Max-Planck-Institut
für Radioastronomie

# 86 GHz VLBI Survey of Ultracompact Radio Emission in Active Galactic Nuclei

MAX-PLANCK-GESELLSCHAFT

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***2015, Ventspils, Latvia***

# Outline

- **Introduction**
  - *mm VLBI, Previous Surveys*
- **Observation**
  - *Source selection, Calibration*
- **Results**
  - *3mm maps*
- **Brightness temperature ($T_B$) and jet physics**
  - $T_b$ - *Population modelling, Adiabatically Expanding jets*
- **Summary**

# Active Galactic Nuclei (AGN)

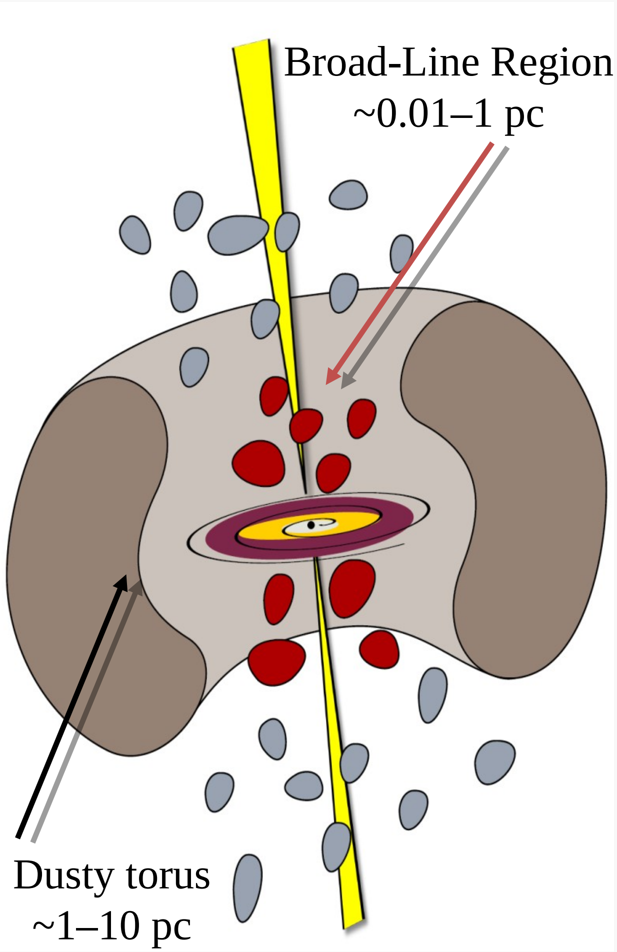
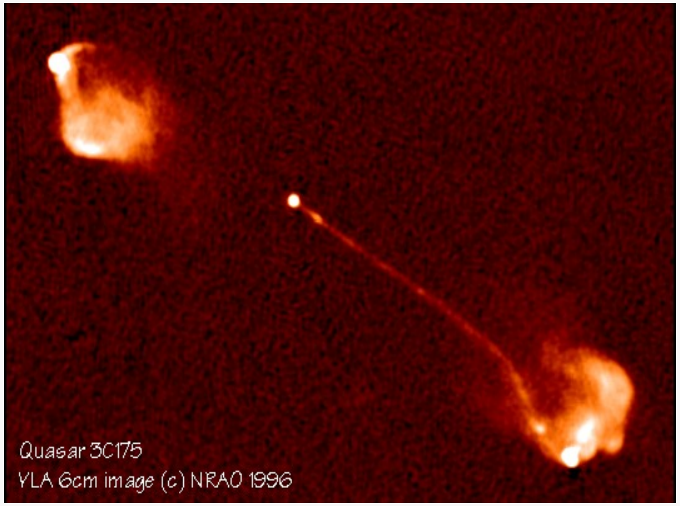
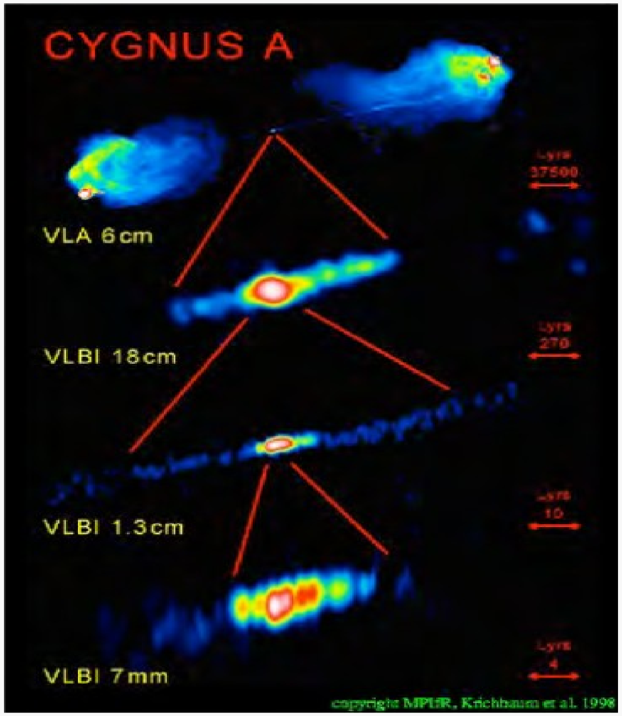


*Image courtesy: Karamanavis,V,MPIfR*

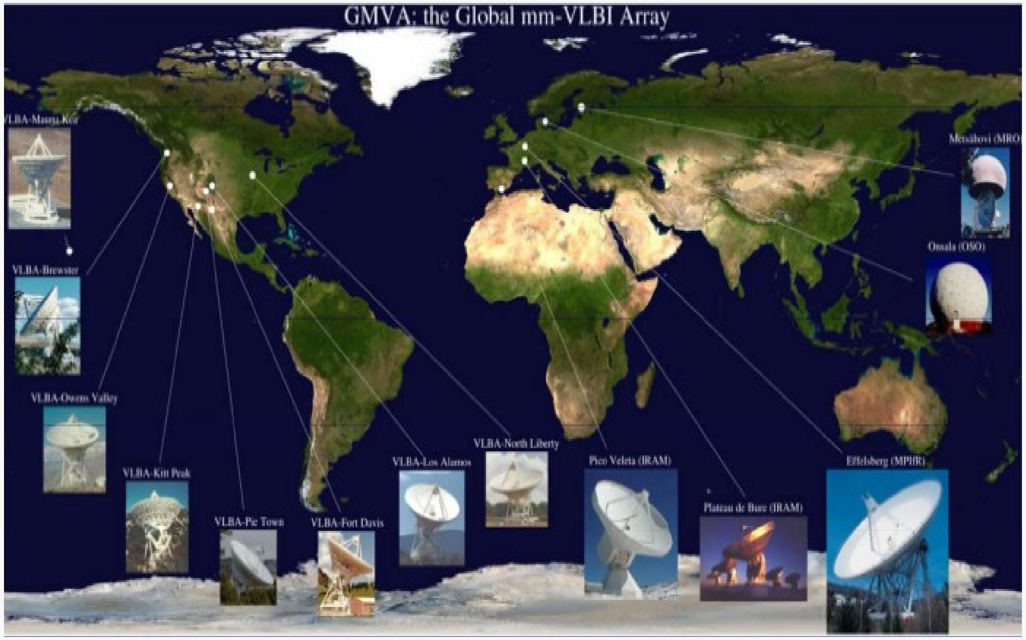
- Normal Galaxy – most of the light comes from visible wavelength – stars, hot gas and HII regions
- Active Galaxies : bright central nuclei with luminosities ~ $10^{37}$ to $10^{40}$ watts
~ $10^5$ times host galaxy > trillion 'suns'
- Active from radio to γ ray waveband
- AGNs are powered by accretion on a supermassive black hole of mass of order $(10^6$-$10^{9)}$ $M_o$ at the centre.
- Only 10% of AGN are radio loud,featuring powerful relativistic jets.



