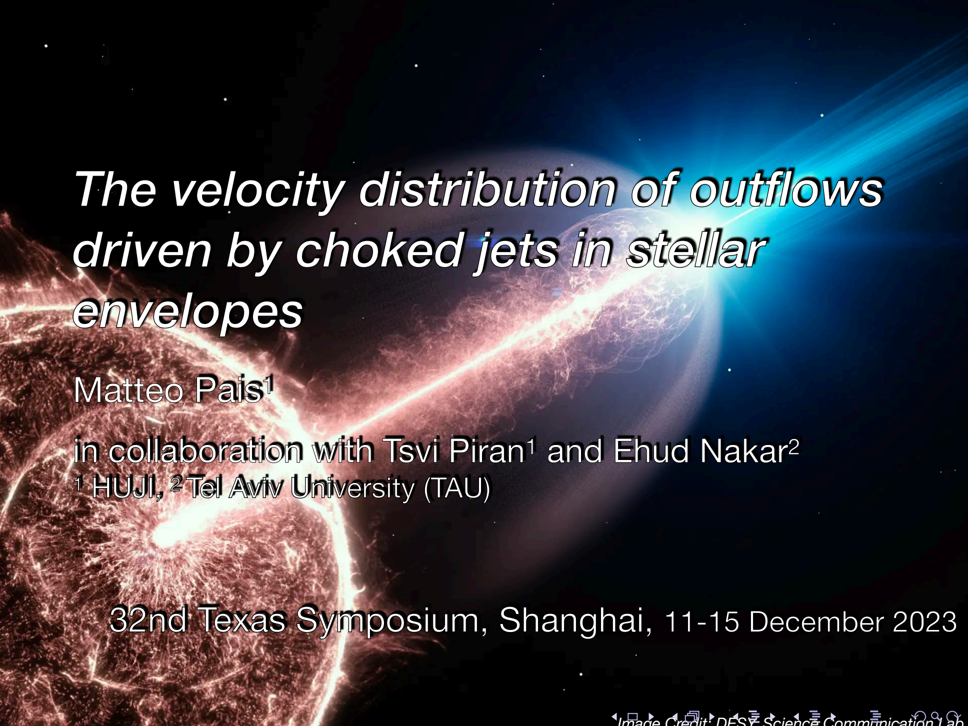

The velocity distribution of outflows driven by choked jets in stellar envelopes

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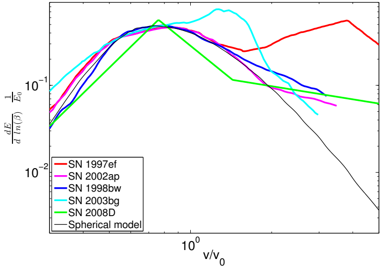
Image Credit: DESY, Science Communication Lab

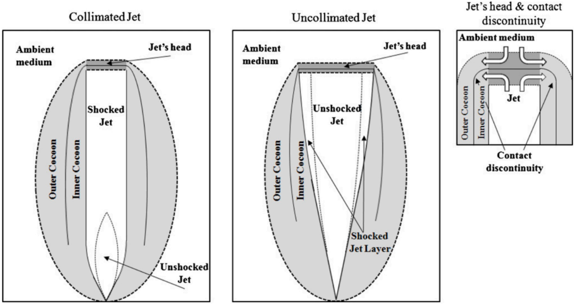
Signatures: high velocity component



SN	Type	E_{tot}[a]	M_{ej}[b]	E_j[a]	M_c[b]	θ_c	Comments
1997ef (1)	Ic-BL	20	8	9	0.4	20°	No GRB
1998bw (2)	Ic-BL	50	11	$\gtrsim 2$	⋯	⋯	llGRB980425
2002ap (3)	Ic-BL	4	2.5	0.3	⋯	⋯	No GRB
2003bg (4)	IIb	5	4.5	1	0.2	20°	No GRB
2008D (5)	Ib	6	7	1.4	⋯	⋯	X-ray burst
2016jca (6)	Ic-BL	50	10	$\gtrsim 2$	⋯	⋯	GRB161219b

