Black hole to breakout: 3D GRMHD simulations of collapsar jets reveal a wide range of transients

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ABSTRACT
We present a suite of the first 3D GRMHD collapsar simulations, which extend from the self-consistent jet launching by an accreting Kerr black hole (BH) to the breakout from the star. We identify three types of outflows, depending on the angular momentum, l, of the collapsing material and the magnetic field, B, on the BH horizon: (i) *subrelativistic outflow* (low l and high B), (ii) *stationary accretion shock instability* (SASI; high l and low B), (iii) *relativistic jets* (high l and high B). In the absence of jets, free-fall of the stellar envelope provides a good estimate for the BH accretion rate. Jets can substantially suppress the accretion rate, and their duration can be limited by the magnetization profile in the star. We find that progenitors with large (steep) inner density power-law indices ($\gtrsim 2$), face extreme challenges as gamma-ray burst (GRB) progenitors due to excessive luminosity, global time evolution in the lightcurve throughout the burst and short breakout times, inconsistent with observations. Our results suggest that the wide variety of observed explosion appearances (supernova/supernova+GRB/low-luminosity GRBs) and the characteristics of the emitting relativistic outflows (luminosity and duration) can be naturally explained by the differences in the progenitor structure. Our simulations reveal several important jet features: (i) strong magnetic dissipation inside the star, resulting in weakly magnetized jets by breakout that may have significant photospheric emission and (ii) spontaneous emergence of tilted accretion disk-jet flows, even in the absence of any tilt in the progenitor.

Key words: gamma-ray bursts — methods: numerical — stars: jets — stars: Wolf–Rayet

1. INTRODUCTION

WR stars are long GRB progenitors but not all WR give a GRB → jet not formed at all or fails to break-out from the star

What are the conditions for a successful relativistic jet launching ?

Analytical estimates + 3D GRMHD simulations that follow the jet from the central BH to the stellar surface

2. ANALYTICAL MODEL OVERVIEW

2.1 Jet launching conditions

$$L_{\rm BZ} \approx 10^{51} M_{\rm BH,5}^2 B_{h,15}^2 a_{-0.1}^2 \,{\rm erg\ s^{-1}} > L_{\rm acc} = \dot{M}c^2 = 4\pi r_g^2 \rho_h \beta_h^r c^3 \approx 2\times 10^{51} M_{\rm BH,5}^2 \beta_h^r \rho_{h,7}\,{\rm erg\ s^{-1}}$$

$$\Phi_h = 4\pi r_h^2 |B_h|$$

→ condition on $\Phi_h \gtrsim \Phi_{h,\rm min} \approx 7\times 10^{27} \frac{\sqrt{\beta_h^r \rho_{h,7}}}{a_{-0.1}}\ {\rm G\ cm^2}$

2.2 Jet engine work time

Accretion from the envelope onto the BH

$\rho \sim \rho_0 r^{-\alpha}$ in the envelope $\rightarrow$ $\dot{M}_d = \frac{8\pi\rho_0}{3}(2GM_{\rm BH})^{1-\frac{\alpha}{3}} t^{1-\frac{2\alpha}{3}}$ corrected for a fraction lost in a wind $\rightarrow$ $\dot{M}_{acc}$

Magnetically arrested disk (MAD): high efficiency of conversion of accretion to jet power: $L \lesssim \dot{M}_{acc} c^2$

3. SET UP

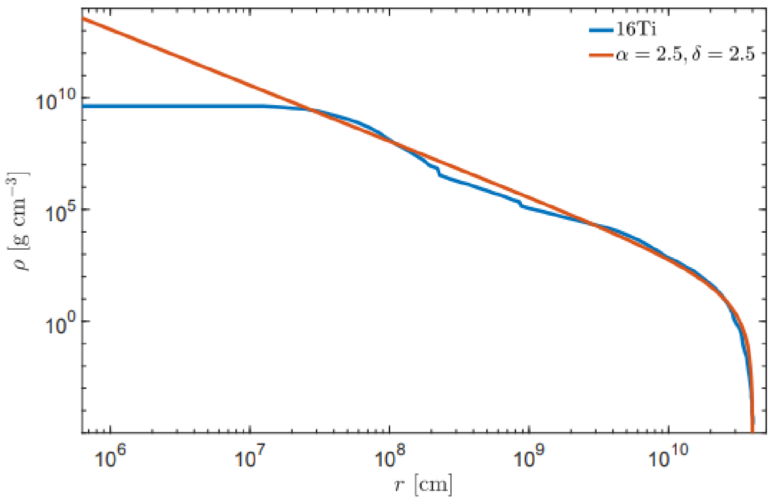
WR star: M = 14 $M_\odot$, R = 4 10^{10} cm + Kerr BH (4 $M_\odot$, a=0.8) at the center

