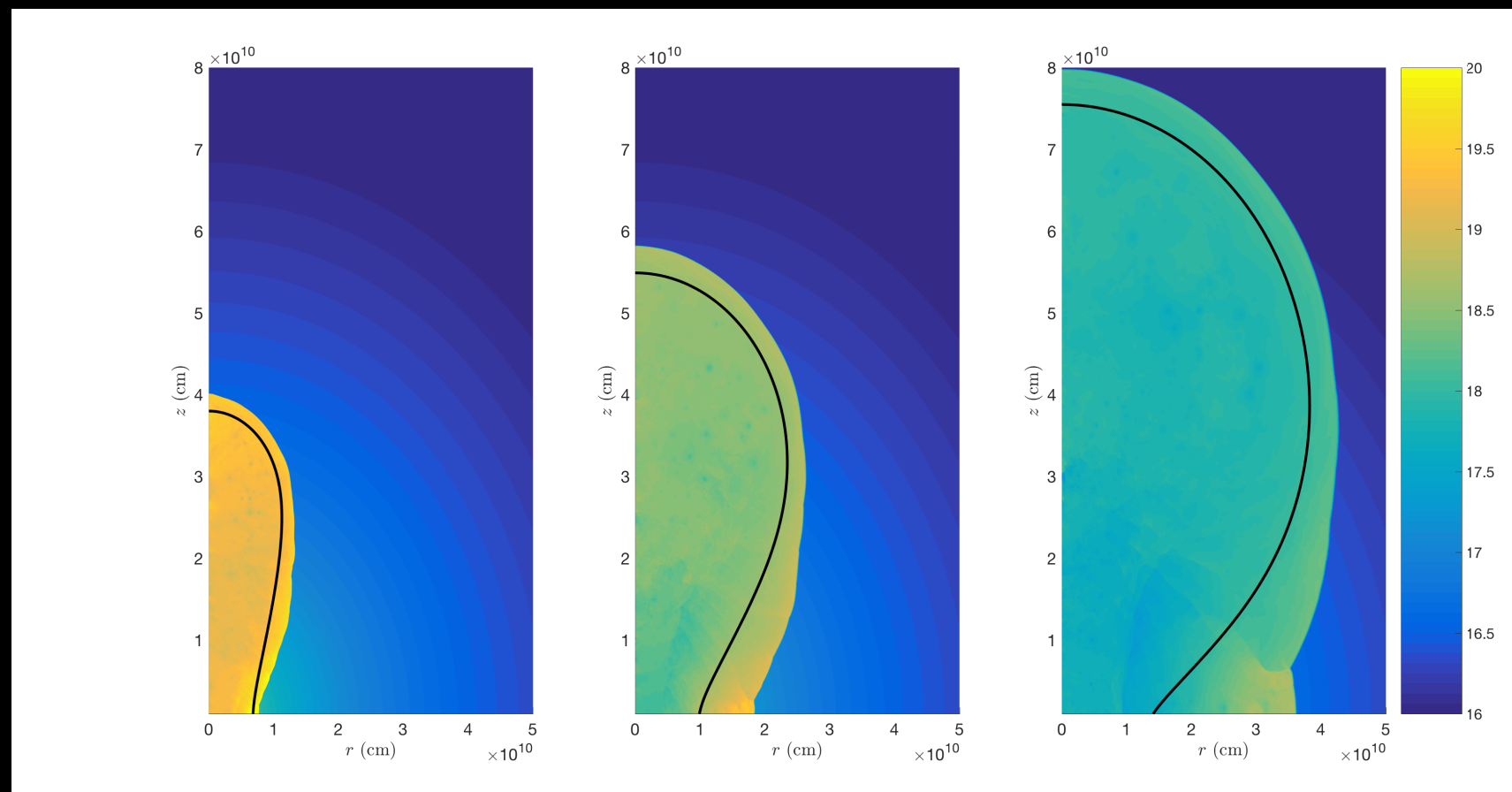


The Propagation of Choked Jet Outflows

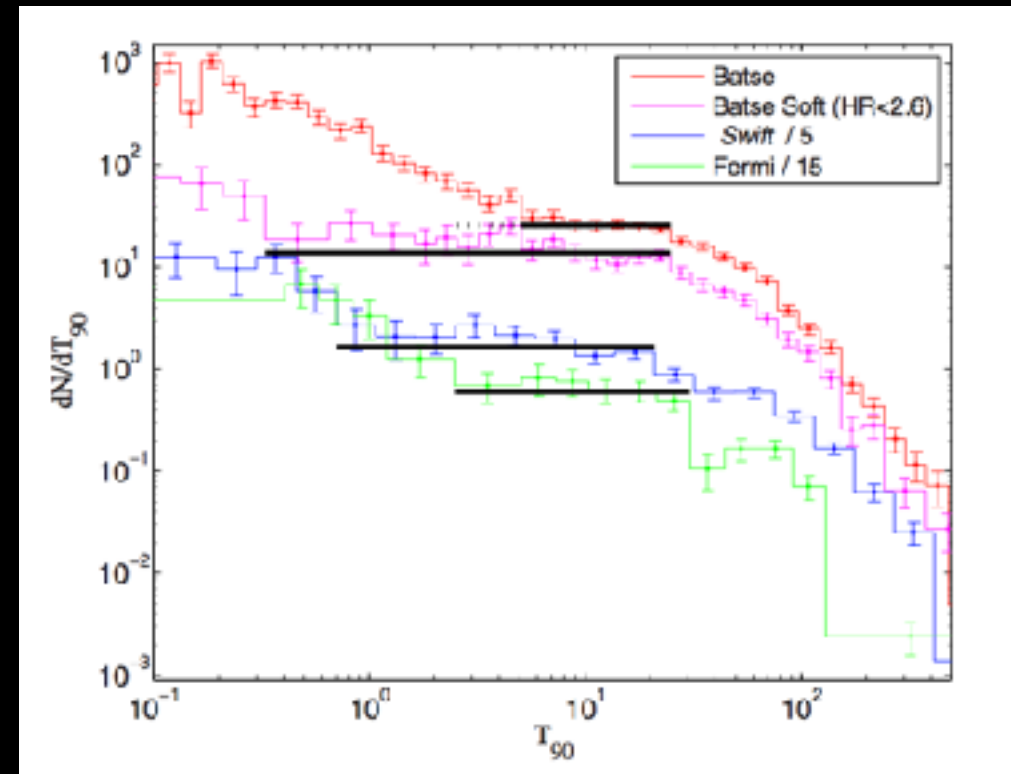
Christopher Irwin, HUJI/TAU

Collaborators: Tsvi Piran (HUJI), Ehud Nakar & Ore Gottlieb (TAU)

