# The LOFAR LBA sky survey: lessons learned

LoL sky survey

F. de Gasperin

The Third National Workshop on the SKA Project

6/10/2021

UHH

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA


LOFAR HBA
Frequency: 120-240 MHz
Resolution: 5” (0.3”)
FoV: 4 deg x 4 deg
Sensitivity: ~100 uJy/b
LOFAR LBA
Frequency: 10-90 MHz
Resolution: 15” (1”)
FoV: 4 deg x 4 deg (multi)
Sensitivity: ~1 mJy/b
HBA
LBA
Birr
Onsala
Irbene
Dutch stations
Chilbolton
Norderstedt
Bałdy
Potsdam
Jülich
Effelsberg
Borówiec
Tautenburg
Łazy
Nançay
Unterweilenbach
Medicina
Atmospheric Opacity
100%
50%
0%
SKA-low
HBA
LBA
IONOSPHERE CUTOFF
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

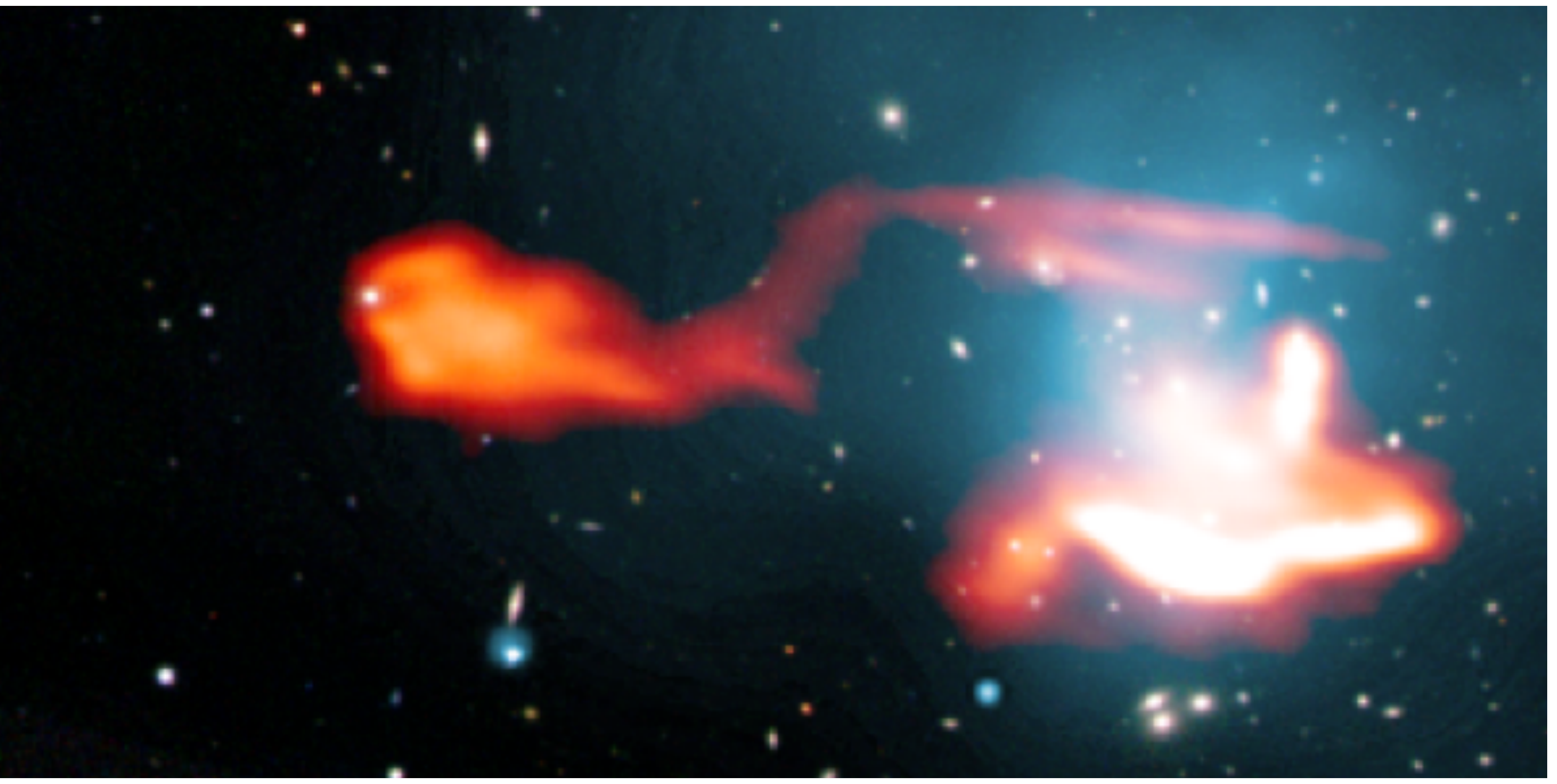
# LBA science

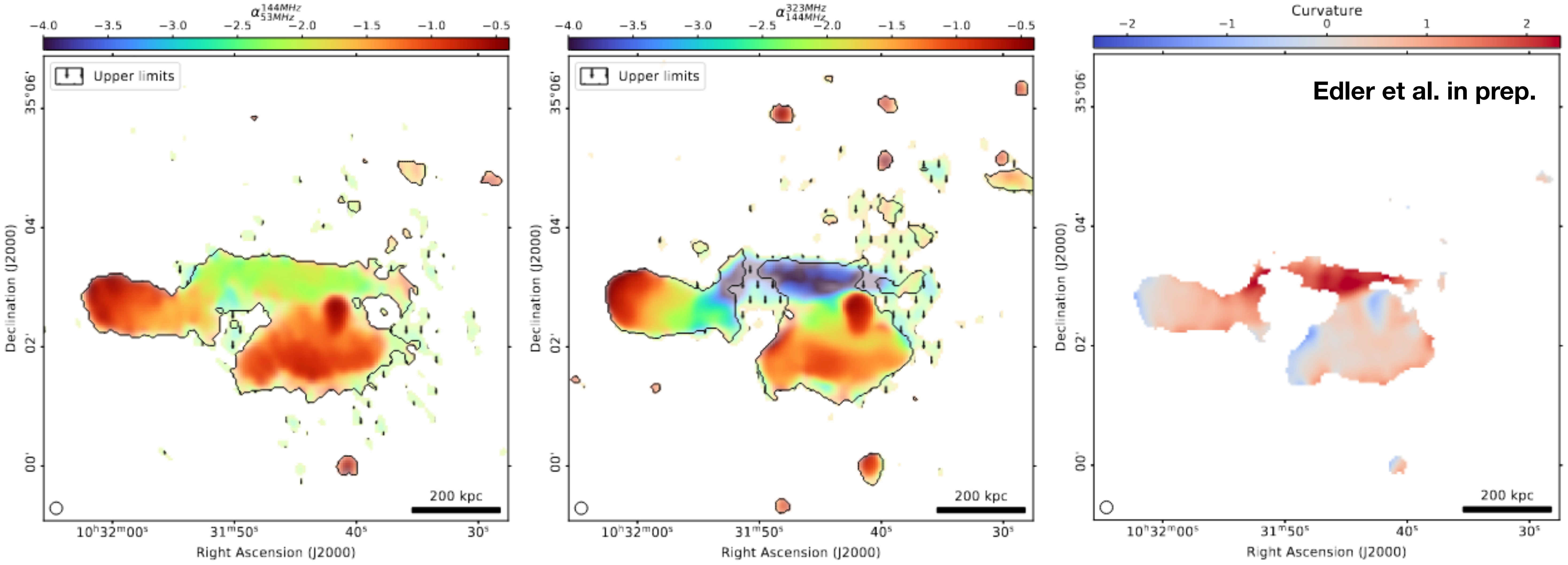

Heesen et al. in prep.
Lusetti et al. in perp.
Edler et al. in prep.
Betteon et al. 2020
Brienza et al. in press.
Vollmann et al. 2020
de Gasperin et al. 2020
Cuciti et al. in perp.
LSS
CR lifecycle
Galaxies
AGN
Galaxy clusters
Dark Matter
Exoplanets
LBA
HBA
Radio halo
-1.7
-1.8
LOFAR 53 MHz
1 Mpc
200 kpc
1′ = 170 kpc
Flux density (mJy beam$^{-1}$)
Right Ascension (J2000)
Declination (J2000)
$\langle\sigma v\rangle$ [cm$^3$/s]
$m_\chi$ [GeV]
$\chi\chi \rightarrow e^+e^-$
$\nu = 54$ MHz (MIN)
thermal DM

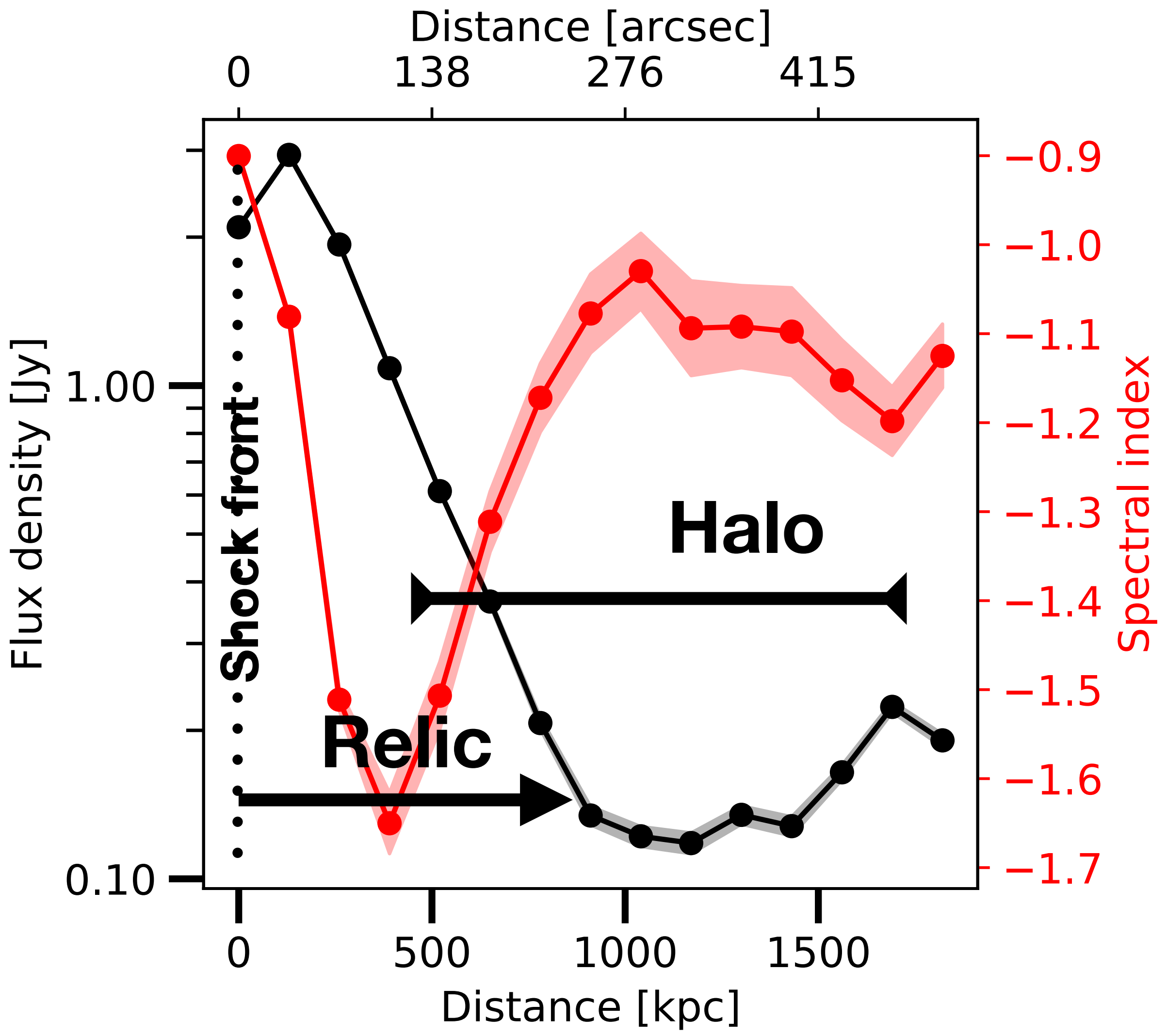
10 arcsec
(3.000 ly)
VLA 1.5 GHz
0,001 arcsec
(0,3 ly)
VLBA 43 GHz
100 arcsec
(30.000 ly)
LOFAR 50 MHz
0,00001 arcsec
(0,003 ly)
EHT 230 GHz
Credits — LOFAR image: F. de Gasperin — VLA image: F. Owen — VLBA image: C. Walker— EHT Image: EHT collaboration

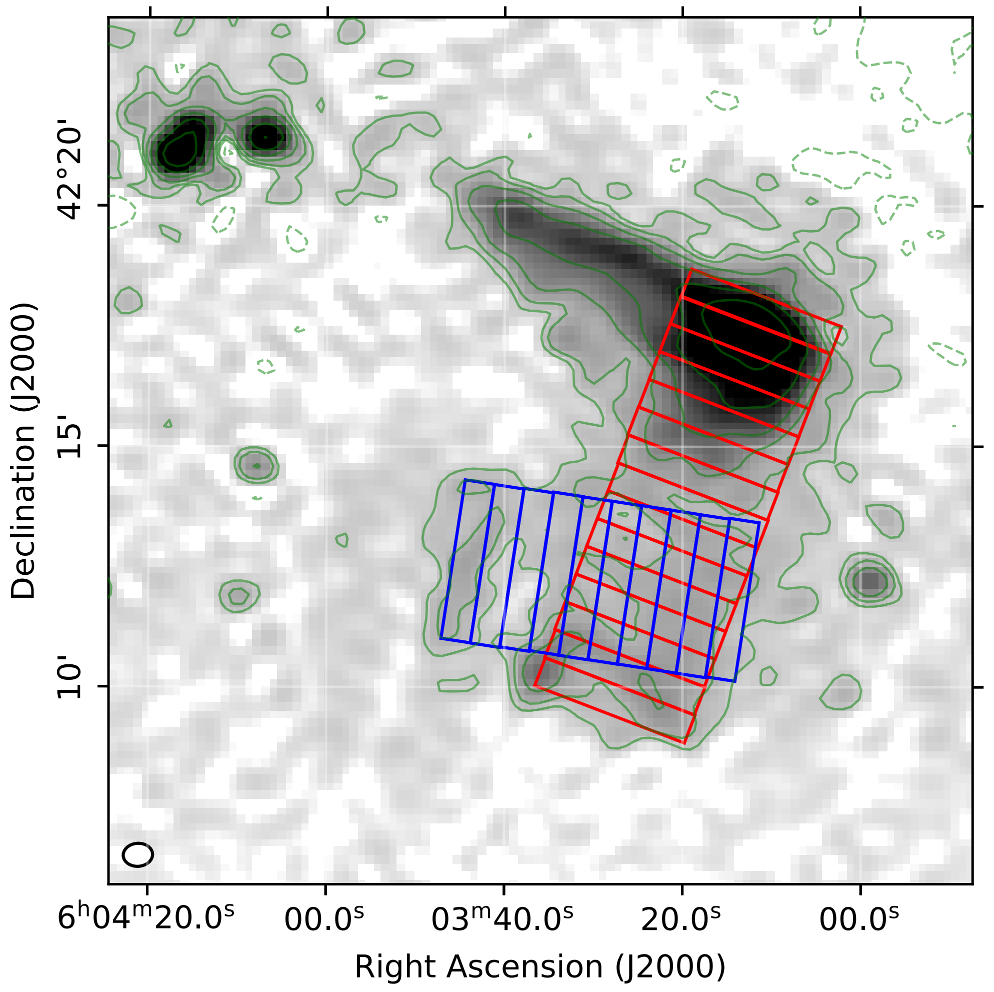
# CR at low-energies in galaxy clsuters

- GReET in Abell 1033 - LBA observations
- Study of the curvature of the GReET
- First detection of the radio halo in Abell 1033

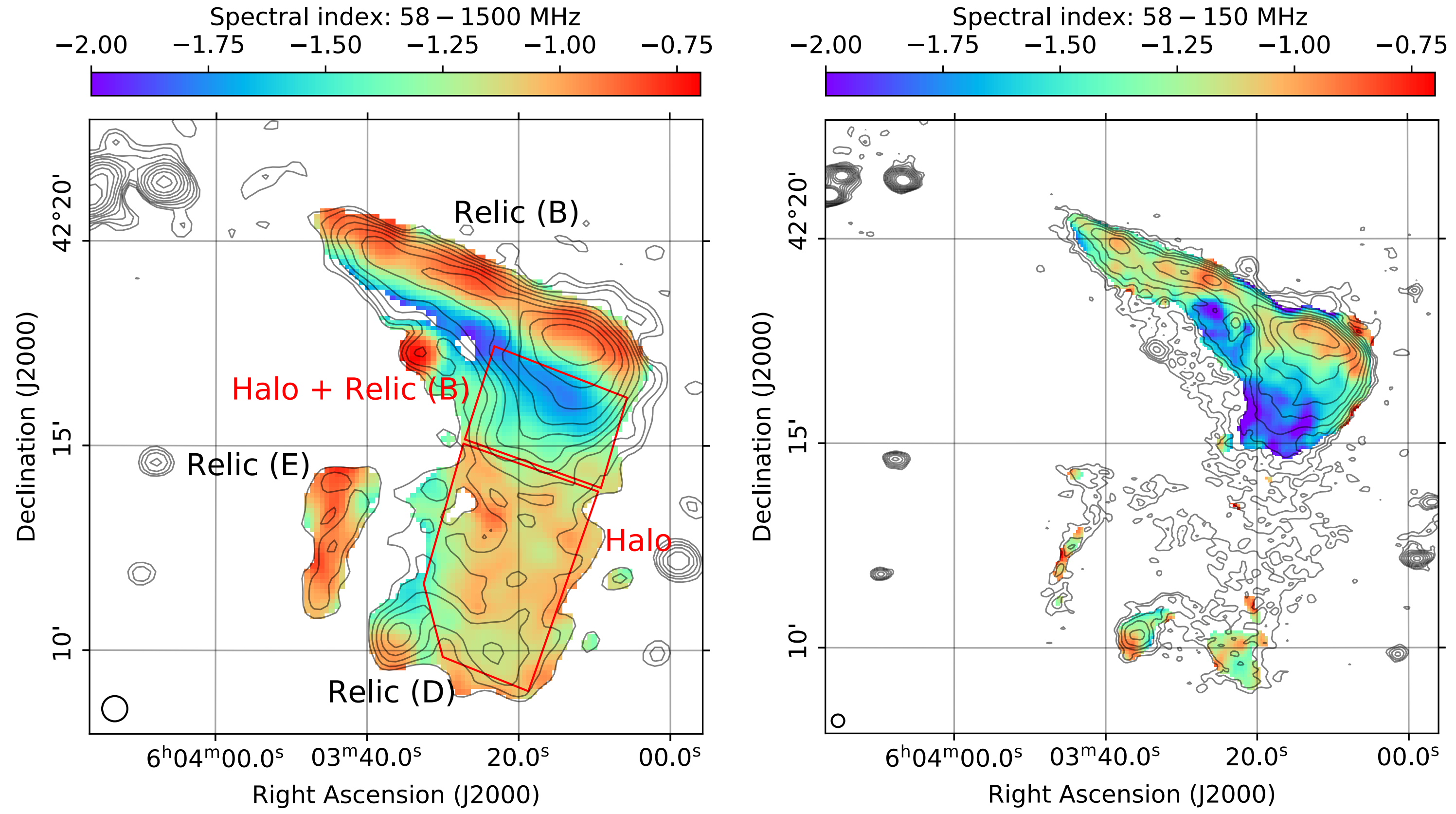





- We can detect CRe 800 kpc downstream of the shock front
- Expected length: 211 kpc (Kang+ 2017)



