Checks for the Self-cal tutorial…

1. Locate the script Selfcal_demo_CASA.py in your working directory:

```
cd open_ALMA_School_2026/analysis/
allegroguestXX/tutorial3a-self_calibration
```

2. Copy the data SPT0418.split.10s.cont.ms to your working directory:

```
cp -r ../../../data_products/tutorial3a-
self_calibration/SPT0418.split.10s.cont.ms .
```

Self-calibration

Overview and tutorial

Hannah Stacey (ALMA Astronomer, ESO Garching)

2nd European ALMA School — Leiden Observatory — January 2026

What factors limit the fidelity of interferometric images?

Signal-to-noise limitations

Noise level of a (perfect) homogeneous interferometer:

$$\text{Noise} = \frac{\sqrt{2}k_B T_{\text{sys}}}{\sqrt{n_b t \Delta\nu} A\eta}$$

where:
T_{sys} - system temperature [K]
n_b - number of baselines
t - integration time [s]
$\Delta\nu$ - bandwidth [Hz]
A - area of apertures [m]
η - aperture efficiency

This is the absolute noise floor and in practice you rarely reach this in an image. Depends on flagging accuracy, calibration & adequate deconvolution

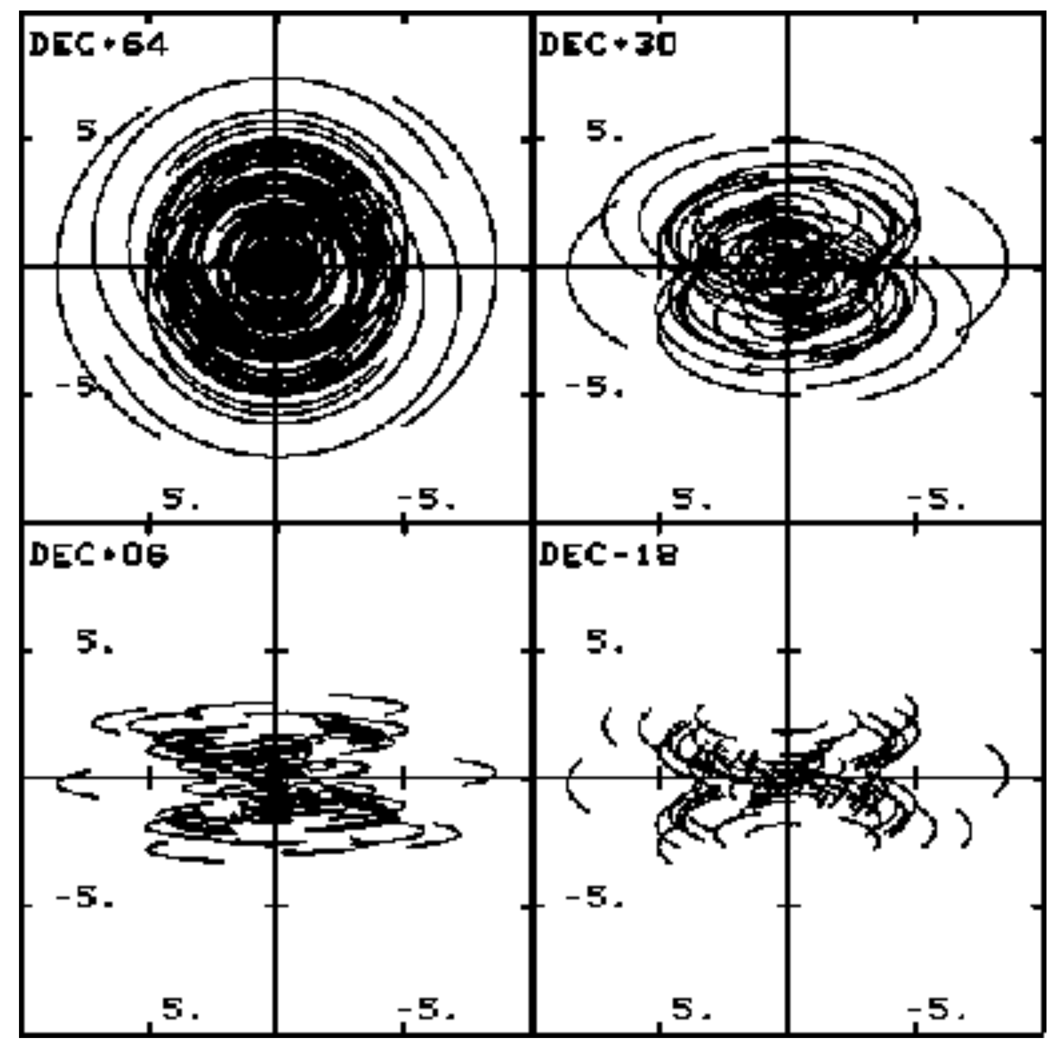
Many factors increase noise level above this value, e.g.

- Calibration errors
- Bad data
- Deconvolution artefacts
- Dynamic range limits

u-v limitations

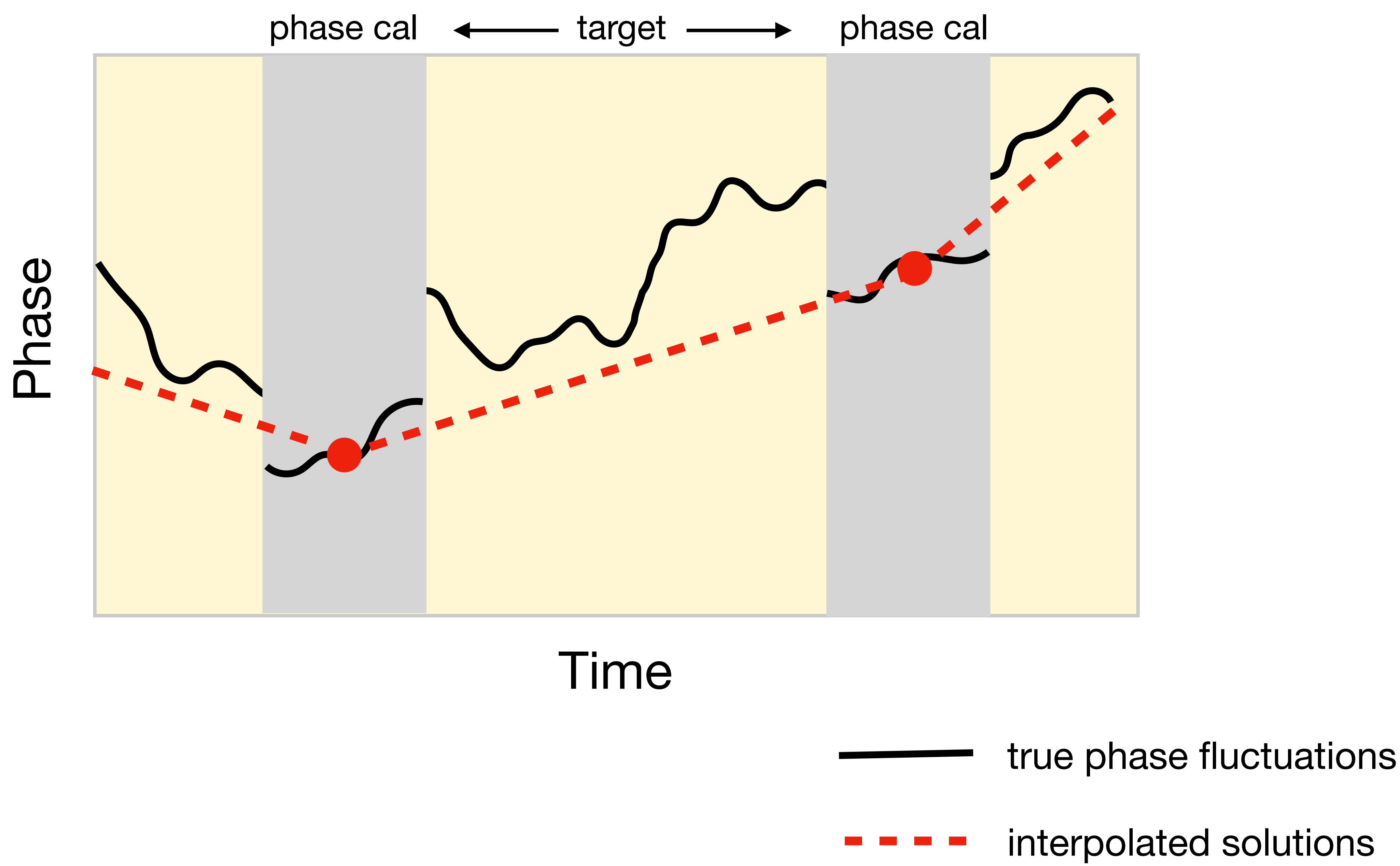
- n telescopes -> ½ n(n-1) baselines

- Outer value of u-v limits resolution
- Inner value of u-v limits sensitivity to large-scale structures
- Density of u-v plane limits image fidelity



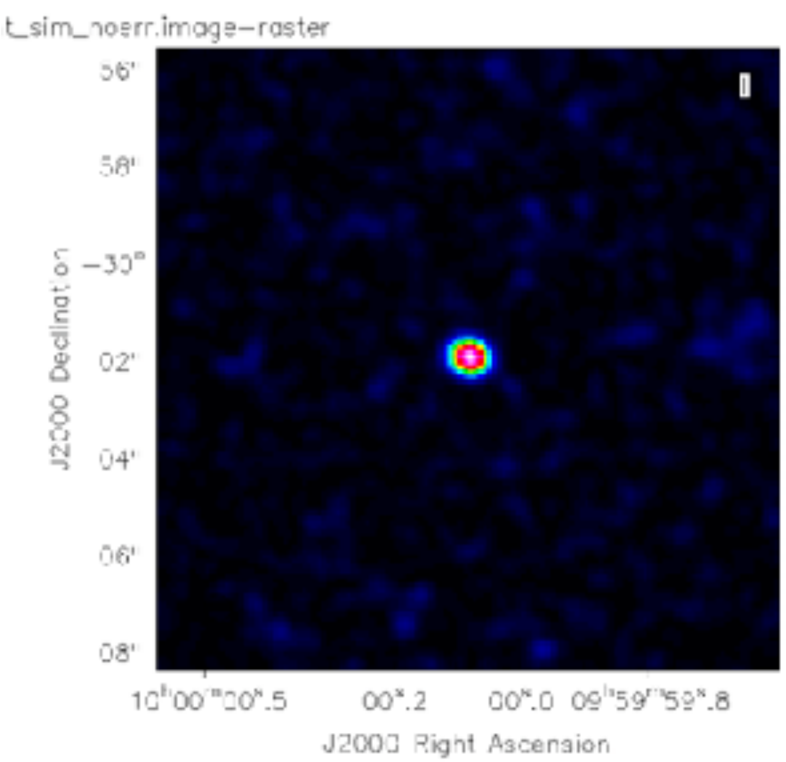
Walker, 1984

Phase transfer limitations



Phase transfer limitations

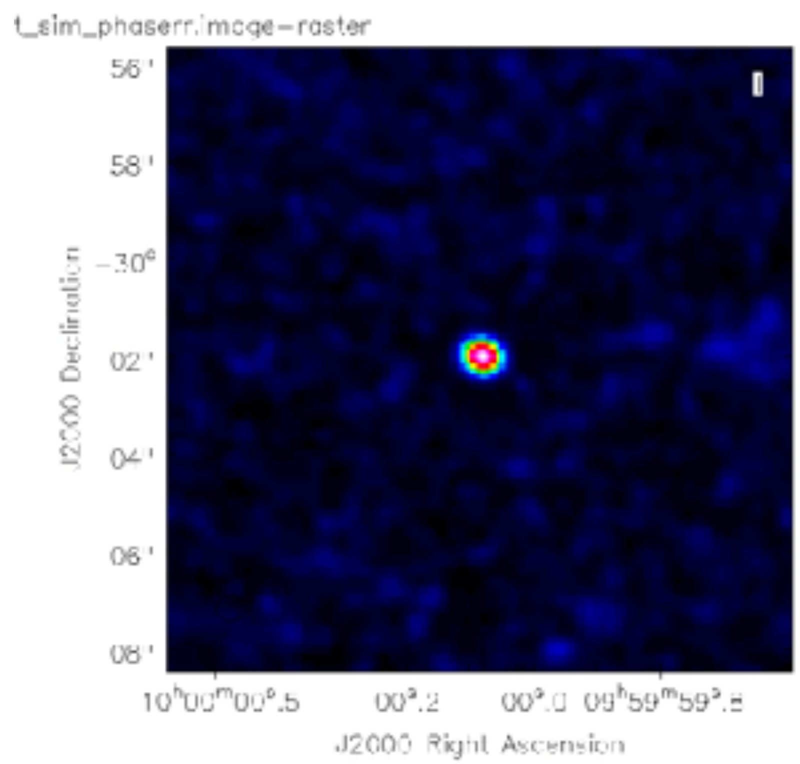
Only gaussian errors



RMS = 8e-3 Jy

DR = 120

1 antenna bad phase

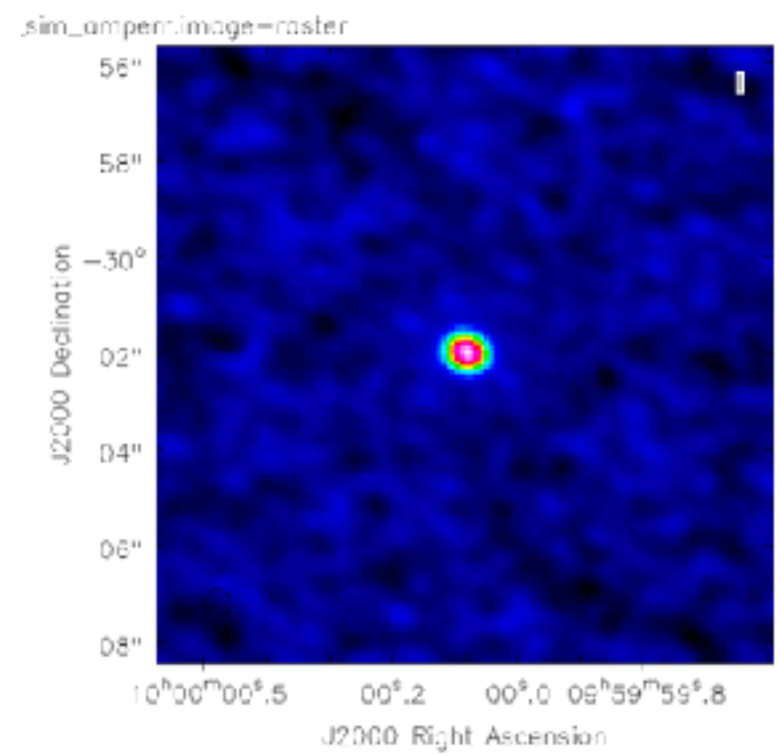


RMS = 1e-2 Jy

DR = 95

Artefacts are anti-symmetric

1 antenna bad amplitude



RMS =2e-2 Jy

DR = 45

Artefacts are symmetric

Dynamic range limitations

Even observations in perfect conditions will be dynamic range (peak/rms) limited due to phase transfer, antenna positions, adequate deconvolution… etc.

