Error Recognition aka how you know you have done something dumb

Joe Callingham (ASTRON)

Bostwana Radio Astronomy School,
Palapye, Botswana
11th of July 2019

Thanks to Ron Ekers, Emil Lenc and Greg Taylor

DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

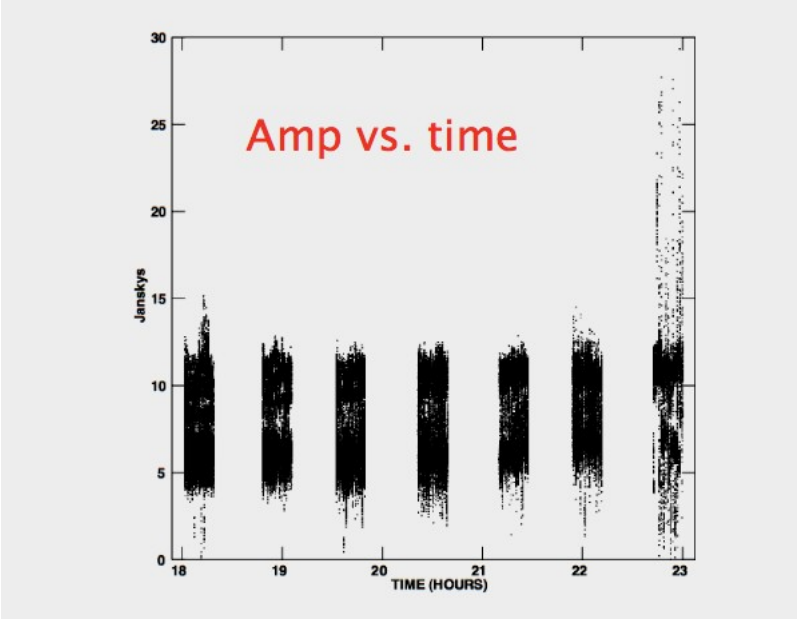
What went wrong?

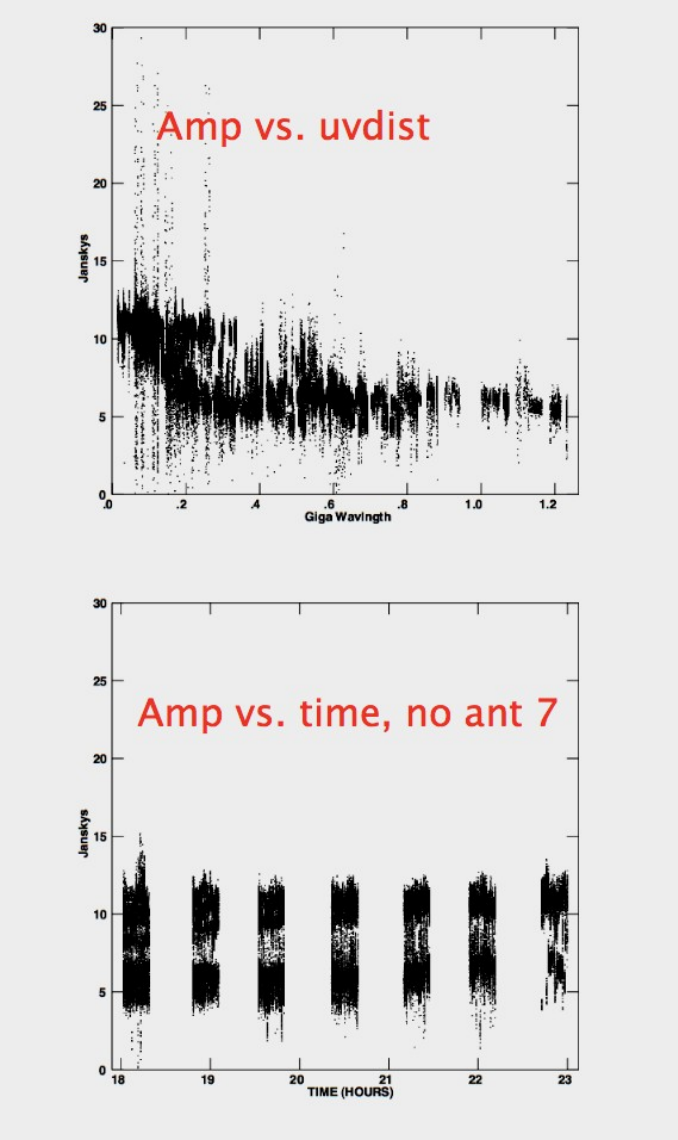
ASTRON

- How do I know I have bad calibration? What is the problem? RFI? Bad phase solution interval? Smearing from averaging?
- How do I know what is making my image bad?
- Note that most errors (besides CLEAN) occur in the aperture plane, not image plane

General Wrongness - calibration

› Wiggles or gradients in phase, gain versus frequency – INSPECT and look for outliers

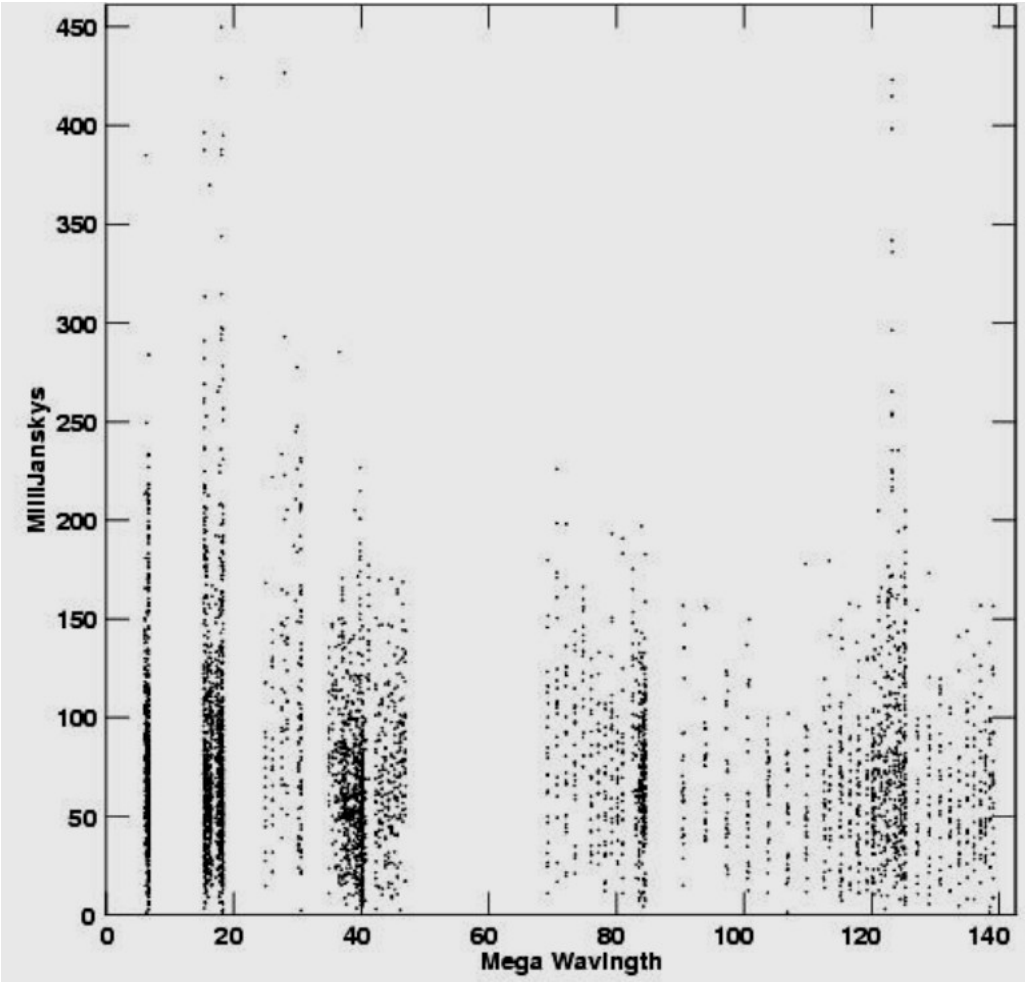




General Wrongness - calibration

ASTRON

› If faint source, hard to identify outliers. All you can do is quack and remove 3 sigma outlier points



What went wrong?

ASTRON

› All calibration problems are in the uv-plane. However, sometimes hard to spot, and only notice in the image plane (says something about the way our brain works).

General Wrongness - image

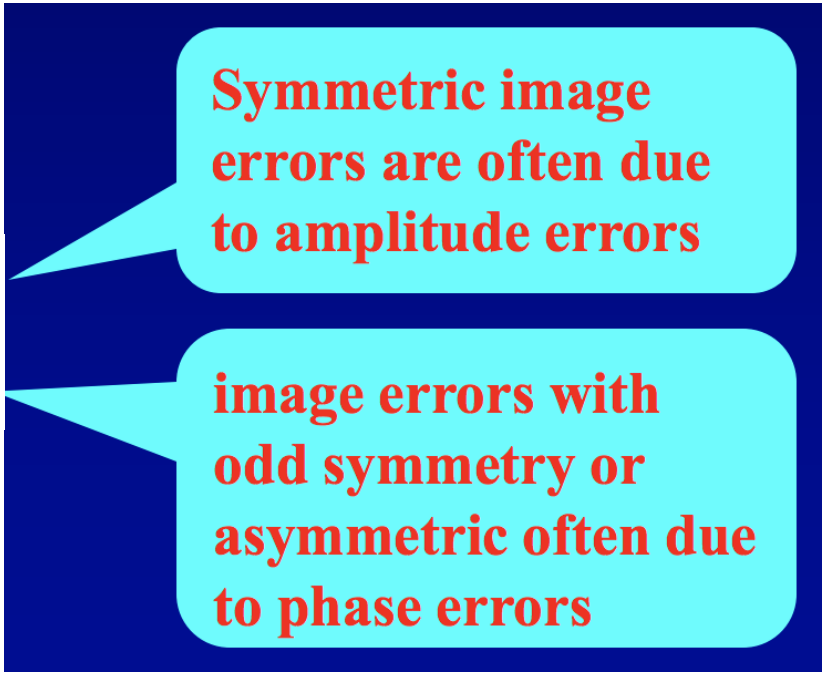
ASTRON

› Look for odd structures – such as streaks, rings

› Symmetric structures are usually a dead giveaway that something is wrong

$$\exp(i\varphi) = \cos\varphi + i\sin\varphi$$

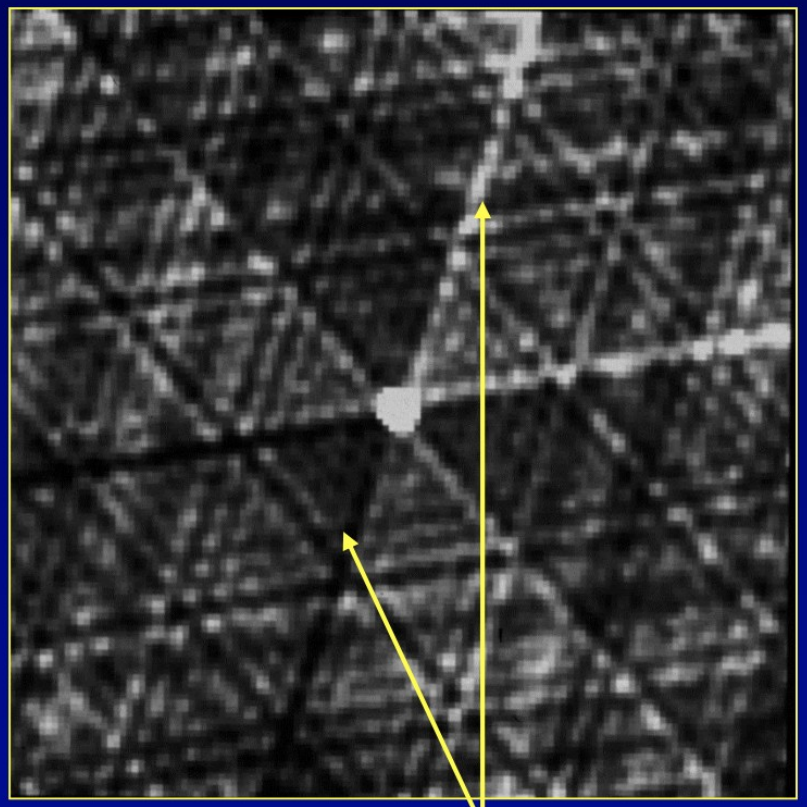
$$\text{Real \& Even} \Leftrightarrow \text{Real \& Even}$$
$$\text{Real \& Odd} \Leftrightarrow \text{Imag \& Odd}$$



