The Propagation of Choked Jet Outflows

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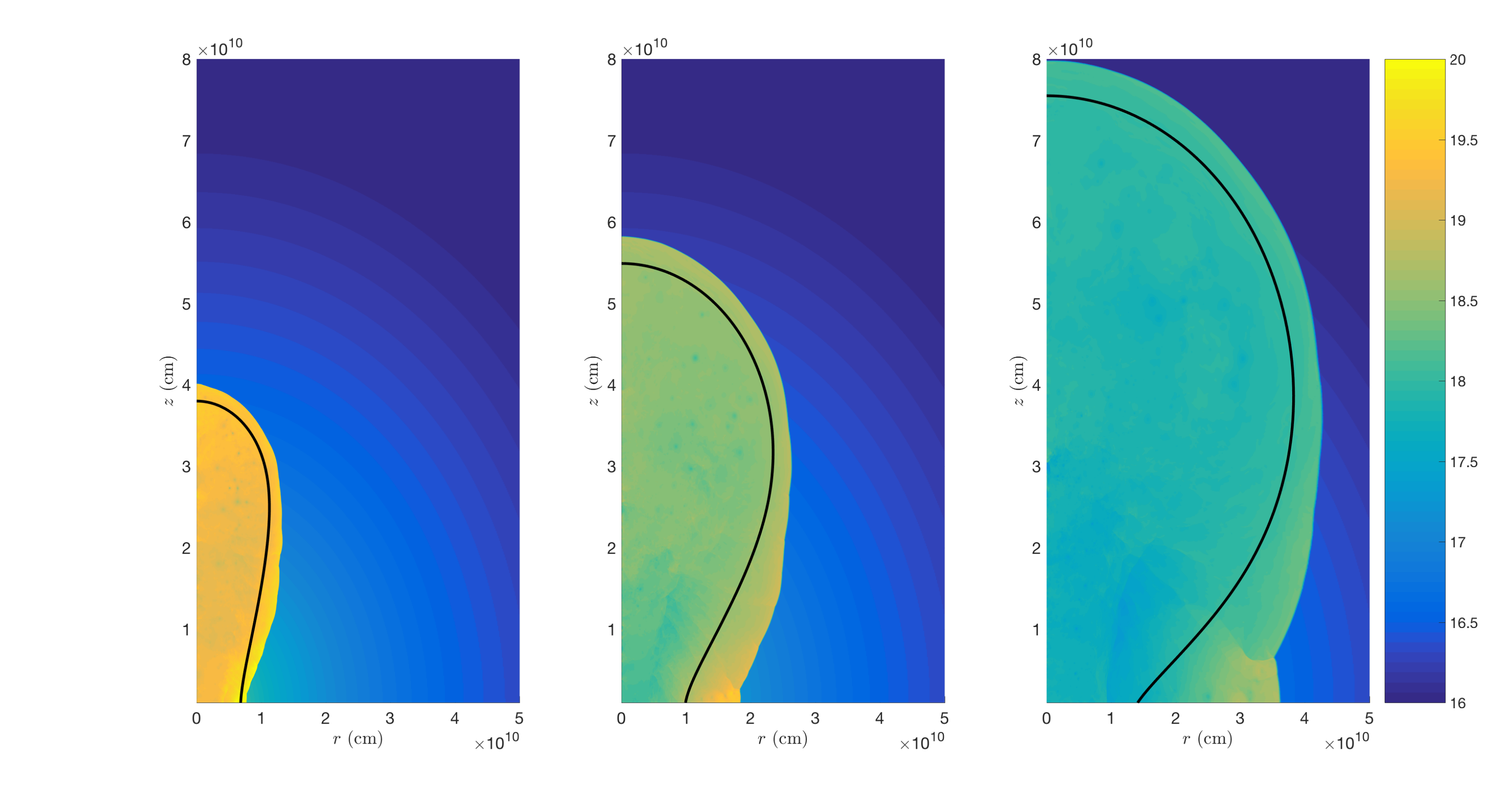

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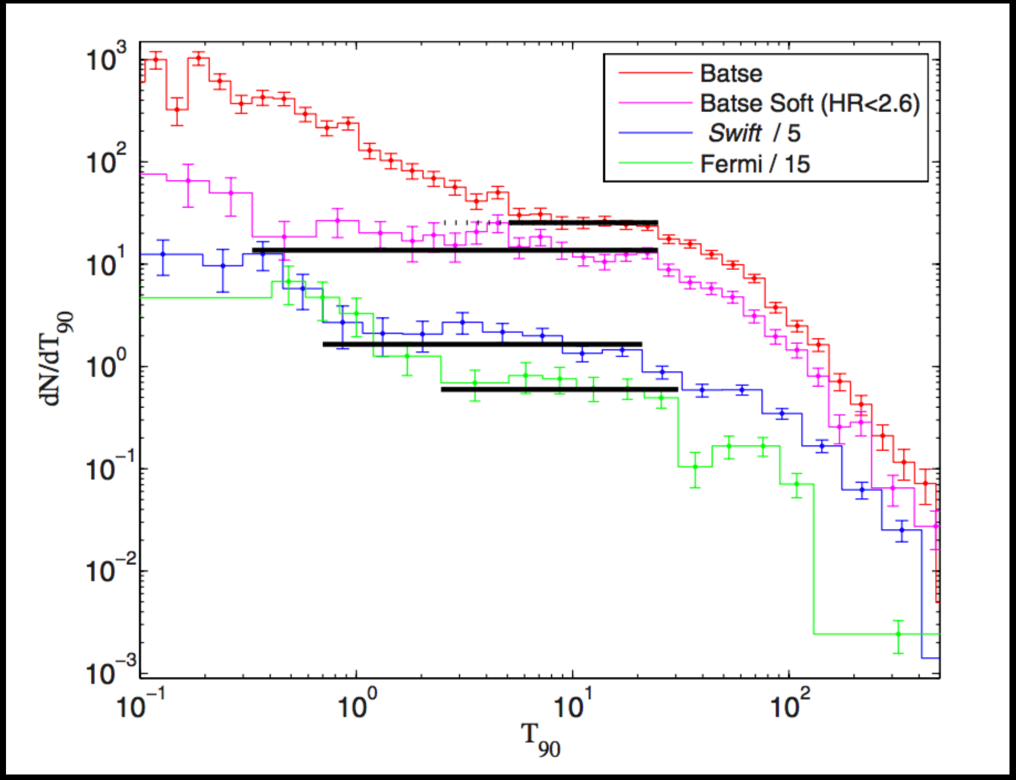
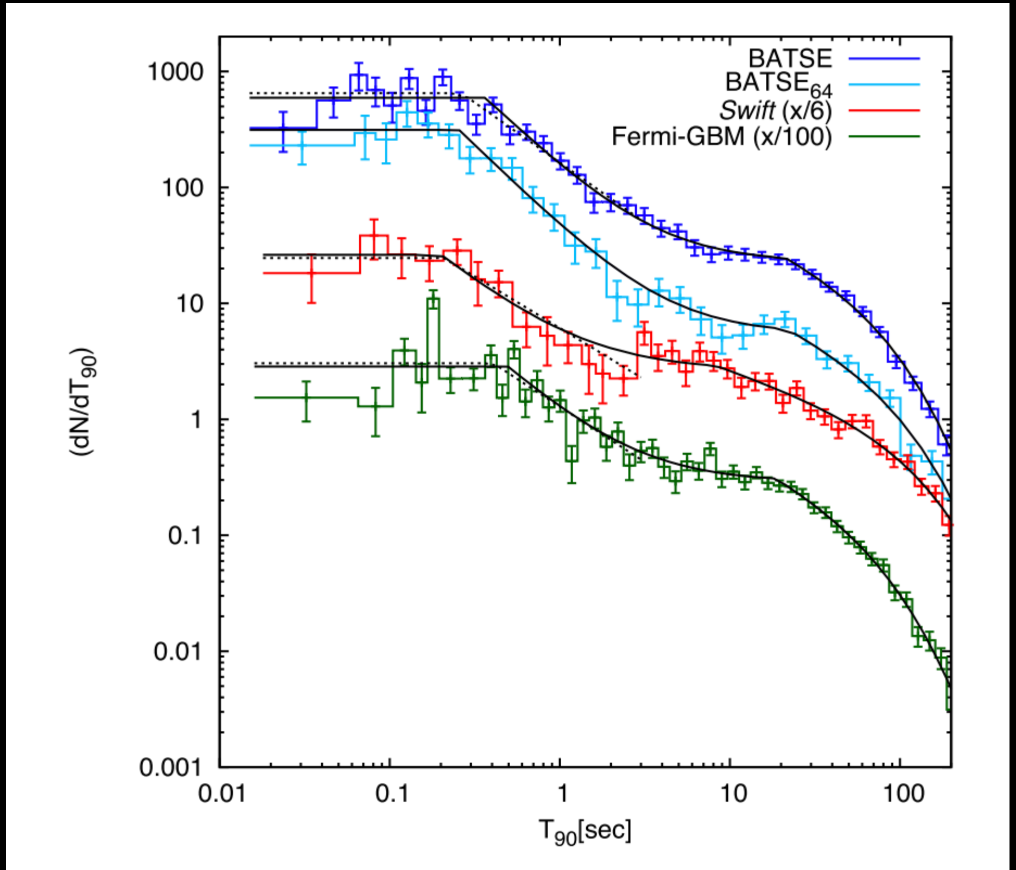
Evidence for Choked Jets in Long GRBs

