Dr. Sidelobes, Or How I Learned To Stop Worrying & Love Simulations

O. Smirnov (Rhodes University & SKA SA)

Introduction

“A high quality radio map is a lot like a sausage, you might be curious about how it was made, but trust me you really don't want to know.”
– Jack Hickish, Oxford

- Interferometry is hard and unintuitive, but we've carved out some comfort zones
- New technologies, new observatories and new surveys will be [already are] boldly going where no man has made sausage before
- Results in surprises – of the good & bad variety
  - Many subtle mechanisms – this talk concentrates on sidelobes

Dr Sidelobes

- Primary beam (PB) sidelobes:
  - Making sure you pick up signal you don't need
- PSF sidelobes:
  - Making sure that signal you don't need shows up where you least need it (i.e. all over your map)

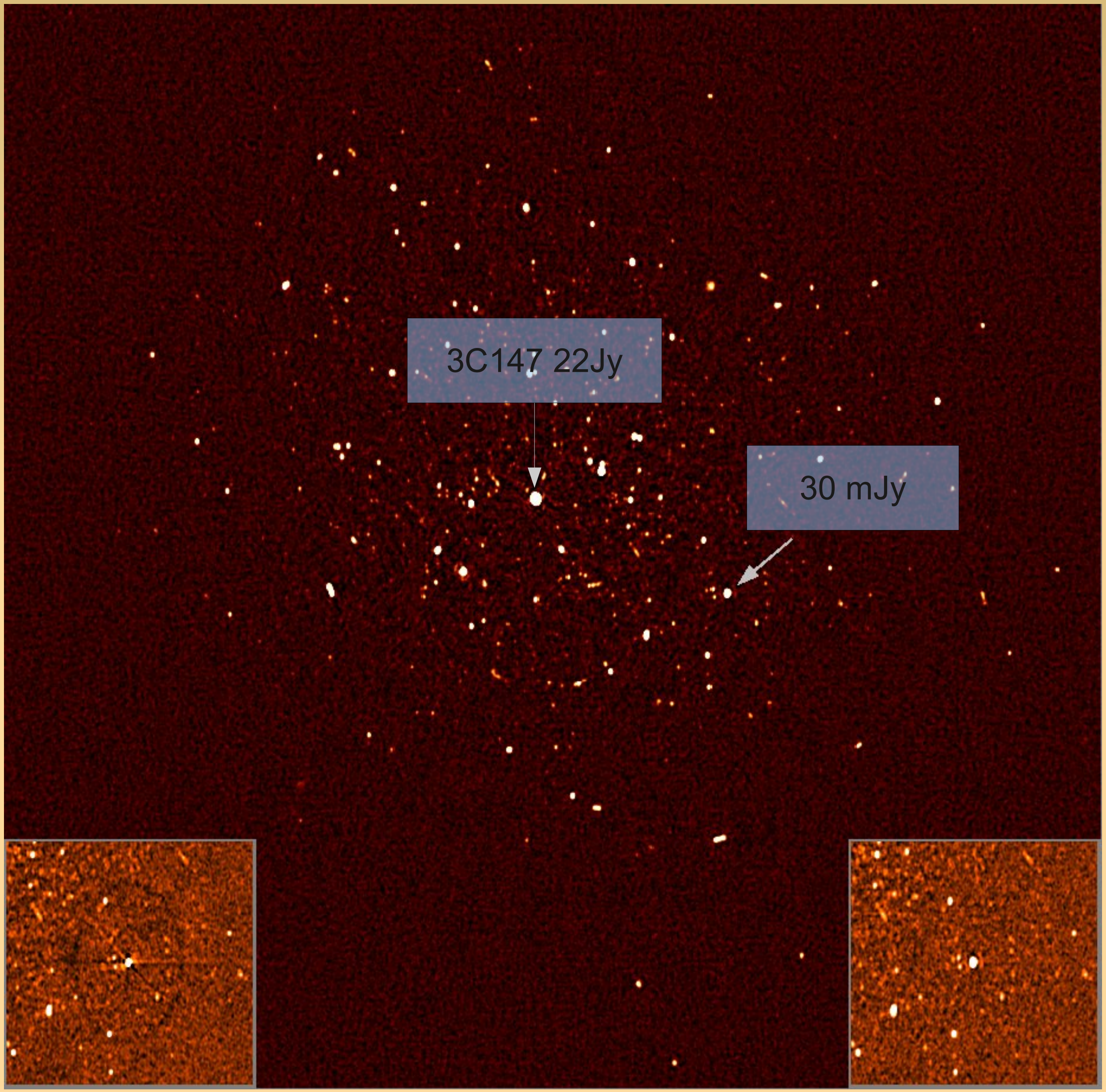
Good News First

3C147 @21cm
12h WSRT synthesis
160 MHz bandwidth

22 Jy peak (3C147)
13.5 μJy noise
1,600,000:1 DR
thermal noise-limited

Regular calibration does not reach the noise, leaves off-axis artefacts due to direction-dependent effects (left inset)

Addressed via *differential gains* (right inset)



JVLA Version

- Recent result from 3GC3 workshop
- 3C147
- JVLA-D @1.4 GHz
- Best image after regular selfcal

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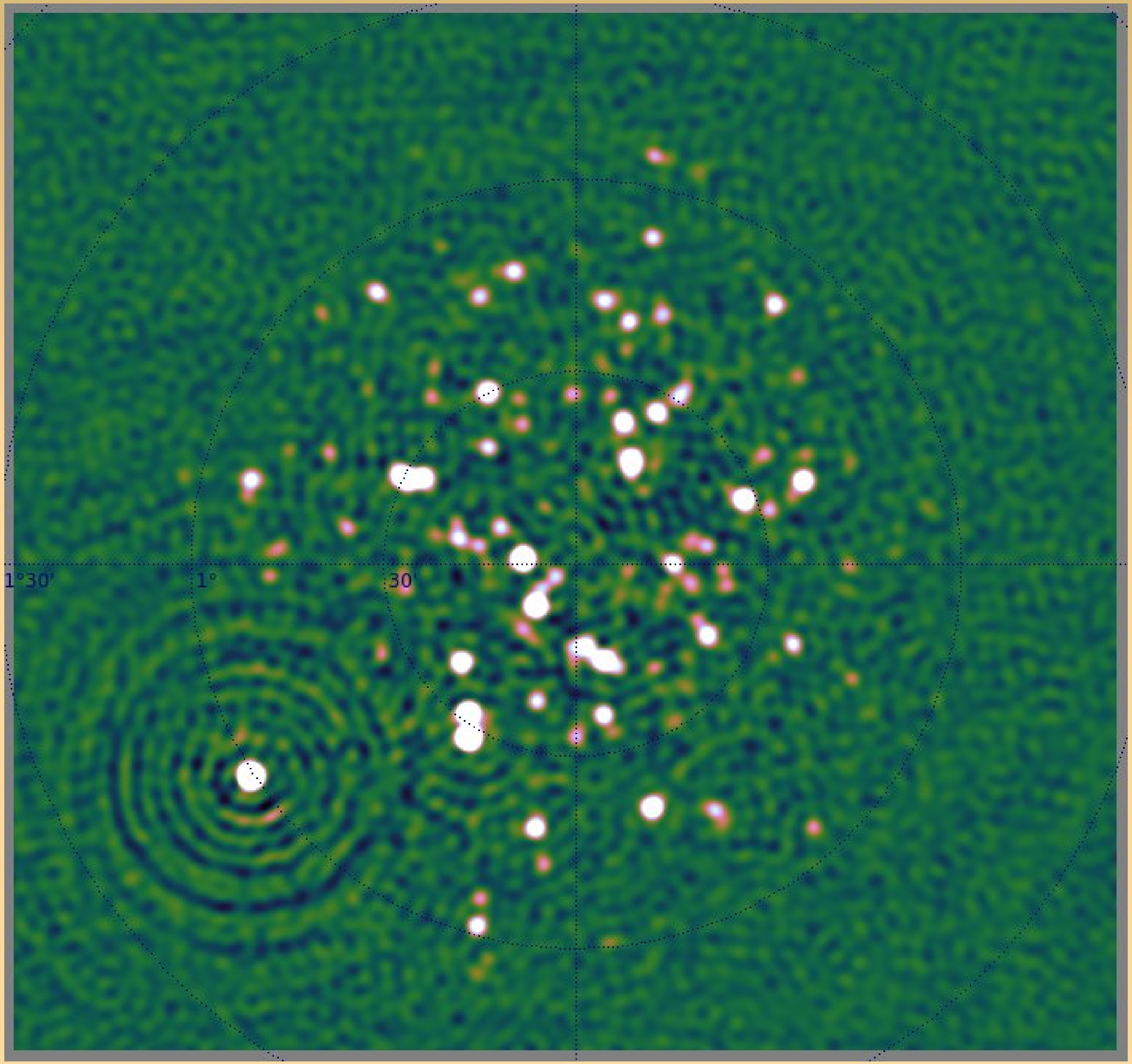
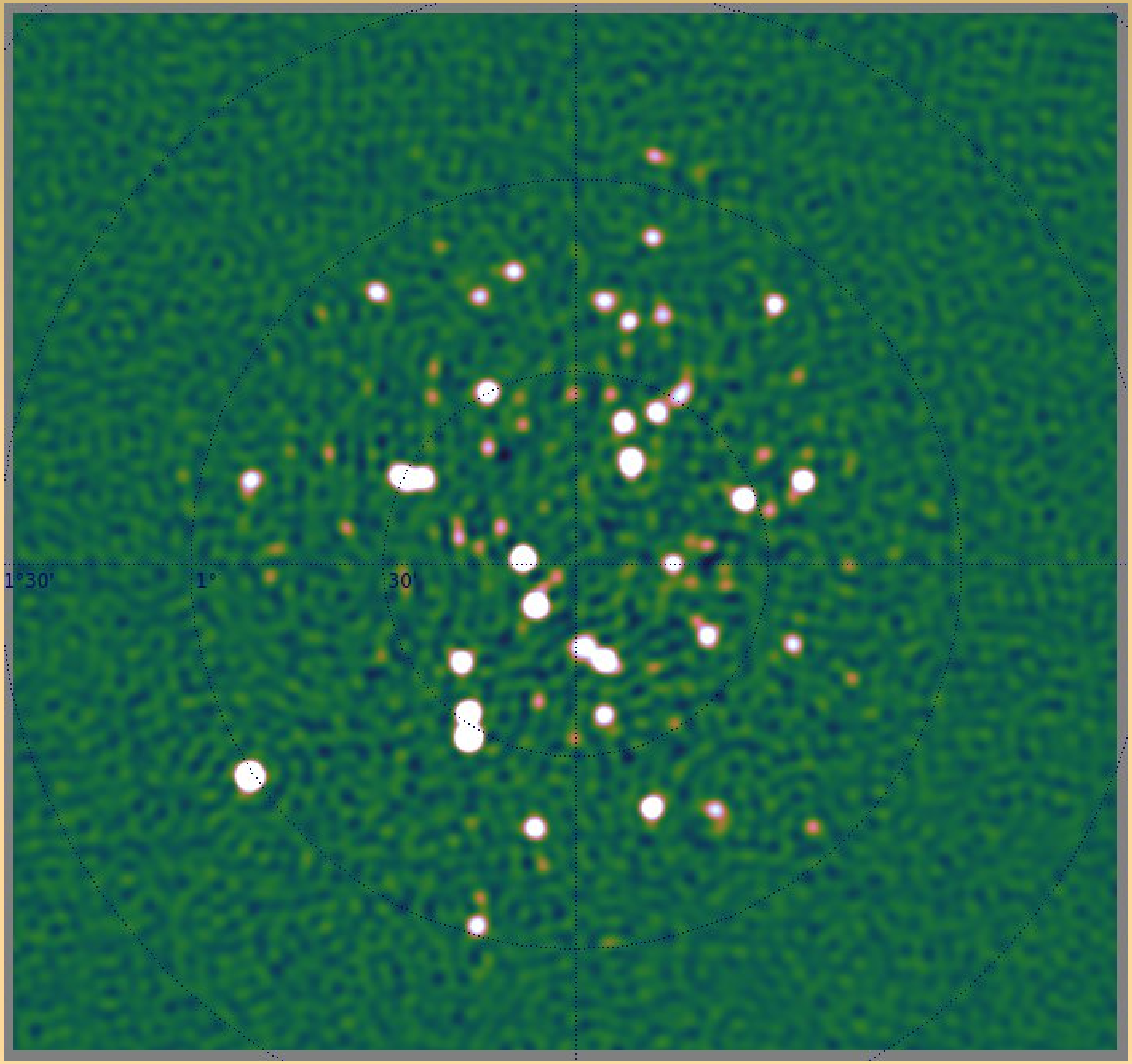
- Best image after regular selfcal
- ...and direction-dependent (DD) calibration on a few sources

