Connections between Radio and High Energy Emission in AGN

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Motivation:

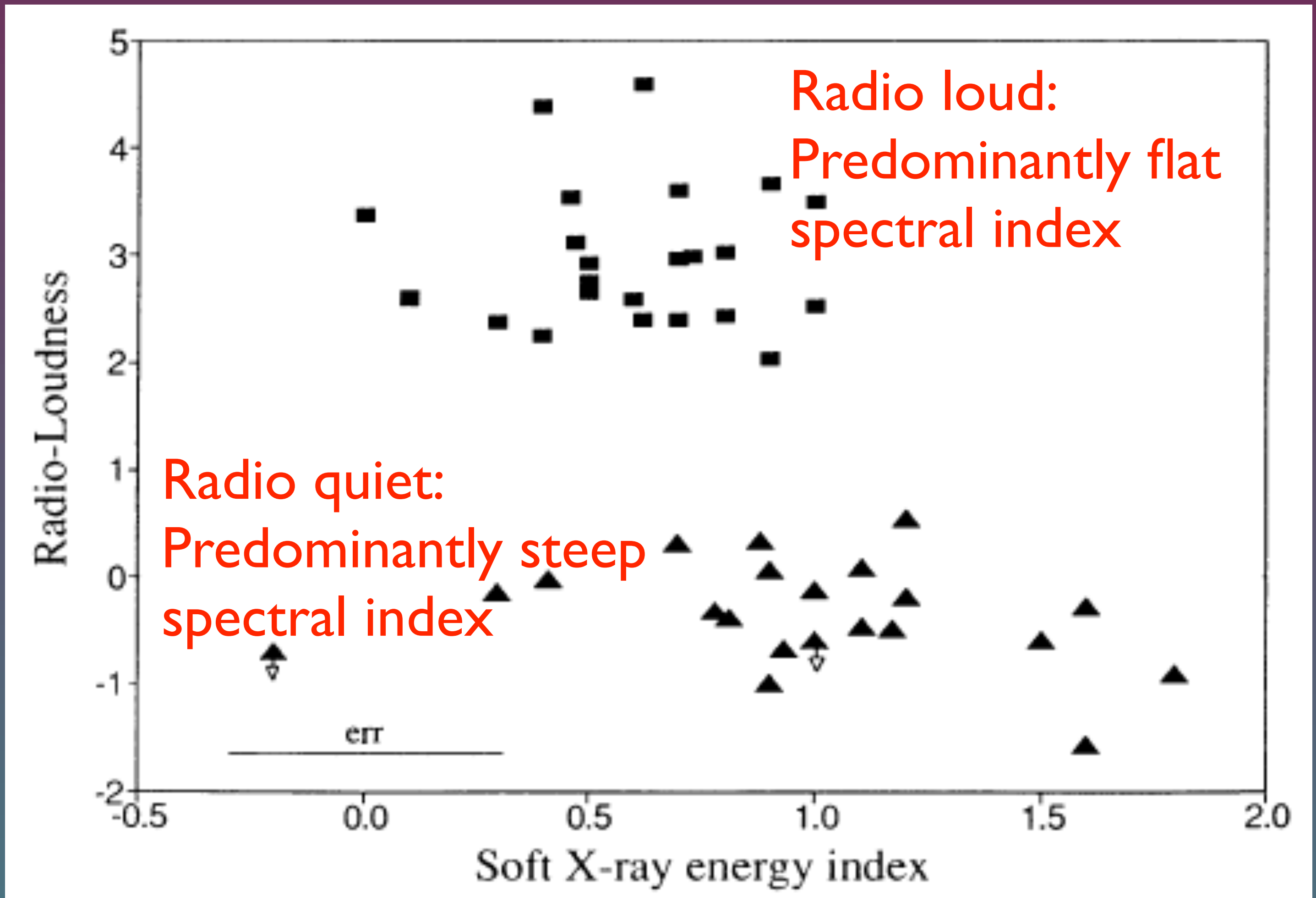
* Partition of Black Hole Gravitational Power into:

  - Disk emission
  - Coronal emission / Advection Dominated Accretion Flows (ADAFs)
  - Jets and Winds

* Parameters of jets in radio-loud objects close to black hole

* Launching of jets from black holes

Origin of X-ray emission

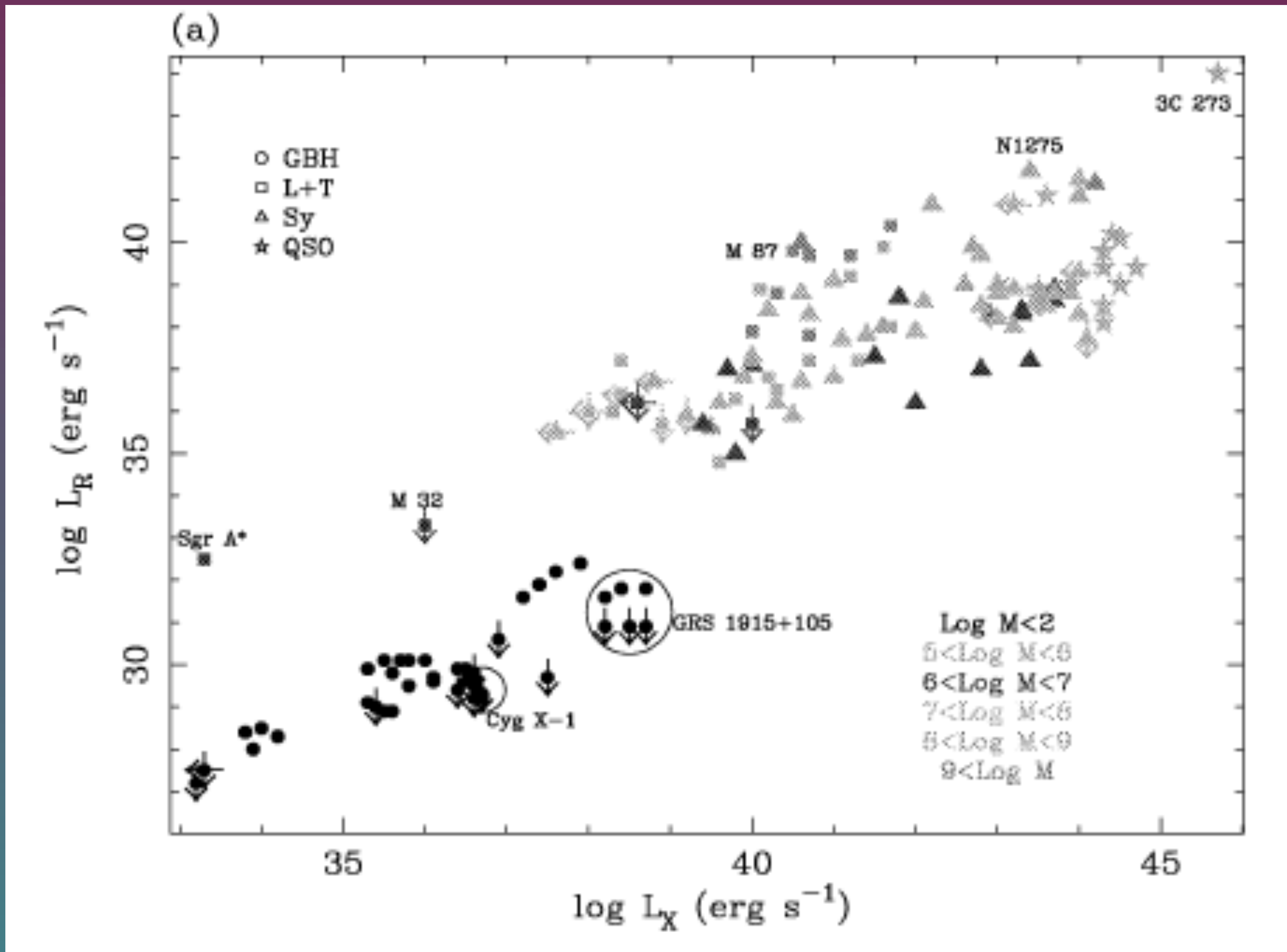


Shastri et al. '93

Two main possible emission mechanisms:

- Comptonization of soft disk photons by hot corona
- Synchrotron or Inverse Compton emission from jet

Black Hole Fundamental Plane



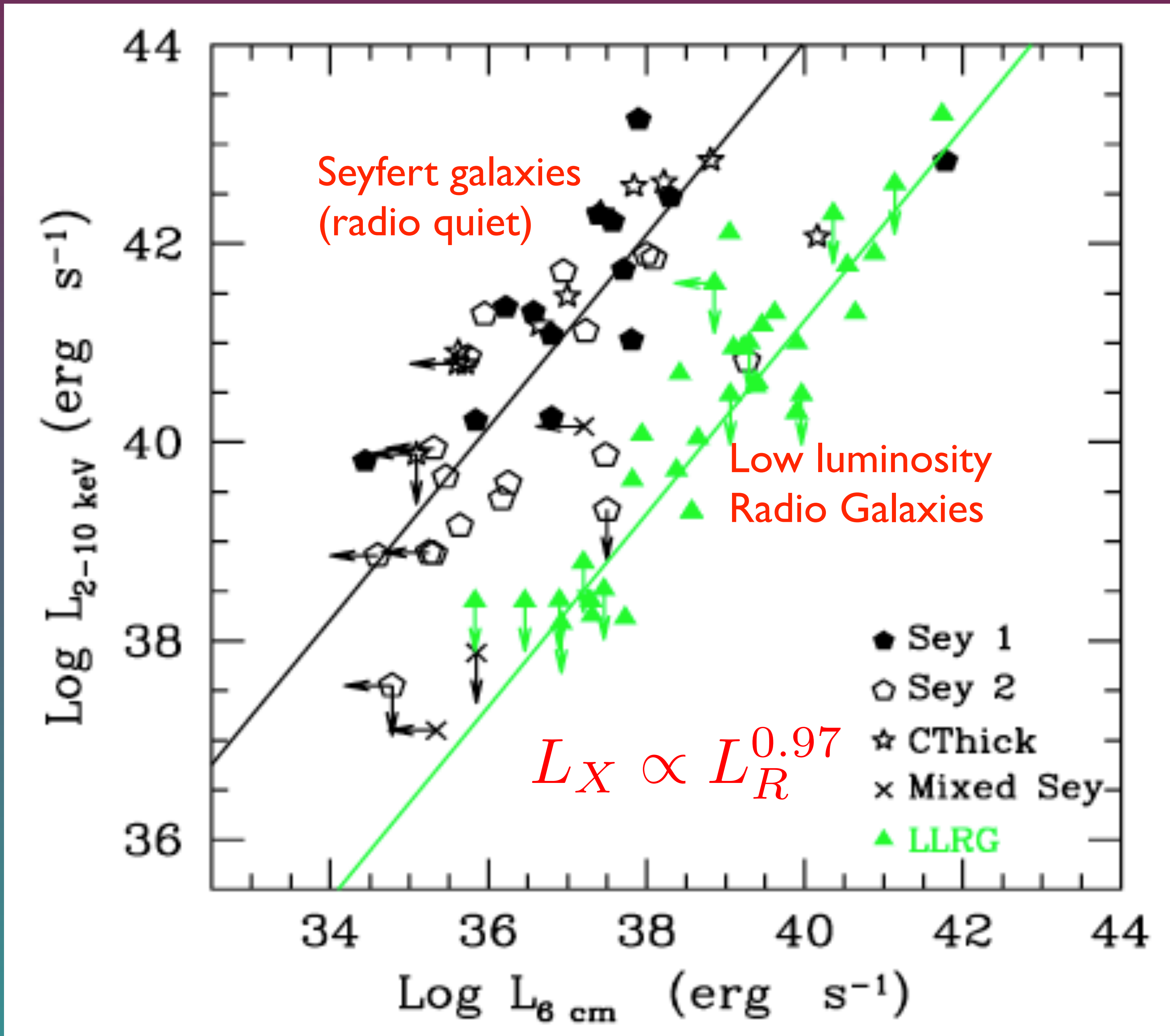
Merloni & Heinz '03
Falcke '04

5 GHZ core luminosity vs 2-10 keV luminosity

Offset in Galactic and Extragalactic correlations due to black hole mass

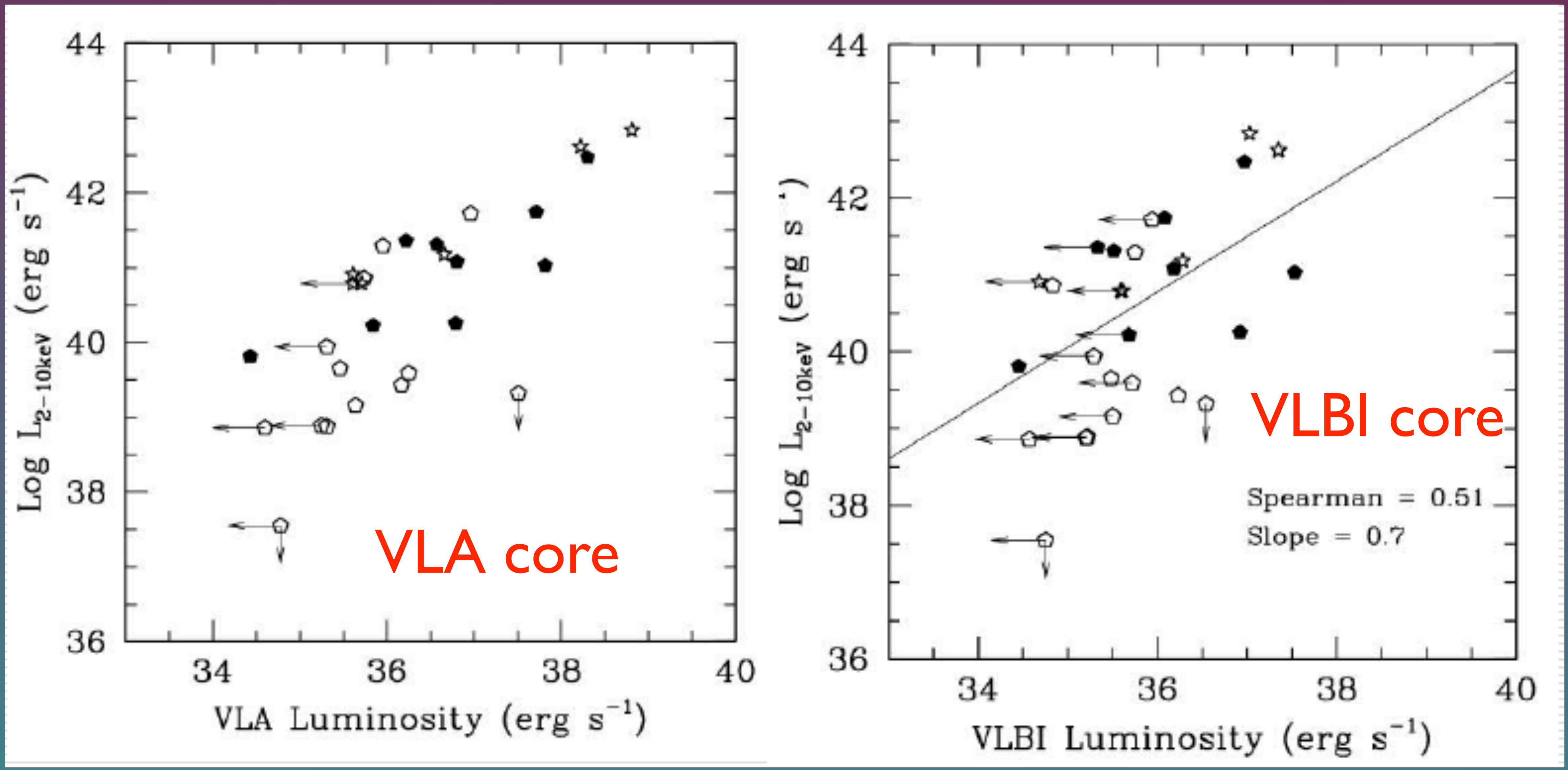
$$\log L_R = 1.05 \log L_X + 0.78 \log M + 7.33$$

