



# Improvements of LoTSS calibration and imaging for DR2 and application to LoTSS-deep fields

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**for the LOFAR Surveys KSP**

# Interferometry

## TRUTH domain

- Ionosphere
- Troposphere
- Beam
- Faraday rotation
- Electronics
- etc
- Sky

baseline

Direction

time

freq

?

« Calibration & imaging algorithms »

## Measurement domain

baseline

time

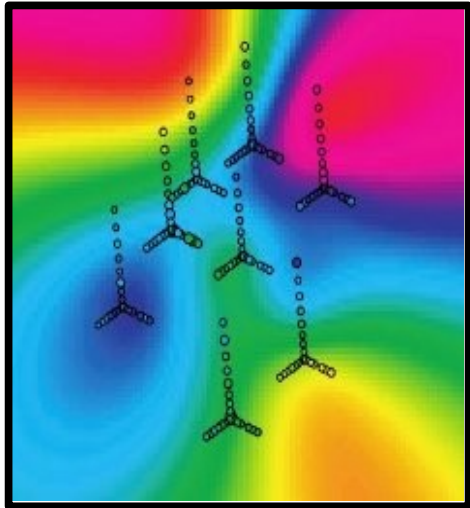
freq

Non-linear operator  $h$

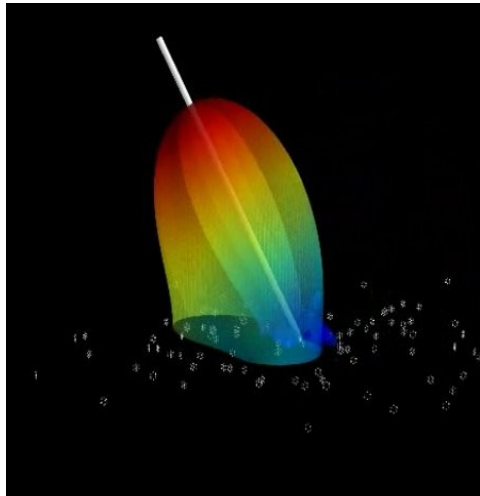
$$V_{pq} = G_p \left( \sum_{i=1}^N B_{pi} K_{pi} I_{pi} F_i \cdot F_i^+ I_{qi}^+ K_{qi}^+ B_{qi}^+ \right) G_q^+$$

Hamaker et al. 1996

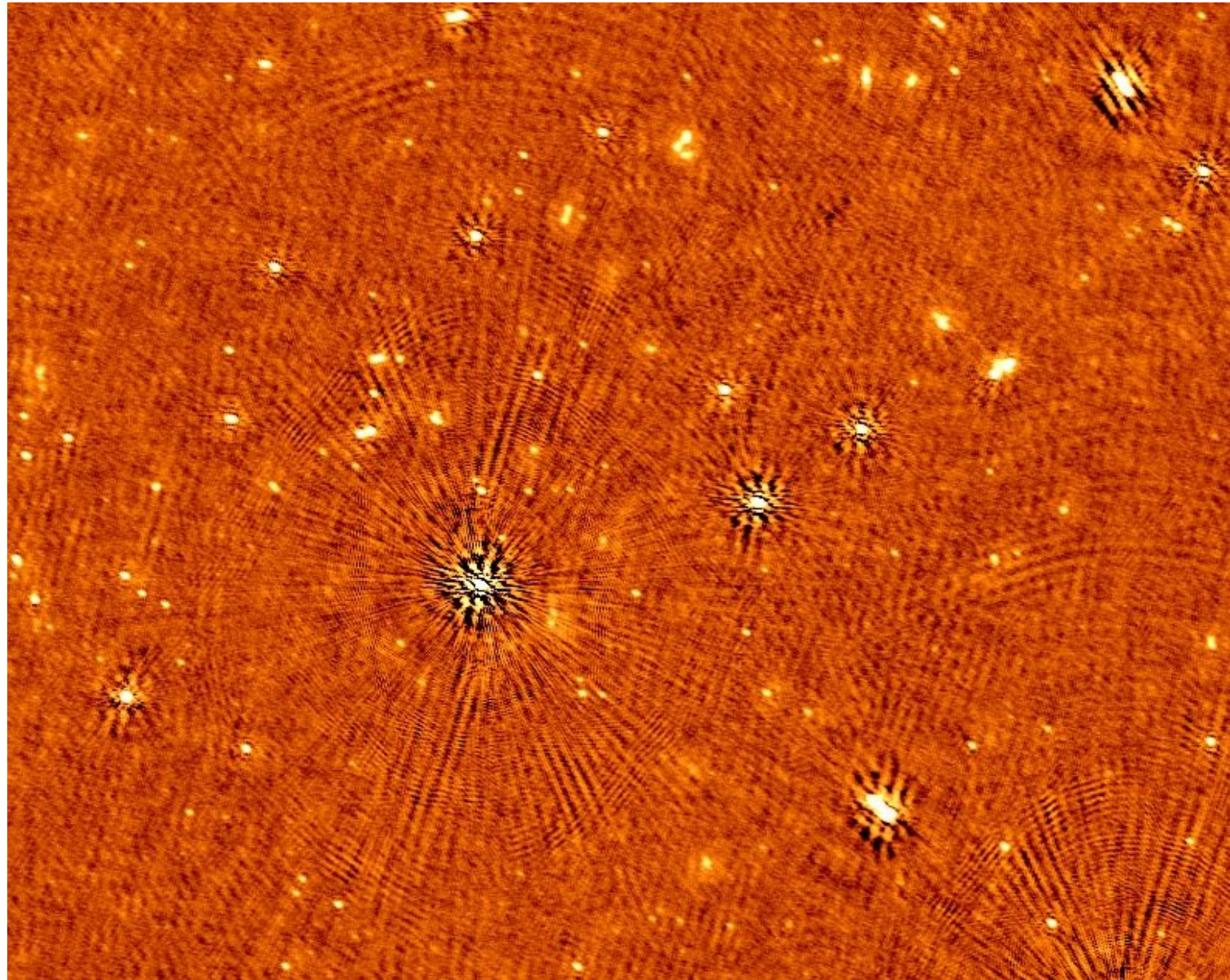
# The best image you can ever get in selfcal



**Ionospheric  
disturbance + Faraday  
rotation**



**Station lobes**



# Interferometry

TRUTH domain

- Ionosphere
- Troposphere
- Beam
- Faraday Rotation
- Electronics
- etc

**Jones Matrices**

- Sky

baseline

Direction

time

freq

« DD-calibration »

Estimate **Jones matrices** given Sky

Non-linear operator **h**

$$V_{pq} = G_p \left( \sum_{i=1}^N B_{pi} K_{pi} I_{pi} F_i \cdot F_i^+ I_{qi}^+ K_{qi}^+ B_{qi}^+ \right) G_q^+$$

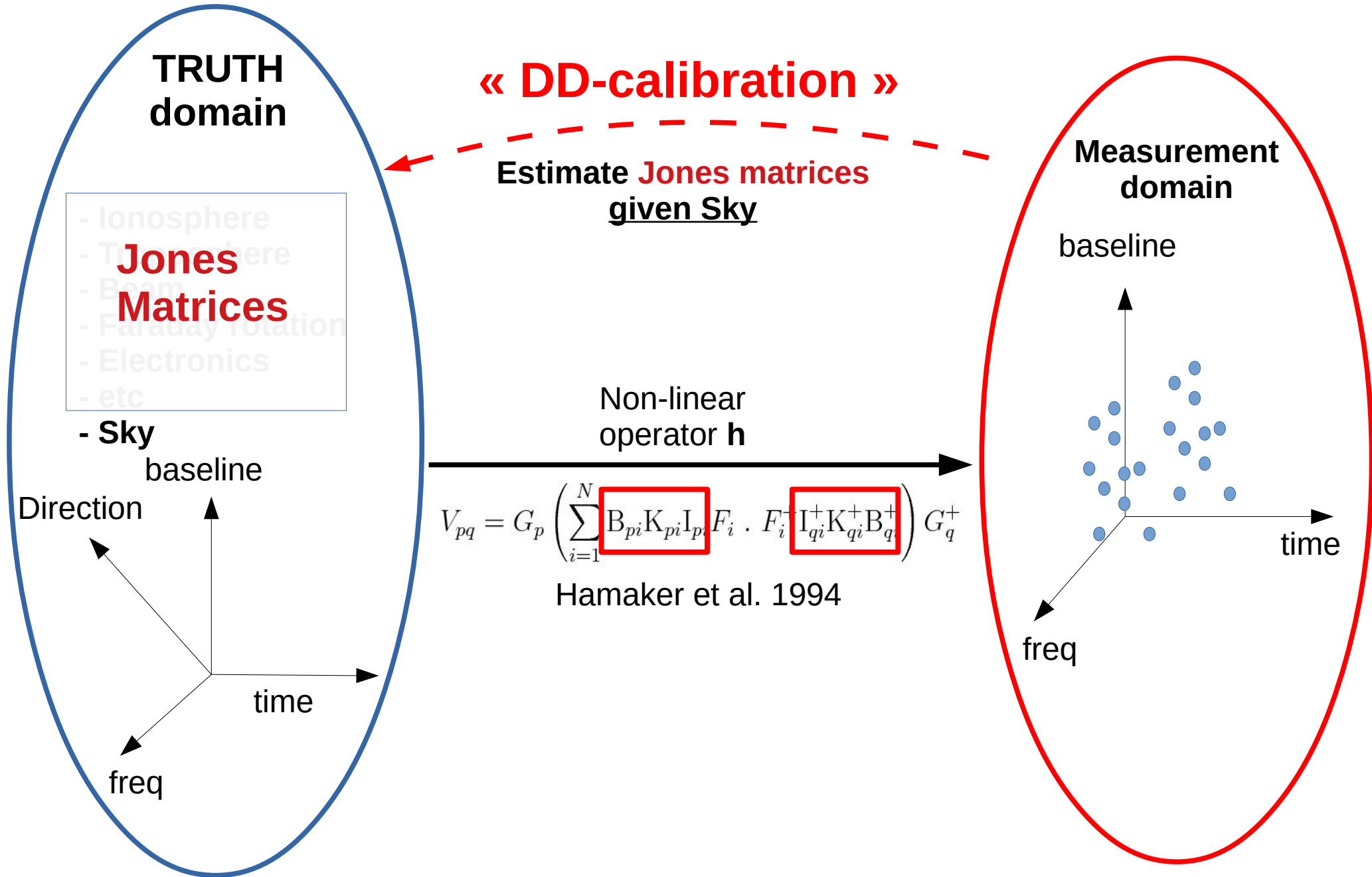
Hamaker et al. 1994

Measurement domain

baseline

time

freq



# Interferometry

TRUTH domain

- Ionosphere
- Troposphere
- Beam
- Faraday Rotation
- Electronics
- etc

**Jones Matrices**

- Sky

baseline

Direction

time

freq

« DD-imaging »

Estimate **Sky**  
given Jones Matrices

Non-linear operator **h**

$$V_{pq} = G_p \left( \sum_{i=1}^N B_{pi} K_{pi} I_p \boxed{F_i \cdot F_i^+} I_{qi}^+ K_{qi}^+ B_{qi}^+ \right) G_q^+$$

