CASA VLBI

WORKSHOP 2020

2-6 NOVEMBER 2020

10. WIDE-FIELD IMAGING

Jack F. Radcliffe
University of Pretoria (RSA) & Manchester (UK)

jack.radcliffe@up.ac.za / @radcliffe (Mattermost)

CASA Common Astronomy Software Applications

JIVE Joint Institute for VLBI ERIC

RadioNet

JUMPING JIVE Joint Institute for VLBI ERIC

Outline

1. Motivation i.e. why do we want to image degrees of the sky with VLBI?
2. Challenges
3. Calibrating wide-field VLBI data*
    a. Phase referencing
    b. Self-calibration
    c. Primary beam correction
4. Conclusions / take-away points

*In particular, highlight the nuances between standard calibration and wide field + how techniques developed for wide-field VLBI can be applicable to standard VLBI observing!

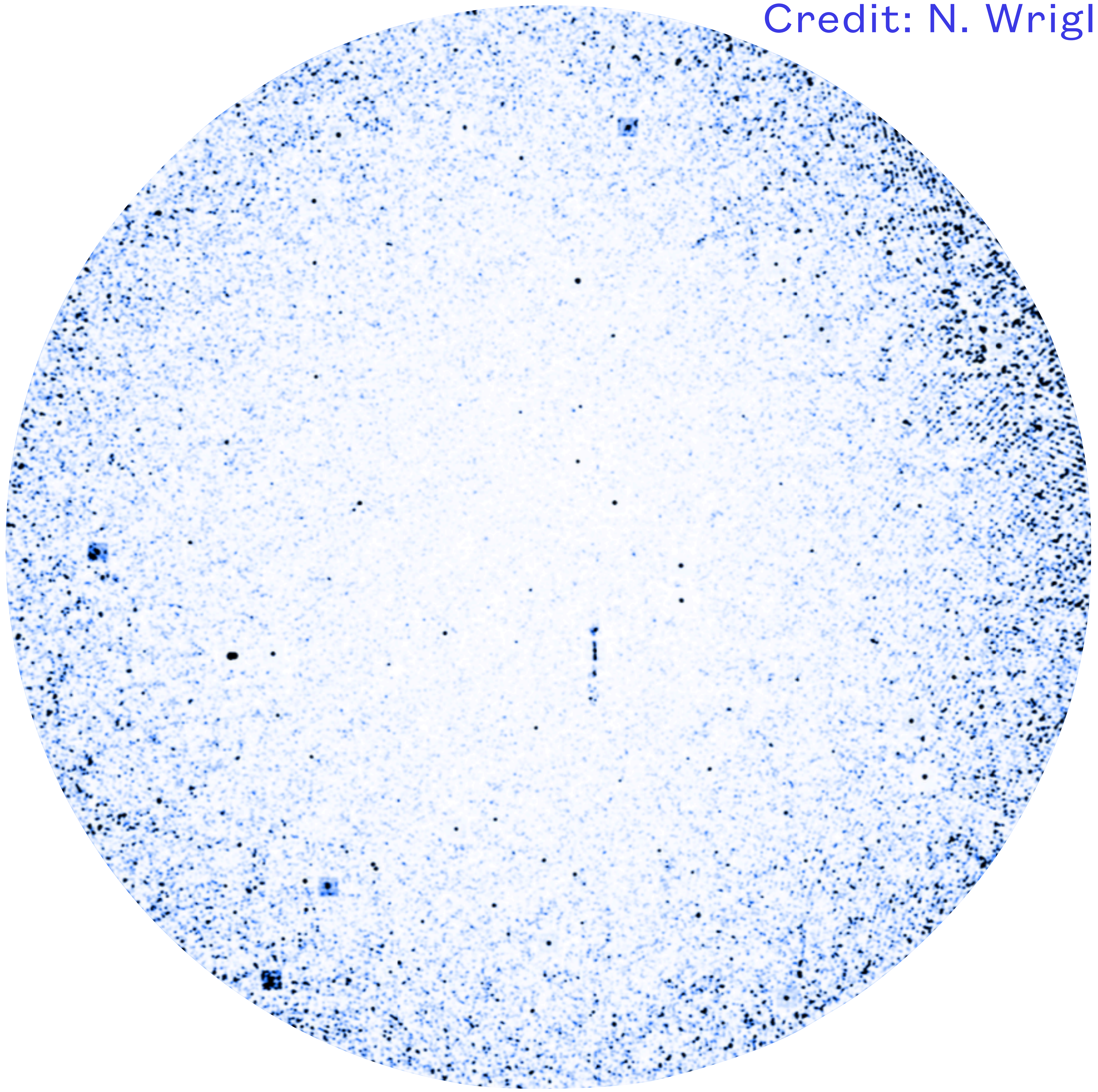
Wide-field VLBI - definition

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?

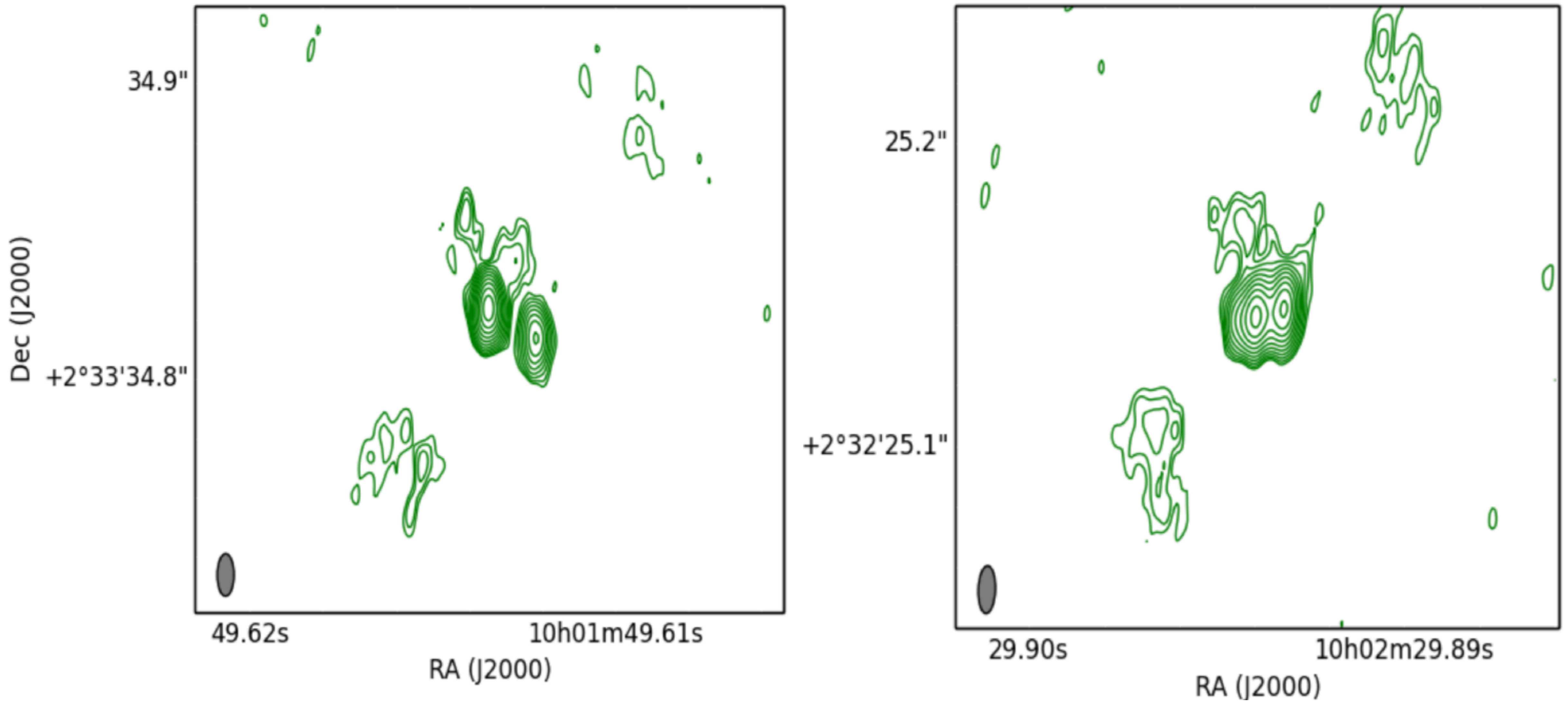
Credit: N. Wrigley

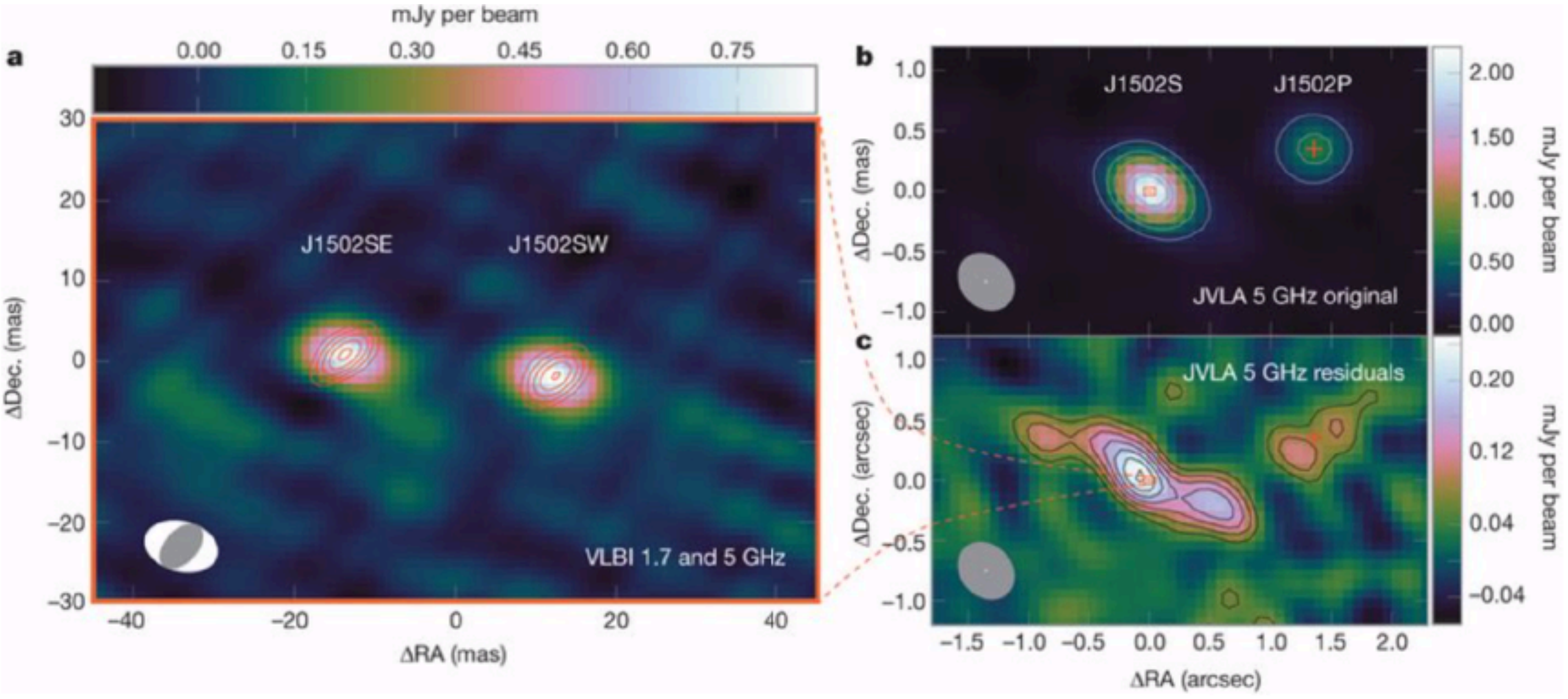


Primary beam corrected
JVLA+MERLIN image of the GOODS-N field

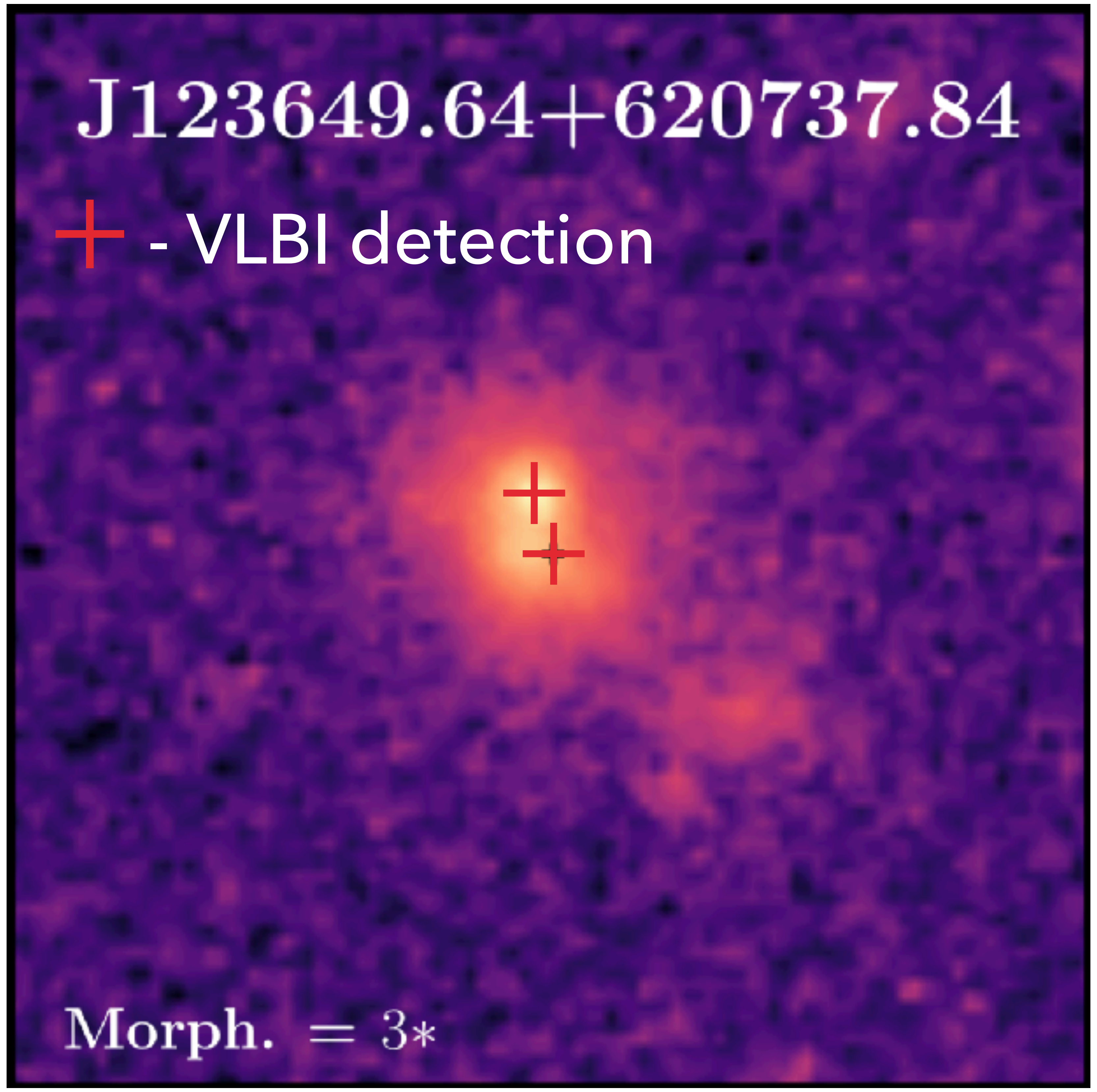
Some science examples - supermassive black hole binaries

Herrera-Ruiz+17





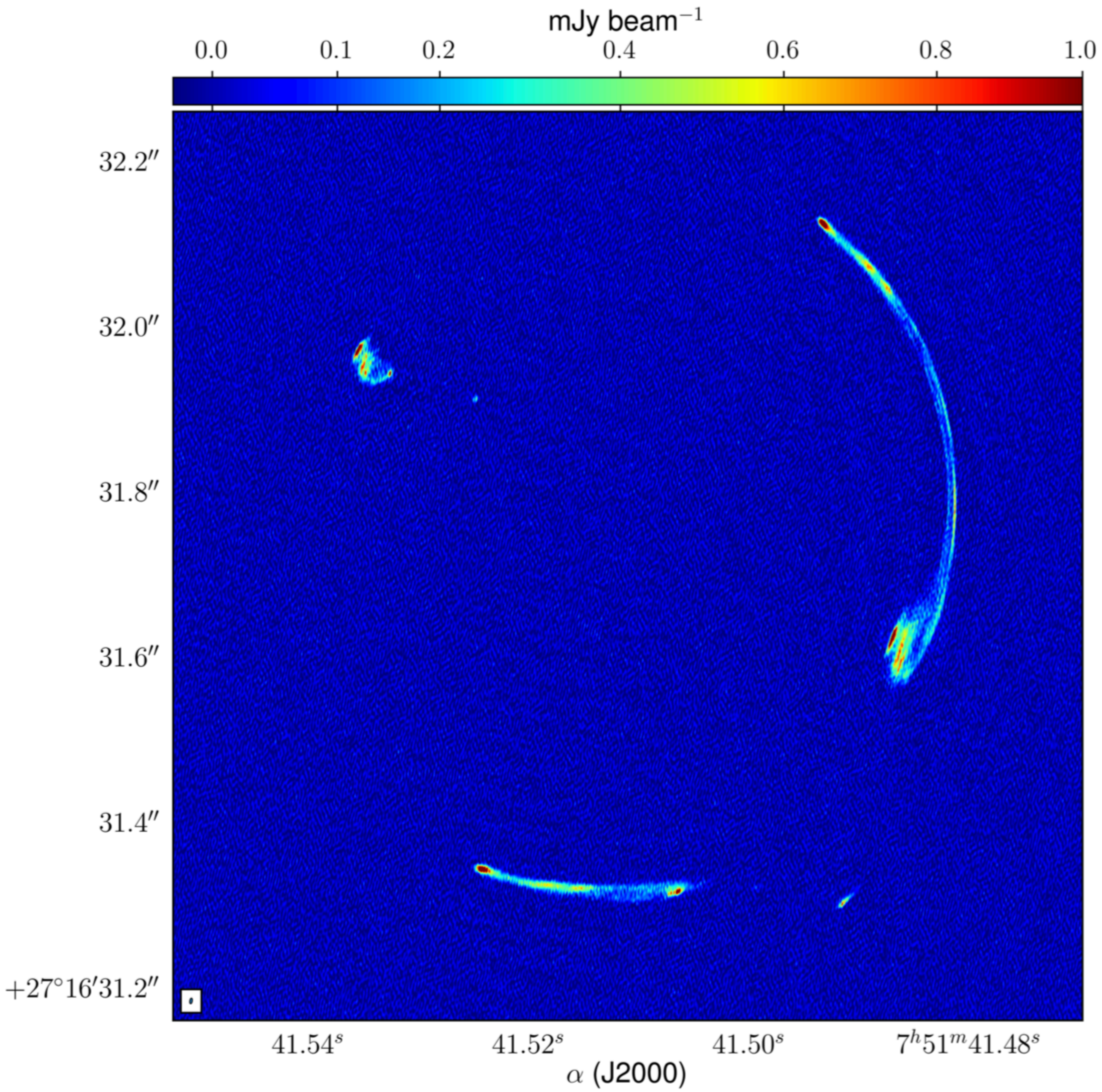
Deane+14



Radcliffe+ in prep.

