Credit: NASA/JPL-Caltech

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


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# Why 86 GHz (~ 3 mm) VLBI Survey ?

- **Angular resolution ~ λ/B**
- **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; Lee et al. 2016; Asada et al. 2014, Mertens et al. 2016*]**

# The Global MM-VLBI Array (GMVA)

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

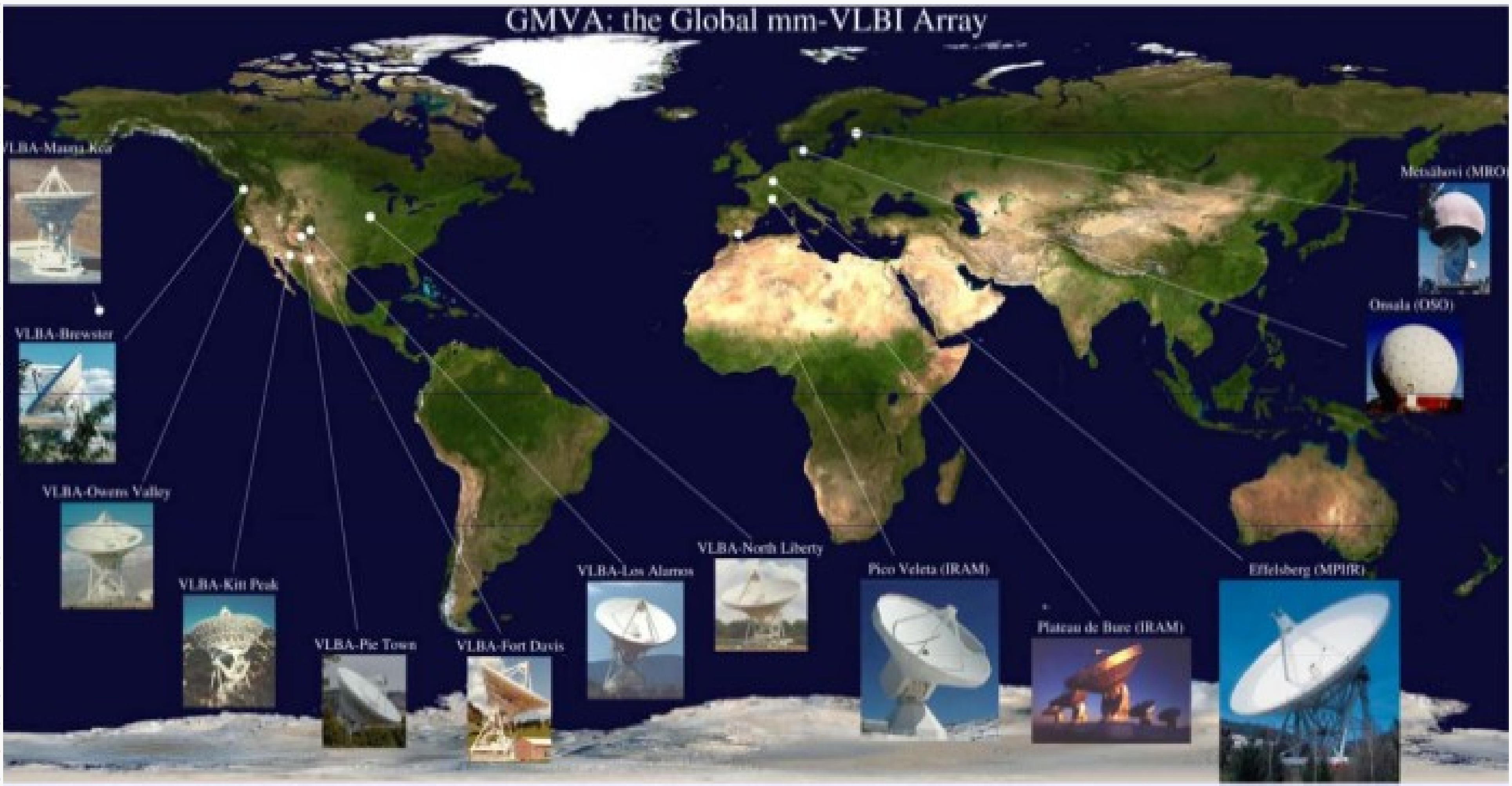
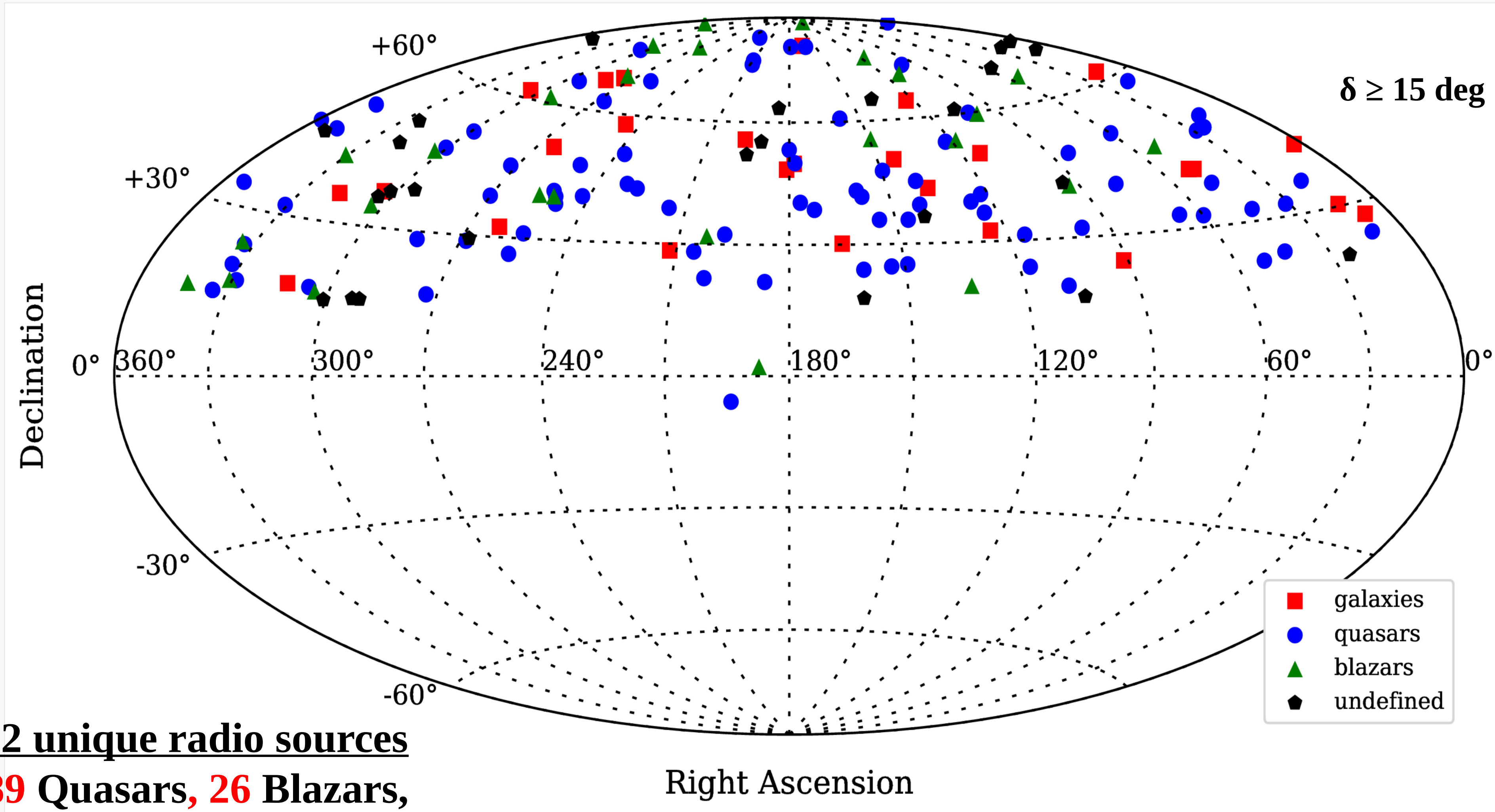



*Image Credit : http://www.mpifr.de/div/vlbi/globalmm*

# 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**

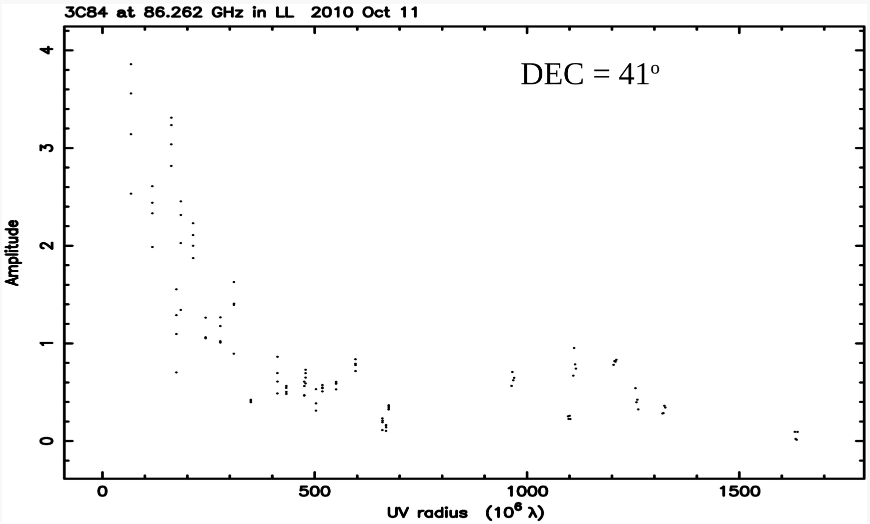
# Results. I : 3mm maps

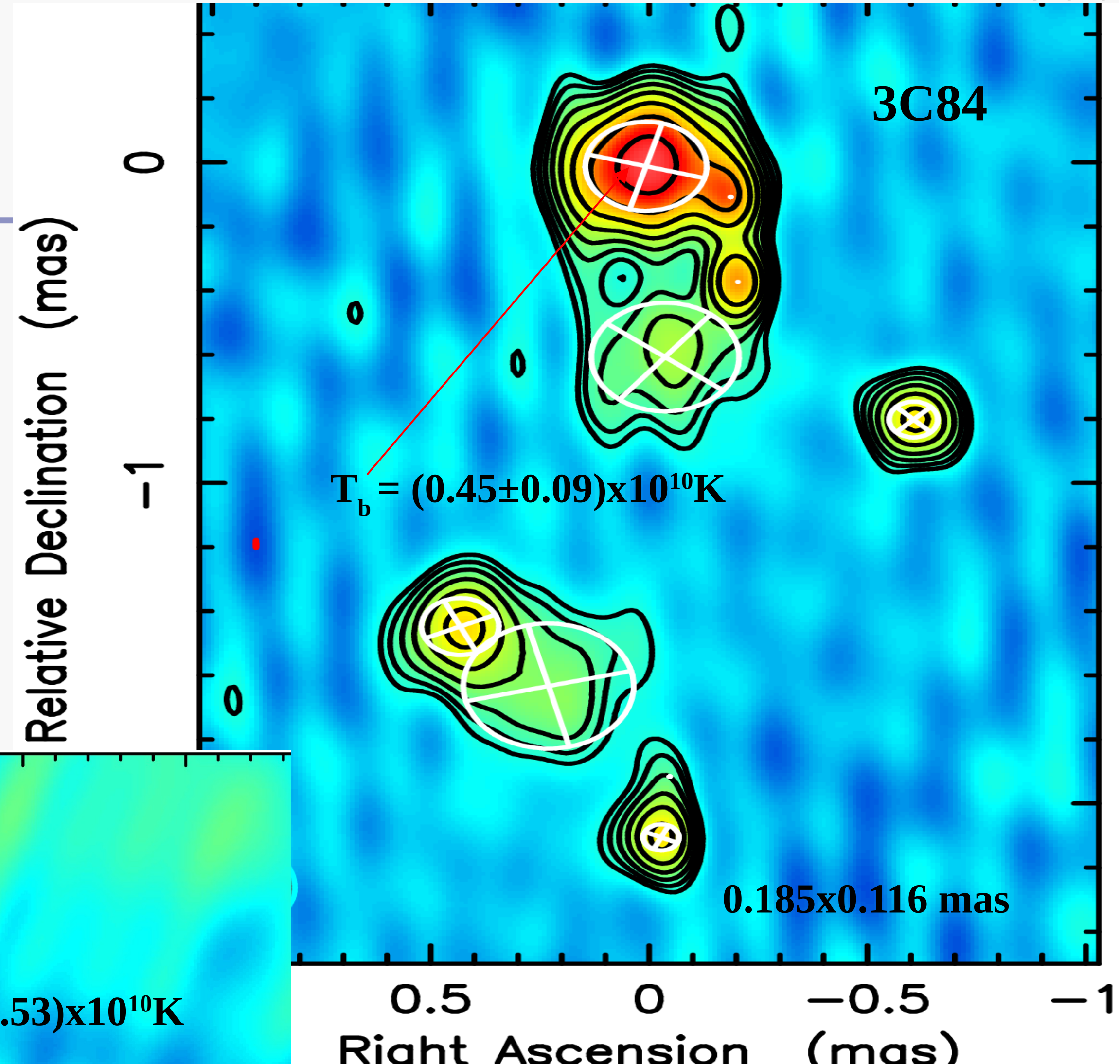
- *Made 3mm maps of 174 (162 unique) radio sources*
- *with very high resolution of 40-100 μas*

