# The influence of the stellar wind on the jets of high-mass microquasars

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Variable Galactic Gamma-Ray Sources V
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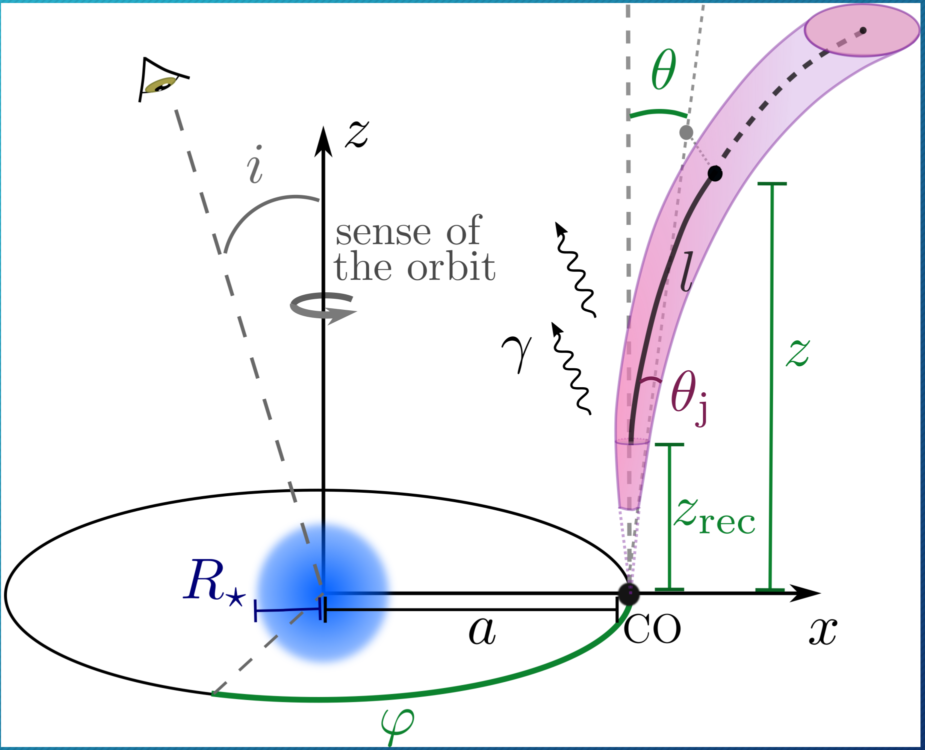
# Physical scenario

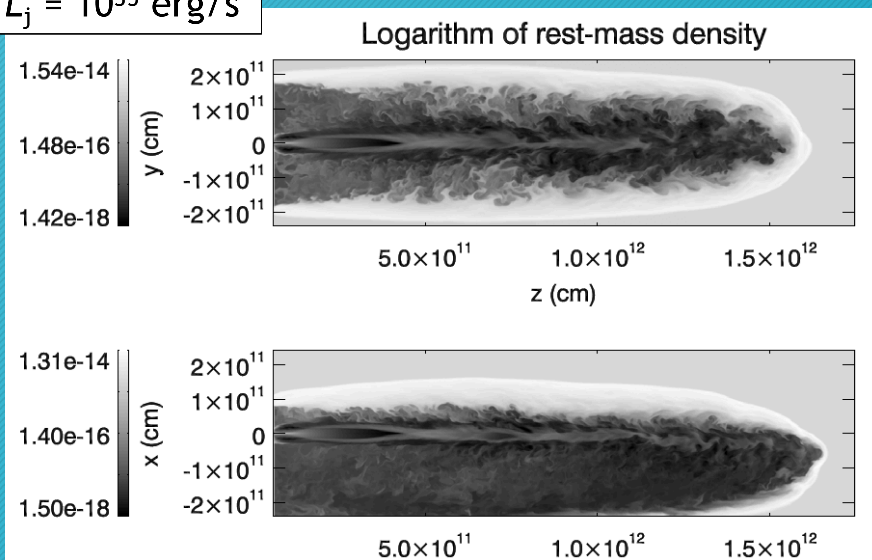
- High-mass microquasar in which a strong stellar wind interacts with the jets in a number of ways:
  - Recollimation shock
  - Bending
  - Large scale helical structure



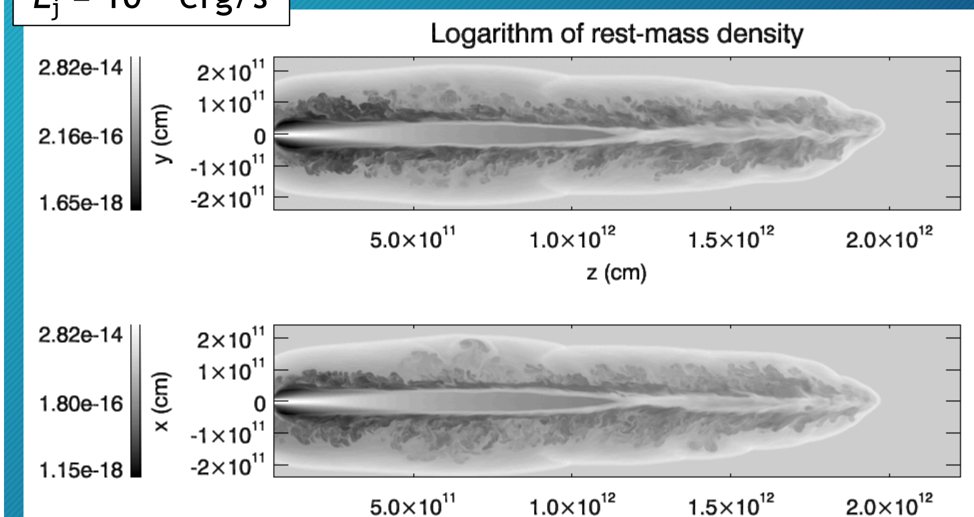
# Wind-jet interaction

- Numerical and analytical studies predict the formation of a recollimation shock at the binary scales