- GRB duration distribution
    - A plateau suggests that many objects do not escape the star to produce typical GRBs
    - This is also seen in short GRBs, albeit with a lower significance
- Early spectroscopy
- Low-luminosity GRBs



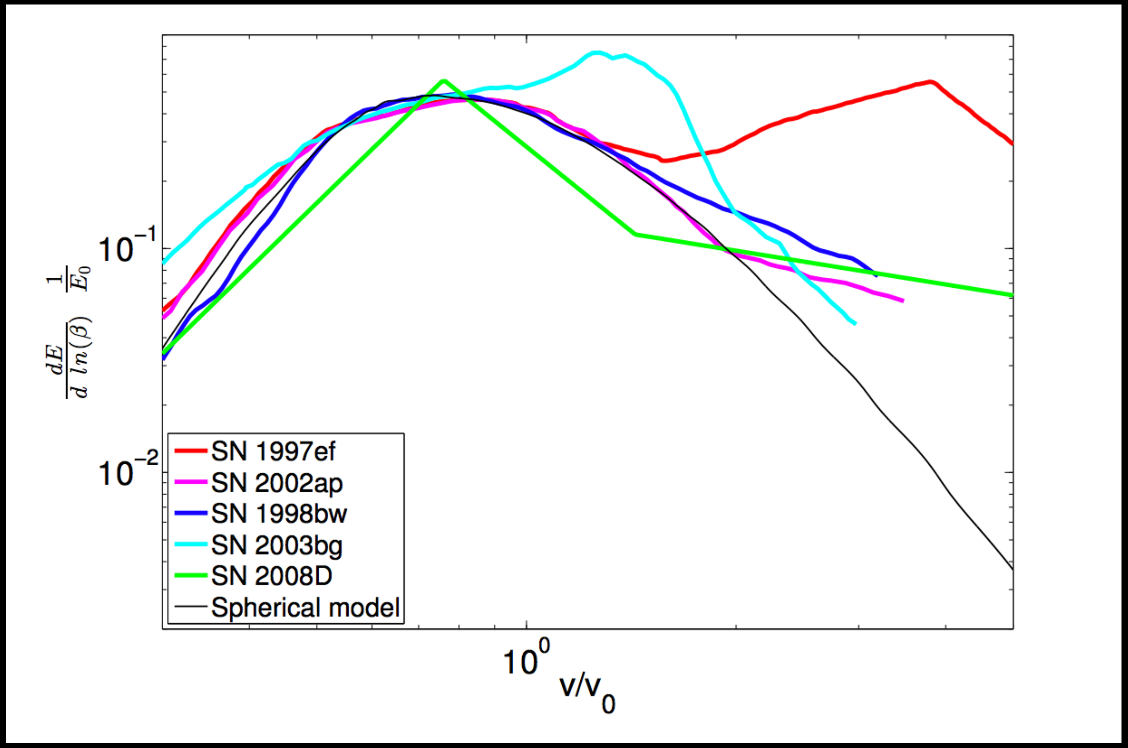
Bromberg+ 2012



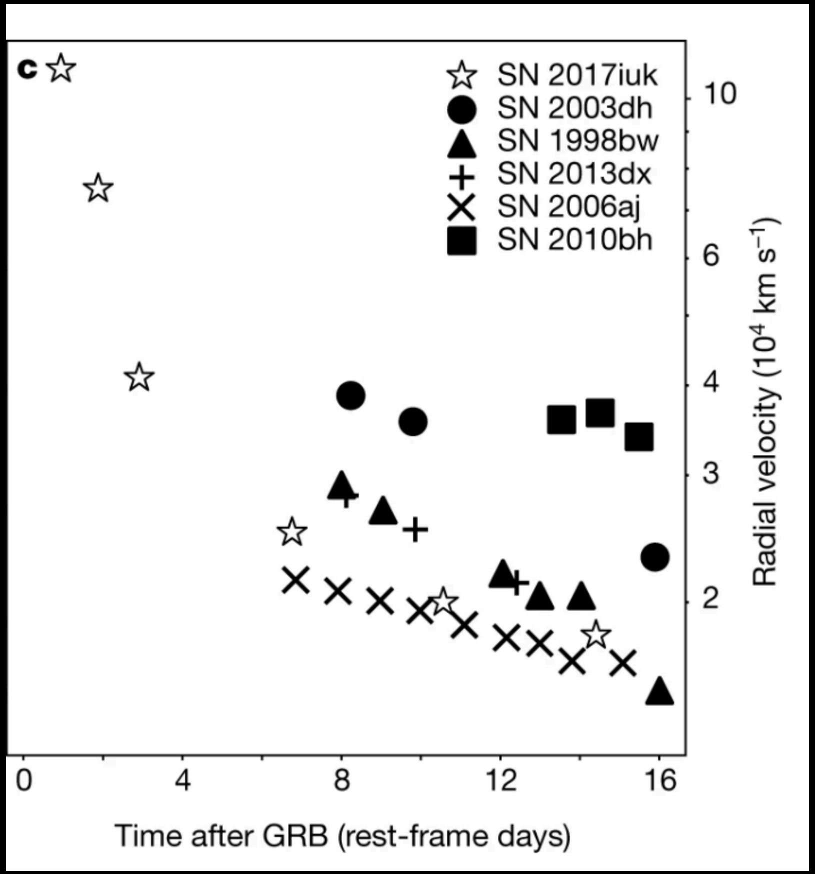
Moharana & Piran 2017

Evidence for Choked Jets in Long GRBs

- Duration distribution
- Early spectroscopy
  - Analysis of some SNe reveal a high-velocity component
  - The mass (~0.1 Msun) and energy (~1 foe) are consistent with expectations for a GRB jet's cocoon
- Low-luminosity GRBs