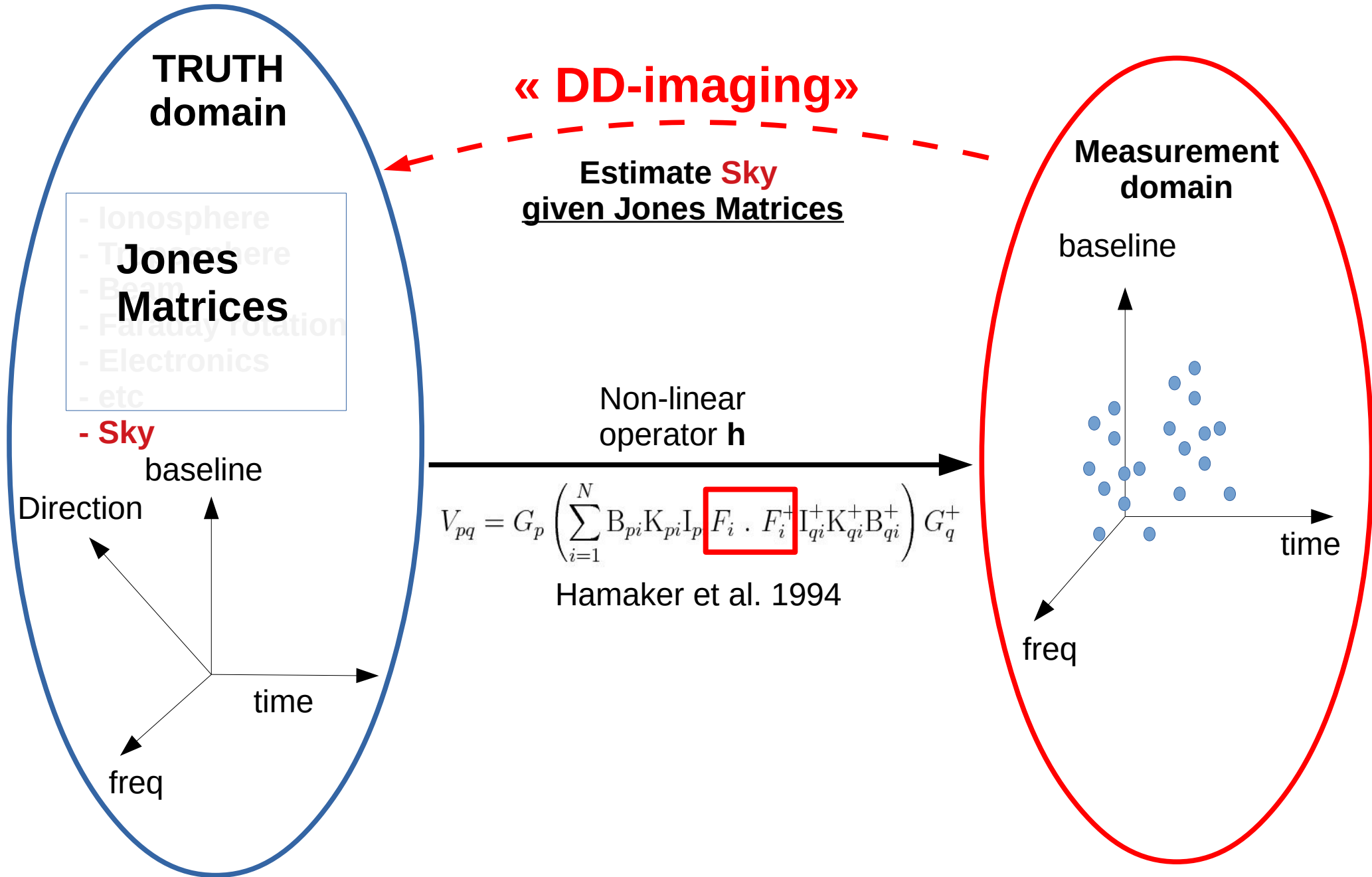
Hamaker et al. 1994

Measurement domain

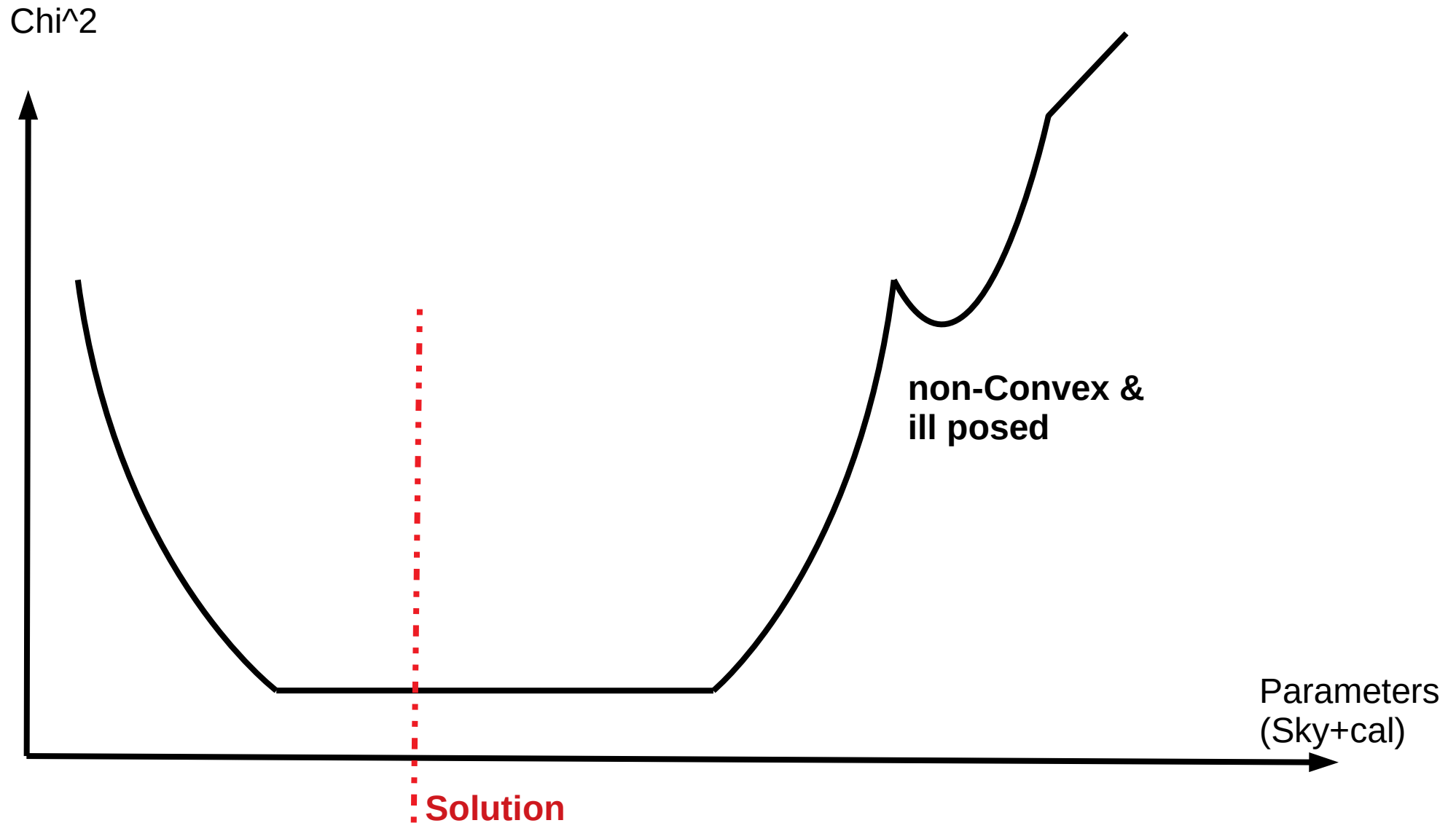
baseline

time

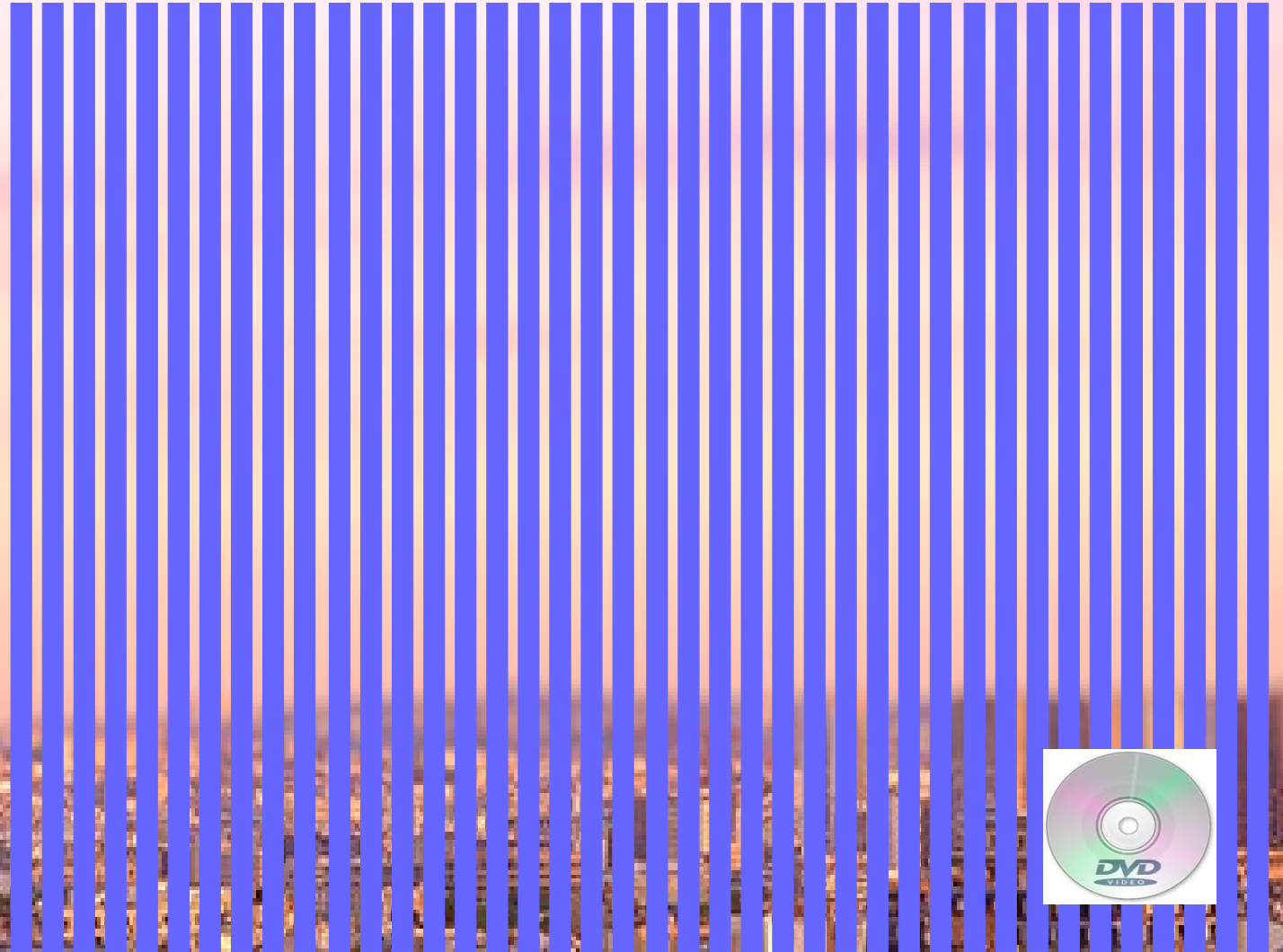
freq



# First issue : Convexity, Conditionning



# Second issue : Data volume



Tier-1 LOFAR Survey : to be observed  
48 Pbytes of Raw data → ~39 Eiffel tower 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**

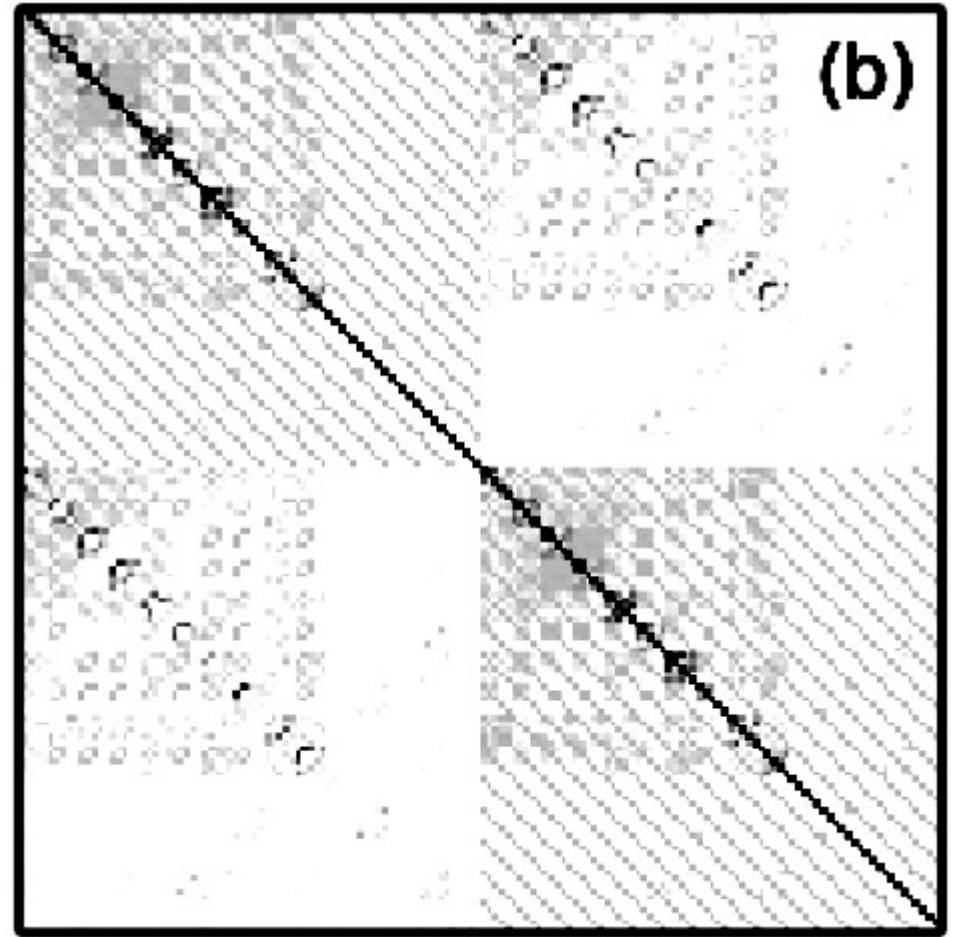


# RIME Calibration

Cost  
function

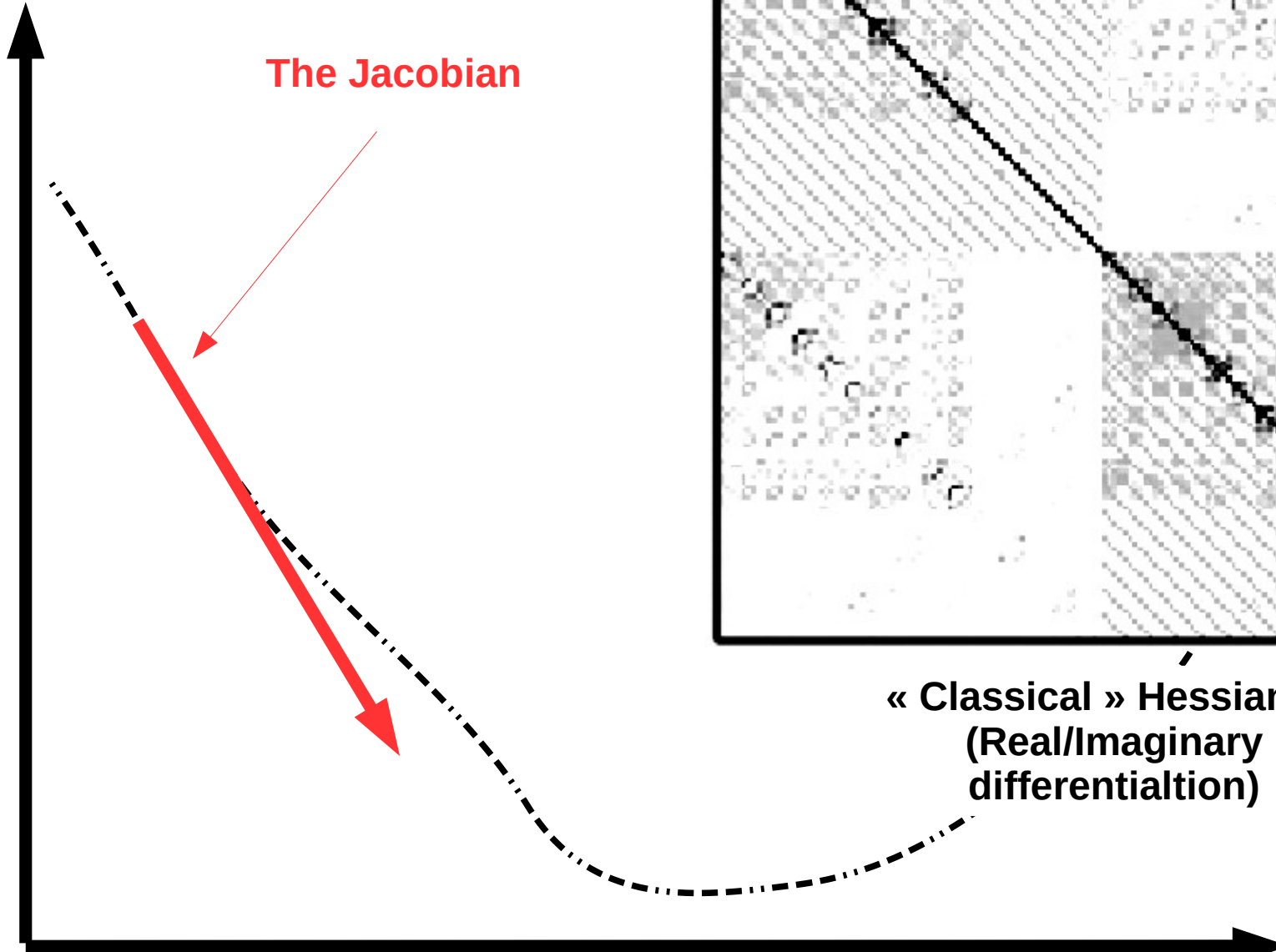
The Jacobian

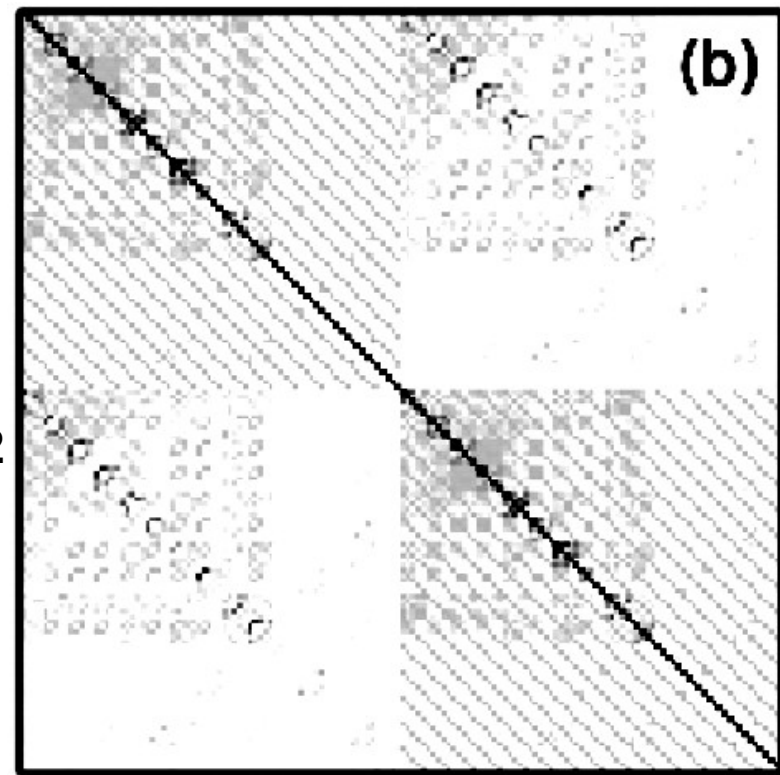
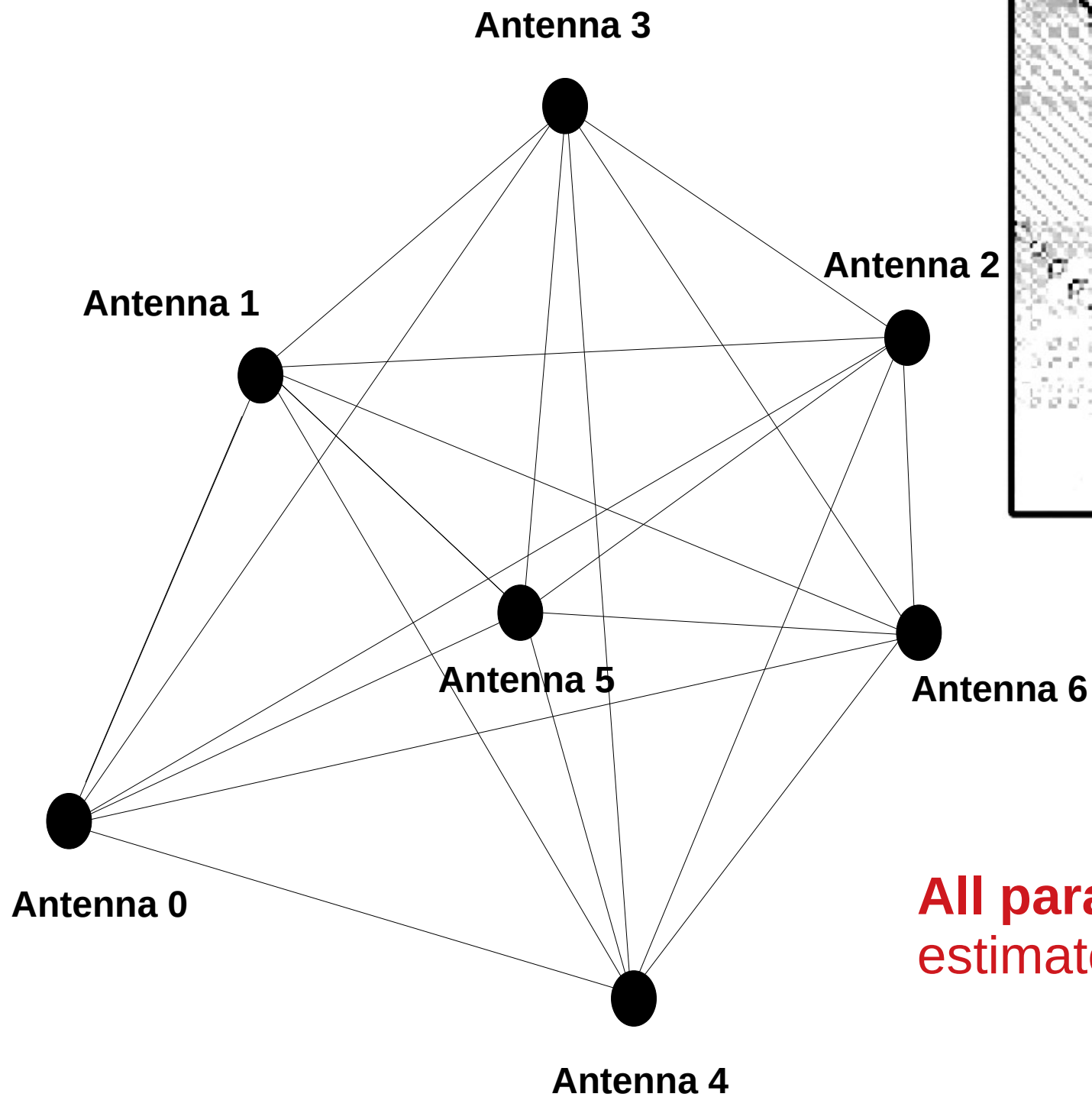
(b)



« Classical » Hessian  
(Real/Imaginary  
differentialtion)

Jones  
Matrices  
values





« Classical » Hessian  
(Real/Imaginary  
differentiation)

