Compact radio jets on sub-parsec scales

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Collaboration

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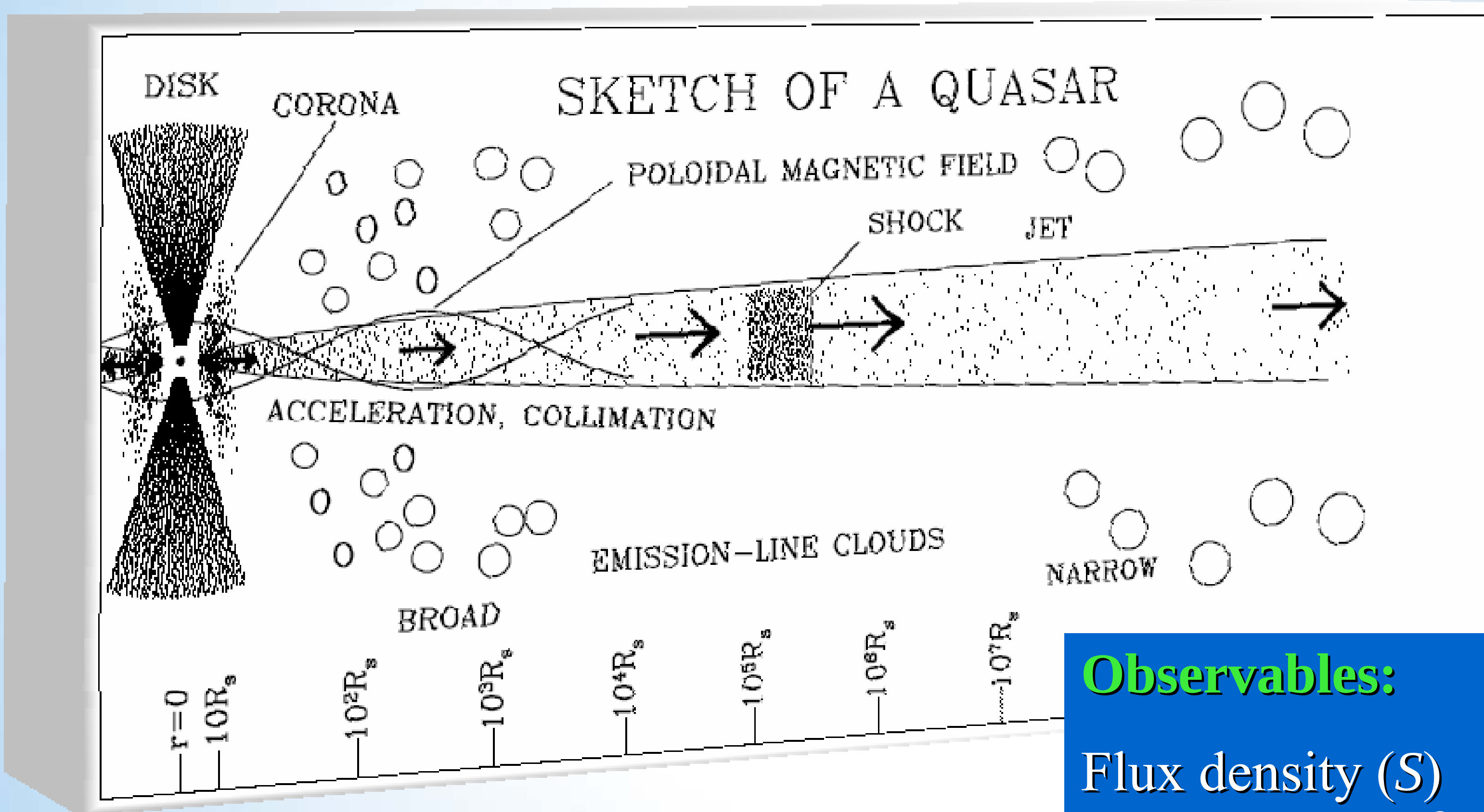
Active Galactic Nuclei (AGN)



Marscher 2005

Observables:

Flux density (S)
Angular Size (θ_{FWHM})
Apparent jet speed (β_{app})
➔ Brightness Temperature T_b

Brightness Temperature

Brightness temperature:

A temperature that a source should have as if it was a black body to radiate a specific intensity $I_\nu = S_\nu / \Omega$

$$T_{\rm b,s} = \frac{2\ln 2}{\pi k_{\rm B}} \frac{S_{\rm tot}\lambda^2}{d^2}(1+z)$$

* Gaussian pattern of brightness distribution

* Source rest frame

Inverse Compton limit:

Whenever T_b **> 10**^{12} **K**, inverse Compton scattering of radio photons dominates, and most of the energy will be radiated in X-ray. (Kellermann & Pauliny-Toth 1969)

Equipartition limit:

Sources radiate at T_b **~ 5 x 10**^{10} **K** when energy densities in relativistic particles and magnetic fields are in equipartition. (Readhead 1994)

High-resolution VLBI surveys enable to statistically study the brightness temperatures of compact radio sources and to test the theoretical models of relativistic outflows (e.g., Marscher 1995).

Relativistic effects and lower limit

Relativistic effects:

Radiation emitted from a jet component moving at a velocity of β with an angle θ_j to the line of sight can be Doppler boosted.

