Leibniz-Institut für Astrophysik Potsdam

AIP

LOFAR observations of the quiet solar corona

C. Vocks, G. Mann, and F. Breitling

Leibniz Gemeinschaft

EUROPÄISCHE UNION
Investition in unsere Zukunft
Europäischer Fonds
für regionale Entwicklung

LAND BRANDENBURG

Bundesministerium
für Bildung
und Forschung

Quiet Sun studies

Objectives:

- Structure of the solar corona
- Density profile in LOFAR's low band range
- Corresponds to upper corona: $\omega > \omega_p = \sqrt{Ne^2 / m_e \varepsilon_0}$
- Transition into solar wind

Observations:

- Dataset from cylce 0
- Discrete frequencies with 5 MHz separation, 19 – 79 MHz

Quiet Sun observations

Solar observations:

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

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

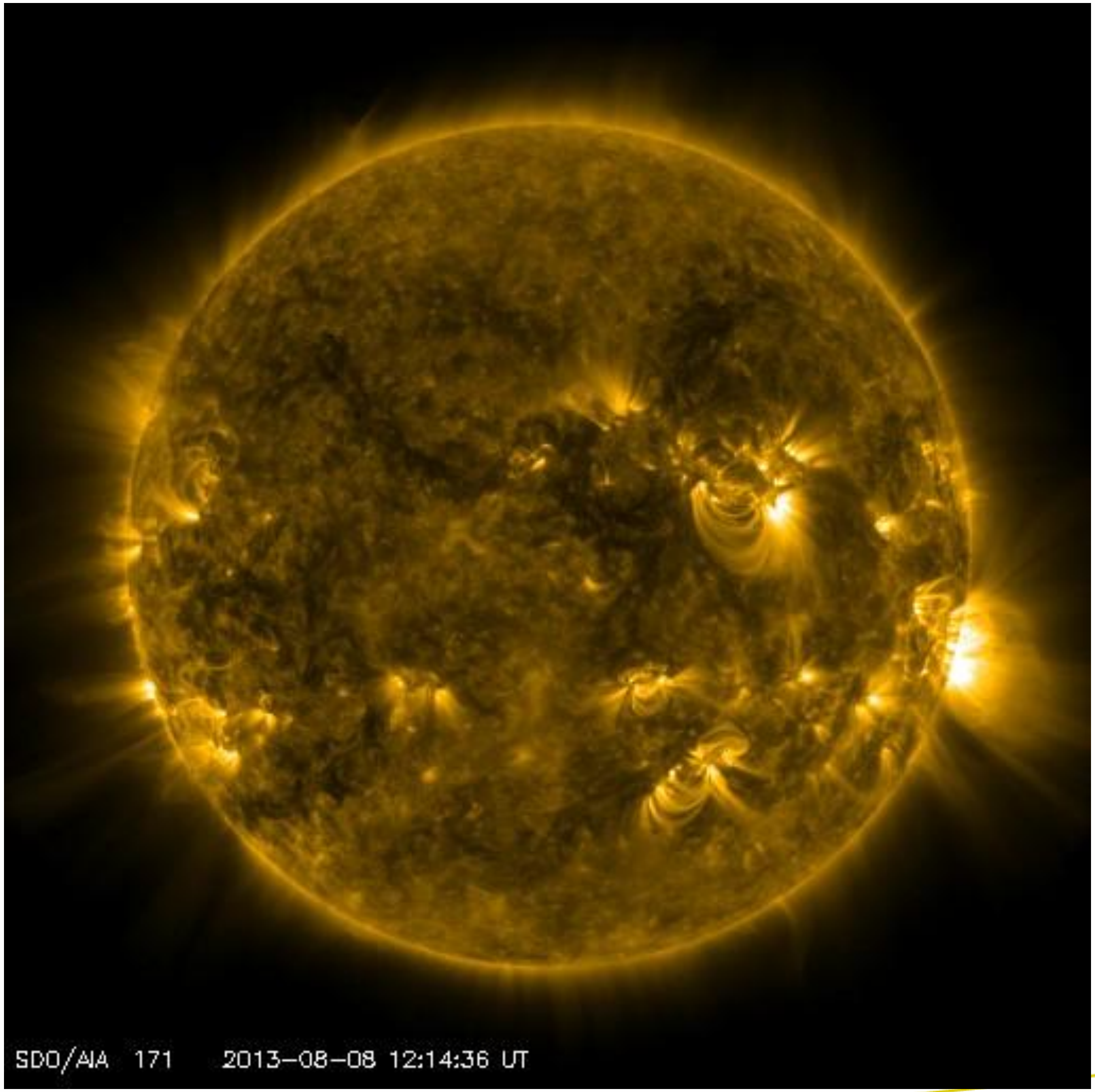
Quiet Sun:

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

→ Aperture synthesis imaging

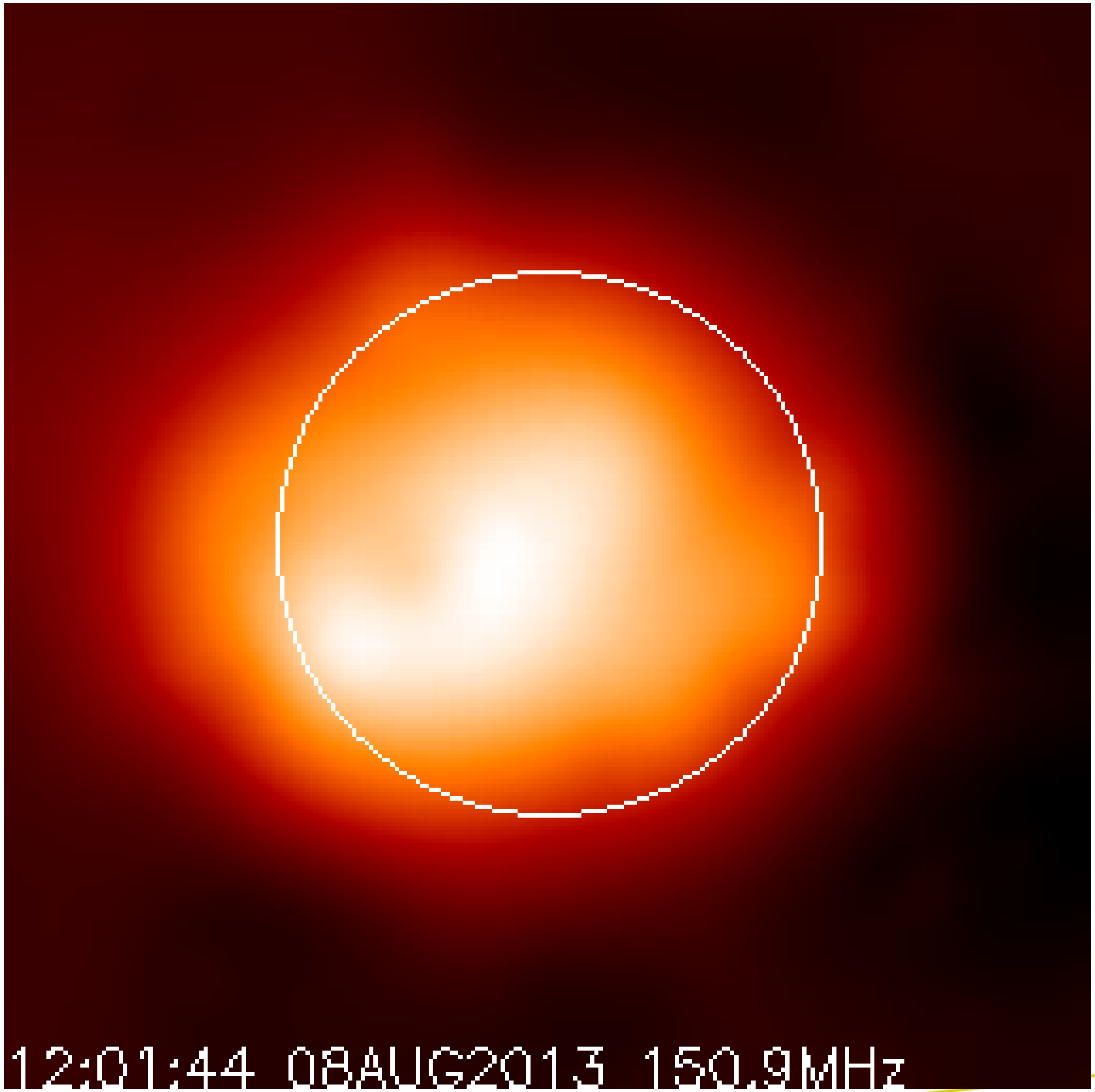
The Sun on 08 August 2013

SDO:



The Sun on 08 August 2013

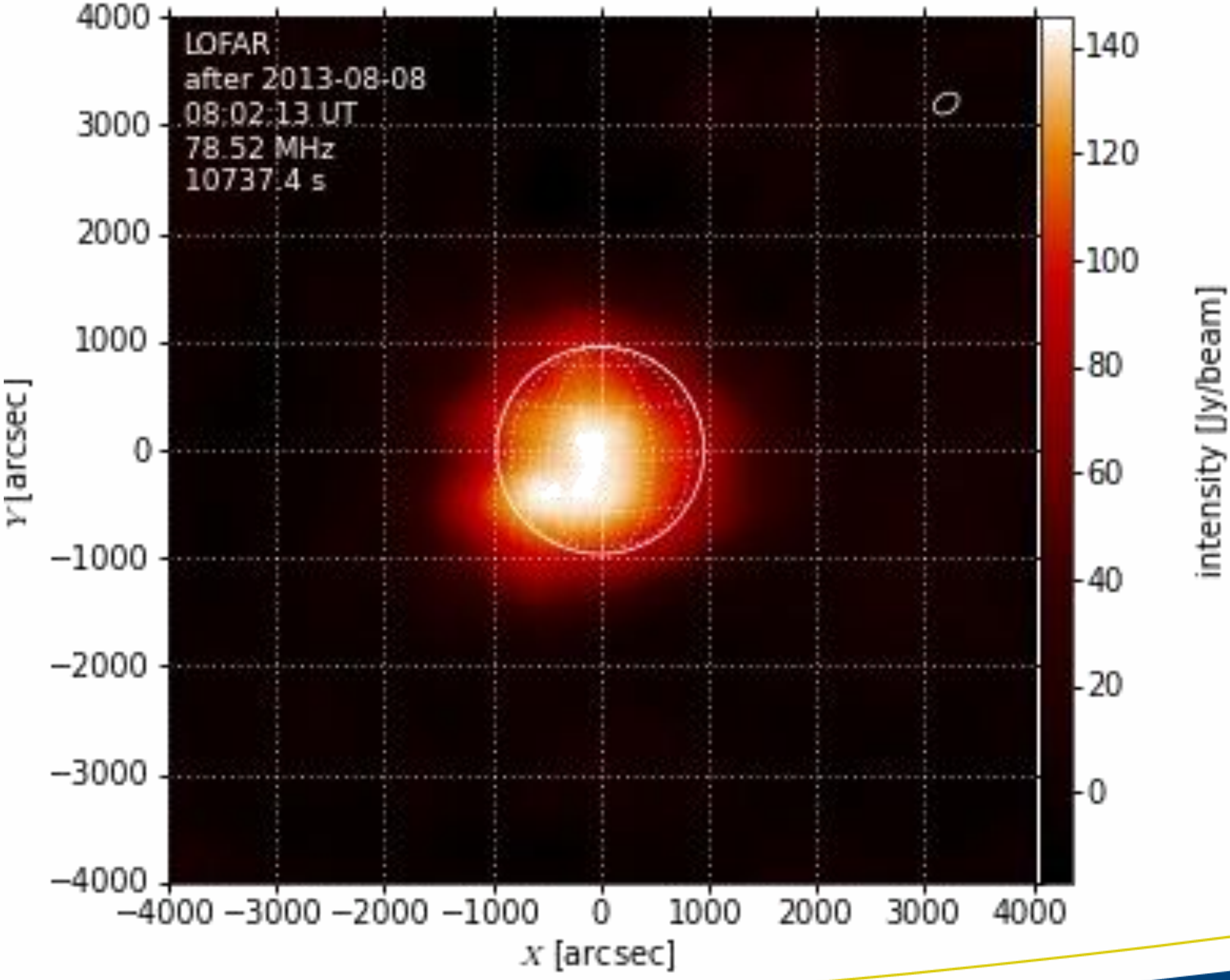
NRH:



Solar corona

Image:

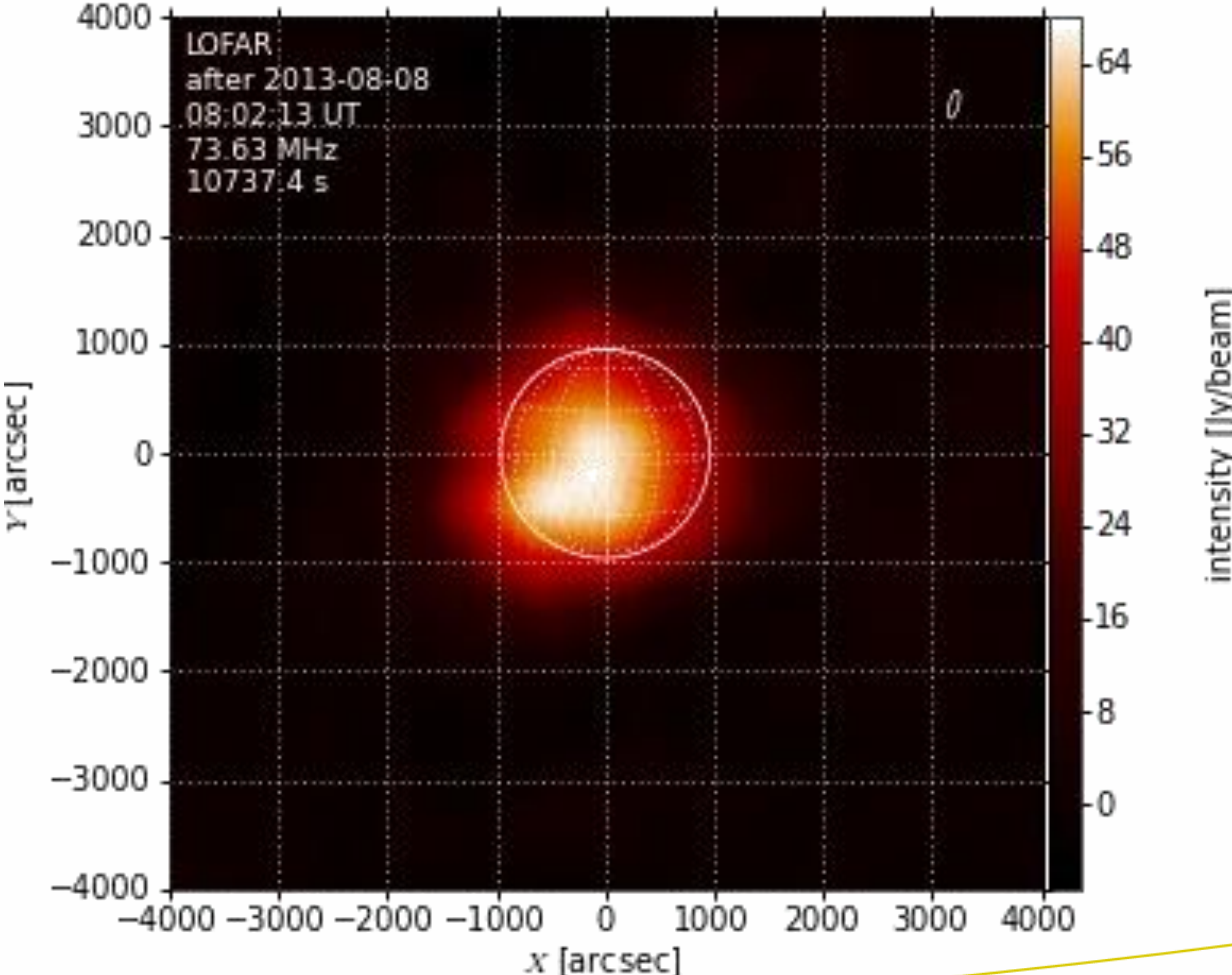
- 79 MHz
- 3 h



Solar corona

Image:

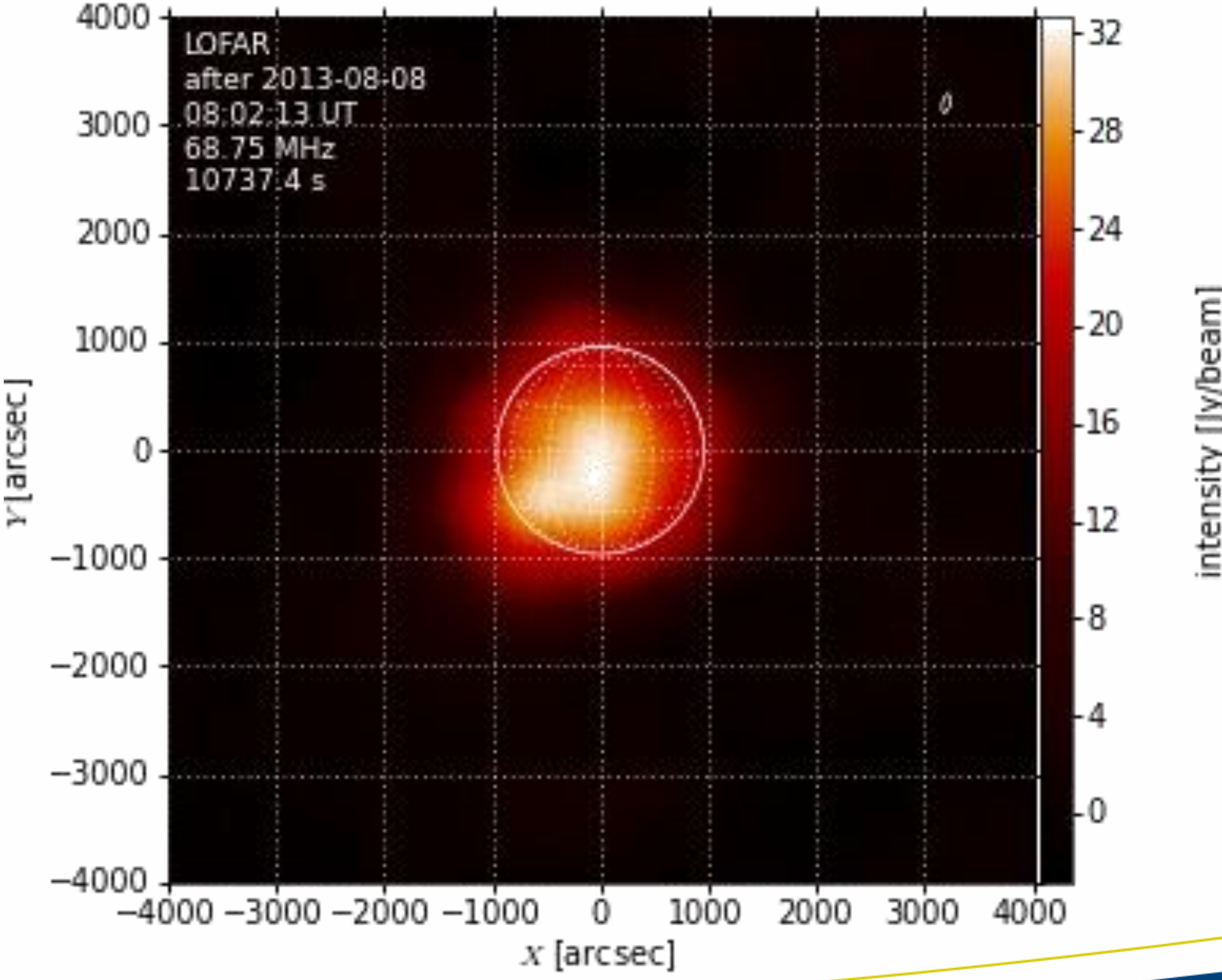
- 74 MHz
- 3 h



Solar corona

<u>Image:</u>

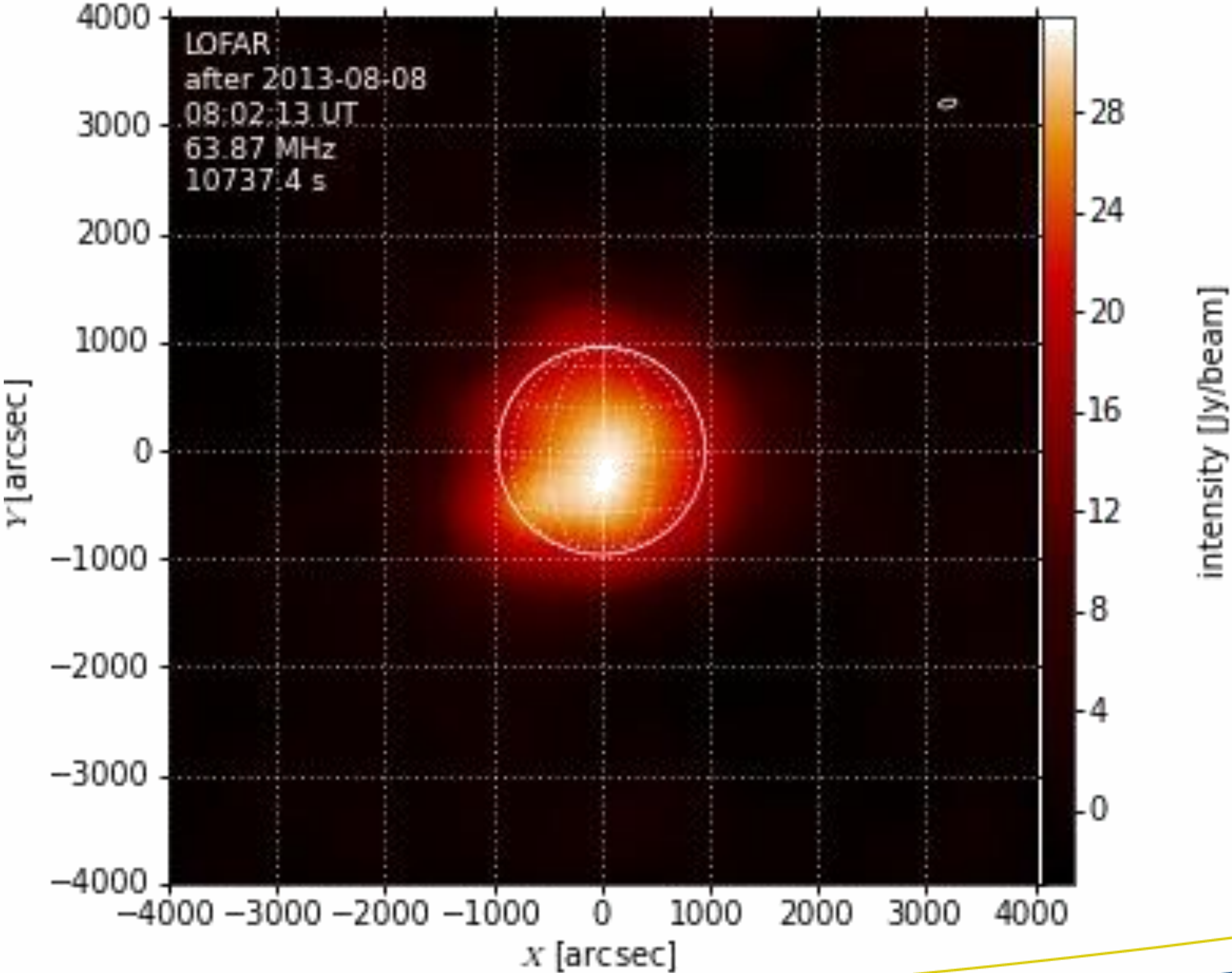
- 69 MHz
- 3 h



Solar corona

Image:

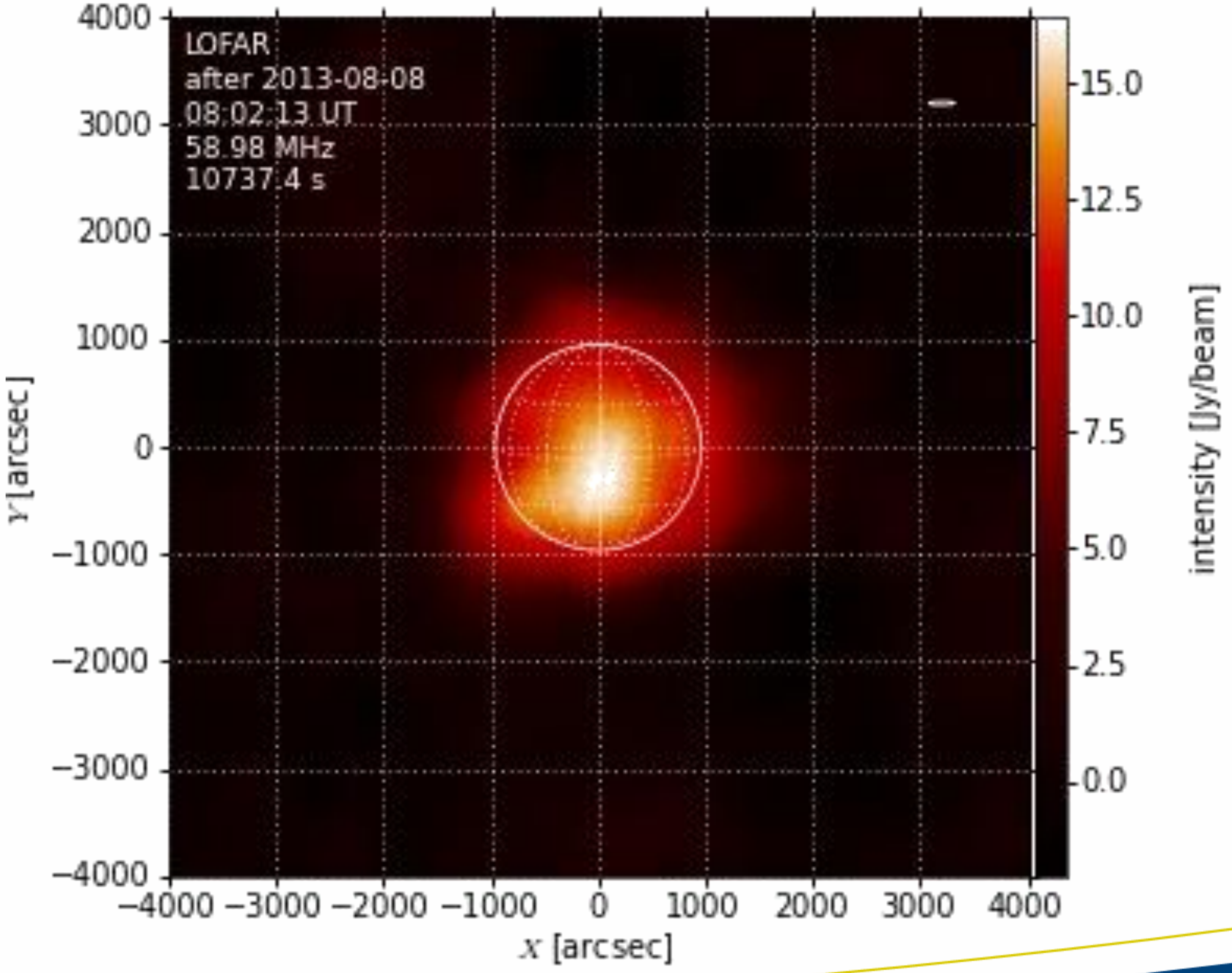
- 64 MHz
- 3 h



Solar corona

Image:

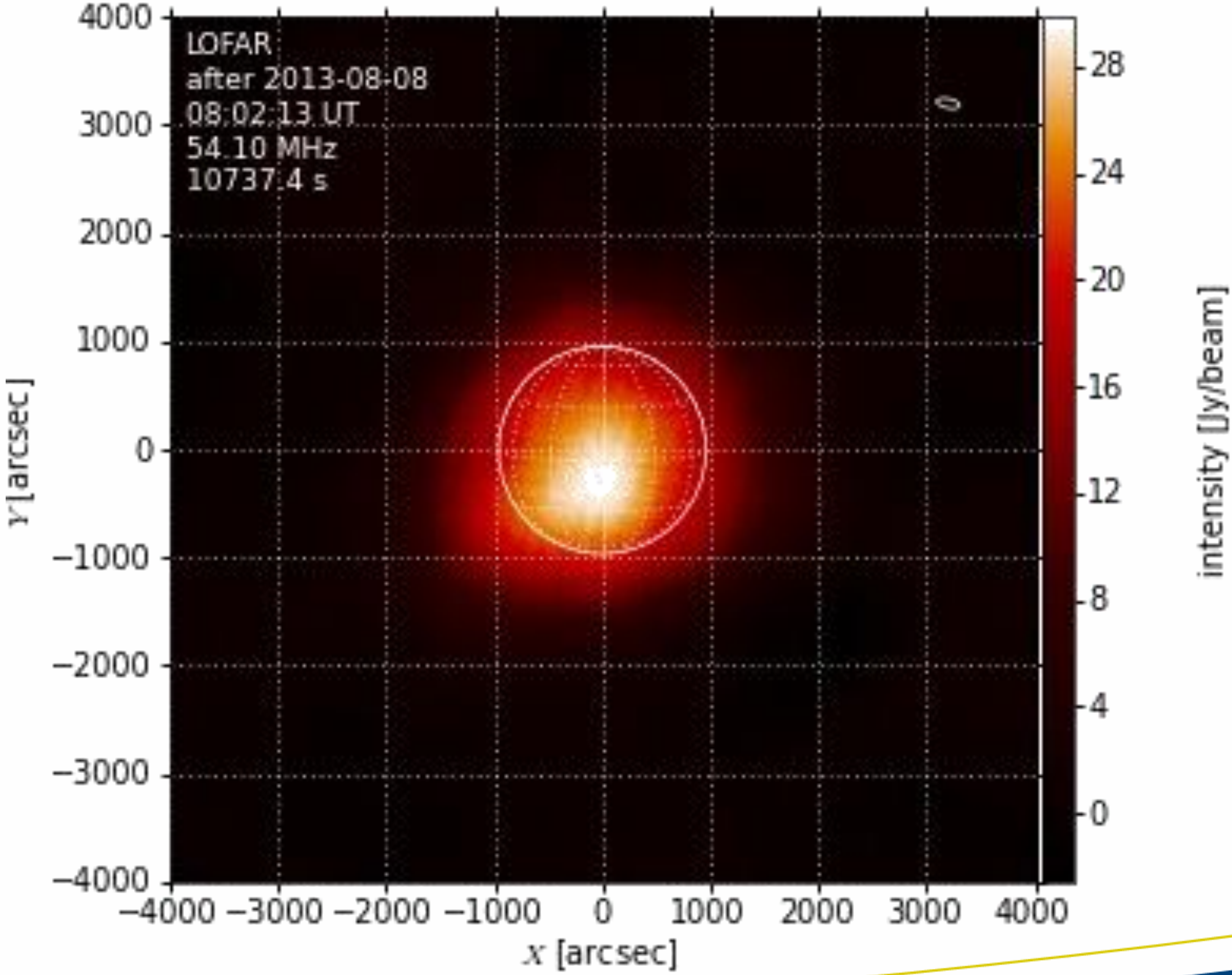
- 59 MHz
- 3 h



Solar corona

Image:

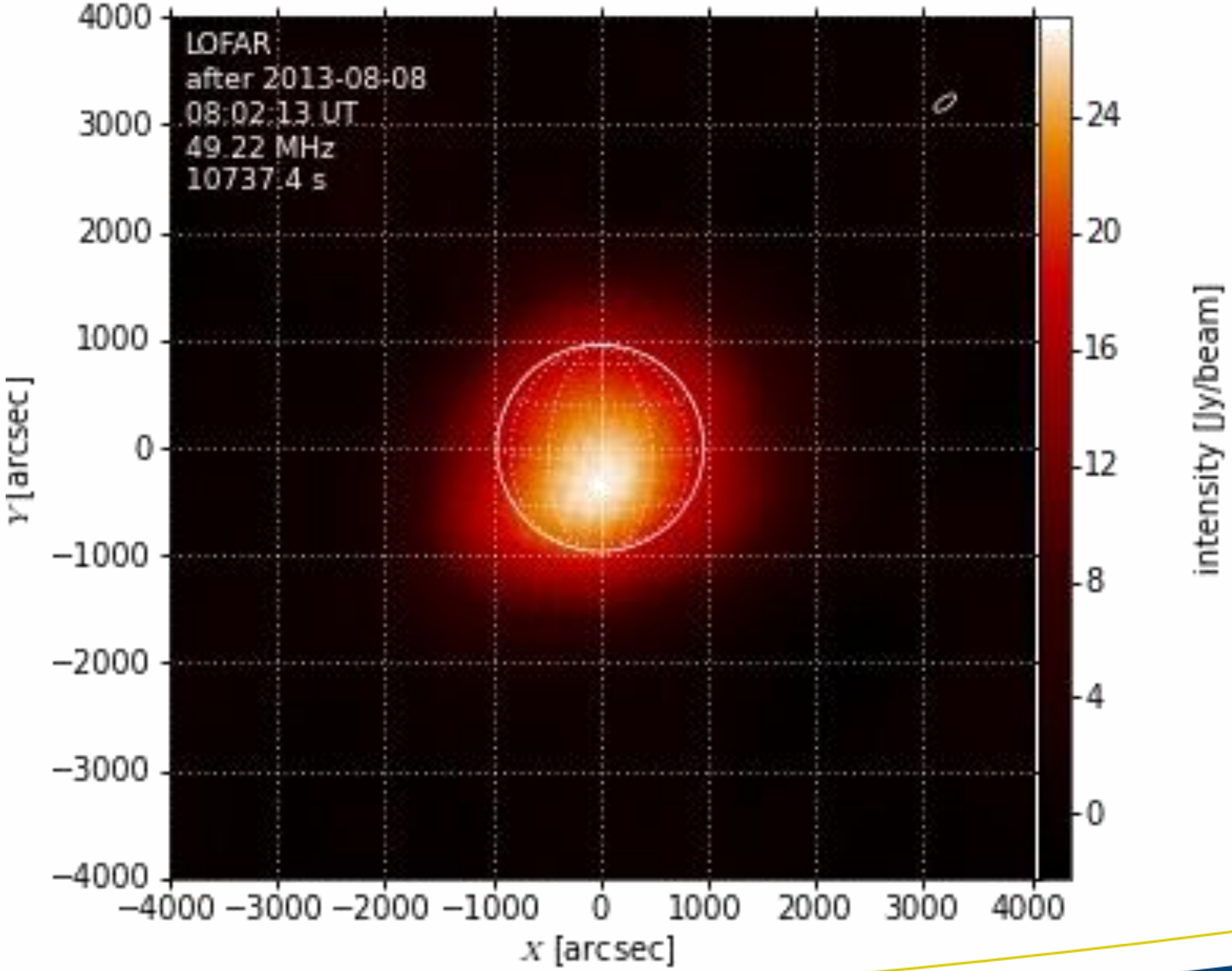
- 54 MHz
- 3 h



Solar corona

Image:

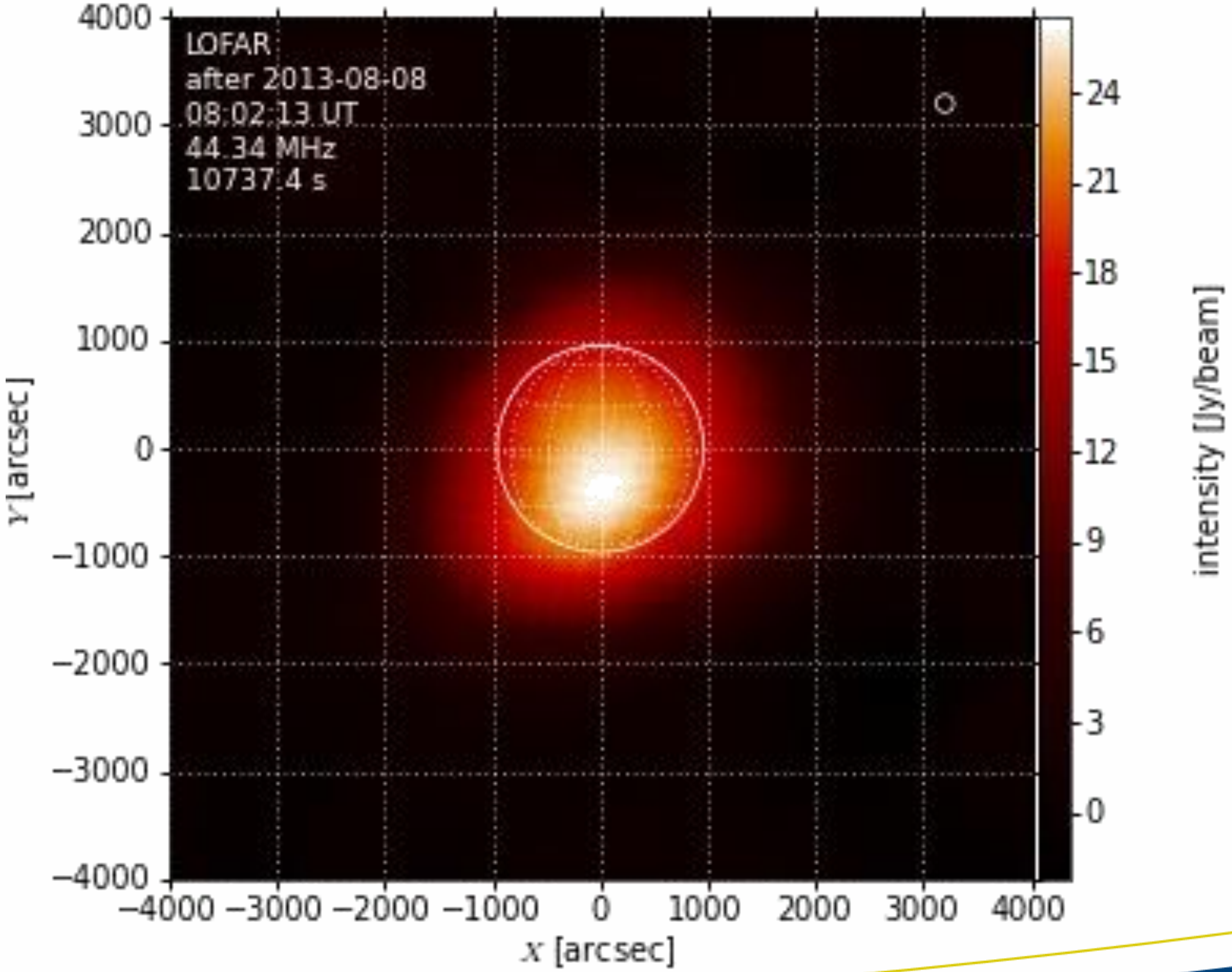
- 49 MHz
- 3 h



Solar corona

Image:

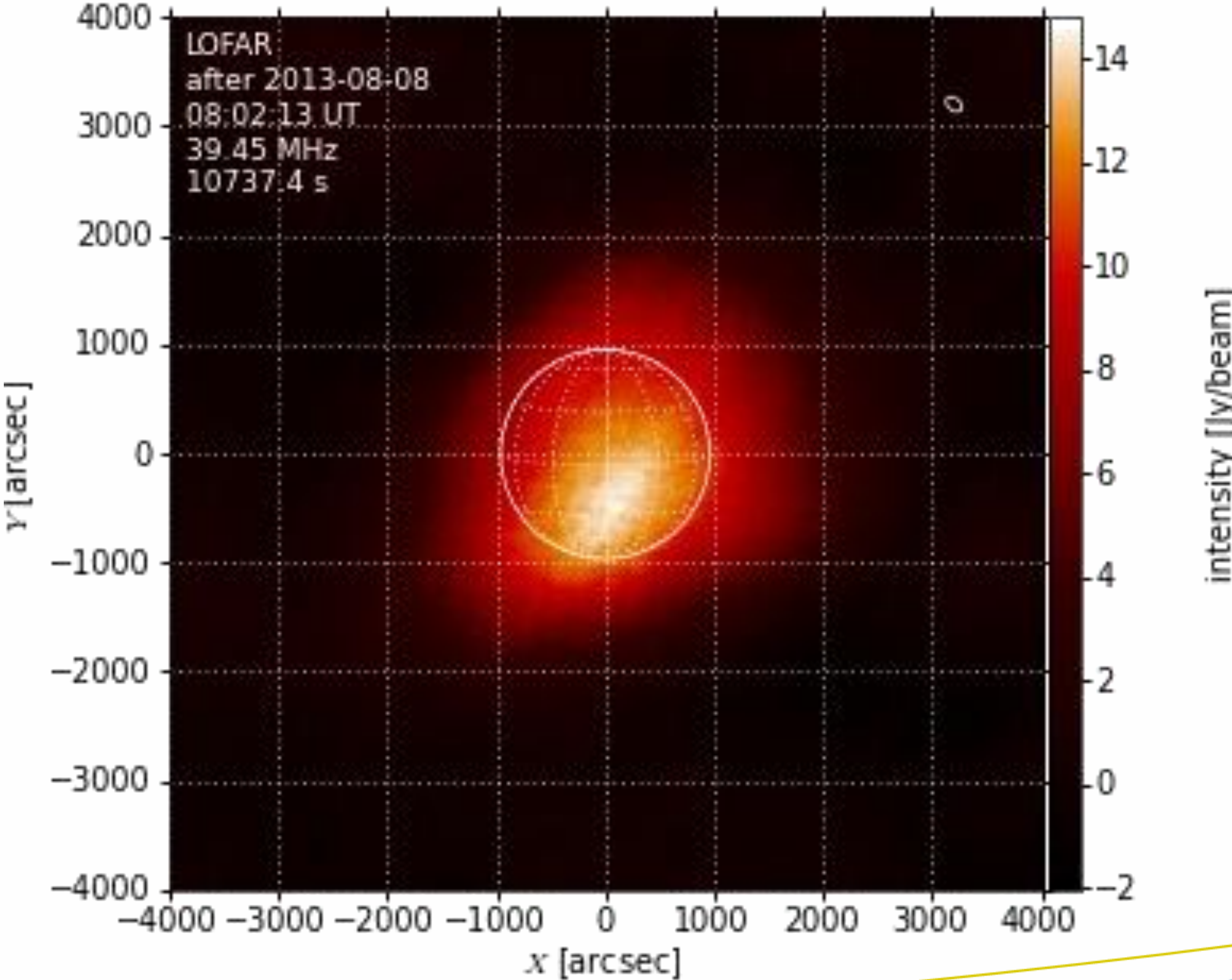
- 44 MHz
- 3 h



Solar corona

Image:

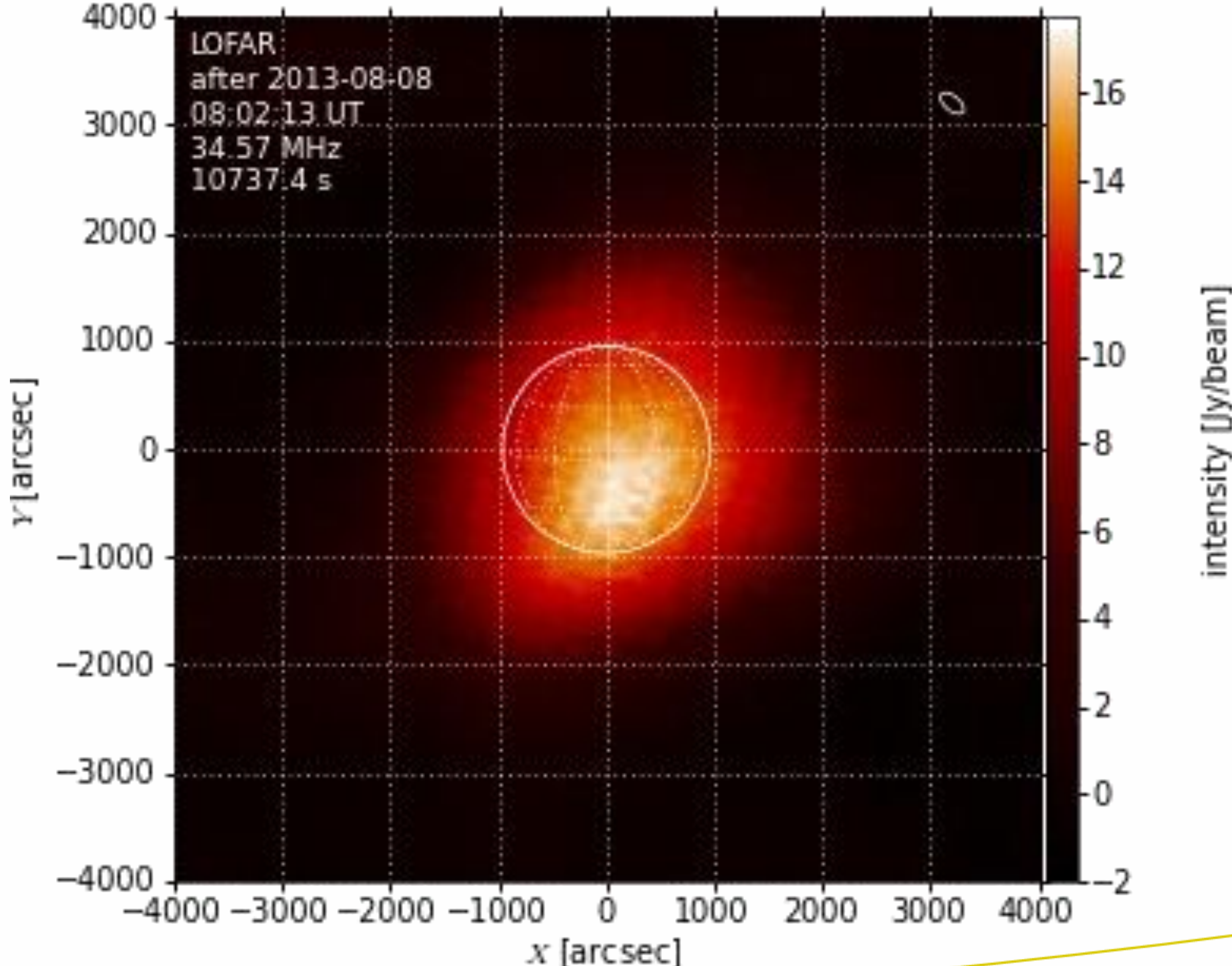
- 39 MHz
- 3 h



Solar corona

Image:

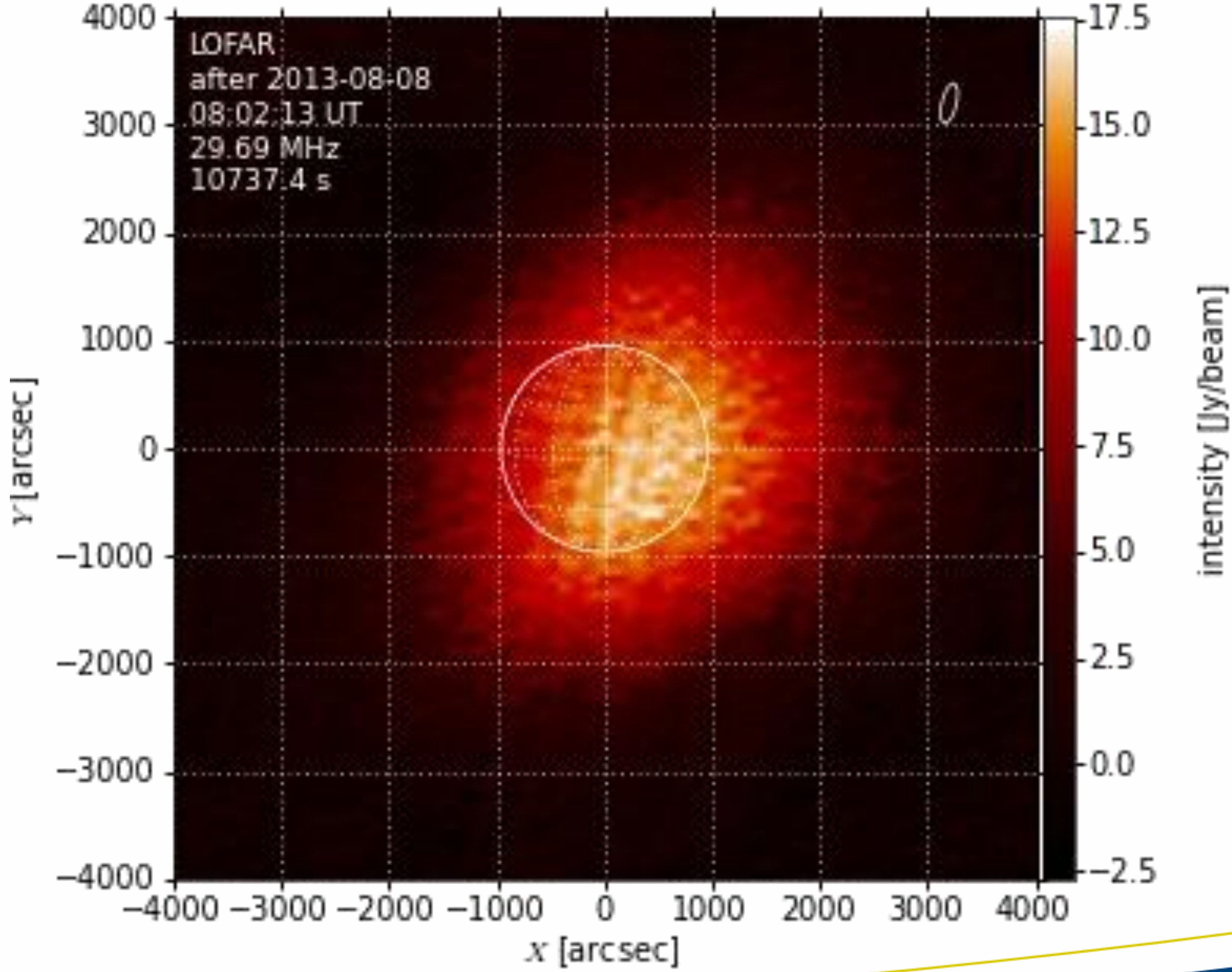
- 34 MHz
- 3 h



Solar corona

<u>Image:</u>

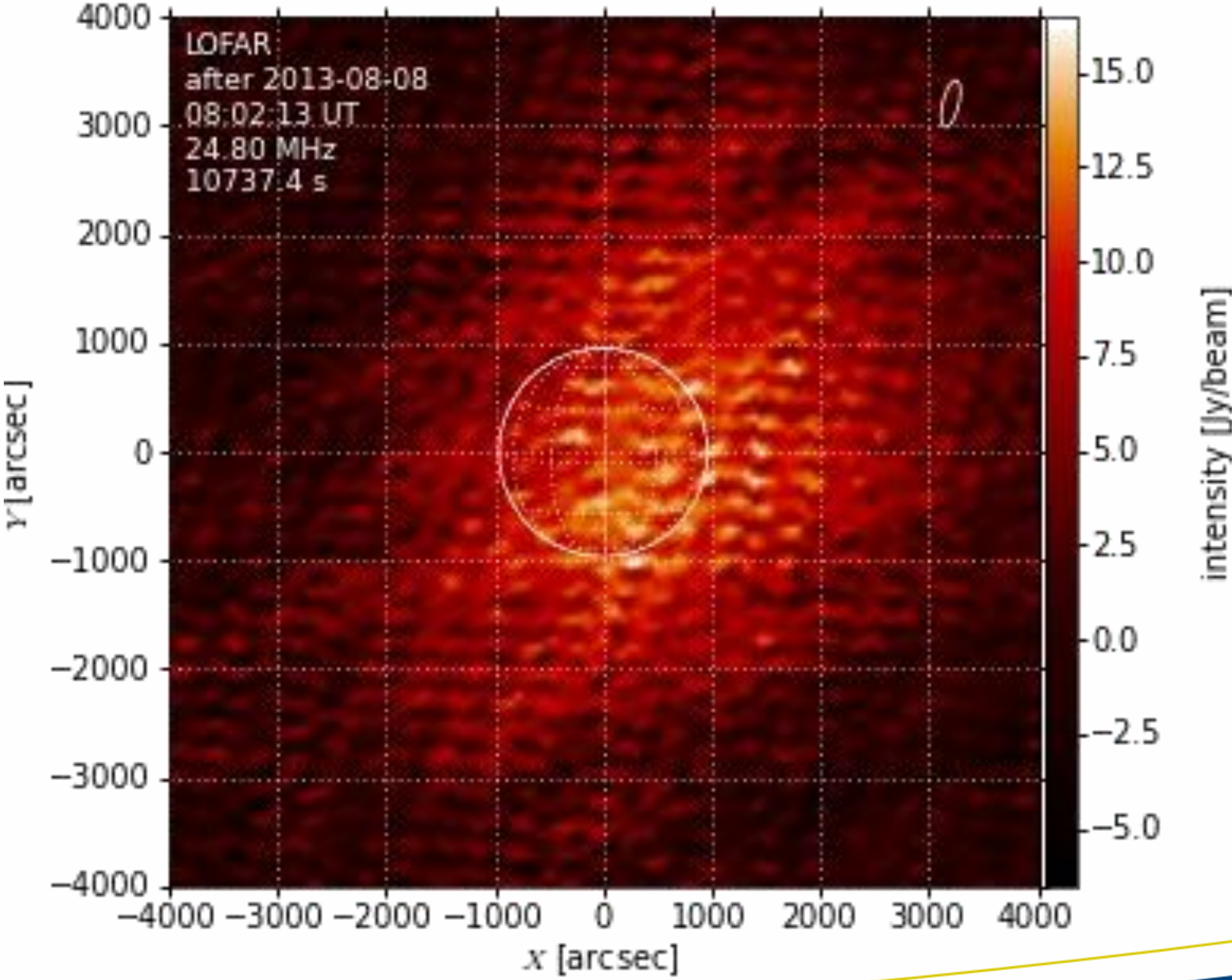
- 29 MHz
- 3 h



Solar corona

Image:

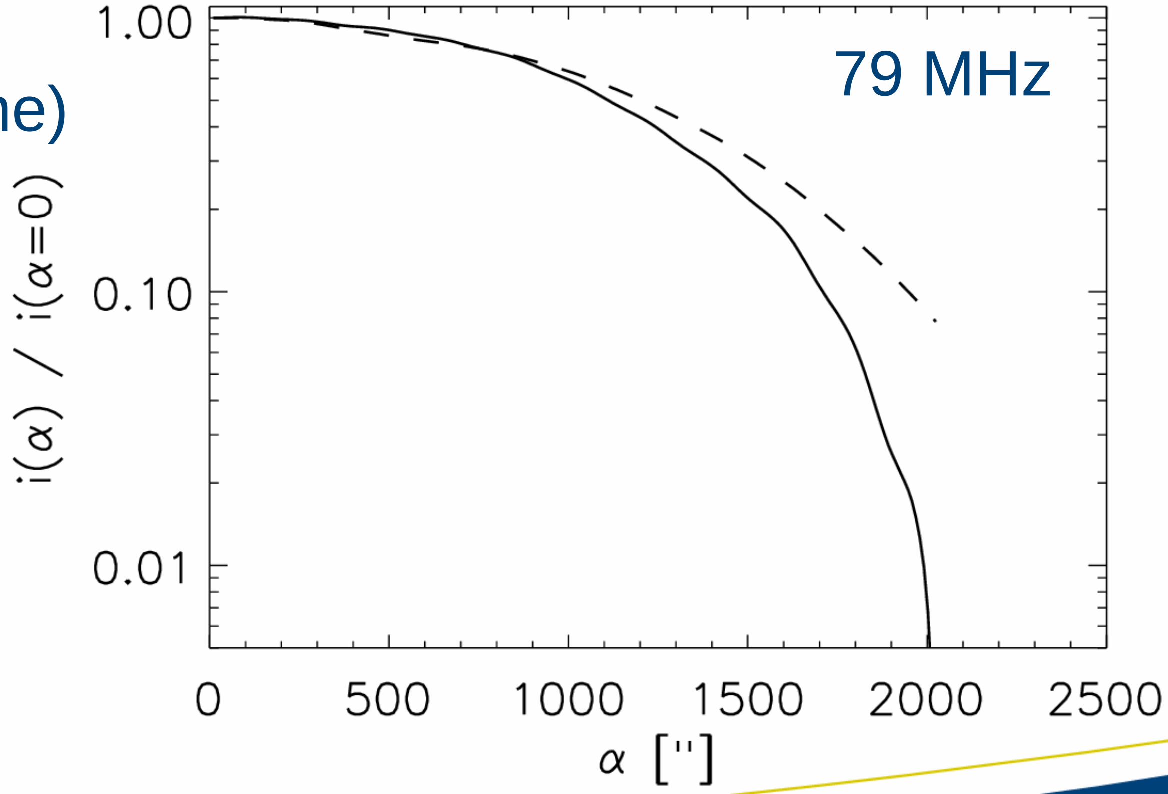
- 24 MHz
- 3 h



Observed intensity profiles

Profiles:

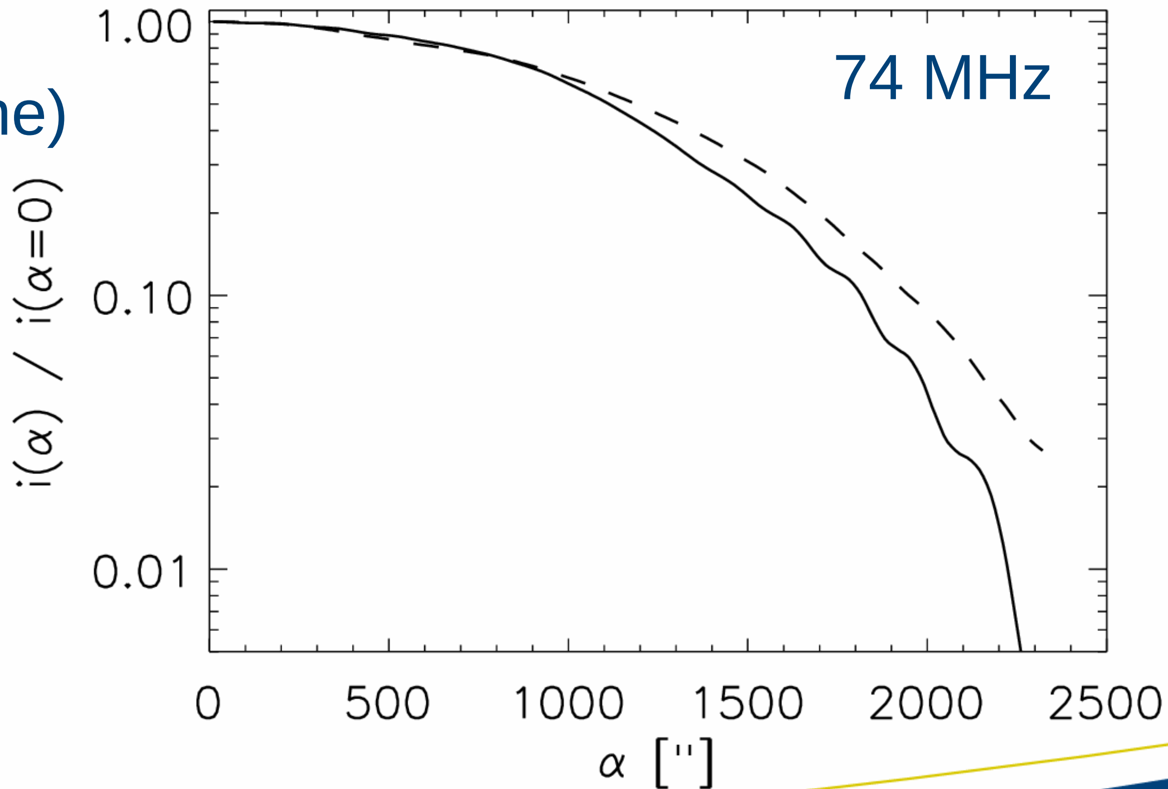
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

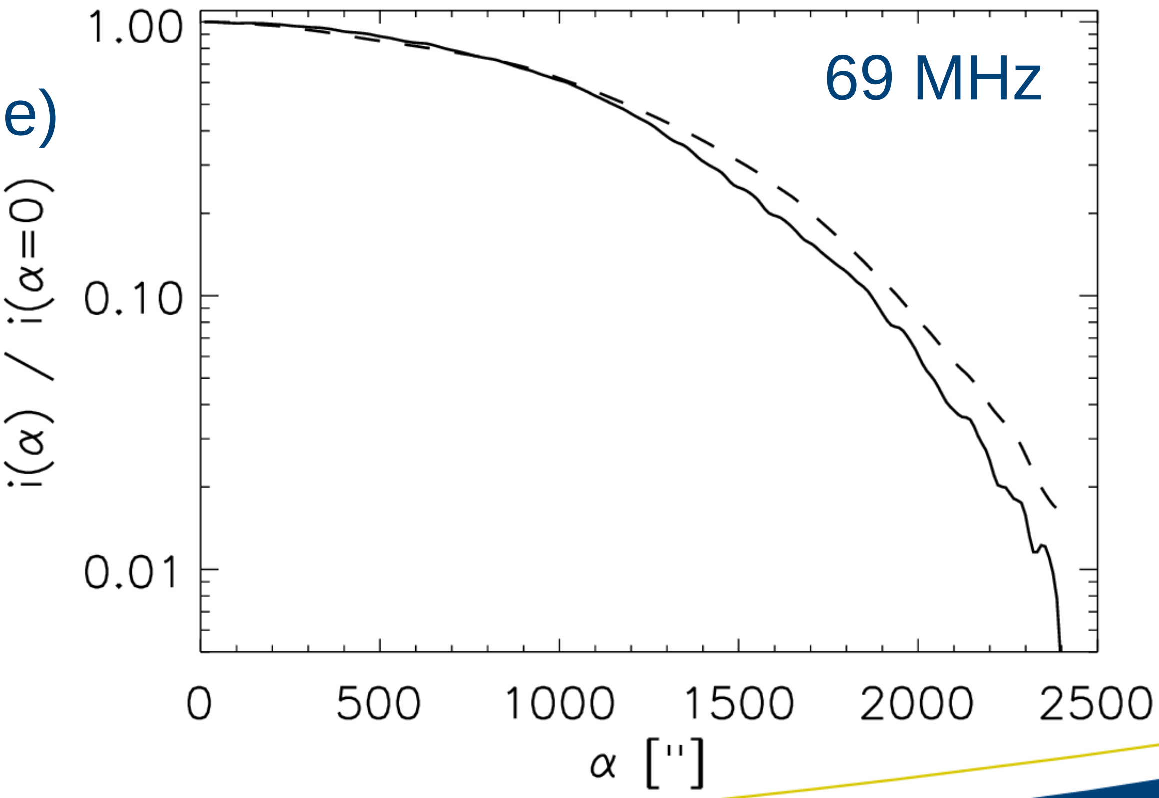
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

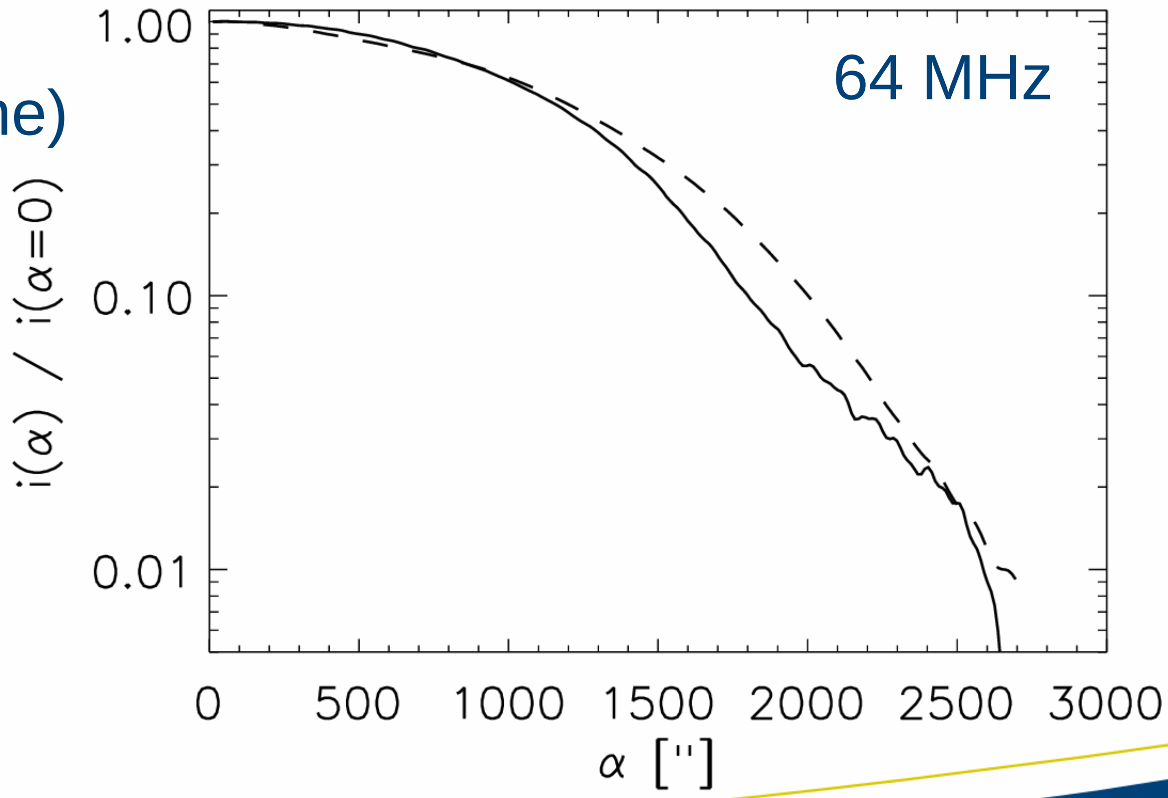
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