Panessa et al 2007



Difference of 3 orders of magnitude in radio luminosity but same slope

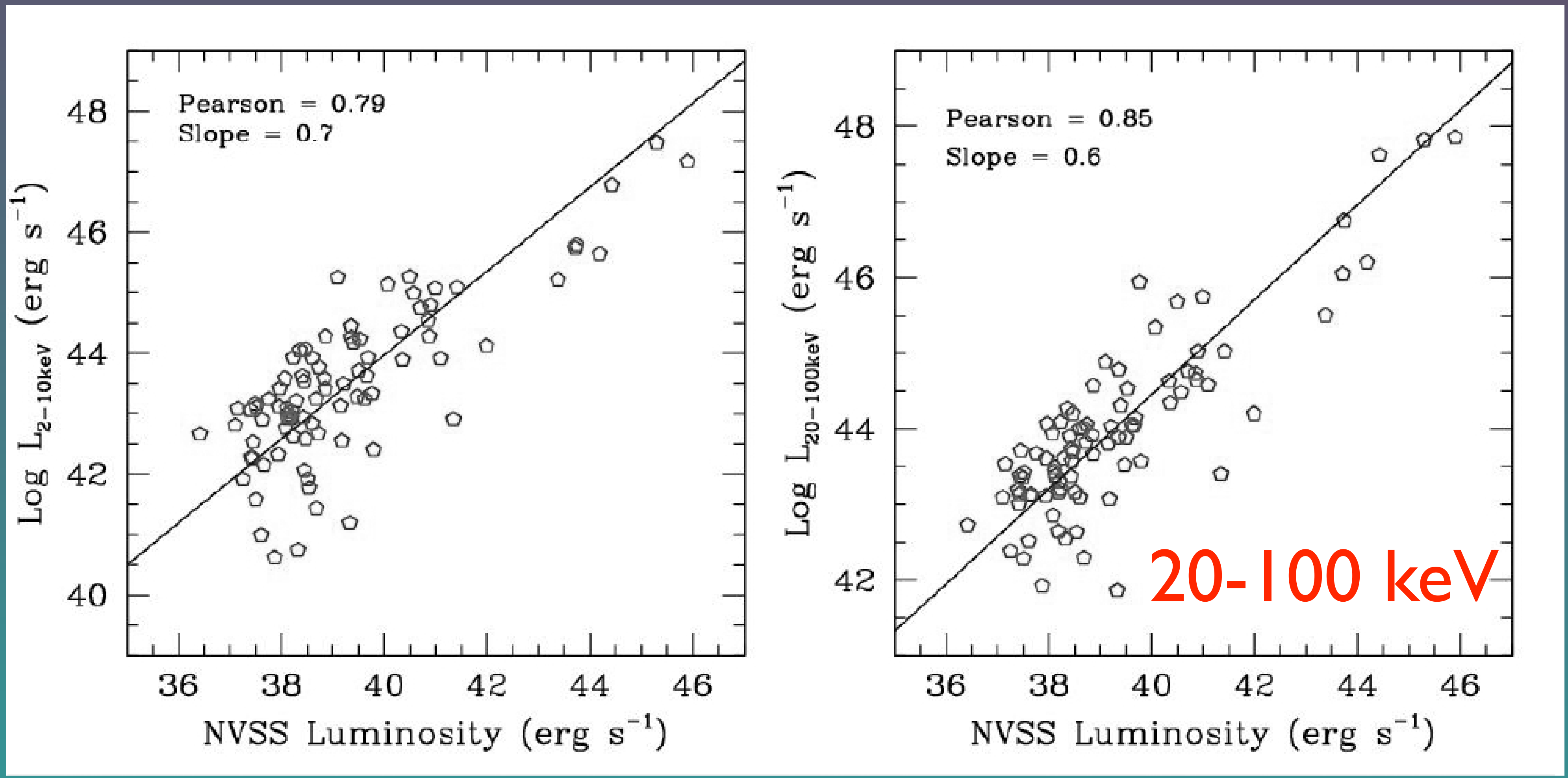
Panessa et al. 2011 - Correlation lost at VLBI resolution



Suggests correlation with jet power rather than luminosity

INTEGRAL Sample

- INTEGRAL 20-40 keV sample; 88 sources (Malizia et al. '09)
- 2-10 keV X-ray data (Malizia et al. + literature)
- NVSS radio data (Maiorano et al. in prep.)



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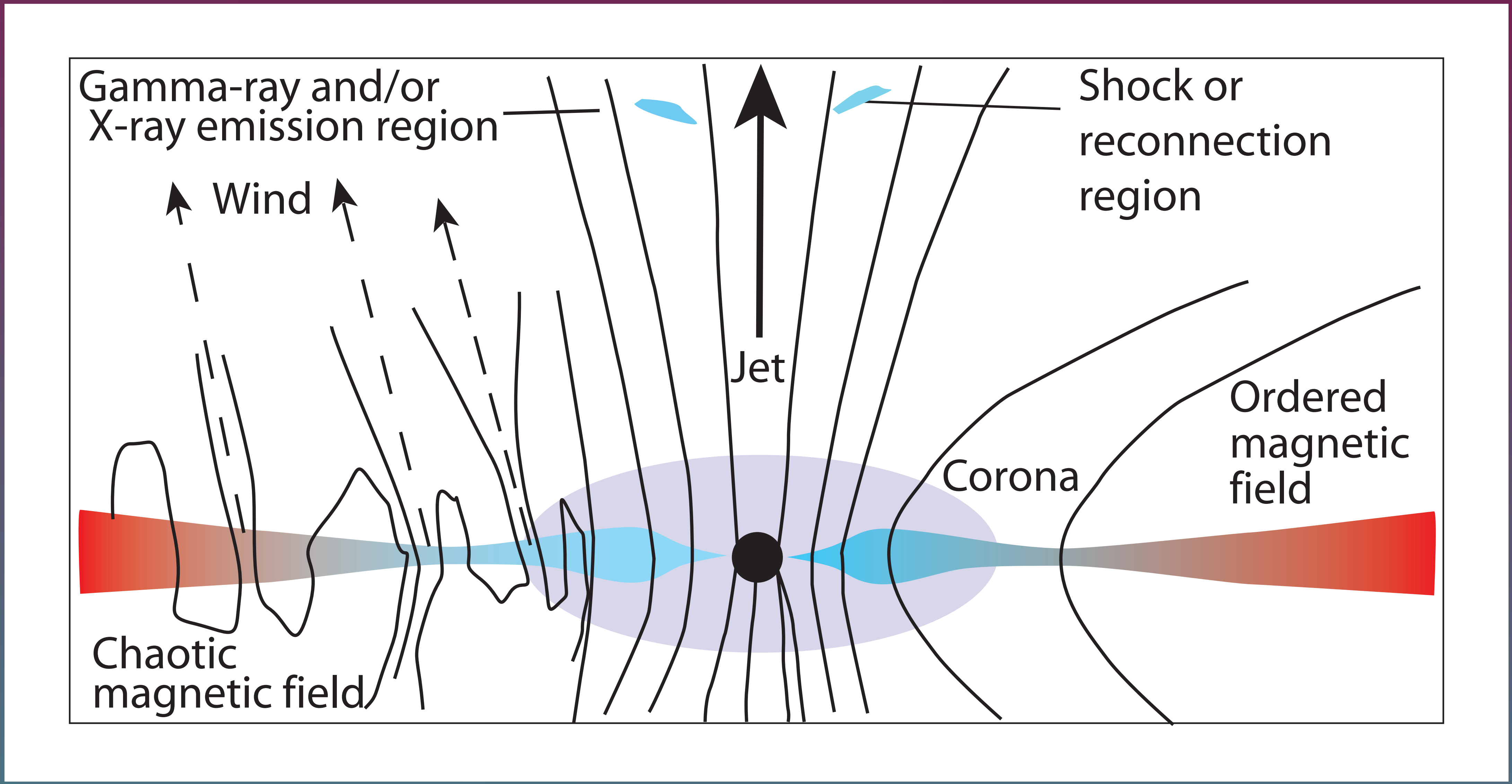
Different modes of X-ray and radio emission



- Disk and corona dissipate gravitational power rapidly
- Jet Poynting flux-dominated, non dissipative
- Jet power manifest on kpc scales

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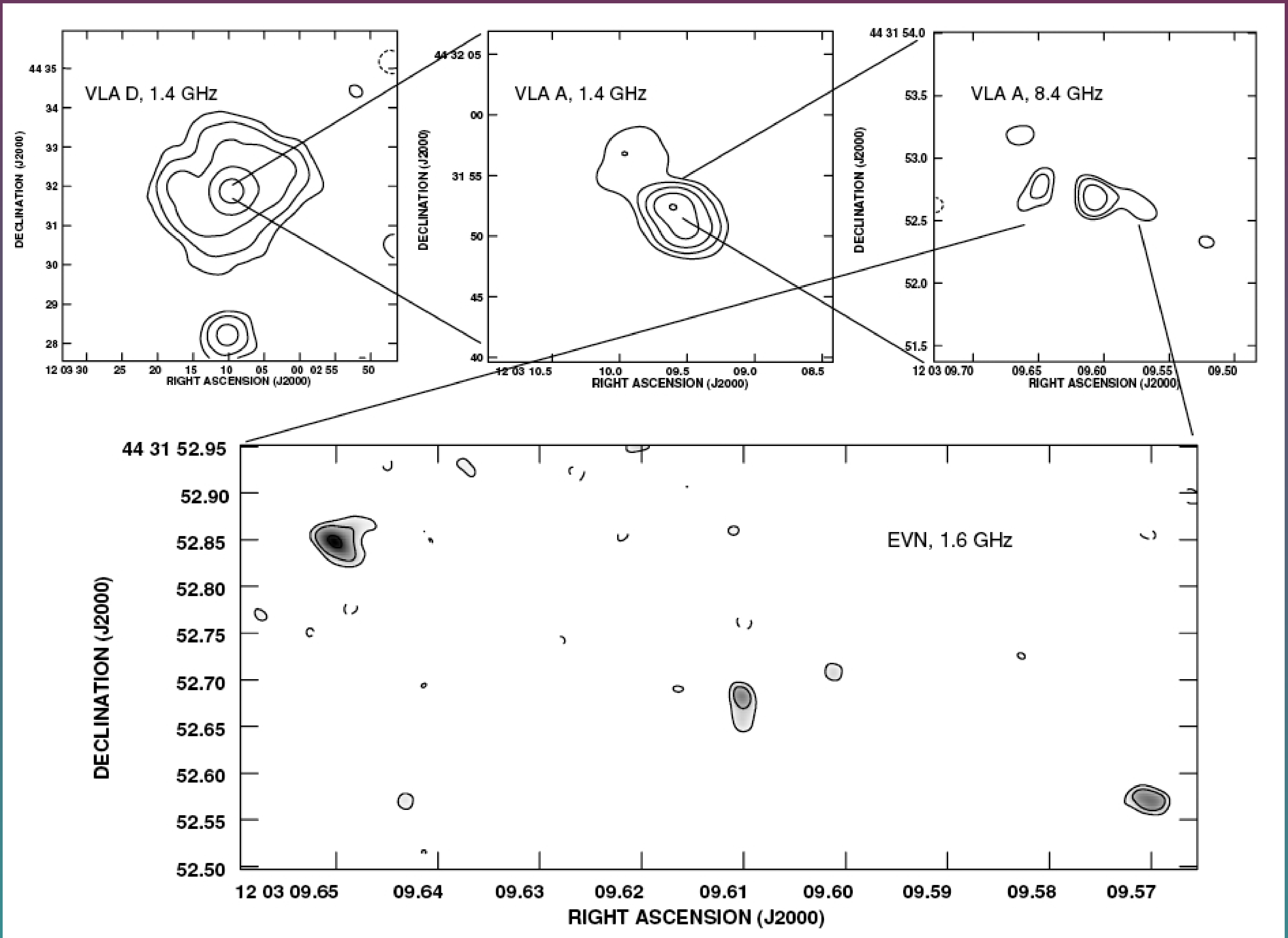
Relationship between radio power and jet power

