ASTRON

Netherlands Institute for Radio Astronomy

Doing LOFAR imaging science

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(Many slides from Tim Shimwell)

ASTRON is part of the Netherlands Organisation for Scientific Research (NWO)

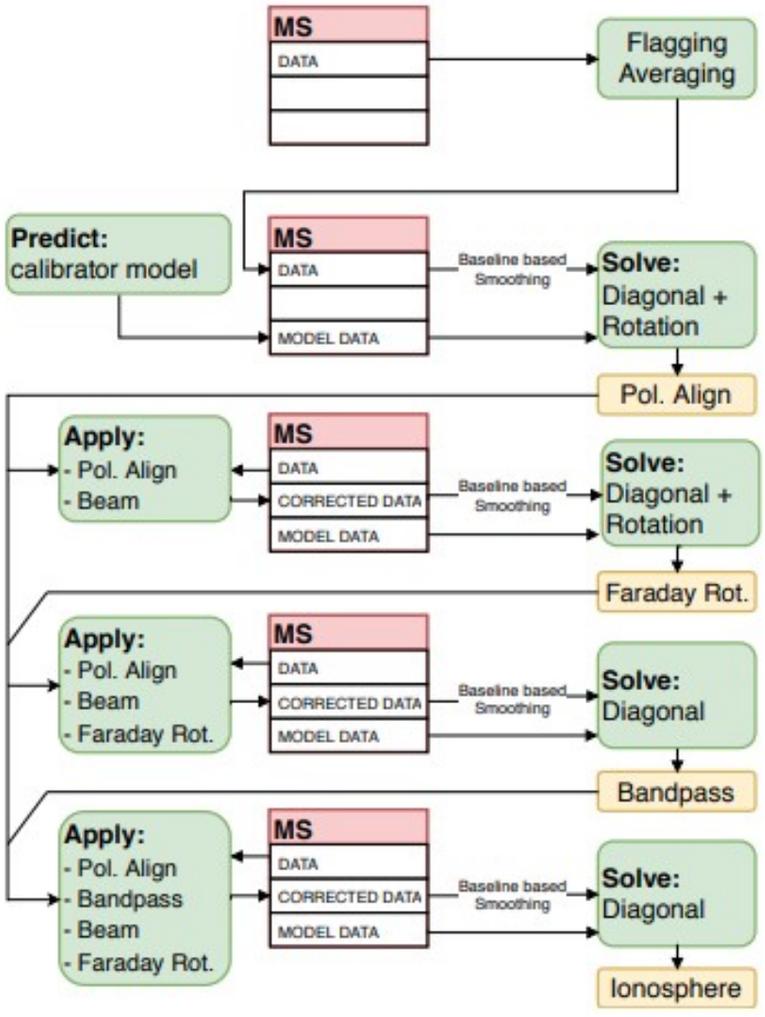
Scientific aims of the LOFAR surveys

Some issues with the LOFAR Two-metre Sky Survey (LoTSS)

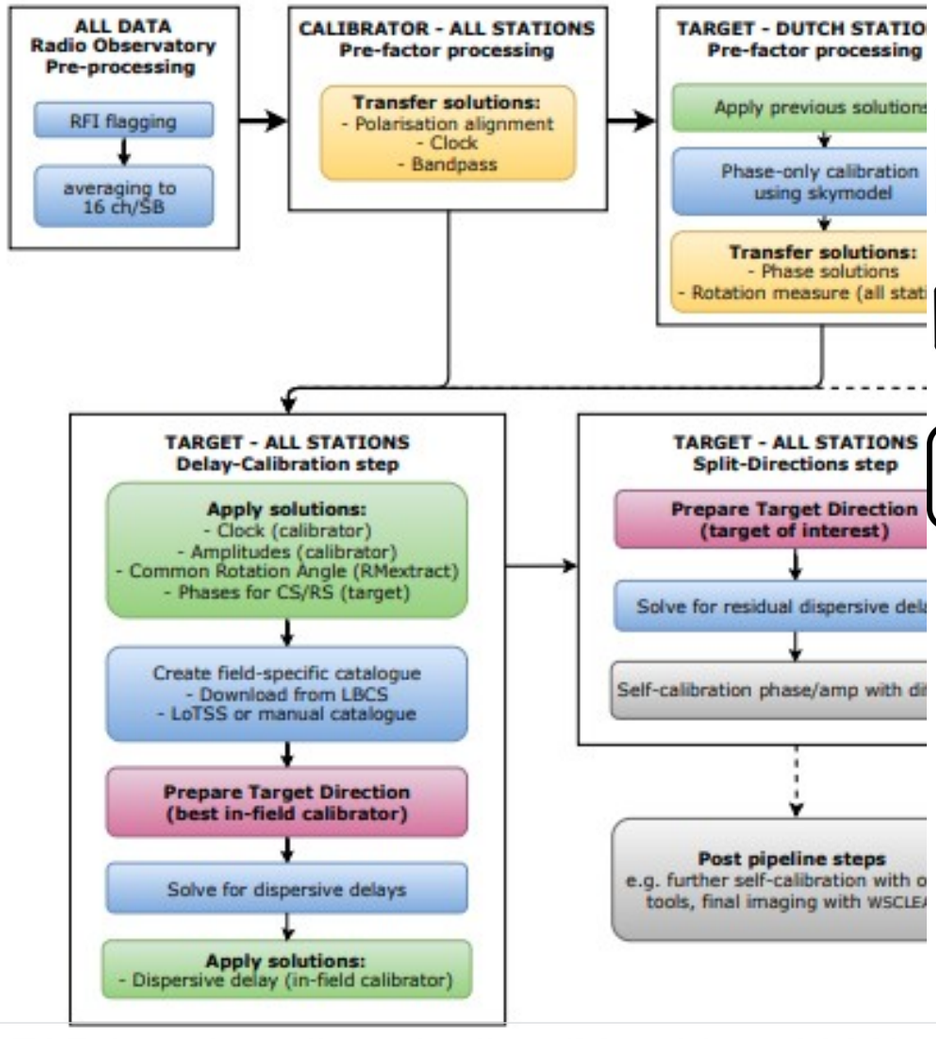
Failed calibration
Variations with declination
Flux density scale
In band spectral index
Point source sizes
Deconvolution
Diffuse emission
Polarisation leakage/fake sources
Galactic imaging
Processing challenges
Observing challenges…

How LOFAR images are produced

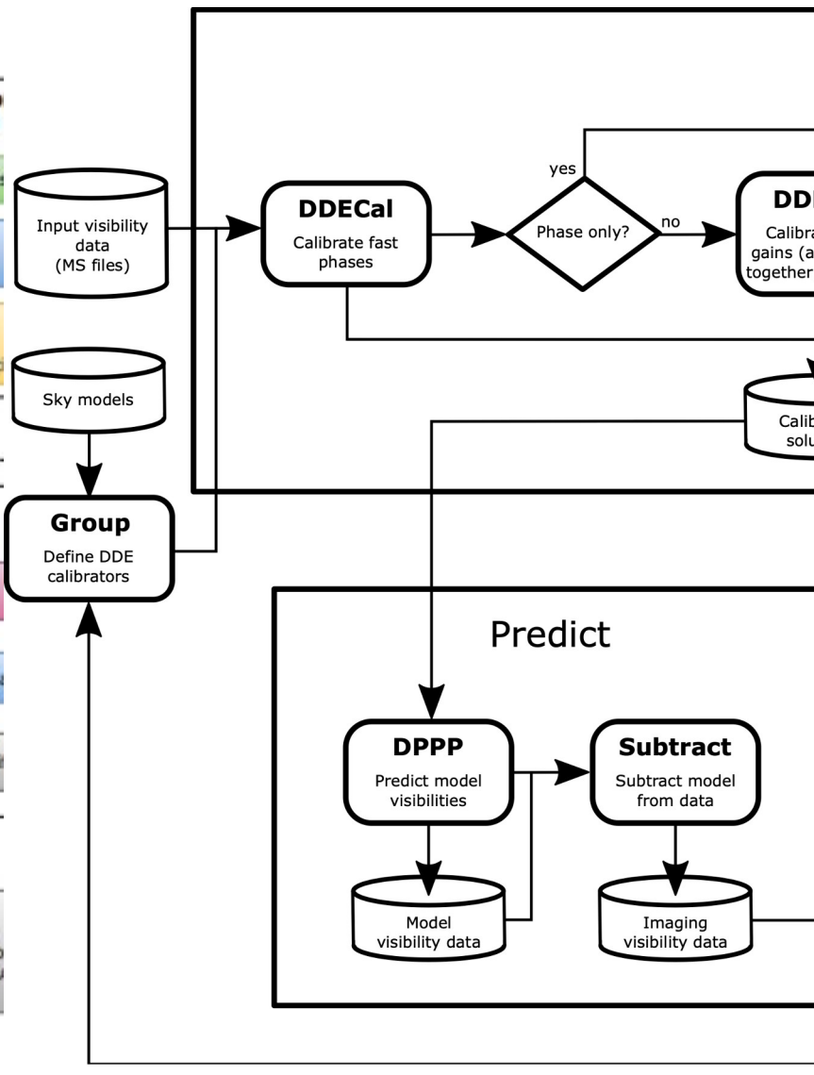
Significant efforts to lower entry barriers through pipelines that produce science ready products and even running these for users
Data are heavily processed!



LINC: LOFAR initial (direction independent) calibration pipeline (de Gasperin 2021)



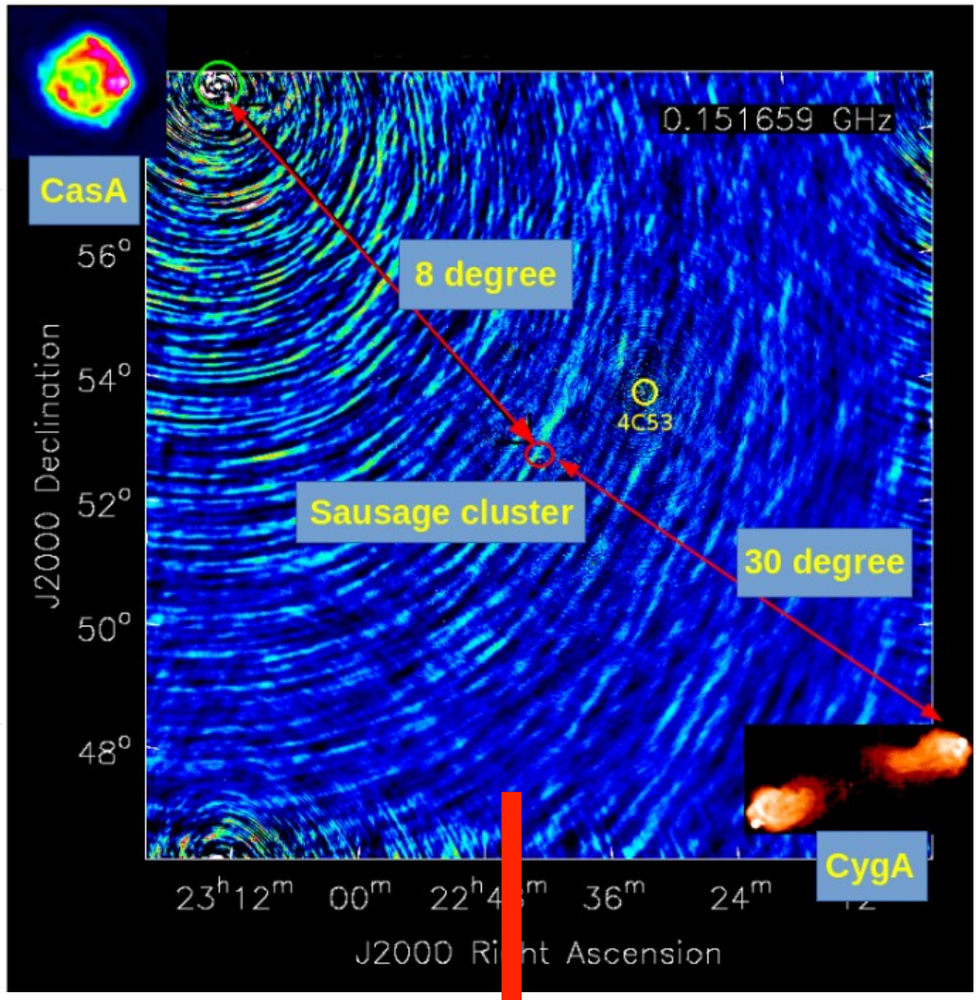
LOFAR long baseline pipeline (Morabito+ 2022)

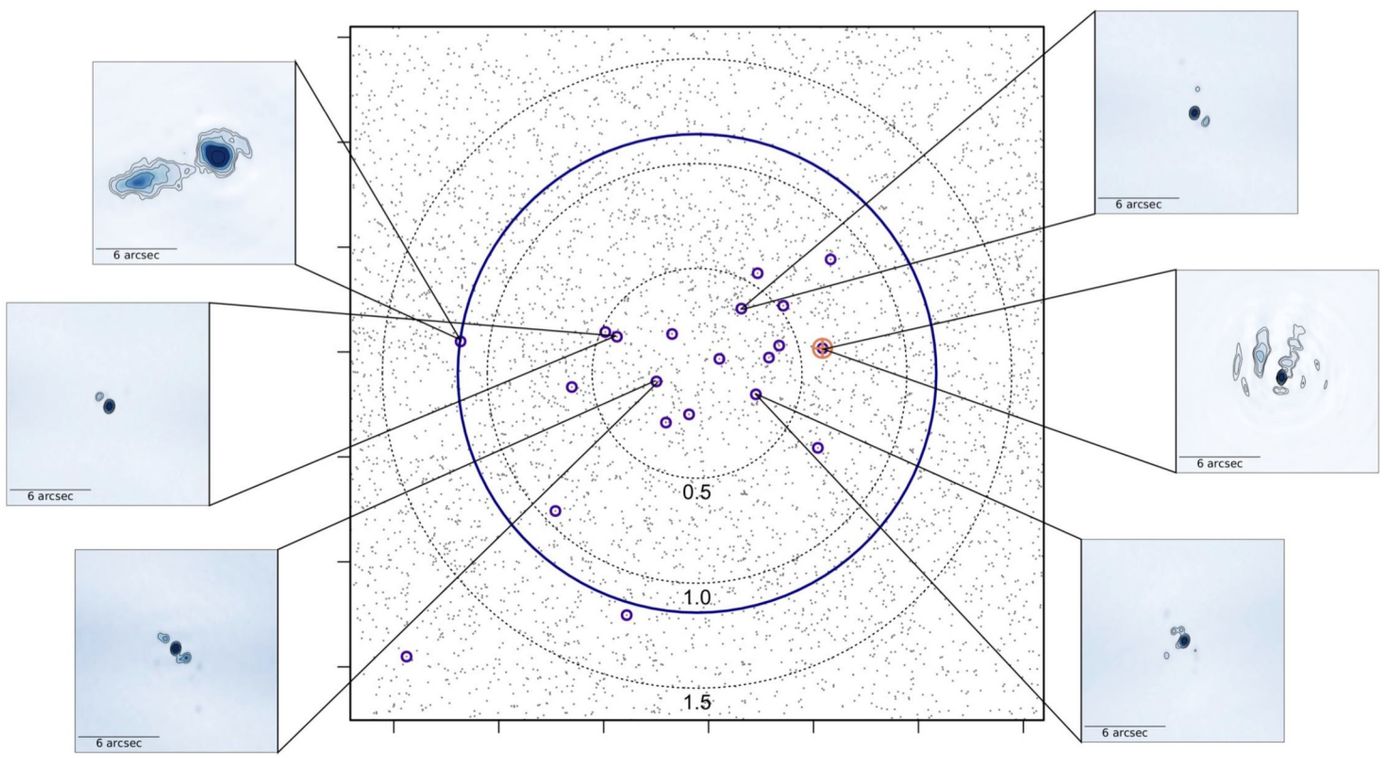


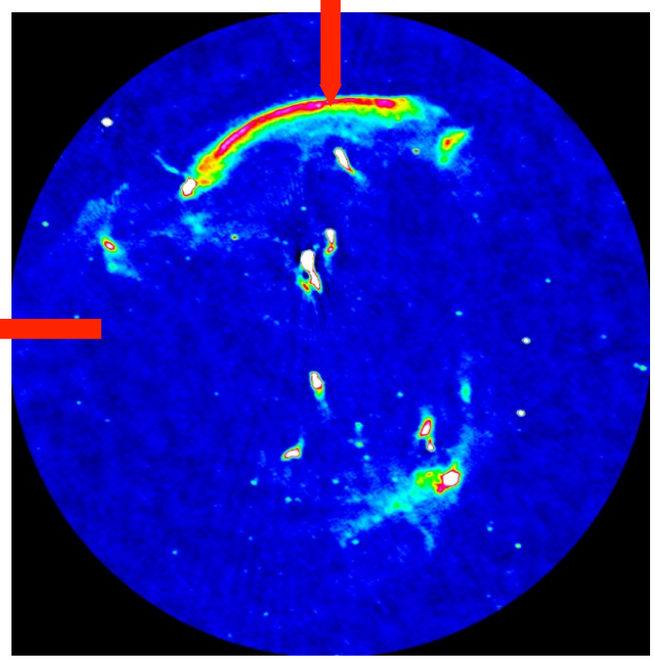
Rapthor HBA NL pipeline
or DDF

How LOFAR images are produced

After about 10-20K core hours a Netherlands-only wide-field LOFAR image is created
After about 100-200K core hours a full ILT resolution wide field can be created (far cheaper if just doing a small region of the sky)







How LOFAR images are produced

During the imaging generally several different products are produced (or sometimes input) and are useful to examine image properties:

Dirty image - the image still convolved by the PSF

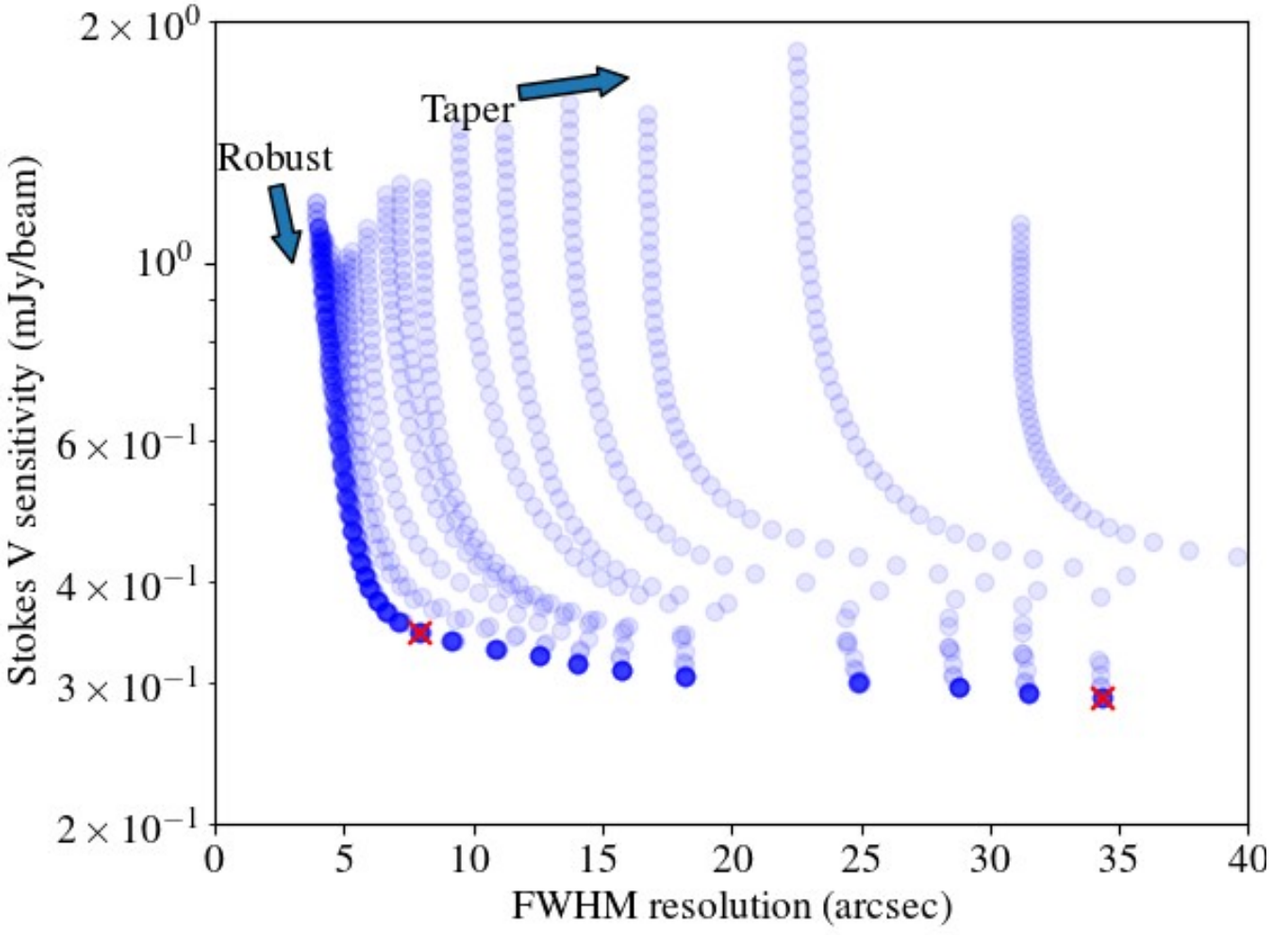
Mask image - tells the imager where to deconvolve

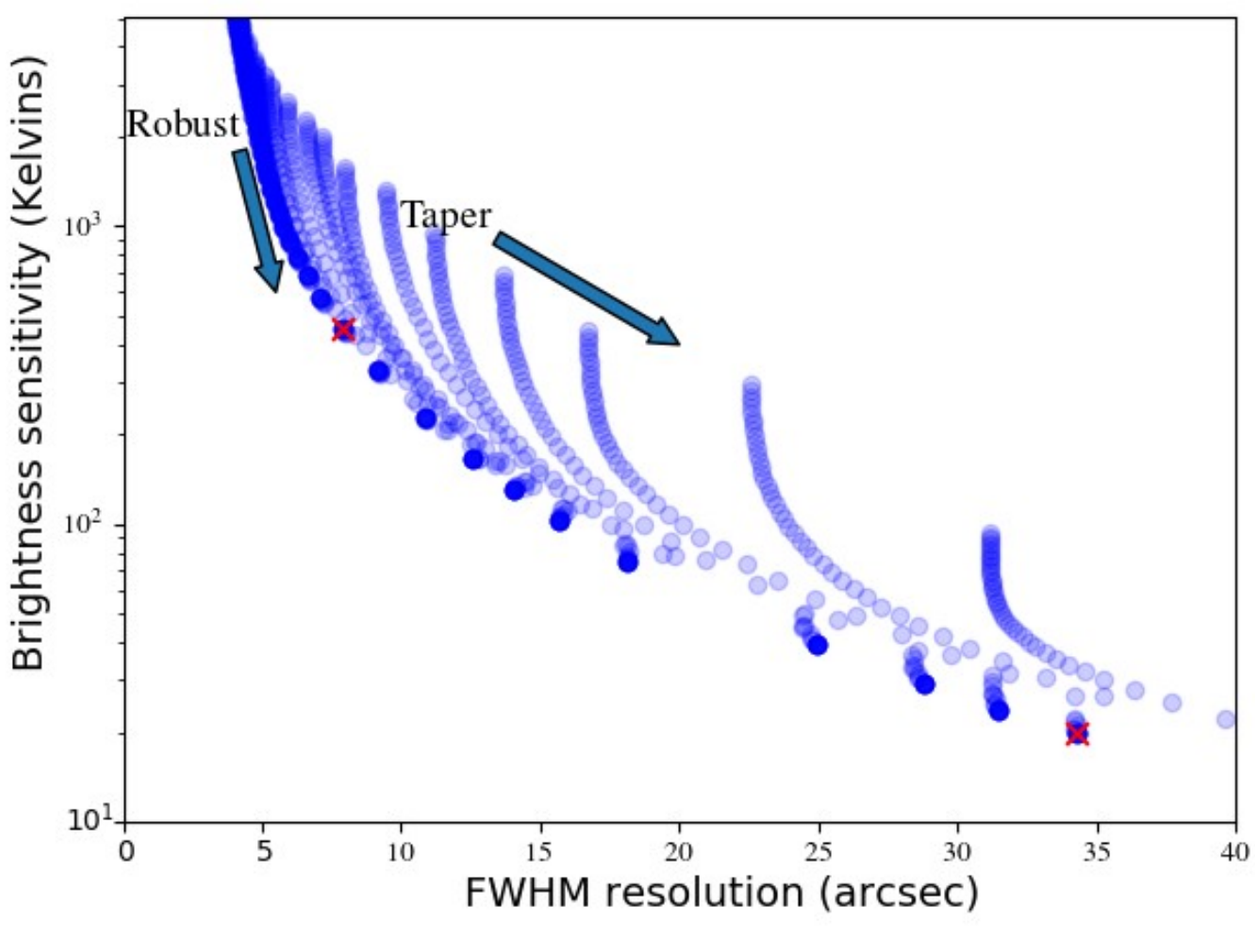
Model image - the clean components from the image

Residual image - image after subtracting clean components multiplied by PSF from dirty image (a noise-like image)

Final image - Residual image + model image convolved by restoring beam.