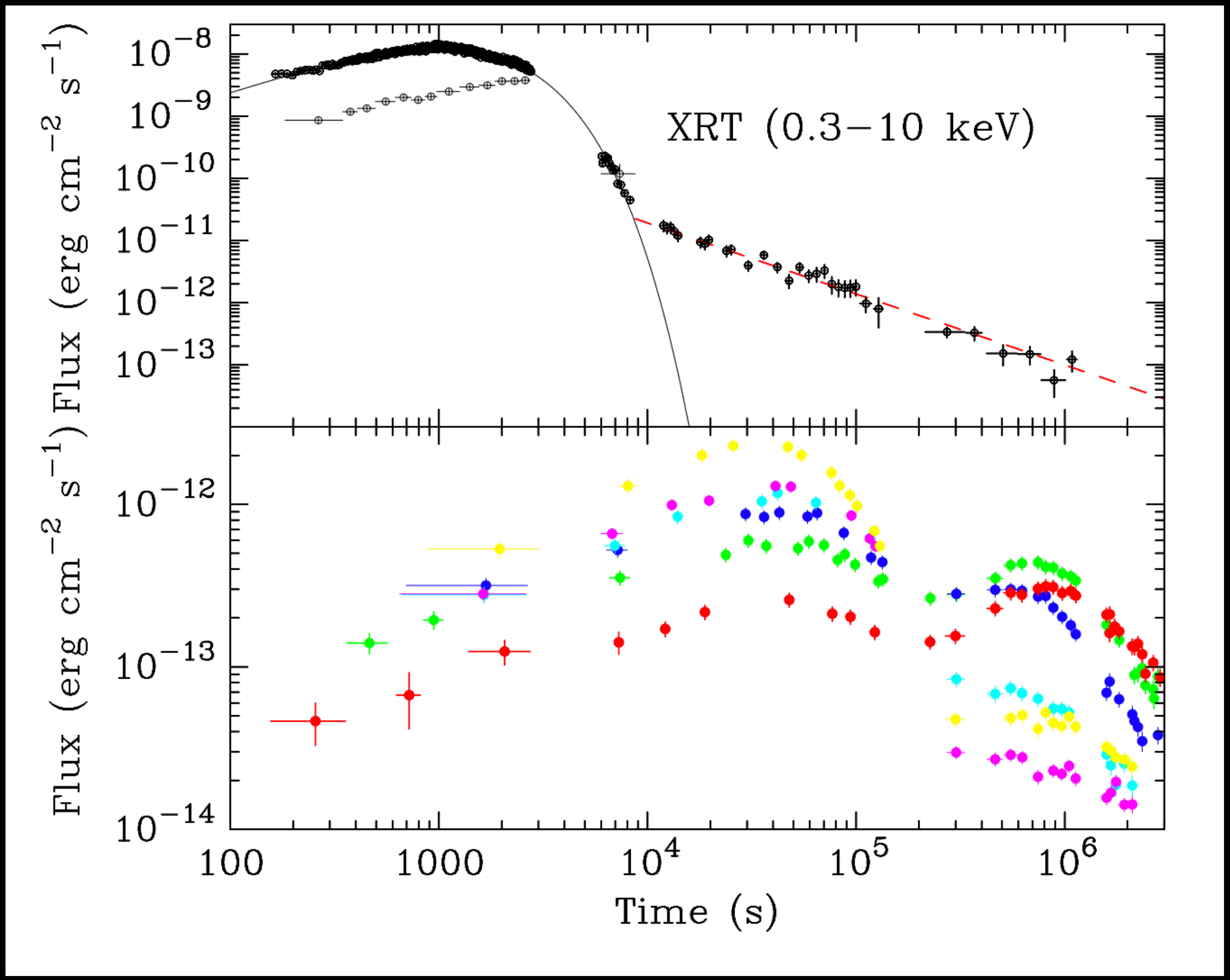
Piran+ 2019



Izzo+ 2019

Evidence for Choked Jets in Long GRBs

- Duration distribution
- Early spectroscopy
- Low-luminosity GRBs
  - LLGRBs are long, faint, soft, and smooth compared to typical GRBs—all features which are expected in a relativistic shock breakout
  - UV/optical cooling emission suggests an extended (~100 Rsun) envelope with sufficient mass (0.01 Msun) to choke a standard GRB jet



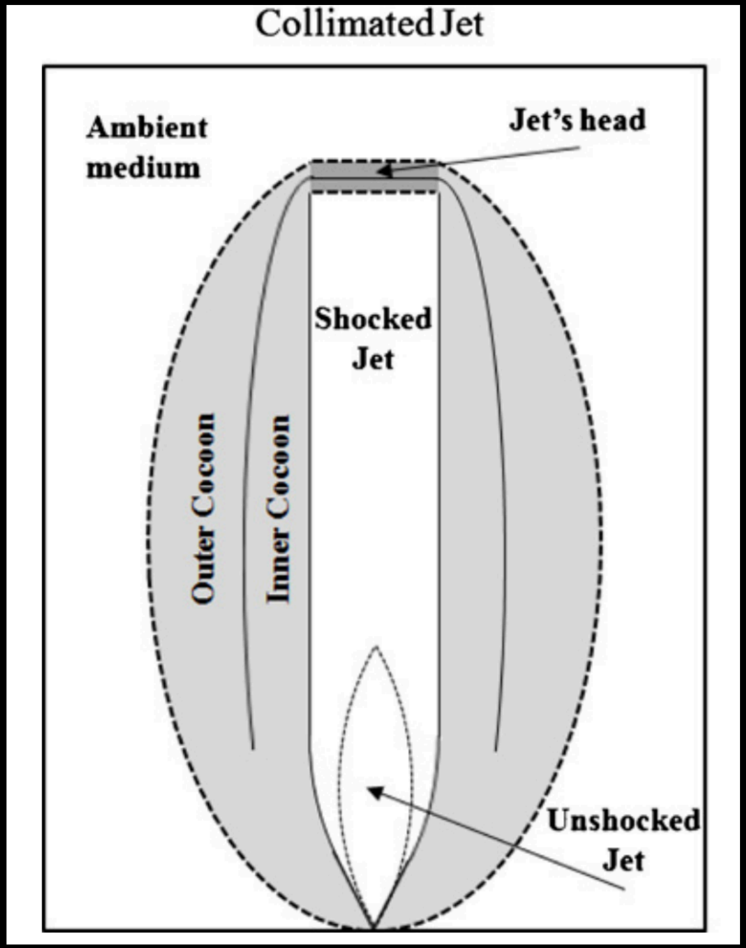
Campana+ 2006

$$t_{\rm bo}^{\rm obs} \sim 20\,{\rm s}\left(\frac{E_{\rm bo}}{10^{46}\,{\rm erg}}\right)^{1/2}\left(\frac{T_{\rm bo}}{50\,{\rm keV}}\right)^{-\frac{9+\sqrt{3}}{4}}$$

Nakar & Sari 2012

A gap in our analytical understanding

Active jet



Bromberg+ 2011

?

Scale-free blast wave

$$R \propto t^{2/(5-\alpha)}$$

Two Key Questions

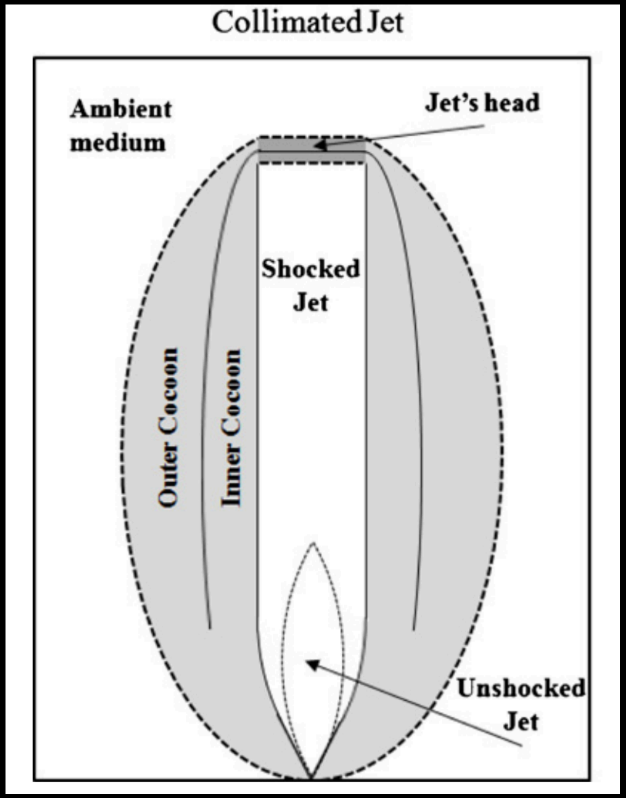
- What happens to a jet-driven outflow after the jet is switched off?
- What can we learn about the jet's properties by studying the 'choked' outflow it leaves behind?

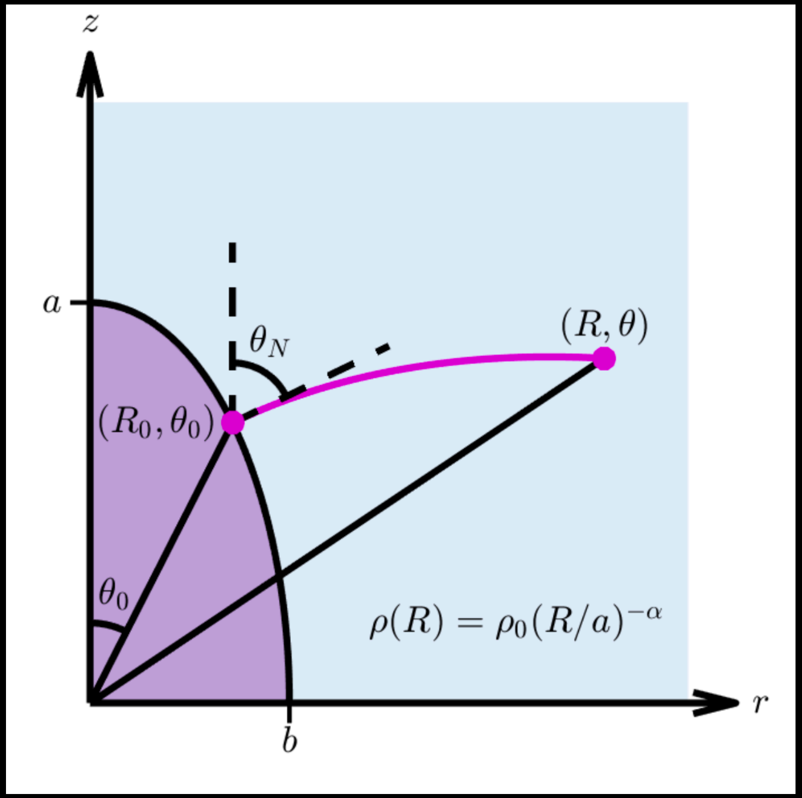
Jet Choking

- Once the jet turns off and all of the jet material flows into the cocoon, we consider the system "choked"

Before

Bromberg+ 2011





After

CMI+ 2019b

luminosity, L_j

duration, t_b

op. angle, θ_0

energy, E_0

initial height, a

initial width, b

- For a collimated relativistic jet, a/b >> 1.

