UNIVERSITEIT VAN PRETORIA
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MANCHESTER 1824
The University of Manchester

OPTICON RadioNet Pilot

# Lecture 11 - Wide-field data processing

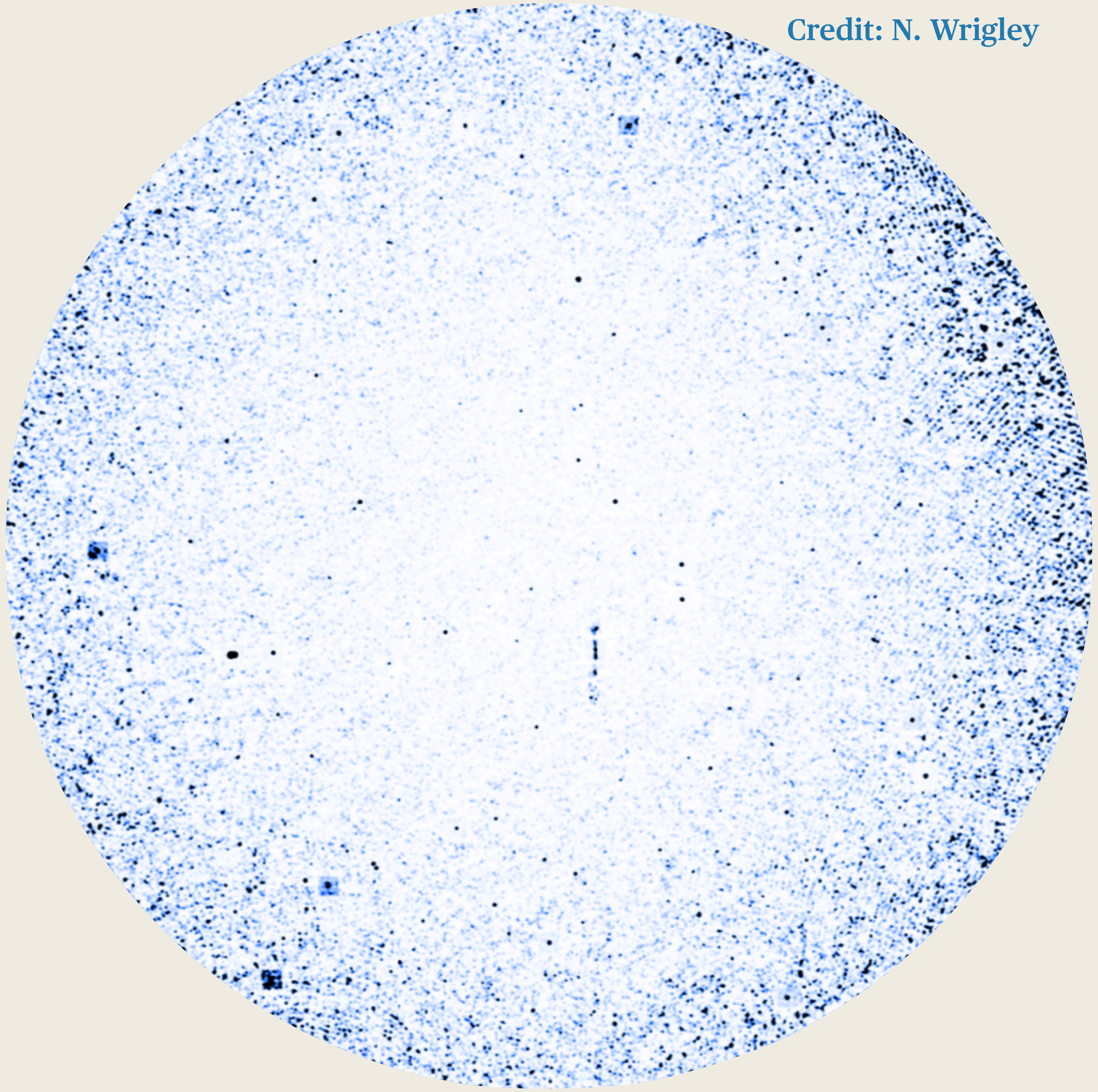
# Wide-field VLBI - definition

***What do we mean by wide-field VLBI?***

- Simply concerned with *imaging the entire primary beam of a VLBI array*
- See multiple science targets in one observations
- Historically, much easier for shorter baseline instruments

*What are the advantages of imaging the entire primary beam?*

Credit: N. Wrigley



Primary beam corrected
JVLA+MERLIN image of the GOODS-N field

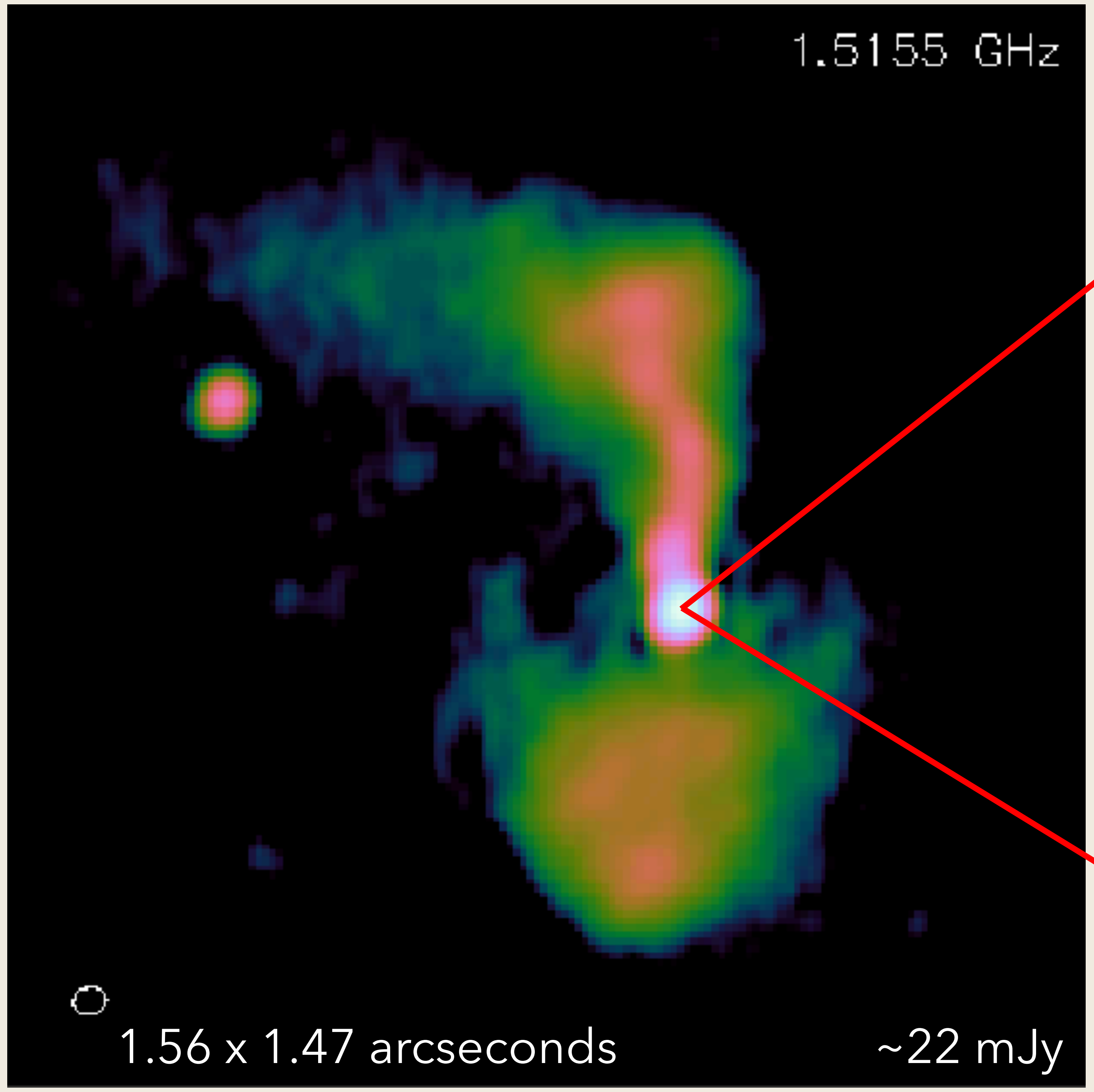
# Outline

1. Why image the whole primary beam?
2. Challenges
3. Wide-field correlation
4. Self-calibration
5. Direction-dependent calibration
6. Calibrating wide-field data with VPIPE

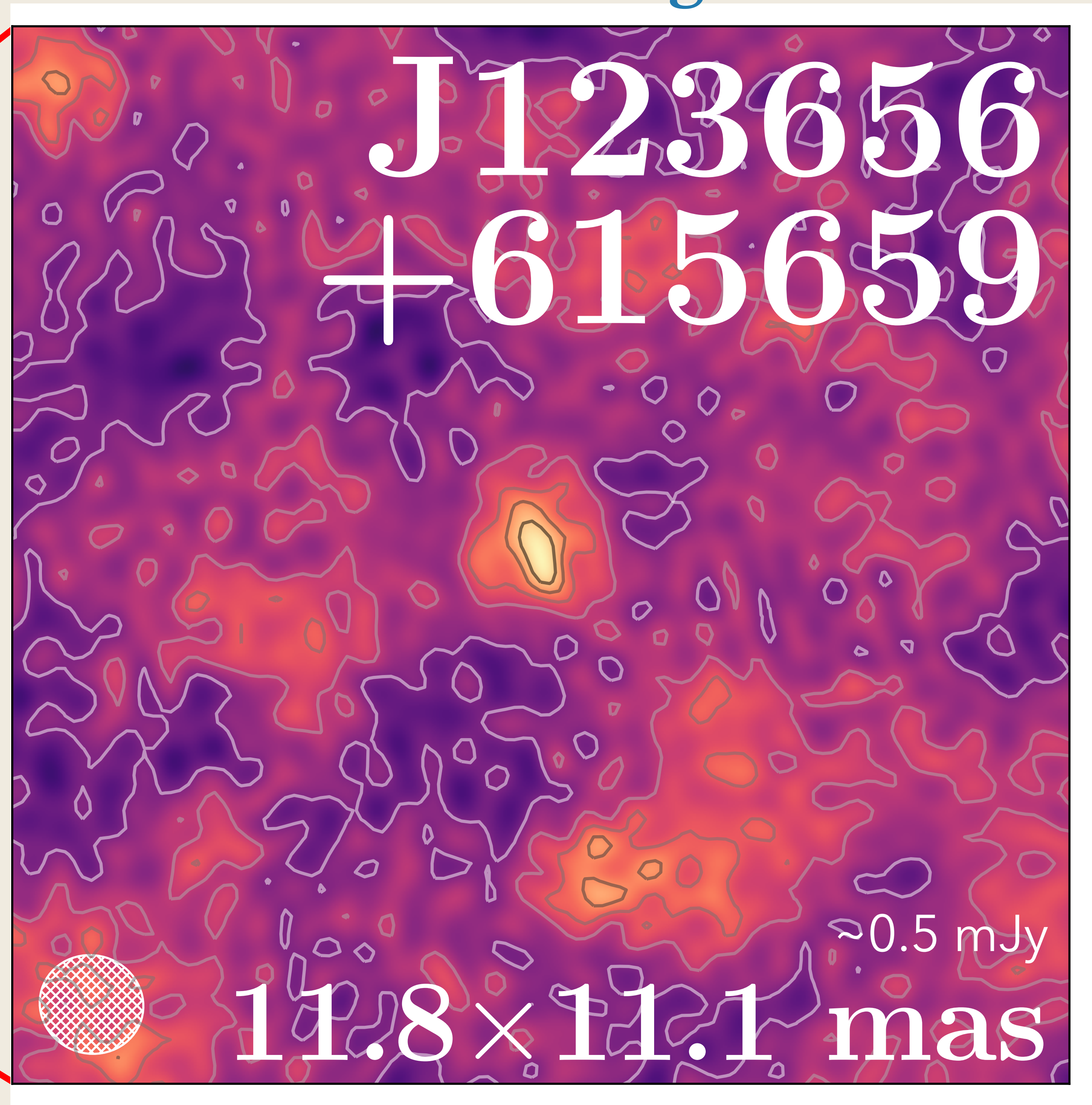
# AGN identification / feedback

- In distant galaxies ($z > 0.1$), a VLBI detection = high brightness temperature cores (>$10^5$ K) = ***AGN!***
- Independent of multi-wavelength data!

VLA - low resolution




VLBI - high resolution




E.G., KEWLEY ET AL., (2000); MIDDELBERG ET AL., (2013); RADCLIFFE ET AL. 2018

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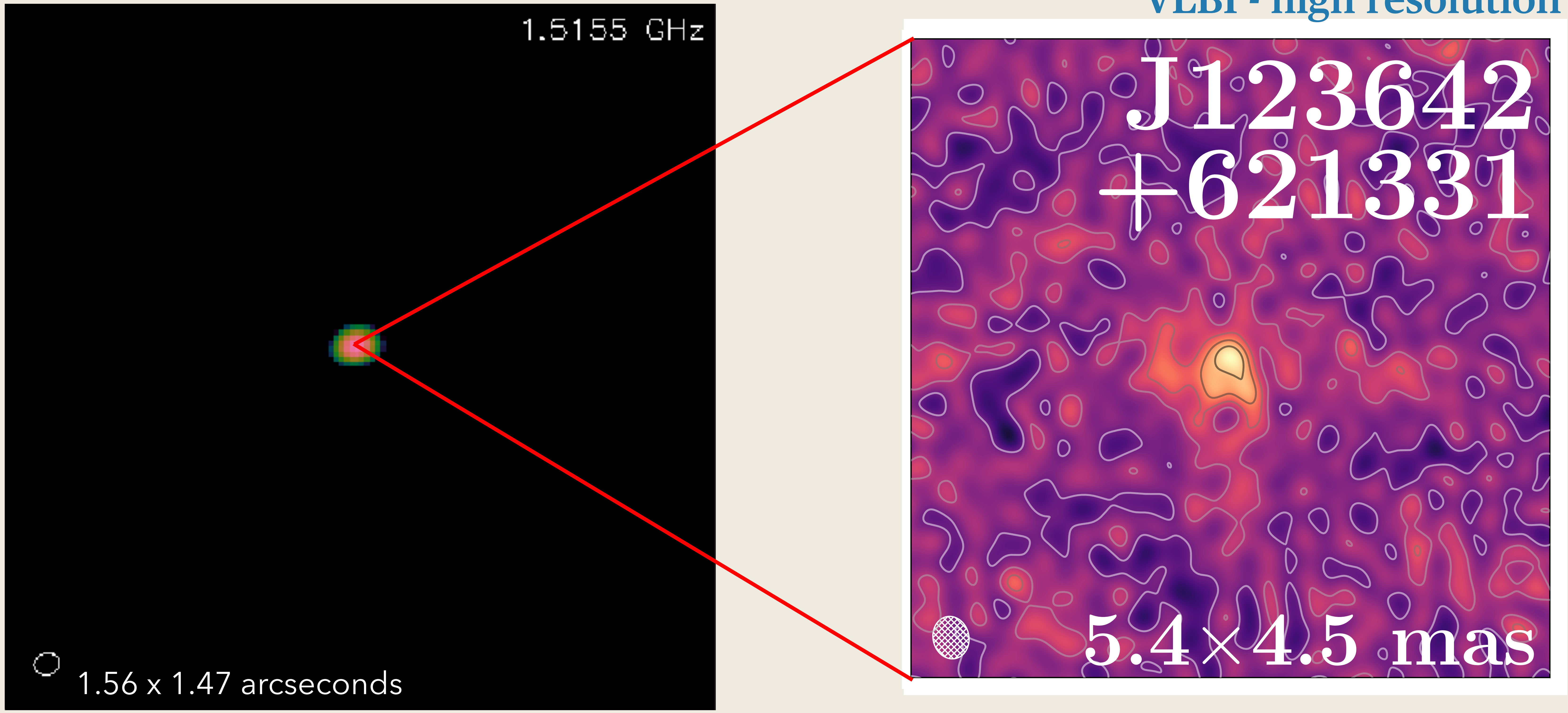
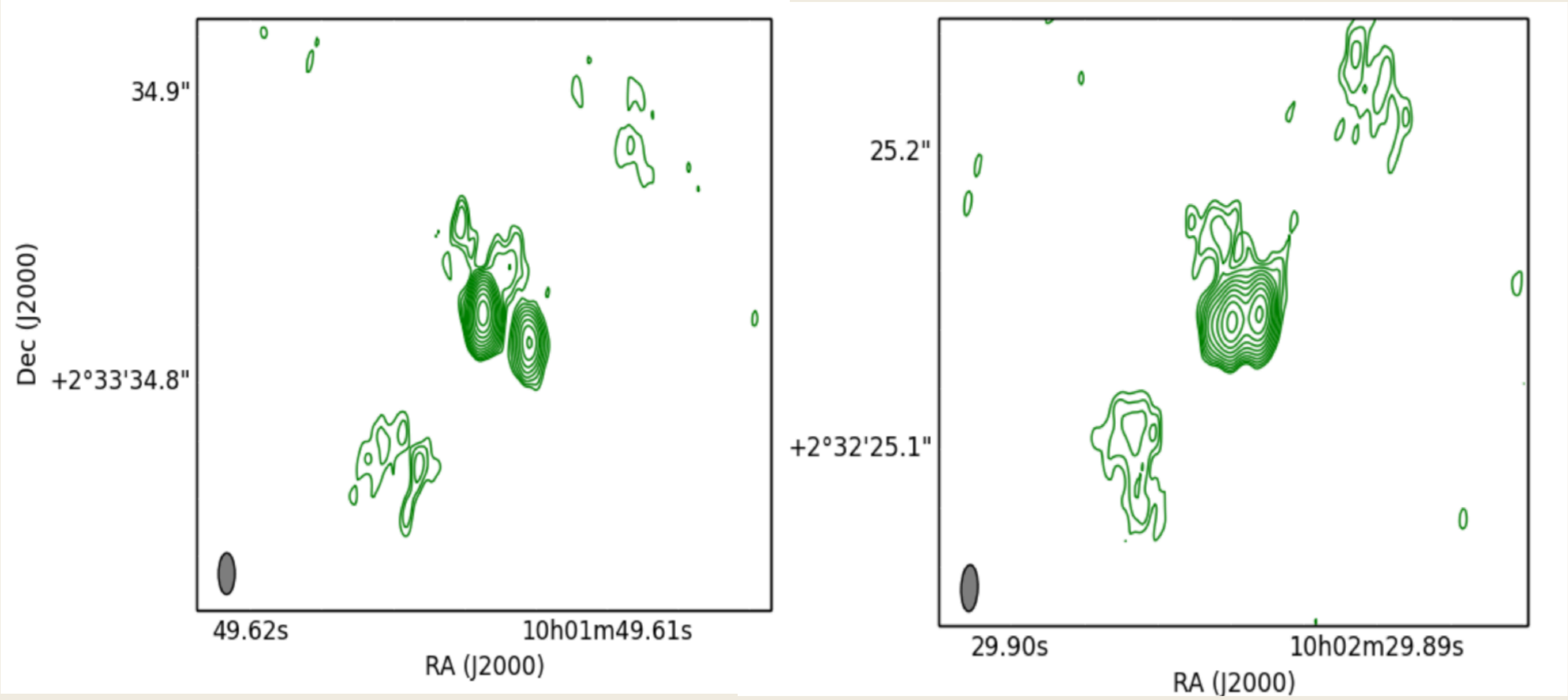



E.G., KEWLEY ET AL., (2000); MIDDELBERG ET AL., (2013); RADCLIFFE ET AL. 2018

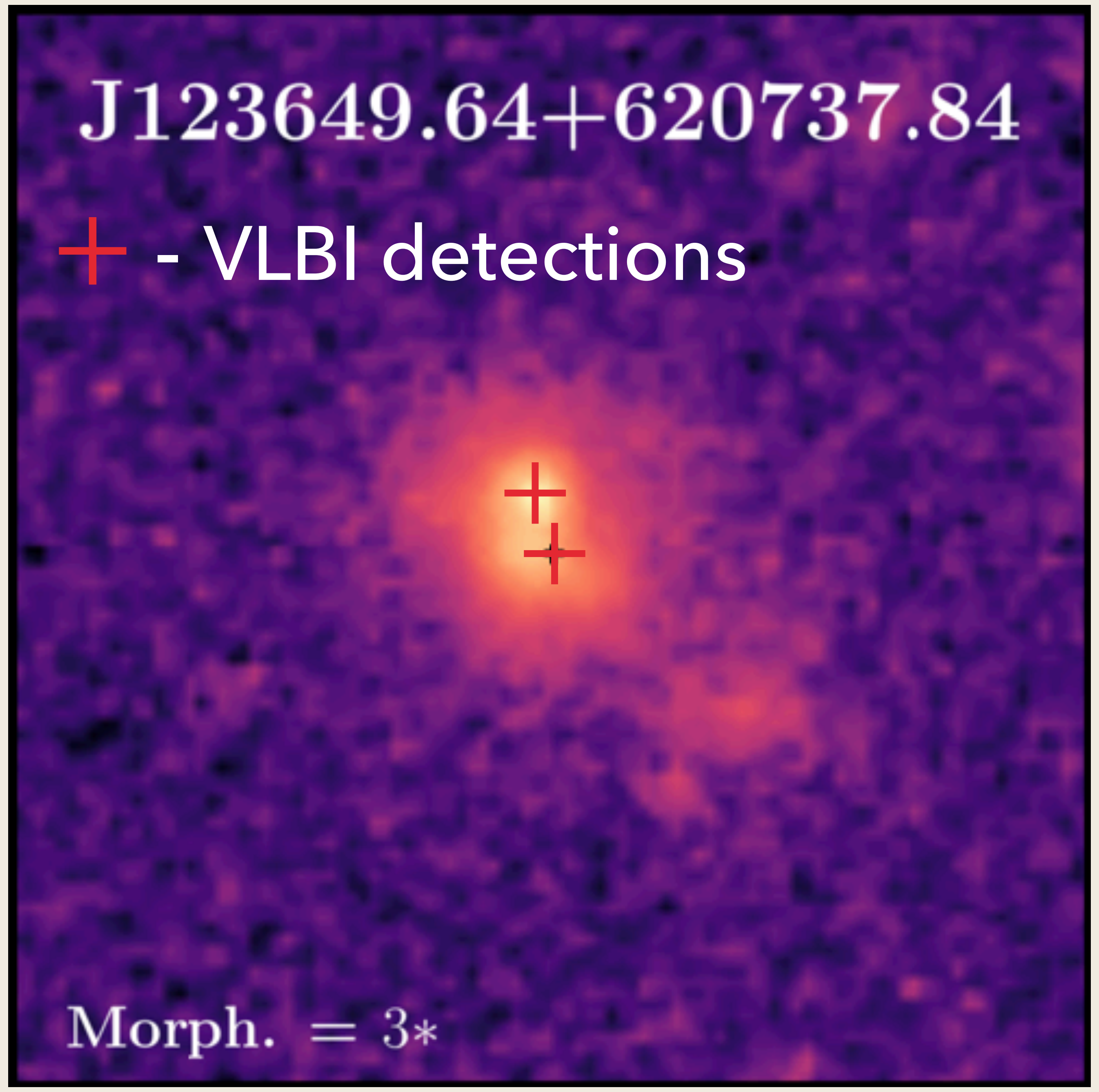
# Supermassive black hole binaries

B-SMBH candidates in COSMOS



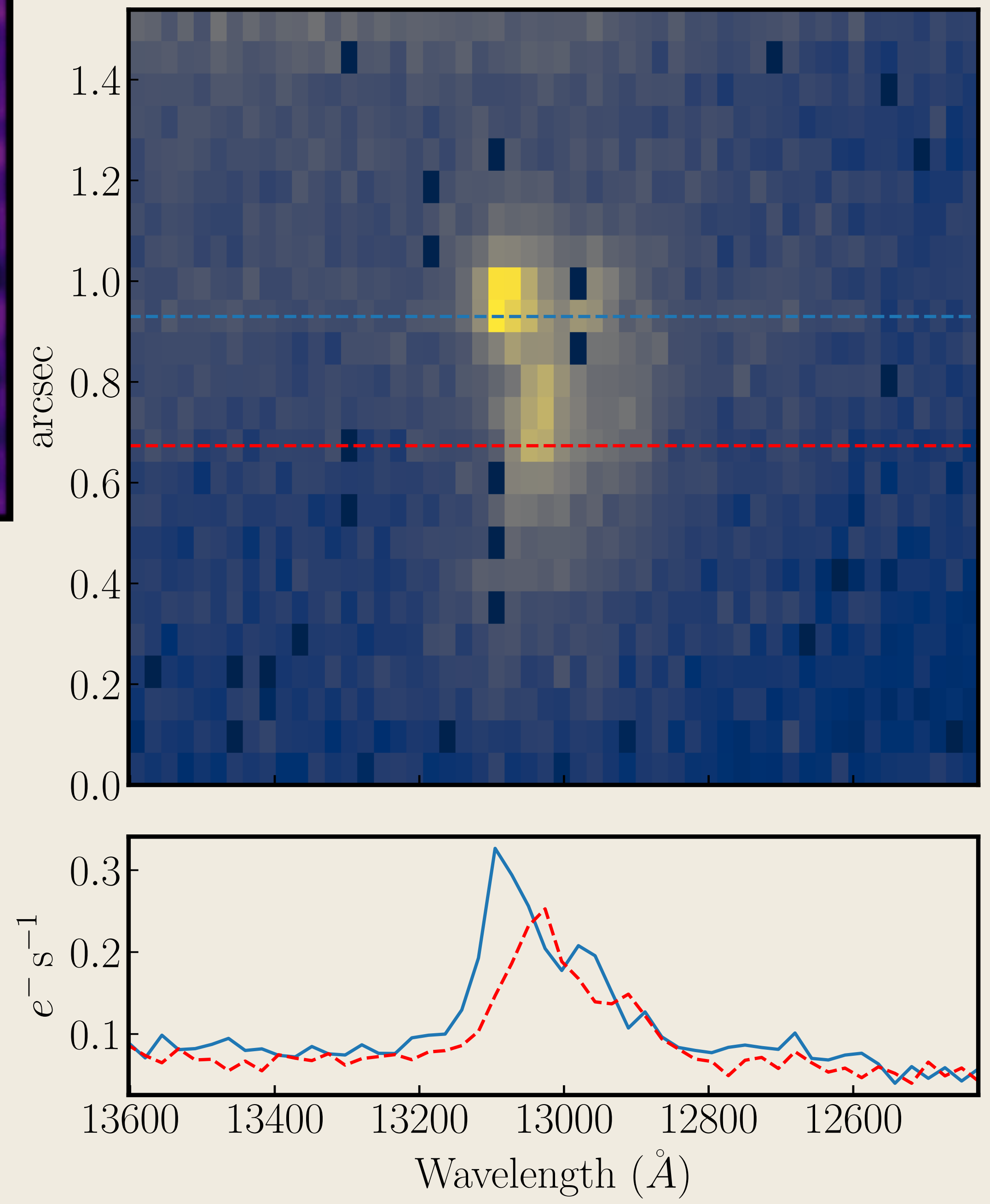

HERRERA-RUIZ ET AL., (2017)

HST near-IR (F125W)