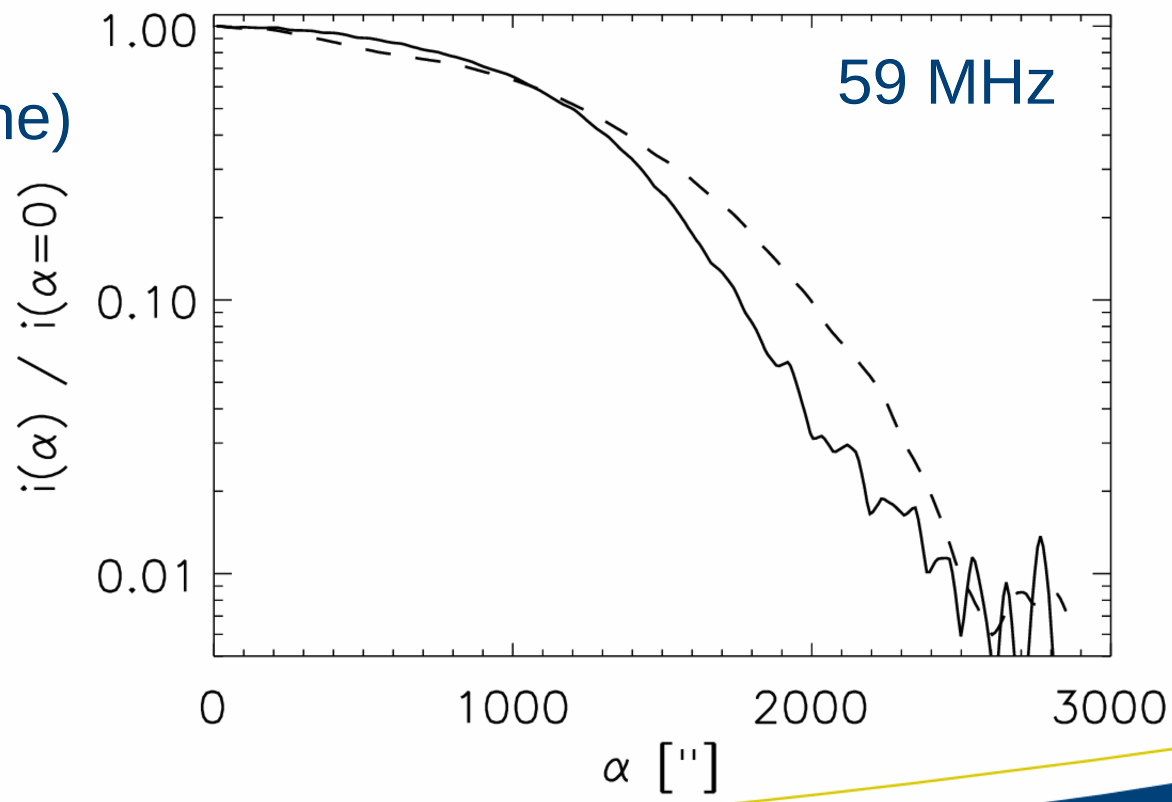
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

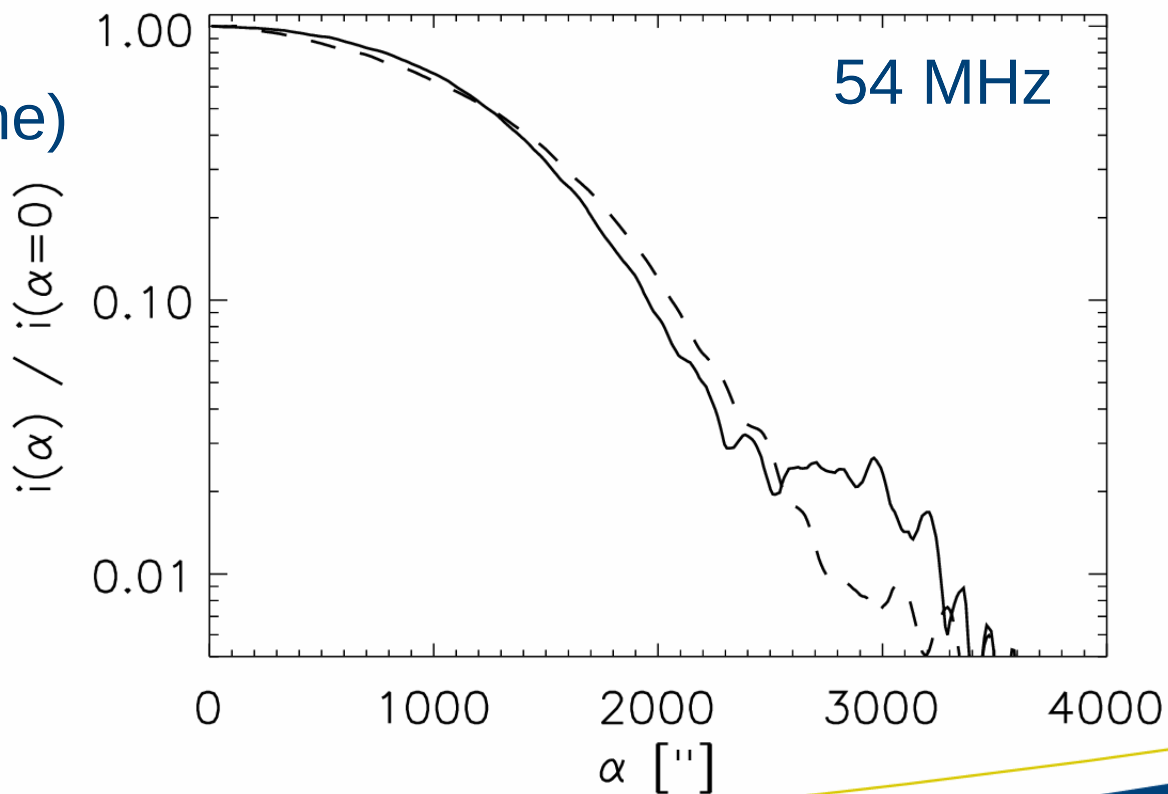
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

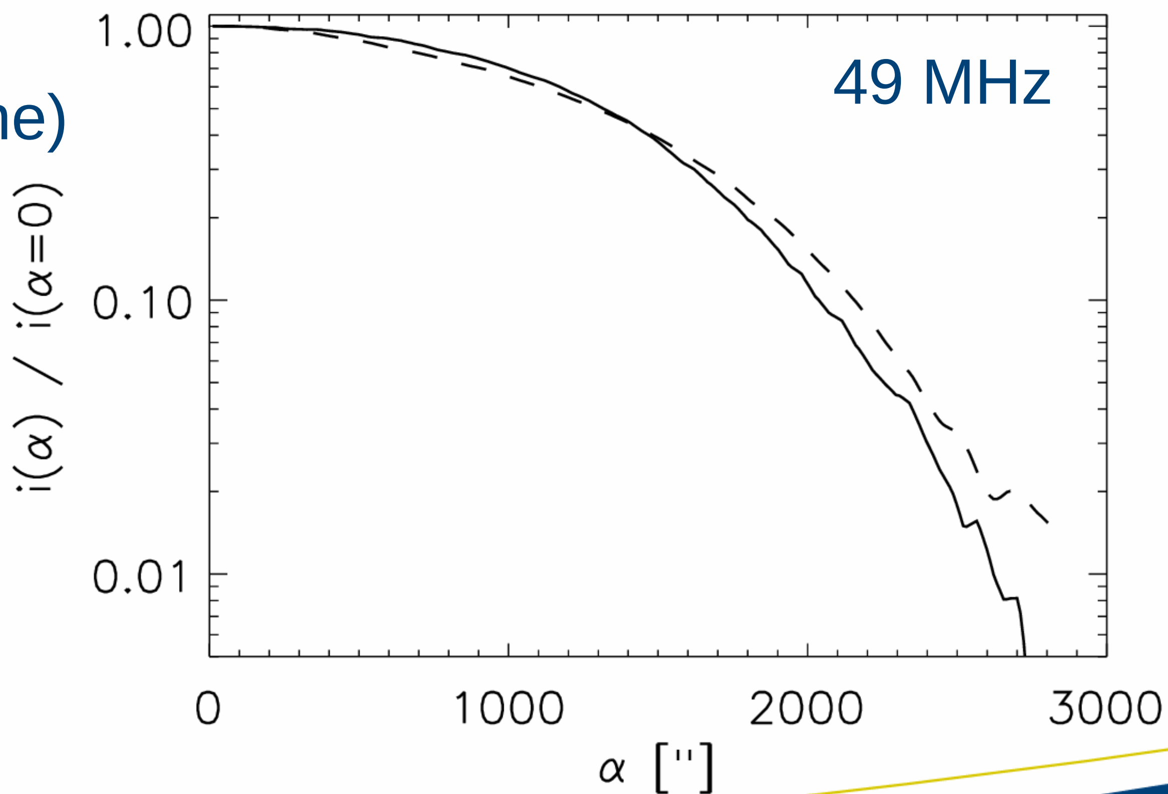
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center

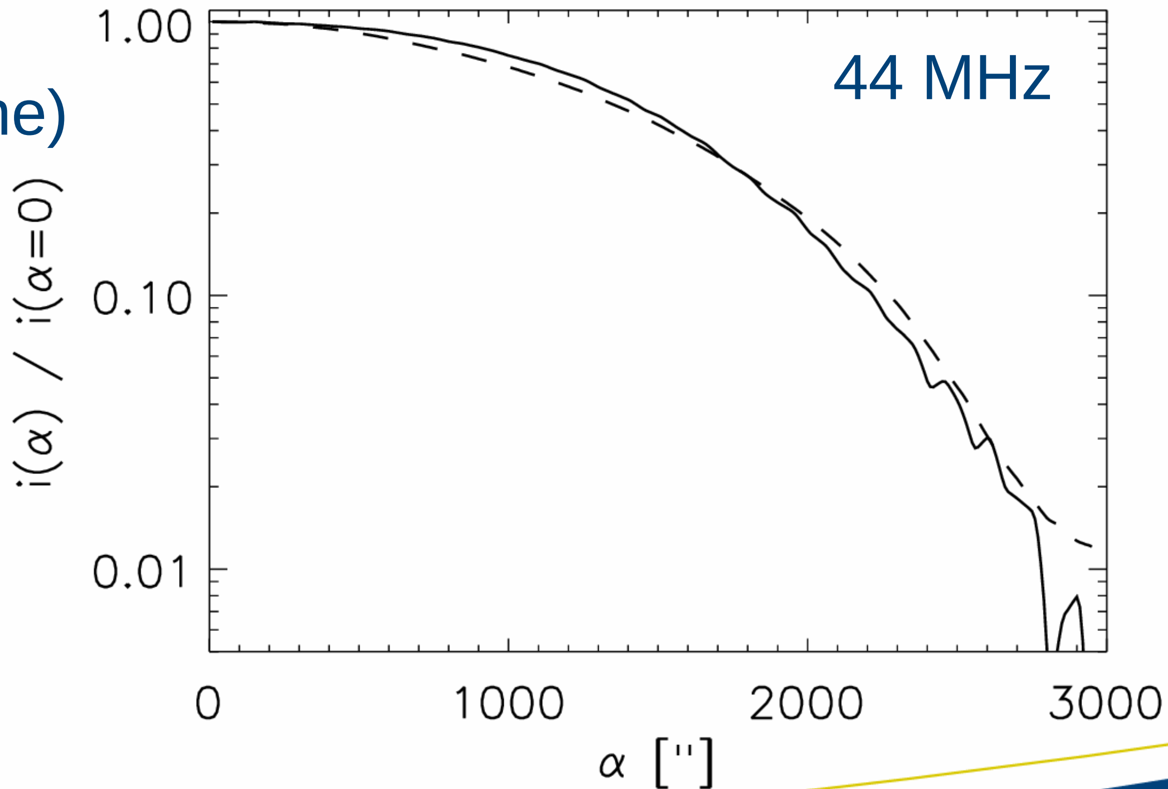


Observed intensity profiles

Solar KSP LOFAR

<u>Profiles:</u>

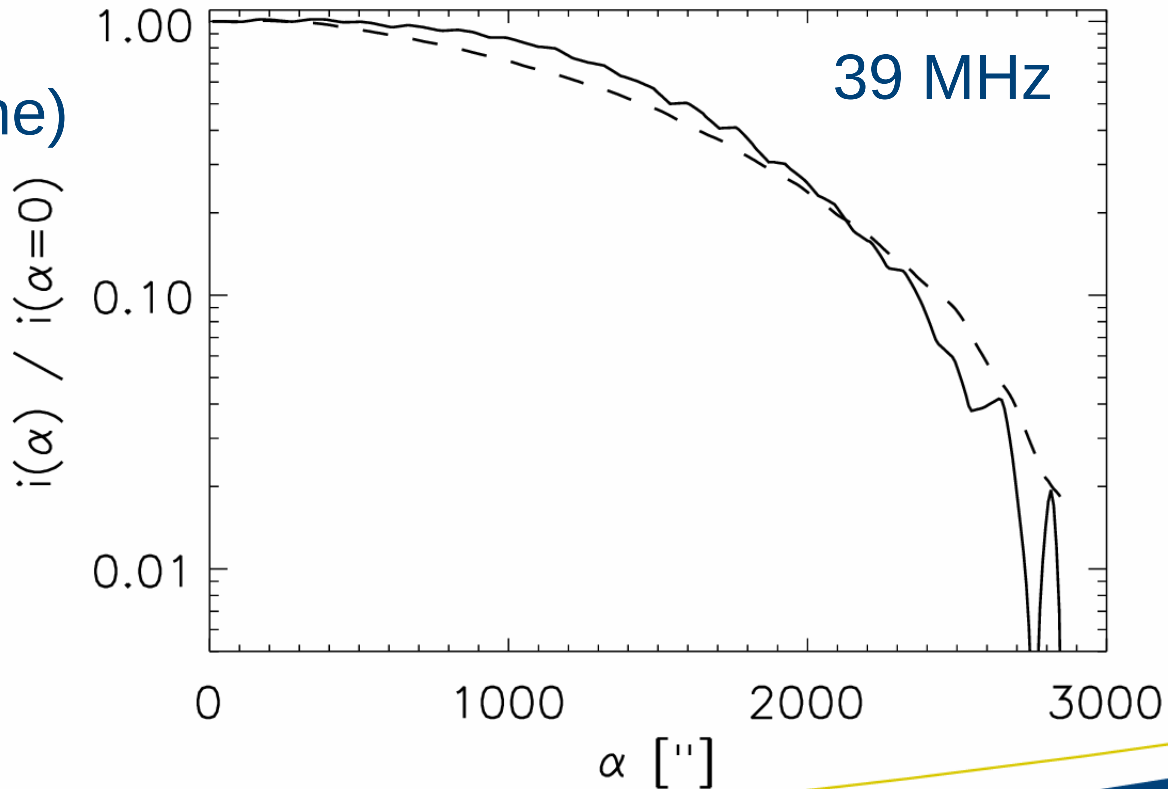
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