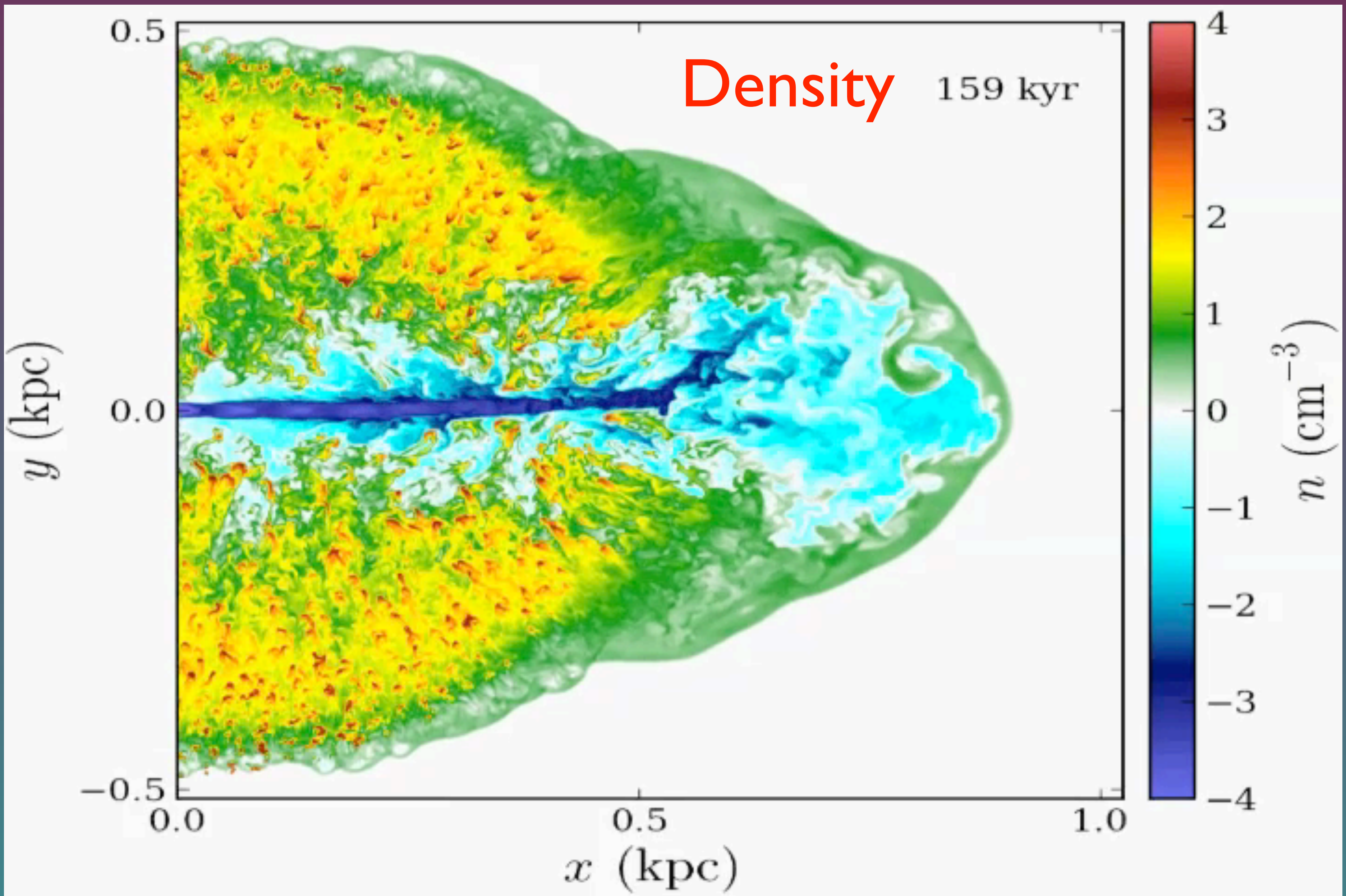
- Not simply a conversion of jet power into luminosity
- Model-dependent, e.g. Shabala et al. '05: Expansion of radio source into 2-component background medium
- Model for Seyferts motivated by observations of NGC 4051

NGC 4051: Giroletti & Panessa '09



~ 19 kpc bubble on large scales fed by jet on small scales

Jet – Interstellar Medium interaction



Powerful 10^{45} ergs s^{-1} jet in 1 kpc fractal medium

Luminosity of bubble

Emissivity

$$j_\nu = \text{Numerical Factors} \times K\, B^{(a+1)/2}\, \nu^{-(a-1)/2}$$
$$N(\gamma) = K\gamma^{-a}$$

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K estimated from electron pressure

$$K \approx \frac{3 p_{\rm tot}}{m_e c^2} \left(\frac{p_e}{p_{\rm tot}} \right) \gamma_1^{(a-2)}$$

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Lower cutoff

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Lower cutoff

Radius and pressure of bubble

$$
\begin{aligned}
R &= At^{3/5} \\
p_{\rm tot} &= \frac{12}{25} \rho_a A^2 t^{-4/5} \\
A &= \left[\frac{125}{384\pi} \frac{F_E}{\rho_a} \right]^{1/5}
\end{aligned}
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Jet energy flux

$$A = \left[\frac{125}{384\pi} \frac{F_E}{\rho_a}\right]^{1/5}$$

Luminosity - Jet Power relation

$$
\begin{aligned}
P_\nu &= j_\nu \times \text{Volume} \\
B &= \text{Equipartition with total pressure}
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INTEGRAL sample: $\nu = 1.4\ \mathrm{GHz}$

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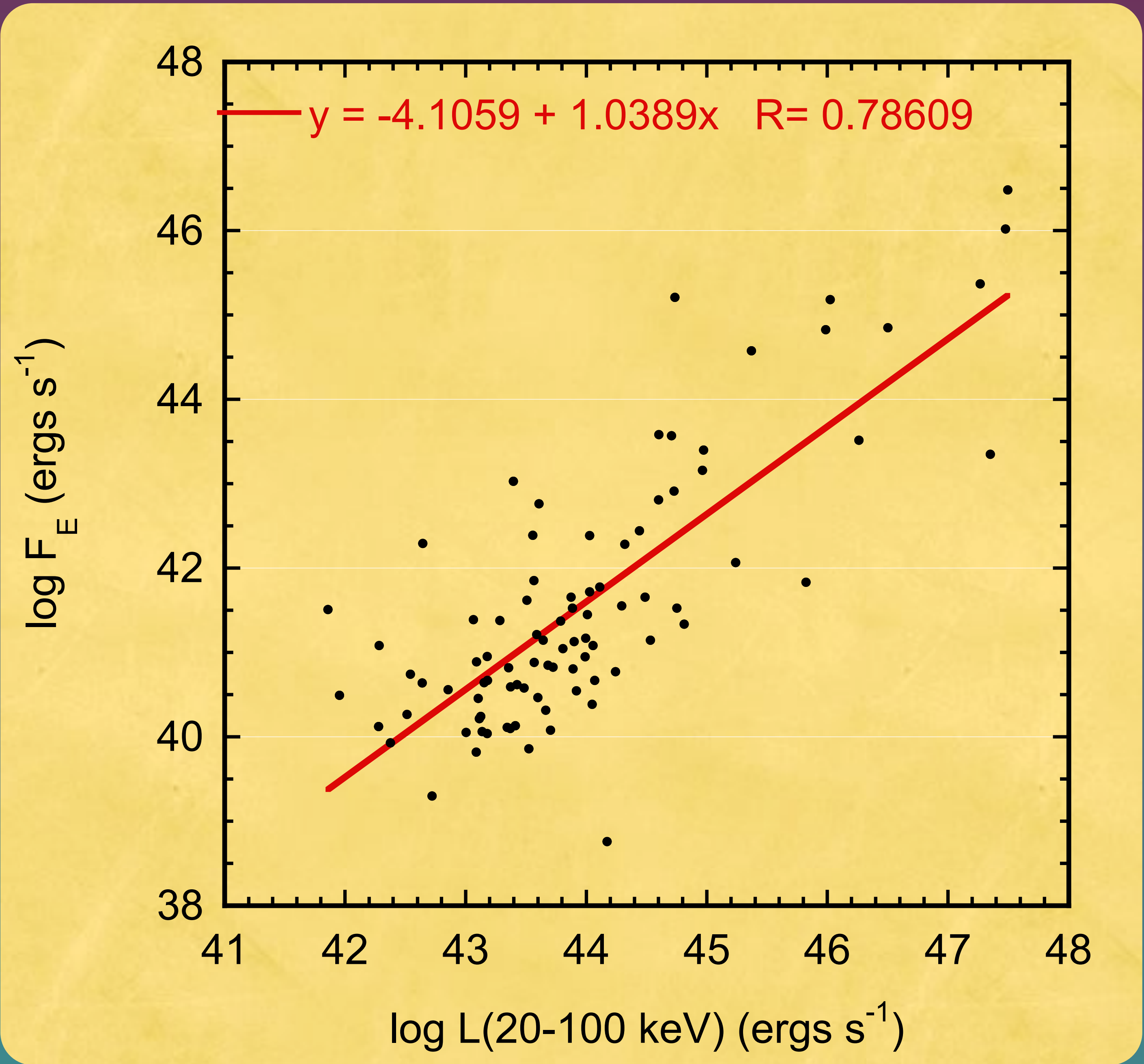
$t \sim 3 \times 10^8\ \mathrm{yr}$

Radio power -> Luminosity

Strongest dependence is on energy flux

$$\begin{aligned} P_\nu &\propto F_E^{(a+11)/10} \\ \Rightarrow F_E &\propto P_\nu^{10/(a+11)} = P_\nu^{0.76} \text{ for } a = 2.2 \end{aligned}$$

