INAF - Osservatorio Astronomico di Padova

INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

MUR Ministero dell'Università e della Ricerca

Image Credit: NASA / SkyWorks Digital

On the outflows driven by choked jets in stellar envelopes

Matteo Pais (INAF-OAPD)

in collaboration with Tsvi Piran[1], Ehud Nakar[2]
[1] HUJI, [2] Tel Aviv University (TAU)

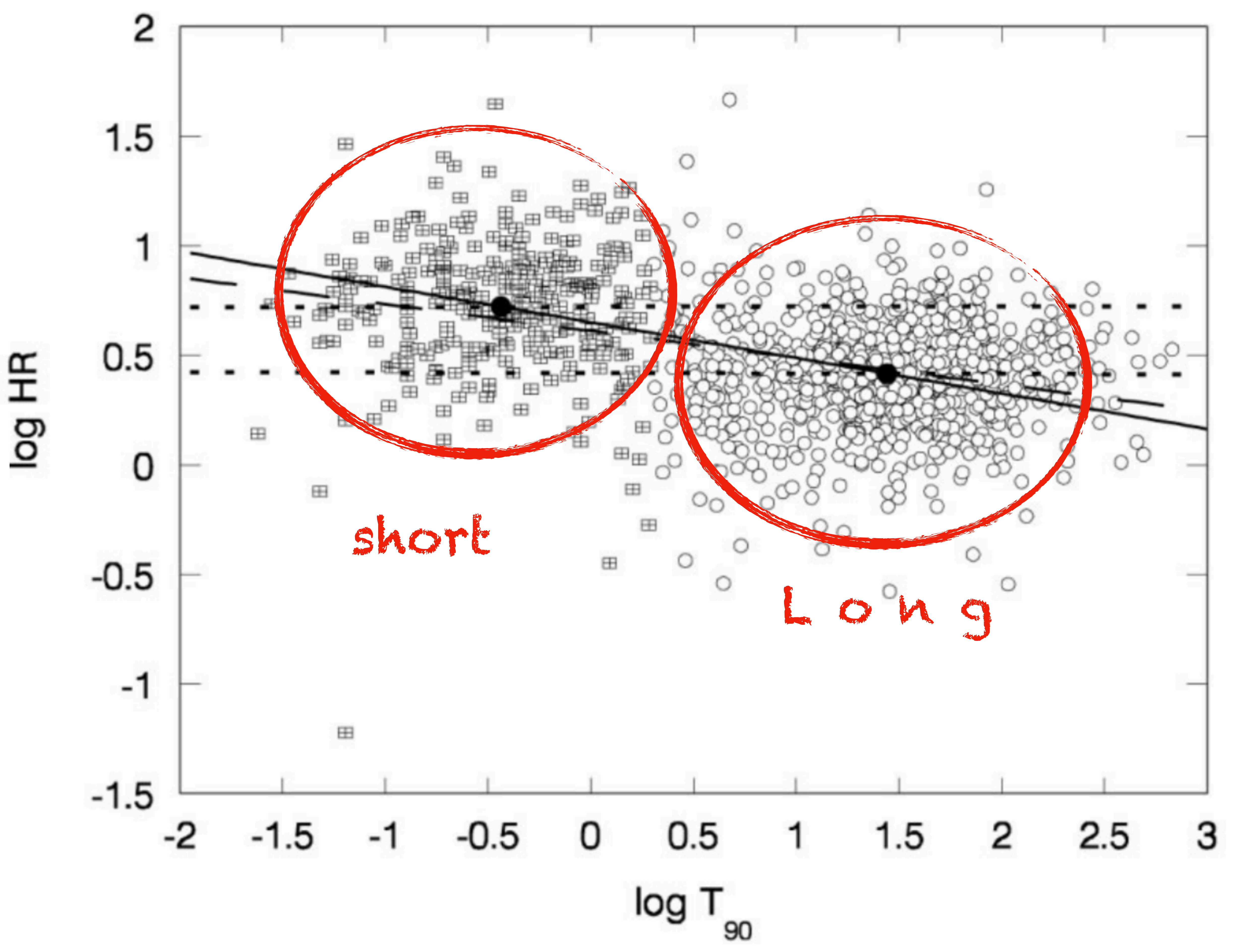
An Extraordinary Journey Into The Transient Sky

Padova, April 2, 2025

Supported by the European Union under NextGenerationEU, via the PRIN 2022 Project “EMERGE: Neutron star mergers and the origin of short gamma-ray bursts",
Prot. n. 2022KX2Z3B (CUP C53D23001150006)

Introduction

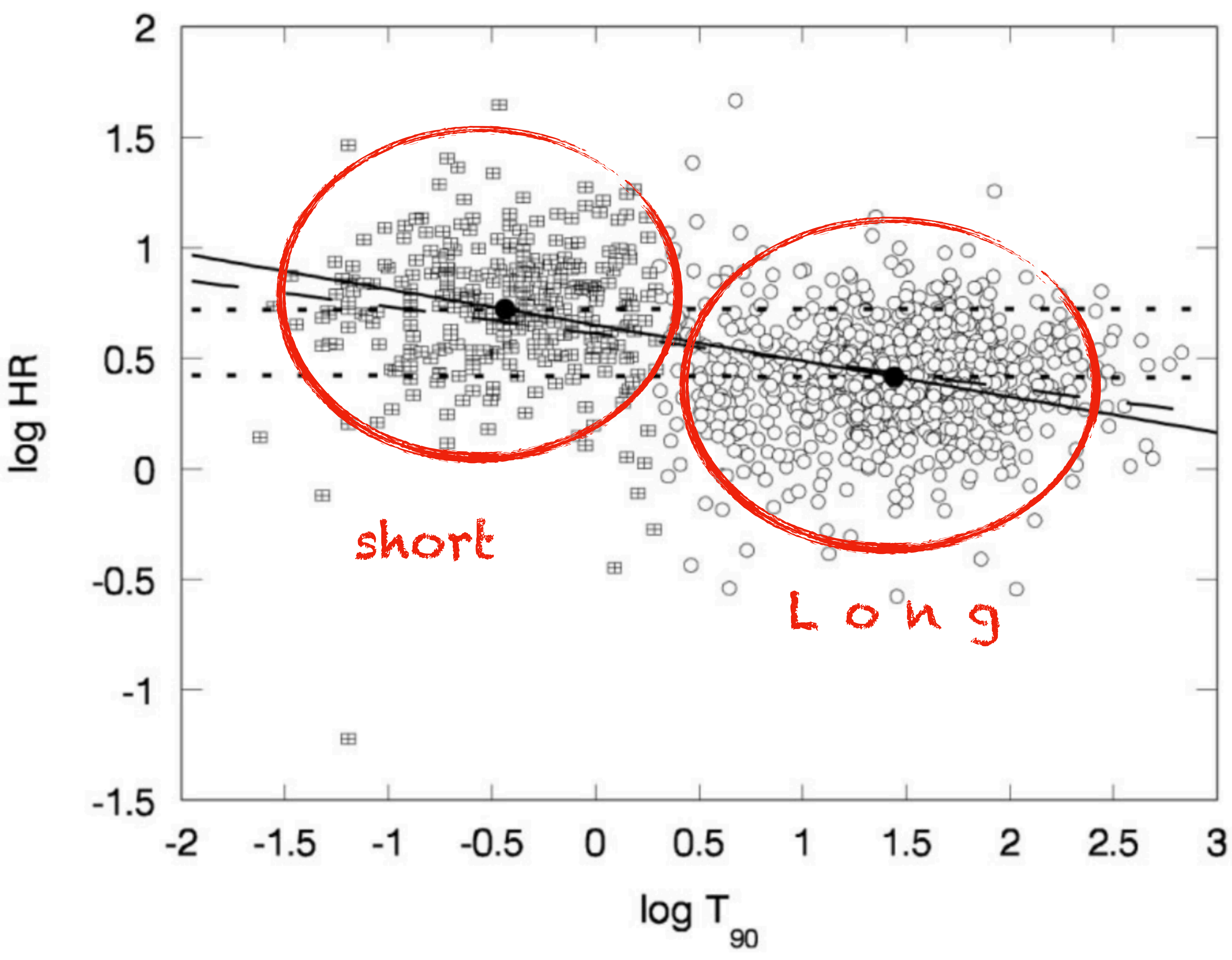
•Gamma-ray bursts (GRBs) are short and intense pulses of soft gamma-rays;



The hardness-duration correlation for BATSE bursts. HR is the ratio of fluence between BATSE channels 3 (100-300 keV) and 2 (50-100 keV), short bursts; s, long bursts; solid line, a regression line for the whole sample; dotted lines, the regressions lines for the short and long samples, respectively. From Qin et al., 2000.

Introduction

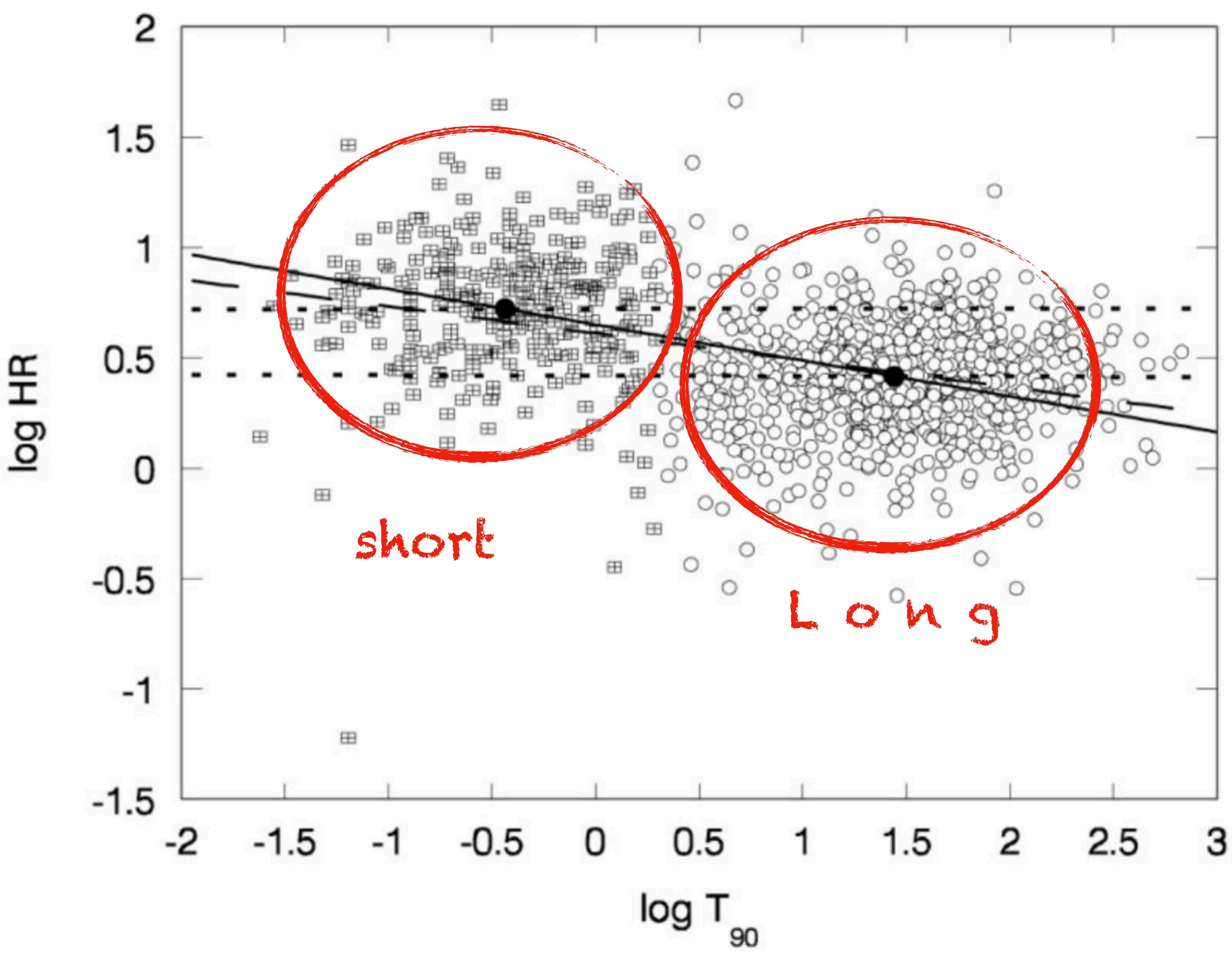
- Gamma-ray bursts (GRBs) are short and intense pulses of soft gamma-rays;
- Duration: $\simeq 10^{-2}$ - 10^{2} s ;
- **long** GRB ($T_{90} \gtrsim 2$ s), **short** GRB ($T_{90} < 2$ s), (Kouveliotou et al., 1993), **however see now GRB 211211A and GRB 230307A** (long GRB with kilonova);
- energetics: $L_{iso} \sim 10^{51-52}$ erg/s, and narrowly beamed;



The hardness-duration correlation for BATSE bursts. HR is the ratio of fluence between BATSE channels 3 (100-300 keV) and 2 (50-100 keV), short bursts; s, long bursts; solid line, a regression line for the whole sample; dotted lines, the regressions lines for the short and long samples, respectively. From Qin et al., 2000.

Introduction

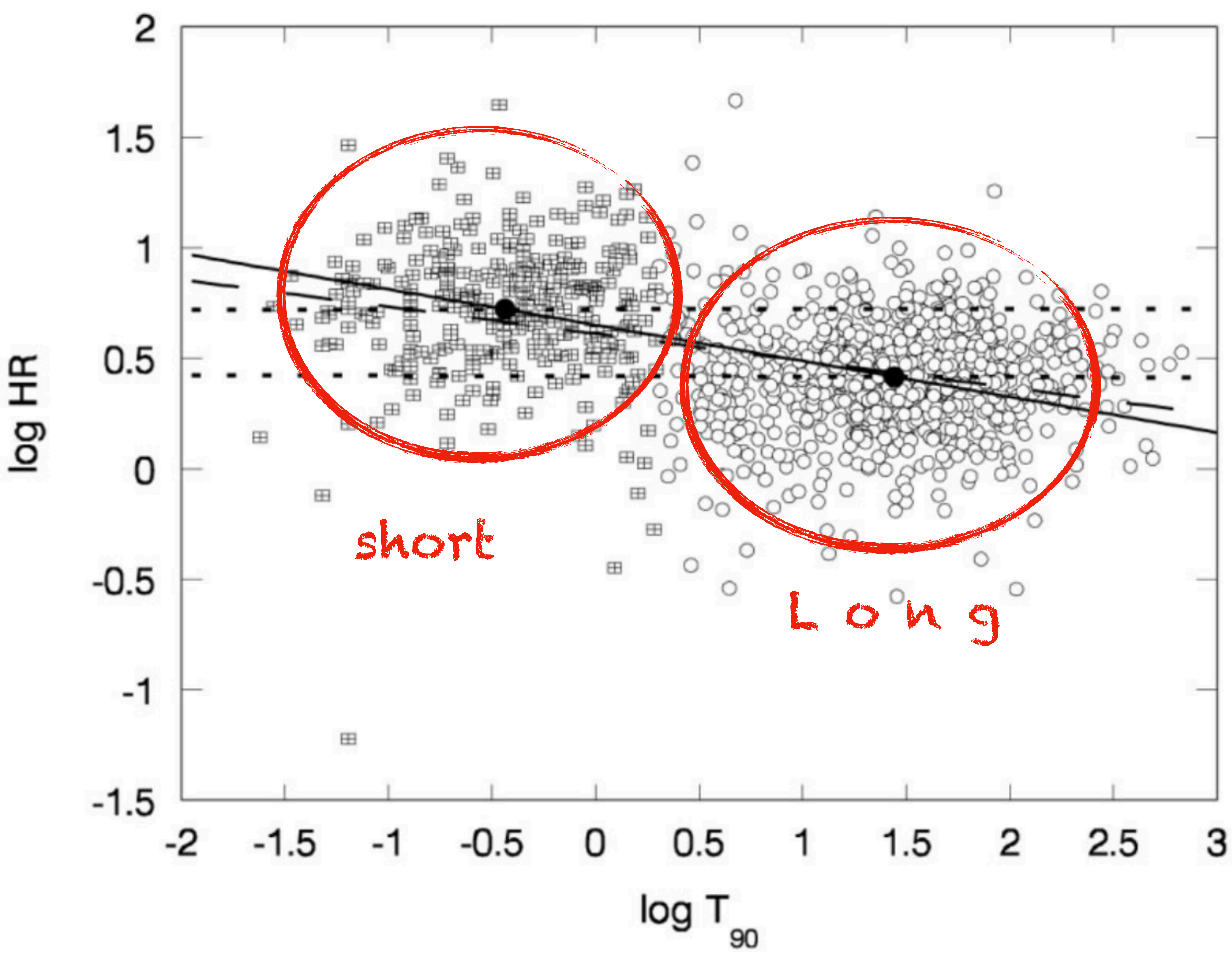
- Gamma-ray bursts (GRBs) are short and intense pulses of soft gamma-rays;
- Duration: $\simeq 10^{-2}$ - 10^{2} s ;
- **long** GRB ($T_{90} \gtrsim 2$ s), **short** GRB ($T_{90} < 2$ s), (Kouveliotou et al., 1993), **however see now GRB 211211A and GRB 230307A** (long GRB with kilonova);
- energetics: $L_{iso} \sim 10^{51-52}$ erg/s, and narrowly beamed;
- Associated to a catastrophic event: **death of star** (Paczynski, '98), **BH mergers** (Paczynski, '91), BNS mergers (Eichler et al., 1989), TDEs...;
- **Collapsar model**: core collapse + bipolar jet driven by a central engine (compact object) (MacFadyen & Woosley 1999; MacFadyen et al. 2001);



The hardness-duration correlation for BATSE bursts. HR is the ratio of fluence between BATSE channels 3 (100-300 keV) and 2 (50-100 keV), short bursts; s, long bursts; solid line, a regression line for the whole sample; dotted lines, the regressions lines for the short and long samples, respectively. From Qin et al., 2000.