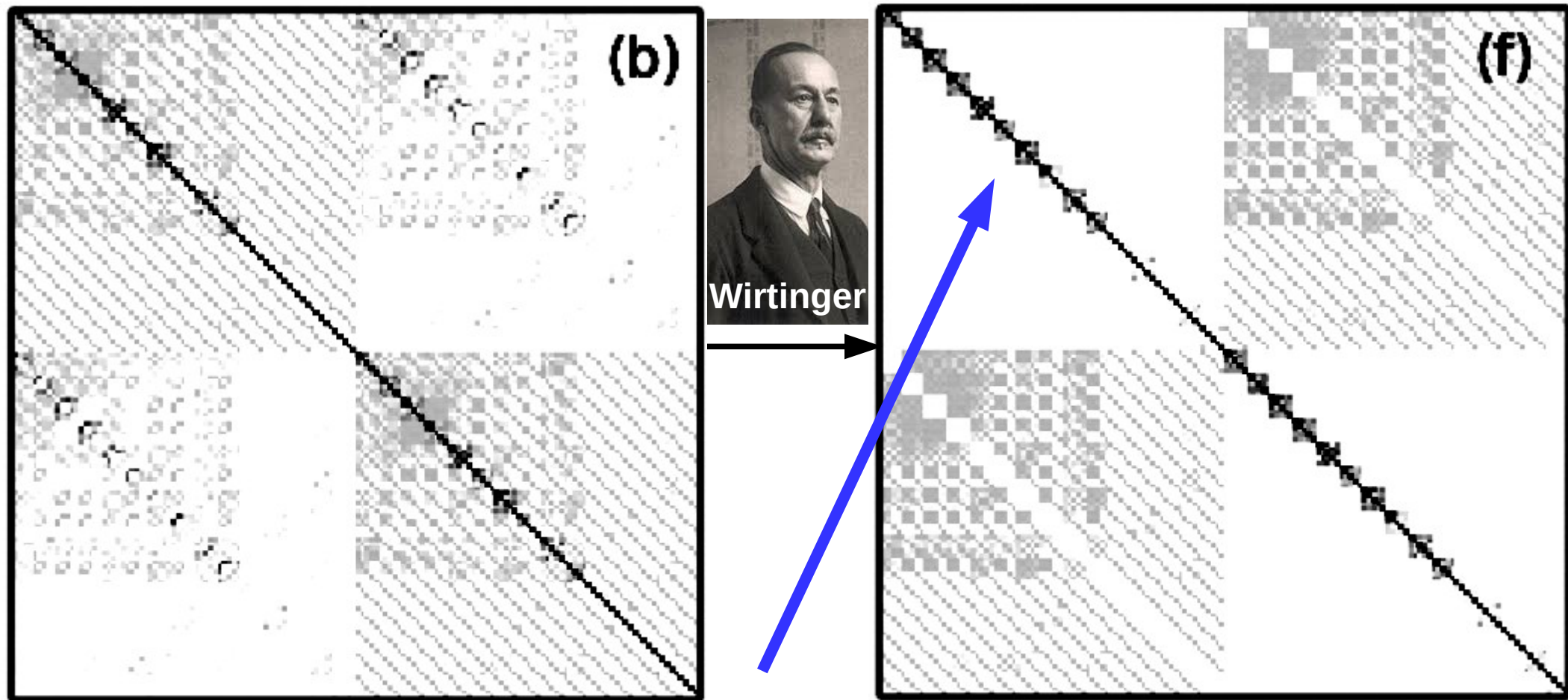
**All parameters** have to be  
estimated using **all data**

# Wirtinger 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

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

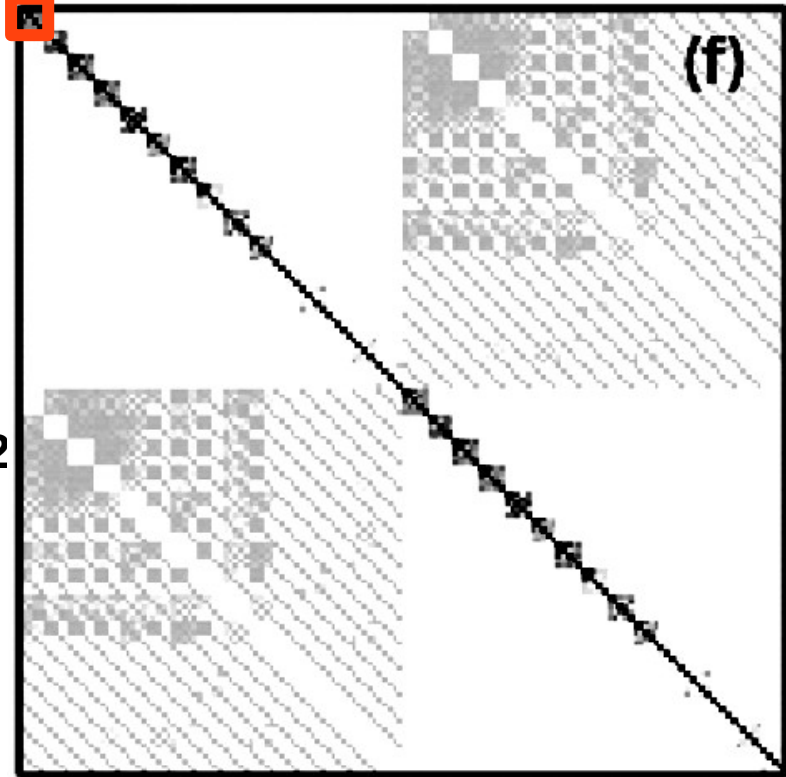
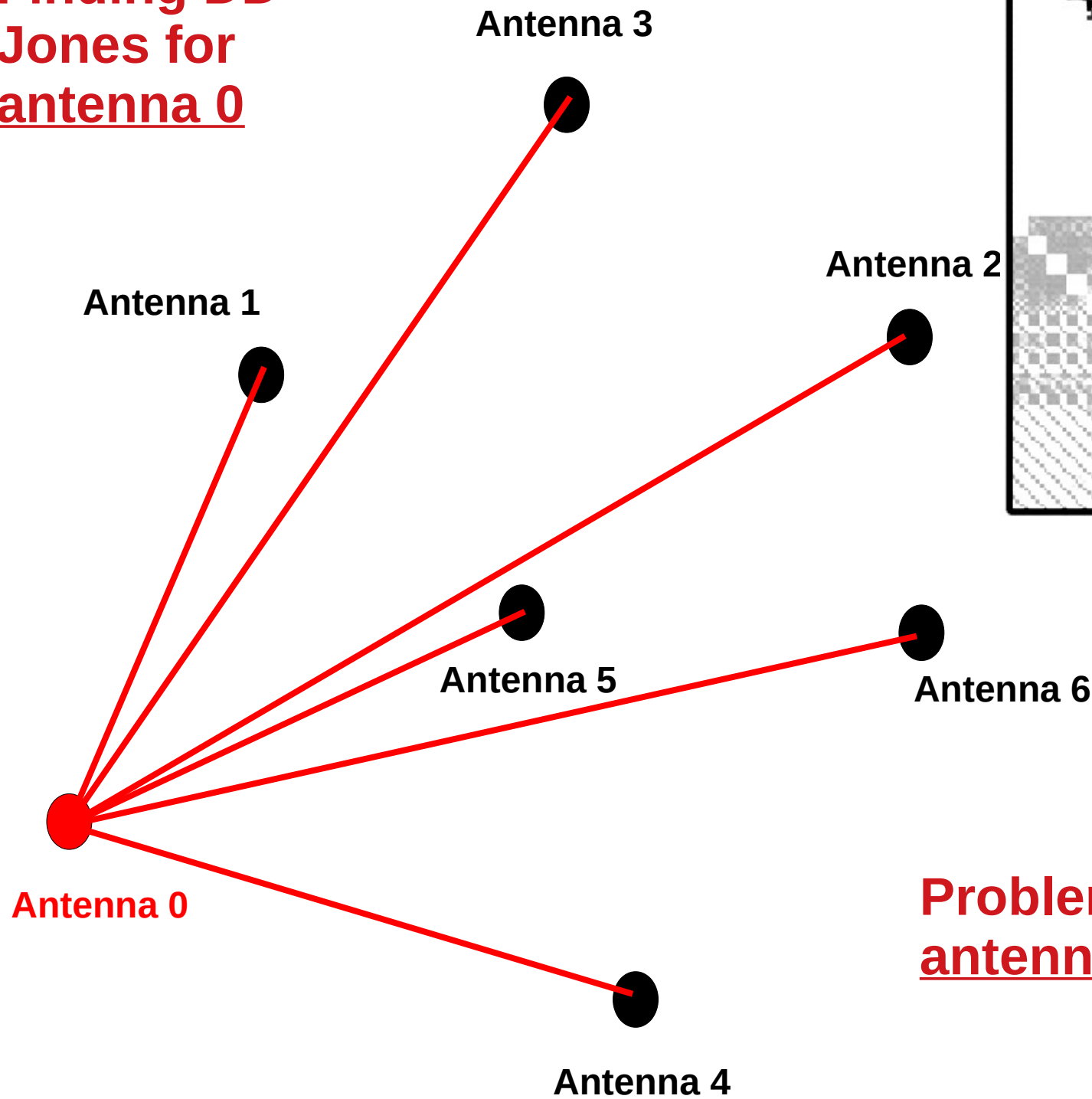


« Classical » Hessian

Those Blocks  
are (Nd x Nd)

Wirtinger Hessian

# Finding DD-Jones for antenna 0

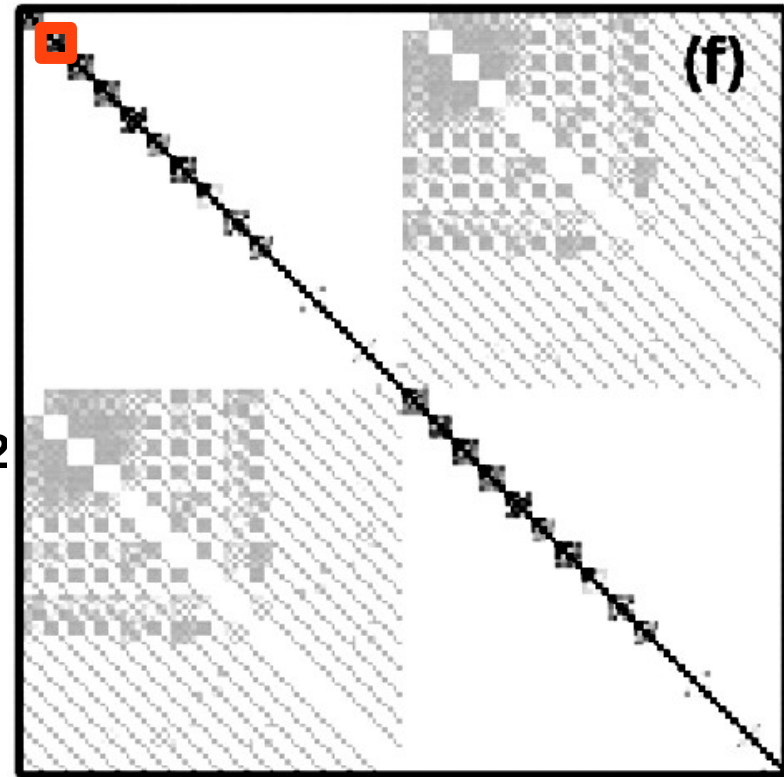
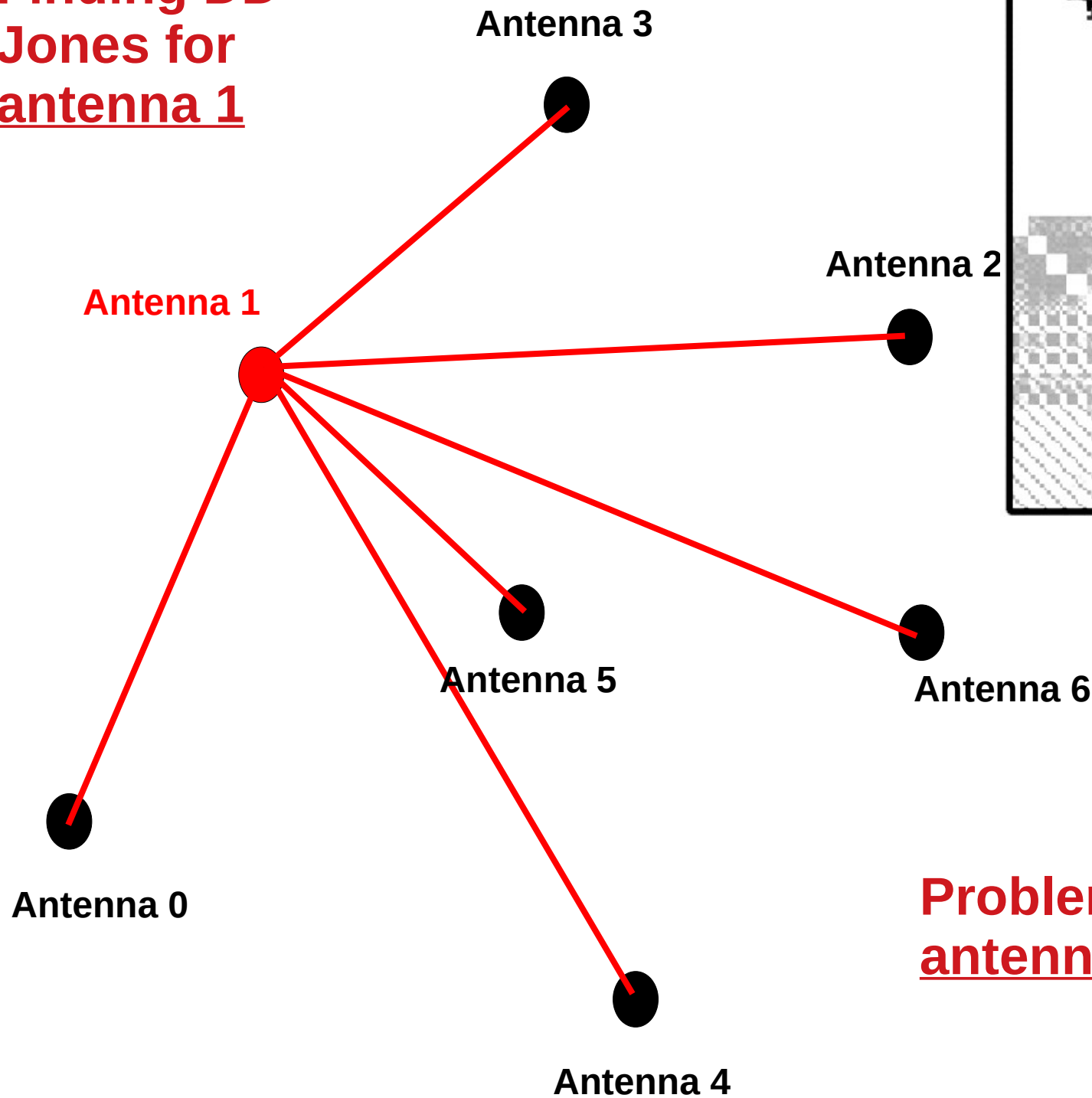