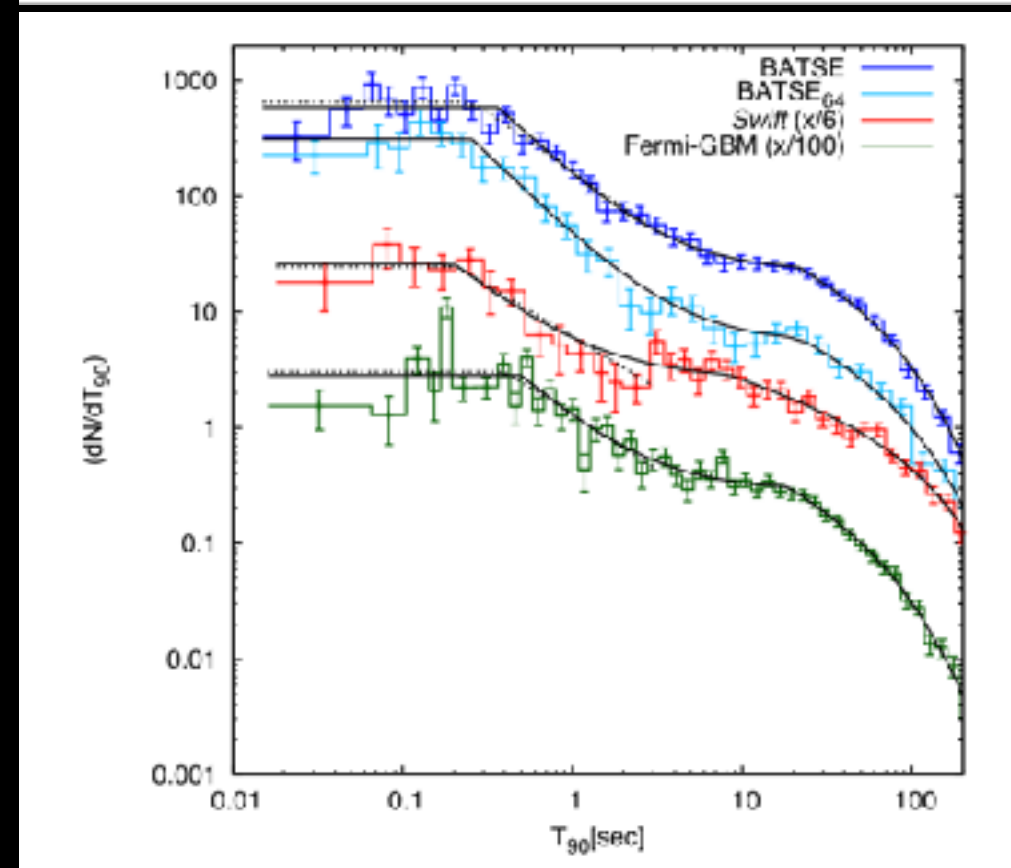


Evidence for Choked Jets in Long GRBs

- 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



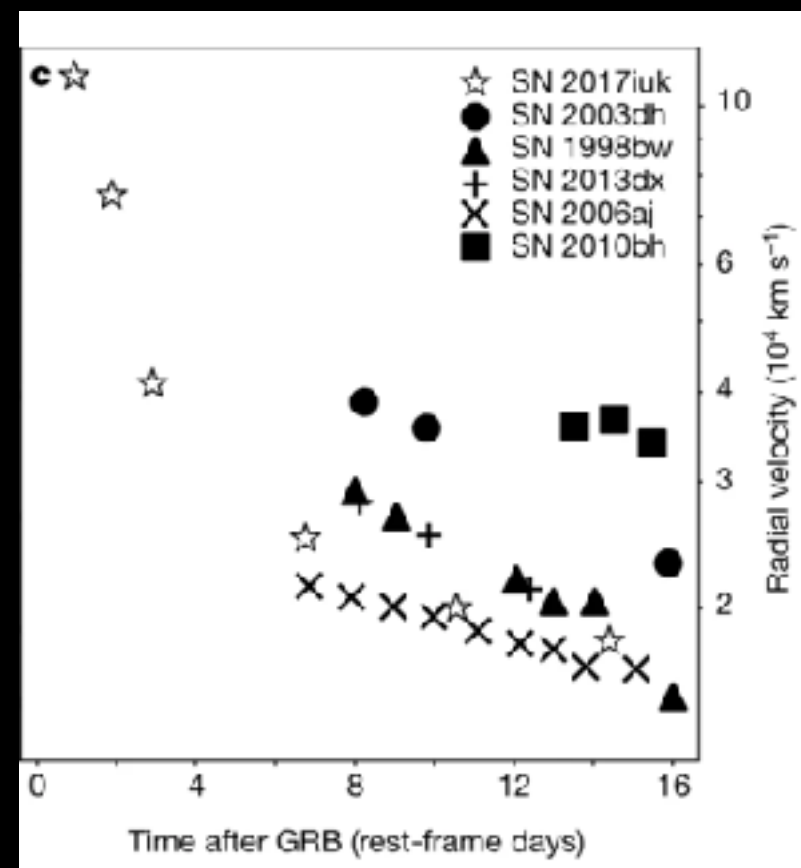
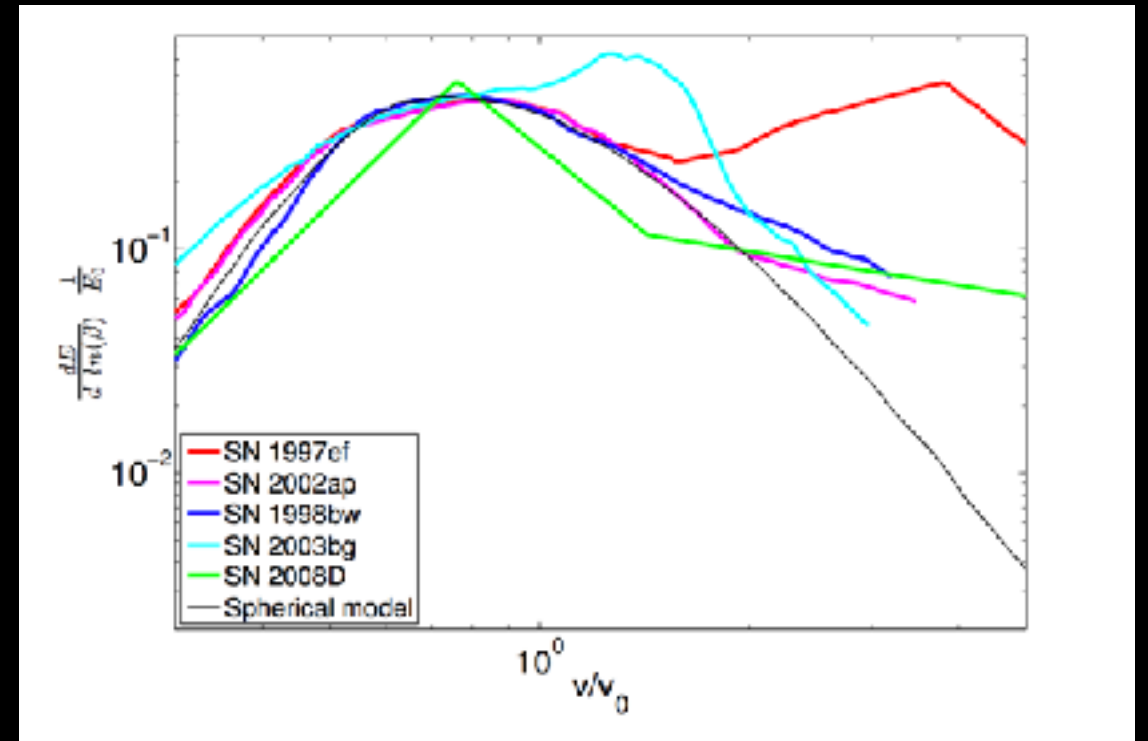
Bromberg+
2012



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 ($\sim 0.1 M_{\text{sun}}$) and energy ($\sim 1 \text{ foe}$) are consistent with expectations for a GRB jet's cocoon
- Low-luminosity GRBs