Introduction

- Gamma-ray bursts (GRBs) are short and intense pulses of soft gamma-rays;
- Duration: $\simeq 10^{-2}$ - 10^{2} s ;
- **long** GRB ($T_{90} \gtrsim 2$ s), **short** GRB ($T_{90} < 2$ s), (Kouveliotou et al., 1993), **however see now GRB 211211A and GRB 230307A** (long GRB with kilonova);
- energetics: $L_{iso} \sim 10^{51-52}$ erg/s, and narrowly beamed;
- Associated to a catastrophic event: **death of star** (Paczynski, '98), **BH mergers** (Paczynski, '91), BNS mergers (Eichler et al., 1989), TDEs...;
- **Collapsar model**: core collapse + bipolar jet driven by a central engine (compact object) (MacFadyen & Woosley 1999; MacFadyen et al. 2001);
- **What are the signatures of a jet?**



The hardness-duration correlation for BATSE bursts. HR is the ratio of fluence between BATSE channels 3 (100-300 keV) and 2 (50-100 keV), short bursts; s, long bursts; solid line, a regression line for the whole sample; dotted lines, the regressions lines for the short and long samples, respectively. From Qin et al., 2000.

Signatures of high velocity

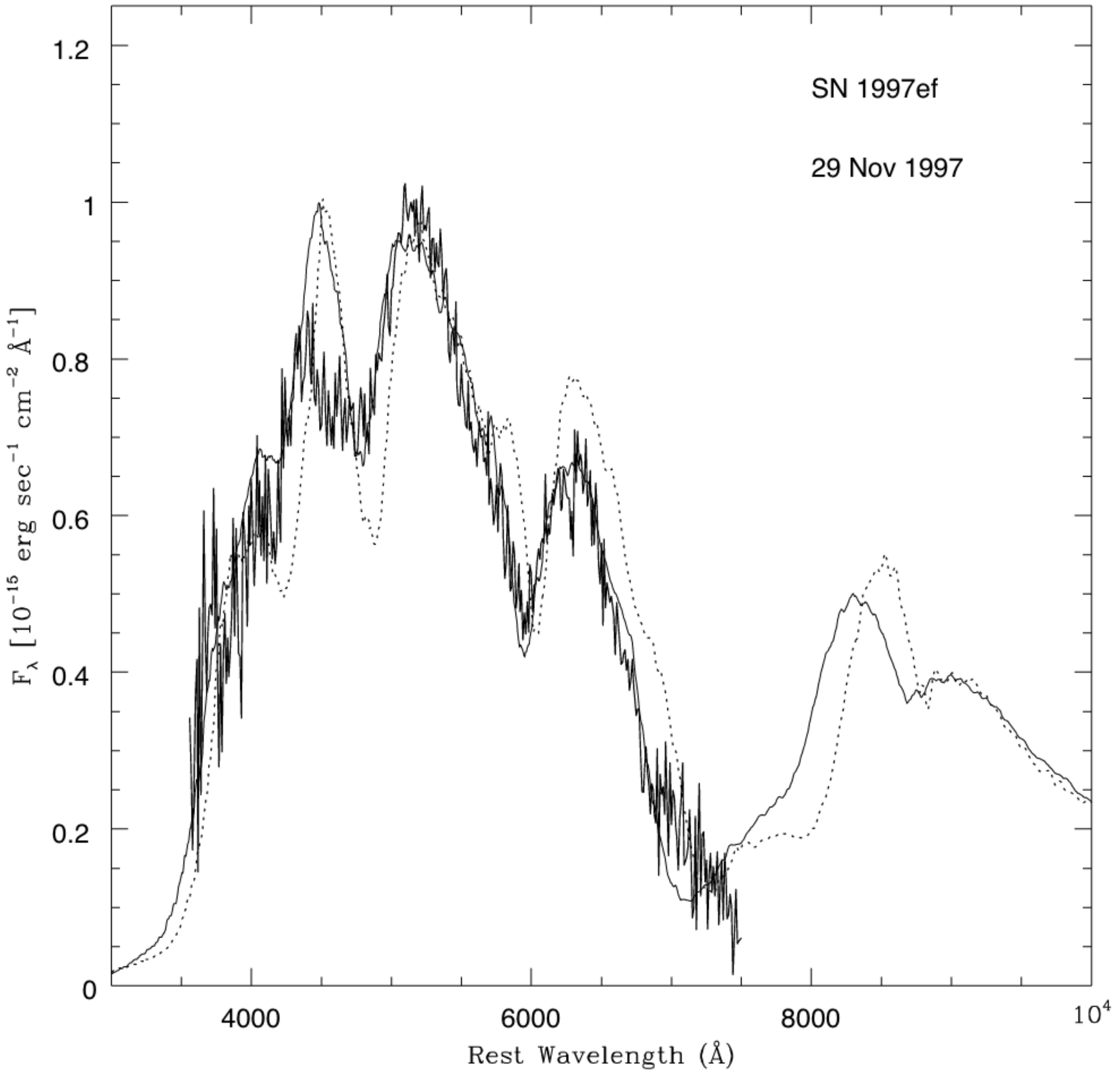


FIG. 1.—Observed, smoothed spectrum of SN 1997ef on 1997 November 29 (*thick line*), compared to two synthetic spectra computed with the CO100 density structure. The fully drawn thin line is a spectrum computed for $t = 9$ days, while the dashed line is a spectrum computed for $t = 11$ days.

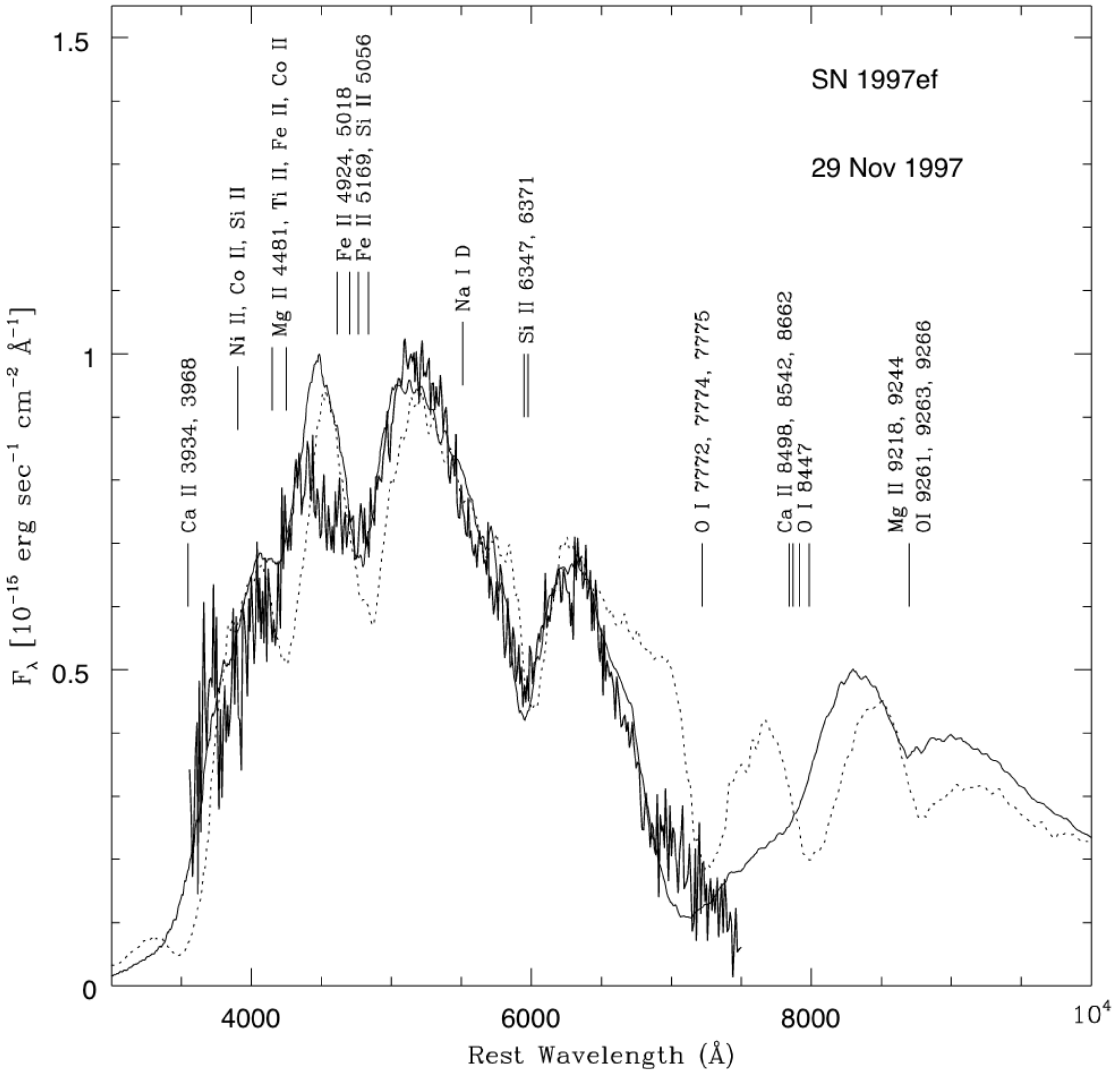


FIG. 2.—Observed, smoothed spectrum of SN 1997ef on 1997 November 29 (*thick line*), compared to two synthetic spectra computed for $t = 9$ days. The dashed line is a spectrum computed with the original model CO100, while the fully drawn thin line is a spectrum computed with the modified outer density described in the text.

from Mazzali et al. (2000)

Signatures of high velocity

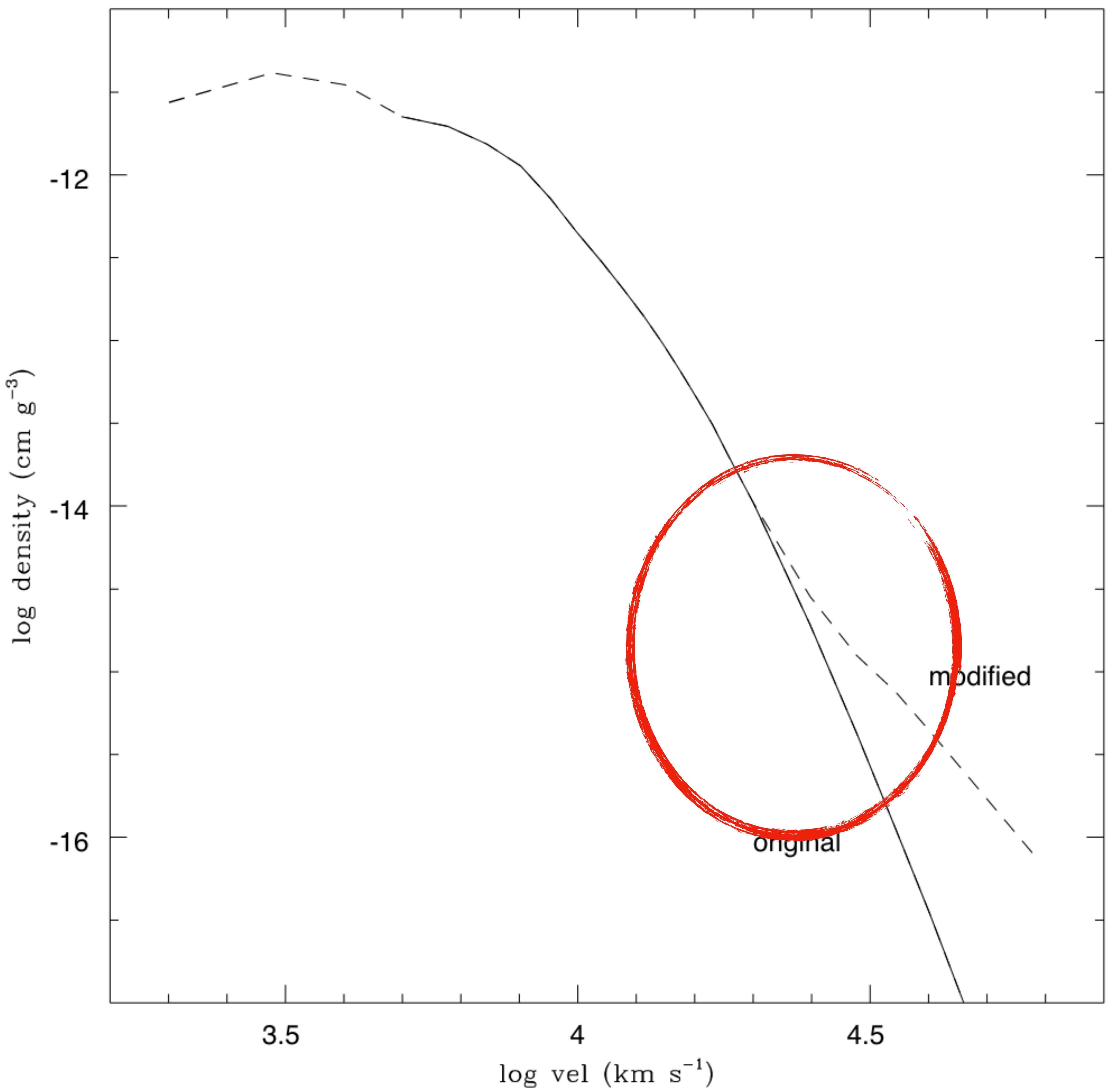
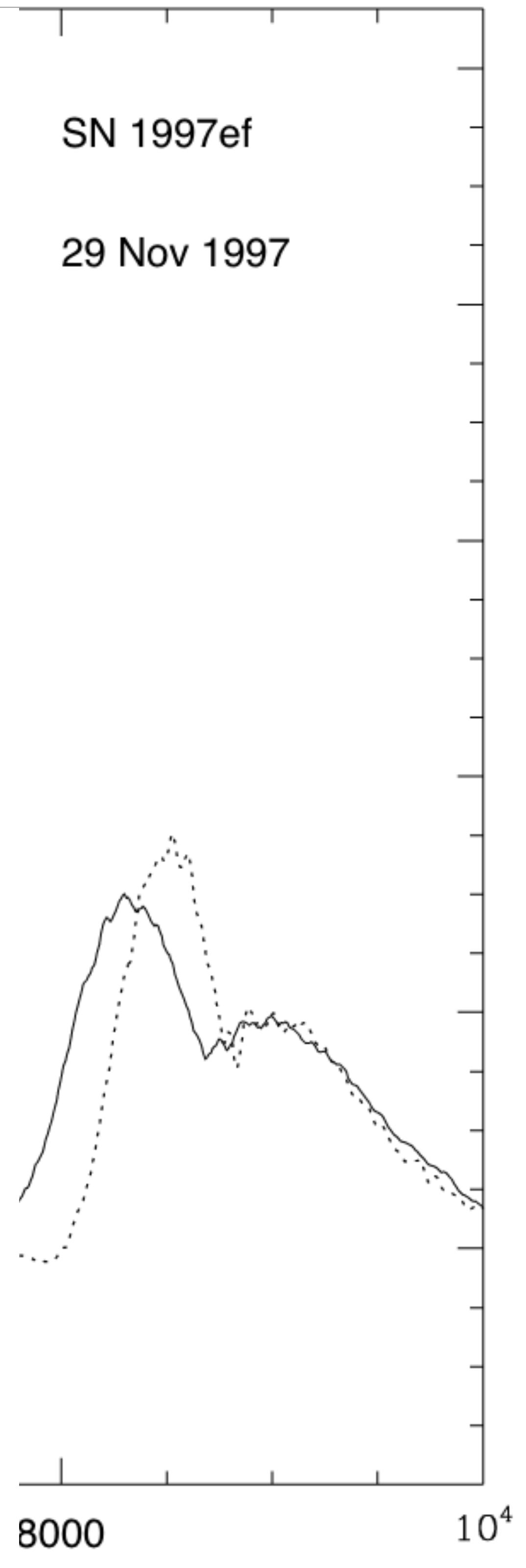


FIG. 8.—Original density structure of the hydrodynamical model CO100 (*solid line*) and the modifications introduced to improve the spectral fits (*dashed line*). The outer part of the modified density structure has a power-law index $n = -4$, while the inner extension has $n = 1$ between $v = 3000$ and $v = 5000$ km s^{-1} and $n = -1$ below $v = 3000$ km s^{-1}.



