The LOFAR Two Meter Sky Survey(s), algorithms and science

LoTSS wide, deep, and ultra-deep

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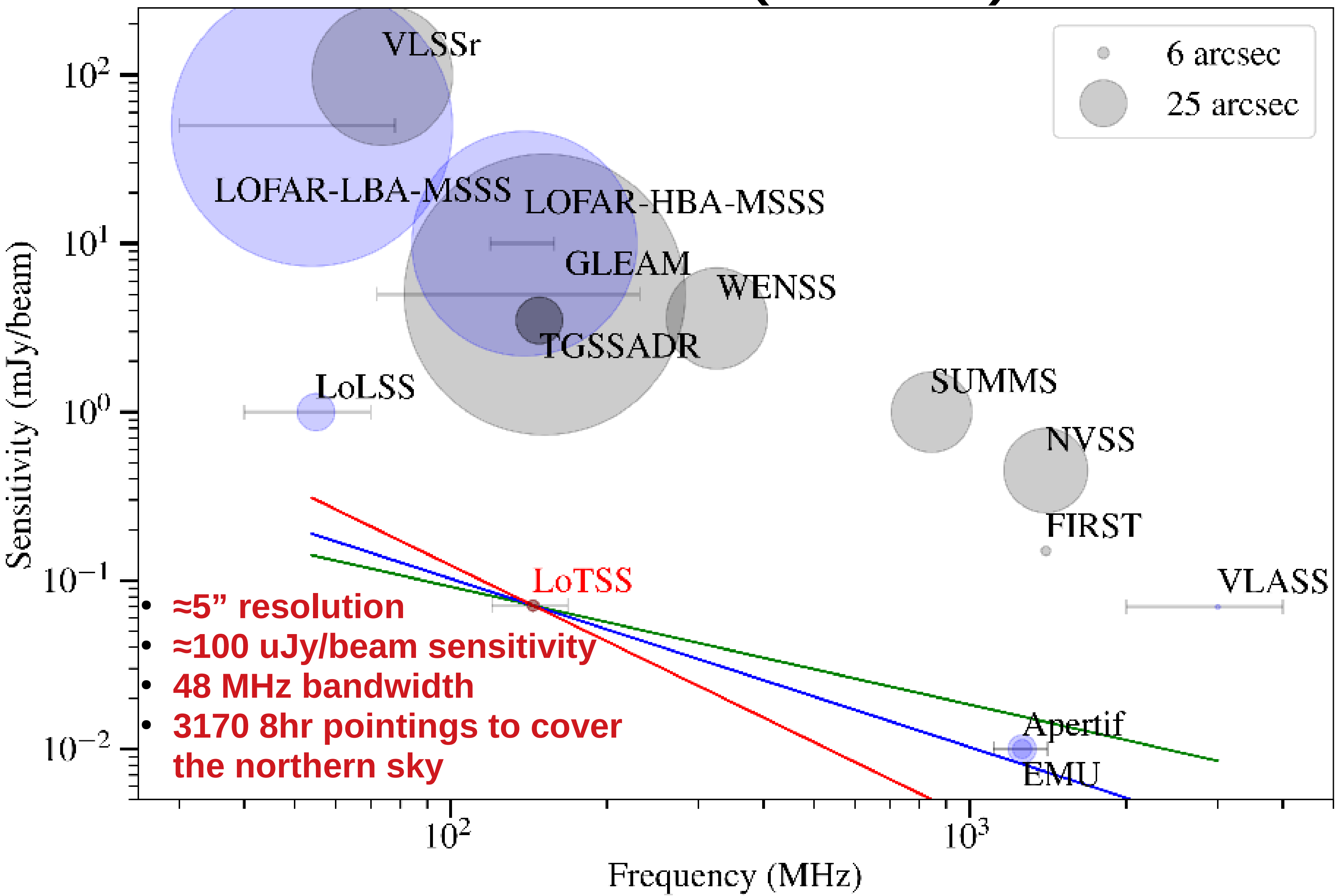
Observatoire de Paris – GEPI/USN

Rhodes University

for the LOFAR Surveys KSP

The LOFAR Two-meter Sky Survey : LOTSS (Tier-1)



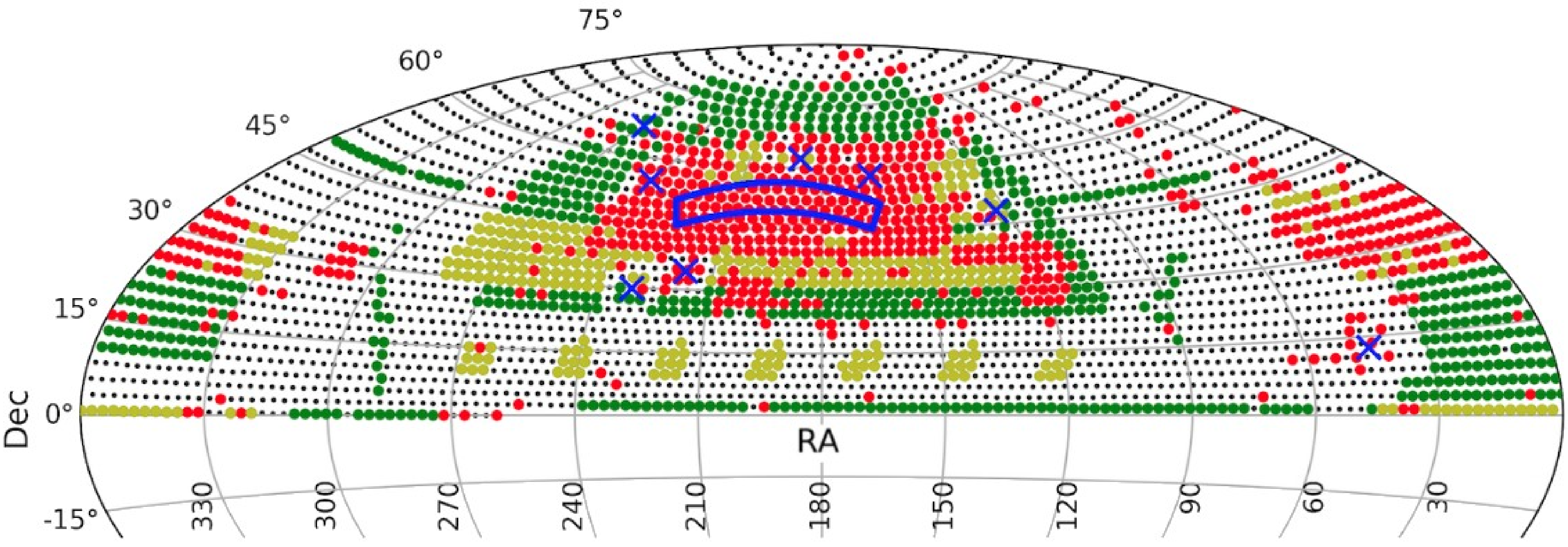
- ≈5" resolution
- ≈100 uJy/beam sensitivity
- 48 MHz bandwidth
- 3170 8hr pointings to cover the northern sky

LOTSS : LOFAR Two-meter Sky Survey

20% of the northern sky is observed.

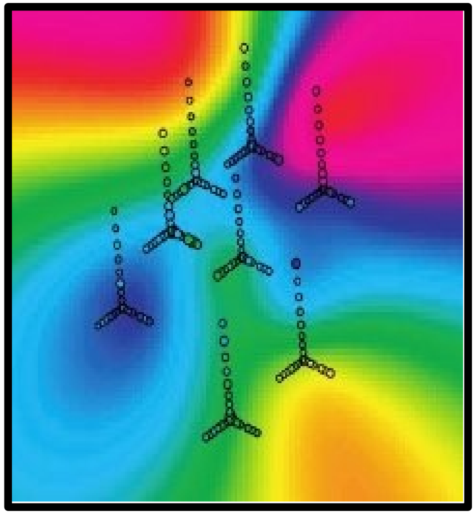
50% of the observed data is partially processed.

Allocated 3750 hrs of observations to reach 50% completeness in 2 years

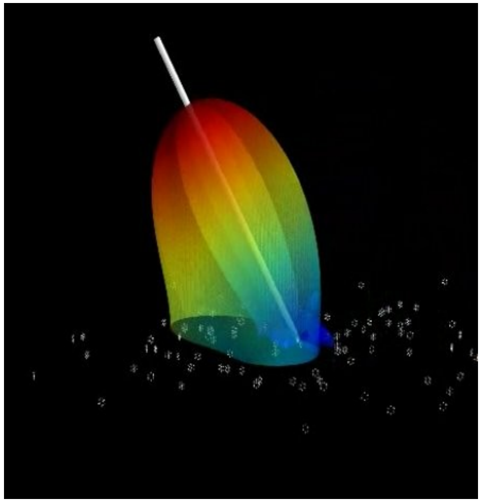


Red observed, yellow observed in next 6 months, green observed in next 2 years.

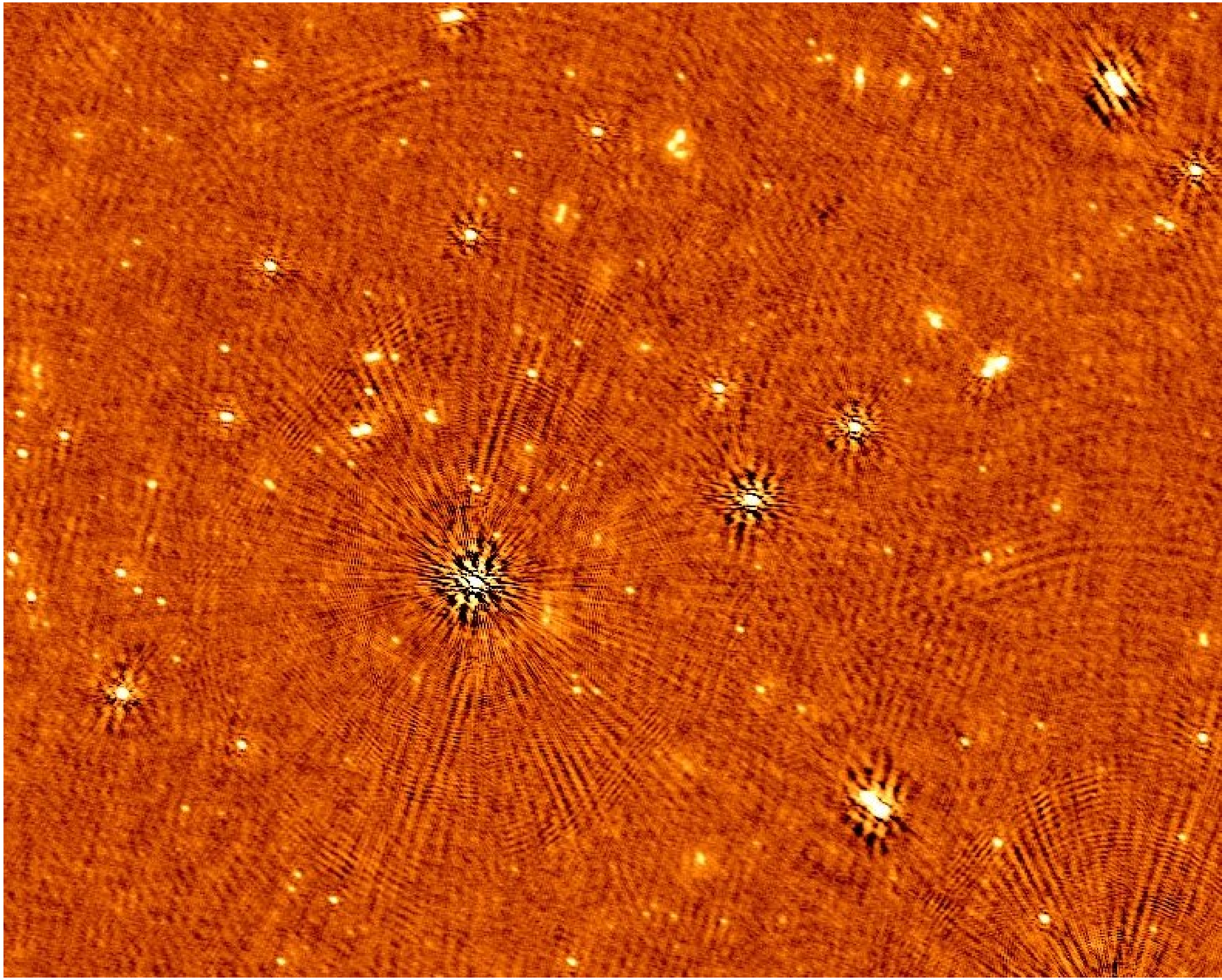
The best image you can ever get in selfcal



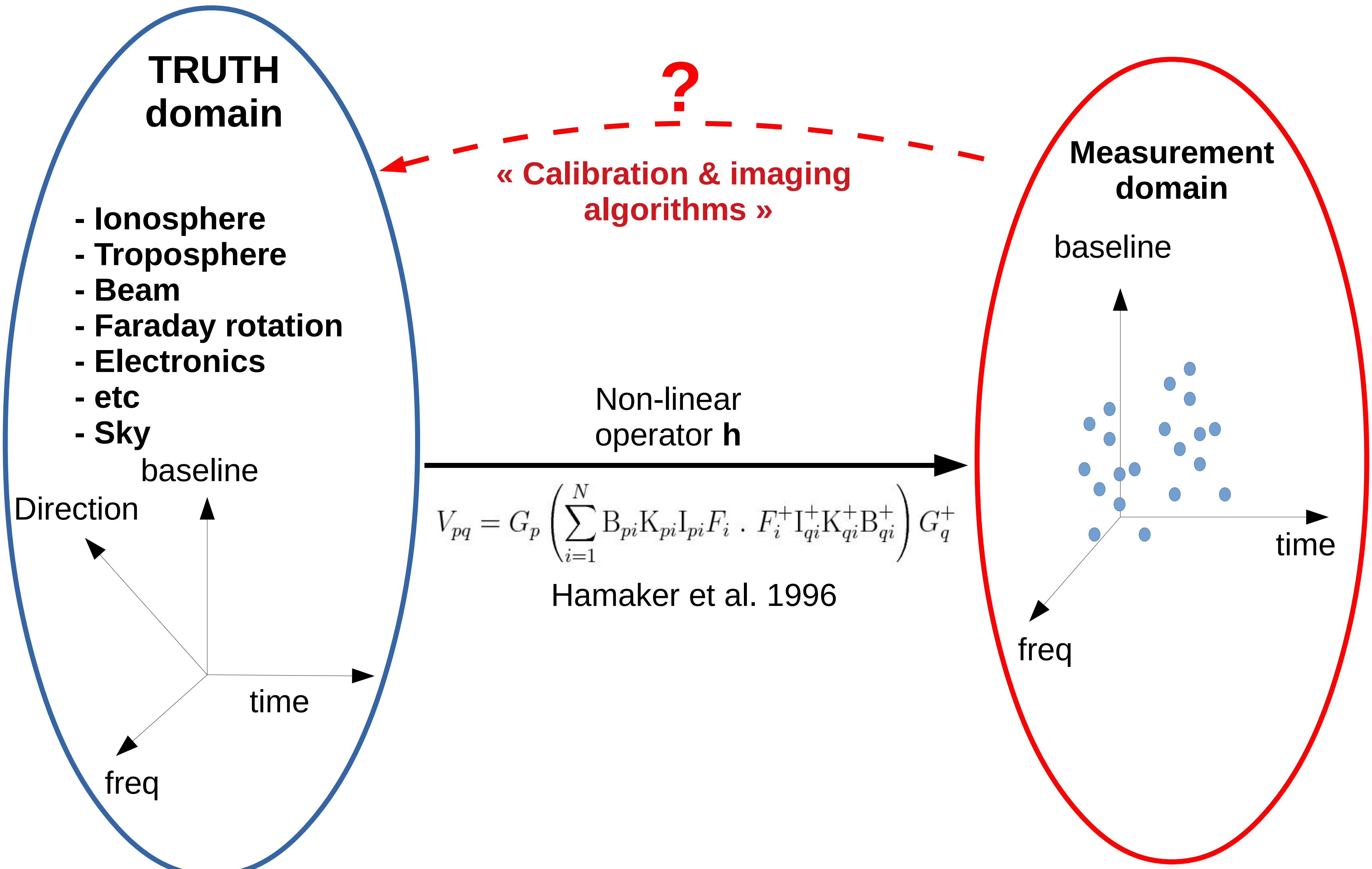
Ionospheric disturbance + Faraday rotation



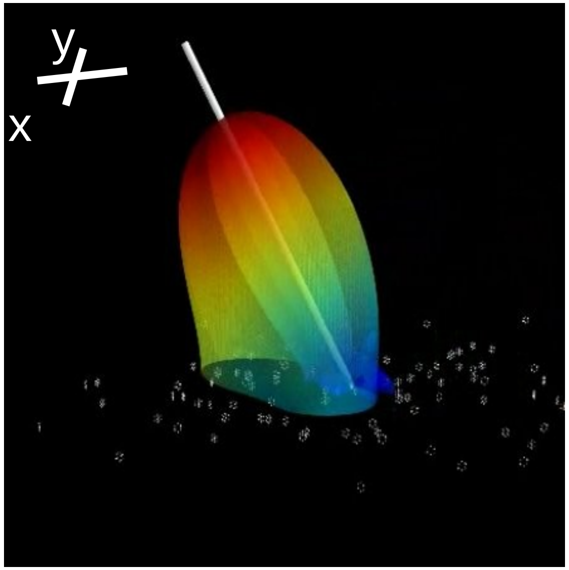
Station lobes

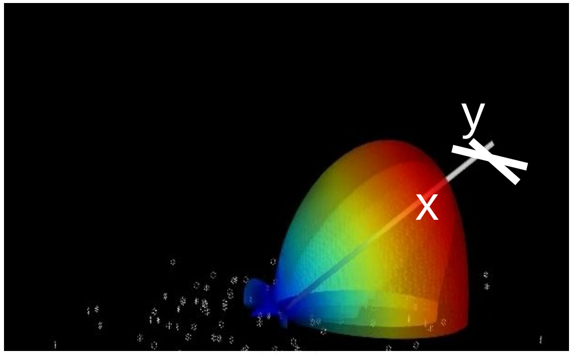


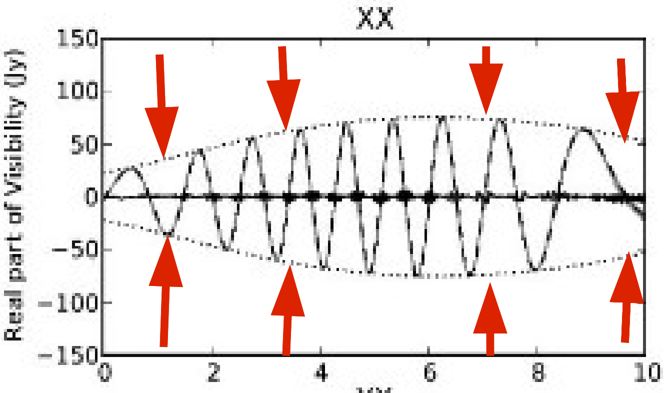
Interferometry



… When Direction Dependent Effects (DDE) become a problem : Beam







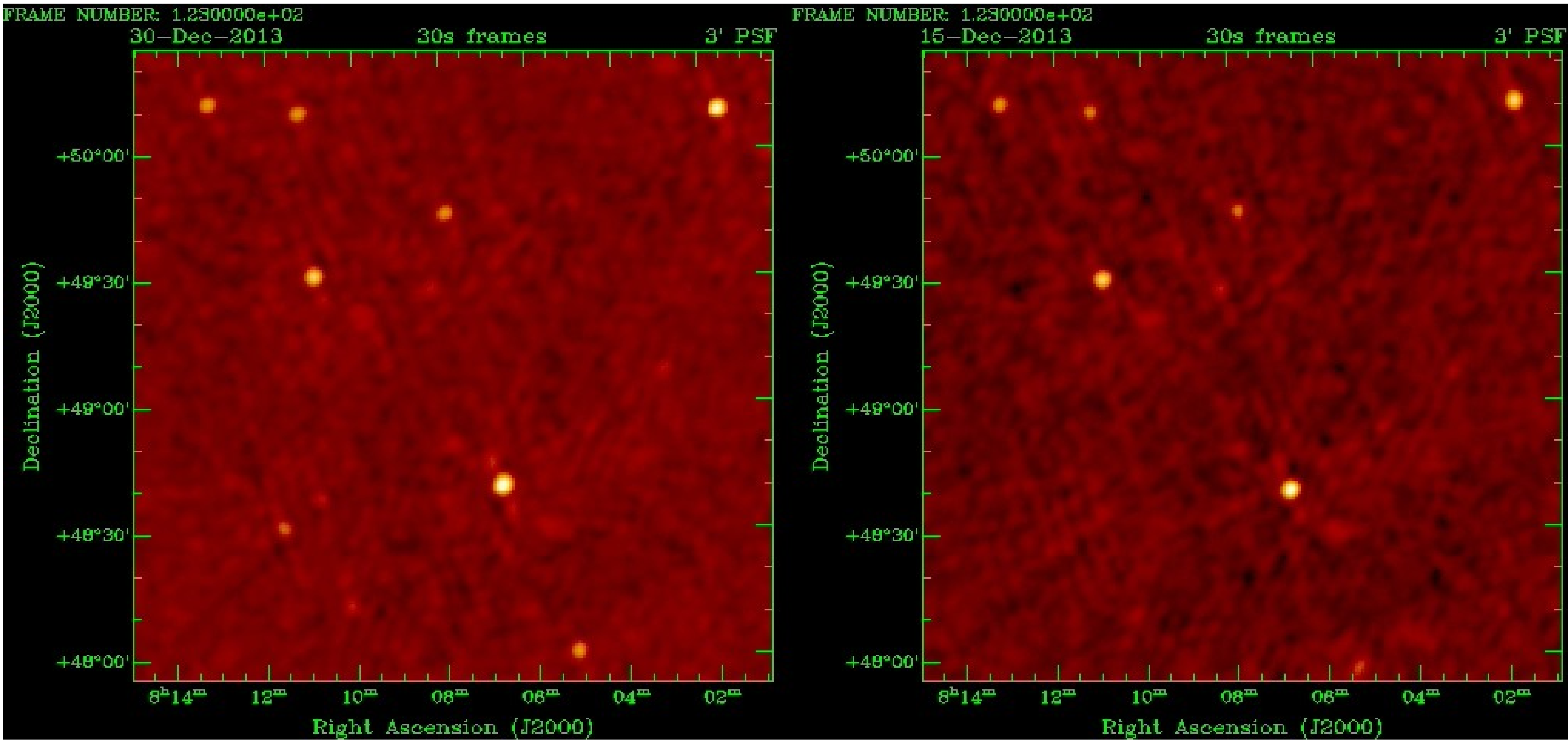
LOFAR stations are phased arrays

- Beam is variable in frequency and time
- Projection of the dipoles in the sky is non trivial
- Beam can be station-dependent
- Individual clock effects