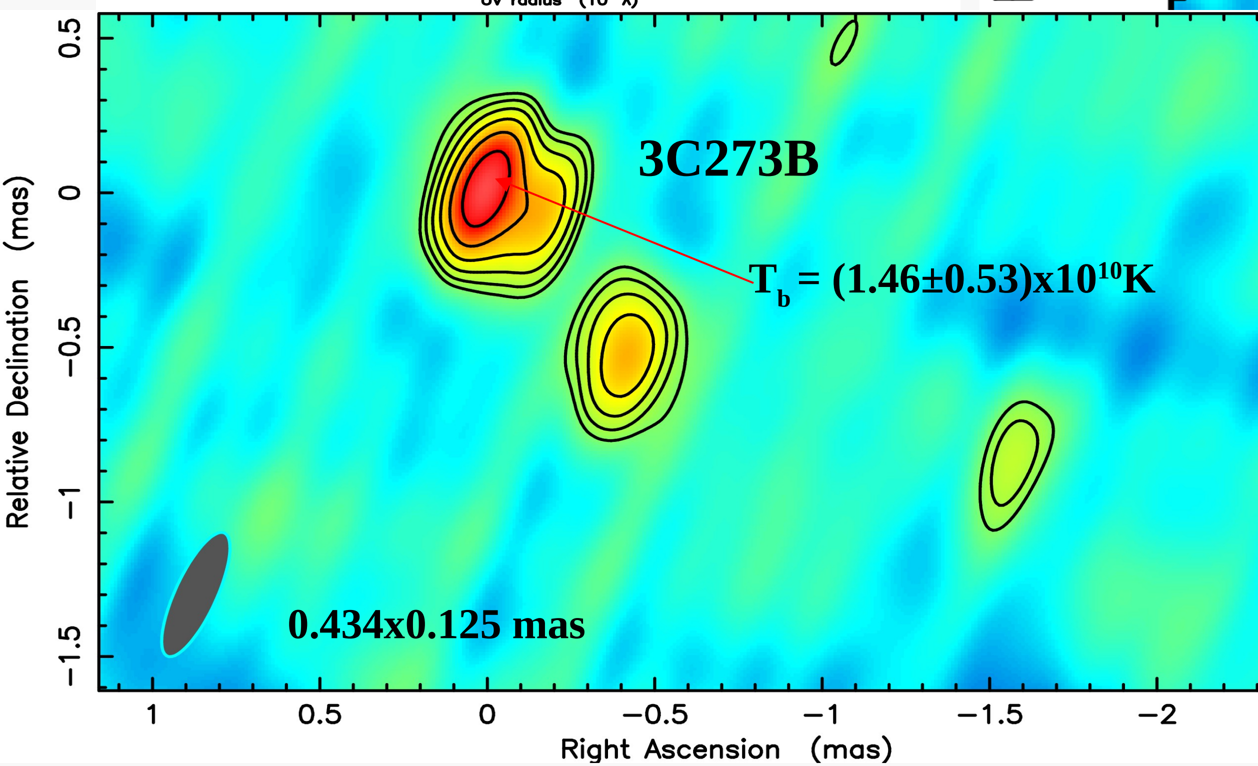
⇓

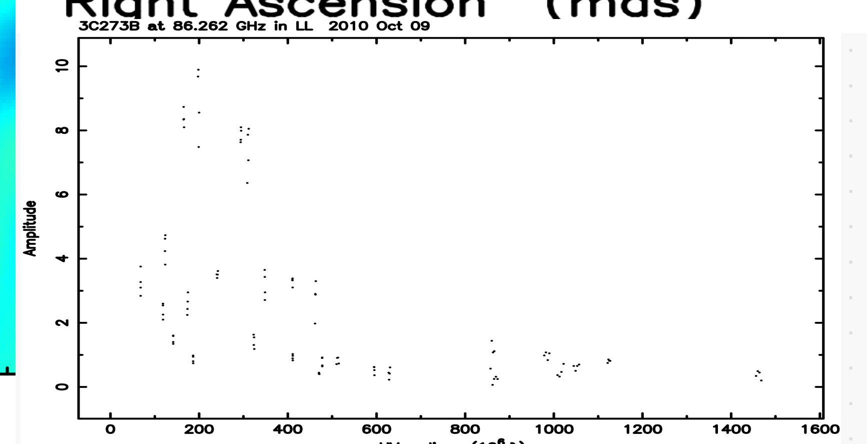
- *FIRST 3mm VLBI maps of 138 radio sources*
- *Increase the database of sources ever imaged with VLBI at 86 GHz by a factor of ~ 1.5*

