Current-Driven Instabilities in the Crab Nebula Jet: Results from Numerical Simultations

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Outline

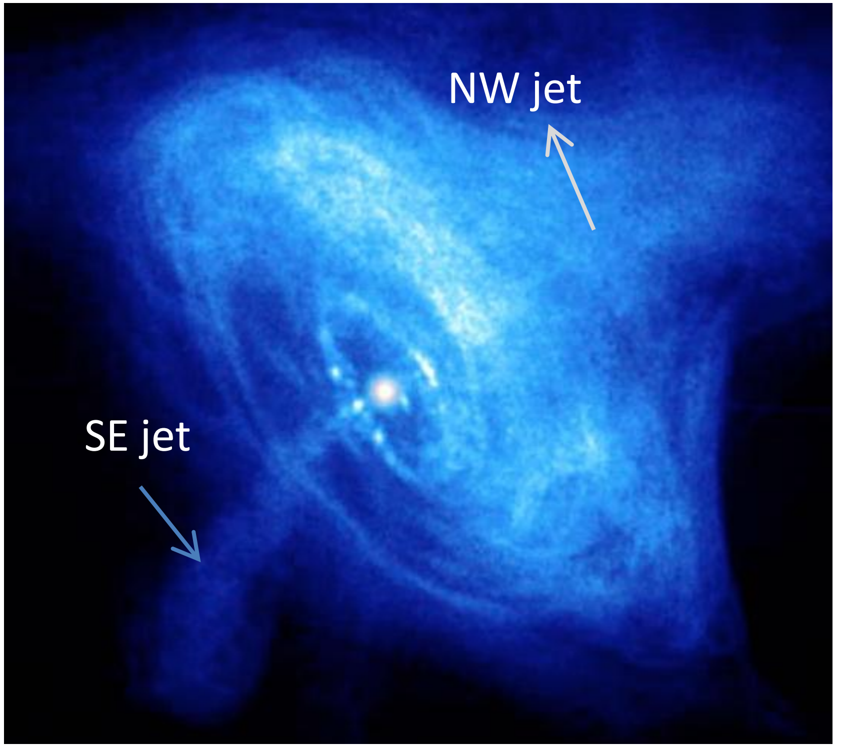
1. *Observational Evidence*

2. *Numerical Models of Relativistic MHD Jets*
   - *2D Axisymmetric models*
   - *3D models → Kink instabilities*

3. *Results*

4. *Summary*

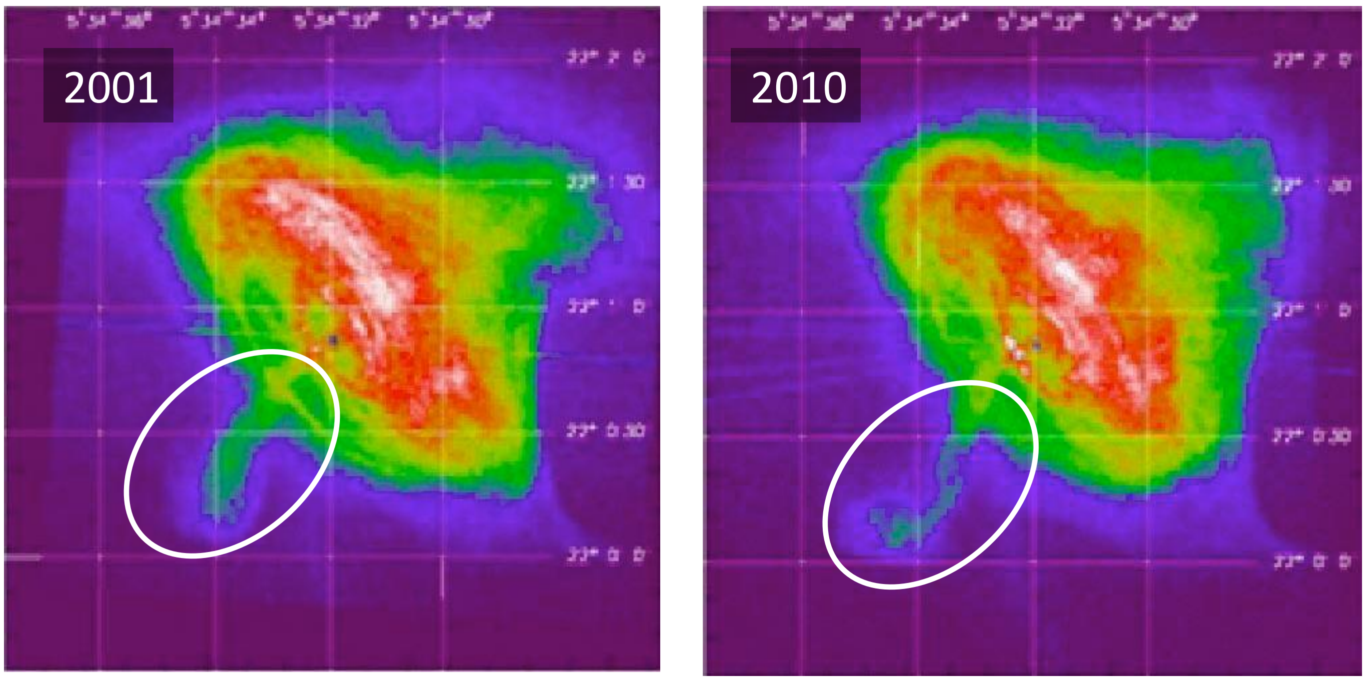
Observational Evidence



- X-ray observations (Chandra) show the emergence of bipolar jets extending to the SE and NW of the pulsar;
- A region of diffuse emission (Anvil) may be associated with shocks and marks the base of the X-ray and optical jet;
- Knots of emission are seen along the jets;
- In the SE jet material flows with v/c~0.4 slowing down to ~0.02 into the nebula;

Jet Wiggling

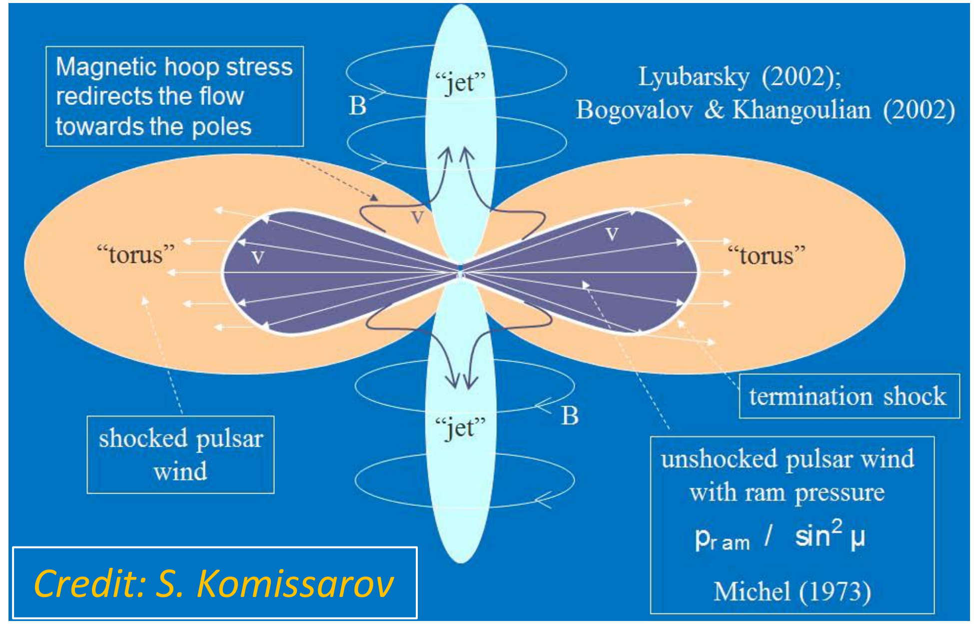
- SE jet morphology is “S” shaped and show remarkable time variability:



- → evidence for some kind of flow instability (Current Driven ?)

On the Origin of the Jet

- Jet forms downstream of the wind termination shock;
- Magnetic fields confine matter towards polar axis;
  → "***tooth-paste***" effect: hoop stress of the azimuthal magnetic field carried by the wind (Lyubarsky 2002).

