Relativistic Jet Acceleration, Collimation & Stability

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The Strongest Magnetic Fields in the Universe, ISSI, Bern, 6 Feb. 2014

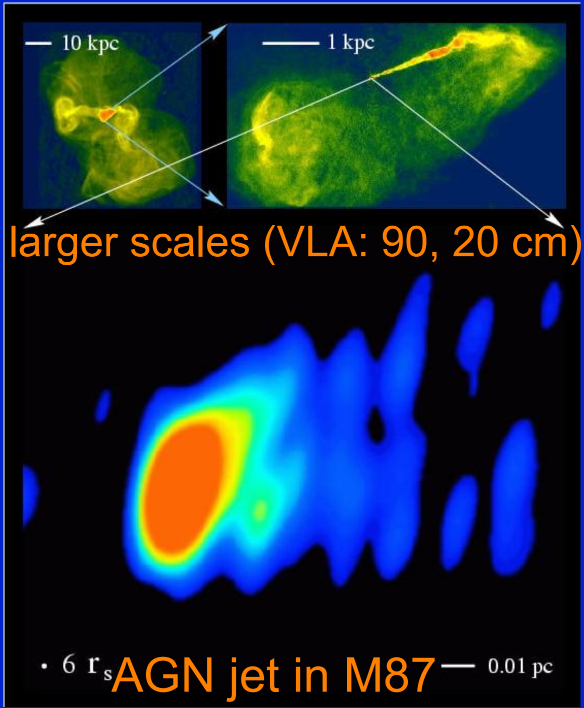
Outline of the talk:

- Magnetic vs. thermal acceleration
- Role of external confinement
- Standard collimation-induced magnetic acceleration: steady, ideal MHD, axi-symmetric
- Problems with this standard picture ⇒ alternatives
- Impulsive magnetic acceleration (JG, Spitkovsky & Komissarov 2011; JG 2012)
- Poynting dominated GRB jet propagating in a star (Bromberg, JG, Lyubarsky & Piran 2014)
- Conclusions

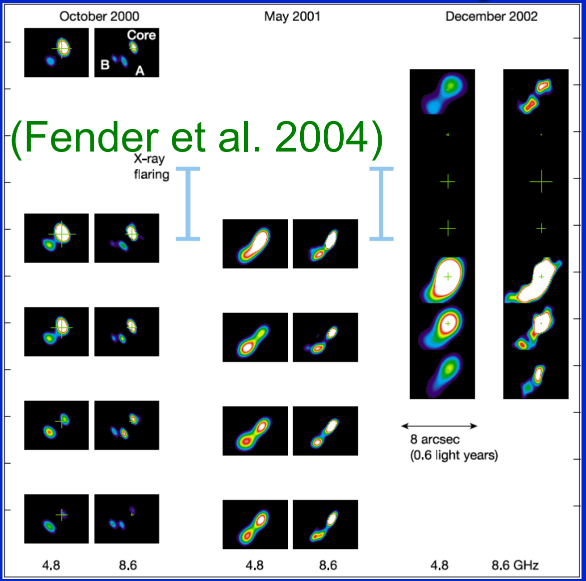
Relativistic Magnetic Acceleration:

- Relativistic ($v \approx c$) outflows/jets are very common in astrophysics & involve strong gravity at the source: PWN (NS), GRBs, AGN (SMBH), μ-quasars (BH/NS)
- Most models assume a steady flow for simplicity, despite observational evidence for time variability

Crab Nebula: X-ray in blue, optical in red



(VLBA @ 43 GHz)



Circinus X-1: an accreting neutron star (shows orbital modulation & Type I X-ray bursts)

Relativistic Magnetic Acceleration:

Is the acceleration magnetic?

✔ ? ✔ ?

PWN (NS), GRBs, AGN (SMBH), μ-quasars (BH/NS)

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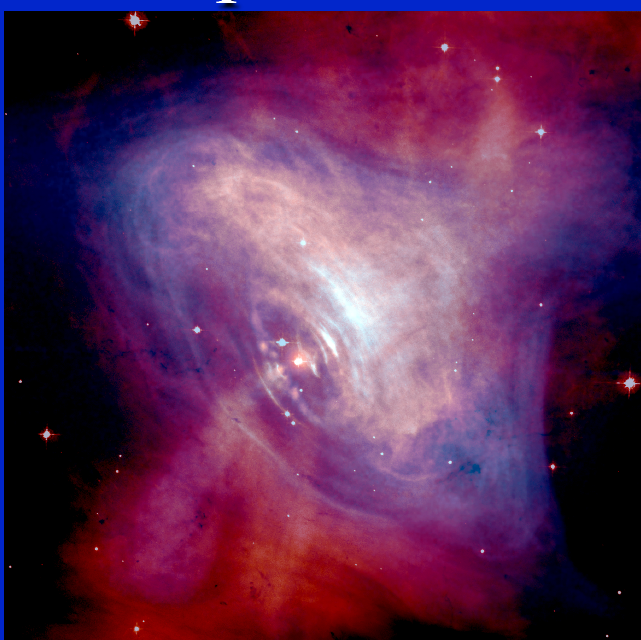

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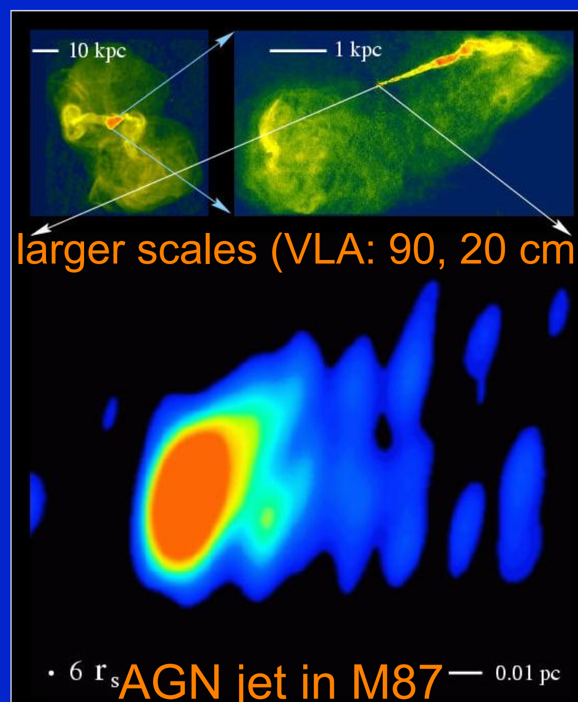
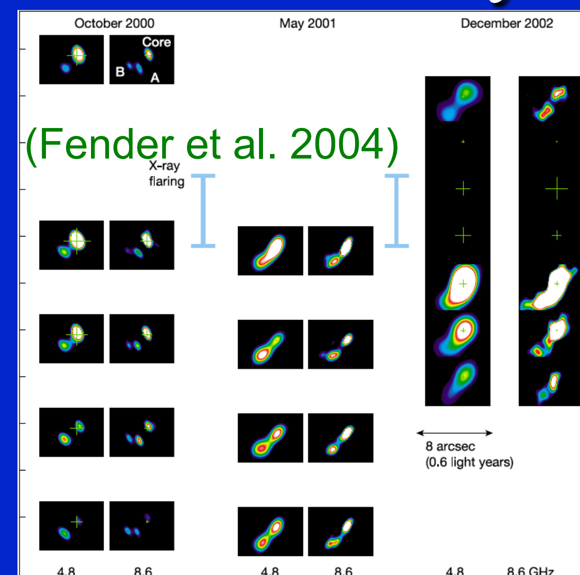


AGN jet in M87 (VLBA @ 43 GHz)

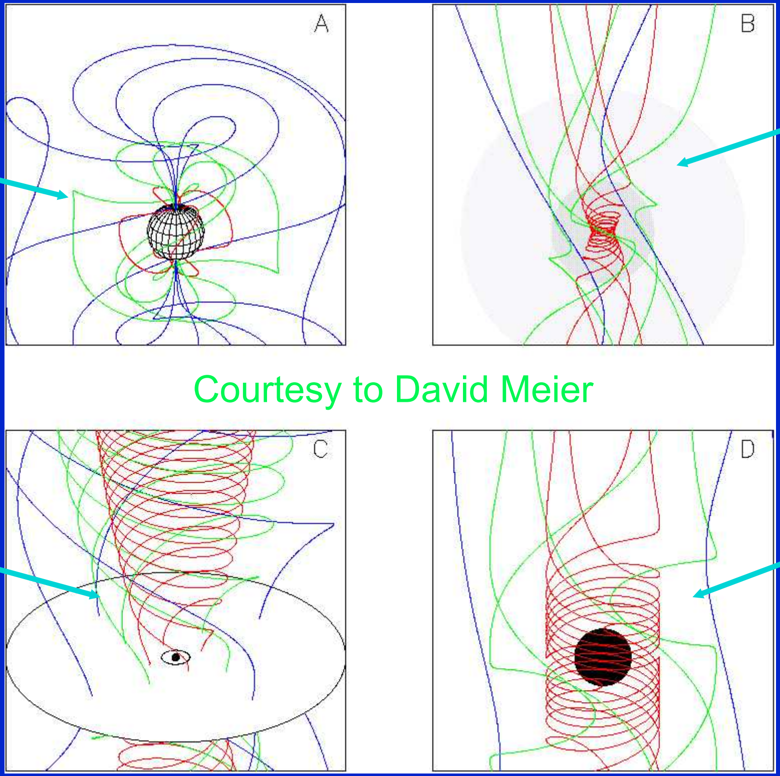


Circinus X-1: an accreting neutron star (shows orbital modulation & Type I X-ray bursts)

All these sources likely share a common basic mechanism, in which relativistic outflows are launched hydromagnetically

Pulsar magnetosphere

Collapsing, magnetized supernova core



Magnetized accretion disks around neutron stars and black holes

Magnetospheres of Kerr black holes

A rapidly spinning central body twists up the magnetic field into a toroidal component & plasma is ejected by the magnetic tension.

