Credit: NASA/JPL-Caltech

Global Millimeter VLBI Array Survey of Ultra-compact Extragalactic Radio Sources at 86 GHz

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EAS, Leiden

The Global MM-VLBI Array (GMVA)

Telescopes - 8 VLBA + 6 European stations (Pv,PdB,Ef,On,Ys,Mh)

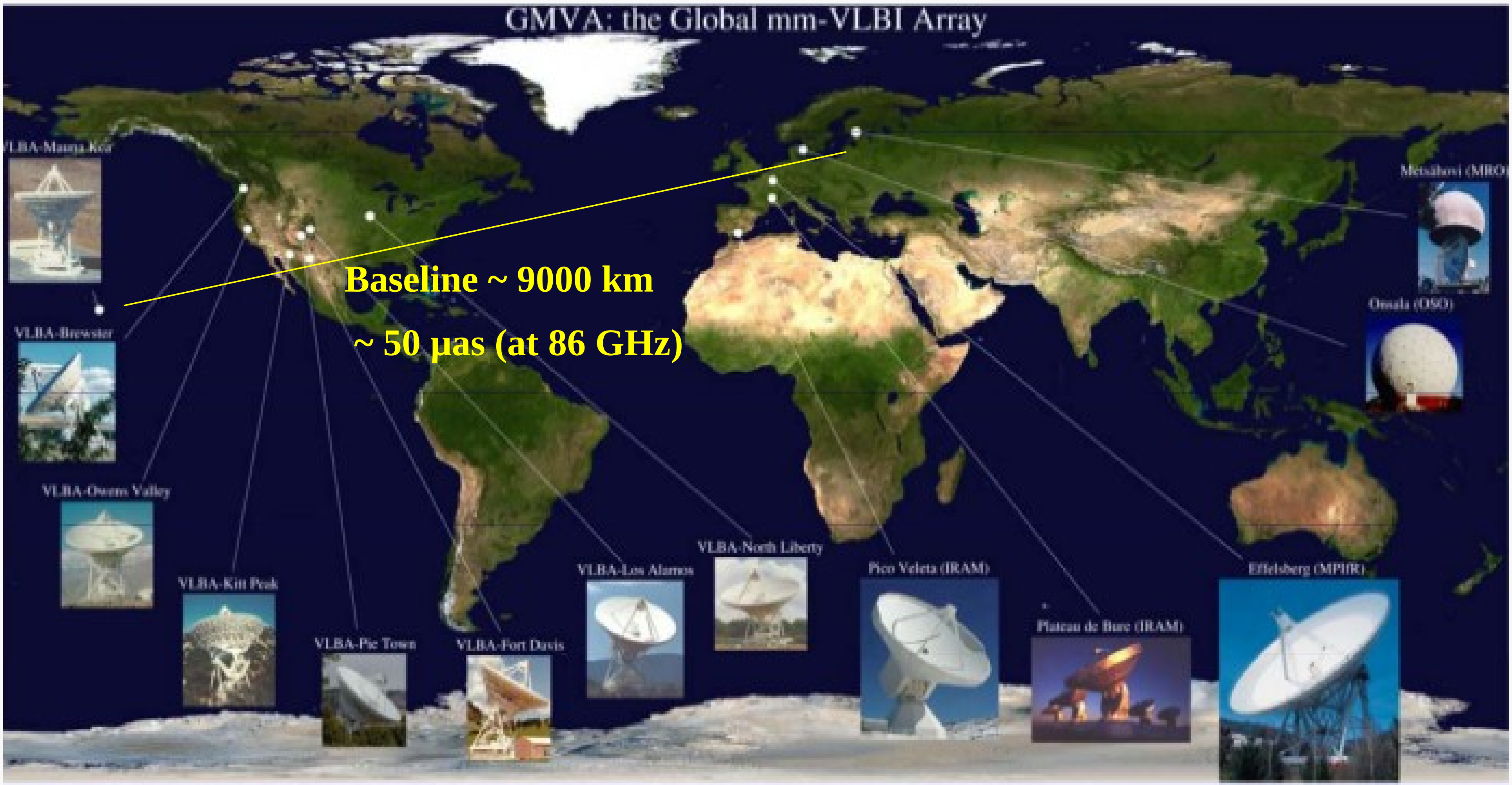
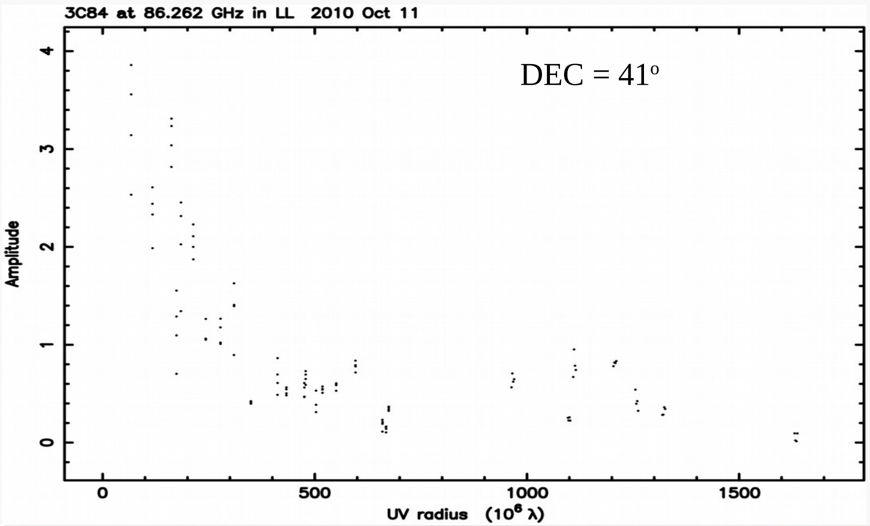
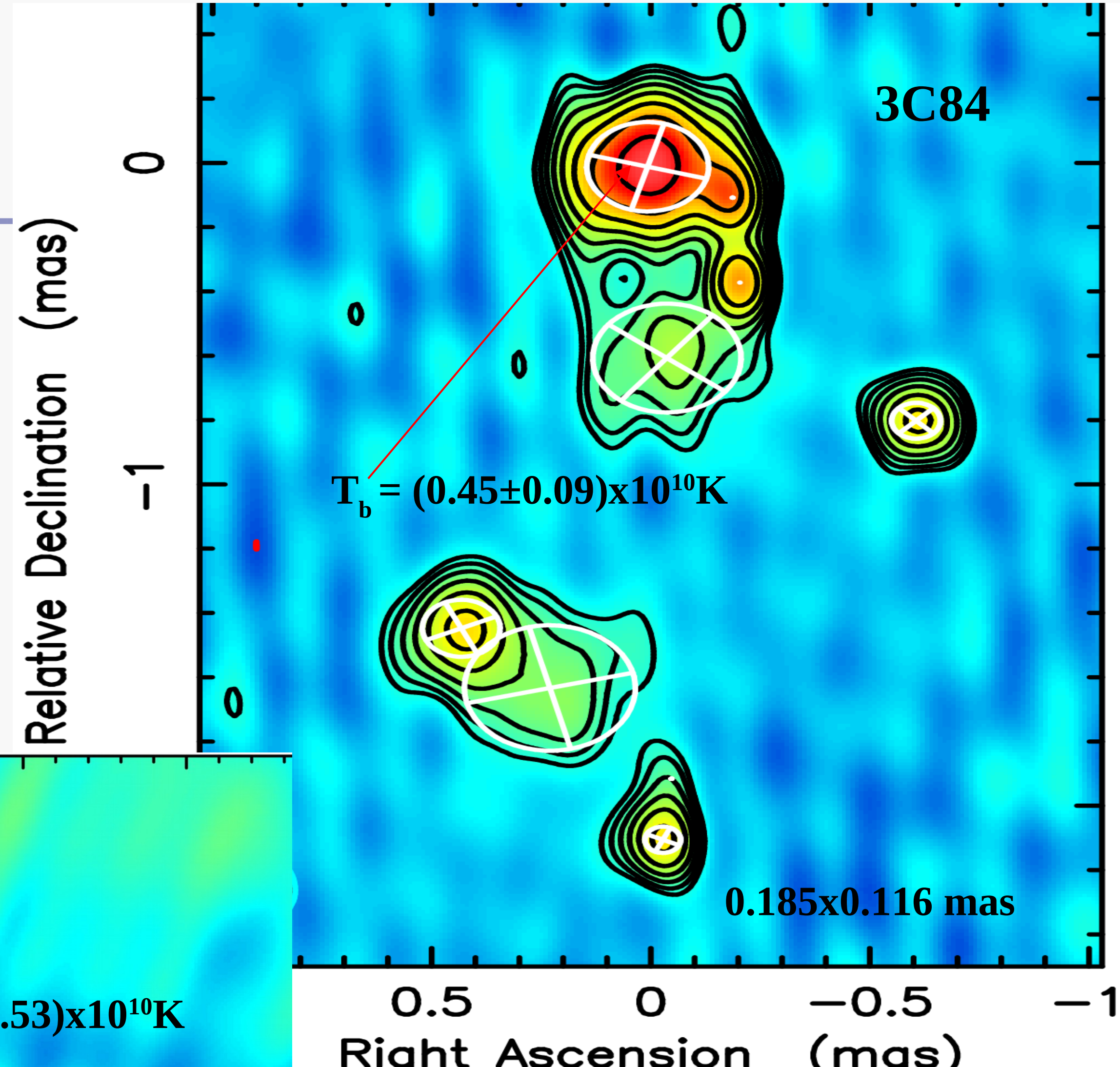


