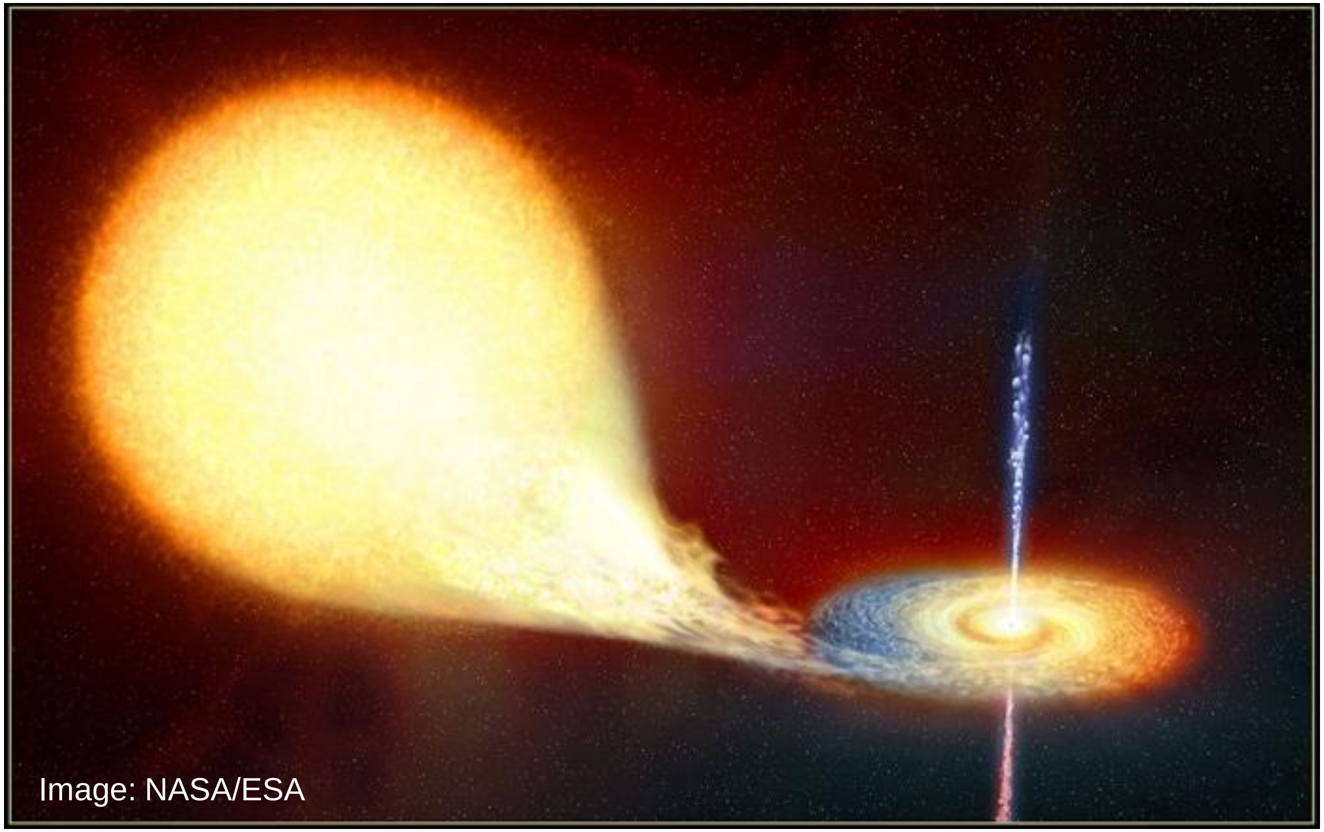
Jets in high-mass microquasars



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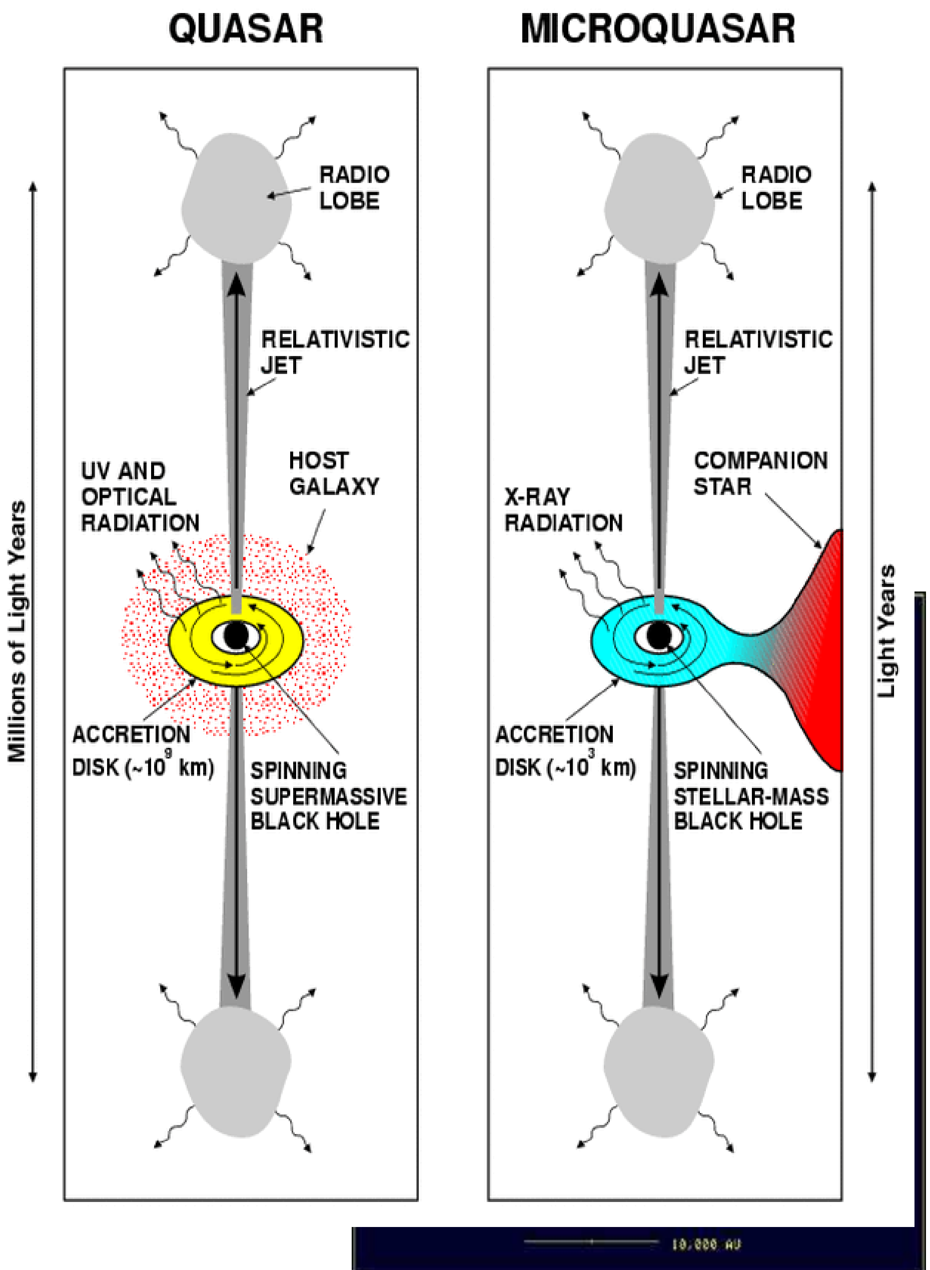
Variable Galactic Gamma-Ray Sources - Heidelberg, 01/12/10

Outline

- Introduction
  - Jets in microquasars
  - Numerical simulations of relativistic jets
- Simulations of jets in high-mass microquasars:
  - 1. Wind-jet interaction in massive X-ray binaries
    - 2D
    - 3D
    - What do we learn
  - 2. Long term evolution of microquasar jets
- Conclusions

Jets in microquasars



- ~15 sources with detected radio-jets (microquasars) in the galaxy.
  - < 10% of total X-ray binaries (Massi '05, Ribó '05).
- Are all radio-emitting X-ray binaries microquasars? (Fender '04)
  - 43 REXBs: 8 HMXBs and 35 LMXBs (Ribó 2005).
- To which extent is this picture (on the left) exact?
  - Accretion process.
    - Continuous vs periodic ejection?
  - Ambient medium.
    - Strong winds, inhomogeneities…
- Numerical simulations of microquasar jets needed to get a better picture!
  - Morphology and dynamics, locations of particle acceleration, variability,..
  - Peter & Eichler '95 (collimation).

Numerical simulations of relativistic jets

Relativistic hydrodynamics: SRHD equations

$$\frac{\partial D}{\partial t} + \nabla \cdot (D\mathbf{v}) = 0 \quad \text{(mass conservation)}$$

$$\frac{\partial \mathbf{S}}{\partial t} + \nabla \cdot (\mathbf{S} \otimes \mathbf{v} + p\mathbf{I}) = 0 \quad \text{(momentum conservation)}$$

$$\frac{\partial \tau}{\partial t} + \nabla \cdot (\mathbf{S} - D\mathbf{v}) = 0 \quad \text{(energy conservation)}$$

STATE VECTOR

$$\mathbf{U} = (D, S^1, S^2, S^3, \tau)$$

FLUX VECTORS

$$\mathbf{F}^i = (Dv^i, S^1 v^i + \delta^{1i}, S^2 v^i + \delta^{2i}, S^3 v^i + \delta^{3i}, S^i - Dv^i)$$

DEFINITIONS

$D = \rho W$: relativistic rest-mass density.

$\mathbf{S} = \rho h W^2 \mathbf{v}$: relativistic momentum density.

$\tau = \rho h W^2 c^2 - p - \rho W c^2$: relativistic energy density.

$\mathbf{v}$: fluid flow velocity.

$W = 1/\sqrt{1 - \mathbf{v}^2/c^2}$: flow Lorentz factor.

FLUID REST FRAME QUANTITIES

ρ: proper rest-mass density.

$h = 1 + \varepsilon/c^2 + p/\rho c^2$: specific enthalpy.

ε: specific internal energy.

p: pressure.