Magnetic vs. Thermal Acceleration:

- Hydromagnetic launching naturally helps avoid a high baryon loading, which can greatly limit the maximal possible asymptotic Lorentz factor Γ_∞

Key difference between thermal and magnetic steady state acceleration of relativistic supersonic flows:

- **Thermal**: fast, robust & efficient
- **Magnetic**: slow, delicate & less efficient

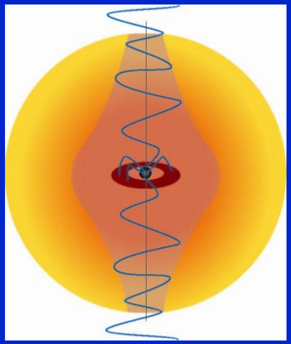
Force balance in Poynting dominated flows:

Does the huge tension of wound up magnetic field (hoop stress) compress the flow towards the axis?

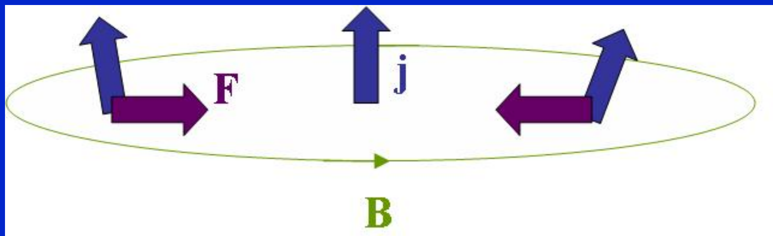
No!

In the current closure region, the force is decollimating.

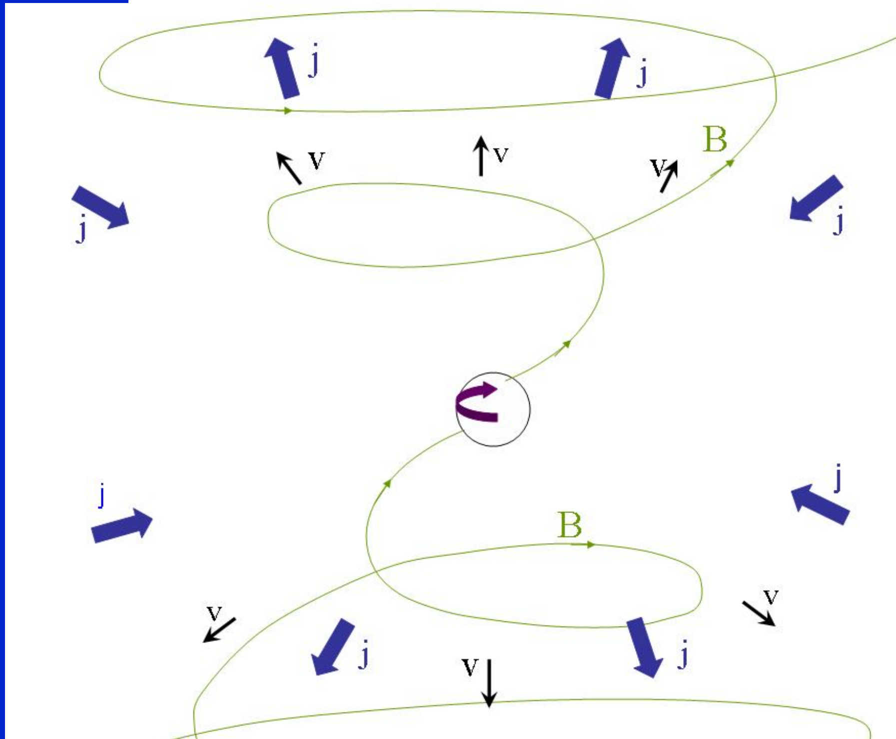
The flow as a whole cannot be collimated without external confinement!



Magnetic hoop stress



$$\mathbf{f} = \frac{1}{c}\,\mathbf{j}\times\mathbf{B}$$



Force balance in Poynting dominated flows:

Total EM force: $\mathbf{f} = \rho_e \mathbf{E} + \frac{1}{c}\mathbf{j}\times\mathbf{B} \approx 0$

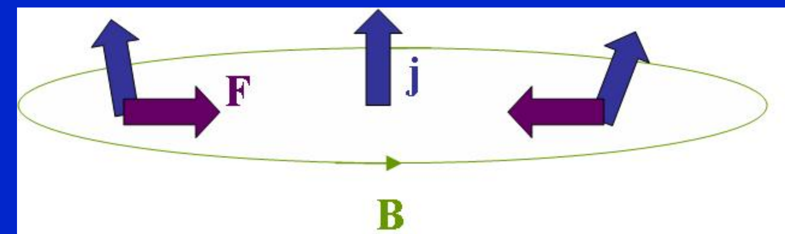
$$\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B} = 0 \qquad \rho_e = \frac{1}{4\pi}\nabla\cdot\mathbf{E}$$

In the far zone, $v \rightarrow c$ and $E \rightarrow B$.

In highly relativistic flows, the Lorentz and electric forces nearly cancel each other.

Acceleration & collimation are only due to a small residual force!

Magnetic hoop stress



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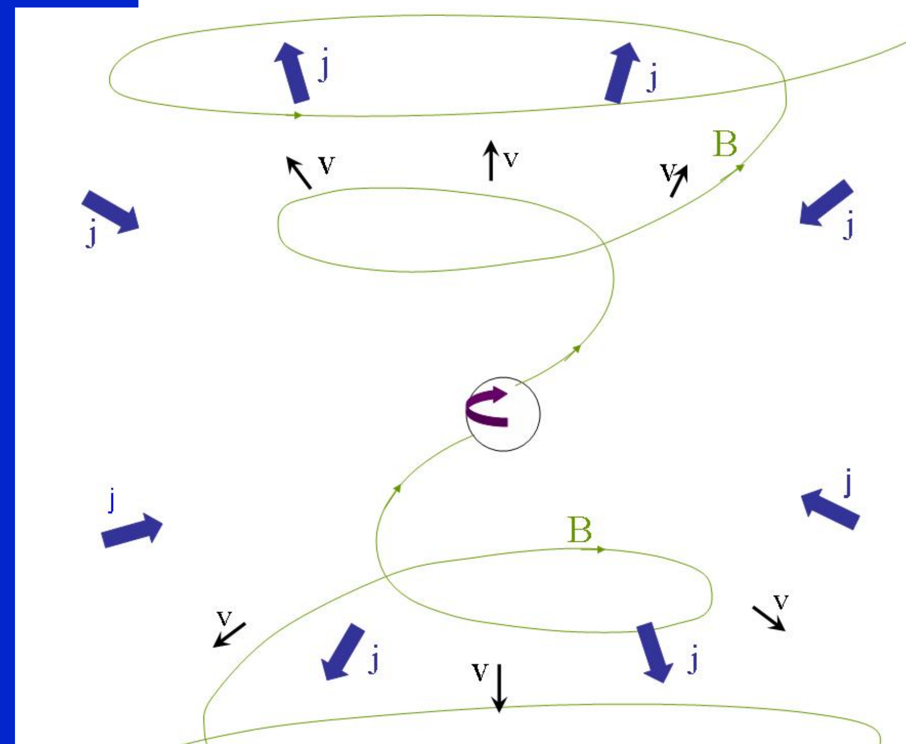


Ideal MHD acceleration: numerical + analytic results (Komissarov+ 09; Lyubarsky 09; Tchekhovskoy+10)

- **Unconfined** flows quickly lose lateral causal contact, become radial & stop accelerating when $\Gamma_\infty \sim \sigma_0^{1/3}$ & $\sigma_\infty \sim \sigma_0^{2/3} \gg 1$ (Goldreich & Julian 1970; Tomimatsu 1994; Beskin et al. 1998)

- **Weak confinement**: $p_{ext} \propto z^{-\alpha}$ with $\alpha > 2 \Rightarrow$ lose lateral causal contact, become conical & stop accelerating later: **loss of causal contact:** $\Gamma_\infty \sim \sigma_0^{1/3}\theta_{jet}^{-2/3}$ $\sigma_\infty \sim (\sigma_0\theta_{jet})^{2/3}$ efficient conversion: $\Gamma_\infty\theta_{jet} < 1$

- **Strong confinement**: $p_{ext} \propto z^{-\alpha}$ with $\alpha < 2 \Rightarrow$ stay in causal contact $\Gamma \propto z^{\alpha/4}$ and reach $\Gamma_\infty \sim \sigma_0$, $\sigma_\infty \sim 1$, $\Gamma_\infty\theta_{jet} \leq 1$

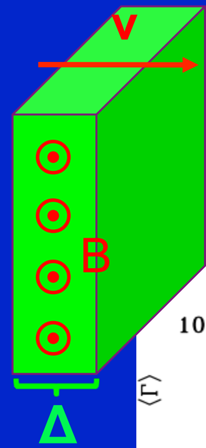
The "σ-problem": for a "standard" steady ideal MHD axisymmetric flow

