Lighting up magnetic jets

3D instabilities and energy dissipation in relativistic MHD jets.

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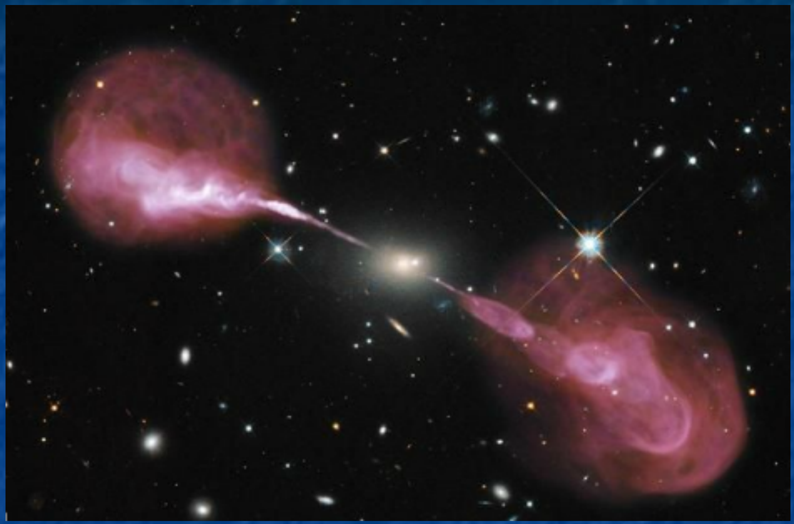
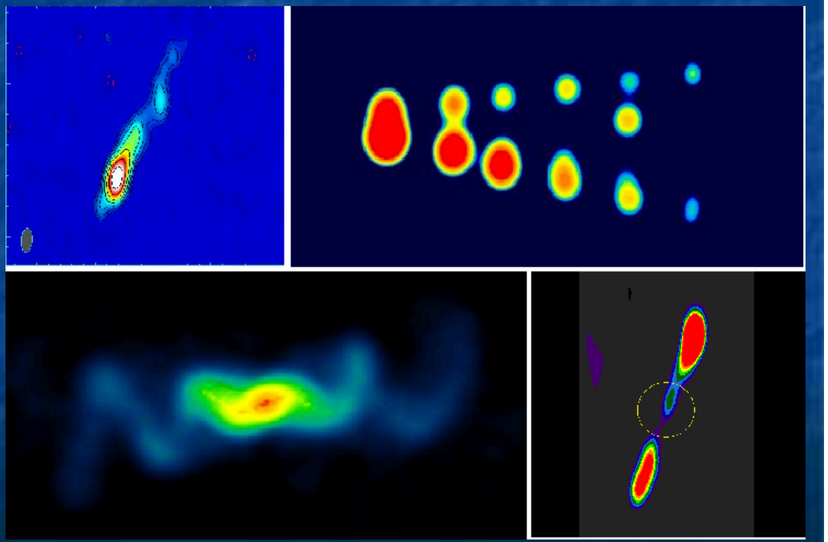
Relativistic jets in astrophysics

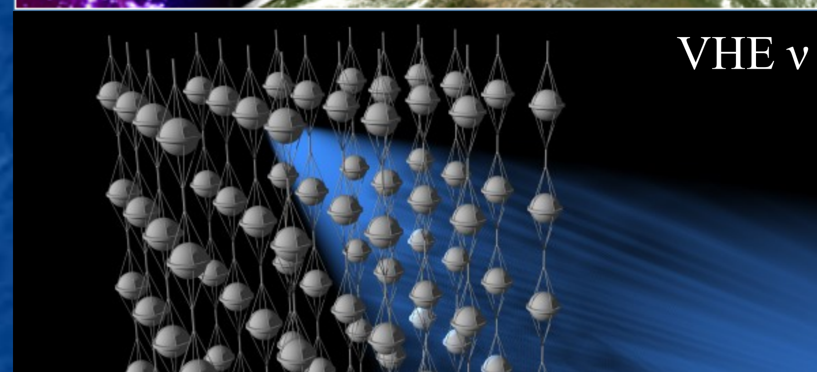
- Relativistic jets are associated with systems that contain compact objects (GRBs, AGNs..).

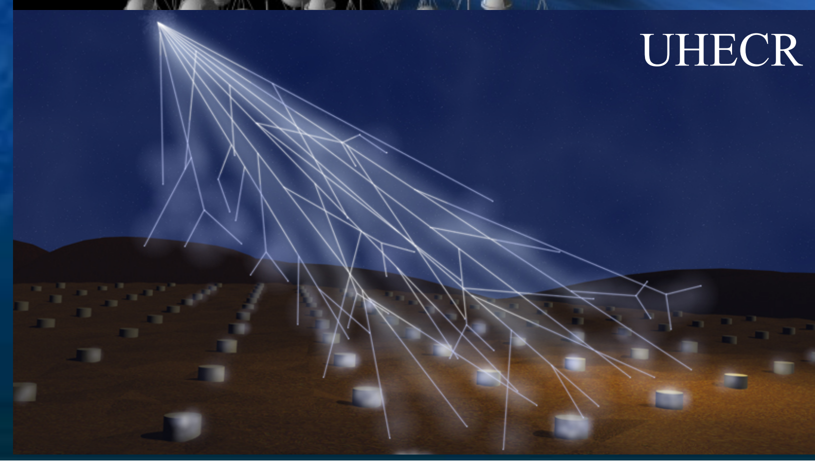




Relativistic jets in astrophysics

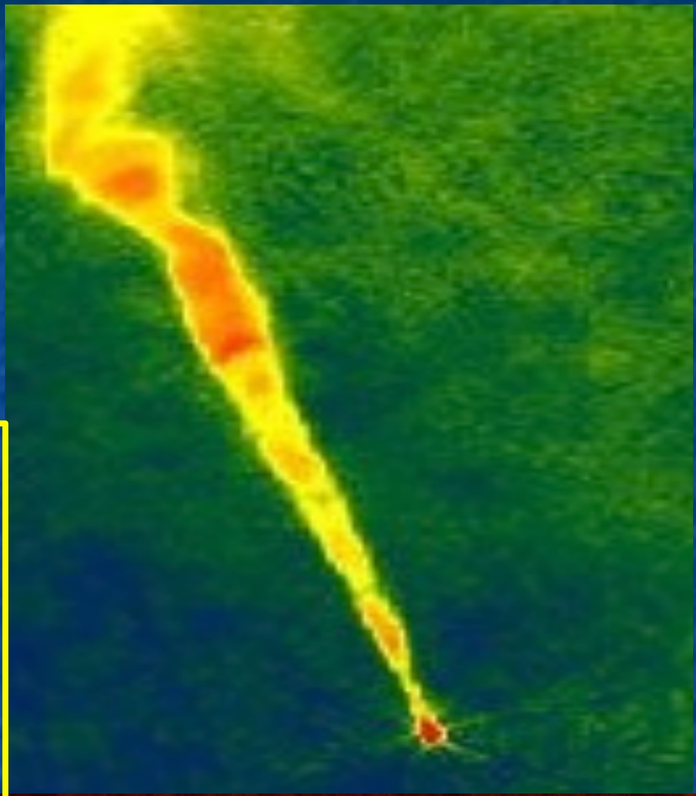
- Relativistic jets are associated with systems that contain compact objects (GRBs, AGNs..).
- Plausible origin for many of the high energy phenomena we observe.
- Despite decades of research they remain largely a mystery:
  - Emission processes ✗
  - Location and mechanism for particle acceleration ✗
  - Jet composition ✗
  - Relativistic motions ✓