997ef on 1997 Novem-
pectra computed with
in line is a spectrum
pectrum computed for

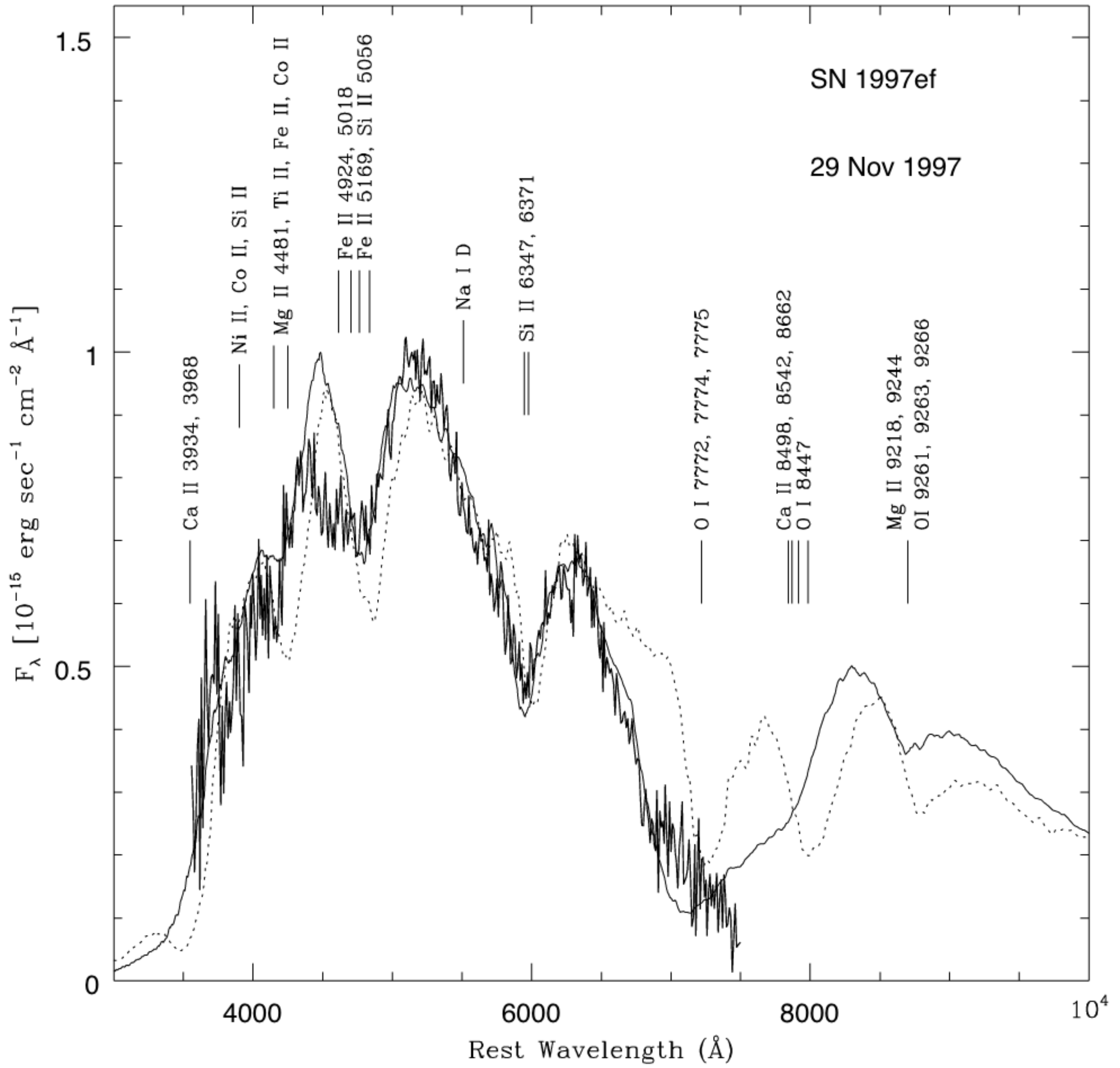


FIG. 2.—Observed, smoothed spectrum of SN 1997ef on 1997 November 29 (*thick line*), compared to two synthetic spectra computed for $t = 9$ days. The dashed line is a spectrum computed with the original model CO100, while the fully drawn thin line is a spectrum computed with the modified outer density described in the text.

from Mazzali et al. (2000)

Signatures of high velocity

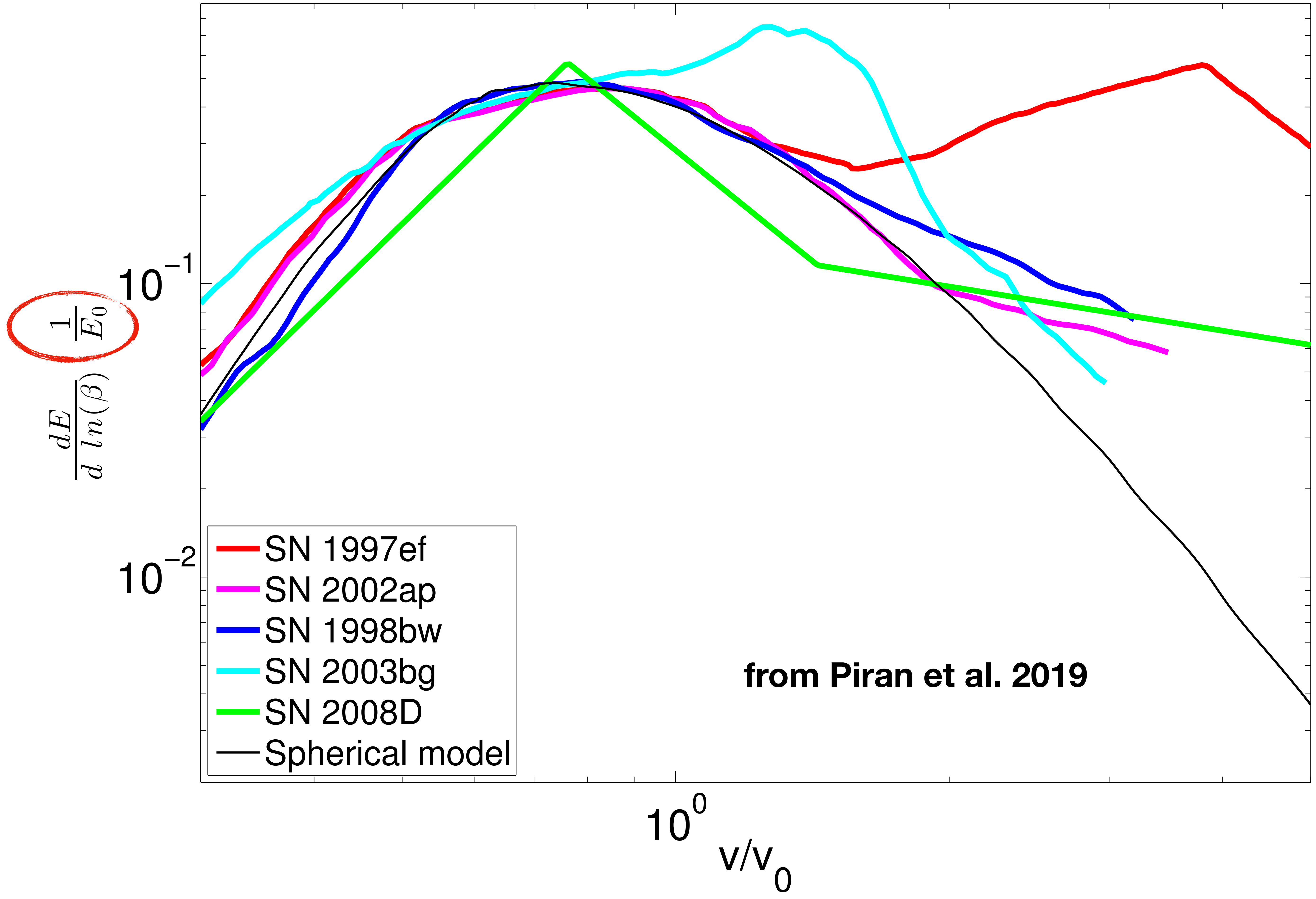


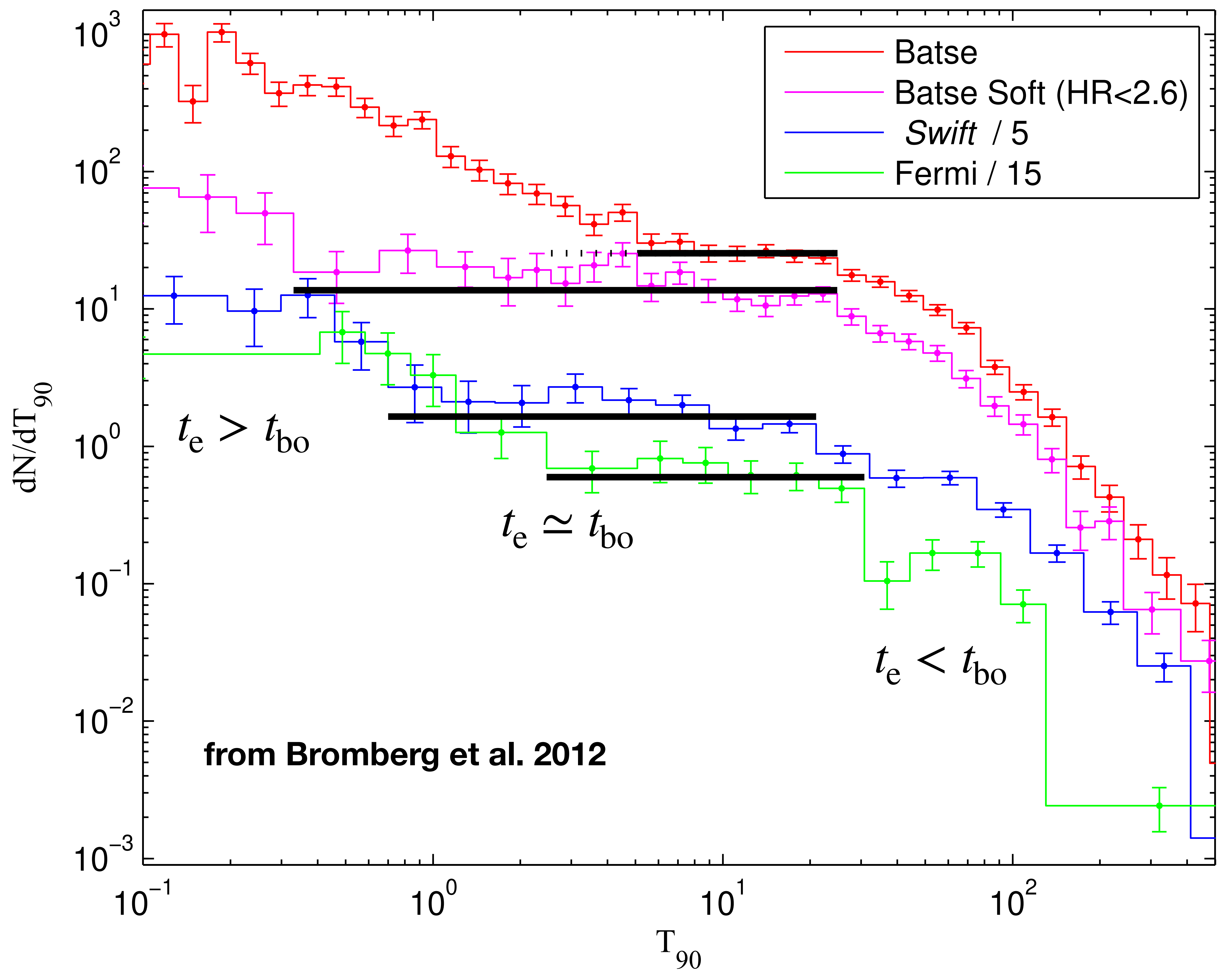
Fig: Energy-velocity distribution as a function of the velocity for various SNe

SN	Type	$E_{\rm tot}$ [a]	$M_{\rm ej}$ [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	⋯	⋯	*ll*GRB980425
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

References. 1. Mazzali et al. (2000) 2. Iwamoto et al. (1998) 3. Mazzali et al. (2002) 4. Mazzali et al. (2009) 5. Mazzali et al. (2008) 6. Ashall et al. (2017).