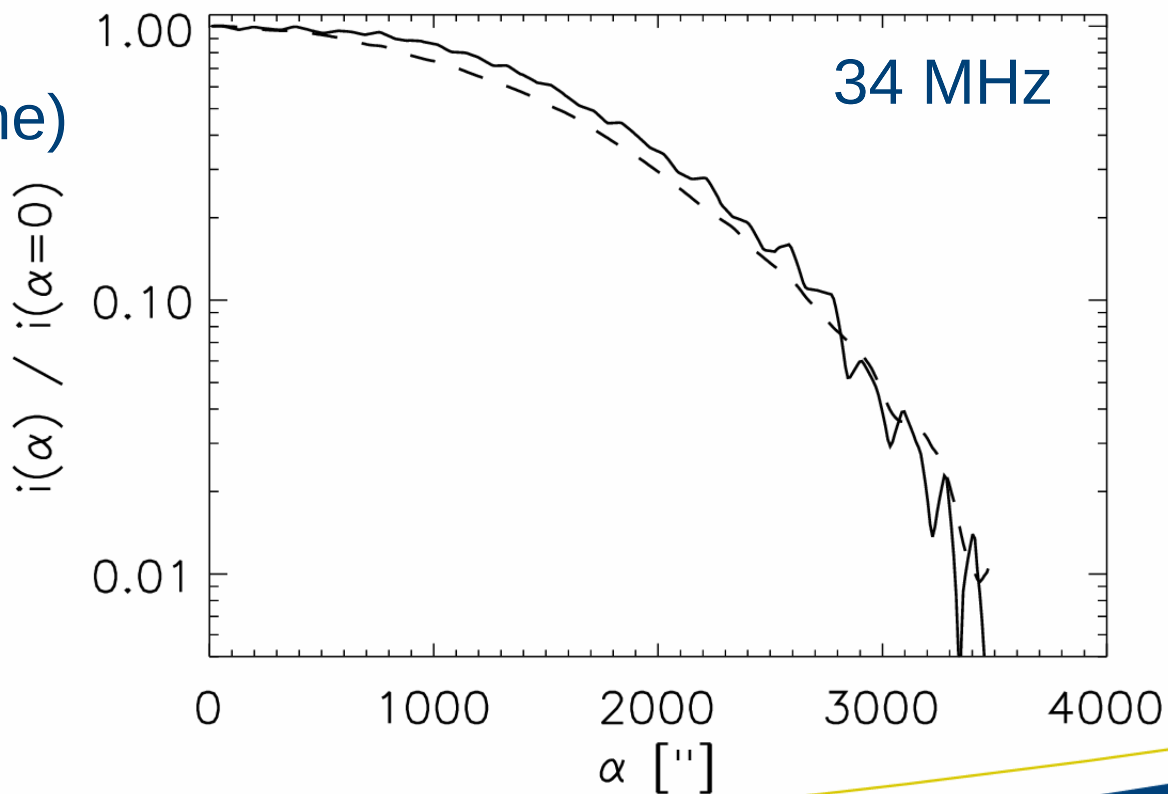
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

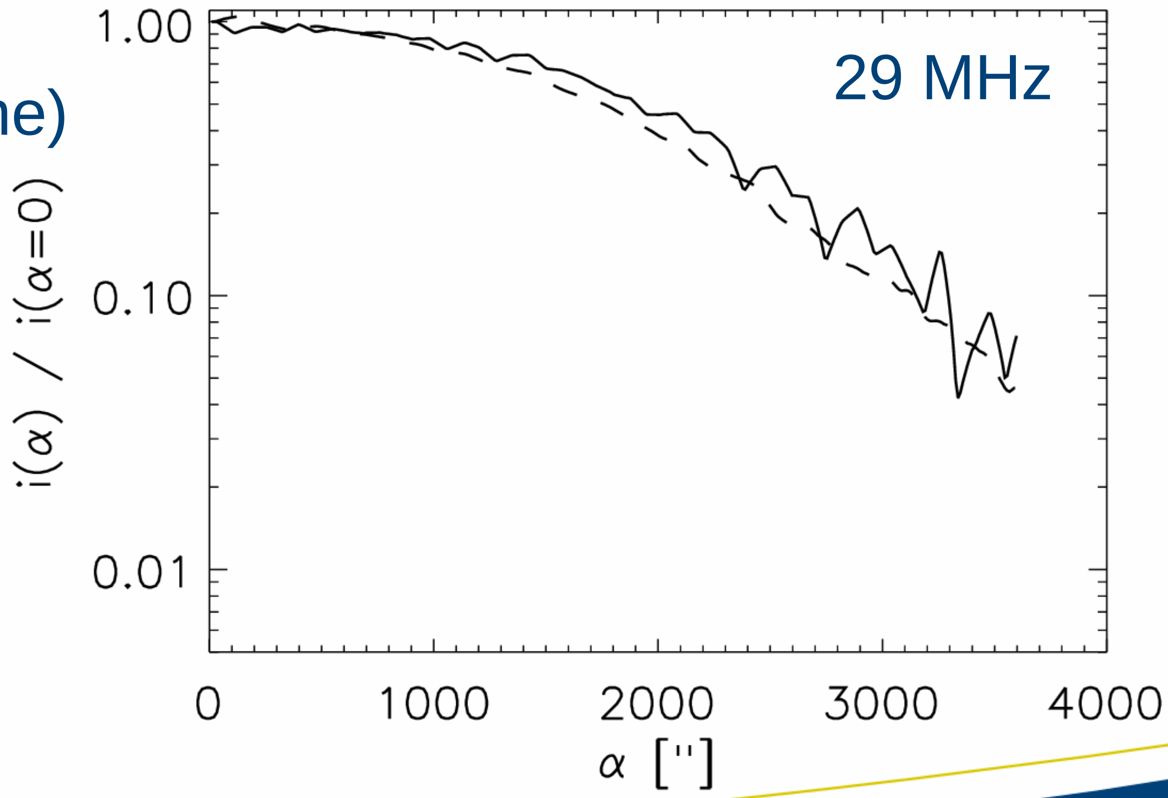
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

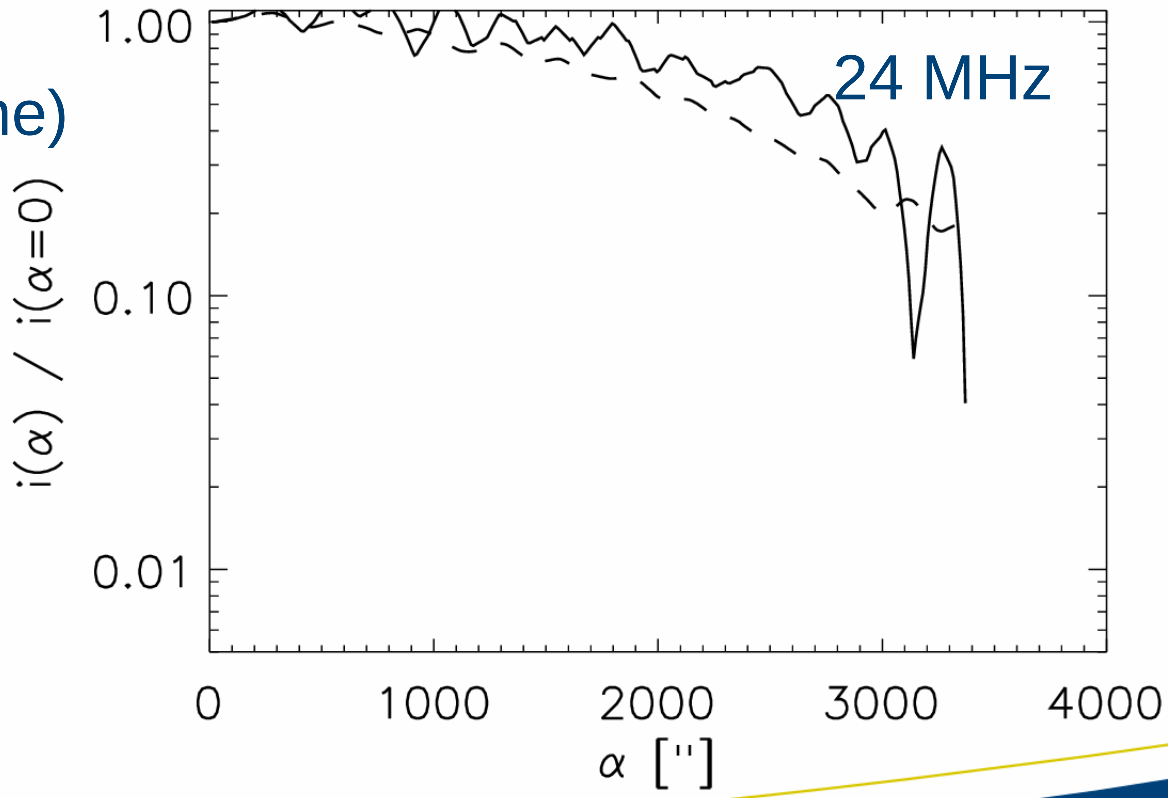
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



Observed intensity profiles

Profiles:

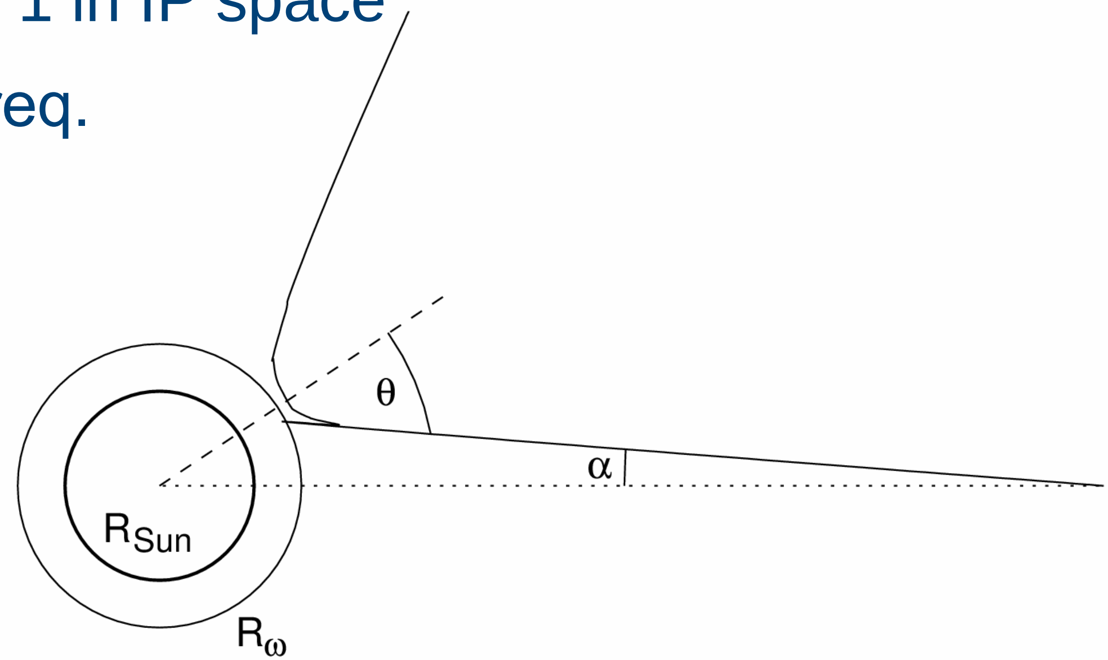
- Averages over azimuth
- Polar (solid line) and equatorial (dashed line) regions
- Normalized to image center