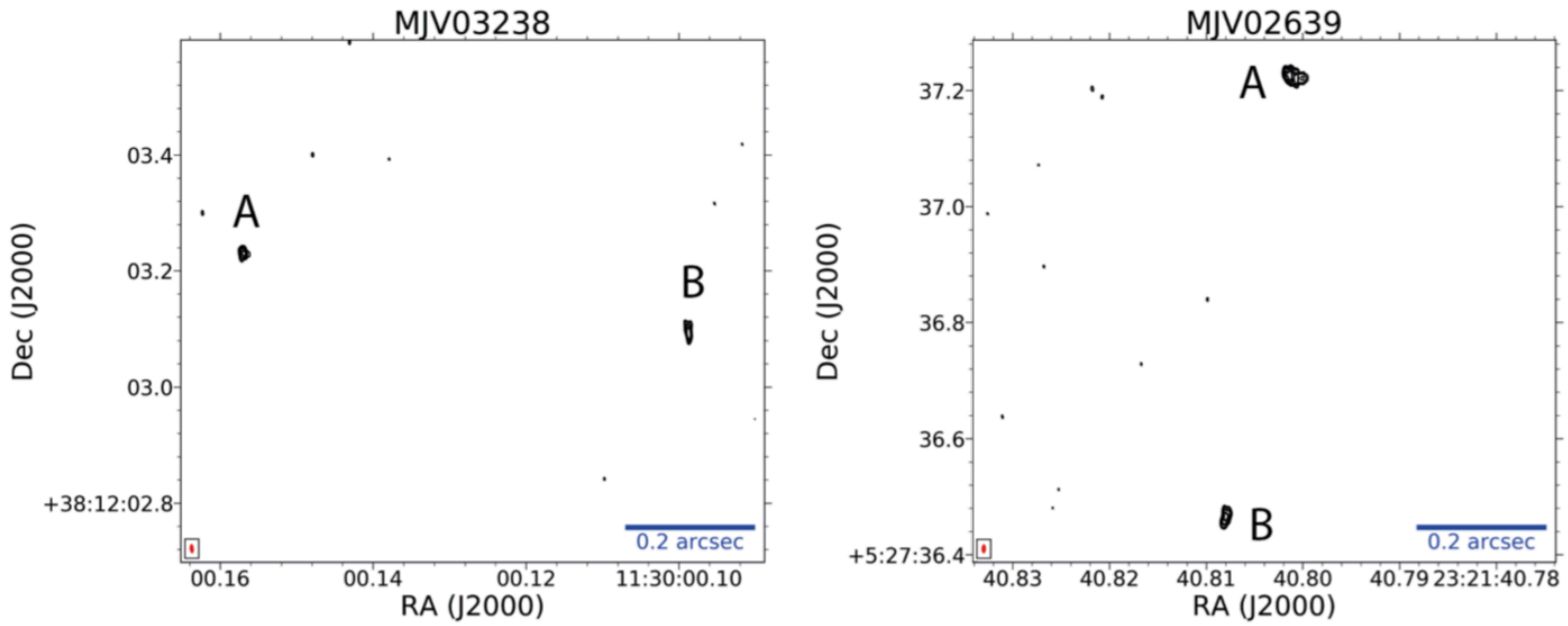
Gravitational lenses

- Rare (~0.3% of VLBI sources)
- Independently measure the sub-structure mass-function within galaxies.
- Unique probing of the low-mass end of the dark matter halo mass-function
- High resolution of VLBI can constrain lens models



Gravitational lenses

- Spingola+19 searched 3640 mJIVE-20 survey sources
- Found two gravitational lenses!

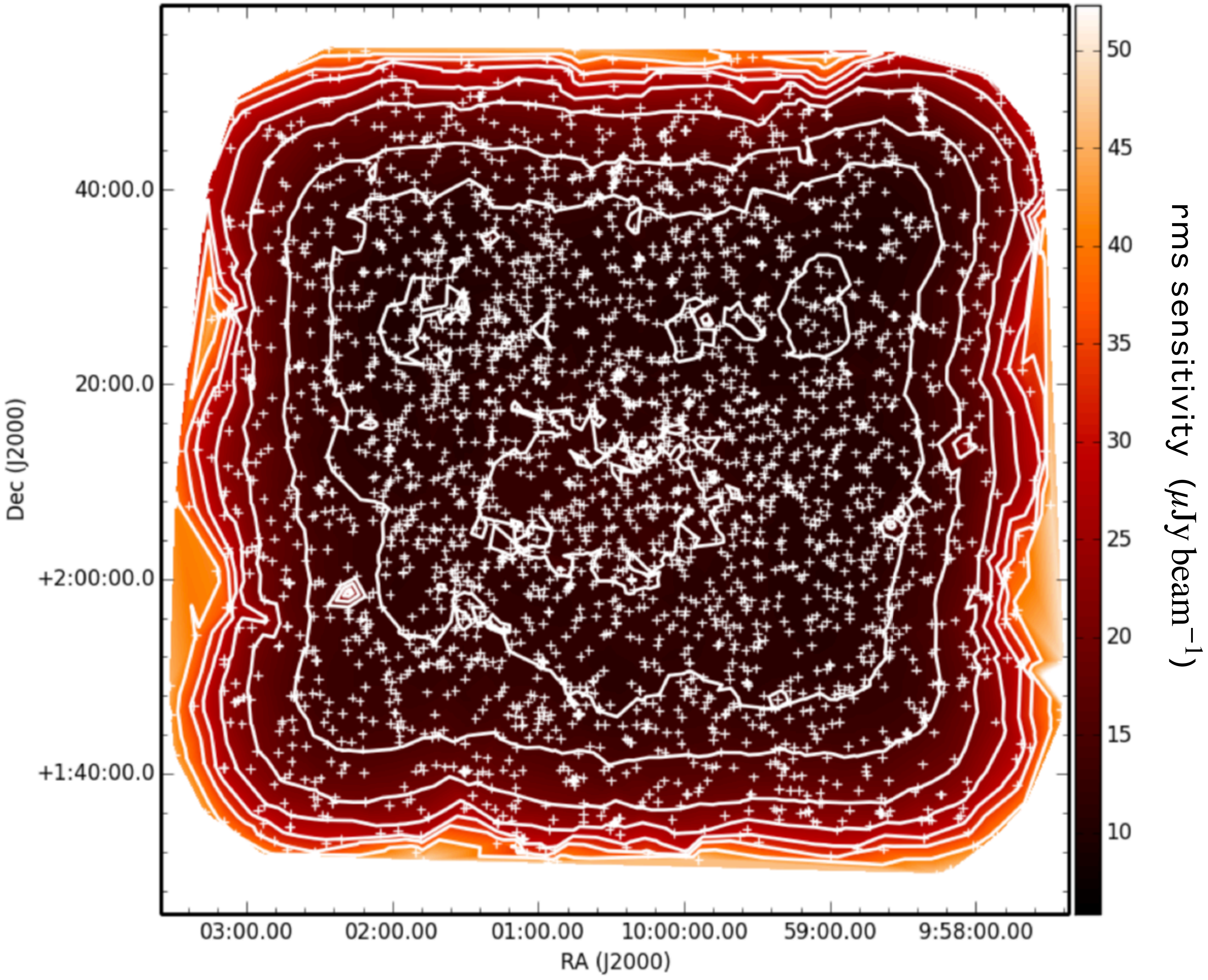


E.G. MIDDELBERG ET AL. 2011, 2013, HERRERA-RUIZ ET AL. 2017, RADCLIFFE ET AL. 2018

AGN surveys

- VLBI detection sure indicator of AGN (high brightness temperatures $> 10^5$ K)
- Use VLBI to understand nature of radio-mode AGN
- Other AGN identification methods are notably incomplete or contaminated.
- *Note - there are many more wide-field VLBI use-cases too (e.g. ISM of nearest galaxies; Morgan+13, supernovae; Radcliffe+19 etc.)!*

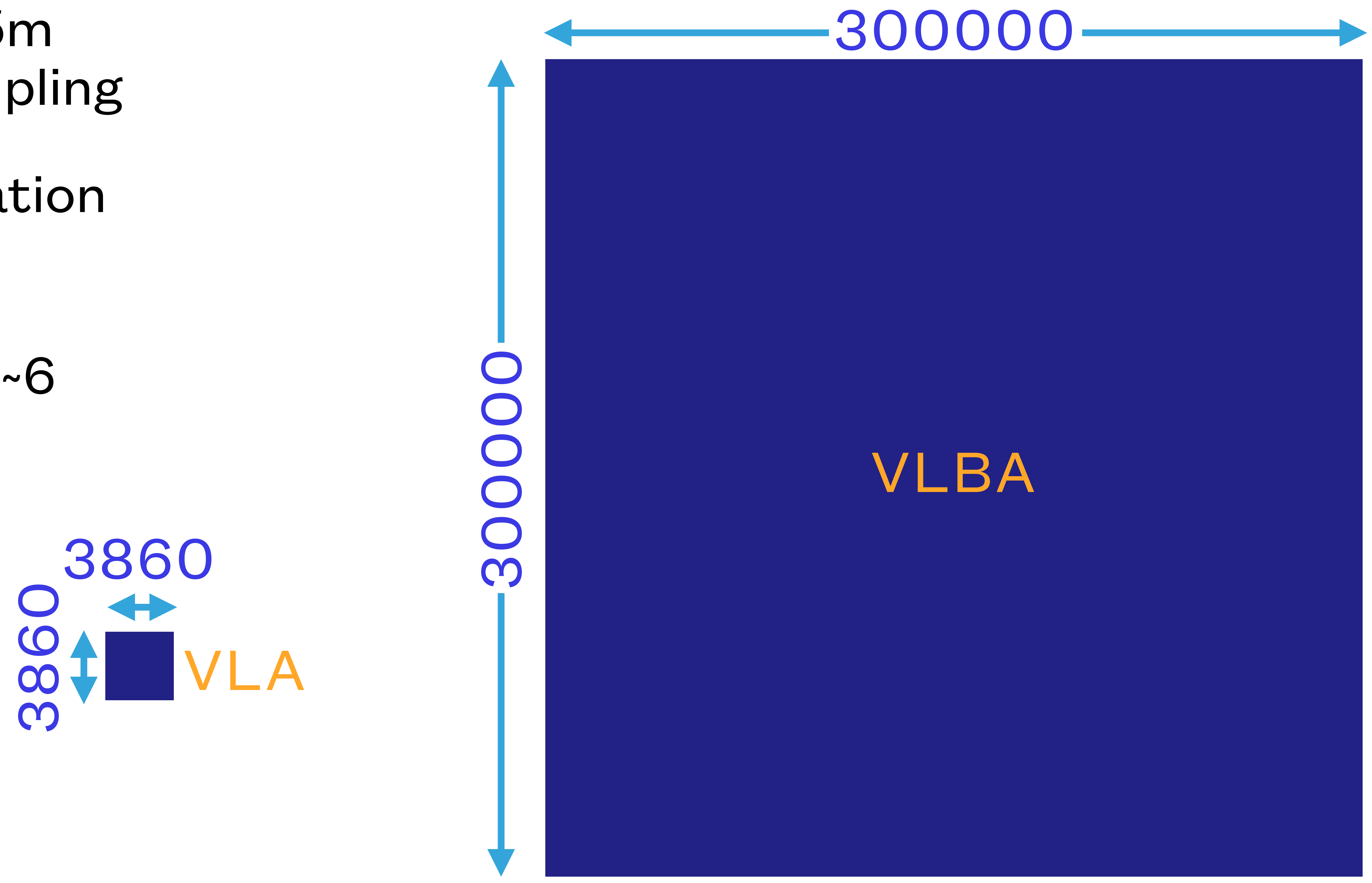
COSMOS-VLBA – 2 degree survey (Herrera-Ruiz+17, 18)



Imaging the entire primary beam - challenges

1. Image sizes

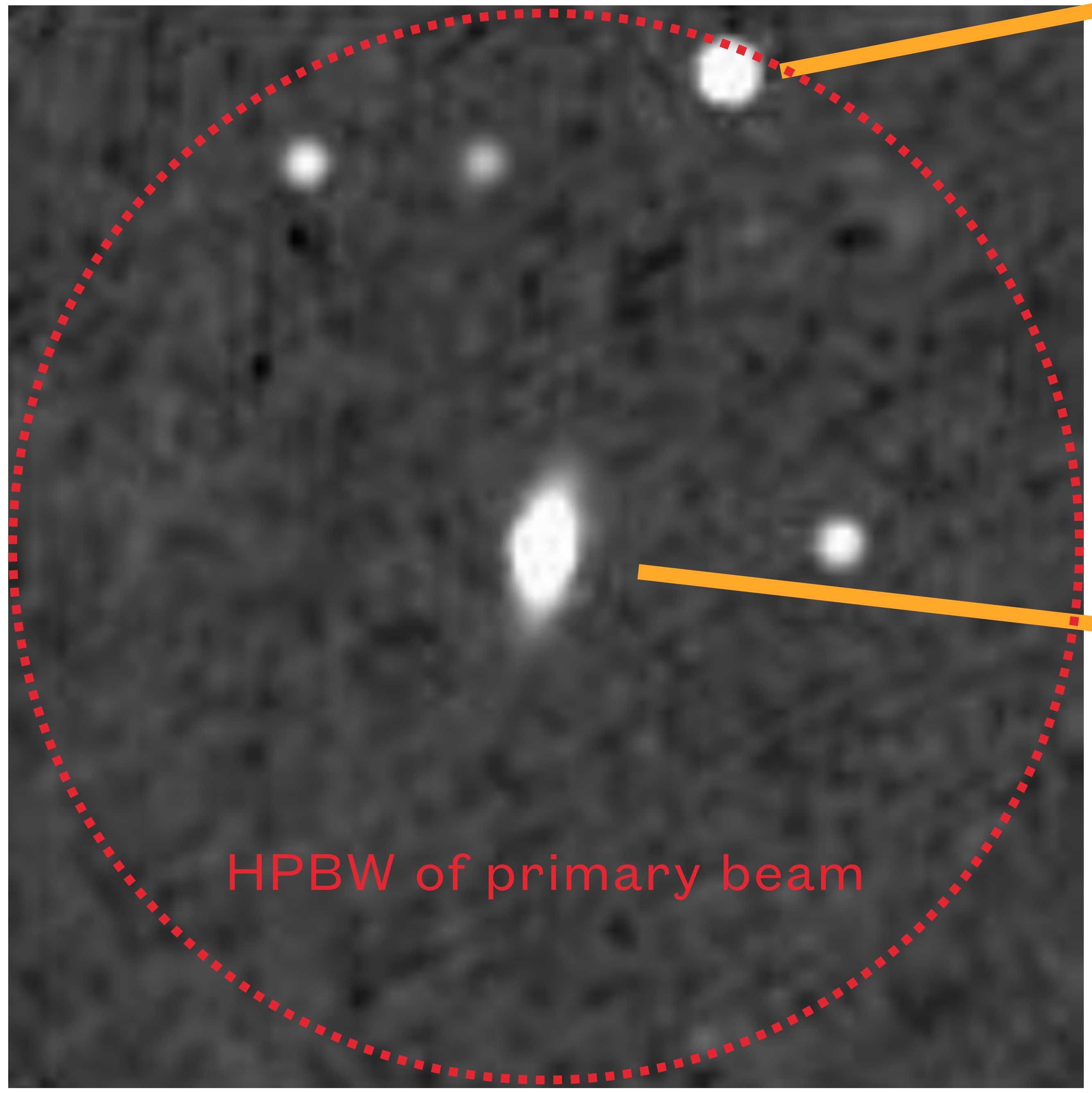
- Assuming ~0.5 degree field-of-view (25m telescopes at 1.4 GHz) w/ Nyquist sampling
  - *Very Large Array* (VLA) A-configuration (1.4” resolution) - $\sim 1.4 \times 10^{7}$ pixels
  - *Very Long Baseline Array* (VLBA) - (~6 mas resolution) - $\sim 1 \times 10^{11}$ pixels

