Jet evolution and energy dissipation in binaries

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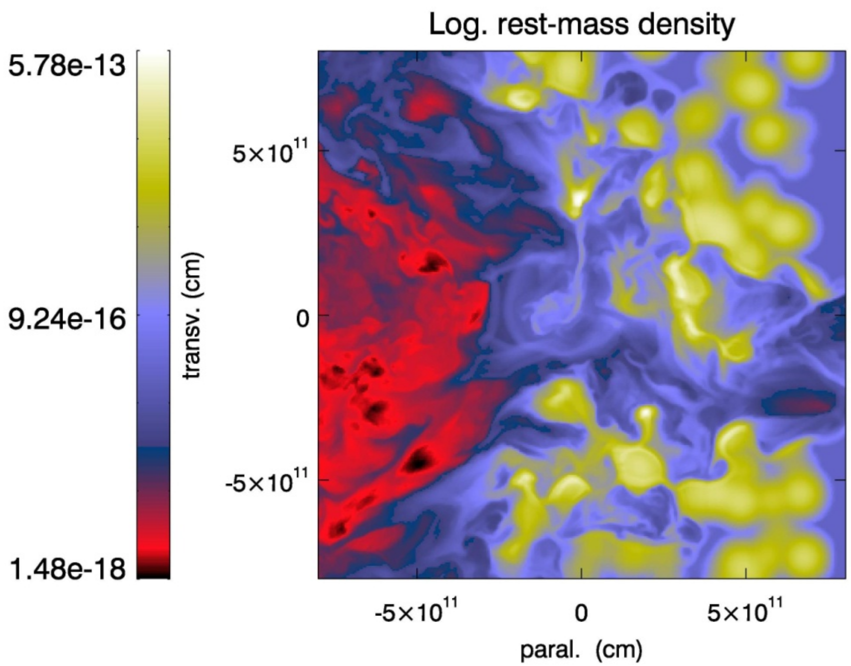
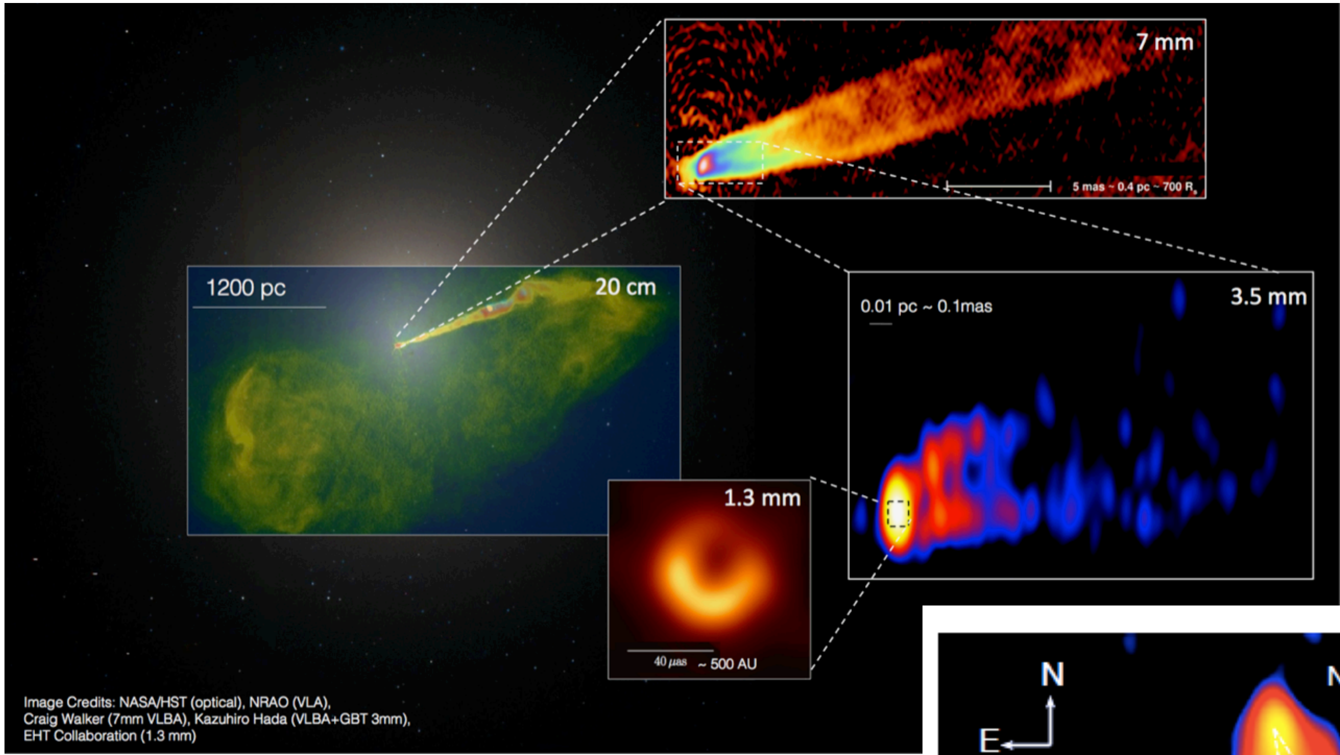
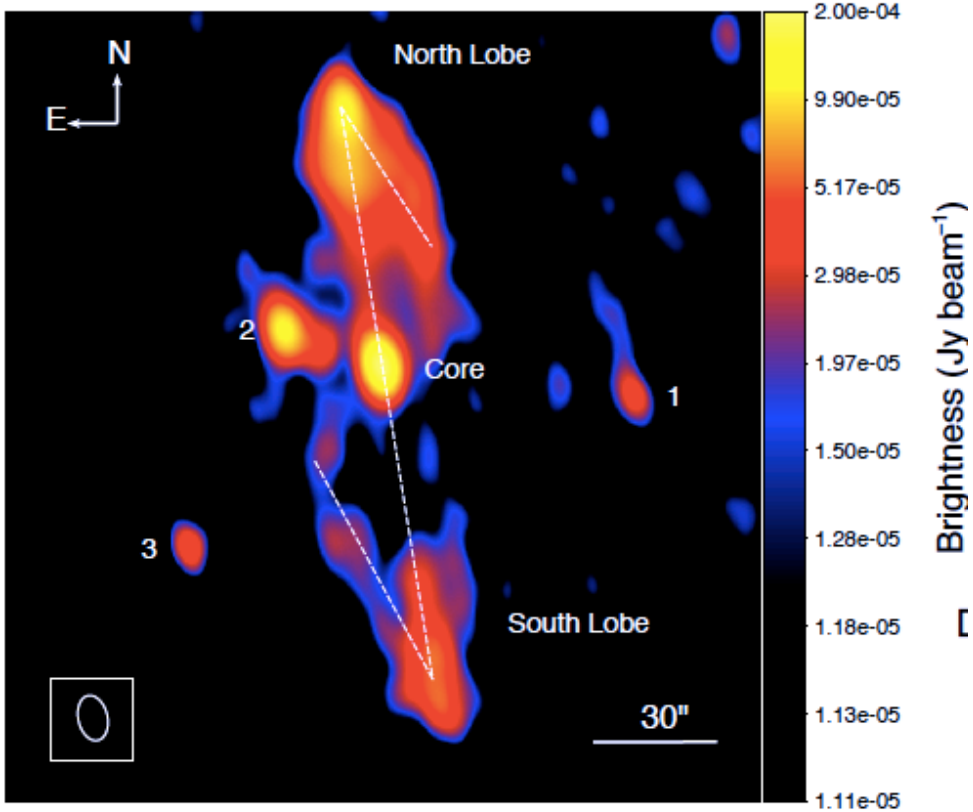


