AIP
Leibniz-Institut für
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LOFAR observations of the quiet solar corona

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Solar observations with LOFAR

The Sun is a strong radio source:

- Thermal: 10^6 K corona
- Non-thermal: Flares, CMEs

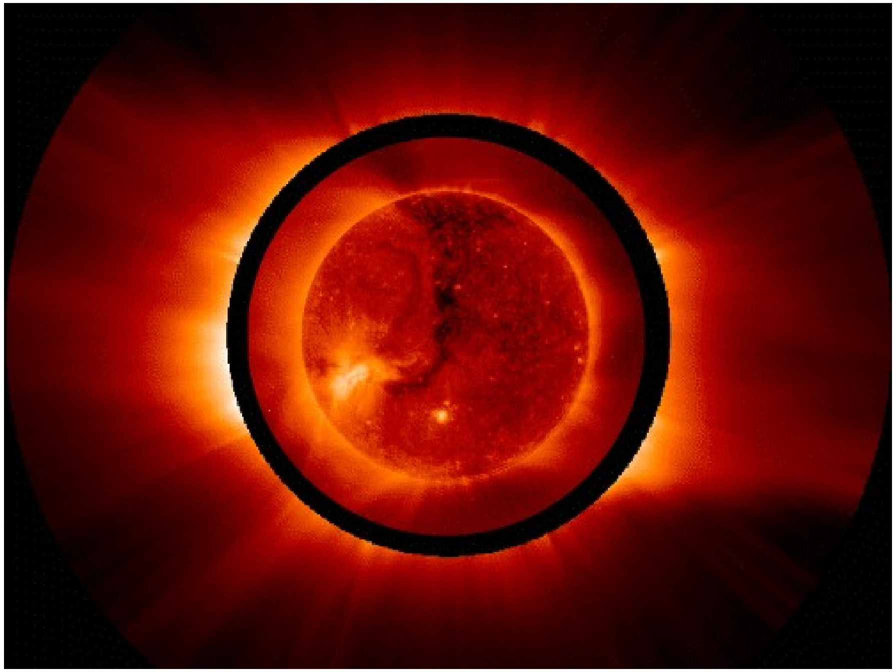
Intensities:

- Thermal: some 10^4 Jy
- Non-thermal: up to 10^8 Jy

Radio wave emission:

- Plasma emission

$$f = \sqrt{Ne^2/(m_e \epsilon_0)}/(2\pi)$$



The frequency f depends only on the density N

Quiet Sun observations

<u>Solar observations:</u>

- The Sun is very dynamic
- Short-lived features associated with radio bursts

→ Snapshot imaging, e.g. 1 s or 0.25 s cadence

<u>Quiet Sun:</u>

- Solar radio emission is fairly constant
- Take advantage of changing baselines in the uv plane

→ Aperture synthesis imaging

Aperture synthesis for the Sun

<u>Special challenge:</u>

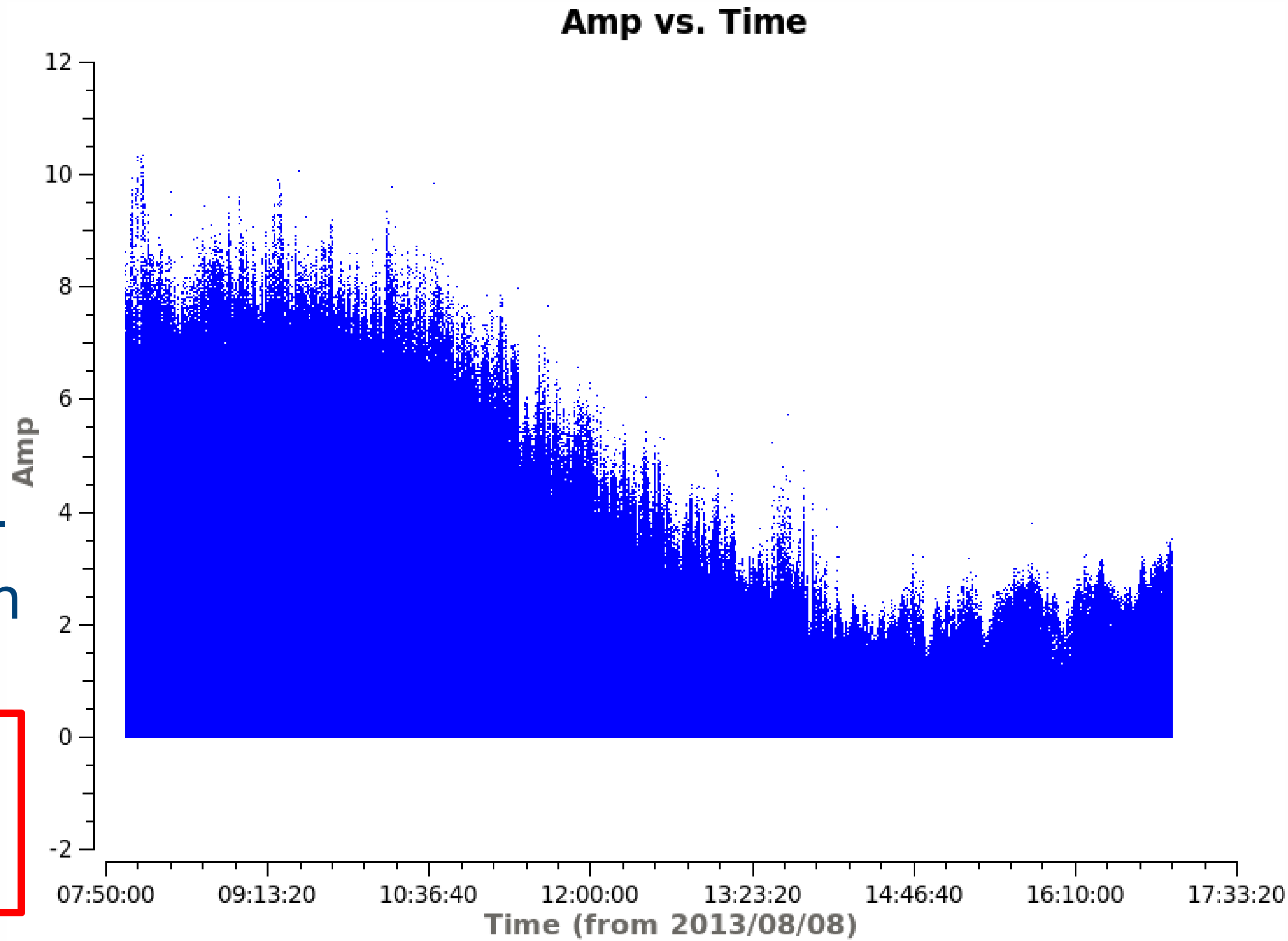
- The Sun is moving in the sky: 2.5’ per hour
- Standard imaging pipeline cannot be used
- Solar imaging pipeline takes this into account
- Imaging with casapy

Calibrator: Taurus A

Calibrator:

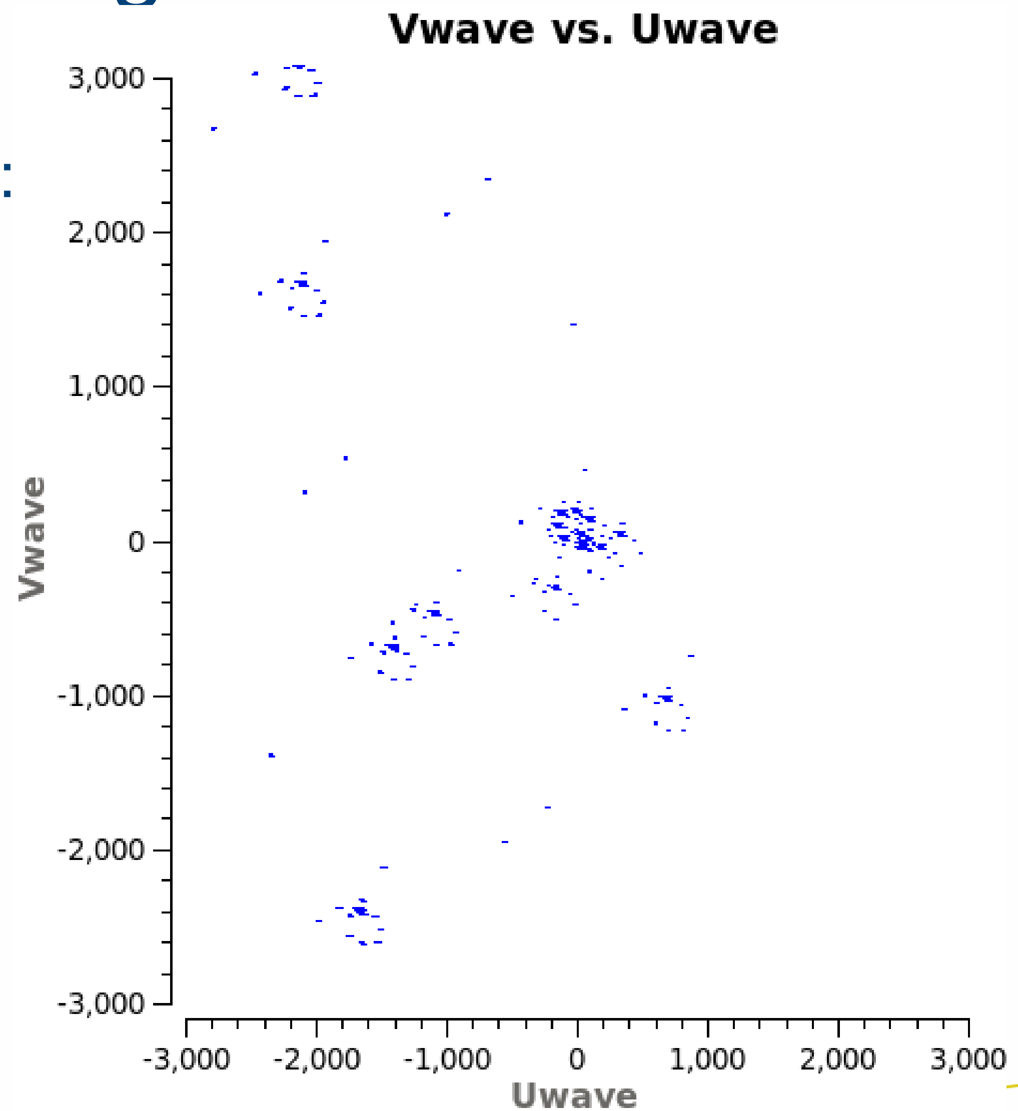
- Sets in the late afternoon
- Intensity drops
- Would be trans-ferred to the Sun

Only the first 3 hours used



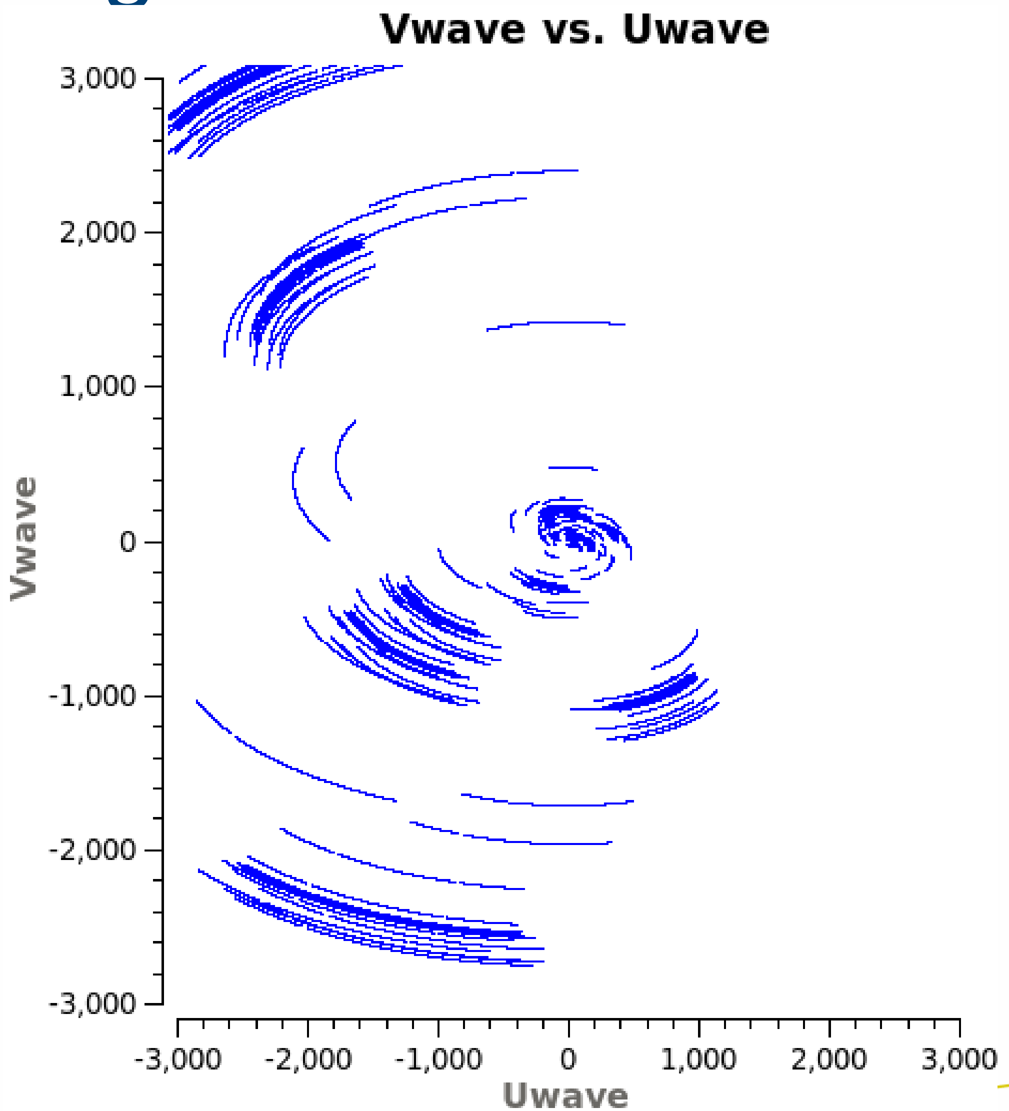
UV coverage

Snapshot image:



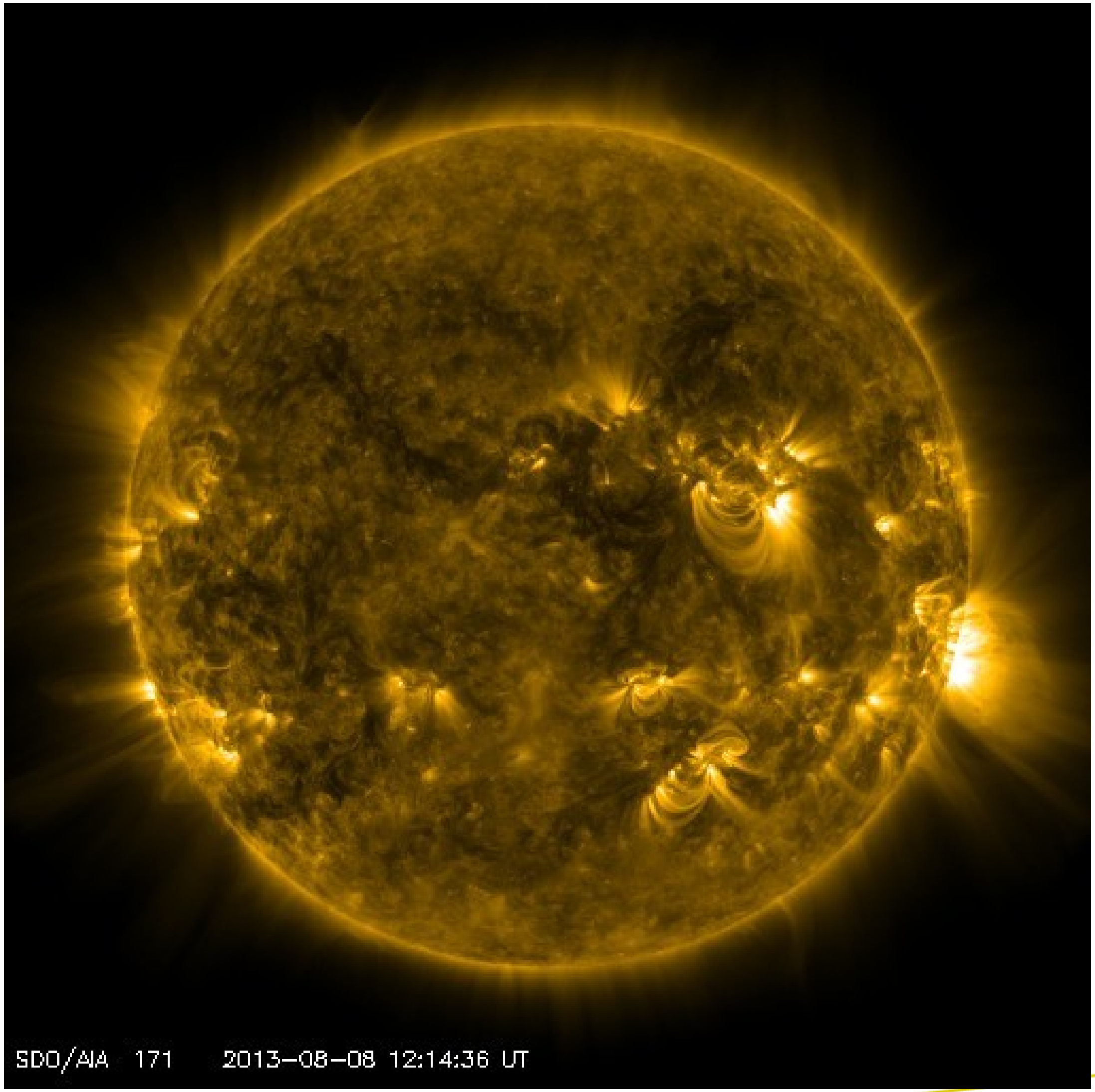
UV coverage

3 h integration:



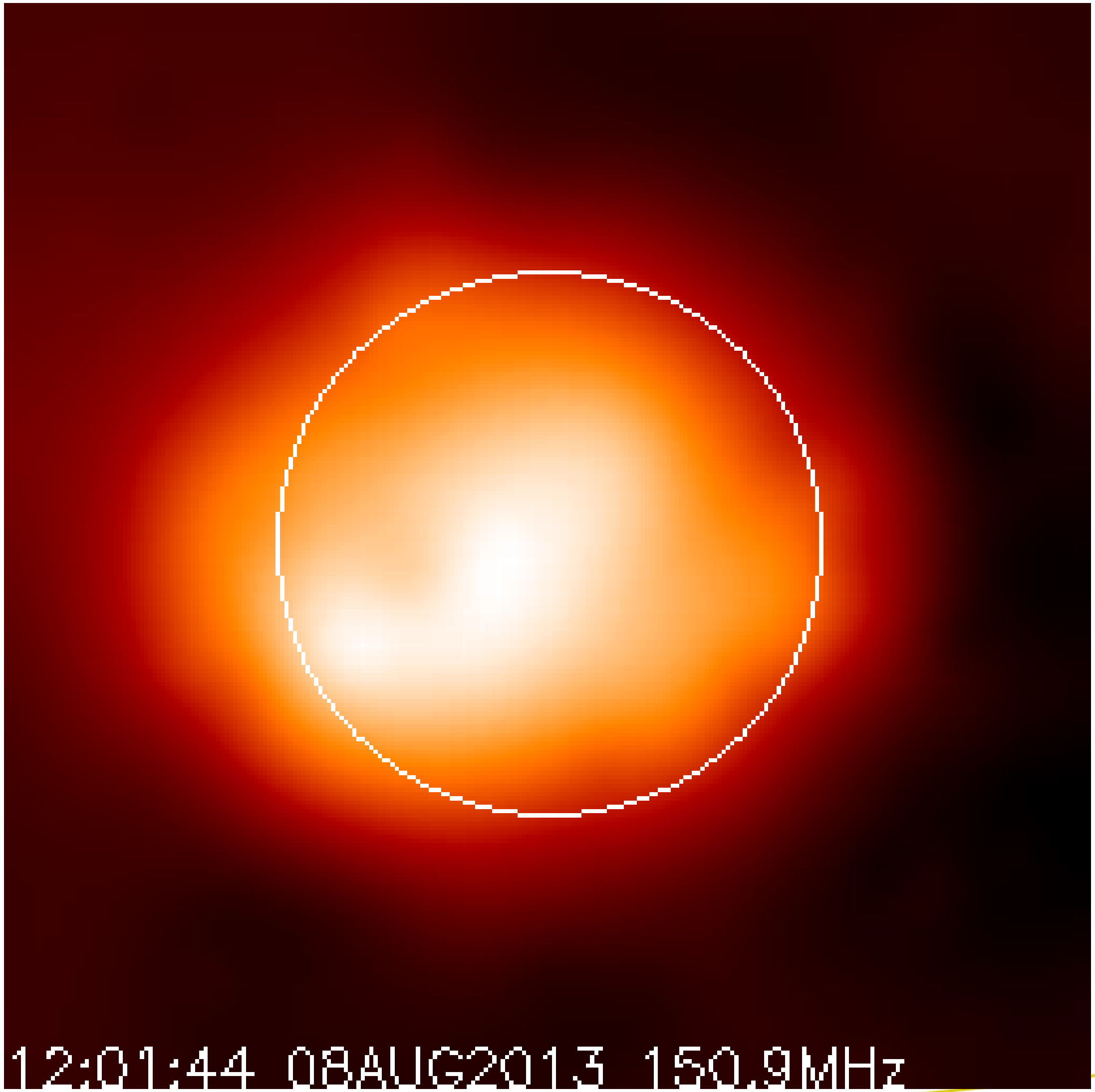
The Sun on 08 August 2013

SDO:



The Sun on 08 August 2013

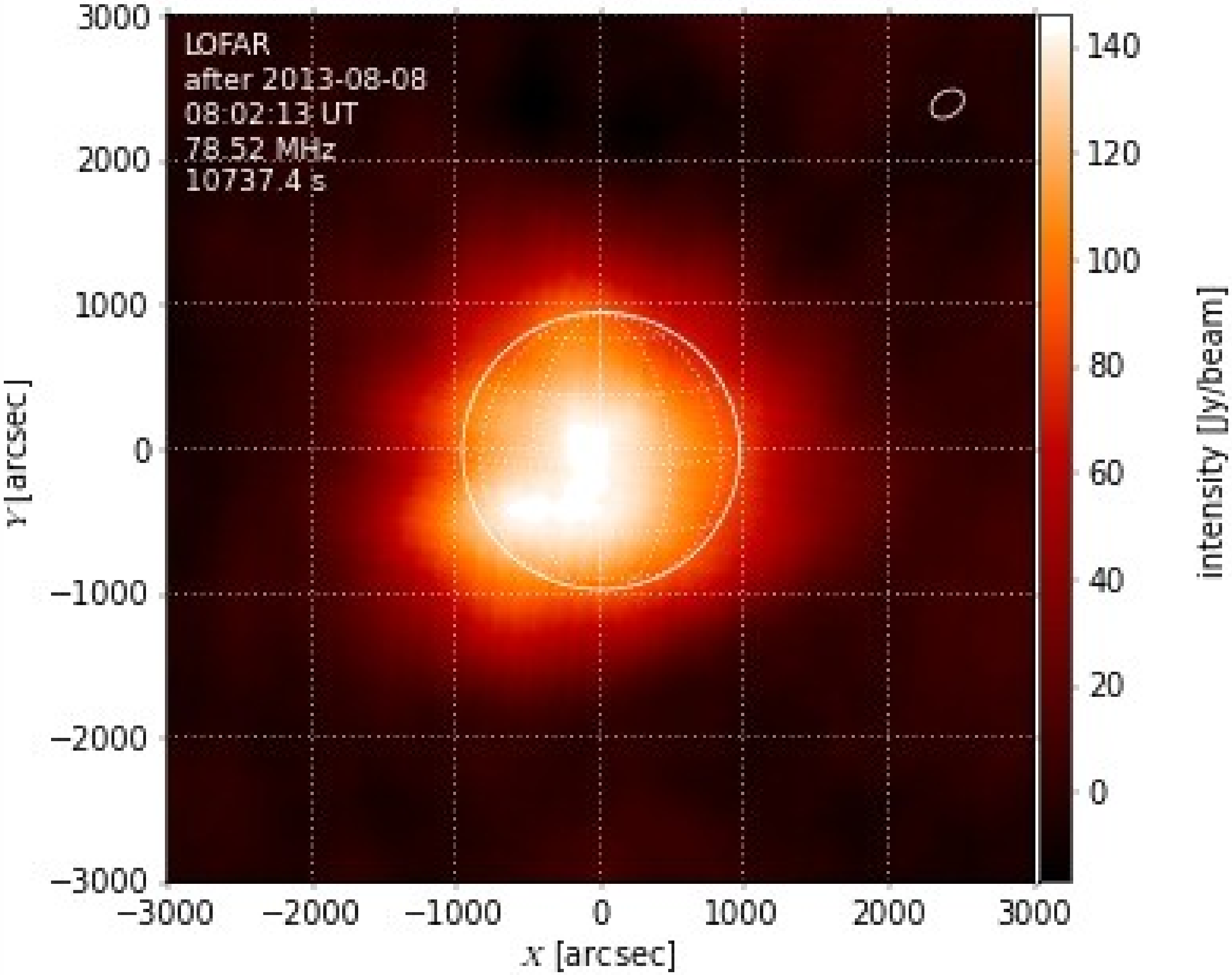
NRH:



Solar corona

Image:

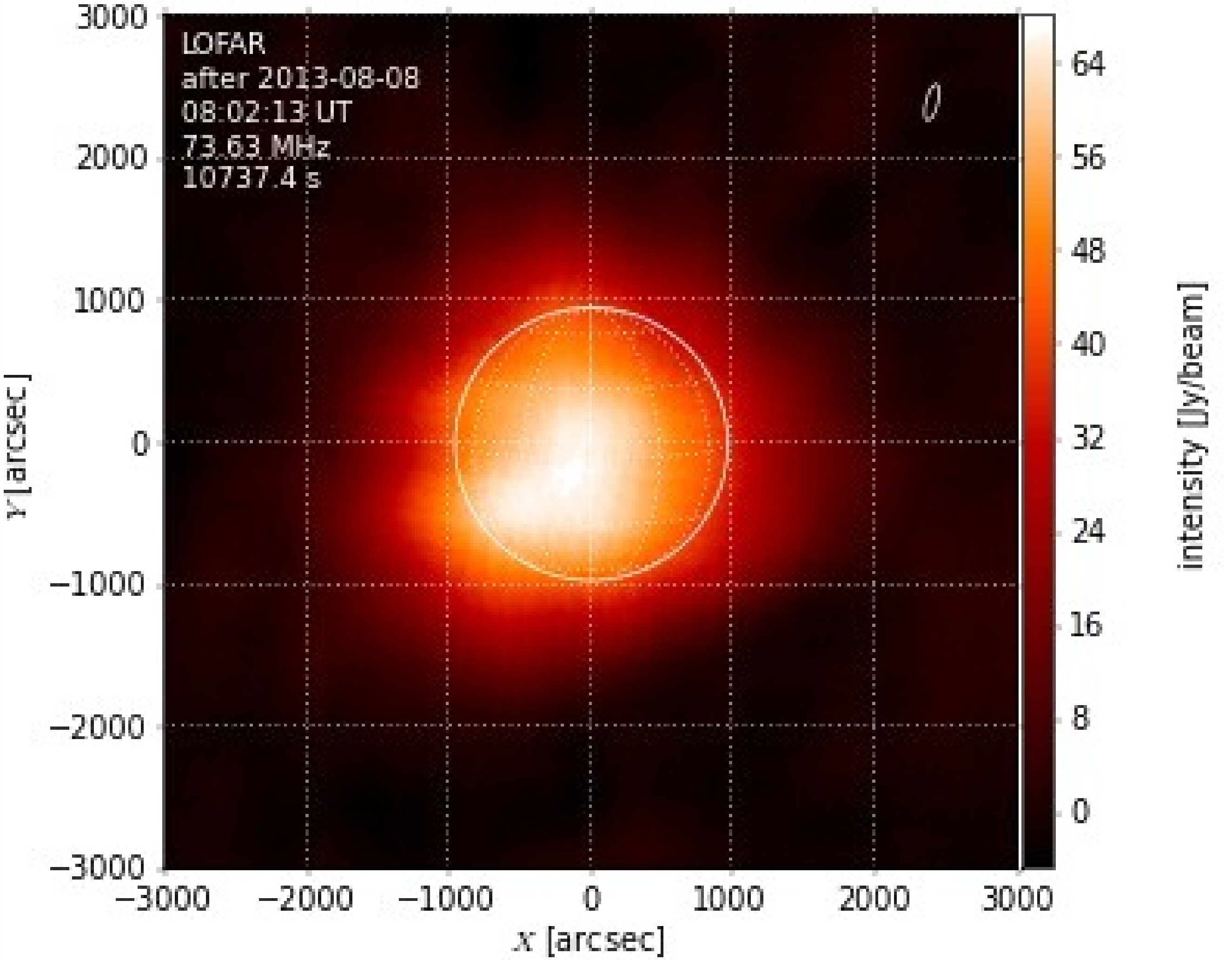
- 79 MHz
- 3 h



Solar corona

<u>Image:</u>

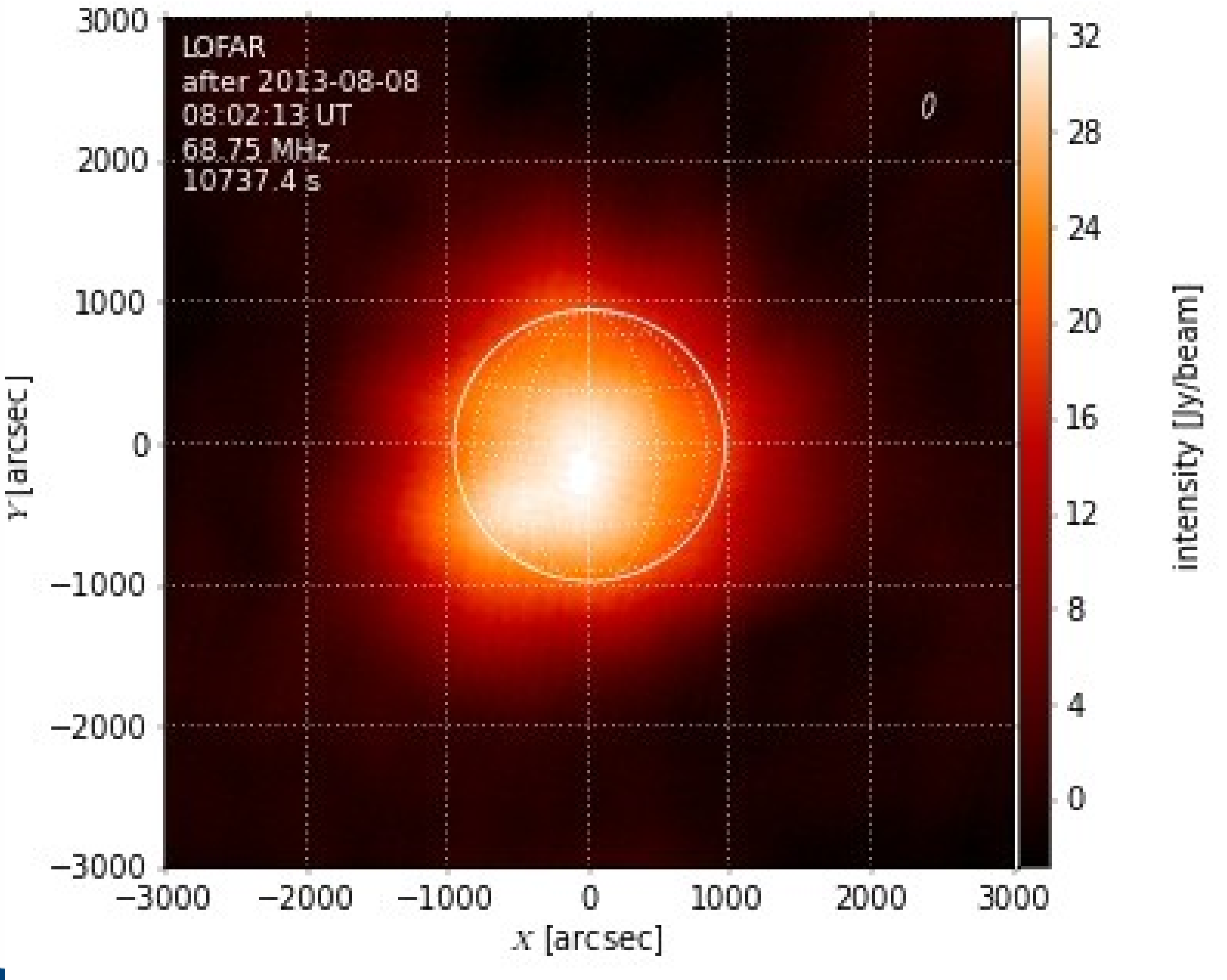
- 74 MHz
- 3 h



Solar corona

Image:

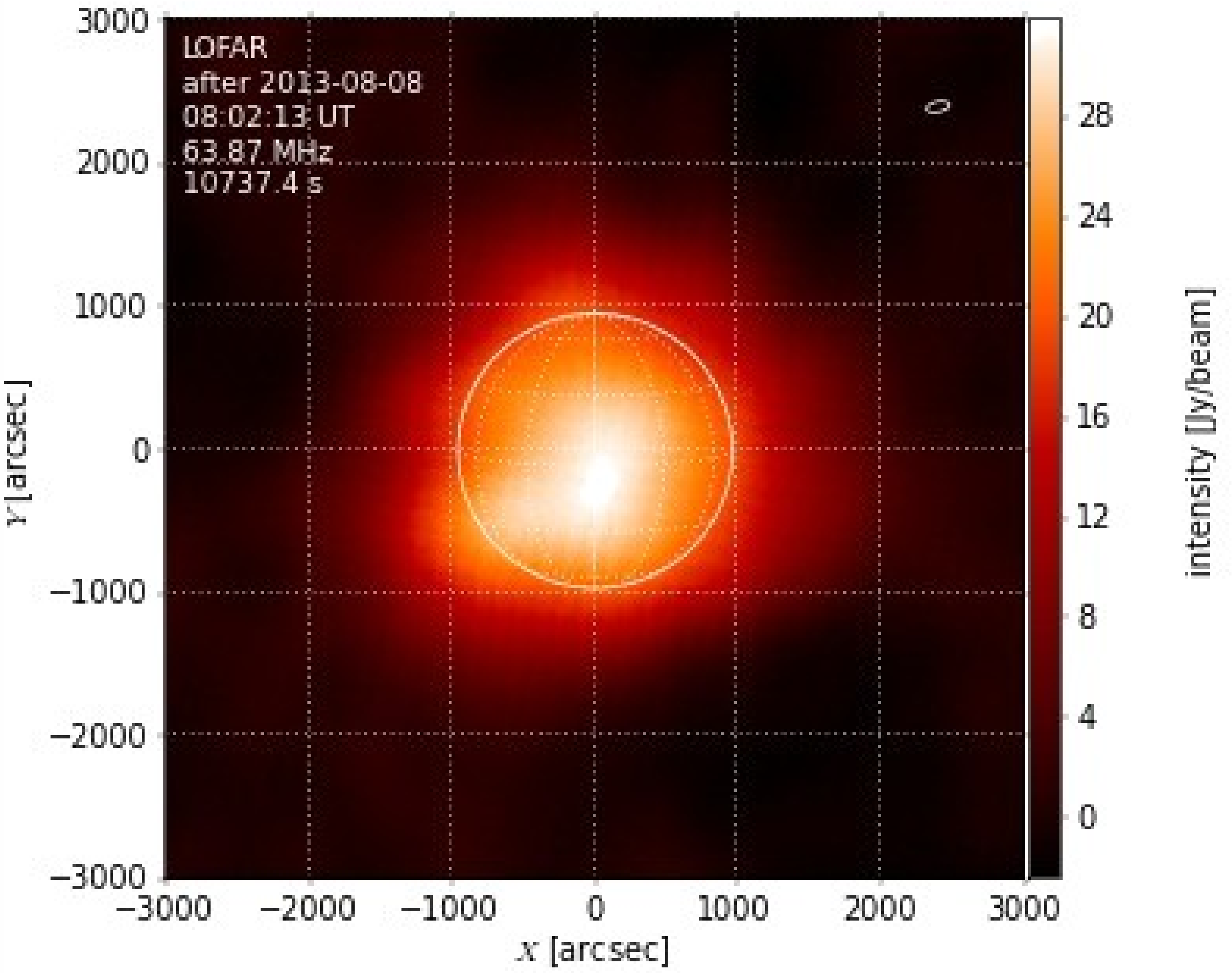
- 69 MHz
- 3 h



Solar corona

Image:

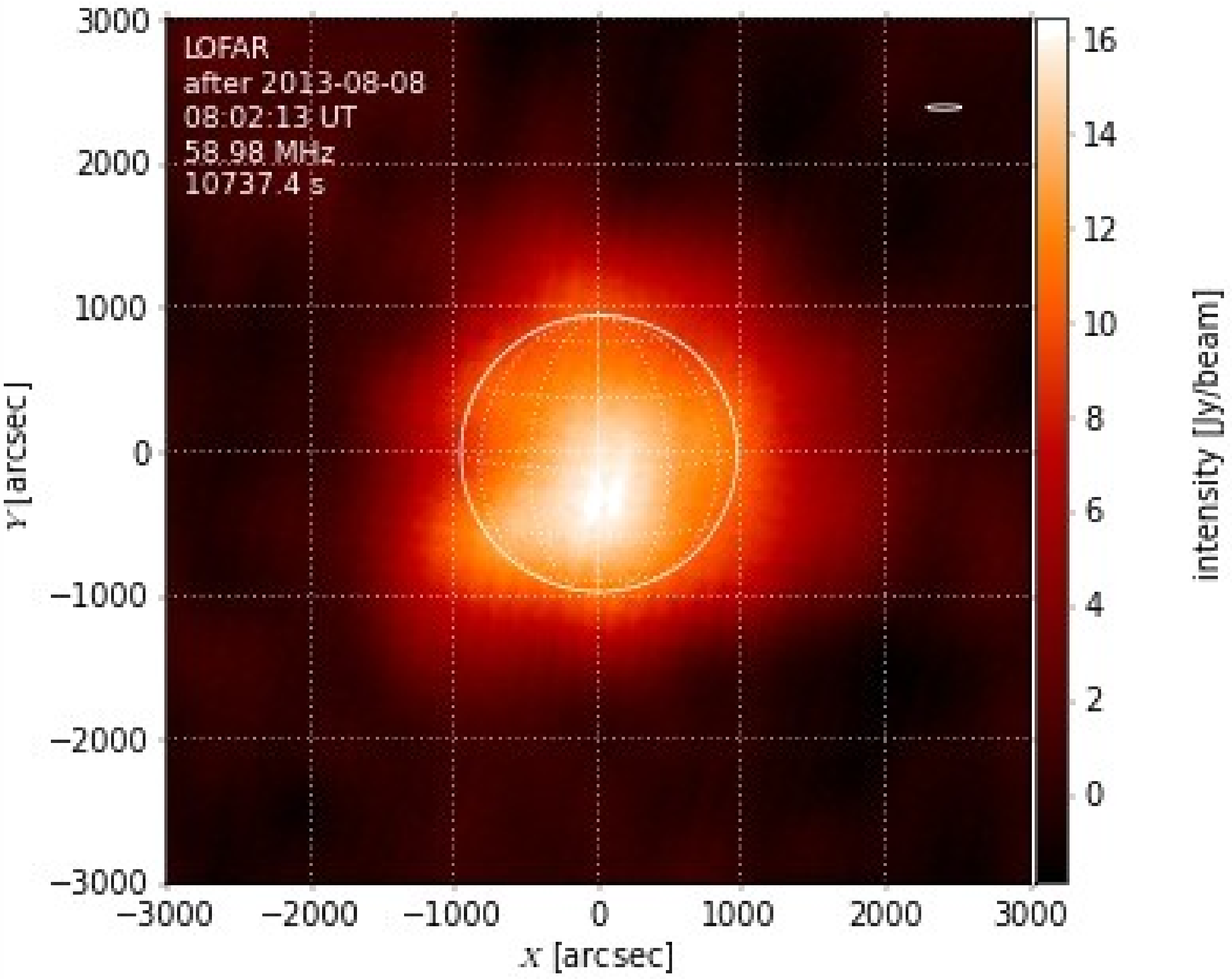
- 64 MHz
- 3 h



Solar corona

Image:

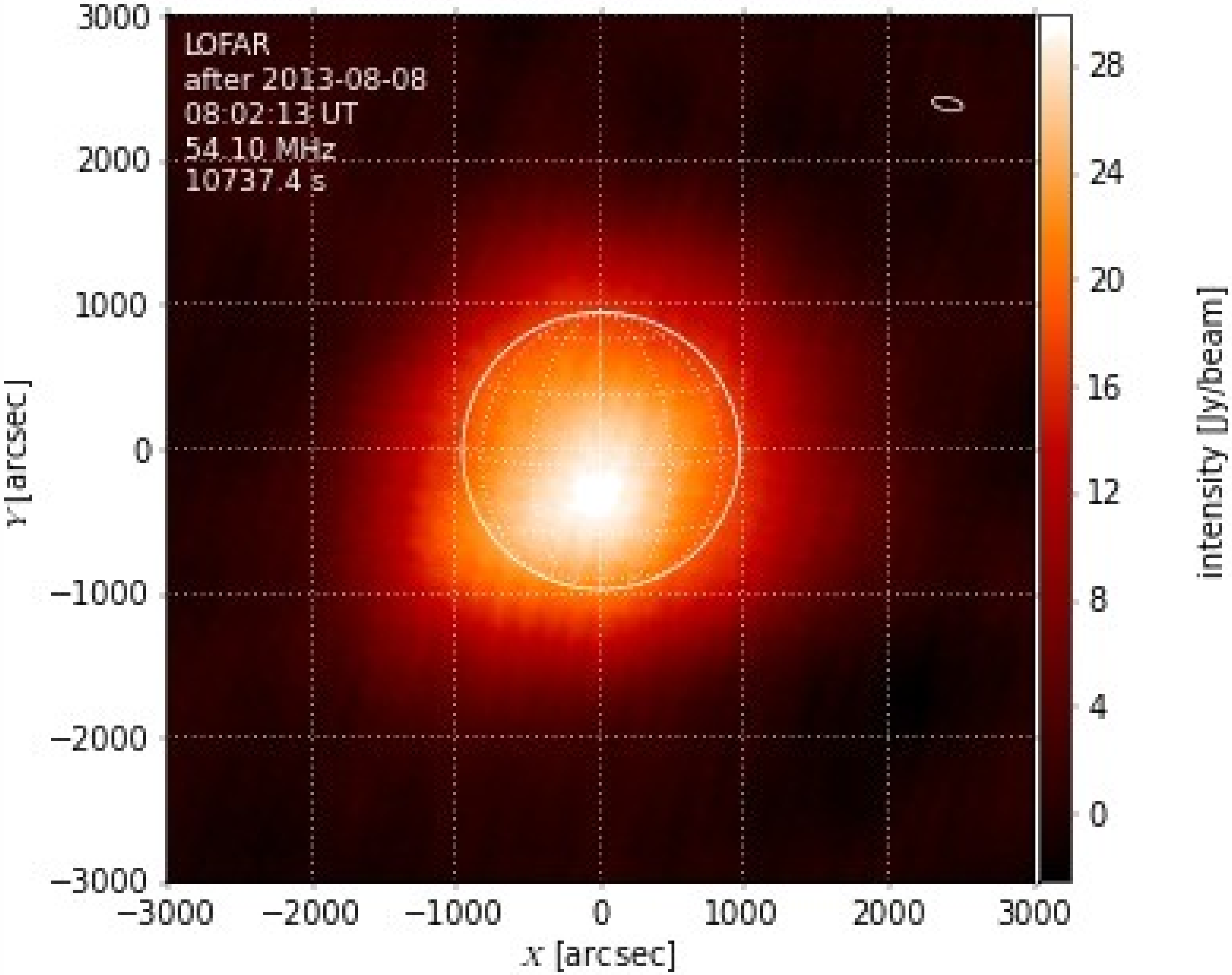
- 59 MHz
- 3 h



Solar corona

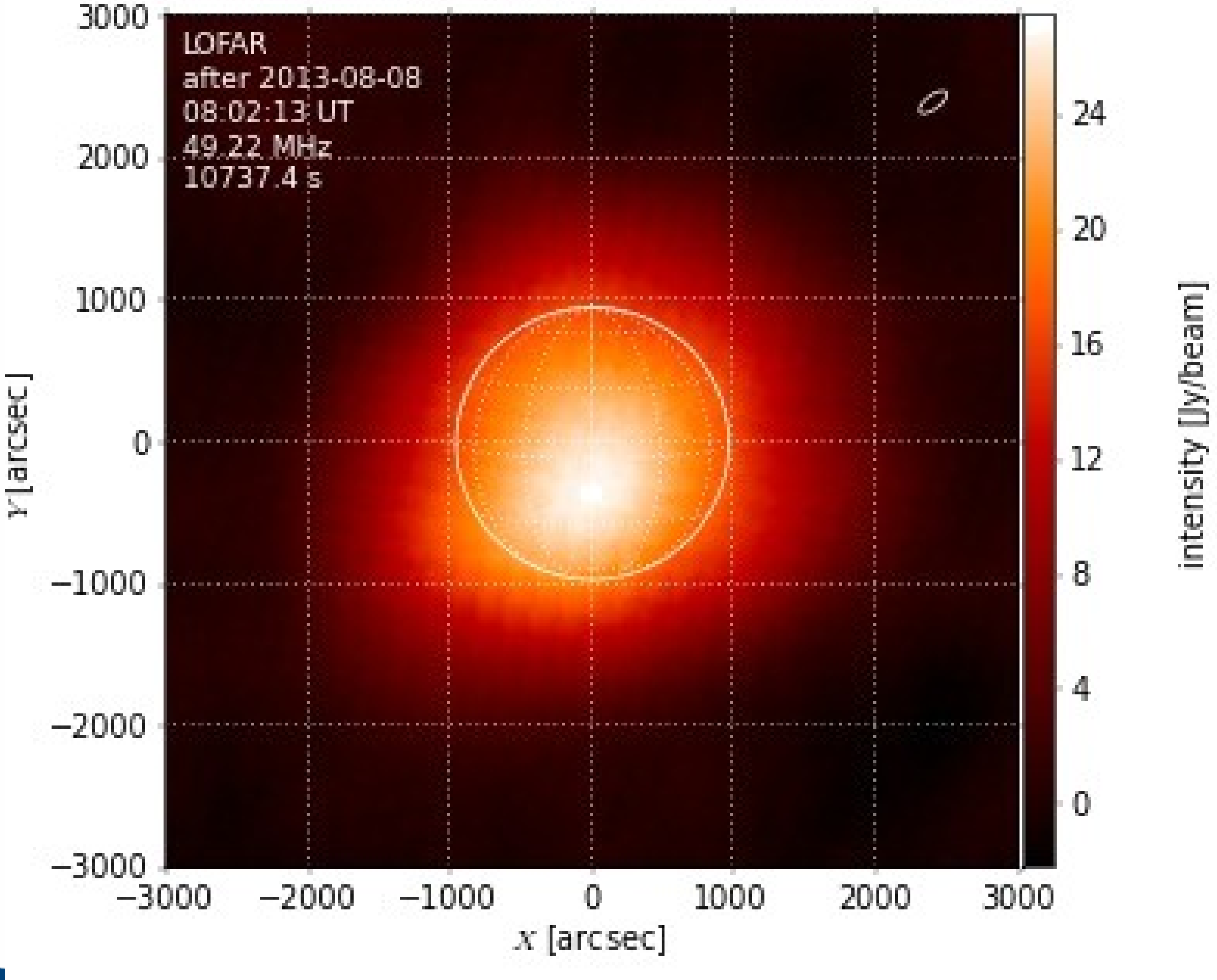
Image:

- 54 MHz
- 3 h



Solar corona

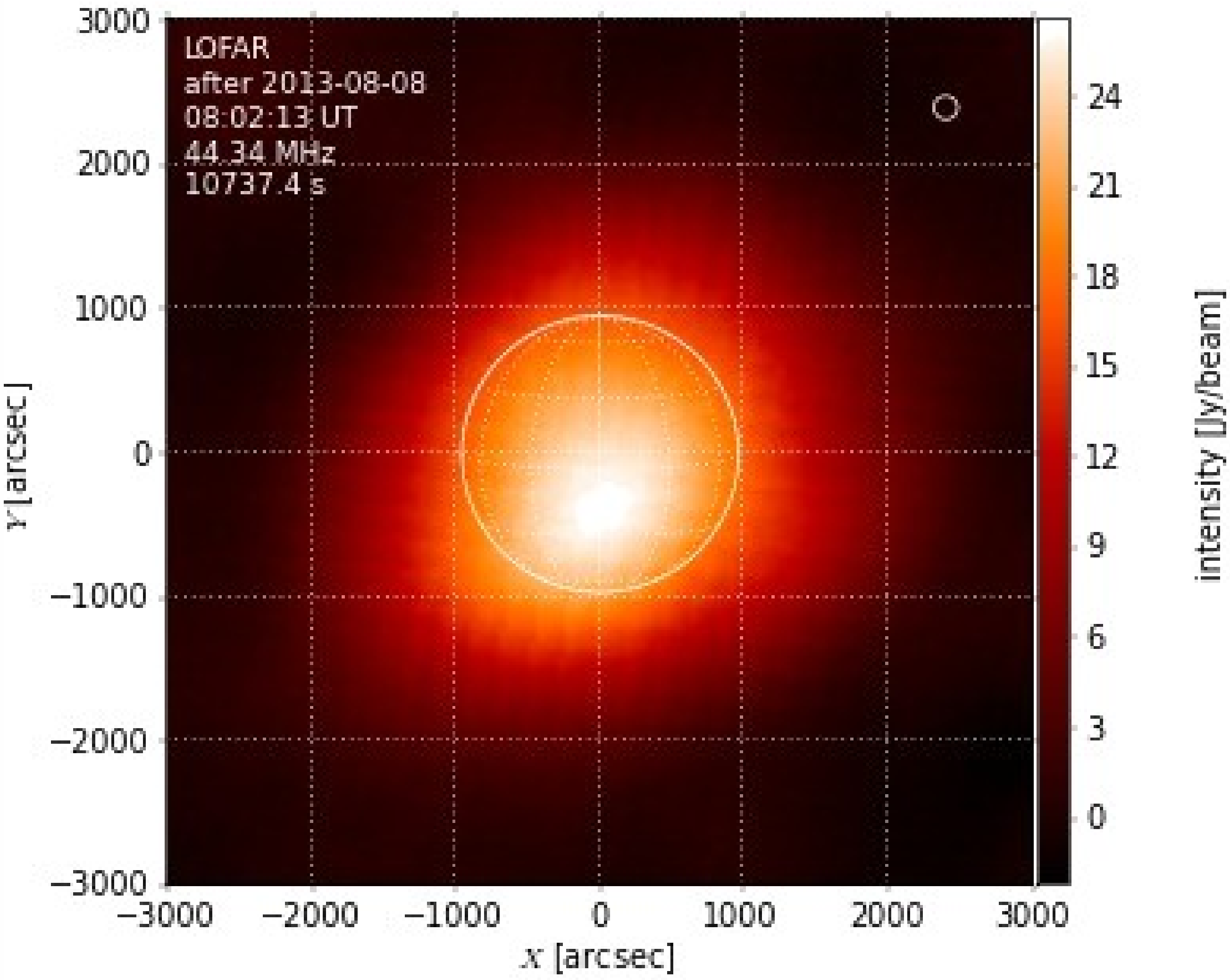
<u>Image:</u>
- 49 MHz
- 3 h



Solar corona

<u>Image:</u>

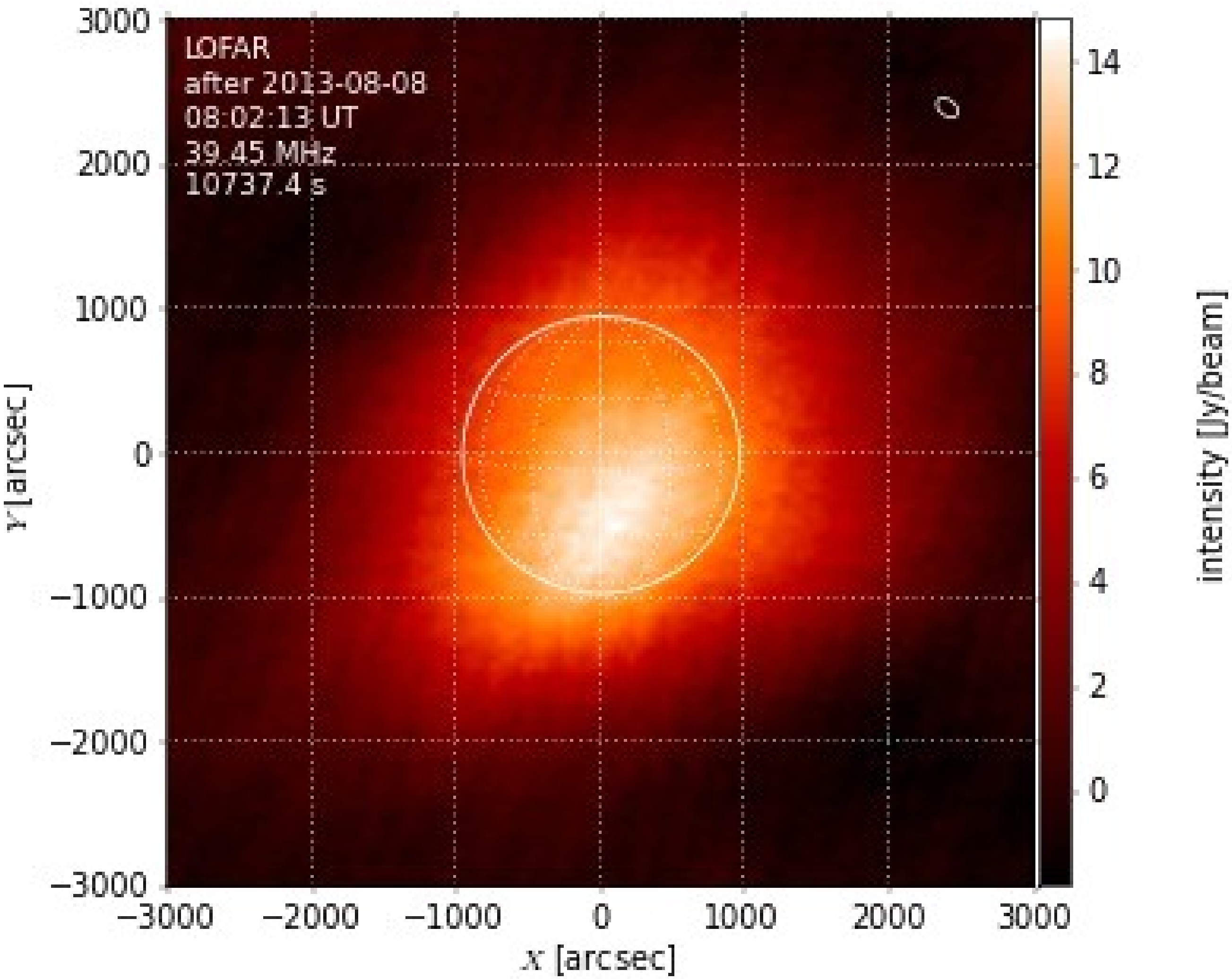
- 44 MHz
- 3 h



Solar corona

Image:

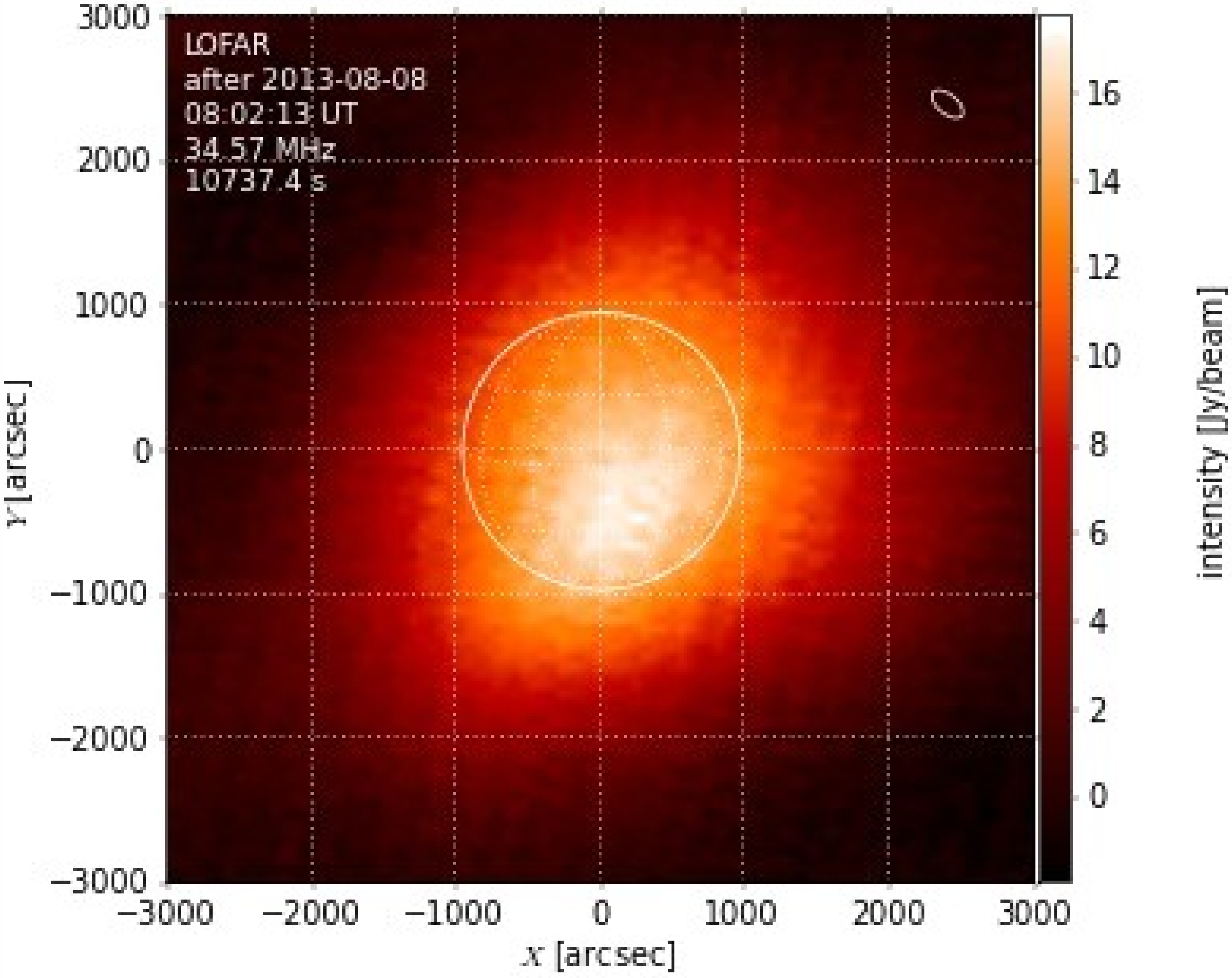
- 39 MHz
- 3 h



Solar corona

Image:

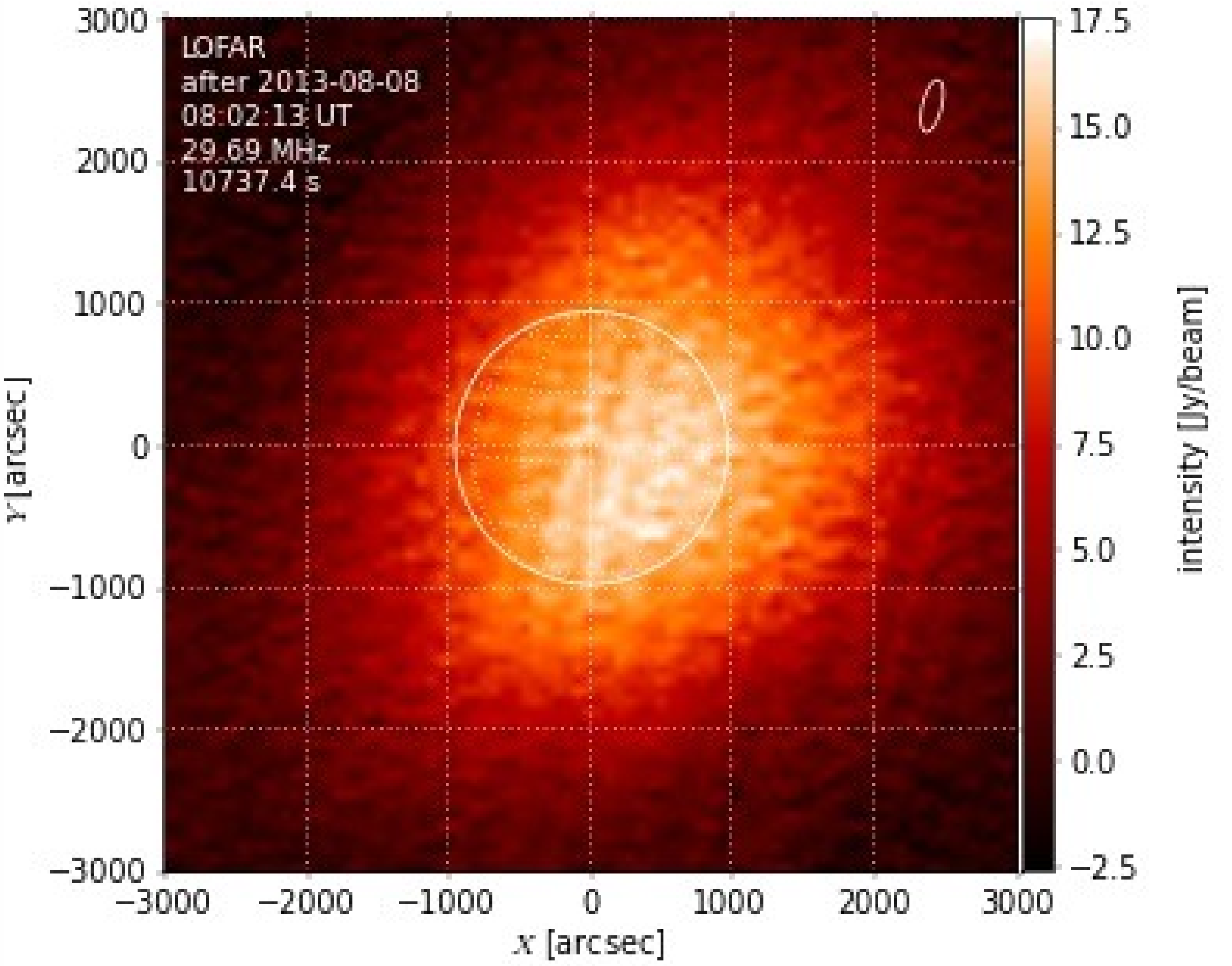
- 34 MHz
- 3 h



Solar corona

Image:

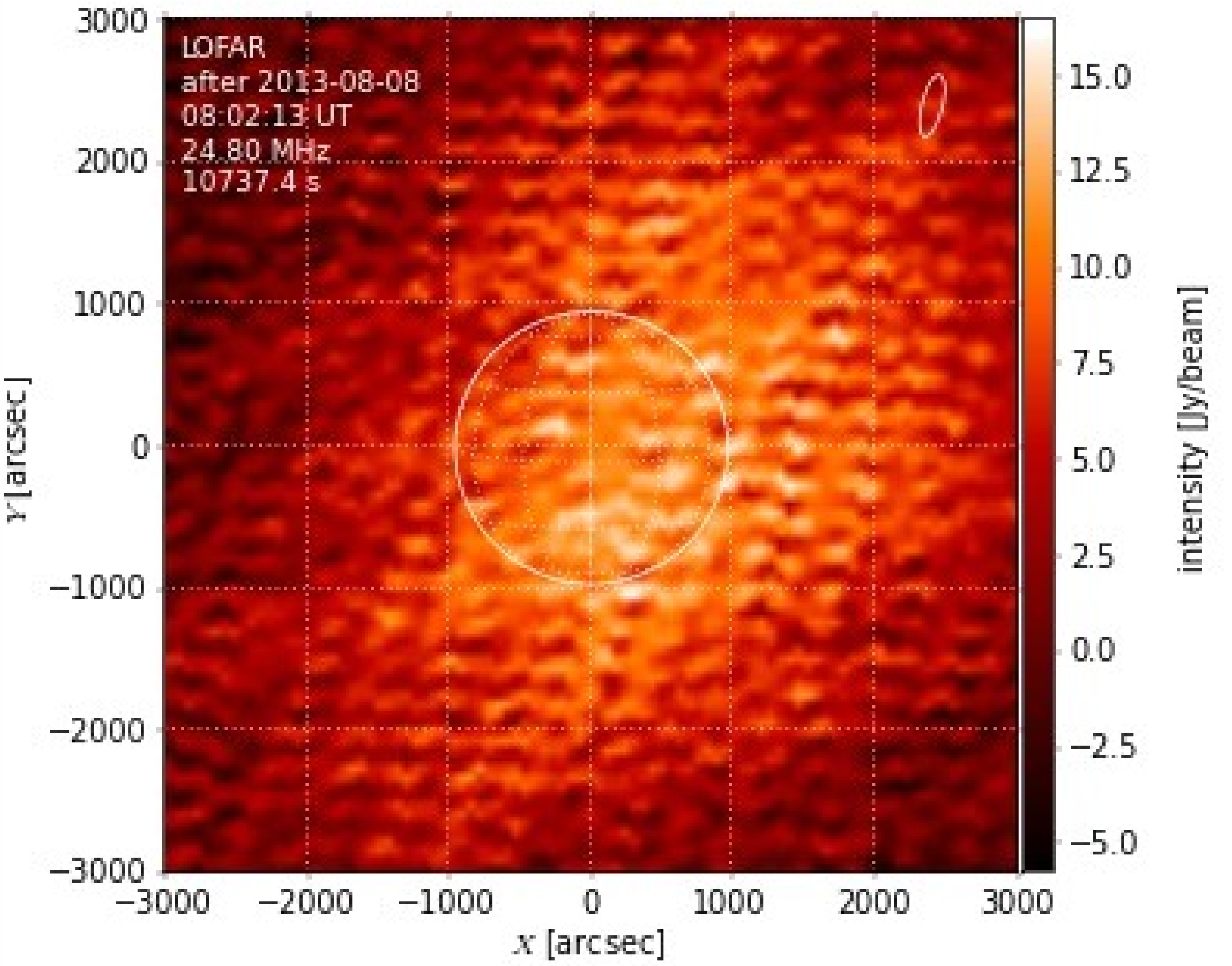
- 29 MHz
- 3 h



Solar corona

Image:

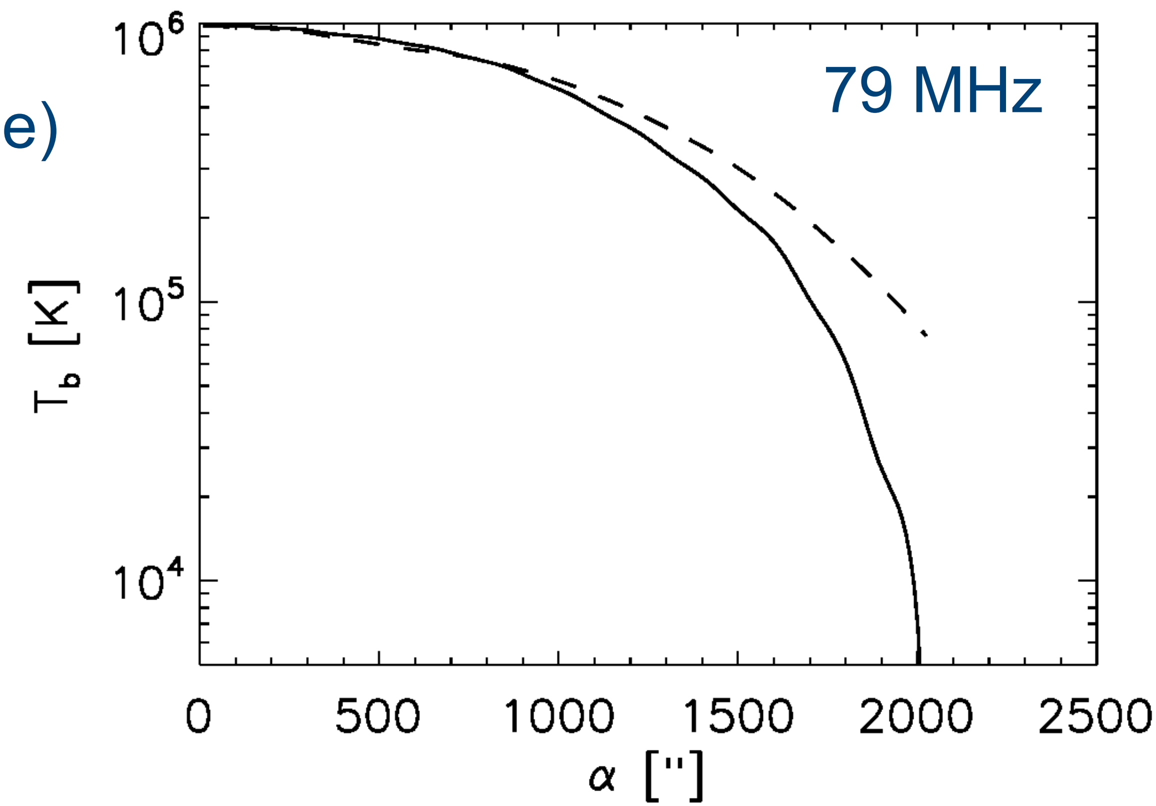
- 24 MHz
- 3 h



Observed intensity profiles

Profiles:

- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Brightness temp. calculated

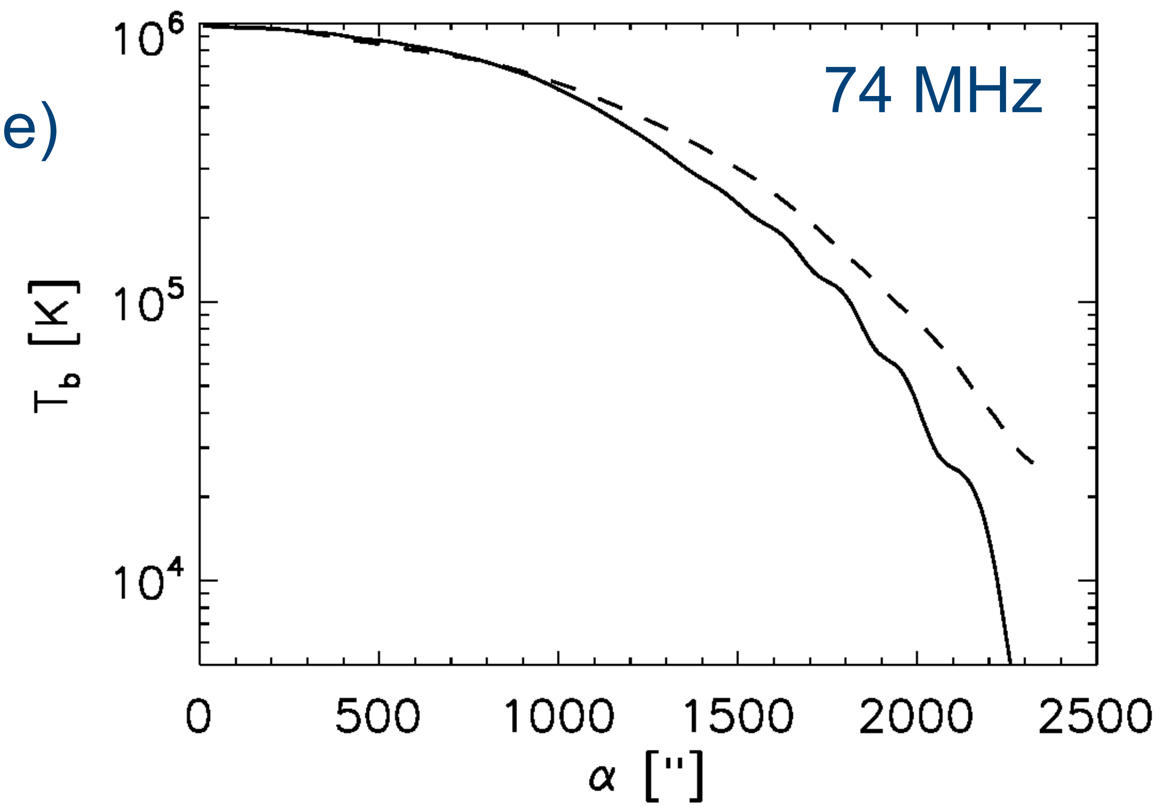


Observed intensity profiles

Solar KSP LOFAR

Profiles:

- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Brightness temp. calculated



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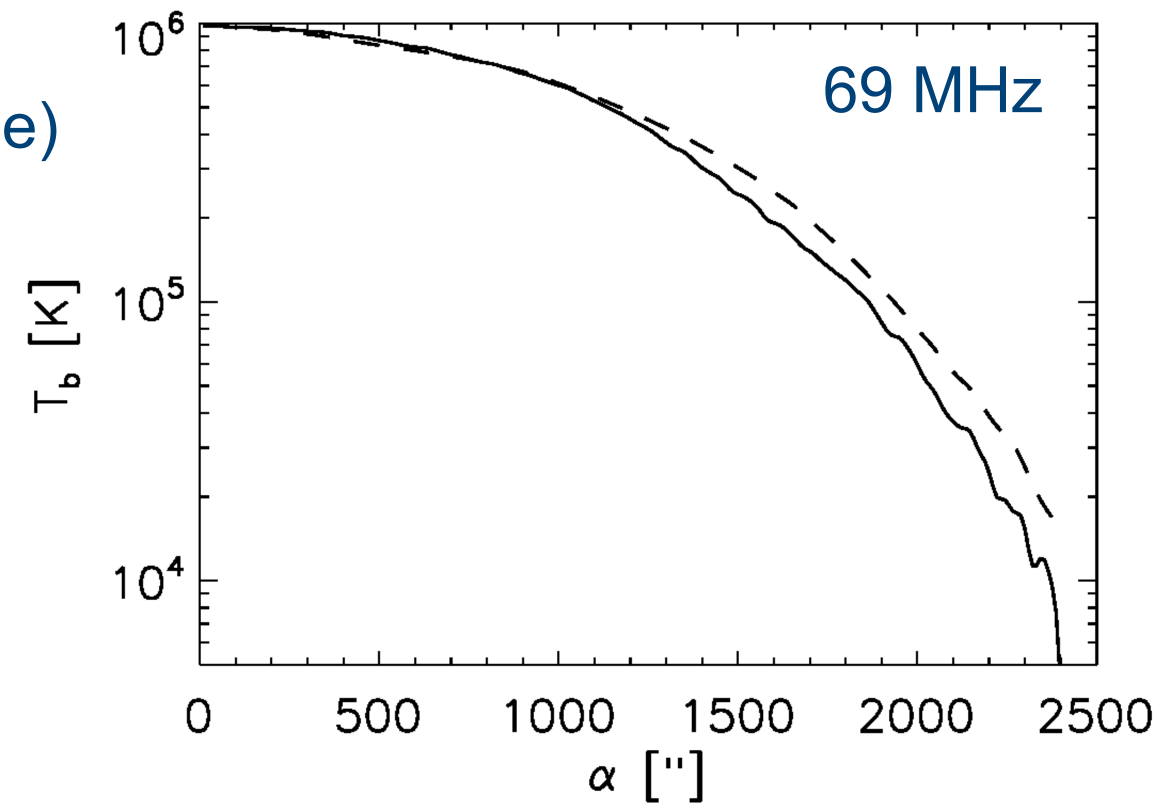