Doppler factor

$$\delta = \frac{1}{\gamma_j(1-\beta\cos\theta_j)}$$

$$\beta = (1-\gamma_j{}^{-2})^{1/2}$$

$$T_b = T_0\delta$$

Apparent jet speed

$$\beta_{app} = \frac{\beta\sin\theta_j}{1-\beta\cos\theta_j}$$

Lower limit of T_b:

Minimum resolvable size d_{min}

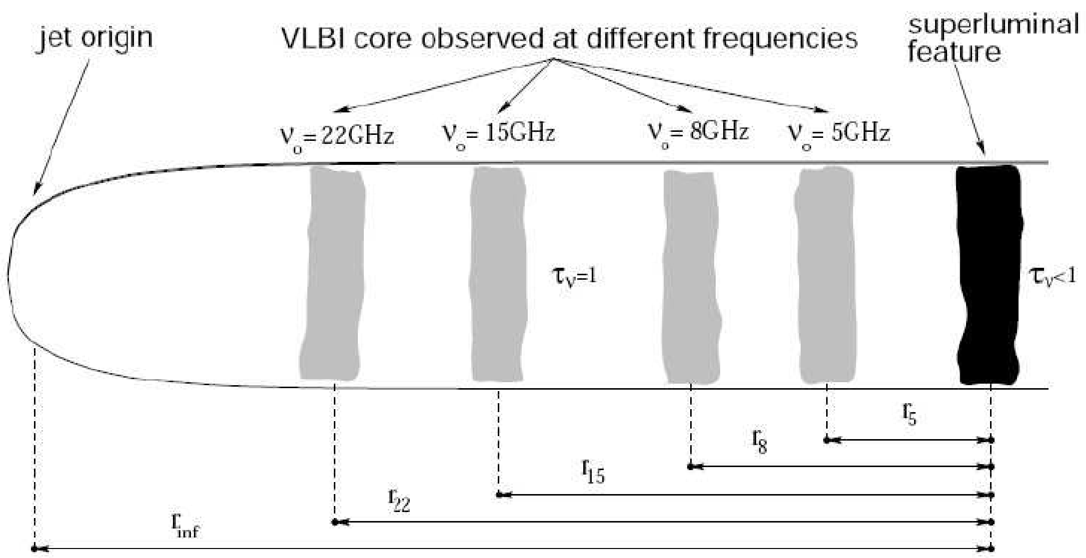
$$d_{min} = 2^{1+\beta/2}\left(\frac{ab\ln 2}{\pi}\ln\frac{SNR}{SNR-1}\right)^{1/2}$$

a,*b*: axes of restoring beam
SNR: signal-to-noise ratio
β : weighting function

When $d < d_{min}$, the lower limit of T_b should be estimated with $d = d_{min}$.

VLBI Core and its opacity effect

Frequency dependent position shift of VLBI core.
Lobanov (1996)



- VLBI core is located at a region where $\tau_\nu = 1$ in the jet.
- Under the equipartition condition, the absolute position of the VLBI core ***r*** is related to the total radiated synchrotron luminosity L_{syn}

$$r = \left[\xi \mathcal{C}_r L_{\rm syn}\{\nu(1+z)\}^{-1/k_{\rm r}}\right]^{1/3} \rm pc$$

In order to investigate the physics of compact radio jets in sub-parsec scale regions, we need to observe them at higher frequencies with high resolution (high resolution VLBI survey).

Database of T_b

❖ High resolution VLBI surveys

- At 2/8 GHz (Pushkarev & Kovalev 2008)
- At 15 GHz (Kovalev et al 2005)
- At 43 GHz (Fey et al.)
- At 86 GHz (Lee et al. 2008)

❖ Criteria on compilation of T_b

- Sources observed at more than two freq.
  - for reliable L_{syn}
- Excluding lower limits of T_b
  - hence no frequency-dependent of T_b
- Recalculating T_b in source frame
- Median values of T_b among multi-epochs
  - in order to take the near equipartition value (Homan et al. 2006)

A global 86 GHz VLBI Survey

Source selection criteria:

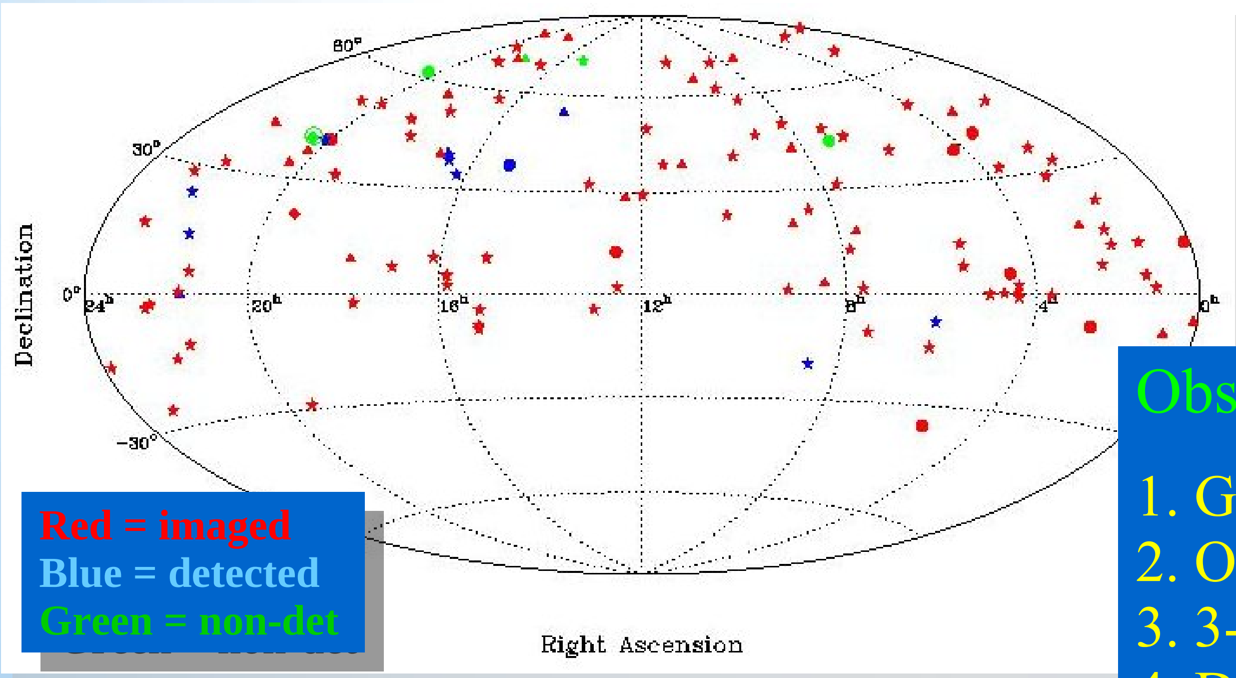
1. Flux density at 86 GHz is S_{86} > 0.3 Jy.
2. Source declination is δ > - 20°.
3. Exclude some bright sources imaged before.