VGGRS V, Barcelona, September 2019

Jets



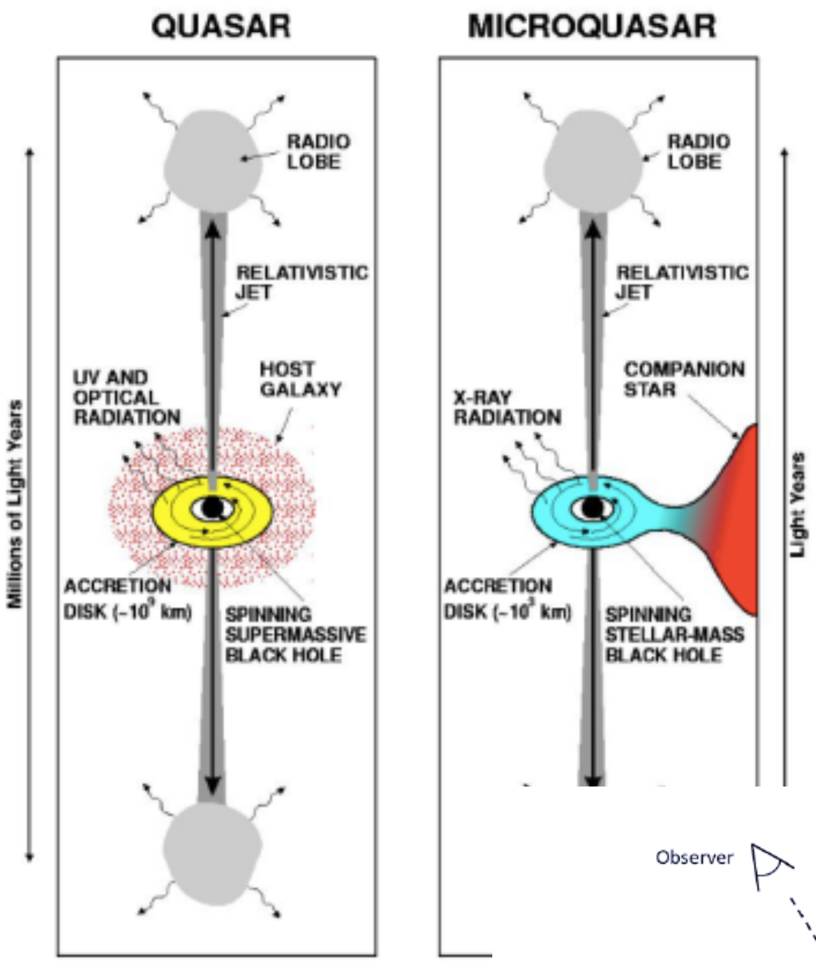
M87
credit: Ciriaco Goddi



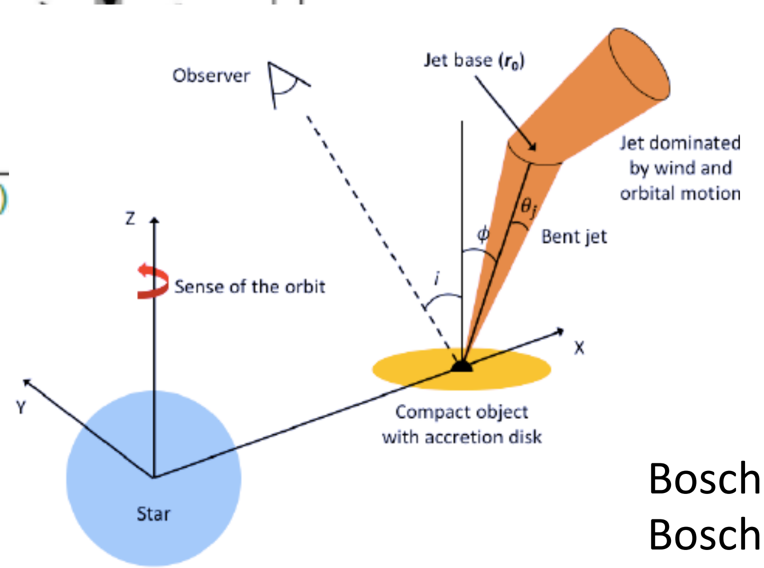
Deep radio view of GRS 1758−258

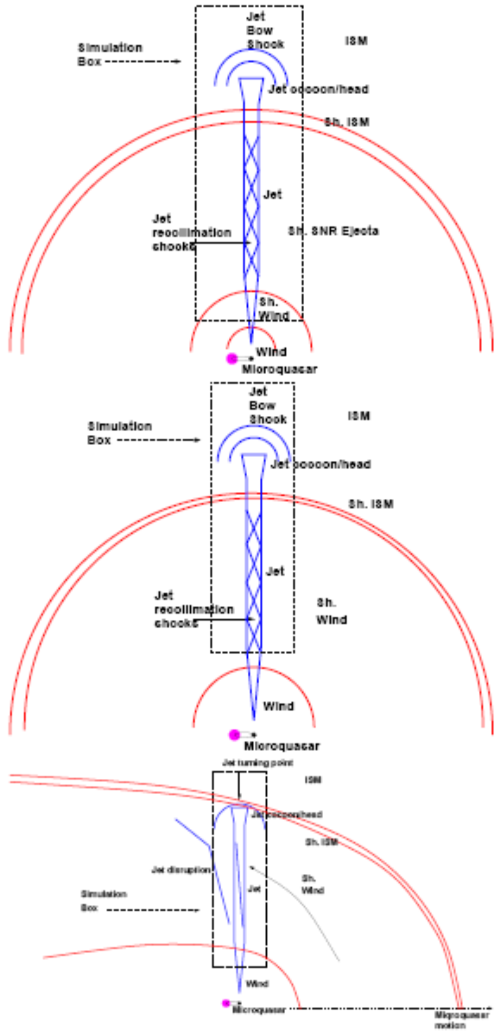
Martí et al. 2017, Nature Communications

