The Interaction of Microquasars with the ISM

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- MKI ($\leq$08/2006)
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The Interaction of Microquasars with the ISM

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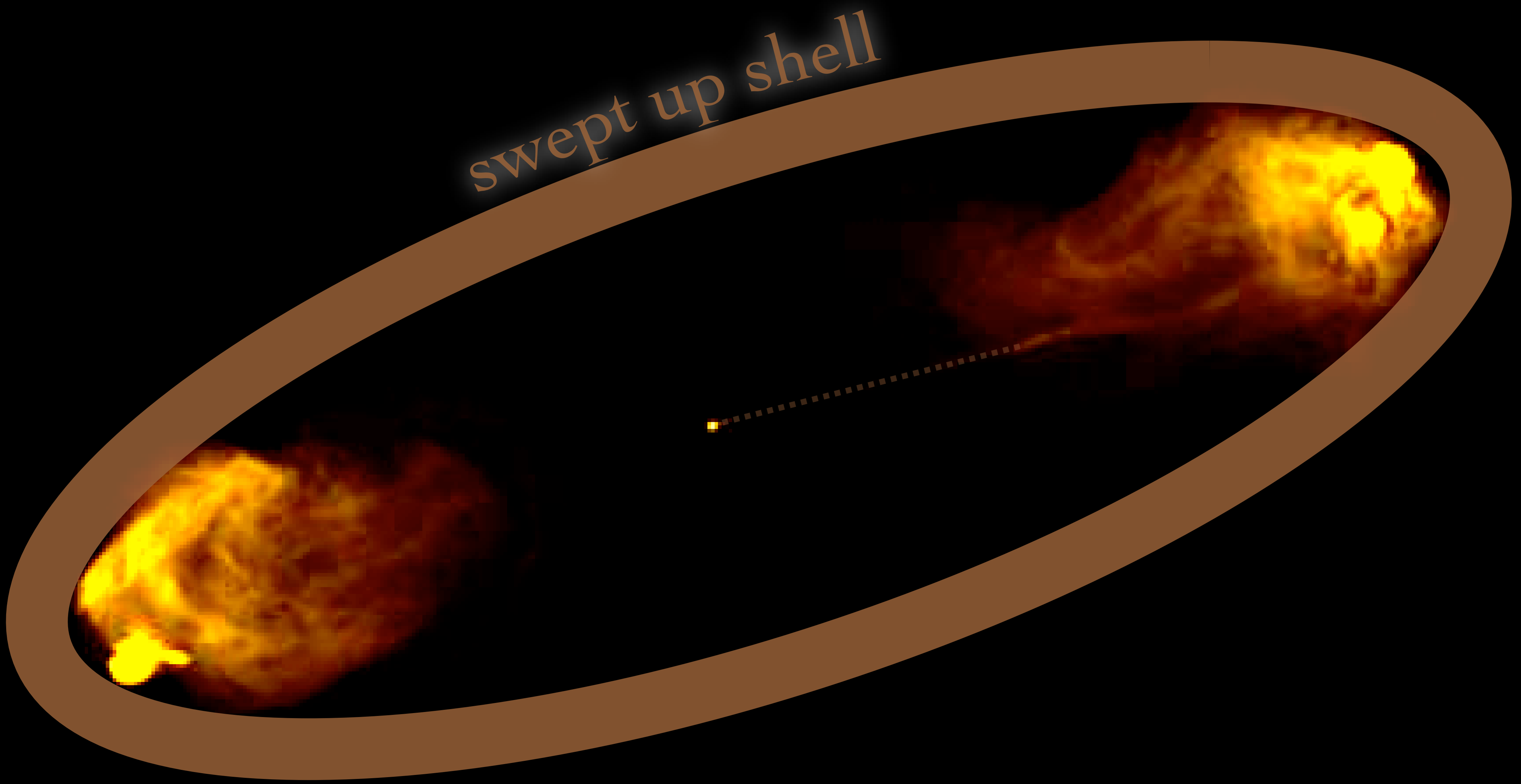
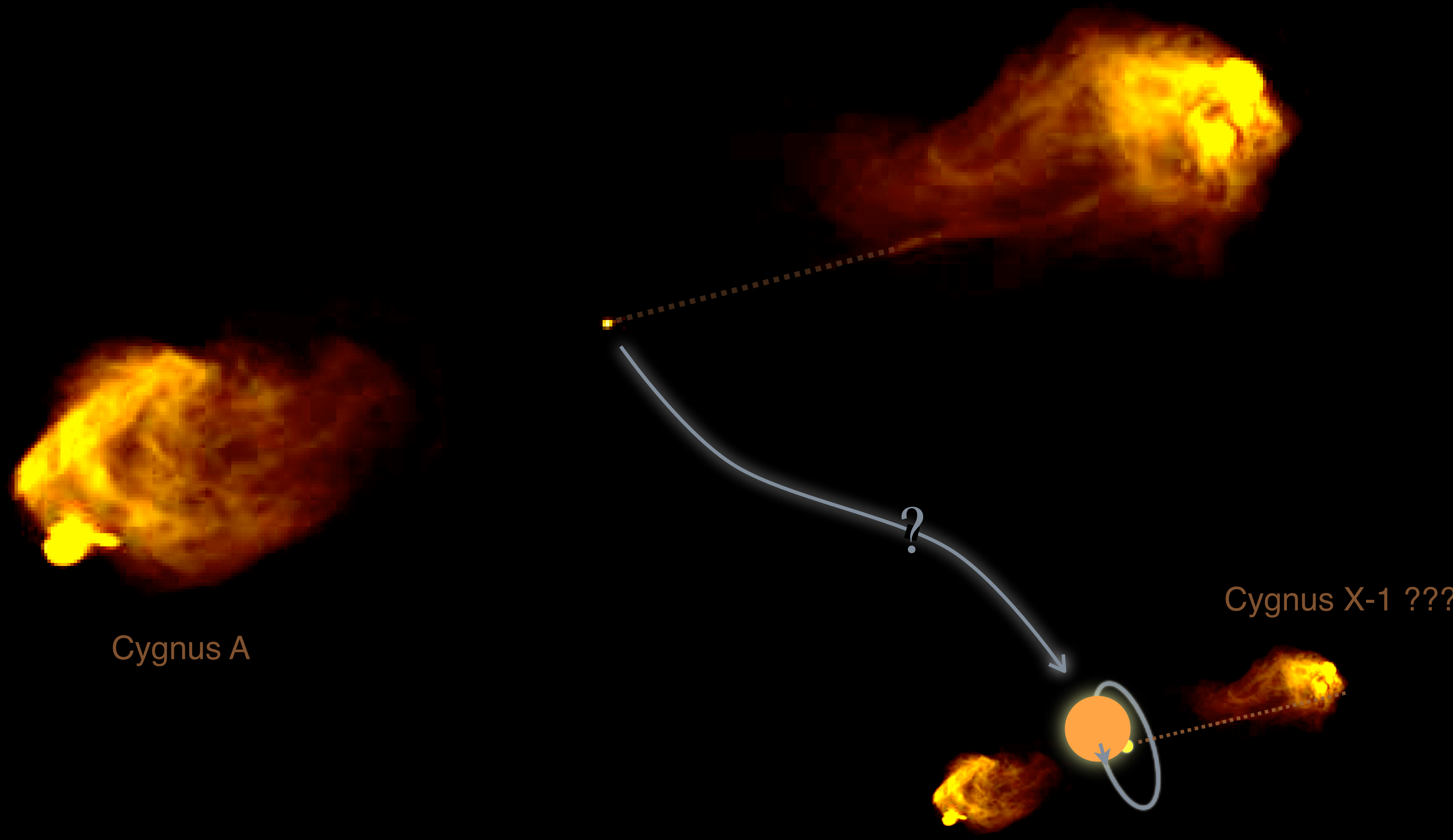
The importance of AGNjet-igm interactions

- Kinetic energy deposition into environment (feedback) can:
  - Stop cooling in gas reservoir
  - Blow away IGM – L_{kin} up to 10^{46} ergs s^{-1}
  - Disrupt accretion flow
  - Seed magnetic field/relativistic particles into environment
  - Induce large scale motions & turbulence into environment

Radio Source Dynamics



Radio Source Dynamics



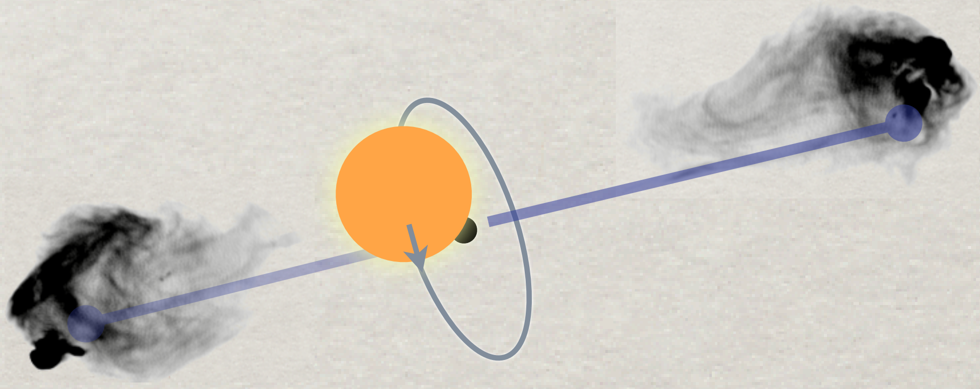
Radio Source Dynamics

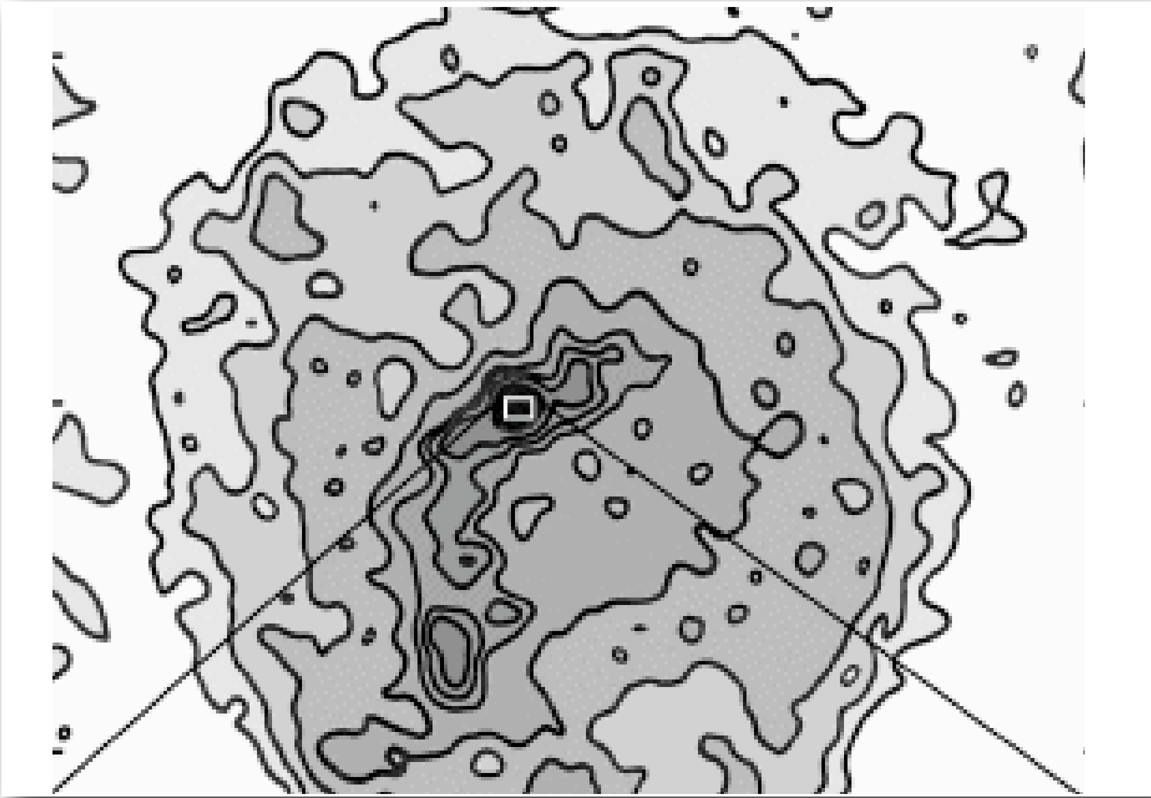
- XRBs make jets
- Jet power can be significant fraction of $L_{\rm Edd}$
- XRB jets must run into the ISM
- What happens then?
  - Radio lobes
  - Thermal shells
  - Hot spots (termination shocks)