Selected 127 sources:

88 QSOs
25 BL Lacs
11 Radio galaxies

Detected 121 sources

Imaged 109 sources



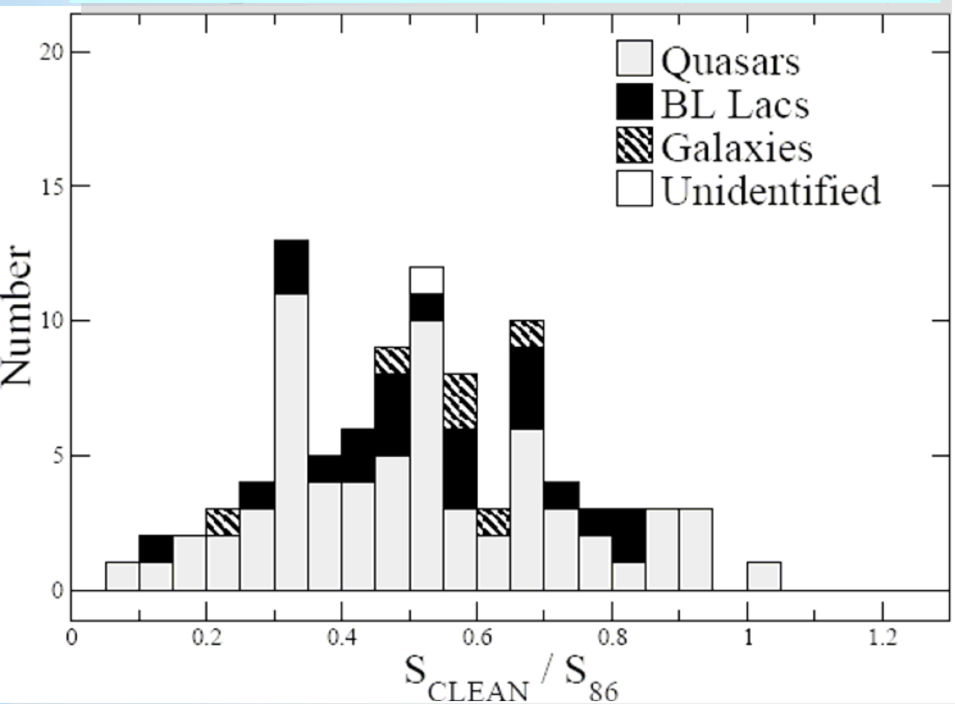
Observations:

1. Global mm-VLBI Array
2. Oct. 2001, Apr/Oct 2002
3. 3-4 scans for each object
4. Detection limit ~ 0.1 Jy

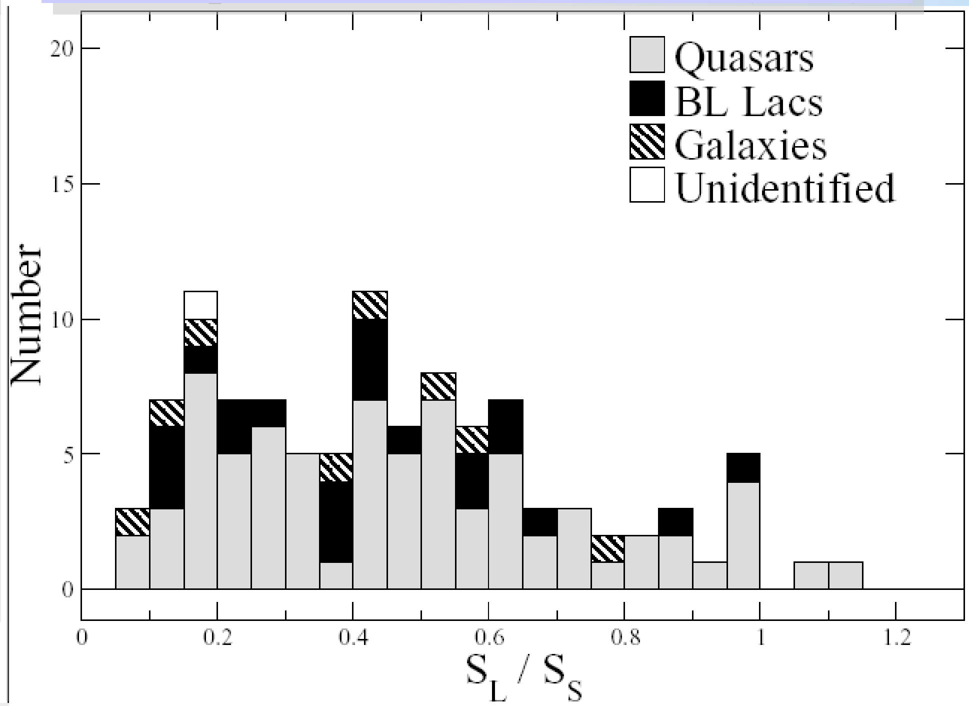
A global 86 GHz VLBI survey:

Source compactness

Compactness in mas scale (S_{CLEAN}/S_{86})