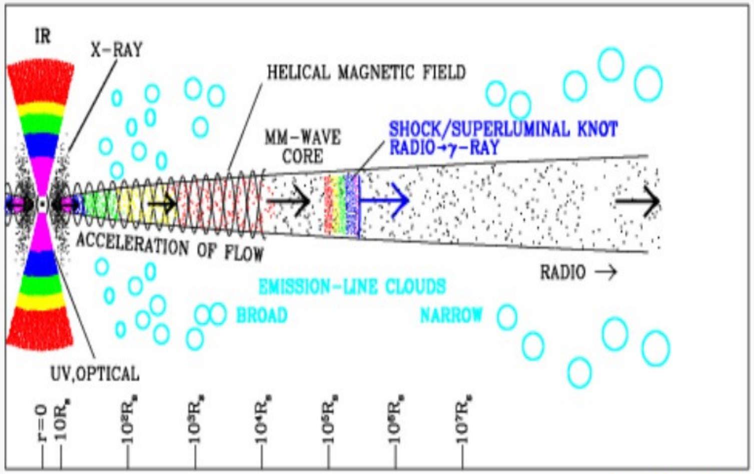
# Why 3mm (86 GHz) VLBI ?



*From Krichbaum et al. 1998*



*Courtesy : http://www.mpifr.de/div/vlbi/globalmm*



*From Marsher et al.*

The Global MM-VLBI Array GMVA
VLBA (8x25m) + (Ef,On,Pv,Pb,Mh,Ys)

- **40 micro-arcsec resolution at 86 GHz** two times that of space VLBI (Radio Astron) at 1.6 GHz.
- 86 GHz VLBI zoom into a linear scale of **$10^3 \sim 10^4$ Schwartzschild radii**

# Previous Surveys

Beasley et.al (1997)

Lonsdale et.al (1998)

Rantakyro et al. (1998)

→ Detection Surveys

Lobanov et.al (2000)

Lee et.al (2007)

**This survey**

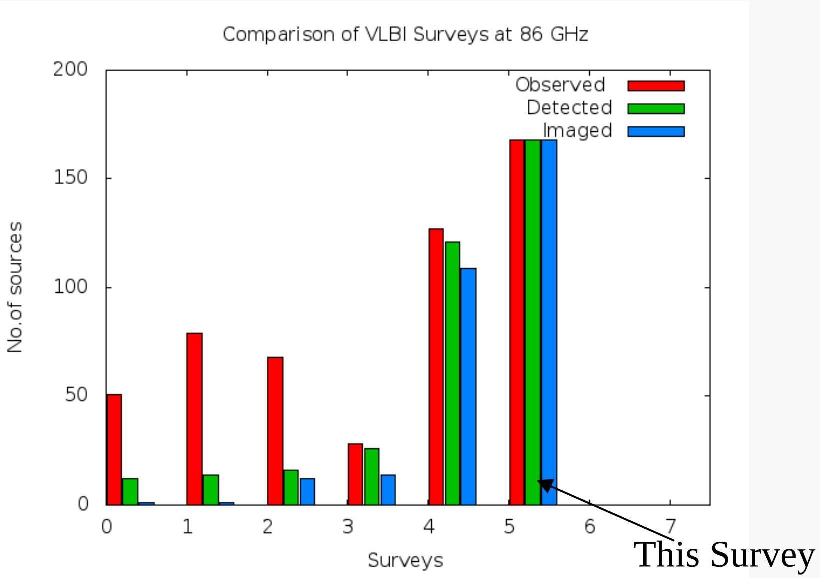
→ Imaging Surveys

- a sample of 162 unique objects

- recording rate of 512 Mbps (double that of last survey ,bandwidth – 128 MHz and 2-bit sampling

100% Detection

-*162 sources detected & Imaged- QSO,Blazar, Galaxies & Unidentified*



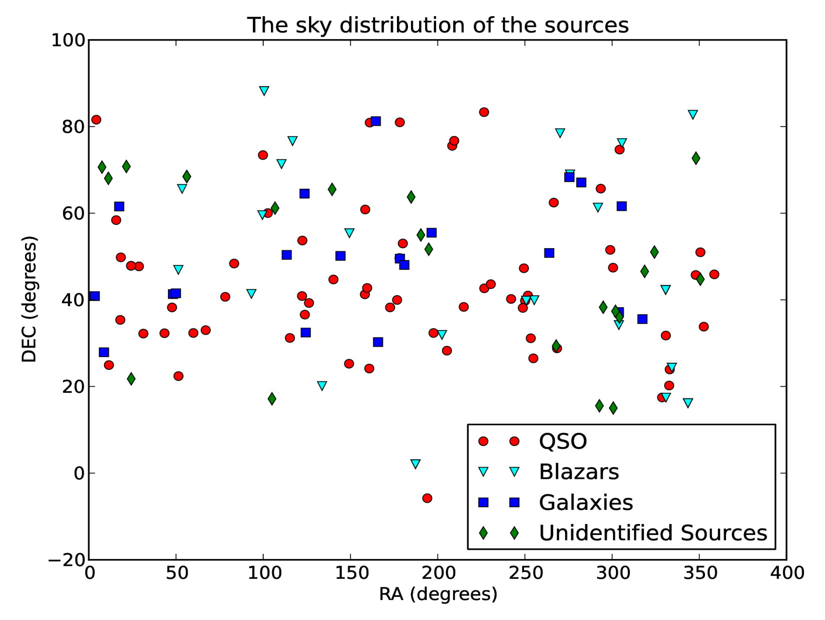
Source selection

- From the 15 GHz VLBA Survey – MOJAVE (Kovalev et.al 2005) and 22 GHz VERA Galactic plane survey (Petrov et.al 2005) for which the corelated flux density ≥ 0.5 Jy and declination δ ≥ -20 degree

- Max.baseline sensitivity ~ 0.1 Jy and image sensitivity ~ 5 mJy/beam

- 8 VLBA + 5 European stations – session in October 2010,May 2011 and October 2011