Image Credit : http://www.mpifr.de/div/vlbi/globalmm

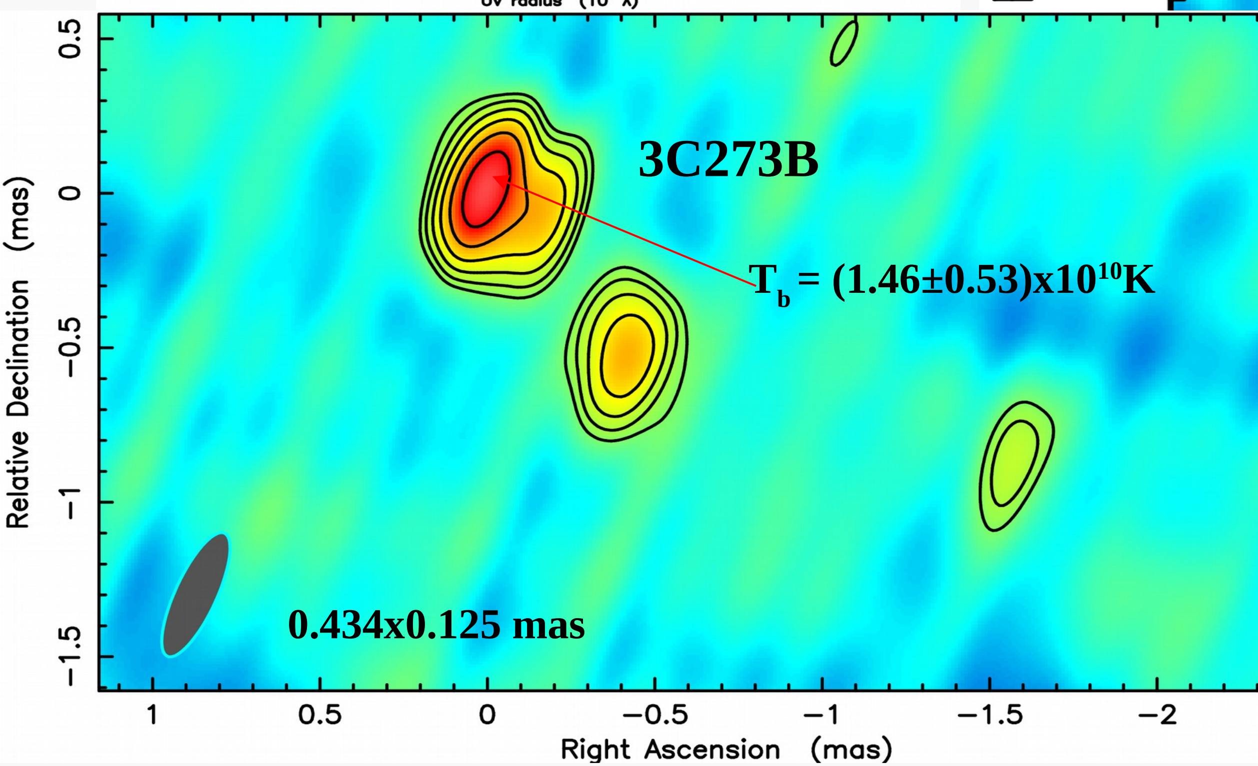
3mm maps



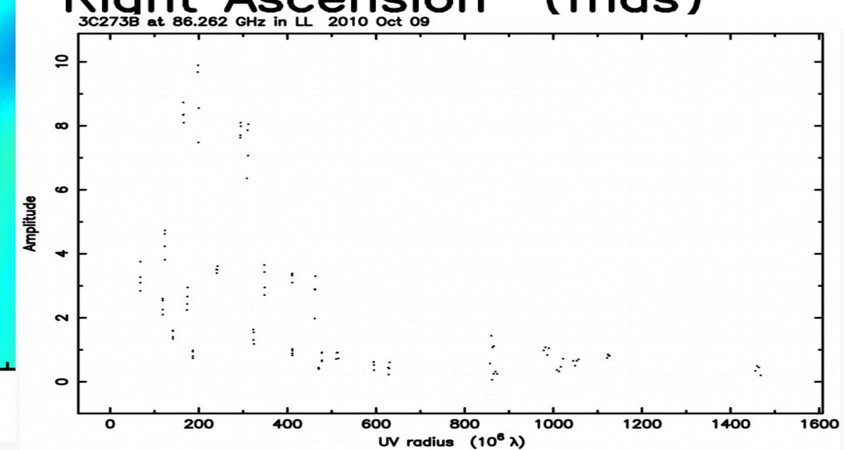
3C84 at 86.262 GHz in LL 2010 Oct 11
DEC = 41°
Amplitude
UV radius (10^6 λ)



3C84
T_b = (0.45±0.09)x10^10K
0.185x0.116 mas
Relative Declination (mas)
Right Ascension (mas)

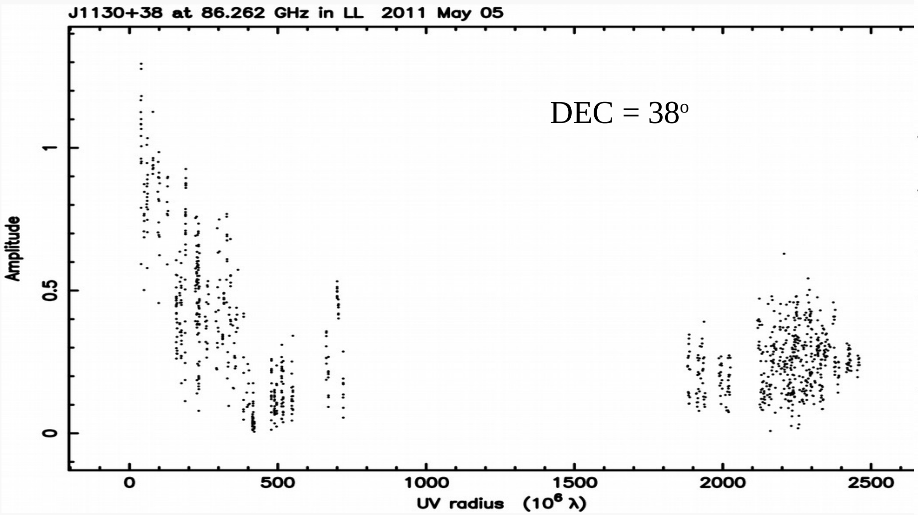


3C273B
T_b = (1.46±0.53)x10^10K
0.434x0.125 mas
Relative Declination (mas)
Right Ascension (mas)

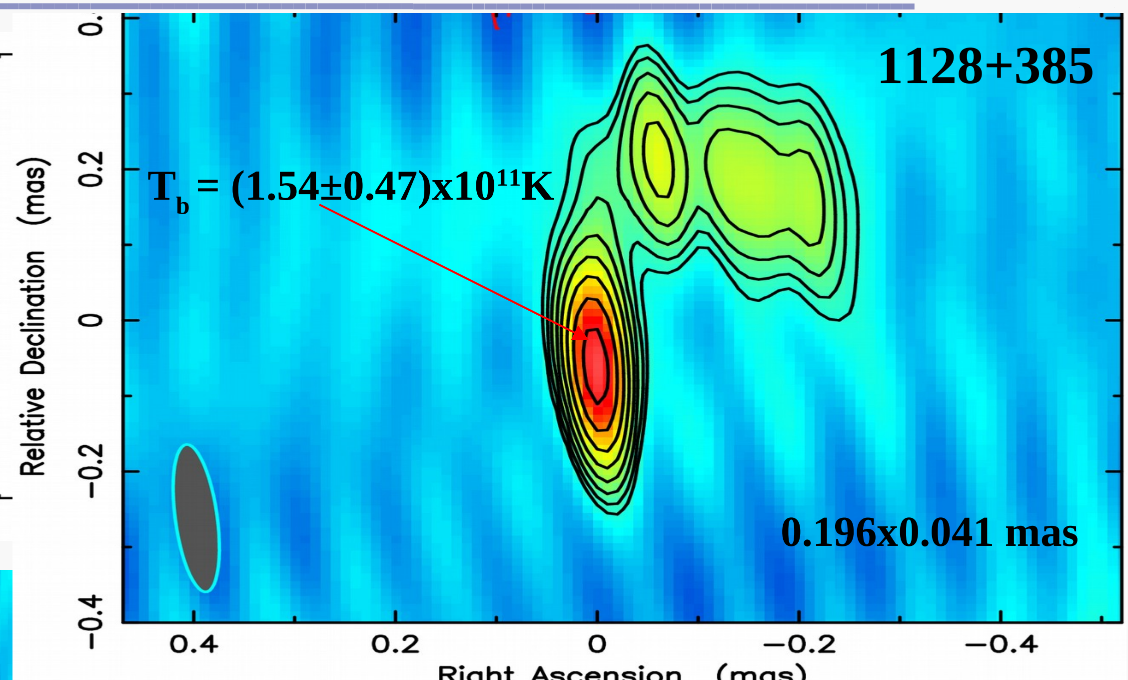


3C273B at 86.262 GHz in LL 2010 Oct 09
Amplitude
UV radius (10^6 λ)