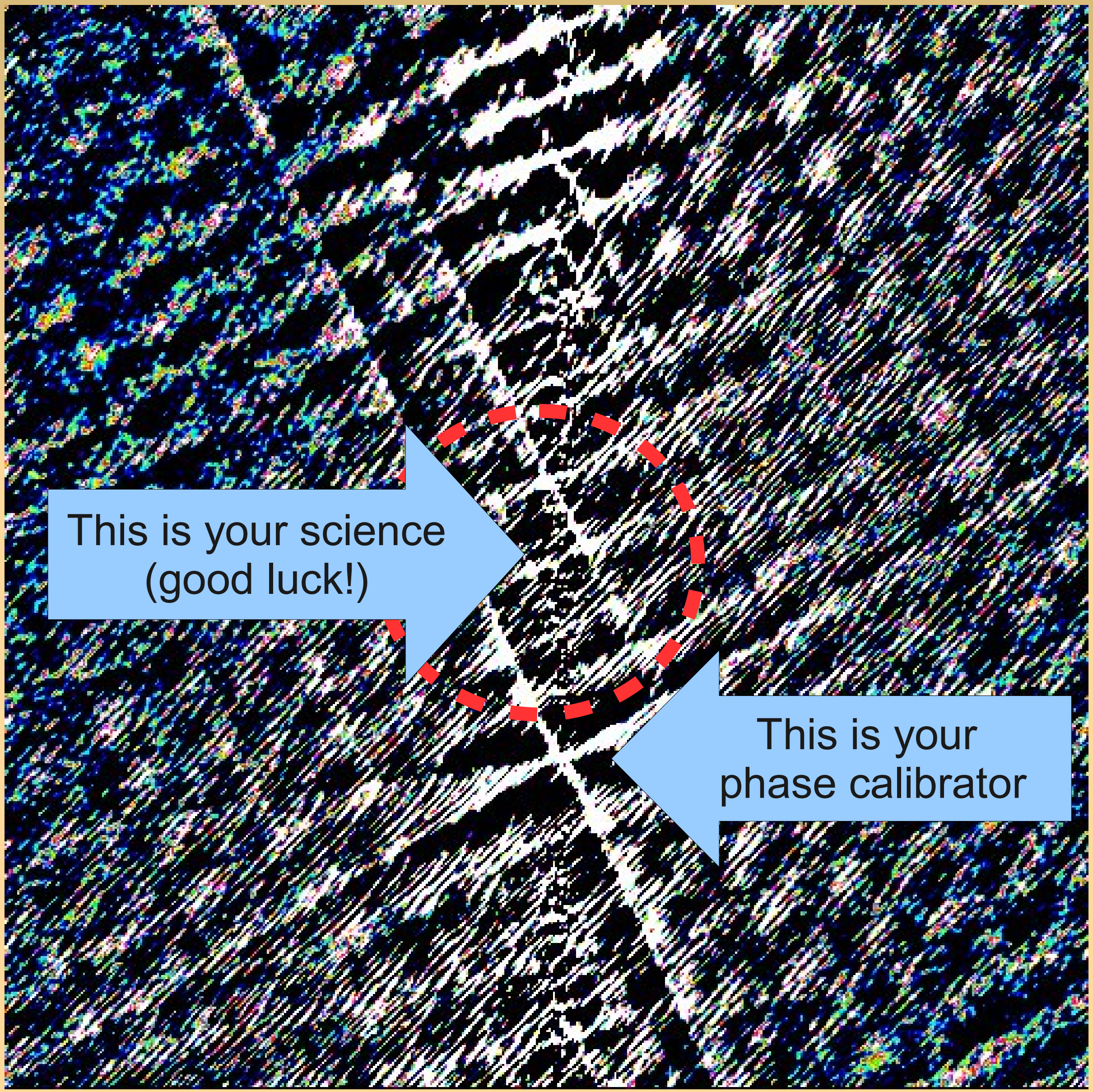
KAT-7 Version



KAT-7 Version



When Primary Beams Go Bad...
(Courtesy of Ian Heywood)



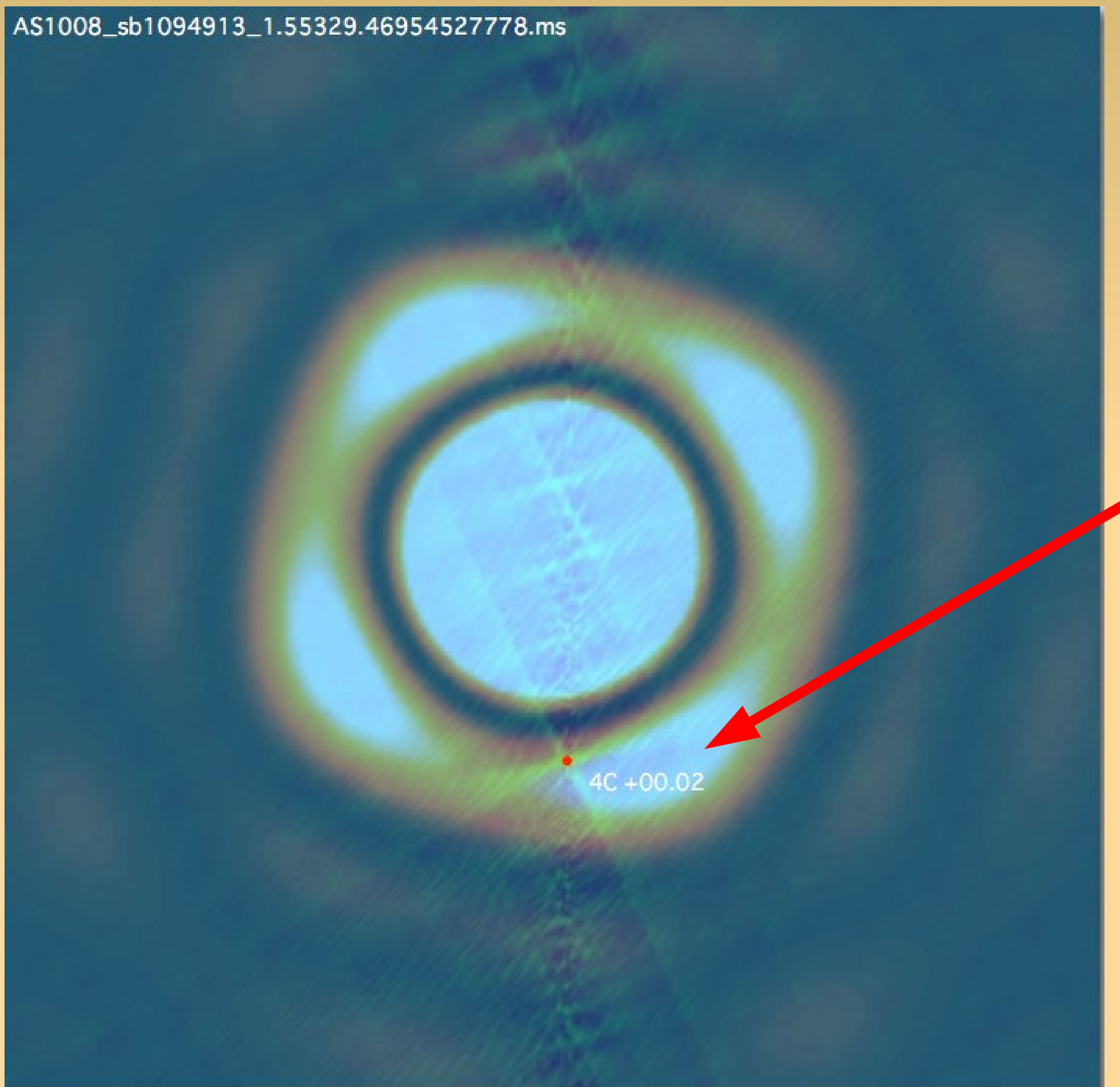
EVLA 8 GHz: Looking for sub-mm galaxies and QSOs in the WHDF.