$L_j = 10^{35}$ erg/s



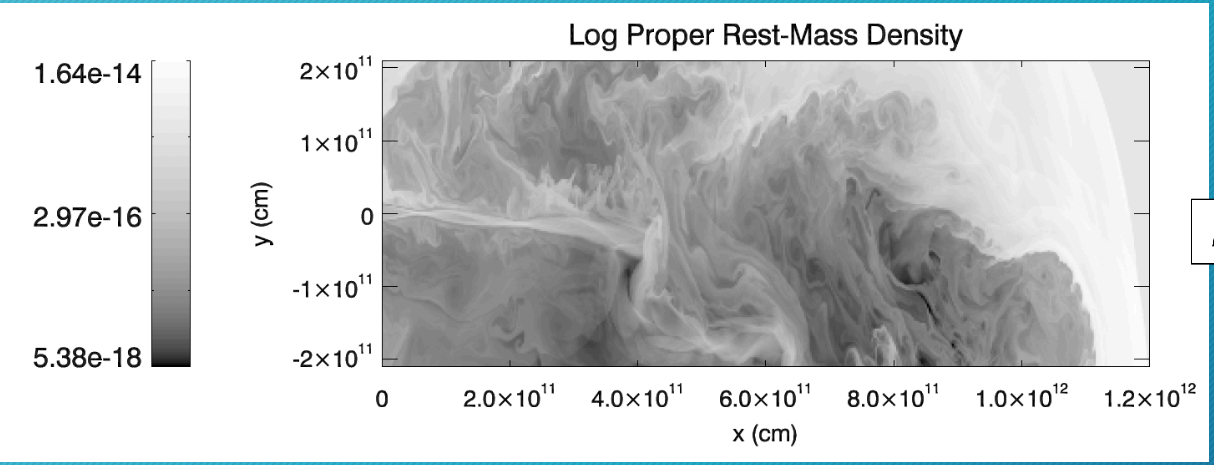

$L_j = 10^{37}$ erg/s



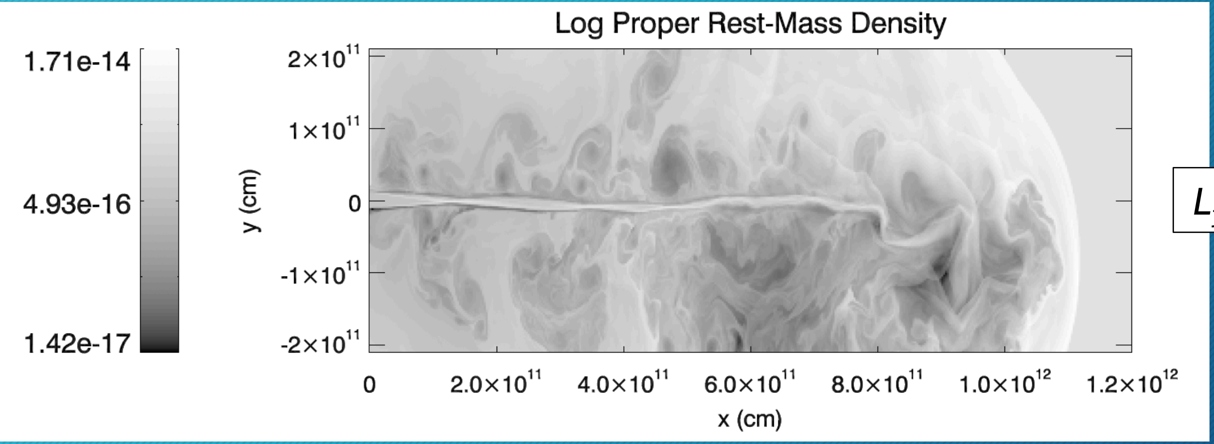

3D relativistic simulations by
Perucho et al. 2010

# Wind-jet interaction

- For low jet powers, jets may be disrupted at very small scales




$L_j$ = 3x10$^{34}$ erg/s




$L_j$ = 10$^{36}$ erg/s

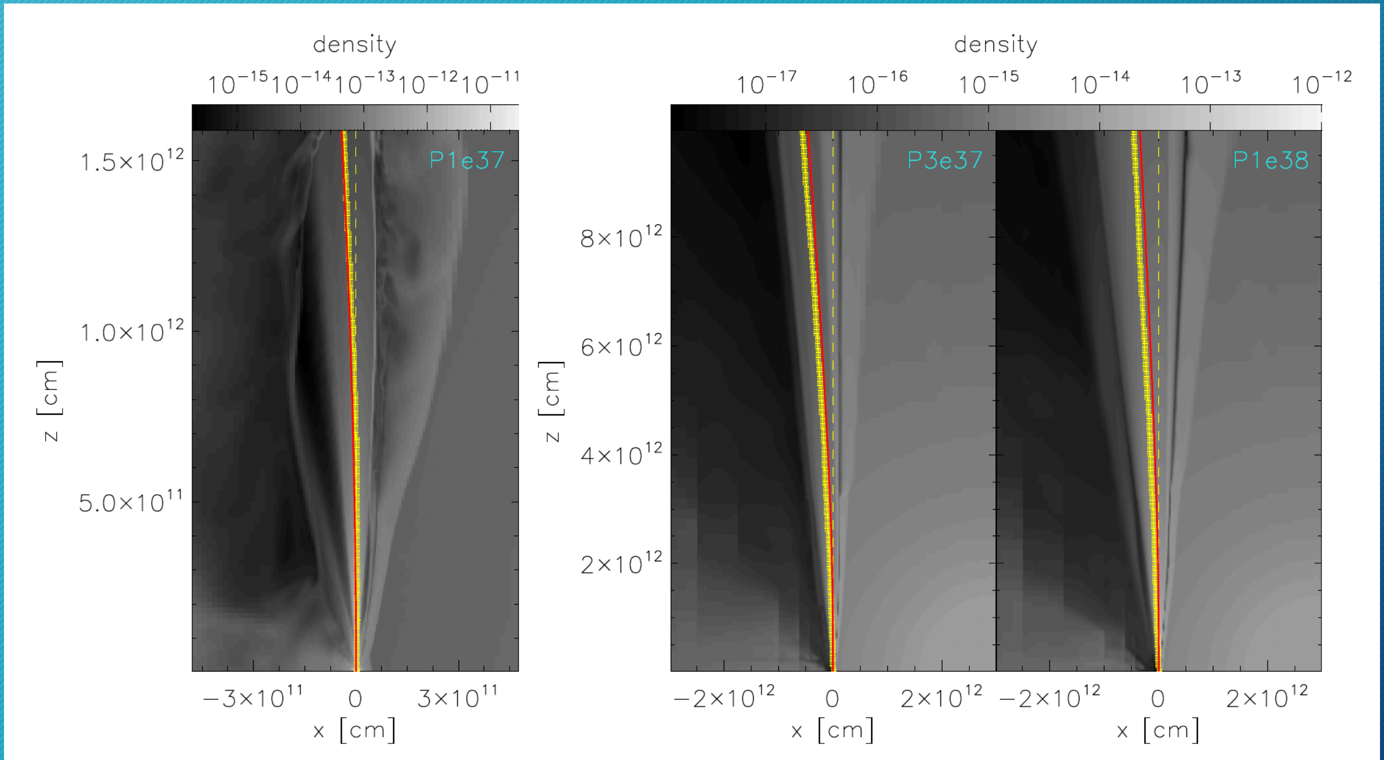
Perucho & Bosch-Ramon 2008

# Wind-jet interaction

- No recollimation for high jet powers:

Bosch-Ramon & Barkov 2016

$$L_{\mathrm{j}} \gtrsim 2.4\times10^{37}\left(\frac{\dot{M}_{\mathrm{w}}}{10^{-6}\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}}\right)\left(\frac{v_{\mathrm{w}}}{2\times10^{8}\mathrm{cm\ s}^{-1}}\right)\frac{\gamma_{\mathrm{j}}\left(\gamma_{\mathrm{j}}-1\right)}{\beta_{\mathrm{j}}}\ \mathrm{erg\ s}^{-1}$$




Yoon et al. 2016

# Wind-jet interaction

- Jets are also bent due to the wind impact on them. For small enough bending angles ($\phi \lesssim 30\,\mathrm{deg}$):

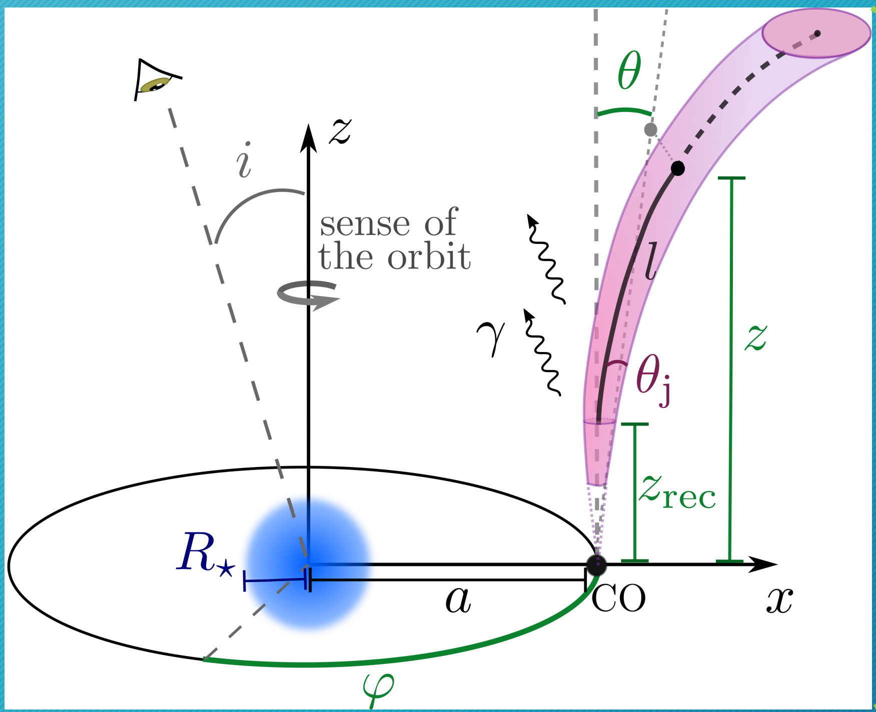
Bosch-Ramon & Barkov 2016

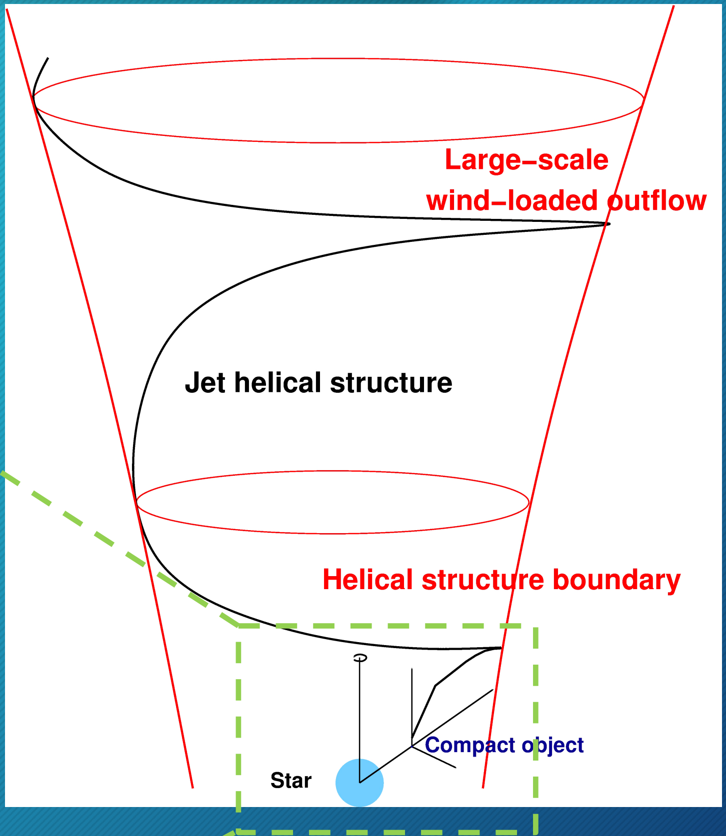
$$\phi \approx 17\left(\frac{L_\mathrm{j}}{10^{37}\mathrm{erg\,s^{-1}}}\right)^{-1}\left(\frac{\theta_\mathrm{j}}{0.1\,\mathrm{rad}}\right)\left(\frac{\dot{M}_\mathrm{w}}{10^{-6}\mathrm{M_\odot\,yr^{-1}}}\right)\left(\frac{v_\mathrm{w}}{2\times10^{8}\mathrm{cm\,s^{-1}}}\right)\frac{(\gamma_\mathrm{j}-1)}{\gamma_\mathrm{j}\,\beta_\mathrm{j}}\,\mathrm{deg}$$

- Bending combined with orbital motion could lead to a helical pattern if the jet is not disrupted before and $\phi > \theta_\mathrm{j}$
- Significant mixing of wind and jet material is expected already within the binary scales

