LOFAR
LBA

LOFAR LBA Sky Survey and LBA Practical Use

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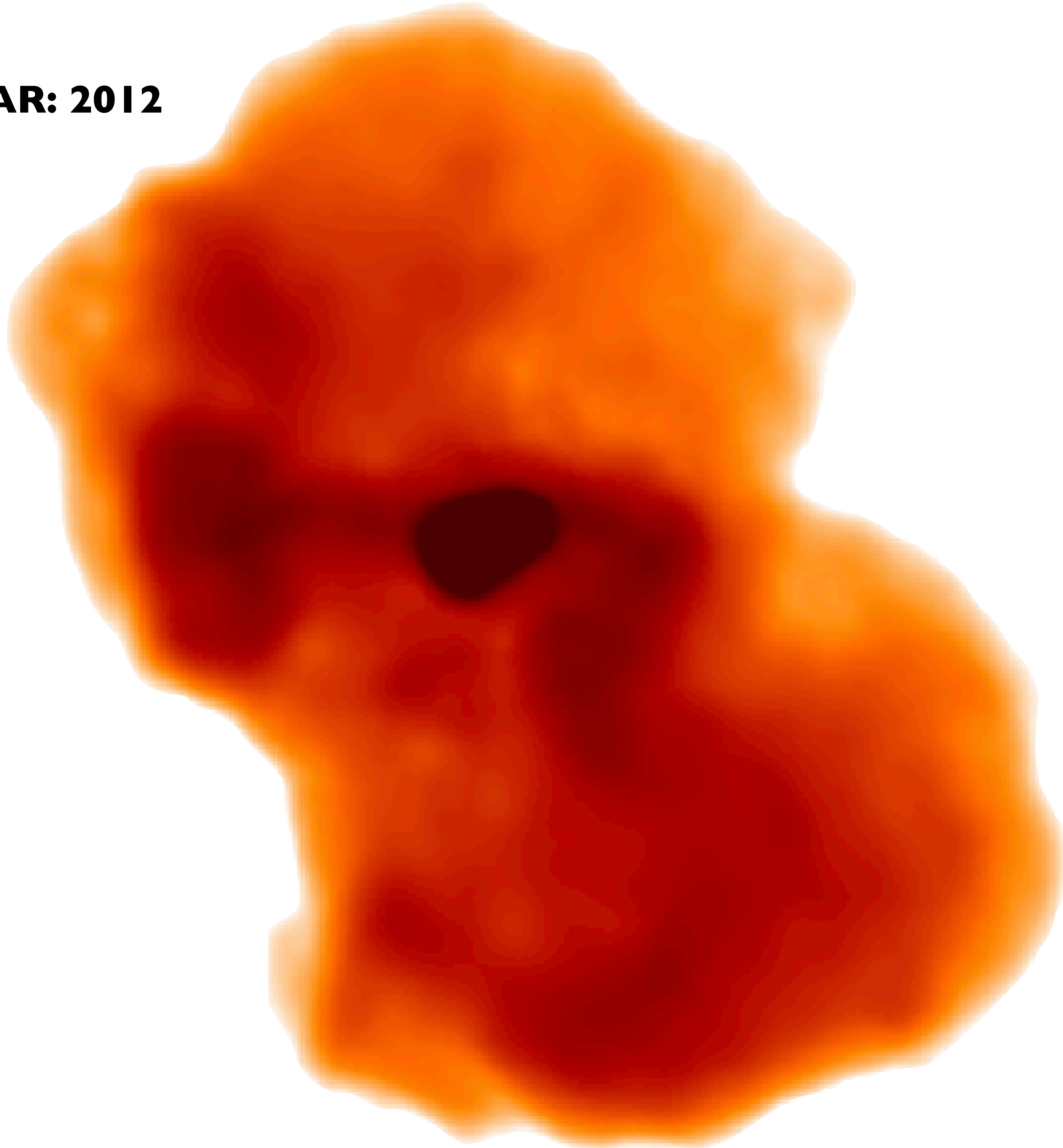
LOFAR School - L'Aquila
04/2023

LOFAR
ASTRON
UH
INAF ISTITUTO NAZIONALE DI ASTROFISICA

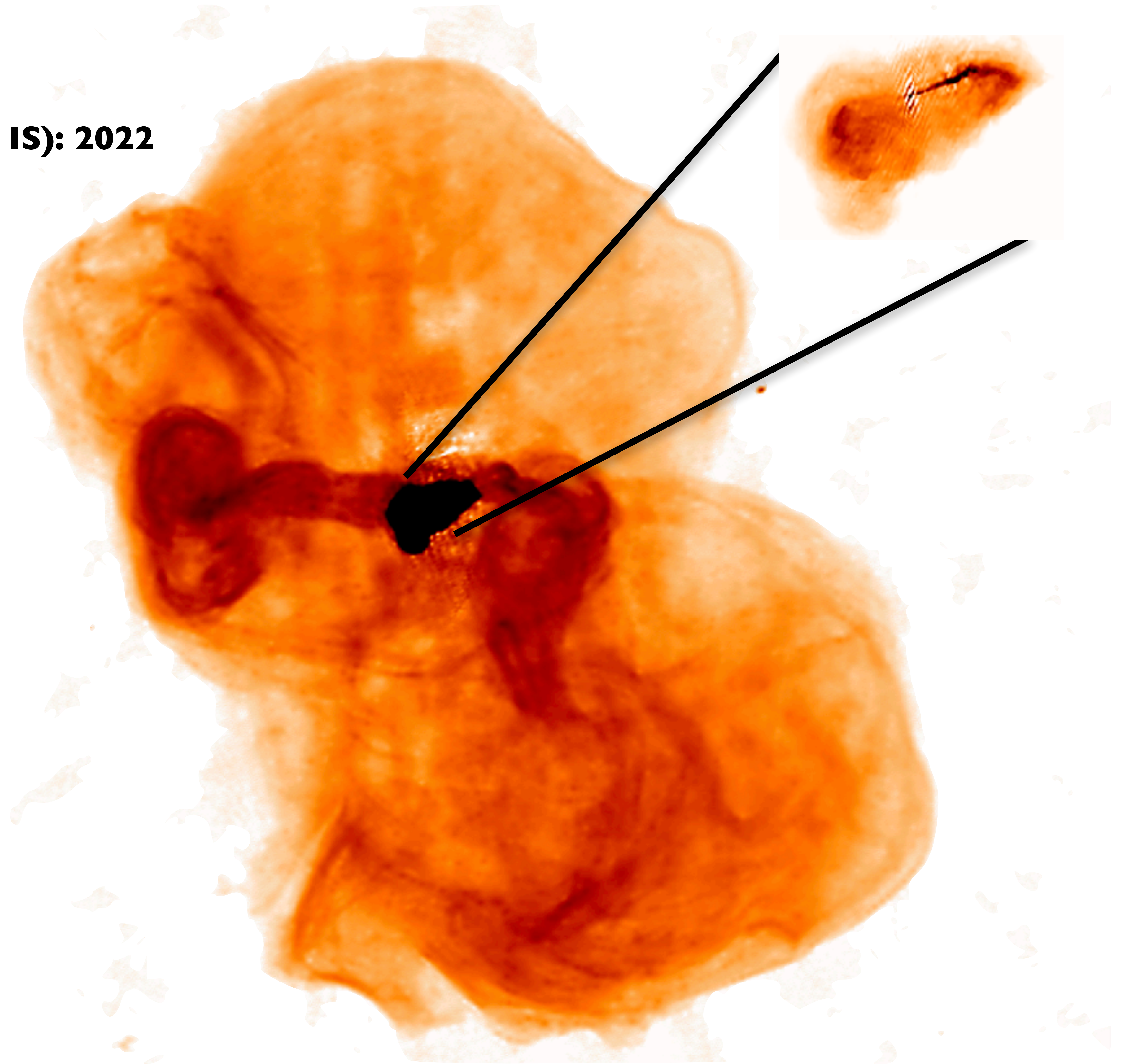
LOFAR evolution

LOFAR: 2012



LOFAR (with IS): 2022

2”-3”



Credits: H. Edler

Processing

Many technical developments required to process large quantities of data with complex processing strategies.

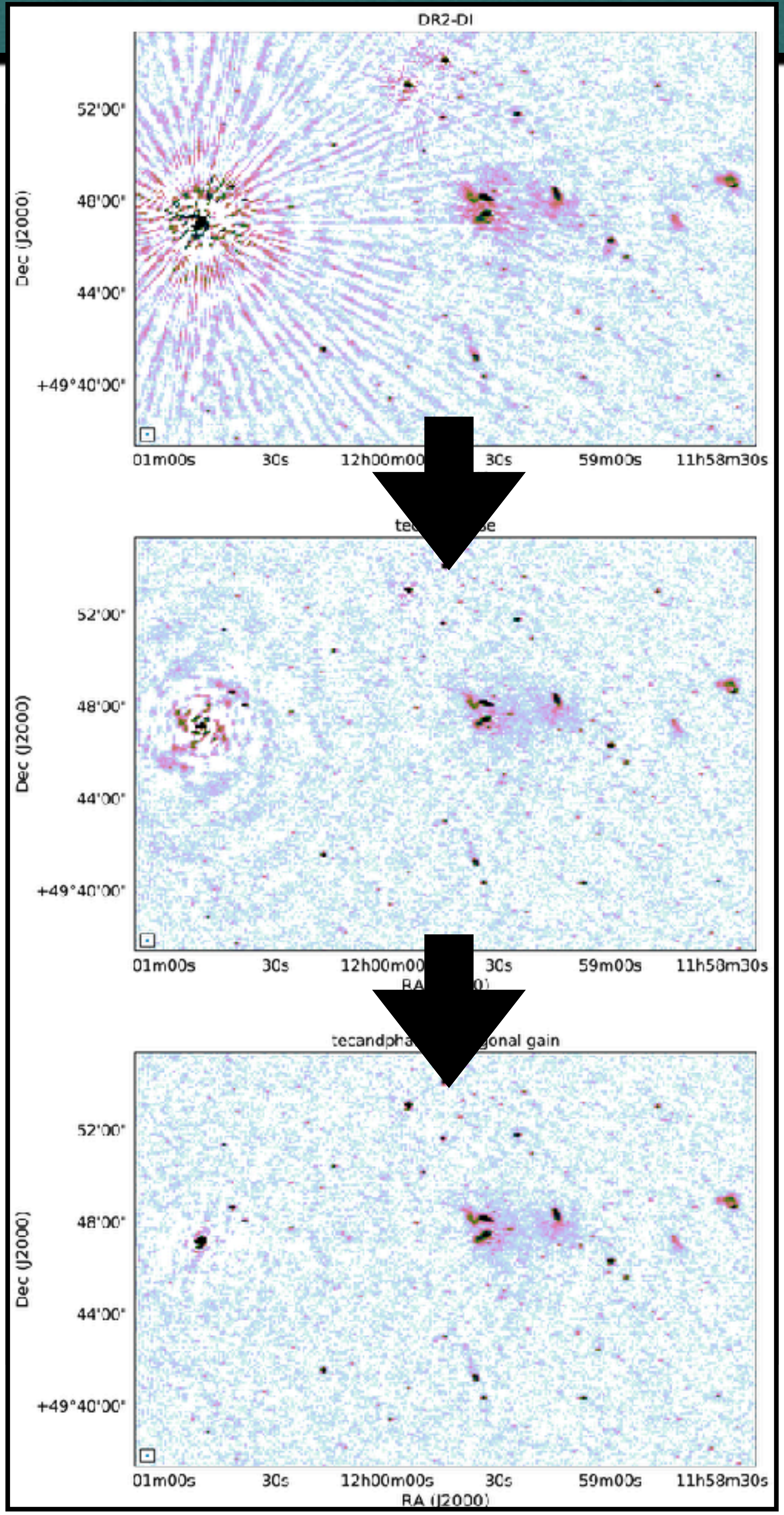
Current processing pipelines includes:

- **HBA Dutch-array** processing: van Weeren+ 2016, Williams+ 2019, Mechev+ 2019, Drabent+ 2019, de Gasperin+ 2019, Shimwell+ 2019, Sabater+ 2021, Tasse+ 2021, van Weeren+ 2021
  - extraction
- **HBA w/ international stations** processing: Morabito+ 2021, Jackson+ 2021, Sweijen+ sub
  - local re-imaging
  - full wide field
- **LBA Dutch-array** processing: de Gasperin+ 2019, 2020, 2021, Williams+ 2021
  - extraction

And use many software packages including:
Offringa+ 2012, 2014, 2016, van der Tol+ 2018, Tasse+ 2014, 2018, Smirnov+ 2015, van Diepen+ 2019, de Gasperin+ 2019

There are also many other ongoing efforts to improve calibration, imaging and processing techniques.

To-date we have accumulated >50PB of data (20PB + 300TB of final products surveys)



Outline

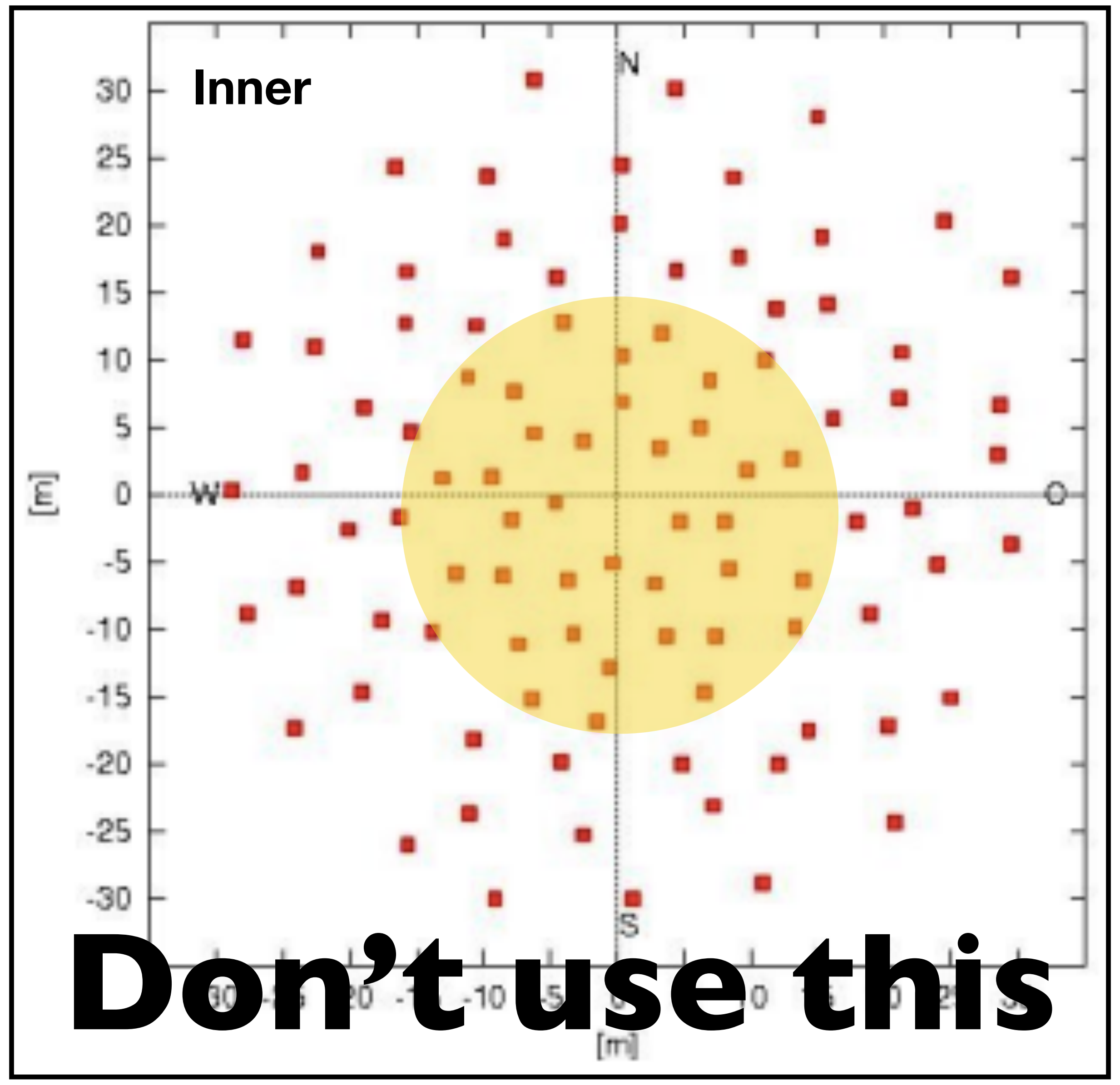
1. LOFAR LBA
2. PiLL
3. LoLSS (54 MHz)
4. What's next?

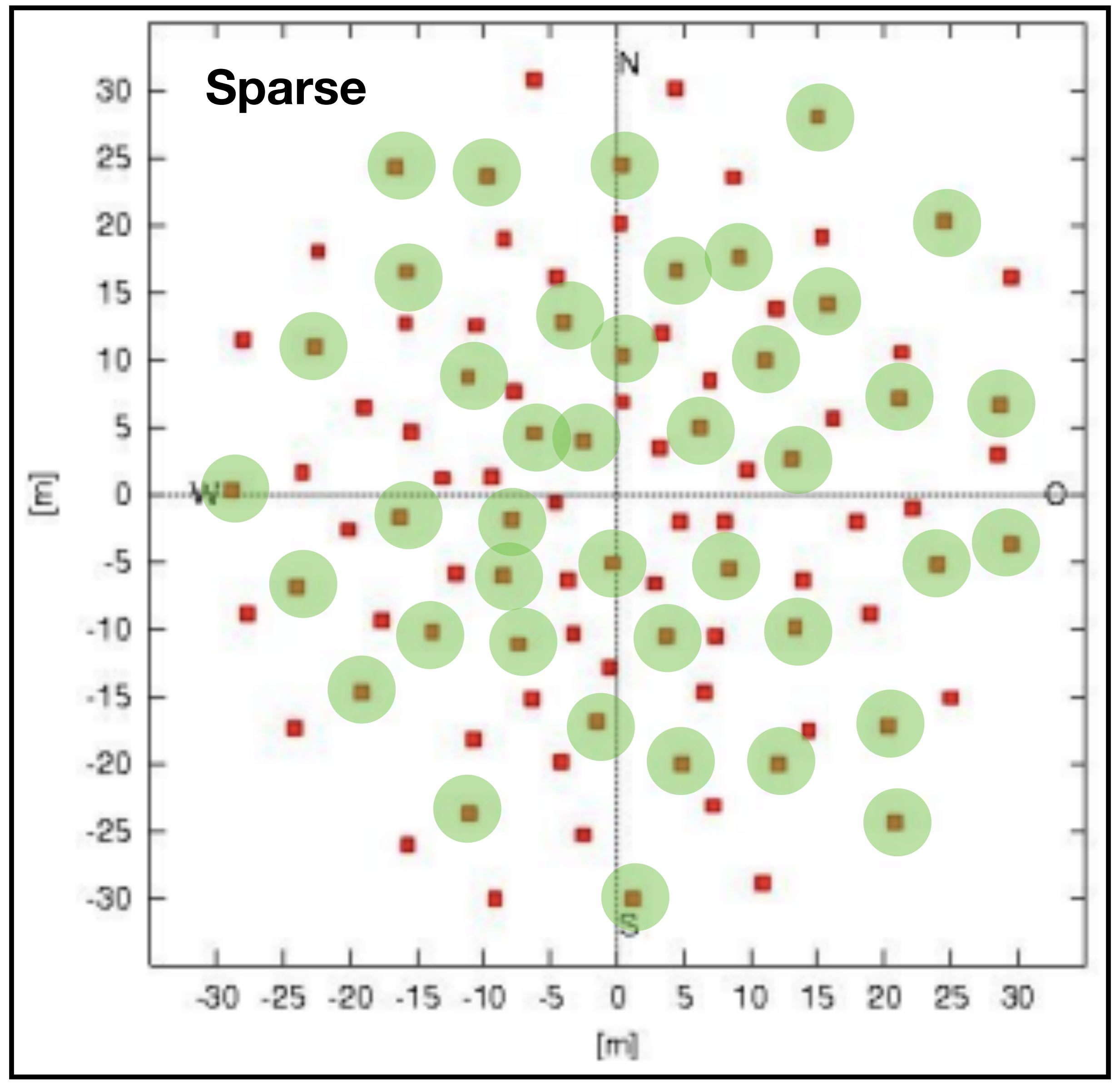

Challenges of the low frequency:
• Data size, up to 10s TB/night
• Complex beam
• Large FoV
• Low S/N
• Ionosphere
HBA
LBA
Birr
Onsala
Irbene
Dutch stations
Chilbolton
Norderstedt
Bałdy
Potsdam
Jülich
Effelsberg
Borówiec
Tautenburg
Łazy
Nançay
Unterweilenbach
Medicina
Rozhen
Atmospheric Opacity
100%
50%
0%
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
HBA
LBA
IONOSPHERE CUTOFF

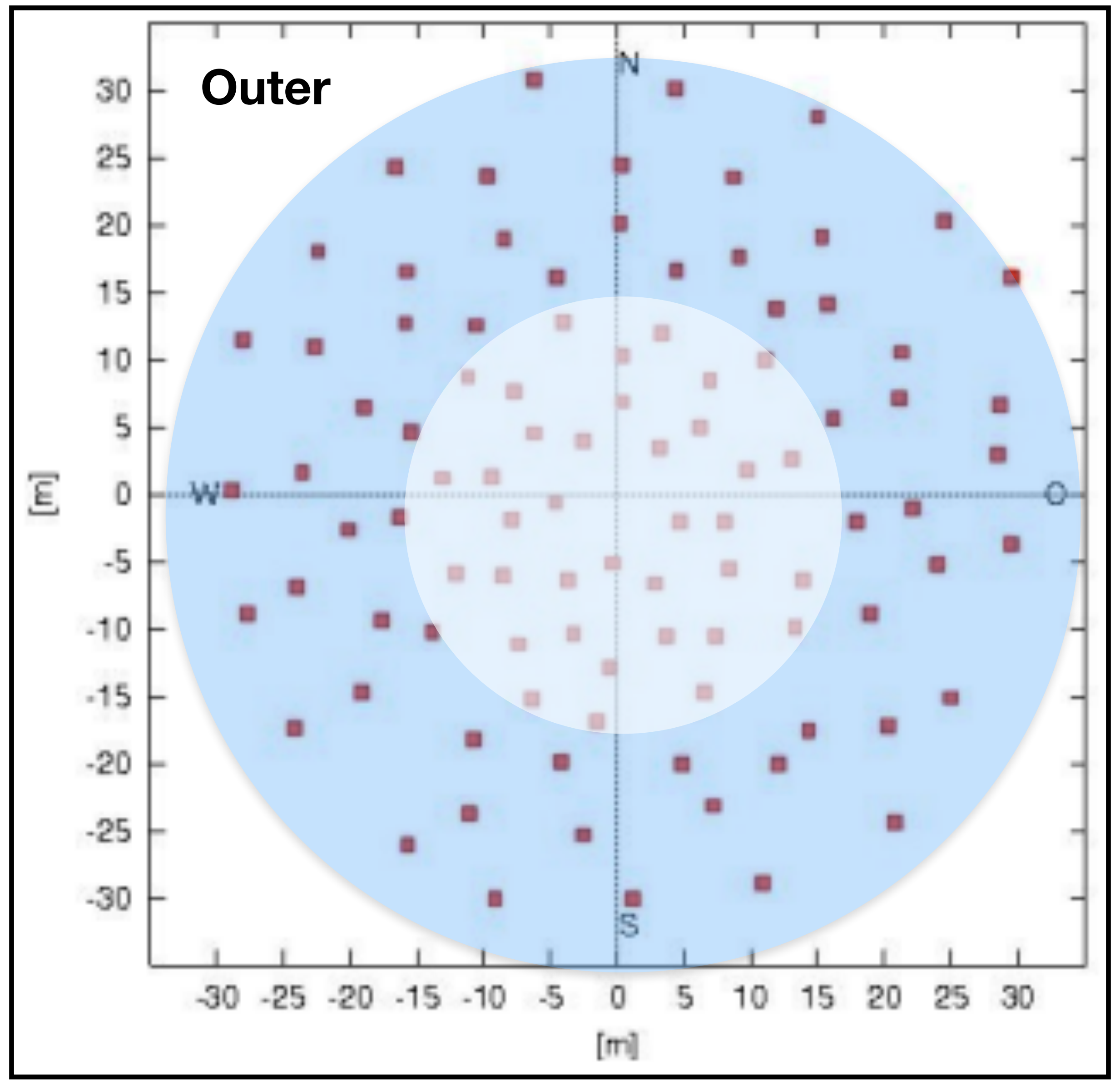
Differences HBA-LBA

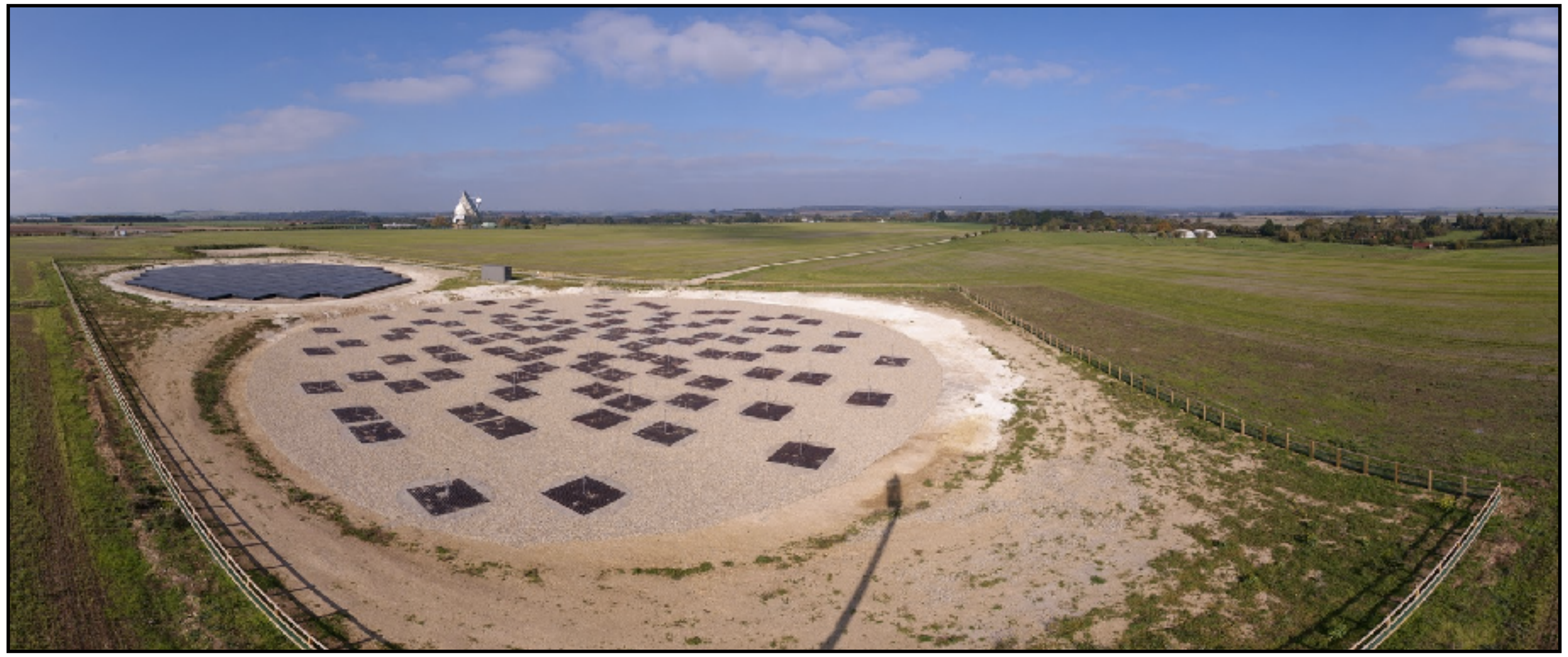
Frequency	• LBA: 10 — 90 MHz • HBA: 120 — 250
Sensitivity	• LBA: 1 mJy/b → ~100 times deeper than competitors • HBA: 0.1 mJy/b
Resolution	• LBA: 15” (1” with international) • HBA: 5” (0.3” with international)
Primary beam FWHM	• LBA: 4 deg (outer) - 6 deg (sparse/LOFAR2.0) • HBA: 4 deg
Bandwidth	488 SB = 96 MHz • 190% fractional (LBA) • 64% fractional (HBA)
Multi beam	Fully exploitable only in LBA (high survey speed, new calibration techniques)

LBA Modes









- **FWHM INNER: 10 deg**
- **FWHM SPARSE: 6 deg**
- **FWHM OUTER: 4 deg**
- **LOFAR 2.0 will remove this limitation!**

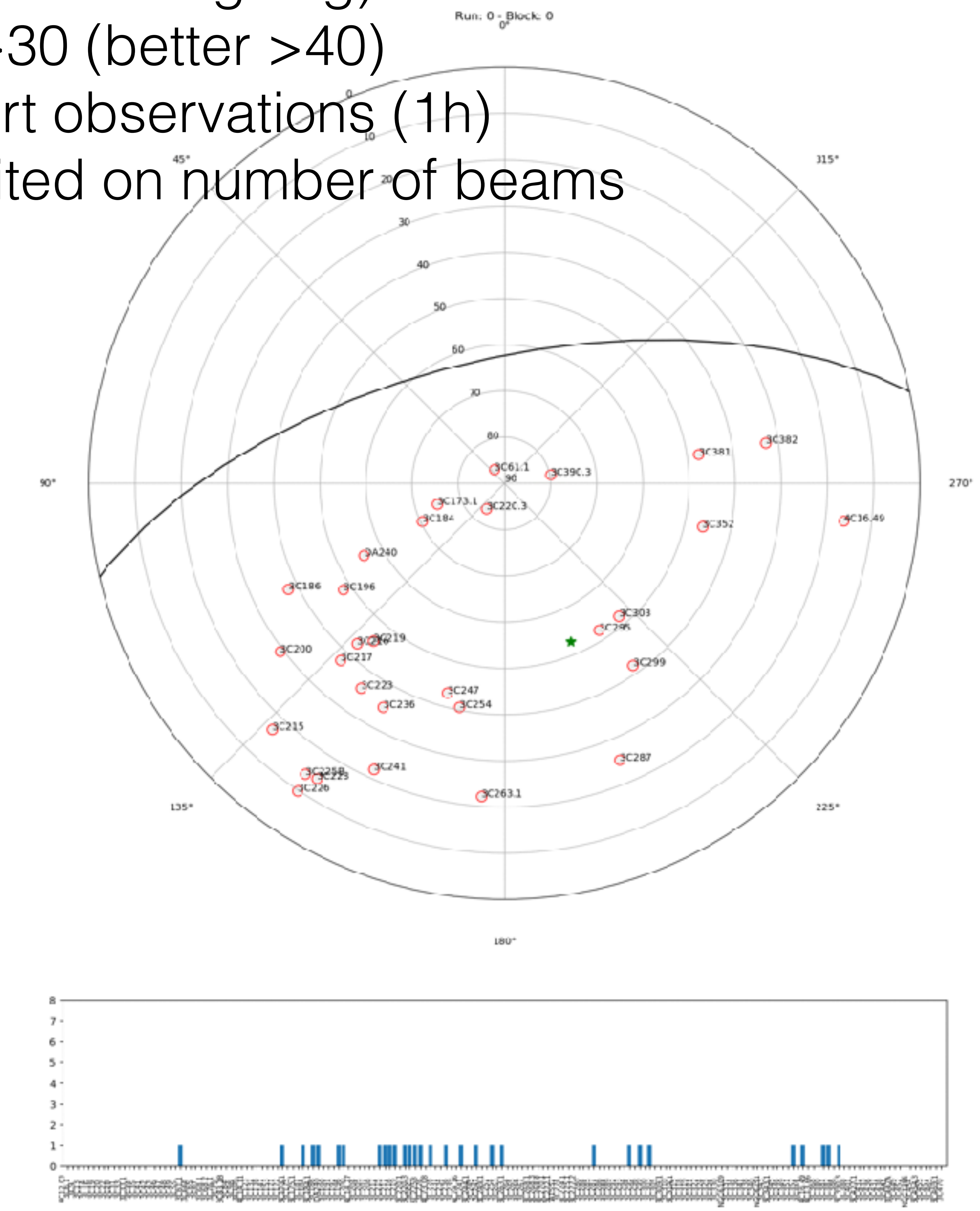
Typical observing mode

Survey mode:
- 3 beams on targets + 1 beam on calibrator
- 42-66 MHz band
- LBA SPARSE
- 2 sec. integration time
- 8 ch/SB freq. resolution

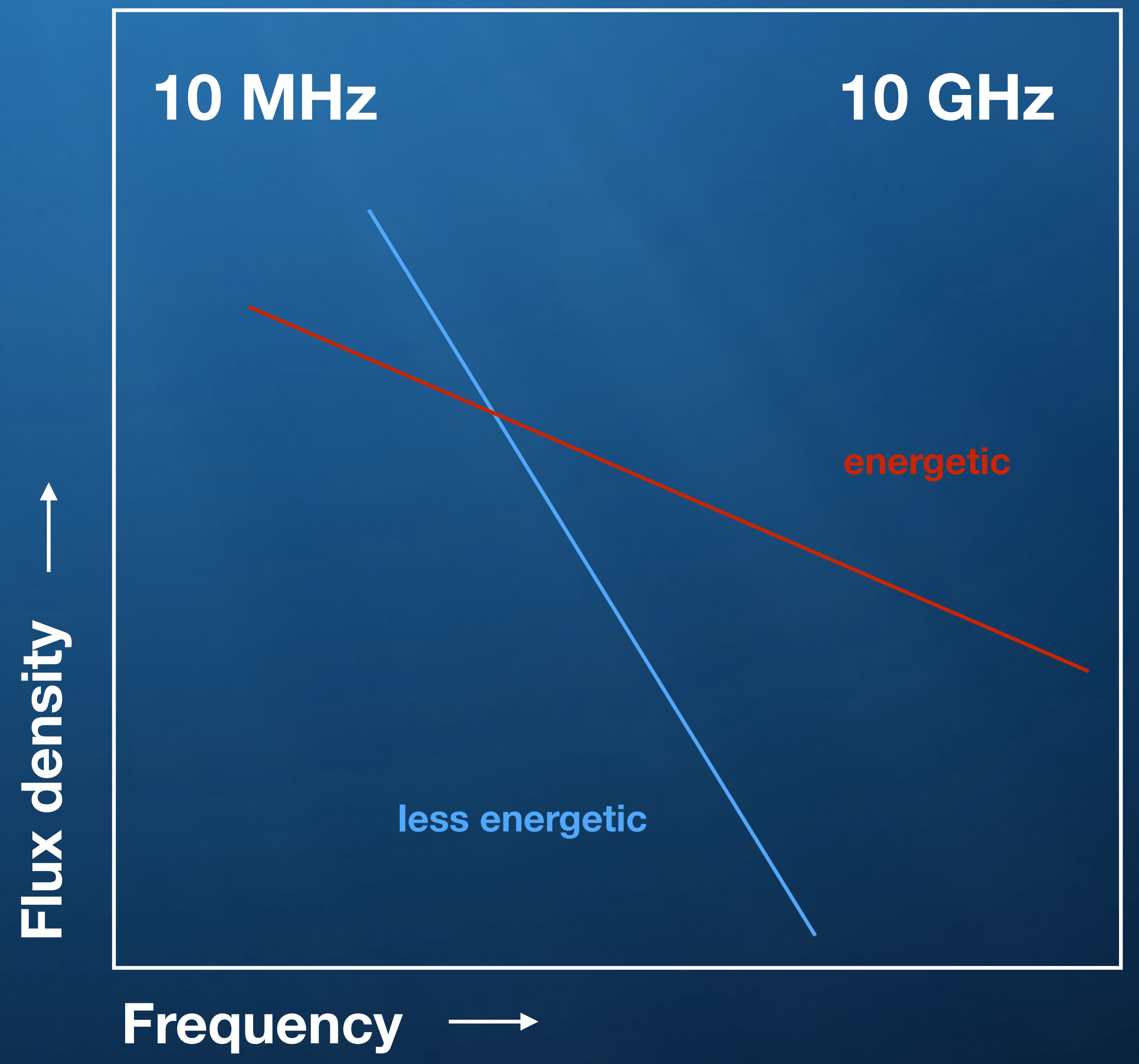
Single target:
- 1 beams on target + 1 beam on calibrator
- e.g. 20-68 MHz
- LBA SPARSE or OUTER
- 2/4 sec. integration time
- 4/8 ch/SB freq. resolution

Co-obs with survey:
- 1 beam on target + 1 beam on calibrator (+ 2 beam on survey)
- the rest as "survey mode"

Common:
- usually no international stations (but first experiments on-going)
- keep elev. >30 (better >40)
- multiple short observations (1h)
- don't be limited on number of beams



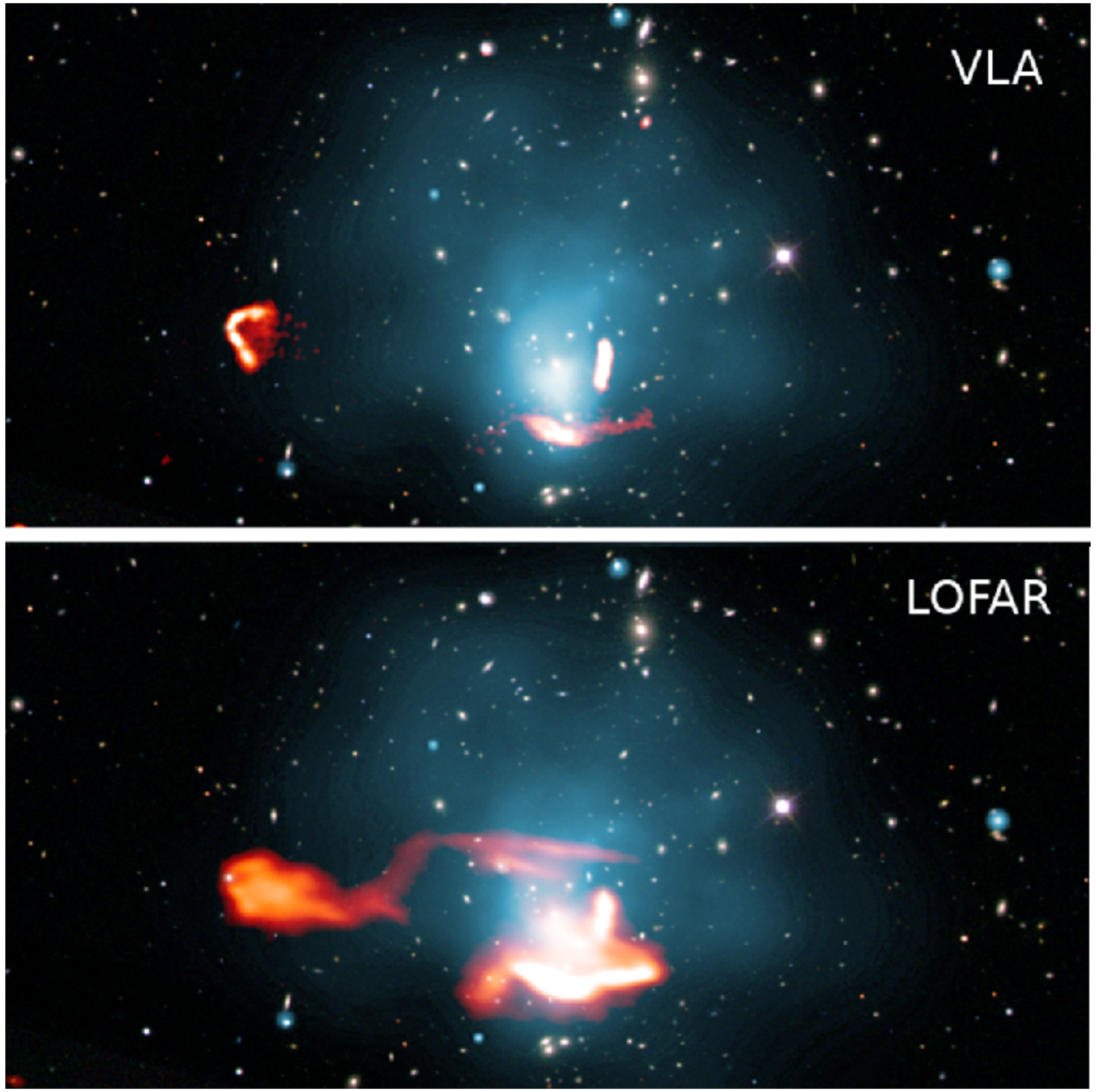
Unveiling the silent majority of *low-energy* phenomena



Why ULF are able to reveal the sea of submerged CR?