--> Strong effects on polarisation

Ionosphere

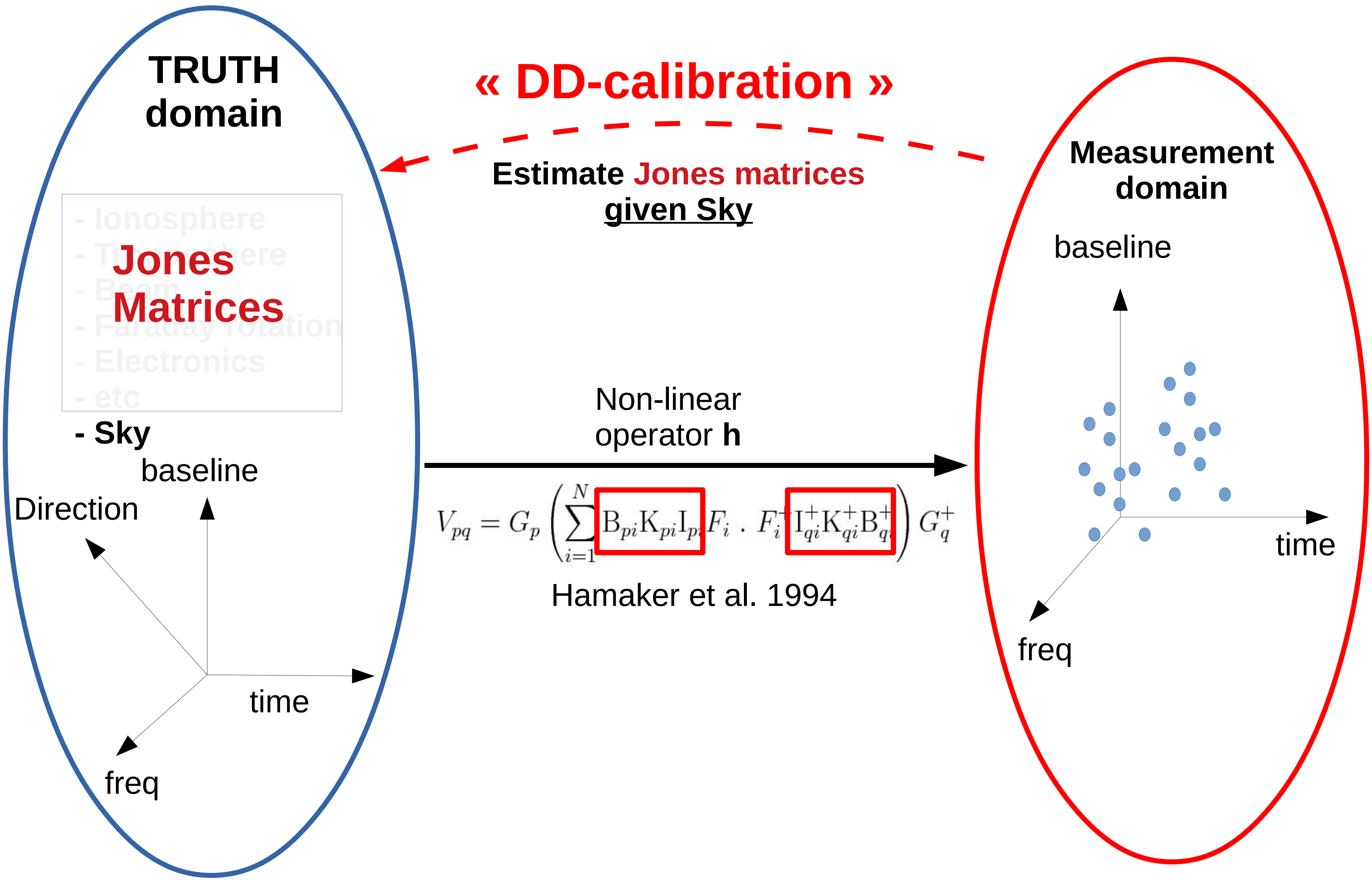
Good ionosphere **Bad ionosphere**



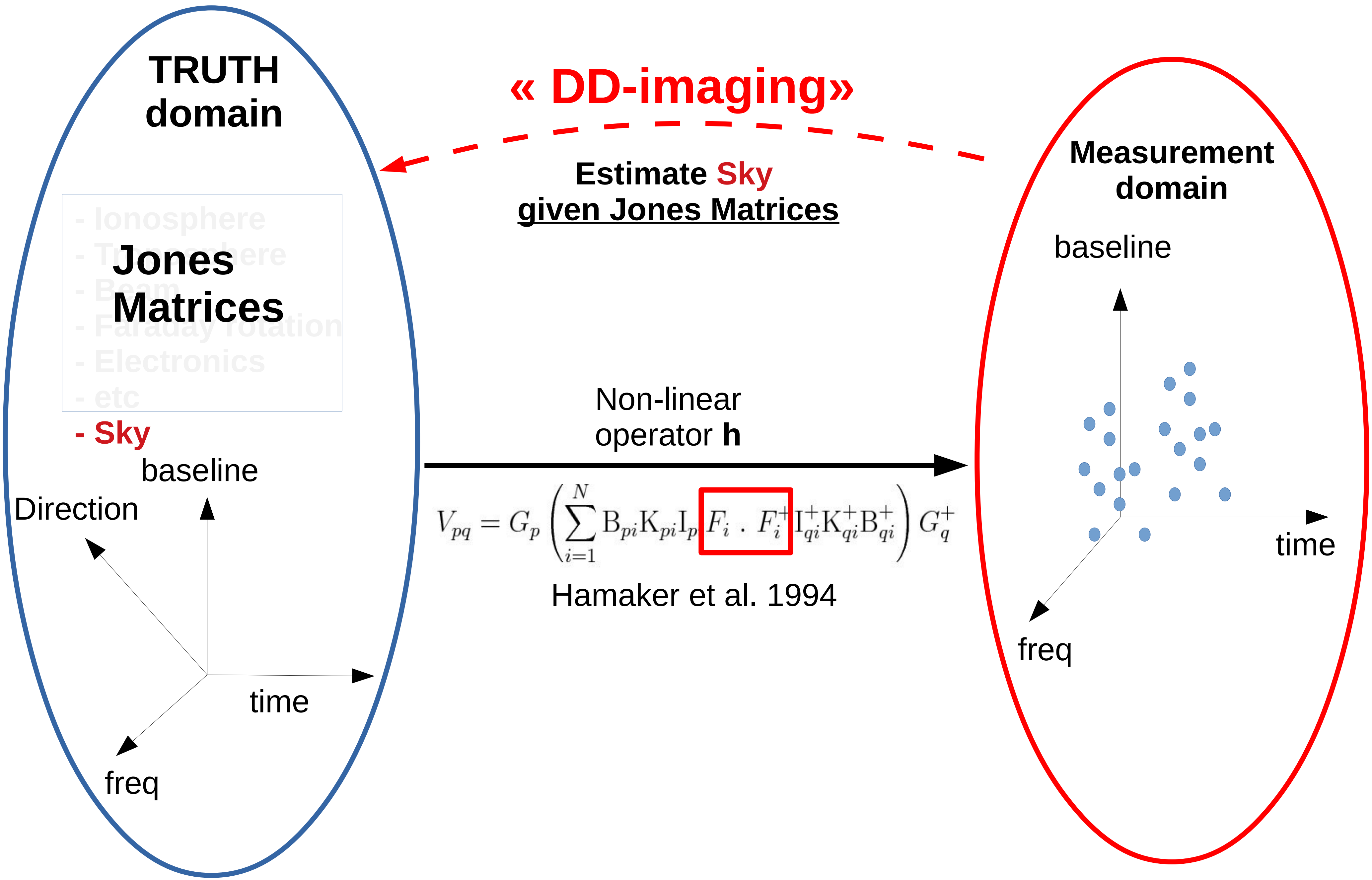
Images have 3 arcmin resolution

Ger de Bruyn & LOFAR EoR team

Interferometry

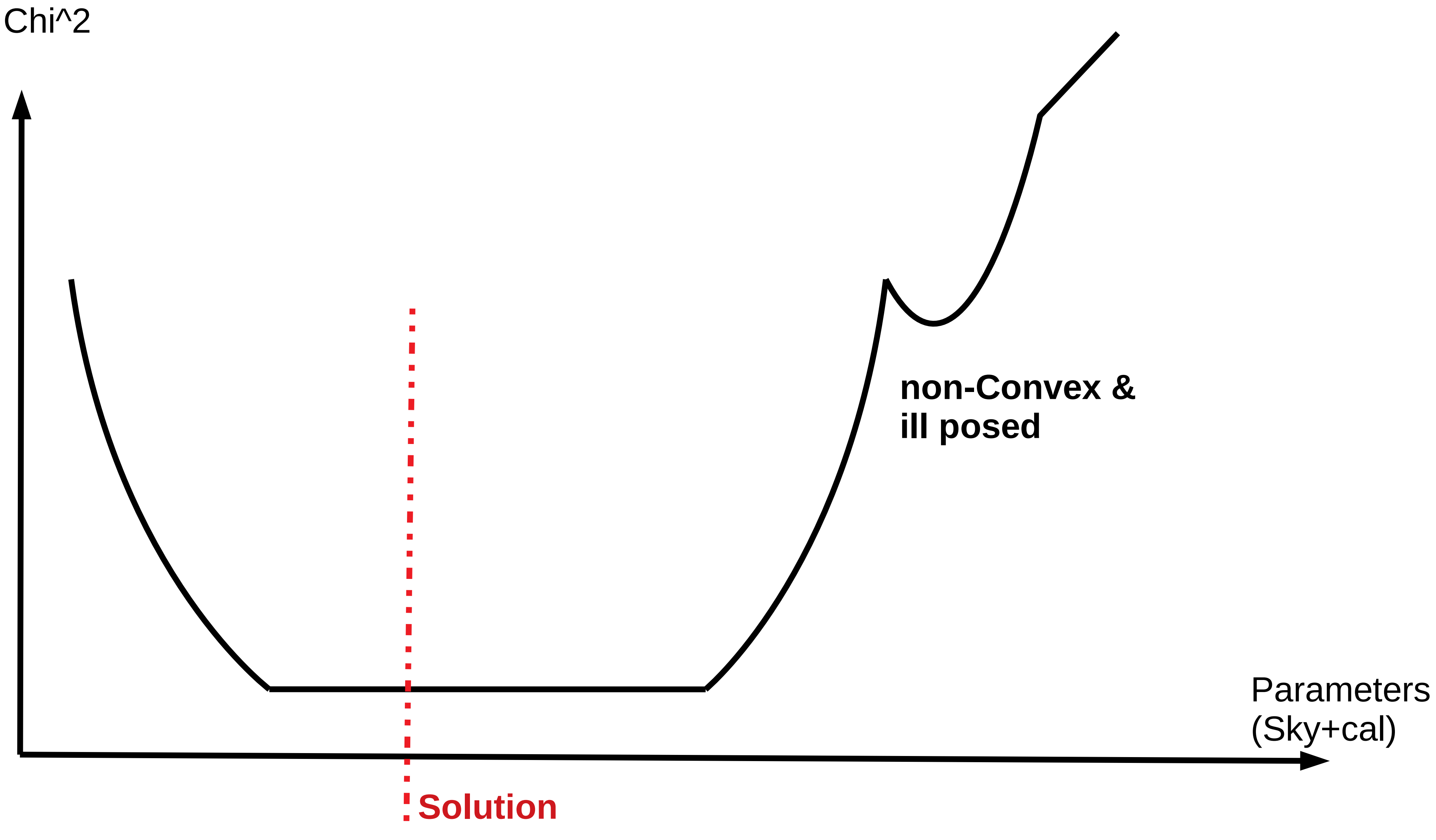


Interferometry

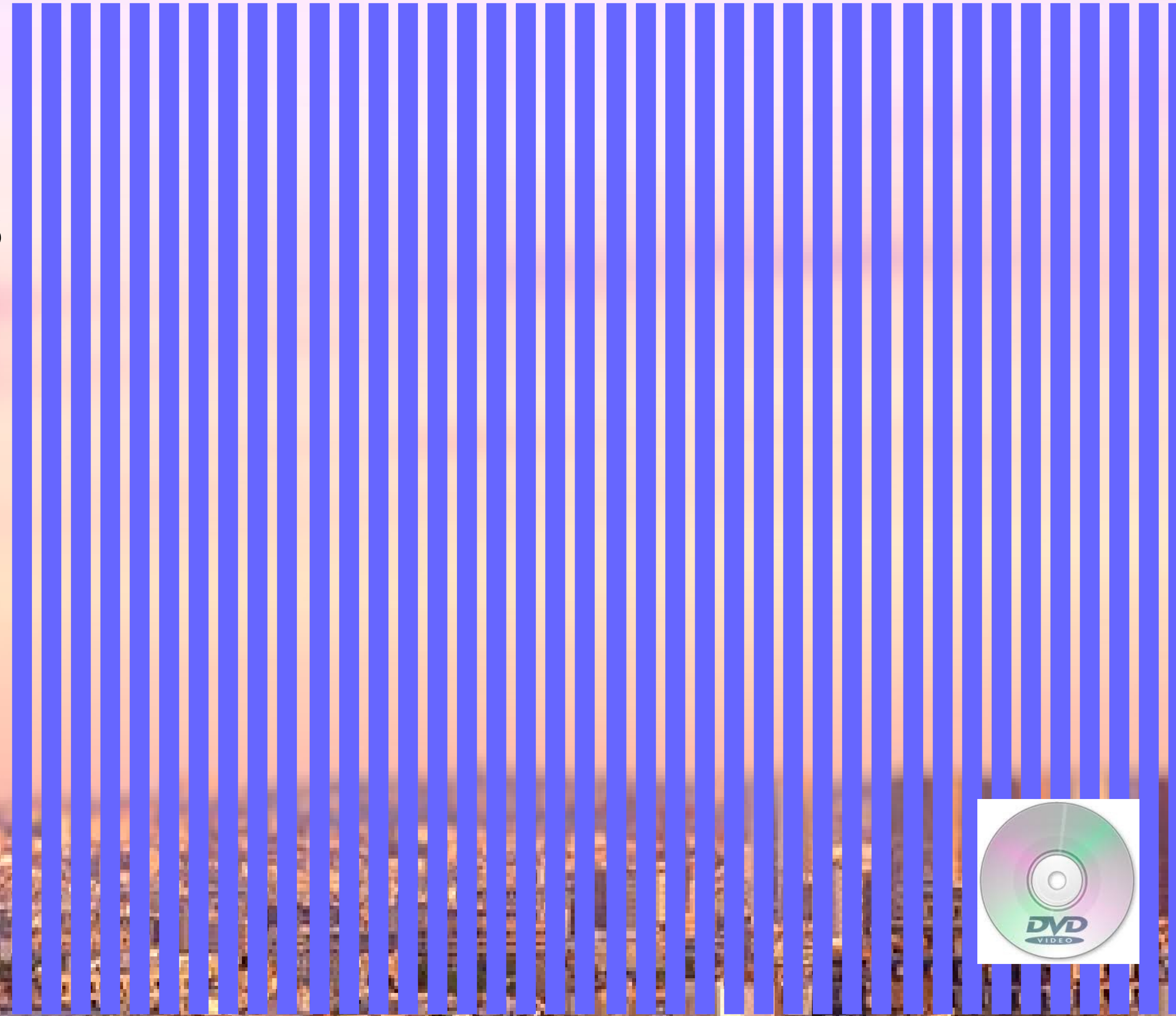


$$V_{pq} = G_p \left(\sum_{i=1}^{N} \mathrm{B}_{pi}\mathrm{K}_{pi}\mathrm{I}_{p} F_i \;.\; F_i^{+} \mathrm{I}_{qi}^{+}\mathrm{K}_{qi}^{+}\mathrm{B}_{qi}^{+} \right) G_q^{+}$$

First issue : Convexity, Conditionning



2nd issue : Data Volumes



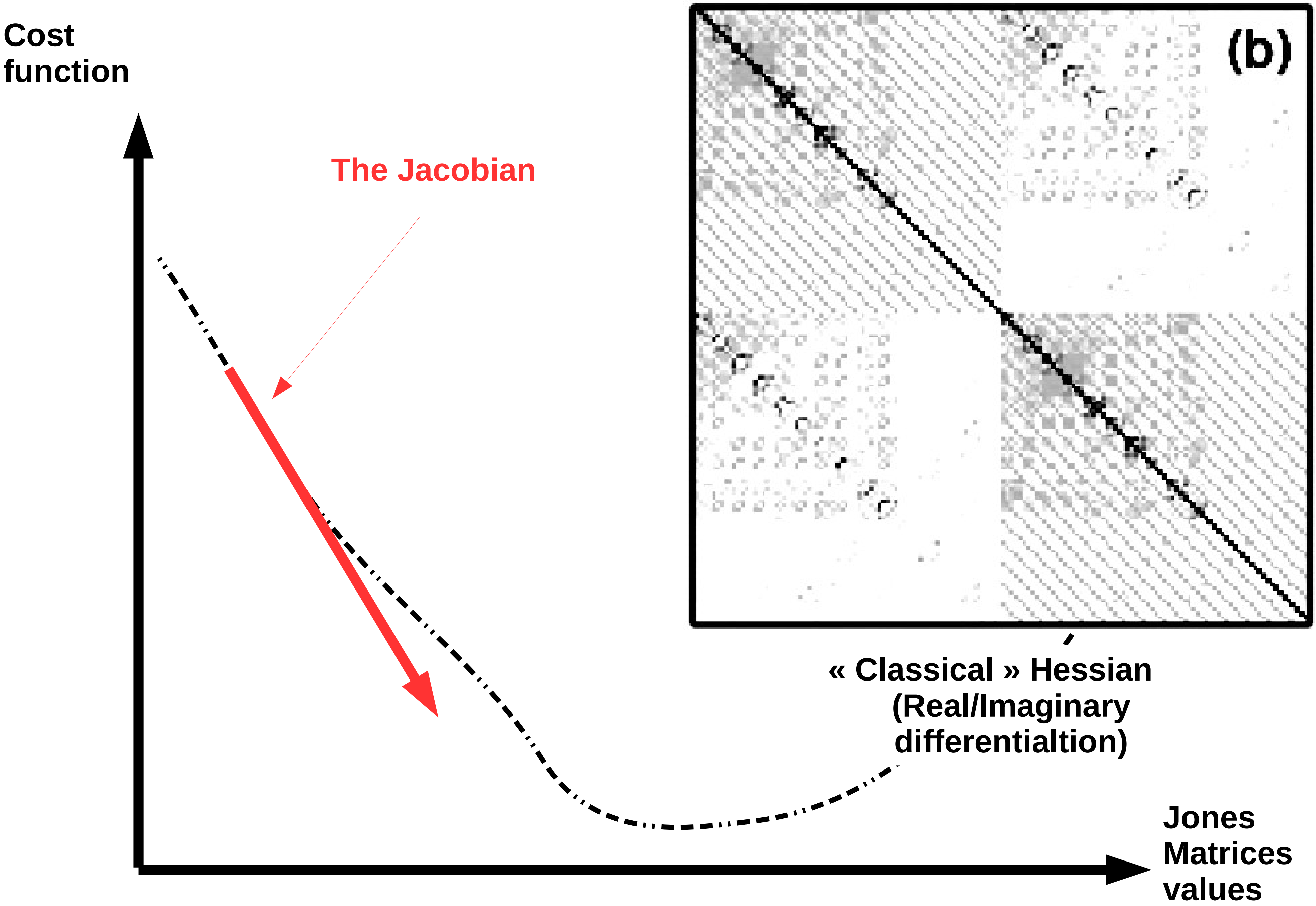
Tier-1 LOFAR Survey : to be observed
48 Pbytes of Raw data → ~39Eiffel towel size dvd stacks

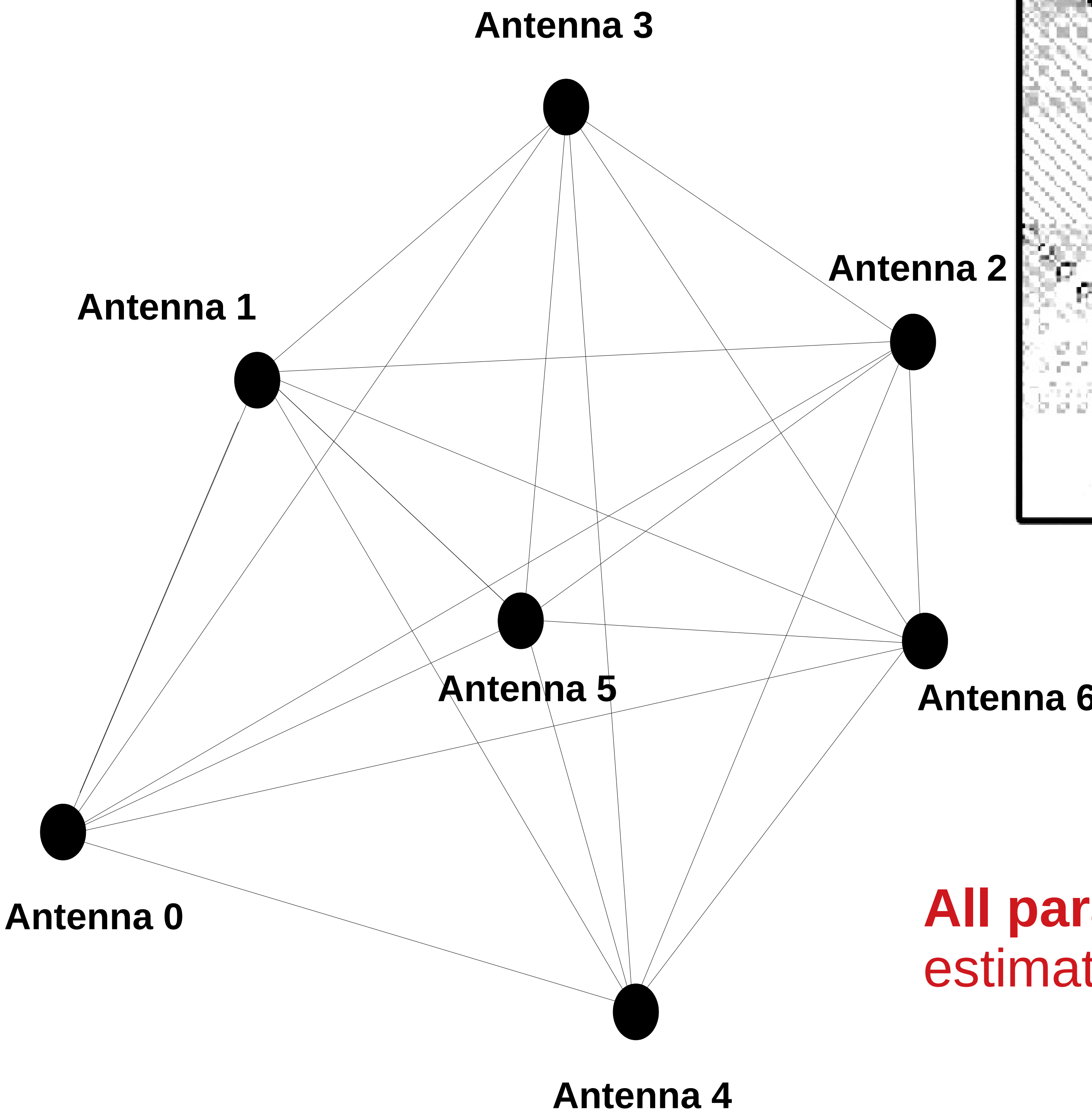
Third issue : software

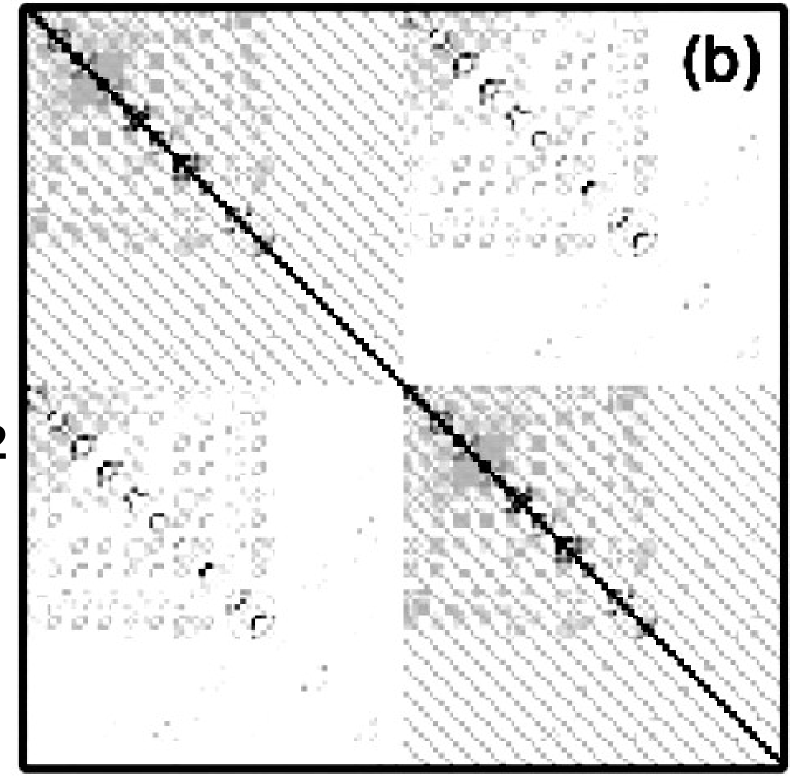
No existing software implementing

(i) generic piecewise constant,
(ii) DD-simultaneous,
(iii) full Jones,
(iv) (Cal+Im) RIME solving

RIME Calibration







« Classical » Hessian (Real/Imaginary differentialtion)

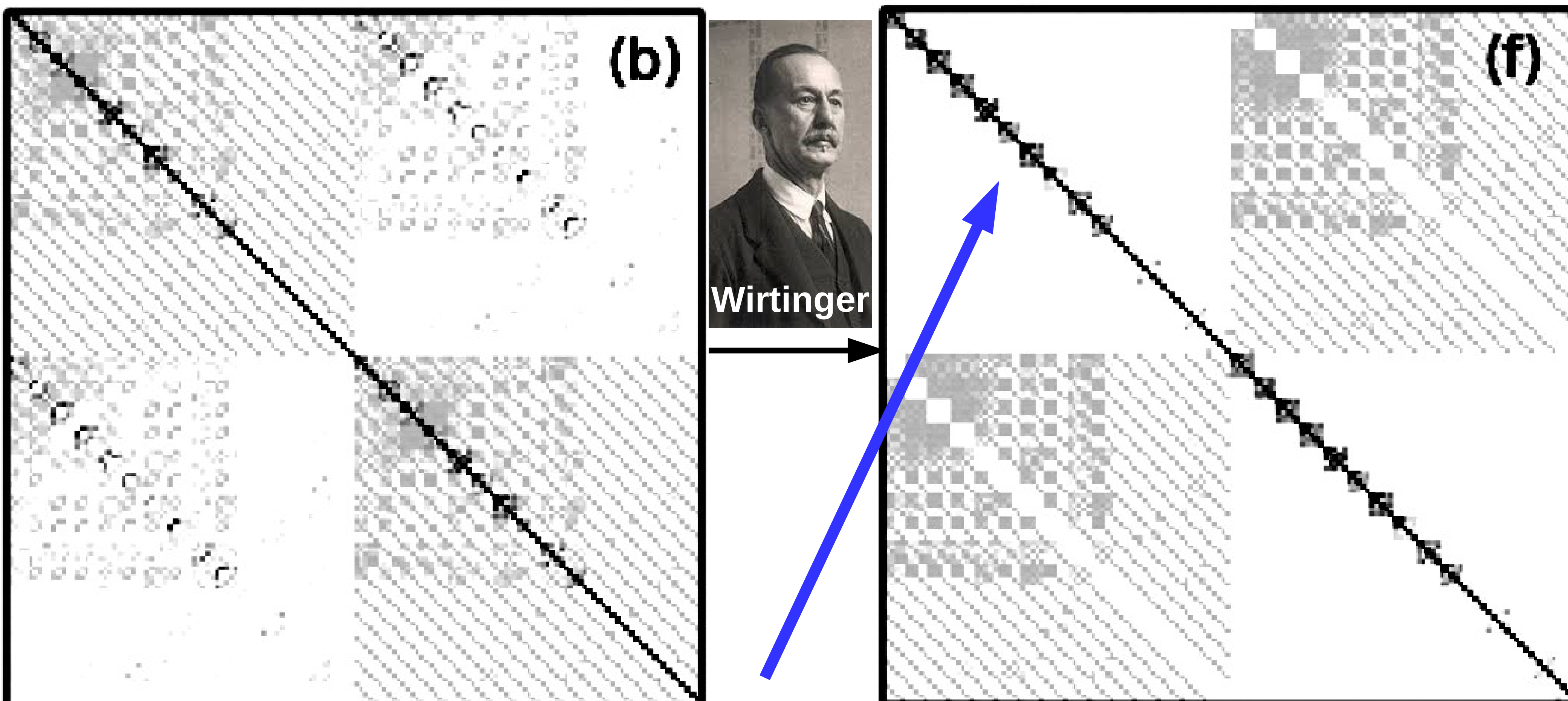
All parameters have to be estimated using **all data**

Complex Optimisation: Jacobian & Hessian

(Read Tasse 2014, Smirnov & Tasse 2015)

Wirtinger derivative definition « reorganises » the process and data : the Jacobian and Hessian become sparse and compact

$$\frac{\partial \overline{z}}{\partial z} = 0 \text{ and } \frac{\partial z}{\partial \overline{z}} = 0$$

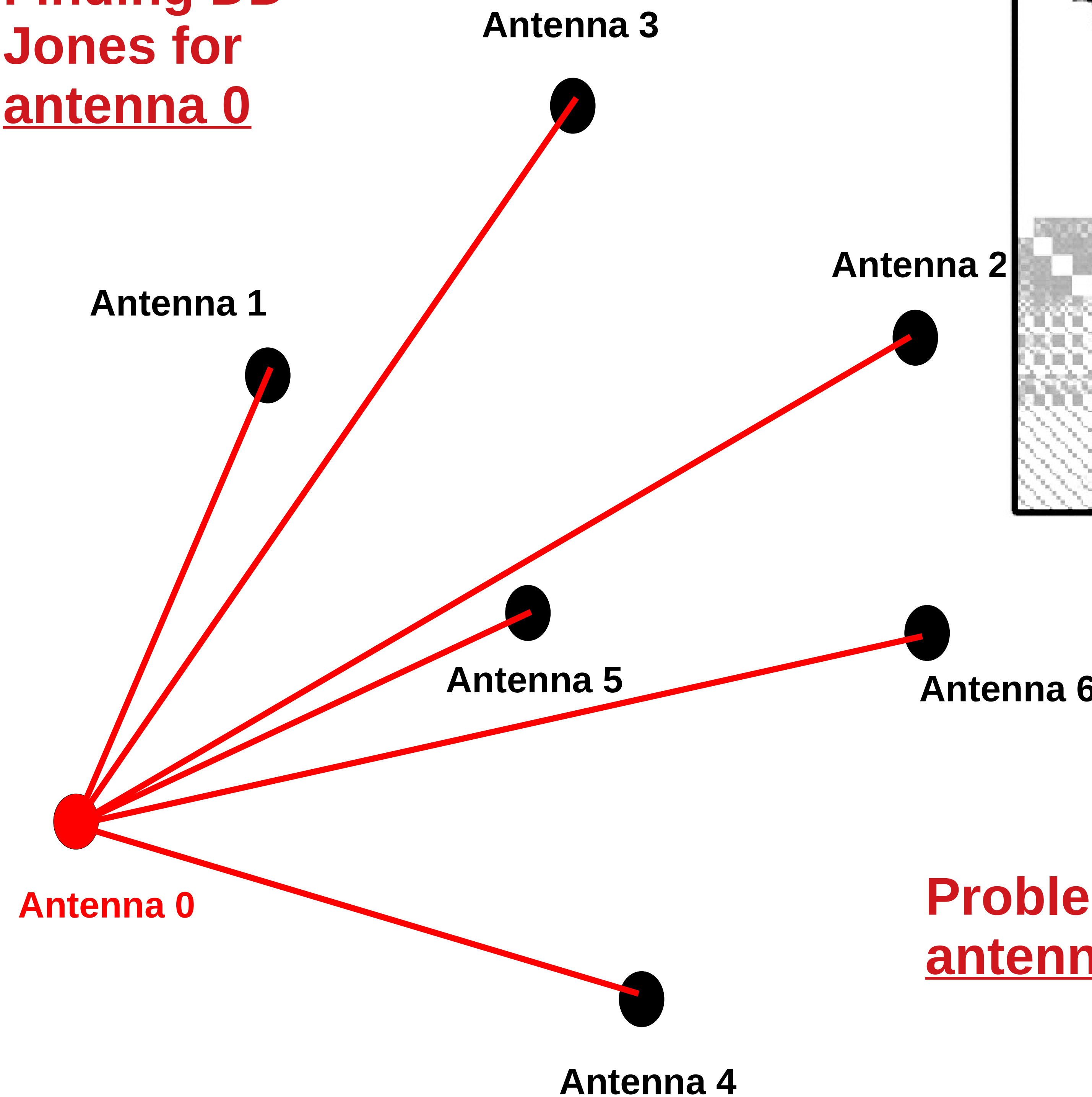


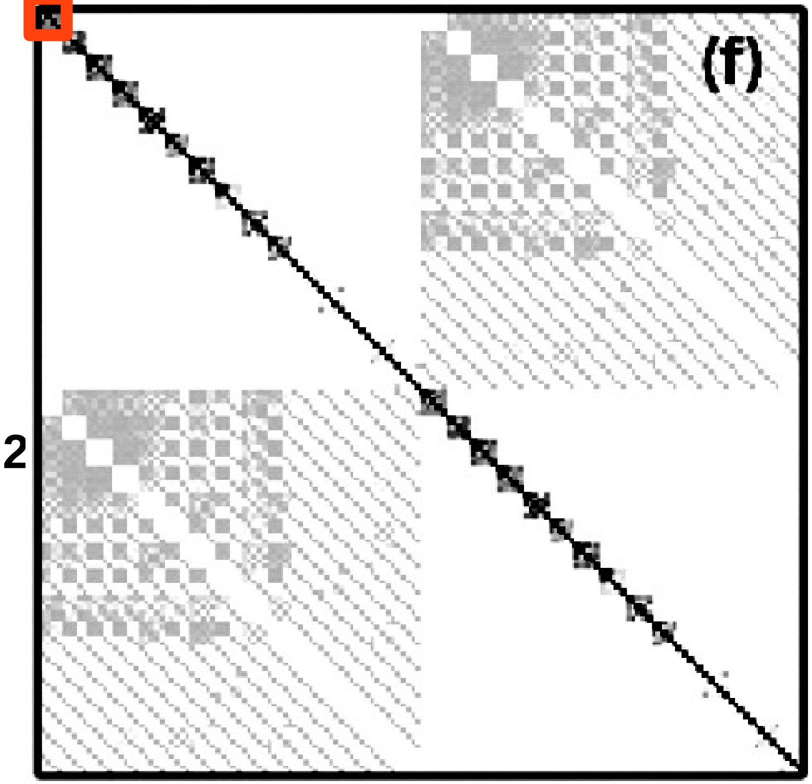
« Classical » Hessian

Those Blocks are (Nd x Nd)

