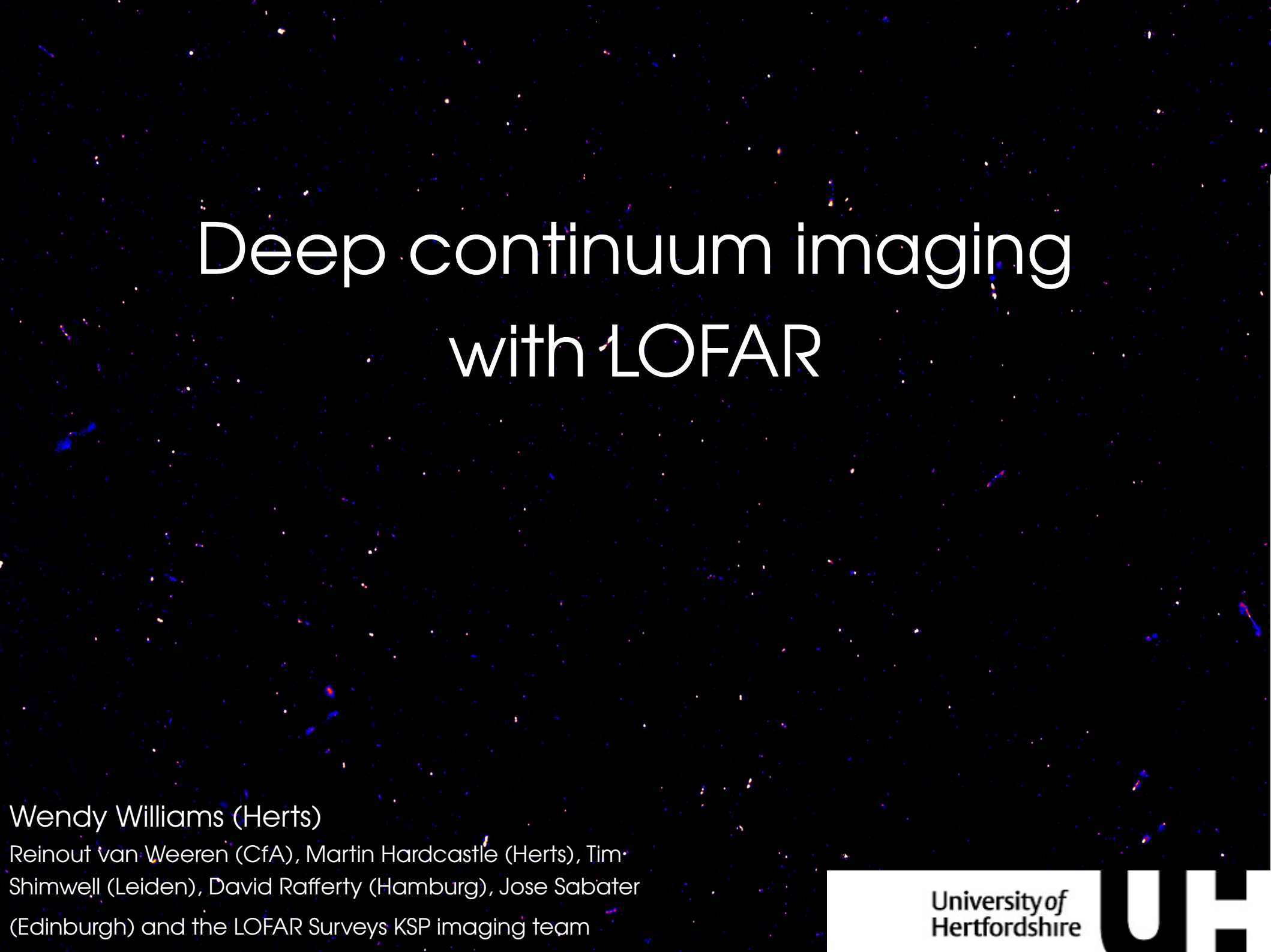
Deep continuum imaging with LOFAR



Wendy Williams (Herts)
Reinout van Weeren (CfA), Martin Hardcastle (Herts), Tim Shimwell (Leiden), David Rafferty (Hamburg), Jose Sabater (Edinburgh) and the LOFAR Surveys KSP imaging team

University of Hertfordshire


HBA
115 – 240 MHz


LBA
(10) 30 – 80 MHz


van Haarlem+ 2013

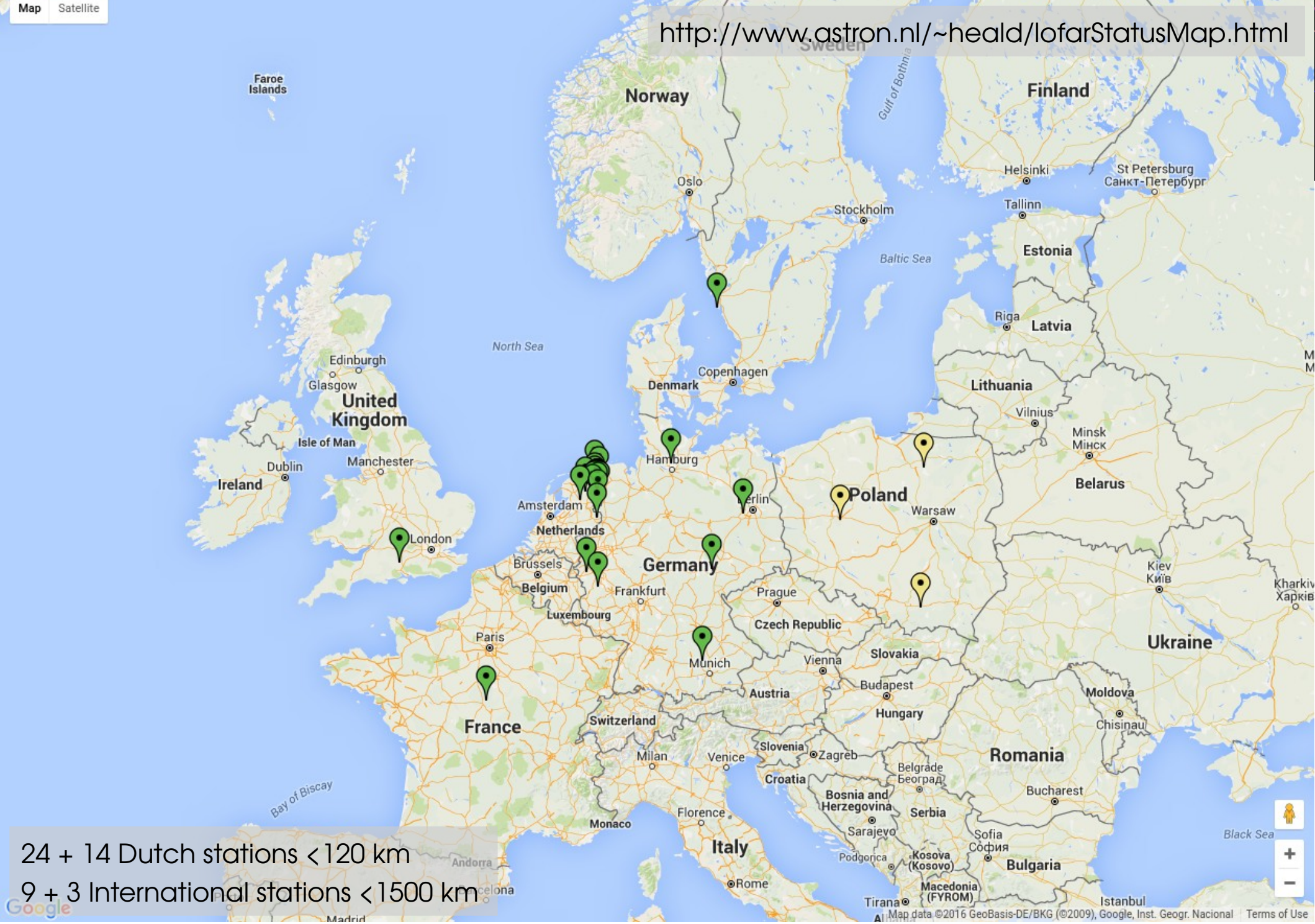
LOFAR stations are phased arrays

- Beams are station-dependent and variable in frequency and time and complex
- Individual clock effects