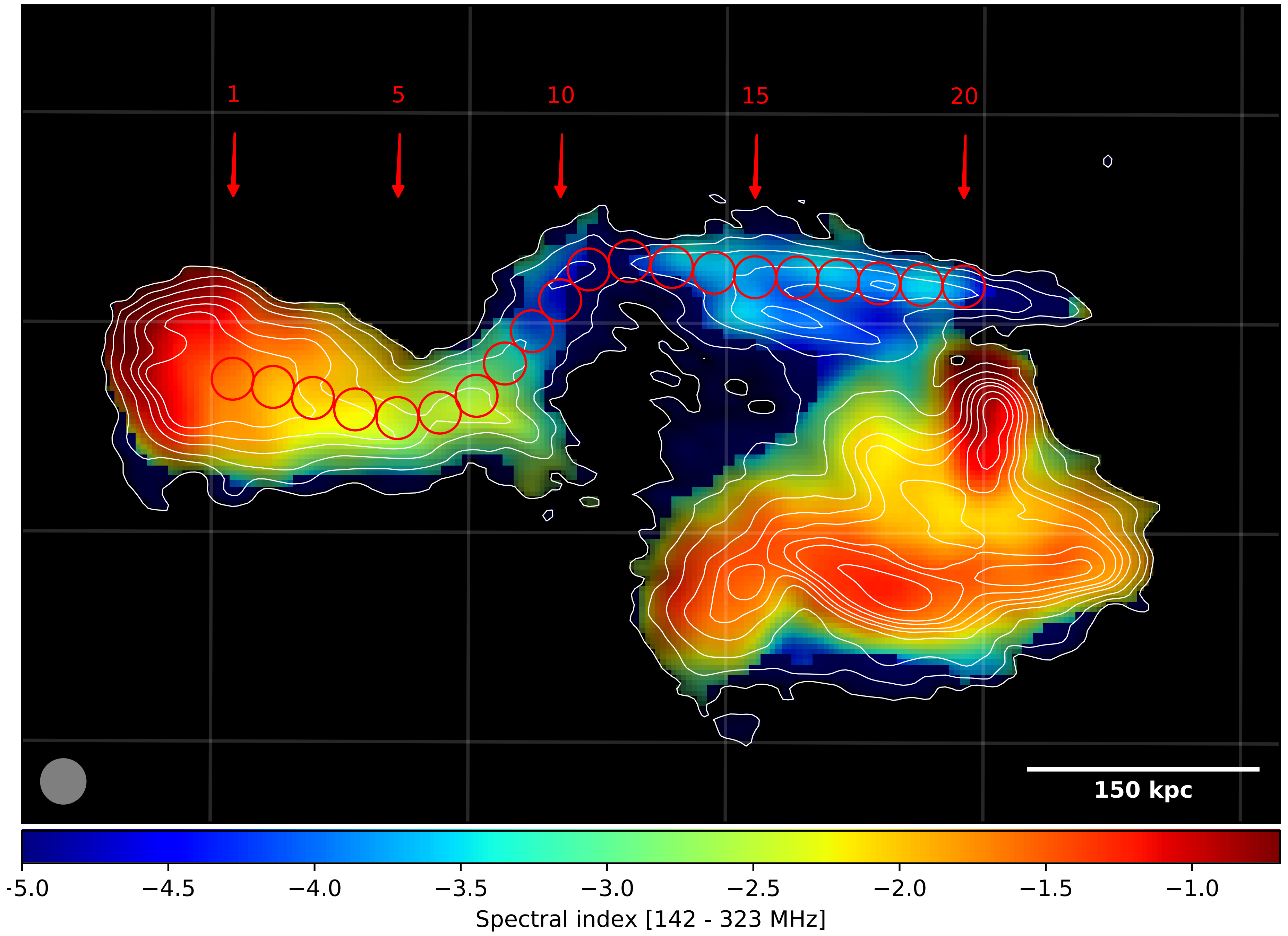
GReETs

de Gasperin+ 2017   Edler+ 2022



Spectra Index: -4

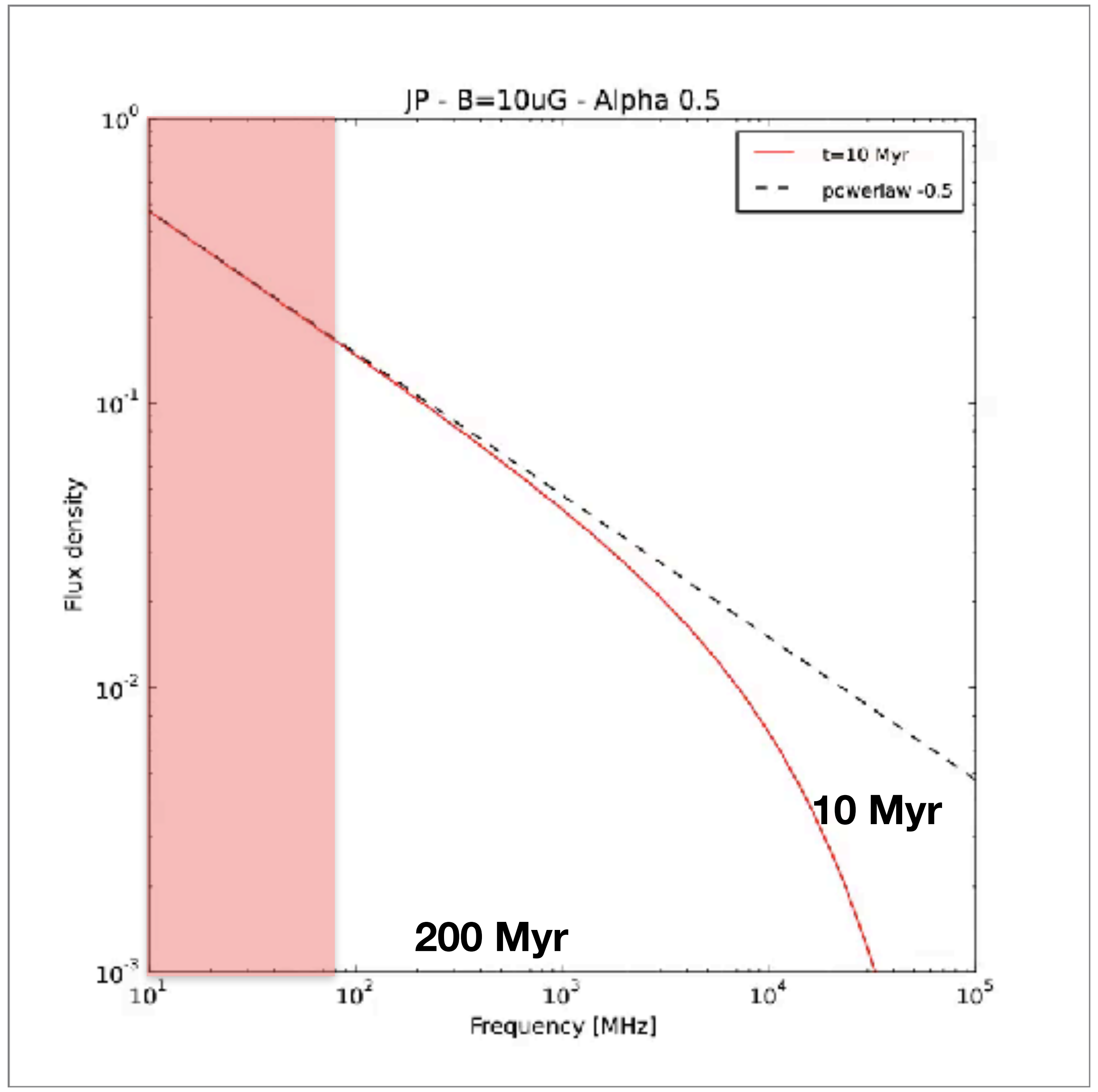
100 yrs of VLA time for detection in L-band



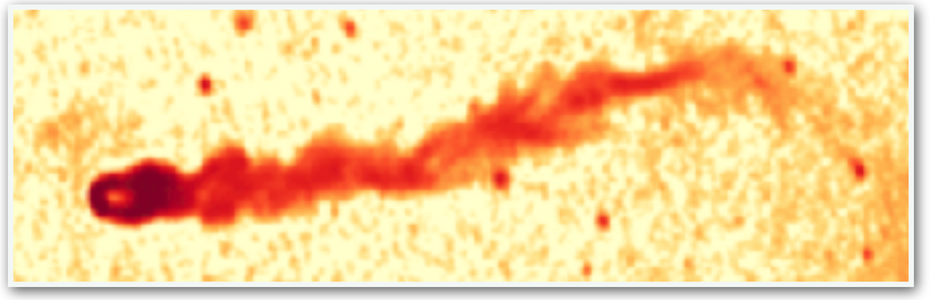
Ultra-low frequencies

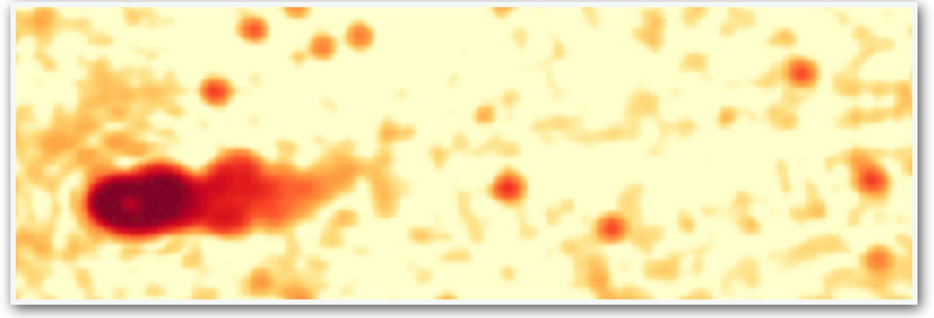
McKean+ 2016

Look back in time up to 1 Gyr

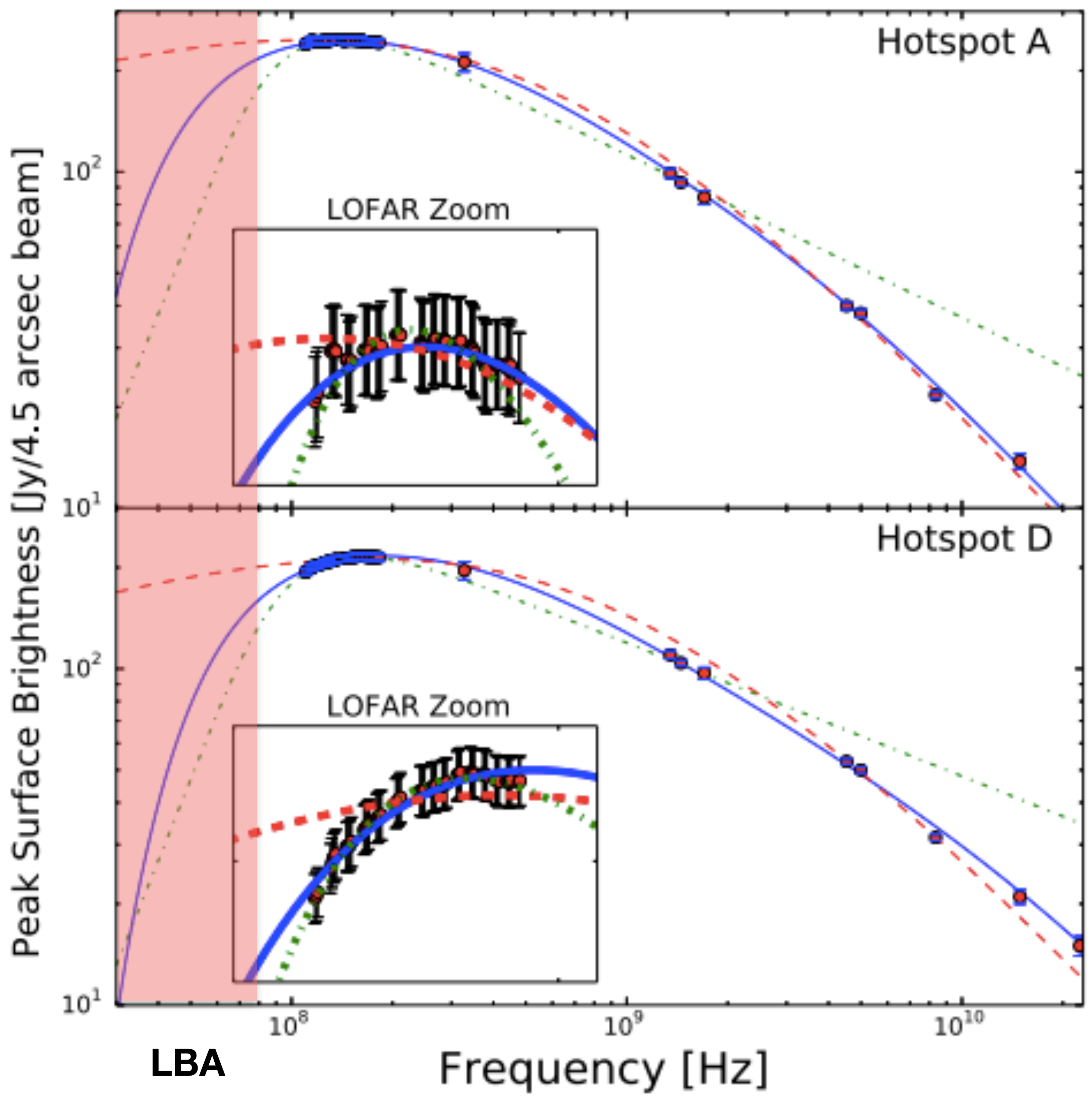


MHz **GHz**



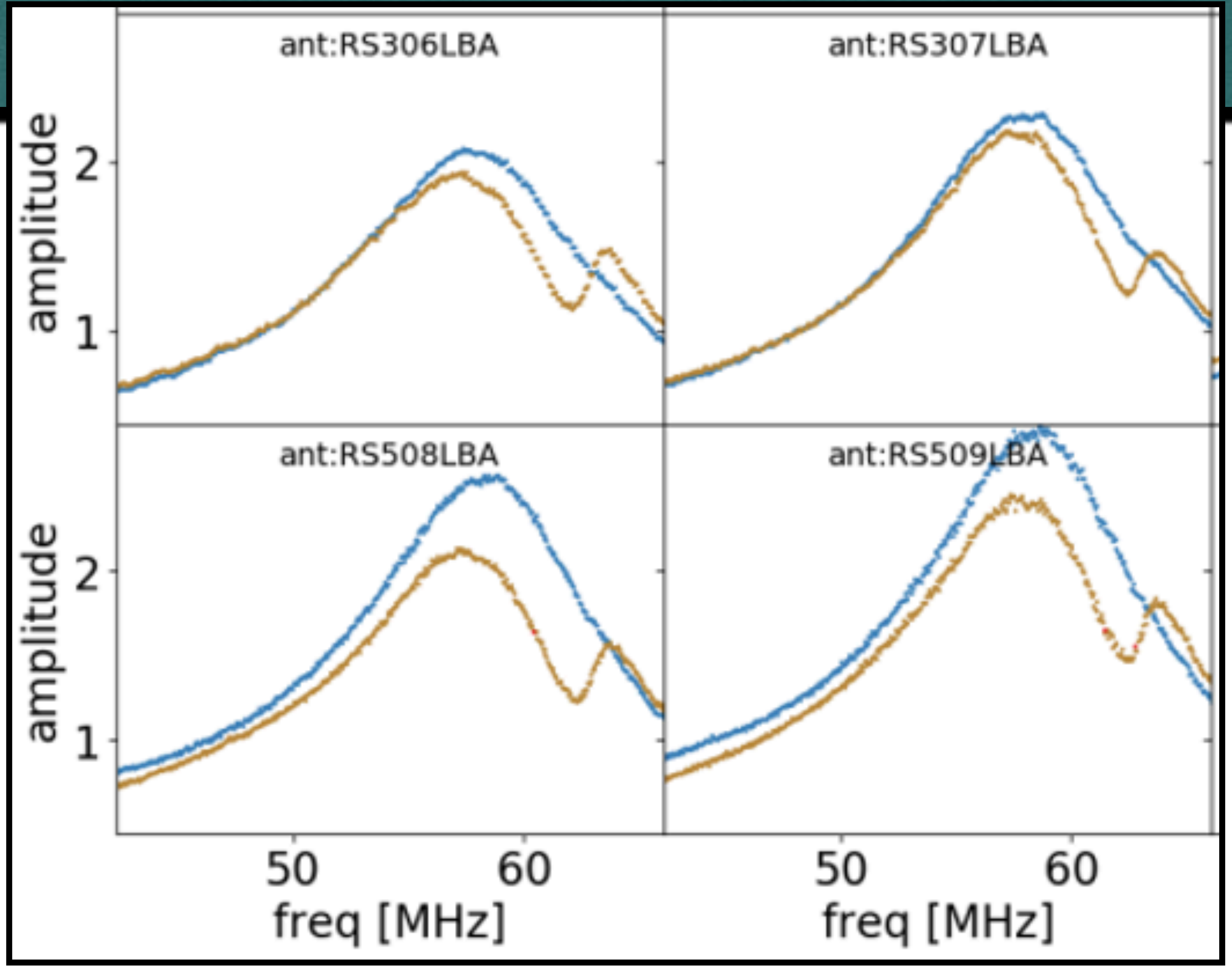


Constrain models

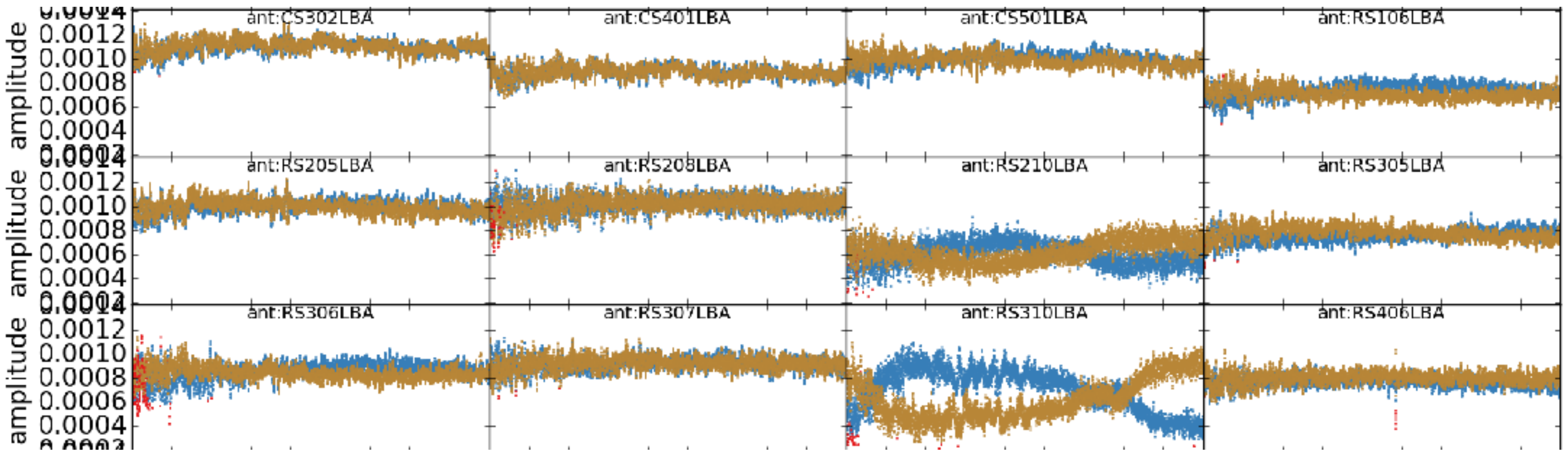



10 arcsec
(3.000 ly)
VLA 1.5 GHz
0,001 arcsec
(0,3 ly)
VLBA 43 GHz
100 arcsec
(30.000 ly)
LOFAR 0.05 GHz
0,00001 arcsec
(0,003 ly)
EHT 230 GHz
Credits — LOFAR image: F. de Gasperin — VLA image: F. Owen — VLBA image: C. Walker— EHT Image: EHT collaboration

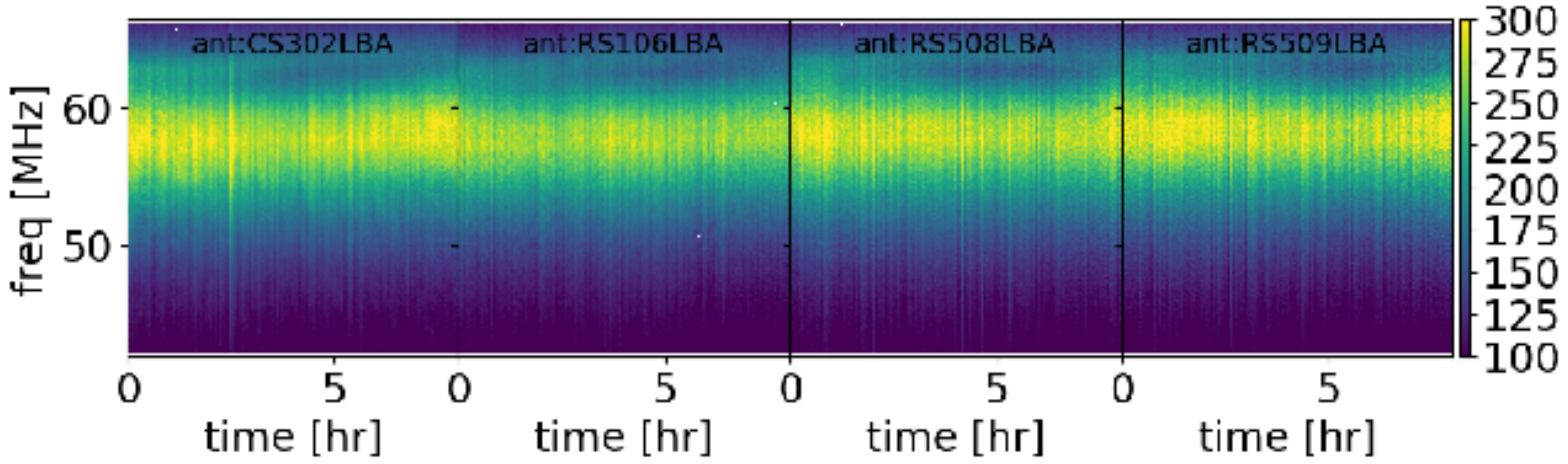
Technical challenges: Beam model

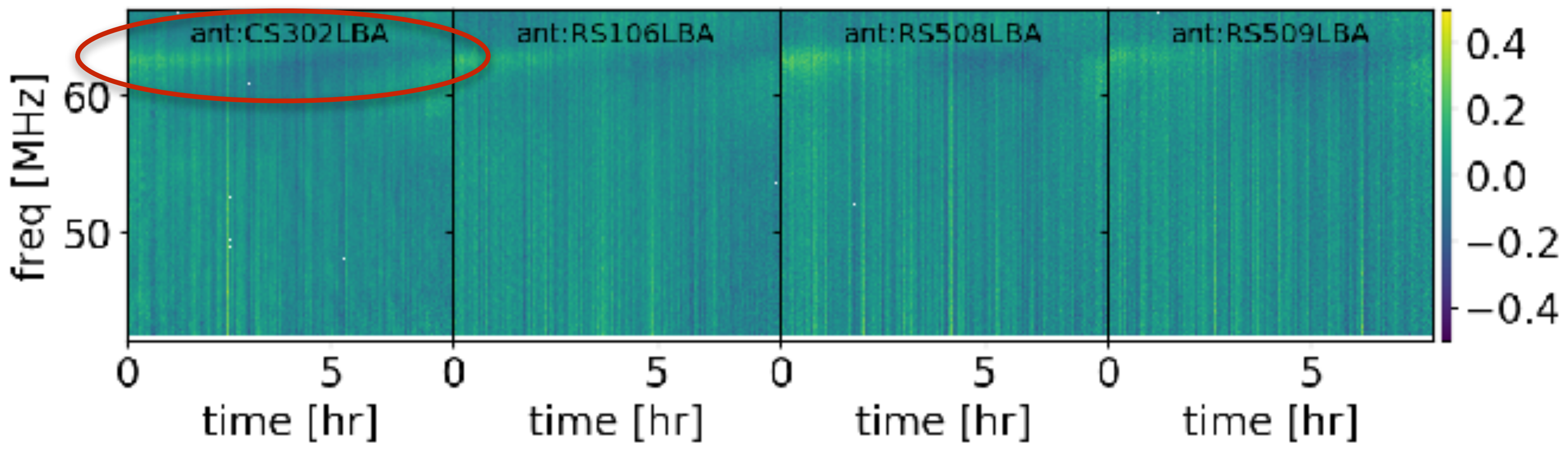


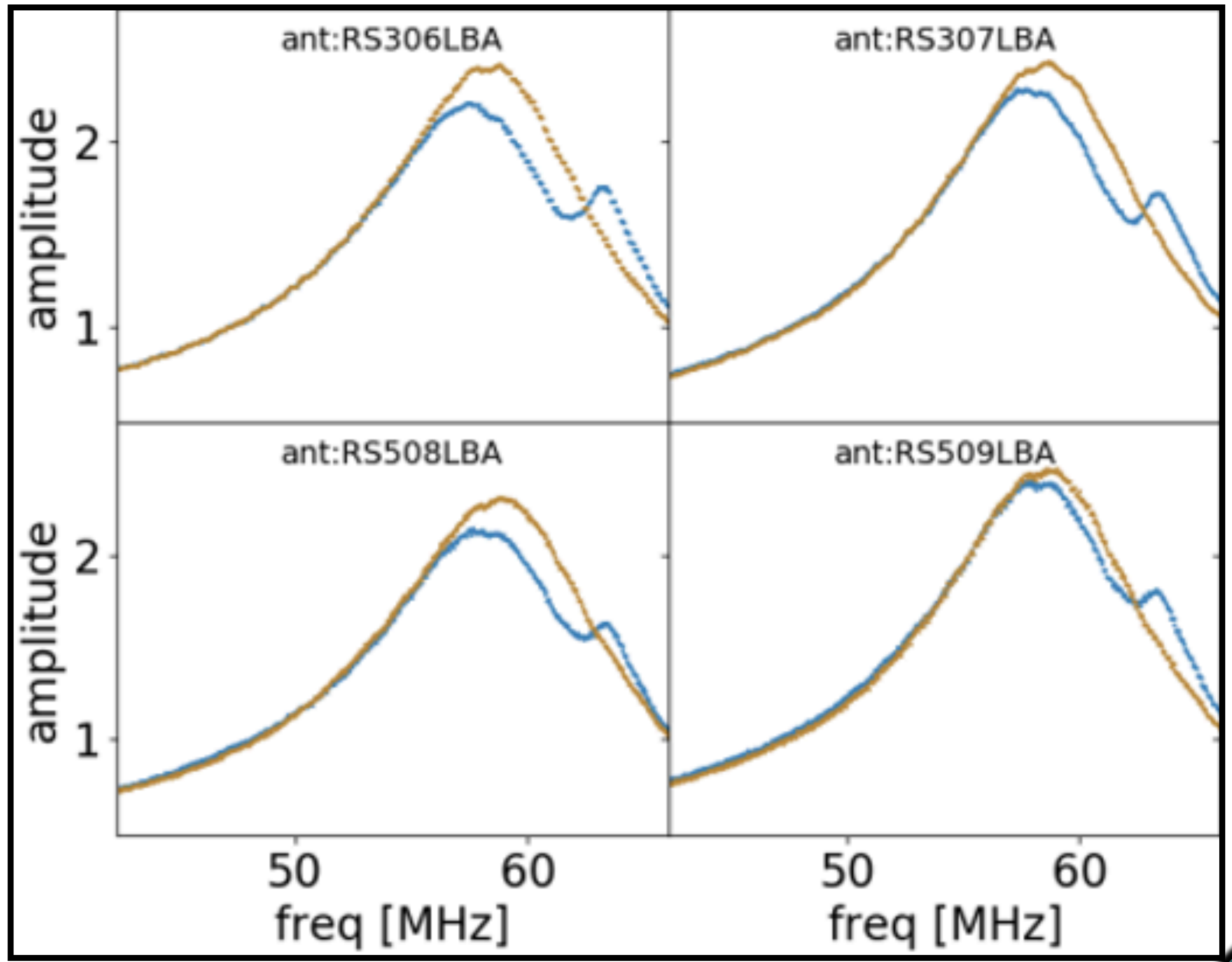
- **Station calibration sub-optimal - holography will help…**



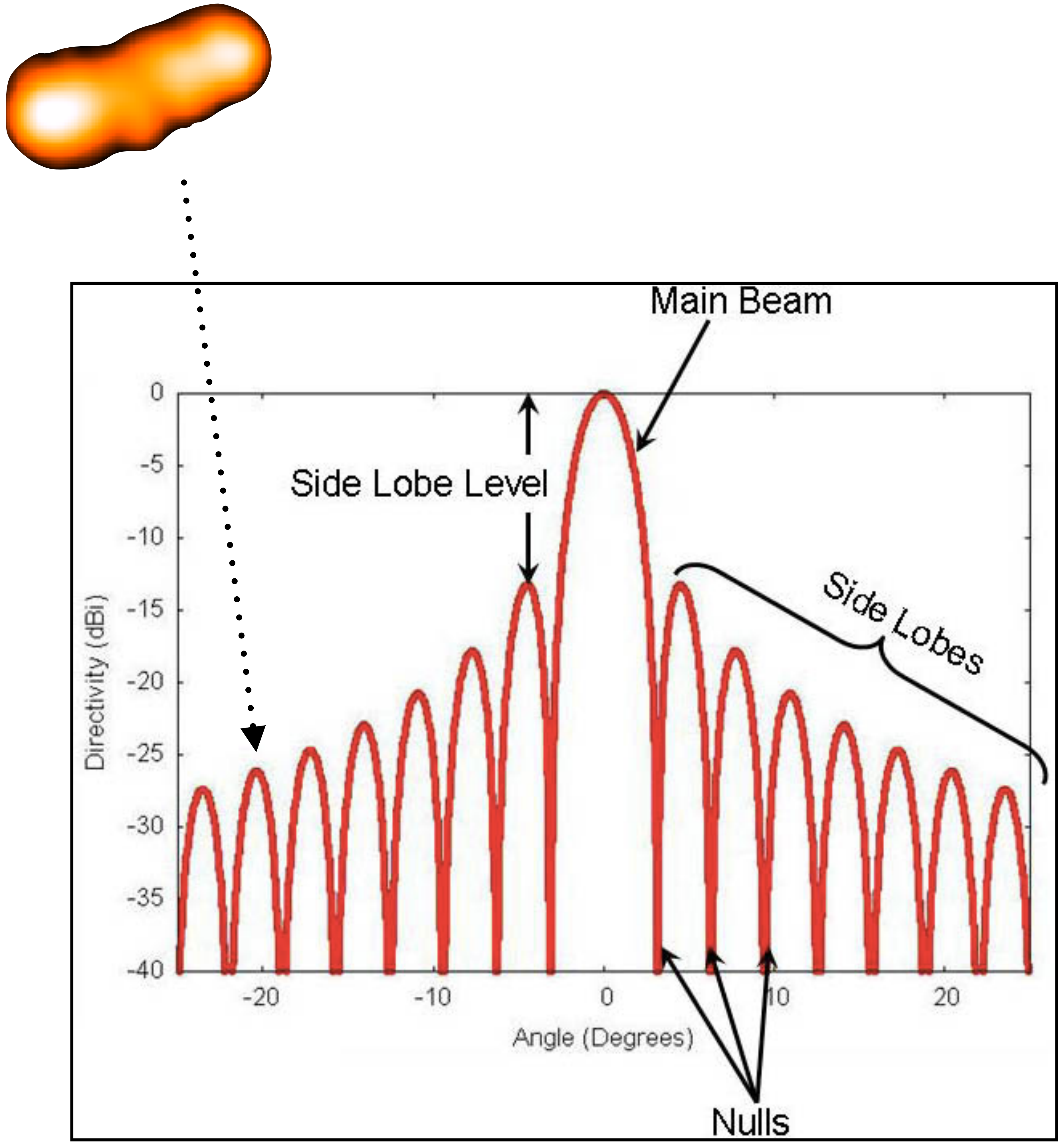
- **Beam model sub-optimal - needs developing**