Lobes

Looking for Lobes in All the Right Places

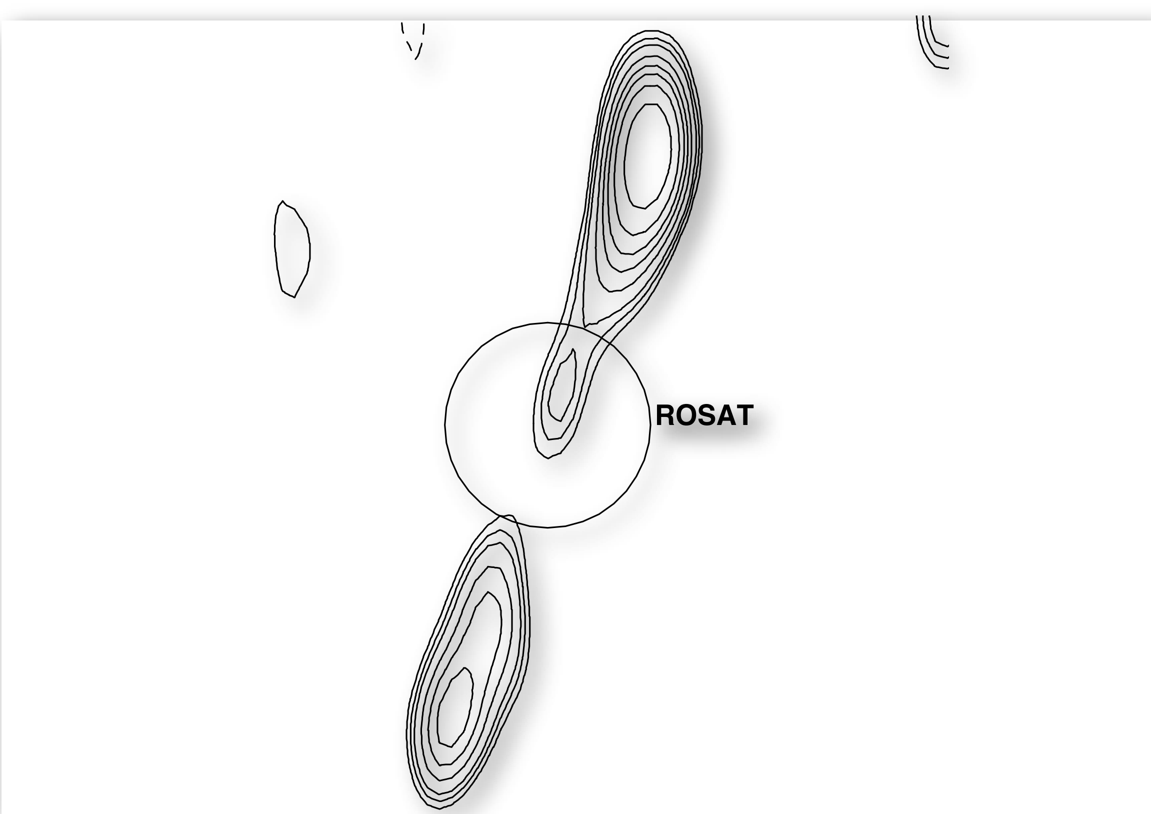
- "*Microquasar*" radio lobes:
  - Do they exist?
  - Are they detectable?
- Probes of jet physics & environment
  - Calorimeters
  - Chronometers
  - Particle sources
- Impact on the Galaxy:
  - Cosmic rays
  - Magnetic field



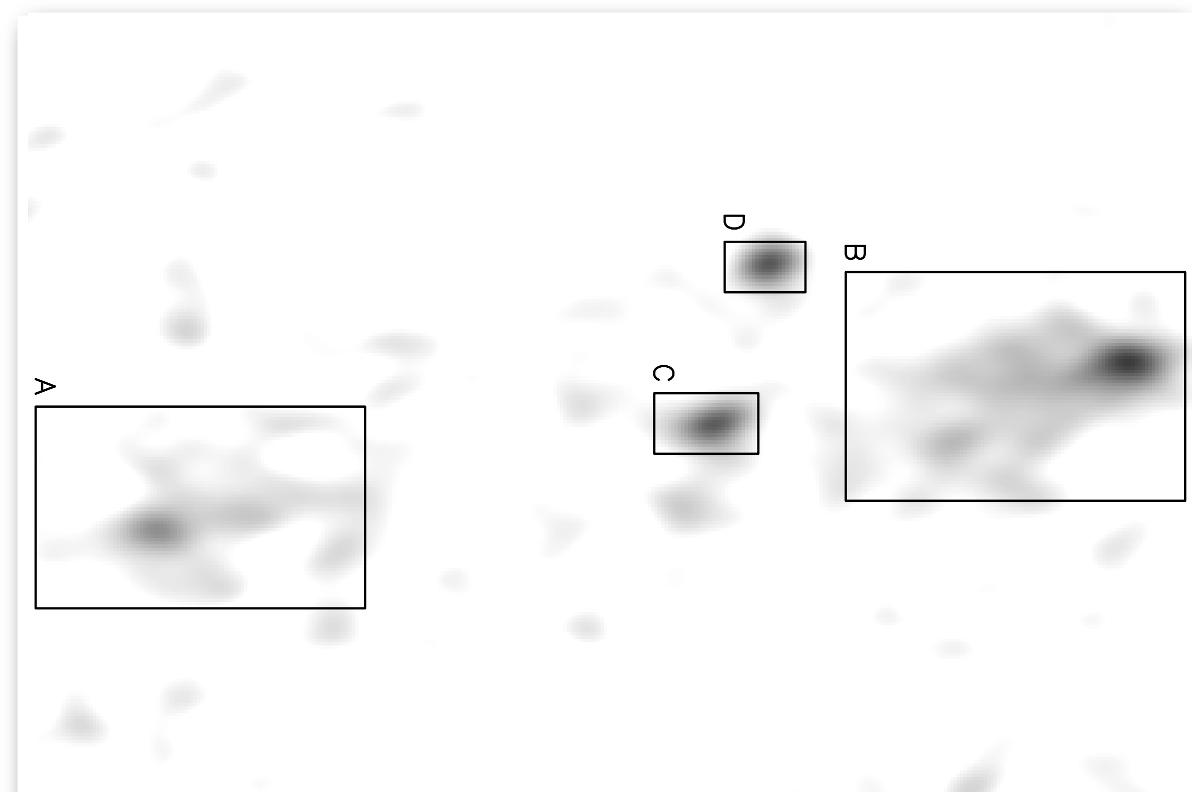


Circinus X-1 (Fender et al. 1999)

SS433 (Dubner et al. 1998)



1E1740.7-2942 (Mirabel et al. 1992)

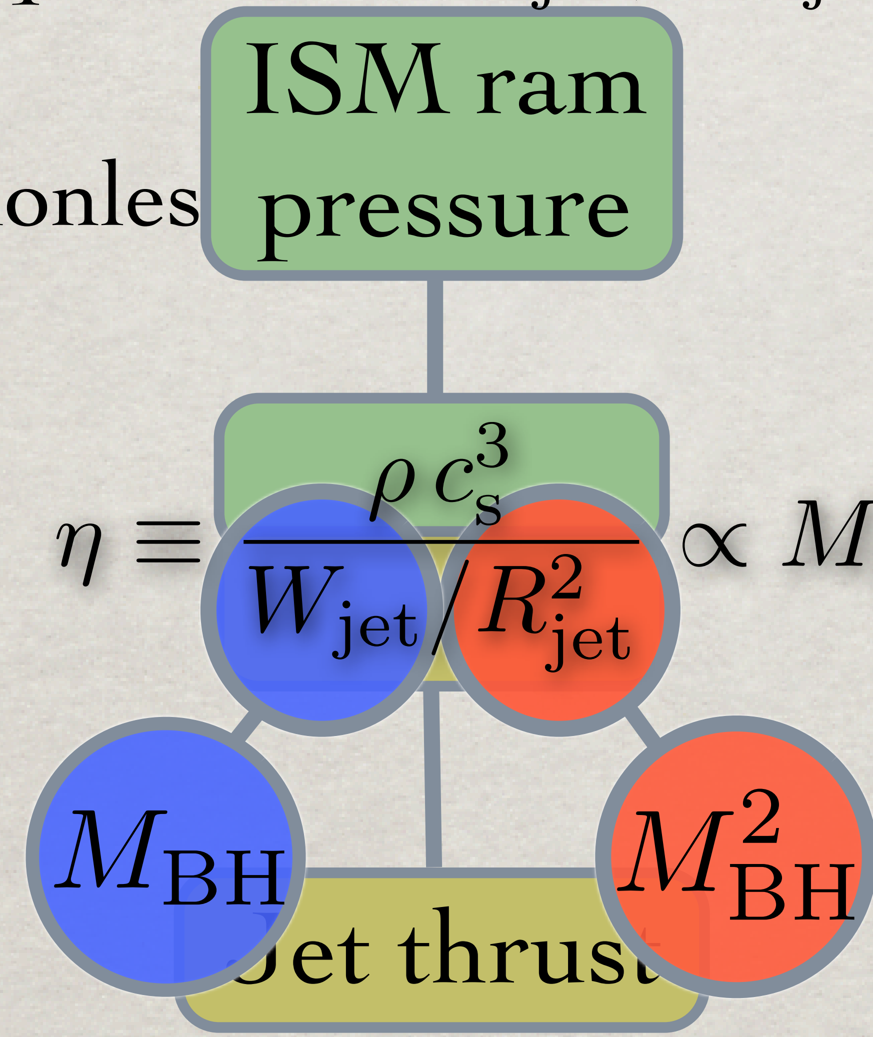


GRS 1758-258 (Hardcastle 2005)