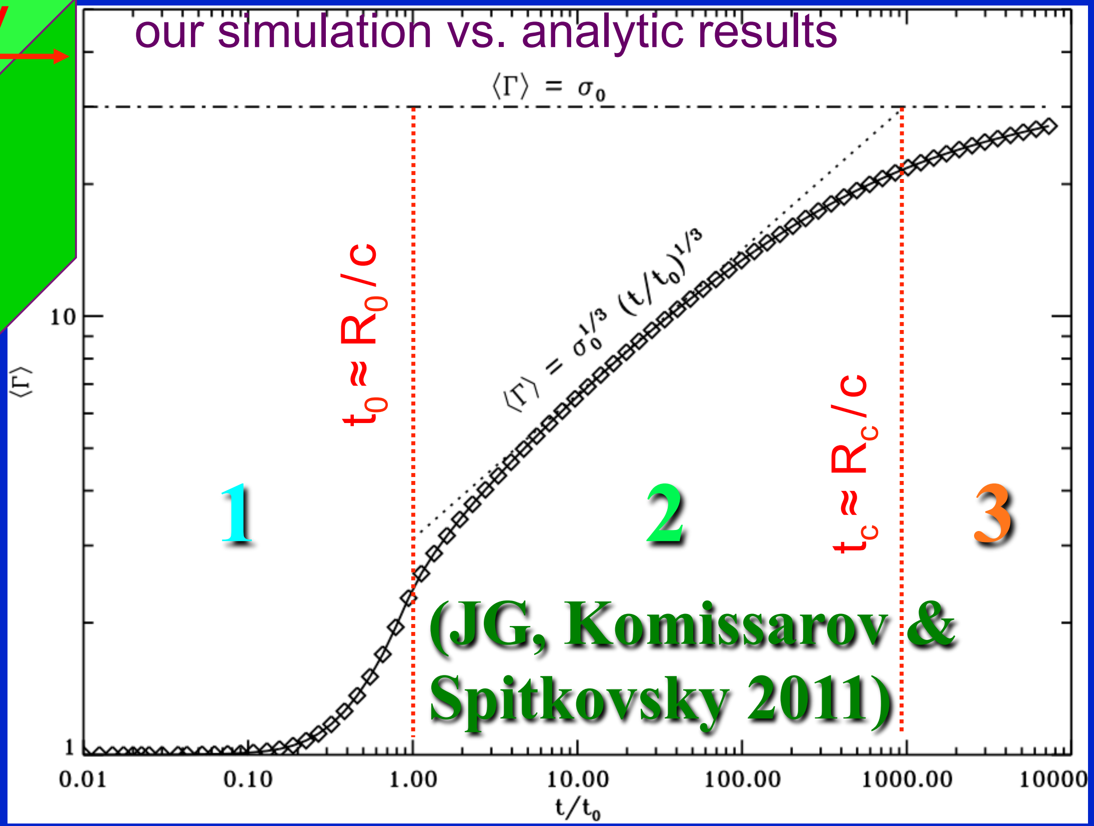
- $\Gamma_\infty \sim \sigma_0^{1/3}$ & $\sigma_\infty \sim \sigma_0^{2/3} \gg 1$ for a spherical flow; $\sigma_0 = B_0^2/4\pi\rho_0 c^2$
- ◆ In PWN the solution is dissipation of the striped wind
- ◆ However, this doesn't work in relativistic jet sources
- Jet **collimation** helps, but not enough: $\Gamma_\infty \sim \sigma_0^{1/3}\theta_{jet}^{-2/3}$, $\sigma_\infty \sim (\sigma_0\theta_{jet})^{2/3}$ & $\Gamma\theta_{jet} \lesssim \sigma^{1/2}$ (~ 1 for $\Gamma_\infty \sim \Gamma_{max} \sim \sigma_0$)
- Still $\sigma_\infty \gtrsim 1 \Rightarrow$ inefficient internal shocks, $\Gamma_\infty\theta_{jet} \gg 1$ in GRBs
- Sudden drop in external pressure can give $\Gamma_\infty\theta_{jet} \gg 1$ but still $\sigma_\infty \gtrsim 1$ **(Tchekhovskoy et al. 2009)** $\Rightarrow$ inefficient internal shocks

Alternatives to the "standard" model

- ~~Axisymmetry~~: non-axisymmetric instabilities (e.g. the current-driven kink instability) can tangle-up the magnetic field & lead to significant dissipation (Begelman; Spruit; Eichler; Lyubarsky; Giannios;…)
- ~~Ideal~~ MHD: a striped wind can dissipate its energy **magnetic energy $\rightarrow$ heat (+radiation) $\rightarrow$ kinetic energy** (Drenkham & Spruit 2002; Lyubarsky 2010)
- ~~Steady-state~~: **effects of strong time dependence** (JG, Komissarov & Spitkovsky 2011; JG 2012a, 2012b)

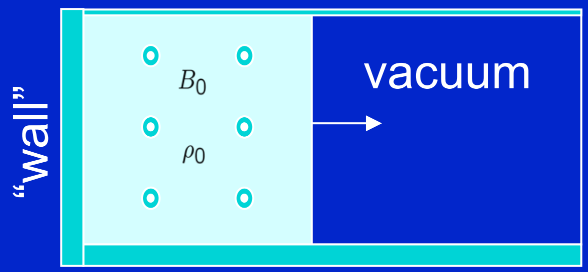
Impulsive Magnetic Acceleration: $\Gamma \propto R^{1/3}$





Useful **case study**:

Initial value of magnetization parameter: $\sigma_0 = \frac{B_0^2}{4\pi\rho_0 c^2} >> 1$

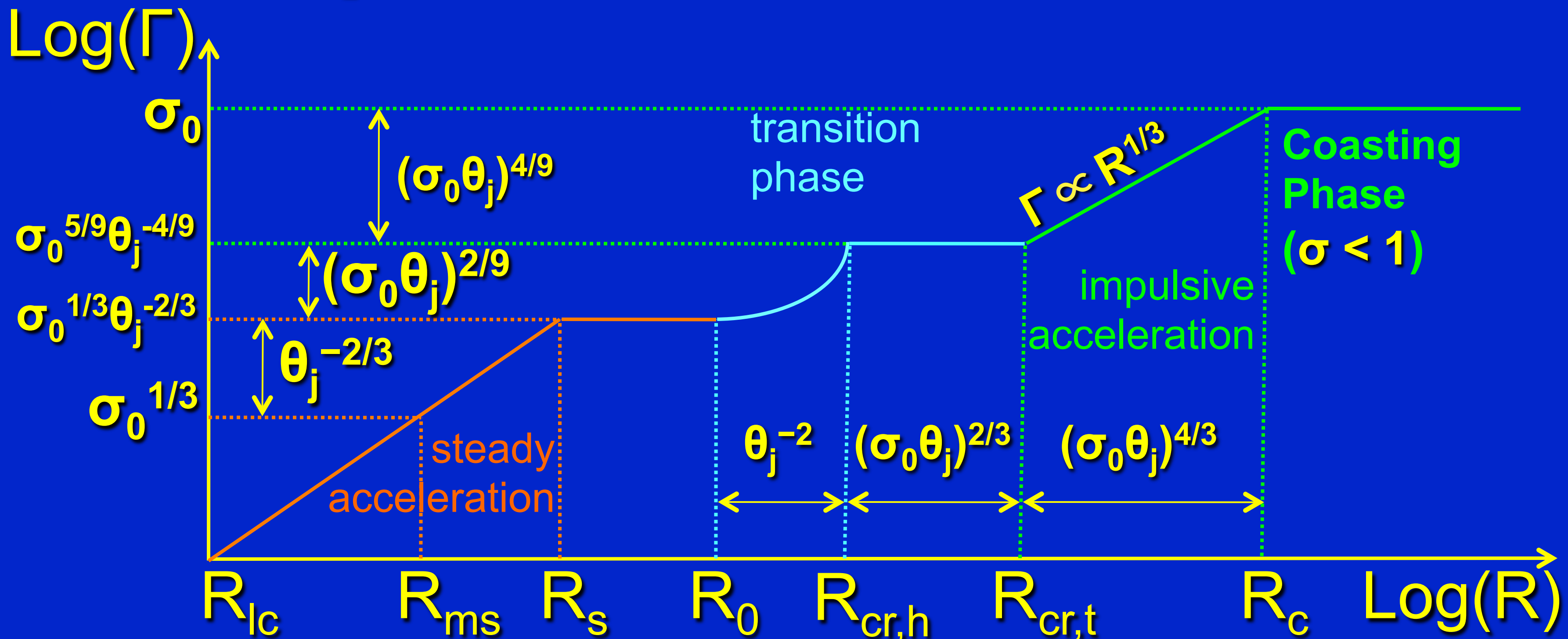


1. $\langle\Gamma\rangle_E \approx \sigma_0^{1/3}$ by $R_0 \sim \Delta_0$
2. $\langle\Gamma\rangle_E \propto R^{1/3}$ between $R_0 \sim \Delta_0$ & $R_c \sim \sigma_0^2 R_0$ and then $\langle\Gamma\rangle_E \approx \sigma_0$
3. At $R > R_c$ the sell spreads as $\Delta \propto R$ & $\sigma \sim R_c/R$ rapidly drops

- **Complete conversion of magnetic to kinetic energy!**
- **This allows efficient dissipation by shocks at large radii**

1^{st} Steady then Impulsive Acceleration

- Our test case problem has no central engine: it may be, e.g., directly applicable for giant flares in SGRs; however:
- In most astrophysical relativistic (jet) sources (GRBs, AGN, μ-quasars) the variability timescale ($t_v \approx R_0/c$) is long enough ($>R_{ms}/c$) that steady acceleration operates & saturates (at R_s)
- Then the impulsive acceleration kicks in & leads to $\sigma < 1$



Many sub-shells: acceleration, collisions

(JG 2012b)