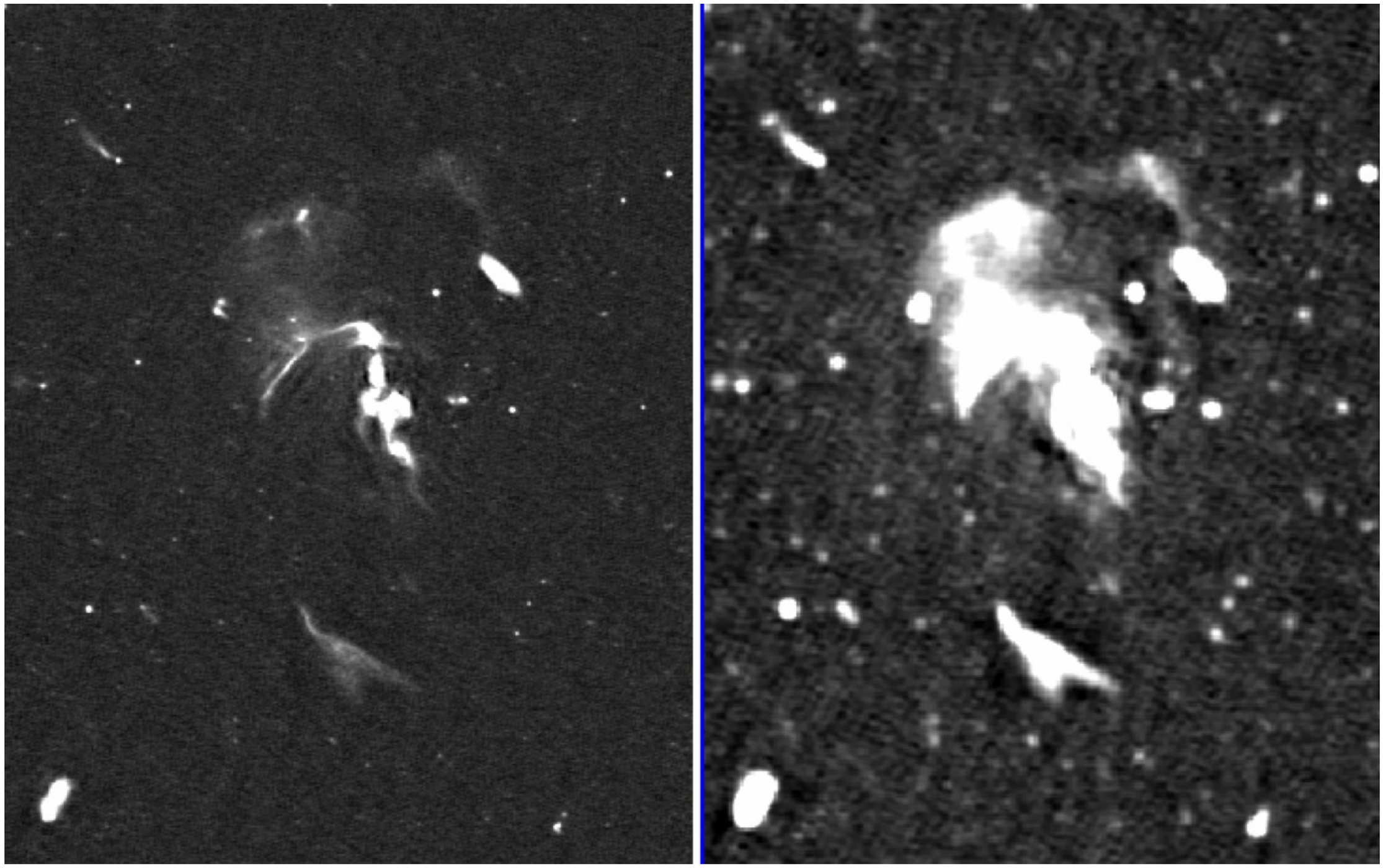
Image production - resolution versus surface brightness sensitivity





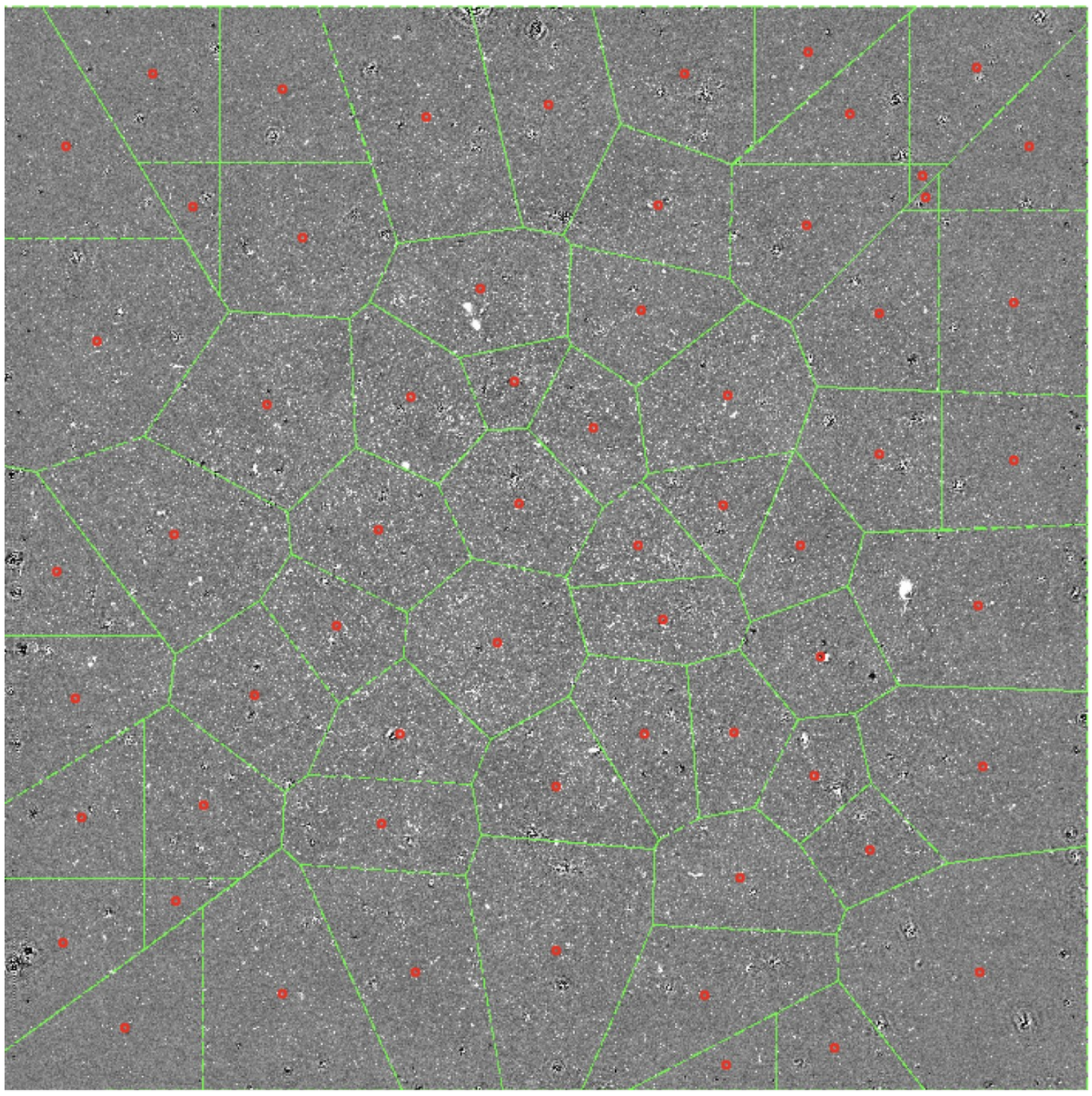
One image cannot necessarily do all the science — You can image data with various weighting of the visibilities to optimise for surface brightness sensitivity or point-source sensitivity.

Image production - resolution versus surface brightness sensitivity



E.g. the galaxy cluster Abell 2034 imaged at high resolution optimised for point-sources (6”; left) or lower resolution for better surface brightness sensitivity (20”; right)

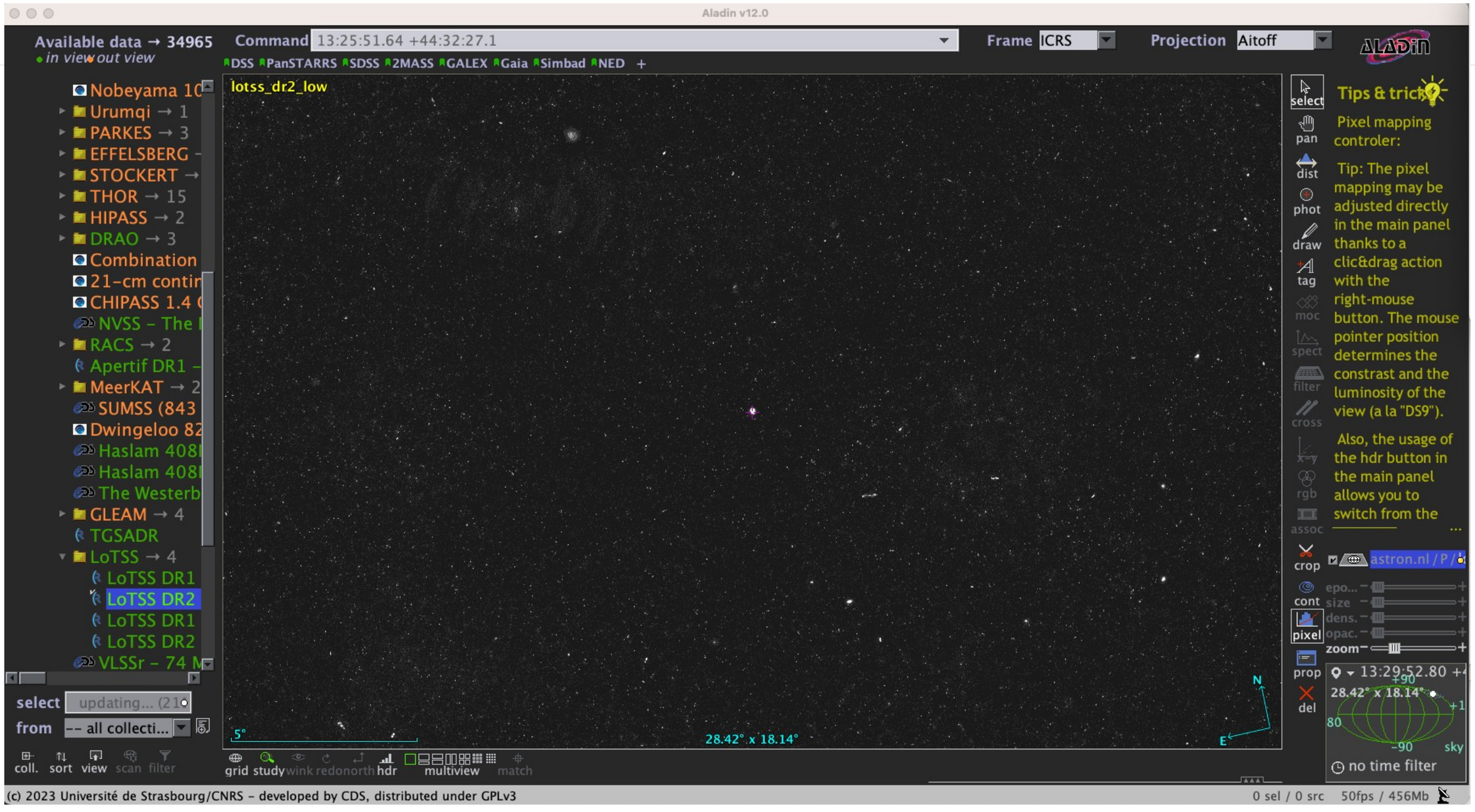
Image production - resolution versus surface brightness sensitivity



Due to ionospheric variations images are created with direction dependent calibration where the target field is split into many different facets. Different facets can have different properties.

Visualising LOFAR images

Many tools for visualising radio data. Good place to start for wide-area public images is Aladin which contains images from several large radio surveys - https://aladin.cds.unistra.fr/
Or for viewing images where you have .fits files ds9 (https://sites.google.com/cfa.harvard.edu/saoimageds9) or CARTA may be more convenient.



Cataloguing LOFAR images

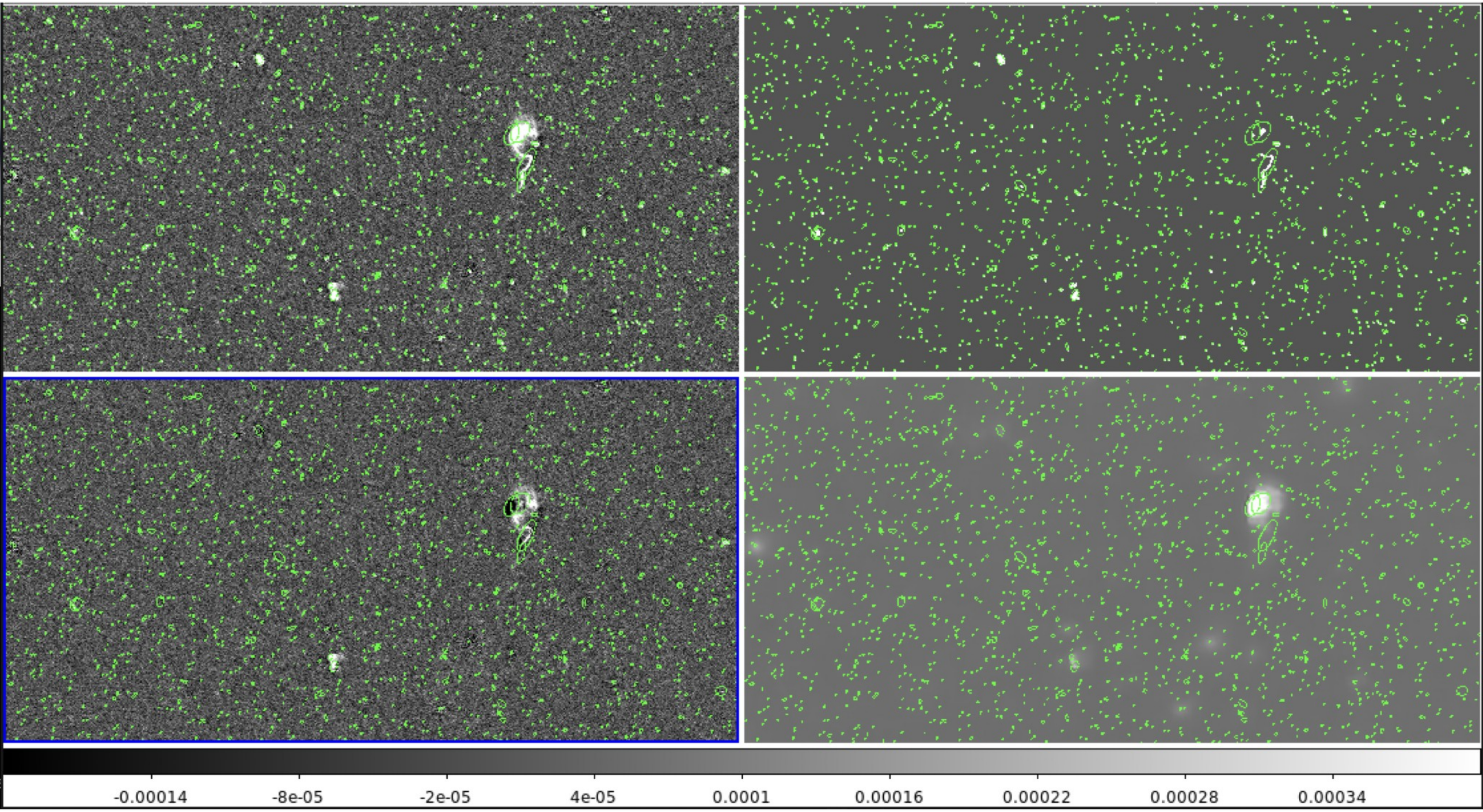
Generally PyBDSF (https://pybdsf.readthedocs.io/en/latest/) is used for cataloguing LOFAR images.

Typical settings:

```
  img = bdsf.process_image(imf, detection_image=appf, thresh_isl=4.0,
thresh_pix=5.0, rms_box=(150,15), rms_map=True, mean_map='zero',
ini_method='intensity', adaptive_rms_box=True, adaptive_thresh=150,
rms_box_bright=(60,15), group_by_isl=False, group_tol=10.0,
output_opts=True, output_all=True, atrous_do=True, atrous_jmax=4,
flagging_opts=True, flag_maxsize_fwhm=0.5,advanced_opts=True,
blank_limit=None, frequency=restfrq)
```

Note that “imf” is primary beam corrected whereas “appf” is apparent flux.
And allows you to write out source lists, Gaussian components, rms maps, source finding residual maps, source finding mask maps, DS9 region files, DP3 compatible source lists.

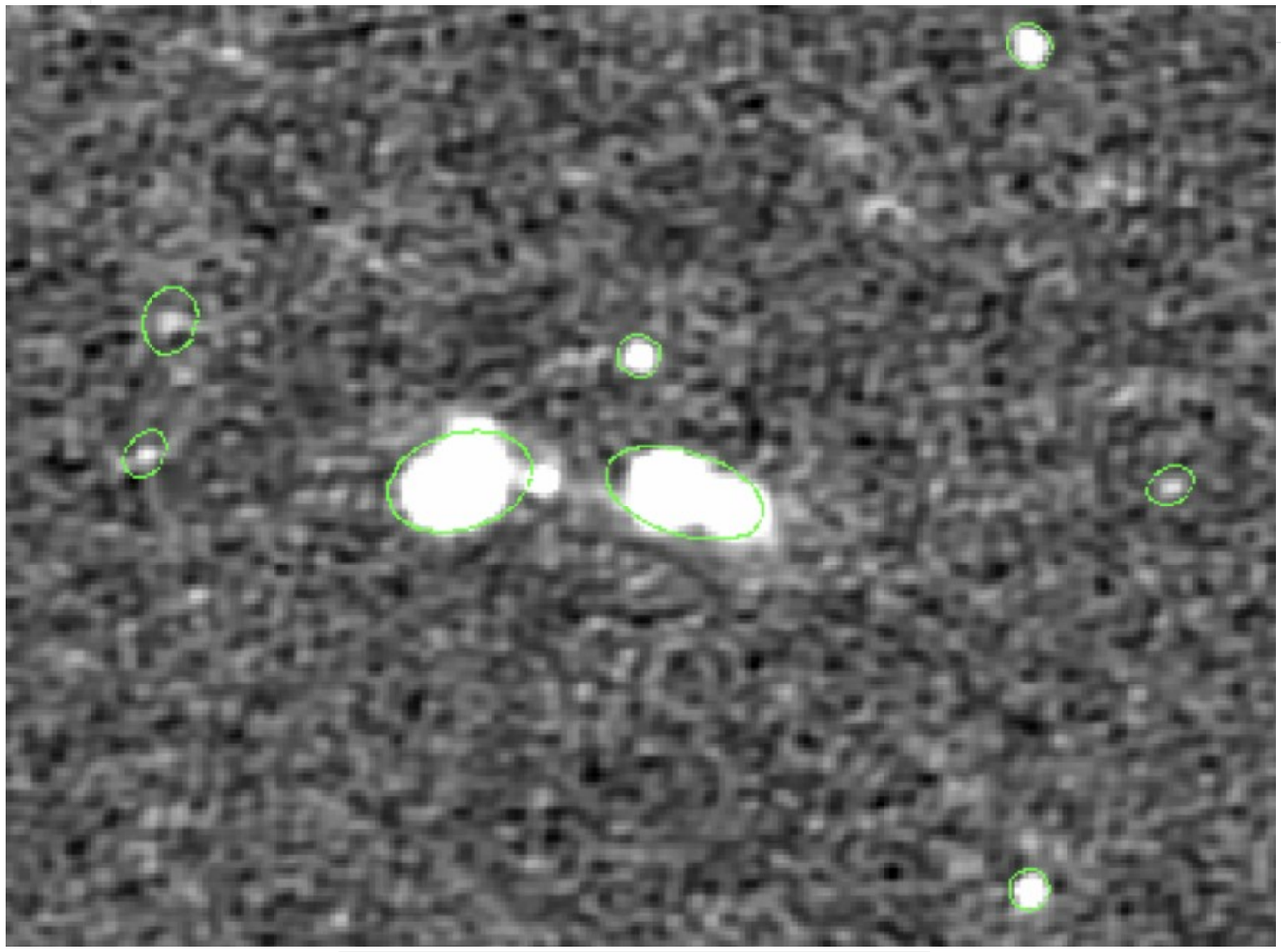
Cataloguing LOFAR images



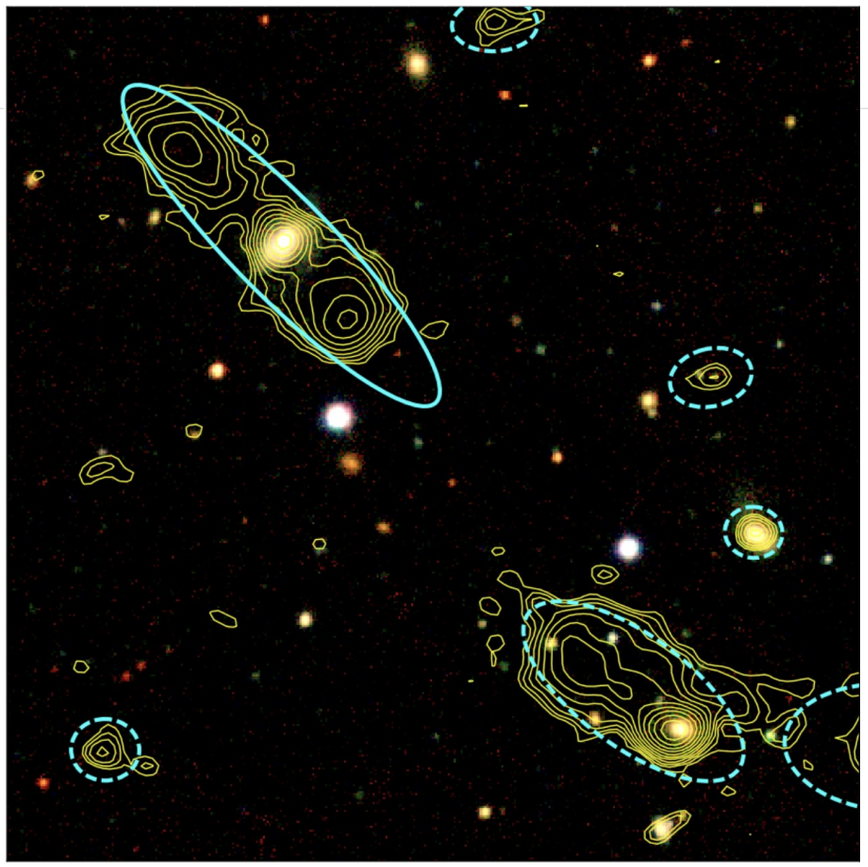
Clockwise from top left: image, PyBDSF mask, PyBDSF residual, PyBDSF rms map.

Cataloguing LOFAR images

Clear issues in e.g. source association which requires manual/automated intervention to group components into real sources. Similarly to get optical IDs and redshifts.



PyBDSF “sources”



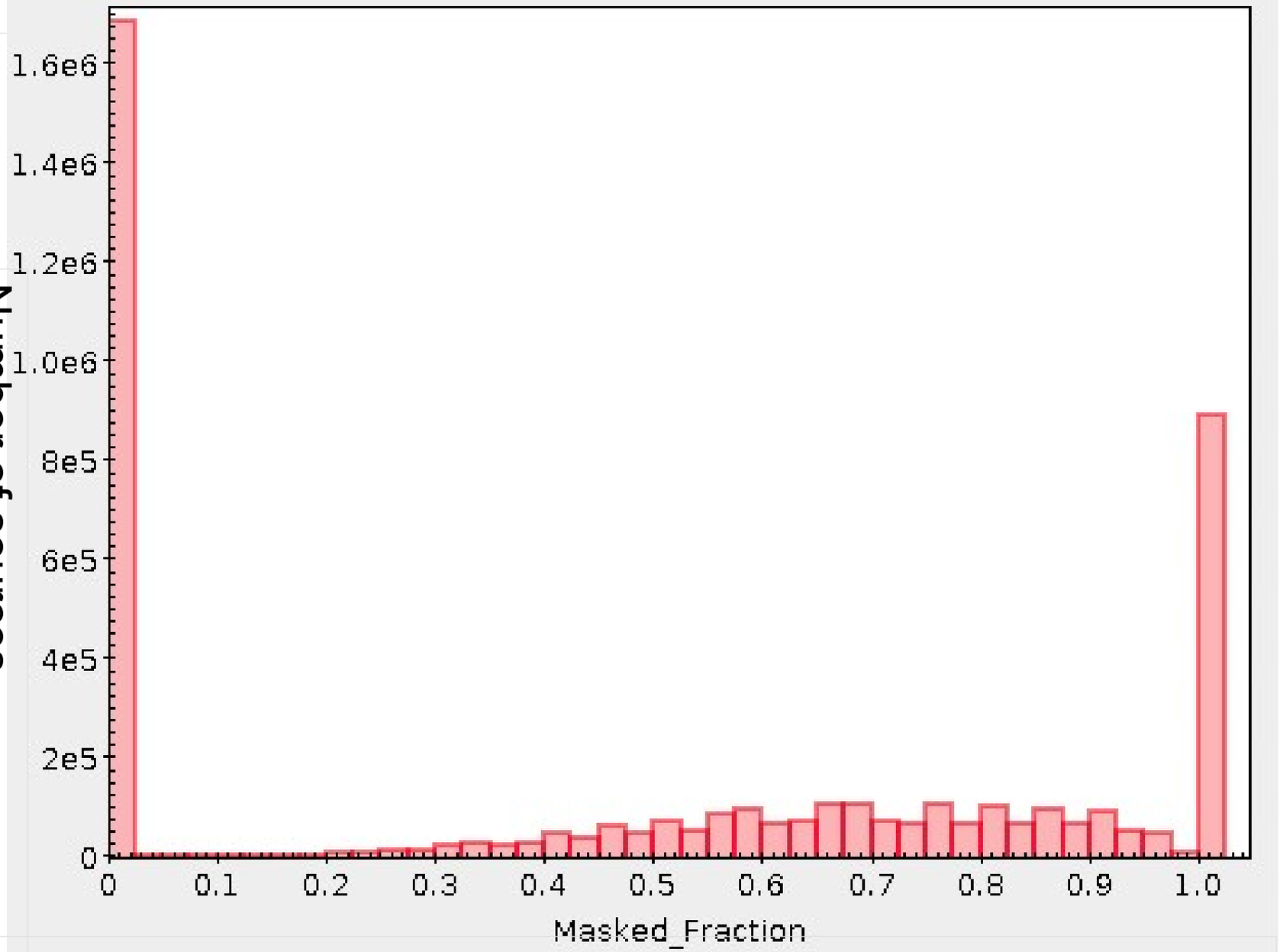
LOFAR galaxy zoo to link components and find optical counterparts (https://www.zooniverse.org/projects/chrismrp/radio-galaxy-zoo-lofar)

Some other issues include characterisation of complex sources and inaccurate noise estimates when source density is v.high (can manually give noise image)

Image fidelity - deconvolution

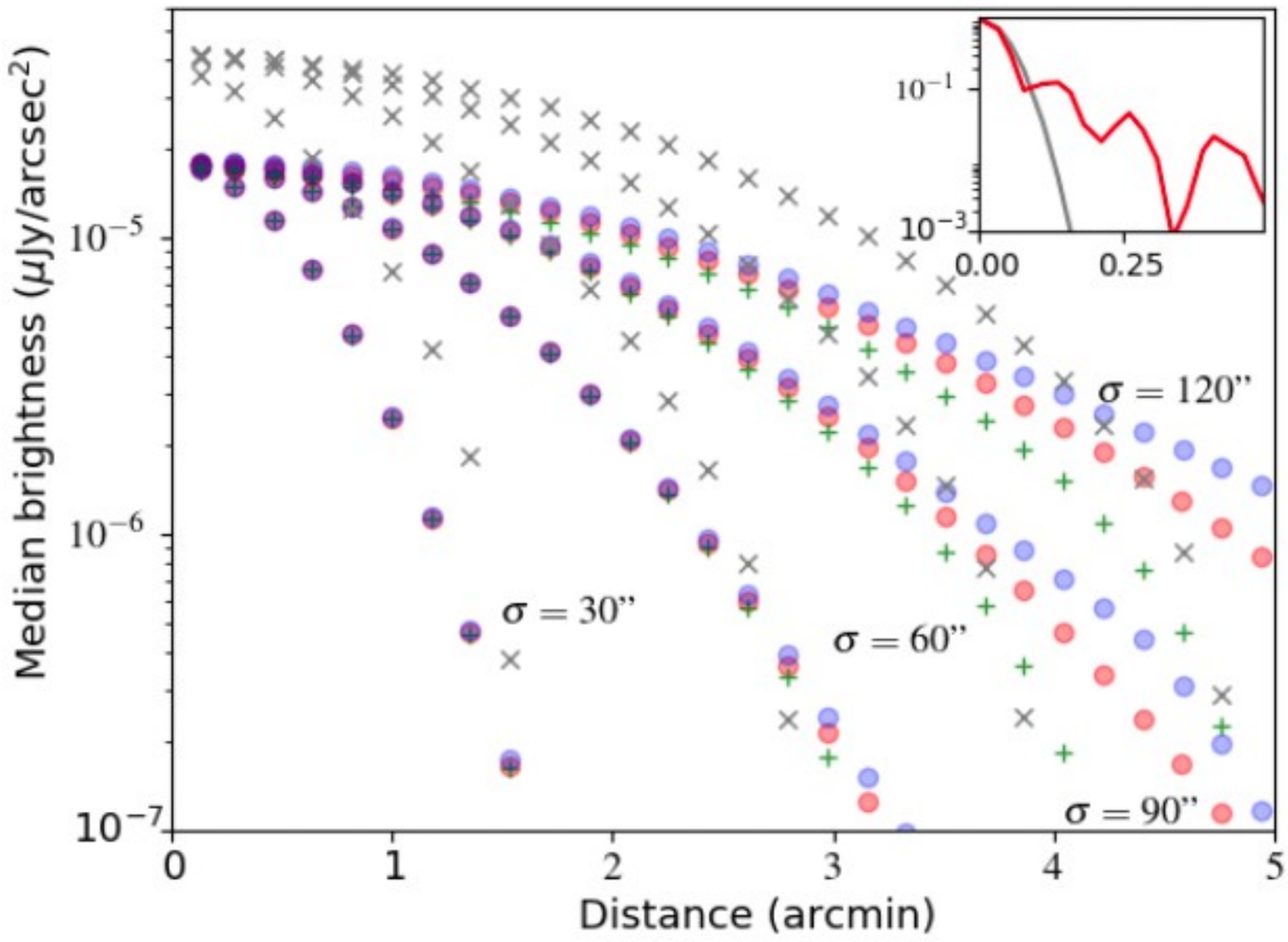
Deconvolving sources is important otherwise they are still convolved with the PSF on the restored image. Often images are formed by combining individual pointings that form a fairly tight mosaic.