Looking for Lobes in All the Right Places

- Critical quantities: $W_{\rm jet}, \quad R_{\rm jet}, \quad p_{\rm ext}, \quad \rho_{\rm ext}$

- Dimensionles



$$\eta \equiv \frac{\rho\, c_{\rm s}^3}{W_{\rm jet}/R_{\rm jet}^2} \propto M_{\rm BH}\, p\, c_{\rm s}$$

Heinz 2002

Looking for Lobes in All the Right Places

- Critical quantities: $W_{\rm jet}, \quad R_{\rm jet}, \quad p_{\rm ext}, \quad \rho_{\rm ext}$
- Dimensionless number:

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- η the same **only** if $p_{\rm ext} c_{\rm ext} M_{\rm BH} = const.$

Heinz 2002

Looking for Lobes in All the Right Places

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- η the same **only** if $p_{\rm ext} c_{\rm ext} M_{\rm BH} = const.$
- But: $(p\, c_{\rm s}\, M)_{\rm AGN} > 10^4\, (p\, c_{\rm s}\, M)_{\rm XRB}$

Heinz 2002

Looking for Lobes in All the Right Places

- $\eta_{XRB} < 10^{-4}\,\eta_{AGN}$
- XRB environment (ISM):

  low pressure, low density compared to AGN environment (IGM)
- XRB radio lobes must be **larger** relative to r_g
- XRB radio lobes must be **dimmer**

Heinz 2002

Looking for Lobes in All the Right Places

- Radio lobe size:

$$R \approx 10\,\mathrm{pc} \left(\frac{\langle W \rangle}{10^{36}\,\mathrm{ergs\,s^{-1}}} \frac{1\,\mathrm{cm^{-3}}}{n_{\mathrm{ISM}}}\right)^{0.2} \left(\frac{t_{\mathrm{age}}}{10^5\,\mathrm{yrs}}\right)^{0.6}$$

$\approx 2 \times 10^{13}\, r_{\mathrm{g}}$

Heinz 2002

Looking for Lobes in All the Right Places

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- Radio luminosity:

$$L_{5\mathrm{GHz}} \approx 1\,\mathrm{Jy}\left(\frac{\langle W\rangle}{10^{36}\,\mathrm{ergs\,s^{-1}}}\right)^{1.3}\left(\frac{t_{\mathrm{age}}}{10^{5}\,\mathrm{yrs}}\right)^{0.4}\left(\frac{n_{\mathrm{ISM}}}{1\,\mathrm{cm^{-3}}}\right)^{0.45}\left(\frac{10\,\mathrm{kpc}}{D}\right)^{2}$$

Heinz 2002

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- Surface brightness:

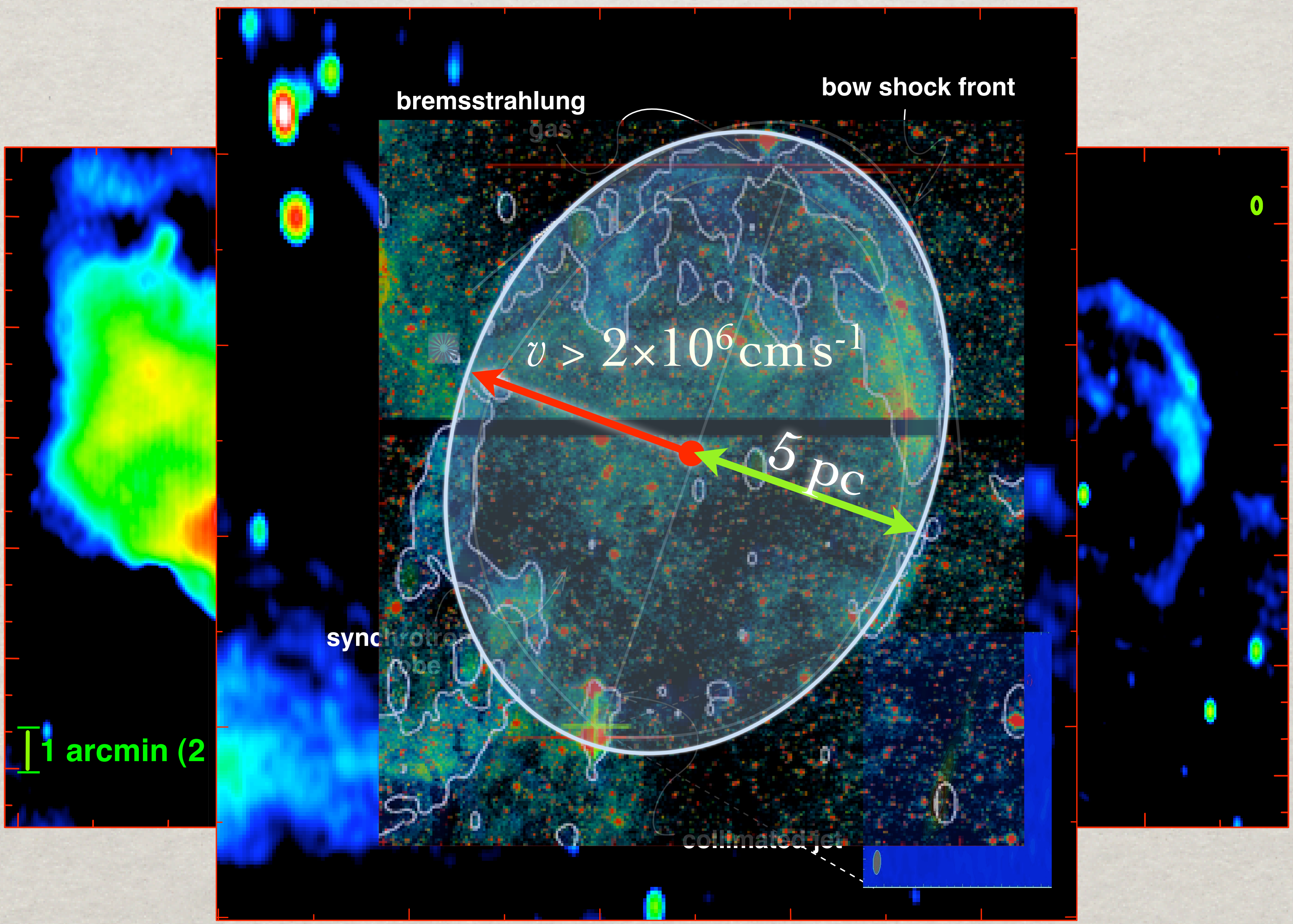
$$T_{\mathrm{B}} \approx 50\,\mathrm{mK}$$

$$S_{5\,\mathrm{GHz}} \approx \frac{20\,\mu\mathrm{Jy}}{\mathrm{arcsec^{-2}}}\left(\frac{\langle W\rangle}{10^{36}\,\mathrm{ergs\,s^{-1}}}\right)^{0.9}\left(\frac{t_{\mathrm{age}}}{10^{5}\,\mathrm{yrs}}\right)^{-0.8}\left(\frac{n_{\mathrm{ISM}}}{1\,\mathrm{cm^{-3}}}\right)^{0.85}$$

Heinz 2002

Shells

Cygnus X-1
The Ring of Fire



Gallo et al. 2005

Cygnus X-1
The Ring of Fire

- Size: 5 pc (diameter)
- Shock temperature: 10^4 K < T < 3×10^6 K
- Shock velocity: 20 km s^{-1} < v < 360 km s^{-1}
- Source age: 2×10^4 yrs < t < 3.2×10^5 yrs
- Power: 10^{36} ergs/s < W < 10^{37} ergs/s

For comparison: $L_{\rm bol} \sim 10^{37}$ ergs s^{-1}

Gallo et al. 2005

Cygnus X-1
The Ring of Fire

- VLBA jet:

Stirling et al. 2001

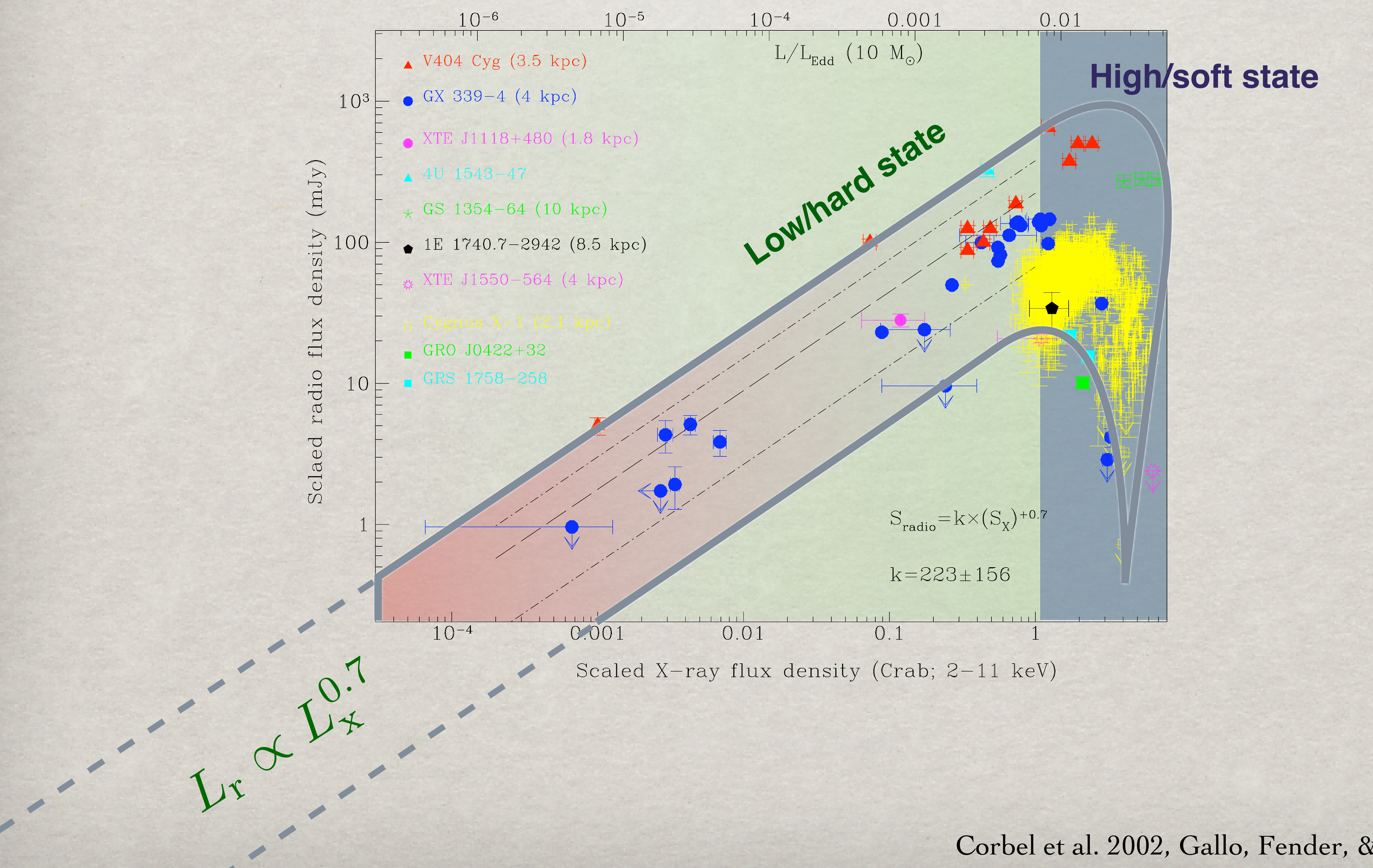
- $W_{\rm jet} \approx 2 \times 10^{33}\,{\rm ergs\,s^{-1}}\, f_{\rm p+}\, f_{\rm fill}^{-2/3}$
- $W_{\rm lobe} > 10^{36}\,{\rm ergs\,s^{-1}}$