B-SMBH candidate in GOODS-N

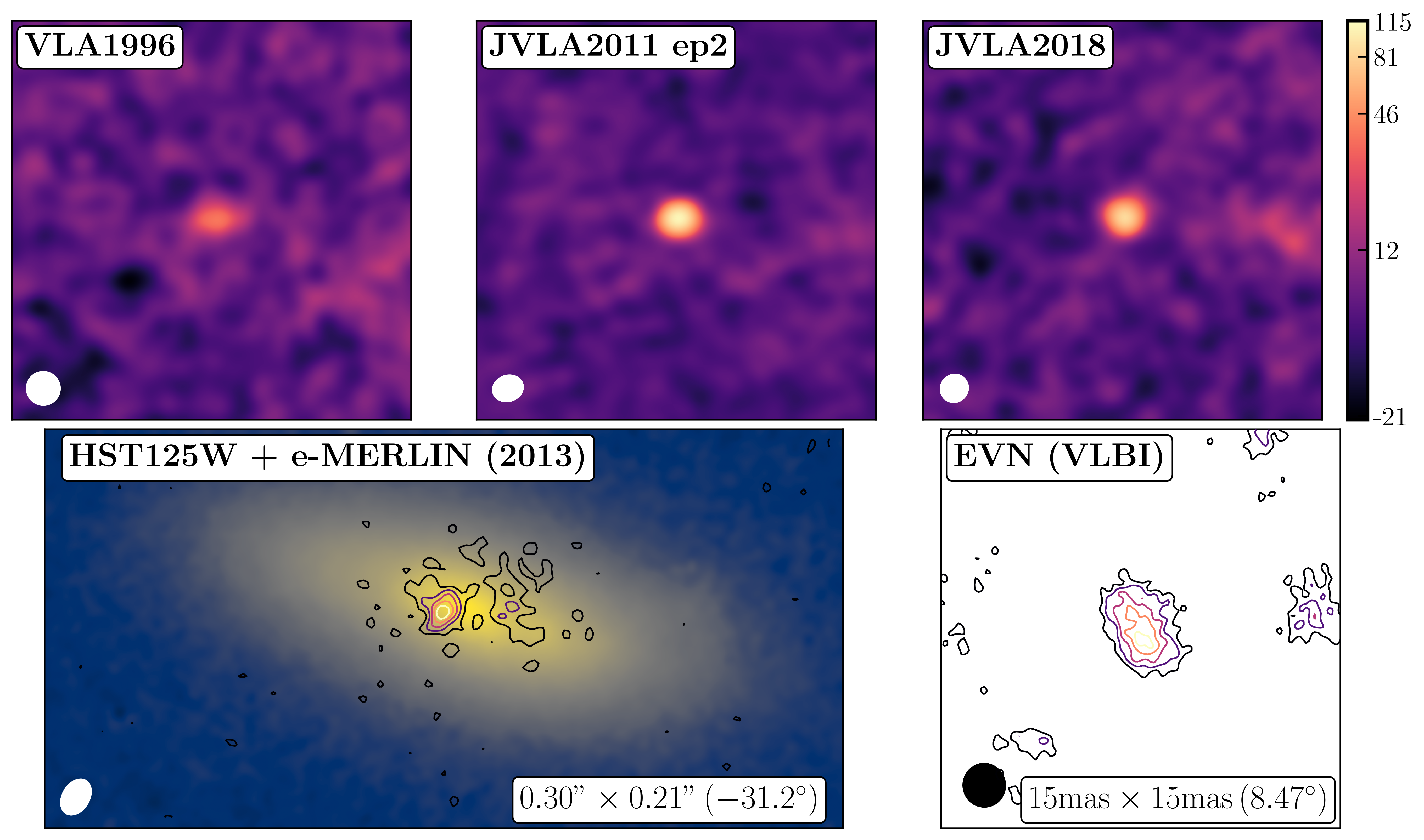
HST GRISM spectrum O[III] line

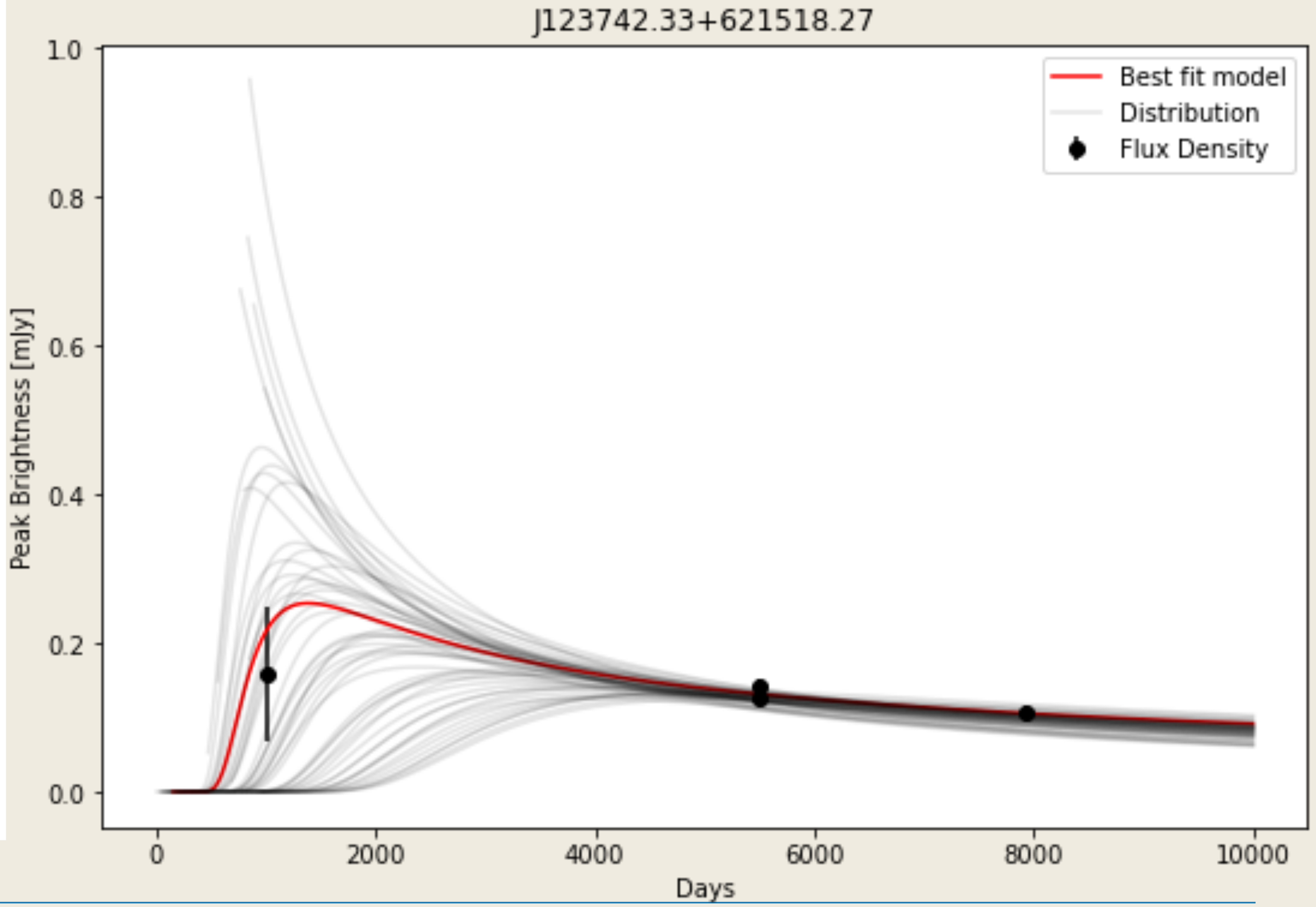



VAN DER DUSSEN ET AL., IN PREP.

# Supernovae

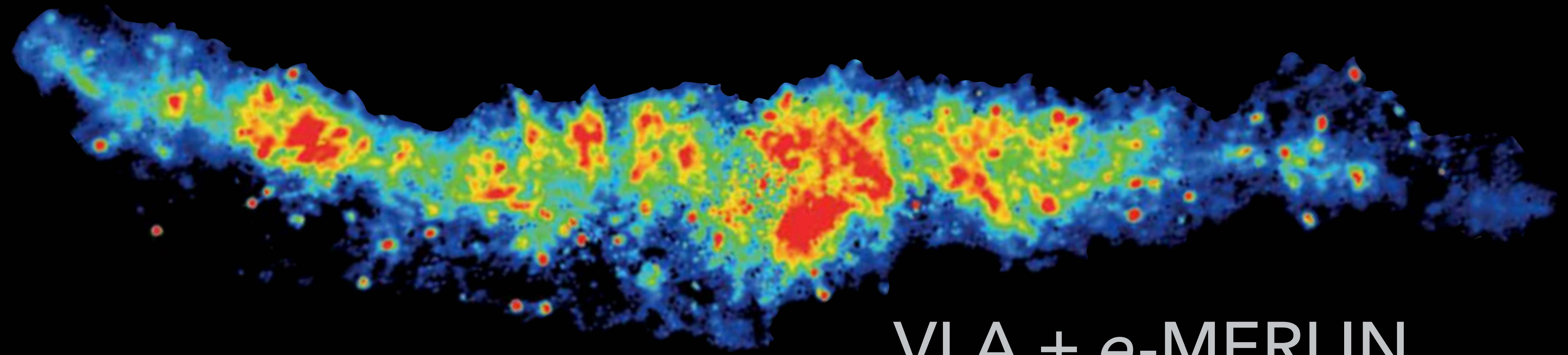
- $z \sim 0.07$ host with pt. source emission appearing between 1996 & 2000
- Luminosity consistent with LLAGN or supernovae ($5 \times 10^{22}\,\mathrm{W\,Hz^{-1}}$)



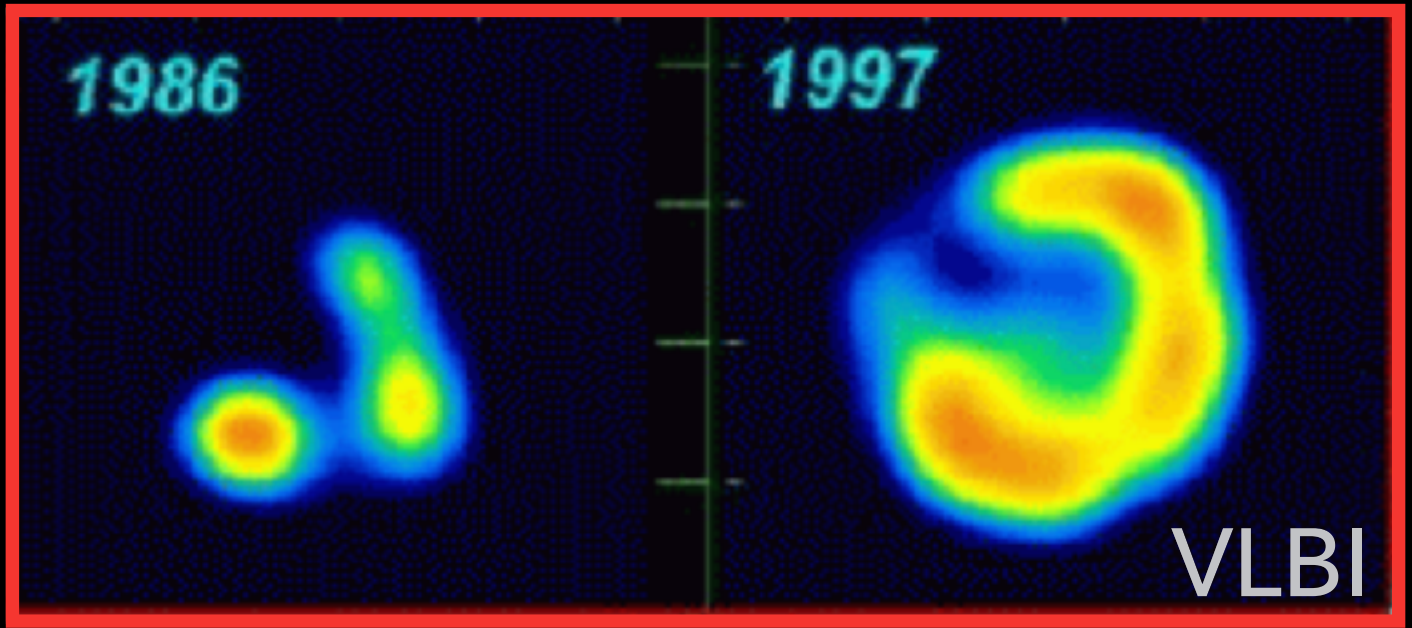



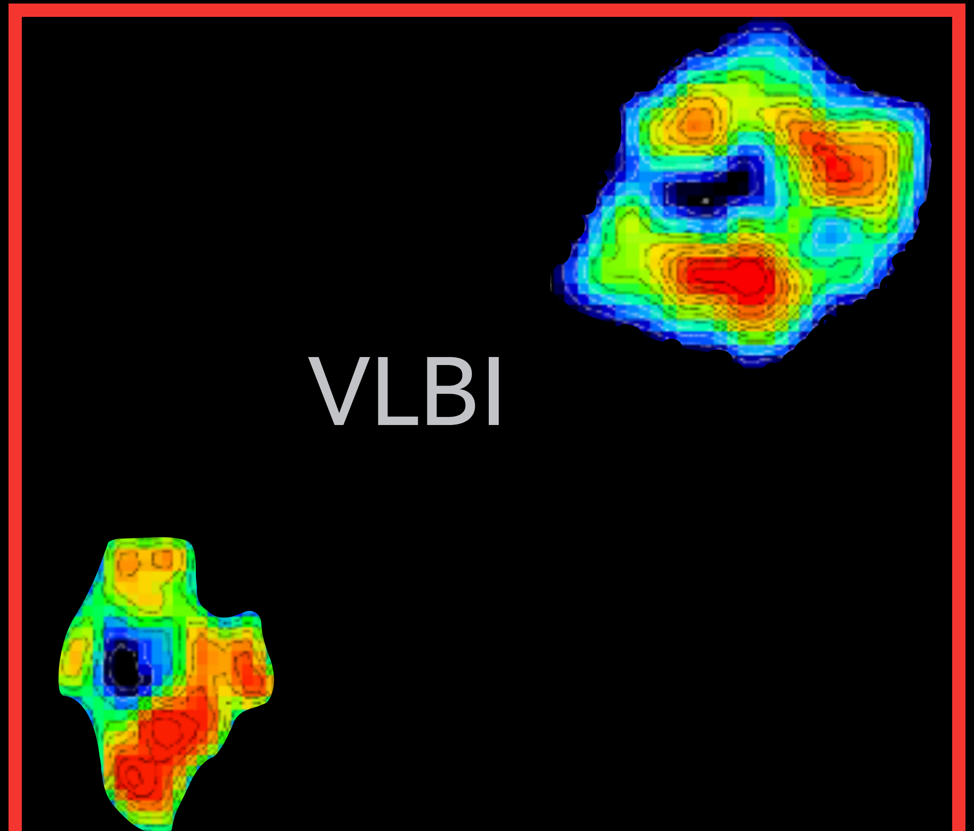
JACK F. RADCLIFFE (jack.radcliffe@up.ac.za)

# Nearby galaxies and our Galaxy

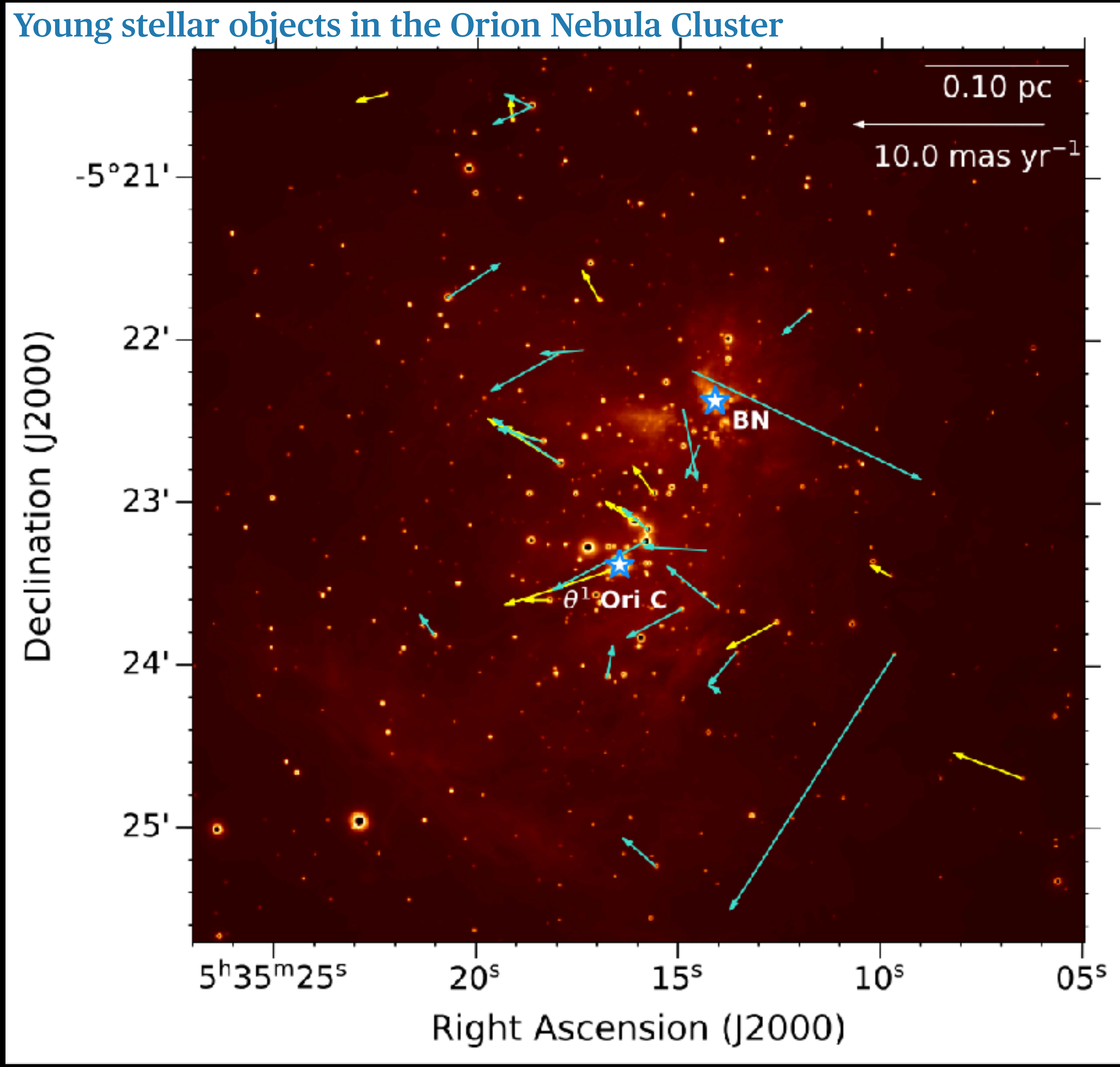



MUXLOW ET AL., (2000)




FENECH ET AL., (2010)



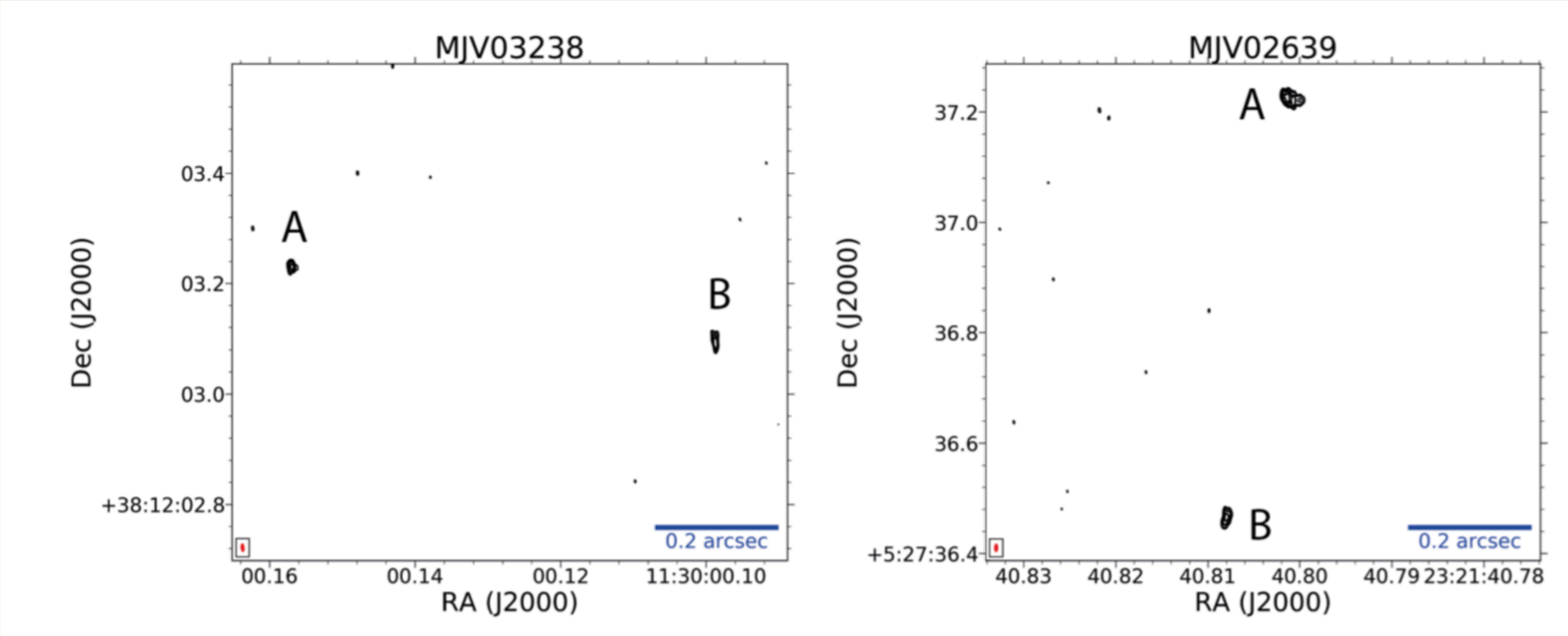

SEE ALSO MORGAN ET AL., (2016); RAMPADARATH ET AL., (2015, 2016)

FORBRICH ET AL., (2022), DZIB ET AL., (2022)

# Gravitational lenses

- Rare (~0.3% of VLBI sources)
- Independently measure the sub-structure mass-function within galaxies.
- High resolution of VLBI can constrain lens models
- Wide-field VLBI can find more of these lenses (see below from mJIVE-20 VLBI survey)

SPINGOLA ET AL. (2019)

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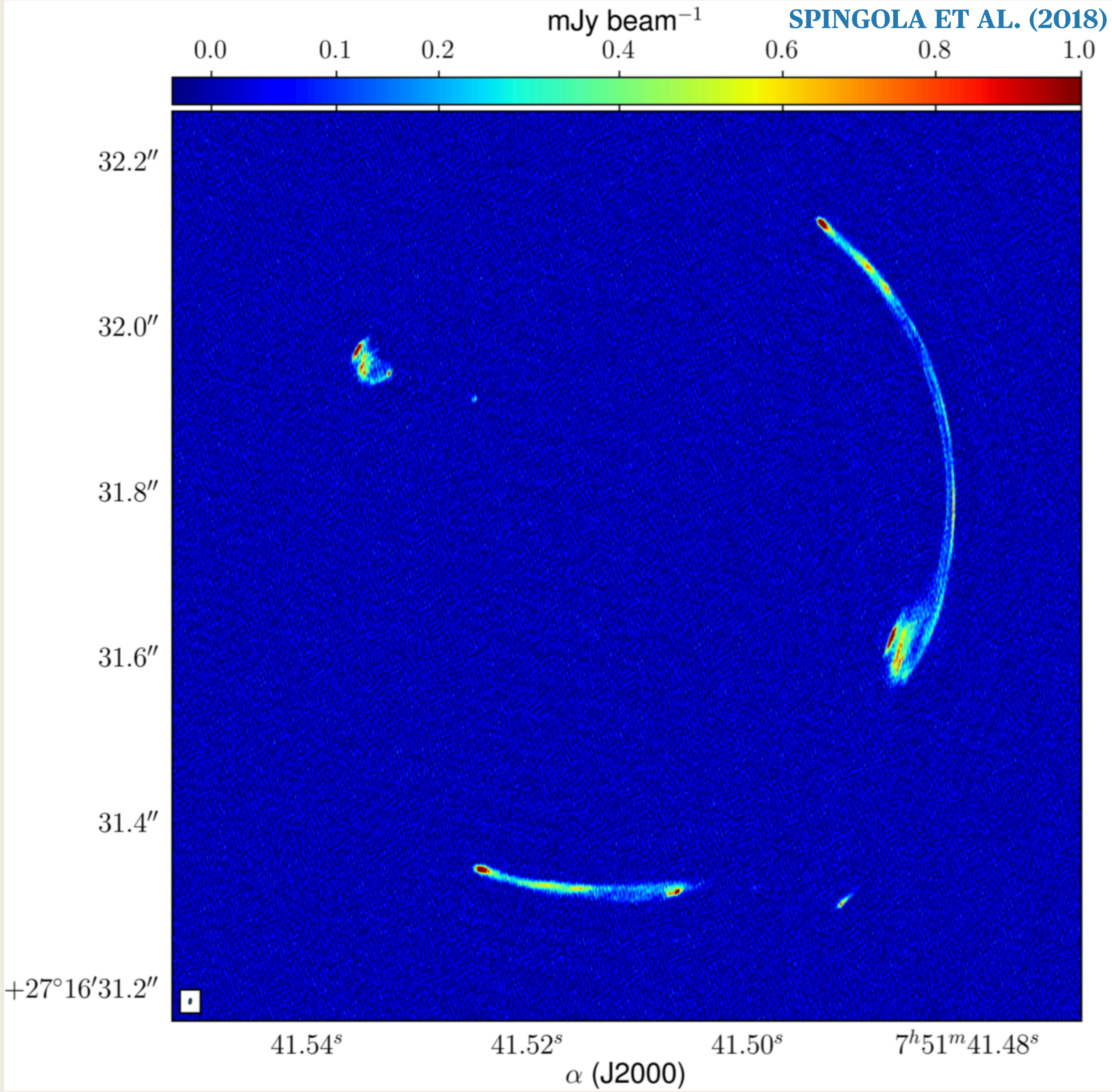

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# Aside - the radio interferometer measurement equation (RIME)

- Recap of the **Radio Interferometry Measurement Equation** (RIME) for antennas $p$ and $q$,

$$\mathsf{V}_{pq} = \boldsymbol{G}_p \left( \iint_{lm} \boldsymbol{E}_p \mathsf{B} K_{pq} \boldsymbol{E}_q^H \frac{\mathrm{d}l\mathrm{d}m}{n} \right) \boldsymbol{G}_q^H$$

**Visibilities** as measured by baseline $pq$

**Sky brightness distribution**

**Directional cosines** (i.e. sky coordinates)

**Direction-independent effects (DIEs)** e.g., bandpass, complex gain errors

$$n = \sqrt{1 - l^2 - m^2}$$

**Phase term**

$$K_{pq} = \exp\left\{ -2\pi i \left[ u_{pq} l + v_{pq} m + w_{pq} (n-1) \right] \right\}$$

**Direction-dependent effects** (**DDEs**)
e.g., primary beam, ionosphere

HAMAKER ET AL., (1996); SMIRNOV ET AL., 2011

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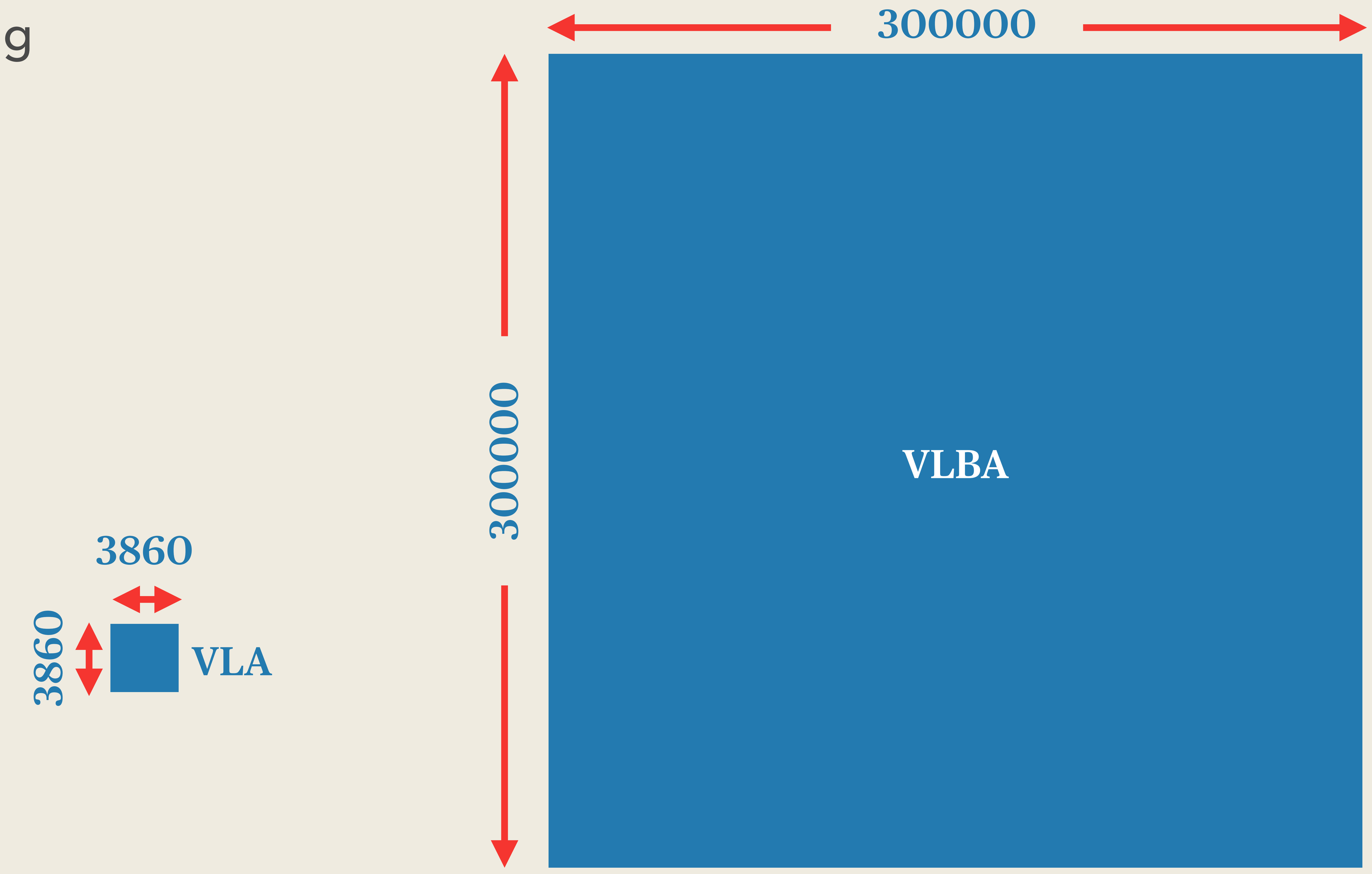
# Imaging the entire primary beam - challenges