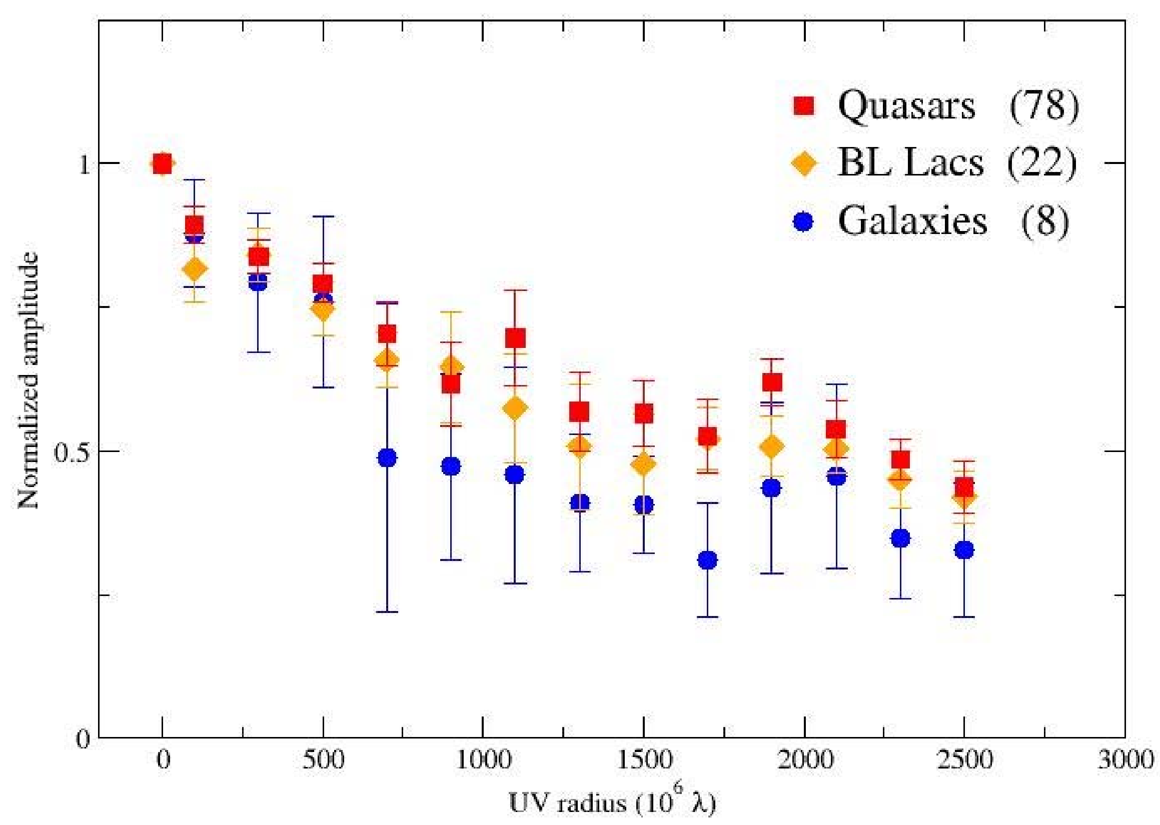


Compactness in sub-mas scale (S_L/S_S)



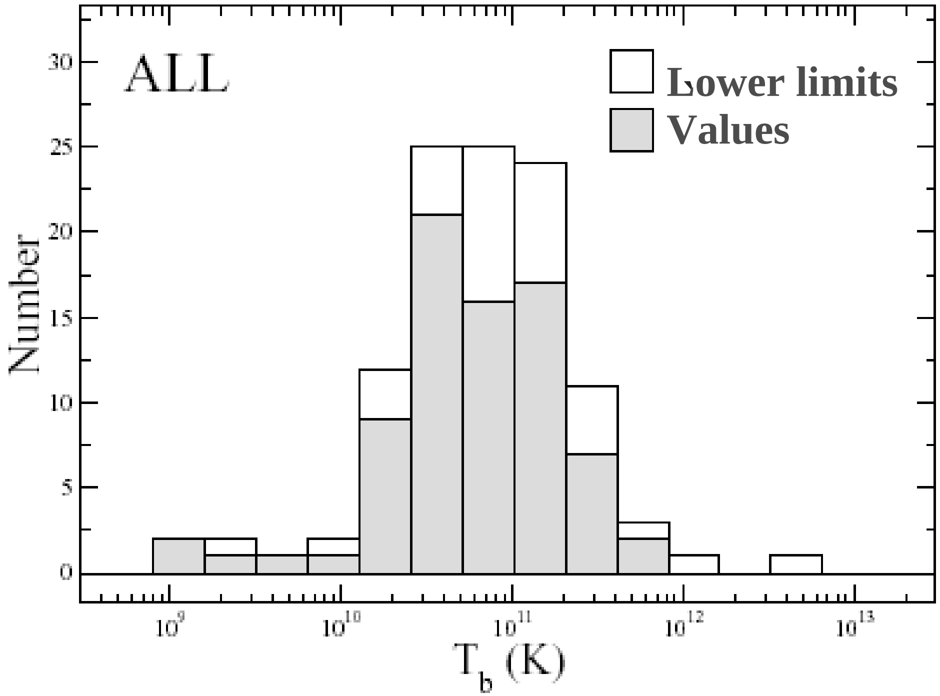
Large fraction of radio emission at 86 GHz is resolved out on mas-scale.
S_L / S_S < 0.5 for many sources.

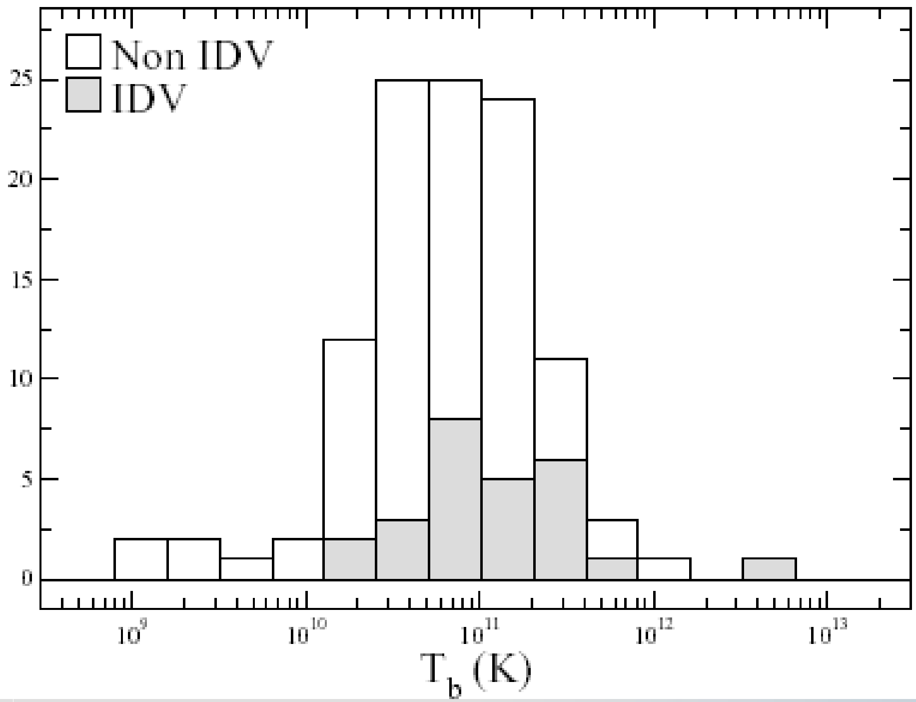
A global 86 GHz VLBI survey:
Normalized visibility amplitudes



