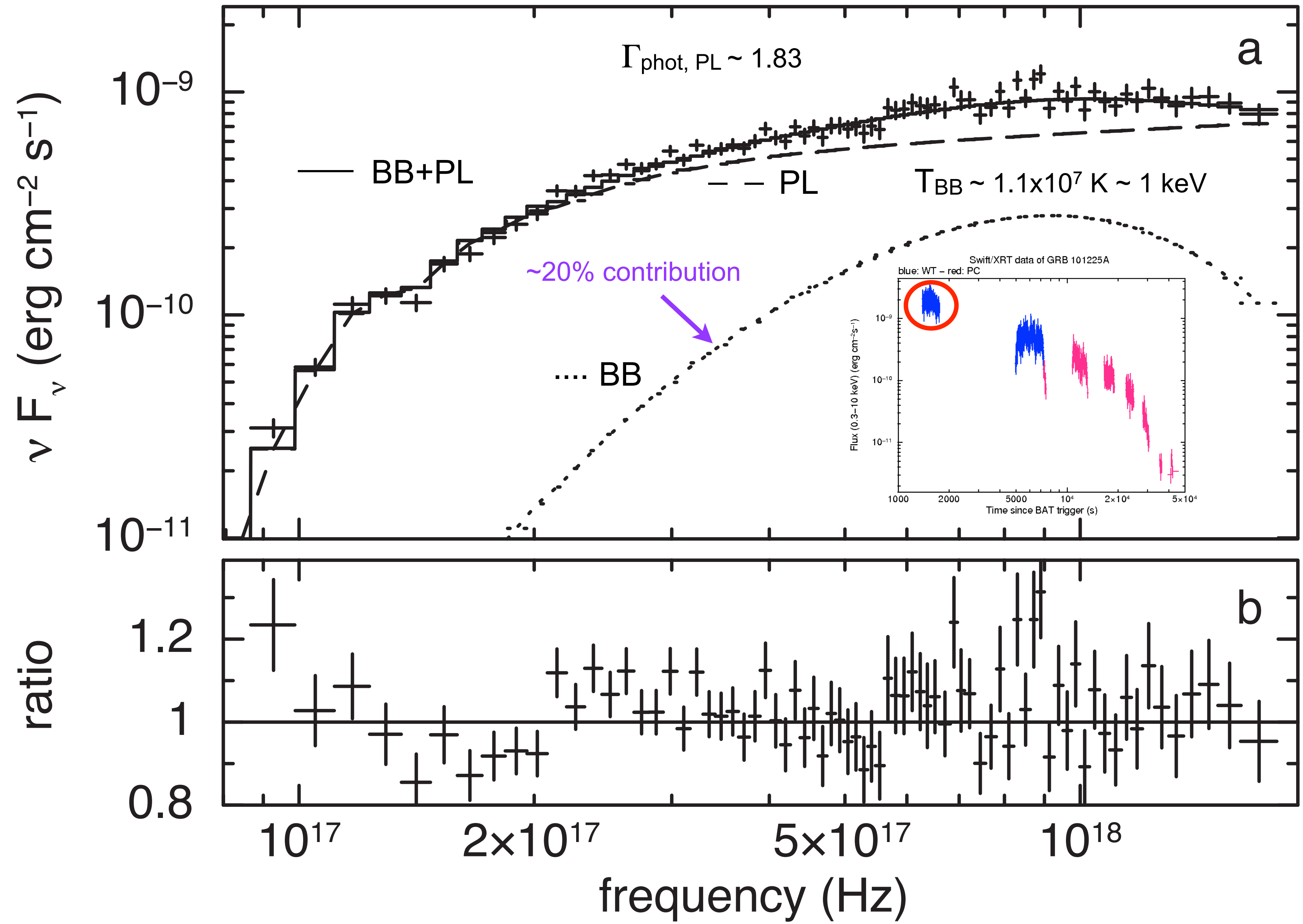
- Because of the low SNR, the BAT spectrum can be fitted by:
    1. PL with photon index **Γ ~ 1.9**.
    2. Cut-off PL (**E_{peak} ~ 38 ± 20 keV**)
    3. BB (**T_{BB} ~ 10.1 ± 1.1 keV**).

- **$E_{\gamma,iso} > 1.4 \times 10^{51}$ erg** (if z=0.33)

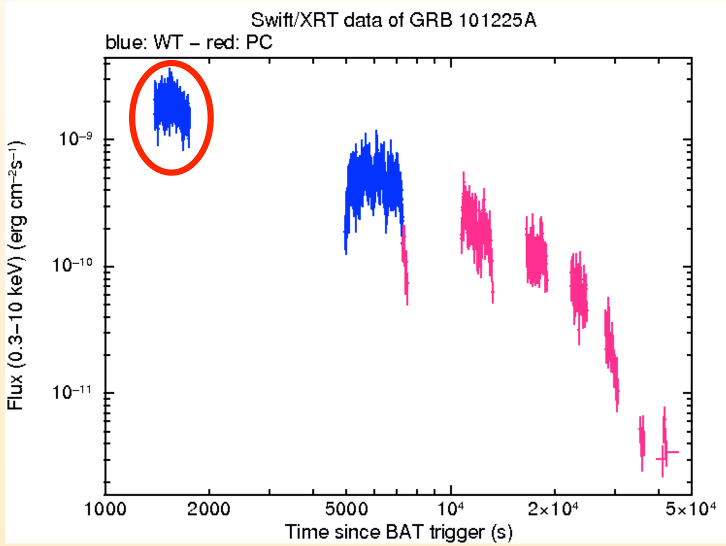


BAT γ-ray LC [15-150 keV]

Spectral fit of the 1st XRT dataset



Evidence #2:
Spectral fit of the 1st XRT dataset



Other possible fits tried:

Model	Γ	kT (keV)	N_H (10^{22} cm^{-2})	χ^2/d.o.f. (F-test)
PL	1.72 ± 0.03		0.24 ± 0.02	468/381
PL+BB	$1.83^{+0.13}_{-0.10}$	0.96 ± 0.13	0.22 ± 0.03	421/379 (1.95×10^{-9})
PL+diskBB	$1.79^{+0.36}_{-0.22}$	1.64 ± 0.35	0.18 ± 0.04	417/379 (3.19×10^{-10})
PL+compt	1.79 ± 0.04	<22	$0.31^{+0.03}_{-0.02}$	424/377 (1.55×10^{-7})

Supplementary Table 1 | Result of different model fits to the X-ray data of the first snapshot. PL is a pure power-law model, PL+black body (BB) a combination of a simple PL and a black body with one temperature while a PL+diskBB includes emission from black bodys with different temperatures, PL+compt includes a comptonized component in addition to the power-law. Γ is the photon index of the power-law, kT the black body temperature, the column density is the total density, including the Galactic absorption. The last column shows the χ^2 of the different fits and the F-test value compared to the simple absorbed PL model.

Evidence #2:
Spectral evolution (1st XRT dataset)