In the LOFAR surveys only 20% of sources are fully deconvolved. 38% are not deconvolved at all. For point sources, this impacts morphology and adds noise.



(if source is deconvolved in all contributing pointings)

Image fidelity - deconvolution



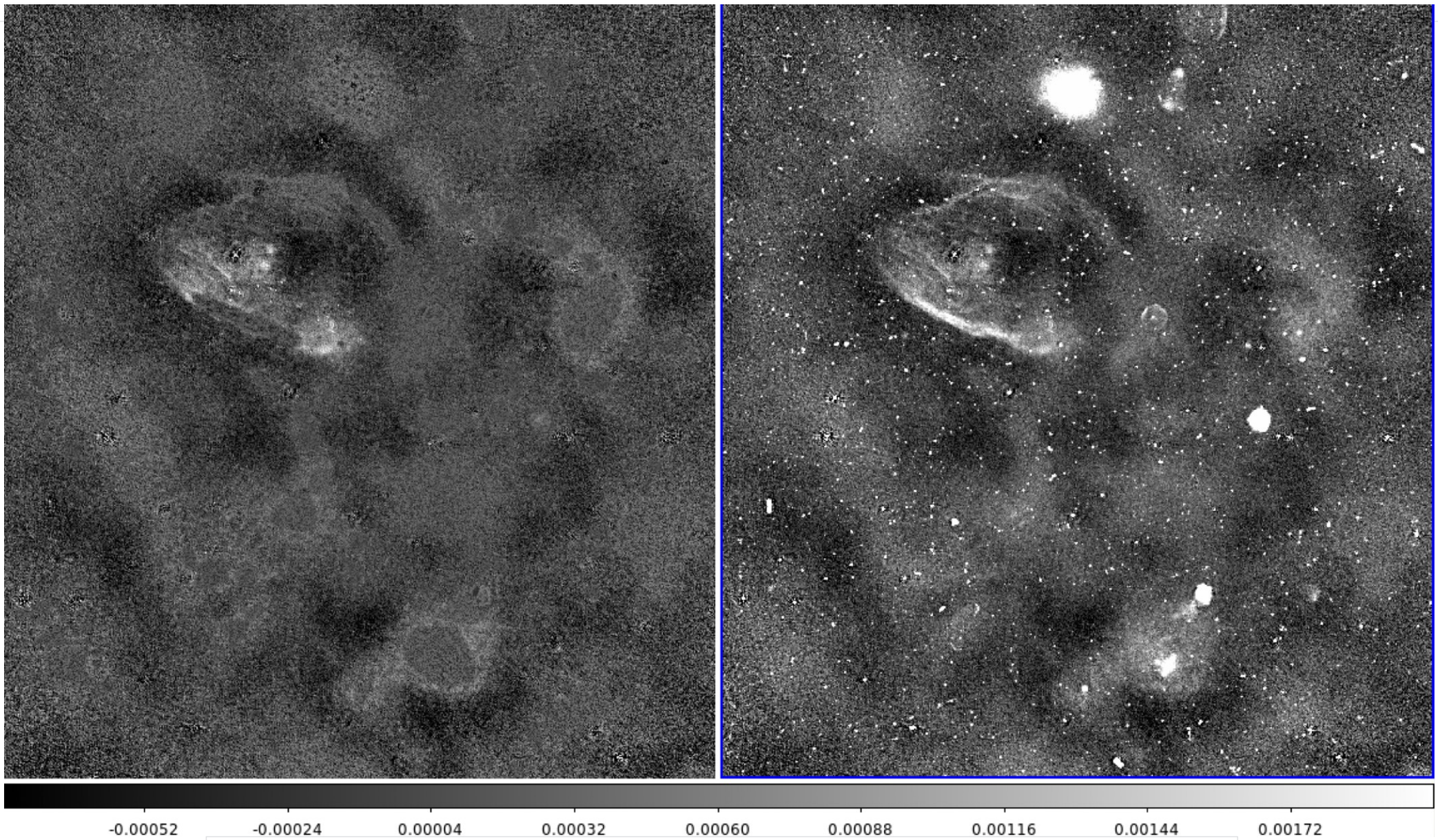
Red o - simulated source profile
Blue o - recovered source profile (in cleaned restored image)
Green + - removed model image (from cleaning) convolved with gaussian
Grey x - Measurement from undeconvolved map

Diffuse source flux measurements are severely wrong (factors >2) or highly misleading for undeconvolved emission.

Image fidelity - deconvolution

How to check the deconvolution?

In addition to the “restored” image (right panel) imagers generally output a “residual” image (left panel) which in the ideal case is noise-like.



Example of emission left in residual image

Image fidelity - sensitivity

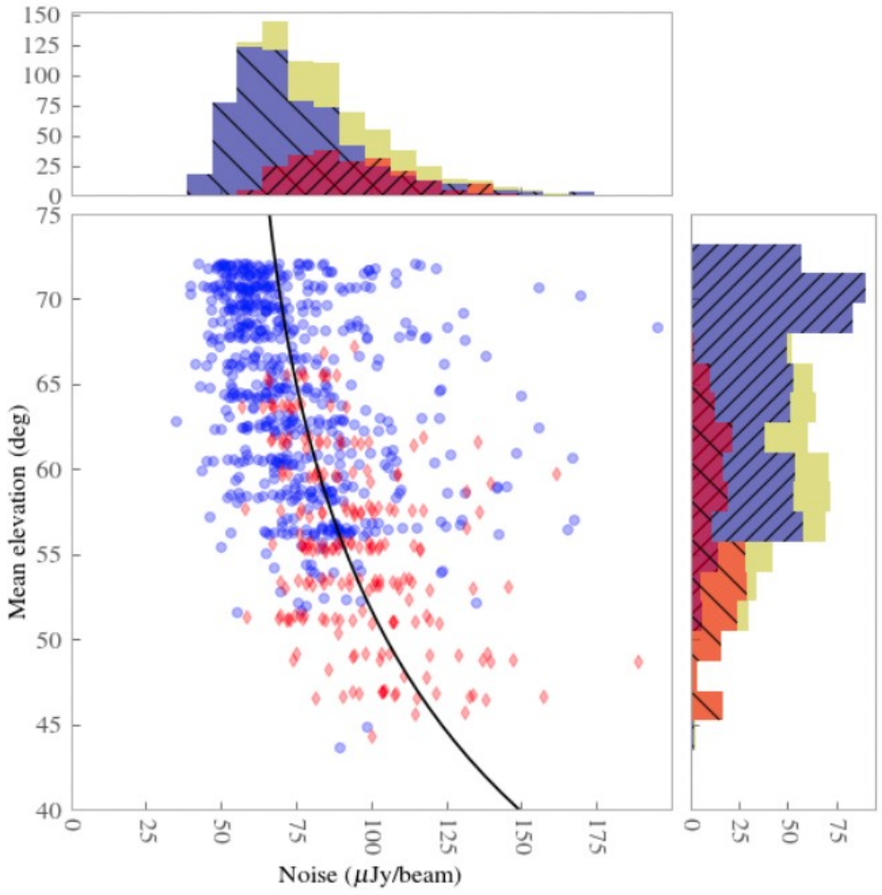
The ☆

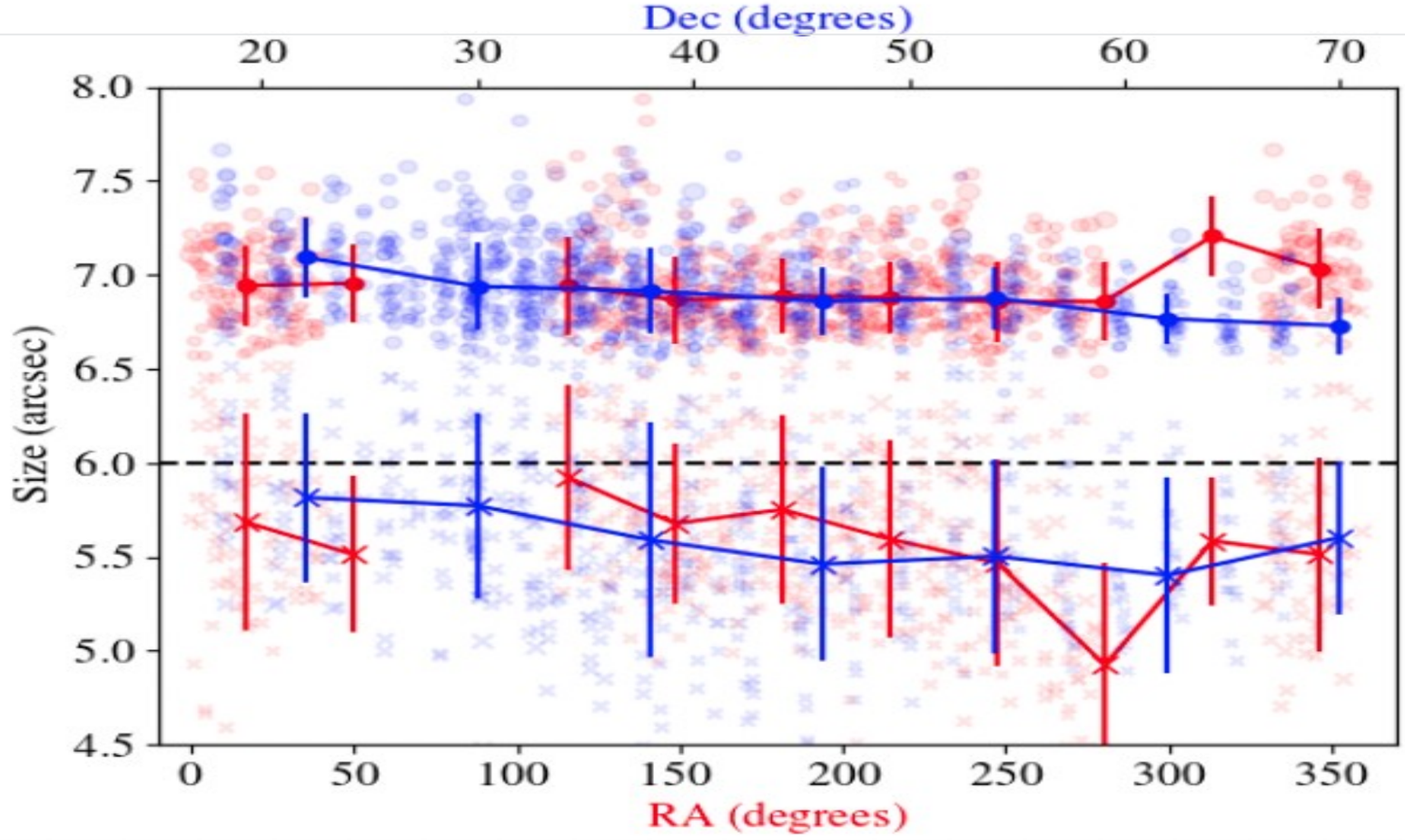


☆

In sensitivity we see the expected 1/cos(ZA)^2 behaviour (roughly). Also compensated for a little by 12hrs (instead of 8) at dec < 20 and larger overlap between pointings due to bigger beam.

For source sizes the PSF gets correspondingly larger with decreasing declination.

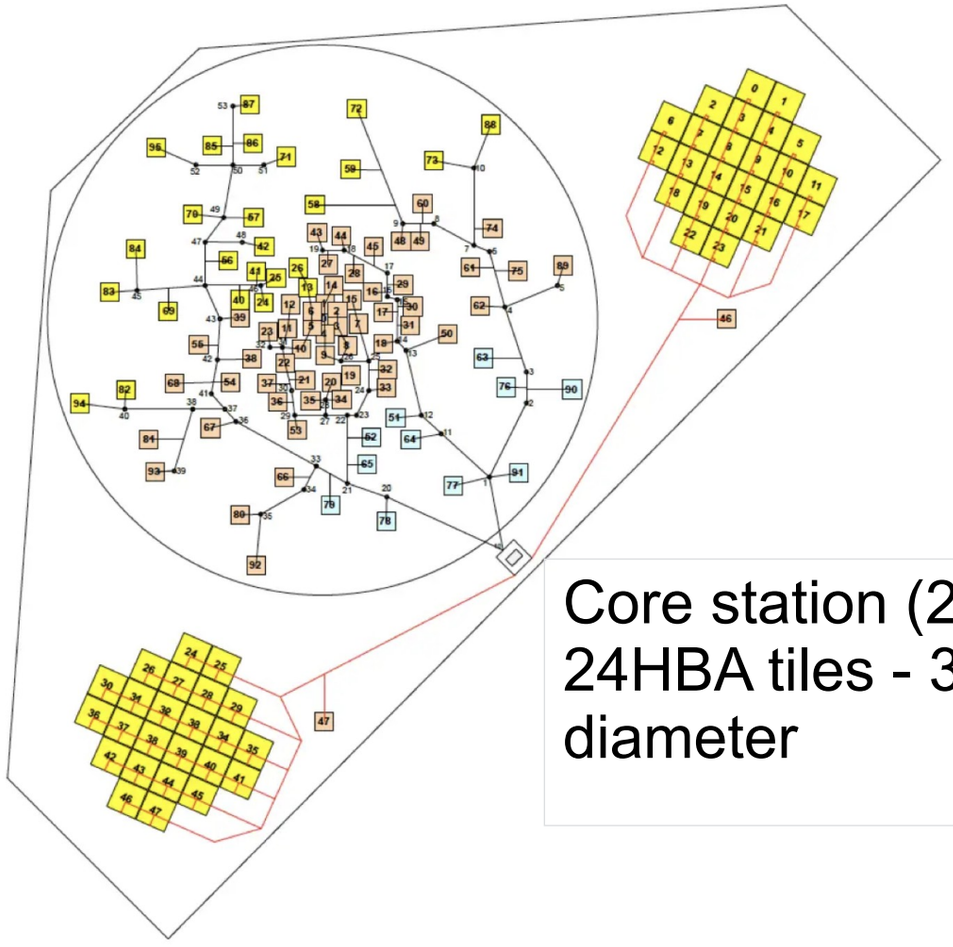




Increased ionospheric effects likely also play some role.

Image fidelity - sensitivity

LOFAR has 24 core stations and 14 remote stations and observations can be taken in different modes (see https://science.astron.nl/telescopes/lofar/lofar-system-overview/technical-specification/lofar-stations/). Example:
HBA dual — Collecting area NL only - 120,000 square metres
HBA dual inner - Collecting area NL only - 100,000 square metres
LOFAR 2.0 can use HBA and LBA at the same time.



Core station (2x 24HBA tiles - 31m diameter

Remote station (48 HBA tiles - 41m diameter

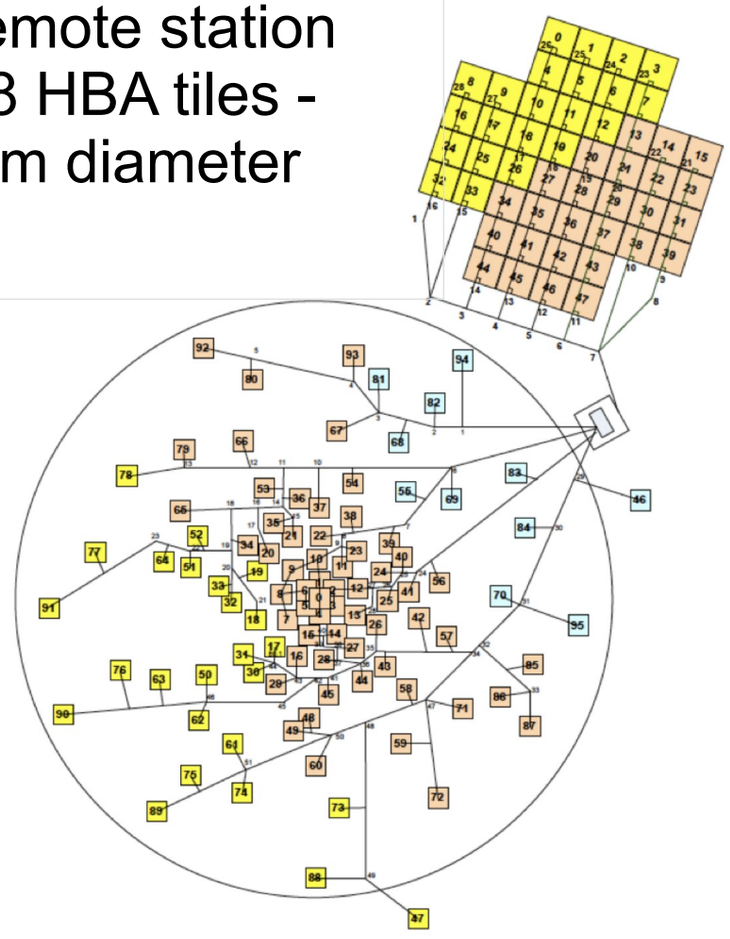
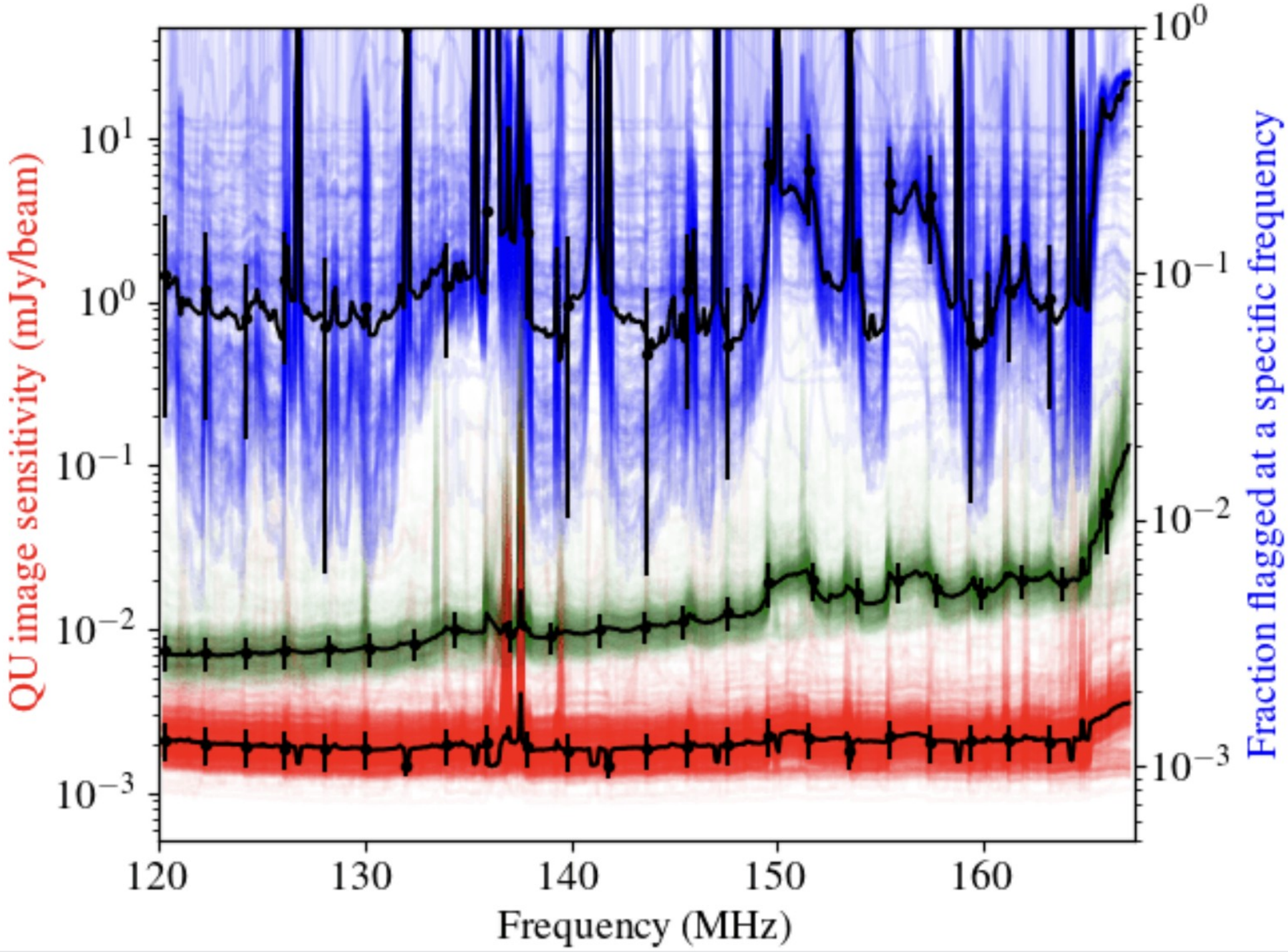


