Leibniz-Institut für Astrophysik Potsdam

AIP

LOFAR observations of the quiet Sun

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und Forschung

LOw Frequency ARray

Solar KSP

LOFAR

LOFAR structure:

- Central core (Exloo, NL)
  24 stations
- 14 remote Stations (NL)
- 9 (+4) International Stations

Frequency range:

- Low Band: 10 – 90 MHz
- High Band: 110 – 250 MHz

New setup: Software telescope

LOFAR: Simple antennae, LBA

Low Band antennae:

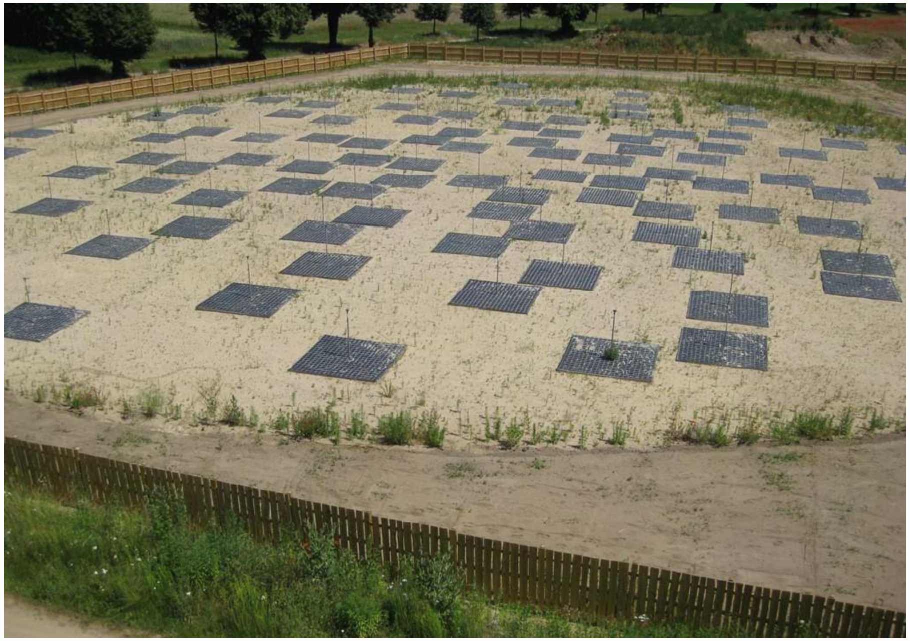
- Low frequencies: 30 – 80 MHz
- Simple dipoles
- 2 polarizations

LOFAR: Simple antennae, HBA

<u>High Band antennae:</u>

- High frequencies:
  120 – 240 MHz
- 16 dipole together
- 2 polarizations
- In Styrofoam block, covered with foil

Antenna fields: Potsdam-Bornim



Completion of fields: LBA: December 2009
HBA: May 2010

Data processing: Station level

<u>Station container:</u>

- Antennae signals are combined
- Digitized
- Frequency channels
- Combined to “station beam”
- Reduction of data rate to 4 Gbit/s

Data are send to central correlator in Groningen

Data processing: Groningen

<u>Central correlator:</u>

- “Cobalt” GPU cluster
- Data from all stations
- Interferometer
- Real-time processing
- Radio maps of the sky
- Further processing
- Long-term Archive

Enormous versatility and flexibility

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

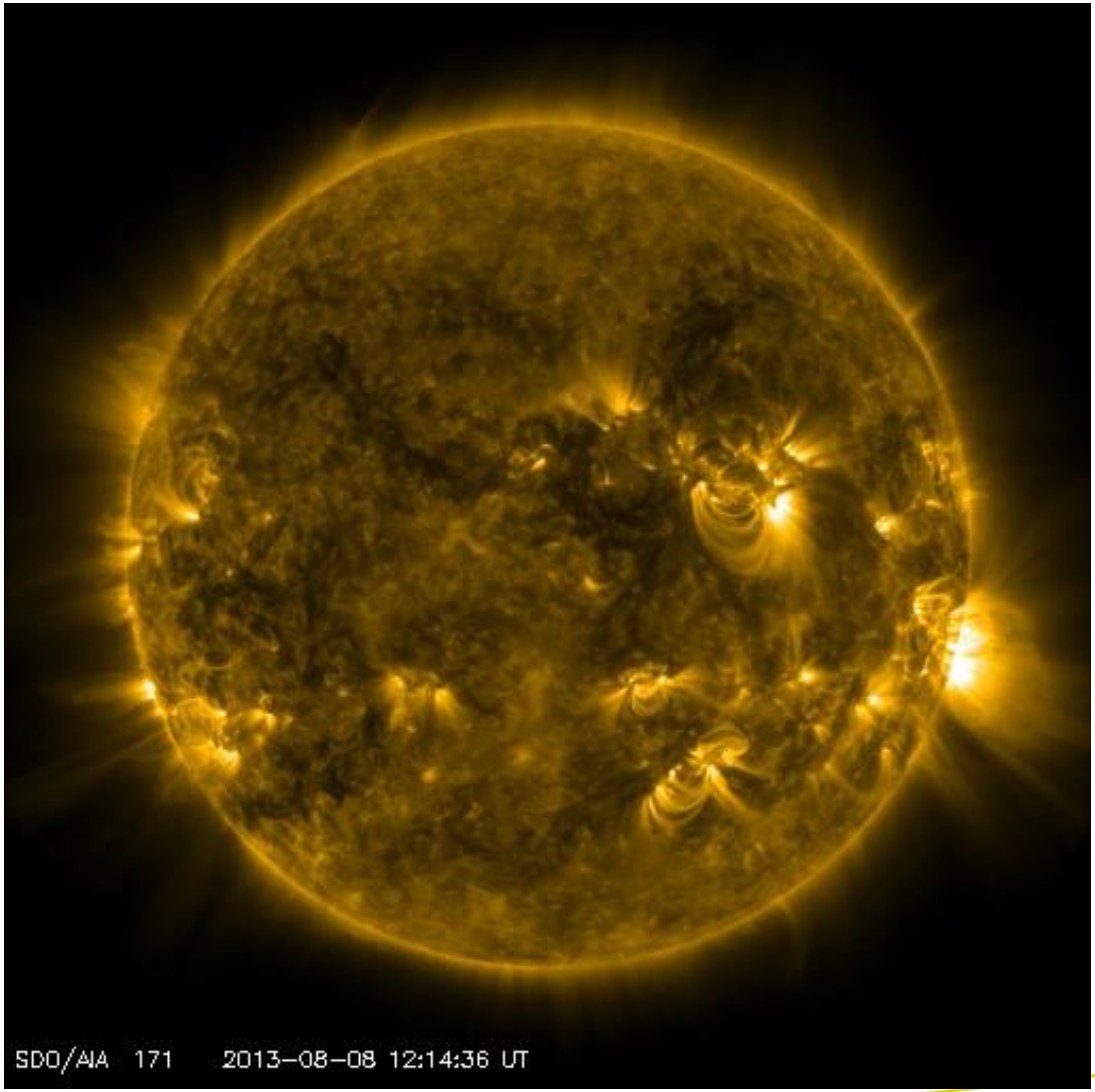
Quiet Sun:

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

→ Aperture synthesis imaging

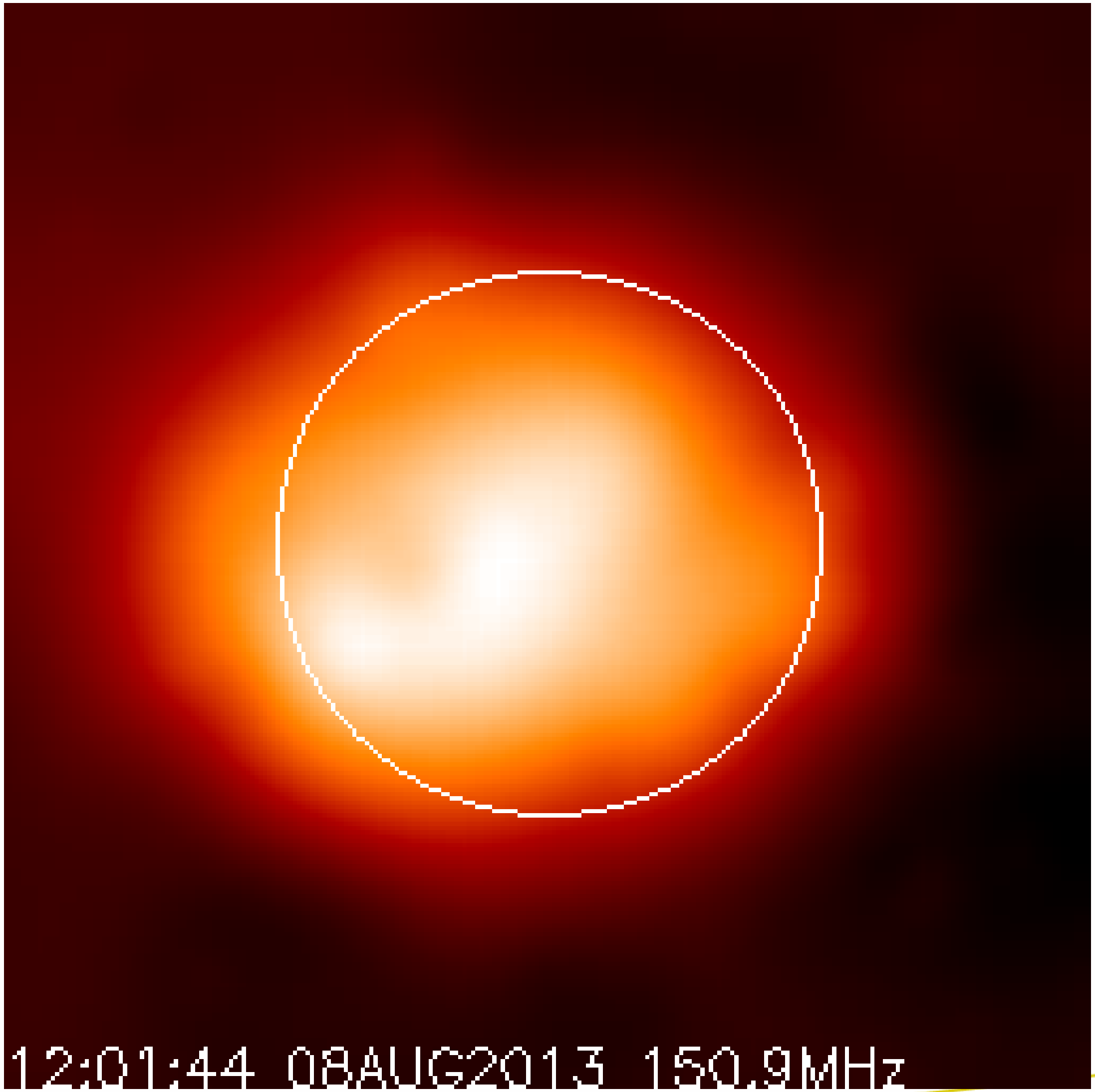
The Sun on 08 August 2013

SDO:



The Sun on 08 August 2013

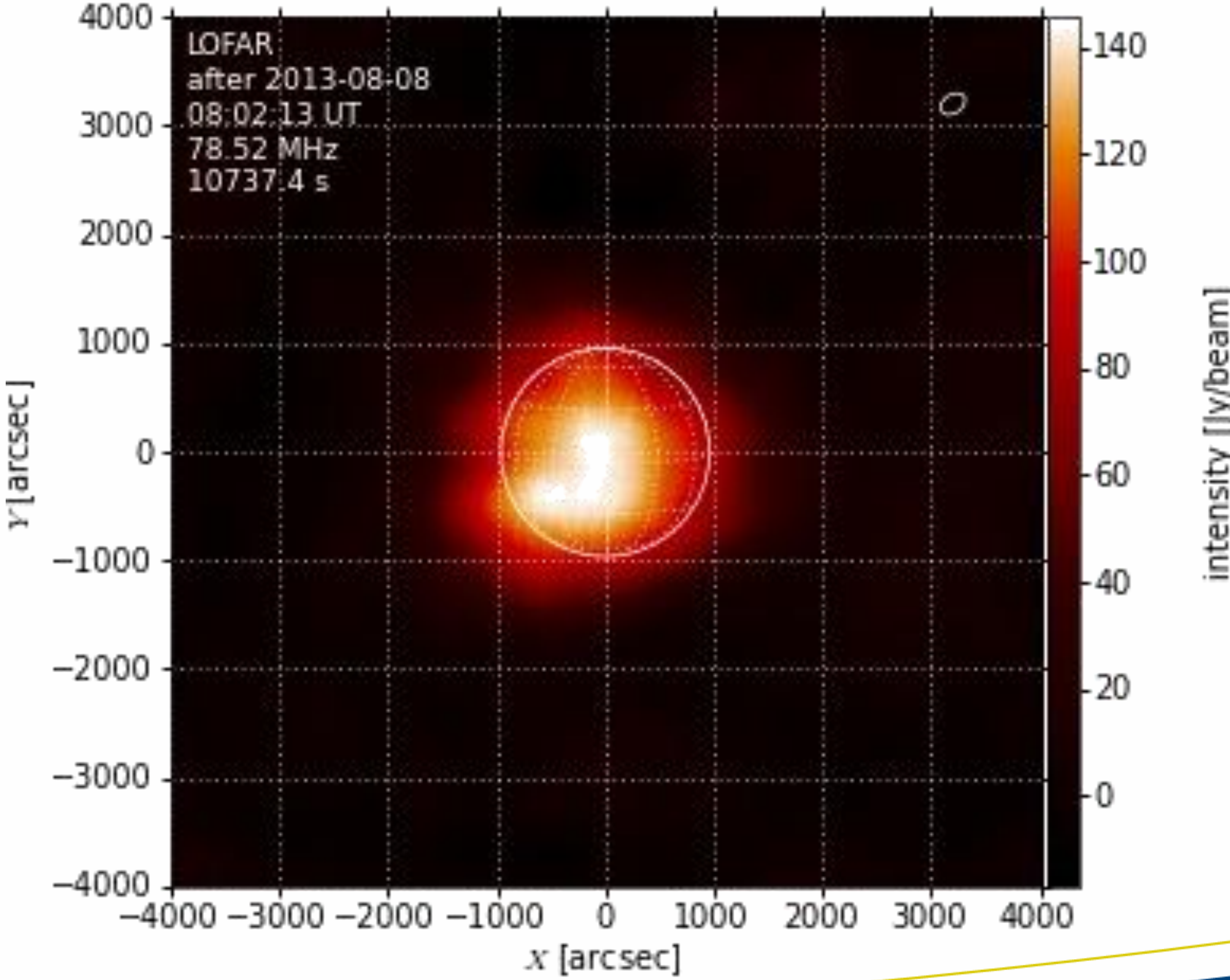
NRH:



Solar corona

Image:

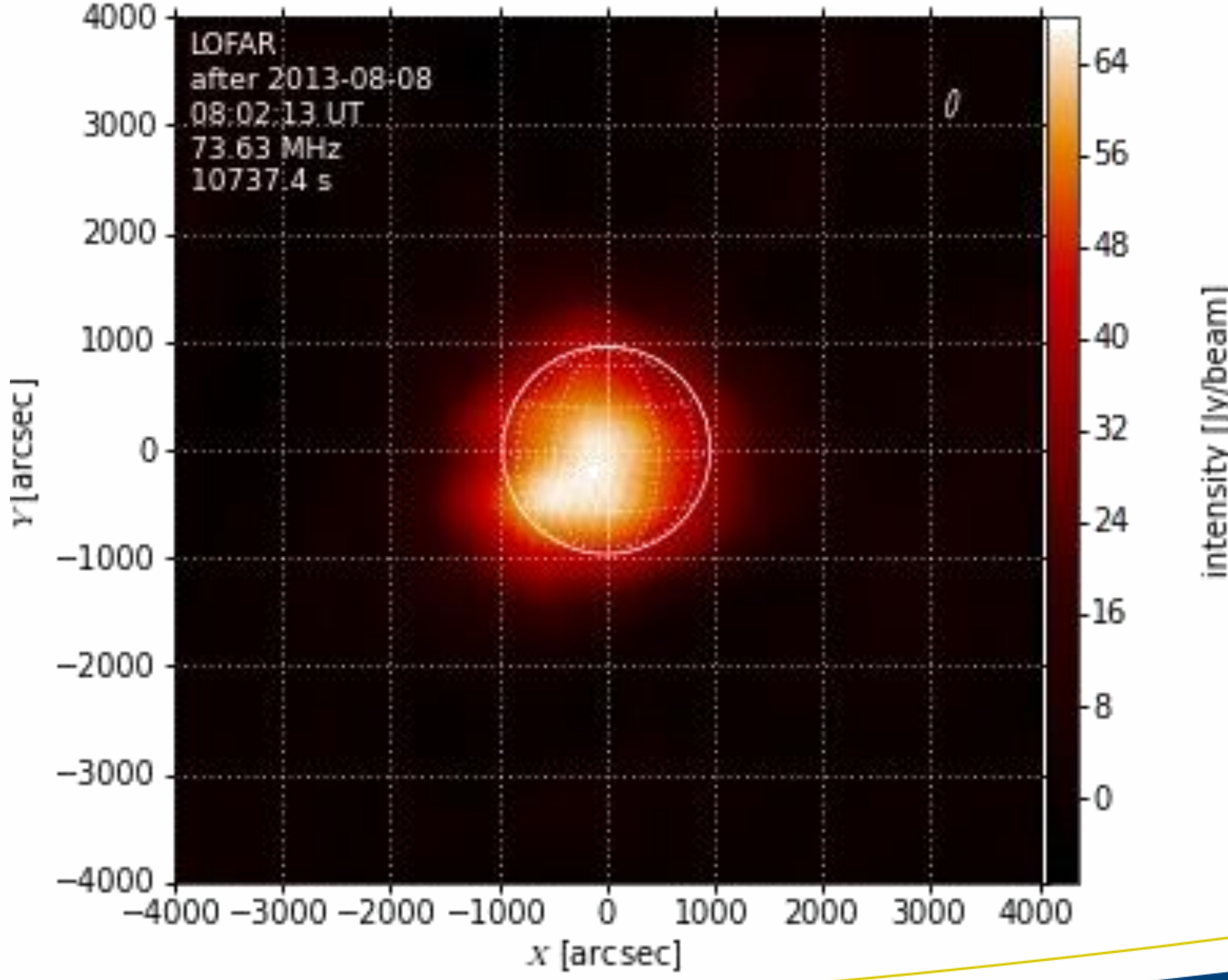
- 79 MHz
- 3 h



Solar corona

Image:

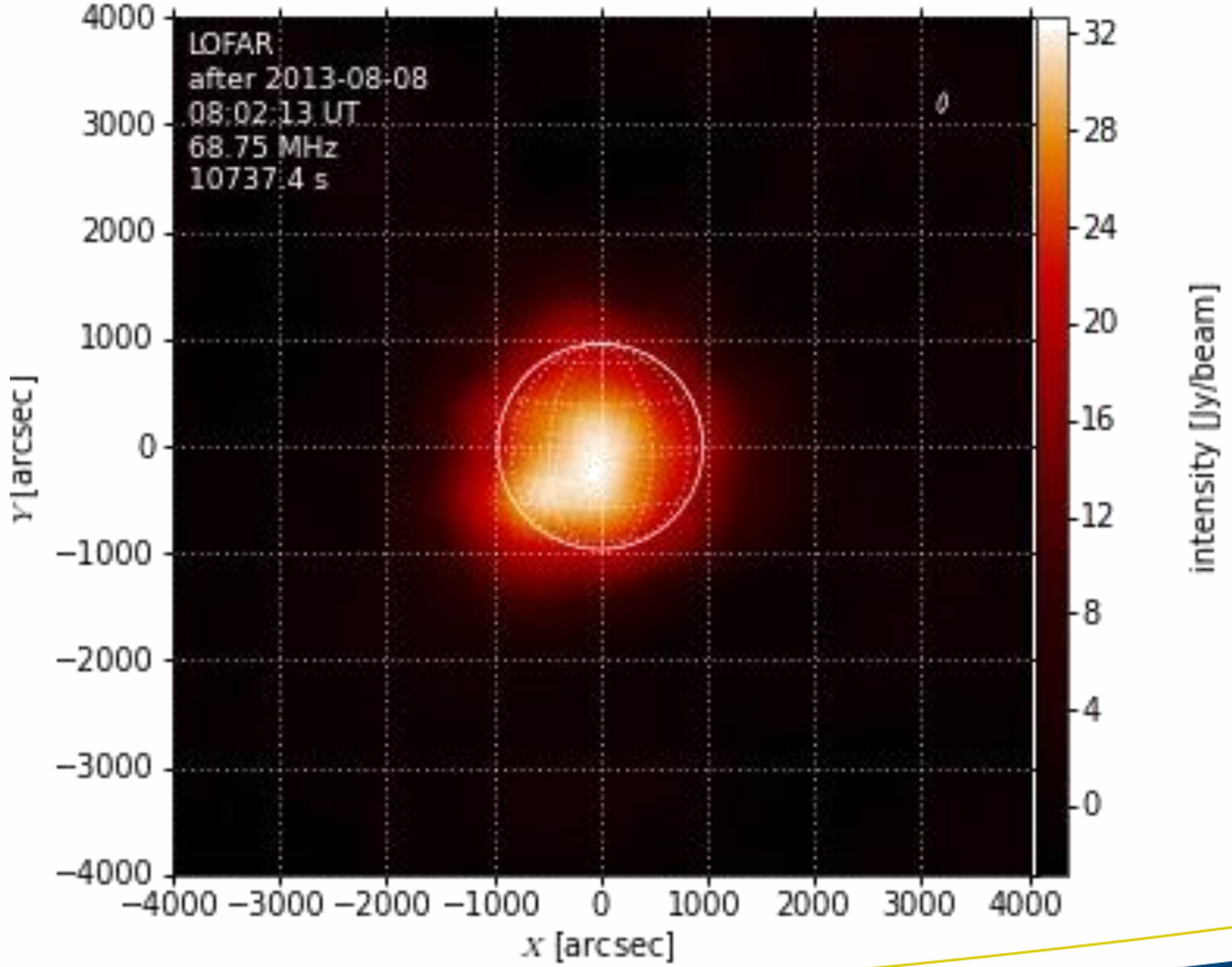
- 74 MHz
- 3 h



Solar corona

Image:

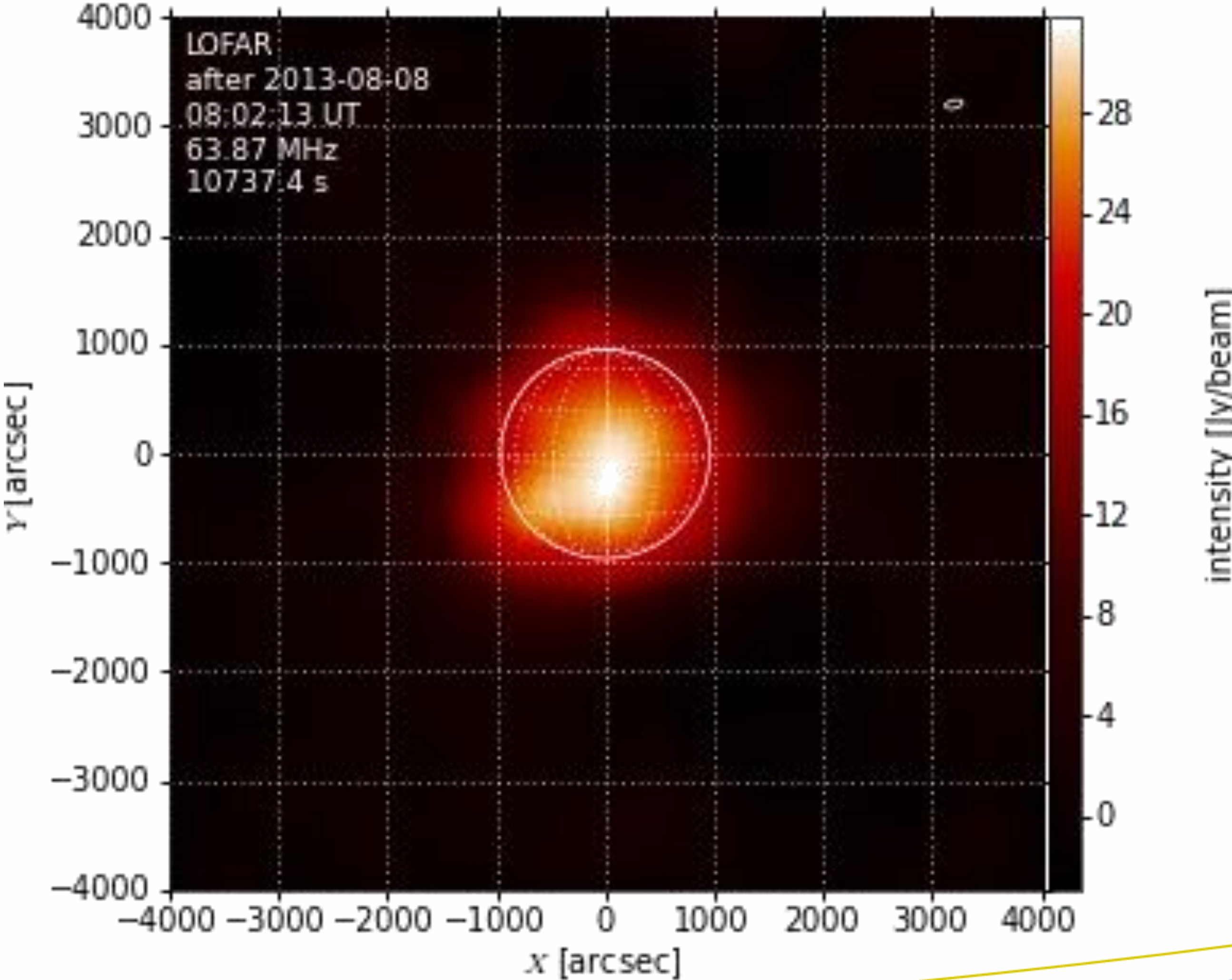
- 69 MHz
- 3 h



Solar corona

Image:

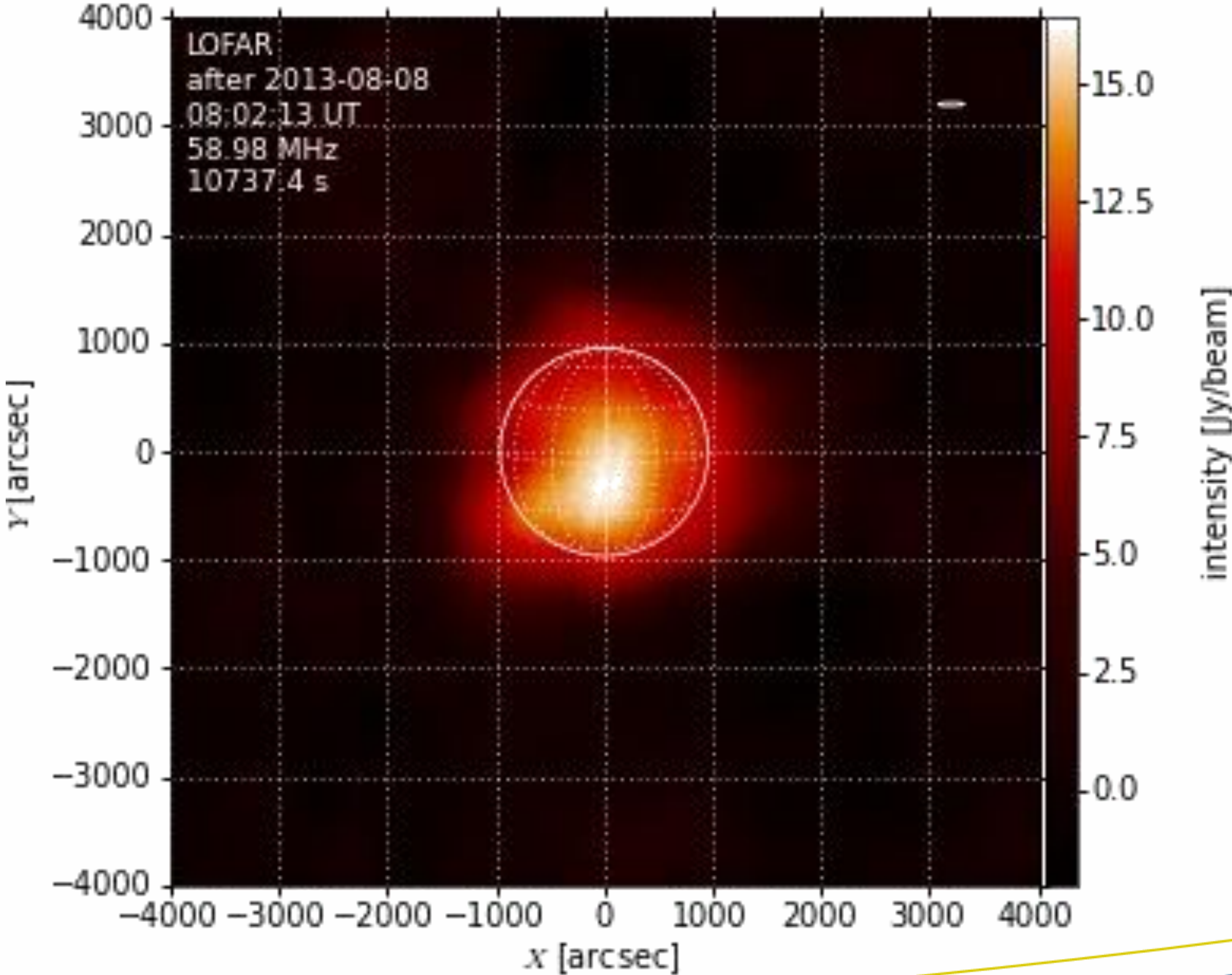
- 64 MHz
- 3 h



Solar corona

Image:

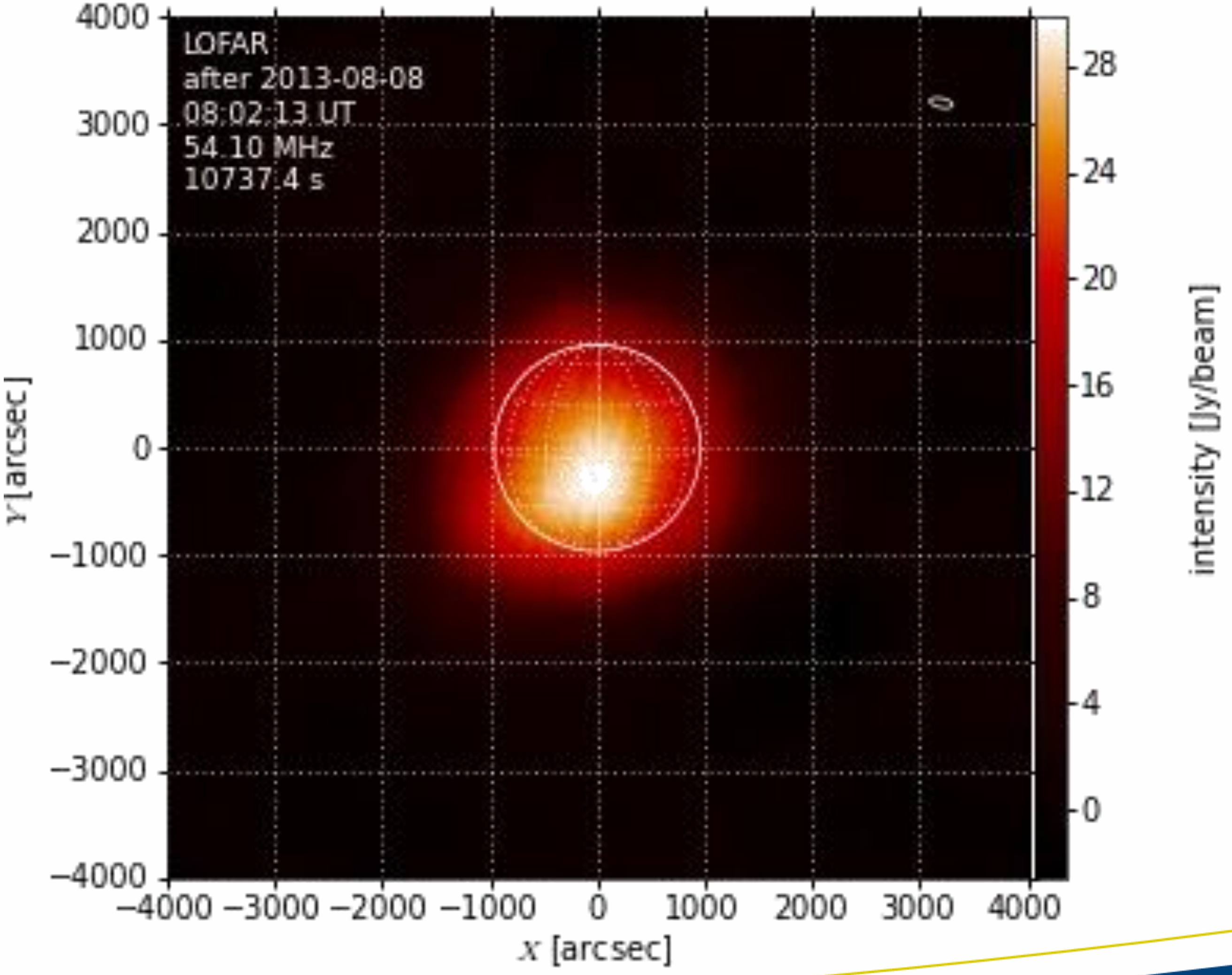
- 59 MHz
- 3 h



Solar corona

Image:

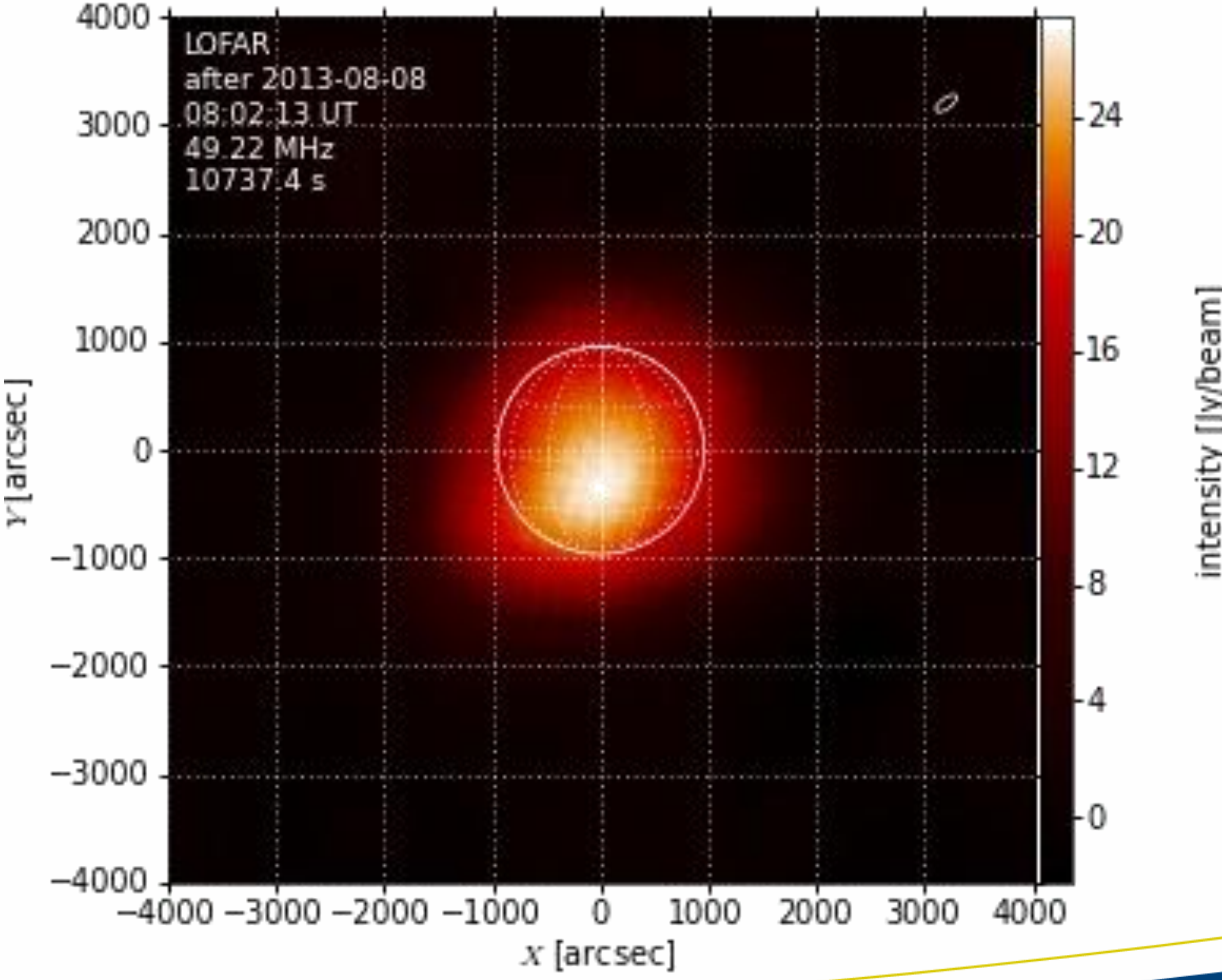
- 54 MHz
- 3 h



Solar corona

Image:

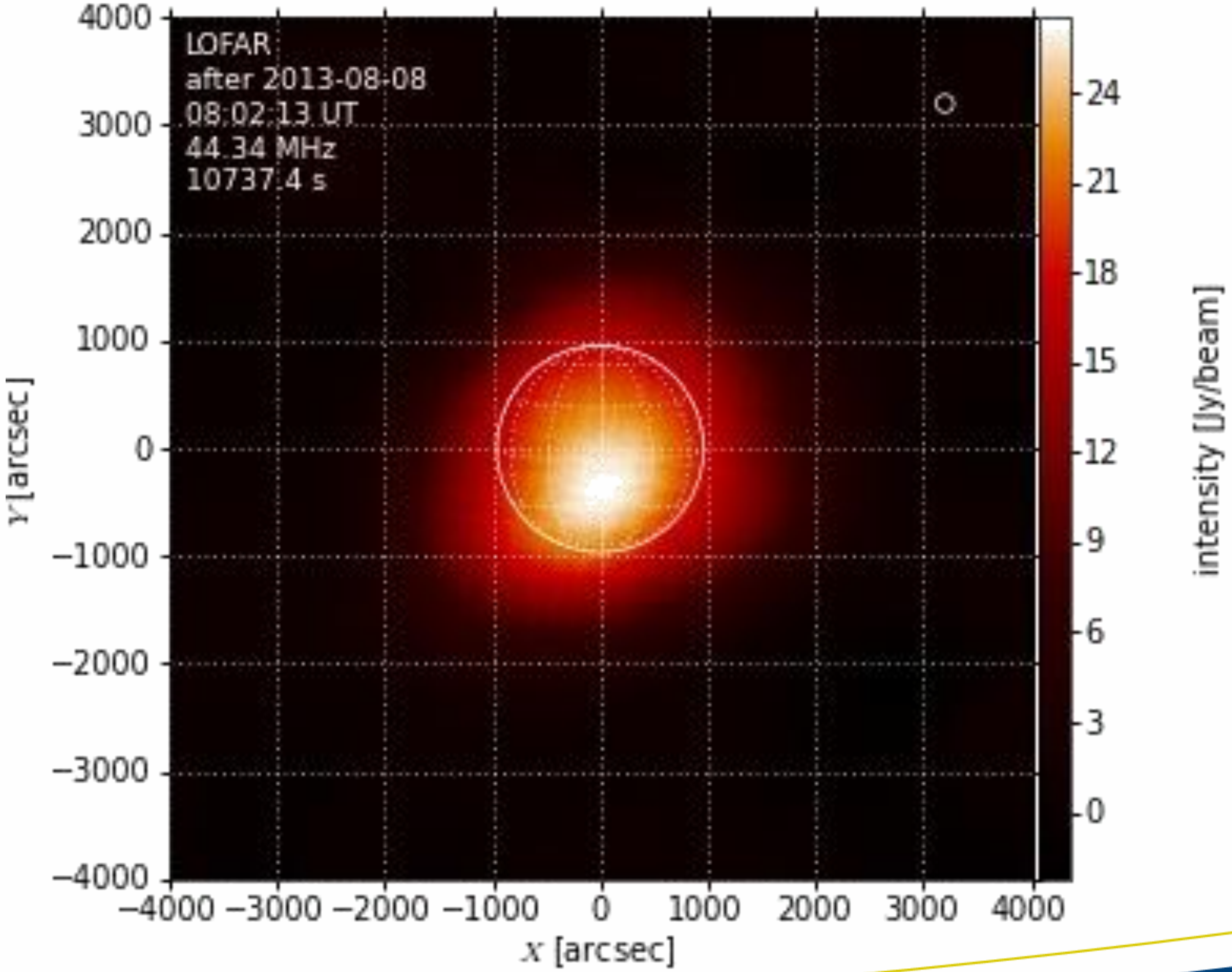
- 49 MHz
- 3 h



Solar corona

<u>Image:</u>

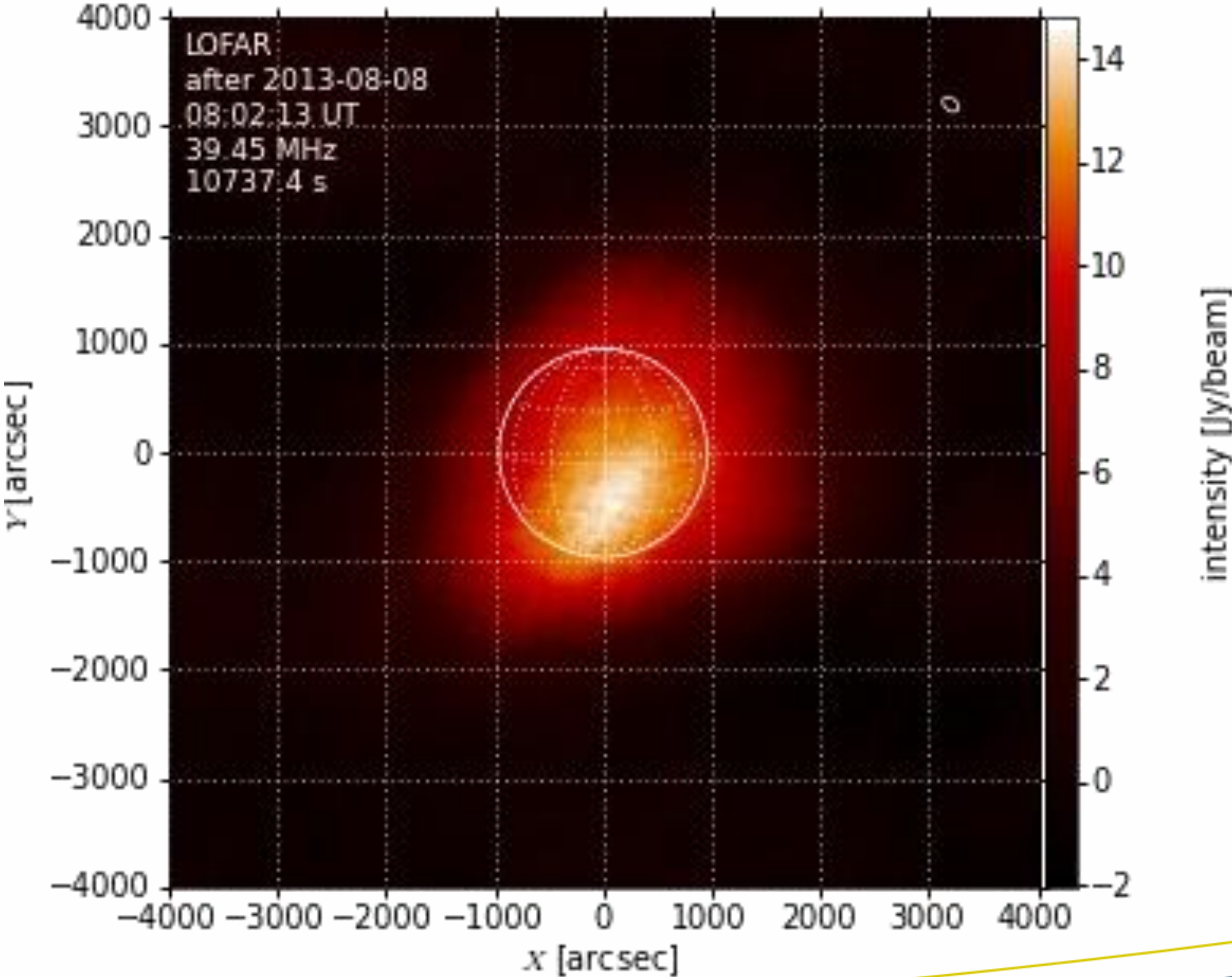
- 44 MHz
- 3 h



Solar corona

Image:

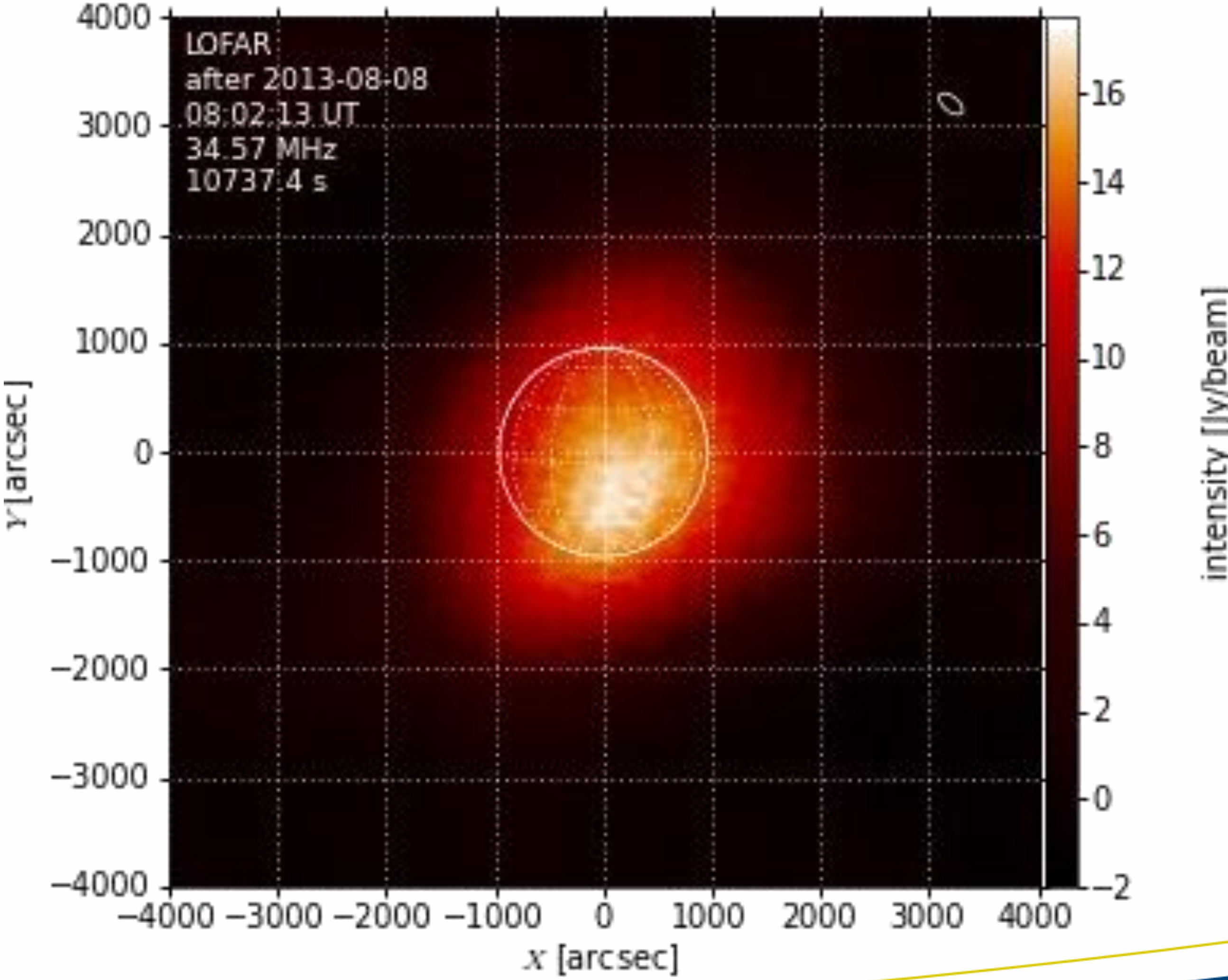
- 39 MHz
- 3 h



Solar corona

Image:

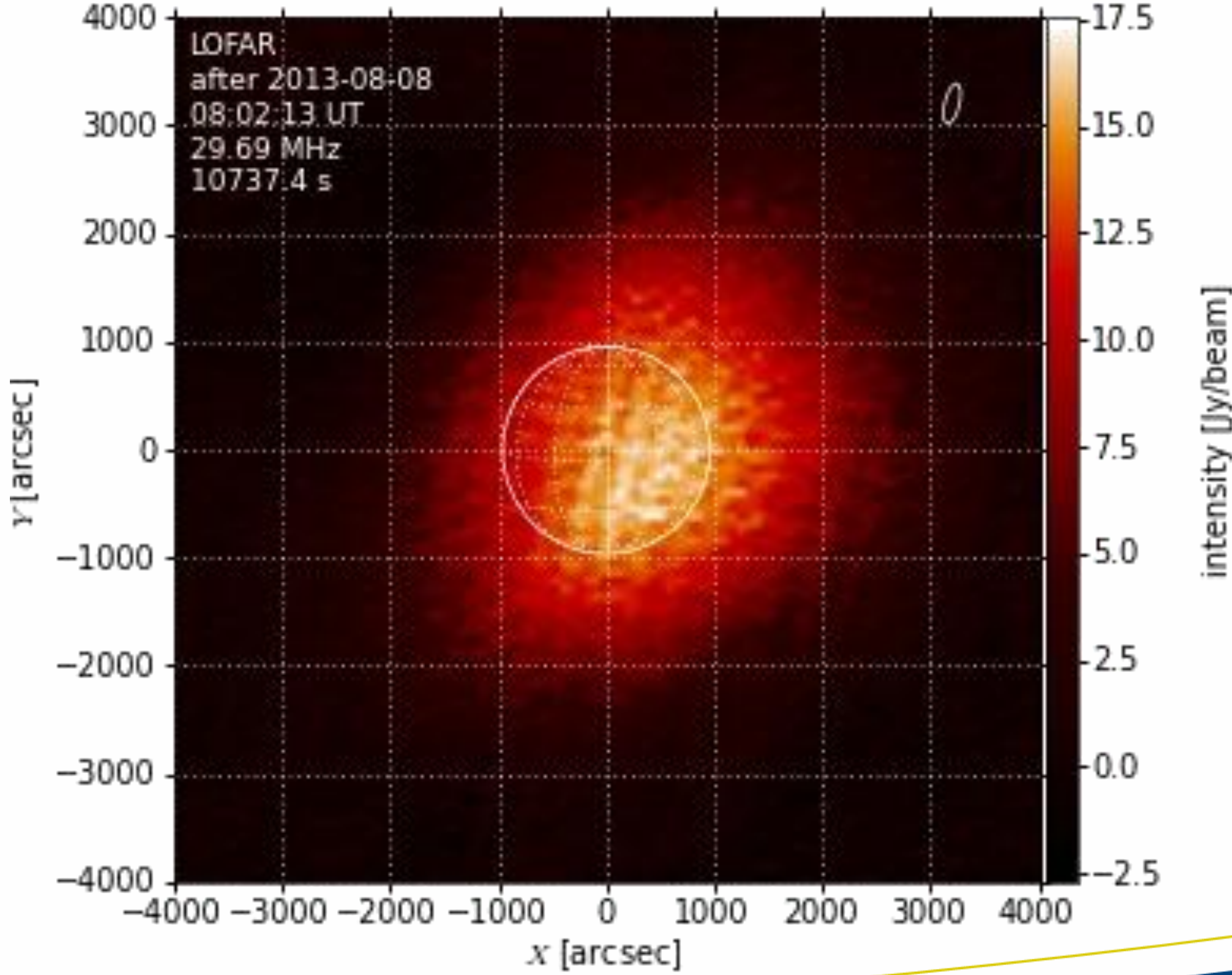
- 34 MHz
- 3 h



Solar corona

Image:

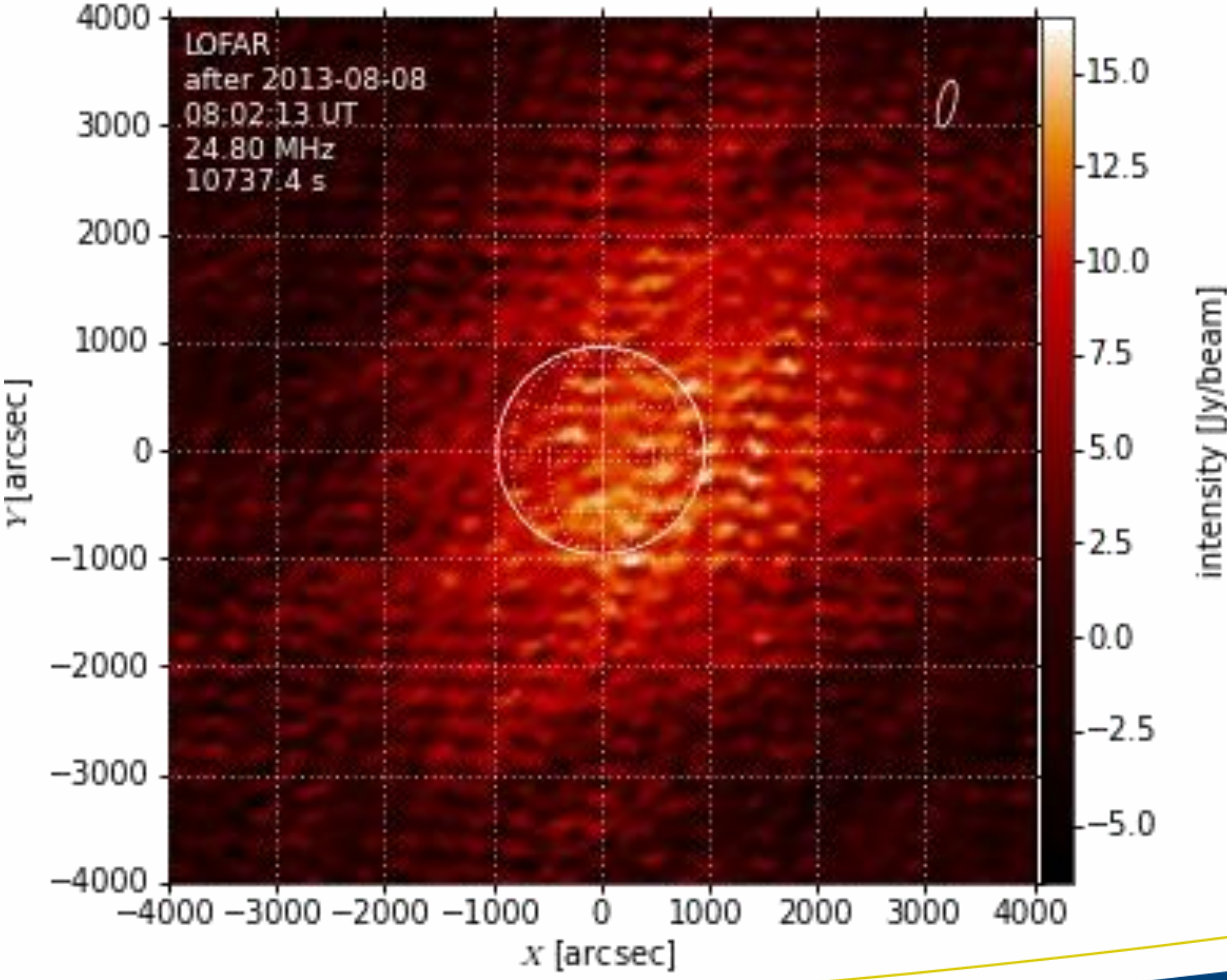
- 29 MHz
- 3 h



Solar corona

Image:

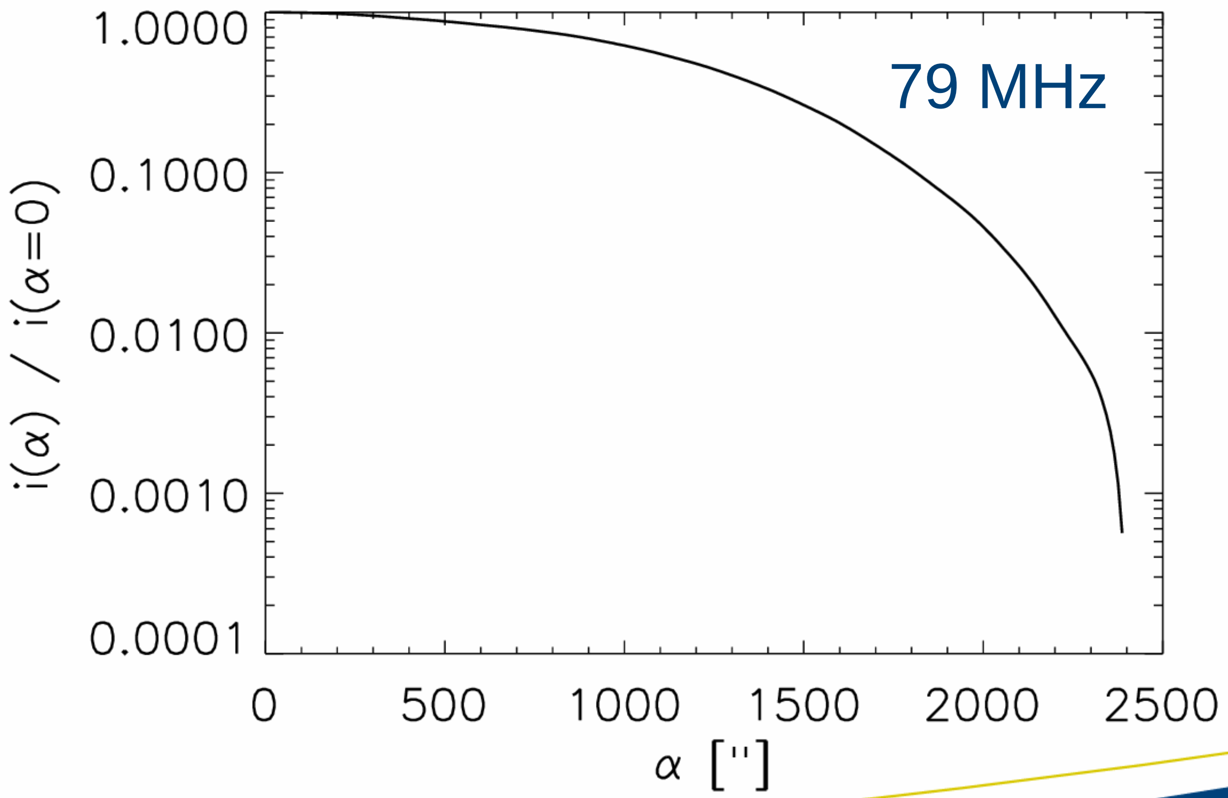
- 24 MHz
- 3 h



Observed intensity profiles

Profiles:

- Average over azimuth
- Normalized to image center



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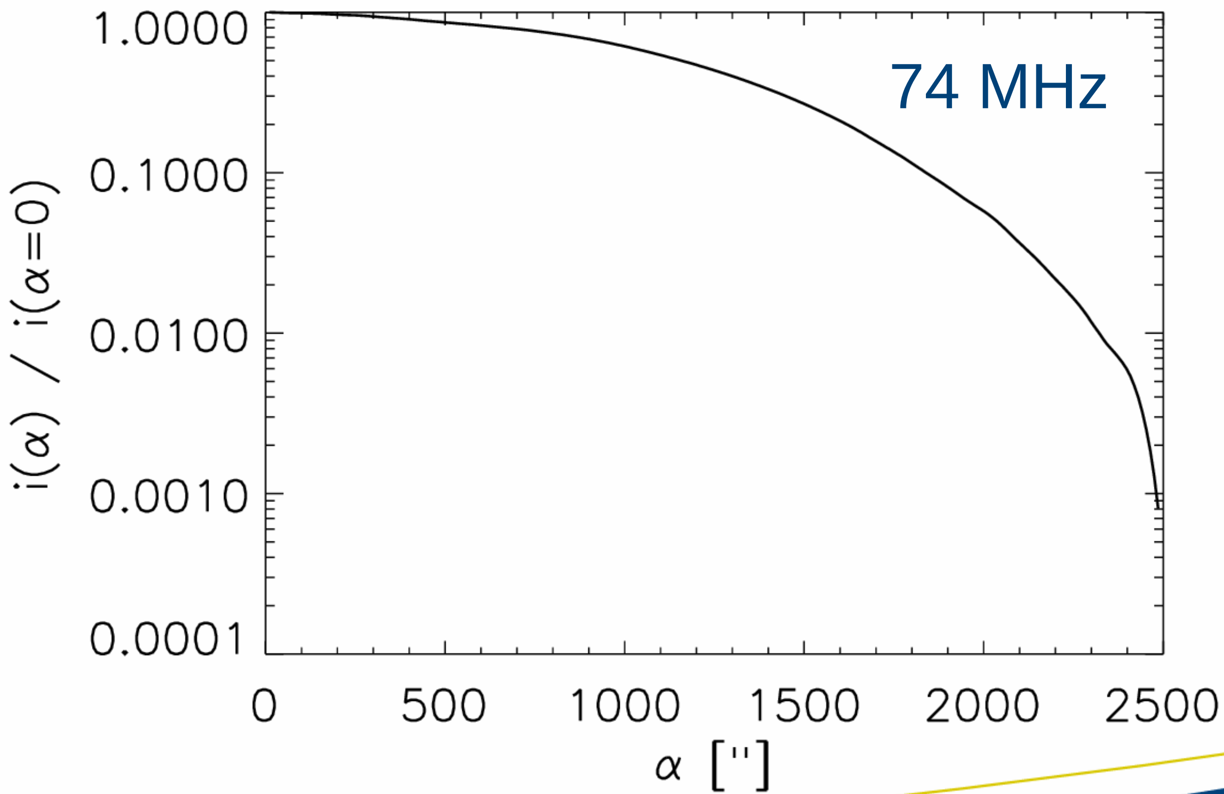

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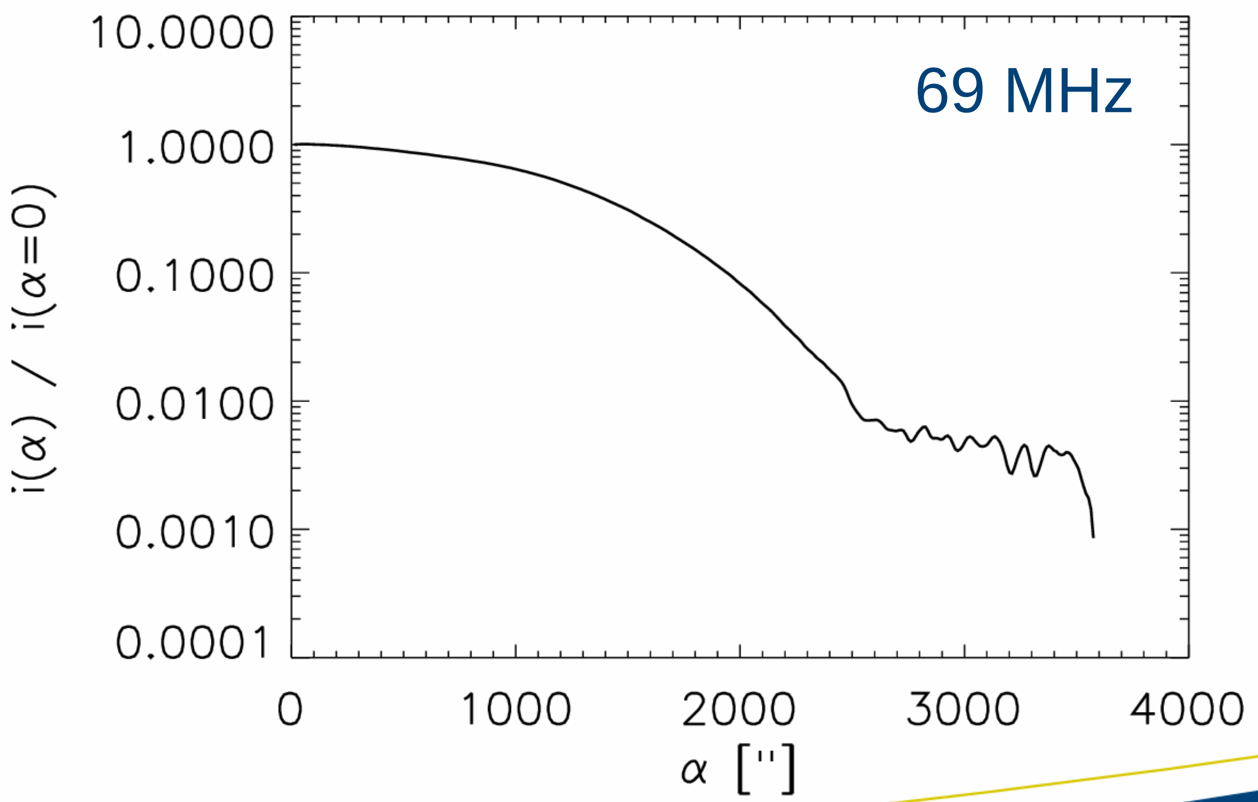

Observed intensity profiles

Profiles:

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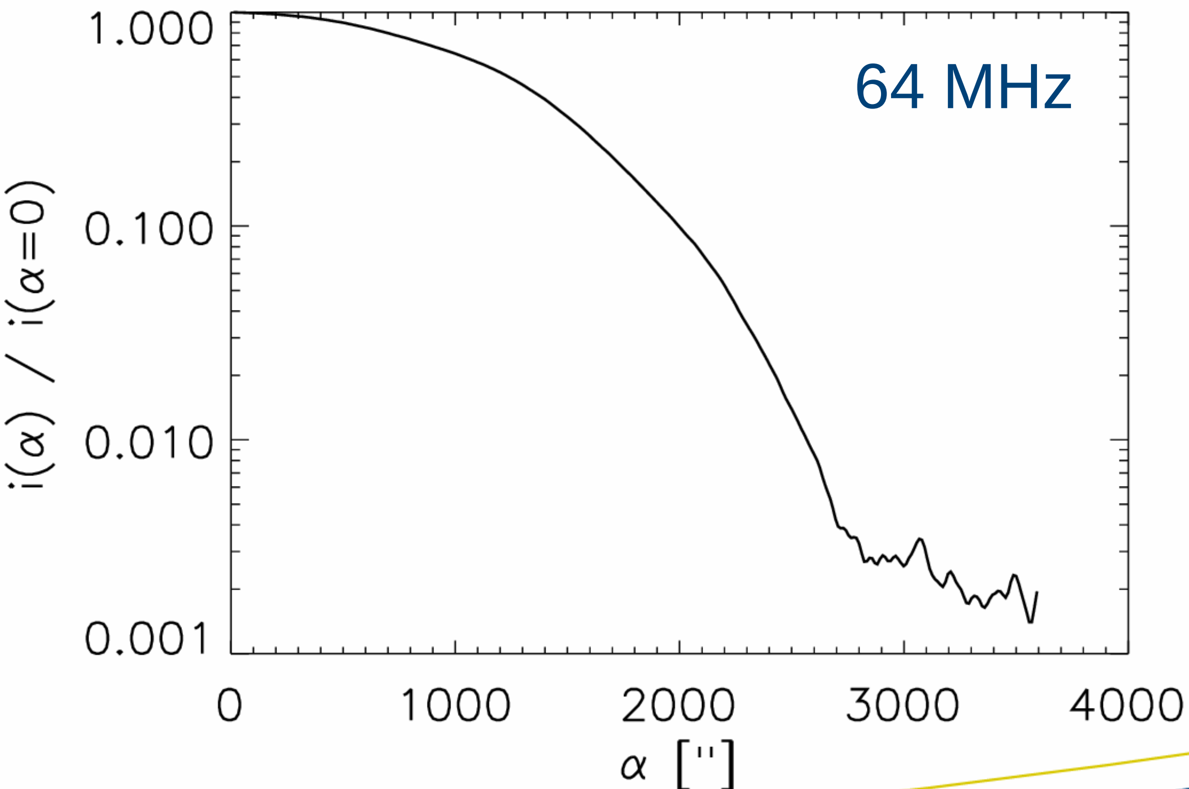
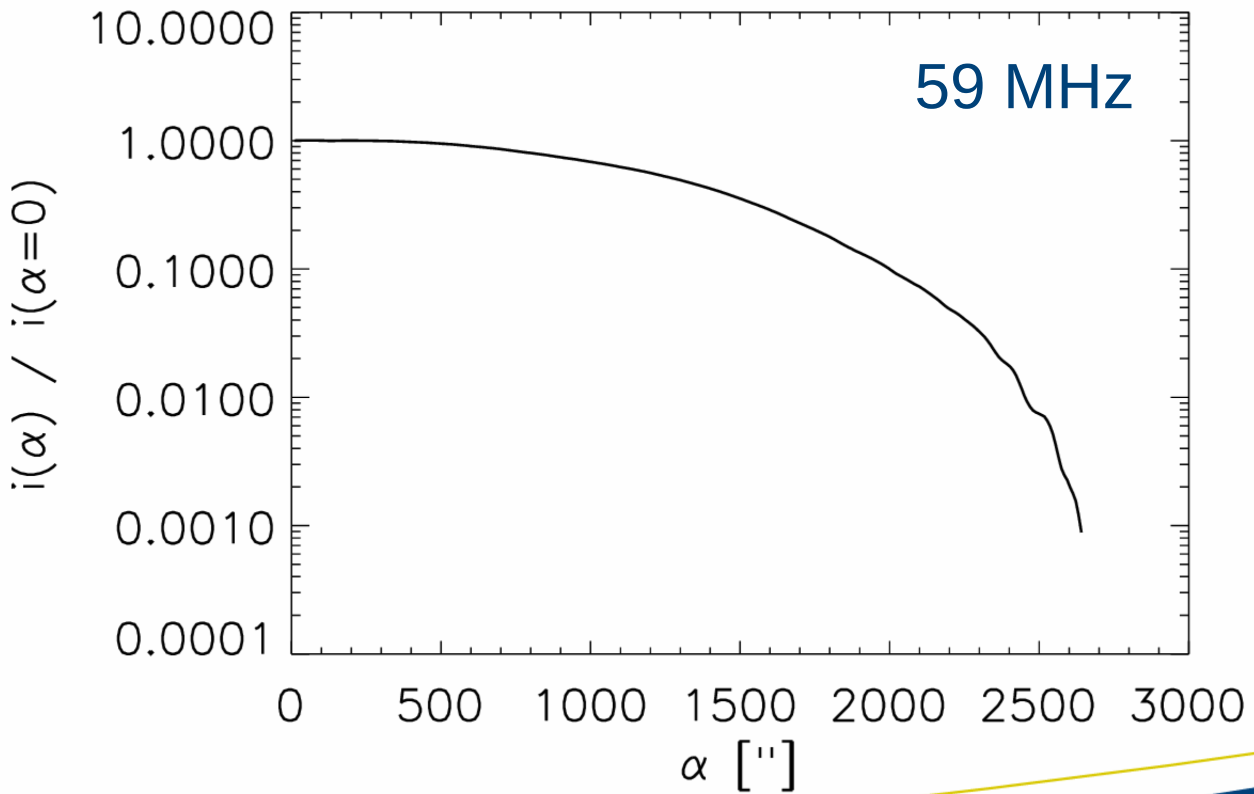
- Normalized to image center



Observed intensity profiles

Profiles:

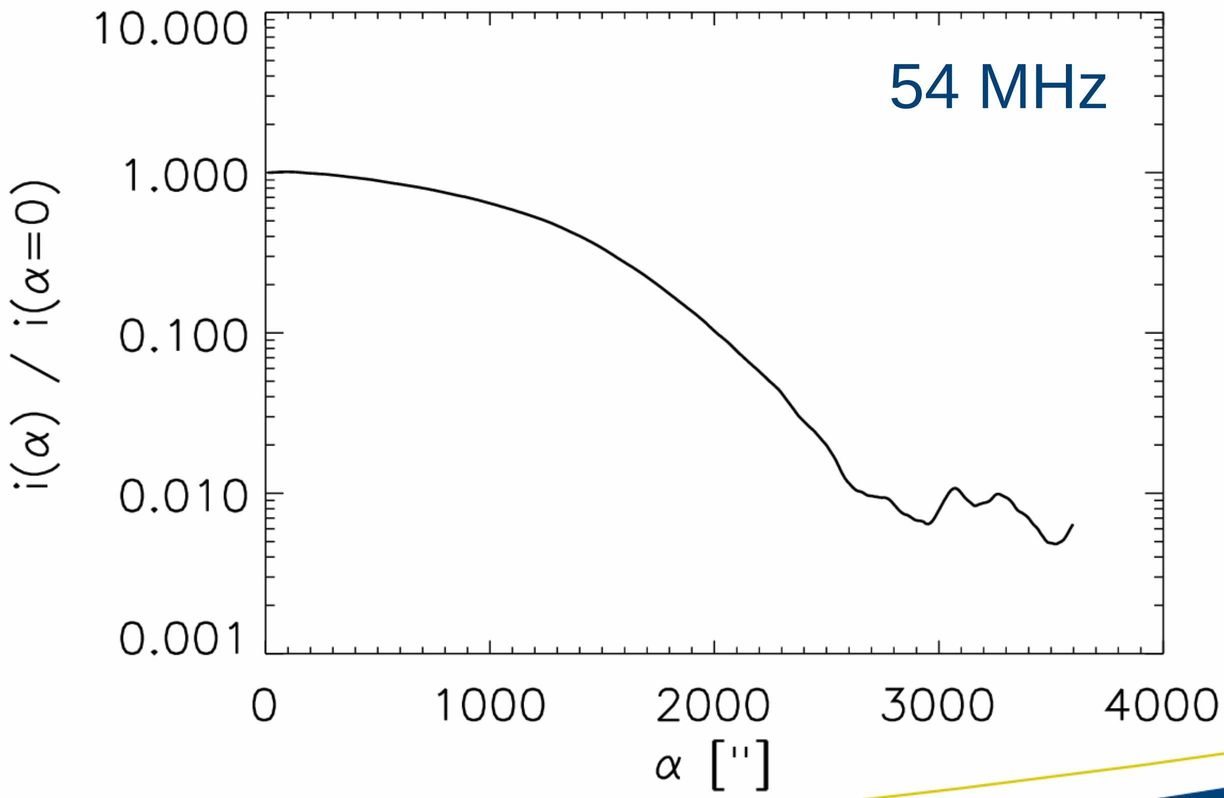
- Average over azimuth
- Normalized to image center



Observed intensity profiles

Profiles:

- Average over azimuth
- Normalized to image center

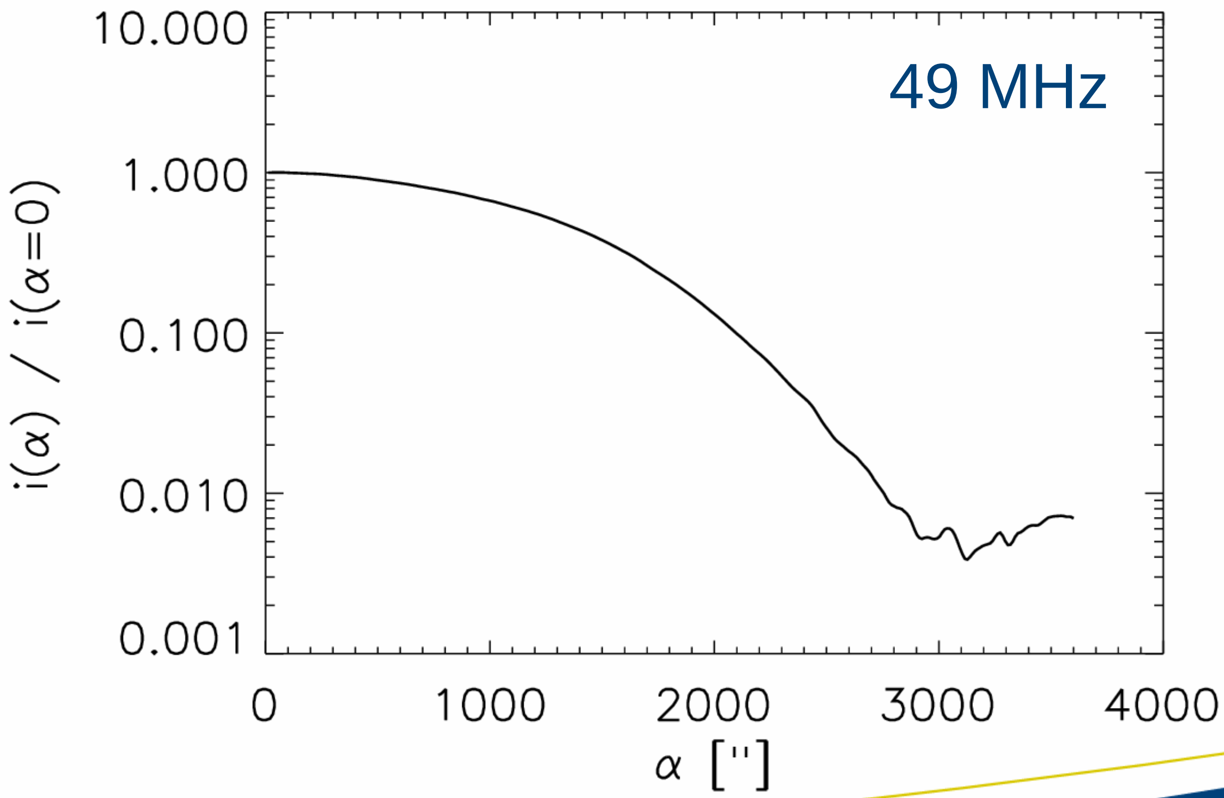


Observed intensity profiles

Solar KSP LOFAR

Profiles:

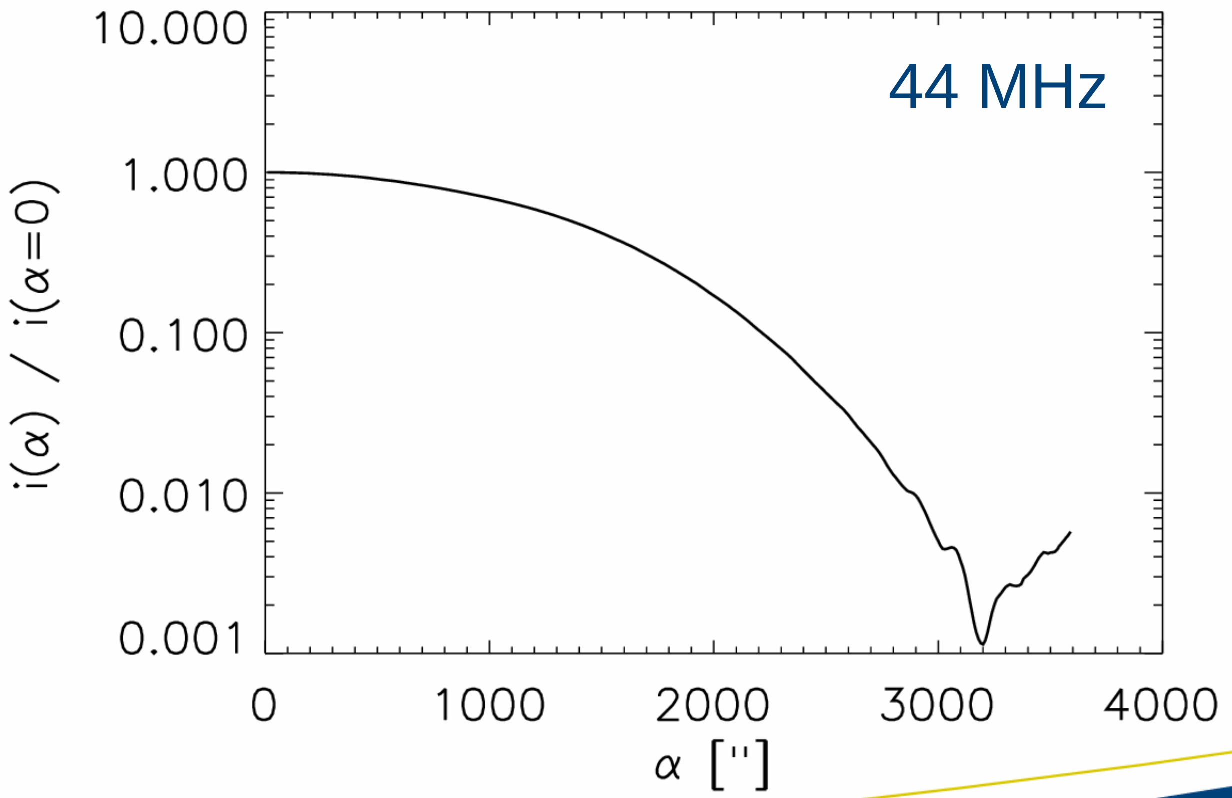
- Average over azimuth
- Normalized to image center



Observed intensity profiles

Profiles:

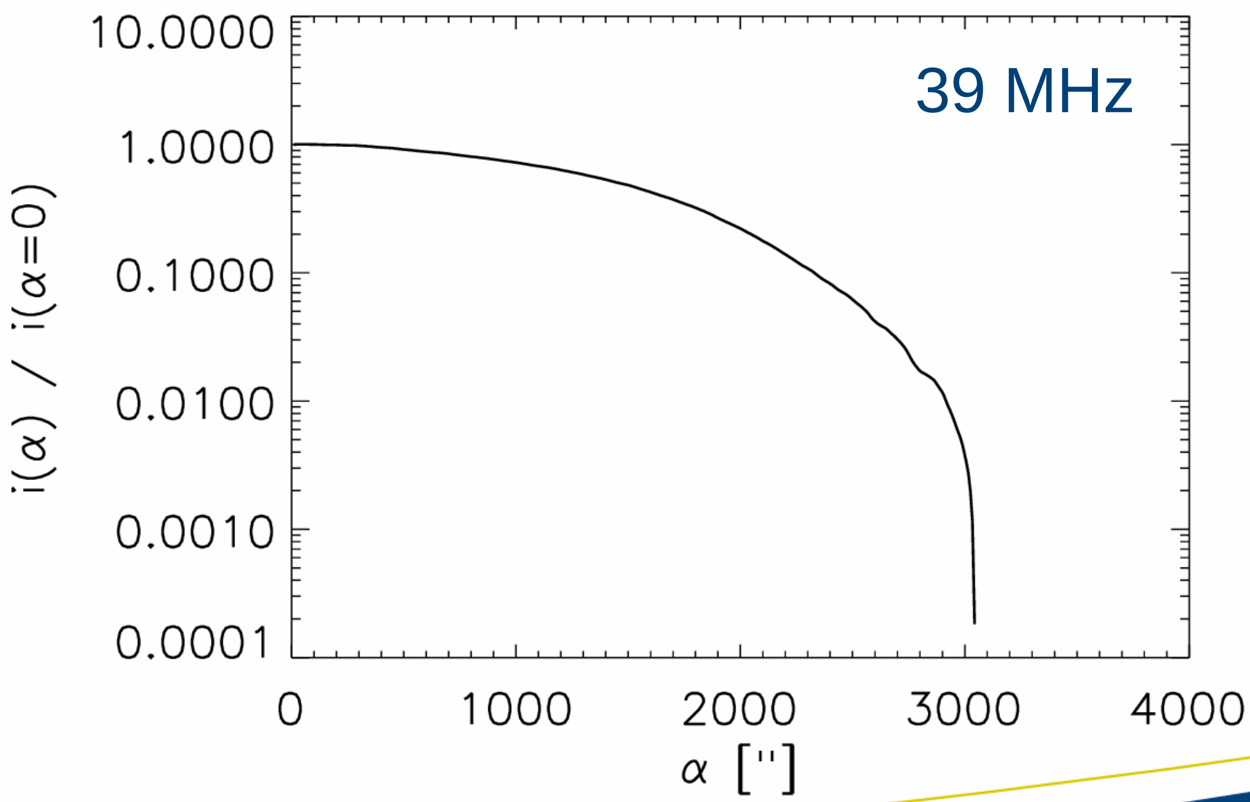
- Average over azimuth
- Normalized to image center



Observed intensity profiles

Profiles:

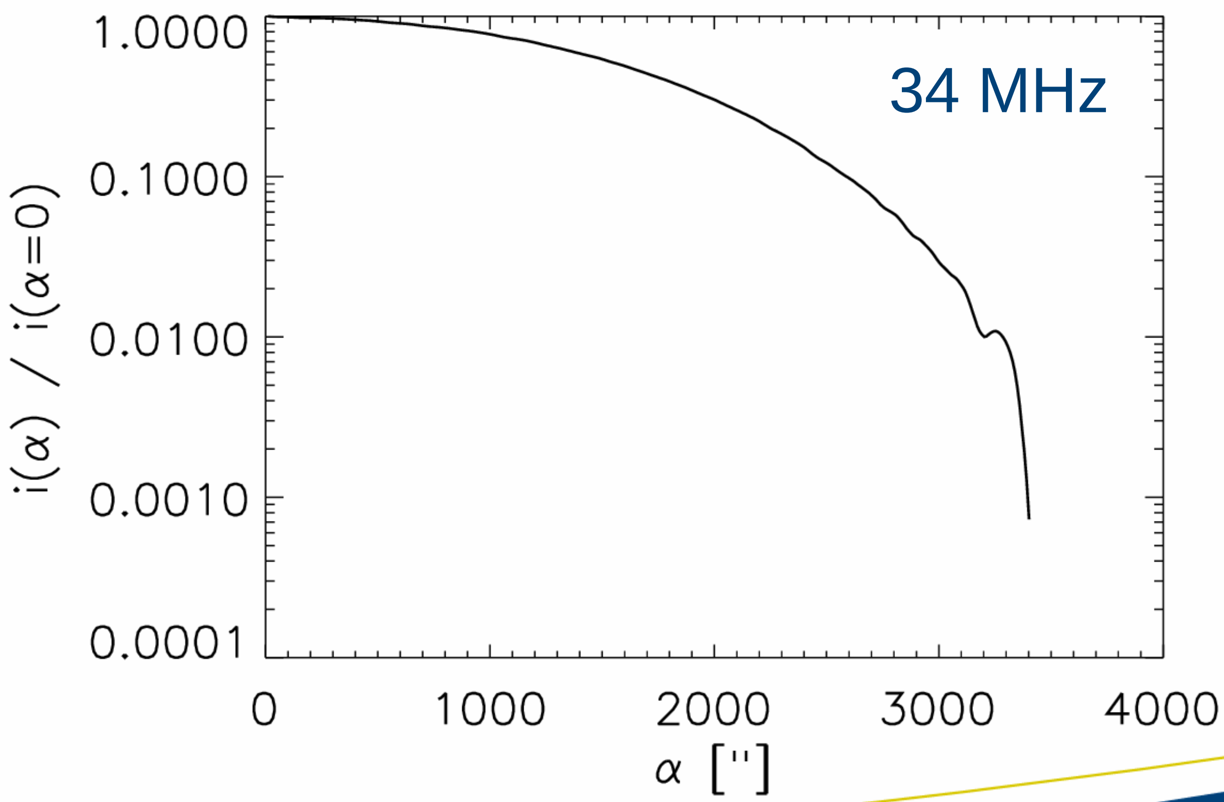
- Average over azimuth
- Normalized to image center



Observed intensity profiles

Profiles:

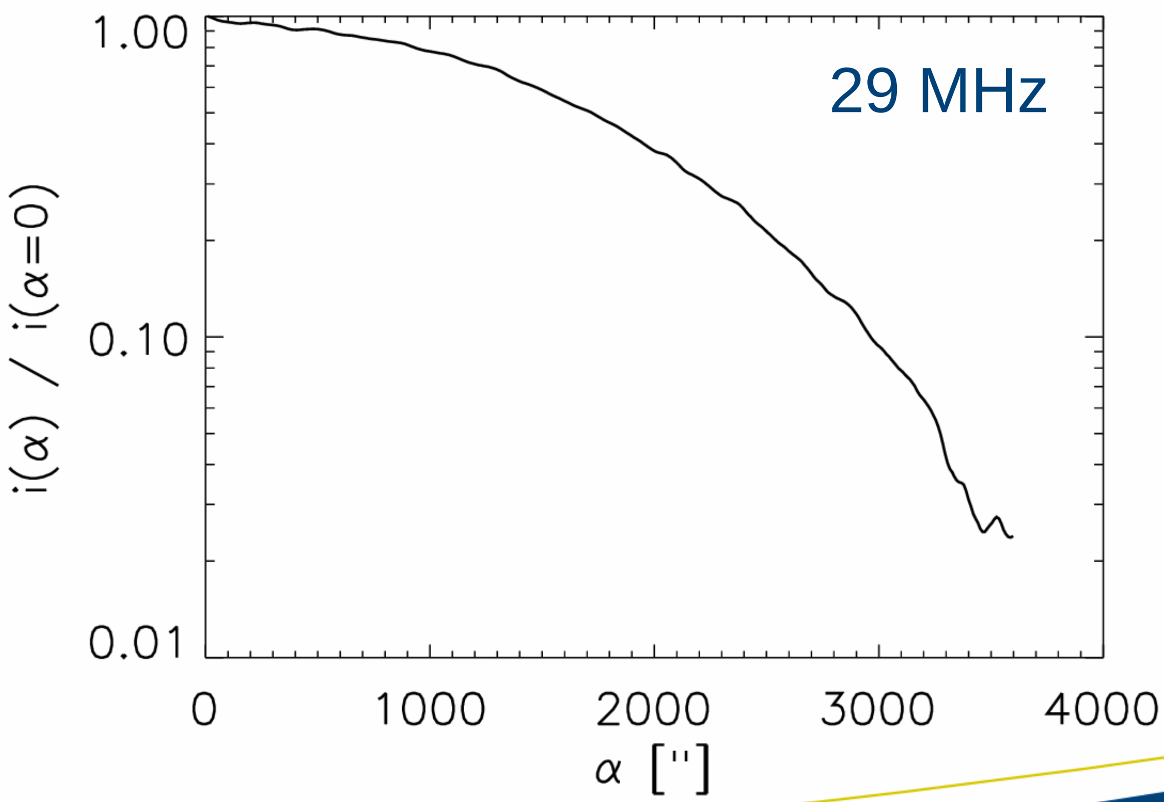
- Average over azimuth
- Normalized to image center



Observed intensity profiles

<u>Profiles:</u>

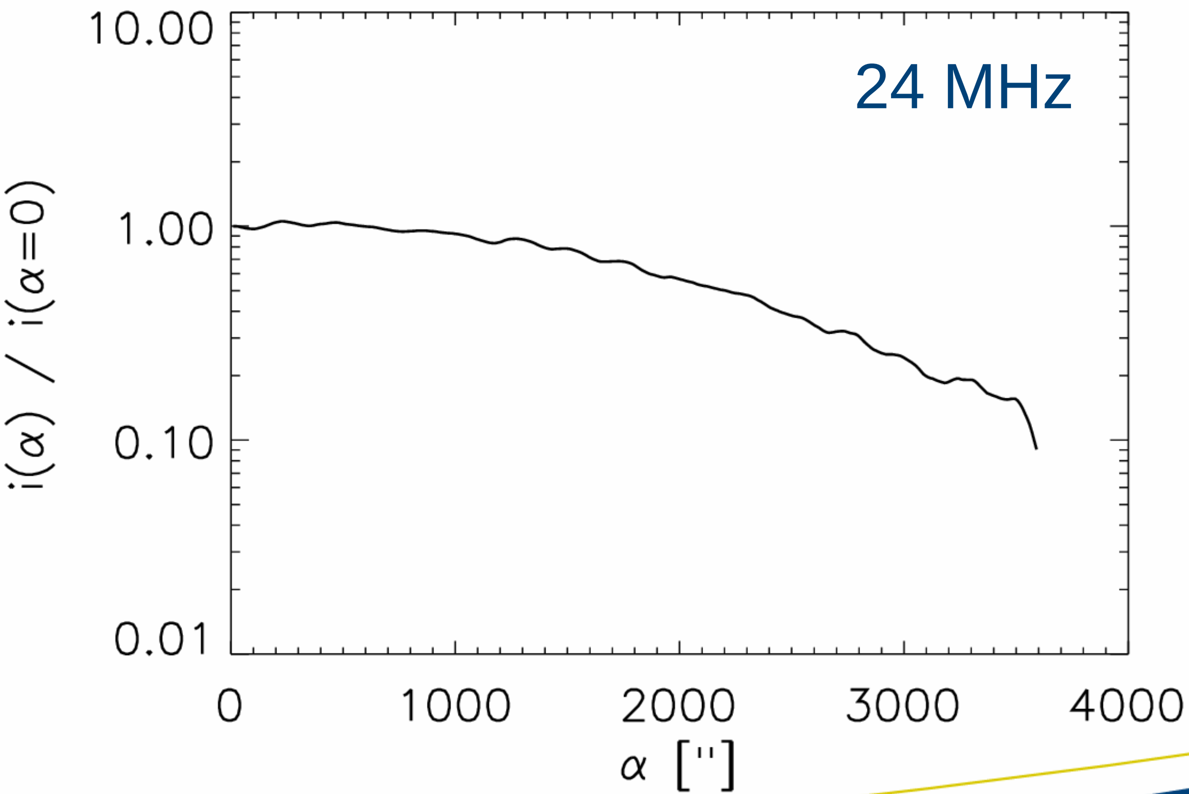
- Average over azimuth
- Normalized to image center



Observed intensity profiles

Profiles:

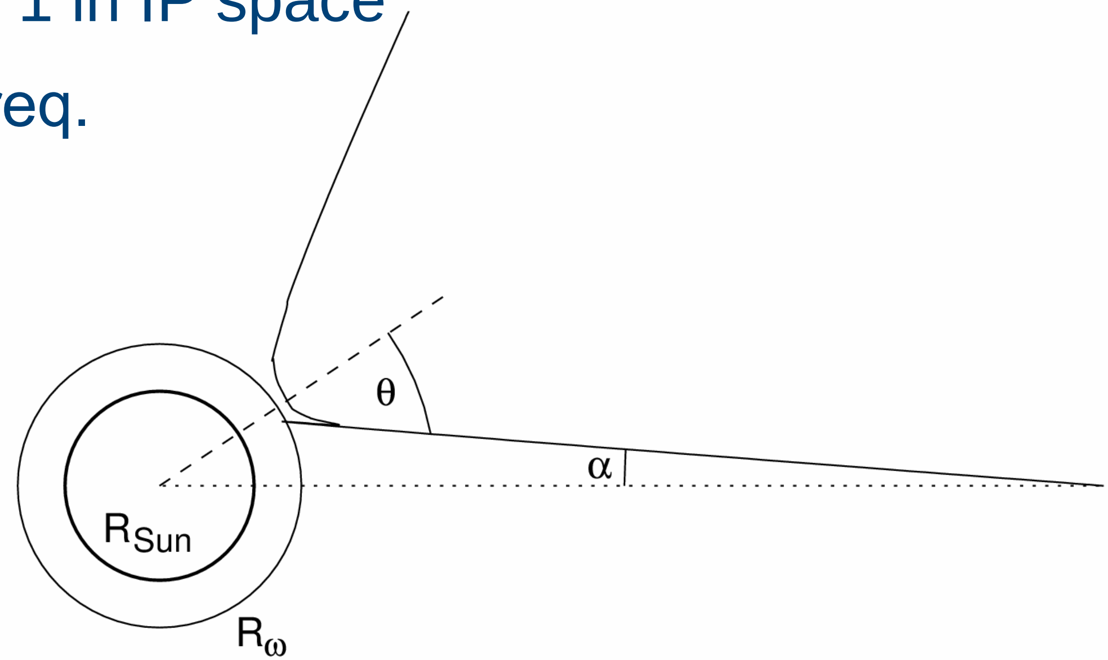
- Average over azimuth
- Normalized to image center



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:

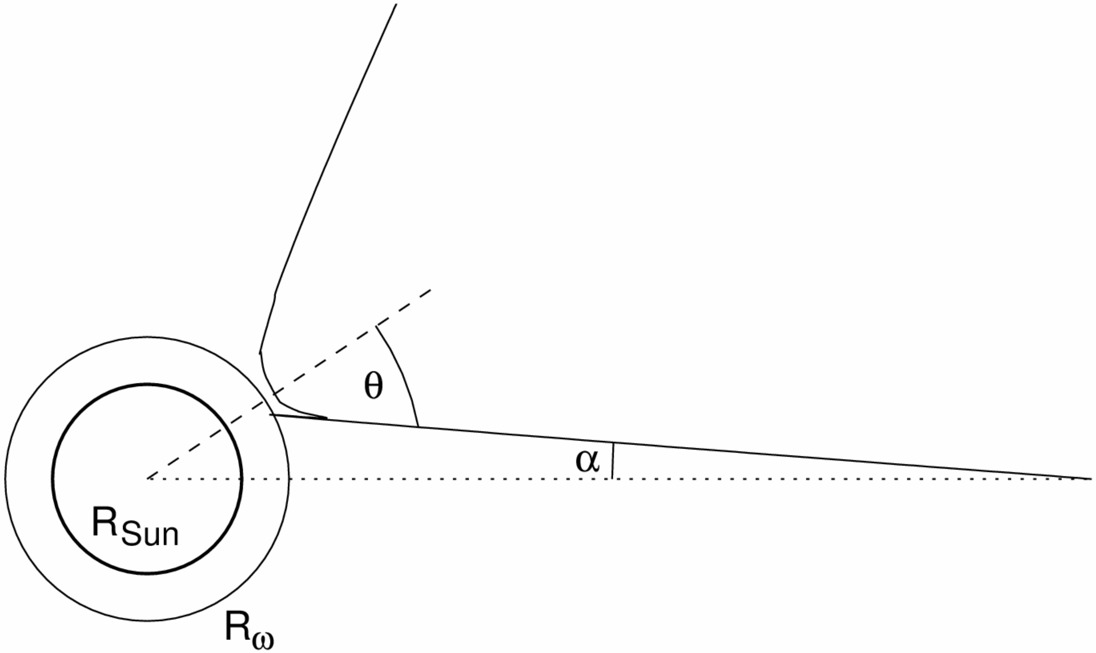
- Proportional to N^2
- Line-of-sight integral

Simple model

<u>Assumptions:</u>

- Intensity dominated by highest density
- Snell's law leads to

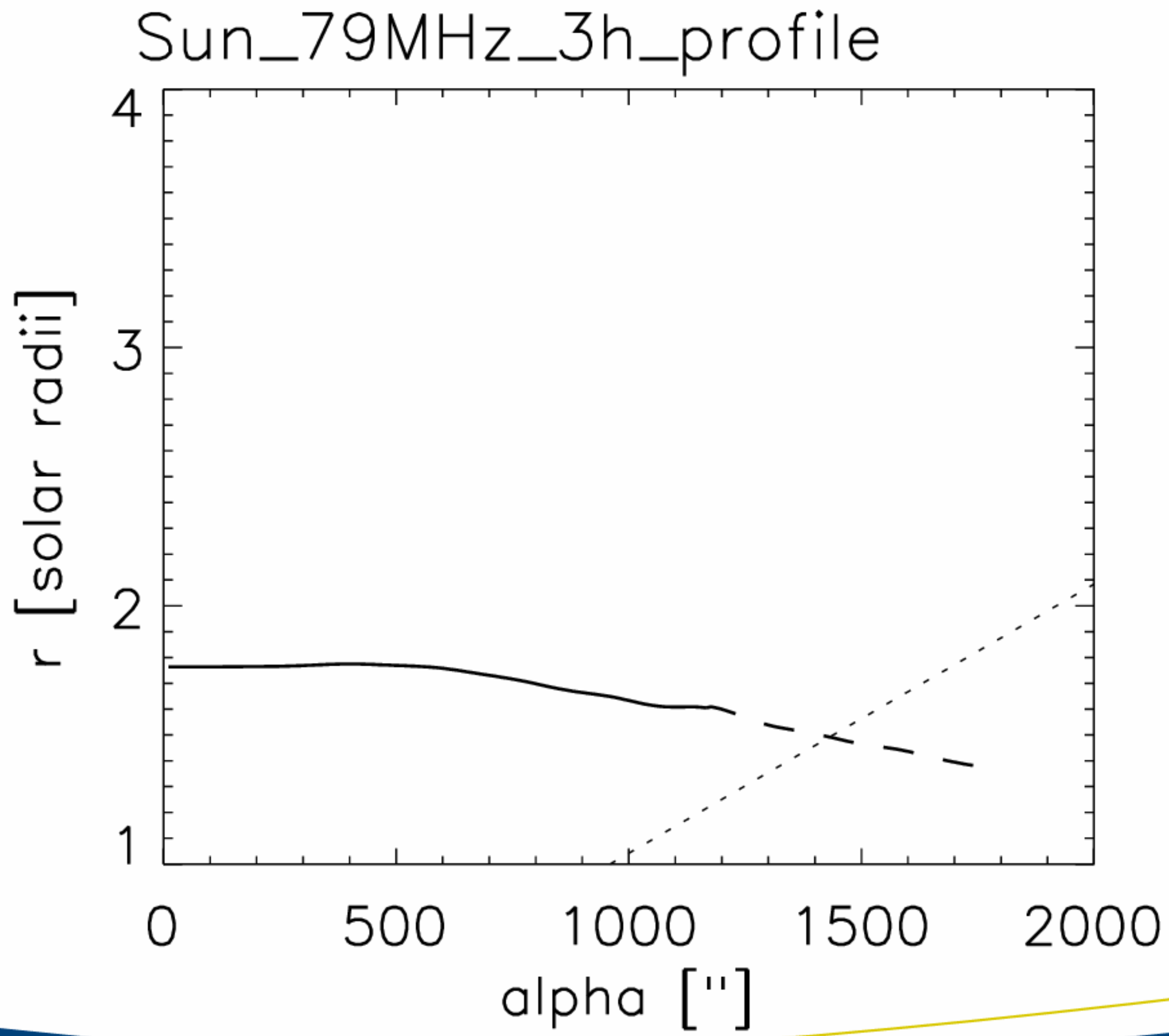
$$\sin(\theta) = n_{\text{source}}$$



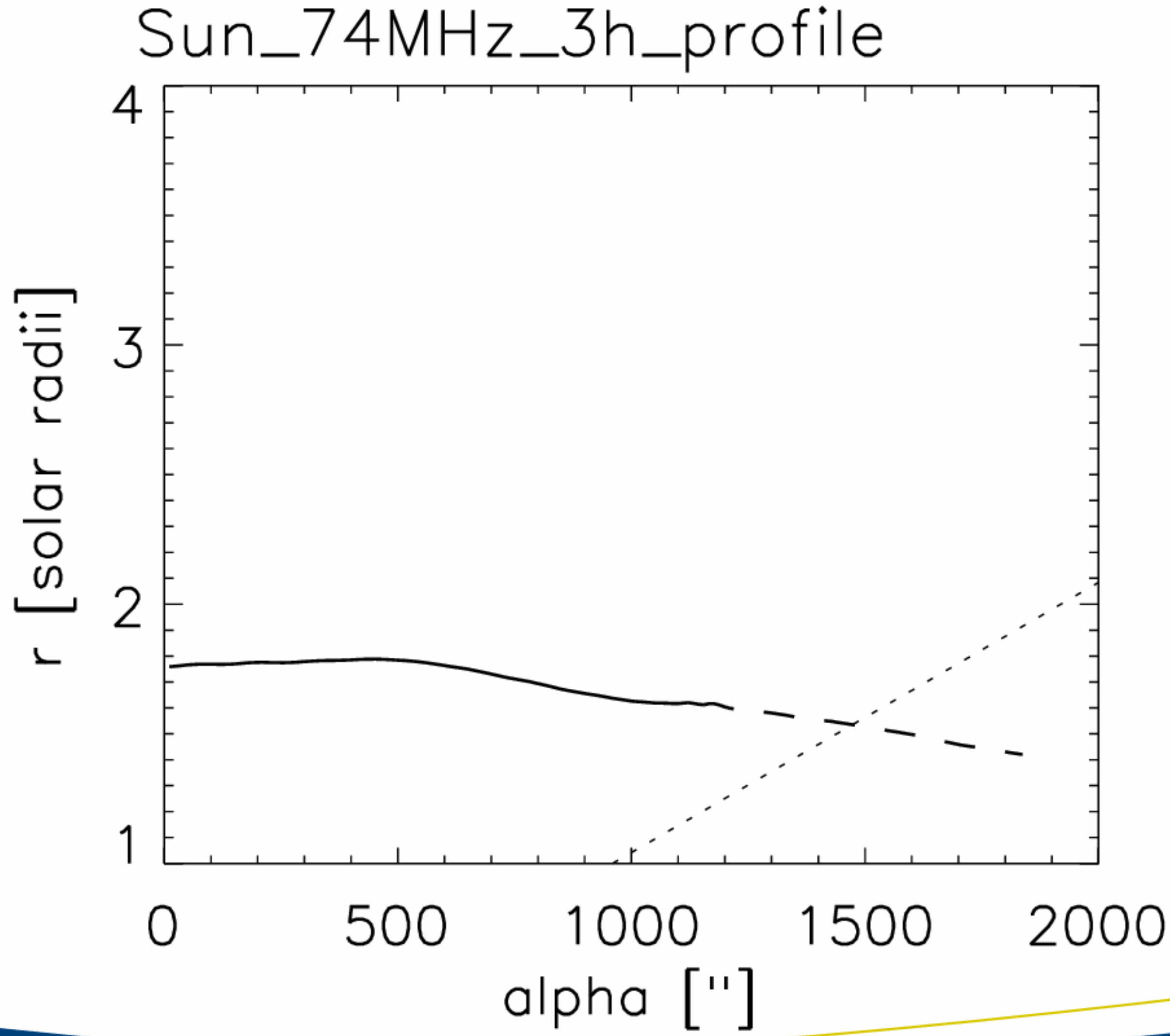
<u>Resulting intensity model:</u>

$$\log\left(\frac{i(\alpha)}{i(\alpha=0)}\right) \propto \left(\frac{\alpha \times 1\mathrm{AU}}{\mathrm{R}\omega}\right)^2$$