Jets



Mirabel & Rodríguez (1998)





Bosch-Ramon, Perucho & Bordas, 2011
Bosch-Ramon & Barkov 2016
Molina & Bosch-Ramon 2018

Gamma-rays from jets: AGN versus μ-quasars

AGN

- At the jet base/formation region:
  - SSC – EC (Poutanen, Ghisellini…)
    - Accretion disc + BLR
    - Synchrotron photons
  - magnetic field reconnection (Giannios, Nalewajko,…)
- At pc-scales
  - jet-star interaction (Barkov, Khangulyan, Bosch-Ramon,…)
  - recollimation shocks (shock-shock interaction, Marscher, Gómez, Agudo…)
    - Hints of shocks close to the radio cores.
- Diffuse emission
  - turbulent/shear particle acceleration (Rieger, Stawarz,…)
    - growing instabilities, entrainment.

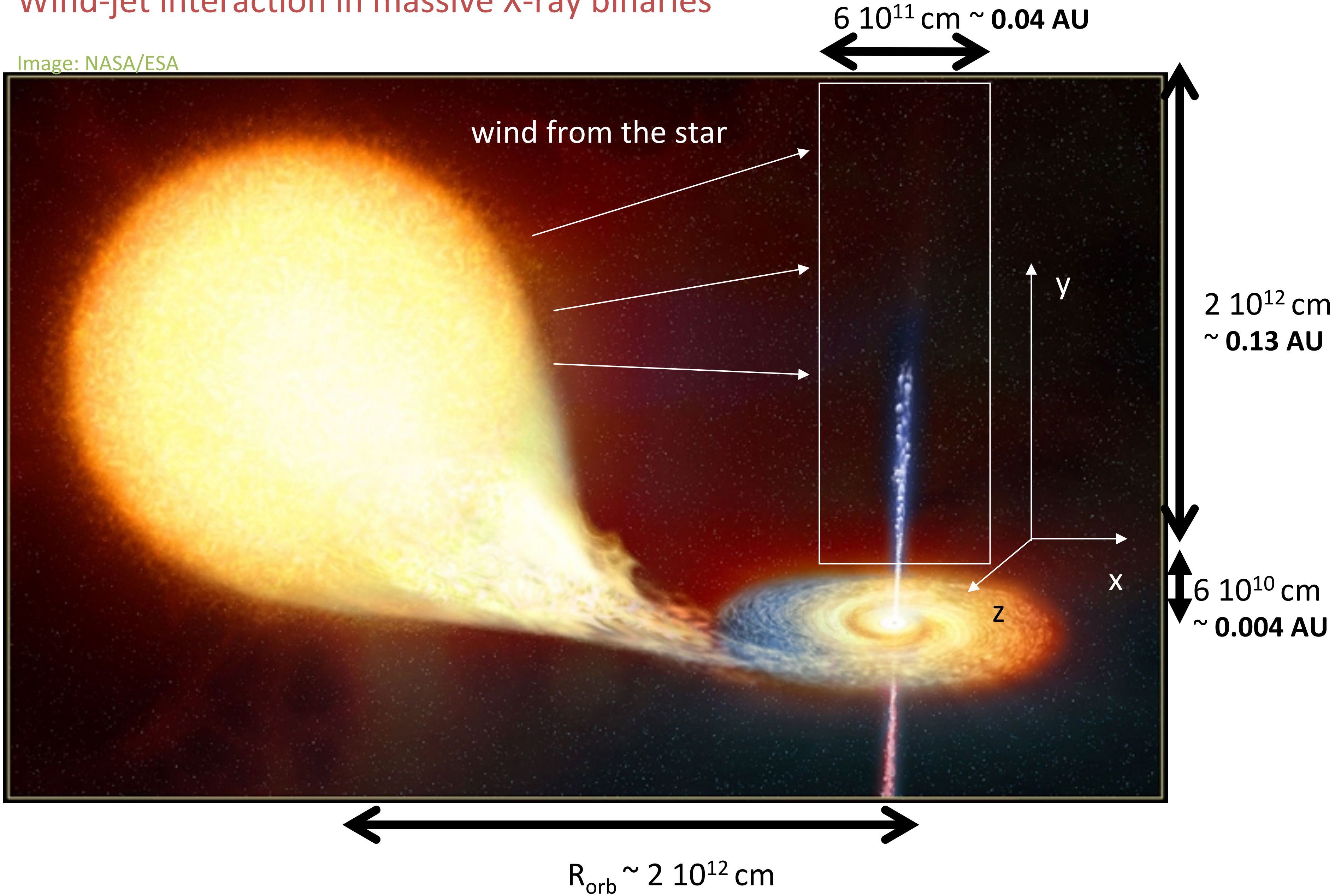
μ-quasars

- At the jet base/formation region:
  - SSC – EC
    - Disc+ Star (e.g., Malyshev et al. ‘13, Zanin et al. ‘16, Cygnus X-1; Zdziarski et al. ’18, Cygnus X-3, Khangulyan et al. ‘18)
    - Synchrotron photons (e.g., Zdziarski et al. ‘17, Cygnus X-1)
  - magnetic field reconnection (?)
- At compact-scales
  - jet-clump interaction
    - Inhomogeneous winds in massive stars. (e.g., Perucho & Bosch-Ramon ‘12, de la Cita et al. ’17).
  - recollimation shocks (shock-shock interaction)
    - Numerical simulations (Perucho et al. ‘10, Yoon et al. ‘16).
- Diffuse emission
  - turbulent/shear particle acceleration
    - growing instabilities, entrainment.

Simulations of jets in high-mass microquasars

Wind-jet interaction in massive X-ray binaries

Image: NASA/ESA



Simulations of wind-jet interaction in X-ray binaries

- Hydrodynamic-cold flow – particle dominated.
  - reasonable at certain distances to the compact object ($B \propto r^{-2}$) and taking dissipation into account. Excepting at 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}).

