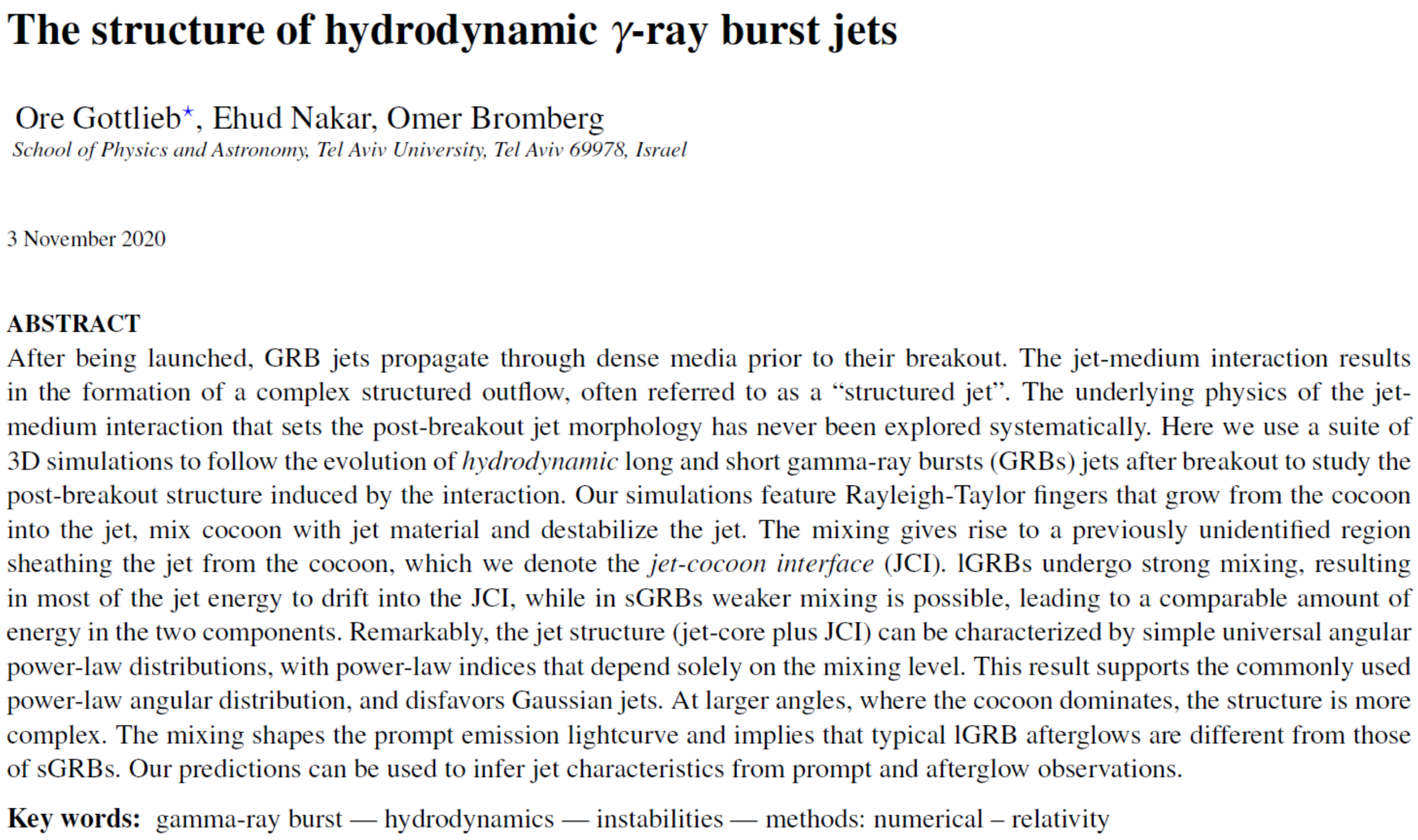
# High-energy Journal Club

Clément Pellouin –
14/12/2020



## The structure of hydrodynamic $\gamma$-ray burst jets

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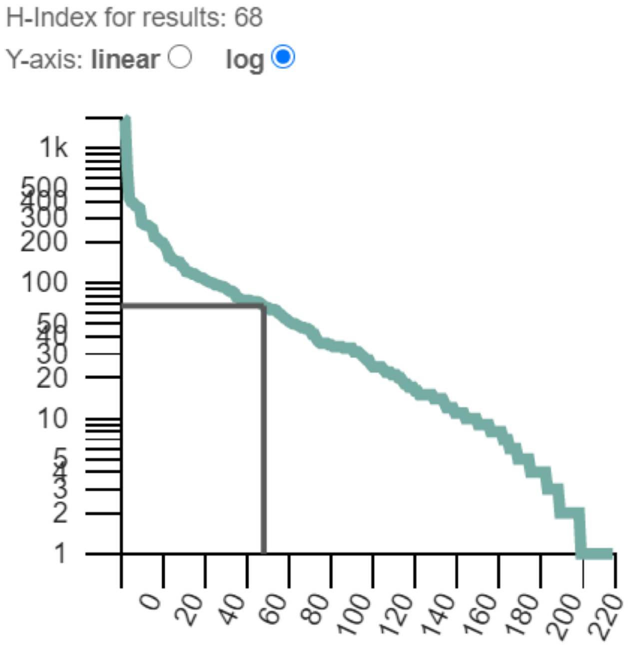
3 November 2020

**ABSTRACT**

After being launched, GRB jets propagate through dense media prior to their breakout. The jet-medium interaction results in the formation of a complex structured outflow, often referred to as a "structured jet". The underlying physics of the jet-medium interaction that sets the post-breakout jet morphology has never been explored systematically. Here we use a suite of 3D simulations to follow the evolution of *hydrodynamic* long and short gamma-ray bursts (GRBs) jets after breakout to study the post-breakout structure induced by the interaction. Our simulations feature Rayleigh-Taylor fingers that grow from the cocoon into the jet, mix cocoon with jet material and destabilize the jet. The mixing gives rise to a previously unidentified region sheathing the jet from the cocoon, which we denote the *jet-cocoon interface* (JCI). lGRBs undergo strong mixing, resulting in most of the jet energy to drift into the JCI, while in sGRBs weaker mixing is possible, leading to a comparable amount of energy in the two components. Remarkably, the jet structure (jet-core plus JCI) can be characterized by simple universal angular power-law distributions, with power-law indices that depend solely on the mixing level. This result supports the commonly used power-law angular distribution, and disfavors Gaussian jets. At larger angles, where the cocoon dominates, the structure is more complex. The mixing shapes the prompt emission lightcurve and implies that typical lGRB afterglows are different from those of sGRBs. Our predictions can be used to infer jet characteristics from prompt and afterglow observations.

**Key words:** gamma-ray burst — hydrodynamics — instabilities — methods: numerical – relativity

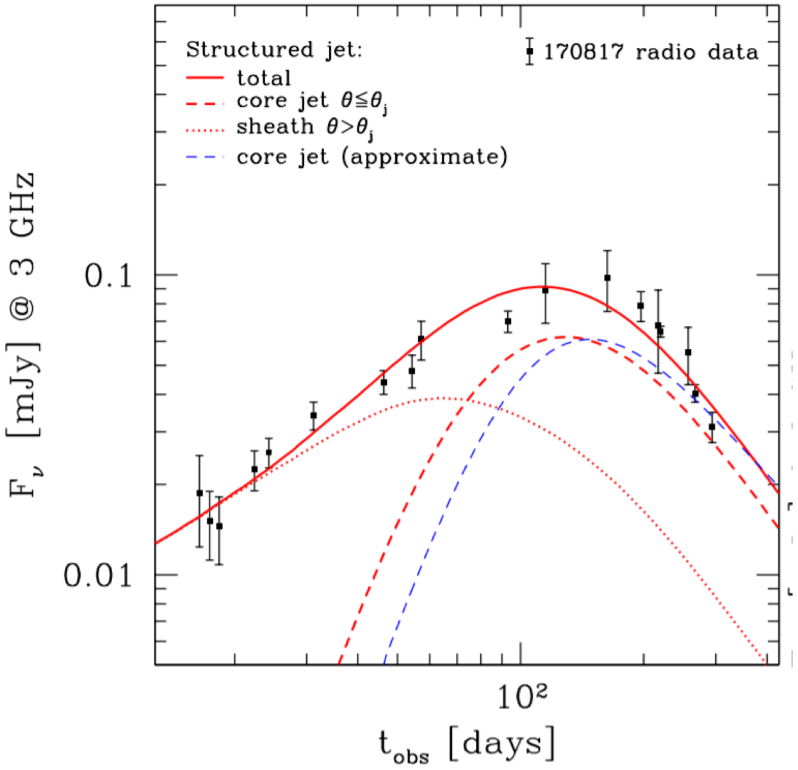


H-Index for results: 68

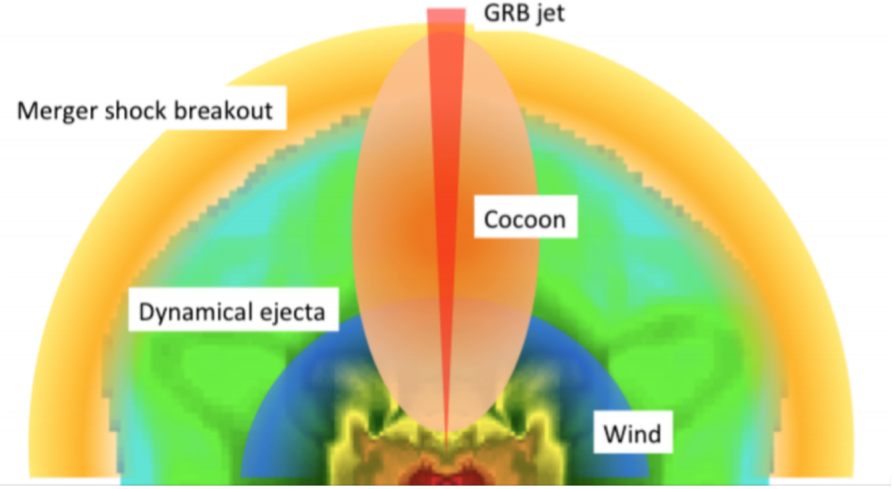
Y-axis: linear ○ log ●

# I- Introduction

- Prompt energetics → collimated jet
- 2 populations of GRBs : lGRBs & sGRBs



*GW 170817 radio afterglow (Duque+19)*



*Unified structure of GRB formation (Teboul & Piran+17)*

Lateral structure :

$$E(\theta) = E_j \times \begin{cases} 1 & \text{, if } \theta < \theta_c \\ \left(\frac{\theta}{\theta_j}\right)^{-\alpha} & \text{, if } \theta > \theta_c \end{cases}$$

$$\Gamma(\theta) = 1 + \left(\Gamma_j - 1\right) \times \begin{cases} 1 & \text{, if } \theta < \theta_c \\ \left(\frac{\theta}{\theta_j}\right)^{-\beta} & \text{, if } \theta > \theta_c \end{cases}$$