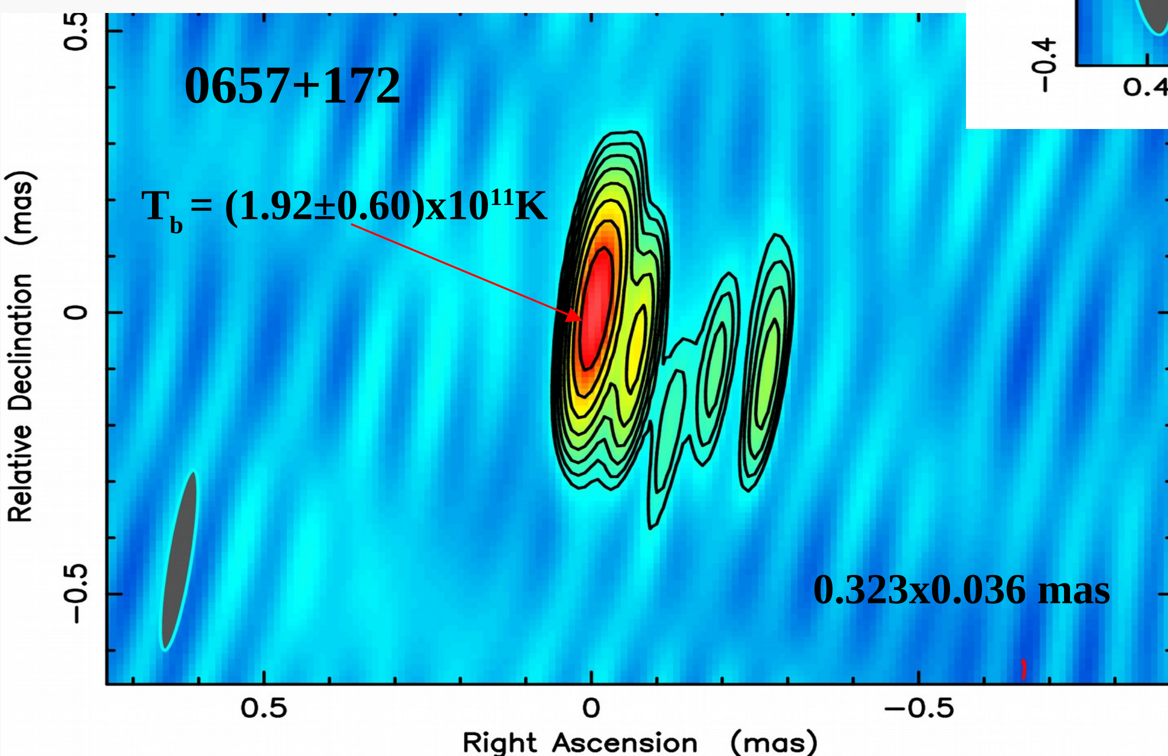
3mm maps



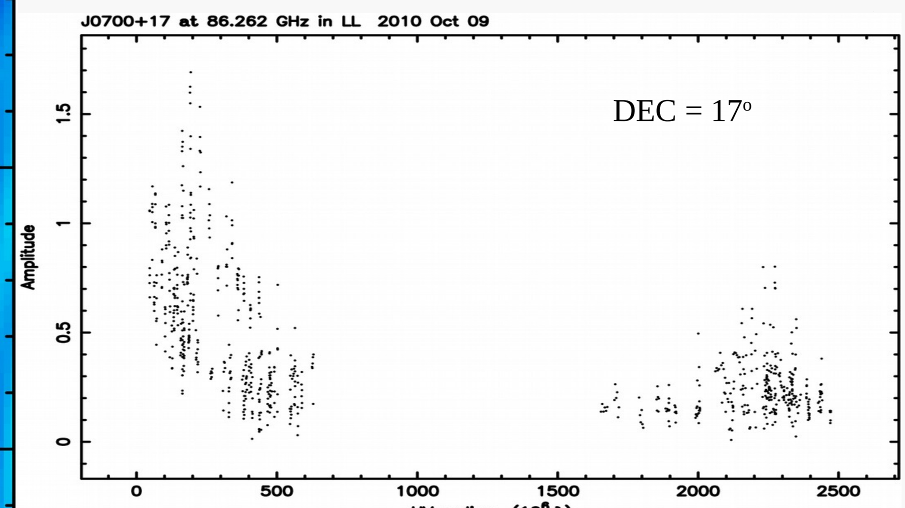
J1130+38 at 86.262 GHz in LL 2011 May 05
DEC = 38°
Amplitude
UV radius (10⁶ λ)



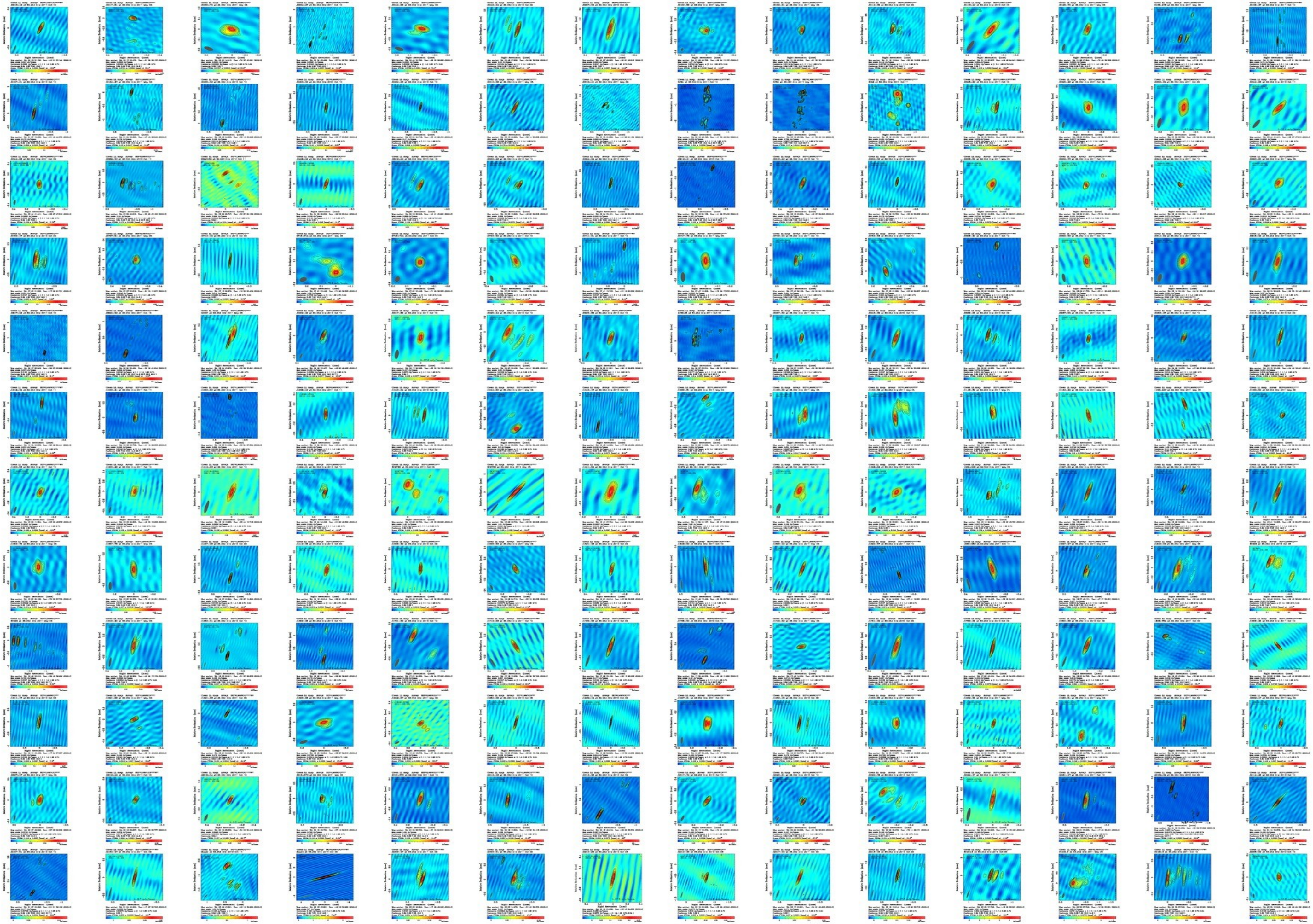
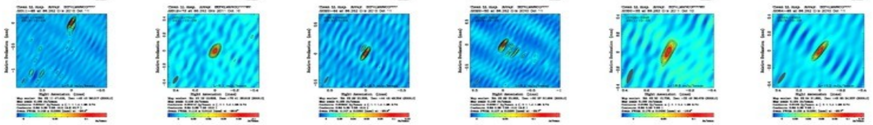
1128+385
T_b = (1.54±0.47)x10¹¹K
0.196x0.041 mas
Relative Declination (mas)
Right Ascension (mas)



0657+172
T_b = (1.92±0.60)x10¹¹K
0.323x0.036 mas
Relative Declination (mas)
Right Ascension (mas)



J0700+17 at 86.262 GHz in LL 2010 Oct 09
DEC = 17°
Amplitude
UV radius (10⁶ λ)

3mm maps of 174 (162 unique) radio sources (Nair et al. 2019, A&A). See https://www3.mpifr-bonn.mpg.de/div/3mmsurvey/

Population modelling for the brightness temperature T_b - *VLBI cores*

Probability density of brightness temperature,

$$p(T_b) \propto \left[\frac{2\gamma_j \left\{ \left(\frac{T_0}{T_b} \right)^{\epsilon} - \left(\frac{T_0}{T_b} \right)^{2\epsilon} - 1 \right\}}{\gamma_j^2 - 1} \right]^{1/2}$$