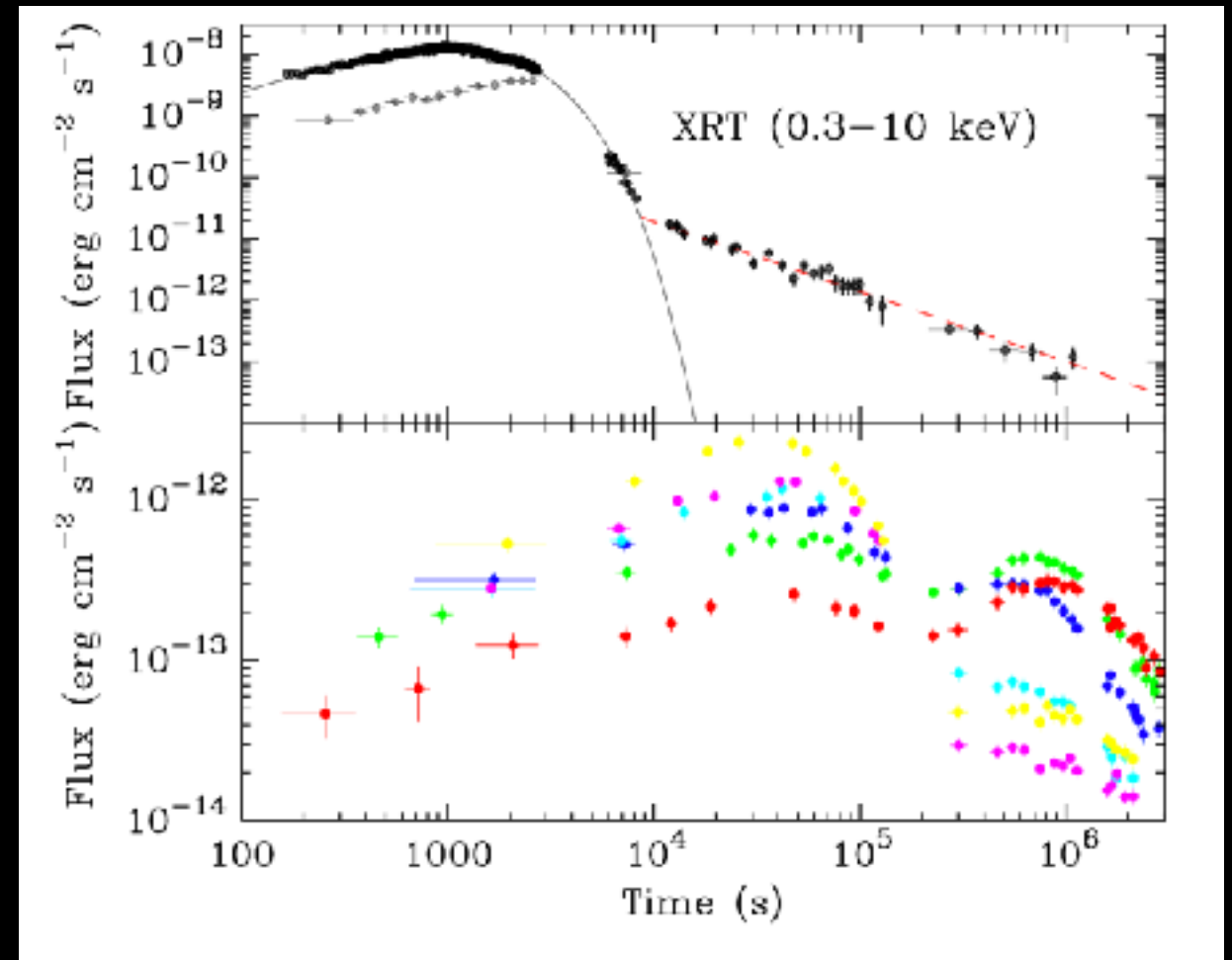


Piran+ 2019

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 ($\sim 100 R_{\text{sun}}$) envelope with sufficient mass (0.01 M_{sun}) to choke a standard GRB jet



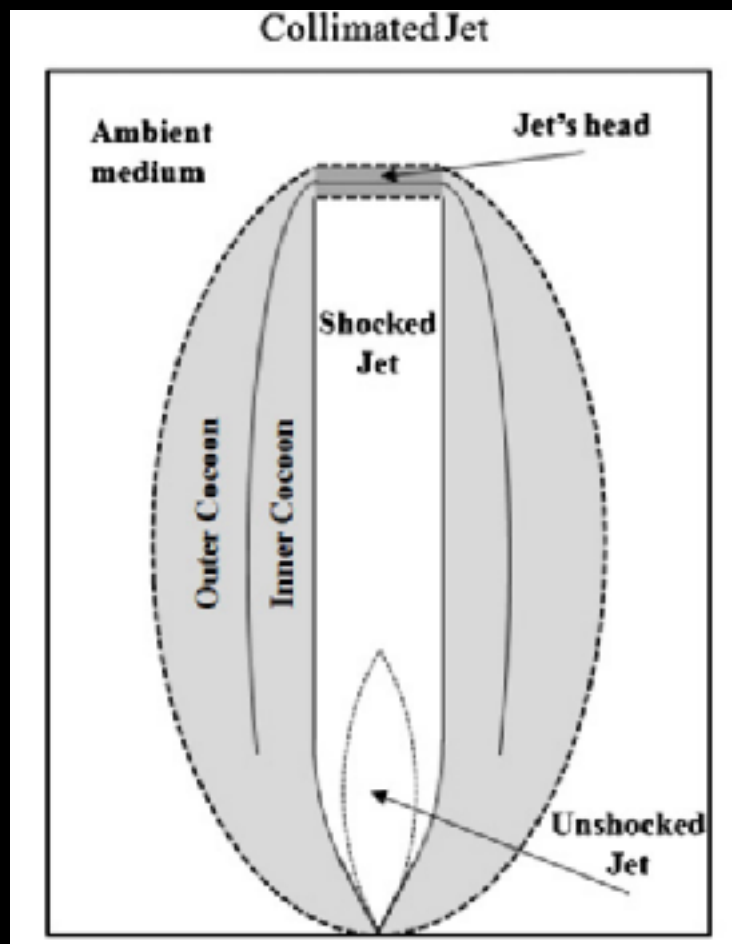
Campana+ 2006

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

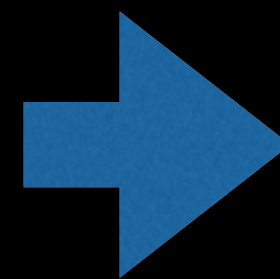
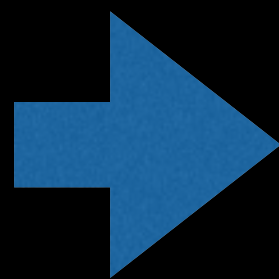
Nakar & Sari 2012

