Structured Jets in Gamma-Ray Bursts

Om Sharan Salafia

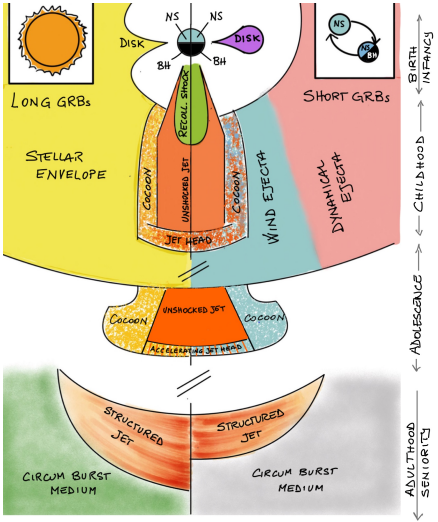
INAF – Osservatorio Astronomico di Brera
INFN – Sezione di Milano-Bicocca
Milan, Italy

2024-02-28

Fast-Evolving Extragalactic Transients Thinkshop

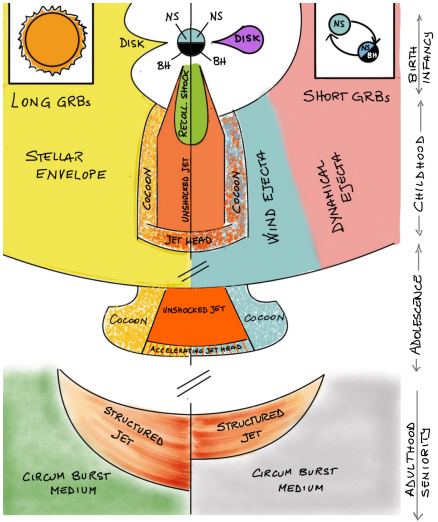
Baita dei Pini
Bormio (SO), Italy

Jet struct...what?



[Salafia & Ghirlanda 2023]

Jet struct...what?

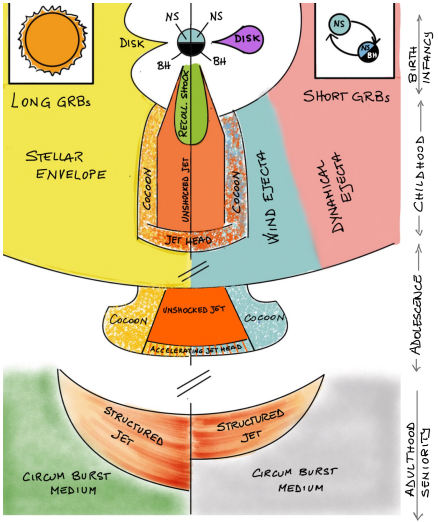


[Salafia & Ghirlanda 2023]

- Fluid structure at fixed lab-frame time

$$\rho'(r,\theta,t), \quad \vec{\beta}(r,\theta,t),$$
$$h(r,\theta,t), \quad \vec{B}(r,\theta,t)$$

Jet struct...what?



[Salafia & Ghirlanda 2023]

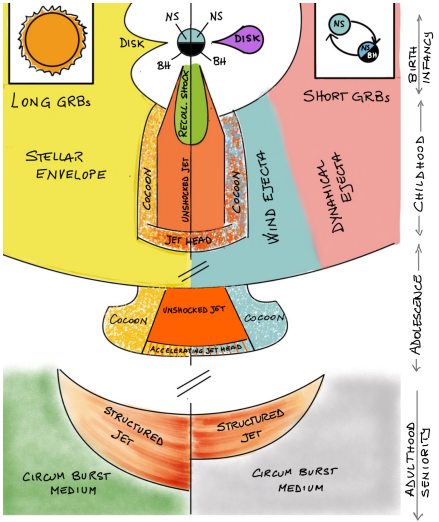
- Fluid structure at fixed lab-frame time

$$\rho'(r,\theta,t), \quad \vec{\beta}(r,\theta,t),$$
$$h(r,\theta,t), \quad \vec{B}(r,\theta,t)$$

- Afterglow ‘initial conditions’

$$E_{\mathrm{K,iso}}(\theta), \quad \Gamma_0(\theta)$$

Jet struct...what?



[Salafia & Ghirlanda 2023]

- Fluid structure at fixed lab-frame time

$$\rho'(r,\theta,t), \quad \vec{\beta}(r,\theta,t),$$
$$h(r,\theta,t), \quad \vec{B}(r,\theta,t)$$

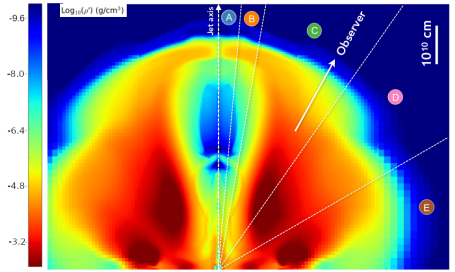
- Afterglow ‘initial conditions’

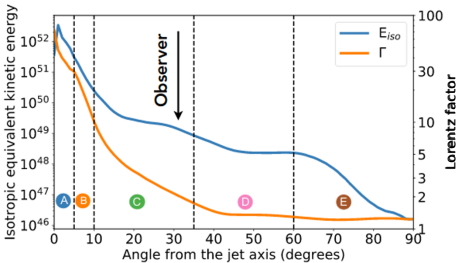
$$E_{\mathrm{K,iso}}(\theta), \quad \Gamma_0(\theta)$$

- ‘Apparent’ structure (prompt emission)

$$E_{\gamma,\mathrm{iso}}(\theta_\mathrm{v}), \qquad L_{\gamma,\mathrm{iso}}(\theta_\mathrm{v}, t_\mathrm{obs}),$$
$$E_\mathrm{peak}(\theta_\mathrm{v}, t_\mathrm{obs})$$