- 3 to 4 scans ~ 6/ 7 minutes duration

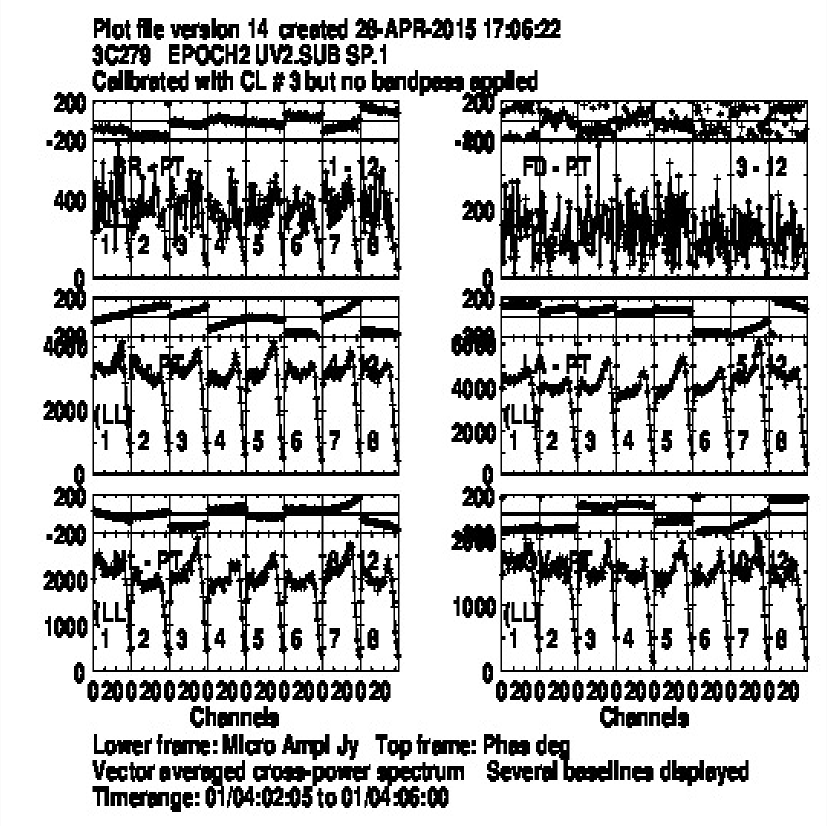


# Calibration

**Correlation at MPIfR**
**DiFX**

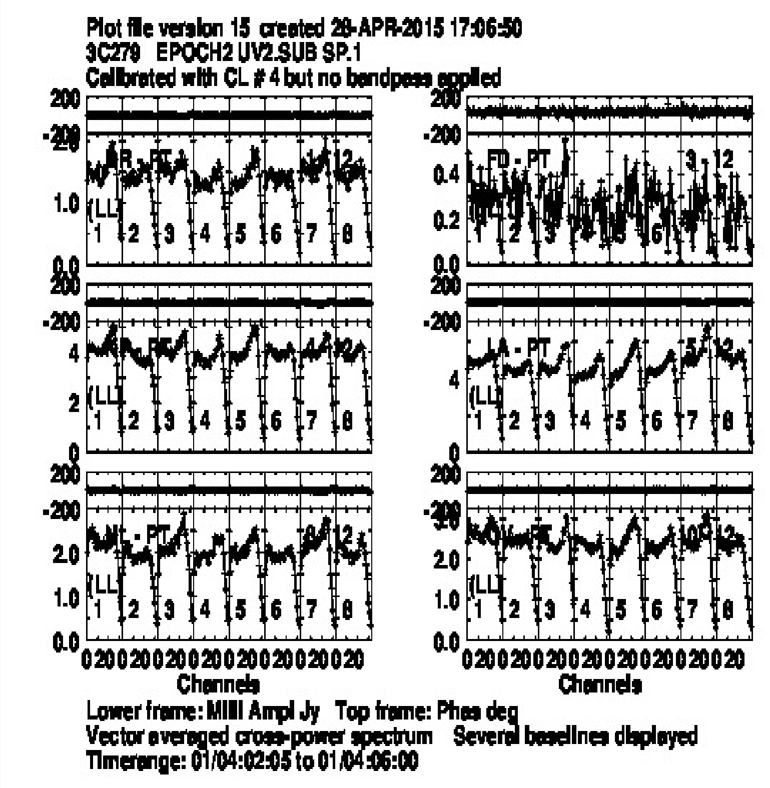
Amp.calibration
FRING
AIPS

**Imaging**
**DIFMAP**
(Shepherd et al. 1994)



Plot file version 14 created 28-APR-2015 17:06:22
3C279 EPOCH2 UV2.SUB SP.1
Calibrated with CL # 3 but no bandpass applied

Lower frame: Micro Ampl Jy Top frame: Phas deg
Vector averaged cross-power spectrum Several baselines displayed
Timerange: 01/04:02:05 to 01/04:06:00

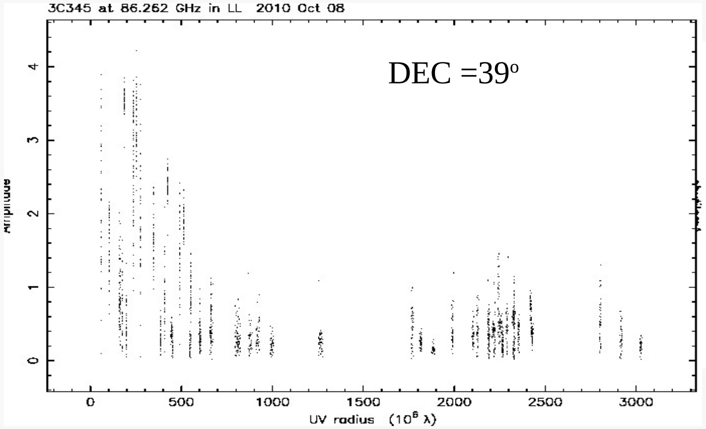


Plot file version 15 created 28-APR-2015 17:06:50
3C279 EPOCH2 UV2.SUB SP.1
Calibrated with CL # 4 but no bandpass applied

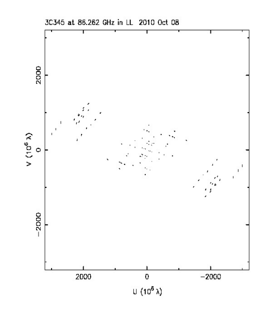
Lower frame: Milli Ampl Jy Top frame: Phas deg
Vector averaged cross-power spectrum Several baselines displayed
Timerange: 01/04:02:05 to 01/04:06:00