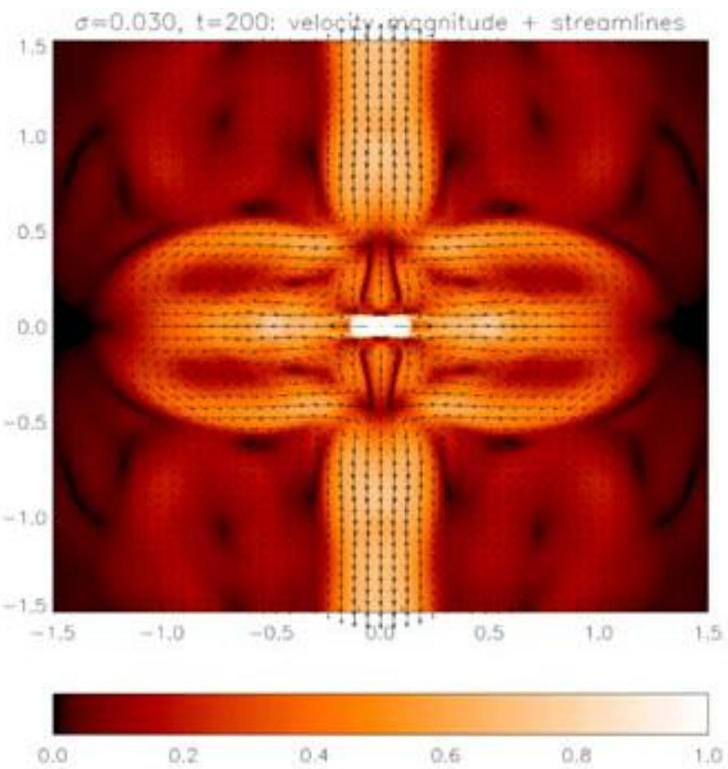


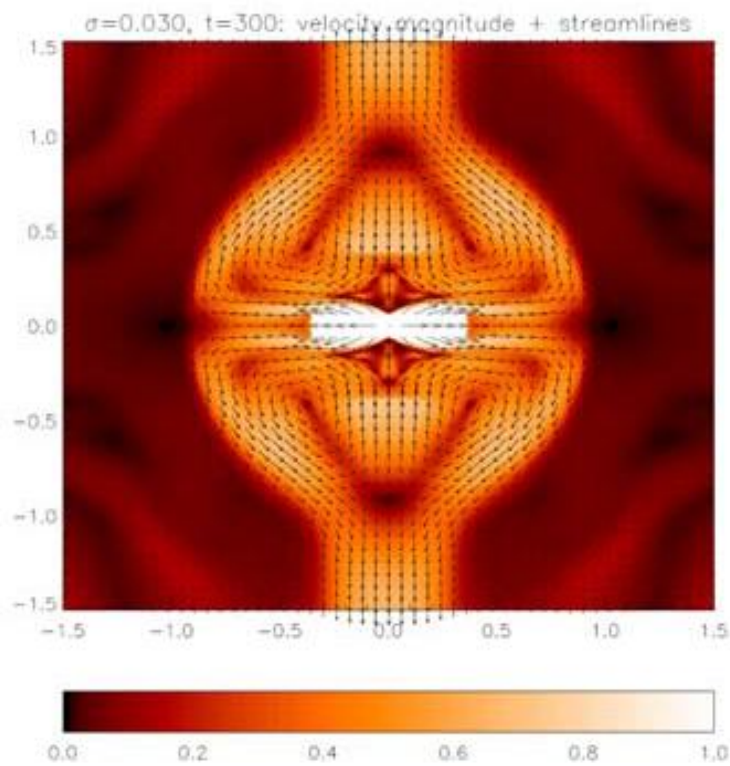
Credit: S. Komissarov

- Models confirmed by 2D axisymmetric numerical simulations (Komissarov & Lyubarski 2003,2004, Del Zanna et al. 2004, Bogovalov et al. 2005)

Jet Origin: Axisymmetric Models

- For moderate/large $\sigma = B^2/(4\pi\rho c^2\gamma^2)$ magnetic hoop stress suppresses high velocity outflows in the equatorial plane and divert them towards the polar axis partially driving the super-fast jet[1]

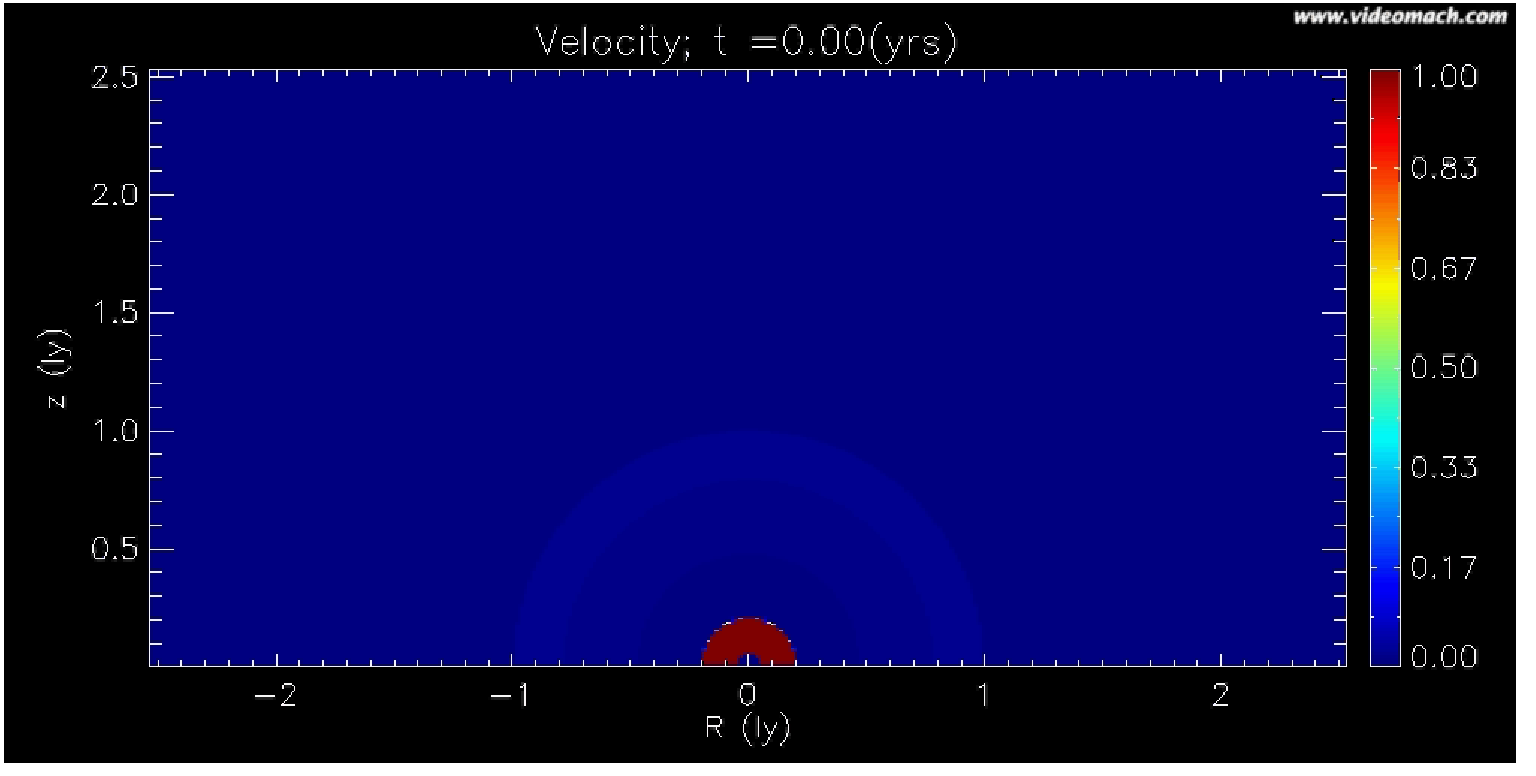




[1]Del Zanna et al, *A&A* (2004) 421,1063

Axisymmetric PWN Models

- Results from 2D axisymmetric simulations predict hollow and hot jets initially carrying purely axial current ($B_\phi \neq 0$, $B_z = B_R = 0$);



- Bz = 0 → Pitch = 0; $1.3 \lesssim Ms \lesssim 2$ (hot jet); $\rho_j / \rho_e \lesssim 10^{-6}$
- Two free parameters: **$0.1 \lesssim \sigma \lesssim 10$** and **$2 \lesssim \gamma \lesssim 4$**;