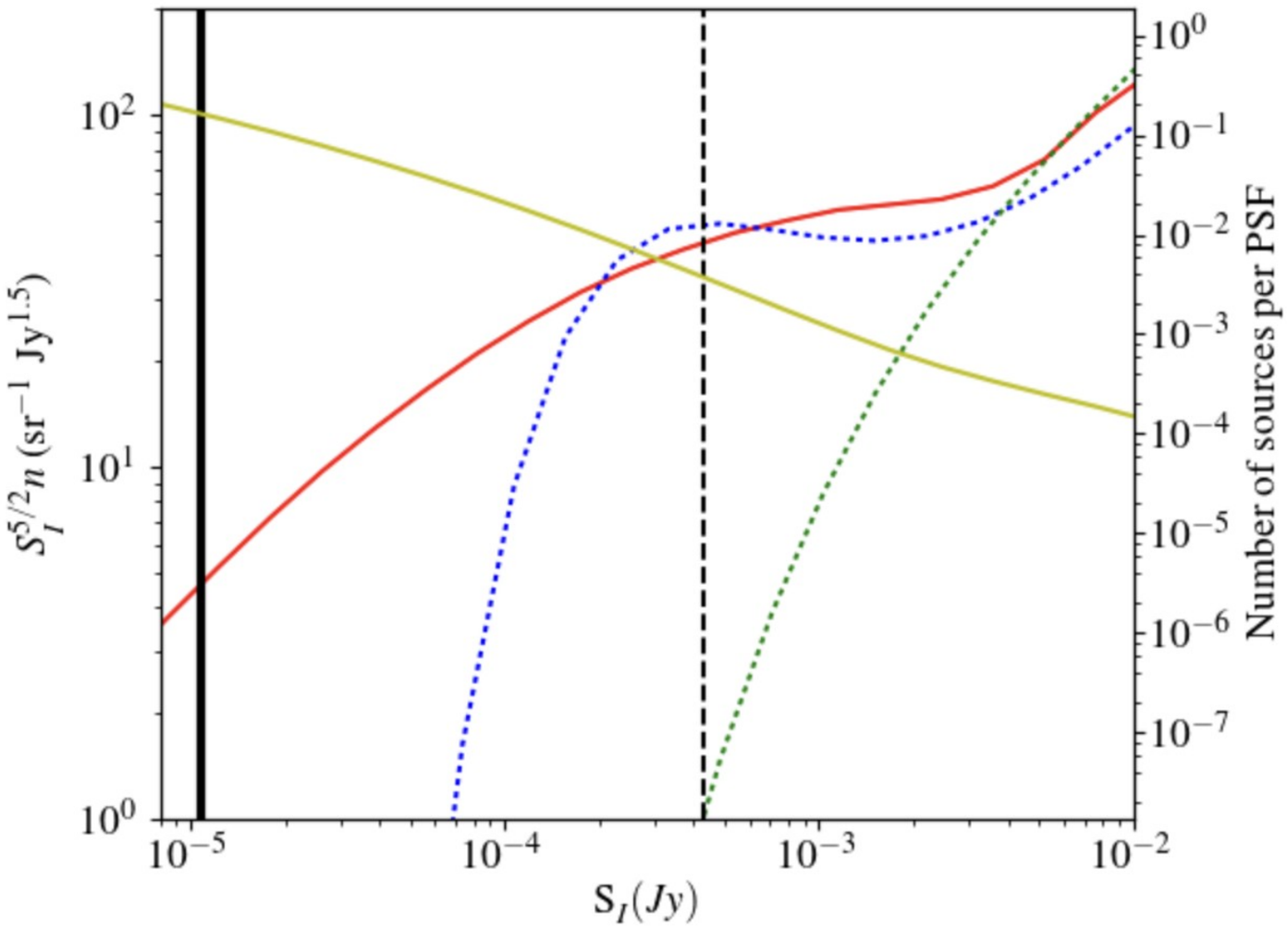
Image fidelity - sensitivity



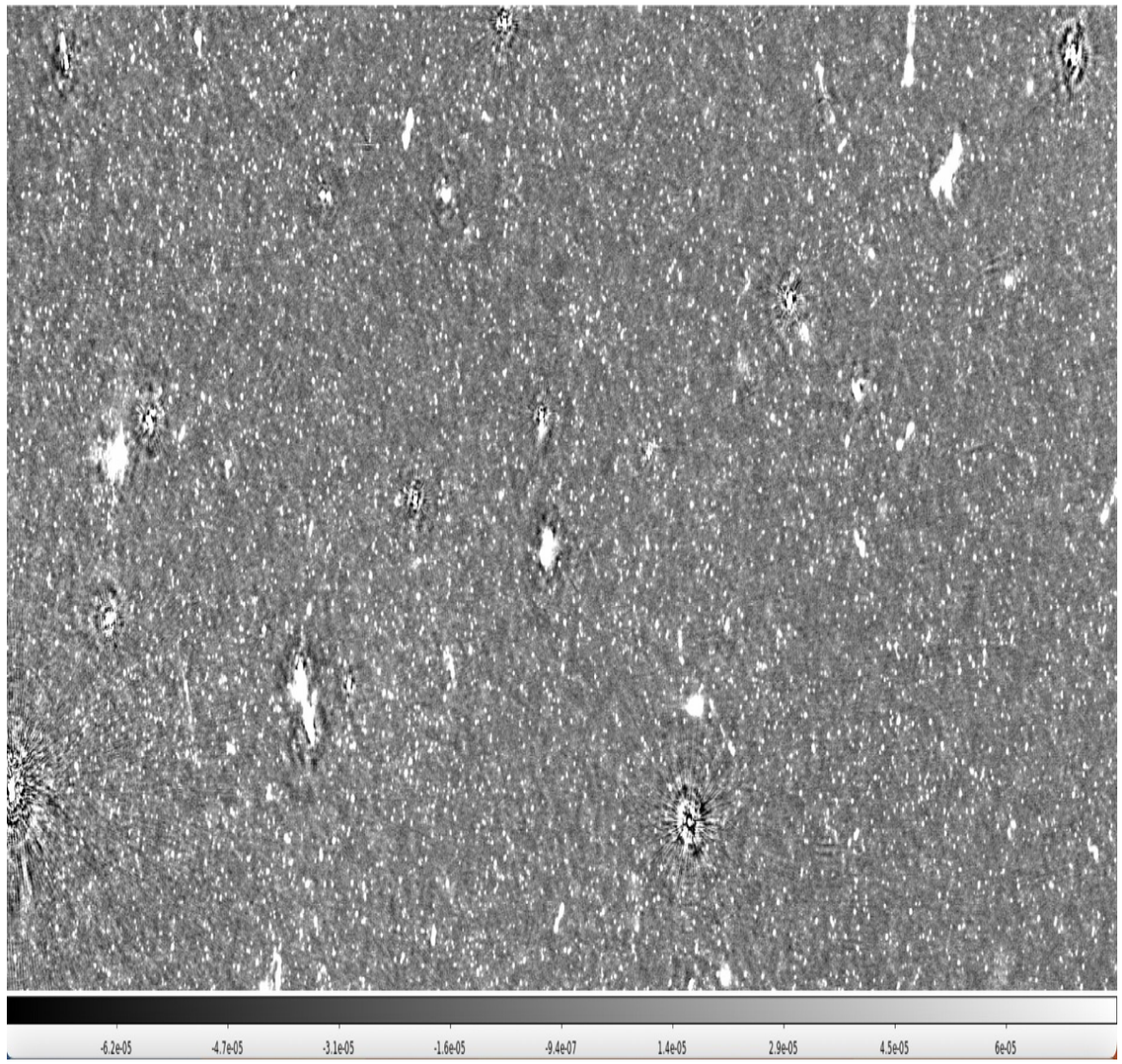
Amount of data flagged due to interference can vary a lot between observations. Generally ~10-20% but some frequencies far worse than others.

Image fidelity - sensitivity

Confusion noise is formed by the population of faint sources with flux densities below some detection/deconvolution threshold.



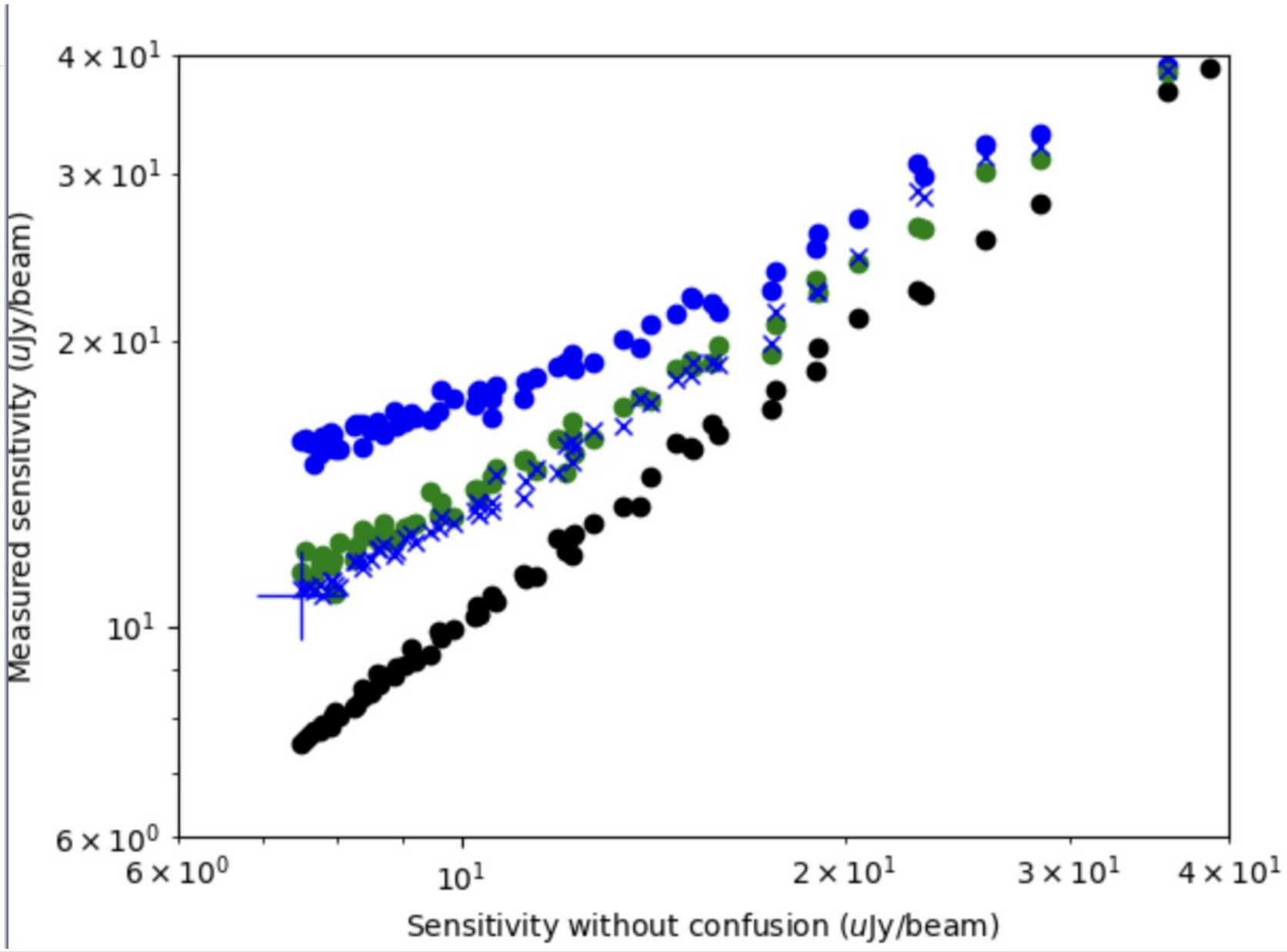
Source counts - Red is source counts (left y-axis). Yellow is number of sources per PSF (right y-axis). Solid black vertical is image sensitivity.



Deep (12uJy/beam) ELAIS map at 6”

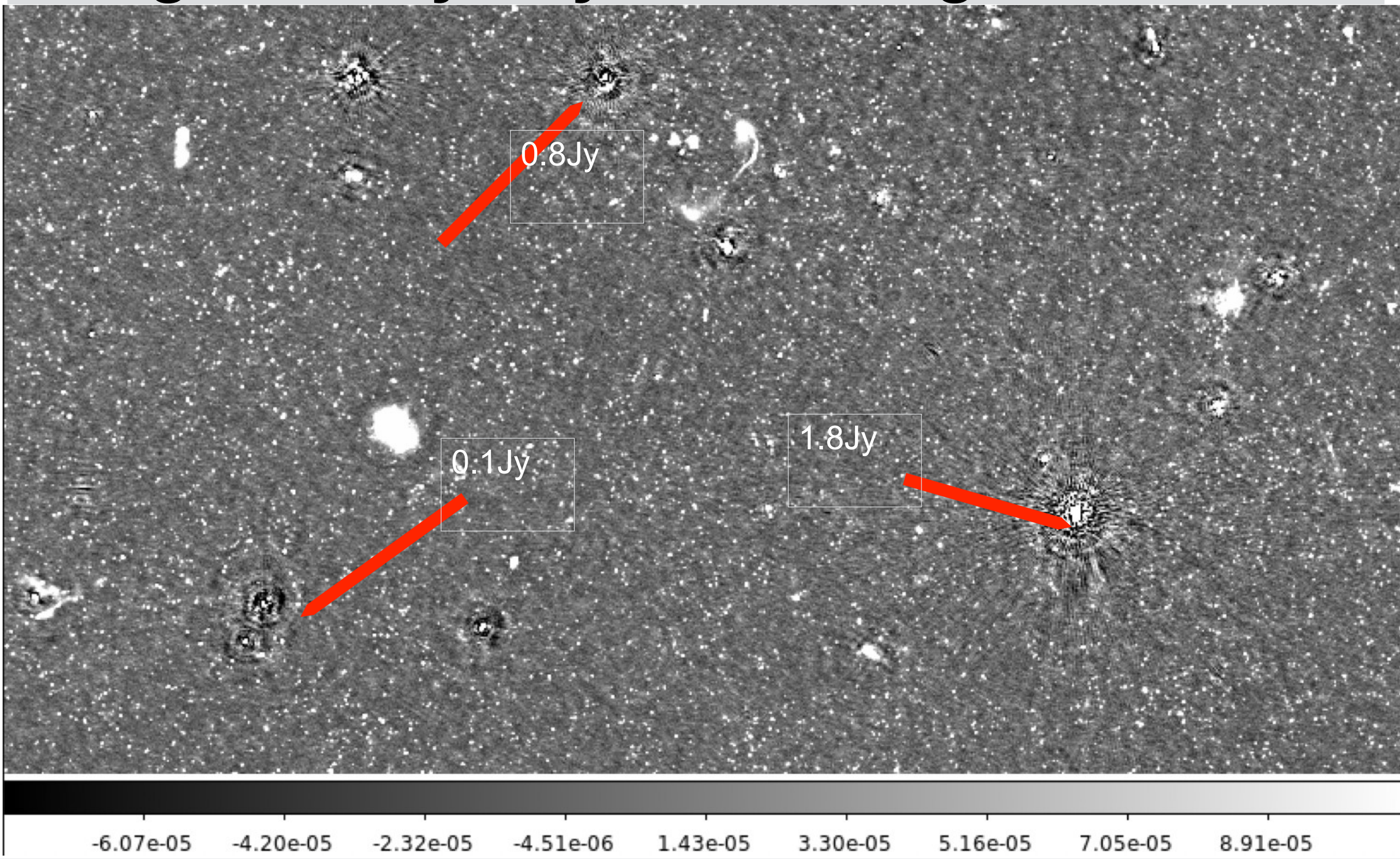
Image fidelity - sensitivity

Confusion noise is formed by the population of faint sources with flux densities below some detection/deconvolution threshold.



Black is theoretical noise without confusion. Green is the measured noise (i.e. including confusion). Ignore blue. Confusion already impacting at ~50uJy/beam at 6”.

Image fidelity - dynamic range



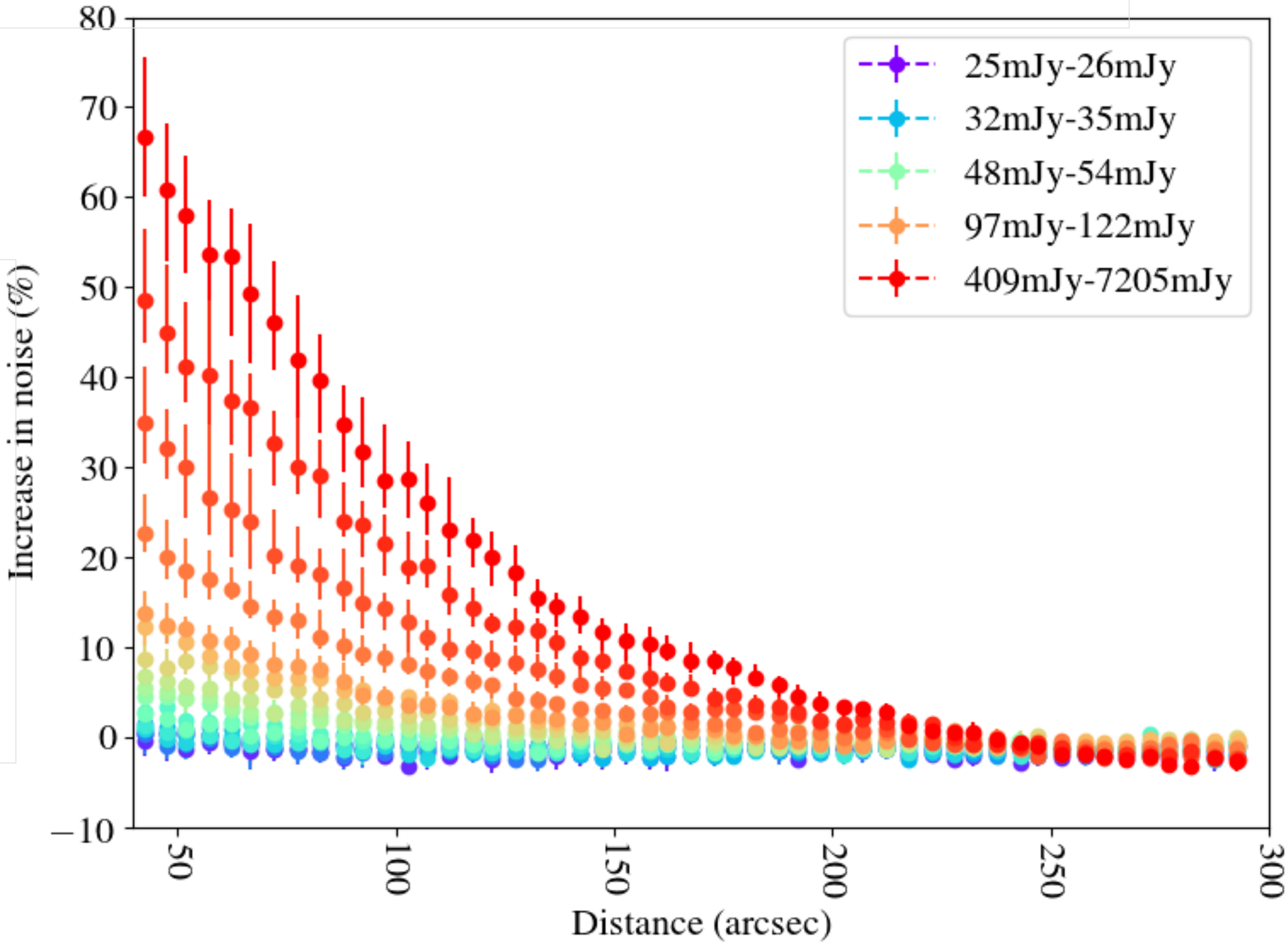
Bright(ish) sources enhance the noise level around them due to calibration imperfections (noise 12uJy/beam)

LoTSS - dynamic range

The

Can characterise the noise enhancements due to bright sources

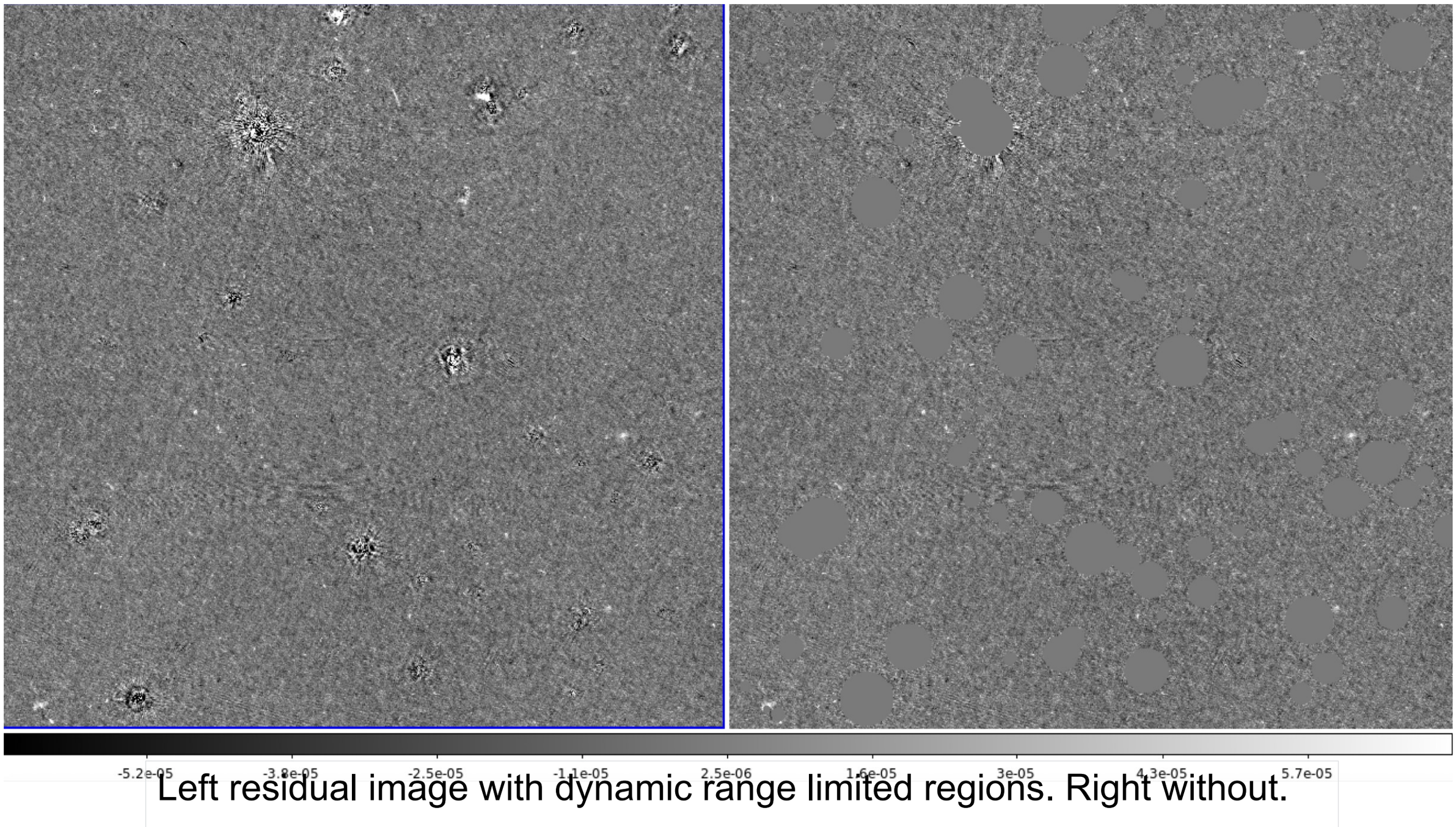
Considering e.g. a 1Jy source then the surrounding 250arcsec region has elevated (>5%) noise.



LoTSS - dynamic range

Can derive some equation (will be different for each observation) e.g.

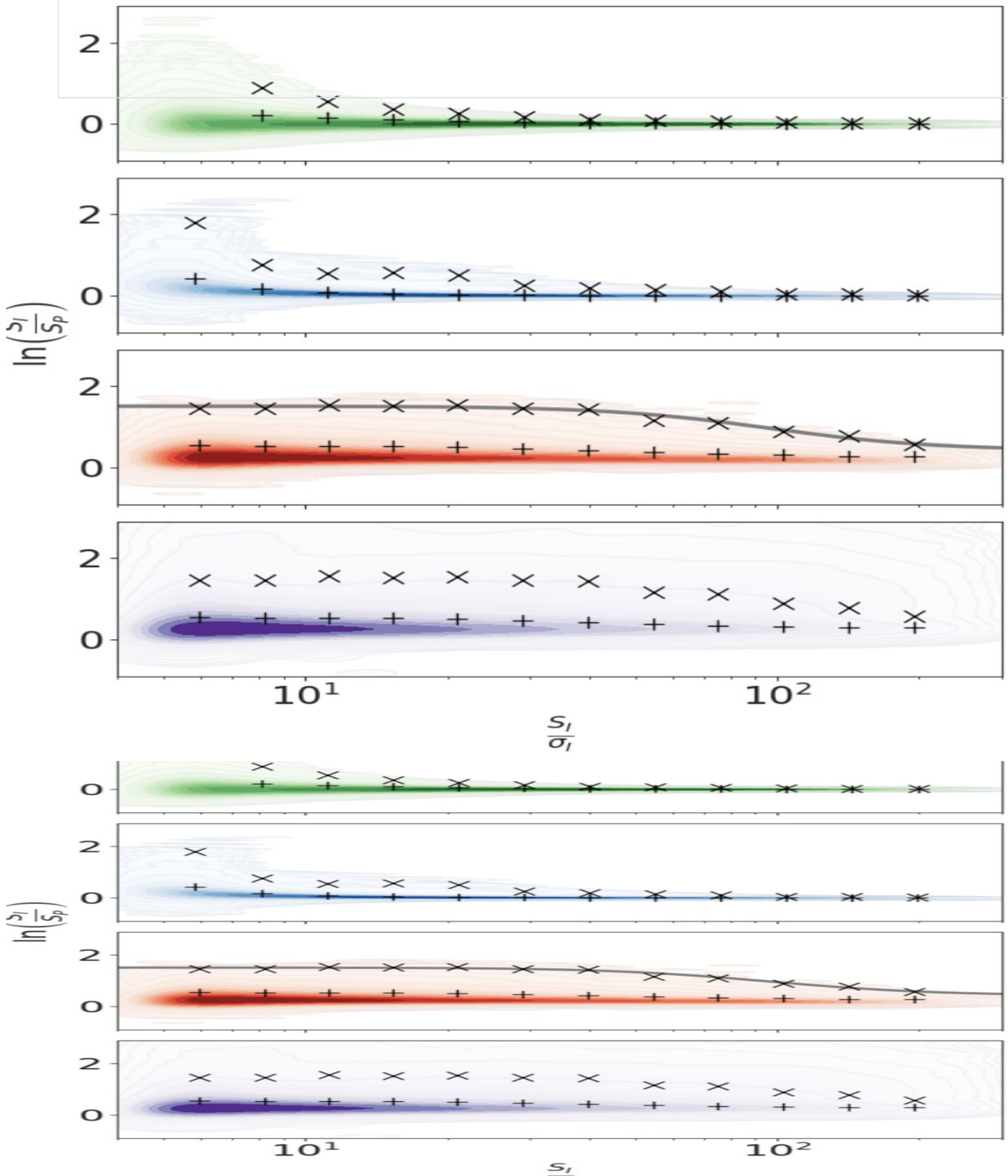
$$A_{Dyn,5\%} = -5.37 \times 10^{-4} + (6.62 \times 10^{-3} \times (1 - e^{-22.7 S_I}))$$



Left residual image with dynamic range limited regions. Right without.

Image fidelity - source sizes

Not possible to definitively separate compact from extended sources. The integrated flux of the peak flux is a good proxy for extension.