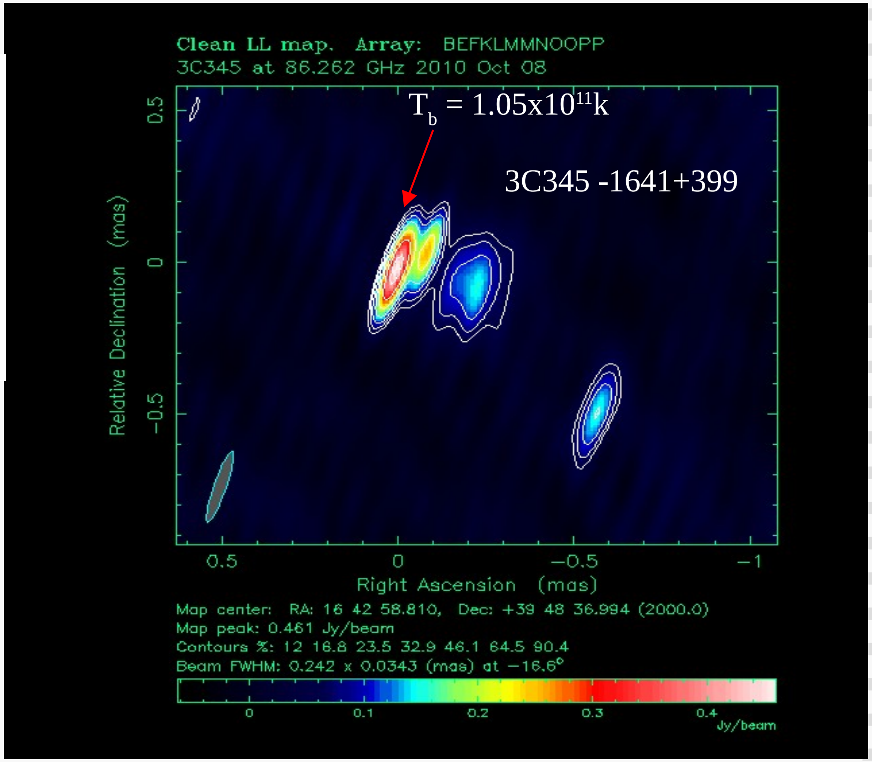
**Fringes obtained for a source 3C279**

# 3 mm maps



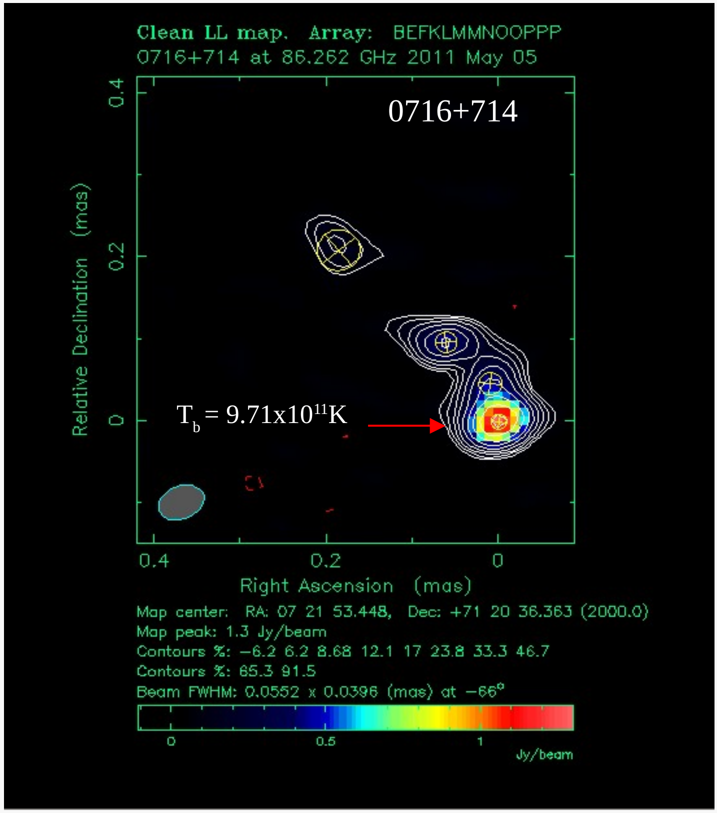
DEC =39°





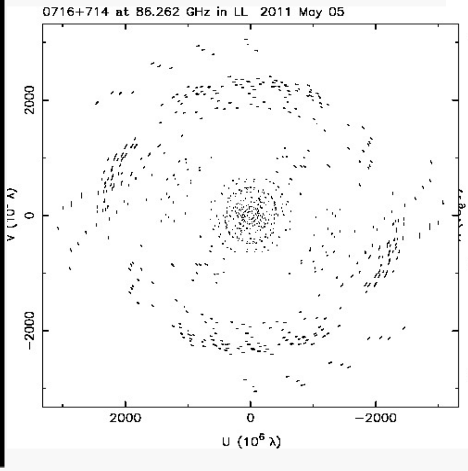
$T_b$ = 1.05x10$^{11}$k

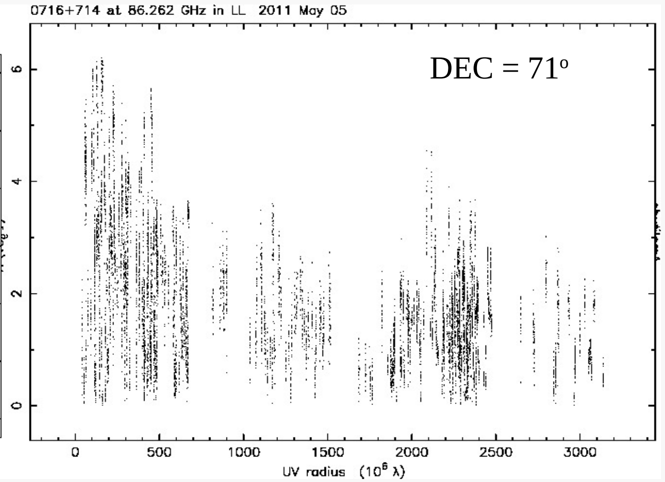
3C345 -1641+399



0716+714

$T_b$ = 9.71x10$^{11}$K

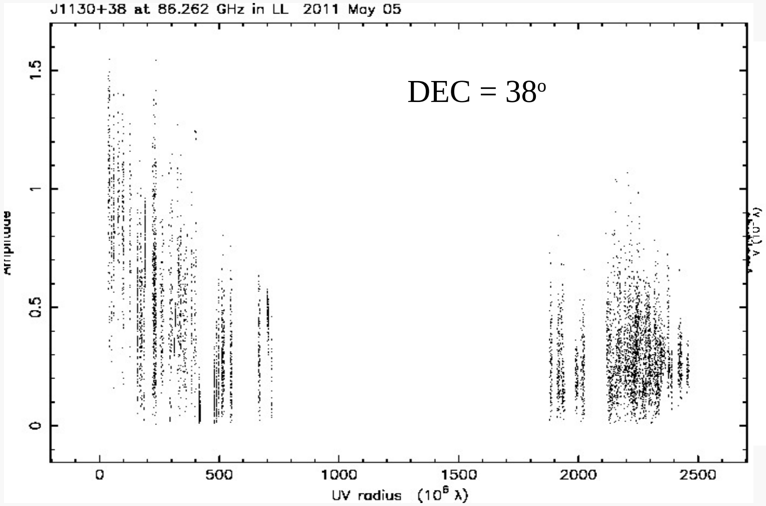




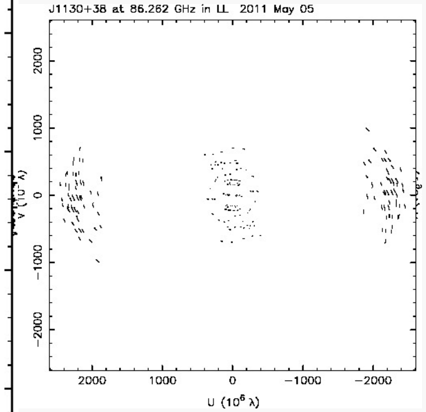
DEC = 71°

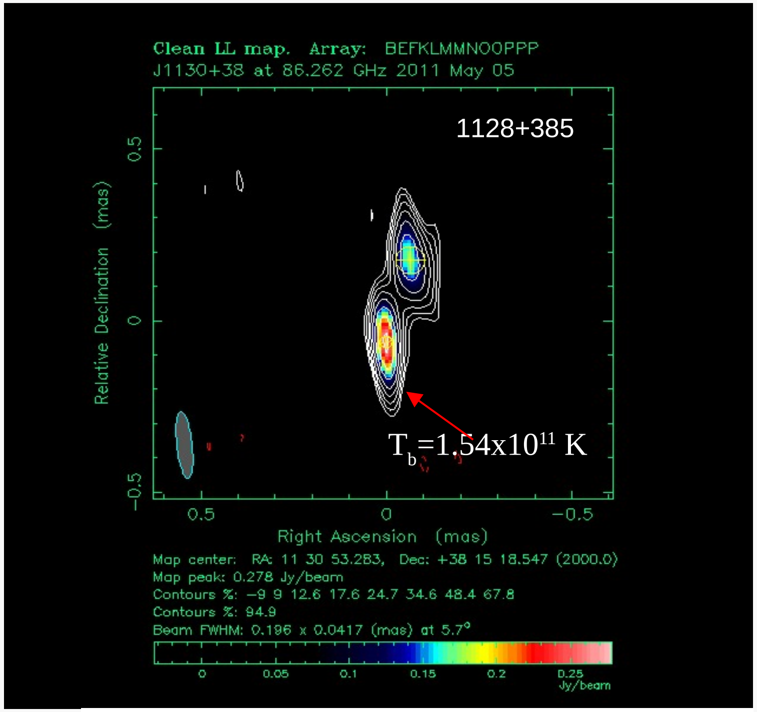
# 3 mm maps

(Nair et al. in prep.)