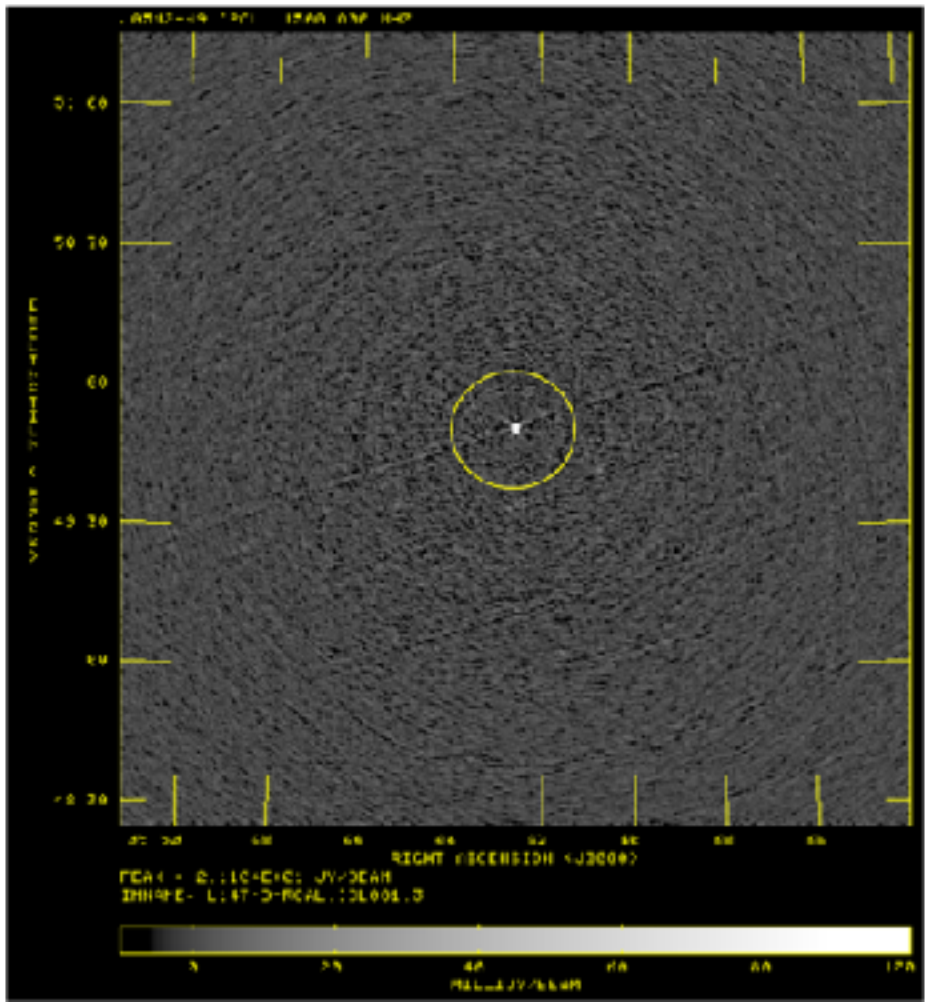
The dynamic range limit (D) due to only random phase errors ($\phi_{\rm err}$) and random amplitude errors ($A_{\rm err}$) is

$$D_\phi \simeq \frac{\sqrt{M}N}{\phi_{\rm err}} \qquad\qquad D_A \simeq \frac{\sqrt{M}N}{A_{\rm err}}$$

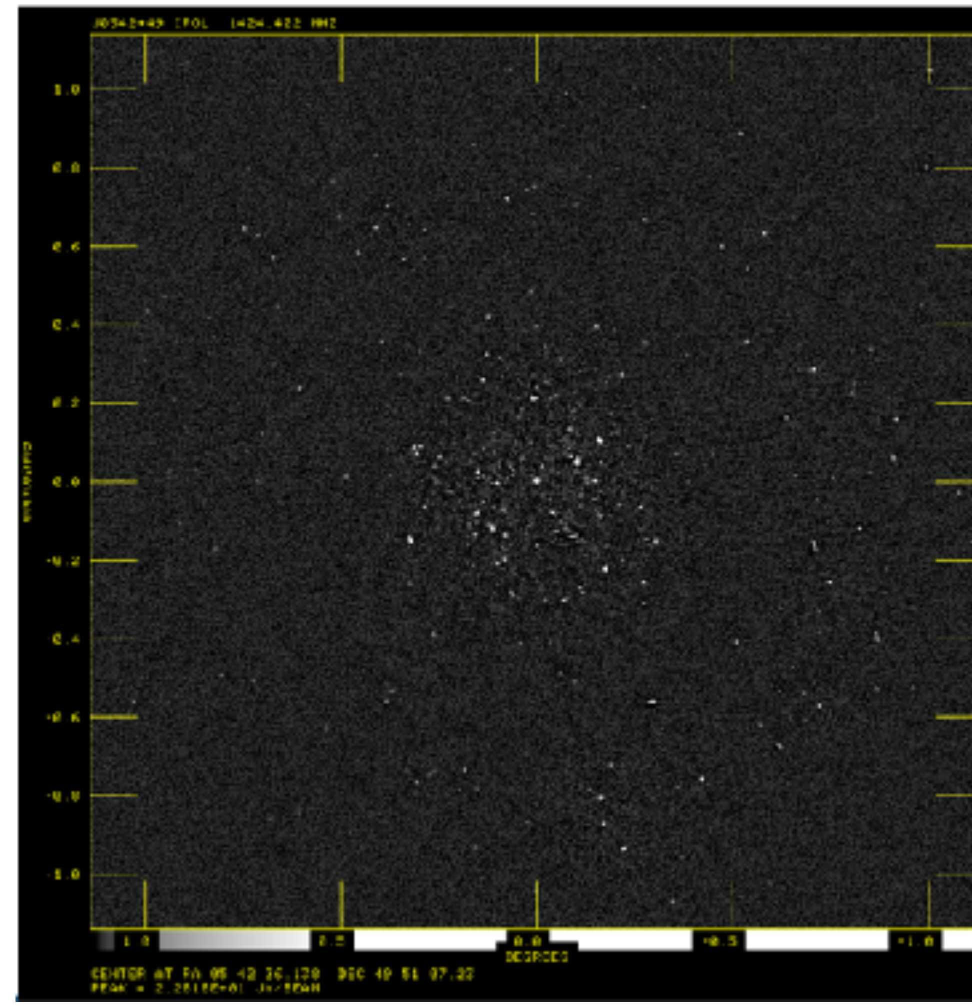
where *M* is the number of scans, *N* the number of antennas
e.g. for 20 deg phase errors on 43 ALMA antennas, $D_\phi \simeq 120\sqrt{M}$

With ALMA you typically can achieve a dynamic range of **50–150** via pipeline calibration (depending on the setup)

…what dynamic range limitations?



Regular calibration
DR = 4000



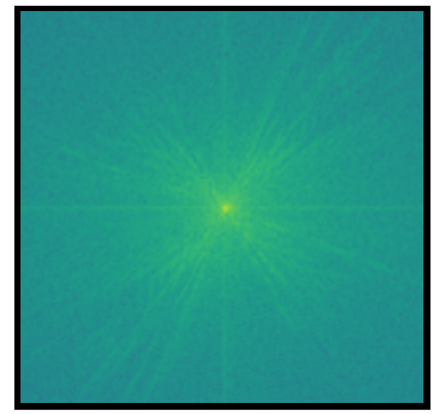
With self-calibration
DR = 3.2 million

Images by Rick Perley and Oleg Smirnov: https://www.astron.nl/gerfeest/presentations/perley.pdf

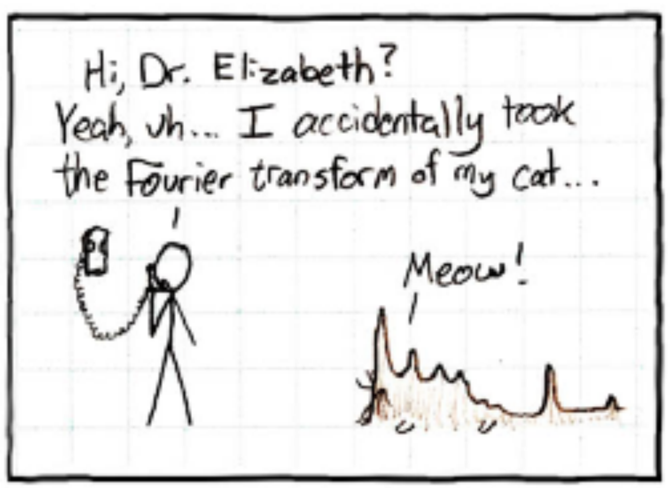
How do we perform this wizardry?

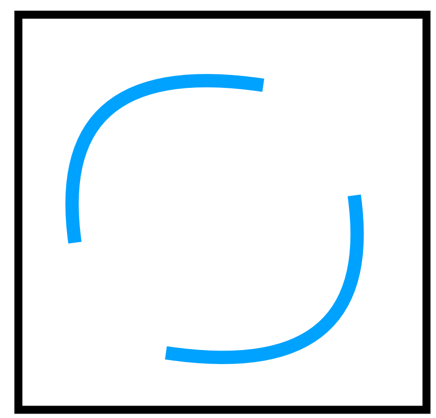
Interferometric imaging recap

FT

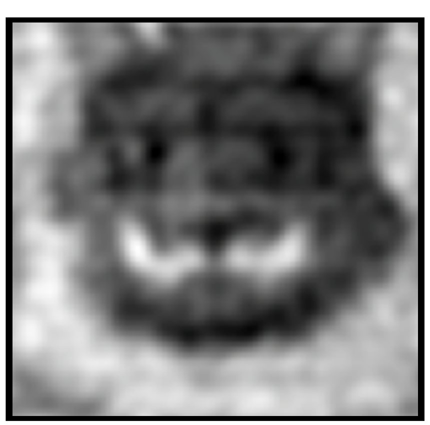


FT of source

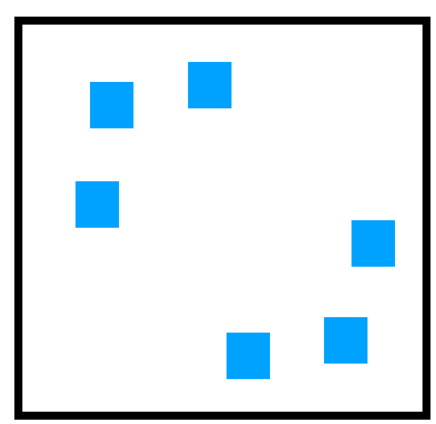




Sampled on u-v tracks



FT



Convolved with sampling fn

(+ interpolated onto a grid)