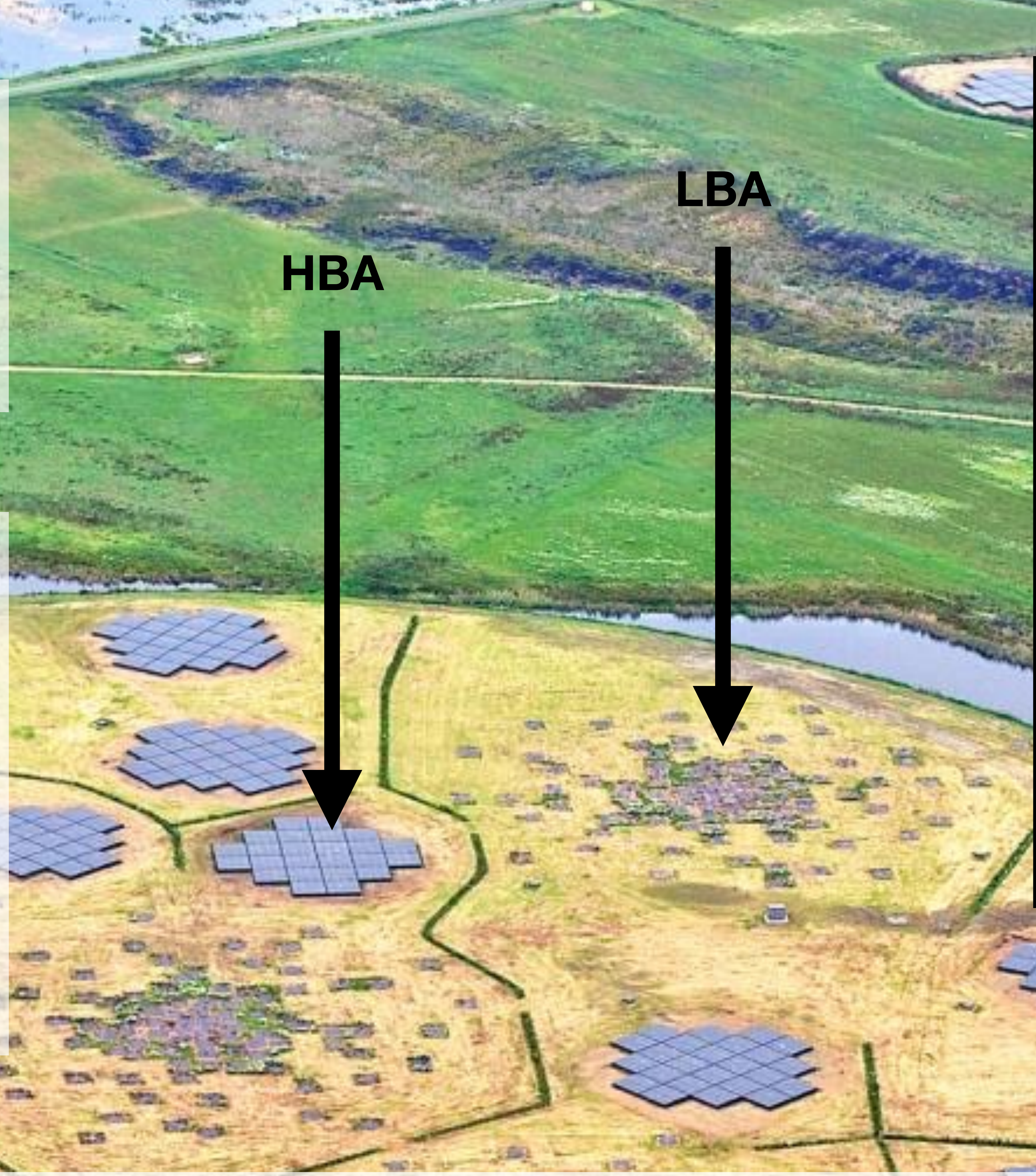

de Gasperin et al. 2020

**LOFAR HBA**
Frequency: 120-240 MHz
Resolution: 5” (0.3”)
FoV: 4 deg x 4 deg
Sensitivity: ~100 uJy/b

**LOFAR LBA**
Frequency: 10-90 MHz
Resolution: 15” (1”)
FoV: 4 deg x 4 deg (multi)
Sensitivity: ~1 mJy/b

**Challenges of the low frequency:**

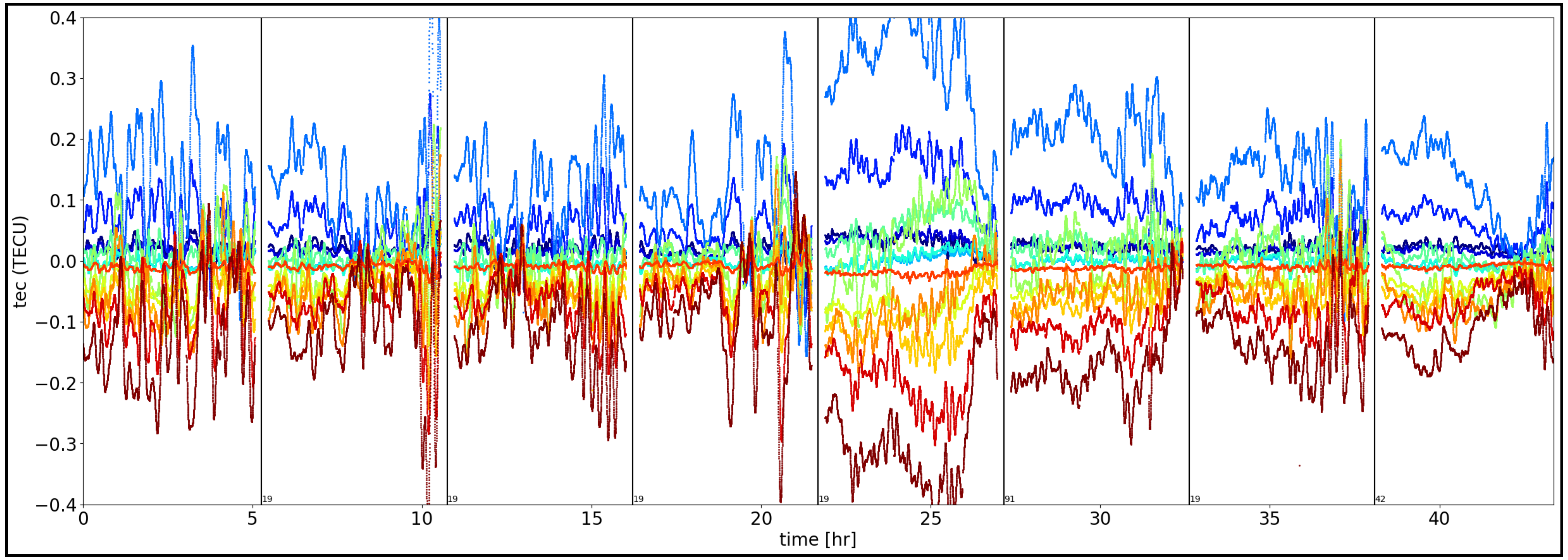
- Data size, up to 10s TB/night
- Complex beam
- Large FoV
- Low S/N
- Ionosphere

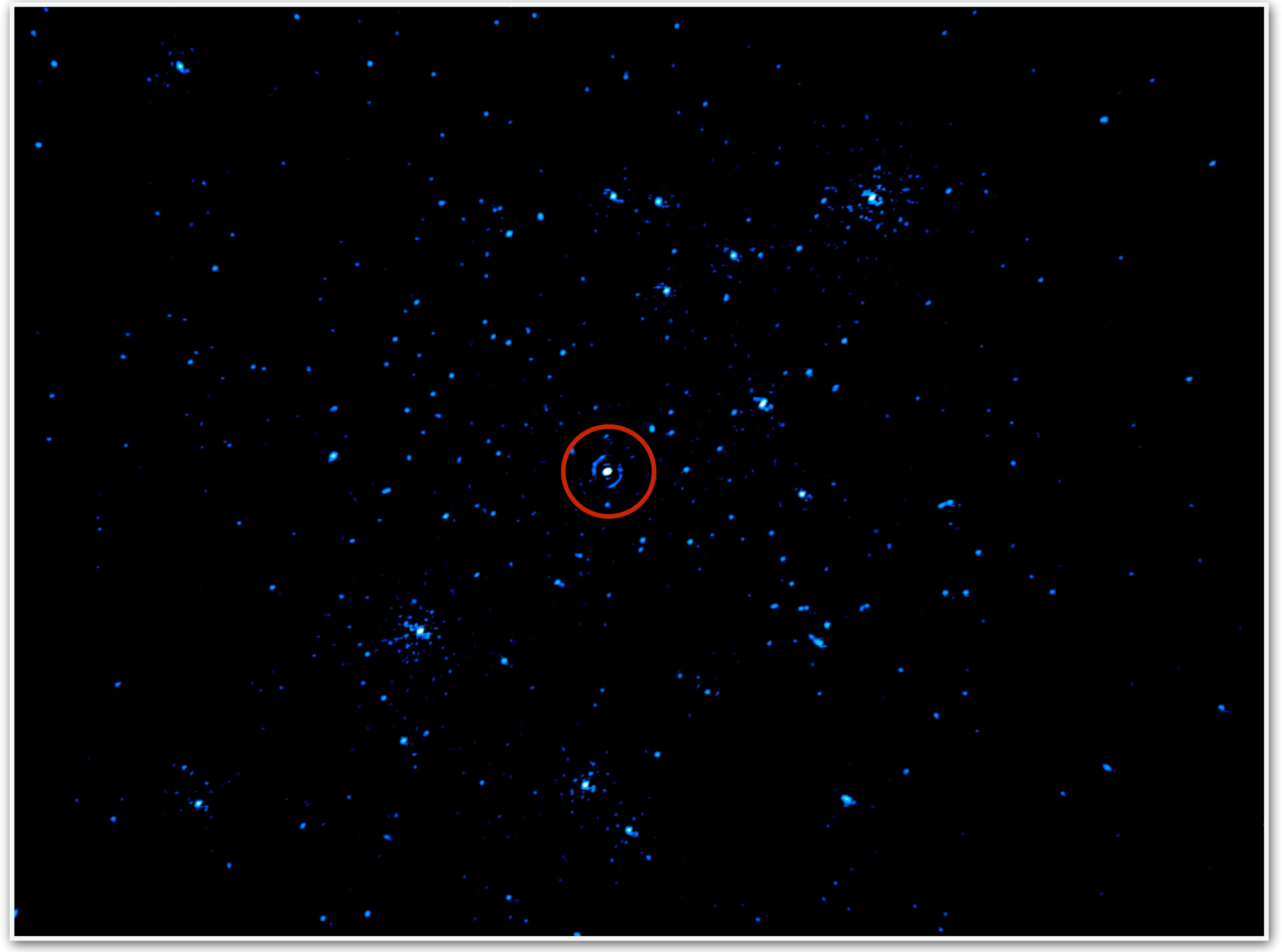


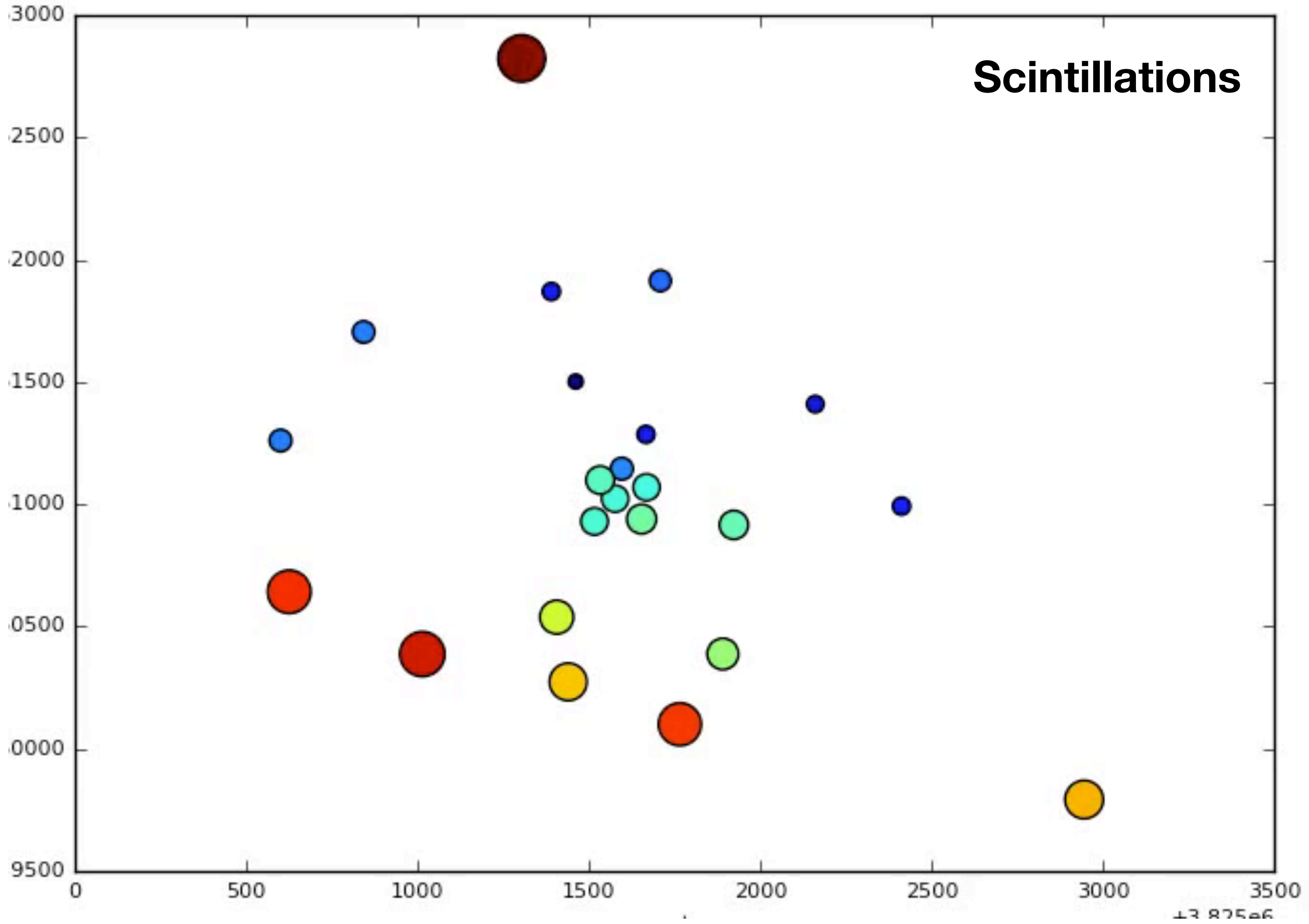


# Importance of the ionosphere effects

de Gasperin+ 2018, A&A, 615, A179






- In radio interferometry we can measure “differential” TEC (total electron content)
- On bright sources (calibrator) we reach milliTECU precision on scales of seconds
- At frequencies <40 MHz, the ionospheric third order becomes non-negligible
- Amplitude are affected though scintillations

$$\Phi^{\text{ion}} = -\frac{2\pi\nu}{c}\int_{\text{LoS}} (n-1)\,\mathrm{d}l$$

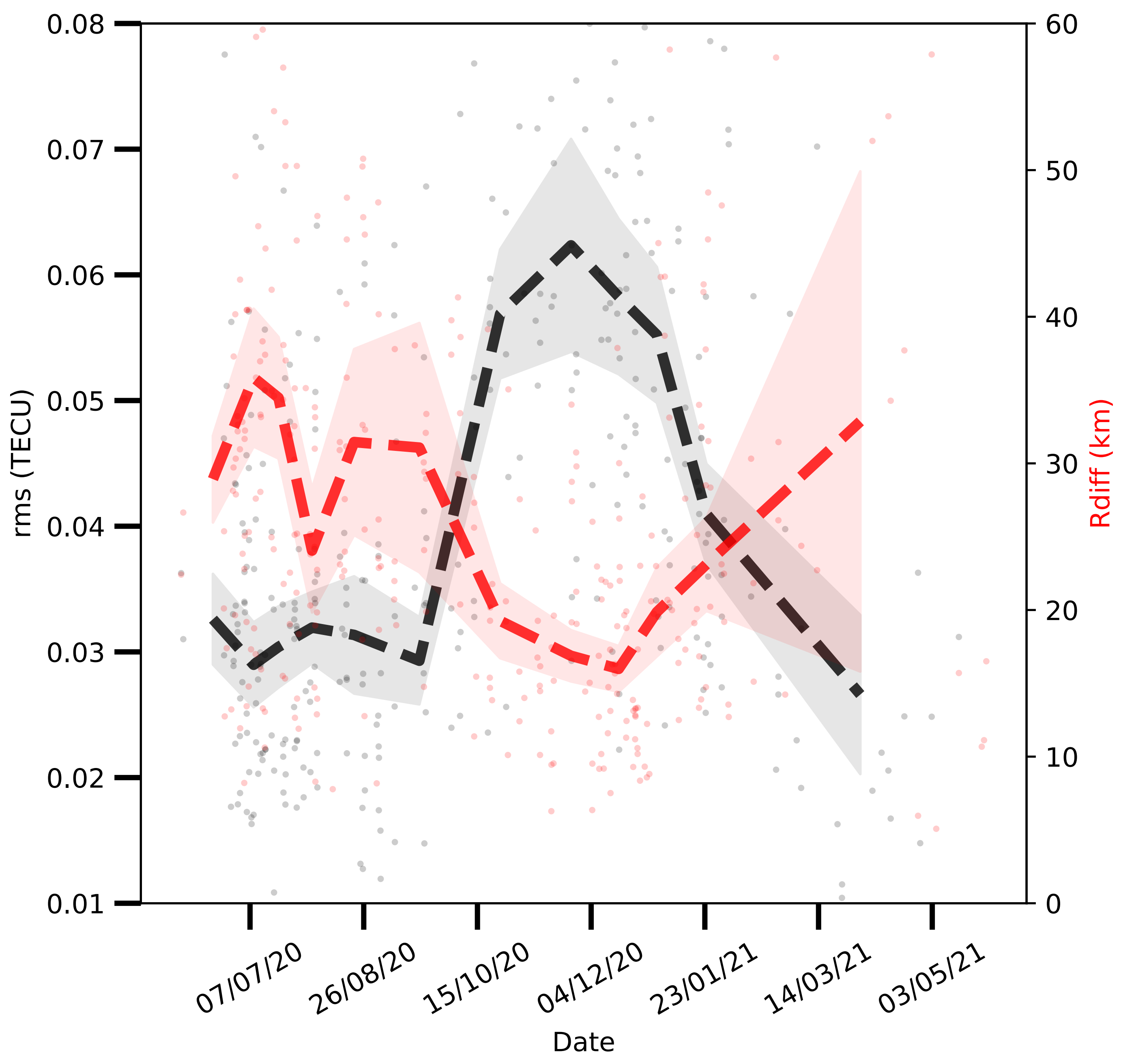
$$n \approx 1 - \frac{q^2}{8\pi^2 m_e \epsilon_0}\cdot\frac{n_e}{\nu^2} \pm \frac{q^3}{16\pi^3 m_e^2 \epsilon_0}\cdot\frac{n_e B\cos\theta}{\nu^3}$$