# Results. I : 3mm maps

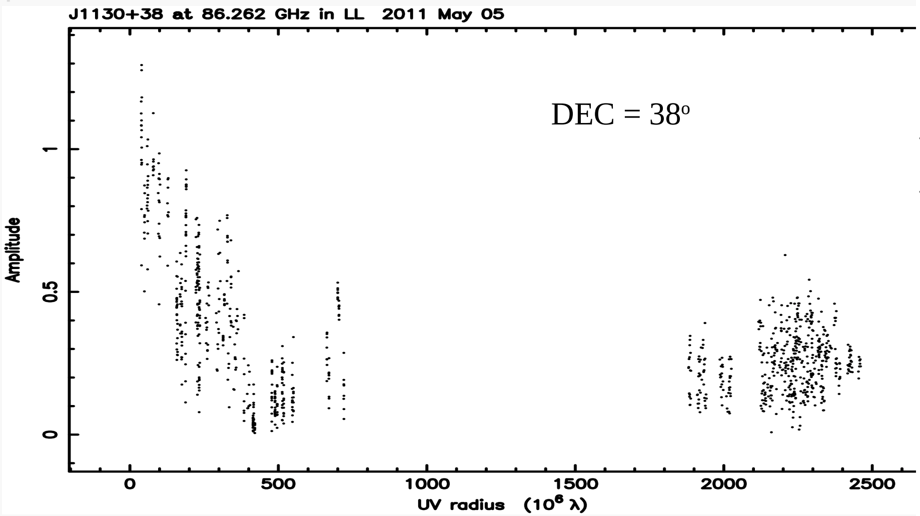


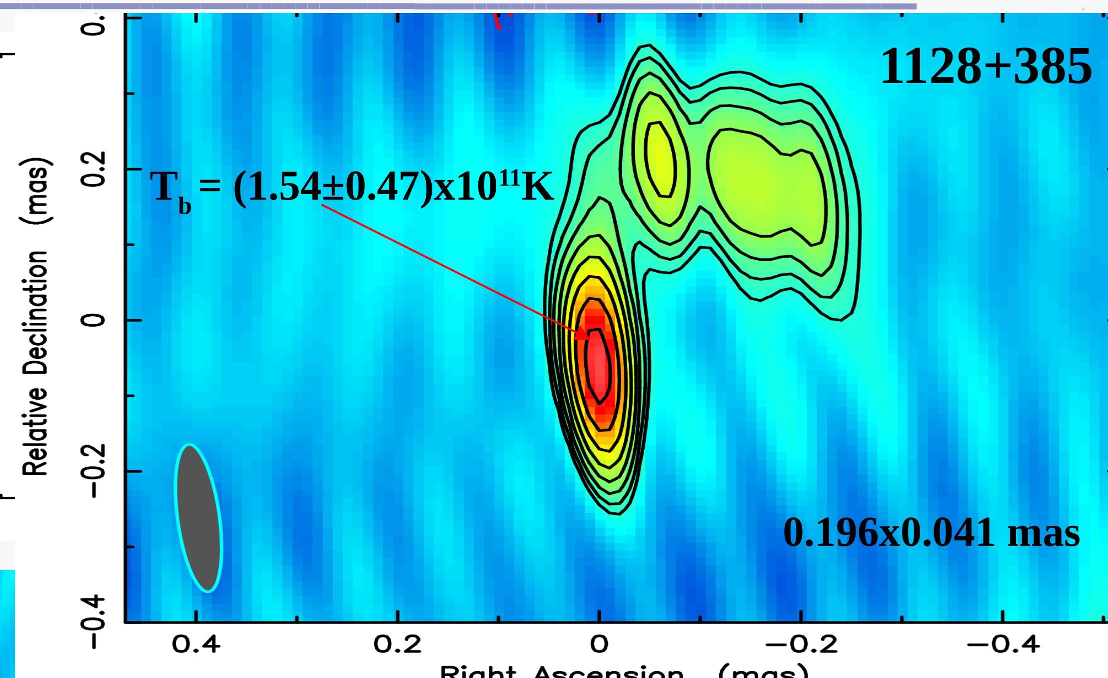



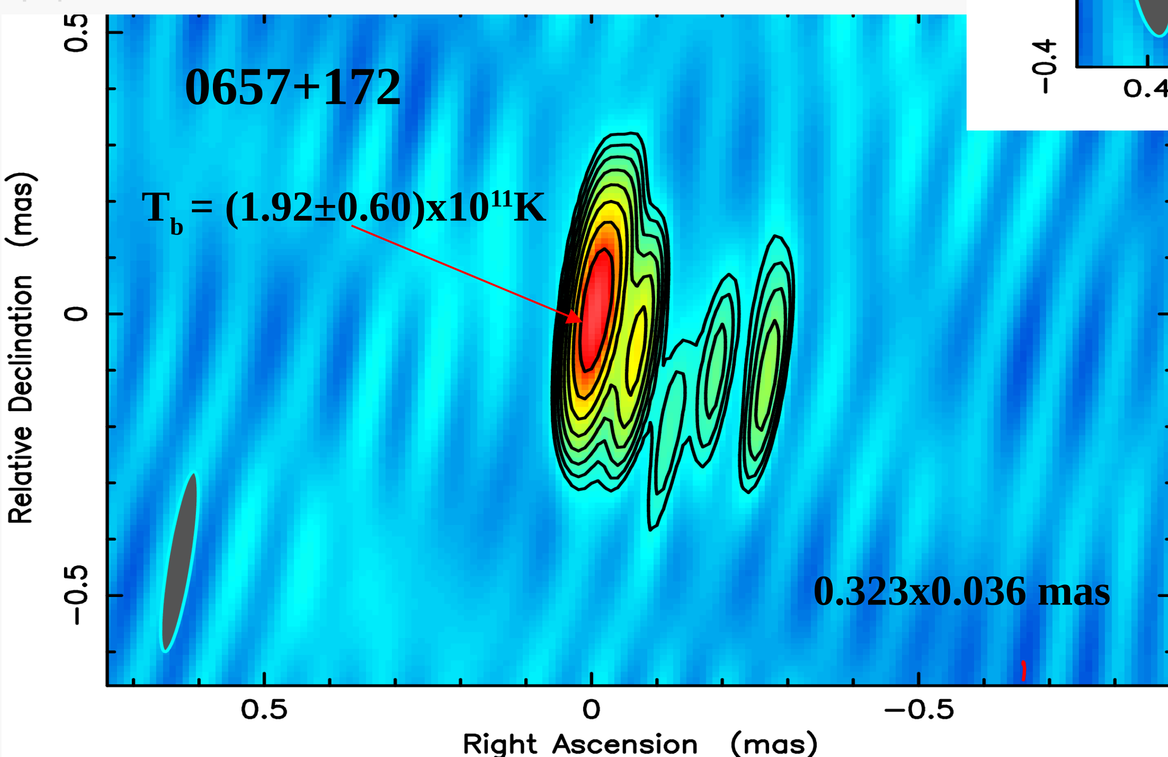



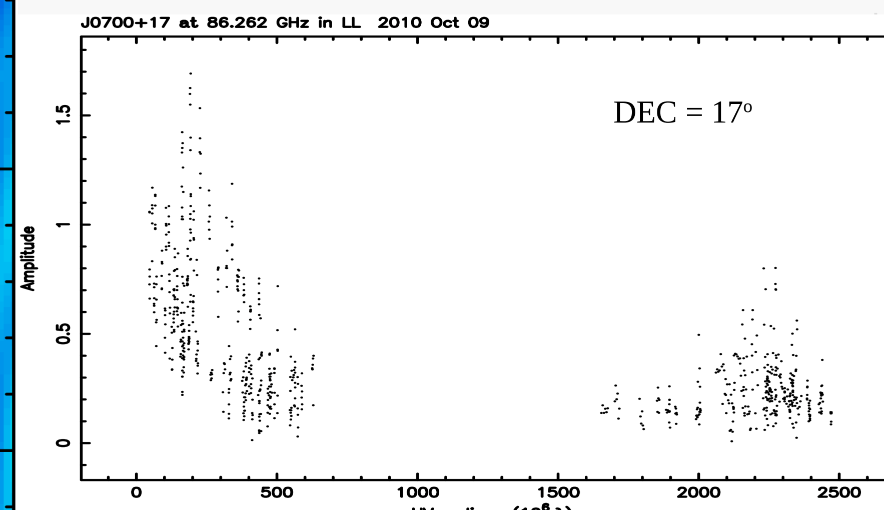



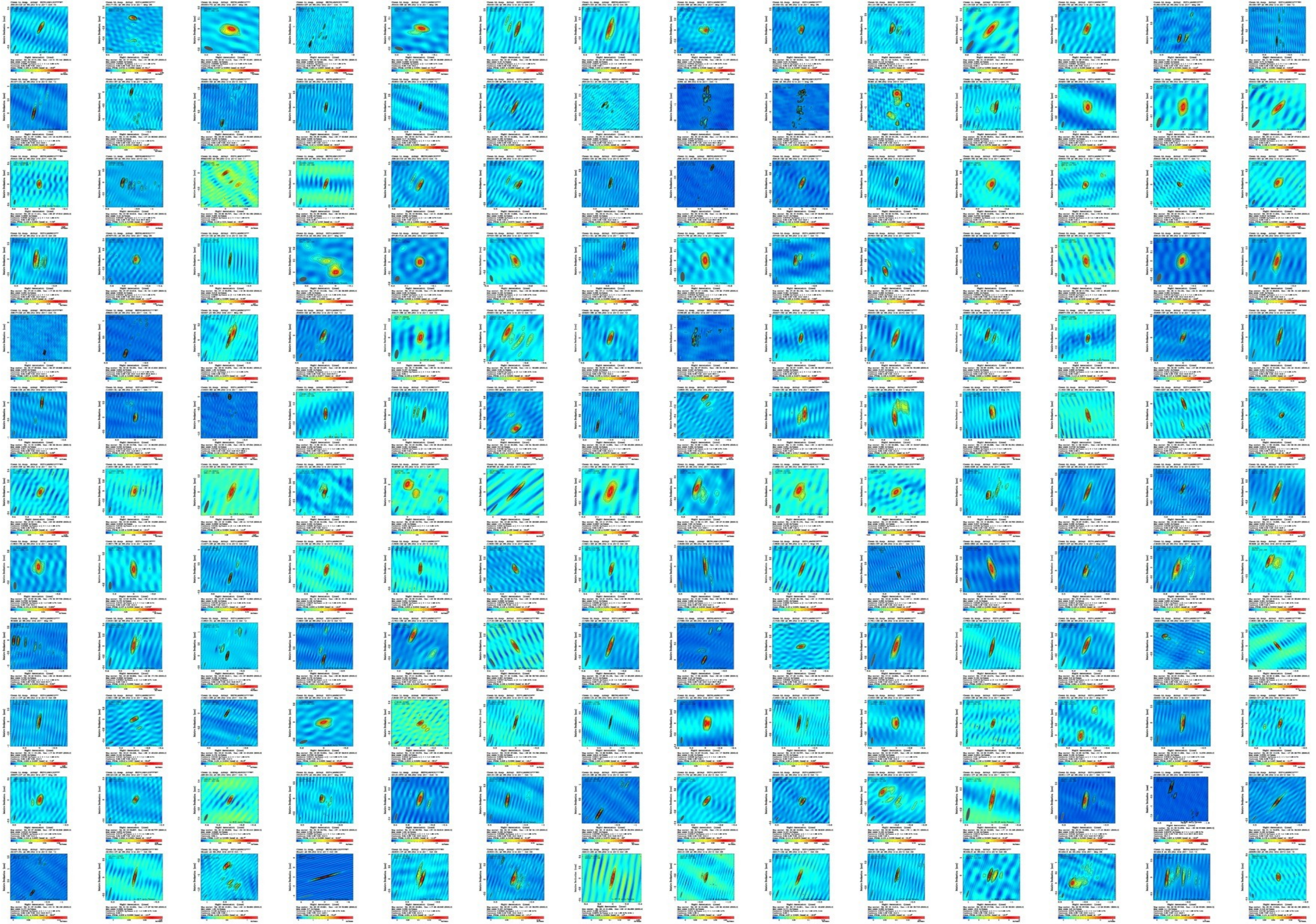
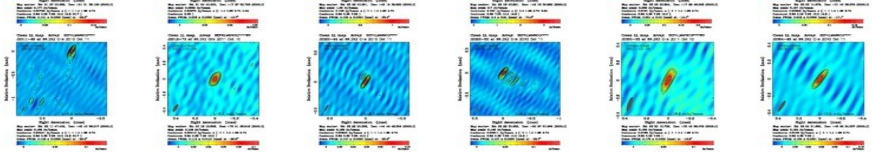
# Results. I : 3mm maps



***3mm maps of 174 (162 unique) radio sources (Nair et.al 2018)***

# Modelling the Source Structure

- **Represented source structure by circular Gaussian Modelfits**
- **Estimated total flux ($S_{tot}$), peak flux ($S_{peak}$), position w.r.t phase center ($r$, $\theta$), FWHM size ($d$)**
- **Estimated brightness temperature :**

$$T_b = \frac{2\ln(2)}{\pi k_B} \frac{S_{tot} \lambda^2 (1+z)}{d^2}$$

# Results. III : Population modelling for the brightness temperature $T_b$ - *VLBI cores*

**Probability density of brightness temperature,**

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

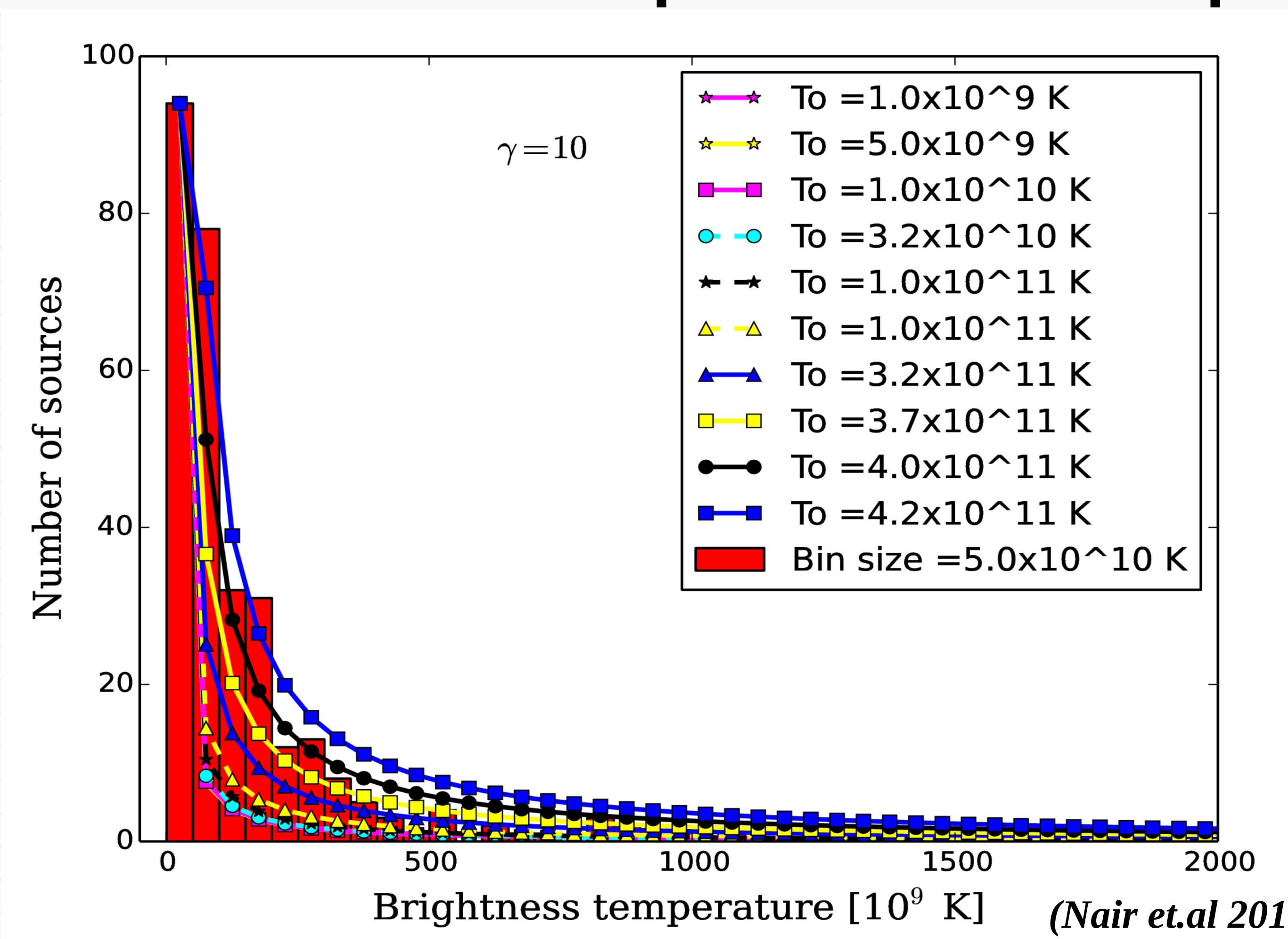
**where $\delta = (T_b / T_0)^{\epsilon}$**