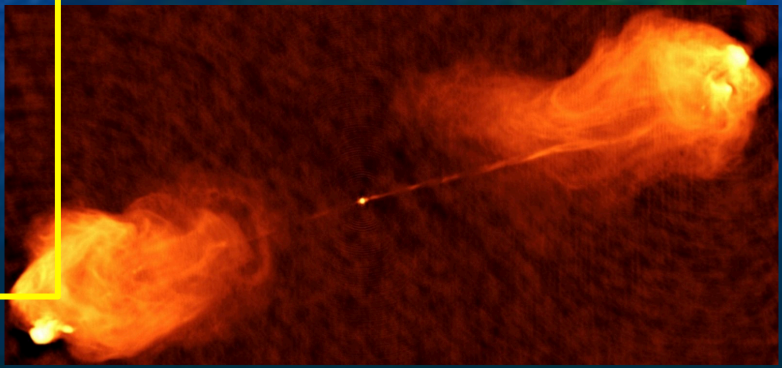




Powering relativistic jet

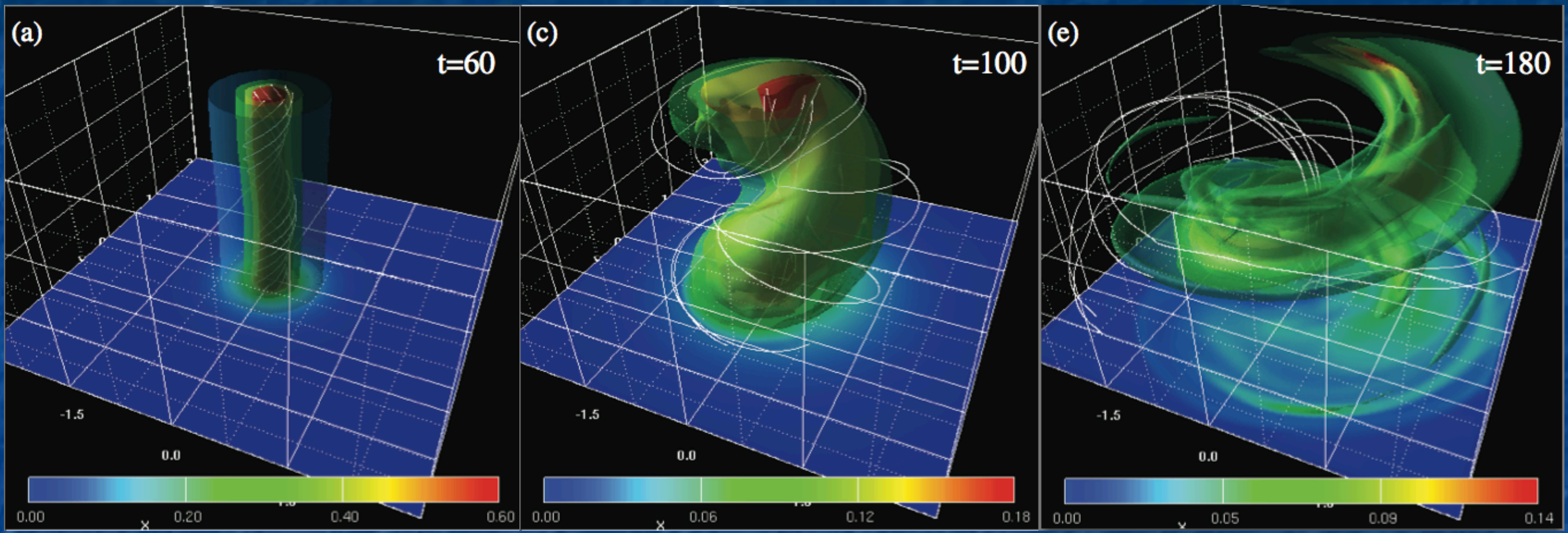
- A commonly accepted powering mechanism: magnetized rotation of a compact object (BH or NS).
- Problem in identifying the location and the mechanism responsible for the dissipation.
- How do the jets survive the journey over many orders of magnitudes in length?





Stability magnetic jets

Mizuno et al. 2012



- Cold jets are unstable to kink modes when B_{Φ} dominates.
- Studied numerically with pre-determined magnetic field configuration.