## 1. Image sizes

- Assuming ~0.5 degree field-of-view (25m telescopes at 1.4 GHz) w/ 3x PSF sampling
  - *Very Large Array* (VLA) A-configuration (1.4″ resolution) - $\sim 1.4 \times 10^7$ pixels
  - *Very Long Baseline Array* (VLBA) - (~6 mas resolution) - $\sim 1 \times 10^{11}$ pixels



# Imaging the entire primary beam - challenges

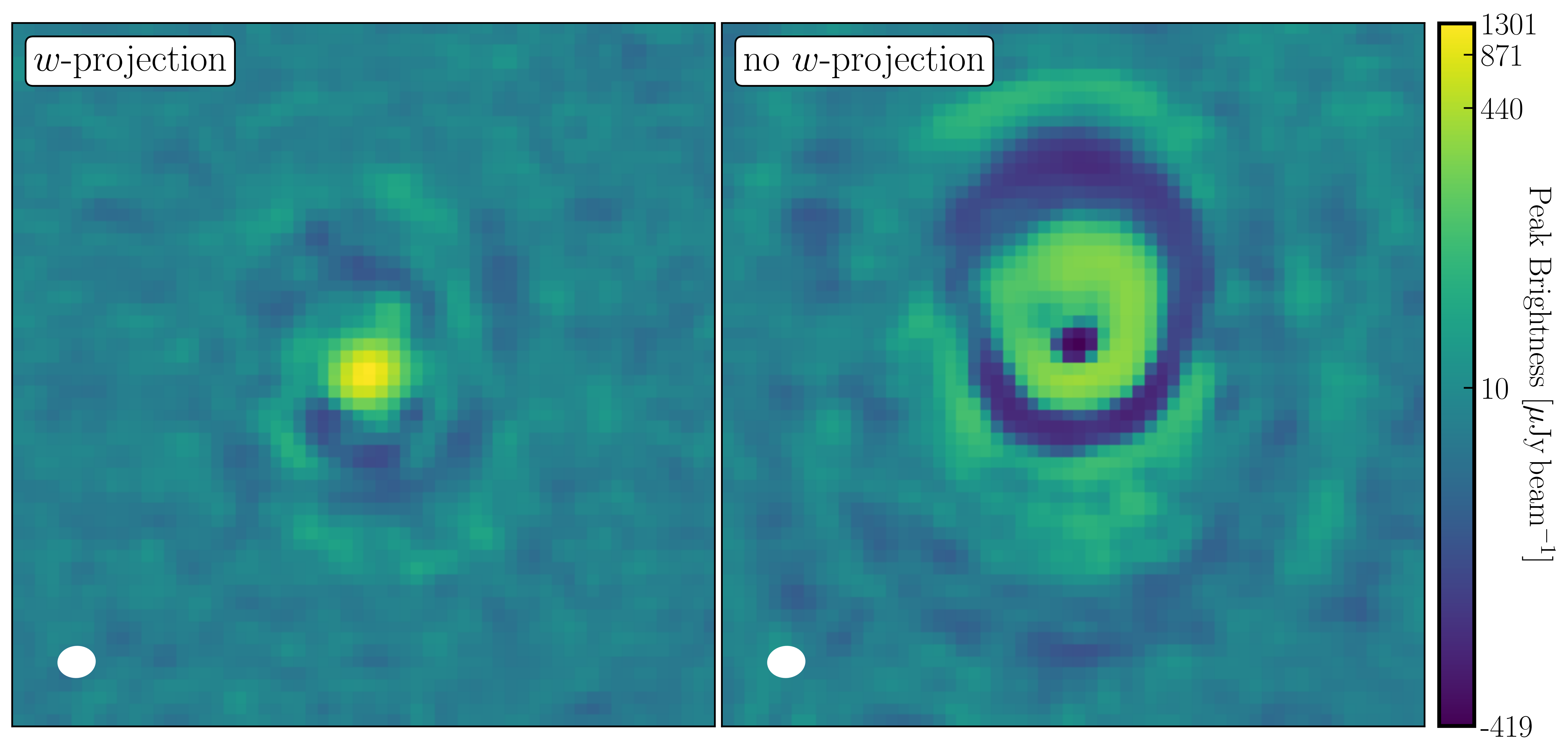
## 2. Non-coplanarity or the *w* term

**Ideal radio interferometer measurement equation**

$$\mathrm{V}(u,v) = \iint_{lm} \mathrm{B}(l,m)\ \exp\left\{-2\pi i\left[ul + vm + w\left(n-1\right)\right]\right\}\frac{\mathrm{d}l\mathrm{d}m}{n}$$

$$*n = \sqrt{1 - l^2 - m^2}$$

***e*-MERLIN - source 7.5' from pointing centre**




- The pesky extra term of:

$$\frac{1}{n}\exp\left[w\left(n-1\right)\right]$$

stops us having a true 2D-FT

- Solving requires calculating and implementing convolutional product. Relatively more computationally expensive

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# Imaging the entire primary beam - challenges

## 3. Smearing

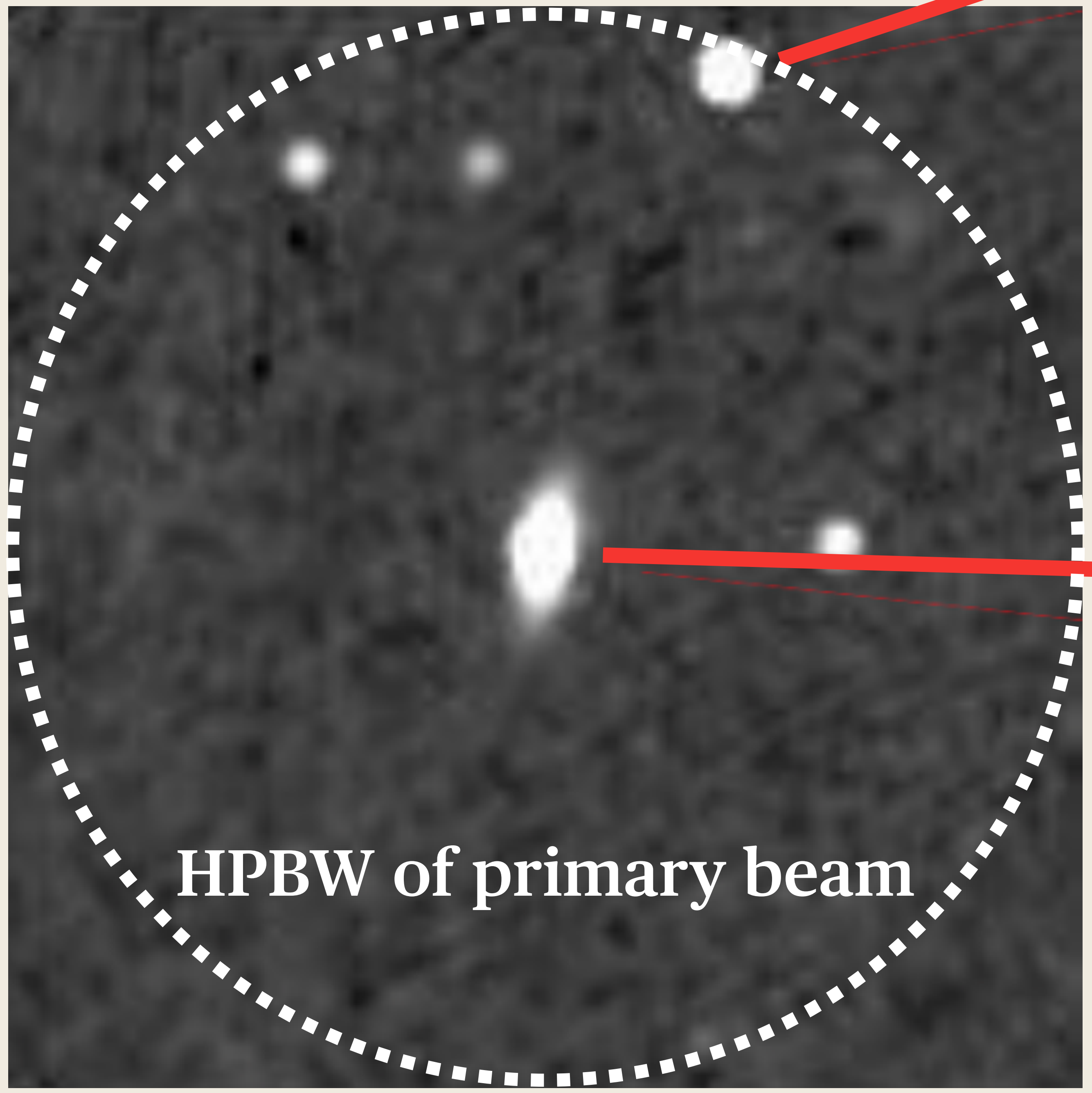
RIME

$$*n = \sqrt{1 - l^2 - m^2}$$

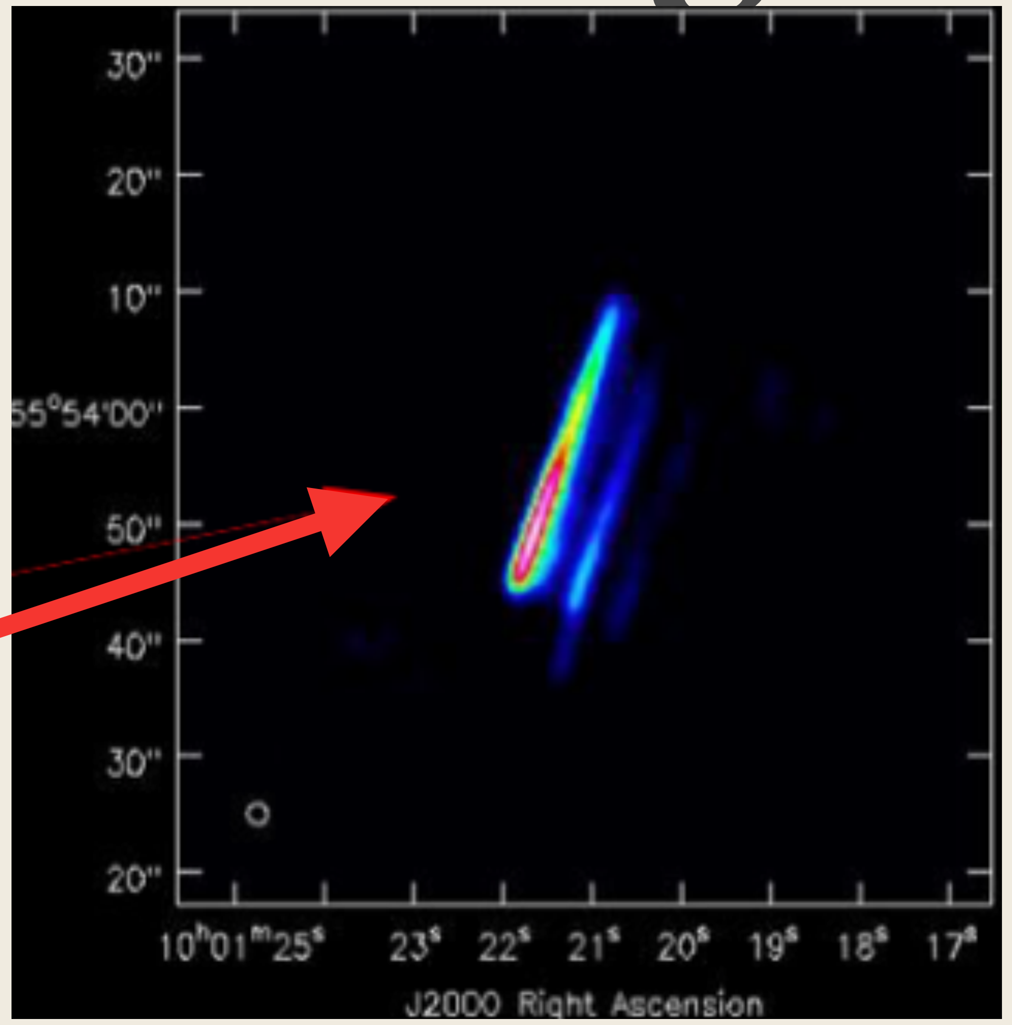
$$\mathrm{V}_{pq} = \iint_{l,m} \mathrm{B}(l,m)\exp\left\{-2\pi i\left(u_{pq}l + v_{pq}m + w_{pq}(n-1)\right)\right\}\frac{\mathrm{d}l\mathrm{d}m}{n}$$

- Caused by averaging of the data in time and frequency (loss of coherence)

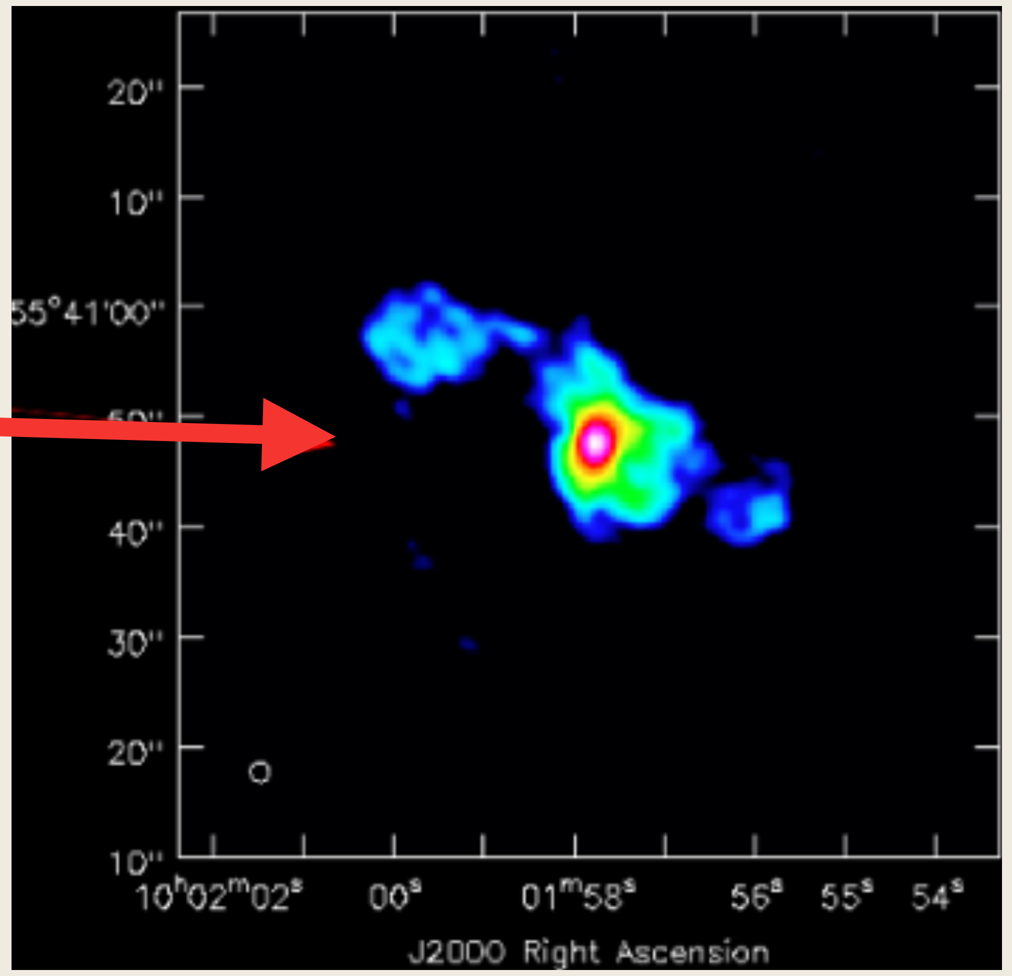
NVSS (VLA) - short baselines




Edge of PB massively smeared




*e*-MERLIN - long baselines




Centre of PB no smearing

Image credit - T. Muxlow

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# Imaging the entire primary beam - challenges

## 3. Smearing

'Post-correlation' RIME

$$*n = \sqrt{1 - l^2 - m^2}$$

$$\langle \mathsf{V}_{pq} \rangle = \frac{1}{\Delta t \Delta \nu} \iint_{t_0,\nu_0}^{t_1,\nu_1} \left[ \iint_{l,m} \mathsf{B}(l,m) \exp\left\{ -2\pi i \left( u_{pq} l + v_{pq} m + w_{pq}(n-1) \right) \right\} \frac{\mathrm{d}l \mathrm{d}m}{n} \right] \mathrm{d}t \mathrm{d}\nu$$

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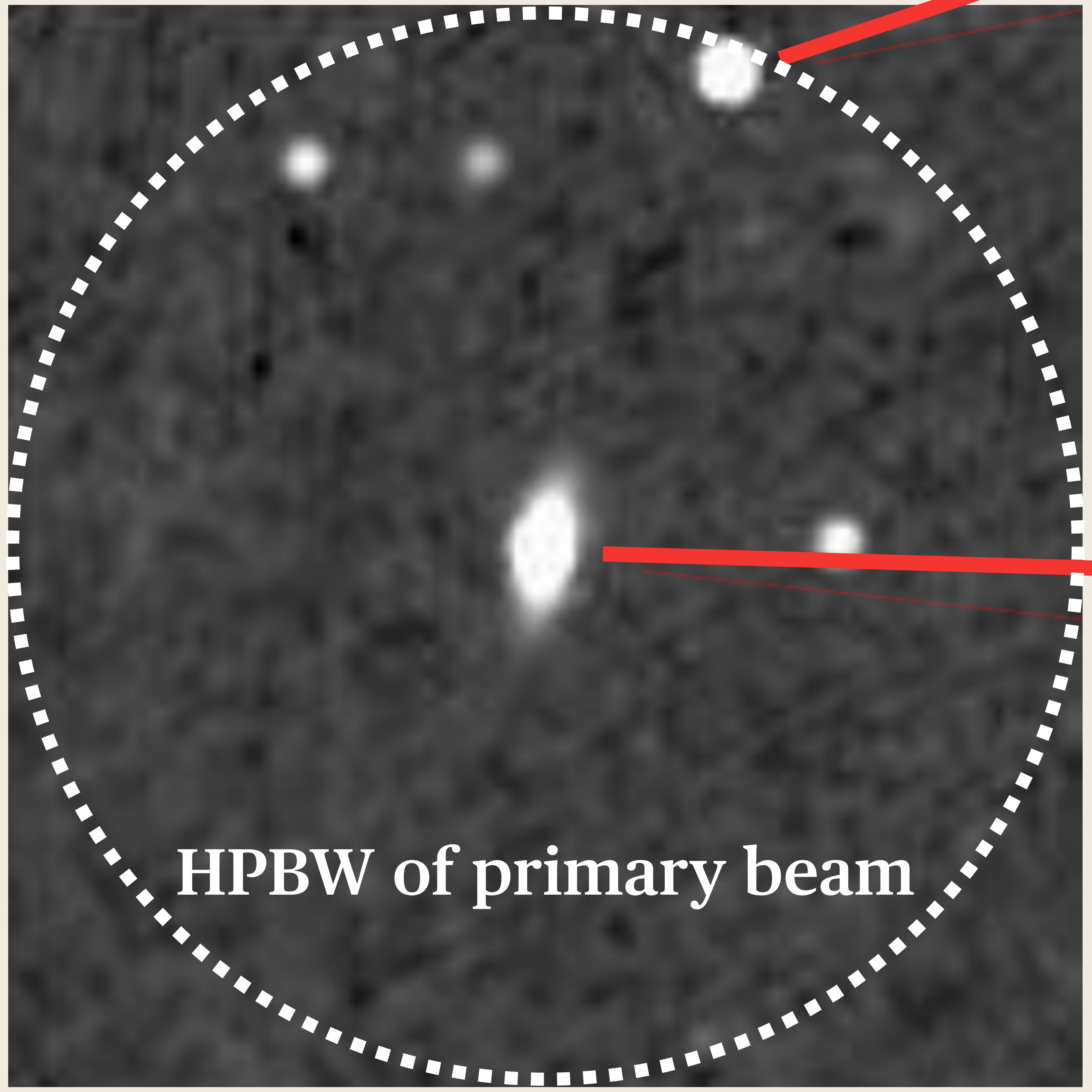


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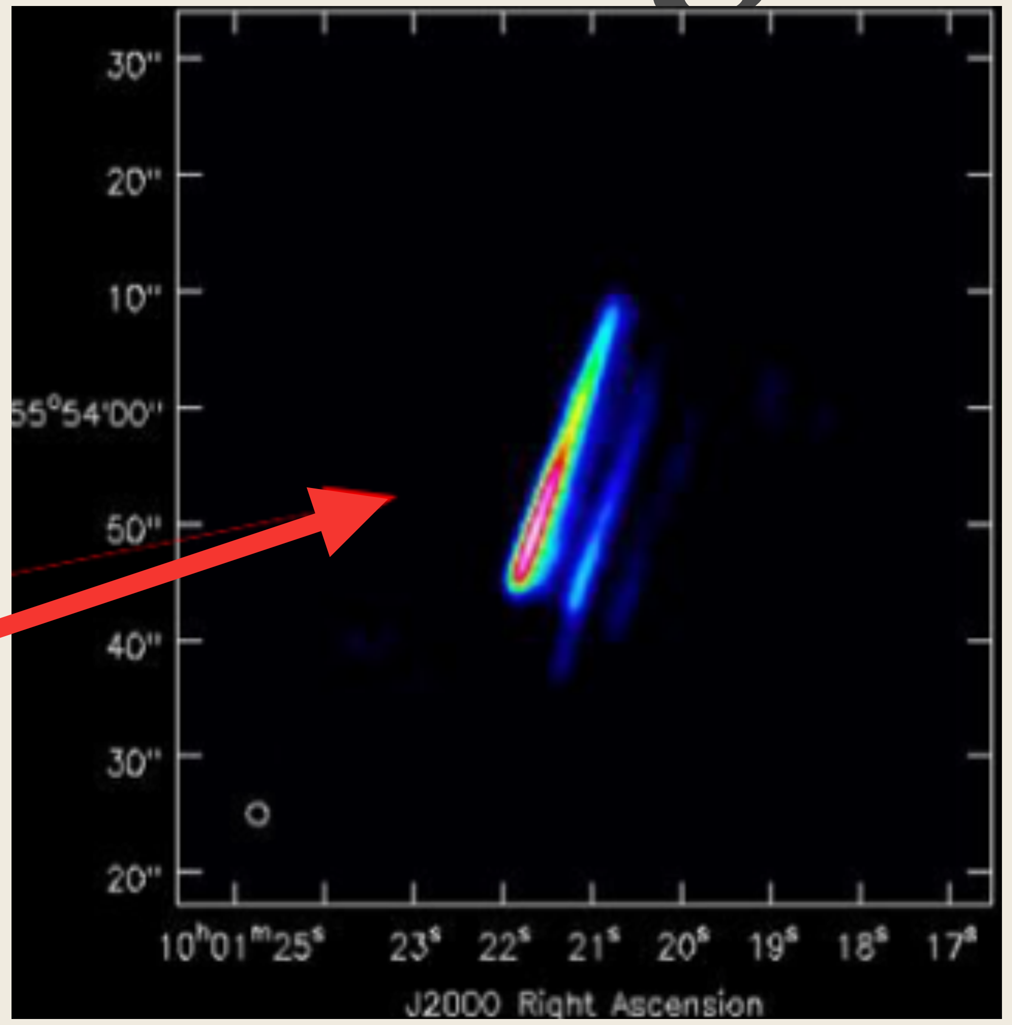


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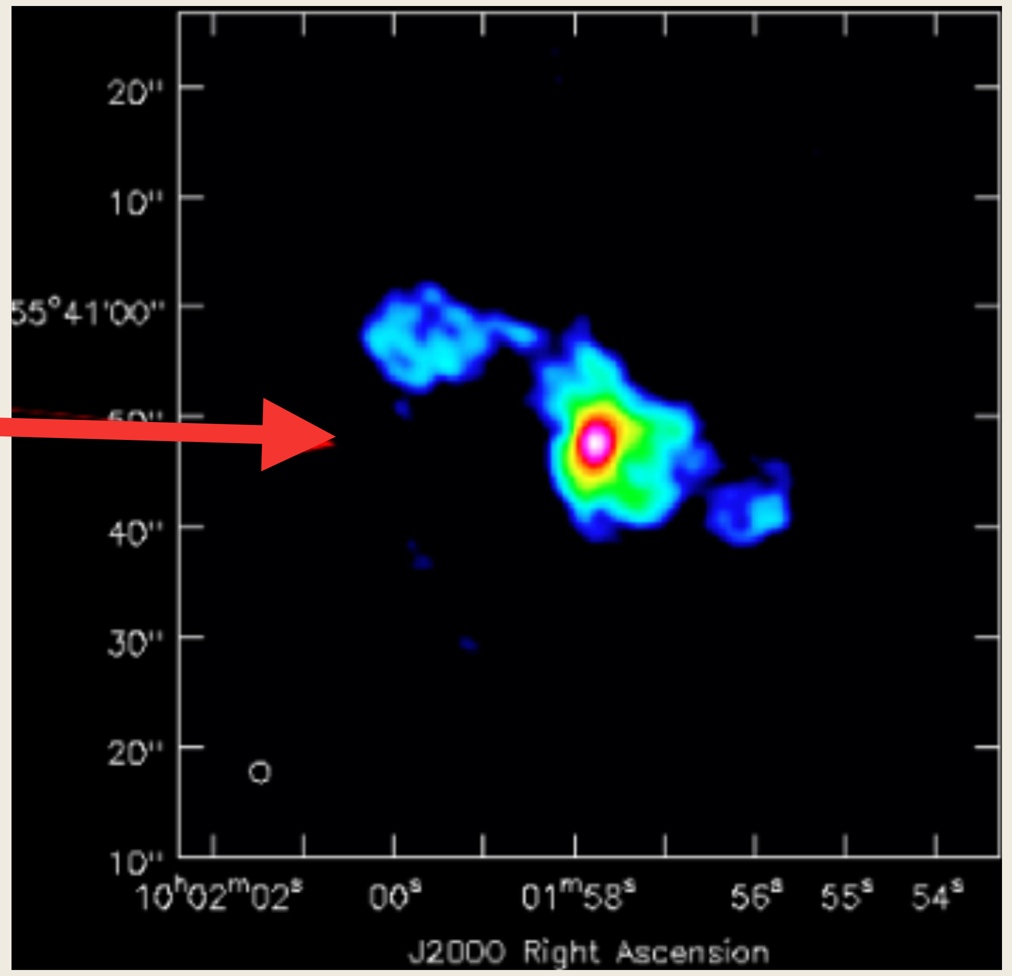


Image credit - T. Muxlow

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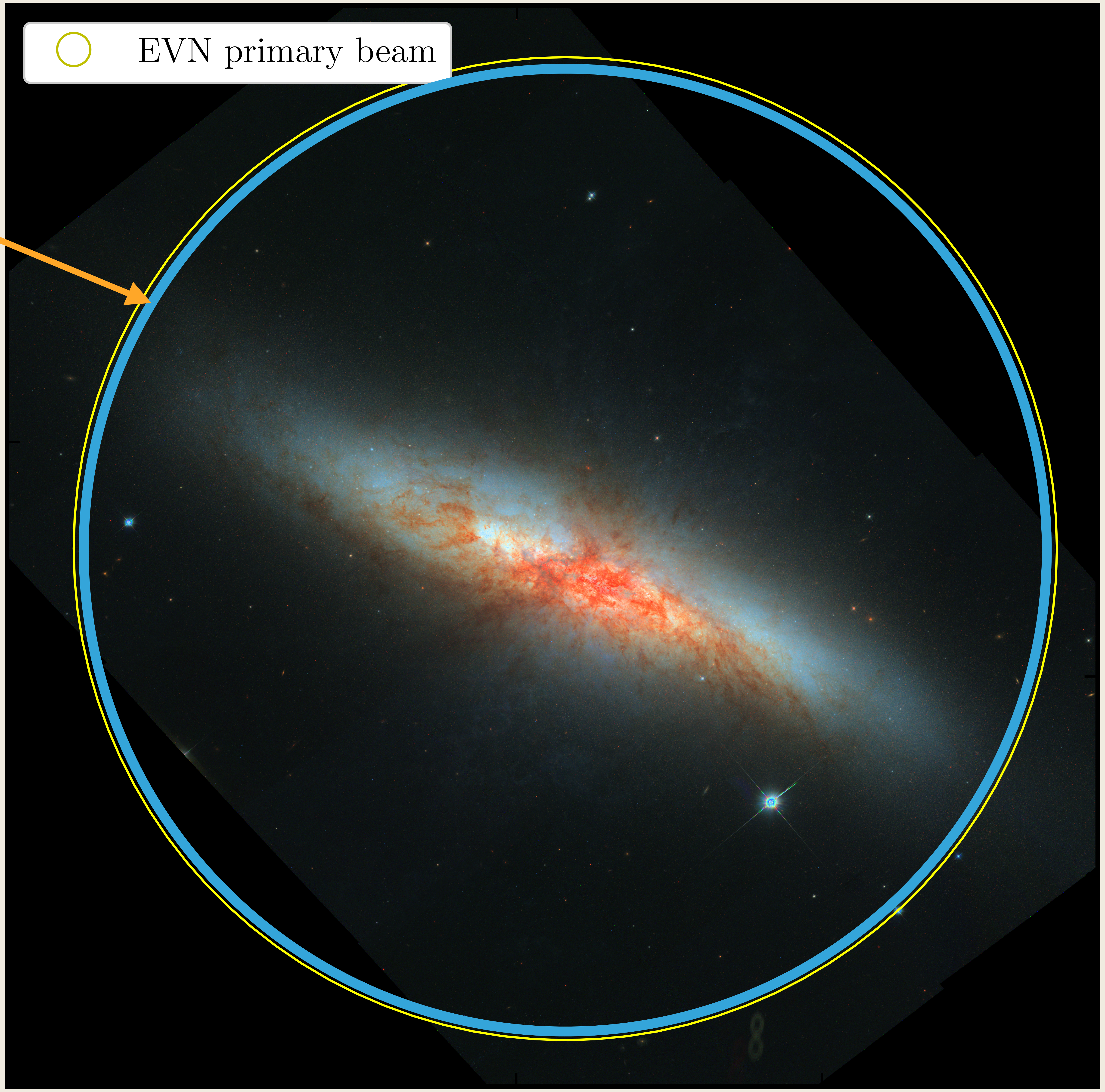
# Standard wide-field correlation

Field-of-view due to smearing

- Correlate at high temporal & frequency resolution to restrain smearing
- *Result* - one huge data set which is 99.99999% noise
- This huge single data set is often TBs* in size
- Often have to shift to different positions which is inaccurate using standard software.