**$T_0$ - intrinsic bright. temp**

**$T_b$ - observed bright. temp**

**$\delta$ - doppler factor**

***(Lobanov et al. 2000)***




***(Nair et.al 2018)***

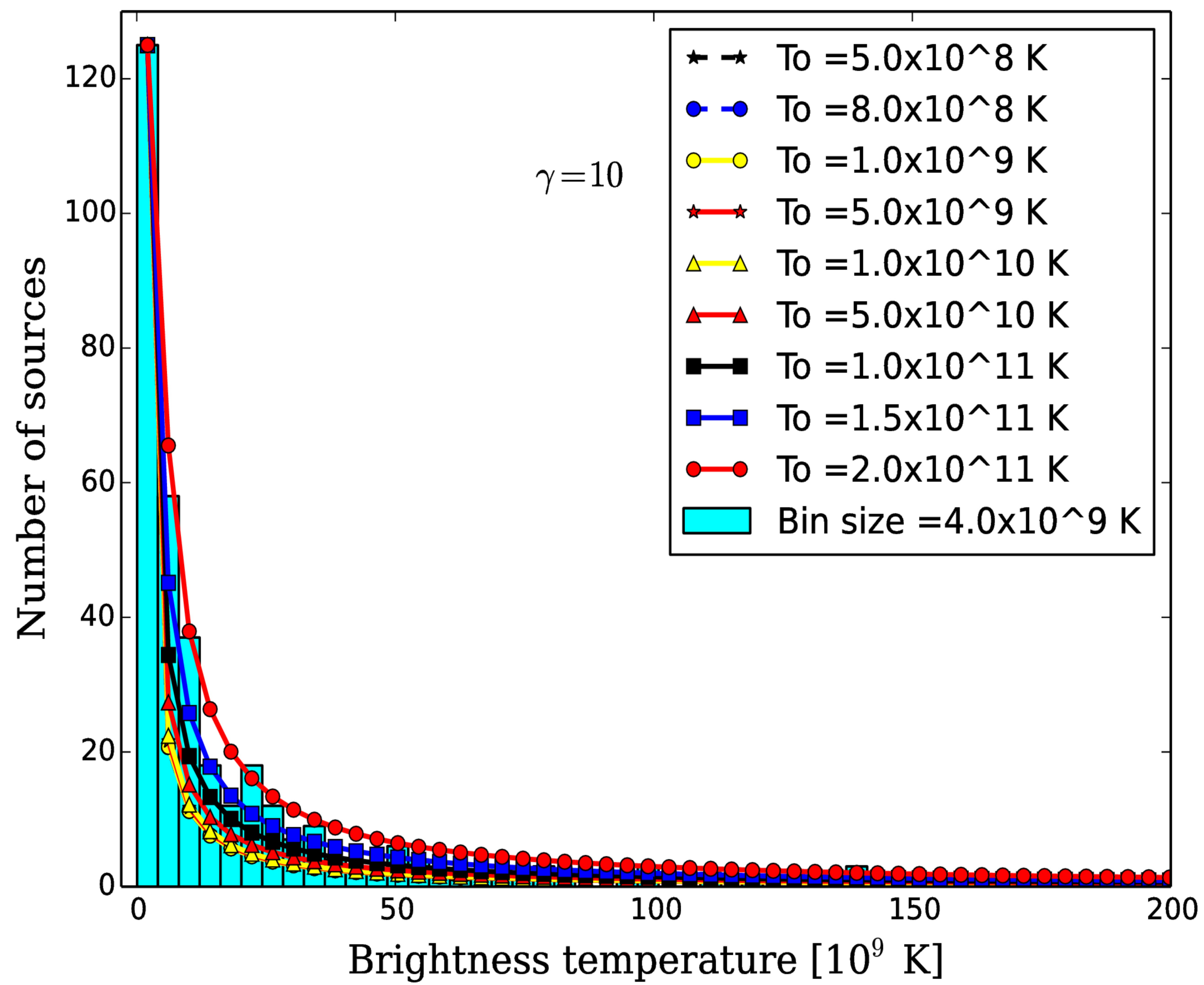
**$T_b$ range :**

**[$1.1 \times 10^9$ K – $5.5 \times 10^{12}$ K]**

**$T_{0,core\ [86\ GHz]}$ = $(3.77 \pm 0.14) \times 10^{11}$ K**

**(*~ Inverse Compton limit, $5 \times 10^{11}$ K, Kellermann & Pauliny-Toth 1969*)**

# Results. III : Population modelling for the brightness temperature $T_b$ – *Jet Components*




***(Nair et.al 2018)***

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

**$T_b$ range :**
**[5.8 x $10^7$ K – 4.0 x $10^{11}$ K]**

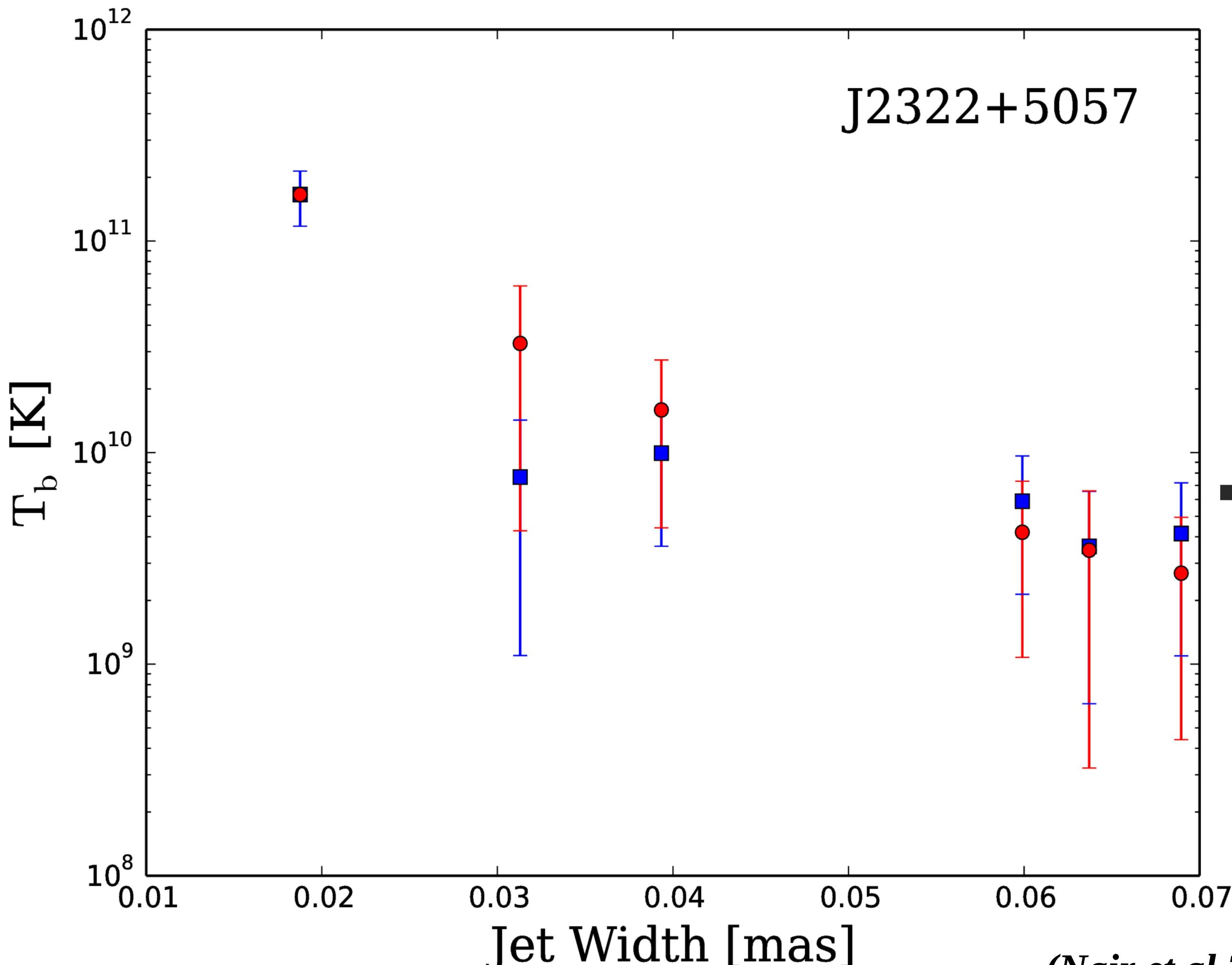
**$T_{0,\mathrm{jet}\ [86\ \mathrm{GHz}]}$ = (1.42±0.19) x $10^{11}$ K**

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

# Results. IV : Do jets expand adiabatically ?

**CORE** - $T_b$ - [1.1 x $10^9$ K – 5.5 x $10^{12}$ K]
**JET** - $T_b$ - [5.8 x $10^7$ K – 4.0 x $10^{11}$ K]

- Inverse-Compton
- Synchrotron
- Adiabatic




*(Nair et.al 2018)*

$$T_{b,J} = T_{b,C}\,(d_J/d_C)^{-\xi}$$

$\xi$ = *[2(2s+1)+3a(s+1)]/6,*

*s = 2.0 , α = -0.5 , a = 1*

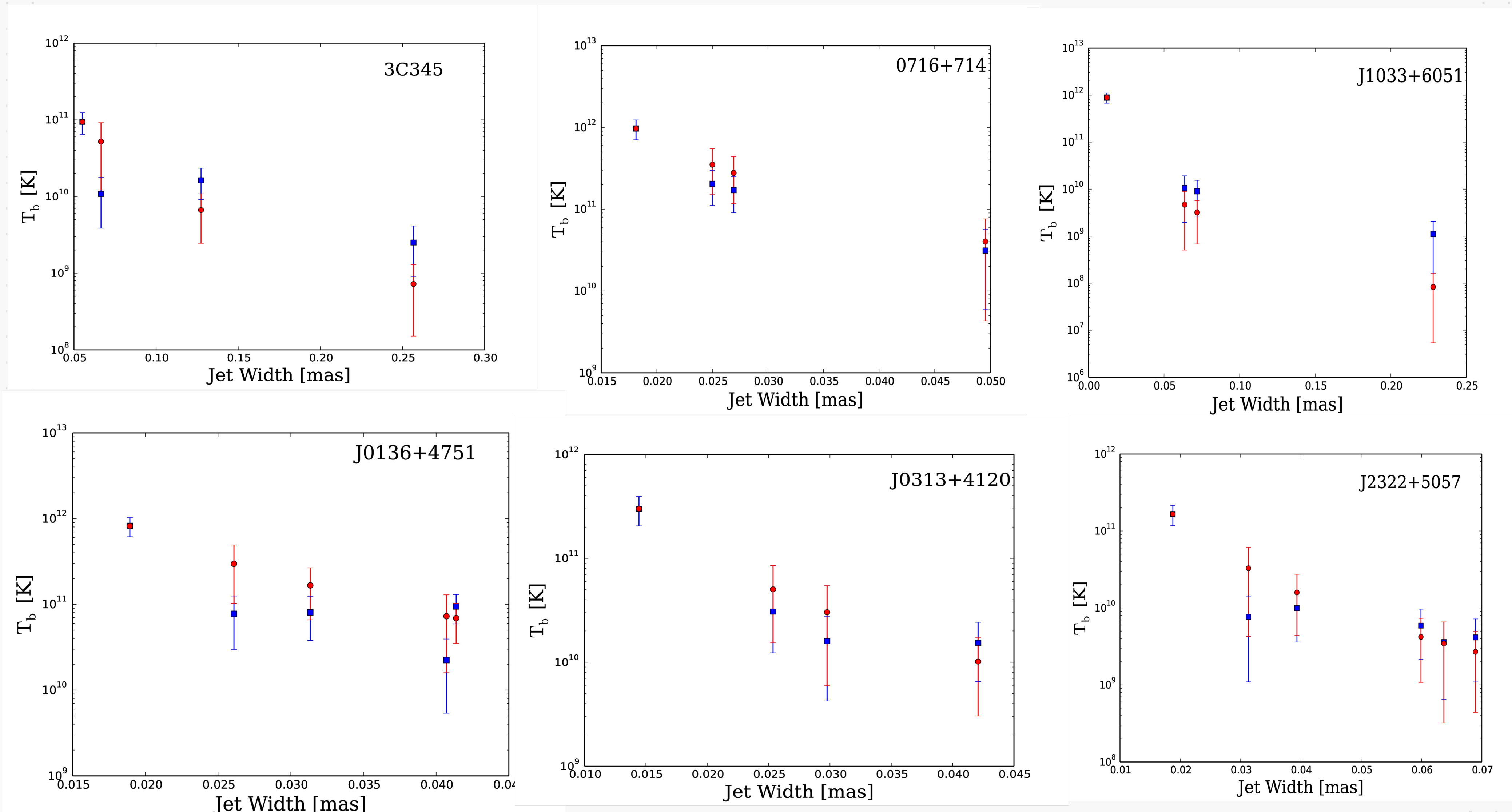
*(Marscher 1990)*

***Blue squares - observed*** $T_b$

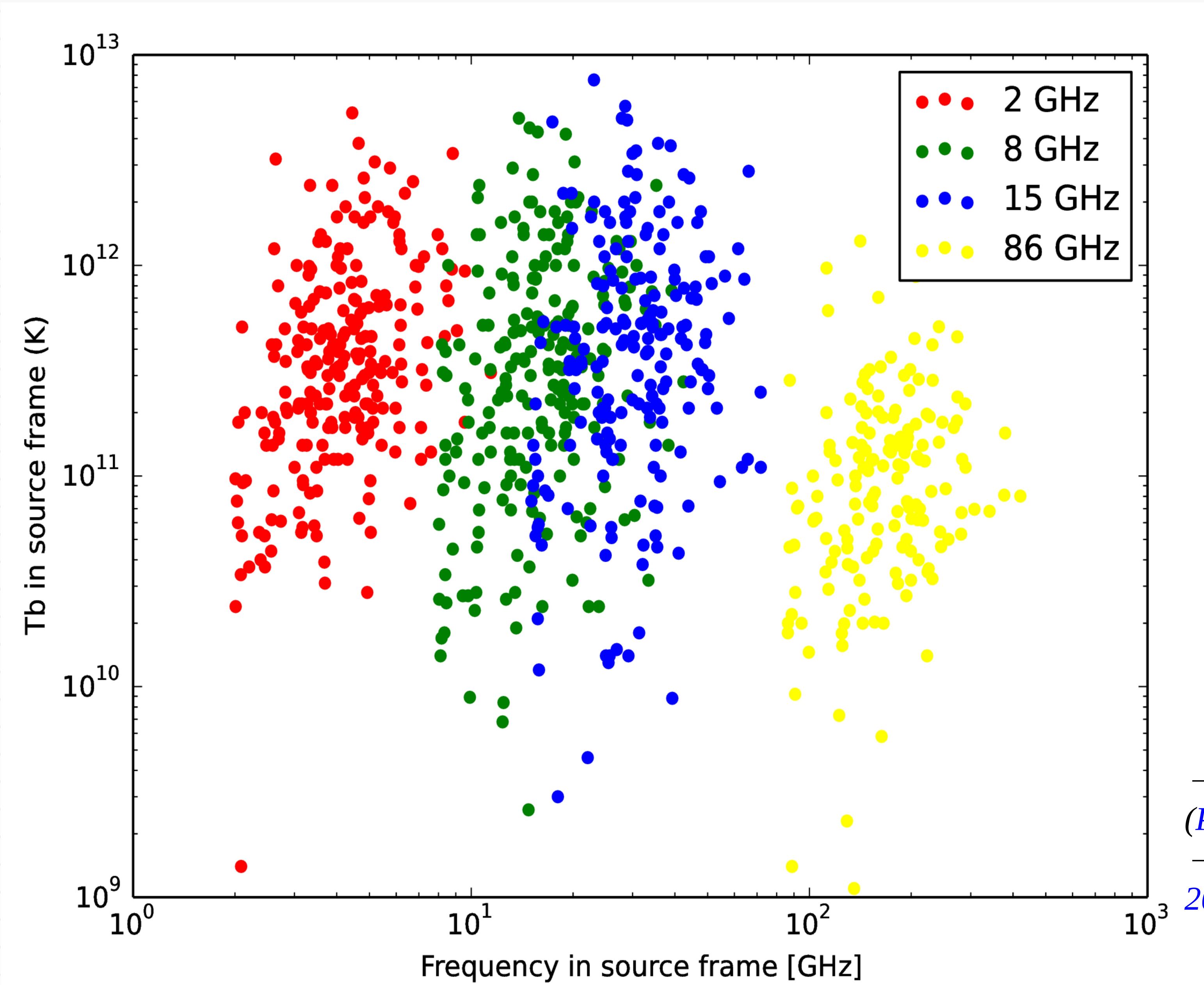
***Red circles - predicted*** $T_b$

***Plane shocks with adiabatic losses dominating the radio emission [cf., Kadler et al. 2004, Pushkarev & Kovalev 2012, Kravchenko et al. 2016].***