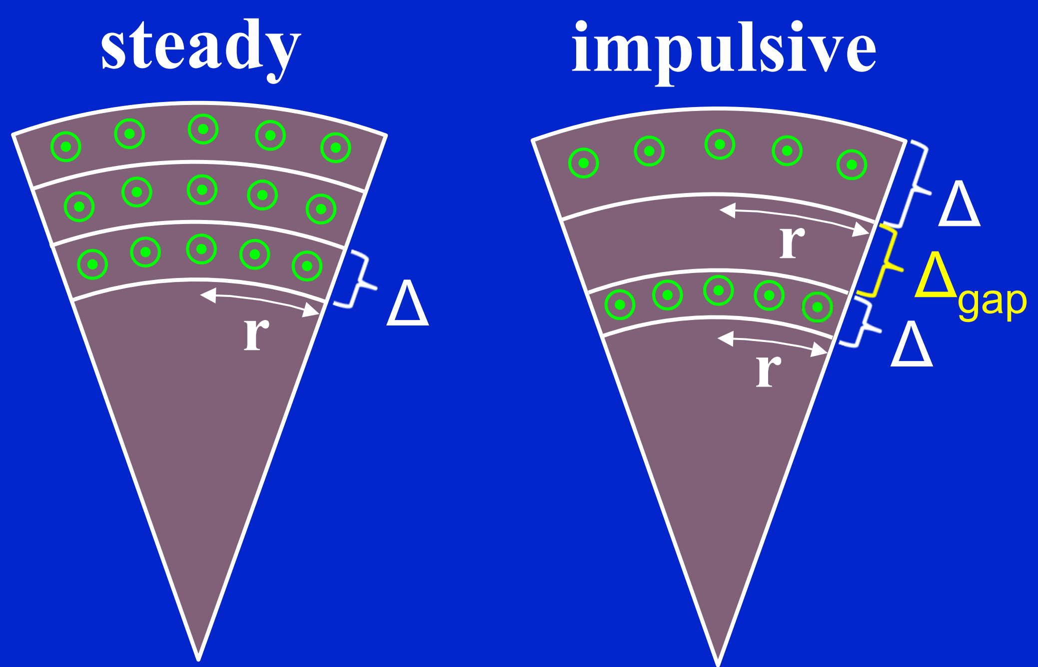
Flux freezing (ideal MHD):

$\Phi \sim B\,r\,\Delta = \textbf{constant}$

$E_{EM} \sim B^2\,r^2\,\Delta \propto 1/\Delta$

$$\frac{\text{total energy}}{\text{rest energy}} = (1+\sigma)\Gamma$$

acceleration $(\Gamma\uparrow) \;\Leftrightarrow\; \sigma\downarrow$



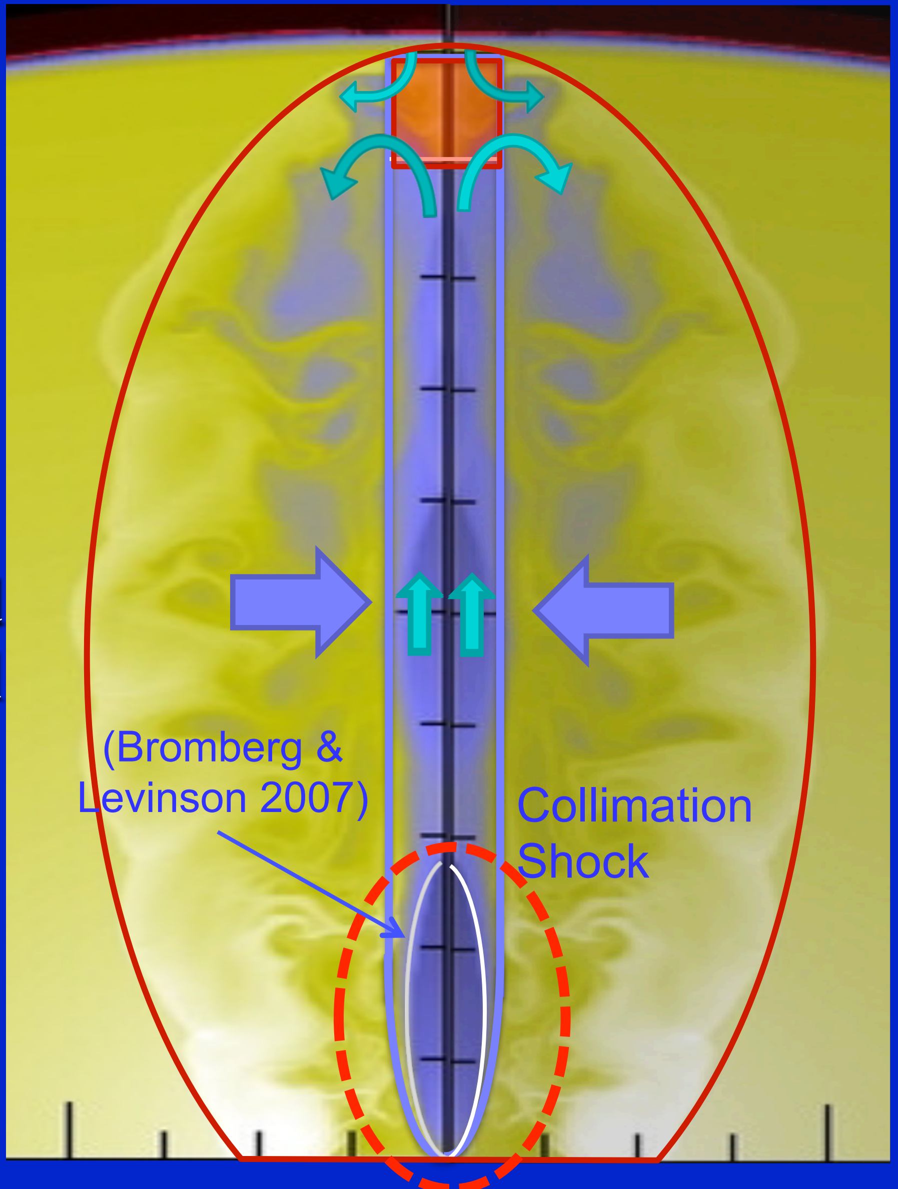
constant shell width Δ

shell width Δ grows

- For a long lived variable source (e.g. AGN), each sub shell can expand by $1+\Delta_{gap}/\Delta_0 \Rightarrow \sigma_\infty = (E_{total}/E_{EM,\infty} - 1)^{-1} \sim \Delta_0/\Delta_{gap}$
- For a finite # of sub-shells the merged shell can still expand
- Sub-shells in GRBs can lead to a low-magnetization thick shell & enable the outflow to reach higher Lorentz factors

Hydrodynamic GRB Jet in its parent star

- The Jet develops a slow-moving 'head', were there is a pressure balance between the shocked jet material & external medium
- At the head jet matter decelerates by a reverse shock, flows sideways & forms a high-pressure cocoon that collimates the jet
- To propagate the head must be fed by jet material & the jet would fail if engine stops before $z_h \cong R(1-\beta)$
- Breakout time (Bromberg et al. 2011)



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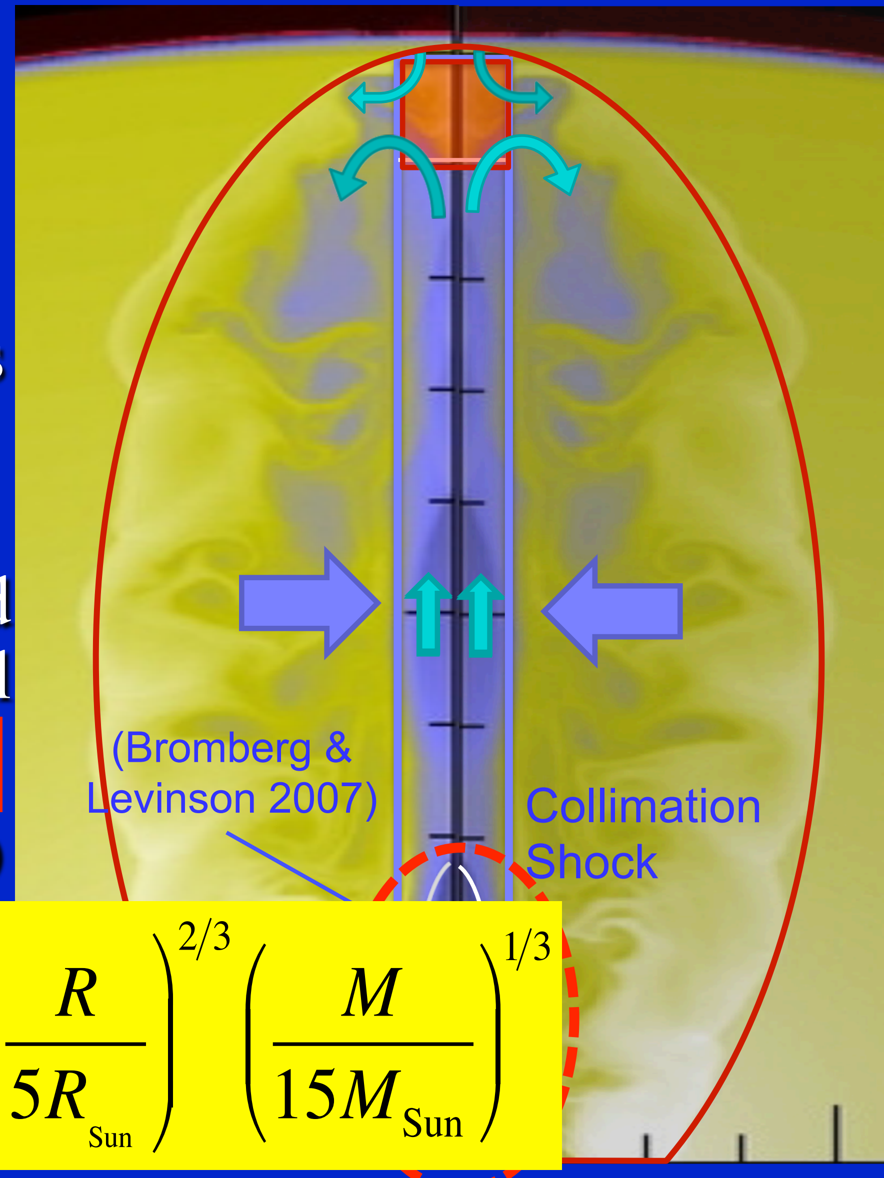
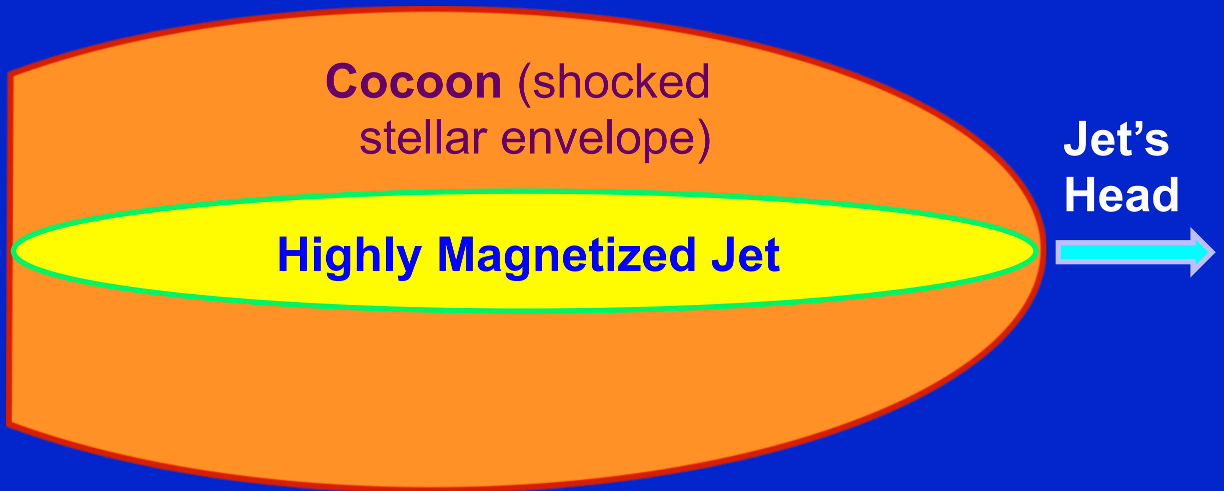