**Wirtinger Hessian**

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

**Problem becomes antenna separable**

# Finding DD-Jones for antenna 1

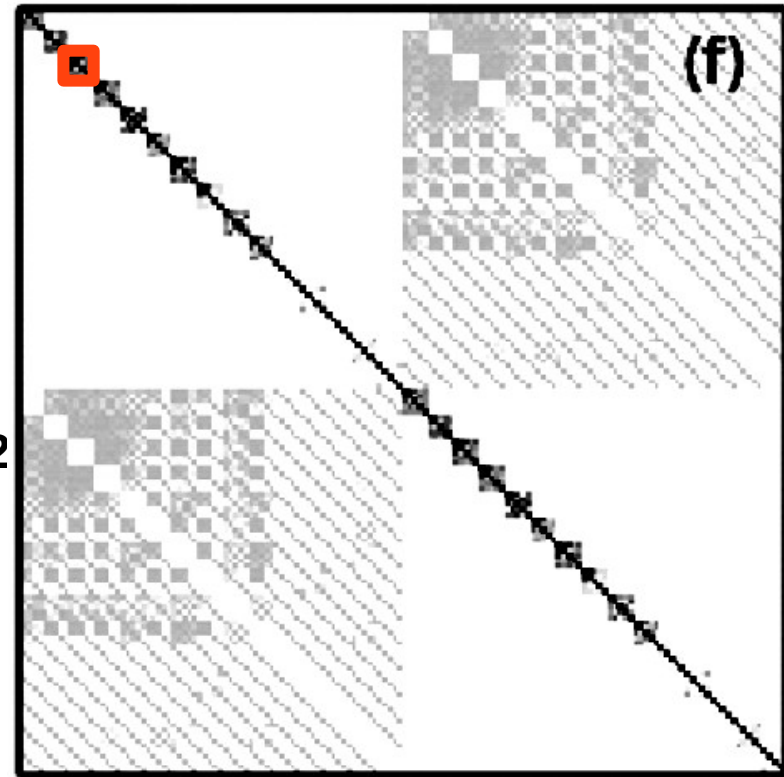
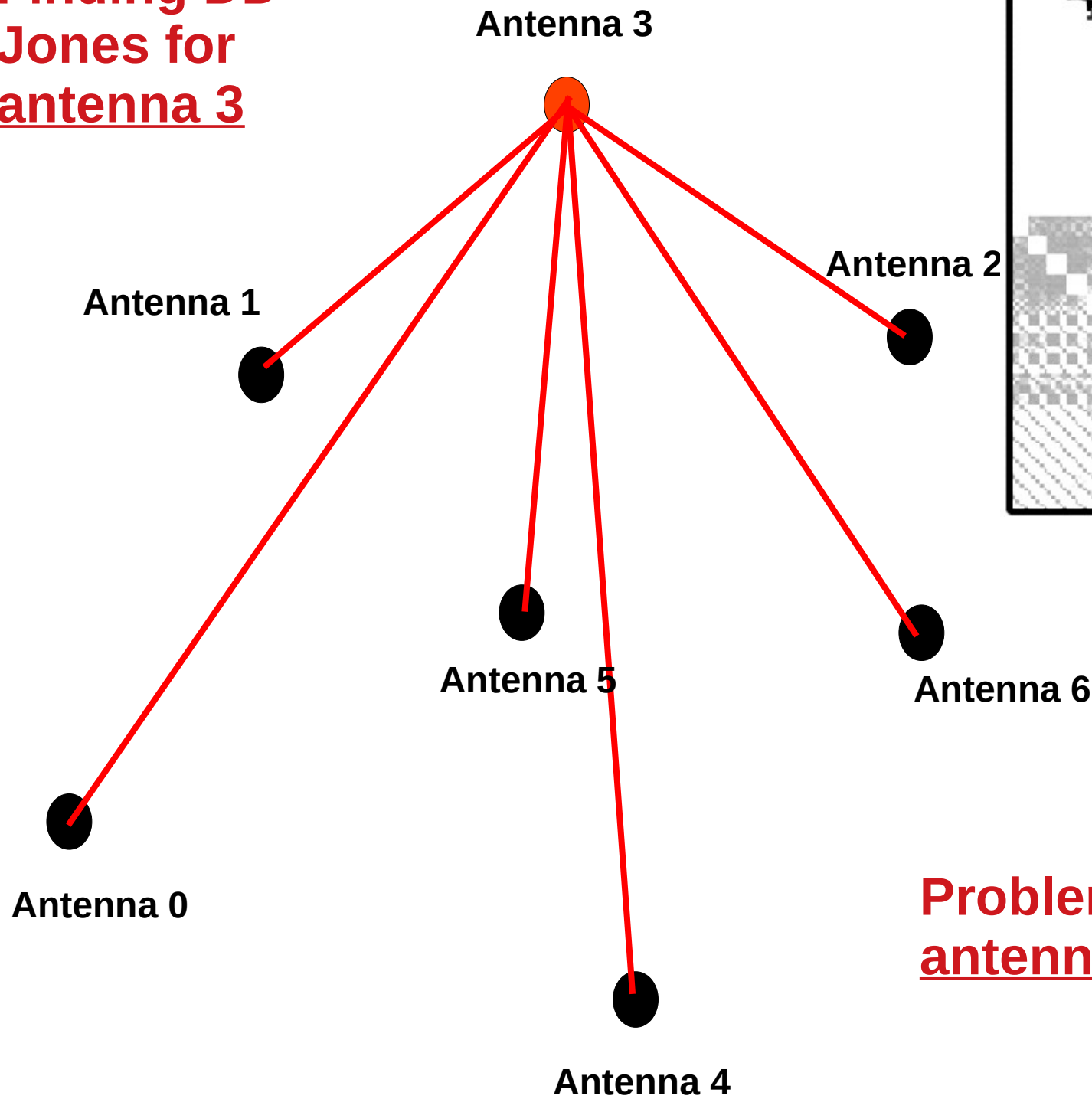


Wirtinger Hessian

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

Problem becomes antenna separable

# Finding DD-Jones for antenna 3



Wirtinger Hessian

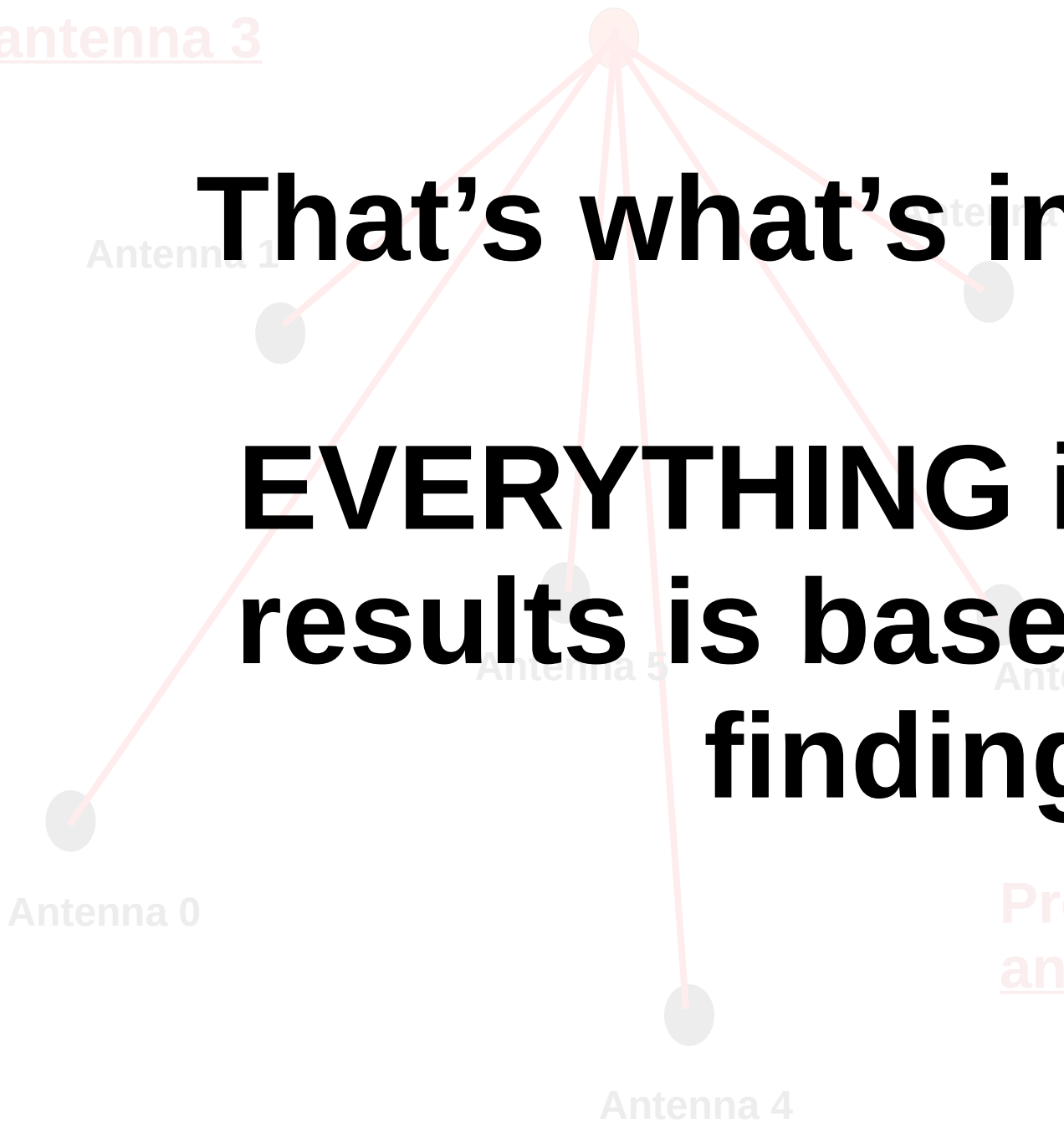
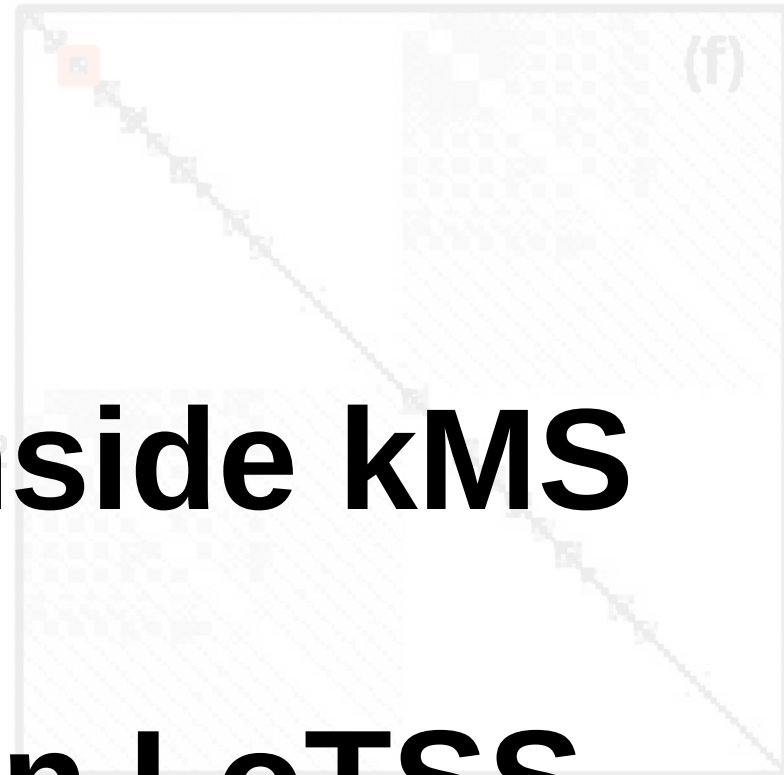
(Tasse 2014,  
Smirnov & Tasse 2015,  
Repetti et al. 2017 )

Problem becomes antenna separable

Finding DD-Jones for antenna 3

**That's what's inside kMS**  
**EVERYTHING in LoTSS**  
**results is based on this**  
**finding**

Problem becomes antenna separable



# Wirtinger algorithms: software

## DDF-pipeline

(Martin Hardcastle, Tim Shimwell, Cyril Tasse, Wendy Williams)

### kiIIMS

(DD-C-RIME solver)

(Tasse 2014, Smirnov & Tasse 2015)

### DDFacet

(DD-I-RIME solver)

Tasse 2018

They talk to each other during DD-selfcal

Wirtinger Jacobian & Hessian

Levenberg-Maquardt

CohJones

(Tasse 14 ; Smirnov & Tasse 15)

Kalman filter

KAFCA

I'm just using this one in the rest of the talk

dealing with *spacially discrete* DD-Jones matrices

Designed to do Wide-Band spectral deconvolution taking generic Beam+Wirtinger DDE solutions into account

Single direction ▼

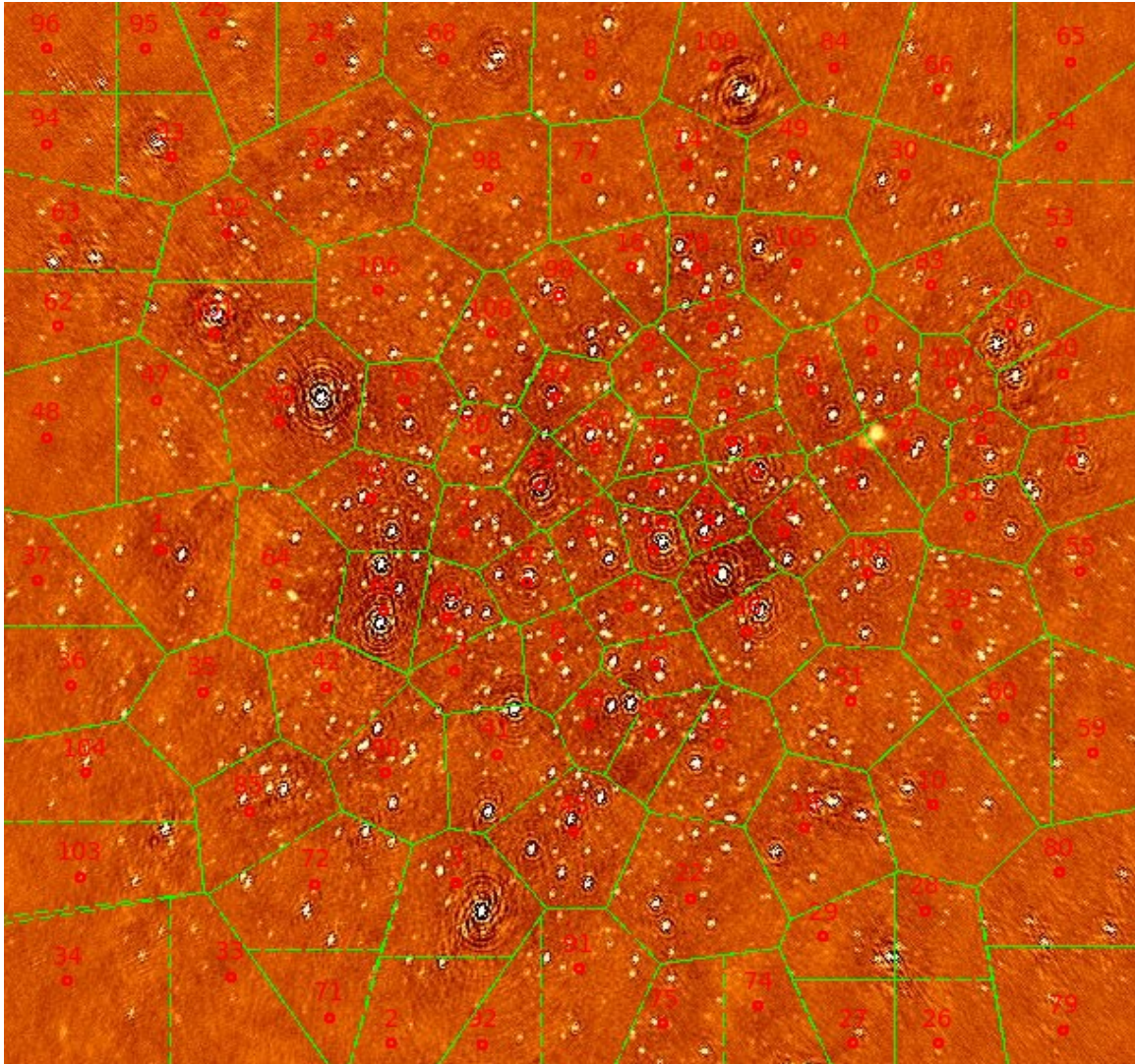
Direction independent : StefCal (Salvini & Wijnholds 2014)



# DDFacet

Tasse et al. 2018

... A facet based imager



- (1) Produces a single tangential plane !  
(no « noise jumps » thanks to the kalman filter, and faceting mode) – *largely inspired from Kogan&Greisen 2009*
- (2) Does full polarisation DDE correction
- (3) Baseline Dependent Averaging  
90 % of the data can be compressed
- (4) Does tessellated images
- (5) Does take time-freq-baseline-direction dependent beam into account
- (6) Continuity between facets
- (7) Takes variable PSF into account  
(DDE, Smearing/Decorrelation)
- (8) Mosaicing (!)
- (9) Some very fancy deconvolution algorithm (SSD)

**8 hours integration with  
LOFAR@~150MHz**

+35°00'

40'

20'

Dec (J2000)

+34°00'

**Without DDE  
correction**

**60 SB**

+33°40'

36m

34m

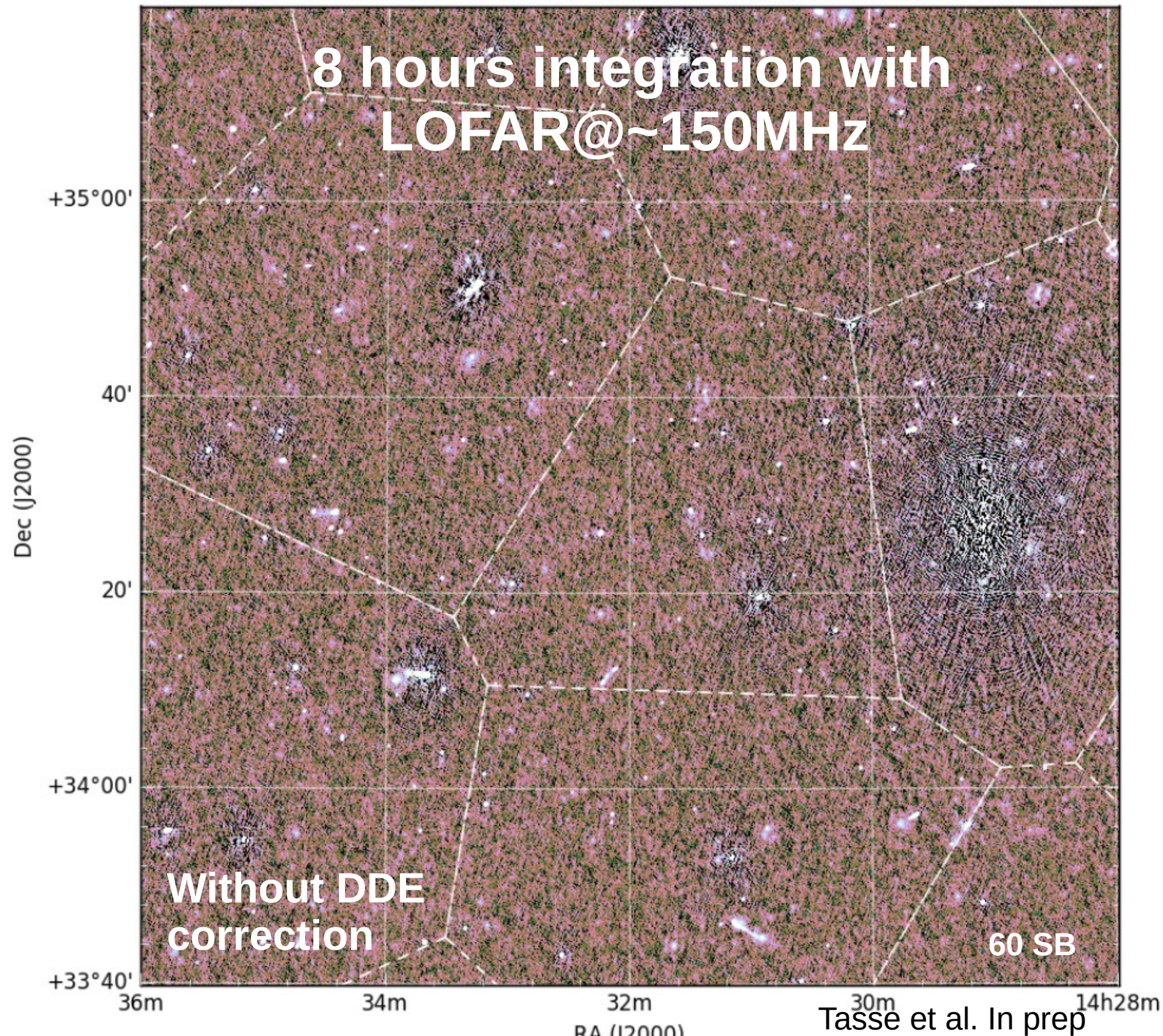
32m

30m

14h28m

RA (J2000)