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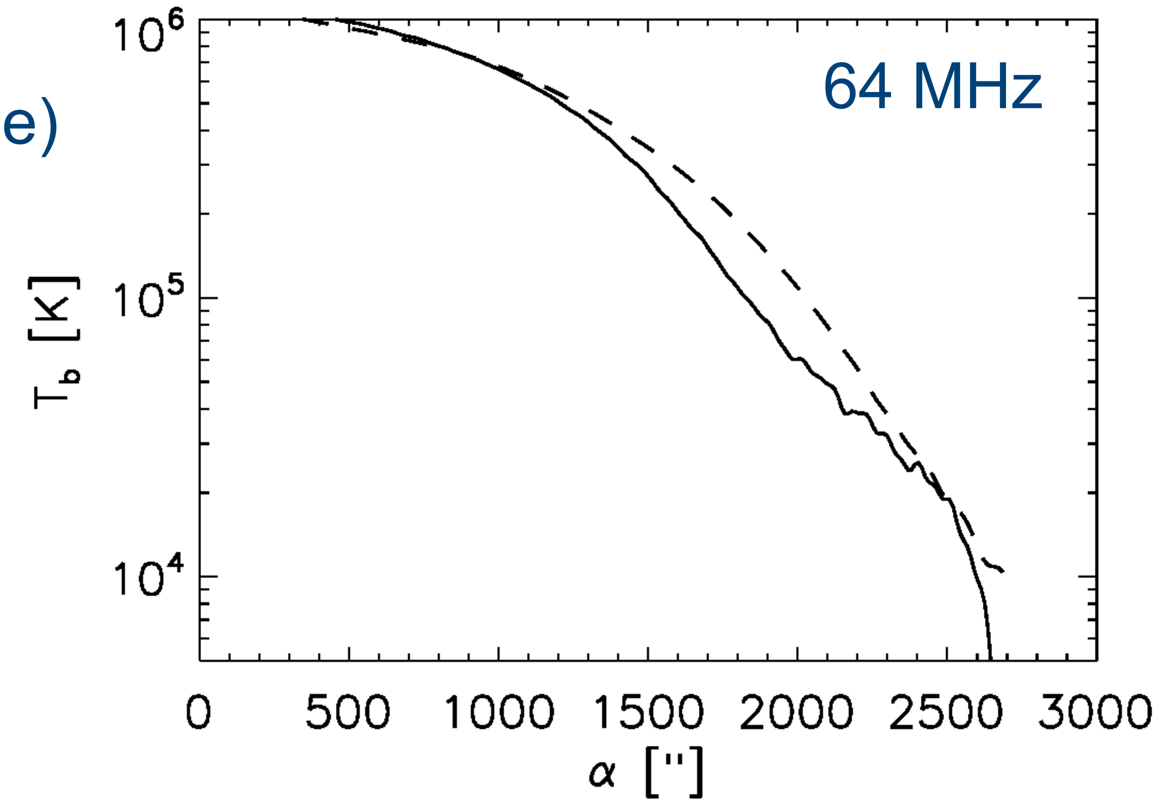

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Solar KSP LOFAR

AIP

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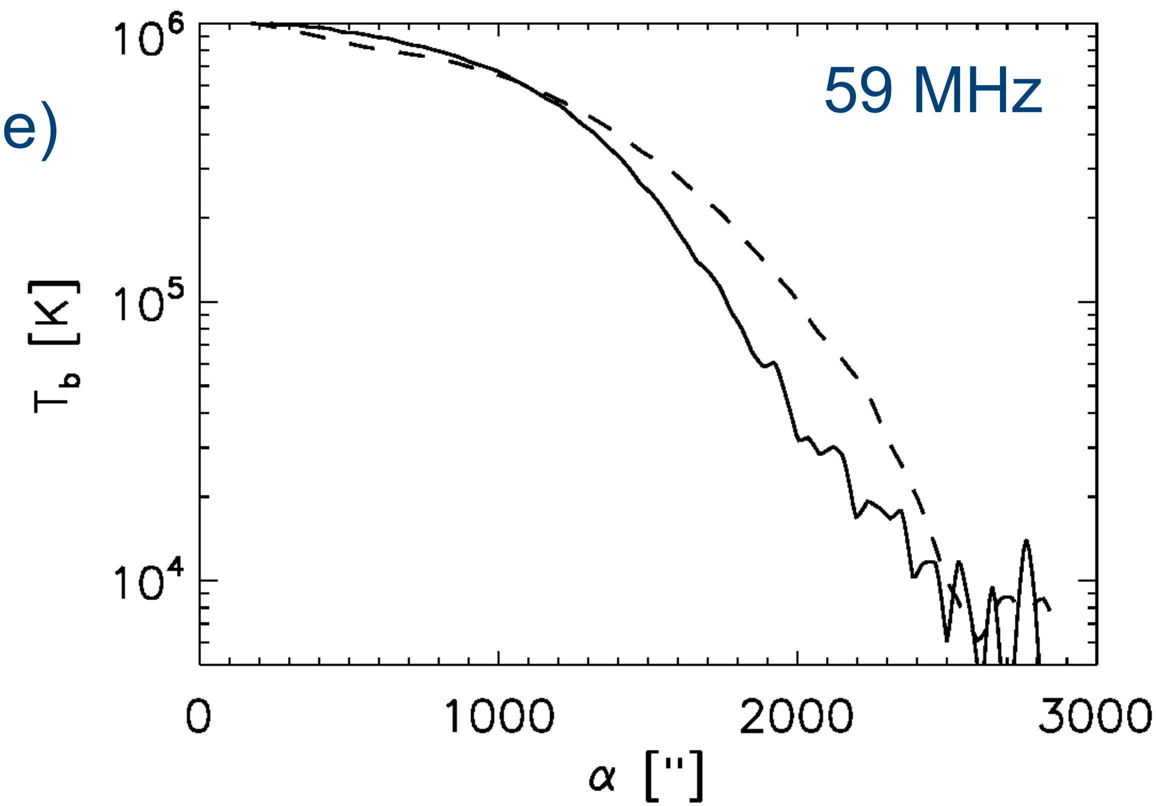

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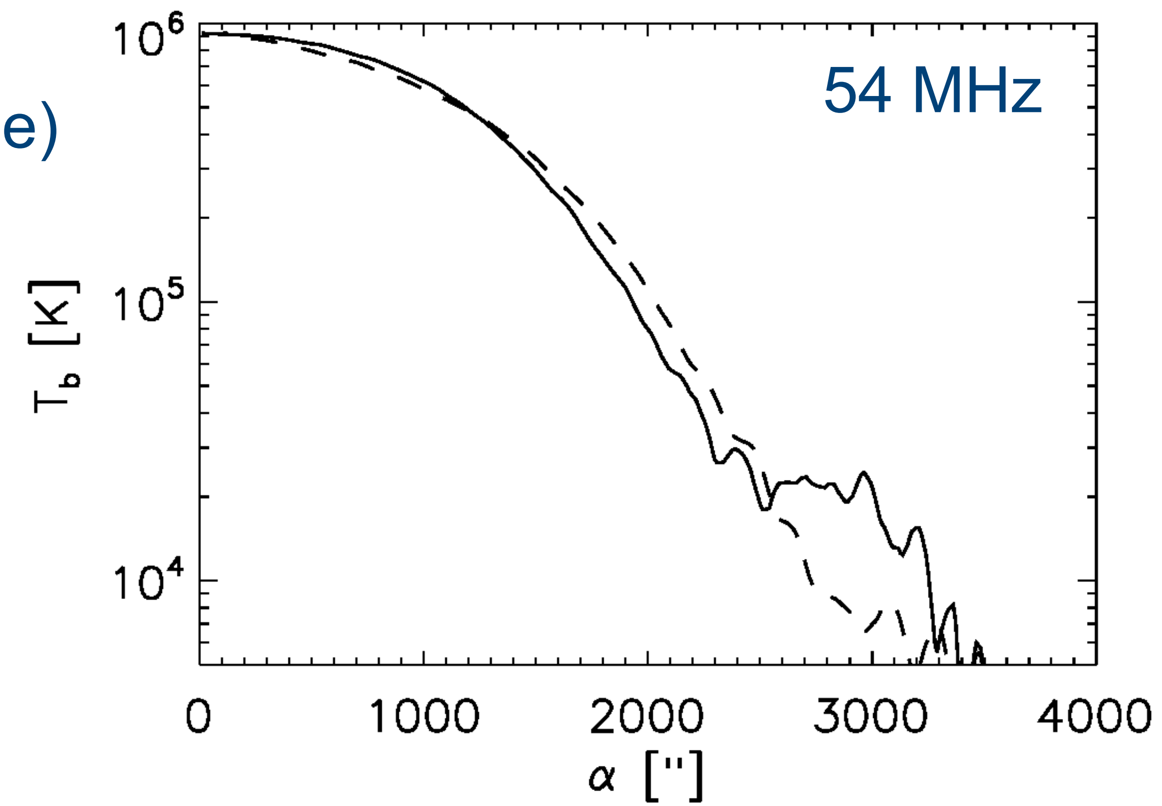

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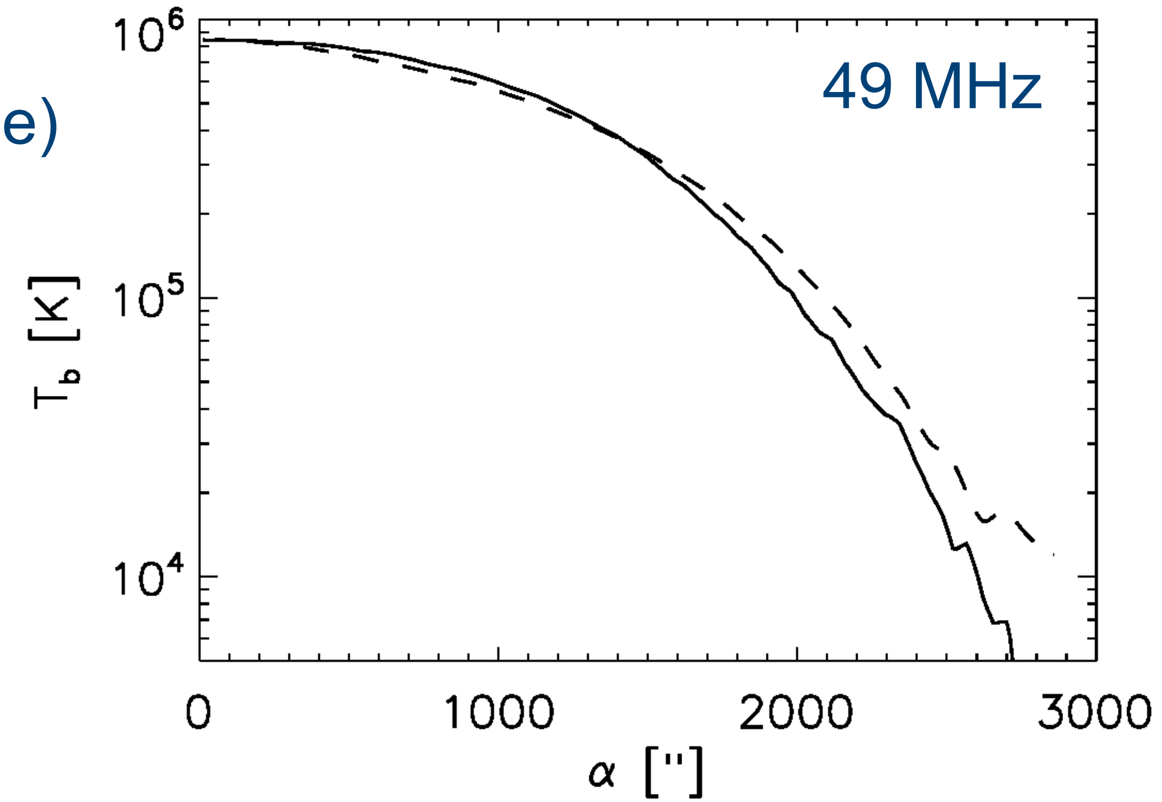

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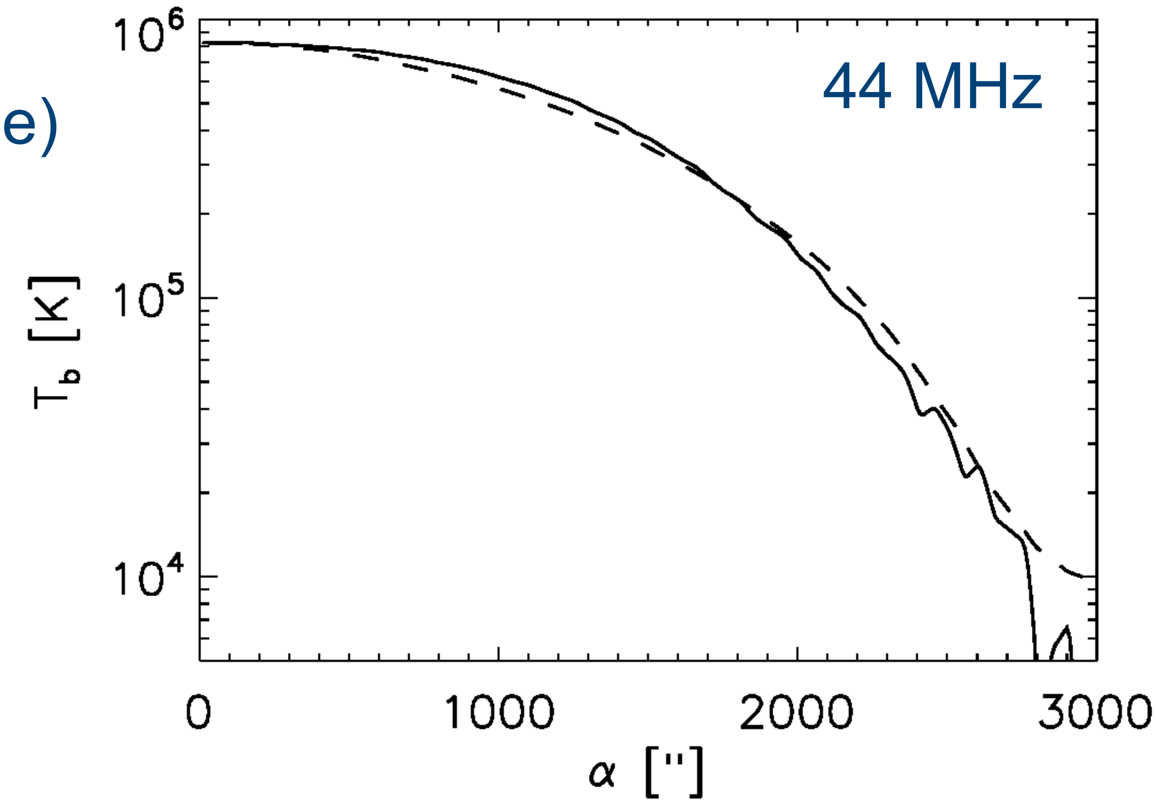