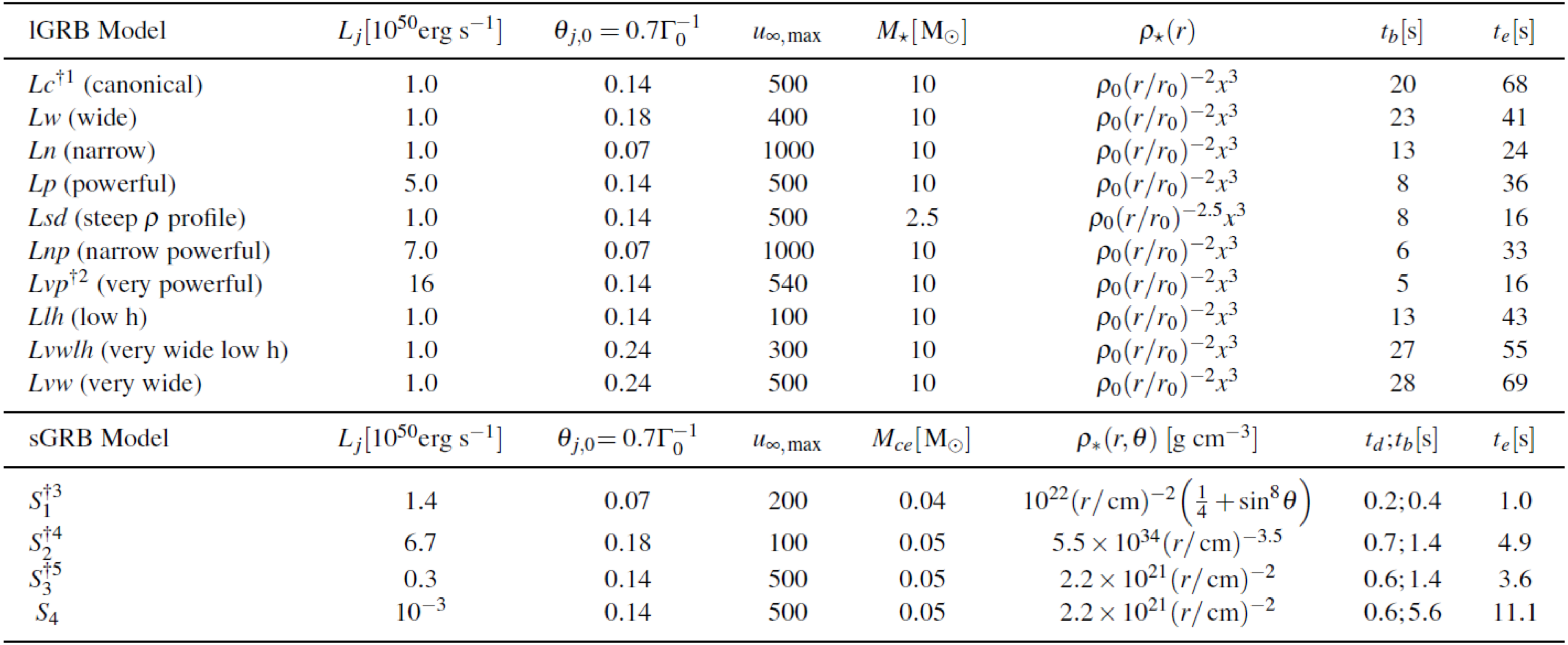
# I- Introduction

2 sites control jet structure :
- Launching site (initial acceleration and collimation)
- **Interaction with surrounding medium during propagation**

3D hydrodynamical simulations :
Turbulent mixing → symmetry breaking → Lateral energy dissipation

Results:
- Direct correlation mixing/lateral structure
- Post-breakout structure with 3 components (jet, JCI, cocoon)

# II- Models

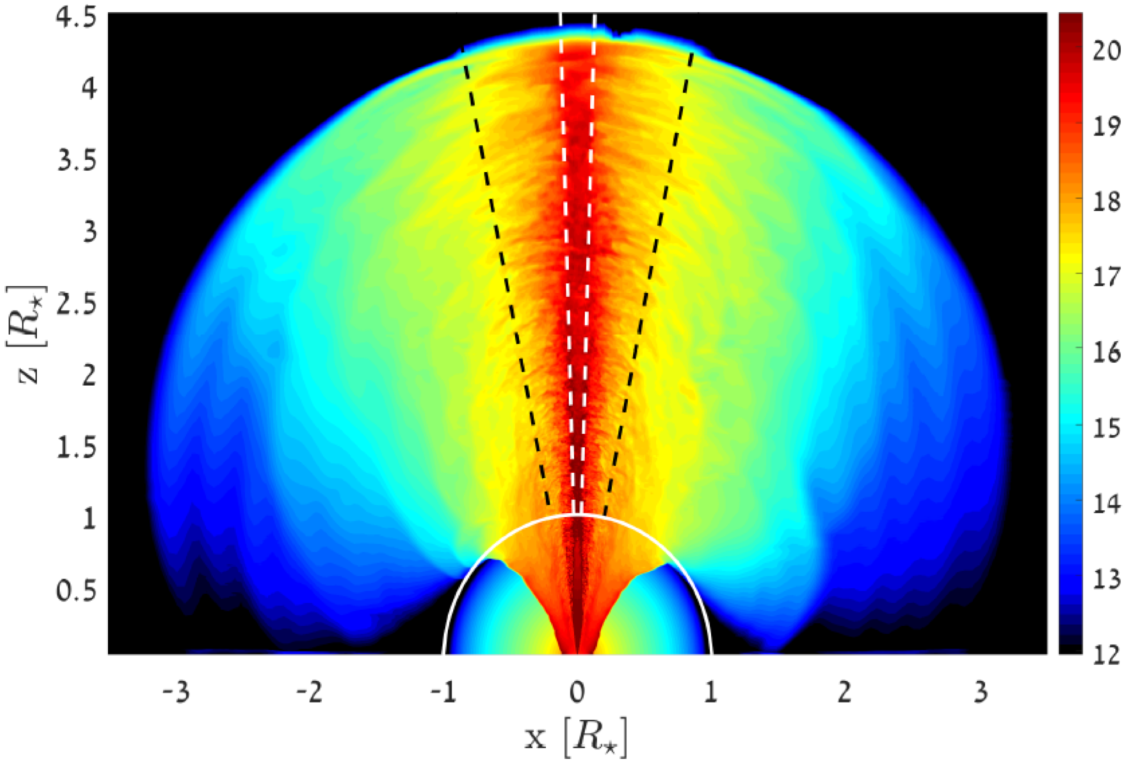


| lGRB Model | $L_j[10^{50}\mathrm{erg\ s^{-1}}]$ | $\theta_{j,0}=0.7\Gamma_0^{-1}$ | $u_{\infty,\max}$ | $M_\star[\mathrm{M_\odot}]$ | $\rho_\star(r)$ | $t_b$[s] | $t_e$[s] |
|---|---|---|---|---|---|---|---|
| *Lc*$^{\dagger1}$ (canonical) | 1.0 | 0.14 | 500 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 20 | 68 |
| *Lw* (wide) | 1.0 | 0.18 | 400 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 23 | 41 |
| *Ln* (narrow) | 1.0 | 0.07 | 1000 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 13 | 24 |
| *Lp* (powerful) | 5.0 | 0.14 | 500 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 8 | 36 |
| *Lsd* (steep $\rho$ profile) | 1.0 | 0.14 | 500 | 2.5 | $\rho_0(r/r_0)^{-2.5}x^3$ | 8 | 16 |
| *Lnp* (narrow powerful) | 7.0 | 0.07 | 1000 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 6 | 33 |
| *Lvp*$^{\dagger2}$ (very powerful) | 16 | 0.14 | 540 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 5 | 16 |
| *Llh* (low h) | 1.0 | 0.14 | 100 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 13 | 43 |
| *Lvwlh* (very wide low h) | 1.0 | 0.24 | 300 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 27 | 55 |
| *Lvw* (very wide) | 1.0 | 0.24 | 500 | 10 | $\rho_0(r/r_0)^{-2}x^3$ | 28 | 69 |
| **sGRB Model** | $L_j[10^{50}\mathrm{erg\ s^{-1}}]$ | $\theta_{j,0}=0.7\Gamma_0^{-1}$ | $u_{\infty,\max}$ | $M_{ce}[\mathrm{M_\odot}]$ | $\rho_*(r,\theta)$ [g cm$^{-3}$] | $t_d;t_b$[s] | $t_e$[s] |
| $S_1^{\dagger3}$ | 1.4 | 0.07 | 200 | 0.04 | $10^{22}(r/\mathrm{cm})^{-2}\left(\frac{1}{4}+\sin^8\theta\right)$ | 0.2;0.4 | 1.0 |
| $S_2^{\dagger4}$ | 6.7 | 0.18 | 100 | 0.05 | $5.5\times10^{34}(r/\mathrm{cm})^{-3.5}$ | 0.7; 1.4 | 4.9 |
| $S_3^{\dagger5}$ | 0.3 | 0.14 | 500 | 0.05 | $2.2\times10^{21}(r/\mathrm{cm})^{-2}$ | 0.6; 1.4 | 3.6 |
| $S_4$ | $10^{-3}$ | 0.14 | 500 | 0.05 | $2.2\times10^{21}(r/\mathrm{cm})^{-2}$ | 0.6; 5.6 | 11.1 |

$$u_{\infty,max} = (\Gamma\beta)_{\infty,max} = \sqrt{h_0^2\Gamma_0^2 - 1}$$

$t_d$ : Delay time
$t_b$ : Breakout time
$t_e$ : Ejection time

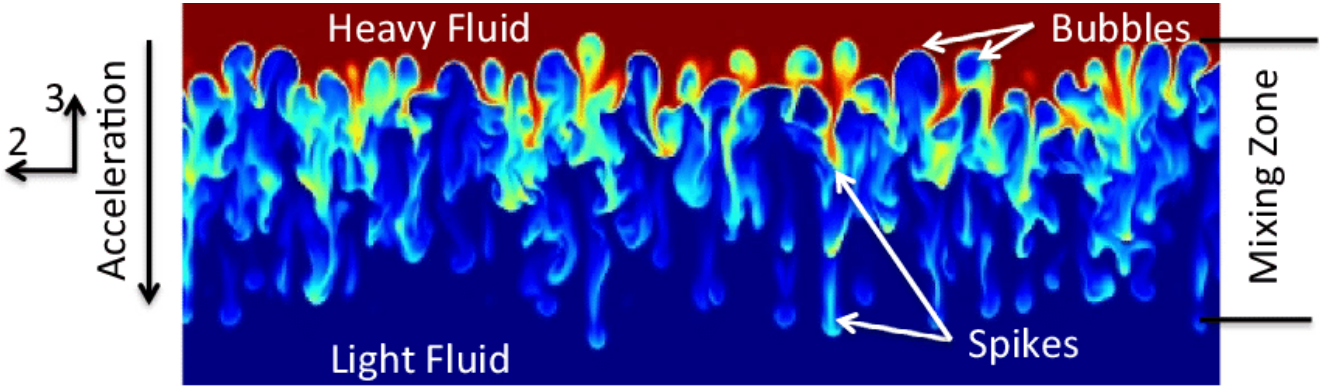
# III- Jet structure inside a dense medium : evolution & mixing



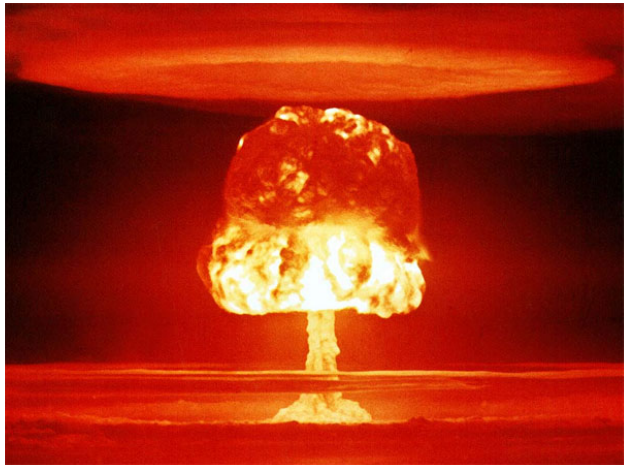
4 regions :
- Jet
- Jet head
- Inner cocoon
- Outer cocoon