  - Low synchrotron filling factor: $f < 10^{-4}$
  - Proton loaded jet: > 500 protons per radio electron

⇒ That explains why the cavity is not filled by radio emission

Heinz 2006

Radio-X-ray Relation



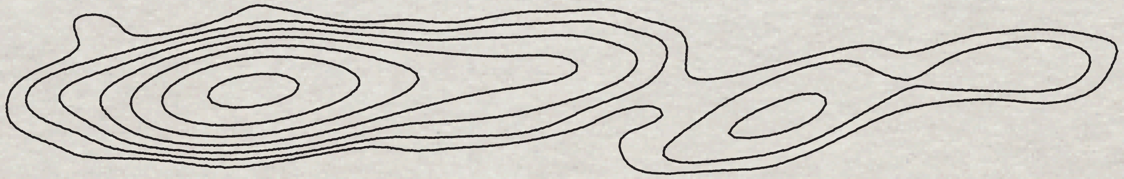
$L_r \propto L_X^{0.7}$

Corbel et al. 2002, Gallo, Fender, & Pooley 2003

Radio power vs Kinetic Power

- Jet power is related to synchrotron core luminosity as:

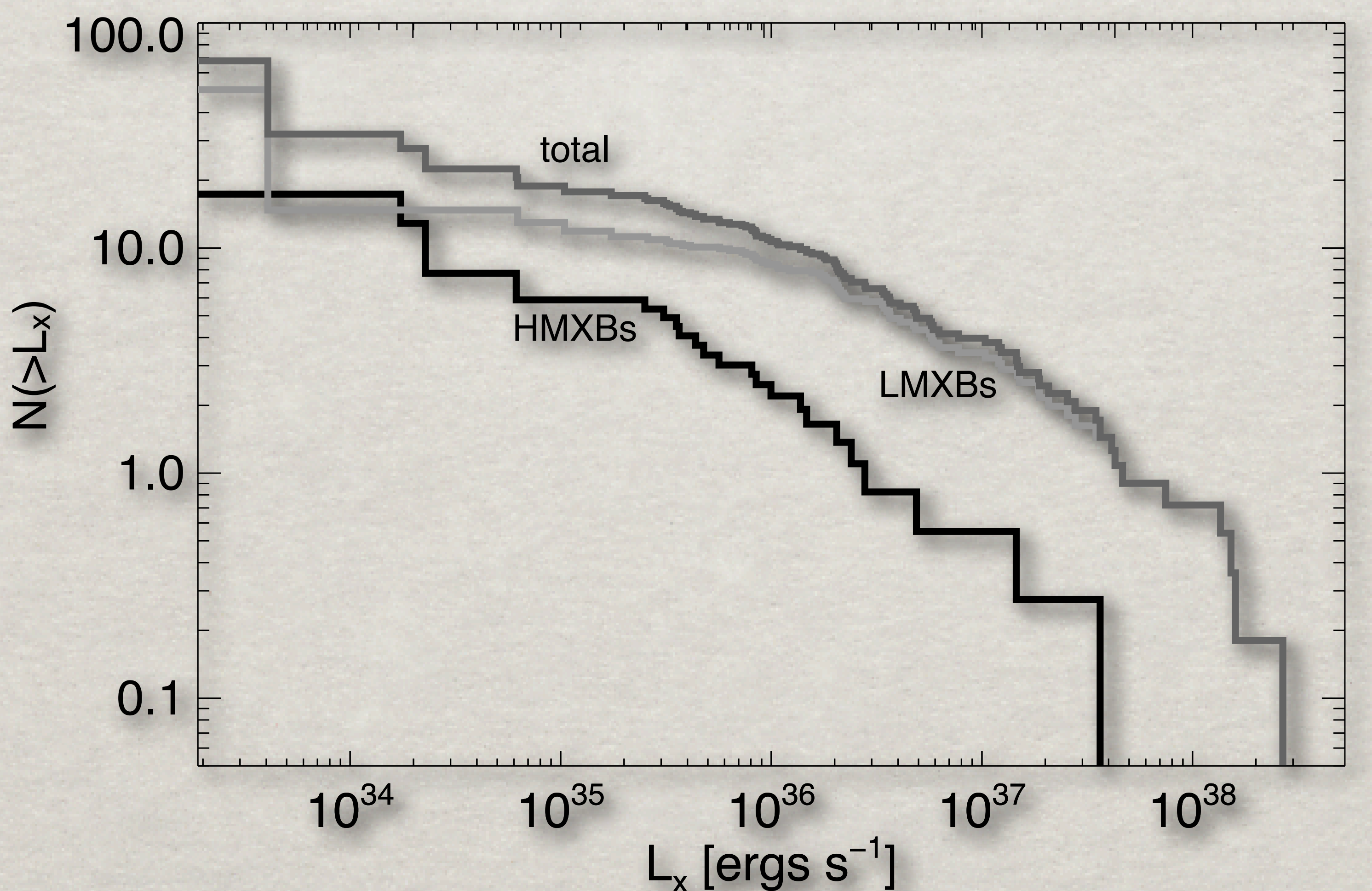
$$L_{\rm r} \propto W_{\rm jet}^{1.42+\frac{2}{3}\alpha_{\rm r}} M^{-\alpha_{\rm r}}$$