Tasse et al. In prep



**8 hours integration with  
LOFAR@~150MHz**

+35°00'

40'

Dec (J2000)

20'

+34°00'

**With DDE correction**

**240 SB**

+33°40'

36m

34m

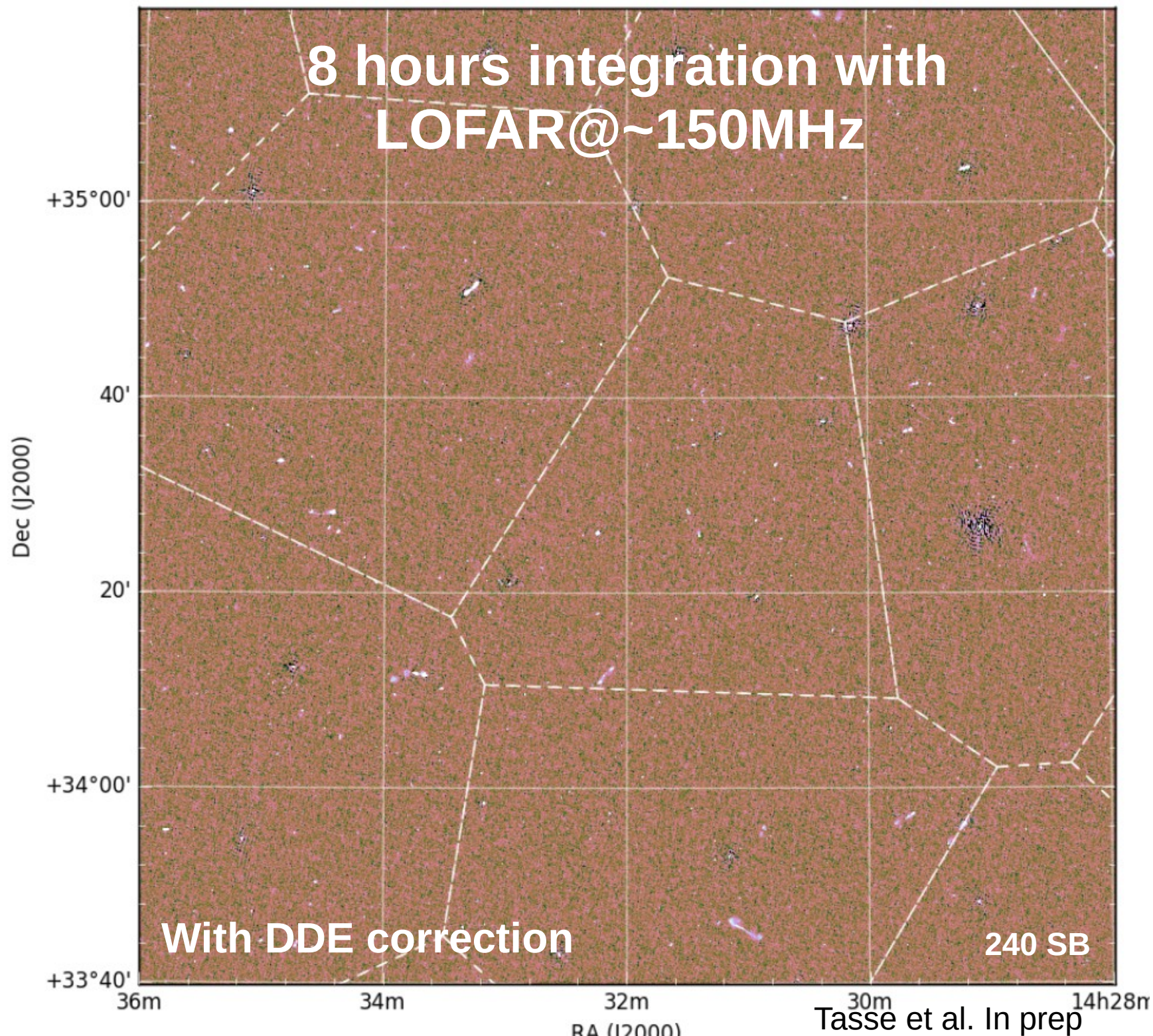
32m

30m

14h28m

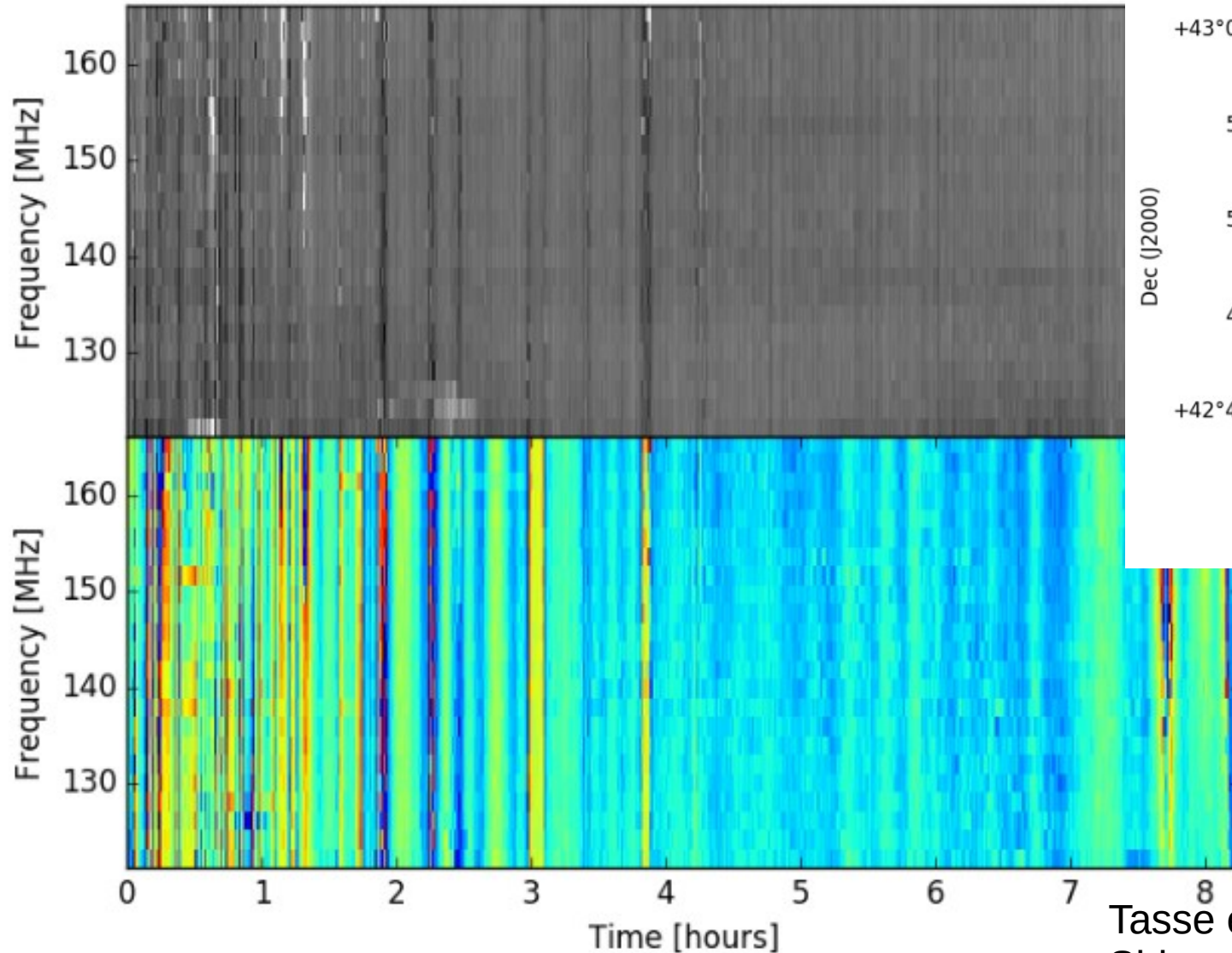
RA (J2000)

Tasse et al. In prep

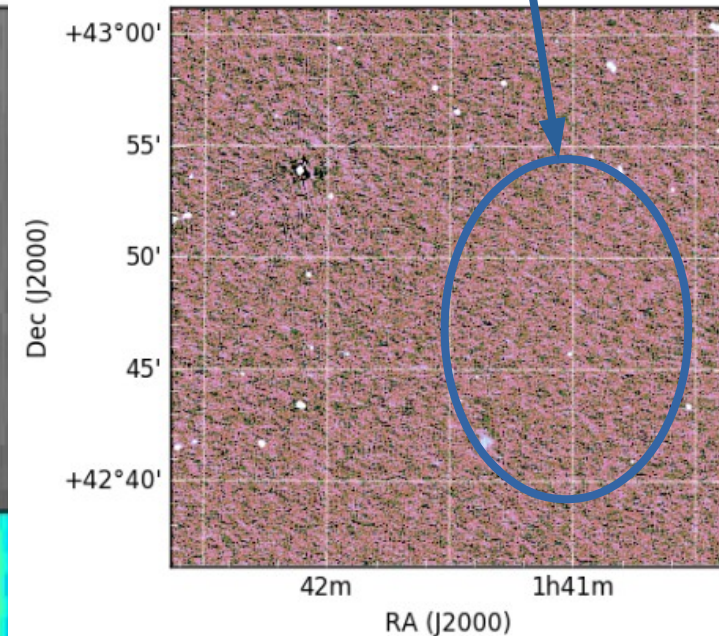


# Ddf-pipeline & LOTSS/DR2 : Gains for different stations

Station RS509HBA



Absorbed  
unmodeled  
emission

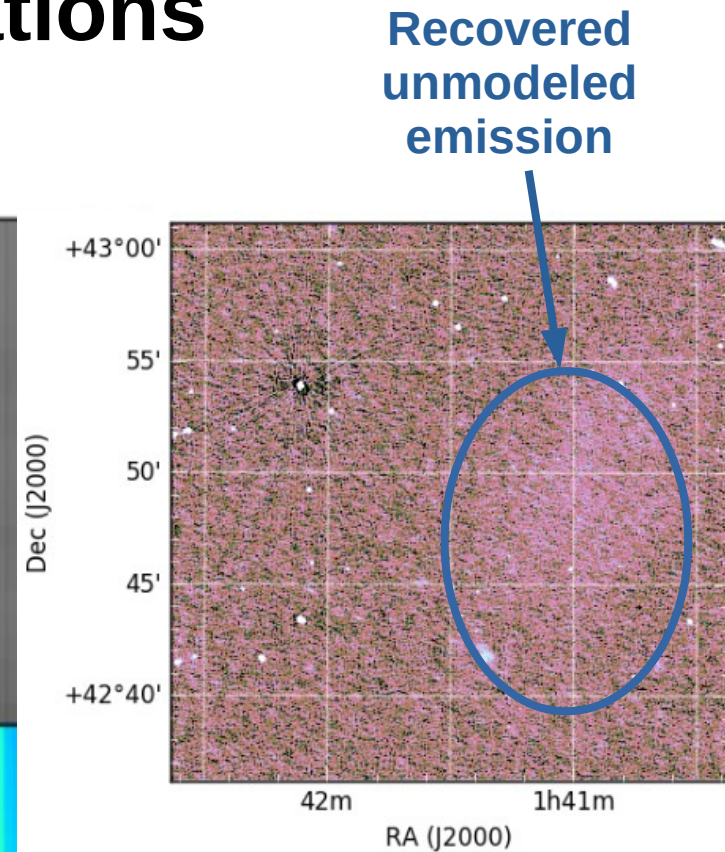
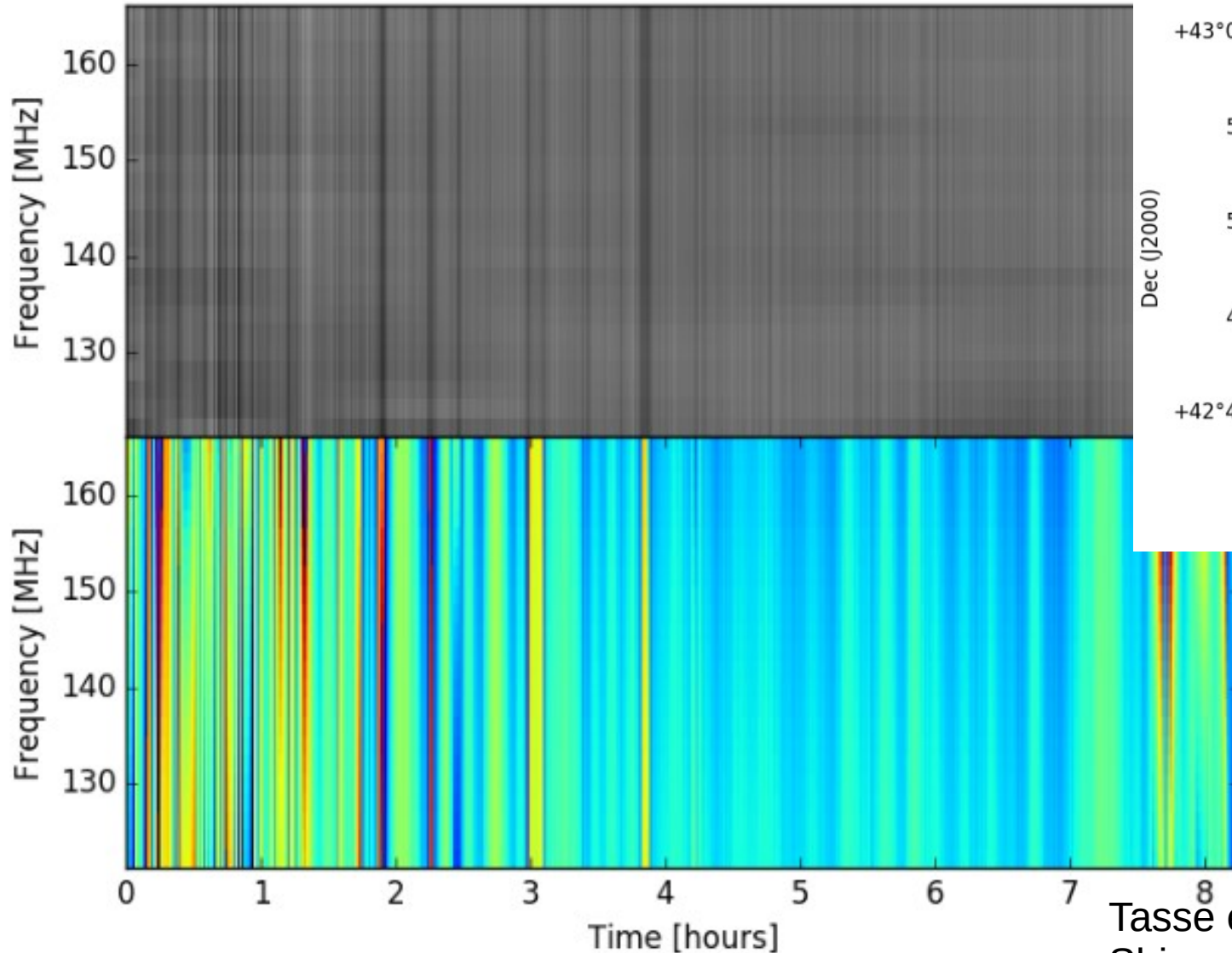