Software telescope

- Deal with it all in calibration
- Versatile

van Haarlem+ 2013


http://www.astron.nl/~heald/lofarStatusMap.html
Map
Satellite
Faroe Islands
Norway
Sweden
Finland
Gulf of Bothnia
Oslo
Helsinki
St Petersburg
Санкт-Петербург
Stockholm
Tallinn
Estonia
Baltic Sea
Riga
Latvia
North Sea
Edinburgh
Glasgow
United Kingdom
Isle of Man
Dublin
Ireland
Manchester
Copenhagen
Denmark
Lithuania
Vilnius
Minsk
Минск
Belarus
Hamburg
Berlin
Poland
Warsaw
Amsterdam
Netherlands
London
Brussels
Belgium
Germany
Frankfurt
Prague
Czech Republic
Luxembourg
Paris
Munich
Vienna
Slovakia
Budapest
Austria
Hungary
Kiev
Київ
Kharkiv
Харків
Ukraine
Moldova
Chisinau
France
Switzerland
Slovenia
Zagreb
Milan
Venice
Croatia
Belgrade
Београд
Romania
Bucharest
Bosnia and Herzegovina
Serbia
Sarajevo
Florence
Monaco
Italy
Sofia
София
Podgorica
Kosova (Kosovo)
Bulgaria
Macedonia (FYROM)
Tirana
Rome
Istanbul
Bay of Biscay
Black Sea
Andorra
Madrid
24 + 14 Dutch stations <120 km
9 + 3 International stations <1500 km
Google
Map data ©2016 GeoBasis-DE/BKG (©2009), Google, Inst. Geogr. Nacional
Terms of Use


http://www.astron.nl/~heald/lofarStatusMap.html
24 + 14 Dutch stations <120 km
9 + 3 International stations <1500 km

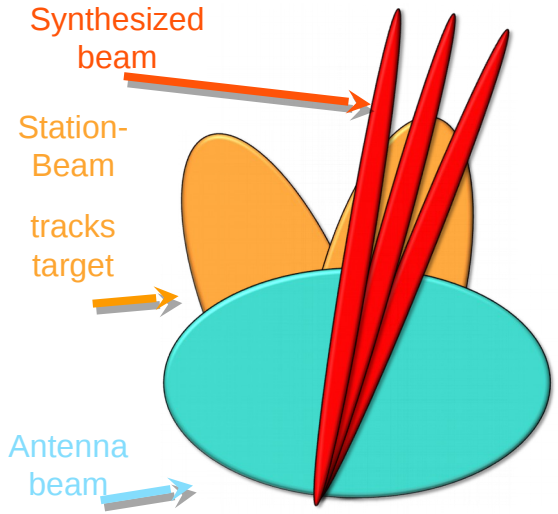
LOFAR Surveys Science

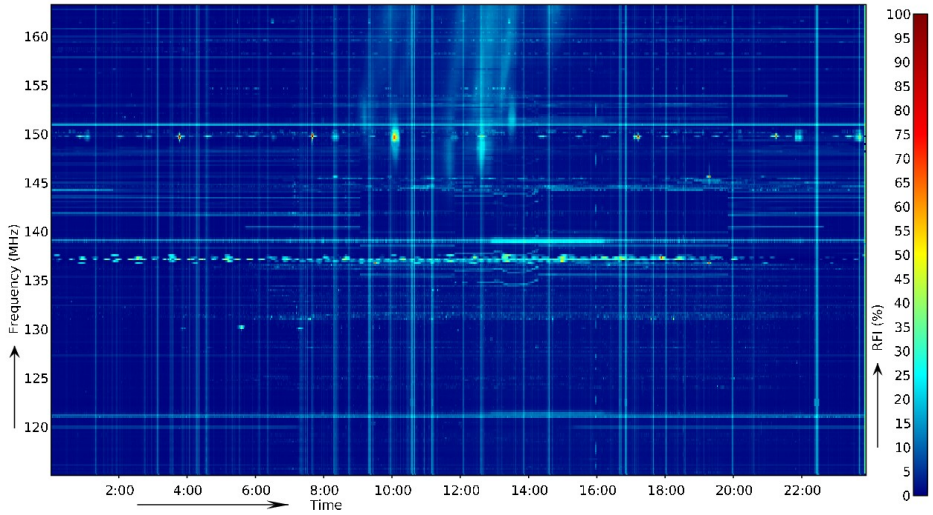
- One survey to rule them all
  - Low z AGN & galaxies
  - SF, AGN at moderate z
  - High z radio sources
  - Clusters
  - Cosmology
- (almost) All require full Dutch resolution and sensitivity
  - 5 arcsec
  - 100 μJy beam^{-1}

Rottgering+ 2010

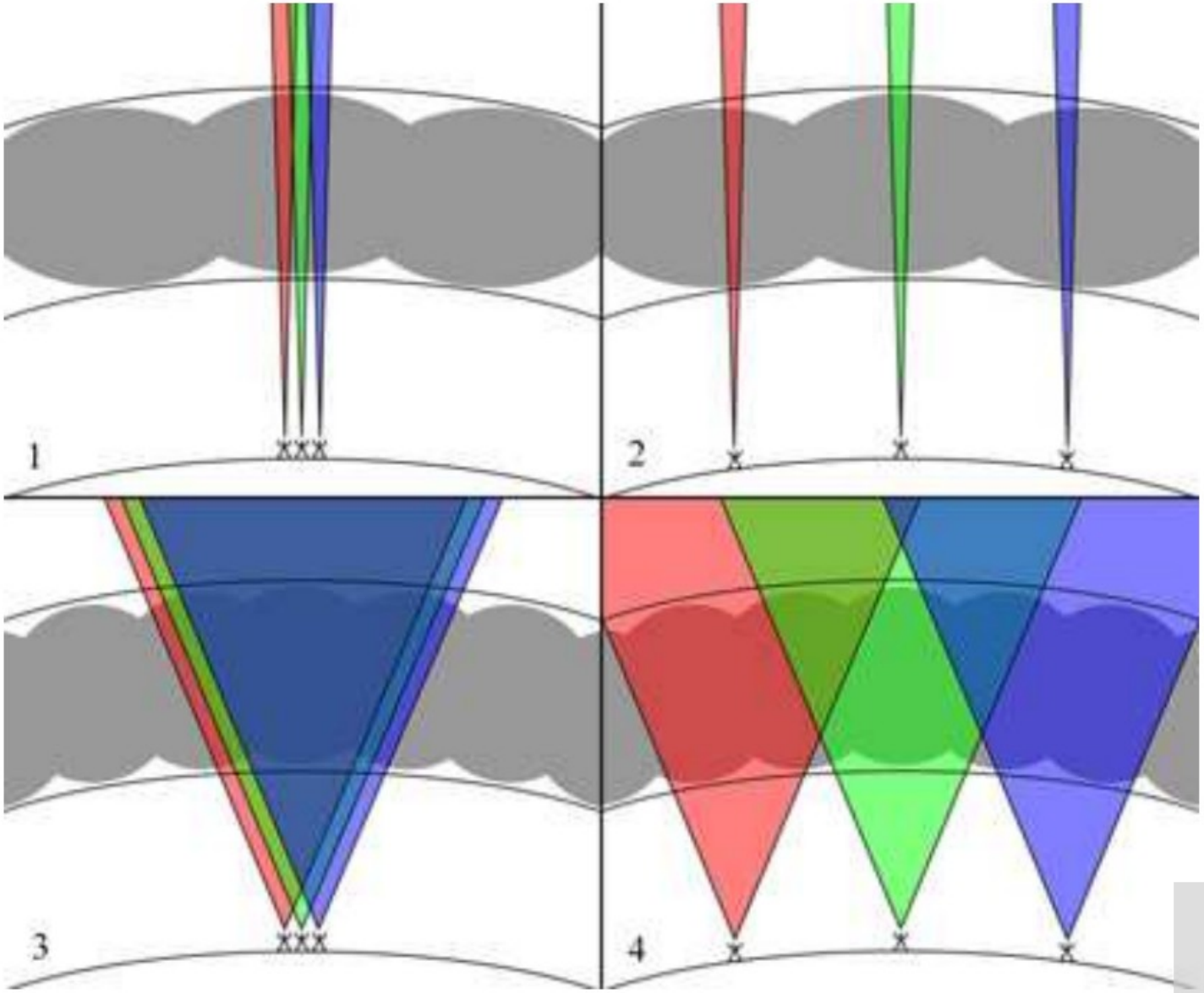
LOFAR Imaging challenges

- Widefield imaging
- RFI
- Station beams
  - Removal of bright sources
- **Data volumes/rates**
- **Ionosphere**