RELATIVISTIC EFFECTS

$$h \geq 1 \ (\varepsilon \geq c^2)$$

$$W \geq 1 \ (v \rightarrow c)$$

Numerical simulations of relativistic jets

- Some things we learned from simulations of extragalactic jets:
  - Jet morphology and dynamics largely governed by the interaction with the external medium (Rayburn 1977, Norman et al. 1982, van Putten 1993, Martí et al. 1994, 1995, 1997, Duncan & Hughes 1994):
    - bow-shock, cocoon (backflow), hot-spots…
  - Stability of relativistic jets (e.g., Hardee & Norman 1988, Rosen et al. 1999, Perucho et al. 2005, 2007, 2010).
  - Long-term evolution of extragalactic jets (e.g., Scheck et al. 2002, Perucho & Martí 2007, Rossi et al. 2008, Meliani et al. 2008).
    - Influence of jet composition, ambient medium…
  - 3D simulations (Nishikawa et al. 1997, 1998; Aloy et al. 1999; Hughes et al. 2002, Perucho et al. 2006, Rossi et al. 2008 …) :
    - helical instabilities, long term evolution…

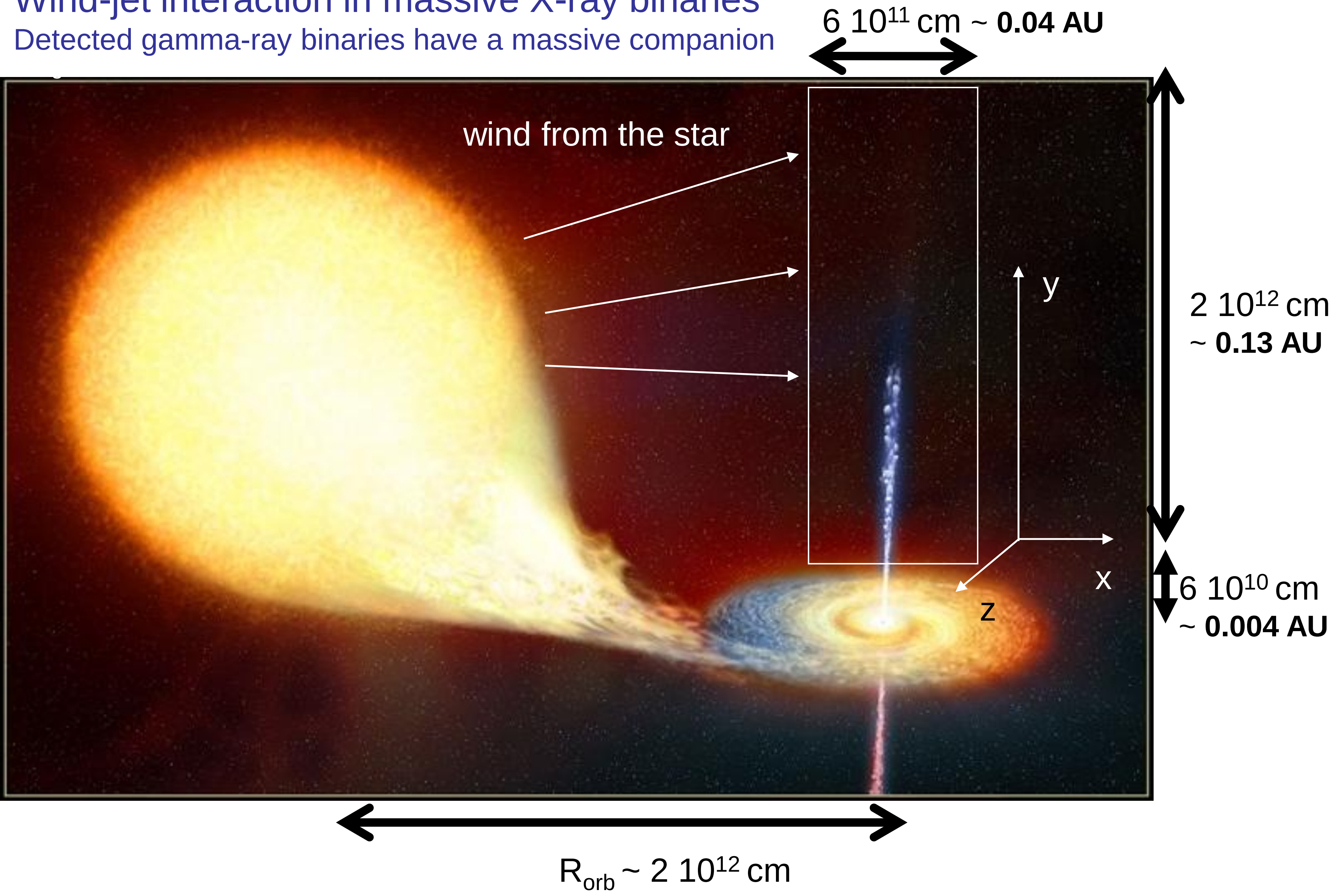
Numerical simulations of relativistic jets

- Some things we learned from simulations of extragalactic jets:
  - RMHD simulations (Nishikawa et al. 1997, 1998; Komissarov 1999; Leismann et al. 2005, Keppens et al. 2008, Mizuno et al. 2007, Komissarov et al. 2007).
    - Morphology, influence of poloidal and toroidal components on the dynamics…
    - Jet acceleration.
  - Link between simulations and observation (Komissarov & Falle 1996, 1997, Gomez et al 1996, 1997, Agudo et al. 2001, Aloy et al. 2003, Roca-Sogorb et al. 2008, Mimica et al. 2008, Perucho et al. 2008):
    - Jet structure and morphology in the parsec-scales.
    - Trailing components, pop-up components, recollimation shocks…
  - Jet formation and collimation mechanisms (e.g., Koide et al. 1998, 2000, Komissarov 2001, McKinney 2005, 2006, Fendt 2006)

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries

Detected gamma-ray binaries have a massive companion



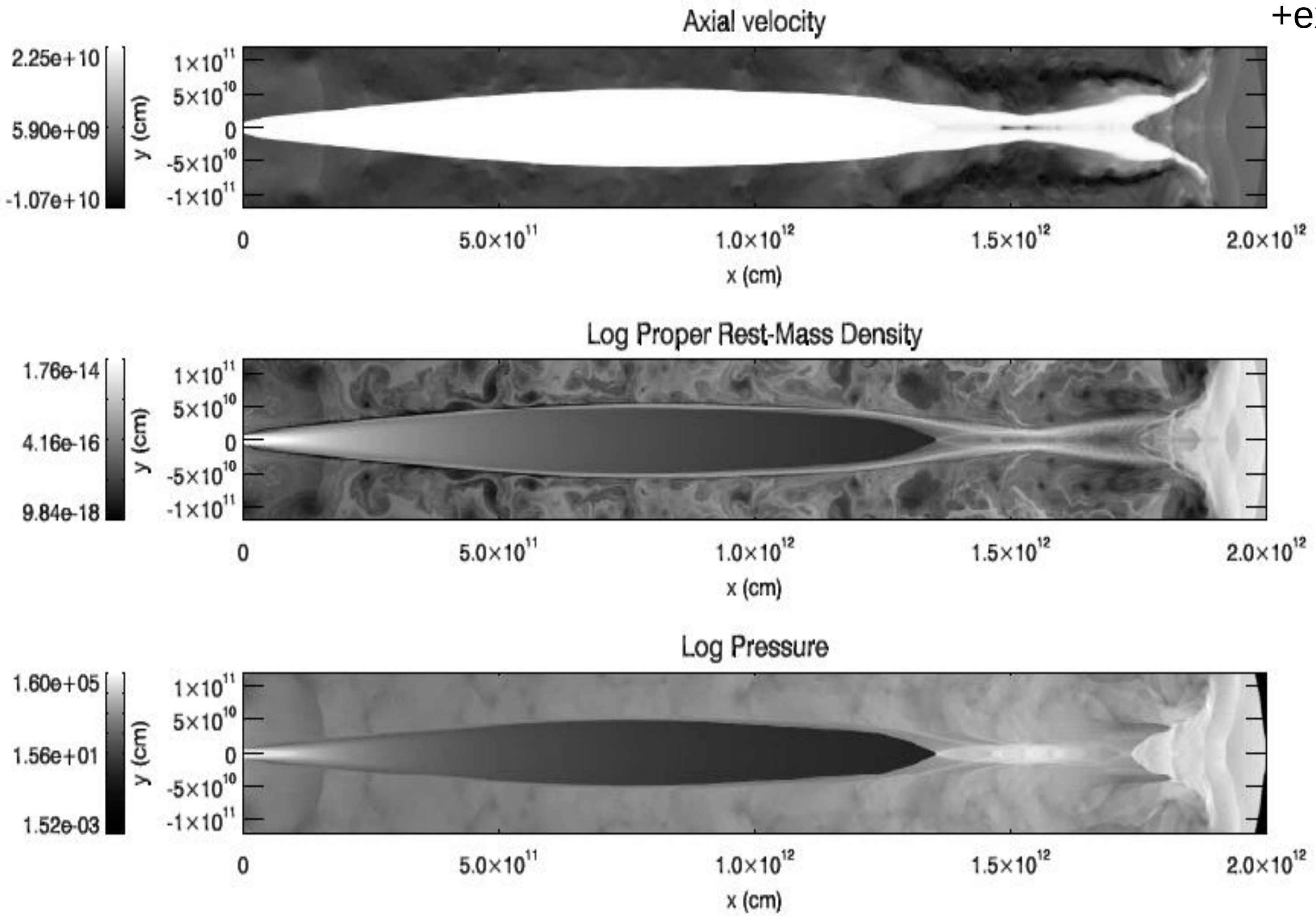
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 2D simulations

2D simulations: Perucho & Bosch-Ramon 2008

320x2400 cells
20x300 R_j
+extended grid

powerful jet (3 10^{37} erg/s)



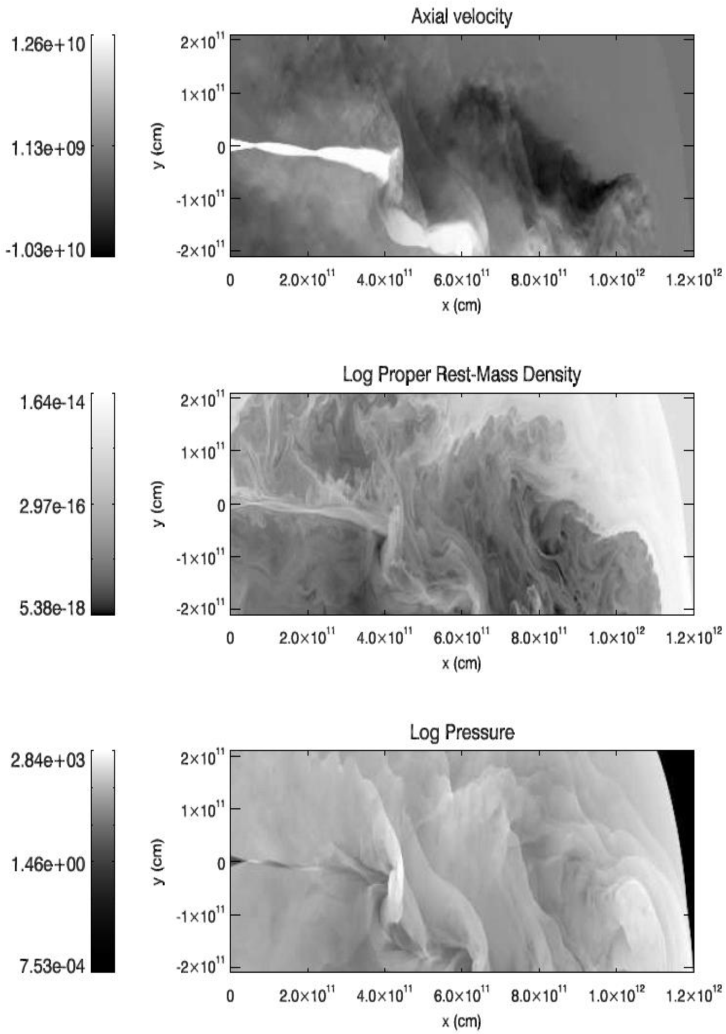
Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 2D simulations