Energy flux – X-ray Luminosity



Almost linear correlation between jet power and X-ray luminosity

$$F_E \propto L_X^{1.04}$$

Somewhat misleading since alternative regression =>

$$L_X \propto F_E^{0.6}$$

Jet power ~ 0.5% of X-ray luminosity – with large deviations from mean

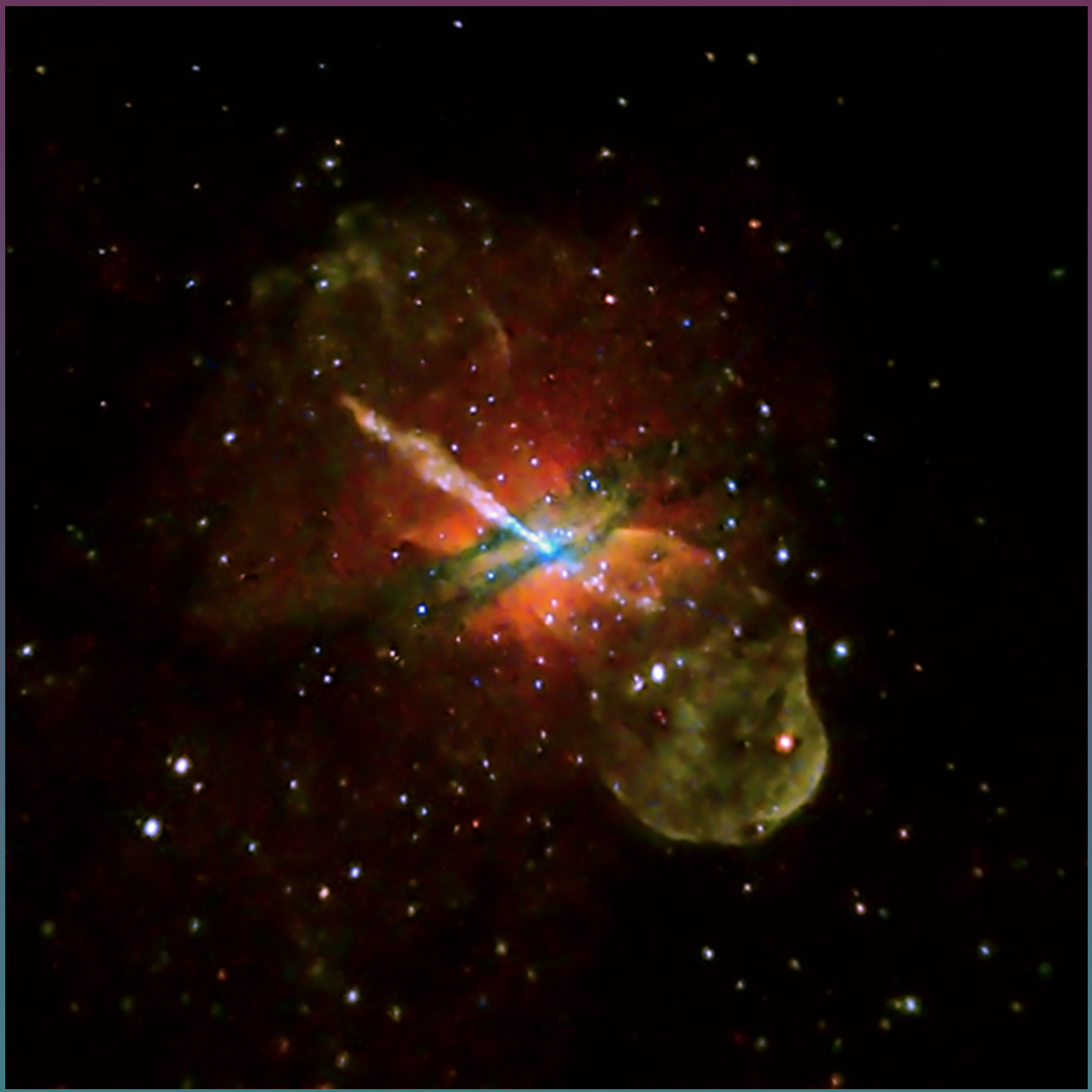
Main points on disk-dominated X-ray AGN

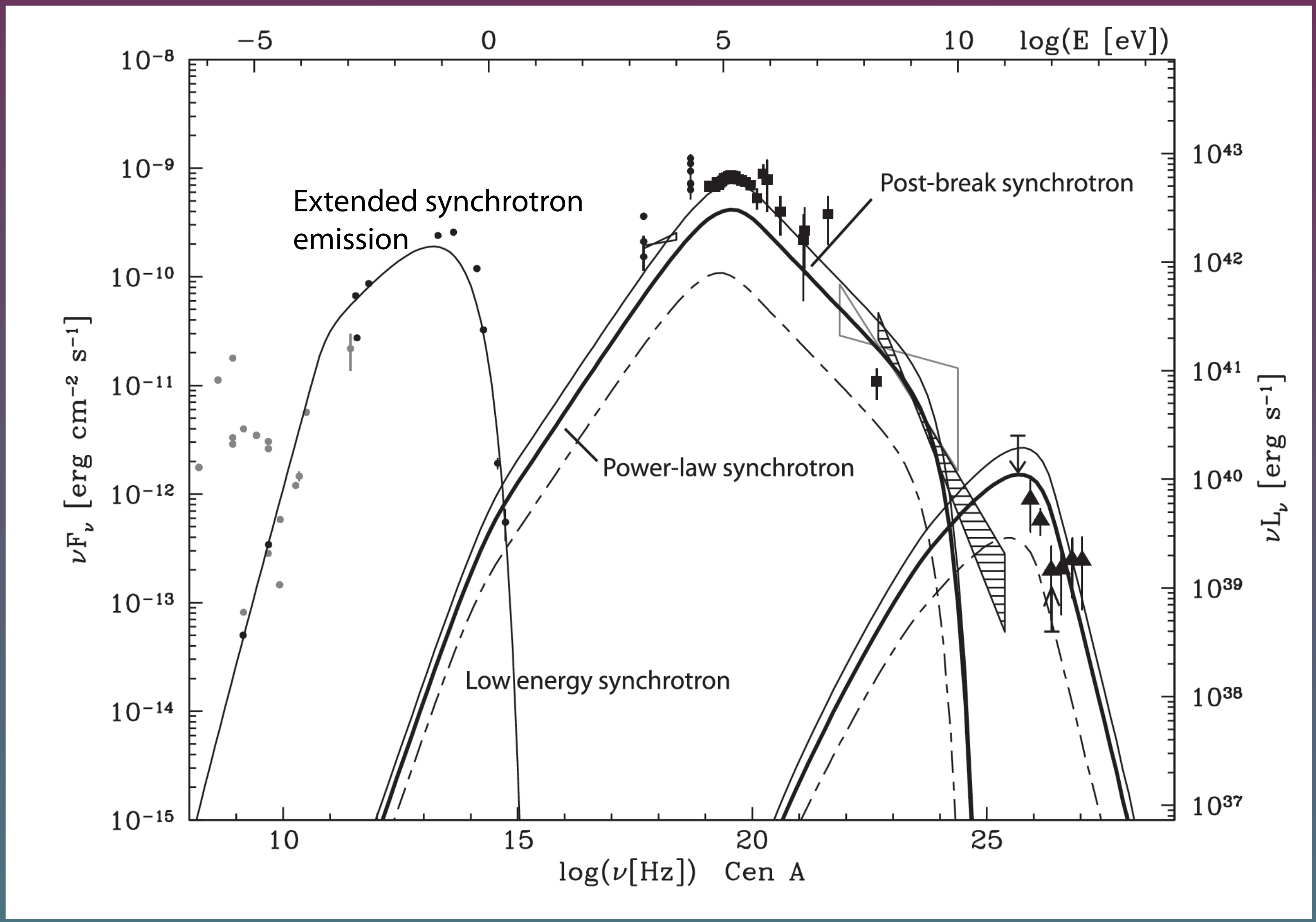
- Need to understand better the relationship between radio and X-ray emission in both radio-loud and radio quiet sources where the X-ray emission is clearly disk coronal emission

- Important to focus on jet power rather than radio luminosity when considering the partition of gravitational power among various modes

- Consideration of the large scale source structure and dynamics useful way of estimating jet power

X-ray jet emission in the Radio-Loud Galaxy Centaurus A

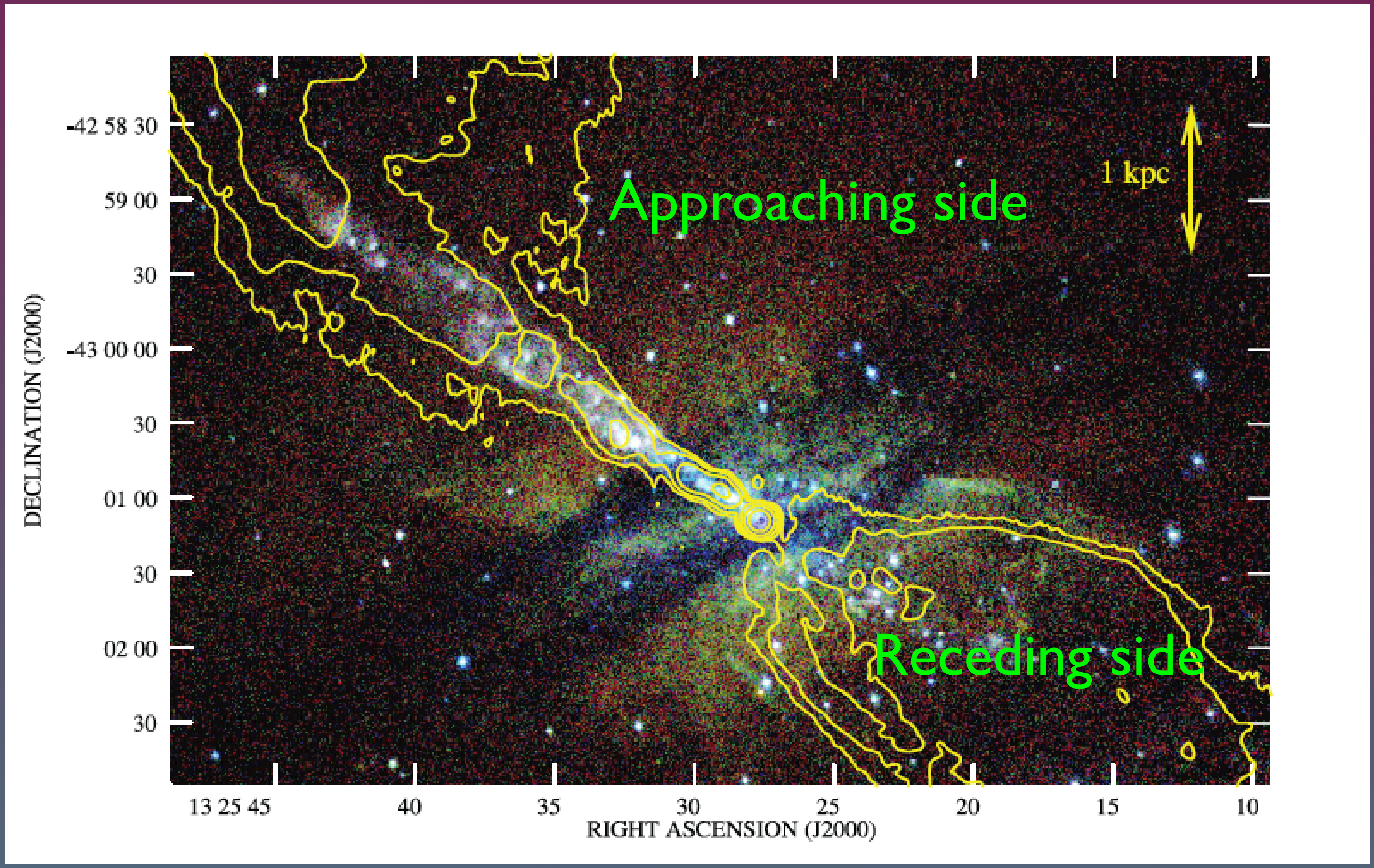




SED of core from Lenain et al ’09

Interaction of jet with ISM

Radio and X-ray Images from Hardcastle et al 2003 and 2007



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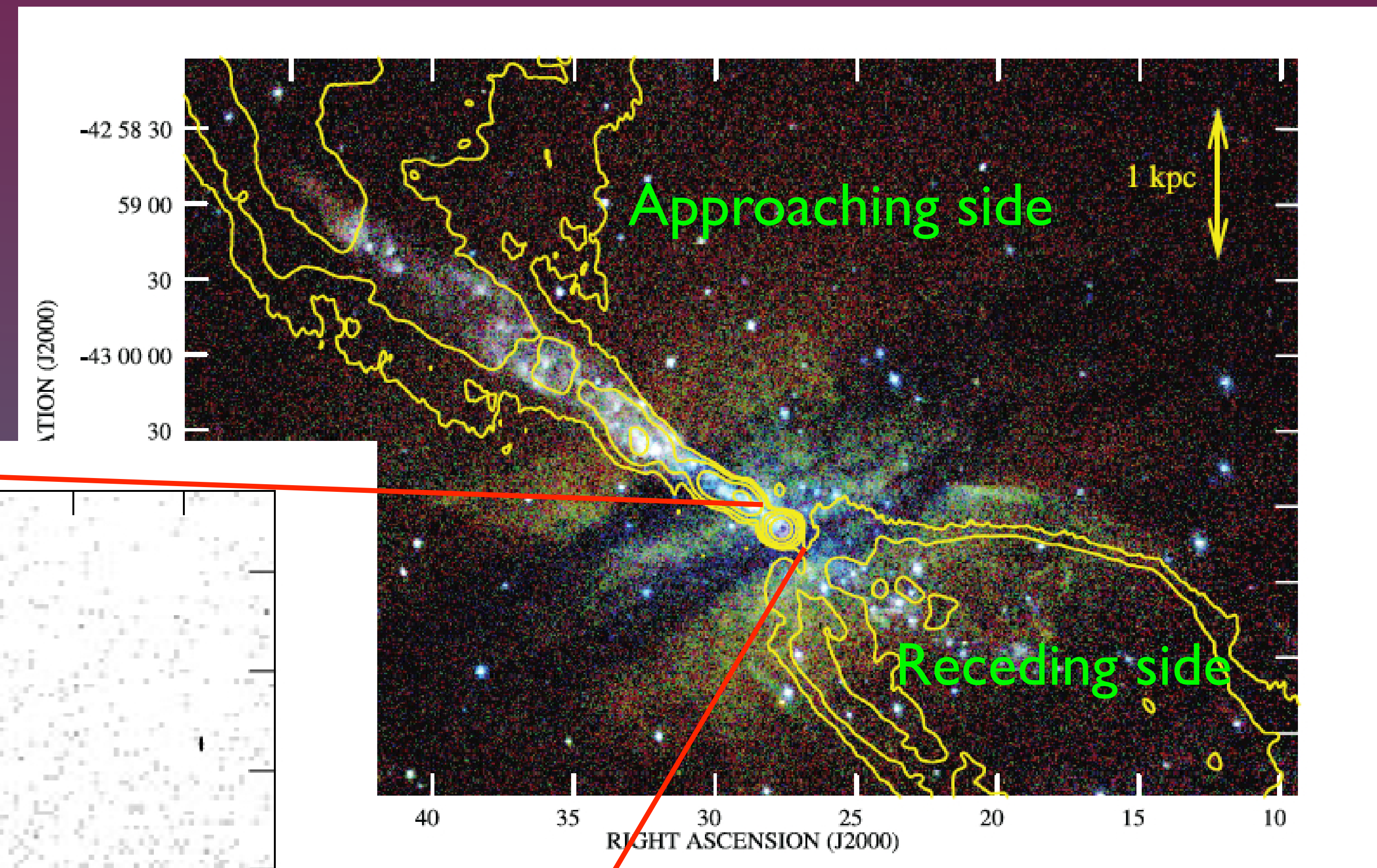