Dominant effect: bright calibrator source rotating through first sidelobe of the primary beam.

(This also has a horrible PSF, being an equatorial field.)

Brightness scale 0~50μJy

Keep Your Friends Close,
and your calibrators as far away as you can...

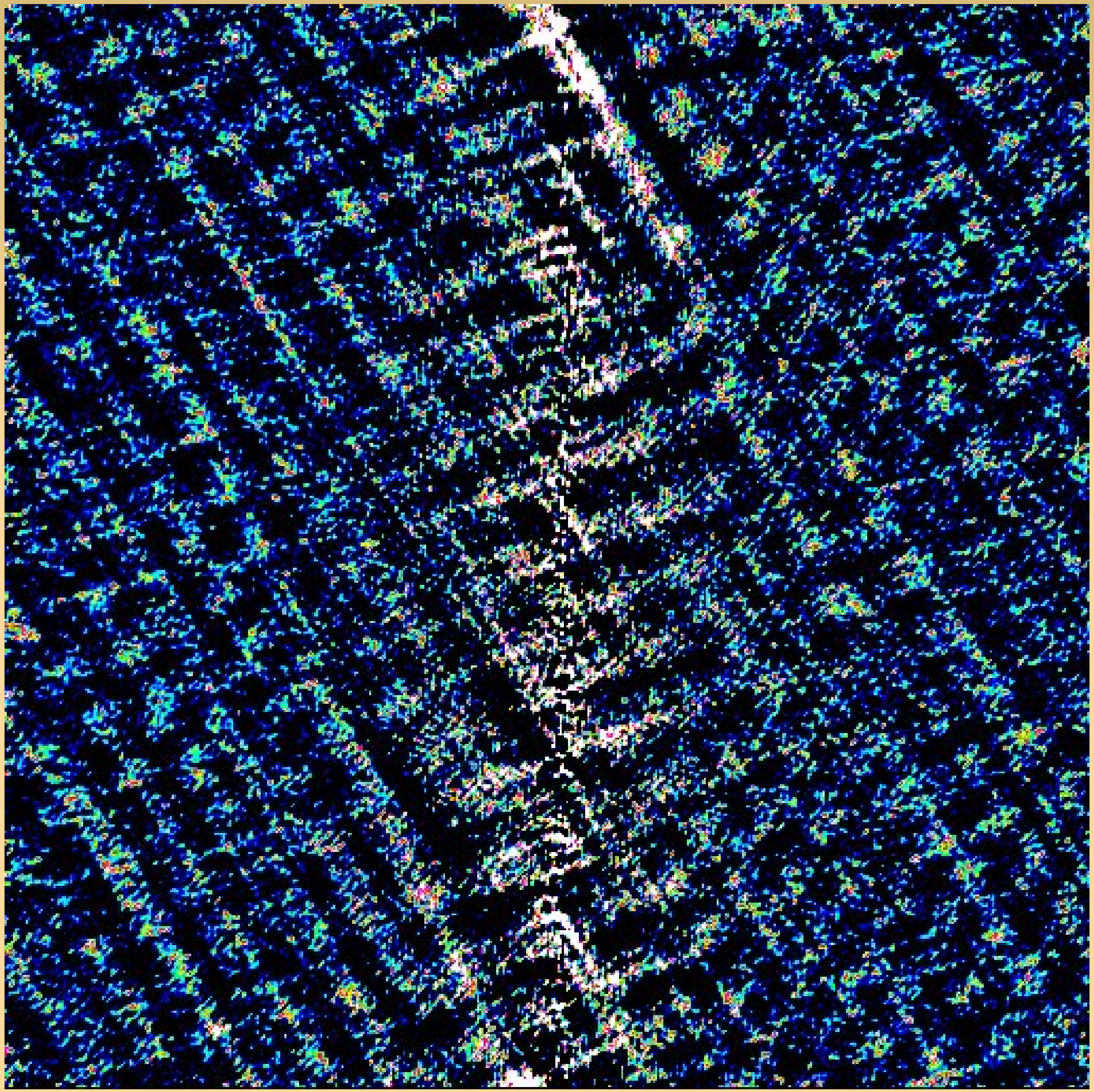


An approximation of the primary beam response, overlaid on top of the image.

As the sky rotates, the sidelobes of the PB sweep over the source, thus making it effectively *time-variable*.

(Brightness scale 0~50μJy)

Deconvolution Doesn't Help...



Residual image, after deconvolution.

The contaminating source cannot be deconvolved away properly, due to its *instrumental* time-variability.

...5 years ago this would observation would probably be a complete write-off.

(Brightness scale 0~50μJy)

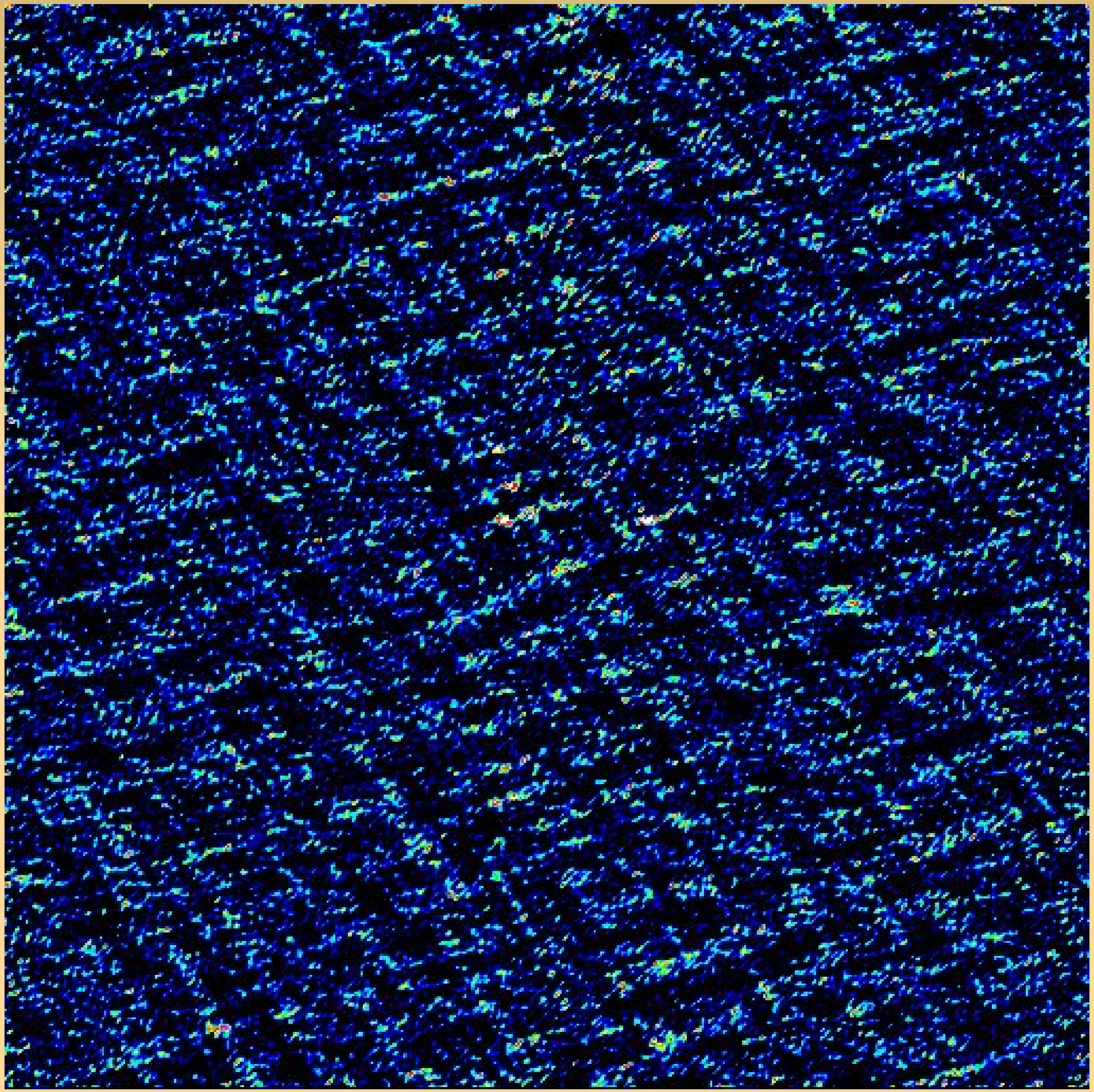
Same Problem Here

The artefacts in this image have the same underlying cause.