Heinz & Sunyaev 2003

Impact on the ISM

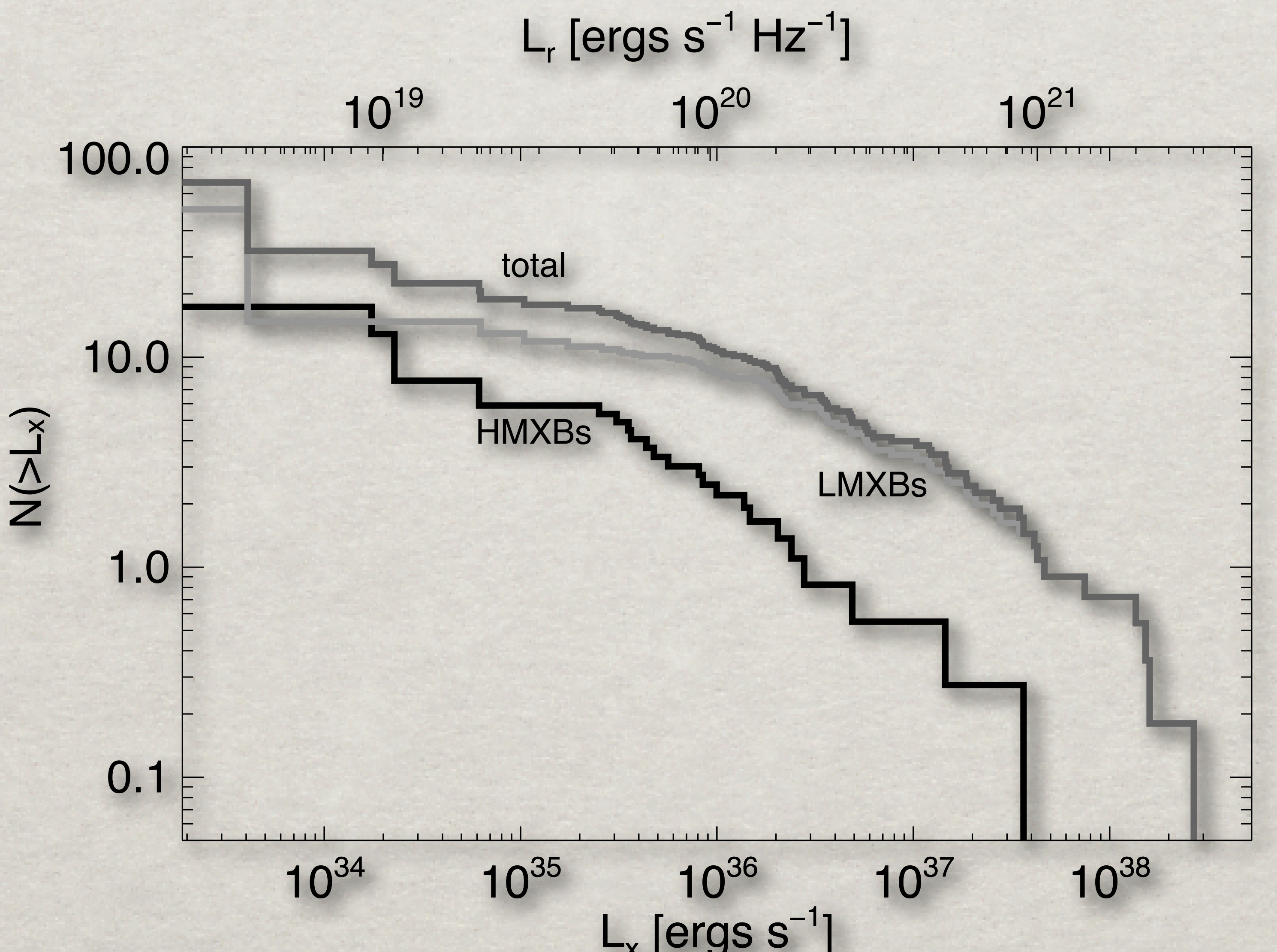
- X-ray



Grimm et al. 2004

Impact on the ISM

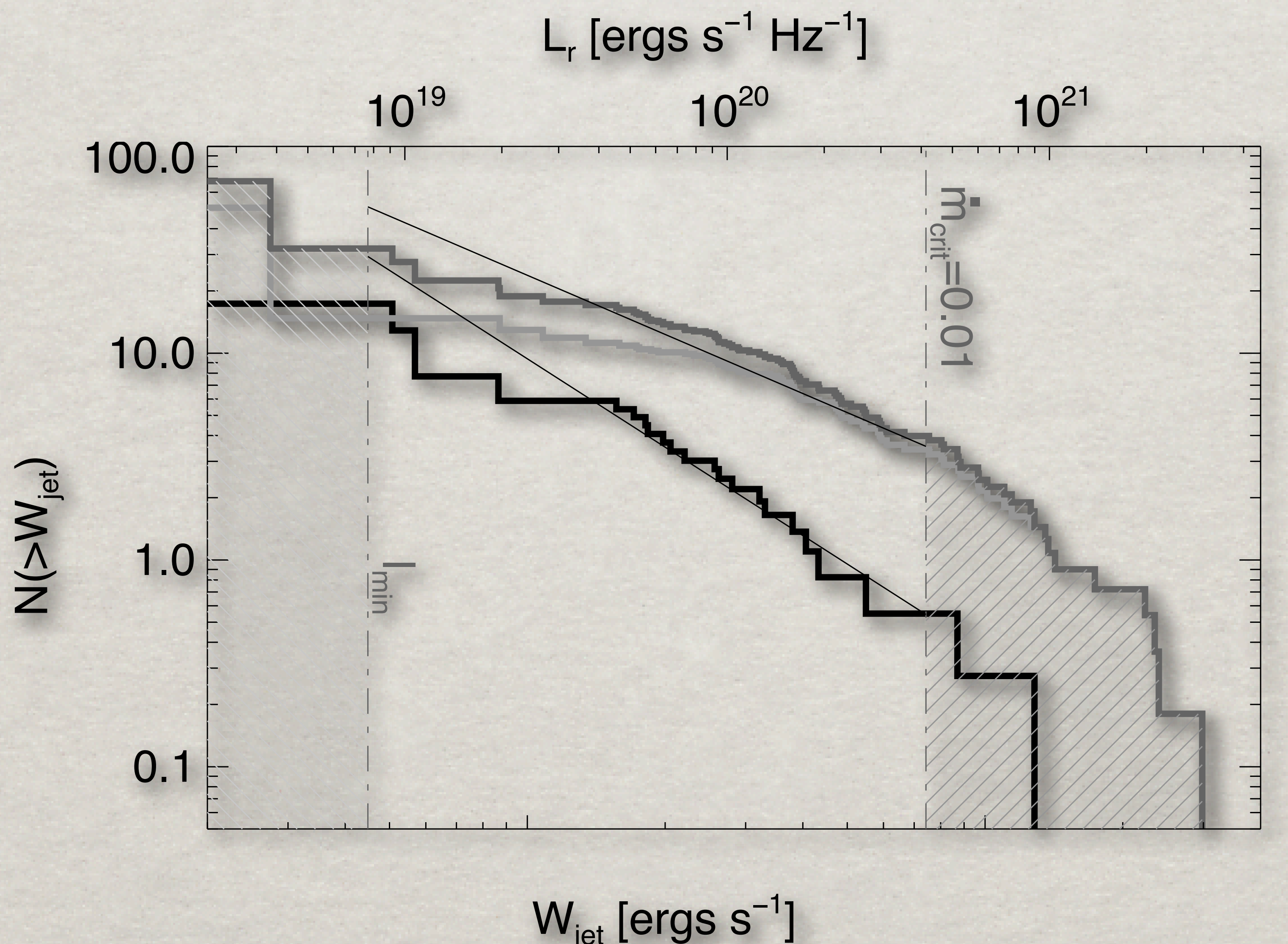
- X-ray → radio



Maccarone & Fender 2005,Heinz & Grimm 2005

Impact on the ISM

- X-ray → radio → jet power ∝ $L_x^{0.42}$



Maccarone & Fender 2005,Heinz & Grimm 2005

Impact on the ISM

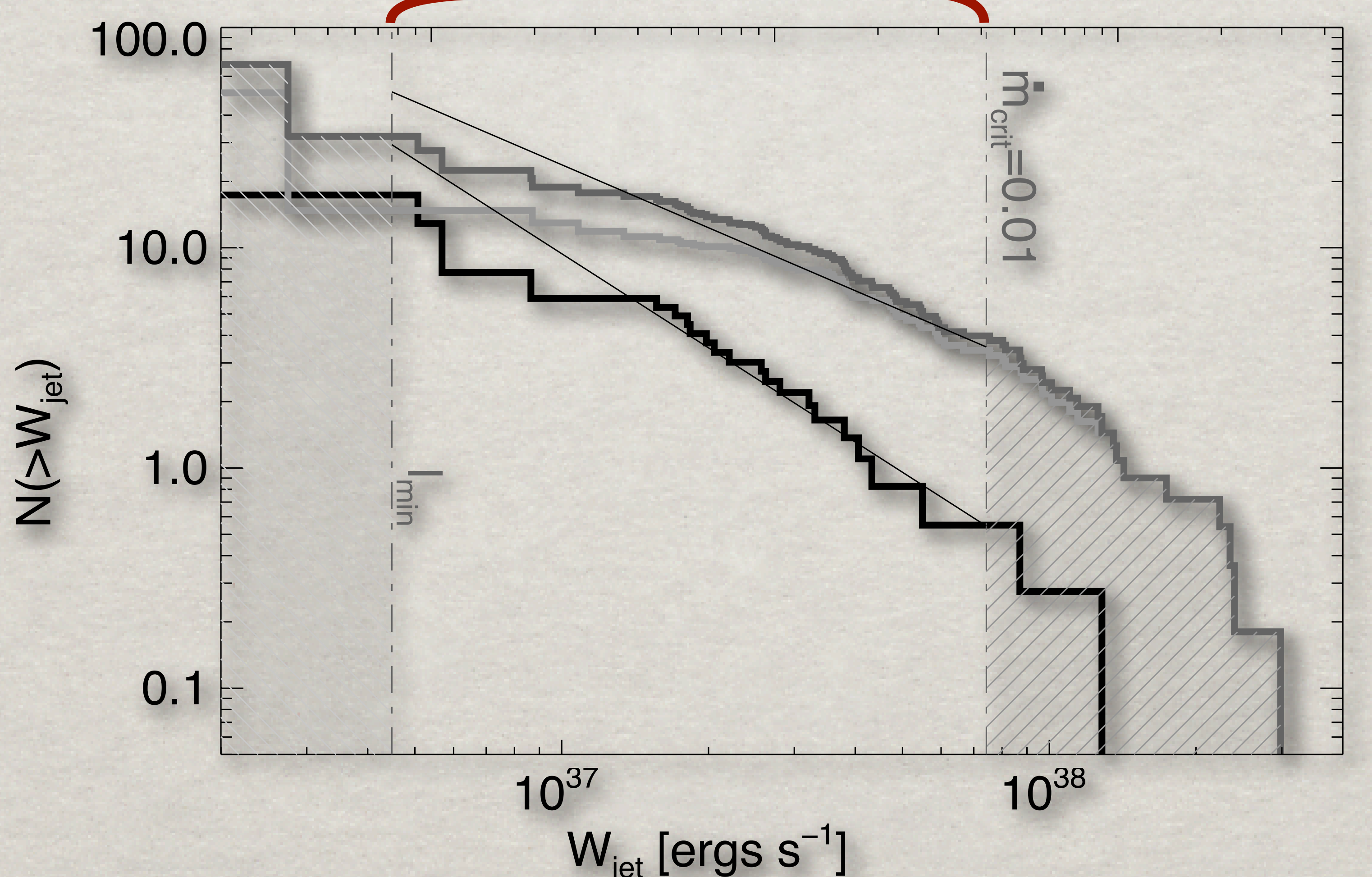
- X-ray → radio → jet power ∝ $L_x^{0.42}$

- Normalization:
  - AGN jets (M87, Cyg A, Perseus A, ...)
  - XRB radio lobes: Cyg X-1

Heinz et al. 2004, Maccarone & Fender 2005,Heinz & Grimm 2005

Impact on the ISM

$$\langle W_{\rm tot} \rangle \approx 5 \times 10^{38}\,{\rm ergs\,s^{-1}}$$



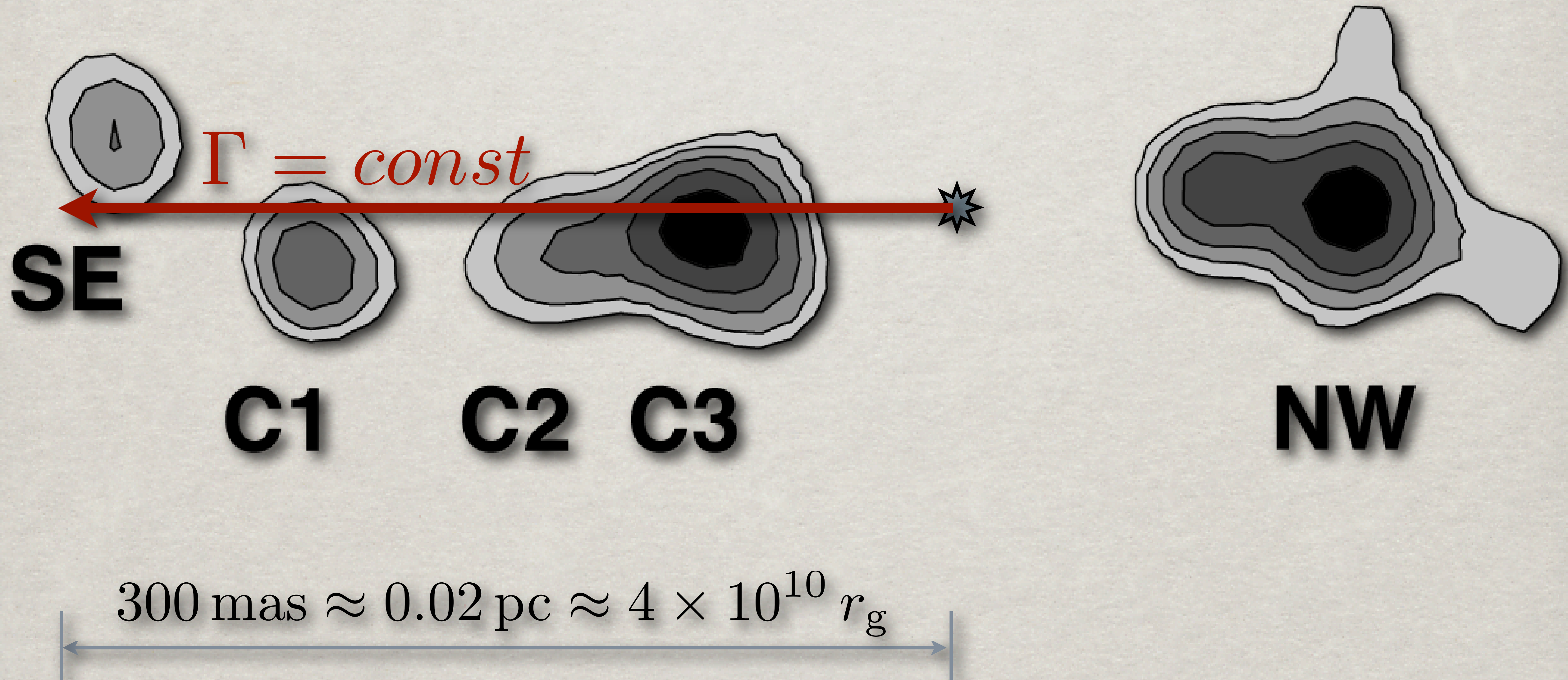
Maccarone & Fender 2005, Heinz & Grimm 2005