From fluid to afterglow initial conditions

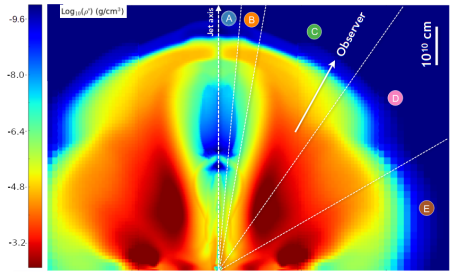


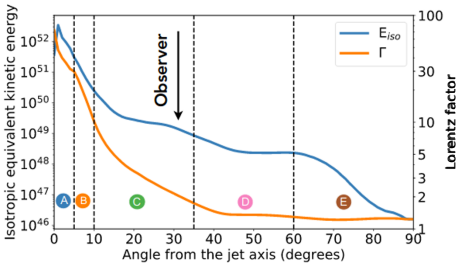


[Lazzati et al. 2018]

From fluid to afterglow initial conditions

$$\Gamma(r,\theta,t) = \frac{1}{\sqrt{1-\beta^2(r,\theta,t)}}$$



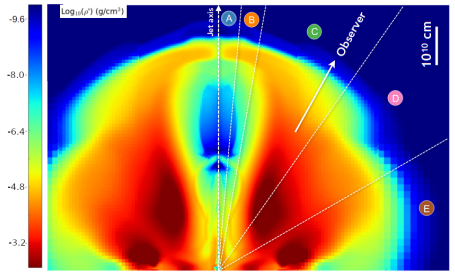


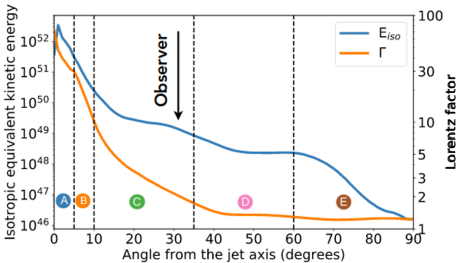
[Lazzati et al. 2018]

From fluid to afterglow initial conditions

$$\Gamma(r,\theta,t) = \frac{1}{\sqrt{1-\beta^2(r,\theta,t)}}$$

$$E_{\mathrm{K,iso}}(\theta,t) =$$
$$4\pi \int r^2 \left(\Gamma(r,\theta,t)-1\right)\Gamma(r,\theta,t)\rho'(r,\theta,t)c^2\,\mathrm{d}r$$





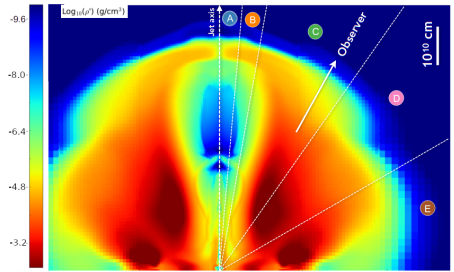
[Lazzati et al. 2018]

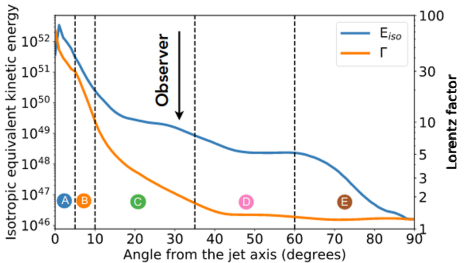
From fluid to afterglow initial conditions

$$\Gamma(r,\theta,t) = \frac{1}{\sqrt{1-\beta^2(r,\theta,t)}}$$

$$E_{\rm K,iso}(\theta,t) =$$
$$4\pi \int r^2 \left(\Gamma(r,\theta,t)-1\right)\Gamma(r,\theta,t)\rho'(r,\theta,t)c^2\,{\rm d}r$$

Coasting (“ballistic”) phase: $E_{\rm K,iso}(\theta,t) \to E_{\rm K,iso}(\theta)$





[Lazzati et al. 2018]

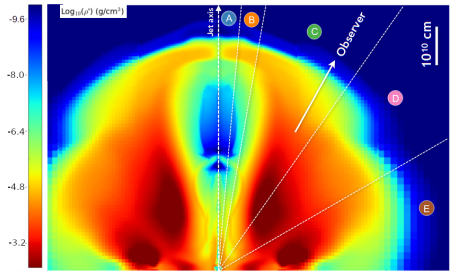
From fluid to afterglow initial conditions

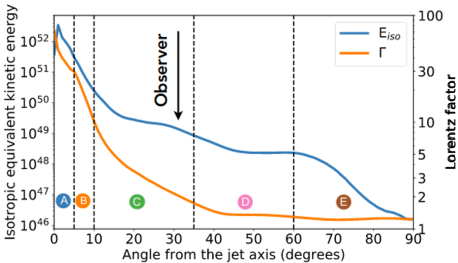
$$\Gamma(r,\theta,t) = \frac{1}{\sqrt{1-\beta^2(r,\theta,t)}}$$

$$E_{\rm K,iso}(\theta,t) =$$
$$4\pi \int r^2 \left(\Gamma(r,\theta,t)-1\right)\Gamma(r,\theta,t)\rho'(r,\theta,t)c^2\,{\rm d}r$$

Coasting (“ballistic”) phase: $E_{\rm K,iso}(\theta,t) \to E_{\rm K,iso}(\theta)$

$$\Gamma_0(\theta) - 1 \stackrel{?}{=} \frac{E_{\rm K,iso}(\theta)}{M_{\rm iso}(\theta)c^2} =$$
$$\frac{E_{\rm K,iso}(\theta)}{4\pi\int r^2\Gamma(r,\theta,t)\rho'(r,\theta,t)c^2\,{\rm d}r}$$





[Lazzati et al. 2018]