Phase and amp error

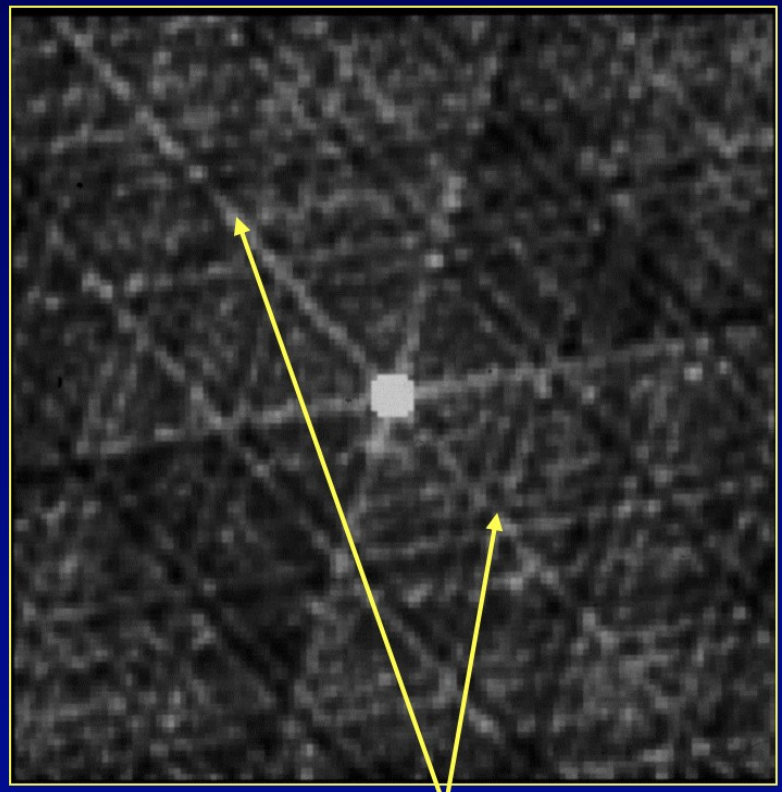
› Can not get rid of beam pattern despite CLEANing deep enough (short burst of bad data – just a bad scan)