Perucho et al. 2010, 2012

# Wind-jet interaction



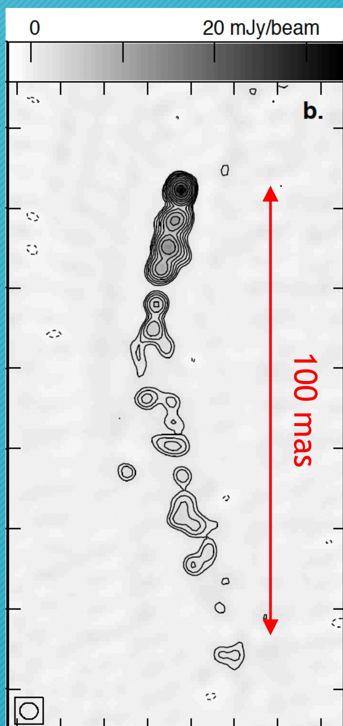




Bosch-Ramon & Barkov 2016

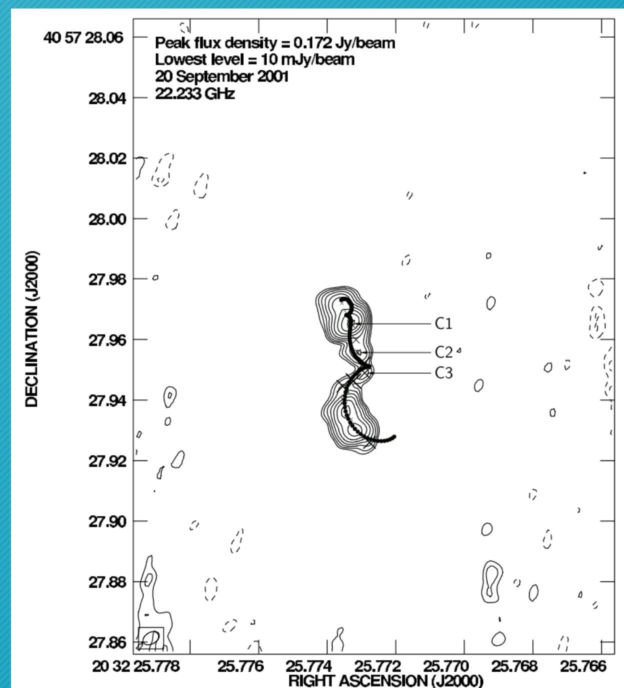
# Wind-jet interaction

Cygnus X-3

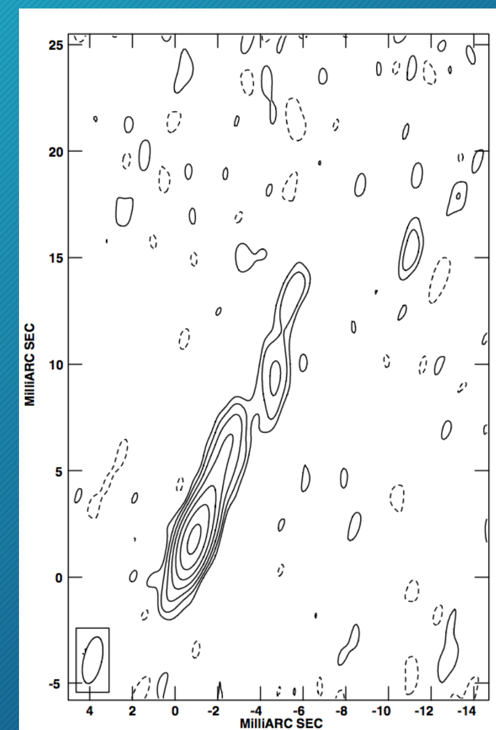
Cygnus X-1?




Mioduszewski et al. 2001




Miller-Jones et al. 2004

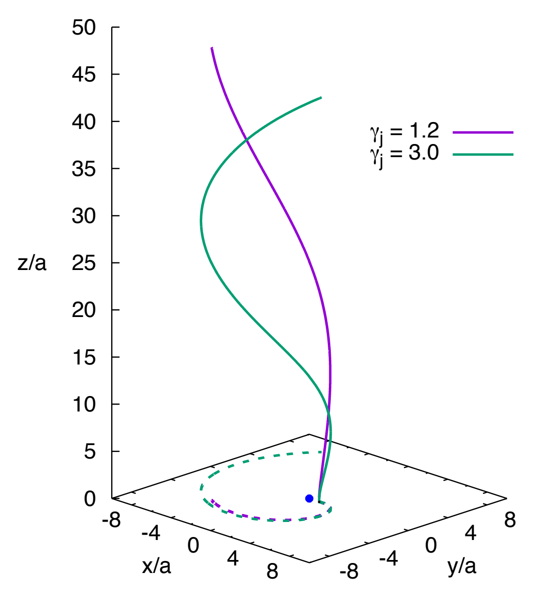



Stirling et al. 2001

# Helical jet model: dynamics

- Jet trajectory is computed from momentum transfer by an isotropic stellar wind
- Within the binary system scales, the jet is bent away from the normal to the orbital plane
- At larger scales, orbital motion makes the jet move towards a helix-like trajectory

| | | |
|---|---|---|
| Mass-loss rate | $\dot{M}_{\rm w}$ | $10^{-6}\ {\rm M}_\odot\ {\rm yr}^{-1}$ |
| Terminal wind speed | $v_\infty$ | $2\times10^{8}\ {\rm cm\ s}^{-1}$ |
| Jet luminosity | $L_{\rm j}$ | $5\times10^{36}\ {\rm erg\ s}^{-1}$ |
| Orbital separation | $a$ | $3\times10^{12}\ {\rm cm}$ |



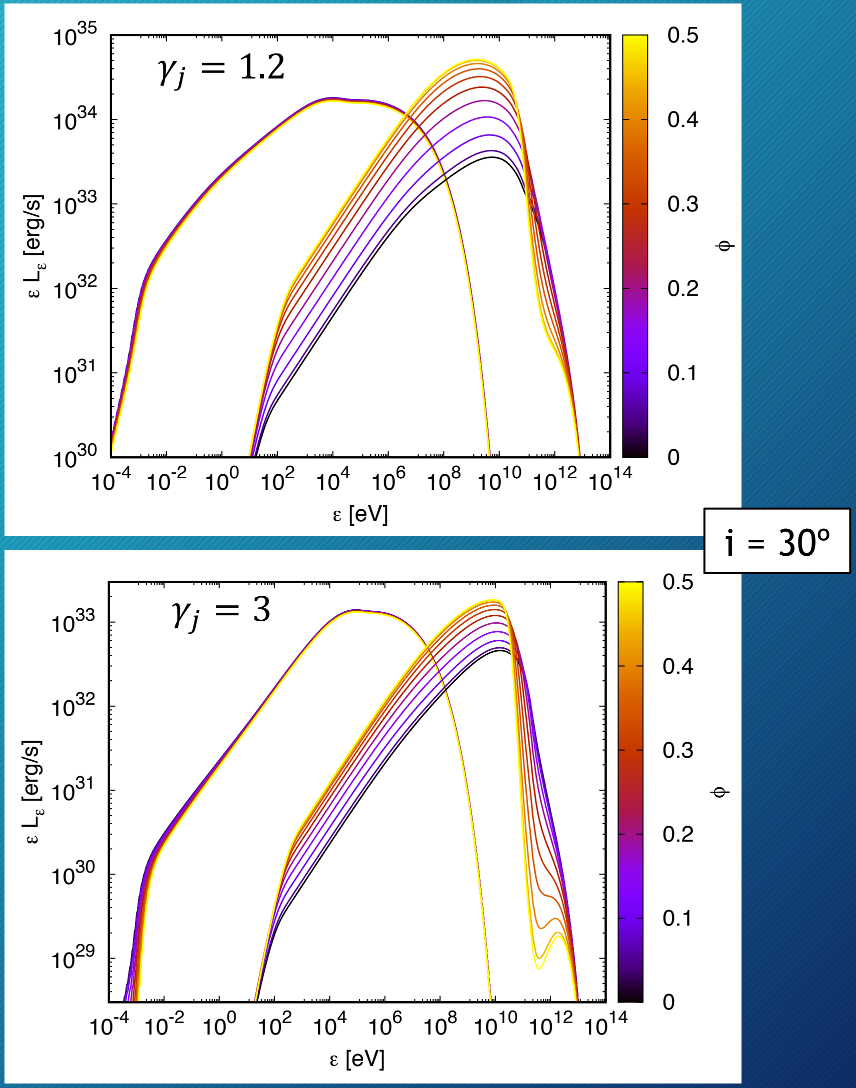
# Helical jet model: radiation

- Nonthermal electrons are injected at the recollimation shock with a power of $0.1L_j$
- Particle distribution computed at each point along the jet
- Cooling:
  - Adiabatic
  - Synchrotron
  - Inverse Compton
- Emission:
  - Synchrotron
  - Inverse Compton
- Absorption:
  - Free-free absorption by wind ions (radio)
  - Gamma-gamma absorption by stellar photons (VHE $\gamma$-rays)