Afterglow initial conditions $\leftrightarrow$ apparent structure

Prompt emission efficiency

$$\frac{\mathrm{d}E_\gamma}{\mathrm{d}\Omega}(\theta) = \eta_\gamma(\theta)\frac{E_{\gamma,\mathrm{iso}}(\theta)}{4\pi}$$

Dante Gabriel Rossetti, “The Damsel of the Sanct Grael”

Afterglow initial conditions $\leftrightarrow$ apparent structure

Prompt emission efficiency

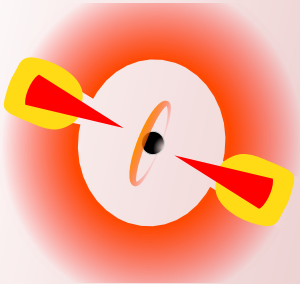
$$\frac{\mathrm{d}E_\gamma}{\mathrm{d}\Omega}(\theta) = \eta_\gamma(\theta)\frac{E_{\gamma,\mathrm{iso}}(\theta)}{4\pi}$$

Apparent structure

$$E_{\gamma,\mathrm{iso}}(\theta_\mathrm{v}) = \iint \frac{\delta^3(\theta,\phi,\theta_\mathrm{v})}{\Gamma(\theta)}\frac{\mathrm{d}E_\gamma}{\mathrm{d}\Omega}(\theta)\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi$$

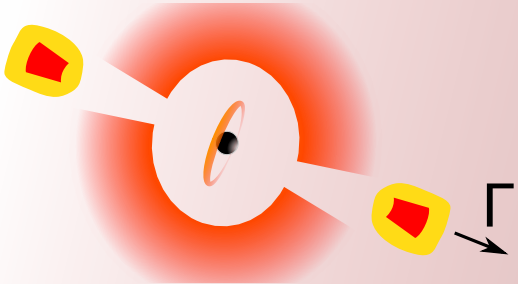
Dante Gabriel Rossetti, “The Damsel of the Sanct Grael”

Observational impact of jet structure: afterglow



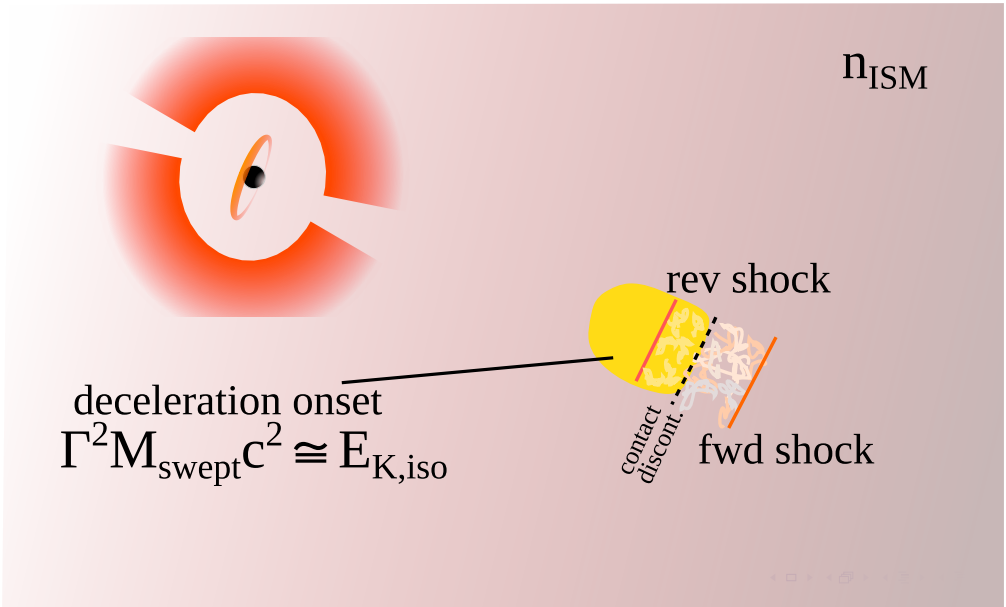
n_{ISM}

Observational impact of jet structure: afterglow

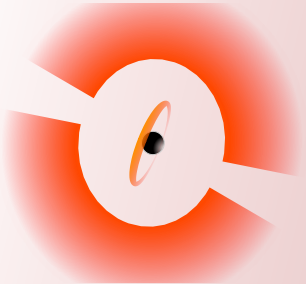


n_{ISM}

Observational impact of jet structure: afterglow

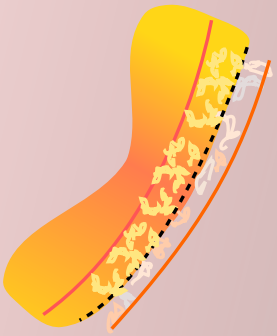


Observational impact of jet structure: afterglow



n_{ISM}

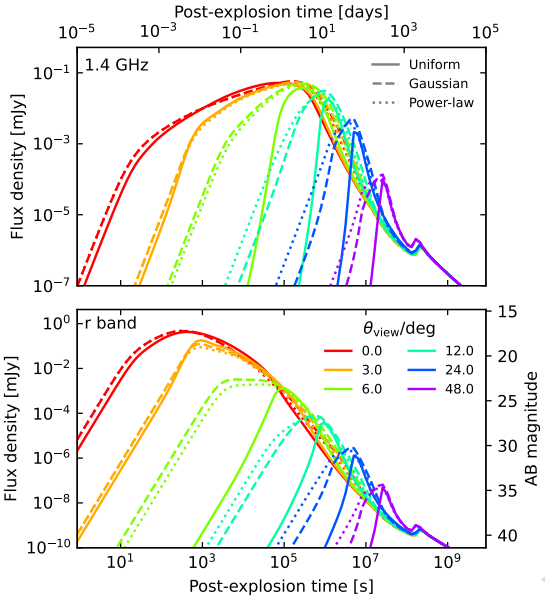
angular structure



deceleration onset

$$\Gamma(\theta,R)^2 M_{swept}(\theta,R) c^2 \cong E_{K,iso}(\theta)$$

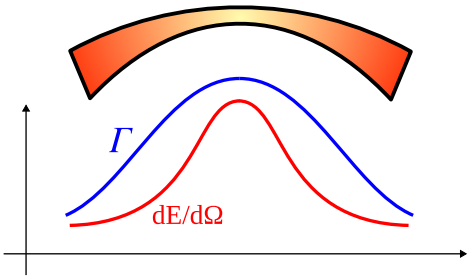
Observational impact of jet structure: afterglow