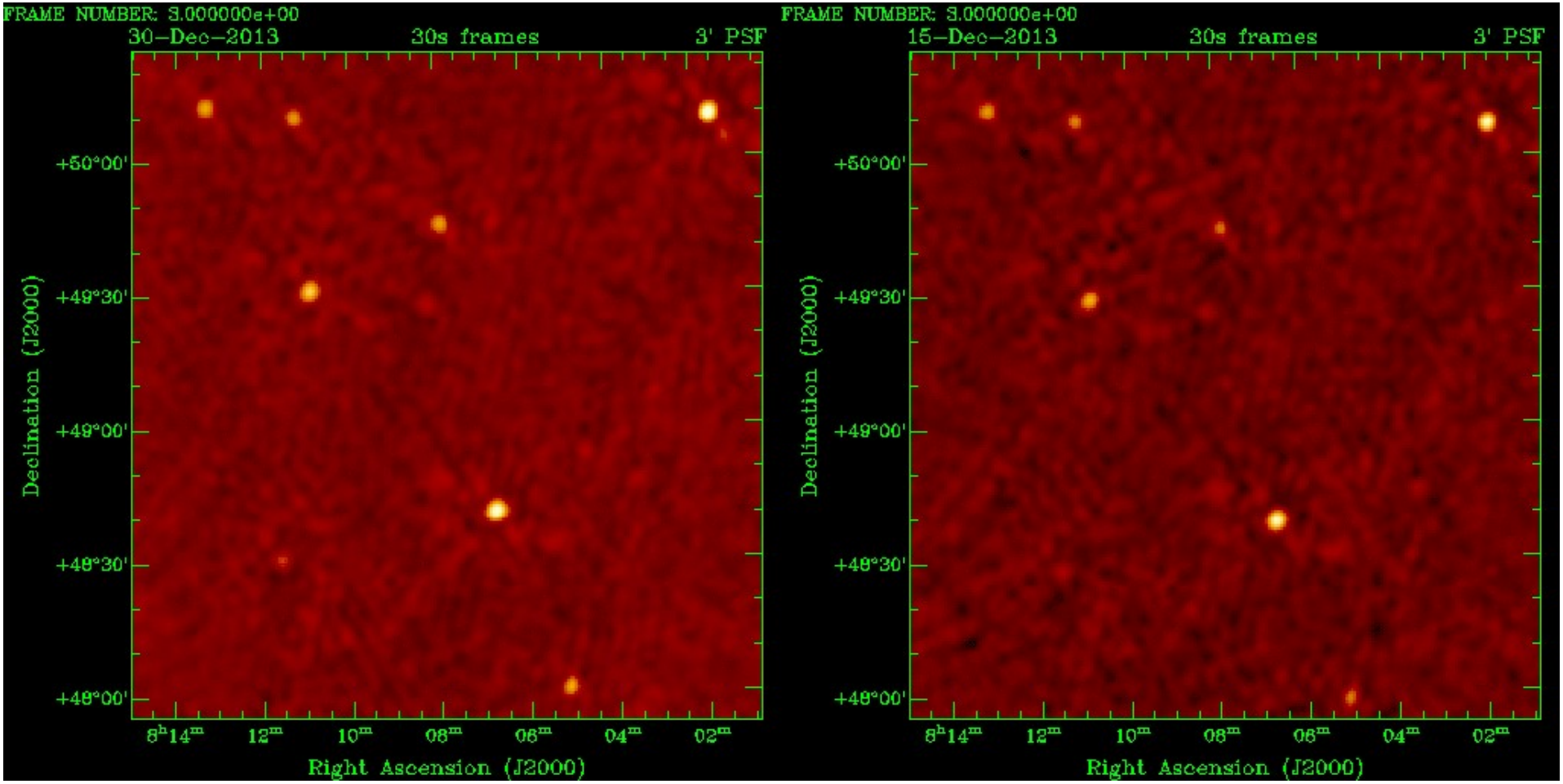


Ionosphere



Intema+ 2009
Lonsdale+ 2005

Ionosphere



LOFAR EoR team

"FACET" calibration

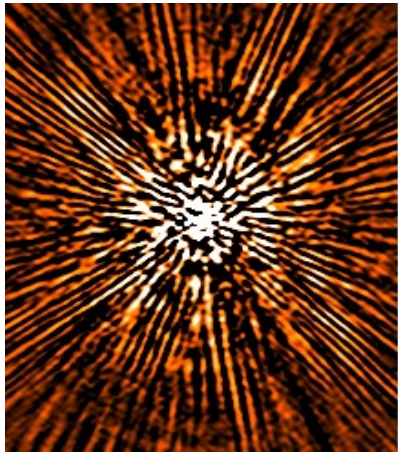
- Built on the ideas of peeling, SPAM (Intema+ 2009), SAGECAL (Yatawatta+ 2013)
- Cut up the sky into discrete patches containing bright calibrator sources
  - Subtract everything else
  - Self-calibrate
  - Image
  - Iterate
    - Improves the subtraction, and produces images of the sky for each facet
- Use the tools that we already have (had 2 years ago)
  - BBS, NDPPP, casapy, PyBDSM

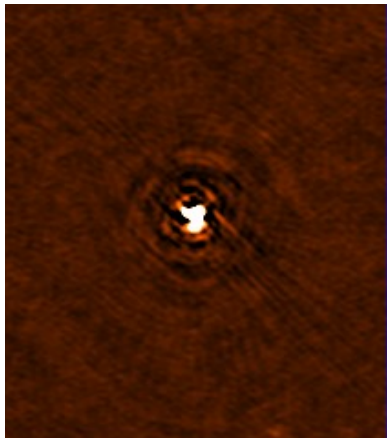
"LOFAR Facet Calibration"
van Weeren, WLW+, 2016, ApJS, 223, 2

Assumptions & degrees of freedom

- The only effects are due to ionosphere and imperfect beam models
  - Only the phases vary on short time scales – ~ seconds
  - The phases can be described by 2 parameters (phase offset and TEC) within 10MHz blocks
  - Amplitudes vary slowly – ~ minutes
  - Vary slowly across the field of view
- E.g. in a 5 min block:
  - Full jones – solve for everything on a longer timescale:
    - 30 directions X 240 subbands X 8 terms = 57,600
  - FACET – solve for physically motivated effects on physically motivated timescales:
    - 30 directions X (4 blocks X (2 terms X 60 intervals) + 24 blocks (4 terms X 1 interval)) = 17,280

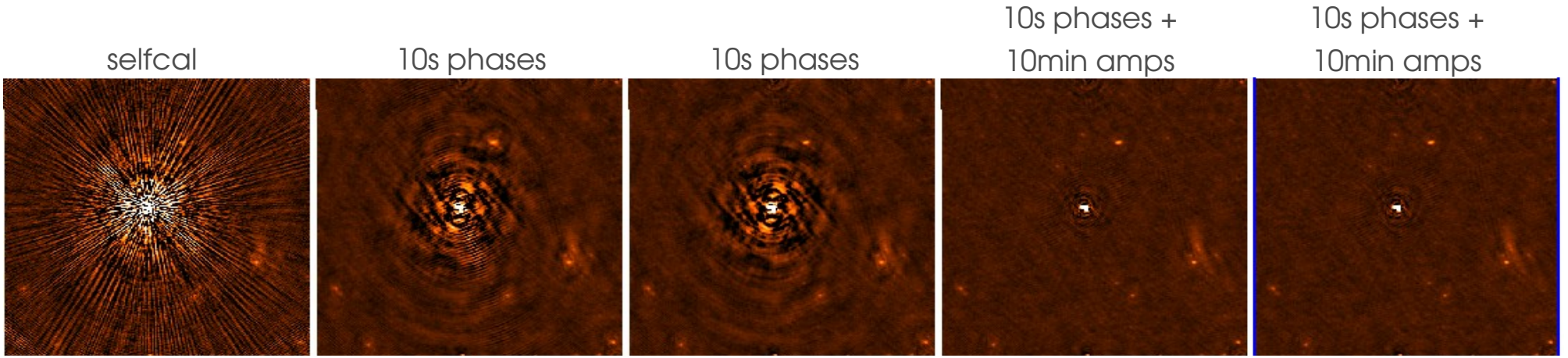
DDE self-calibration





- Apply DI solutions
  - Image
- Solve for fast scalarphase & TEC (in groups of 5–6 bands or ~10MHz)
  - 10 s
- Solve for slow amplitudes in each 2MHz band
  - Pre-apply fast phases
  - 5–20 min