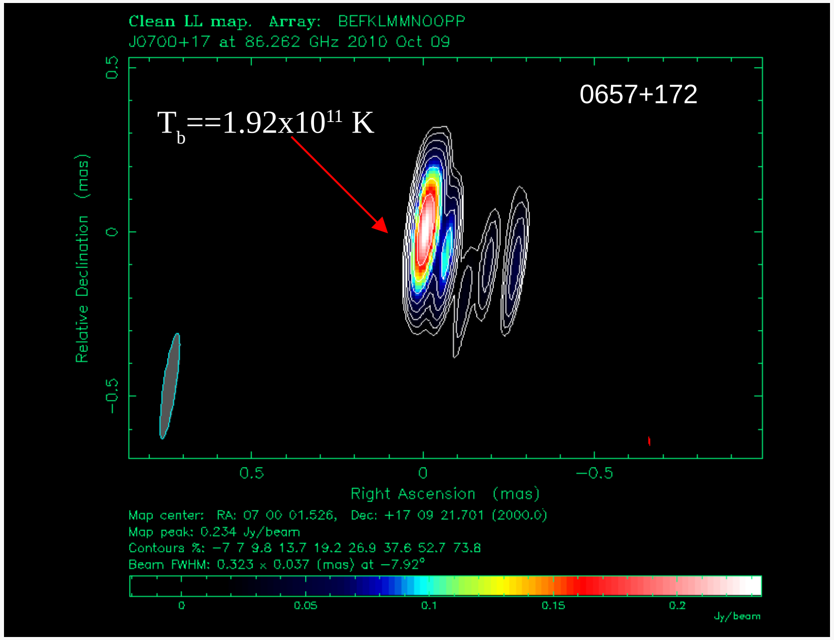
DEC = 38°





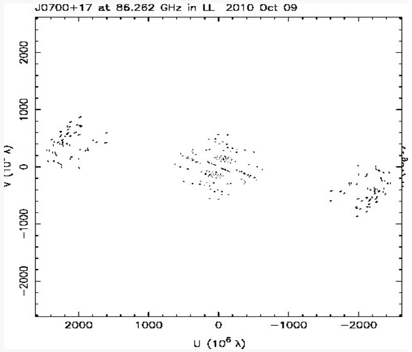
1128+385

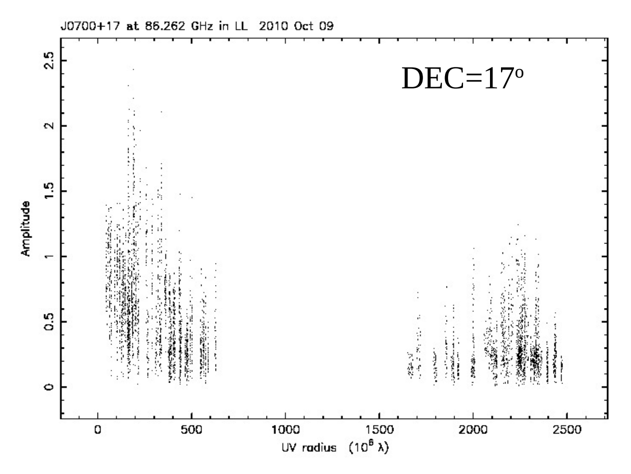
$T_b$=1.54x10$^{11}$ K



0657+172

$T_b$==1.92x10$^{11}$ K





DEC=17°

# Brightness Temperature ($T_B$)

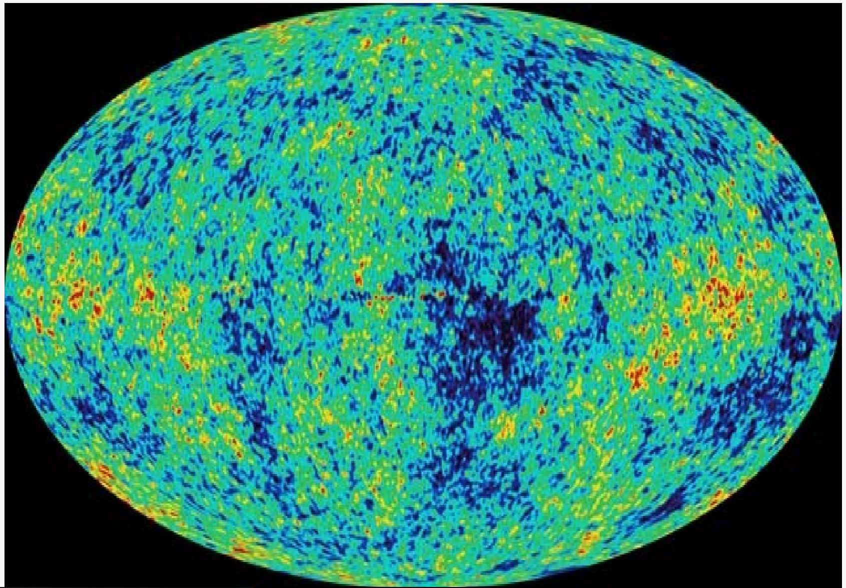
Brightness temperatures :

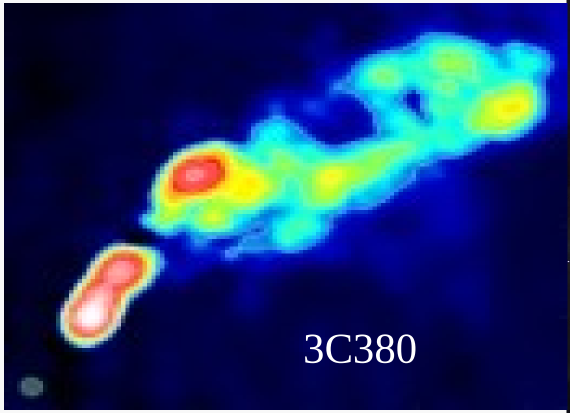
“Blank Sky” ~ 2.73 kelvin (thermal big bang BB radiation)

Sun at 300 MHz, 50,000 kelvin (mostly non thermal)

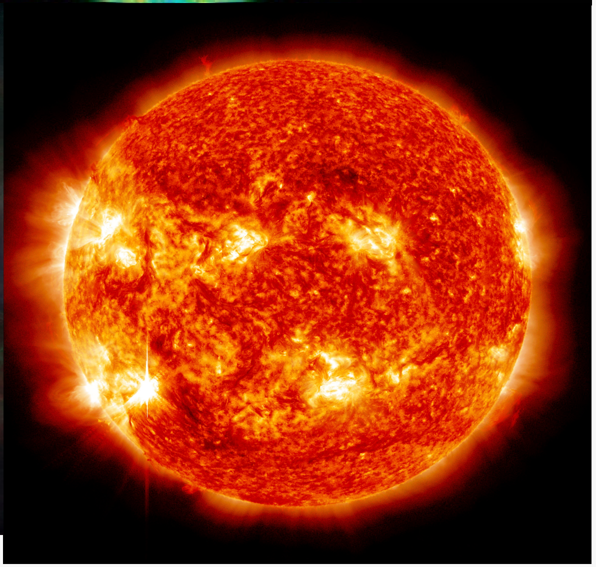
Orion Nebula at 300 GHz, 10-100 kelvin (“warm” thermal Molecular clouds)

Quasars at 5 GHz ~ $10^{12}$ kelvin (non thermal synchrotron)





Courtsey : Google images



This is not a physical temperature but a measure of the energy density of the electrons and magnetic fields that generate radio emission via non thermal emission mechanisms (synchrotron)

# Brightness Temperature ($T_B$)

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

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

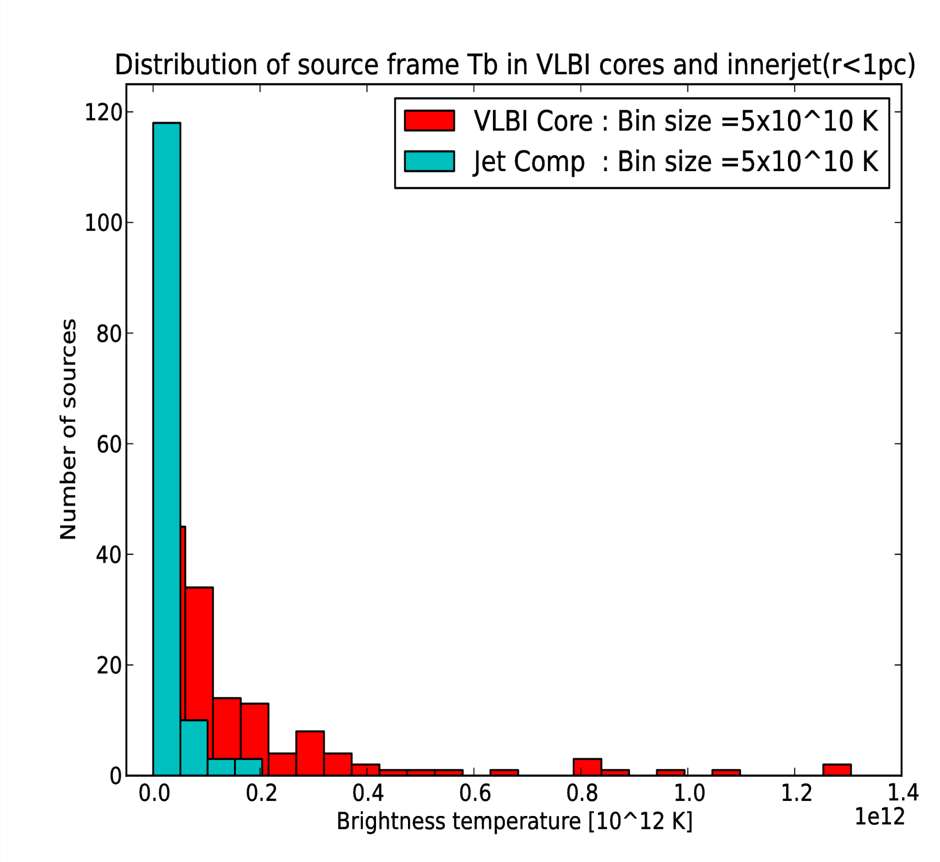
Minimum resolvable size of the gaussian model comp, →