Code GRMHD (H-AMR ; Liska et al) follows grav. Collapse, disk formation, jet launching and propagation

<u>Initial structure</u>

- density $\rho(r) = \rho_0 \left(\frac{r}{r_h}\right)^{-\alpha} \left(1 - \frac{r}{R_\star}\right)^{\delta}$

  normalized to have M = M_*



- angular momentum

  spherically symmetric $\ell(r)$ [?]

$$l(r) = \begin{cases} \omega_0 \left(\frac{r^2}{r_g}\right)^2 & r < 70 r_g \\ \omega_0 (70^2 r_g)^2 & r > 70 r_g \end{cases}$$

- magnetic field

  uniform in the $\hat{z}$ direction in a core of radius $r_c = 10^8$ cm and dipolar outside

$$\sigma = \frac{B^2}{4\pi\rho c^2} \text{ (comoving)} \quad ; \quad \sigma_{max} = 25 \sim \Gamma_\infty$$

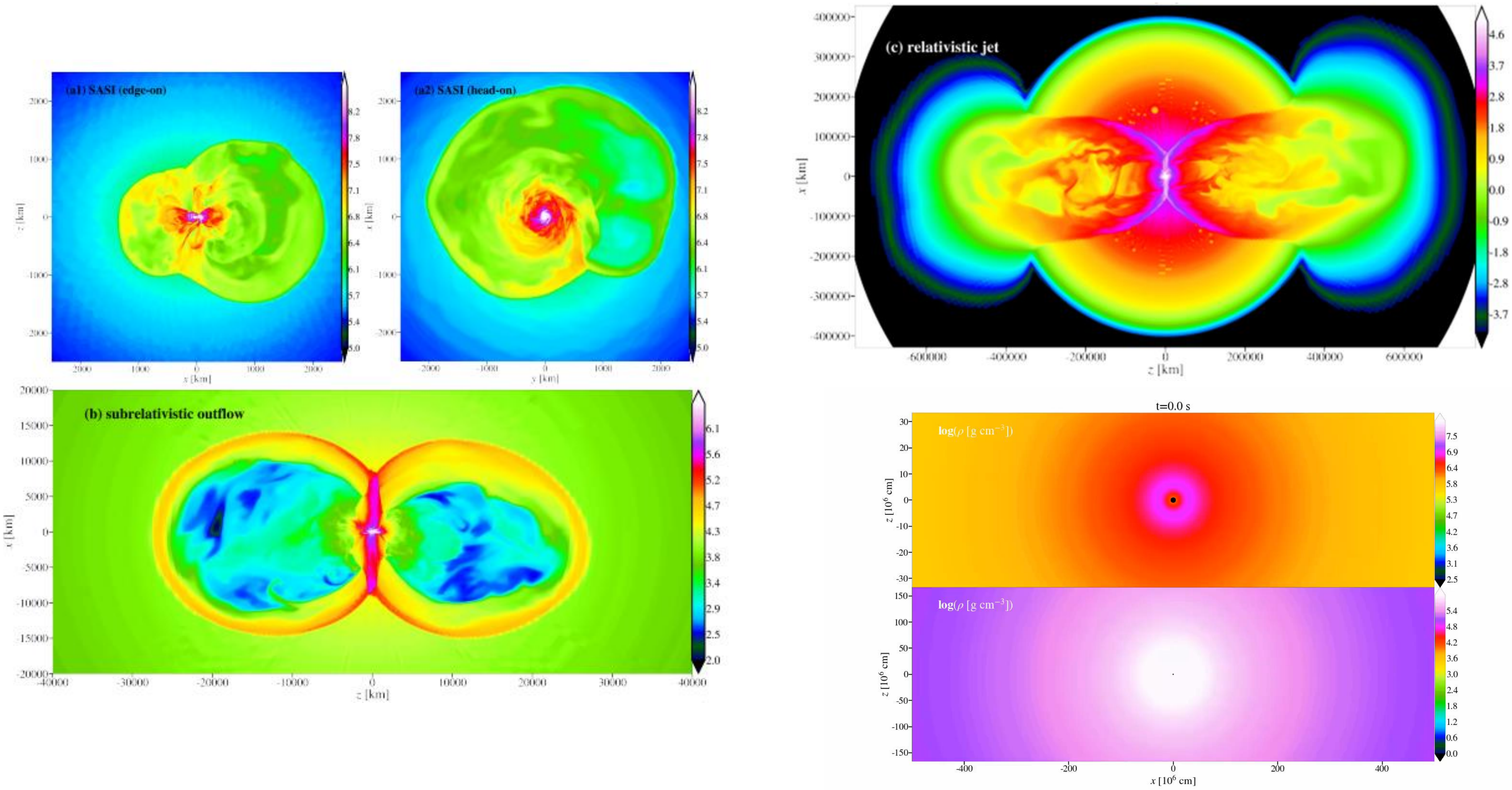
4. OUTFLOW

4.1 GRB jet launching

Formation of a disk necessary for jet launching $\rightarrow$ $r_{circ}(j) \gtrsim r_{ISCO}$

4.2 Types of outflows

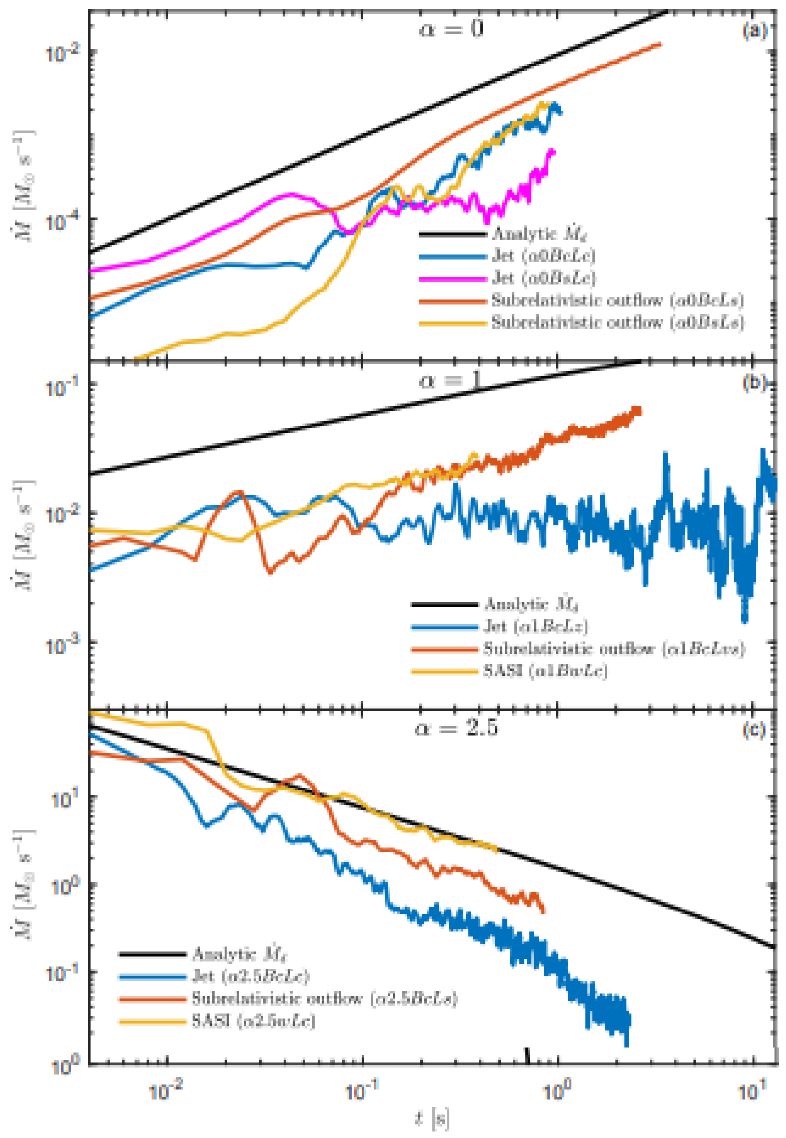
		disk $r_{\rm circ} \gtrsim r_{\rm ISCO}$	no disk $r_{\rm circ} < r_{\rm ISCO}$
BZ jet	$\Phi_h \gtrsim \Phi_{h,\rm min}$	Relativistic jet	Subrelativistic outflow
no jet	$\Phi_h \lesssim \Phi_{h,\rm min}$	SASI	Gravitational collapse