Radio galaxies are less compact than quasars and BL Lacs;
Unified paradigm (Urry & Padovani 1995)

A global 86 GHz VLBI survey: **Distribution of T_b**

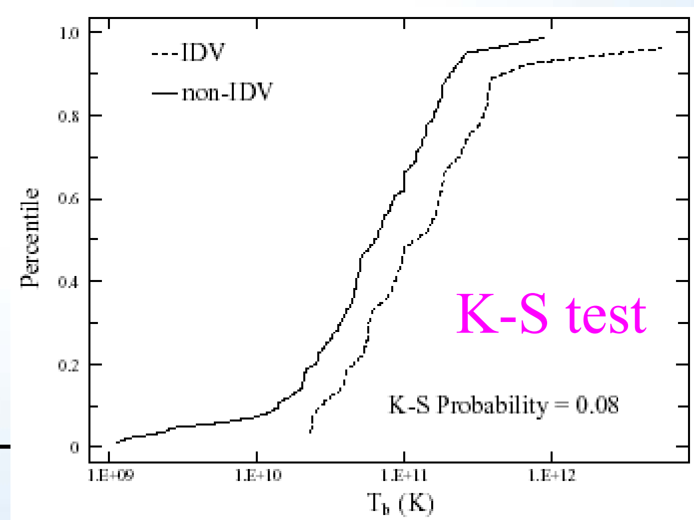




Median of $T_b = 7 \times 10^{10}$ K
For 1% of sources $T_b > 1 \times 10^{12}$ K
For 8% of sources $T_b > 3 \times 10^{11}$ K

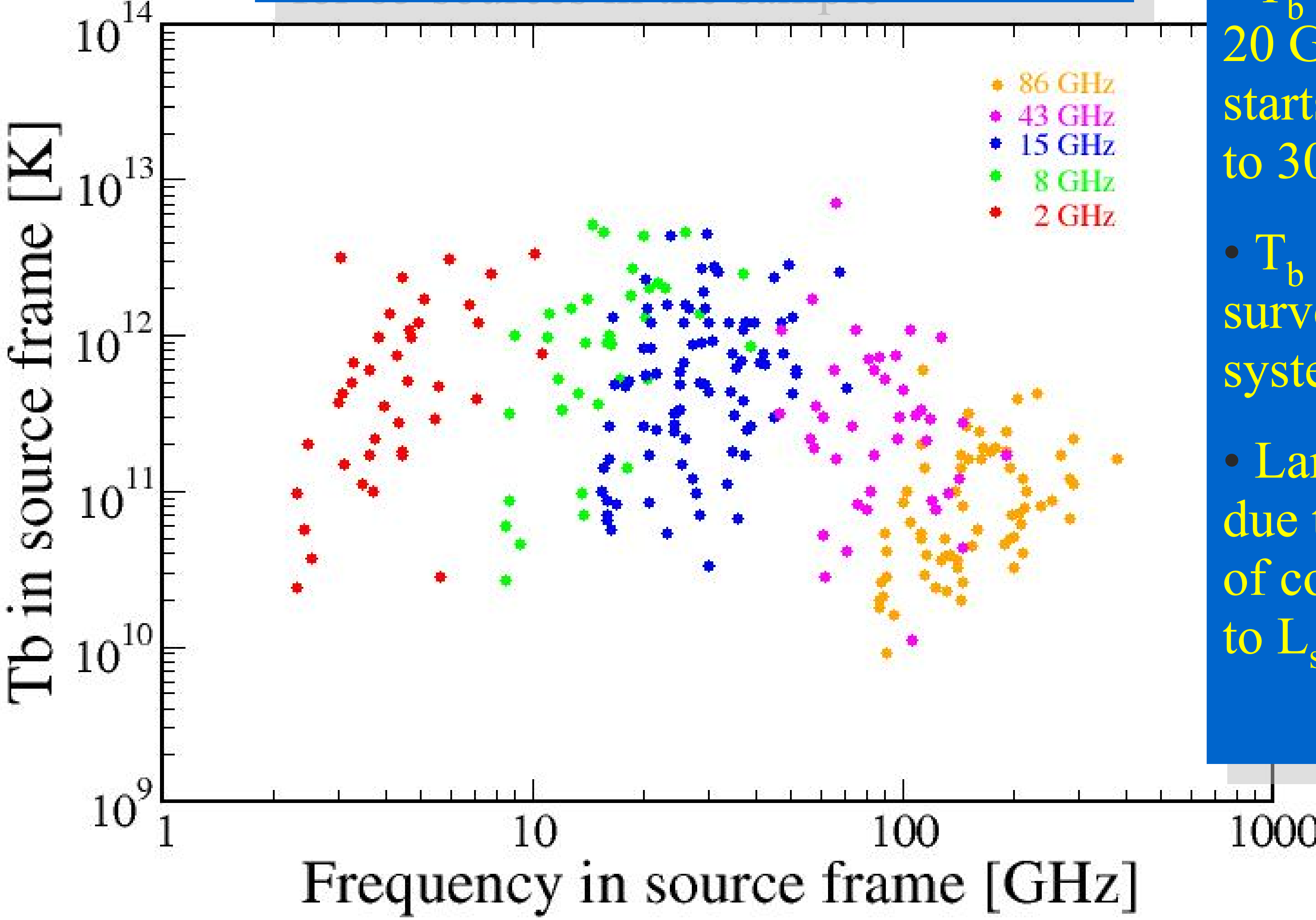
Lower limits obtained taking into account the **minimum resolvable size**

IDV sources have higher T_b for their cores than non-IDV.