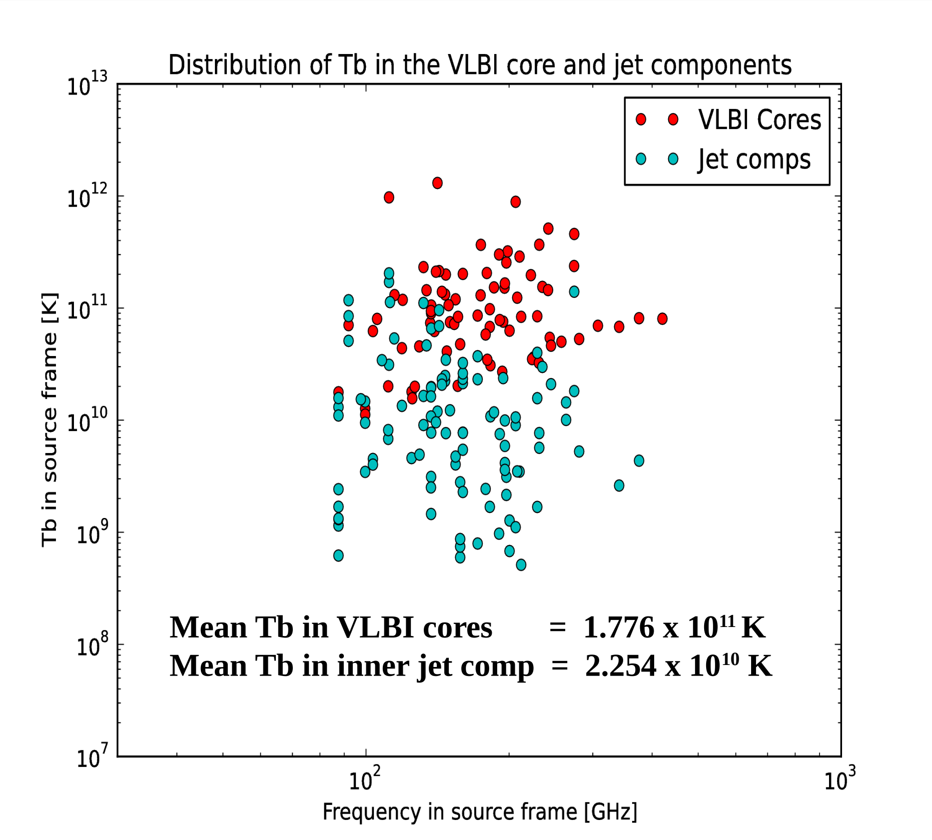
$$d_{min} = \left\{\frac{2^{(1+\beta)/2}}{\pi}\right\}\left\{\pi ab\ln 2 \ln\frac{(SNR+1)}{(SNR)}\right\}^{(1/2)}$$

(A.P. Lobanov 2005)

(e.g. SNR = 6.5; Beam ( a x b ) = ( 0.1 x 0.07 mas) => $d_{\text{min}}$ = 0.035mas)

# Brightness Temperature ($T_B$) distribution


Distribution of source frame Tb in VLBI cores and innerjet(r<1pc)

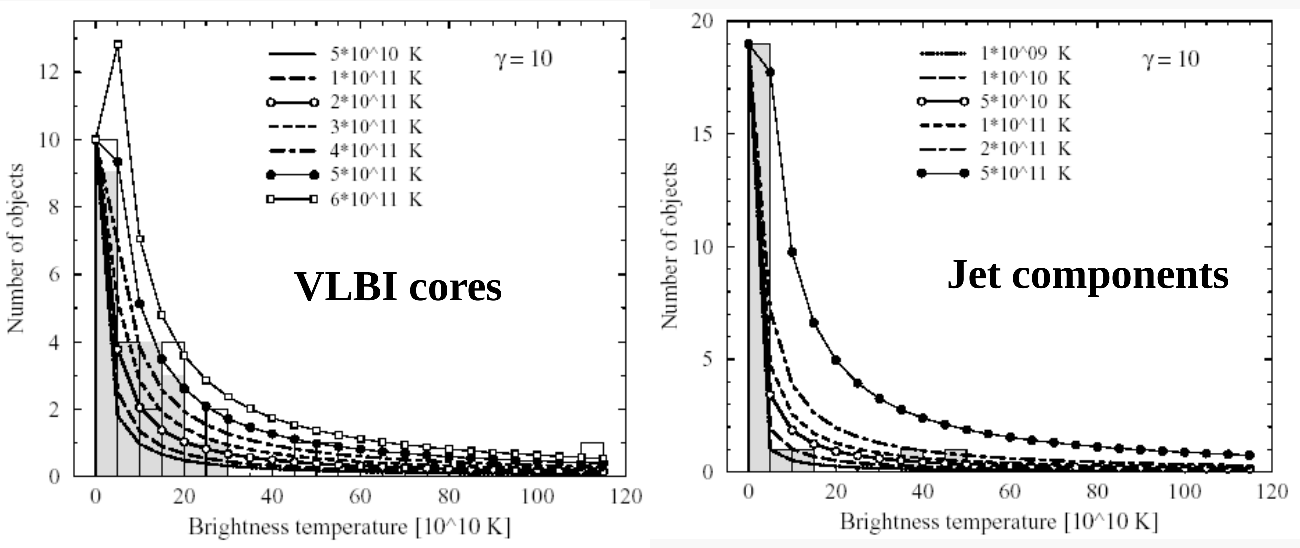

Distribution of Tb in the VLBI core and jet components

**Mean Tb in VLBI cores = $1.776 \times 10^{11}$ K**
**Mean Tb in inner jet comp = $2.254 \times 10^{10}$ K**

- Difference in the average Tb distribution measured in the cores and inner jet components by a factor of ~ 10.

$T_b$ distribution is approximately concentrated within $T_b < 4\text{x}10^{11}$ kelvin for VLBI cores and within $T_b < 5.0\text{x}10^{10}$ kelvin for inner jet components. The $T_b$ of VLBI cores are in certain agreement with the inverse compton limit (~ $5\text{x}10^{11}$ K) and $T_b$ of jet components are also in agreement with the equipartition limit (~ $5\text{x}10^{10}$ K).

# Population modelling for the jet brightness temperature $T_B$



Lobanov et al .2000

$$T_{\text{int},core} = 1 \sim 4 \times 10^{11}\, K$$

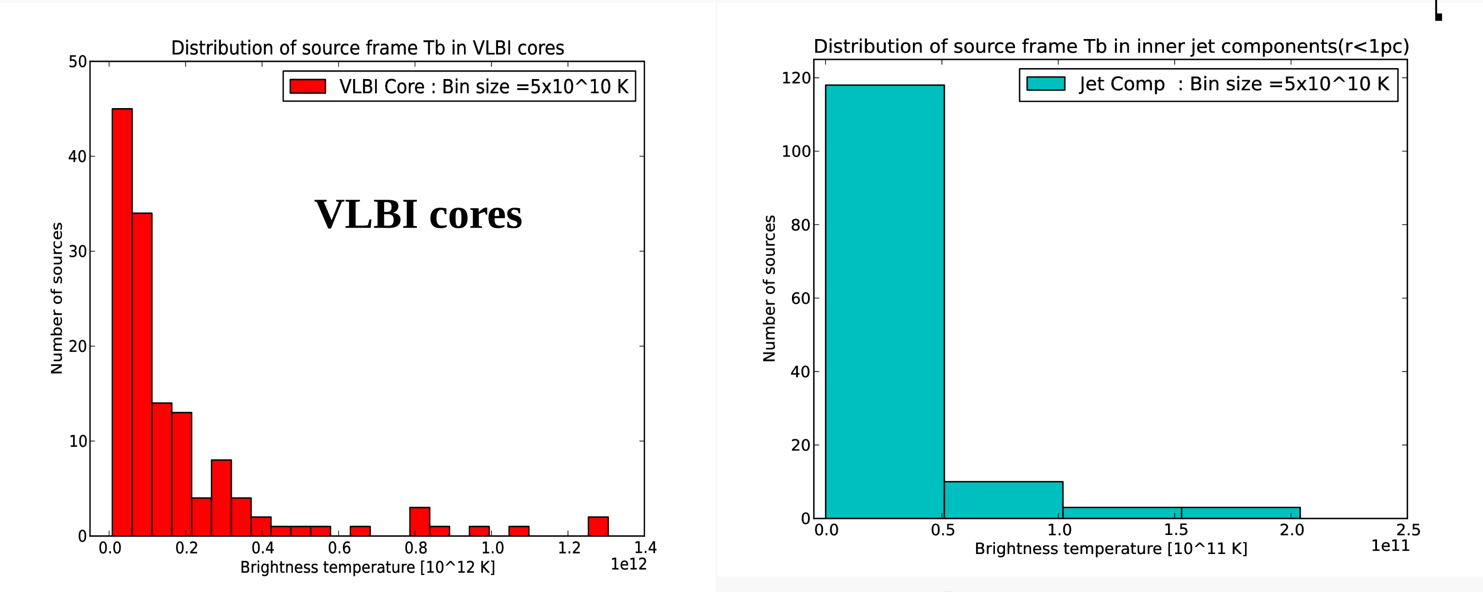
$$(\sim \text{Inverse compton limit})$$

$$T_{\text{int},\, jet} \leq 5 \times 10^{10}\, K$$

$$(\sim \text{Equipartition limit})$$

Probability density of brightness temperature (theoretical model)