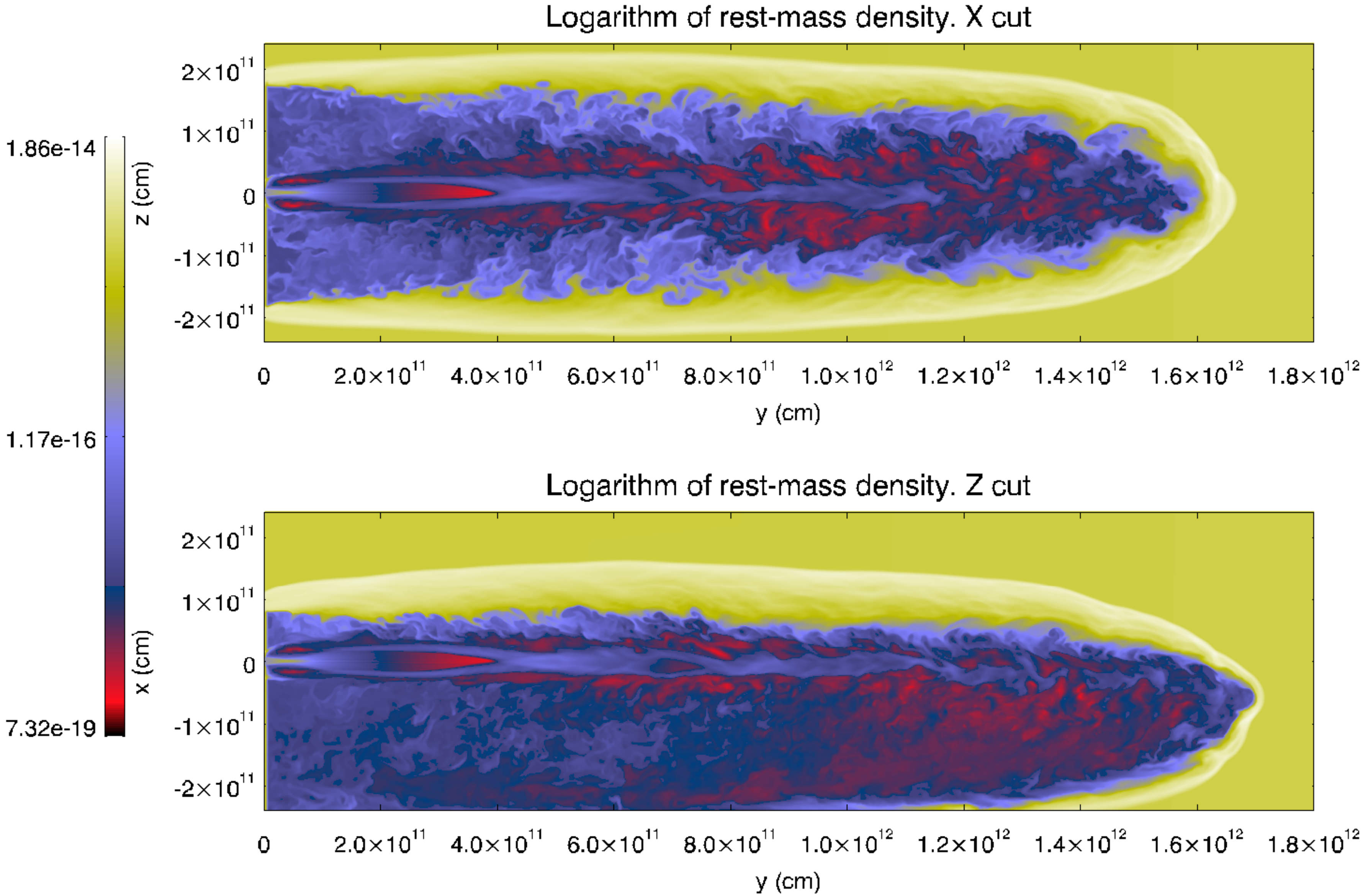
	WIND	JET 1	JET 2
Power (erg/s)		10^{35}	10^{37}
Velocity (cm/s)	$2\ 10^{8}$	$1.7\ 10^{10}$	$1.7\ 10^{10}$
Density ($g \cdot cm^{-3}$)	$2.8\ 10^{-15}$	$0.088\ \rho_w$	$8.8\ \rho_w$
Temperature (K)	10^{4}	10^{10}	10^{10}
Mach number	220	16.6	16.6
Pressure ($dyn \cdot cm^{-2}$)	$1.5\ 10^{-3}$	7.1	$7.1\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

Perucho, Bosch-Ramon & Khangulyan (2010)

Perucho & Bosch-Ramon (2008)

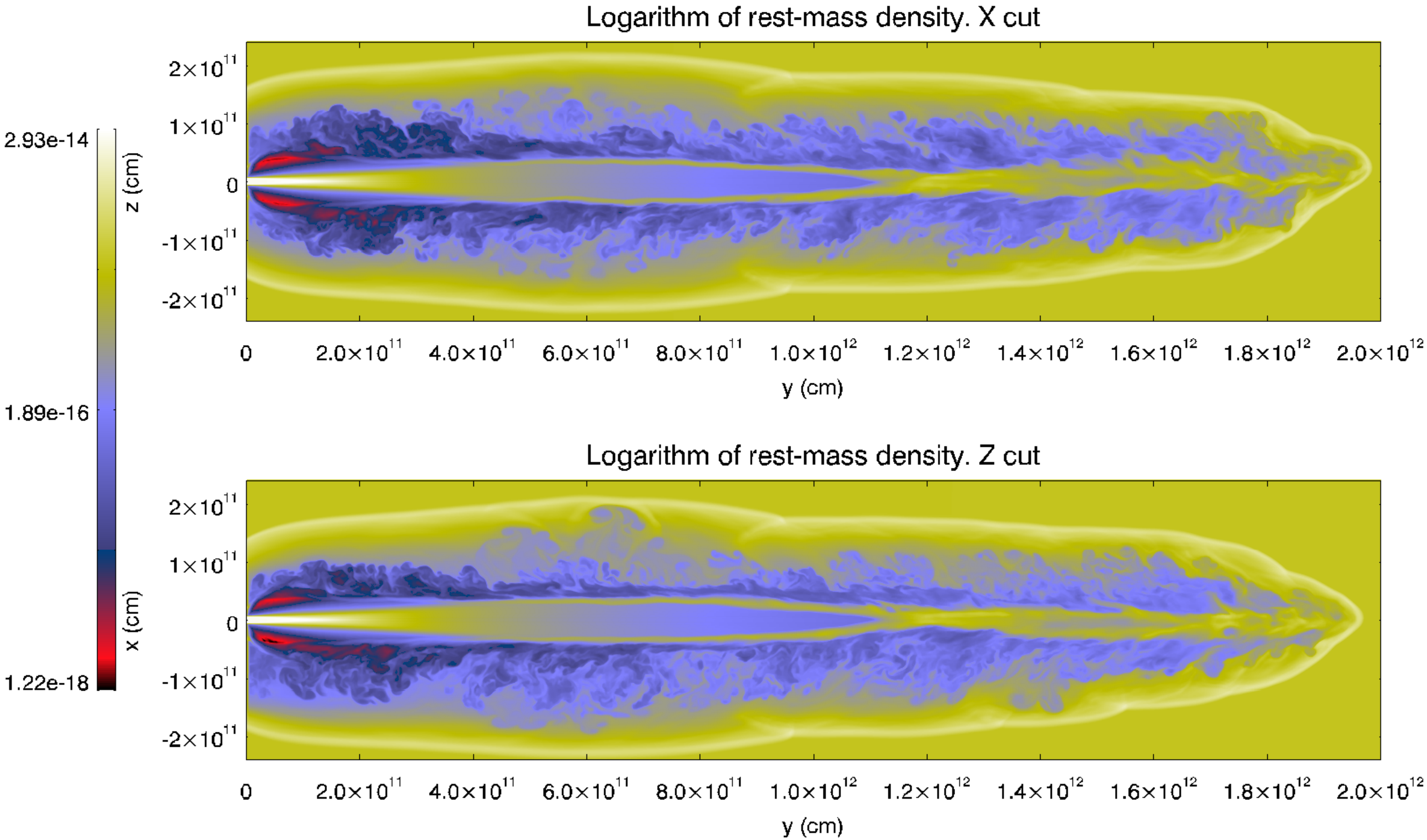
Simulations of jets in high-mass microquasars