A gap in our analytical understanding

Active jet



Bromberg+ 2011



Scale-free
blast wave

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

Two Key Questions

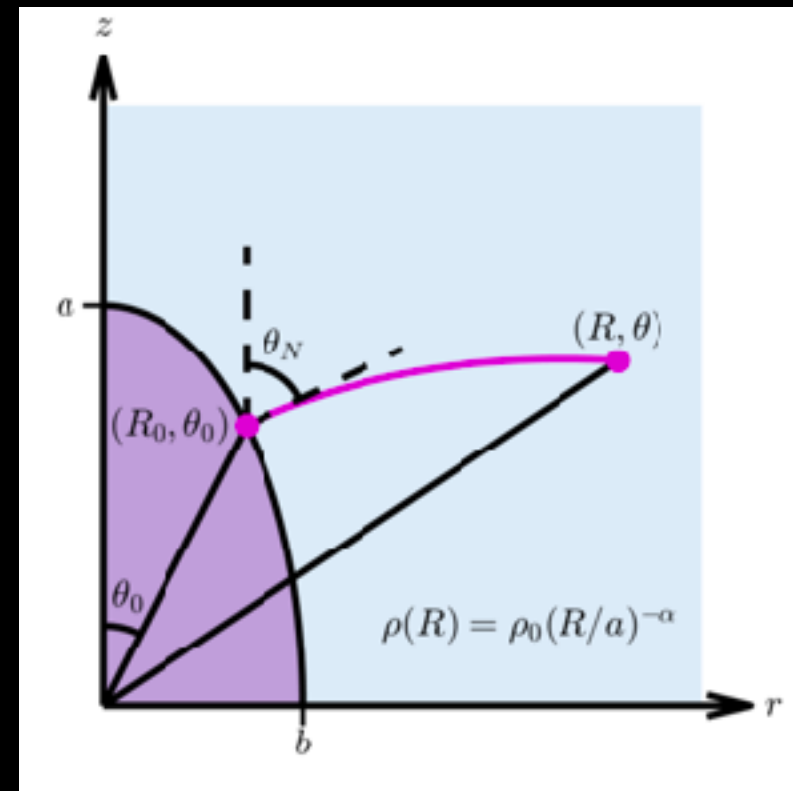
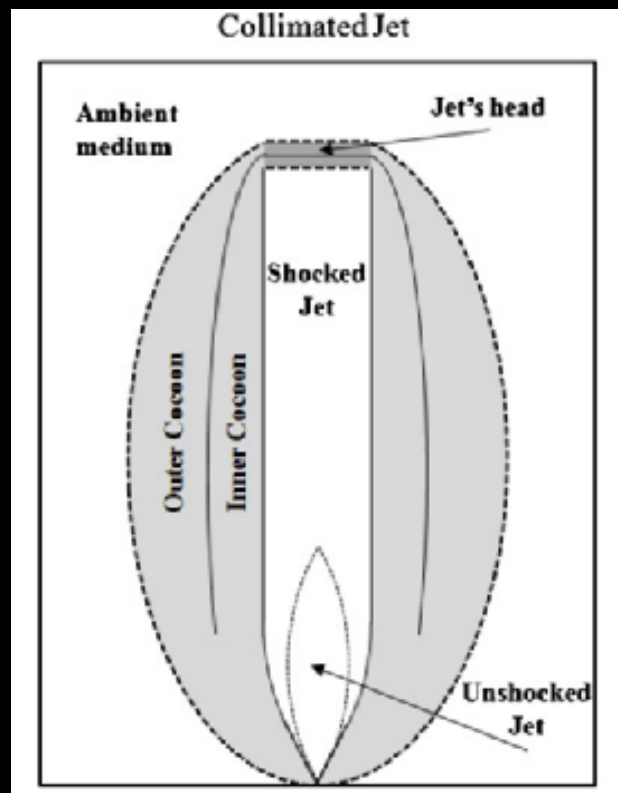
- What happens to a jet-driven outflow after the jet is switched off?
- What can we learn about the jet's properties by studying the 'choked' outflow it leaves behind?

Jet Choking

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

Before

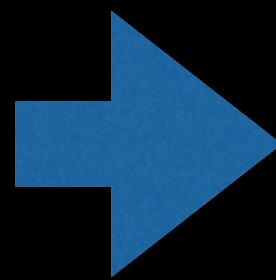
Bromberg+ 2011



After

CMI+ (in prep)

luminosity, L_j
 duration, t_b
 op. angle, θ_0



energy, E_0
 initial height, a
 initial width, b

- For a collimated relativistic jet, $a/b \gg 1$.

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:

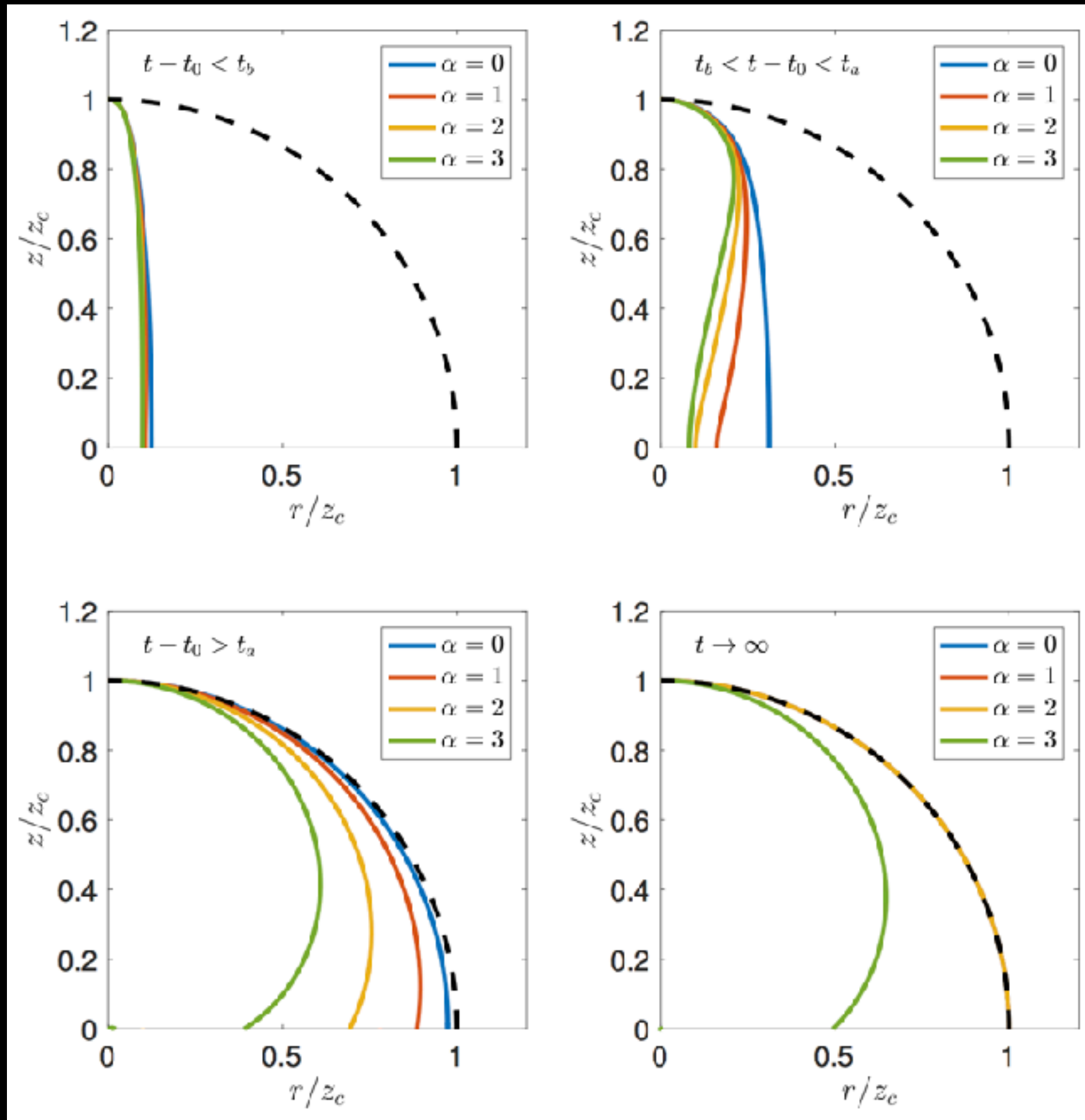
- The time for the width to double, t_b
- The time for the height to double, t_a

$$t_b \sim t_0 \sim \left(\frac{\rho b^4 a}{E_0} \right)^{1/2} .$$
$$t_a \sim \left(\frac{\rho a^5}{E_0} \right)^{1/2} \sim \left(\frac{a}{b} \right)^2 t_b$$

- 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. $t \gg t_a$ ($z_c \gg 2a$): The outflow becomes scale-free.

Overview of Results



CMI+
in prep.