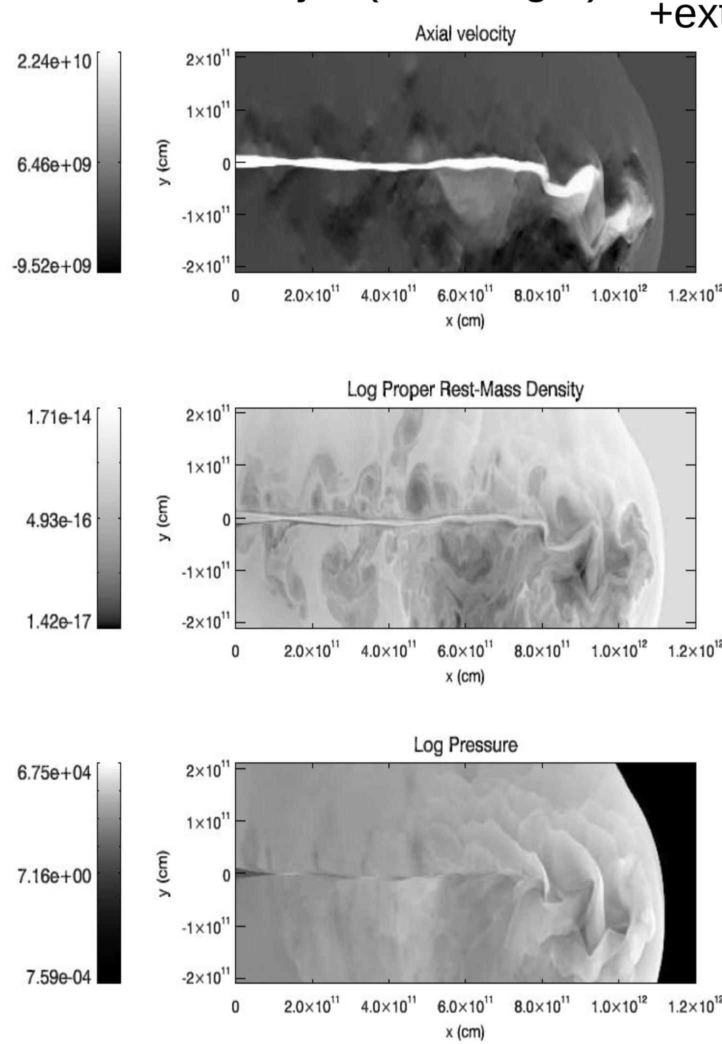
2D simulations: Perucho & Bosch-Ramon 2008

1920x1600 cells
120x200 R_j
+extended grid

weak jet ($3\ 10^{34}$ erg/s)



mild jet (10^{36} erg/s)



Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Numerical Setup

- Ratpenat is a 3D RHD code that combines MPI and OMP parallelization.

- The simulations have been performed in Mare Nostrum (Barcelona Supercomputing Centre):
  - Distributed in nodes with 4 processors each.

- 32 nodes (128 processors).
  - Total of 320x320x1280 cells.

  - Numerical box: 40x40x10 R_j per node.
    - The jet is divided in slices along the axis.
    - Extended radial region makes it (100x100x10 R_j per node).

  - Resolution: 4 cells per jet radius at injection in the central region plus total of 80 cells in the extended region (320x320x40 cells per node).
    - The effective resolution is 16 cells per jet radius, because the jet expands very fast from injection.

Perucho, Bosch-Ramon & Khangulyan 2010

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Input data

	WIND	JET 1	JET 2
Power (erg/s)		10^{35}	10^{37}
Velocity (cm/s)	$2\ 10^{8}$	$1.7\ 10^{10}$	$1.7\ 10^{10}$
Density ($g\cdot cm^{-3}$)	$2.8\ 10^{-15}$	$0.088\ \rho_w$	$8.8\ \rho_w$
Temperature (K)	10^{4}	10^{10}	10^{10}
Mach number	220	16.6	16.6
Pressure ($dyn\cdot cm^{-2}$)	$1.5\ 10^{-3}$	7.1	$7.1\ 10^{3}$

Perucho, Bosch-Ramon & Khangulyan 2010

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations
Hypotheses

- Hydrodynamic-cold flow – particle dominated.
  - reasonable at certain distances to the compact object ($B_{\parallel} \propto r^{-2}$) and taking dissipation into account. Excepting strong shocks.
  - $T_j << m_p c^2/k_B$

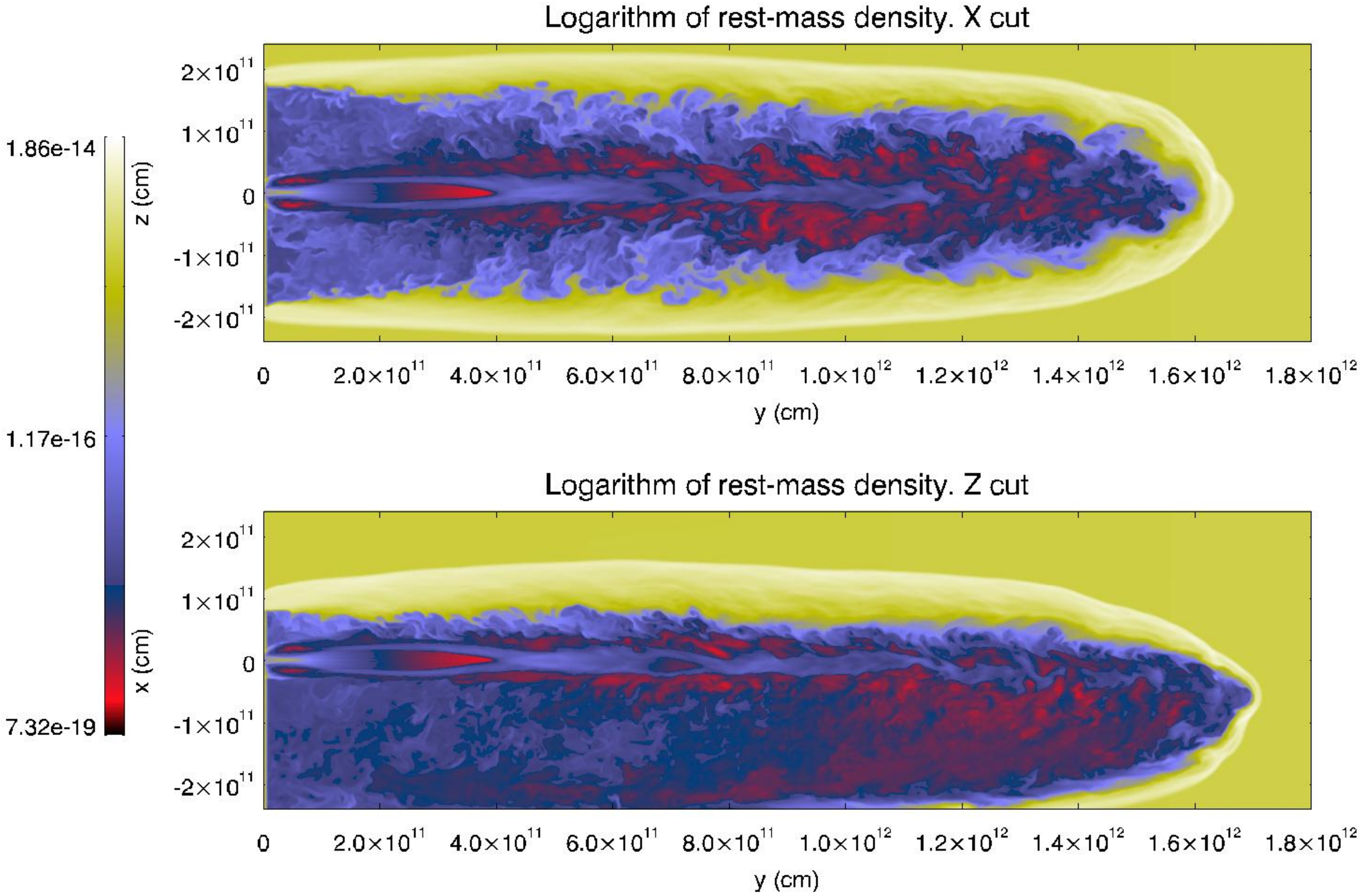
- stellar wind from a massive O-type star ($dM/dt = 10^{-6}$ $M_{sun}\,yr^{-1}$).
  - continuous in the simulation time-scales (100 -1000s).
  - compact object at the same orbital position during the simulation time-scales (100-1000s vs T > 100,000 s).
  - homogeneous (constant density up to R_{orb}).