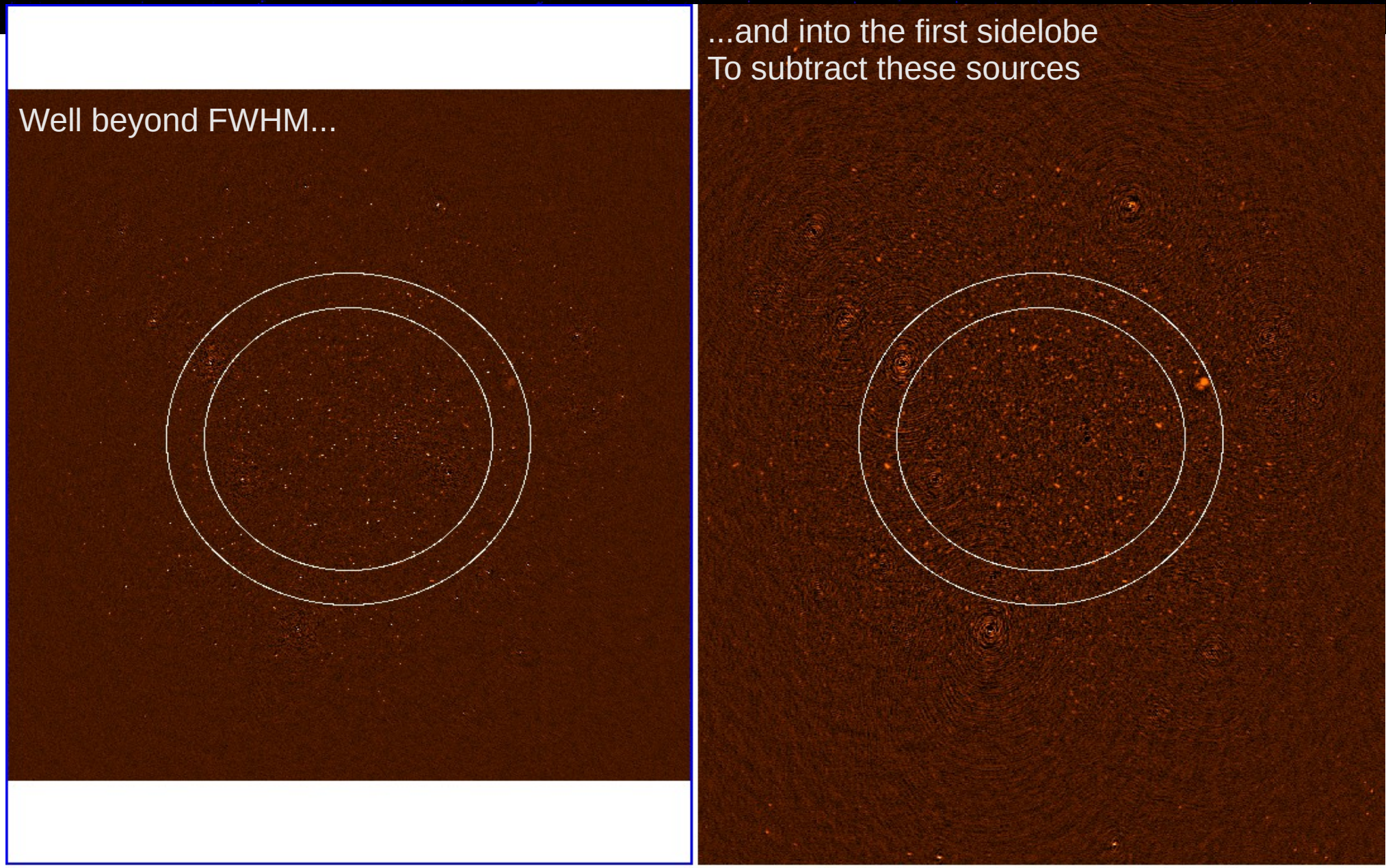
DDE self-calibration



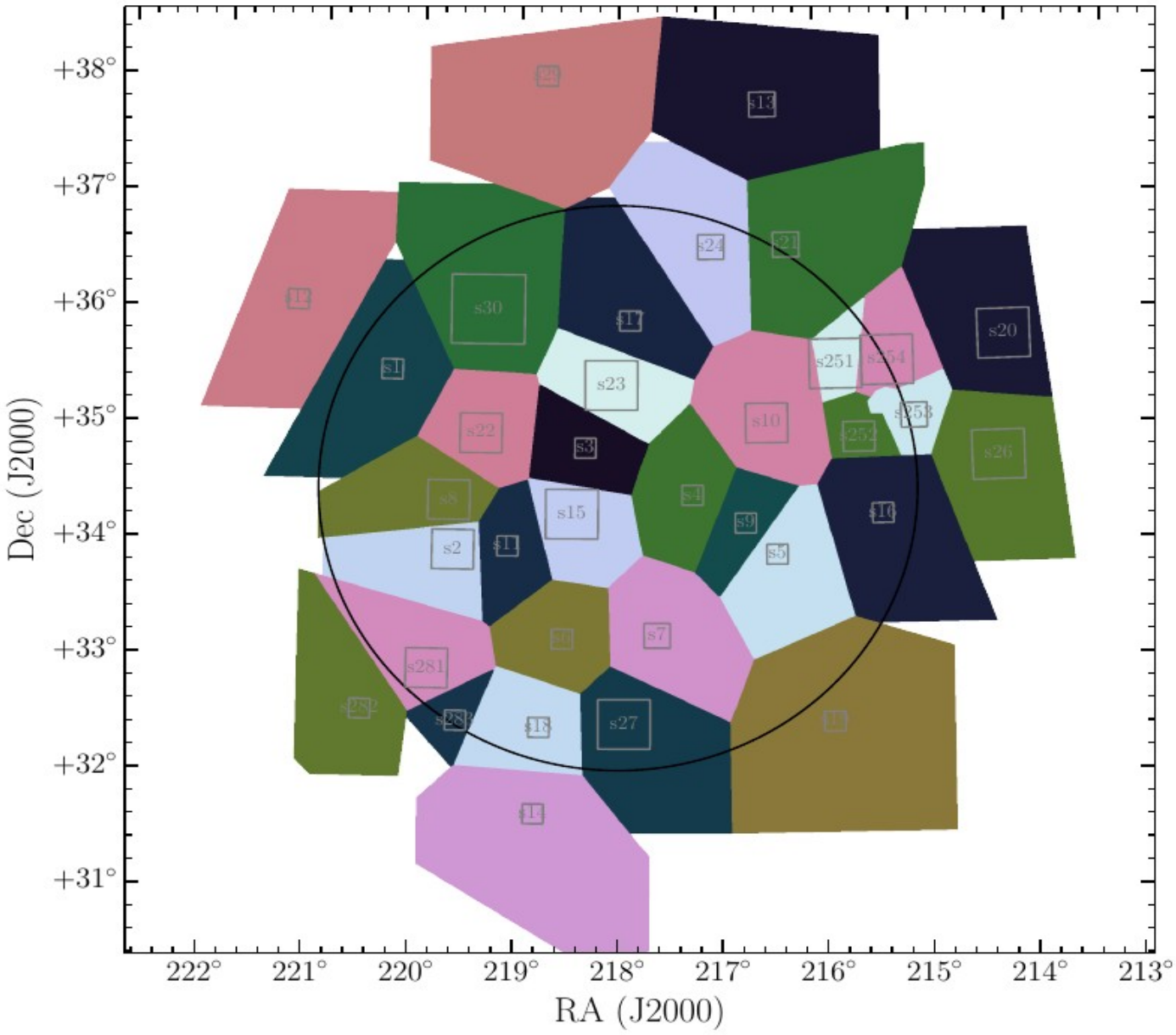
Bootes observation

- Calibrator
  - 10 min
  - Station clock, amplitude, phase offset
- Target
  - 8 hrs
  - 200 SB (40 MHz) bandwidth
    - Flagging
    - Calibration transfer
    - Averaging
    - Beam correction
    - Direction independent calibration