Stability magnetic jets

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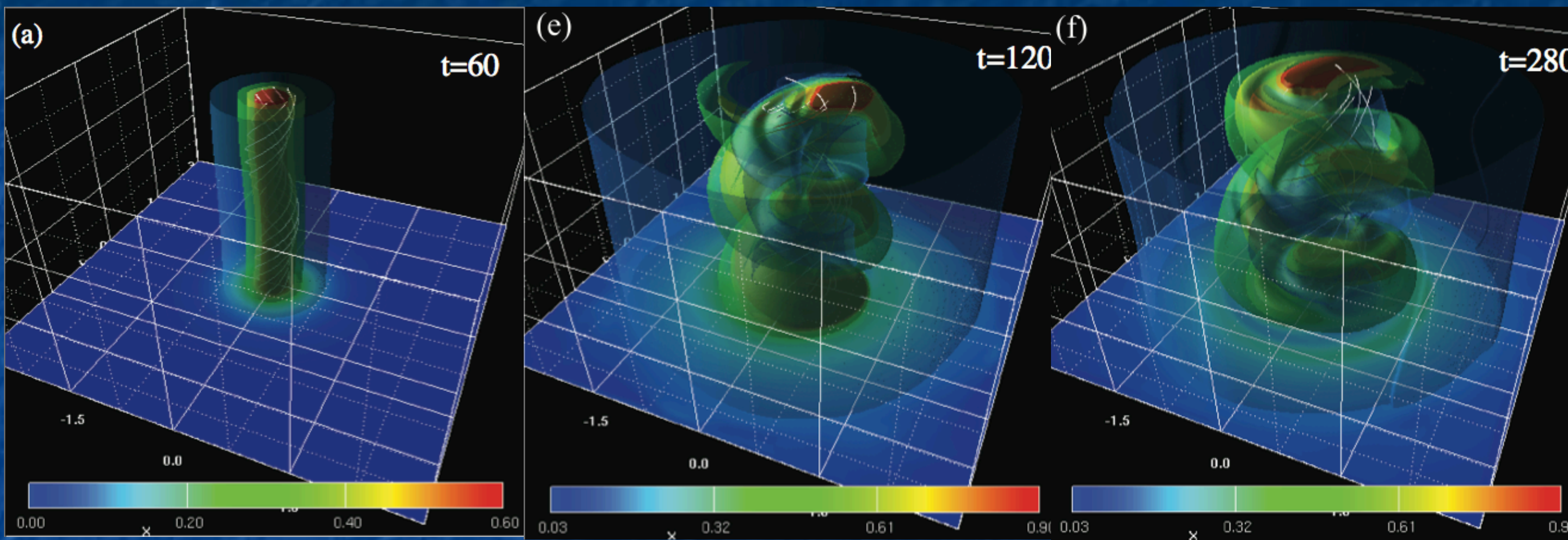
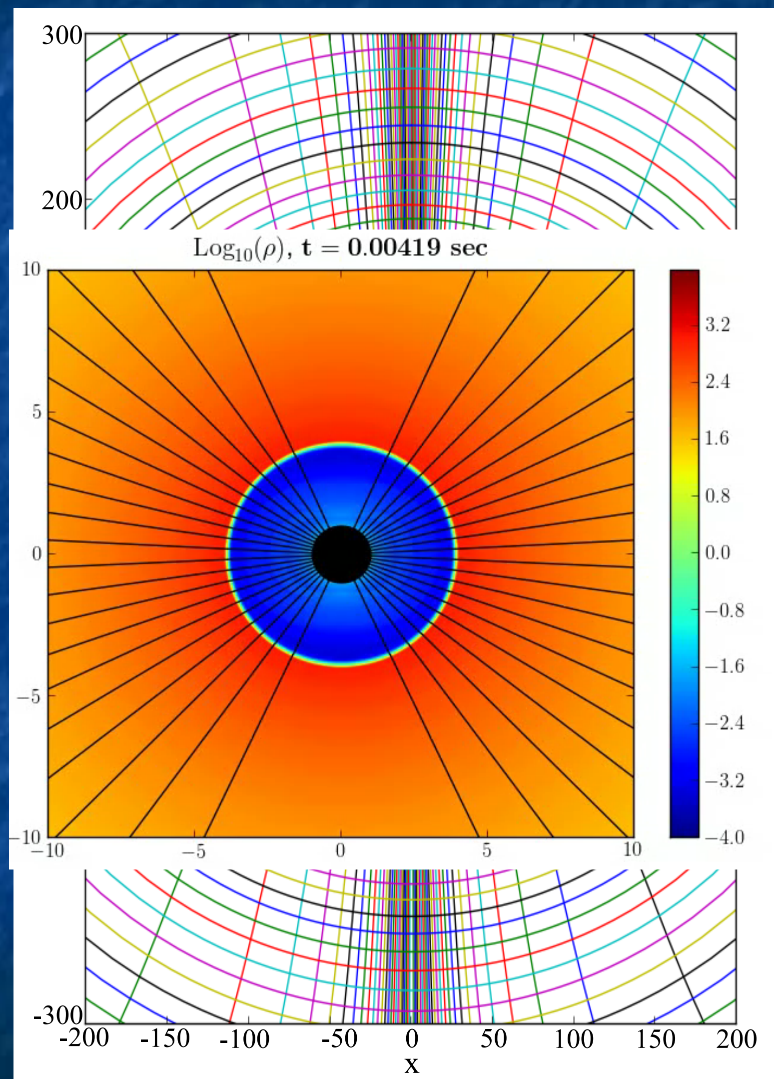


- Analytic works found that in time independent, infinite jets $B_p \approx B_\Phi$.
- Kink takes longer to grow, jet is not disrupted.
- What is the “physical” configuration of the jet? .

Simulating “physical” jets

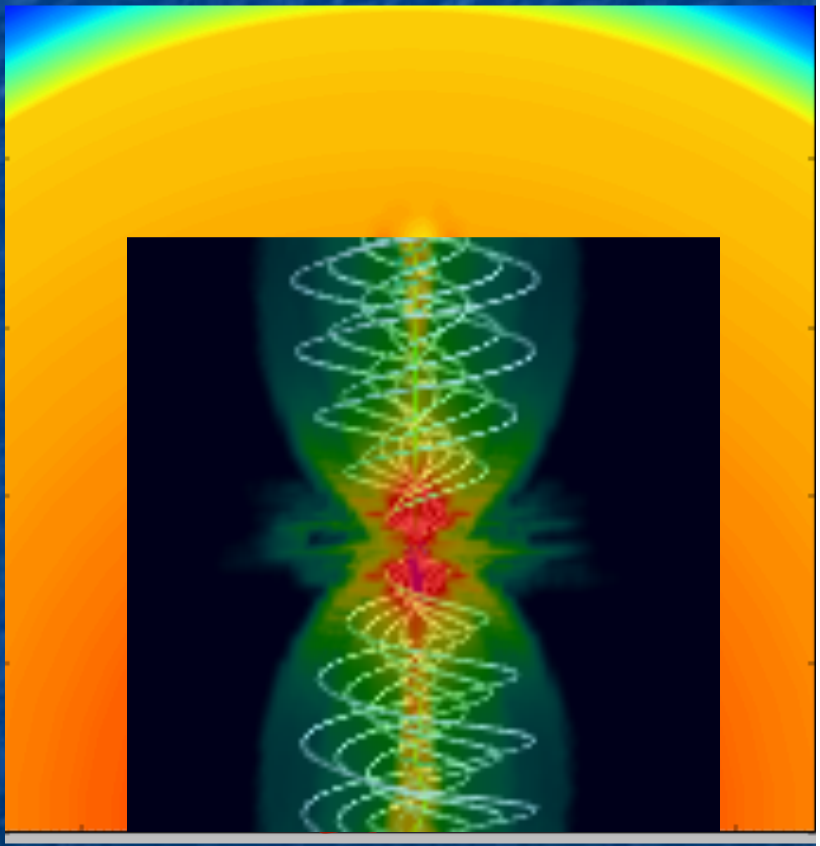
- HARM: GRMHD fixed grid Godunov scheme. Conserves fluxes to machine precession (Gammie+03; McKinney+09, AT+11).
- Grid cells are collimated toward the axis.
- We place a rotating monopole in a fixed background medium.
- The rotation winds the field lines generating toroidal field that expands outwards.
- The medium blocks the toroidal field from expanding. Toroidal pressure is built up from the rotation, and collimates the poloidal field lines (Uzdensky +06,07; Bucciantini+ 07,08,09).