**Raw DDE  
solutions**

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

# Ddf-pipeline & LOTSS/DR2 : Gains for different stations

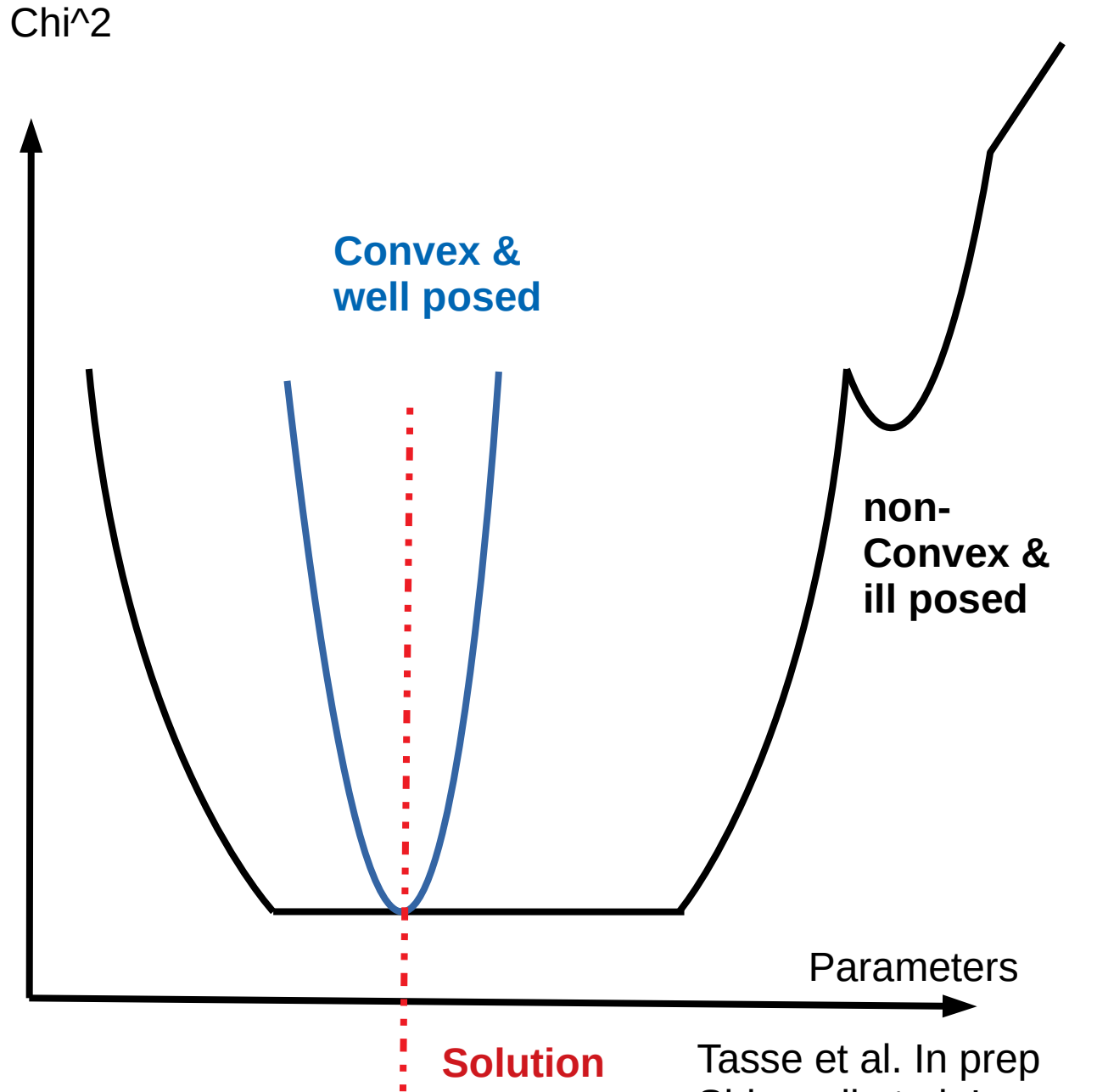
Station RS509HBA



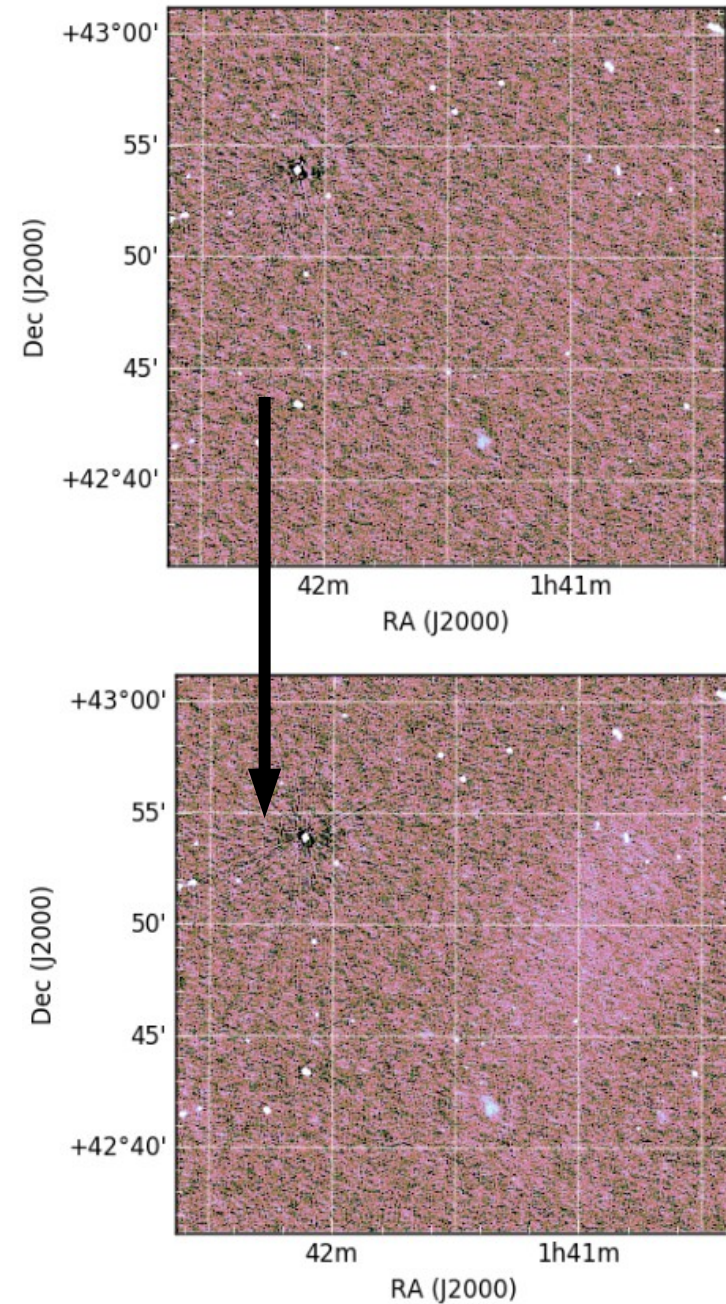
**Smoothed DDE solutions**

Tasse et al. In prep  
Shimwell 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**

# Fully automatic pipeline....

LoTSS\_DR2\_high

**15 nodes running at Hertfortshire (@Hardcastle's cluster) are enough to reduce LoTSS data flow 24/7**

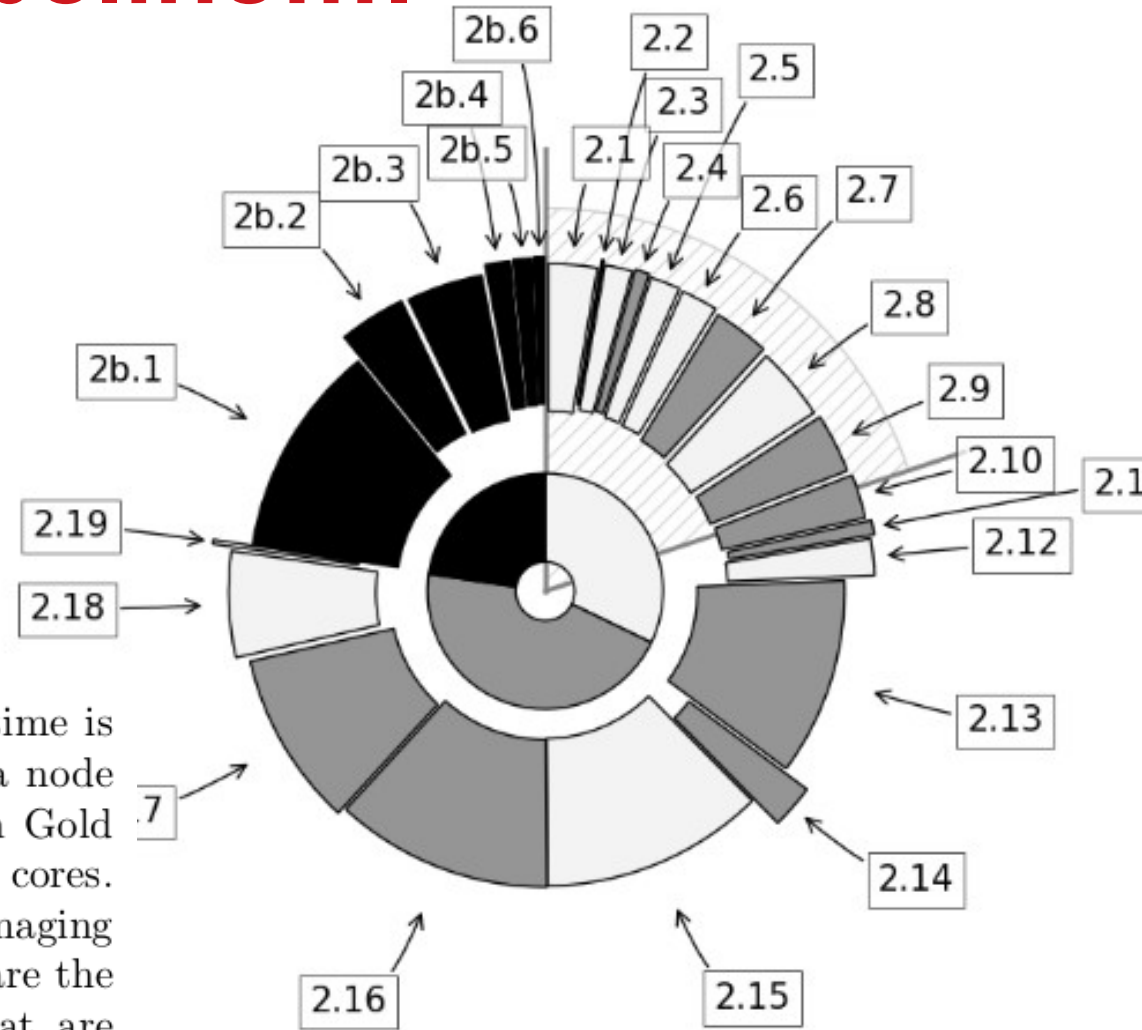
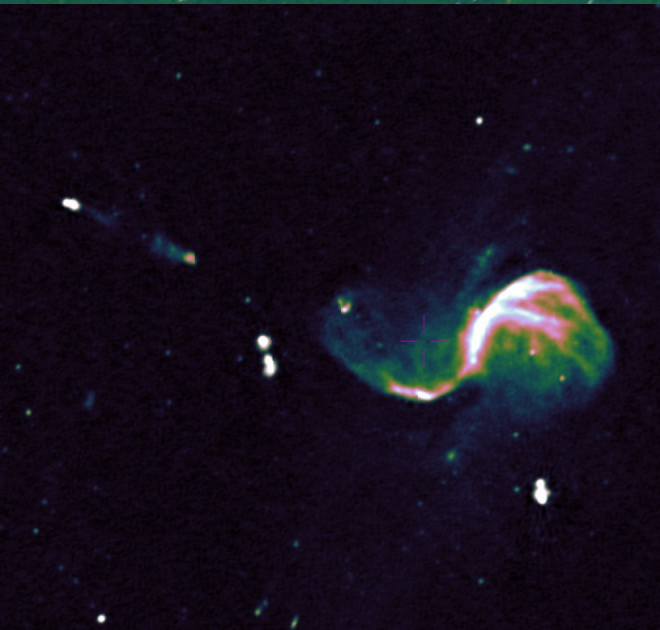
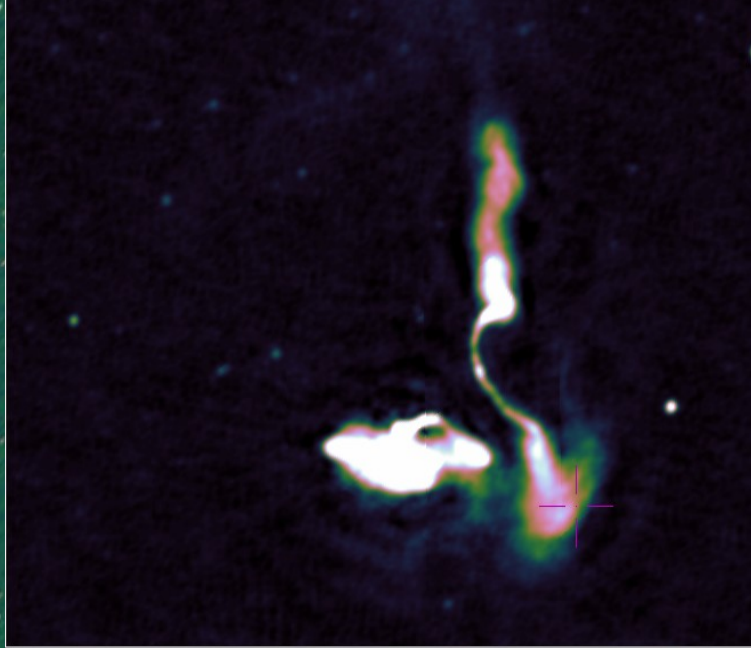
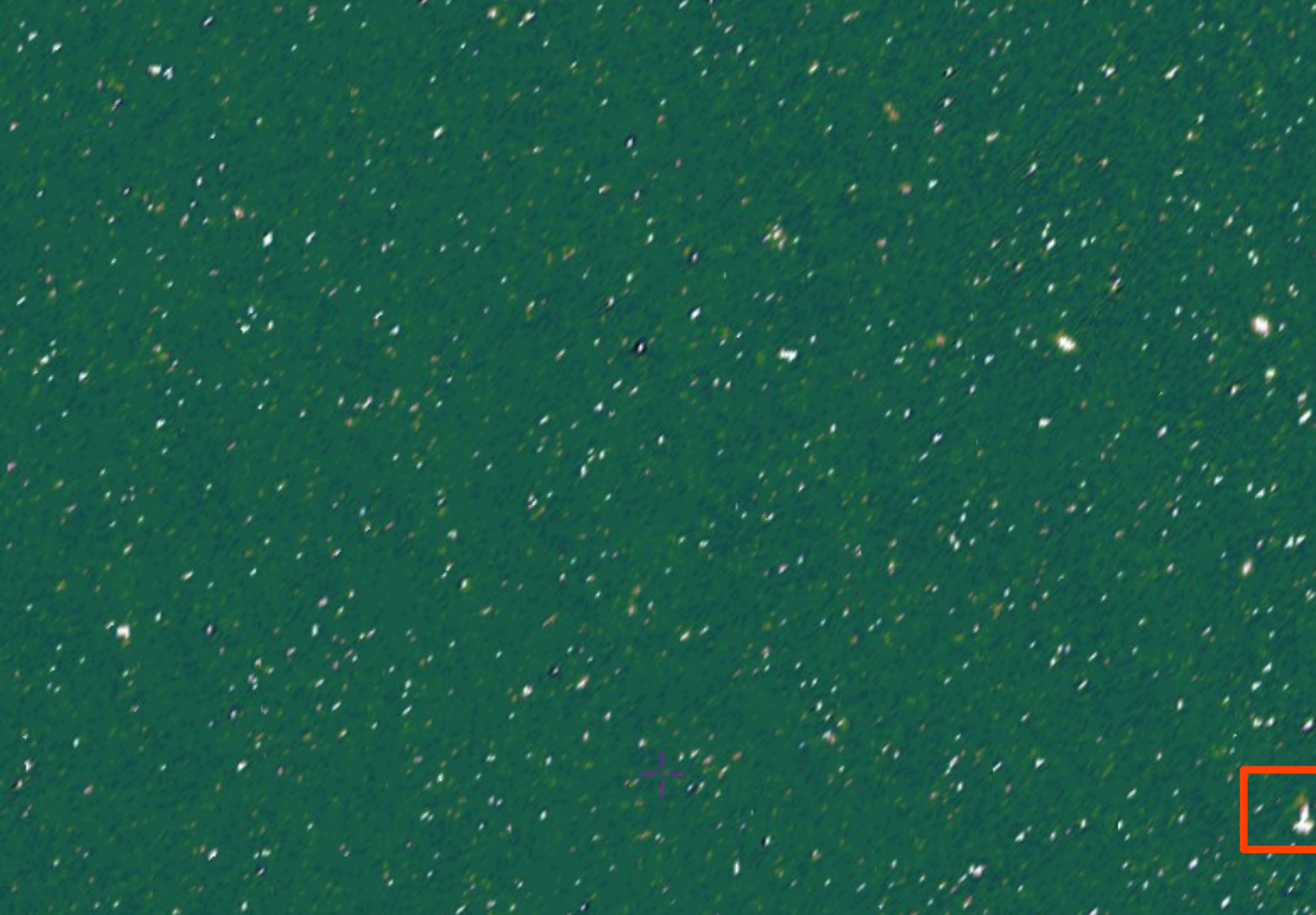


Fig. 2: This pie graph show how the computing time is distributed across the different steps of AI. 2 on a node equipped with 192 GBytes RAM and 2 Intel Xeon Gold 6130 CPU@2.10GHz, giving 32 physical compute cores. The lighter and darker grey areas represent the imaging and calibration steps respectively. The black area are the miscellaneous tasks (additional data products) that are done once the DI and DD self-calibration loops have completed. The dashed area is a quarter representing a day. The total run time is  $\sim 5$  days, so 15 such nodes are necessary to reduce the 8 hours LoTSS pointings in real-time.