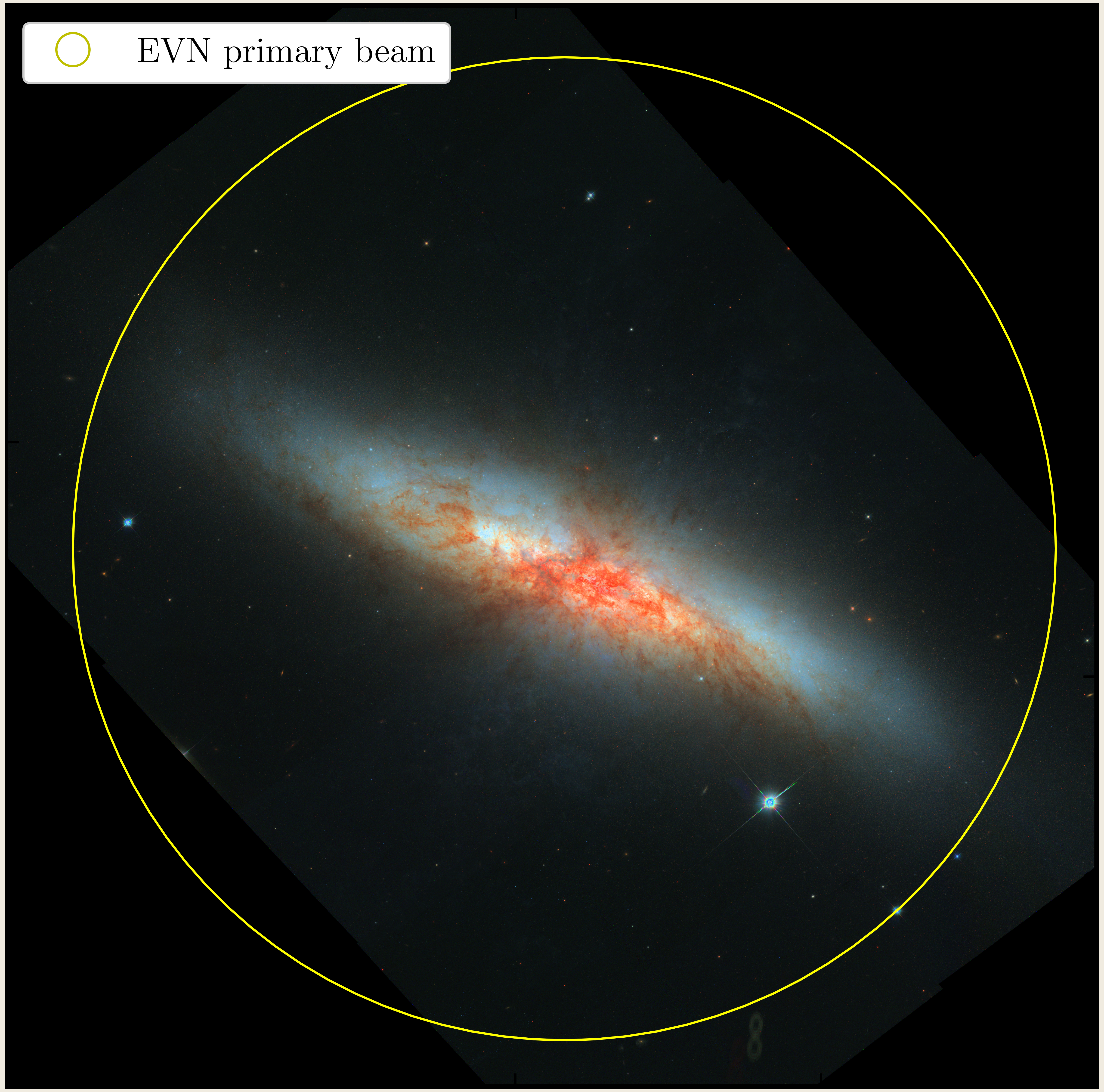

*Note a 22 telescope, 12 hour EVN observation @ 1 Gbps ~ 10 TB

# Multiple phase-centre correlation

1. Split data into time chunks
2. Correlate each chunk at very high time & frequency resolution to prevent smearing
3. Copies & phase shift to multiple locations in primary beam
4. Average in time & frequency

*Result* - you receive lots of small (in FoV and size) *data sets at different positions* across the primary beam so it's easily parallelisable!

- Choice of phase centres is up to the user and could cover entire primary beam, or just some known sources of interest e.g. VLA positions etc.




MORGAN ET AL., (2011); DELLER ET AL., (2011); KEIMPEMA ET AL., (2015)

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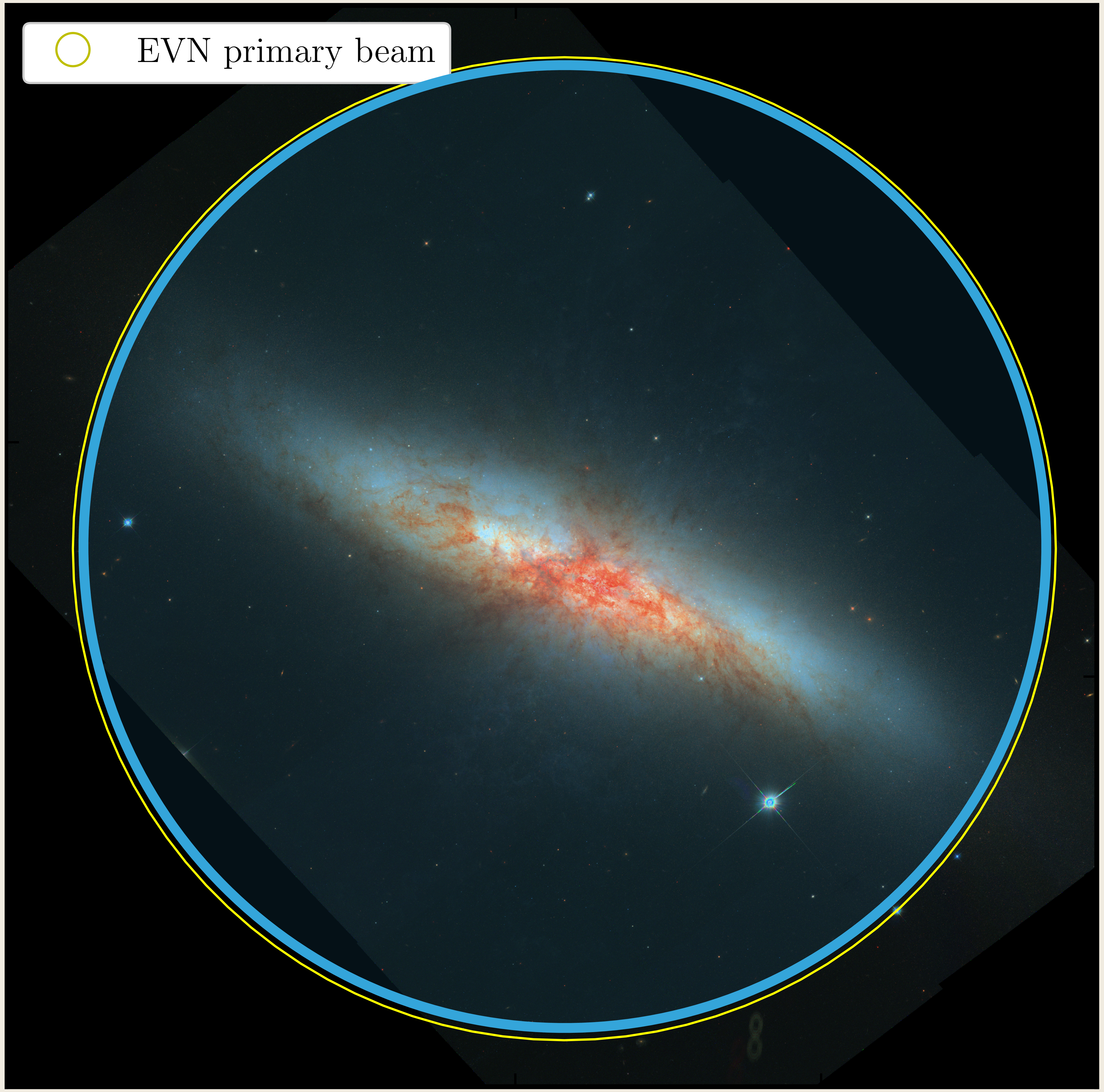


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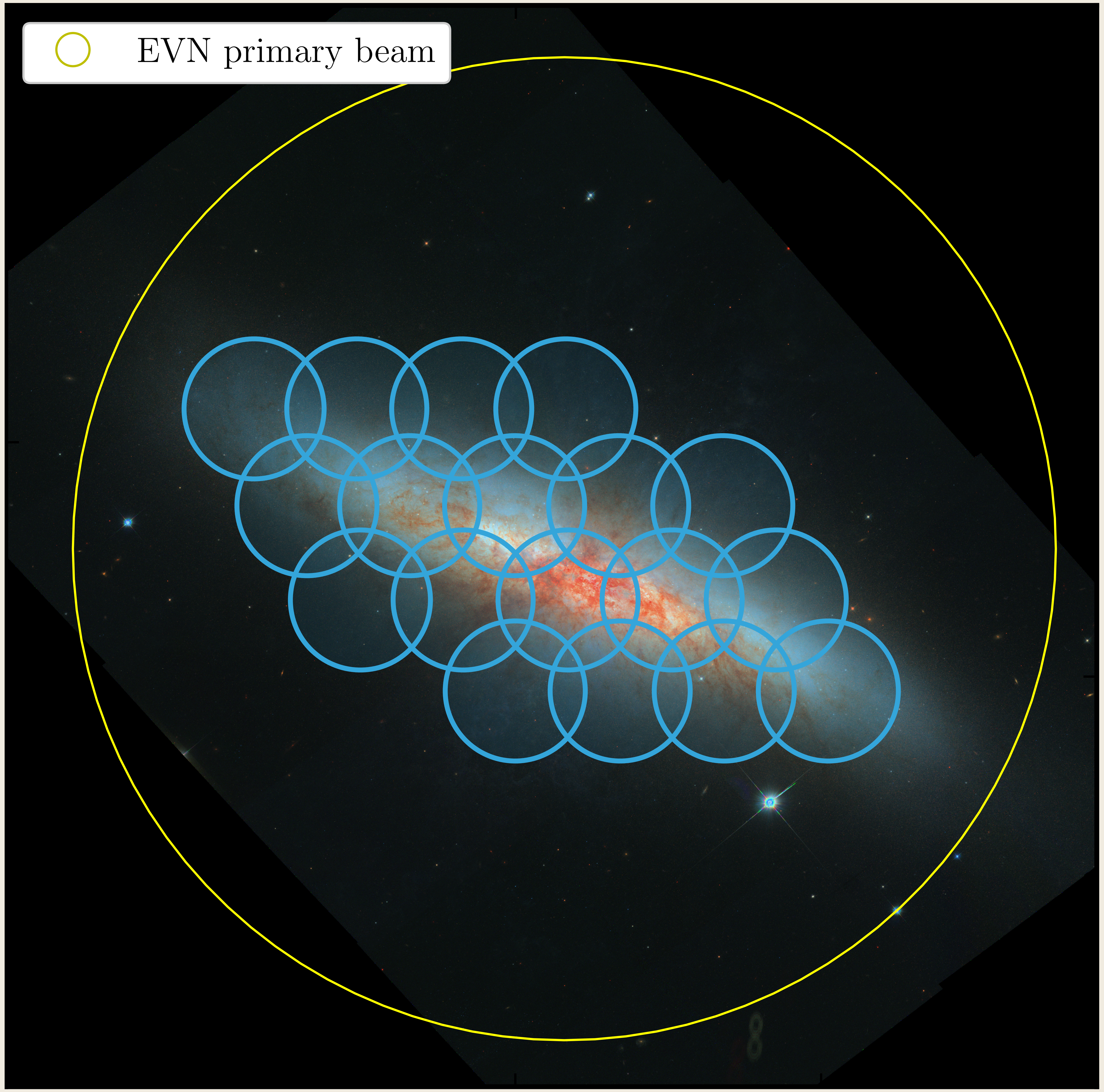


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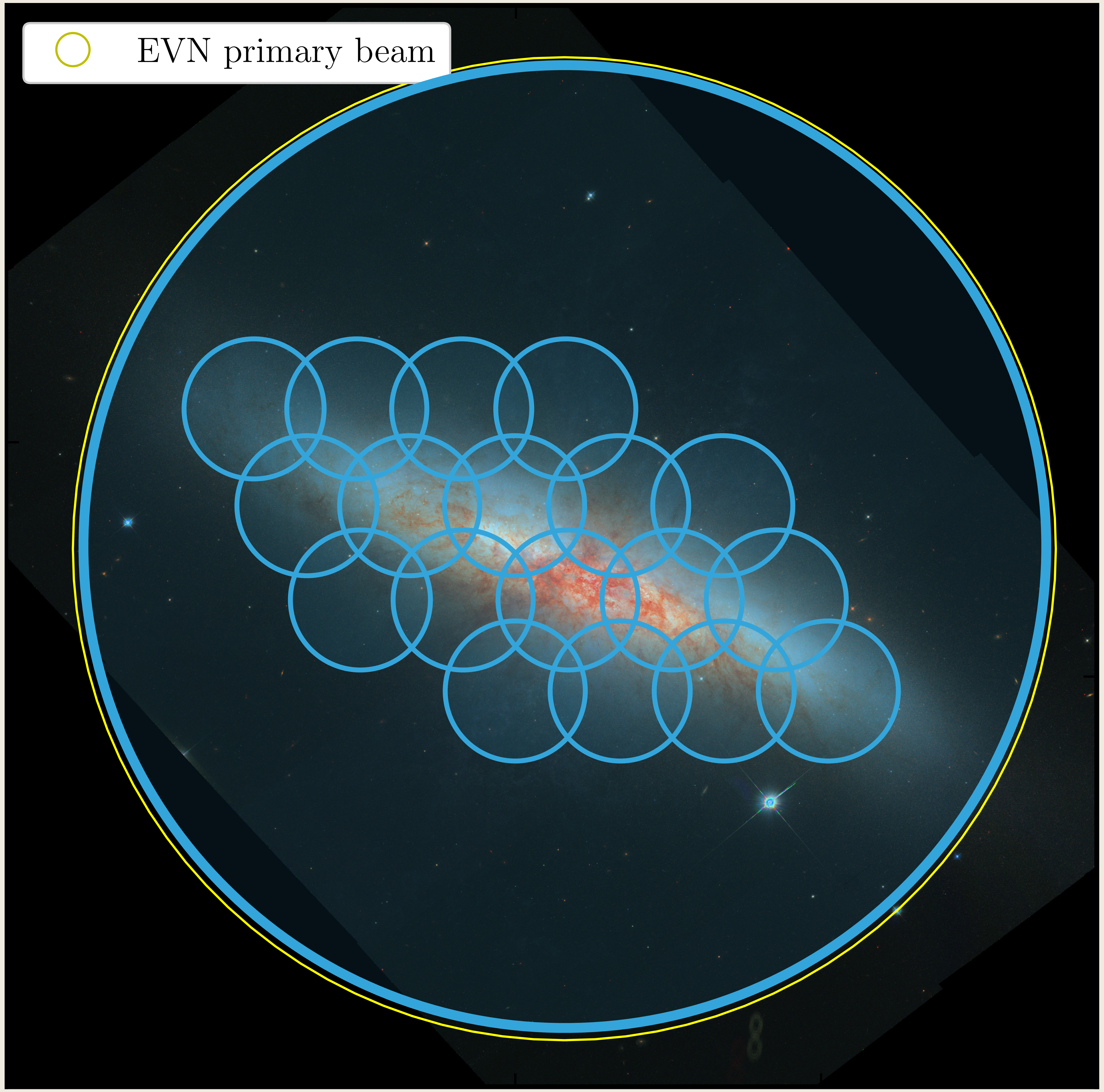


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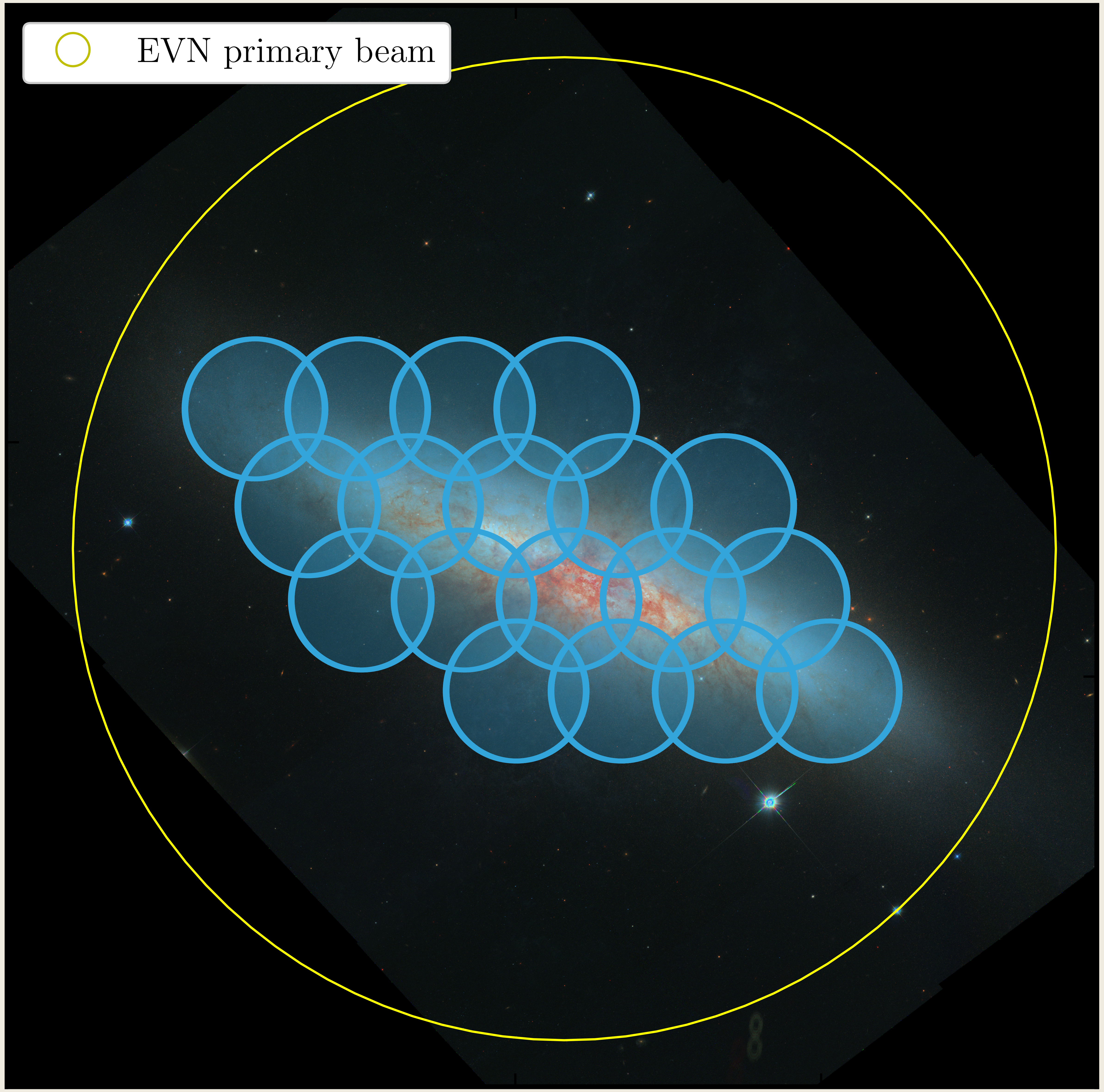
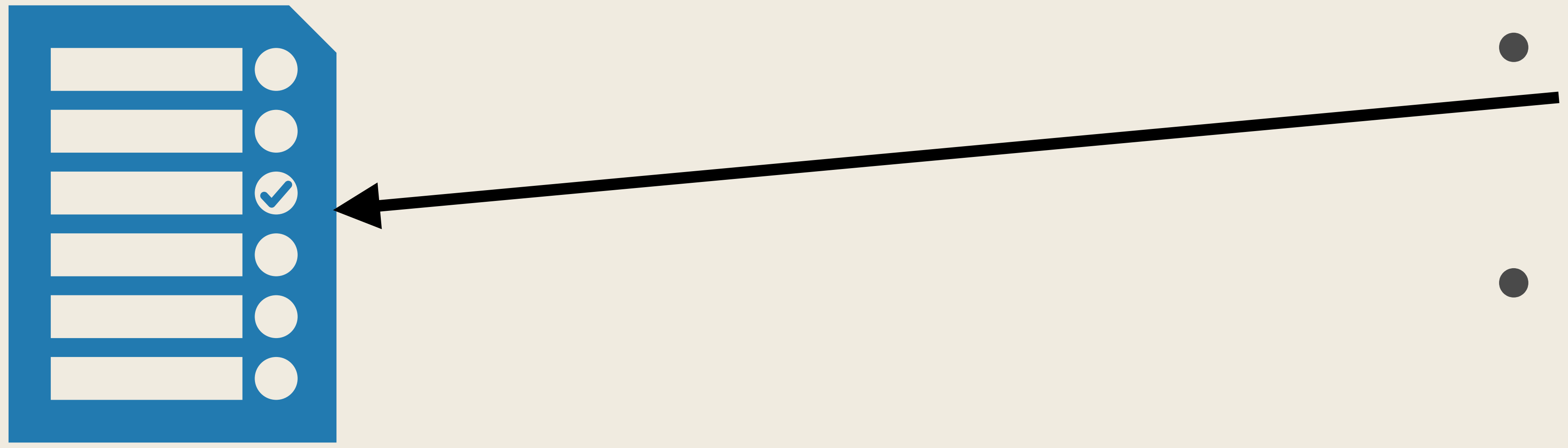


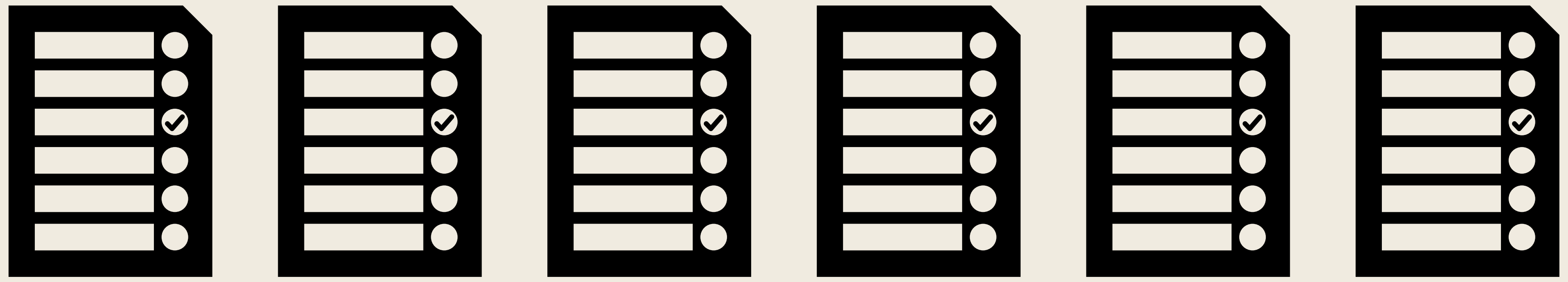

MORGAN ET AL., (2011); DELLER ET AL., (2011); KEIMPEMA ET AL., (2015)

# Phase referencing



- Typically, one phase centre will contain the phase, bandpass and fringe finders sources.
- Most importantly - **standard VLBI phase referencing applies**
- Calibration tables & flagging tables derived can then be applied to ALL other target fields
- Easily parallelisable so calibration is very quick

Other phase centres



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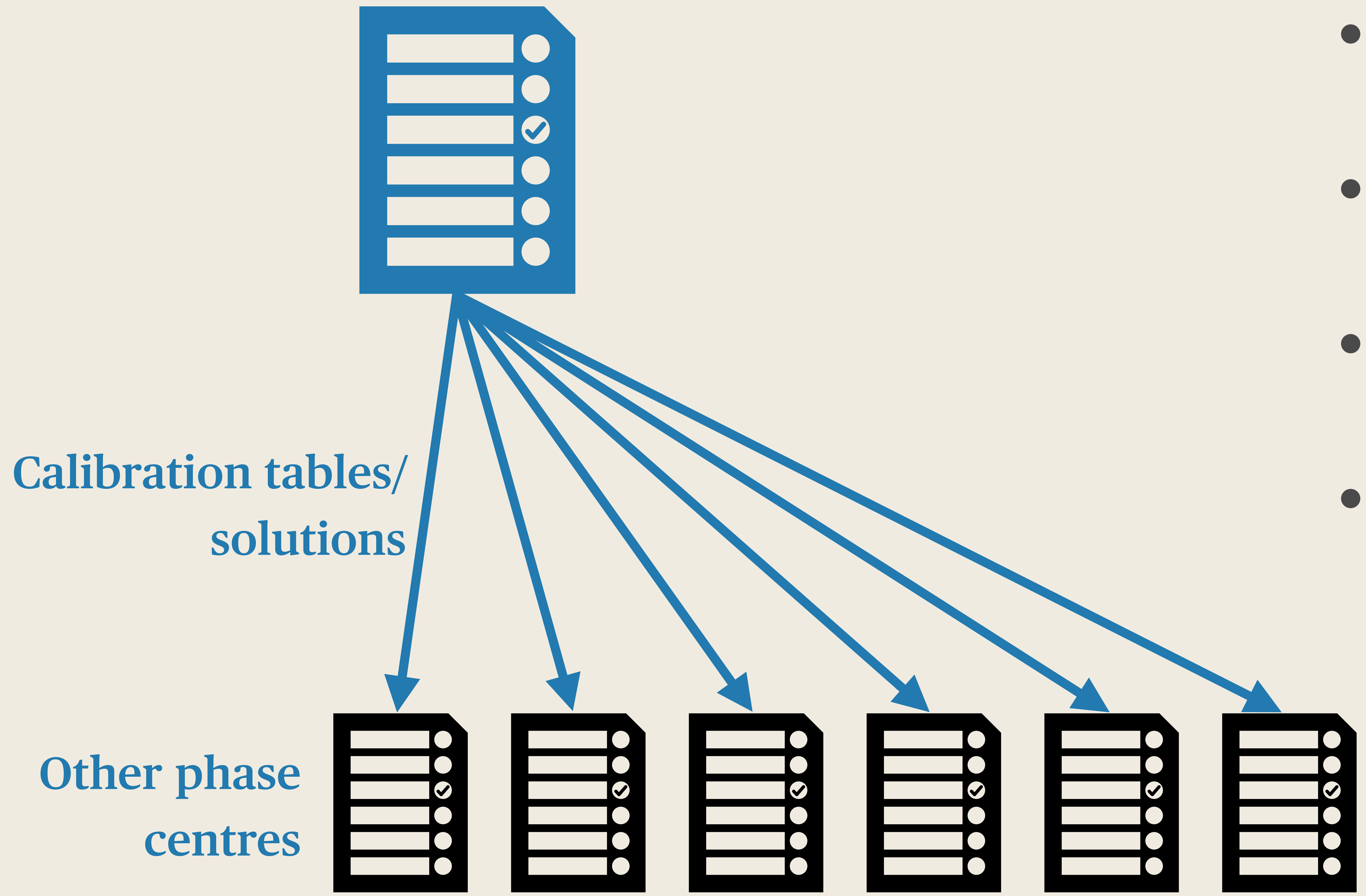


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# Self-calibrating wide-field VLBI data

- Atmospheric effects correlated on short baselines **but not** on longer baselines
- Often uncorrelated at different locations within the target field too…
- Also, the number density of VLBI sources (and their flux densities) lower due to the ‘resolving out’/ spatial filtering effect.