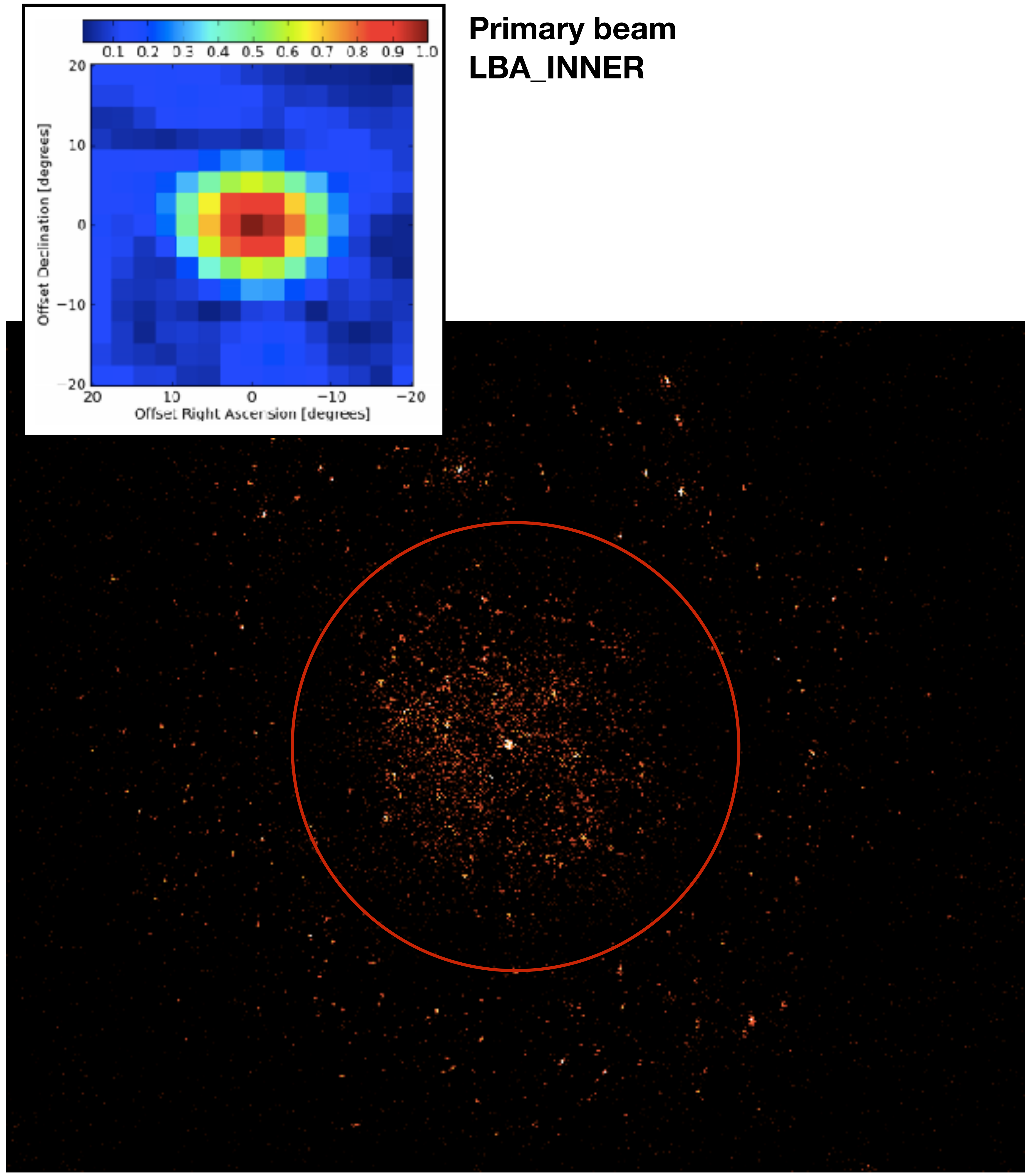




Technical challenges: Side lobes



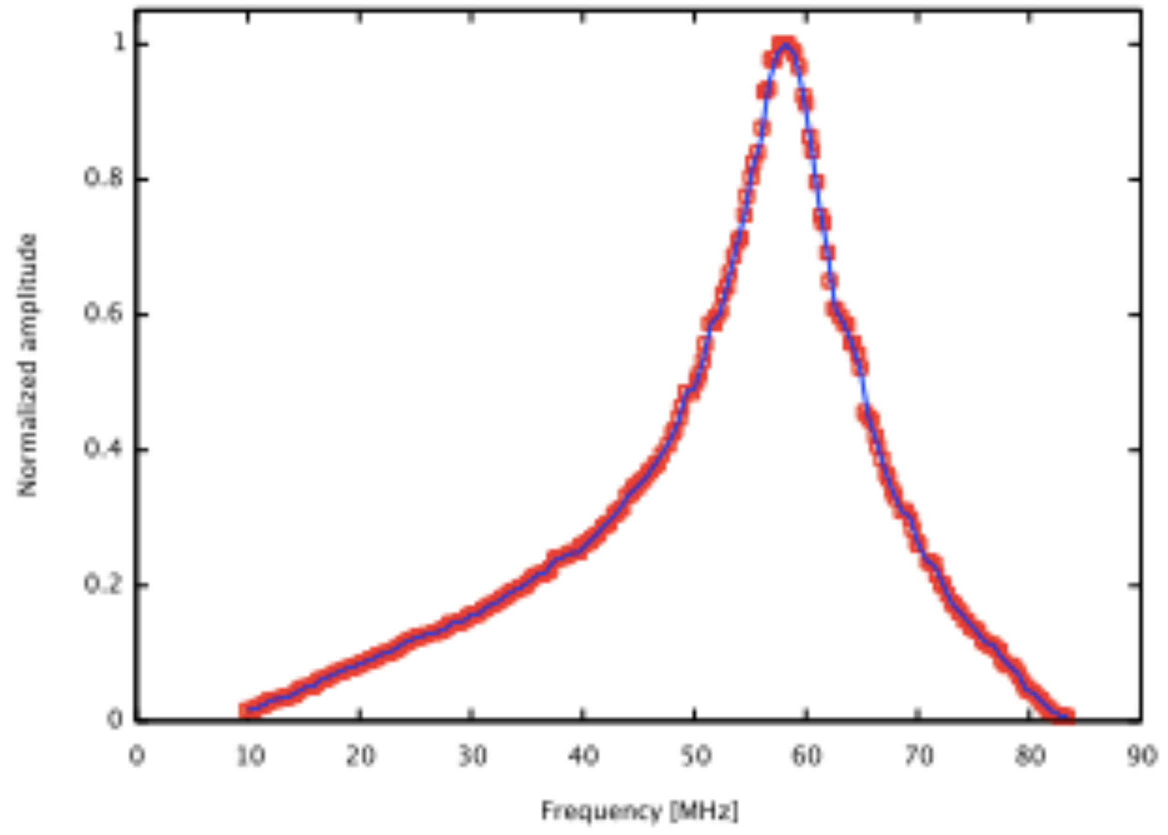
Demix is suboptimal



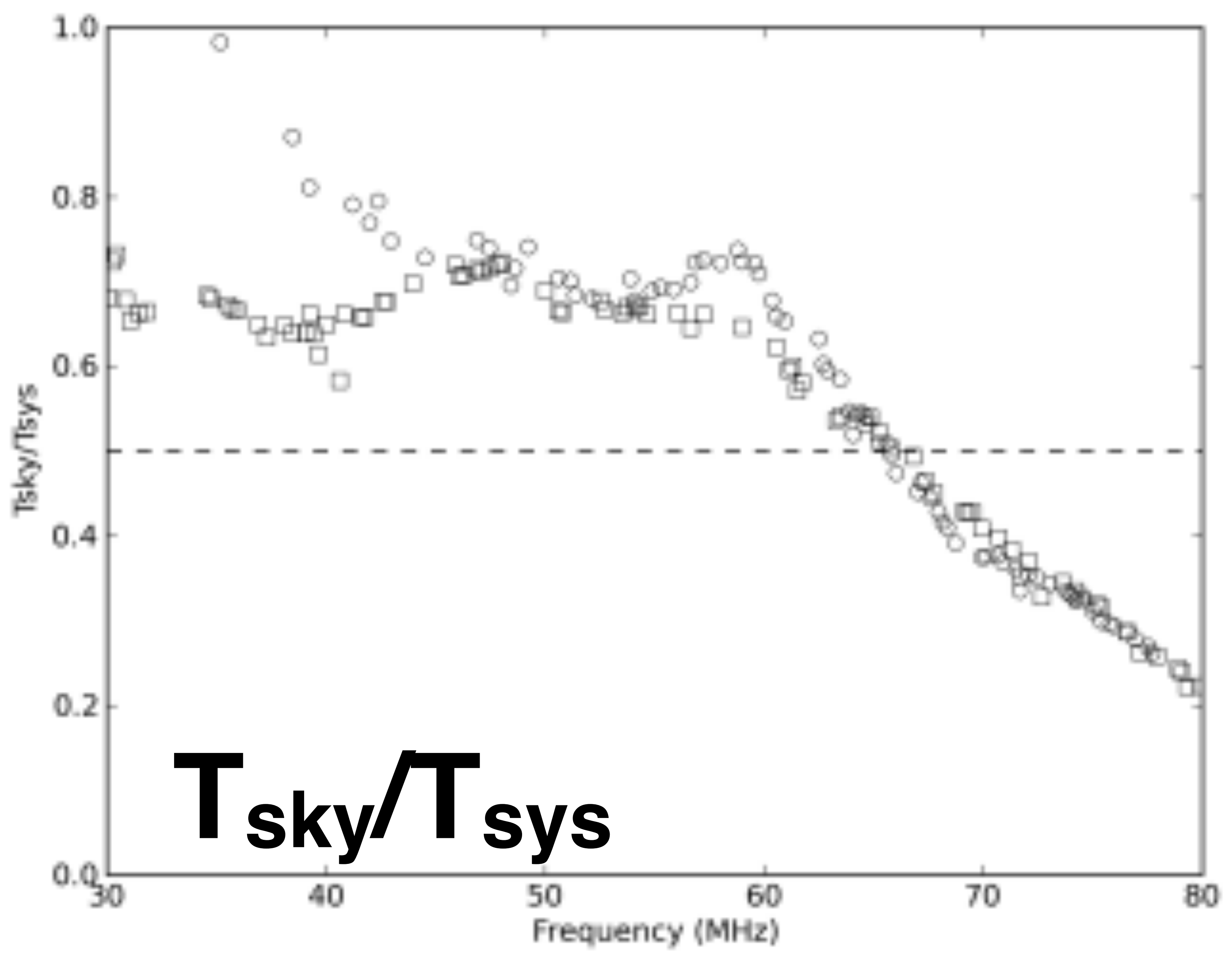
Primary beam
LBA_INNER

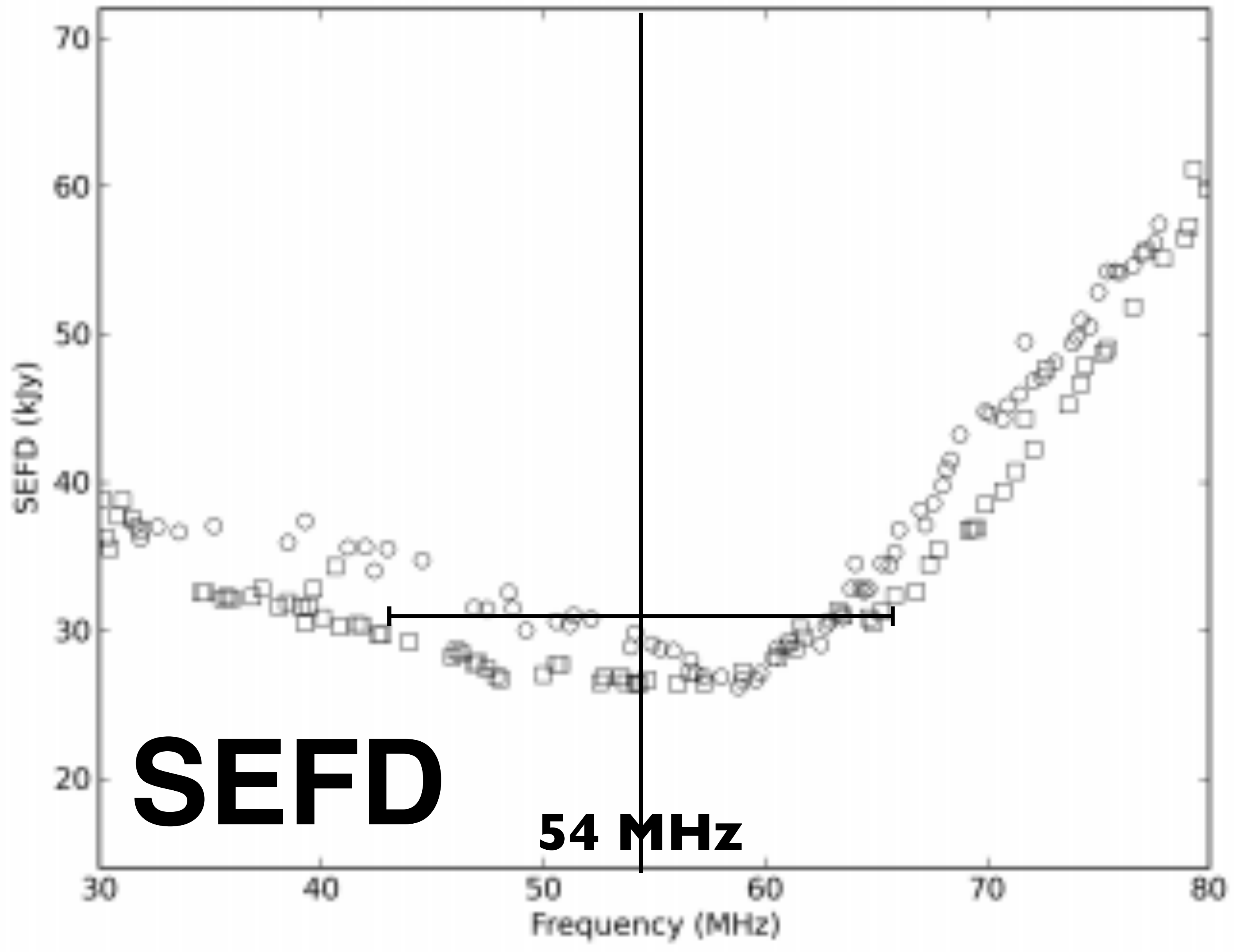
Subtractions is suboptimal (smearing + DD effects)

Technical challenges: Low-sensitivity

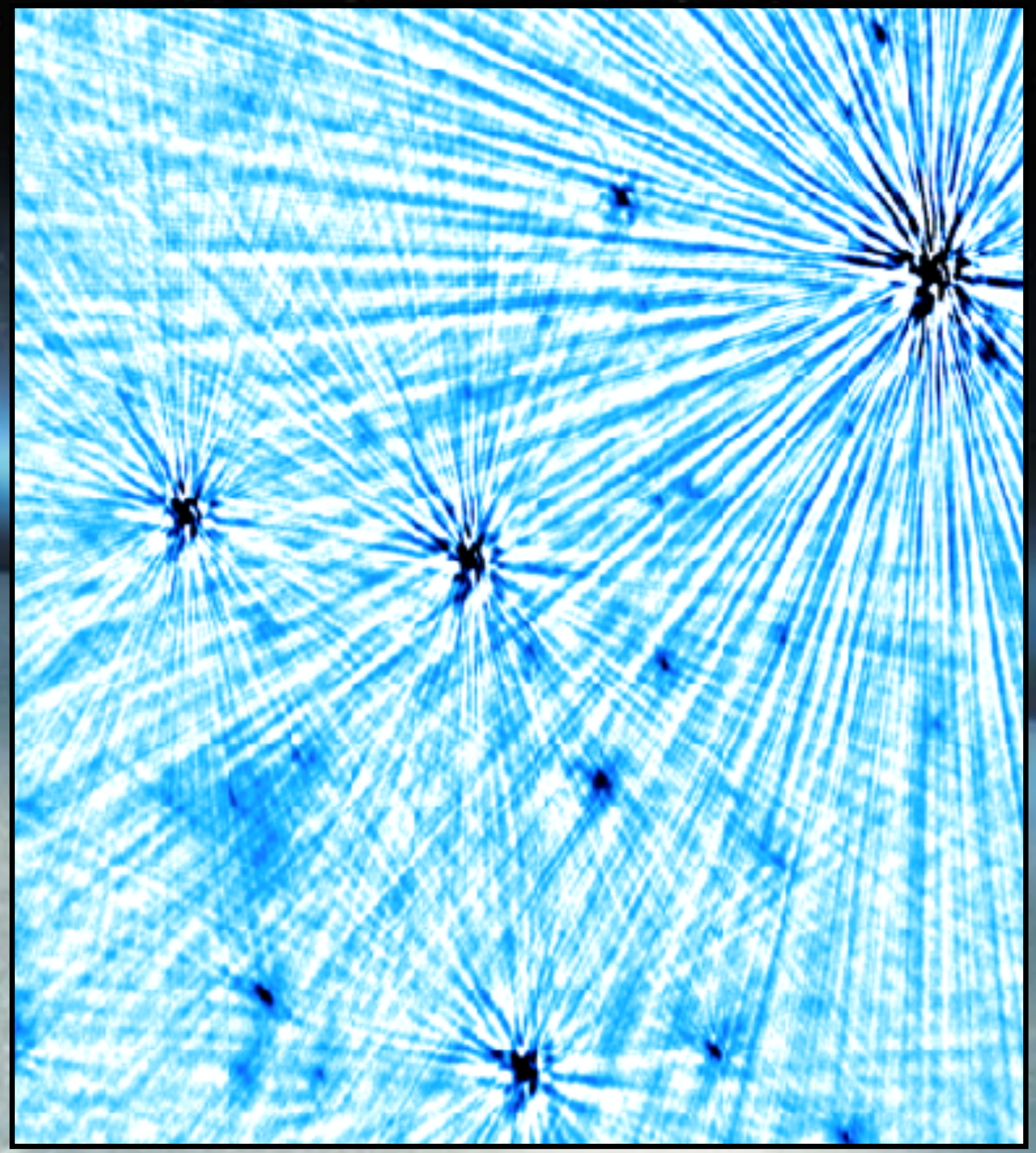


- T_{sky} dominates below 65 MHz
- Don't look at the bandpass
- Look at the SEFD
- 54 MHz is the sweet spot





Technical challenges: Ionosphere



Technical challenges: Ionosphere

Phase rotation on interferometer:

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

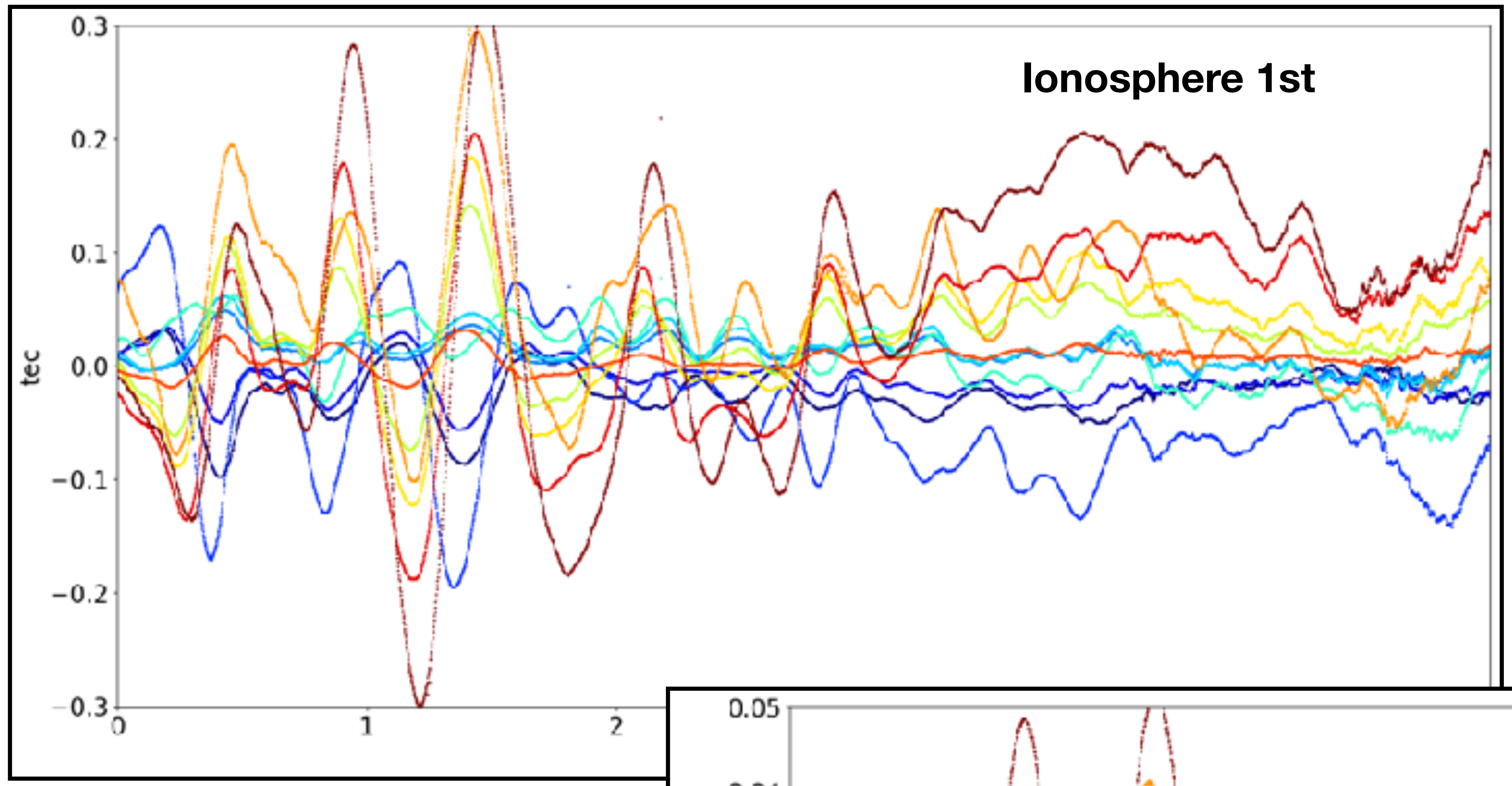
At frequencies <10 MHz: reflection

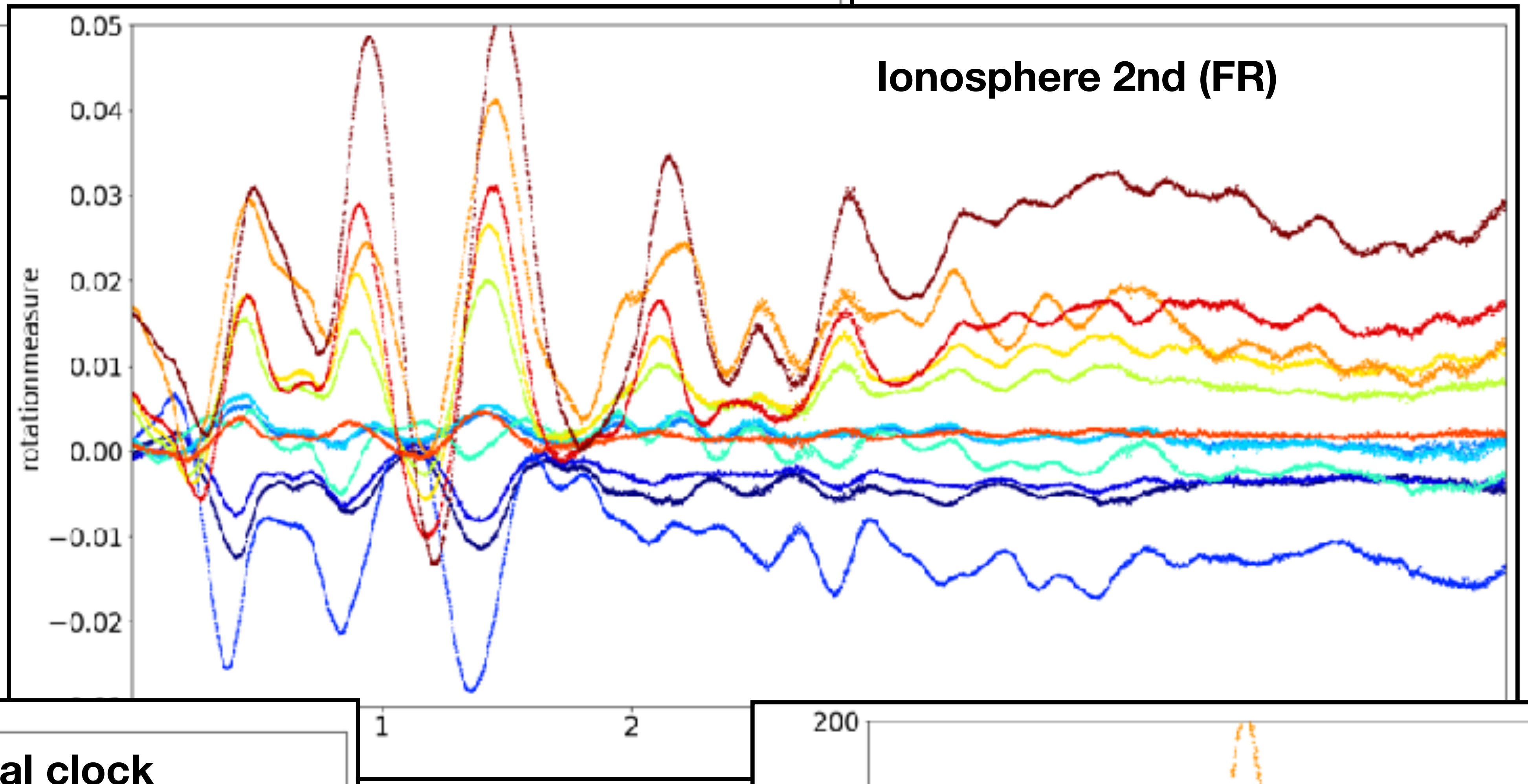
Refractive index:

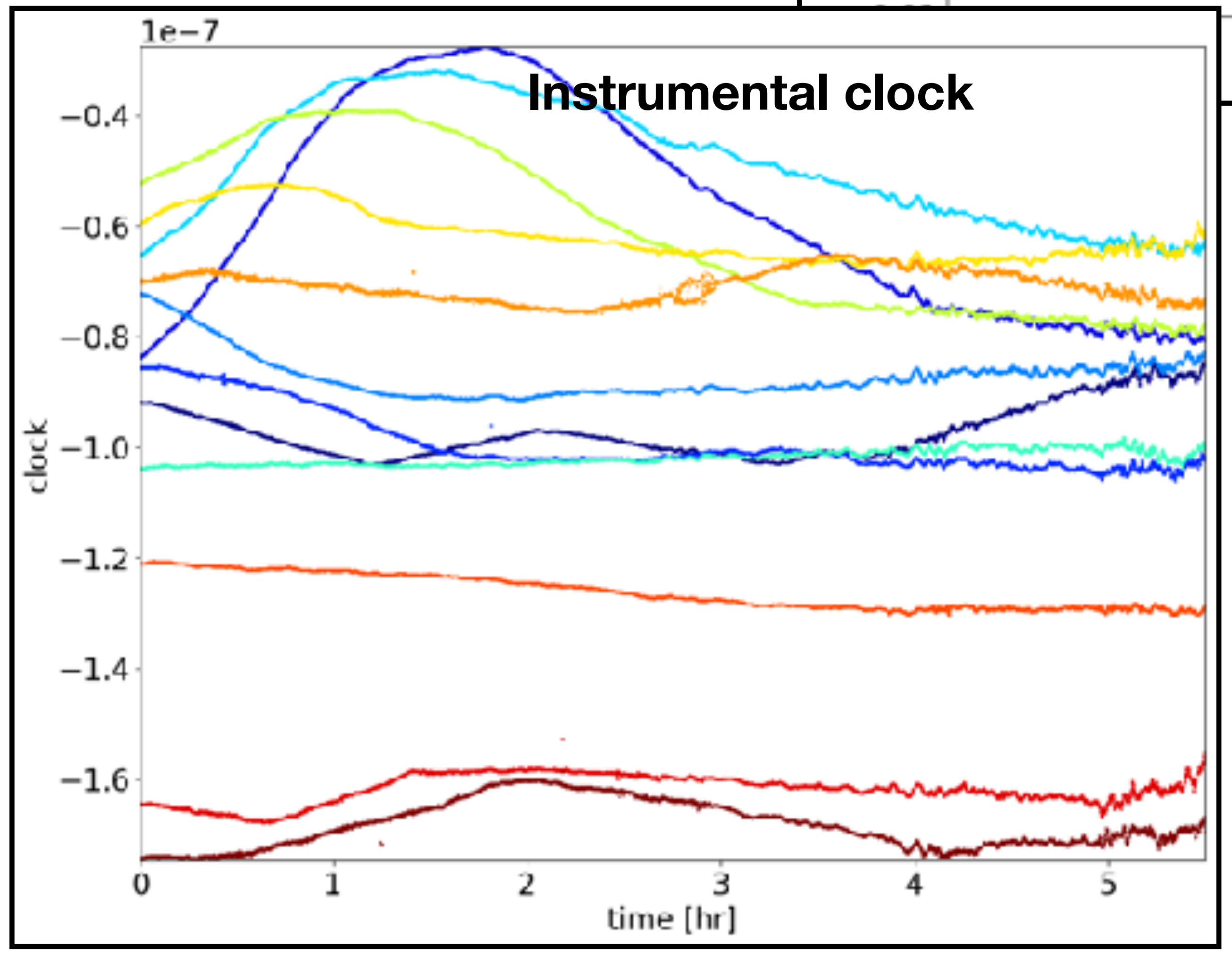
$$n = 1 - A \cdot \frac{n_e}{\nu^2} \pm B \cdot \frac{n_e B \cos\theta}{\nu^3} - C \cdot \frac{n_e^2}{\nu^4} - D \frac{n_e B^2 (1+\cos^2\theta)}{\nu^4},$$

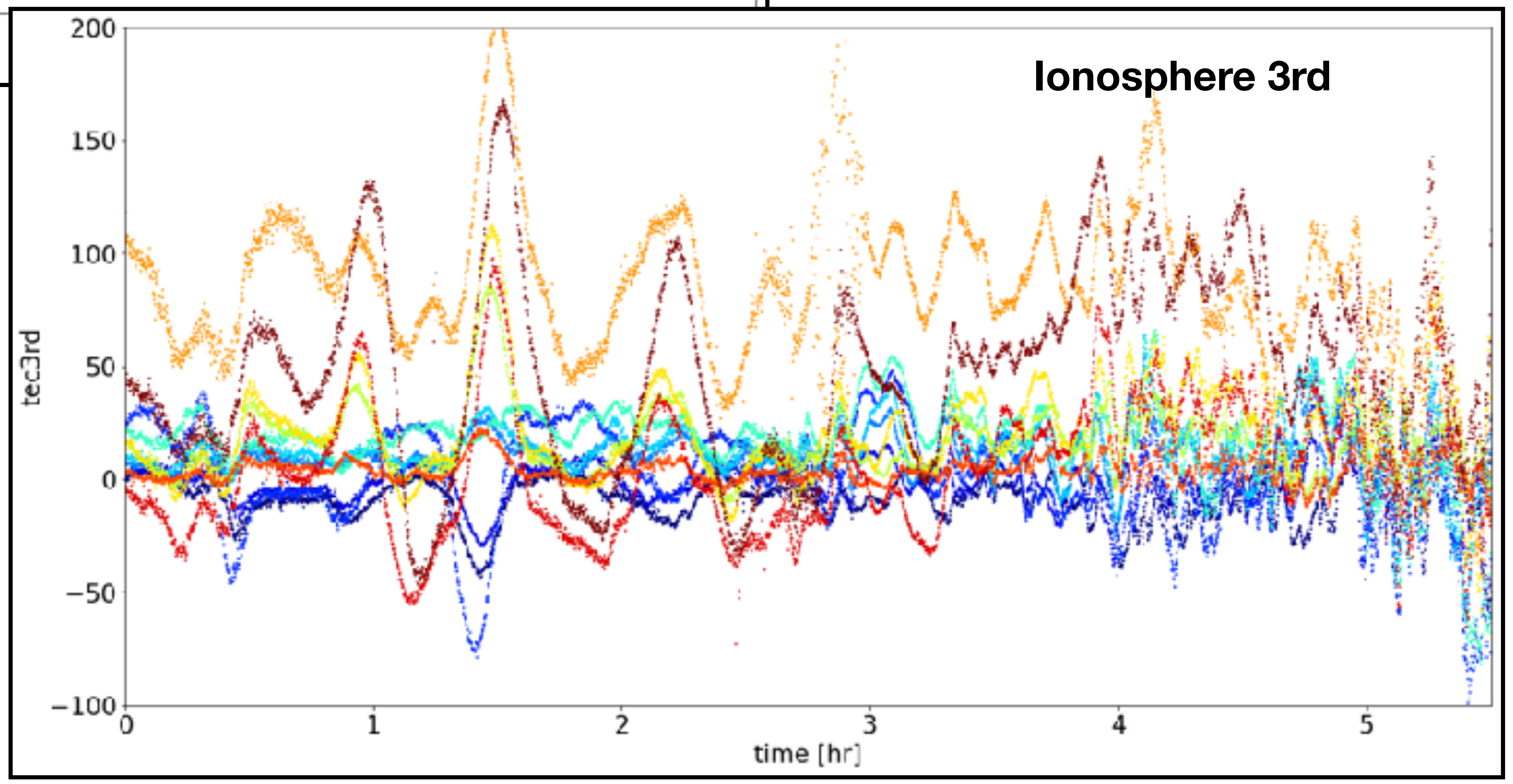
- B and n_e dependency: ionosphere physical properties!
- Frequency dependency: effect is stronger at low frequencies!
- +/- sign of second term: Faraday rotation!

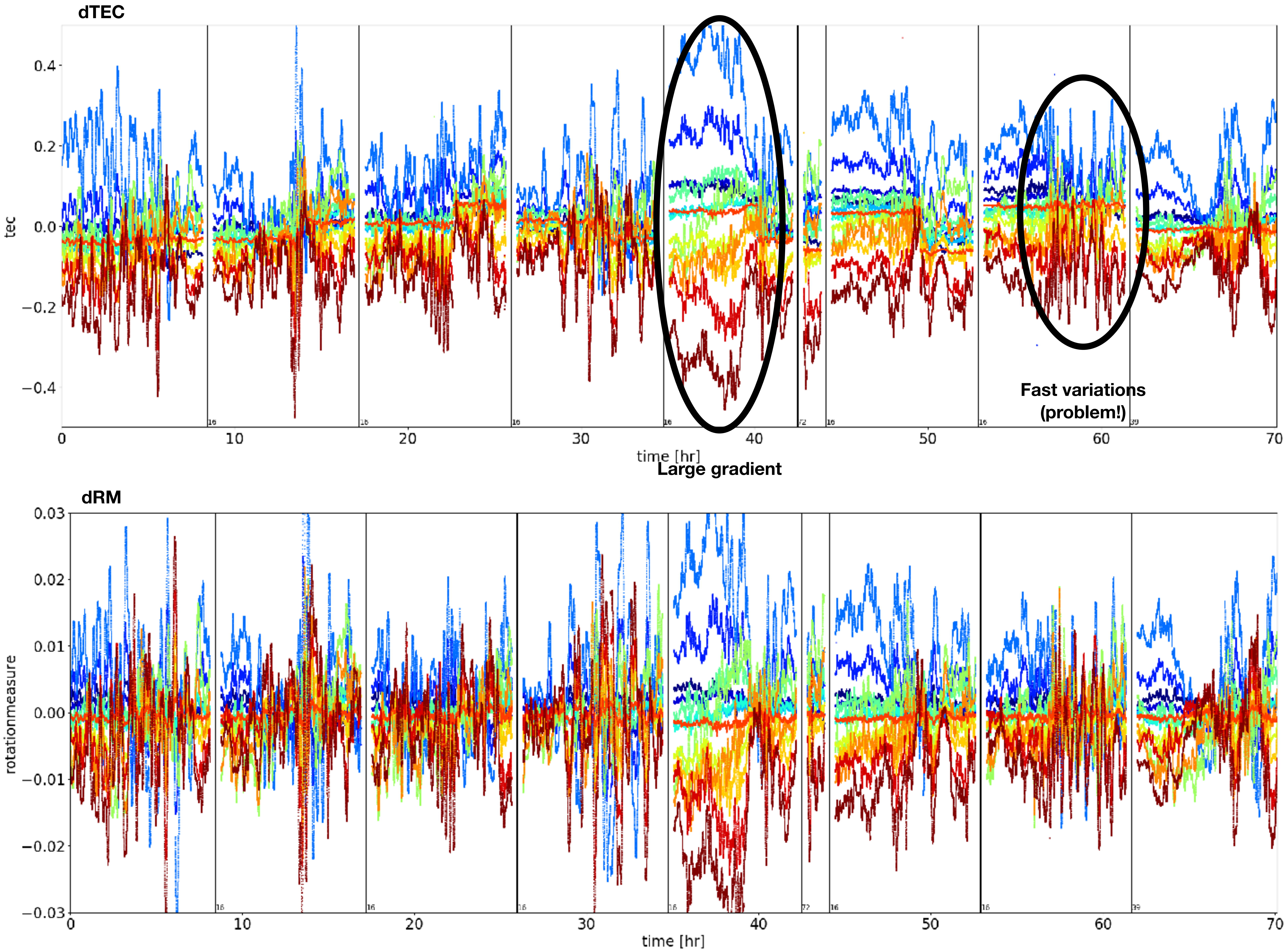
High precision: milli-TEC
No accuracy (only differential values)







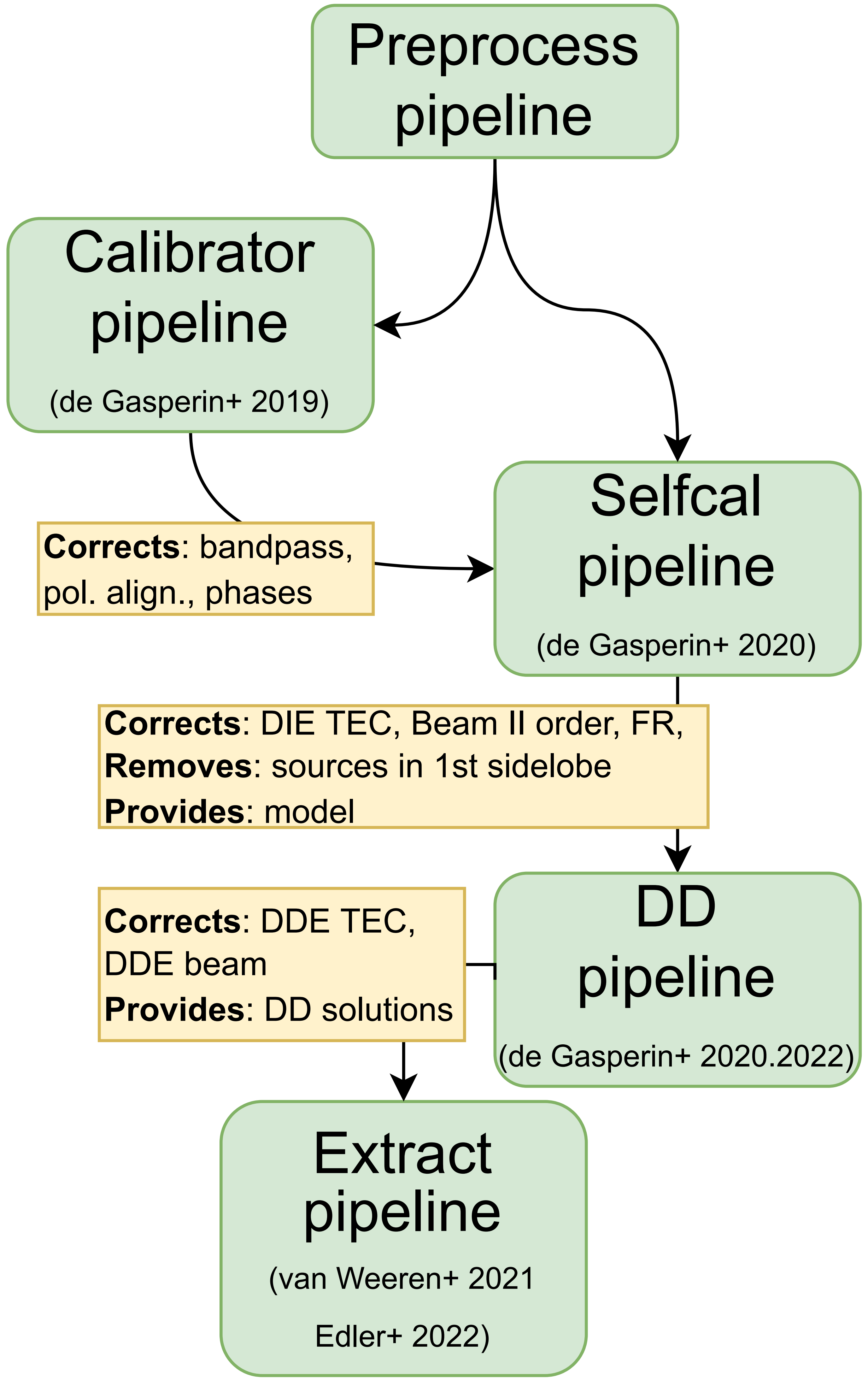



dTEC
tec
0.4
0.2
0.0
−0.2
−0.4
0
10
20
30
40
50
60
70
time [hr]
Large gradient
Fast variations
(problem!)
dRM
rotationmeasure
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
time [hr]

Outline

1. LOFAR LBA
2. PiLL
3. LoLSS (54 MHz)
4. What's next?

Pipeline for LOFAR LBA (PiLL)



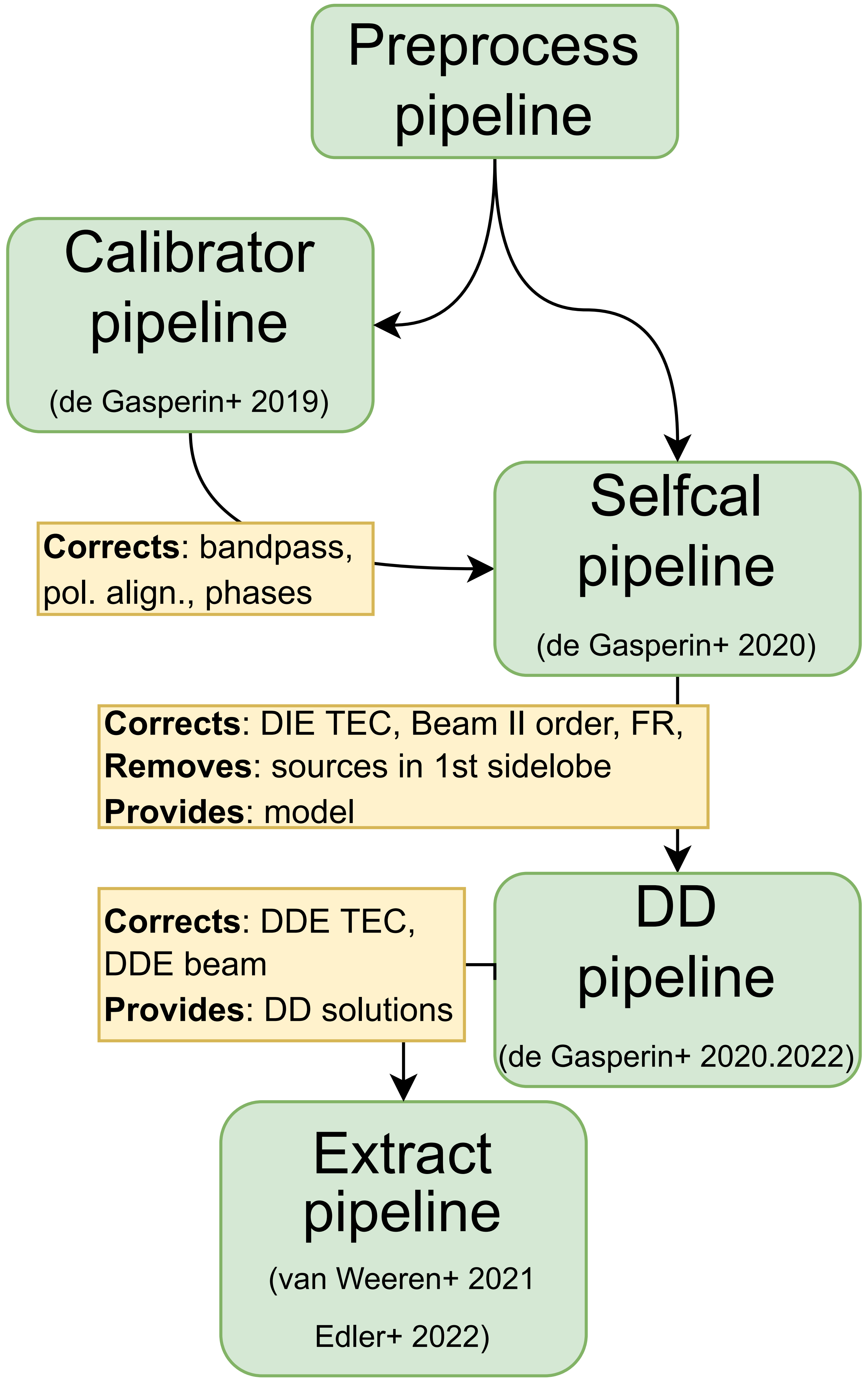
Get the code:
github.com/revoltek/LiLF

Get the docker/singularity:
- $ docker pull revoltek/pill:20220805
- $ singularity build pill.simg docker://revoltek/pill:20220805