**Light gray : DD-Imaging**  
**Dark gray : DD-calibration**



10.77° x 6.416°





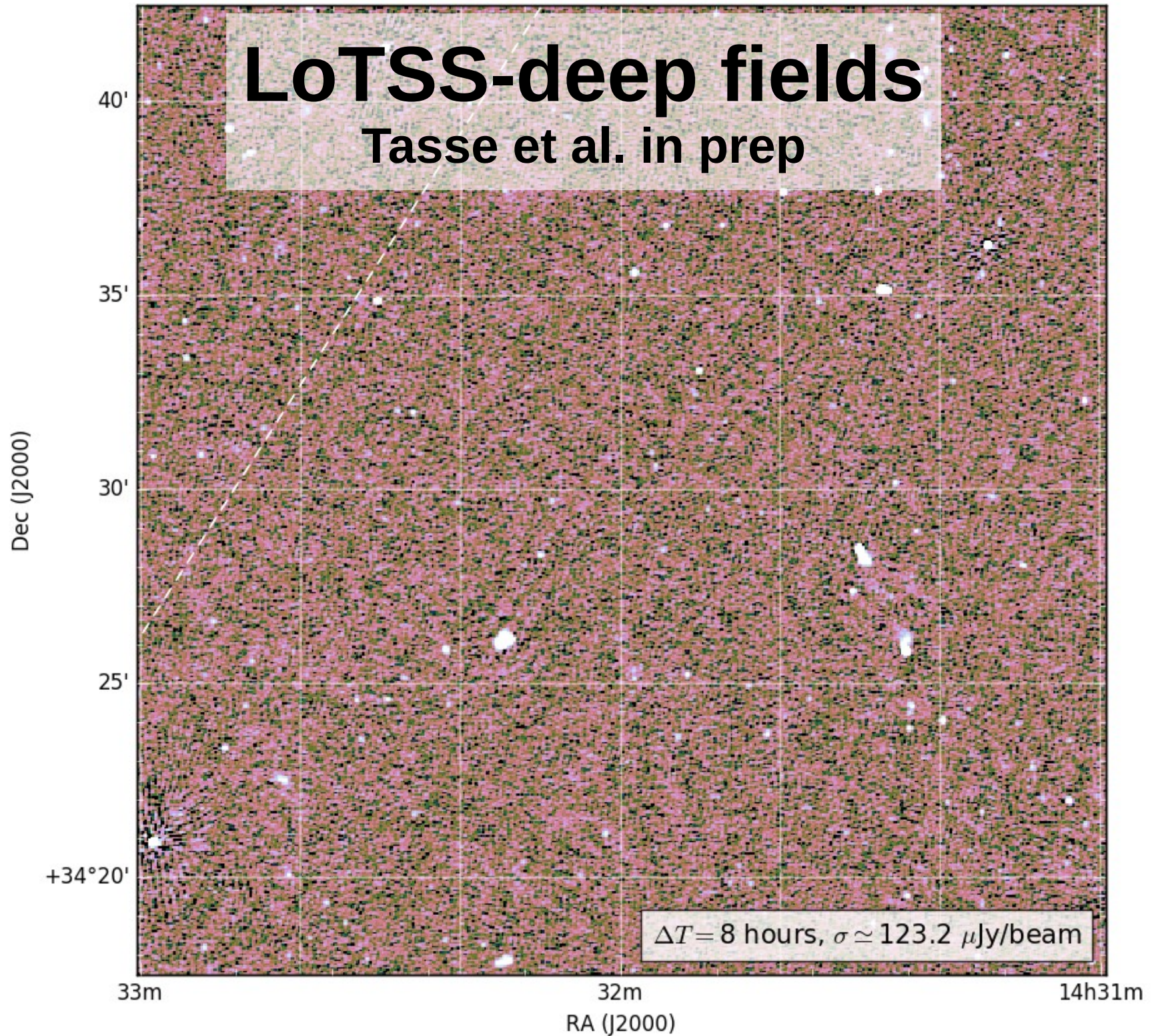






# LoTSS-deep fields

Tasse et al. in prep



# LoTSS-deep fields

Tasse et al. in prep

Dec (J2000)

+34°20'

40'  
35'  
30'  
25'

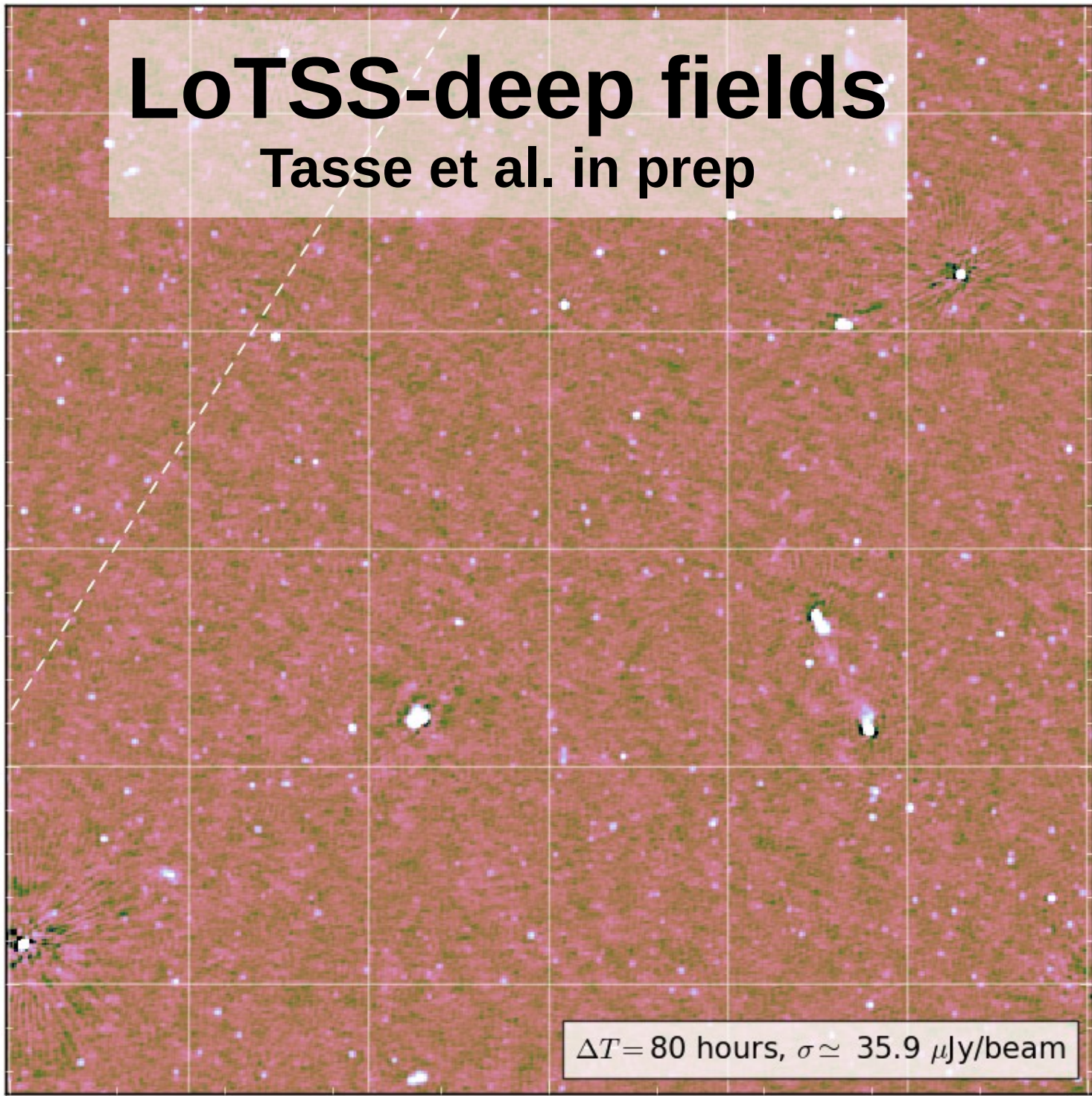
RA (J2000)

33m

32m

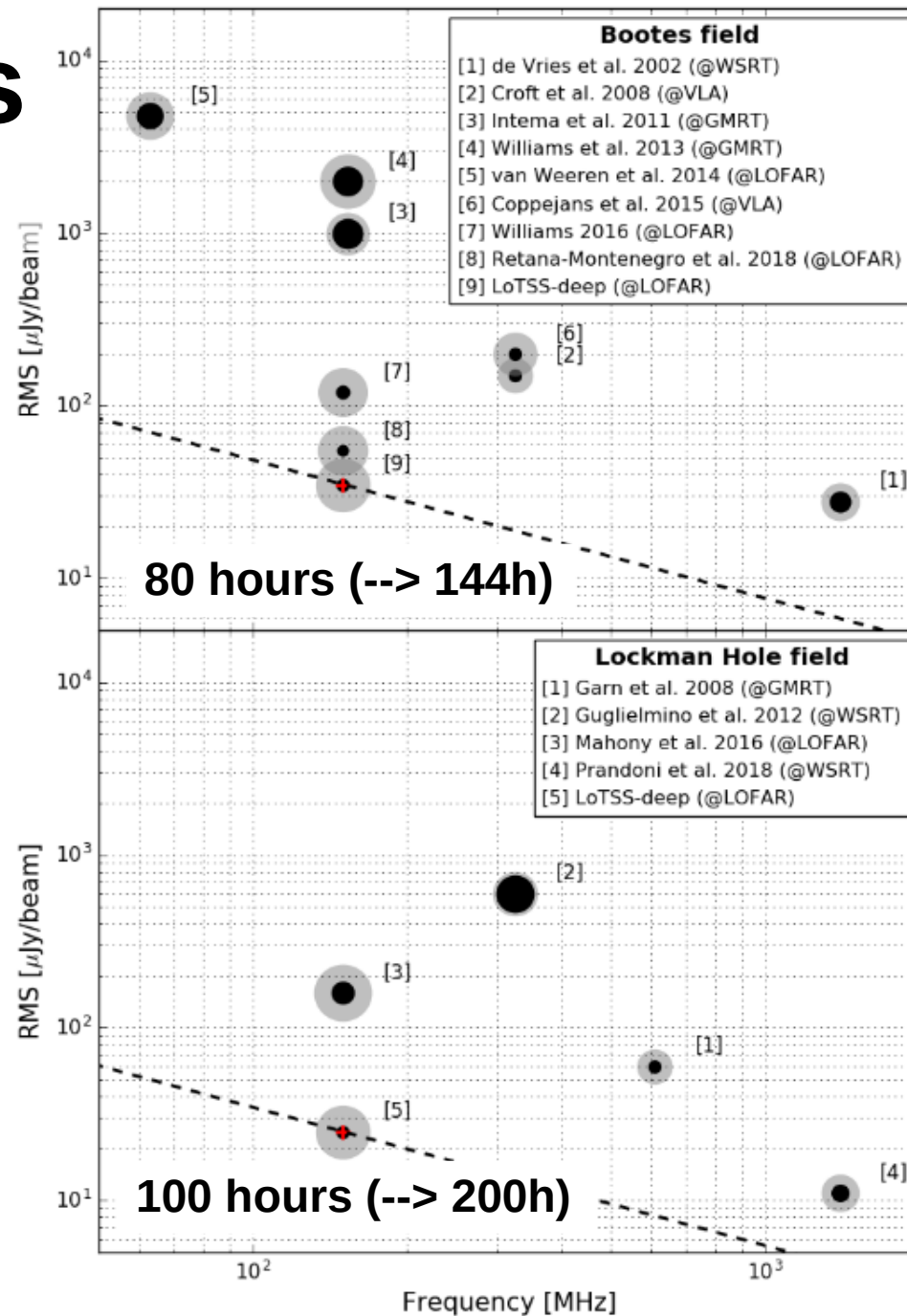
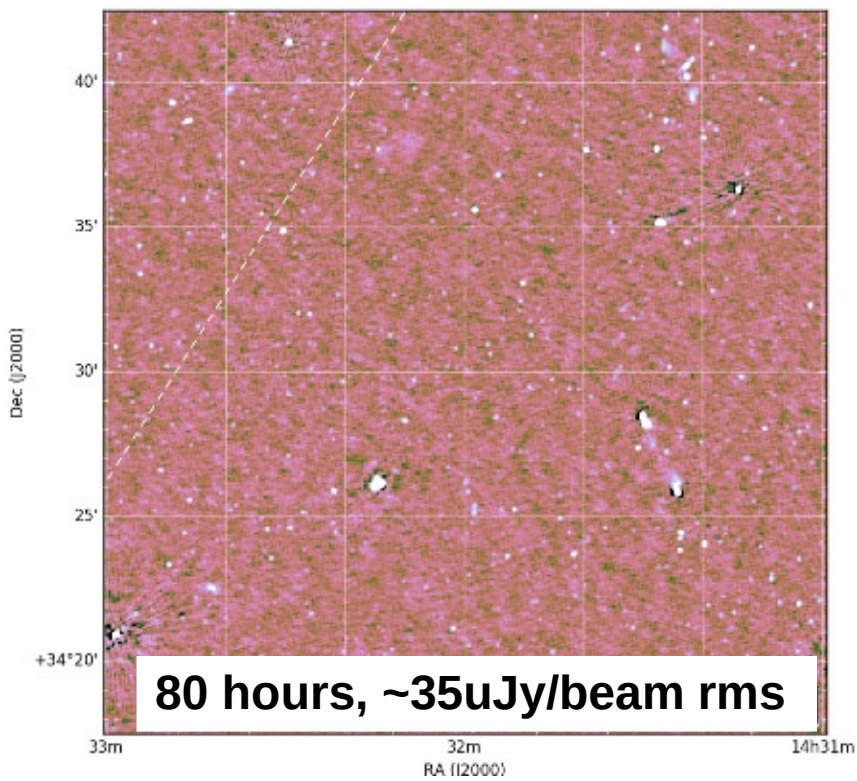
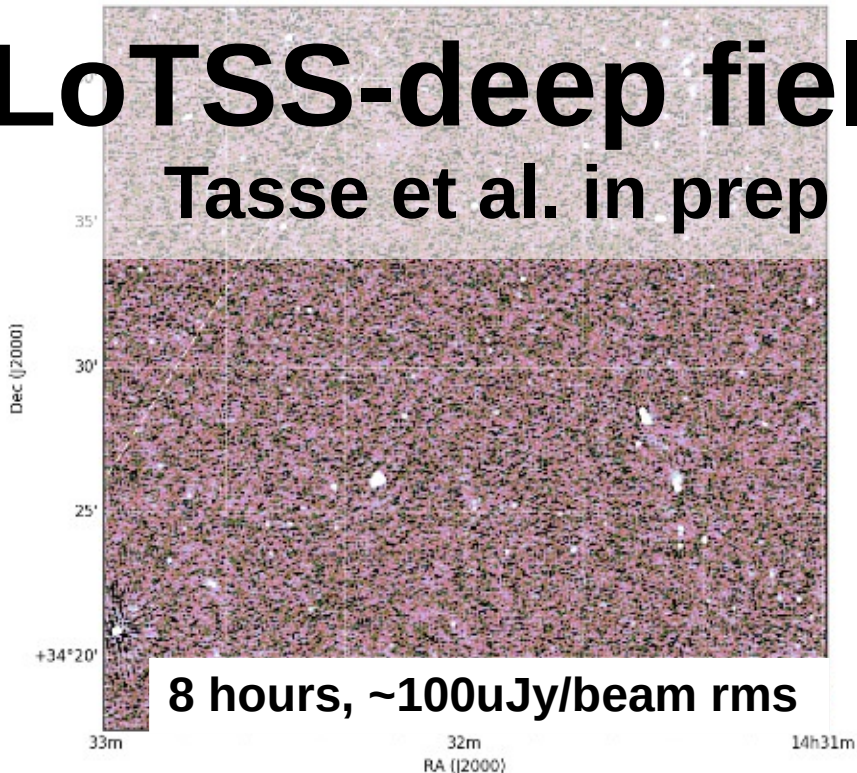
14h31m

$\Delta T = 80$  hours,  $\sigma \simeq 35.9 \mu\text{Jy}/\text{beam}$



# 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



# ELAIS-N1

(~160h integration  
Sabater-Montes et al. in prep)

~20 uJy/beam rms

# ELAIS-N1

(~160h integration  
Sabater-Montes et al. in prep)

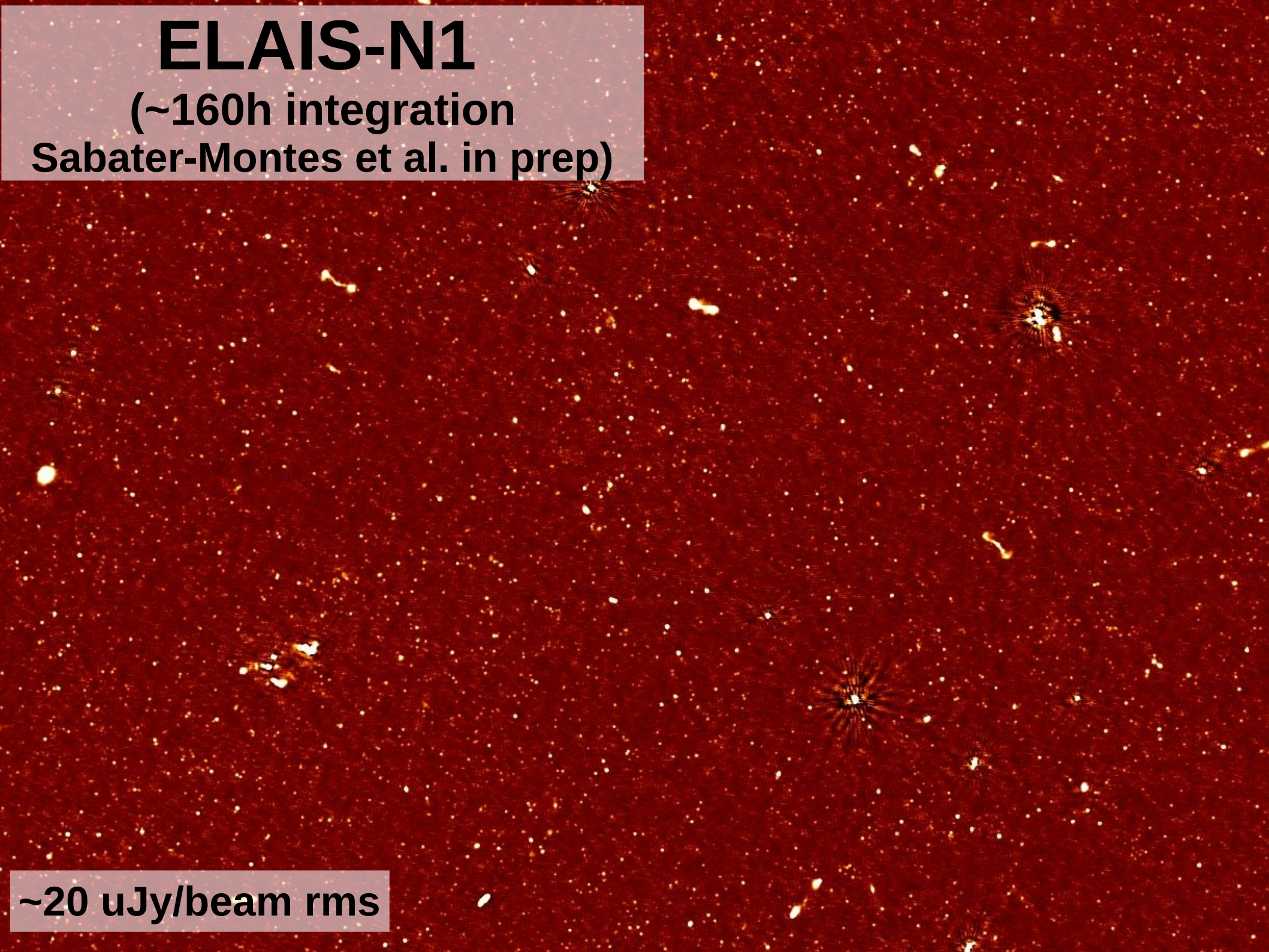
~20 uJy/beam rms

The image displays a vast field of galaxies, primarily in shades of red and brown, indicating a deep X-ray observation. The galaxies are scattered across the frame, with some appearing as bright, elongated structures and others as fainter, more diffuse clouds. The overall appearance is that of a rich, multi-colored galaxy cluster or field.