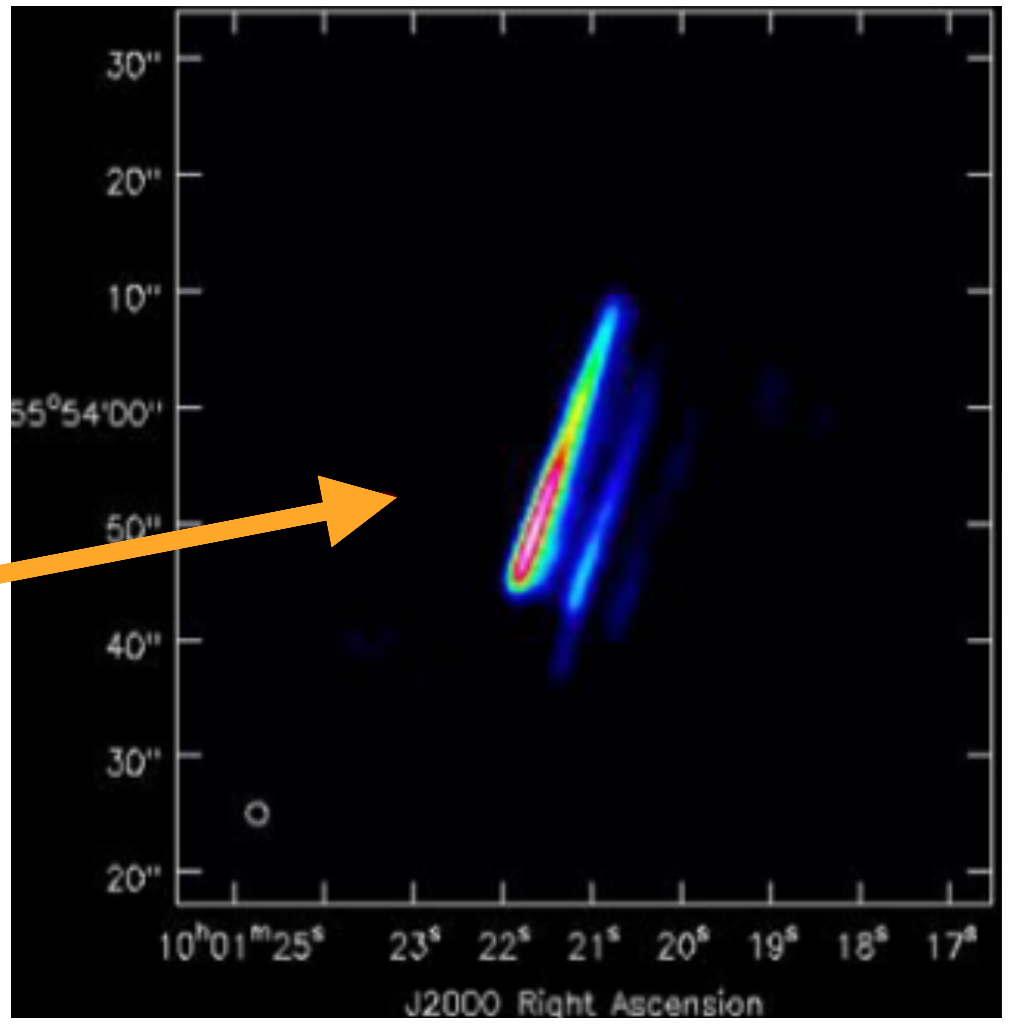


Imaging the entire primary beam - challenges

2. Smearing

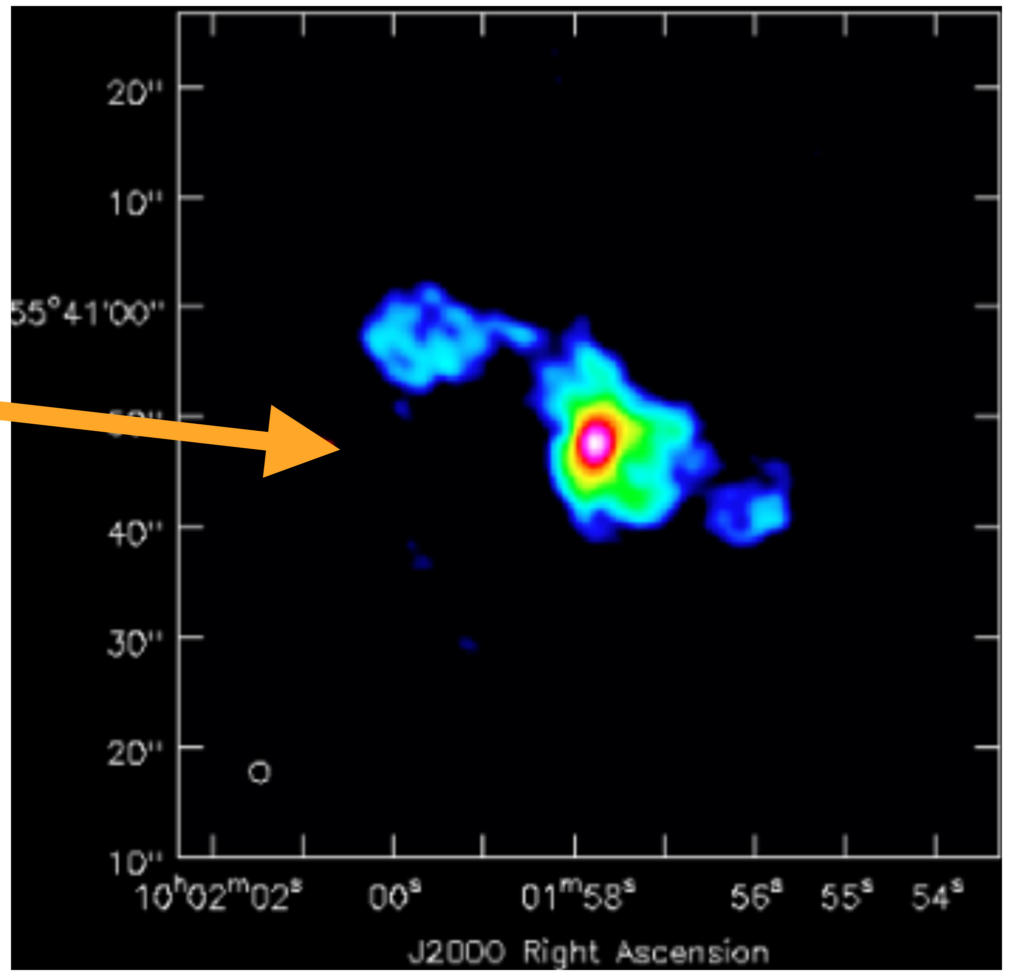
NVSS (VLA) - short baselines





Edge of PB massively smeared

e-MERLIN - long baselines



Centre of PB no smearing

Image credit - T. Muxlow

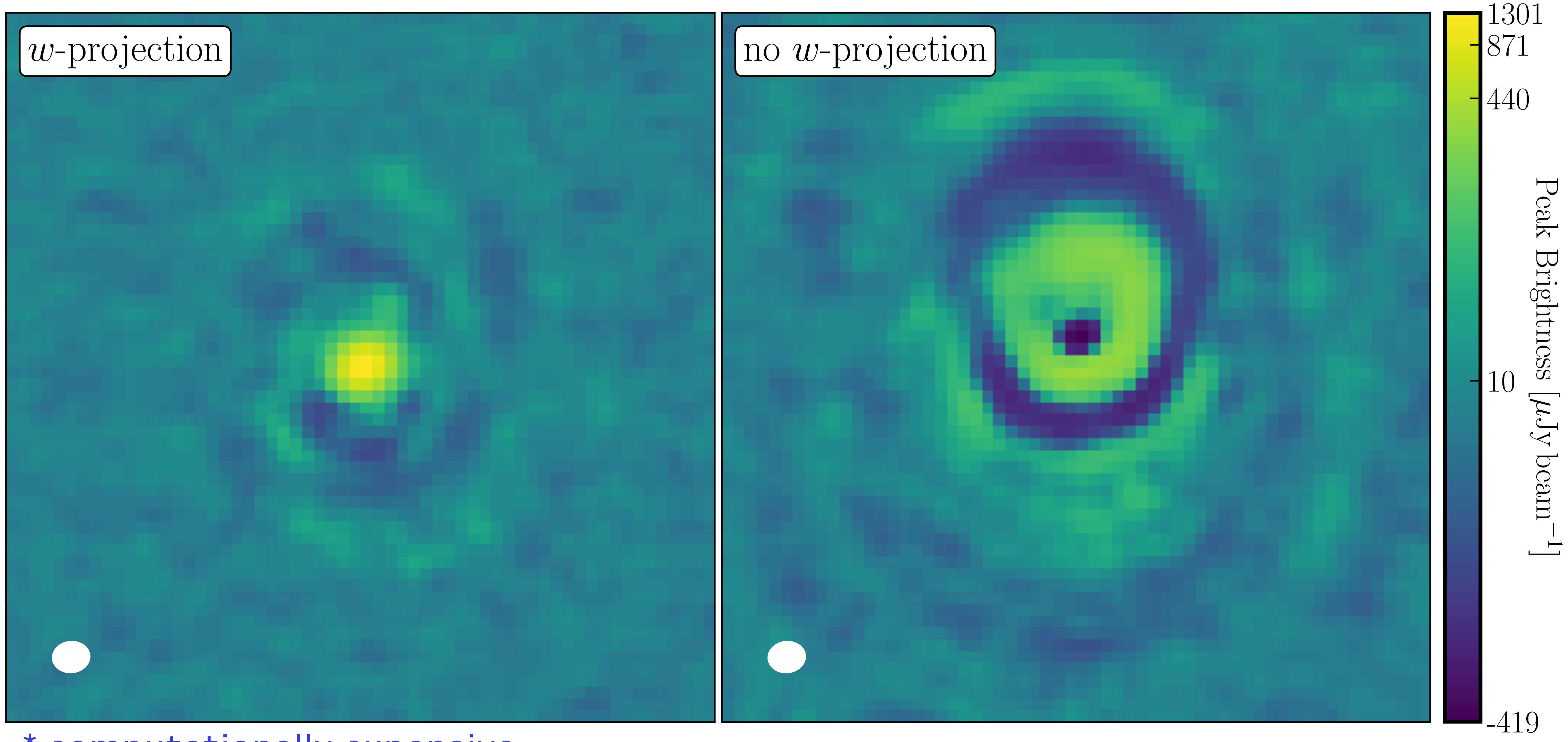
Imaging the entire primary beam - challenges

3. Non-coplanarity or the w term

Ideal RIME

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

e-MERLIN - source 7.5' from pointing centre



* computationally expensive

- The pesky extra term of:

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

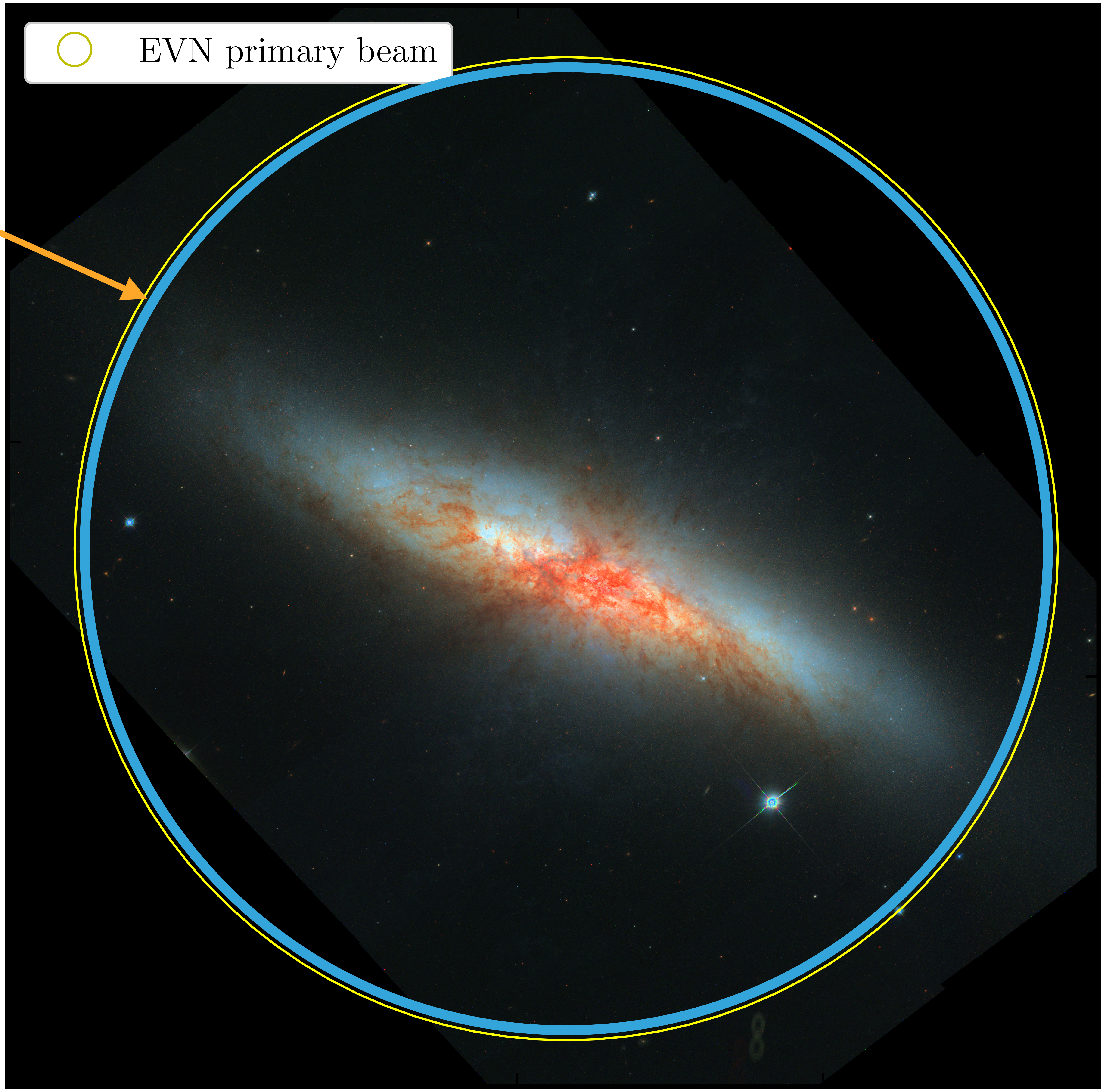
* $n = \sqrt{1 - l^2 - m^2}$

stops us having a true 2D-FT

Severity of these issues $\propto$ baseline length & distance from phase centre

Solutions - standard 'wide-field' correlation

Field-of-view due to smearing



- Correlate at high temporal & frequency resolution

Result - monolithic and 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 in the primary beam which is inaccurate using standard software.

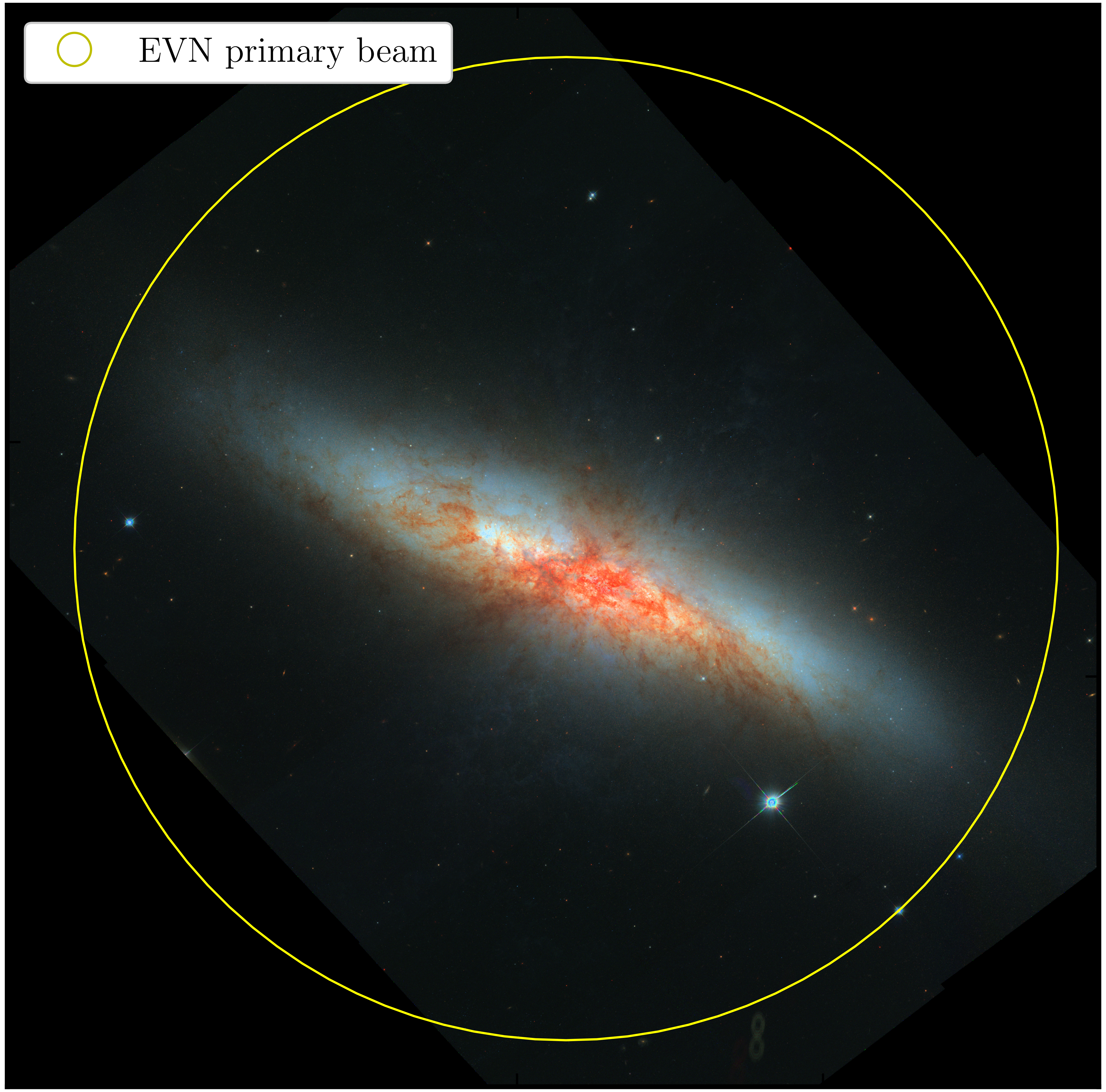
*Note: a 22 telescope, 12 hour EVN observation @ 1 Gbps > 15 TB

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.



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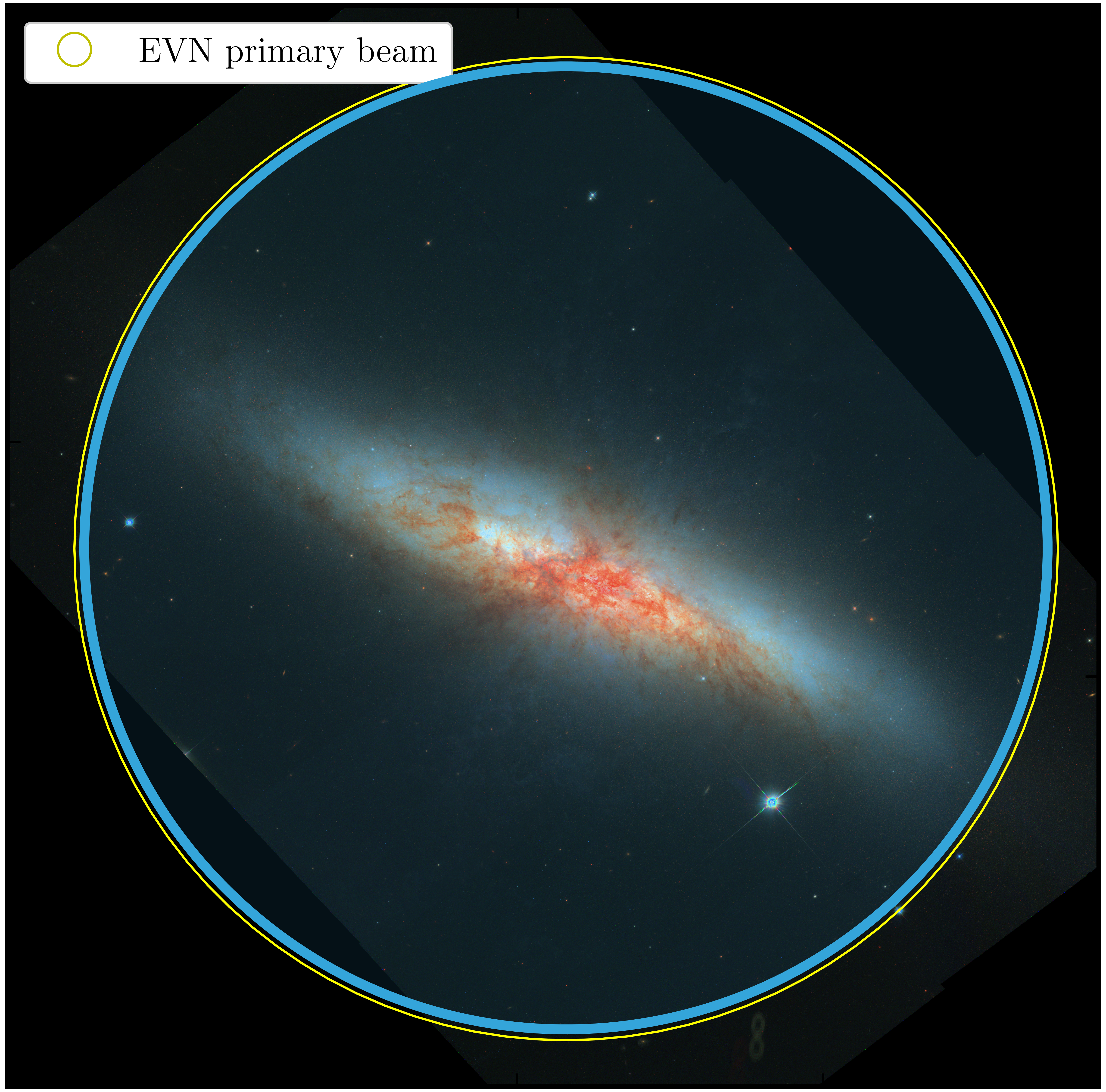

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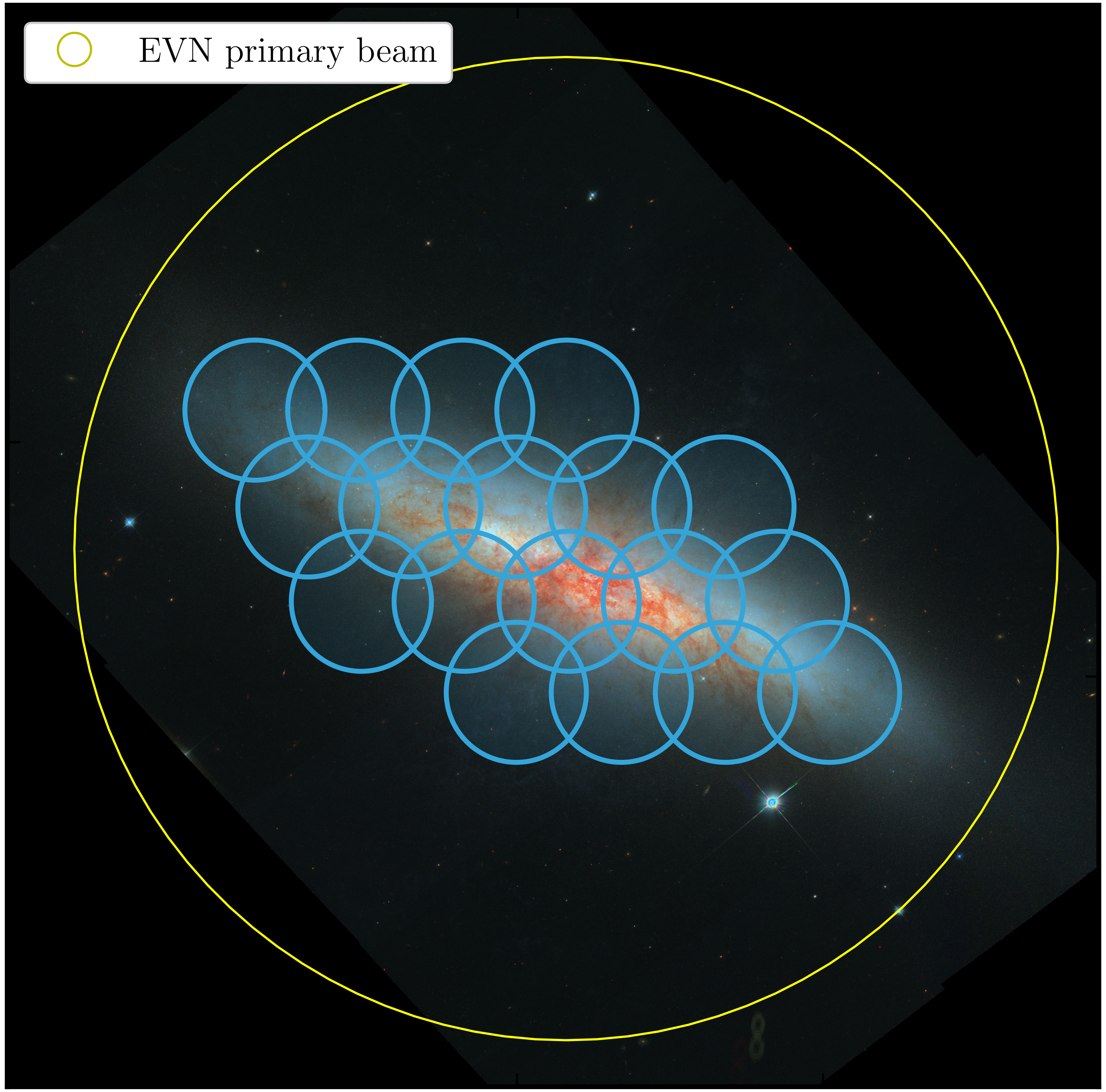