Jet 1 t = 977 s

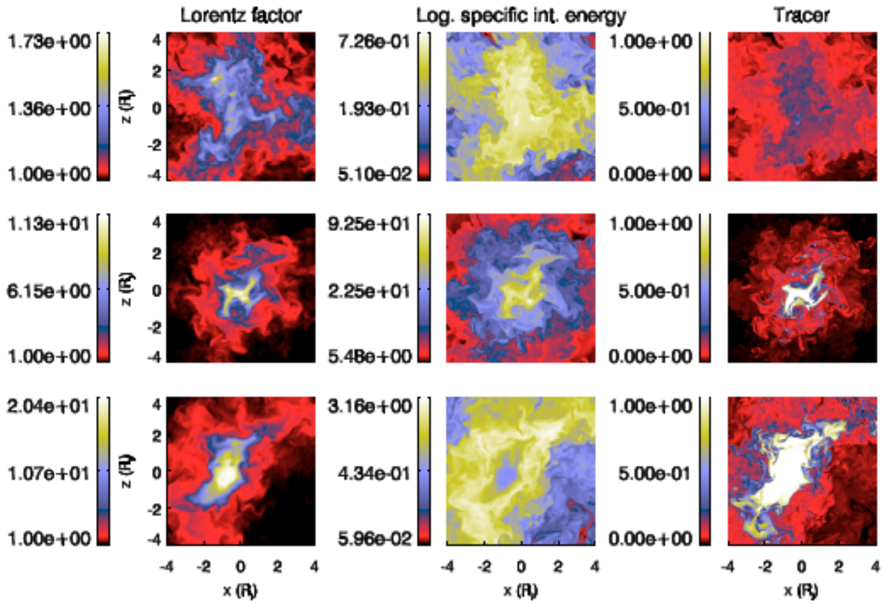


Simulations of jets in high-mass microquasars

Jet 2 t = 192 s



Instabilities



cold

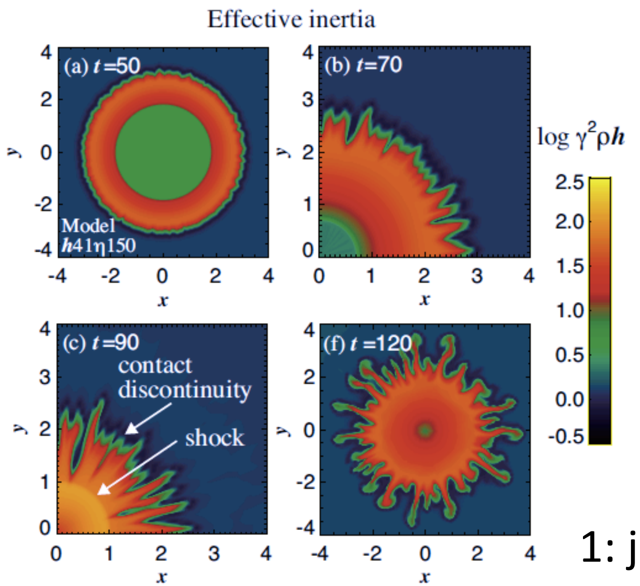
hot

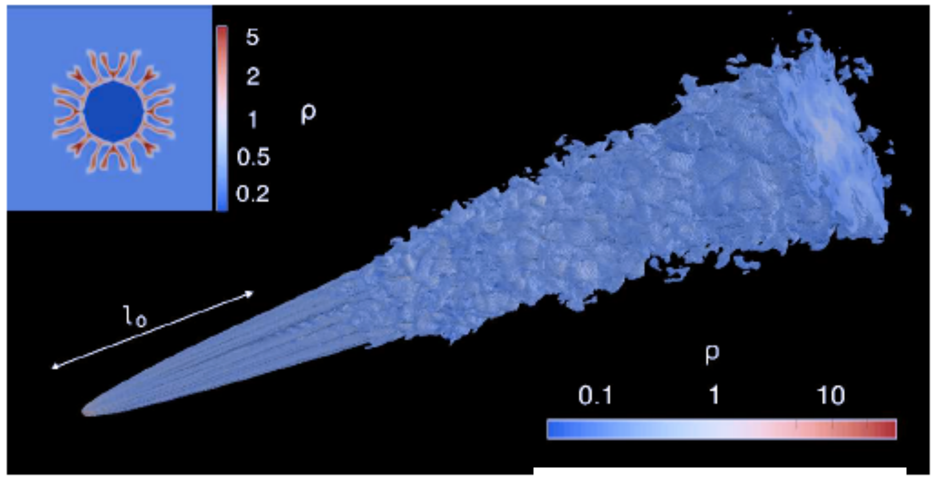
cold

Lorentz factor

Perucho et al. 2005, 2010: KH instability. The disruption process can be slow if the growing modes have small wavelengths.