Shape at infinity

- Instead of a sphere, the asymptotic shape for $\alpha > 2$ is

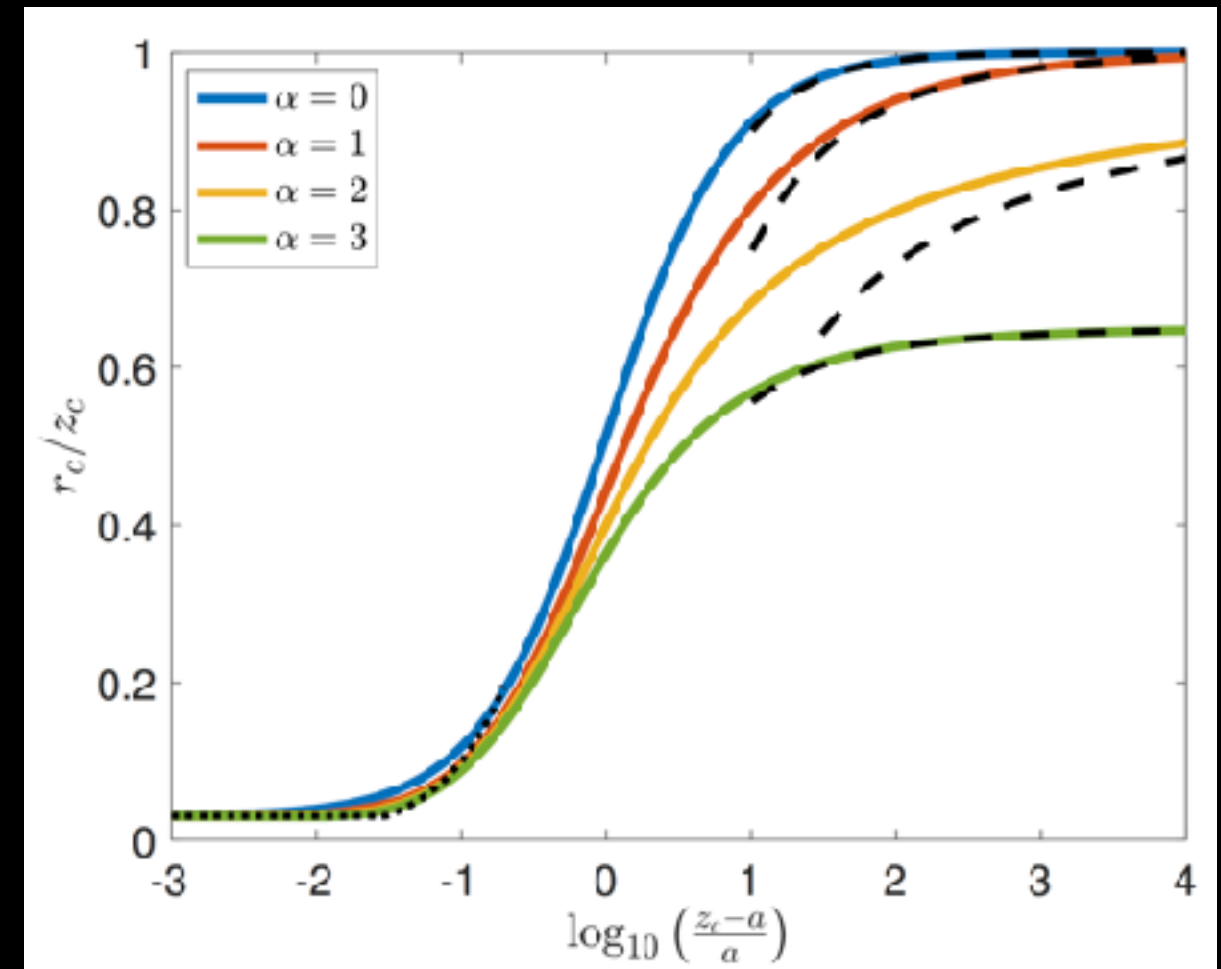
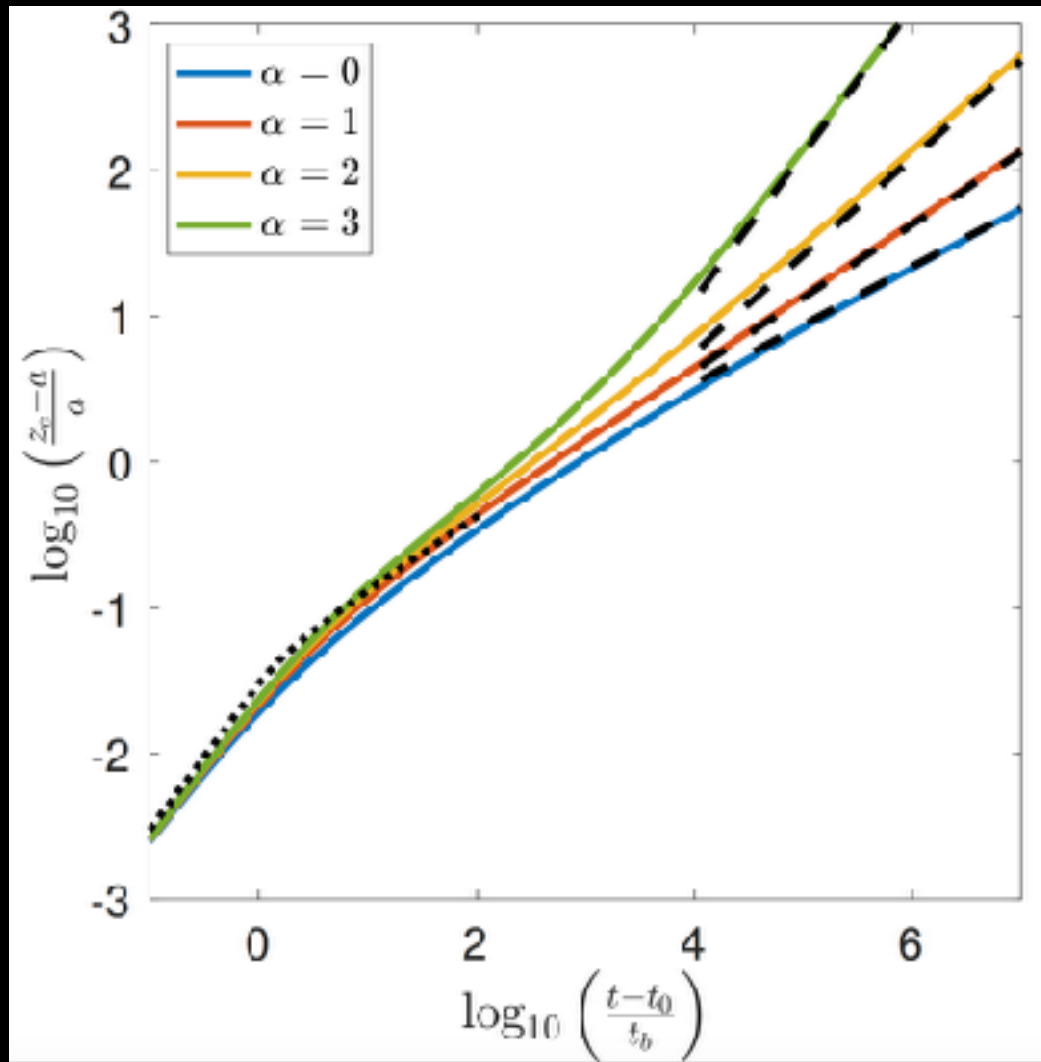
$$R(\theta) \approx z_c [\cos(k_\alpha \theta)]^{-1/k_\alpha}$$

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

- 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 $\alpha = 3$ is a cardioid