Wirtinger Hessian

Finding DD-Jones for antenna 0



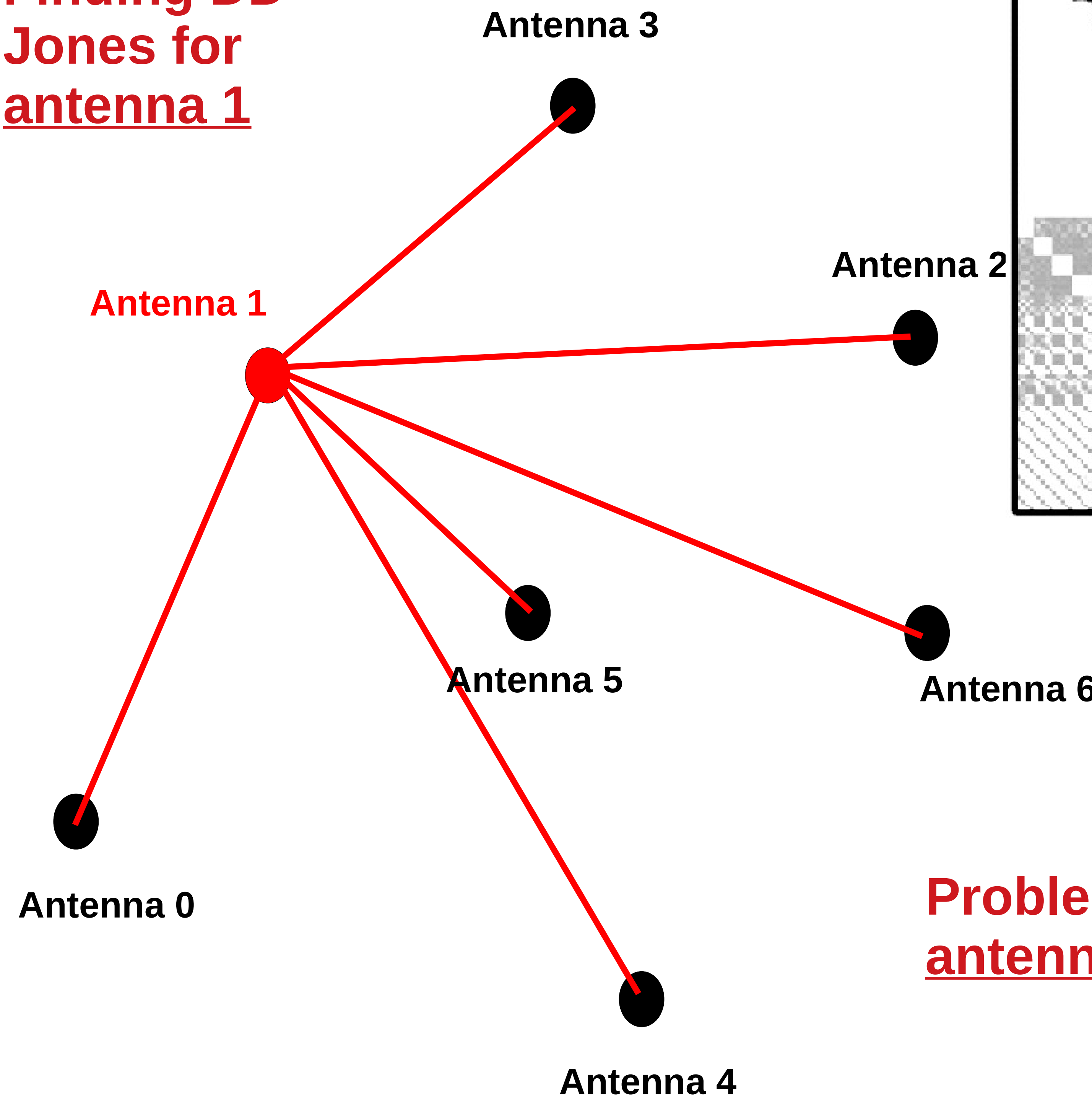


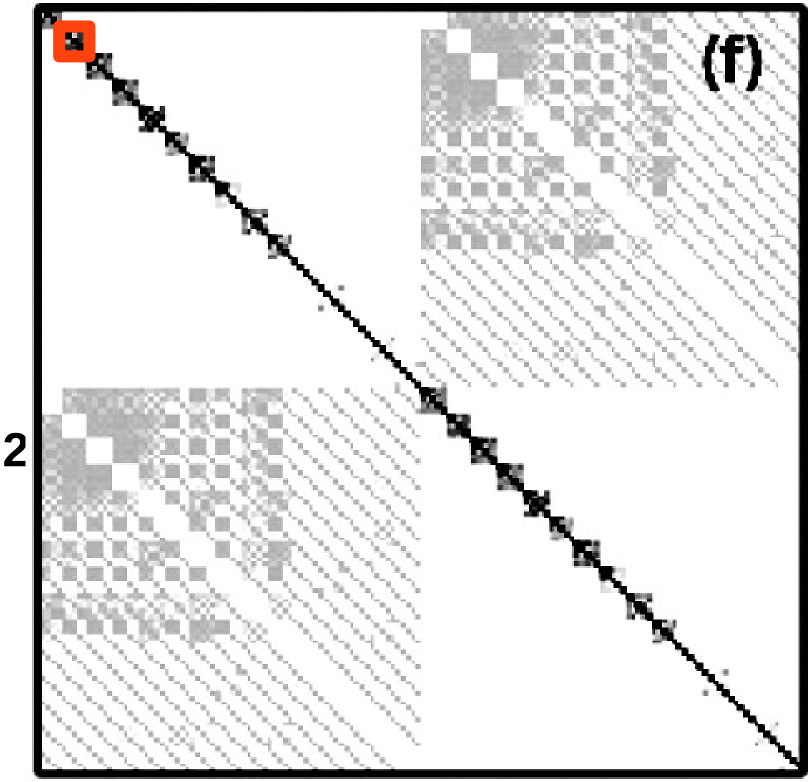
Wirtinger Hessian

(Tasse 2014,
Smirnov & Tasse 2015,
Repetti et al. 2017 *)*

Problem becomes antenna separable

Finding DD-Jones for antenna 1



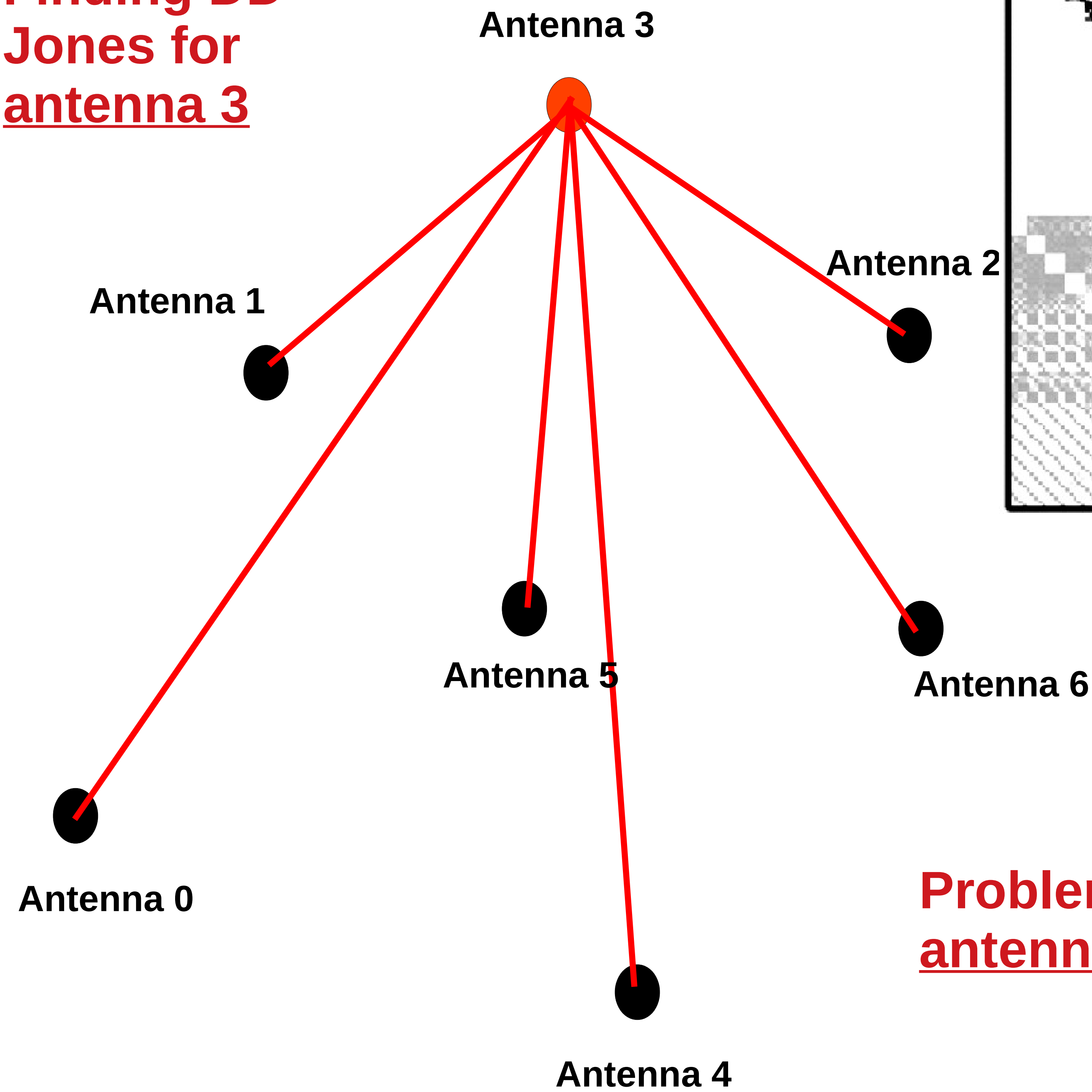


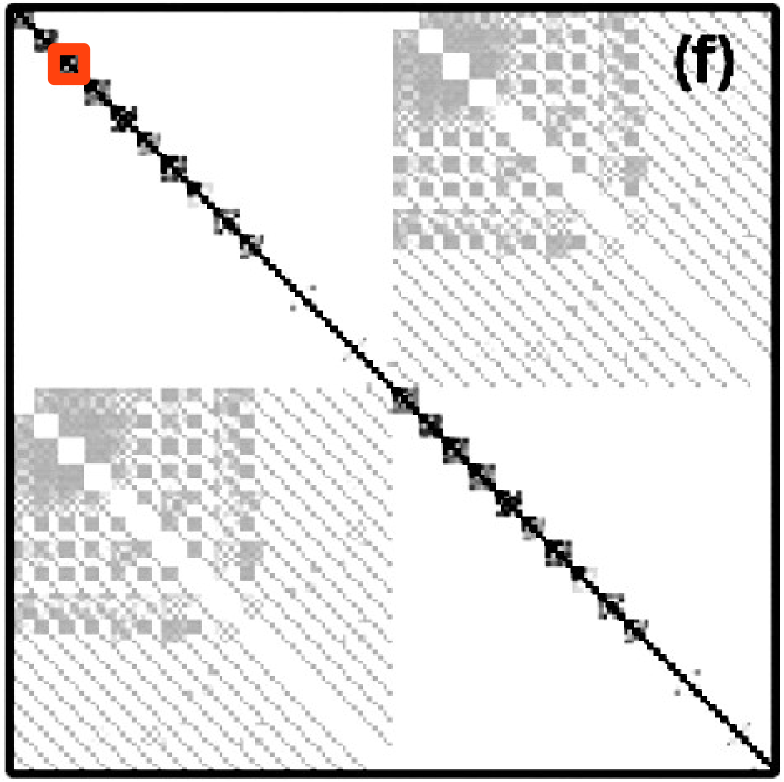
Wirtinger Hessian

(Tasse 2014, Smirnov & Tasse 2015, Repetti et al. 2017 *)*

Problem becomes antenna separable

Finding DD-Jones for <u>antenna 3</u>

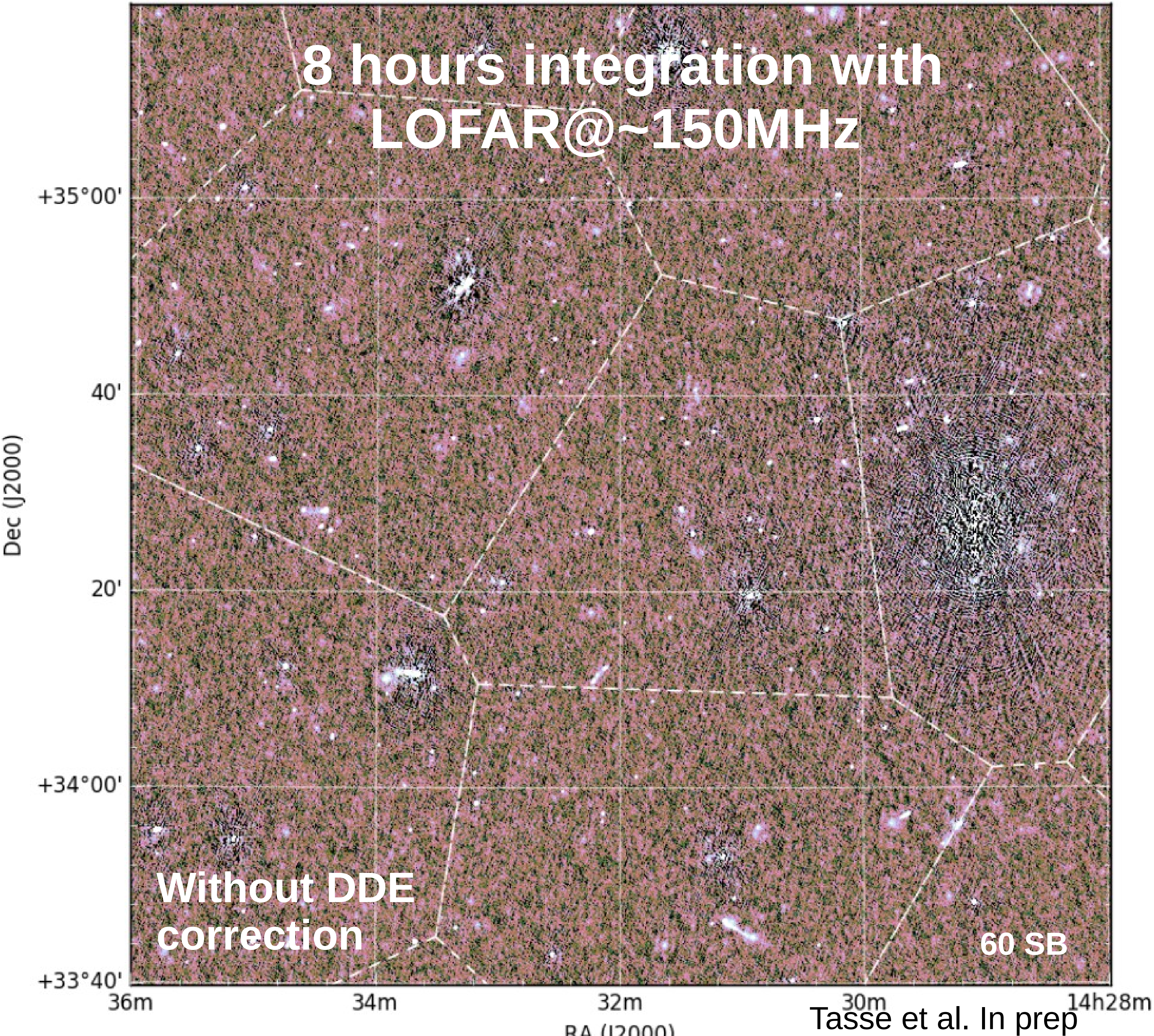




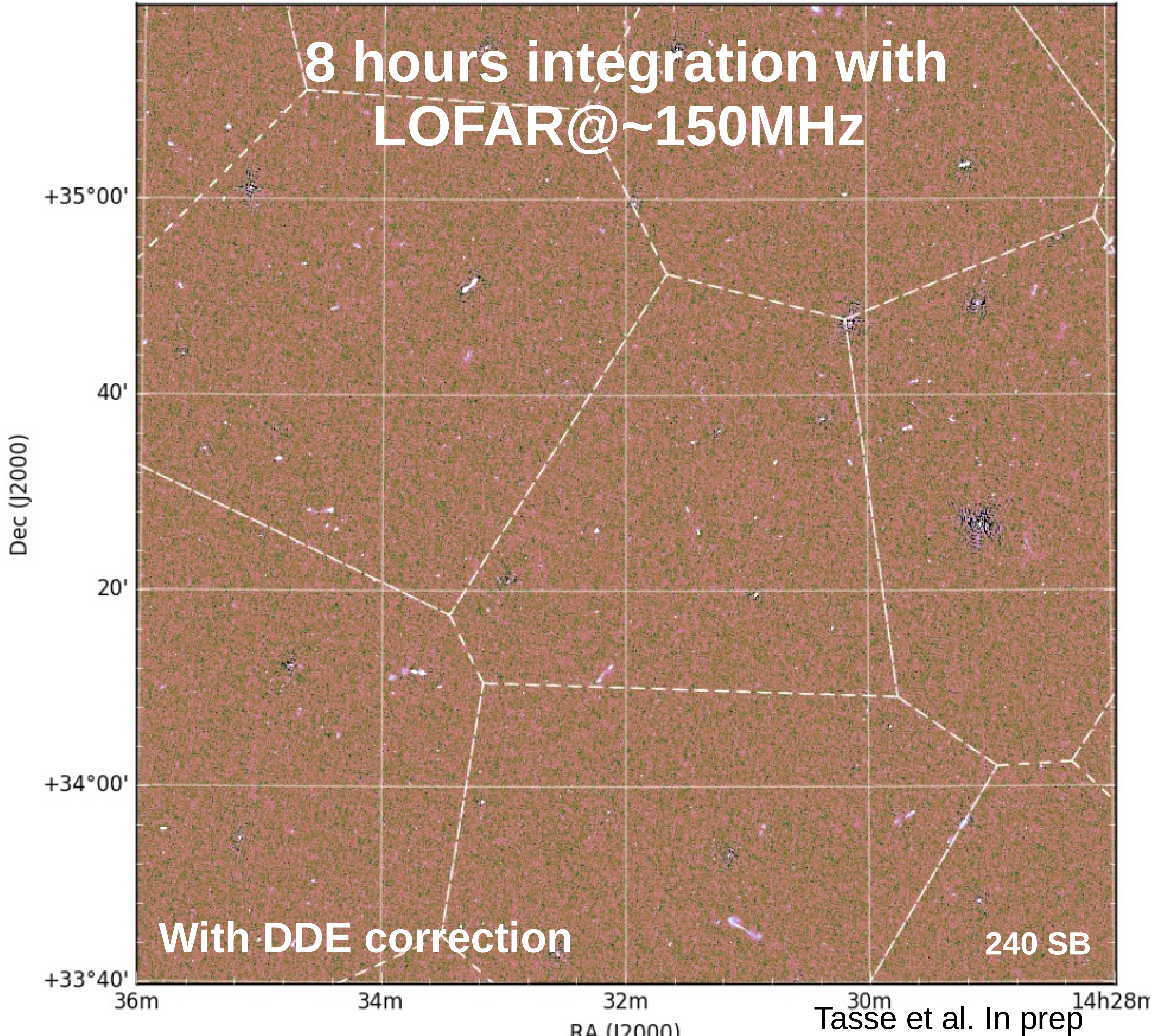
Wirtinger Hessian

(Tasse 2014,
Smirnov & Tasse 2015,
Repetti et al. 2017 *)*

Problem becomes <u>antenna separable</u>

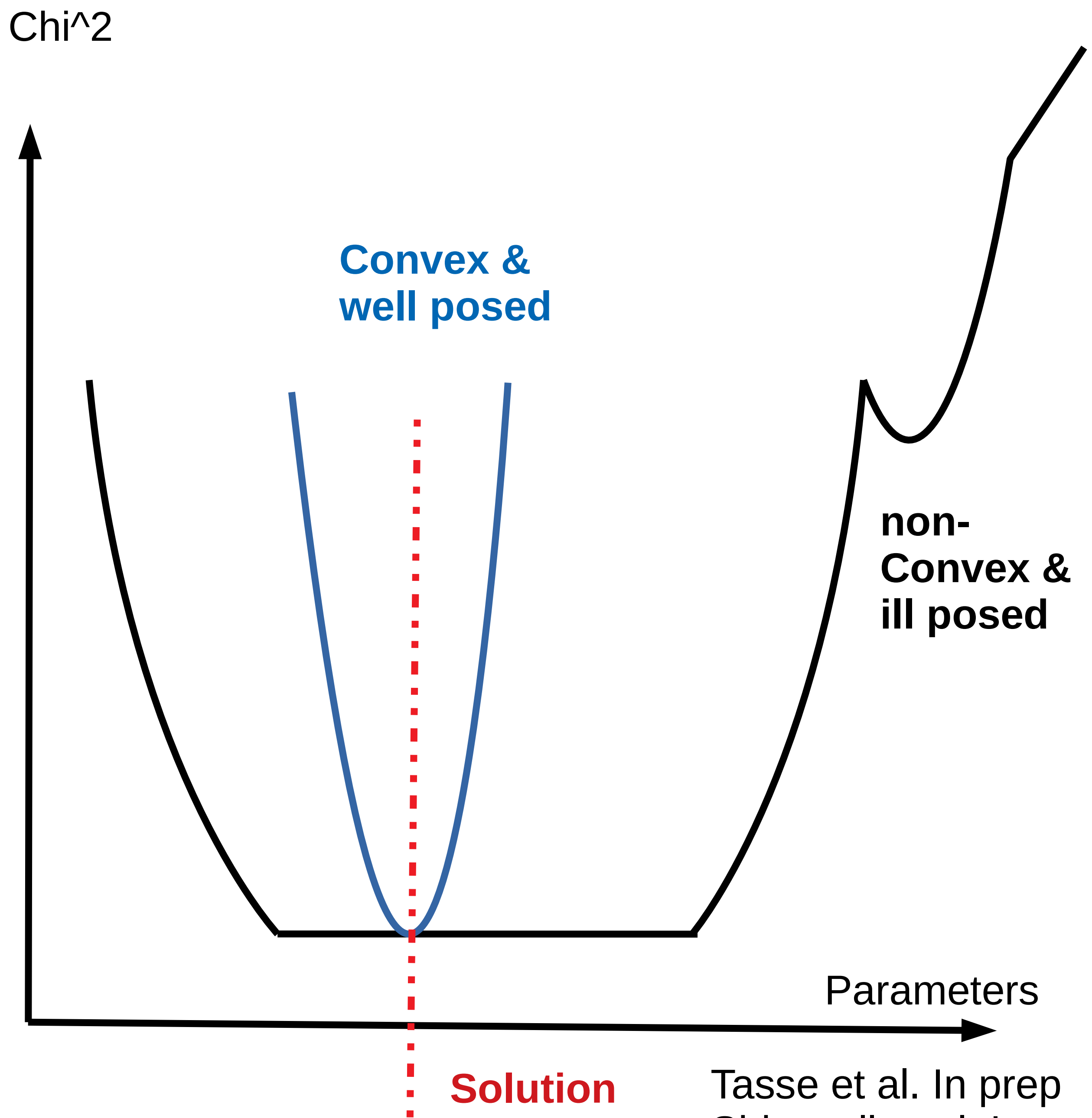


Tasse et al. In prep

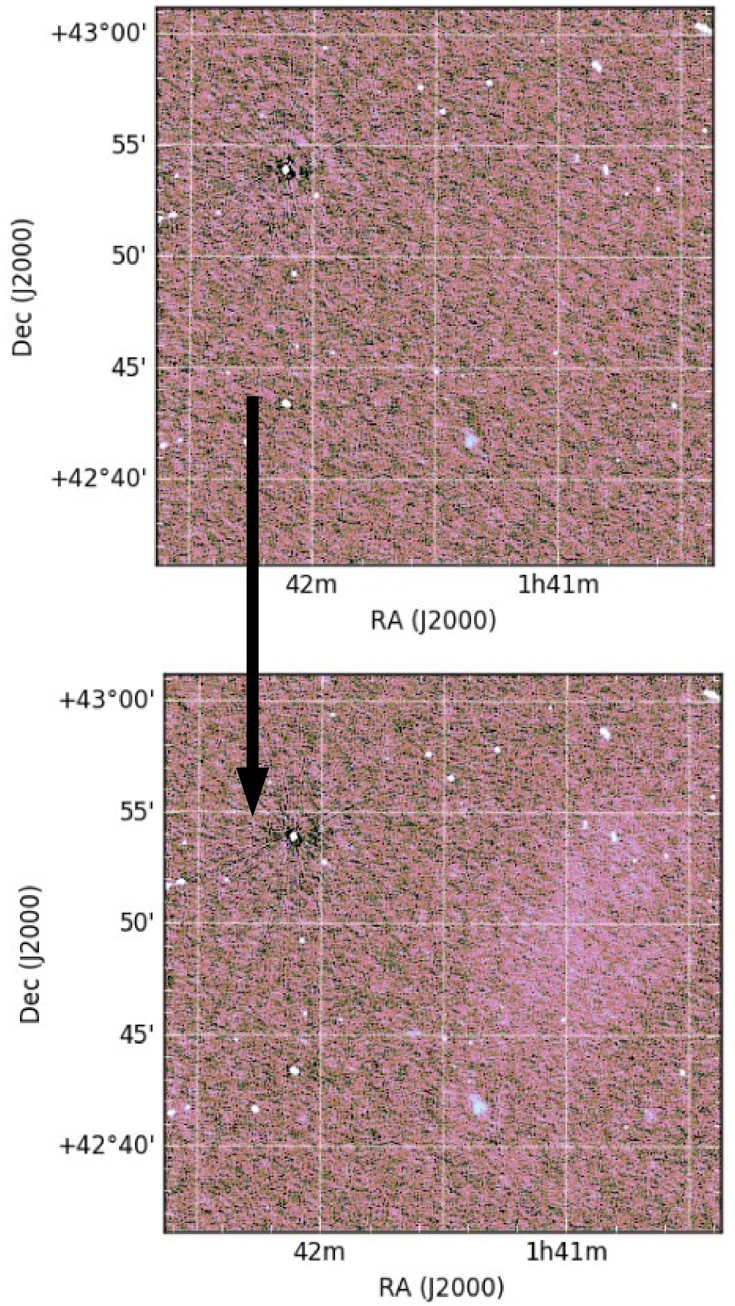


Tasse et al. In prep

Convexity, Conditionning

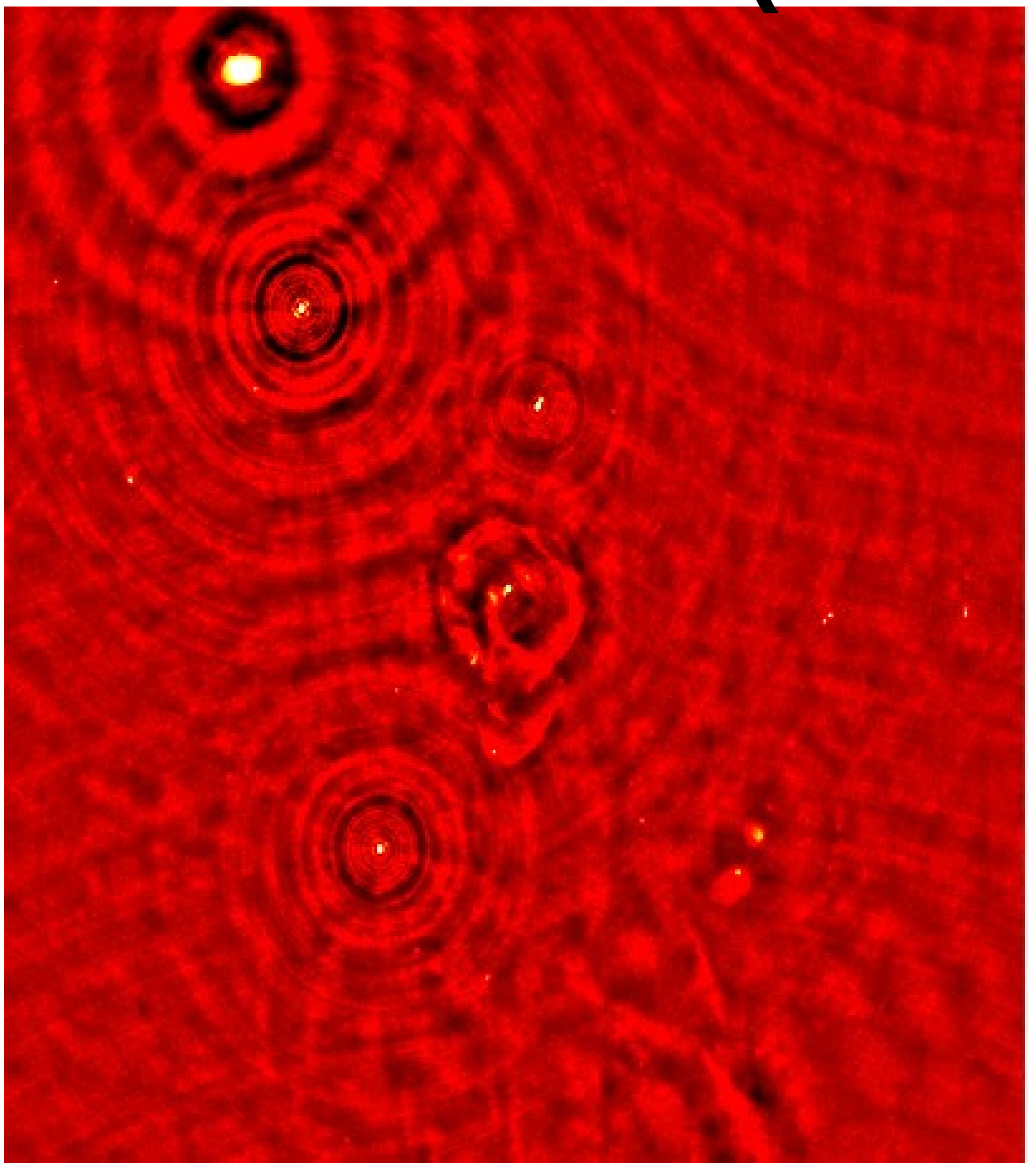


Tasse et al. In prep
Shimwell et al. In prep

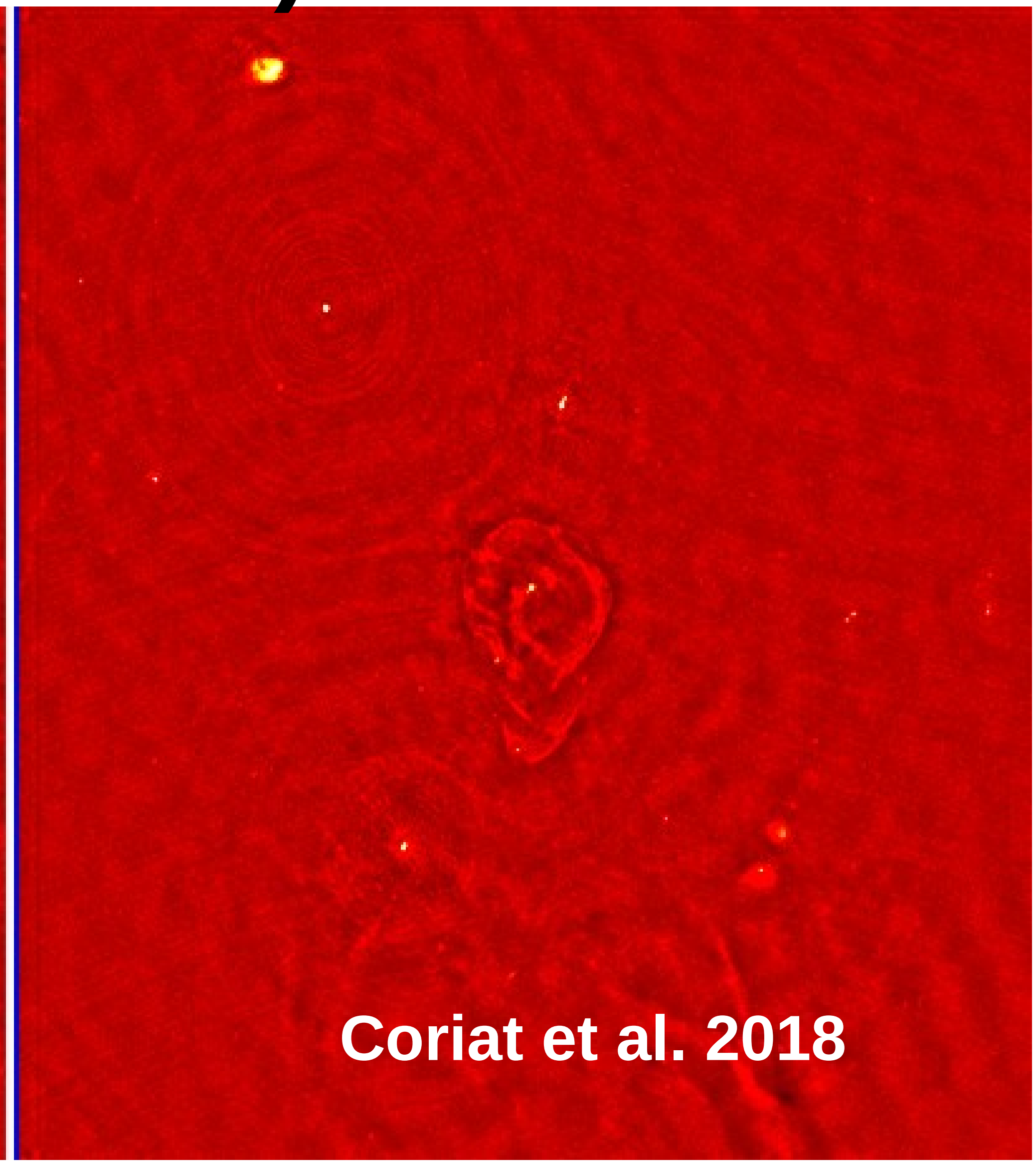


See also
Yatawatta et al. 2017, 2018
Repetti et al. 2017

And it also works on ATCA data (Circinus a)