Jet Propagation

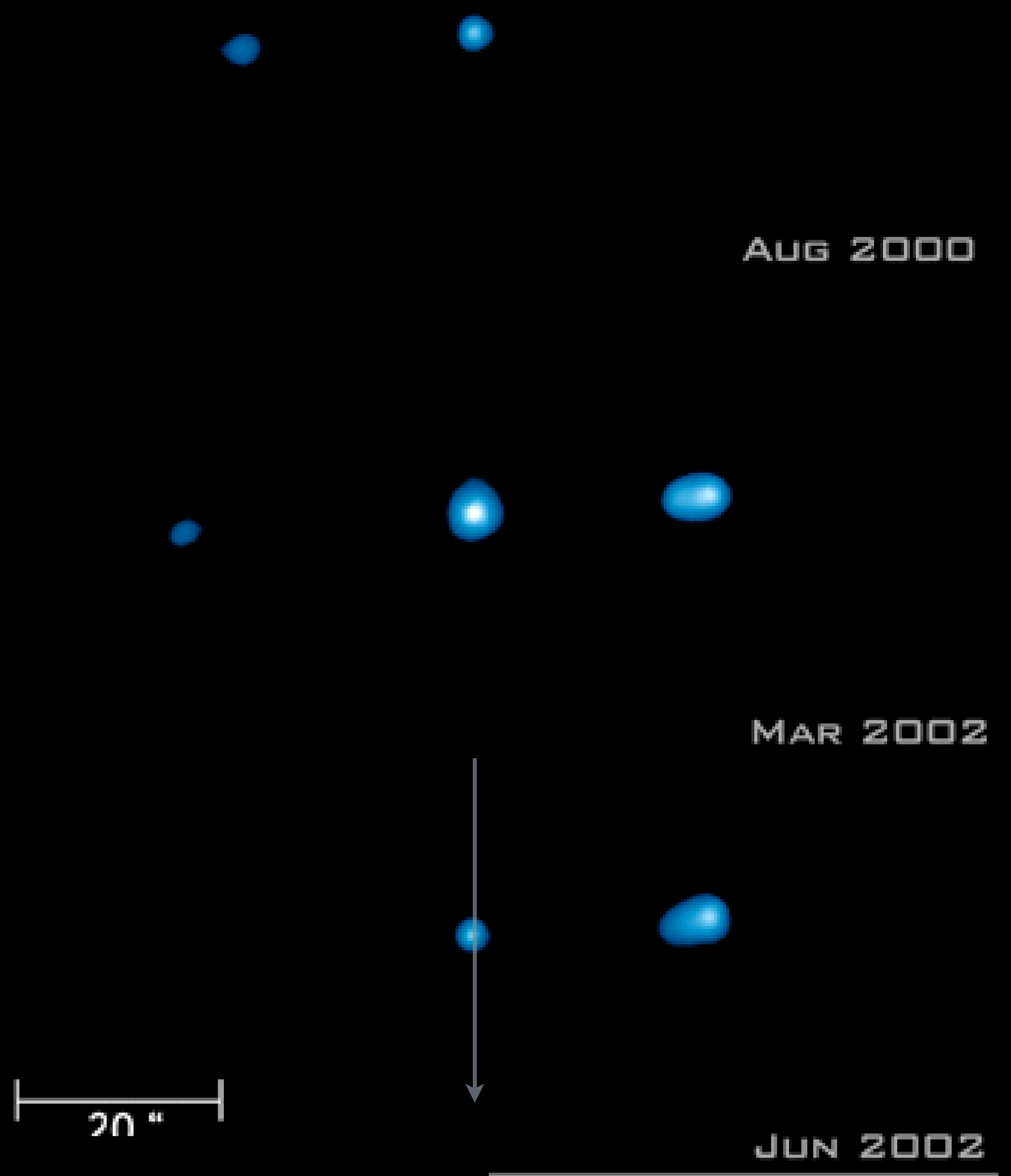
(diagnostics)

GRS 1915+105

Textbook Example of Superluminal motion



XTE J1550-564 Hots Spots



Corbel et al. 2002

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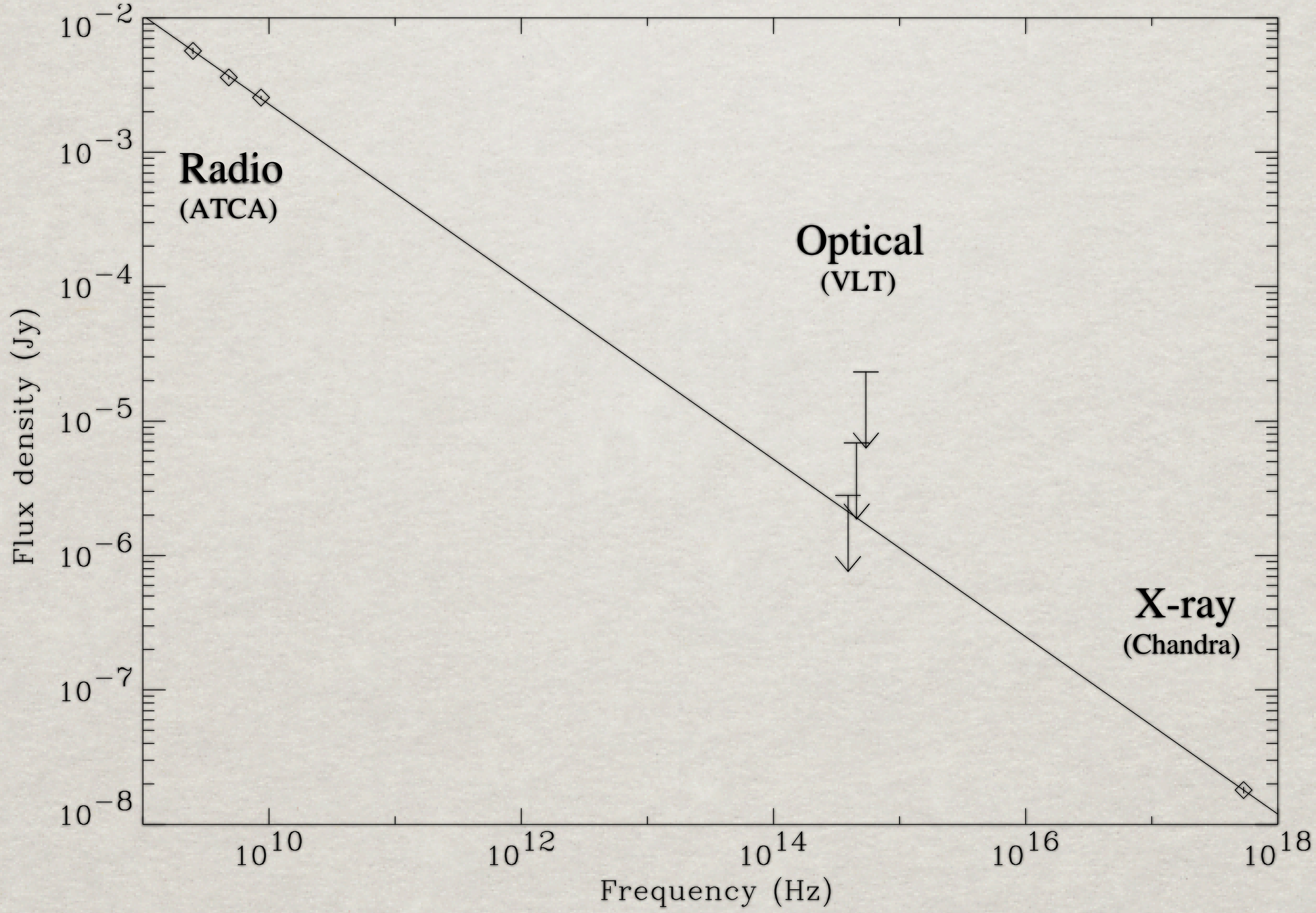