Jet Models

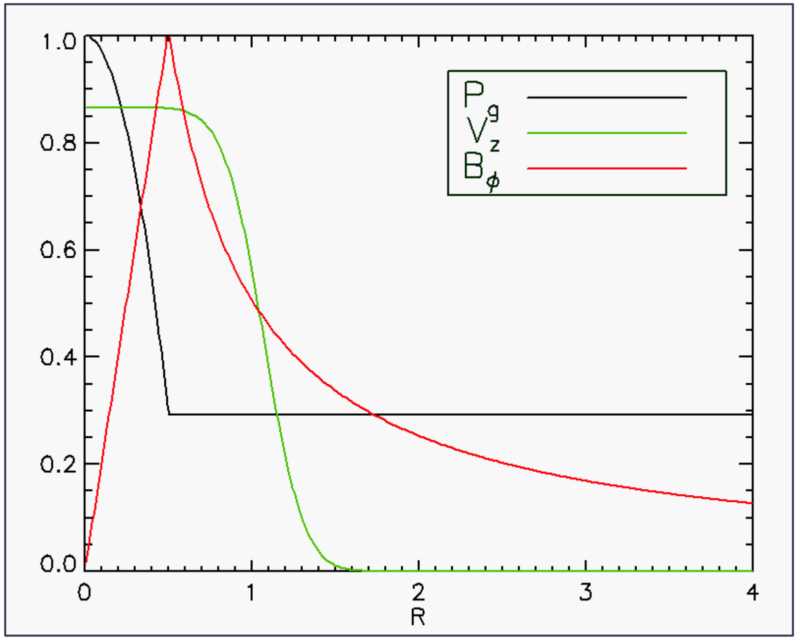
- We consider a 2-parameter (γ, σ) family of light, hot jets with $\rho_j/\rho_e = 10^{-6}$; $M_s = 1.7$;

$$v_z(R) = \sqrt{1 - \frac{1}{\gamma_j^2}\psi\left(\frac{R^8}{R_j^8}\right)} \qquad B_\phi(R) = \begin{cases} B_m \dfrac{R}{a} & \text{for} \quad R \leqslant a\,, \\ B_m \dfrac{a}{R}\psi\left(\dfrac{R^6}{R_j^6}\right) & \text{for} \quad R > a\,, \end{cases}$$

with ($B_m^2 \propto \sigma$).

- Radial momentum balance holds across the beam

$$\left(\frac{\partial p}{\partial r} - \frac{w\gamma^2 v_\phi^2}{r}\right)\hat{\boldsymbol{r}} \quad = \quad (\nabla\cdot\boldsymbol{E})\,\boldsymbol{E} + \boldsymbol{J}\times\boldsymbol{B}$$



Equations and Numerical Method

- We solve the equations of a relativistic perfectly conducting fluid describing energy/momentum and particle conservation (relativistic MHD equations)

$$\frac{\partial(\rho\gamma)}{\partial t} + \nabla\cdot(\rho\gamma\mathbf{v}) = 0\,,$$

$$\frac{\partial\mathbf{m}}{\partial t} + \nabla\cdot[w\gamma^2\mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} - \mathbf{E}\mathbf{E}] + \nabla p_t = 0\,,$$

$$\frac{\partial\mathbf{B}}{\partial t} - \nabla\times(\mathbf{v}\times\mathbf{B}) = 0\,,$$

$$\frac{\partial\mathcal{E}}{\partial t} + \nabla\cdot(\mathbf{m} - \rho\gamma\mathbf{v}) = 0\,,$$

$$\mathbf{m} = w\gamma^2\mathbf{v} + \mathbf{E}\times\mathbf{B}$$

$$\mathcal{E} = w\gamma^2 - p + \frac{\mathbf{B}^2 + \mathbf{E}^2}{2} - \rho\gamma$$

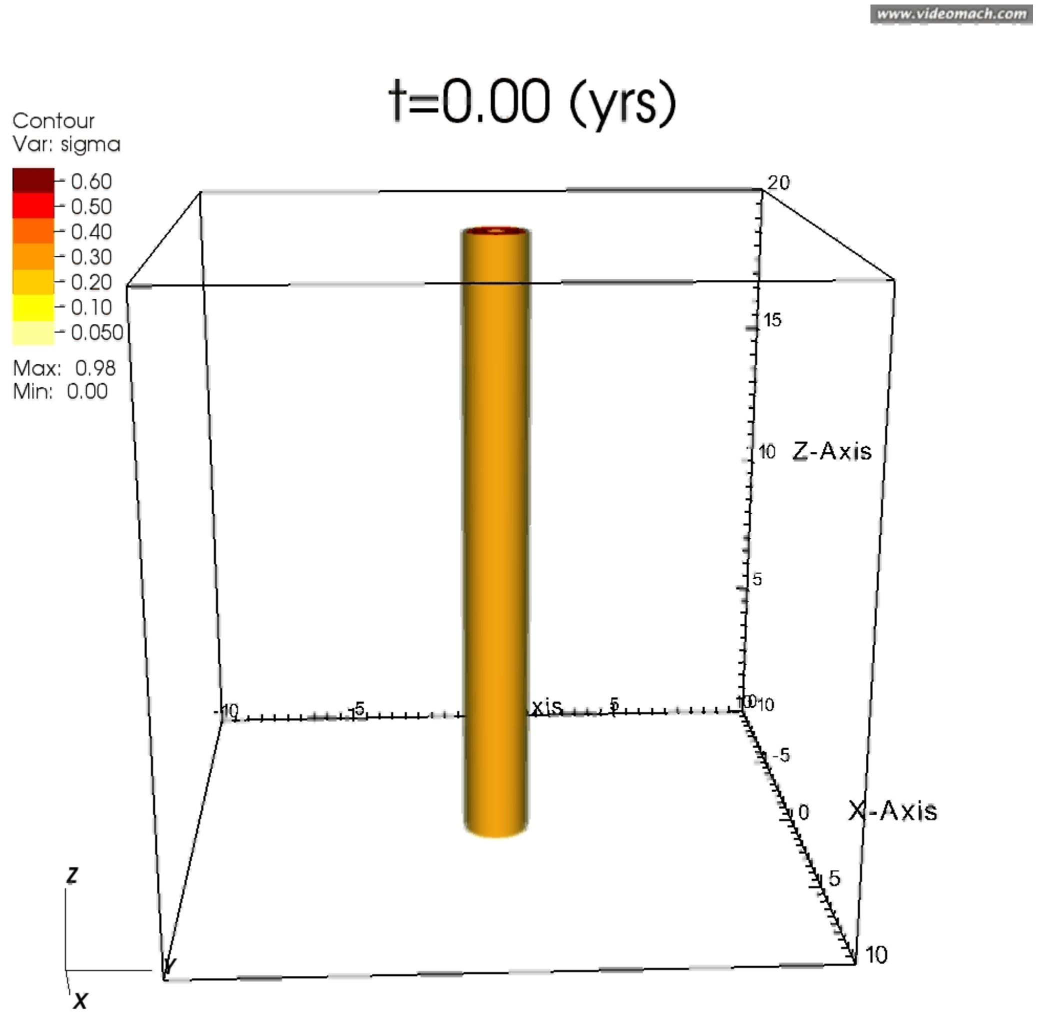
$$w = \rho + \frac{\Gamma p}{\Gamma - 1}$$

- We use the PLUTO[1,2] code for astrophysical fluid dynamics (*http://plutocode.ph.unito.it*);
- Linear reconstruction + HLLD Riemann solver;
- Numerical resolution 320 x 320 x 768 zones (≈ 20 zones on the jet).

[1]Mignone et al, *ApJS* (2007) 170, 228; [2]Mignone et al, *ApJS* (2012) 198, 7

Instabilities in Periodic Jets

- These jet configurations are unstable to a variety of modes, mainly KH and CD;
- For non-zero velocities KH and CD modes mix up[1].
- At large magnetizations, the m=1 CD mode (kink) prevails.
- At large velocities KH modes prevails.