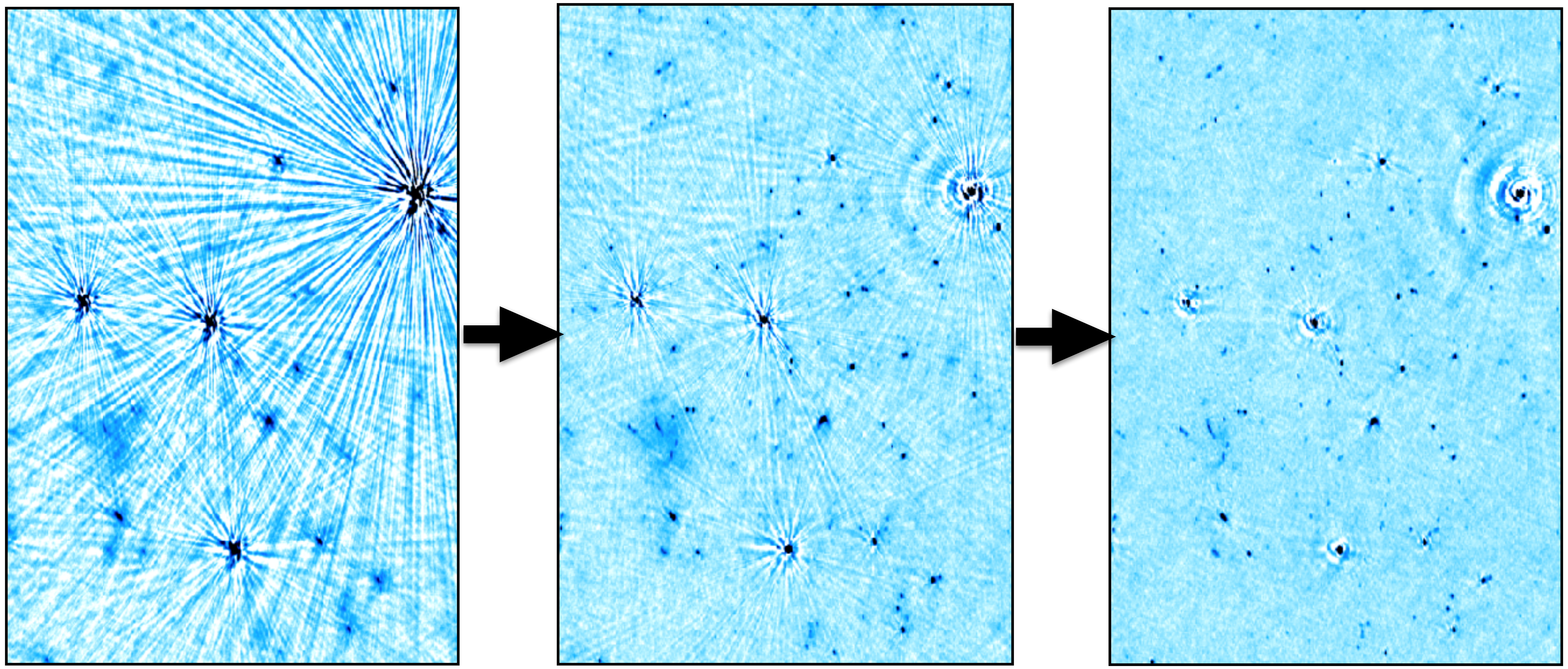
Run the code:
1. stage the data online
2. run the preprocess pipeline
3. run the calibrator pipeline (in the cal dir)
4. run the timesplit+self+dd pipelines (in the target dir)
5. OPTIONAL: run the extract pipeline

Check out the README in Github

Strategy



1. Calibrator calibration
2. Direction independent calibration (5 mJy/b - 45”)
3. Direction dependent calibration (1 mJy/b - 15”)



Corrections:
- **Instrumental (beam, bandpass, delays…)**

Corrections:
- **Direction independent ionosphere**

Corrections:
- **Direction dependent ionosphere**

Pipeline for LOFAR LBA (PiLL)

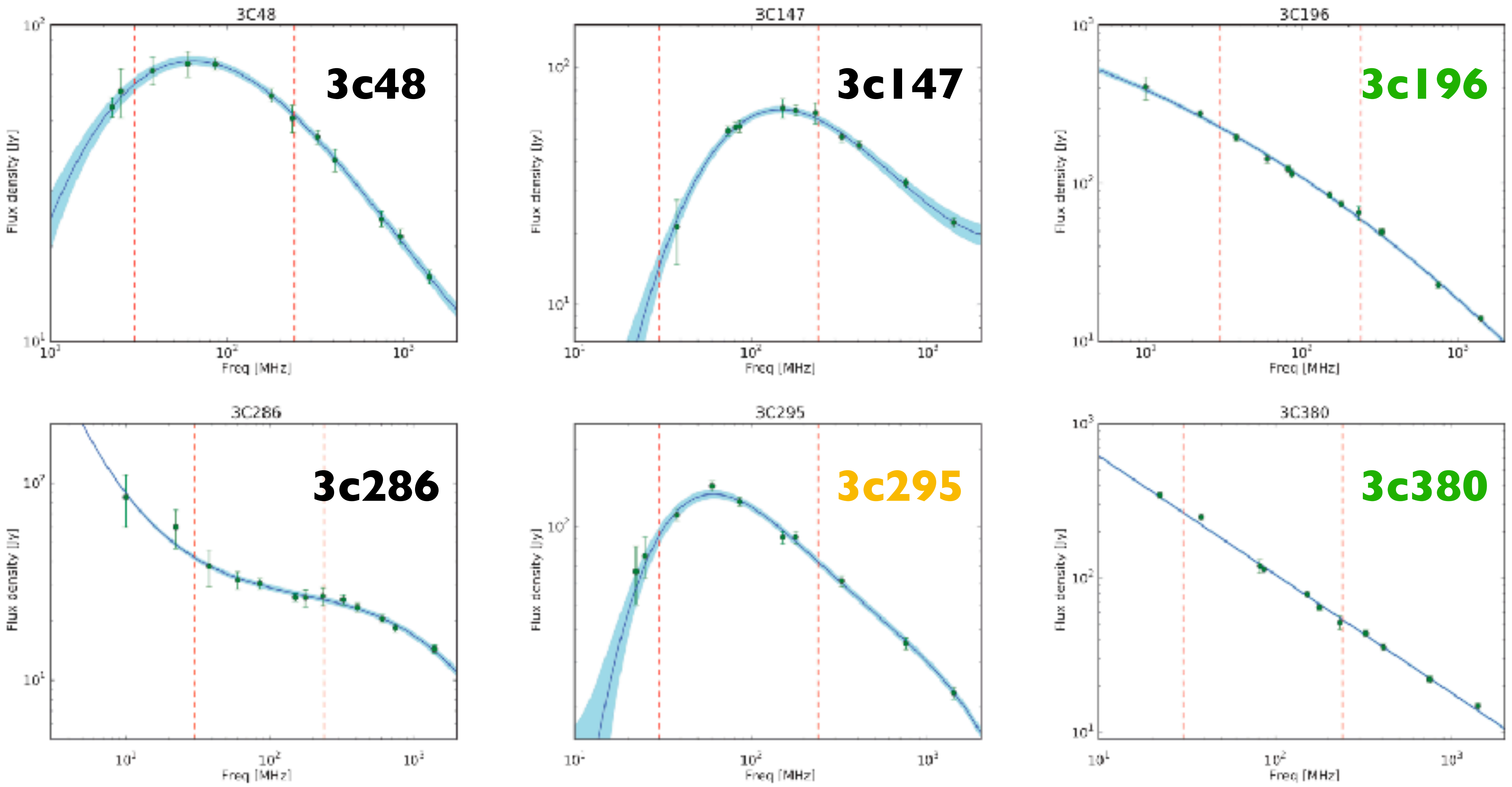
- Preprocess pipeline
- Calibrator pipeline
- Target pipeline
  - Timesplit
  - Self-cal
  - DD-cal
- Extraction

- **(Parallel staging and) download data**
- **Flag low-elevation (<15 deg)**
- **Rescaling**
- **Averaging**
- **Renaming following a standardised name convention**

Pipeline for LOFAR LBA (PiLL)

- Preprocess pipeline
- Calibrator pipeline
- Target pipeline
  - Timesplit
  - Self-cal
  - DD-cal
- Extraction

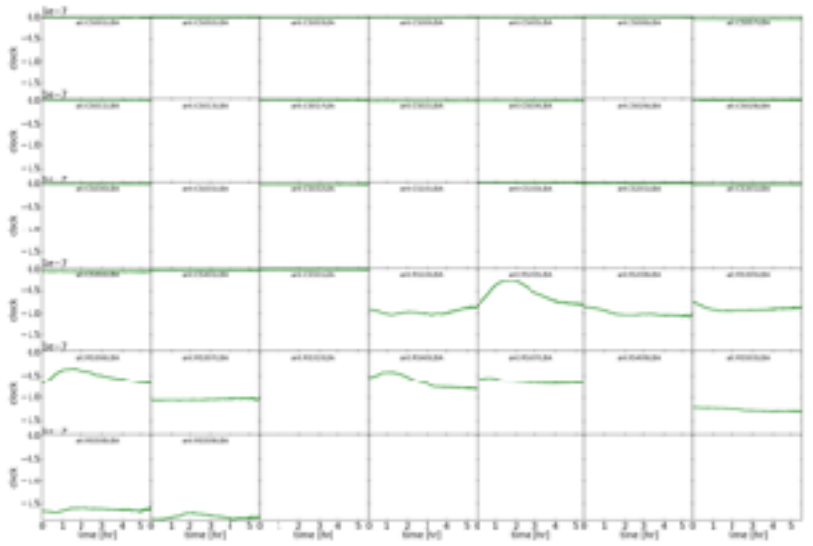
- **Solve**
  - **-cross-delay**
  - **-Faraday rotation**
  - **-bandpass**
  - **-phases (clock + ionosphere)**
- **Flag bad stations**
- **Imaging (optional)**



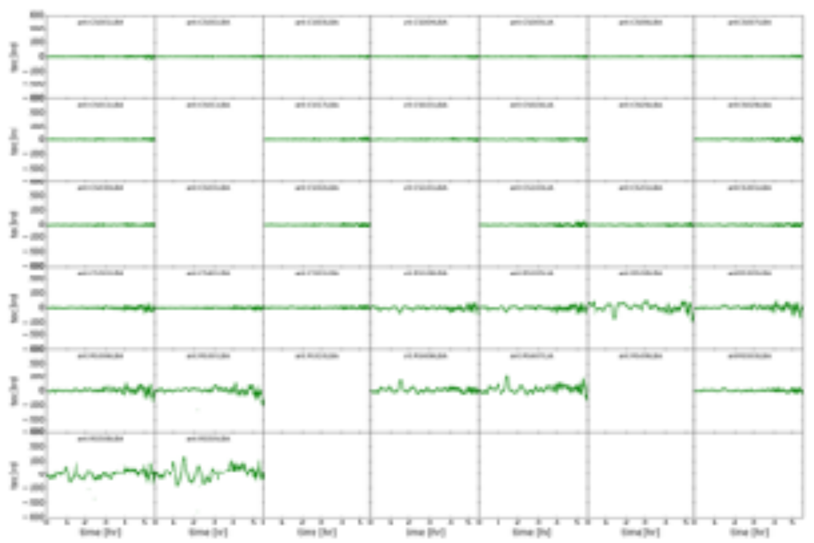
Calibrator pipeline (PreFactor 3)

de Gasperin+ 2019

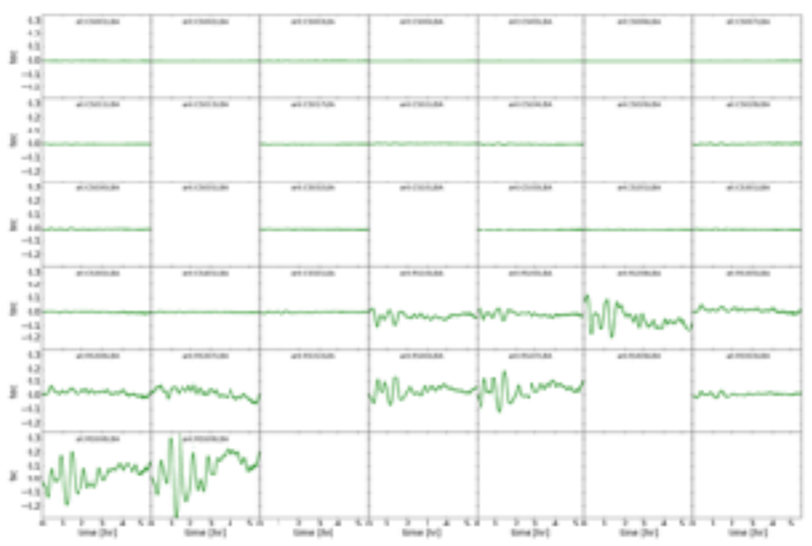
Clock

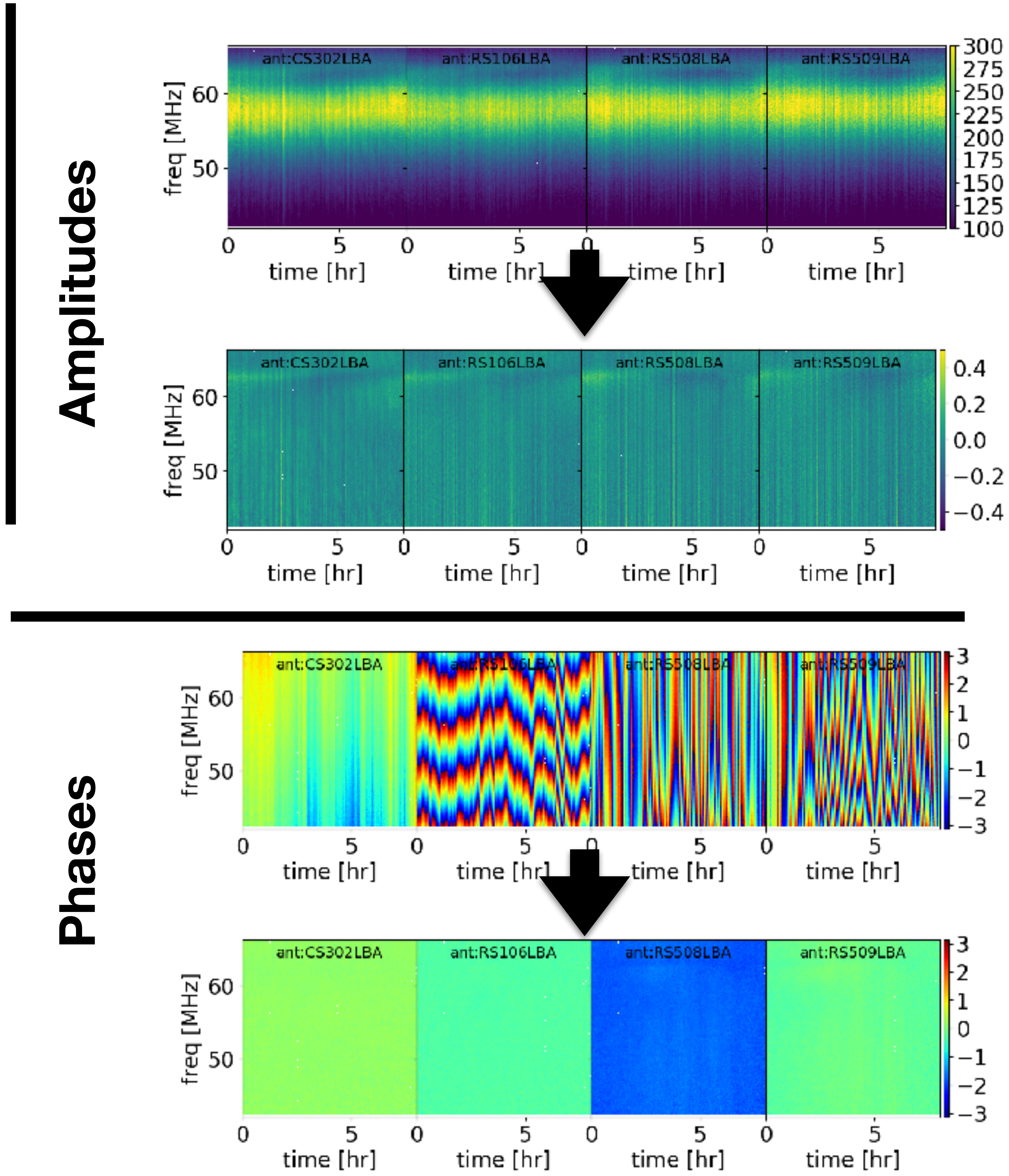


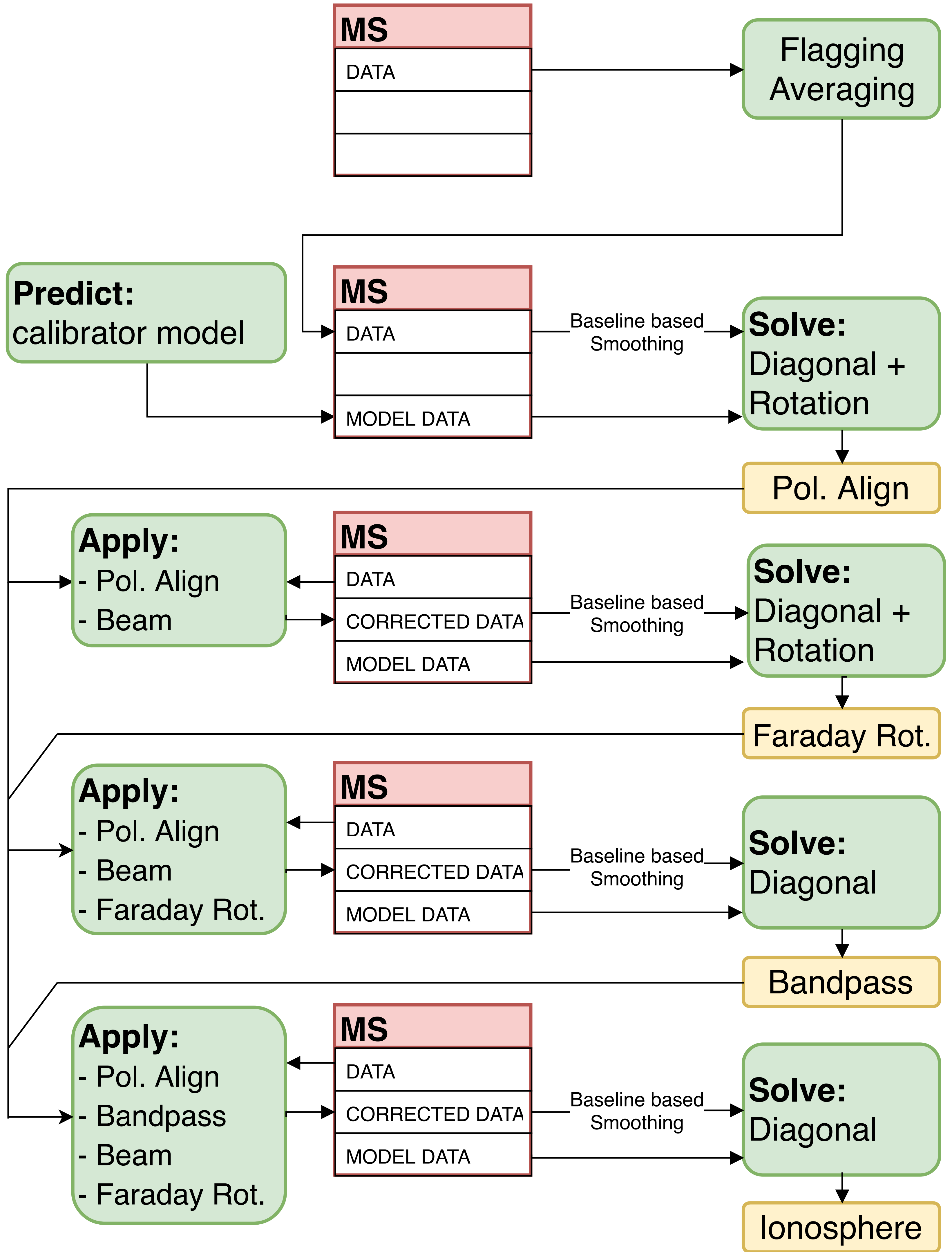
TEC



TEC (3rd order)







Pipeline for LOFAR LBA (PiLL)

- Preprocess pipeline
- Calibrator pipeline
- Target pipeline
  - Timesplit
  - Self-cal
  - DD-cal
- Extraction

- **Apply solutions**
- **Combine all SBs in a single MS**
- **Flagging**
- **Split in time (1h) for parallelisation**

Pipeline for LOFAR LBA (PiLL)

- Preprocess pipeline
- Calibrator pipeline
- Target pipeline
  - Timesplit
  - Self-cal
  - DD-cal
- Extraction

- **Solve fast-time for TEC**
- **Remove sources from 1st side-lobe**
- **Solve slow-time G for II order beam errors**
- **Self-cal cycles**

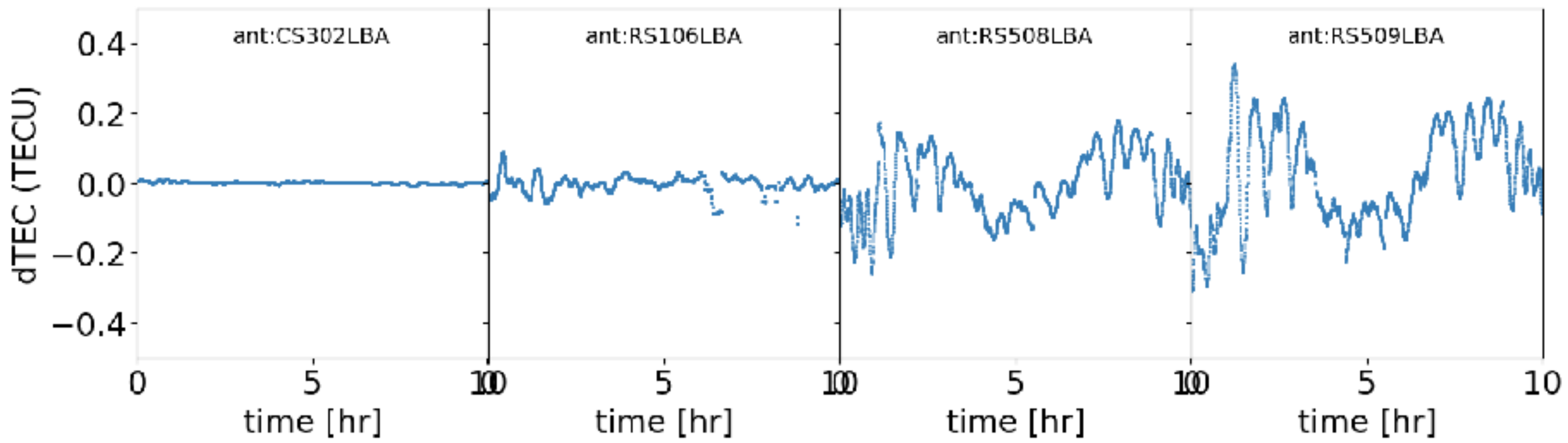
Outcome:

- <5 mJy/b, beam=45” (beam corrected)

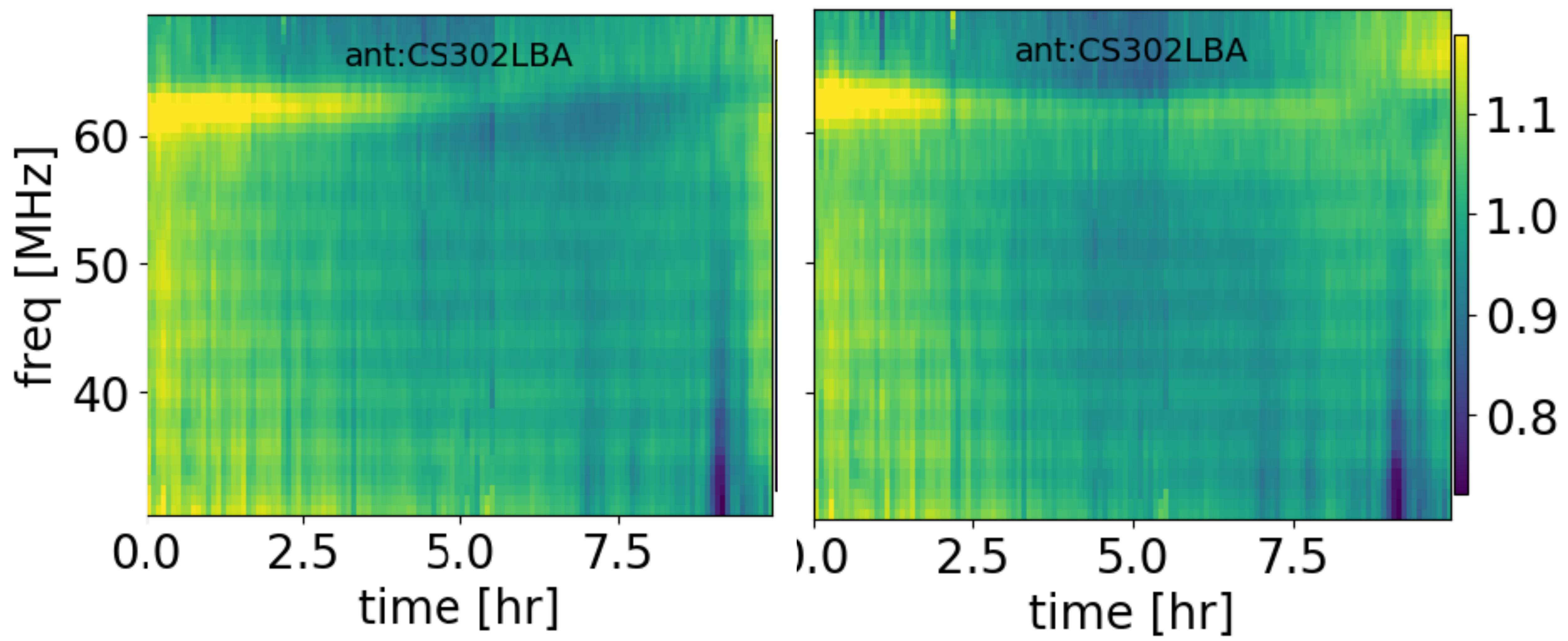
Self-calibration

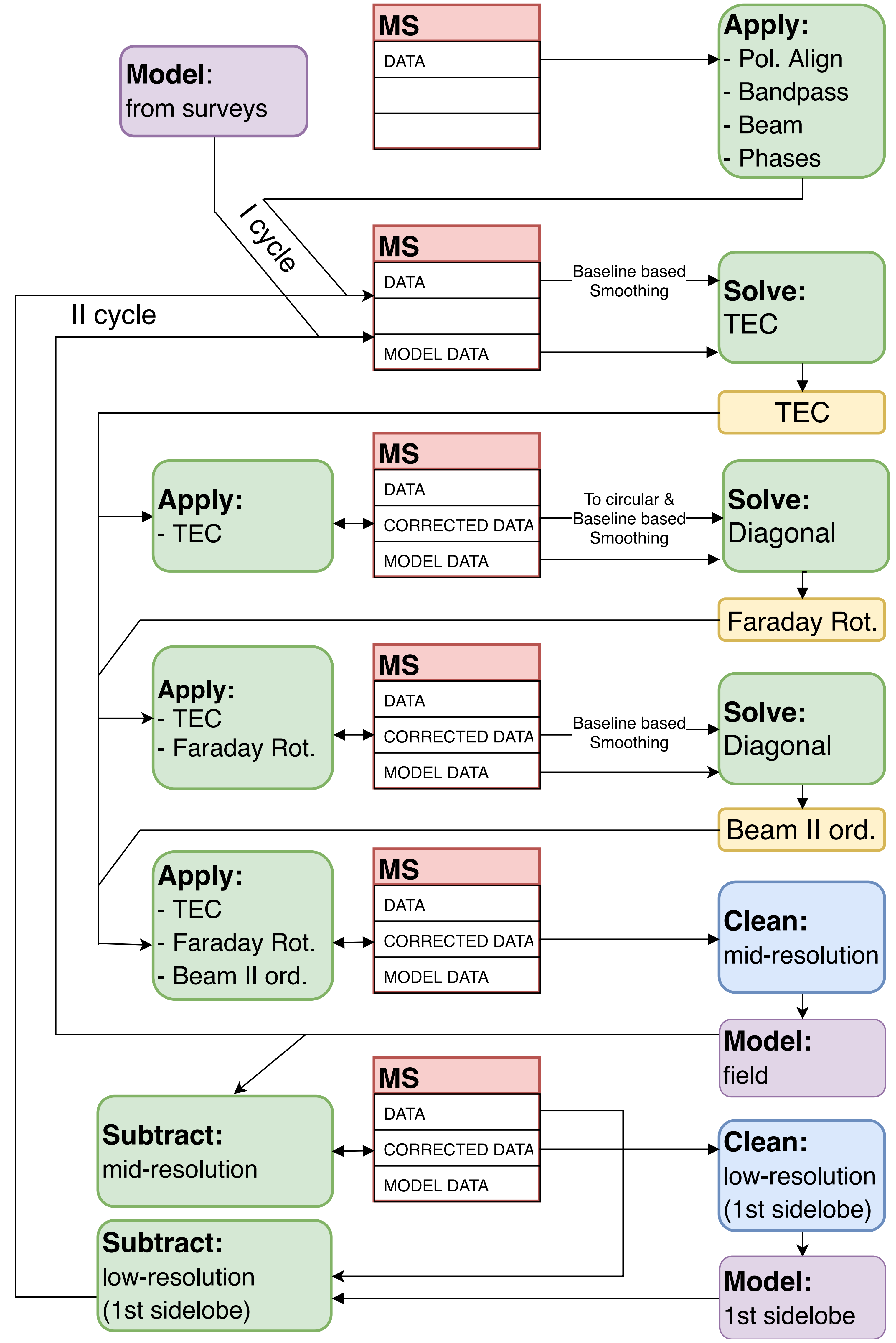
de Gasperin+ 2020

TEC delay correction (direction independent)



II order beam correction (amplitude)

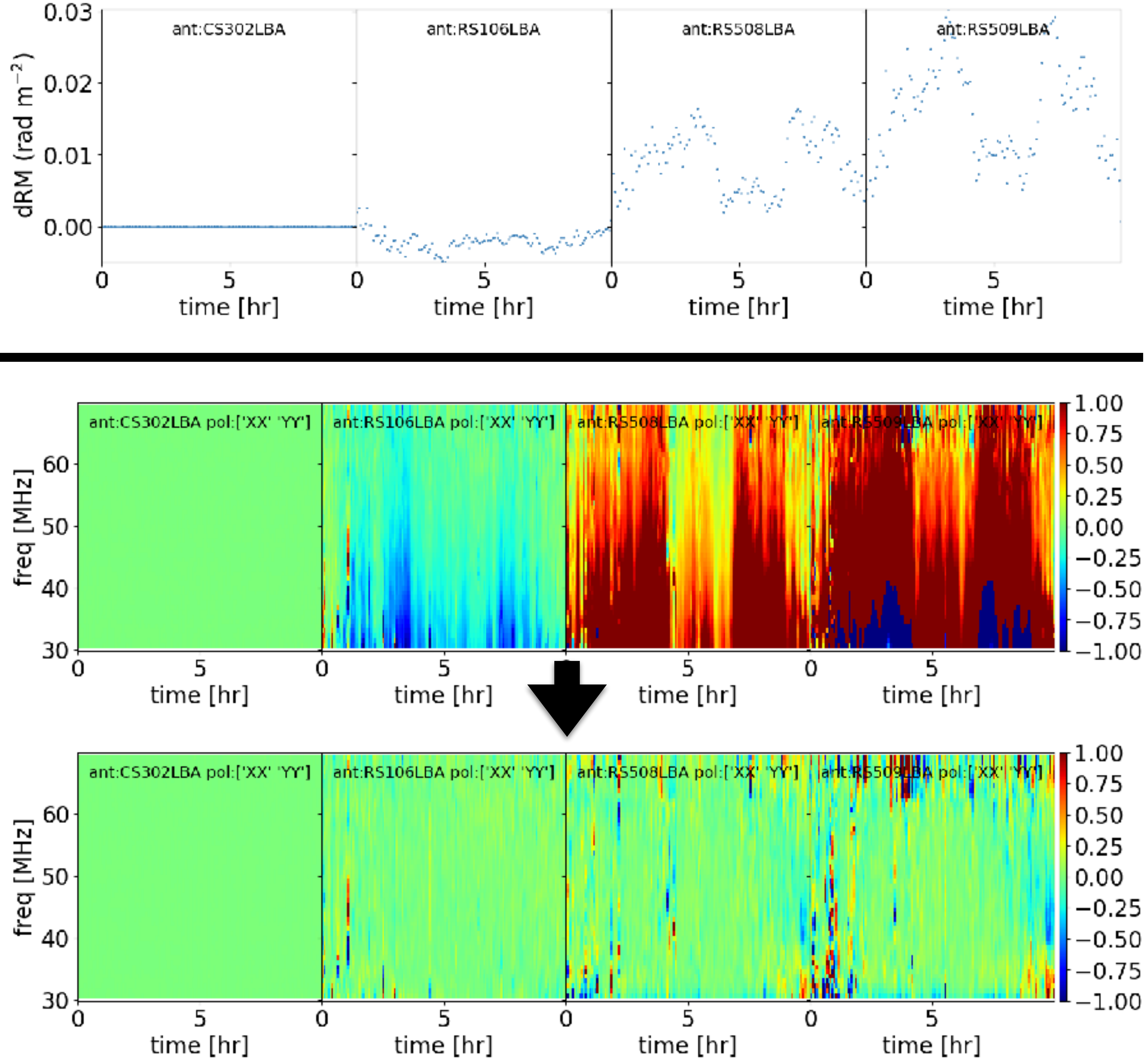


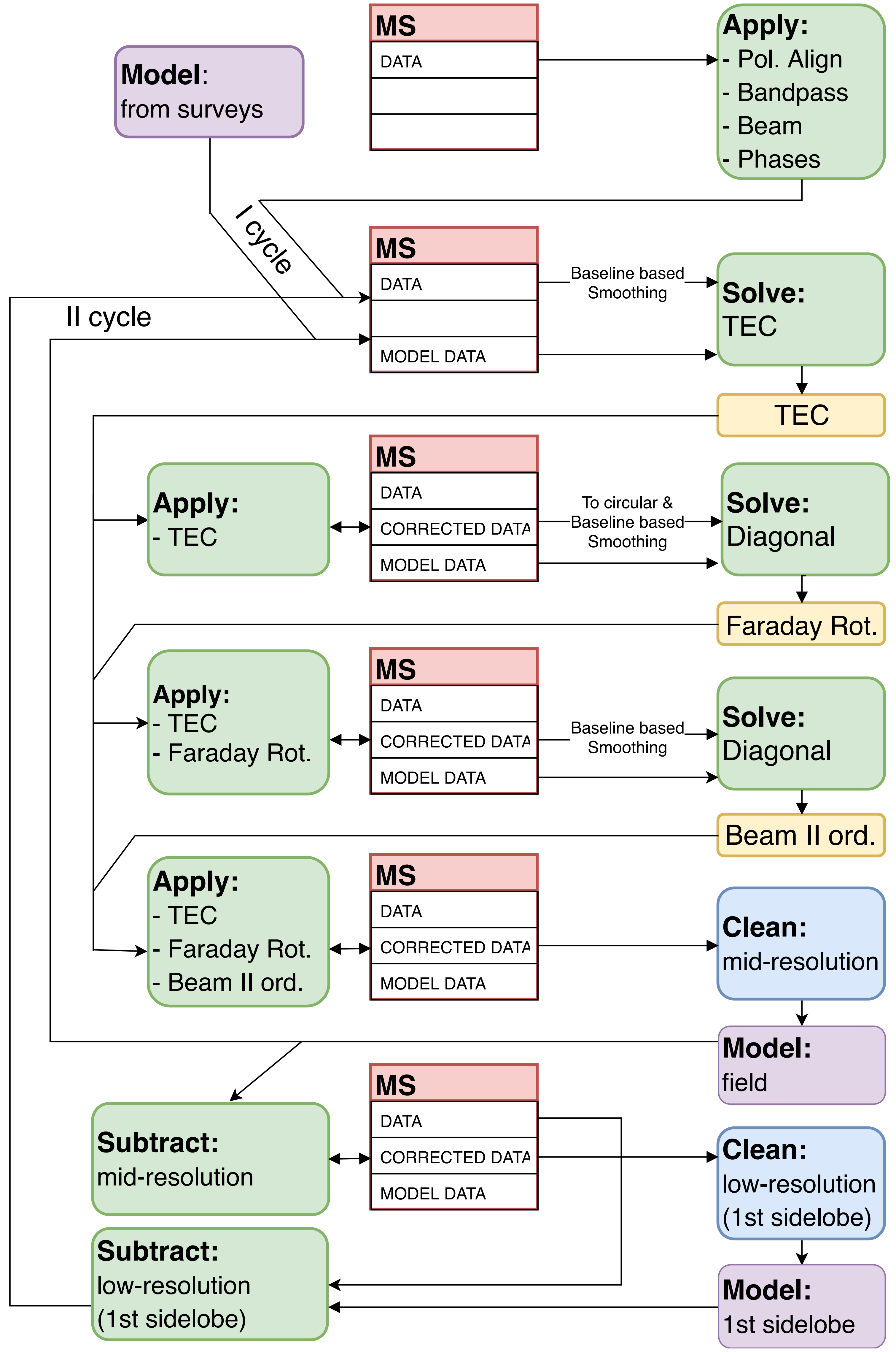


Self-calibration

de Gasperin+ 2020

Faraday rotation correction





Direction-dependenta calibration

- Download pipeline
- Calibrator pipeline
- Target pipeline
  - Timesplit
  - Self-cal
  - DD-cal
- Extraction

- **Still in developing**
- **Solve for fast DD-TEC**
- **Solve for slow beam-amp**

Outcome:

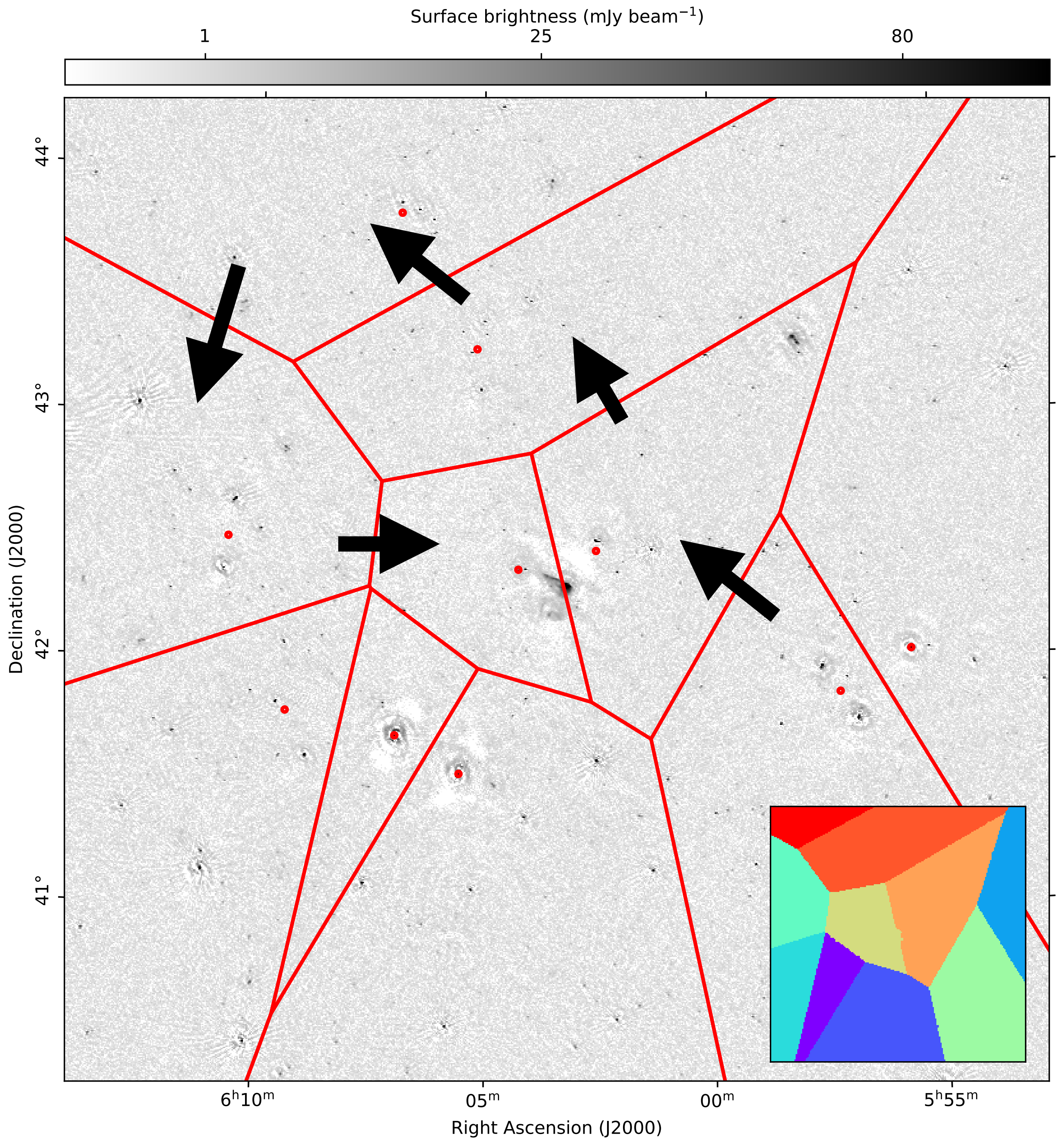
- <2 mJy/b, beam=15” (beam corrected)
- V-stokes
- Source-subtracted low-resolution

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

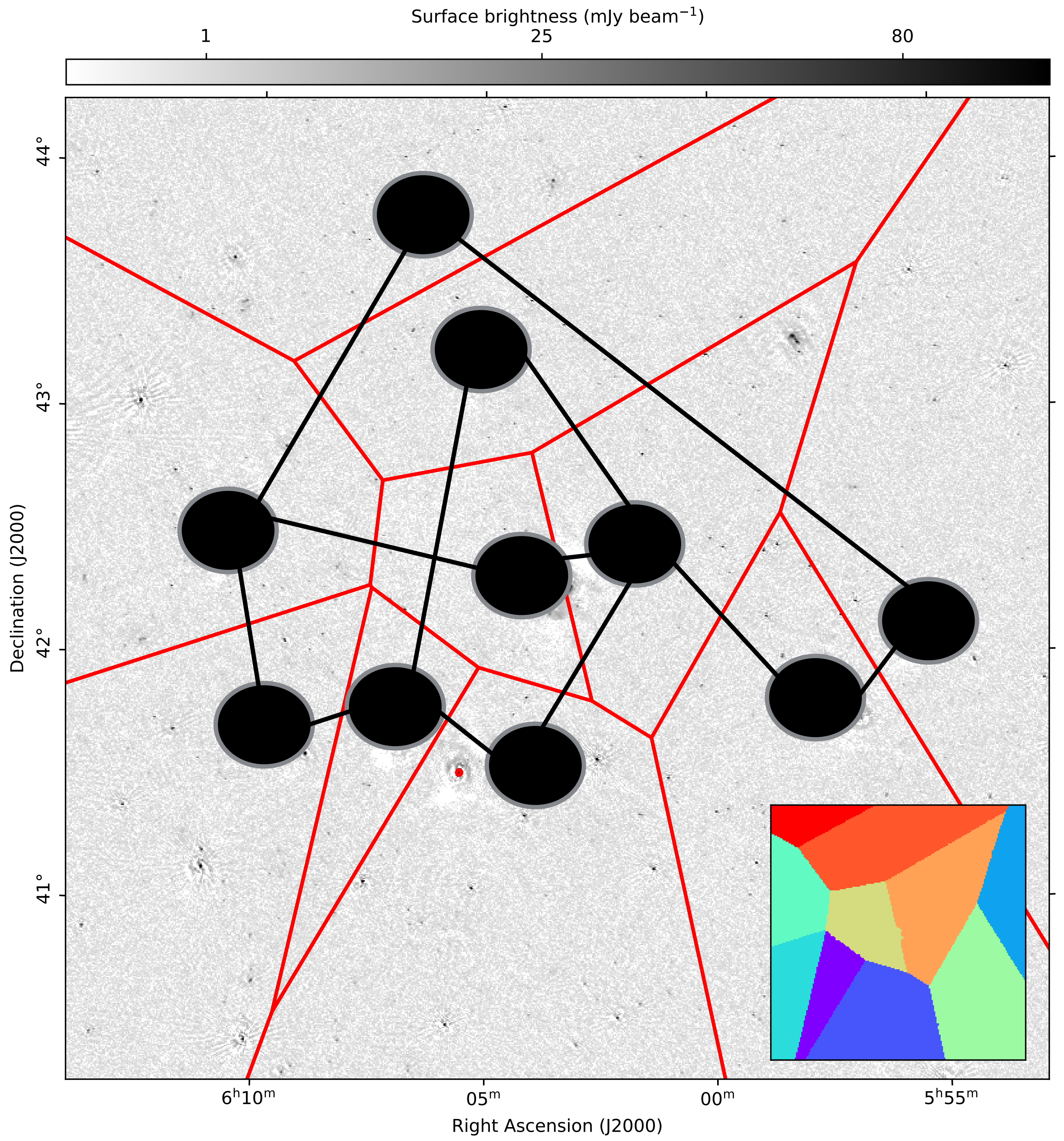


Advantages:
- Scalable
- Easy-to-implement

Parallel calibration

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

Example: KillMS, DP3



Advantages:
- Possibly faster
- More precise

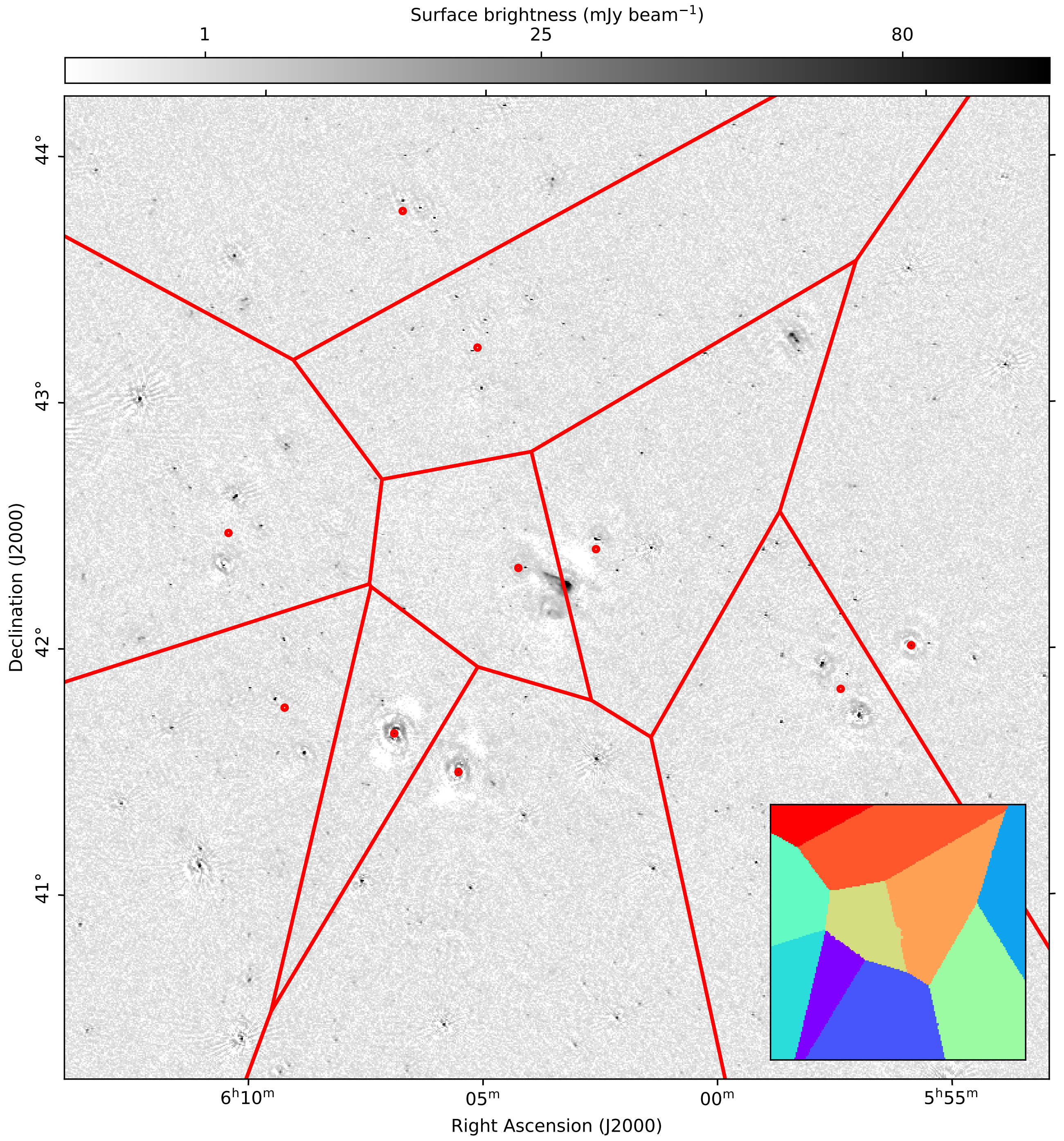
de Gasperin+ 2021, A&A, 642, A85

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



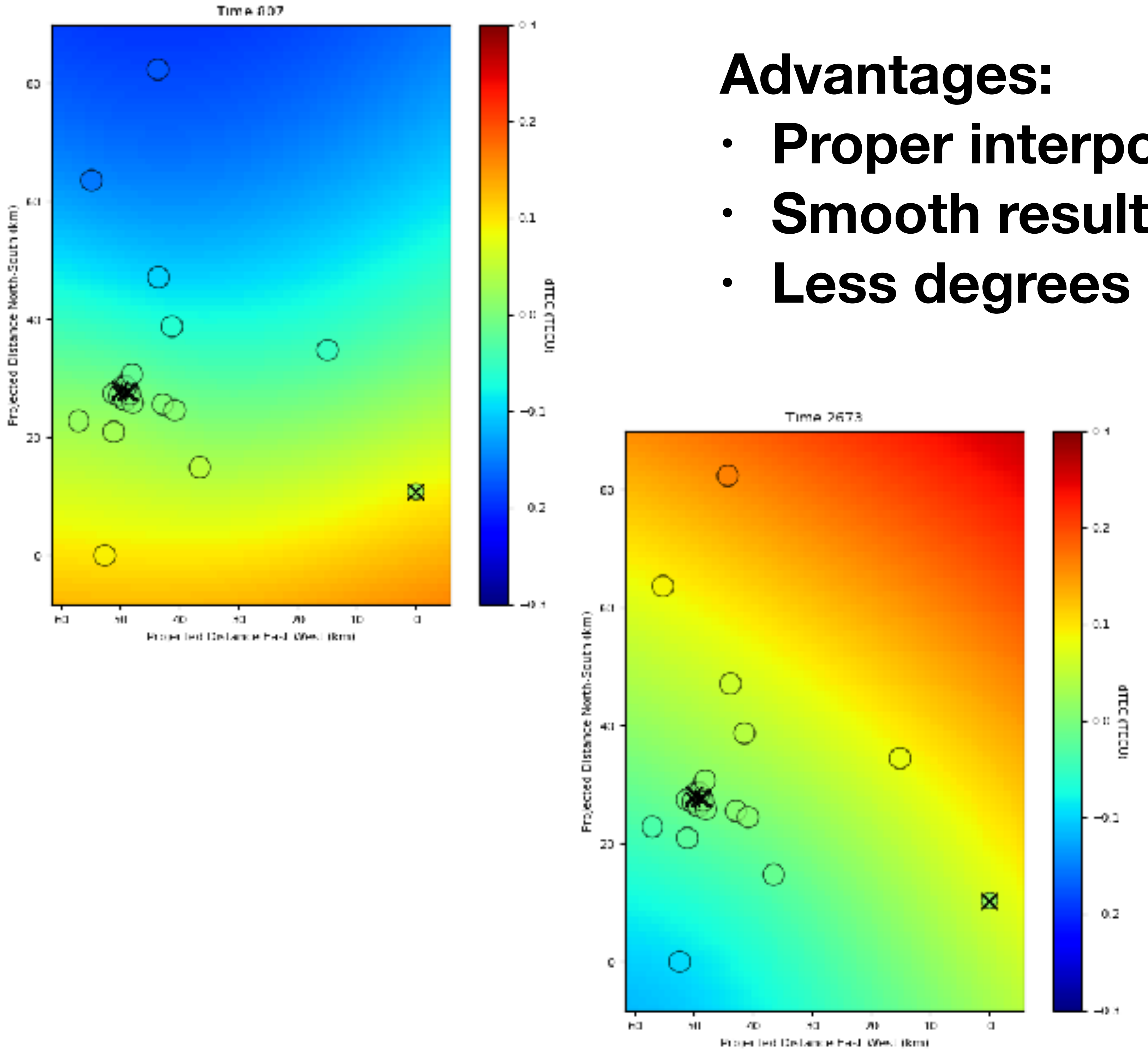
Advantages:
- Fast
- Scalable
- Easy-to-implement

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

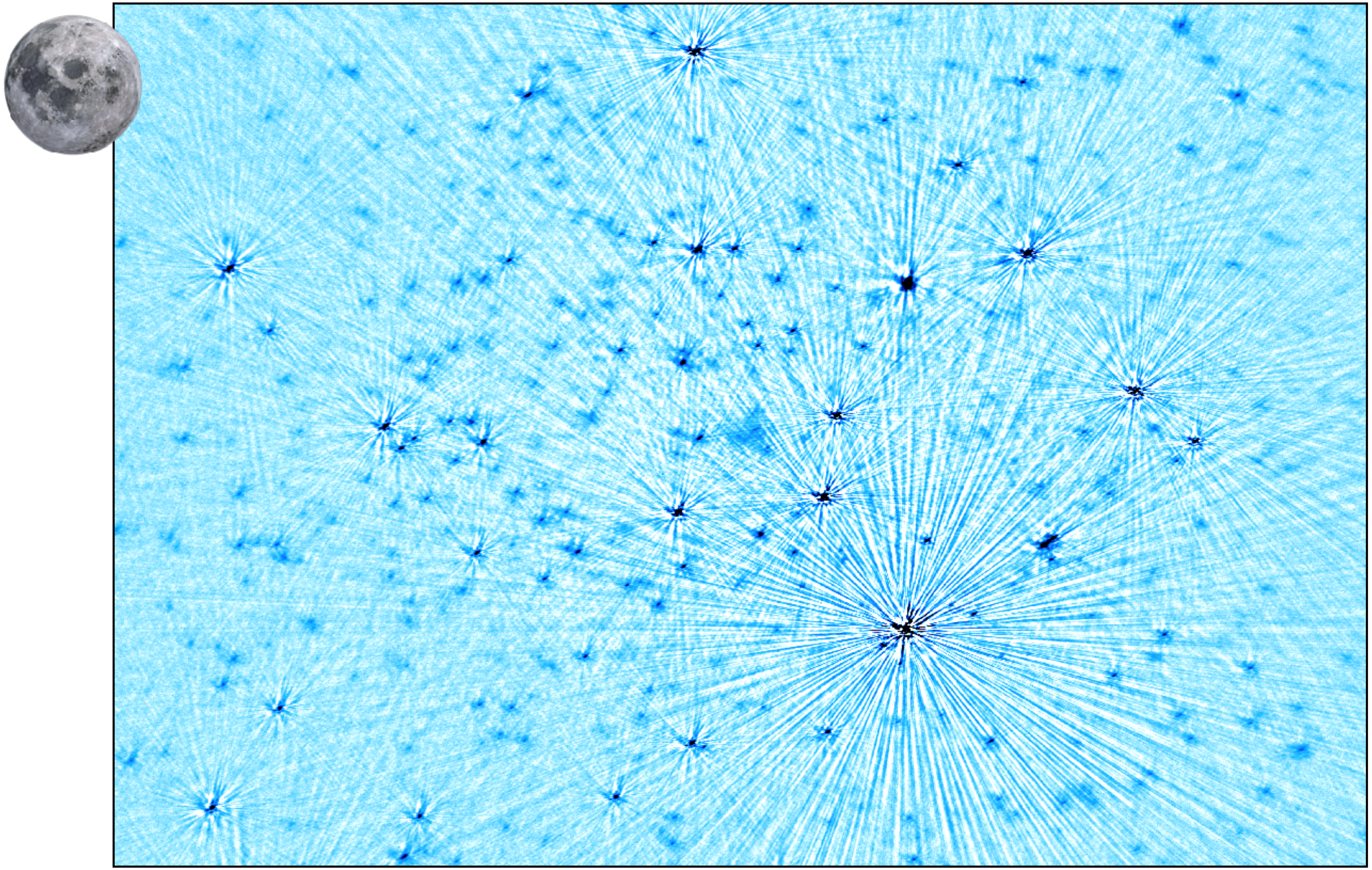
Example: WSclean + IDG



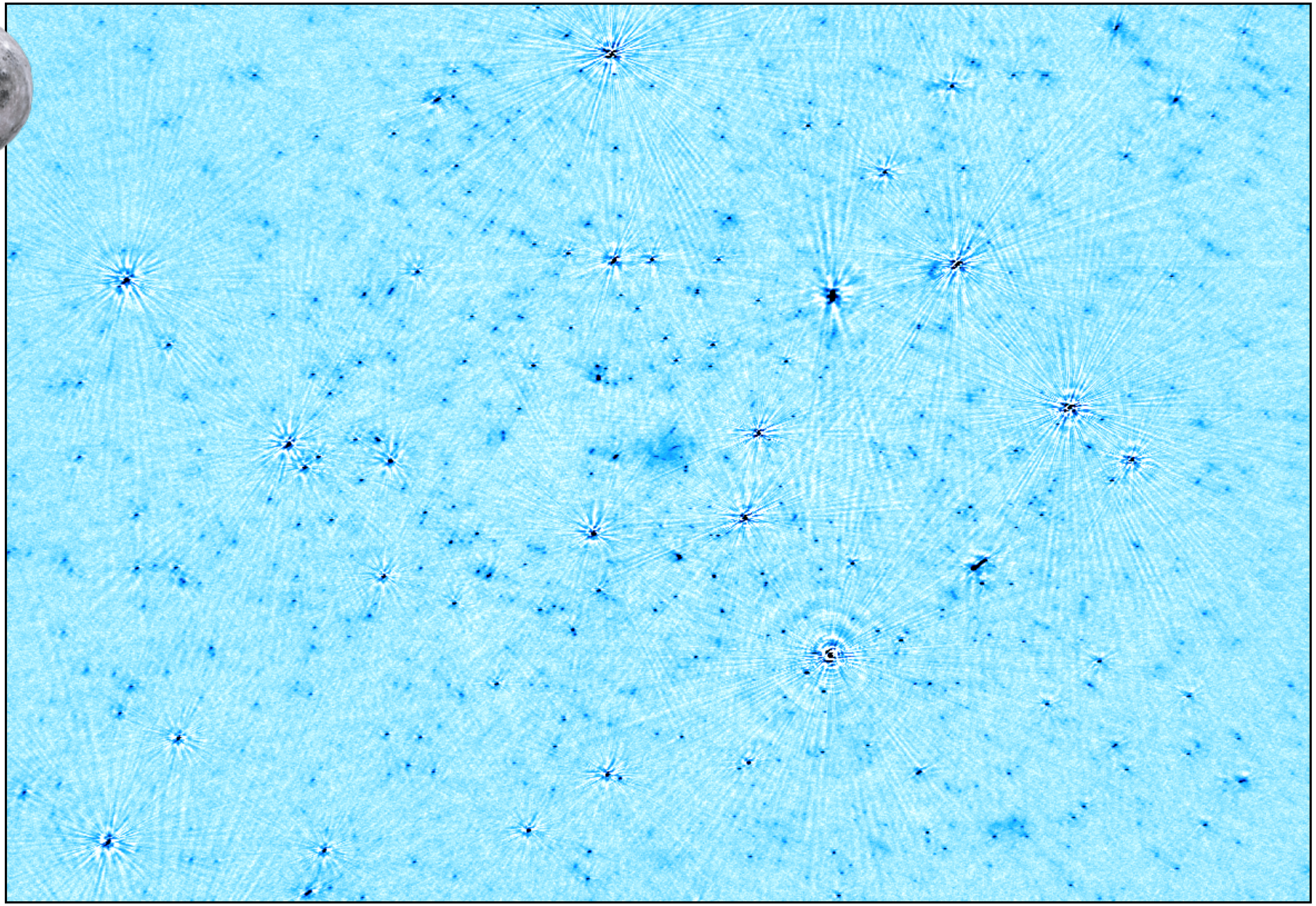
Advantages:
- Proper interpolation
- Smooth result
- Less degrees of freedom

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

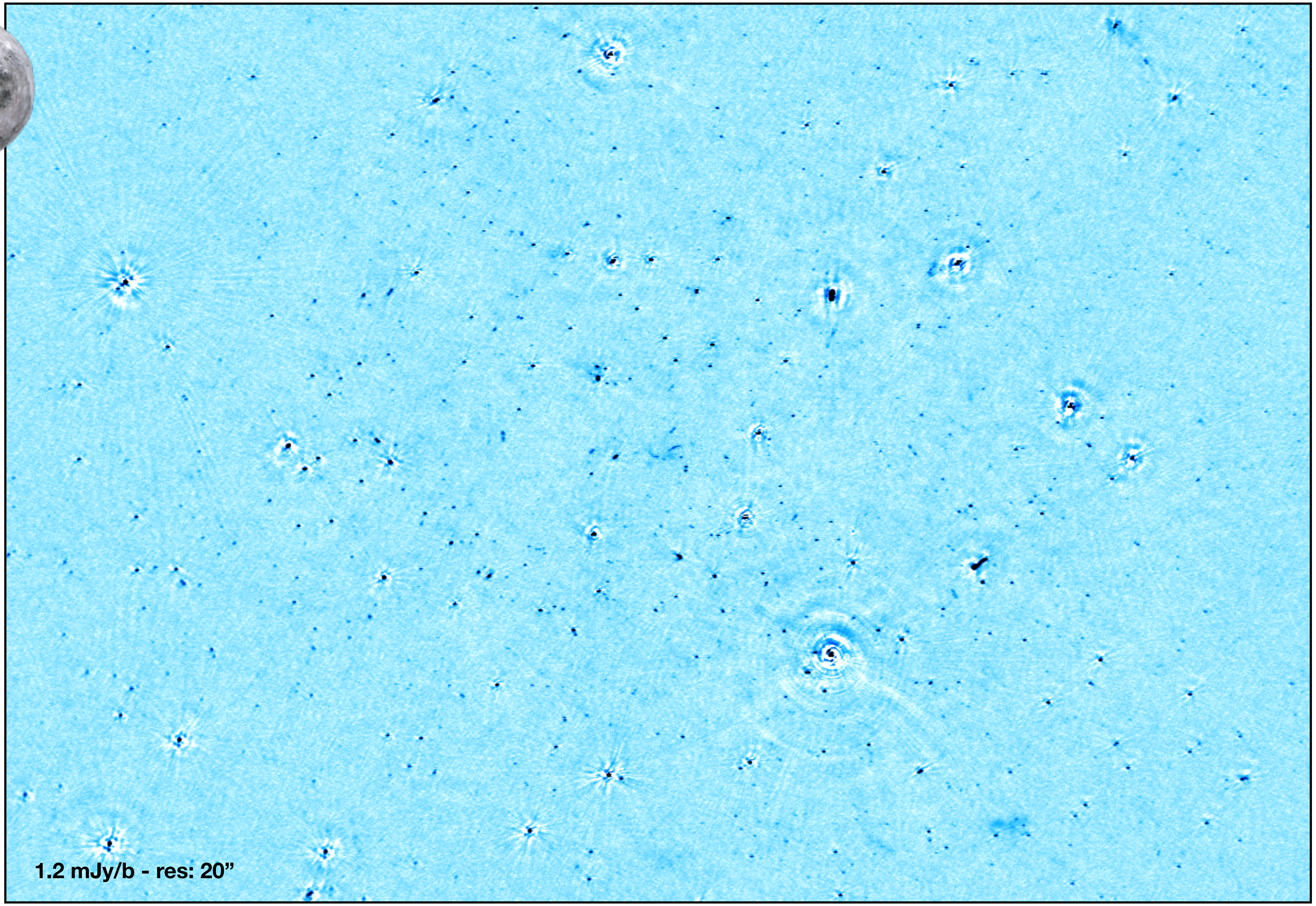
No ionospheric correction



DI ionospheric correction



DD ionospheric correction



Direction-dependenta calibration

- Download pipeline
- Calibrator pipeline
- Target pipeline
  - Timesplit
  - Self-cal
  - DD-cal
- Extraction

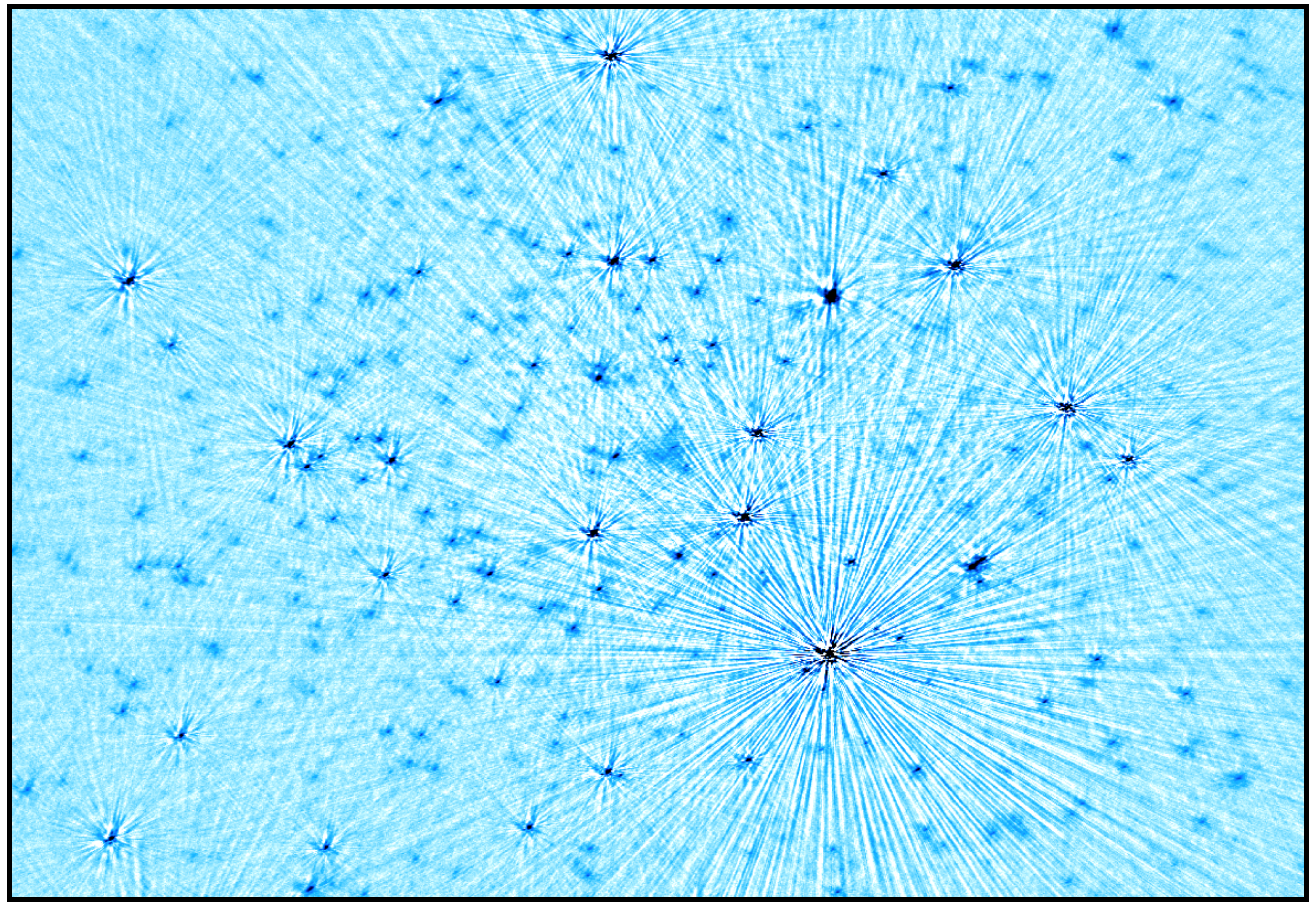
- **Subtract all sources but a small region**
- **Averaging**
- **Self-cal on that region**

Outcome:

- ~1 mJy/b, beam=15”
- Higher fidelity for extended sources

Limitations

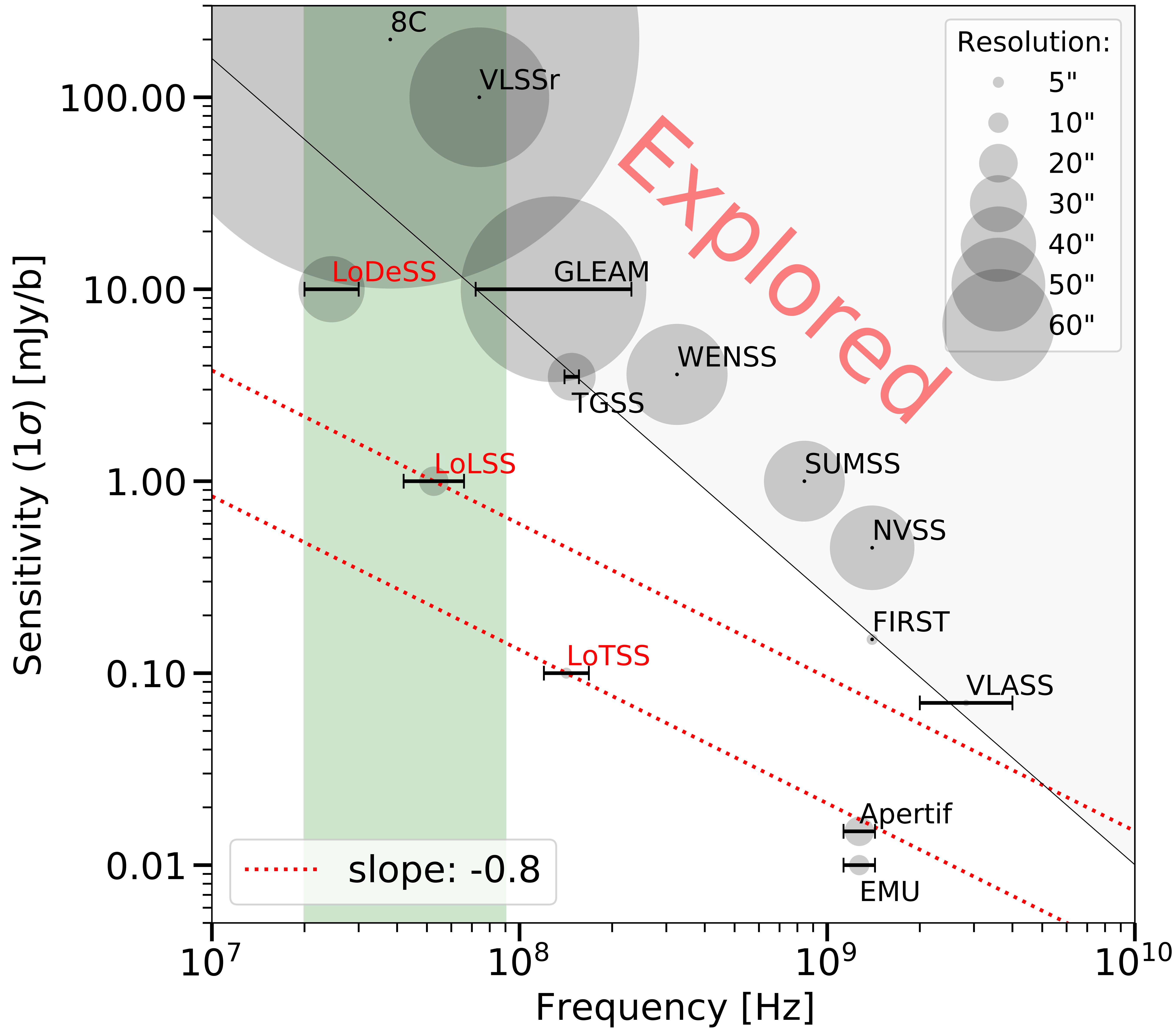
- Bad **ionosphere** can prevent even basic imaging
- **Bright sources** in the field or just outside can severely limit the dynamic range
- The **sun** should be rather far away (>30-40 deg) if you need short baselines
- Some **facets** might have low S/N and provide inaccurate flux densities
- Very **extended emission** (covering multiple facets) is rather untested



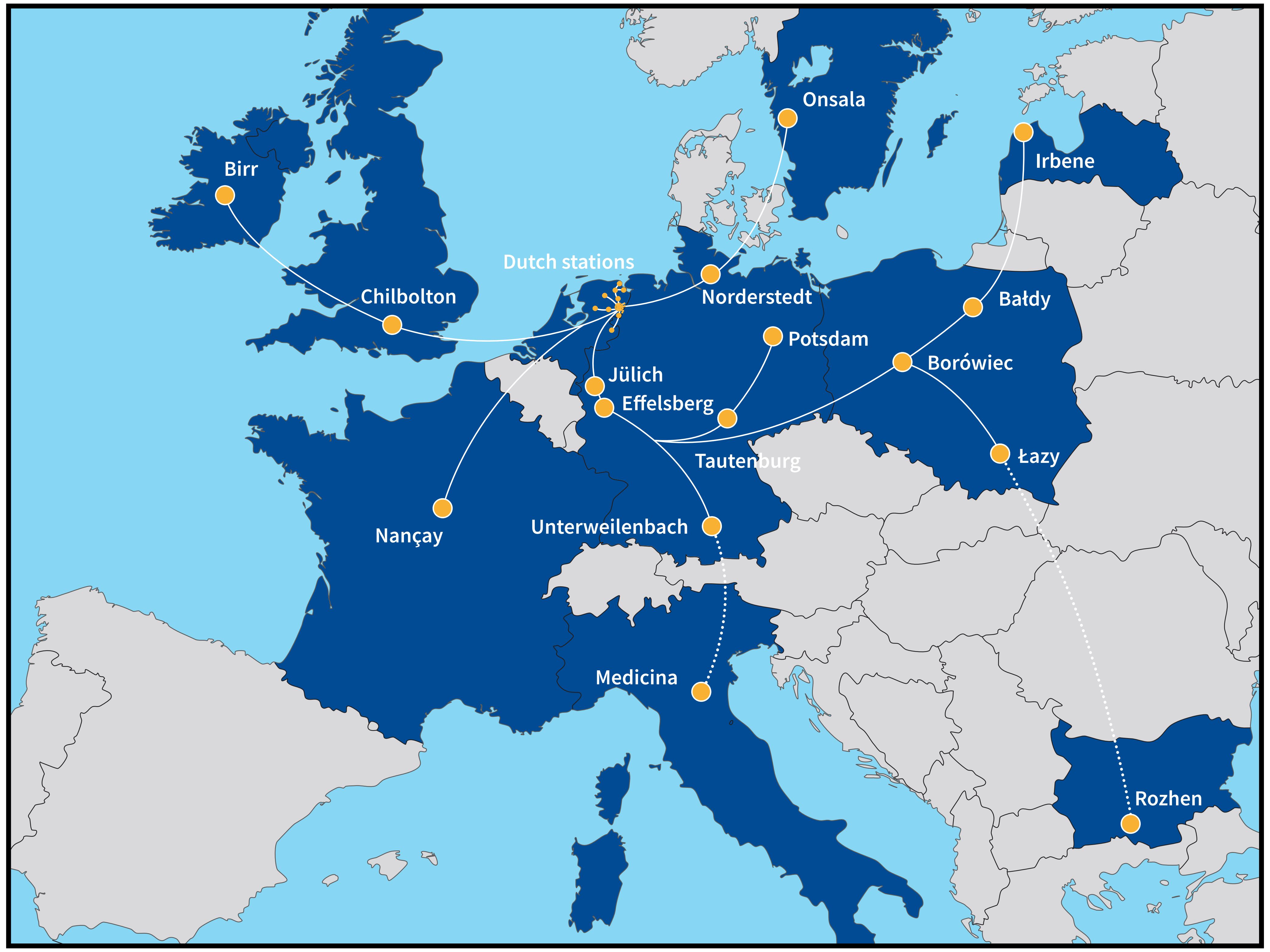
Outline

1. LOFAR LBA
2. PiLL
3. LoLSS (54 MHz)
4. What's next?

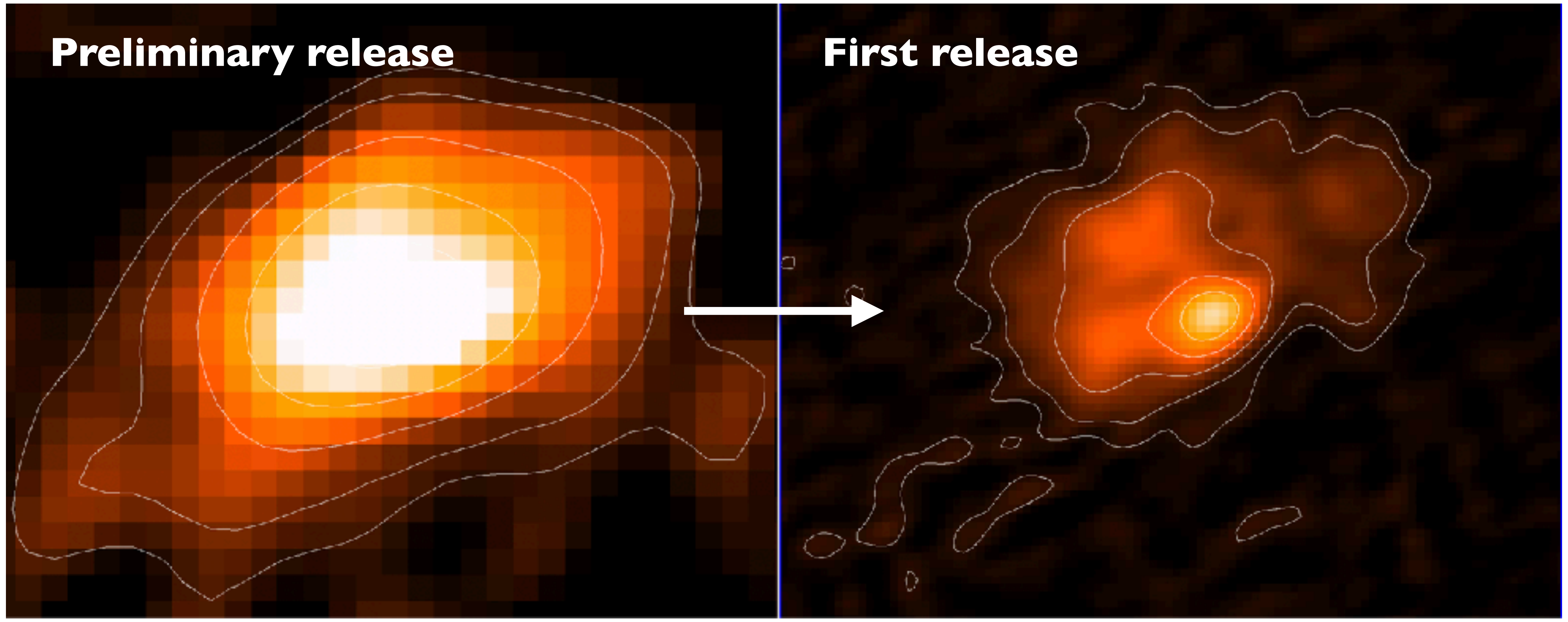
LOFAR Surveys



- **LOFAR Two Metre Sky Survey: 120 - 168 MHz**
- **LOFAR LBA Sky Survey: 42 - 66 MHz**
- **LOFAR Decametre Sky Survey: 14 - 30 MHz** (Groeneveld's talk)