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

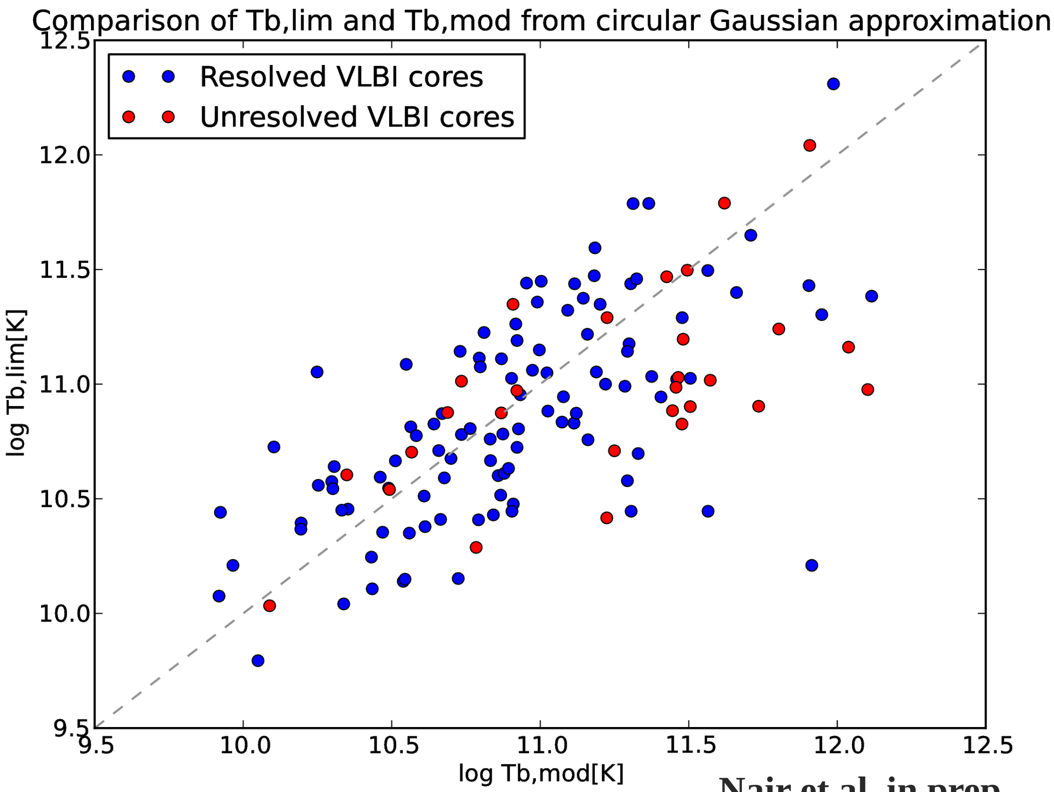


where $T_b = \delta\, To$

$\delta$ is the doppler factor

**(Nair et al in prep.)**

# Correlation between $T_b$ measured from Gaussian model fitting the source and $T_b$ estimated directly from the interferometric visibility



**Nair et al. in prep**

Assumptions are made like the followng:

- *The interferometric visibility is expressed as*

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

- *Angular extent of the emitting region:-*

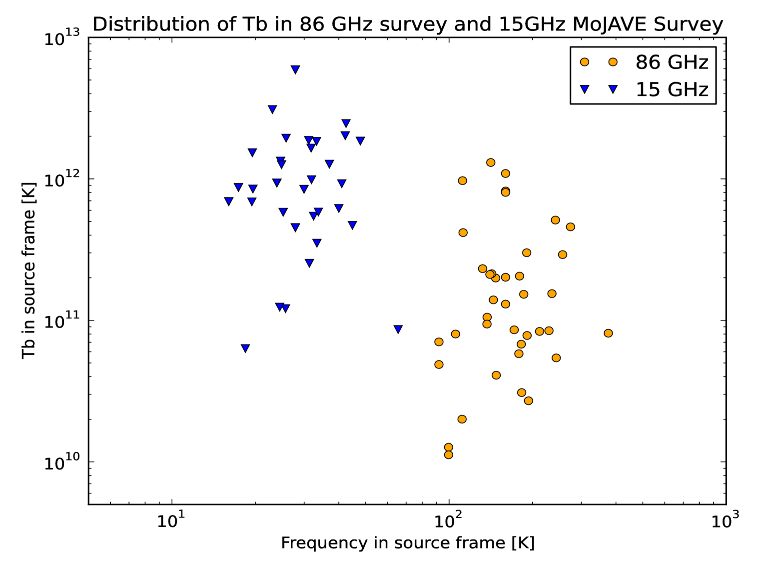
$$\theta = \frac{2\sqrt{\ln 2}\,\lambda\sqrt{\ln\frac{V_q+\sigma_q}{V_q}}}{(\pi B)}$$

Lobanov 2015

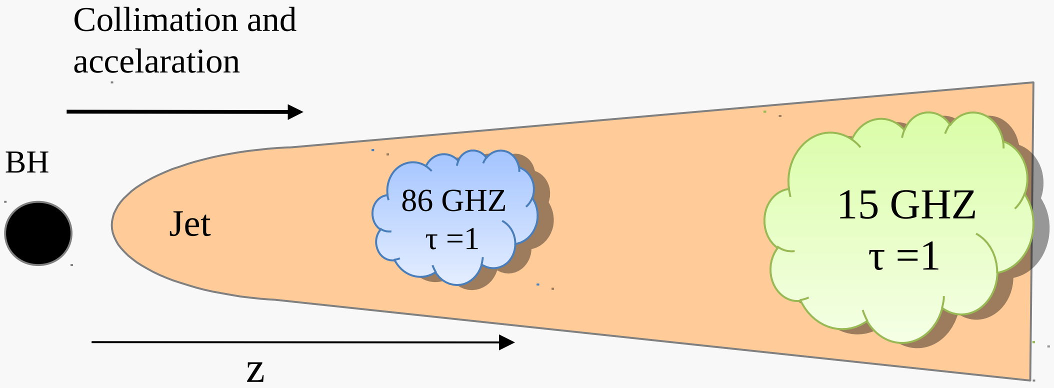
$$T_{b,limit} = \frac{\pi B^2}{2k}\left(V_q+\sigma_q\right)\left(\ln\frac{V_q+\sigma_q}{V_q}\right)^{-1}$$

The limiting $T_{b,lim}$ are essentially equal to $T_{b,mod}$ estimated from imaging method – one to one correspondance