Direction independent calibration

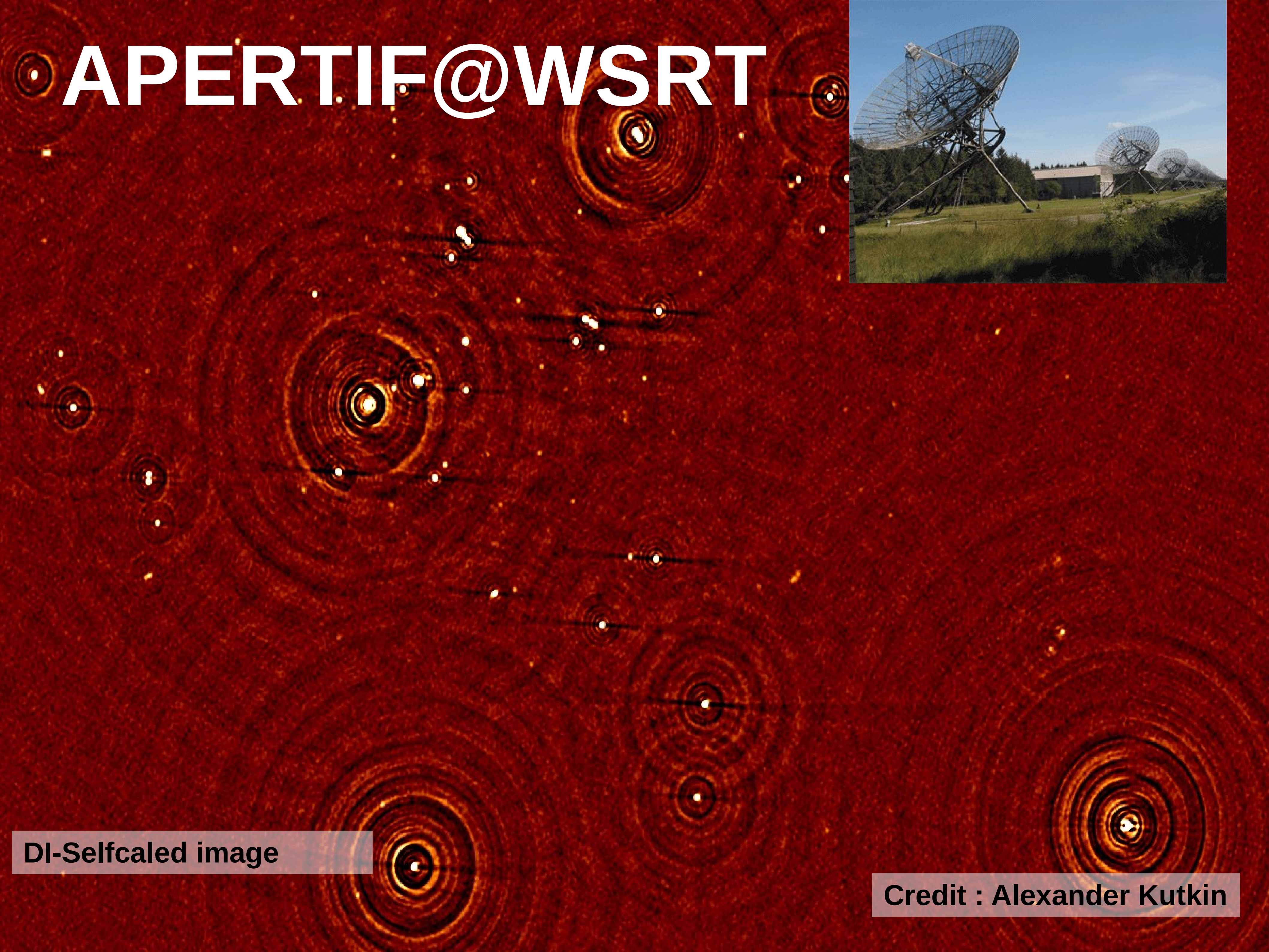


DDE with Wirtinger

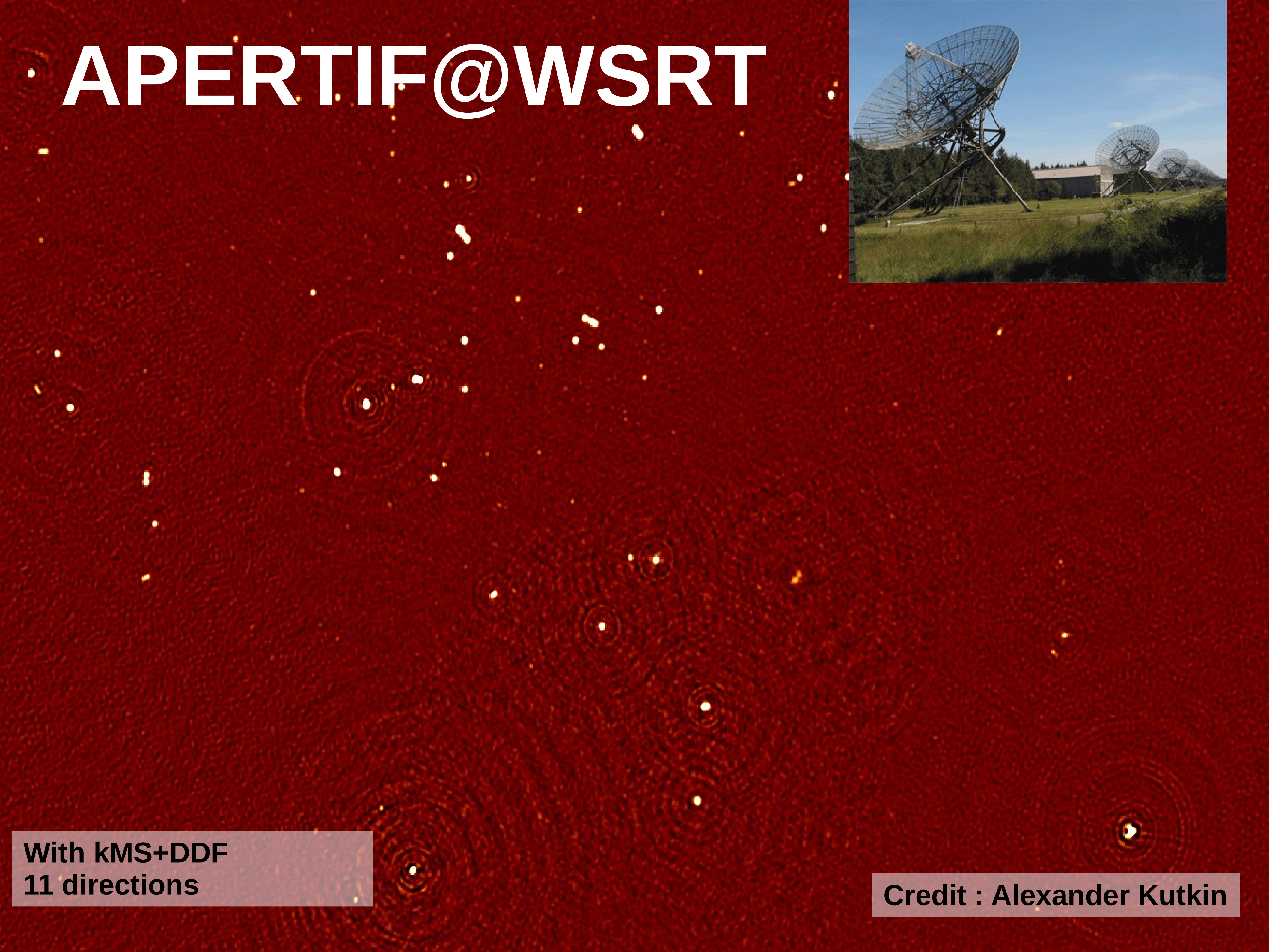
And it also works on VLA data

VLA beam model used to construct the Jones matrices

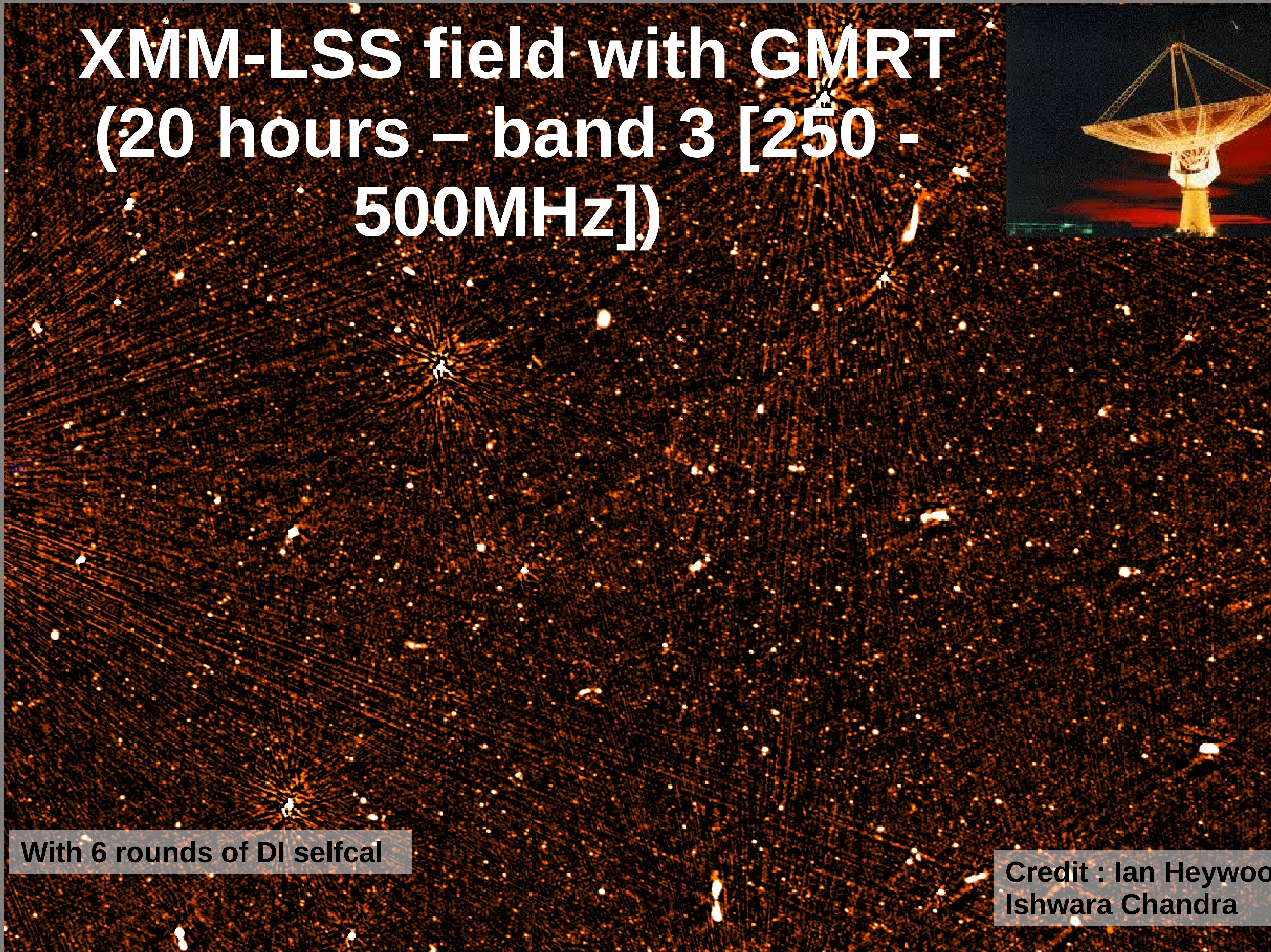
APERTIF@WSRT



APERTIF@WSRT



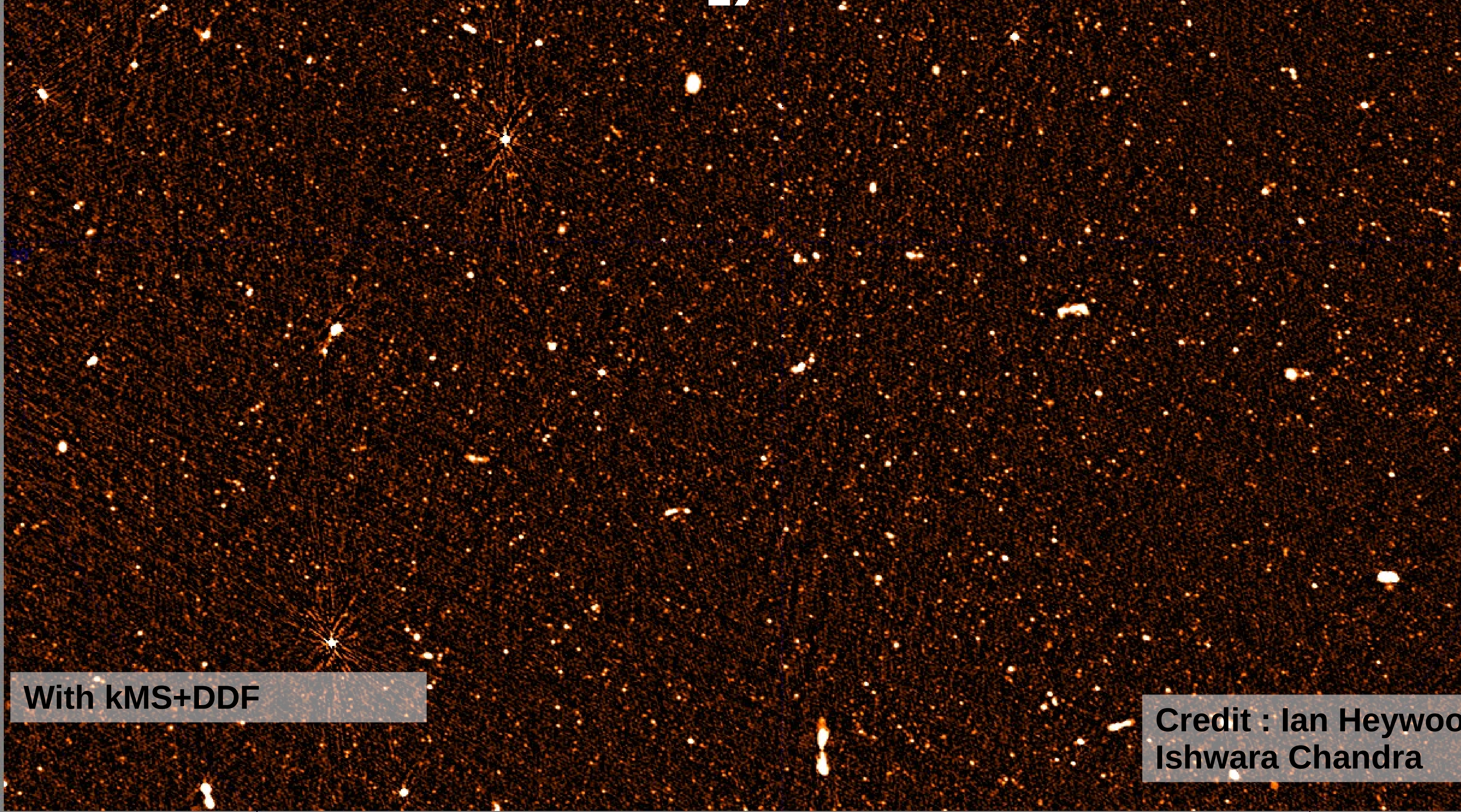
XMM-LSS field with GMRT (20 hours – band 3 [250 - 500MHz])



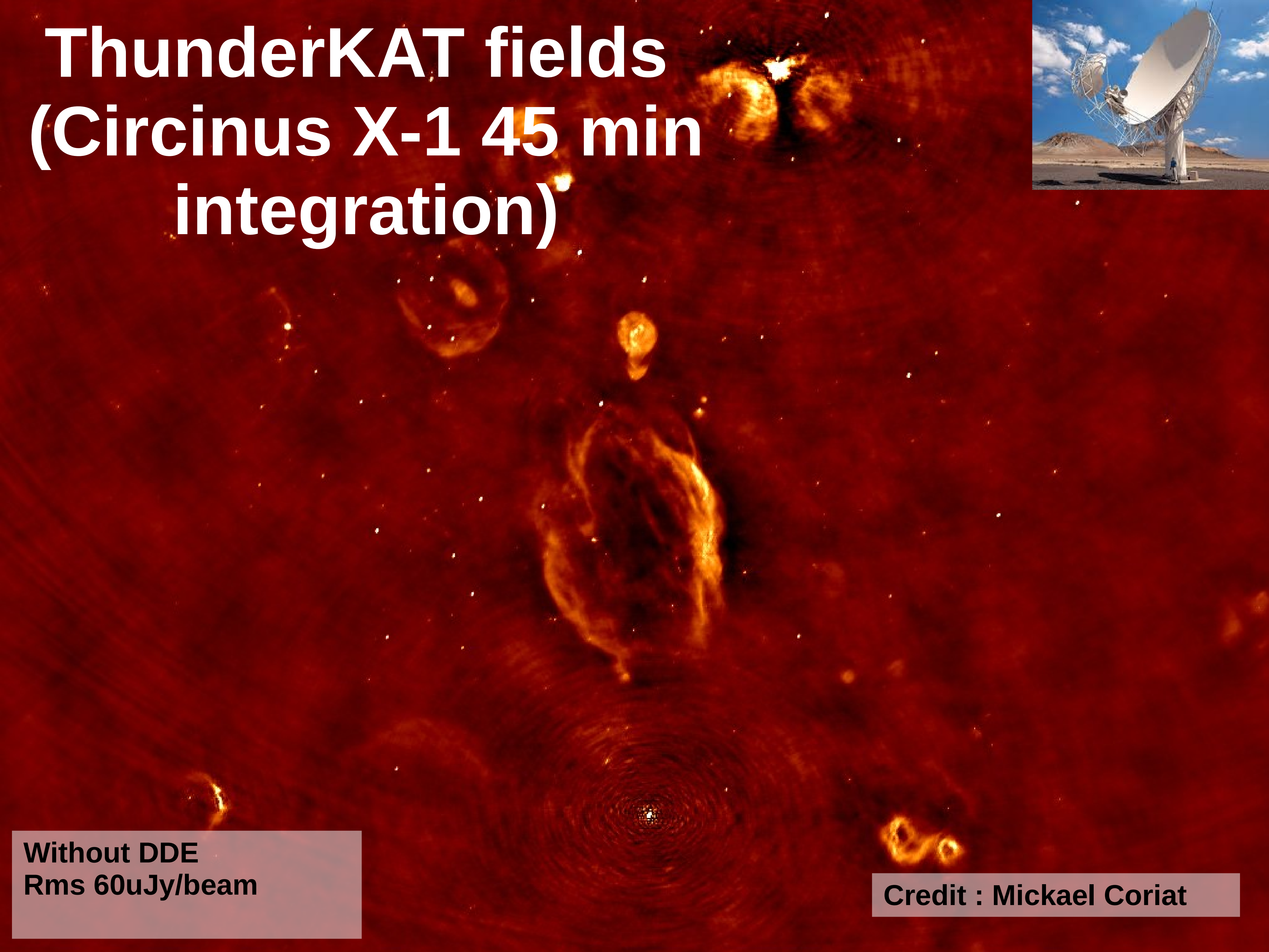
With 6 rounds of DI selfcal

Credit : Ian Heywoo
Ishwara Chandra

XMM-LSS field with GMRT (20 hours – band 3 [250 - 500MHz])



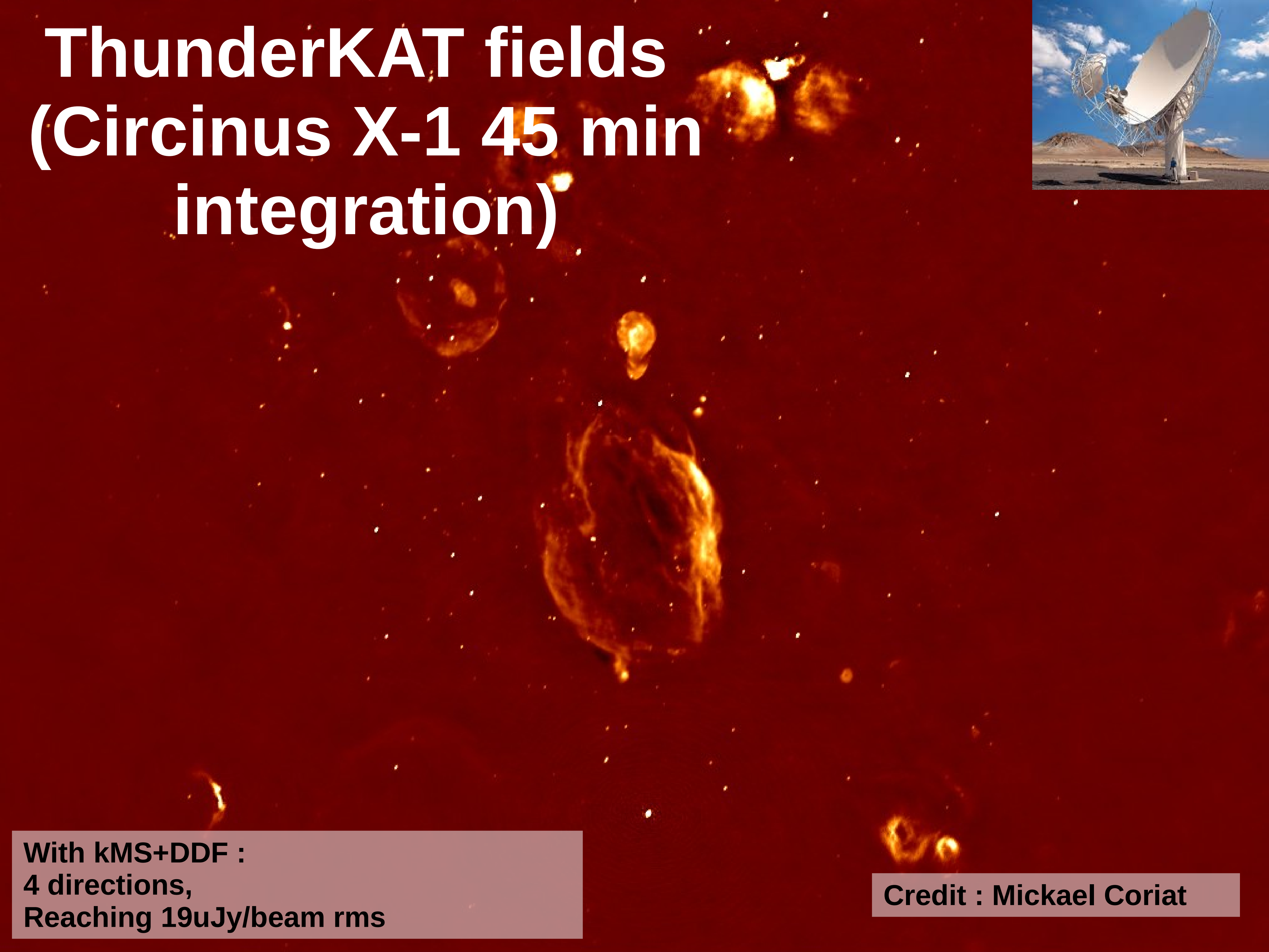
ThunderKAT fields (Circinus X-1 45 min integration)



Without DDE
Rms 60uJy/beam

Credit : Mickael Coriat

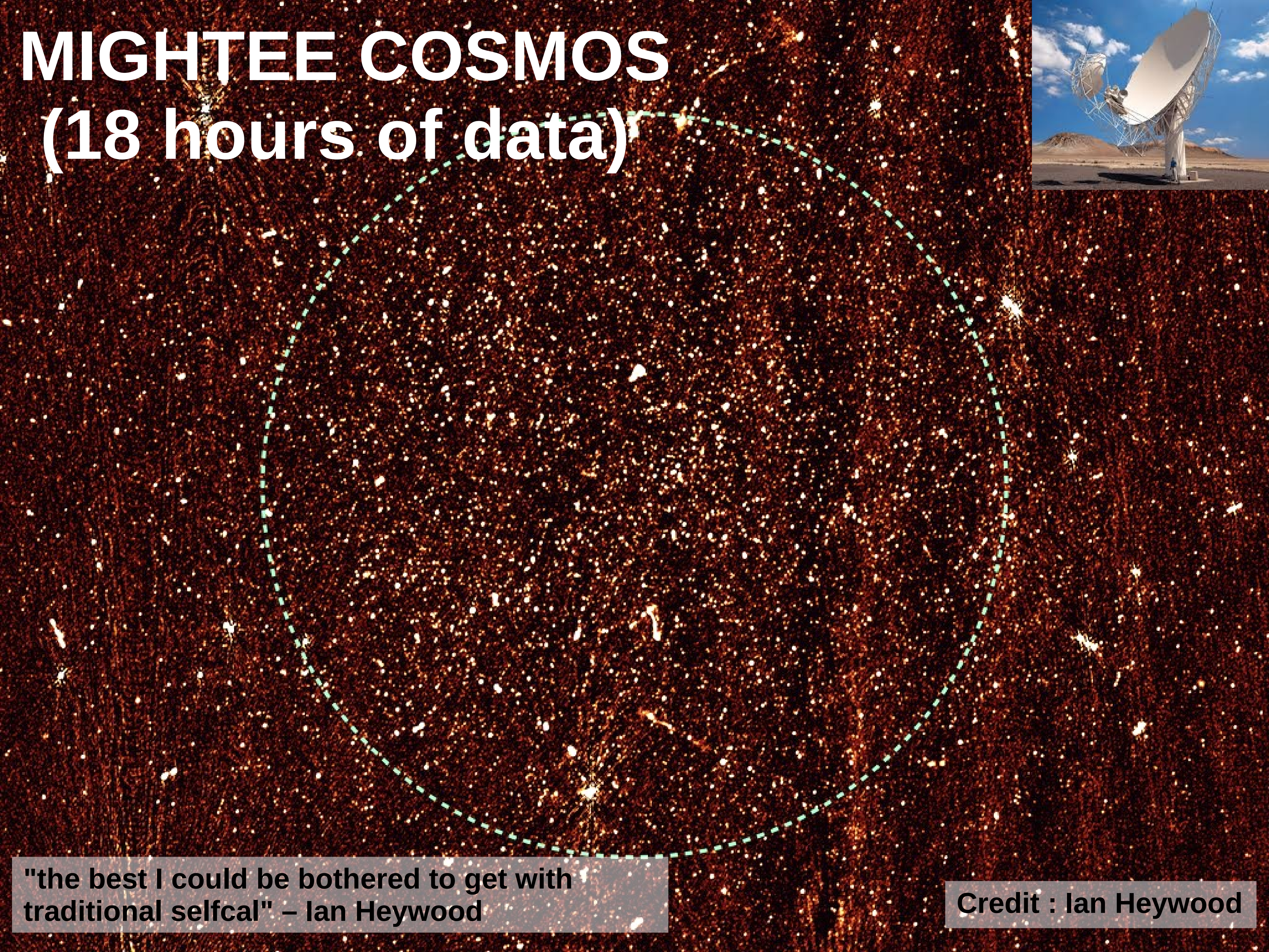
ThunderKAT fields (Circinus X-1 45 min integration)