**Delay**

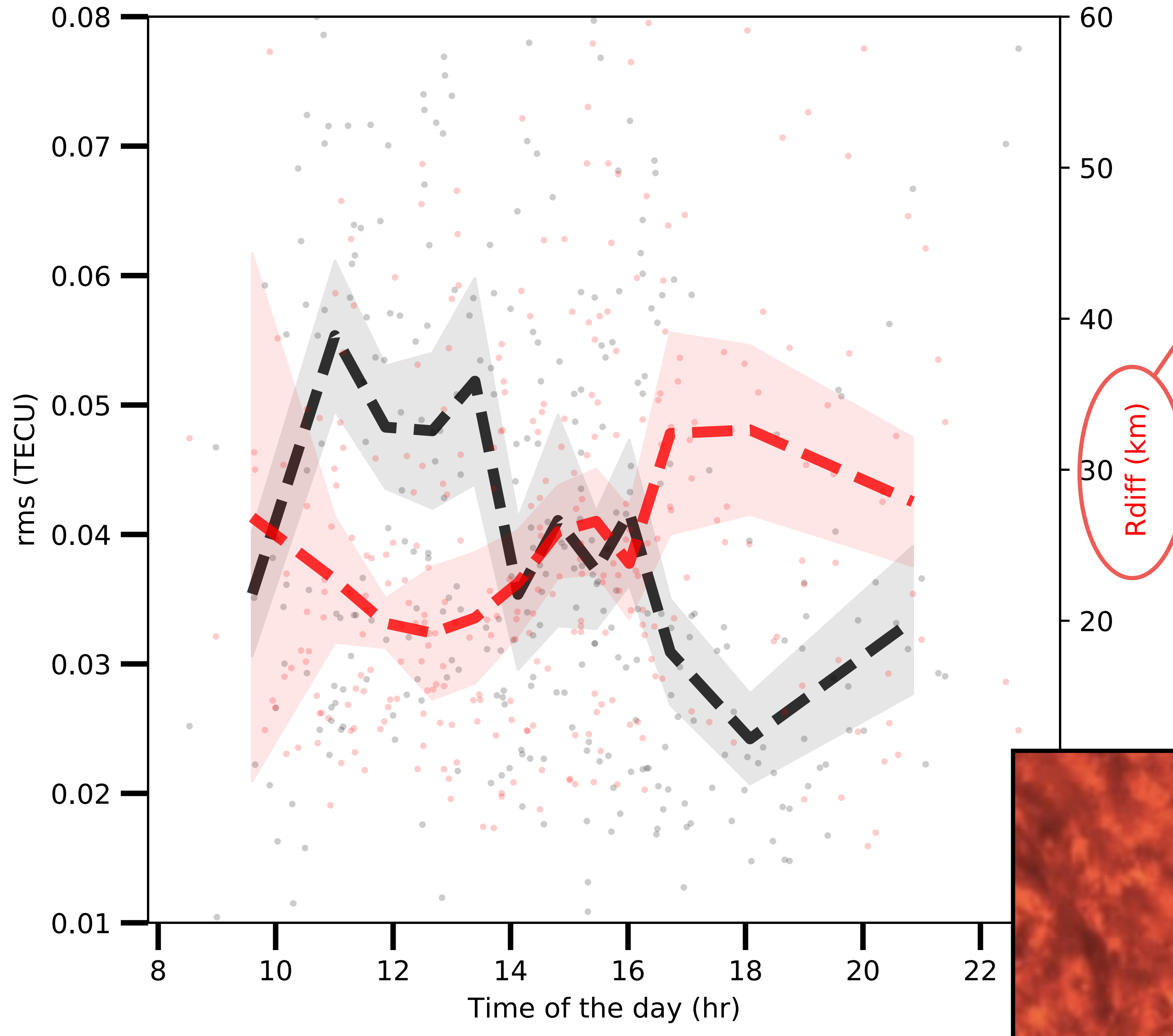
**Faraday Rotation**

# Observe in the right moment

## Date

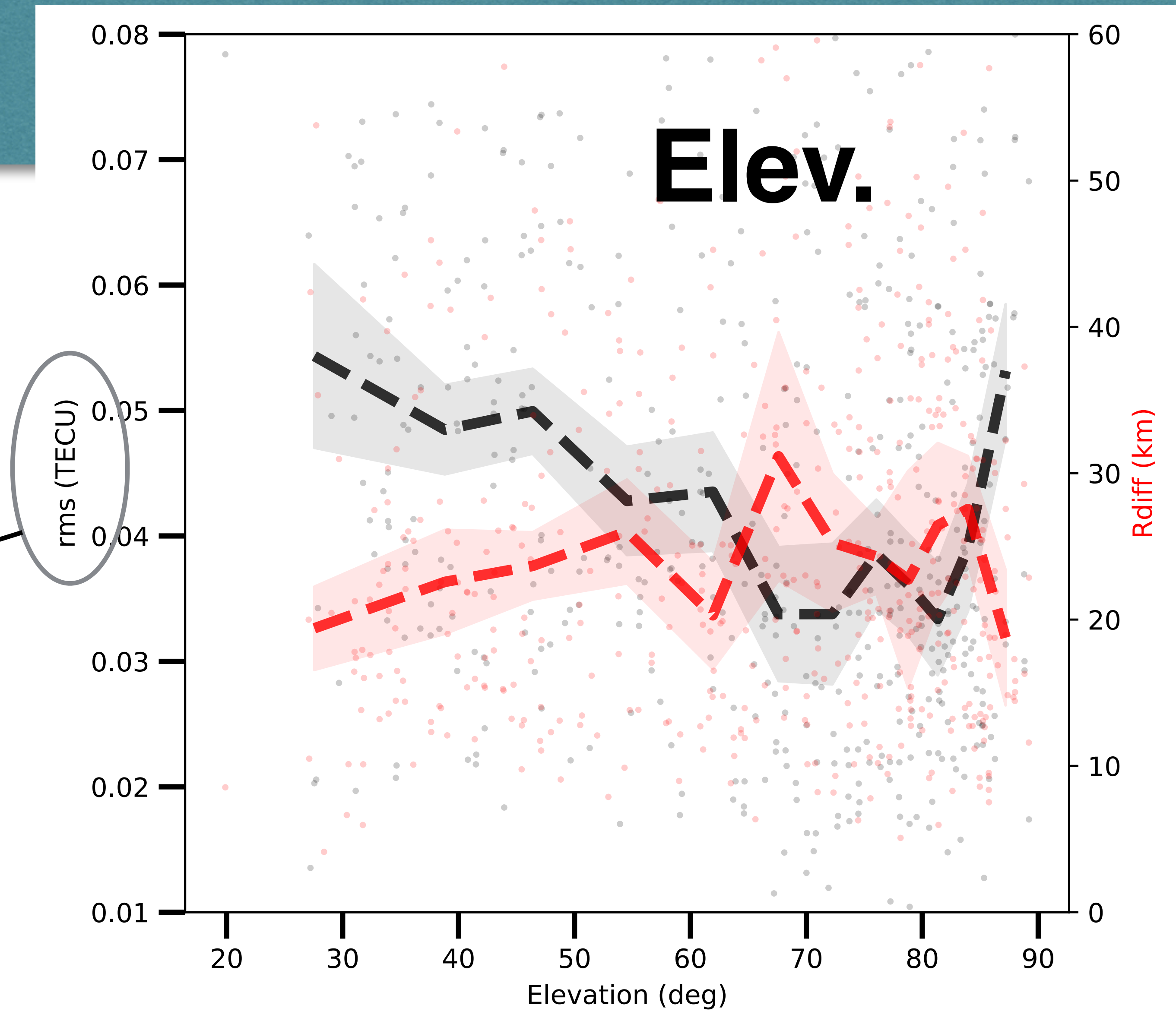



## Time of the day

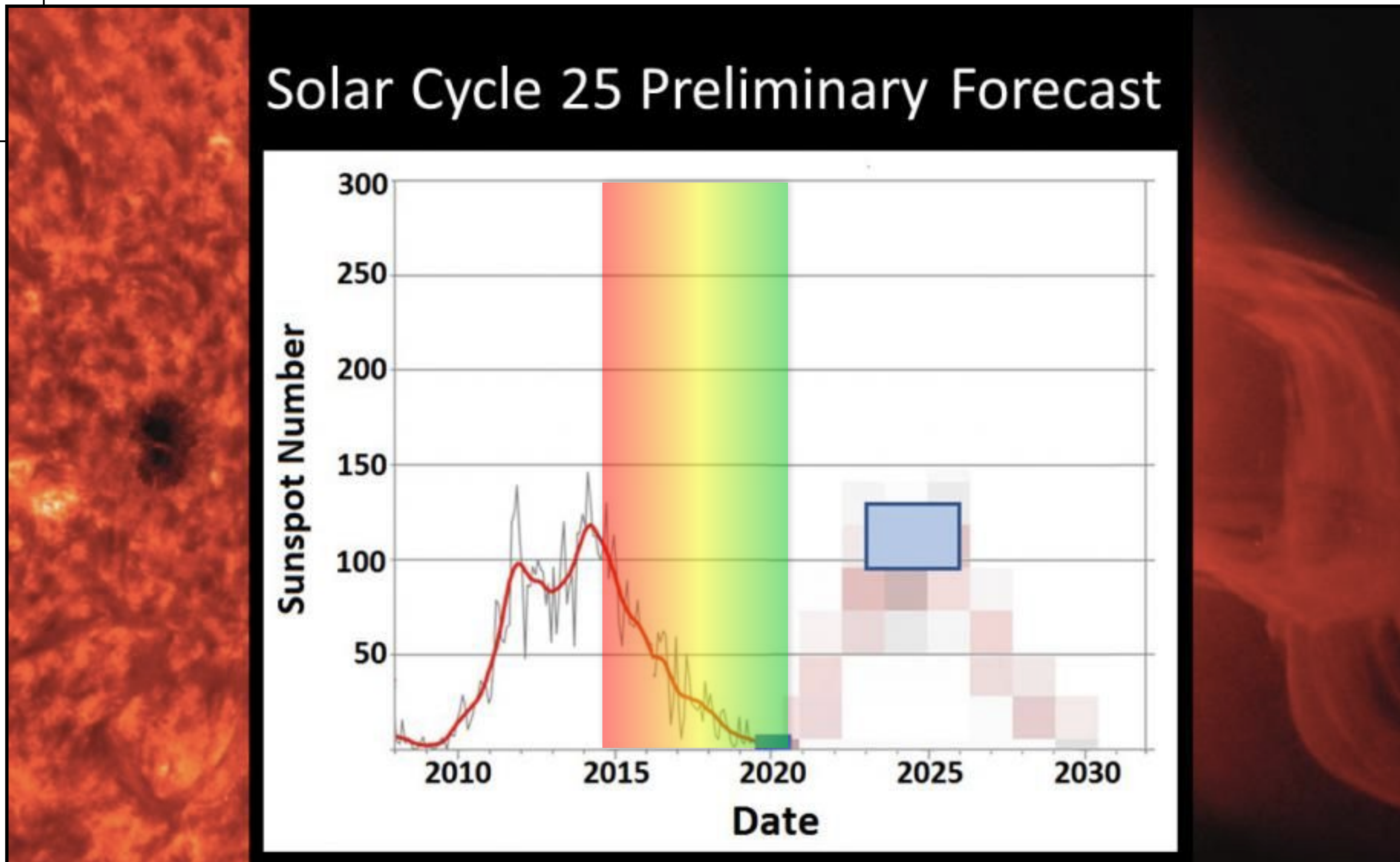



dTEC rms (RS)

Diffractive radius



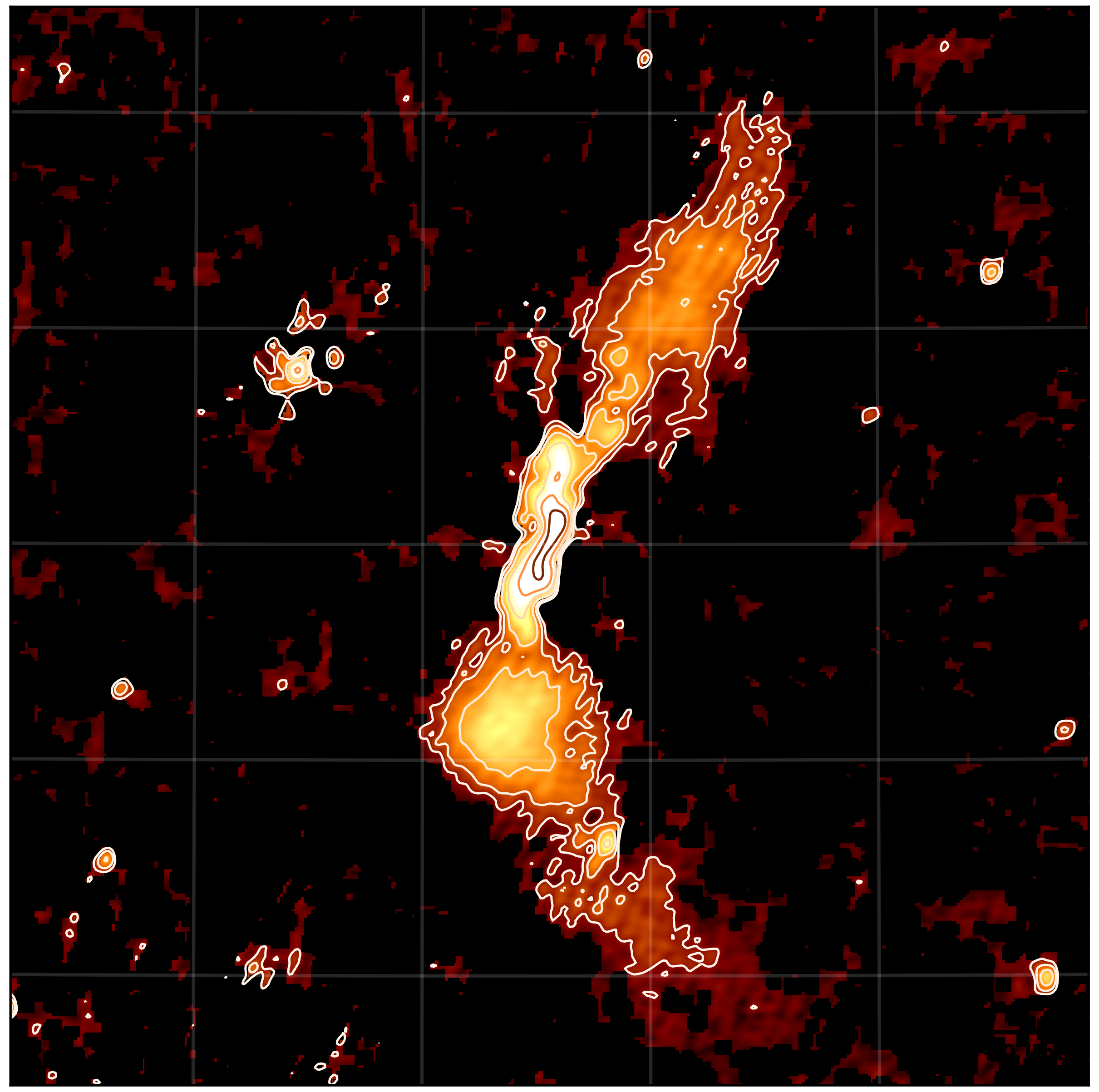

- From summer to winter the conditions worsened
- No strong dependence with the time of the day (maybe better evenings?)
- Expected dependency with elevation
- Global Geomagnetic Activity indexes: some relation (with the $A_p$>~25 then you have a geomagnetic storm)