# Results. IV : Do jets expand adiabatically ? - *More examples*



# Results. V : $T_b$ as a function of frequency



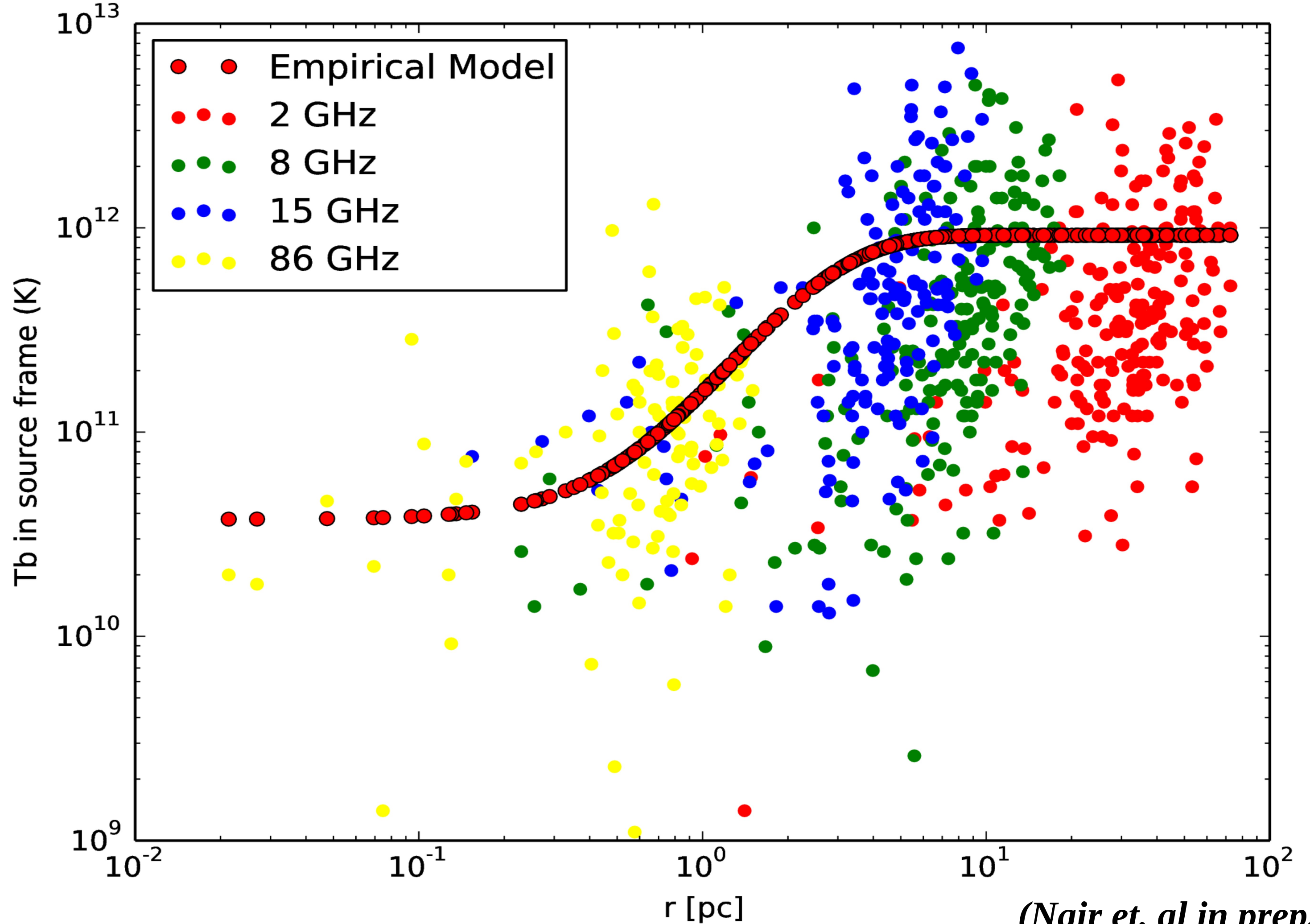

- **$T_b$ at 86 GHz are systematically lower**

- **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)*

# Results. V : $T_b$ as a function of distance of cores from central black hole

$$T_b = T_{in} + (T_m - T_{in}) \{1 - (r \,\mathrm{csch}\, r)^a\}$$ *Lee et. al 2016*




(Nair et. al in prep.)

$T_{in} = 3.7 \times 10^{10}$ K

**Best fit for $T_m = (7.96 \pm 0.47) \times 10^{11}$ K**

$a = 0.65 \pm 0.19$

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

# Conclusions

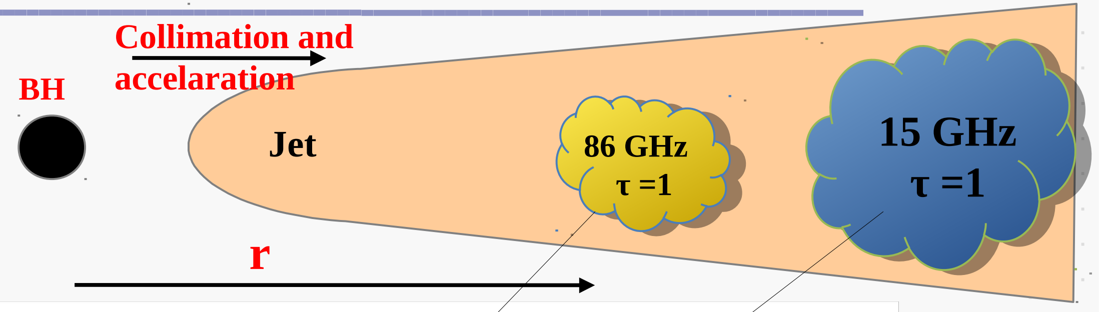
- A large 86 GHz VLBI survey of compact radio sources
- 100% detection rate, 3 mm maps of 162 sources
- Source structure is represented with Gaussian model fits, accounting for resolution limits.
- $T_0$ for VLBI cores = $(3.77 \pm 0.14) \times 10^{11}$ K for $\gamma = 10$, IC limit
- $T_0$ for inner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