Molina et al. 2019

# Helical jet model: radiation

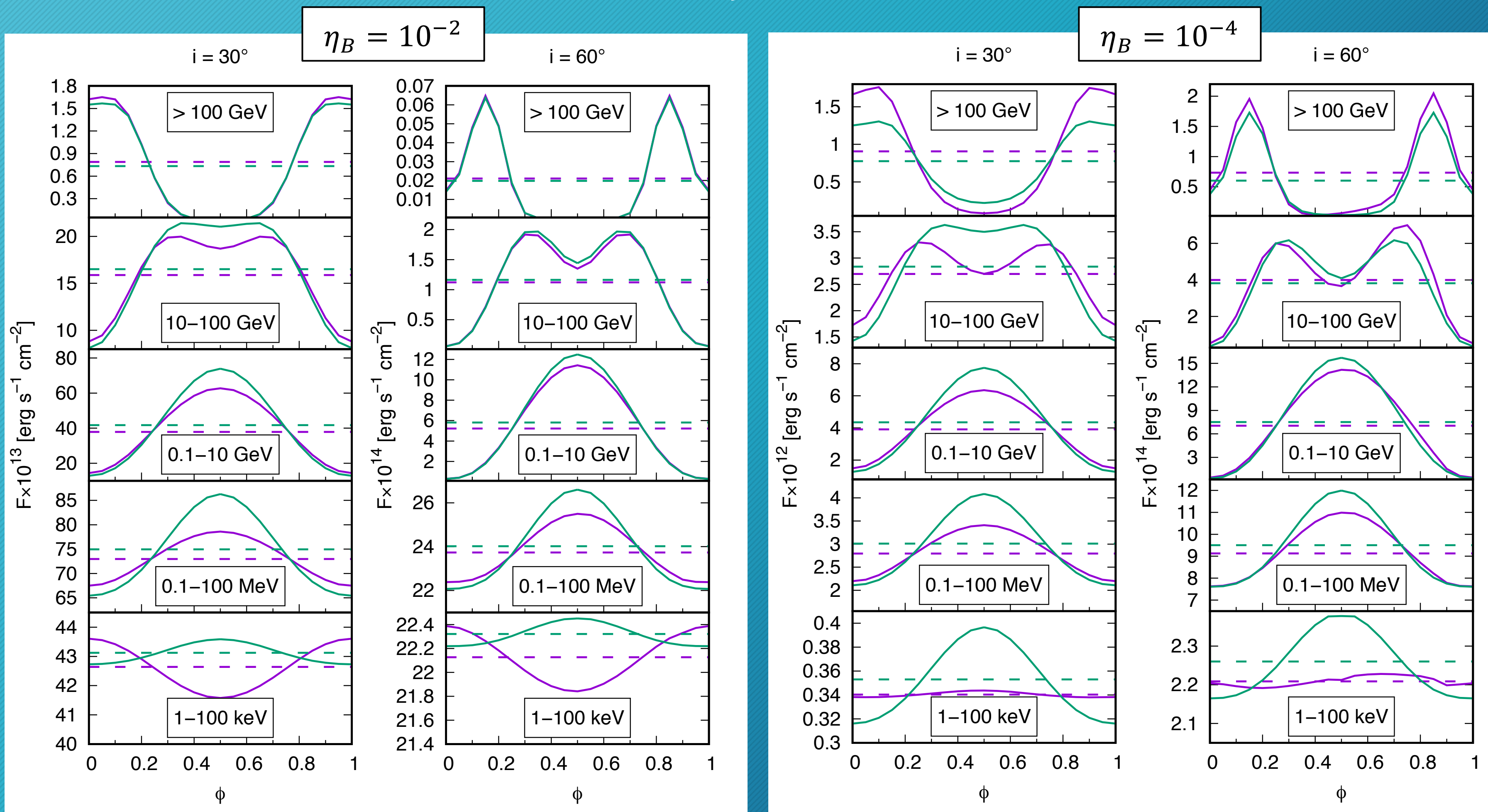
- For higher $\gamma_j$, the change in the Doppler boosting does not compensate for the increased energy losses, except for very small inclinations
- The helical structure enhances absorption and affects the IC emission