But here, the dominant source is at the centre (where PB variation is minimal) and the "offending" sources are relatively faint.

But we did address them via differential gains...

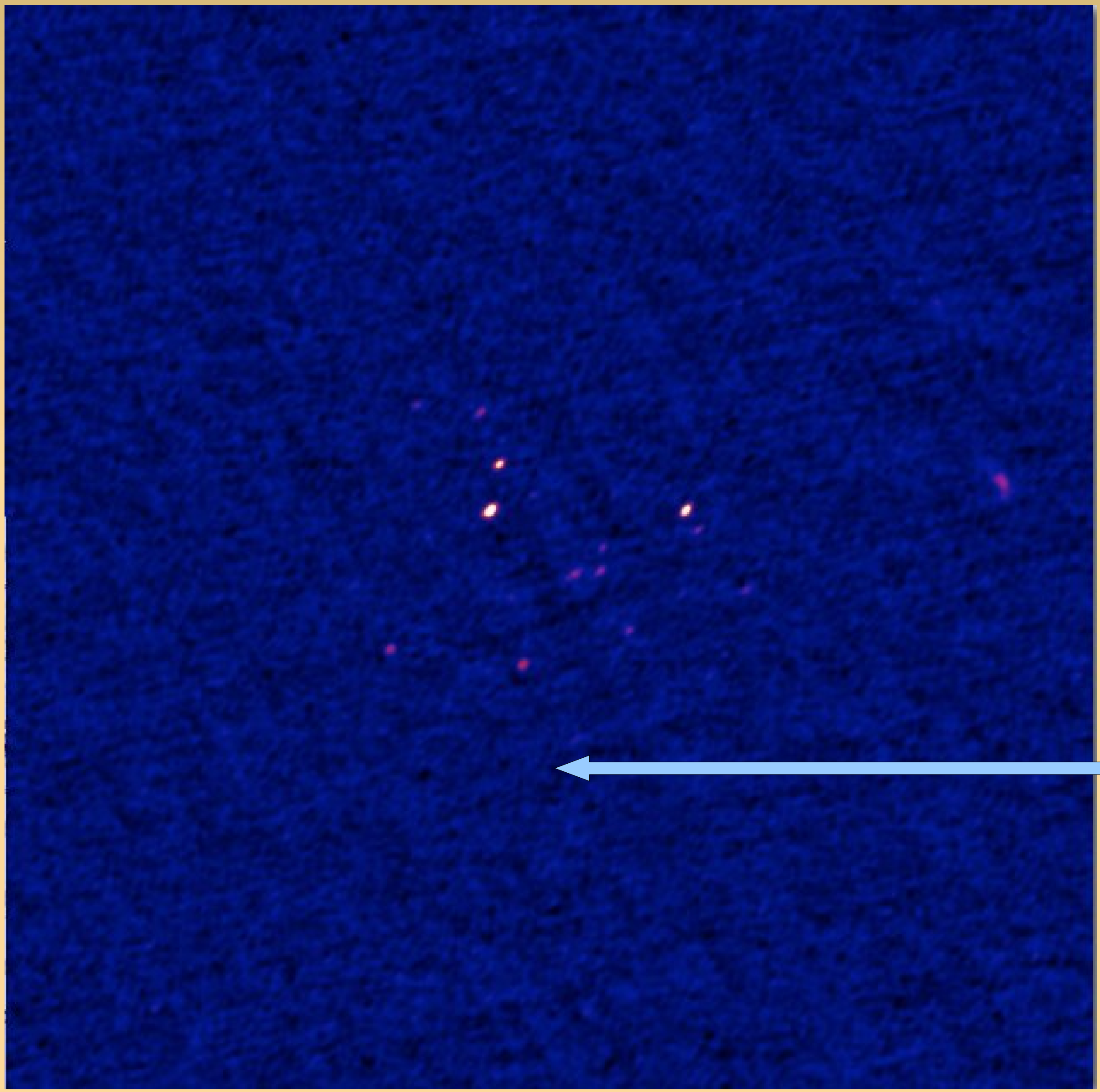
Differential Gains To The Rescue



Residual image after applying differential gain solutions to the contaminating source

Brightness scale 0~50μJy

Multi-Band Image



Multi-band residual image: noise-limited, no trace of contaminating source.

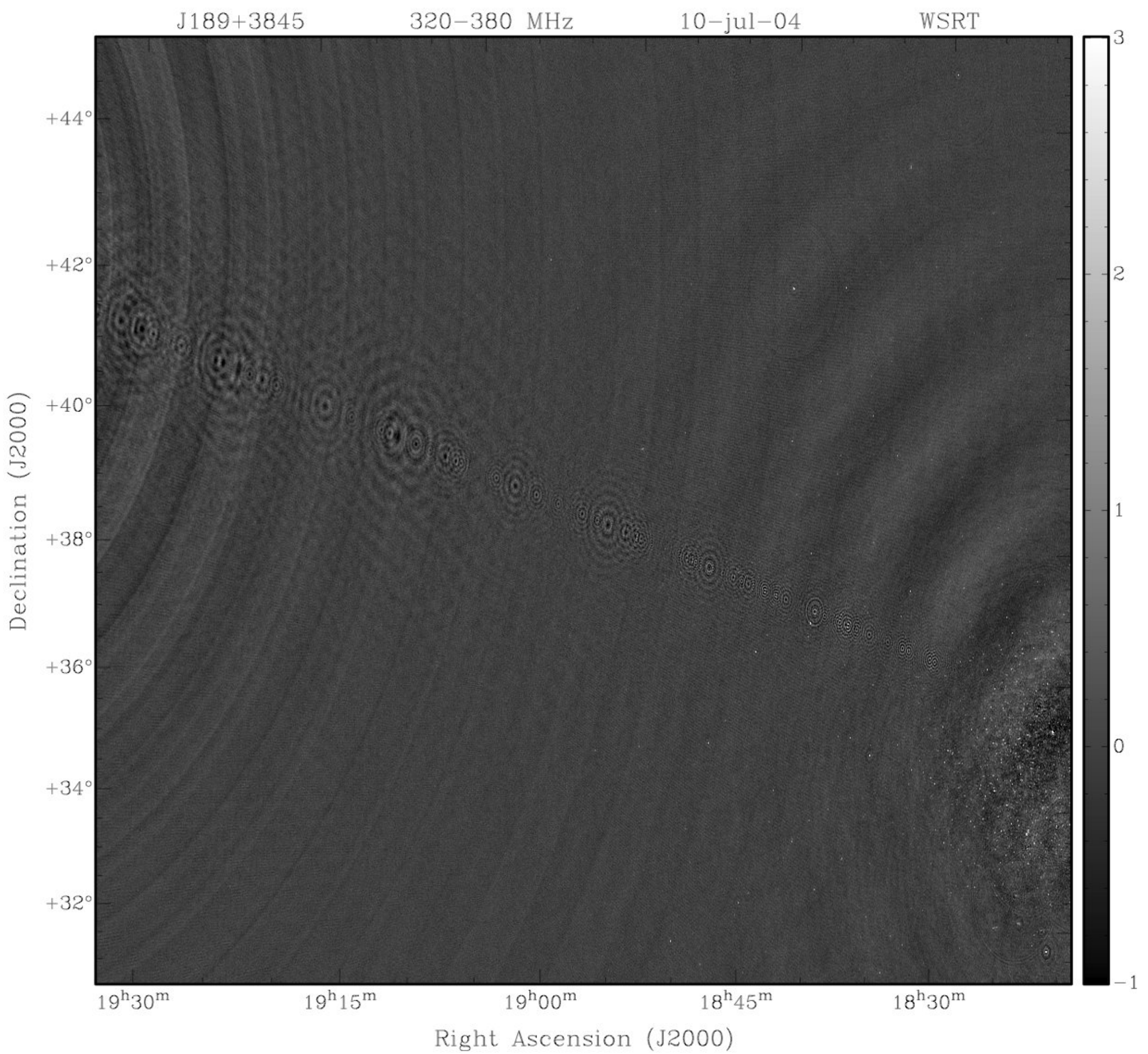
Phase calibrator used to be here

Brightness scale 0~50μJy

Flush With Success

- 3C147, WHDF, LOFAR maps: some real successes
- Thermal noise-limited maps are being produced
  - Though nowhere near routinely...
  - T&Cs apply: extended sources are still notoriously hard to deconvolve
  - ….though new algorithms are emerging
- Is this the light at the end of the tunnel?