Gourgouliatos & Komissarov 2018 a,b





$$\Psi_2 - \Psi_1 < 0, \qquad \Psi = \rho h \gamma^2 (\Omega R^2)^2,$$

$$M = \gamma \Omega R / (\gamma_s c_s),$$

1: jet

2: ambient medium

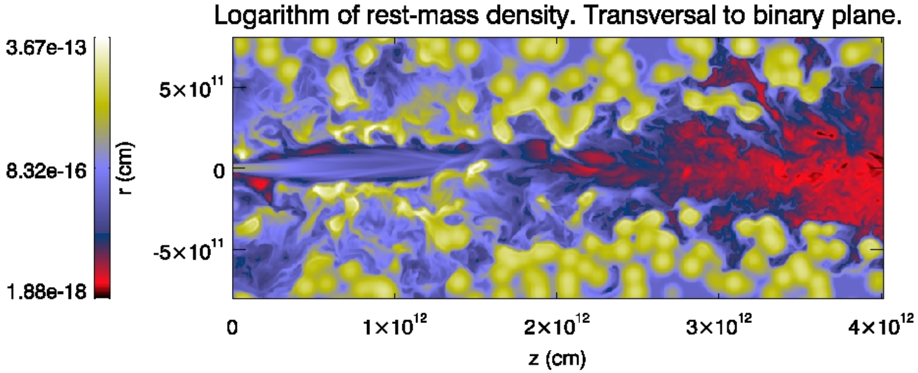
$$\frac{\rho_1 h_1' \gamma_1^2}{\rho_2 h_2' \gamma_2^2} > 1, \quad h' := 1 + \frac{\Gamma^2}{\Gamma - 1}\frac{p}{\rho},$$

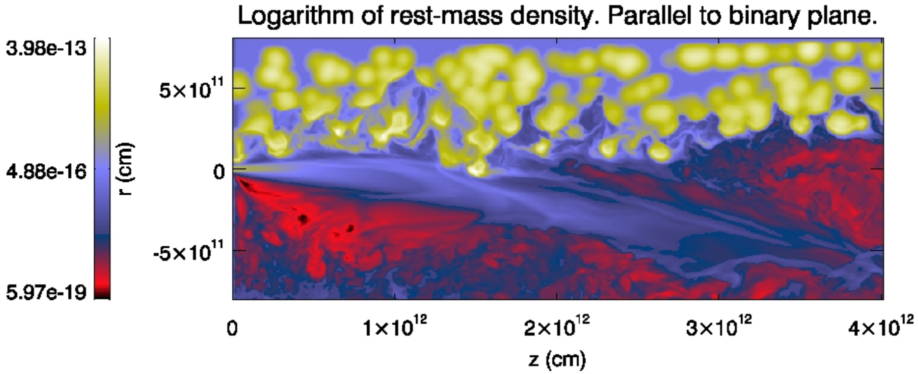
Matsumoto & Masada 2013

Matsumoto, Aloy, Perucho 2017

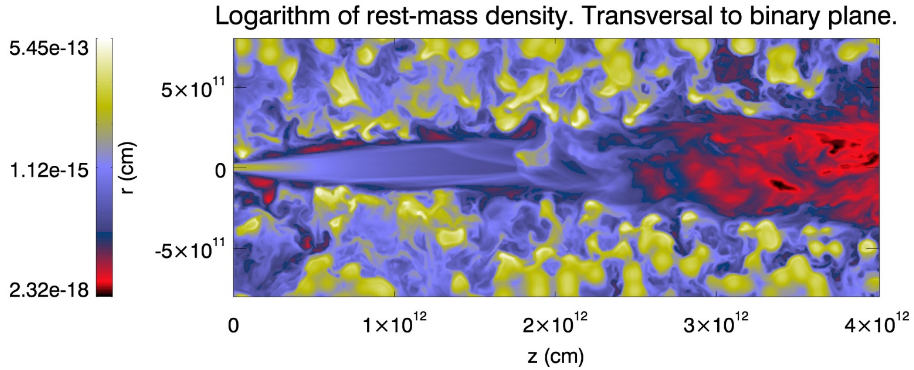
Simulations of jets in high-mass microquasars

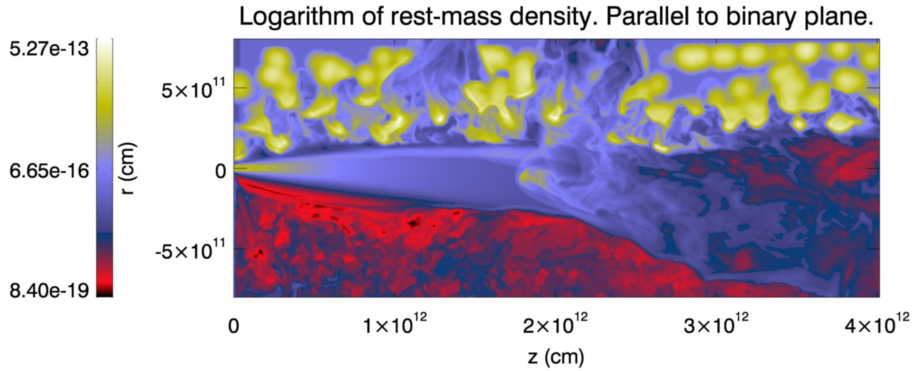
Inhomogeneous wind. $P_j = 3\ 10^{36}$erg/s

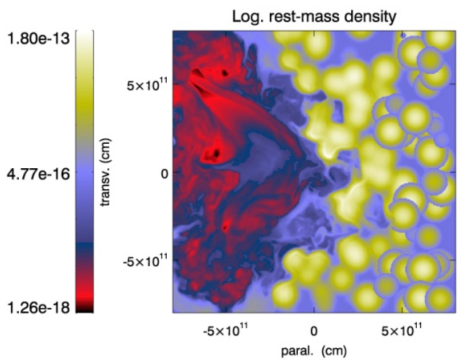


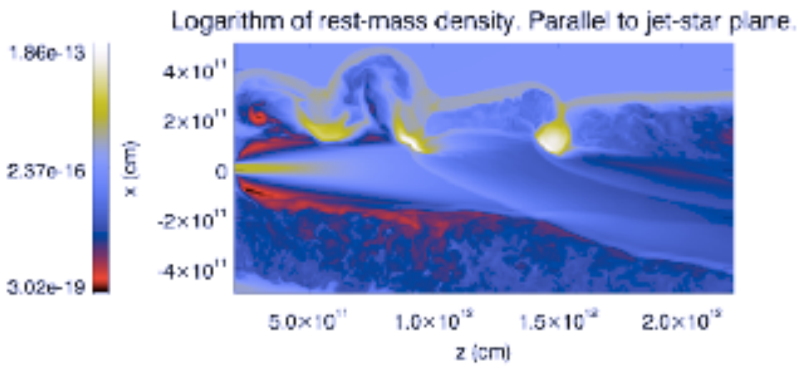


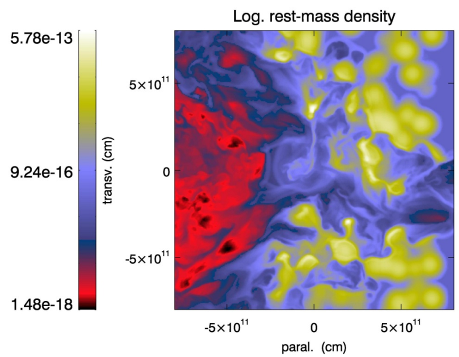
Inhomogeneous wind. $P_j = 10^{37}$erg/s