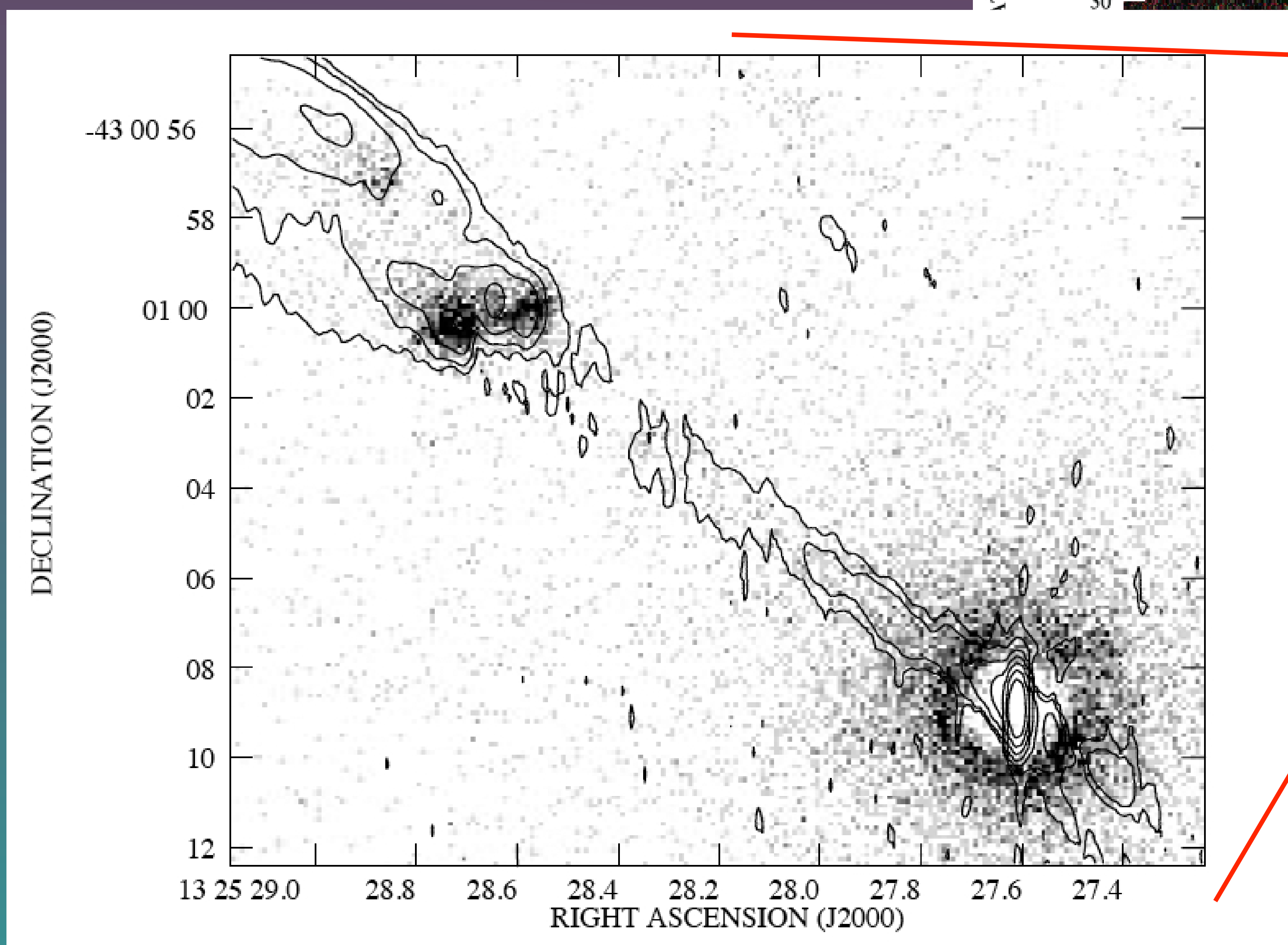

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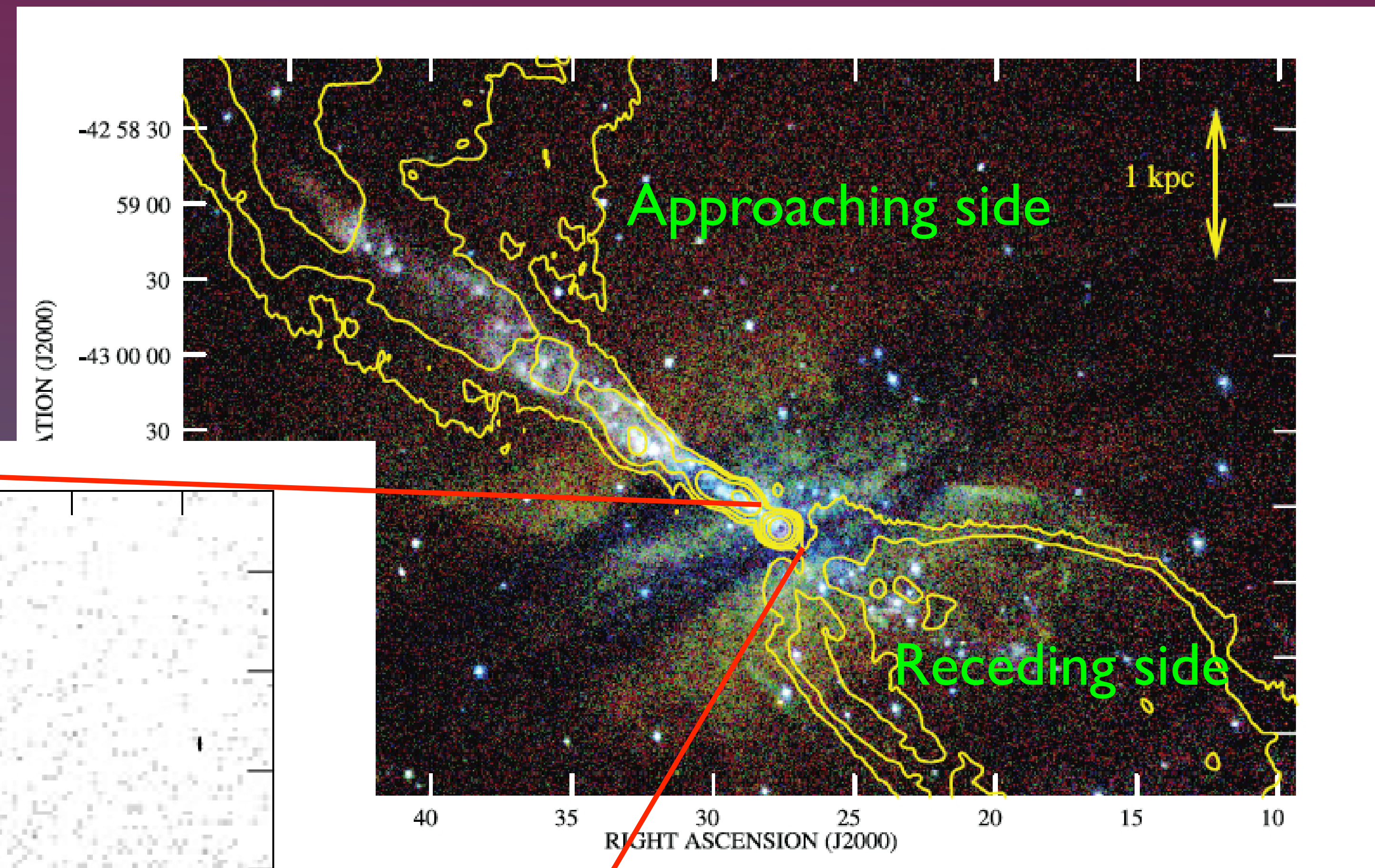
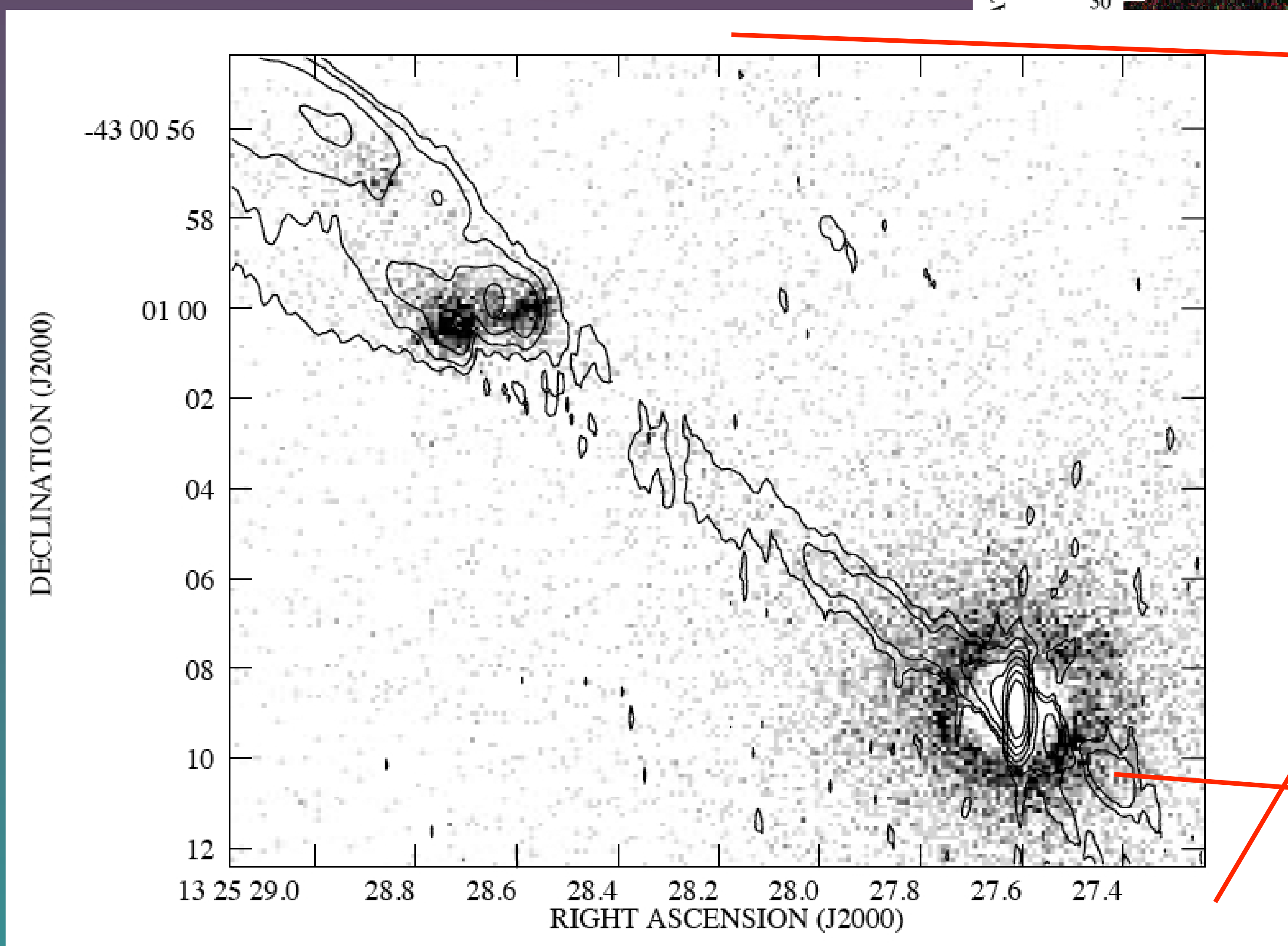
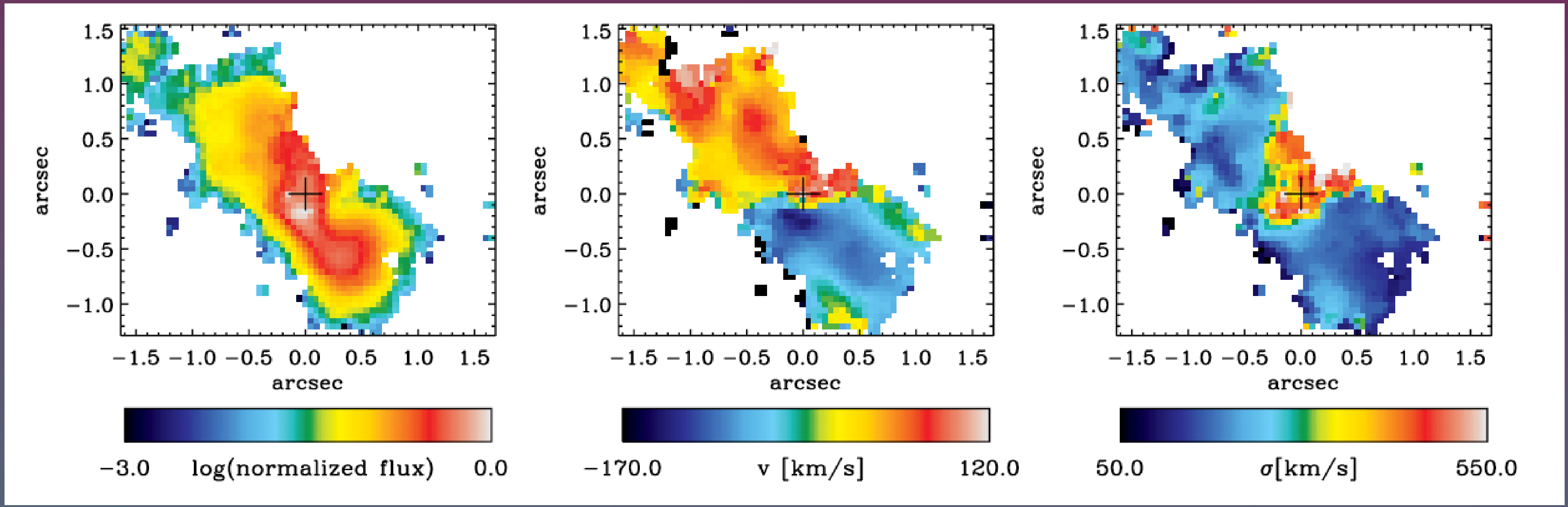




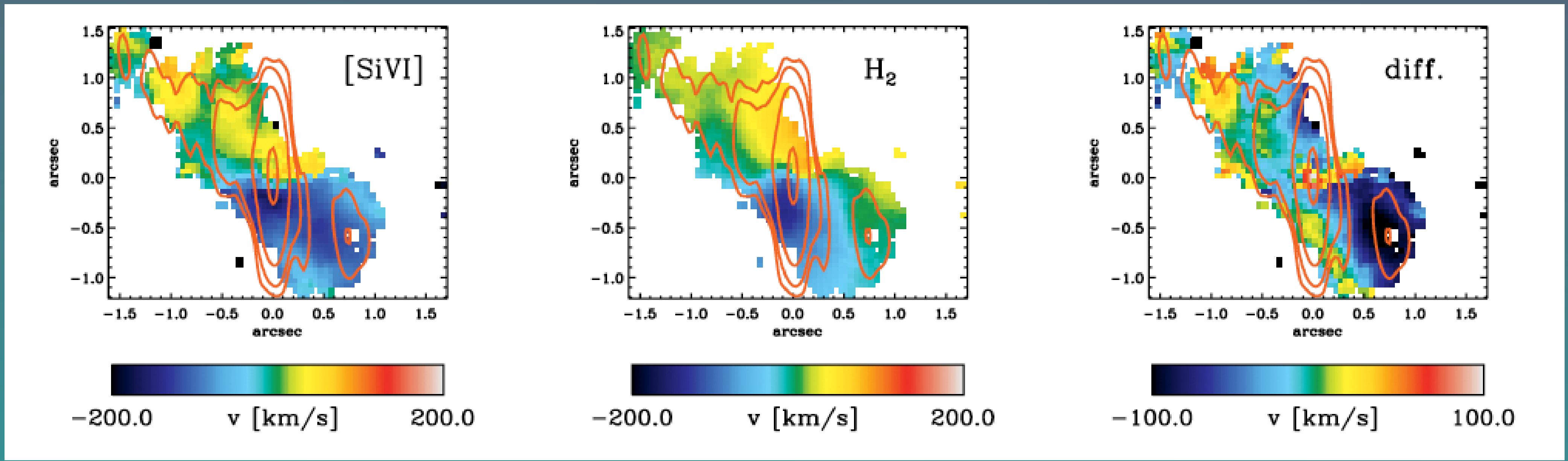
Radio knot SW of nucleus

Velocity of [SiVI] – 0.12" SINFONI – VLT

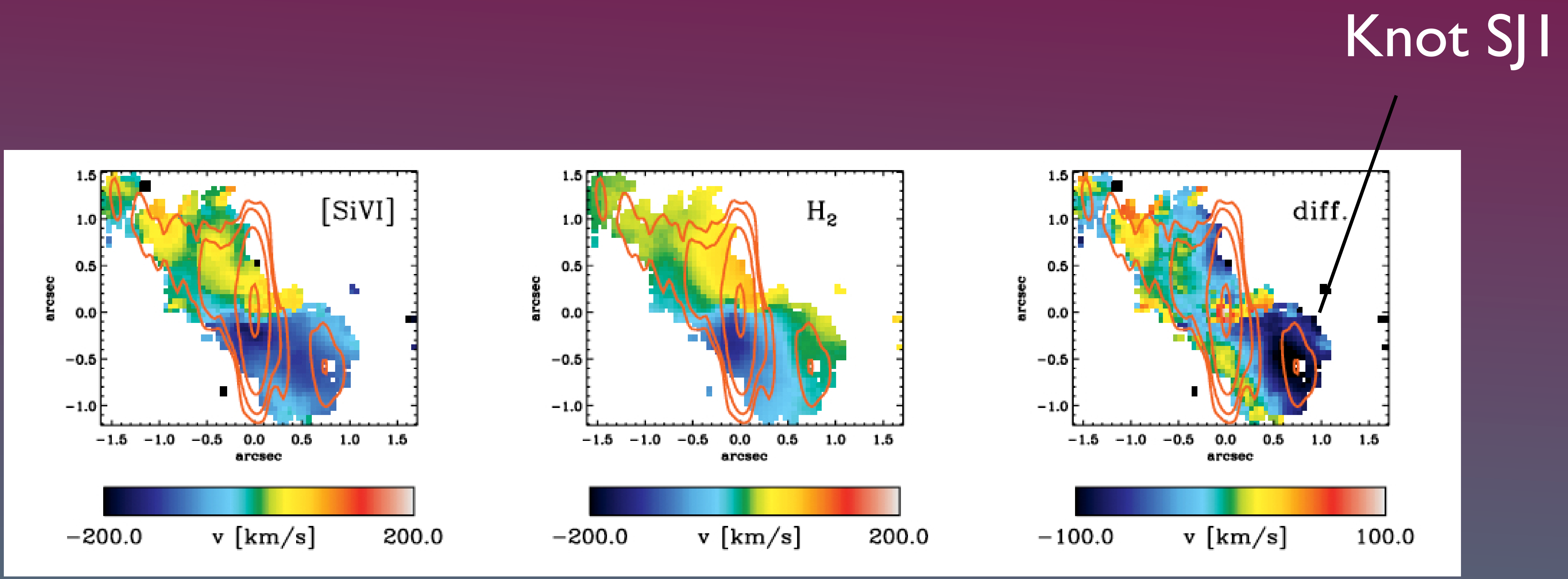
Neumayer et al. 2007



Corrected for rotation:



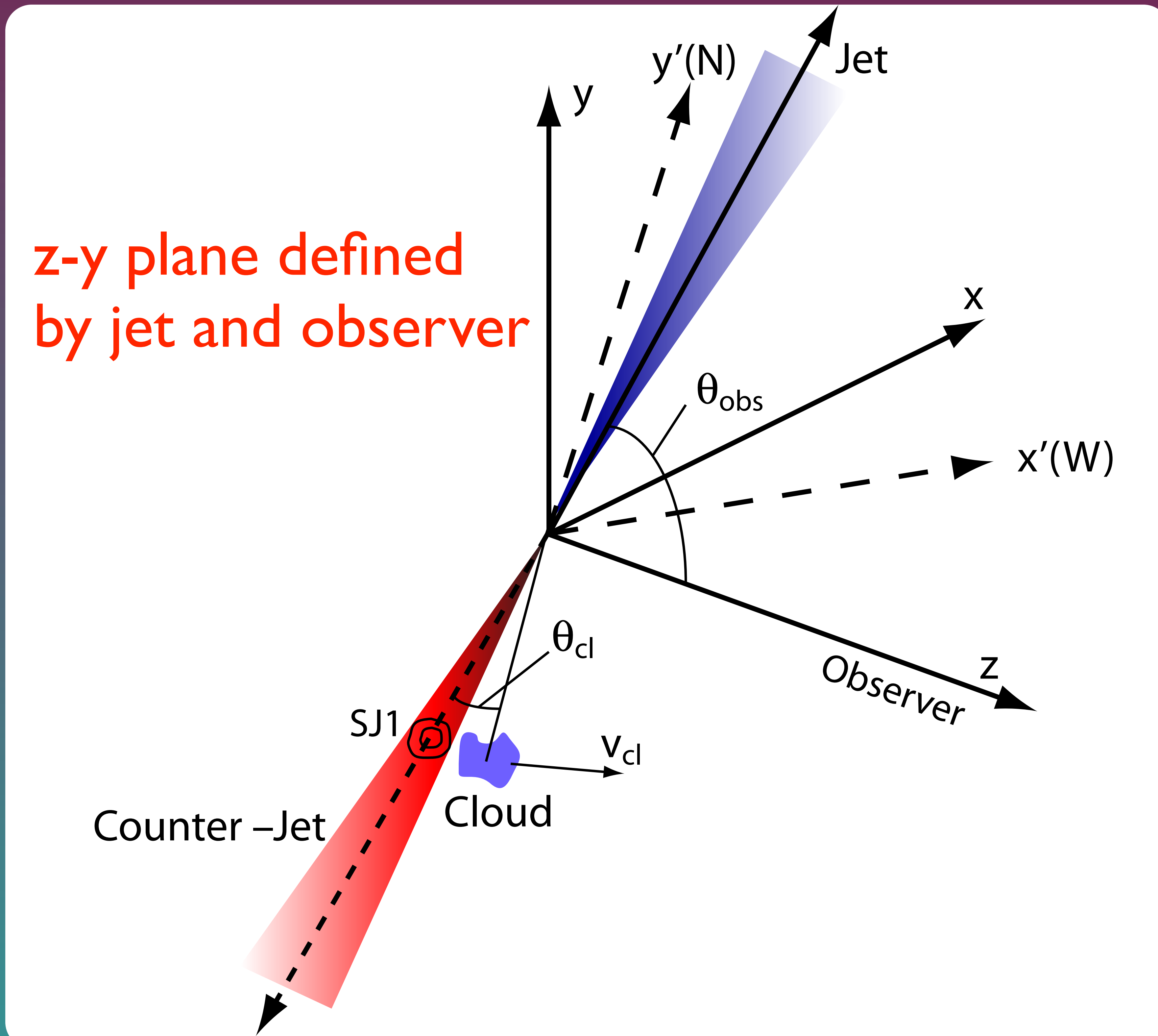
Why is [SiVI] blue-shifted?



Redshifted emission on approaching side and blueshifted on receding side at first counterintuitive

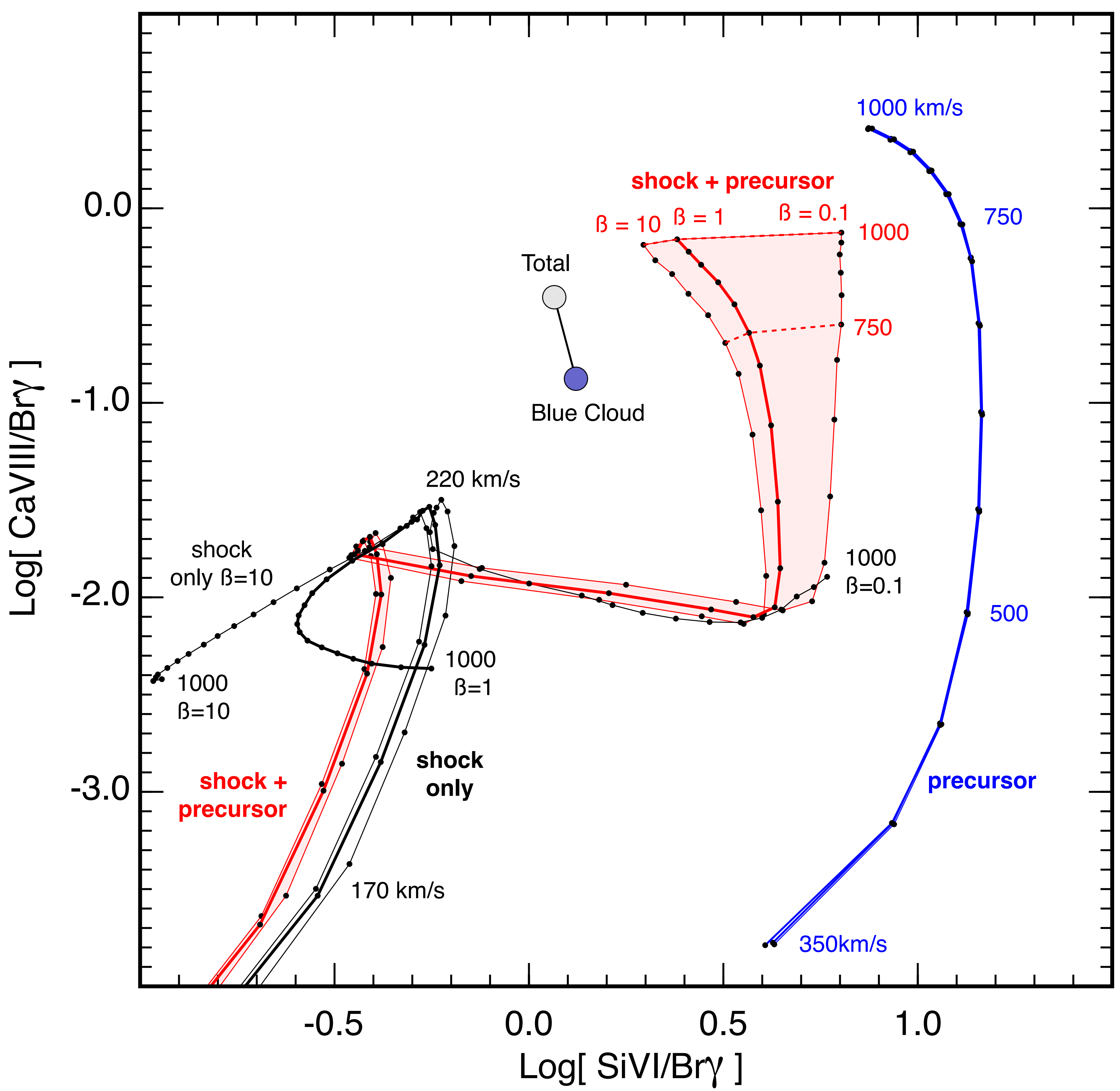
Expect entrained clouds to be moving with jet

Geometry



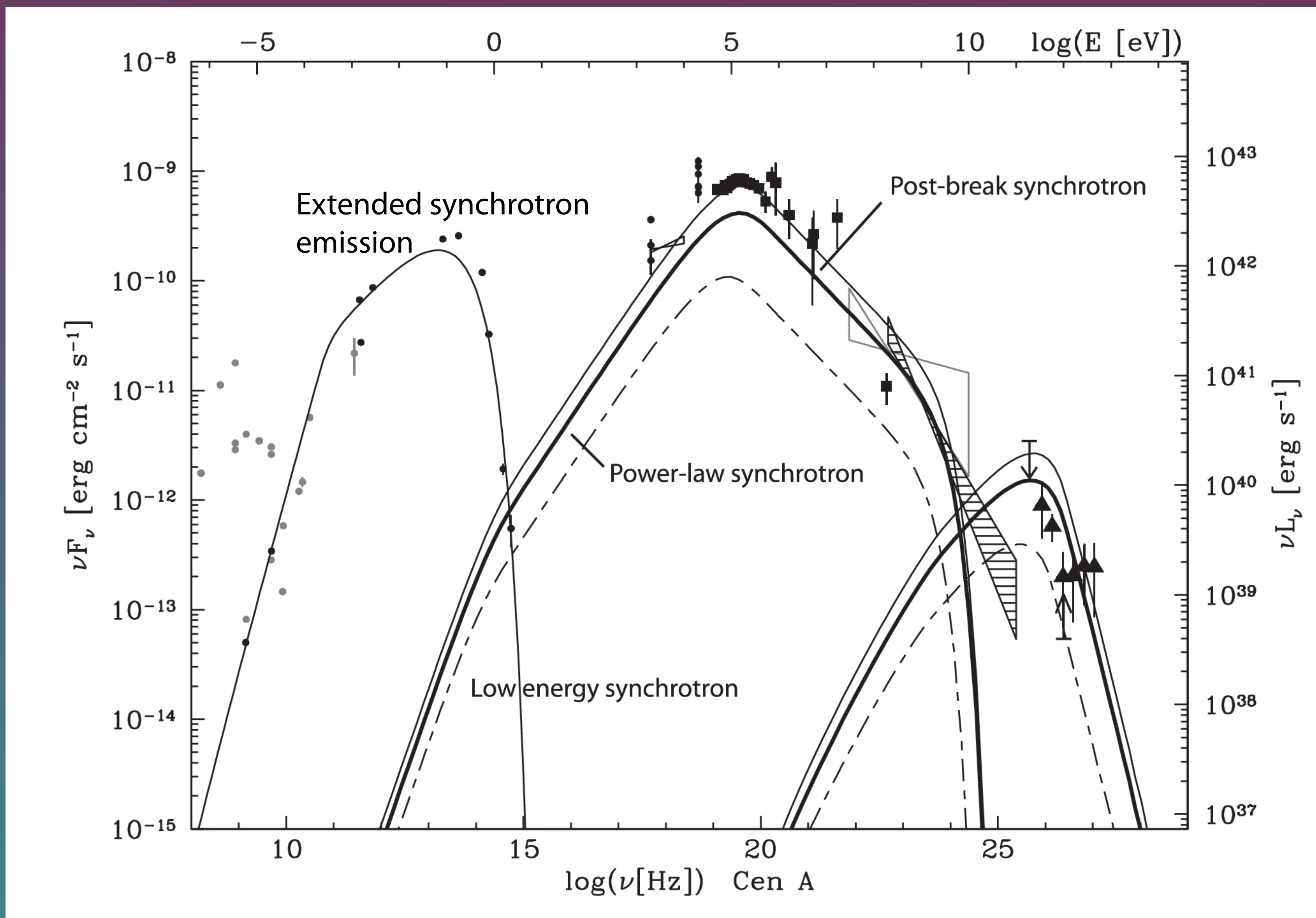
y
y′(N)
Jet
z-y plane defined
by jet and observer
x
θobs
x′(W)
θcl
z
Observer
SJ1
vcl
Cloud
Counter –Jet

Shock models (MAPPINGS)



High energy emission from the core

Synchrotron + Inverse Compton model fits to the high energy emission from the core of Cen A – Lenain et al. 2009



Model Lorentz factor = 15
Inclination ~ 25°

Estimates from VLBI observations (Tingay et al. 01)