With kMS+DDF :
4 directions,
Reaching 19uJy/beam rms

Credit : Mickael Coriat

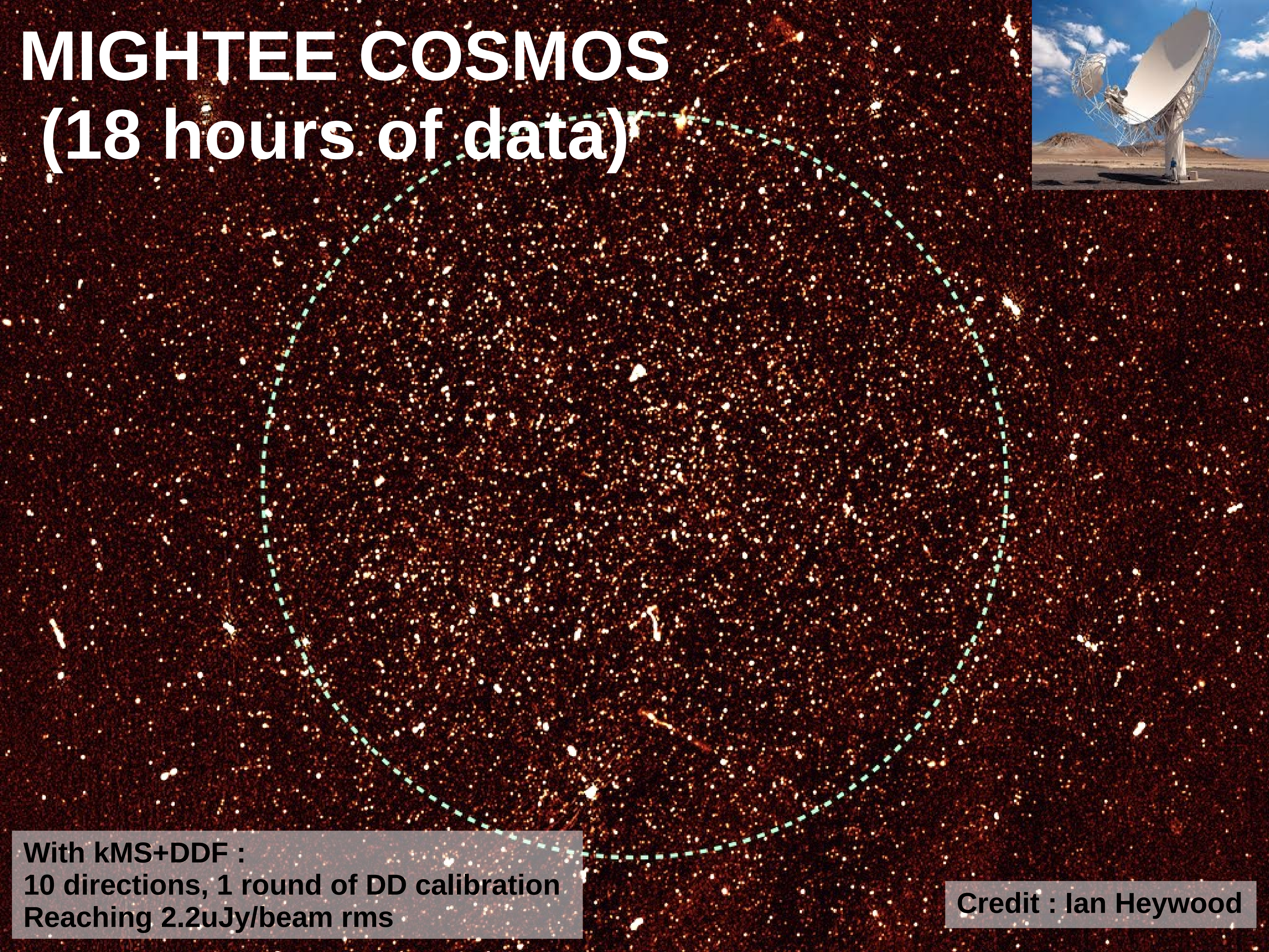
MIGHTEE COSMOS
(18 hours of data)



"the best I could be bothered to get with traditional selfcal" – Ian Heywood

Credit : Ian Heywood

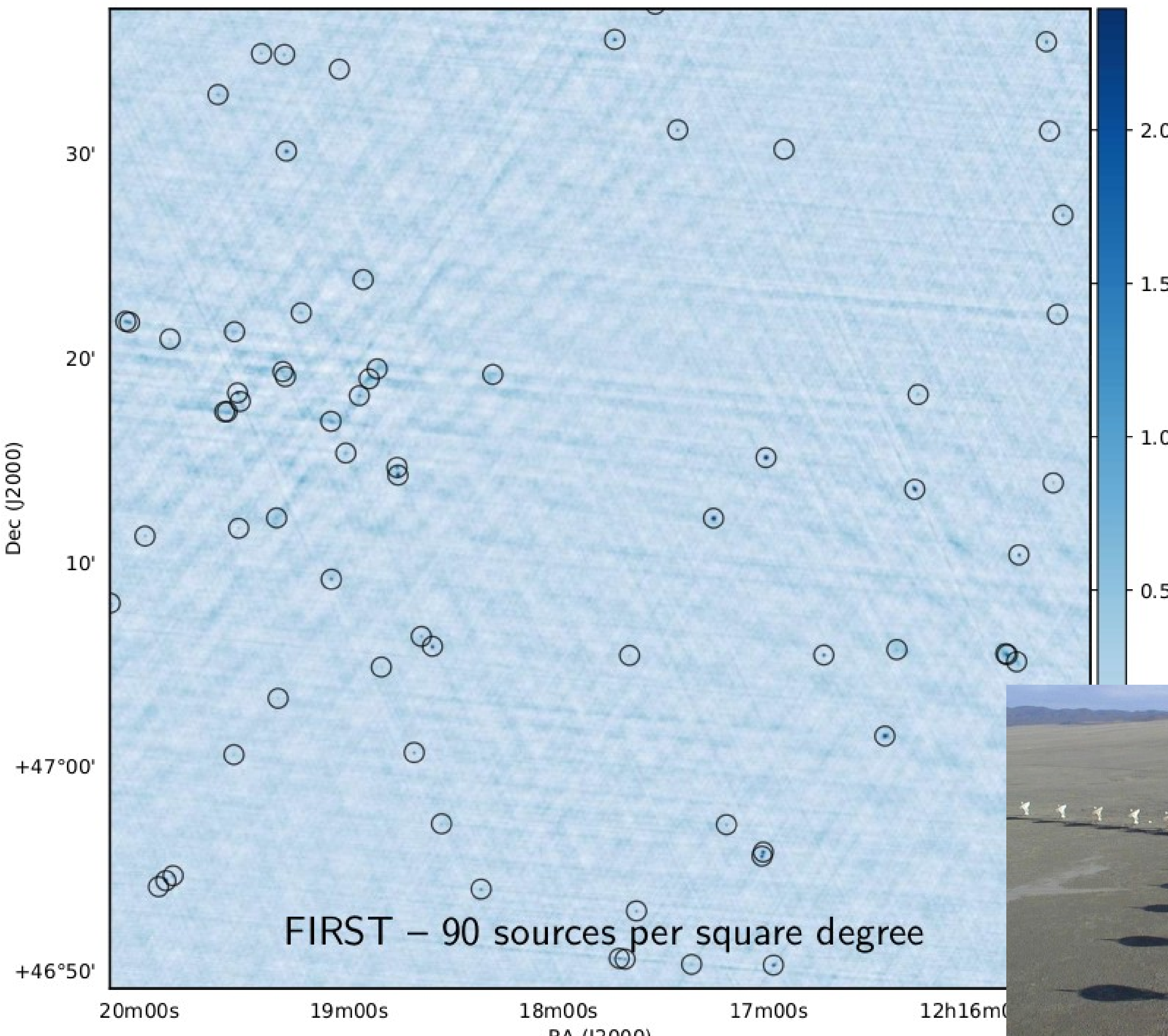
MIGHTEE COSMOS
(18 hours of data)



With kMS+DDF :
10 directions, 1 round of DD calibration
Reaching 2.2uJy/beam rms

Credit : Ian Heywood

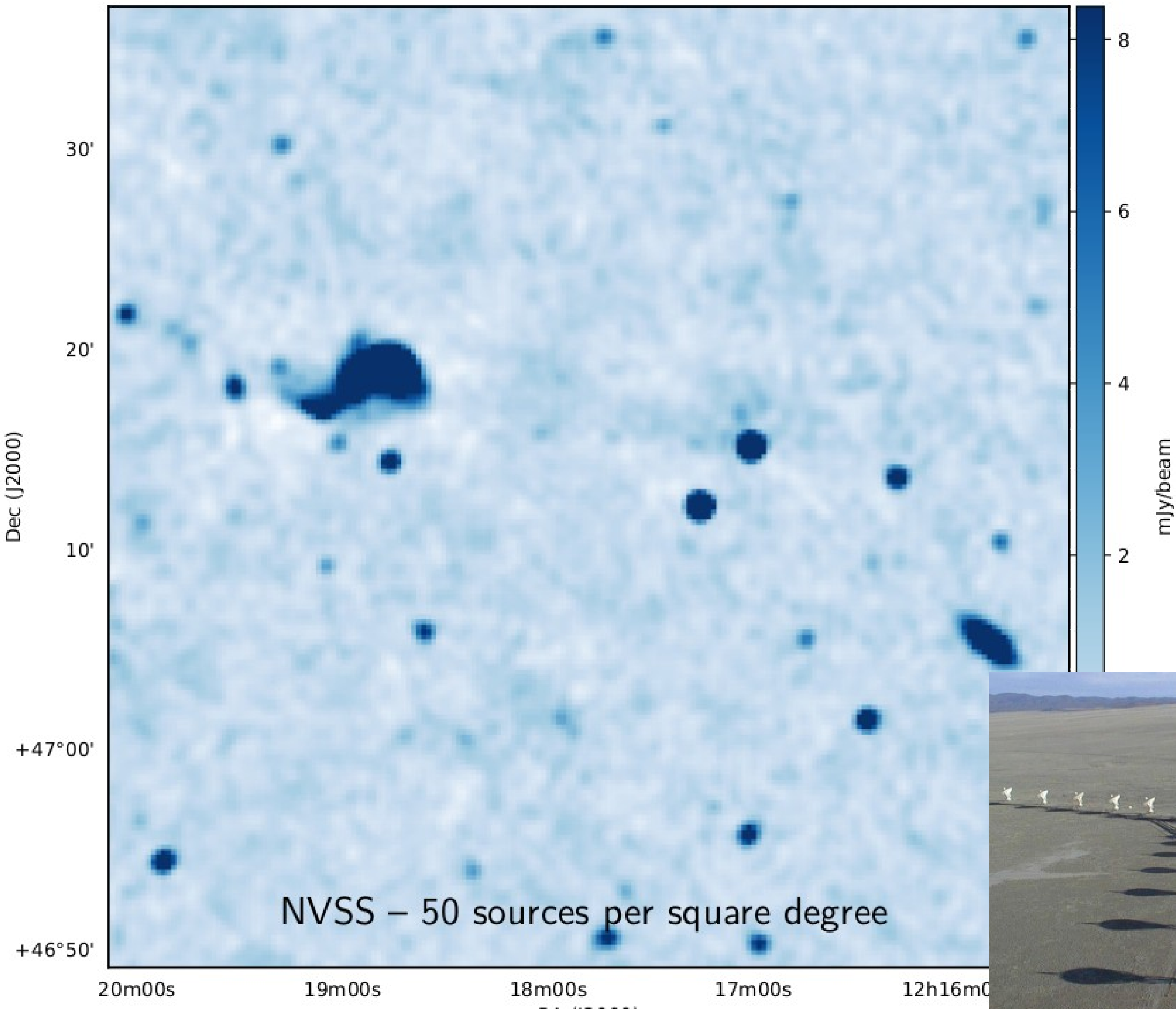
LOTSS – First Data Release



Extended configuration

VLA

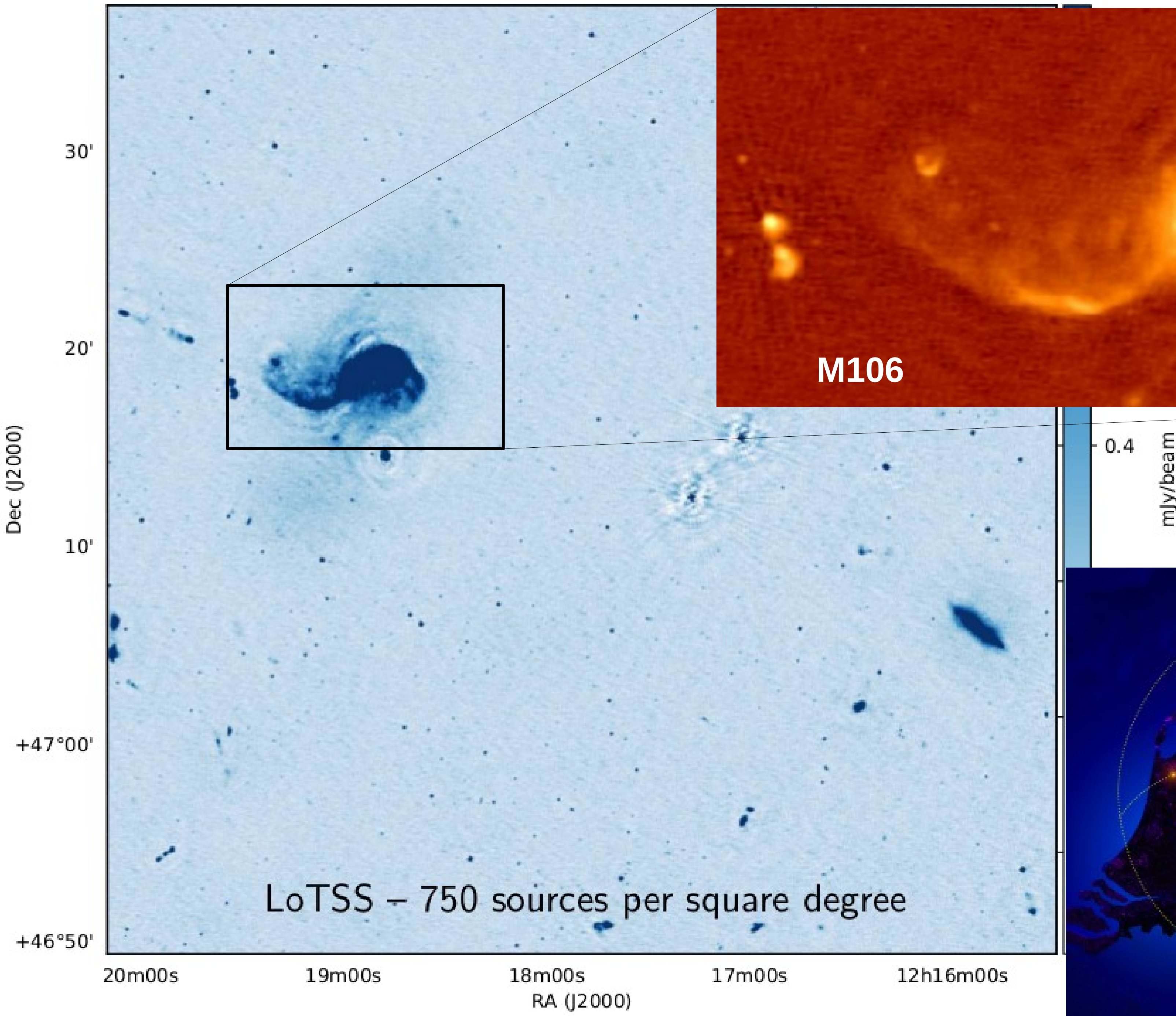
LOTSS – First Data Release



Compact configuration

VLA

LOTSS – First Data Release



LOFAR

A quick *entracte*

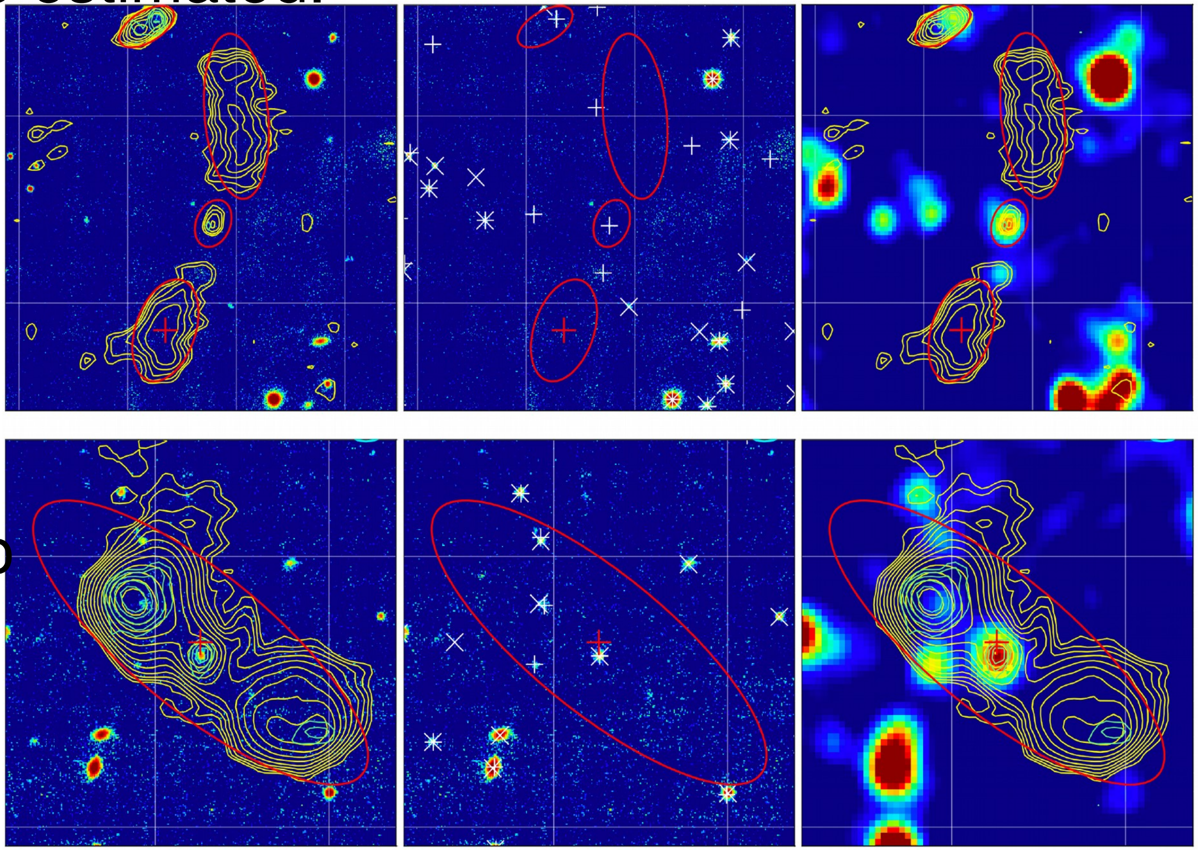
LoTSS data release 1

325,694 entires in the raw PyBDSF catalogue.

Corresponds to 318,520 radio sources after deblending, artefact rejection and joining multiple component sources (including extensive efforts to visually inspect ~10,000 sources).

231,716 have counterparts in Pan-STARRS or WISE and for these photometric redshifts are are estimated.

	Number	Number with ID	ID fraction
All Sources	318,520	231,716	0.73
LR	299,730	221,269	0.74
LGZ	11,989	7,144	0.60
Deblending	2,435	2,338	0.96
Bright galaxy	965	965	1.00
No ID possible	3,401	0	0.00



The final LoTSS-DR1 catalogue contains radio sources, optical counter parts and photometric redshifts.

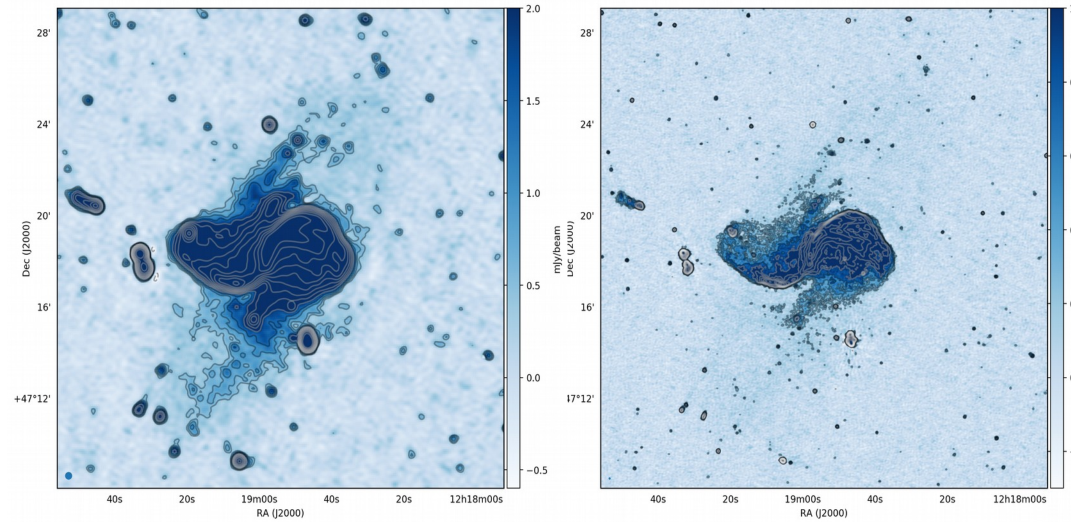
Williams, Duncan, Hardcastle, Sabatar et al.

Examples of LOFAR galaxy zoo entries showing

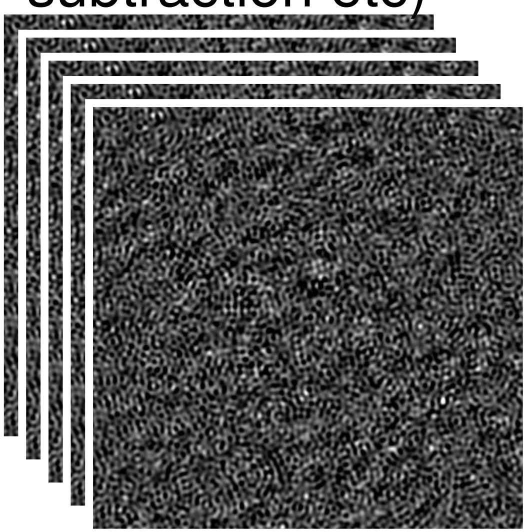
New data products in LoTSS -DR2

Current pipeline products:

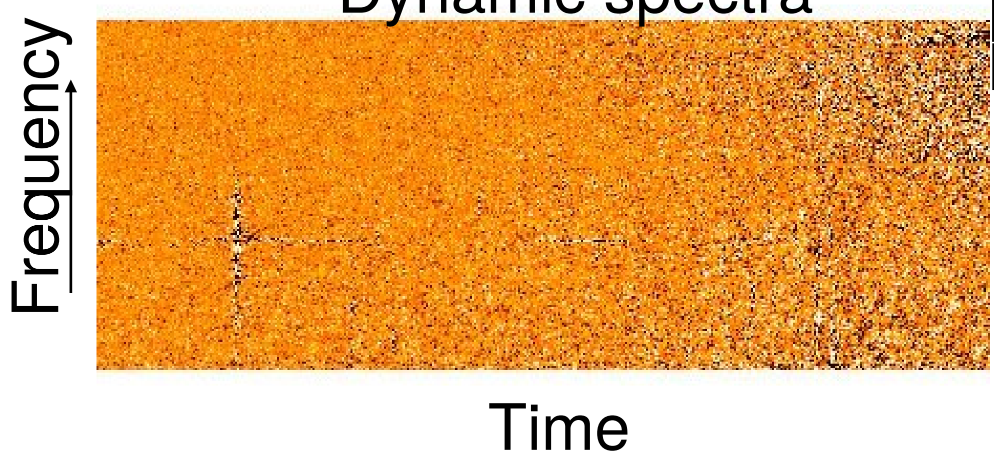
- 6” resolution Stokes I image
- 20” resolution Stokes I image
- 3 channel images over band
- 20” resolution Stokes V image
- 20” resolution Stokes QU cubes (480 planes)
- Very low resolution Stokes QU cubes (480 planes)
- Dynamic spectra of targeted sources
- Data calibrated in a particular direction with all other source subtracted (allows easy reimaging, source subtraction etc)



Stokes I images at high (6”) and low (20”) resolution



Dynamic spectra



To enable further processing we also keep:

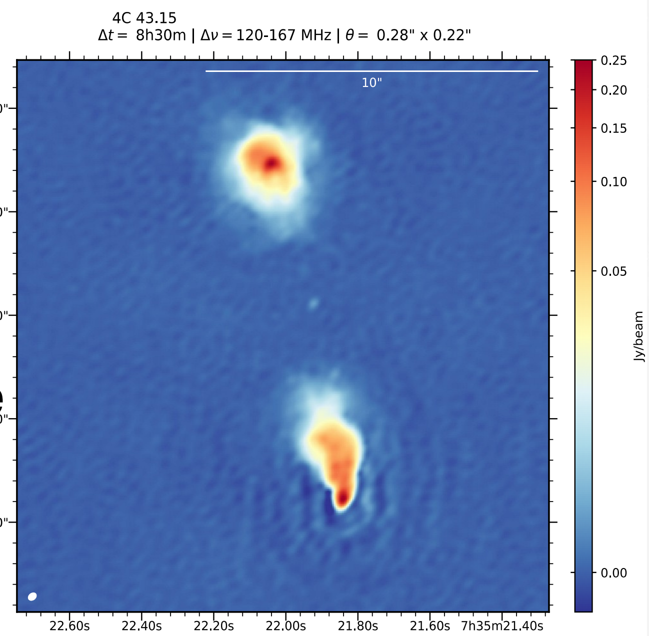
- Facet layout
- Calibration solutions
- Data

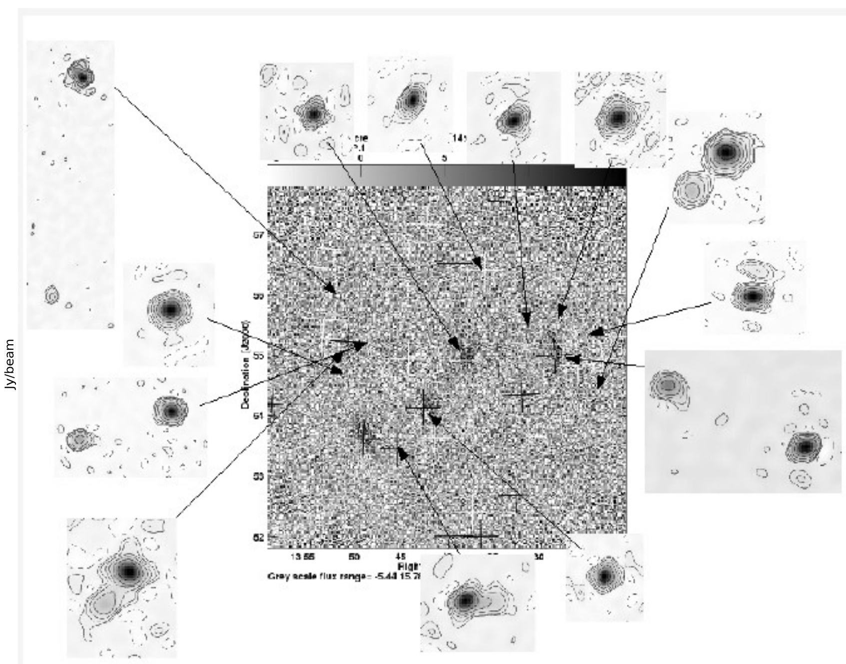
Furthering the LOFAR surveys

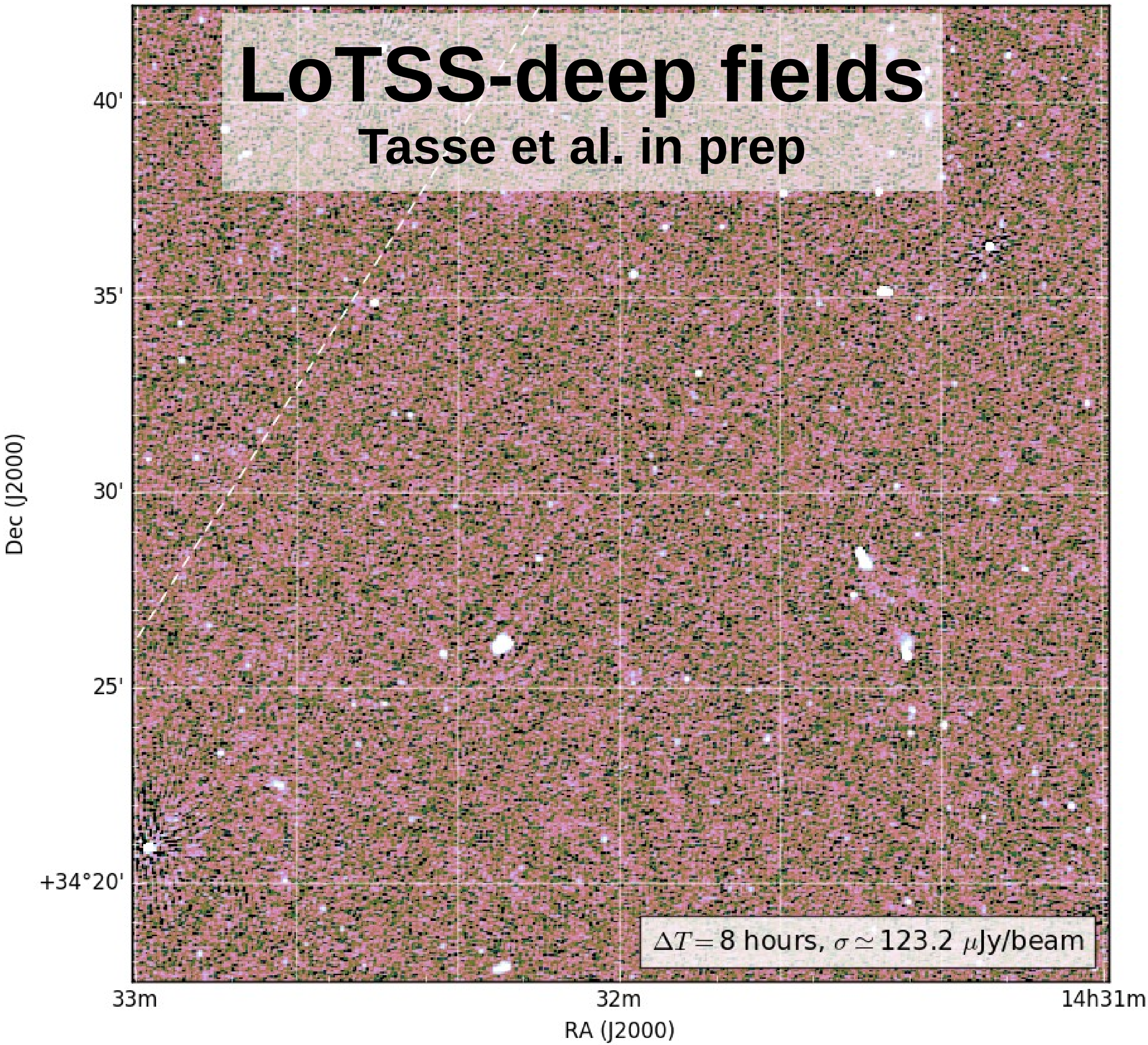
Optical followup — WEAVE-LOFAR (Smith+ 2016) will use WEAVE on the WHT and soon begin obtaining spectra for ~a million LOFAR sources.