(a1) SASI (edge-on)
(a2) SASI (head-on)
(b) subrelativistic outflow
(c) relativistic jet
z [km]
x [km]
y [km]
t=0.0 s
log(ρ [g cm⁻³])
log(ρ [g cm⁻³])
z [10⁶ cm]
x [10⁶ cm]

5. ACCRETION RATE

comparison simulation/analytical formula $\dot{M}_d \propto t^{1-\frac{2\alpha}{3}}$

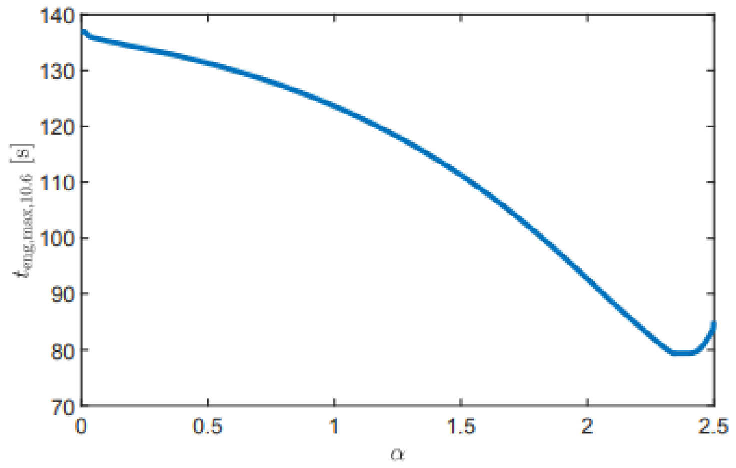


satisfactory especially if there is no jet

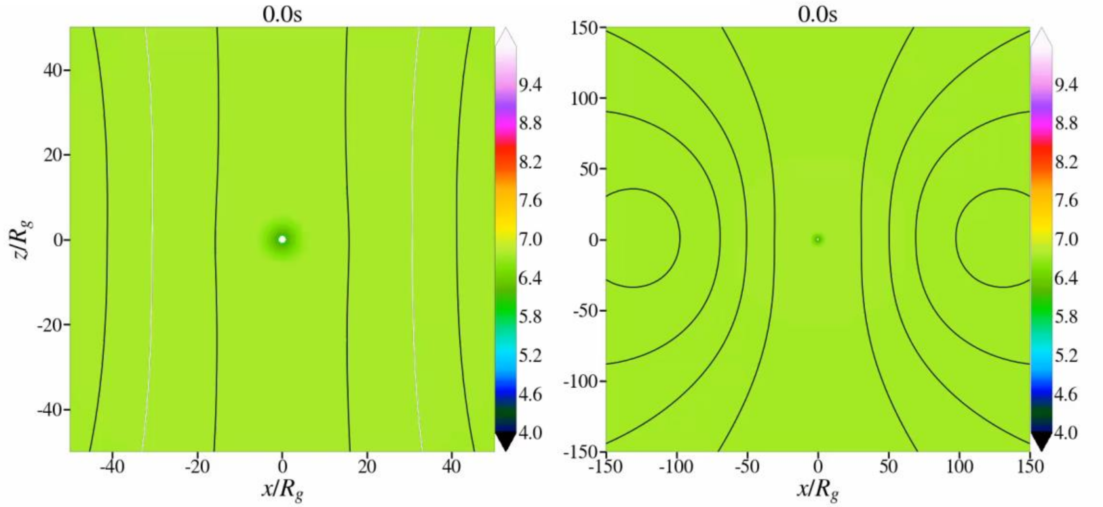
6. JET WORK-TIME & LUMINOSITY

6.1 Engine activity

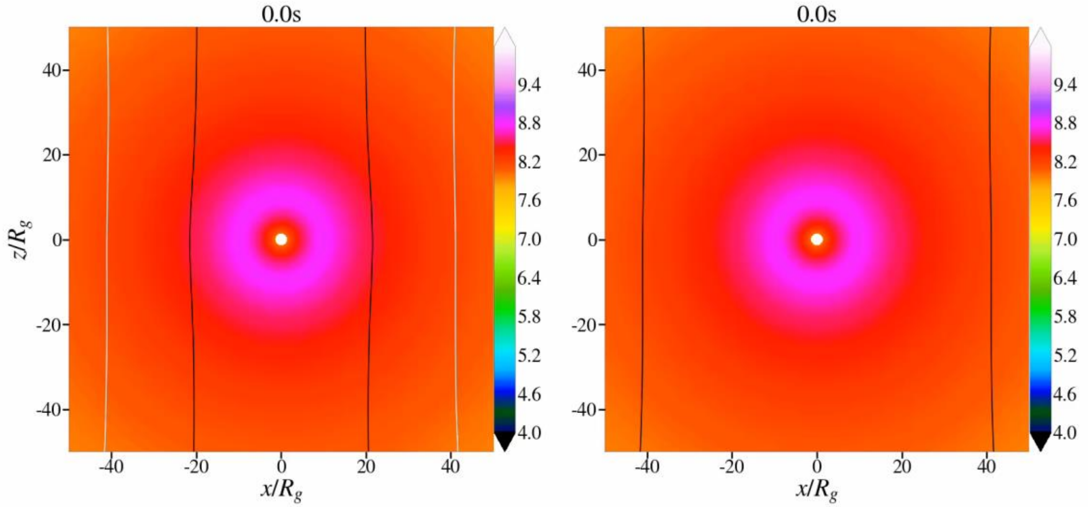
$t_{eng,max} \equiv$ entire accretion time (α)



but often $t_{eng} \ll t_{eng,max}$ and difficult to reach $t_{eng} \gtrsim 10$ s