Kompaneets Approximation

- We utilize the well-known Kompaneets approximation, which involves 3 assumptions:

    1. The cocoon drives a strong shock into the external medium.
    2. The local expansion velocity is always normal to the cocoon surface.
    3. The postshock pressure, P_{ps}, is similar to the volume-averaged pressure of the cocoon, i.e.

    $$P_{ps}(t) = \frac{\lambda(\gamma - 1)E_0}{V_c(t)}$$

    where E_0 is the cocoon energy, γ is the adiabatic index,V is the cocoon volume, and λ is an order-unity constant

Equation of Motion

- Assumptions 1 and 2 let us write two expressions for normal velocity: one from shock jump conditions, the other from geometry in polar coordinates:

$$\sqrt{\frac{\gamma+1}{2}\frac{P_{ps}(t)}{\rho(R)}} = v(R,t) = \frac{|\partial\theta/\partial t|}{\sqrt{1/R^2 + (\partial\theta/\partial R)^2}}$$

- This PDE can be solved subject to the initial condition

$$\theta(R,t)|_{t=t_0} = \theta_i(R_i)$$

to yield the shape of the shock over time.

Dynamical Regimes

- The cocoon evolution has two characteristic timescales:
  - The time for the width to double, t_b
  - The time for the height to double, t_a

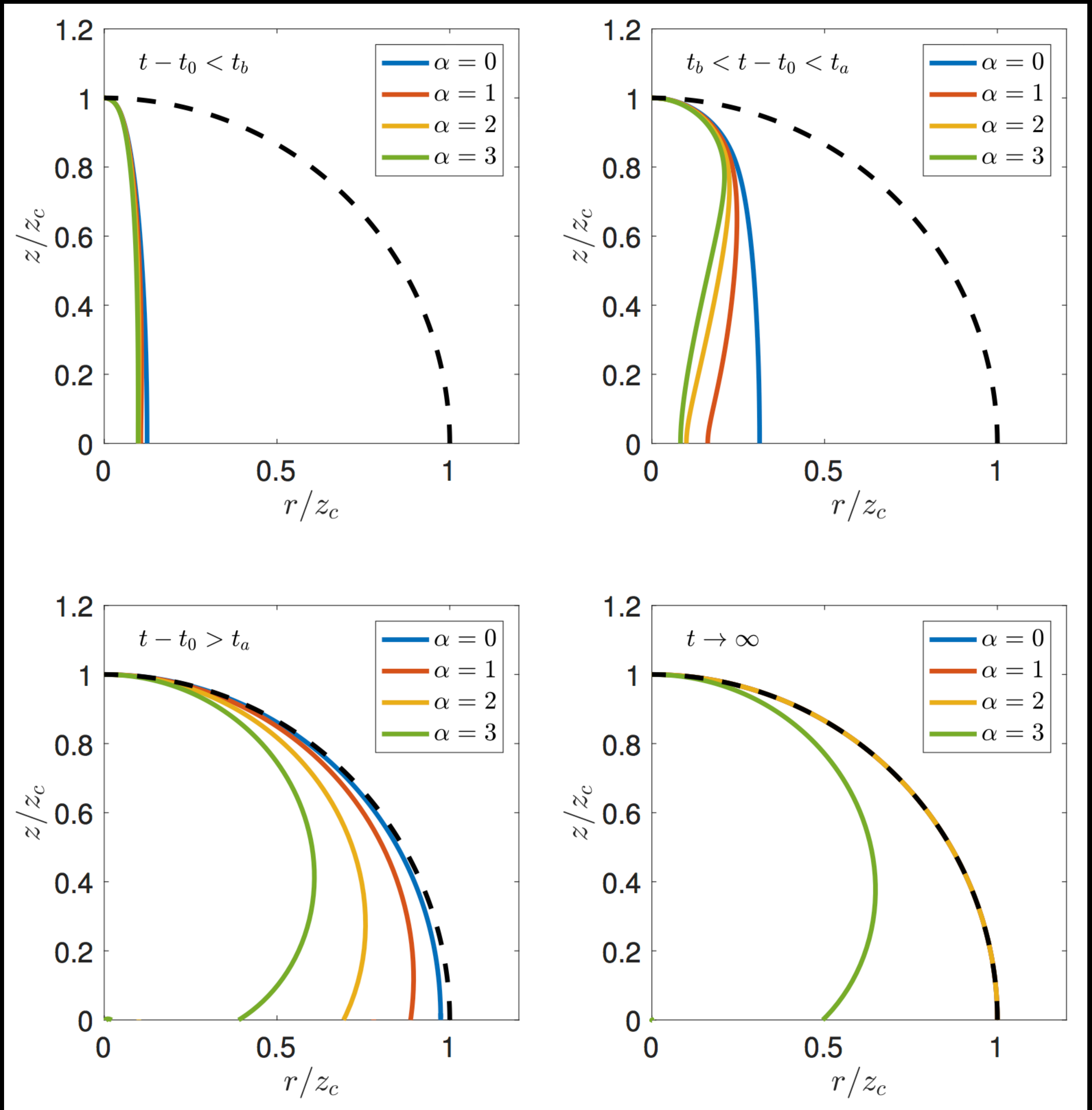
$$t_b \sim t_0 \sim \left(\frac{\rho b^4 a}{E_0}\right)^{1/2}.$$

$$t_a \sim \left(\frac{\rho a^5}{E_0}\right)^{1/2} \sim \left(\frac{a}{b}\right)^2 t_b$$

- Evolution proceeds in three phases:

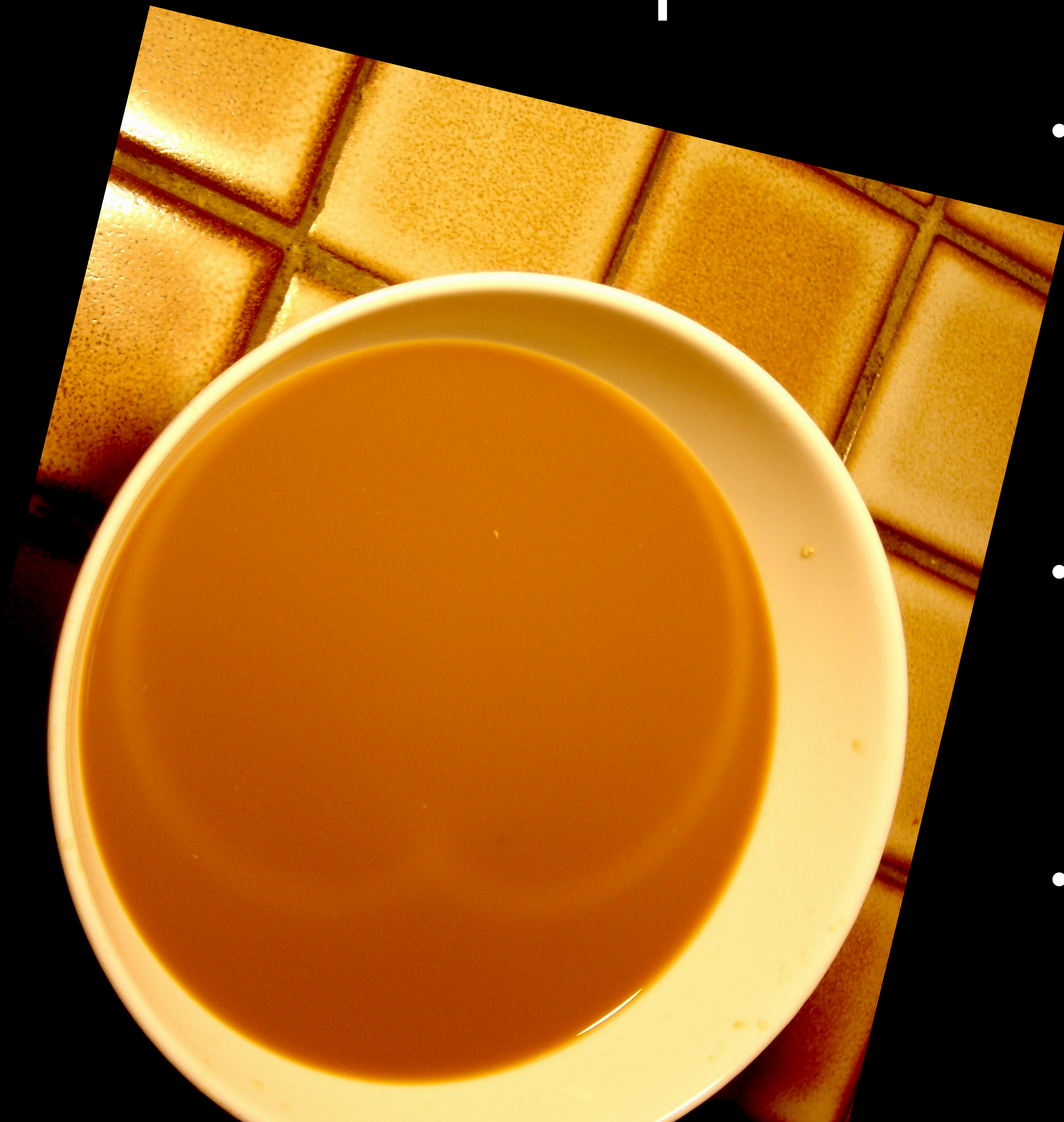
1. $t < t_b$ ($r_c < 2b$ and $z_c < 2a$). The cocoon volume is roughly constant and the pressure does not change much.
2. $t_b < t < t_a$ ($r_c > 2b$, but $z_c < 2a$): The pressure starts to drop due to sideways expansion. Most of the expansion takes place near the tip, where the density is lowest.
3. $t >> t_a$ ($z_c >> 2a$): The outflow becomes scale-free.