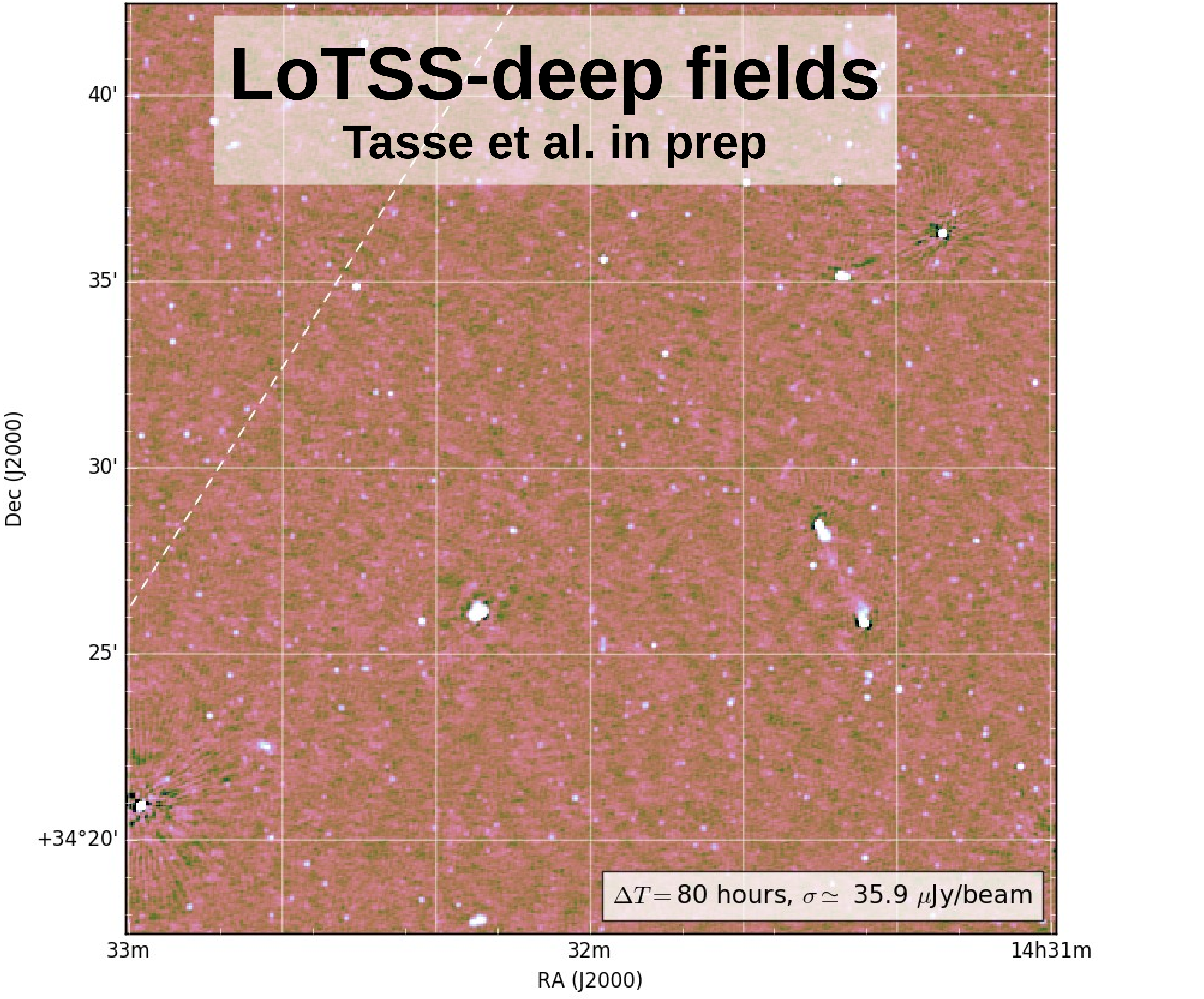
Radio recombination lines — LoTSS data have sufficient frequency resolution for spectral line work and the data are being analysed to search for RRLs (e.g. Emig+ 2018).

0.3arcsec resolution — LOFAR surveys data are recorded using the full international LOFAR array allowing for 0.3” imaging over the entire surveyed region (images from Sweijen, van Weeren, Jackson, Morabito+)





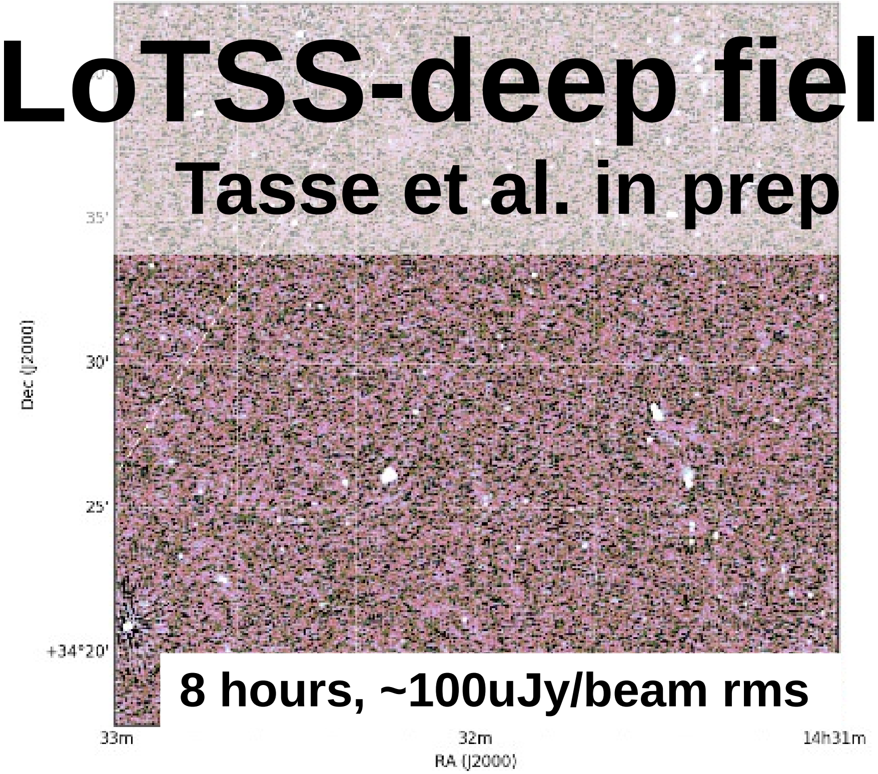

LoTSS-deep fields
Tasse et al. in prep
$\Delta T = 8$ hours, $\sigma \simeq 123.2$ μJy/beam
40'
35'
30'
25'
+34°20'
Dec (J2000)
33m
32m
14h31m
RA (J2000)

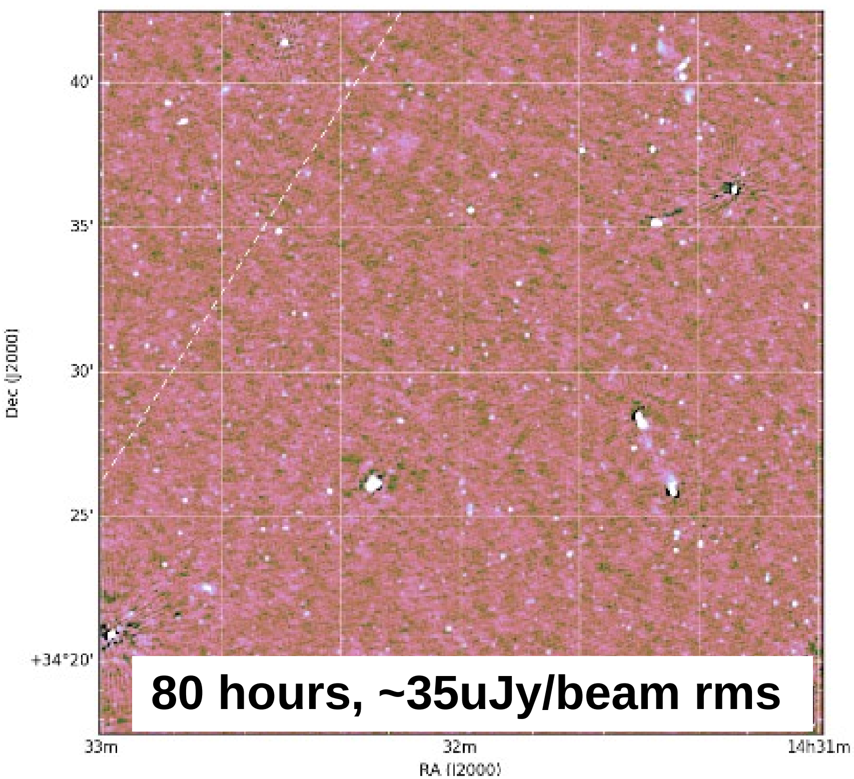


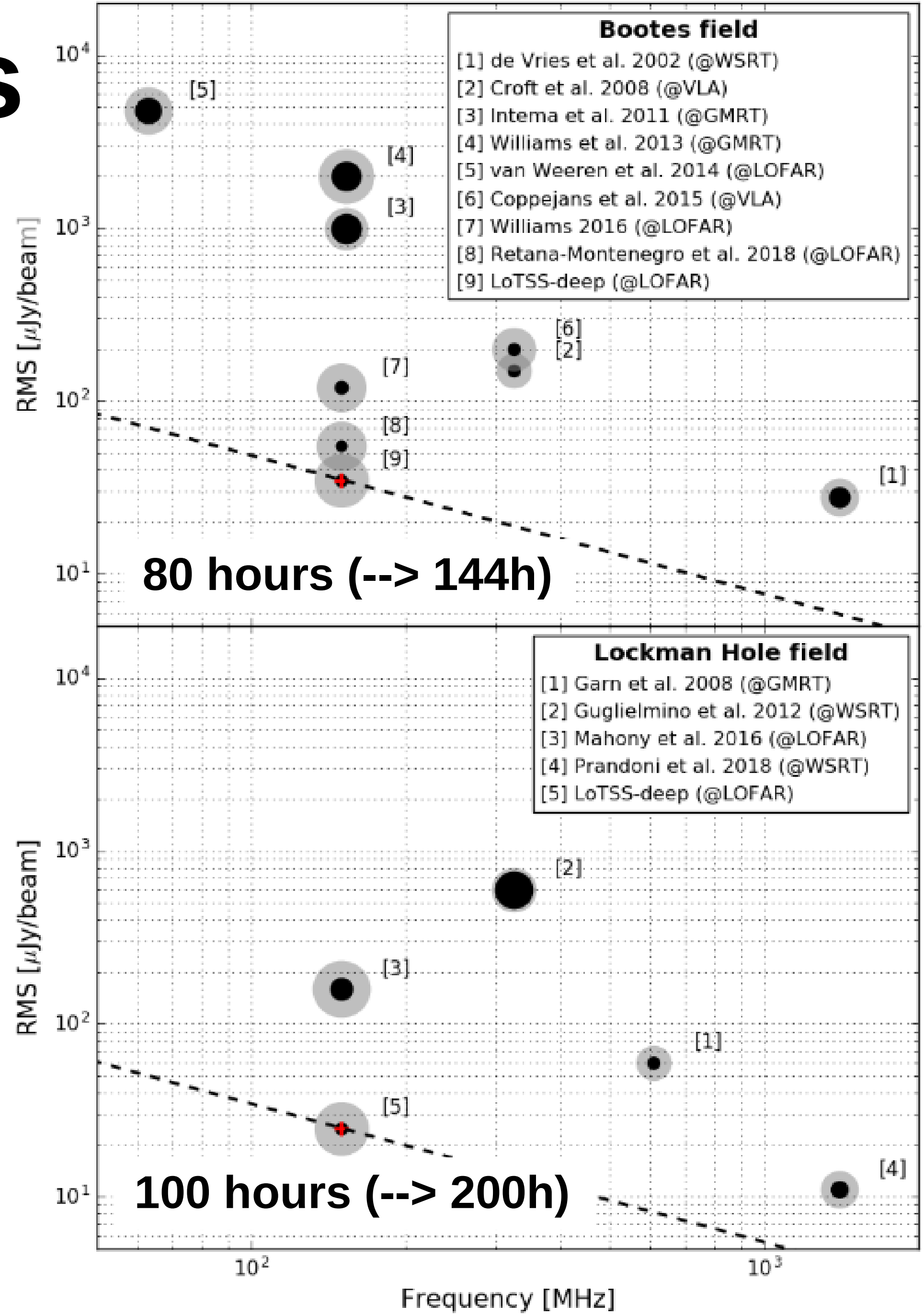
LoTSS-deep fields
Tasse et al. in prep
$\Delta T = $ 80 hours, $\sigma \simeq$ 35.9 μJy/beam
Dec (J2000)
40'
35'
30'
25'
+34°20'
RA (J2000)
33m
32m
14h31m