$$t_b \cong 15\,\mathrm{sec}\left(\frac{L_{\mathrm{iso}}}{10^{51}\,erg/s}\right)^{-1/3}\left(\frac{\theta_0}{10^\circ}\right)^{2/3}\left(\frac{R}{5R_{\mathrm{Sun}}}\right)^{2/3}\left(\frac{M}{15M_{\mathrm{Sun}}}\right)^{1/3}$$

GRB Jet propagation in its parent star: highly magnetized vs. hydrodynamic jets

- The flow must decelerate to match it's head velocity, but for high-σ a shock can't do it ⇒ the jet converges near its head
- Narrower head ⇒ larger head velocity ⇒ faster jet breakout
- Relativistic head ⇒ less energy into cocoon & supernova
- The head velocity is independent of the detailed jet structure ⇒ simplifies the model & allows (semi-) analytic solutions

(Bromberg, JG, Lyubarsky & Piran 2014)



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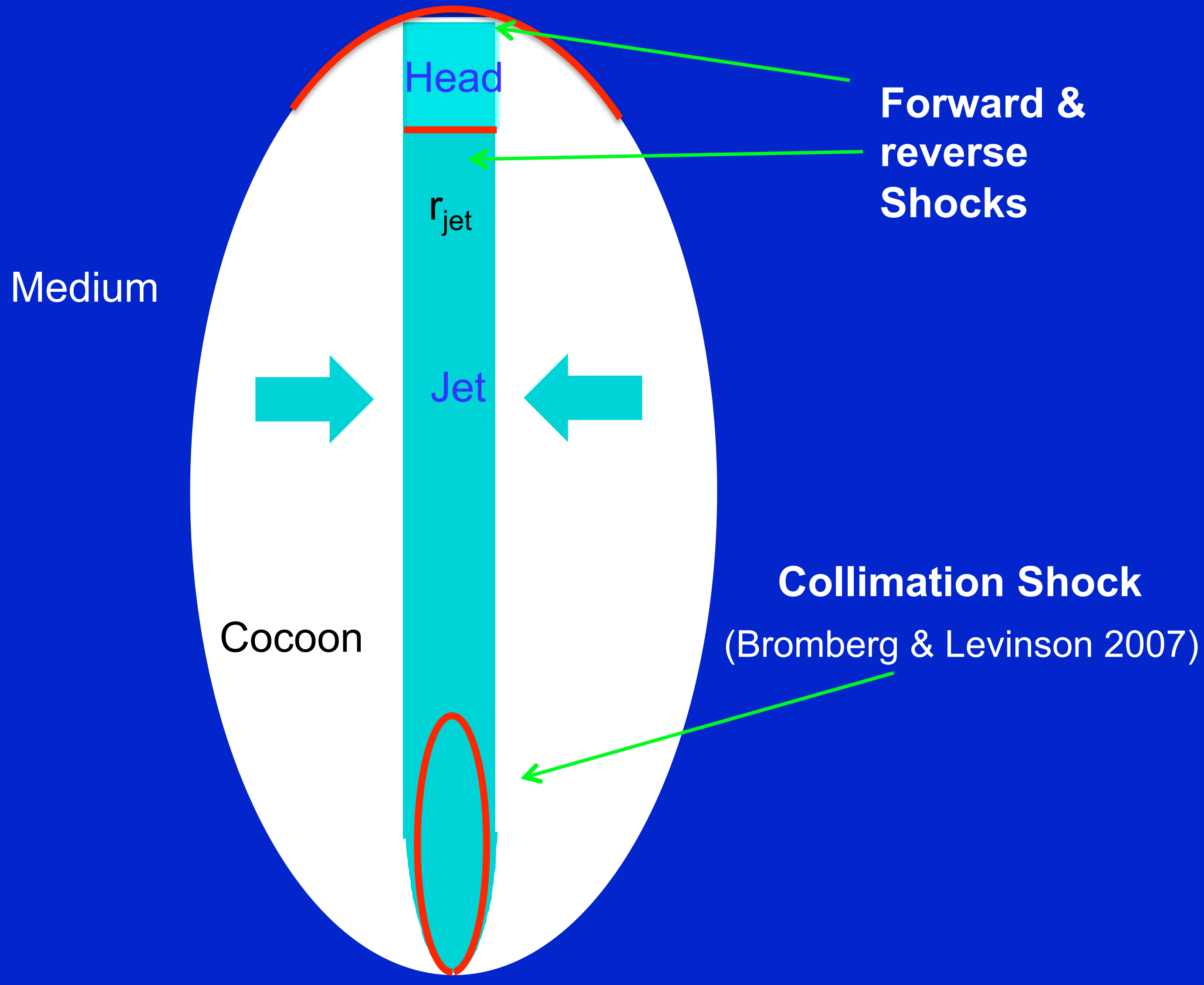
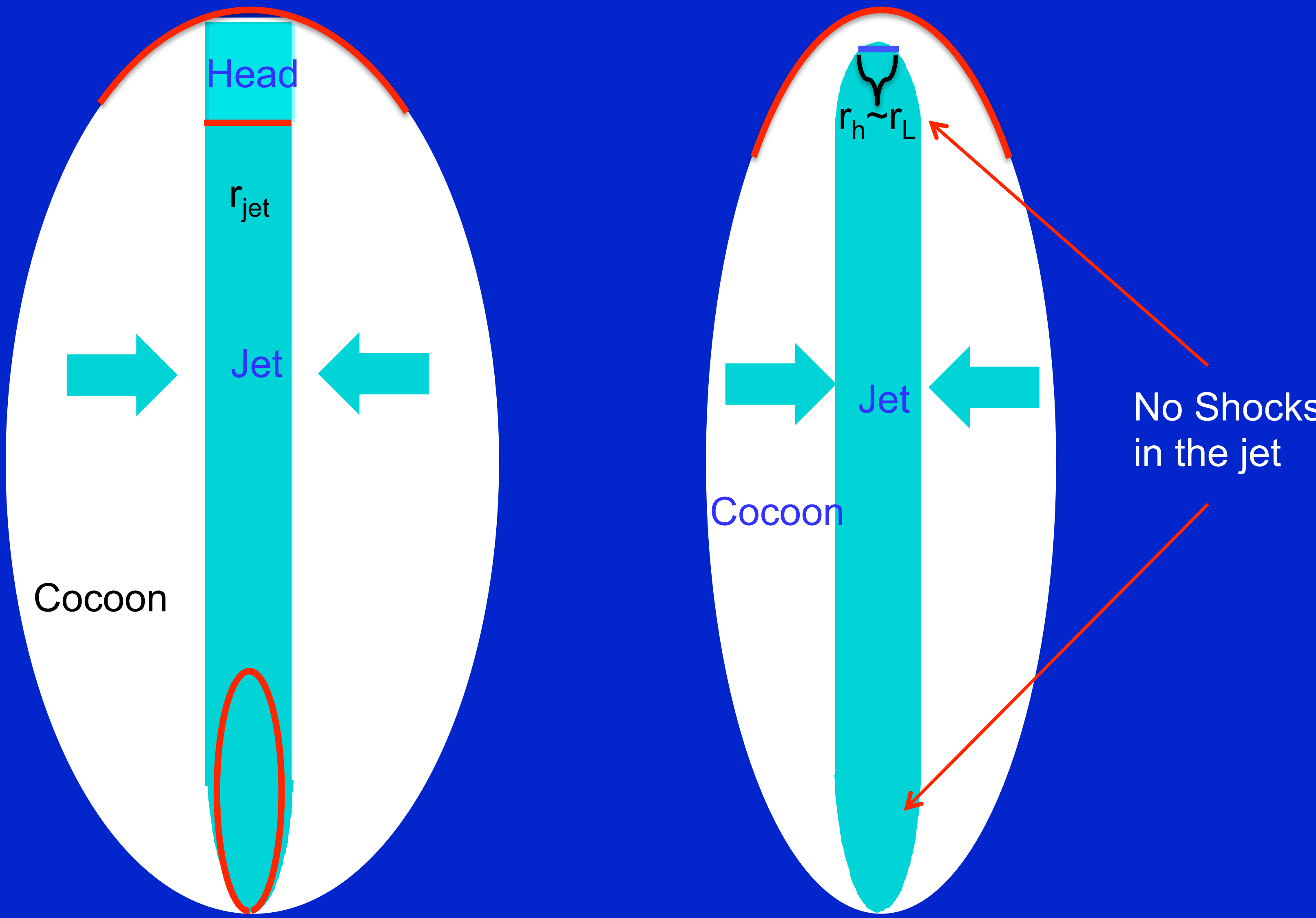
- The head velocity is independent of the detailed jet structure ⇒ simplifies the model & allows (semi-) analytic solutions
- Levinson & Begelman (2013): current-driven instabilities dissipate most of the magnetic field → a hydrodynamic jet
- This is still unclear & strongly affects the jet dynamics