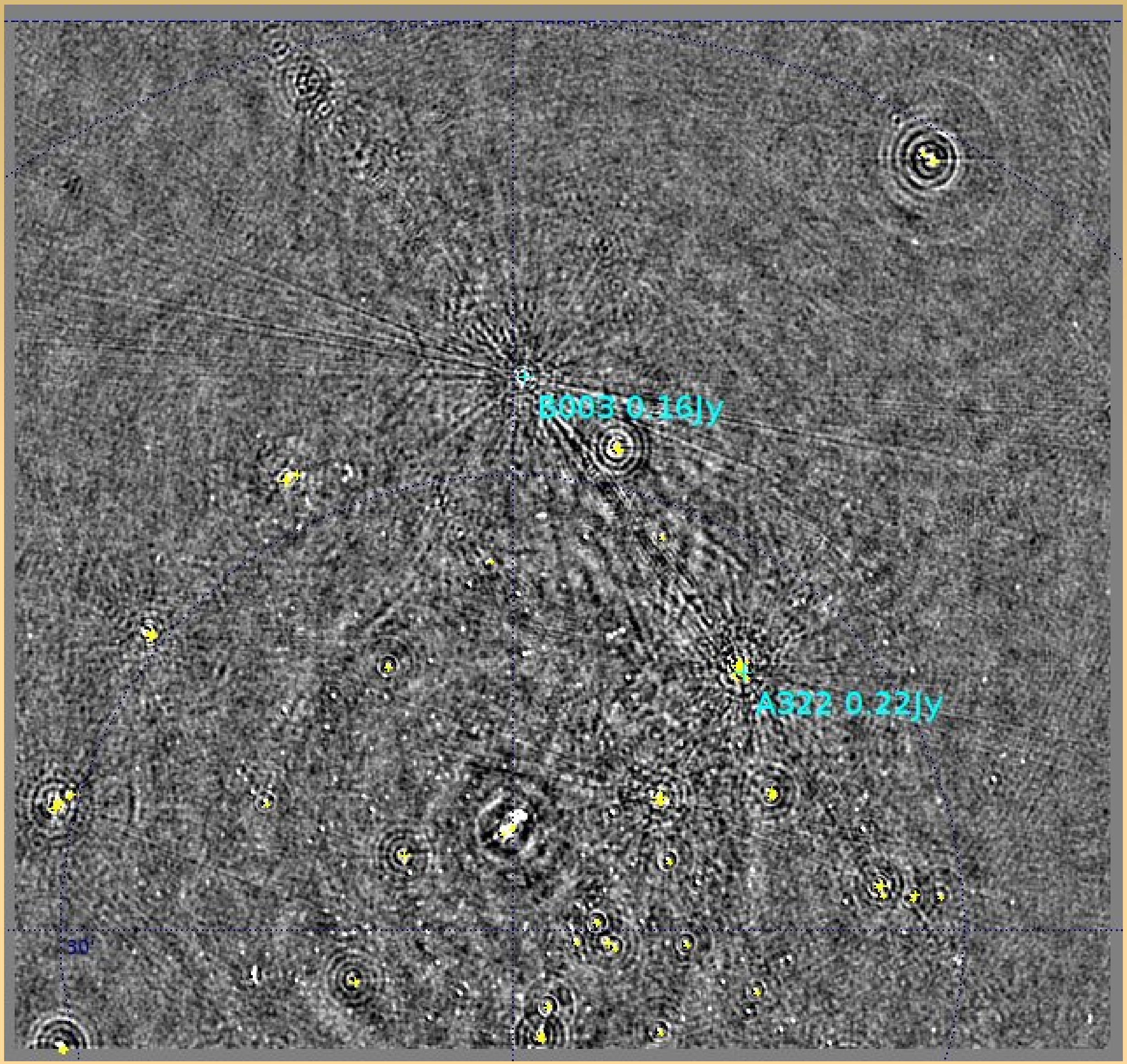
2004: The Ghosts Of Cyg A



WSRT 92cm observation of J1819+3845 by Ger de Bruyn

- String of ghosts connecting brightest source to Cyg A (20° away!)
- "Skimming pebbles in a pond"
- Positions correspond to rational fractions (1/2, 1/3, 2/3, 2/5, etc...)
- Wasn't clear if they were a one-off correlator error, a calibration artefact, etc.
  - (...and if you did low-frequency in 2004, you had it coming anyway.)

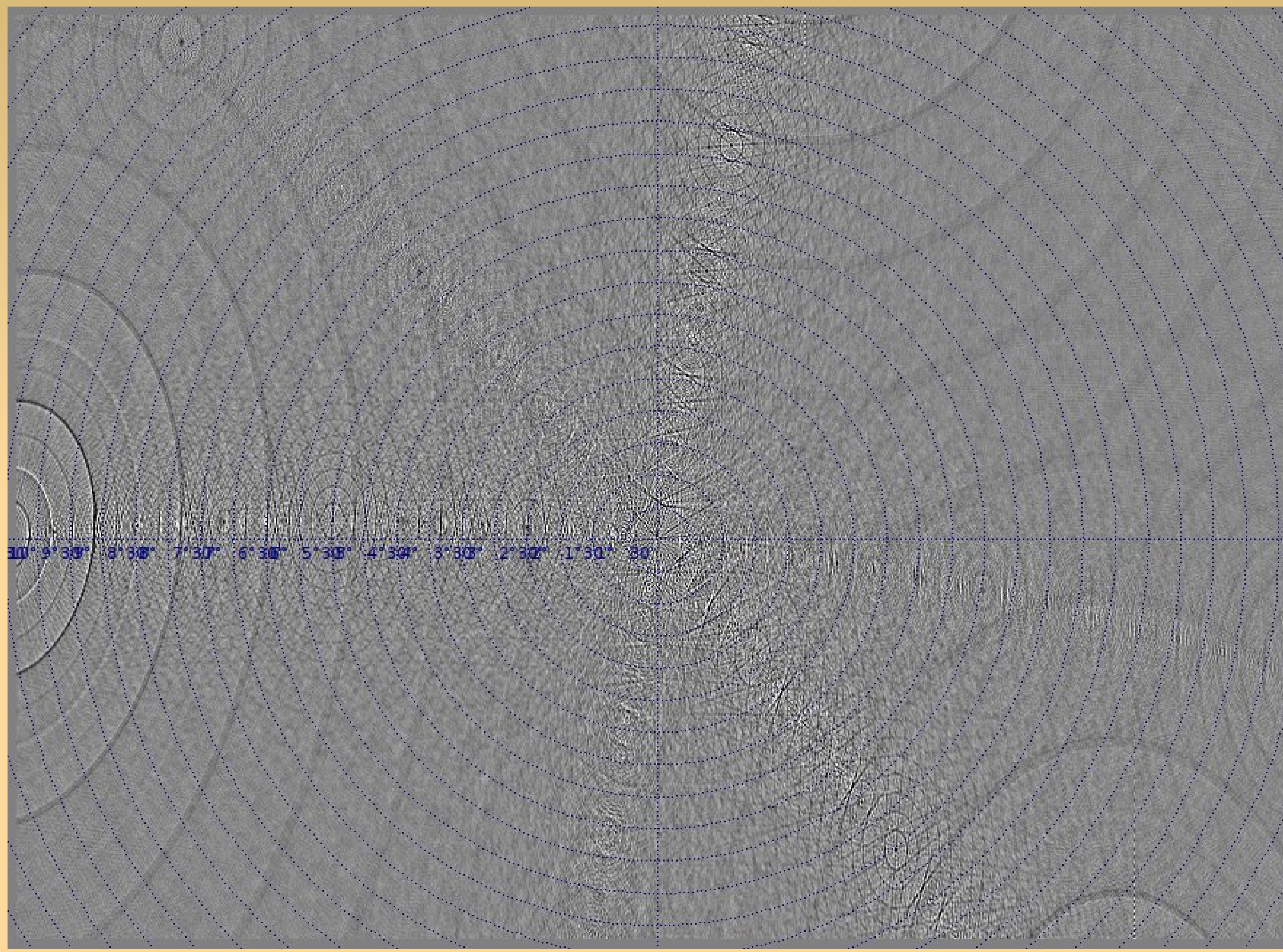
2010: Ghosts Return



WSRT <u>21cm</u> observation

- ...with intentionally strong instrumental errors
- String of ghosts extending through dominant sources A (220 mJy) and B (160 mJy)
- Second, fainter, string from source A towards NNE
- Qualitatively similar to Cyg A ghosts

If You Can Simulate It...