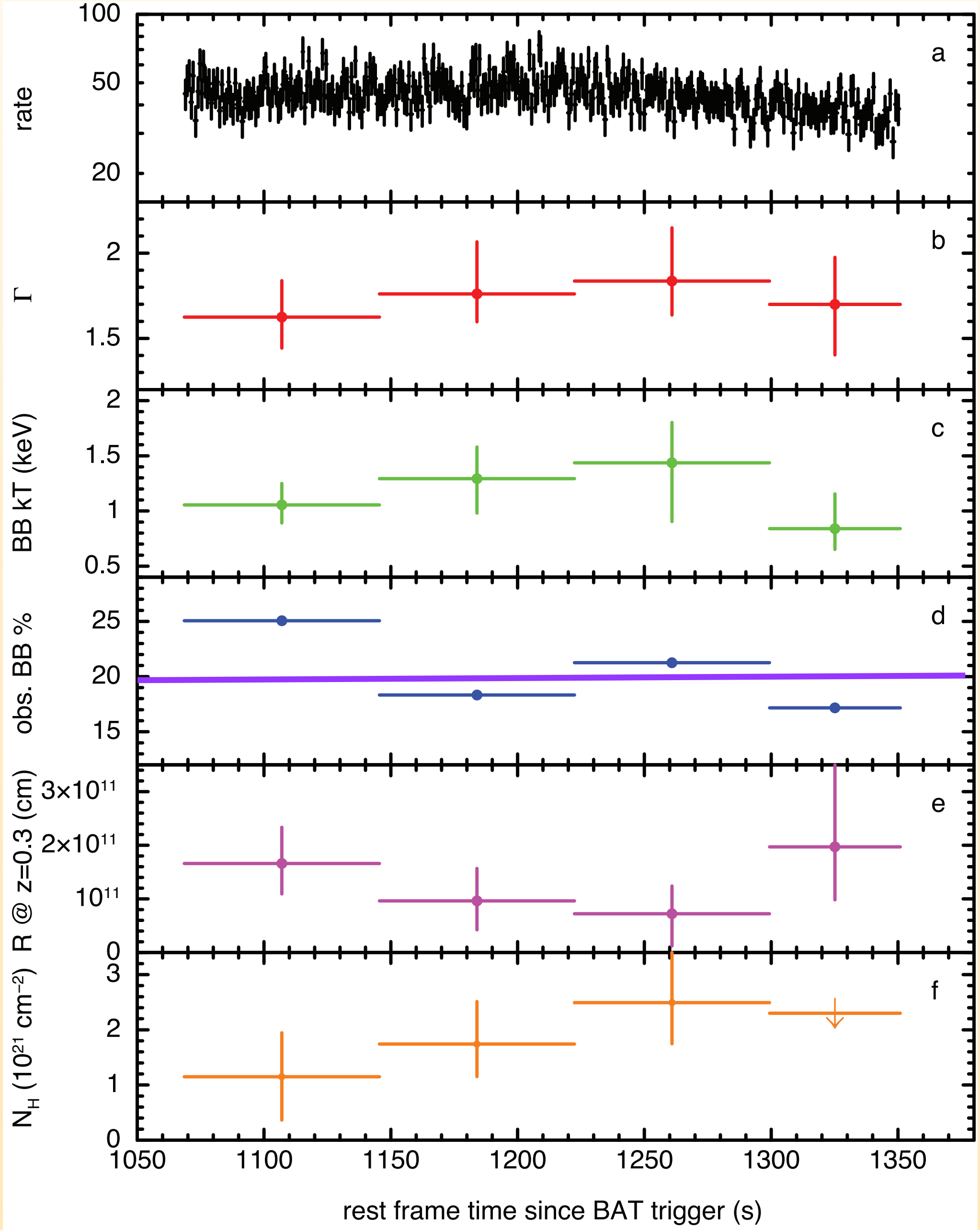
Little time evolution of $\Gamma_{phot,\,PL} \sim 1.83$

Little time evolution of $T_{BB} \sim 1$ keV

20% average BB contribution

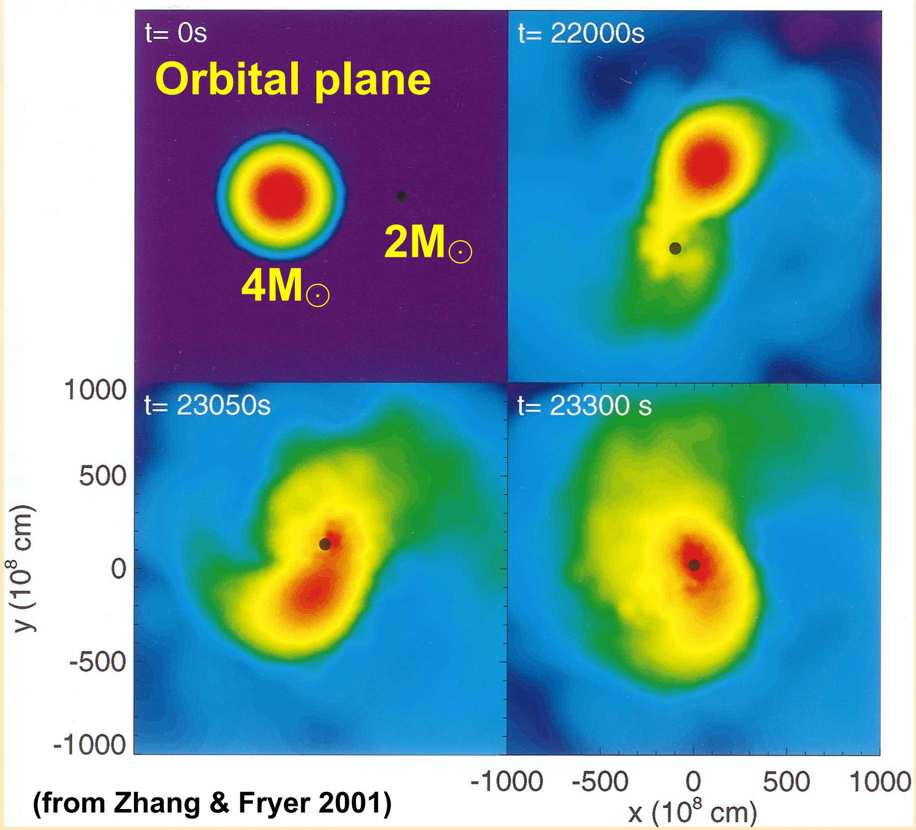
BB size ($R_{BB} \sim 2R_{\odot}$) constant

Absorbing column density in X-rays (galactic contribution in the line-of-sight: 7.9×10^{20} cm^{-2})



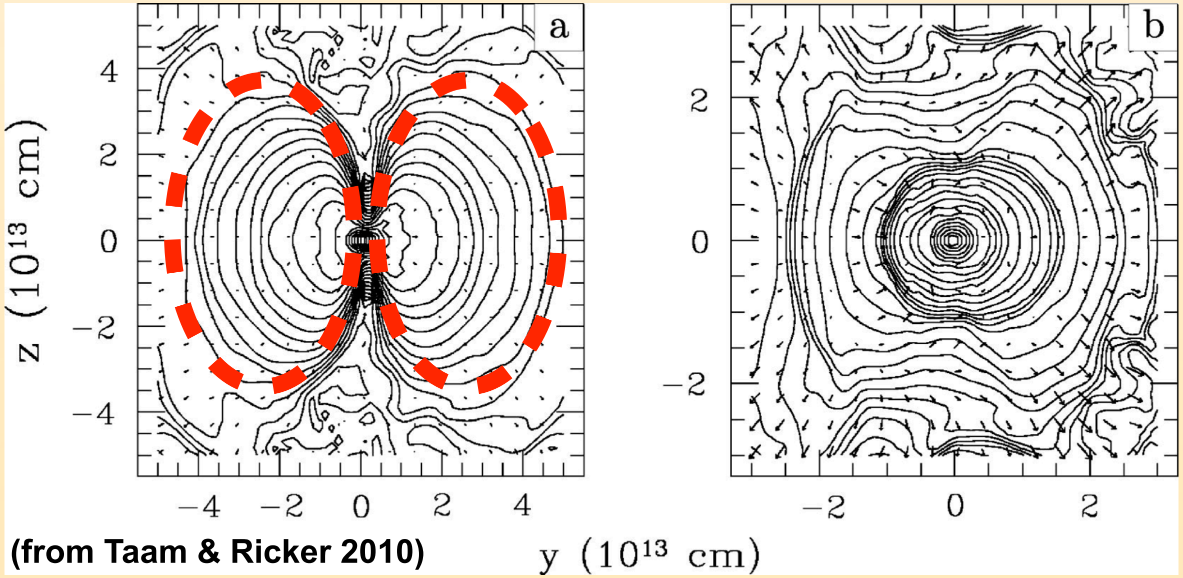
The motive for the stellar murder: 1) A dense, toroidal CE-shell

- Suggestion: the progenitor system is a He-star / NS merger.
- Existing theoretical possibility(e.g., Fryer & Woosley 1998; Zhang & Fryer 2001; Barkov & Komissarov 2011).
- When the secondary star leaves the main sequence and expands, it engulfs the NS, leading to a ***CE phase*** and the ejection of the hydrogen envelope and part of the He core as the remnant spirals into the centre of the second star.