Evolution of the outflow's height and width

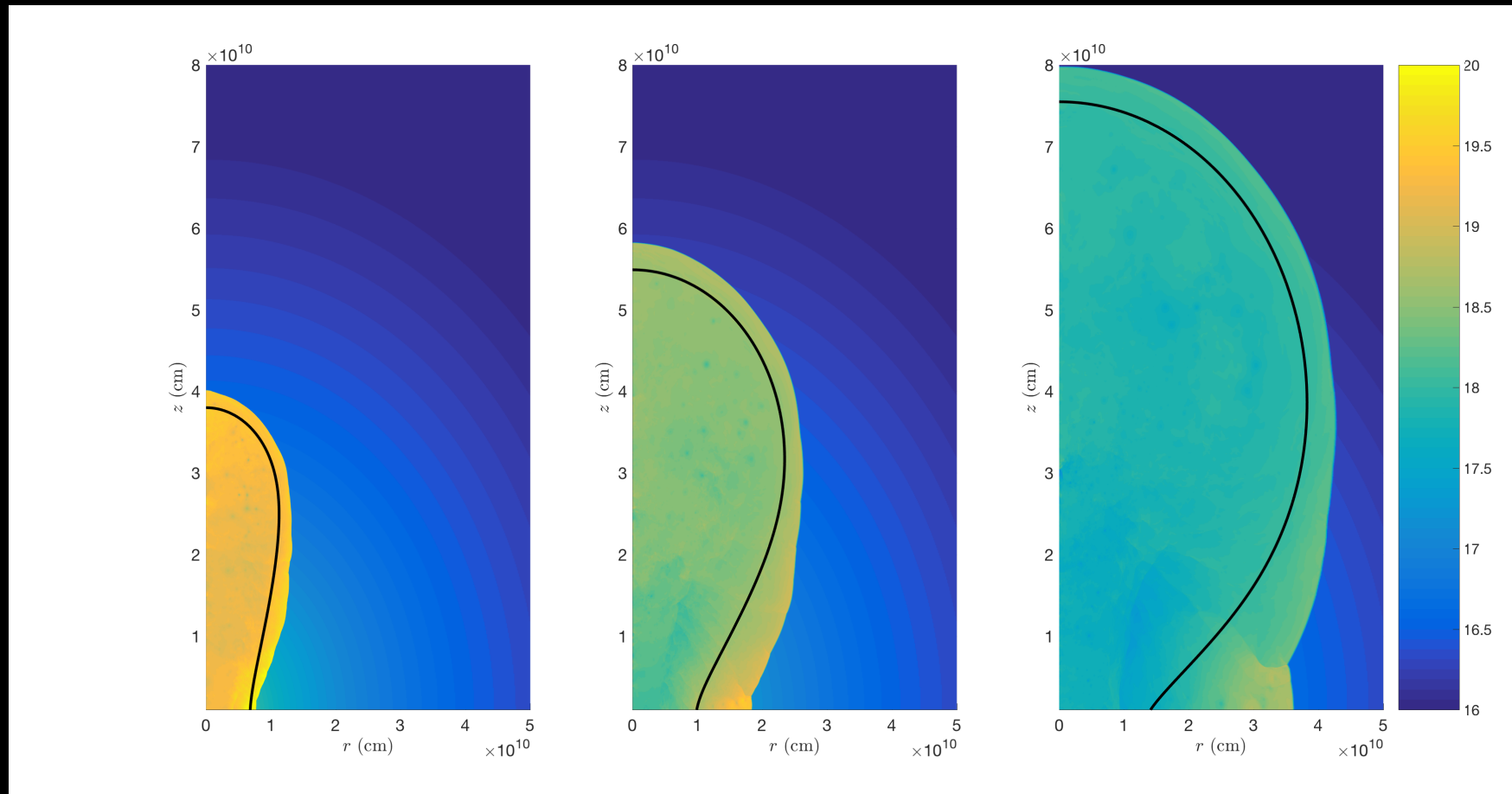


$$z_c \simeq \begin{cases} a + b(t/t_0 - 1), & t \lesssim 2t_0 \\ a + b(2t/t_0 - 3)^{1/2}, & 2t_0 \lesssim t \ll t_a \\ a \left(\frac{5-\alpha}{2} C_\alpha^{-1/2} \frac{b^2}{a^2} \frac{t}{t_0} \right)^{2/(5-\alpha)}, & t \gg t_a \end{cases}$$

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

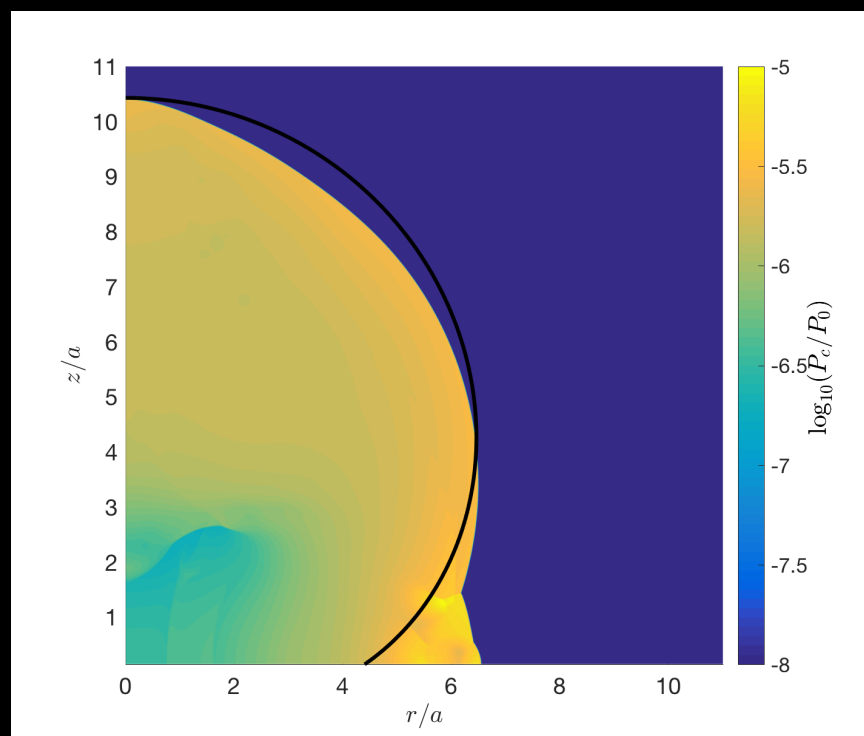
$$\zeta(z_c) \equiv \frac{(z_c/a)^{|k_\alpha|} - 1}{|k_\alpha|}$$