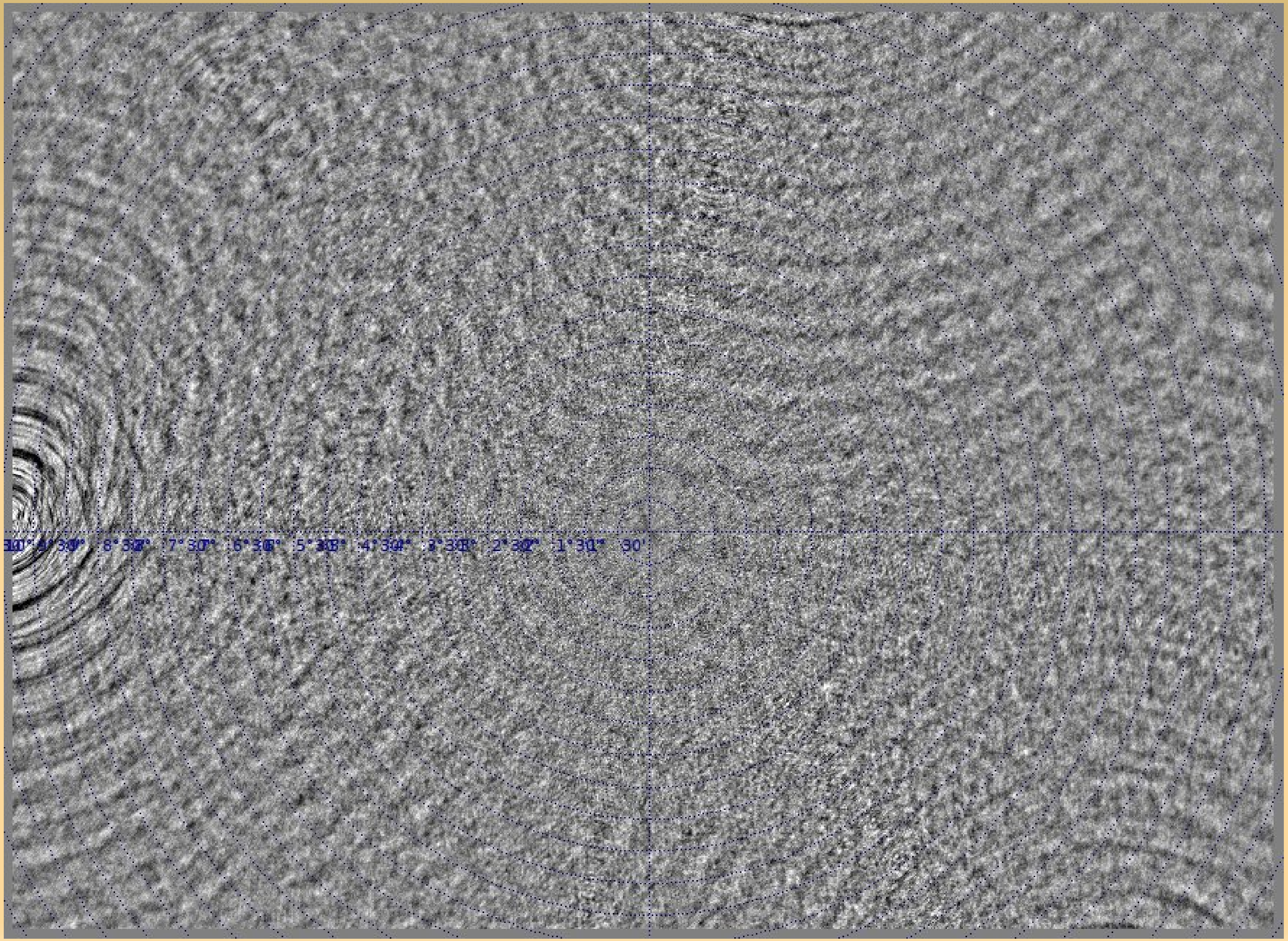


- Eventually nailed via simulations

Ghosts In The (Selfcal) Machine

- Ghosts arise due to *missing flux* in the calibration sky model
- Mechanism: selfcal solutions try to compensate for this by moving flux around
  - Not enough DoFs to do this perfectly
  - ...so end up dropping flux all over the map
  - ...with a lot of help from the good Dr Sidelobes
- Regular structure in this case due to WSRT's redundant layout = regular sidelobes
  - JVLA, MeerKAT: "random" (but not Gaussian!)

JVLA Ghost Sim

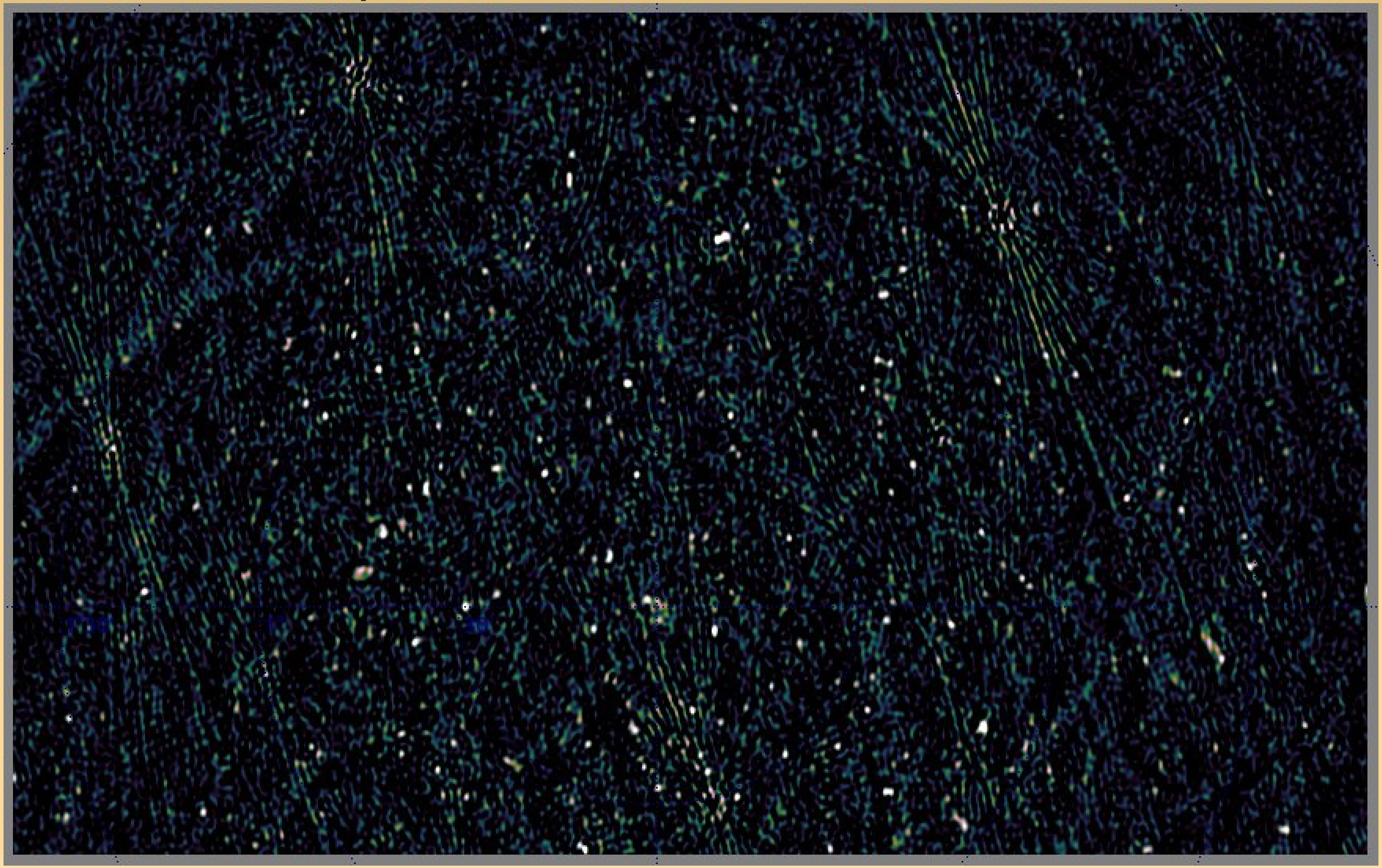


Ghastly Questions

- Does selfcal always introduce ghosts?
  - YES. But most of the time they're buried in the noise.
  - ...unless you have a complete sky model (i.e. if all your science targets are known in advance)
- Why don't we always see them?
  - Not enough sensitivity
- Will they average out?
  - NO. Push the sensitivity, they pop out.
- What will they do to my statistical detections (hello EoR)?
  - Dunno. Simulations needed.
- What else is that redistributed flux doing?