10 deg phase error



anti-symmetric ridges

20% amp error



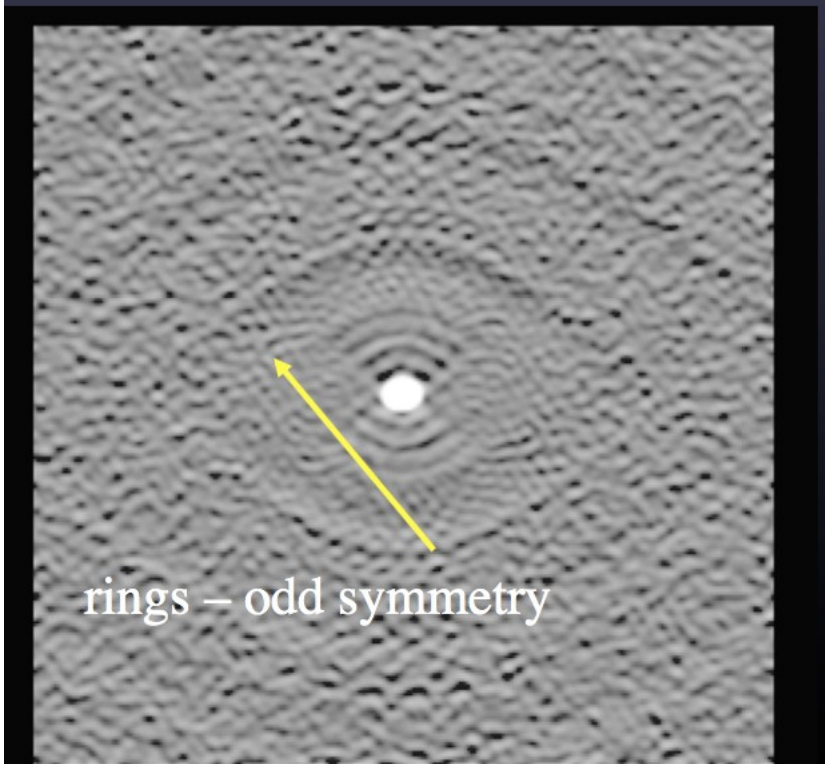
symmetric ridges

Persistent errors over most of observations

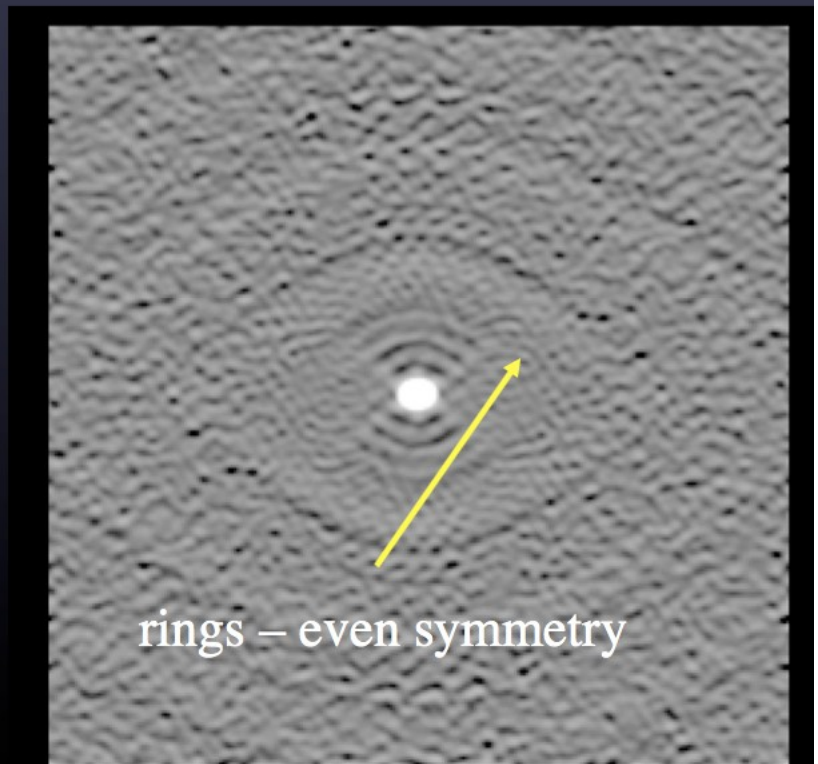
ASTRON

NOTE: 10 deg phase error to 20% amplitude error cause similar sized artifacts

10 deg phase error for one antenna all times
rms 2.0 mJy



20% amp error for one antenna all times
rms 2.3 mJy



CLEANing

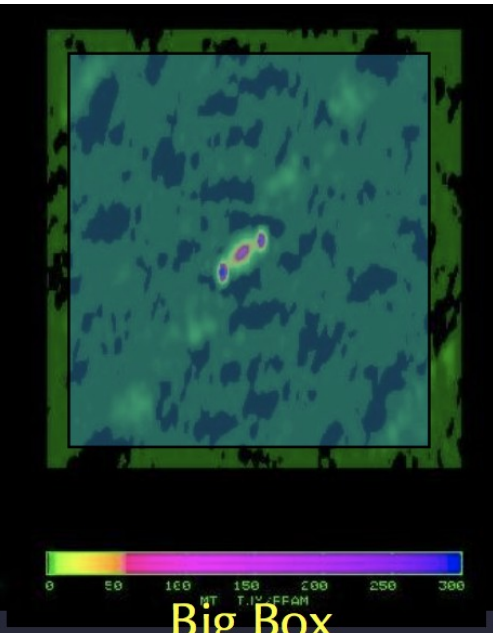
ASTRON

Tight Box

One small clean box

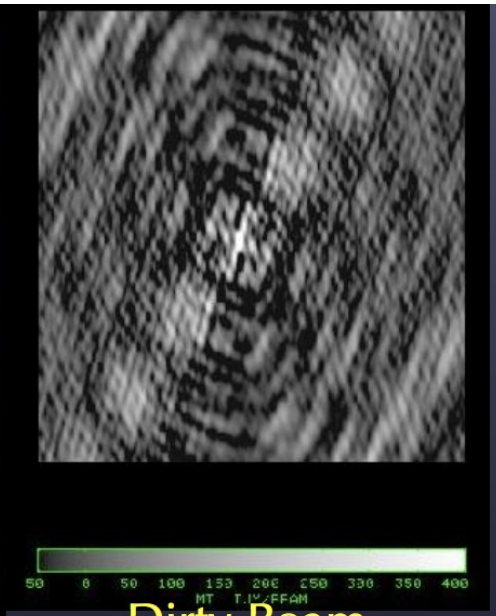
Middle Box

One clean box around all emission



Big Box

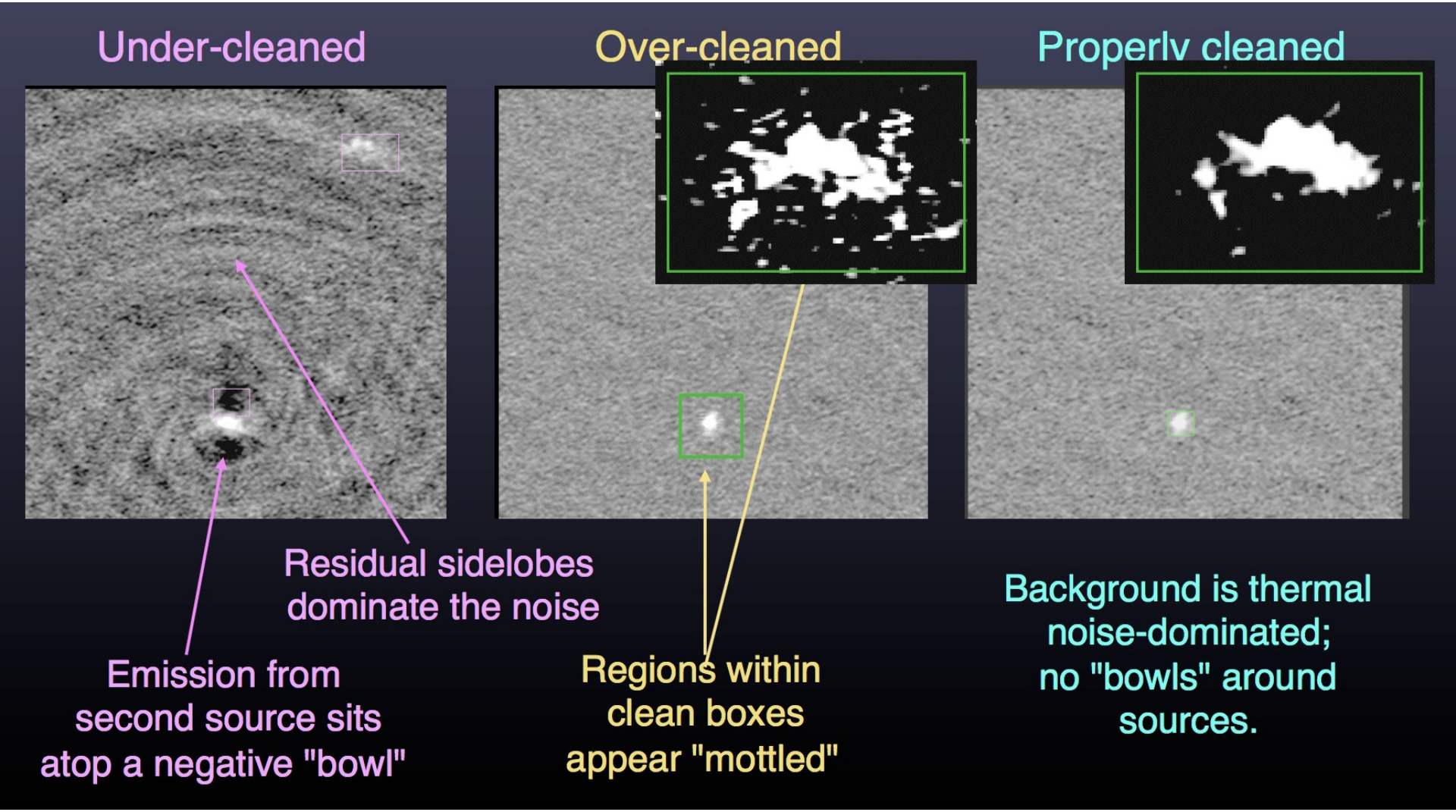
Clean entire inner map quarter



Dirty Beam

Make box as small as possible to avoid cleaning noise interacting with sidelobes

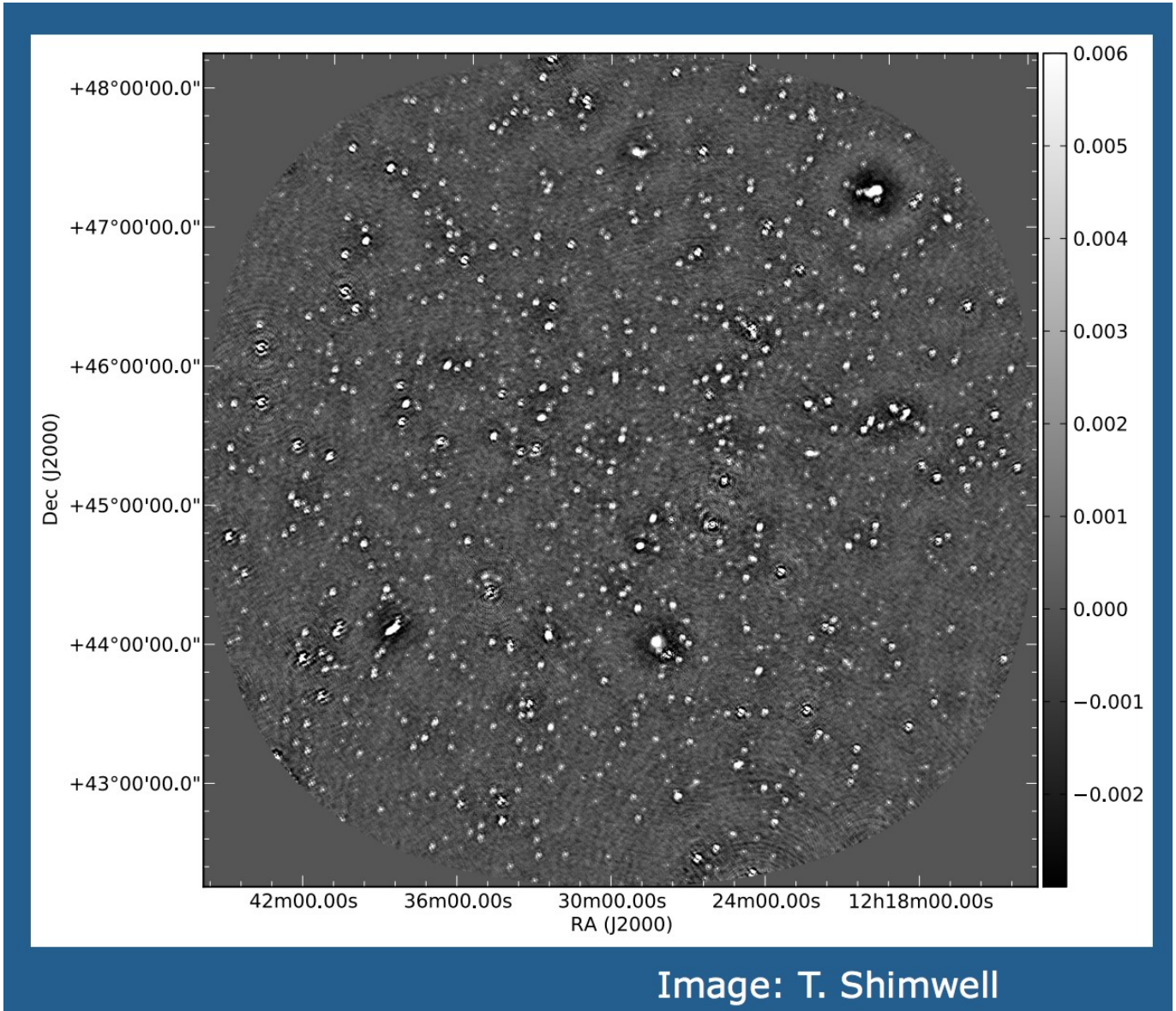
Under/over cleaning



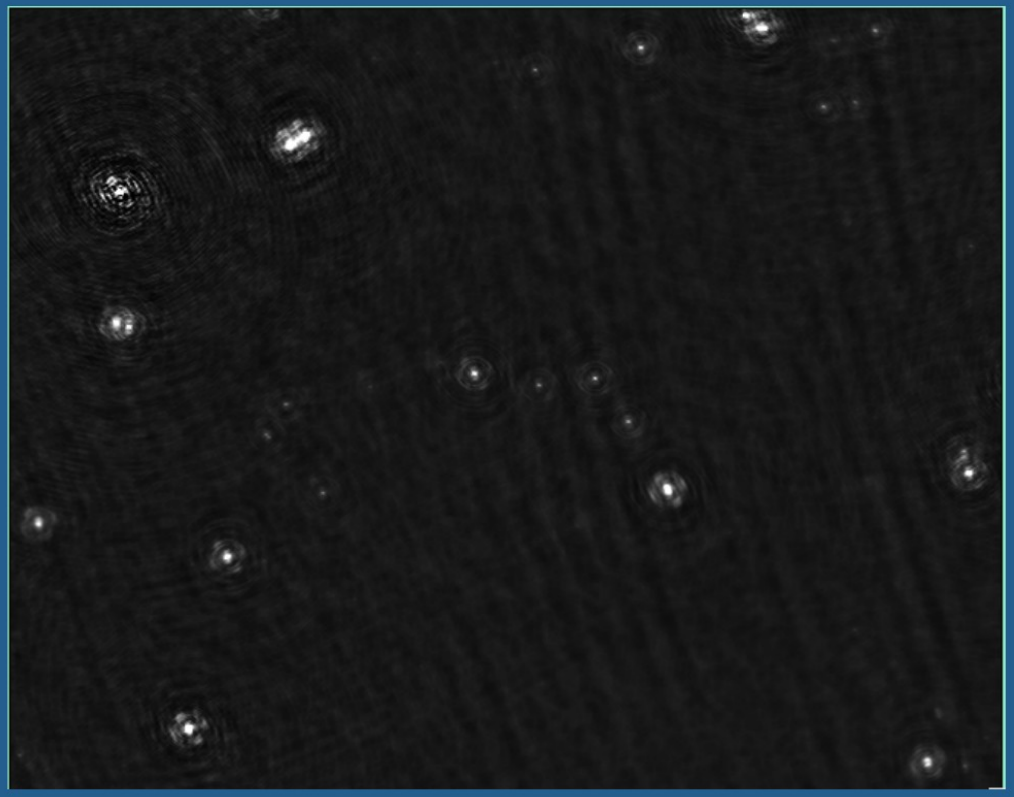
CLEANing

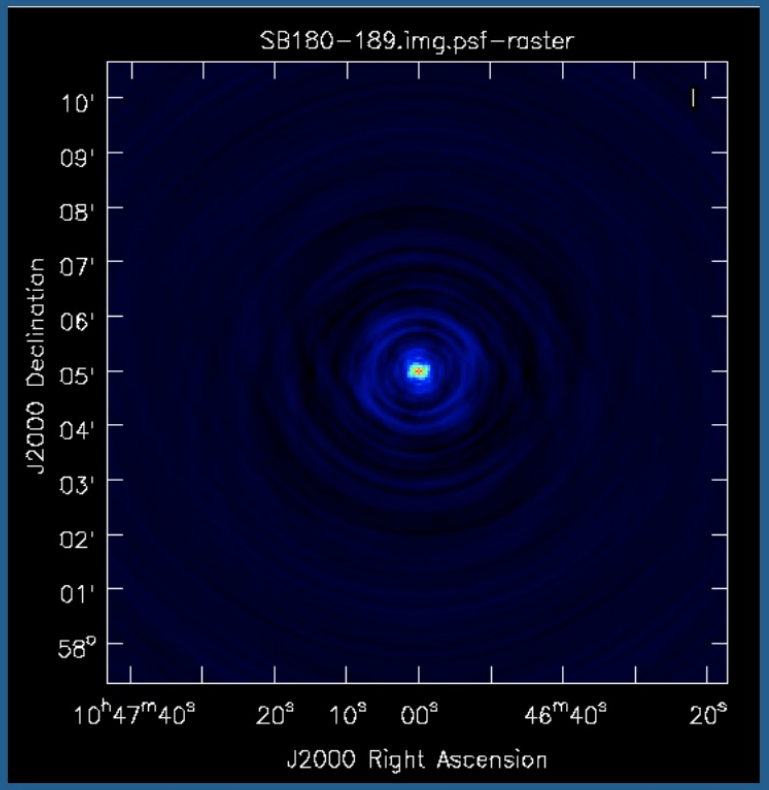
ASTRON

› Negative bowls from undercleaning



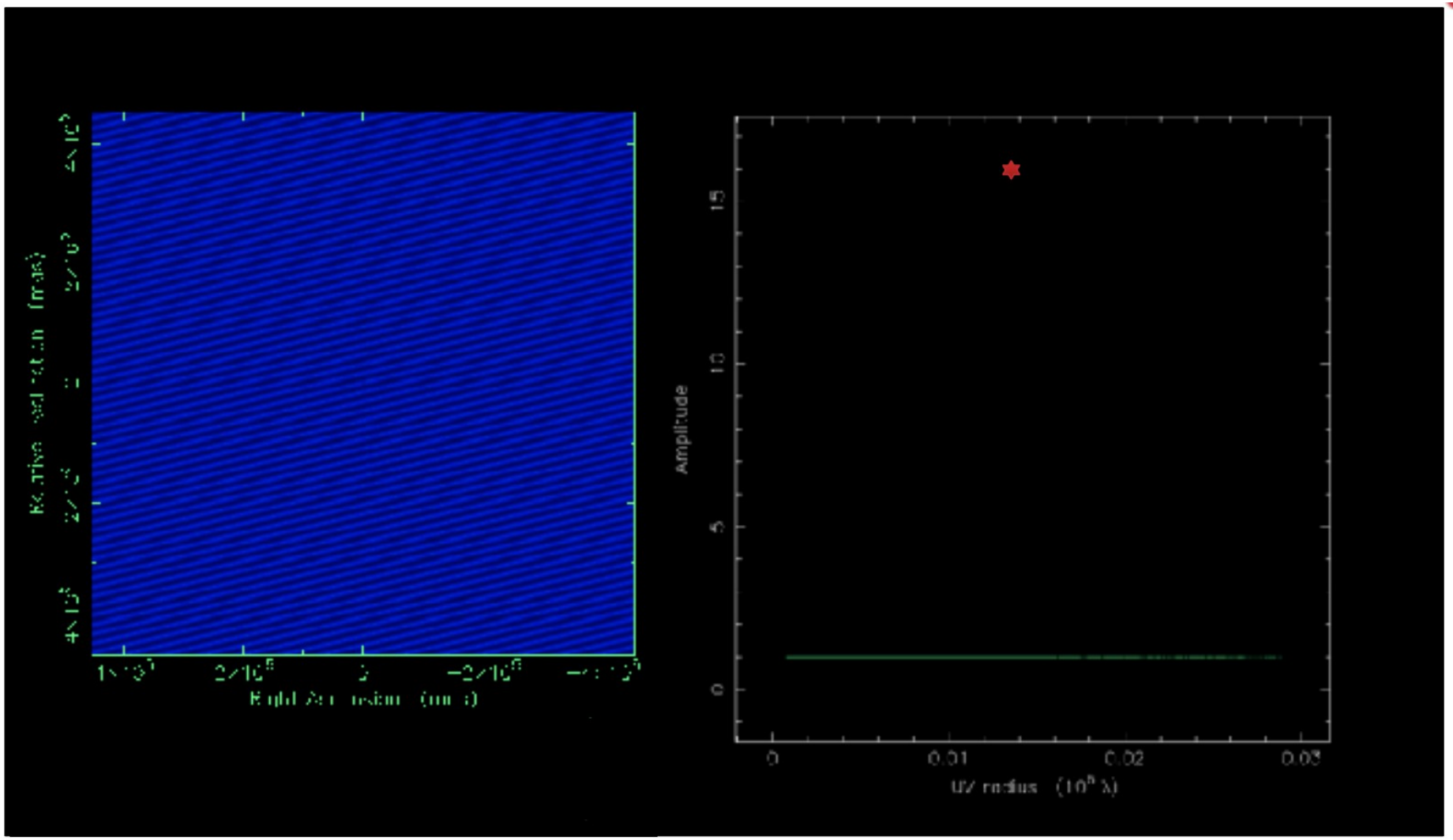
CLEANing





› If artefacts look similar to the psf, you have undercleaned.