# III- Jet structure inside a dense medium : evolution & mixing

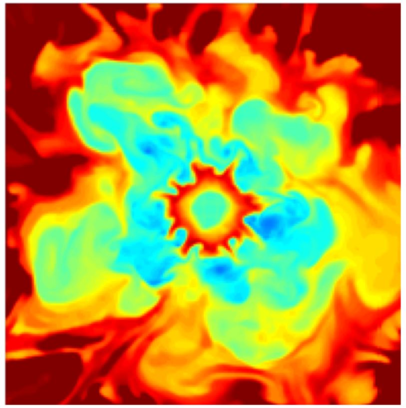
Rayleigh-Taylor instability :



*Schwarzkopf+15*



*Nuclear mushroom*



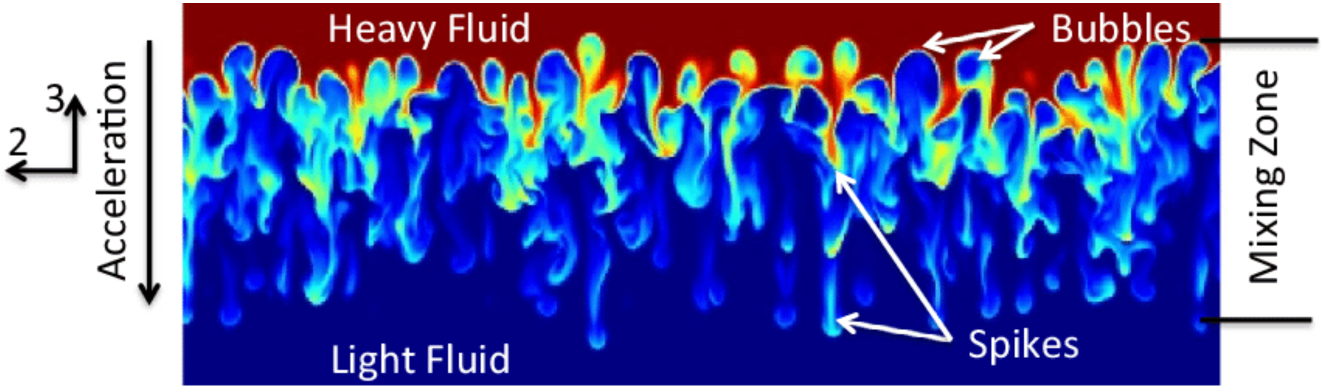
*2D cut of the jet*

Instability growth if

$$\widetilde{L_c} = \frac{\rho_j h_j \Gamma_j^2}{\rho_c h_c \Gamma_c^2} > 1$$

# III- Jet structure inside a dense medium : evolution & mixing

Rayleigh-Taylor instability :



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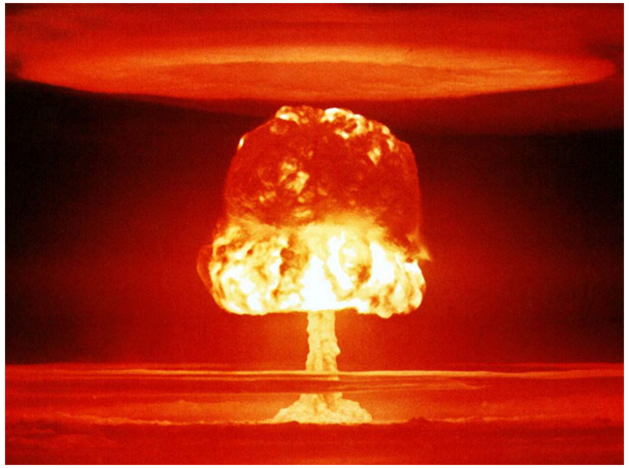

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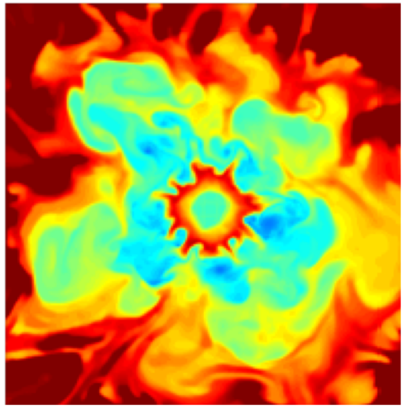


*2D cut of the jet*

Richmeyer-Meshkov instability accelerates fingers growth

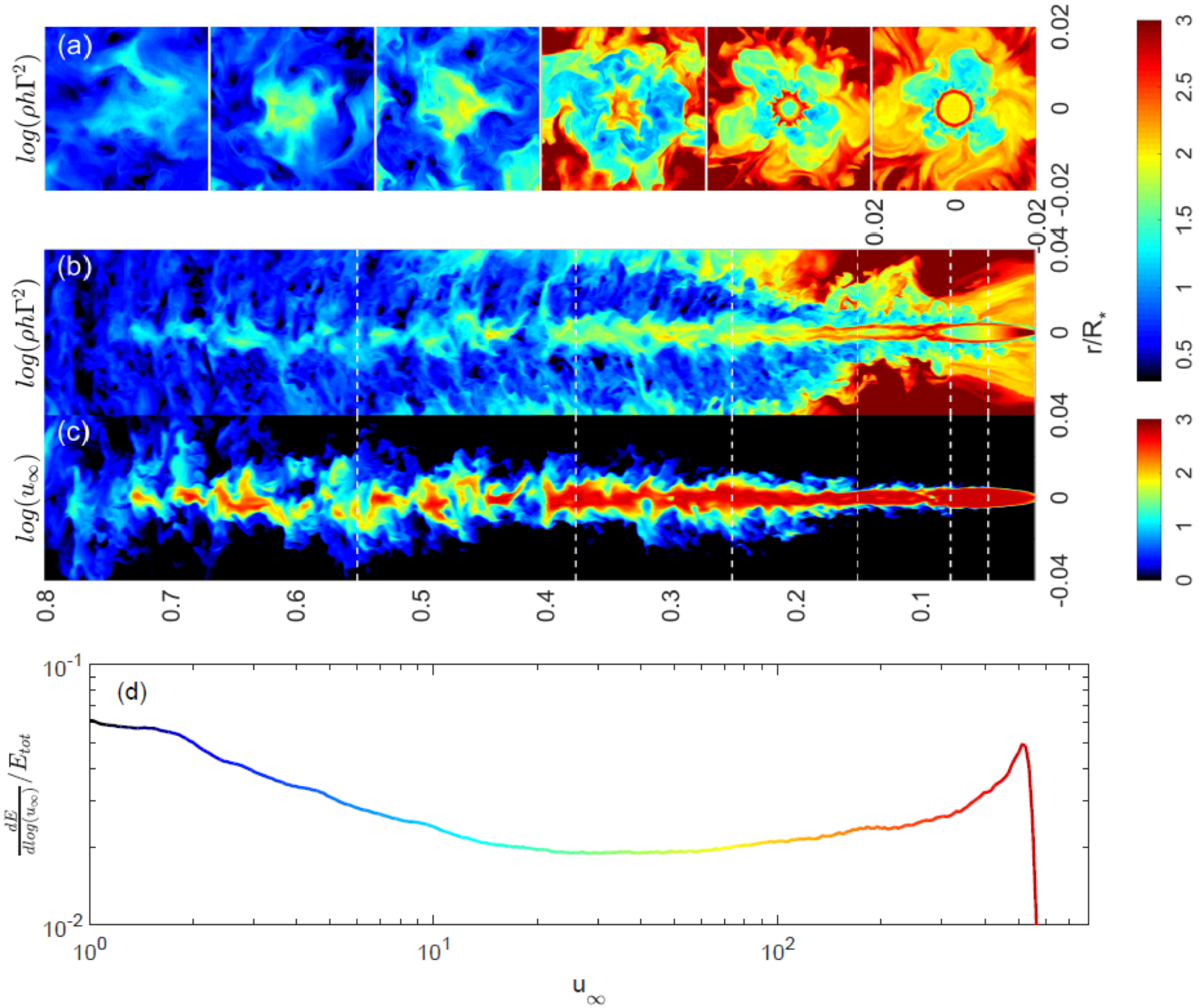
Relativistic Kevin-Helmoltz instability too slow

# III- Jet structure inside a dense medium : evolution & mixing

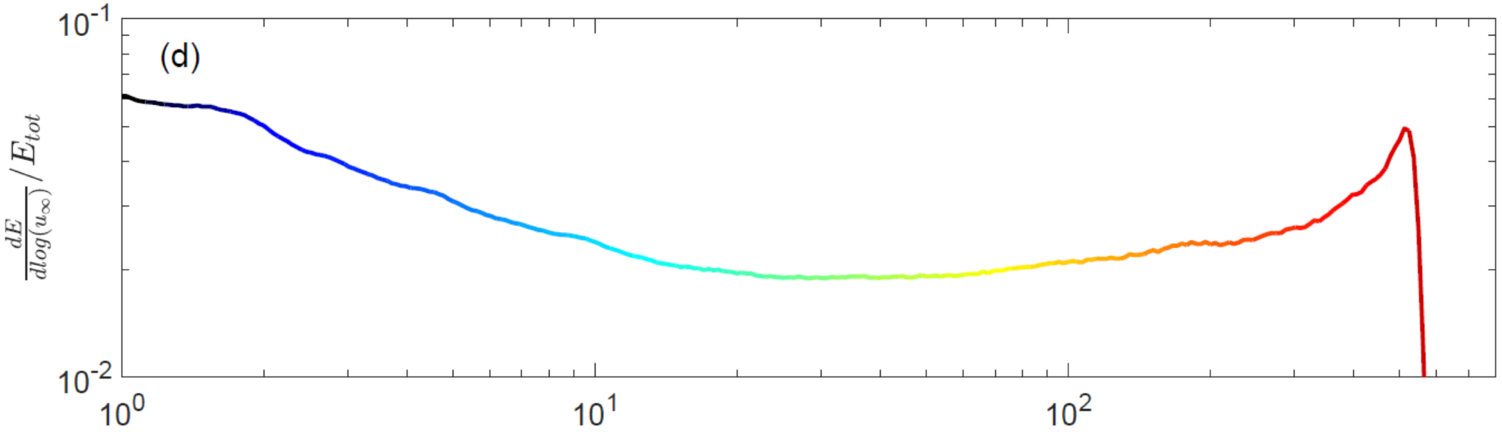
Enthalpy density

Terminal proper velocity
(no further mixing)

Total energy distribution
(excluding rest mass)



# III- Jet structure inside a dense medium : evolution & mixing



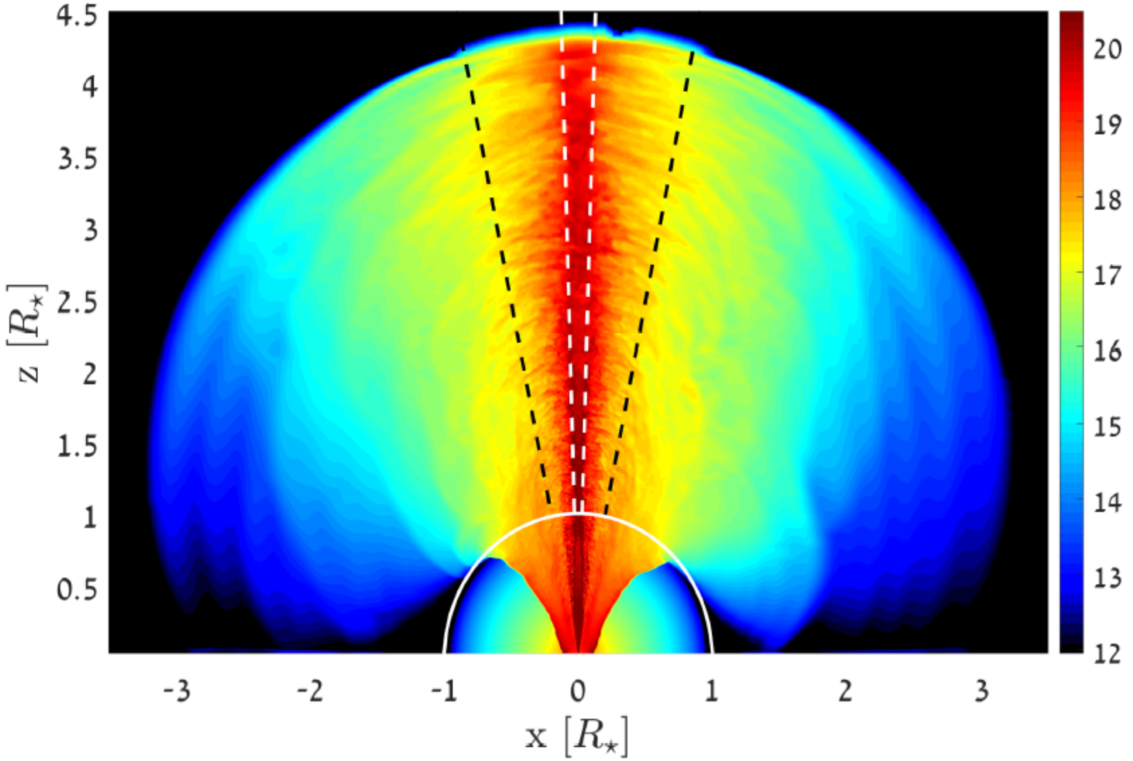
Intense mixing → flatter energy distribution

More mixing ?