(from Piran et al. 2019)

- Broad absorption lines as markers in CCSNe;
- Energy-velocity distribution from broad absorption lines;



(from Bromberg et al. 2011)

- $$\rho_{\rm j} h_{\rm j} \Gamma_{\rm j}^2 \Gamma_{\rm h}^2 (\beta_{\rm j} - \beta_{\rm h})^2 + P_{\rm j} = \rho_a h_a \Gamma_{\rm h}^2 \beta_{\rm h}^2 + P_a; \quad (1)$$
- $$\beta_{\rm h} = \frac{1}{1 + \tilde{L}^{-1/2}} \quad (2)$$
- $$\tilde{L} \equiv \frac{\rho_{\rm j} h_{\rm j} \Gamma_{\rm j}^2}{\rho_a} \simeq \frac{L_{\rm j}}{\Sigma_{\rm j} \rho_a c^3} \quad (3)$$

Simulation setup

2D cylindrical RHD simulations performed with PLUTO (Mignone, 2007):

- jet injected through a nozzle with $\Sigma_{\rm j} = \pi r_{\rm j}^2$;
- jet density injected via:

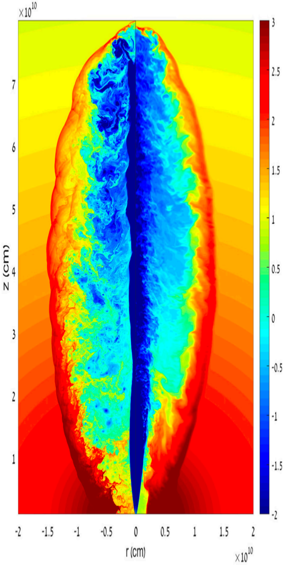
$$\rho_{\rm j} h_{\rm j} = \frac{L_{\rm j}}{\Sigma_{\rm j} \Gamma_{0,{\rm j}}^2 c^3} \qquad P_{\rm j} = (h_{\rm j} - 1) \frac{\rho_{\rm j} c^2}{4} \quad (4)$$

with $\Gamma_{0,{\rm j}} = 1/(1.4\theta_{\rm j})$, $h_{\rm j} = 100$

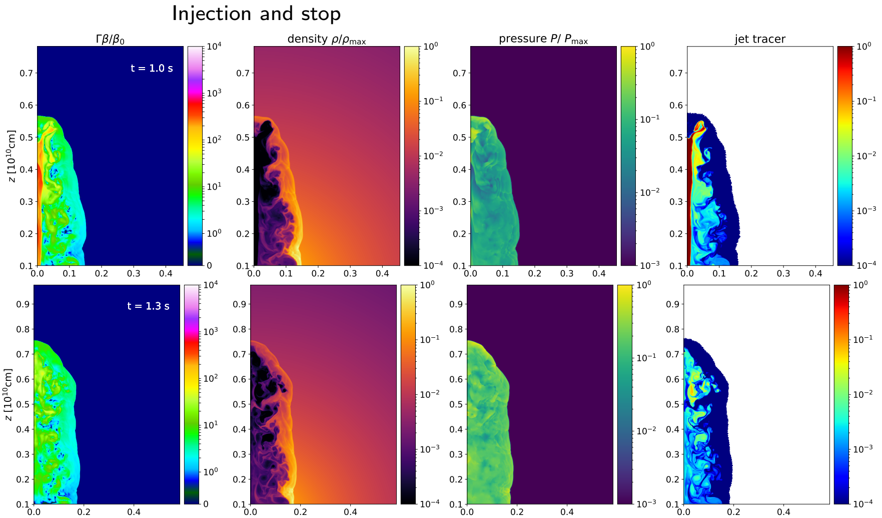
- Stellar density profile:

$$\rho(R) = \begin{cases} \rho_* \left(\frac{R_*}{R} - 1 \right)^2 + \rho_0, & \text{for } R \leq R_* \ , \\ \rho_0, & \text{for } \ R > R_* \ . \end{cases} \quad (5)$$