RFI



General Rule of Thumb

ASTRON

- 5 sigma to believe structure and you should reach 3 to 5 times the theoretical predicted noise level

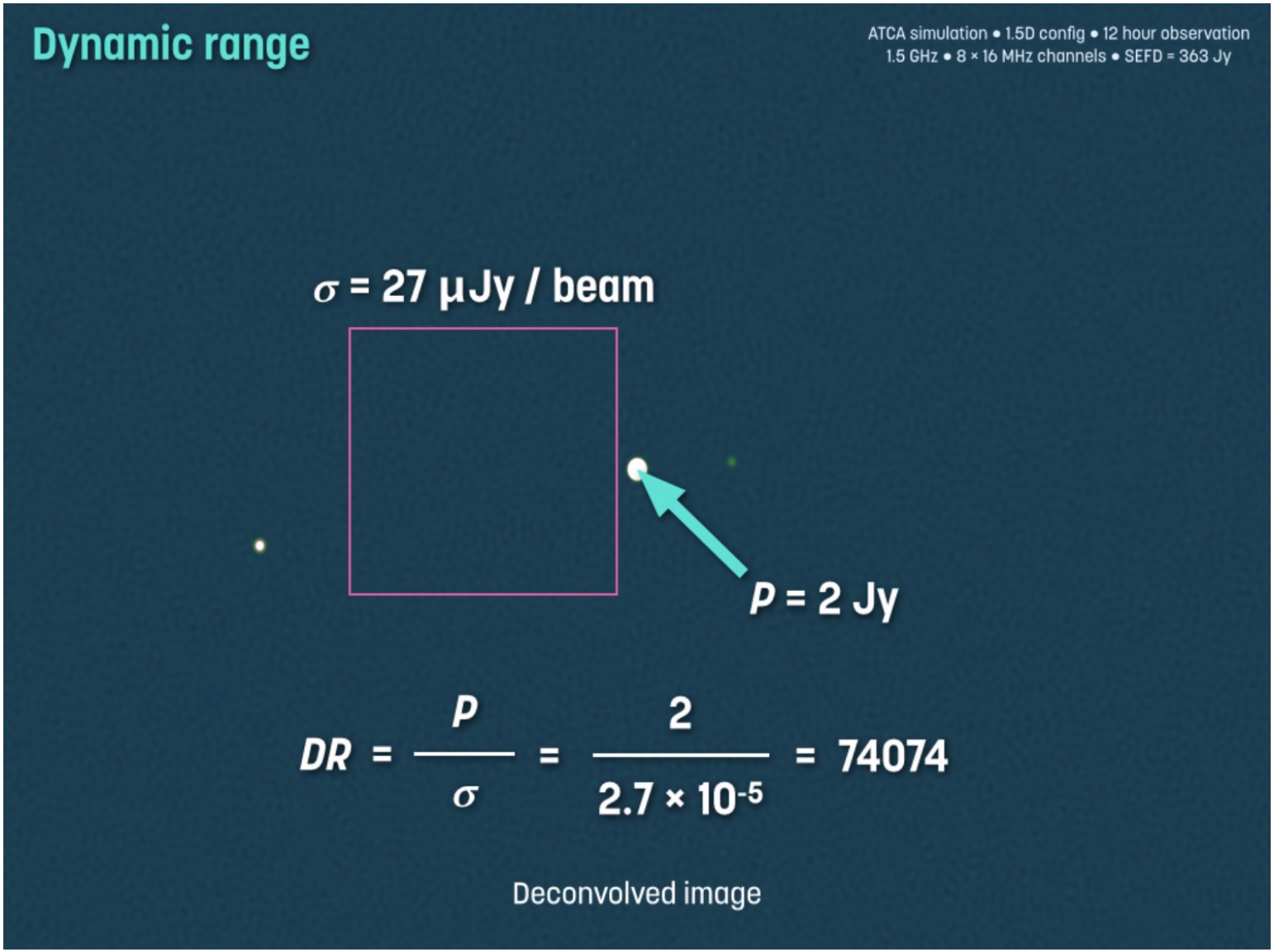
$$S_{rms} = \frac{2kT_{sys}}{A_{eff}\sqrt{N_A(N_A-1)t_{\mathrm{int}}\Delta v}}$$

- Error artefacts can be additive or multiplicative

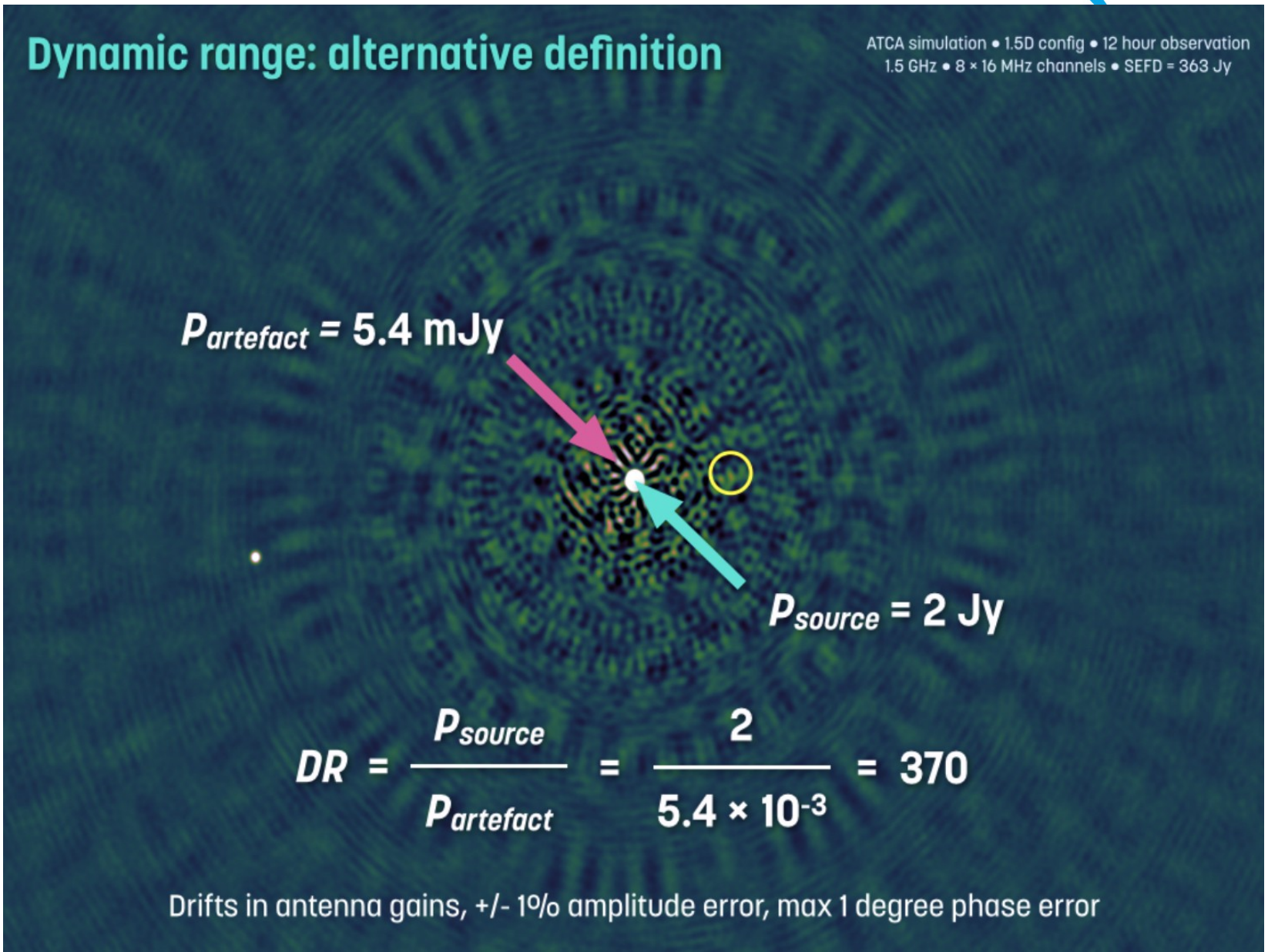
- So you can only improve on this by:
  - Bigger/more efficient antennas (Aeff , hA) or more (N)
  - Lower noise Rx and/or Tsky (observing conditions)
  - Observe for longer/wider bandwidth

Dynamic Range

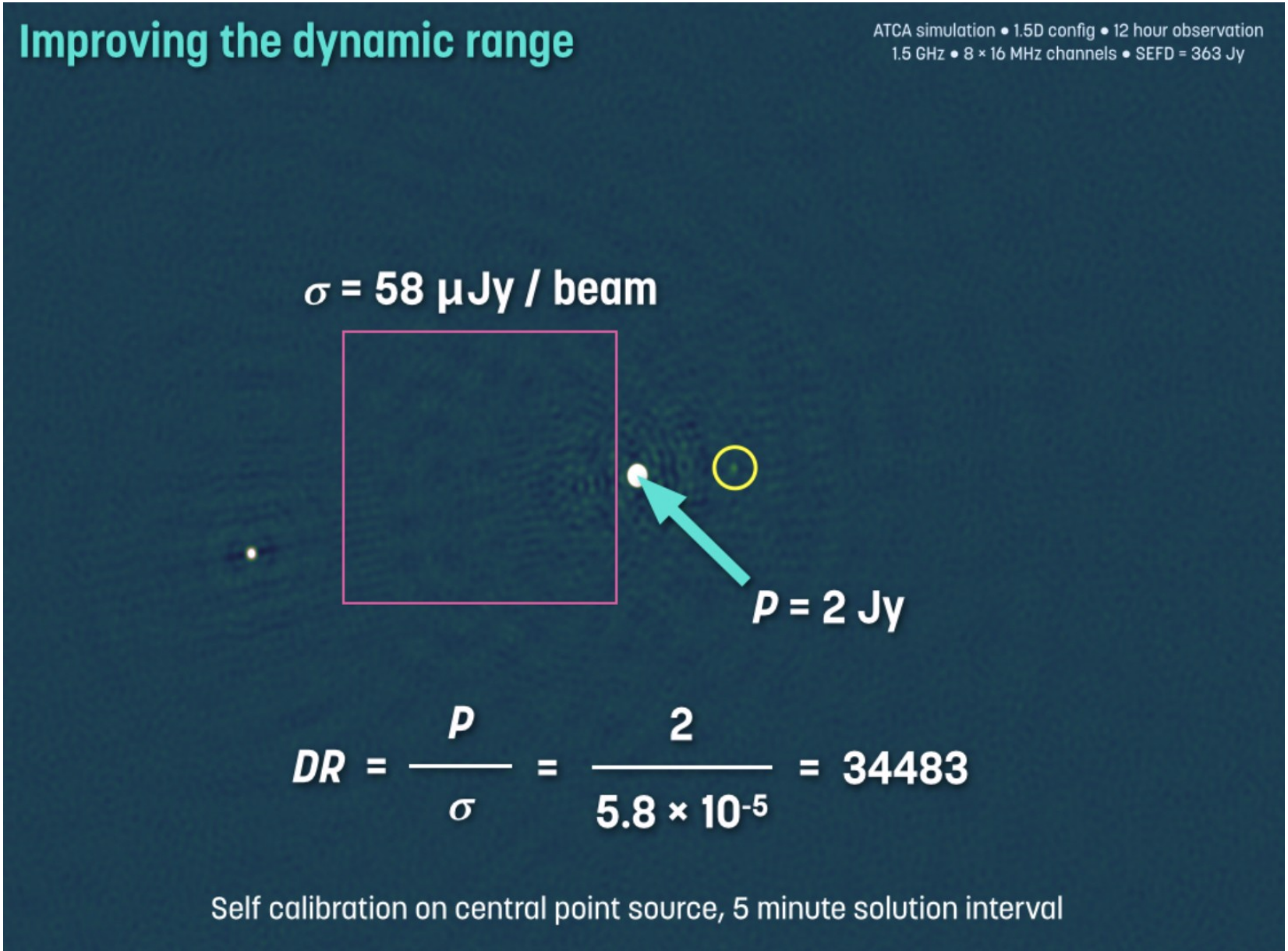
› What is dynamic range and what counts as high?