Scale velocity: $v_0 = \sqrt{\frac{2E_0}{M_{\rm ej}}}$

Distribution of the duration of GRBs

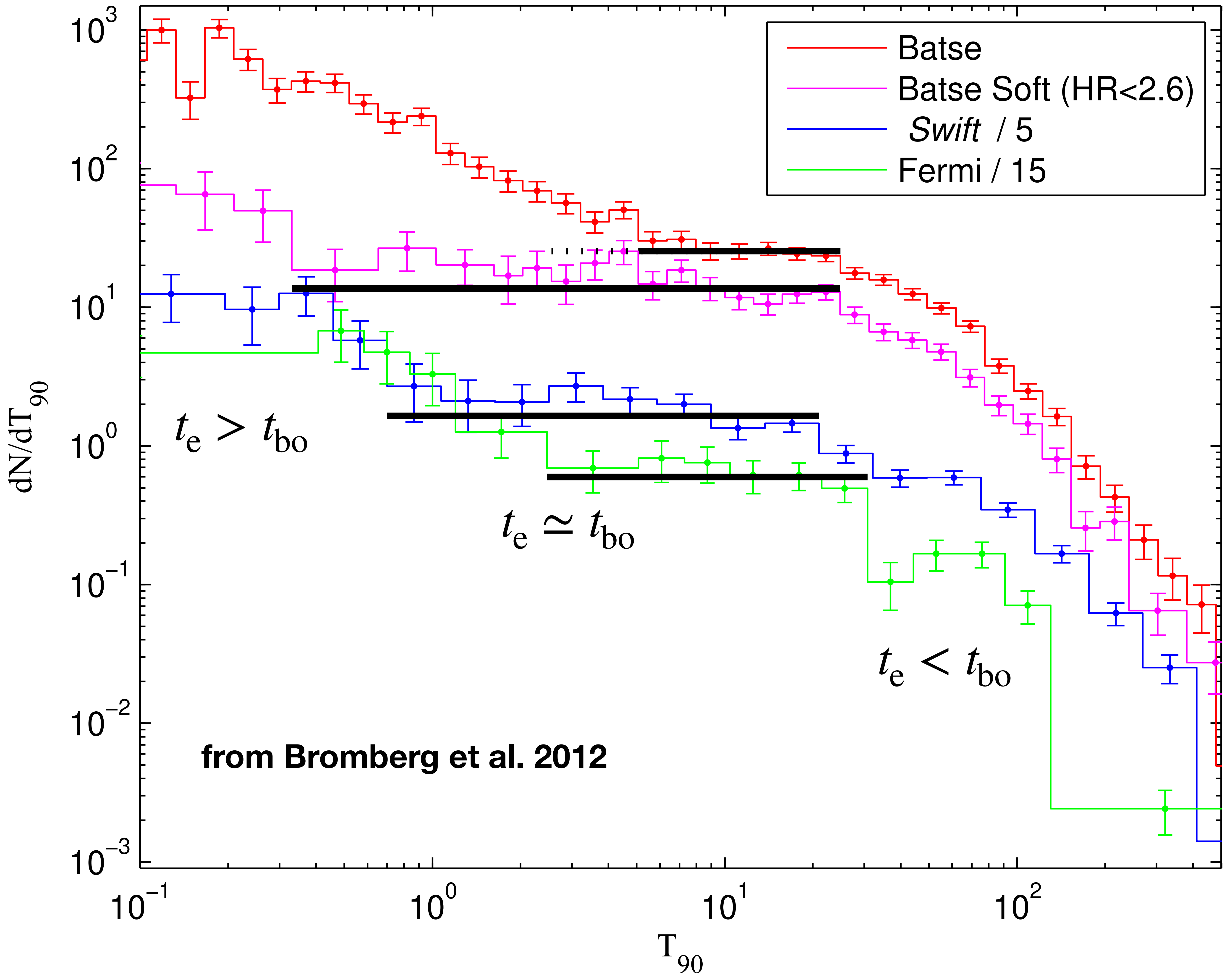


Distribution of GRB events with respect to their T_{90}

Estimate for jet breakout:

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

Distribution of the duration of GRBs



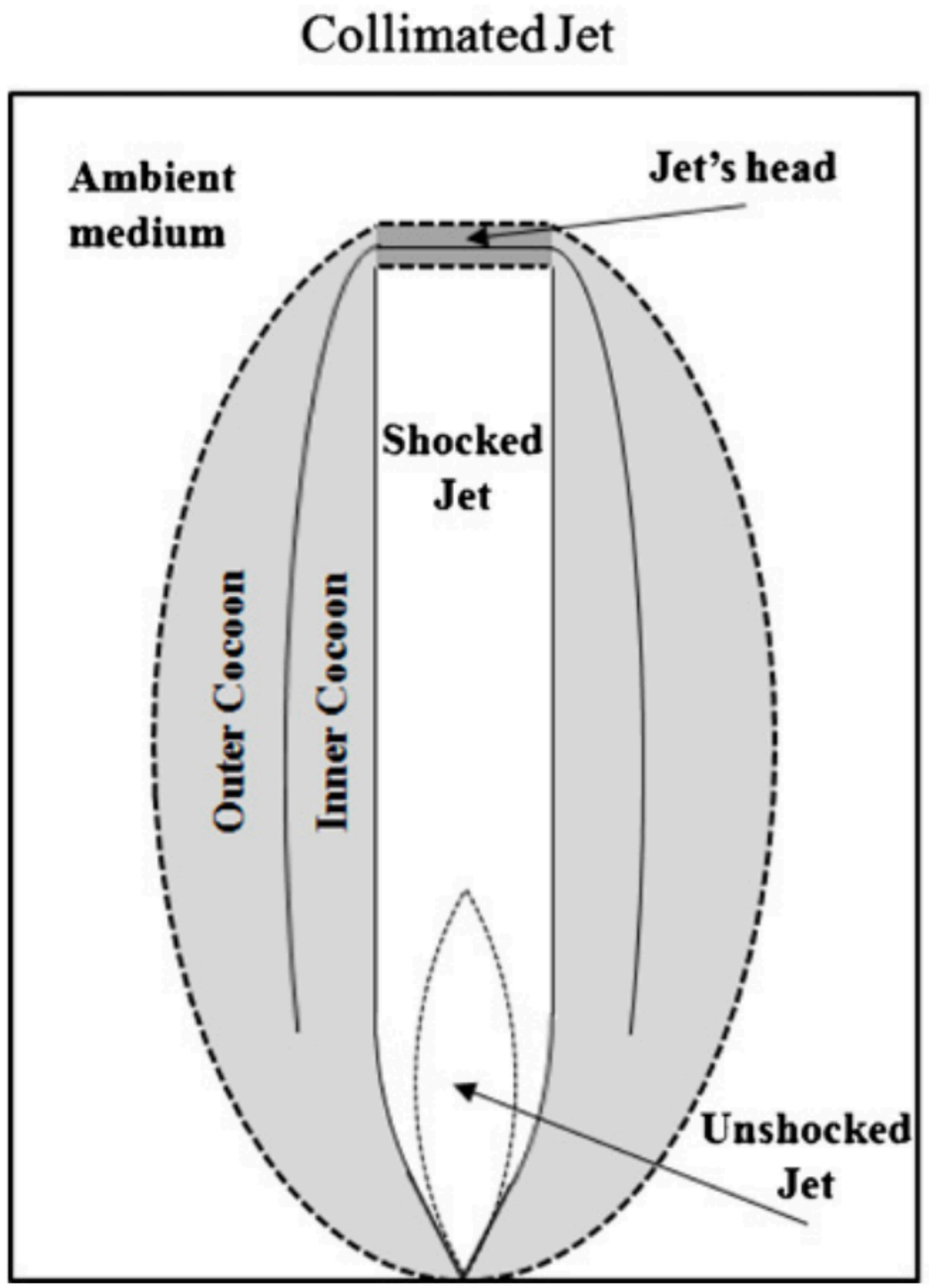
Distribution of GRB events with respect to their T_{90}

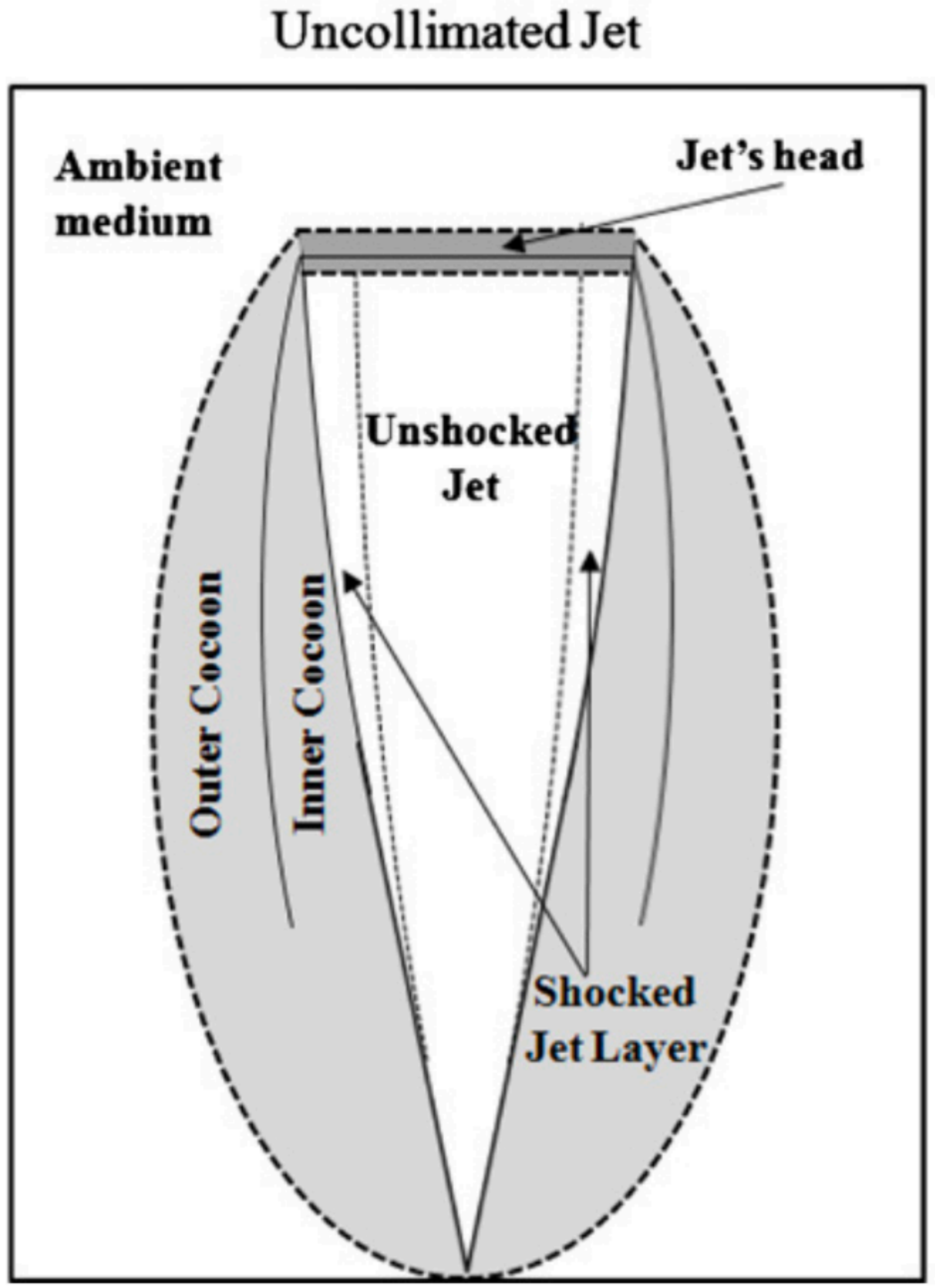
Estimate for jet breakout:

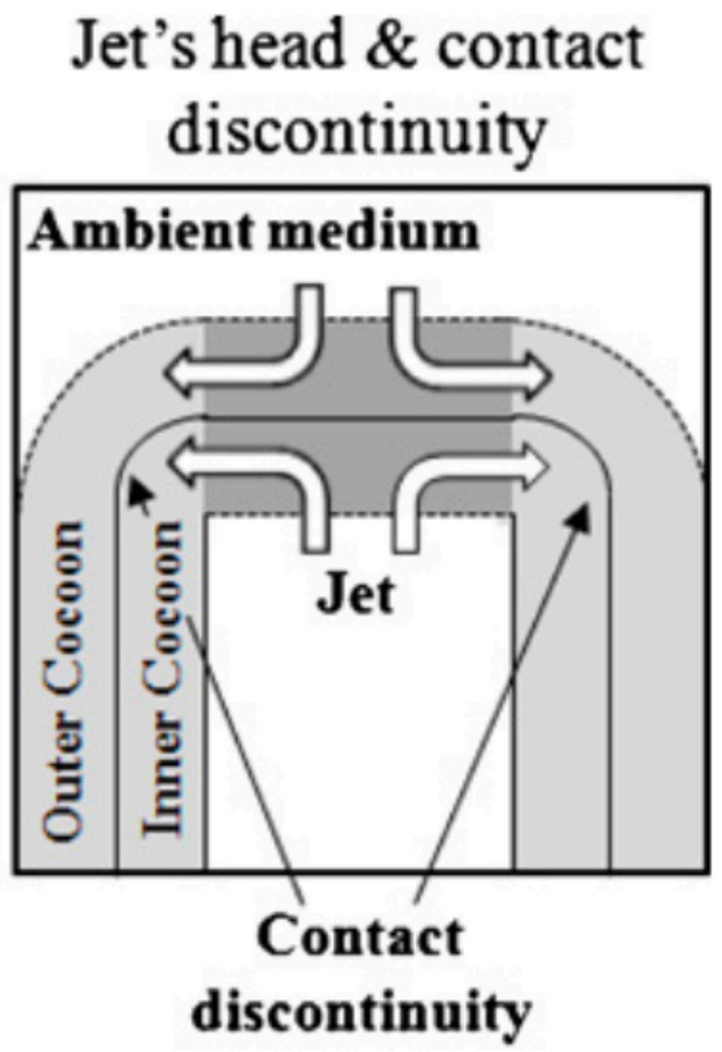
$$t_{bo} \simeq 15 \text{ sec} \left(\frac{L_{iso}}{10^{51} \text{ erg/s}}\right)^{-1/3} \left(\frac{\theta}{10^\circ}\right)^{2/3} \left(\frac{R}{5R_\odot}\right)^{2/3} \left(\frac{M_*}{15M_\odot}\right)^{1/3}$$

- Jets (try to) drill their way out of the star;
- Some collapsars (or a large fraction) harbor a jet, ($t_\gamma \simeq t_{bo} - t_e$) ;
- Not all these jets might be able to break out ($t_e < t_{bo}$)

Jet - matter interaction







from Bromberg et al. (2011)

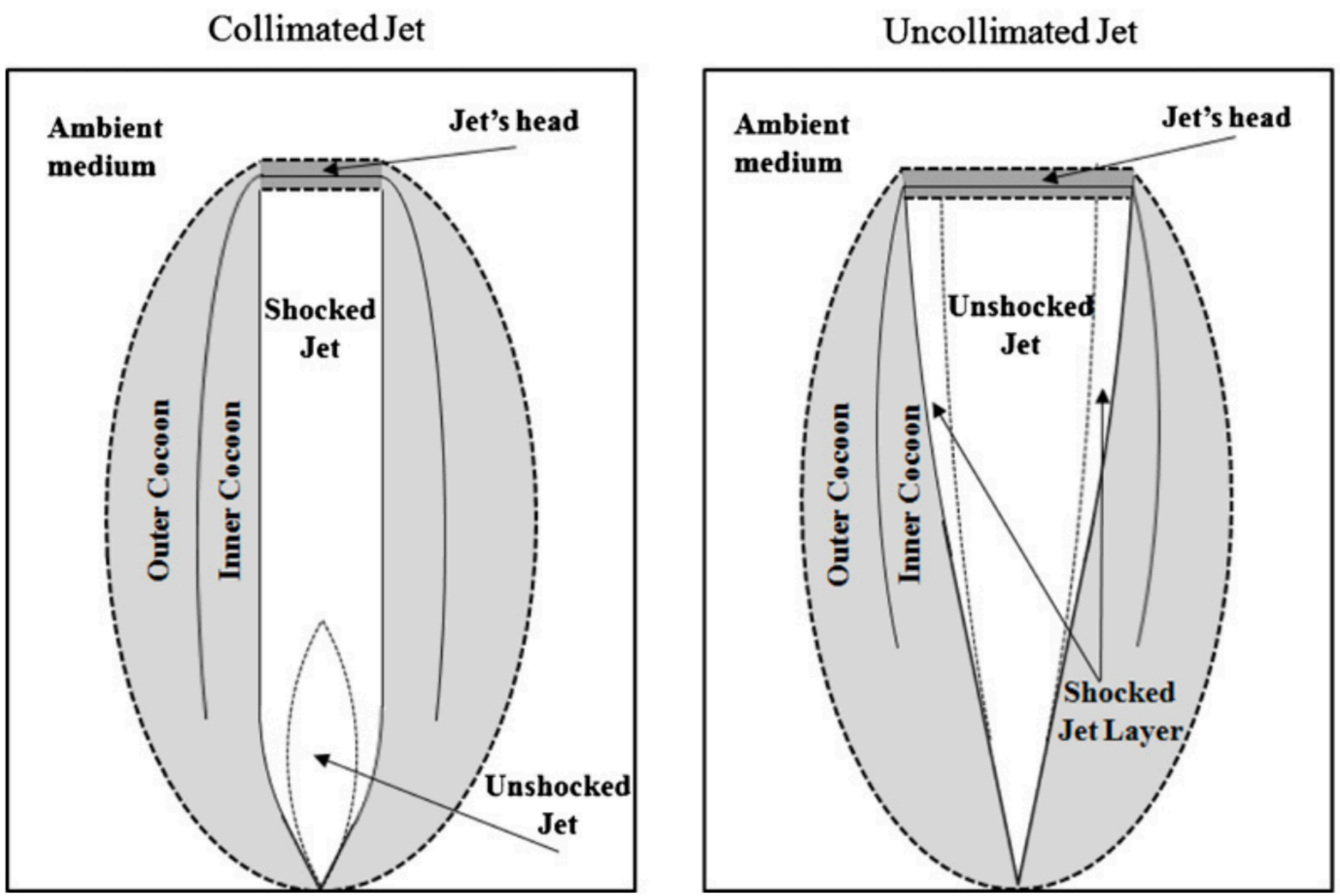
from Hamidani & Ioka (2021)