(from Zhang & Fryer 2001)

Plane perpendicular to the orbital motion



(from Taam & Ricker 2010)

The ejecta forms a ***broad torus with a narrow, low-density funnel*** along the rotation axis.

The motive for the stellar murder: 2) The central engine

- When the neutron star reaches the centre, after ~ 5 orbits (T_{CE} ~ 1.5 yr), angular momentum forms a disk around the remnant of the merger, allowing for the formation of:
  - ***GRB-like jet. (looks like a "collapsar-induced" jet; a stellar mass BH forms).***
  - Magnetar remnant, (though not insurmountable, this is important to explain the very long duration of the GRB).

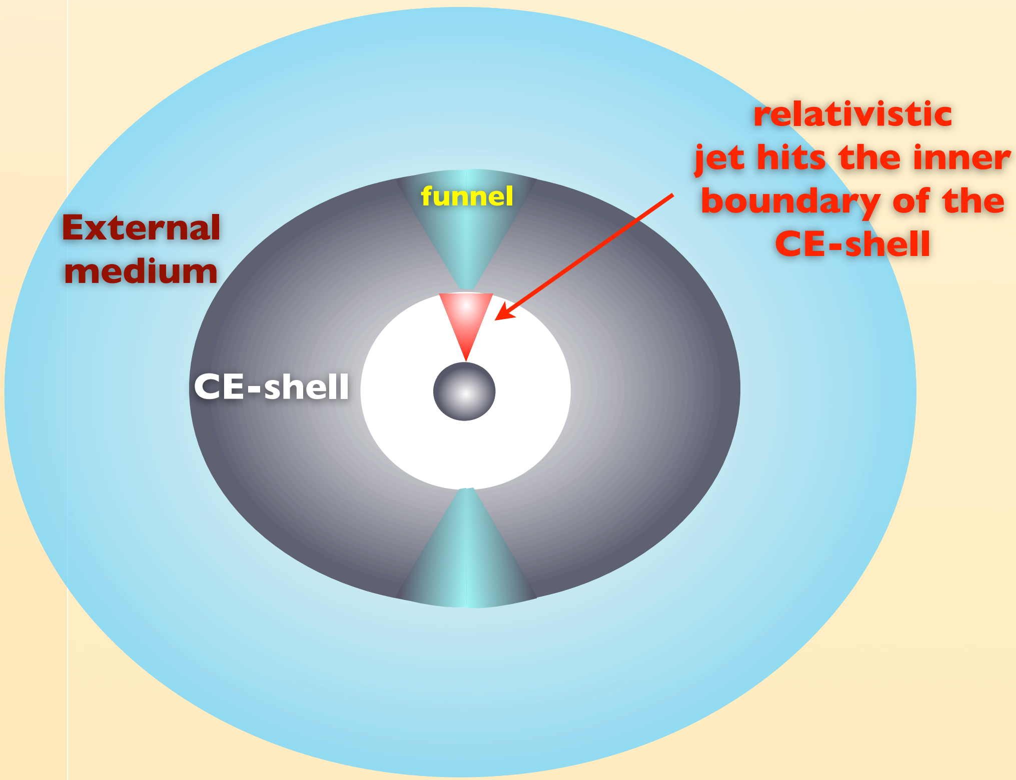
The motive for the stellar murder:
3) The jet breaks the stellar jail through a hole!

- By the time of merger ($T_{CE} \sim 1.5$ yr), the CE-shell may have traveled (close to the escape velocity) to a distance

$$\mathbf{R}_{\rm debris} \approx (3-5) \times t_{\rm orbit} v_{\rm escape} = (3-5) \times \frac{2\pi R_{\rm orbit}^{3/2}}{(GM)^{1/2}} \frac{(2GM)^{1/2}}{R_{\rm orbit}^{1/2}} \approx (27-45) \times R_{\rm orbit}$$

$$\approx \text{few} \times \mathbf{10^{14}}\,\text{cm}$$

- Stage 1: The jet propagates until it hits the CE-shell



About 80 sec after the GRB

The motive for the stellar murder:
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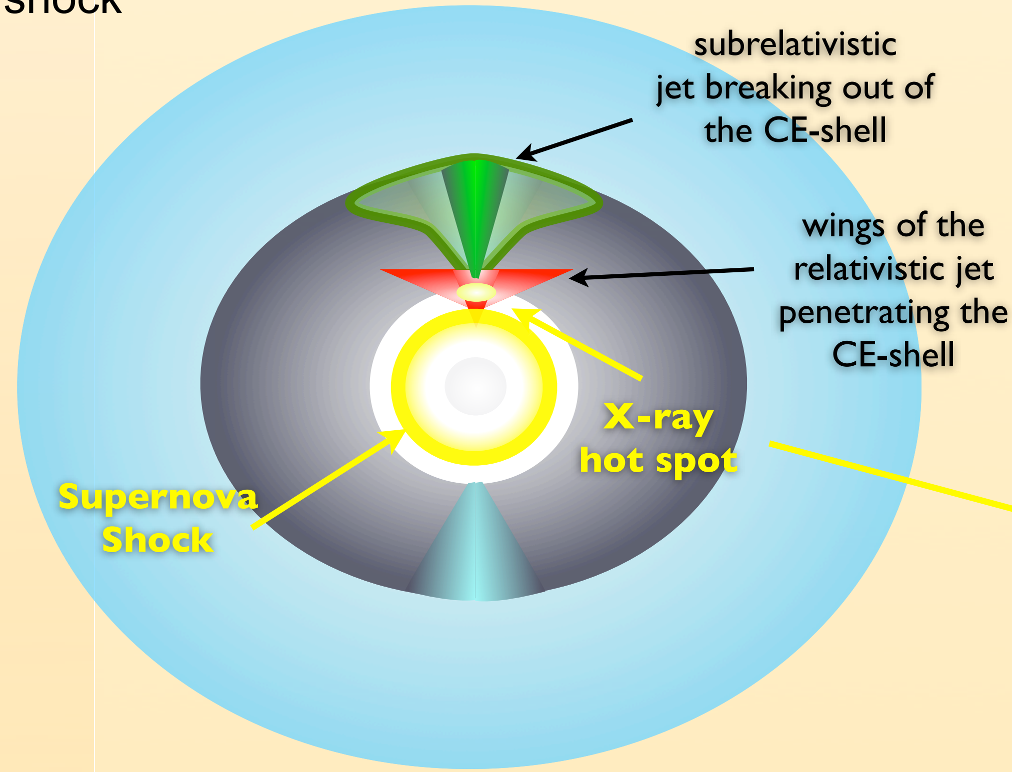
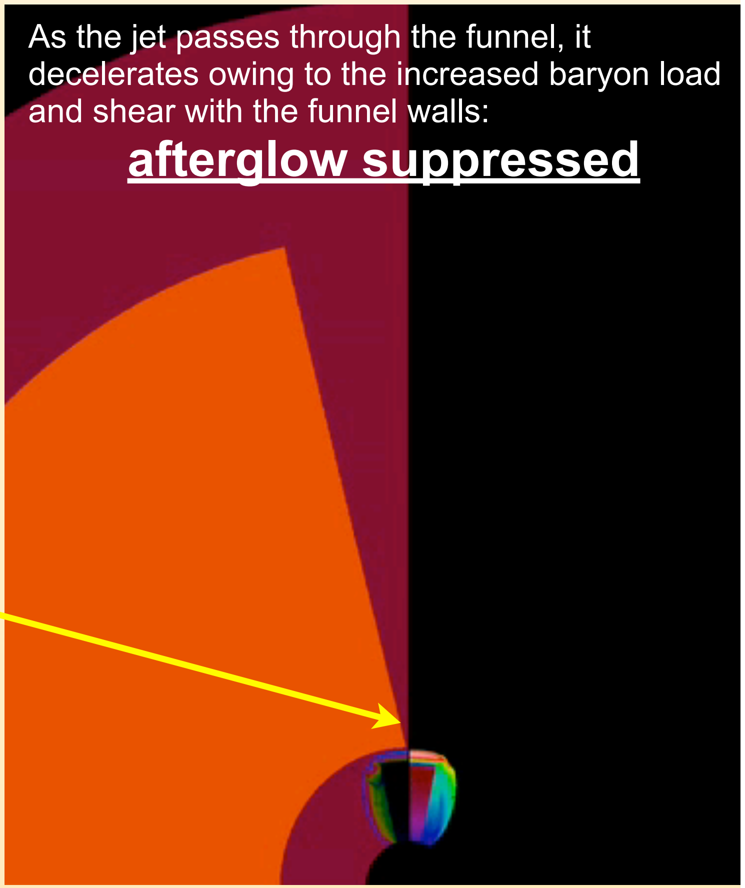
$$
\begin{aligned}
\mathbf{R}_{\rm debris} &\approx (3-5)\times t_{\rm orbit} v_{\rm escape} = (3-5)\times \frac{2\pi R_{\rm orbit}^{3/2}}{(GM)^{1/2}}\frac{(2GM)^{1/2}}{R_{\rm orbit}^{1/2}} \approx (27-45)\times R_{\rm orbit} \\
&\approx \text{few} \times \mathbf{10^{14}}\,\text{cm}
\end{aligned}
$$