- Larger jet opening angle
- Higher jet specific enthalpy
- Lower jet luminosity
- Higher medium density

→ sGRBs have stabler jets

# IV- The post-breakout structure



3 regions :

- Core
  - ultra-relativistic: $u_\infty \geq \frac{1}{5} u_{\infty,max}$
  - narrow core angle: $\theta_j = \left(\frac{1}{3} - \frac{1}{5}\right) \theta_{j,0}$
- Cocoon
  - newtonian: $u_\infty \lesssim 3$
  - large angles: $\theta \geq \theta_c \simeq 0.3\, rad$
  - Energy: $E_c \simeq \mathrm{L}_j t_b$
- Jet-Cocoon Interface (JCI)
  - mildly relativistic
  - intermediate angles: $\theta_j \leq \theta \leq \theta_c$

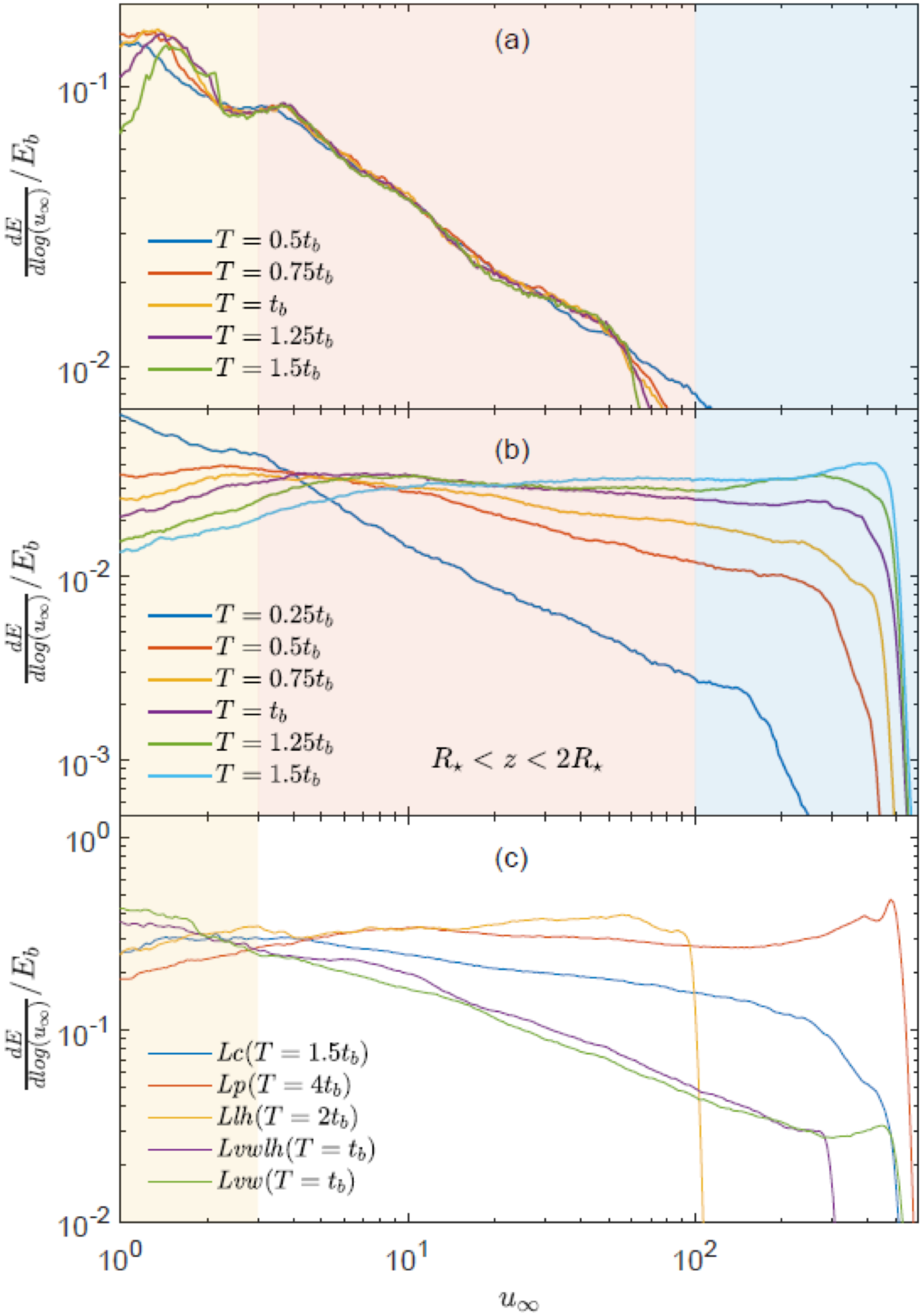
$T = t - t_b$

$E_j + E_{JCI} \simeq L_j T$

$\lambda = E_j / L_j T$ : mixing parameter

In the JCI, $E_{iso} \propto \theta^{-\delta}$ , $\delta = f(\lambda)$

# IV- The post-breakout structure (lGRBs)



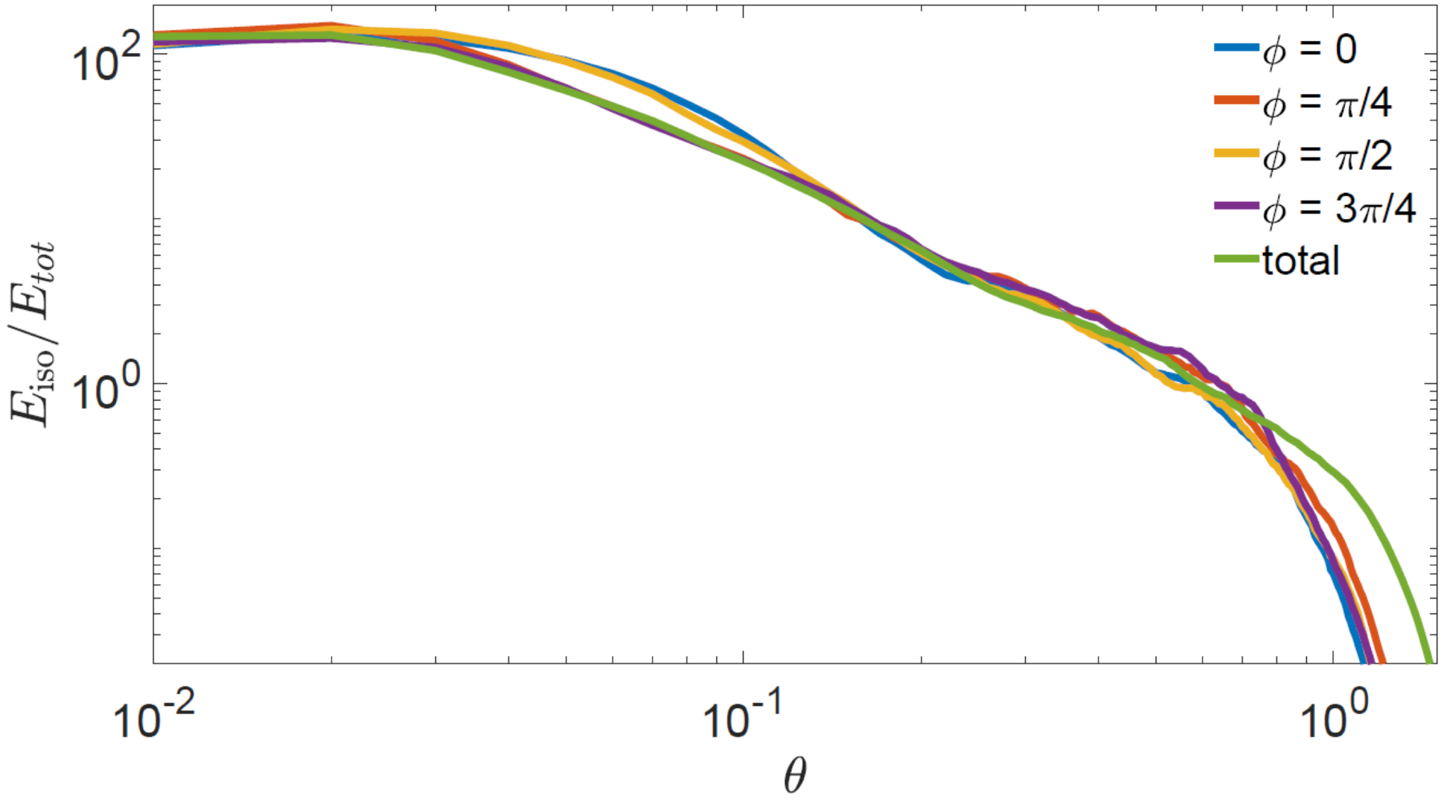
Energy distribution of the first slice of matter that breaks out, at various times

Energy distribution of matter between $R_\star$ and 2 $R_\star$ at various times

Overall energy distribution when the jet head reaches 10 $R_\star$, for different models