MORGAN ET AL. 2011, DELLER ET AL . 2011, KEIMPEMA ET AL . 2015

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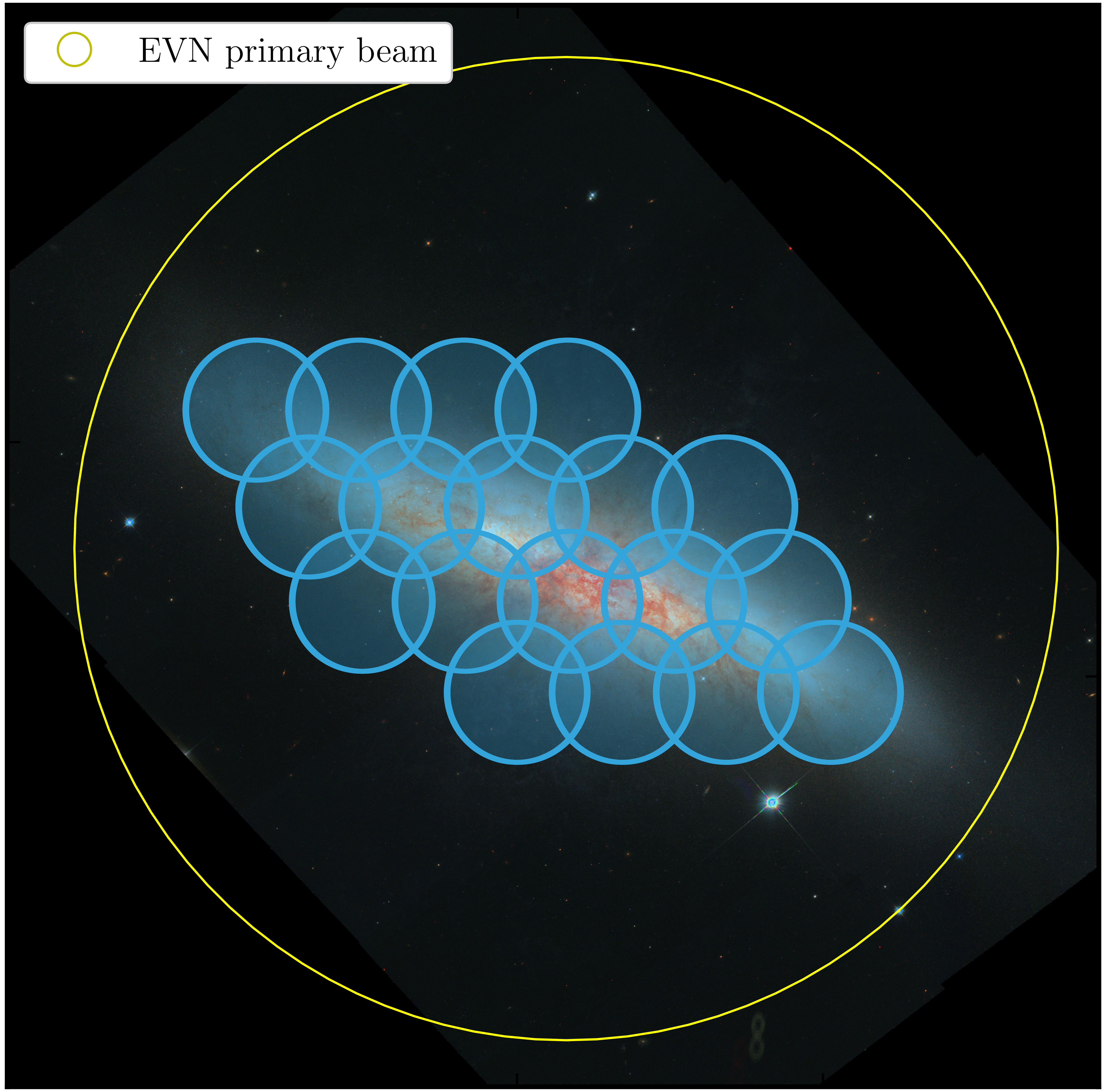


Calibrating wide-field VLBI data

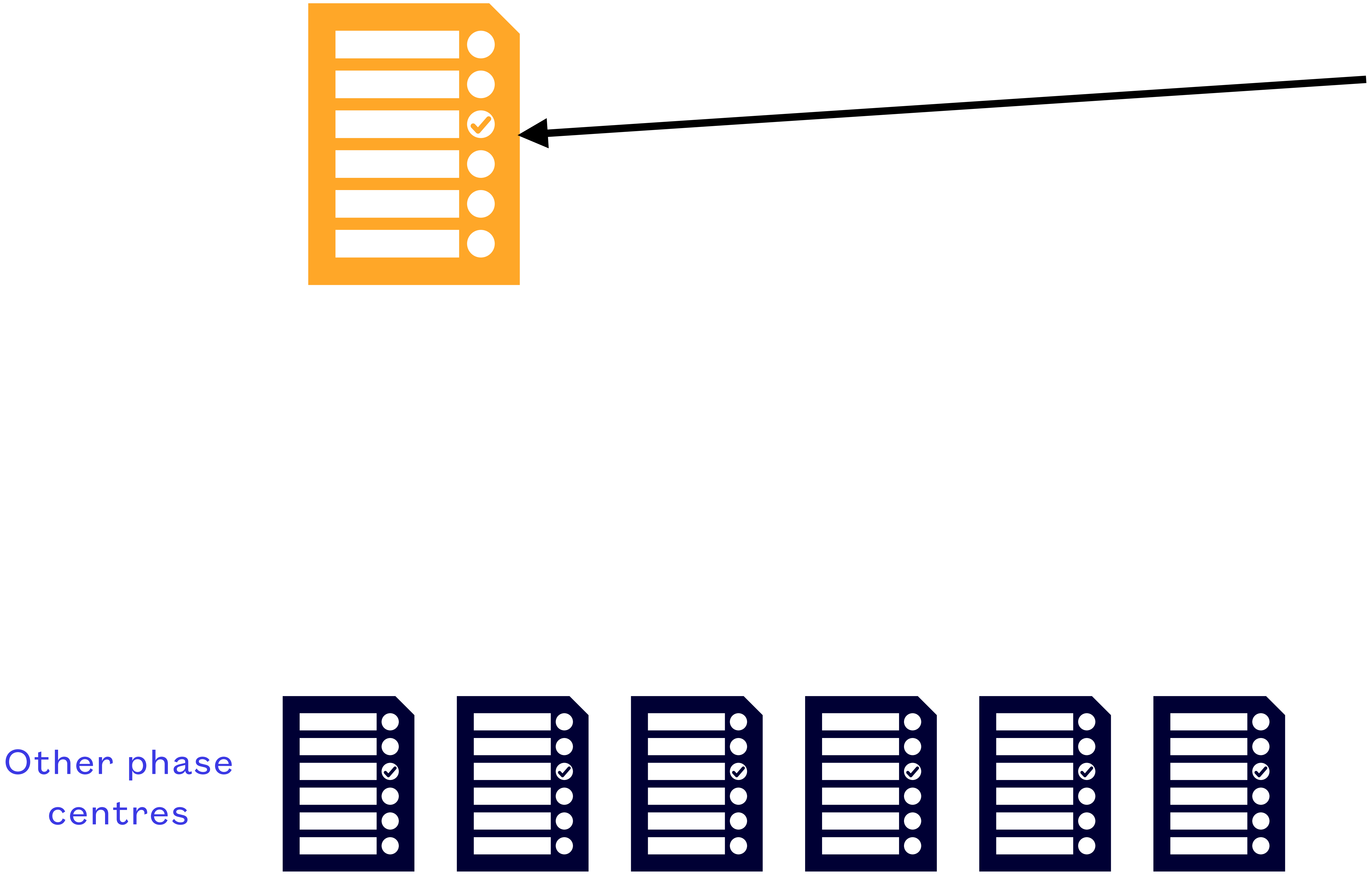
- Calibrating wide-field VLBI data is much easier than you'd think. There are three areas that are different from standard VLBI data processing,
  a. Applying solutions in phase referencing
  b. Self-calibration
  c. Primary beam corrections

- In addition, there are many pipelines that have been developed (e.g. rPICARD, Janssen+19), or in development (e.g. cm-VLBI pipeline & EVN CASA pipeline), that can make standard calibration much easier.

A shameless plug - the cm-VLBI pipeline

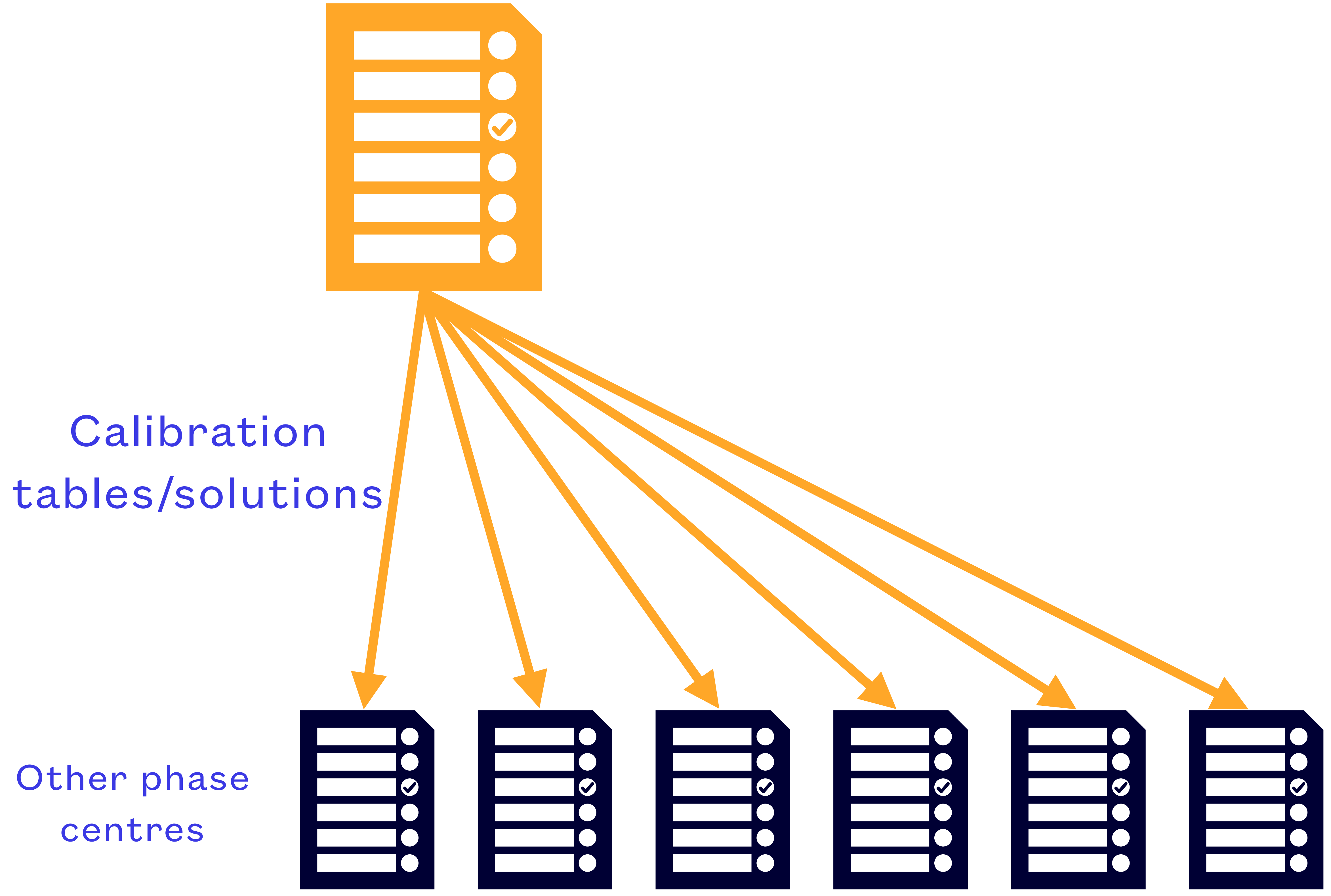
- cm-VLBI pipeline based in CASA (v5.7+/6.1+) currently in development (current v0.8) - https://github.com/jradcliffe5/VLBI_pipeline - **it needs some testers please :)!** Nb. it's modular so works with other pipelines.
- Currently does the following,
  - A priori calibration for EVN & VLBA data (e.g. 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.
- In development,
  - Primary beam correction schemes
  - Multi-source self-calibration (and direction dependent calibration too)
  - Parameter automation (e.g. source finding, calibration solution intervals etc.)

Phase referencing



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

Phase referencing



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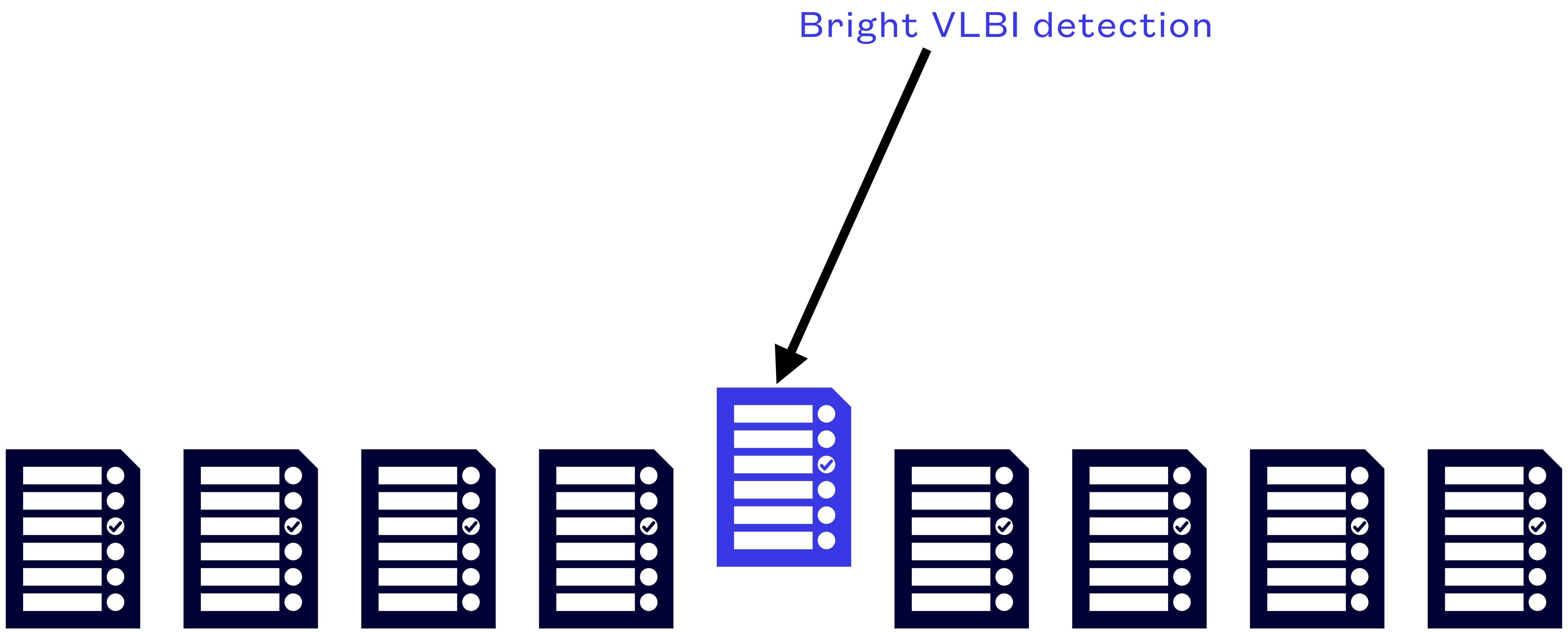
Self-calibrating VLBI data

- Atmospheric effects correlated on short baselines **but not** on longer baselines (>500 km)
- Often uncorrelated at different locations within target field too…
- Also, the number density of VLBI sources (and their flux densities) lower due to the ‘resolving out’/ spatial filtering effect.

Self-calibration solution 1

In-beam phase referencing

- 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 detections so…



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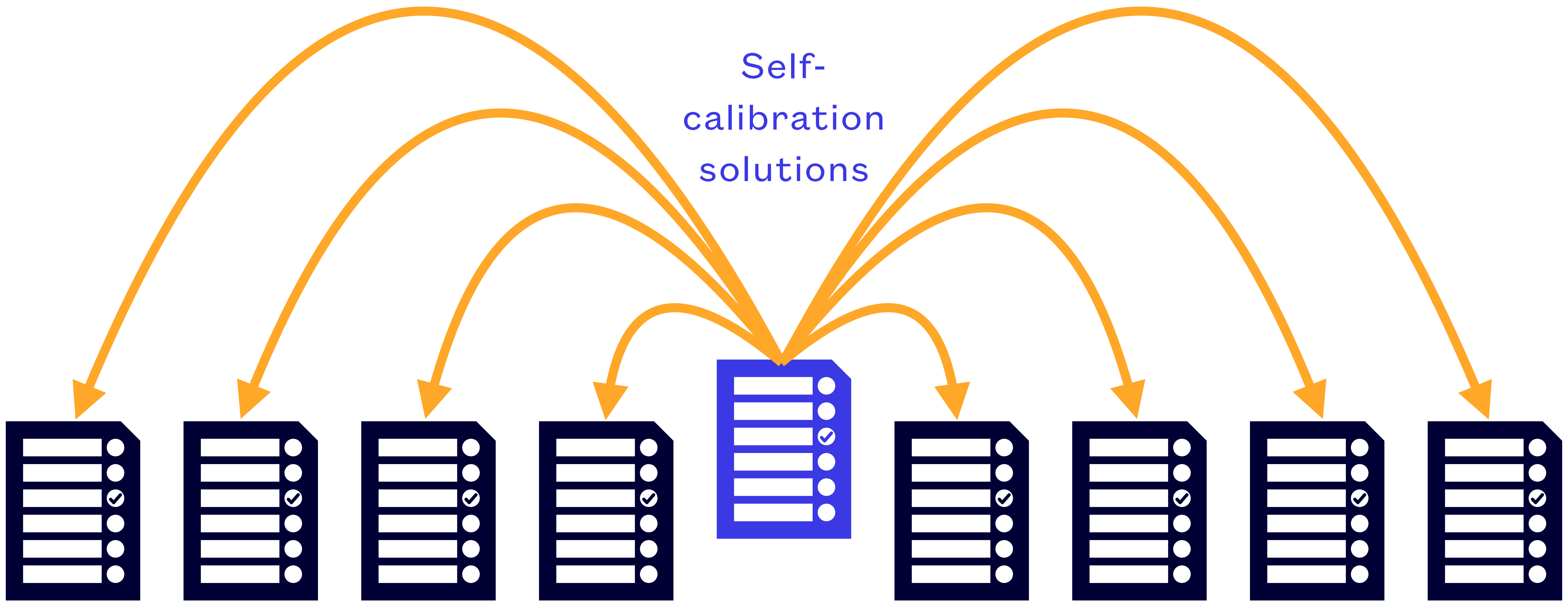
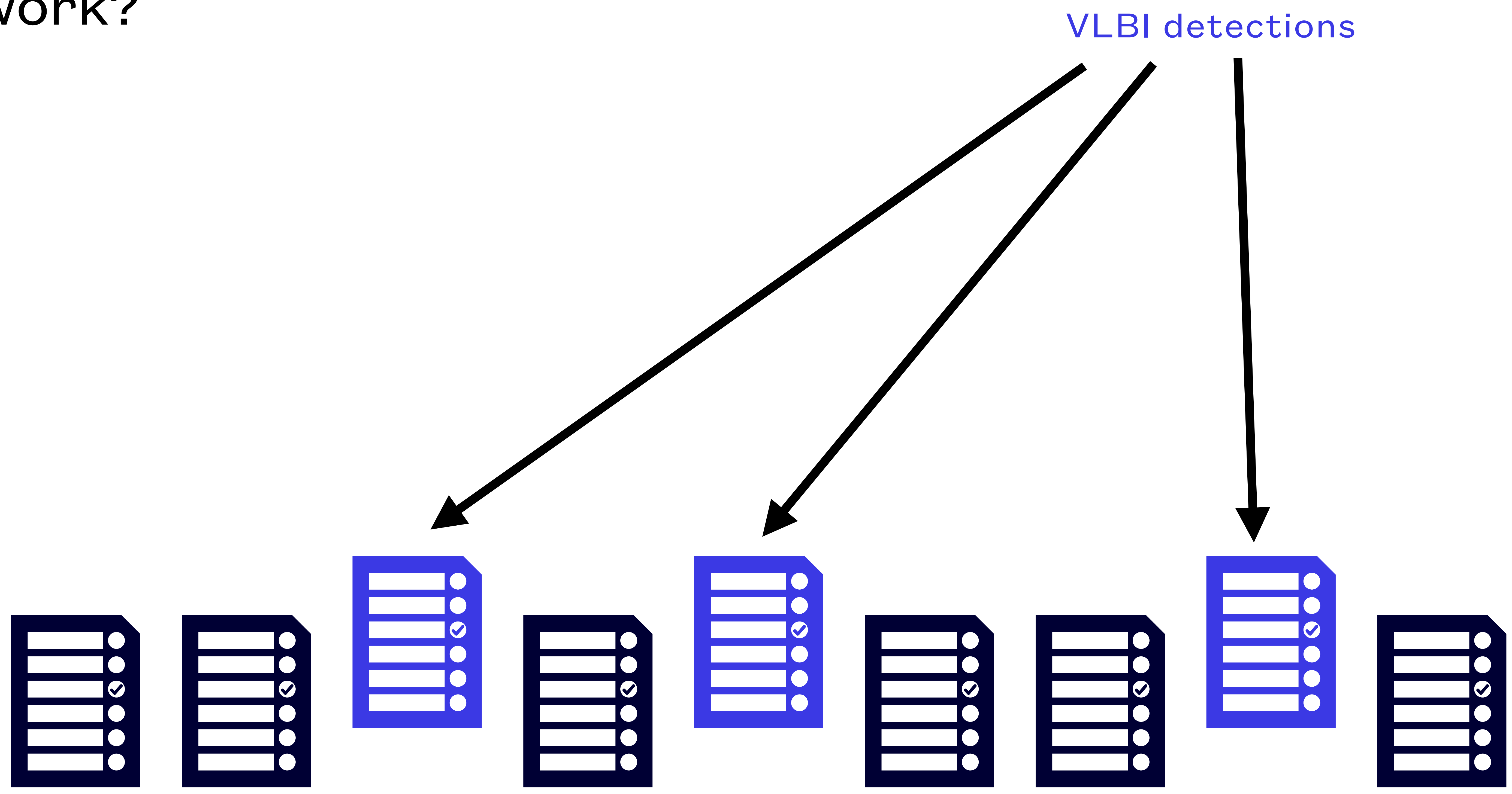