Dynamic Range



Self-Cal and dynamic range



Additive or multiplicative

ASTRON

- some errors add to visibilities

$$V + \epsilon \quad \Leftrightarrow \quad I + \mathcal{F}\epsilon$$

- others *multiply* or *convolve* visibilities
  - multiplication ⇔ convolution in conjugate planes

$$V\epsilon \quad \Leftrightarrow \quad I * \mathcal{F}\epsilon$$

  - convolution ⇔ multiplication in conjugate planes

$$V * \epsilon \quad \Leftrightarrow \quad I\,\mathcal{F}\epsilon$$

Additive

ASTRON

$$V + \epsilon \Leftrightarrow I + \mathcal{F}\epsilon$$

- adds to visibilities ⇔ adds to image
  - unconnected to real sources in the image
  - may make “fake” sources
- sources of additive errors:
  - noise
  - Interference (RFI, cross talk)
  - Sources outside beam (confusion, sun)
  - DC offsets

Multiplicative

ASTRON

$$V\epsilon \Leftrightarrow I * \mathcal{F}\epsilon \qquad V * \epsilon \Leftrightarrow I\mathcal{F}\epsilon$$

- others *multiply* or *convolve* visibilities
  - multiplication ⇔ convolution in conjugate planes
    - » examples - multiplicitive: sampling, gain errors, atmosphere, missing spacings
    - » Examples - convolution: primary beam, gridding

Phase Errors and Dynamic Range

ASTRON

Image is formed by Fourier transform

- $I(x) = \int V(u)\, \mathrm{e}^{i2\pi ux}\, \mathrm{d}u$
  - Each baseline contributes at position u_k and complex conjugate -u_k in the visibility plane

Evaluating the term in the integral for each of the $[N(N\text{-}1)/2]\text{-}1$ good baselines gives $2\cos(2\pi u_k x)$

Bad baseline gives $2\cos(2\pi u_0 x - \phi_\varepsilon)$

- $\sim 2[\cos(2\pi u_0 x) + \phi_\varepsilon \sin(2\pi u_0 x)]$ for small ϕ_ε (in radians)

- The image integral thus sums to

$$I(x) = 2\varphi_\epsilon \sin(2\pi u_0 x) + 2 \sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k x)$$

Phase Errors and Dynamic Range

ASTRON

- The synthesised beam is given by

$$B(x)=2\sum_{k=1}^{N(N-1)/2}\cos(2\pi u_k x) \quad = N(N\text{-}1) \text{ for } u = 0$$

- Deconvolution is the subtraction of the beam from the image leaving the residual error

$$R(x)=\left[2\varphi_\epsilon \sin(2\pi u_0 x)+2\sum_{k=1}^{N(N-1)/2}\cos(2\pi u_k x)\right]-2\sum_{k=1}^{N(N-1)/2}\cos(2\pi u_k x)$$
$$=2\varphi_\epsilon \sin(2\pi u_0 x)$$

  - an 'odd' sinusoidal function of amplitude $2\phi_\epsilon$, period $1/u_0$

Calibration errors and dynamic range

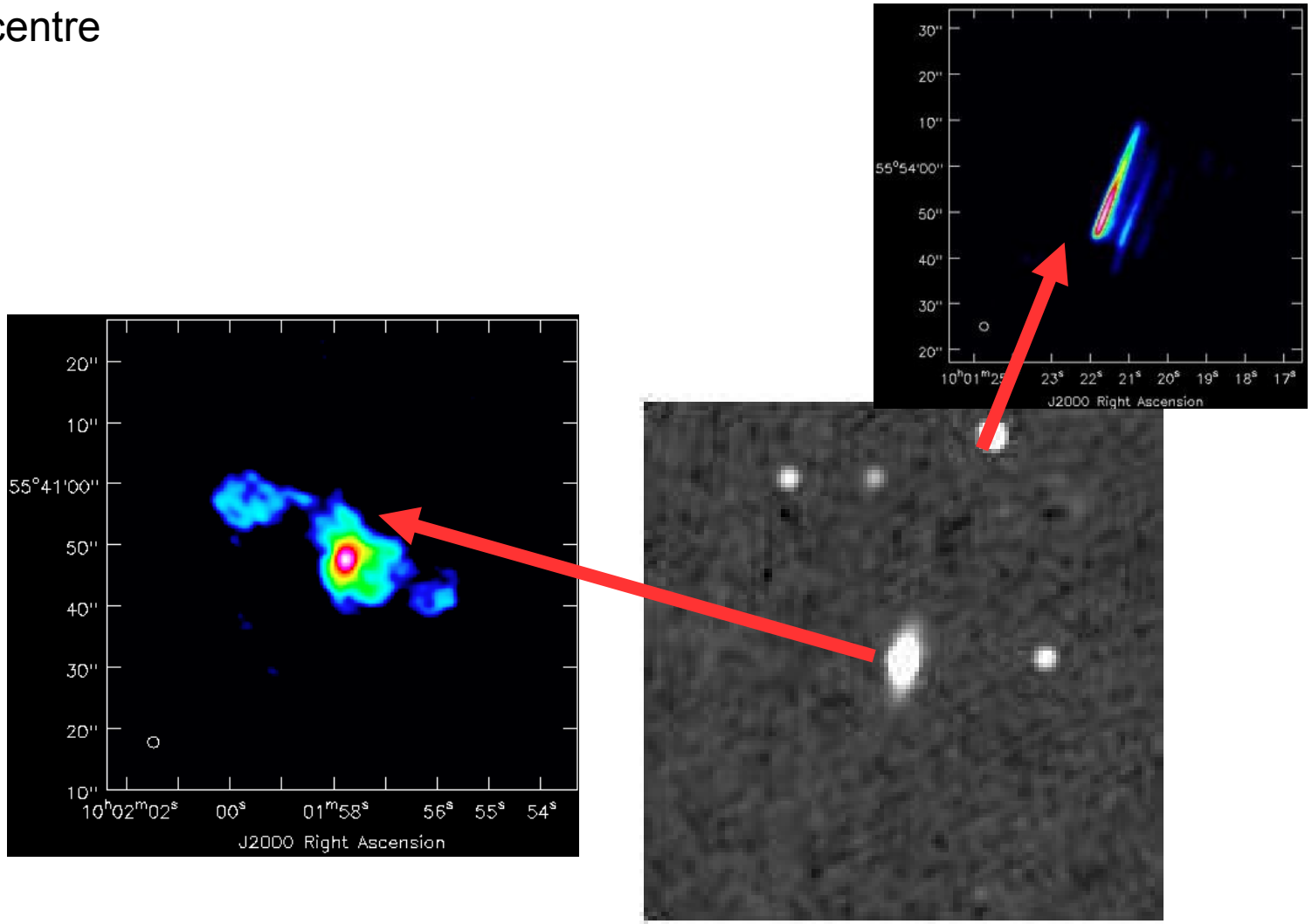
ASTRON

- For small phase error ϕ_ε, large N, the ratio of the peak / noise residual is thus
  - Dynamic range $D_B(\phi_\varepsilon) \sim I(x) / R(x) \sim N^2 / \sqrt{2}\,\phi_\varepsilon$
    - e.g., radians (5°)~0.09
- Amplitude error ε on a single baseline has the effect

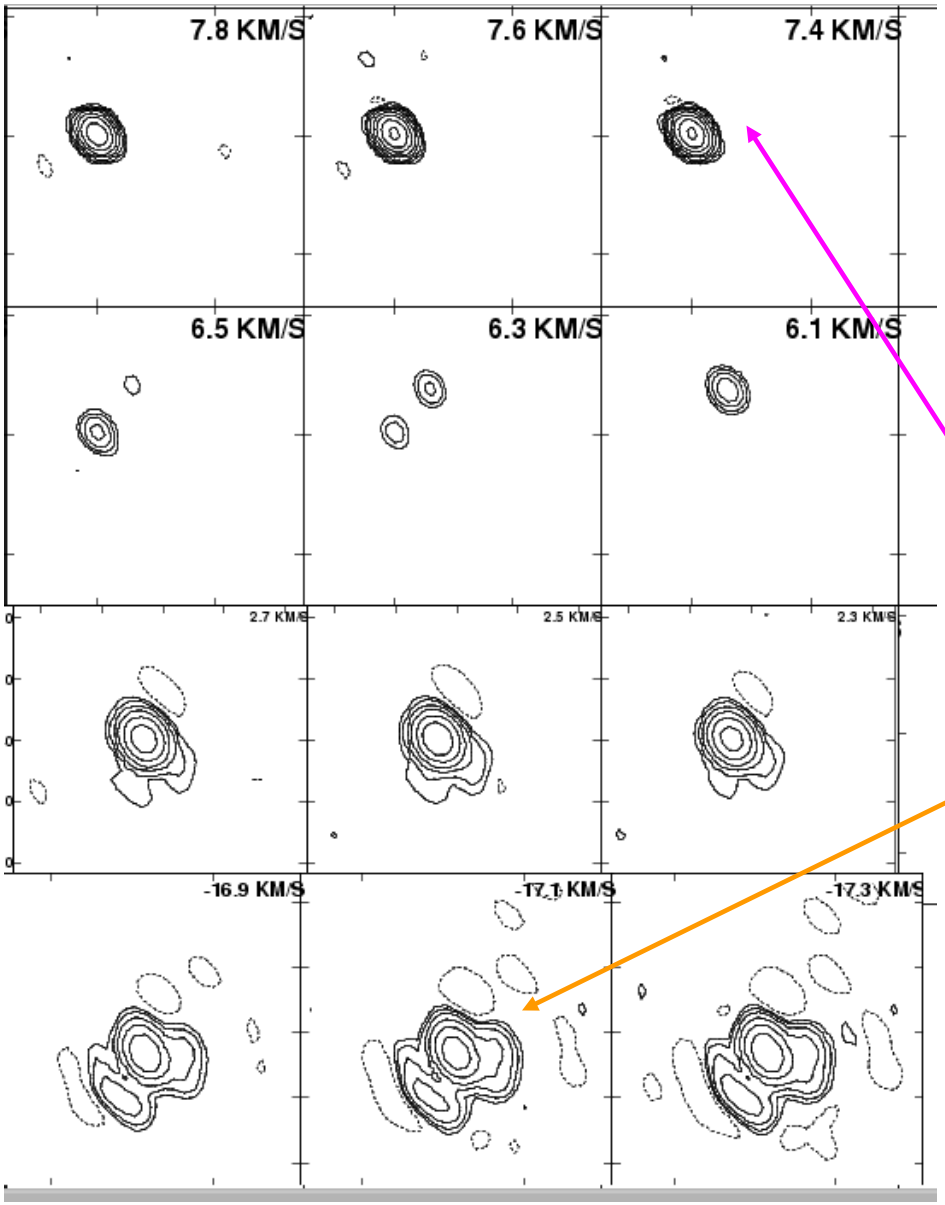
  $V(u) = (1+\varepsilon)\delta(u - u_0)\, e^{-i\phi}$ leading (via a cos function) to
  - Dynamic range $D_B(\varepsilon) \sim N^2 / \sqrt{2}\,\varepsilon$
- **A phase error of 5° is as bad as a 10% amp error**
- **Phase errors are sin (odd), amp are cos (even)**

Smearing

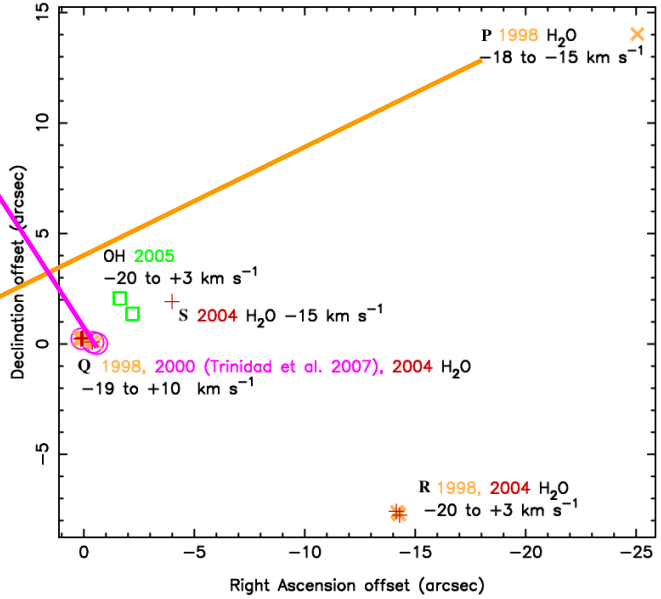
› If you average in time or bandwidth too much, sources away from your pointing centre will be smeared, with it worse the more you average or further from the pointing centre