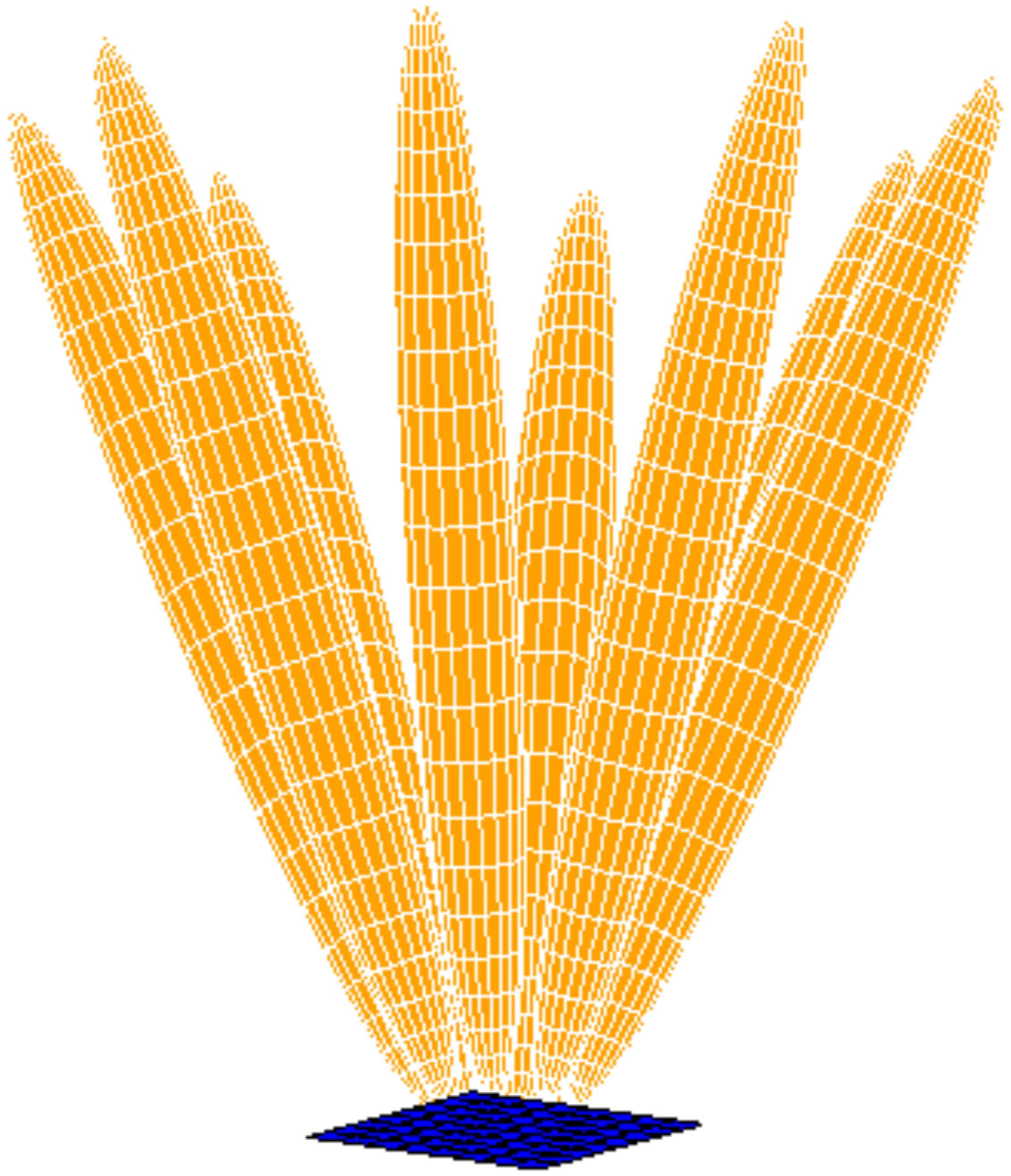


# Multi beam observations

## We really need to learn how to do multi-beaming observations!

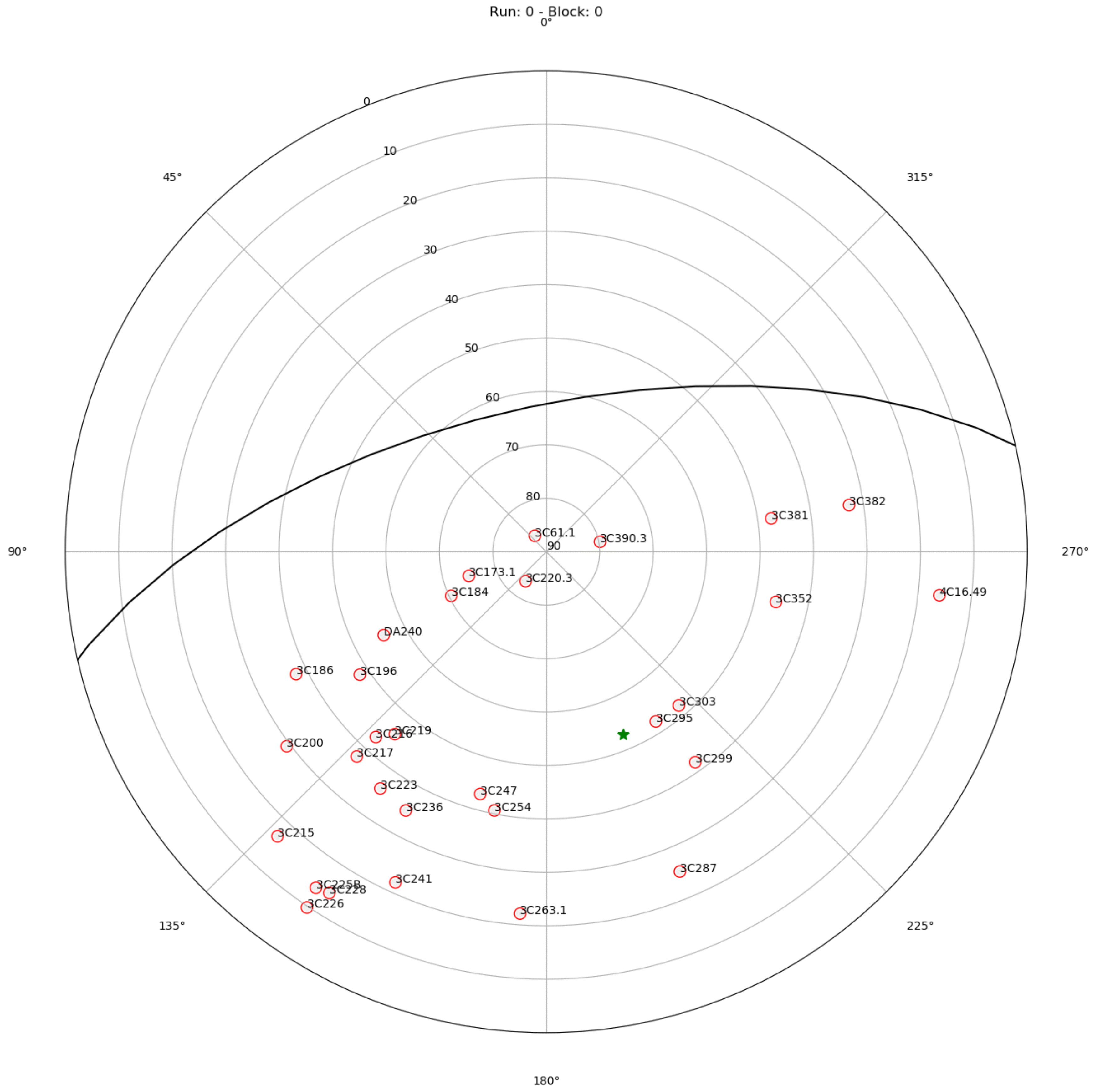
- Important improvement in survey speed
- You might need a small band for a project but a long observing campaign (e.g. transients)
- For a truly multi-bean telescope we might think to allocate time*band

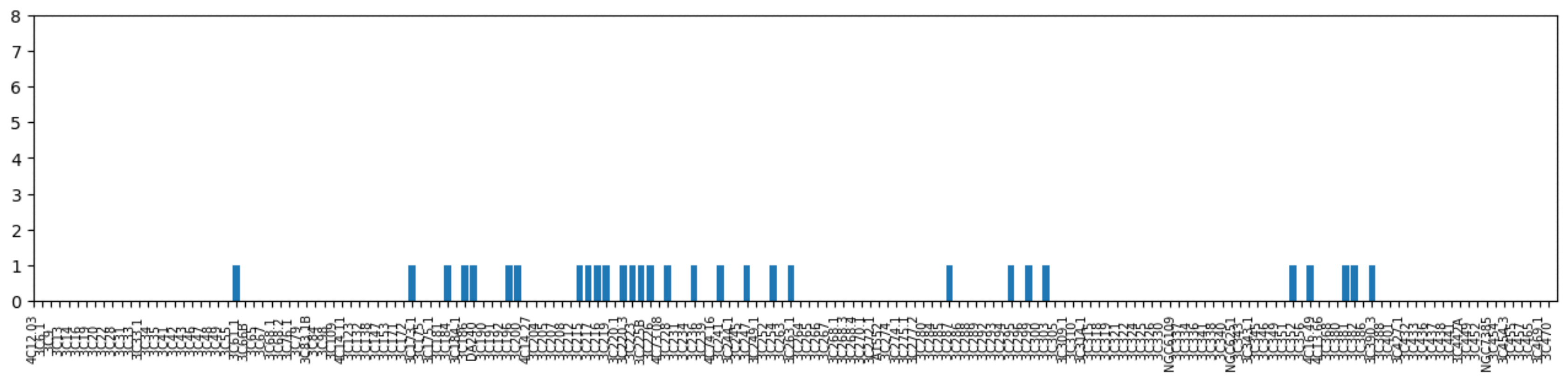




**173 sources**
**8 hrs synthesis per source**
**30 beams at the same time**

**A total of only 48 hrs of telescope (instead of 1384)**



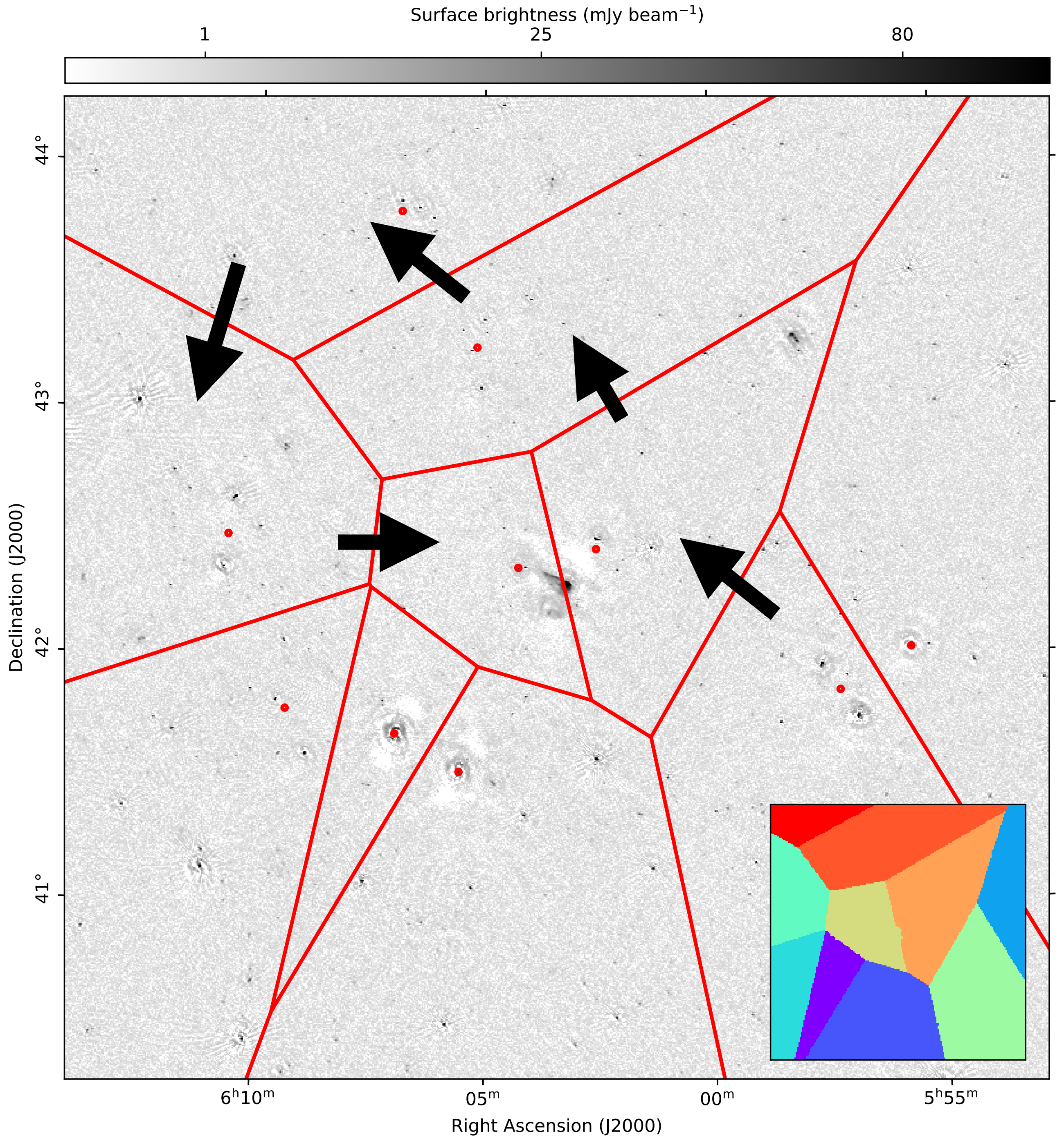



# Strategies: calibration

## Serial calibration

1. Find the brightest source in the field (dd-calibrator)
2. Remove the flux from everything else (e.g. subtraction, smearing)
3. Calibrate
4. Move to the next

Example: DP3

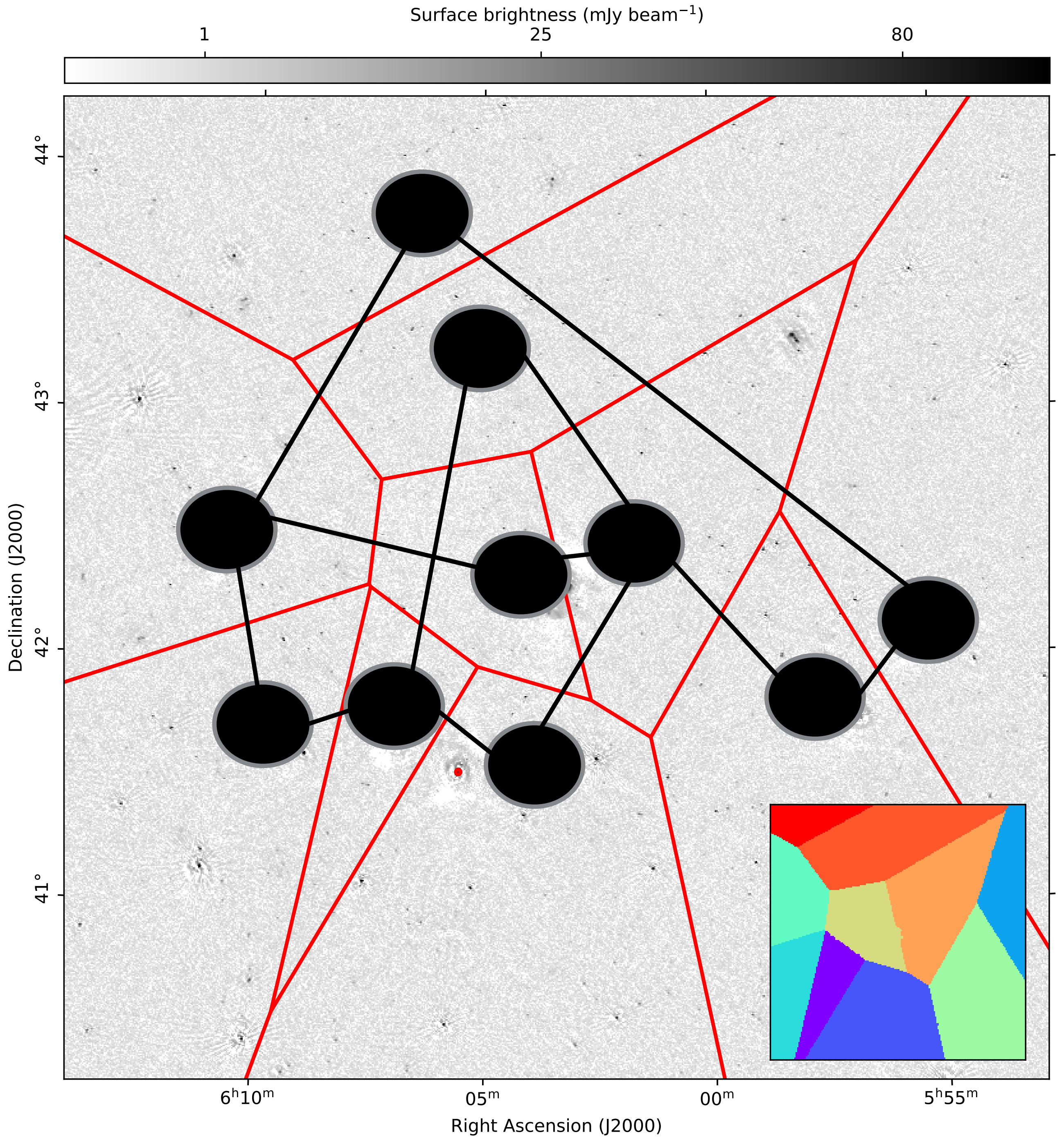



**Advantages**:
- Scalable
- Easy-to-implement

## Parallel calibration

1. Find brightest sources in the field (dd-calibrators)
2. Calibrate

Example: KillMS, DP3




**Advantages**:
- Possibly faster
- More precise

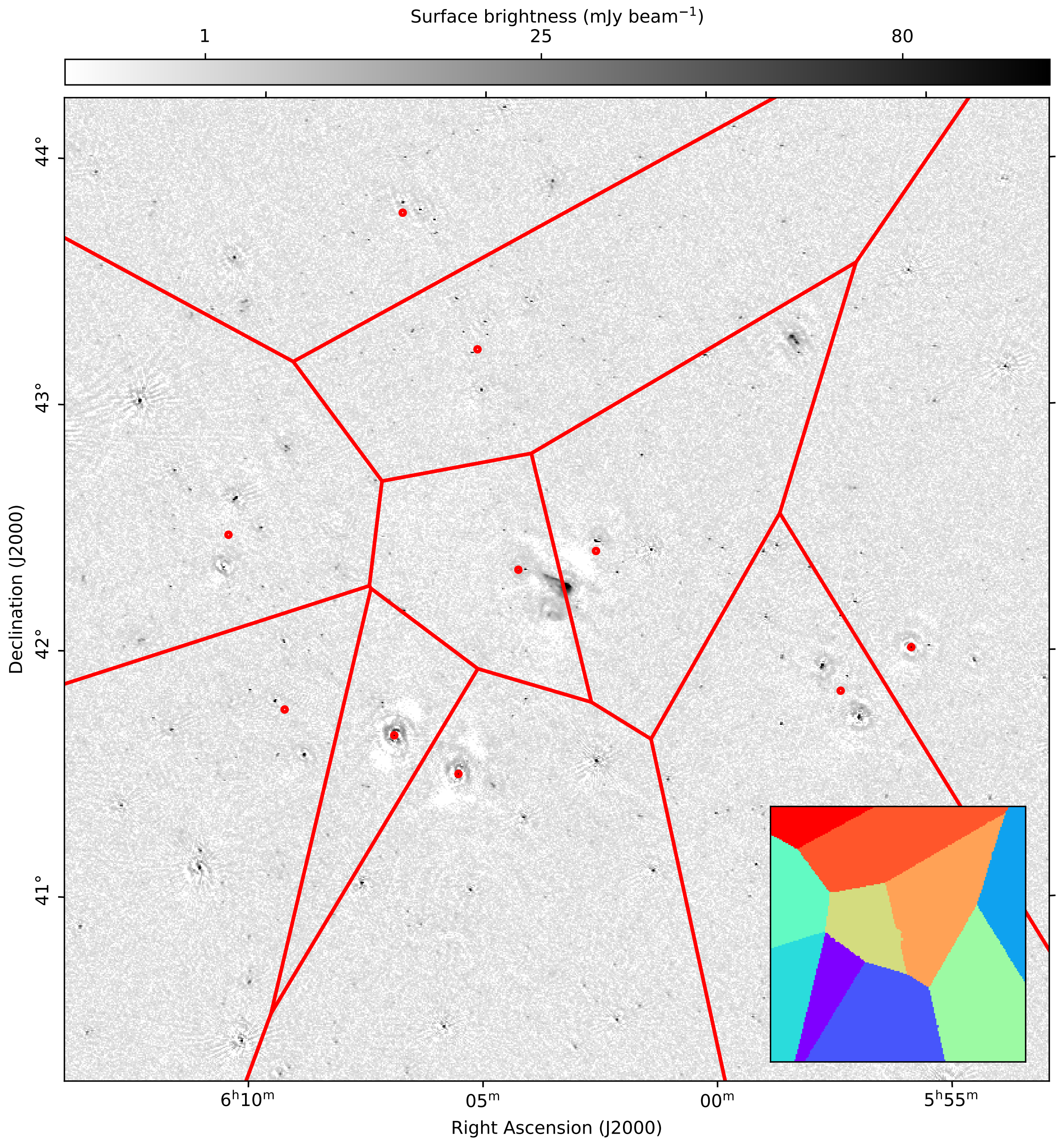
**de Gasperin+ 2021, A&A, 642, A85**

# Strategies: imaging

## Facet imaging

1. Find solutions in “enough” directions
2. Isolate the flux coming from each region of the map where the solution applies
3. Image each region
4. Stitch the regions together (or use a special imager)