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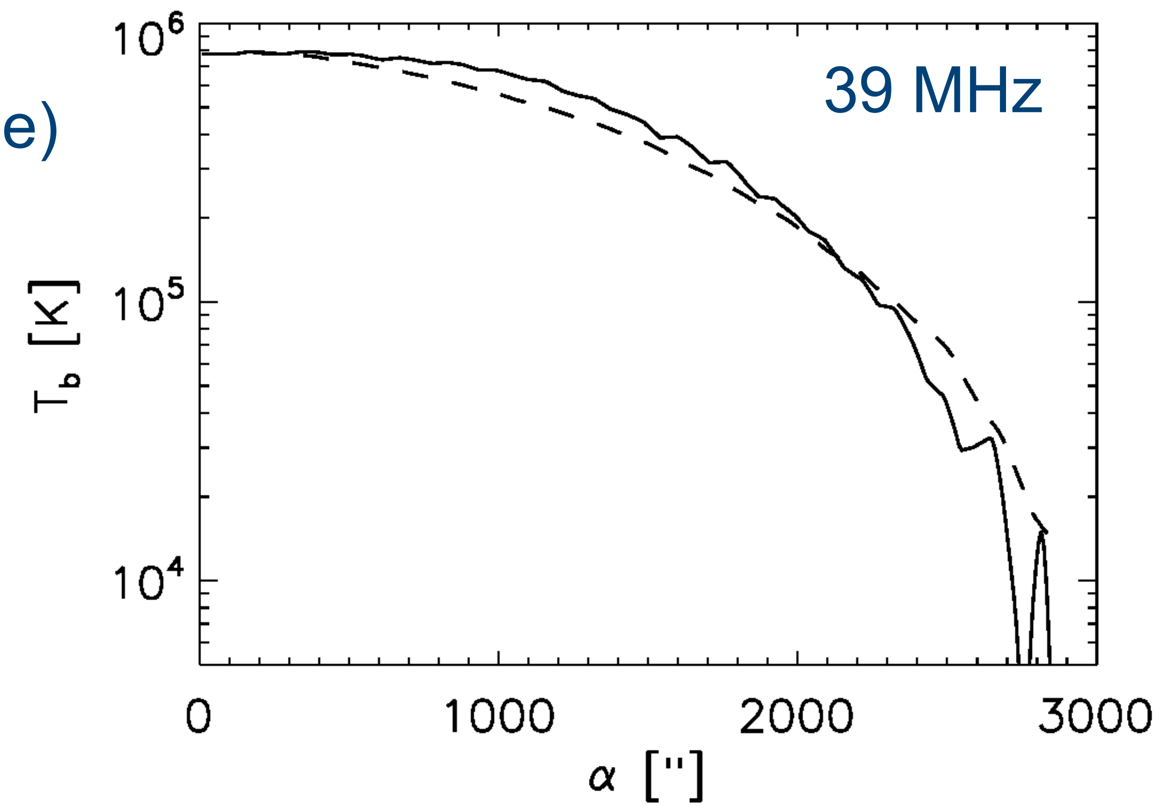

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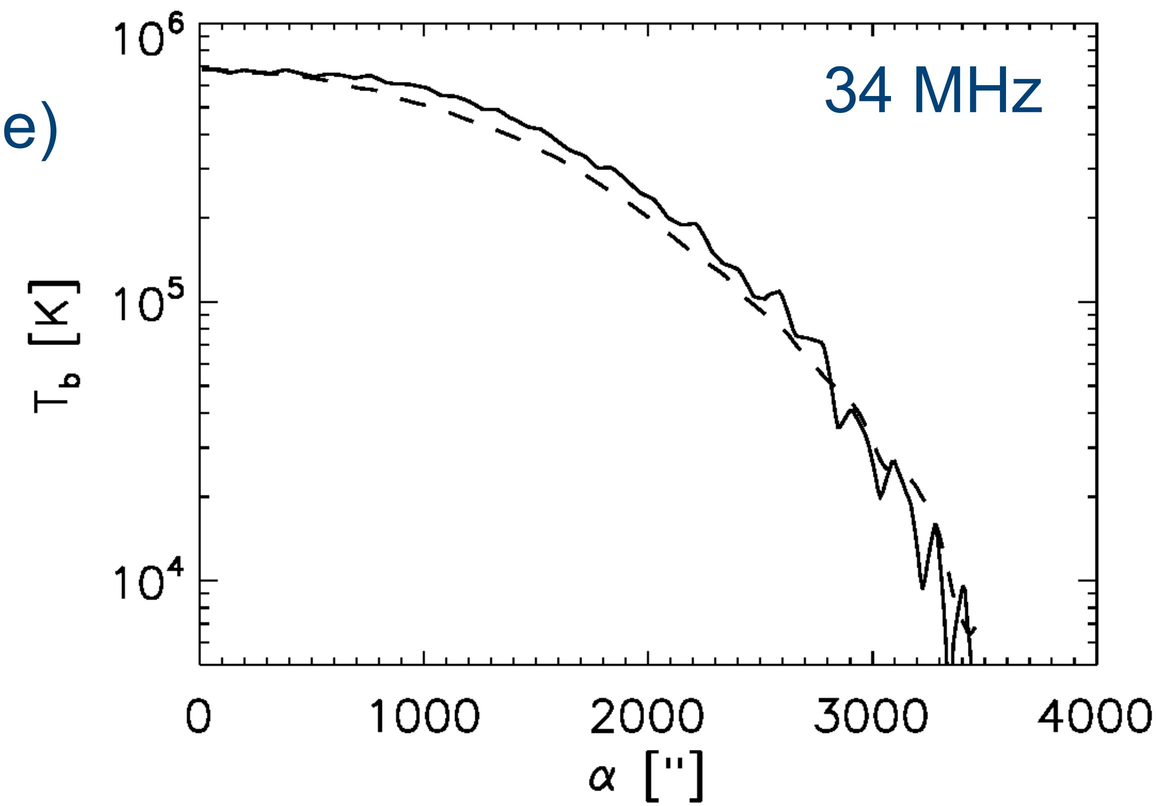

Observed intensity profiles

Solar KSP LOFAR

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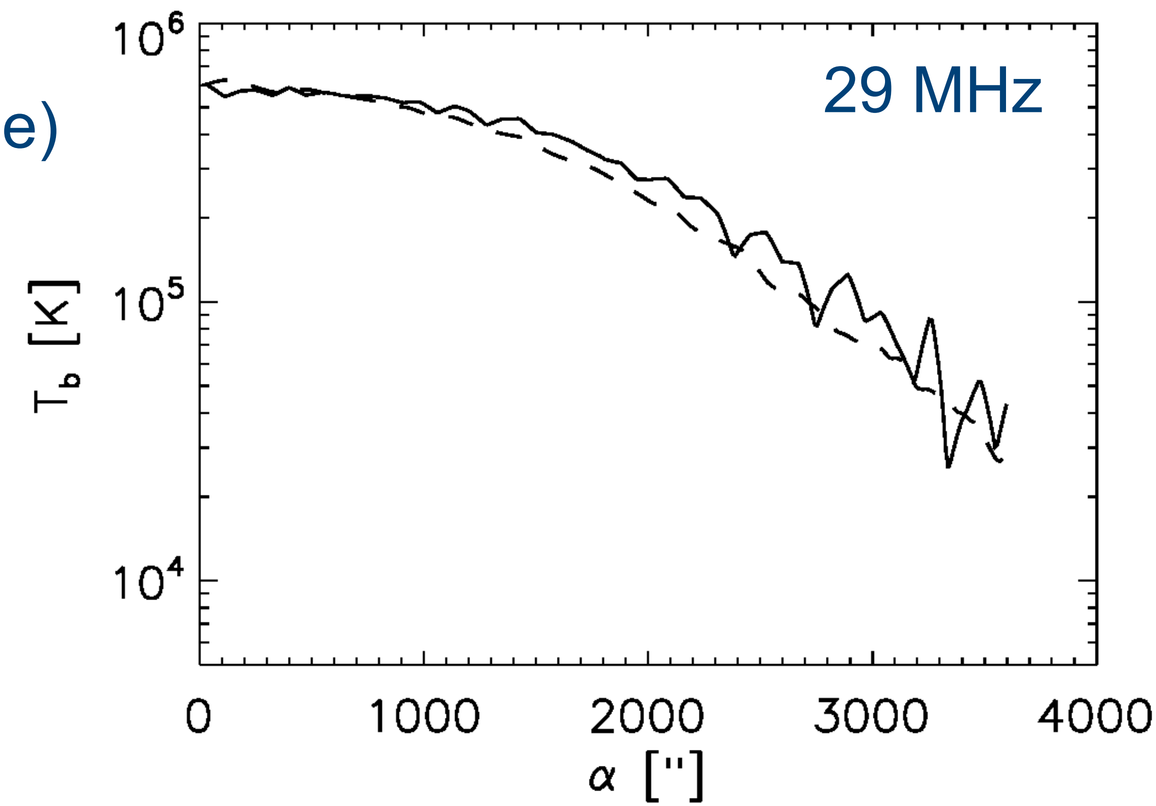

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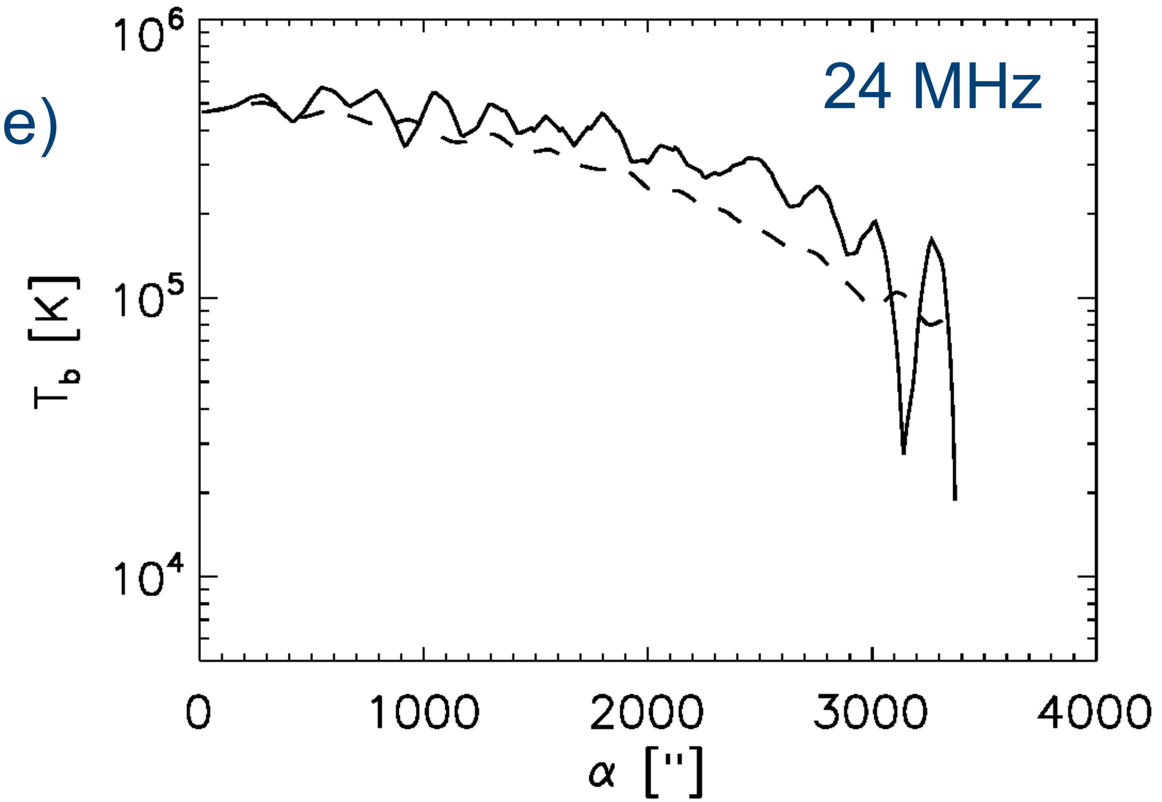
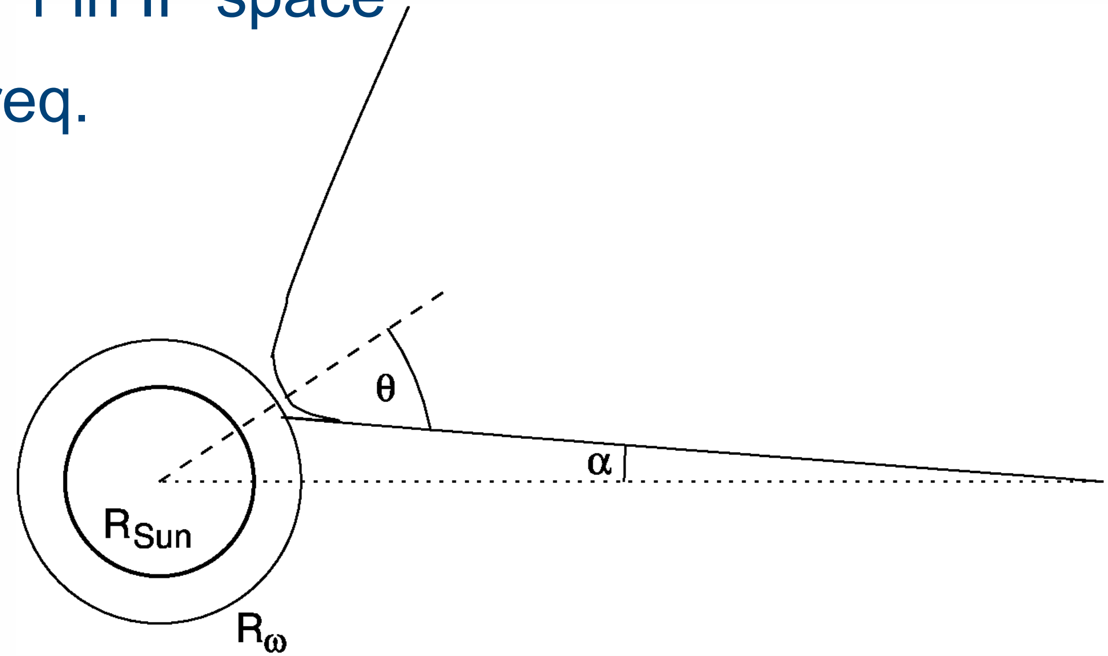


Coronal intensity profiles

Radio wave ray path:

- $n = (1 - \omega_p^2 / \omega^2)^{1/2} = 1$ in IP space
- $n \rightarrow 0$ near plasma freq.
- Total reflectance



Free-free emission:

- Proportional to N^2
- Line-of-sight integral
- Absorption of radio waves in the corona also has to be considered

Ray-tracing simulation of i(α)

Local hydrostatic density model: $$\frac{N(r)}{N_\omega} = \exp\left(\frac{1}{H_0}\left(\frac{1}{r} - \frac{1}{R_\omega}\right)\right)$$

Plasma frequency equals obs. freq.: $$N_\omega = N(R_\omega) = \frac{\omega^2 m_e \epsilon_0}{e^2}$$

Pressure scale height: $$H_0 = \frac{k_B T}{0.6\, m_p\, g_\odot} \frac{1}{R_\odot^2}$$