Image reconstruction

'dirty map' True source 'dirty beam'

$$I'(x,y) = I(x,y) * S(x,y)$$

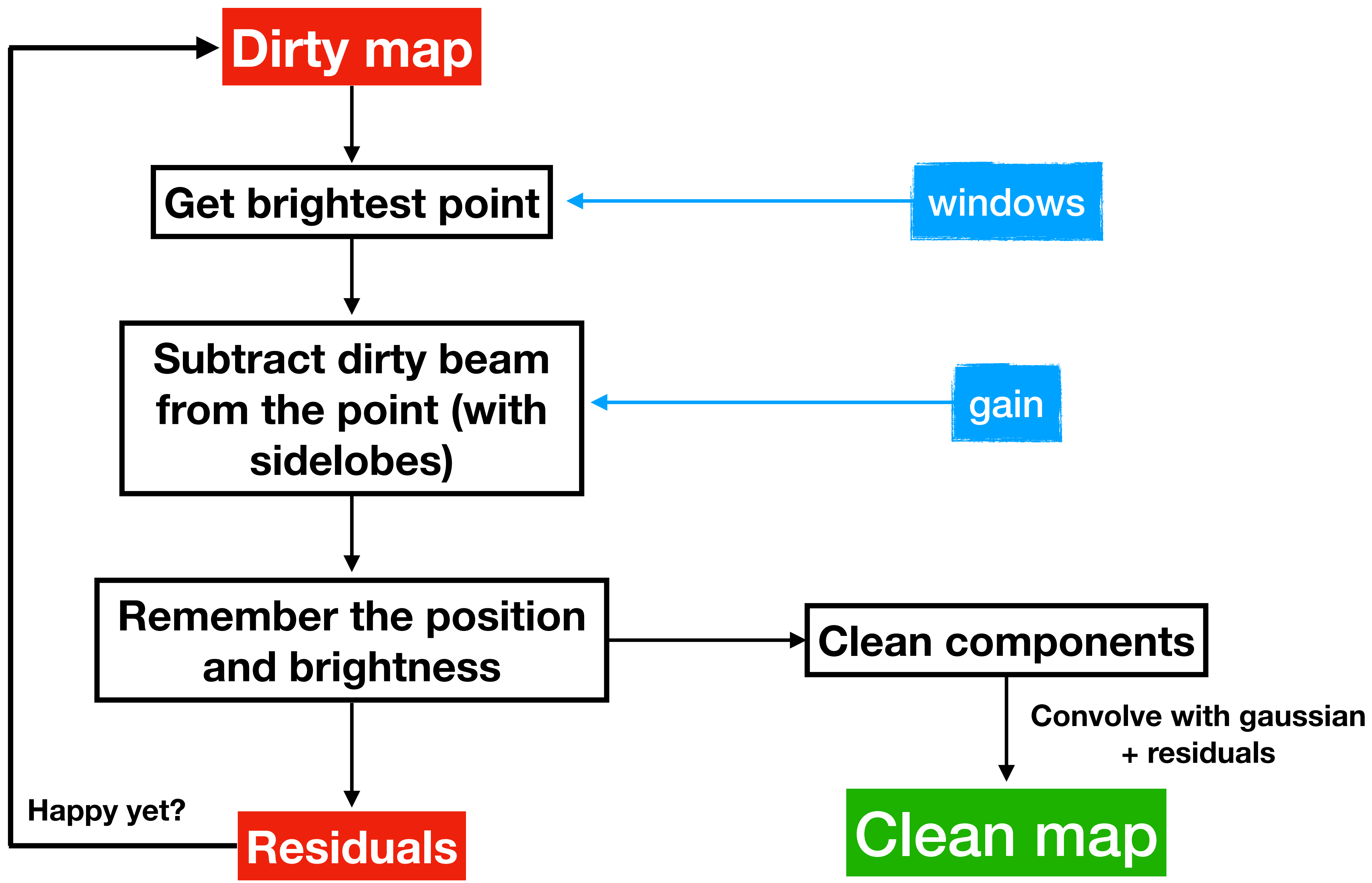
FT FT FT

sampling fn

$$V'(u,v) = V(u,v) \times S(u,v)$$

We measured this

Högbom CLEAN



Self-calibration

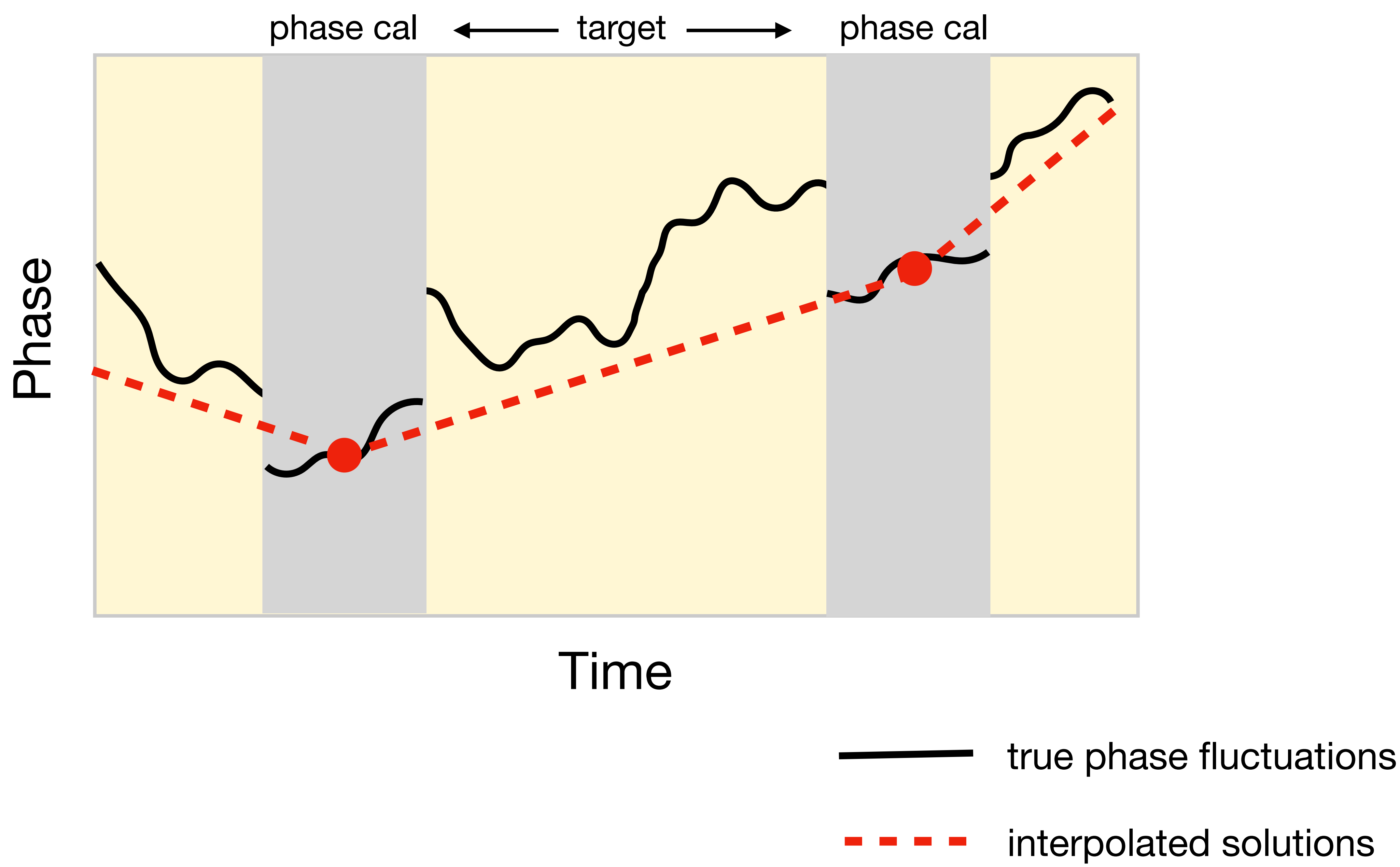
- … is just regular gain calibration
- Need model to correct -> can use CLEAN model!

  Solve for complex gain of each telescope

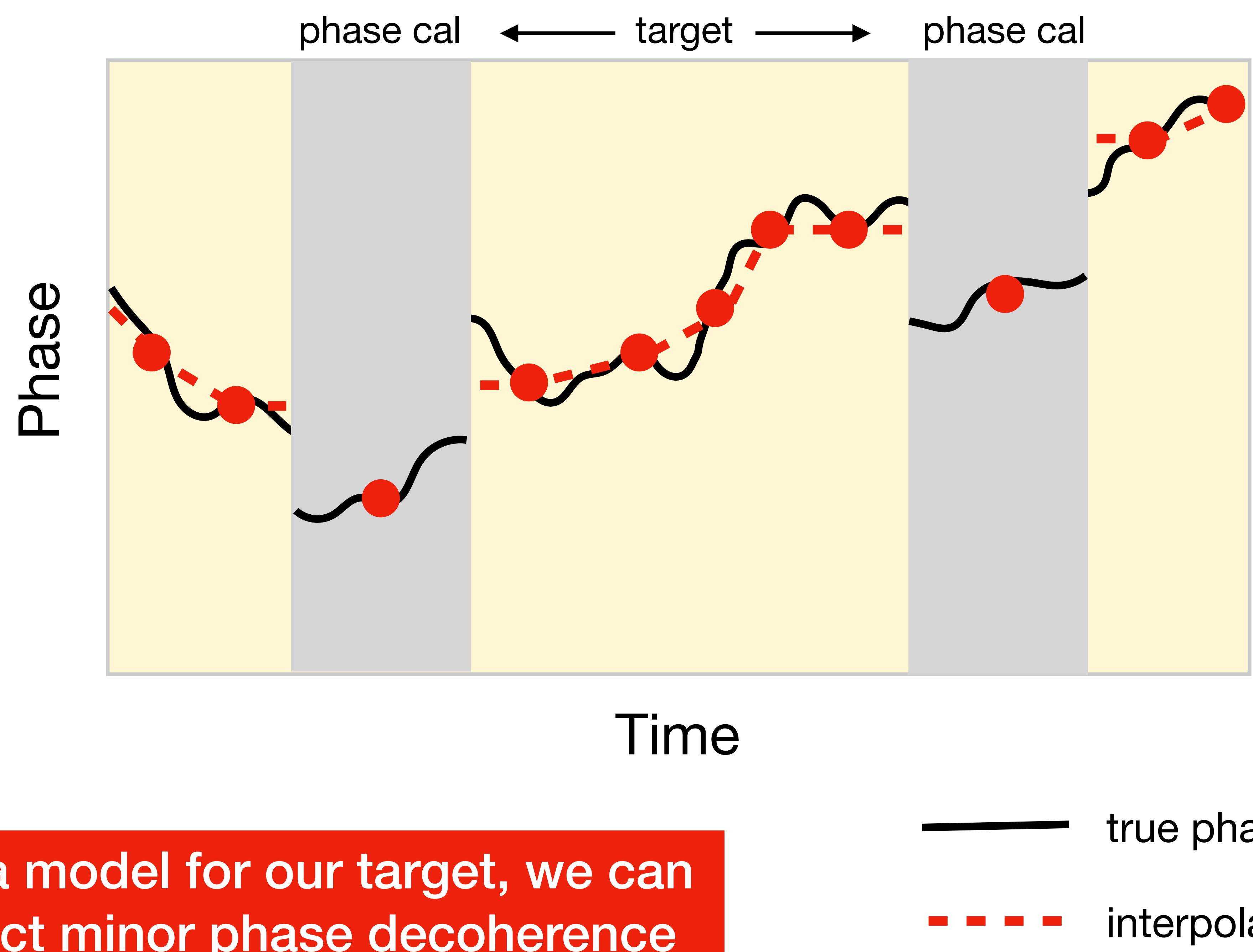
  $V'_{ij} = g_i\, g_j\, V_{ij}$

  Repeat for corrected visibilities
- Is this legitimate? Yes - errors associated to individual antennas. We have free parameters g_i, g_j… n_{tel} and n_{bas} constraints.
- Caveats: need to have good signal-to-noise, lose absolute positional information