Molina et al. 2019

# Helical jet model: radiation

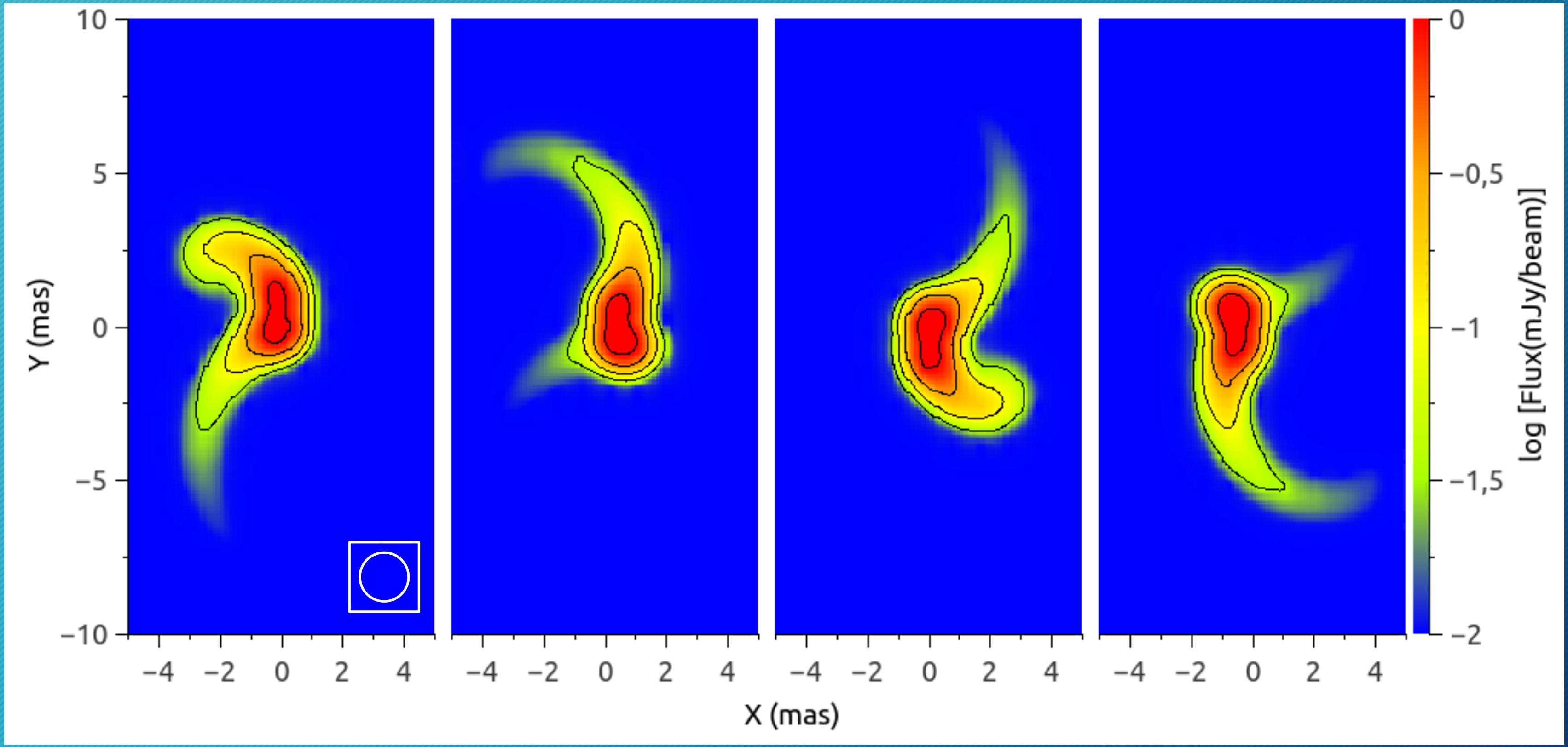
$\gamma_j = 3$




Molina et al. 2019

# Helical jet model: radiation

Simulated radio maps at 5 GHz



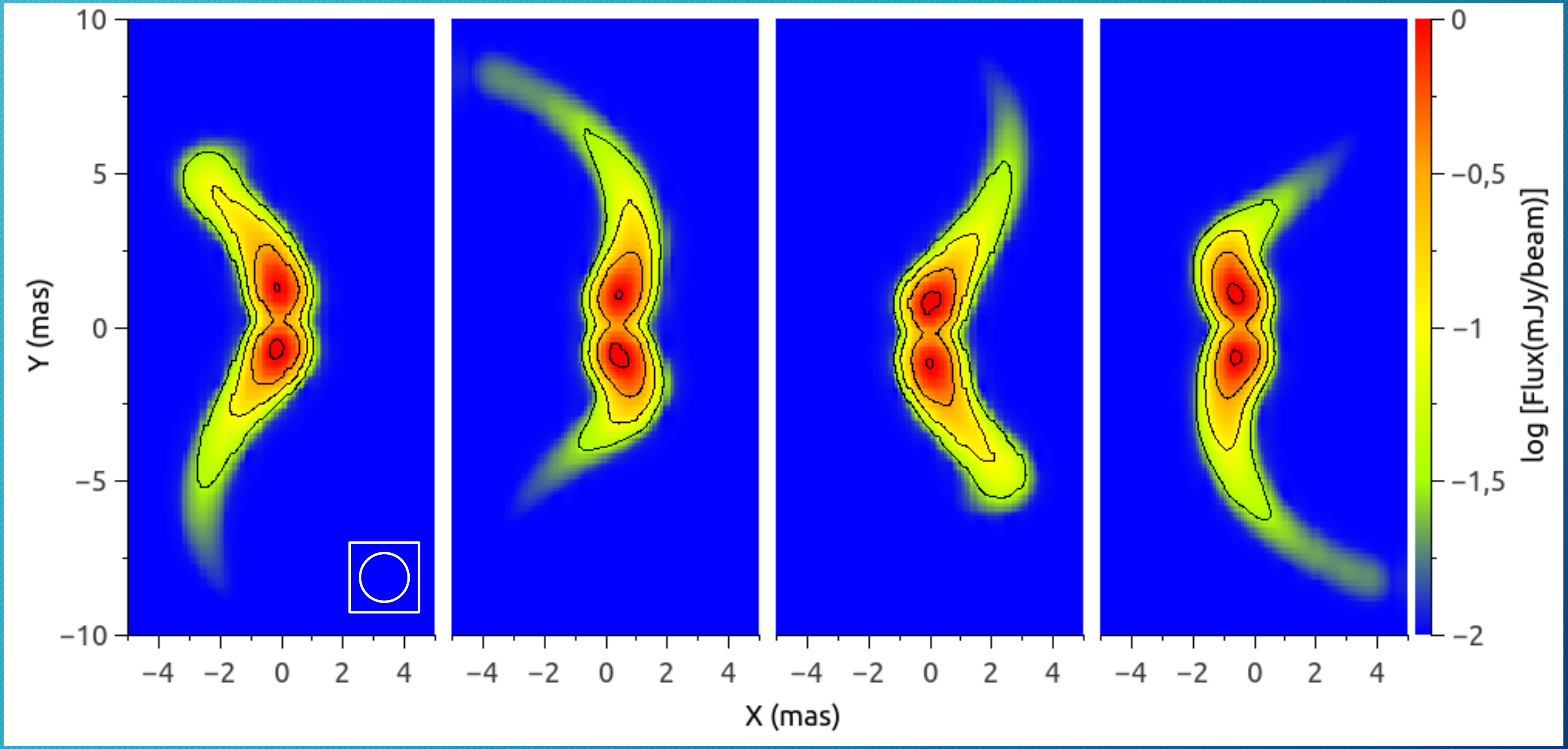

$i$ = 30º

$\eta_{\mathrm{NT}} = 1\ \%$

Molina & Bosch-Ramon 2018

# Helical jet model: radiation

Simulated radio maps at 5 GHz




$i$ = 60º

$\eta_{NT} = 1\ \%$

Molina & Bosch-Ramon 2018

# Summary

- Jet-wind interaction must be considered when studying HMMQ jets
- Dynamical effects:
  - Jet bending
  - Recollimation shock
  - Jet disruption
  - Helical structure at larger scales
- Non-thermal radiation:
  - Angle dependent quantities affected by the presence of a helical jet structure (IC, $\gamma\gamma$, Doppler boosting)
  - Light curve asymmetry owing to helical structure
    - Highly concentrated emission reduces this effect
  - Radio is absorbed at small scales, but could be used to trace the helical structure at larger scales

# Backup slides

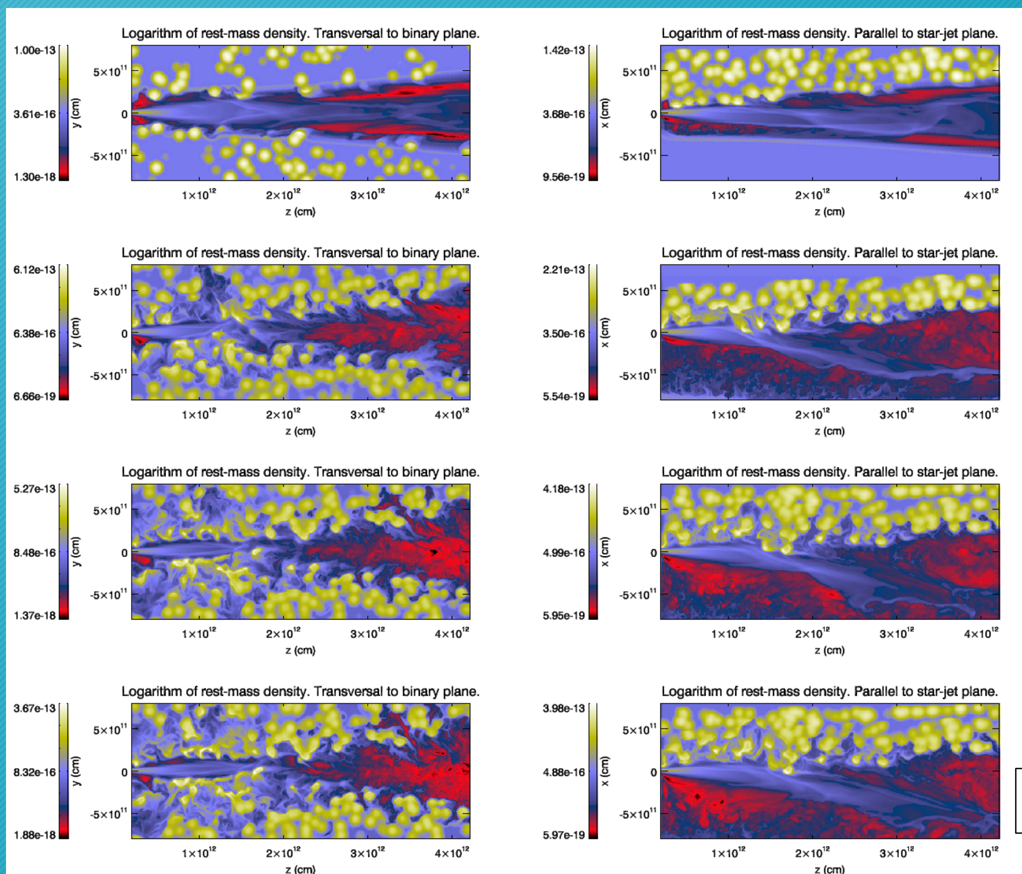
# Simulations parameters

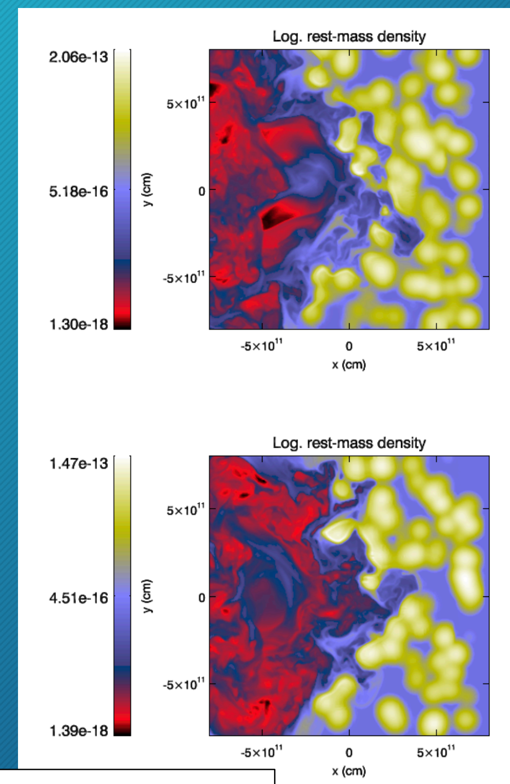
| Parameter | Perucho+ 2008 | Perucho+ 2010 | Perucho+ 2012 | Yoon+ 2016 |
|---|---|---|---|---|
| Orbital separation | $3\times10^{12}\mathrm{cm}$ | $2\times10^{12}\mathrm{cm}$ | $2\times10^{12}\mathrm{cm}$ | $3\times10^{12}\mathrm{cm}$ |
| Initial jet speed | $10^{10}\mathrm{cm/s}$ | $1.7\times10^{10}\mathrm{cm/s}$ | $10^{10}\mathrm{cm/s}$ | $3\times10^{9}\mathrm{cm/s}$ |
| Wind mass loss rate | $10^{-6}\mathrm{M_\odot/yr}$ | $10^{-6}\mathrm{M_\odot/yr}$ | $10^{-6}\mathrm{M_\odot/yr}$ | $10^{-5}\mathrm{M_\odot/yr}$ |
| Wind speed | $2\times10^{8}\mathrm{cm/s}$ | $2\times10^{8}\mathrm{cm/s}$ | $2\times10^{8}\mathrm{cm/s}$ | $2.5\times10^{8}\mathrm{cm/s}$ |