Overview of Results



CMI+
2019b

Shape at infinity



- Instead of a sphere, the asymptotic shape for α>2 is

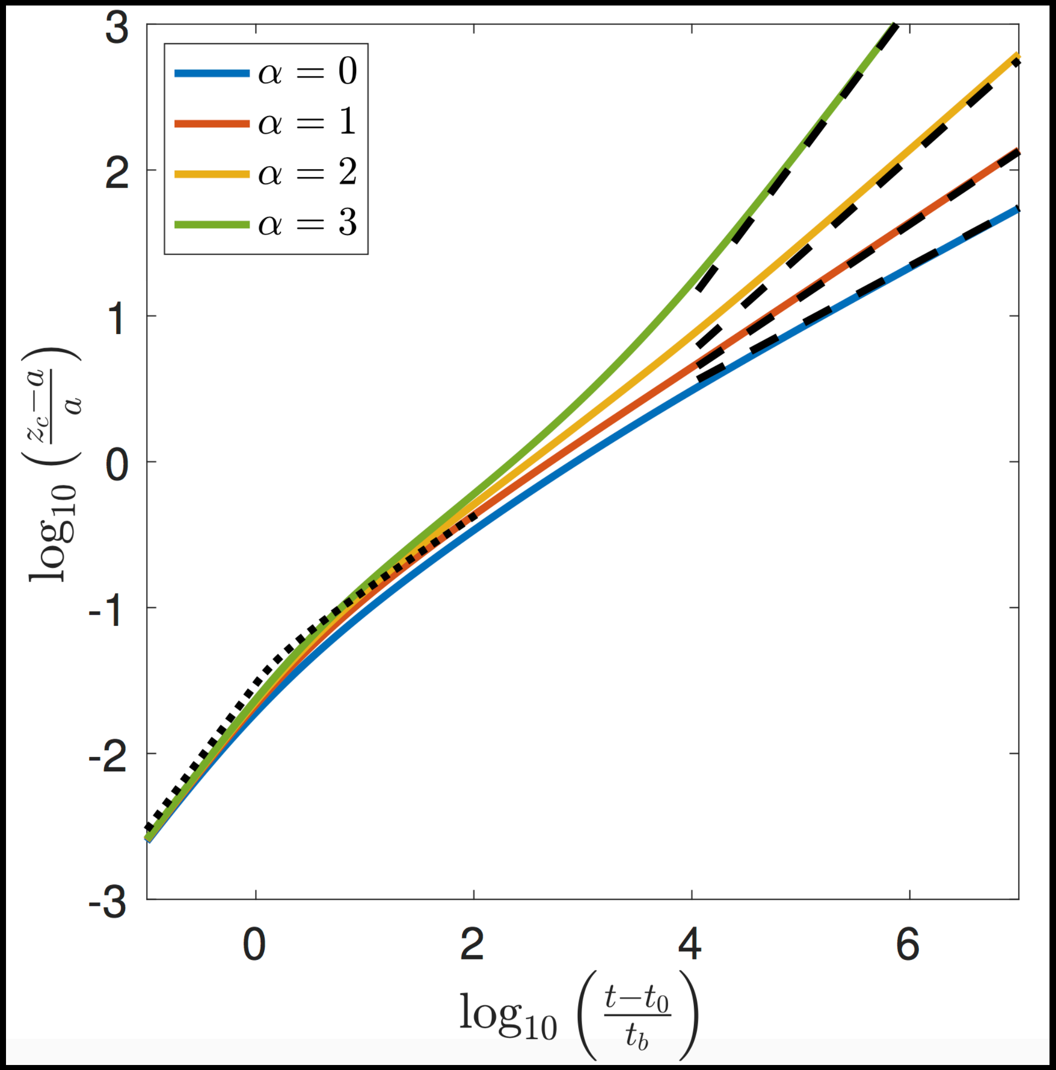
$$R(\theta) \approx z_c \left[\cos(k_\alpha \theta)\right]^{-1/k_\alpha}$$

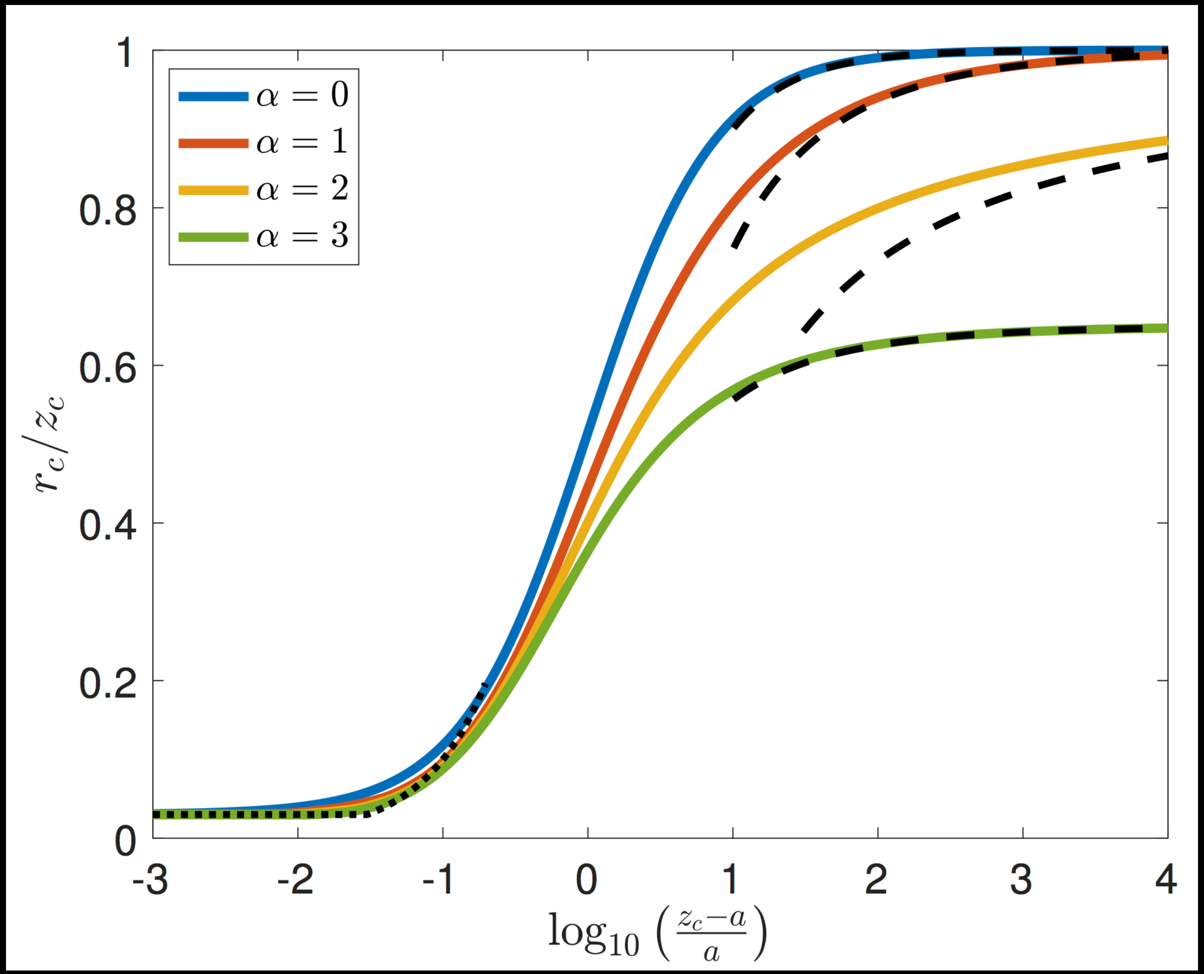
$$k_\alpha \equiv \frac{2-\alpha}{2}$$

- The limiting shape is the same as if two point explosions were set off at z=+a and z=-a (Korycansky 1992)