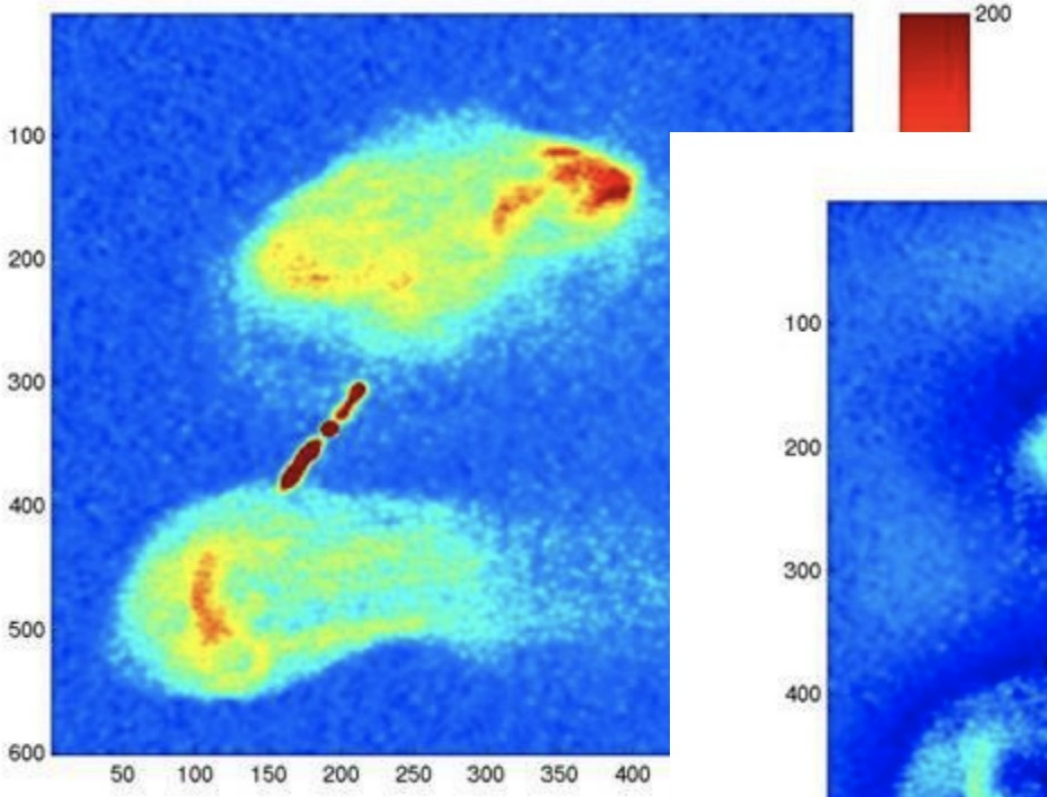
Time Smearing



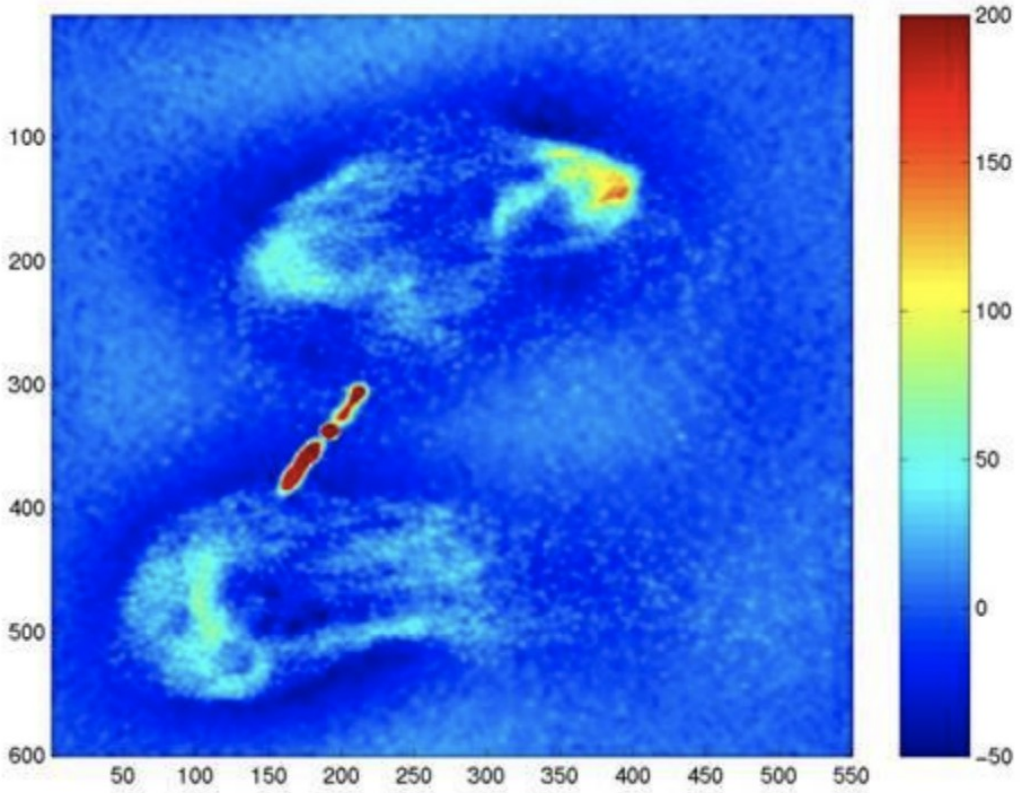
› Tangential



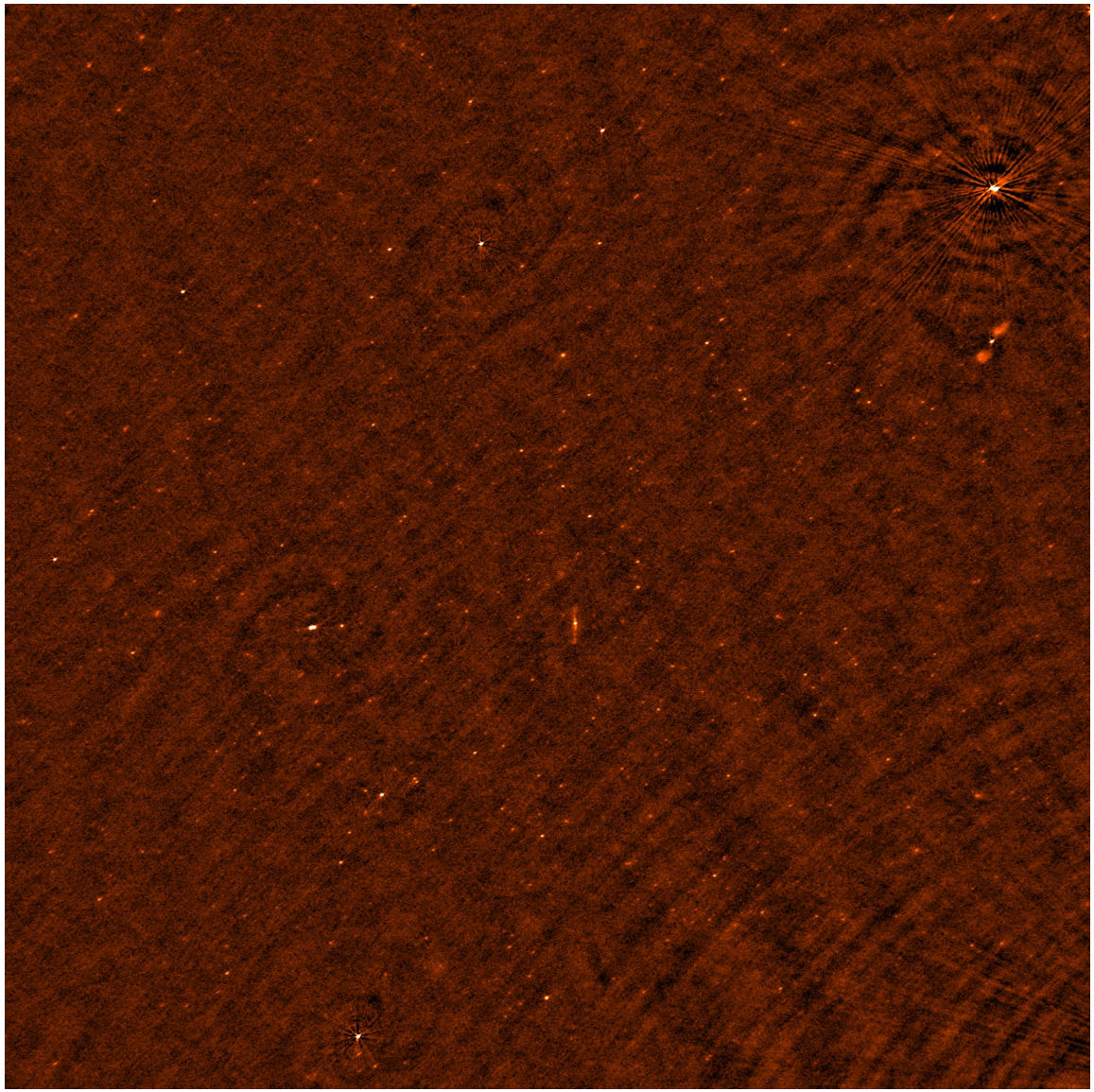
Missing short baselines



No short baselines →



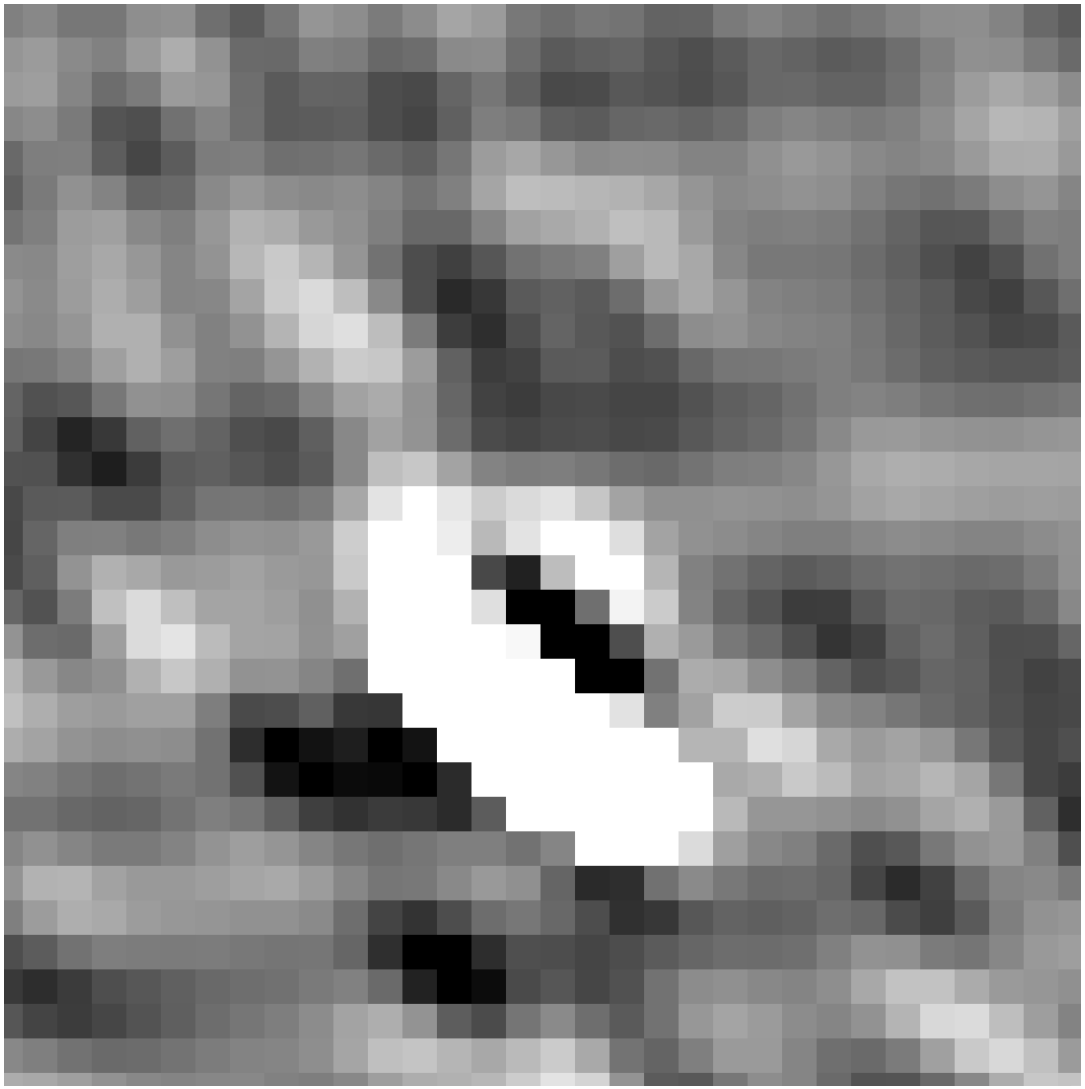
Bright source in sidelobe



Example of sleuthing

ASTRON

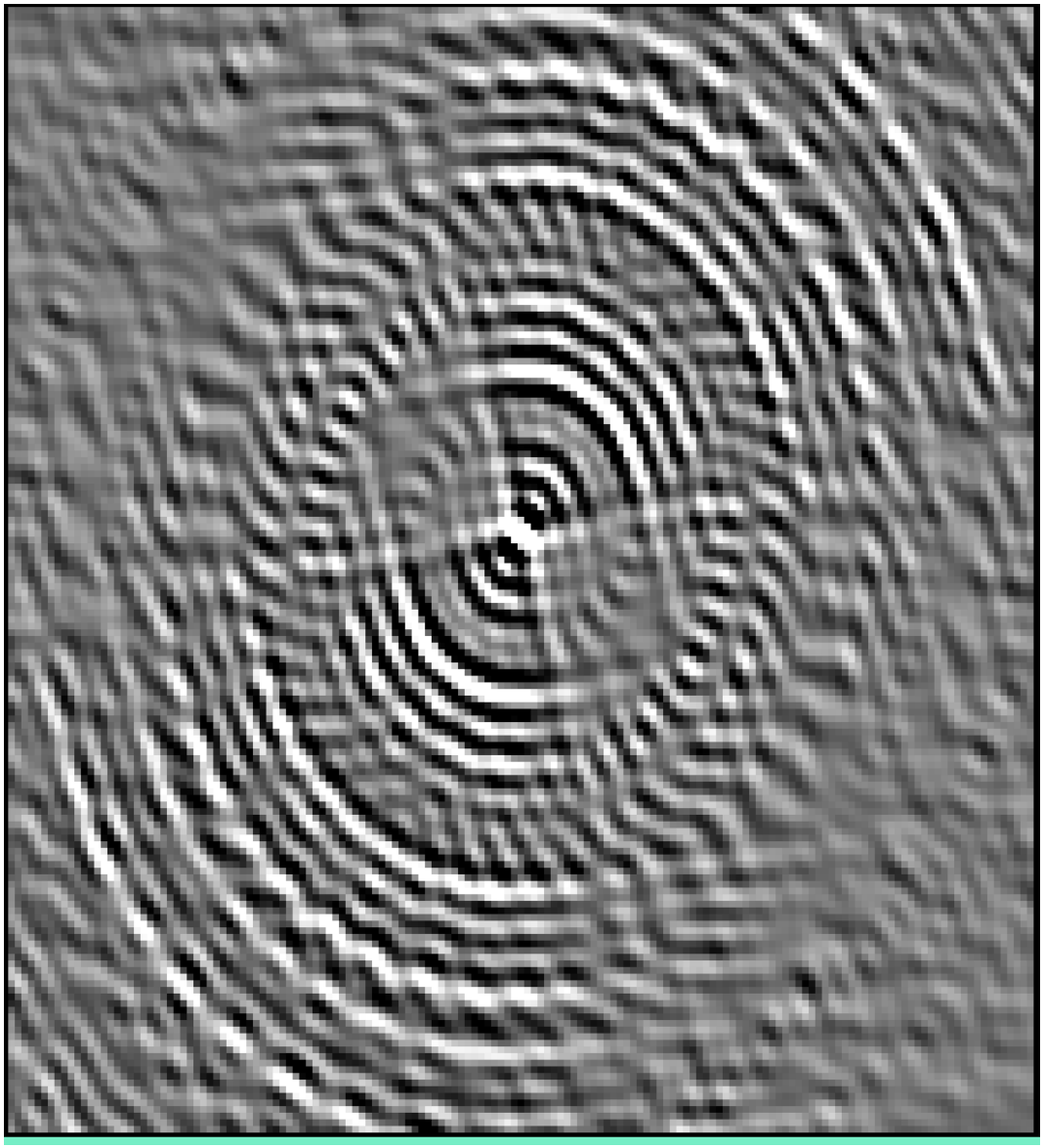