Phase transfer limitations

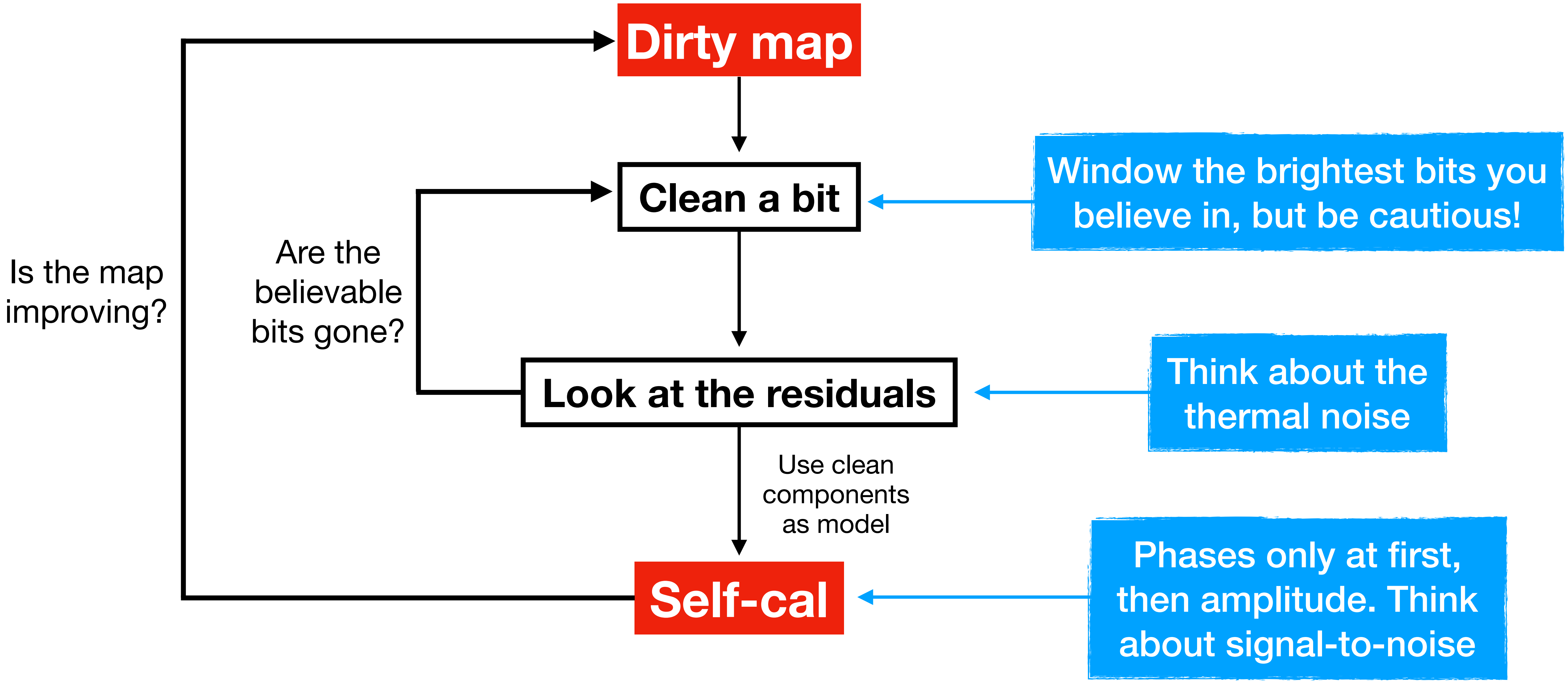


Phase transfer limitations

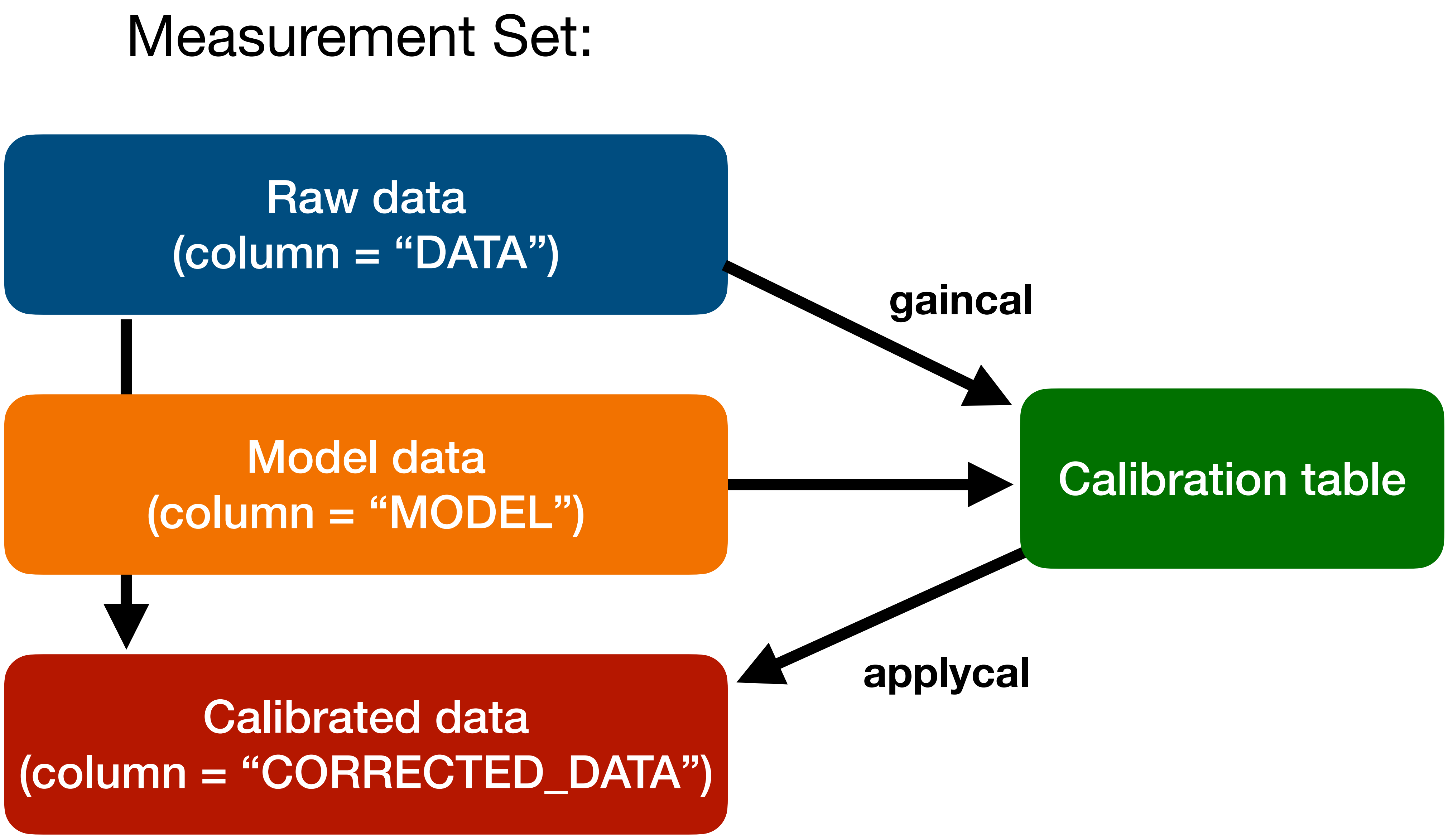


With a model for our target, we can correct minor phase decoherence

CLEAN & self-calibration in practice



Quick reminder about calibration workflow in CASA

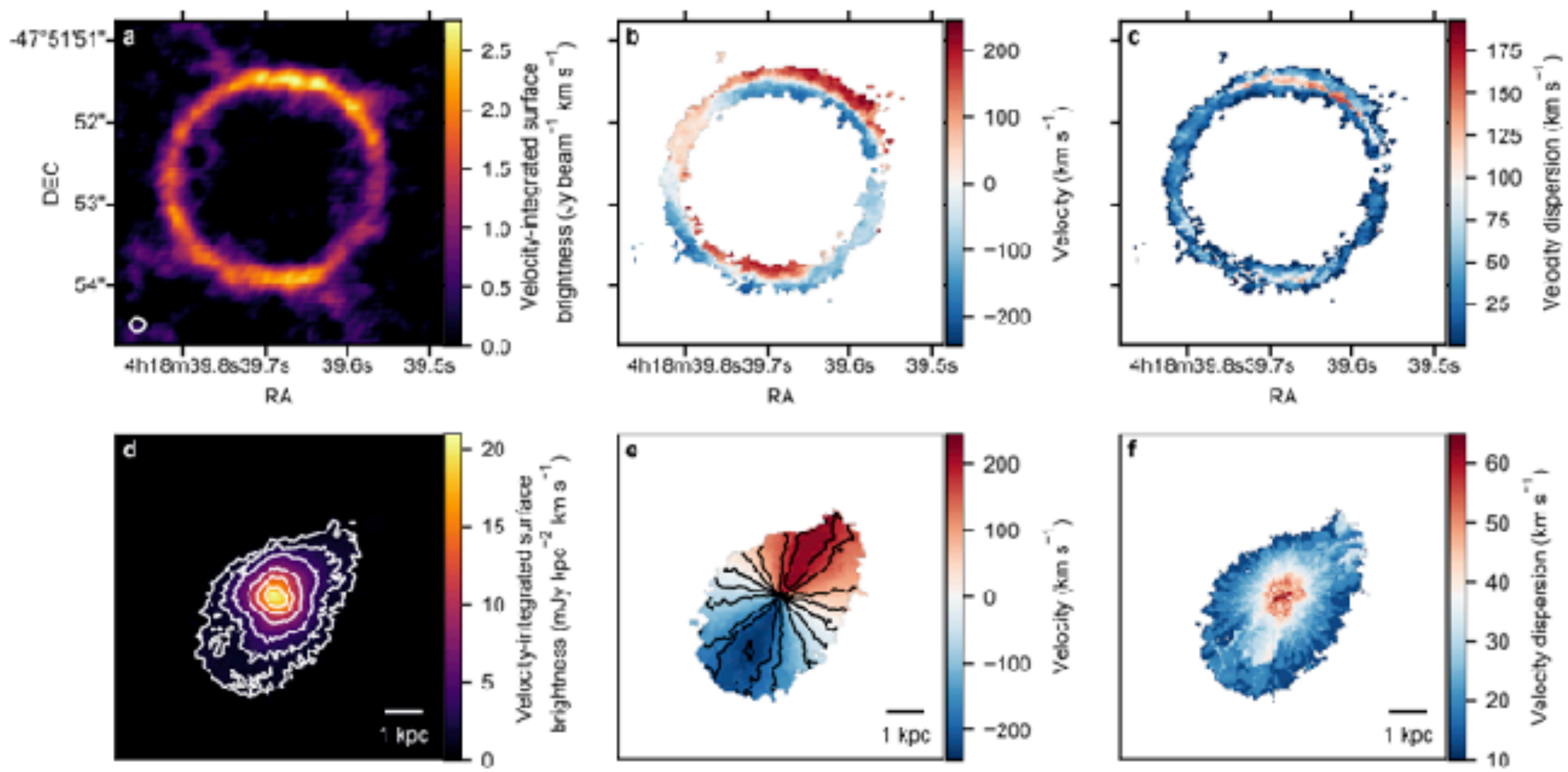


Self-calibration tutorial

We will do some self-calibration with ALMA data of a gravitational lens that generated a 2020 Nature paper