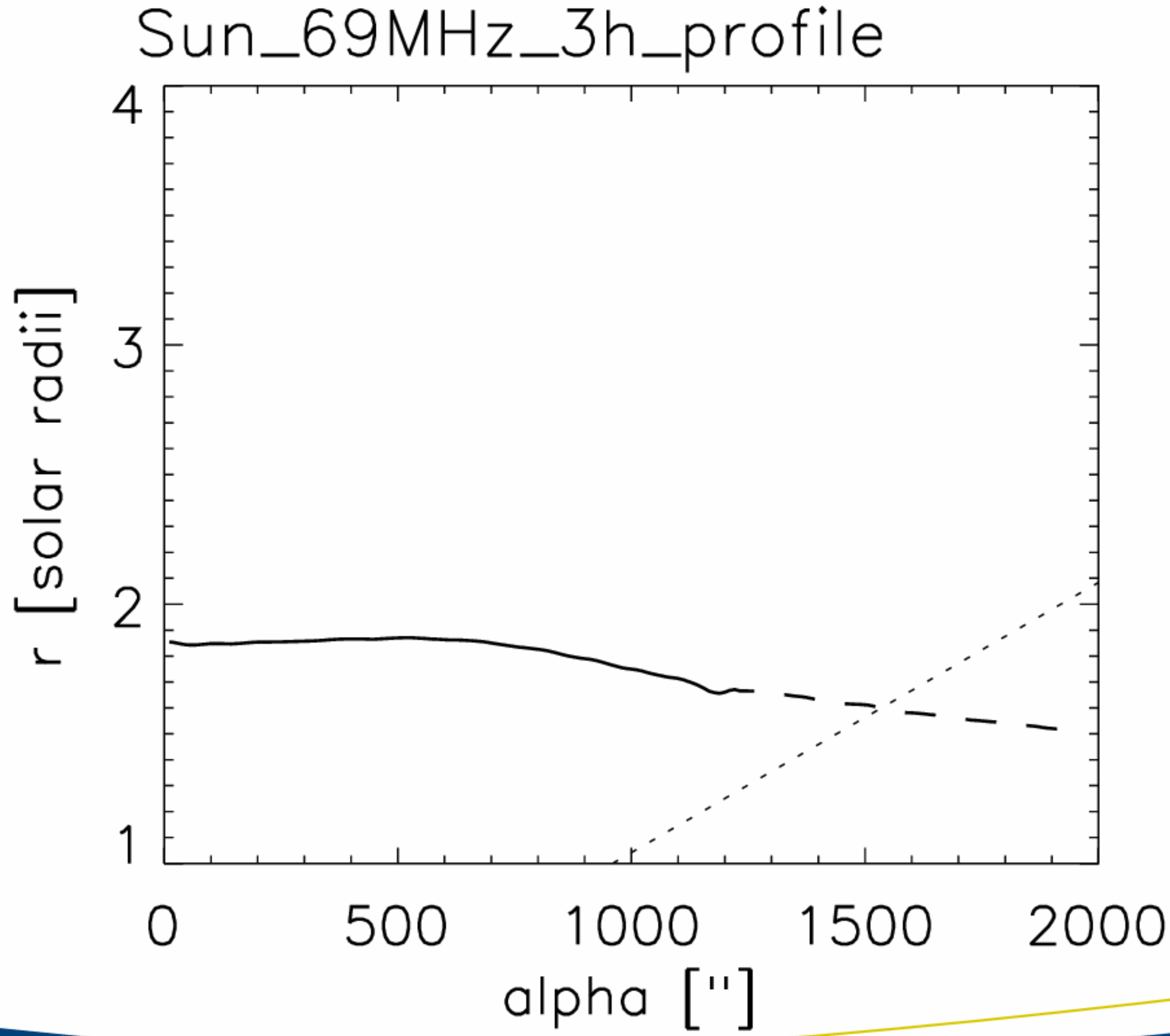
Resulting solar radii r = Rω



Resulting solar radii r = Rω



Resulting solar radii r = Rω



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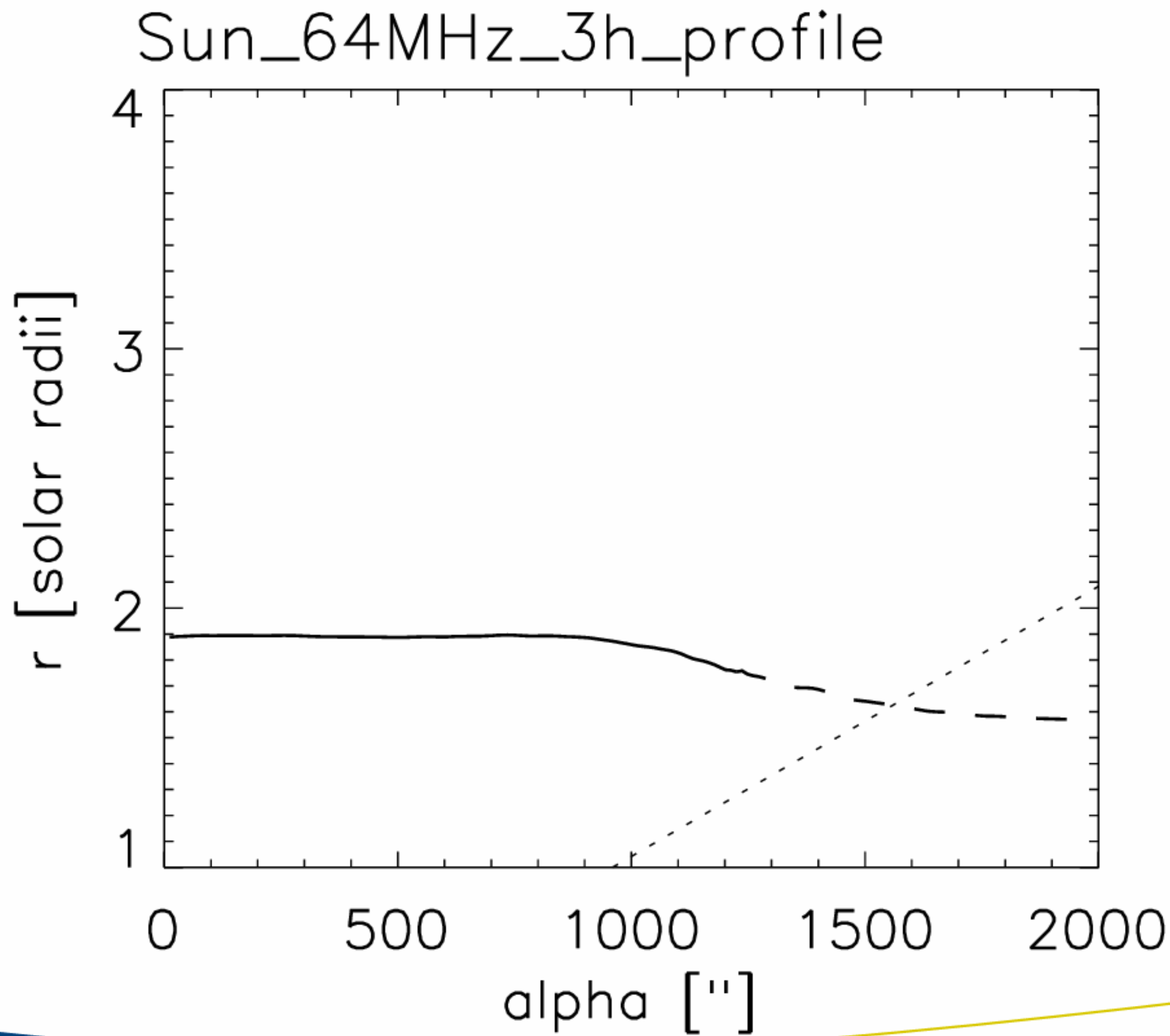
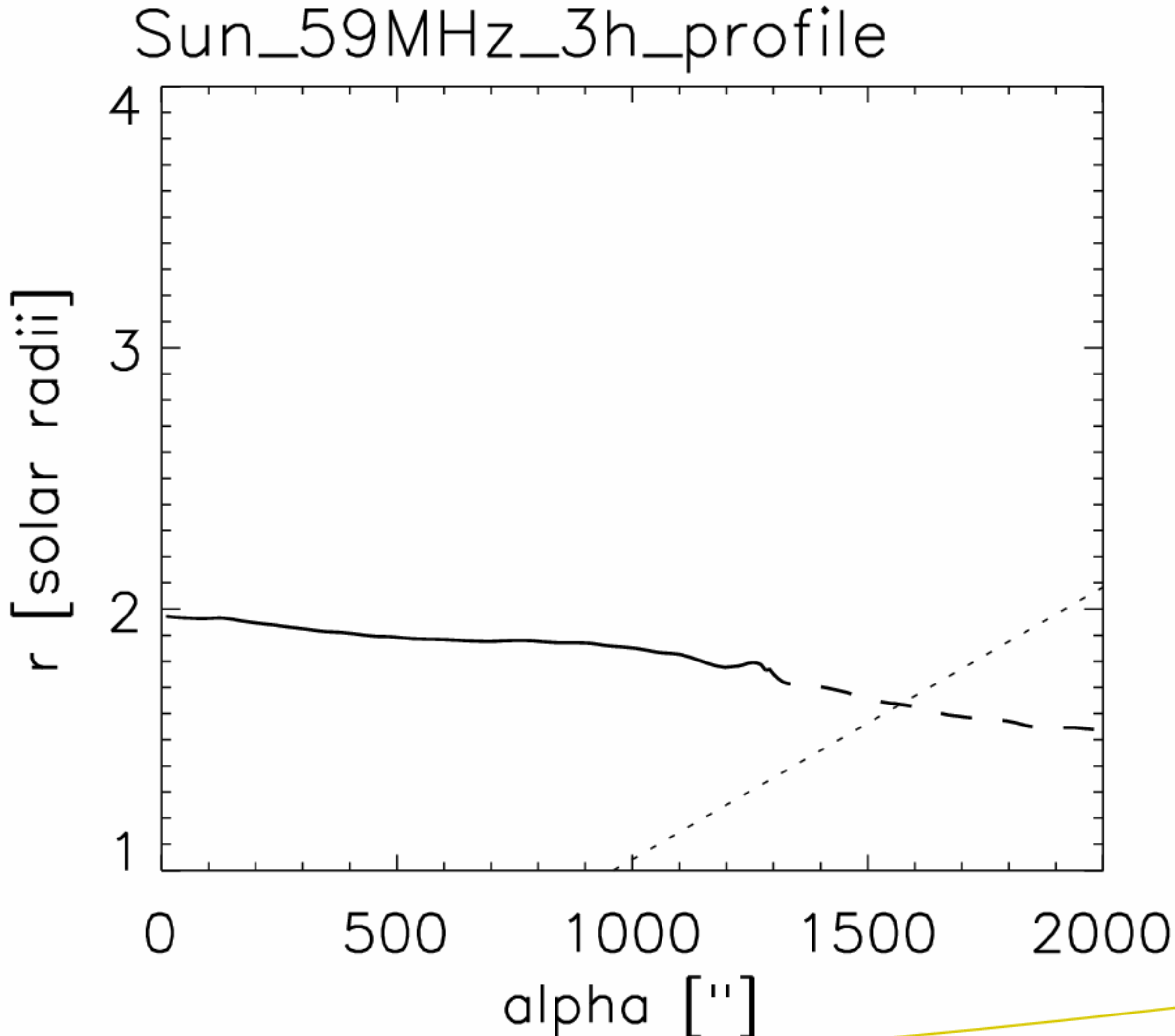
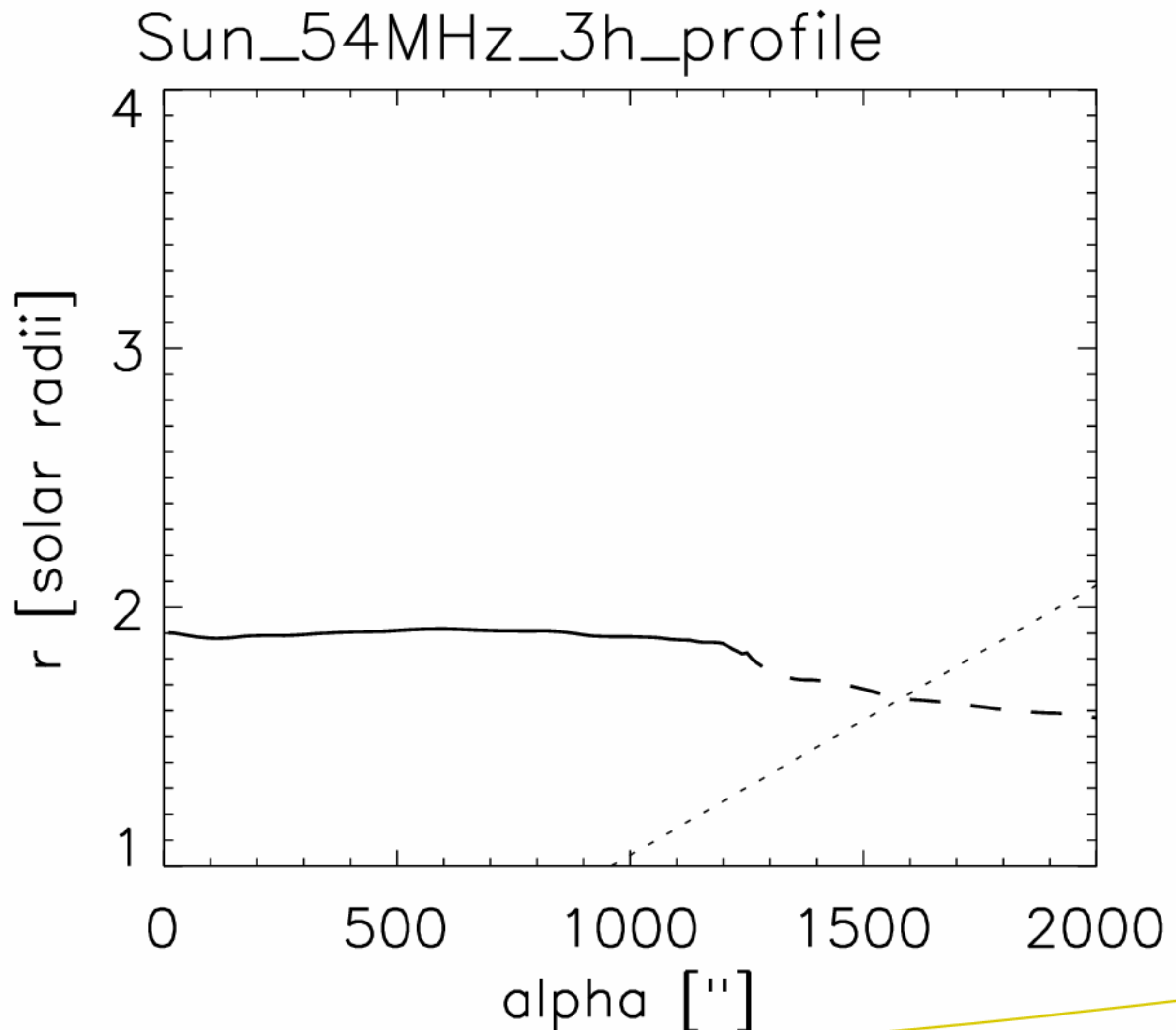