- Interestingly, the shape for α=3 is a cardioid

Evolution of the outflow's height and width



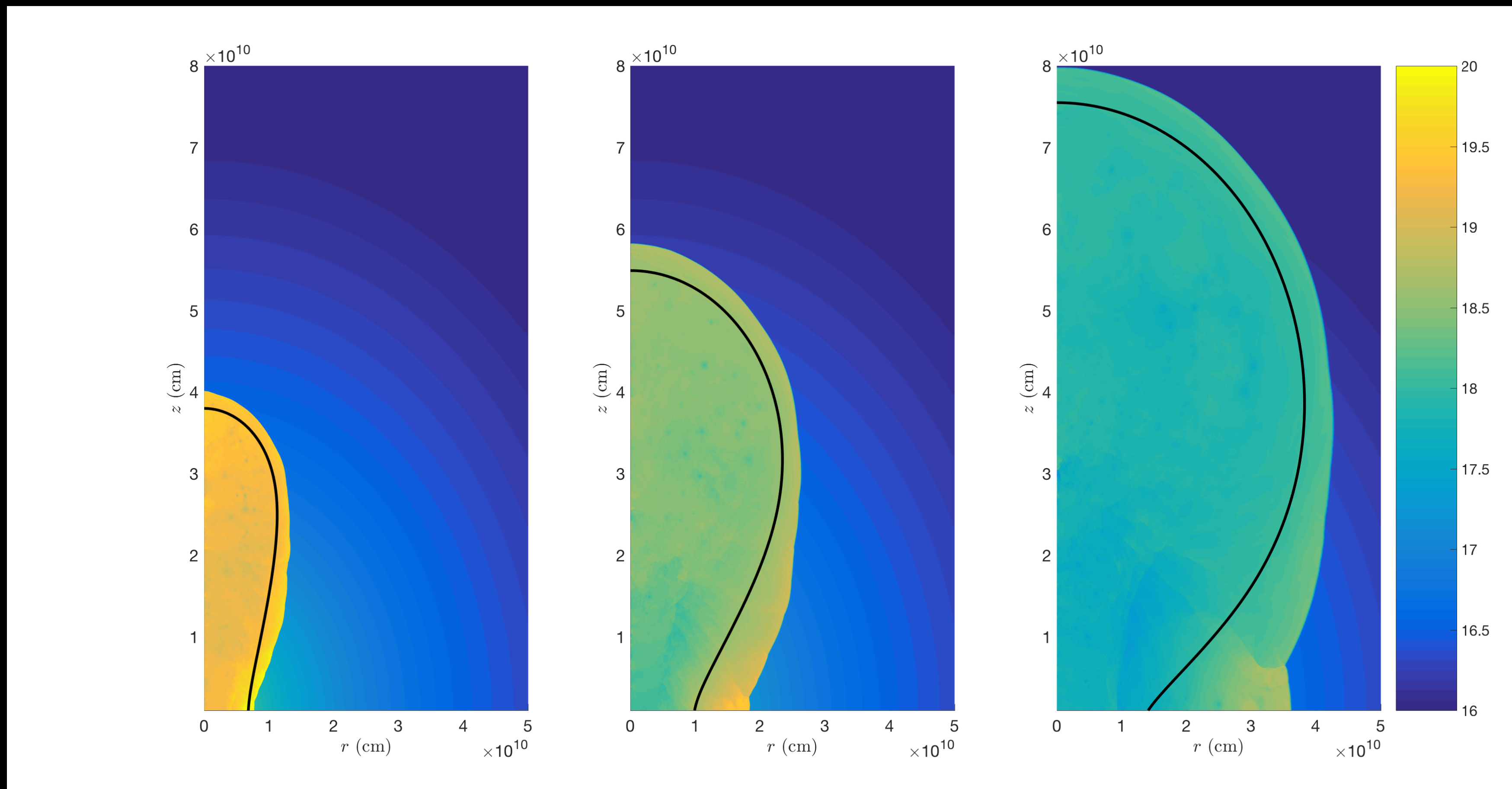


$$r_c \simeq \begin{cases} b, & z_c - a \ll b \\ z_c - a, & b \ll z_c - a \ll a \\ f_\alpha z_c \left(1 - A_\alpha/\zeta\right), & z_c \gg 2a \end{cases}$$

$$z_c \simeq \begin{cases} a + b(t/t_0 - 1), & t \lesssim 2t_0 \\ a + b\left(2t/t_0 - 3\right)^{1/2}, & 2t_0 \lesssim t \ll t_a \\ a\left(\frac{5-\alpha}{2} C_\alpha^{-1/2} \frac{b^2}{a^2} \frac{t}{t_0}\right)^{2/(5-\alpha)}, & t \gg t_a \end{cases}$$

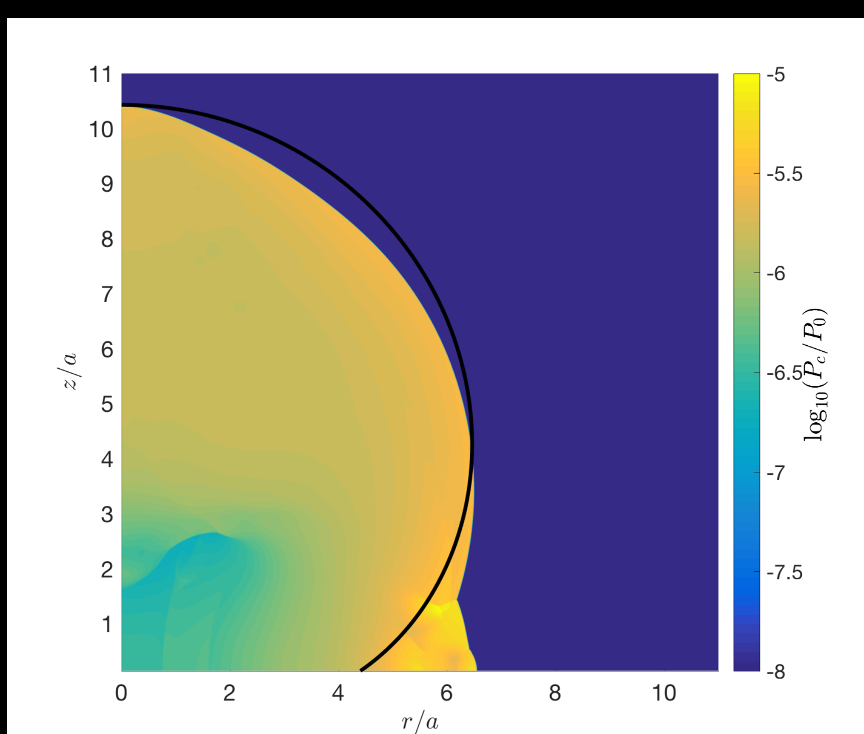
$$\zeta(z_c) \equiv \frac{(z_c/a)^{|k_\alpha|} - 1}{|k_\alpha|}$$