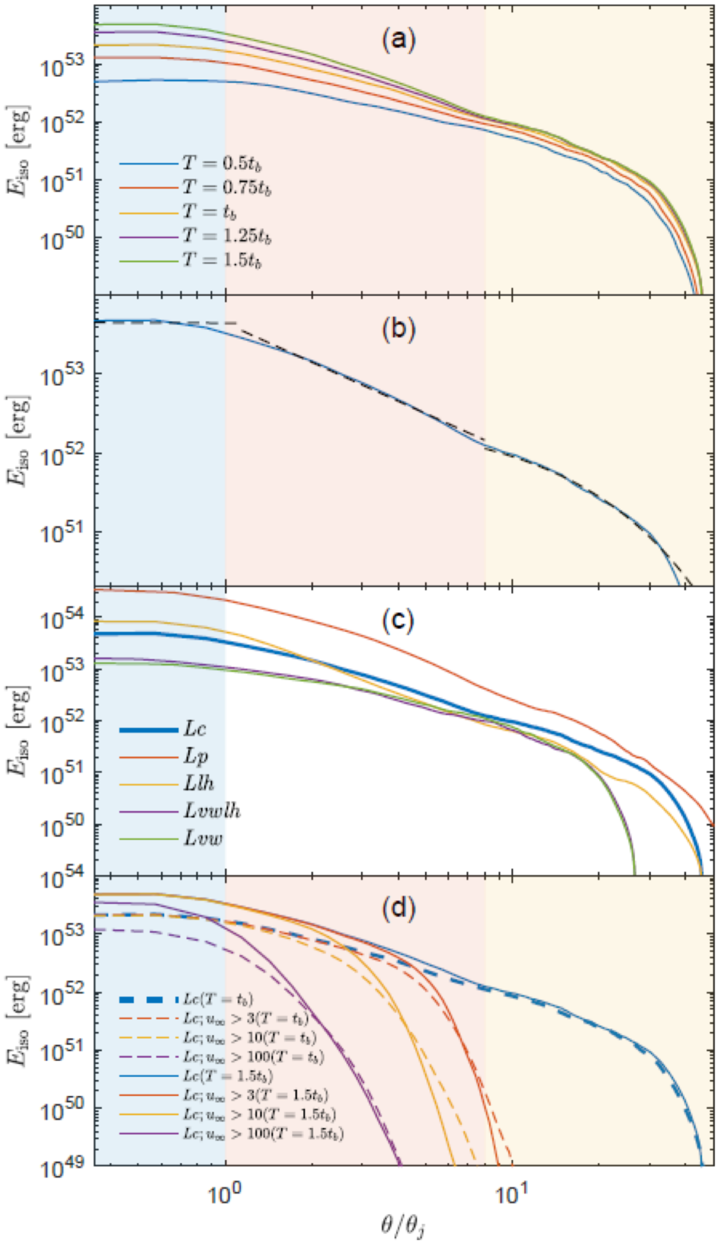
# IV- The post-breakout structure (lGRBs)

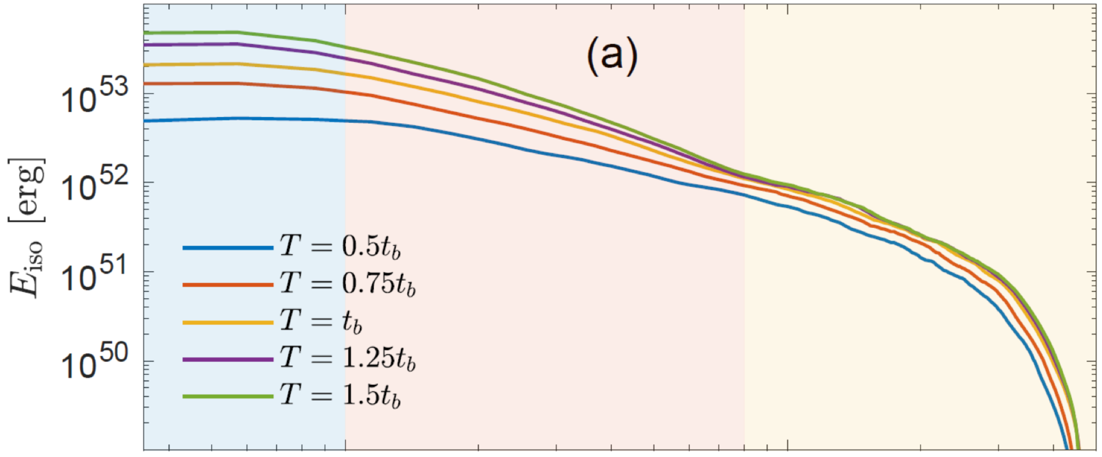
Is the post-breakout structure strongly asymmetric ?



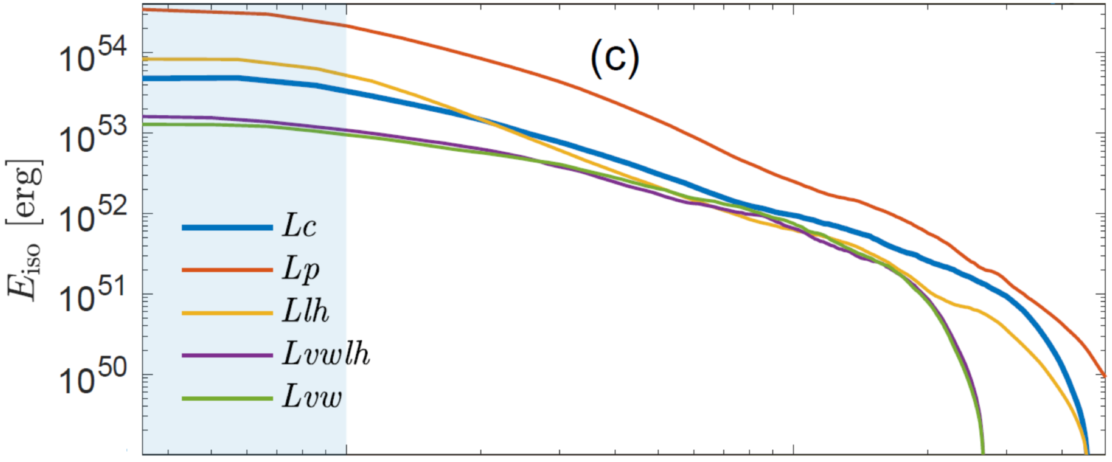
*Energy distribution, sliced at different angles φ*

# IV- The post-breakout structure (lGRBs)



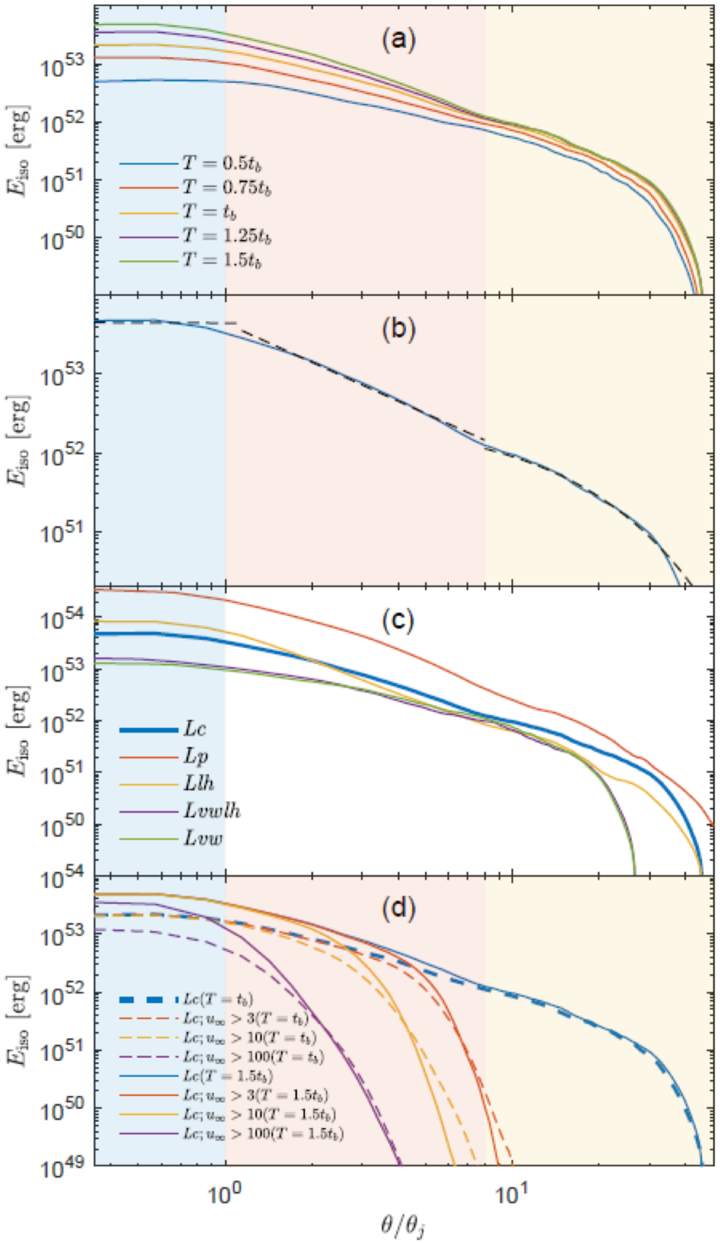


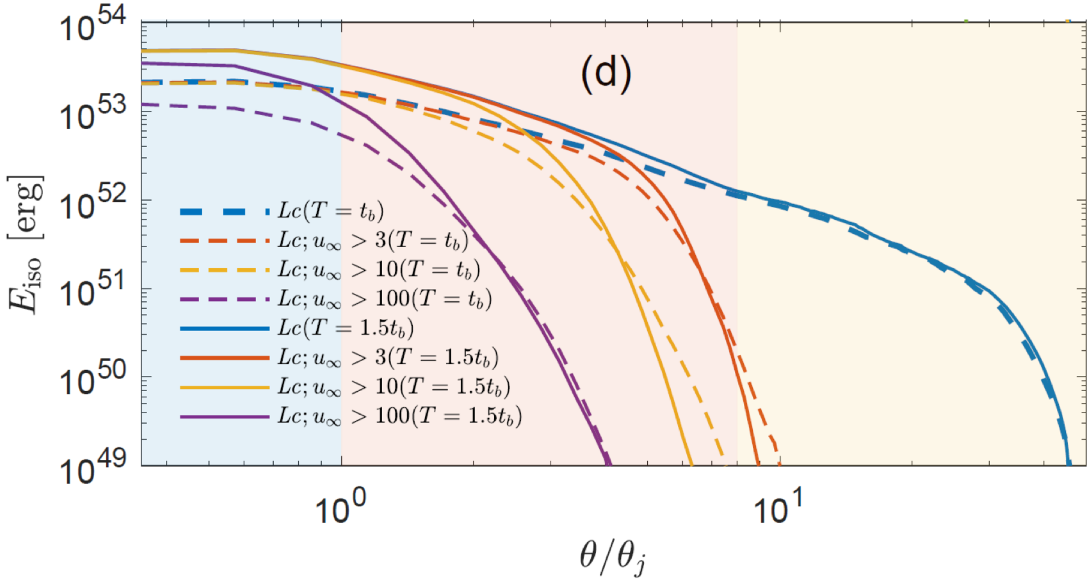
*Angular energy distribution at various times*



*Angular energy distribution, different models*

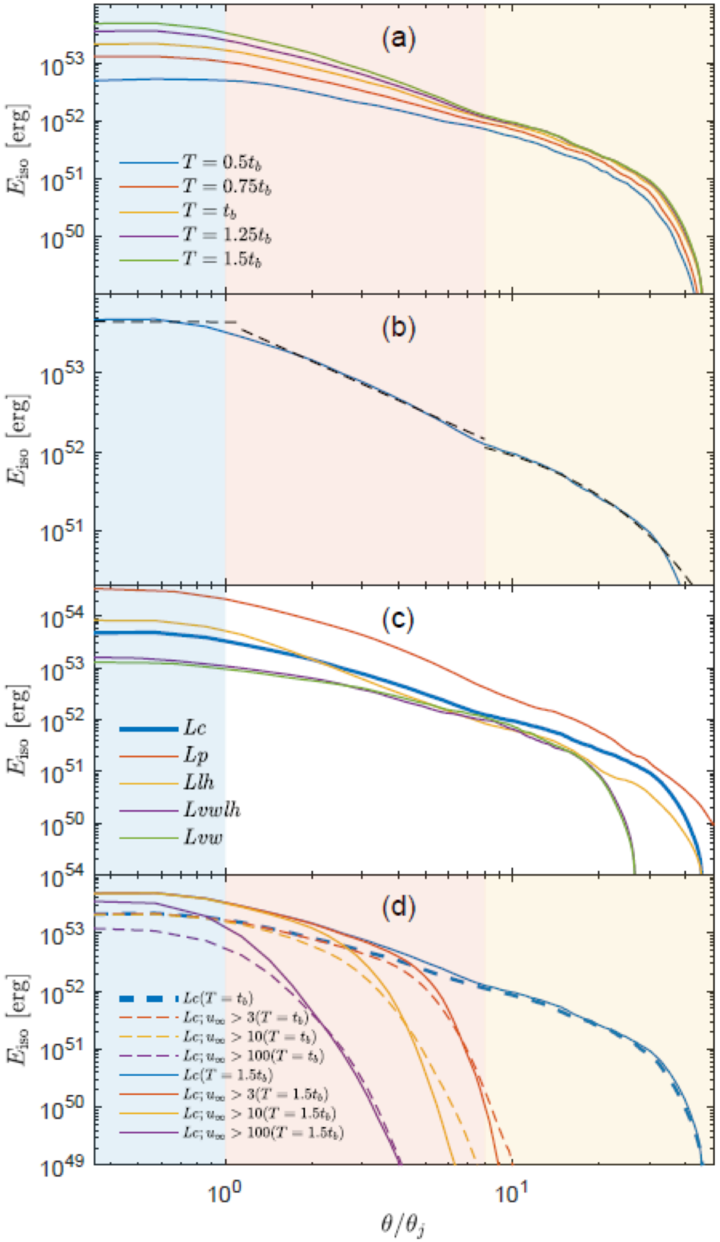
# IV- The post-breakout structure (lGRBs)