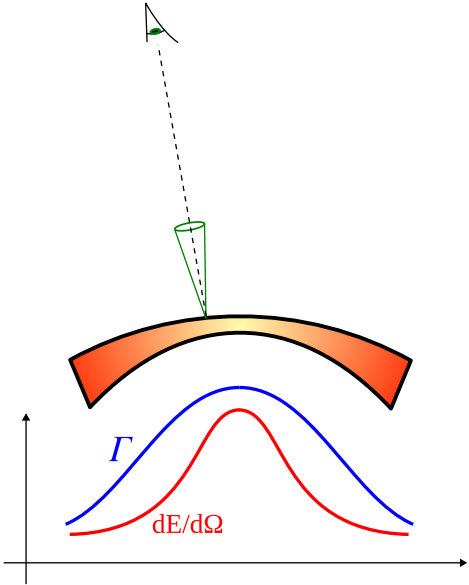
Observational impact of jet structure: prompt emission

?

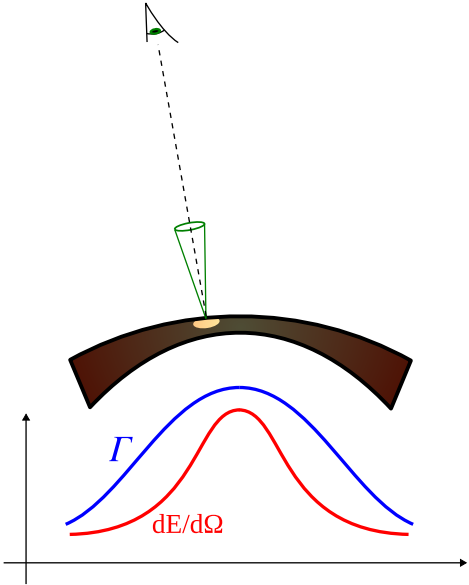
Observational impact of jet structure: prompt emission



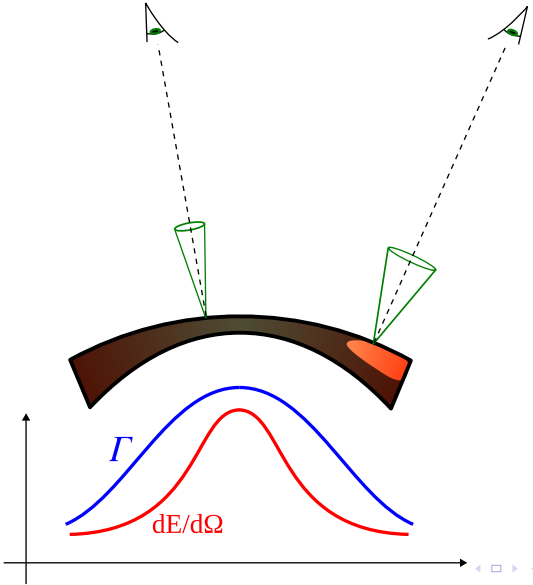
Observational impact of jet structure: prompt emission



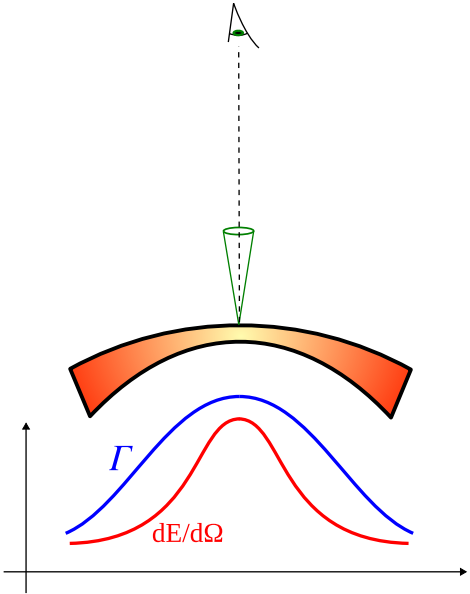
Observational impact of jet structure: prompt emission



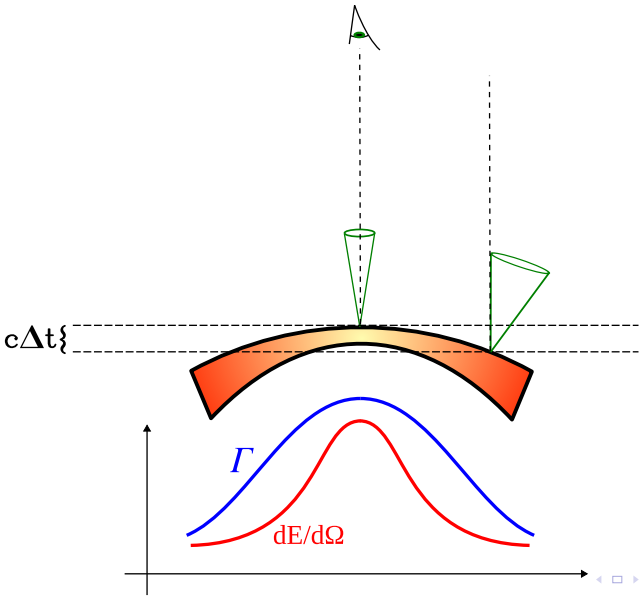
Observational impact of jet structure: prompt emission