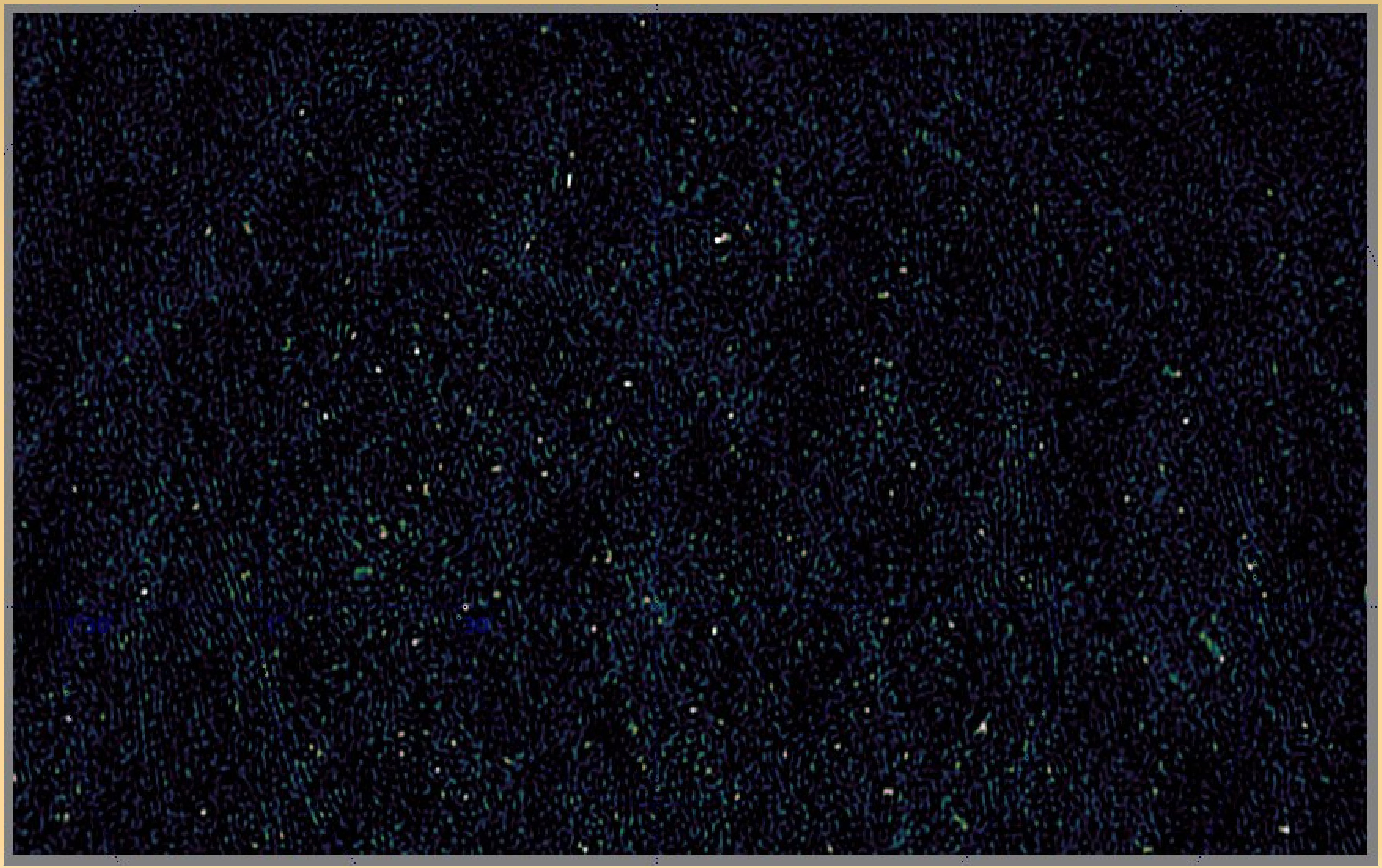
Ghosts, The Flip Side

- WSRT "Field From Hell" (Abell 773 @300 MHz), residual map



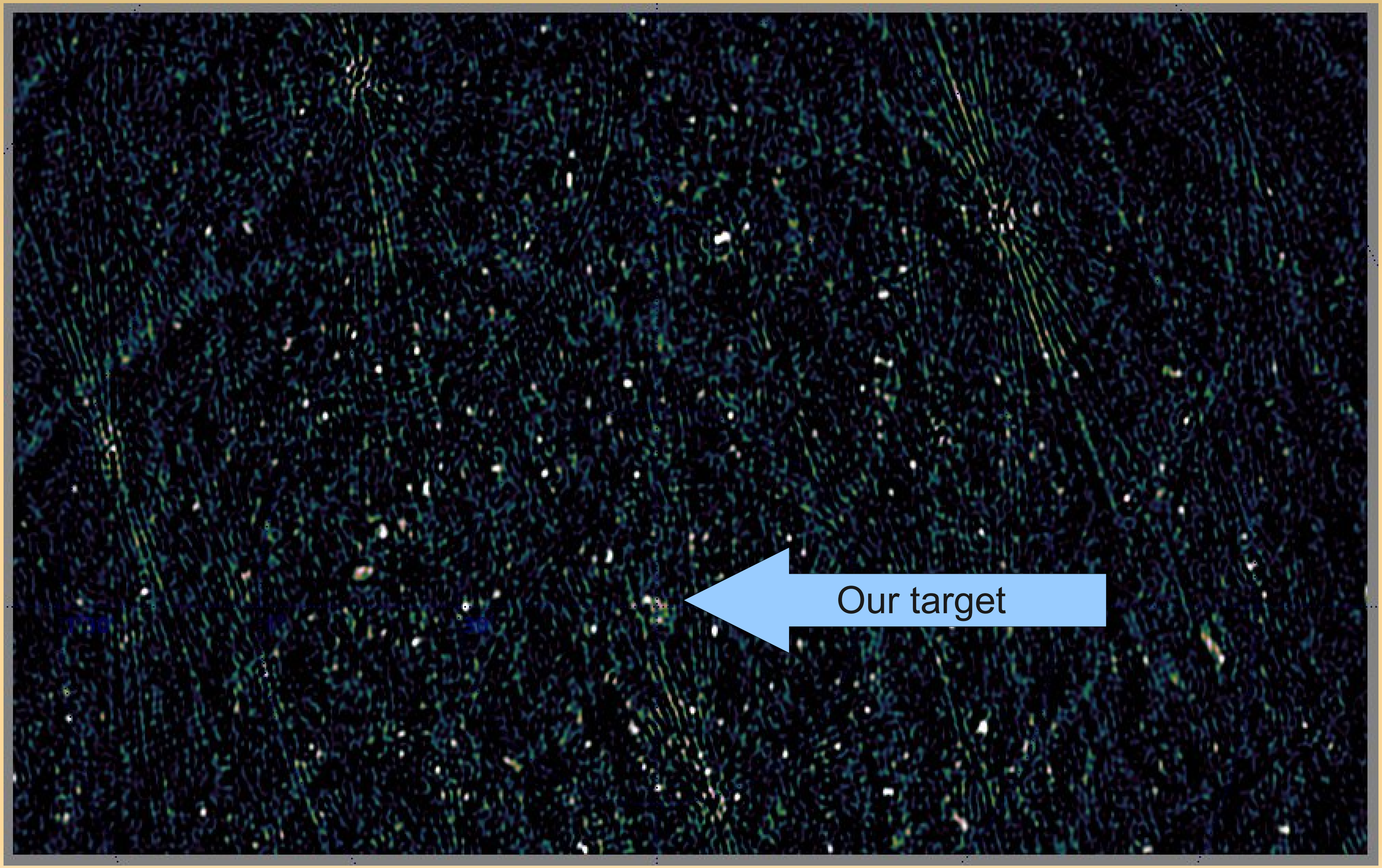
Getting There, Right?