Corbel et al. 2002, Tomsick et al. 2003

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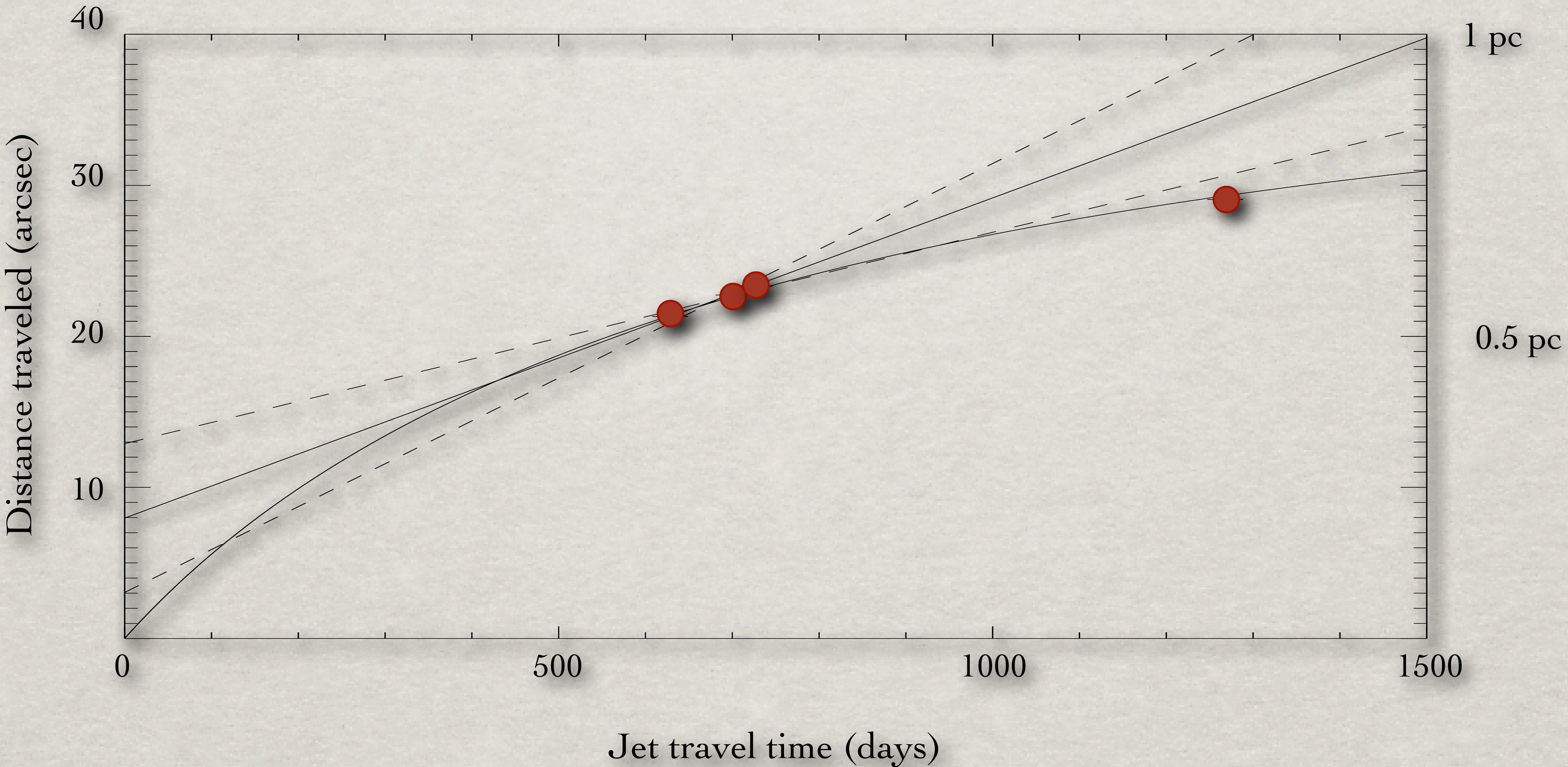
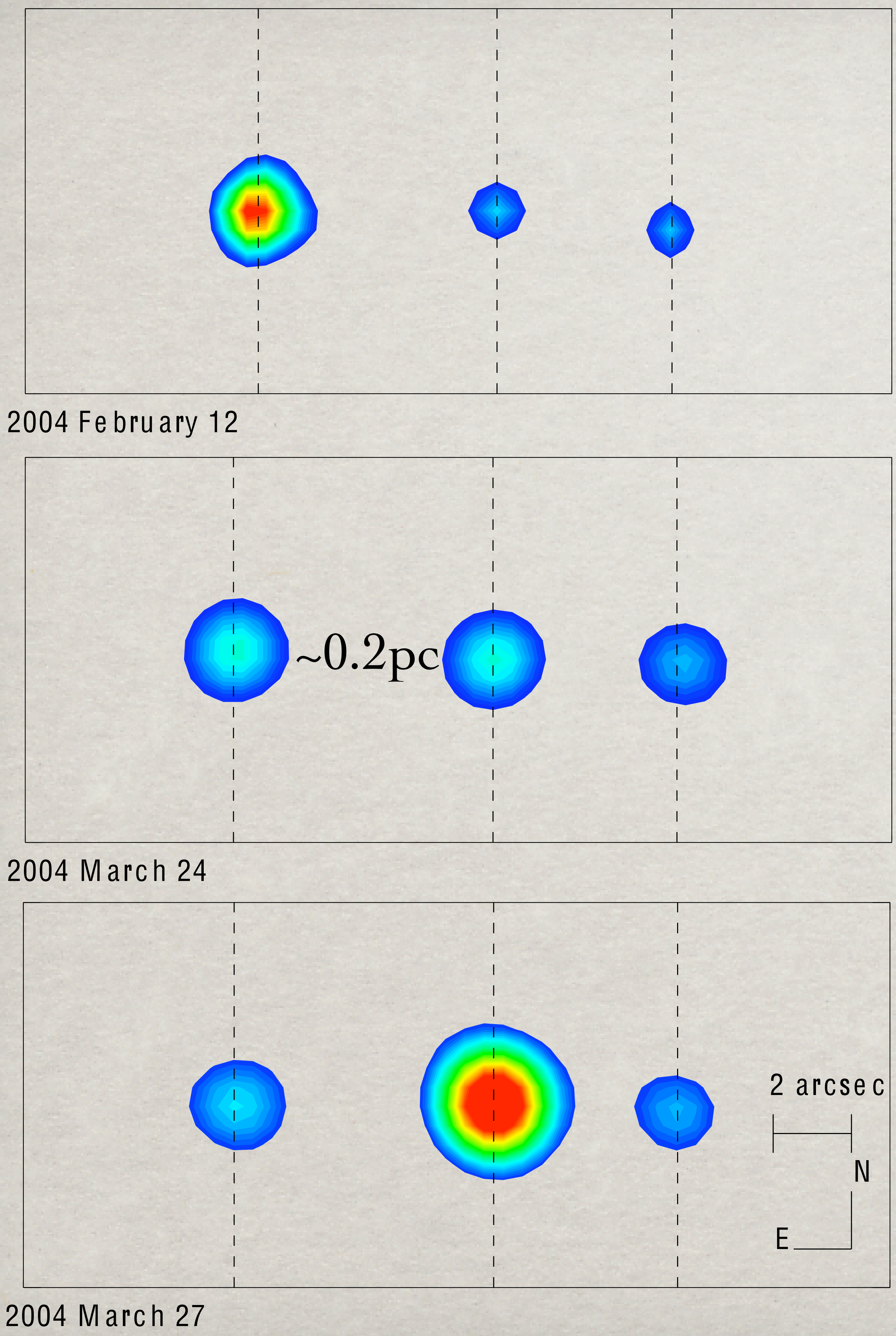
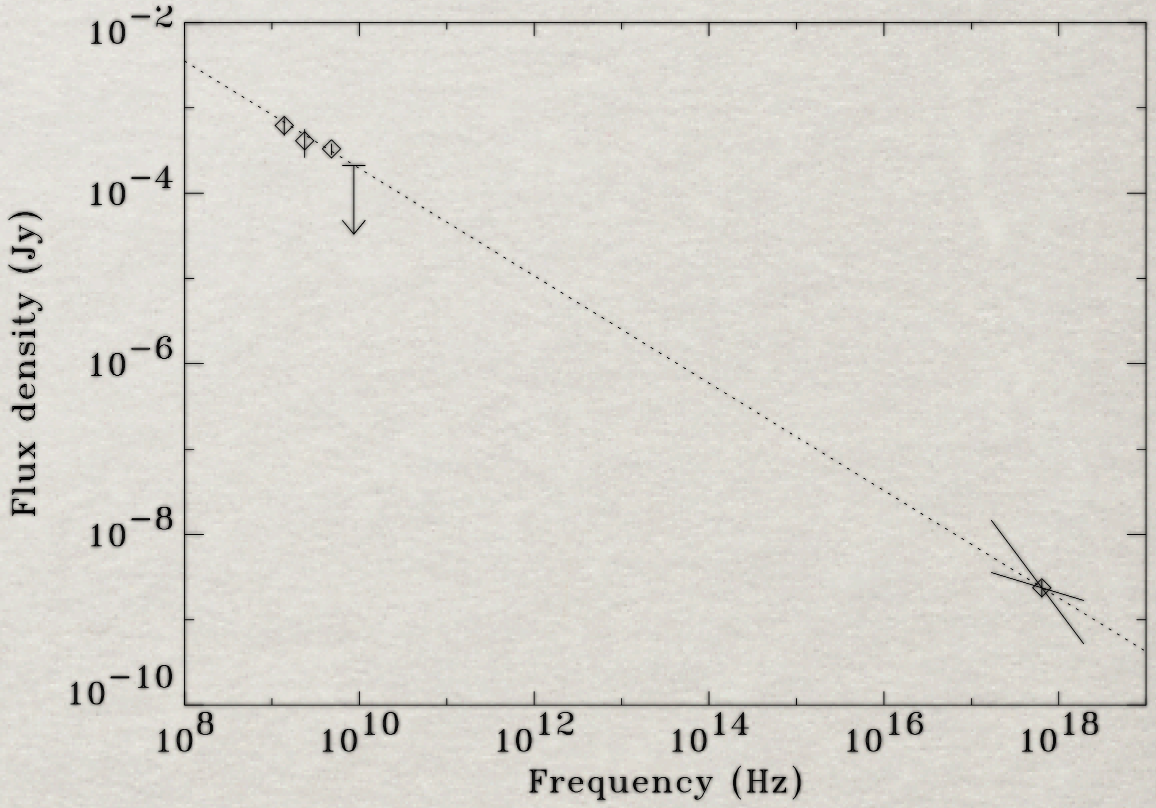