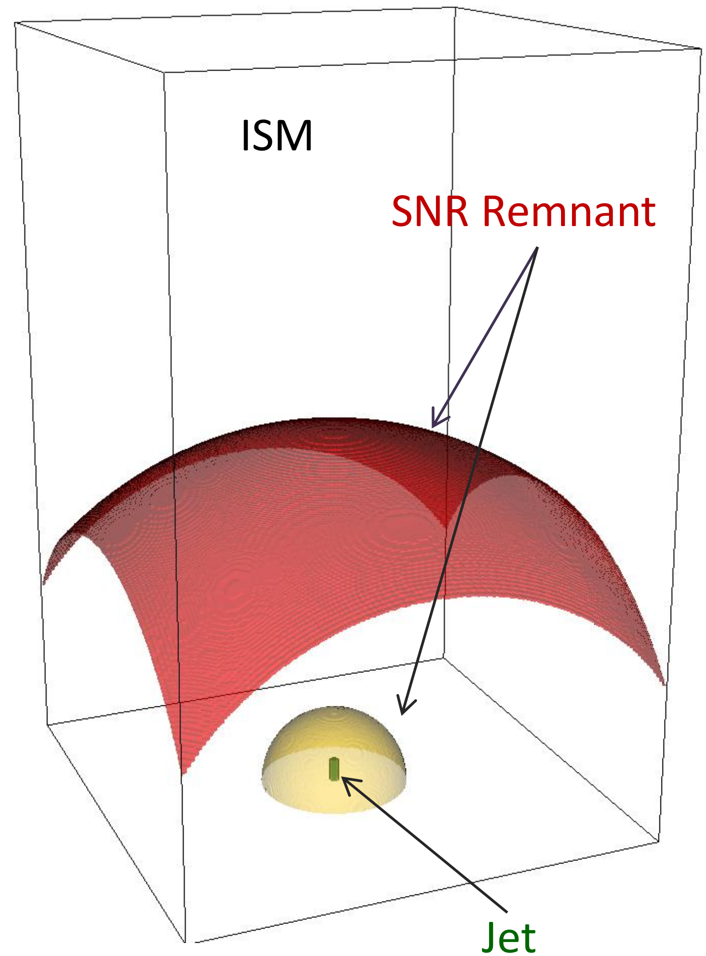


$\sigma = 1; \gamma = 2$

[1]Bodo et al. *MNRAS* (2013, accepted)

A More Realistic 3D Scenario

- We consider a 3D Cartesian domain with $x,y \in [-0.8, 0.8]$ (ly), $z \in [0, 2.5]$ (ly).
- Freely expanding supernova ejecta ($3\ M_{sun}$, $E = 10^{51}$ erg) for $0.2 < r < 1$ (ly)
- Pulsar wind structure not considered: jet already formed as the result of the collimation process;
- Supersonic injection nozzle at the lower z-boundary.



Simulation Cases

- γ and σ are free parameters. We consider slow and and fast jets with weak, moderate and strong magnetic fields (6 cases)

	$\gamma = 2$	$\gamma = 4$
$\sigma = 0.1$	A1	B1
$\sigma = 1$	A2	B2
$\sigma = 10$	A3	B3

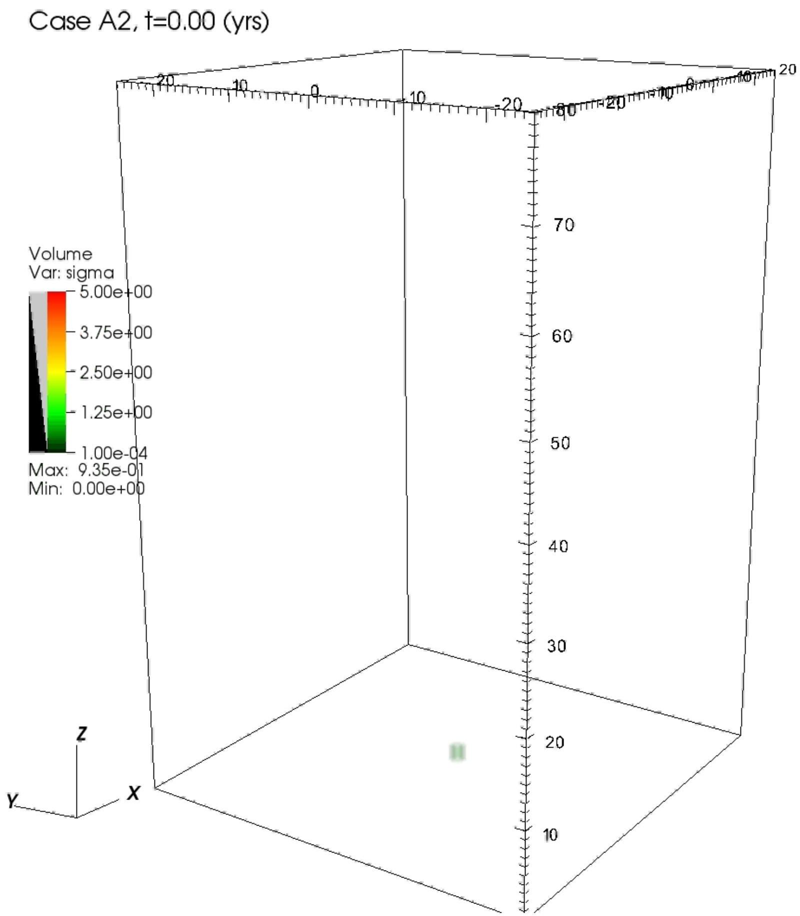
(axes: γ →, σ ↓)