Lorentz factor > 1.12
Inclination between 45^0 and 80°

Parameters of photoionization models

$$U = \frac{\text{No. density of ionising photons}}{\text{Atomic no. density}} = \frac{n_{\rm ph}}{n}$$

$$\alpha = \text{Spectral slope of flux density}$$

$$\text{Flux density} \quad F_\nu \propto \nu^{-\alpha}$$

$$\text{Typically} \quad \alpha \approx 1.4$$

$$\text{and} \quad \log U \approx -2$$

Lenain et al. models of X-ray synchrotron => $\alpha \approx 0.39$

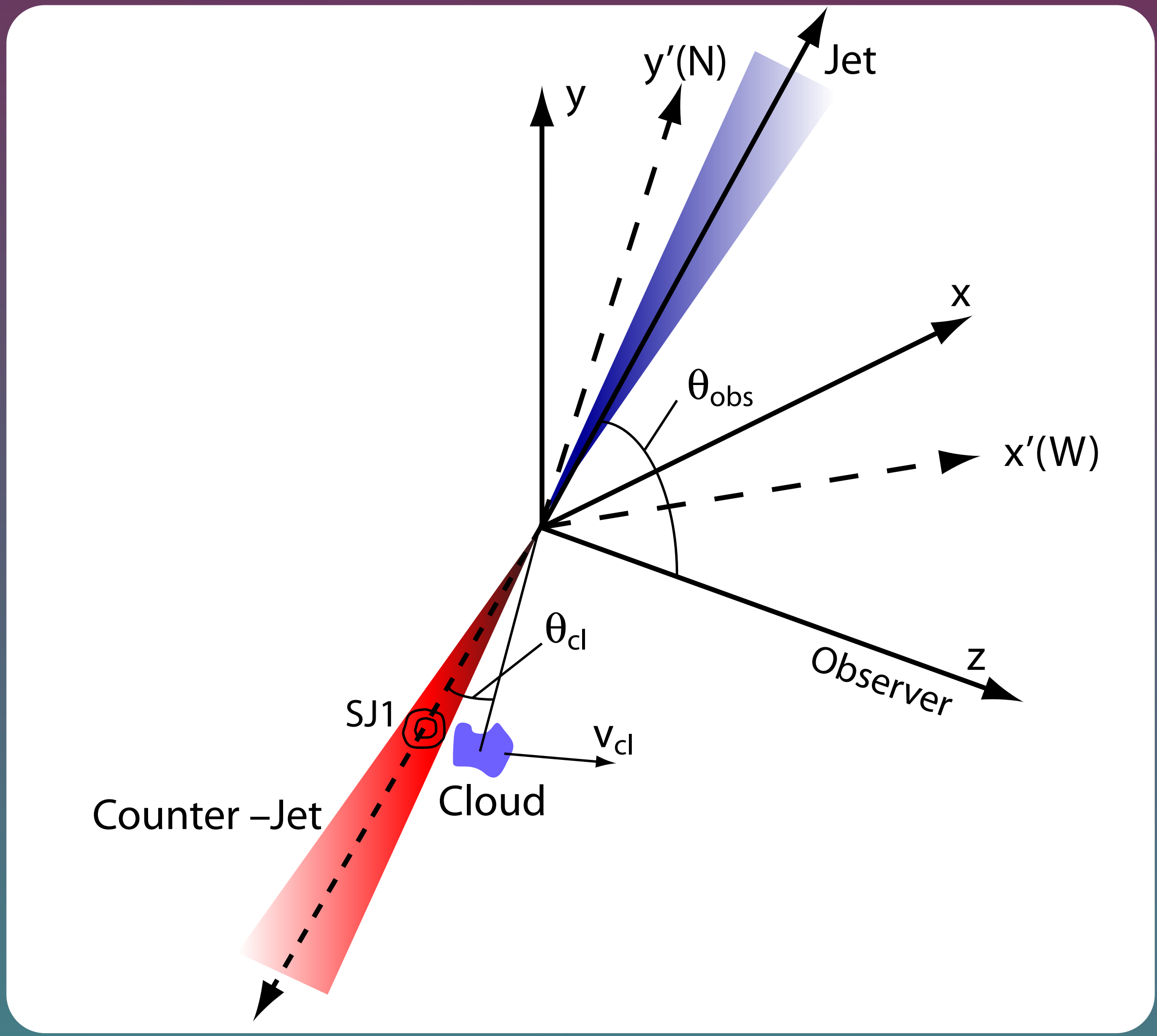
Flux of ionizing photons

Lorentz factor

Doppler factors:

$$\delta_{\rm obs} = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm obs})}$$

$$\delta_{\rm cl} = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm cl})}$$



Ionizing flux (cont.)

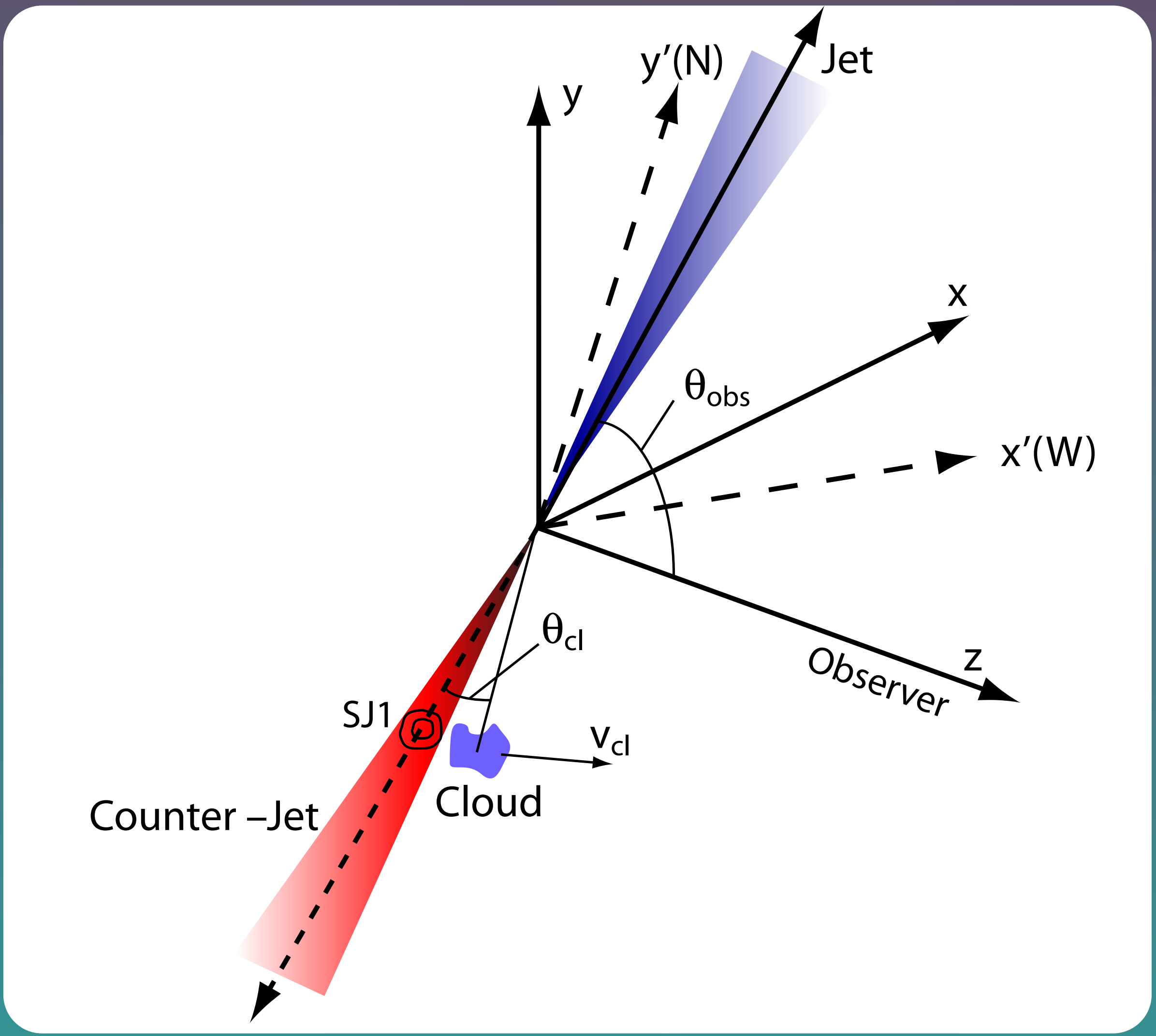
$$N_{\rm ph} = \int_{\nu_0}^{\infty} N_{\rm ph}(\nu)\, d\nu$$

$$= \frac{1}{c}\left(\frac{D_A}{D_{\rm cl}}\right)^2 \left(\frac{\delta_{\rm cl}}{\delta_{\rm obs}}\right)^3 \int_{\delta_{\rm obs}\delta_{\rm cl}^{-1}\nu_0}^{\infty} \frac{F_{\rm obs}(\nu_{\rm obs})}{h\nu_{\rm obs}}\, d\nu_{\rm obs}$$

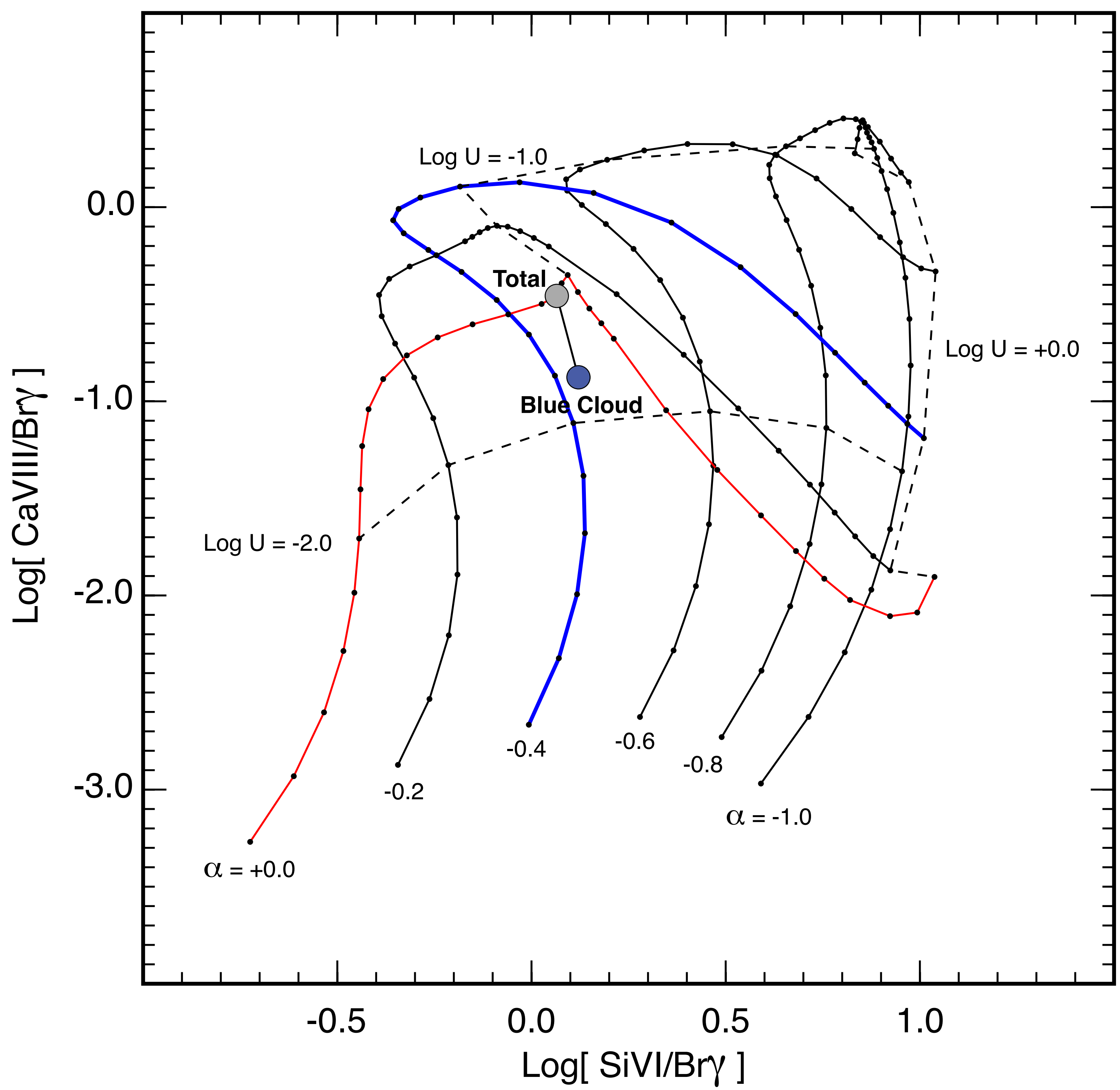
$$\frac{D_A}{D_{\rm cl}} = \frac{\text{Distance to Cen A}}{\text{Distance of cloud from core}}$$