LoTSS-deep fields

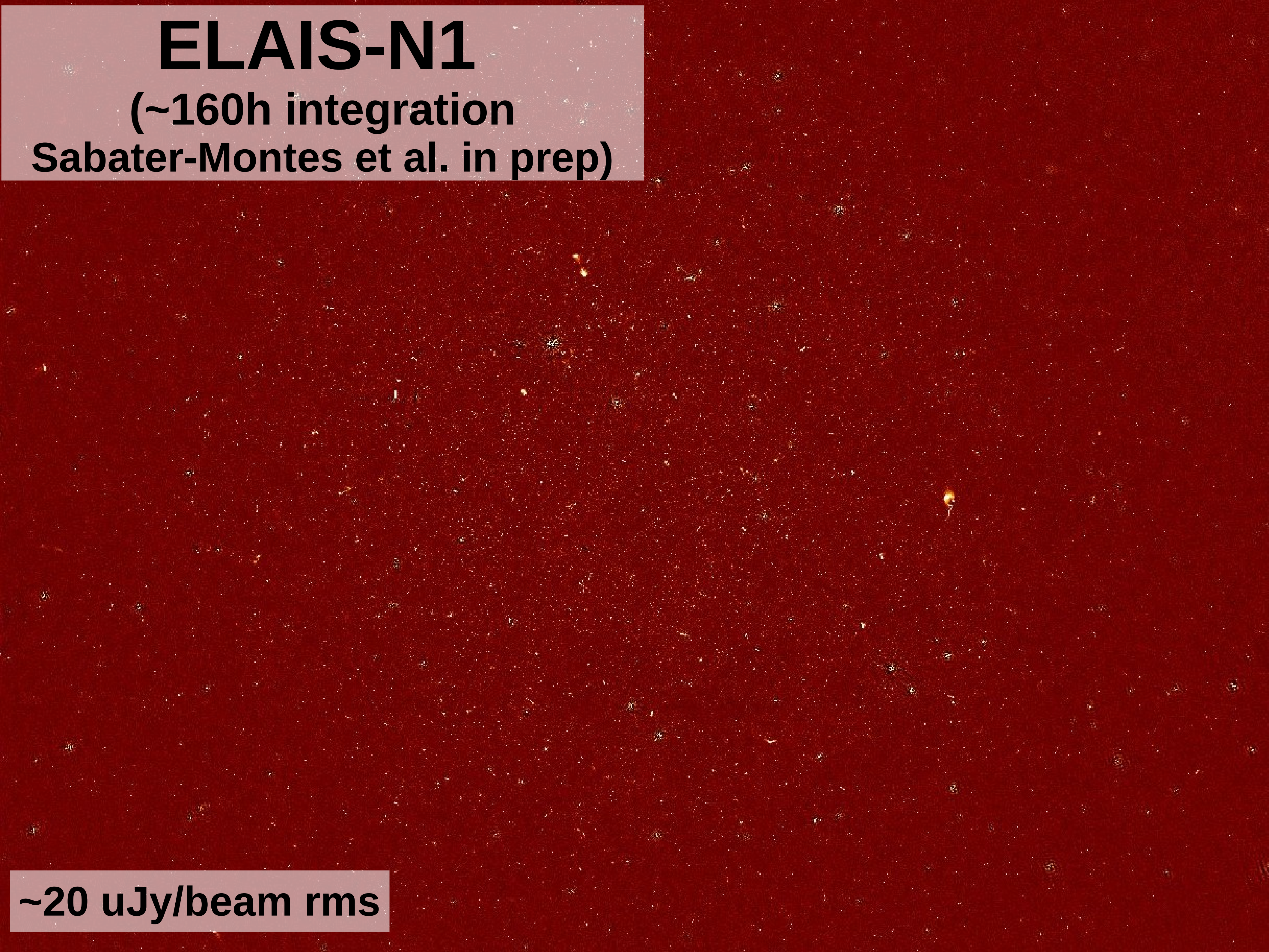
Tasse et al. in prep

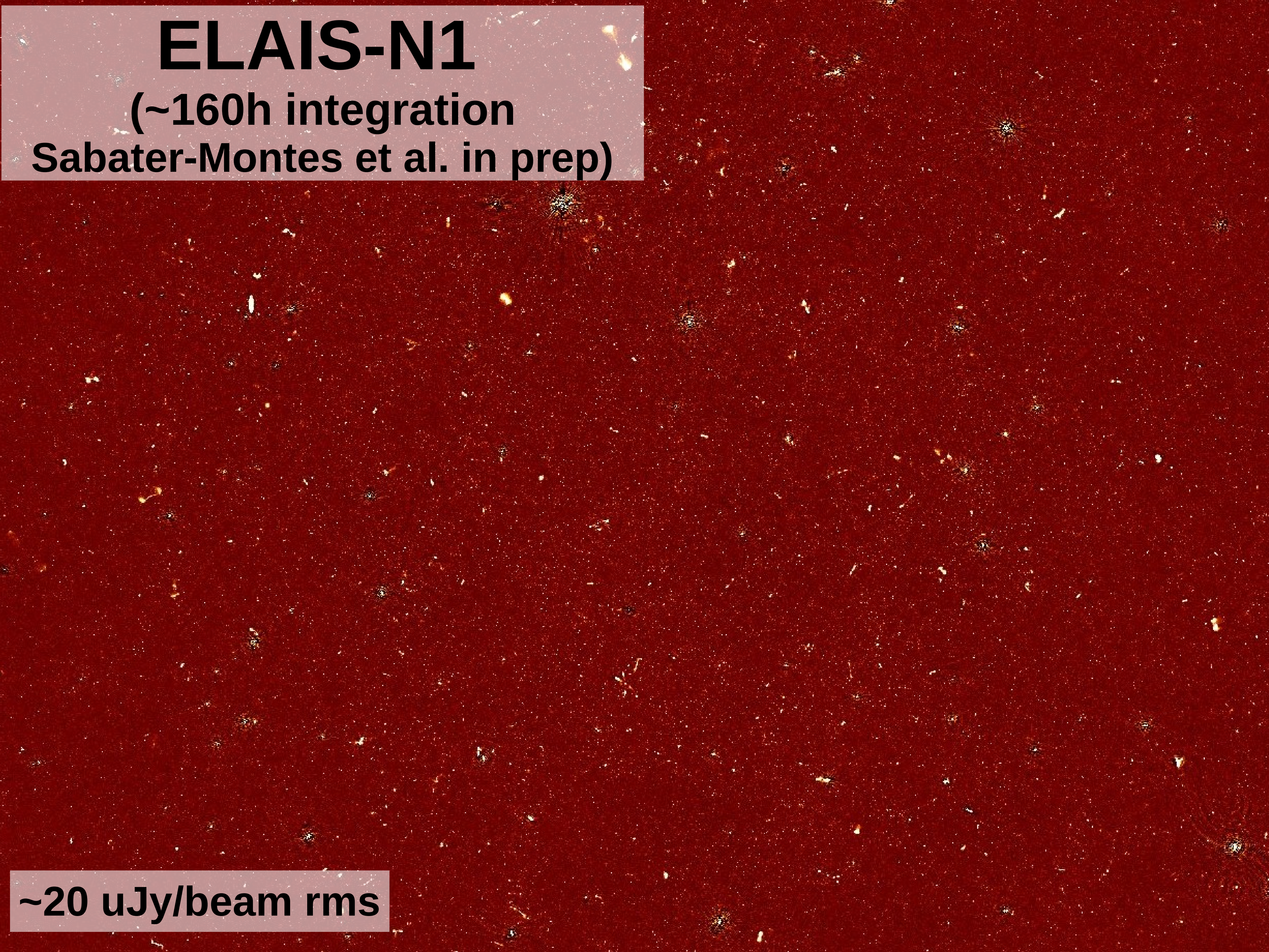






+ ELAIS-N1
+ NCP


ELAIS-N1
(~160h integration
Sabater-Montes et al. in prep)
~20 uJy/beam rms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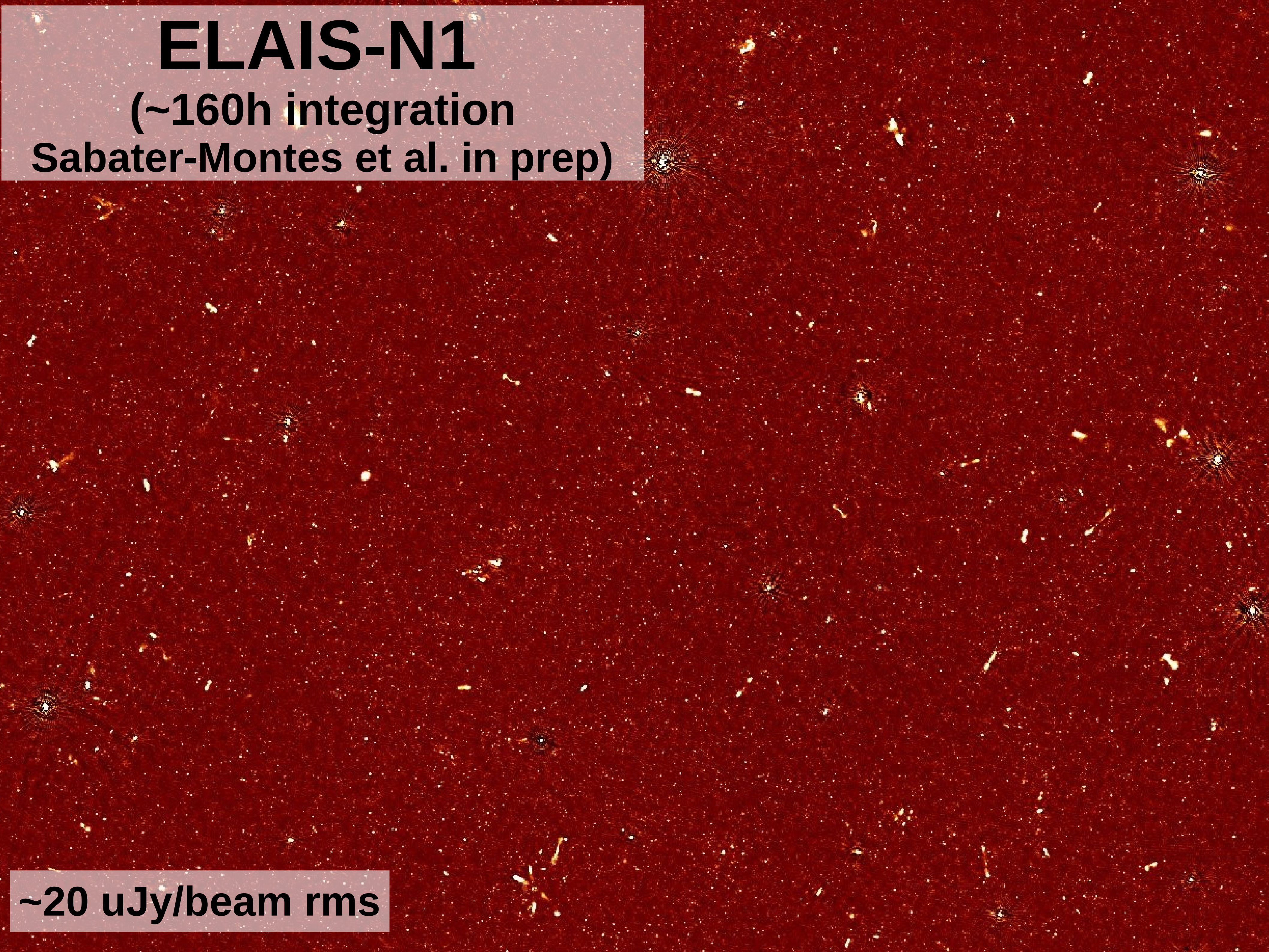
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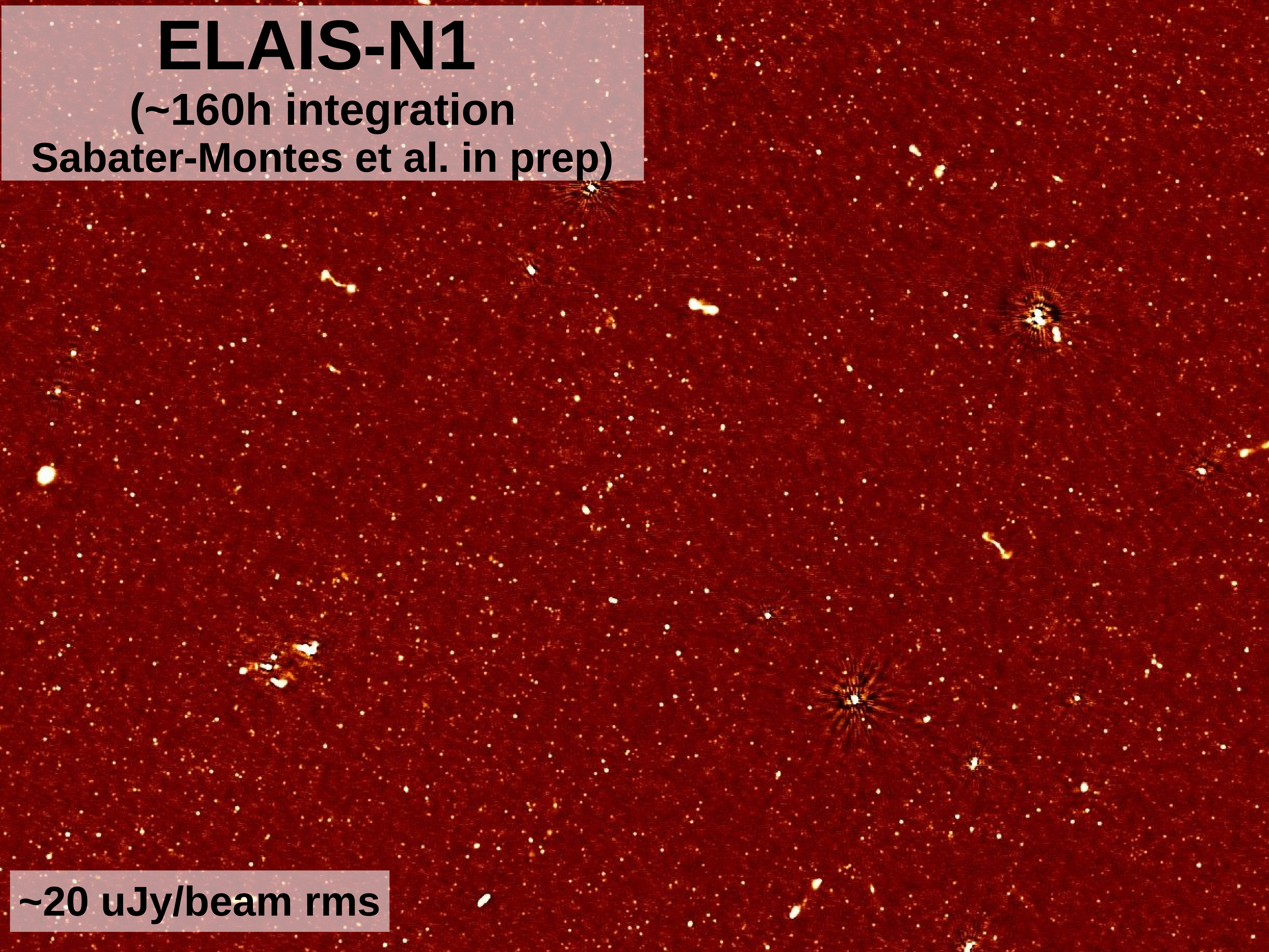
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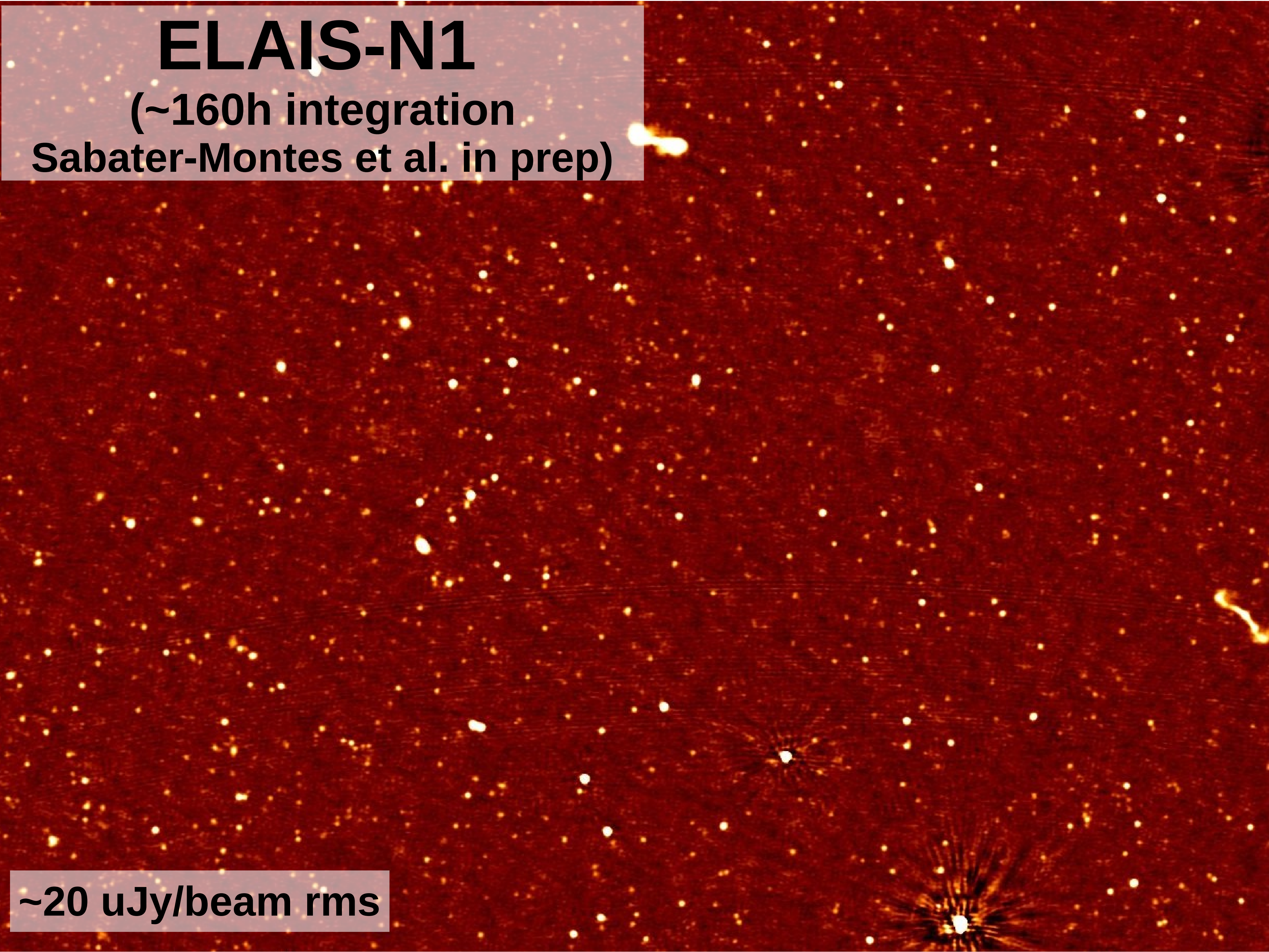
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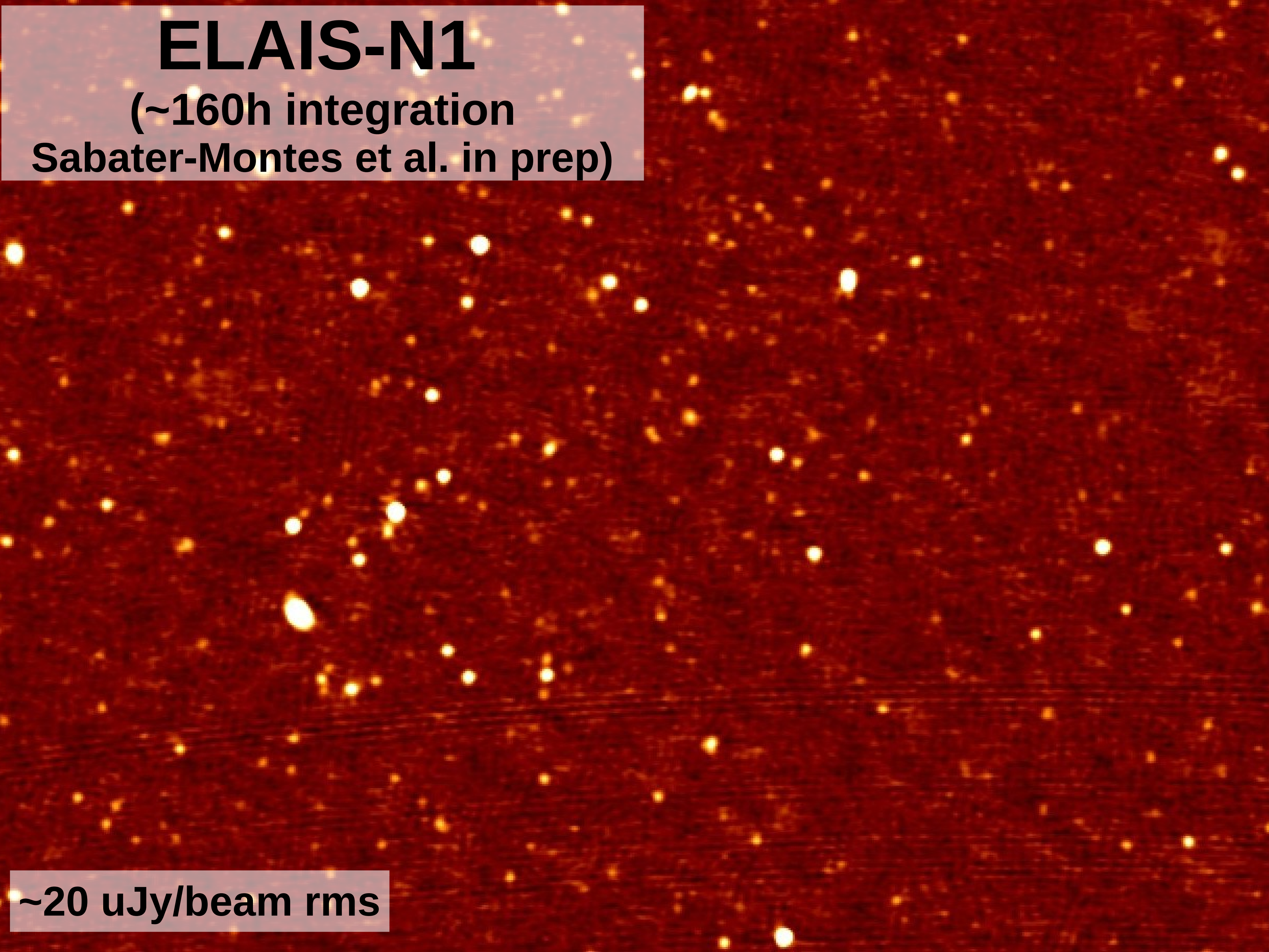
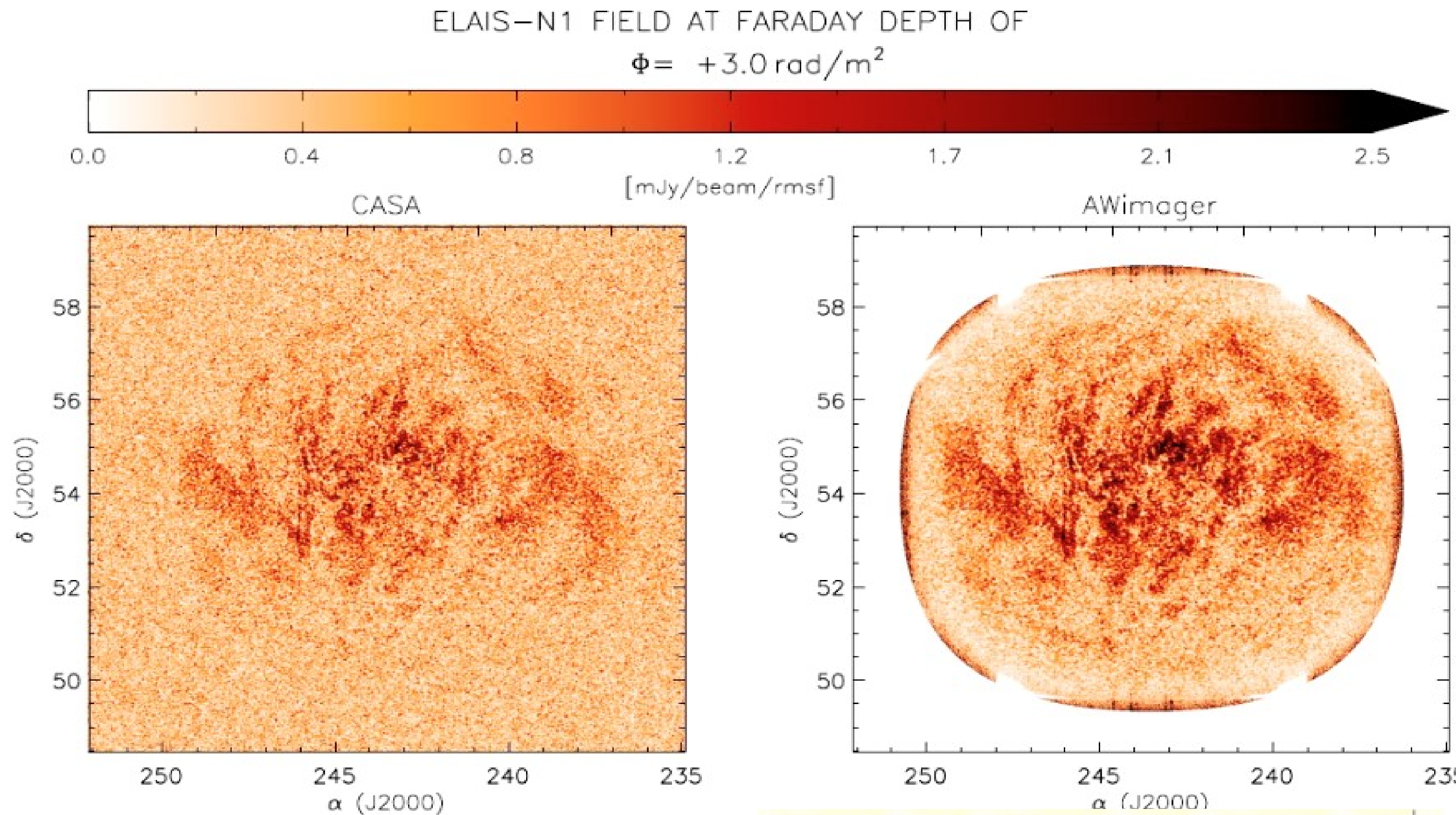
Sabater-Montes et al. in prep)
~20 uJy/beam rms

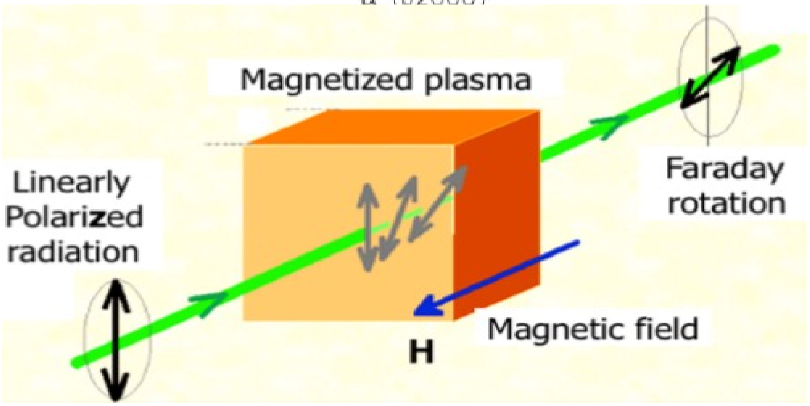

ELAIS-N1
(~160h integration
Sabater-Montes et al. in prep)
~20 uJy/beam rms

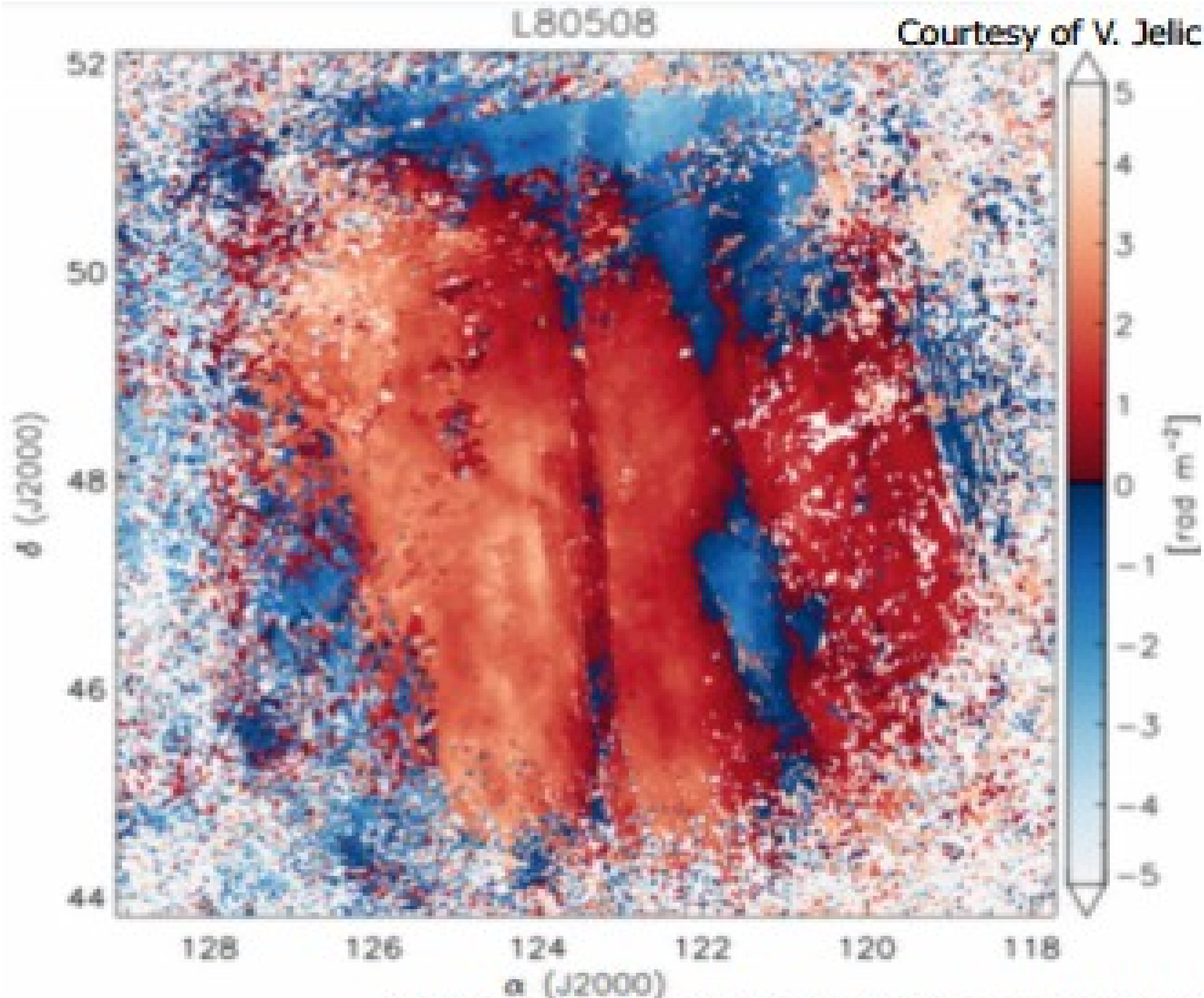
Mesure de rotation ELAIS



Credit: Vibor Jelic

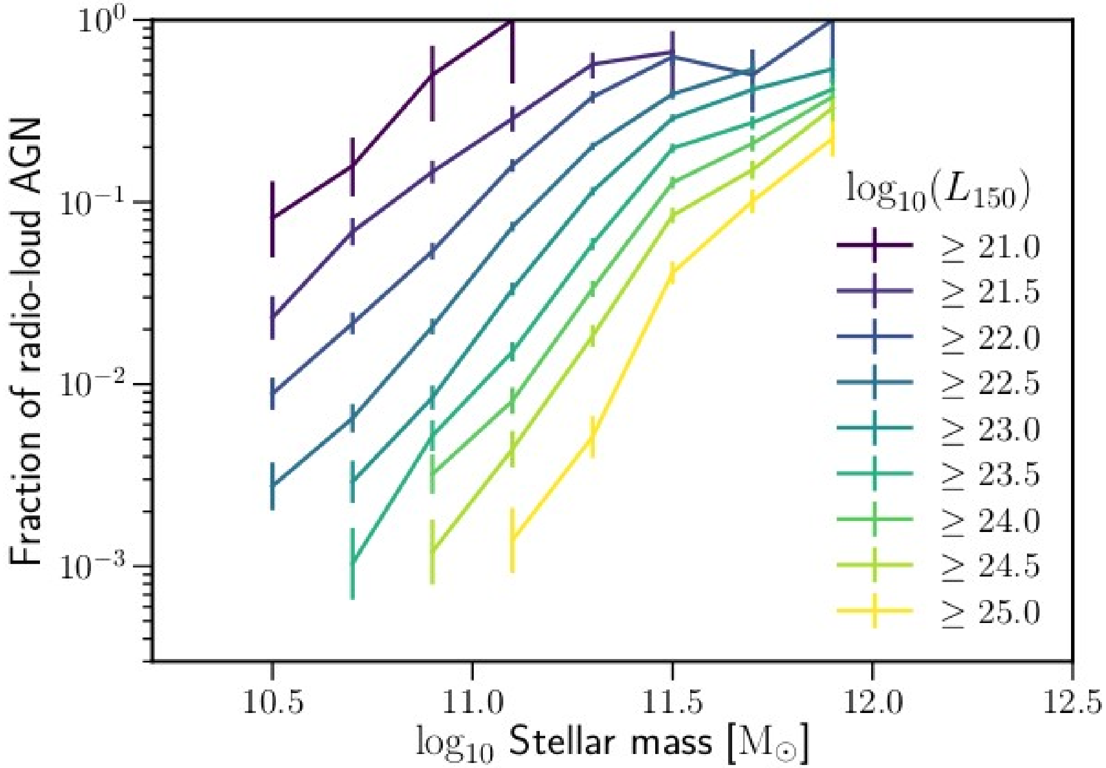
Faraday rotation converts Q in U stokes, and angle depends on lambda^2

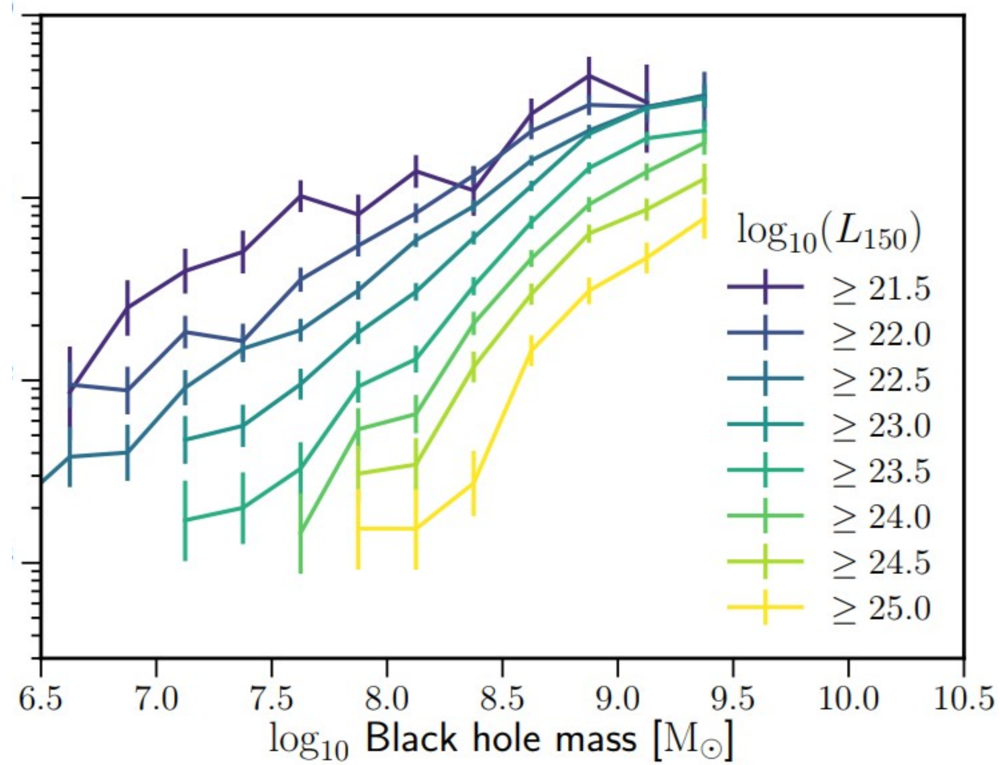




3C196, -5 rad m^{-2} < Φ < + 5 rad m^{-2}, FWHM ~ 4′

In the local universe, AGN in massive galaxies *are always on*





Stellar mass

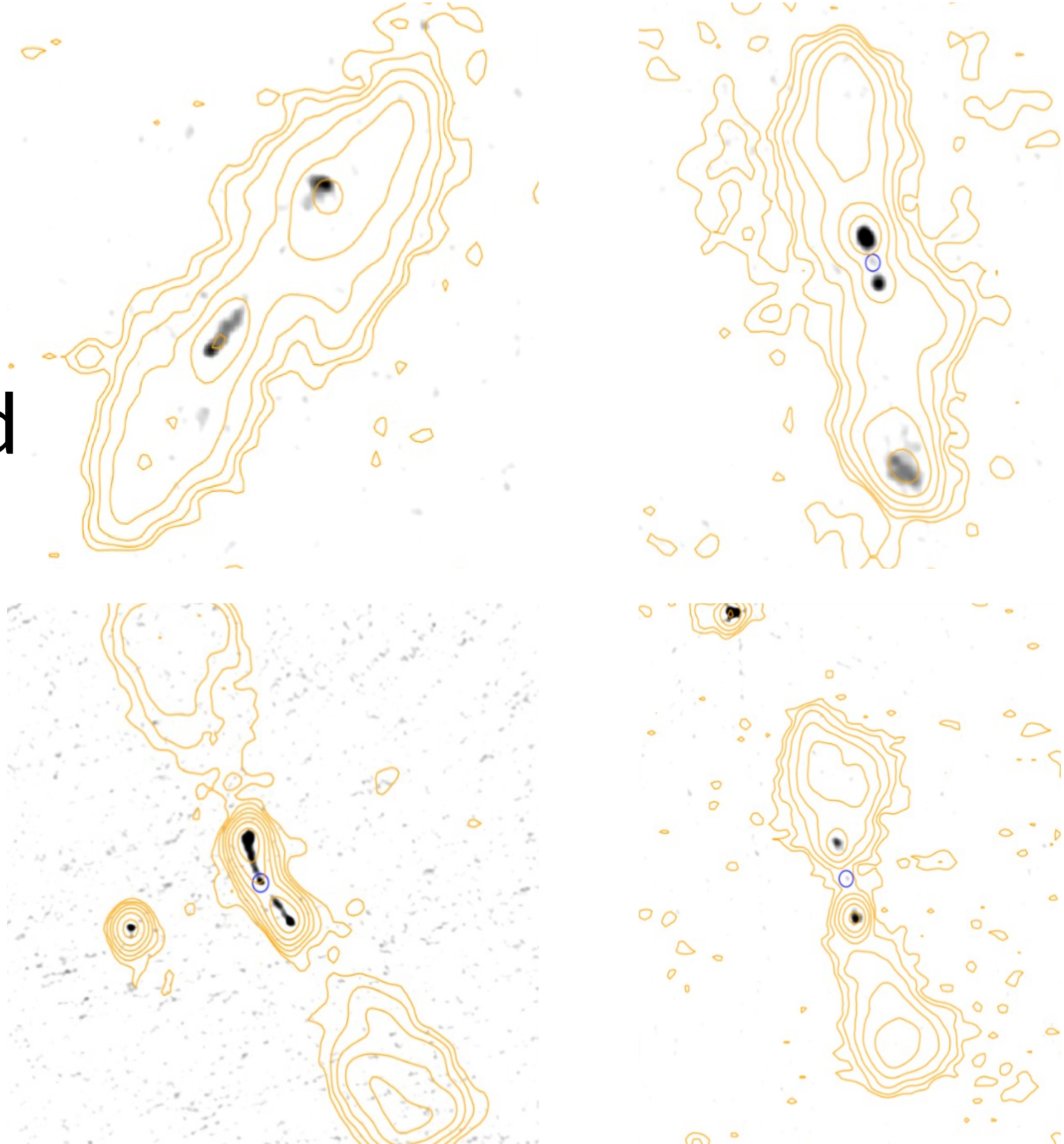
Black-Hole mass

Sabater et al.

Relic AGN or restarted?