Comparison with Simulations

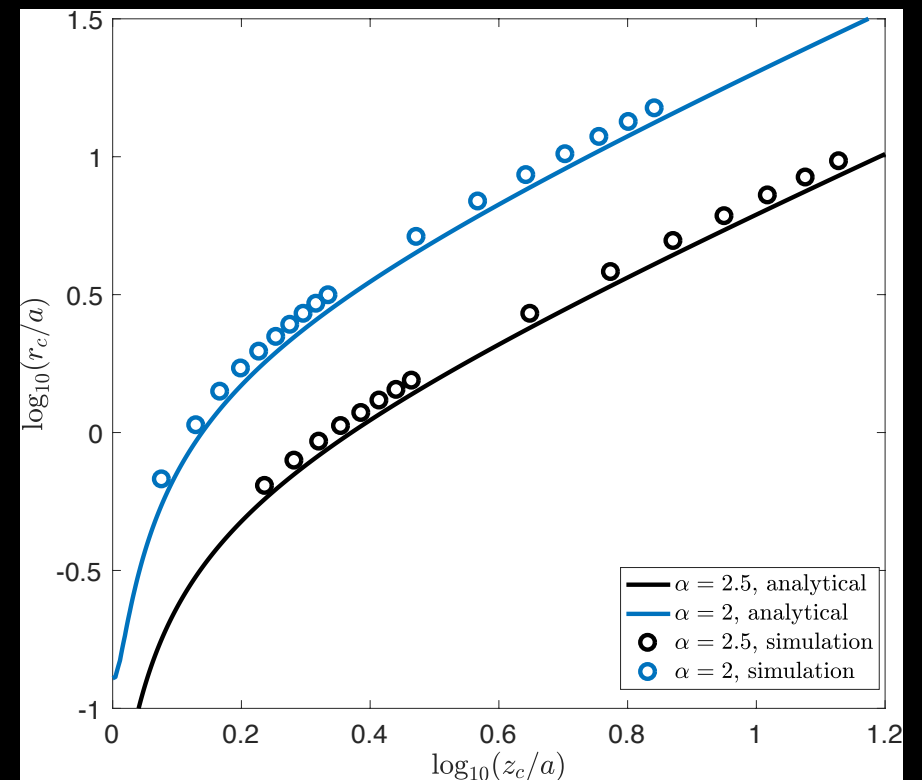


$\alpha=2$

CMI+ in prep.



$\alpha=2.5$



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:

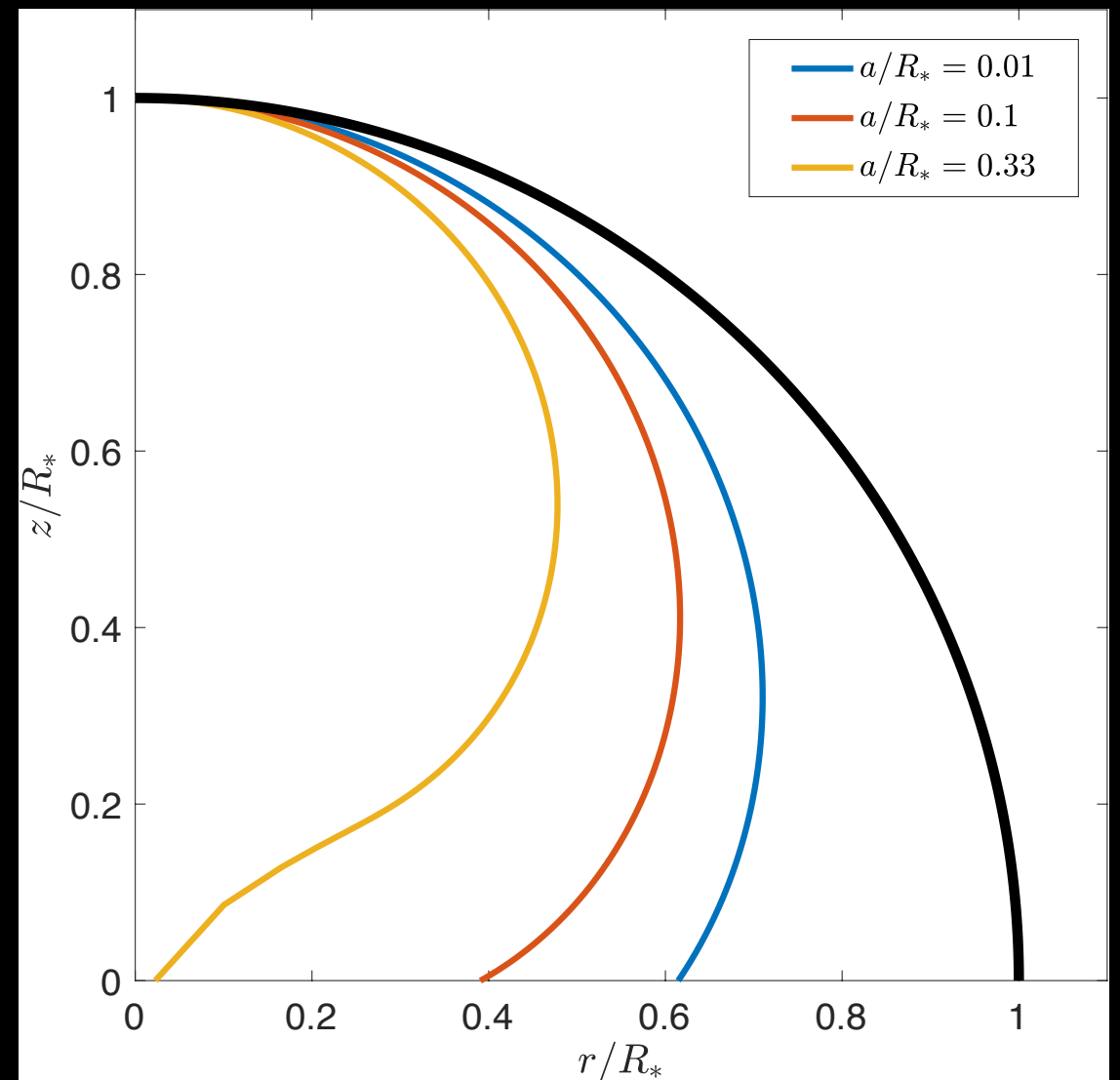
$$a \sim \begin{cases} z_c - r_c, & z_c - r_c \gtrsim z_c/2 \\ [z_c^{-\alpha} (z_c - r_c)^2]^{1/(2-\alpha)}, & z_c - r_c \ll z_c/2 \end{cases}$$

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

$$t_j \theta_{op}^{-2} \sim \left(\frac{\rho(z_c) z_c^5}{E_0} \right)^{1/2} \left(\frac{z_c - r_c}{z_c} \right)^{q_\alpha} \quad q_\alpha \equiv \begin{cases} (5 - \alpha)/2, & z_c - r_c \gtrsim z_c/2 \\ (5 - \alpha)/(2 - \alpha), & z_c - r_c \ll z_c/2 \end{cases}$$