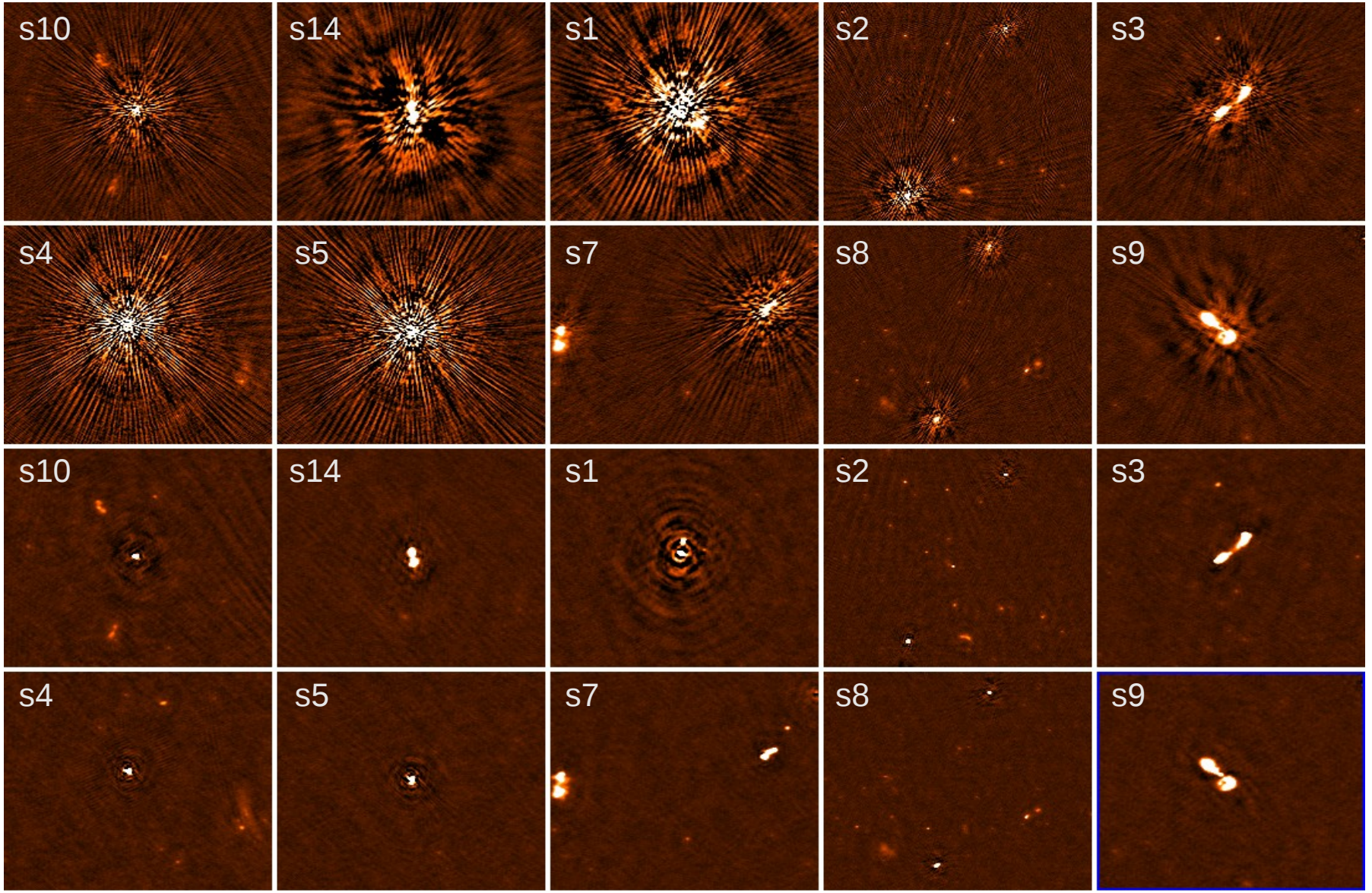
Preparing the 'residual' data



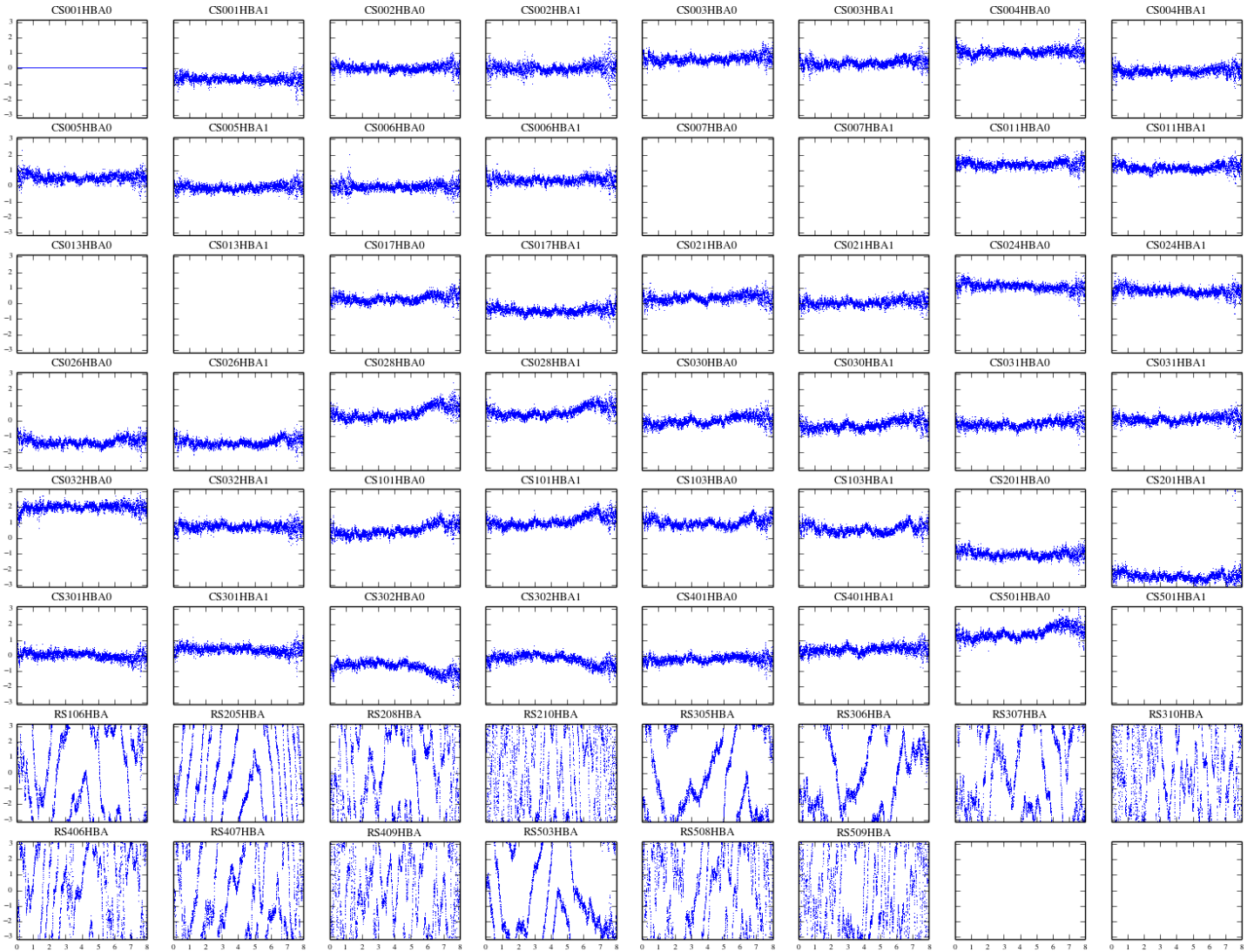
Bootes facets



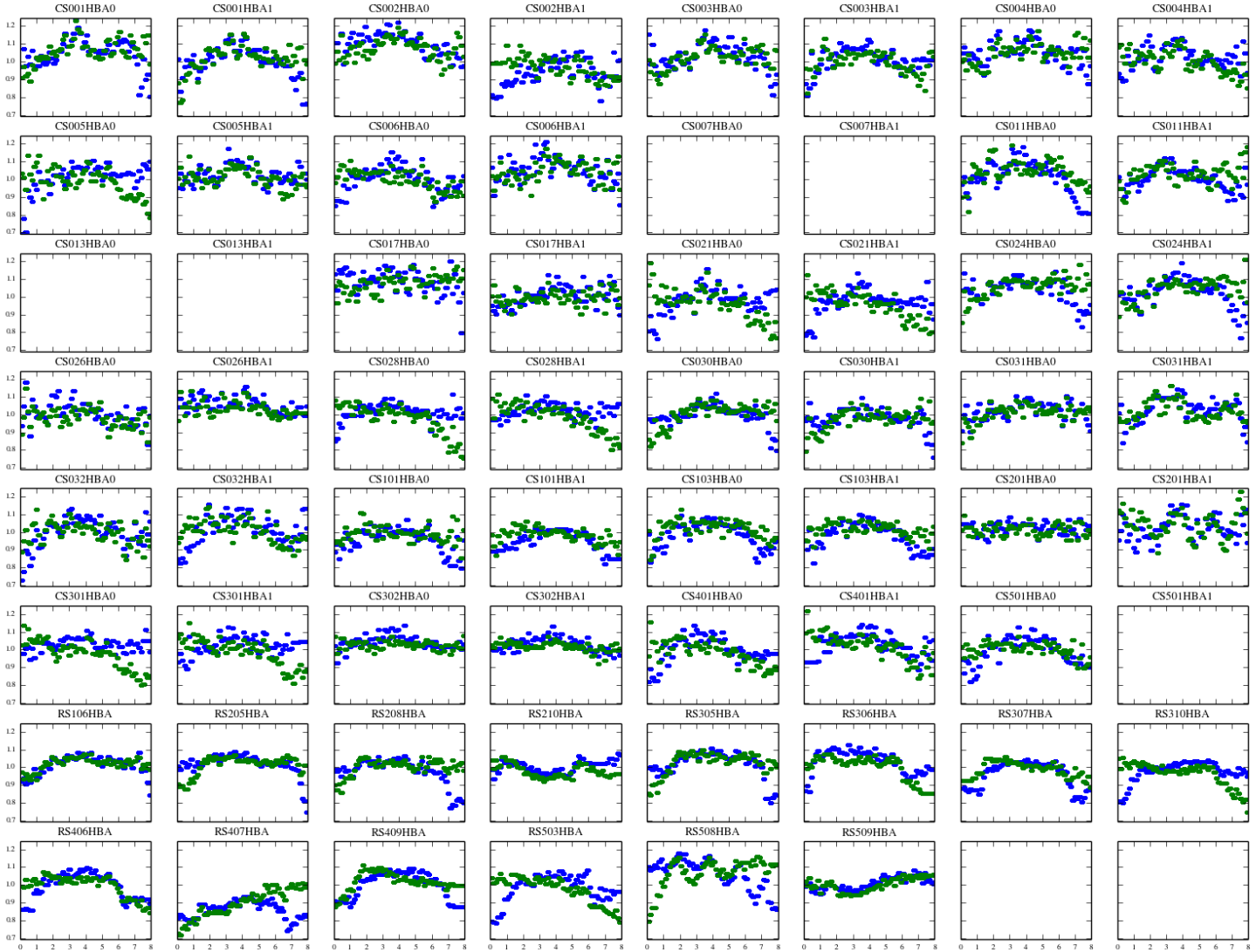
DDE calibrator gallery



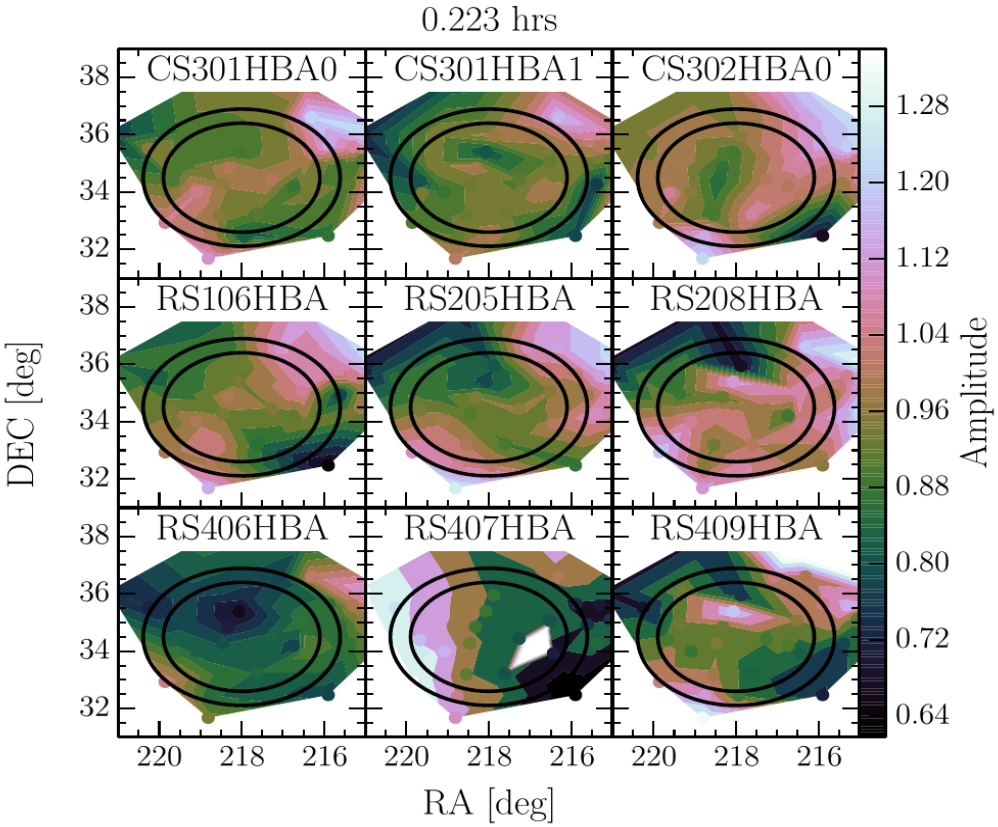
Fast phases

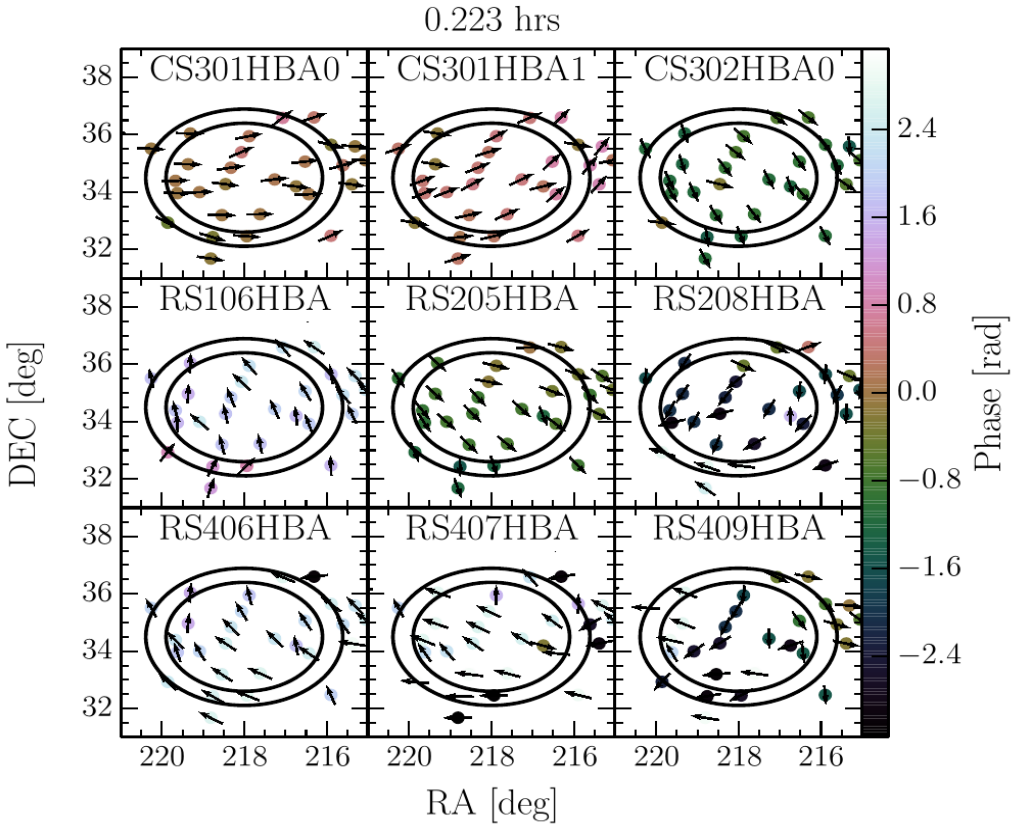

CS001HBA0
CS001HBA1
CS002HBA0
CS002HBA1
CS003HBA0
CS003HBA1
CS004HBA0
CS004HBA1
CS005HBA0
CS005HBA1
CS006HBA0
CS006HBA1
CS007HBA0
CS007HBA1
CS011HBA0
CS011HBA1
CS013HBA0
CS013HBA1
CS017HBA0
CS017HBA1
CS021HBA0
CS021HBA1
CS024HBA0
CS024HBA1
CS026HBA0
CS026HBA1
CS028HBA0
CS028HBA1
CS030HBA0
CS030HBA1
CS031HBA0
CS031HBA1
CS032HBA0
CS032HBA1
CS101HBA0
CS101HBA1
CS103HBA0
CS103HBA1
CS201HBA0
CS201HBA1
CS301HBA0
CS301HBA1
CS302HBA0
CS302HBA1
CS401HBA0
CS401HBA1
CS501HBA0
CS501HBA1
RS106HBA
RS205HBA
RS208HBA
RS210HBA
RS305HBA
RS306HBA
RS307HBA
RS310HBA
RS406HBA
RS407HBA
RS409HBA
RS503HBA
RS508HBA
RS509HBA