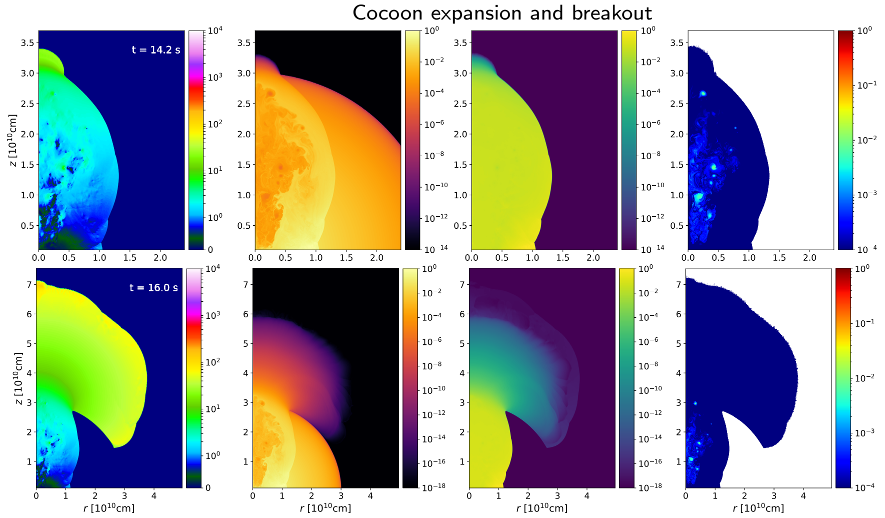
- given given the physical scales R_*, ρ_*, E_0, v_0, $t_{\rm e}$, we can scale the parameters of our system $R_* = \lambda R'_*$, $E_0 = \eta E'_0$ such that $t_{\rm e} = \lambda t'_{\rm e}$ and $\rho_* = \eta \lambda^{-3} \rho'_*$ to fix $\tilde{L}$ and $z_{\rm ch}/R_*$.



(from Harrison et al., 2018)

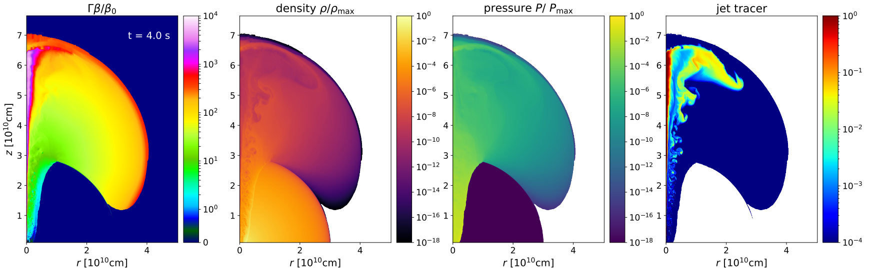


Injection and stop
$\Gamma\beta/\beta_0$
density ρ/ρ_{max}
pressure P/P_{max}
jet tracer
t = 1.0 s
t = 1.3 s
$z\ [10^{10}\mathrm{cm}]$



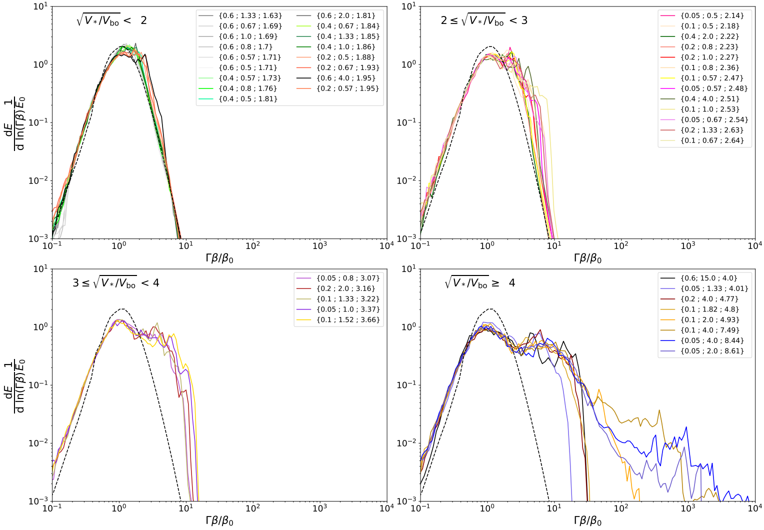
Cocoon expansion and breakout
t = 14.2 s
t = 16.0 s
z [10^{10}cm]
r [10^{10}cm]