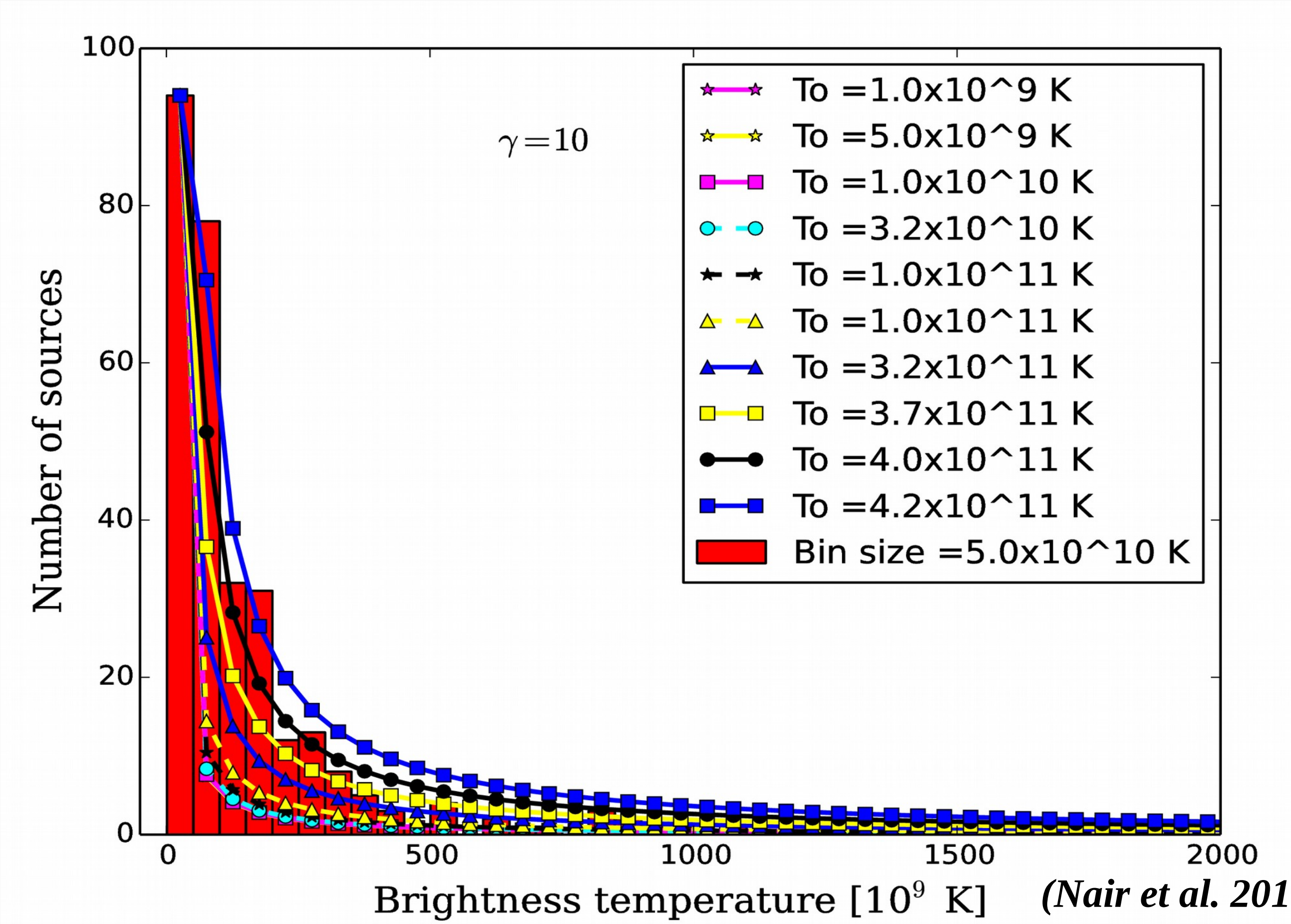
where $\delta = (T_b / T_0)^{\epsilon}$

T_0 - intrinsic bright. temp

T_b - observed bright. temp

δ - doppler factor

(Lobanov et al. 2000)



(Nair et al. 2019, A&A)

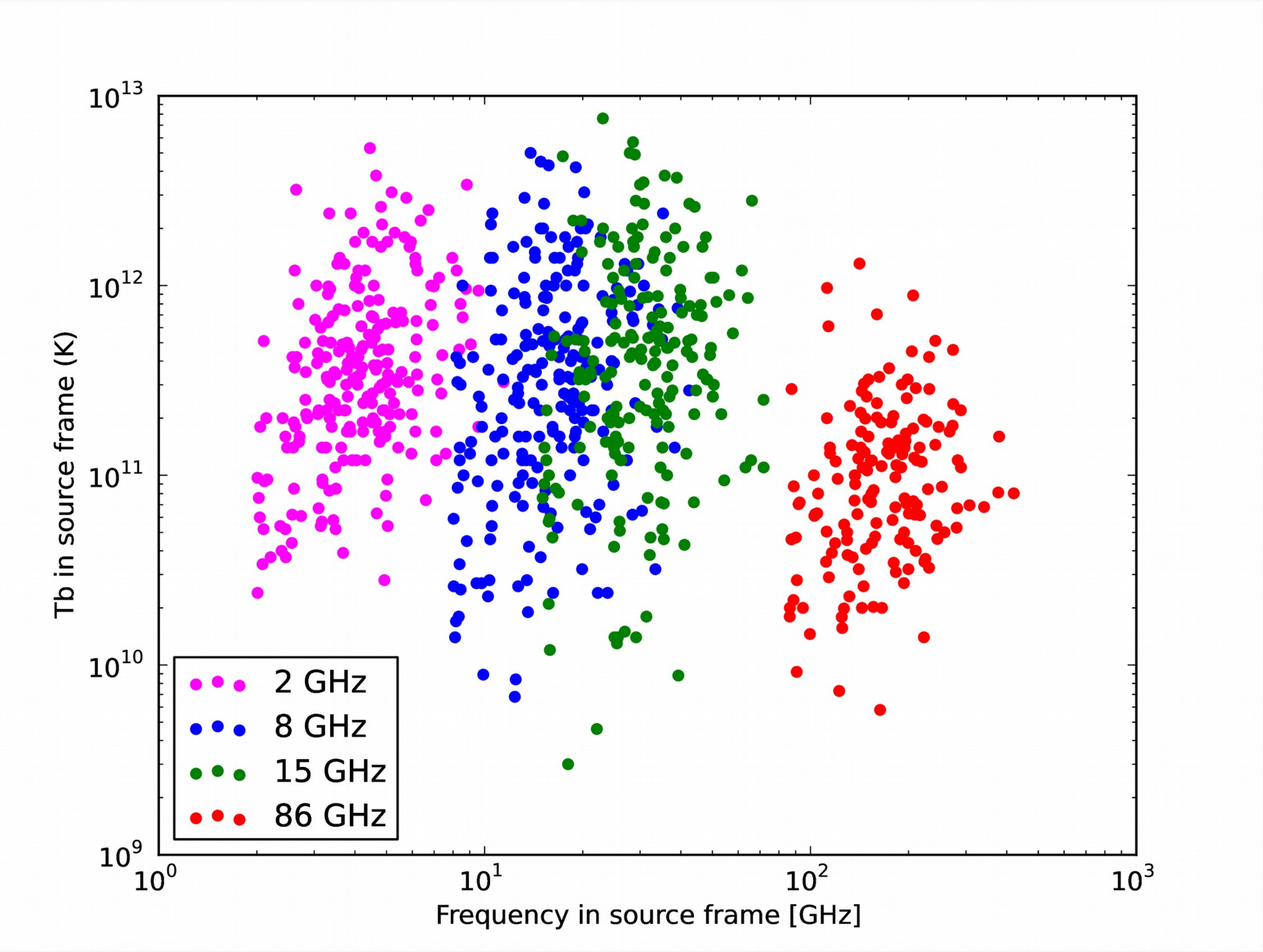
T_b range :

[1.1 x 10^9 K – 5.5 x 10^{12} K]

$T_{0,\mathrm{core}\ [86\ \mathrm{GHz}]}$ = (3.77±0.14) x 10^{11} K

(*~ Inverse Compton limit, 5x10^{11} K, Kellermann & Pauliny-Toth 1969*)

T_b of VLBI cores as a function of frequency

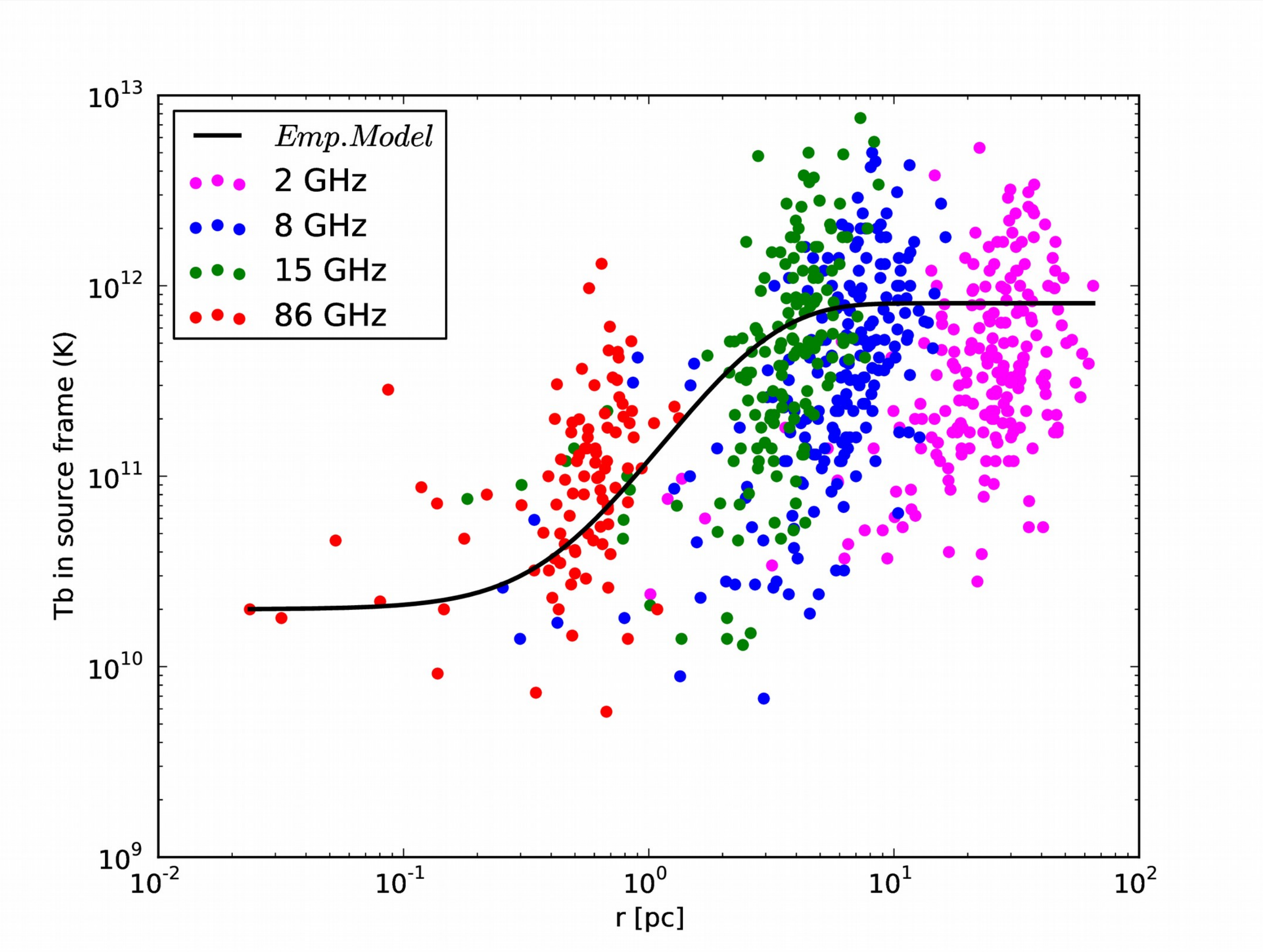


- **T_b at 86 GHz is lower**
- **Decrease of T_b at 86 GHz – kinematics of jets, acceleration or deceleration scenarios(*Marscher 1995*) ?**