Slow amplitudes



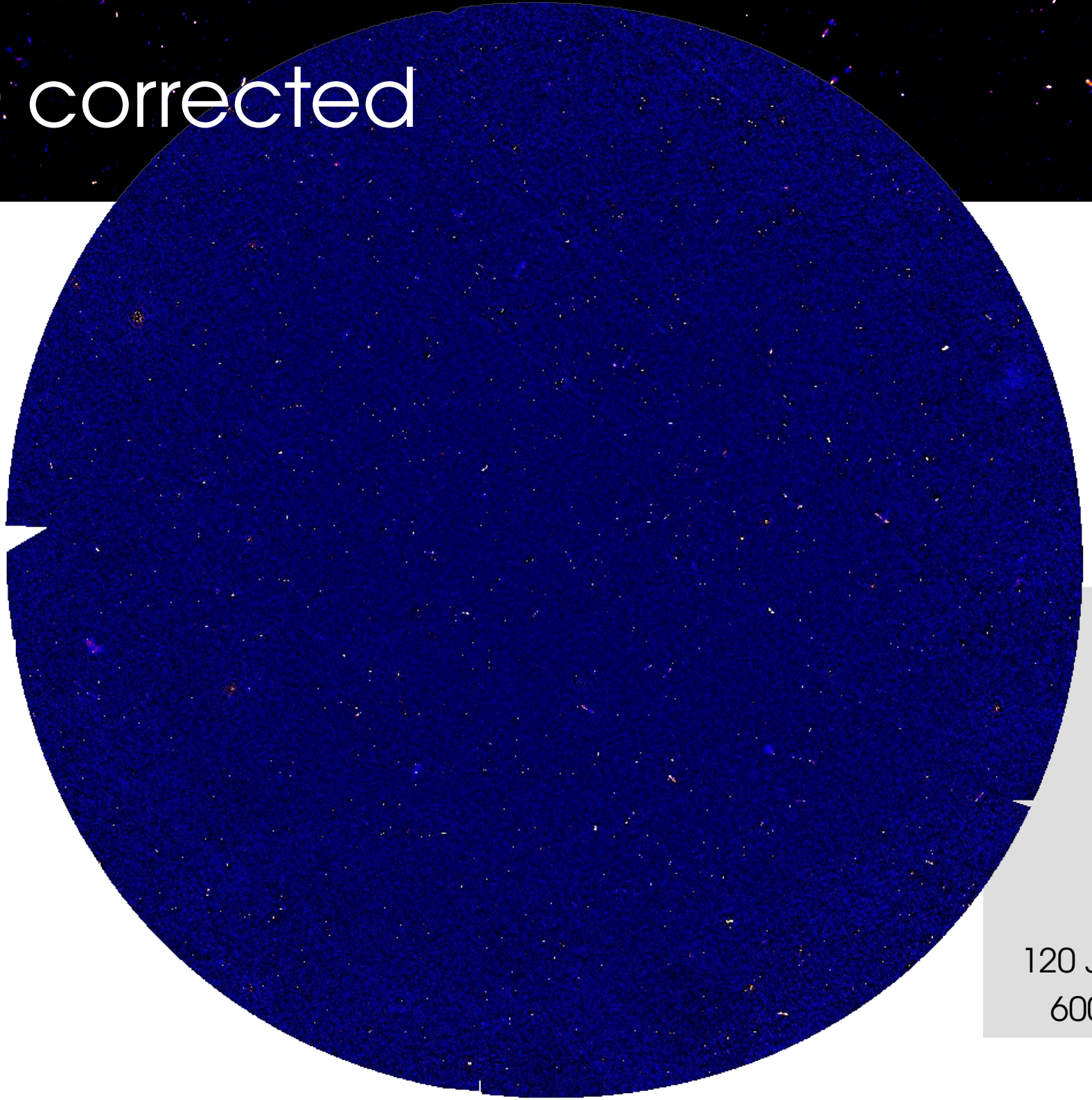
Solution snapshots in time



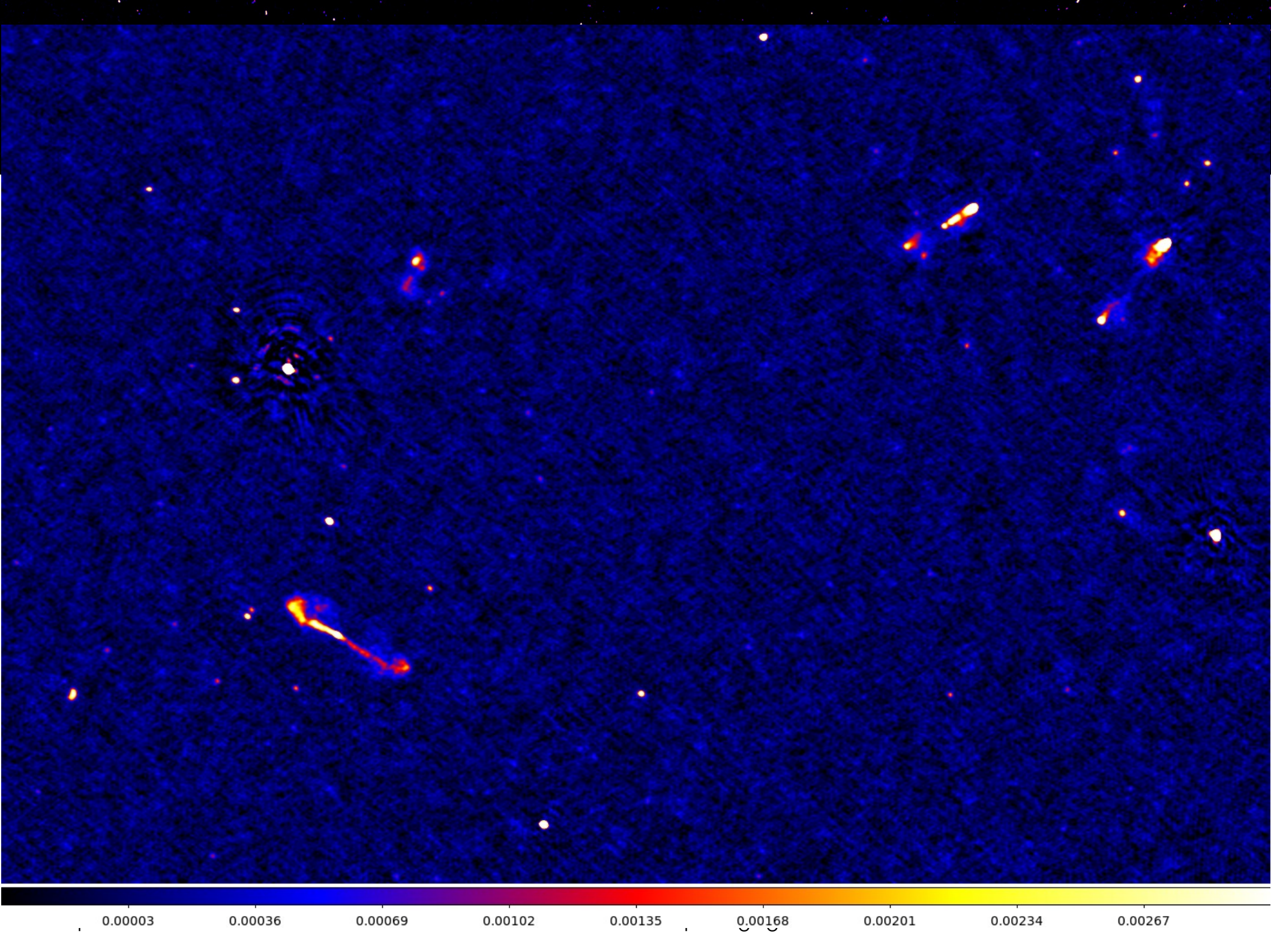


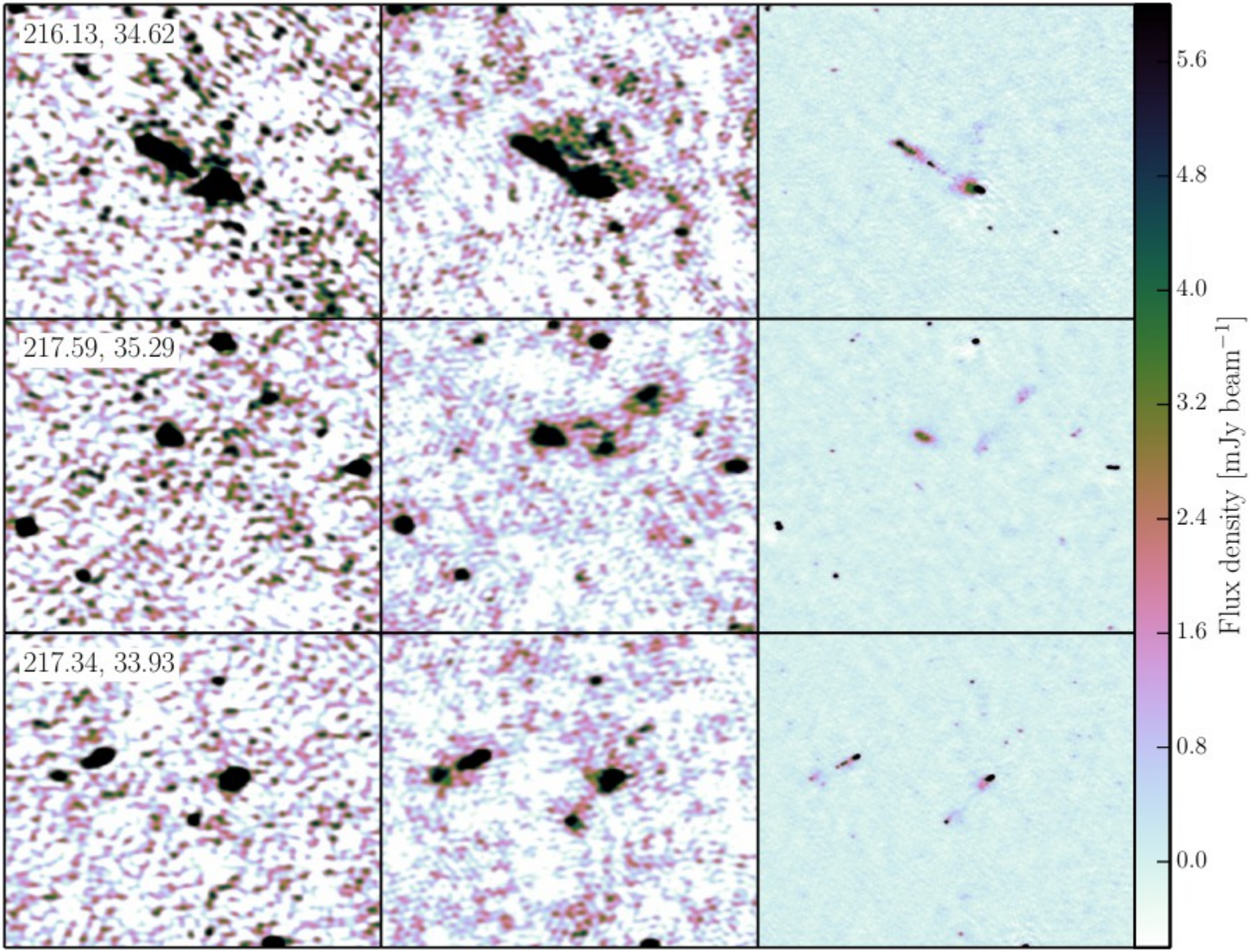
Direction-independant

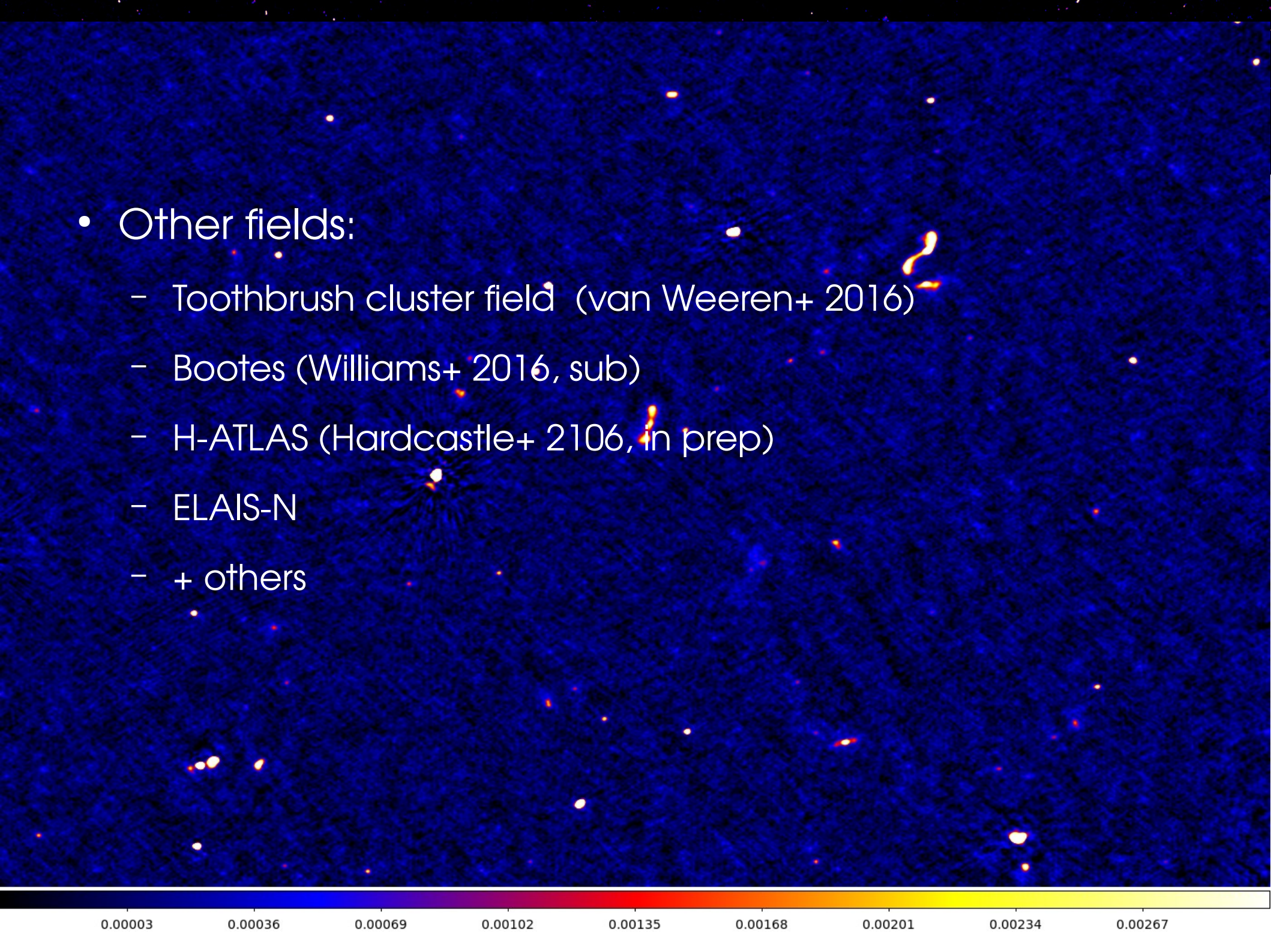
DD corrected



40 MHz
1 channel
200 SB
16k X 16k
Stokes I
5.6" x 7.4"
19 deg^2
120 Jy $beam^{-1}$
6000 sources


0.00003
0.00036
0.00069
0.00102
0.00135
0.00168
0.00201
0.00234
0.00267


216.13, 34.62
217.59, 35.29
217.34, 33.93
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0
Flux density [mJy beam^{-1}]


• Other fields:
– Toothbrush cluster field (van Weeren+ 2016)
– Bootes (Williams+ 2016, sub)
– H-ATLAS (Hardcastle+ 2106, in prep)
– ELAIS-N
– + others
0.00003
0.00036
0.00069
0.00102
0.00135
0.00168
0.00201
0.00234
0.00267

Issues

- Approximate reduction time for a survey pointing on 24 processors, >64GB
  - Staging and downloading – 3 weeks!
    - Due to storing the data at high time/freq resolution for maximum use across survey science cases – incl. long baseline imaging and spectral line studies
  - DI calibration, imaging and subtraction – 1 week
  - DD calibration & imaging – 3 weeks
    - Use of newer algorithms – will yield factor ~4 improvements
- Are we still dynamic range limited?

Next steps

- Go wide…
  - FACTOR (https://github.com/lofar-astron/factor)
    - ASTRON pipeline version of facet calibration
    - From single fields to routinely producing 'science-ready' images
    - Also making it easier for 'new' LOFAR users to get their science out
- Go deeper…
  - Advanced calibration (Cyril Tasse)
    - Wirtinger-Kalman filters
    - Joint deconvolution