- Stage 2: Jet-shell interaction resulting in the formation of a reverse shock



About 4700 sec after the GRB



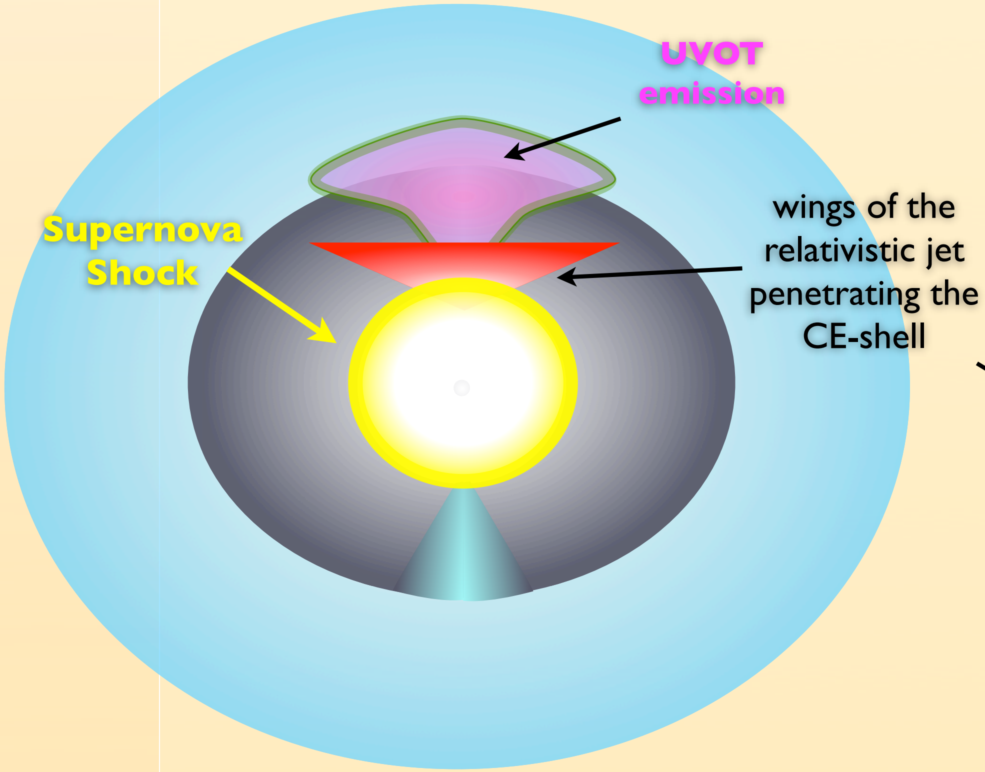
The motive for the stellar murder:
3) The jet breaks the stellar jail through a hole!

- By the time of merger (T_{CE} ~ 1.5 yr), the CE-shell may have traveled (close to the escape velocity) to a distance

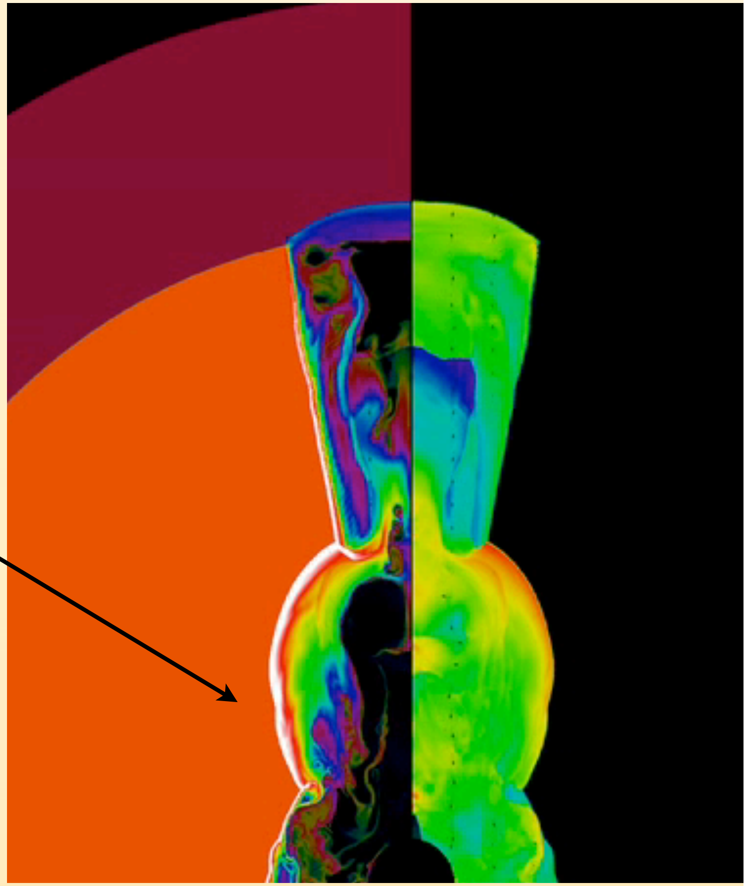
$$\mathbf{R}_{\mathrm{debris}} \approx (3-5)\times t_{\mathrm{orbit}} v_{\mathrm{escape}} = (3-5)\times \frac{2\pi R_{\mathrm{orbit}}^{3/2}}{(GM)^{1/2}} \frac{(2GM)^{1/2}}{R_{\mathrm{orbit}}^{1/2}} \approx (27-45)\times R_{\mathrm{orbit}}$$

$$\approx \mathrm{few} \times \mathbf{10^{14}}\,\mathrm{cm}$$

- Stage 3: Small fraction of the jet breaks out of the shell producing an expanding bubble.



Few hours
after the GRB



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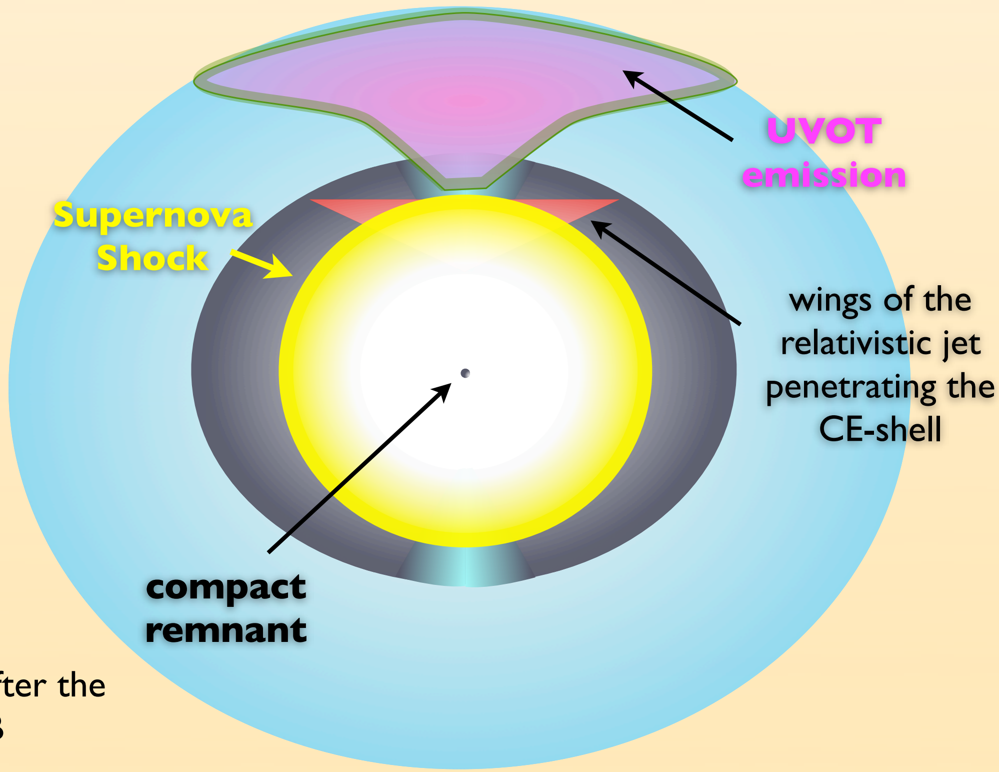
$$\approx \text{few} \times \mathbf{10^{14}}\,\text{cm}$$