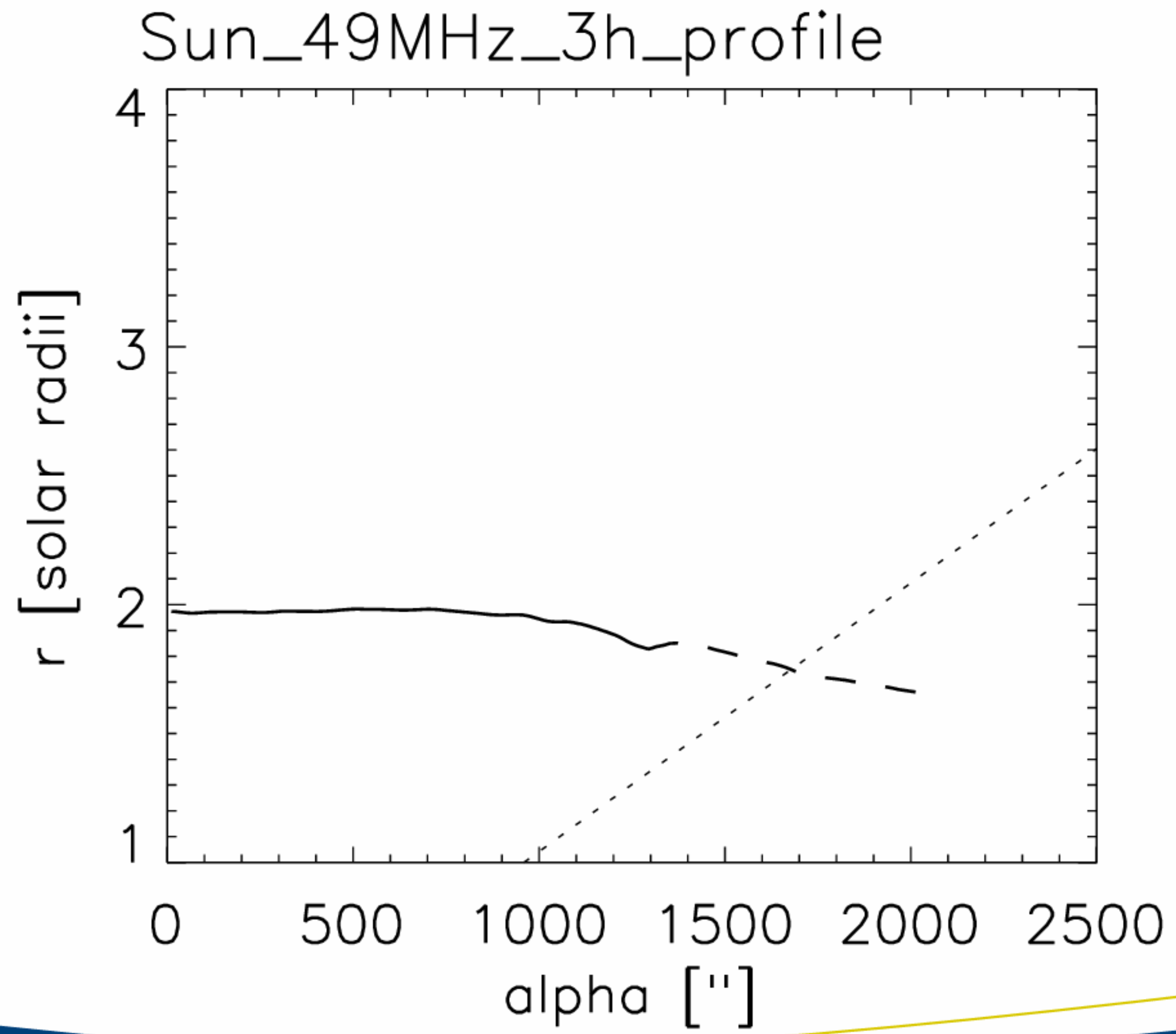
Resulting solar radii r = Rω



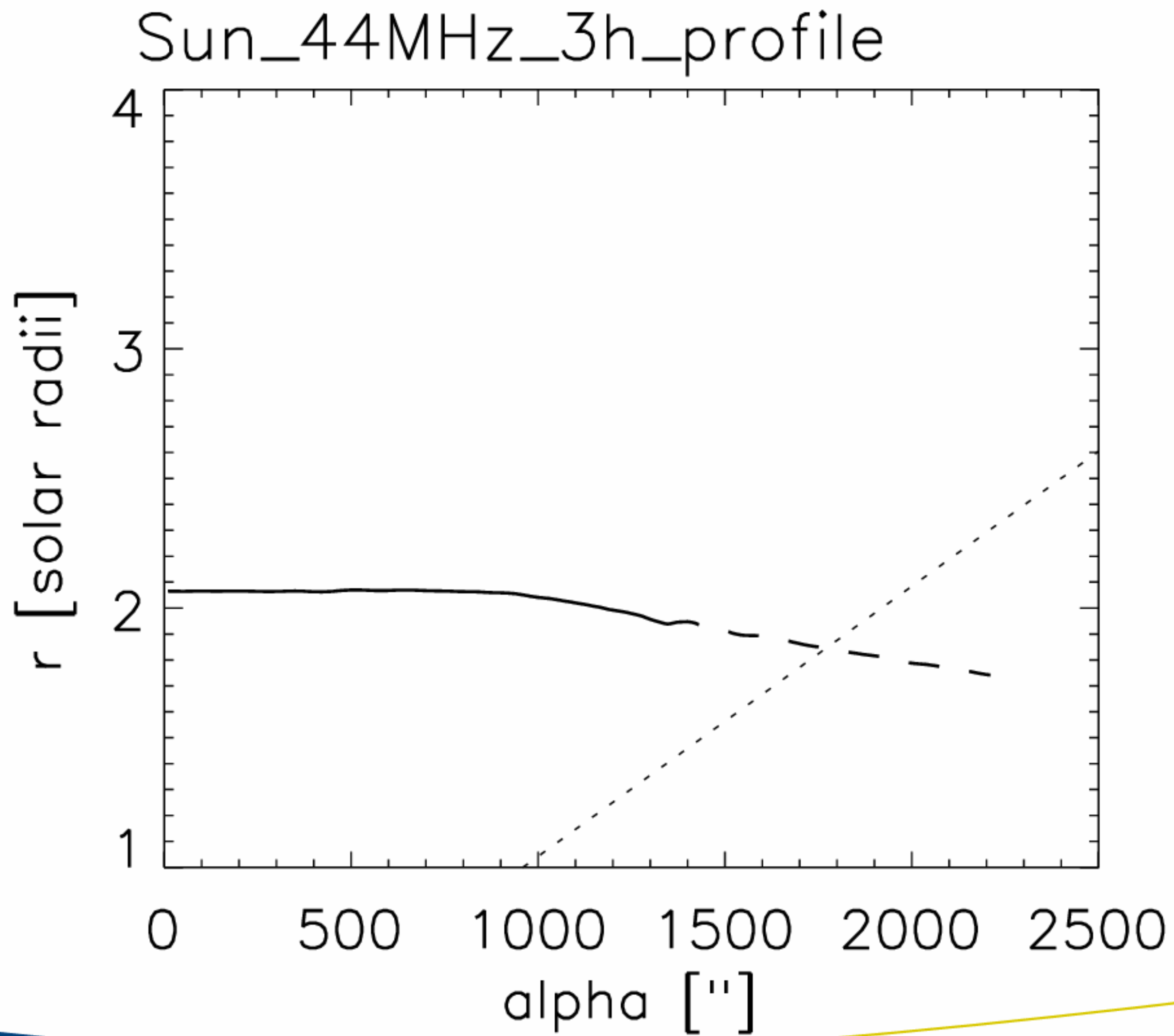
Resulting solar radii r = Rω



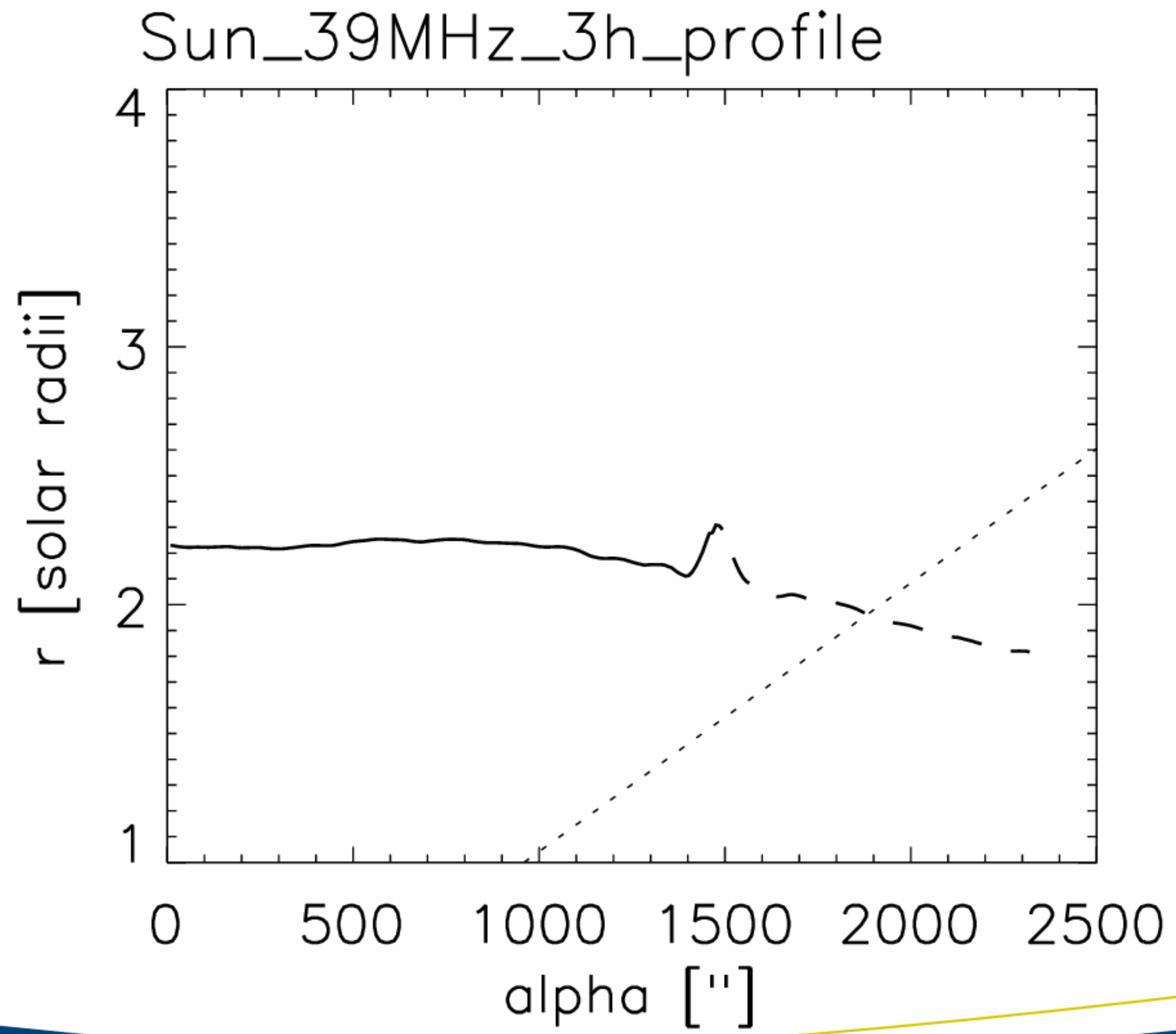
Resulting solar radii r = Rω



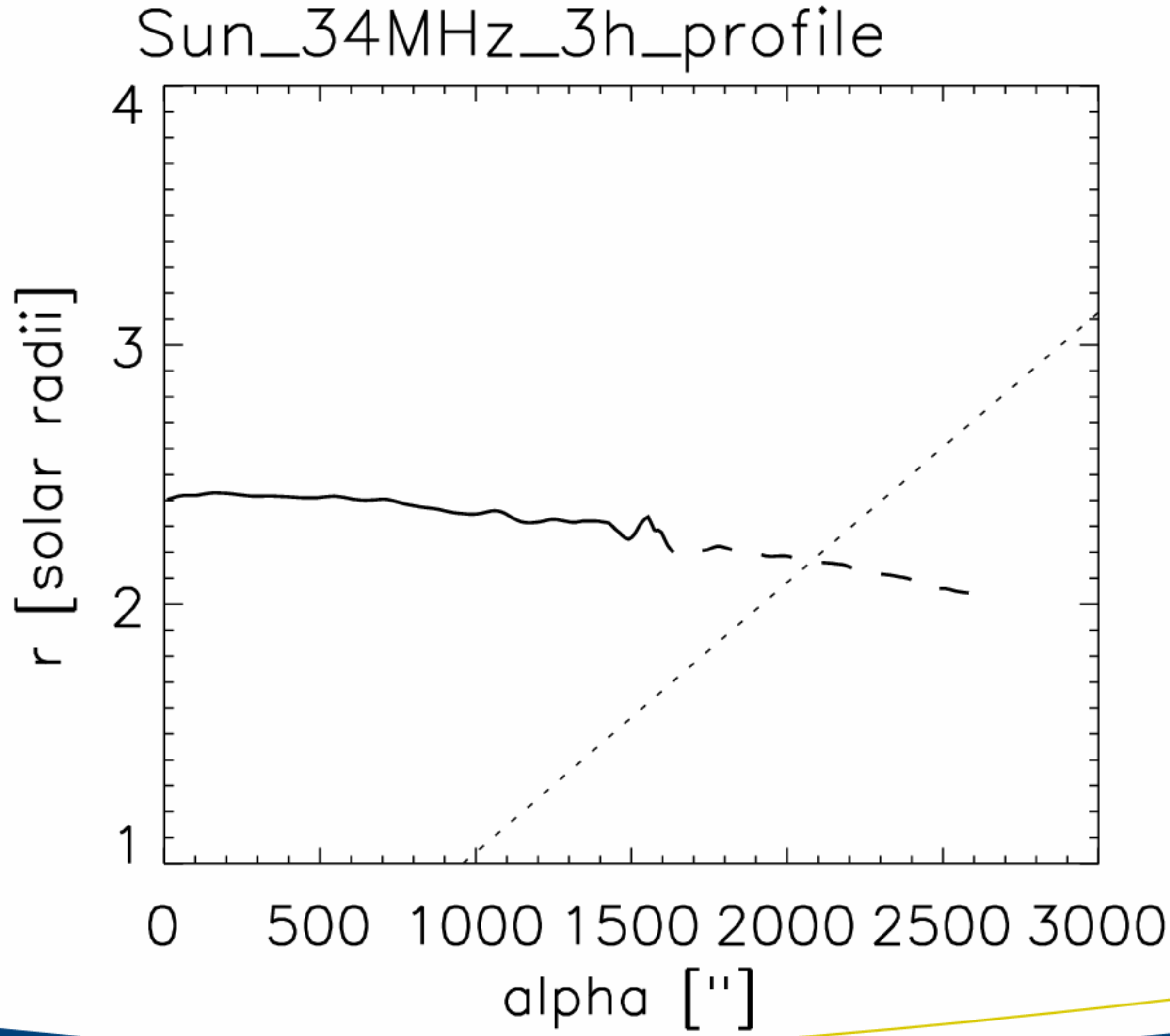
Resulting solar radii r = Rω



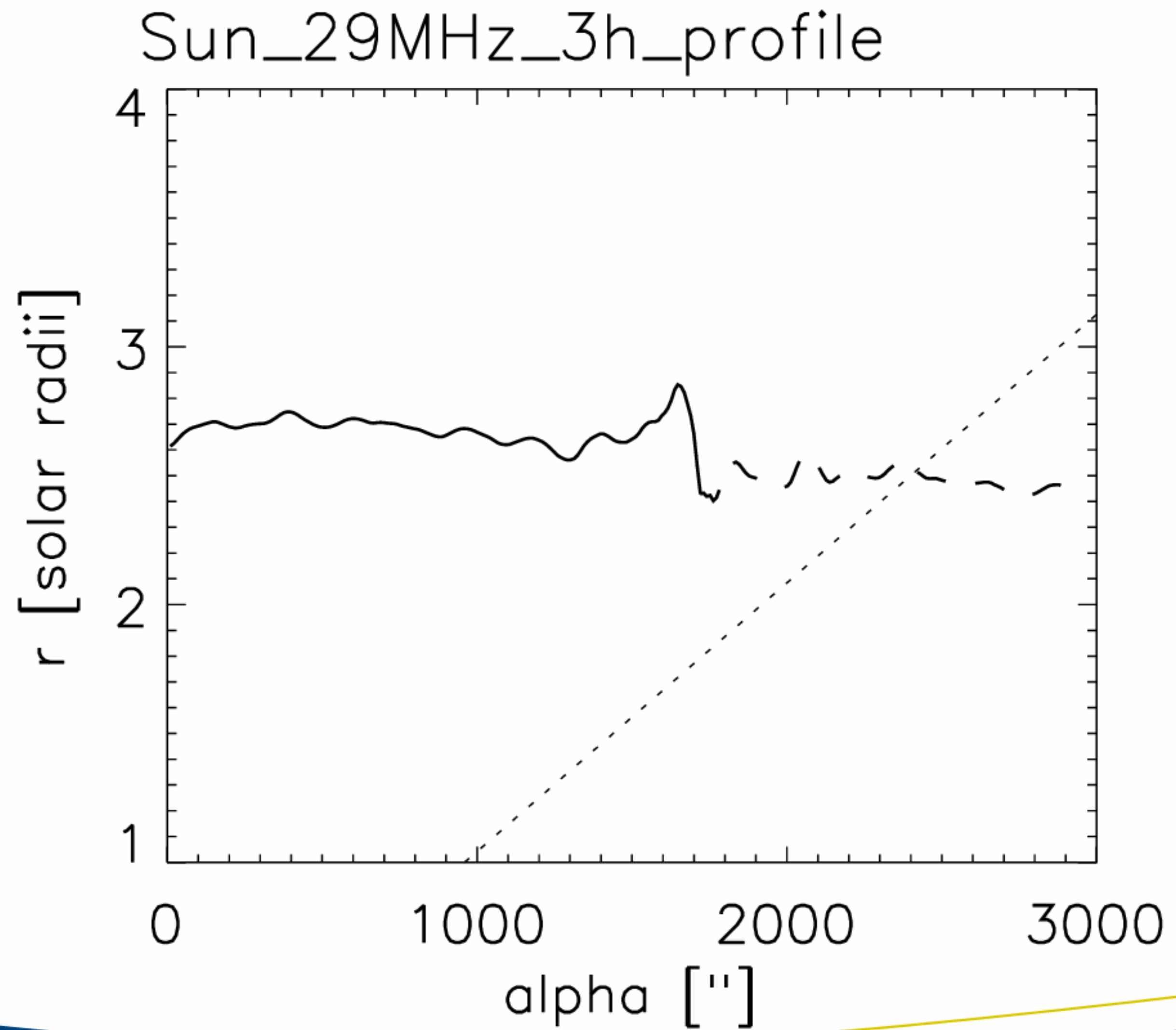
Resulting solar radii r = Rω



Resulting solar radii r = Rω



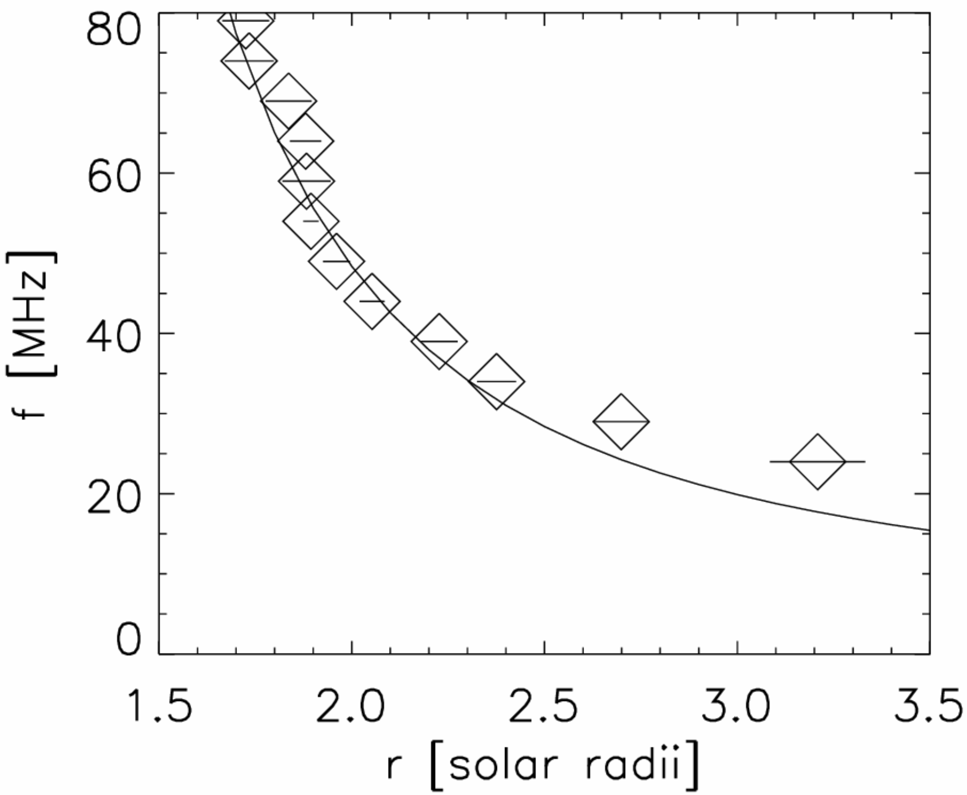
Resulting solar radii r = Rω



Solar radius from LOFAR data

Fit with density model:

- Hydrostatic model
  (Mann et al., 1999)
- Model parameters:
  - ➢ $T = 1.3 \cdot 10^6$ K
  - ➢ $N_0 = 6.0 \cdot 10^{15}$ m^{-3}



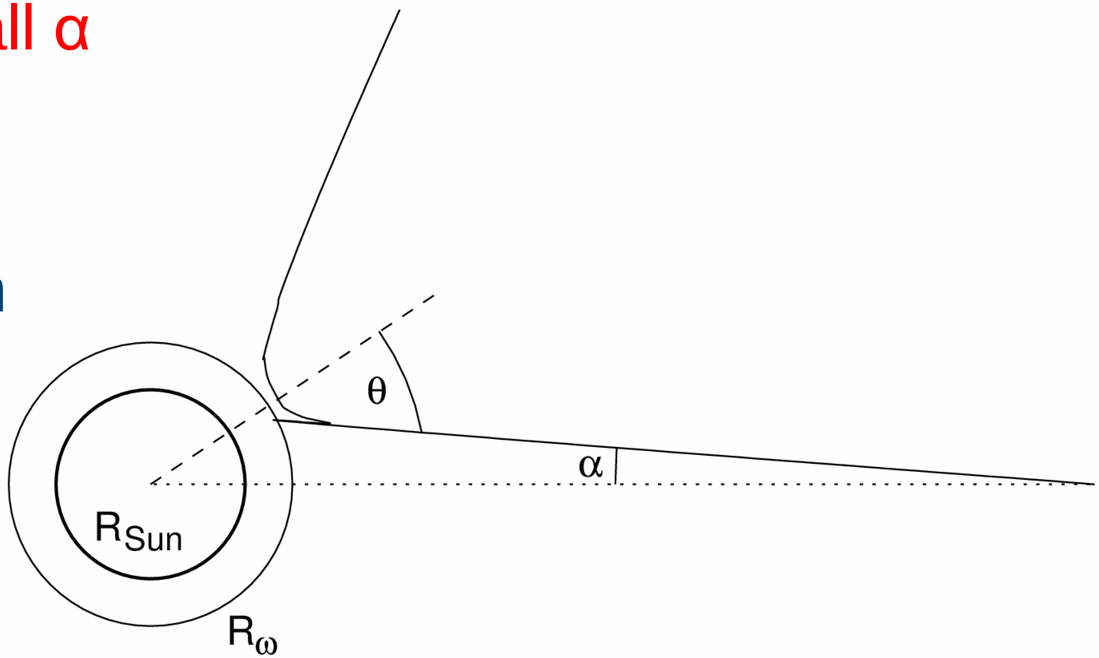
LOFAR imaging provides coronal density models

The model is too simple…

Local maxima for small α

Increasing α:

- Curvature of ray path leads to longer path length



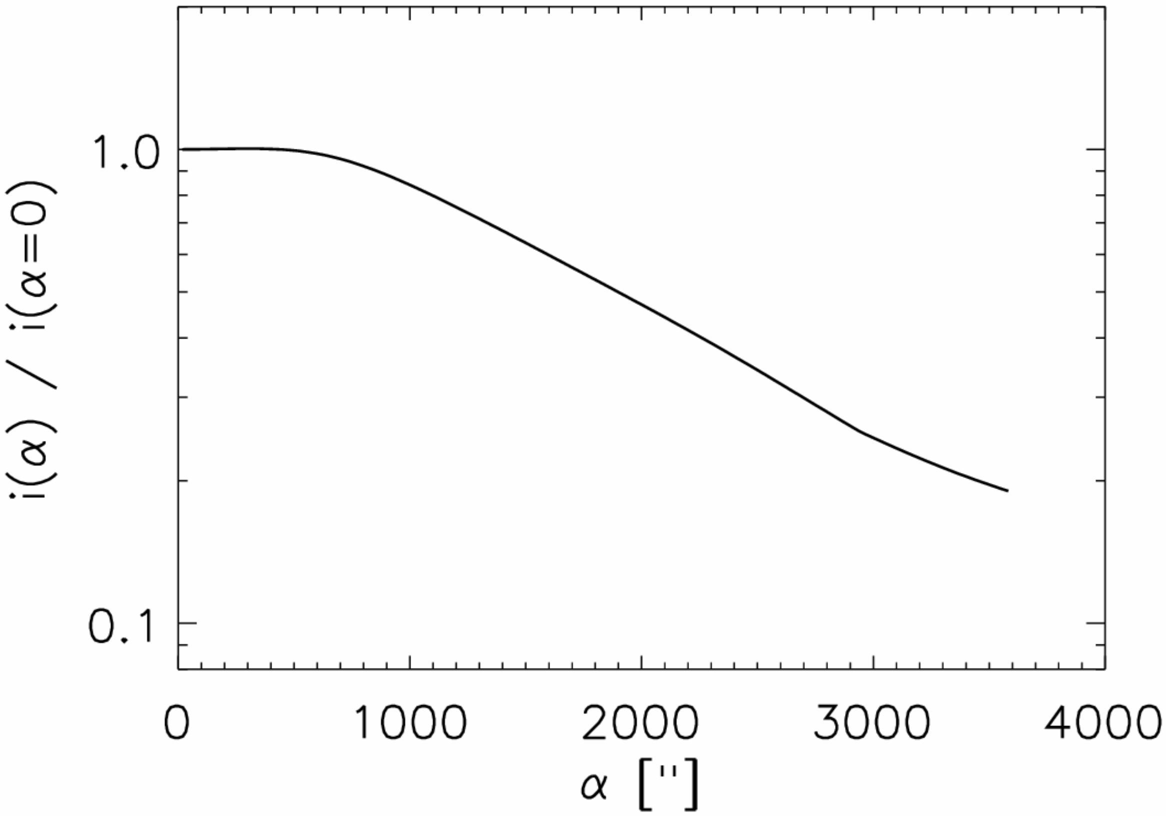
- Line-of-sight integral yields higher values

- Absorption of radio waves in the corona also has to be considered

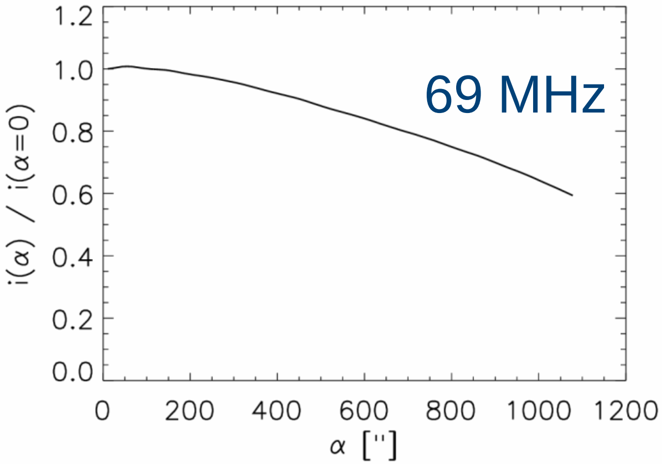
Ray-tracing simulation

Coronal parameters:

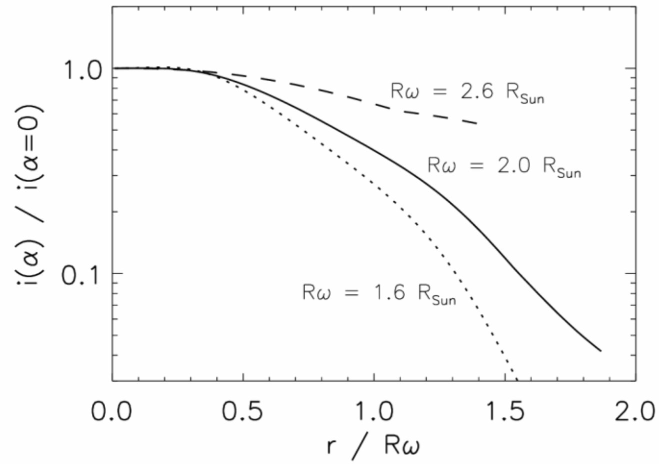
- $T = 1.4 \cdot 10^6$ K
- $R\omega = 2\ R_{Sun}$
- f = 60 MHz
- beam size: 150''



Next step: Inversion problem



observed



model

<u>Multiple dependencies:</u>

- Mainly Rω, which is sought for
- But also coronal temperature
- Search for best fit

Summary and conclusions

<u>Quiet Sun observations:</u>

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

<u>Analysis of solar images:</u>

- Refraction is important in the corona
- Simple wave propagation model leads to a surprisingly good density profile
- More accurate approach is still necessary