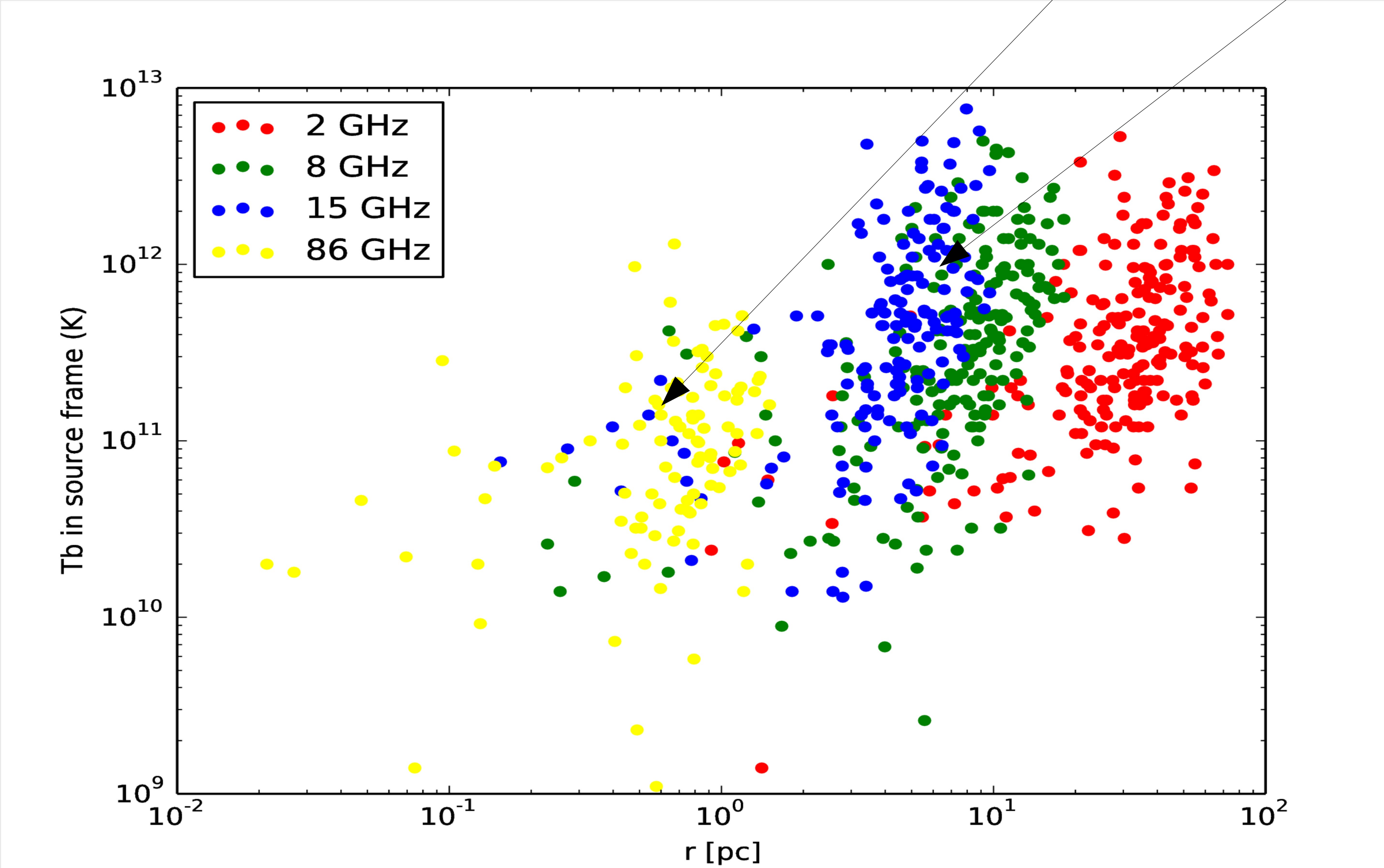
***Thank You***

# Results. V : Radio luminosity and jet parameters to convert frequency to linear coordinate along the jet

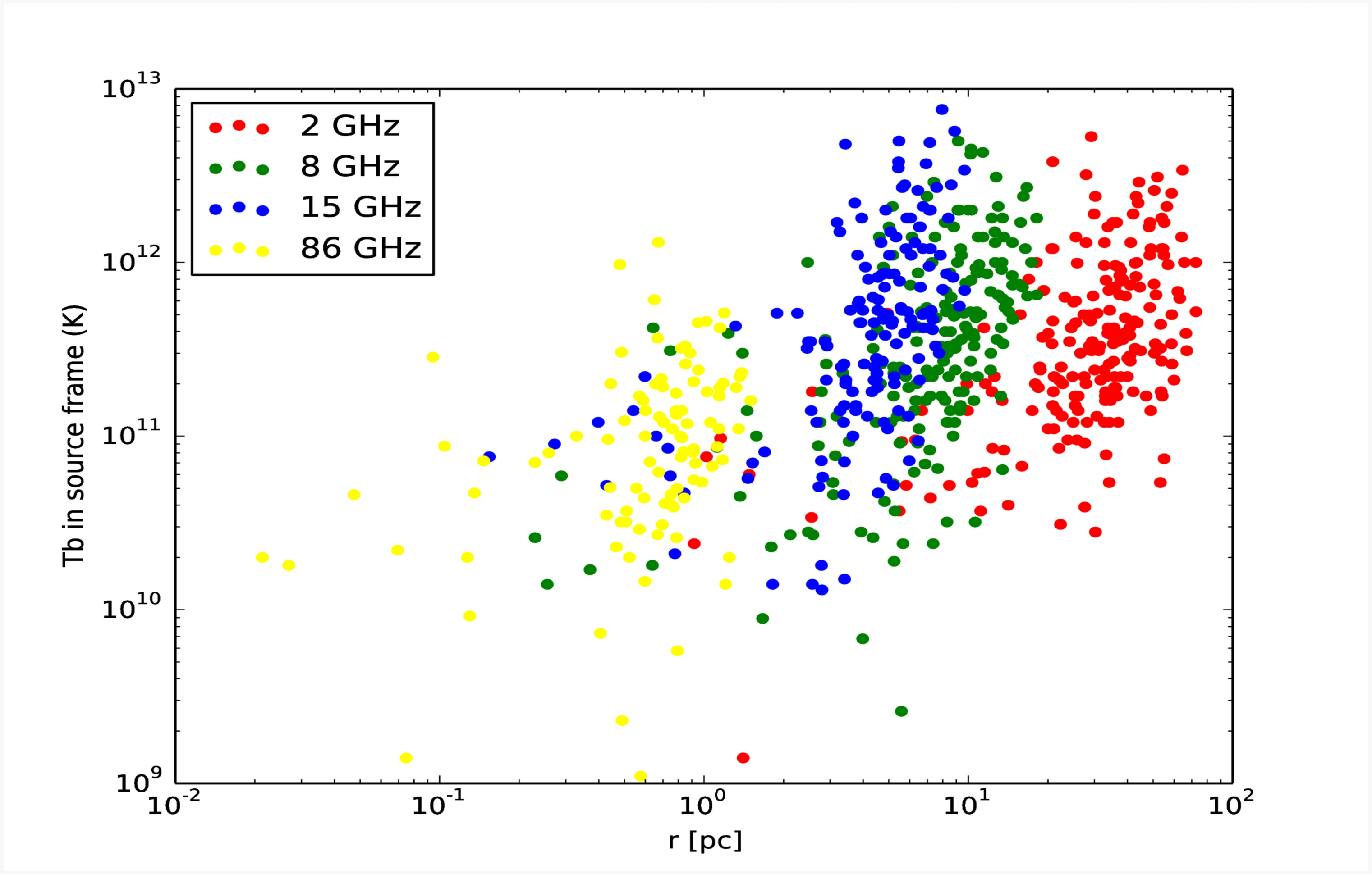
$$r = \left\{ \xi C_r L_{syn} \left\{ \upsilon \left( 1 + z \right) \right\}^{\frac{-1}{k_r}} \right\}^{1/3} pc$$

***(Lee et al. 2016)***



# Radio luminosity and jet parameters to convert frequency to linear coordinate along the jet




Assuming the equipartition between the jet particle energy and the magnetic field energy,the total radiated synchrotron power from the emission region extending from $r_{min}$ to $r_{max}$ in the jet is

$$L_{syn} = \frac{1}{8} k_e \Lambda \gamma_j^2 c B^2 r^2 \varphi^2 \qquad \text{where} \quad \Lambda = \ln\left(\frac{r_{max}}{r_{min}}\right)$$

# Radio luminosity and jet parameters to convert frequency to linear coordinate along the jet

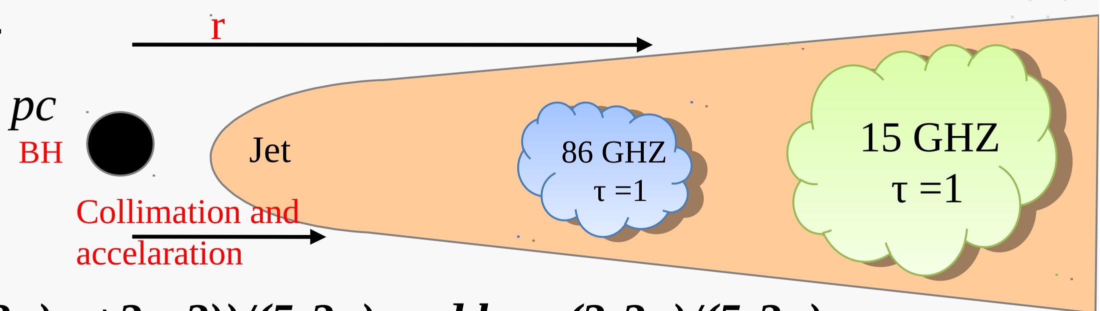
***The observed VLBI core at any given frequency is located at a region where the optical depth due to SSA, $\tau_s$ = 1 in the jet.***

$$\tau_s = C_2(\alpha)\, N_1 \left\{\frac{eB_1}{(2\pi m e)}\right\}^{\varepsilon} \delta^{\varepsilon} \frac{\varphi_0}{r^{(\epsilon m+n-1)}} \frac{1}{\upsilon^{(\varepsilon+1)}}$$

***(Rybicki & Lightman 1979)***

***where $\varepsilon = (3/2) - \alpha$ and $C_2(\alpha) = 8.4\times10^{10}$ .Equating $\tau_s = 1$, the physical distance of the VLBI core from the central engine as***

$$r = \left\{ \upsilon^{-1}(1+z)^{-1} B_1^{k_b} \left\{6.2\times10^{18} C_2(\alpha)\,\delta_j^{\epsilon} N_1 \varphi_o\right\}^{\frac{1}{\epsilon+1}} \right\}^{\frac{1}{k_r}} pc$$




***where $B=B_1(r/r_1)^m$ and $N=N_1(r/r_1)^n$ and $k_r=((3-2\alpha)m+2n-2))/(5-2\alpha)$ and $k_b = (3-2\alpha)/(5-2\alpha)$***

***m=1 and n=2 can be assumed.***

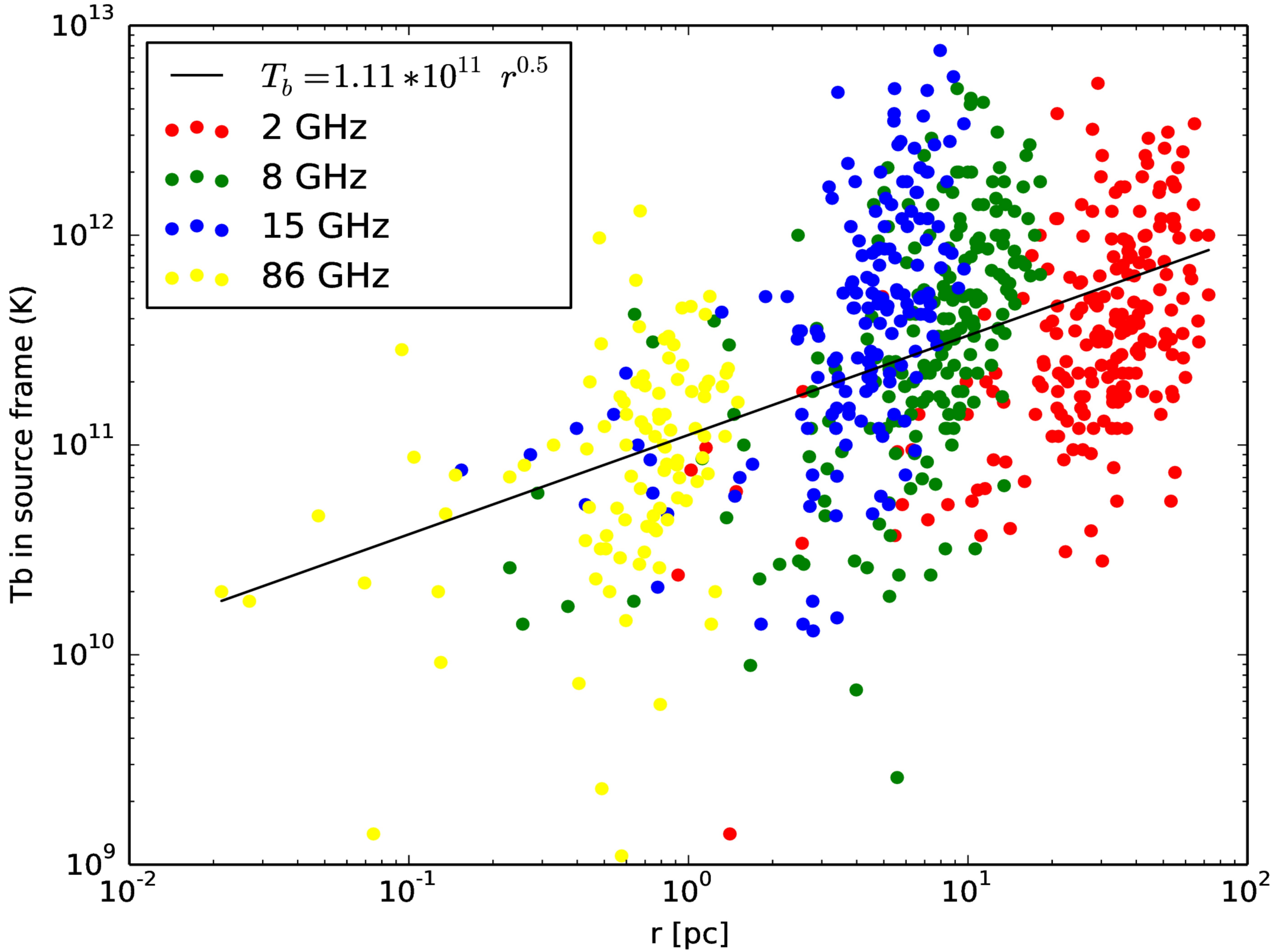
***The absolute position of VLBI core r is related with total radiated synchrotron luminosity $L_{syn}$ as***

$$r = \left\{ \xi C_r L_{syn} \{\upsilon(1+z)\}^{\frac{-1}{k_r}} \right\}^{1/3} \quad pc$$

***(Lee et al. 2016)***

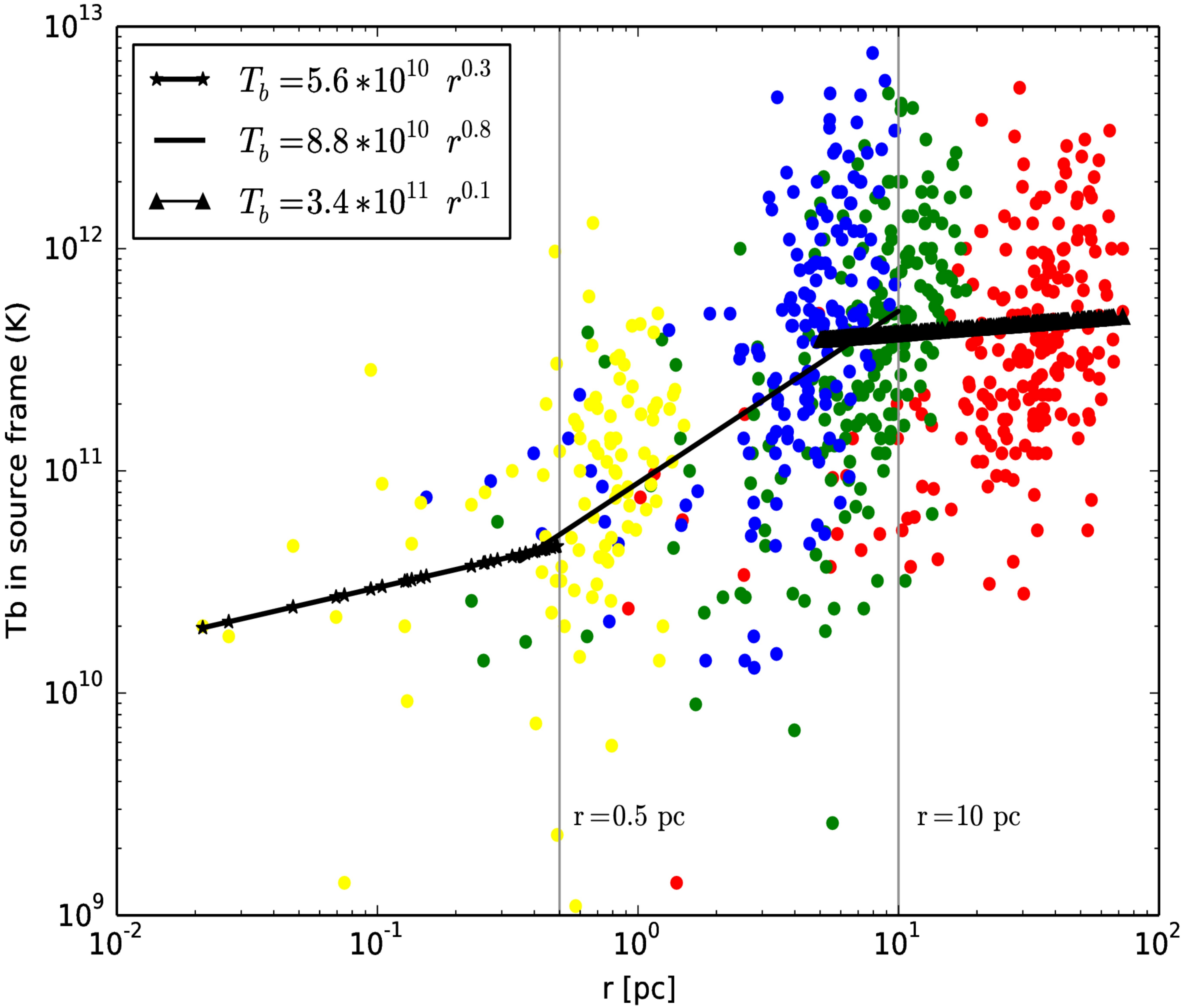
***$L_{syn}$ can be calculated from $L_{syn} = 4\pi D_L^2 F_t$ where $F_t$ is the flux density of core and total core flux can be obtained by integrating $F_t$ over dv (over the range of frequencies say 2, 8, 15, 86 GHz )***