# Clumpy wind

- Clumpy winds make disruption more likely to occur

Time



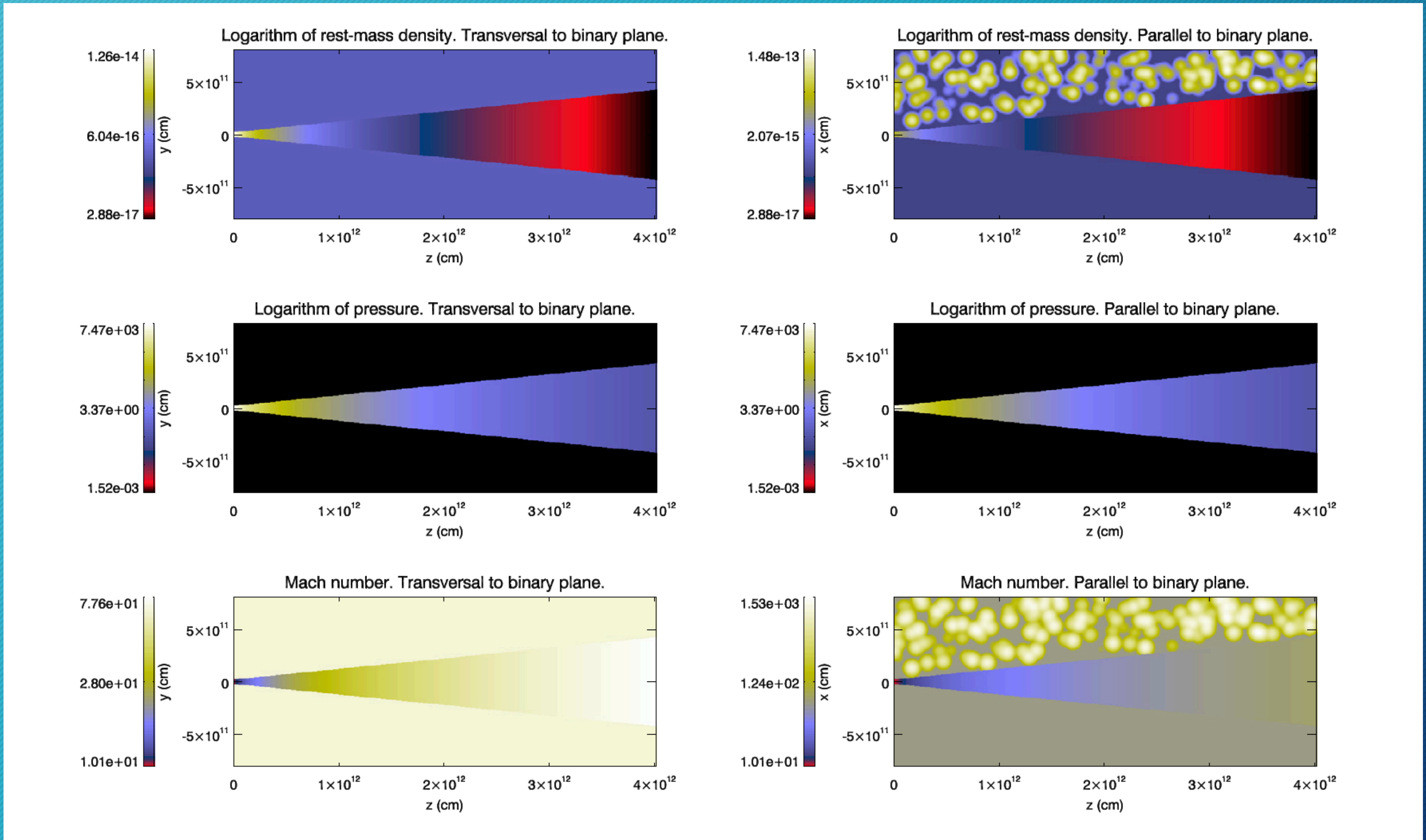

Z

$L_j$ = 3x10$^{36}$ erg/s

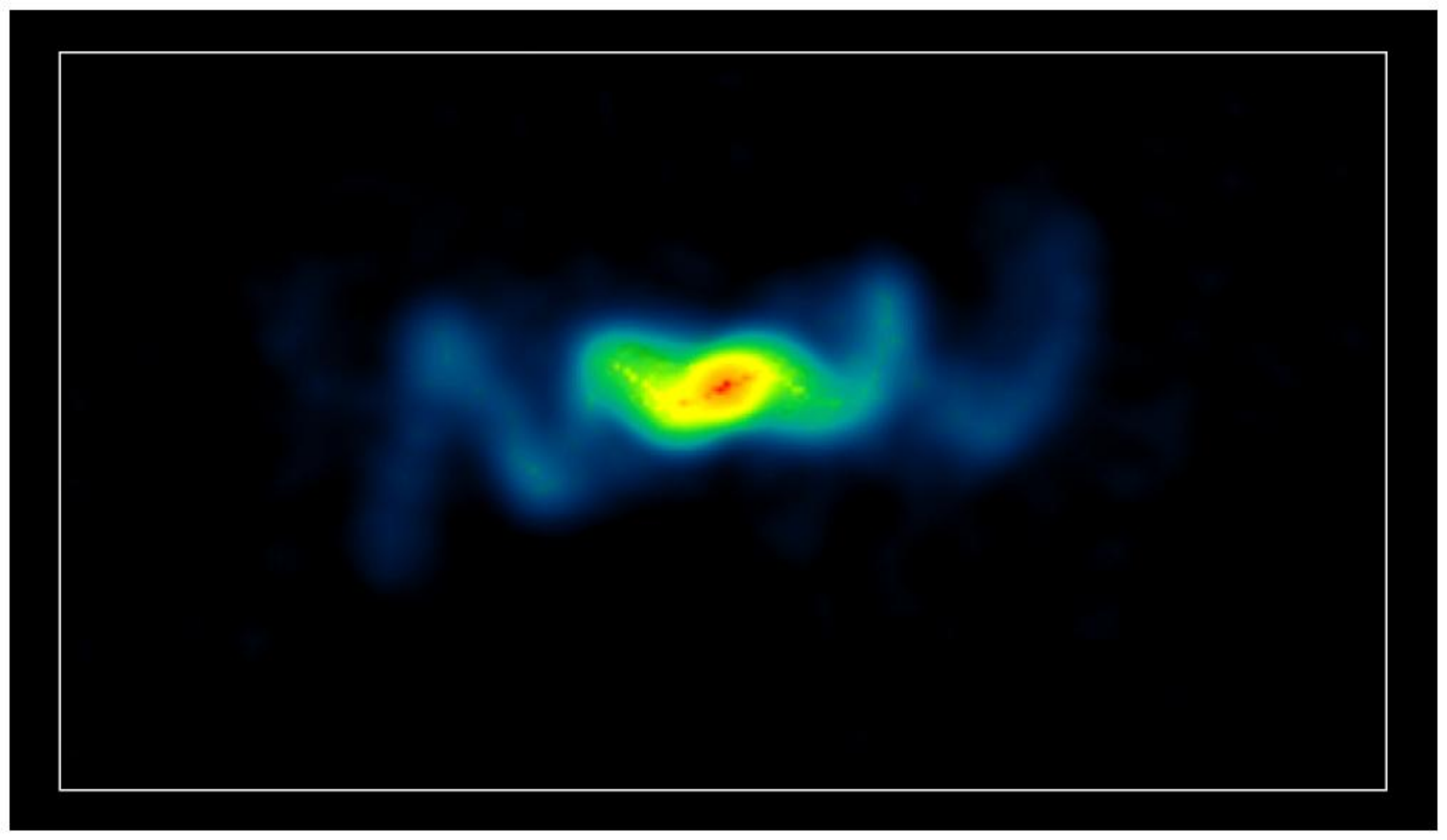
Perucho & Bosch-Ramon 2012

# Clumpy wind

## Initial conditions



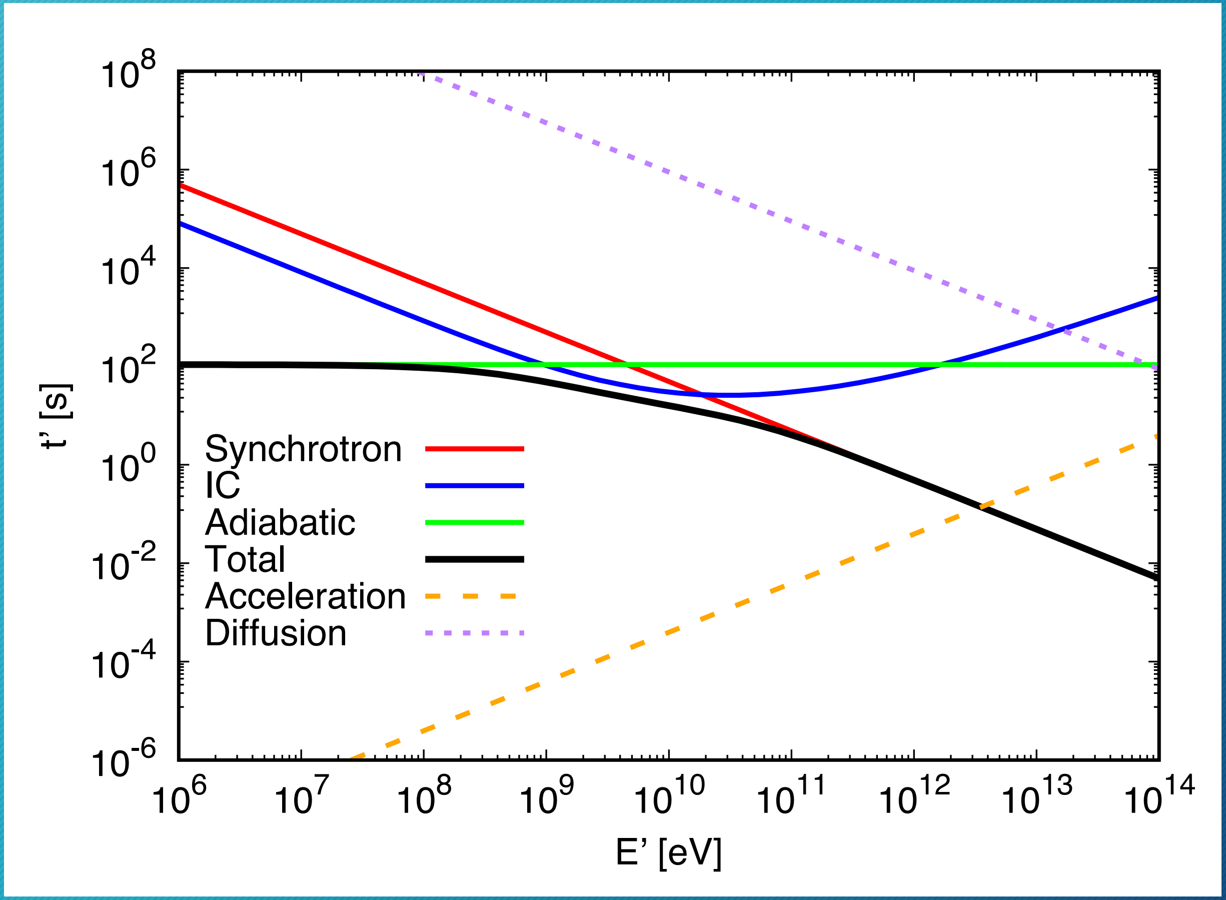
# SS433



# Model parameters

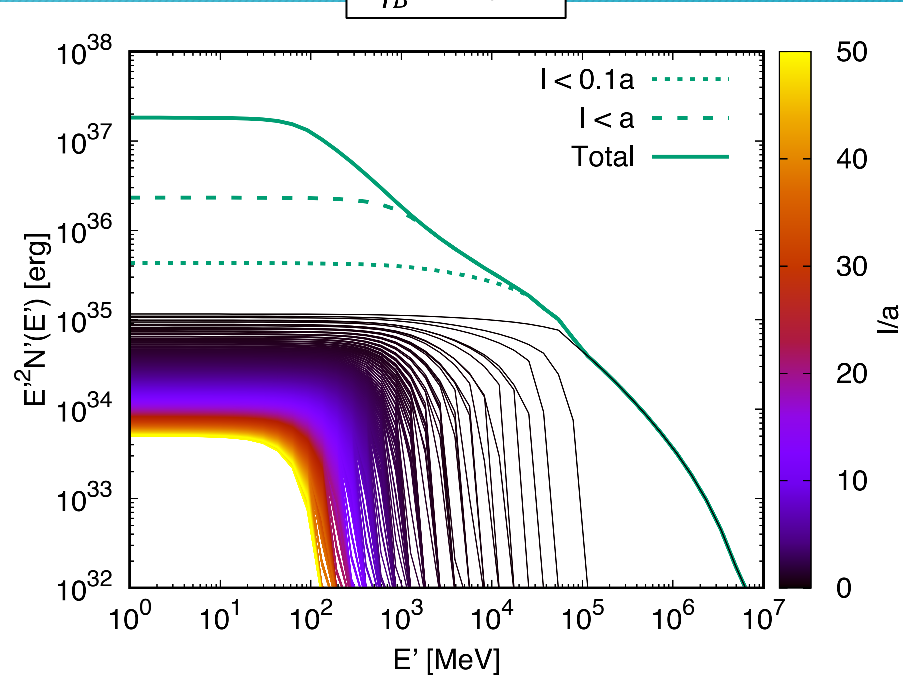
| Parameter | | Value |
|---|---|---|
| Stellar temperature | $T_\star$ | $4 \times 10^4$ K |
| Stellar luminosity | $L_\star$ | $10^{39}$ erg s$^{-1}$ |
| Mass-loss rate | $\dot{M}_{\rm w}$ | $10^{-6}$ M$_\odot$ yr$^{-1}$ |
| Terminal wind speed | $v_\infty$ | $2 \times 10^8$ cm s$^{-1}$ |
| $\beta$-*law* exponent | $\hat{\beta}$ | 0.8 |
| Jet luminosity | $L_{\rm j}$ | $5 \times 10^{36}$ erg s$^{-1}$ |
| Non-thermal energy fraction | $\eta_{\rm NT}$ | 0.1 |
| Acceleration efficiency | $\eta_{\rm acc}$ | 0.1 |
| Jet half-opening angle | $\theta_{\rm j}$ | 0.1 rad |
| Orbital separation | $a$ | $3 \times 10^{12}$ cm |
| Orbital period | $T$ | 4 days |
| Distance to the observer | $d$ | 3 kpc |
| Jet Lorentz factor | $\gamma_{\rm j}$ | 1.2 , 3 |
| Magnetic pressure fraction | $\eta_B$ | $10^{-4}$ , $10^{-2}$ , 1 |
| System inclination | $i$ | $0^\circ$ , $30^\circ$ , $60^\circ$ |