A dynamically cold disk galaxy in the early Universe

F. Rizzo[1], S. Vegetti[1], D. Powell[1], F. Fraternali[2], J. P. McKean[2,3], H. R. Stacey[2,3,1] & S. D. M. White[1]



Checks for the Self-cal tutorial…

1. Locate the script Selfcal_demo_CASA.py in your working directory:

   ```
   cd open_ALMA_School_2026/analysis/
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   ```

2. Copy the data SPT0418.split.10s.cont.ms to your working directory:

   ```
   cp -r ../../../data_products/tutorial3a-
   self_calibration/SPT0418.split.10s.cont.ms .
   ```

Warning!

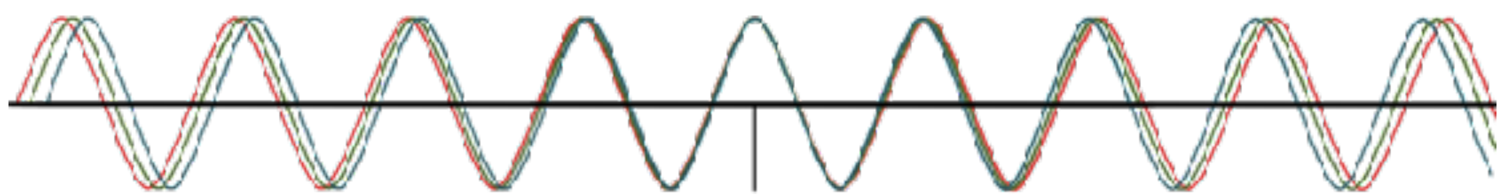
This is not a pipeline. Always consciously choose inputs into tasks and look at the outputs. Do not proceed blindly.

Step 0: Some pre-checks

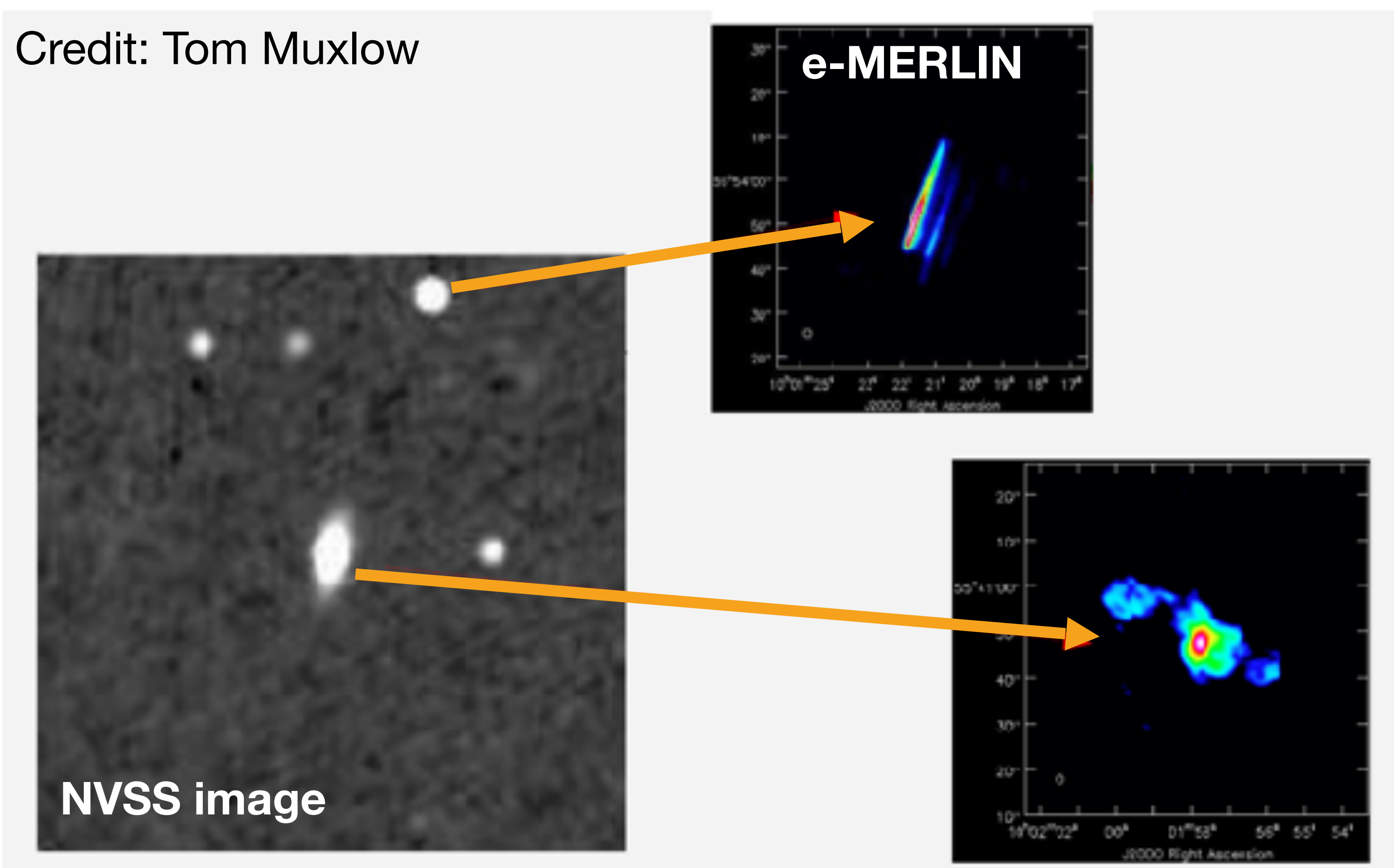
- We begin with a continuum-only data set (3 spws)
- Averaging your data in frequency and time greatly speeds up imaging and calibration, but also corrupts your data. So we will first check how much averaging we can get away with.
- mysteps=[0]

Step 0: Some pre-checks

Bandwidth smearing (chromatic aberration)



increasing radius ← pointing centre → increasing radius



Effect is radial smearing, corresponding to radial extent of measurements in uv plane. Amplitude loss can be approximated by

$$R_b = \frac{I}{I_0} \simeq \frac{1}{\sqrt{1+\beta_{\max}}}$$

where $$\beta = \frac{\Delta\nu}{\nu}\frac{\Delta\theta}{\theta_{\text{beam}}}$$