Perucho, Bosch-Ramon & Khangulyan 2010

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

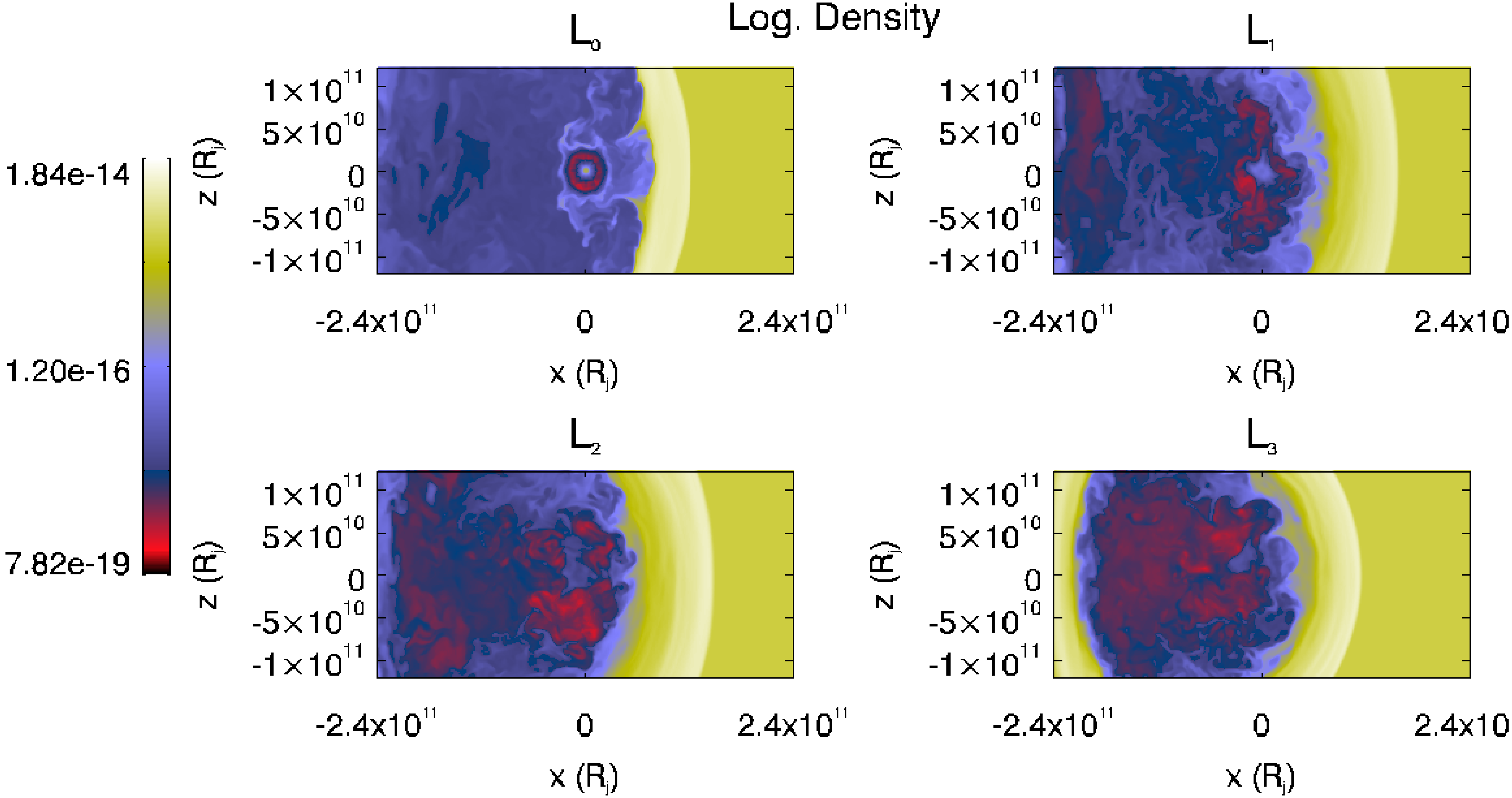
Jet 1 t = 977 s



Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 1 t = 977 s



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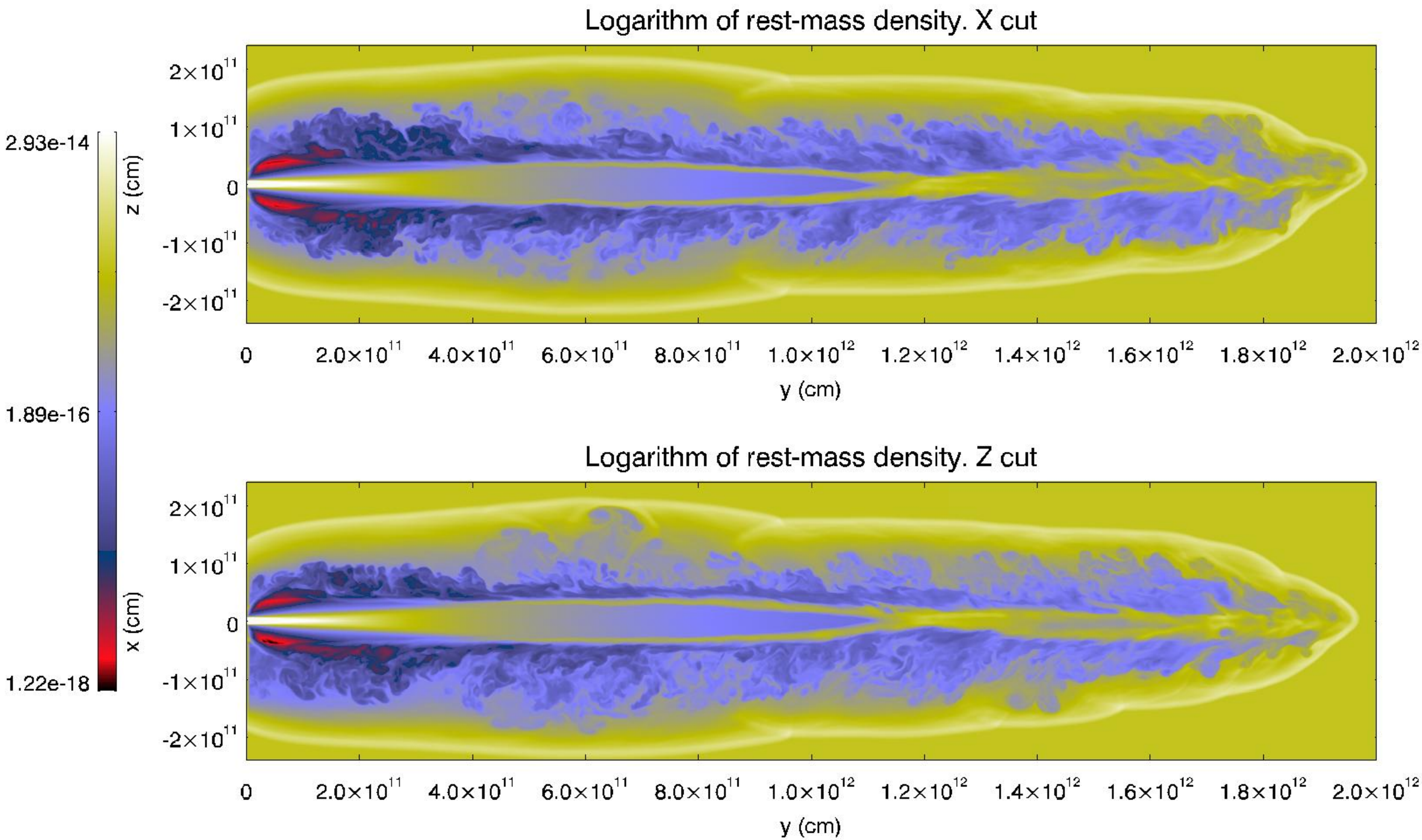
Simulations of jets in high-mass microquasars

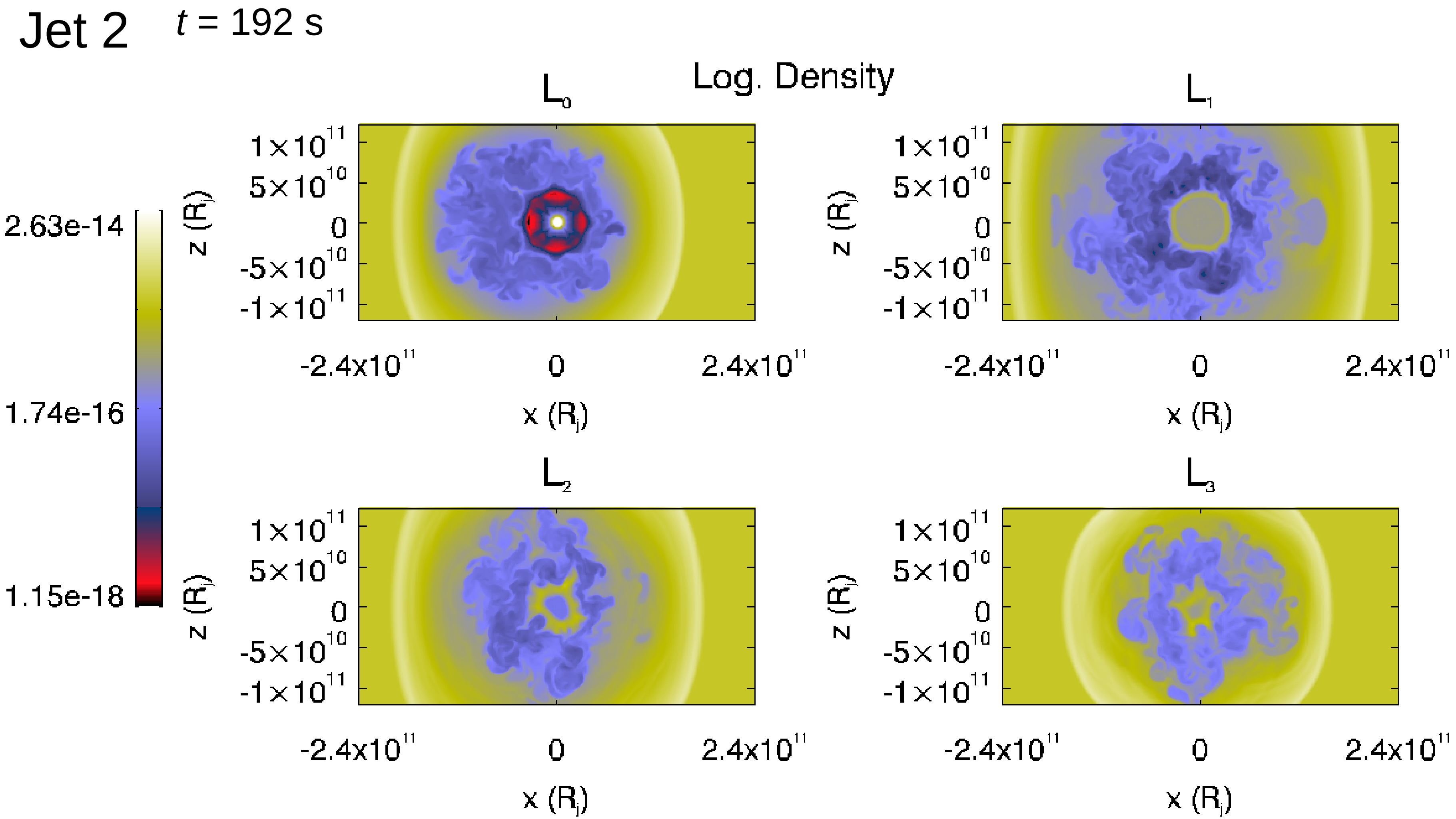
Wind-jet interaction in massive X-ray binaries: 3D simulations

Jet 2 *t* = 192 s



Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations



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Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: What do we learn

- There are strong interactions in the evolution of jets in massive binaries:
  - Recollimation shocks within the cocoon, but also within the wind region. These shocks are generated in the binary region if (see Perucho & Bosch-Ramon 2008):

Jet-cocoon interaction

$$T_{\mathrm{j},0} < 3\times 10^{14}\cdot\left(\frac{L_\mathrm{j}}{10^{36}\,\mathrm{erg\,s^{-1}}}\right)\cdot\left(\frac{3\times 10^{9}\,\mathrm{cm\,s^{-1}}}{V_\mathrm{bs}}\right)\cdot \left(\frac{3\times 10^{11}\,\mathrm{cm}}{R_\mathrm{c}}\right)^2\cdot\left(\frac{10^{-15}\,\mathrm{g\,cm^{-3}}}{\rho_{\mathrm{j},0}}\right)\mathrm{K},$$

Jet-wind interaction

$$T_{\mathrm{j},0} < 3\times 10^{13}\cdot\left(\frac{\rho_\mathrm{w}}{2.8\times 10^{-15}\,\mathrm{g\,cm^{-3}}}\right)\cdot\left(\frac{V_\mathrm{w}}{2\times 10^{8}\,\mathrm{cm\,s^{-1}}}\right)^2\cdot \left(\frac{10^{-15}\,\mathrm{g\,cm^{-3}}}{\rho_{\mathrm{j},0}}\right)\mathrm{K},$$

Fulfilled for supersonic, mildly relativistic jets.