Self-calibration solution 2

Multi-source self-calibration (MSSC)

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



*parallelised via `mpicasa`

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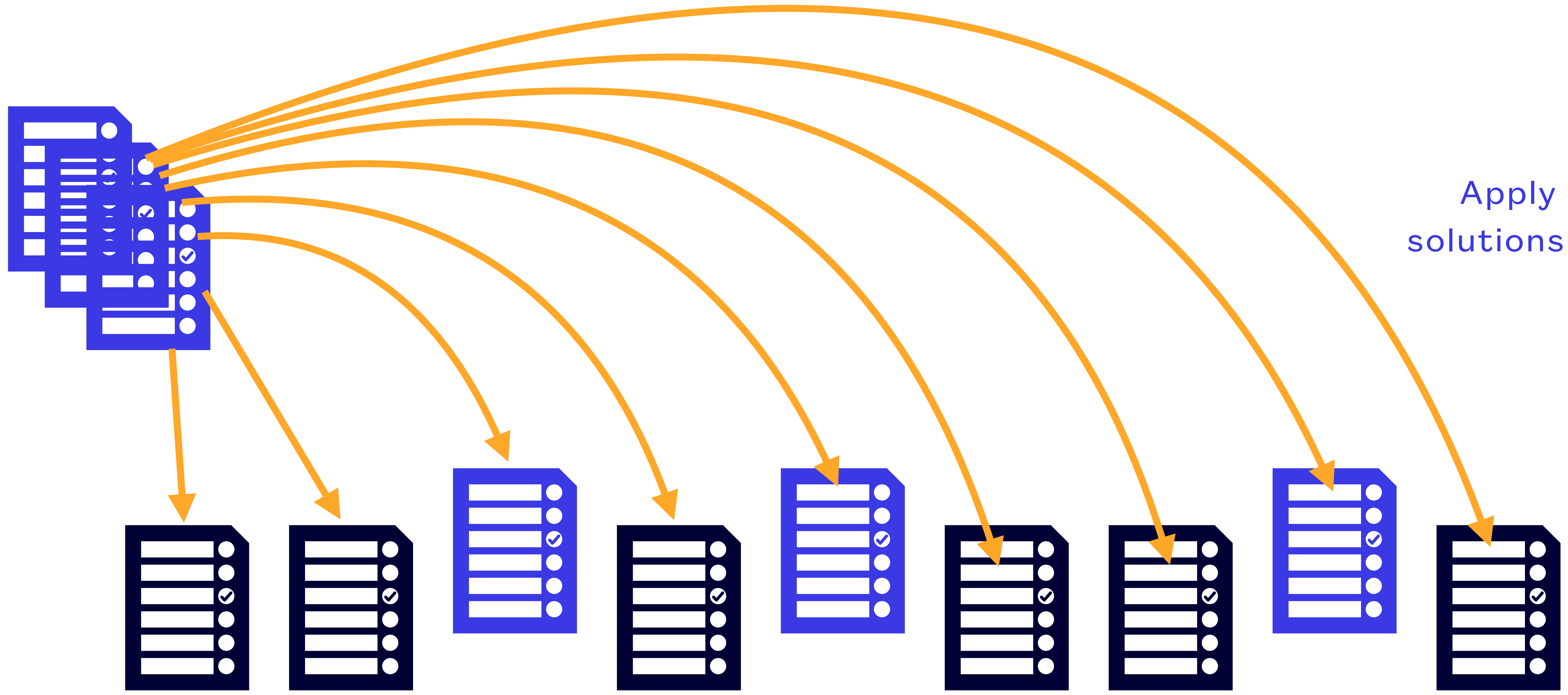

Apply self-calibration solutions to all other phase centres

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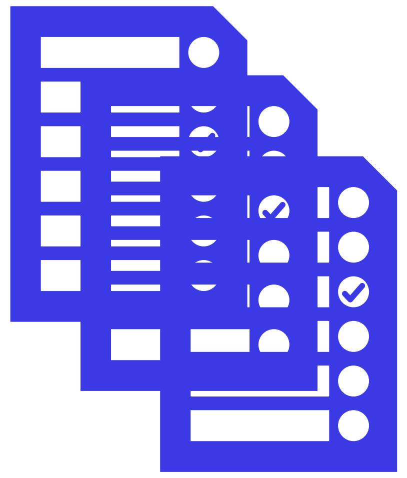
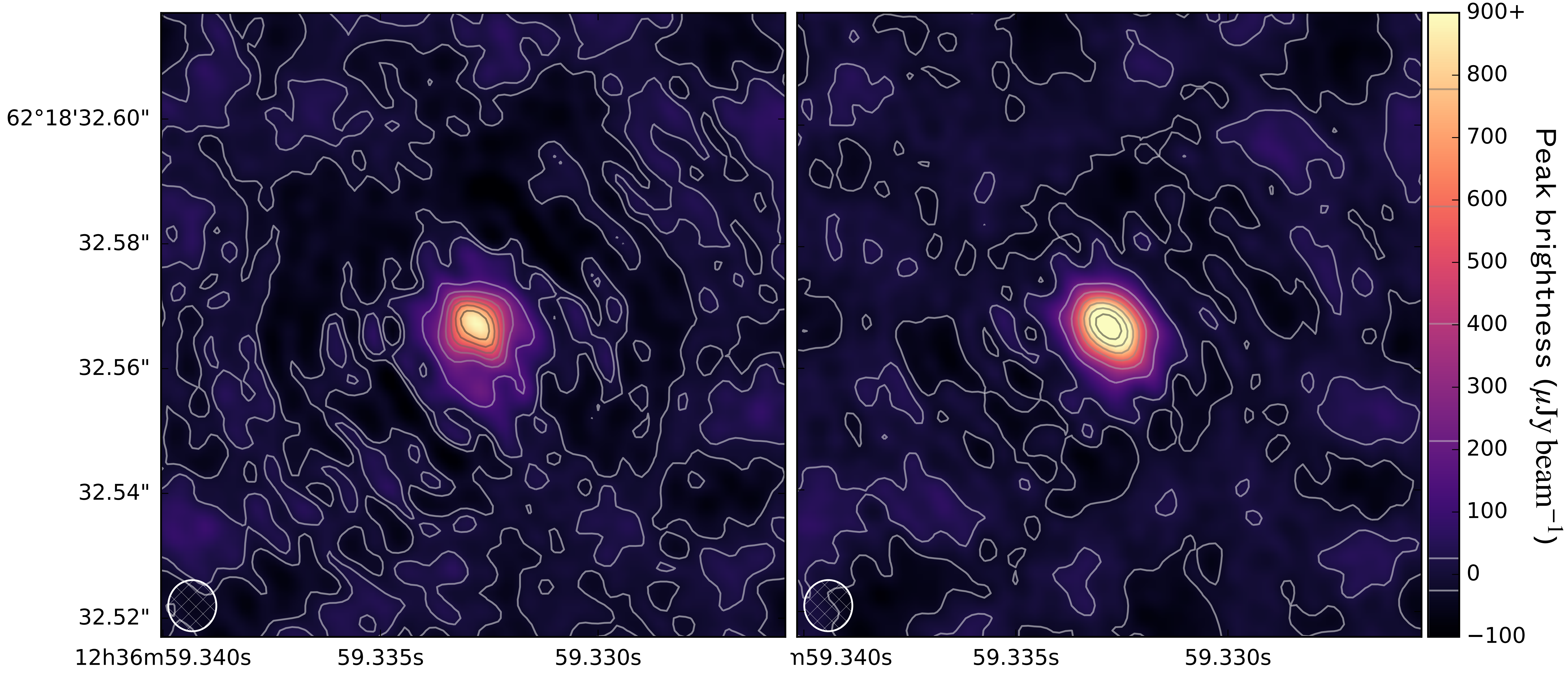


Image phase centres again (& repeat process if neccessary)

Multi-source self-calibration

Standard phase referencing
S/N ~ 43

MSSC
S/N ~ 113

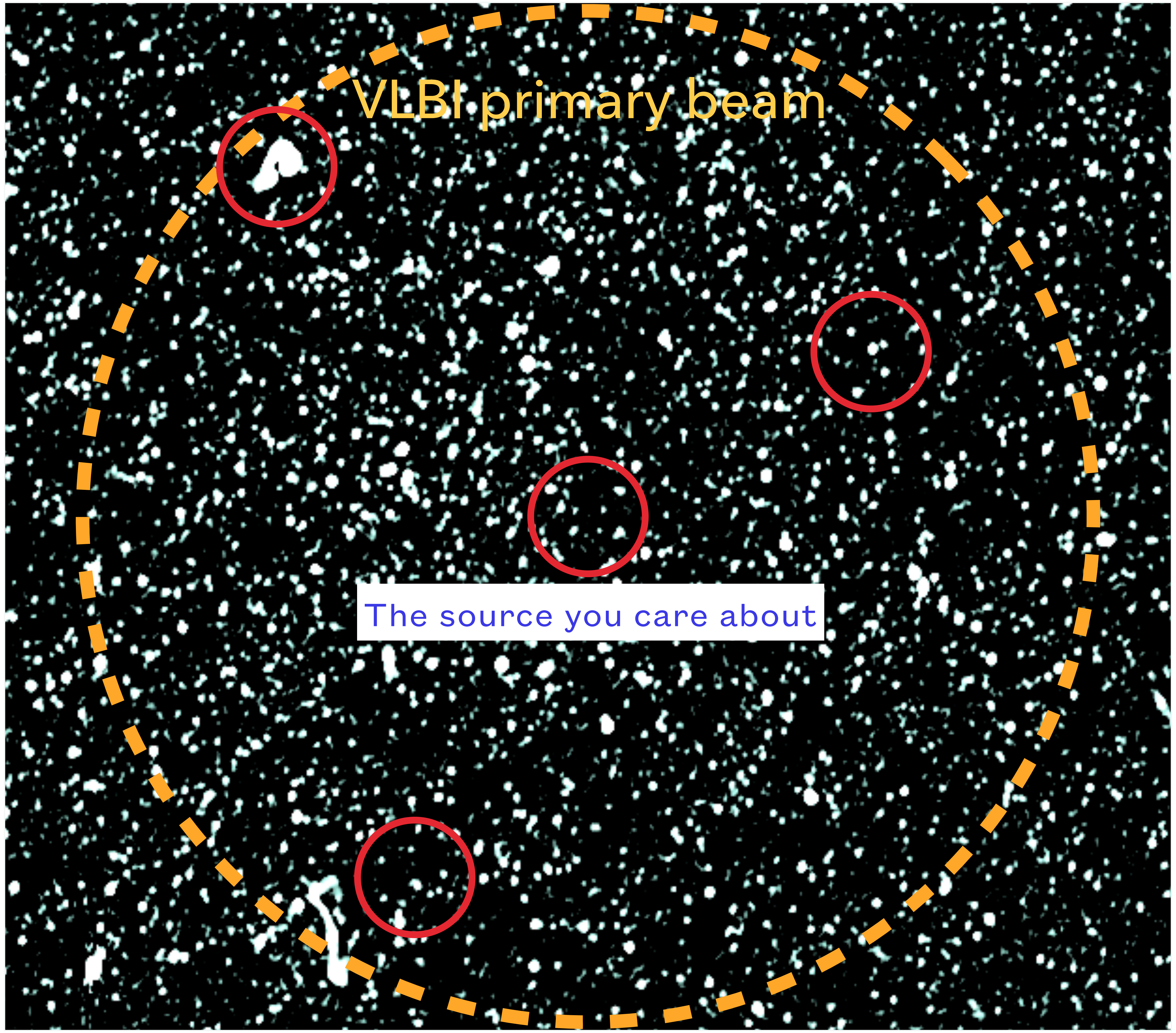


- Code publicly available for AIPS - https://github.com/jradcliffe5/multi_self_cal
- CASA version in testing stage - https://github.com/jradcliffe5/MSSC_CASA

MSSC - not just for wide-field data sets

Phase centres

- 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…



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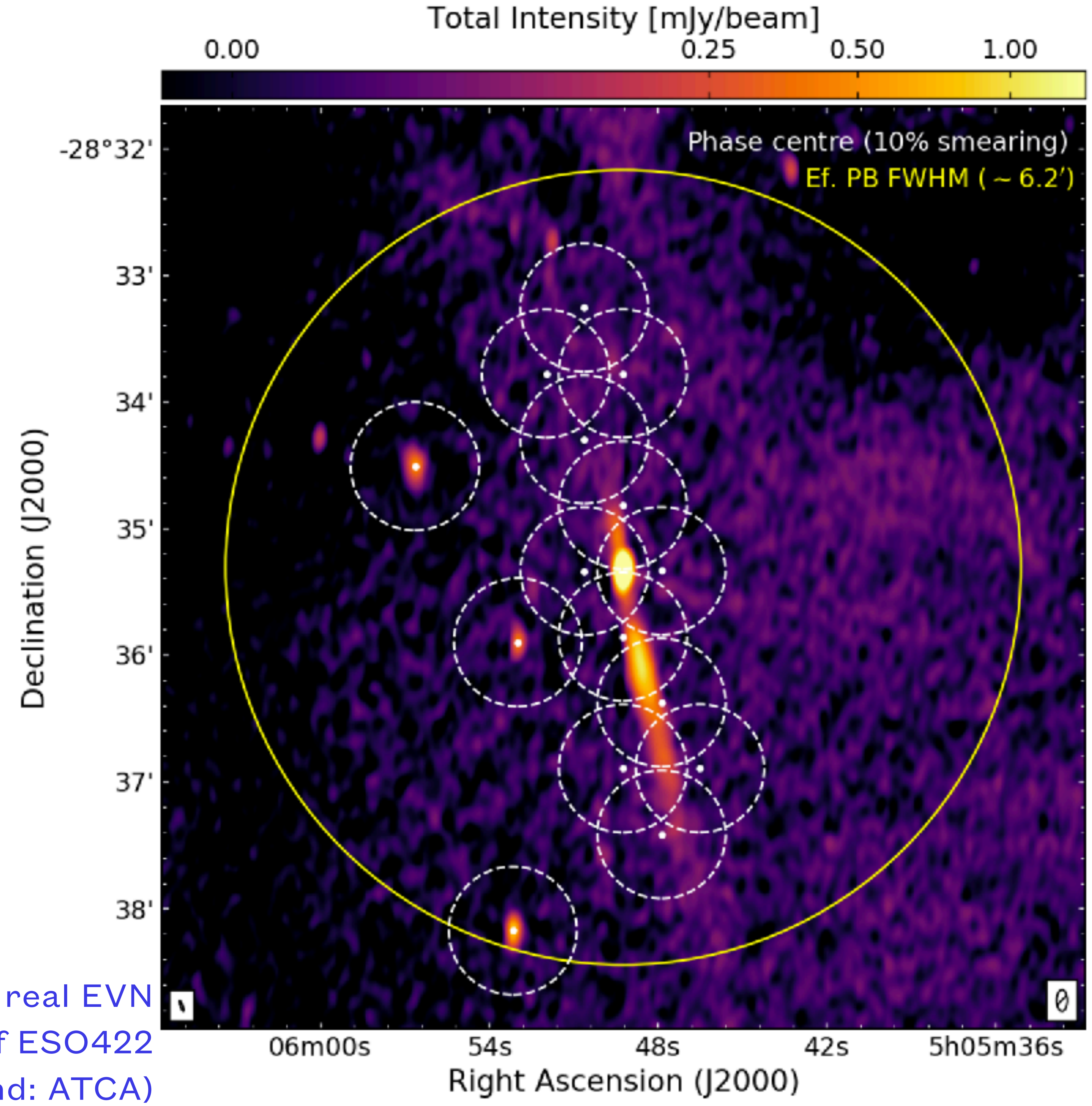


Example from real EVN observation of ESO422 (background: ATCA)

The primary beam problem - the final frontier for wide-field imaging

- Primary beams are *the most ubiquitous direction dependent effect* (DDE) that affects all wide-field radio observations.

- Recap of the **Radio Interferometry Measurement Equation** (RIME; Smirnov+11) for antennas p and q,

Sky brightness distribution

Visibilities as measured by baseline pq

Directional cosines (i.e. sky coordinates)

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

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

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

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, ionospheric dispersions

- More of a problem for heterogeneous arrays (i.e. most VLBI arrays) as we shall see next.