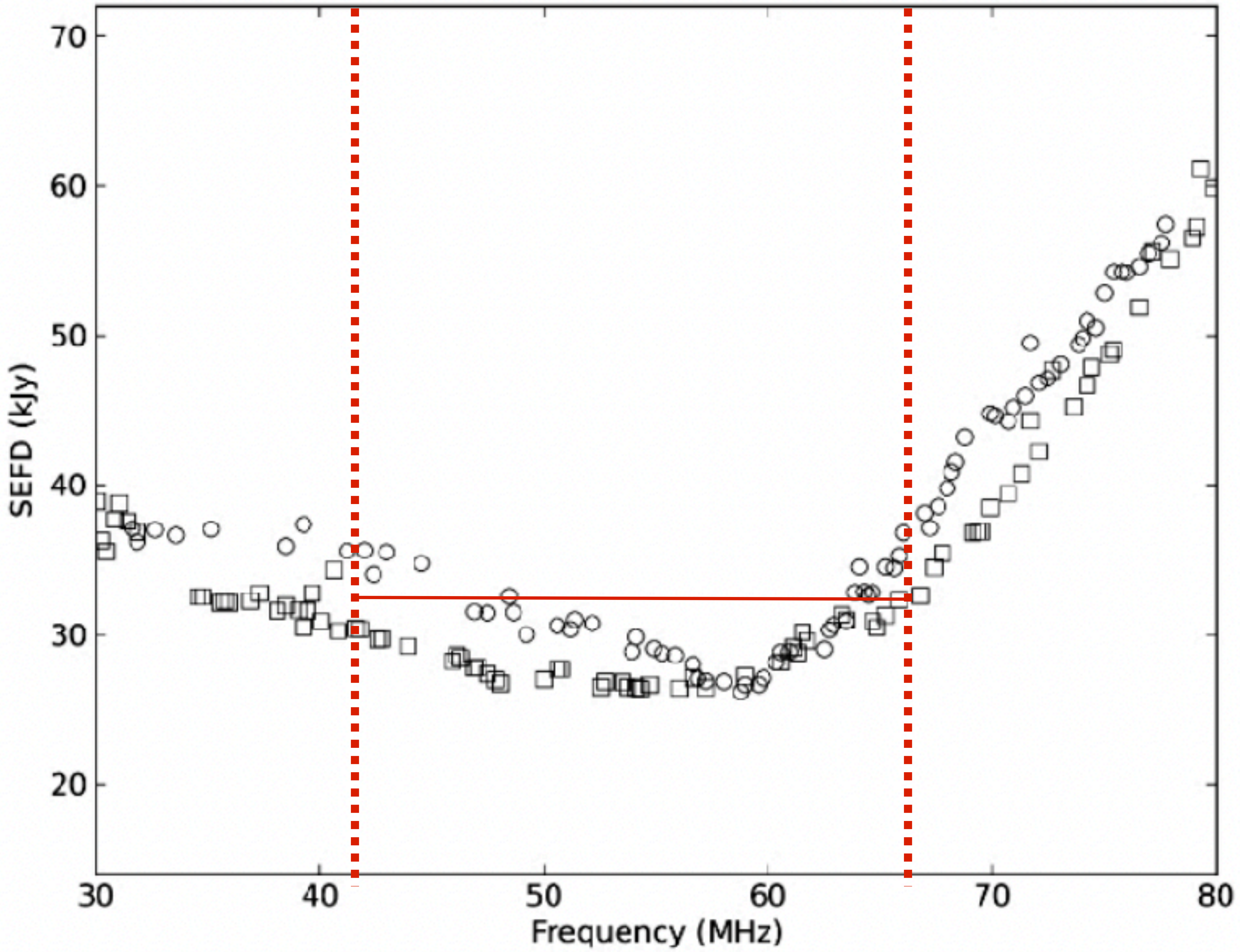


LoLSS status

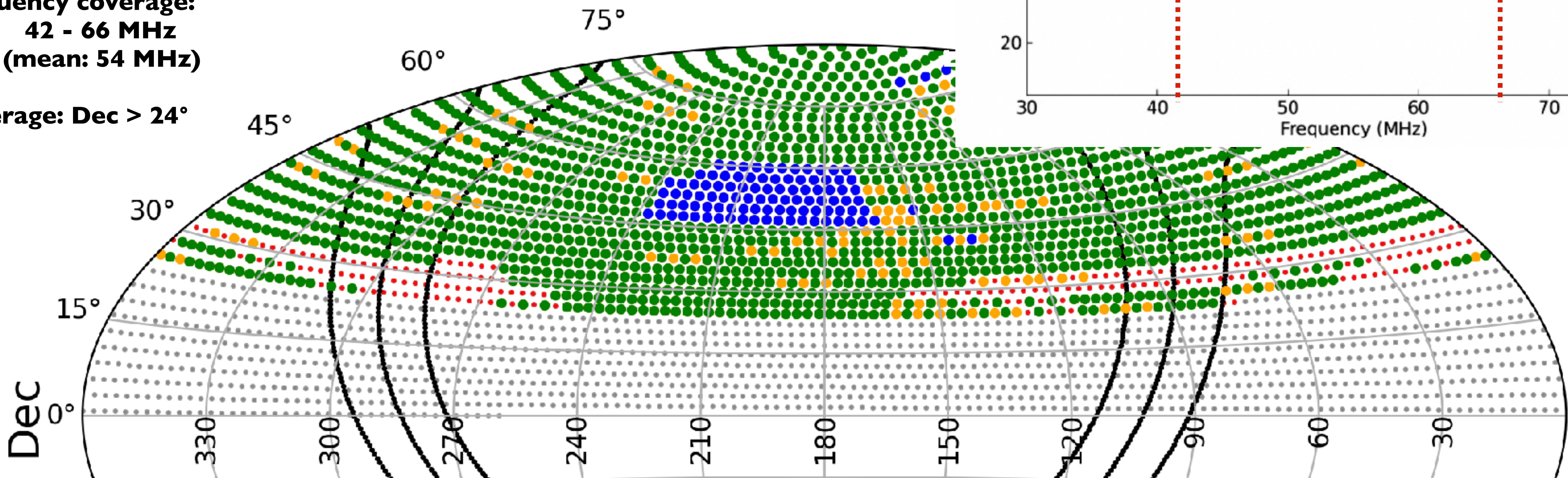


2021:
LoLSS
• res.:
• sens.

2022:
LoLSS
• res.:
• sens.

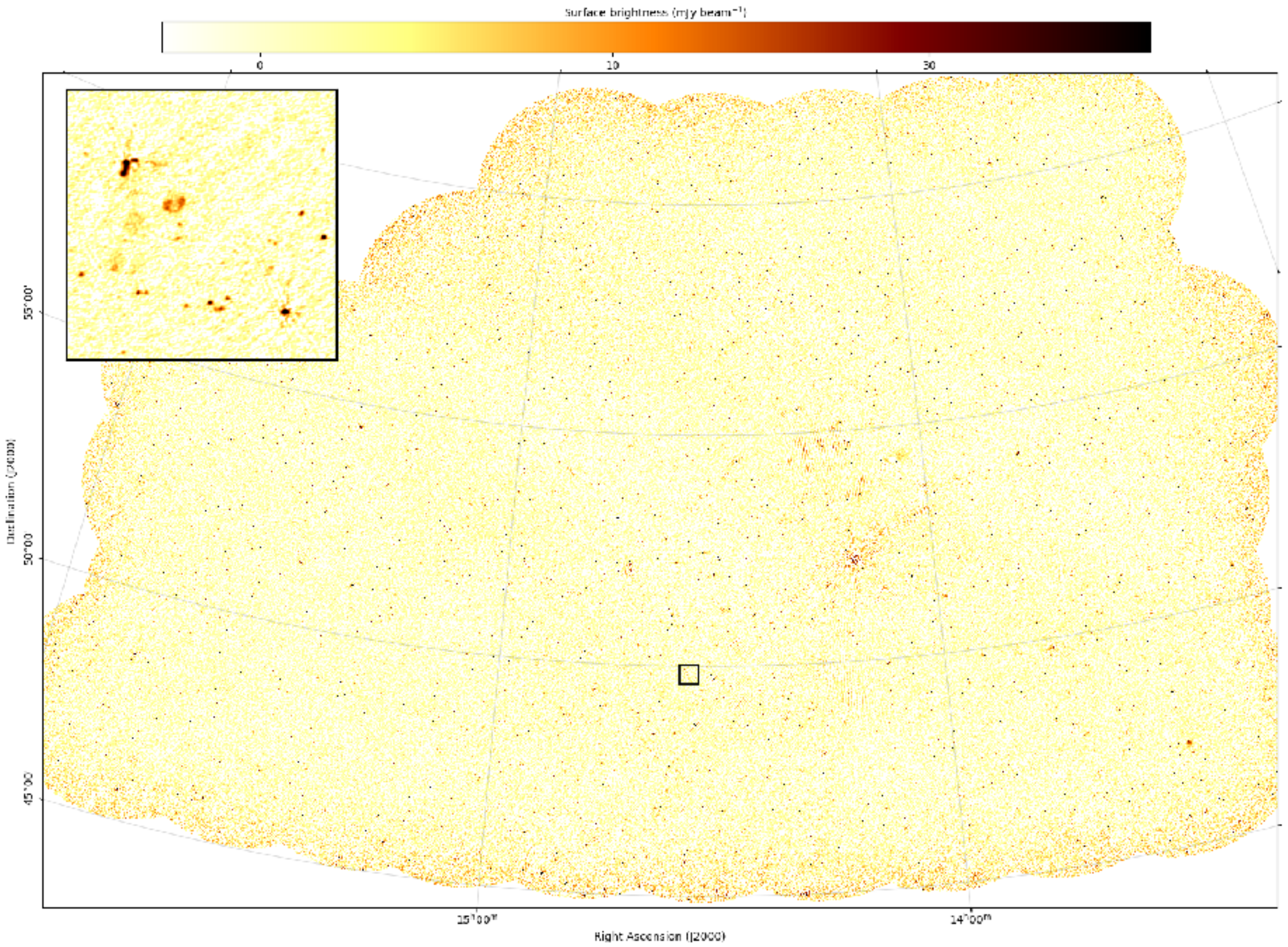


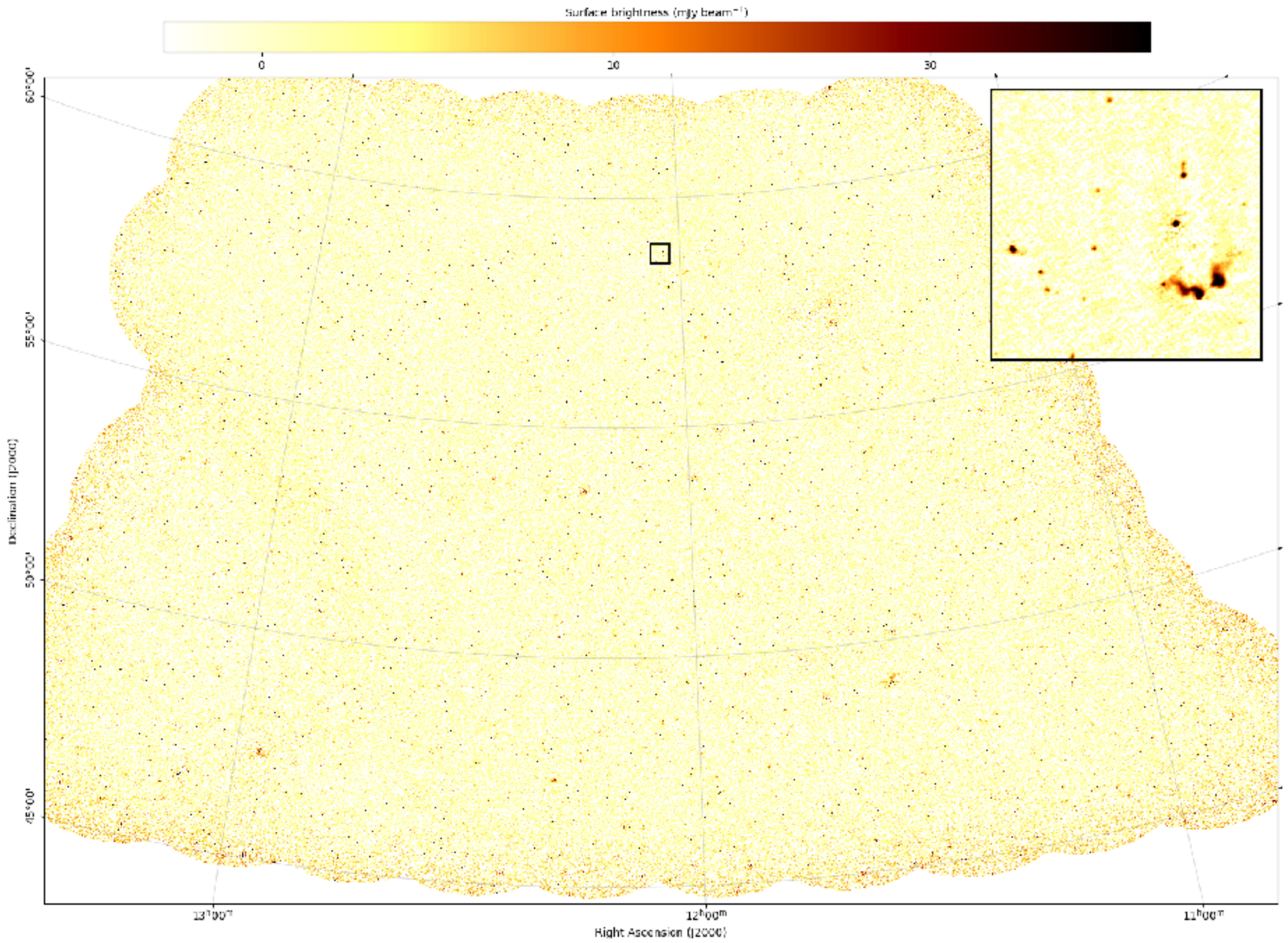
- **Frequency coverage:**
  42 - 66 MHz
  (mean: 54 MHz)
- **Coverage: Dec > 24°**



LoLSS DR1 data

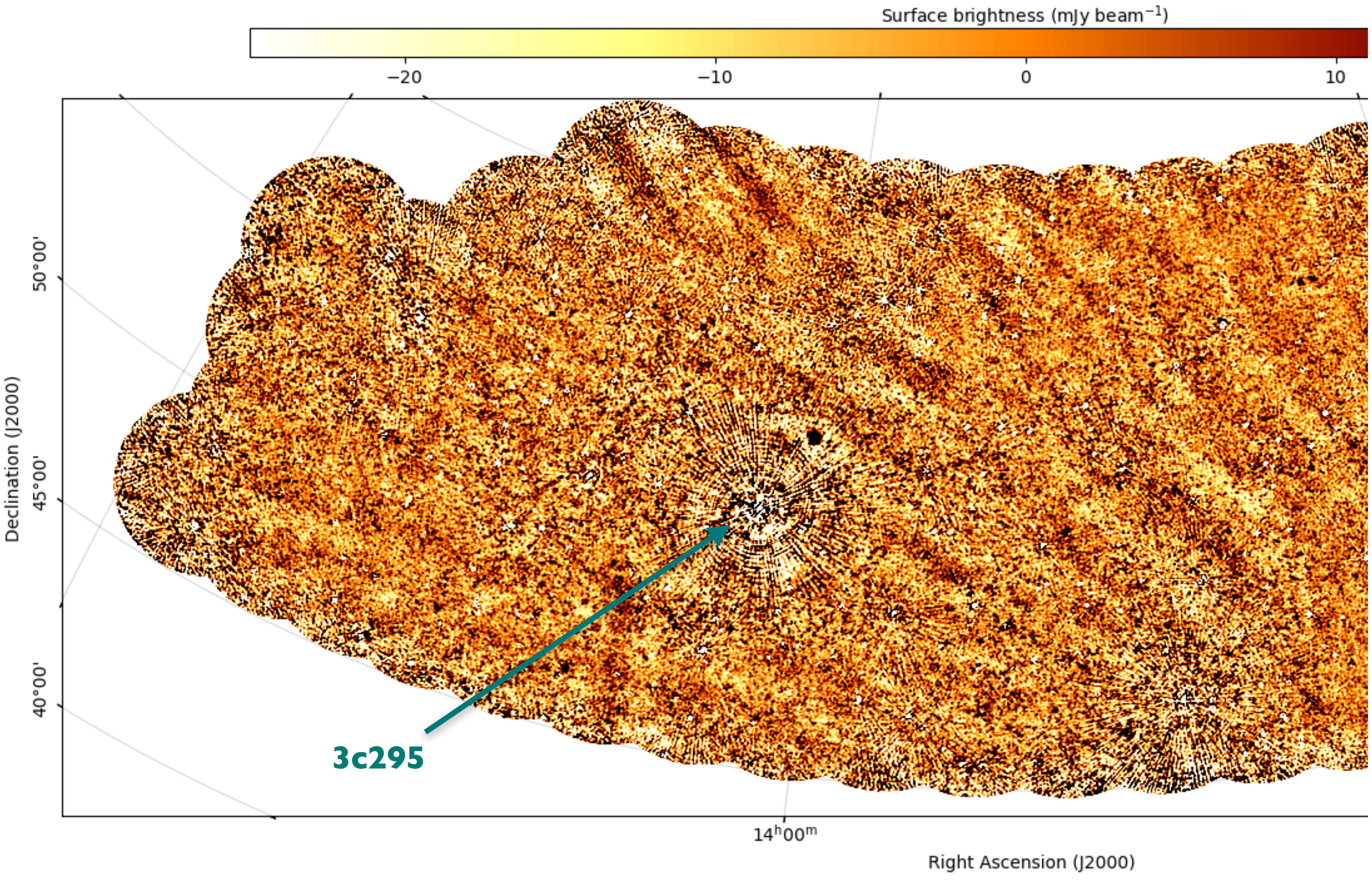
de Gasperin+ in prep.

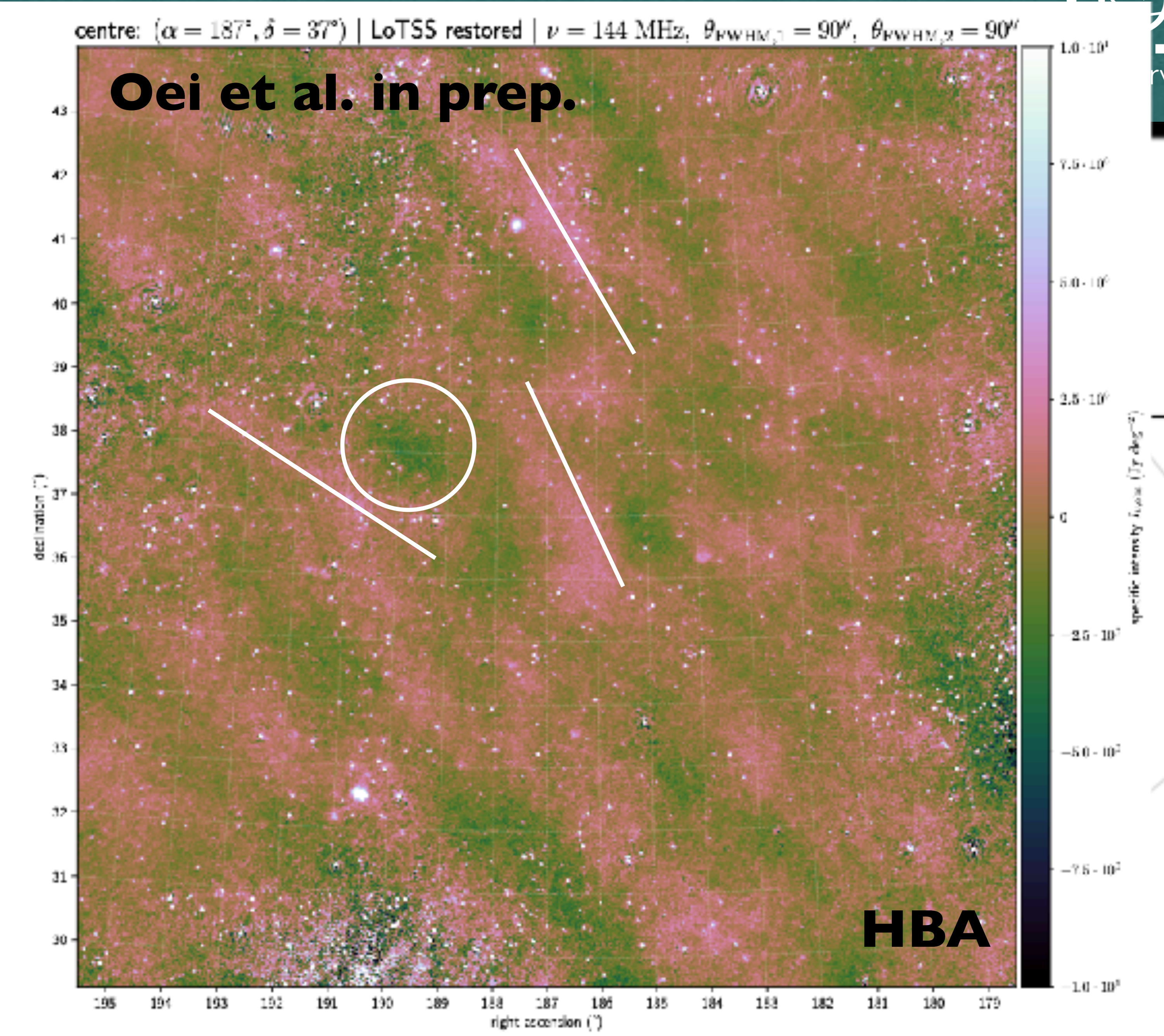


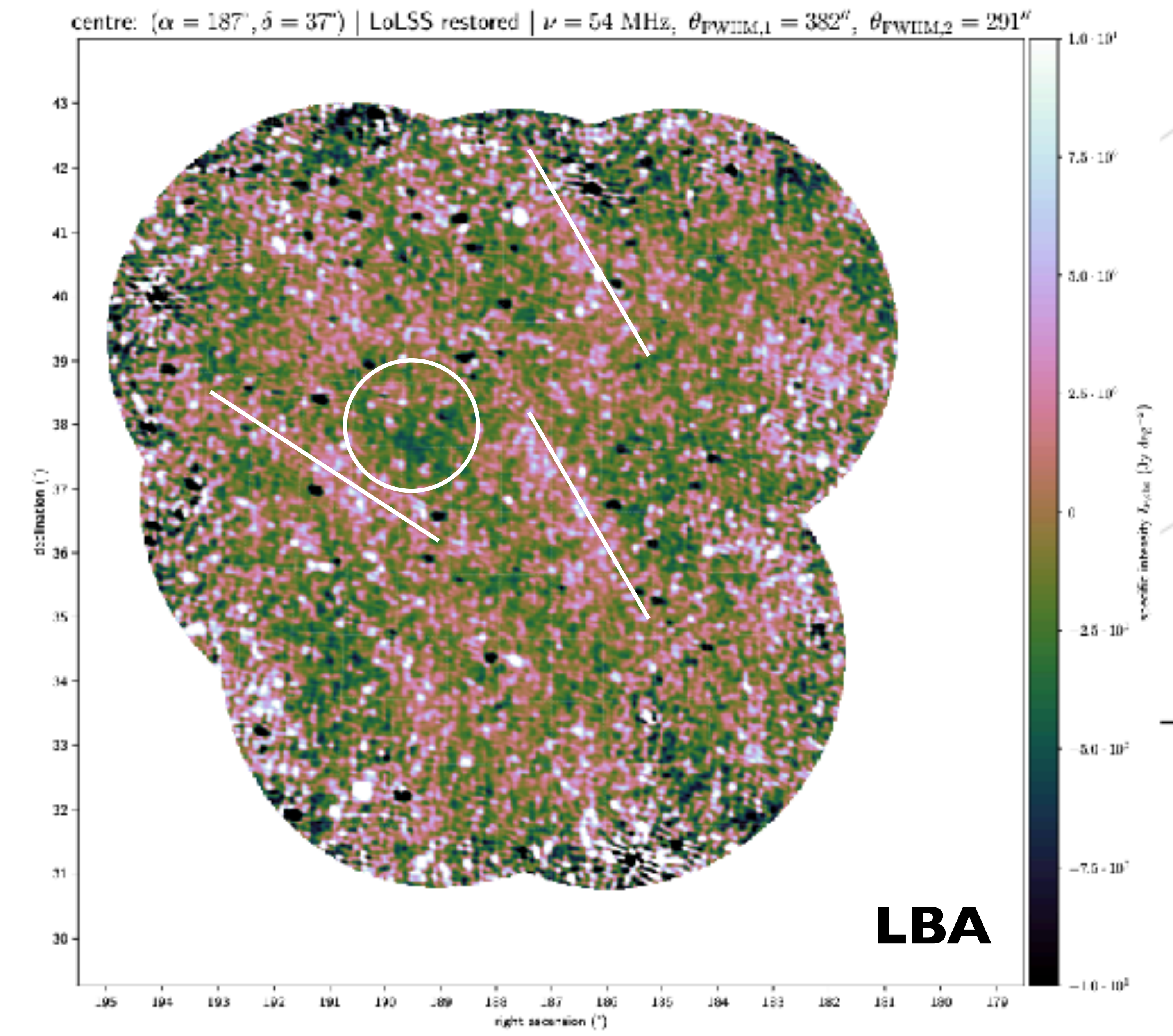


- Area: 650 deg^2
- Stokes: I, V
  Image format: 2 large fits, 95 mosaic fits, hips
- Catalogue: sources (42,463)
- Solutions: direction-dependent for re-imaging/extraction

LoLSS low resolution



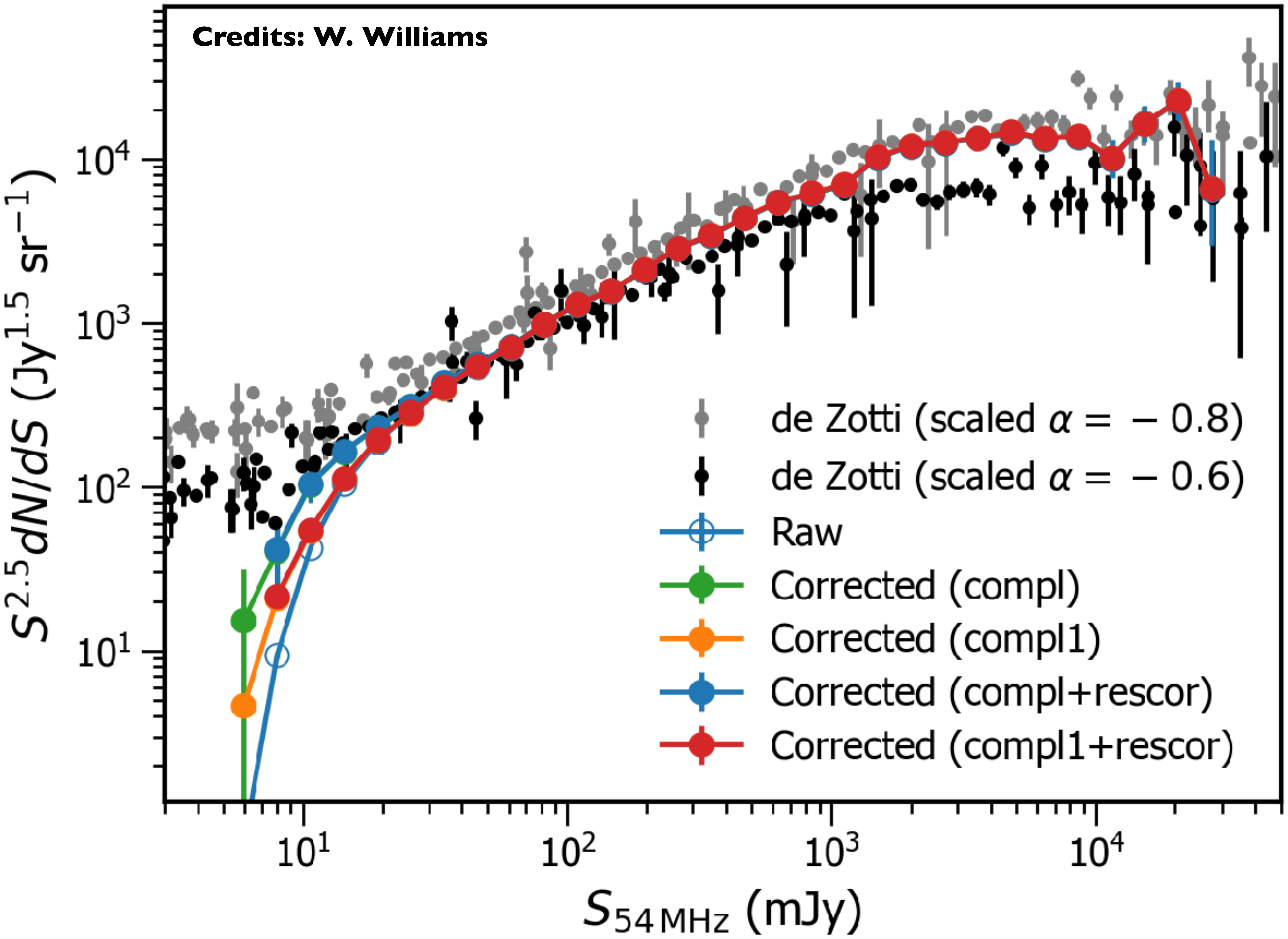


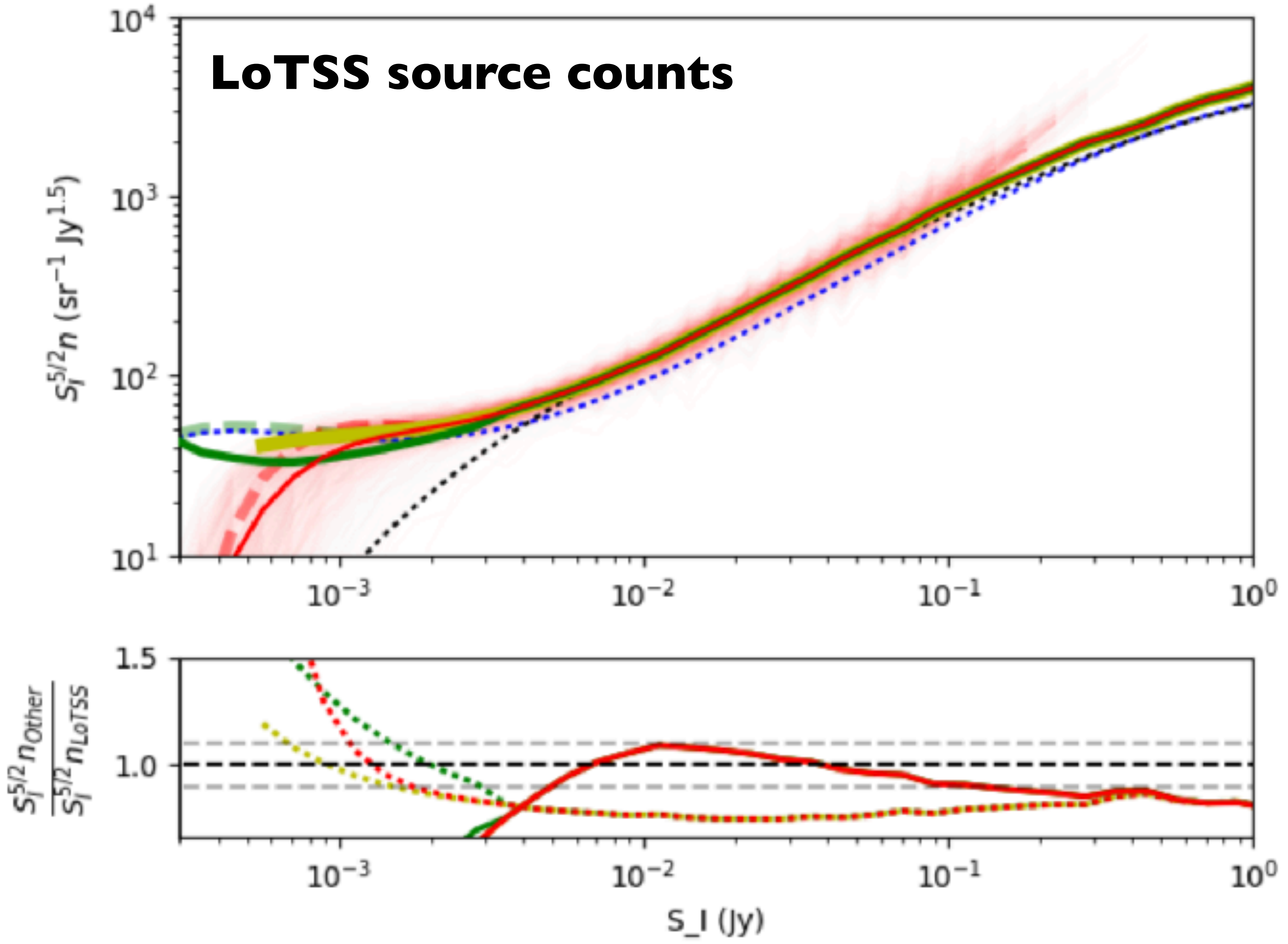


LoLSS sensitivity

Median rms noise: 1.6 mJy/b
Most common rms noise value: 1.5 mJy/b

LoLSS source count

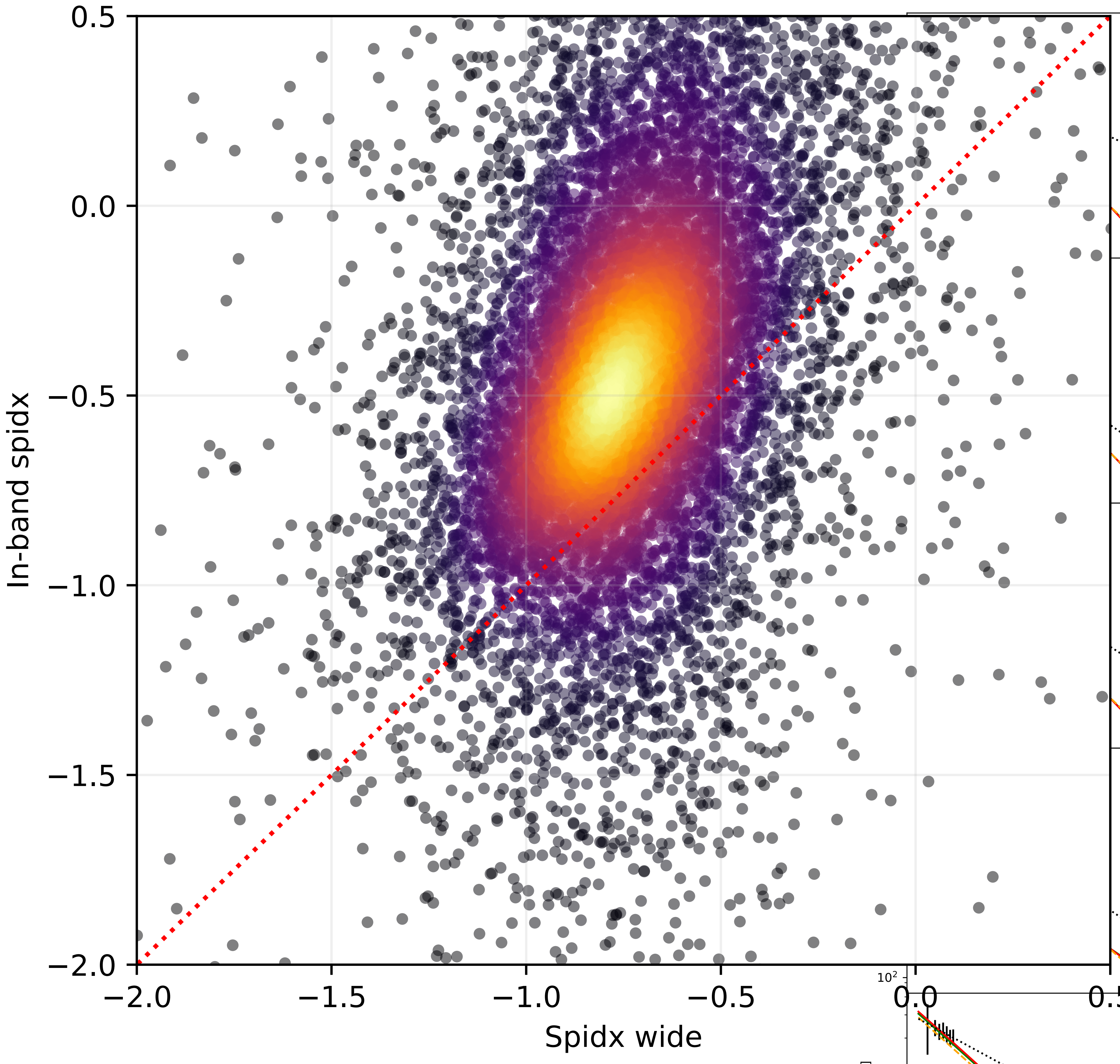


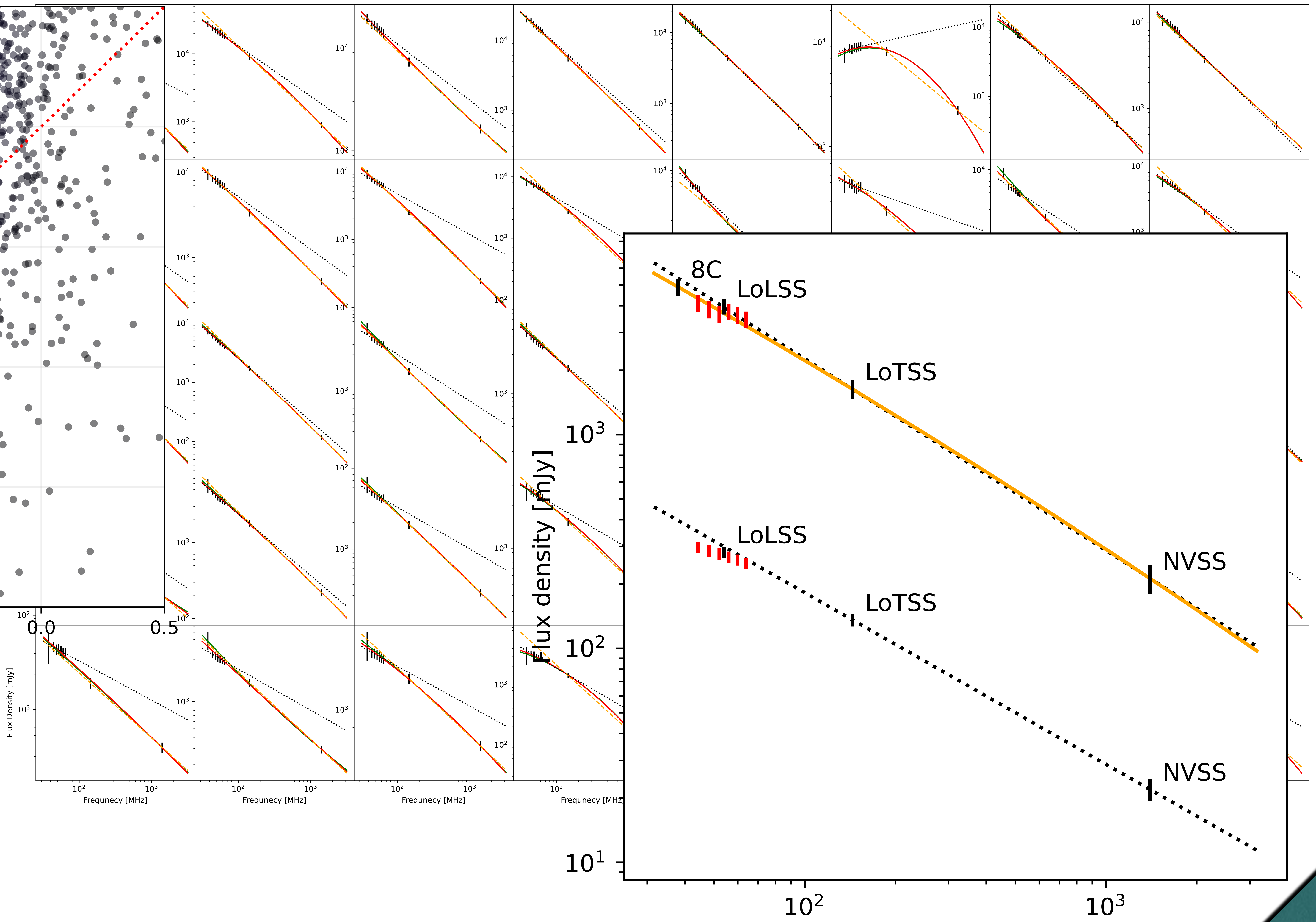


LoLSS not deep enough to see SF galaxy turnover: need deep fields

High flux sources: steep (-0.8)
Low flux sources: flat (-0.6)