- Stage 4: As the SN shock expands beyond the CE-shell, we observe a small bump in the light curve at ~30 d.

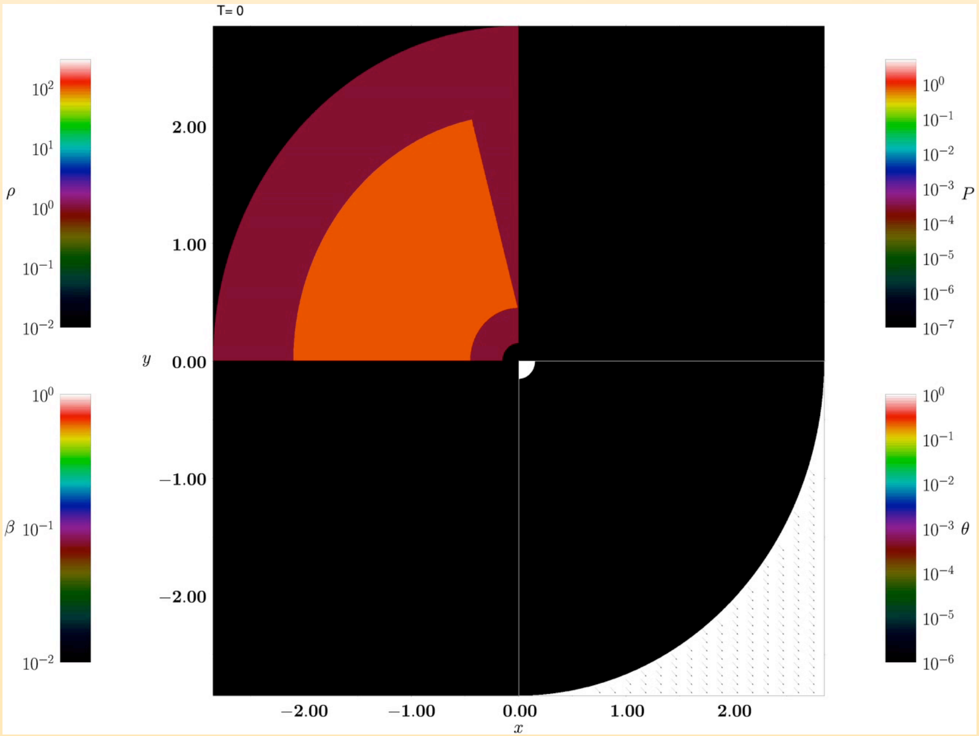
This He/NS merger scenario naturally assumes the production of a relatively small amount of radioactive Ni, **leading to a weak SN**



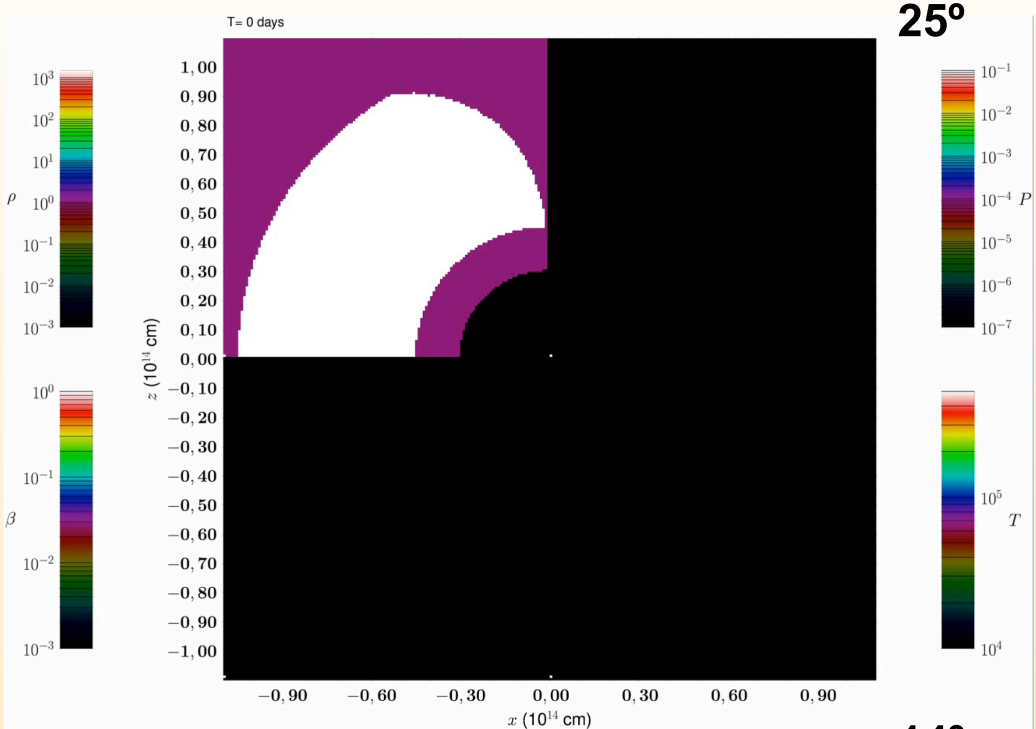
A detailed model for the jet “breakout”

- Using the MRGENESIS code (Mimica et al. 2009) we can compute 2D RHD models (>50 models explored with typical resolutions of 50000x900 cells - close to AMR models-).

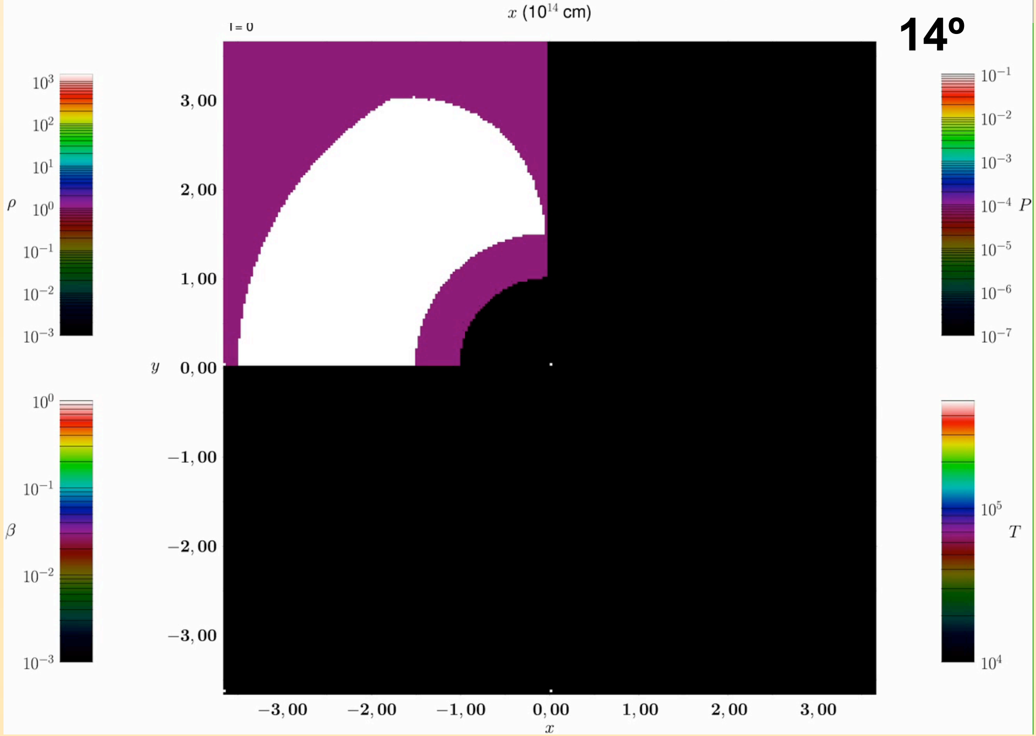
  1. Third-order finite-volume code.
  2. Explicit RK3 + PPM + Marquina.
  3. Method of lines.
  4. MPI/OpenMP hybrid parallelization (scaling up to ~10.000 CPUs).