Ram pressure balance:

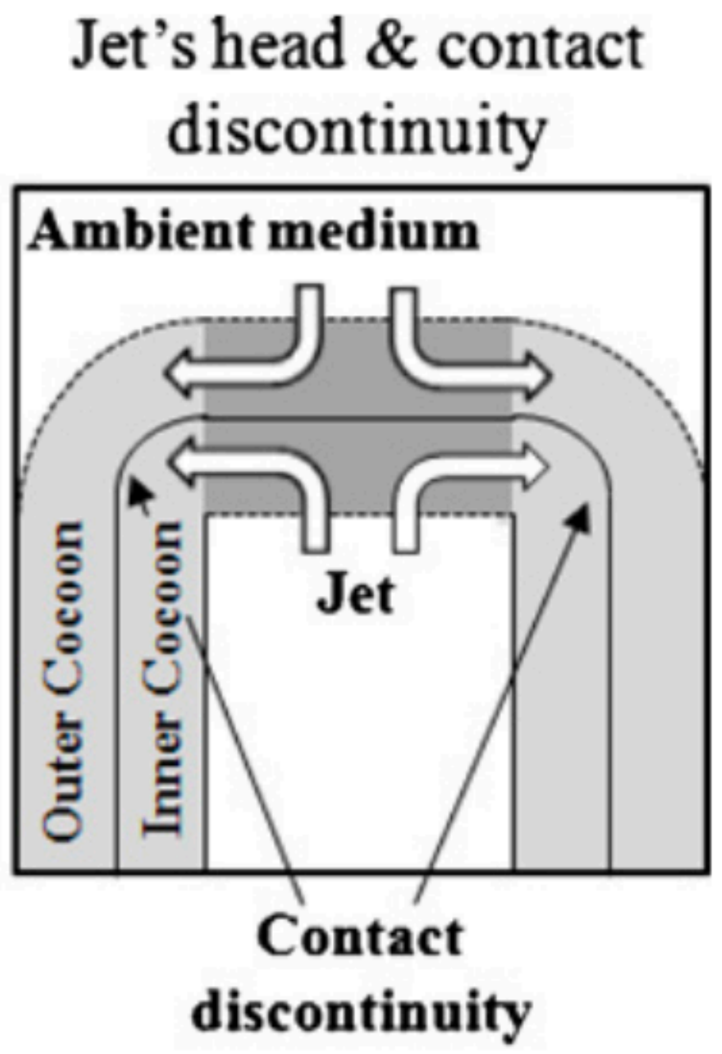
$$\rho_j h_j \Gamma_j^2 \Gamma_h^2 (\beta_j - \beta_h)^2 + P_j = \rho_a h_a \Gamma_a^2 \Gamma_h^2 (\beta_h - \beta_a)^2 + P_a$$

from Bromberg et al. (2011)

Jet - matter interaction



from Bromberg et al. (2011)



from Bromberg et al. (2011)

from Hamidani & Ioka (2021)

Ram pressure balance:

$$\rho_{\rm j} h_{\rm j} \Gamma_{\rm j}^2 \Gamma_{\rm h}^2 (\beta_{\rm j} - \beta_{\rm h})^2 + P_{\rm j} = \rho_a h_a \Gamma_a^2 \Gamma_{\rm h}^2 (\beta_{\rm h} - \beta_a)^2 + P_a$$

Jet head dynamics:

$$\beta_{\rm h} = \frac{\beta_{\rm j} - \beta_a}{1 + \tilde{L}^{-1/2}} + \beta_a$$

Jet collimation parameter

$$\tilde{L} \equiv \frac{\rho_{\rm j} h_{\rm j} \Gamma_{\rm j}^2}{\rho_a h_a \Gamma_a^2} \simeq \frac{L_{\rm j}}{\Sigma_{\rm j} \rho_a c^3 \Gamma_a^2}$$

Height of the jet after end of injection:

$$z_{\rm choke} = \int_0^{t_{\rm choke}} \beta_{\rm h} c \, {\rm d}t \simeq \beta_{\rm h} c t_{\rm choke} = \frac{\beta_{\rm h} c}{1 - \beta_{\rm h}} t_{\rm e}$$

Simulation setup

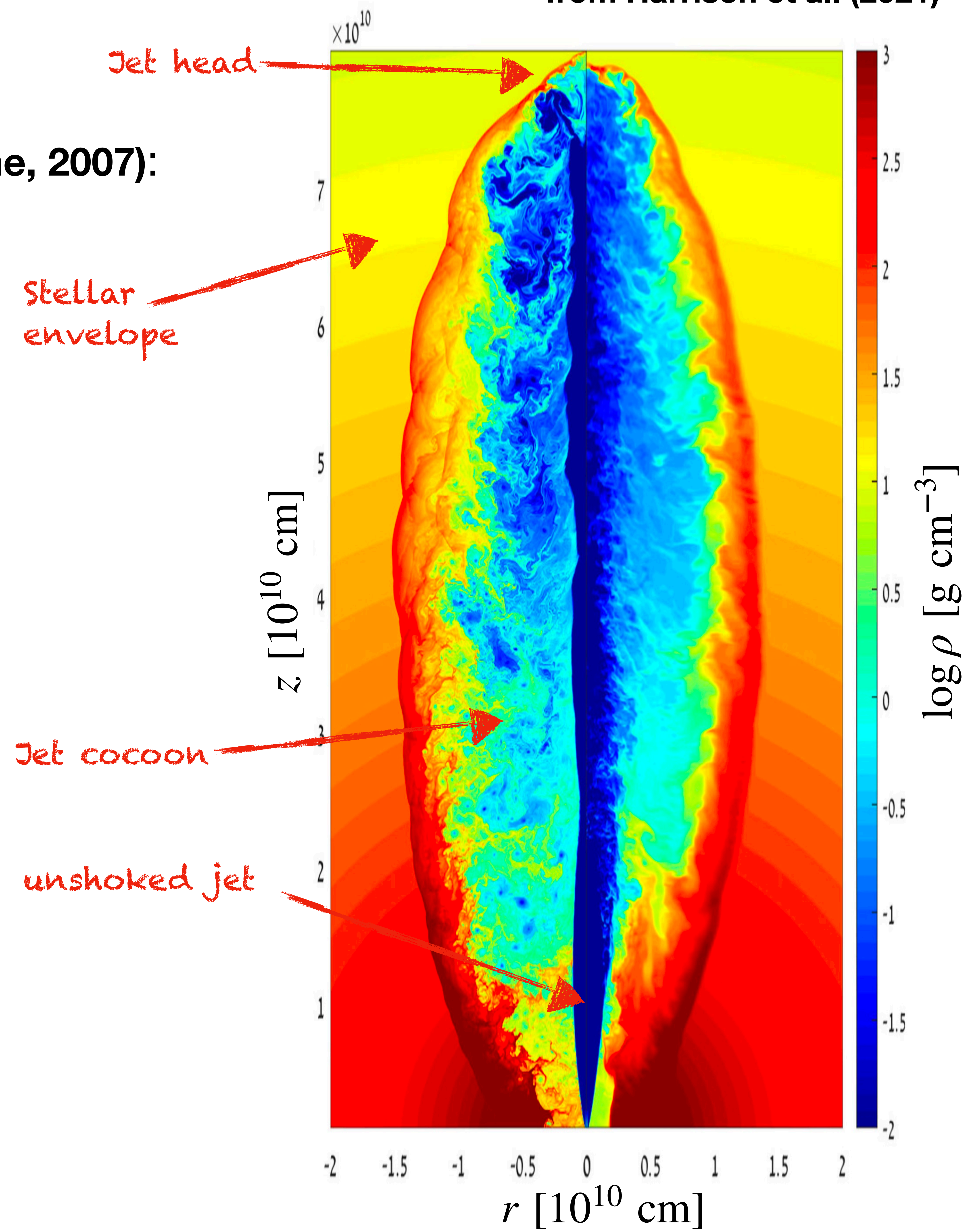
from Harrison et al. (2021)

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

- Jet injected through a narrow nozzle w/ $\Sigma_\mathrm{j} = \pi r_\mathrm{j}^2$
- Relativistic energy flux $L_\mathrm{j} = \int_\Sigma T^{0z}\,\mathrm{d}\Sigma_{0z} = \rho_\mathrm{j} h_\mathrm{j} c^2 \Gamma_\mathrm{j}^2 \beta_\mathrm{j} c$

$$\rho_\mathrm{j} = \frac{L_\mathrm{j}}{h_\mathrm{j} c^3 \Gamma_\mathrm{j}^2 \beta_\mathrm{j}} \qquad P_\mathrm{j} = \frac{h_\mathrm{j} - 1}{4} \rho_\mathrm{j} c^2$$

with $\Gamma_{0,\mathrm{j}} \simeq 1/(1.4\theta_\mathrm{j})$, $h_\mathrm{j} = 100$, $E_0 = 10^{51}$ erg ;



Simulation setup

from Harrison et al. (2021)

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

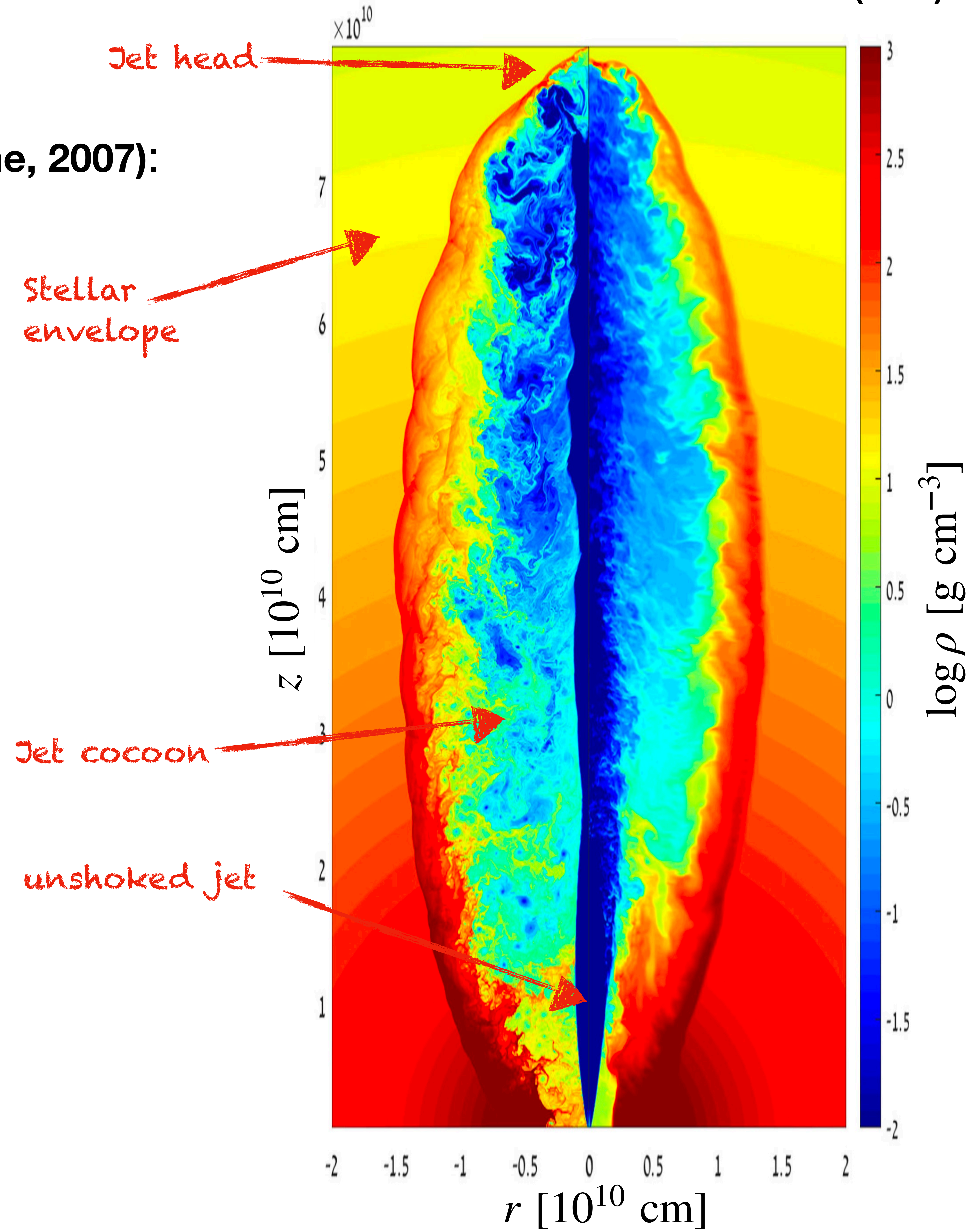
- Jet injected through a narrow nozzle w/ $\Sigma_j = \pi r_j^2$
- Relativistic energy flux $L_j = \int_\Sigma T^{0z}\, d\Sigma_{0z} = \rho_j h_j c^2 \Gamma_j^2 \beta_j c$

$$\rho_j = \frac{L_j}{h_j c^3 \Gamma_j^2 \beta_j} \qquad P_j = \frac{h_j - 1}{4} \rho_j c^2$$

with $\Gamma_{0,j} \simeq 1/(1.4\theta_j)$, $h_j = 100$, $E_0 = 10^{51}$ erg ;

- density profile for the stellar atmosphere:

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



Simulation setup

from Harrison et al. (2021)

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

- Jet injected through a narrow nozzle w/ $\Sigma_j = \pi r_j^2$
- Relativistic energy flux $L_j = \int_\Sigma T^{0z}\, d\Sigma_{0z} = \rho_j h_j c^2 \Gamma_j^2 \beta_j c$

$$\rho_j = \frac{L_j}{h_j c^3 \Gamma_j^2 \beta_j} \qquad P_j = \frac{h_j - 1}{4} \rho_j c^2$$

with $\Gamma_{0,j} \simeq 1/(1.4\theta_j)$, $h_j = 100$, $E_0 = 10^{51}$ erg ;

- density profile for the stellar atmosphere:

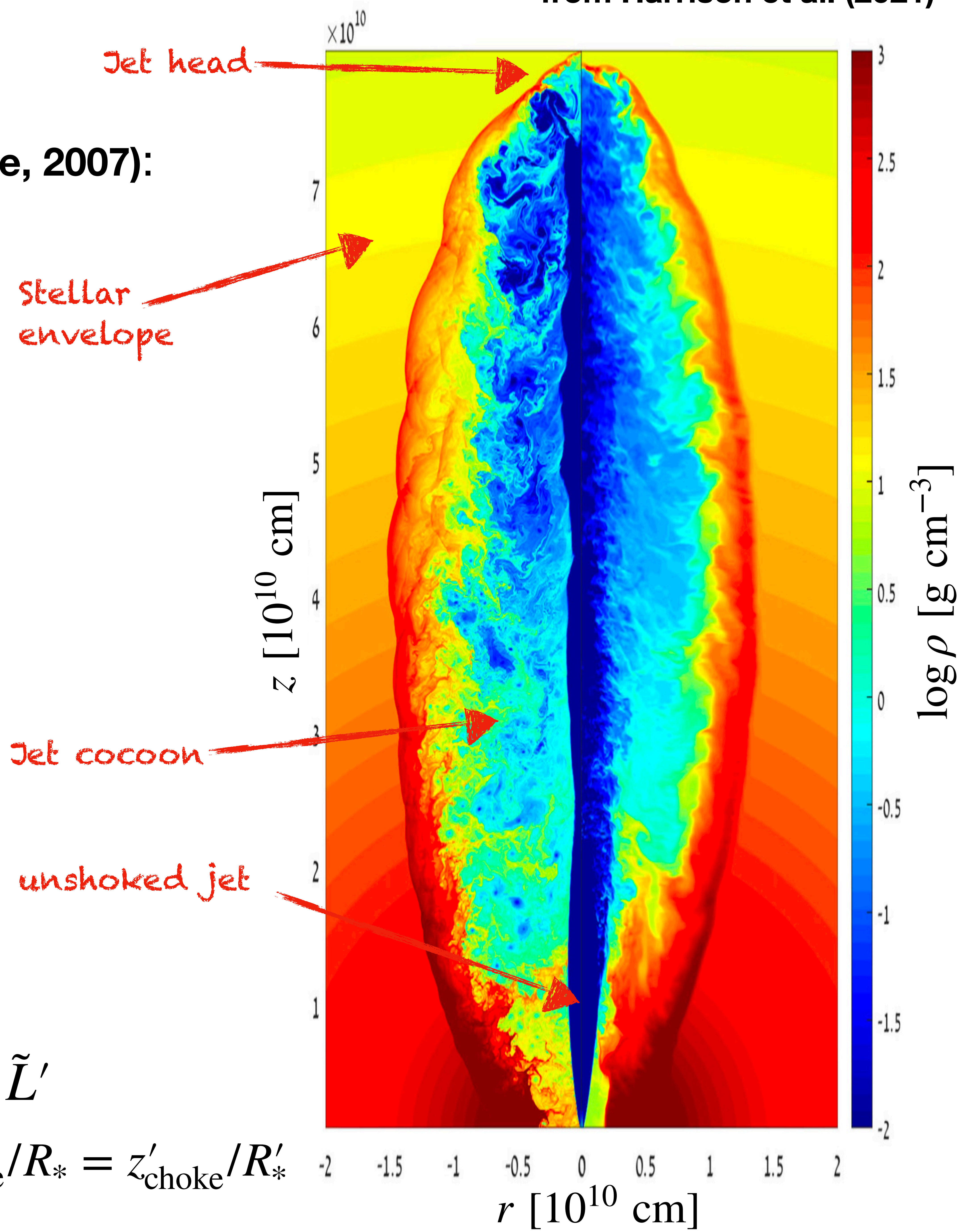
$$\rho(R) = \begin{cases} \rho_* \left(\frac{R_*}{R} - 1 \right)^2 + \rho_0, & \text{for } R \leq R_* \, , \\ \rho_0, & \text{for } R > R_* \, . \end{cases}$$

- We can scale our system via following transformations:

$$R_* = \lambda R'_* \qquad E_0 = \eta E'_0$$

$$\Longrightarrow \quad t_e = \lambda t'_e \qquad \rho_* = \eta \lambda^{-3} \rho'_*$$

$$\Longrightarrow \quad \tilde{L} = \tilde{L}' \qquad z_{\rm choke}/R_* = z'_{\rm choke}/R'_*$$



Choked jets simulations

- Injection phase lasting for ~ few s (1 s in this picture);

from Pais, Piran, Nakar (2023)

Choked jets simulations

- Injection phase lasting for ~ few s (1 s in this picture);
- Jet choking (few tenths of second);

from Pais, Piran, Nakar (2023)

Choked jets simulations

- Injection phase lasting for ~ few s (1 s in this picture);
- Jet choking (few tenths of second);
- Cocoon Expansion and breakout;

from Pais, Piran, Nakar (2023)

Choked jets simulations

- Injection phase lasting for ~ few s (1 s in this picture);
- Jet choking (few tenths of second);
- Cocoon Expansion and breakout;
- Breakout and star blanketing.

from Pais, Piran, Nakar (2023)

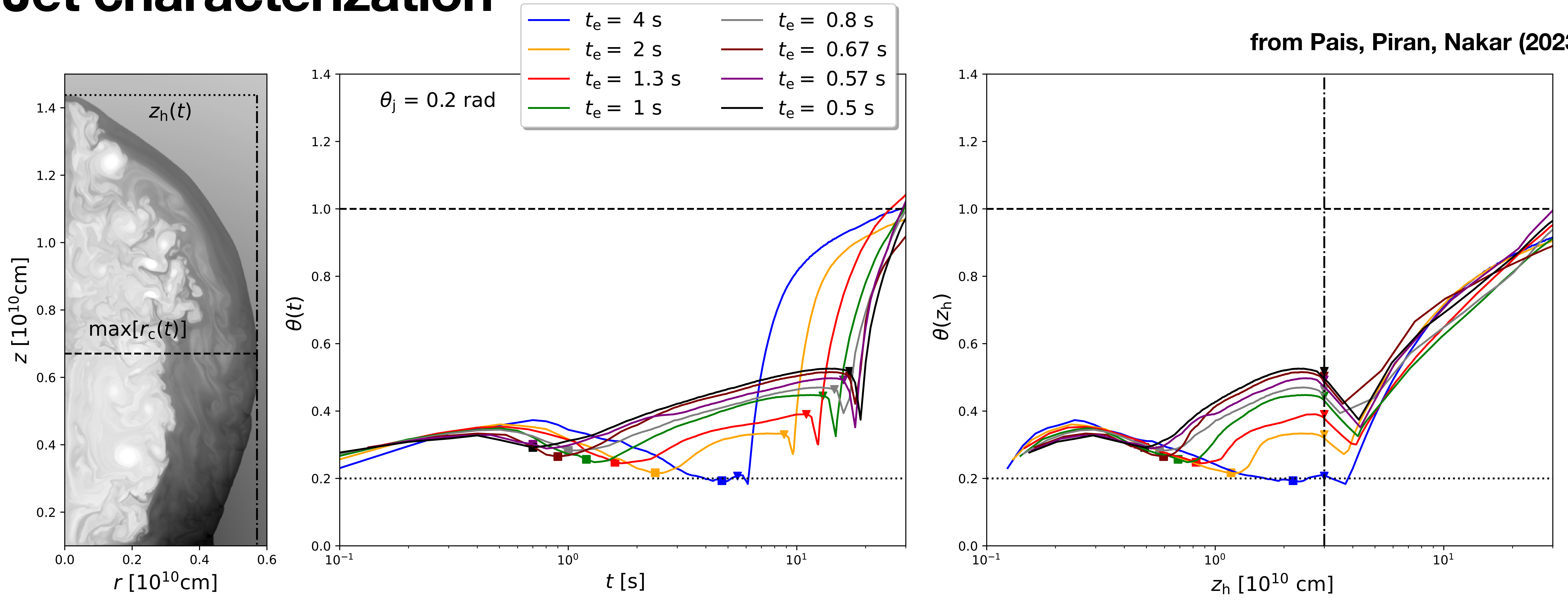
Successful jets simulations

- Injection phase lasting for ~ few s (1 s in this picture);
- Injection continues or stops before jet is $\simeq (2/3)R_*$
- Breakout;
- Jet material spreading sideways;

from Pais, Piran, Nakar (2023)

Jet characterization

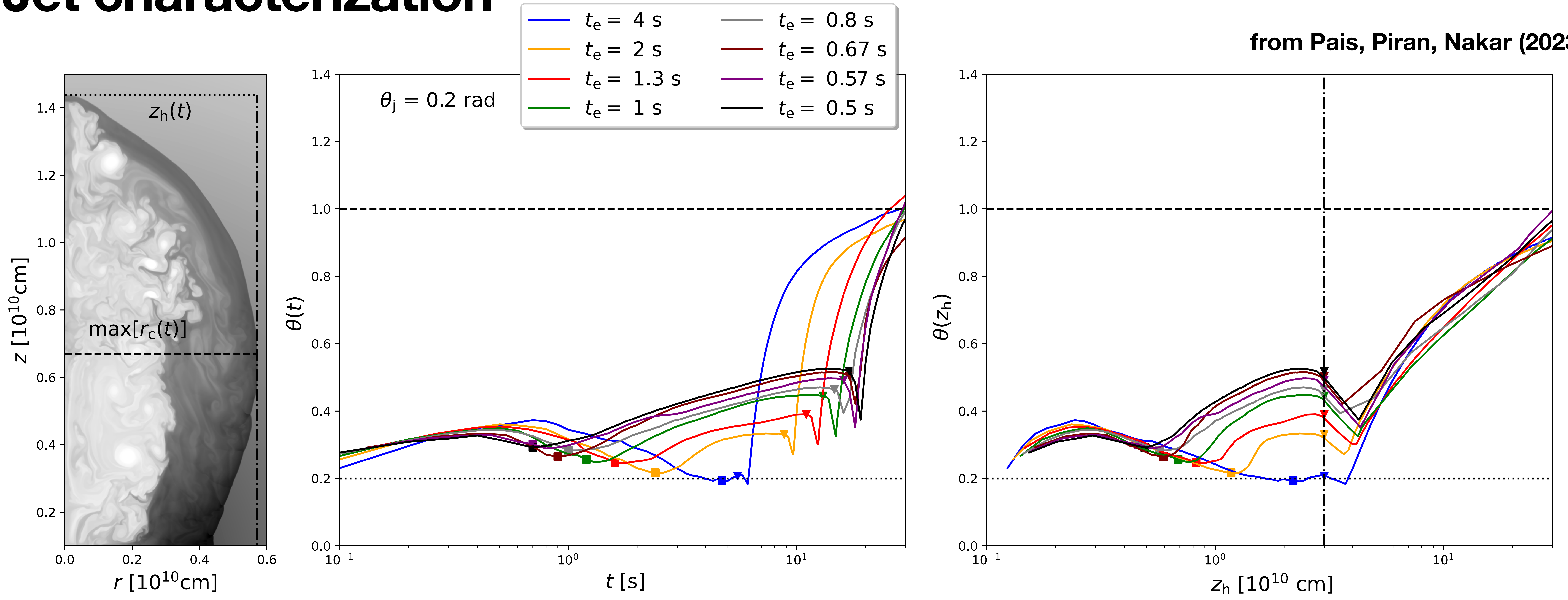
from Pais, Piran, Nakar (2023)



- Does the choking height mirror the energy-velocity distribution?

Jet characterization

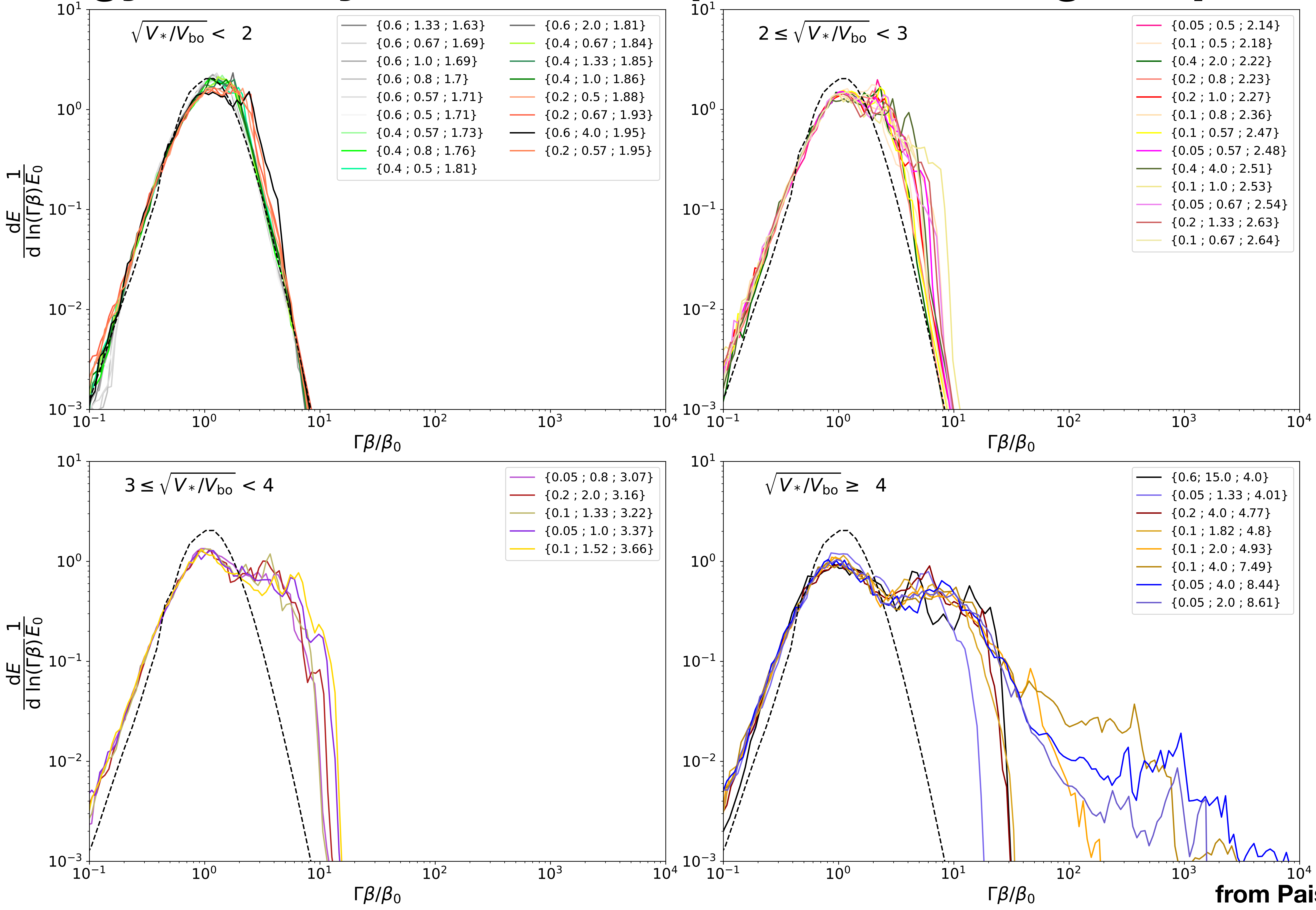
from Pais, Piran, Nakar (2023)



- Does the choking height mirror the energy-velocity distribution?
- Good correlation with jet-cocoon volume vs total volume:

$$\beta_0 = \sqrt{2E/Mc^2} \qquad \langle \rho_* \rangle \simeq \langle \rho_{\rm cocoon} \rangle \quad \Longrightarrow \quad \boxed{\beta_{\rm bo} \simeq \beta_0 \sqrt{\frac{V_*}{V_{\rm bo}}}}$$

Energy-velocity distribution (at the homologous phase)

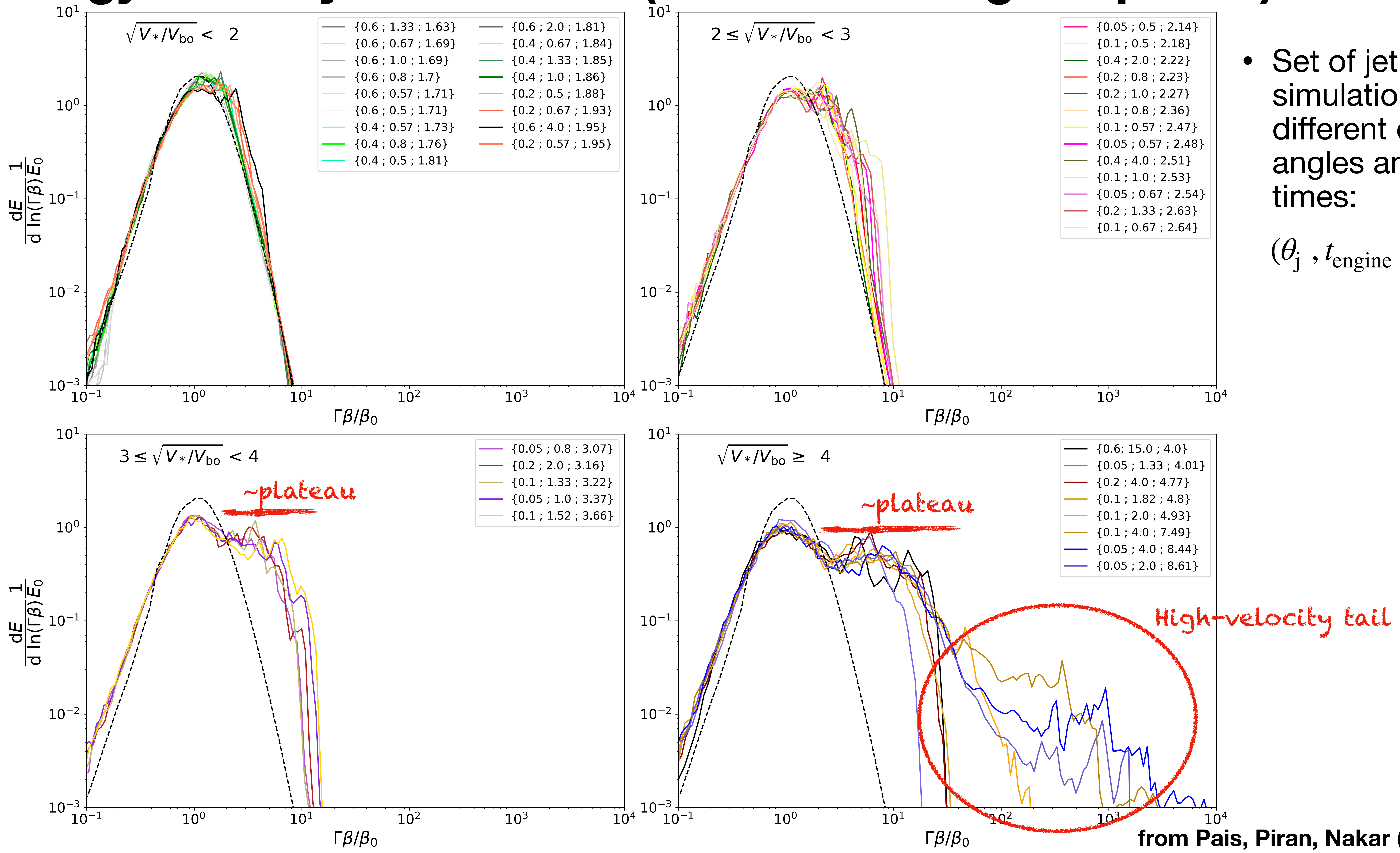


- Set of jet simulations for different opening angles and engine times:

$$(\theta_j\ , t_{engine}\ , \sqrt{V_*/V_{bo}})$$

from Pais, Piran, Nakar (2023)