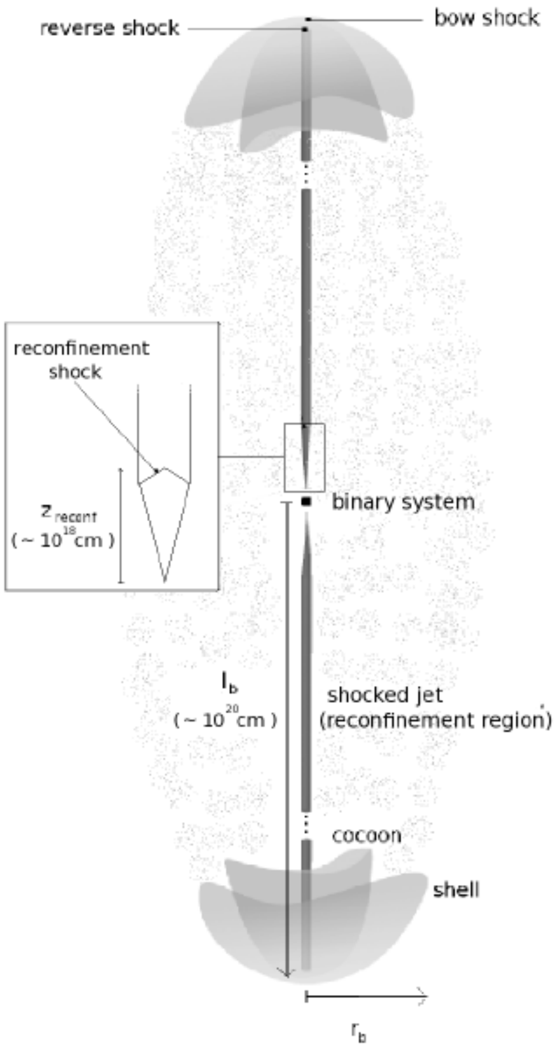


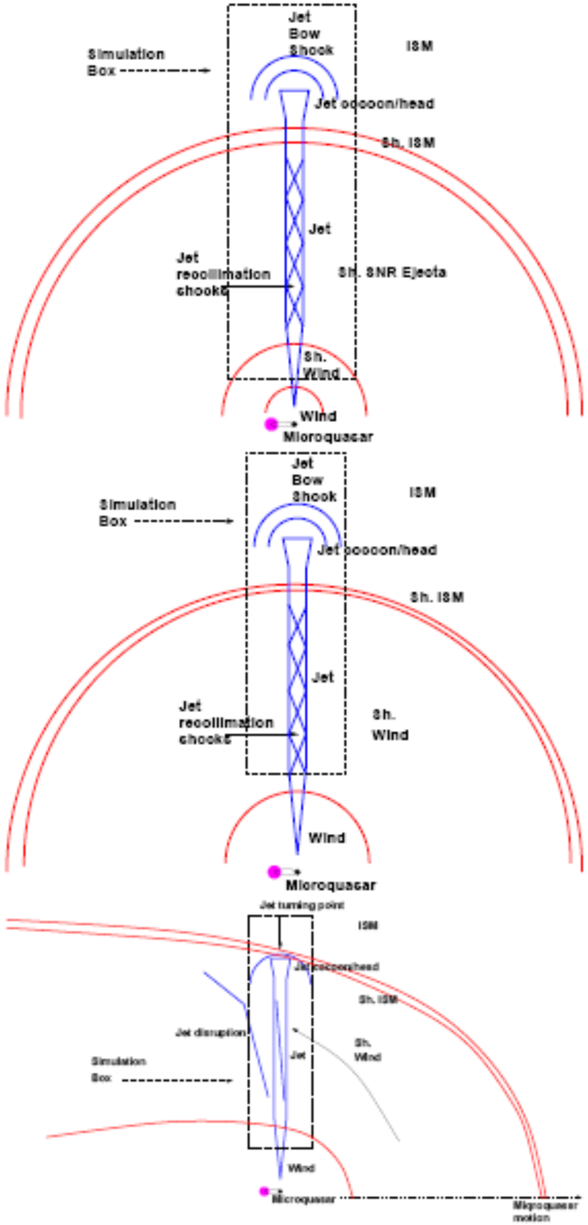
Perucho, Bosch-Ramon & Barkov (A&A, 2017)

Long-term evolution

Bordas, Bosch-Ramon, Paredes, Perucho 2009.

Bosch-Ramon, Perucho, Bordas 2011.





Evolution: AGN versus μ-quasars

AGN

- BLR – NLR (sub-pc – 1 kpc)
- ISM – IGM pressure gradient (1 kpc – 100 kpc)
- Fairly homogeneous IGM (> 50 - 100 kpc)

μ-quasars

- (Inhomogeneous?) wind (10^{10}-10^{18} cm)
- Shocked wind/Supernova remnant/ISM (10^{18}-10^{19} cm)
- ISM (> 10^{19} cm)

Evolution: AGN versus μ-quasars

AGN

- BLR – NLR (sub-pc – 1 kpc)
  - Mass-load and dissipation:
    - Interactions with clouds and stars.
    - Instabilities.
    - Recollimation shocks.
  - Fast variability
    - Compact regions or small-scale interactions.
  - FRI / FRII dichotomy starts at 100 pc – 1 kpc.

μ-quasars

- (Inhomogeneous?) wind (10^{10}-10^{18} cm)
  - Mass-load and dissipation:
    - Interactions with the wind and clumps ($\leq 10^{13}$ cm).
    - Instabilities.
    - Recollimation shocks.
    - Coriolis.
    - Expansion (reacceleration?)
  - Fast variability
    - Compact regions or small-scale interactions.
  - Are there any FRI μ-quasars?

Evolution: μ-quasars

- 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

$$T_{j,0} < 3\times10^{14}\cdot\left(\frac{L_j}{10^{36}\,\mathrm{erg\,s^{-1}}}\right)\cdot\left(\frac{3\times10^{9}\,\mathrm{cm\,s^{-1}}}{V_{\mathrm{bs}}}\right)\cdot\left(\frac{3\times10^{11}\,\mathrm{cm}}{R_c}\right)^2\cdot\left(\frac{10^{-15}\,\mathrm{g\,cm^{-3}}}{\rho_{j,0}}\right)\mathrm{K},$$

Jet-wind interaction

$$T_{j,0} < 3\times10^{13}\cdot\left(\frac{\rho_w}{2.8\times10^{-15}\,\mathrm{g\,cm^{-3}}}\right)\cdot\left(\frac{V_w}{2\times10^{8}\,\mathrm{cm\,s^{-1}}}\right)^2\cdot\left(\frac{10^{-15}\,\mathrm{g\,cm^{-3}}}{\rho_{j,0}}\right)\mathrm{K},$$

Fulfilled for supersonic, mildly relativistic jets.