› Source that could be being resolved but weird shape and negative feature:



Example of sleuthing

ASTRON

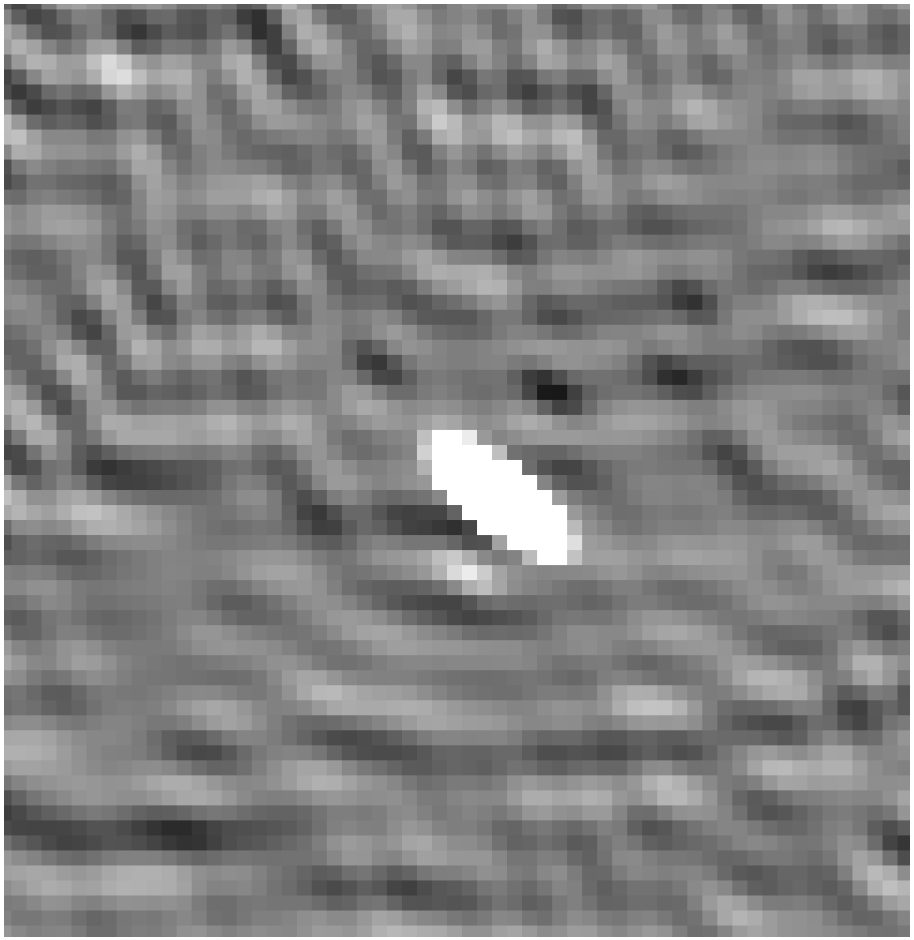
› Beam



Example of sleuthing

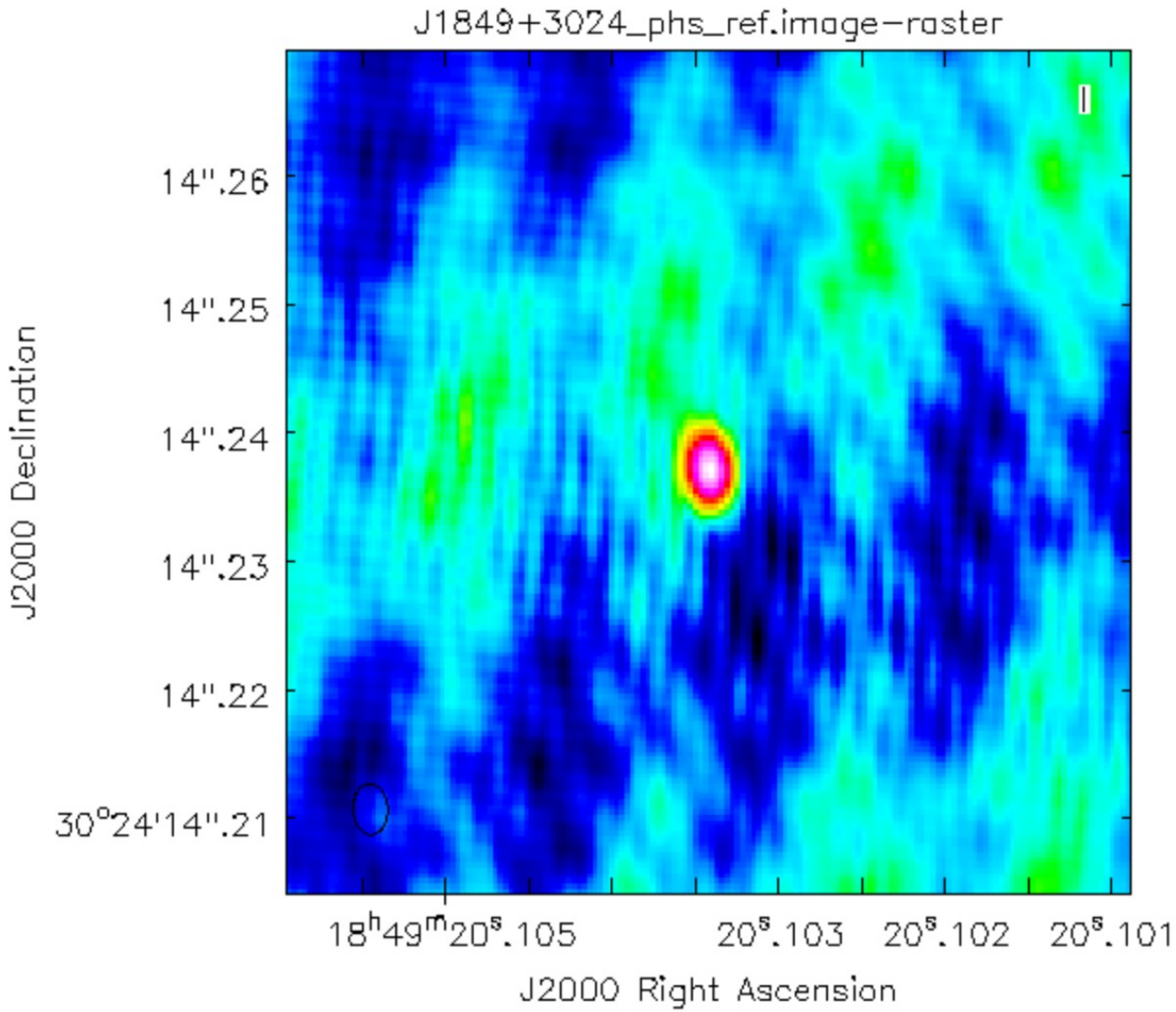
ASTRON

- Worried could be overcleaning, clean box too large, or phase error.
- Doing one iteration of phase self-cal, source disappears and main source straightens up