→ *2 and 8 GHz data (Pushkarev & Kovalev 2012)*
→ *15 GHz data (Kovalev et. al 2005)*

Evolution of T_b of VLBI cores as a function of distance from central black hole

$$T_b = T_0 + (T_m - T_0)\{1 - (r \operatorname{csch} r)^a\}$$



$T_0 = 2.0\text{x}10^{10}$ K

Best fit for T_m = (8.09 ± 0.48)x10^{11} K

a = 0.85 ± 0.24

$T_b(r)$ dependence shape expected for MHD acceleration (Vlahakis & Königl 2004)

Evolution of Doppler factor and Lorentz factor as a function of distance from central BH

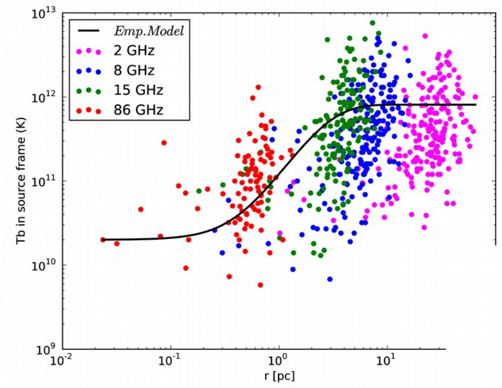
$$\delta = \frac{1}{\gamma_j (1 - \beta \cos\theta_j)} \quad \text{where} \quad \beta = \frac{1}{(1 - \gamma_j^{-2})^{1/2}}$$

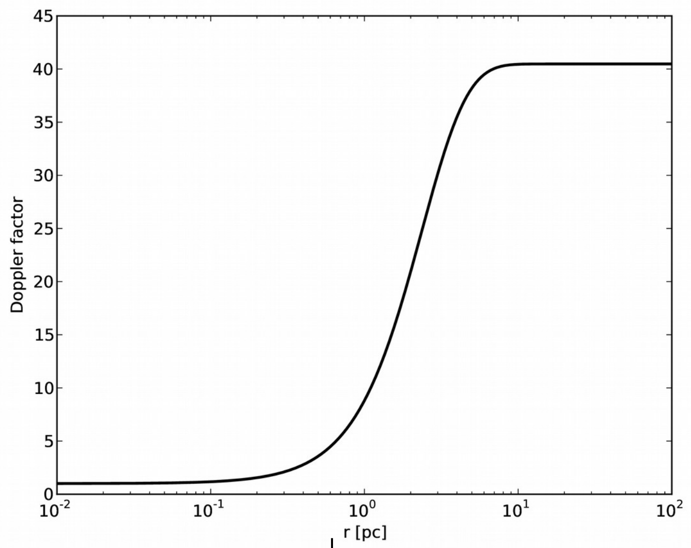
$$\delta^2 \sin^2\theta_j \gamma_j^2 - 2\delta\gamma_j + (1 + \delta^2 \cos^2\theta_j) = 0$$

$$\gamma_j = \frac{1 - \cos\theta_j (1 - \delta^2 \sin^2\theta_j)^{1/2}}{\delta \sin^2\theta_j}$$

$T_b = \delta\, T_0$ –> $T_b(r) = \delta(r)/\delta_0 \,.\, T_0(r)$

$\delta(r) = \delta_0 + [1 + (T_m/T_0 - 1)\,\{1 - (r \,\mathrm{csch}\, r)^a\}]$



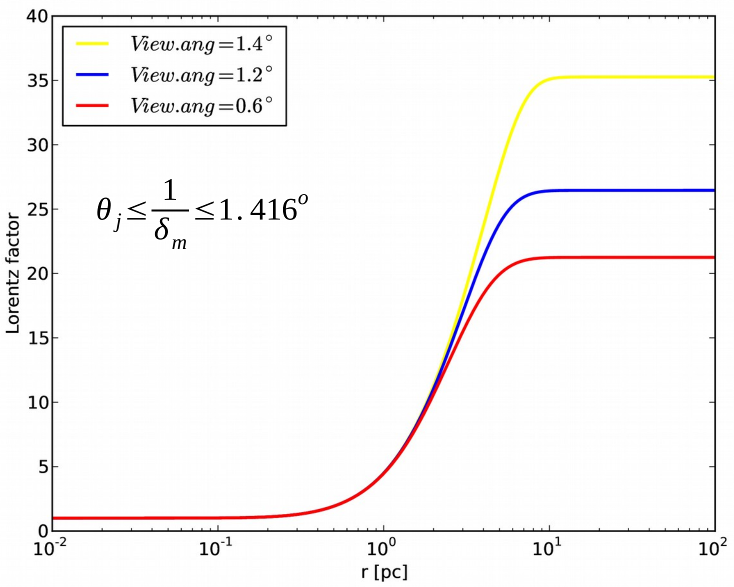


T_0 = 2.0x10[10] K

T_m = (8.09±0.48)x10[11] K

a = 0.85±0.24

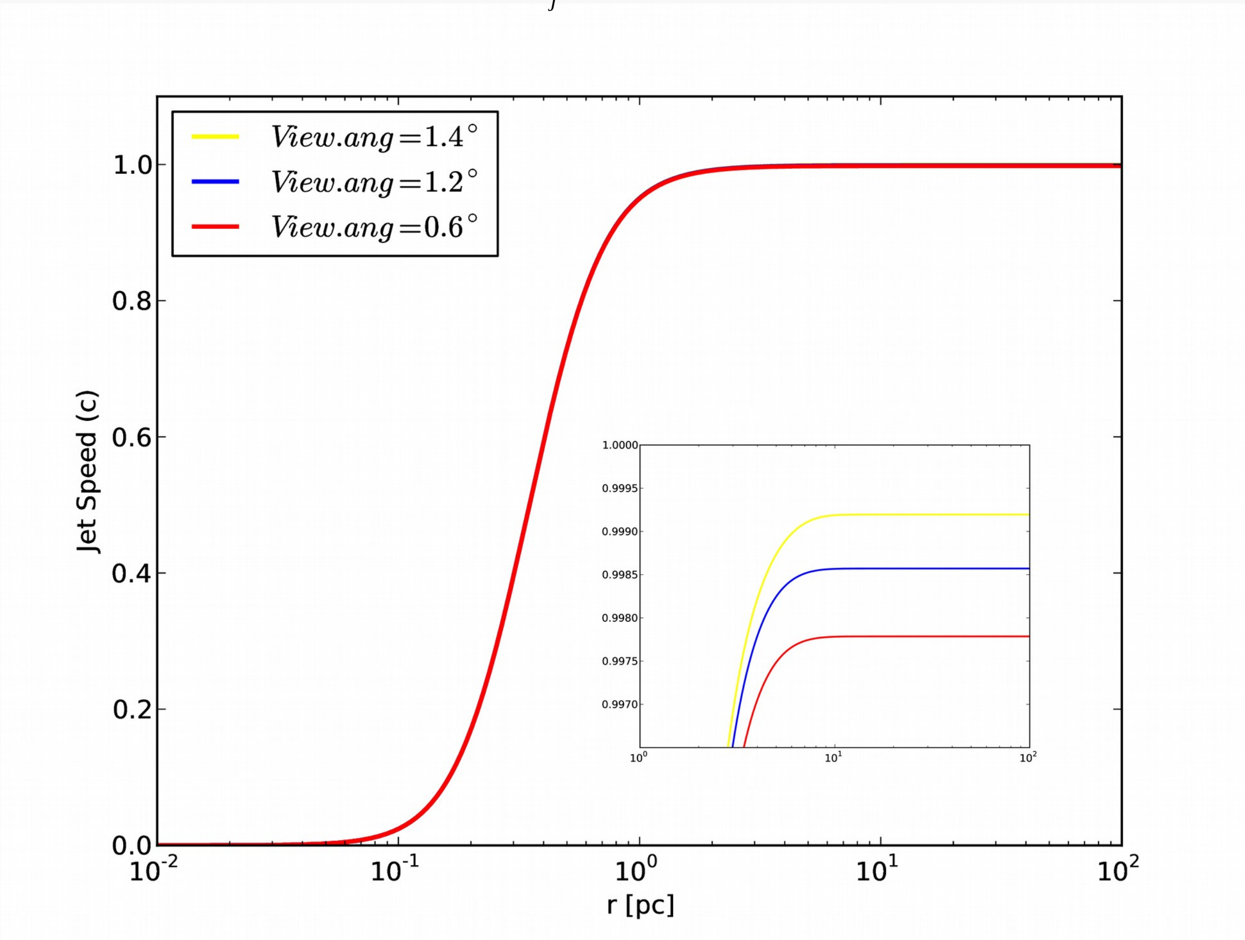
δ_0 is the Dopp. factor at r = r_{min}



The inferred Doppler factor increases from δ_0=1 to δ_m~ 41 in a similar way as the brightness temp does.