(Bromberg & Tchekhovskoy 2015)

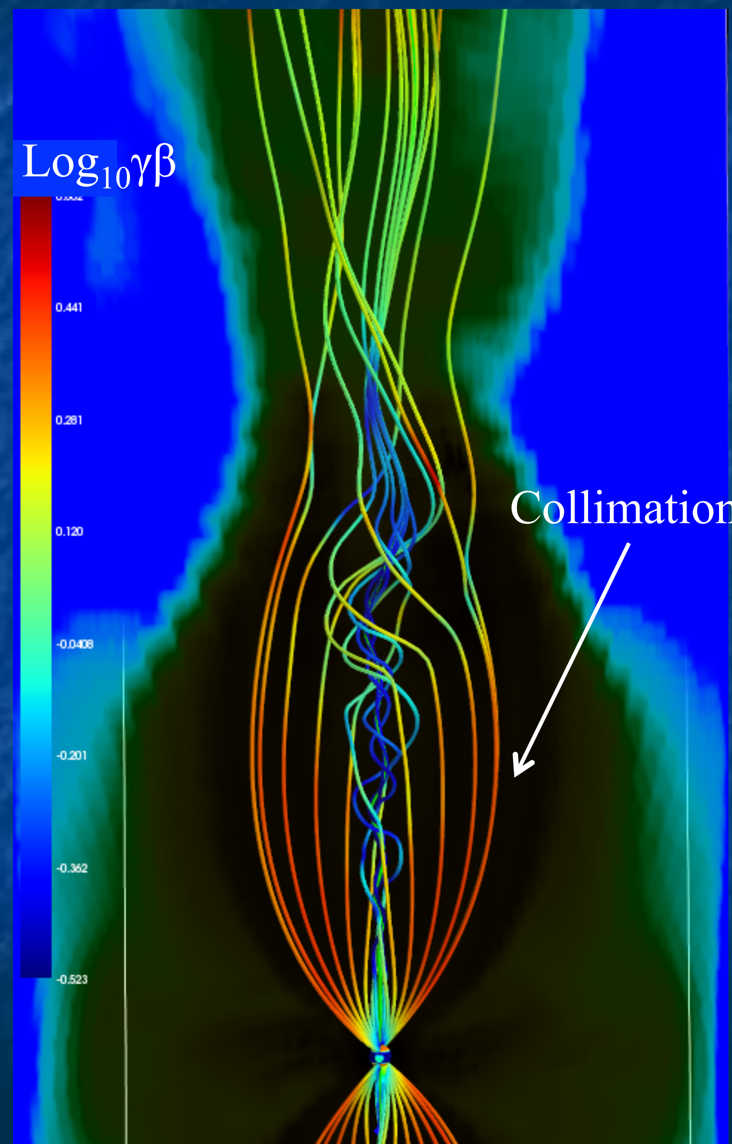
Physics of a propagating jet

- The propagating jet is surrounded by a cocoon: Applies pressure on the jet and maintains its collimation.
- At the bottom of the jet $P_j > P_c$, the jet material expands freely.
- B_p falls faster than B_Φ: field lines are mostly toroidal.
- However, no kink.



Magnetic dissipation in the jet

- The jet is collimated when it "feels" the medium.
- Extra pressure from hoop stress creates a nozzle.
- Converging field lines decelerate



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Magnetic dissipation in the jet

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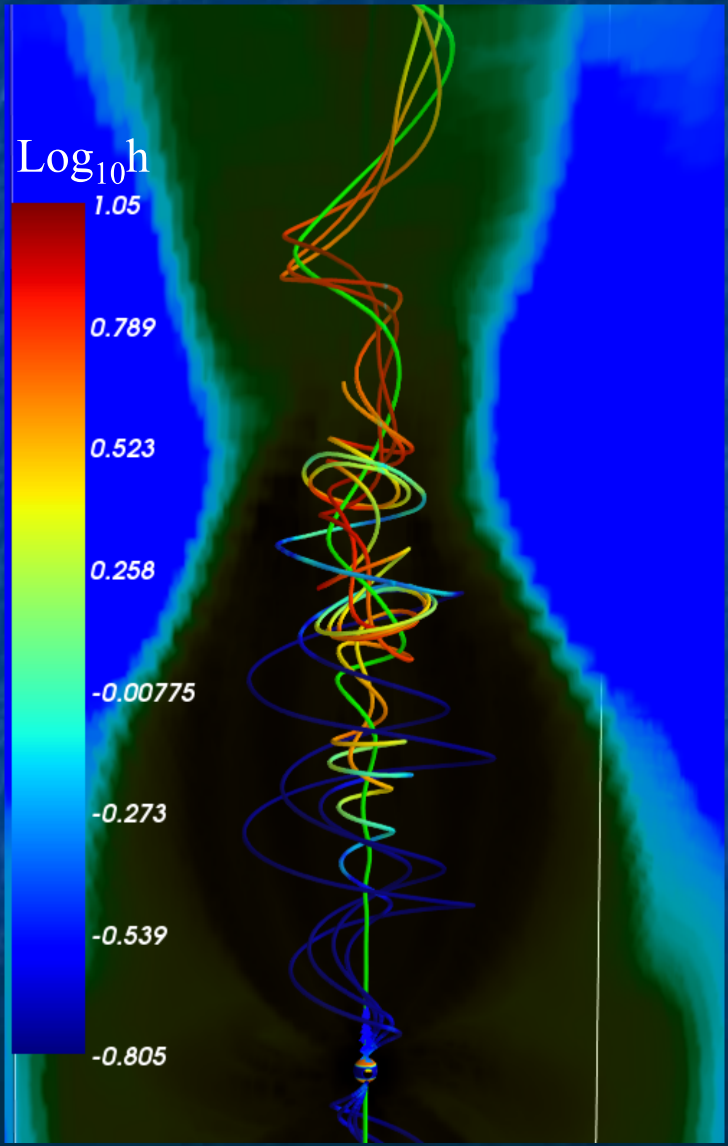
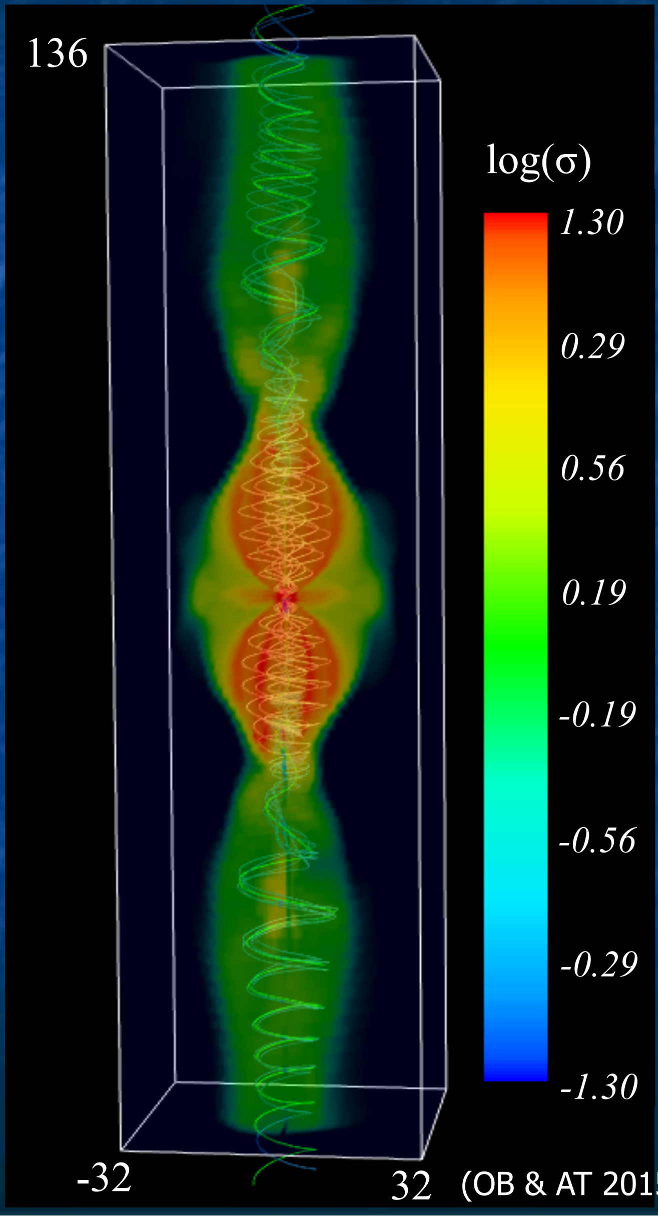
- Extra pressure from hoop stress creates a nozzle.
- Converging field lines decelerate and begin kink.
- The dissipation creates heat and releases the extra twist.
- B_p / B_Φ increases – stable to further kink.