# Energy losses

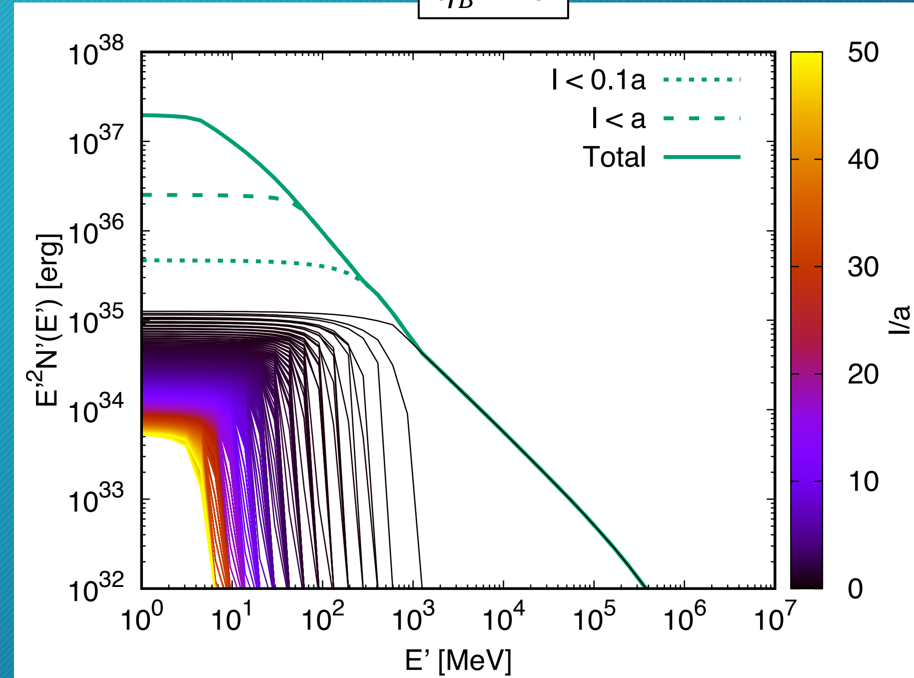


# Particle distribution

$\eta_B = 10^{-2}$

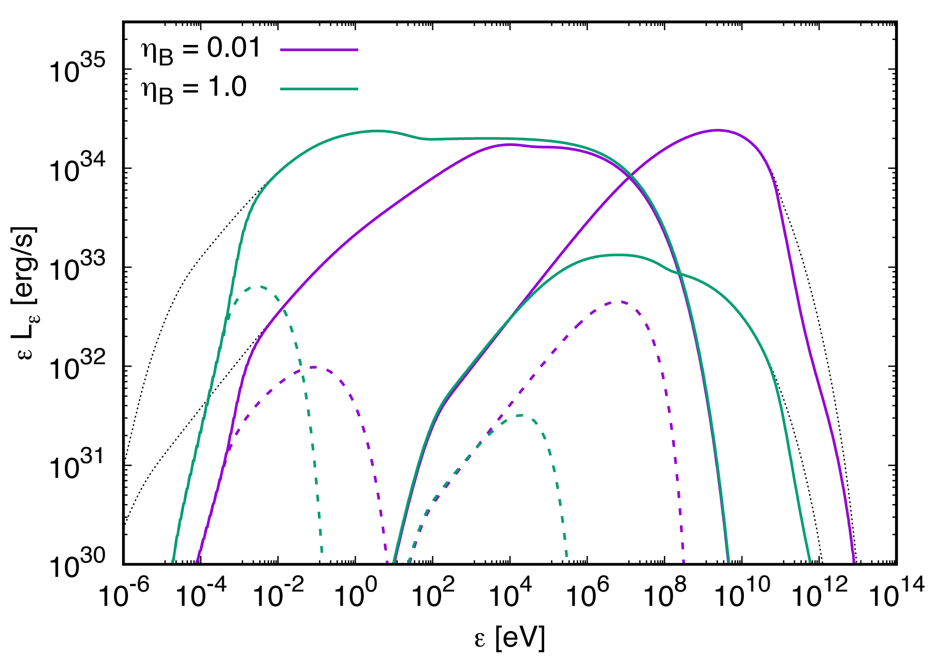



$\eta_B = 1$

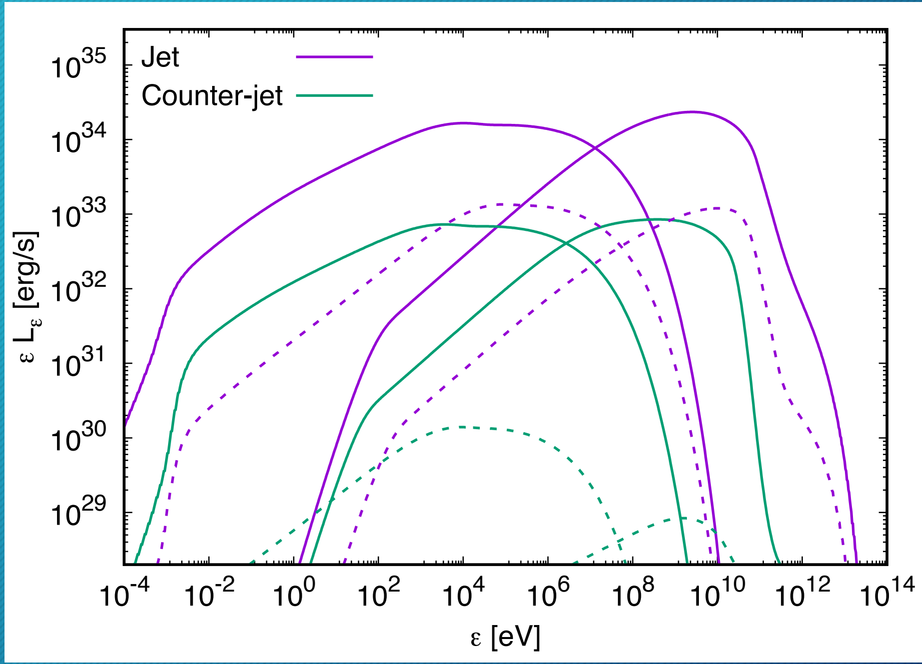


# SEDs

i = 30º



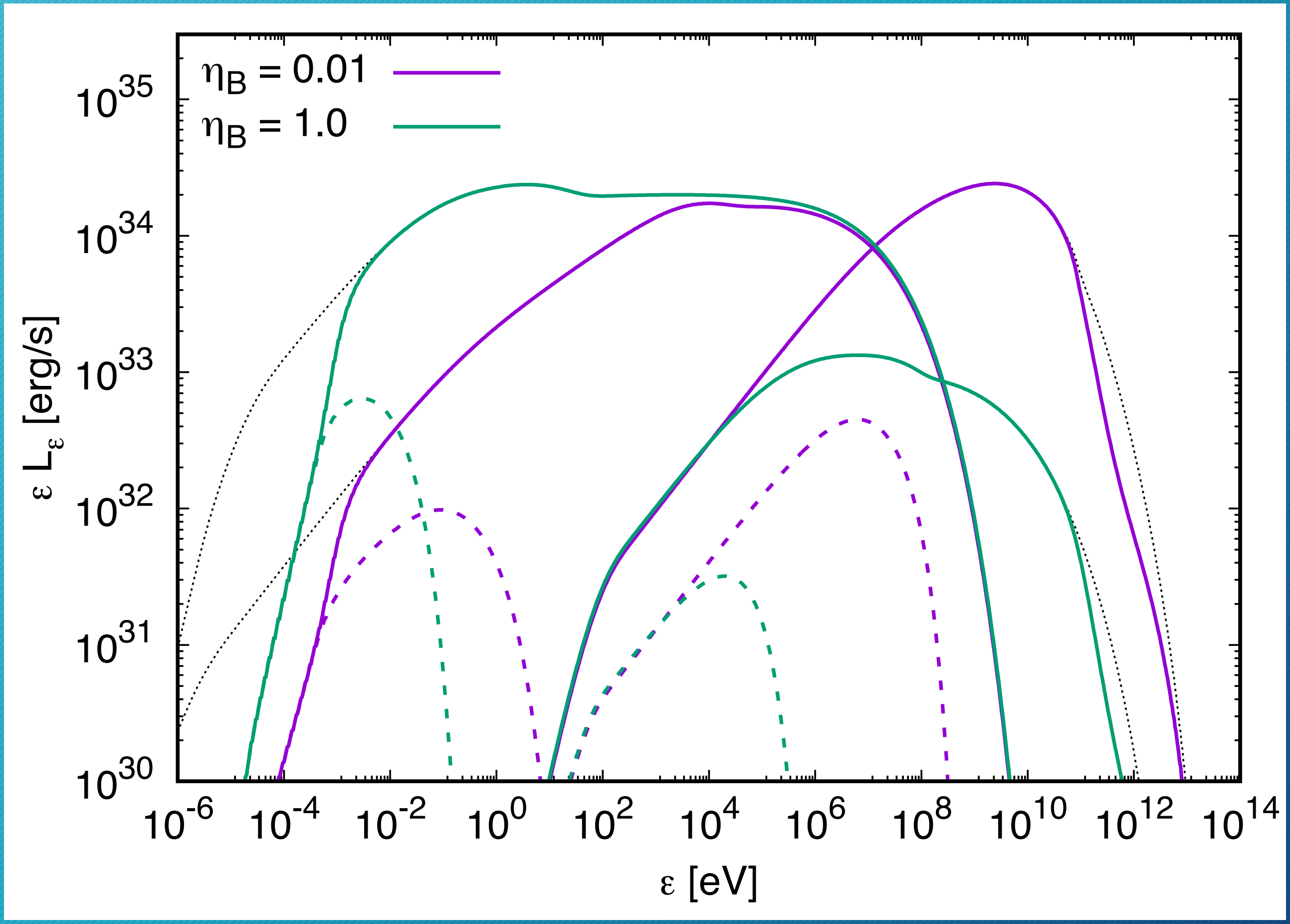
$\eta_B$ = 0.01
$\eta_B$ = 1.0
$10^{35}$
$10^{34}$
$10^{33}$
$10^{32}$
$10^{31}$
$10^{30}$
ε L_ε [erg/s]
$10^{-6}$ $10^{-4}$ $10^{-2}$ $10^{0}$ $10^{2}$ $10^{4}$ $10^{6}$ $10^{8}$ $10^{10}$ $10^{12}$ $10^{14}$