Change of T_b in a jet

Quasi-simultaneous multi-frequency T_b for 85 sources in the sample

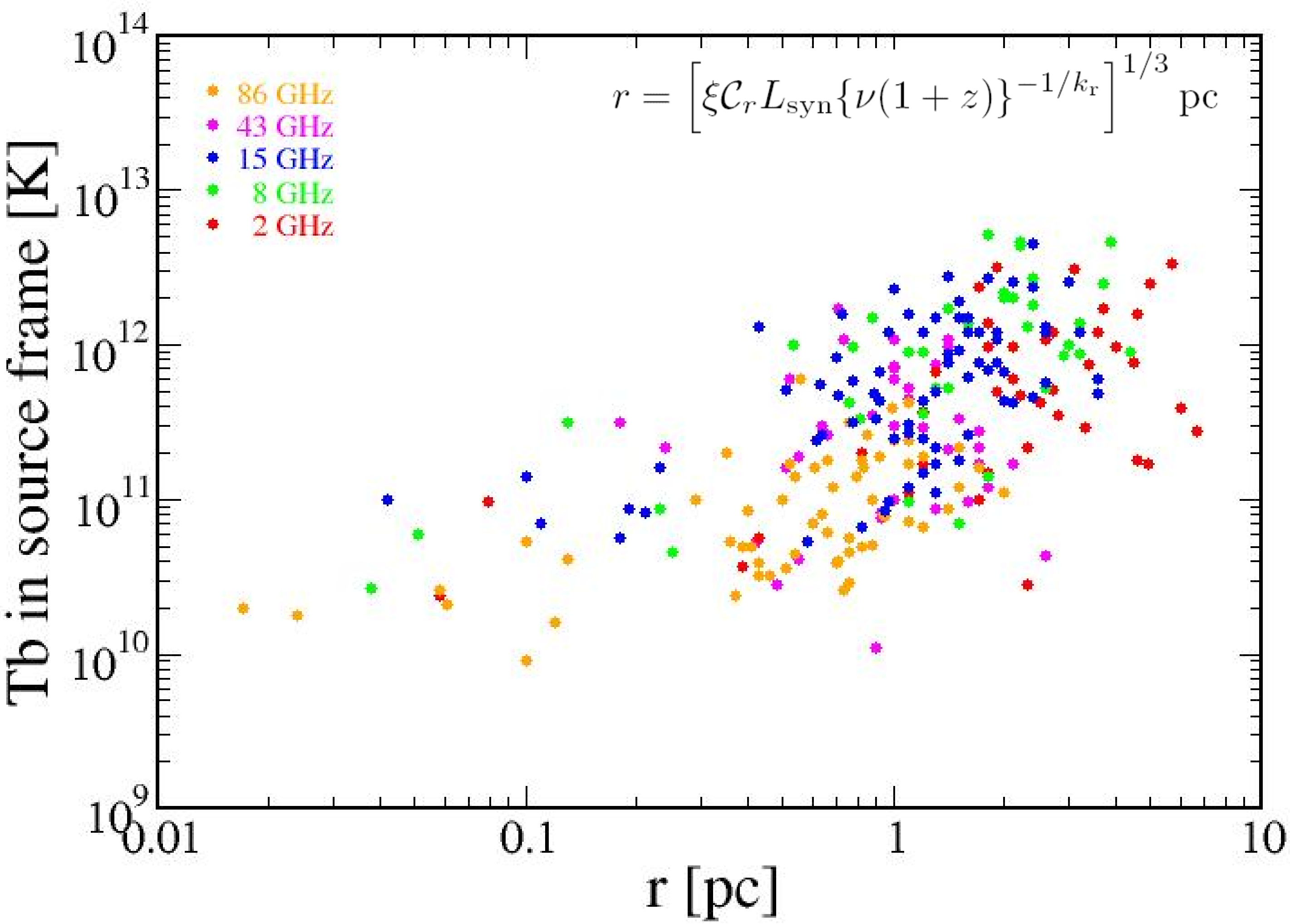


Change of Tb

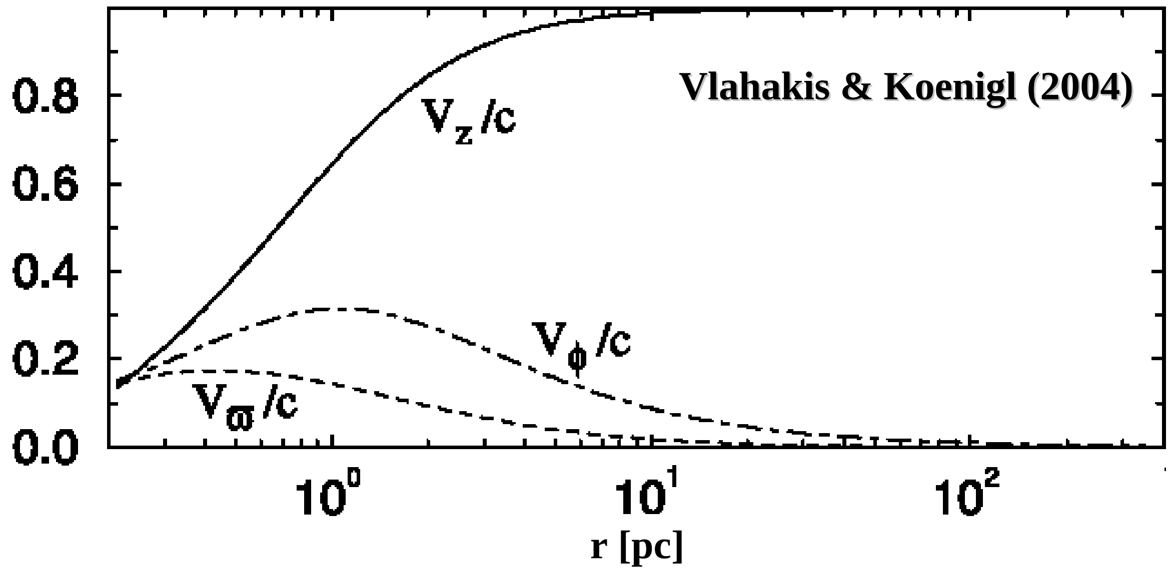
- T_b increases up to 20 GHz and then starts to decrease up to 300 GHz.
- T_b from mm-VLBI surveys appear to be systematically low.
- Large scatter of T_b due to the dependence of core abs. position to L_{syn}.