See https://safe.nrao.edu/wiki/pub/Main/RadioTutorial/BandwidthSmearing.pdf

Step 0: Some pre-checks

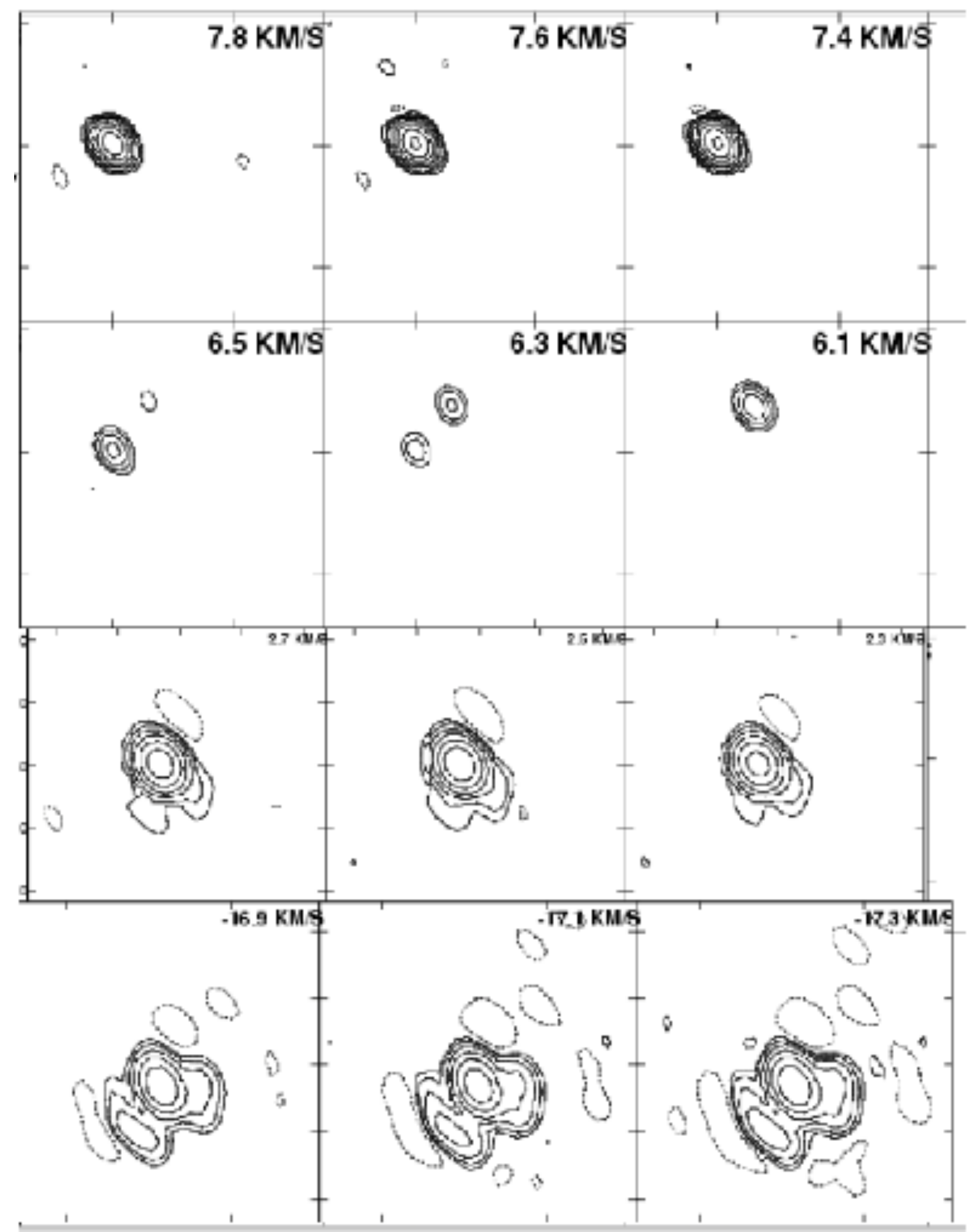
Time smearing

- Time-average smearing (de-correlation) produces tangential smearing
- Not easily parameterised, but amplitude loss roughly approximated by

$$R_t = \frac{I}{I_0} \simeq 1 - \eta \left(\frac{\Delta\theta}{\theta_{\mathrm{beam}}} \right)^2 \tau^2$$

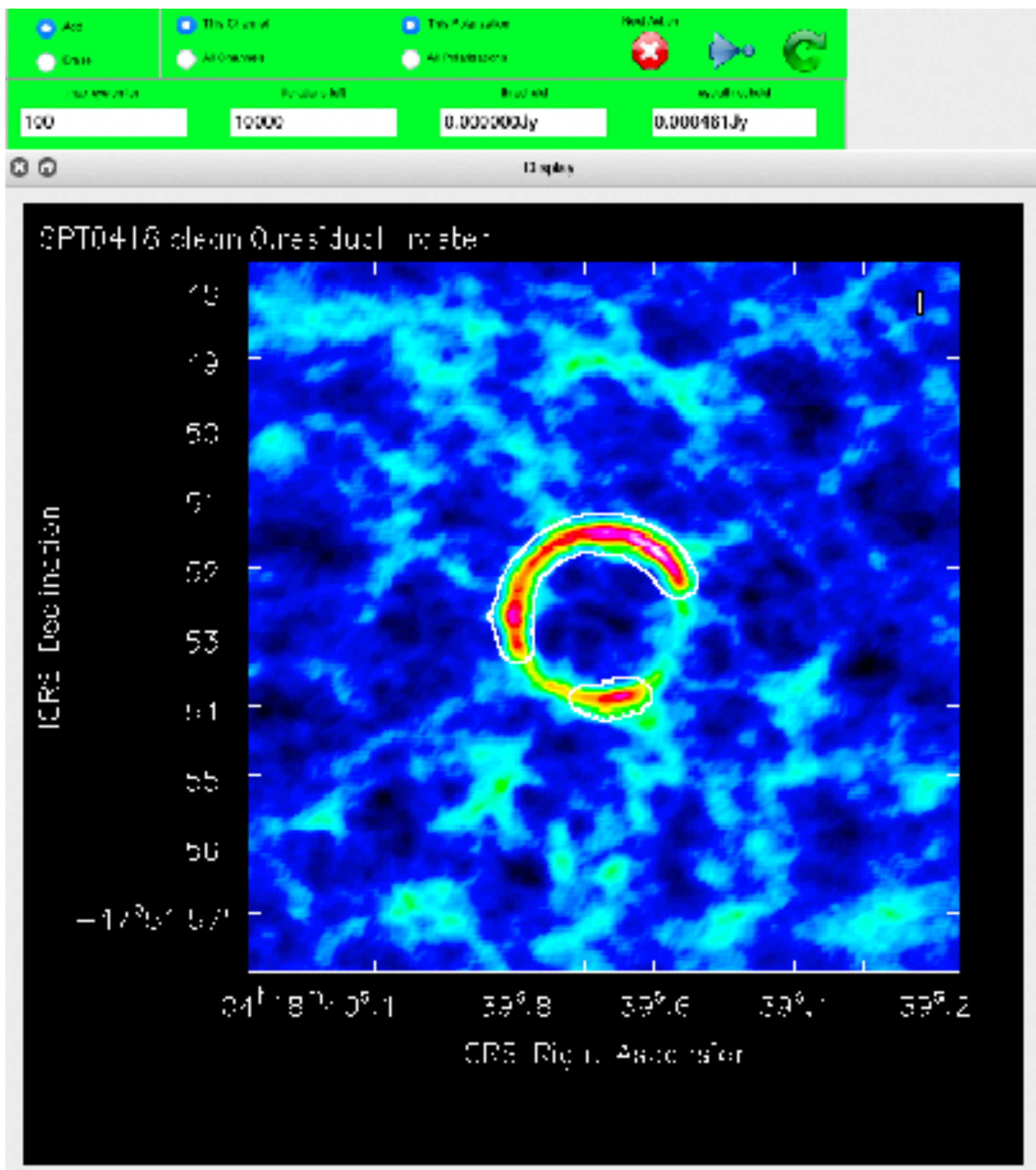
where $\eta \approx 1 \times 10^{-9}$

See https://www.cv.nrao.edu/vla/hhg2vla/node12.html

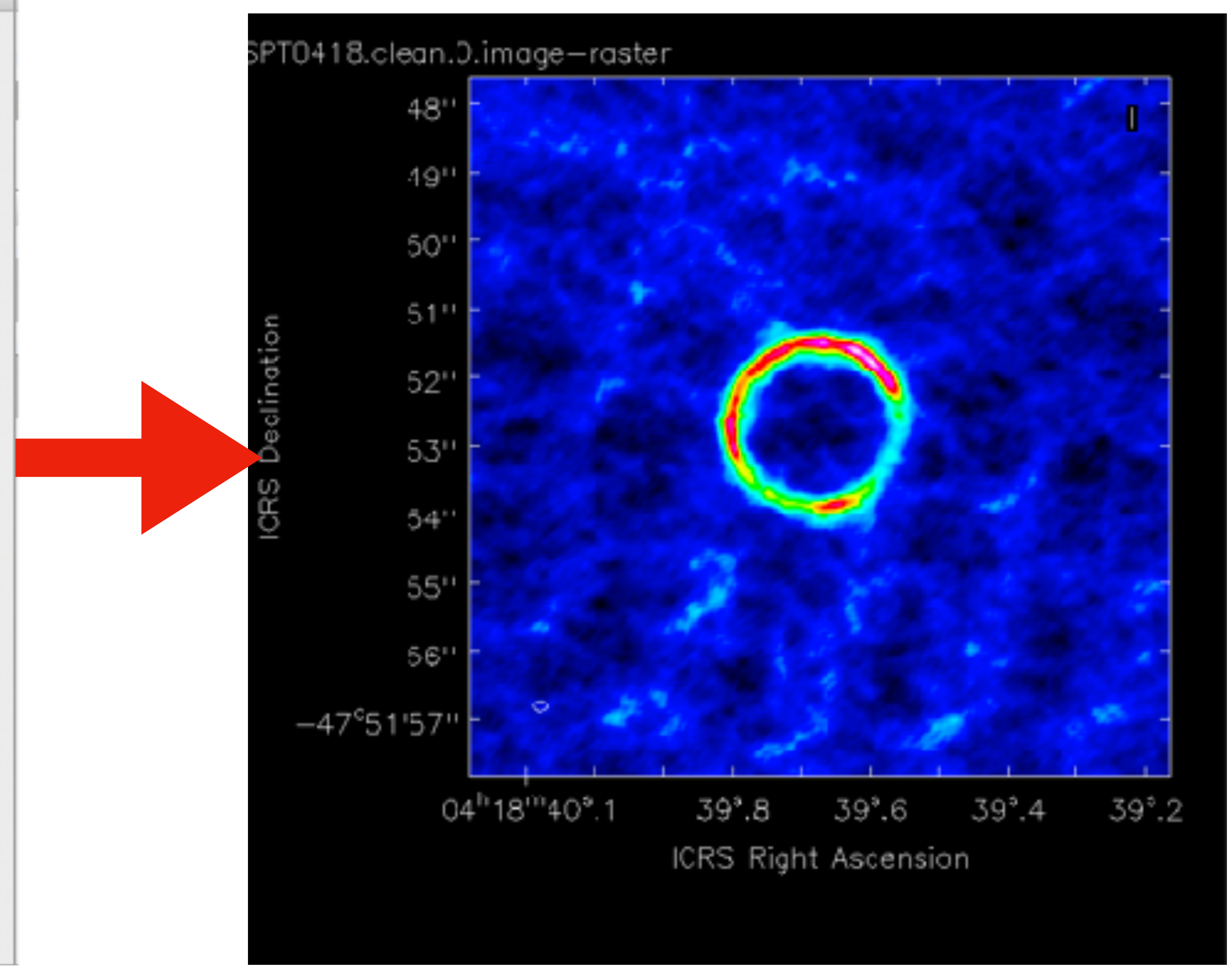


Credit N. Jackson

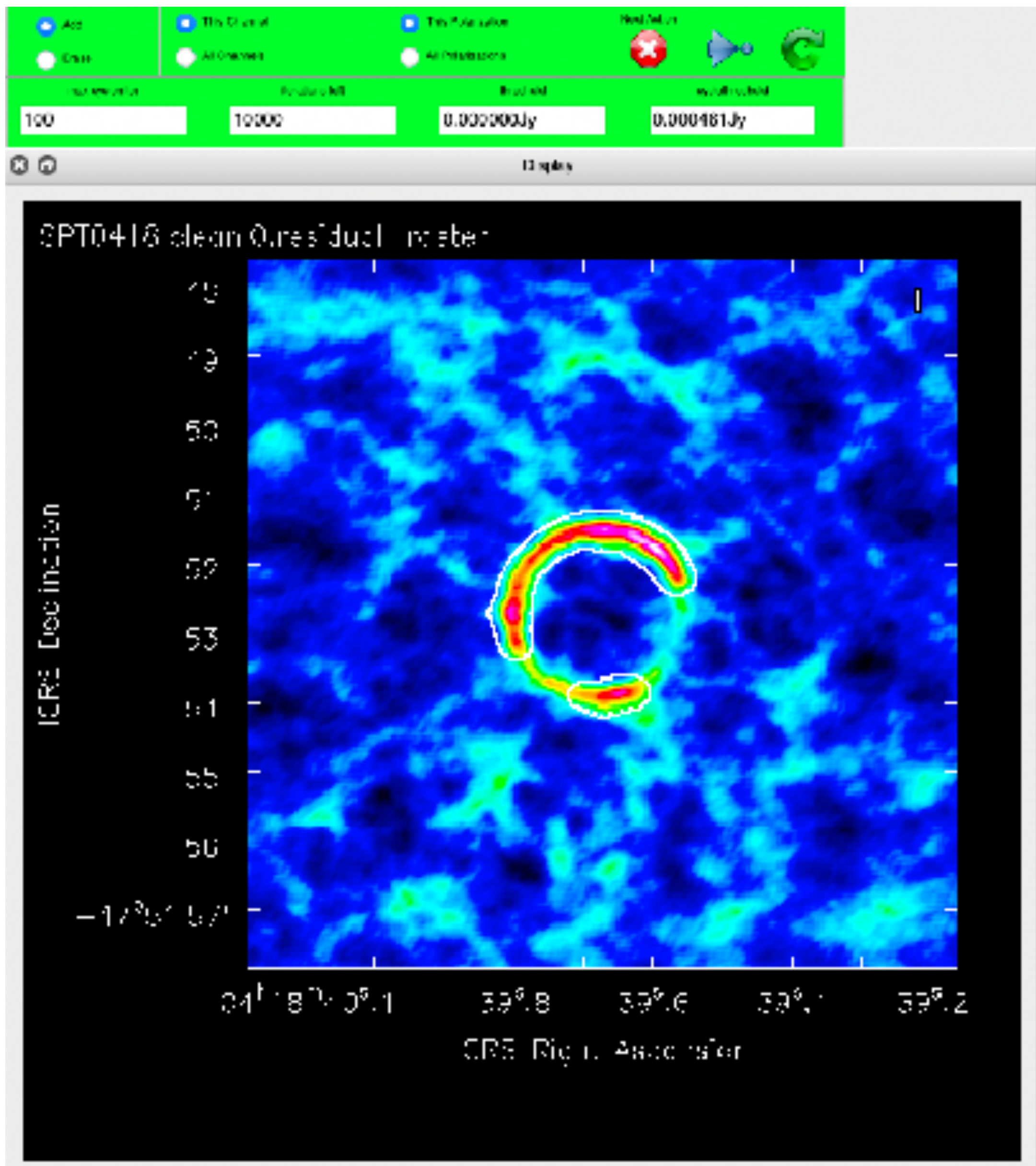
Step 1: Make an image with tclean



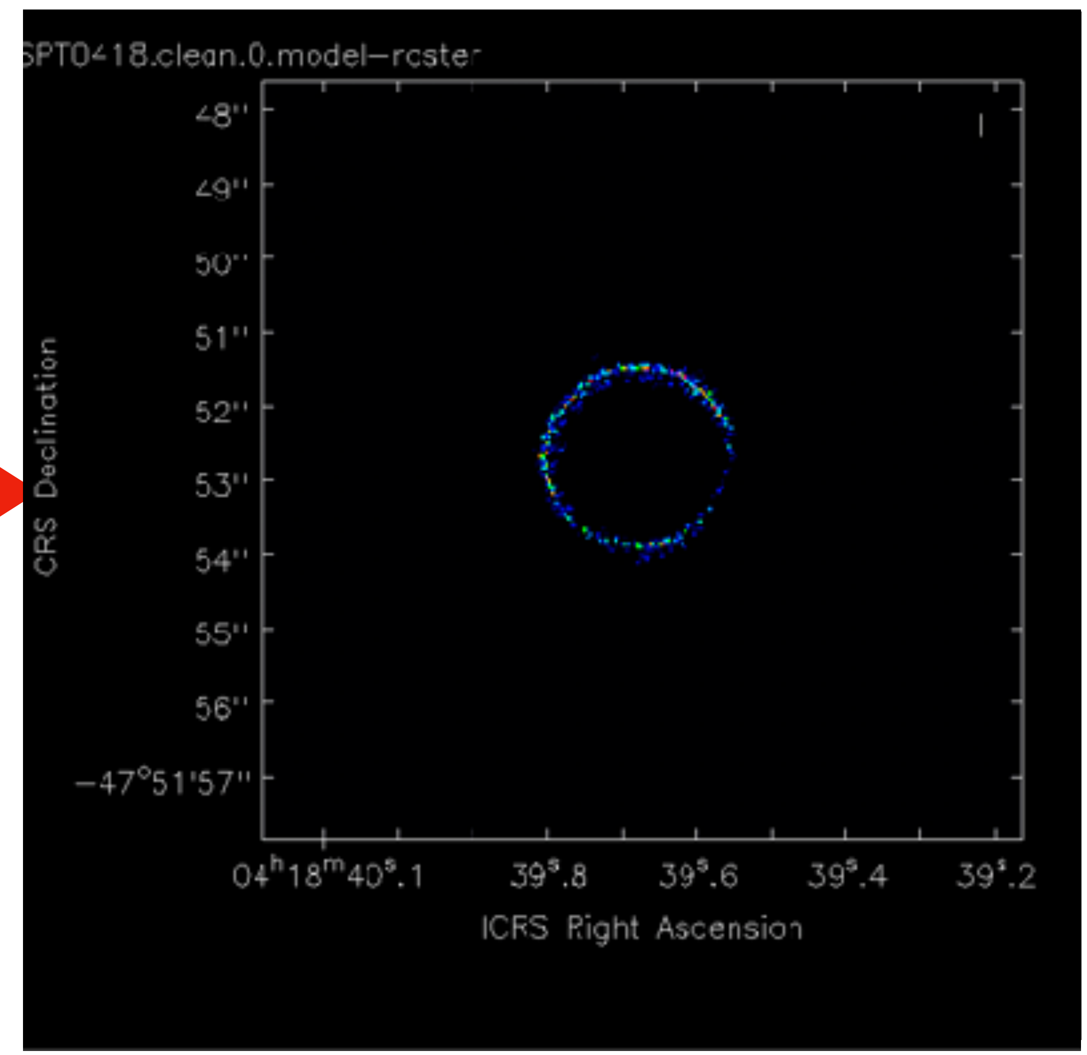
```
------------------------------------------------------------ Make PSF -----
 [SPT0418.clean.0] Theoretical sensitivity (Jy/bm):2.31139e-05
 Time to fit Gaussian to PSF 0.015402
 Beam : 0.189669 arcsec, 0.163934 arcsec, -83.2743 deg
```



Step 1: Make an image with tclean



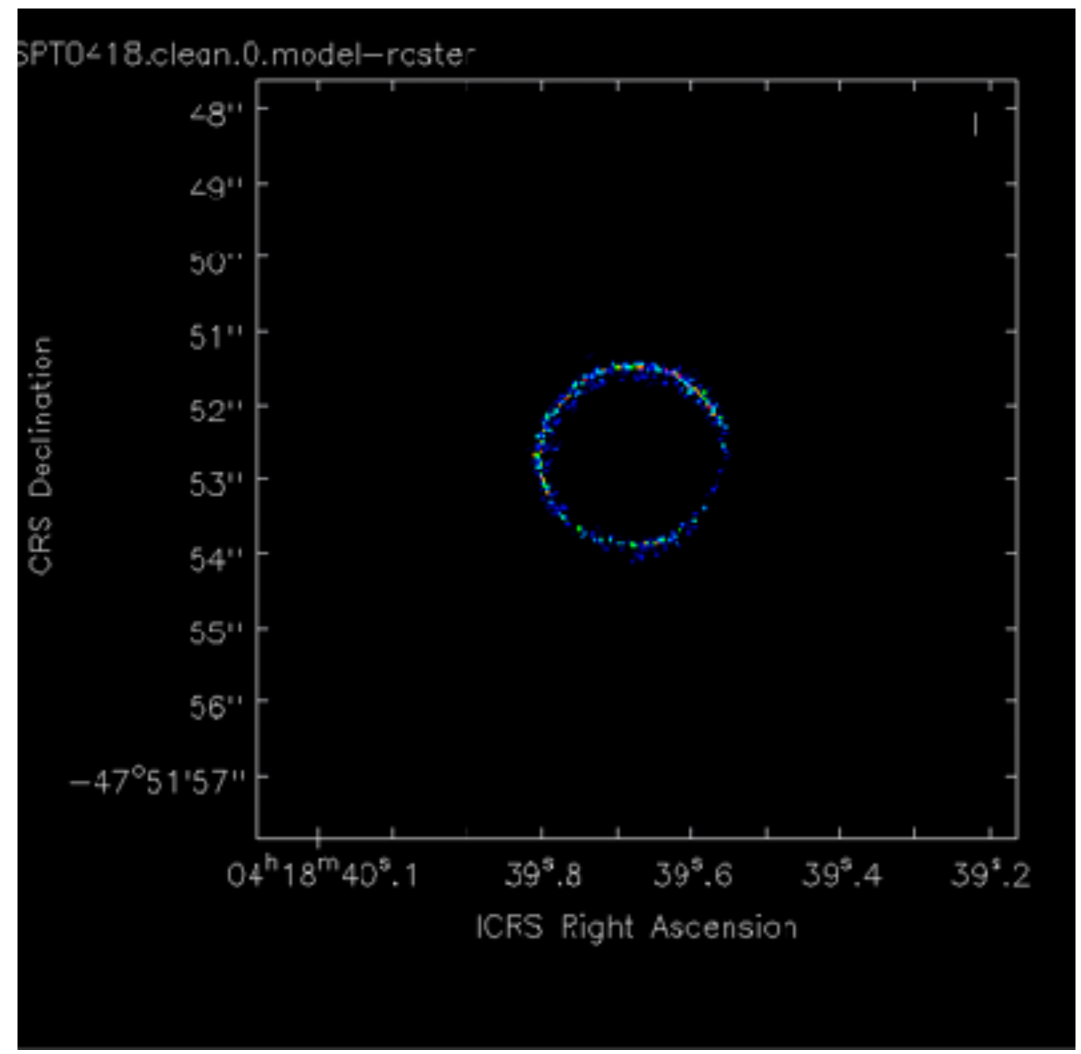
Clean components!



Step 2: Write your model into the MODEL_DATA column

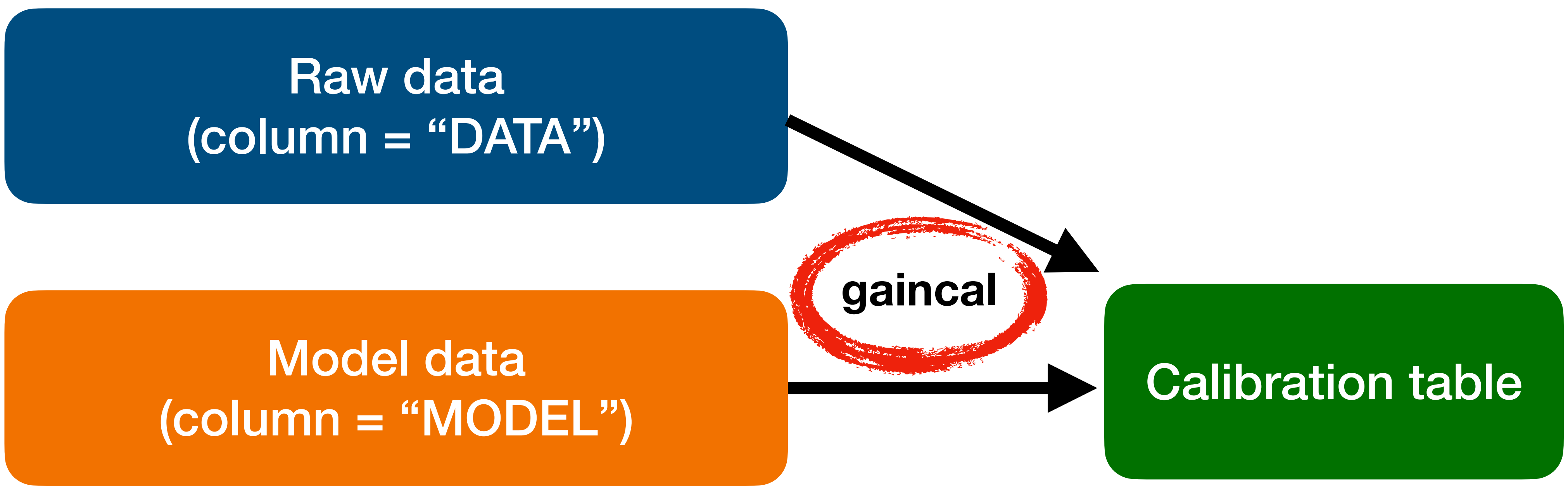
- Using the task “ft” we can Fourier Transform this model into the MODEL_DATA column of the measurement set

- ft(vis=‘mydata.ms’, model=‘myfirstimage.model’, usescratch=True)



Quick reminder about calibration workflow in CASA