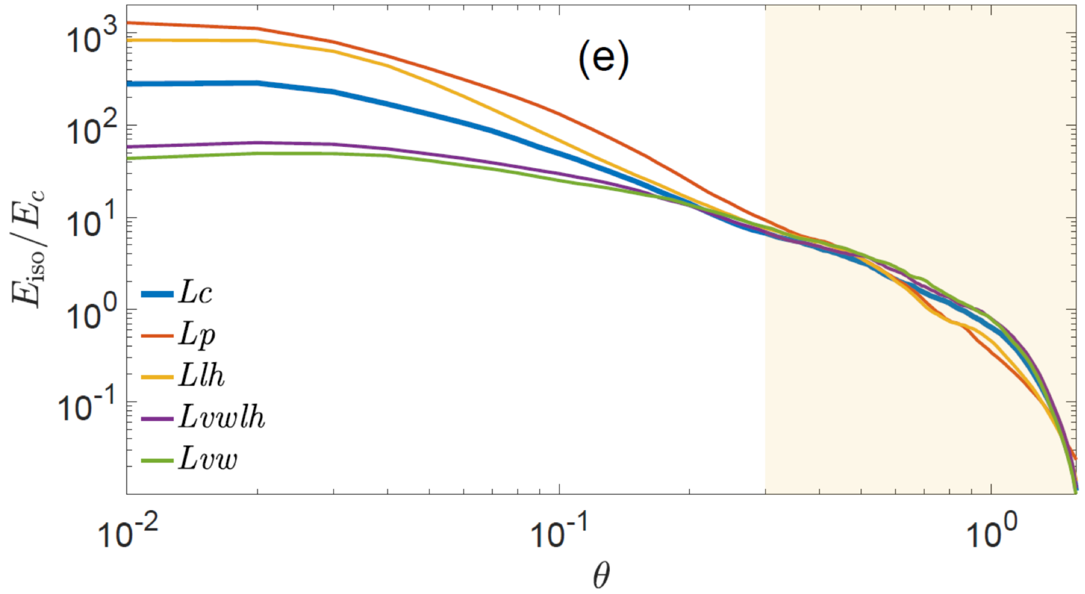




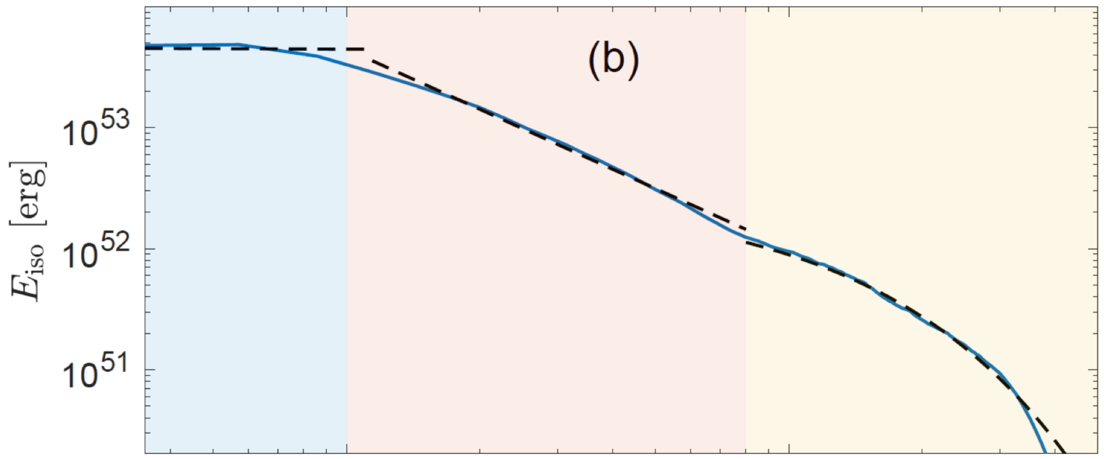
*Angular energy distribution at various times*

# IV- The post-breakout structure (lGRBs)



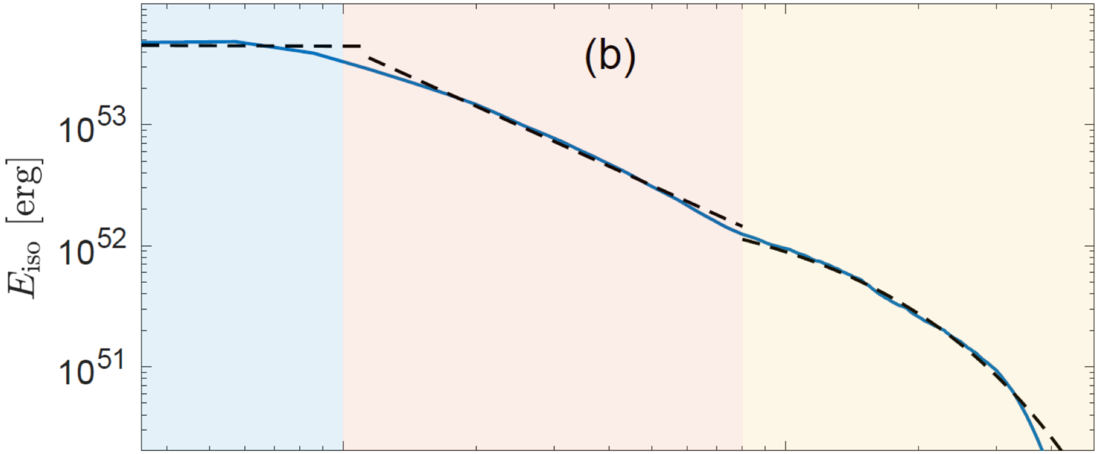


*The cocoon starts at the same angle for all models*



*Fit at a given time, with 3 distinct components*

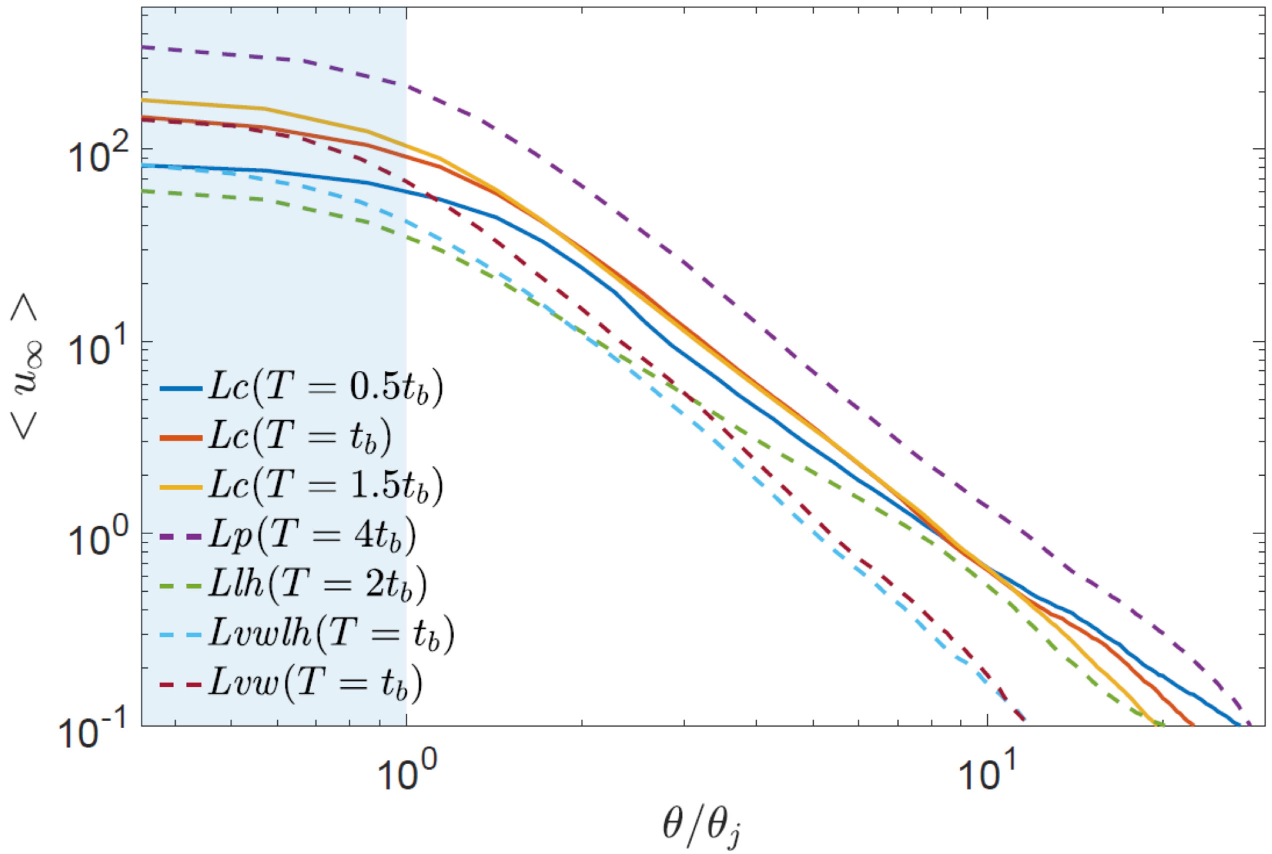
# IV- The post-breakout structure (lGRBs)



*Fit at a given time, with 3 distinct components*

$$E_{iso}(\lambda) \simeq \begin{cases} \lambda E_0 & \text{, if } \theta < \theta_j \\ \lambda E_0 \left(\dfrac{\theta}{\theta_j}\right)^{-\delta} & \text{, if } \theta_{\rm j} < \theta < \theta_c \\ \lambda E_0 \left(\dfrac{\theta_c}{\theta_j}\right)^{-\delta} e^{-f_c(\theta-\theta_c)} & \text{, if } \theta_{\rm c} < \theta \end{cases}$$

# IV- The post-breakout structure (lGRBs)



$$u_\infty\left(\frac{\theta}{\theta_j}\right) = \begin{cases} < u_{\infty,j} > & \text{, if } \theta < \theta_j \\ < u_{\infty,j} > \left(\frac{\theta}{\theta_j}\right)^{-p_u} & \text{, if } \theta > \theta_j \end{cases}$$