(Bromberg & Tchekhovskoy 2015)

Above the collimation region

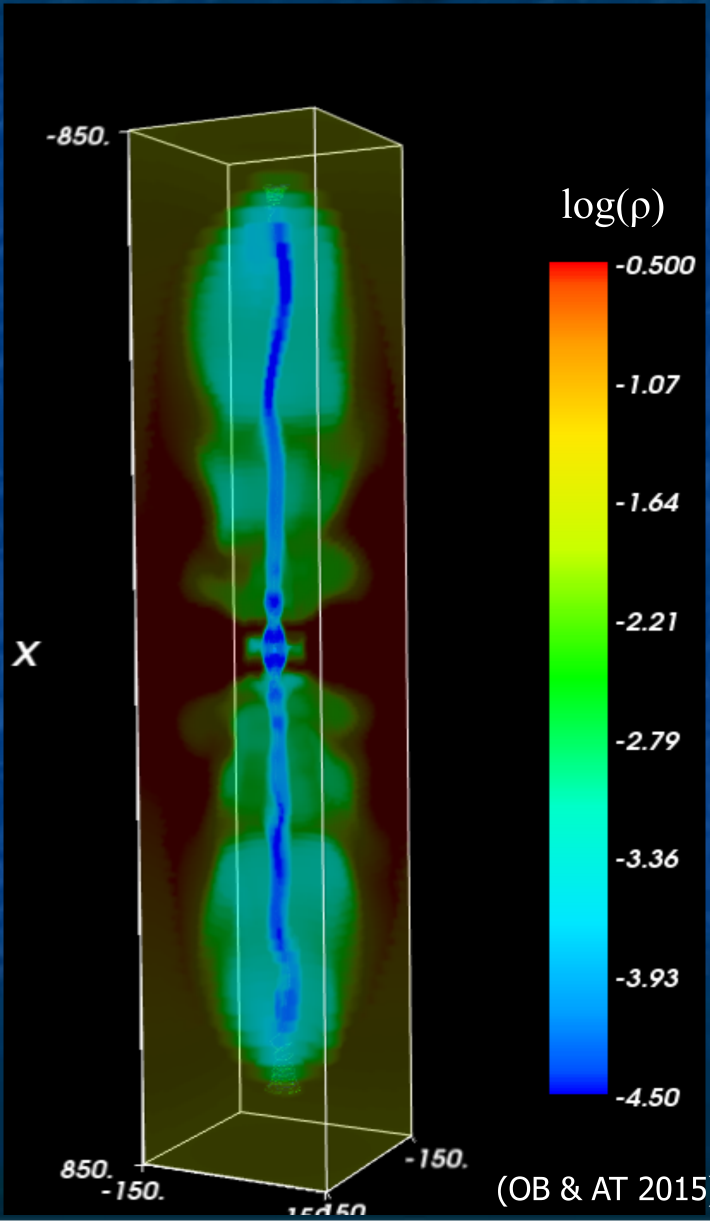
- Dissipation: $B_p \approx B_\Phi$ and P_{th}
- Relaxes when: $P_B \approx P_{th}$.
- A “hydrodynamic jet with a tweak”.



(OB & AT 2015)

Above the collimation region

- Dissipation: $B_p \approx B_\Phi$ and P_{th}
- Relaxes when: $P_B \approx P_{th}$.
- A "hydrodynamic jet with a tweak":
- Global kink modes can perturb the jet as a whole.
- Larger effective cross section: jet slows down.
- Analytic model.