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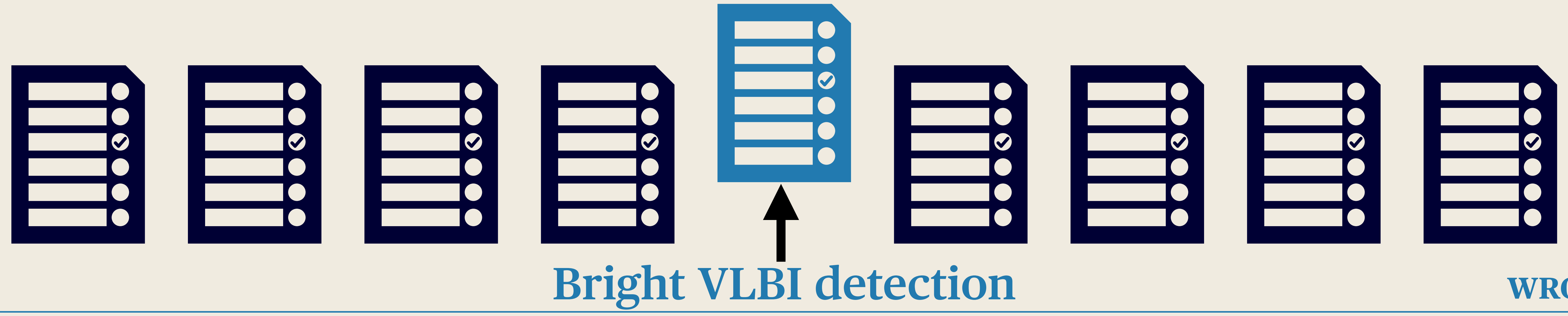
# In-beam phase referencing / self-calibration

- Put a phase-centre on a bright source within the target field and use this to derive self-calibration solutions.
- Then, apply solutions to all other phase centres.
- However, only some target fields have bright enough VLBI sources → limits the number of fields




WROBEL ET AL . 2000, GARRETT ET AL. 2005

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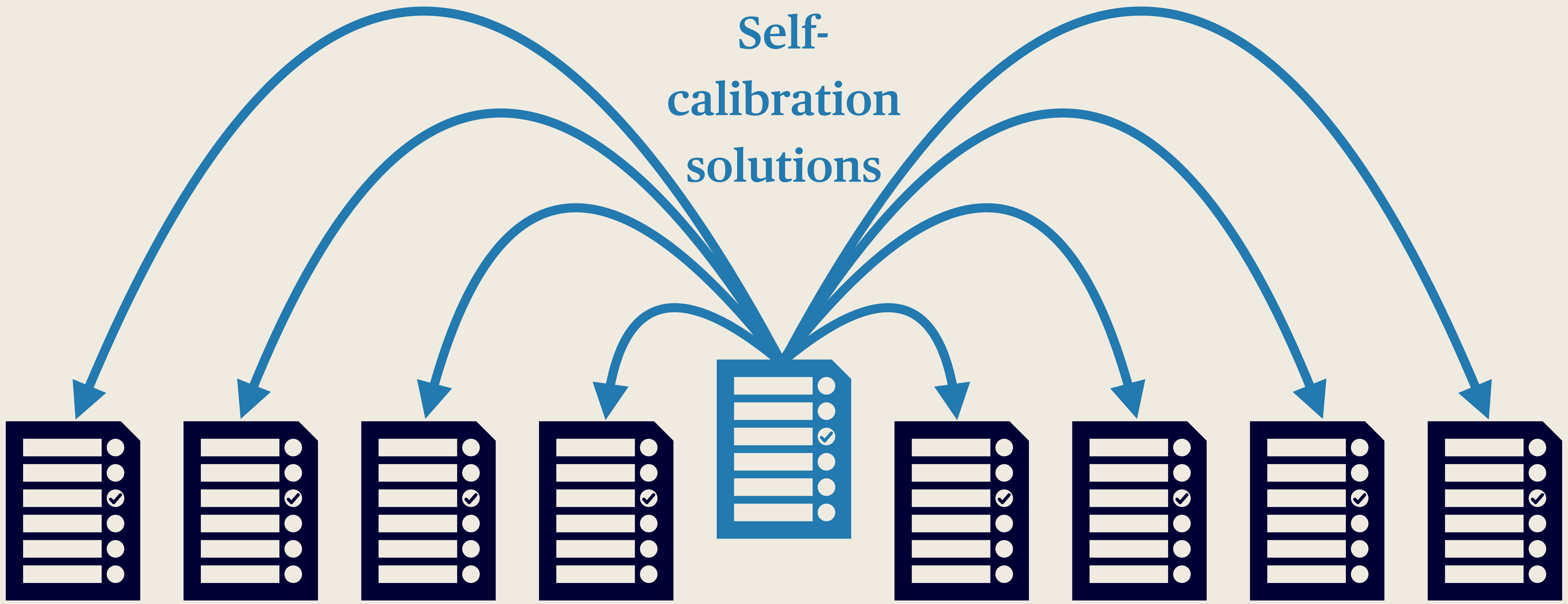
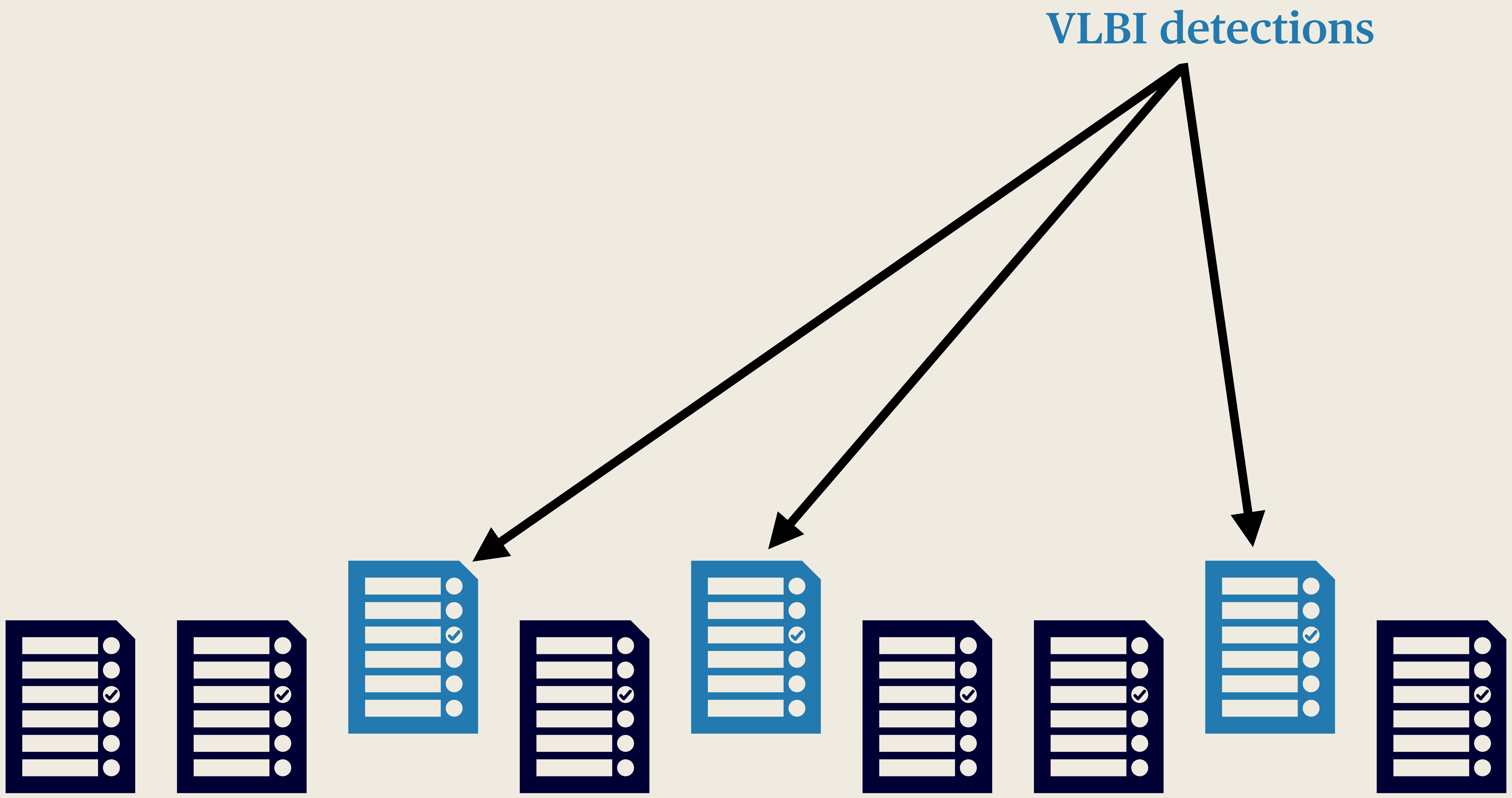



WROBEL ET AL . 2000, GARRETT ET AL. 2005

# Multi-source self-calibration

- Use combined response (via *uv* stacking) of detected target sources to derive self-calibration solutions.
- So how does it work?




MIDDELBERG ET AL., (2013); RADCLIFFE ET AL., (2016)

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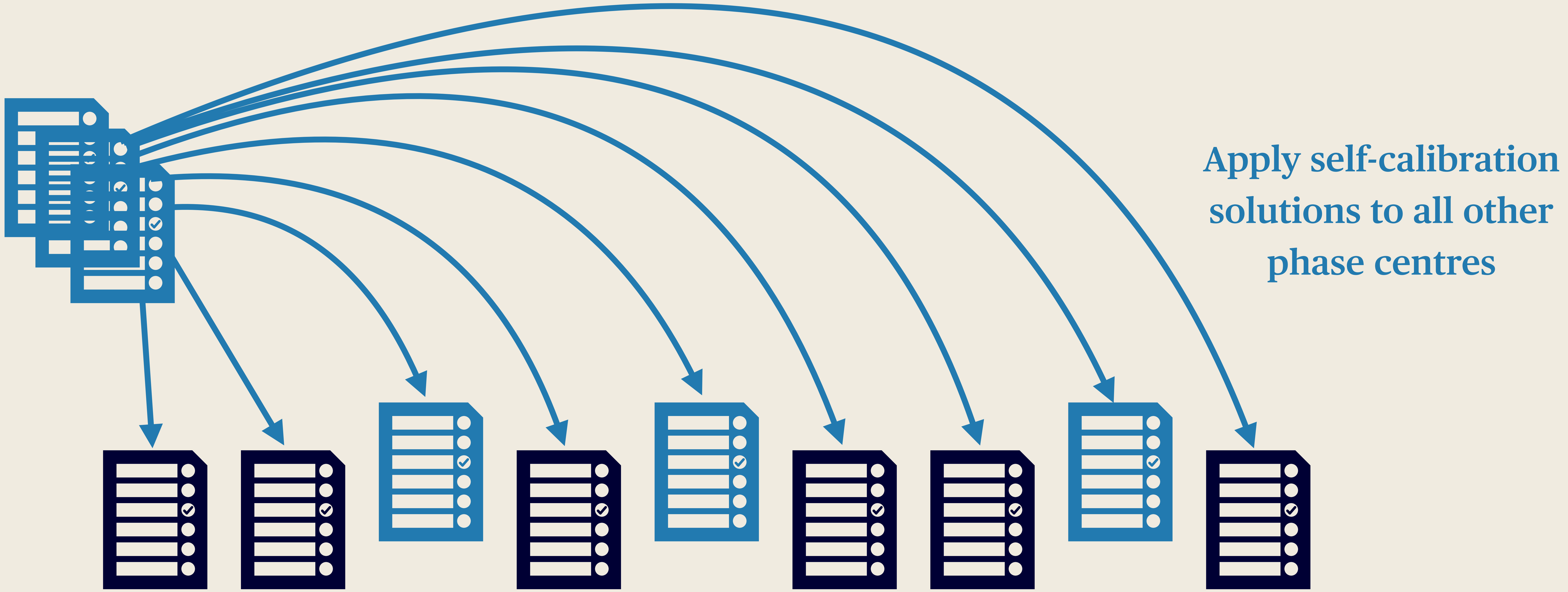


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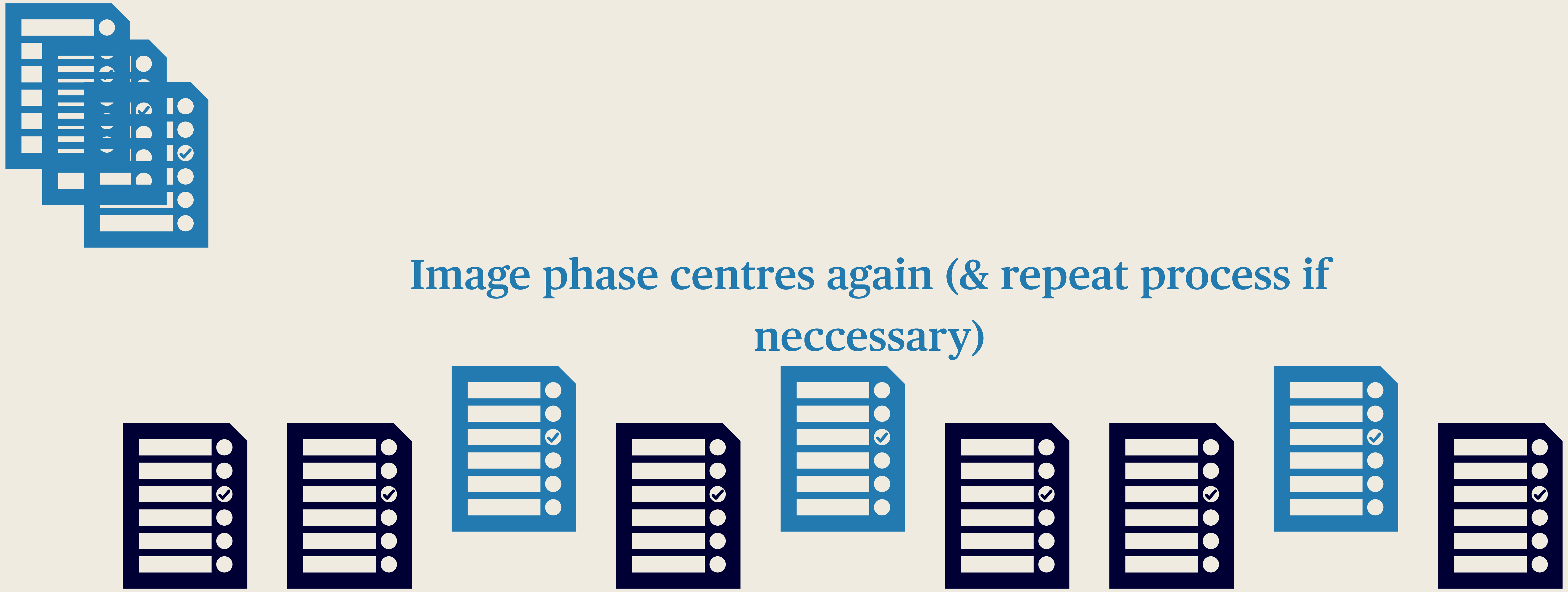


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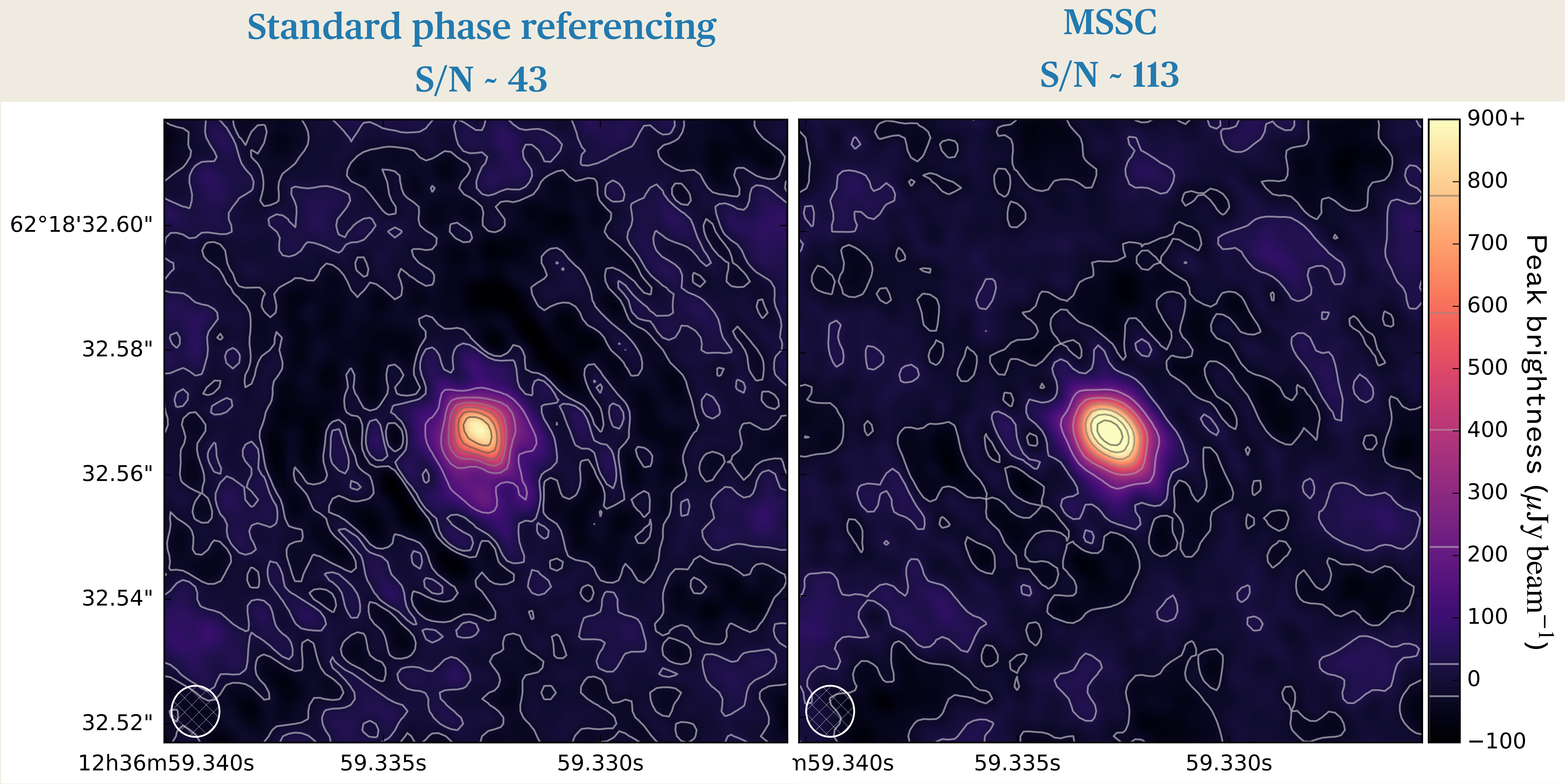
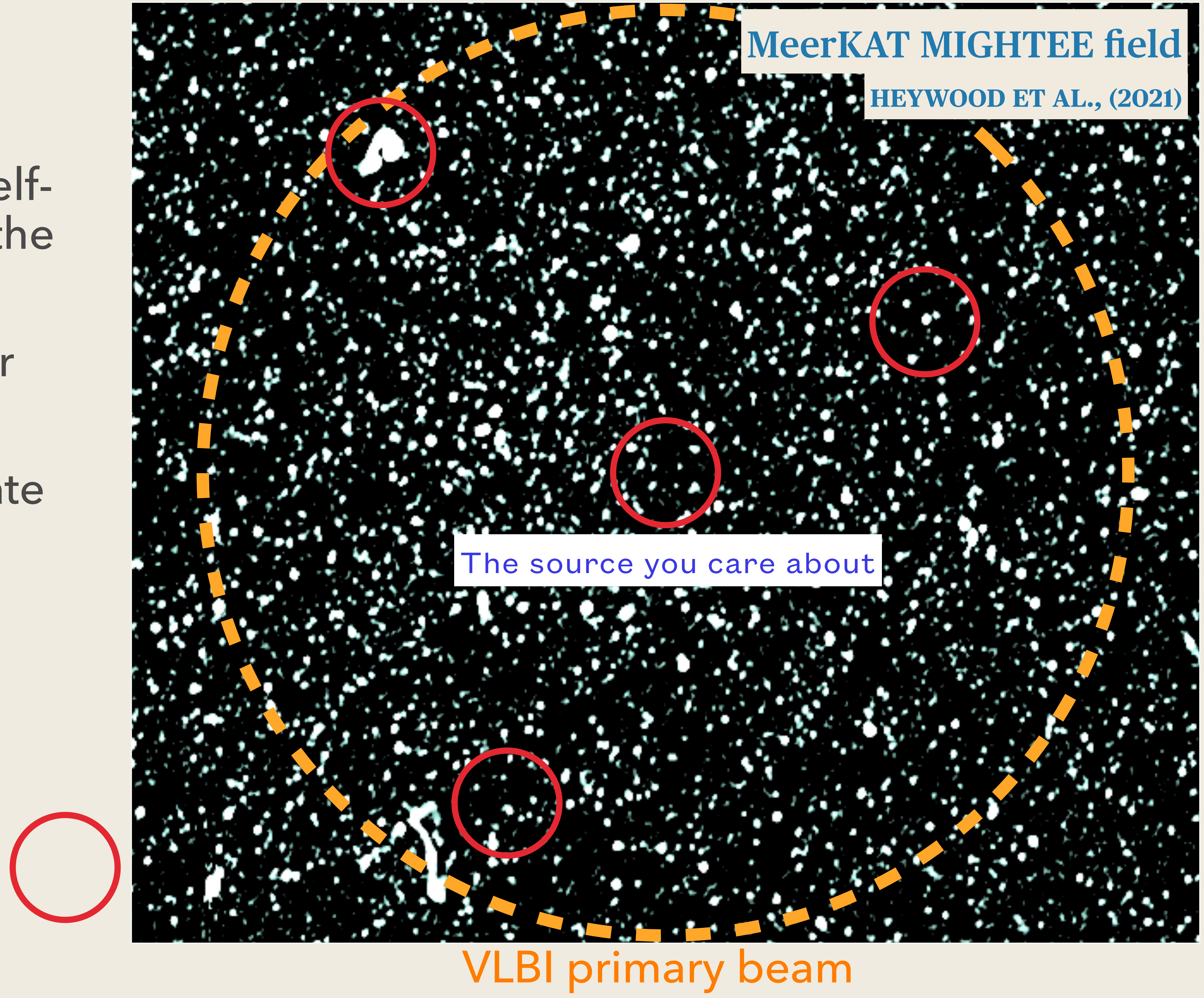



- Code publicly available for AIPS - https://github.com/jradcliffe5/multi_self_cal
- CASA version in beta as part of VPIPE (see later)

MIDDELBERG ET AL., (2013); RADCLIFFE ET AL., (2016)

# MSSC - not just for wide-field data sets

- Standard VLBI targets just a small FoV in the centre that may not provide enough S/N for self-calibration, **but** there's other radio sources in the FoV.
- Use multiple phase centre correlation on other potential sources in the primary beam
- Then you may have enough S/N to self-calibrate VLBI data-set
- Plus you may find something interesting…



# Direction-dependent effects

- To the RIME, we had the corrupting effects being parameterised as a Jones chain:

$$\mathsf{V}_{pq} = \iint_{lm} \boldsymbol{J}_p \frac{\mathsf{B}(l,m)}{n} \exp\left\{-2\pi i \left[u_{pq}l + v_{pq}m + w_{pq}(n-1)\right]\right\} \boldsymbol{J}_q^H \, \mathrm{d}l\mathrm{d}m$$

$$\mathsf{V}_{pq} = \iint_{lm} \boldsymbol{J}_p K_p \mathsf{B}(l,m) K_q^H \boldsymbol{J}_q^H \, \mathrm{d}l\mathrm{d}m$$

- Can be split into direction-independent ($\boldsymbol{G}$) and direction-dependent effects, DDEs ($\boldsymbol{E} = \boldsymbol{E}(l,m)$)

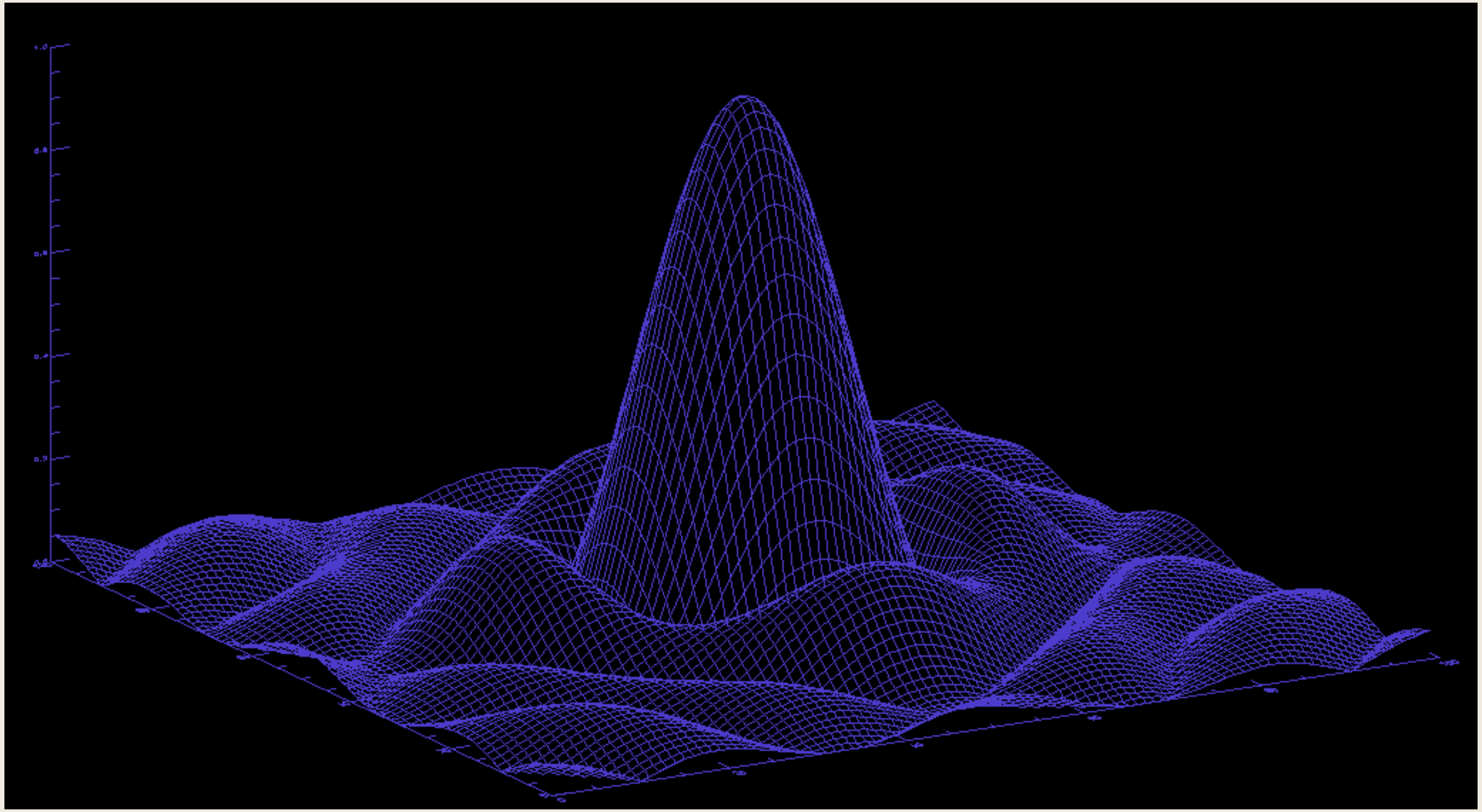
$$\mathsf{V}_{pq} = \boldsymbol{G}_p \left( \iint_{lm} \boldsymbol{E}_p K_p \mathsf{B}(l,m) K_q^H \boldsymbol{E}_q^H \, \mathrm{d}l\mathrm{d}m \right) \boldsymbol{G}_q^H$$

- These $\boldsymbol{E}$ terms causes your interferometer to effectively ‘see’ a different sky on each baseline and can cause errors. Most are calibrated away through observational design / strategies (e.g., phase referencing).
- Some are not, and can change over your field-of-view…

# Primary beams

- Primary beams are *the most ubiquitous direction dependent effect* (DDE) that affects **all** wide-field radio observations.
- For small sized images, delay centre = primary beam maxima so often no need to correct!
- For large images, we need to deal with this attenuation.
- More of a problem for heterogeneous arrays (i.e. most VLBI arrays) as we shall see next.