# Do jets decelerate ?



**Nair et al., in prep.**


Collimation and accelaration

BH

Jet

86 GHZ
τ =1

15 GHZ
τ =1

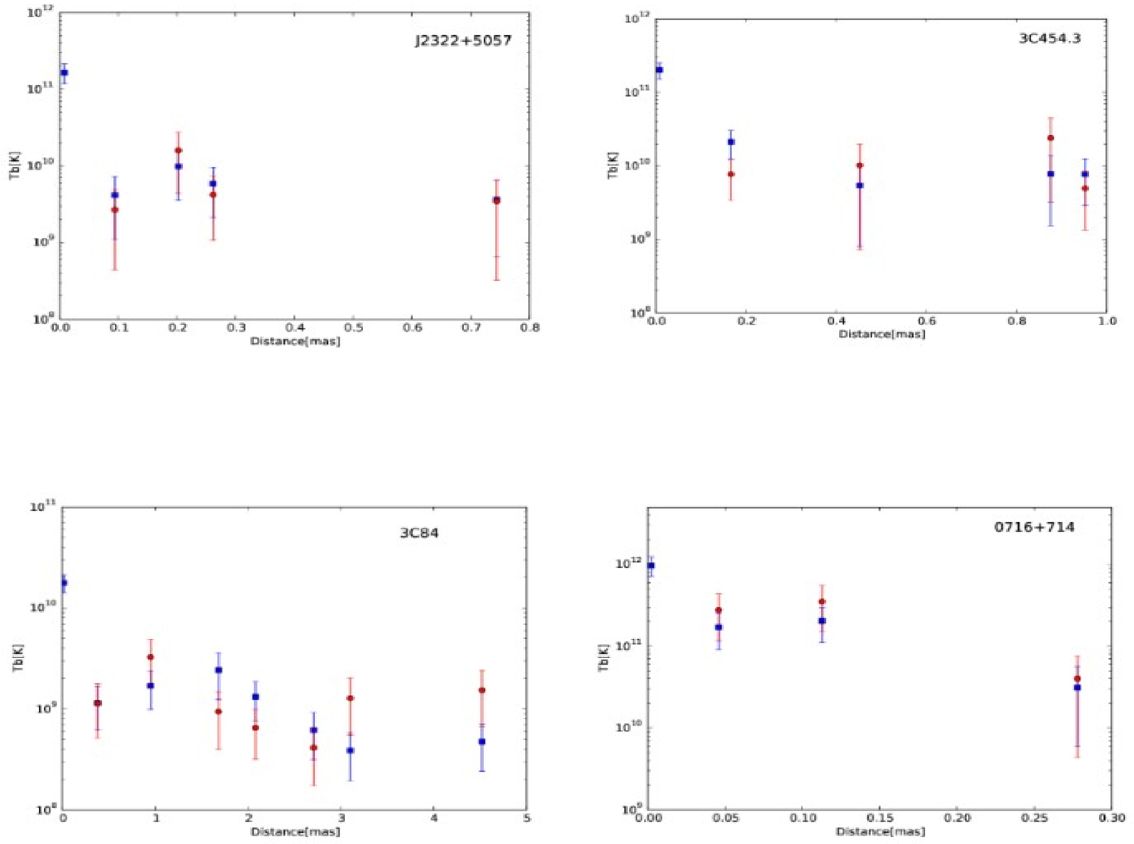
z

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

- $T_b$ at 86 GHz are sytematically lower than $T_b$ at 15 GHz Decrease of $T_o$ at 86 GHz – strong argument towards a theoretical decelerating jet model (Marsher 1995).

- This supports the theoretical model that the relativistic electron-positron pair plasma up-scatter the photons produced outside the jet into X-rays and γ rays. This will basically decelerate the jet and decreases the Lorentz factor along the jet.

# Do Jets expand adiabatically ?



**Nair et al., in prep.**

Assumptions are made like the following:

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

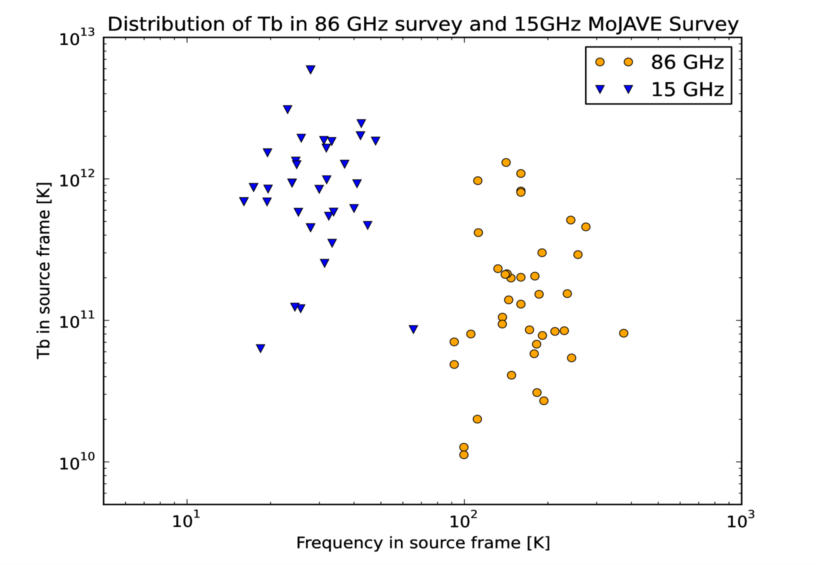
$\xi = [2(2s+1)+3a(s+1)]/6.$

$s=2.0$, $\alpha = -0.5$, $a=1$

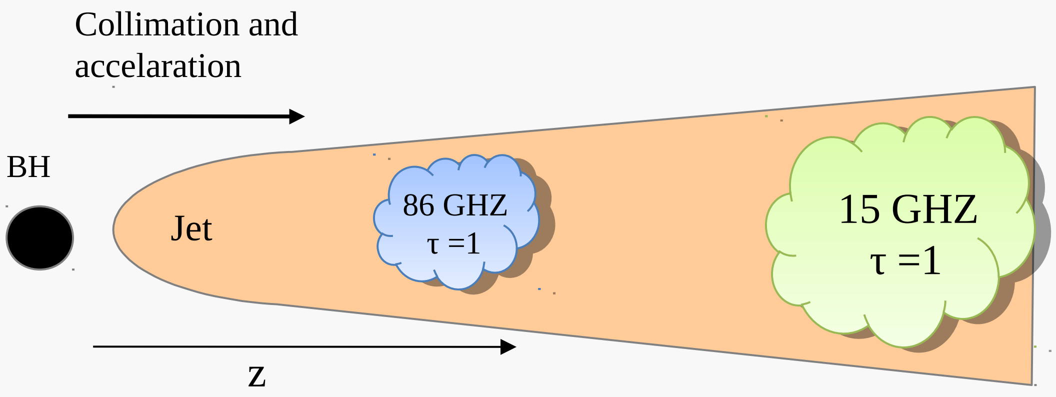
(Lobanov et al. 2000) & Marsher 1990

Red circles are the predicted $T_B$ in shocks with adiabatic losses dominating the radio emission. Blue circles are the observed $T_B$

# Do jets decelerate ?



**Nair et al., in prep.**



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

- $T_b$ at 86 GHz are sytematically lower than $T_b$ at 15 GHz

Decrease of $T_o$ at 86 GHz – strong argument towards a theoretical decelerating jet model (Marsher 1995).

- This supports the theoretical model that the relativistic electron-positron pair plasma up-scatter the photons produced outside the jet into X-rays and γ rays. This will basically decelerate the jet and decreases the Lorentz factor along the jet.

# Summary

1. We conducted a large global 86 GHz VLBI survey of compact radio sources using a global 3mm VLBI array.

2. The survey is the largest and most sensitive one ($rms_{Image} < 5$ mJy/beam) with a detection rate of 100% out of 168 sources and a total set of images of 168 sources.

3. We estimated brightness temperatures ($T_b$) of the cores and secondary jet components from the measurements of flux densities and sizes of the components, taking into account resolution limits of the data.

4. The $T_b$ of the cores are higher than those of the secondary jet components and the $T_b$ distribution is within $T_b < 4x10^{11}$ kelvin for VLBI cores and within $T_b < 5.0x10^{10}$ kelvin for inner jet components.

5. For sources with sufficient structural detail, there is an agreement with the predicted $T_B$ in shocks with adiabatic losses and measured $T_b$.

6. $T_b$ at 86 GHz are systematically lower than $T_b$ at 15 GHz. Decrease of $T_o$ at 86 GHz provides an argument towards a theoretical decelerating jet model

*Thank You*

*Questions  ?*