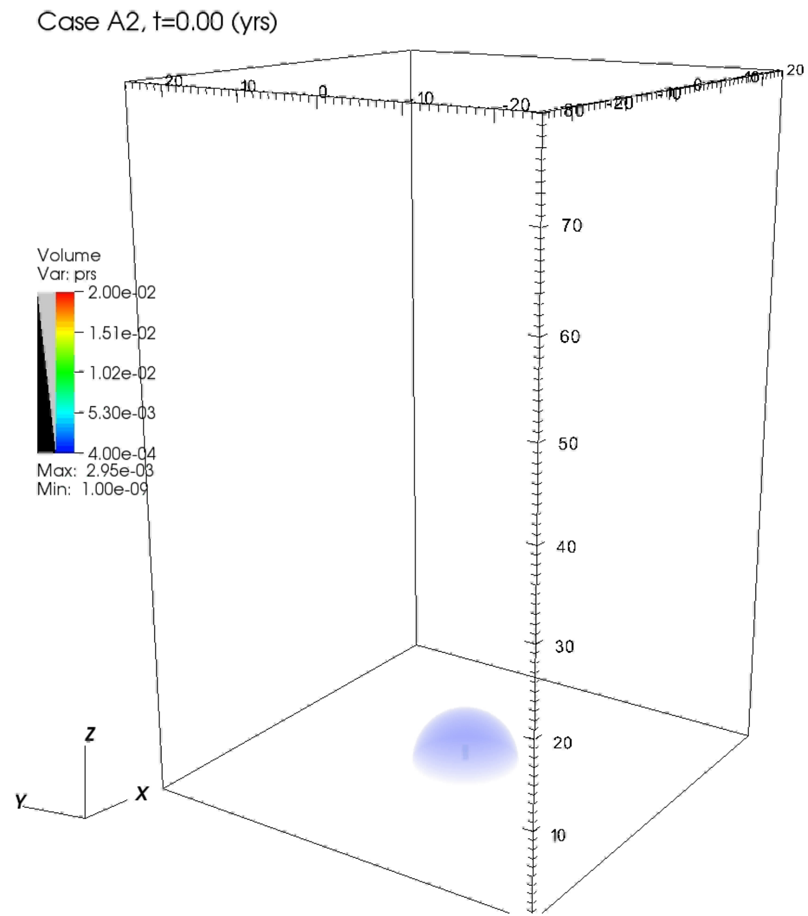
Results: Case A2

	γ = 2	γ = 4
σ = 0.1	A1	B1
σ = 1	A2	B2
σ = 10	A3	B3

σ

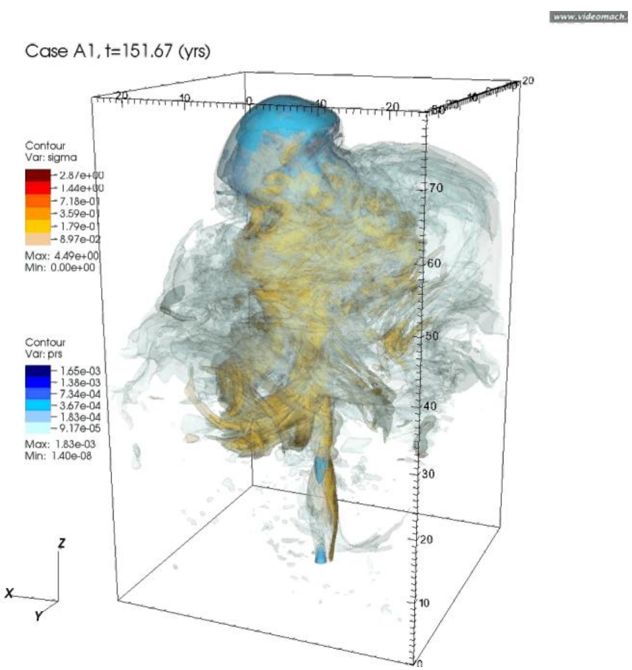
p

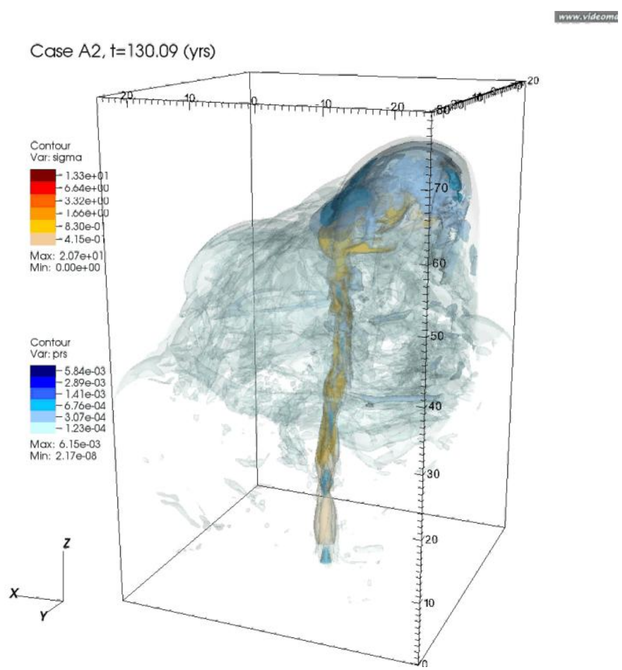


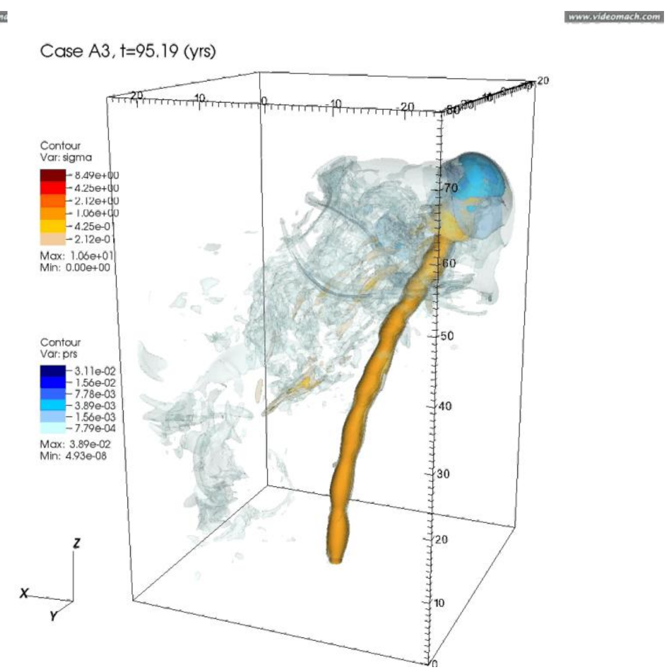


General Features: low speed jets

- Low speed jets advance slowly ($v_{head} < 0.02$) ← large density contrast;
- Evolve entirely inside the remnant;
- Larger σ drive magnetically supported jets and show the largest deflections;

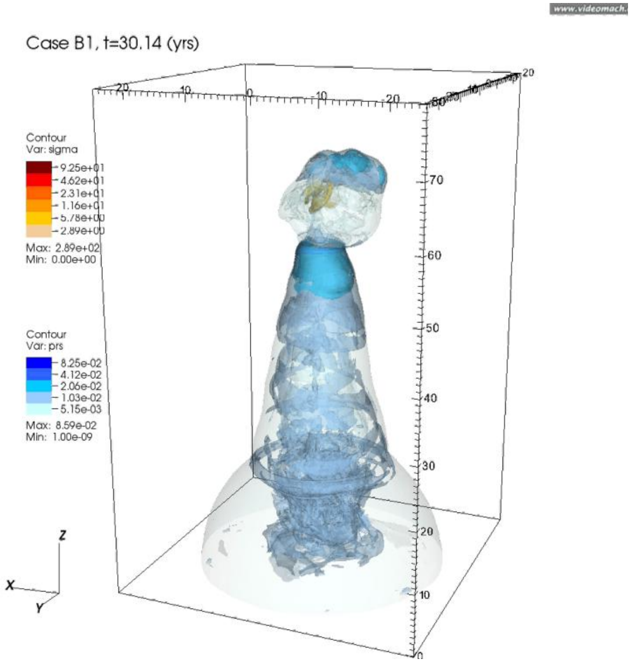


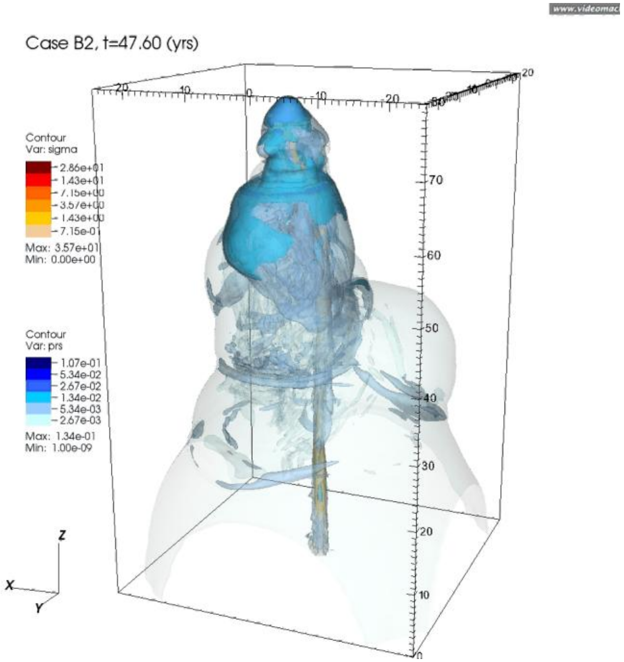


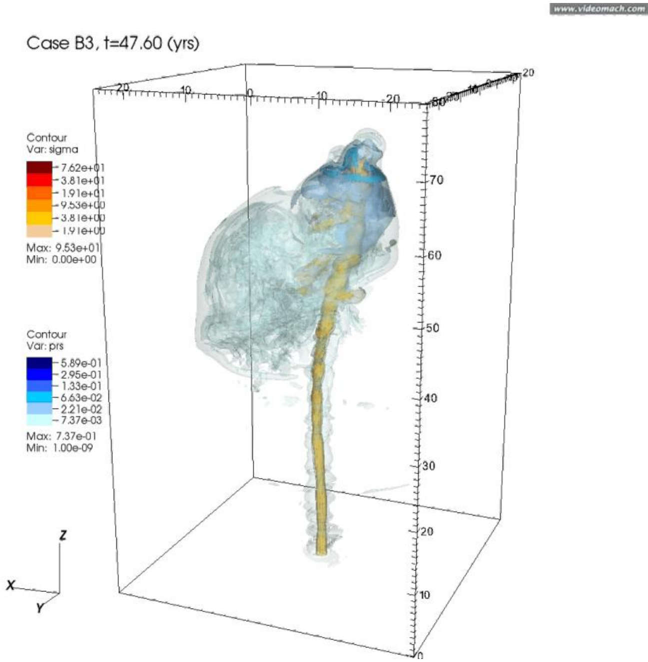


General Features: high speed jets

- High-speed jets propagete faster ($v_{head} < 0.05$);
- Reach the outer supernova remnant after ≈ 50 years;
- For large σ deflections are present but smaller than low speed jets → Lorentz factor has a stabilizing effect.