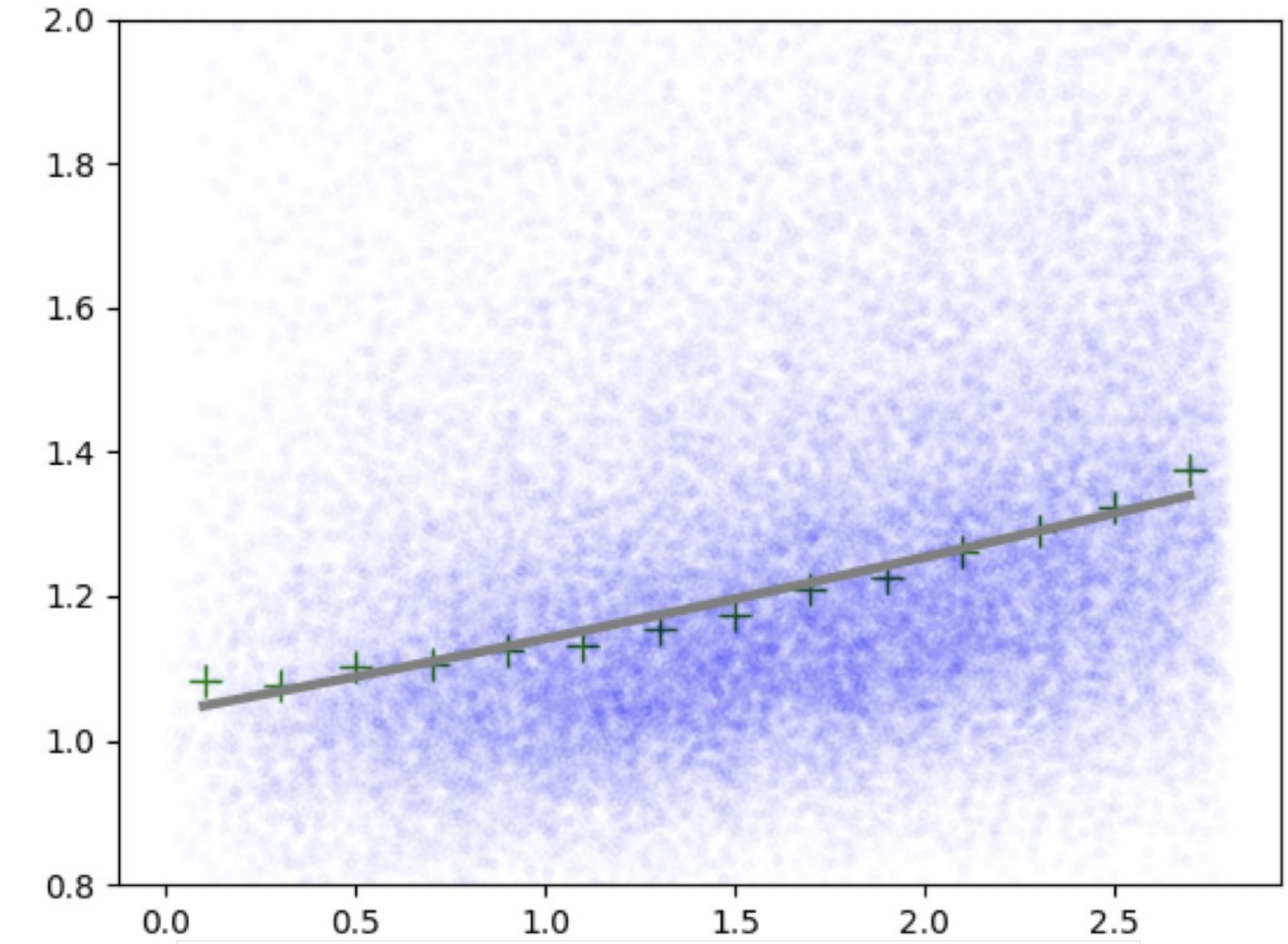


Simulated Total/Peak where noise on measurements is uncorrelated.

Simulated sources injected into map and recovered with PyBDSF (i.e. real correlation of noise on measurements)

Measurements of real source distribution (very different from simulations)

Image fidelity - source sizes



Due to e.g. time- and bandwidth-smearing sources become more extended away from the pointing centre. Also the facets used for calibration are larger in these regions meaning less precise calibration.

Image fidelity - source sizes.

Systematically increasing average source size (ignore red points) with decreasing declination

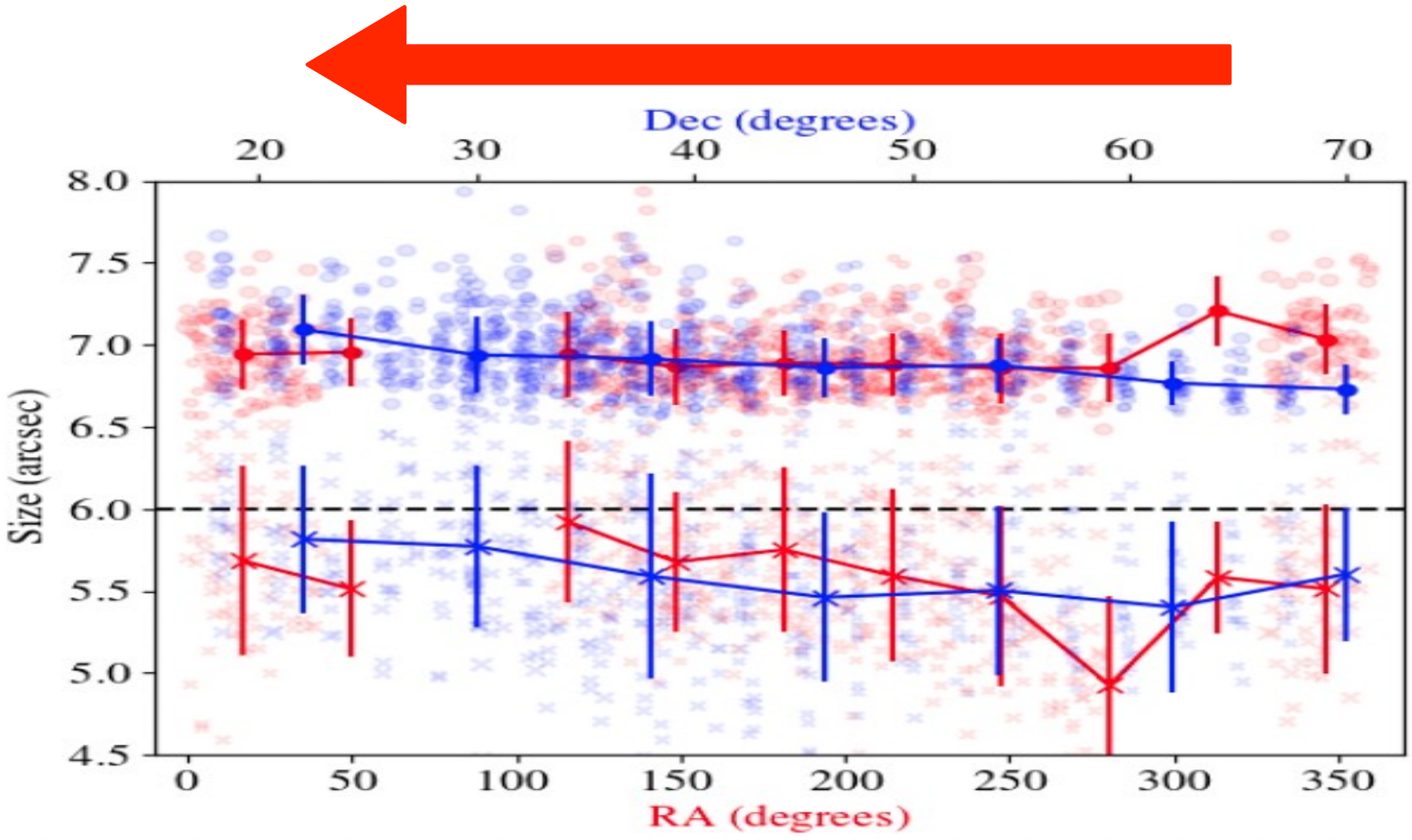


Image fidelity - flux density scale

LOFAR HBA has flux density scale issues thought to be related to the beam models. When e.g. using a calibrator in one location to derive the flux density scale the results are slightly different from using a calibrator in a different location.

Implication is that the flux density scale of LOFAR HBA images needs checking and scaling (LBA better)

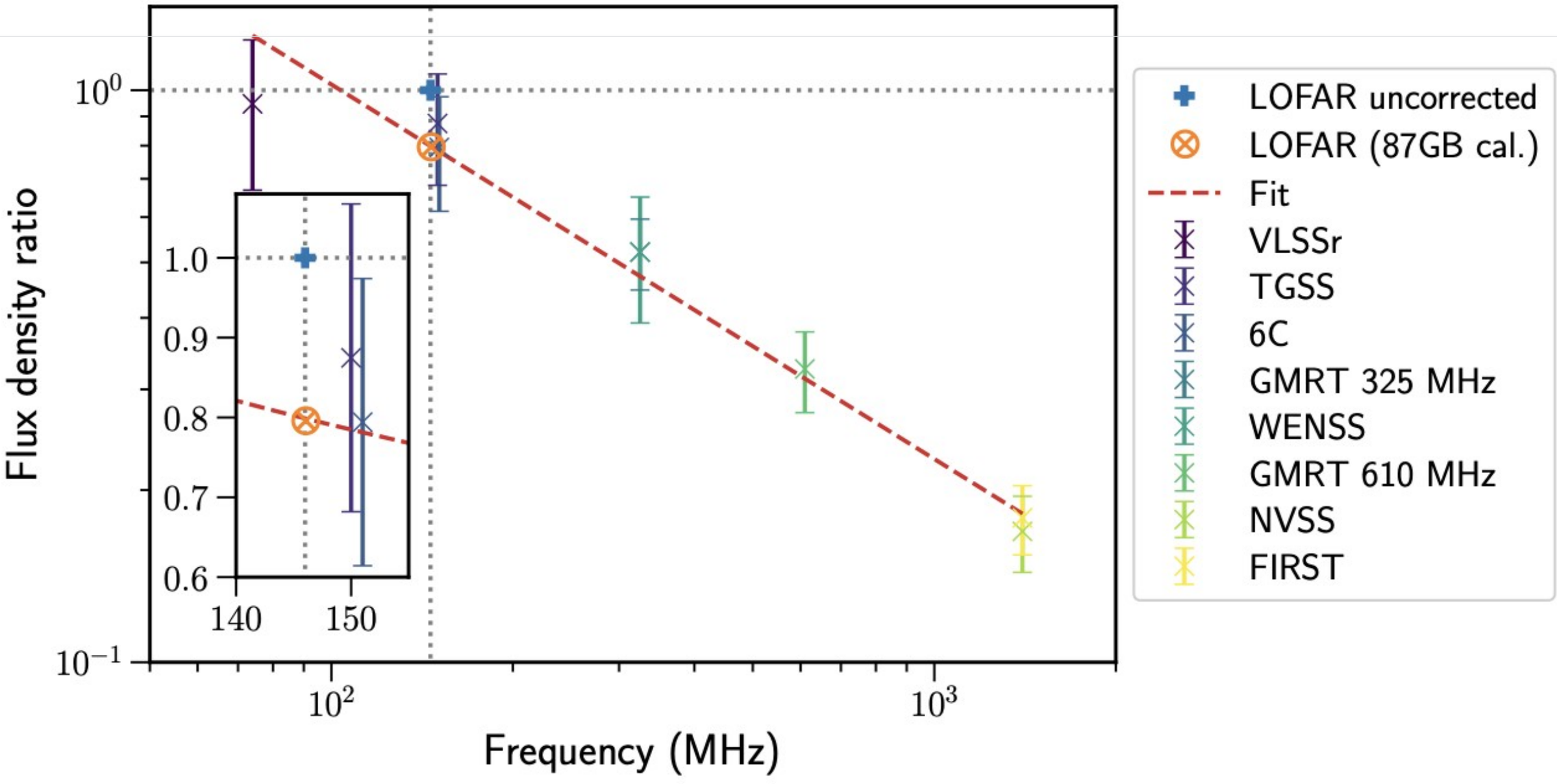
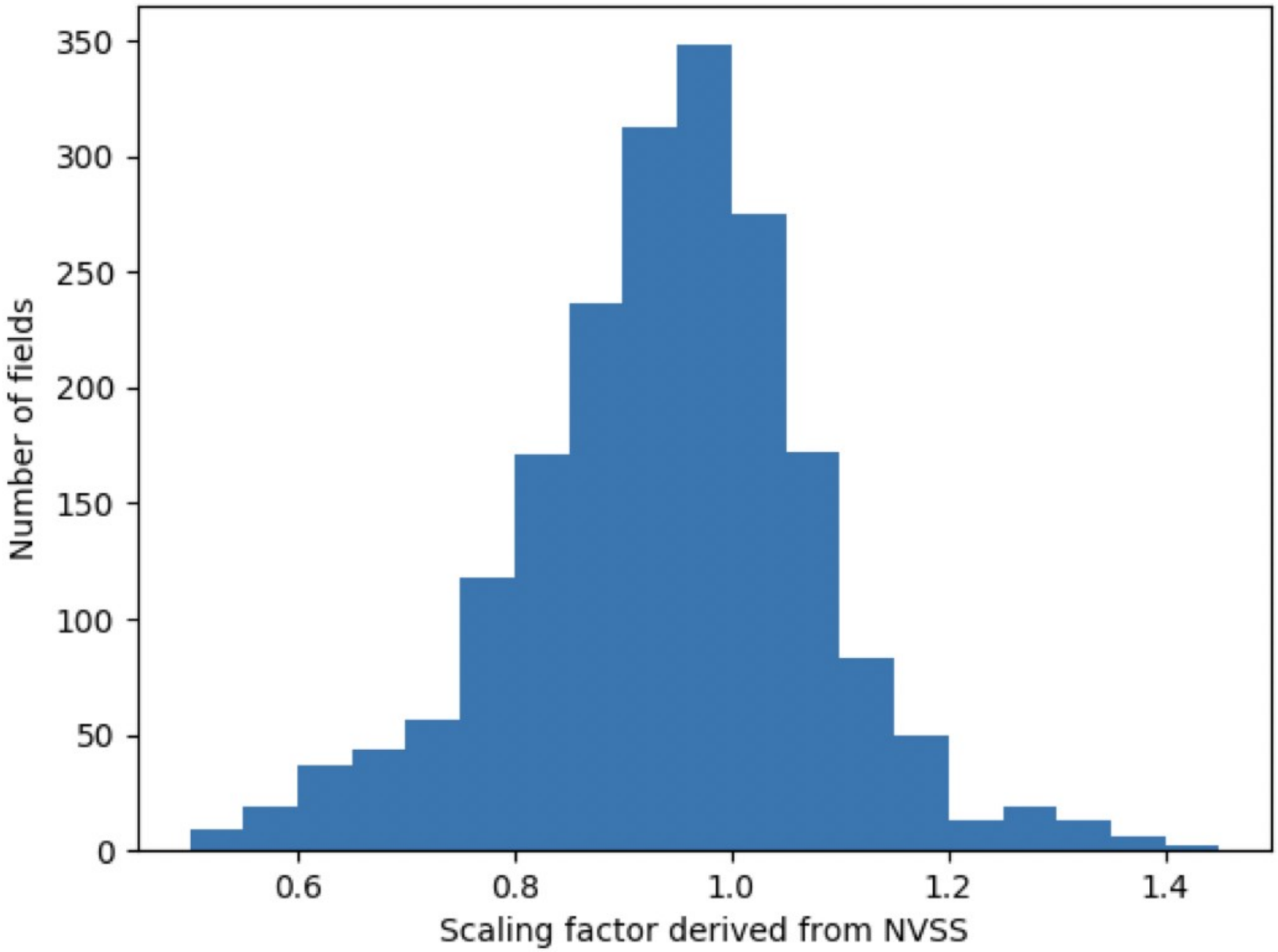
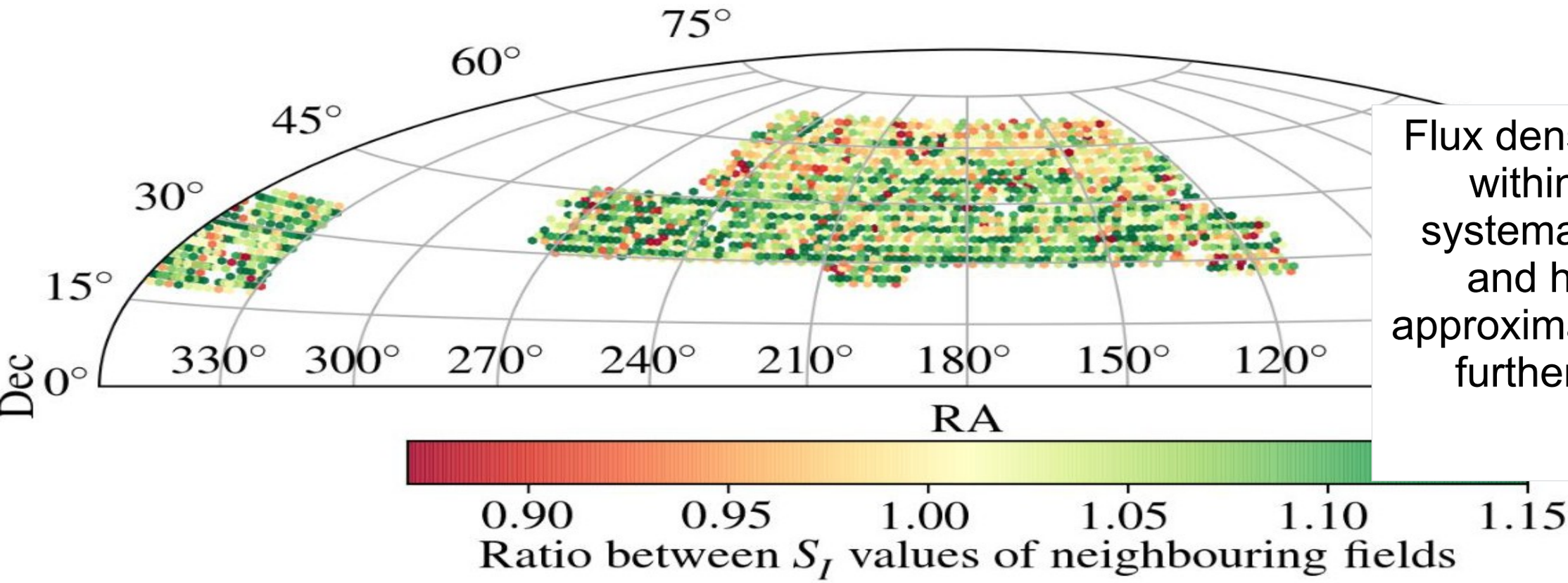


Image fidelity - flux density scale

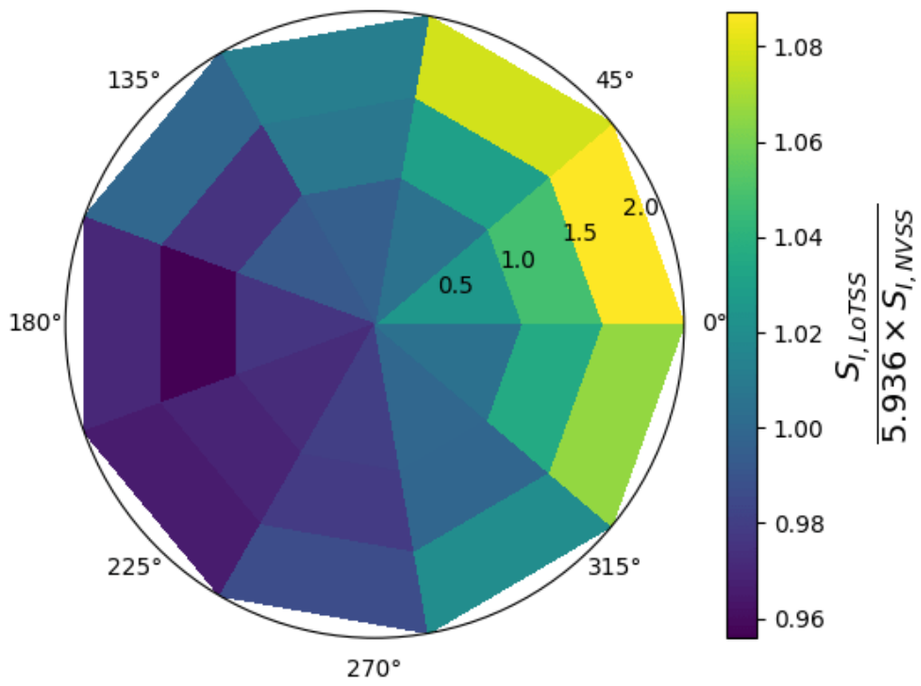
Derived scaling factors for ~2,000 fields.
Big variation and despite best efforts there is a very large uncertainty in the flux density scale (~20%).



LoTSS flux density scale



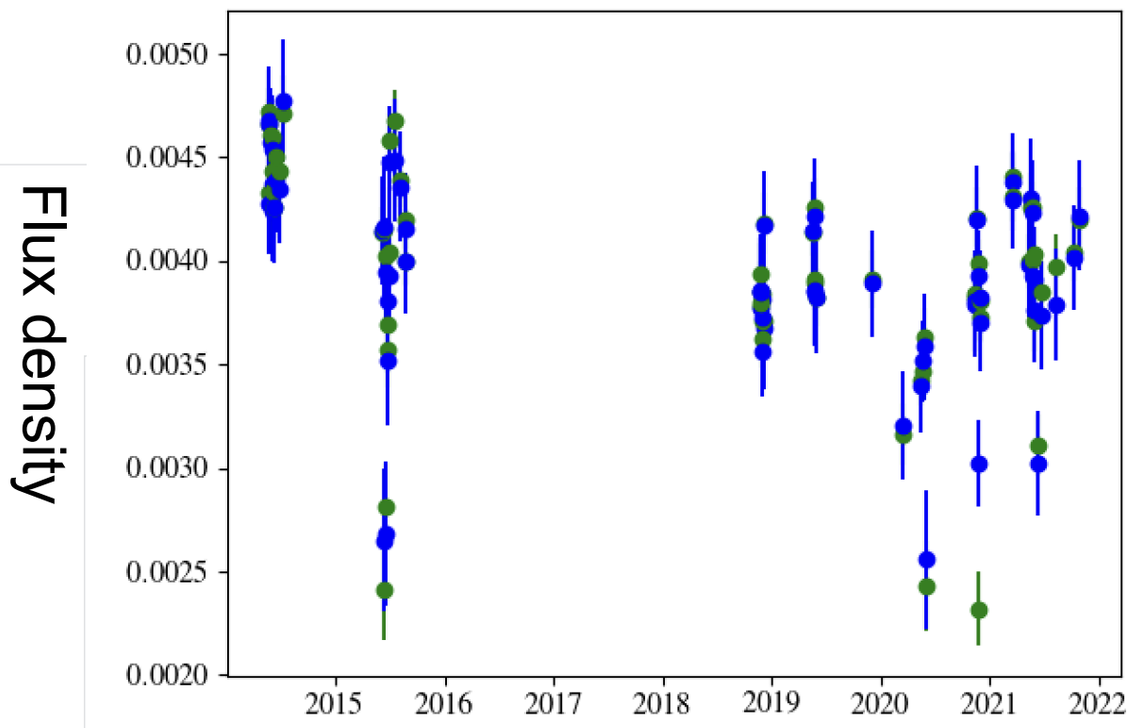
Flux density scale within 10% systematic error and has an approximately 10% further error.



Northern region of a given pointing systematically brighter than southern region.
Complicates flux scale and apparently more severe at lower dec. Still being investigated but fortunately largely cancels out in mosaicing

LoTSS— flux density scale

A simpler way of showing flux density issues is to examine deep field observation.
80 nights observing at around same LST.
Histograms of total to peak flux shown for exact same compact sources in each epoch after alignment of flux density - big variation still.
Some sources are genuinely variable but all show some degree of variation.