Measurement Set:

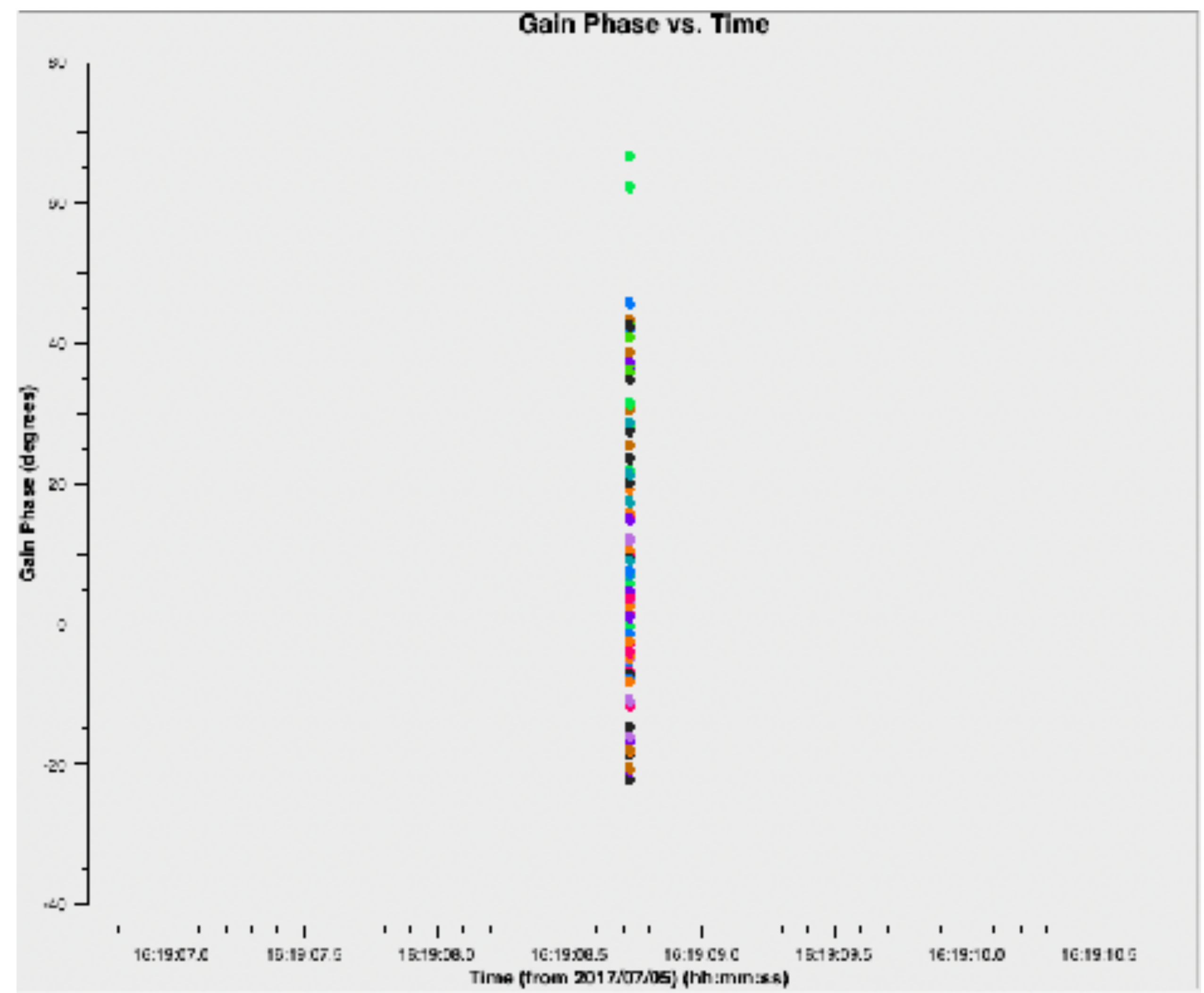


Step 3: Derive gain solutions

- Using the task “gaincal” we will derive just 1 phase solution per antenna for the whole observation

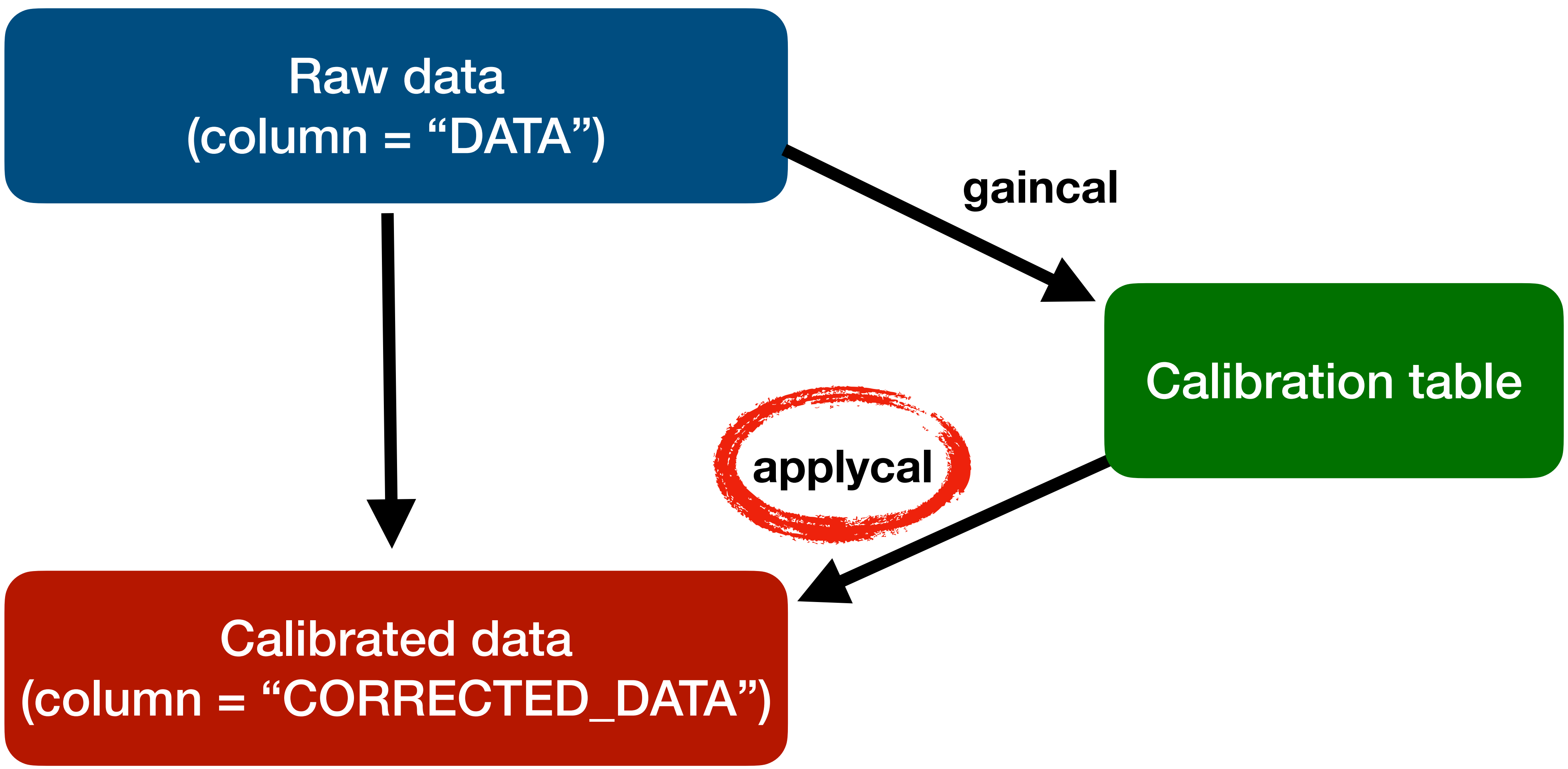
- gaincal(vis=‘mydata.ms’,
  caltable=‘mydata.ms.p_inf’,
  solint=‘inf’,
  refant=[‘??’,’??’..]*,
  calmode=‘p’,
  combine=‘spw,scan’)

  *you can use plotants() to find a good reference antenna



Quick reminder about calibration workflow in CASA

Measurement Set:

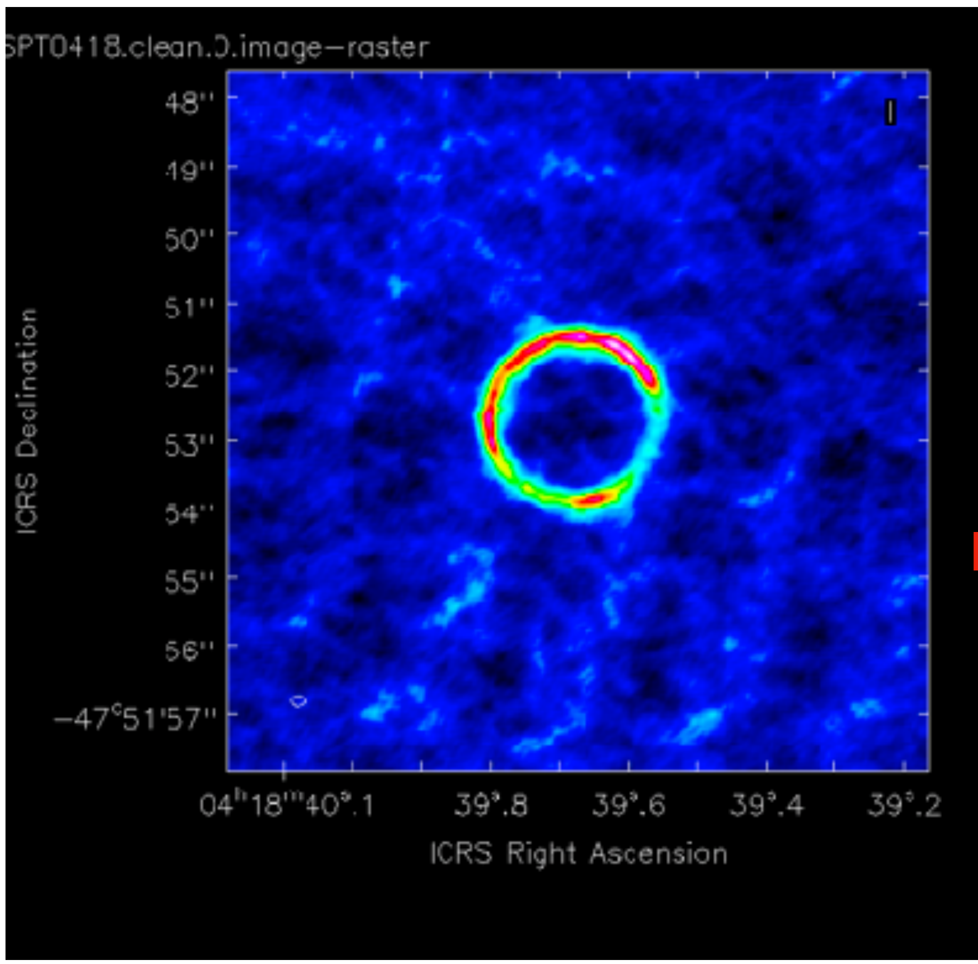


Step 4: Apply gain solutions

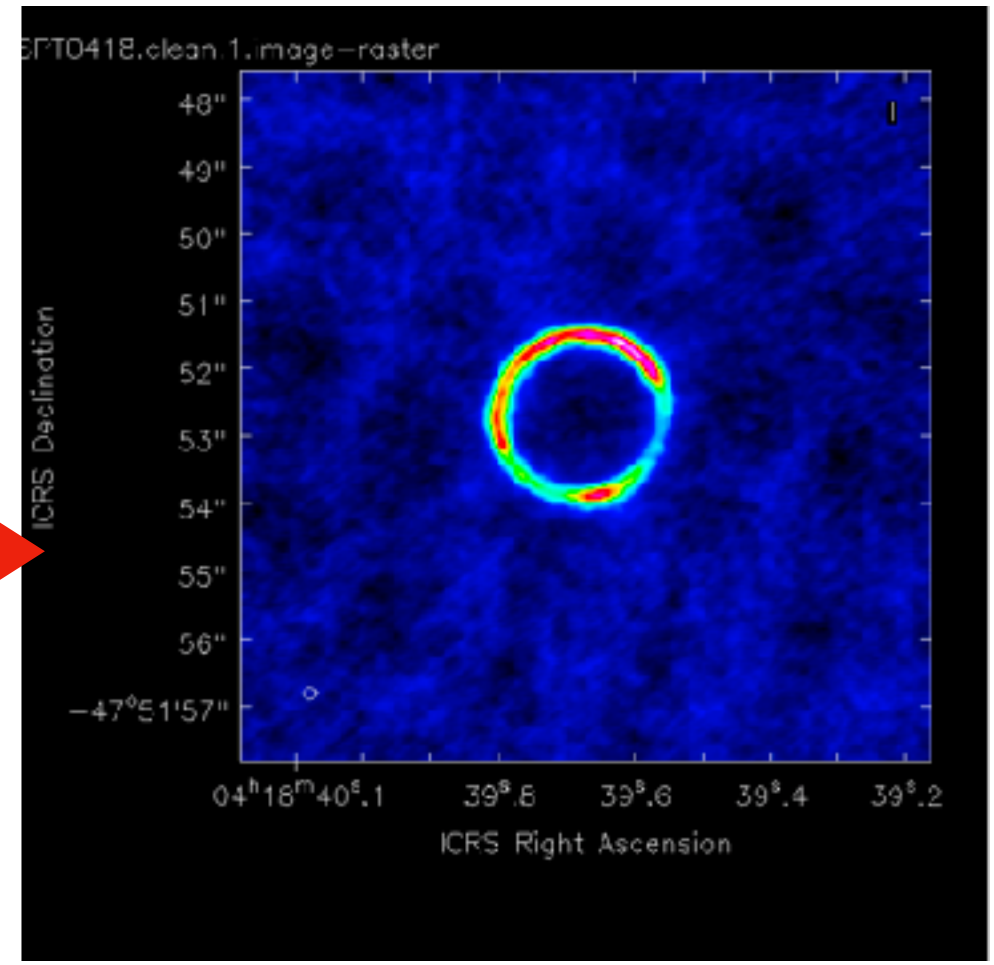
- Using the task “applycal” we apply these solutions, creating a CORRECTED_DATA column in the measurement set
- applycal(vis=‘mydata.ms’,
  gaintable=‘mydata.ms.p_inf’,
  spwmap=[0,0,0])
- Missing solutions will flag the data!

Step 5: Make a new image

Before



After



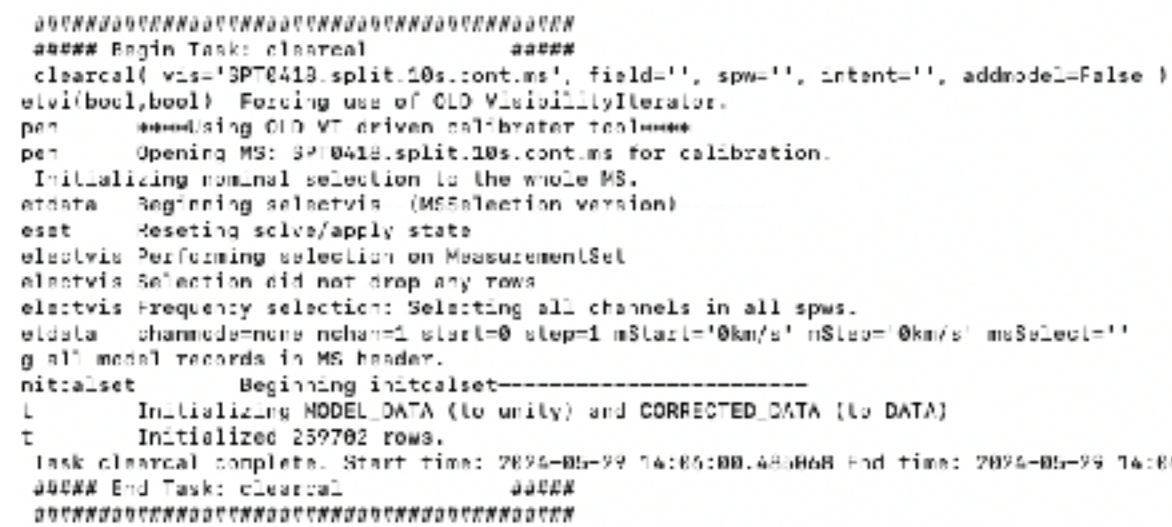
- This time we set **datacolumn="corrected"** to use CORRECTED_DATA
- How do the rms noise and peak flux density compare?

Step 6: Replace the model

- Now we have a better model for our target, we can replace the MODEL_DATA column

- First clear the model and corrected data:
  clearcal(vis='mydata.ms')

- Then FT the new model into the measurement set:
  ft(vis='mydata.ms', model='mysecondimage.model', usescratch=True)

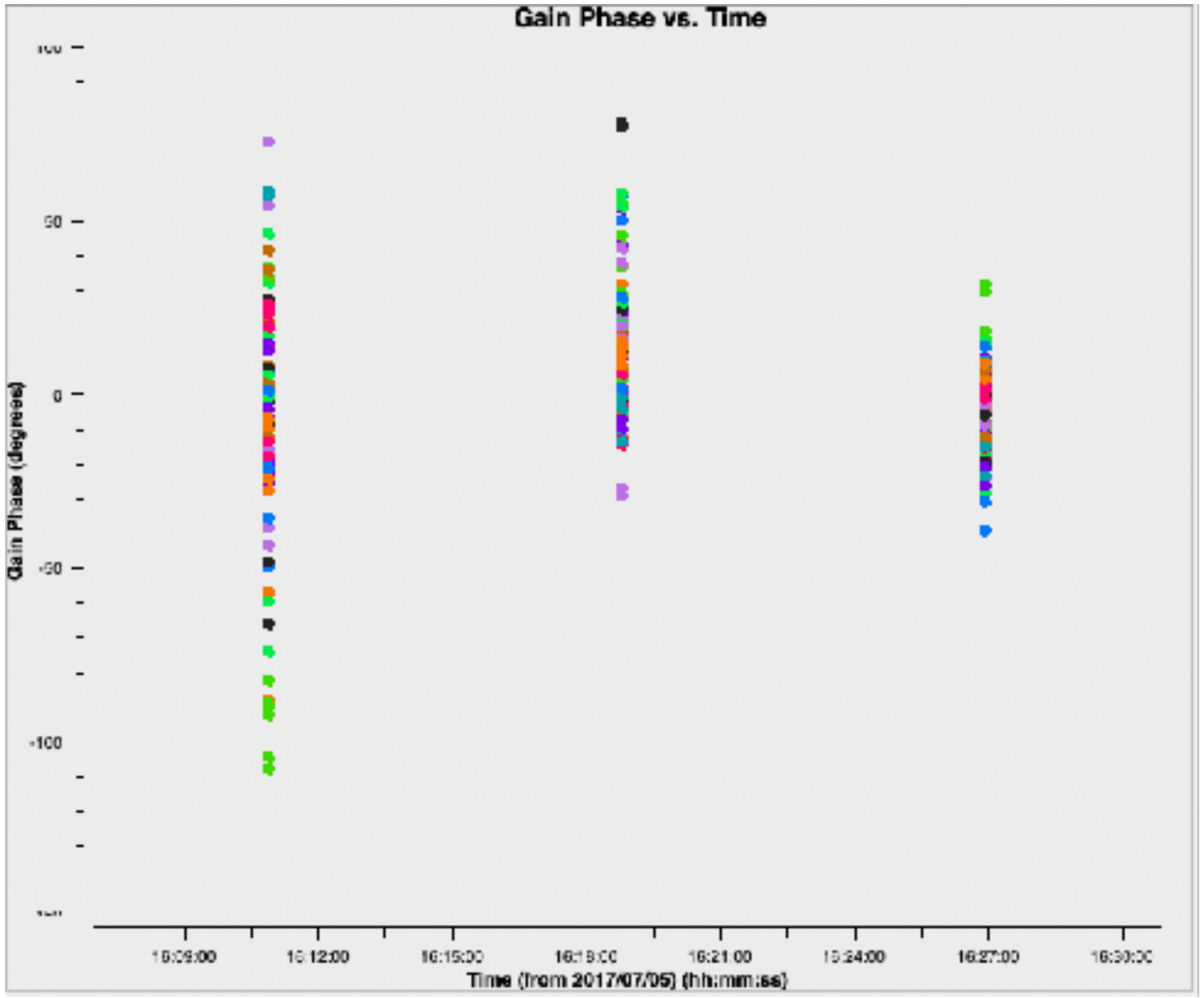