Pure angular structure until $\theta \sim 20\,°$

# IV- The post-breakout structure (lGRBs)

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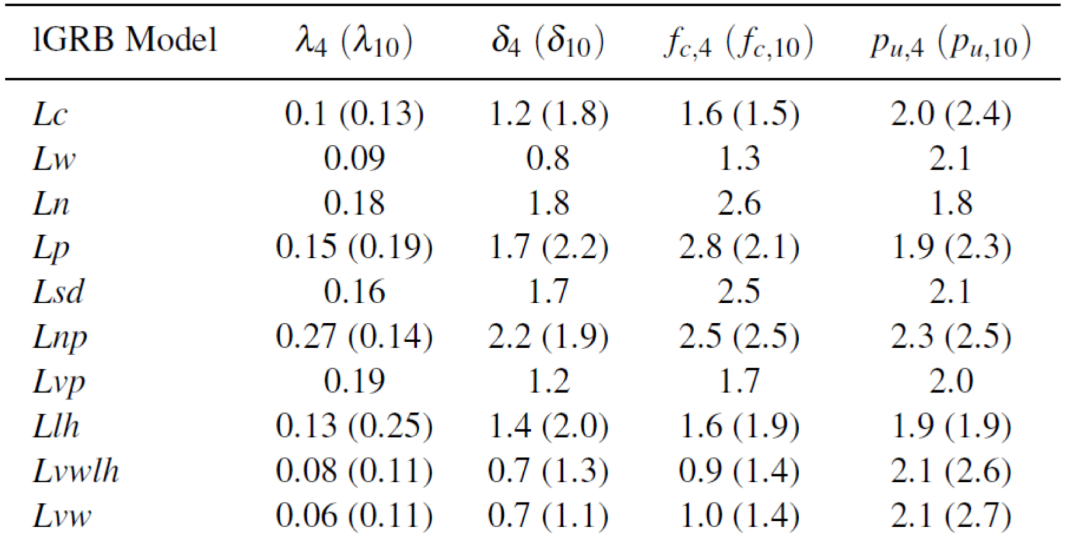
At later times, mixing drops:

- more energy in the core jet (λ increases)
- steeper energy decrease slope (δ increases)
- Steeper velocity gradient ($p_u$ increases)



| lGRB Model | $\lambda_4$ ($\lambda_{10}$) | $\delta_4$ ($\delta_{10}$) | $f_{c,4}$ ($f_{c,10}$) | $p_{u,4}$ ($p_{u,10}$) |
|---|---|---|---|---|
| *Lc* | 0.1 (0.13) | 1.2 (1.8) | 1.6 (1.5) | 2.0 (2.4) |
| *Lw* | 0.09 | 0.8 | 1.3 | 2.1 |
| *Ln* | 0.18 | 1.8 | 2.6 | 1.8 |
| *Lp* | 0.15 (0.19) | 1.7 (2.2) | 2.8 (2.1) | 1.9 (2.3) |
| *Lsd* | 0.16 | 1.7 | 2.5 | 2.1 |
| *Lnp* | 0.27 (0.14) | 2.2 (1.9) | 2.5 (2.5) | 2.3 (2.5) |
| *Lvp* | 0.19 | 1.2 | 1.7 | 2.0 |
| *Llh* | 0.13 (0.25) | 1.4 (2.0) | 1.6 (1.9) | 1.9 (1.9) |
| *Lvwlh* | 0.08 (0.11) | 0.7 (1.3) | 0.9 (1.4) | 2.1 (2.6) |
| *Lvw* | 0.06 (0.11) | 0.7 (1.1) | 1.0 (1.4) | 2.1 (2.7) |

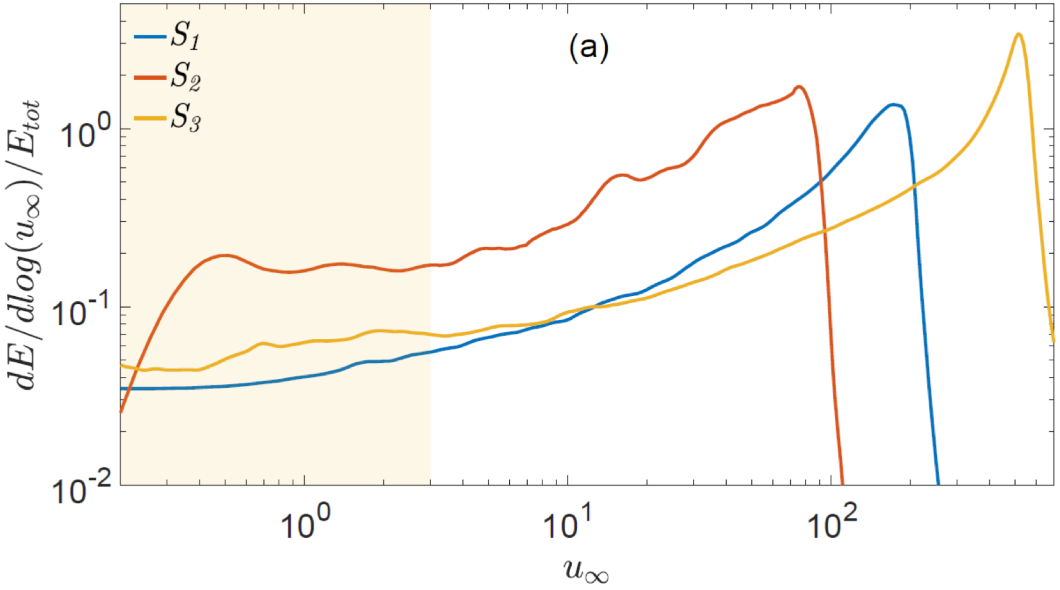
# IV- The post-breakout structure (sGRBs)

Similar as lGRBs with less dense surrounding medium

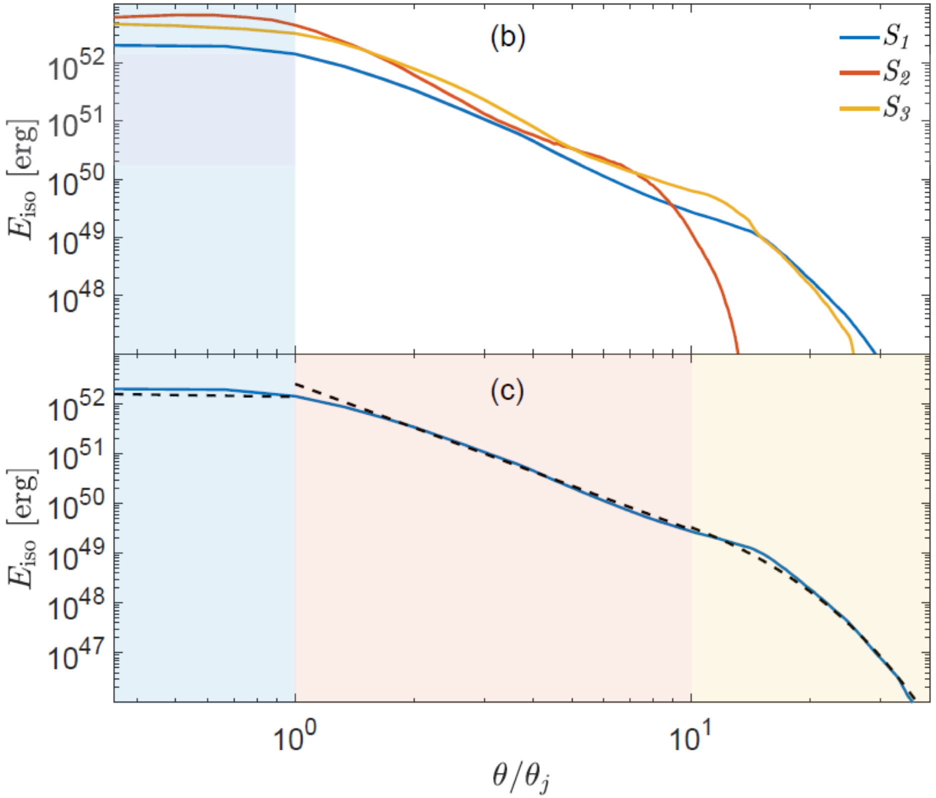
→ more collimated & stabler jets

→ higher λ, δ

→ cocoon extending to smaller angles



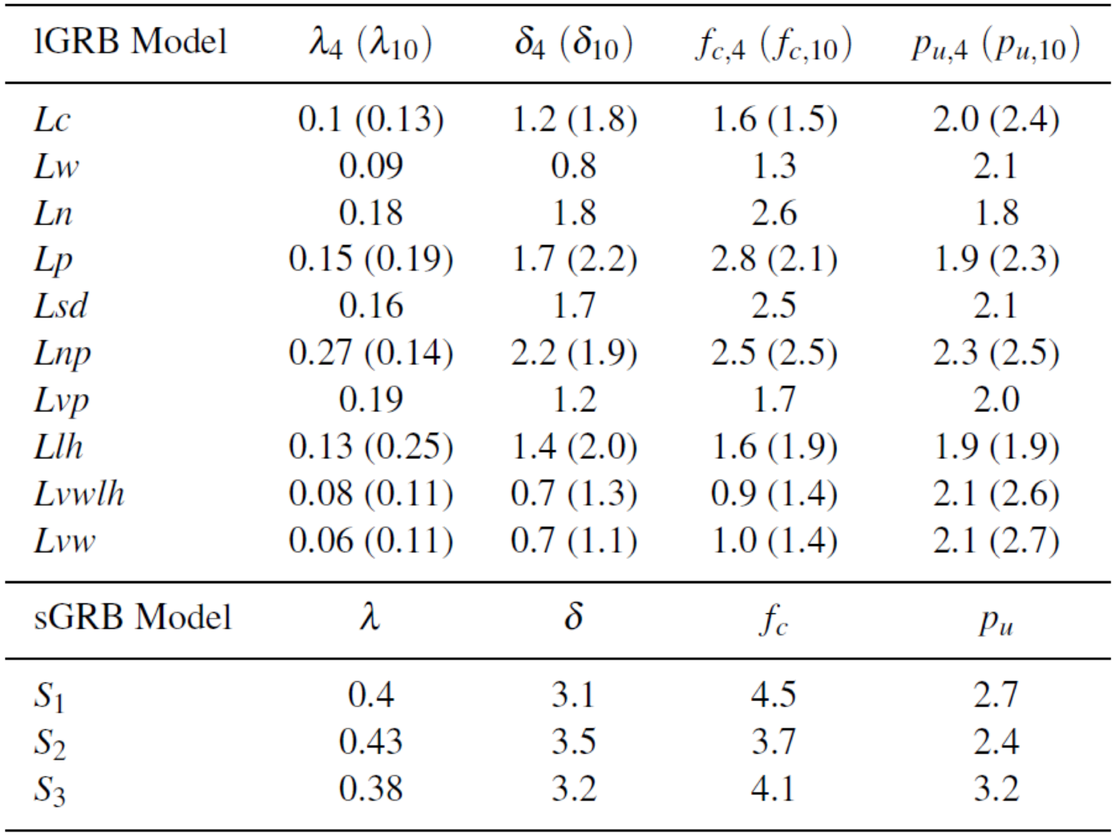
*Overall energy distribution when the jet head reaches 10 R⋆, for different models*