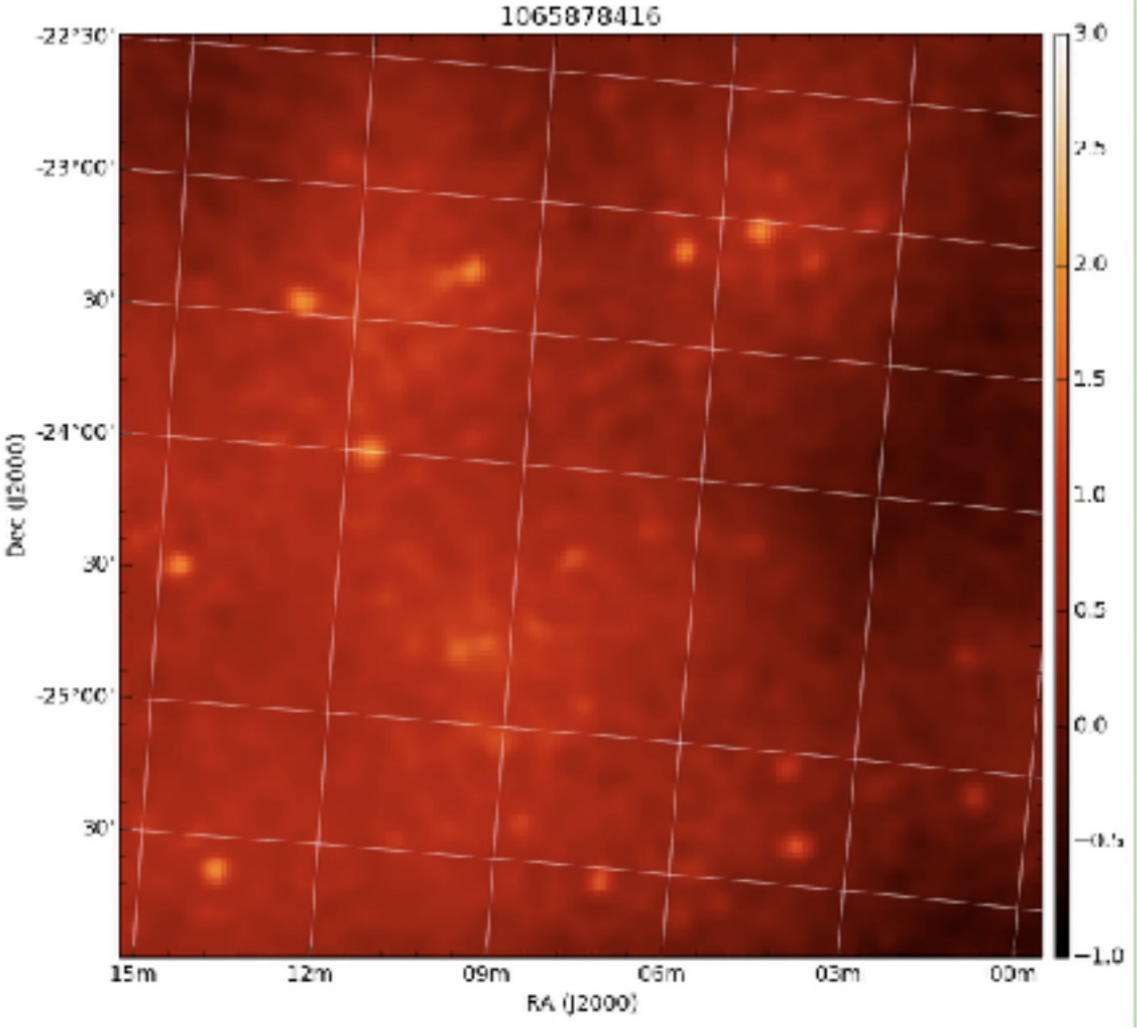


Quiz!

› What error are you seeing here?



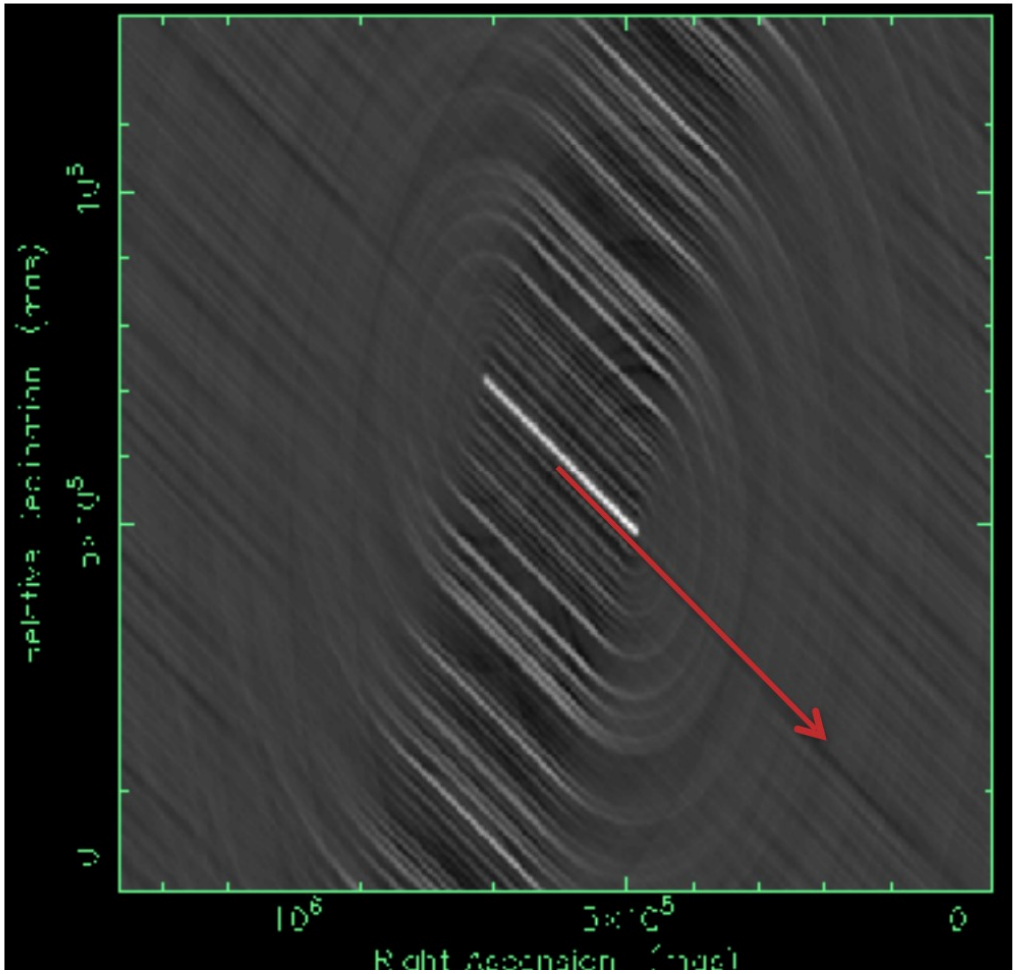
Quiz!



Low frequency MWA obs.

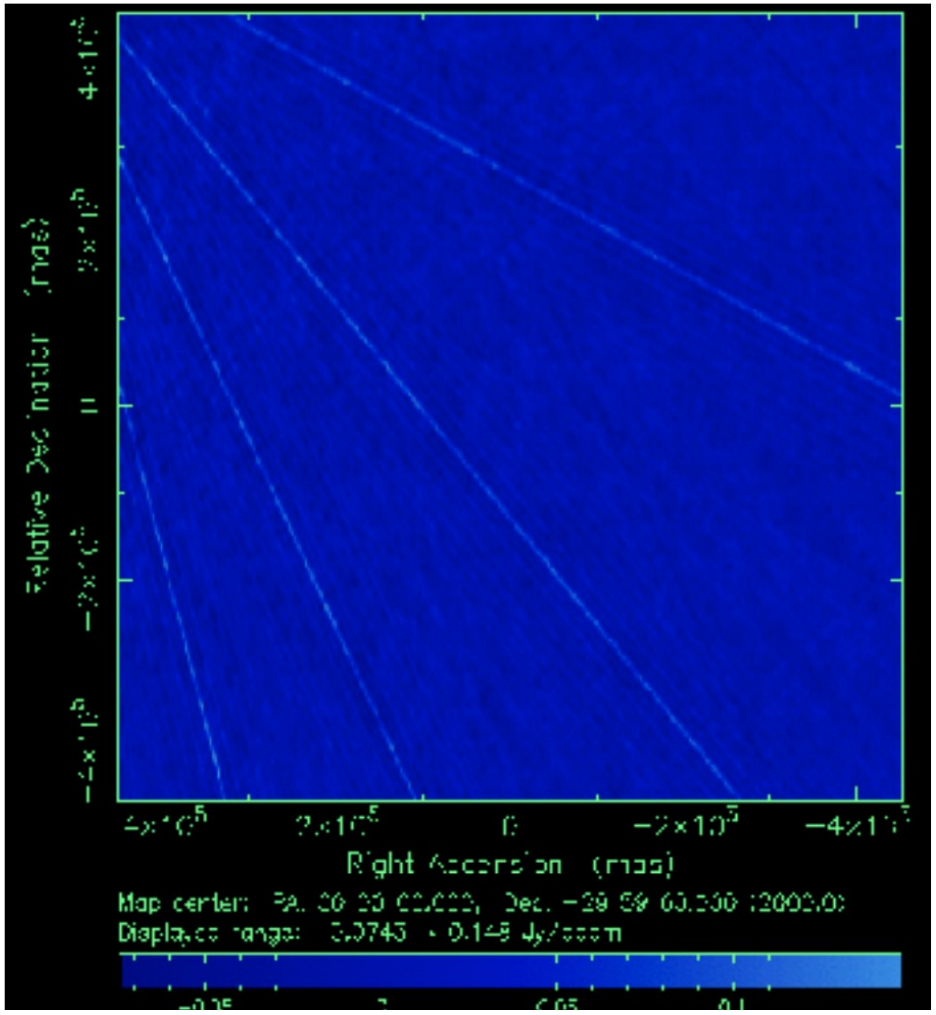
A. Heat haze
B. Antenna deformation
C. Ionosphere
D. Compression artifacts

Quiz!



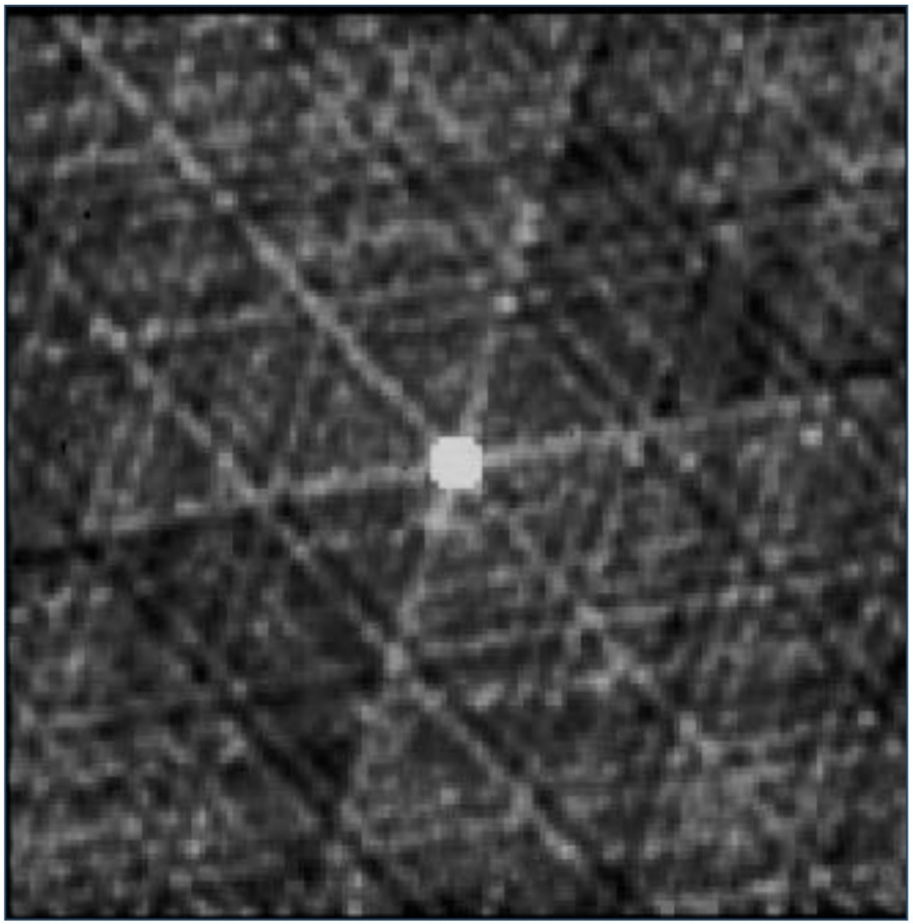
A. Amplitude errors
B. Cosmic ray
C. Bandwidth smearing
D. RFI

Quiz!



A. Amplitude errors
B. Phase of moon incorrect
C. Position-dependent errors
D. Source outside imaged field

Quiz!



A. Amplitude errors
B. Tartan from wrong clan
C. Data stored in HEX
D. Phase errors

Conclusions and tips

ASTRON

- u-v plane
  - Look for outliers
  - Check gains and phases
  - Look for residuals (data – model)
- Image plane
  - Do the defects look like the dirty beam?
  - Additive or multiplicative?
  - Symmetry properties?
  - Relate to possible data errors
  - Deconvolution problems