```
##########################################
##### Begin Task: clearcal           #####
 clearcal( vis='SPT0418.split.10s.cont.ms', field='', spw='', intent='', addmodel=False )
elvi(bool,bool)  Forcing use of OLD VisibilityIterator.
per      ****Using OLD VI driven calibrater tool****
per      Opening MS: SPT0418.split.10s.cont.ms for calibration.
 Initializing nominal selection to the whole MS.
etdata   Beginning selectvis  (MSSelection version)
eset     Reseting solve/apply state
electvis Performing selection on MeasurementSet
electvis Selection did not drop any rows
electvis Frequency selection: Selecting all channels in all spws.
eldata   chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect=''
g all model records in MS header.
nitcalset        Beginning initcalset--------------------------
L        Initializing MODEL_DATA (to unity) and CORRECTED_DATA (to DATA)
t        Initialized 259702 rows.
 Task clearcal complete. Start time: 2024-05-29 14:06:00.485868 End time: 2024-05-29 14:06
##### End Task: clearcal             #####
##########################################
```

Step 7: Derive better gain solutions

- Using the task "gaincal" we will derive 1 solution per scan. This time, you will have 3 solutions per antenna.

- gaincal(vis='mydata.ms', caltable='mydata.ms.p_scan', solint='inf', refant=['??','??'…], calmode='p', combine='spw', gaintable='mydata.ms.p_inf', spwmap=[0,0,0])

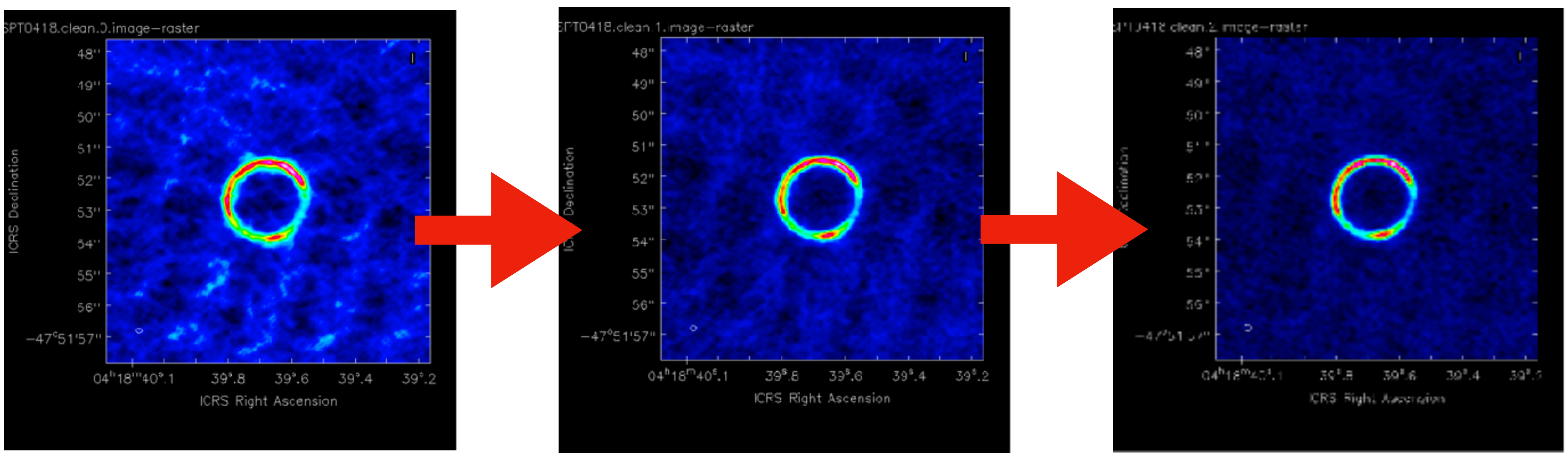


Step 8: Apply better gain solutions

- Using the task “applycal” we apply both calibration tables, passing them as a list
- applycal(vis=‘mydata.ms’, gaintable=[‘mydata.ms.p_inf’,’mydata.ms.p_scan’], spwmap=[[0,0,0],[0,0,0]])
- Remember, applycal will flag data with missing solutions!

Step 9: Make your final image

No self cal | combine="spw,scan" | combine="spw"



- Open with "imview" or CARTA and compare:
  - Rms noise
  - Peak flux density
  - Beam size

Final remarks

- For Cycle 10+ data, ALMA pipeline now attempts self-calibration. From current cycle, also for mosaics. But it is sometimes worth doing manual self-cal yourself to see if you can do a better job.
- Remember to set “pbcor=True” for your final image so you have the primary beam corrected image.
- If you have spectral line data, apply your calibration solutions to that, too!
- See also the i-TRAIN resources for another ALMA self-calibration tutorial: https://almascience.eso.org/euarcdata/itrain06/Self-Calibration_Basic.pdf

Free resources for the enthusiastic

- Richards et al. 2022, “Self-calibration and improving image fidelity for ALMA and other radio interferometers”, ALMA Memo 620 (link)
- Brogan et al. 2018, “Advanced Gain Calibration Techniques in Radio Interferometry”, Proceedings of the 2014 Synthesis Imaging Workshop (link)
- Taylor, Carilli & Perley, eds. 1999, “Synthesis Imaging in Radio Astronomy II”, Vol. 180, Astronomical Society of the Pacific Conference Series (link)
- Thompson, Moran & Swenson, 2017, “Interferometry and Synthesis in Radio Astronomy” (link)