Evolution of jet speed as a function of distance from central black hole

$$\gamma_j = \frac{1 - \cos\theta_j \left(1 - \delta^2 \sin^2\theta_j\right)^{1/2}}{\delta \sin^2\theta_j} \longrightarrow \beta = \frac{1}{\left(1 - \gamma_j^{-2}\right)^{1/2}}$$



$T_b(r)$, $\delta(r)$, $\gamma(r)$, $\beta(r)$ dependence shape – matches very well with magnetically driven, accelerating jet model (Vlahakis & Königl 2004; Lyubarsky 2009)

→ Such acceleration from sub-pc to pc scales reported in cases like NGC 6251 (Sudou et al.2000, 0.13c ~0.42 c), Cygnus A (Boccardi et al.2016), NGC 315 (Cotton et al. 1999, 0.75 c ~ 0.95 c) M87 (Asada et al.2014, 0.01 c ~ 0.97 c) 3C 345 (Unwin et al.1997, Lobanov & Zensus 1999, for highly relativistic speeds, γ_∞ ~ 35)

Summary

- **A large 86 GHz VLBI survey of compact radio sources**
- **100% detection rate, 3 mm maps of 162 sources**
- **Source structure is represented with Gaussian model fits, accounting for resolution limits.**
- **T_0 for VLBI cores = $(3.77 \pm 0.14) \times 10^{11}$ K for $\gamma = 10$, IC limit**
- **T_0 for inner jet components = $(1.44 \pm 0.19) \times 10^{11}$ K**
- **Multi-frequency measurements of brightness temperature suggest that on scales of ~ 100-10000 gravitational radii, the MHD acceleration play an important role in the compact jets.**

Thank You

3 mm Survey Webpage

millimeter VLBI array survey of ultracompact extragalactic radio sources at 86 GHz - Google Chrome

webmail.astron.nl | Global millimeter VLBI arr

https://www3.mpifr-bonn.mpg.de/div/3mmsurvey/

Apps For quick access, place your bookmarks here on the bookmarks bar. Import bookmarks now...

Global millimeter VLBI array survey of ultracompact extragalactic radio sources at 86 GHz

If you intend to use these data in a publication, we ask that you cite Nair et al., 2019, A&A, 622, A92 and please contact us so we can add a link to our external publications page, and ask that you include the following acknowledgment: "This research has made use of data obtained with the Global Millimeter VLBI Array (GMVA), which consists of telescopes operated by the MPIfR, IRAM, Onsala, Metsahovi, Yebes, and the VLBA. The VLBA is an instrument of the National Radio Astronomy Observatory. The National Radio Observatory is a facility of the National Science Foundation operated under the cooperative agreement by Associated Universities. The data were correlated at the MPIfR in Bonn, Germany." External publication page: https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/

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Image Parameters

Number of modelfit components:

0 Submit

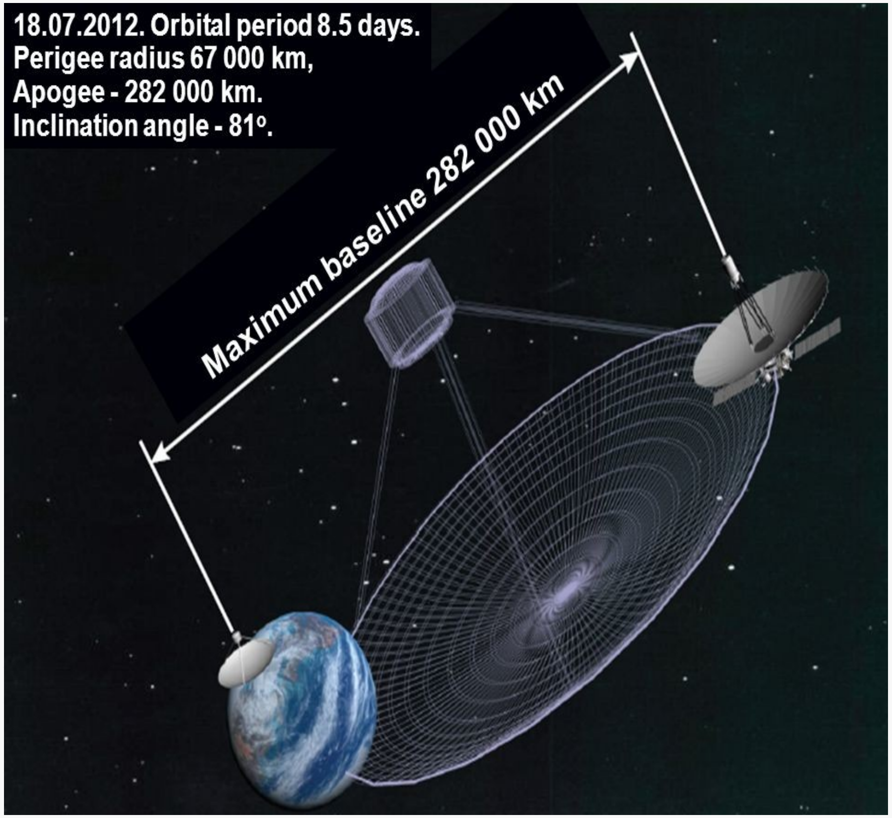
Projected baseline length [Mλ] for the measured flux density listed in the previous column

Source (J2000)	Obs	$S_{86\ GHz}$	S_S	B_S	S_L	B_L	B_a	B_b	B_{PA}	S_t	S_p	σ	ξ_r	Components
J0013+4051	C	0.79	0.656 ± 0.020	56	0.192 ± 0.006	3136	159	35	-16.8	436	317	8	1.43	2
J0017+8135	B	0.18	0.263 ± 0.018	60	0.075 ± 0.004	3062	74	35	62.1	143	81	2	1.36	2
J0030+7037	B	0.34	0.363 ± 0.026	65	0.115 ± 0.009	3070	76	36	66.5	155	92	3	1.34	2
J0034+2754	C	0.07	0.124 ± 0.015	54	0.156 ± 0.021	3086	262	36	-14.2	159	60	2	1.04	5
J0044+6803	B	0.17	0.315 ± 0.023	65	0.097 ± 0.006	3034	75	36	70.4	133	99	3	1.15	2
J0046+2456	A	0.47	0.252 ± 0.019	59	0.137 ± 0.009	3060	267	37	-15.0	235	160	6	1.17	2
J0057+3021	A	0.48	0.361 ± 0.023	58	0.233 ± 0.017	3060	308	37	-14.5	306	226	8	1.07	1
J0102+5824	B	3.11	3.579 ± 0.037	44	0.336 ± 0.020	3050	59	43	-19.5	2221	1075	19	1.58	3

https://www3.mpifr-bonn.mpg.de/cgi-bin/gmva_showimageparameters.cgi?by=bl&order=asc&n=

https://www3.mpifr-bonn.mpg.de/div/3mmsurvey/

Frequency dependence of brightness temperature in compact jets → RadioAstron



RadioAstron (Spektr-R)
[Image credit: Astro Space Center, Russia]

- Resolved out flux problem?
- Or a real intrinsic decrease of T_b at higher frequencies? → MHD-driven acceleration

- Comparable resolutions (uv-spacings) can be obtained for lower frequencies with space baselines → **RadioAstron**

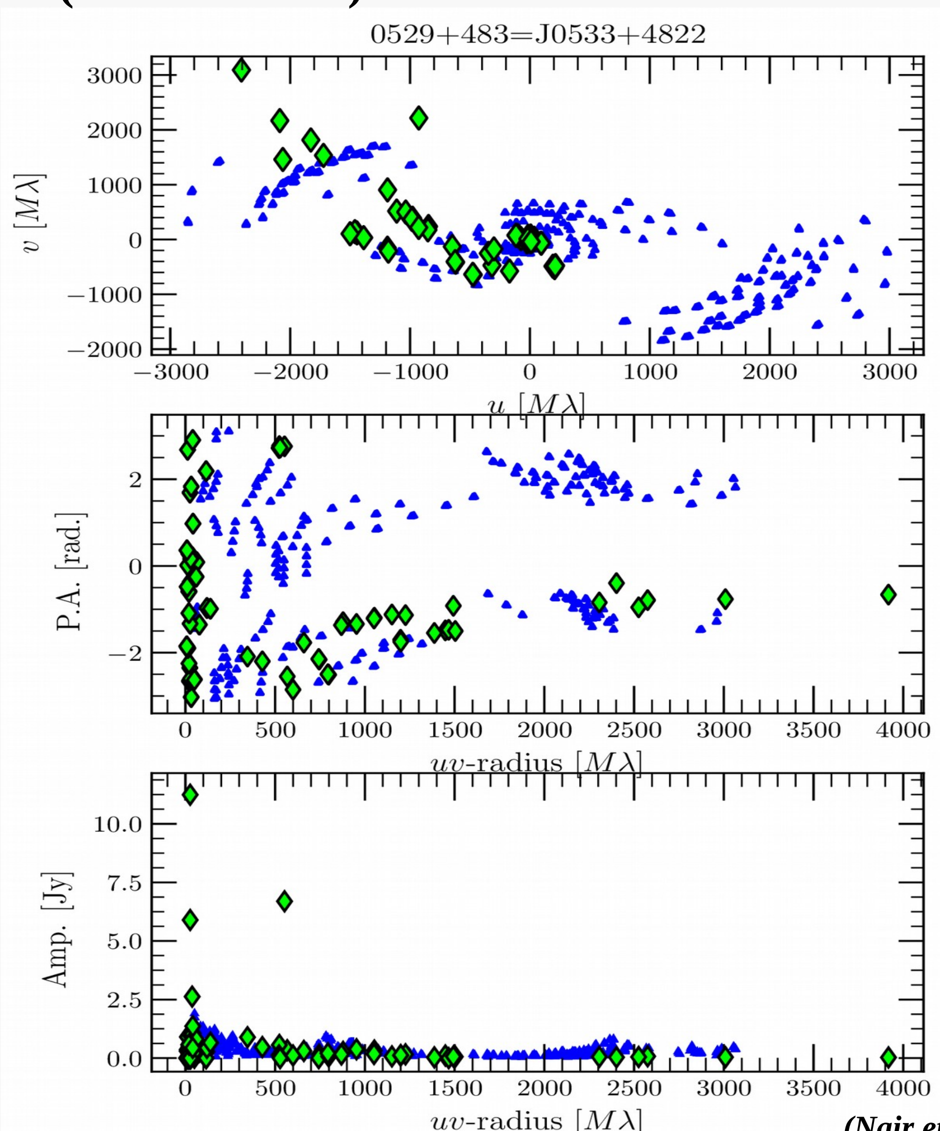
- **T_b at similar *uv* spacings from Radio-Astron (1.6 GHz, 5 GHz or 22 GHz) and GMVA (86 GHz)**