# ELAIS-N1

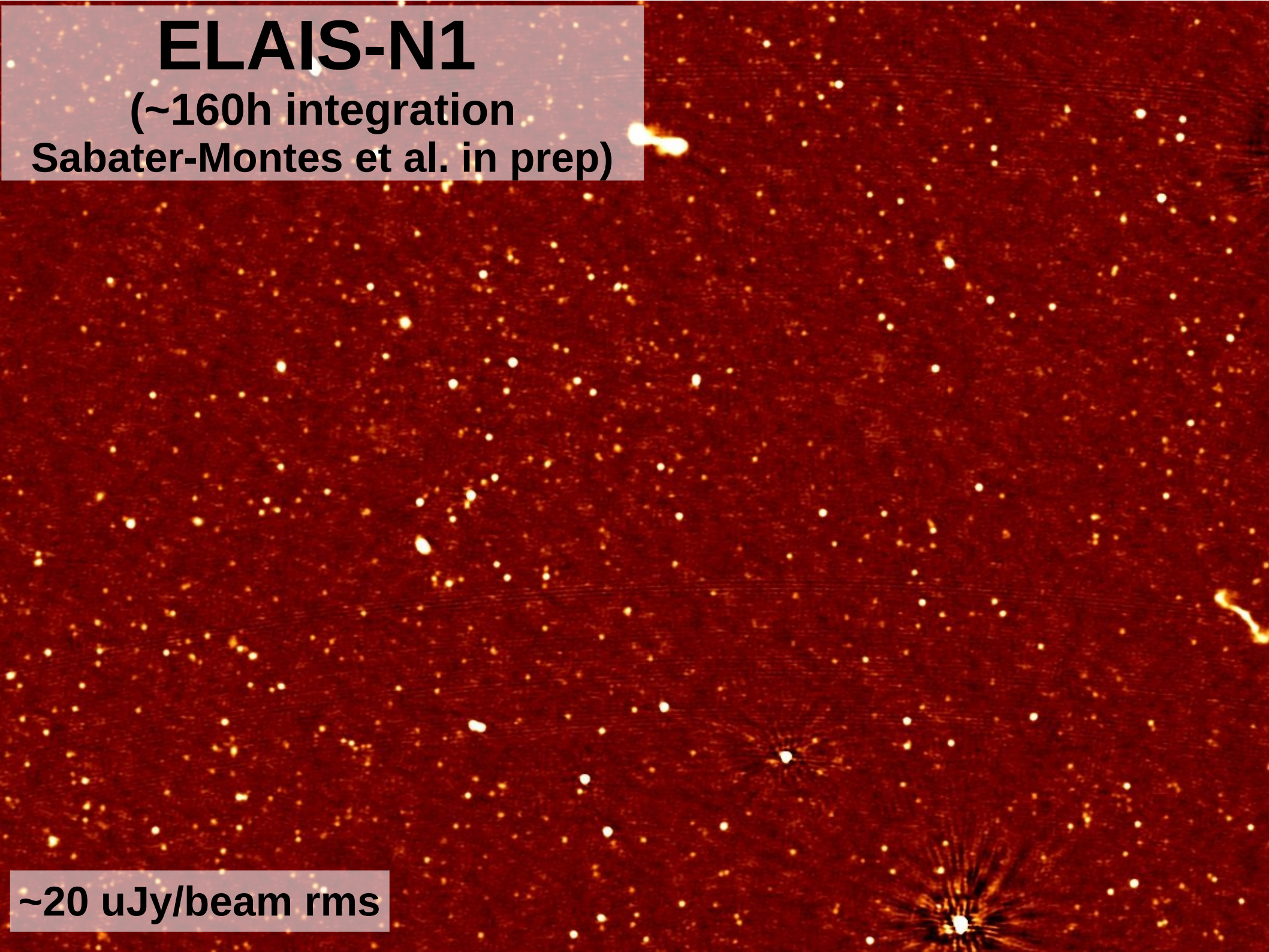
(~160h integration  
Sabater-Montes et al. in prep)

~20  $\mu\text{Jy}/\text{beam}$  rms



# ELAIS-N1

(~160h integration  
Sabater-Montes et al. in prep)



~20 uJy/beam rms

# ELAIS-N1

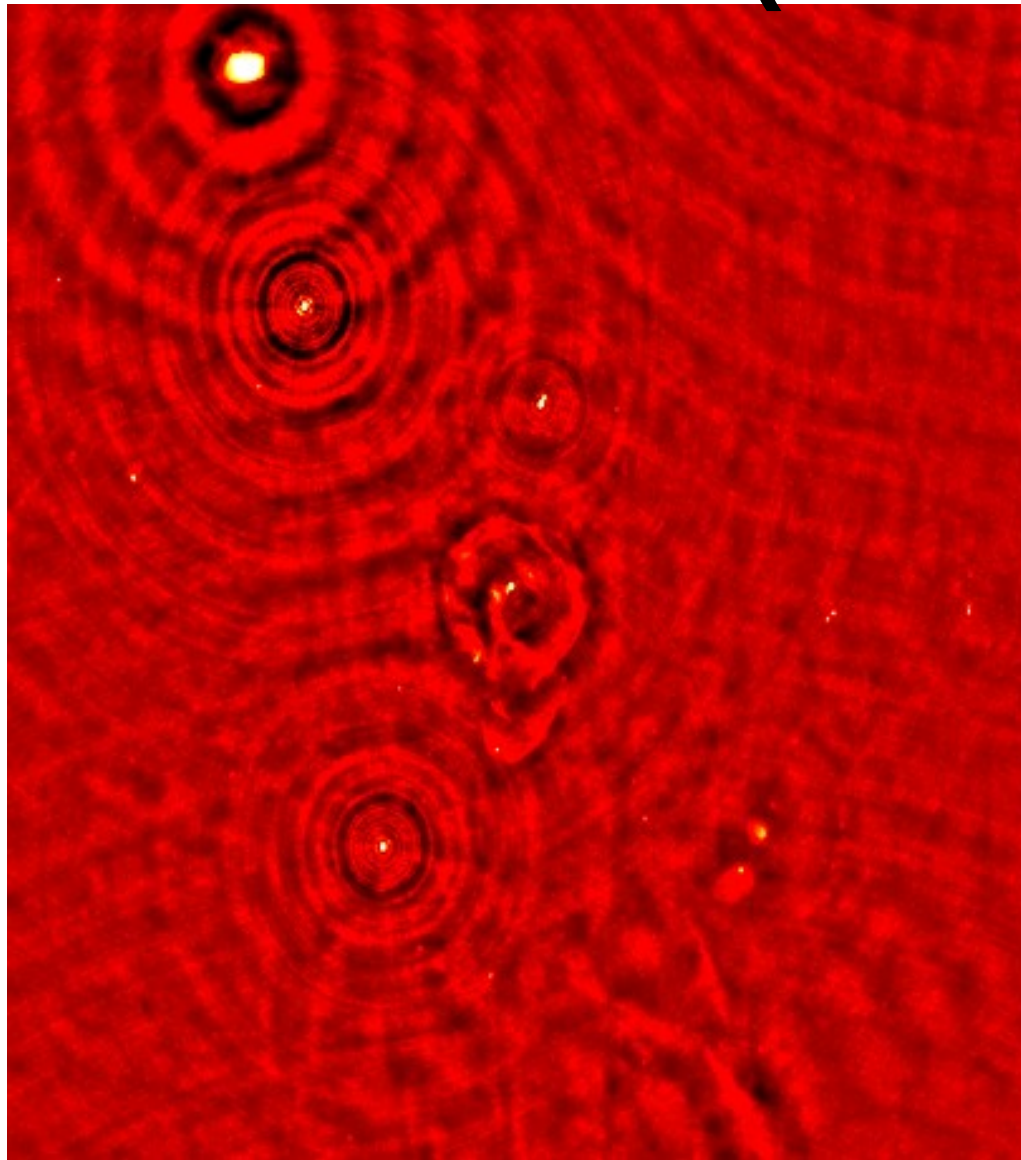
(~160h integration  
Sabater-Montes et al. in prep)

~20  $\mu\text{Jy}/\text{beam}$  rms

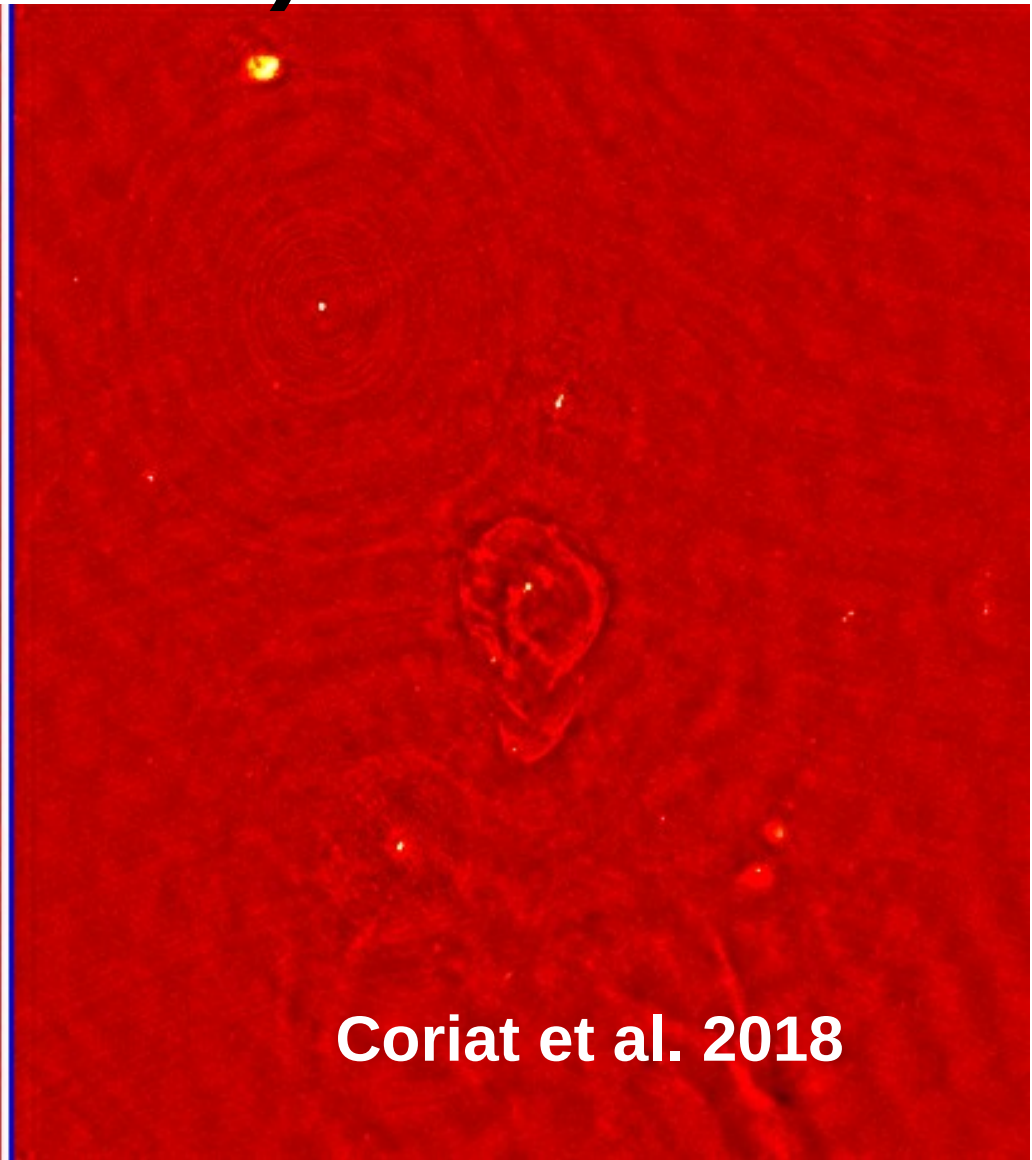


**Thank you !**

# And it also works on ATCA data (Circinus a)

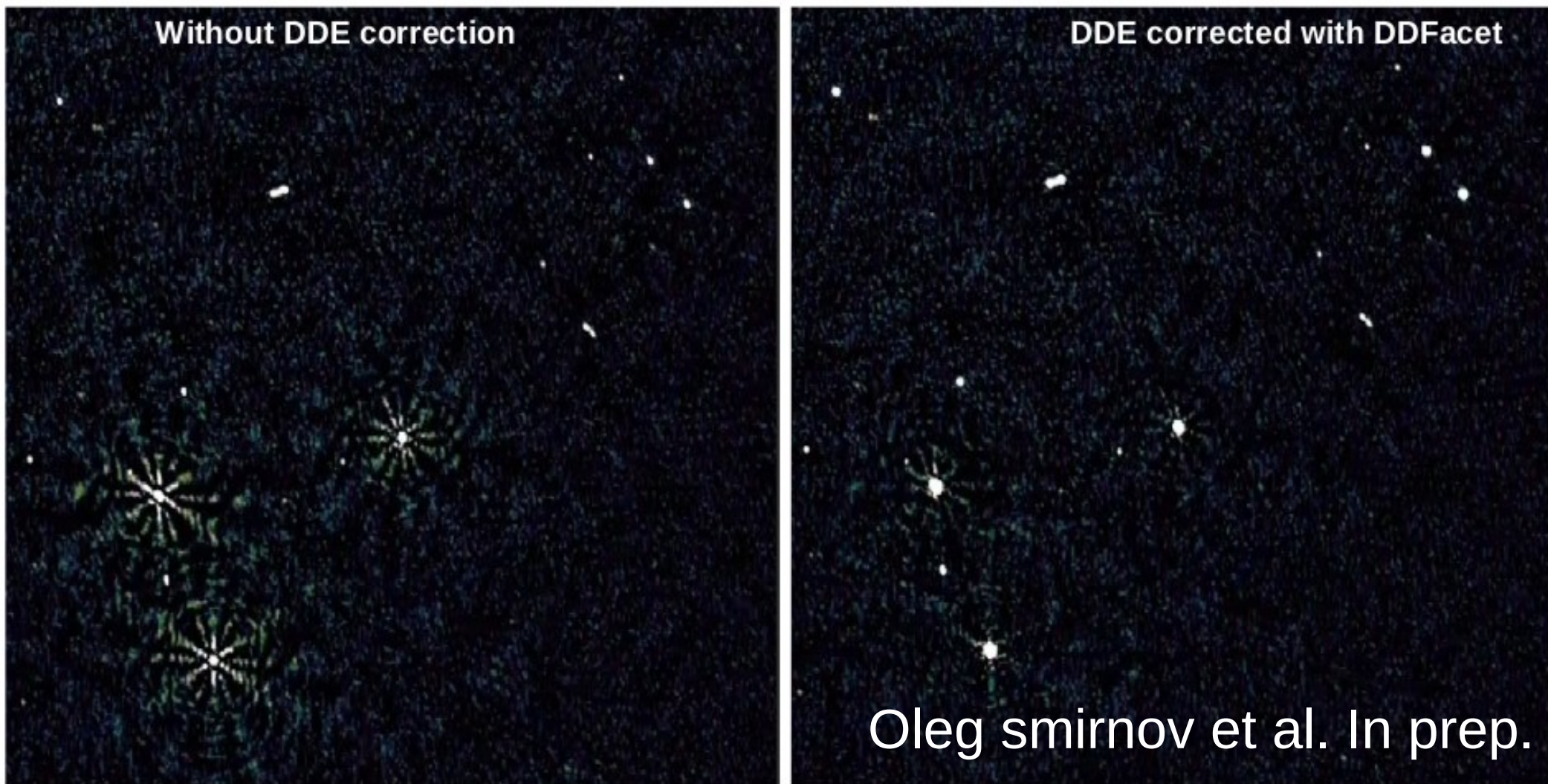


**Direction independent calibration**



**DDE with Wirtinger**

# And it also works on VLA data



VLA beam model used to construct the Jones matrices



# APERTIF@WSRT



DI-Selfcaled image

Credit : Alexander Kutkin

# APERTIF@WSRT



With kMS+DDF  
11 directions

Credit : Alexander Kutkin

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



With 6 rounds of DI selfcal

Credit : Ian Heywood  
Ishwara Chandra

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



With KMS+DDF

Credit : Ian Heywood  
Ishwara Chandra

# 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 19  $\mu$ Jy/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 2.2  $\mu$ Jy/beam rms

Credit : Ian Heywood