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

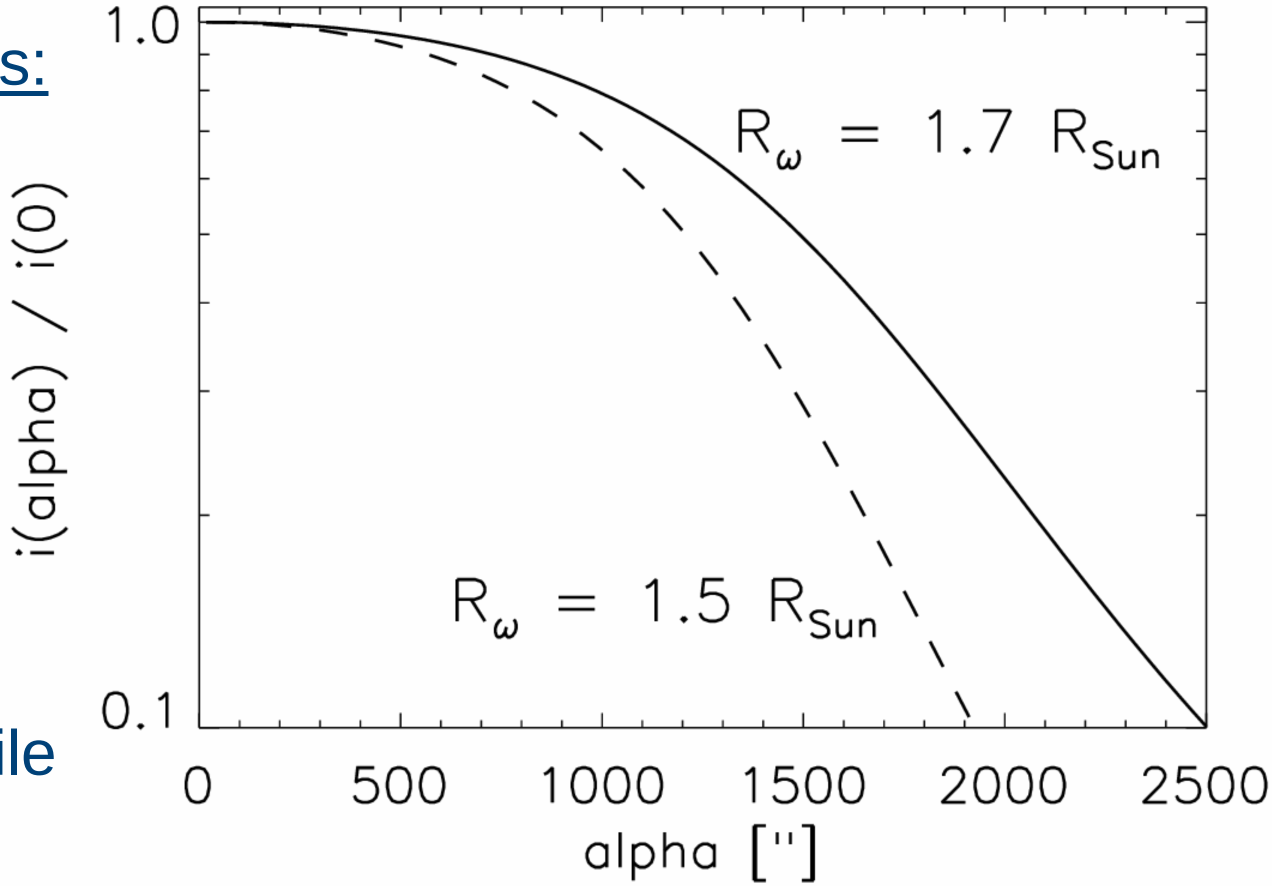
Model parameters: R_ω and coronal temperature, T

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

R_ω – dependence of sim. results

Model parameters:

- T = 1.4 MK



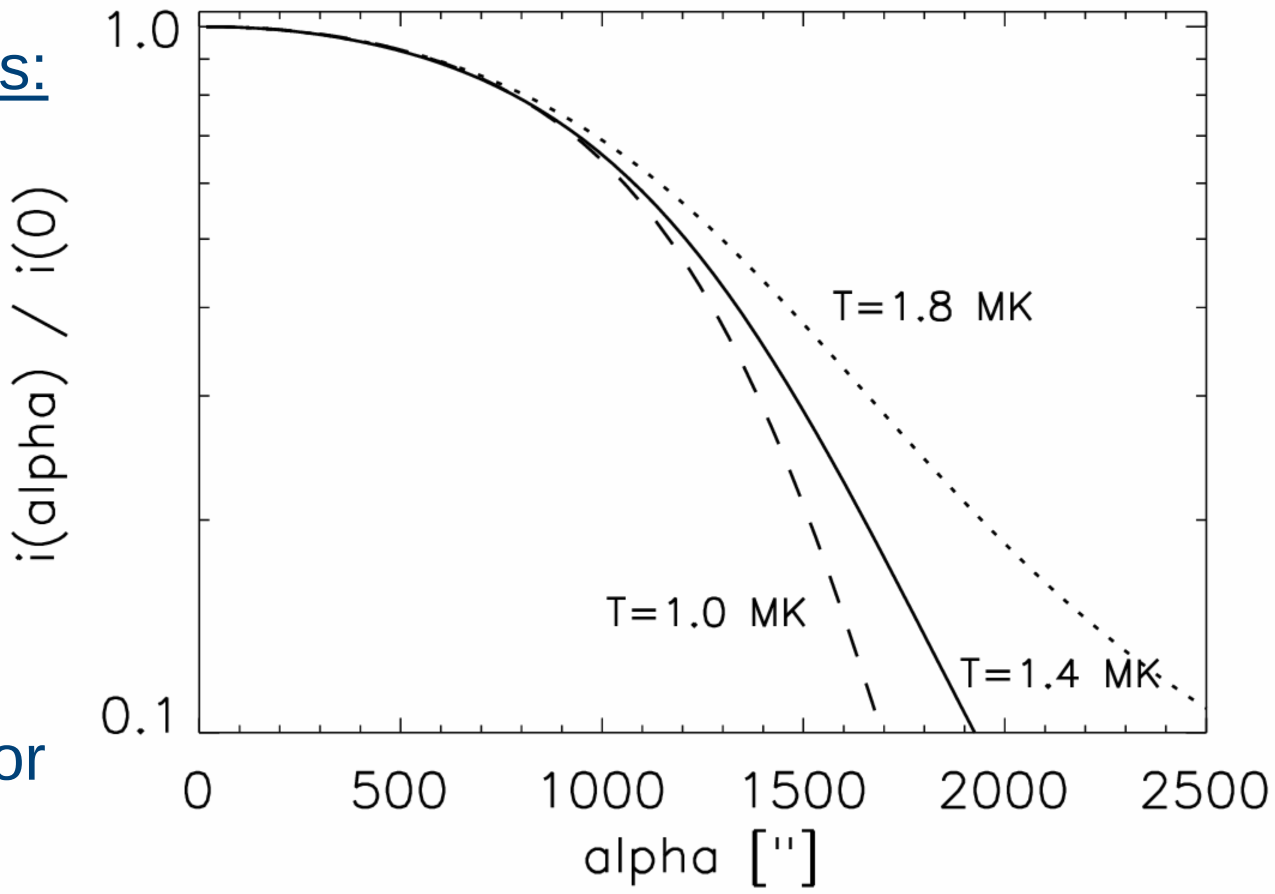
Result:

- The whole profile scales with R_ω

T – dependence of sim. results

Model parameters:

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



Result:

- Variation only for higher α

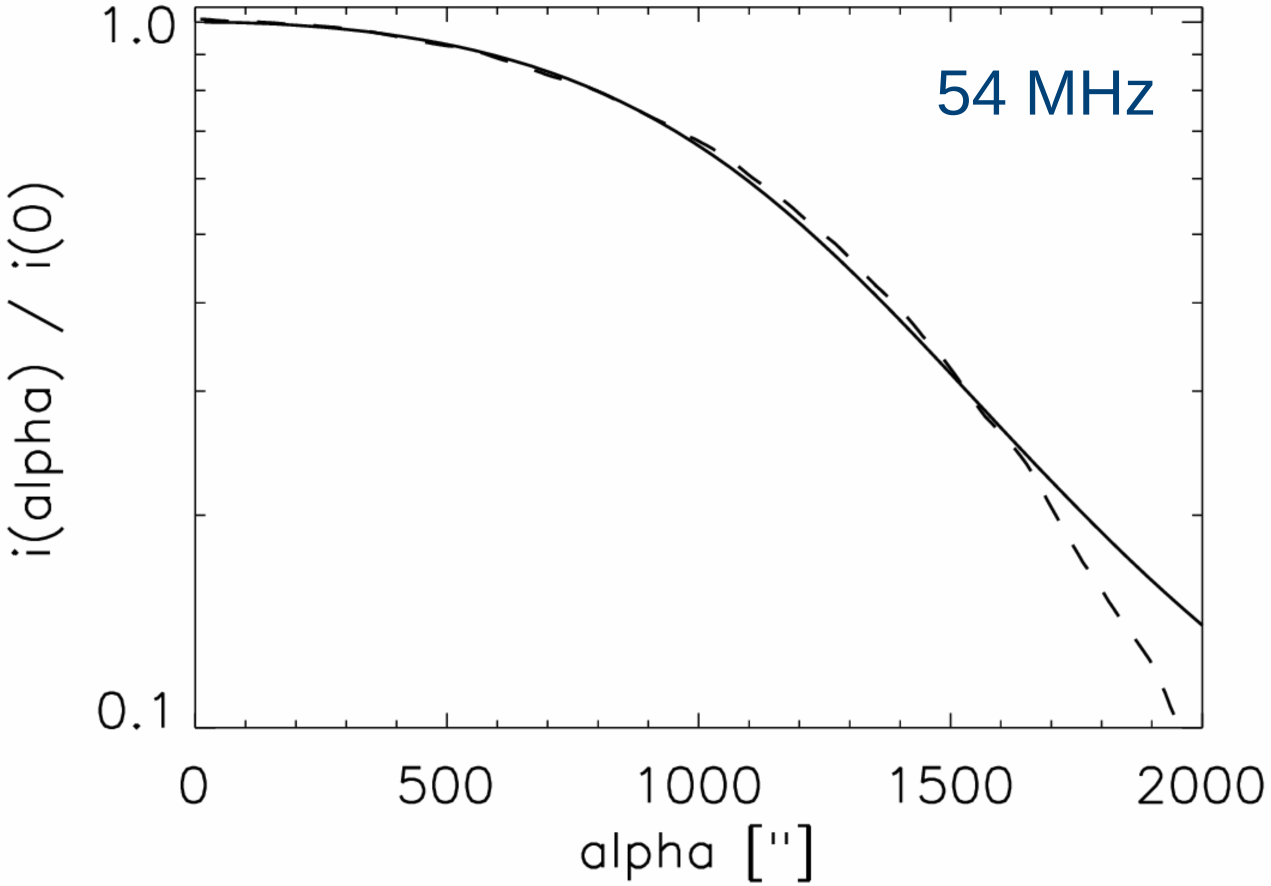
Fit simulations to observations

Observation:

- Polar profile
- Dashed line

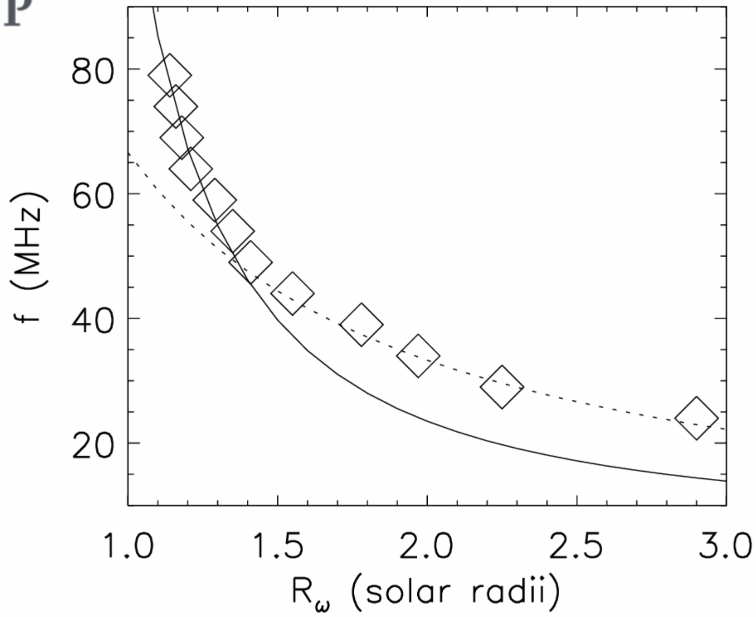
Simulation:

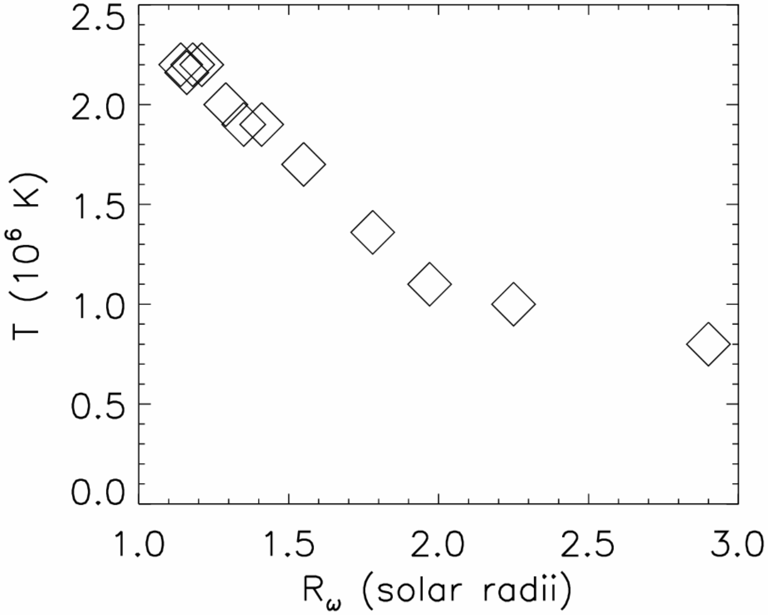
- $R_\omega = 1.35\ R_{Sun}$
- T = 1.9 MK
- Solid line



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:

- Improve uv coverage by aperture synthesis
- Example: 8 August 2013, 3 h observation time

Analysis of solar images:

- Refraction is important in the corona
- Observed intensity profiles can be fitted to ray-tracing simulations
- LOFAR observations provide coronal density and temperature profiles