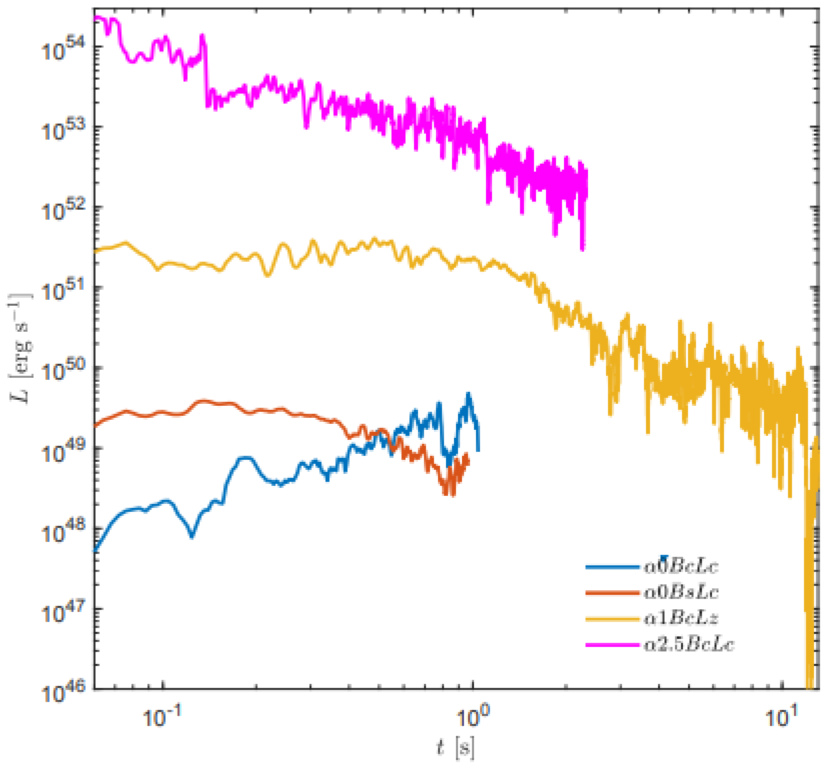


α = 0 : small scale turbulence disrupts ordered B



α = 1 : longer lasting jet (but still problems to reach 10 s

6.2 Luminosity



α = 1 preferred

can maintain a steady luminosity for a longer time

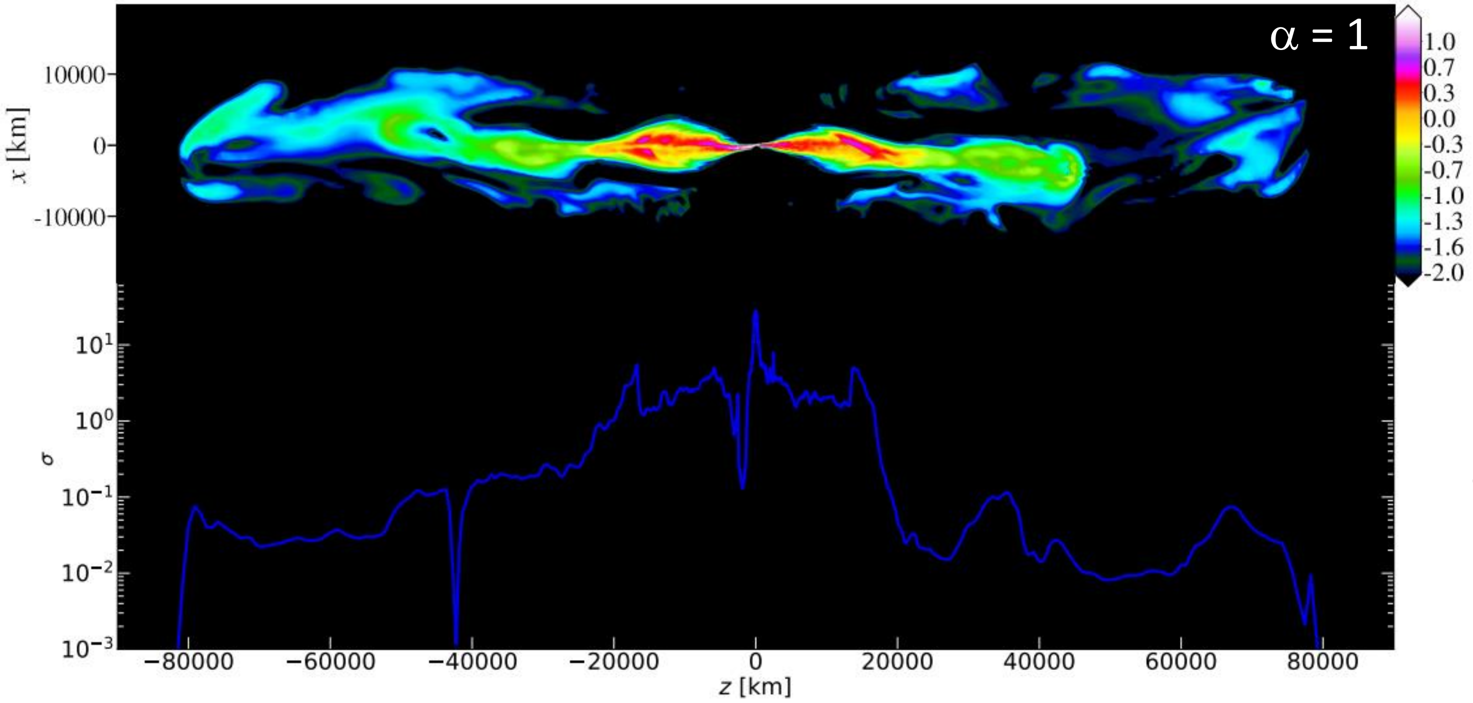
7. JET EVOLUTION

7.1 Tilt of the disk

jet – cocoon – star interplay

good (or bad) for the prompt light curve ?

7.2 Magnetic dissipation



reduction of σ to $\sigma \ll 1$
during jet propagation

magnetized jet ⟶ hydro jet, bright photosphere

(to be confirmed)

8. IMPLICATIONS TO BREAKOUT & EMISSION

8.1 Breakout

…

8.2 Prompt emission

magnetic dissipation at the collimation nozzle ($\tau > 10^3$)

$\sigma \sim 0.01$ above nozzle $\rightarrow$ conversion of magnetic into thermal energy

$\rightarrow$ efficient photospheric emission

variability: mixing during jet propagation or
directly related to central engine activity (preferred)

$\rightarrow$ photospheric models for the prompt emission of GRBs favored

9. SUMMARY & DISCUSSION

production of a relativistic jet: two main conditions for success

(i) jet power > ram pressure of infalling material: $L_{BZ} > \dot{M}_{acc}c^2$

(ii) accretion disk must form: $r_{circ} > r_{ISCO}$

+ $\rho \propto r^{-\alpha}$ with $0.5 < \alpha < 1.5$ favored in the envelope

magnetic dissipation heats the jet $\longrightarrow$ bright photospheric emission expected

if these conditions are not satisfied, various possible outcomes:

$\longrightarrow$ SASI, sub-relativistic outflow, grav. collapse

limitation: neutrino processes not included in the study (left for future work) [role of polar funnel ?]