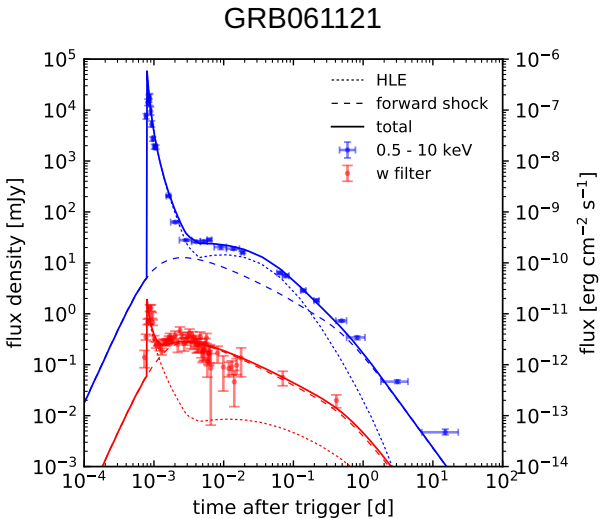
Observational impact of jet structure: prompt emission



Observational impact of jet structure: prompt emission

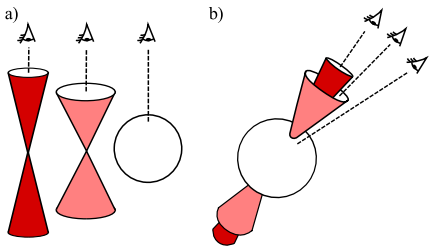


High latitude ‘latecomer’ prompt emission

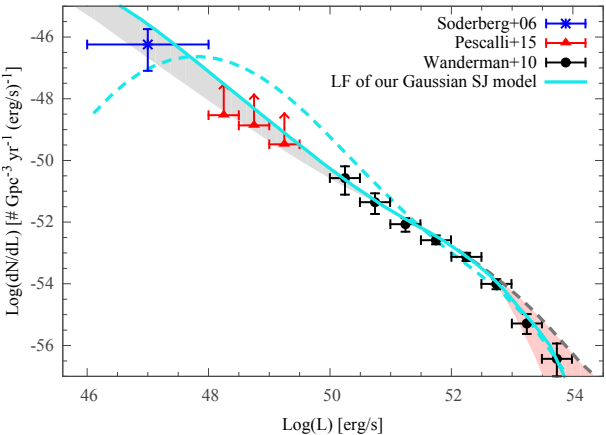


[Oganesyan et al. 2020, see also Panaitescu 2020]

Jet structure → luminosity function



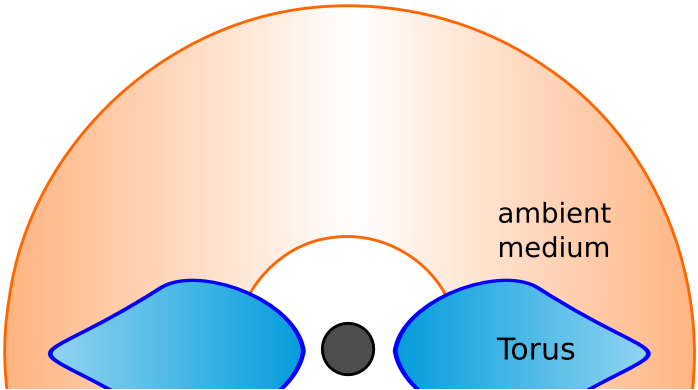
[Lipunov et al. 2001]
[see also Rossi et al. 2002]



[Salafia et al. 2015]

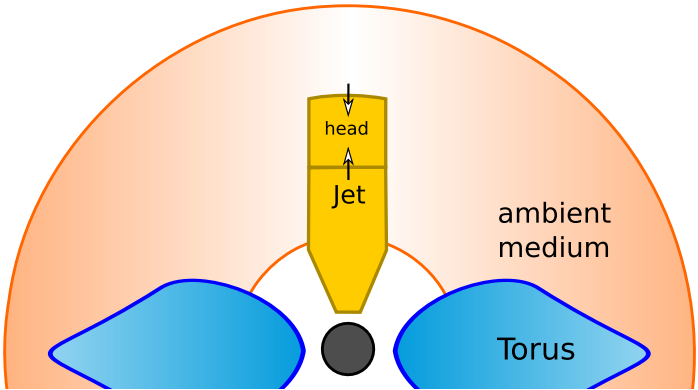
What determines the jet structure?

Jet propagation and breakout



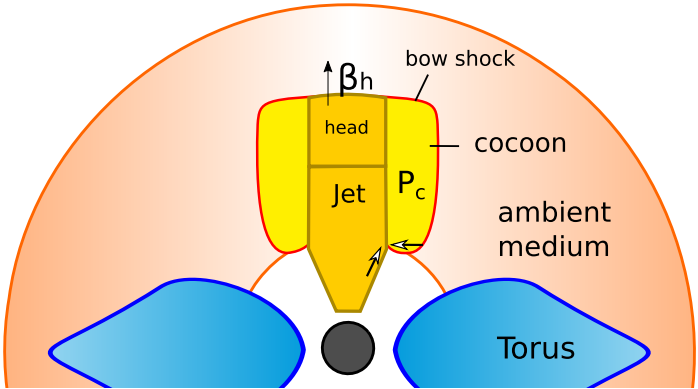
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