Knockin primary beam holographic scan



# Homogeneous arrays

- Assume DIEs ($\boldsymbol{G}$) are calibrated and no other DDEs are present so $\boldsymbol{E}$ are just the primary beam voltages.
- For an homogeneous array (e.g., MeerKAT, VLA, ASKAP etc.), a standard assumption is that the primary beam for each telescope is identical ($\boldsymbol{E}_p = \boldsymbol{E}_q = \boldsymbol{E}$ for all $p,\ q$) and non-varying with time so $\boldsymbol{E}(t, l, m) \equiv \boldsymbol{E}(l, m)$.
- This means that *each baseline observes the same apparent brightness distribution* thus,

$$\mathsf{B}_{\text{app}} = \boldsymbol{E}\mathsf{B}\boldsymbol{E}^H$$

- Standard imaging algorithms recover an image by *assuming that each baseline observes the same apparent brightness distribution / common sky*. Due to this, all of the baselines can be gridded so their projected baseline vectors form the *uv* plane,

$$\mathsf{V}(u, v) \approx \iint_{lm} \mathsf{B}_{\text{app}} \exp\left\{-2\pi i\left[ul + vm + w(n-1)\right]\right\} \mathrm{d}l\mathrm{d}m$$

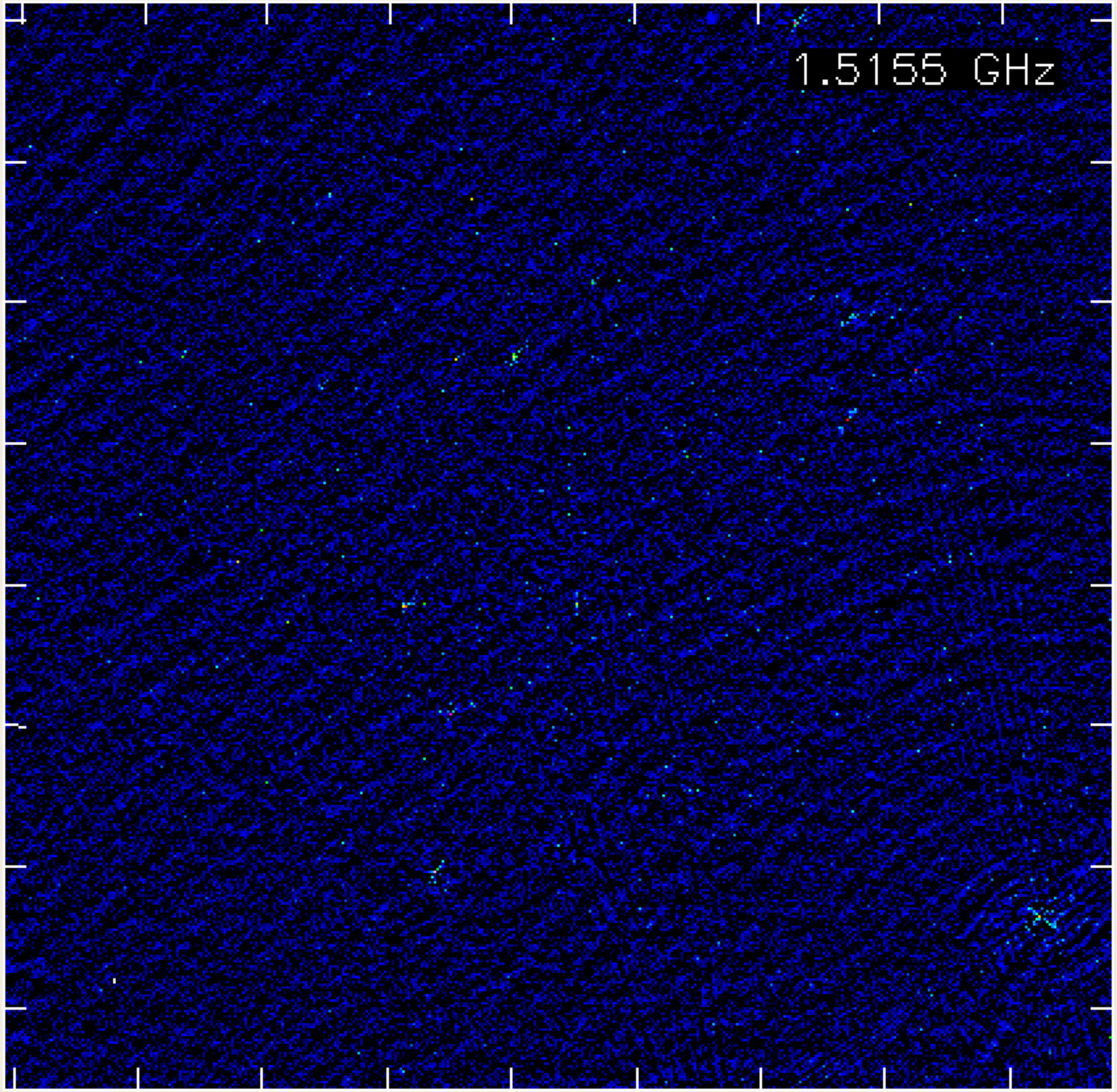
# Homogeneous arrays

- This is our standard imaging problem and can gridded, inverted, and de-convolved to recover $B_{app}$.
- We can then recover the true sky brightness distribution via,

$$B(l,m) = \frac{B_{app}}{|\boldsymbol{E}(l,m)|^2}$$

- Images generated will simply be the true brightness attenuated by some power beam
- Thus the true source flux density can be recovered by dividing the image with the power beam response.

The GOODS-N field as seen by the VLA



JACK F. RADCLIFFE (jack.radcliffe@up.ac.za)

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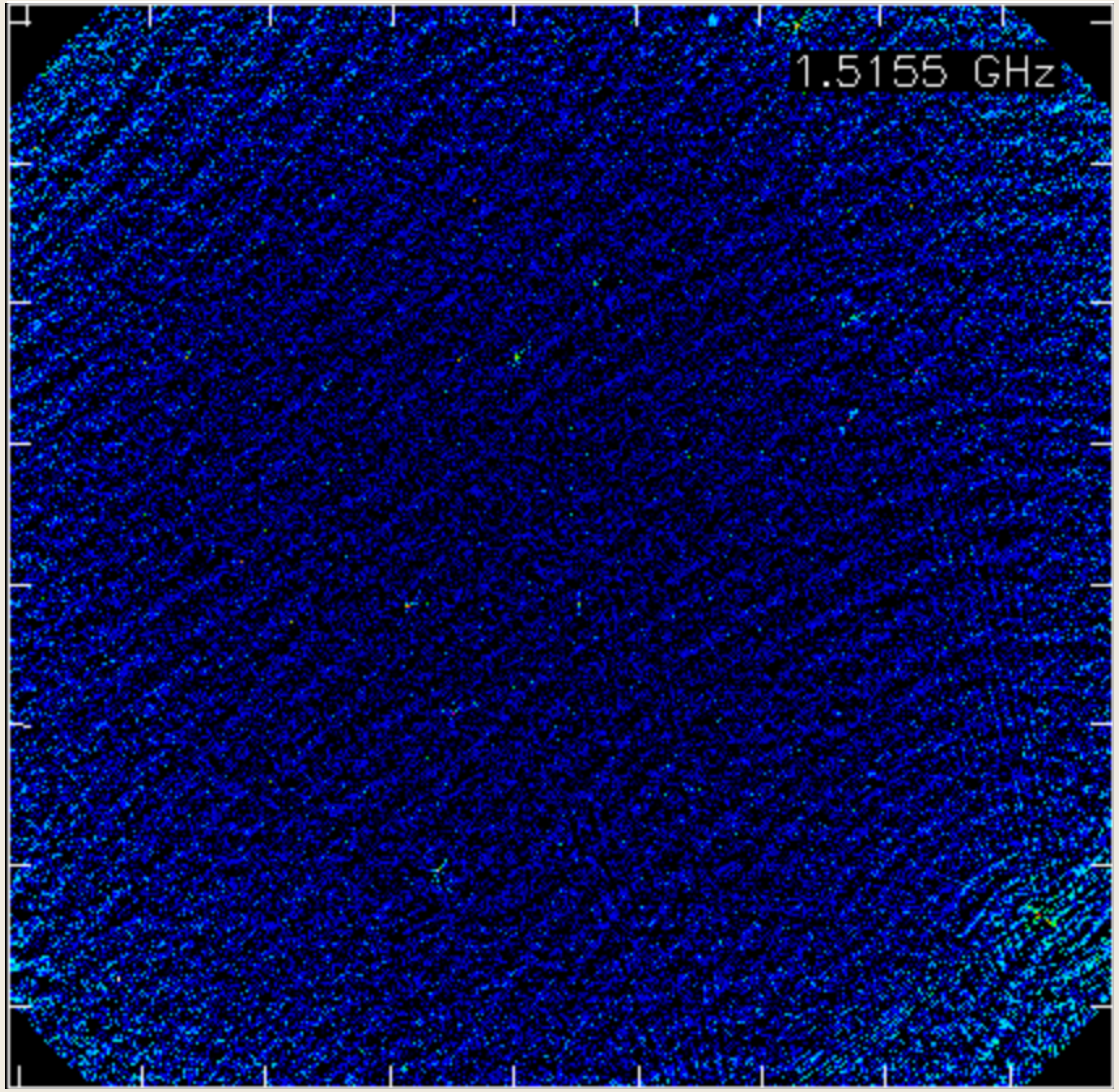


JACK F. RADCLIFFE (jack.radcliffe@up.ac.za)

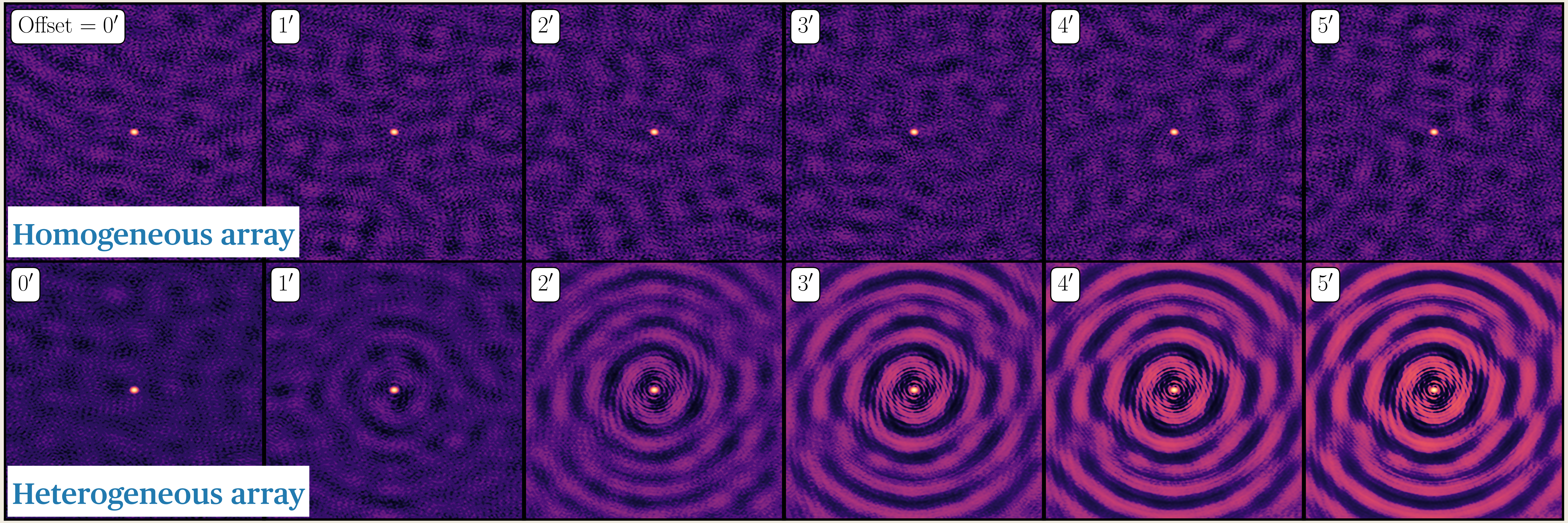
RADCLIFFE/COETZER ET AL., (IN PREP.)

# Heterogeneous arrays

- Not so simple for a heterogeneous array. Big issue comes from the following,

$$\mathsf{B}_{\mathrm{app},\,pq} = E_p \mathsf{B} E_q^H \neq \mathsf{B}_{\mathrm{app},\,pq} \quad \text{for all } p, q$$

- i.e. **each baseline *does not* observe the same apparent brightness distribution**
- This manifests as a *direction-dependent, antenna independent, and dominant, amplitude (and phase…) error.* →



# Primary beam correction schemes

- With beam models / approximations of the primary beam, how do we apply these corrections for heterogeneous arrays (and wide-field VLBI data)?
- Currently three ways,
  - A. Image plane correction (primarily homogeneous arrays only)
  - B. 'Differential' / step-wise primary beam correction
  - C. $uv$-plane correction i.e. $a$-projection

# A. Image plane correction

- Can calculate total power beam, $P_{\mathrm{T}}$, for heterogeneous array via,

$$P_{pq}(l,m) = \frac{\boldsymbol{E}_p\boldsymbol{E}_q^* + \boldsymbol{E}_q\boldsymbol{E}_p^*}{2\sqrt{W_p(\nu)W_q(\nu)}}$$

$$P_{\mathrm{T}} = \sum_{i,j=0;j>i}^{N_{\mathrm{ant}}} P_{pq}$$

Baseline primary beam

Voltage beam for antenna p/q

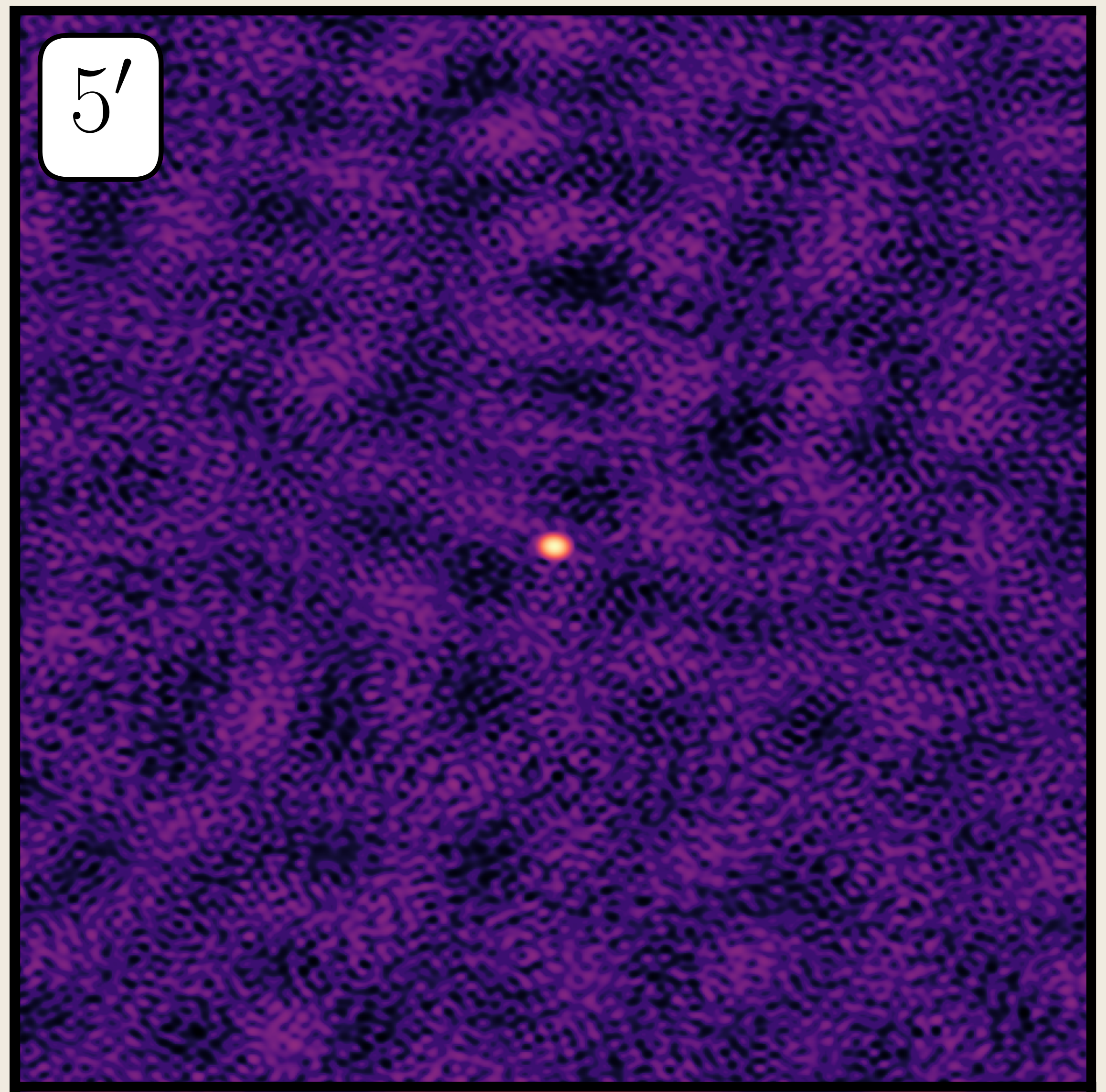
Weights of antenna $p$ / $q$

(Weighted) sum over all baselines

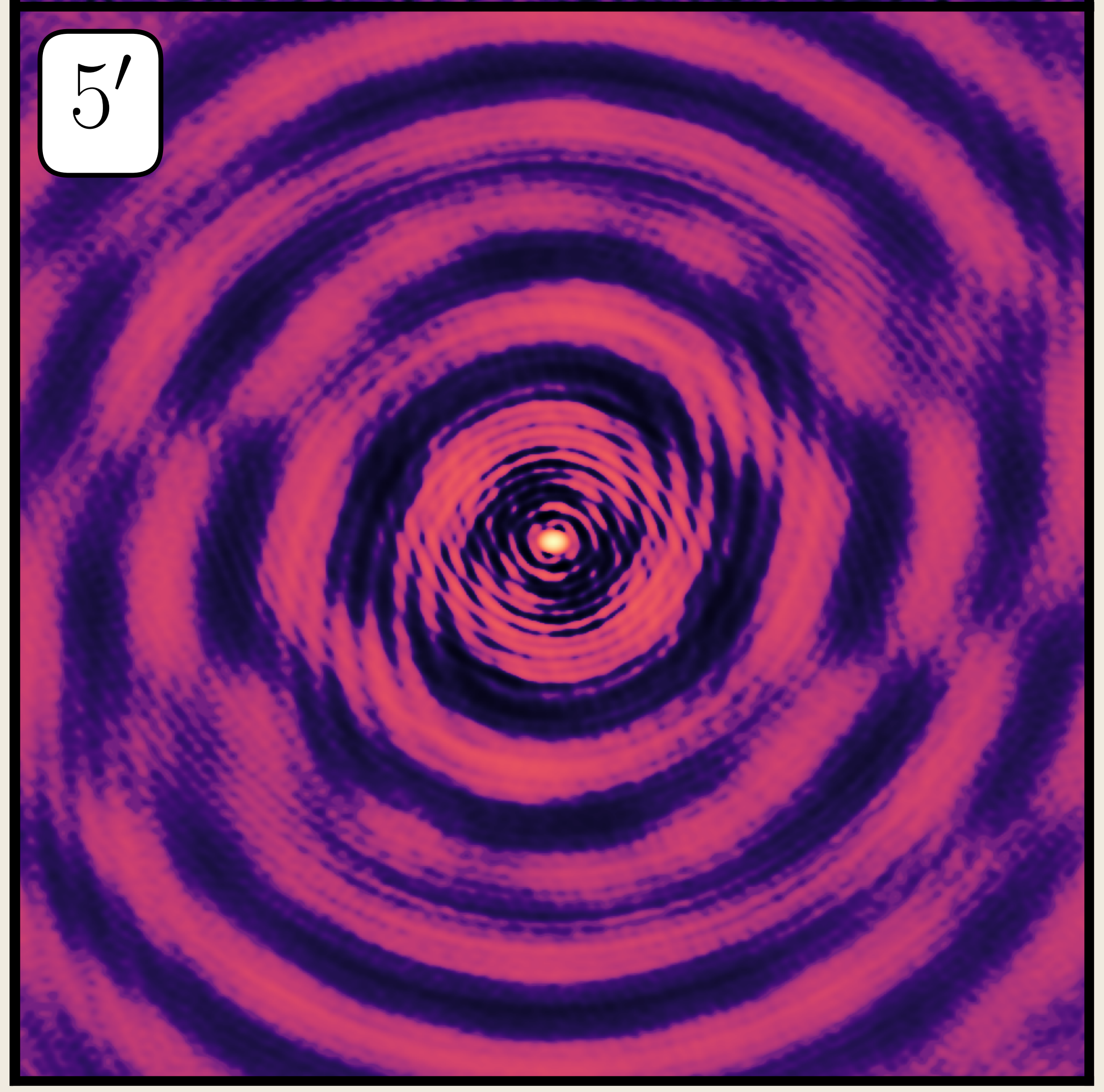
and divide subsequent image by $P_{\mathrm{T}}$.

- Provides a scalar shift in the image plane (partially fixing flux densities) but **does not** correct for the direction-dependent antenna independent errors.
- You can fix amplitude errors for some sources via self-calibration but crucially not all.

Homogeneous array




Heterogeneous array



# B. ‘Differential’ / step-wise primary beam correction

- Correct each phase centre in $uv$ plane using **CASA complex gain table** with a singular value for each antenna’s primary beam voltage, evaluated at centre of the phase centre (where $l = l_{\rm pc}$ and $m = m_{\rm pc}$). Effectively does the following to each baseline,

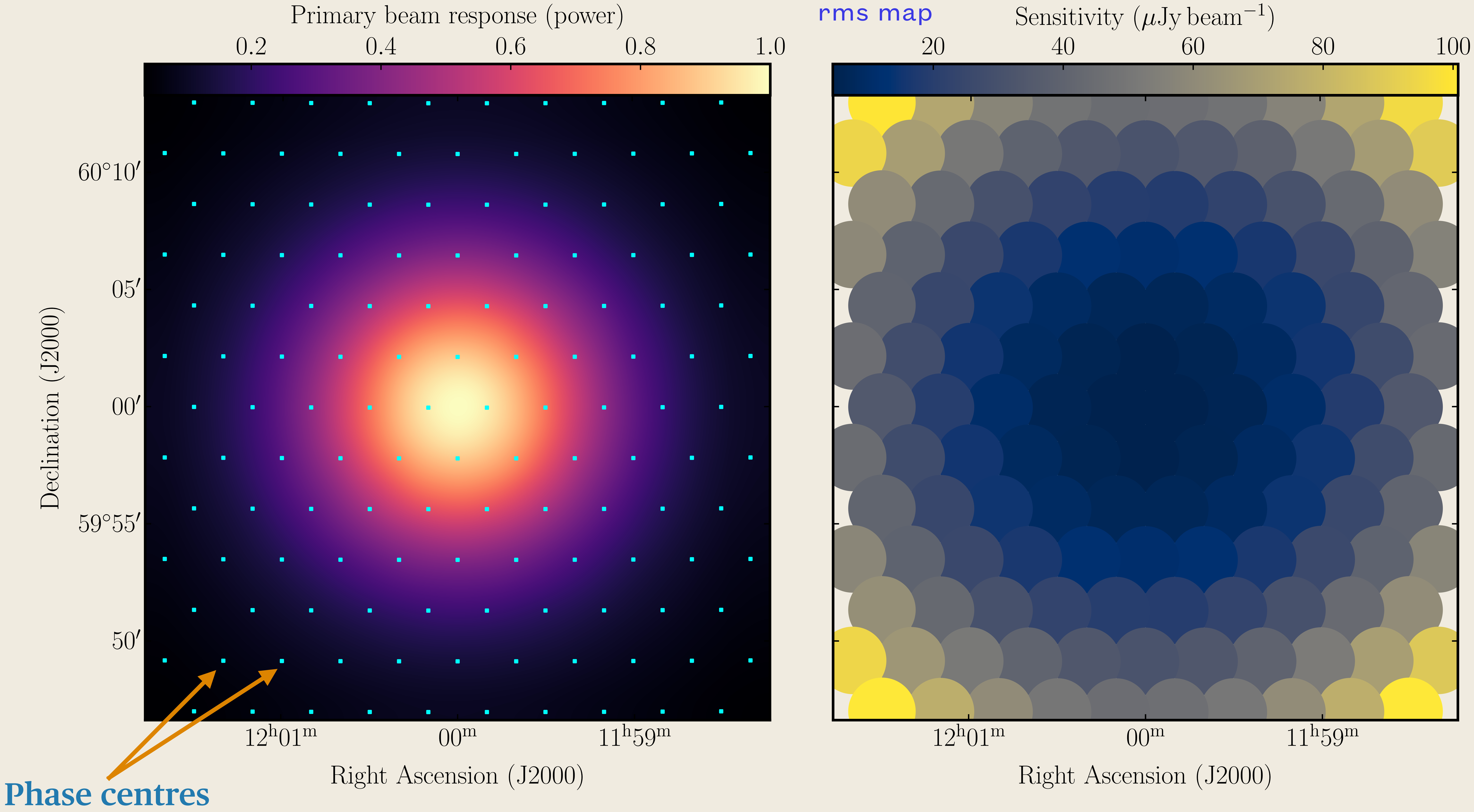
$$\mathsf{V}_{pq,\rm obs}(l_{\rm pc}, m_{\rm pc}) = \frac{\mathsf{V}_{pq,\rm obs}}{\boldsymbol{E}_p(l_{\rm pc}, m_{\rm pc})\boldsymbol{E}_q^H(l_{\rm pc}, m_{\rm pc})}$$

- (Sometimes conducted) → outside of the phase centre centre, calculate error difference between real primary beam response and *uv* corrected response, and correct in the image plane to recover true fluxes.
- Note that this *only ‘perfectly’ corrects amplitude errors* at *centre* of each phase centre.
- Residual amplitude errors proportional to $\nabla \left| \boldsymbol{E}_p \boldsymbol{E}_q^H \right|$ , distance from centre of phase centre & primary beam model errors **but errors are much, much smaller** than image plane only correction!