*(b) Angular energy distribution, different models*

*(c) 3-segments fitting*

# IV- The post-breakout structure (sGRBs)



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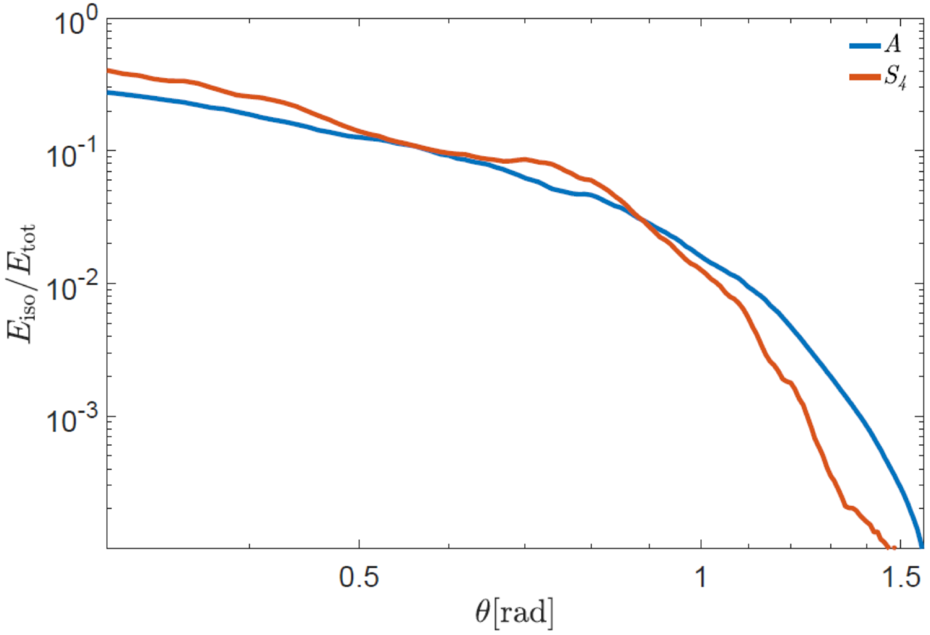
| *Lvwlh* | 0.08 (0.11) | 0.7 (1.3) | 0.9 (1.4) | 2.1 (2.6) |
| *Lvw* | 0.06 (0.11) | 0.7 (1.1) | 1.0 (1.4) | 2.1 (2.7) |
| sGRB Model | $\lambda$ | $\delta$ | $f_c$ | $p_u$ |
| $S_1$ | 0.4 | 3.1 | 4.5 | 2.7 |
| $S_2$ | 0.43 | 3.5 | 3.7 | 2.4 |
| $S_3$ | 0.38 | 3.2 | 4.1 | 3.2 |

A model with lower luminosity :



→ Closer to lGRBs shapes

# IV- The low-luminosity sGRBs problem

**Breakout time is 10x too long !**

Possible explanations:

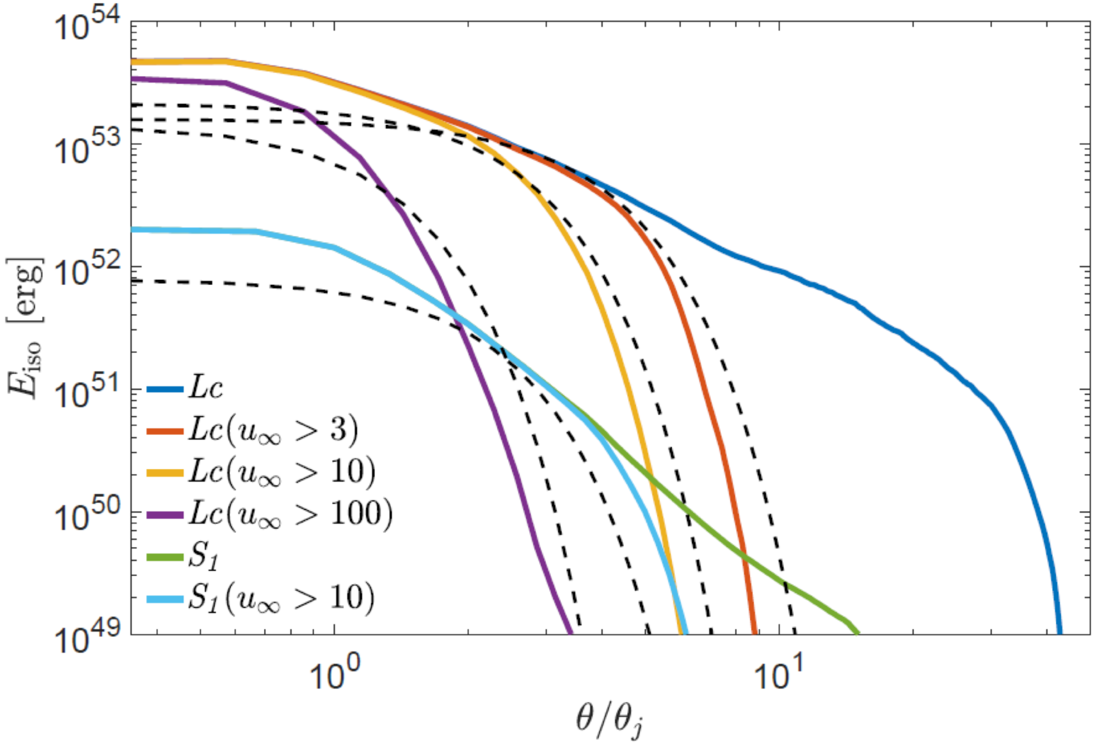
- Ejected mass may be too high
- Ejecta might be highly anisotropic

With this we can produce sGRBs but might not account for r-process elements in the Universe…

Another explanation:

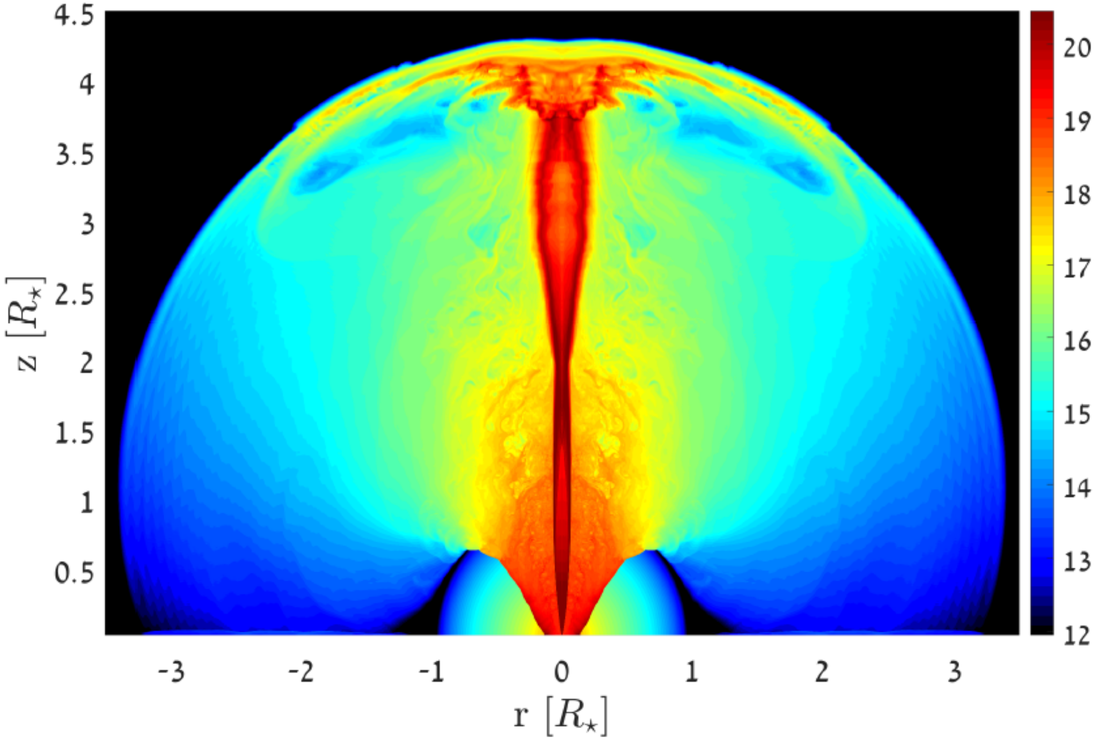
- Weakly magnetized jet → fewer instabilities → faster propagation → more luminosity

# IV- Gaussian or power-law angular profile ?

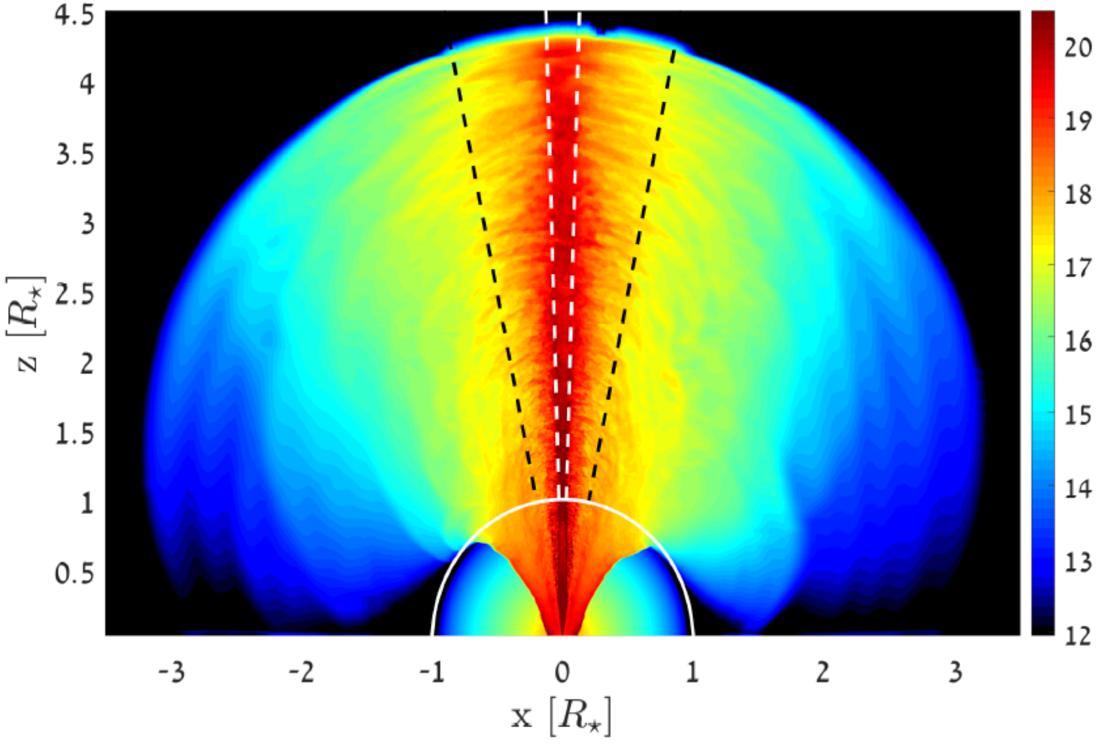


*"As expected these distributions are incompatible with gaussian fits"*

# IV- 2D vs. 3D



*2D hydrodynamic simulation*



*3D hydrodynamic simulation*

# V- Emission

Prompt :

- light curves, spectra with temporal evolution
- some jets may not live long enough to produce a GRB
- higher mixing :
  - → lower radiative efficiency
  - → high temporal efficiency variability
  - → alteration of off-axis emission

Afterglow :

- long and short GRBs : different light curves
- if mixing is weak (like in most sGRBs) :
  - → if $\theta_{obs} < \theta_j$, afterglow similar to top-hat
  - → if $\theta_{obs} > \theta_j$, afterglow peaks at late time, with a more complex rising phase (hump & peak, 2 peaks)
- If mixing is high (most likely in lGRBs) :
  - → if $\theta_{obs} < \theta_j$, early profile similar to top-hat, but decrease shallower
  - → if $\theta_{obs} > \theta_j$, rise, peak, shallow decrease, fast decrease

# VI- Summary

- Rayleigh-Taylor instabilities between cocoon and jet pre-breakout → mixing

Mixing → Transition layer : JCI

- In lGRBs, after T = $t_b$, uniform energy distribution for jet in the star

In sGRBs, less mixing → more energy in the core

- Prior to breakout, almost all injected energy → cocoon

After breakout, cocoon energy constant, injection in core & JCI

- lGRBs: more energy in the JCI of due to higher $\lambda$, larger JCI
- GRB distribution of $E_{iso}$ and velocity follow a power law after the core
- 2D simulations of limited accuracy
- The presence of a magnetic field can stabilize the jet