- These strong shocks are candidate locations for particle acceleration and high-energy emission.
  - the emission of gamma-rays produced at such a site reduces the absorption by interaction with stellar photons.

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: What do we learn

- The position of the recollimation shock depends on the cocoon pressure (Falle 1991): $z_s \propto P_c^{-1/2}$;
  - From Scheck et al. (2002) and Perucho & Martí (2007): $v_{bs} \propto t^{\alpha}$

    $P_c \propto t^{-1-\alpha/2}$ $\quad z_s \propto t^{1/2+\alpha/4}$ for a homogeneous ambient

    $P_c \propto t^{-2}$ $\quad z_s \propto t$ for $\rho_a \propto z^{-2}$
  - We can compute the time (t_3) at which the recollimation shock will reach $z = 2 \times 10^{12}$ cm
    - With $z_s(t_2) = 1.1 \times 10^{12}$ cm and $t_2 \simeq 210$ s

      for $\rho_a \propto z^{-2}$: $t_3 \simeq 2\,t_2 \simeq 400$ s
  - We compare this time with the time at which the recollimation shock will be determined by the pressure of the shocked wind: $P_w \sim 10^2$ erg cm^{-3}
    - With $P_c \simeq 10^3$ erg cm^{-3} at $t_2 = 210$ s

$$t \simeq \sqrt{P_{c,0}/P_w}\, t_2 \simeq 3\,t_2 \approx 2\,t_2$$

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: What do we learn

- Instabilities develop in the outer layers and propagate to the whole jet (in the form of surface or first body helical modes) after the strong recollimation shock: This can destroy the jet.
  - Could be the case in the TeV X-ray binary LS 5039 (see Moldón et al. 2008 – arXiv:0812.0988 – and Ribó et al. 2008).
  - Betterobservational resolution could show the effect of the wind in the jet.

- Only powerful jets ($P_j > 10^{37}$ erg/s) in massive binaries may be able to propagate collimated out of the binary region.

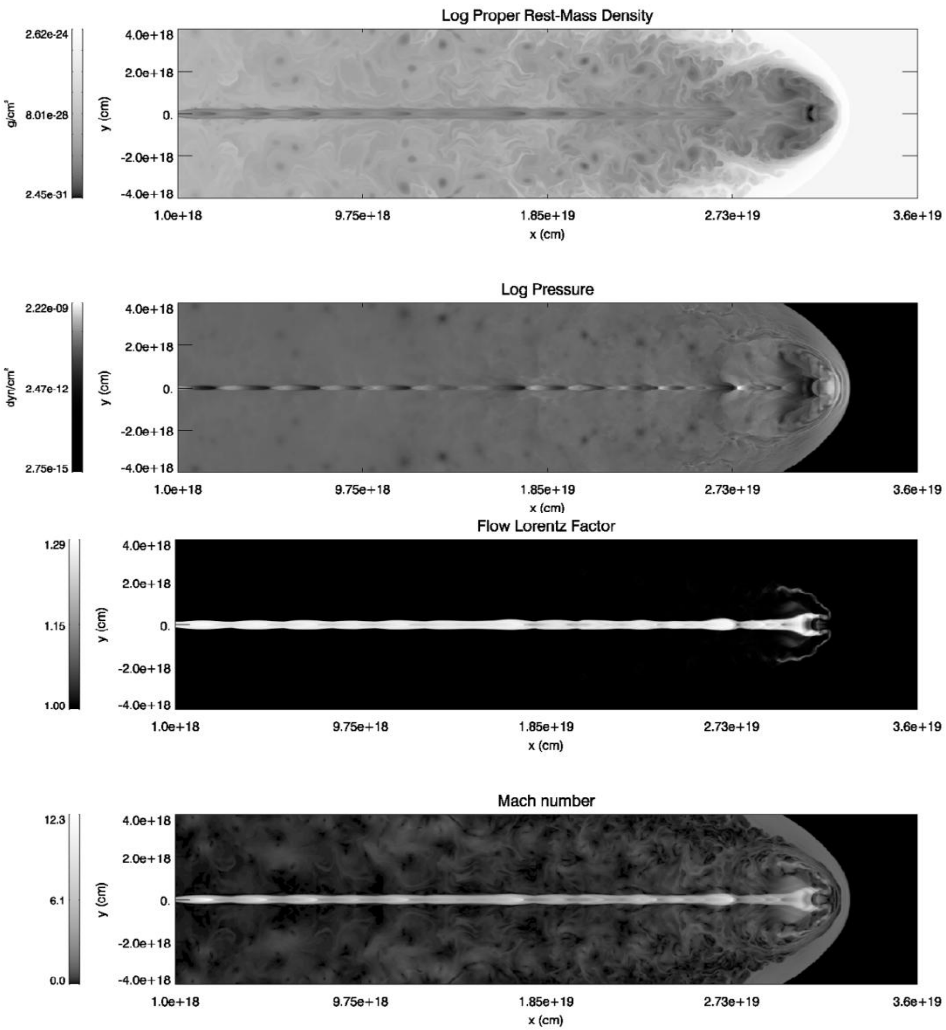
- Frustrated jets may not be observed in radio at large distances.

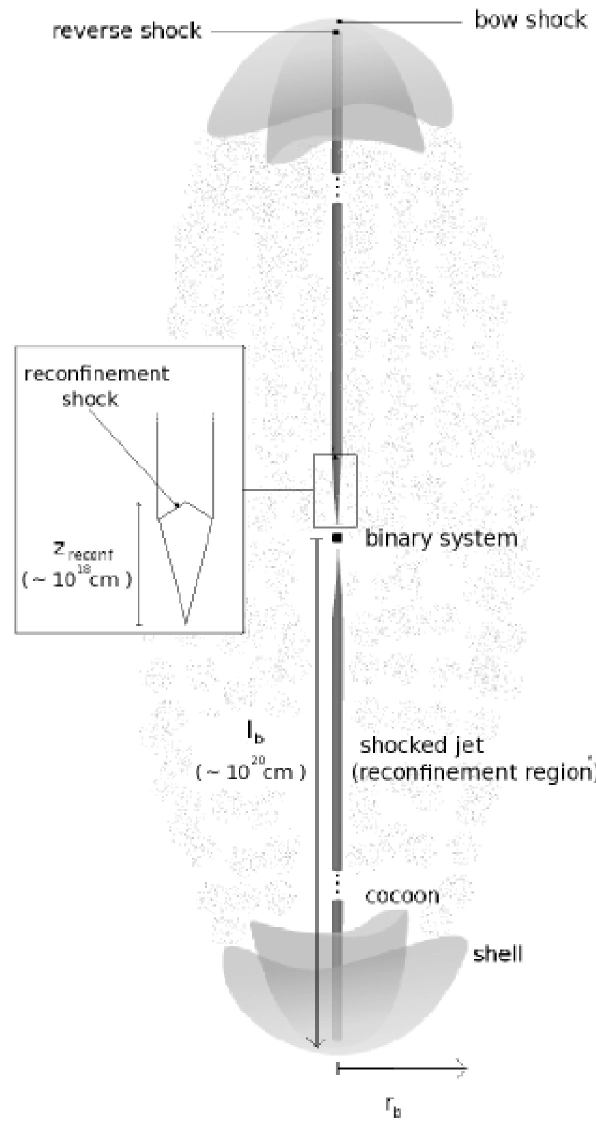
- The luminosity function derived by Grimm et al (2003) predicts 3 HMXBs with $L_X=10^{35}$ erg/s.
  - Following Fender et al. (2005), such HMXB with a 10 M_{sun} Black Hole, the jet could have a kinetic power between 10^{35} and 10^{38} erg/s.
  - We deduce that there is room for a few (~10) such sources, with $L_X \leq 10^{35}$ erg/s, in our Galaxy.

Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

- Bordas, Bosch-Ramon, Paredes, MP 2009. SEE TALK BY P. BORDAS.





Simulations of jets in high-mass microquasars

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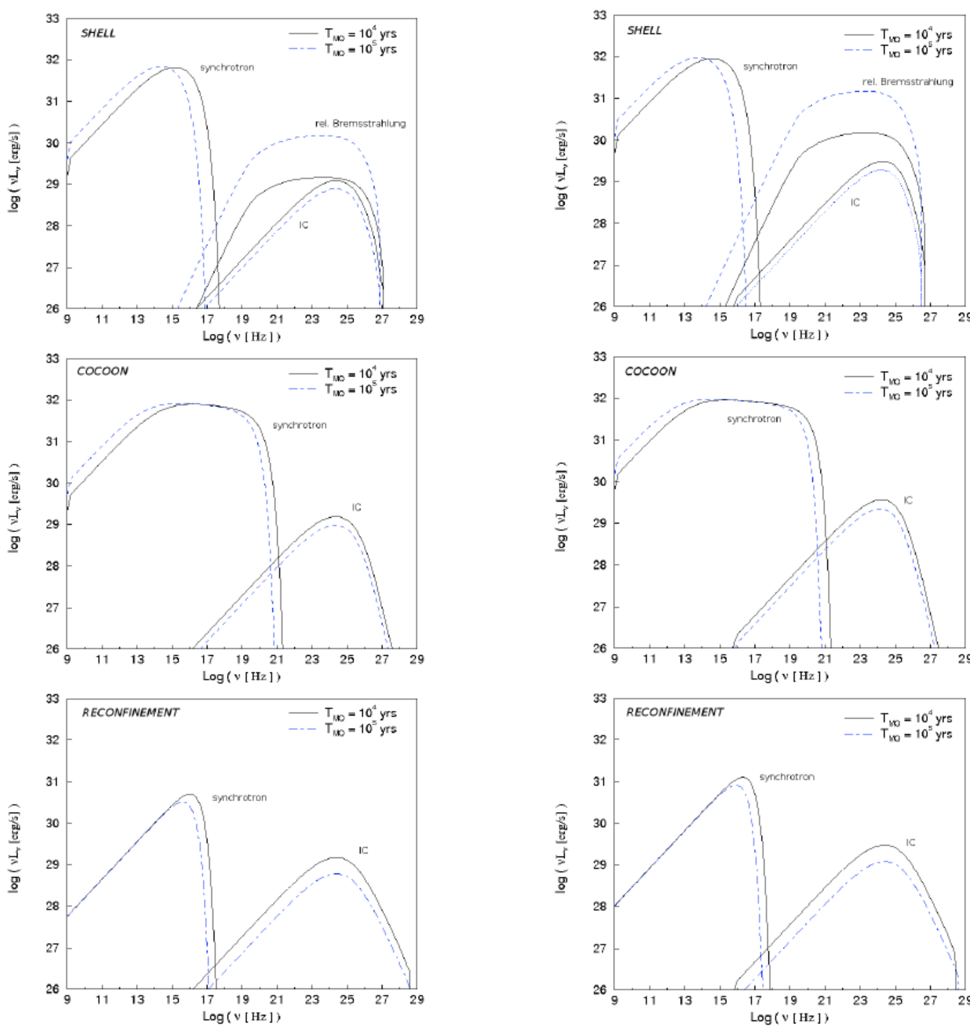
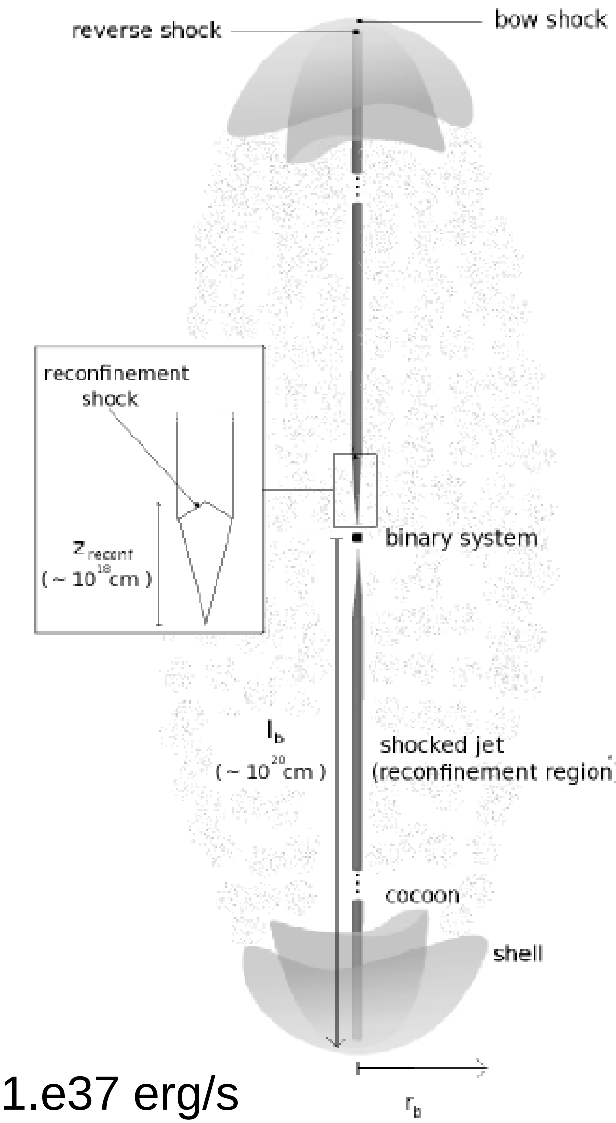