Example: DDFacet



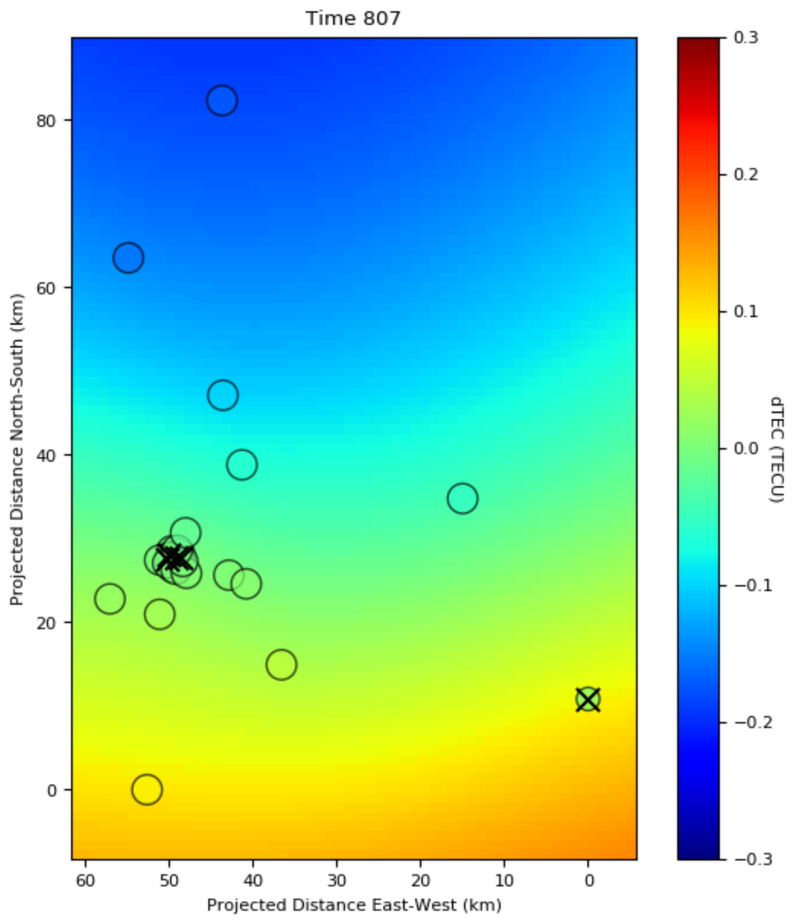

**Advantages**:
- Fast
- Scalable
- Easy-to-implement

de Gasperin+ 2021, A&A, 642, A85

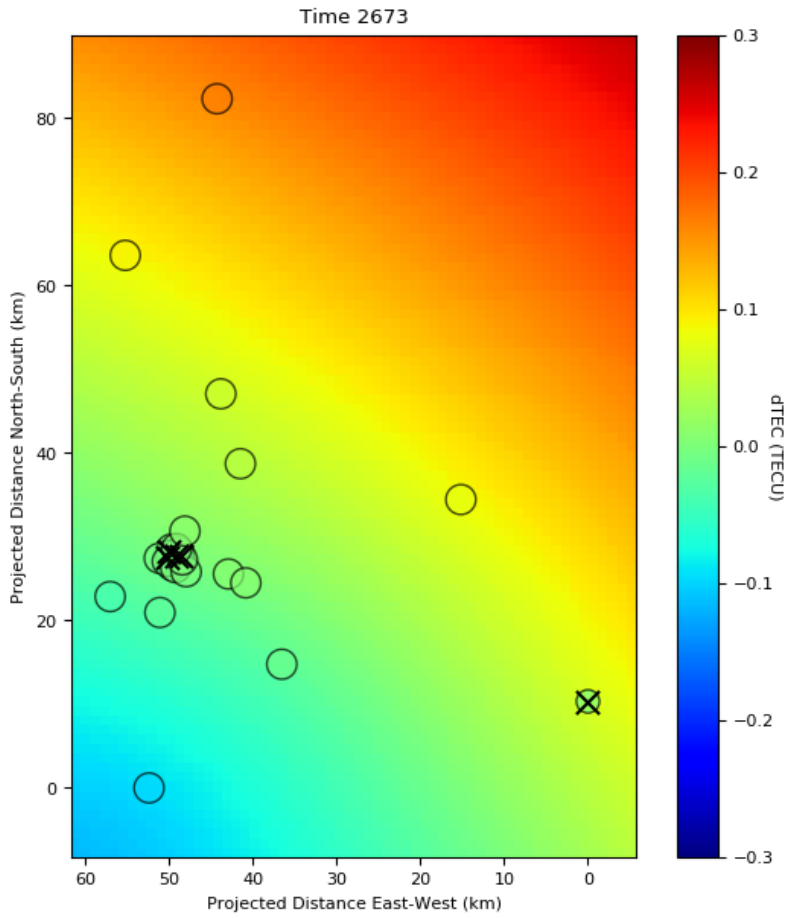
## Screens

1. Find solutions in “enough” directions
2. Interpolate the solutions on a screen (assumptions!)
3. Image the entire field while applying the screen

Example: WSclean + IDG

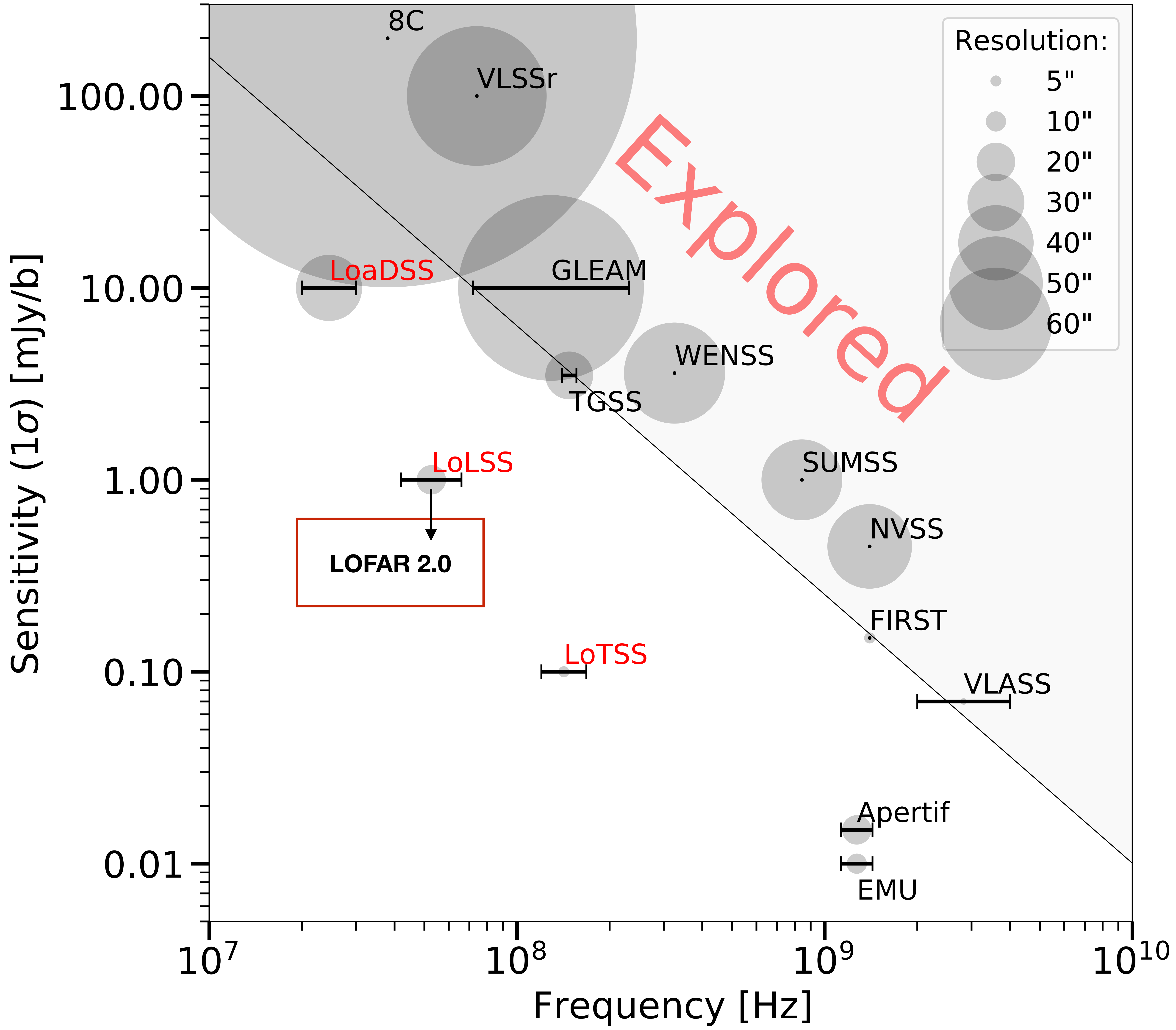



**Advantages**:
- Proper interpolation
- Smooth result
- Less degrees of freedom




de Gasperin+ 2018, A&A, 615, A179

# LOFAR Surveys




**LoTSS** (LOFAR Two-metre Sky Survey; Shimwell et al. 2016), is a wide area survey at 120 - 168 MHz that uses the High Band Antenna (HBA) system of LOFAR.

**LoLSS** (LOFAR LBA Sky Survey; de Gasperin et al 2021), is the sibling survey of LoTSS carried on in the frequency range 42 - 66 MHz using the LOFAR Low Band Antenna (LBA) system.

**LoDSS** (LOFAR Decameter Sky Survey), is the first attempt to map the sky at 12-30 MHz.

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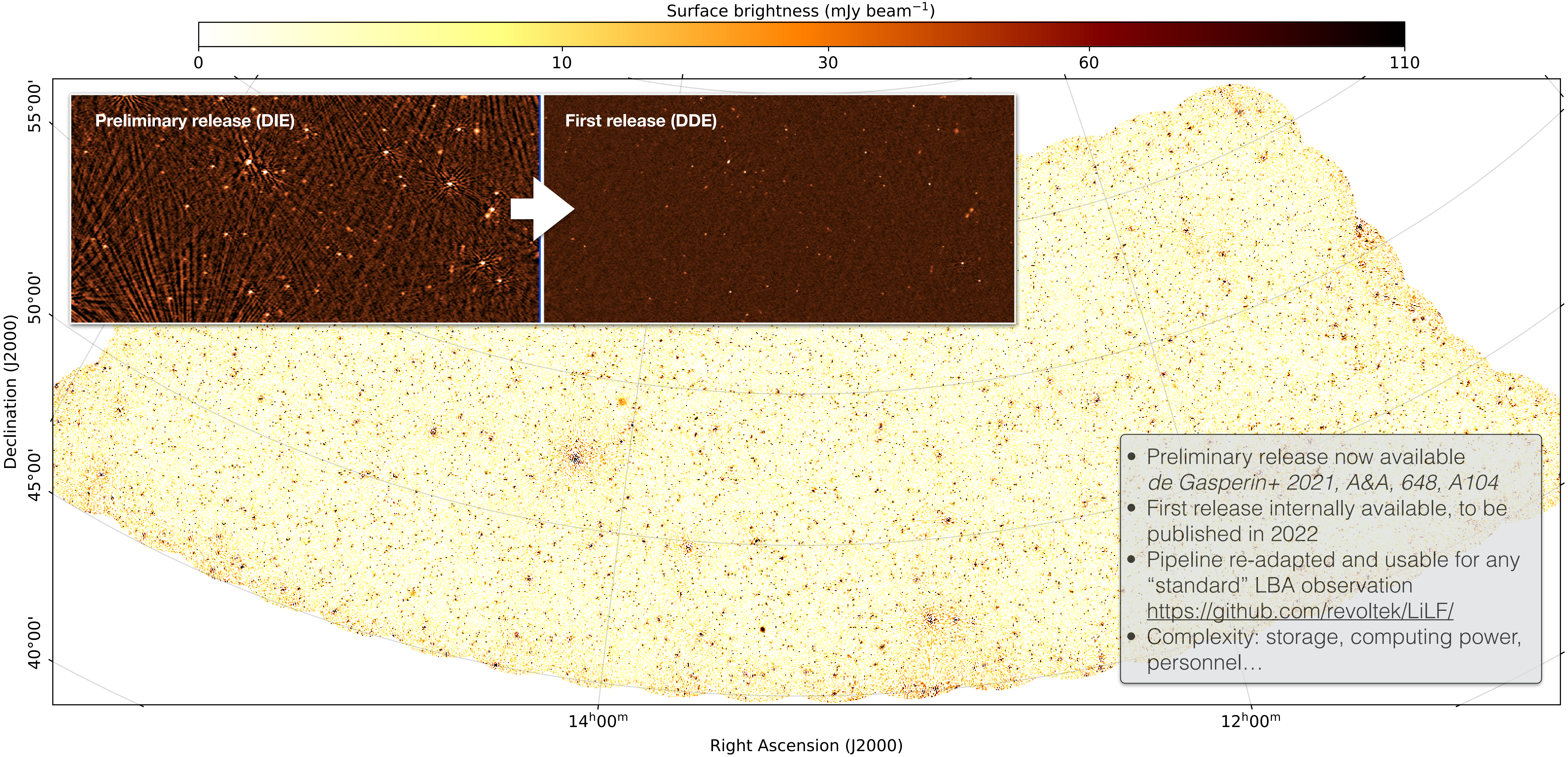
**Improvements** with LOFAR 2.0:
- Better sensitivity (few 100s uJy/b with typical observation)
- Better beam shape
- Better ionospheric solutions

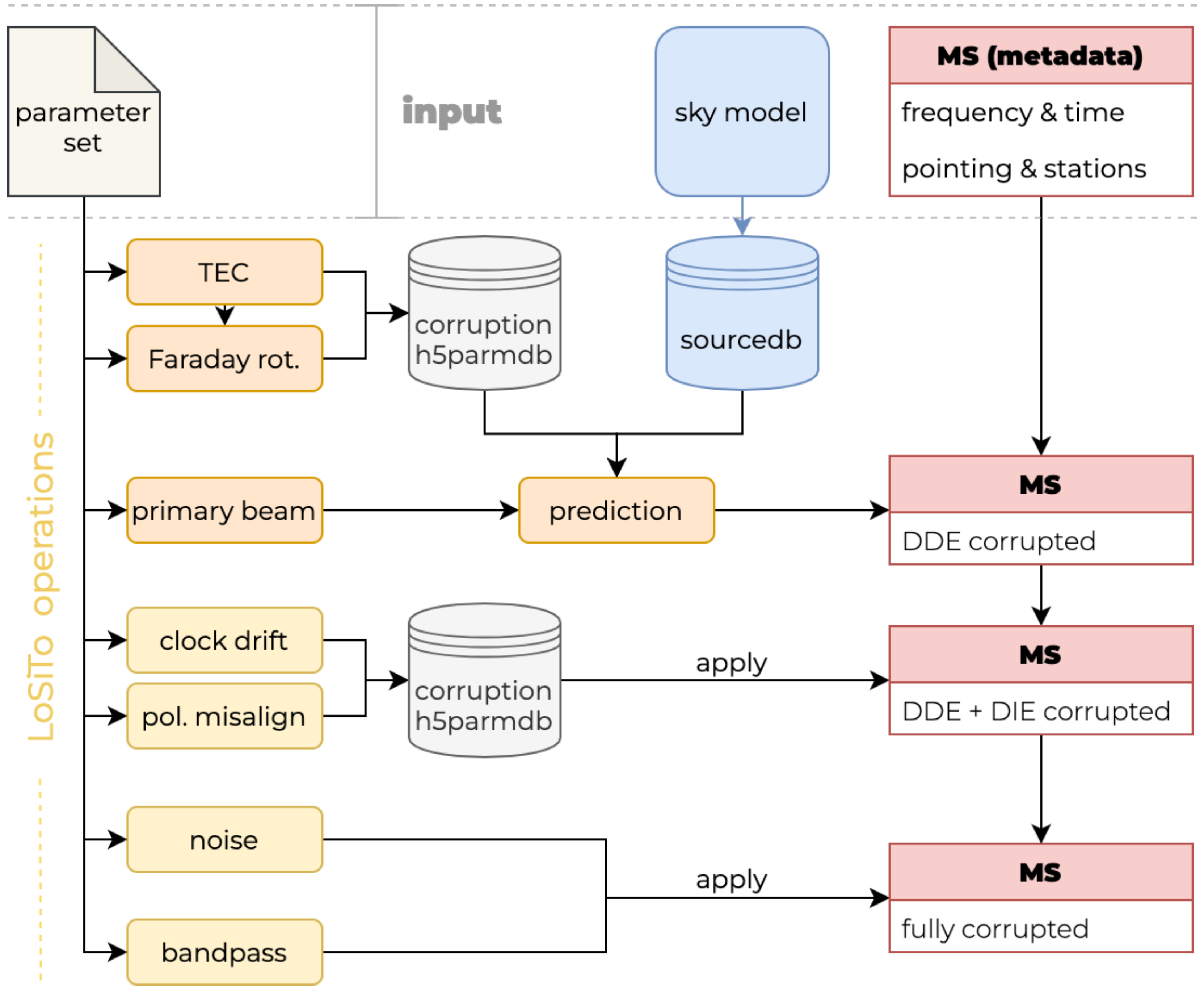
**Implying**:
- Higher dynamic range in sub-optimal ionospheric conditions
- Imaging the lower half of LBA band