Energy-velocity distribution (at the homologous phase)



- Set of jet simulations for different opening angles and engine times:

$$(\theta_j\ , t_{\text{engine}}\ , \sqrt{V_*/V_{bo}})$$

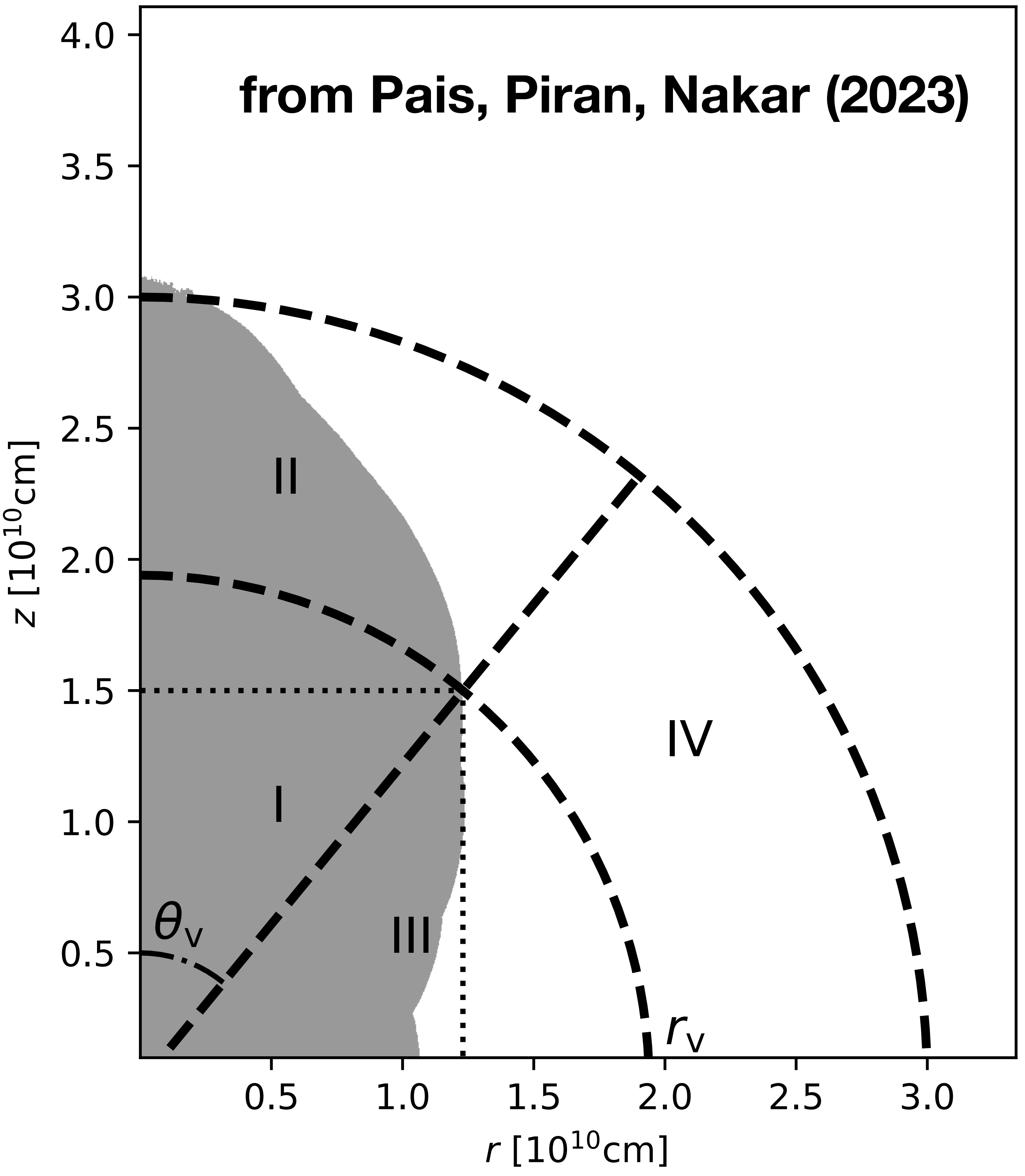
from Pais, Piran, Nakar (2023)

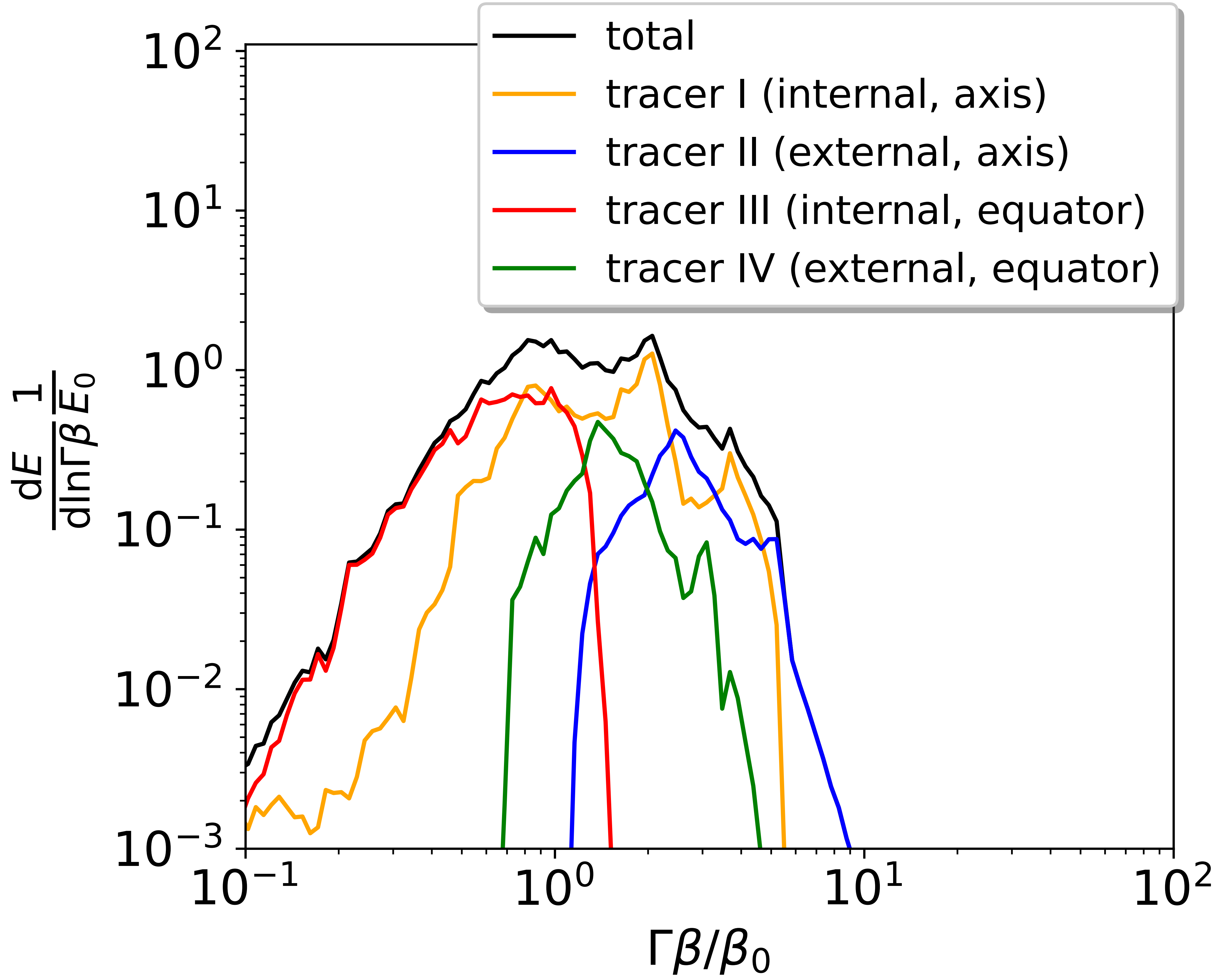
Cocoon volume - choking height correlation

from Pais, Piran, Nakar (2023)

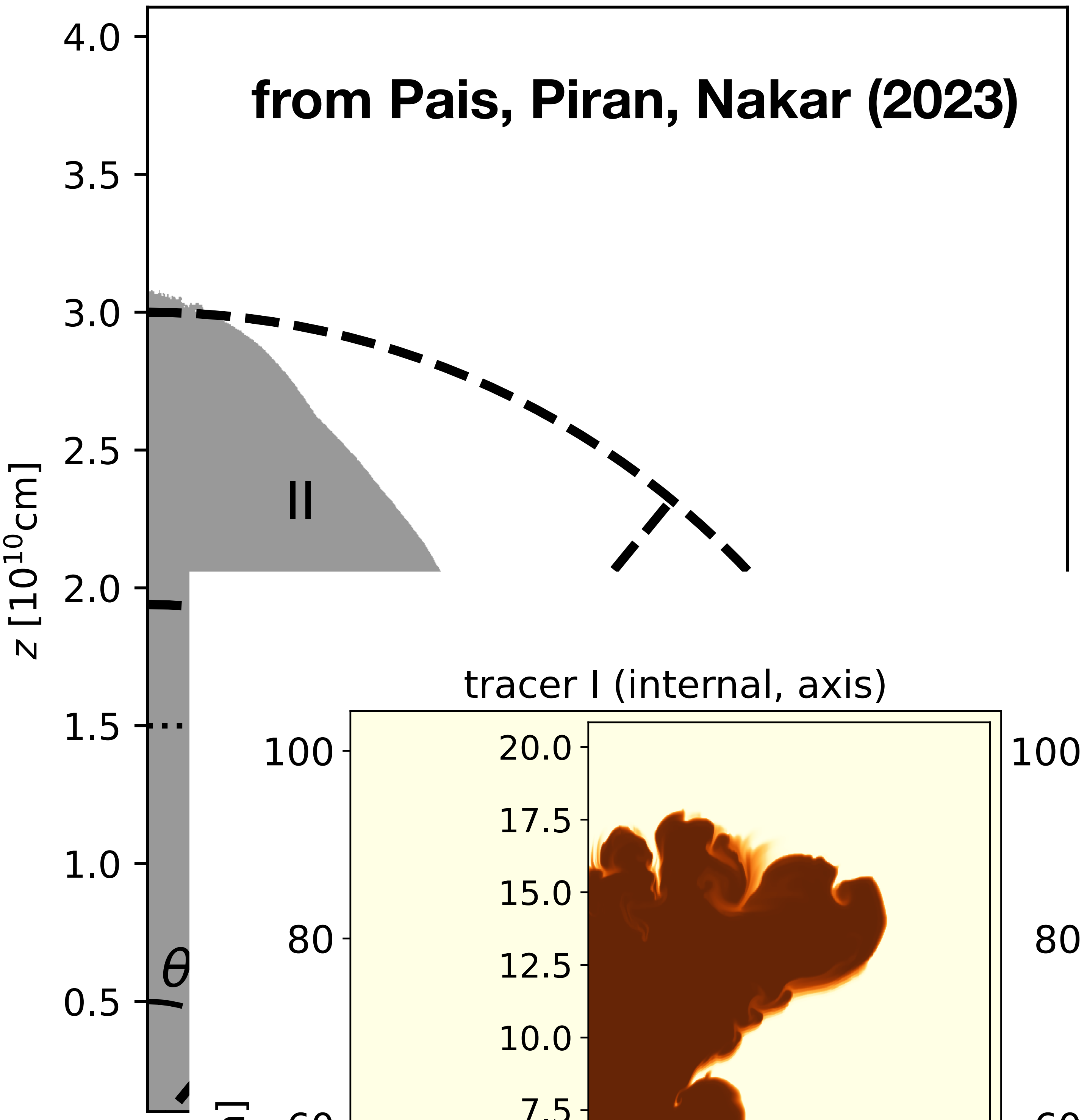
Correlation between $z_{\rm choke}$ and cocoon volume

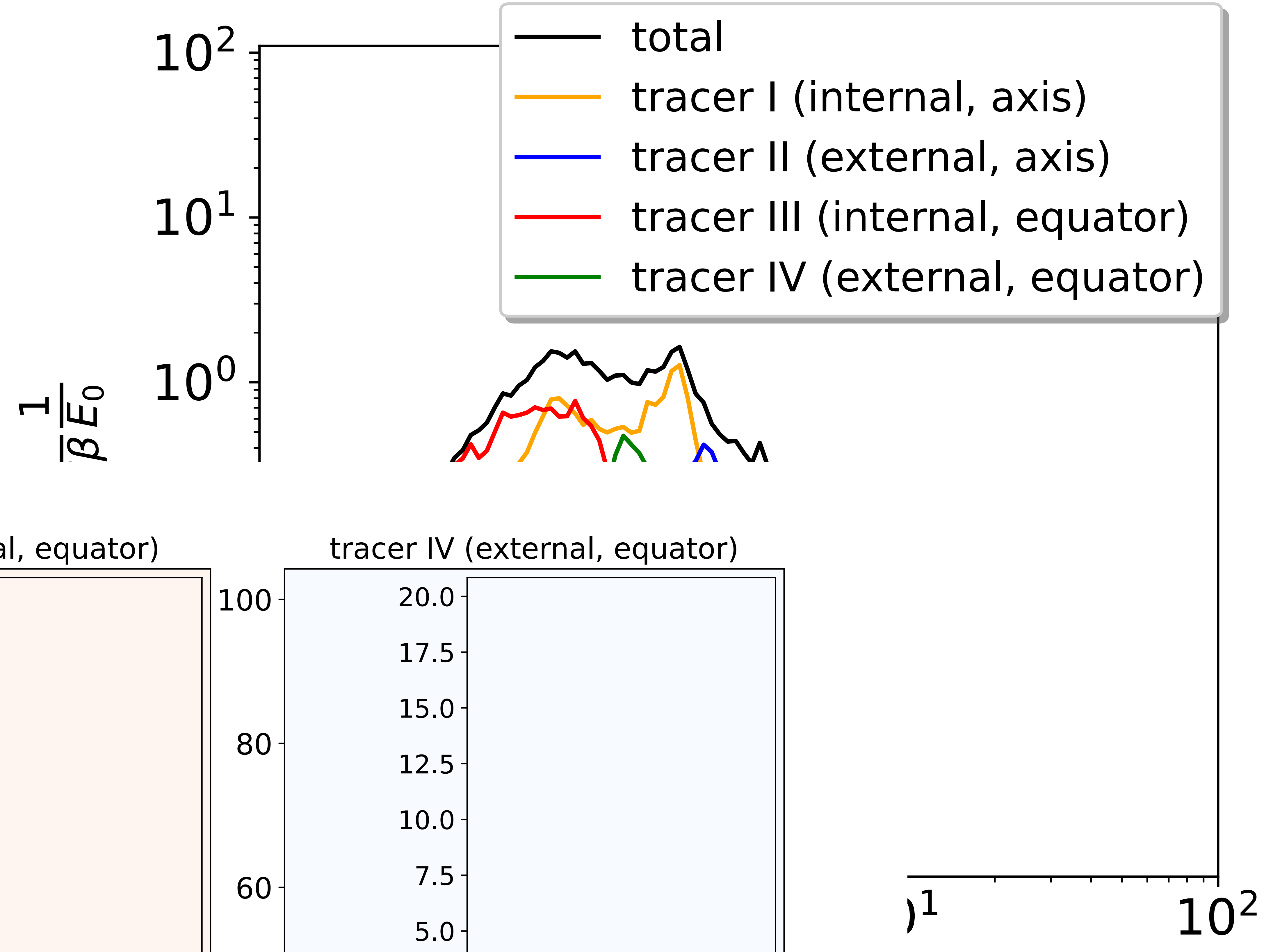
Origin of the ejecta with different velocities