0.1 cm-3 1. cm-3 Pj=1.e37 erg/s



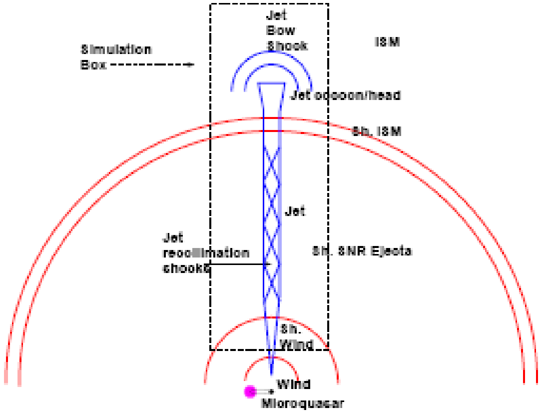
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

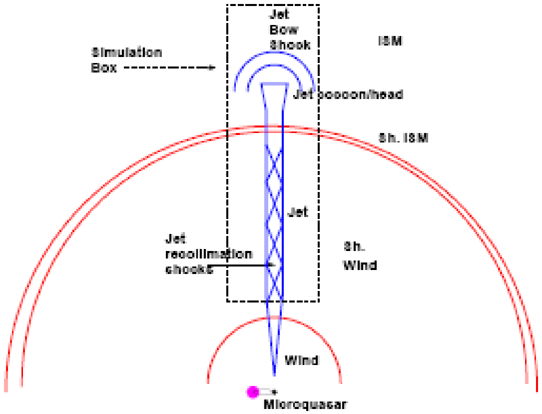
Bosch-Ramon, Perucho & Bordas, in preparation

3 scenarios (P_k = 3.e36 erg/s):

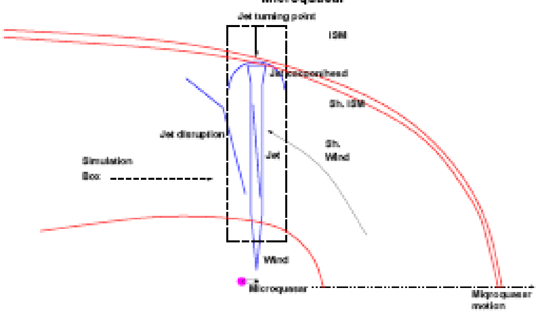
-Case 1: young MQ (t<1.e5 yrs), inside the hot SNR.



-Case 2: older MQ (t~1.e5 yrs), the jet has left the SNR and propagates in the wind-wind/ISM shock-ISM



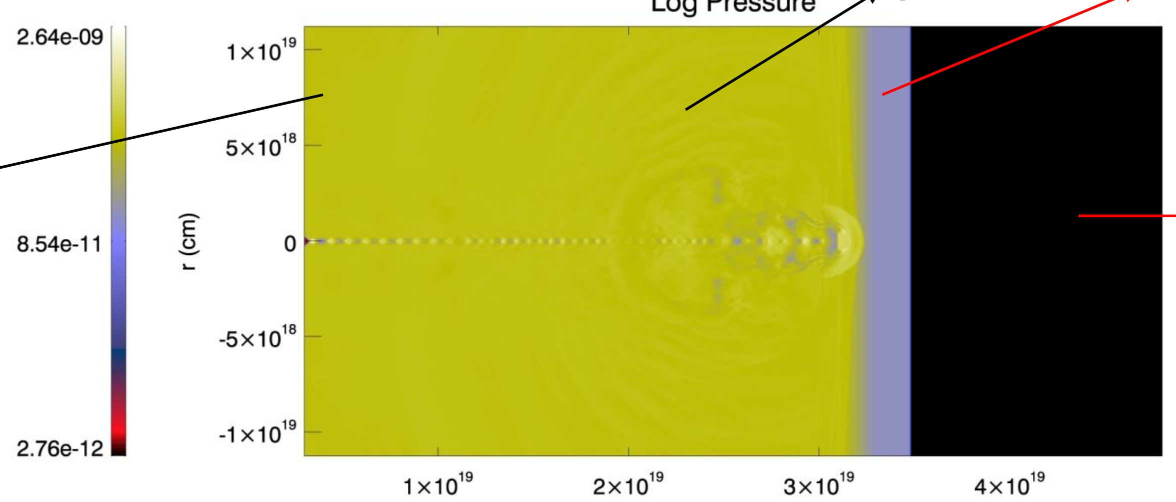
-Case 3: Similar to case 2 (t~1.e6 yrs), with a bow-shock generated by the propagation of the binary through the ISM. The shocked wind impacts the jet from the side. Slab jet.



Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Case 1: young MQ (t<1.e5 yrs), inside the hot SNR.