LoLSS spectral properties





- **No friction with LoTSS flux scale**
- **We cannot check the flux scale of LBA extrapolating linear spectra**
- **Prediction for LoDeSS**

LoLSS: deliverables

Check out the data release I at:
https://www.lofar-surveys.org/lolss.html

Images:

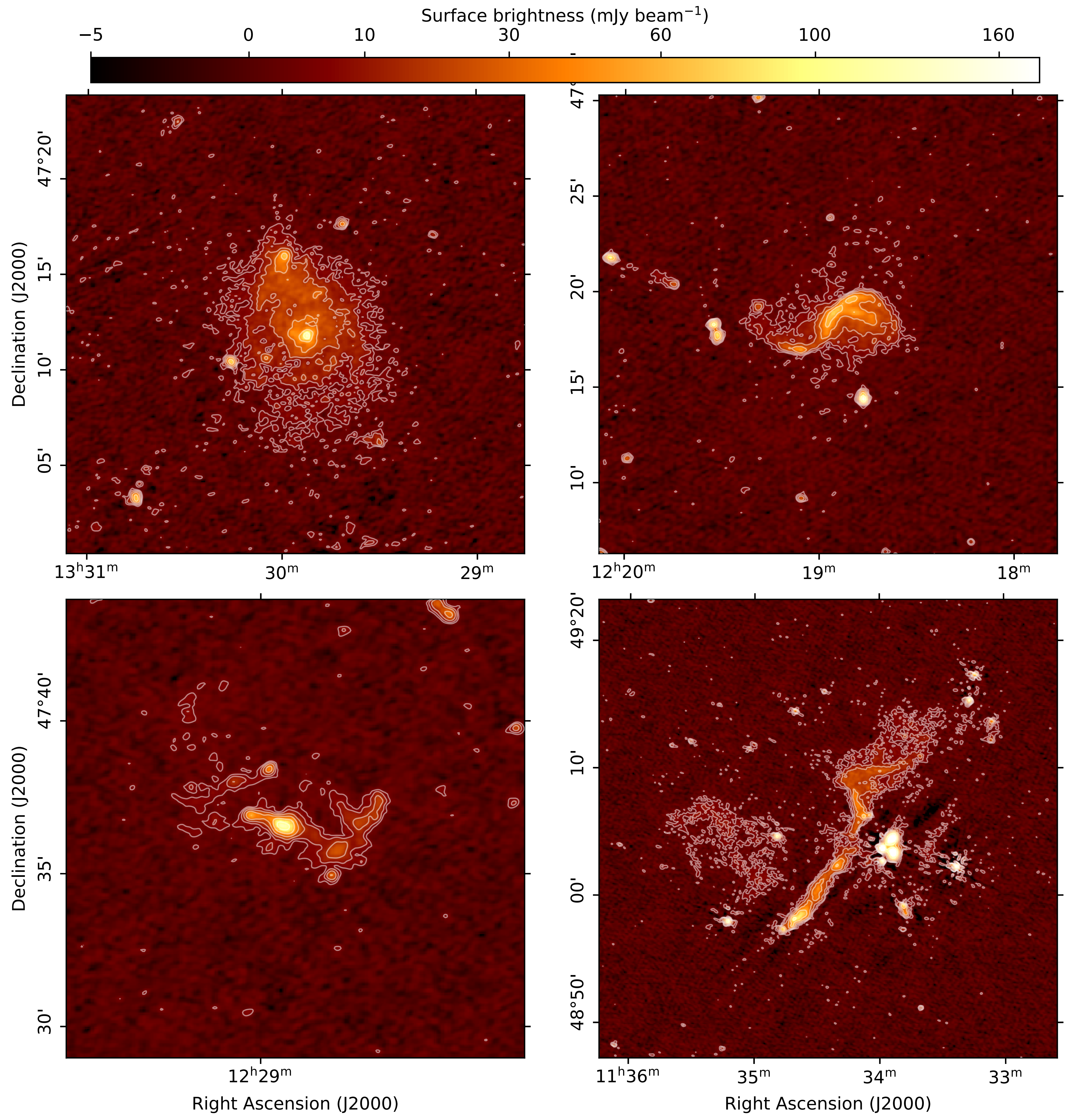
- Mosaiced images: Stokes-I & Stokes-V
  - ToUse: Download mosaic (no PB corr. needed) or cutouts (coming soon)
- HIPS images (Stokes-I only)
  - ToUse: Aladin → Load URL
- Low-resolution source-subtracted mosaiced image

Catalogues:

- Source catalogue (42,463 entries)
  - ToUse: download - good for cross-match and initial tests. Flux density estimation better from images
- Gaussian component catalogue
- Source+Gaussian component in-band catalogues: 44, 48, 52, 56, 60, and 64 MHz
- Spectral index catalogue (planned)

Data:

- DIE corrected + DDE solutions
  - ToUse: extract pipeline - currently has to be arranged



Interested in using the data?
Fill the SKSP wiki - LoLSS projects page

Outline

1. LOFAR LBA
2. PiLL
3. LoLSS (54 MHz)
4. What's next?

LOFAR 2.0 requirements

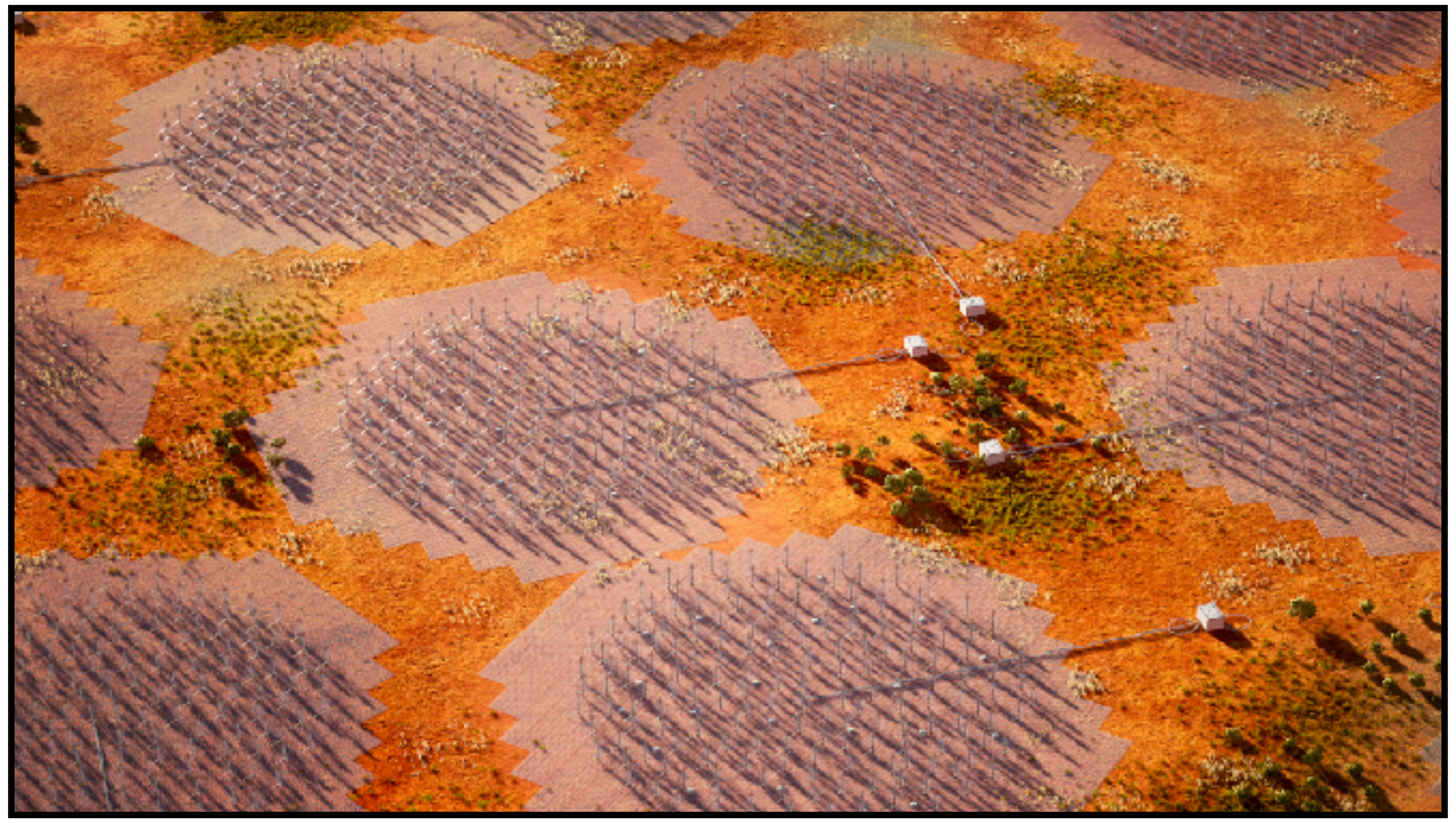
- Leverage existing investments
  - hardware (stations, networks, data centres)
  - algoritms, software, pipelines
  - community's collected brainpower
- Remain unique and scientifically impactful (in SKA era):
  - lowest frequencies
  - highest resolution
  - versatility
- Evolution: continuous community support & productivity
- Financially, technically feasible on a 3-10 year timescale

LOFAR

LOFAR 2.0 Vs SKA-low (ph.1)

LOFAR 2.0:
- Reaches 2x lower frequencies
- 10x higher sensitivity

SKA-low (ph.1)
- Reaches 2x higher frequencies
- 10x greater collecting area



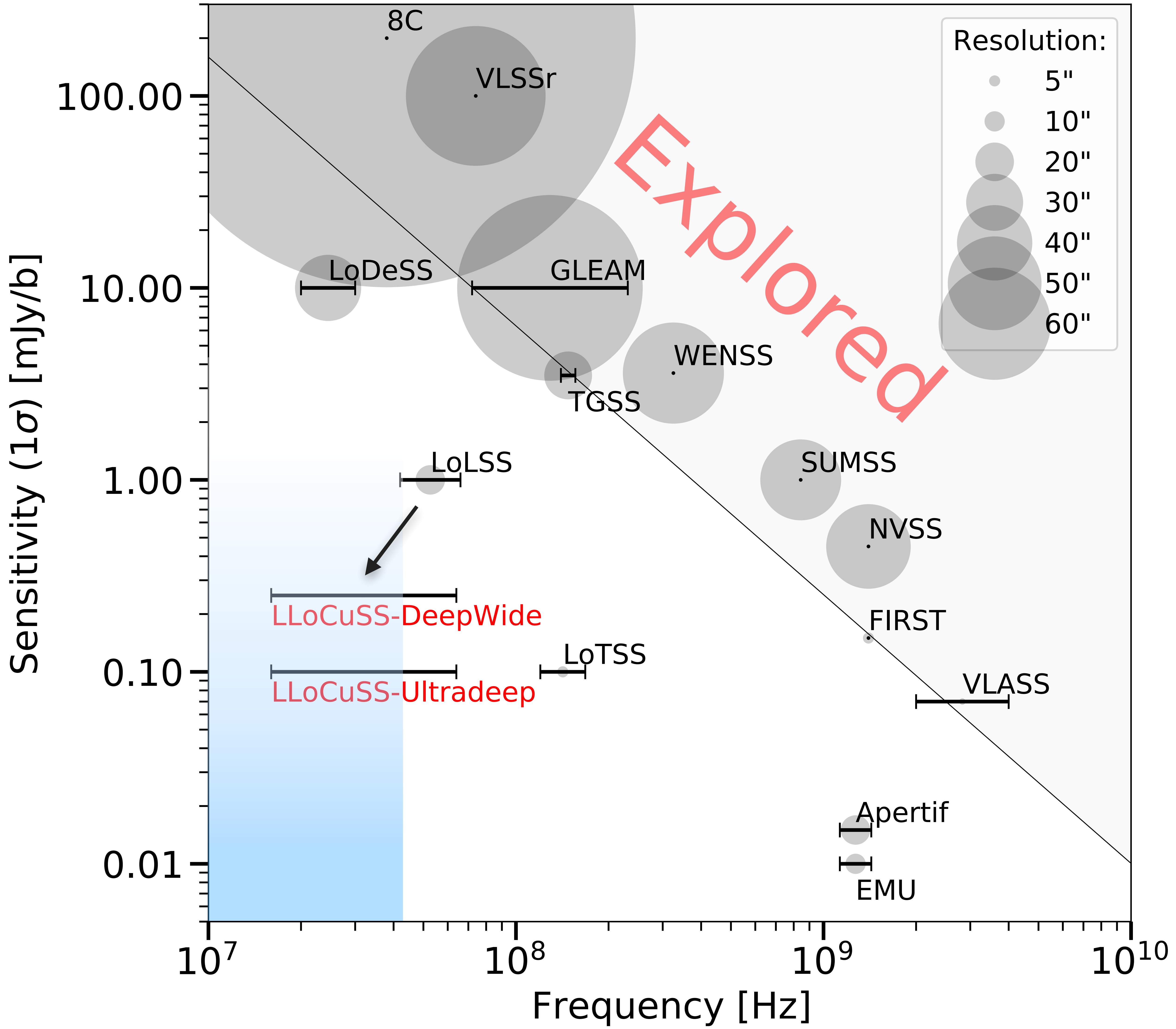
SKA Low

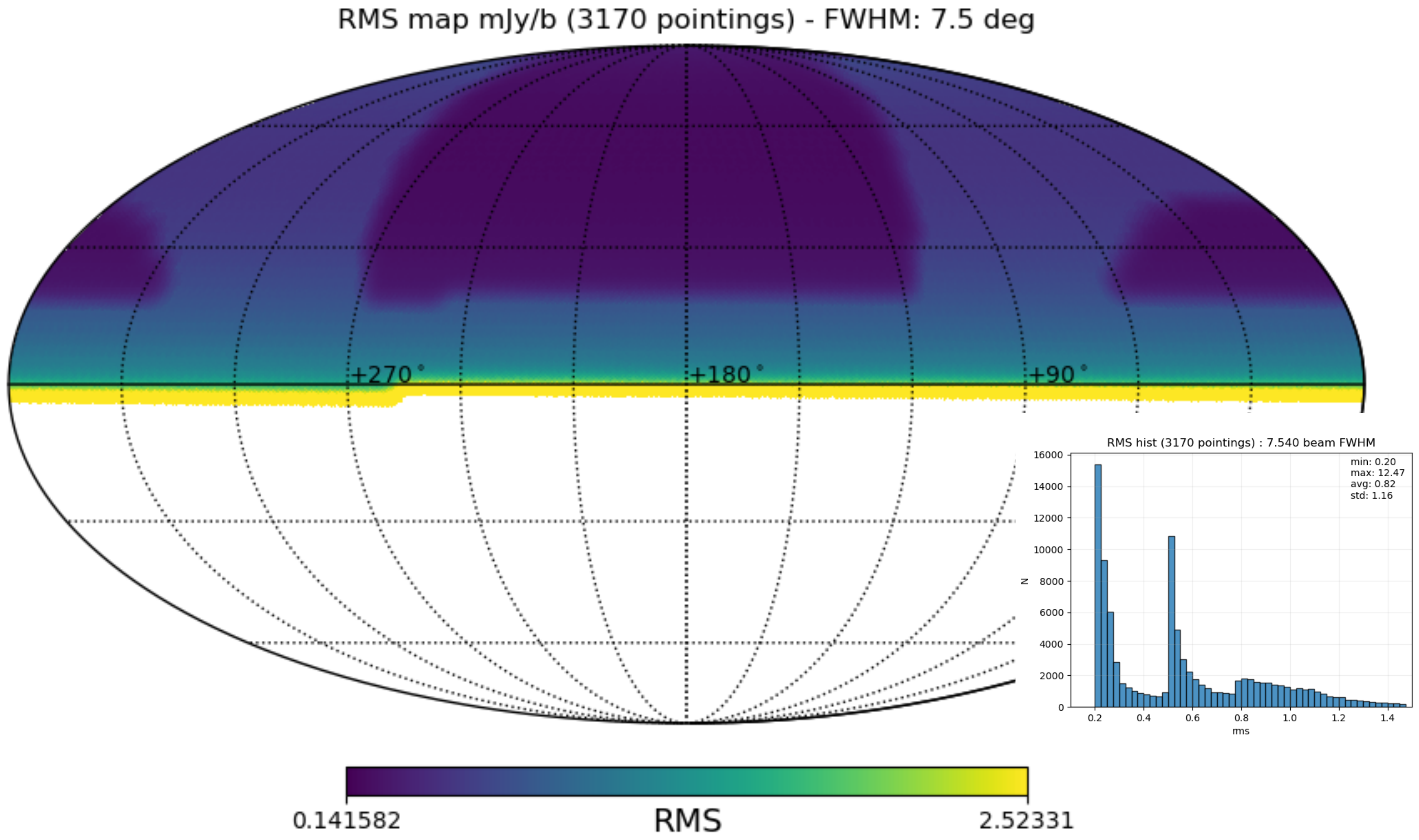
LOFAR 2.0 upgrades

LOFAR 2.0 (stage 1) station upgrade includes:

- **Dual band**: enabling simultaneous observation capability for Low Band Antennas and High Band Antennas
- **Receivers**: 48 LBA or 48 HBA → 96 LBA and 48 HBA
- **Clock**: distribution of a central clock to all NL stations (White Rabbit)
- **Linearity**: improving receiver linearity
- **Hardware**: redesigning and replacing of station electronics, including digital processing systems and receiver units; LOFAR Mega Mode (Cobalt 2.0, simultaneous observations for several science cases)

LBA LOFAR Community Sky Survey





- **Band: 16 – 64 MHz**
- **Resolution:**
  1” (upper half of the band)
  15” (lower half of the band)

Wide Survey (2004 hrs):
- Coverage: Dec > 0°
- Sensitivity: 500–800 μJy beam^{-1}

Deep-Wide Survey (5830 hrs):
- Coverage: Dec > 20°, |b| > 23°
- Sensitivity: 350 μJy beam^{-1}

Ultra-deep Fields (100 hrs per field):
- Sensitivity: 130 μJy beam^{-1}

Contacts

- **LOFAR LBA Sky Survey (LoLSS)**

  Reference person: Francesco de Gasperin
  For deep fields: Wendy Williams

  Data at: www.lofar-surveys.org/lolss.html

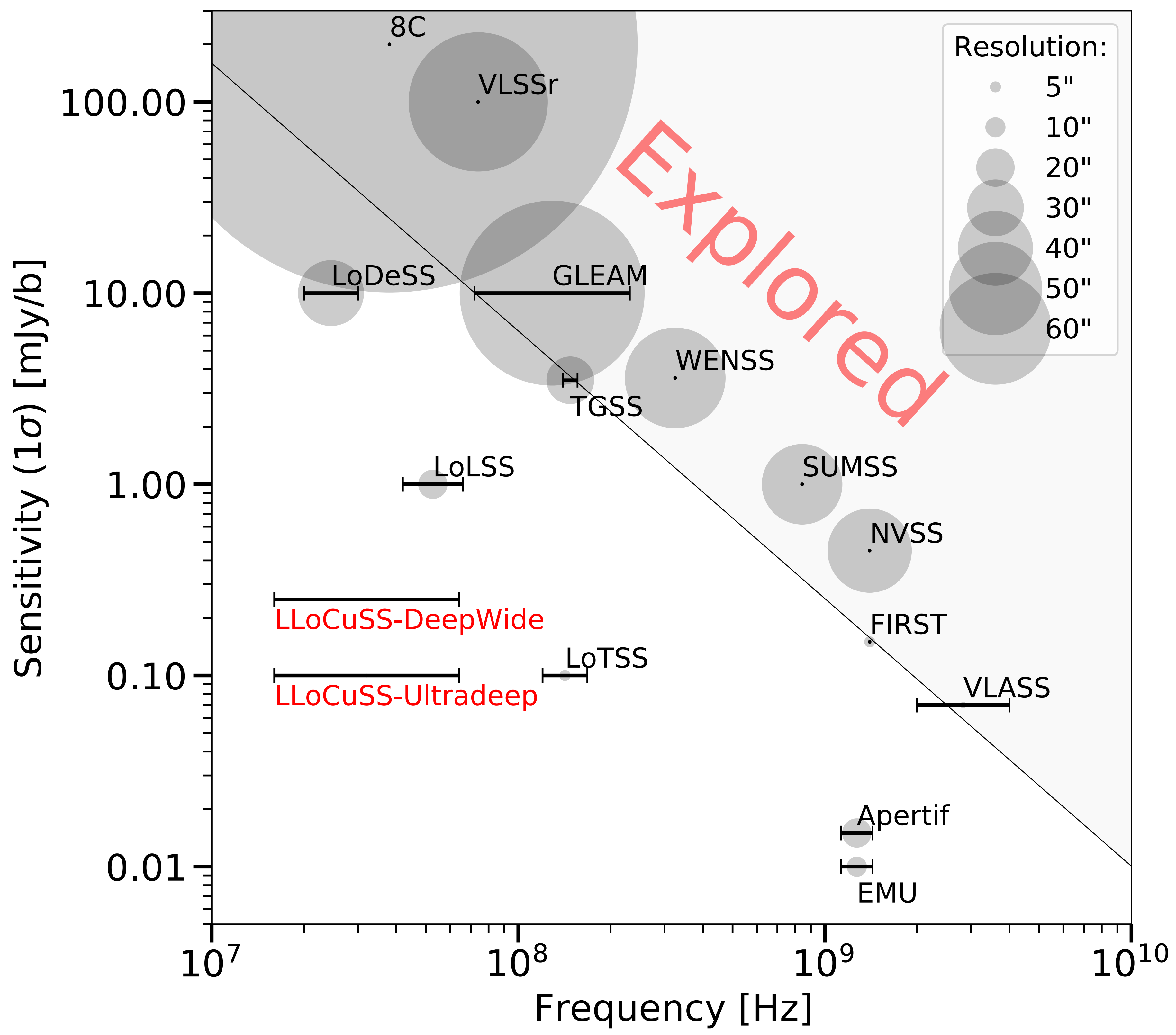
- **LBA LOFAR Community Sky Survey (LLoCuSS)**

  Reference persons: Francesco de Gasperin / Reinout van Weeren

- **LBA data reduction**

  Reference persons: Francesco de Gasperin
  and Henrik Edler (present at the conf.)

  Code, docker and docs at: github.com/revoltek/LiLF

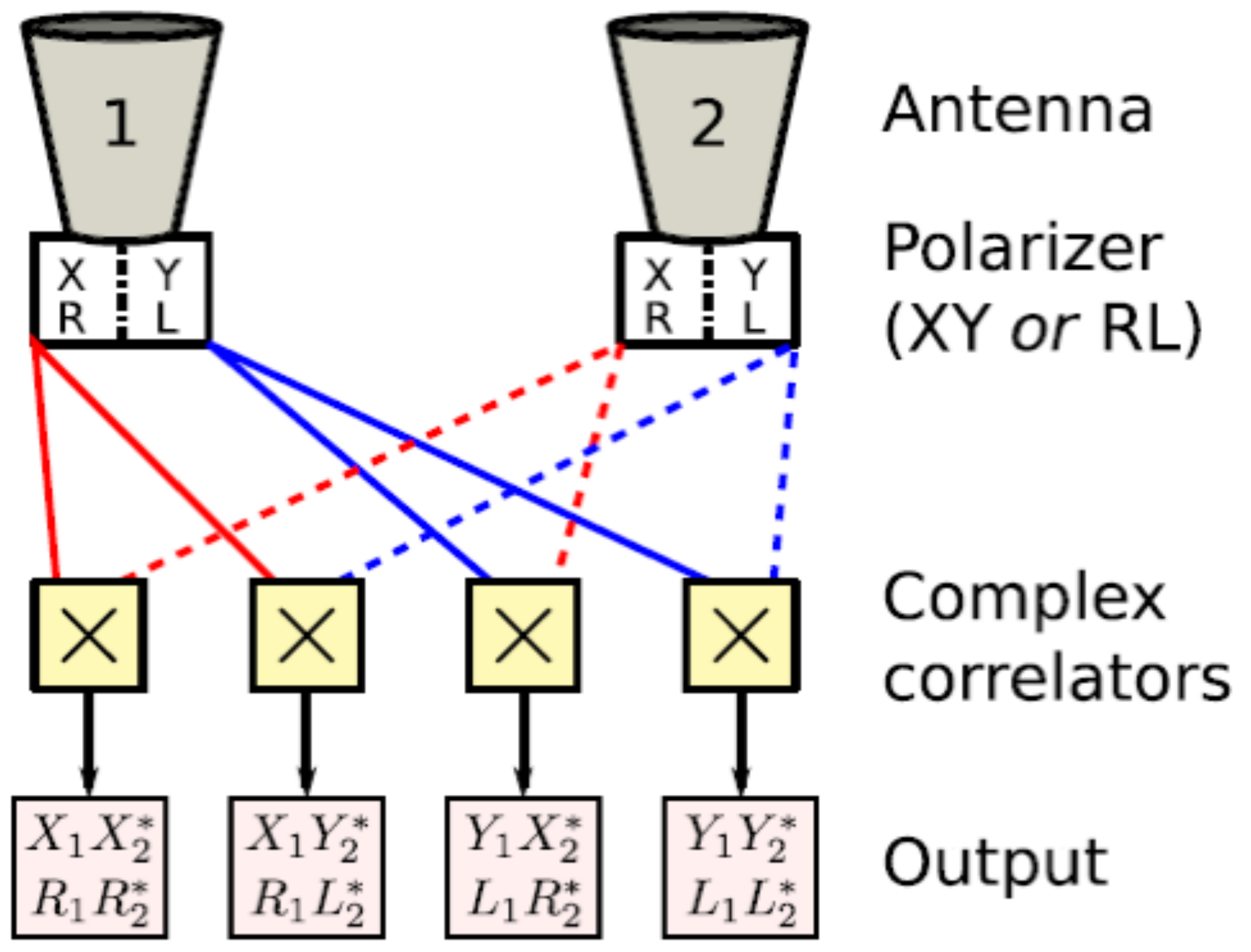


- Ideal visibilities (now in 2x2 matrix form):

$$\boldsymbol{V}(u,v) = \iint \boldsymbol{I}_c(l,m)e^{-2\pi i(ul+vm)}dl\,dm$$

- with $\boldsymbol{V} = \begin{pmatrix} V_{rr} & V_{rl} \\ V_{lr} & V_{ll} \end{pmatrix}$ or $\boldsymbol{V} = \begin{pmatrix} V_{xx} & V_{xy} \\ V_{yx} & V_{yy} \end{pmatrix}$

- A full polarization correlator produces visibilities for all cross-products:
  RR, RL, LR, LL or XX, XY, YX, YY
  - Short-hand notation: $RR_{ij} = R_i R_j^* = V_{rr,ij}$, etc.



RIME

- Measured visibilities on baseline j,k:

$$V_{jk}^{obs} = \iint [\boldsymbol{J}_j \boldsymbol{I}_c(l,m) \boldsymbol{J}_k^{+}] e^{-2\pi i(u_{jk}l + v_{jk}m)} dl\, dm$$

- The Jones matrix $\boldsymbol{J}$ is a complex 2x2 matrix that captures antenna-based signal corruptions
- The format of $\boldsymbol{J}$ often depends on the feed basis (RL or XY)

- Examples for RL

$$\boldsymbol{J} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \boldsymbol{J} = \begin{pmatrix} g_R & 0 \\ 0 & g_L \end{pmatrix} \qquad \boldsymbol{J} = \begin{pmatrix} e^{2\pi i \nu \tau_R} & 0 \\ 0 & e^{2\pi i \nu \tau_L} \end{pmatrix}$$

$$\boldsymbol{J} = \begin{pmatrix} 1 & d_{LR} \\ d_{RL} & 1 \end{pmatrix} \qquad \boldsymbol{J} = \begin{pmatrix} e^{+i\theta} & 0 \\ 0 & e^{-i\theta} \end{pmatrix}$$

RIME

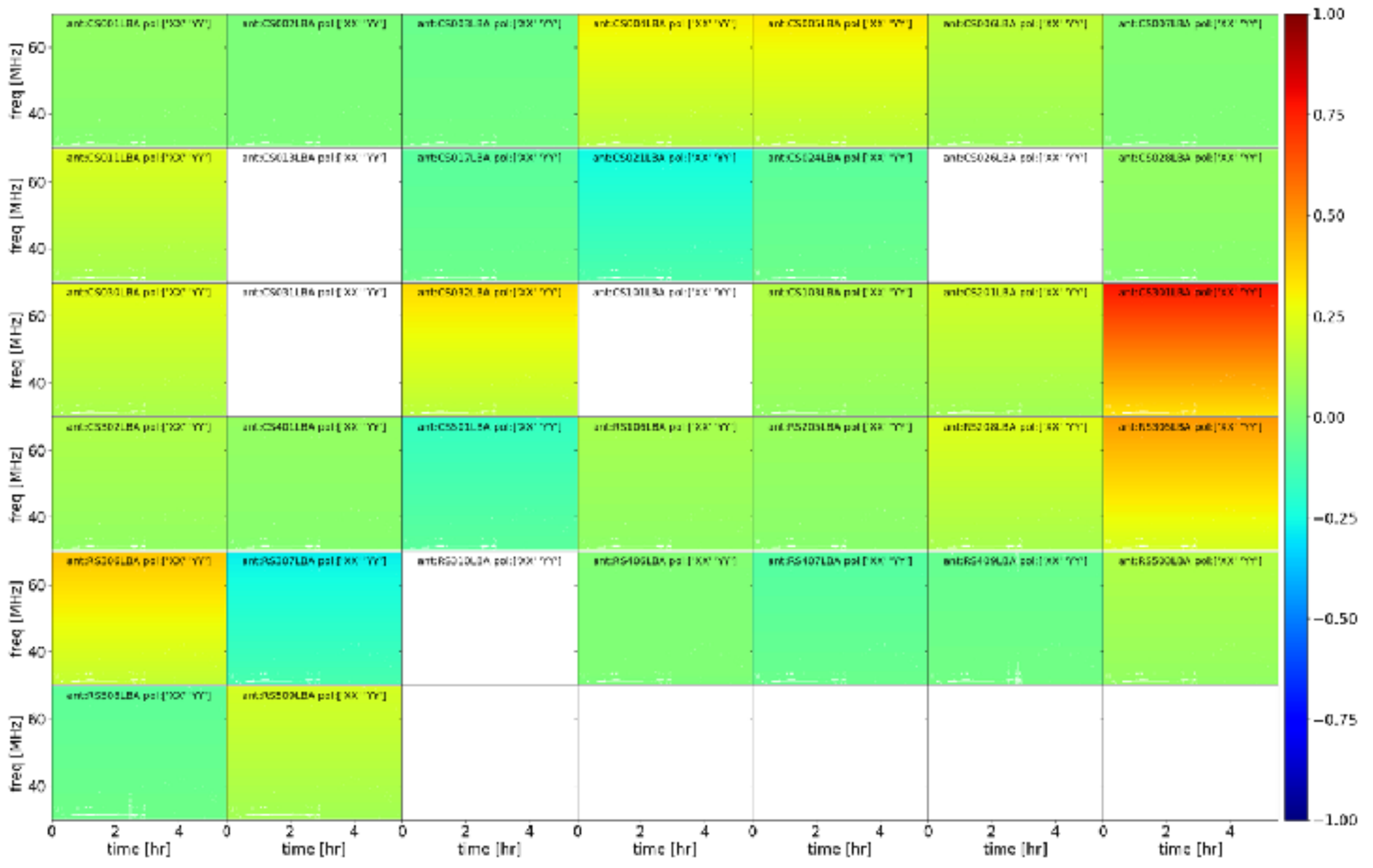
- In practice, a Jones matrix is a product of many(!) effects (components) along the signal path

- $J_i = F_i T_i P_i X_i E_i D_i G_i B_i K_i$
  - F_i = ionospheric effects
  - T_i = tropospheric effects
  - P_i = parallactic angle
  - X_i = linear polarisation position angle
  - E_i = antenna voltage pattern, gaincurve
  - D_i = polarisation leakage
  - G_i = electronic gain
  - B_i = bandpass response
  - K_i = geometry

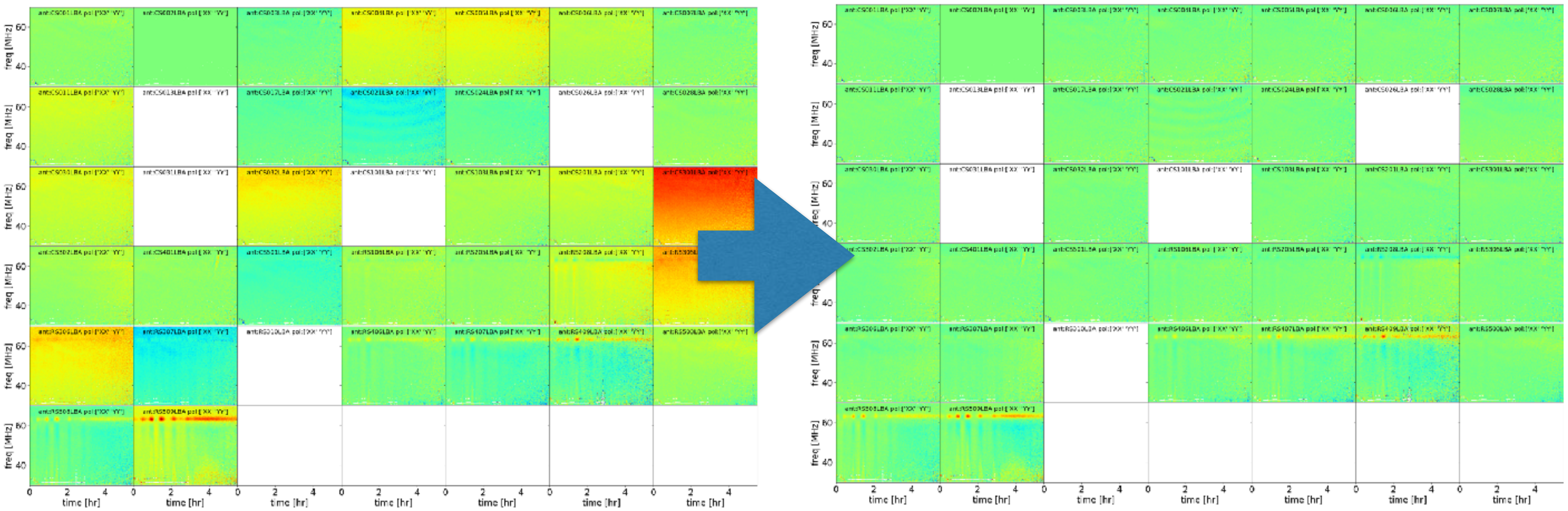
- Apply solutions left to right: opposite to signal path direction
- Components are typically difficult to separate.
- Some components commute (can reorder), some don't

RIME

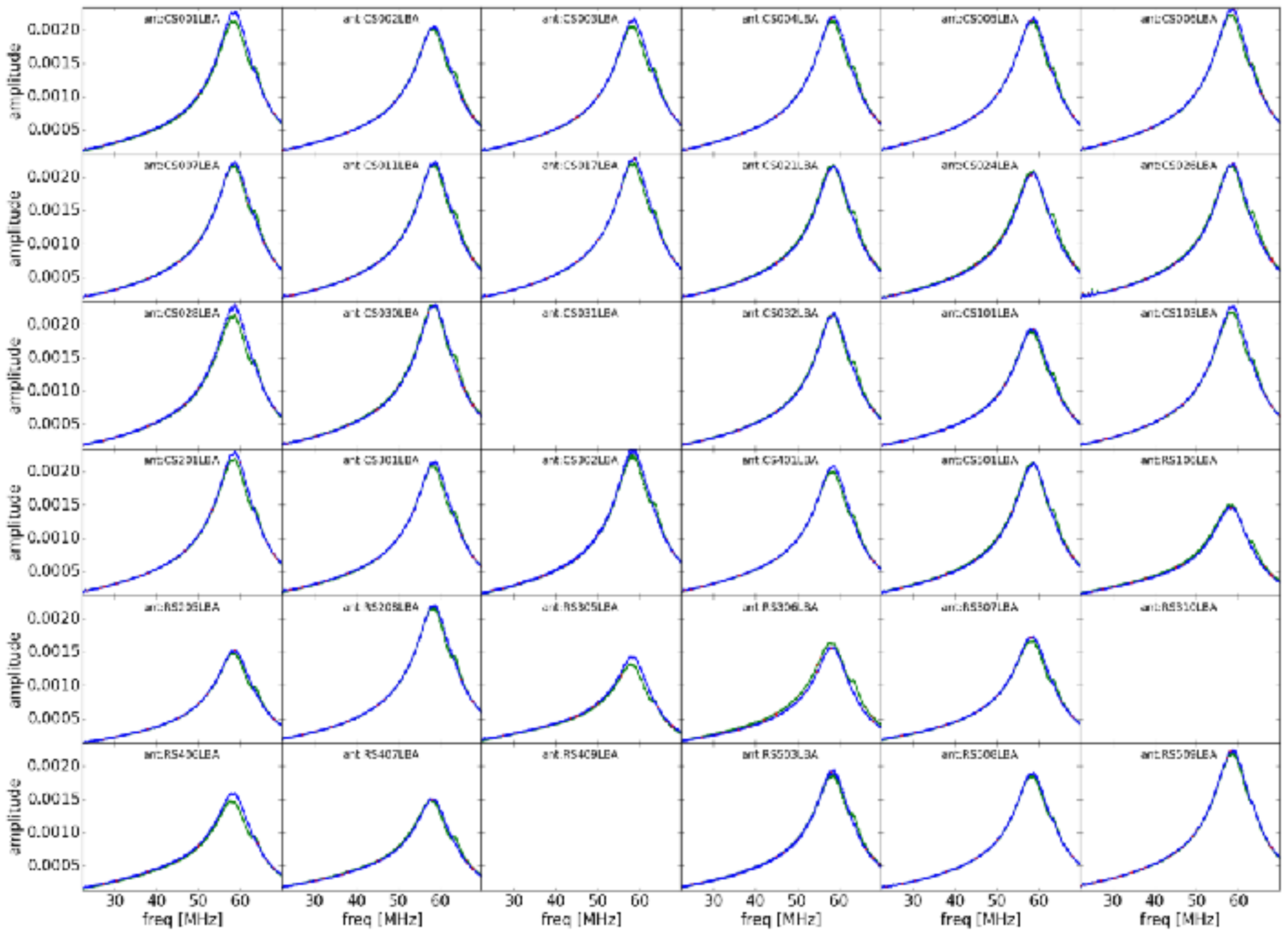
Polarisation alignment is calculated from XX-YY phases in LoSoTo