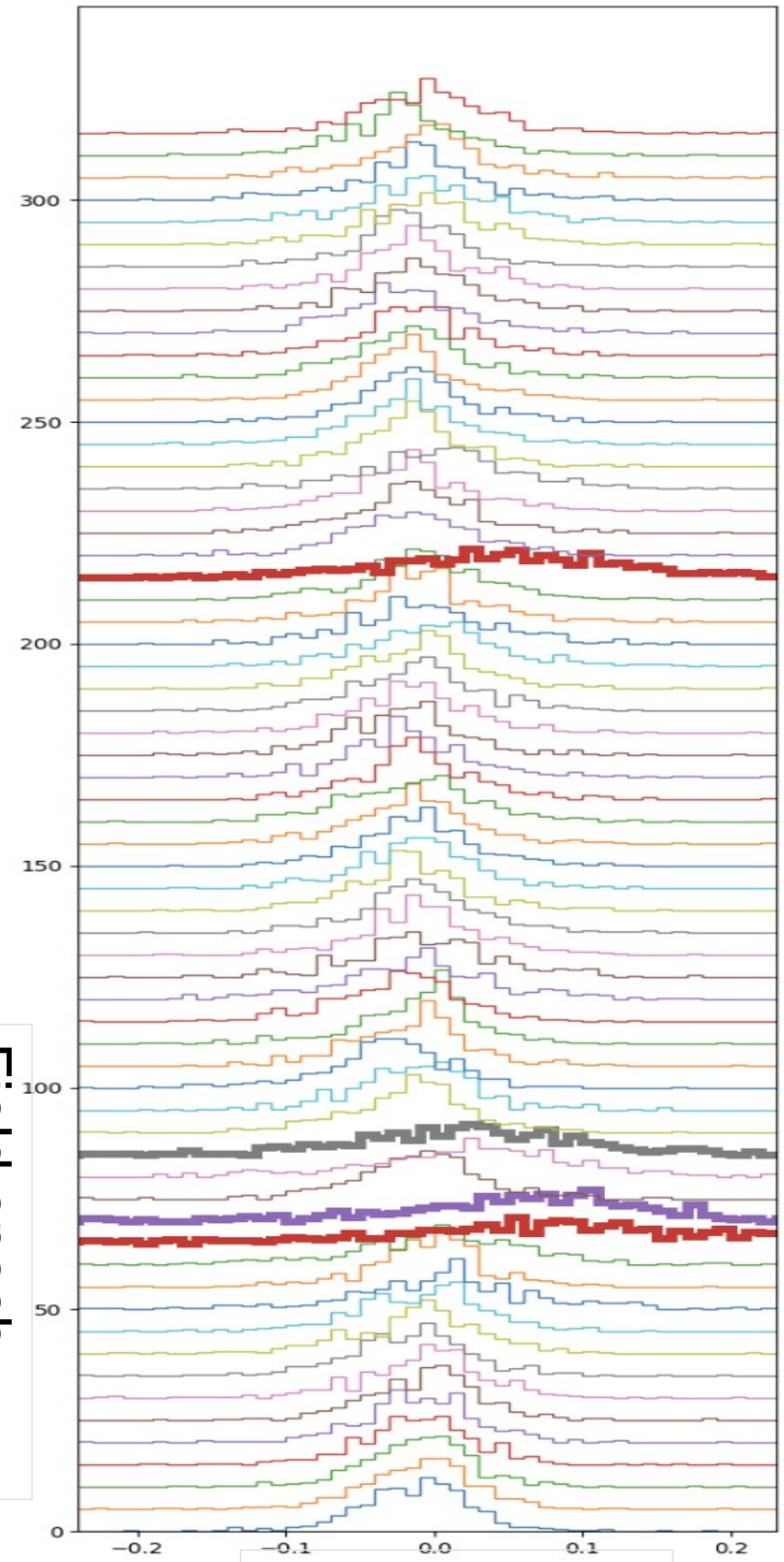
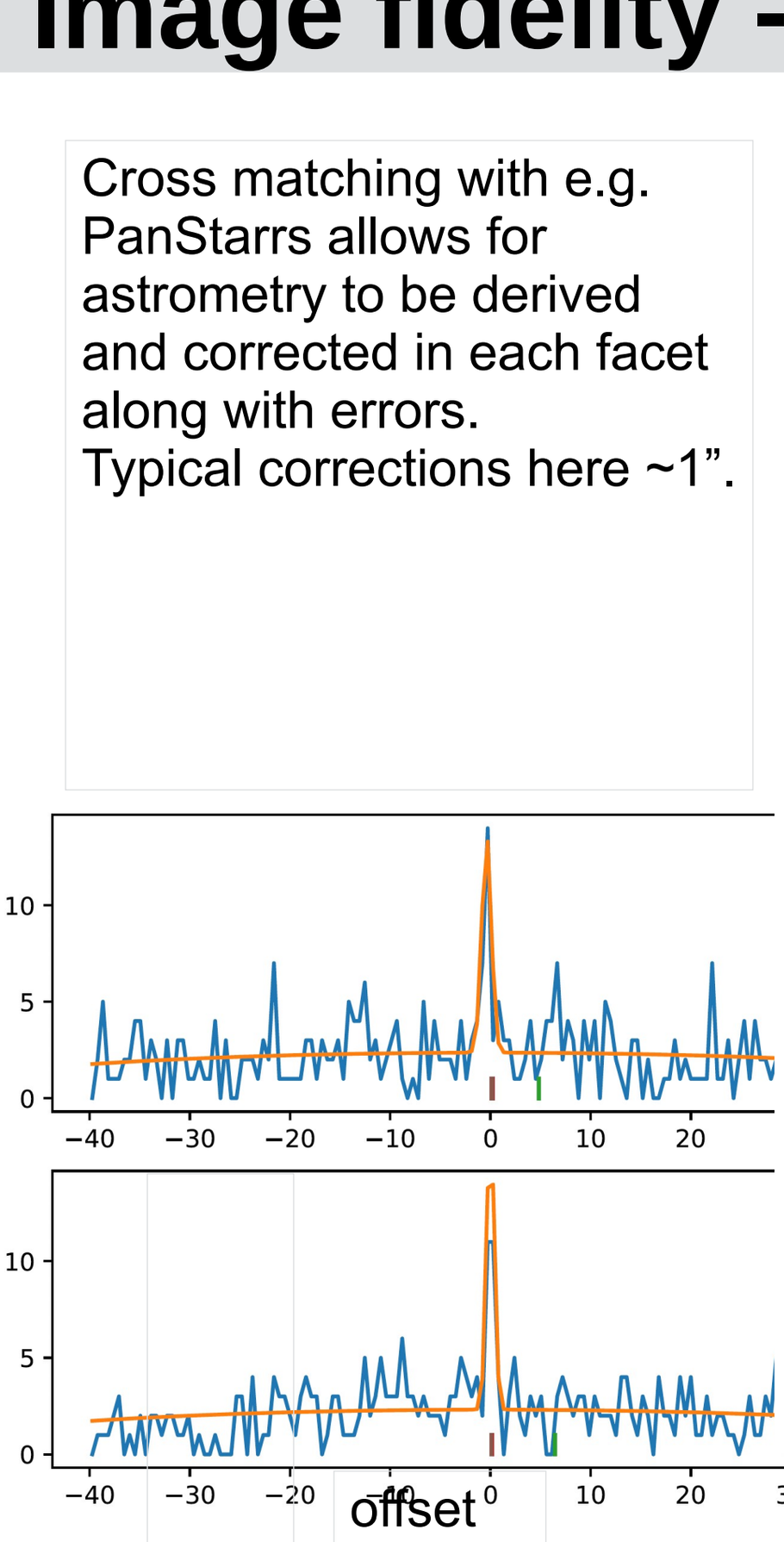


Image fidelity - astrometry

Cross matching with e.g. PanStarrs allows for astrometry to be derived and corrected in each facet along with errors.
Typical corrections here ~1”.



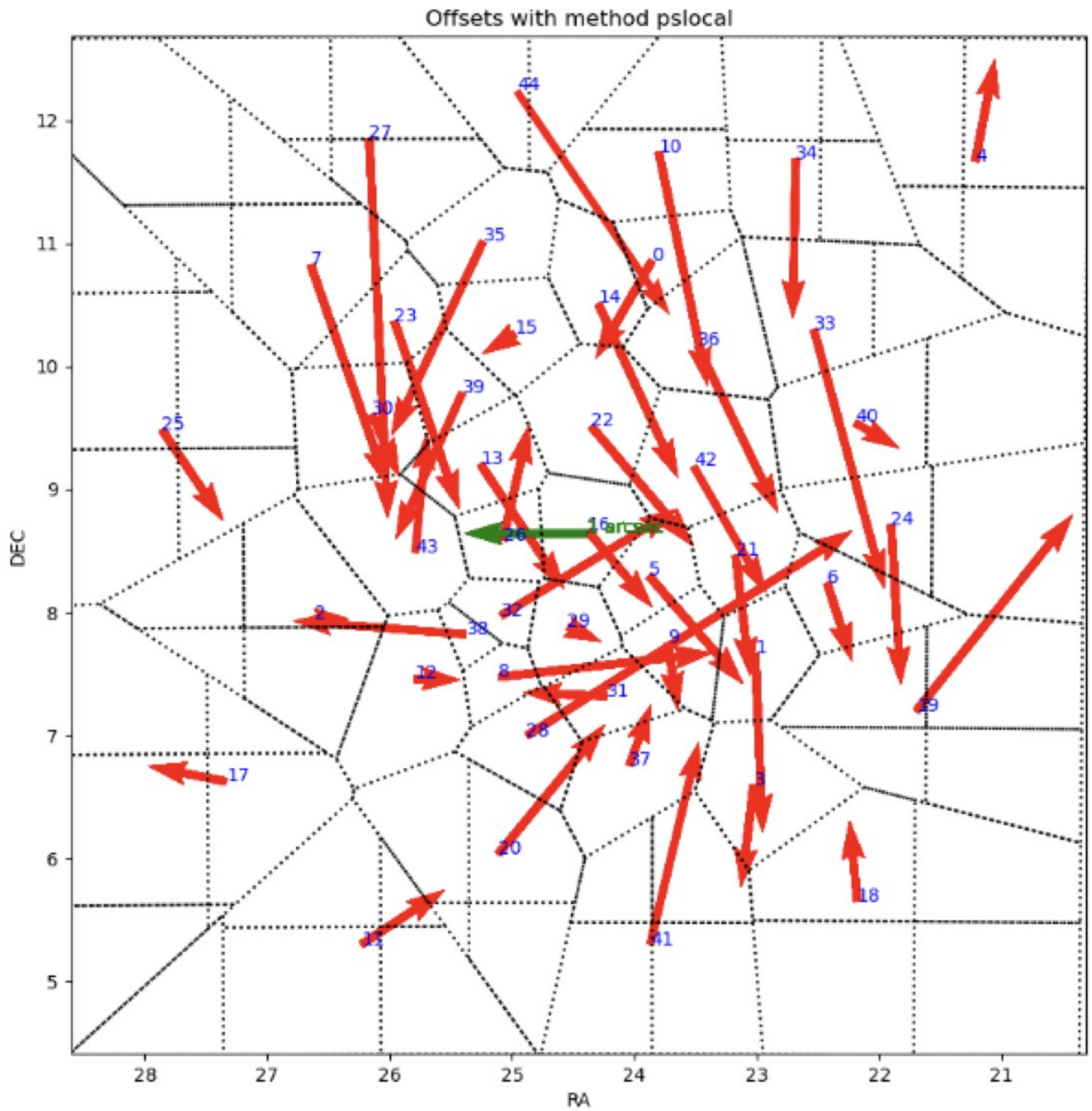
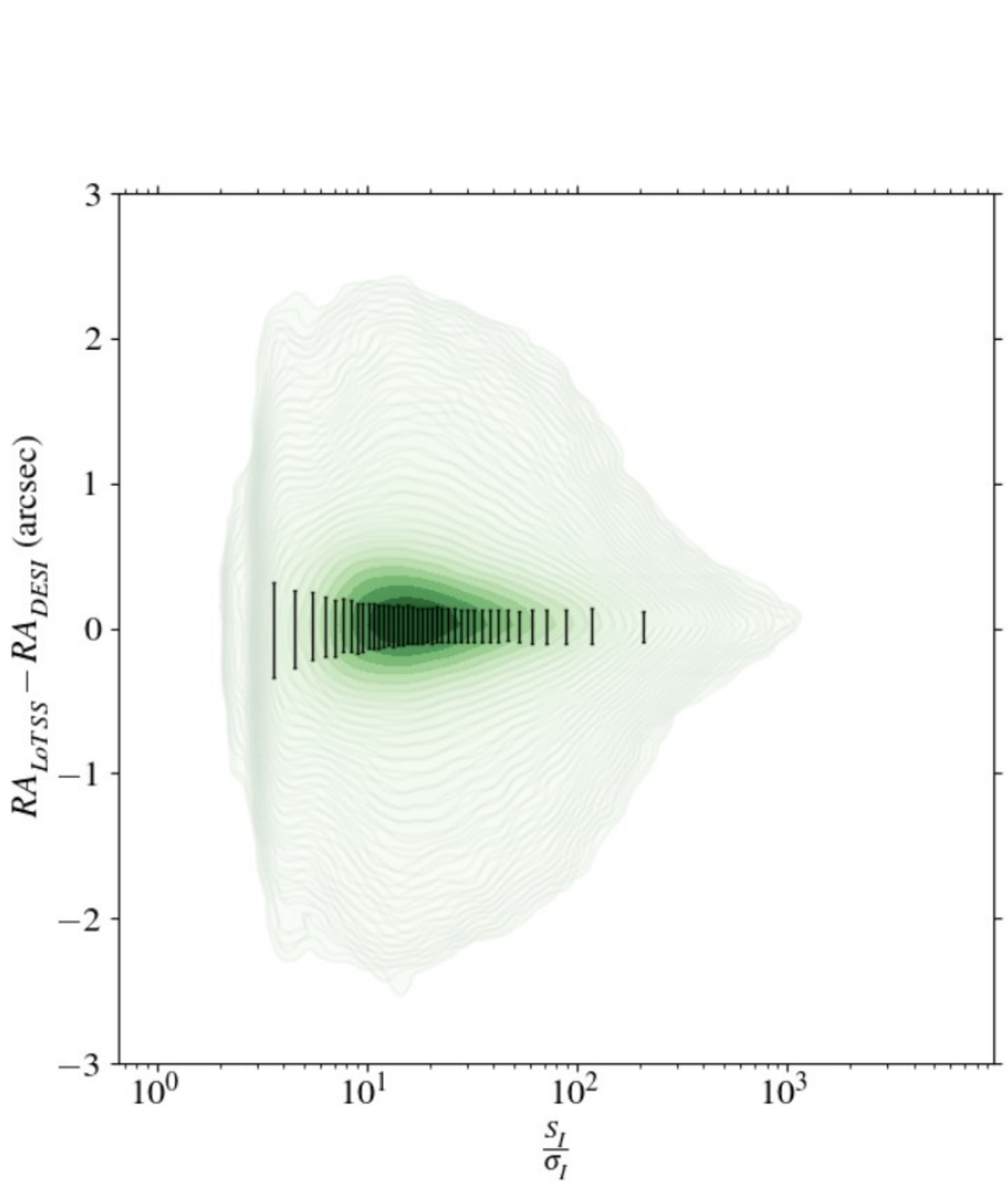


Image fidelity - astrometry

Can then quantify astrometric accuracy on final images and examine things like flux density dependance.



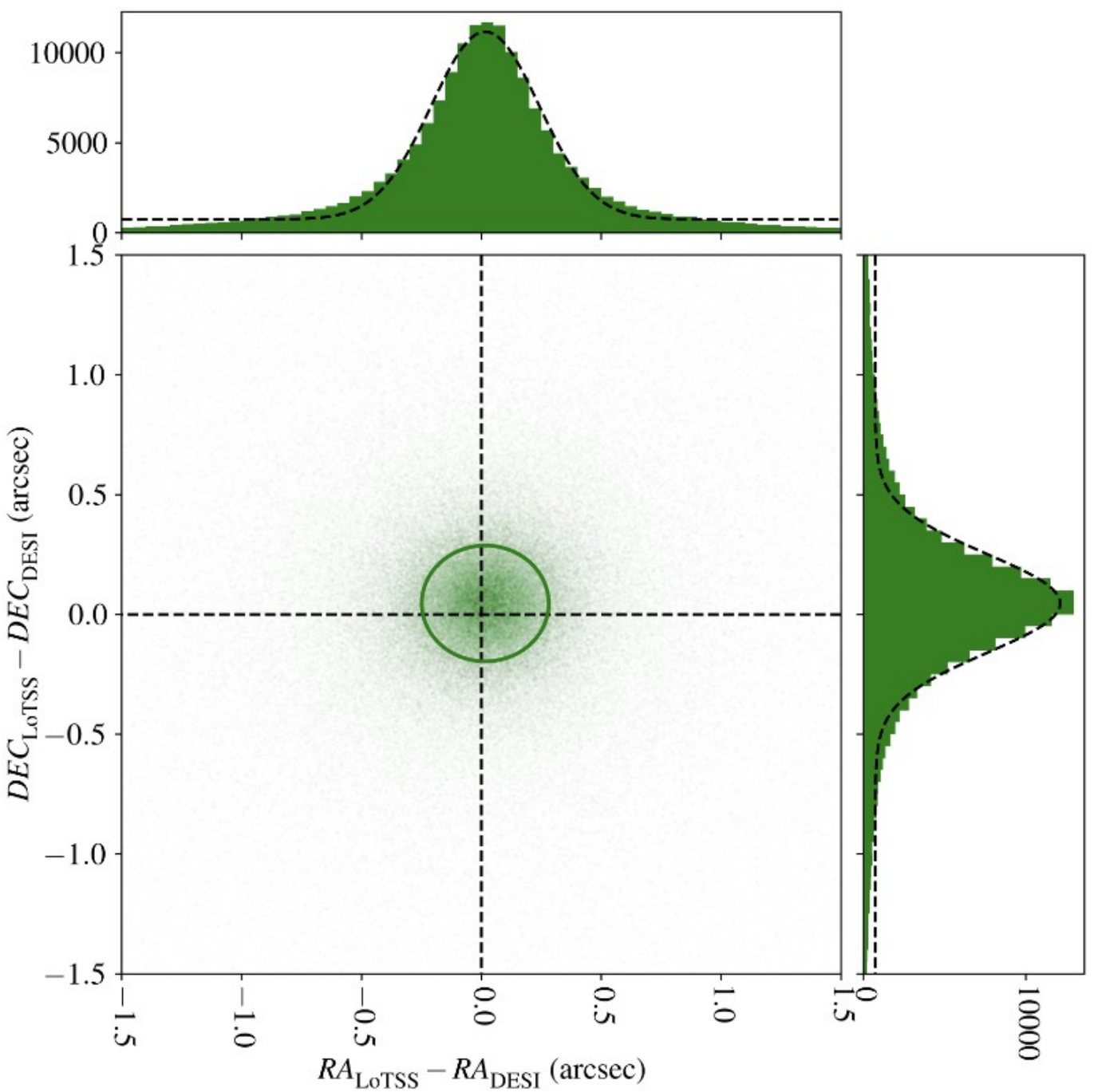
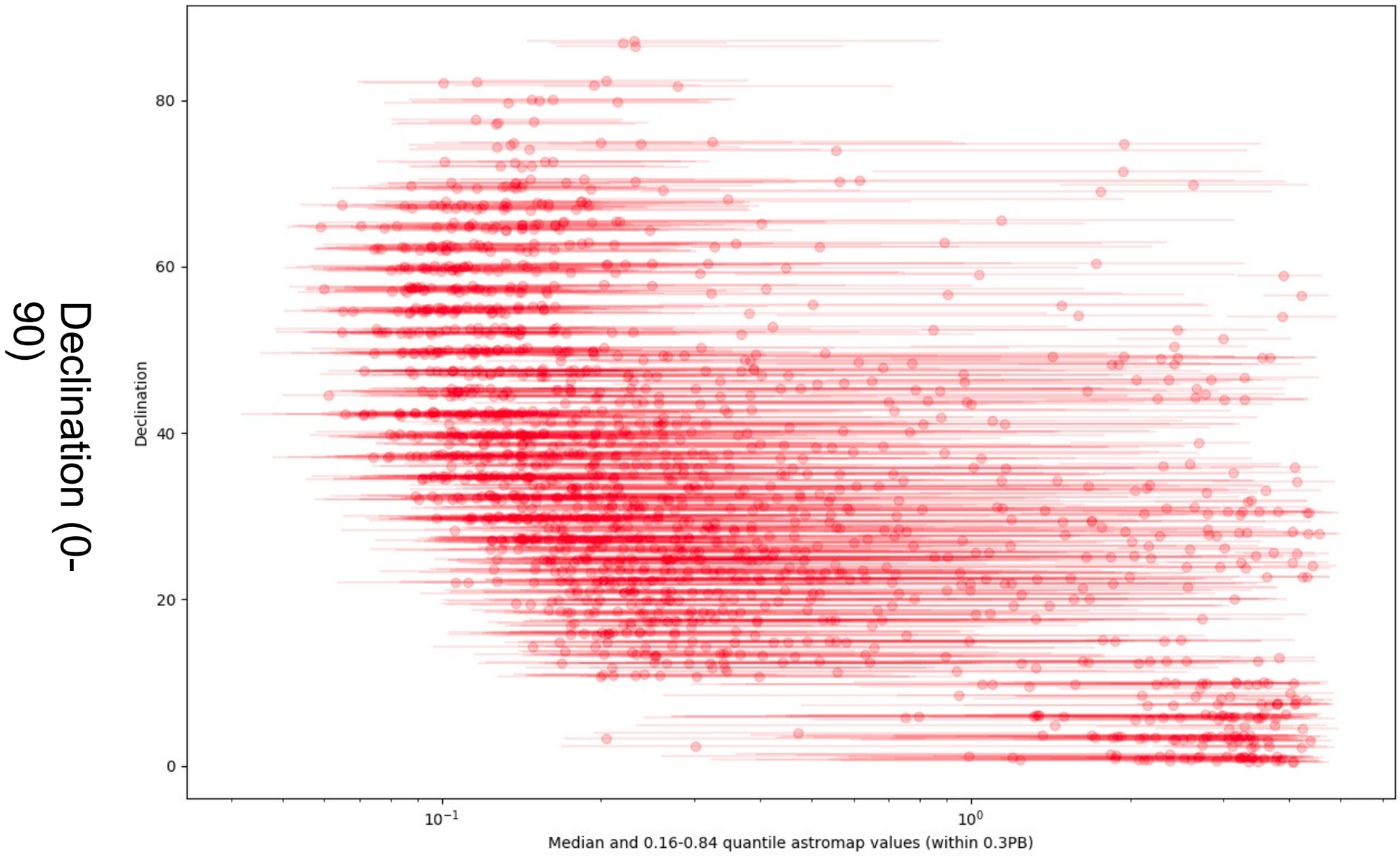


Image fidelity - astrometry

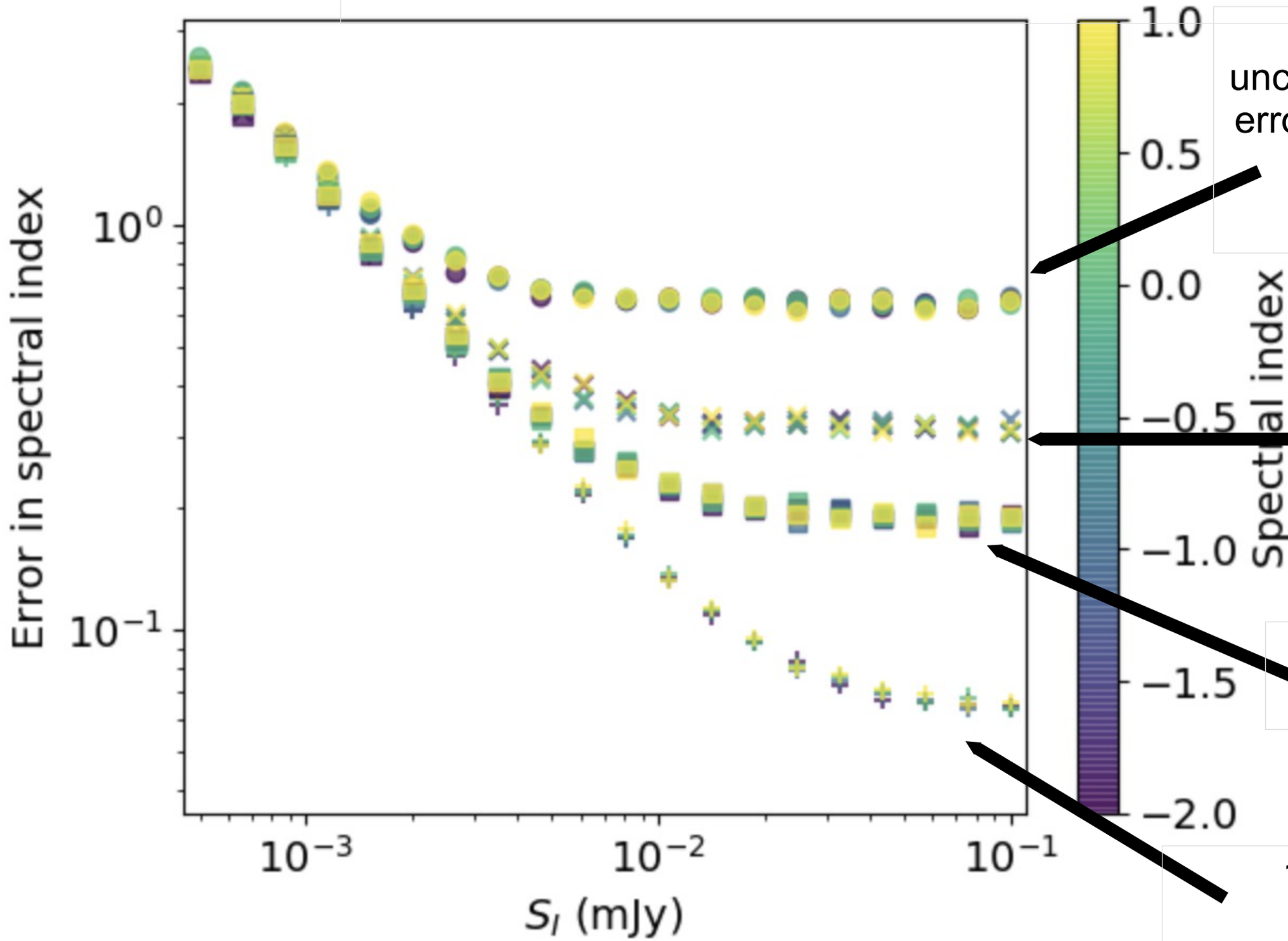
Also trends with e.g. galactic latitude and declination.



Astrometric error (arcsec) - range 0.1 to 10arsec.

Image fidelity - In-band spectral index

Low fractional bandwidth and uncertainty in alignment of in-band flux density scale limits accuracy of spectral index.