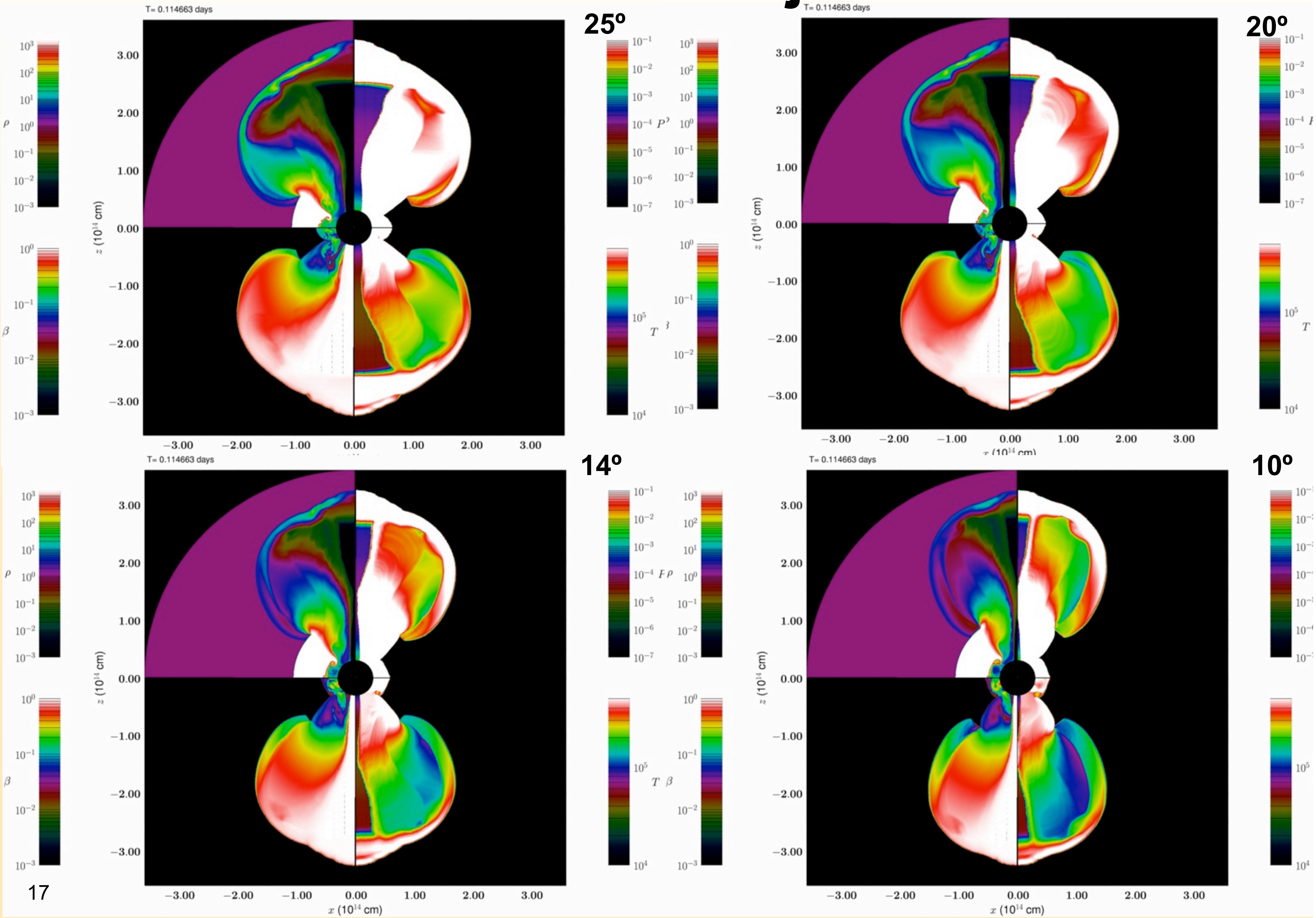
25º



14º



A detailed model for the jet “breakout”



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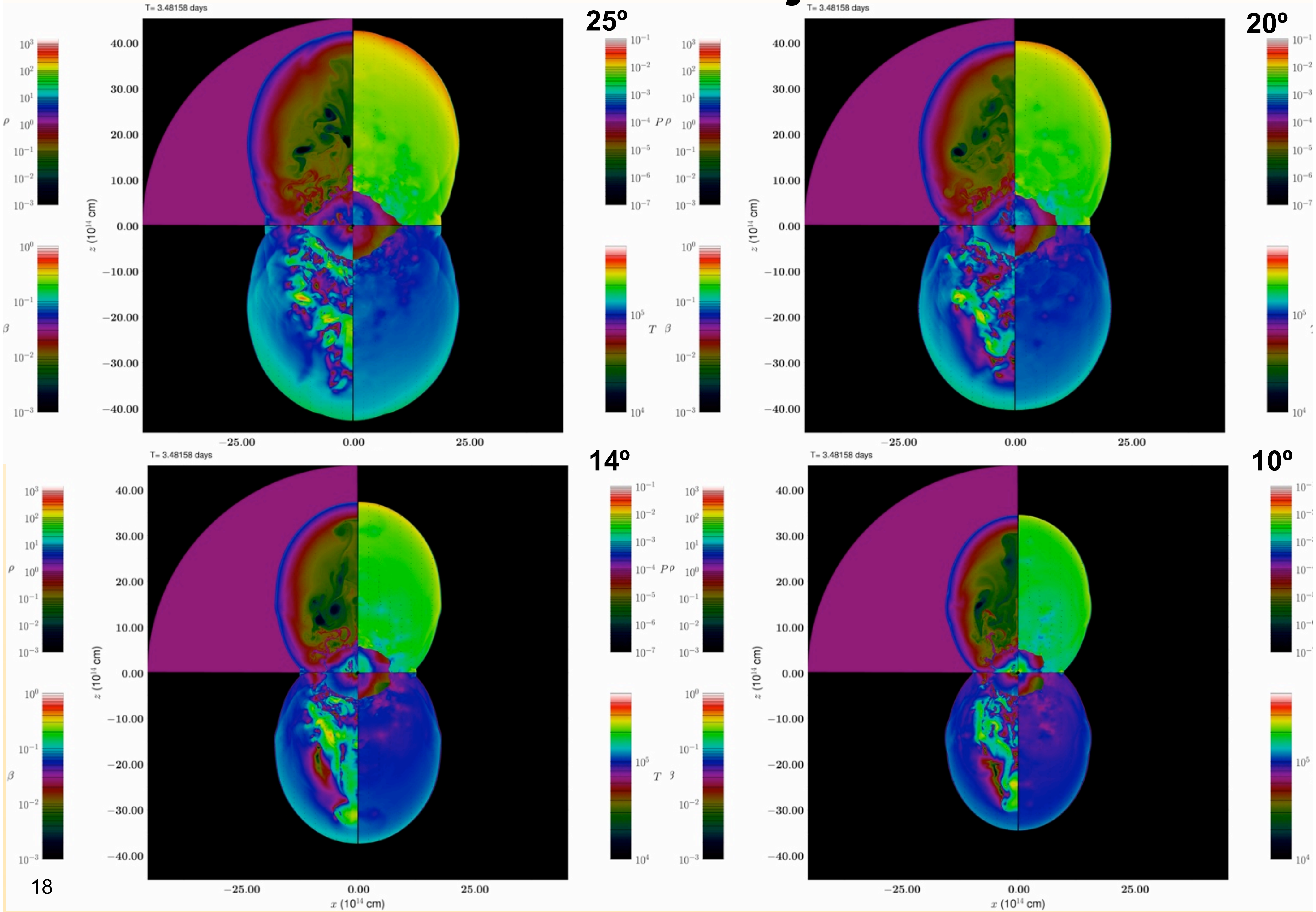

A detailed model for the jet "breakout"

- Using a radiative transport code (Mimica et al. 2009) we can compute synthetic multifrequency LCs for our models using for the emission/ absorption the recipes of Anderson et al. (2009):
  1. Emission: bremsstrahlung-BB.
  2. Absorption: (modified) Kramers.