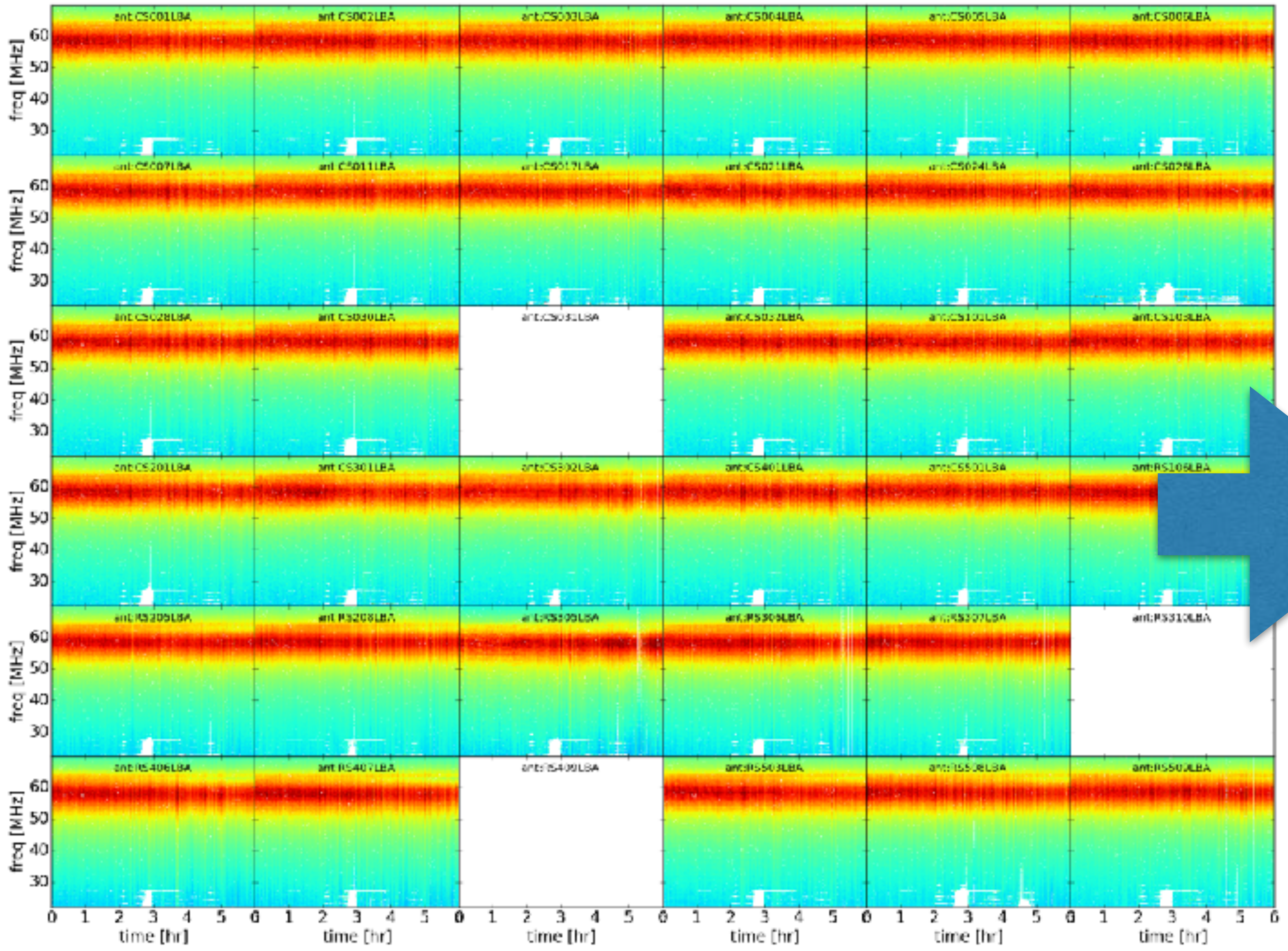


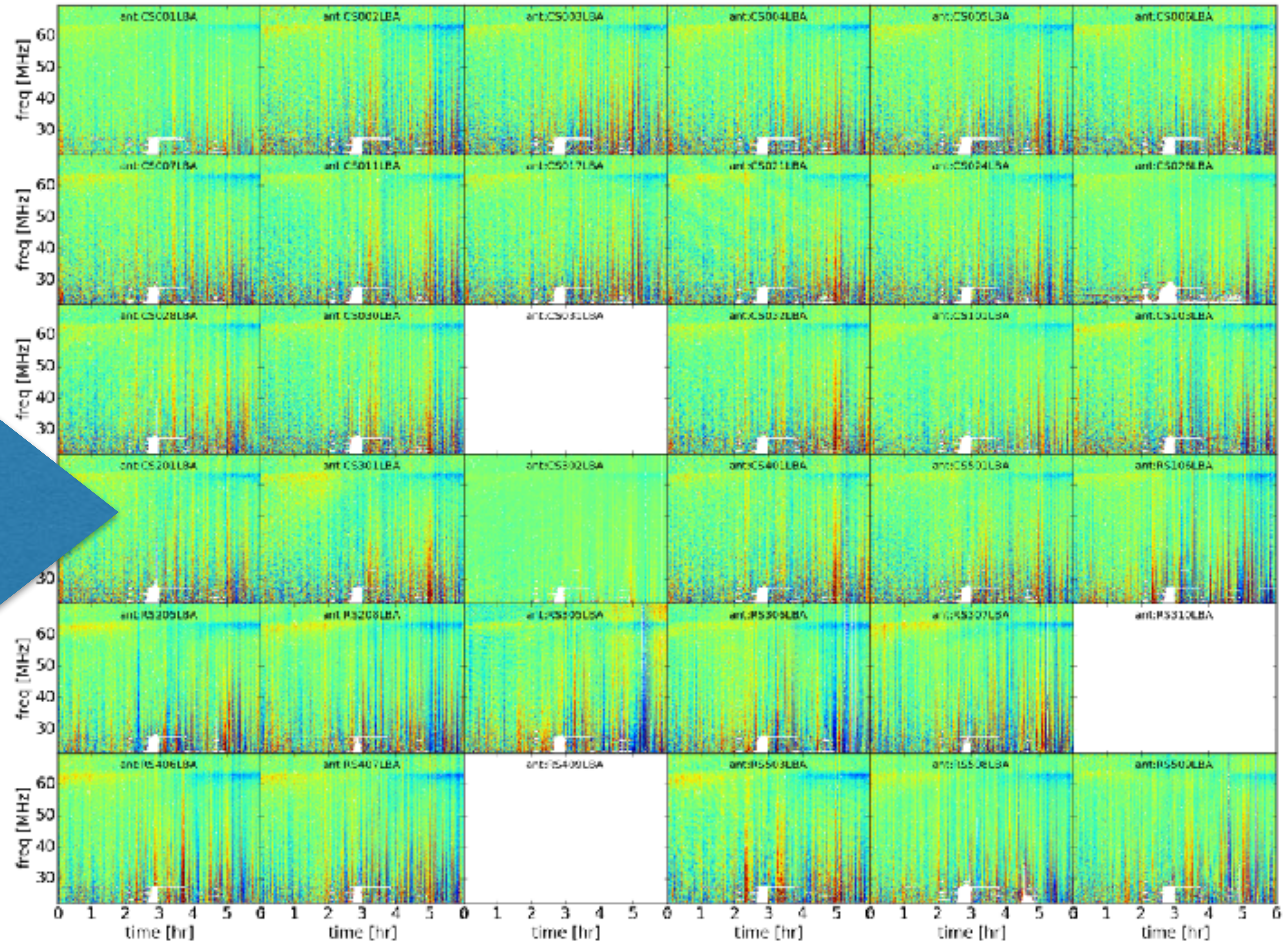
(very few free parameters: 1 delay per station)



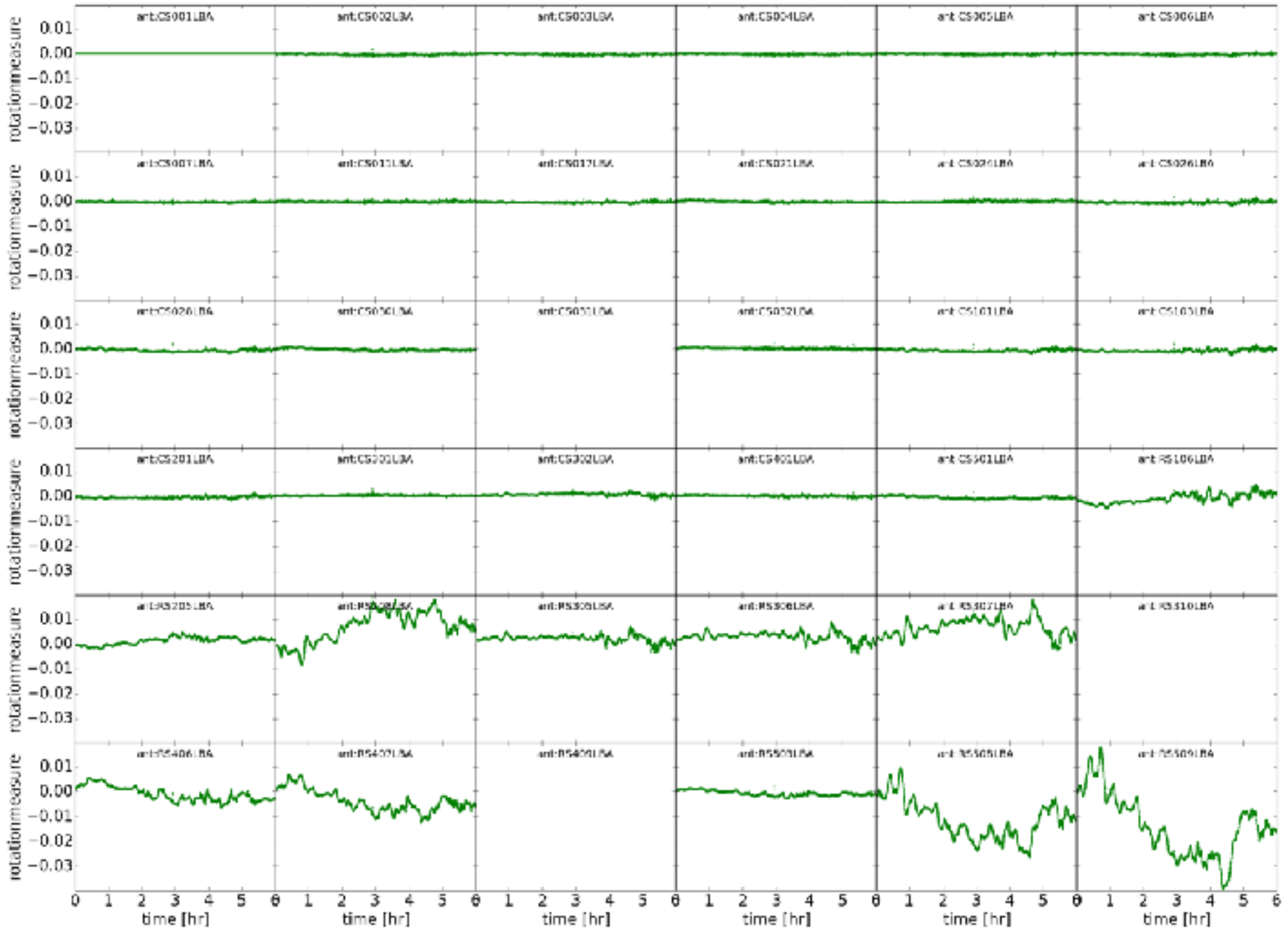
Bandpass is calculated from XX and YY amp solutions in LoSoTo averaging in time

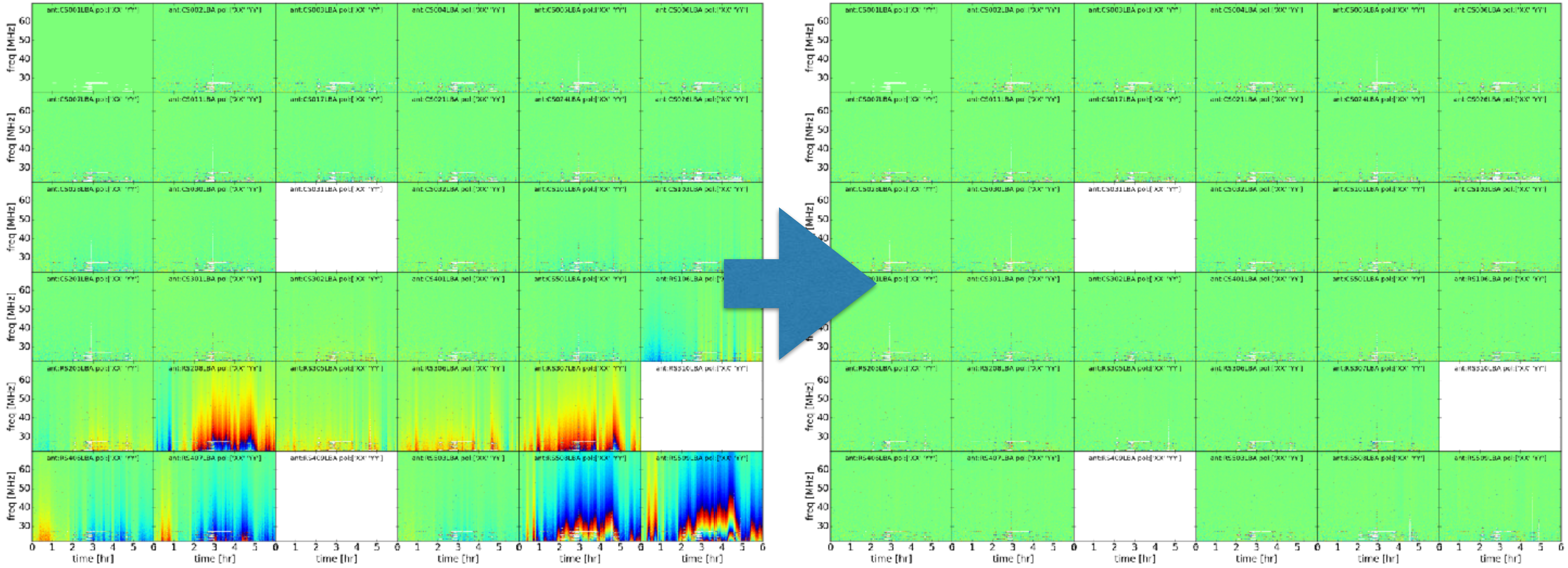




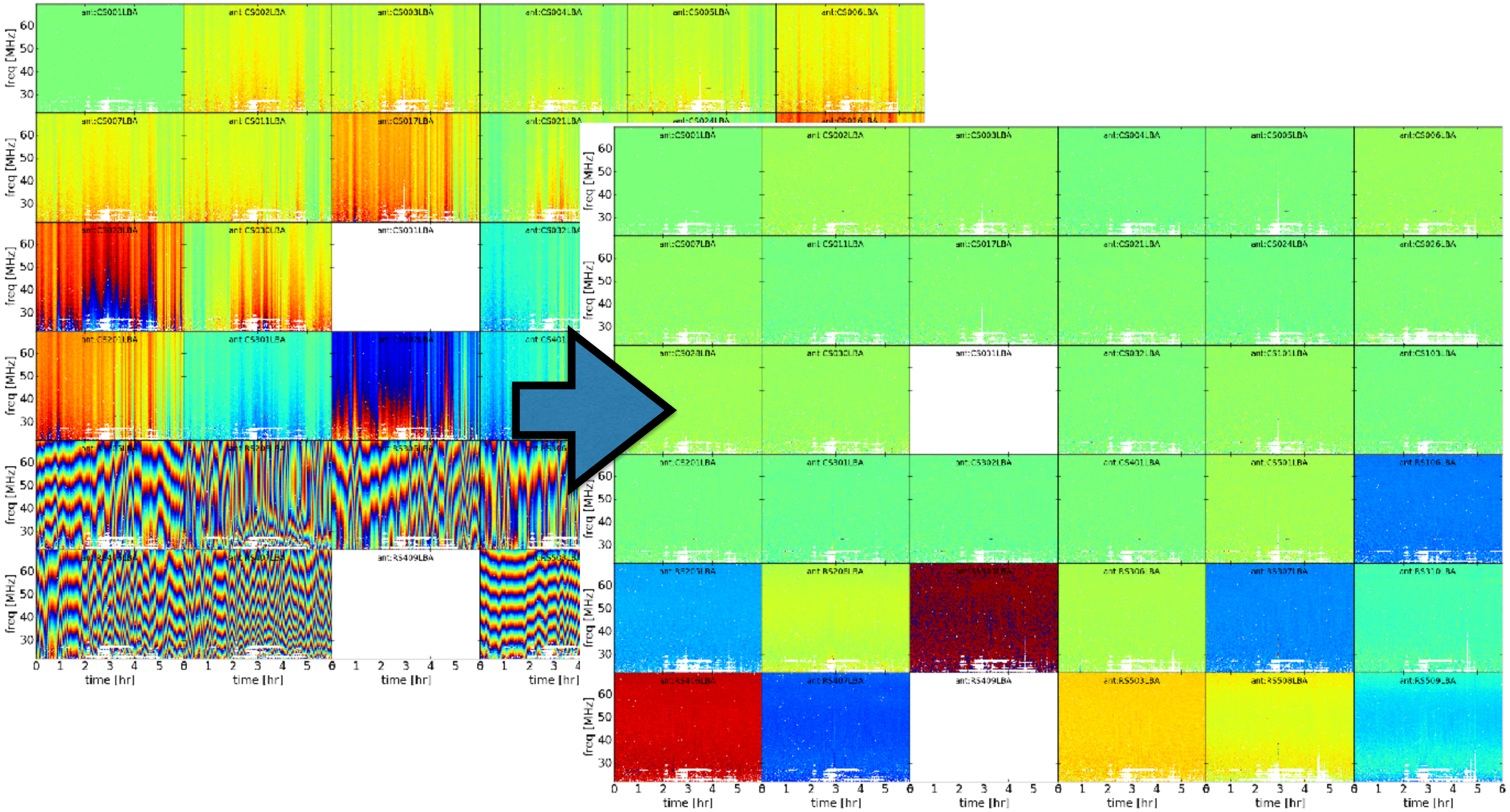


Faraday rotation is calculated from rotational phase Jones matrix ($\propto 1/f^2$) in LoSoTo

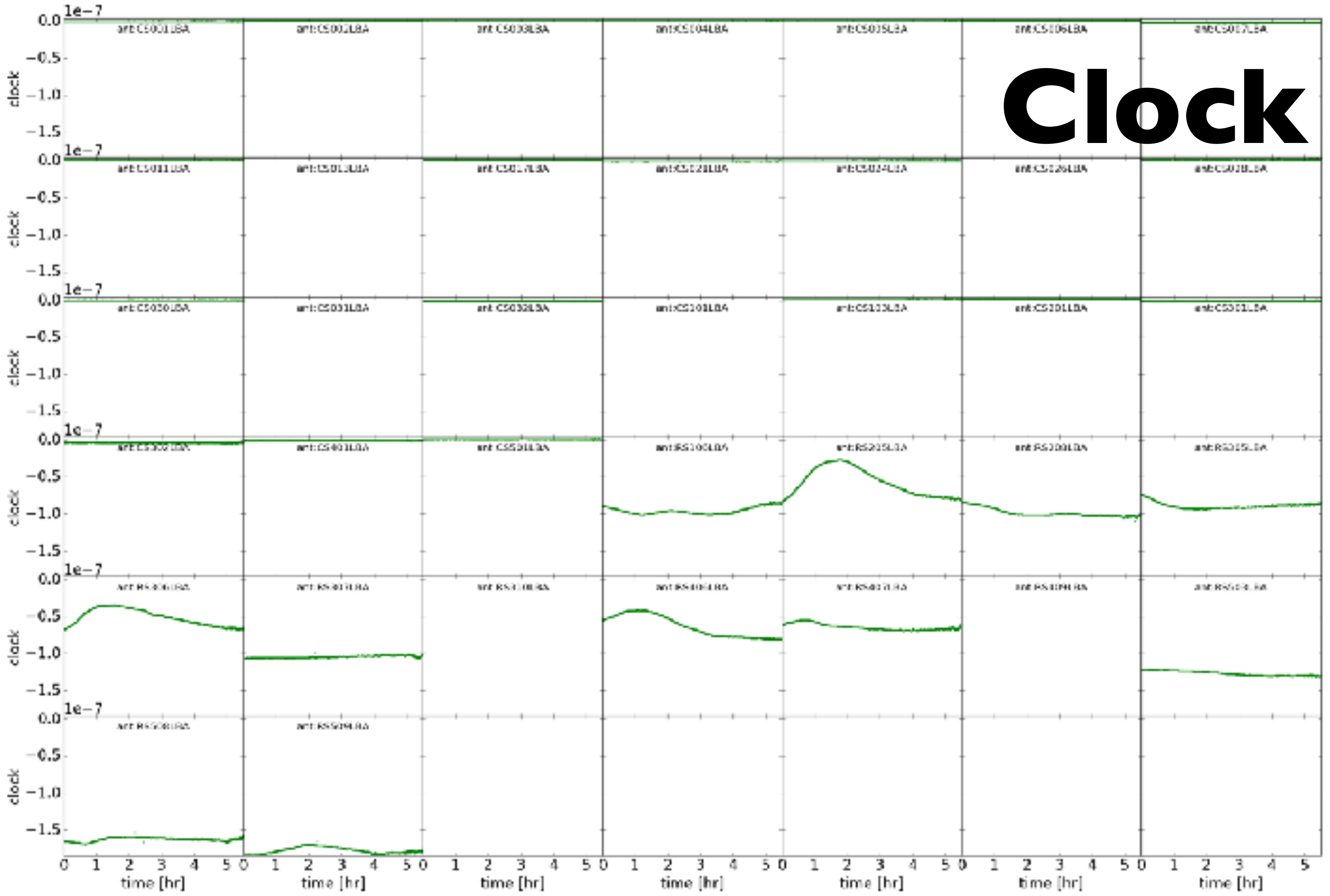


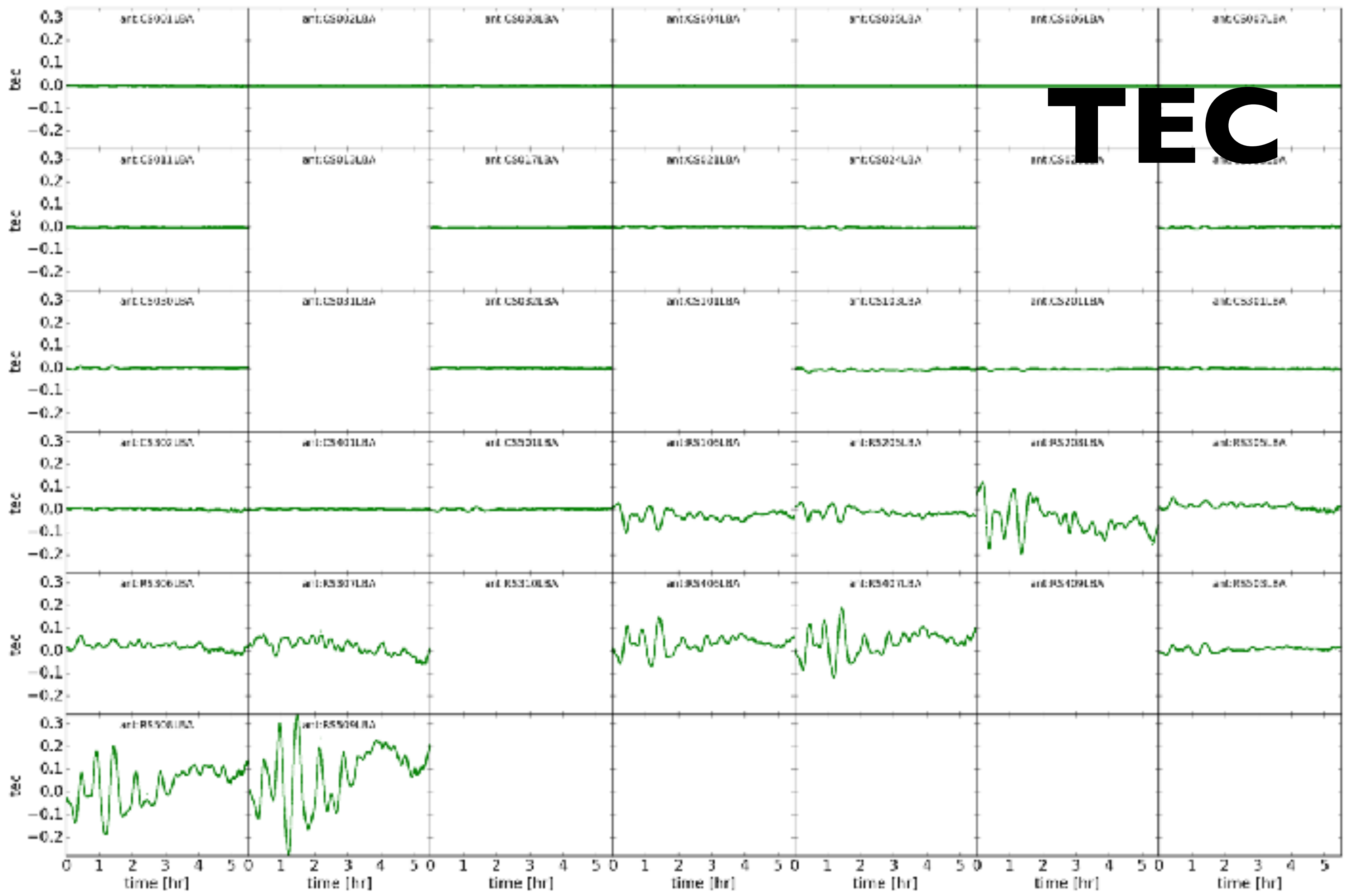


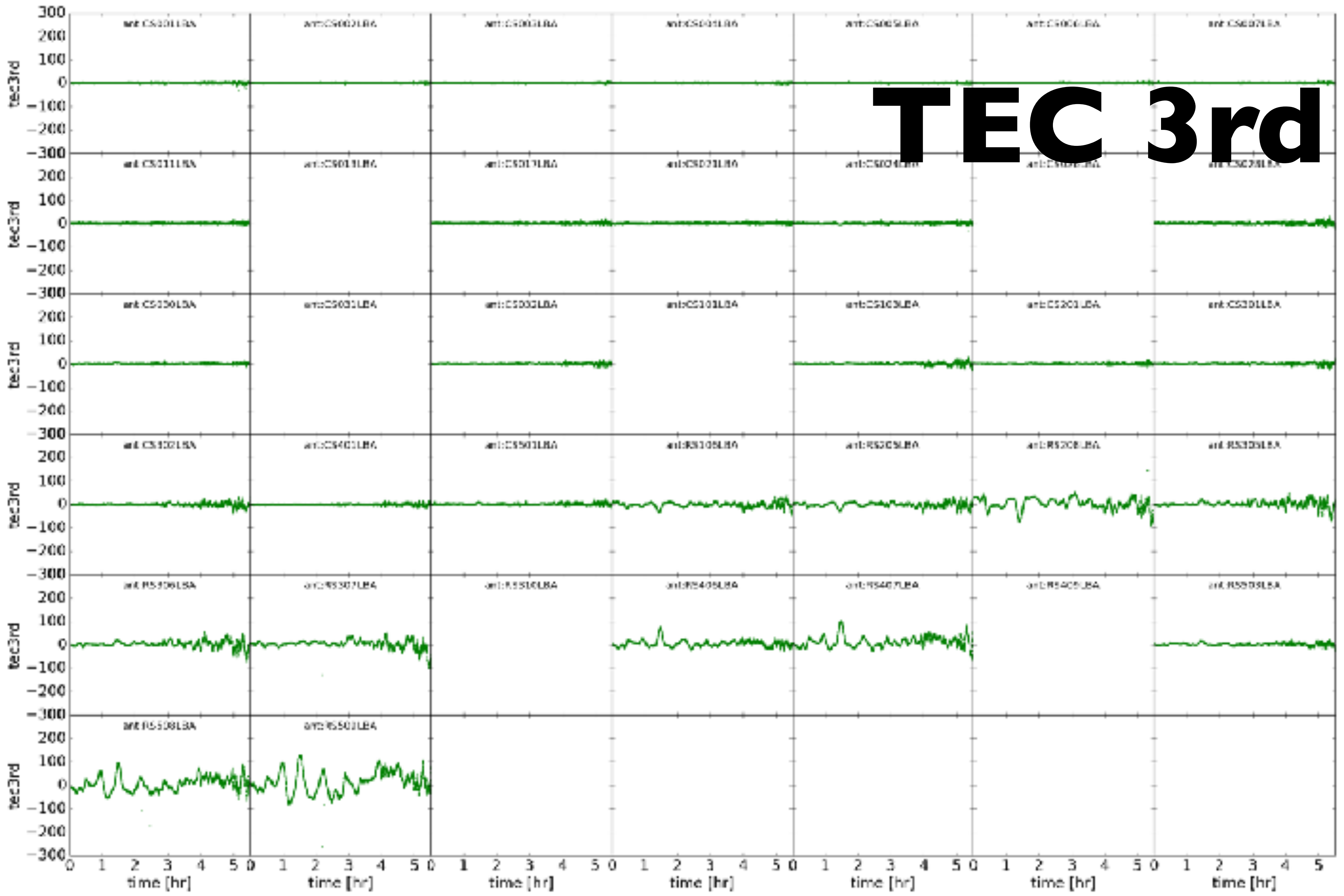
Systematic effect	Type of Jones matrix[a]	Ph/Amp/Both[b]	Frequency dependency	Direction dependent?	Time dependent?
Clock drift	Scalar	Ph	$\propto \nu$	No	Yes (many seconds)
Polarisation alignment	Diagonal	Ph	$\propto \nu$	No	No
Ionosphere - 1st ord. (dispersive delay)	Scalar	Ph	$\propto \nu^{-1}$	Yes	Yes (few seconds)
Ionosphere - 2sn ord. (Faraday rotation)	Rotation	Both	$\propto \nu^{-2}$	Yes	Yes (few seconds)
Ionosphere - 3rd ord.	Scalar	Ph	$\propto \nu^{-3}$	Yes	Yes (few seconds)
Ionosphere - scintillations	Diagonal	Amp	–	Yes	Yes (few seconds)
Dipole beam	Full-Jones	Both	–	Yes	Yes (minutes)
Bandpass	Diagonal	Amp	–	No	No



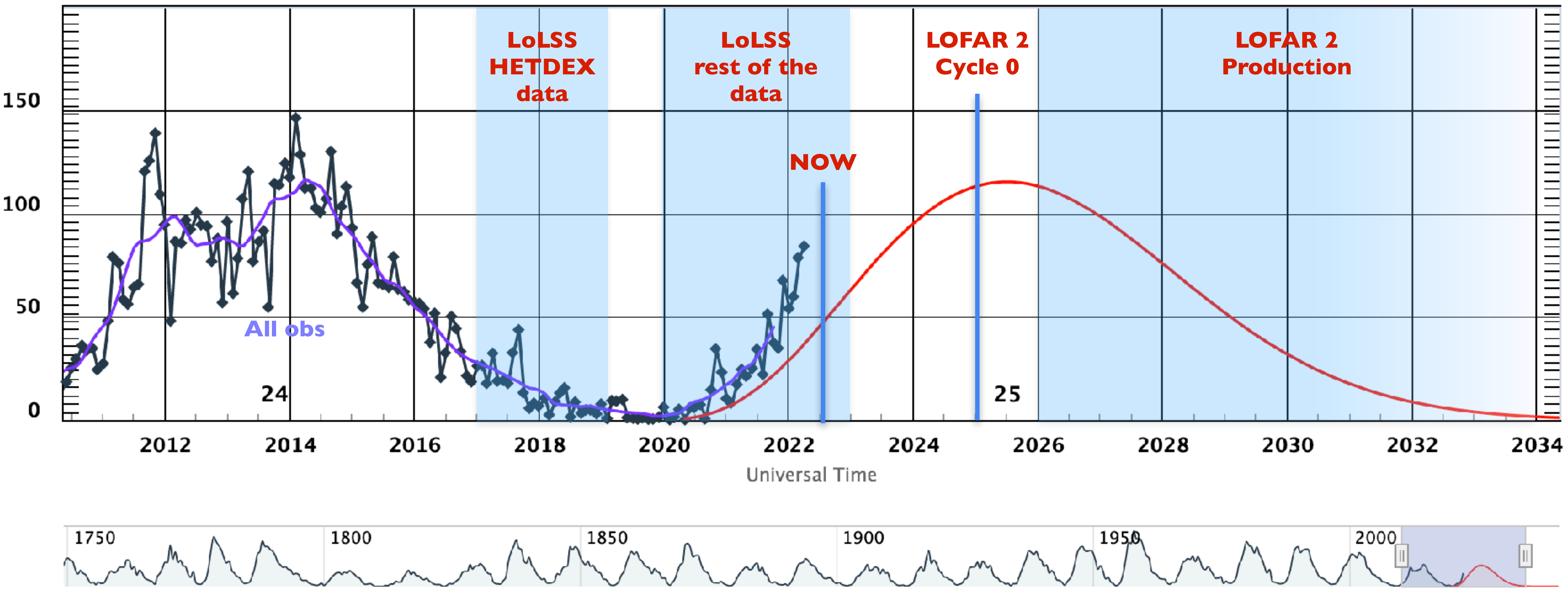
Clock/TEC/TEC3rd separations is calculated from XX+YY phase solutions in LoSoTo





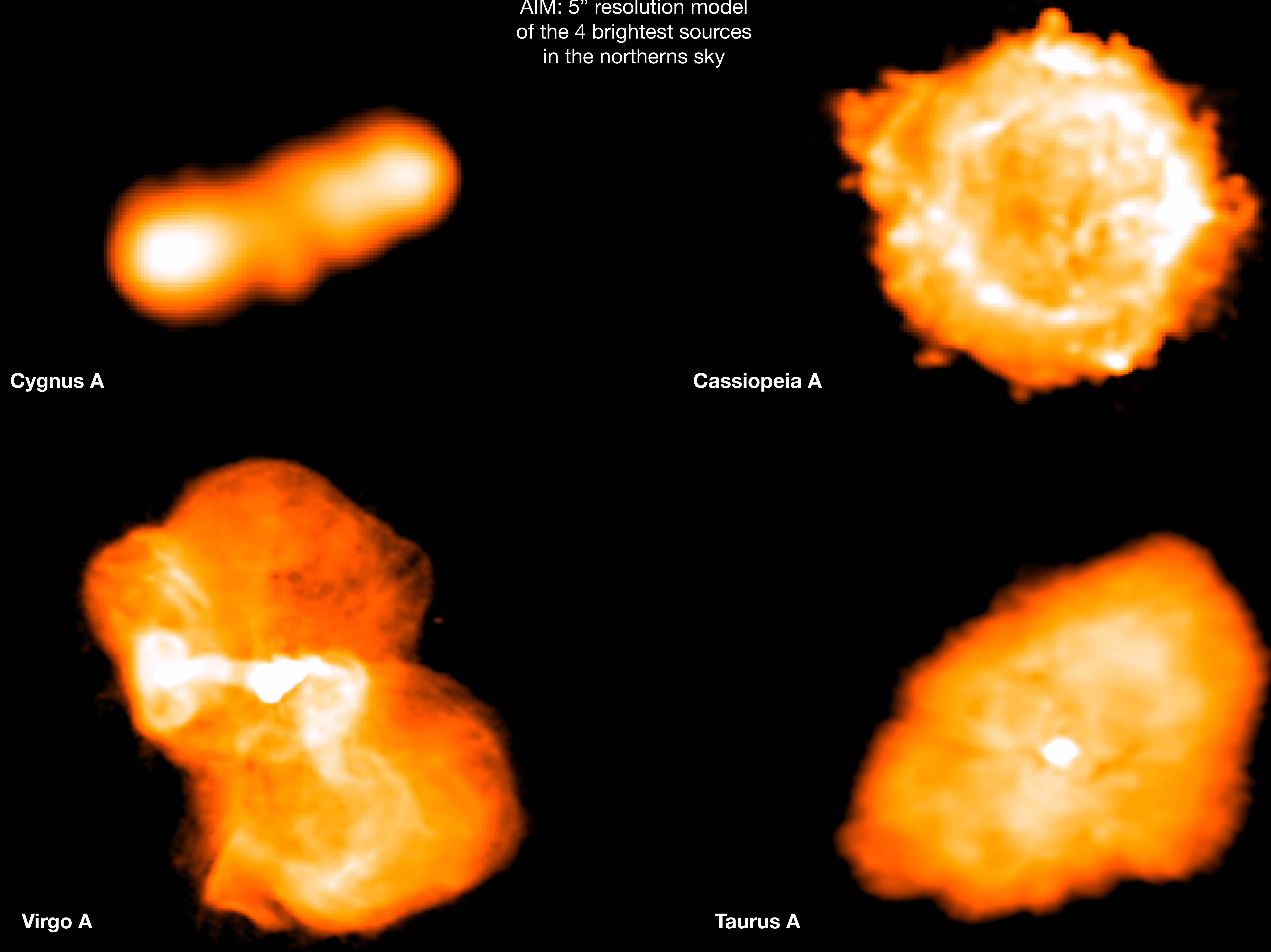


Solar Cycle



LoLSS
HETDEX
data
LoLSS
rest of the
data
LOFAR 2
Cycle 0
LOFAR 2
Production
NOW
150
100
50
0
All obs
24
25
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
2032
2034
Universal Time
1750
1800
1850
1900
1950
2000

LOFAR LBA A-Team survey:
AIM: 5” resolution model
of the 4 brightest sources
in the northerns sky




1 arcmin
Cygnus A
Cassiopeia A
Virgo A
Taurus A
de Gasperin+ 2020