# B. 'Differential' / step-wise primary beam correction

- Available in AIPS and CASA
  - For VLBA - AIPS task CLVLB
  - For EVN - https://github.com/jradcliffe5/EVN_pbcor (Radcliffe+18, Keimpema & Radcliffe in prep.)
- CASA implemented in VPIPE.

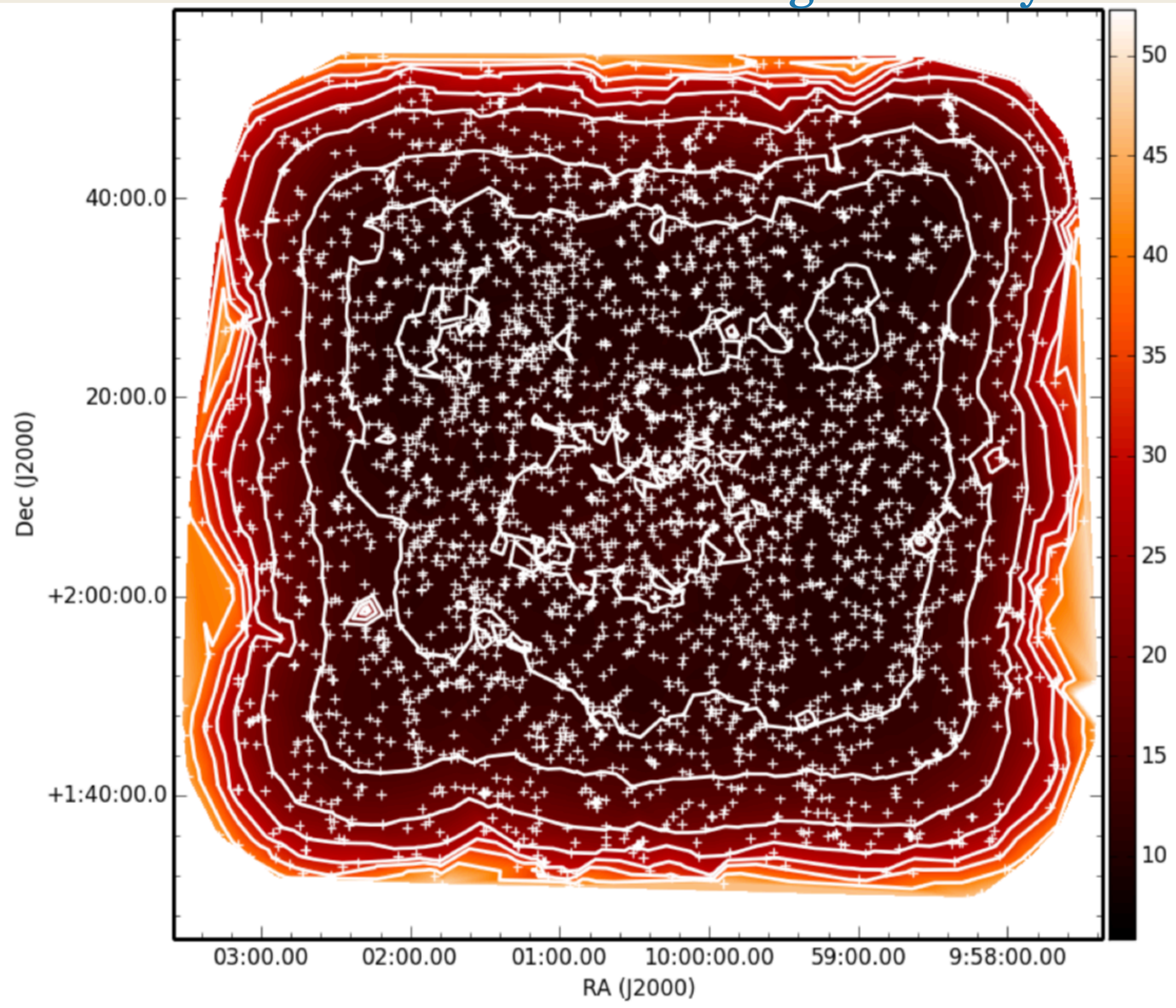
12 hour simulated EVN observation (central rms $\sim 4\,\mu\mathrm{Jy\ beam}^{-1}$)



# B. ‘Differential’ / step-wise primary beam correction

- This is the current method used in published wide-field VLBI studies.

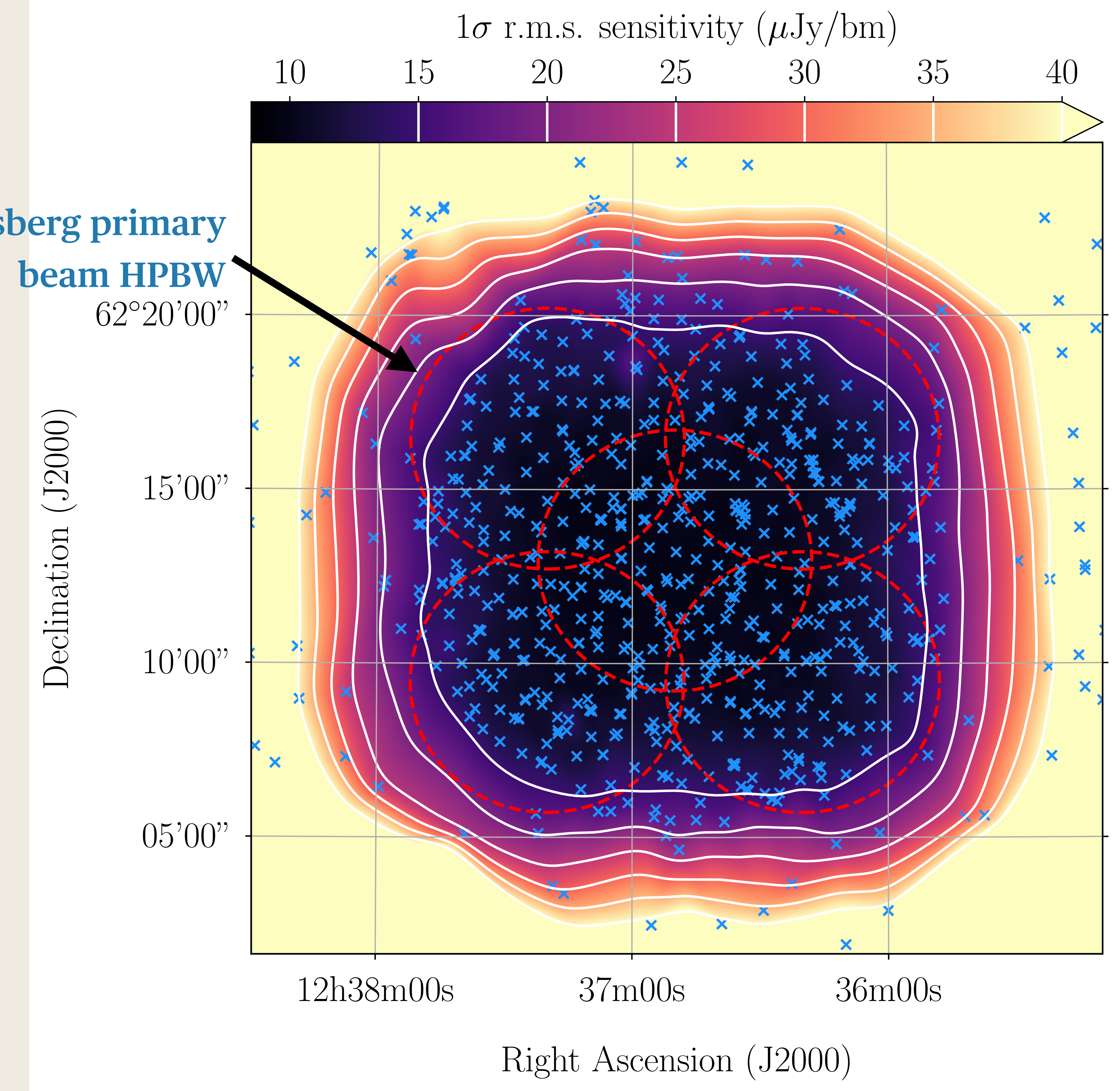
COSMOS-VLBA - 2 x 2 degree survey




HERRERA-RUIZ ET AL., 2017, 2018)

GOODS-N EVN survey

Effelsberg primary beam HPBW

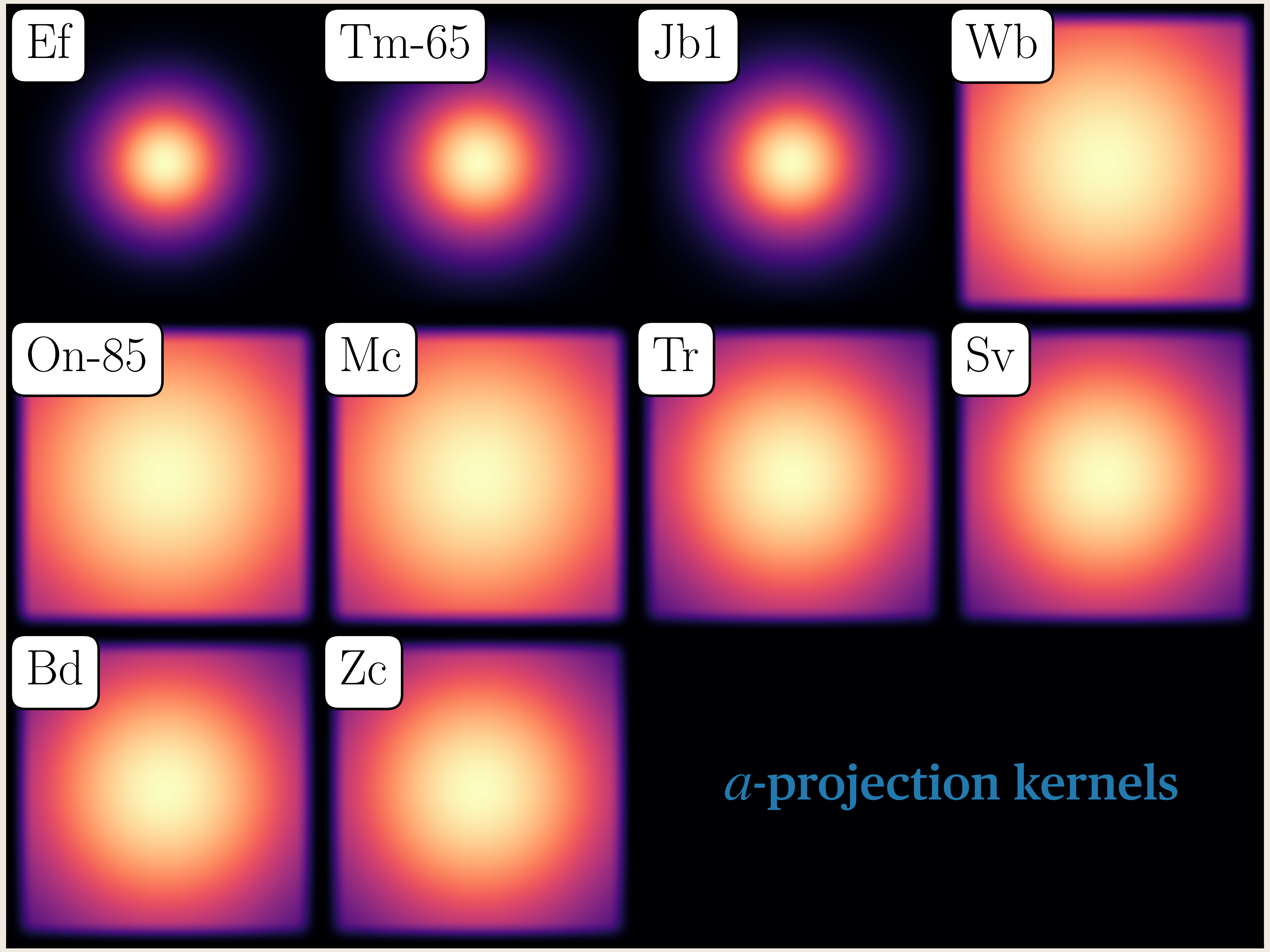



RADCLIFFE ET AL., (2018)

# C. *a*-projection

*Same 12 hour simulated EVN observation (central rms $\sim 4\,\mu\mathrm{Jy\,beam}^{-1}$)

- New method corrects for primary beam response while gridding visibilities.
- Implemented in the `Image Domain Gridder` (IDG) as part of the `wsclean` imaging package (not CASA).
- Will correct for primary beam effects with smaller error than other methods.
- Method can also implement:
  - More complex beams (e.g., true frequency dependence - i.e. not $1/\lambda$, beam rotation of sidelobes, beam squints)
  - And other direction-dependent effects (e.g. pointing errors, TEC dispersion etc.)



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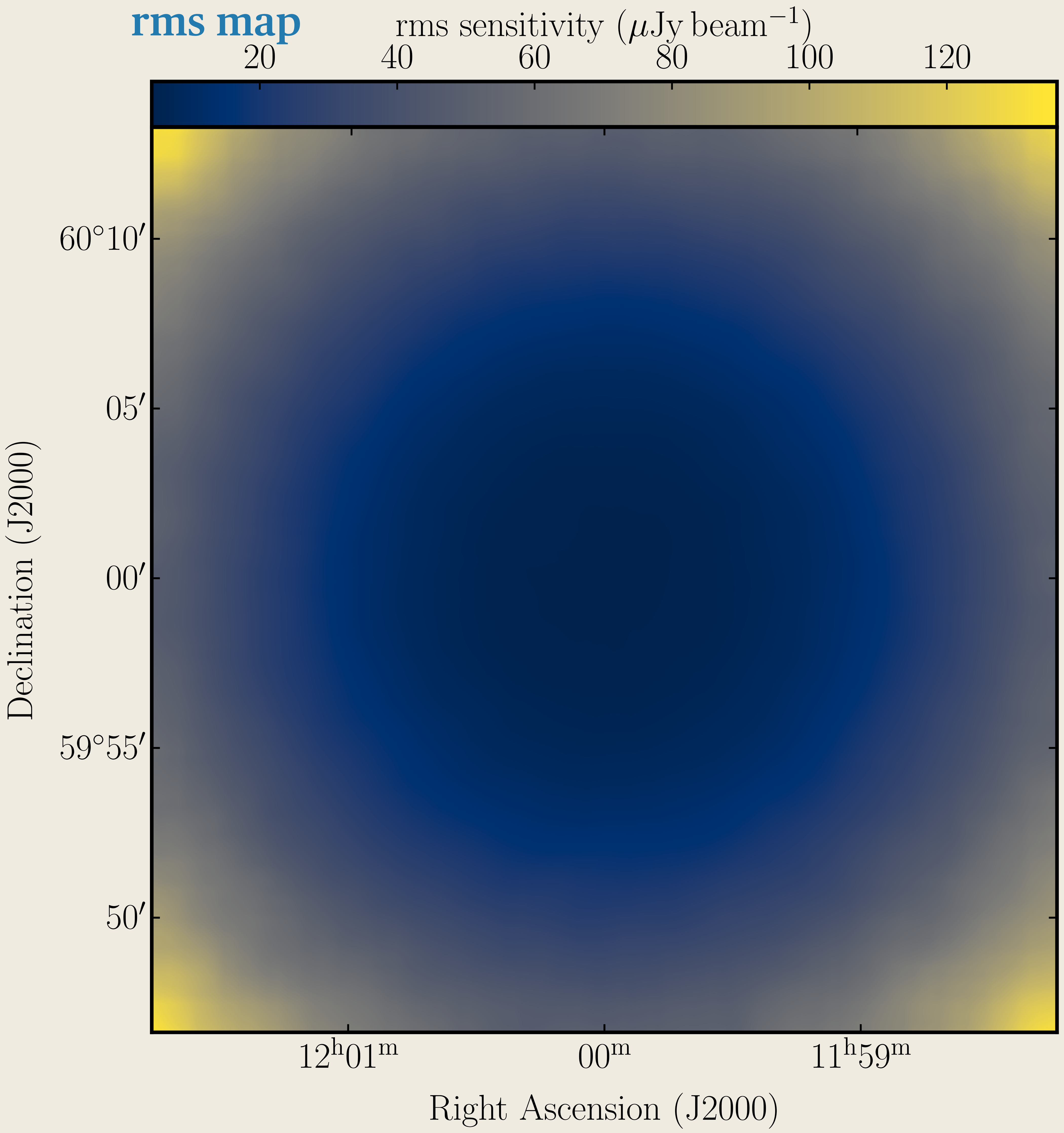
**rms map**



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# Wide-field imaging / *w*-term

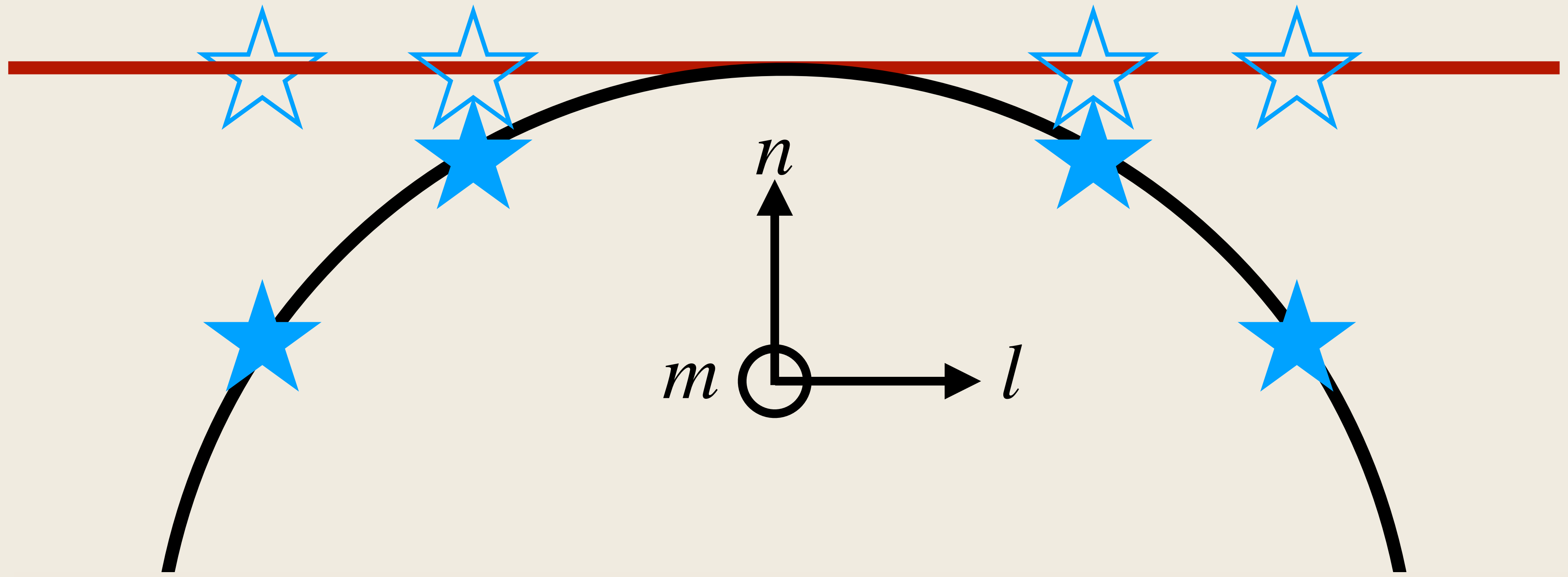
- Other direction dependent effect is the non-coplanar term (or the $w$-term),

$$\mathsf{V}(u, v, w) = \iint_{lm} \frac{\mathsf{B}(l, m)}{n} \exp\left\{-2\pi i \left[ul + vm + w\,(n-1)\right]\right\} \mathrm{d}l\mathrm{d}m$$

$$\rightarrow \mathsf{V}(u, v, w) = \iint_{lm} W\,\mathsf{B}(l, m) \exp\left\{-2\pi i \left[ul + vm\right]\right\} \mathrm{d}l\mathrm{d}m \quad \text{where} \quad W = (1/n)\exp\left[w(n-1)\right]$$

- 3D visibility function $\mathsf{V}(u, v, w)$ can be transformed into a 3D image volume $\mathsf{B}(l, m, n)$ but non-physical as only $l, m$ are directional cosines (i.e., 2D)
- Our lovely 2D Fourier transform now does not hold…

# Wide-field imaging - 3D to 2D

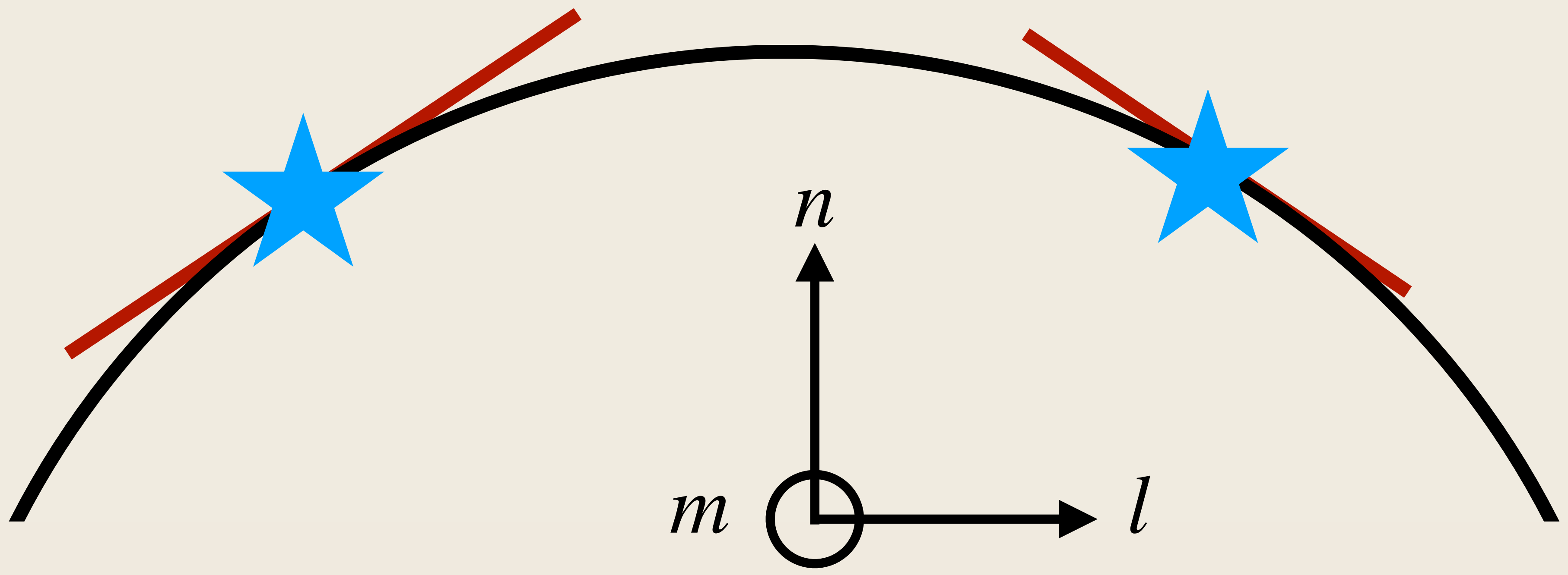



- The only non-zero values of $(l, m)$ lie on the surface of a sphere of unit radius defined by $n = \sqrt{1 - l^2 - m^2}$
- The sky brightness consisting of a number of discrete sources are transformed onto the surface of this sphere.
- The two-dimensional image is recovered by projection onto the tangent plane at the pointing centre

*How do we achieve this?*

1. Faceting - split field into multiple projected images and stitch together
2. Deal with the *w*-term directly (deal with the distortion when imaging)

# 1. Faceting




- Oldest method in the book - takes advantage of small-field approximation ($l, m \rightarrow 0$) so $W \sim 1$ so our image sphere is approximated by pieces of smaller tangent planes.

**Result** → each sub-field can use the standard 2D FFT!

- Errors increase quadratically away from centre but ok if enough sub-fields are selected
- Facets can be chosen to cover known sources or overlap to complete coverage of primary beam

**Important:** multi-phase centre correlation experiments effectively does this! Only need to make small 'facet' images!

# 2. Dealing with *w* directly

- Other algorithms allow you to deal with the *w*-term directly when imaging (to produces a contiguous image). Examples include w-stacking and w-projection (shown next).
- To return the visibility equation to a 2D Fourier transform, the *w*-projection algorithm convolves the visibilities with the *w*-term i.e.,

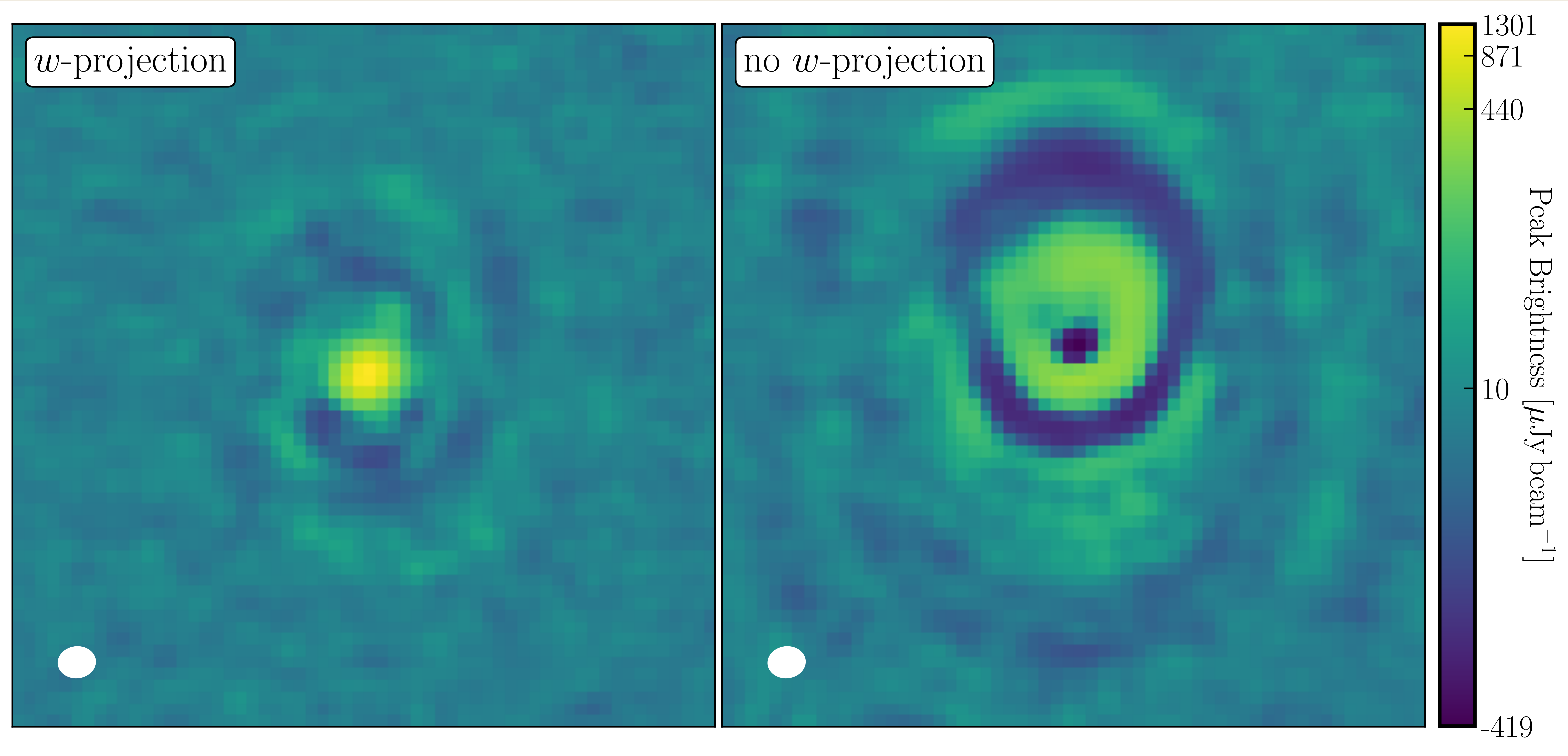
$$\mathsf{V}(u, v, w=0) * \mathfrak{F}\left(\exp\left[-2\pi i w\,(n-1)\right]\right) = \iint_{lm} \frac{\mathsf{B}(l, m)}{n} \exp\left[-2\pi i(ul + vm)\right] \mathrm{d}l\mathrm{d}m$$

- Dependent on zenith angle, coplanarity of array and FoV.
- Deconvolution assumes constant PSF but PSF slightly changes over the image so **Cotton-Schwab algorithm** automatically used to correct for this.