10% alignment uncertainty limits to 0.8 error on spectral index

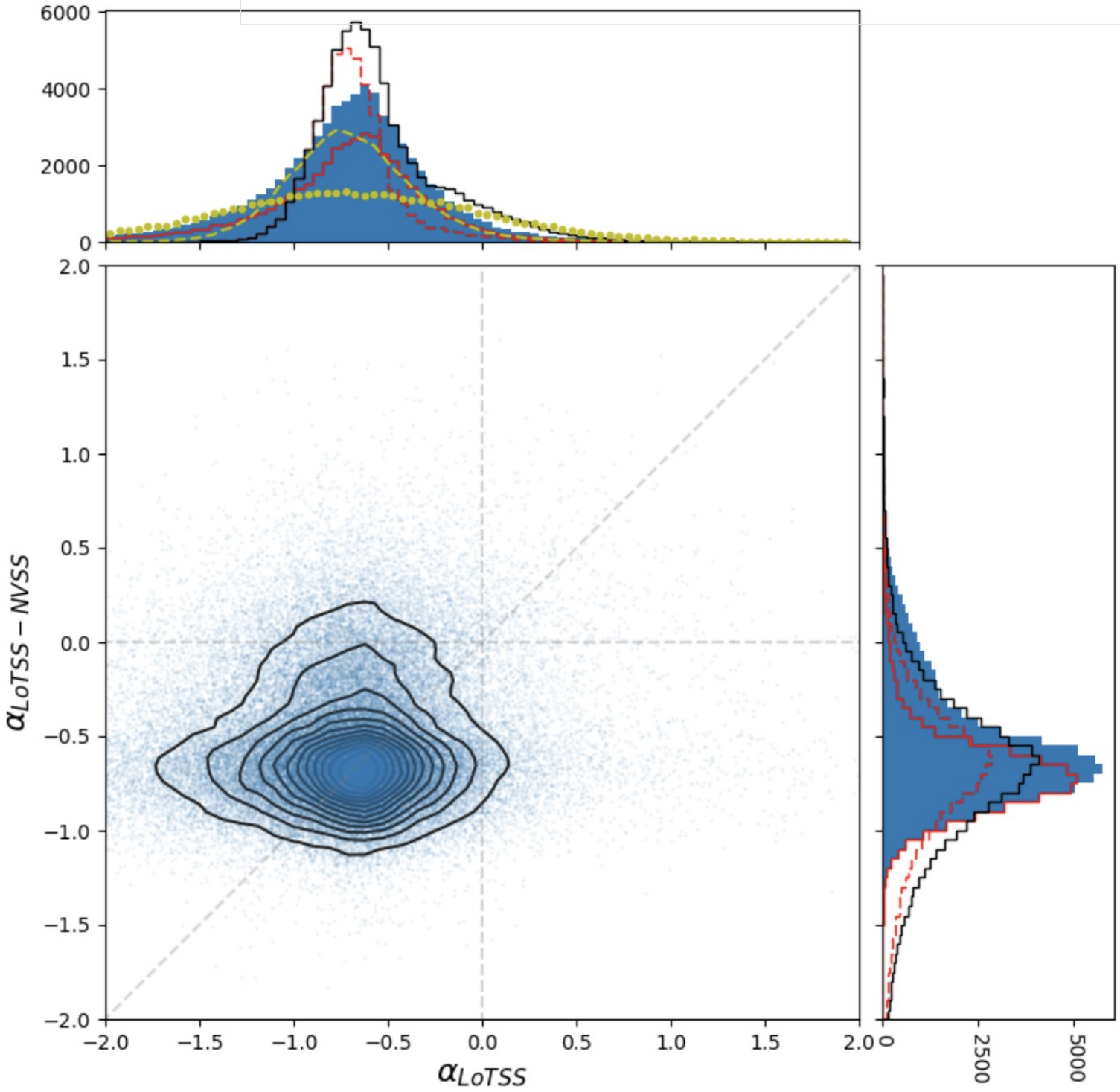
5% to 0.3

3% to 0.2

1% to 0.05

LoTSS - inband spectral index

Meaningful (spectral index error 0.2) spectral indexes can be derived for large numbers of sources (many only detected in LoTSS)



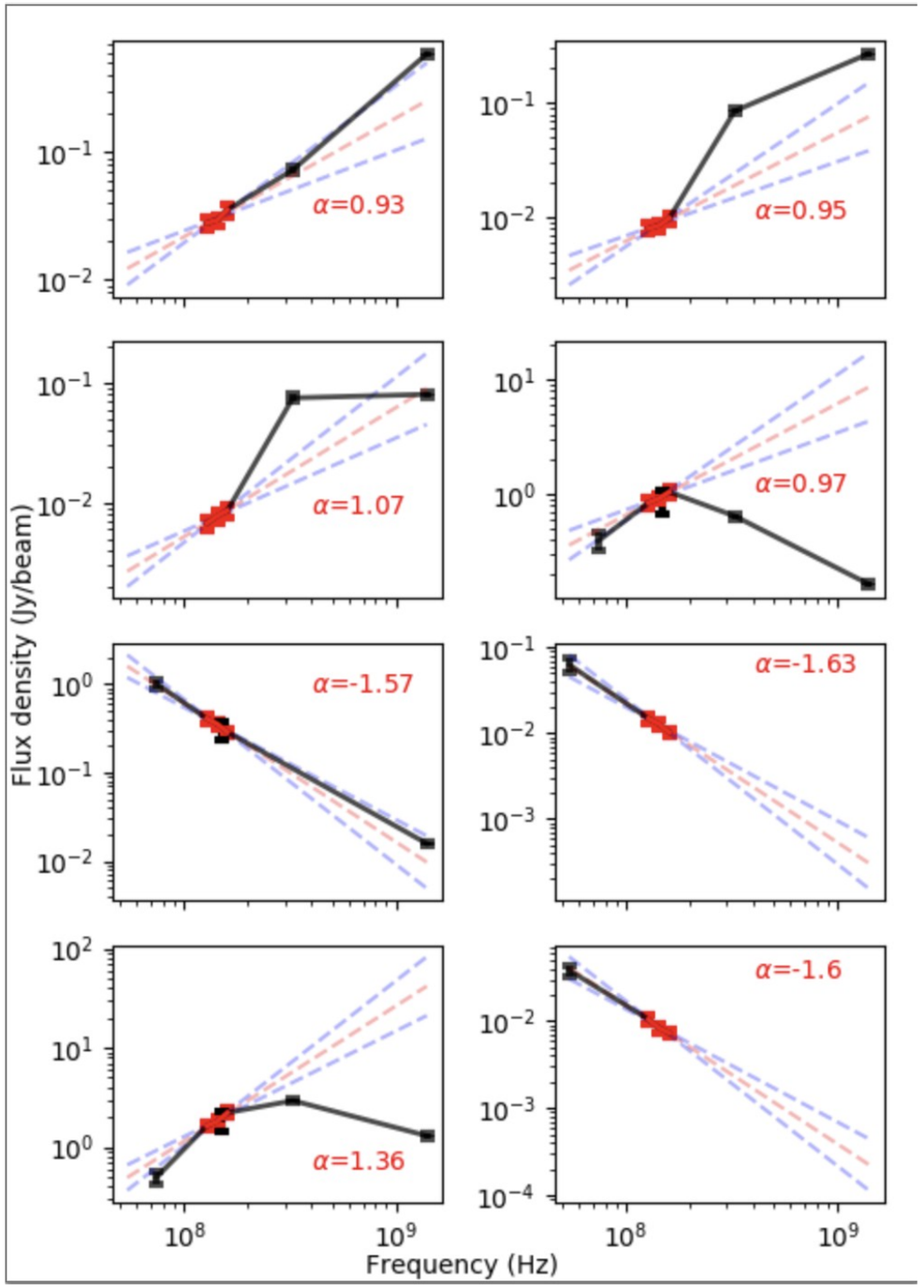
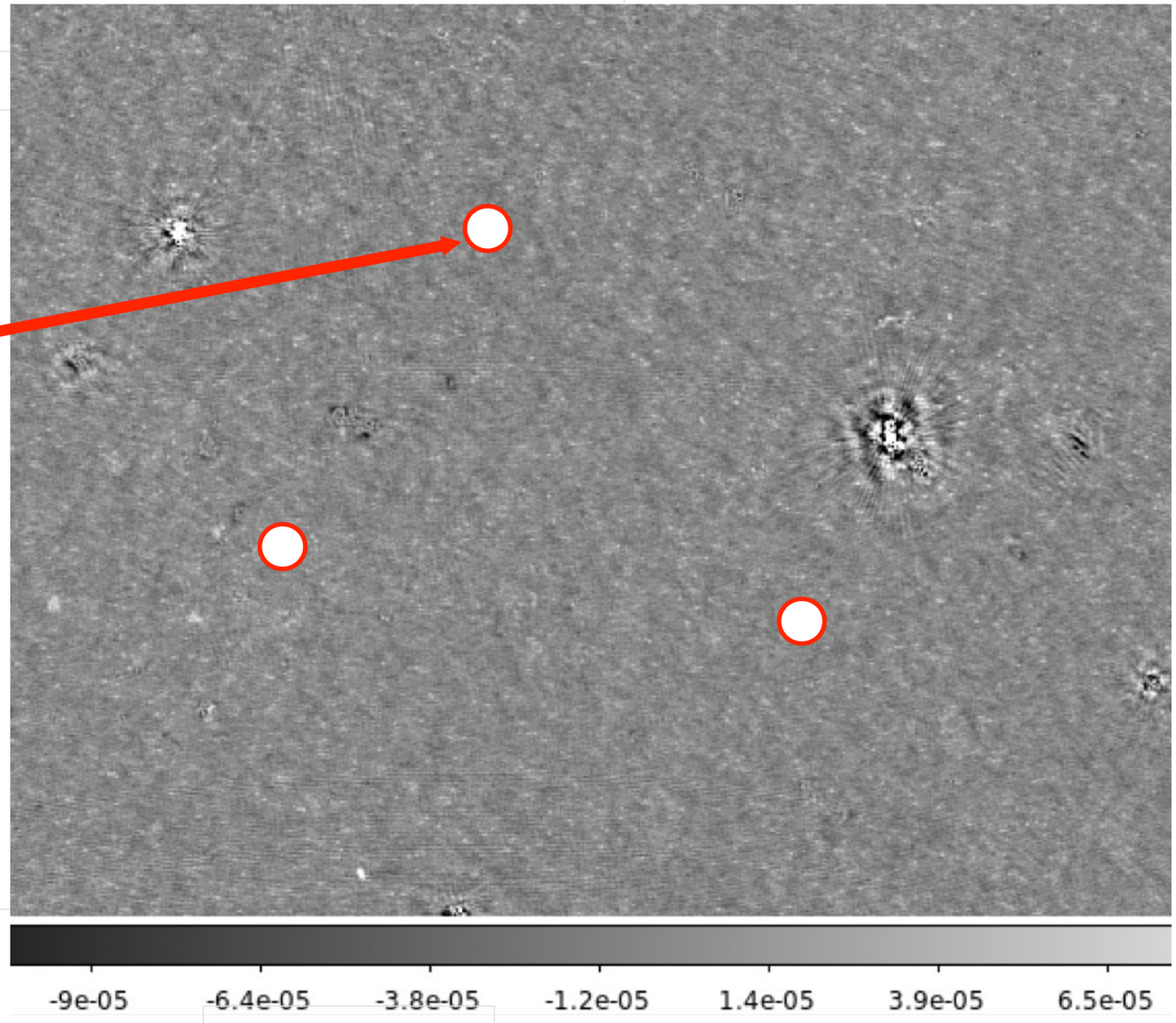


Image fidelity - completeness (also diffuse structure)

Useful to know how complete your image is to objects of different flux densities.

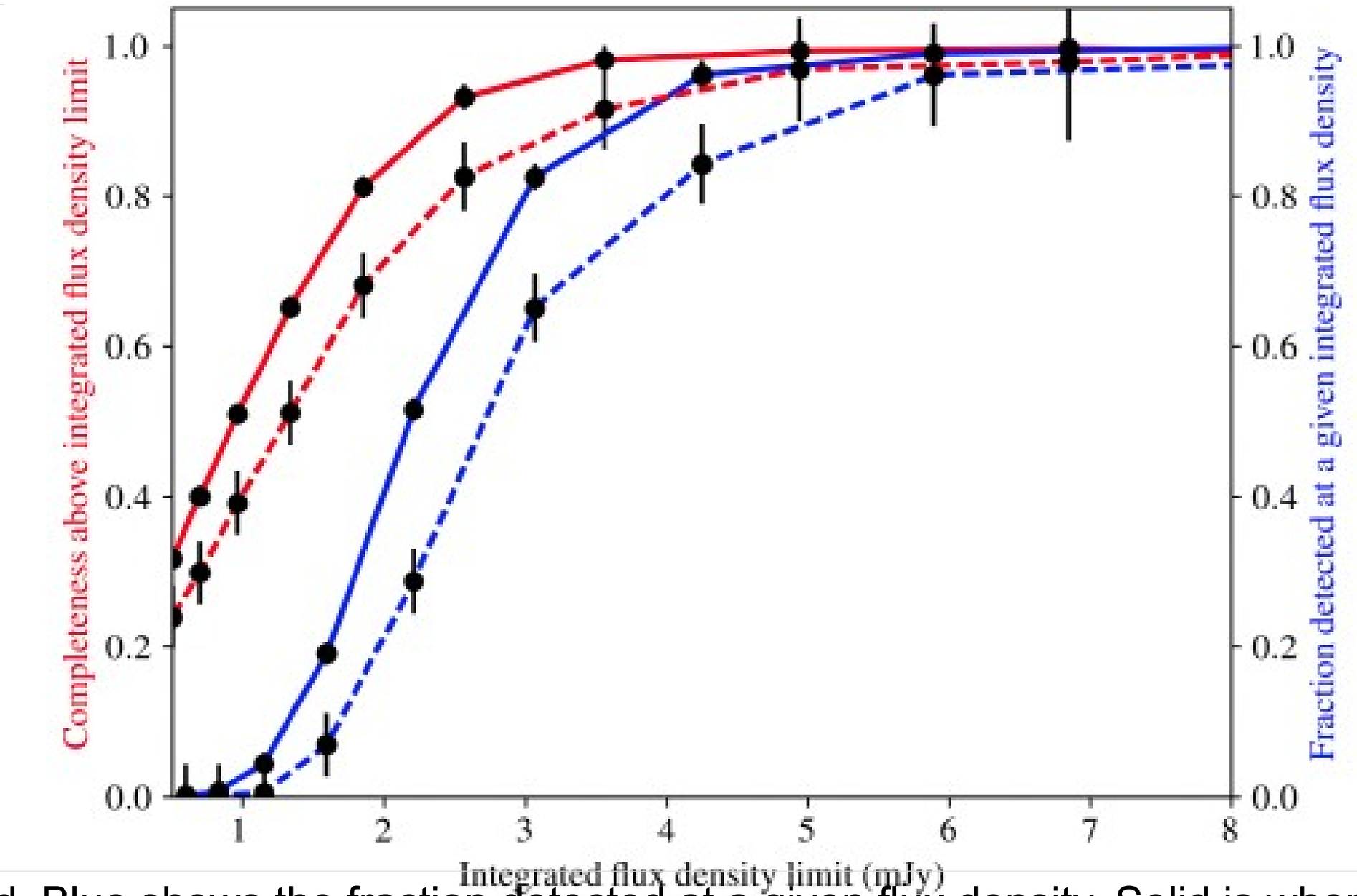
Simple approach is:
1) injecting sources into the residual image
2) running PyBDSF on resulting image
3) examine number detected to injected as a function of flux density.



Elais N-1 residual image

Image fidelity - completeness (also diffuse structure)

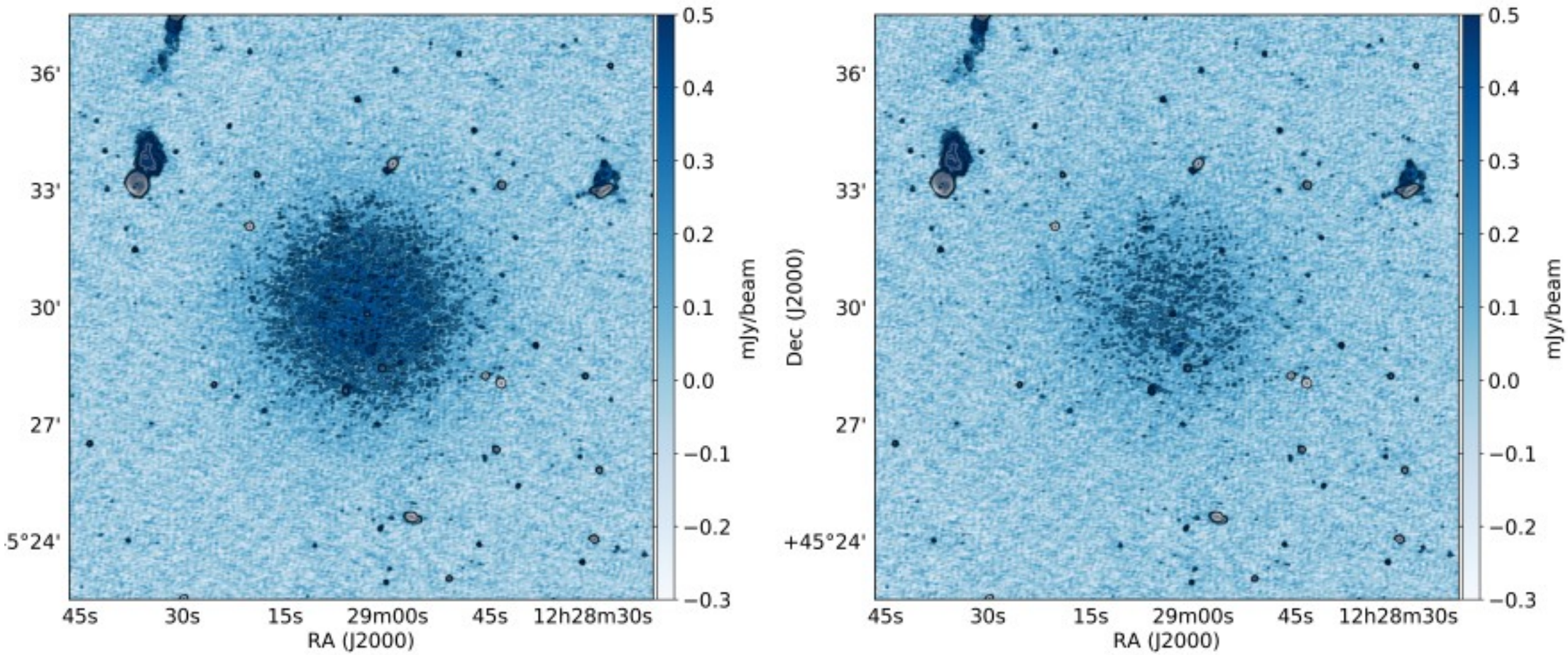
Sources that are not deconvolved will not be in the sky models used for calibration. As a result their emission can be suppressed.



Ignore red. Blue shows the fraction detected at a given flux density. Solid is when we quantify this with injections into the image plane. Dashed is when we quantify it with injections into the uv-plane distorting sources for ionosphere and recalibrating.

Image fidelity - completeness (also diffuse structure)

Sources that are not deconvolved will not be in the sky models used for calibration. As a result their emission can be suppressed.



Left: simulated. Right: recovered after calibration without source in model.

Only 60% of unmodelled diffuse emission (e.g. halos, galaxies etc) remains after calibration.

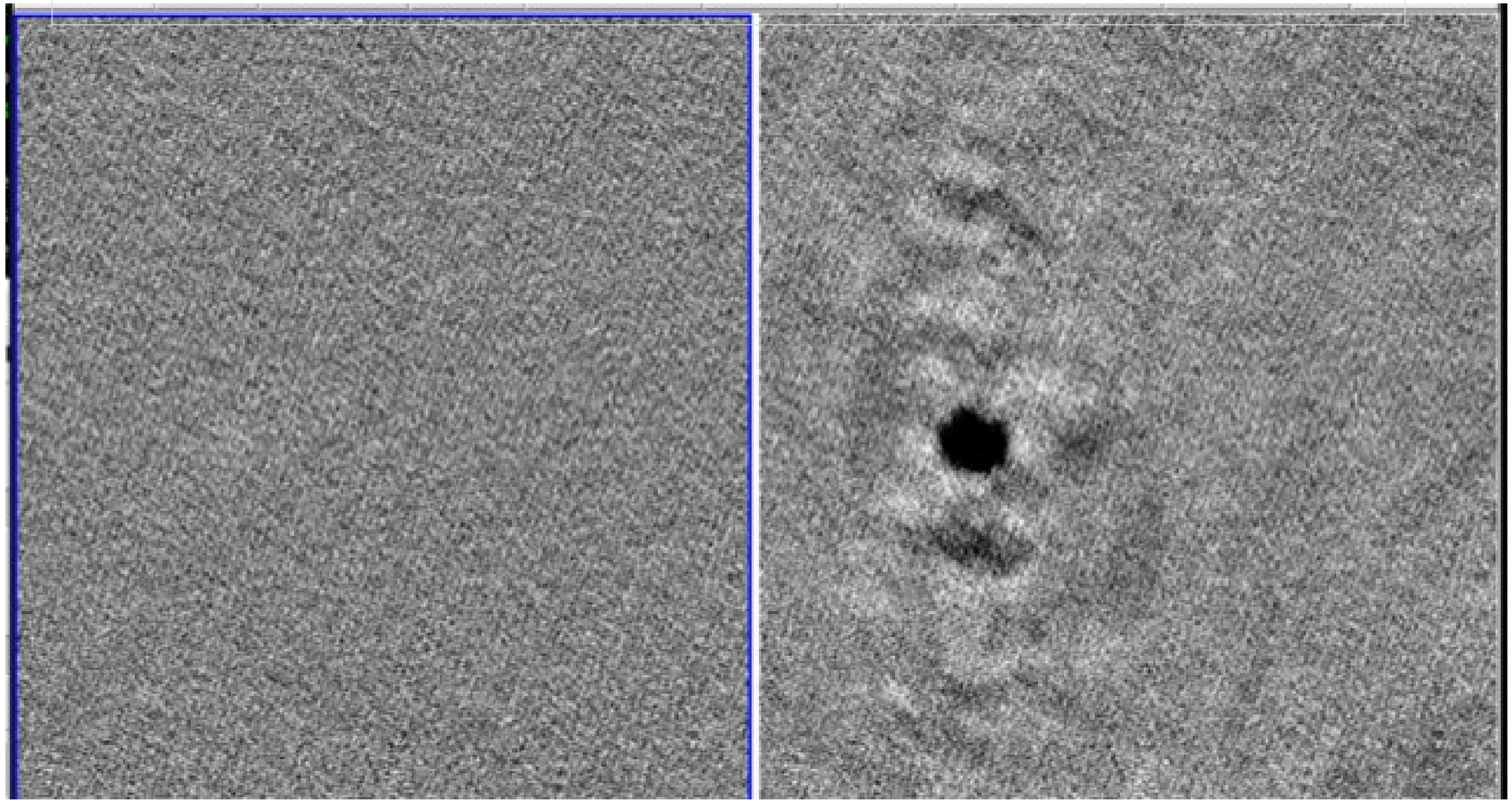
Image fidelity - leakage

Leakage is when flux density in Stokes I leaves an artefact in Stokes V.

Sky is not very polarised so can assume Q=U=V=0 (we can use a model to break this assumption but we don't have good models).

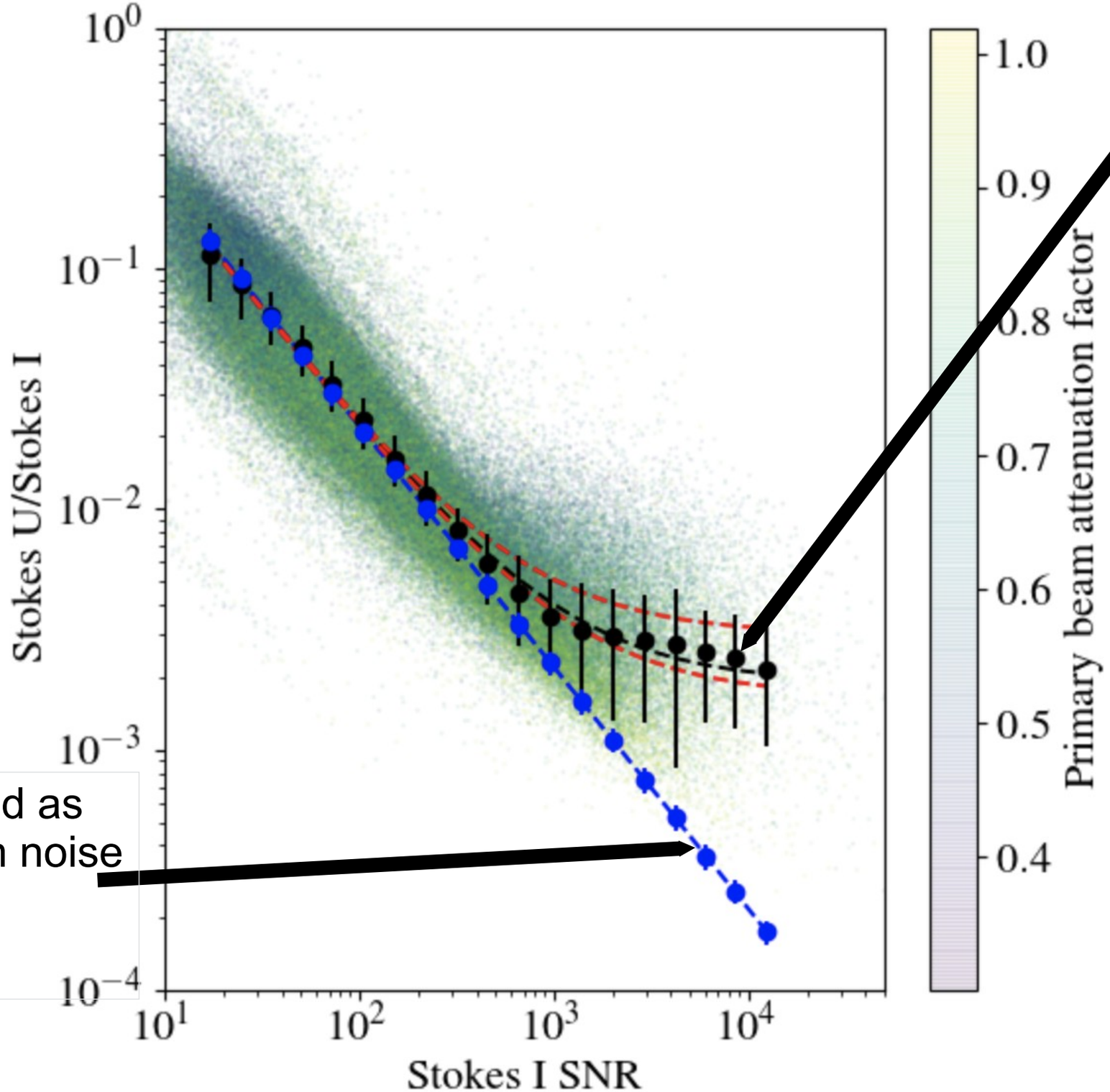
This dramatically improves leakage from I to Q,U or V.

Left: Stokes V after calibration with Q=U=V=0. Right: without



LoTSS leakage

Attempts to characterise leakage by analysing Q, U or V signals in apertures around of Stokes I sources.