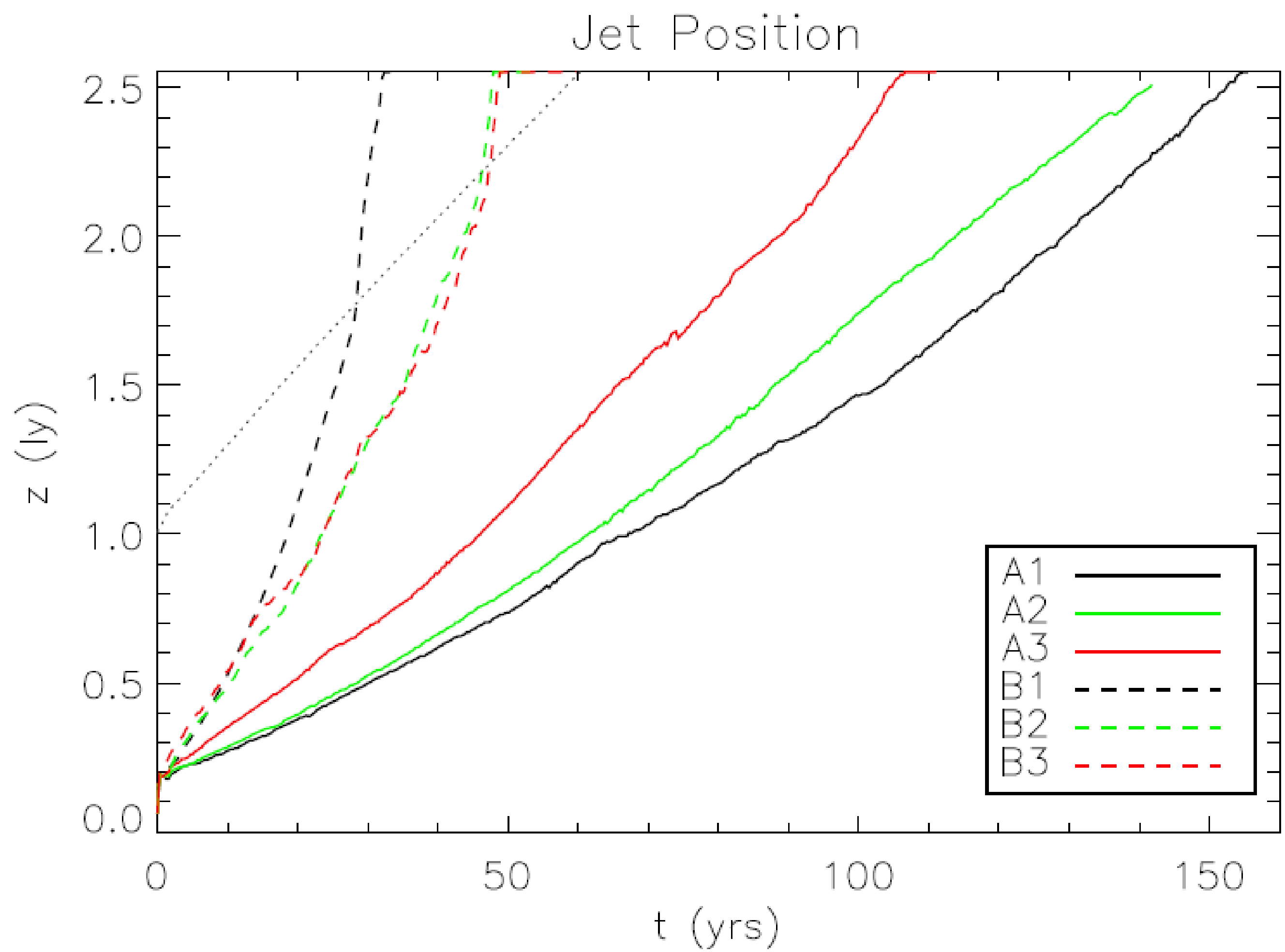






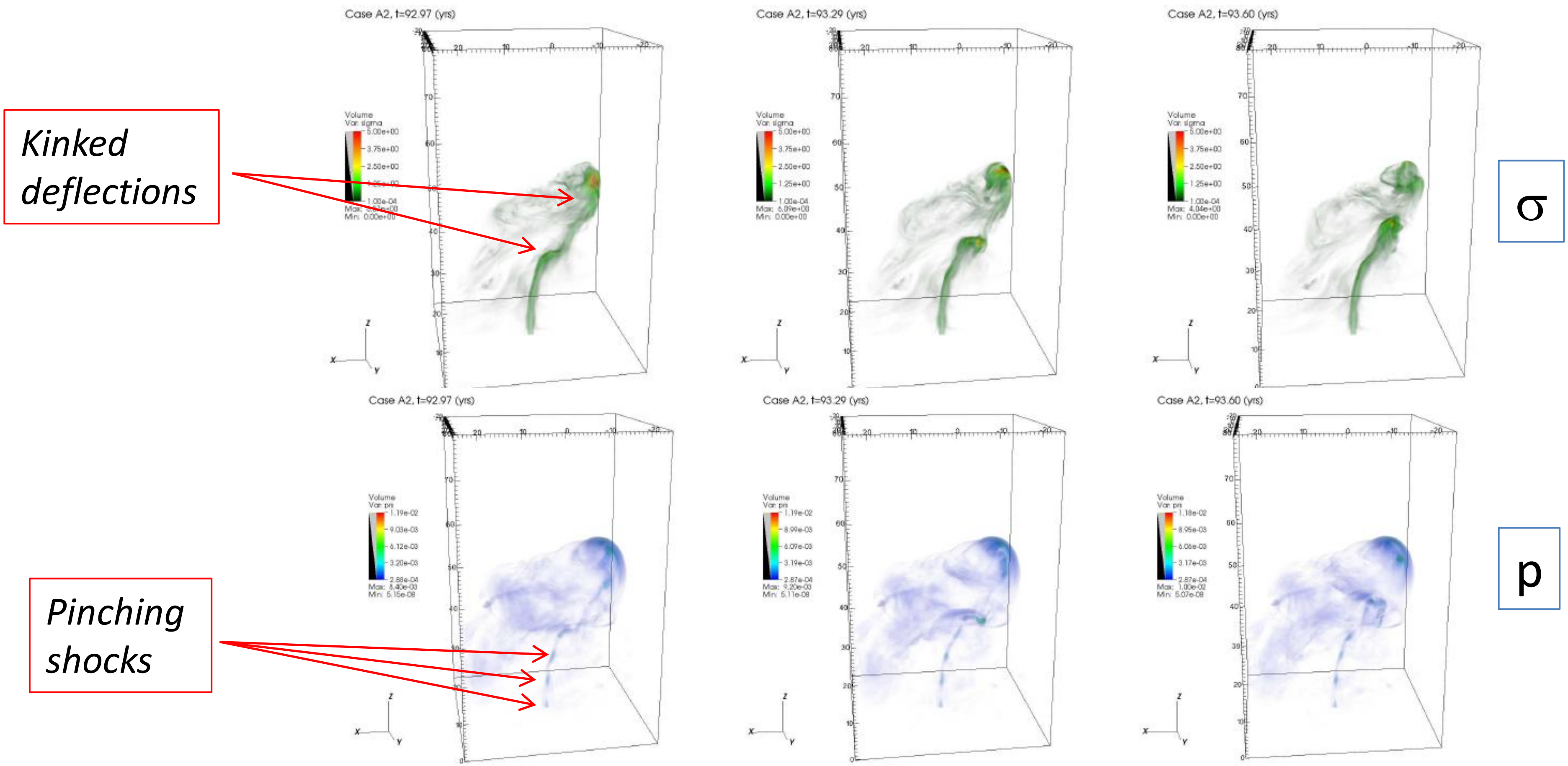
Propagation Speed

- Jets with γ=4 “drill out” of the remnant in less than 50 years…



Jet Structure

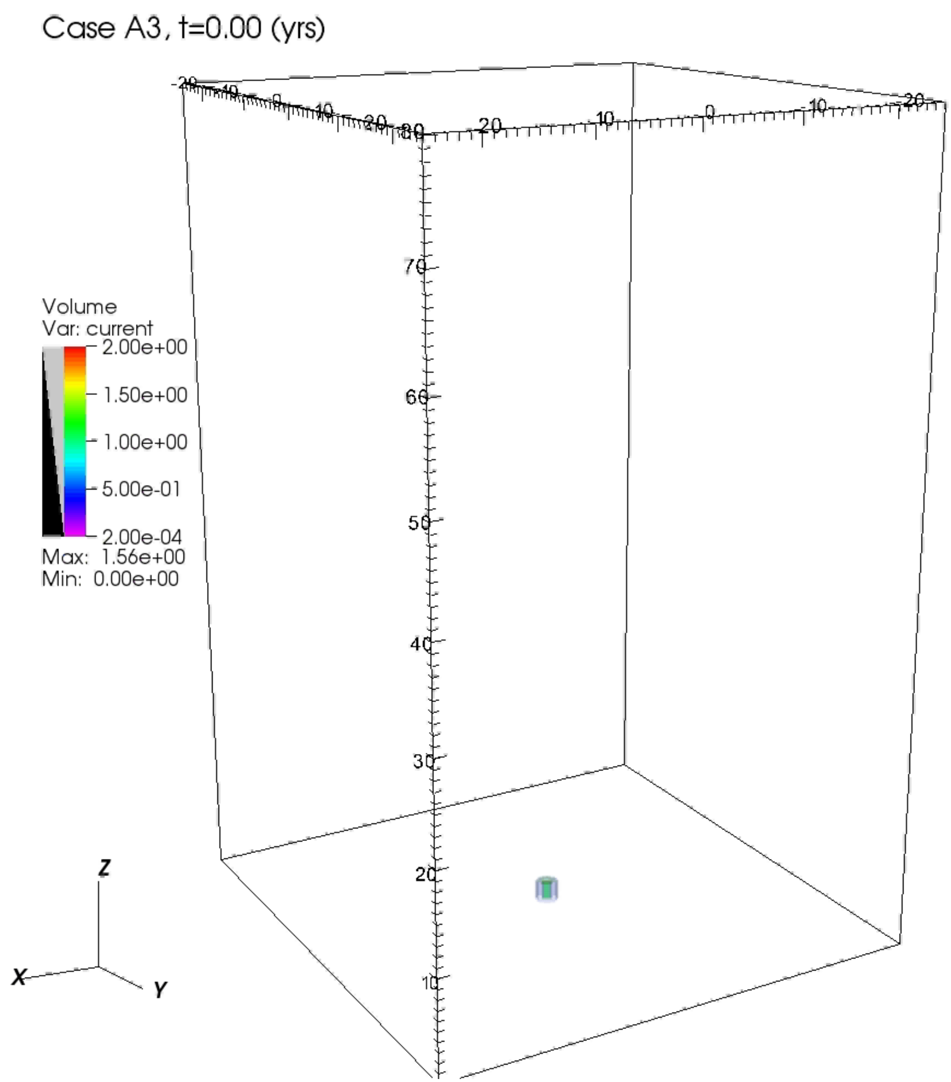
- ***Back-end regions:*** quasi-periodic stationary pinch (m=0) shocks;
- ***Front-end regions:*** jet fragmentation at deflection sites forming short-lived unstable structures;



Jet Structure

- Front-end regions:
  - rapid variability
  - strong interaction with the ambient