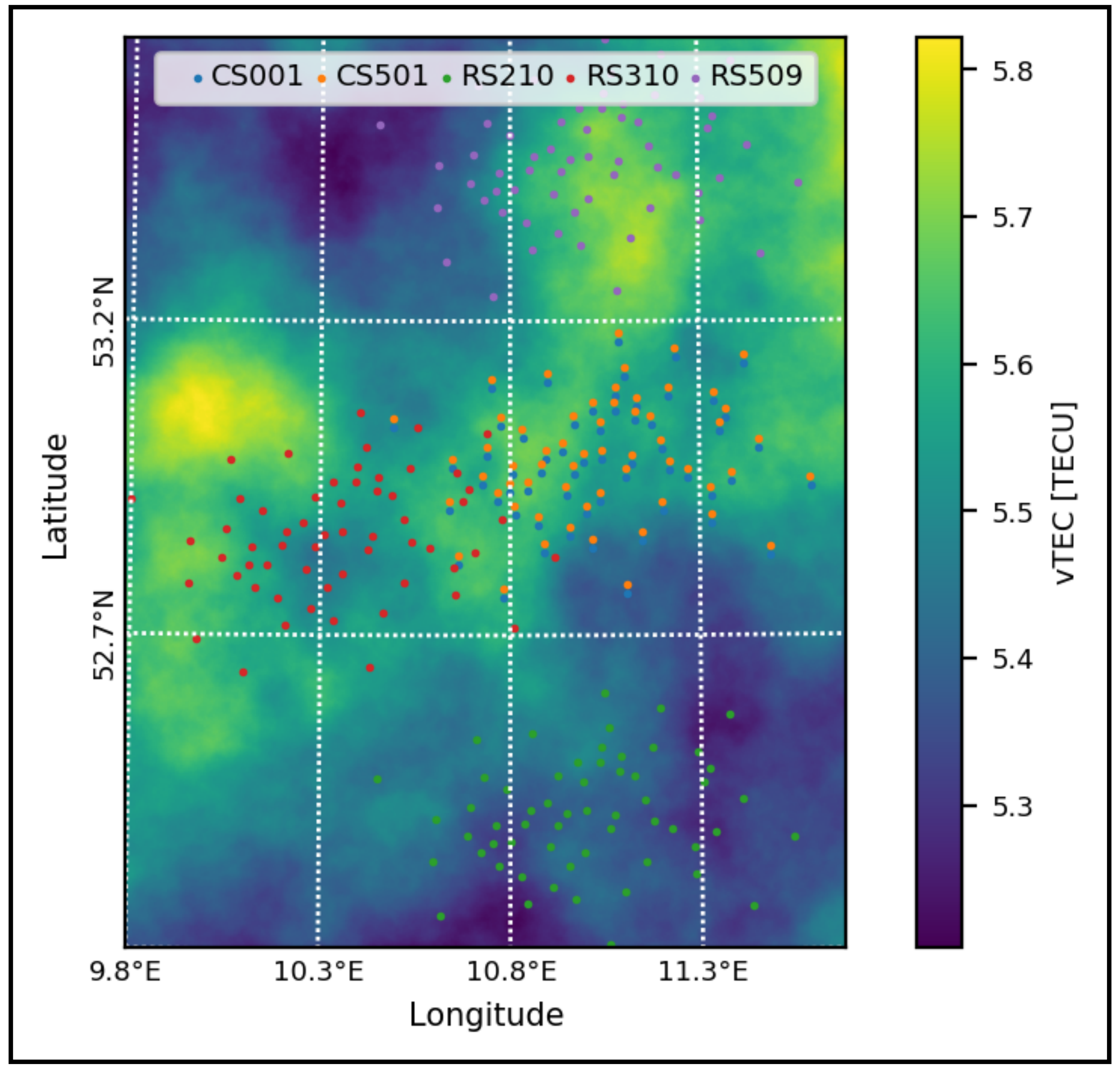
# LoLSS - LOFAR LBA Sky Survery

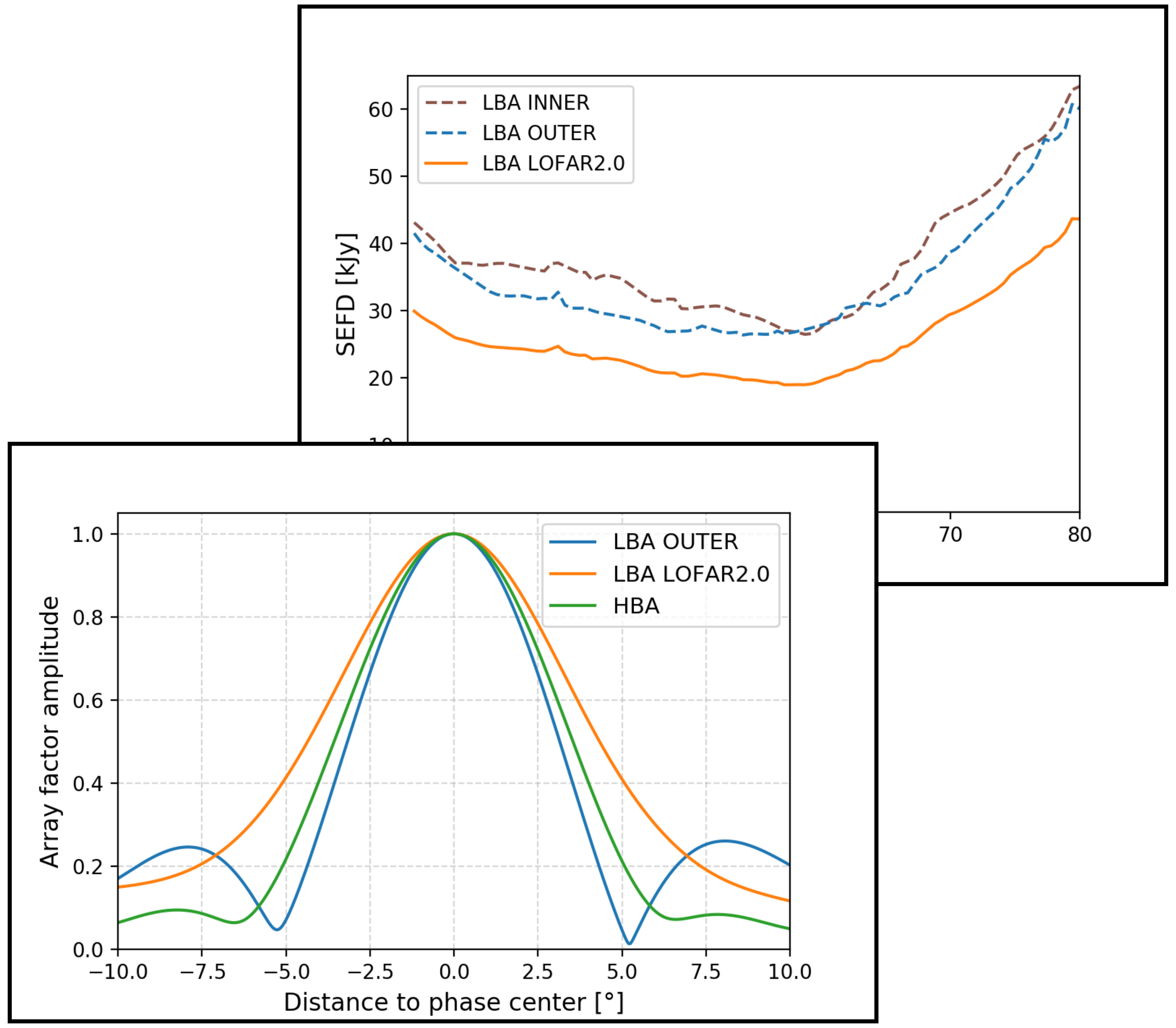


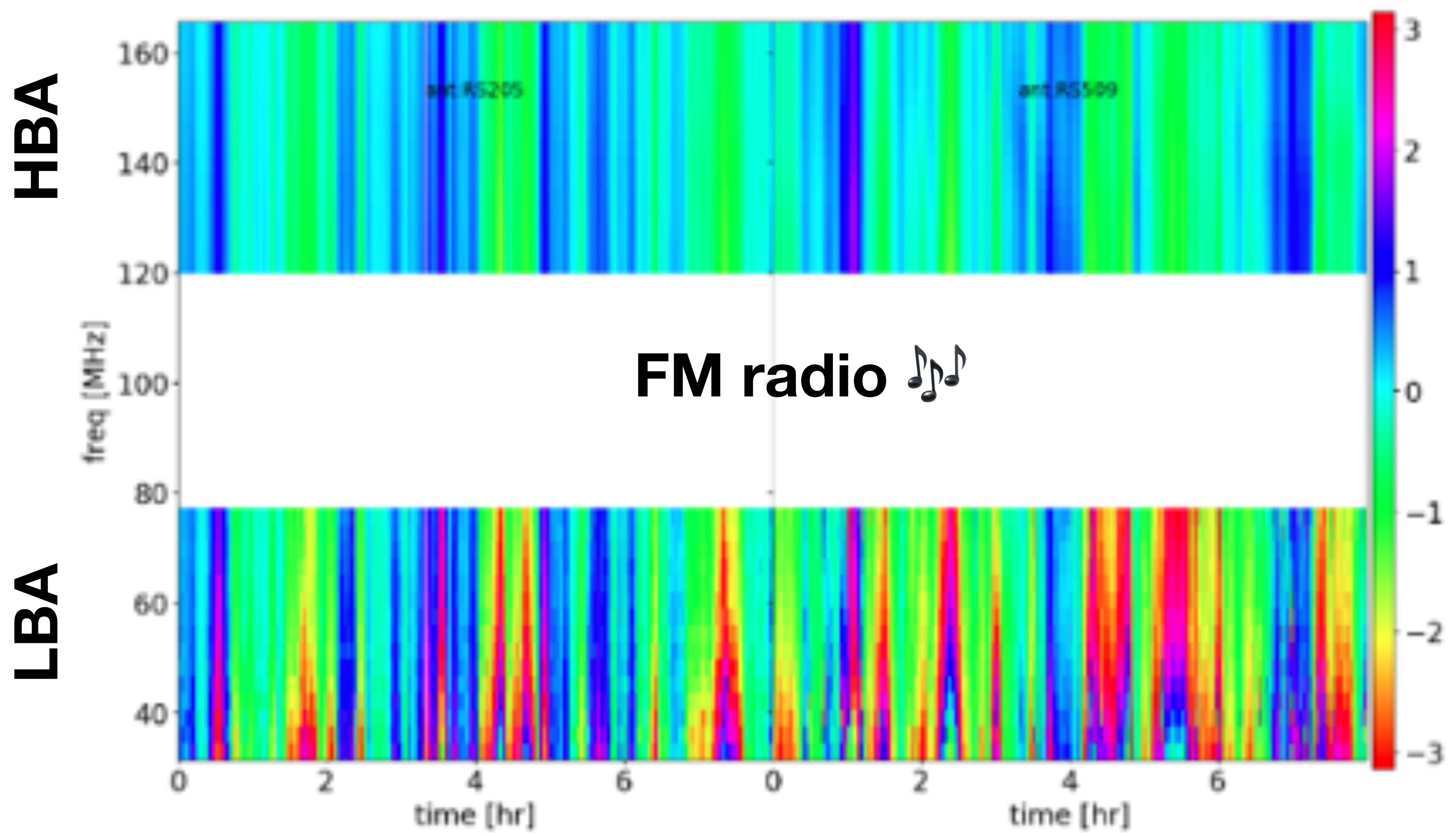

- Preliminary release now available *de Gasperin+ 2021, A&A, 648, A104*
- First release internally available, to be published in 2022
- Pipeline re-adapted and usable for any "standard" LBA observation https://github.com/revoltek/LiLF/
- Complexity: storage, computing power, personnel…

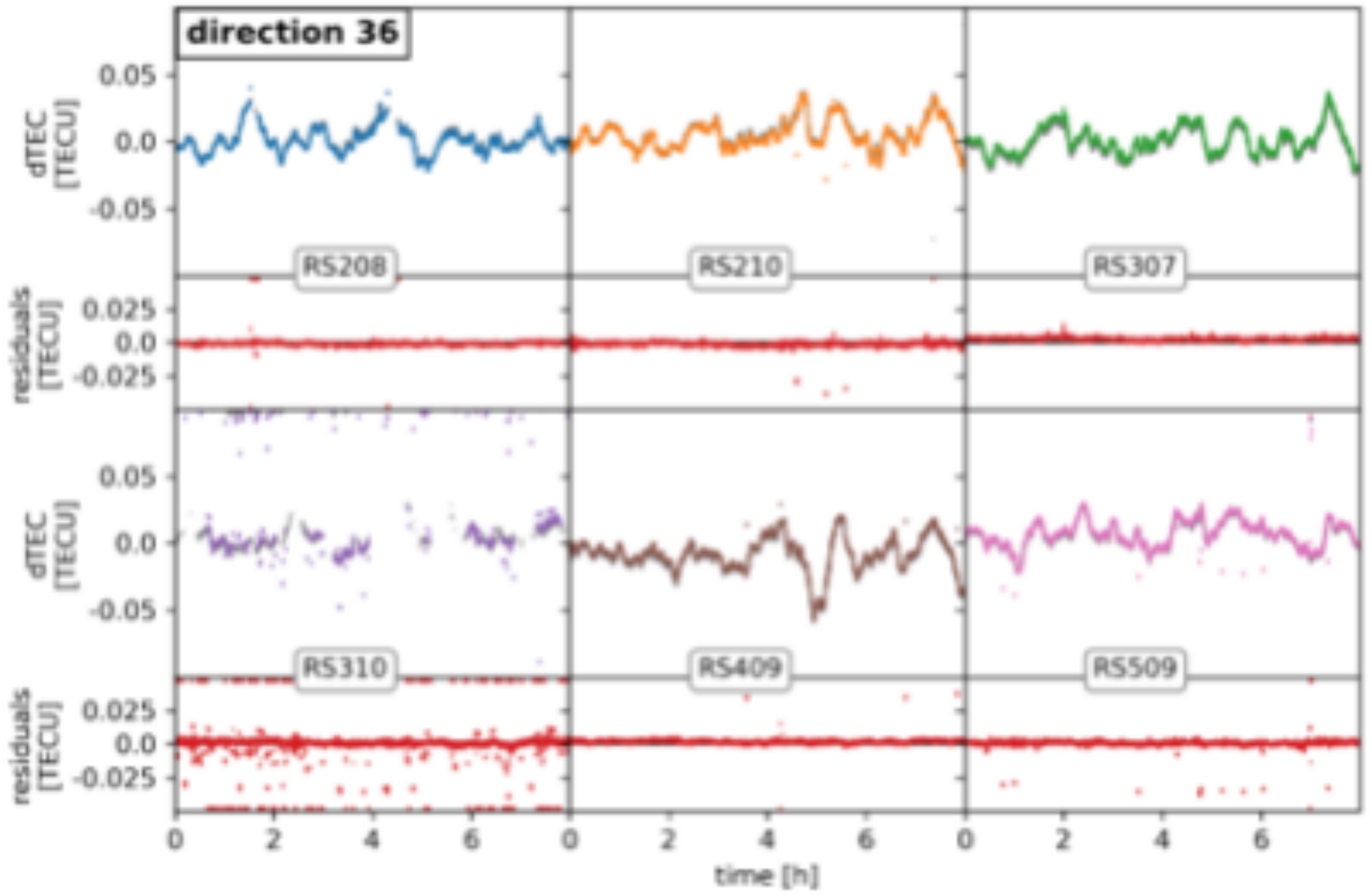
# Simulations simulations simulations



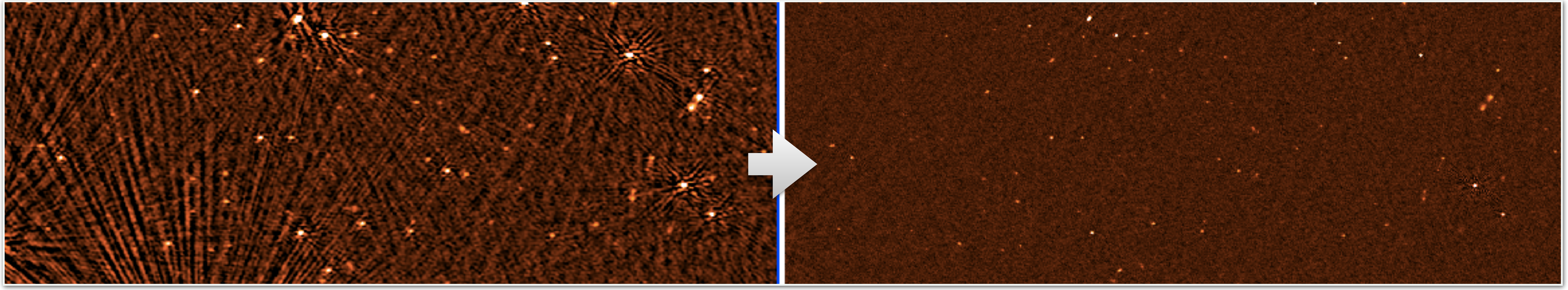




- **LoSiTo**: LOFAR Simulation Tool
- LOFAR 2.0 simulated data: simultaneous HBA+LBA observations including all known systematics
- Test of calibration strategies

**Edler, de Gasperin, Rafferty**
**A&A, 652, A37**

# Conclusions

- Low-freq radio astronomy (e.g. LOFAR) and the ionosphere are tightly interconnected.
- Important to figure out how to use multi-beam.
- Two main **calibration** approaches:
  - Serial calibration (exploiting subtraction, “Peeling”, smearing)
  - Parallel calibration
- Two main **imaging** approaches:
  - Facet imaging
  - Screen imaging
- Simulations of the telescope performance should be planned in advance.



- If you are a member of LOFAR Surveys KSP - check out the First Data Release of LoLSS
- Otherwise stay tuned for the public release in 2022

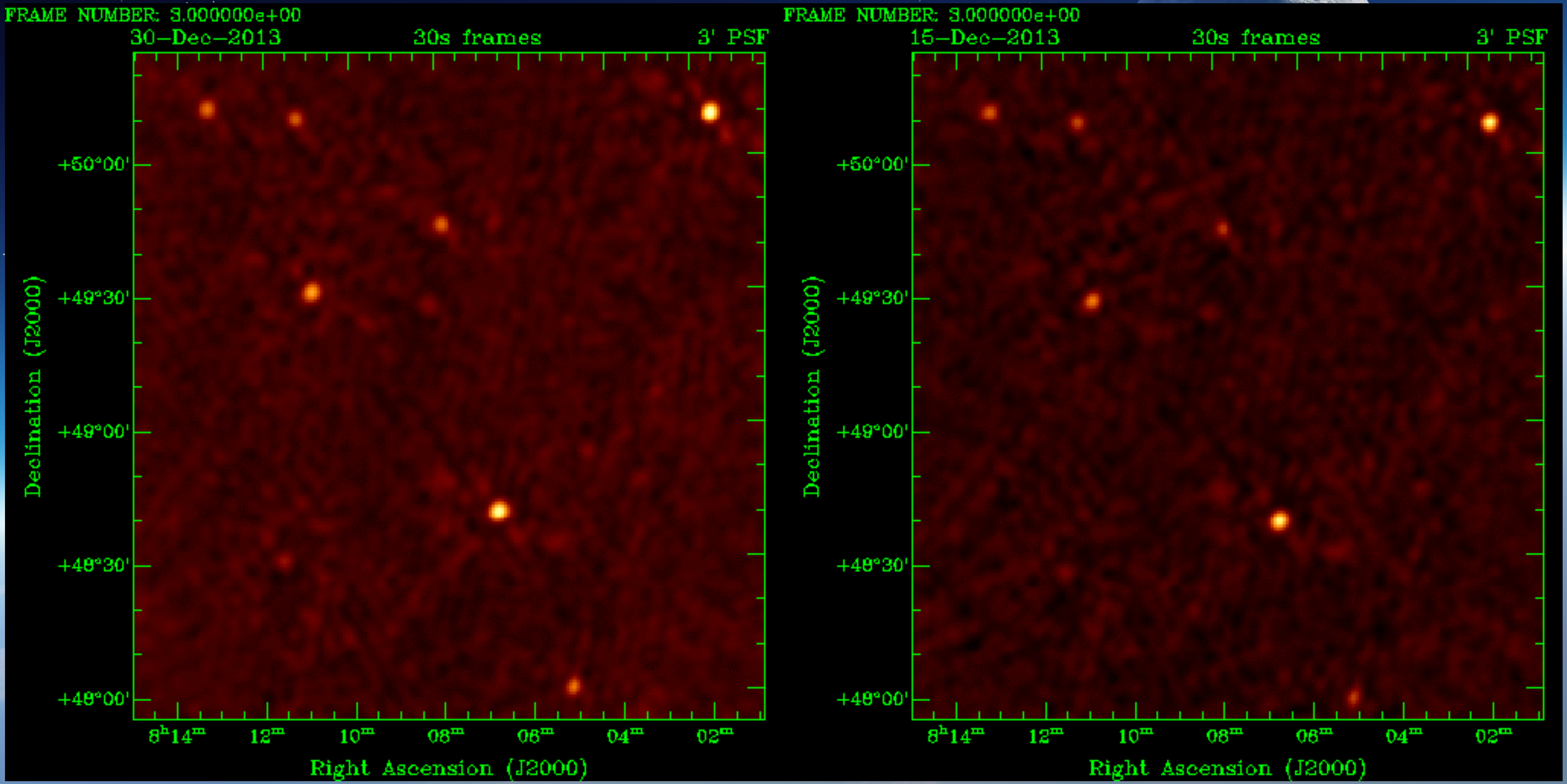
# LOFAR Surveys

| **Survey** | Calibration | Imaging | CPU Time (core hour) |
|---|---|---|---|
| **LoTSS (120-168 MHz)** | Simultaneous (killMS) | Facet imaging (DDF) | 6,000 CH / field |
| **LoLSS (42-66 MHz)** | Serial (DP3) | Facet imaging (DDF) | 1,000 - 2,000 CH / field |
| **LoDSS (12-15 MHz)** | Serial (DP3) | Screen (WSc+IDG) | TBD |
| **LoTSS - LB (120-168 MHz)** | Serial (DP3) | Facet + Screen (WSc+IDG) | 260,000 CH / field |