# Results. V : $T_b$ as a function of distance of cores from central black hole – *simple power law fit*




$T_b \sim r^{0.5}$

# Results. V : $T_b$ as a function of distance of cores from central black hole – *multiple power law fit*




**0.01 pc < r < 0.5 pc**

$$T_b \sim r^{0.3}$$

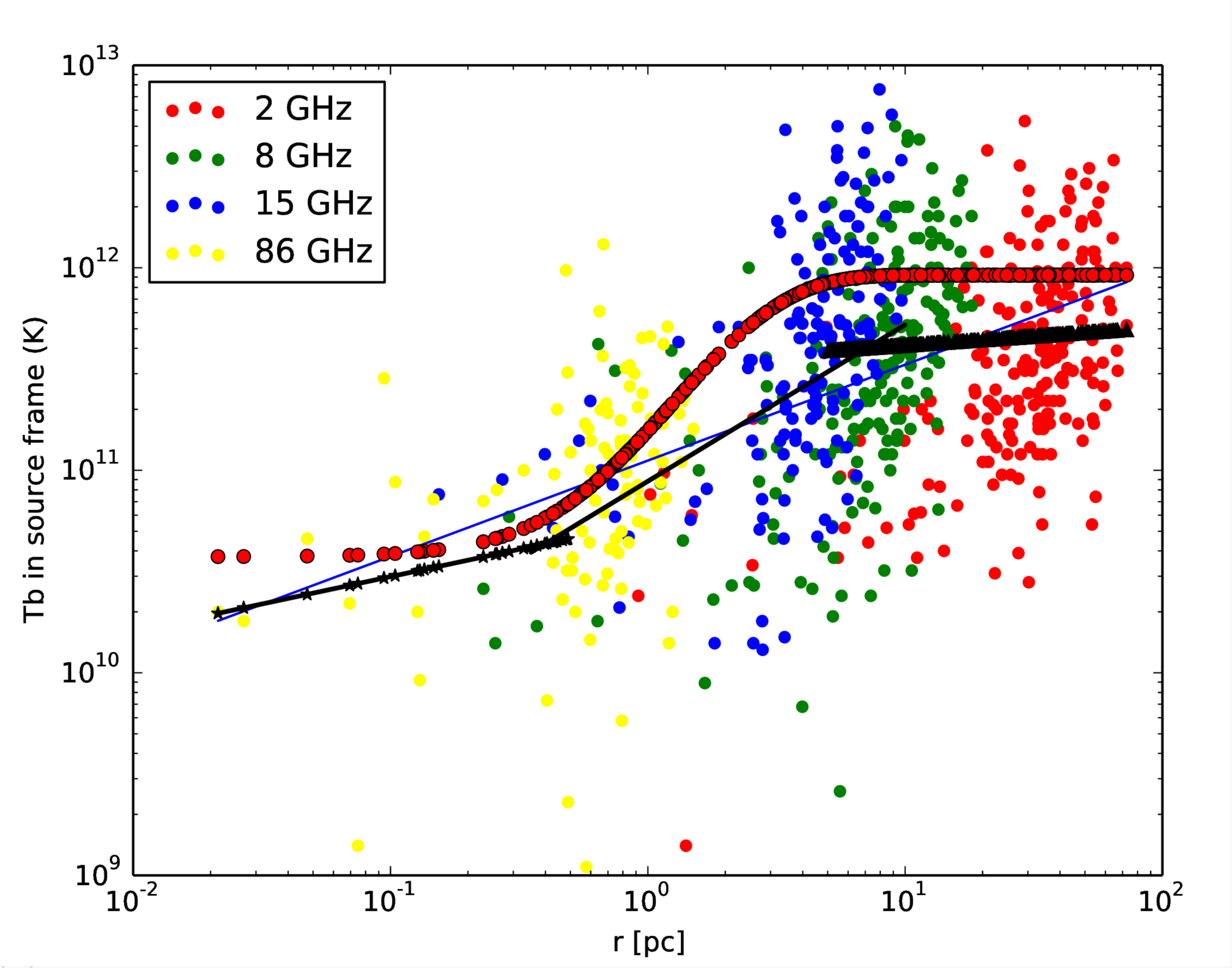
**0.35 pc < r < 10 pc**

$$T_b \sim r^{0.8}$$

**5 pc < r < 100 pc**

$$T_b \sim r^{0.1}$$

# Result V : $T_b$ as a function of distance of cores from central black hole – *All models*




***- $T_o(r)$ dependence expected for an MHD jet (dotted line) (Vlahakis & Königl 2004) on observed $T_b$***

# Brightness Temperature ($T_b$)

$$T_b = \frac{2\ln(2)}{\pi k_B} \frac{S_{\rm tot}\lambda^2(1+z)}{d^2}$$

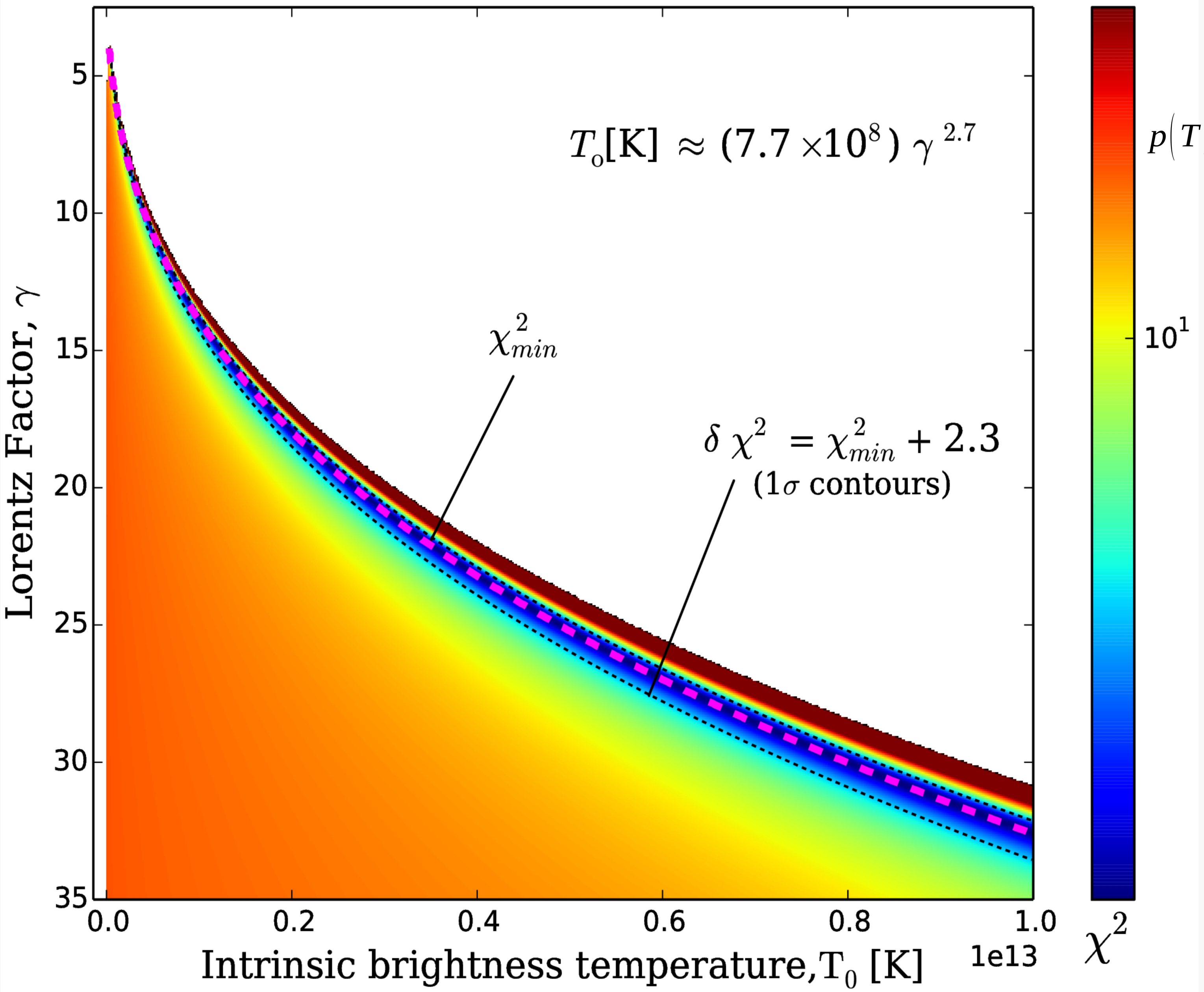
**Minimum resolvable size of the Gaussian component,** ➡

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

***( A.P. Lobanov 2005 )***

***And if $d < d_{min}$ , then the lower limit of $T_b$ is obtained with $d = d_{min}$.***

# Result. III : 2D - $\chi 2$ distribution plot ($\gamma$ - $T_0$)




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

**$T_0 = 10^7$ K – $10^{13}$ K**

**$\gamma$ = 1.1 – 35**

***Fit is degenerating in the $\gamma$-$T_0$ space (along the narrow strip in the 2D - $\chi 2$ distribution)***

**$T_0 = 7.7 \times 10^8\ \gamma^{2.7}$**

# Population modelling for the brightness temperature $T_B$

**Probability density of brightness temperature (theoretical model)**

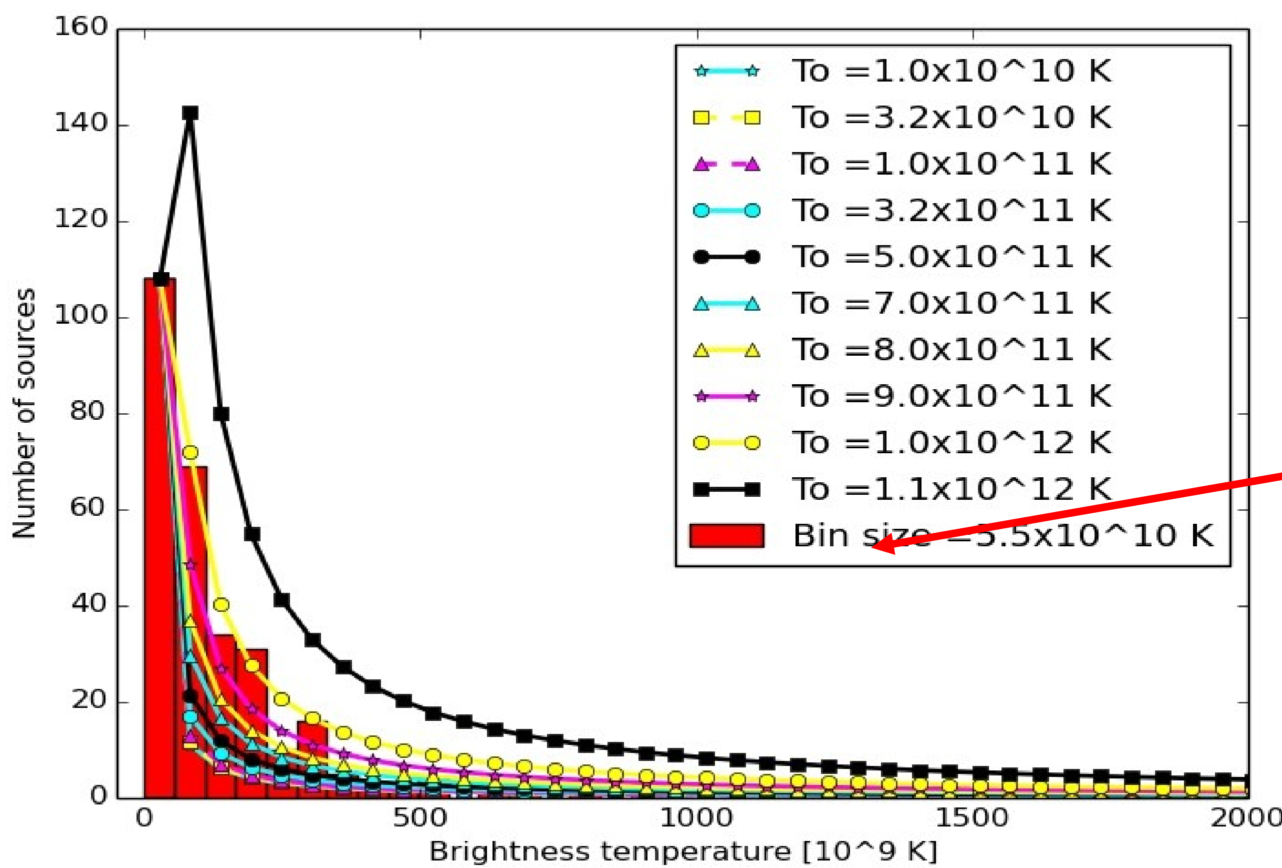
$$p(Tb)=\left[\frac{2\gamma_j\left\{\left(\frac{T_o}{T_b}\right)^{\epsilon}-\left(\frac{T_o}{T_b}\right)^{2\epsilon}-1\right\}}{\gamma_j^2-1}\right]^{1/2}$$