$$= \frac{\sin(\theta_{\rm obs} + \theta_{\rm cl})}{\psi_{\rm cl}}$$

Projected angular distance of cloud from core



Results of photoionization calculations



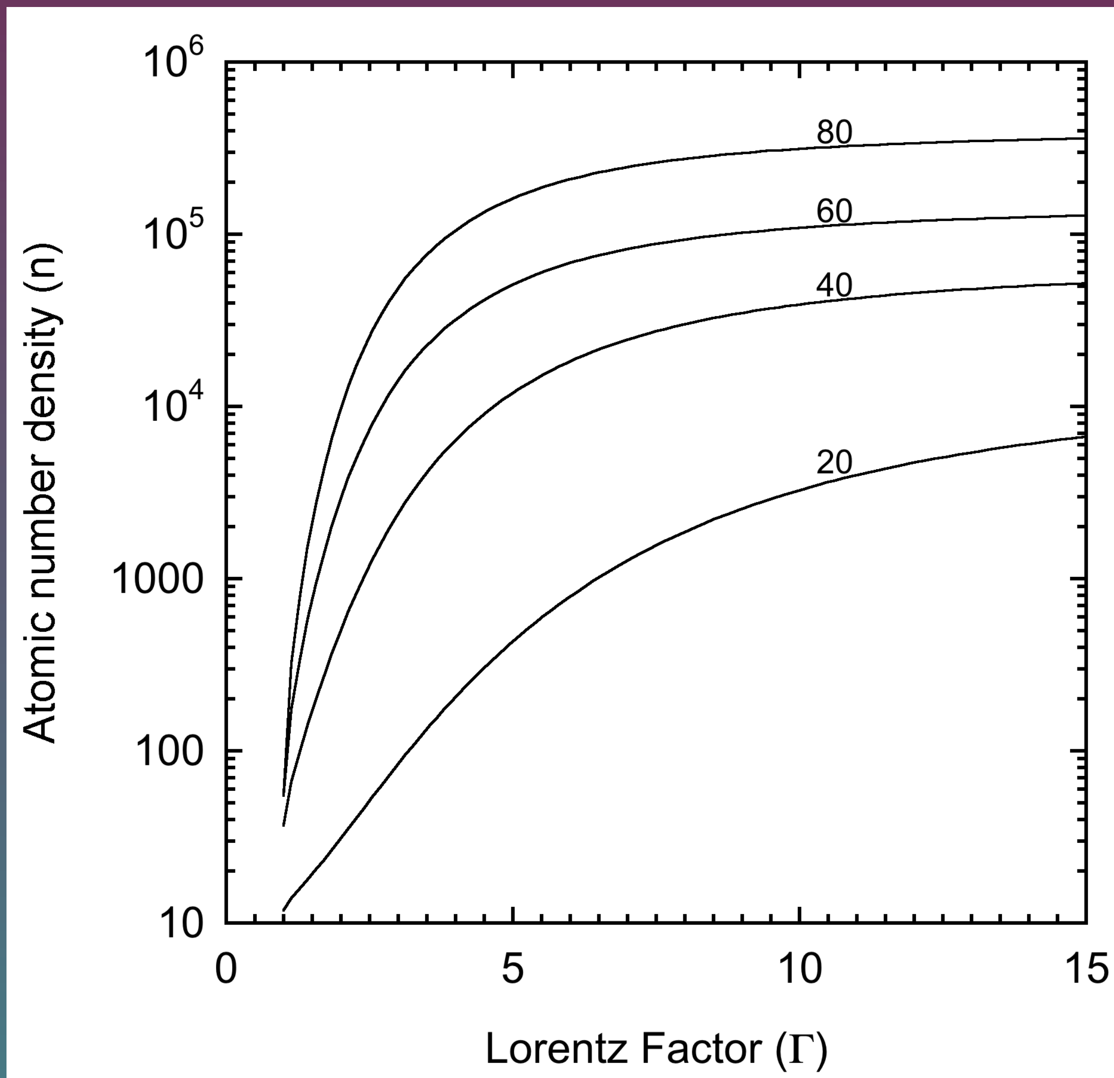
Optimal MAPPINGS model very close to the slope derived from high energy models

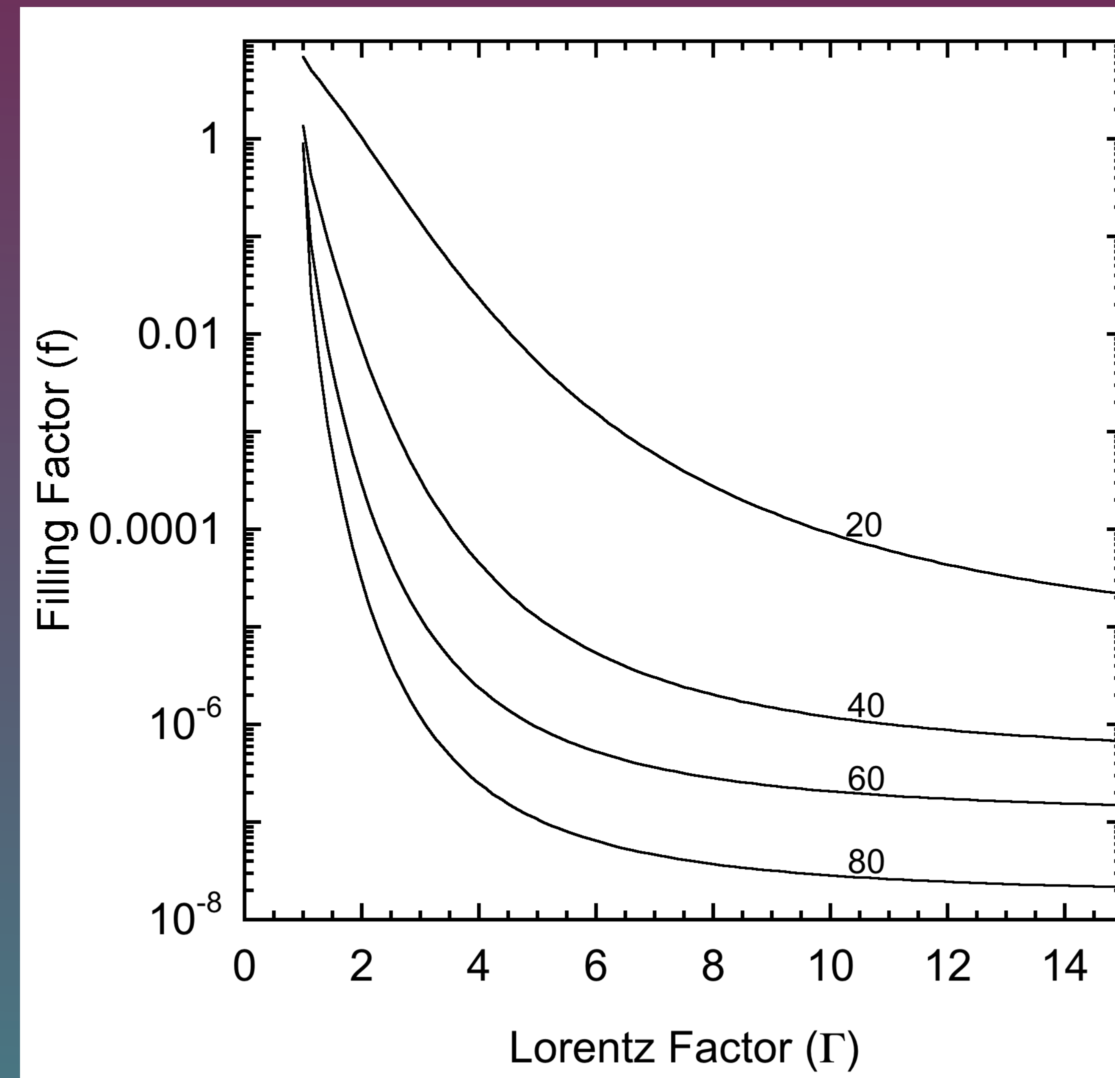
and .....

quite different from standard AGN models

log U = -1.9 typical of dusty photoionization models (Dopita et al. 2002)

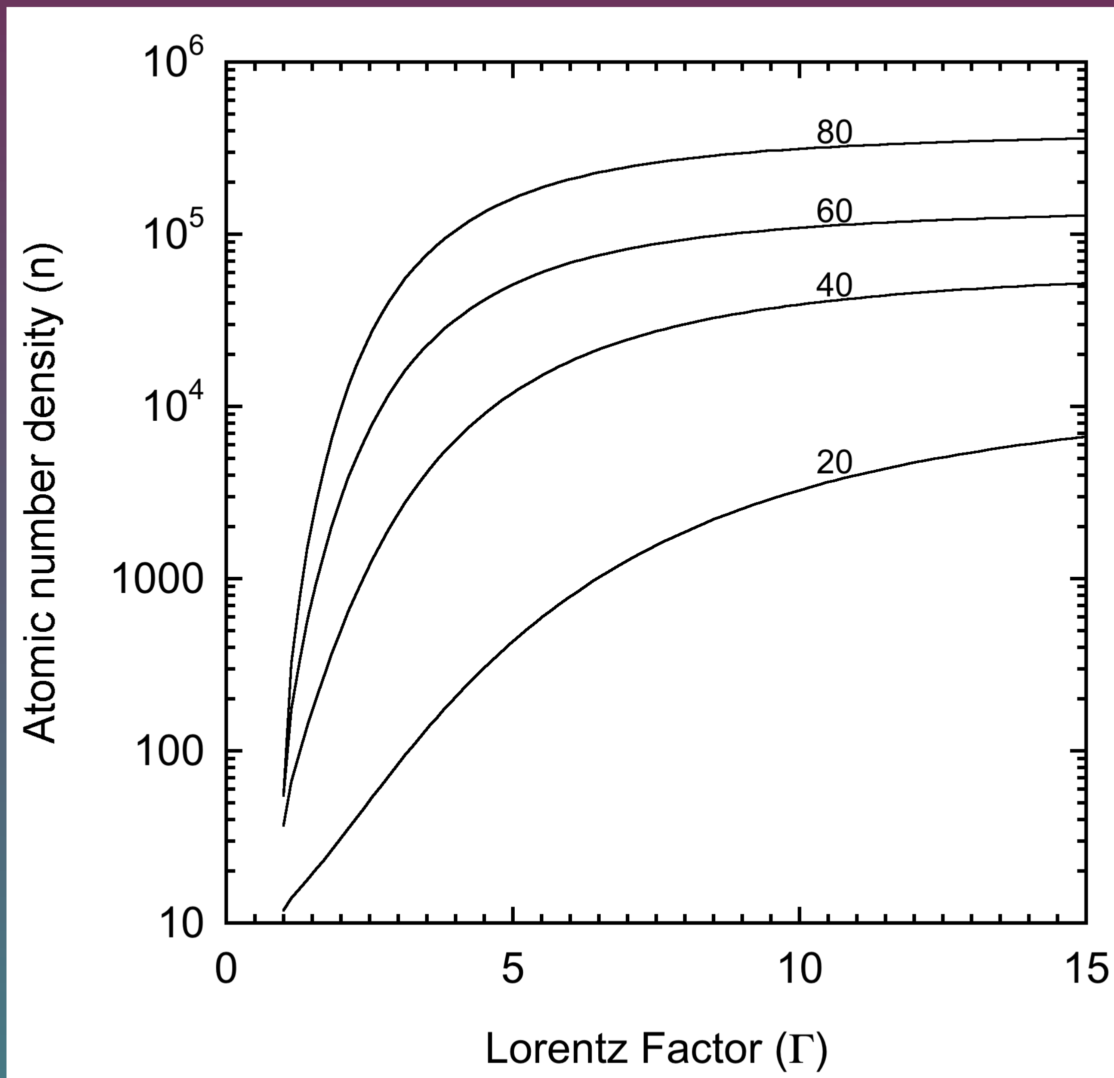
Density and filling factor

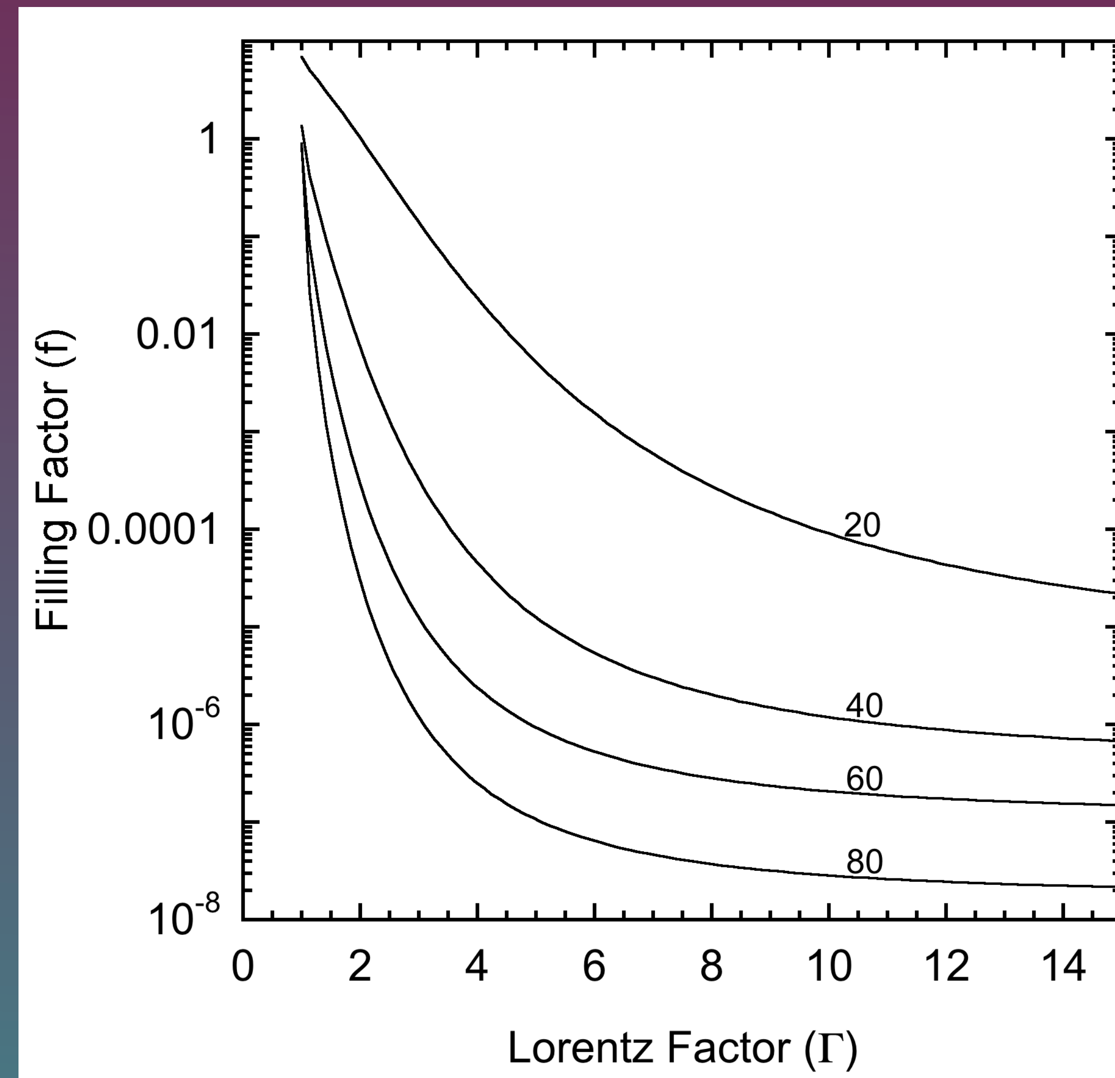




Indicates modest Lorentz factors < 5

Density and filling factor





Typical filling factors for entire Narrow Line Region in AGN ~ few x 10^{-2} – 10^{-4}

Indicates modest Lorentz factors < 5

Conclusions for Centaurus A

- Blue-shifted cloud in the core of Centaurus A photoionized by high energy emission from base of jet

- But ... beamed emission from jet consistent with low Lorentz factor not 15 as claimed by high energy model

- Greater consistency with deductions from VLBI data

- Need for substantial revision of models for high energy emission

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