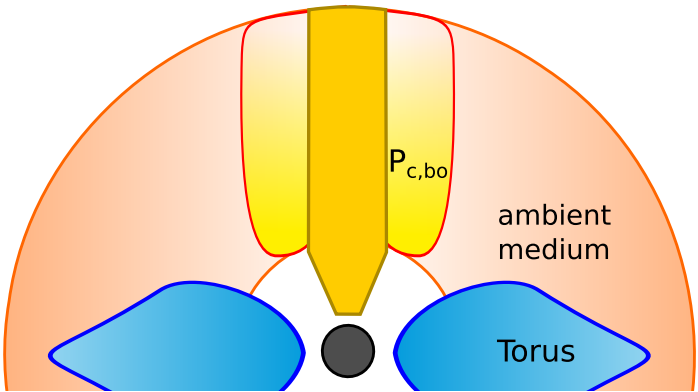
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



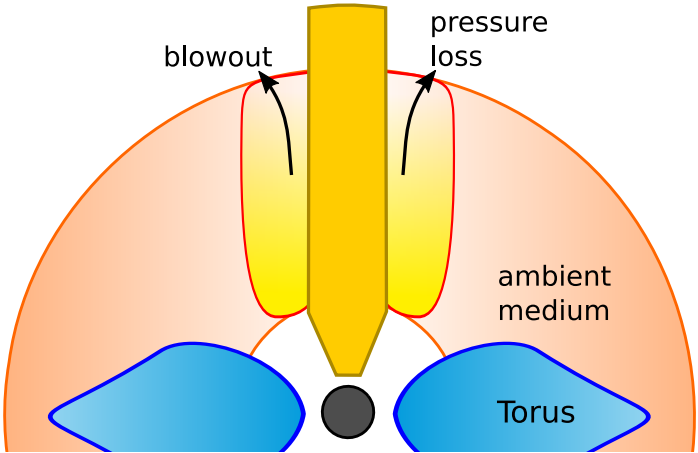
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



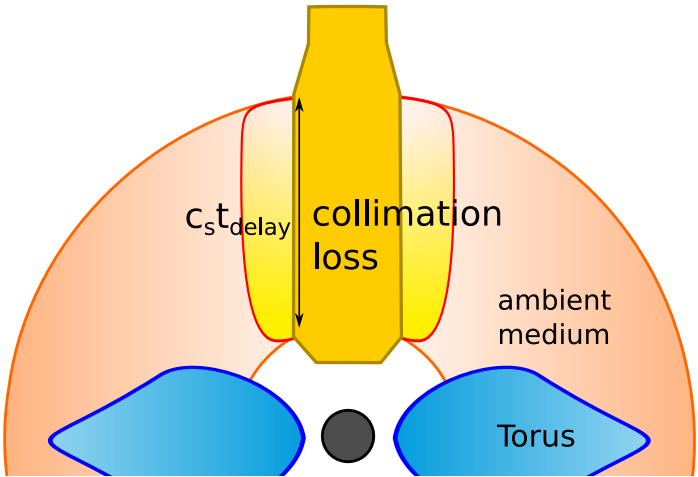
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



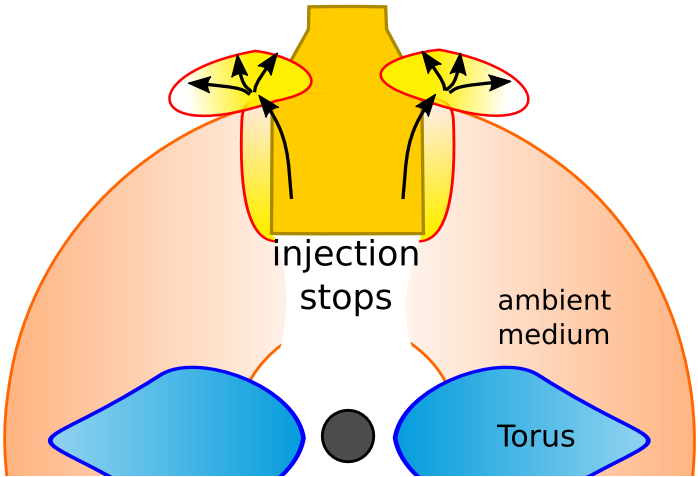
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



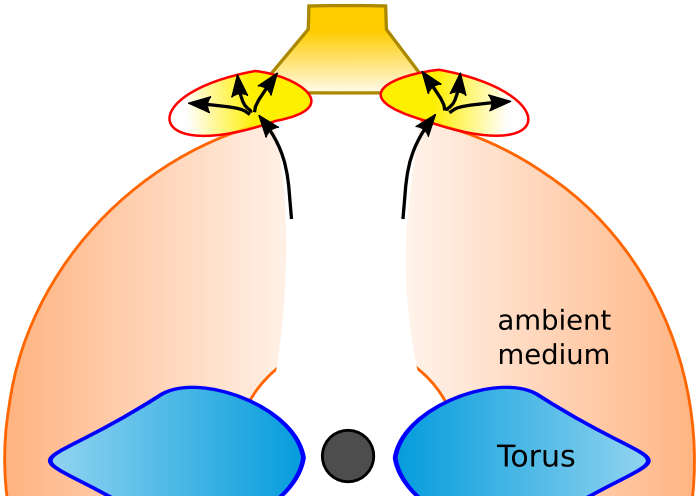
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



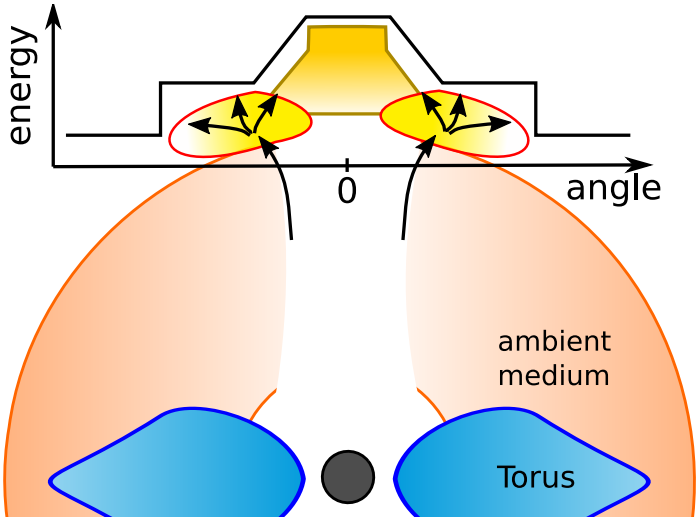
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