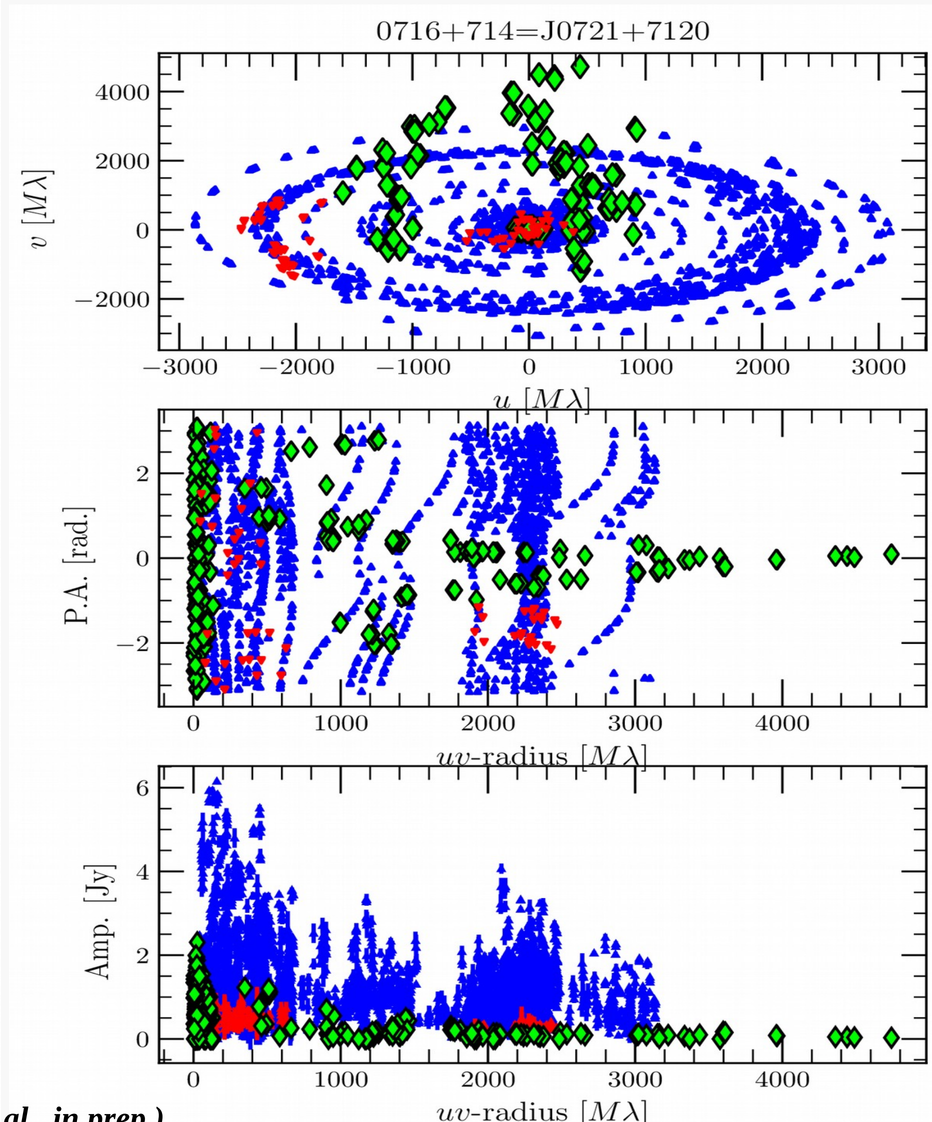
- 254 sources from GMVA and 165 sources from RA with **106 sources** common in both surveys.

Results: Visibility matching from RadioAstron (1.6 GHz, 5 GHz, 22 GHz) and GMVA (86 GHz)

Matching criteria :

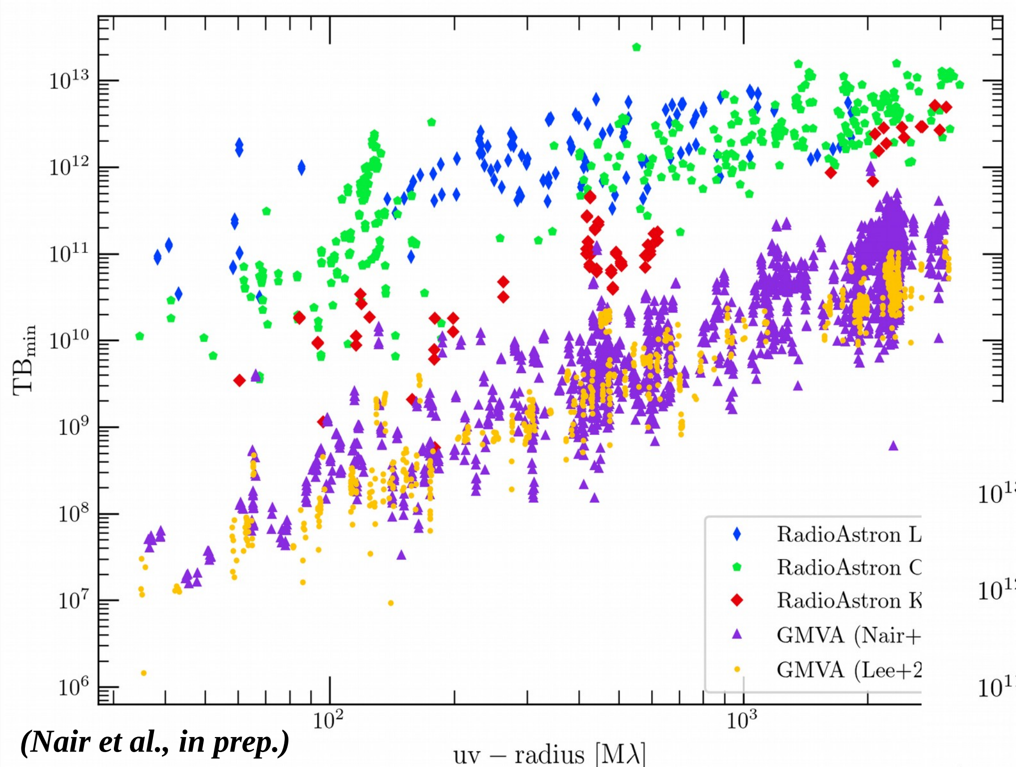
- **The closeness of the visibilities in polar coordinates (in units of $M\lambda$) between GMVA and RA**
- **GMVA *uv*-point within 10% *uv*-radii and 10% position angle of RA *uv*-point**





(Nair et al., in prep.)

Results: T_b at similar *uv*-spacings from RadioAstron (1.6 GHz, 5 GHz, 22 GHz) and GMVA (86 GHz)

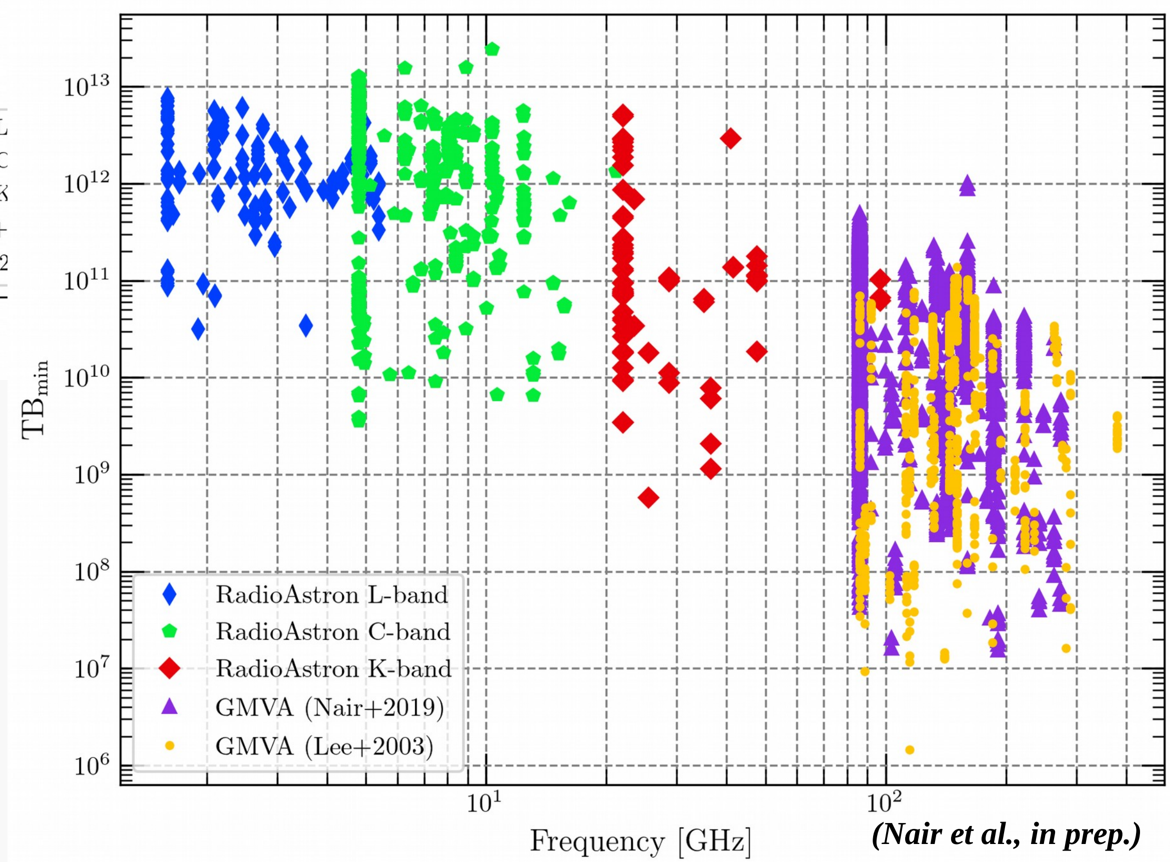


(Nair et al., in prep.)