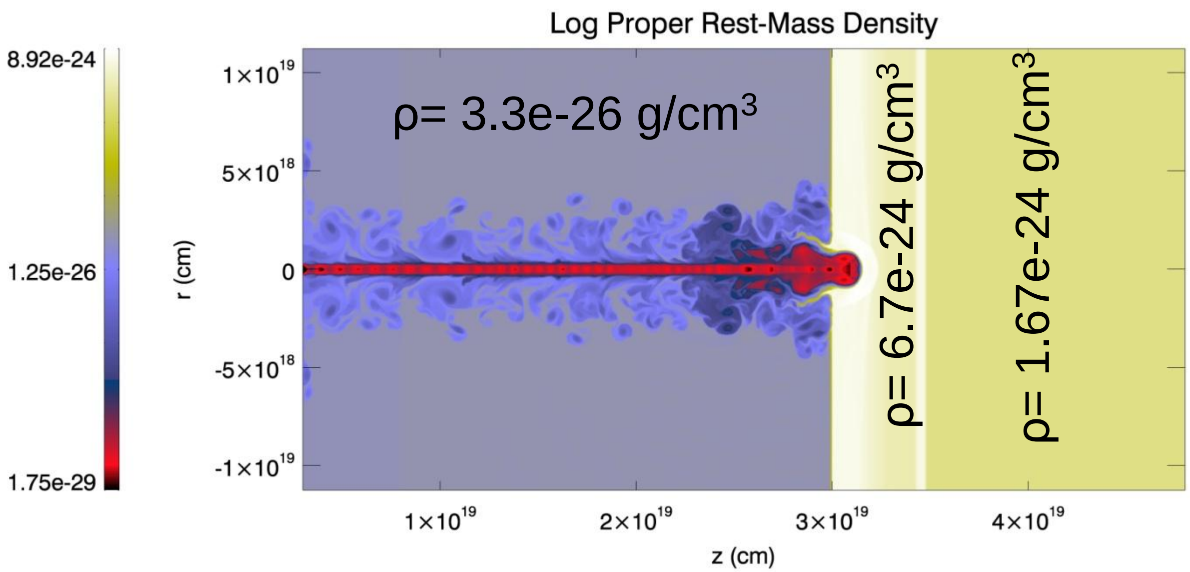
SNR

Shocked ISM

Shocked wind
z<8.e18 cm

ISM

t=9.e3 yrs



Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

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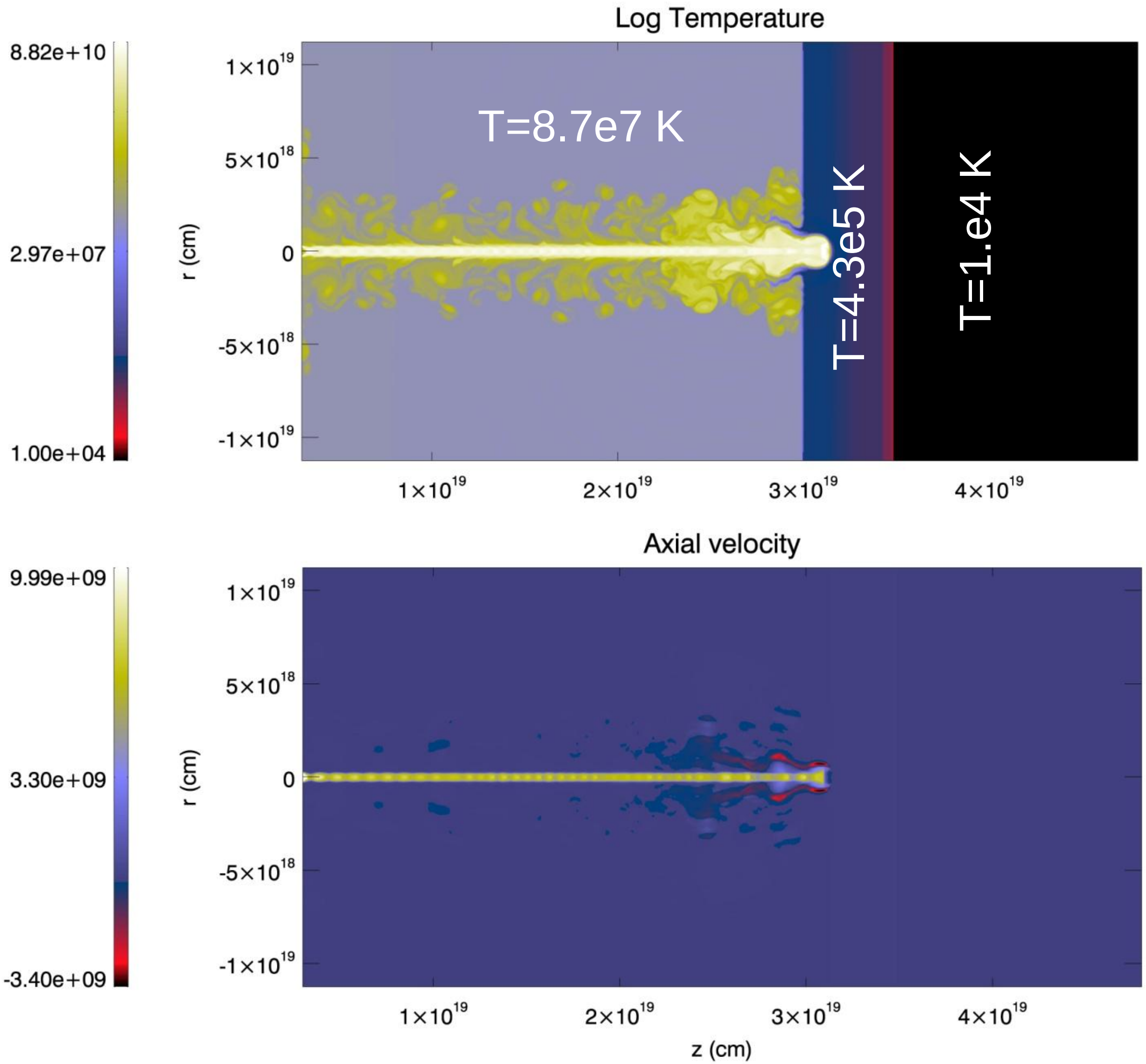


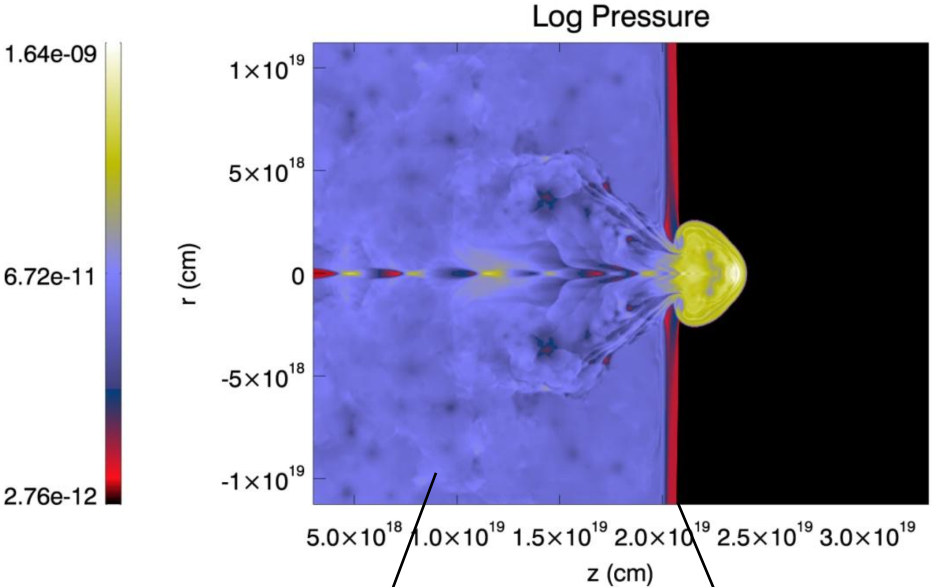
t=9.e3 yrs

Simulations of jets in high-mass microquasars

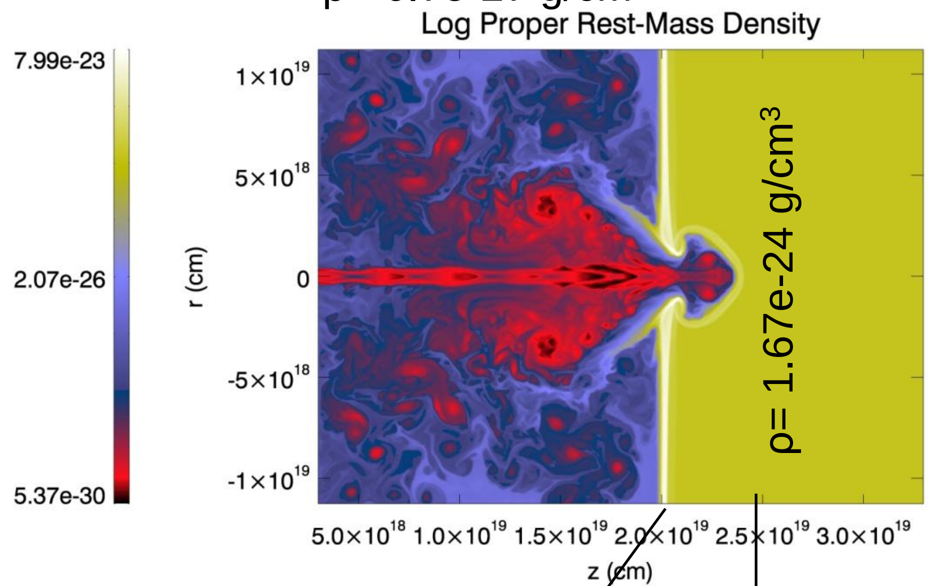
Long-term evolution of microquasar jets

-Case 2: older MQ (t~1.e5 yrs), the SNR has dissipated and the jet propagates in the wind-wind/ISM shock-ISM

t=9.8e3 yrs



ρ= 6.7e-27 g/cm³



Shocked wind

Shocked ISM

ρ= 1.1e-22 g/cm³

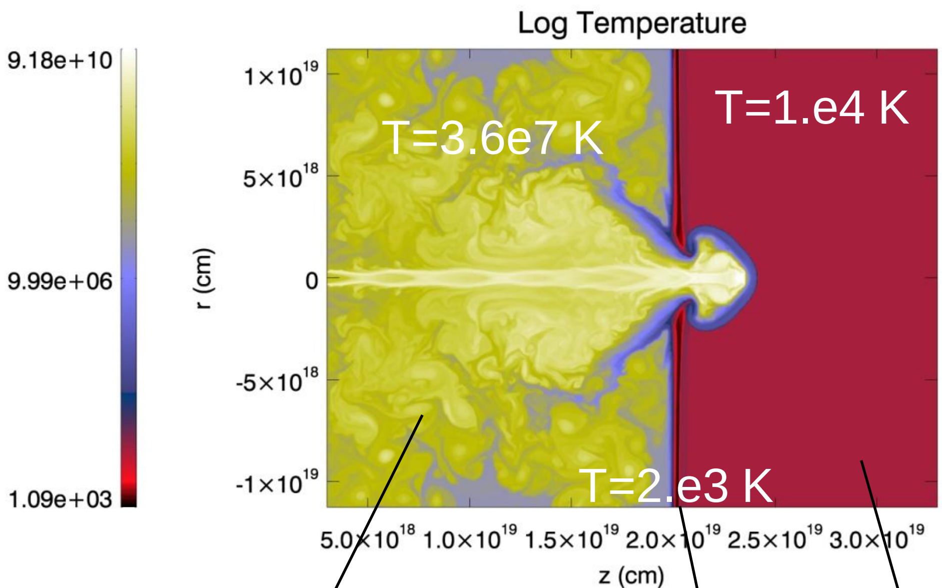
ISM

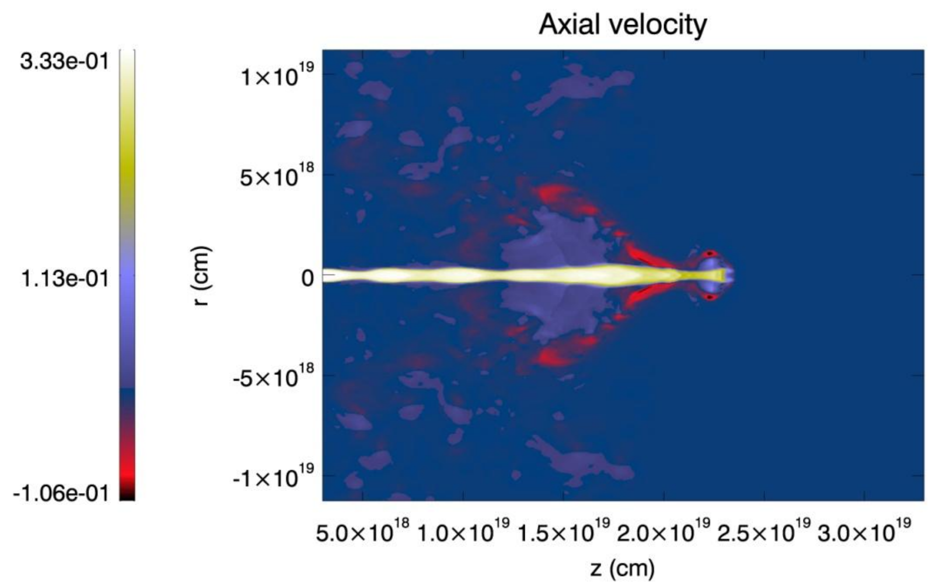
Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