Comparison with Simulations

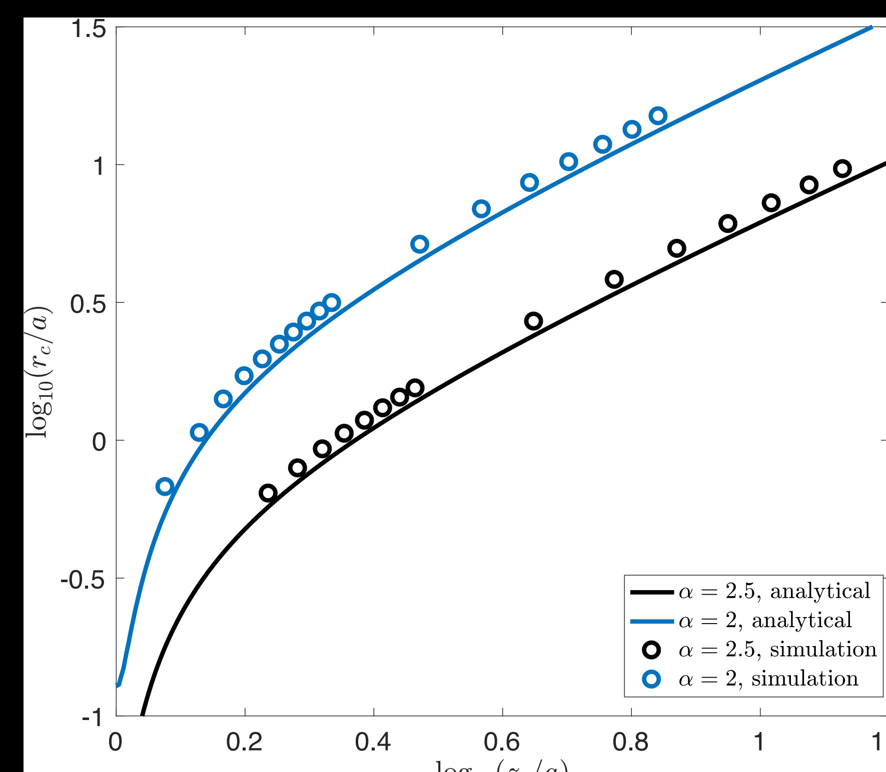


α=2

CMI+ in prep.



α=2.5



Extracting Constraints on the Jet Parameters

- **How do we glean information about the jet even if we don't observe it directly?**

- Suppose observations can provide estimates for the energy of the outflow, E_0, along with its height, z_c, and width, r_c

- In a spherical model, we have the constraint $L_j t_j = E_0$ —and that's it

- However, with information on the asphericity, it is possible to estimate the radius, a, where the jet deposited its energy:

$$a \sim \begin{cases} z_c - r_c, & z_c - r_c \gtrsim z_c/2 \\ [z_c^{-\alpha}(z_c - r_c)^2]^{1/(2-\alpha)}, & z_c - r_c \ll z_c/2. \end{cases}$$

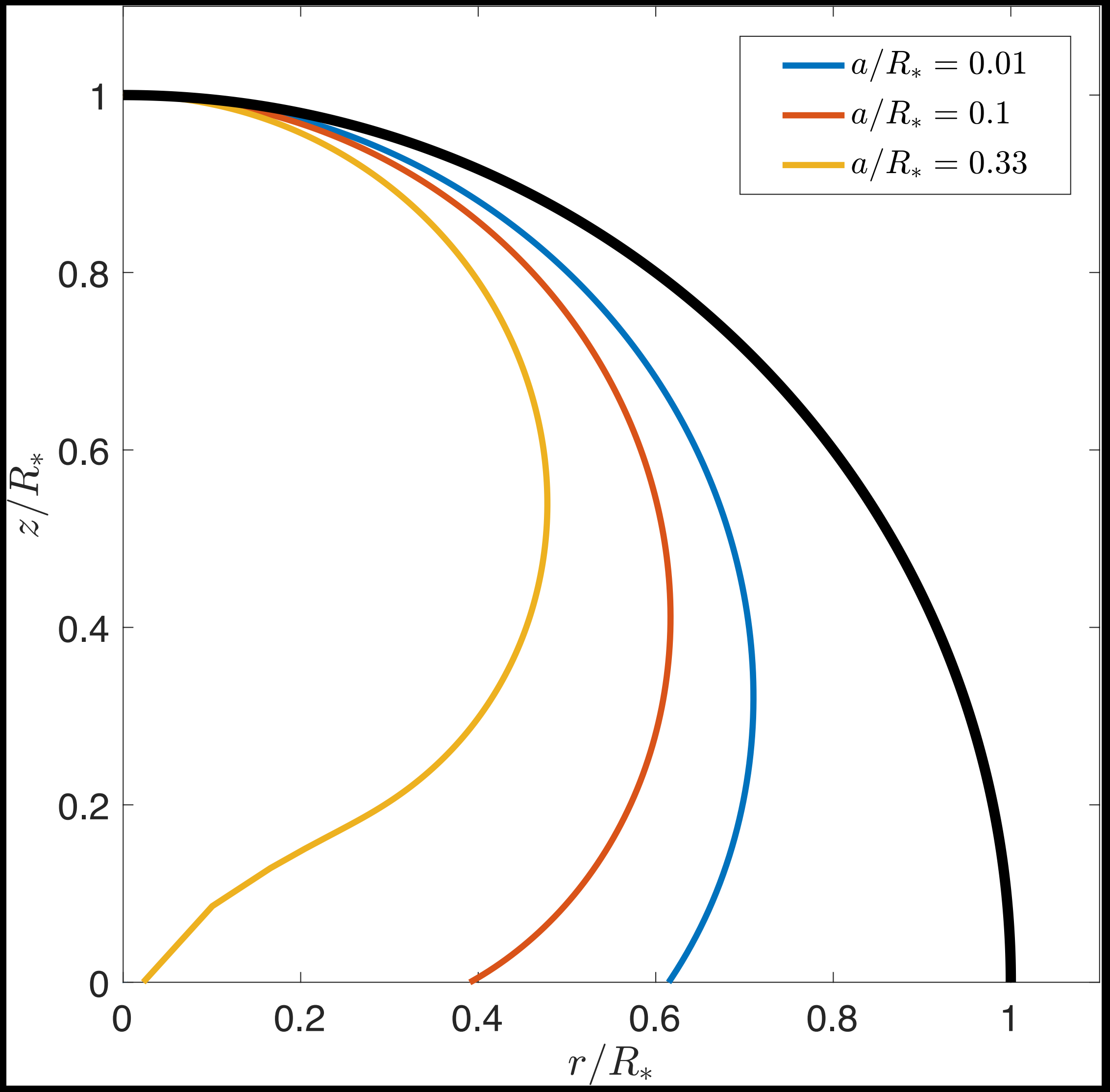
- If the density at z_c is also known, this translates into a constraint on the jet duration and opening angle:

$$t_j \theta_{op}^{-2} \sim \left(\frac{\rho(z_c) z_c^5}{E_0}\right)^{1/2} \left(\frac{z_c - r_c}{z_c}\right)^{q_\alpha}$$

$$q_\alpha \equiv \begin{cases} (5-\alpha)/2, & z_c - r_c \gtrsim z_c/2 \\ (5-\alpha)/(2-\alpha), & z_c - r_c \ll z_c/2 \end{cases}$$