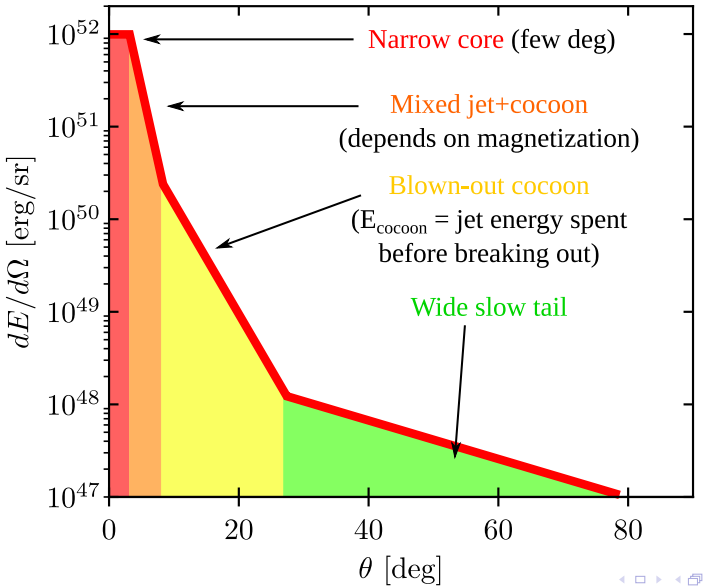
[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet propagation and breakout



[See e.g. Matzner 03, Bromberg+11, Salafia+19, Lazzati & Perna 19, Hamidani+20,21, Gottlieb+18,20,21,22,23 ...]

Jet structure after breakout



Two regimes

$E_{\rm jet}$ = jet total energy
$E_{\rm cocoon}$ = energy spent to breakout = energy in cocoon

- $E_{\rm jet} \lesssim E_{\rm cocoon}$: jet structure dominated by jet-progenitor interaction

Two regimes

$E_{\rm jet}$ = jet total energy
$E_{\rm cocoon}$ = energy spent to breakout = energy in cocoon

- $E_{\rm jet} \lesssim E_{\rm cocoon}$: jet structure dominated by jet-progenitor interaction
  $\rightarrow$ imprint of both central engine and progenitor vestige (especially properties along axis)

Two regimes

$E_{\rm jet}$ = jet total energy
$E_{\rm cocoon}$ = energy spent to breakout = energy in cocoon

- $E_{\rm jet} \lesssim E_{\rm cocoon}$: jet structure dominated by jet-progenitor interaction
  - $\rightarrow$ imprint of both central engine and progenitor vestige (especially properties along axis)
  - $\rightarrow$ details of original jet structure washed out (?) [Nativi+22]

Two regimes

$E_{\rm jet}$ = jet total energy
$E_{\rm cocoon}$ = energy spent to breakout = energy in cocoon

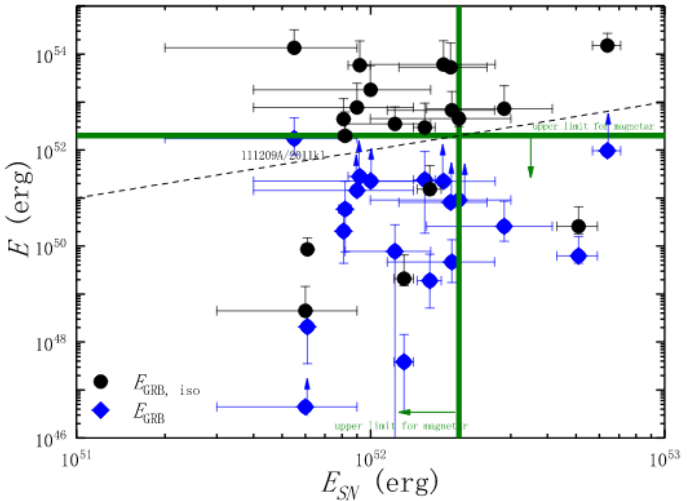
- $E_{\rm jet} \lesssim E_{\rm cocoon}$: jet structure dominated by jet-progenitor interaction
  - $\rightarrow$ imprint of both central engine and progenitor vestige (especially properties along axis)
  - $\rightarrow$ details of original jet structure washed out (?) [Nativi+22]
- $E_{\rm jet} \gg E_{\rm cocoon}$: dominated by central engine [Urrutia+21]

Two regimes

$E_{\rm jet}$ = jet total energy
$E_{\rm cocoon}$ = energy spent to breakout = energy in cocoon