Two comments:

- in photospheric model with $R_{ph} \sim 10^{11\text{-}13}$ cm, the ESD at the end of the prompt emission cannot be the HLE of the last flashing shell. It must correspond to an effective behavior of the central engine.
- the main radiative process during the prompt phase is not synchrotron but comptonized photospheric emission
- in the proposed model how to explain long and smooth light curve ? (not specific to this model)

High efficiency photospheric emission entailed by formation of a collimation shock in gamma-ray bursts

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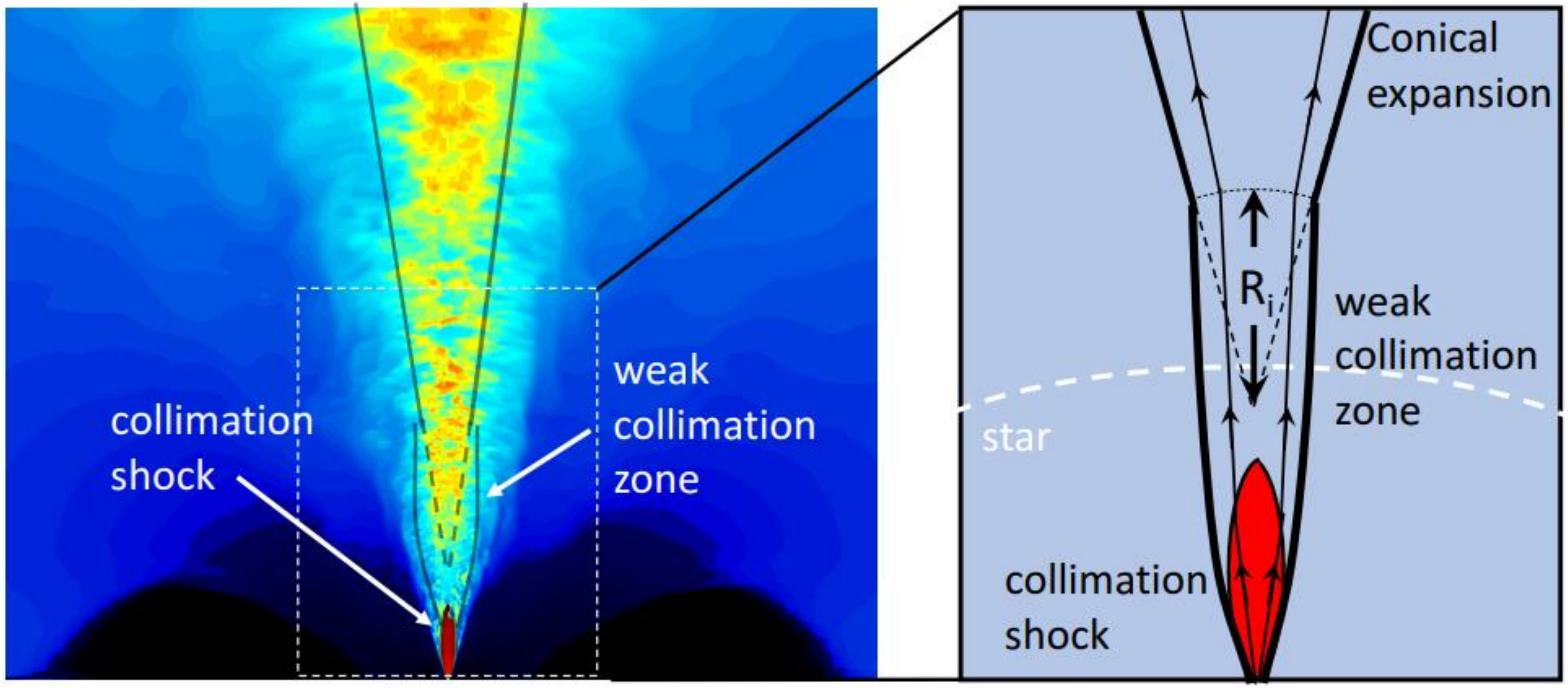
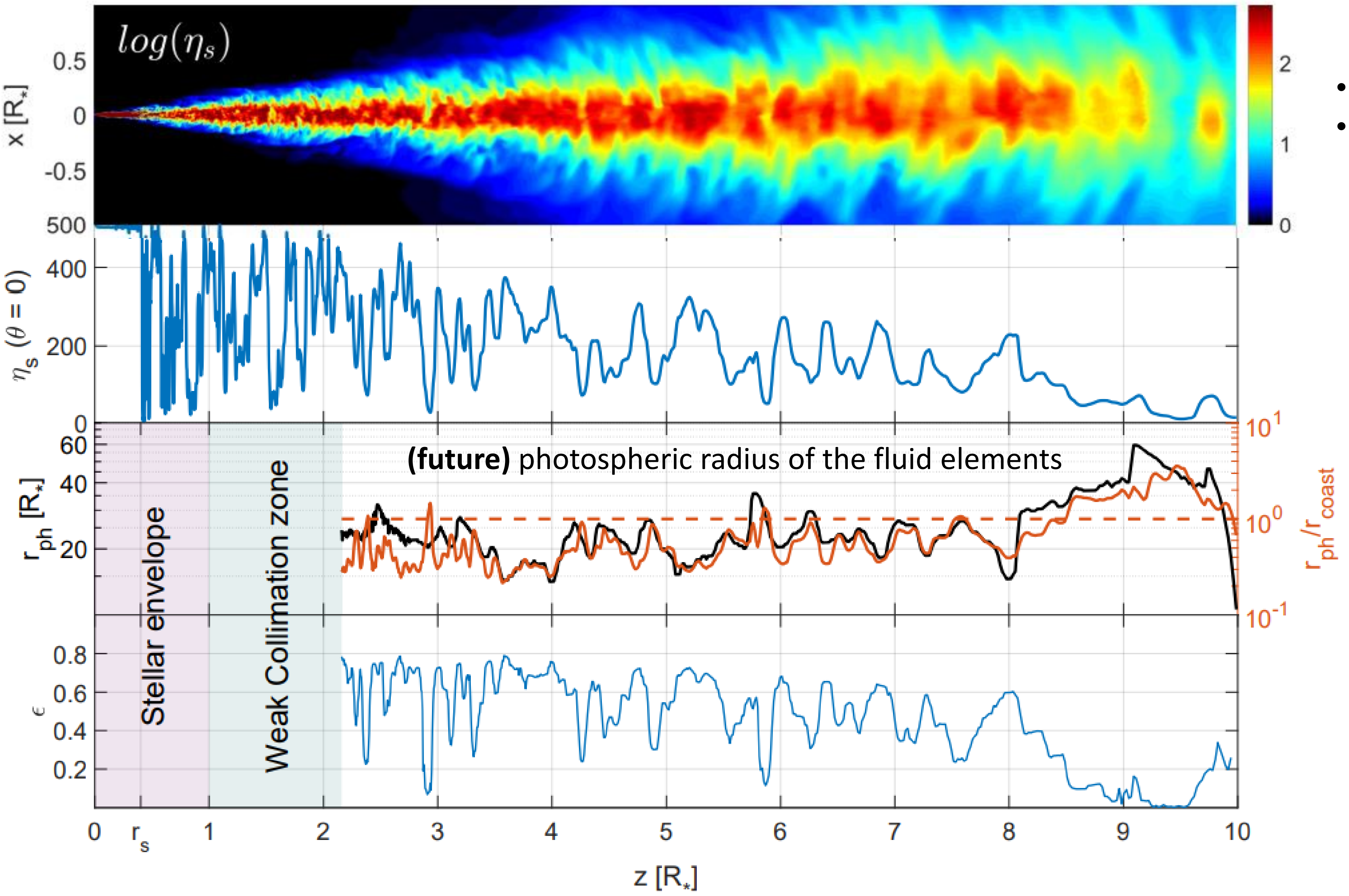


initial propagation is nearly cylindrical → reduced cooling until conical expansion starts
→ brighter photosphere, increased efficiency



- rest frame time t=55 s
- jet's head at 10 R_*