# Ionosphere

Calm

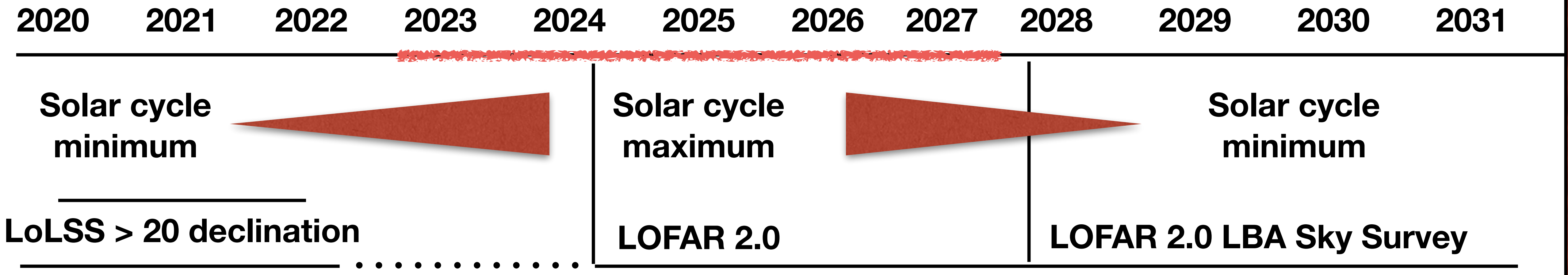
Active

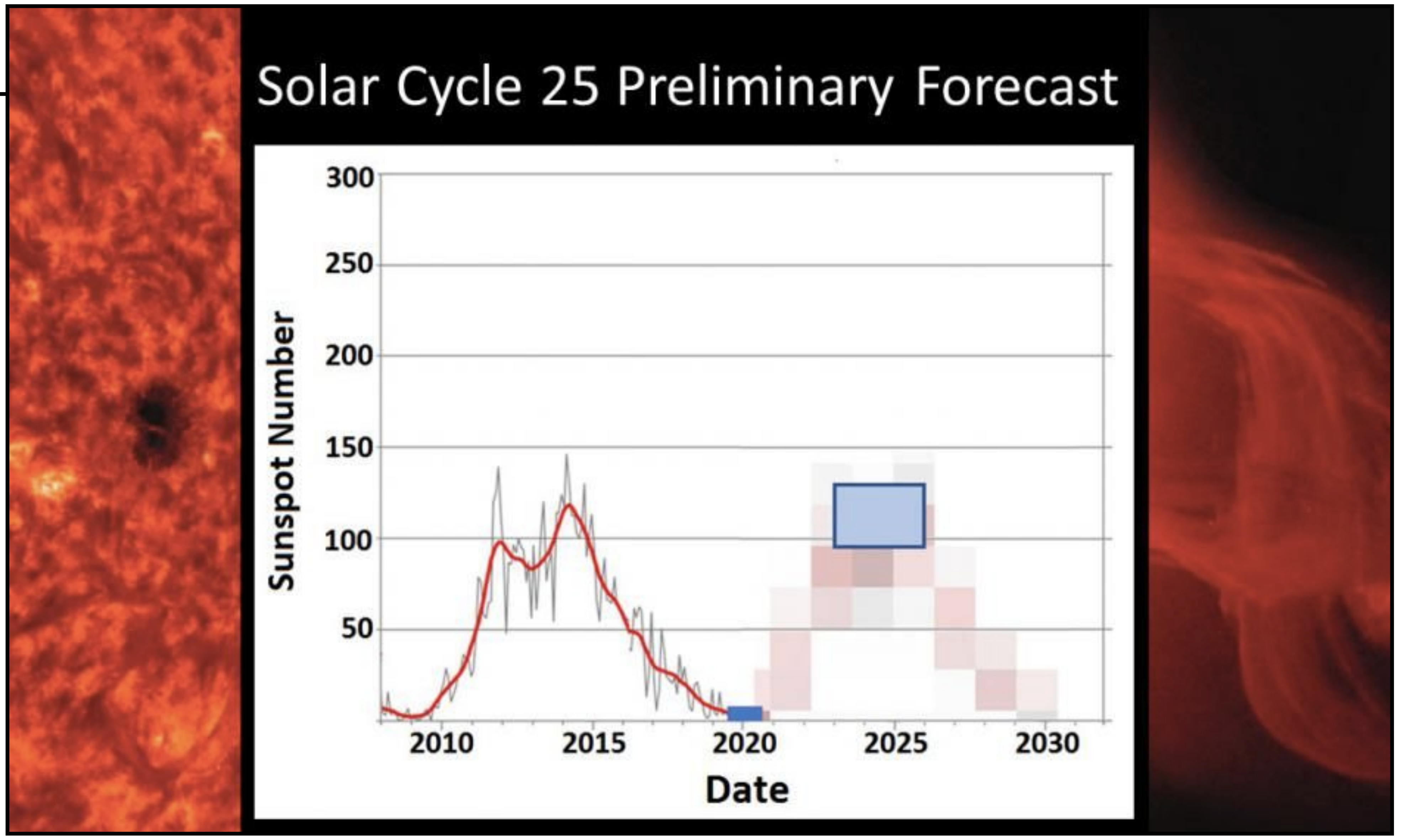


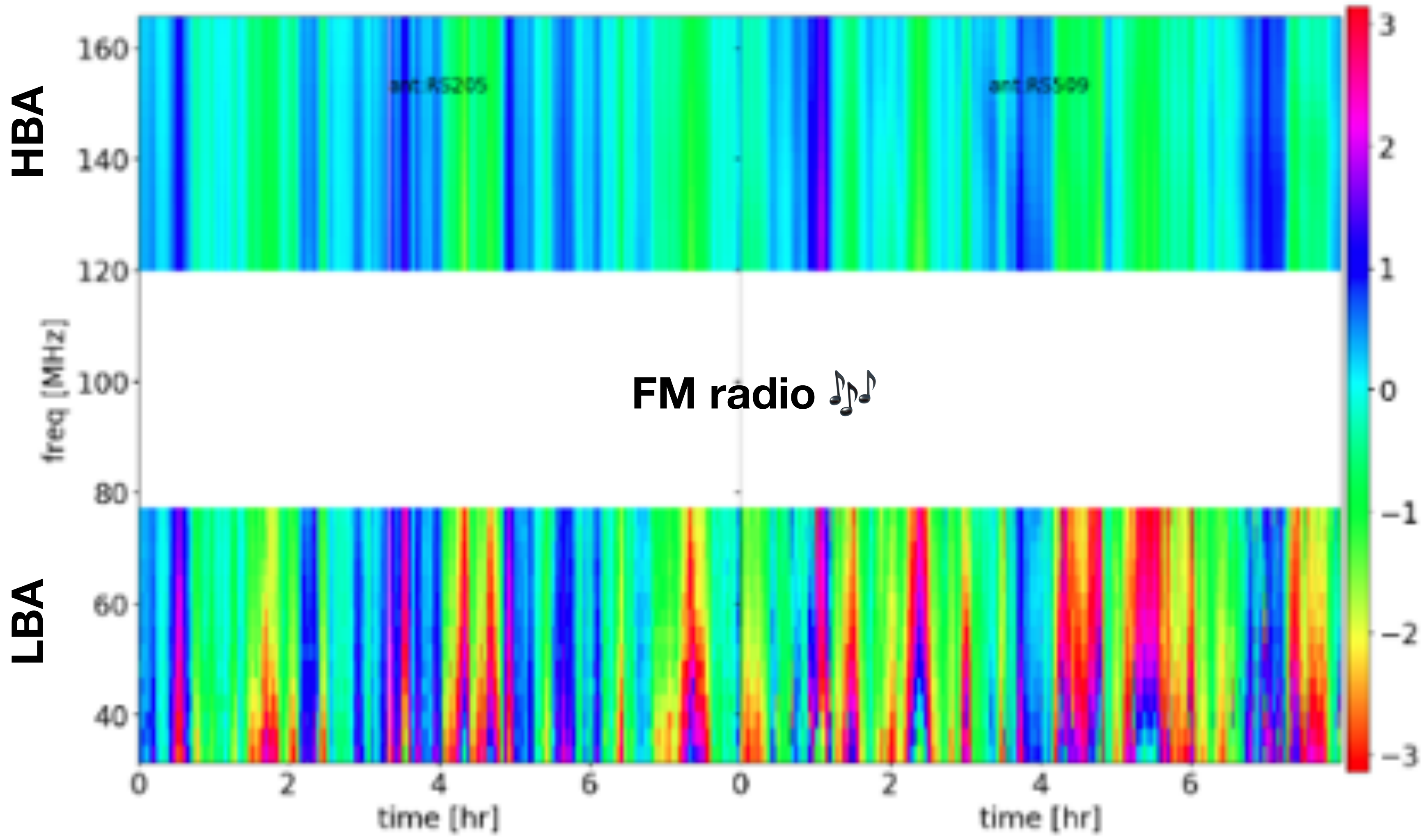

Credits: de Bruyn

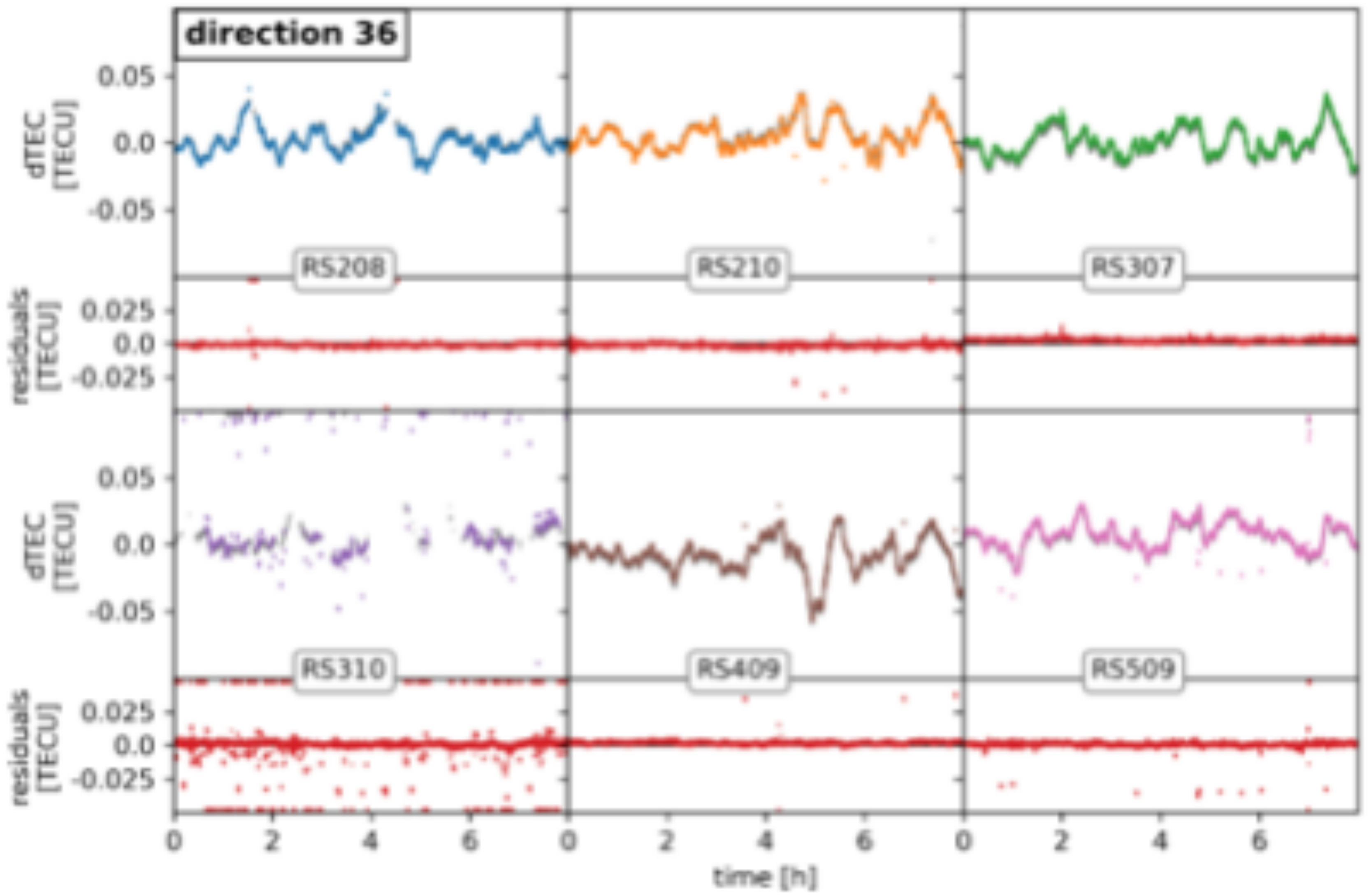
# LOFAR 2.0

Edler, de Gasperin, Rafferty, A&A in press.
arXiv:2105.04636 + talk in JG session




- LoSiTo: LOFAR Simulation Tool
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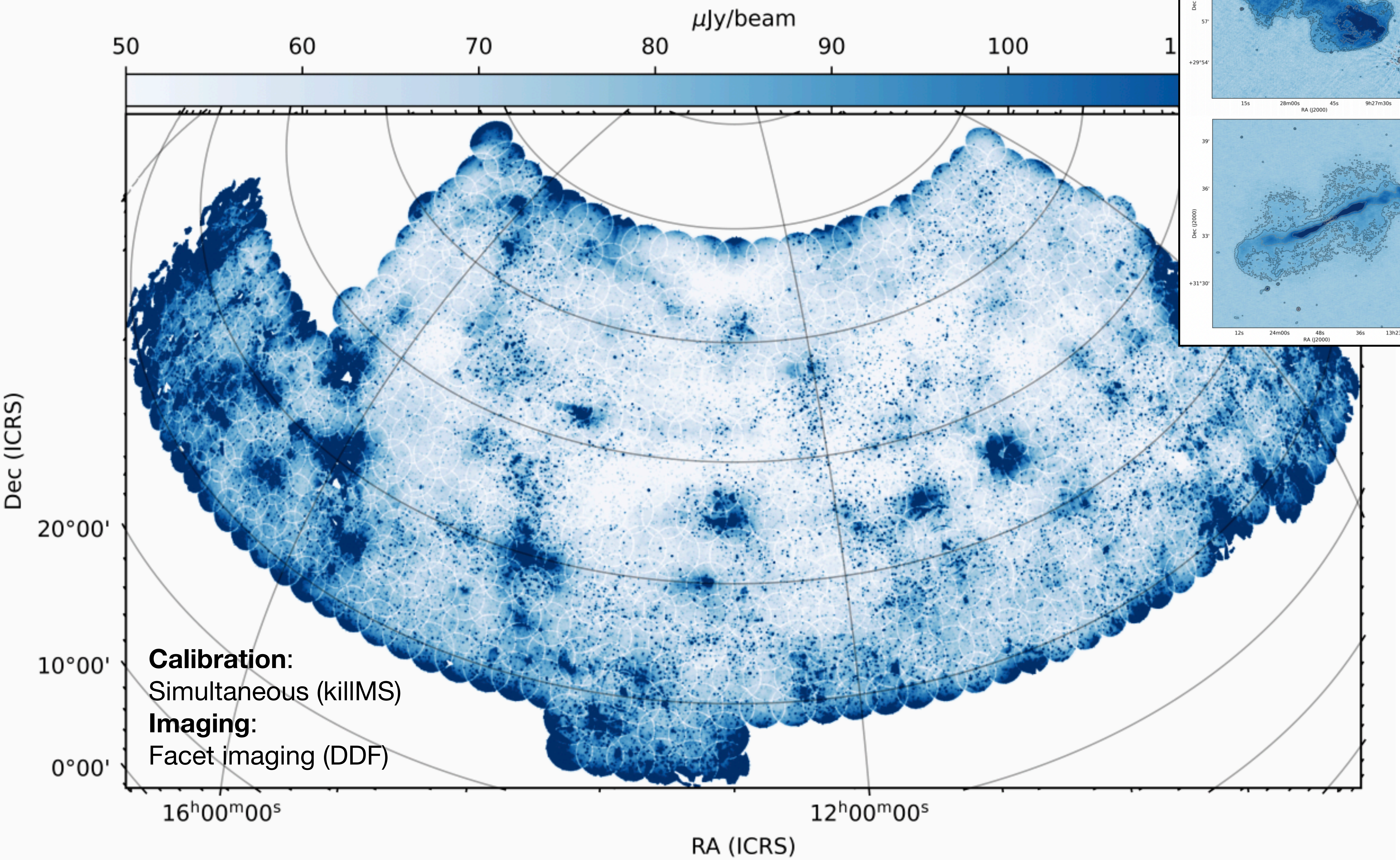
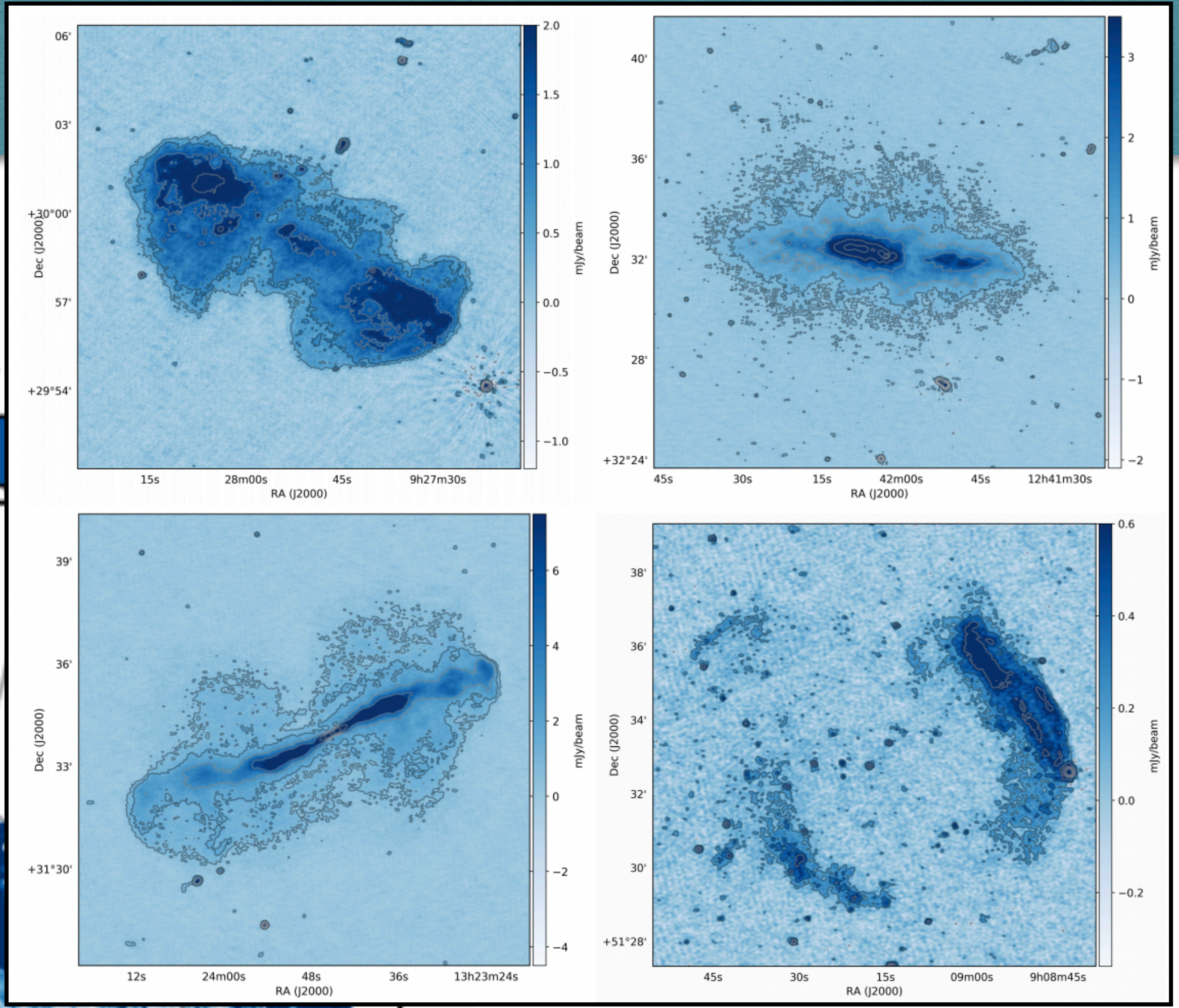
- Test of calibration strategies

# LoTSS - LOFAR Two Metre Sky Survey

Shimwell et al. in prep.



**Calibration**:
Simultaneous (killMS)
**Imaging**:
Facet imaging (DDF)

# LOFAR - Long Baselines

Sweijen et al in prep.