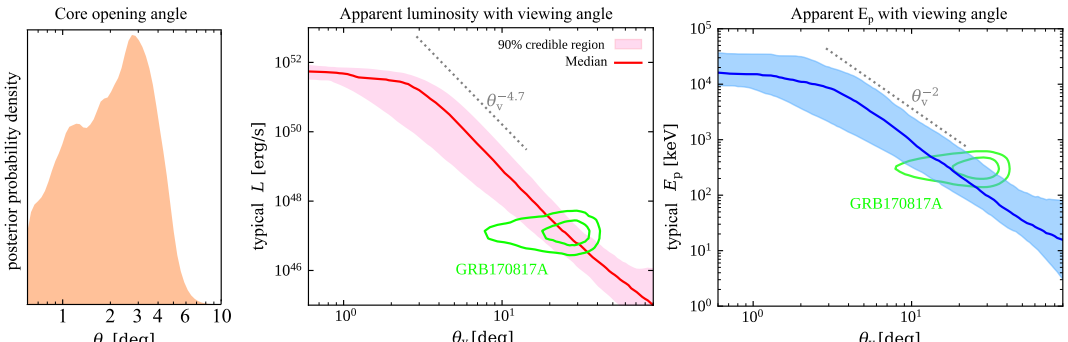
- $E_{\rm jet} \lesssim E_{\rm cocoon}$: jet structure dominated by jet-progenitor interaction
  - $\rightarrow$ imprint of both central engine and progenitor vestige (especially properties along axis)
  - $\rightarrow$ details of original jet structure washed out (?) [Nativi+22]
- $E_{\rm jet} \gg E_{\rm cocoon}$: dominated by central engine [Urrutia+21]
  - $\rightarrow$ opportunity to study jet-launching mechanisms? Look for most energetic jets (ultra-long?) / most tenuous progenitor vestiges (BHNS?)

Quasi-universal jet structure?



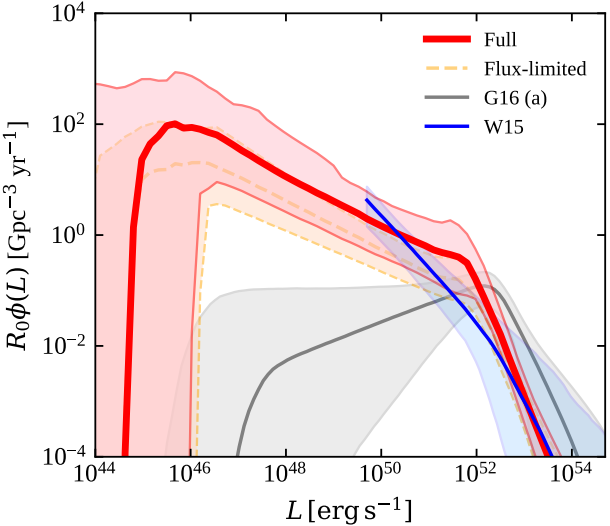
[Lu et al. 2018]

Quasi-universal jet structure in short GRBs



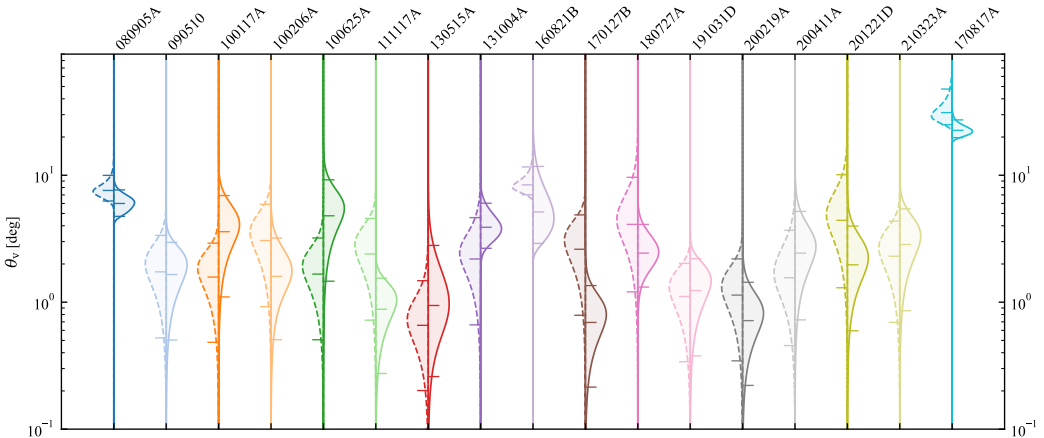
[Salafia et al. 2023]

Quasi-universal jet structure in short GRBs: luminosity function



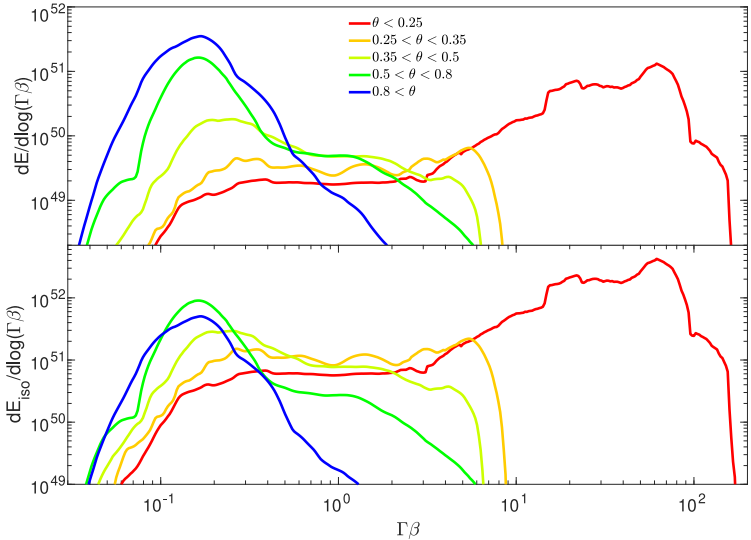
[Salafia et al. 2023]

Quasi-universal jet structure in short GRBs: viewing angles



[Salafia et al. 2023]

Pitfalls: afterglow description



[Nakar & Piran 2018]

Summary

- Many definitions of ‘jet structure’: each useful in different contexts, most imply (sometimes hidden) simplifications
- Structure can teach us about jet-progenitor interaction, but possibly also about central engine in some cases
- Structure likely impacts the energy/luminosity distribution of the prompt emission, at least to some extent
- Quasi-universal structure is attractive for unification (e.g. explains extreme diversity of GRBs wrt the associated SNe)
- Many pieces of evidence indicate some intrinsic variability is present though
- Impact of jet structure on various emission components yet to be fully explored