The primary beam problem - 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. 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,

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

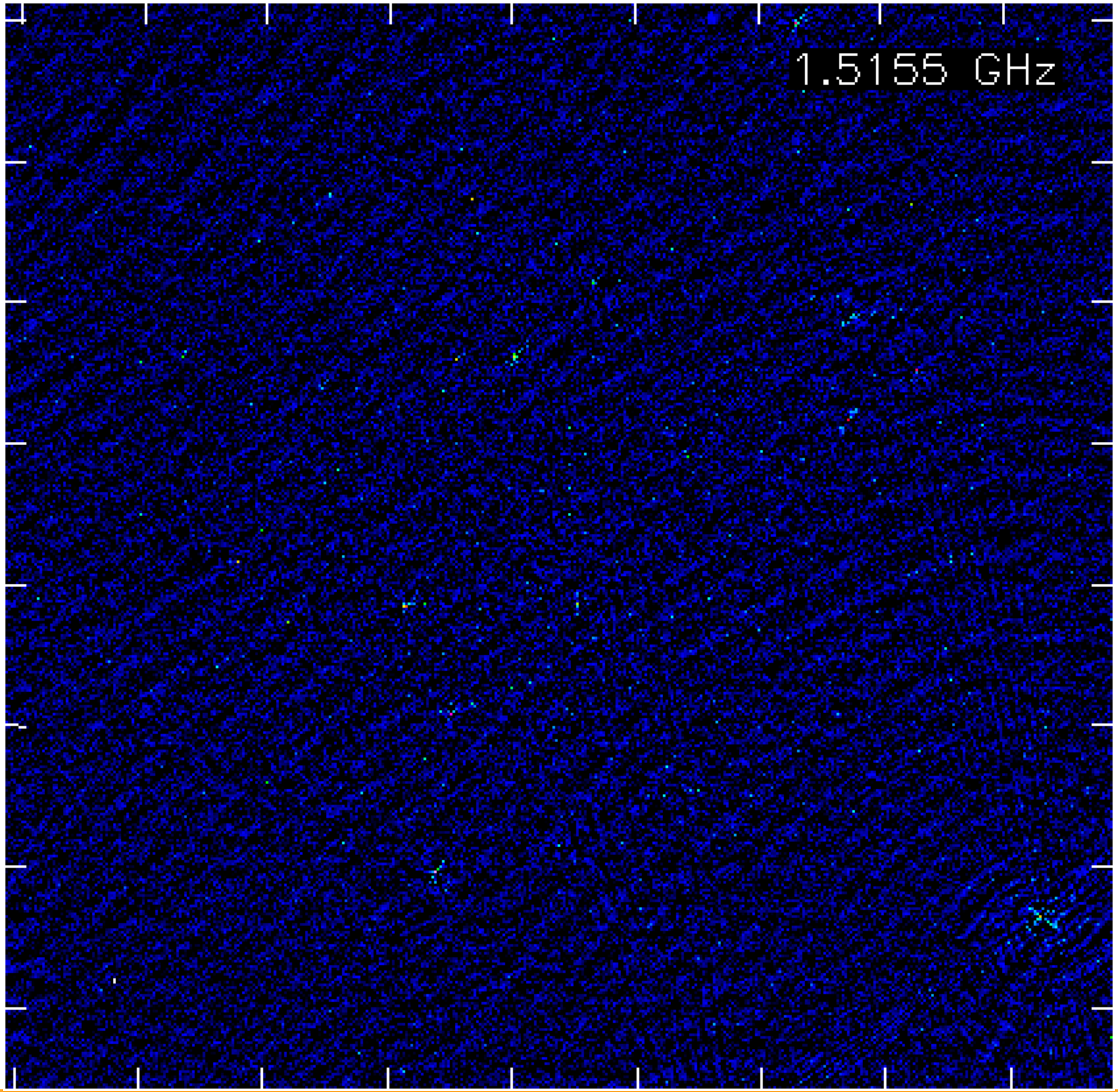
Homogeneous arrays

- 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



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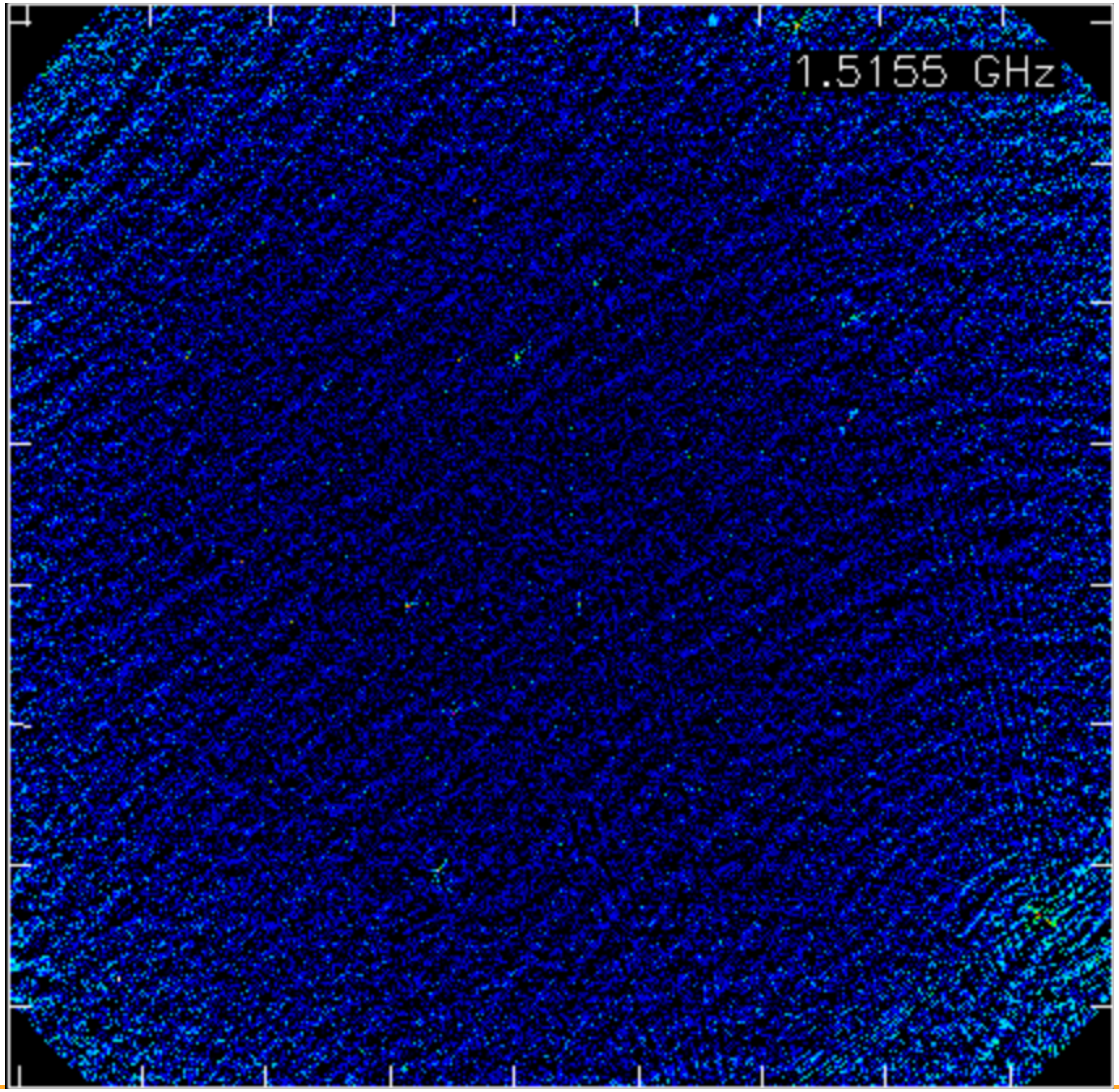


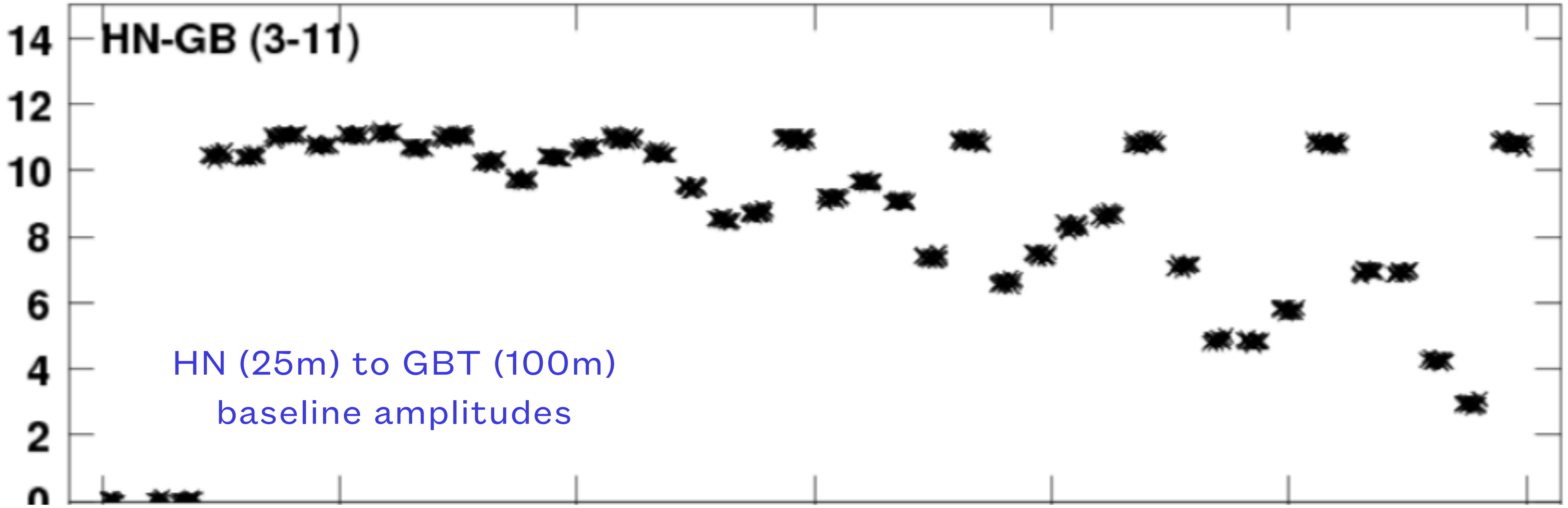
Heterogeneous arrays

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

$$\mathsf{B}_{\mathrm{app},\,pq} = \boldsymbol{E}_p \mathsf{B} \boldsymbol{E}_q^H \neq \mathsf{B}_{\mathrm{app},\,pq} \quad \text{for all } p, q$$

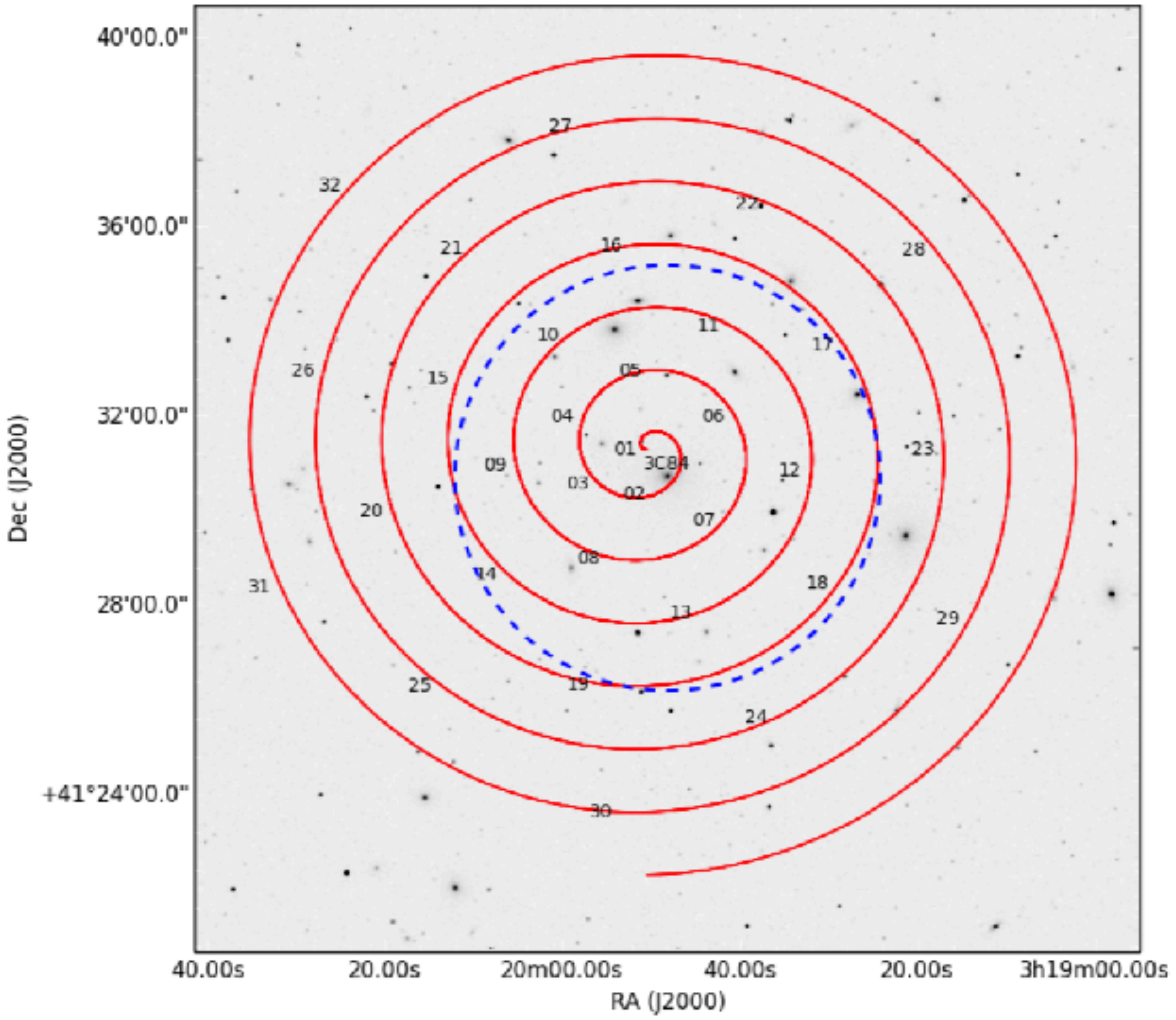
- i.e. **each baseline *does not* observe the same apparent brightness distribution**

- This manifests as a *direction-dependent, antenna independent, and dominant, amplitude (and phase…) error.* e.g.



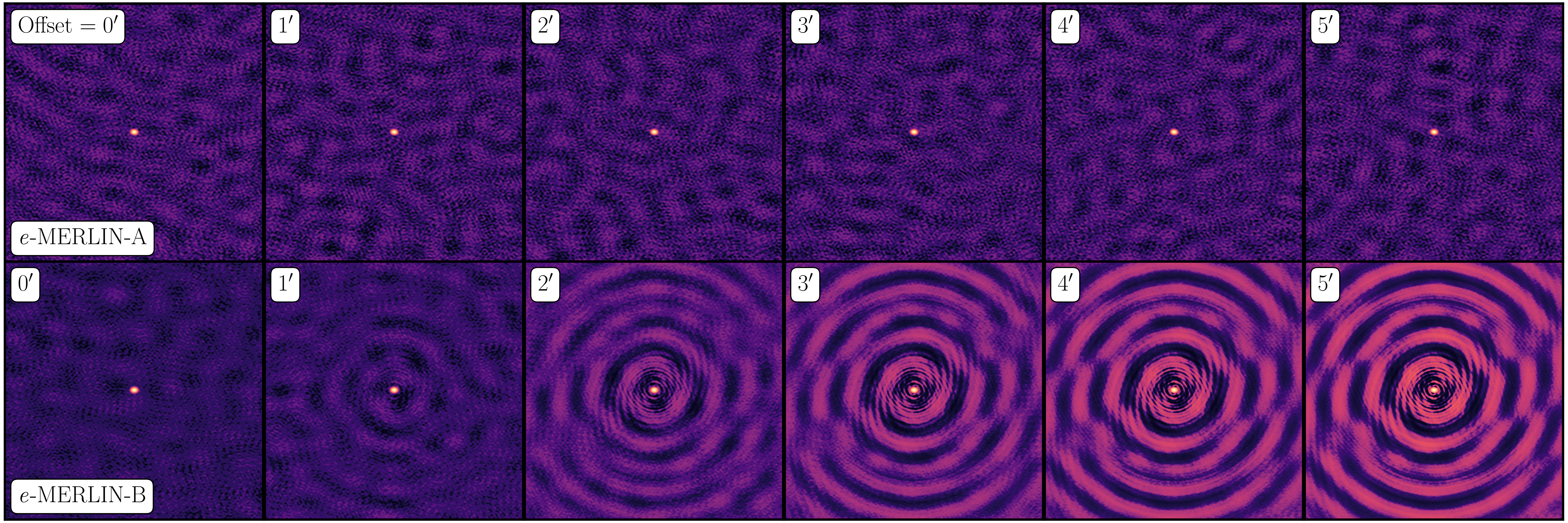
HN (25m) to GBT (100m) baseline amplitudes

VLBA + GBT observations of 3C84 (Herrera-Ruiz+18)



Heterogeneous arrays

- This is more of a problem for very heterogeneous arrays (e.g. the EVN) and can drastically limit dynamic range quite close to the pointing centre.
- Below is a simple simulation of *e*-MERLIN-A (approx. homogeneous) and *e*-MERLIN-B (heterogeneous with two telescope sizes) arrays observing on a point source with dynamic range of 1000 at different offsets from pointing centre.

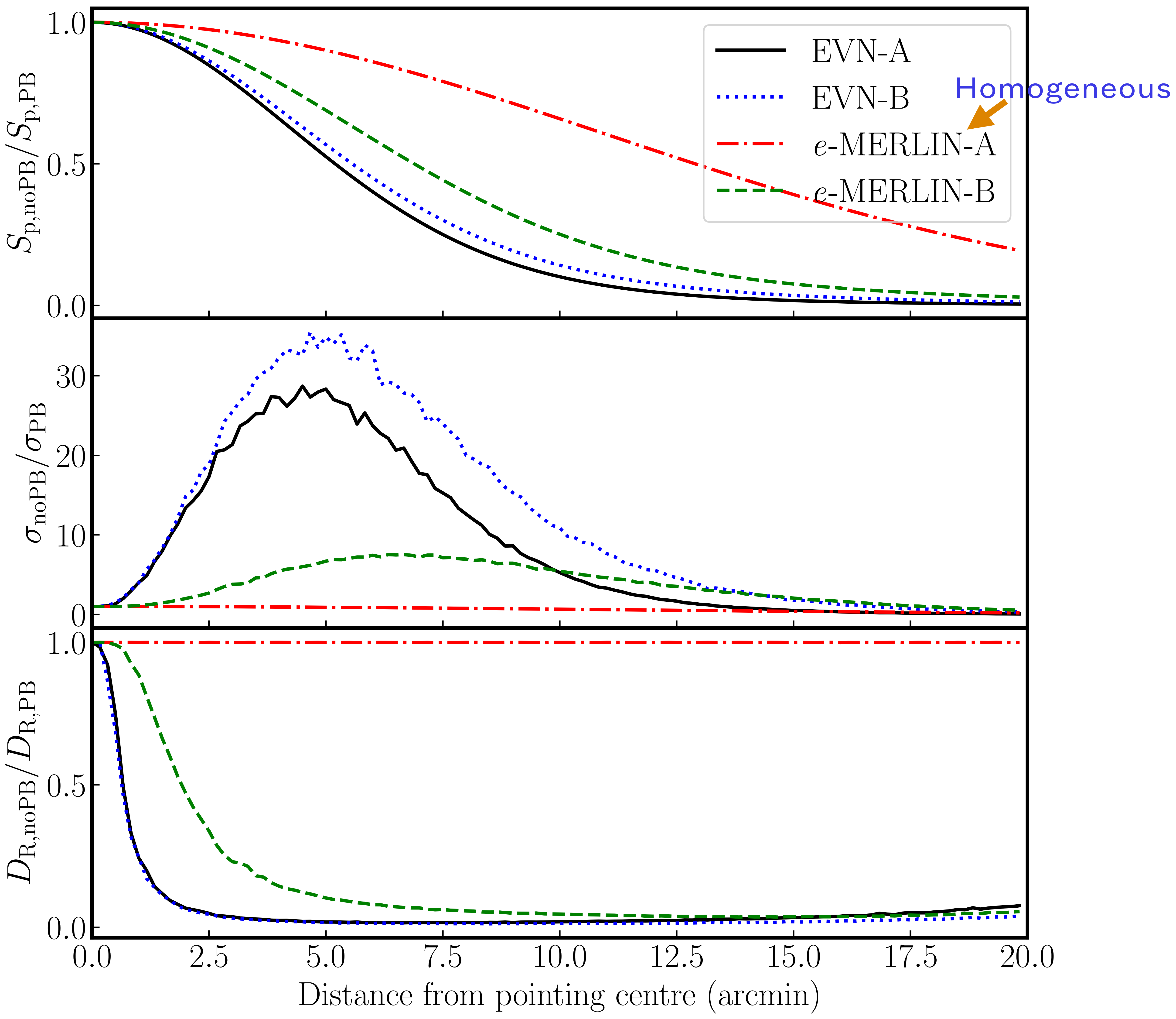


Heterogeneous arrays

- This can be even more severe for EVN arrays:

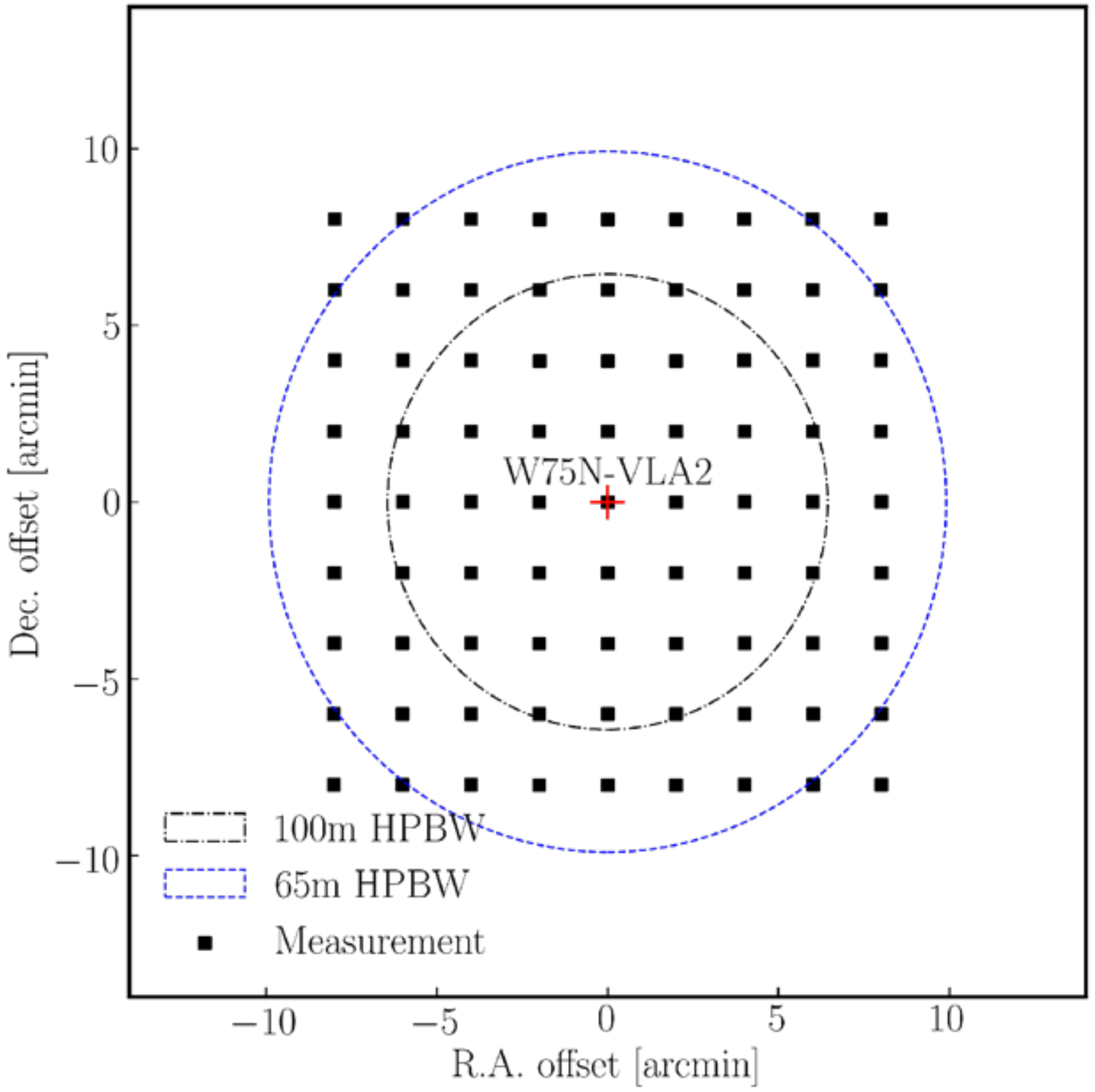
Simulation name	Stations	N_{ant}	$N_{pb,unique}$
e-MERLIN-A	Jb-2, De, Kn, Pi, Da	5	1
e-MERLIN-B	Jb-1, De, Kn, Pi, Da	5	2
EVN-A	Jb-1, Ef, Tm-65, Wb, On-85, Tr, Sv, Bd, Zc, Ur	10	4
EVN-B	Jb-1, Ef, Tm-65, Wb, On-85, Tr, Sv, Bd, Zc, Ur, De, Kn, Pi, Da, Cm	15	5

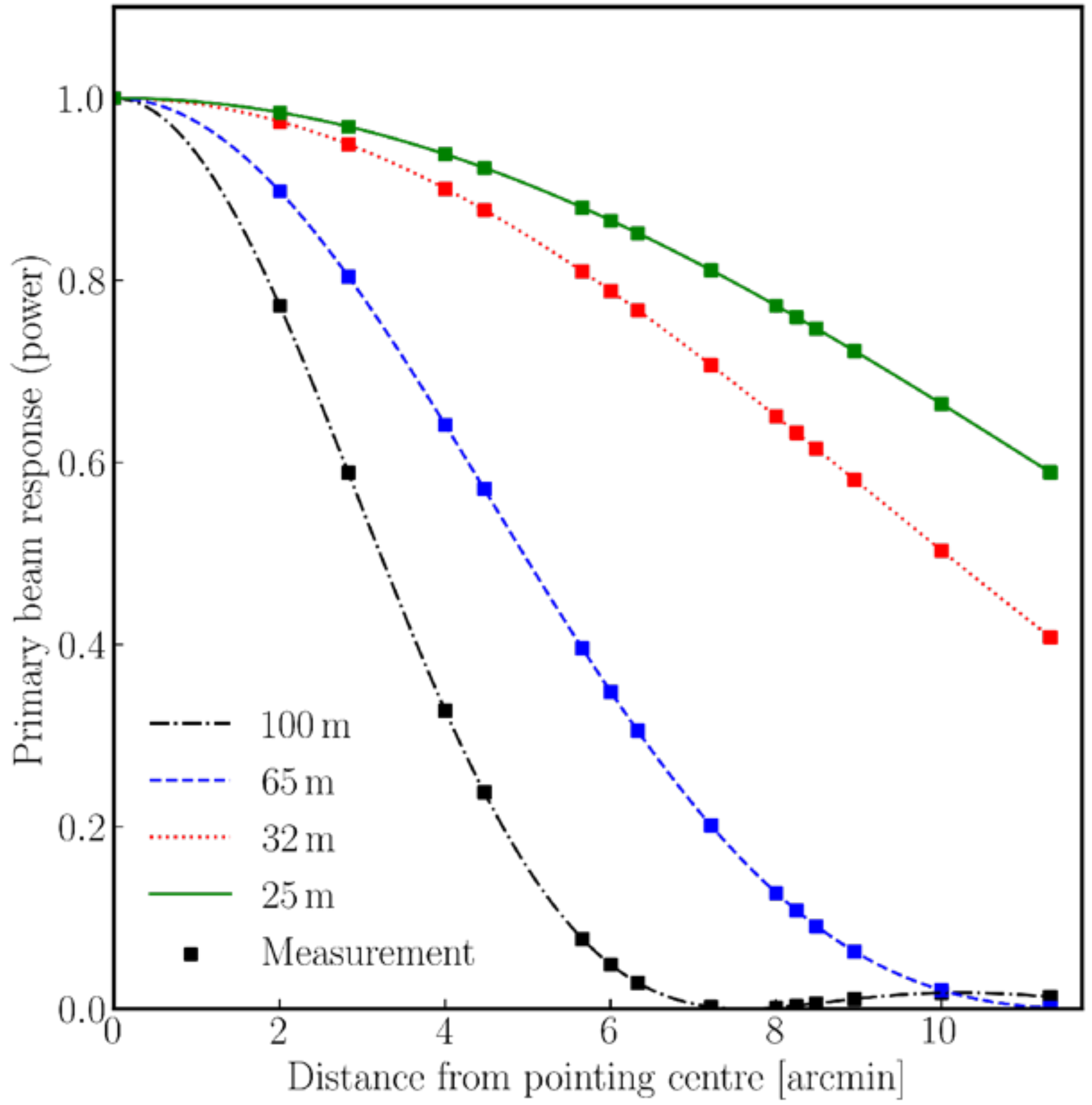
- This error is proportional to source dynamic range so primary beam errors not too severe at low S/N.
- Will become ever more important with increasing VLBI bandwidths and inclusion of sensitive (phased-up) elements e.g. MeerKAT / SKA.
- To correct this effect, we need models of the primary beams!



Primary beam models - current status

- VLBA and GBT estimates exist (e.g. Middelberg+2013)
- Some for e-MERLIN (Wrigley 2016) but about to be updated for whole array.
- Only a few at 1-2 GHz for the EVN but all is about to change! Accepted proposal (EVN + e-MERLIN joint effort) to map EVN stations.
- Current primary beam models at 1-2 GHz are crude estimates (taking into account blockages etc.; see Radcliffe+18)





Mapping the primary beam of EVN and e-MERLIN stations at 1.6 GHz by observing bright maser source W75N-VLA2. Results expected in Q2 2021.

Primary beam correction schemes

- With beam models / approximations at hand, 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_T, for heterogeneous array via,

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

Baseline primary beam → $P_{pq}(l,m)$

Voltage beam for antenna p/q

Weights of antenna p / q

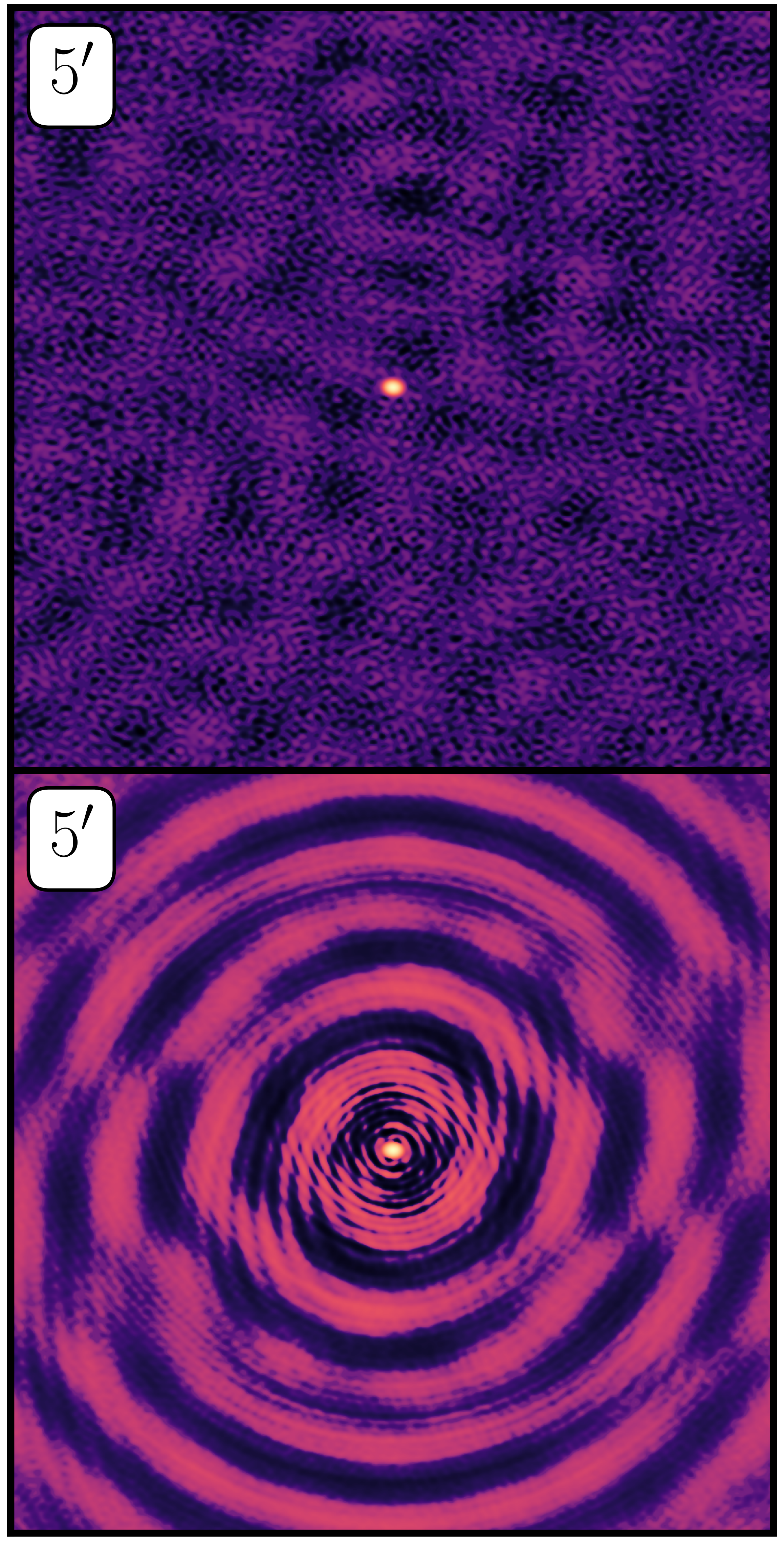
$$P_\mathrm{T} = \sum_{i,j=0;j>i}^{N_\mathrm{ant}} P_{pq}$$

(Weighted) sum over all baselines

- and divide subsequent image by P_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

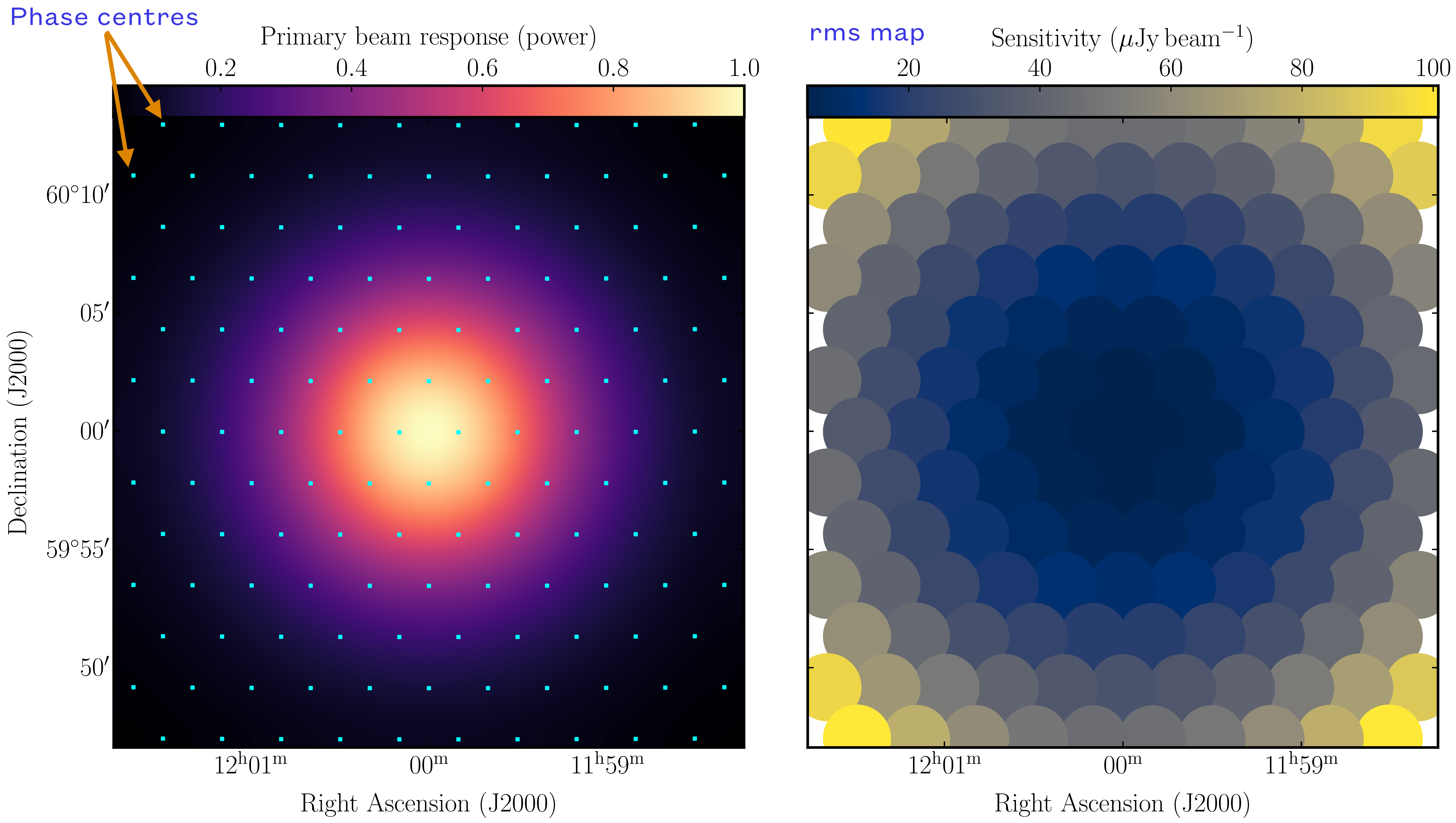
- Correct each phase centre in uv plane using gain table with a singular value for each antenna's primary beam voltage, evaluated at centre of the phase centre (where $l = l_{\rm pc}$ and $m = m_{\rm pc}$). Effectively does the following to each baseline,

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

- (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 smaller** than image plane only correction!

b. 'Differential' / step-wise primary beam correction

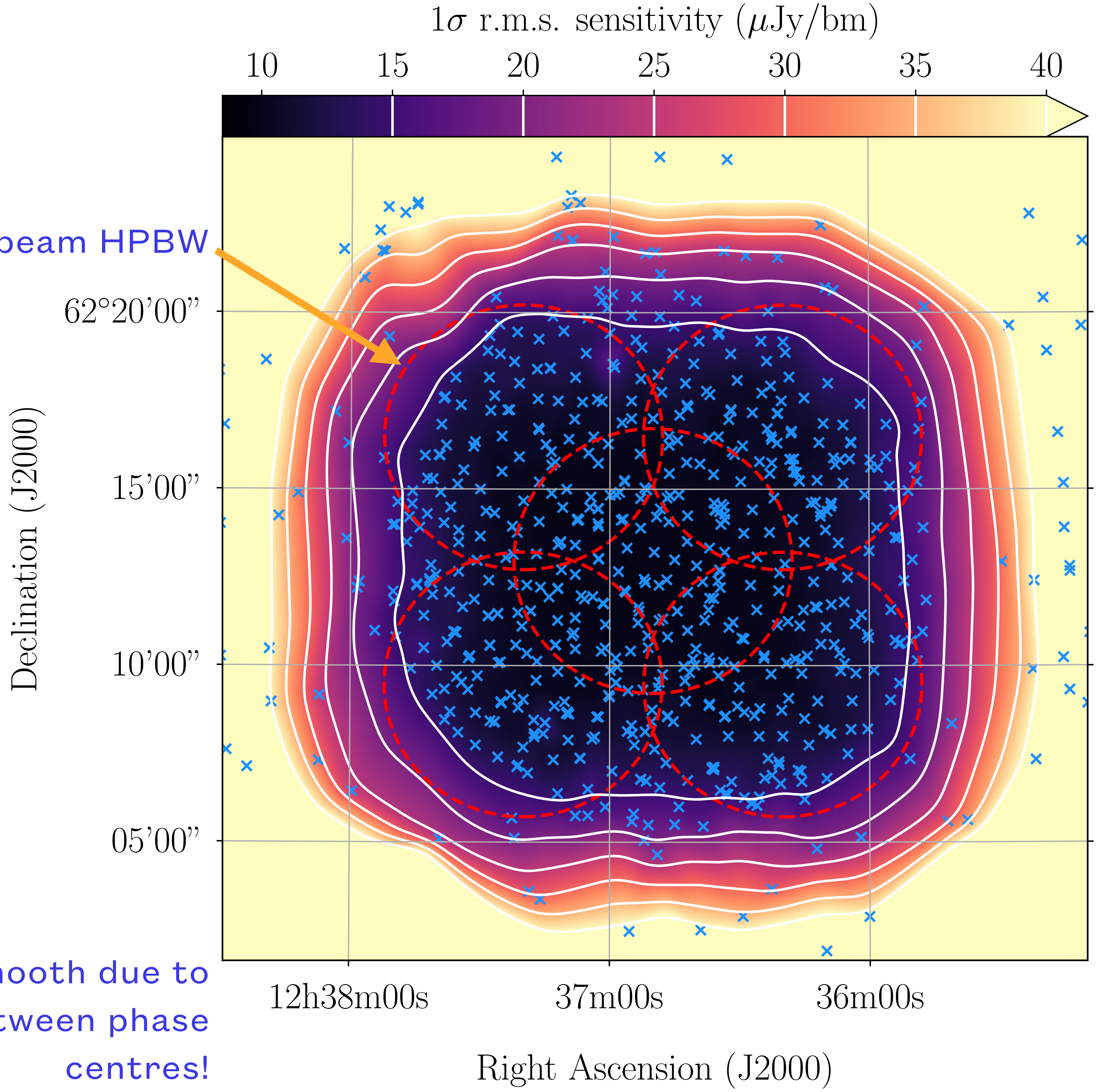
- 12 hour simulated EVN observation (central rms $\sim 4\,\mu\mathrm{Jy\,beam}^{-1}$)



b. 'Differential' / step-wise primary beam correction

- This is the current method used in published wide-field VLBI studies.
- *AIPS*
  - For VLBA - AIPS task CLVLB (Middelberg+13, Herrera-Ruiz+18)
  - For EVN (using Parseltongue) - https://github.com/jradcliffe5/EVN_pbcor (Radcliffe+18) or given by the EVN pipeline output.
- CASA conversions currently being tested.