Hydrodynamic Jet Propagation (Bromberg+ 2011)



Magneticic Jet Propagation

(Bromberg, JG, Lyubarsky & Piran 2014)



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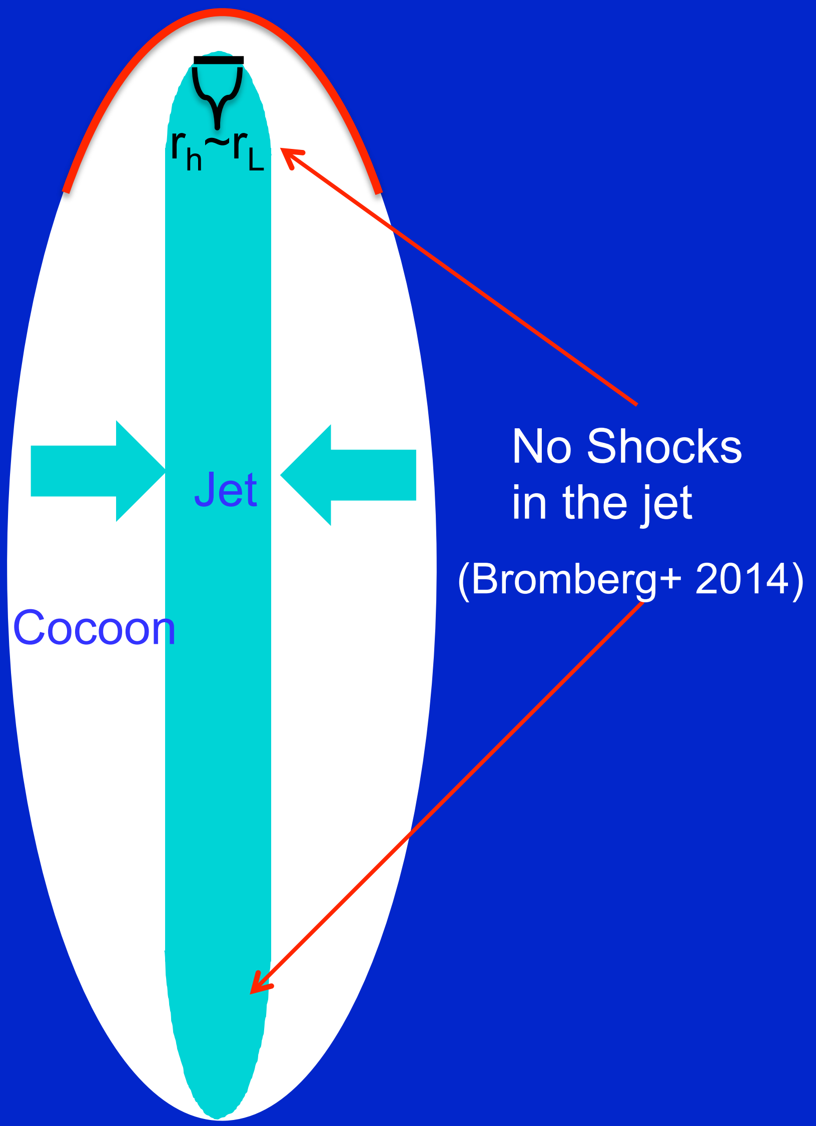


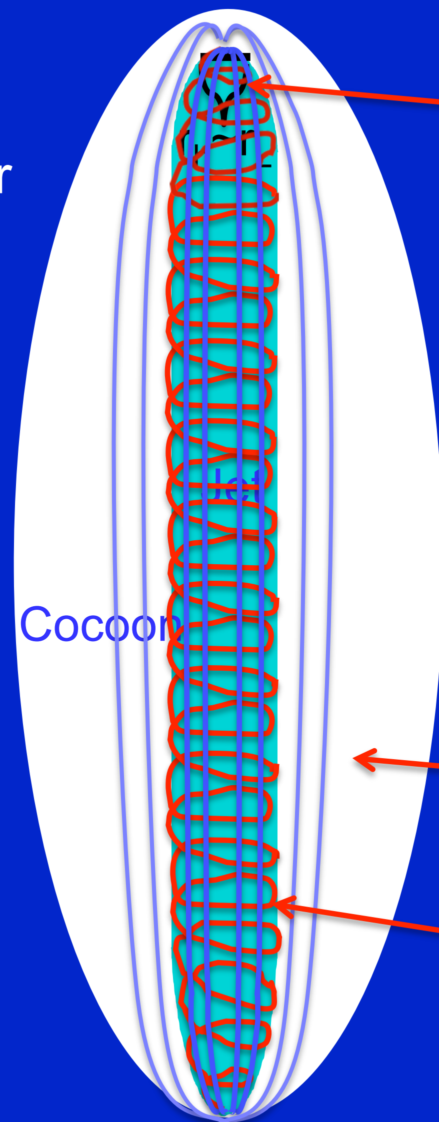
Magneticic Jet Propagation

<u>Stability of the jet</u>

Purely toroidal fields suffer from the kink instability

But as the jet is in lateral equilibrium, $B'_{ø} \sim B'_{p}$ and this helps to make it more stable

Our analysis shows the the jet is at most only mildly unstable and is likely crosses the star largely intact.



$$r_h \cong r_L \left(\frac{L_j}{\pi r_L^2 \rho c^3} \right)^{1/6}$$

Bromberg+ 2014 ; Levinson & Begelman 2012

The cocoon radius evolves like a cylindrical BM / ST solution. Uniform pressure in r direction

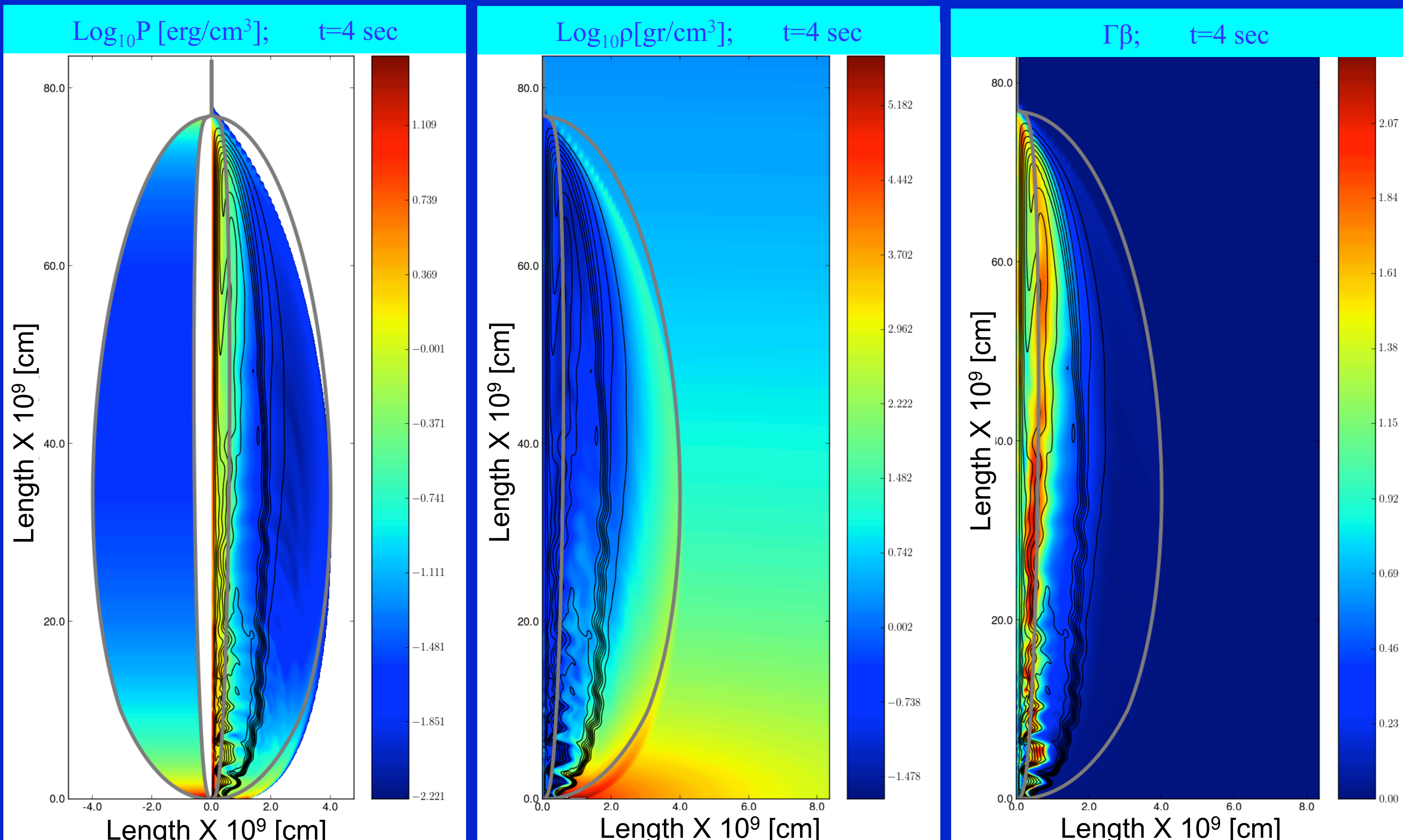
$$r_c(z) \sim \rho(z)^{-1/6} \sqrt{z_h - z}$$