The decrease in T_b at higher frequencies also observed in similar *uv*-spacings

- **The apparent decrease of T_b at higher frequencies reflect the jet composition and dynamics (Marscher 1995)**

- **Extreme physical conditions (ultra strong magnetic fields, mono-energetic electron plasma, or relativistic protons) in the innermost region in the jet ?**



(Nair et al., in prep.)

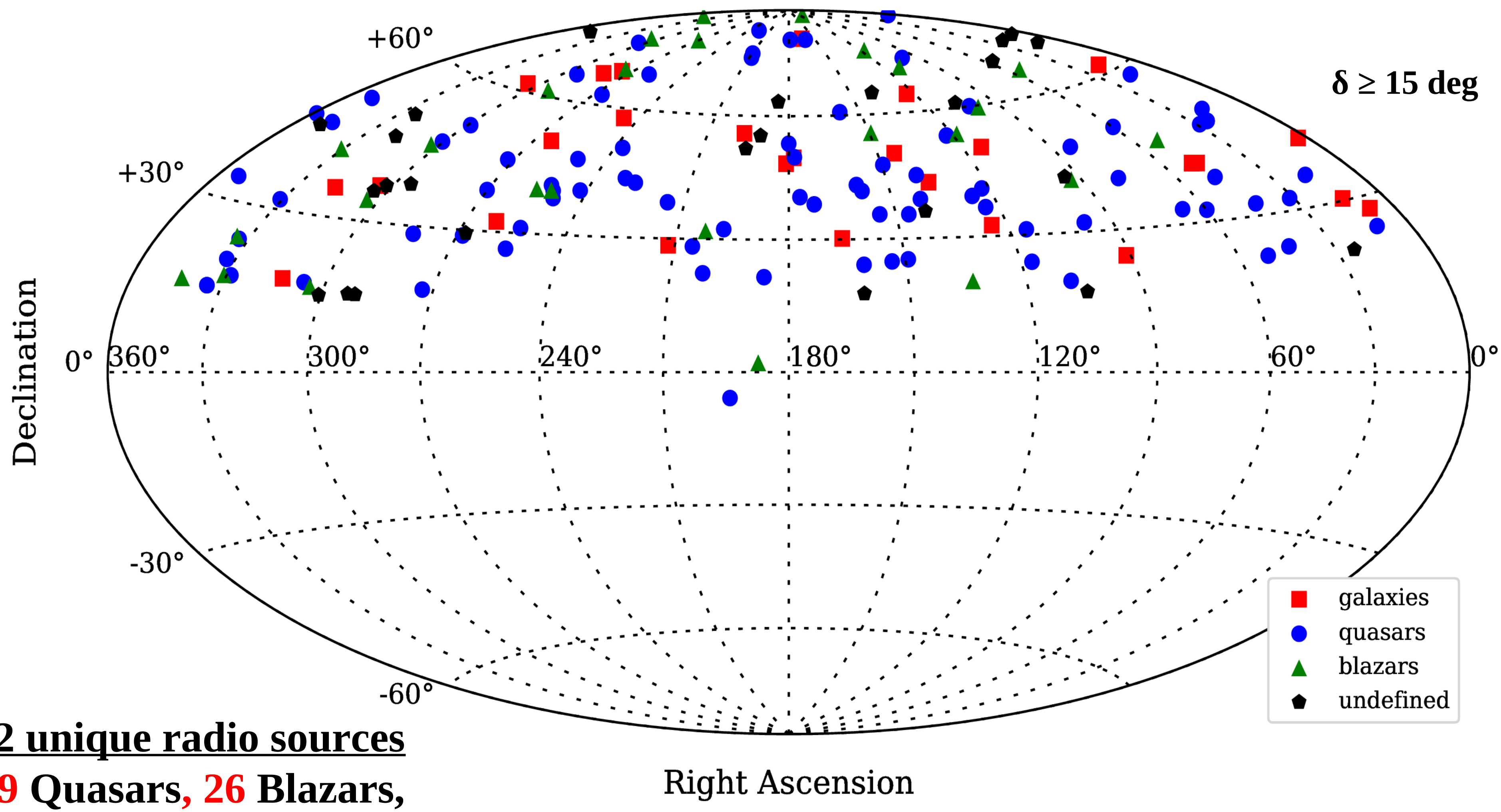
86 GHz (~ 3 mm) VLBI Survey

- **Synchrotron radiation, optically thin at mm wavelengths**
- **Unique tool to look at the inner jets of AGN ("VLBI cores")**
- **~ 50 µas resolution at 86 GHz (B ~ 9000 km)**
- **A linear scale as small as 10^3 - 10^4 Schwartzschild radii**

↓

- **86 GHz VLBI zoom into a region where acceleration and collimation of relativistic jets takes place** [***Vlahakis & Königl 2004; Asada et al. 2014, Lee et al. 2016, Mertens et al. 2016***]

Sky Distribution of Survey Targets



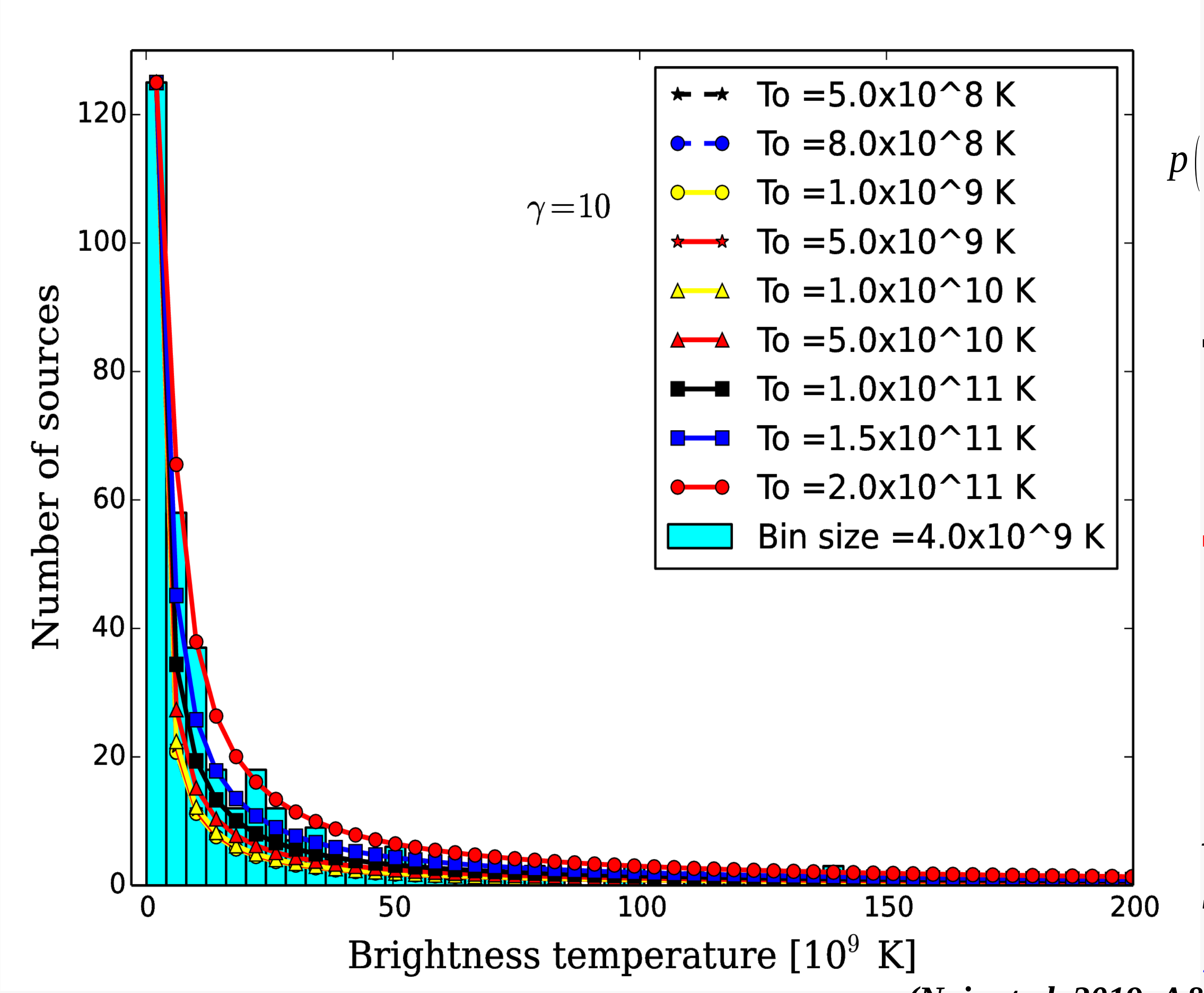
<u>**162 unique radio sources**</u>

- 89 Quasars, 26 Blazars, 22 Galaxies & 25 unidentified sources.

<u>**Source Selection**</u>

- **From 15 GHz VLBA Survey – MOJAVE (*Kellermann et al. 2004, Kovalev et al. 2005, Lister et al. 2009*)**
- **Observations – Oct 2010, May 2011 & Oct 2011**

Population modelling for the brightness temperature T_b – *Jet Components*



$$p(T_b) \propto \left[\frac{2\gamma_j \left\{ \left(\frac{T_0}{T_b} \right)^{\epsilon} - \left(\frac{T_0}{T_b} \right)^{2\epsilon} - 1 \right\}}{\gamma_j^2 - 1} \right]^{1/2}$$

T_b range :

[5.8 x 10^7 K – 4.0 x 10^{11} K]

$T_{0,\text{jet [86 GHz]}}$
= (1.42±0.19) x 10^{11} K

(slightly greater than Equipartition limit, 5x10^{10} K, Readhead 1994)

(Nair et al. 2019, A&A)