-Case 2: older MQ (t~1.e5 yrs), the jet has left the SNR and propagates in the wind-wind/ISM shock-ISM

t=9.8e3 yrs





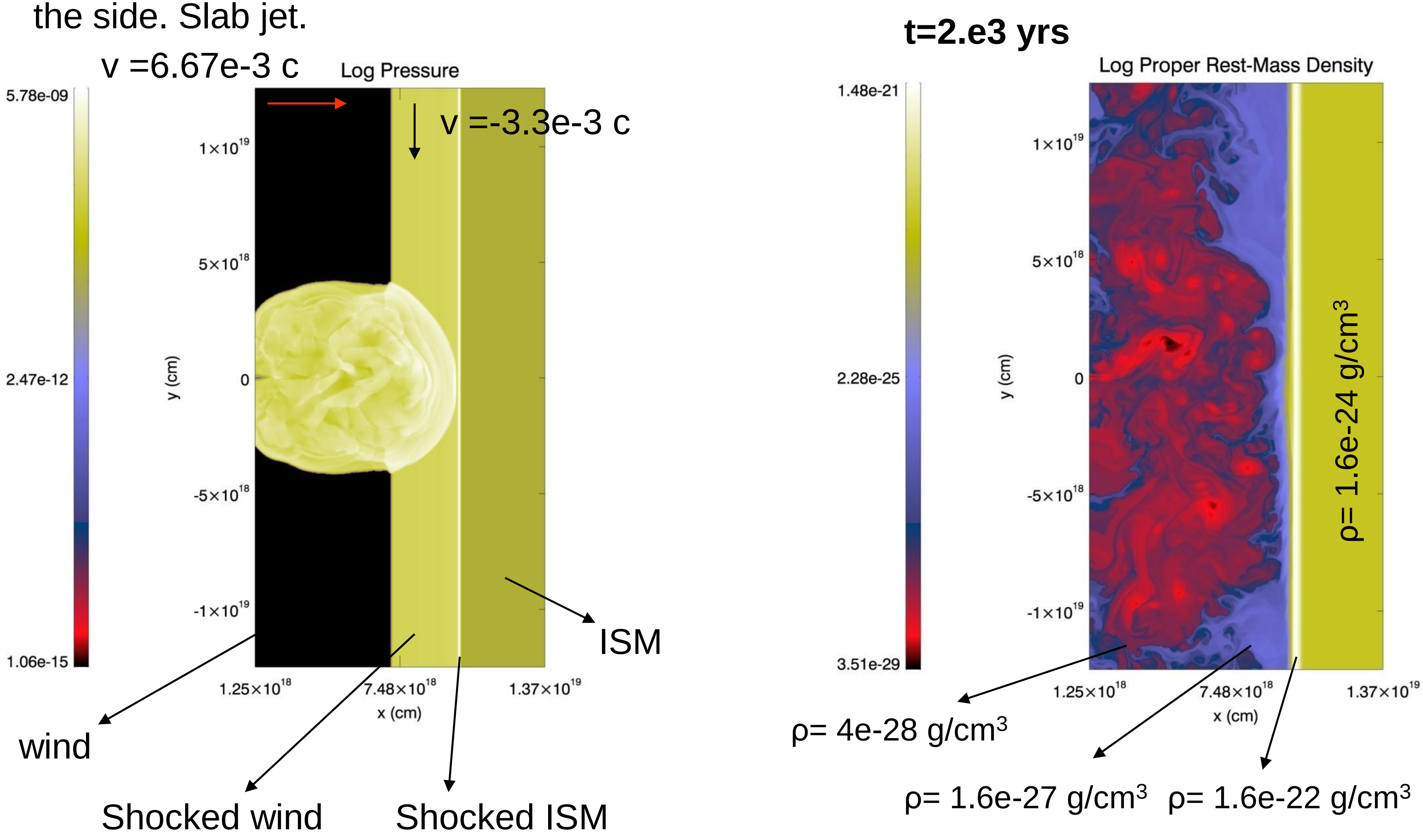
Shocked wind

Shocked ISM ISM

Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

Case 3: Similar to case 2 (t~1.e6 yrs), with a bow-shock generated by the propagation of the O-star through the ISM. The shocked wind impacts the jet from the side. Slab jet.



Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets

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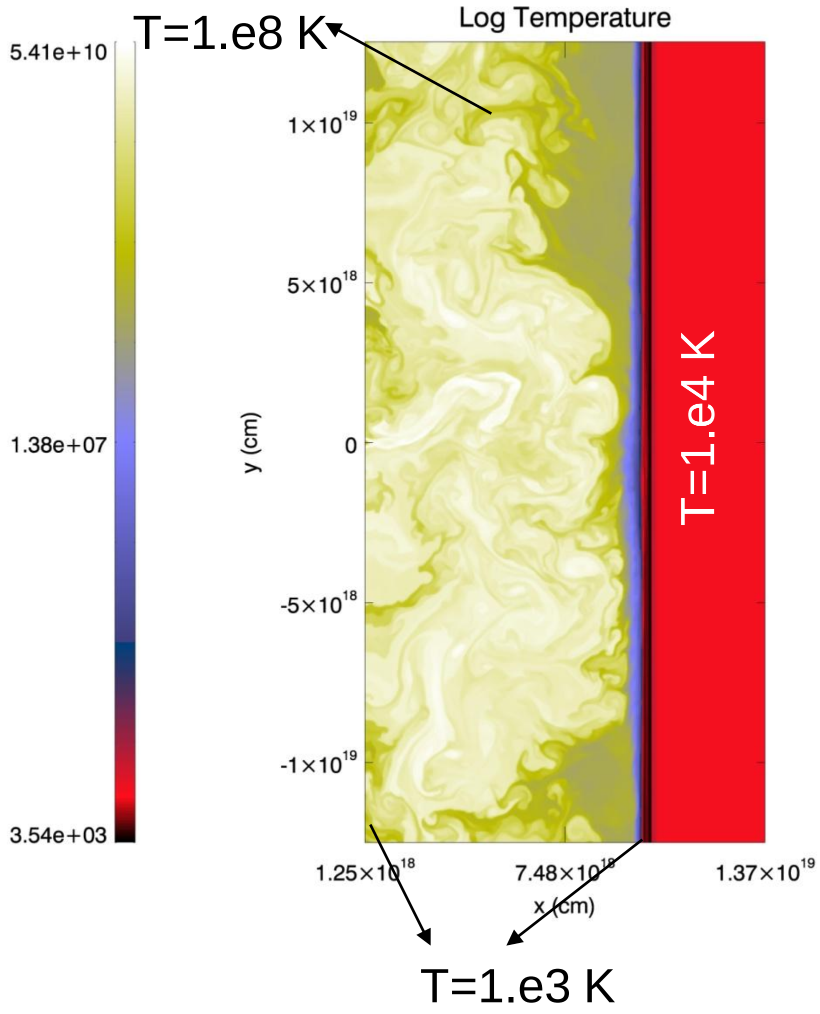
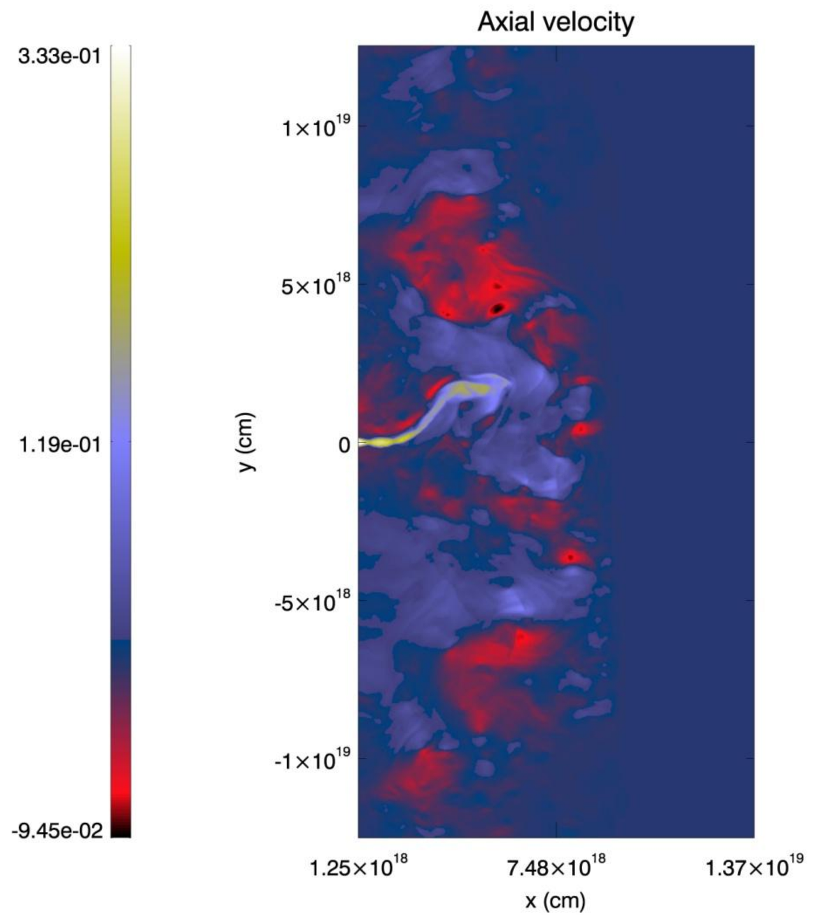
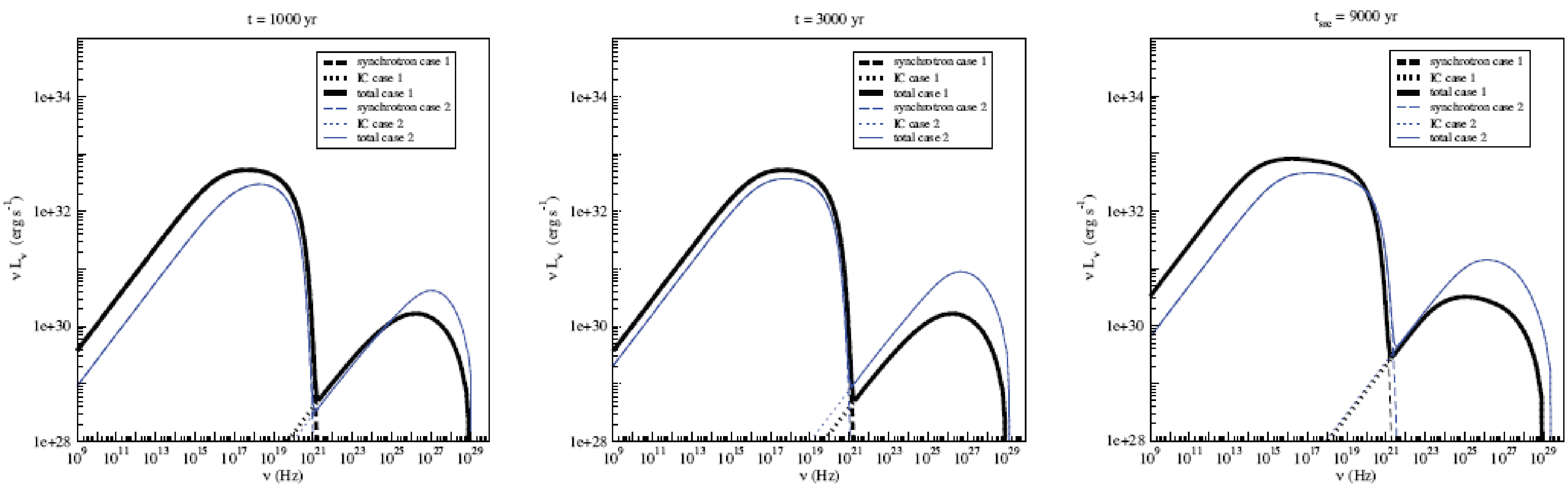


t=2.e3 yrs



Simulations of jets in high-mass microquasars

Long-term evolution of microquasar jets



Conclusions

- Simple numerical simulations give important information about:
  - Sites of high-energy emission.
  - Jet stability and propagation.
  - Hints for the lost jets in REXBs and radio-quite XBs.
  - Long-term evolution and interaction with the inhomogeneous ambient.

- Further work:
  - Realistic scenarios:
    - expansion of the jet in decreasing density wind at larger scales + growing instabilities (now calculating for $P_j = 10^{37}$ erg/s). DONE.
    - Direct impact of the wind onto the jet when the head of the jet is far.
    - Effect of non-homogeneous wind. ONGOING.
  - Improved physics:
    - RMHD simulations, eos…

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries: 3D simulations

Inhomogeneous wind