(OB & AT 2015)

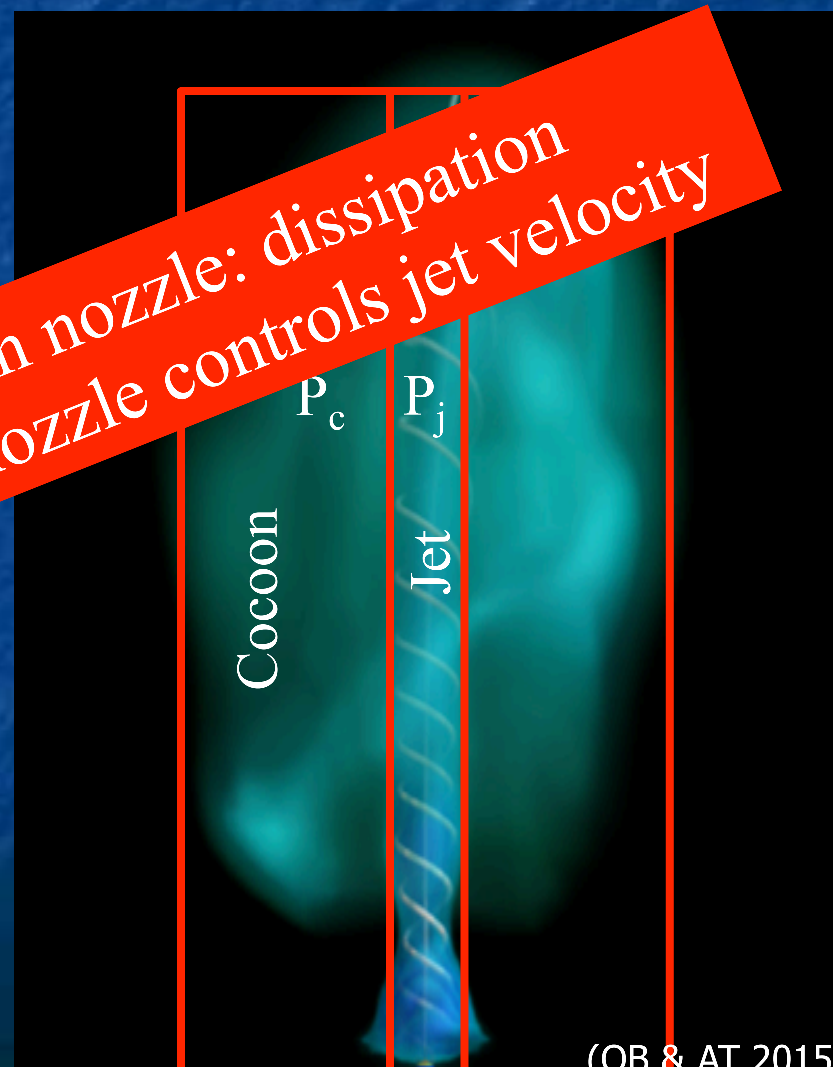
Global jet stability criterion

- The jet and the cocoon are modeled as rectangles.
- The jet is stable if $t_h < t_{kink}$

$$\Lambda \equiv \frac{t_{kink}}{t_h} \approx 10\left(\frac{L_j}{\ldots}\right)^{1/6}$$

- I… steeper … the jet accelerates … becomes more stable as it propagates upward.

I. Local kink modes at collimation nozzle: dissipation
II. Global kink mode above the nozzle controls jet velocity



(OB & AT 2015)

Implications:
I GRBs: jet breakout

- The stability of the jet's head to external kink depends on the value of $\Lambda \; \alpha \; (L_j / \rho_{ext} \, c^3 z_h^2)^{1/6}$.
- When $\Lambda>1$ the jets head is relatively stable and propagates at a velocity

$\beta_h \sim 0.3(L_{49.5} R_{11} \gamma_{0.3}{}^4 / M_{10\odot})^{1/3}$

- It'll break out of the star after $t_b \sim 10$ s.

(Bromberg & Tchekhovskoy 2015)

II. GRBs: failed jets

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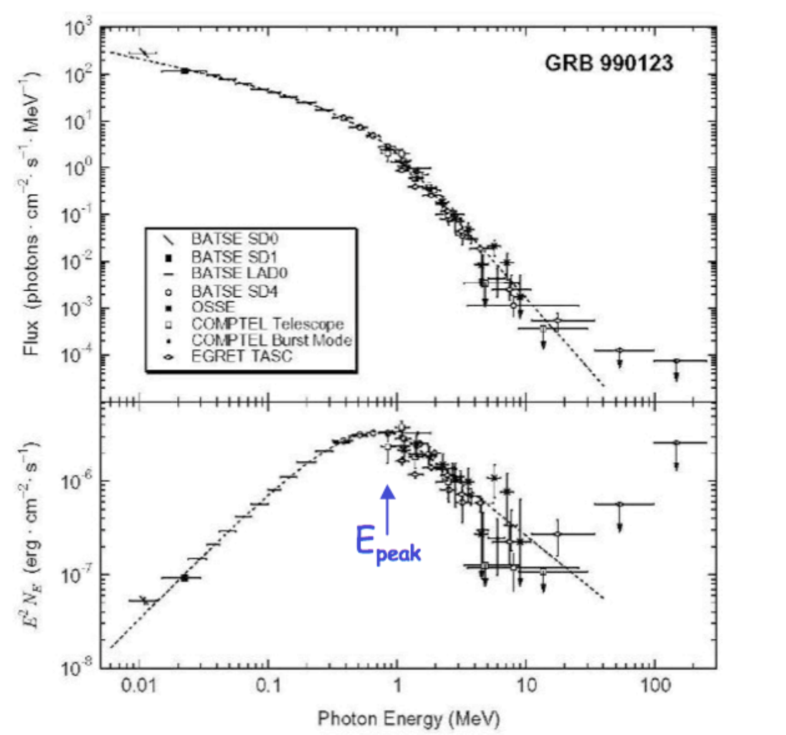
  $\beta_h \sim 0.3(L_{49.5} R_{11} \gamma_{0.3}^{\ 4} / M_{10\odot})^{1/3}$
- It'll break out of the star after $t_b \sim 10$ s.
- When $\Lambda<1$ the jet's head become unstable and it's velocity decreases dramatically.
- As a result $t_b >> 10$s and a typical GRB jet will fail to breakout.
- Minimal luminosity $L_{iso}=3\times10^{49}$ erg/s.

(Bromberg & Tchekhovskoy 2015)

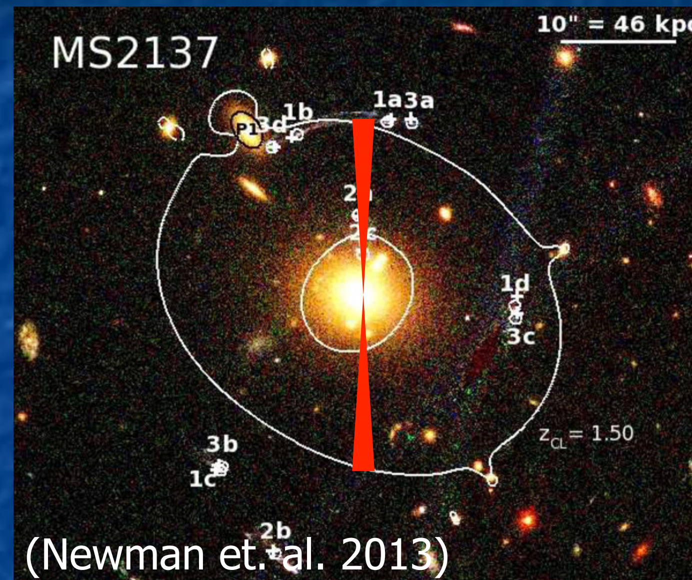
III. GRBs: σ problem

- σ problem: need to transfer the magnetic energy to the radiating particles (accelerating the bulk + generating non thermal particles).
- Local kink modes lead to σ~1 near the source – close but no cigar.
- After breakout the jet material can accelerate to high Γ due to P_{th}.
- The sudden expansion of the jet can lead to further reduction in σ (AT+10) : internal shocks?
- Individual shells can cool faster and become magnetized again (Granot 11). further reconnection?