Simulating a successful jet



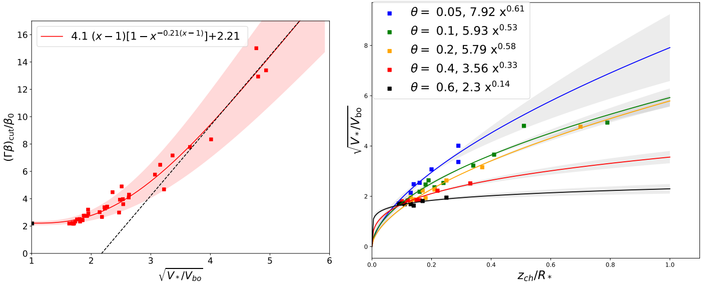
- Successful jet spreads its high-$\Gamma\beta$ material outside and sideways
- Signature holds for some time till substantial deceleration

Energy-velocity distribution



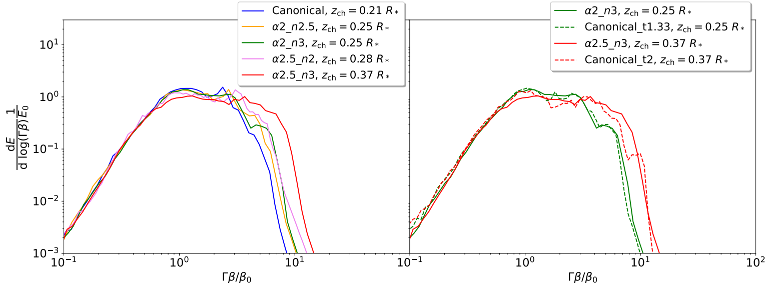
- Given $\beta_0 = \sqrt{2E/Mc^2}$ and assuming $\langle\rho_*\rangle \simeq \langle\rho_{\rm cocoon}\rangle$ we get $\beta_{\rm bo} \simeq \beta_0\sqrt{\frac{V_*}{V_{\rm bo}}}$
- cutoff around $\simeq 1/4\max({\rm d}E/{\rm d}\log\beta)$;

Cocoon volume and correlation with $z_{\rm ch}$



- Correlation between $\beta\Gamma$-cutoff and volume;
- Correlation between chocking height and shocked volume at $t = t_{\rm bo}$

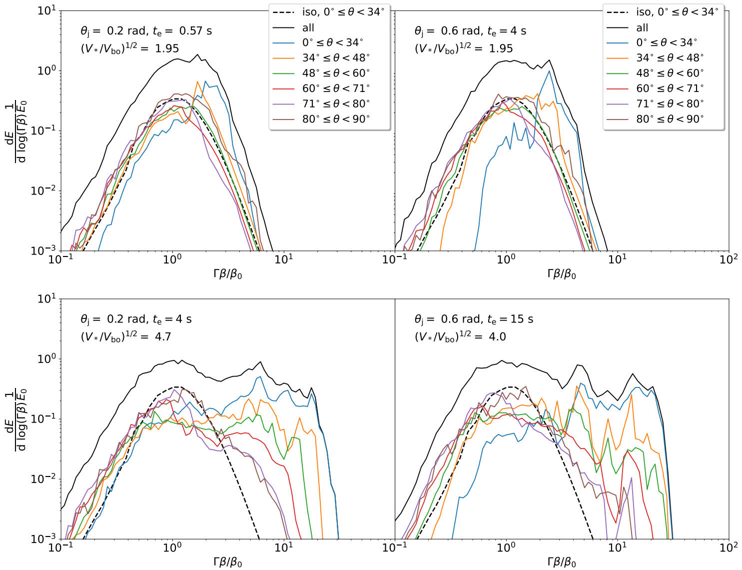
Effect of density profiles



- Generalized density profile: $\rho(R) = \rho_* \,(x)^{-\alpha}\,(1-x)^n$, with $x = R/R_*$;
- Mapping one profile to the other:

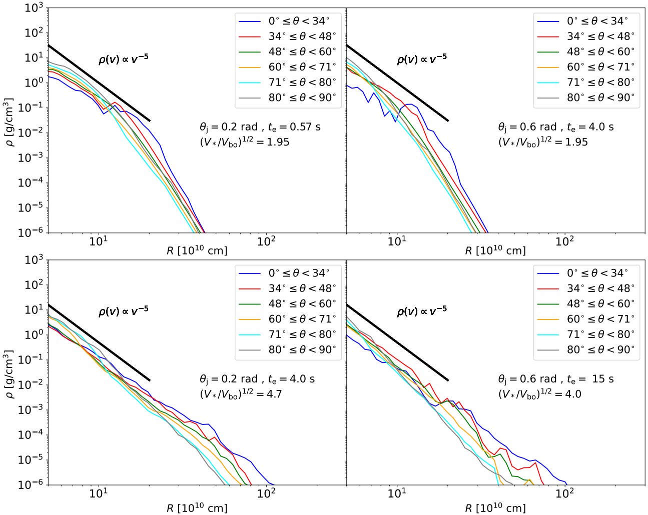
Jets	t_e [s]	θ_j [rad]	$\rho(r)$	z_{ch}/R_*	t_{bo} [s]
Canonical	1	0.2	$\propto R^{-2}(R_* - R)^2$	0.21	13.9
α2_n2.5	1	0.2	$\propto R^{-2}(R_* - R)^{2.5}$	0.25	11.2
α2_n3	1	0.2	$\propto R^{-2}(R_* - R)^3$	0.25	9.5
α2.5_n2	1	0.2	$\propto R^{-2.5}(R_* - R)^2$	0.28	6.8
α2.5_n3	1	0.2	$\propto R^{-2.5}(R_* - R)^3$	0.37	4.0
Canonical_t1.33	1.33	0.2	$\propto R^{-2}(R_* - R)^2$	0.25	11.5
Canonical_t2	2	0.2	$\propto R^{-2}(R_* - R)^2$	0.37	8.3