The radiation transport equation states the intensity of the radiation in terms of the emission, j_ν, and absorption, α_ν, coefficients

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu. \tag{1}$$

along the path, s, of the photon. Here are considered straight lines.

3.2.1. Thermal emission

The theoretical emission and absorption coefficients (Rybicki & Lightman 1979) of thermal-bremsstrahlung (free-free) emission are described in this section. First of all we define the variable

$$x = \frac{h\nu}{kT} \tag{2}$$

where h is the Planck constant, ν is the frequency of the radiation, k is the Boltzmann constant and T is the temperature of the fluid in the rest frame.

Then, for a plasma with a Maxwellian distribution of velocities the emission coefficient per unit of frequency, ν, takes the form

$$j_\nu = \frac{1}{4\pi} 6,8 \times 10^{-38} Z^2 \frac{\rho^2}{m_p^2} T^{-1/2} e^{-x} \bar{g}_{\rm ff}(\nu, T)\,\mathrm{erg\ s^{-1}\ cm^{-3}\ Hz^{-1}}. \tag{3}$$

Following the Kramer's law for opacity the absorption coefficient, which depends also on frequency, is determined by the relation $\alpha_\nu = j_\nu / B_\nu$, where B_ν is the blackbody intensity. In this way

$$\alpha_\nu \simeq 4.1 \times 10^{-23} Z^2 \frac{\rho^2}{m_p^2} T^{-7/2} x^{-3} (1 - e^{-x}) \bar{g}_{\rm ff}(\nu, T)\,\mathrm{cm^{-1}}. \tag{4}$$

In these equations ρ is the rest mass density, m_p the proton mass, $\bar{g}_{\rm ff}$ the temperature averaged Gaunt factor for free-free transitions and $Z = \mu_i/\mu_e$, where $\mu_e = 2/(1+X)$ and $\mu_i = 4/(1+3X)$. The variable X is the relative abundance of hydrogen and we have chosen the typical value $X = 0.71$.

The temperature has been calculated considering that the total pressure is given by adding the gas pressure and the radiation pressure,

$$P = \frac{k}{\mu m_H} \rho T + \frac{1}{3} a T^4 \tag{5}$$

where m_H ($\approx m_p$) is the mass of the hydrogen atom and $\mu = (1/\mu_e + 1/\mu_i)^{-1} \approx 4/(3+5X)$ the mean molecular weight in units of m_H.

A detailed model for the jet "breakout"

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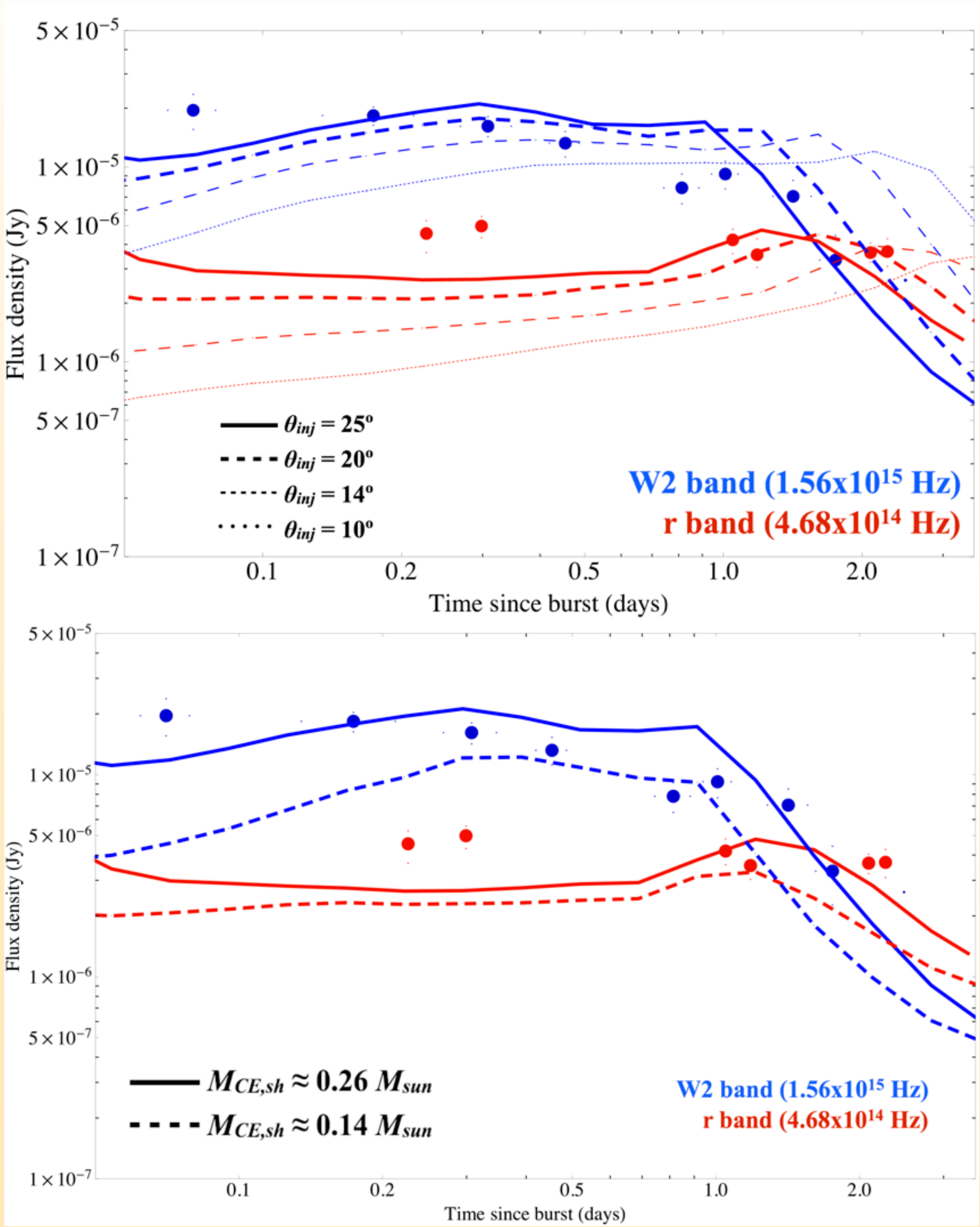
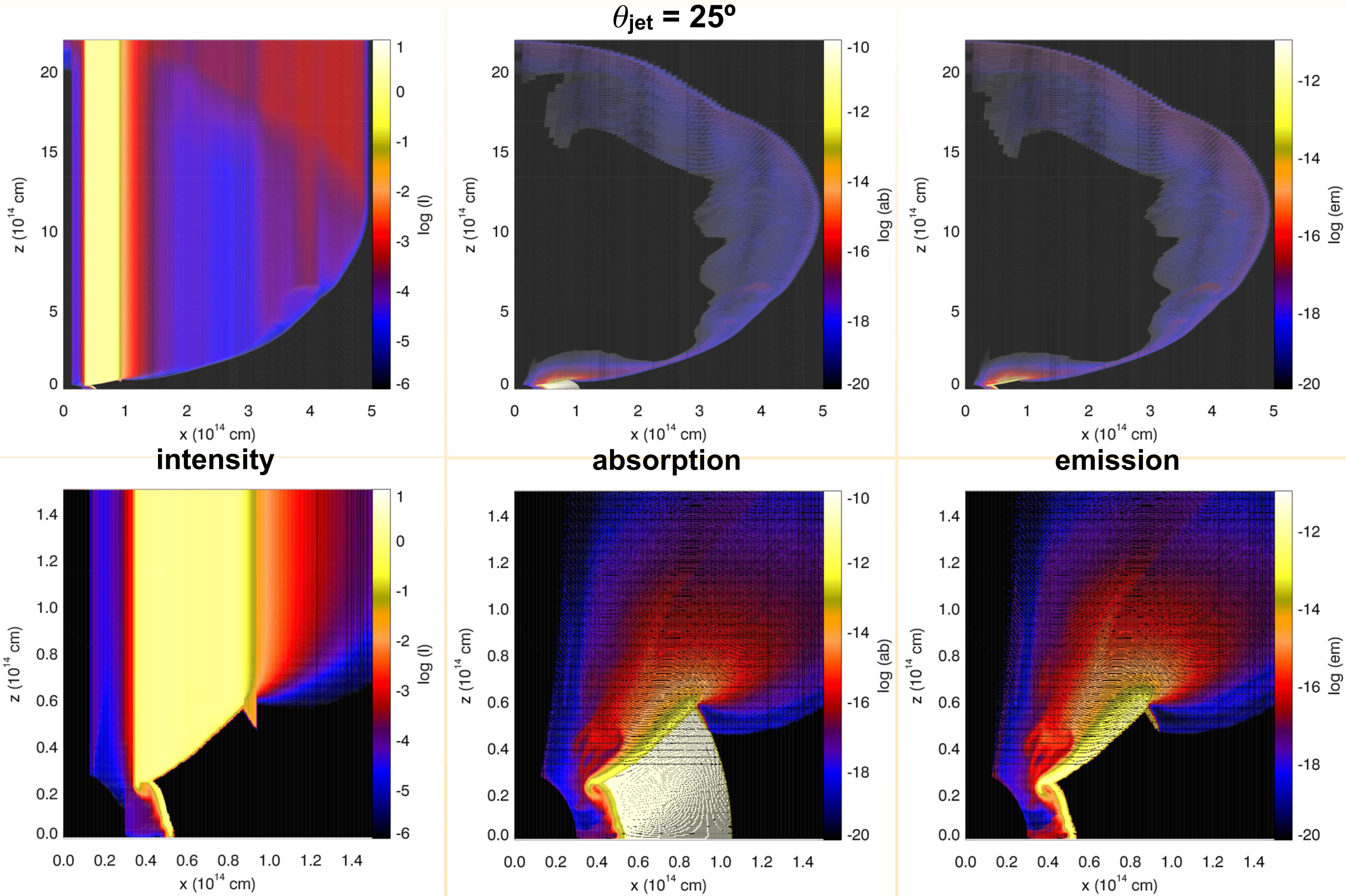
  1. Emission: bremsstrahlung-BB.
  2. Absorption: (modified) Kramers.
- Shell is hot enough ($T>10^4$ K, $n\sim7\times10^{-13}$ cm^{-3}), that it is fully ionized, (note differences with, e.g., Badjin, Blinnikov, Postnov'13).
- Parametric study favors:
  1. Wider jets (q >20º).
  2. Massive shells ($M>0.15M_\odot$).