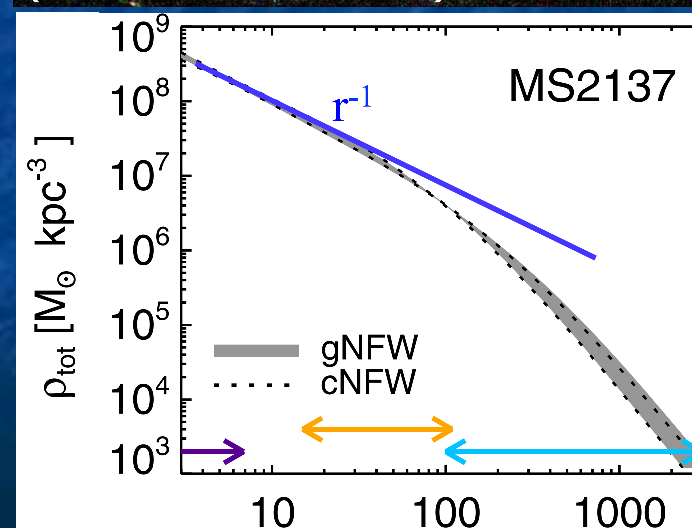


IV. AGNs: FRI vs. FRII

- Galaxy clusters have a flat density profile at r<100 kpc which becomes steeper at a larger radius.
- If ρ is shallower than r^{-2}, the head decelerates.
- A minimal luminosity for the jet to "break out": $L_{min} \sim 4\times10^{45}$ erg/s
- If $L<L_{min}$ the jet becomes unstable inside the core and may even stall.



(Newman et. al. 2013)



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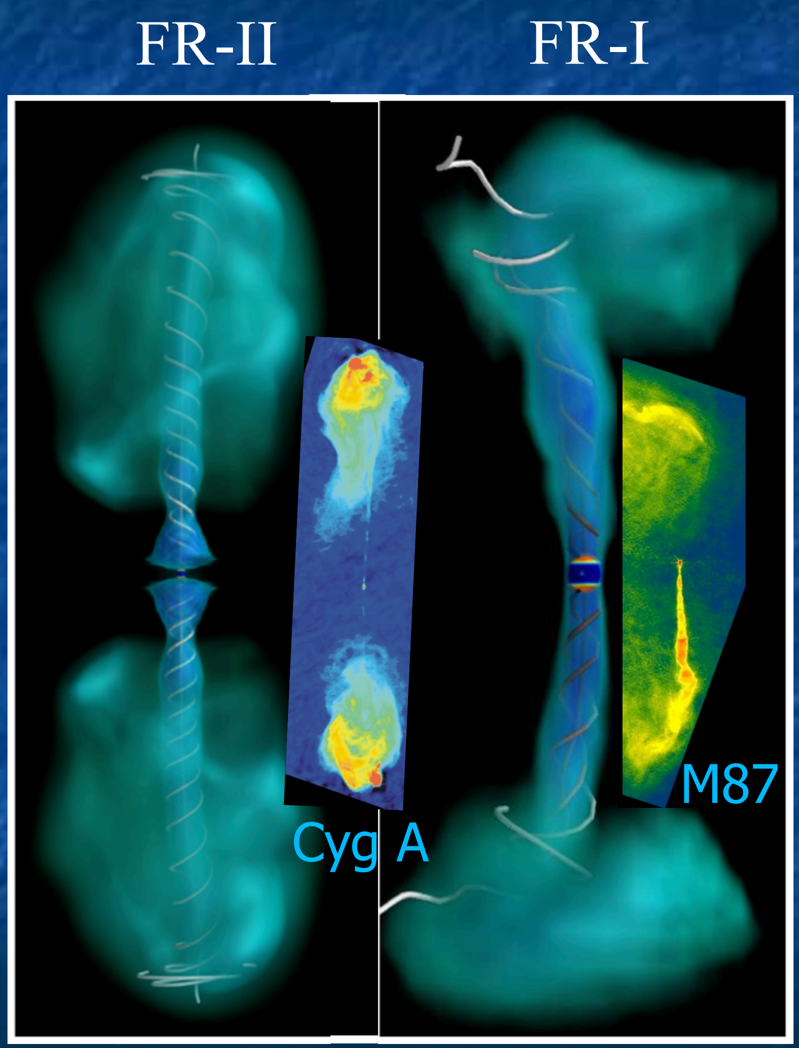
- If $L < L_{min}$ the jet becomes unstable inside the core and may even stall.
- More energy is dissipated along the jet's body. The jet will appear wider and brighter.
- May explain the difference between FR-I and FR-II galaxies.



(Tchekhovskoy & O.B. in prep)

IV: Magnetars & LGRBs

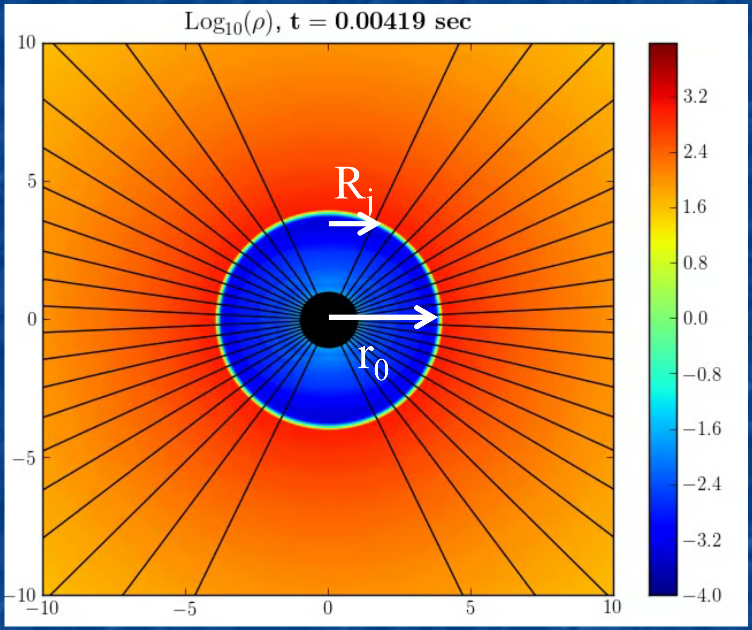
- The formation of a jet involves two time scales:
  - The time to collimate the jet and to start propagating:

$$\frac{L_j}{R_j^2} \geq \eta \cdot \rho_0 c^3 \qquad t_j \approx 10\frac{r_0}{c}$$

  - The time to develop a large kink:

$$t_{kink} \approx \frac{20\pi R_j}{c}$$

- $t_{kink} > t_j$ Condition for breaking out of cavity.