Observed Stokes (Q, U or V) / Stokes I ratio.
— **V leakage 0.06%**
- Q or U leakage 0.2%

Q, U, V replaced as Gaussian random noise

LoTSS leakage

Byproduct though is that if there is a real bright polarised (>~10mJy) source then fake polarised sources are created.
Example: 9Jy source at 0.5% polarised produces many spurious sources (normally expect one per square deg but here apparent density is several times higher)

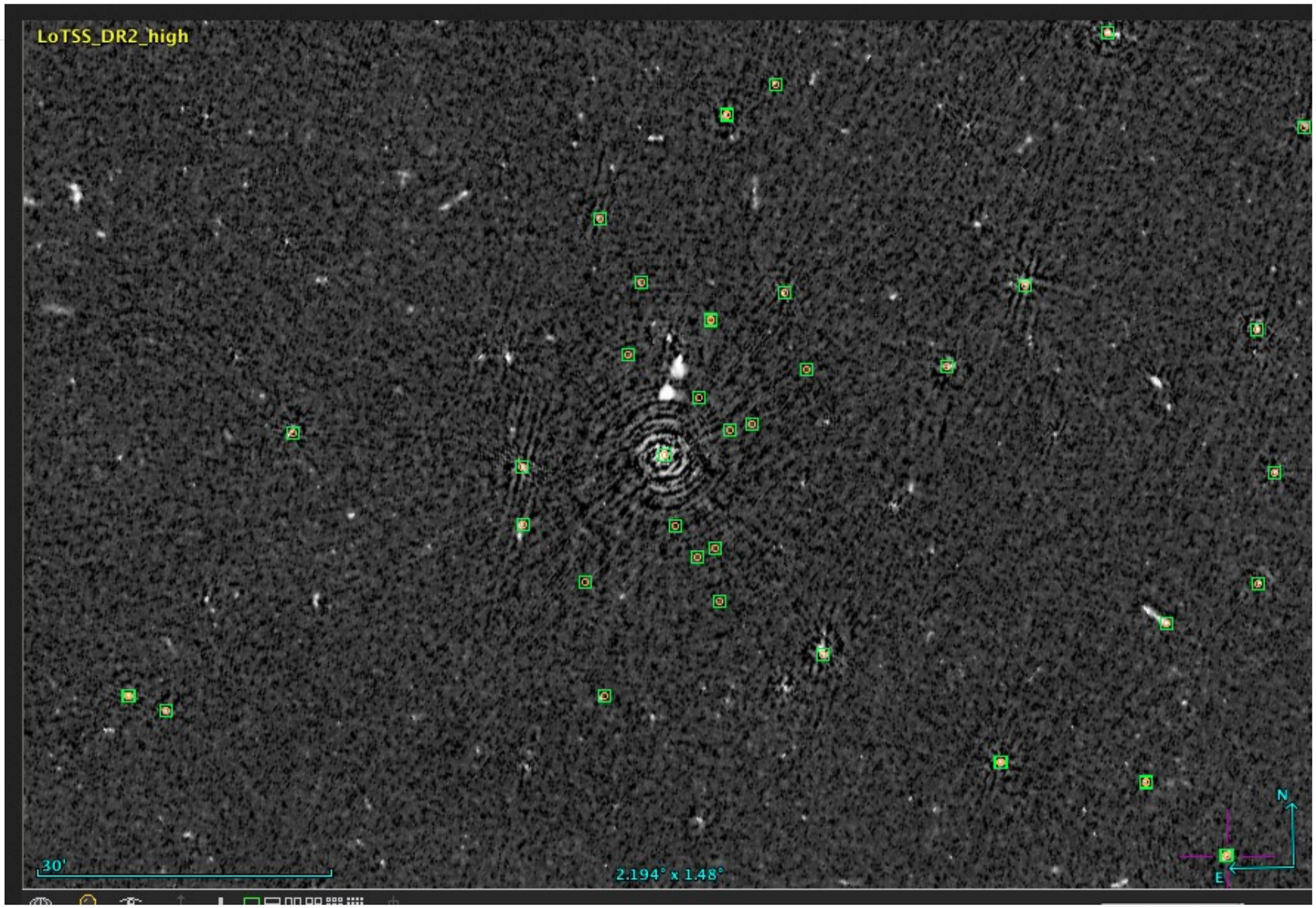
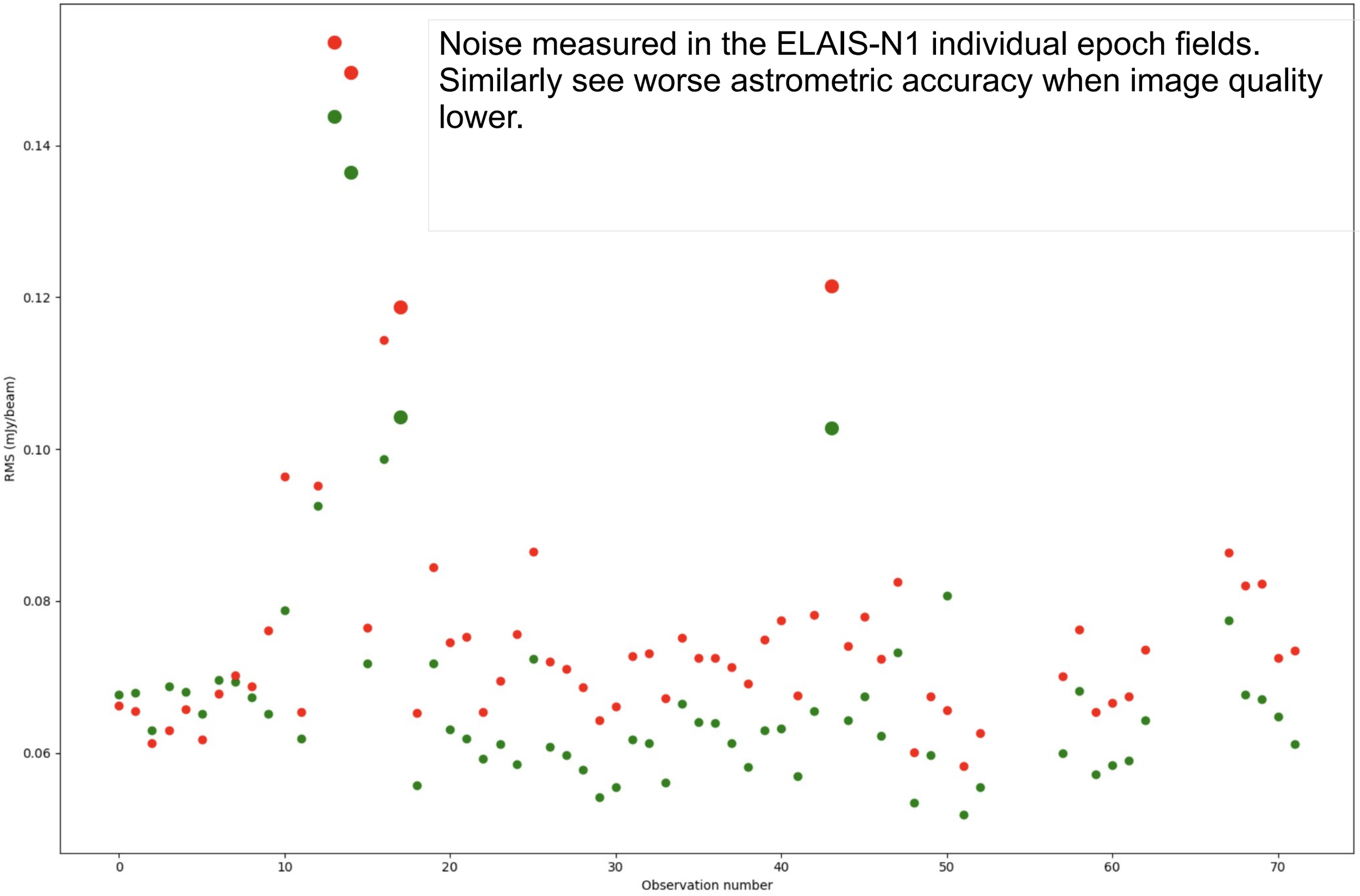


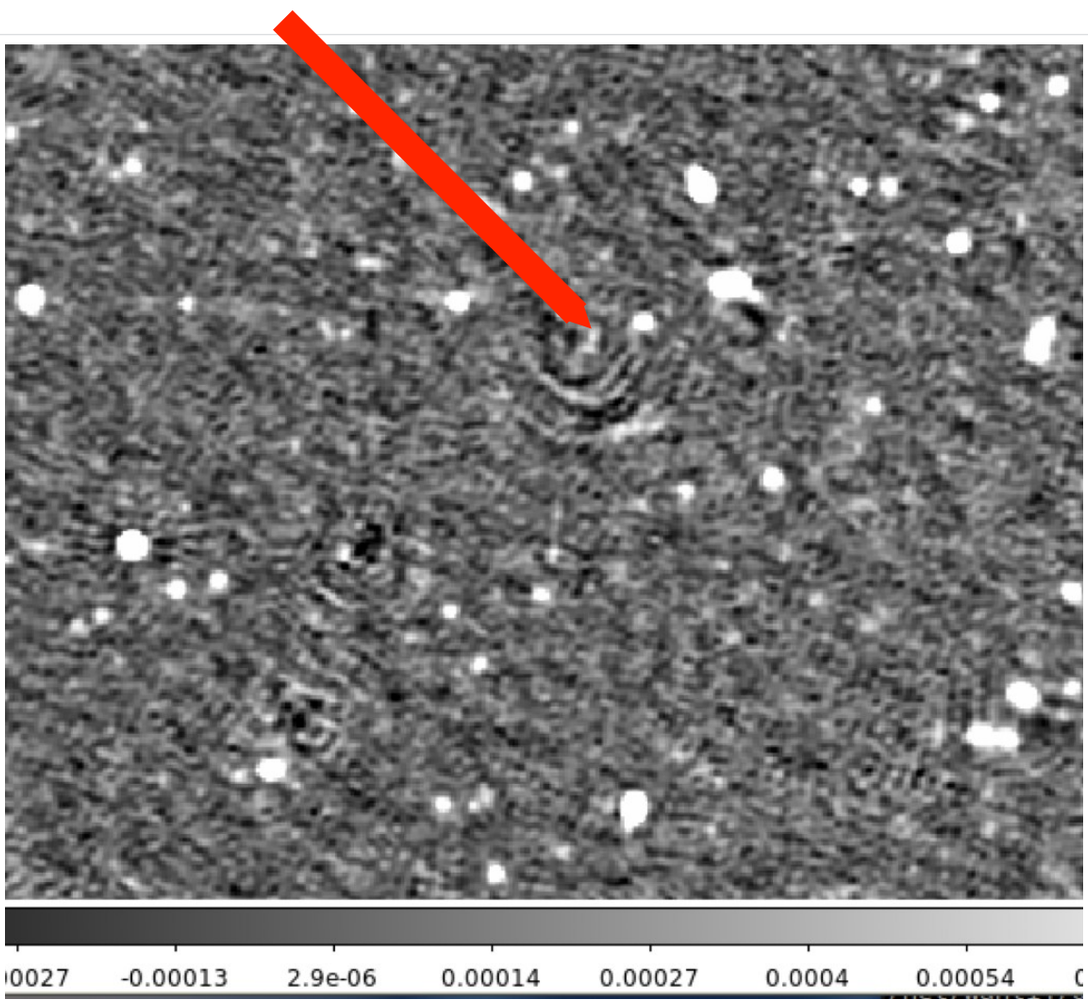
Image fidelity - ionosphere

Noise measured in the ELAIS-N1 individual epoch fields. Similarly see worse astrometric accuracy when image quality lower.

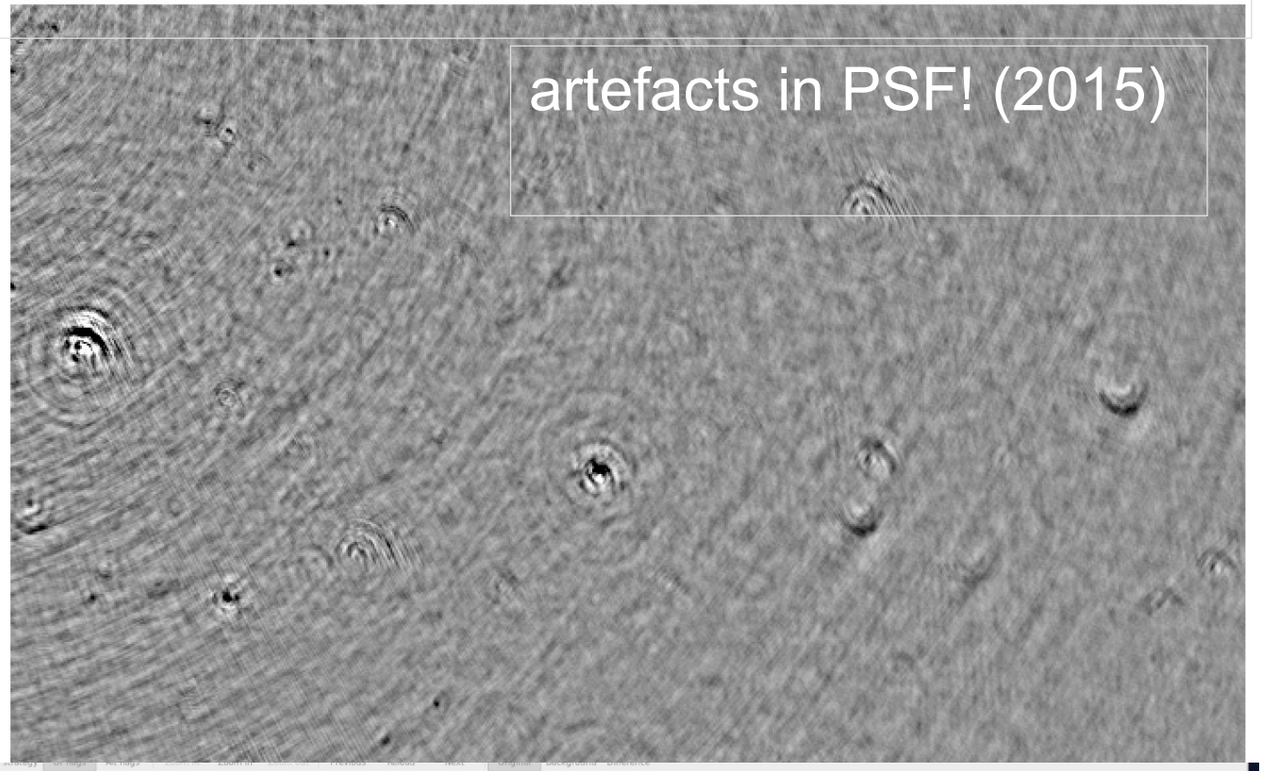


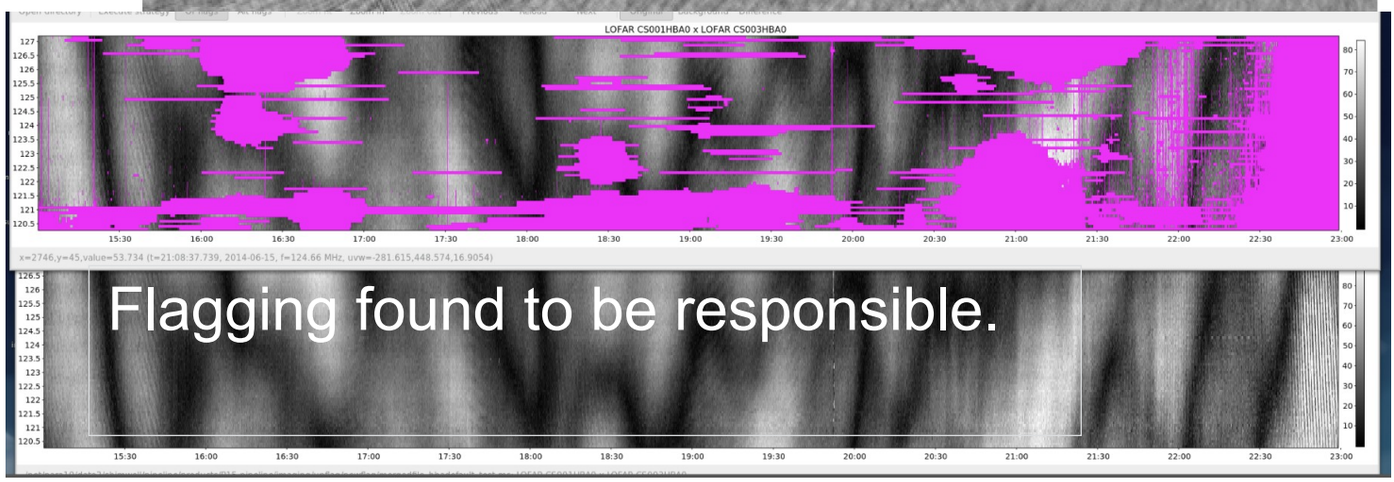
Other strange artefacts?

Whirlpool type artefacts of unknown origin?



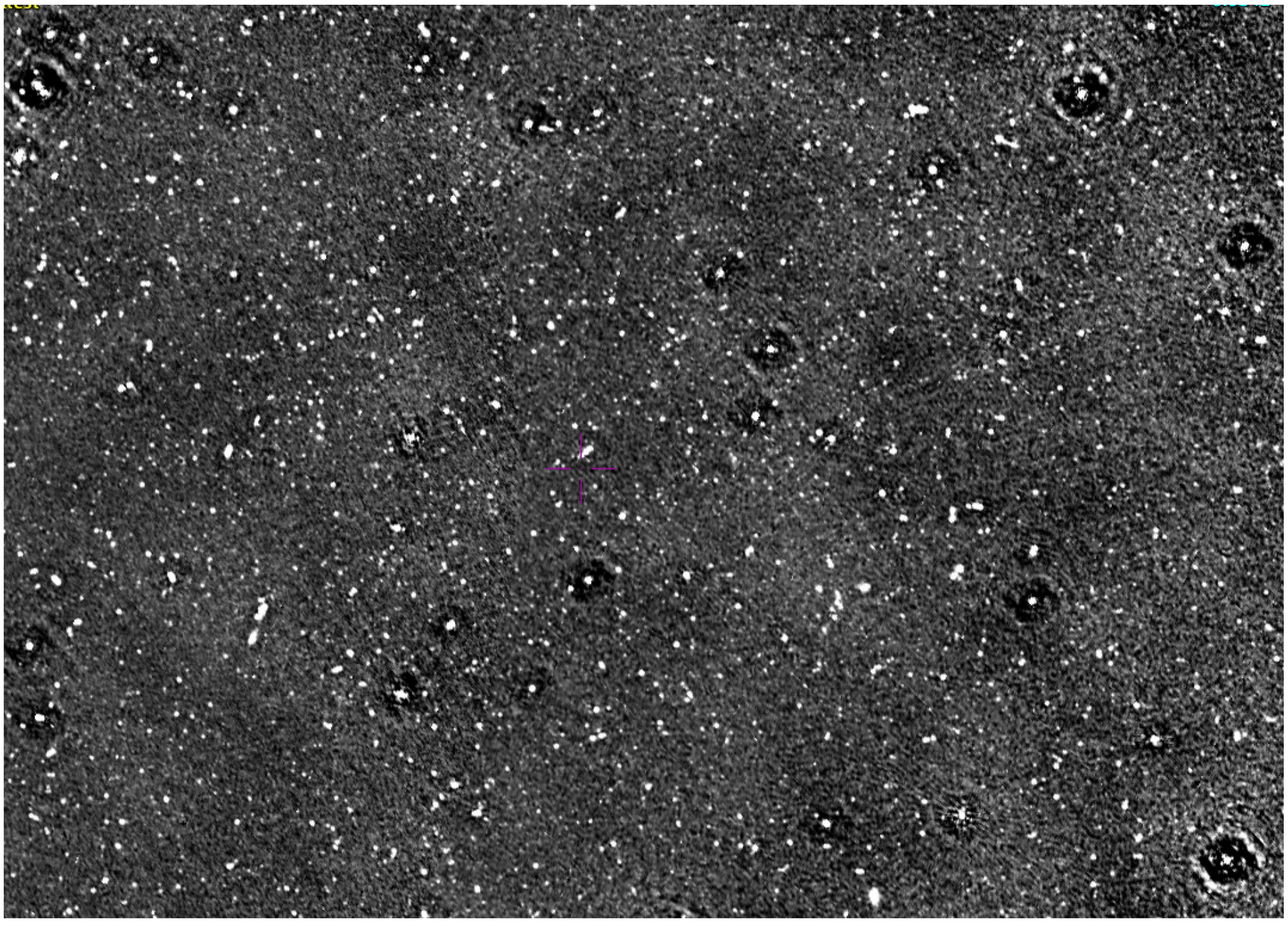
Previously (back in 2015) we managed to create similar artefacts in the PSF due to flagging but artefacts can also be caused by aliasing when imaging and poor quality sky models. Present cause unknown…





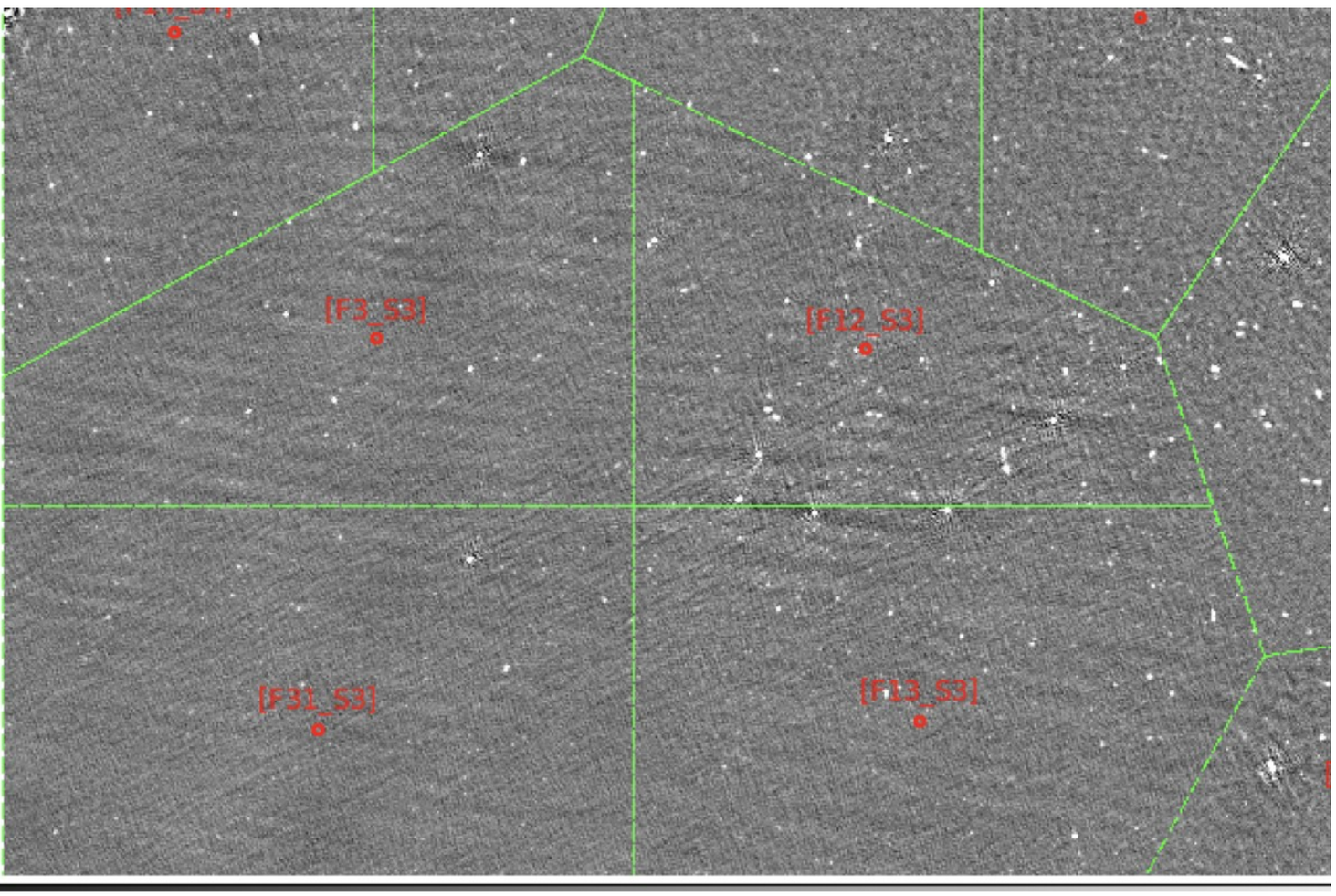
Other strange artefacts?

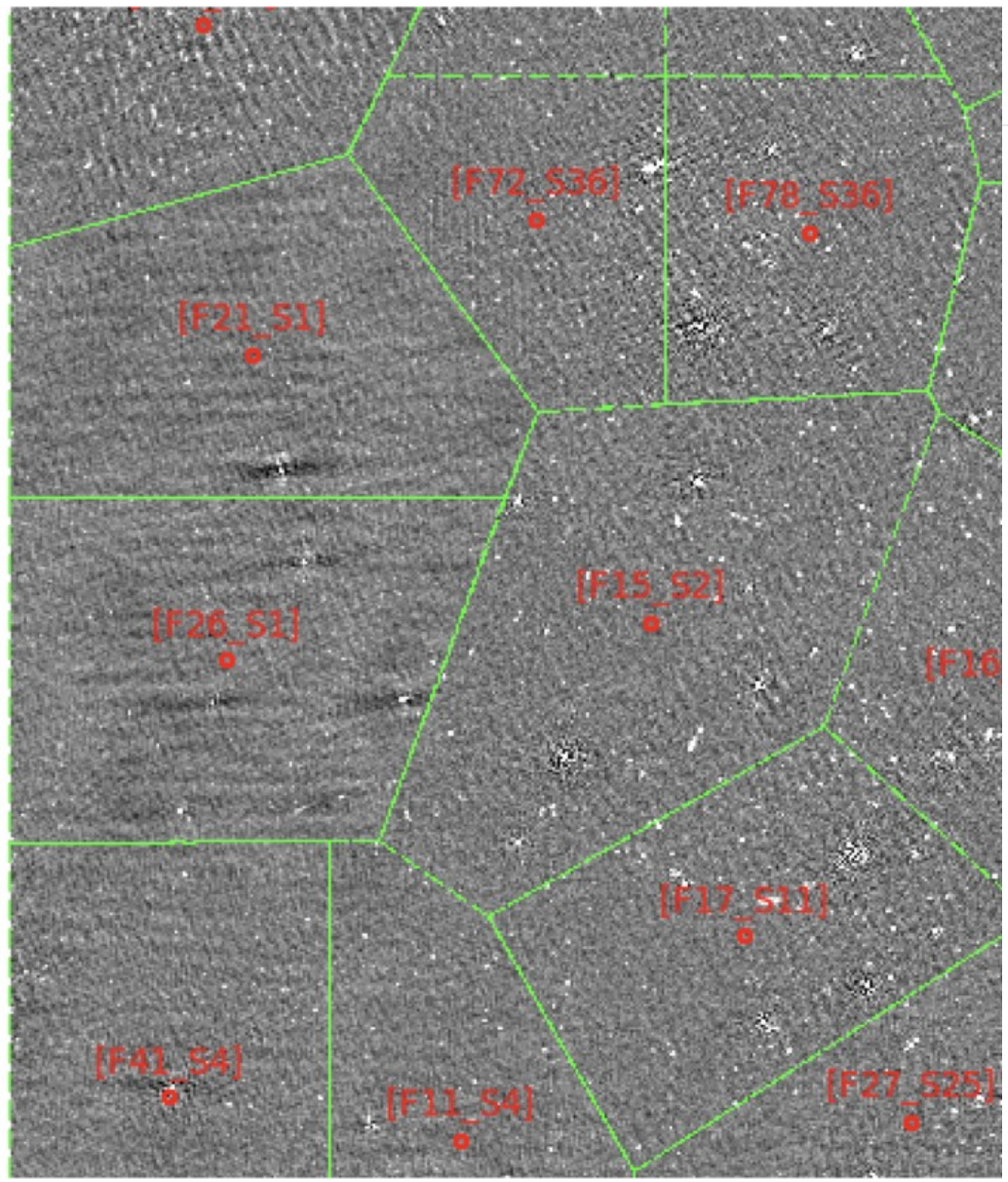
Strange negative holes around brightish compactish sources - caused by removal of Cassiopeia A from the data.



Other strange artefacts?

Calibration performed for each facet in the image. Sometimes the calibration can diverge giving a variety of artefacts.
Left subtle failure. Right quite clear one.





Summary

Radio astronomy (particularly those from LOFAR) images are never perfect
In some cases imperfections limit science potential (e.g. flux density scale limits cosmological applications)
Most science cases are fine
Need to carefully quantify errors.