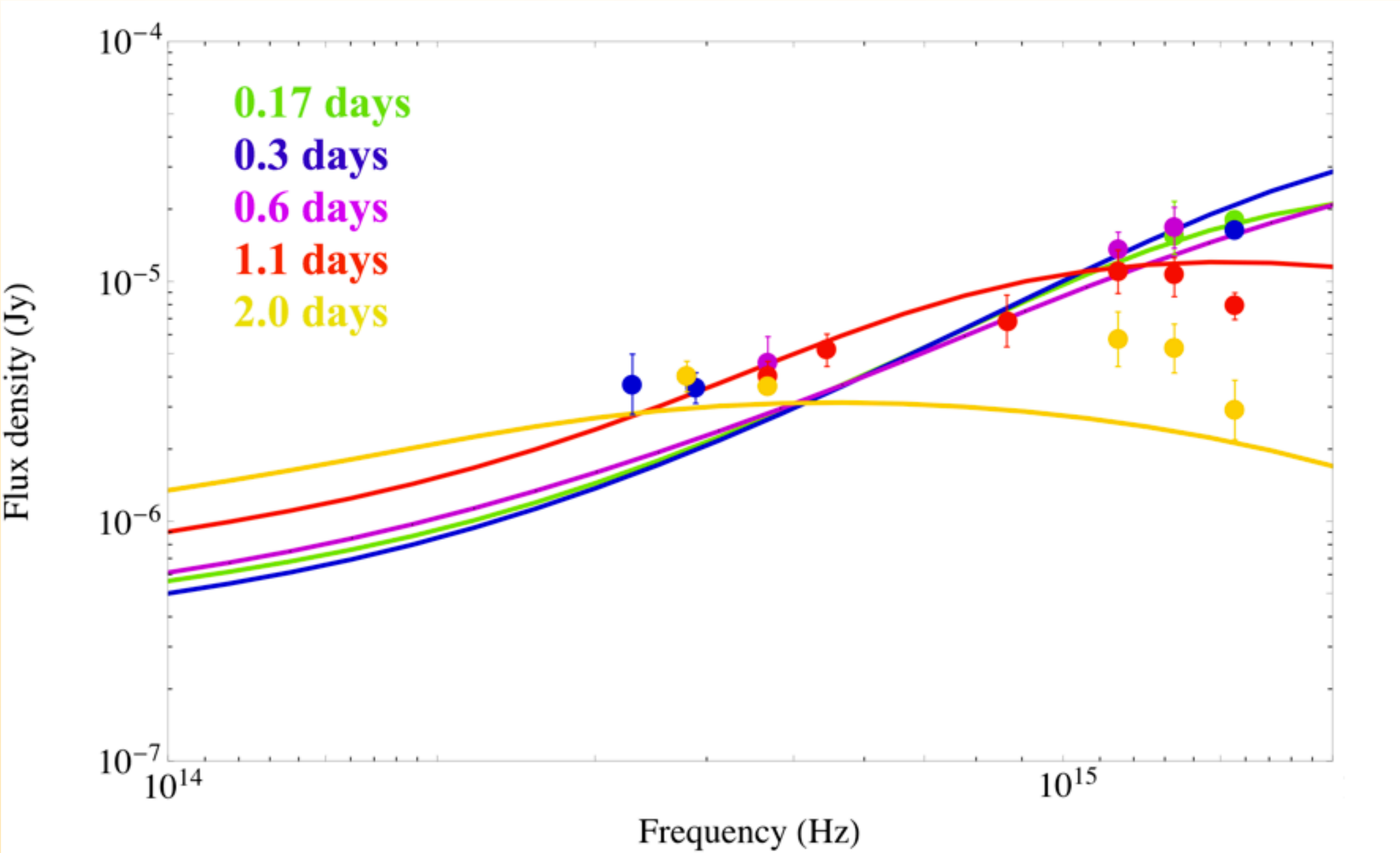


A detailed model for the jet “breakout”



A detailed model for the jet "breakout"

θ_{jet} = 25º



Conclusions

- GRB 101225A seems to be a rather unusual LGRB associated to a SN without classical afterglow and with a BB component (*class defining event*, but not the only one!).
- In favor of our model:
  - ☑ Existing progenitor model.
  - ☑ *Consistency* with numerical simulations.
  - ☑ Simple explanation of the X-ray hot spot and UVOIR evolution.
  - ☑ Explains faint SN (fainter than any other observed).
  - ☑ Numerical models reveal a generic way of preventing an standard afterglow (jet/CE-shell interaction). Work on going.
- Against our model:
  - ✳ Need of specific CE-geometry and high density, though justify from numerical models.
  - ✳ More elaborated modeling required: RMHD, non-thermal emission (Newtonian shocks), Comptonization of X-rays in the dense CE-shell, ionization (if the shell is cool), etc.
- **The Christmas burst is likely the result of a stellar murder: stars may have found new ways to die!.**