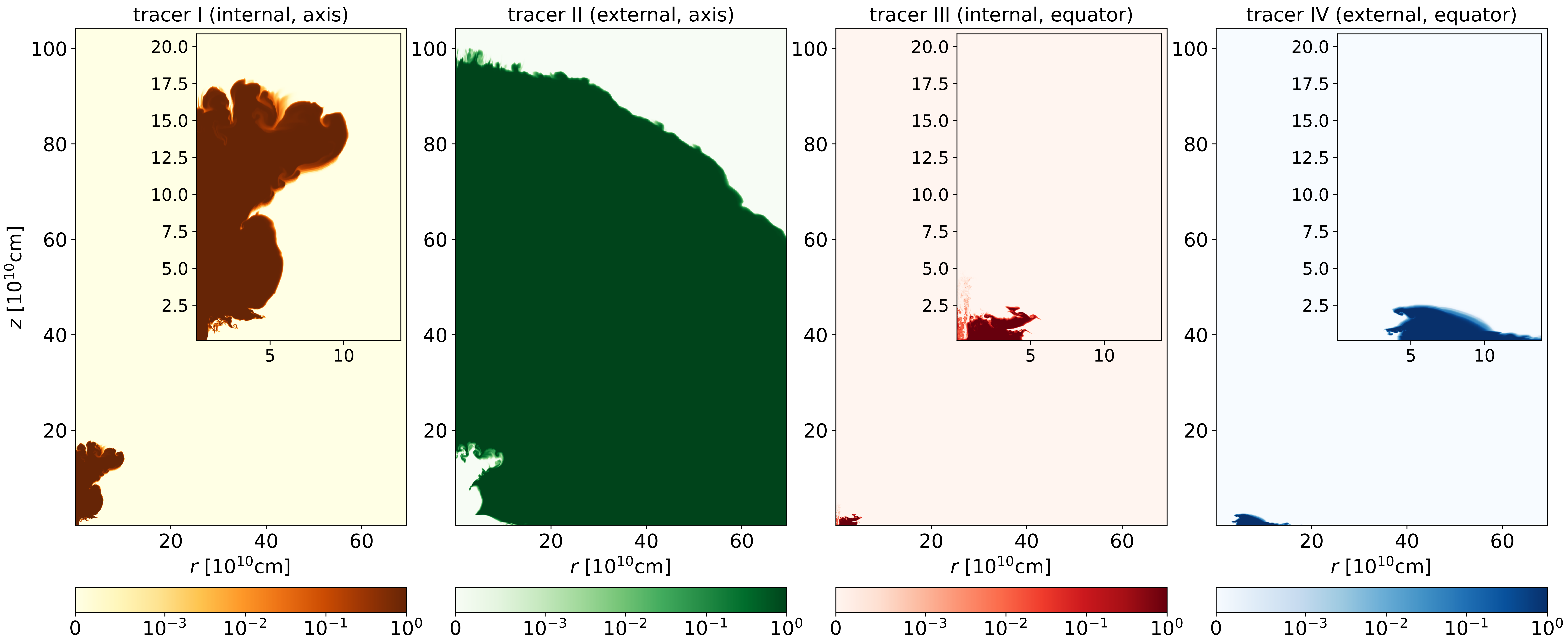




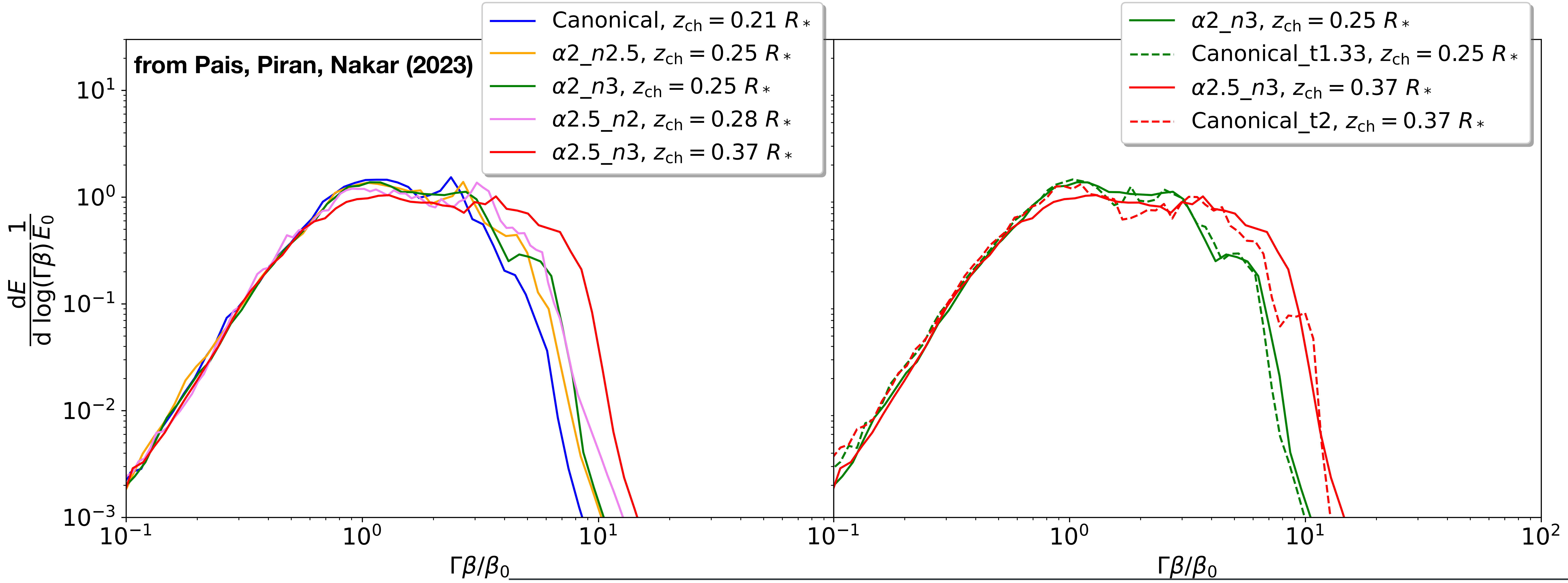
Origin of the ejecta with different velocities







Effect of different stellar profiles at the homologous phase

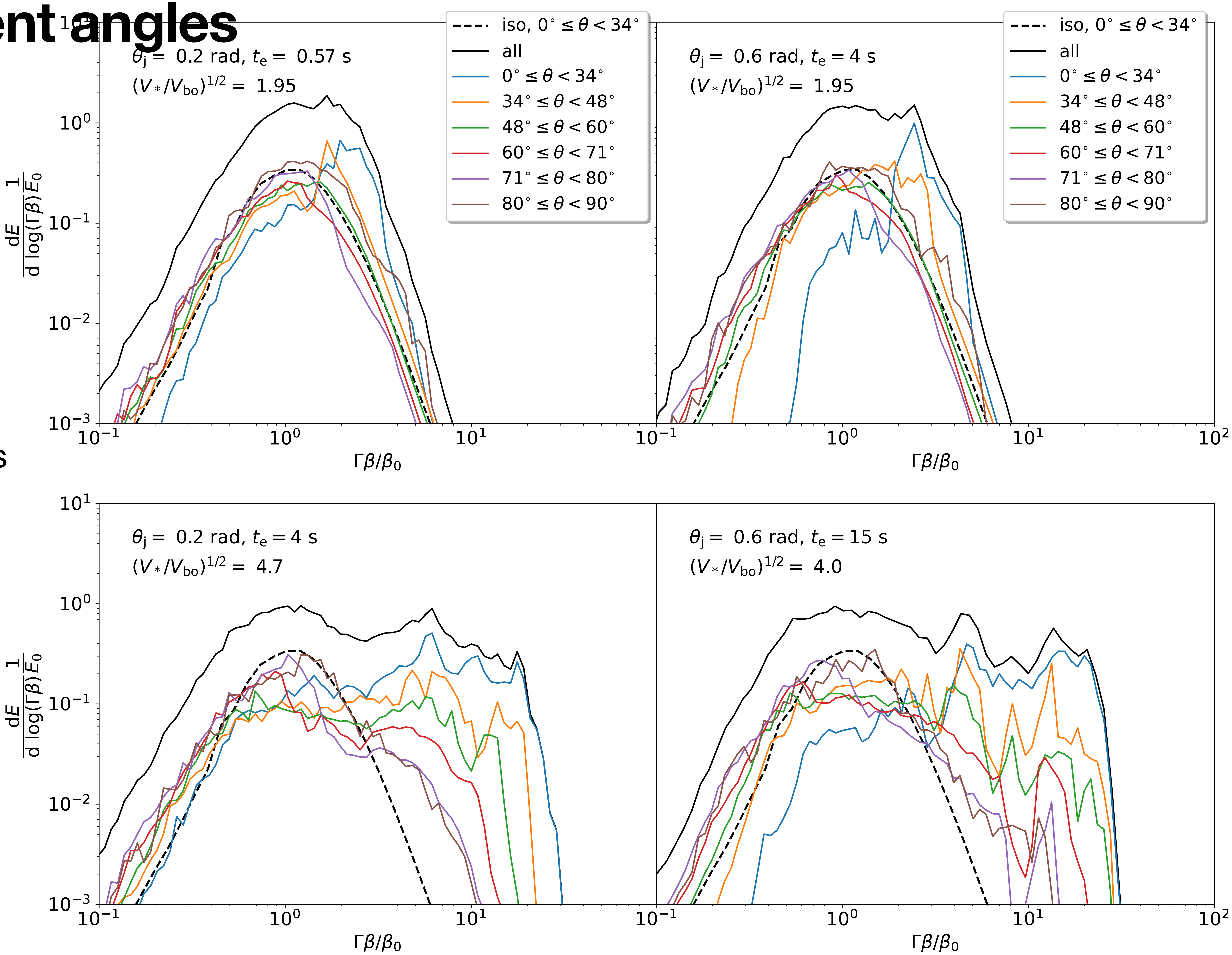


Generalized profile:

$$\rho(R) = \rho_*\,(x)^{-\alpha}\,(1-x)^n$$

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 angles



Different jet parameters…

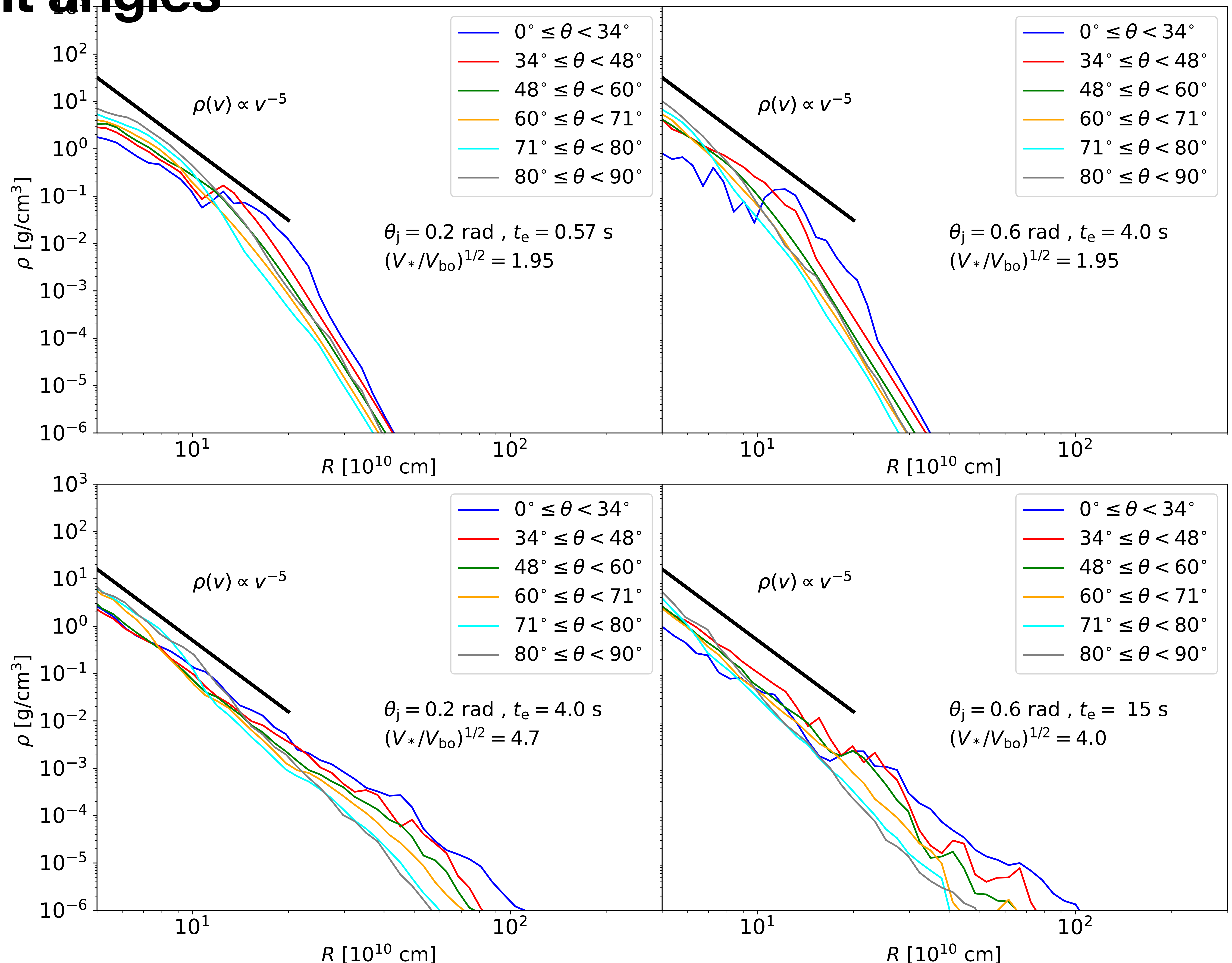
Same volume ratio produces similar distributions

Profiles at different angles

Different jet parameters…

Same volume ratio produces similar distributions

$$\rho(R) \simeq v^{-5}E(v)$$



Takeaway points / Summary

- jets choked (not too deep) **provide a natural explanation to the fast material seen in the early spectra of stripped-envelope SNe without LGRB**;
- SNe not associated with GRBs **possibly harbor choked** jets while LGRBs contain a successful jet;
- All jet-driven explosions with $z_{\rm choke} \simeq R_*$ have a **roughly constant amount of energy per logarithmic scale** in $\Gamma\beta$;
- jets, even if choked, carry a significant amount of energy at high-velocity matter;
- However, to observe broad absorption lines, we need a choking at $z_{\rm choke} \simeq R_*$;
- Off-axis material will become optically thin faster, disappearing earlier in the spectra, making the observation less likely… ;
- Our results can be easily scaled for longer jets and bigger stars according to our scaling relations, generalizing the result;