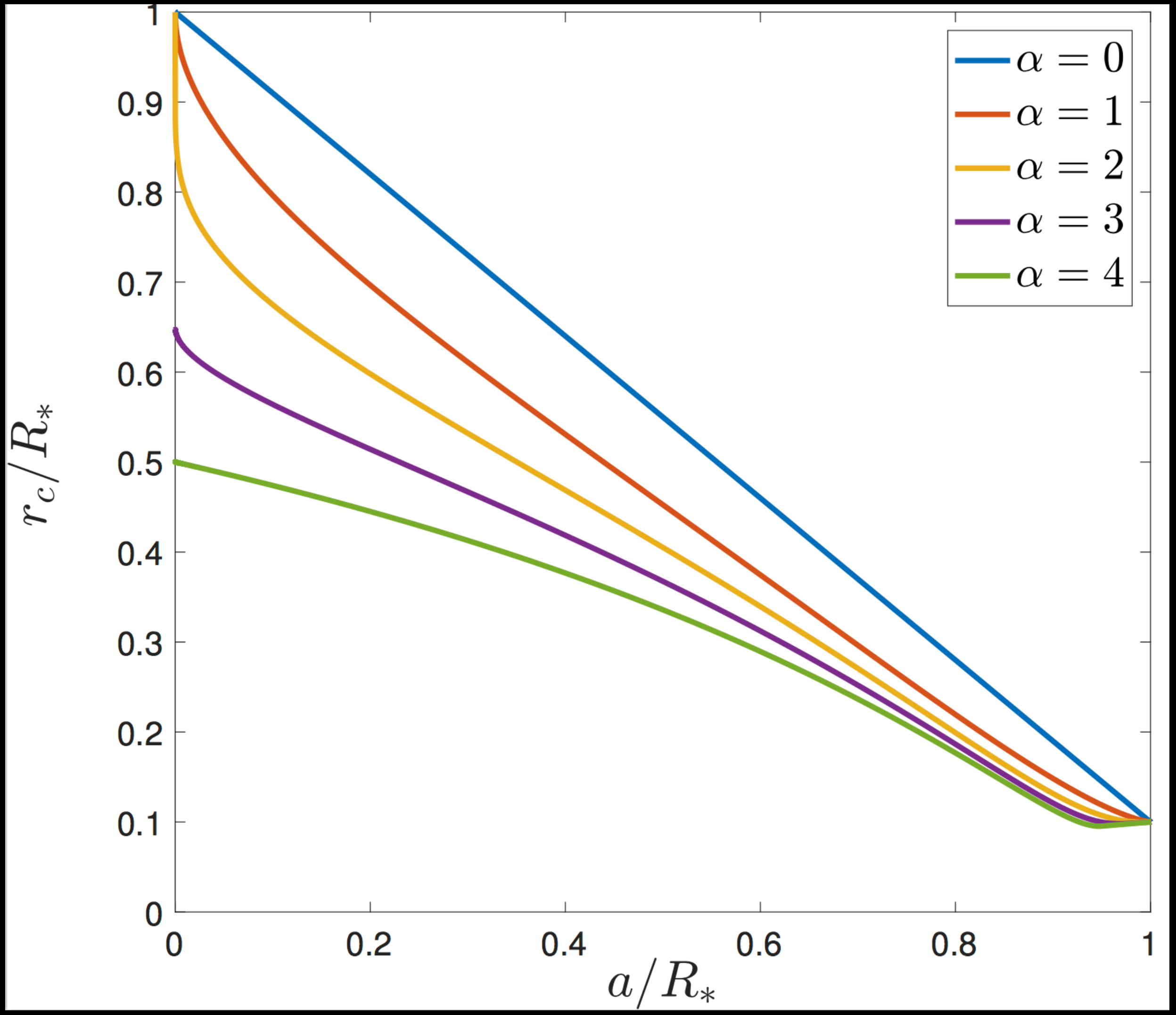
Future Applications

- AGN bubbles (CMI+ 2019a)
- Shock breakout signature
  - The breakout signal is sensitive to deviations from sphericity; it may be possible to use this to constrain the choking radius
- Cocoon cooling emission
- Distribution of velocity with mass



Future Applications

- AGN bubbles (CMI+, submitted)
- Shock breakout signature
- Cocoon cooling emission
  - The timescale of cooling emission enables an estimate of the mass swept up by the cocoon, M_c
- Distribution of velocity with mass

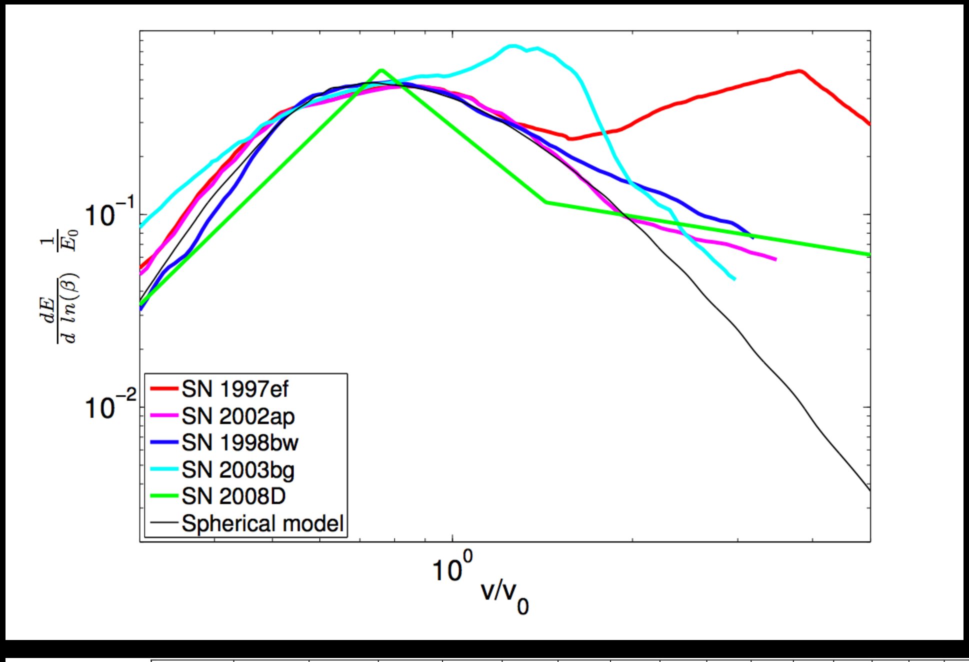


At breakout:

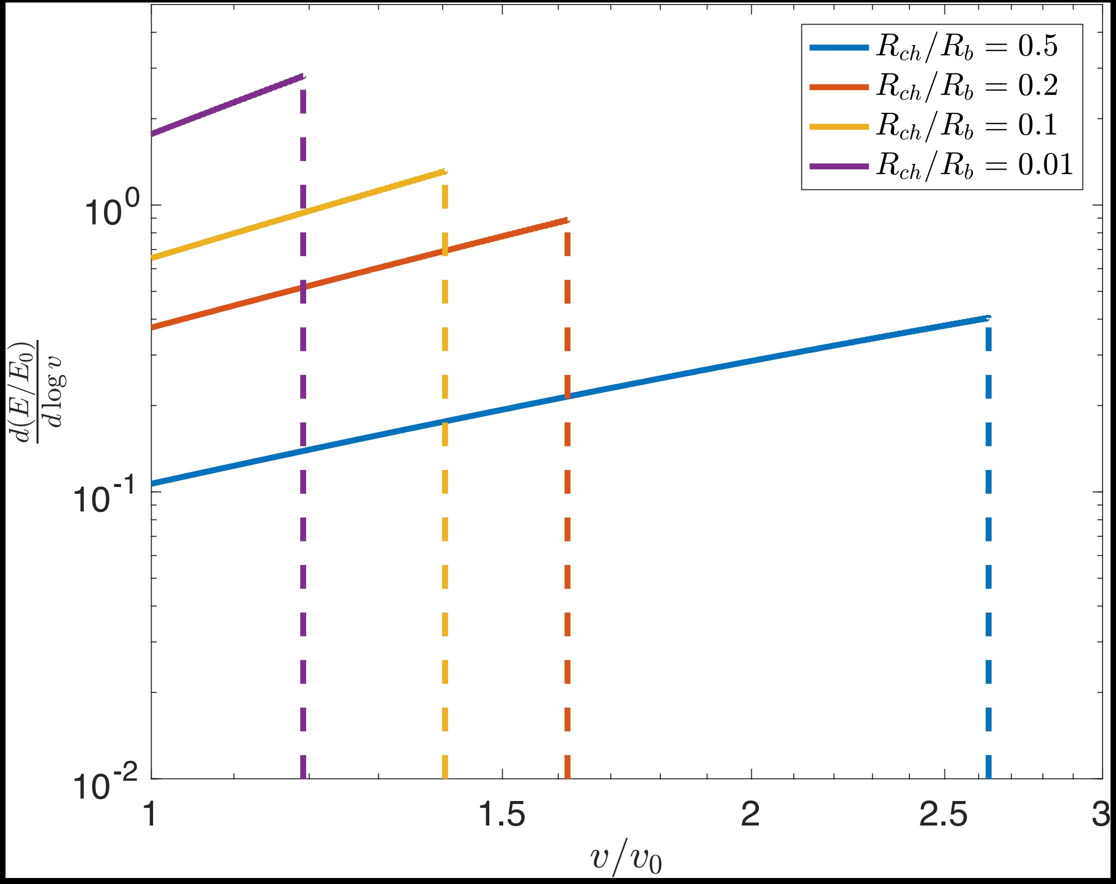
$$z_c \sim R_*$$
$$r_c/z_c \sim (M_c/M_*)^{1/2}$$

Future Applications

- AGN bubbles (CMI+, submitted)
- Shock breakout signature
- Cocoon cooling emission
- Distribution of velocity with mass
  - Can be calculated and compared to observations to estimate choking location and jet energy



Piran+ 2019



PRELIMINARY

Conclusions

- Choked jet outflows are inherently aspherical, and that asphericity carries valuable information about the central engine’s properties

- There are many potential avenues to constrain the shape of the outflow through observations

- If the shape of the shock is constrained, a lot can be learned about the jet’s properties, even if you don’t see the jet itself