Model parameters: R_ω and coronal temperature, T

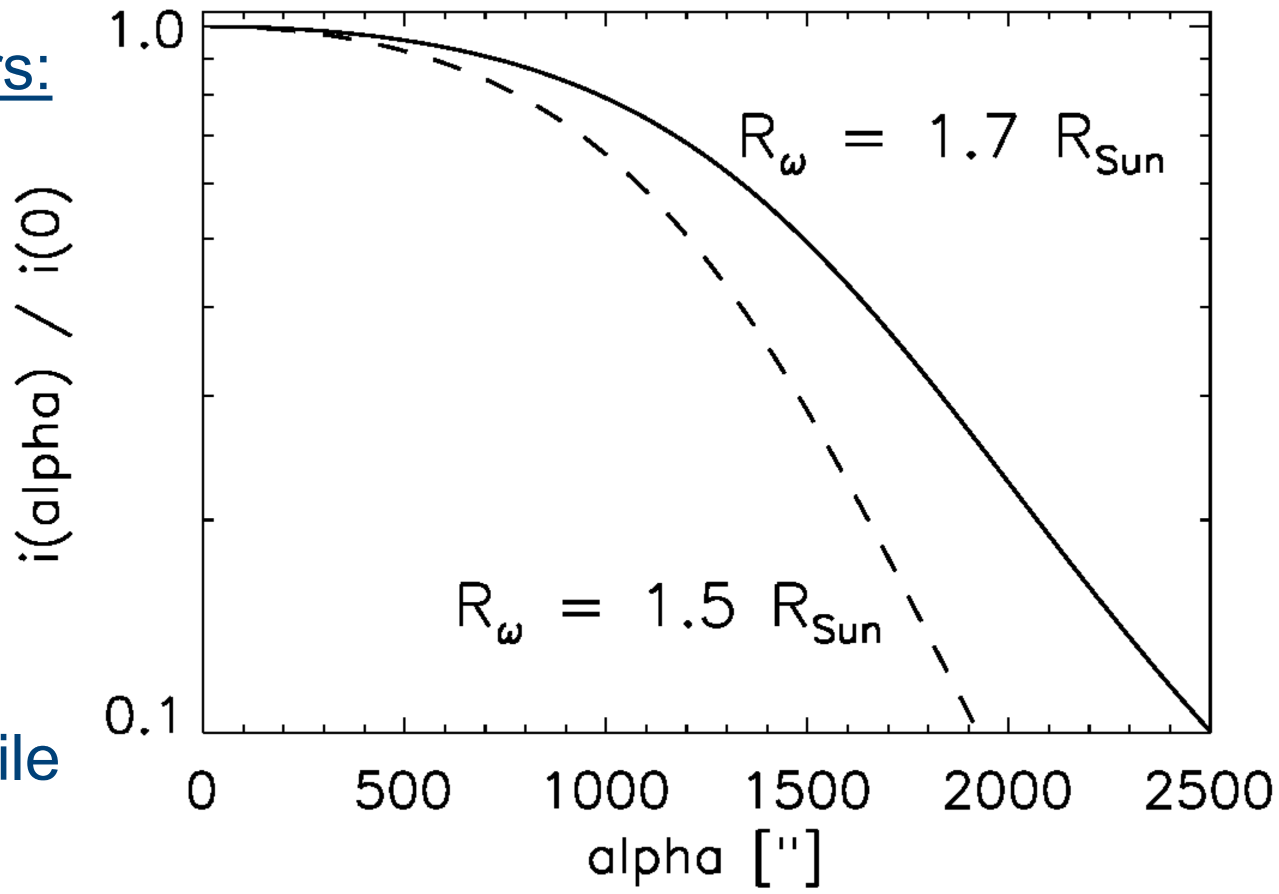
Temperature dependence:
- Scale height H_0
- Rayleight-Jeans law

R_ω – dependence of sim. results

Solar KSP

Model parameters:

- T = 1.4 MK



Result:

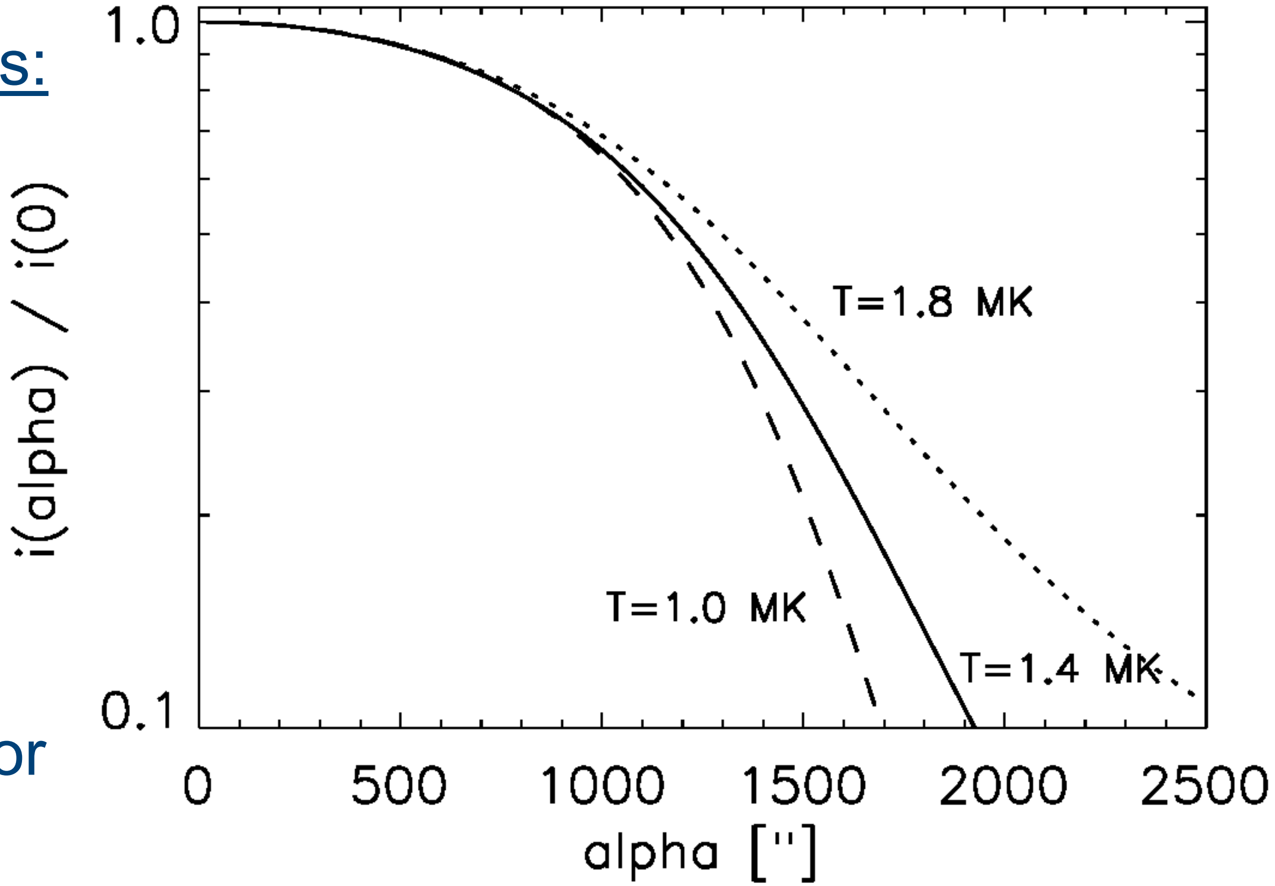
- The whole profile scales with R_ω

T – dependence of sim. results

Solar KSP

Model parameters:

- $R_\omega = 1.5\ R_{Sun}$



Result:

- Variation only for higher α

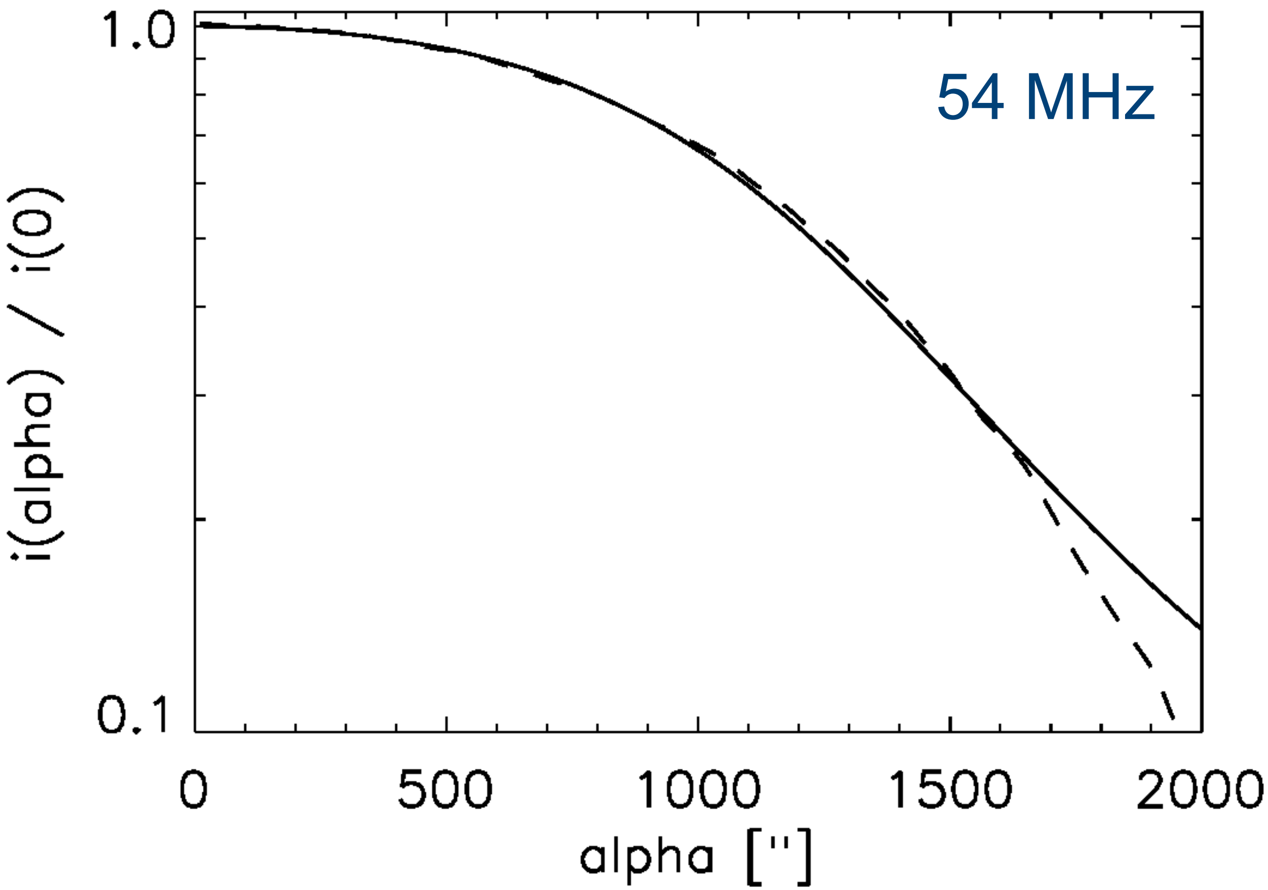
Fit simulations to observations

Observation:

- Polar profile
- Dashed line

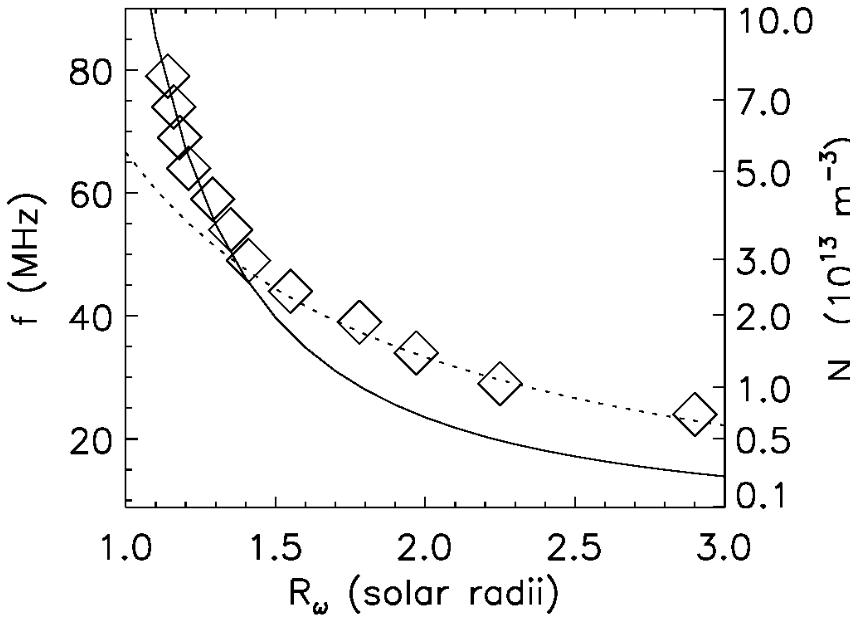
Simulation:

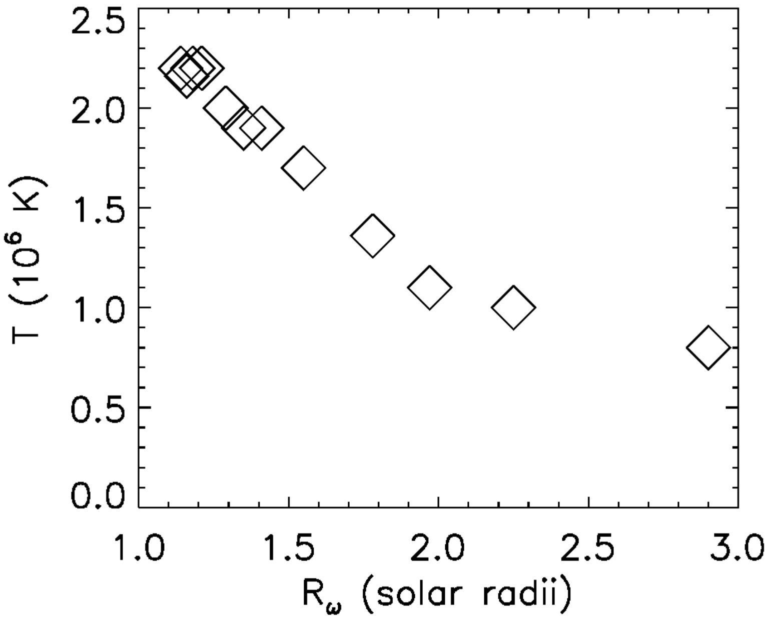
- $R_\omega = 1.35\ R_{Sun}$
- T = 1.9 MK
- Solid line



Each profile provides values for R_ω and T

Coronal density and T profiles





Solid line:

- Hydrostatic model
- $N = 1.6\ 10^{14}\ m^{-3}$ at coronal base
- T = 2.2 MK, consistent with fits

Dotted line:

- $1/r^2$ density profile
- Solar wind

Summary and conclusions

Quiet Sun observations with LOFAR:

- Earth's rotation can be used to improve uv coverage
- Radio Sun appears bigger with decreasing frequency
- But the Sun does not appear disk-like
- Coronal refraction has to be considered when analyzing LOFAR images
- Ray-tracing simulations allow for fitting coronal parameters
- Coronal density and temperature profiles
- Transition into the solar wind observed