# Result of correcting for *w*

*e*-MERLIN - source 7.5’ from pointing centre

- Result:



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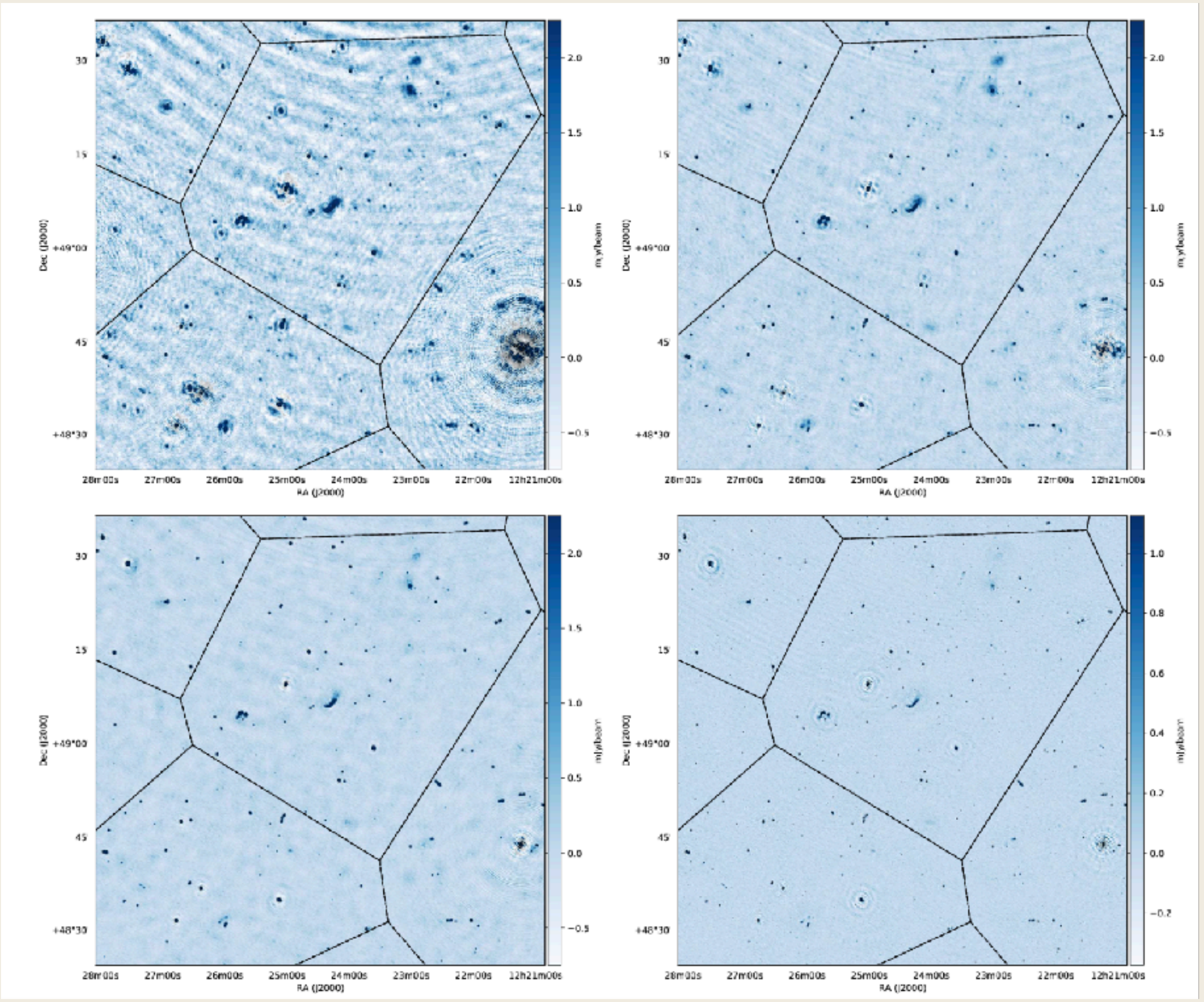
# Other direction dependent effects

- Other DDEs includes tropospheric / ionospheric corruptions across FoV, pointing errors etc etc.,
- Need specialised software (e.g., killMS, DDFacet) normally. Not in CASA…

DDE facet calibration in LOFAR

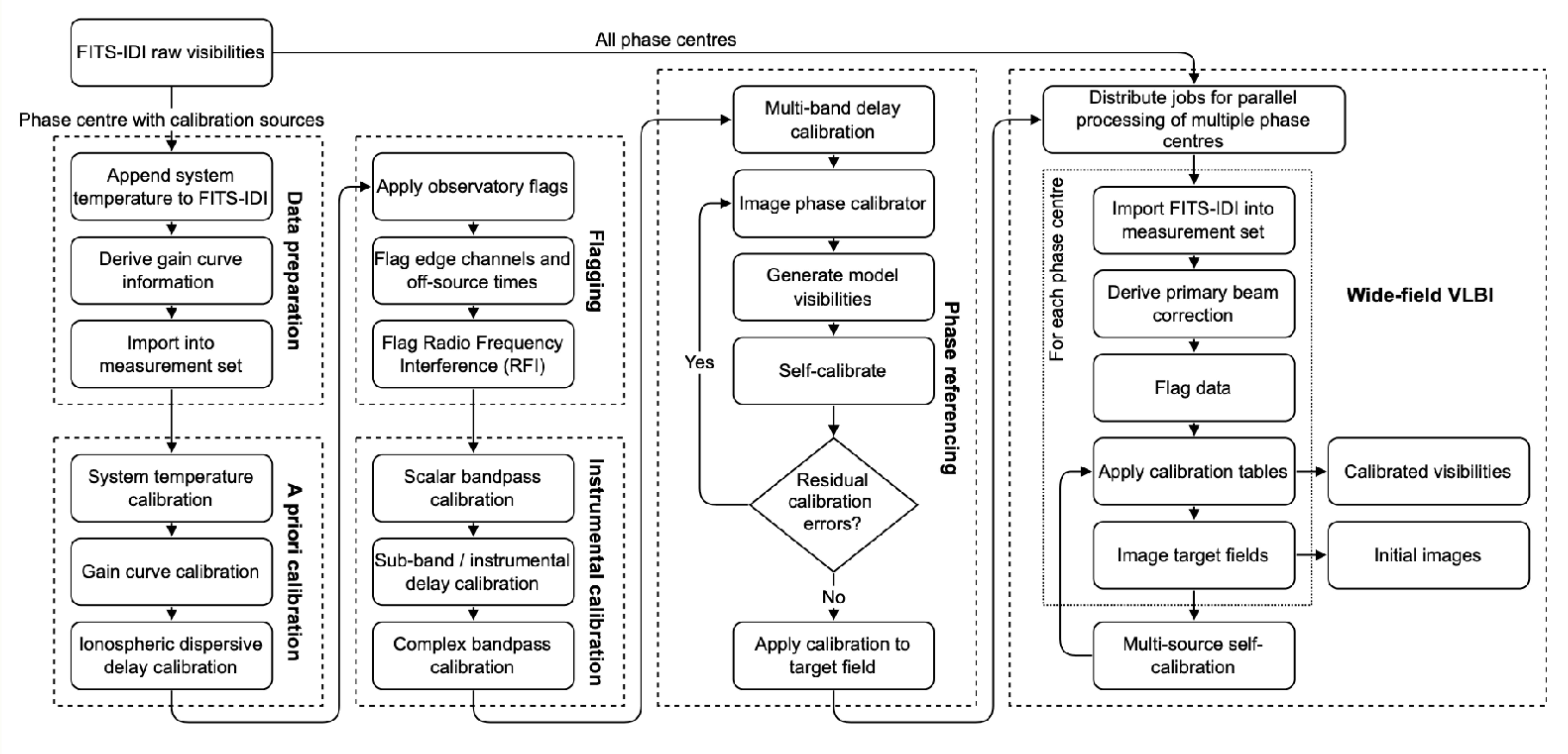


SHIMWELL ET AL., (2019)

# VLBI pipeline (VPIPE)

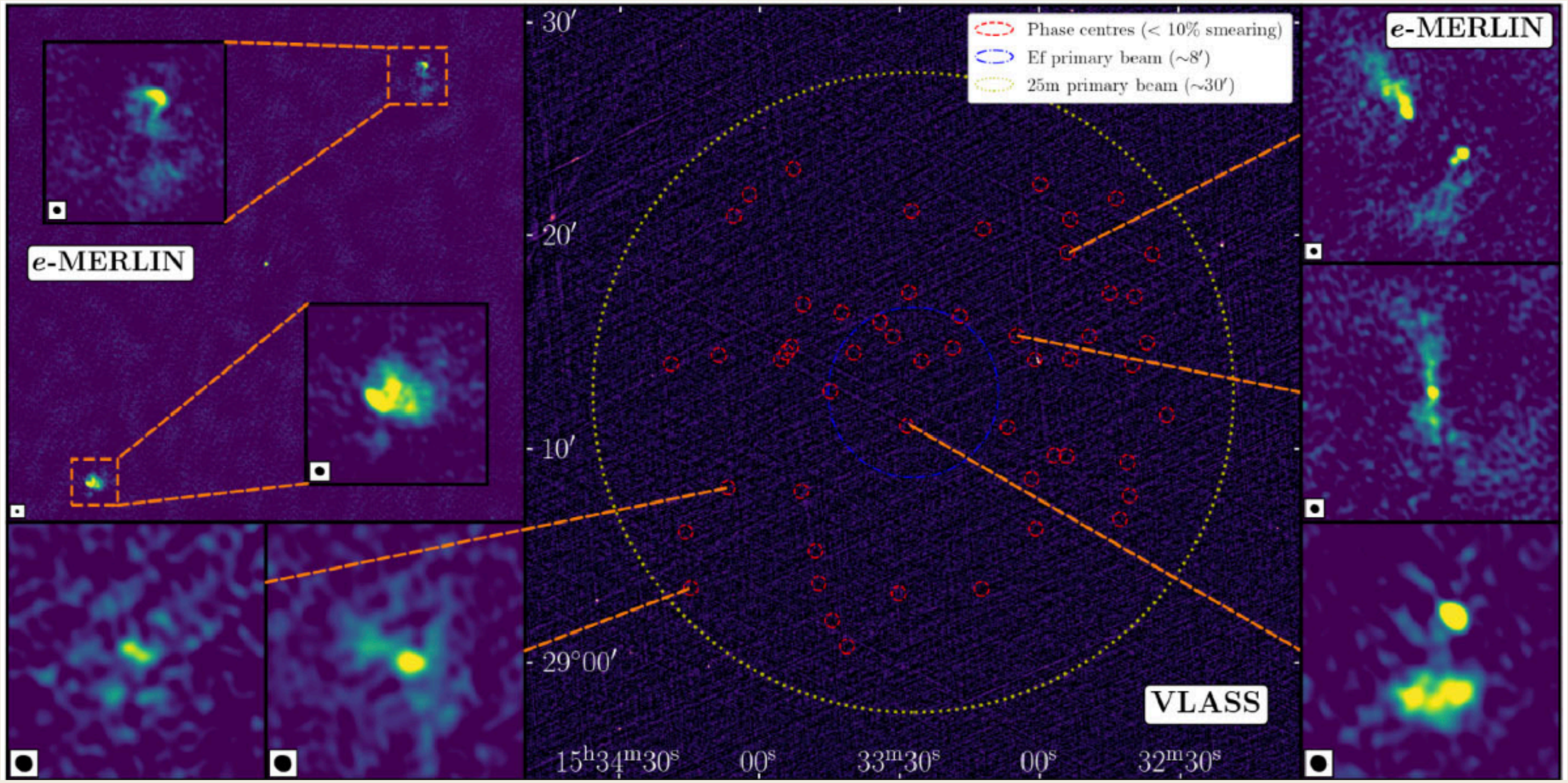
- VLBI PIPEline (VPIPE) based in CASA v6.5+ (currently at v1.0) - https://github.com/jradcliffe5/VLBI_pipeline - Nb. it's modular so works with other pipelines e.g., (rPICARD; see Janssen lecture!).
- Currently does the following,
  - A priori calibration for EVN & VLBA data (e.g. $T_{sys}$, gaincurves, ionospheric dispersive delays)
  - Fully parallelised a priori, flagging, phase referencing, and self-calibration via casampi (continuum only at the moment)
  - Support for use on HPC clusters controlled by SLURM / PBS Pro (+ usable on local machines)
  - Built for wide-field VLBI surveys, but direction-independent calibration works for normal data too.
- Wide-field features:
  - Primary beam correction
  - Multi-source self-calibration (and direction dependent calibration too)
  - Parameter automation (e.g., source finding, calibration solution intervals etc.)

# Example VPIPE run for wide-field EVN data



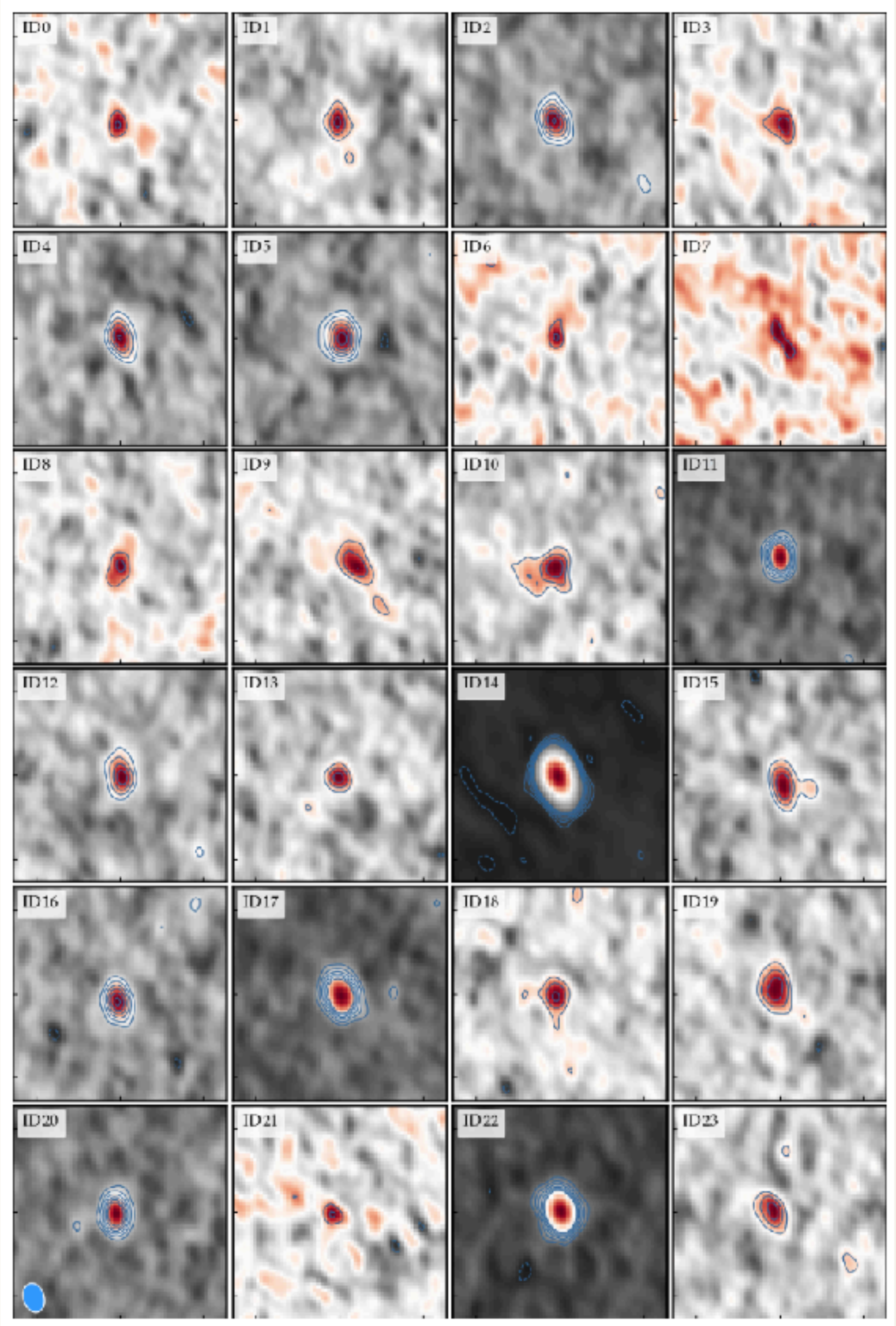
# Surveys using VPIPE

## SPARCS-N wide-field VLBI survey




NJERI ET AL., (2023)

## VLBA-CANDELS GOODS-N survey

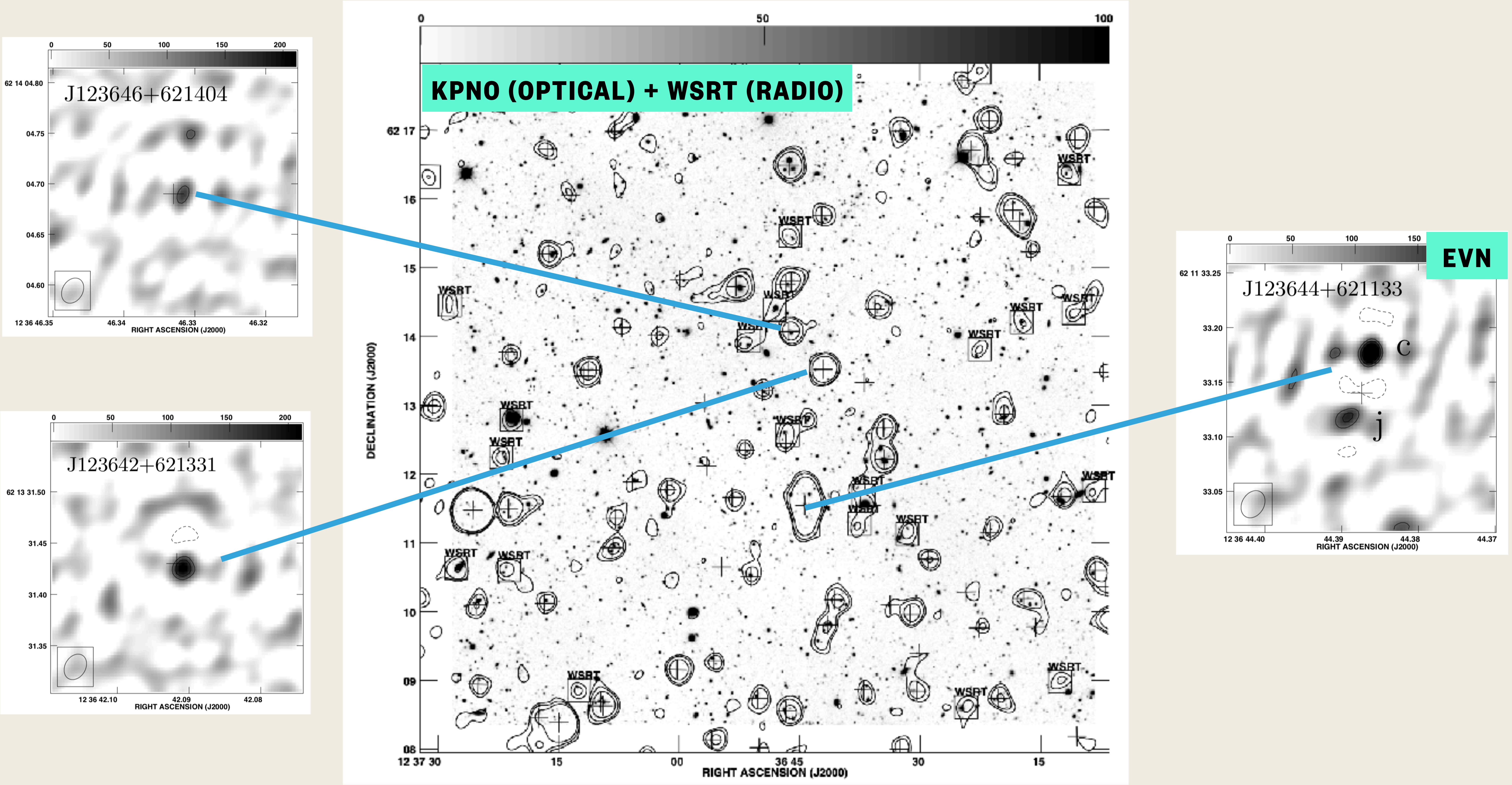



DEANE ET AL., (SUBMITTED)

# With these advancements...

We went from this 23 years ago,

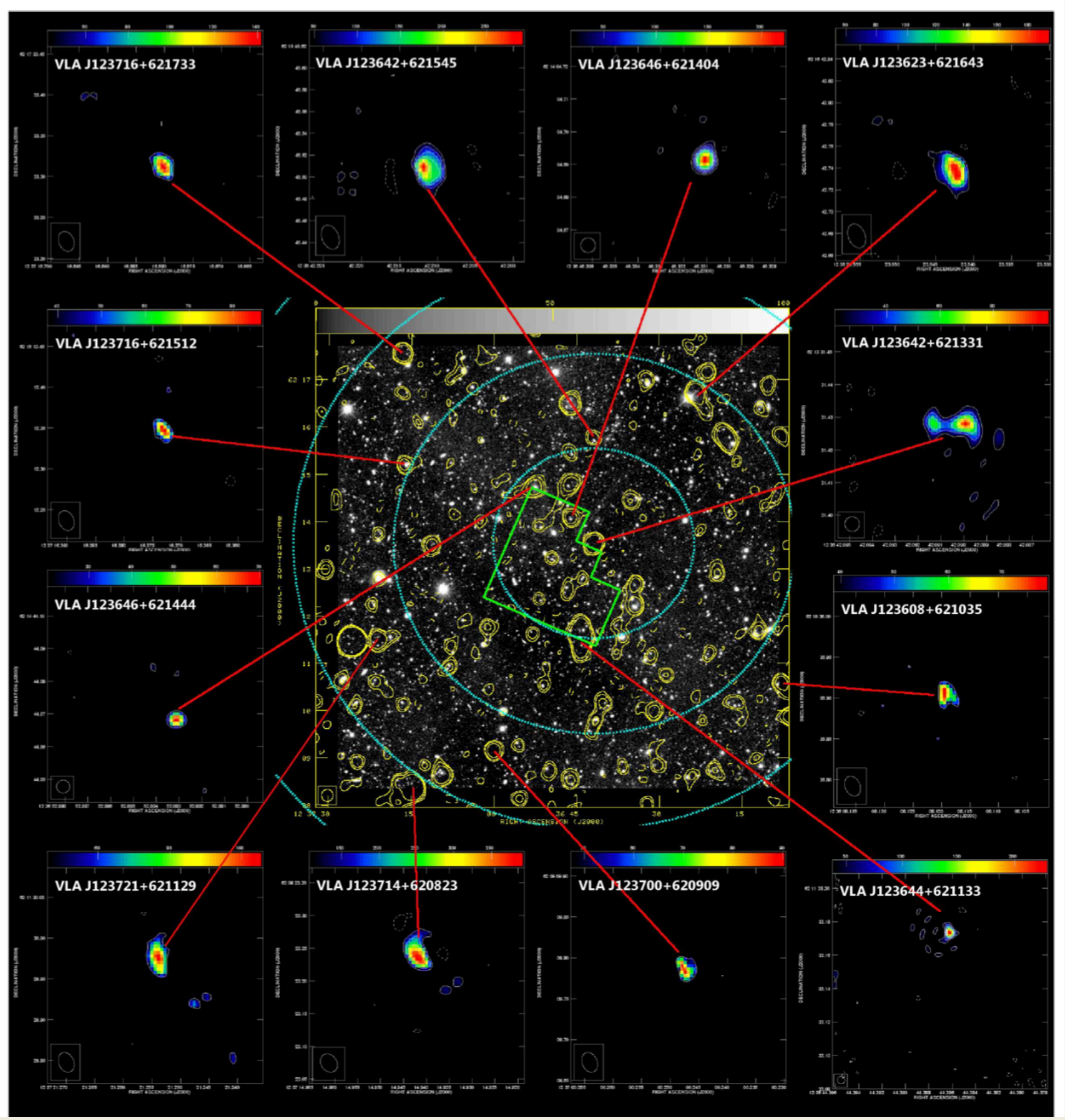
GOODS-N Deep Field




GARRETT ET AL., (2000)

# … to …

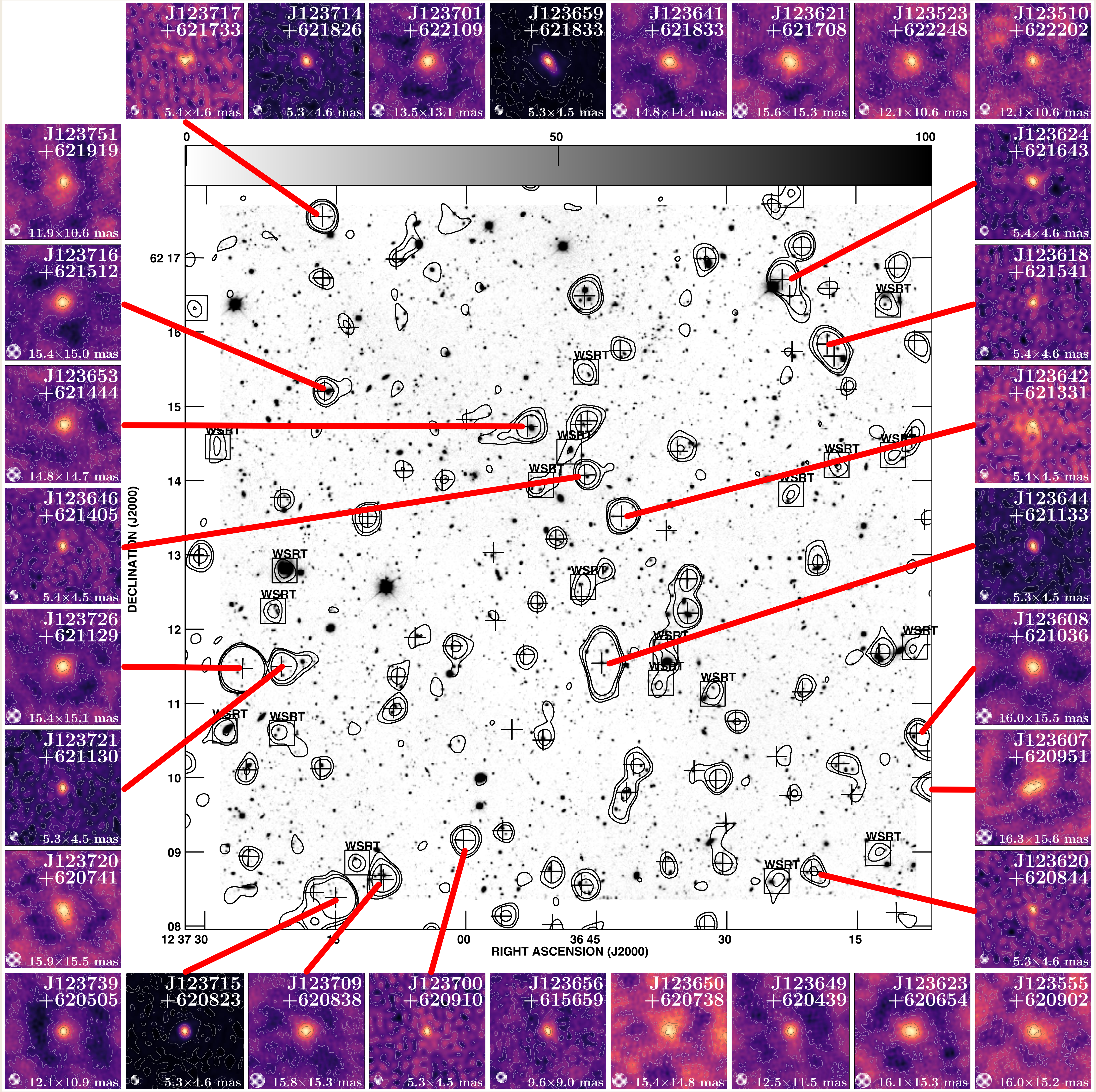
Observed 19 years ago




CHI ET AL., (2012) / OBSERVED 2004

# And finally!

RADCLIFFE ET AL., (2018)



**Key takeaways**

- Wide-field VLBI has many use cases and could be useful to your science.
- Calibration is simple and additional steps easily parallelised (and becoming user-friendly!)
- Additional calibration techniques required for wide-field observations e.g., MSSC, primary beam corrections but are all available (and easy to use)

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# Questions?

This event has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004719

## Job Opportunities in South Africa!

- **Three postdoctoral positions** (2+1 yr matched to SARAO) available in VLBI at Pretoria (contact me!).
- **PhD, MSc positions available** for 2024 under SARChI research chair (contact John McKean; mckean@astro.rug.nl)