ε [eV]

Jet
Counter-jet
$10^{35}$
$10^{34}$
$10^{33}$
$10^{32}$
$10^{31}$
$10^{30}$
$10^{29}$
ε L_ε [erg/s]
$10^{-4}$ $10^{-2}$ $10^{0}$ $10^{2}$ $10^{4}$ $10^{6}$ $10^{8}$ $10^{10}$ $10^{12}$ $10^{14}$
ε [eV]

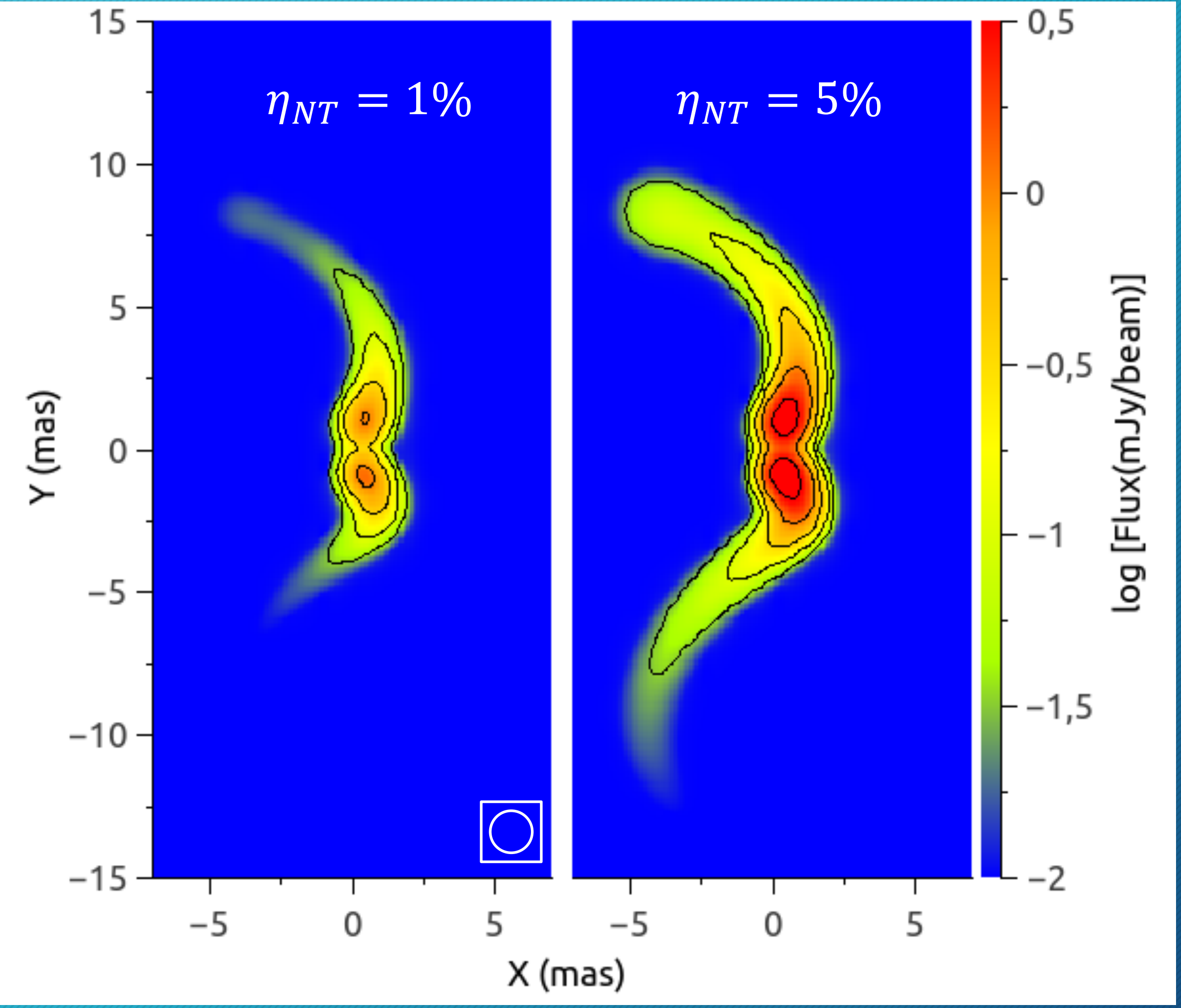
# SEDs

i = 30°



$\eta_B$ = 0.01
$\eta_B$ = 1.0
ε L_ε [erg/s]
10^35
10^34
10^33
10^32
10^31
10^30
10^-6
10^-4
10^-2
10^0
10^2
10^4
10^6
10^8
10^10
10^12
10^14
ε [eV]

# Effect of the energy fraction




Molina & Bosch-Ramon 2018