$$P_c(z) \sim \rho(z)^{2/3} (z_h - z)^{-1}$$

$$r_j \sim P_c(z)^{-1/4}$$

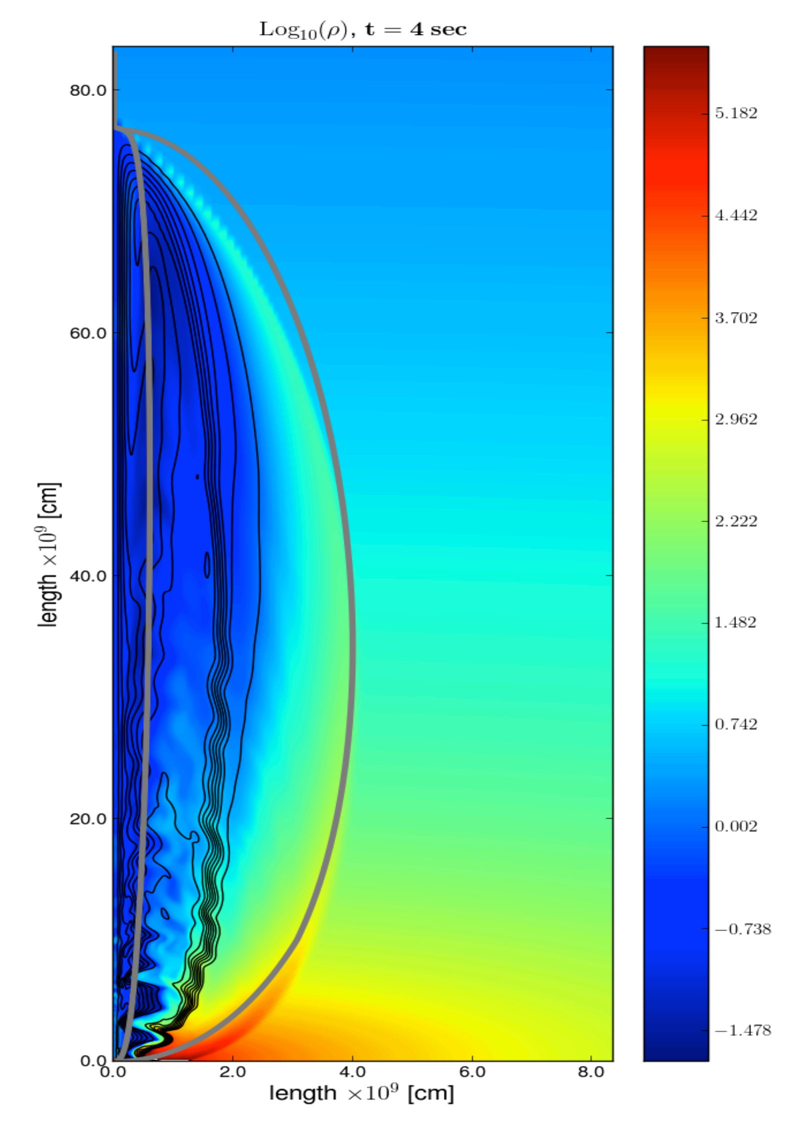
Comparison with Simulations

(Bromberg & Tchekhovskoy 2014 in prep)



Magnetic jet breakout time

(Bromberg & Tchekhovskoy 2014 in prep)



- The jet becomes relativistic deep in the star.
- It crosses the star at a time comparable to R/c
- The engine minimal activity time in this case:

$$t_b \cong \left(\frac{R}{\beta c}\right)(1-\beta) \cong \frac{R}{2\Gamma^2 c}$$

(Bromberg, JG, Lyubarsky & Piran 2014b)

Magnetic jet breakout time

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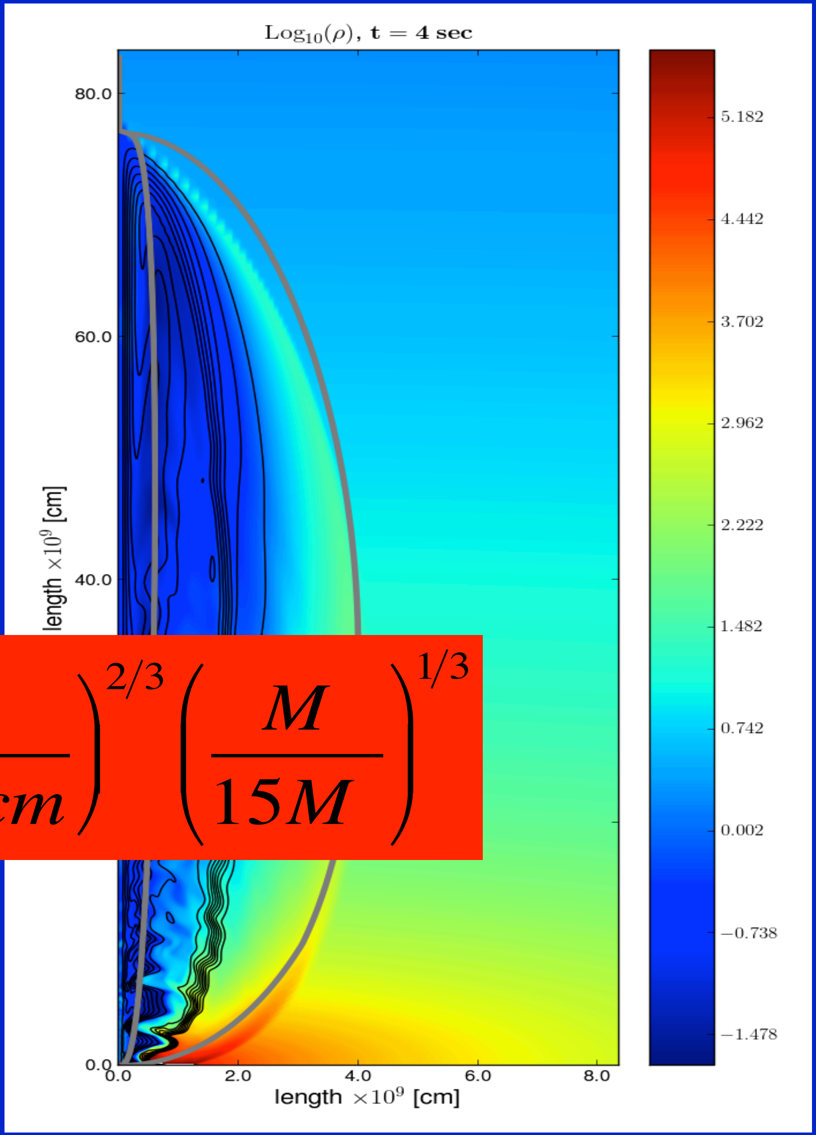

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(Bromberg, JG, Lyubarsky & Piran 2014b)

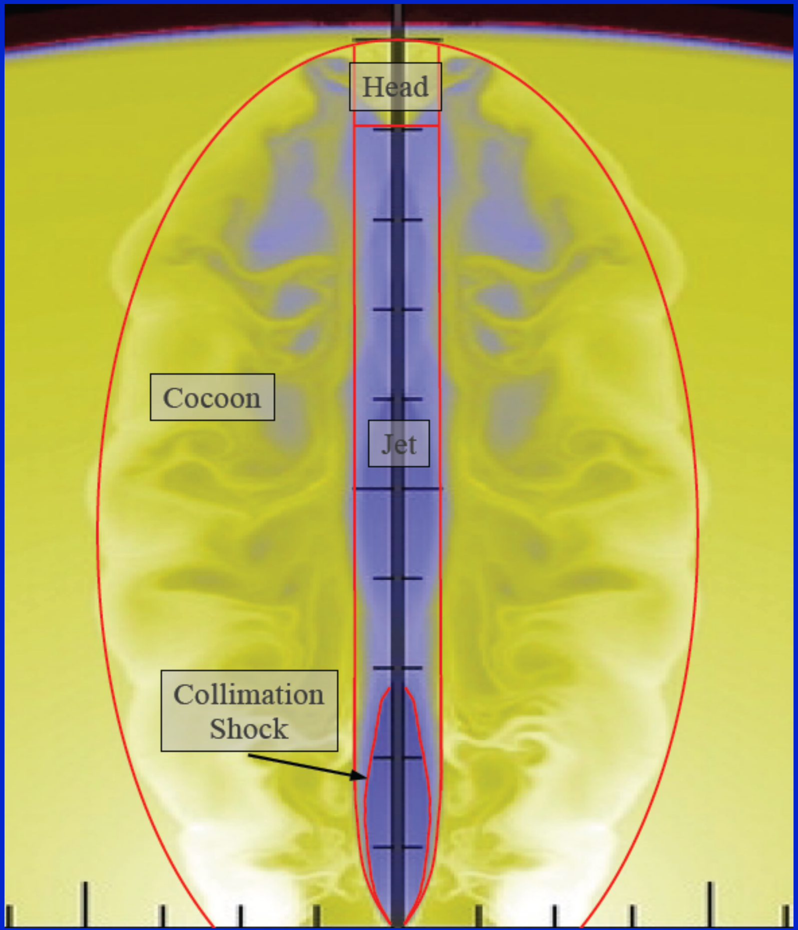
Breakout times comparison:

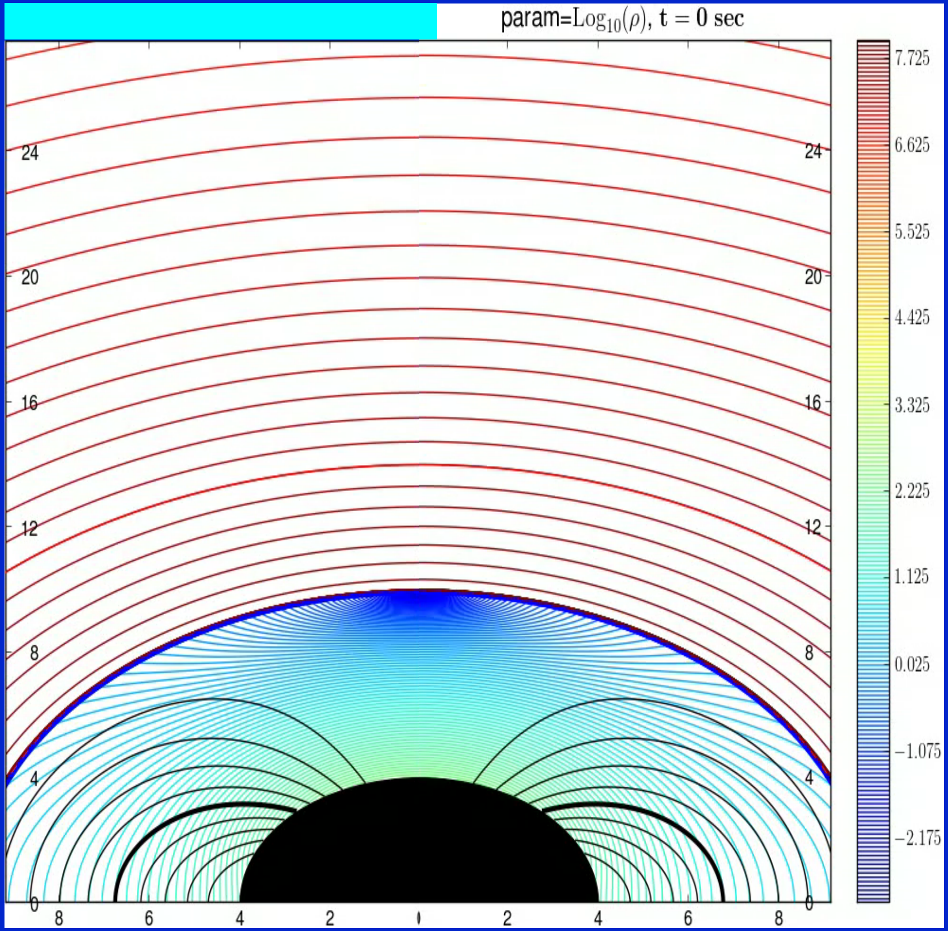
Bromberg et al 2011a

$$t_b \cong 15\sec\left(\frac{Liso}{10^{51}erg/s}\right)^{-1/3}\left(\frac{\theta_0}{10^\circ}\right)^{2/3}\left(\frac{R}{5R_\odot}\right)^{2/3}\left(\frac{M}{15M_\odot}\right)^{1/3}$$

Bromberg+ 2014

$$t_b \cong 1.8\sec\left(\frac{Liso}{10^{51}erg/s}\right)^{-1/3}\left(\frac{r_L}{5*10^7 cm}\right)^{2/3}\left(\frac{M}{15M_\odot}\right)^{1/3}$$





Bromberg & Tchekhovskoy 2014 in prep

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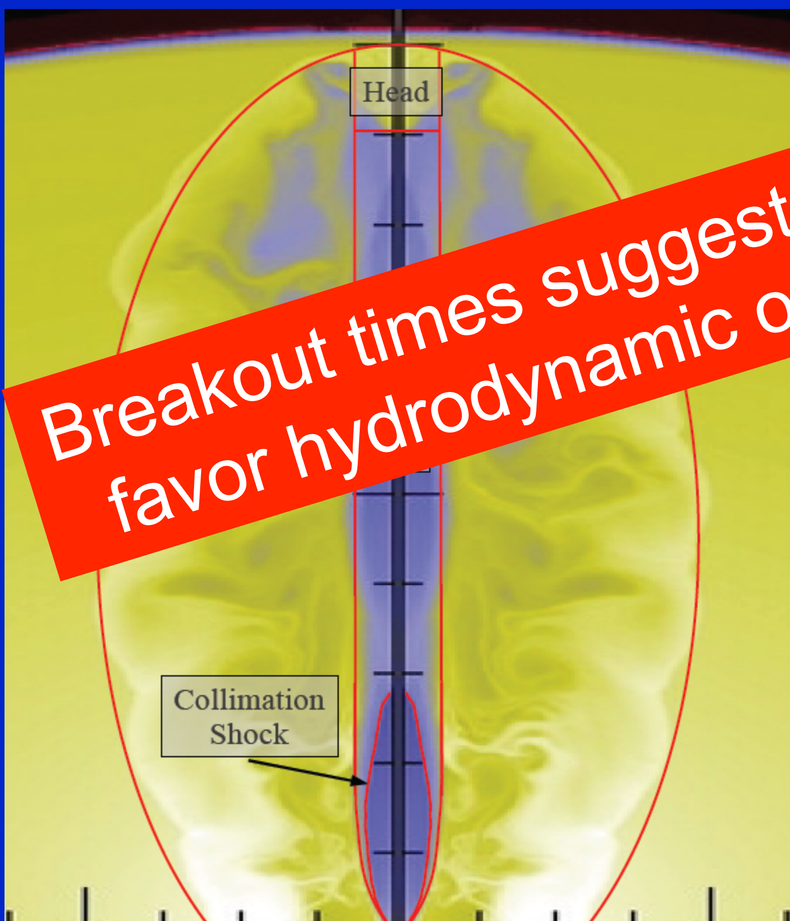

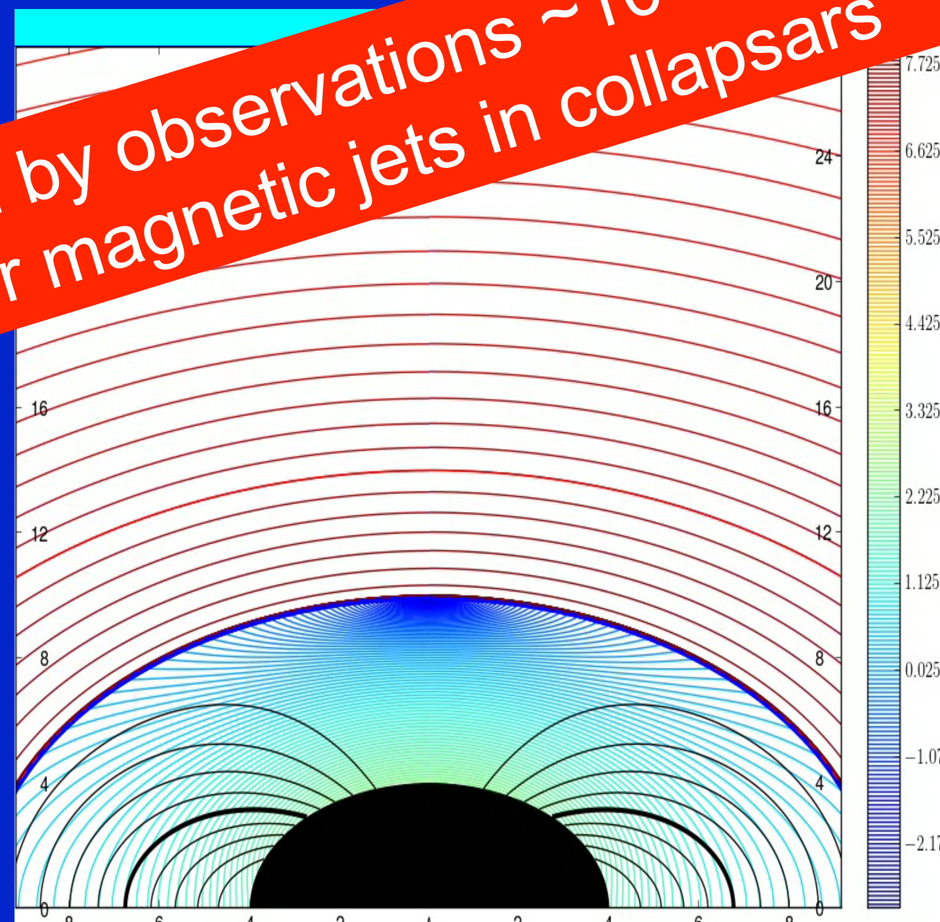

Bromberg & Tchekhovskoy 2014 in prep

Breakout times suggested by observations ~10-15 sec favor hydrodynamic over magnetic jets in collapsars

Conclusions:

- Magnetic acceleration:
  - Helps avoid large baryon loading
  - Requires external confinement
  - Is tightly related to the jet collimation
- Impulsive magnetic acceleration:
  - Can help reach kinetic energy dominance
  - Allows efficient dissipation in internal shocks
- Poynting dominated GRB jet propagating in a star
  - Analytic solution: the jet's head is relativistic throughout most of the star
  - Smaller breakout time, less energy injected into cocoon
  - Observational implication: long GRB durations, the SN