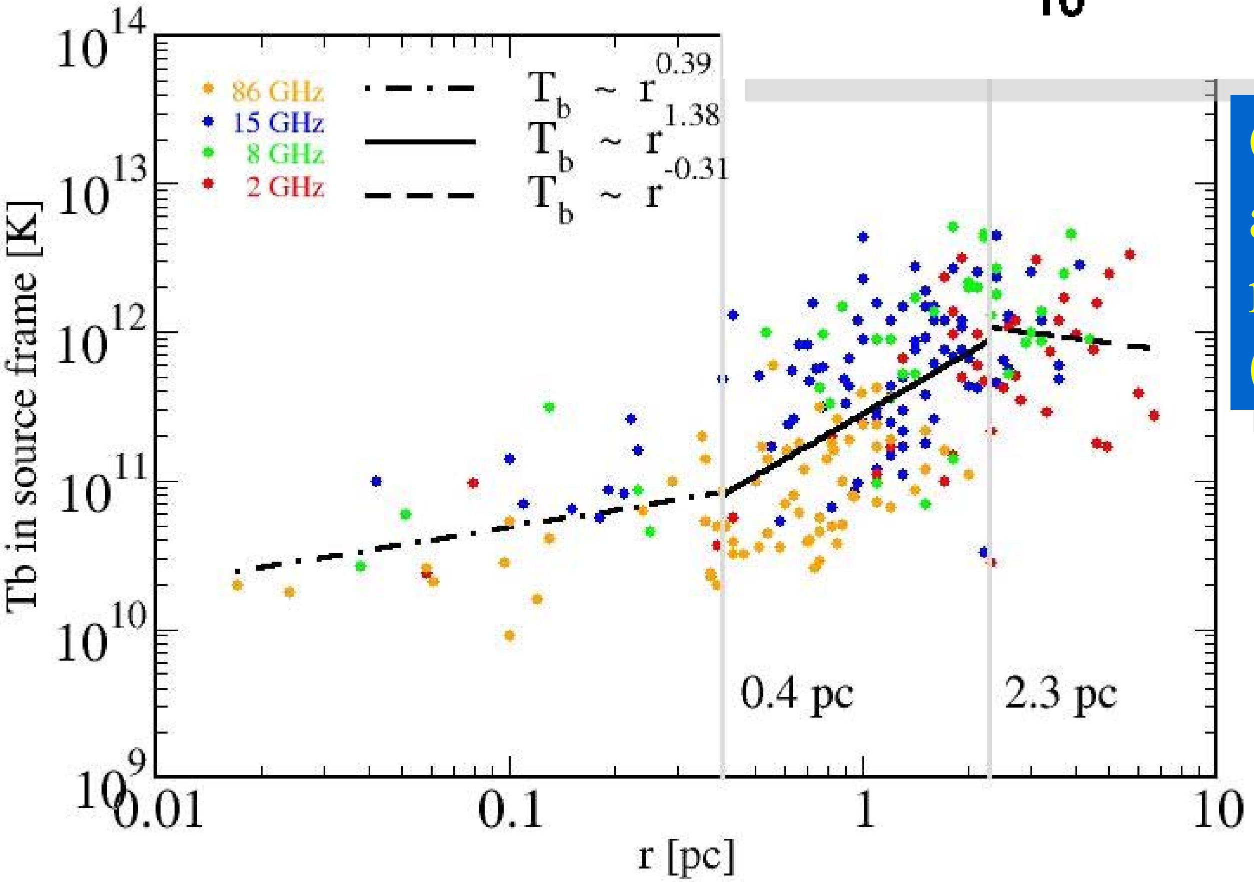
Change of T_b in a jet

Derived from Blandford & Königl 1979 and Königl 1981



Change of T_b in a jet

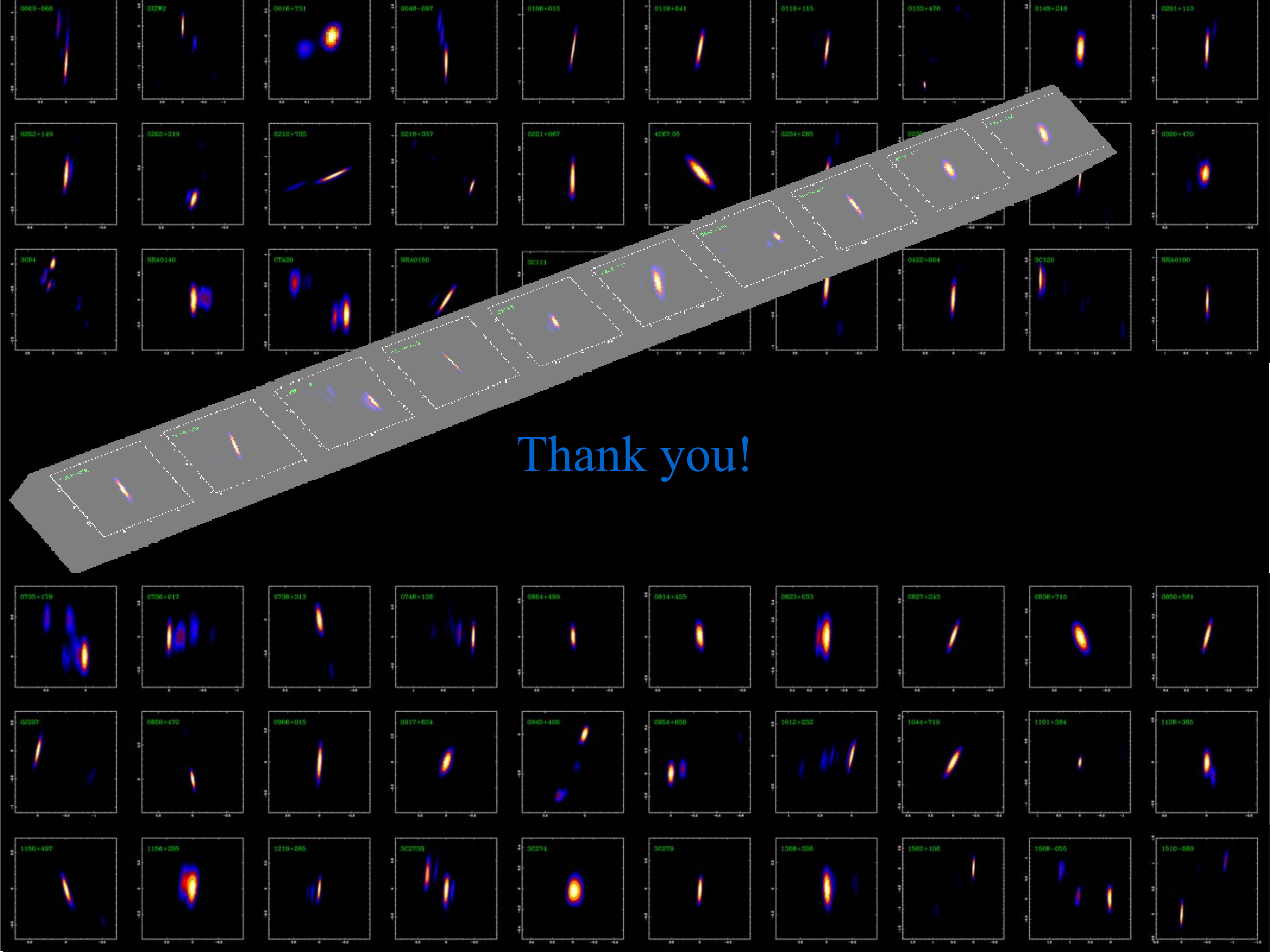




Compact jets may be accelerated by magnetohydrodynamic (MHD) forces.

Summary

1. **High-resolution VLBI surveys** enable to statistically study the brightness temperatures of compact radio sources and to test the theoretical models of relativistic outflows.
2. **The VLBI cores** of the compact radio sources are optically thick at a given frequency.
3. **Under the equipartition condition** between the magnetic field energy and particle energy density, the absolute distance of the VLBI core can be predicted.
4. **From the database** of high resolution VLBI surveys at five frequencies (2, 8, 15, 43, and 86 GHz) the brightness temperatures in the rest frame are investigated in the sub-parsec regions of the compact radio sources.
5. **From the vicinity of the central engine**, the brightness temperatures increase slowly and then rise with steeper slope, implying that the jets are collimated and accelerated by the magnetically driven force, as predicted by Vlahakis and Koenigl (2004).


Thank you!

Appendix: absolution position of VLBI core

- **The total radiated synchrotron power radiated from the emission region of $r_{min} < r < r_{max}$ in a jet (Blandford & Konigl 1979):**