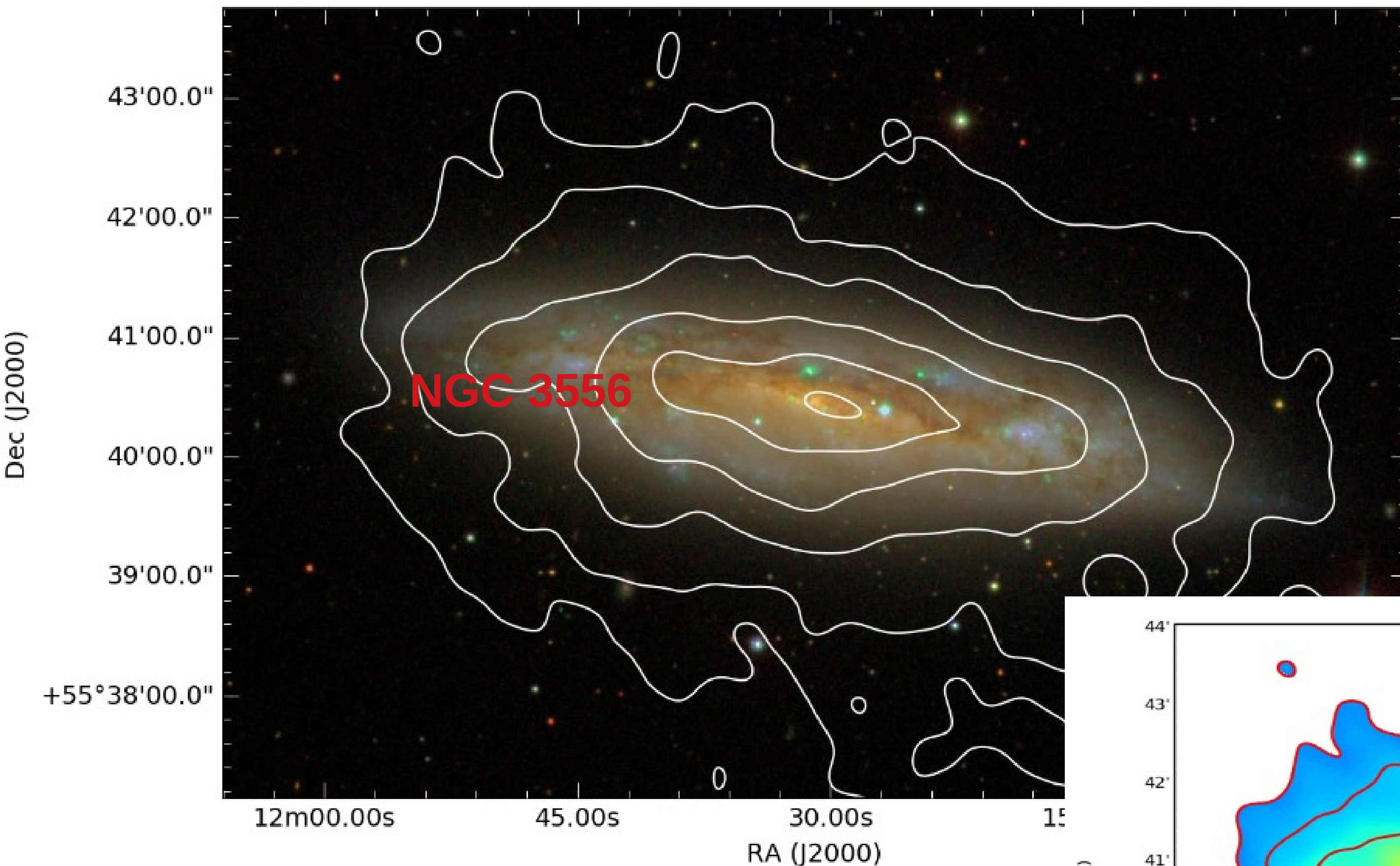
Jet dynamics

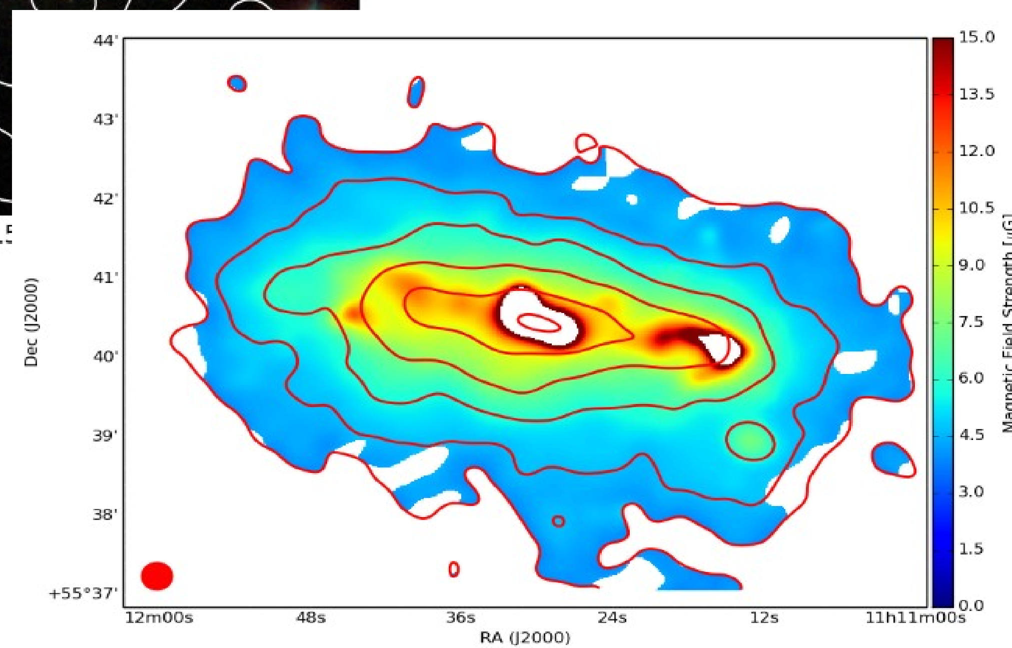
Feedback and duty cycle



Mahatma et al.

Nearby galaxies





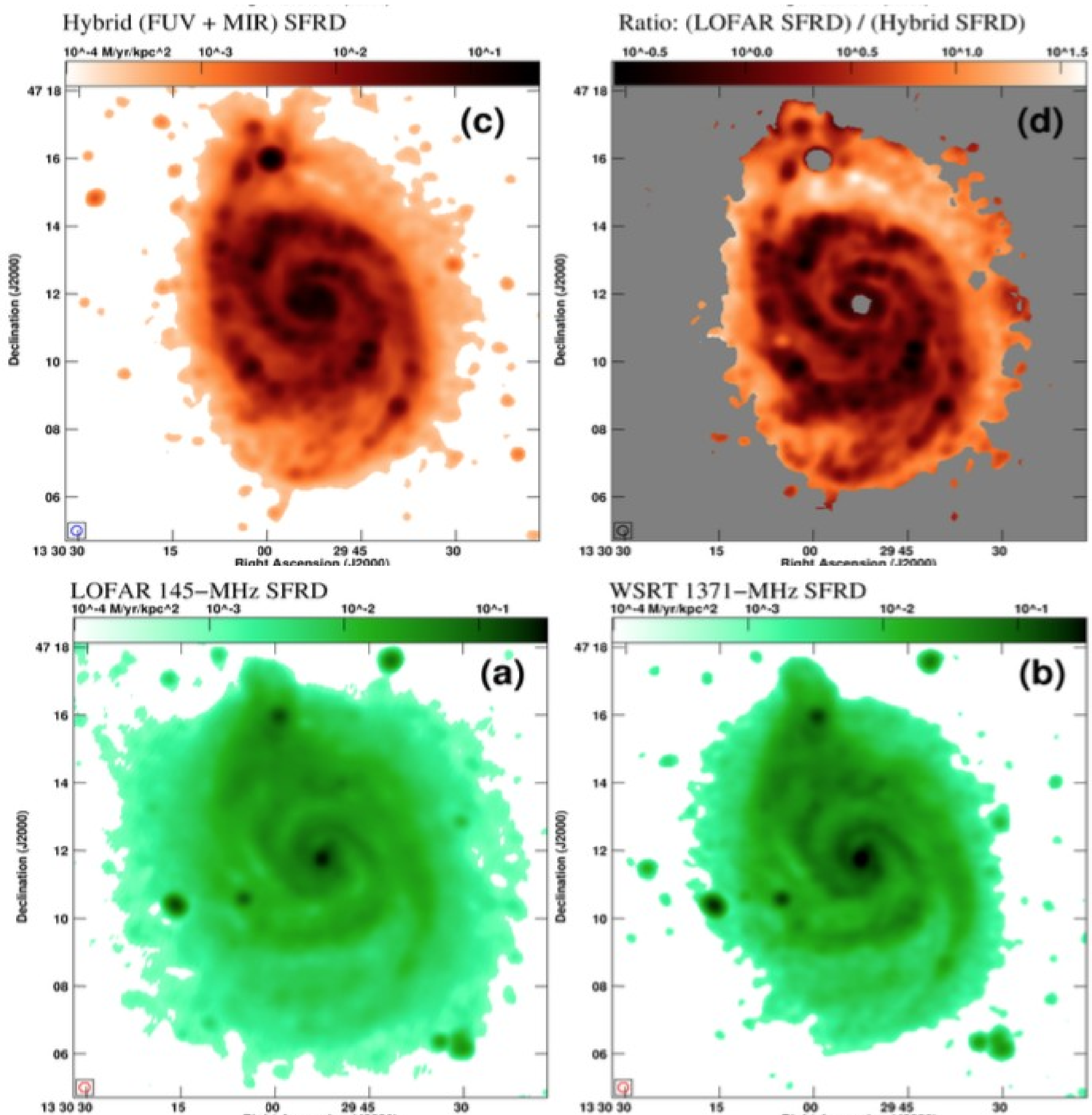
Miskolczi et al.

- Cosmic rays emitting synchrotron in a galactic Haloe
- Constrains on CR Energy, magnetic field and galactic winds speed

Nearby galaxies

- Study the Radio to Star Formation relation (FIR & UV)

- Cosmic ray electron transport



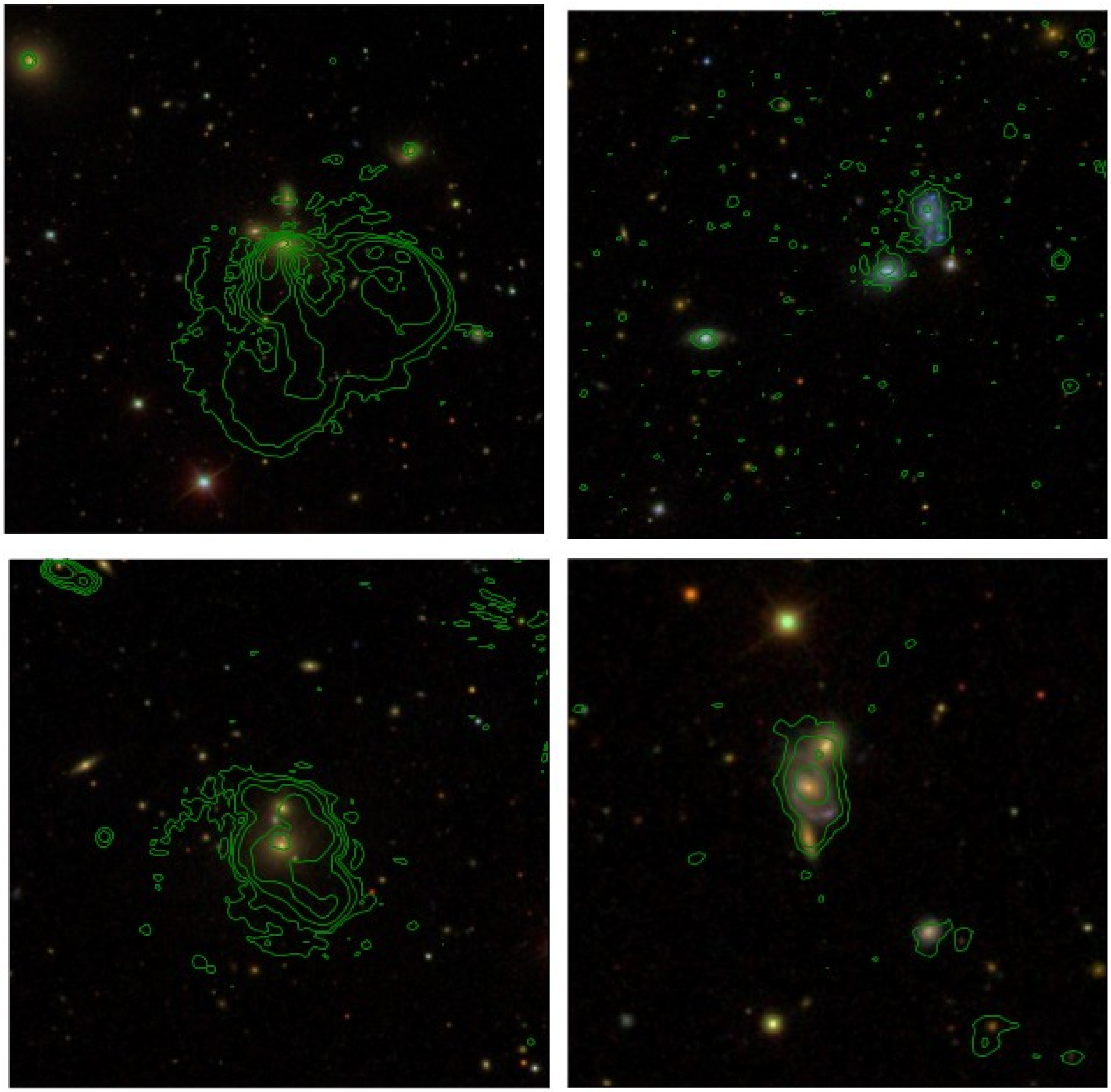
Heesen et al.

Nearby galaxy groups

Nikiel-Wroczyński et al. In prep

Using
- SDSS
- NVSS
- FIRST

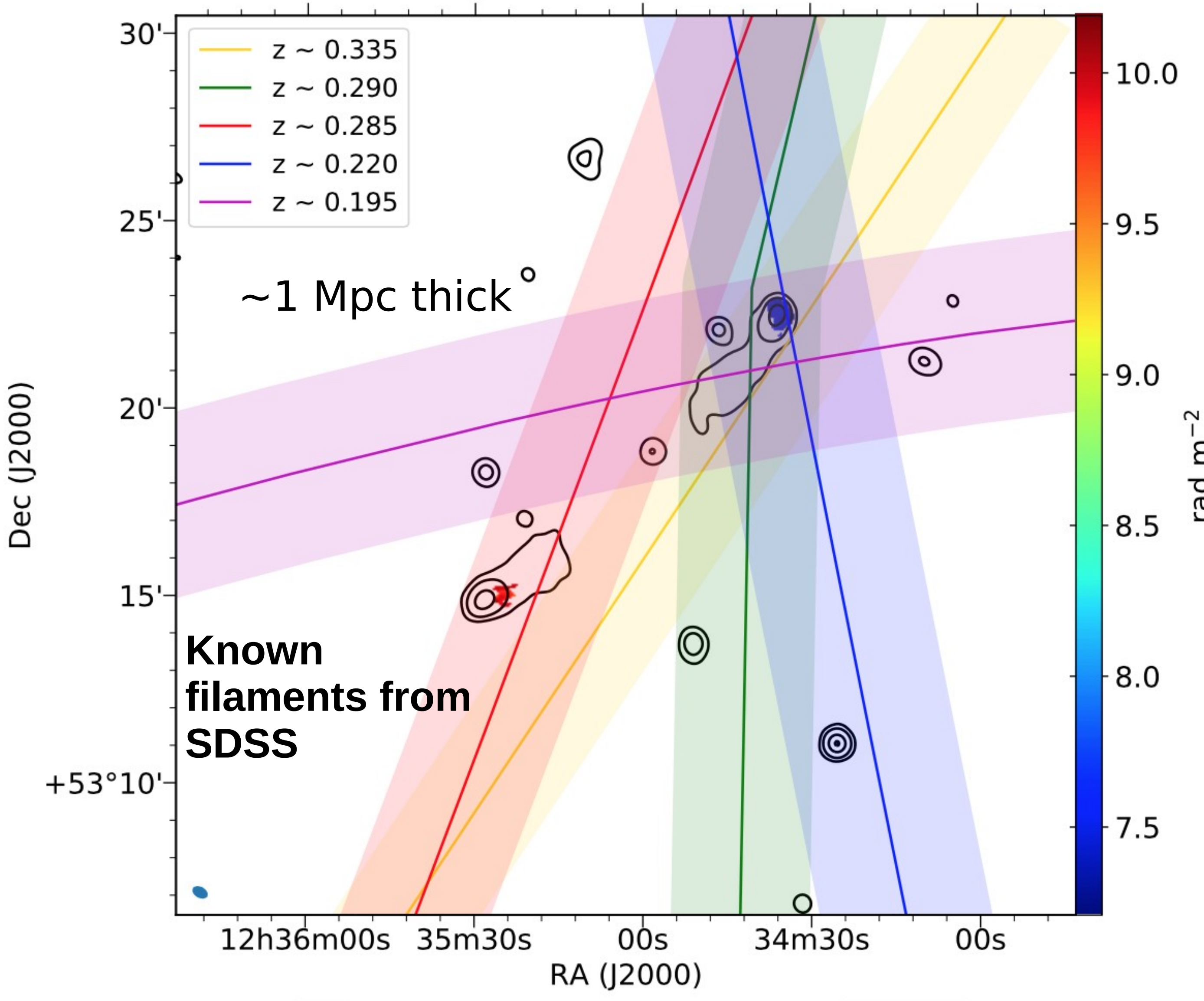
- 17/107 show signs of intergalactic structure
- Study of the magnetic field of the IGM



LSS Filaments

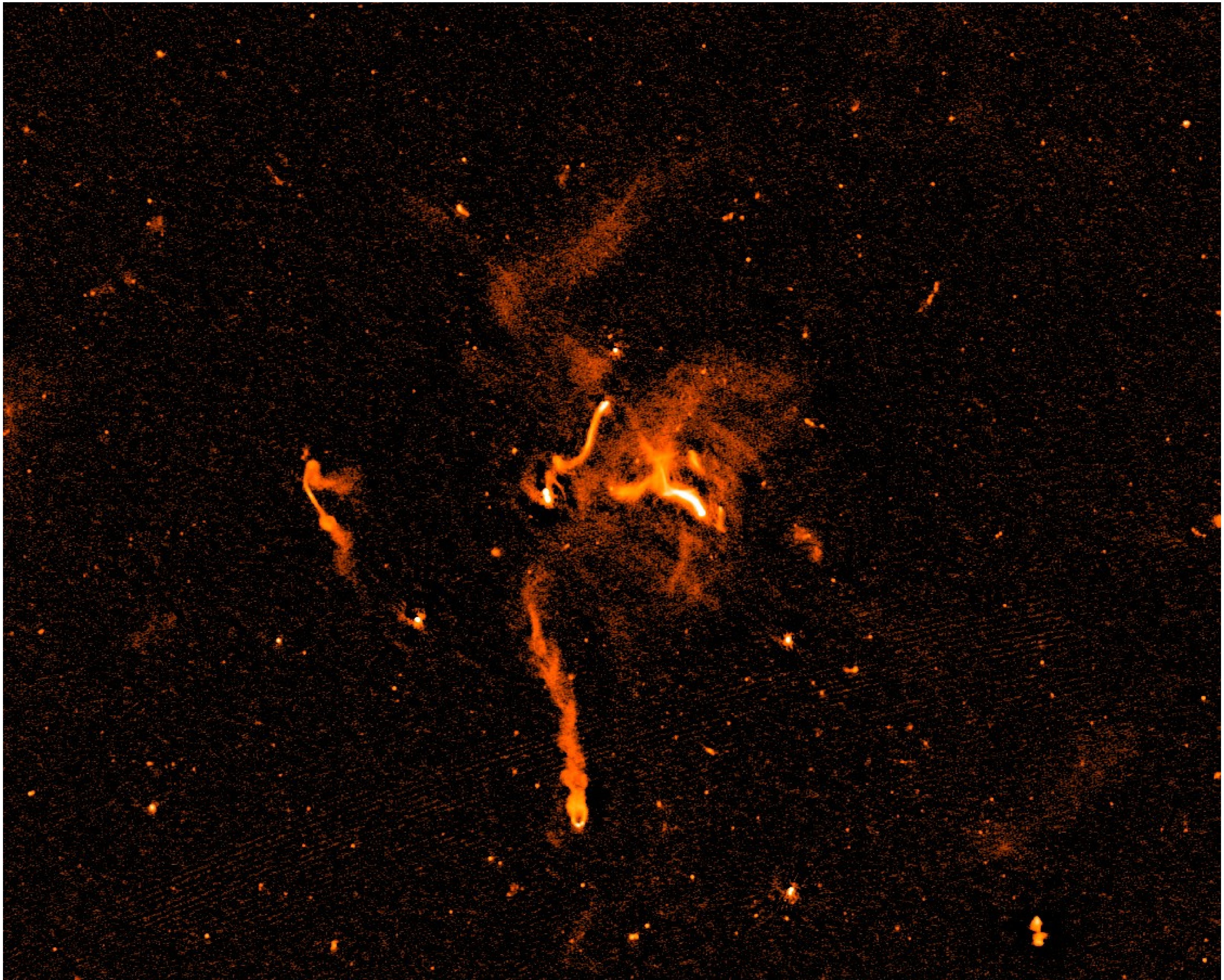
- Relativistic electrons don't do RM
- How large? 3.4 Mpc
- Lobes expanding in an empty region
- Large-scale structure filaments ? from SDSS by Chen+15, 16

Excess of 3 filaments for North lobe



O'Sullivan et al.

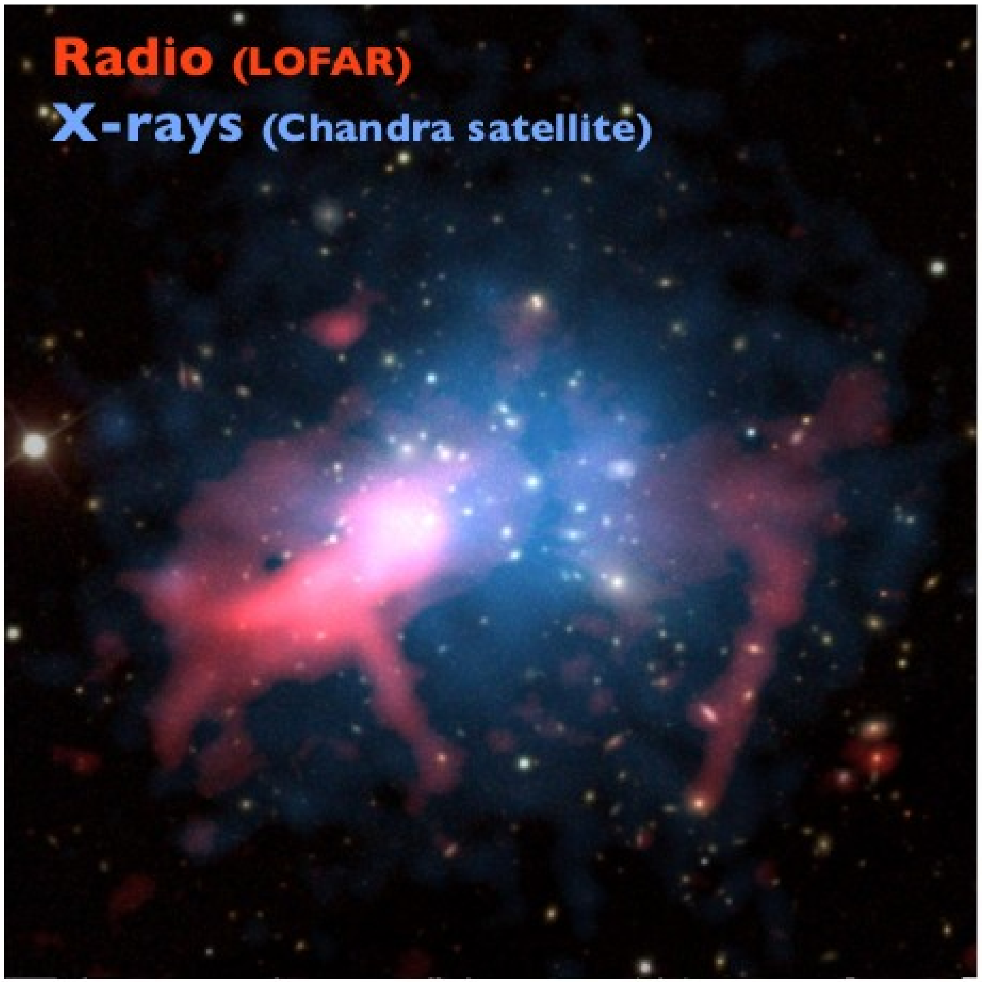
Galaxy clusters



Galaxy clusters

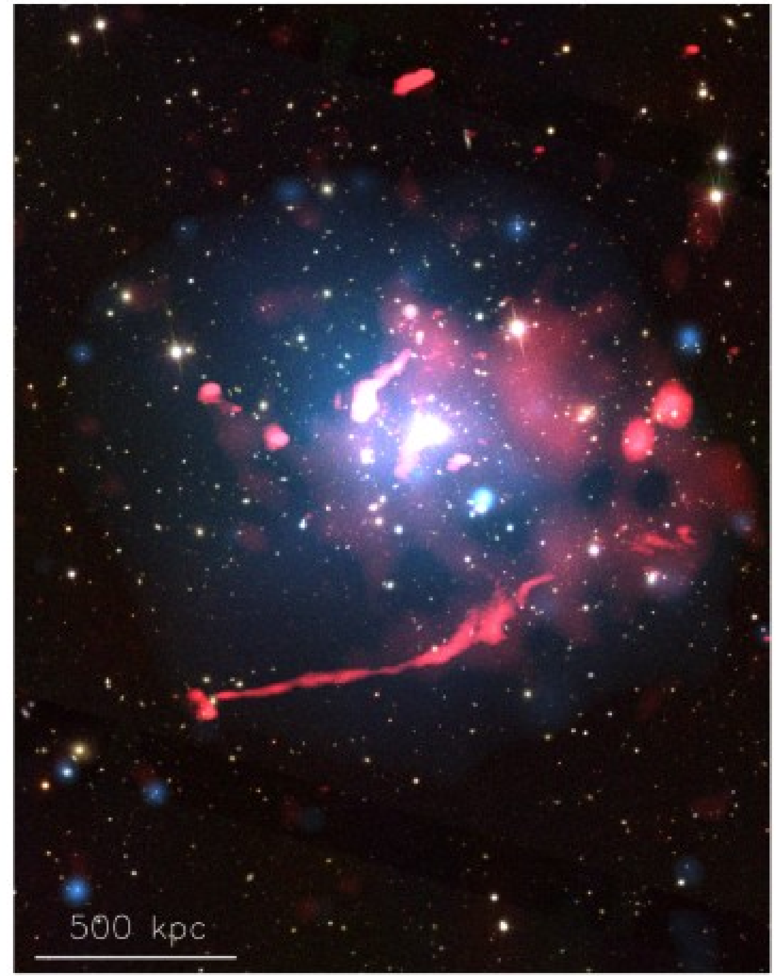
See Chiara Ferarri talk

Abell 1914



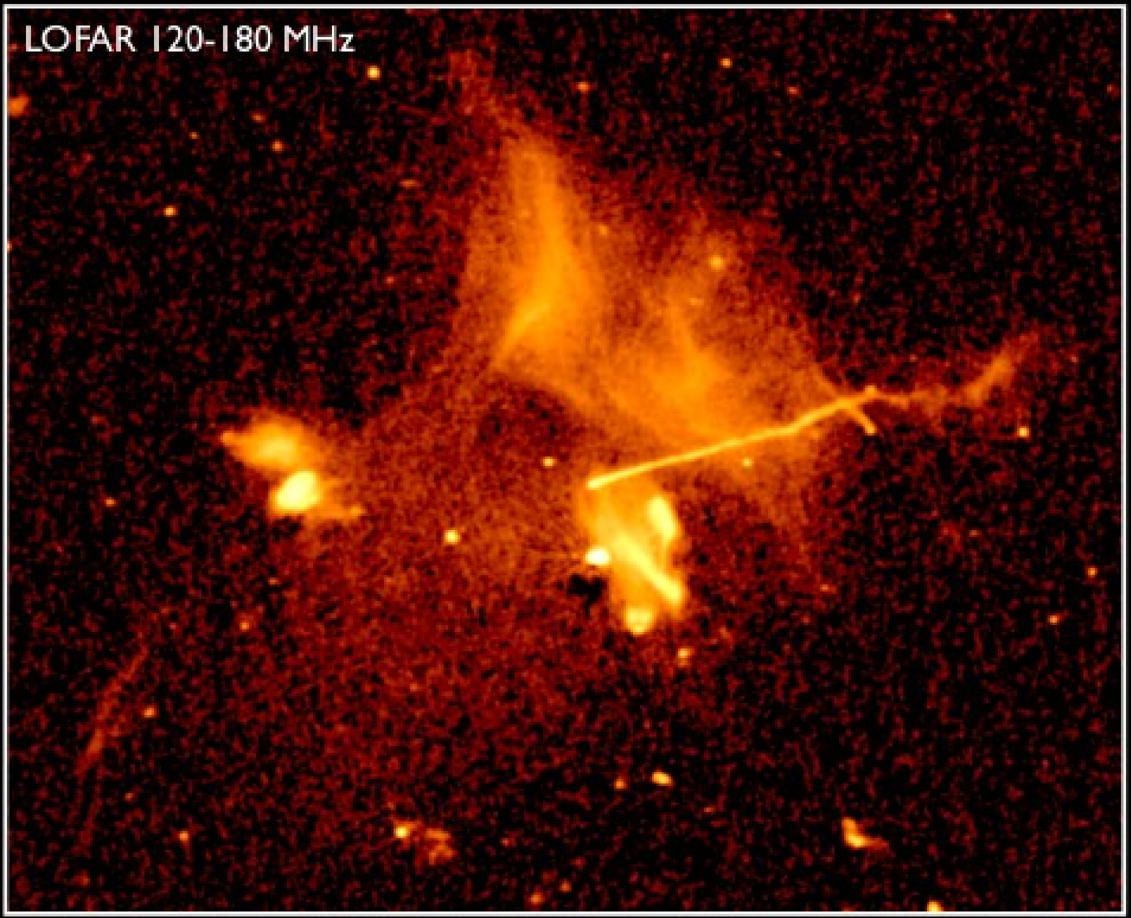
Mandal+ (2018, in prep)

Abell 1132

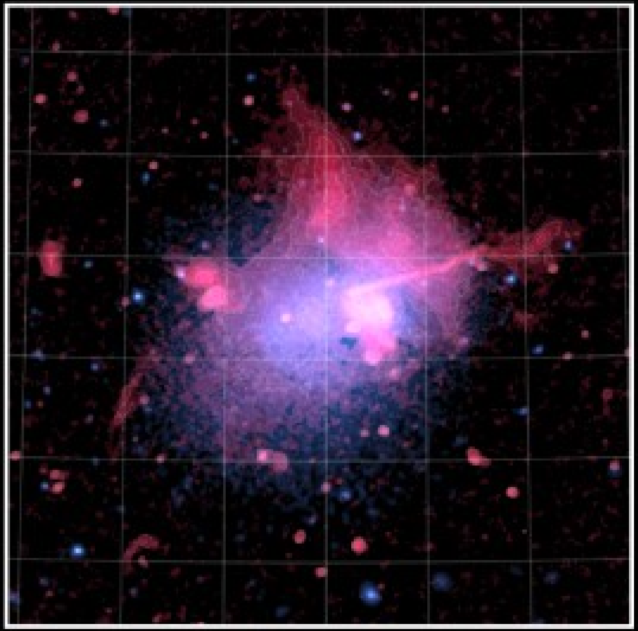


Wilber+ (2017)

ABELL 2256



Radio (LOFAR)
X-rays (XMM)



- Merging cluster
- z = 0.05

Van Weeren et al. In prep

Thank you !