EVN primary beam correction on real data (Radcliffe+18)



Nb. rms map is smooth due to interpolation between phase centres!

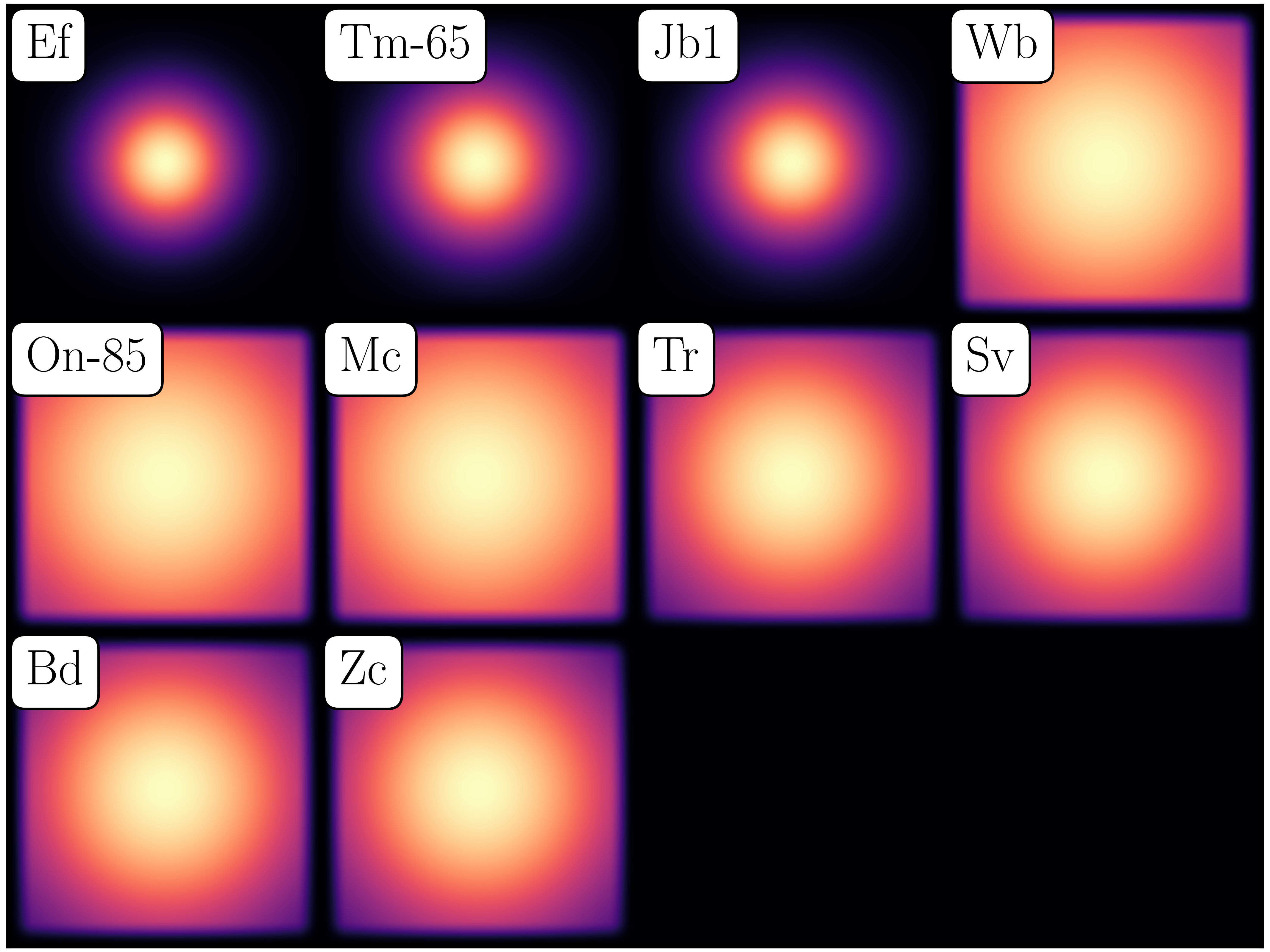
c. a-projection

*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.
- 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 etc.)
  - And other direction-dependent effects (e.g. pointing errors, TEC dispersion etc.)

All these correction schemes implemented / planned in cm-VLBI pipeline (not native to CASA)

a-projection kernels



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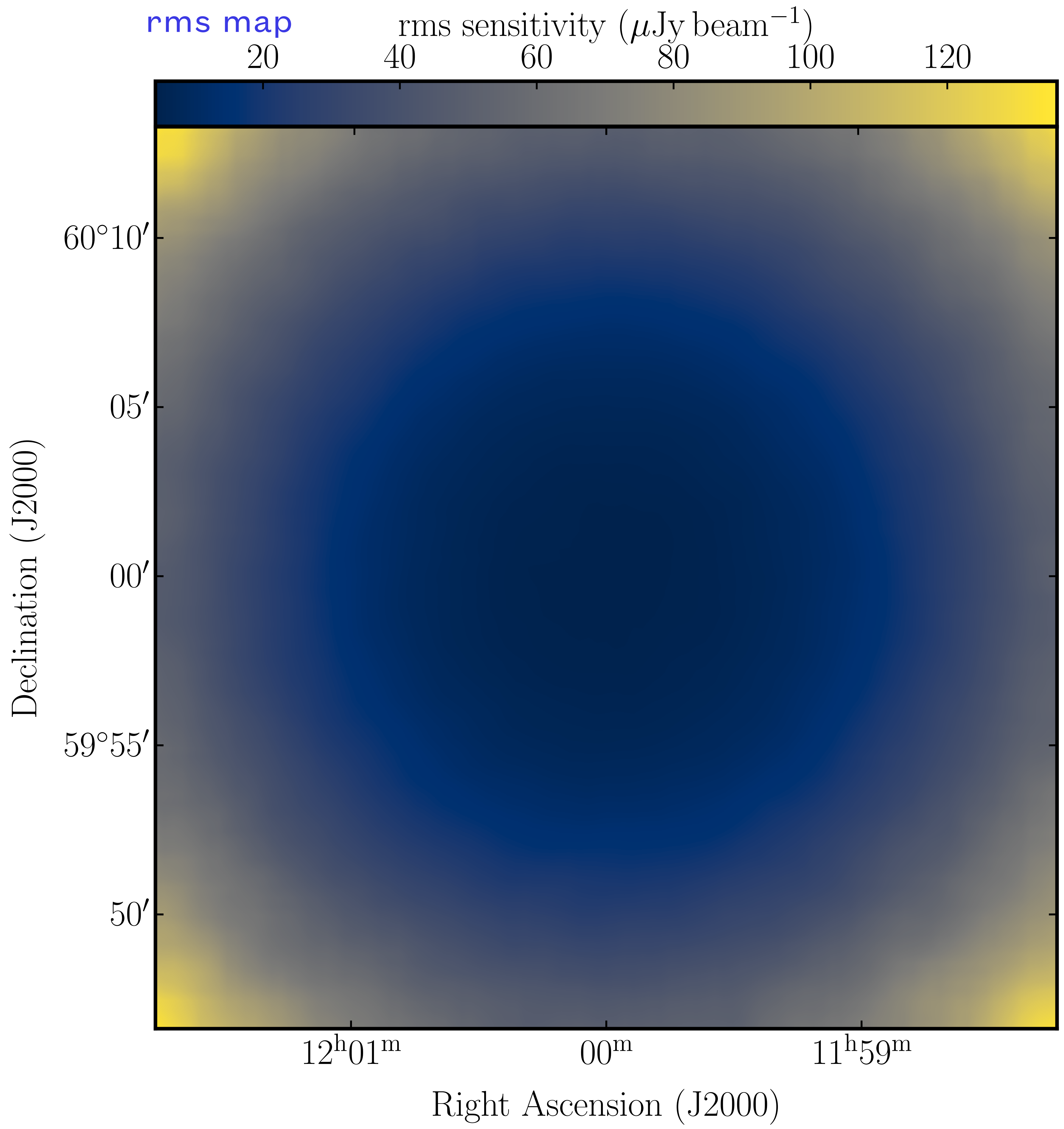
rms map

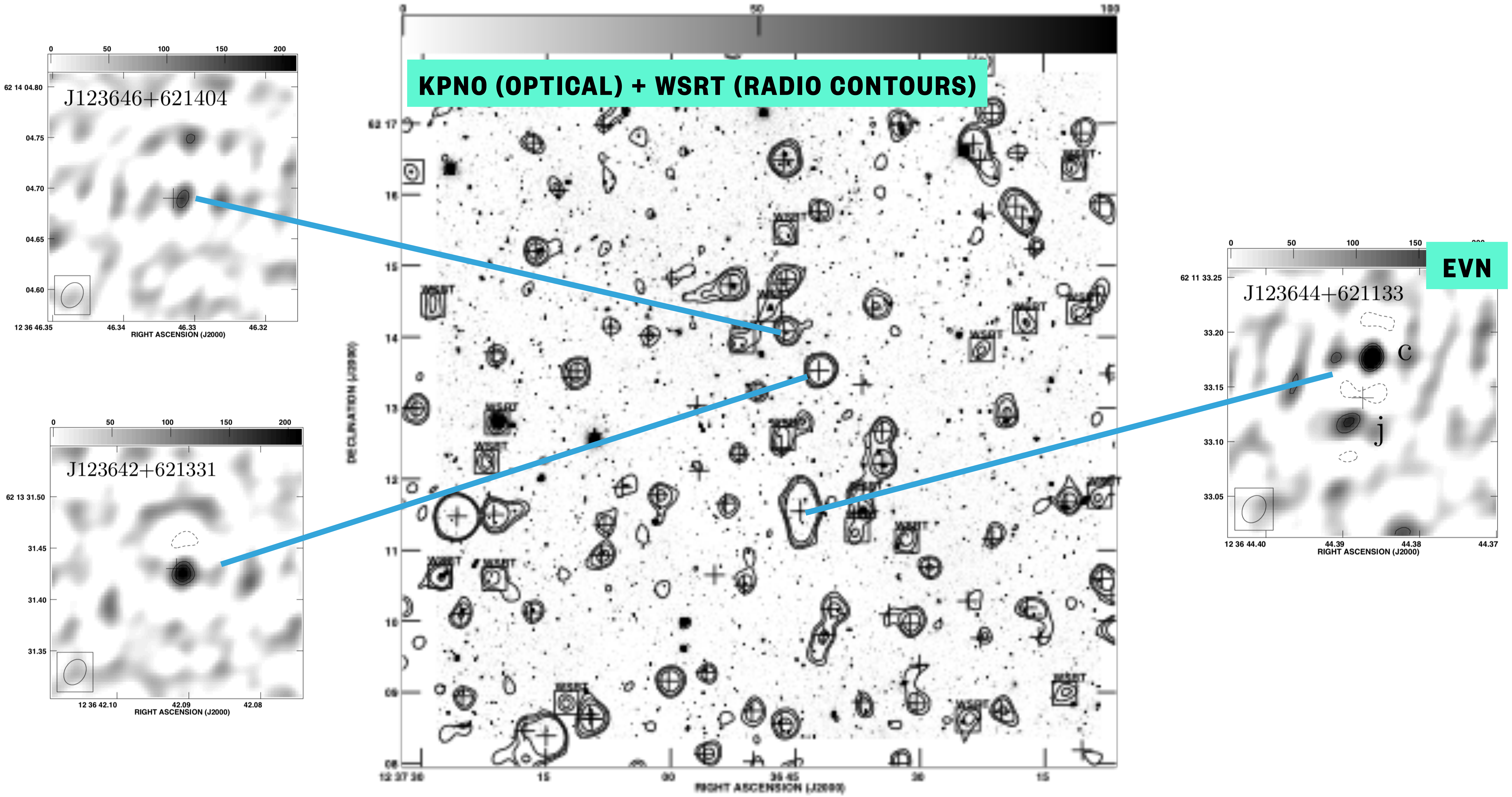


All these correction schemes implemented / planned in cm-VLBI pipeline (not native to CASA)

With these advancements...

We went from this 19 years ago in the GOODS-N field

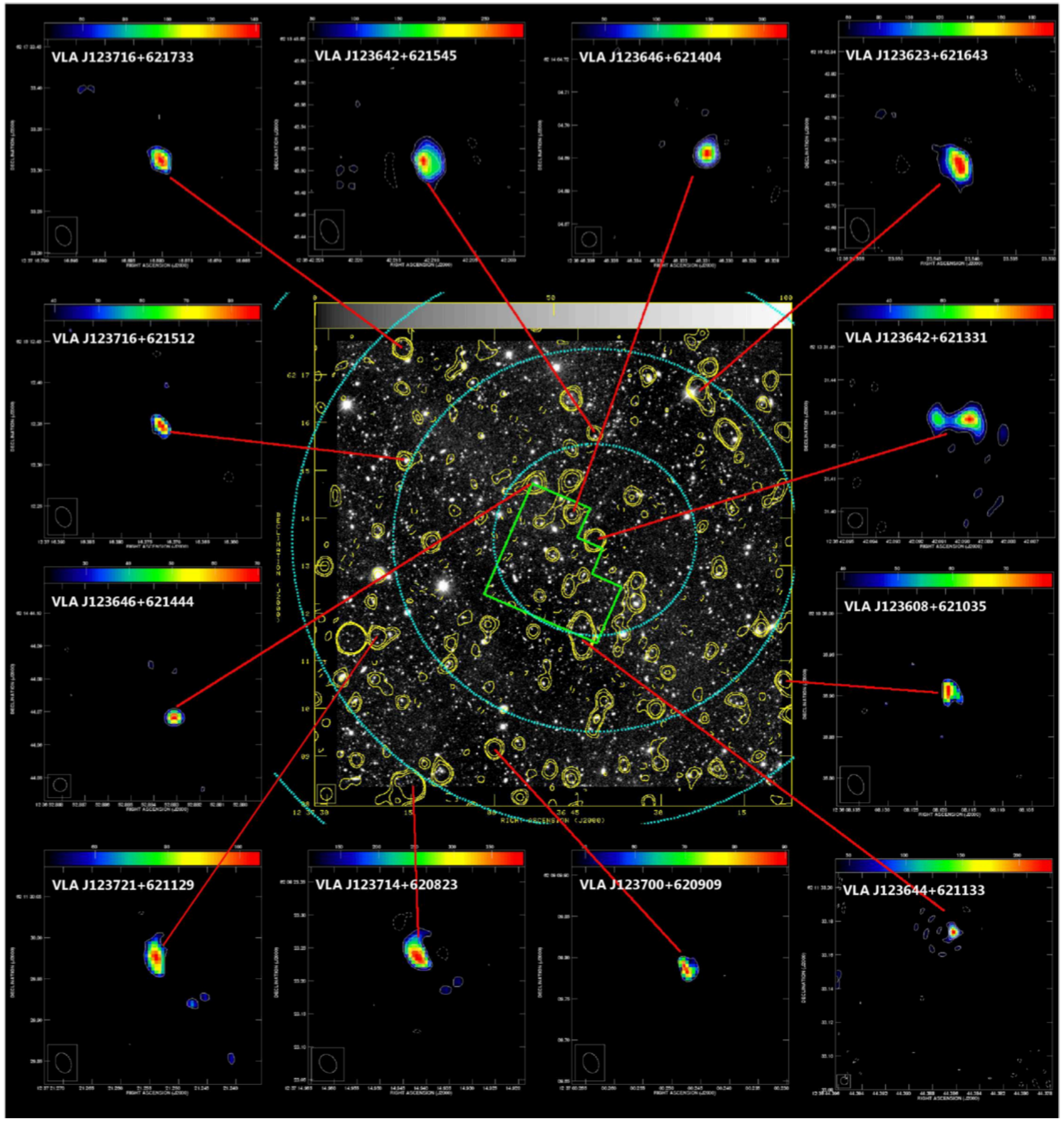
Garrett+00



... to ...

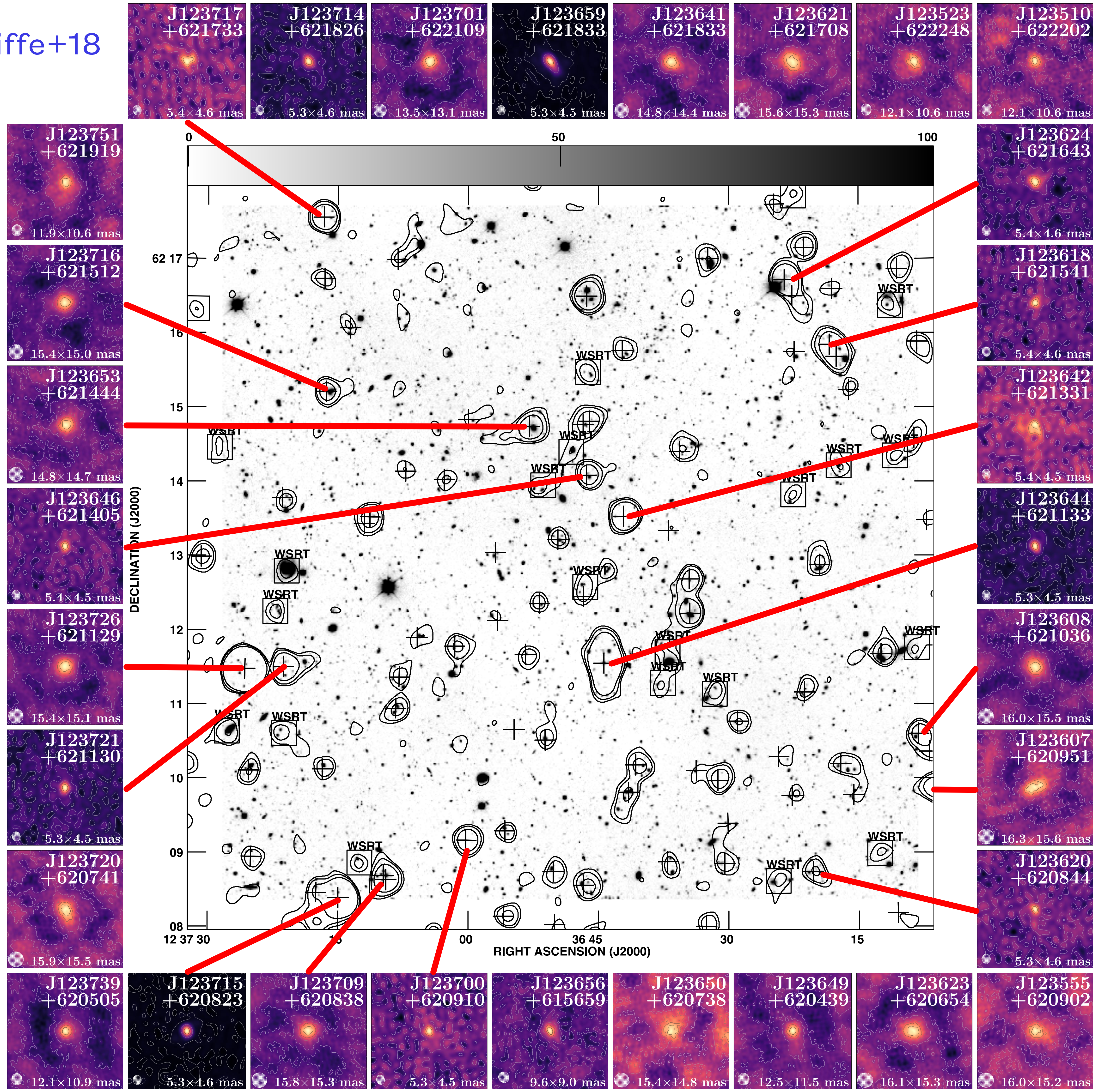
Chi+13

Observed 15 years ago



And finally!

Radcliffe+18



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 applicable to standard VLBI observations e.g. MSSC.
- Final hurdle of primary beam correction of heterogeneous arrays currently being overcome.

THANKS TO OUR SPONSORS:

JUMPING JIVE
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