$$L_{\rm syn} = \frac{1}{8} k_{\rm e} \Delta \gamma_{\rm j} \beta_{\rm j} c B^2 r^2 {\phi_{\rm o}}^2$$

$\Delta = \ln(r_{max} / r_{min})$, γ_j: Lorentz factor of a jet, β_j: jet speed, Φ_o : jet opening angle

- **Optical depth to synchrotron (see Rybicki & Lightman 1979):**

$$\tau_{\rm s}(r) = C_2(\alpha) N_1 \left(\frac{e B_1}{2\pi m_{\rm e}} \right)^{\epsilon} \frac{\delta^{\epsilon} \phi_{\rm o}}{r^{(\epsilon m + n - 1)} \nu^{\epsilon + 1}}$$

- **The physical distance of the observed VLBI core from the central engine when optical depth equals to unity:**

$$r = [\nu^{-1}(1+z)^{-1} {B_1}^{k_{\rm b}} \{6.2 \cdot 10^{18} C_2(\alpha) {\delta_{\rm j}}^{\epsilon} N_1 \phi_{\rm o}\}^{1/(\epsilon+1)}]^{1/k_{\rm r}} {\rm pc}$$

B1, N1 : magnetic field and electron density at 1 pc from the central engine,

Appendix: absolution position of VLBI core

- Under the equipartition condition, the absolute position of the VLBI core ***r*** is related to the total radiated synchrotron luminosity ***Lsyn***

$$r = \left[\xi \mathcal{C}_r L_{\rm syn} \{\nu(1+z)\}^{-1/k_{\rm r}}\right]^{1/3} \mathrm{pc},$$

$$\xi = 1.1 \cdot 10^{-37} \frac{8}{k_{\rm e}\Delta} \left[6.2 \cdot 10^{18} C_2(\alpha)\right]^{1/k_{\rm r}(\epsilon+1)}$$

$$\mathcal{C}_r = \frac{\left[B_1{}^{k_{\rm b}} (\delta_{\rm j}{}^{\epsilon} N_1 \phi_{\rm o})^{1/(\epsilon+1)}\right]^{1/k_r}}{\gamma_{\rm j}\beta_{\rm j} c B^2 \phi_{\rm o}{}^2},$$