- For strong magnetization → formation of twisted helical structures.



$J=\nabla\times B$

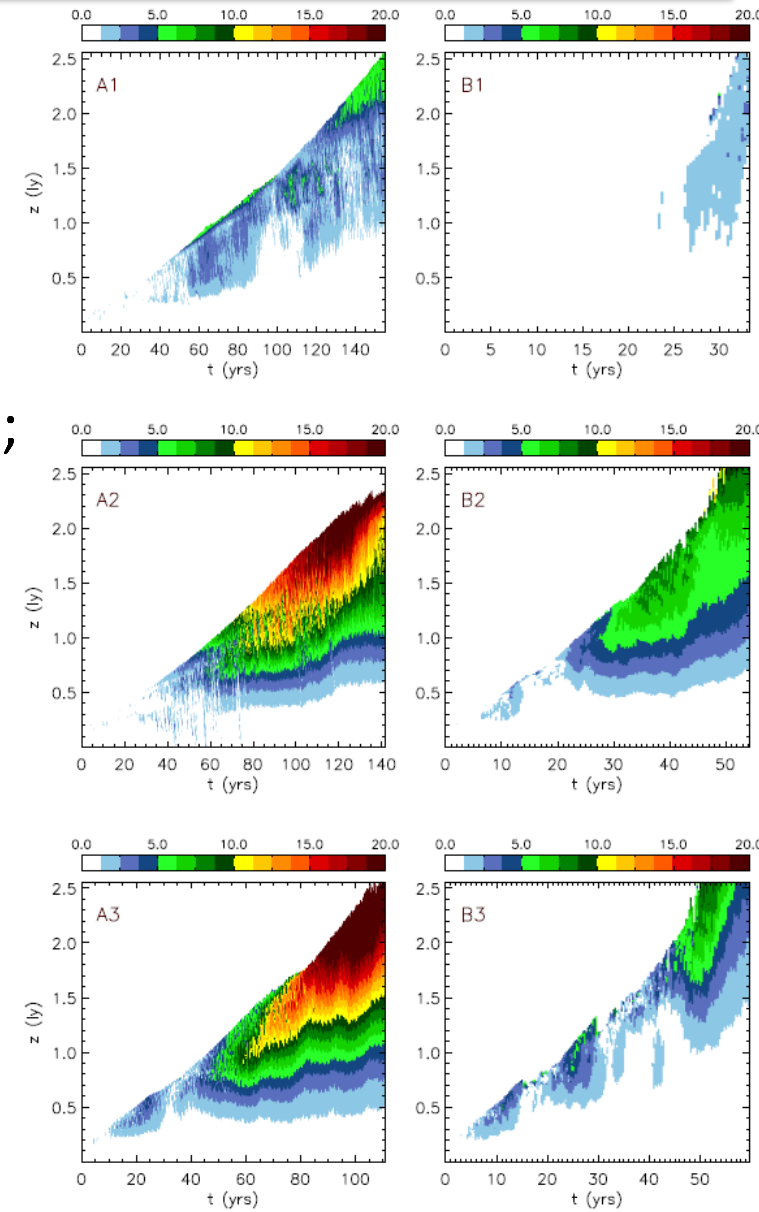
Jet Deflections

- Center of mass → amount of deflection;

- Low-speed ($\gamma \approx 2$), magnetized ($\sigma \gtrsim 1$) jets show the largest bending ($\gtrsim 20\ R_j$);

- Larger Lorentz factors ($\gamma \approx 4$) have a stabilizing effect[1];

- Weakly magnetized jets less affected by the growth of instability;

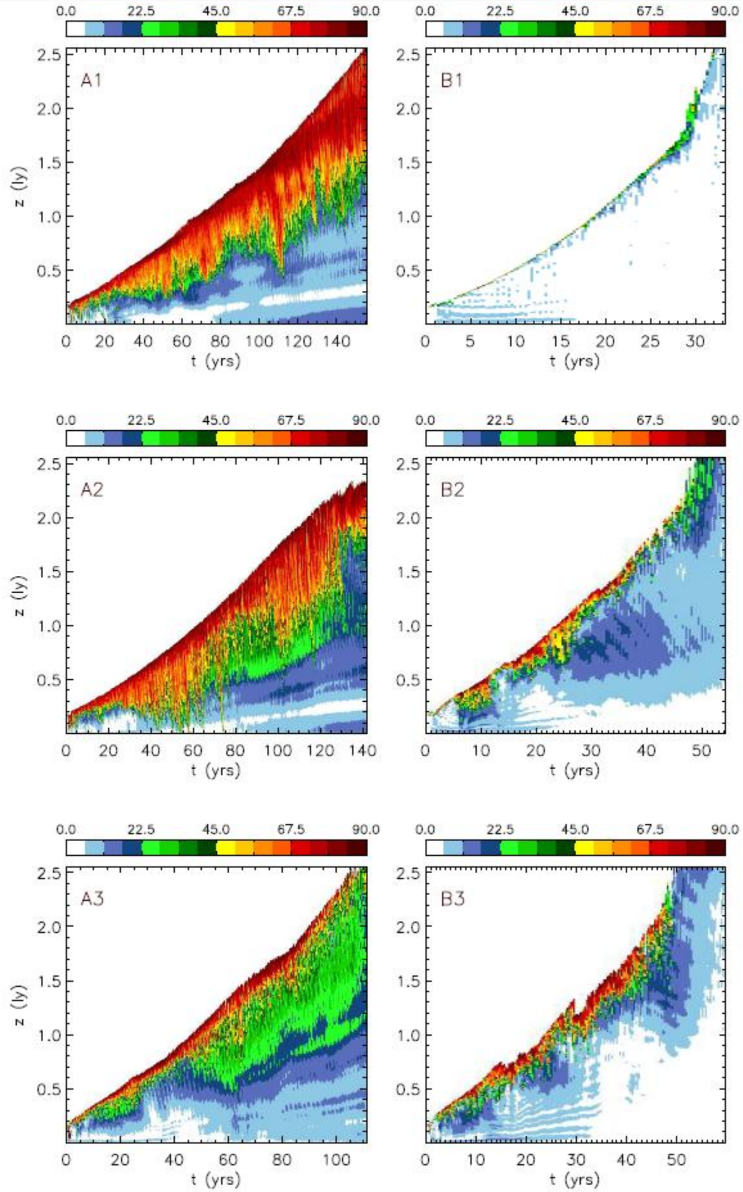


[1]Bodo et al. *MNRAS* (2013, accepted)