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  - The time to develop a large kink:

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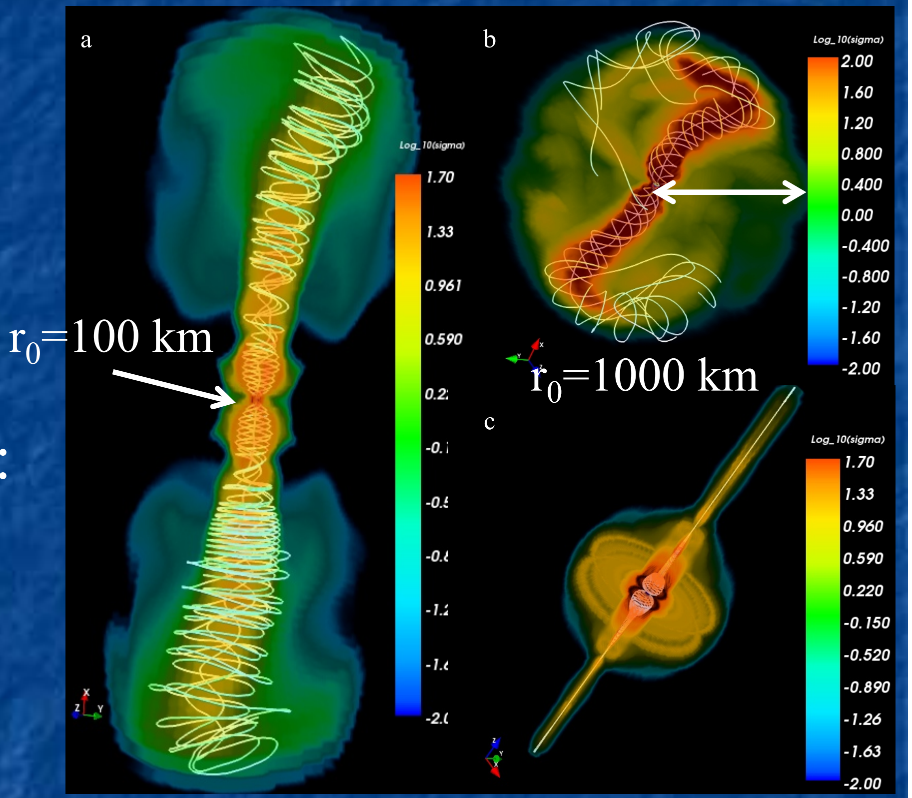
- If $t_{kink} < t_j$ the jet will not be able to propagate out.



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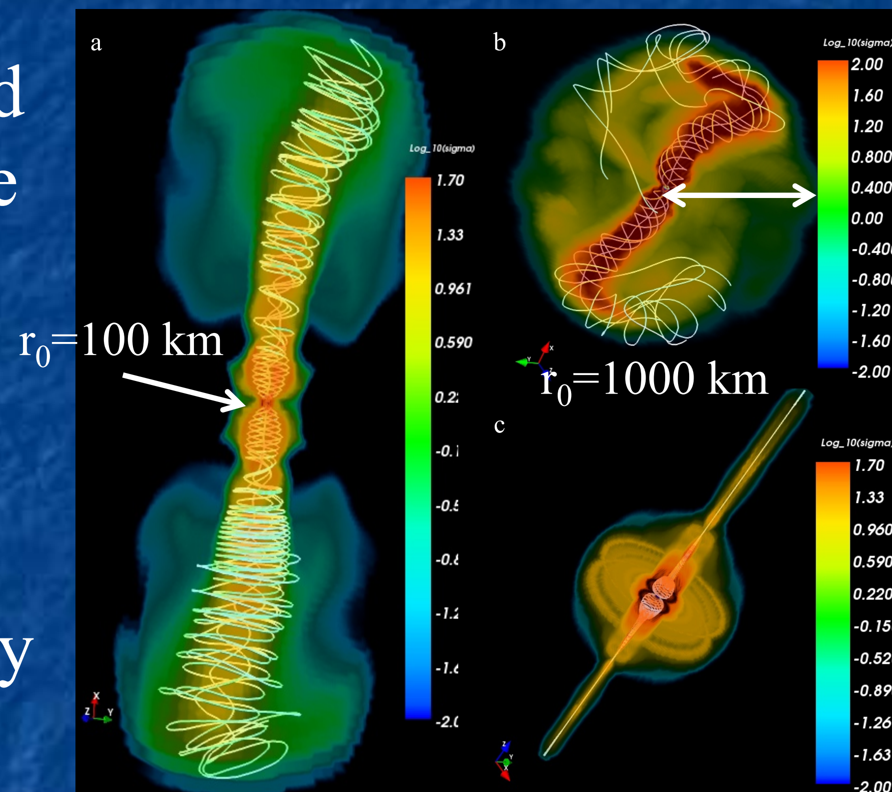
IV: Magnetars & LGRBs

- Magnetars are born in such cavities.
- Following the core collapse and the SN core bounce, it takes the magnetar a few sec to cool to a level where its magnetosphere becomes high σ (Metzger 11)
- By that time the SN shock is a few 1000 km away, and a cavity forms.
- The cavity is too large for a typical GRB jet to propagate stably.



(O.B. & Tchekhovskoy in prep)

IV: Magnetars & LGRBs

- The wobbling jet blows a magnetic bubble at the center of the star, which will eventually contain the entire rotational energy of the magnetar~10^{52} erg.
- May lead to a super luminous SN.

(O.B. & Tchekhovskoy in prep, credit A. Tchekhovskoy)

Conclusions

- The interaction of a jet with the medium results in a growth of two types of kink modes:
  - A local mode: efficient dissipation of magnetic energy at the collimation point (High energy emission zones?).
  - A global mode: bodily deforms the jet and controls the jet velocity.
- Global mode growth depends on the density profile. In shallow profiles the jet decelerates. It becomes unstable and can eventually stall.
- Partially solves the σ problem and produce failed jets in GRBs, explain the FRI-FRII dichotomy, poses challenges to the magnetar model for LGRBs.
- Much more to come (properties of the reconnection layers, solar flairs…).