- These strong shocks are candidate locations for particle acceleration and high-energy emission.
  - gamma-rays produced at such height above the orbital plane may suffer less absorption by interaction with stellar photons.

- 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 and generate turbulent regions.

Evolution: AGN versus μ-quasars

AGN

- ISM – IGM pressure gradient.
  - FRIIs: Recollimation shocks.
  - FRIs: turbulent mixing, strongly decelerated.
- Fairly homogeneous IGM (> 50 - 100 kpc).
  - Hot-spot + bow-shock.
  - Turbulent mixing and dissipation.
  - Gamma-rays from lobes (no short variability)

μ-quasars

- Shocked wind / Supernova remnant / ISM
  - Jet collimation by overpressured, shocked external gas.
    - Collimation shocks.
- ISM (> 10^{18}-10^{19} cm).
  - Hot-spot + bow-shock.
  - Are there any large-scale FRI μ-quasars?

Evolution: μ-quasars

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

- Bow shocks and reverse shocks at jet/ISM interaction can accelerate particles to VHE (e.g., Bordas et al. '09).

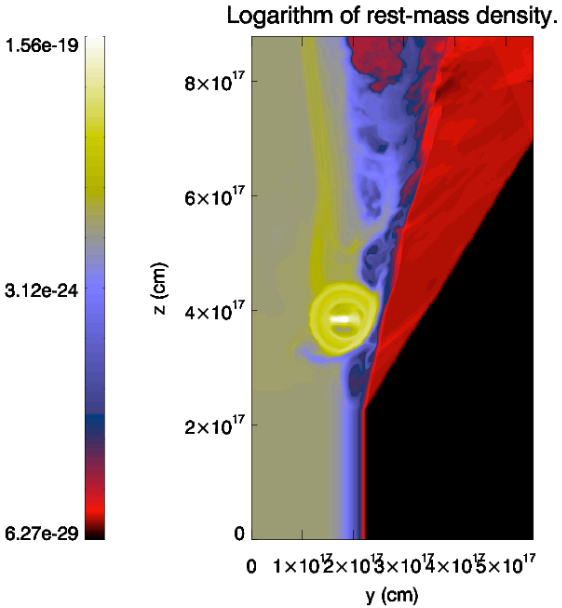
- Frustrated jets may not be observed in radio at large distances, but still be gamma-ray bright due to strong dissipation (FRI μ-quasars?).

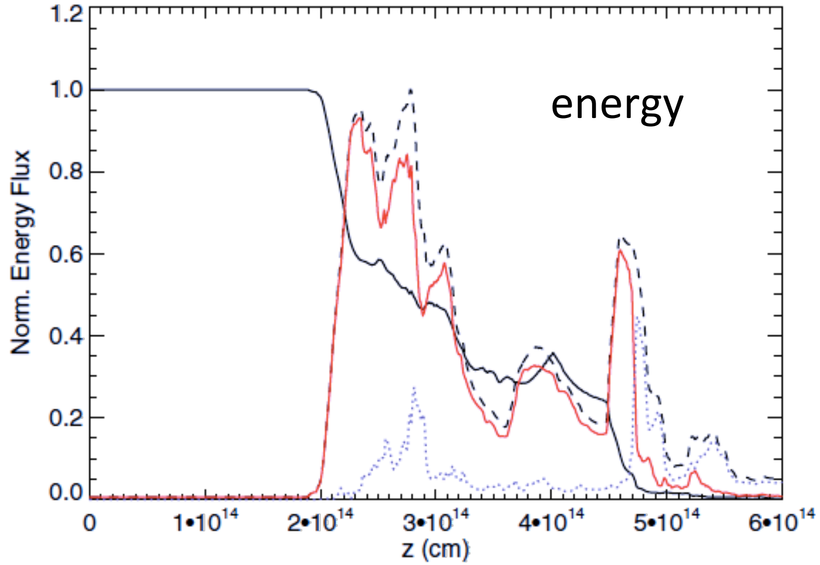
- The luminosity function derived by Grimm et al (2003) predicts 3 HMXBs with $L_X=10^{35}$ erg/s.
  - Following Fender et al. (2005), in HMXB with a 10 M_{sun} black hole, the jet could have a kinetic power between 10^{35} and 10^{38} erg/s.
  - We deduce that there is room for a few (~10) FRI μ-quasars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

Summary

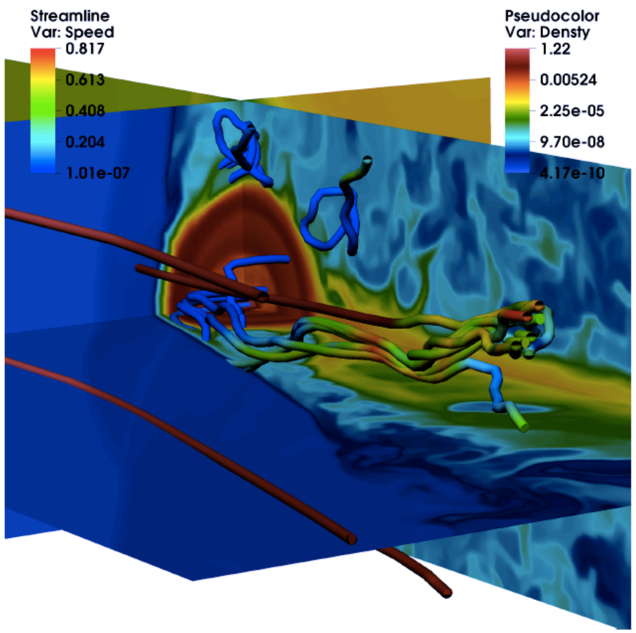
- Gamma-rays can be produced in a wide range of scales and scenarios in microquasar jets.
  - Faster variability:
    - Jet-wind clump interactions.
    - Recollimation shocks.
    - IC of stellar photons by relativistic electrons.
    - Instabilities.
  - Slower variability:
    - turbulent mixing at parsec-scales.
- The evolution of AGN jets and microquasar jets can be very different, as influenced by very different environments (beware of comparisons).
  - Where are the microquasar FRIs?

AGN jet- cloud interaction





Bosch-Ramon, Perucho & Barkov (A&A, 2012)
Perucho, Bosch-Ramon & Barkov (A&A, 2017)



3D simulation of a stellar-wind entering the jet at z ≈100 pc.

Shock propagating towards the jet axis.
Upstream wave in the shear layer.