Flow Direction

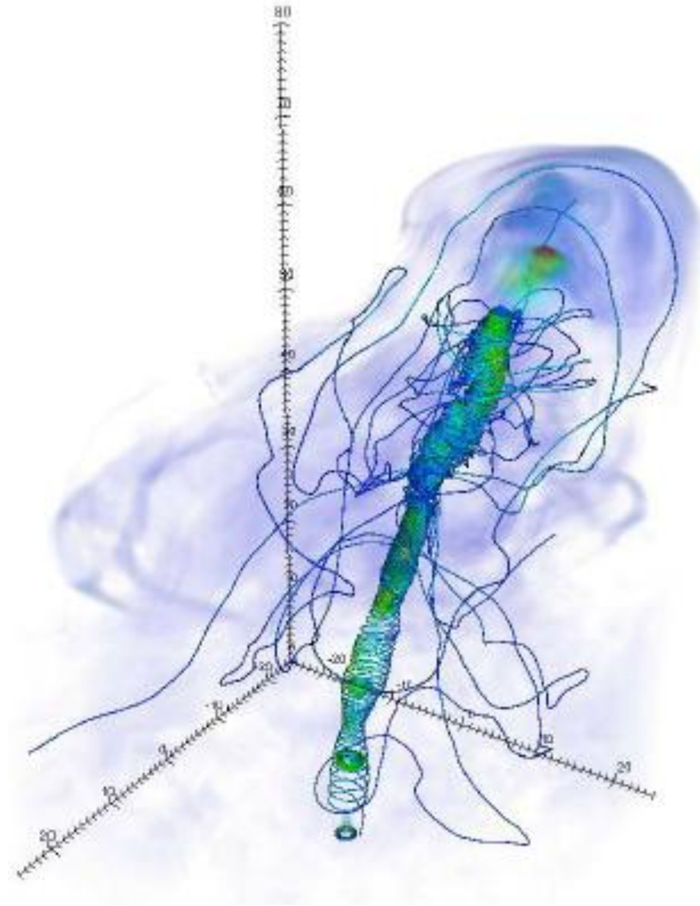
$$\bar{\theta}_{\pm} = \mathrm{acos}\left\langle \frac{v_{z,\pm}}{|\boldsymbol{v}|}, \chi_j \right\rangle$$

- Change in trajectory → variation of the average propagation velocity.
- Low-speed jets → large-scale curved structure with θ gradually changing from 0◦ (base) to 90◦ (head);
- High-speed jets stabilized by the larger inertia, build large kicks at the head.



Magnetic Fields

- Magnetic field remains mainly toroidal or helical during the propagation;
- Azimuthal field “shields” the core preventing interaction with the surrounding[1].
- Poynting flux efficiently diverted at the termination shock and scattered via the backflow to feed the cocoon.
- Magnetic field dissipates and becomes turbulent in the cocoon (→ randomization[2])

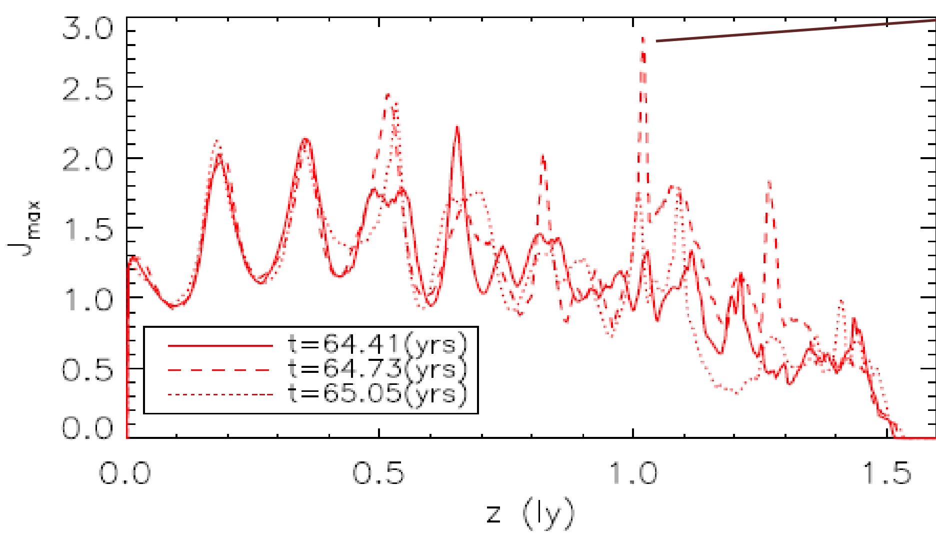


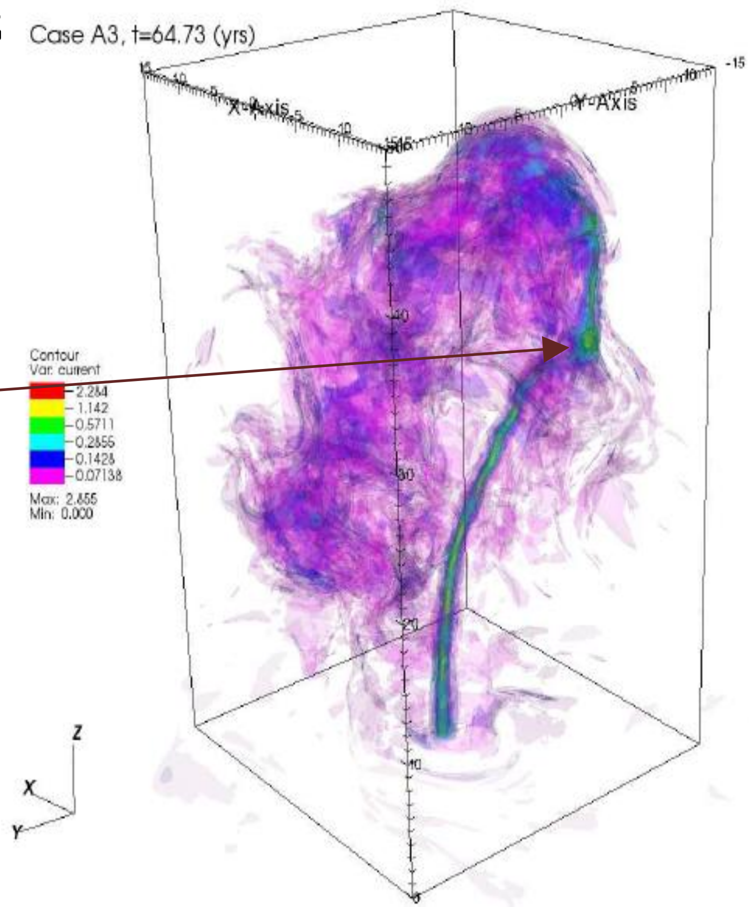
[1]Mignone et al, *MNRAS* (2010) 402, 7; [2]Porth et al., MNRAS (2013)

Current Sheets

- Current sheets localized in two regions:
  - at conical pinch shocks
    → quasi-steady, periodic
  - at jet "kinks" → short-lived episodes

- Magnetic reconnection
  → particle acceleration regions ?





Summary

- 3D models of azimuthally confined relativistic jets are very different from 2D axisymmetric models:

  - Kink-unstable non-axisymmetric structures with large time-variability;
  - Large σ ($\gtrsim 1$) leads to considerable jet deflections, one-sided propagation;
  - Jet wiggling progressively more pronounced towards the jet head
  - Larger Lorentz factors → stabilizing effect;
  - Multiple shocks observed at pinching regions and deflection sites where flow changes direction;

- Low-speed ($\gamma \lesssim 2$), moderately/highly magnetized jets ($\sigma \simeq$ 1-10) are promising candidates for explaining the morphology of the Crab jet.
- Future models will consider the jet-torus connection in 3D

Thank you