**where $T_b = \delta$ To**

**$\delta$ is the doppler factor**

**Lobanov et al.2000**

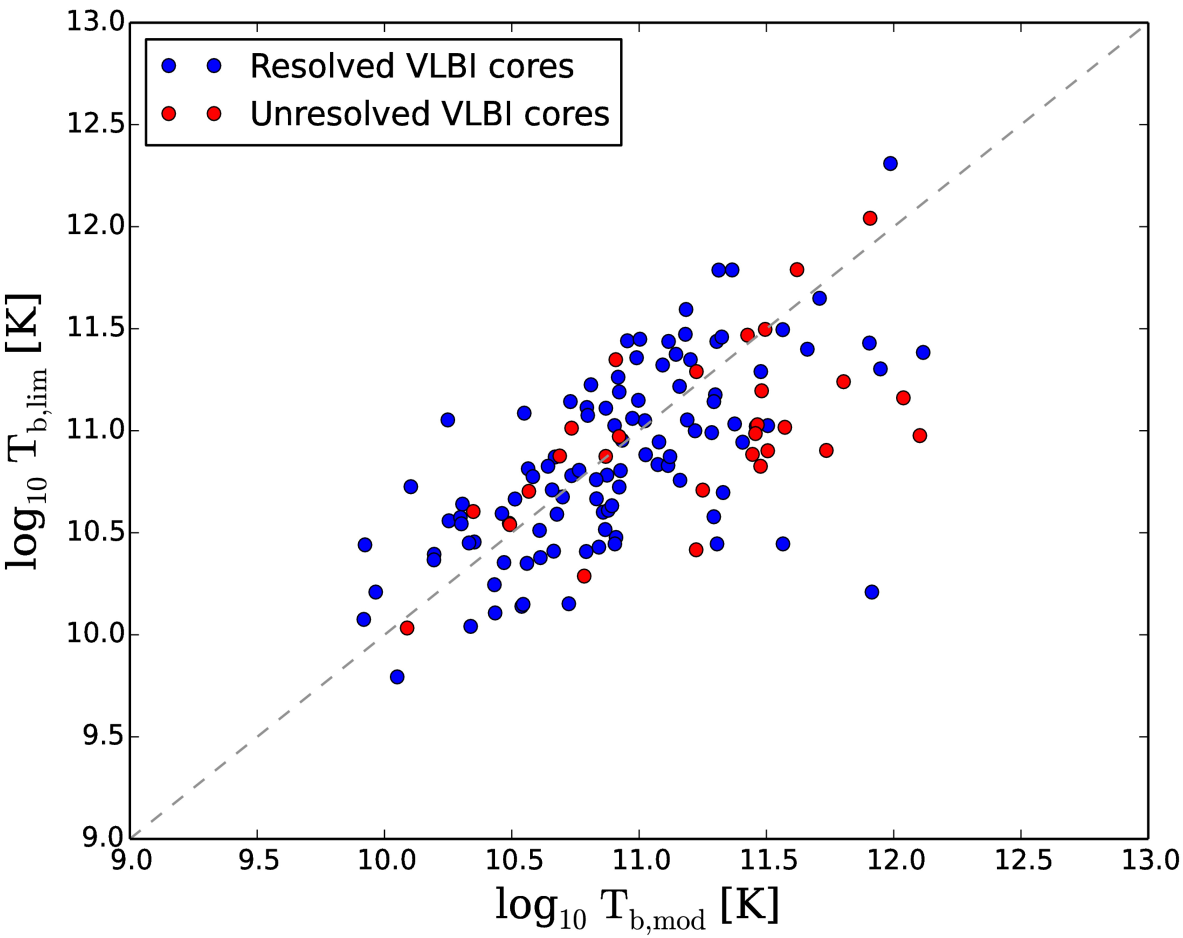
$$T_B=2\log(2)\frac{\pi}{k_B}\frac{S_{tot}\lambda^2(1+z)}{d^2}$$




**For $\gamma = 10$, the best fit $T_0$ = $(3.77\pm0.14)\times10^{11}$ K, and the model distribution rapidly grows discrepant from the observed one at $T_0 > 1.0\times10^{12}$ K.**

# Results. II : $T_b$ Gaussian model fitting & $T_b$ from interferometric visibility

**$T_{b,lim}$ at uv-radii within 10% of $B_{max}$ in the data**




- ***The interferometric visibility***

$$V = V_q e^{-i\Phi_q}$$

- ***Angular extent of the emitting region,***

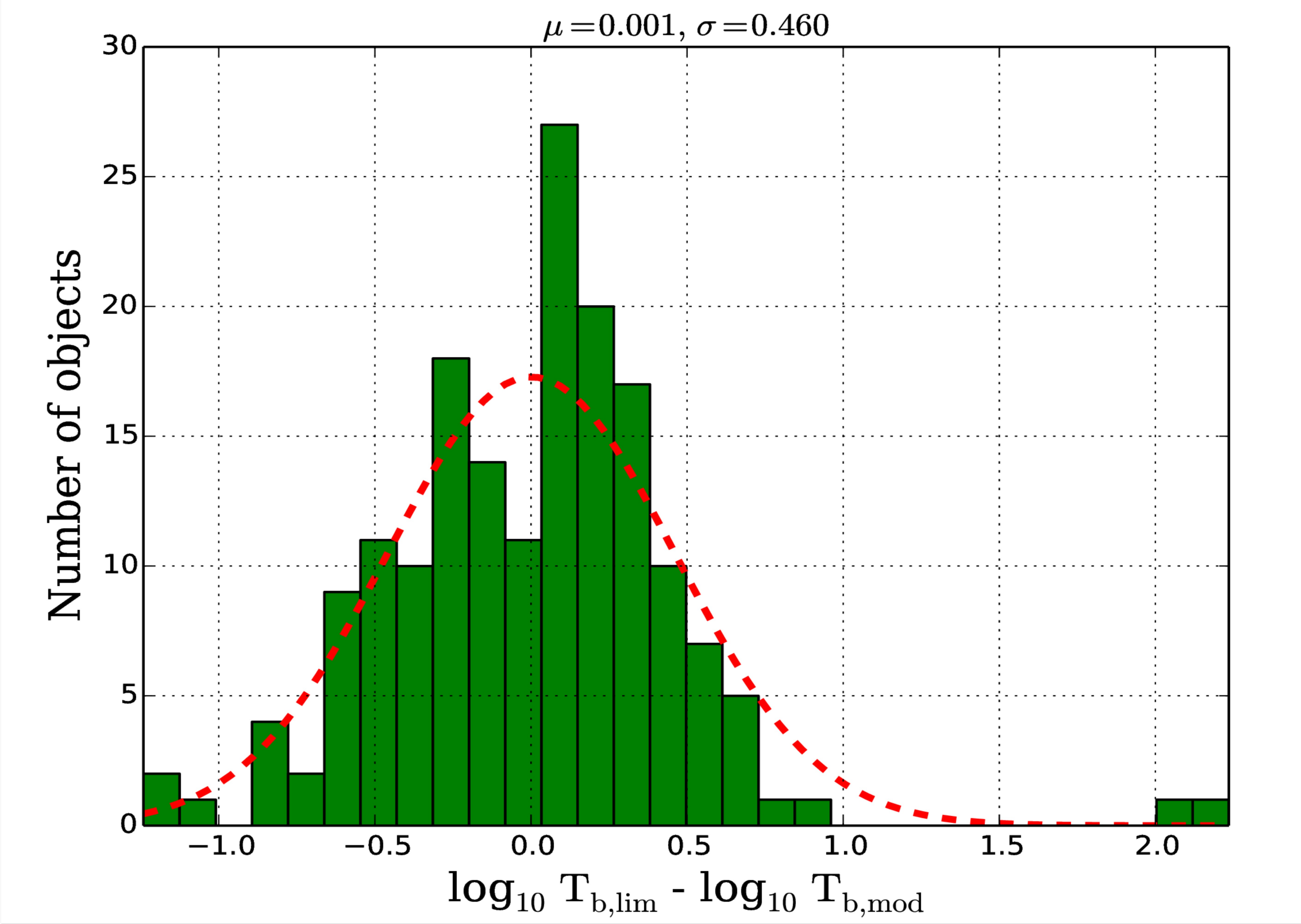
$$\theta = \frac{2\sqrt{\ln 2}\,\lambda\sqrt{\ln\frac{V_q+\sigma_q}{V_q}}}{(\pi B)}$$

$$T_{b,lim} = \frac{\pi B^2}{2k}\left(V_q+\sigma_q\right)\left(\ln\frac{V_q+\sigma_q}{V_q}\right)^{-1}$$

**Lobanov A.P 2015**

**The limiting $T_{b,lim}$ agrees with $T_{b,mod}$ estimated from imaging method**

# Results. II : $T_b$ Gaussian model fitting & $T_b$ from interferometric visibility




**The limiting $T_{b,lim}$ agrees with $T_{b,mod}$ estimated from imaging method**

# Modelling of inner jet : jet accelaration will be studied , based on modelling the evolution of brightness temperature

Modelling steps :

1. General idea : Brightness temperature observed at different frequencies and converted into linear distances from the central engine reflect two major processes in a relativistic plasma: accelaration of the plasma and energy losses in the plasma – inverse compton,synchrotron, or adiabatic.

2. Doppler boosting : Accelaration described by the velocity $\beta_j(z)$ and the corresponding Lorentz factor $\Gamma_j(z)$ results in an observed brightness temperature

$$T_b(z) = T_o\ \varepsilon(z)\ [\delta_j(z)]^{n-\alpha} = T_o\ \varepsilon(z)\ [\ \Gamma_j(z)\ [1 - \beta_j(z) \cos\theta]^{n-\alpha}\ ]{-1}$$

Where ε(z) is the energy loss factor, α – spectral index and power law index n depends on the geometry of the emitting region (with n = 1 for a homogenous sphere).

3. Energy losses : The energy losses $\varepsilon(z) = z^{\xi}$ can be derived from for eg. Lobanov & Zensus (1999),Marsher(1990),yielding:

$\xi = ((11-s)-a(s+1))/8$ inverse- Compton losses

$\xi = -(4(s-1)+3a(s+1))/6$ synchrotron losses

$\xi = (s(5-2s)-3a(s+1))/6$ adiabatic losses

## Testing different accelaration models

1.Accelaration by radiation pressure : Following a model by Bodo et al.(1985), the evolution of jet speed due to radiation pressure accelaration can be described by the following eqn.

$$\Gamma_j^2 \beta_j \left(1 - \frac{\beta_j^2}{\beta_s^2}\right) \frac{d\beta_j}{d\zeta} = \frac{\beta_s^2}{r(\zeta)} \frac{d\, r(\zeta)}{d\zeta} - \frac{r_g}{r_0 \zeta^2} + \Gamma_j F(\zeta, \beta_j) \frac{r_g}{r_0} \frac{L_{bh}}{L_{edd}} ,$$

2.Accelaration by tangled magnetic field : Following a model by Heinz and Begelman (2000)

$$\Gamma_j(\zeta) = \Gamma_0 \zeta^{p/4} \left[1 - A_\Lambda(\zeta^{1-p/2} - 1)\right]^{(5b-6)/(4b-4)} ,$$

3.Vlahakis and Konigl Model – MHD model

$$T_b = \frac{\alpha + 5/3}{\alpha + 1} \frac{c^2}{2k_B} \kappa \nu^{-\alpha-2} \int \kappa_e \delta^{\alpha+3} \left[\frac{B^2}{\gamma^2} + 2\frac{\delta}{\gamma} (\boldsymbol{B} \cdot \hat{n}) \left(\boldsymbol{B} \cdot \frac{\boldsymbol{V}}{c}\right) - \frac{\delta^2}{\gamma^2} (\boldsymbol{B} \cdot \hat{n})^2\right]^{(\alpha+1)/2} d\ell_{co} .$$