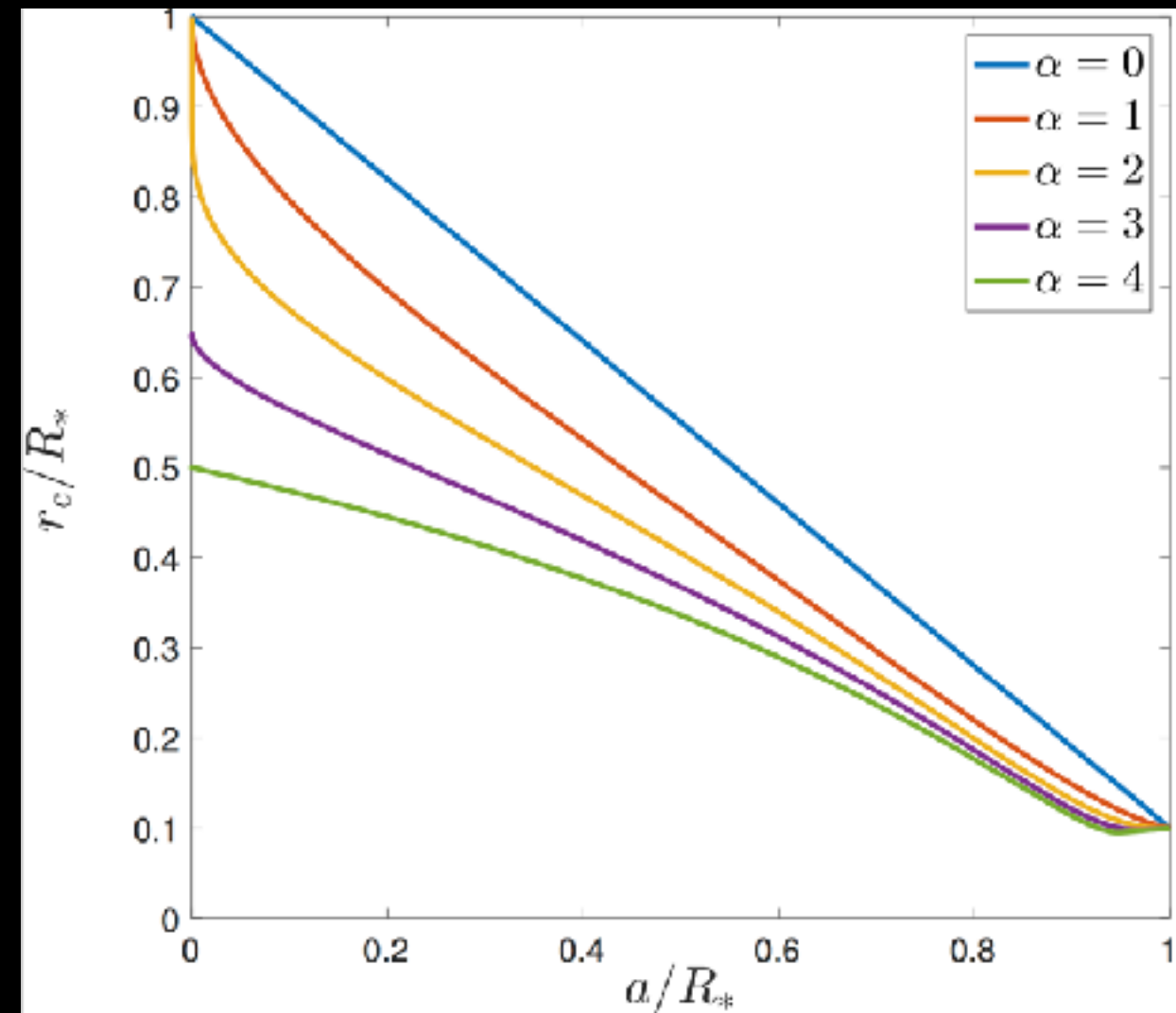
Future Applications

- AGN bubbles (CMI+, submitted)
- 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

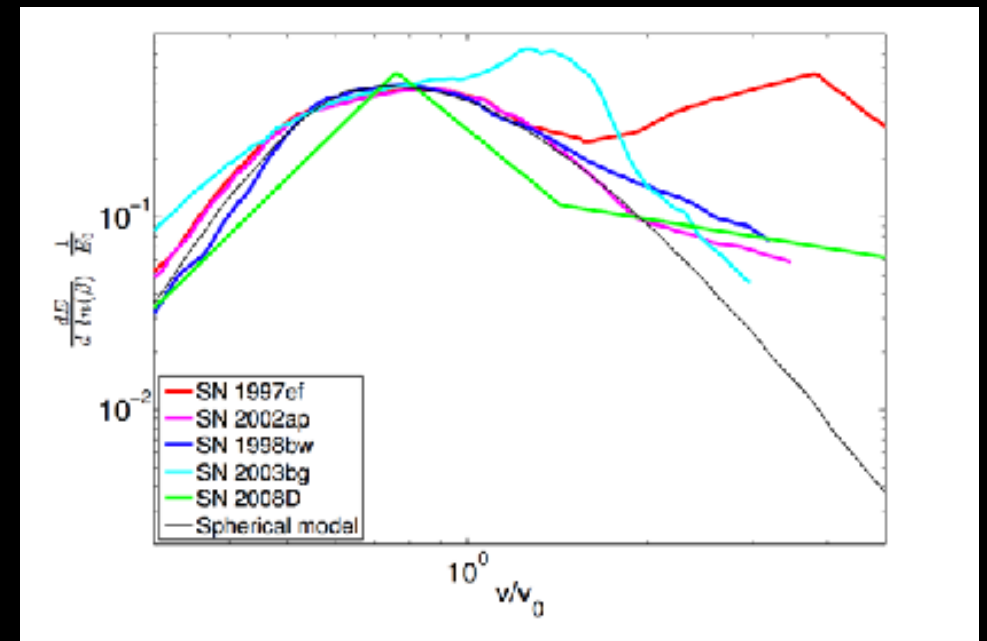


At breakout:

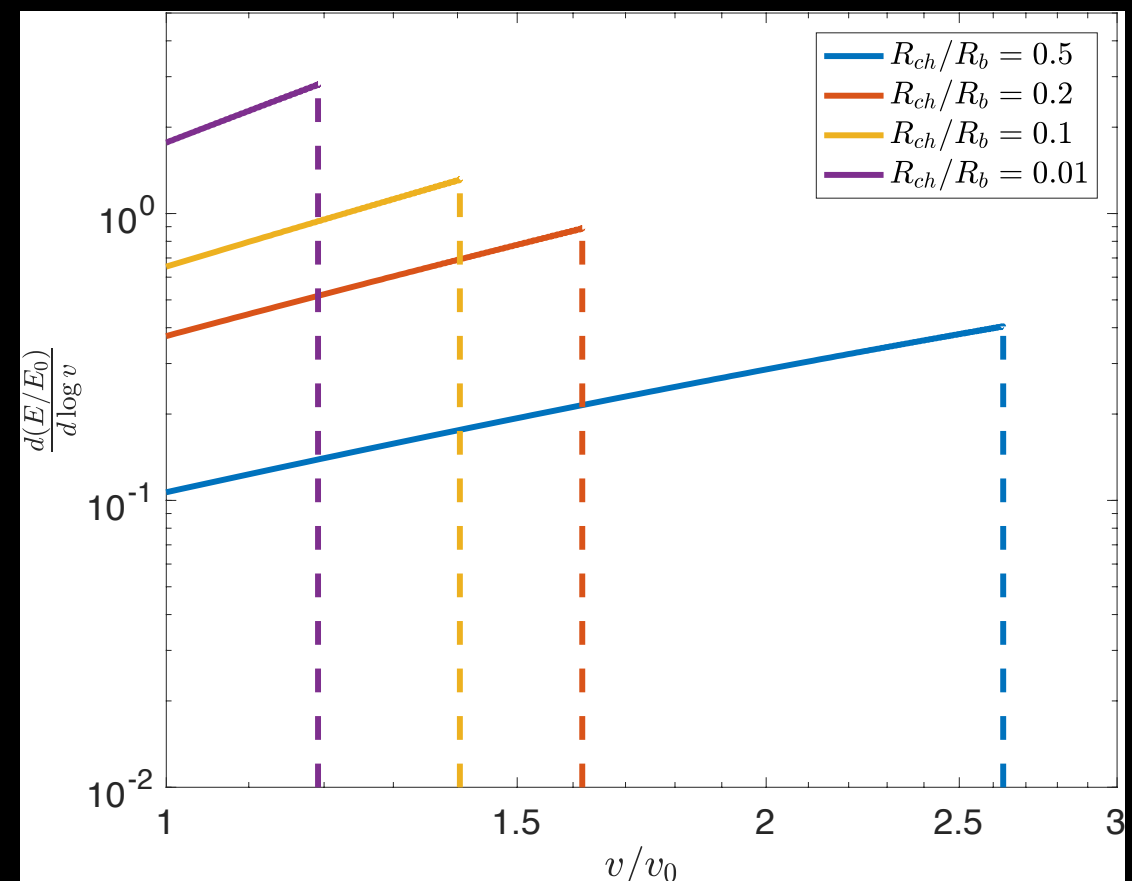
$$z_c \sim R_*$$
$$r_c/z_c \sim (M_c/M_*)^{1/2}$$

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