**29x more core hours vs LoTSS**

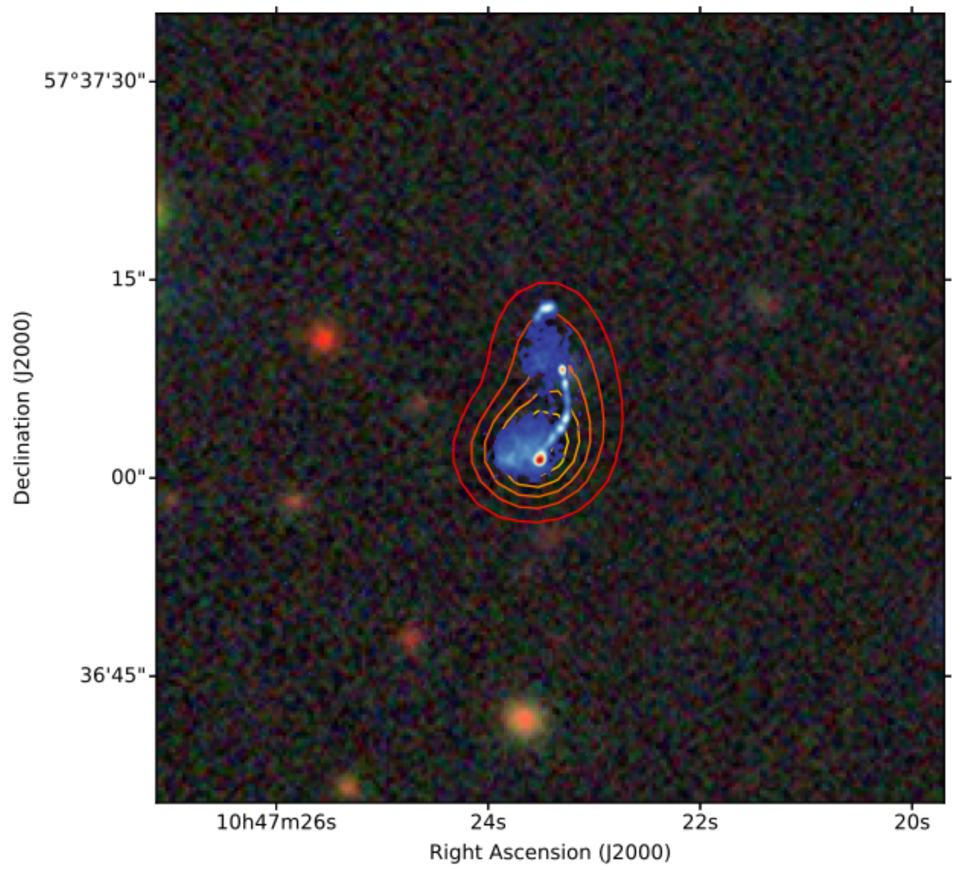
- 260k CH for a widefield image
- 500-600k CH/yr for LoTSS at SURFsara

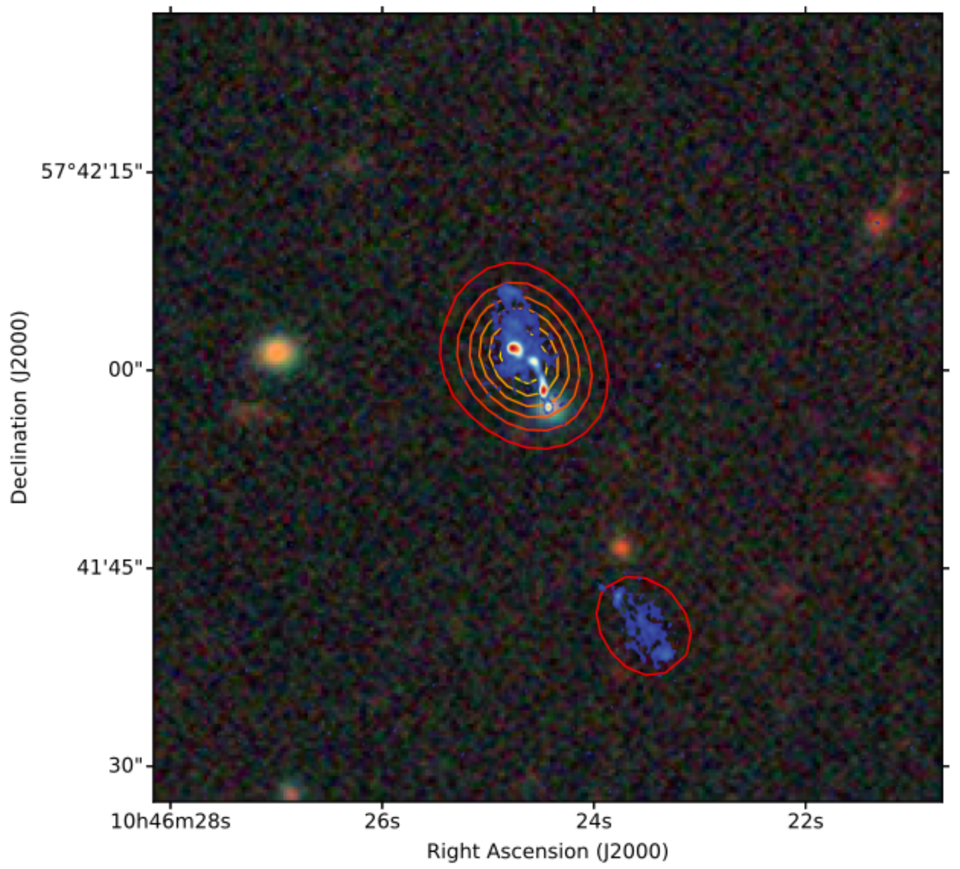
**Long wall time**

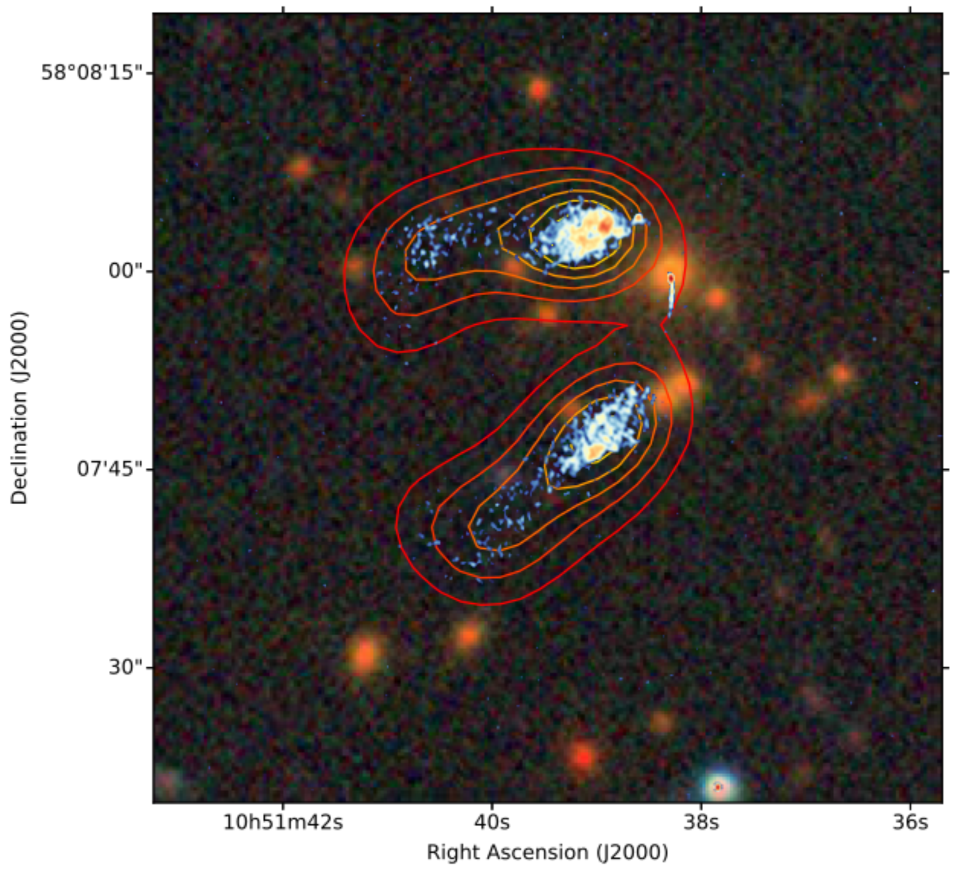
- ($N_{facet}$ + 1) days for subtract
- 5-7 $N_{facet}$ days for imaging

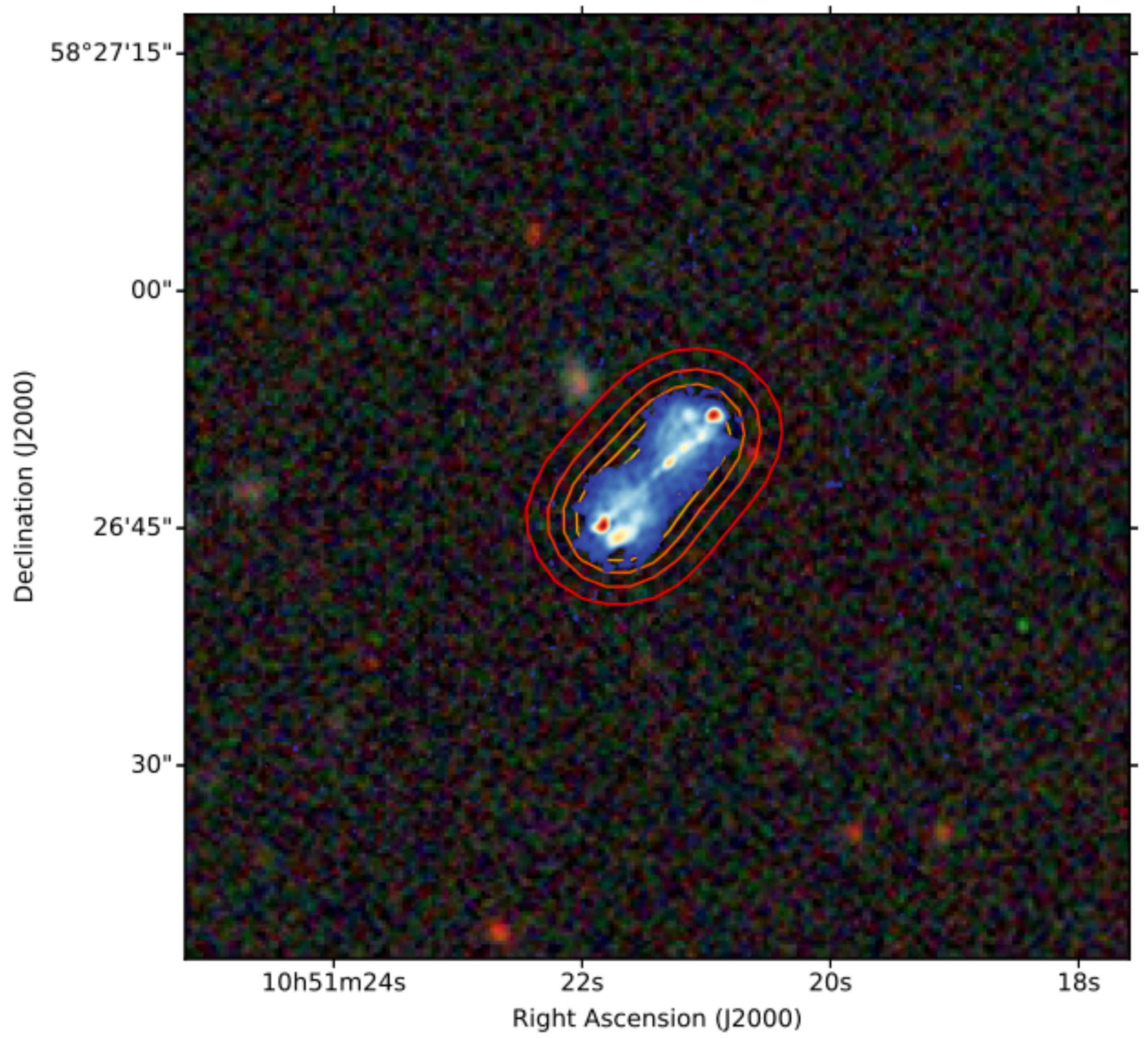
**Large images**

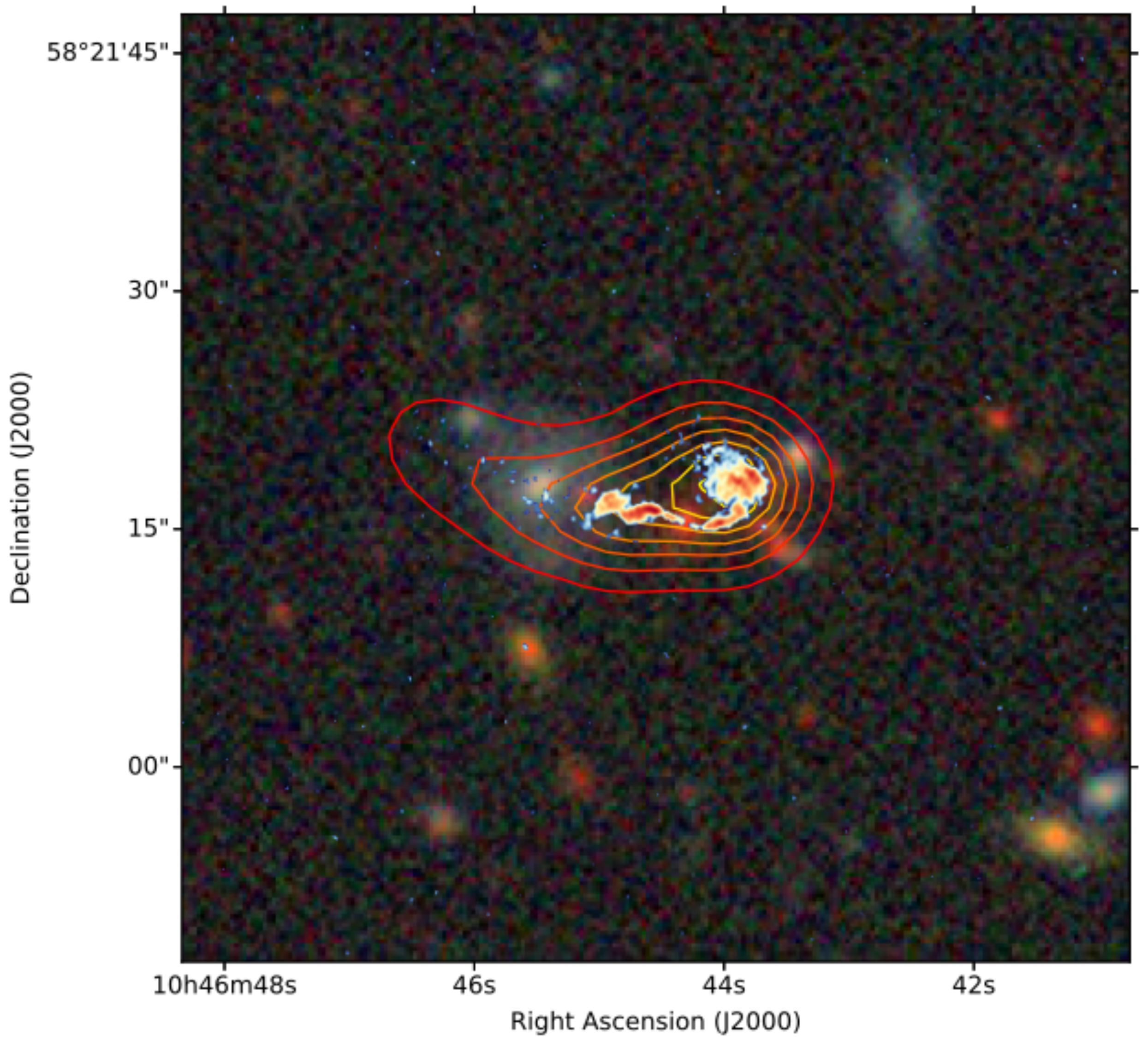
- 83,000 x 83,000 pixels
- Single pointing (7 giga px) needs more pixels than FIRST (~6 giga px)



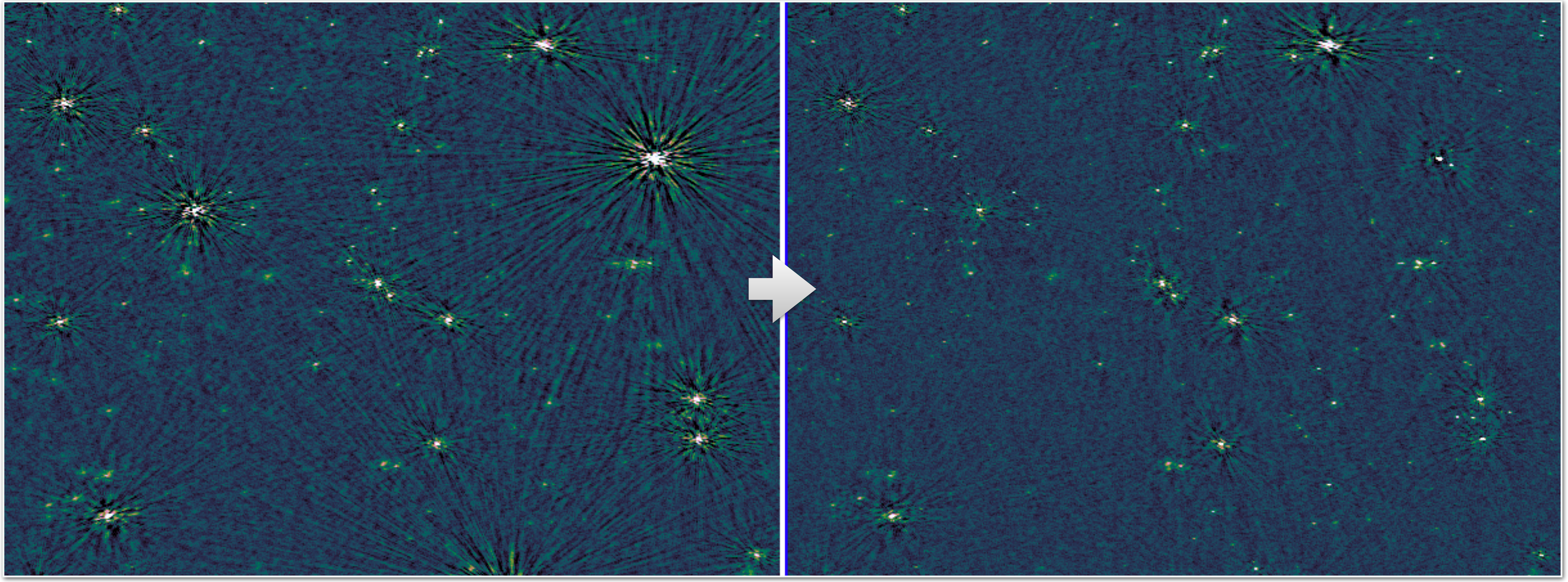



# LoDSS - LOFAR Decametre Sky Survey

Credits: van Weeren



**Calibration**:
Serial (DP3)
**Imaging**:
Screen (WSc+IDG)

# Computing resources

Sweijen et al in prep.

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- 500-600k CH/yr for LoTSS at SURFsara

**Long wall time**

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- 5-7 $N_{facet}$ days for imaging

**Large images**

- 83,000 x 83,000 pixels
- Single pointing (7 giga px) needs more pixels than FIRST (~6 giga px)

**Compute nodes**

**CPU** - 2x Intel Xeon 6126 12C @ 2.6 GHz

**RAM** - 384 GB

**GPU** - Nvidia Quadro RTX 5000 (optionally)

**Storage** - >4 TB local scratch

**Number** - 20 (for LH)