Profiles at different viewing angles



- profiles with $\simeq$ same volume fraction but different t_e and θ_j

Profiles at different viewing angles

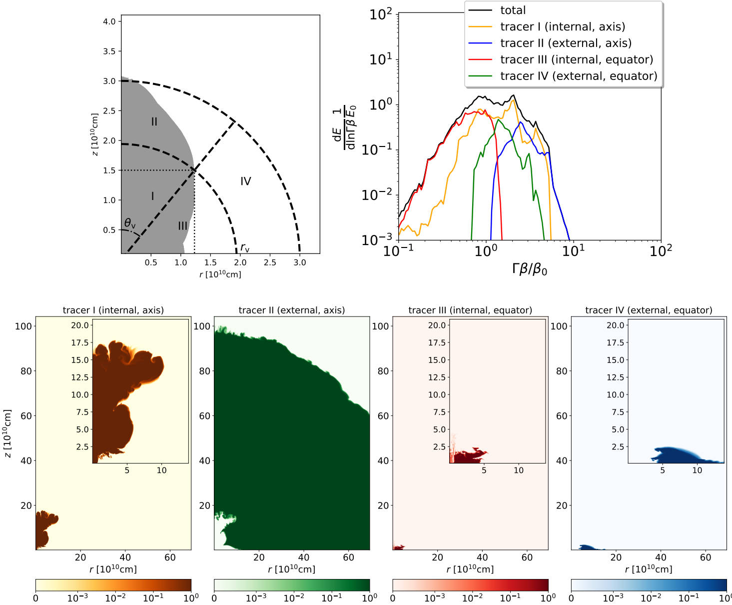


- same but with density profiles: $\rho(R) \simeq v^{-5}E(v)$

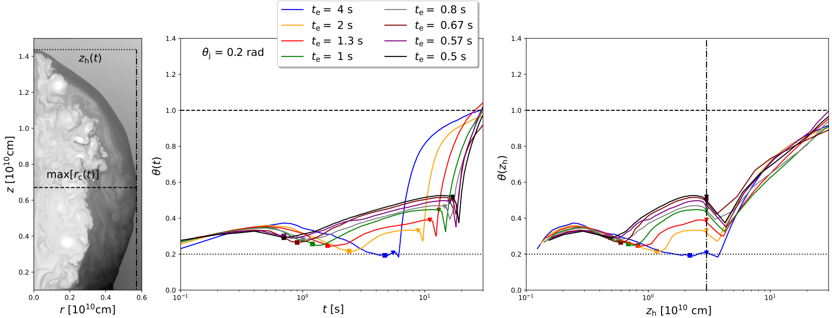
Summary

- **all jet-driven explosions** with $z_{\rm ch} \simeq R_*$ **have roughly constant amount of energy per logarithmic scale of the proper velocity** $(\Gamma\beta)$.
- the plateau of the energy-velocity distribution starts in all cases at $v_0 = \sqrt{E_0/M_*}$;
- the maximal velocity of the plateau depends mostly on the cocoon volume upon breakout, with $\beta_{\rm bo} = \beta_0\sqrt{V_*/V_{\rm bo}}$:
  For $\sqrt{V_*/V_{\rm bo}} < 3$ then $\beta_{\rm max} \simeq \beta_{\rm bo}$, for $\sqrt{V_*/V_{\rm bo}} > 3$ then $\beta_{\rm max} > \beta_{\rm bo}$ and it can become mildly relativistic.
- the smaller $V_{\rm bo}(\theta_{\rm j}, z_{\rm ch})$ the higher the terminal velocity;
- on-axis pole material faster than equatorial material (shallower density profile).
- jets, even if choked, carry a significant amount of energy at high-velocity matter;
- to observe broad absorption lines we need a choking at $z_{\rm ch} \simeq R_*$;
- off-axis material will become optically thin faster, disappearing earlier in the spectra, making the observation less likely;
- SNe not associated with GRBs possibly harbor choked jets while LGRBs must contain a successful jet;
- **jets choked (not too deep) provide a natural explanation to the fast material seen in the early spectra of stripped envelope SNe without LGRB**;

Origin of the ejecta with different velocities



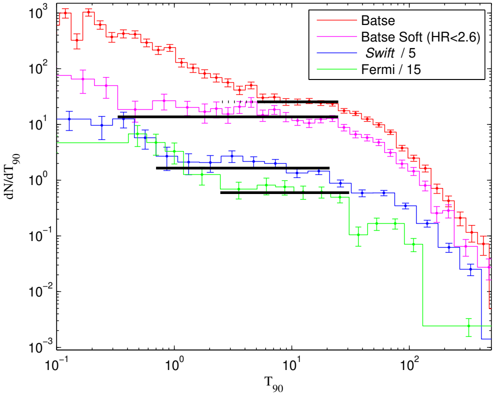
Characterizing the jets



- Does the choking position $z_{\rm h}$ mirror the energy-velocity distribution?
- Is there any other indicative parameter?

- Given $\beta_0 = \sqrt{2E/Mc^2}$ and assuming $\langle \rho_* \rangle \simeq \langle \rho_{\rm cocoon} \rangle$ we get $\beta_{\rm bo} \simeq \beta_0 \sqrt{\dfrac{V_*}{V_{\rm bo}}}$

Distribution of duration of GRBs



(from Bromberg et al., 2012)

$$t_{\rm bo} \simeq 15 \text{ sec} \cdot \left(\frac{L_{\rm iso}}{10^{51} \text{ erg/sec}}\right)^{-1/3} \left(\frac{\theta}{10^{\circ}}\right)^{2/3} \left(\frac{R_*}{5R_\odot}\right)^{2/3} \left(\frac{M_*}{15M_\odot}\right)^{1/3} \quad (6)$$

- Jets (try to) drill their way out of the star;
- Some collapsars (or maybe all) harbor a jet;
- Not all these jets are able to break out ($t_{\rm e} < t_{\rm bo}$);