Corbel et al. 2002, Tomsick et al. 2003

1H 1743-341

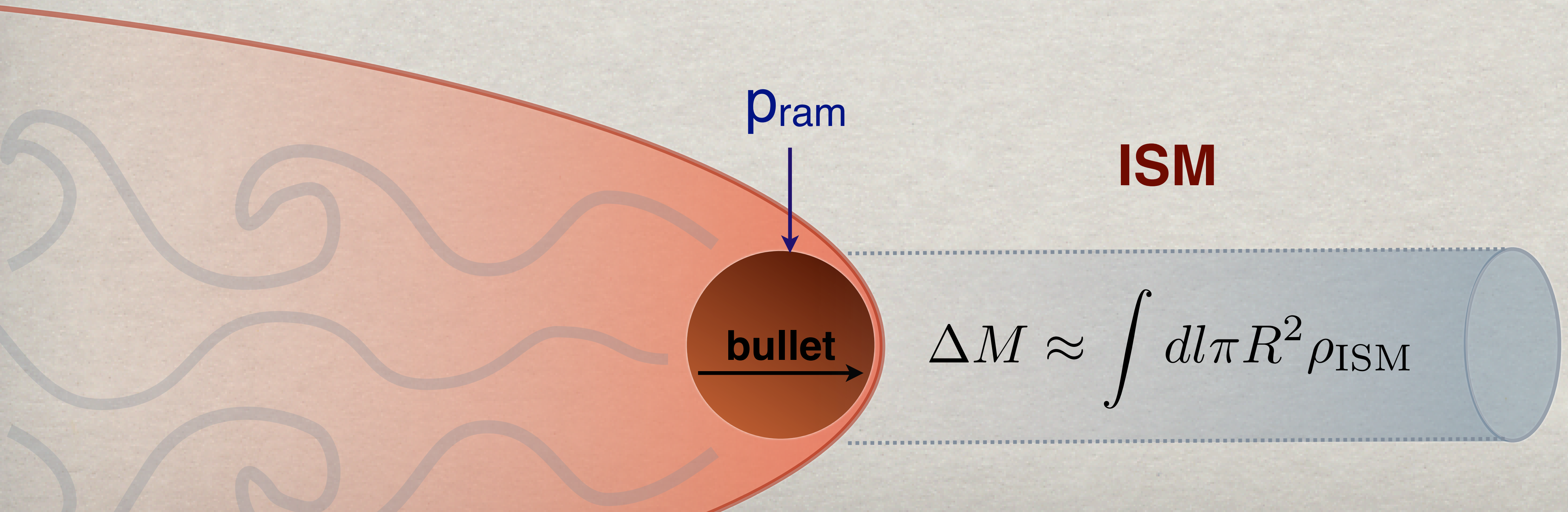




Corbel et al. 2005

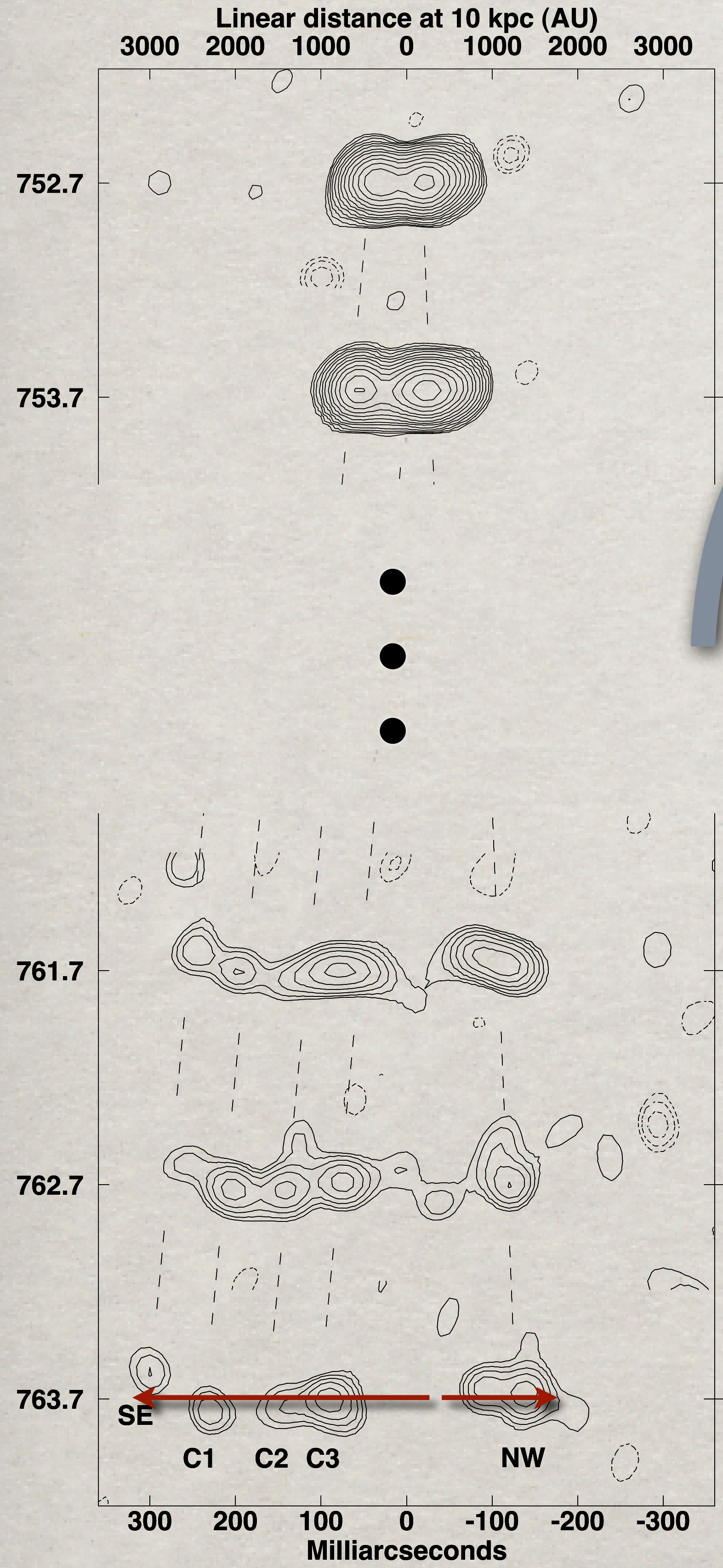
Bullet Dynamics

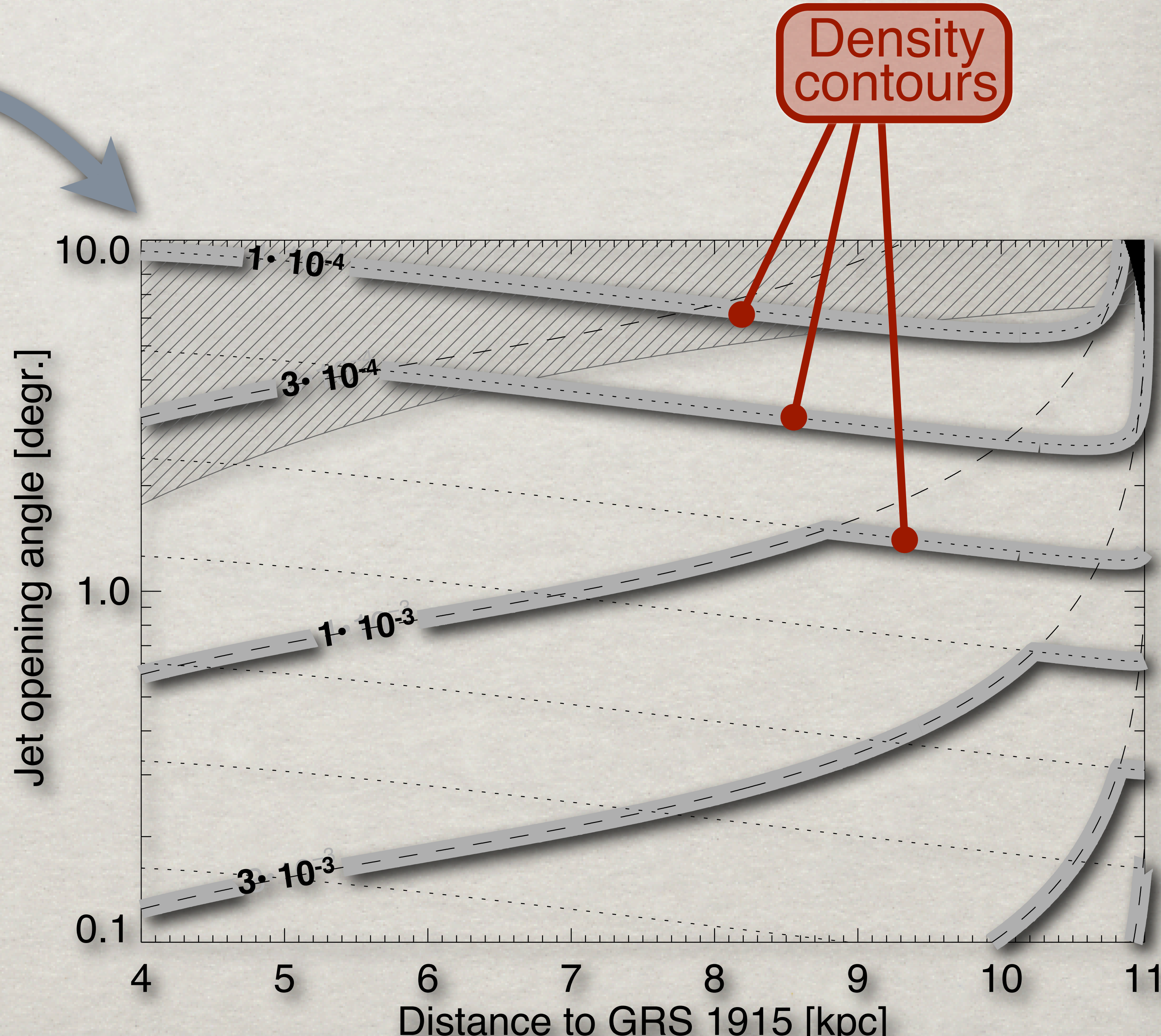
- $d\,(\beta\Gamma) = -C_{\rm d}\Gamma^2\beta c\, d\Delta M$
- Ram pressure (dynamical friction) $C_{\rm d} \approx 1/3$
- Ram pressure confinement: $p_{\rm b} \approx p_{\rm ram}$



Heinz & Aloy 2006

GRS 1915+105

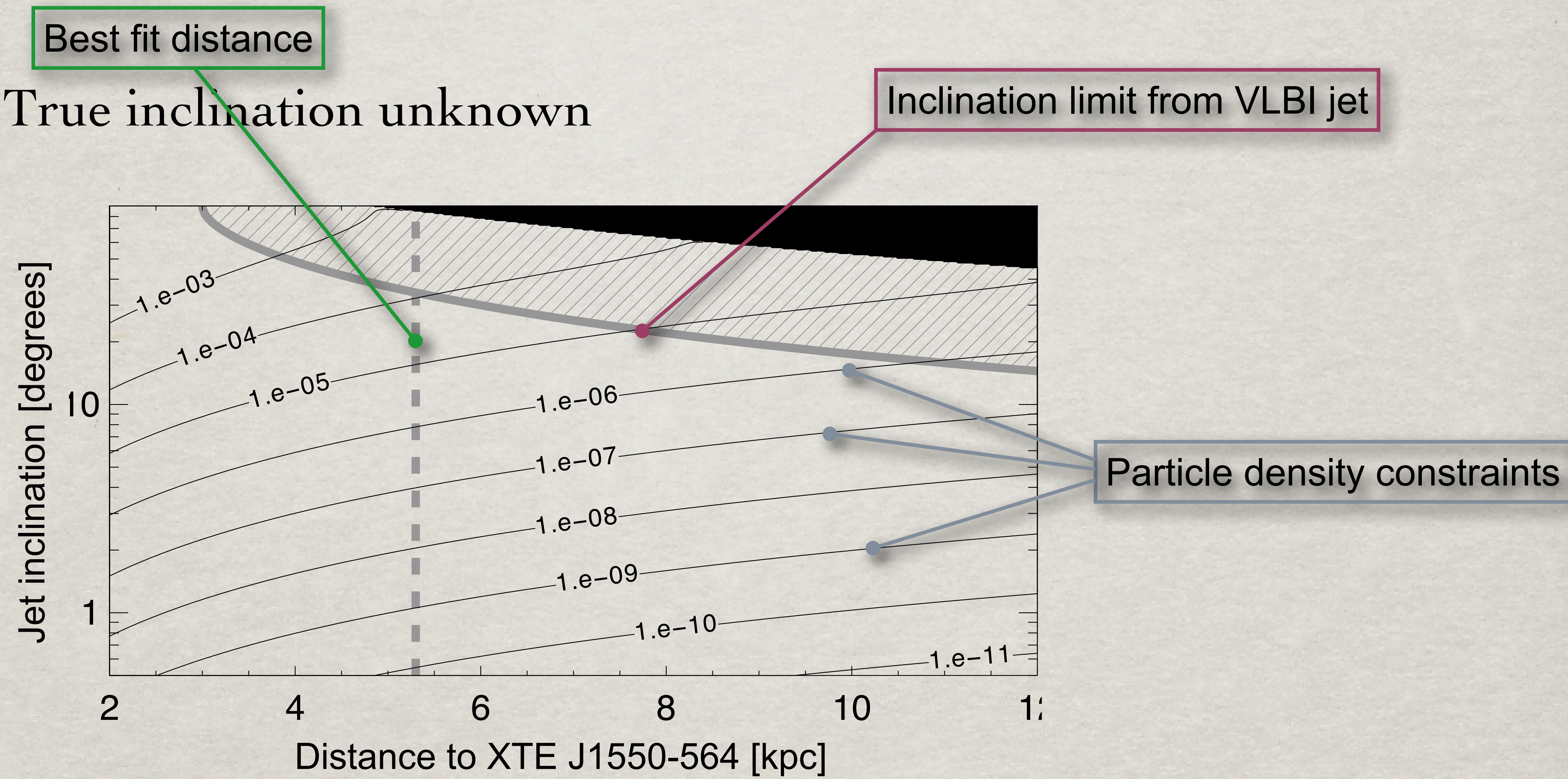




Heinz & Aloy 2006

XTE J1550-564

- True inclination unknown



- Implication: **low** density environment ... $n < 10^{-4}\ \mathrm{cm}^{-3}\ \alpha_{1^\circ}^{-2}$

Heinz & Aloy 2006

XTE J1550-564

- For jets in GRS 1915+105, XTE J1550-564, GRO J1655-40:

- Unless microquasar jet opening angles are pathologically small:

These jet must have excavated dark radio lobes

Heinz & Aloy 2006

Summary

- Wrt. the ISM, microquasars do the same things AGN jets do - qualitatively
- The ISM provides a much weaker barrier against the jet thrust
  - Thus: XRB lobes are bigger and dimmer
- Analysis of shocked shells (e.g., Cyg X-1) powerful diagnostic
  - Jet power: $\langle W_{\rm tot} \rangle \approx 5 \times 10^{38}\,{\rm ergs\,s^{-1}}$
  - Composition: > 500 protons per radio electron
- Jet propagation into ISM: decelerating hot spots
  - dynamical probes of environment:
  - fossil radio lobes (like in AGNs)