- After diligent (direction-dependent) calibration



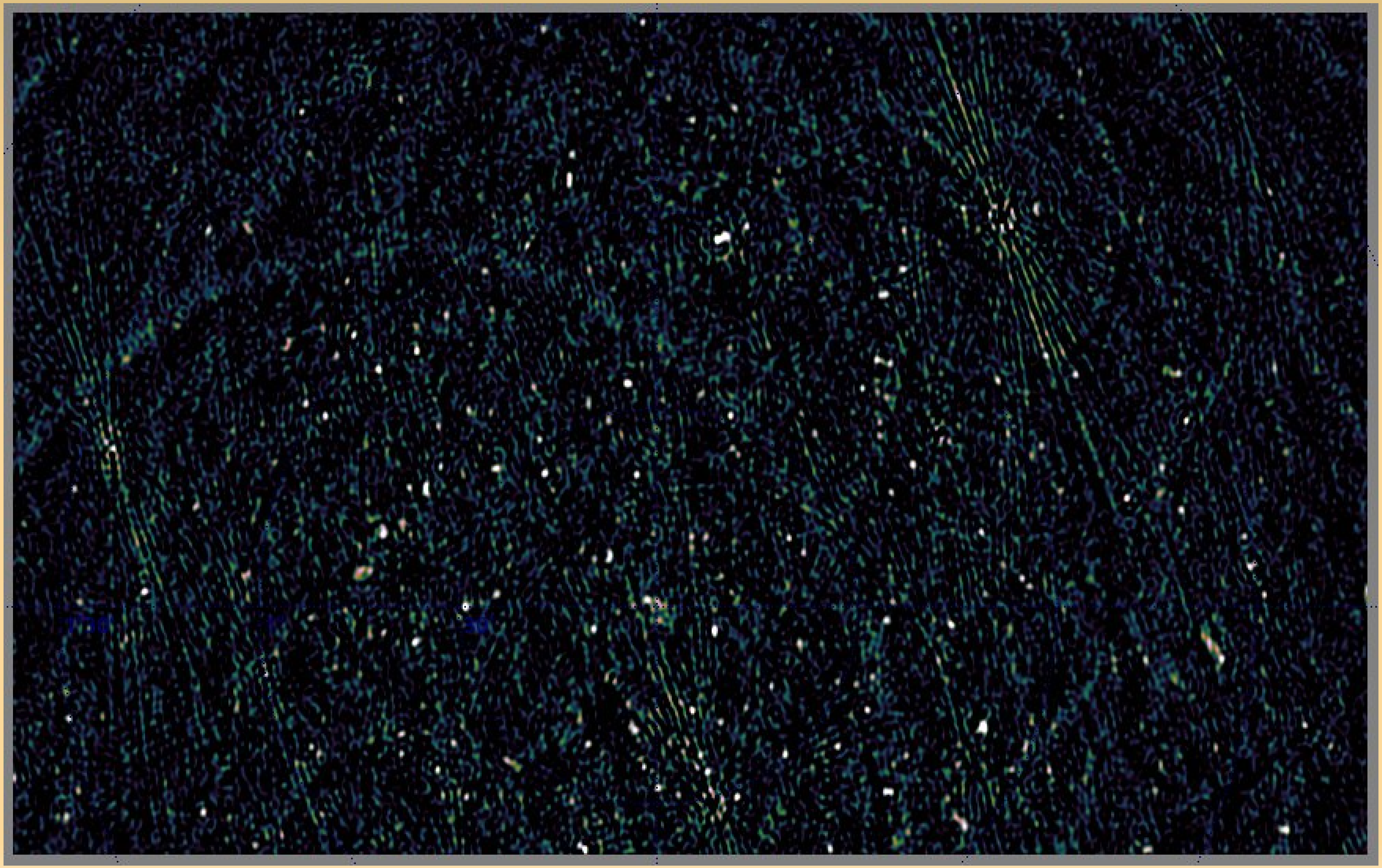
Noise-limited Is Not Always Good

- Suppression of non-model sources

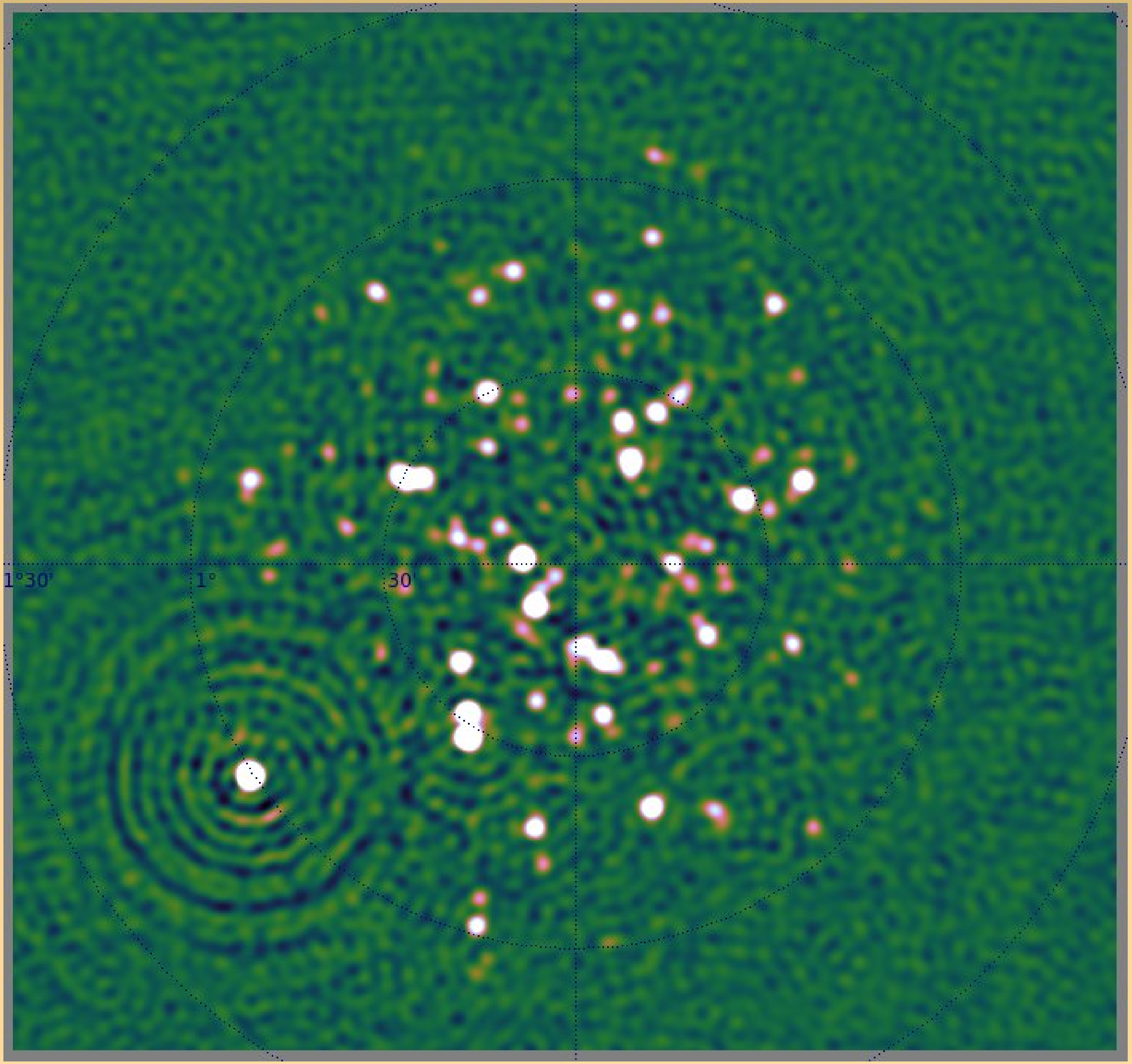


The Dangers Of Direction-Dependent Solutions

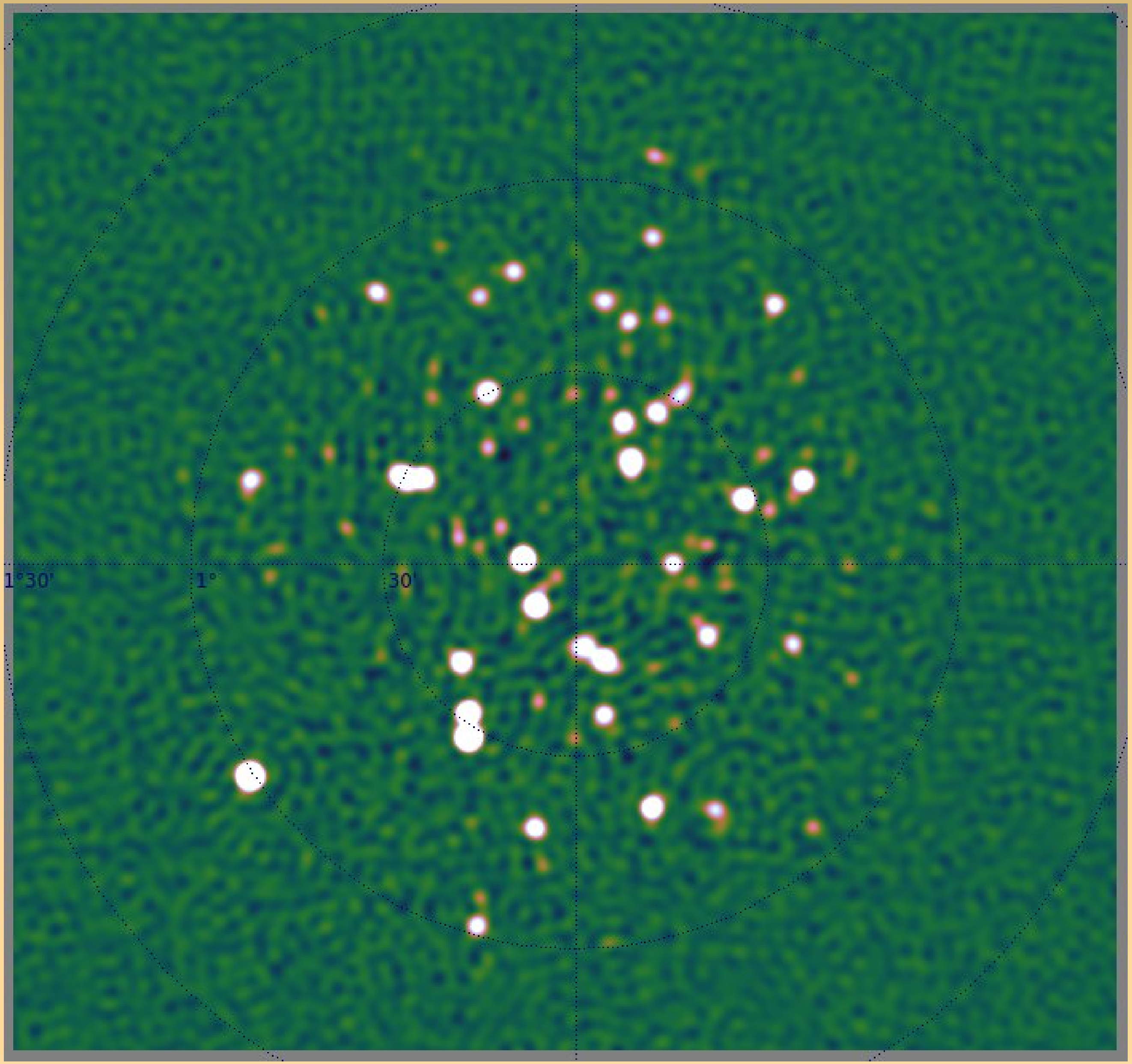
- Suppression is less with more conservative calibration



KAT-7 Source Suppression



KAT-7 Source Suppression



Ghosts & Source Suppression

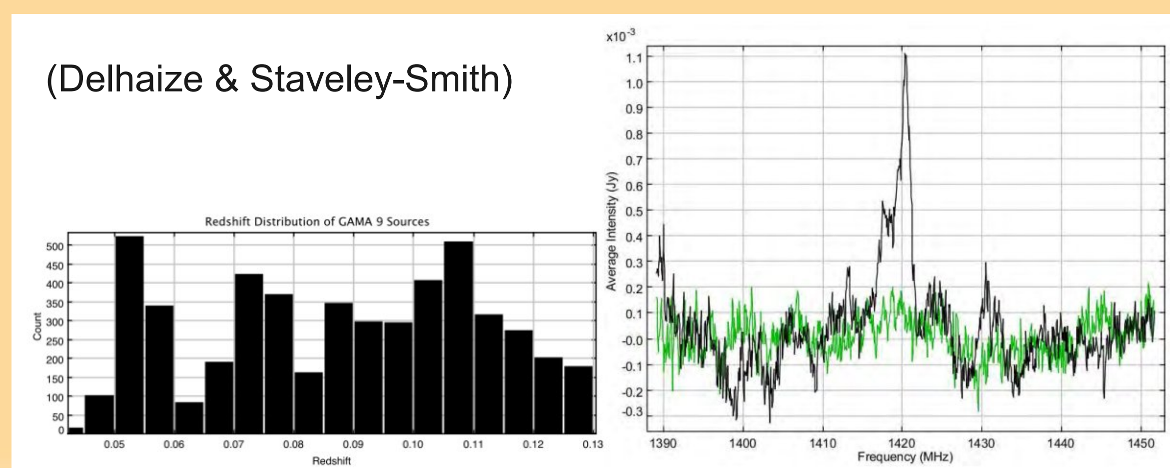
- Both ghosts and suppression operate via the same mechanism, and Dr Sidelobes pulls the strings
- Ghosts are usually buried in the noise
- Suppression always present with selfcal, but more severe with DD calibration (more DoFs...)
  - **A noise-limited map is not necessarily a good science map!**

"What if we were to somehow break the thermal noise barrier, but all we'd find beneath would be the bones of Jan [Noordam]'s enemies?"
– Anon., 3GC-II Workshop

(names and places changed to protect the guilty)

Spectral Line Stacking:
Picking over the bones of Jan's enemies

- Individual lines hidden in the noise
  - So apply priors from optical surveys...
  - ...by shifting each spectrum to its known redshift
  - ...and probe the total signal by co-adding spectra
- Lines add up, noise suppressed by $\sim N^{-2}$
- For bonus points, use optical positions to stack sources that are sub-noise in radio



(Delhaize & Staveley-Smith)

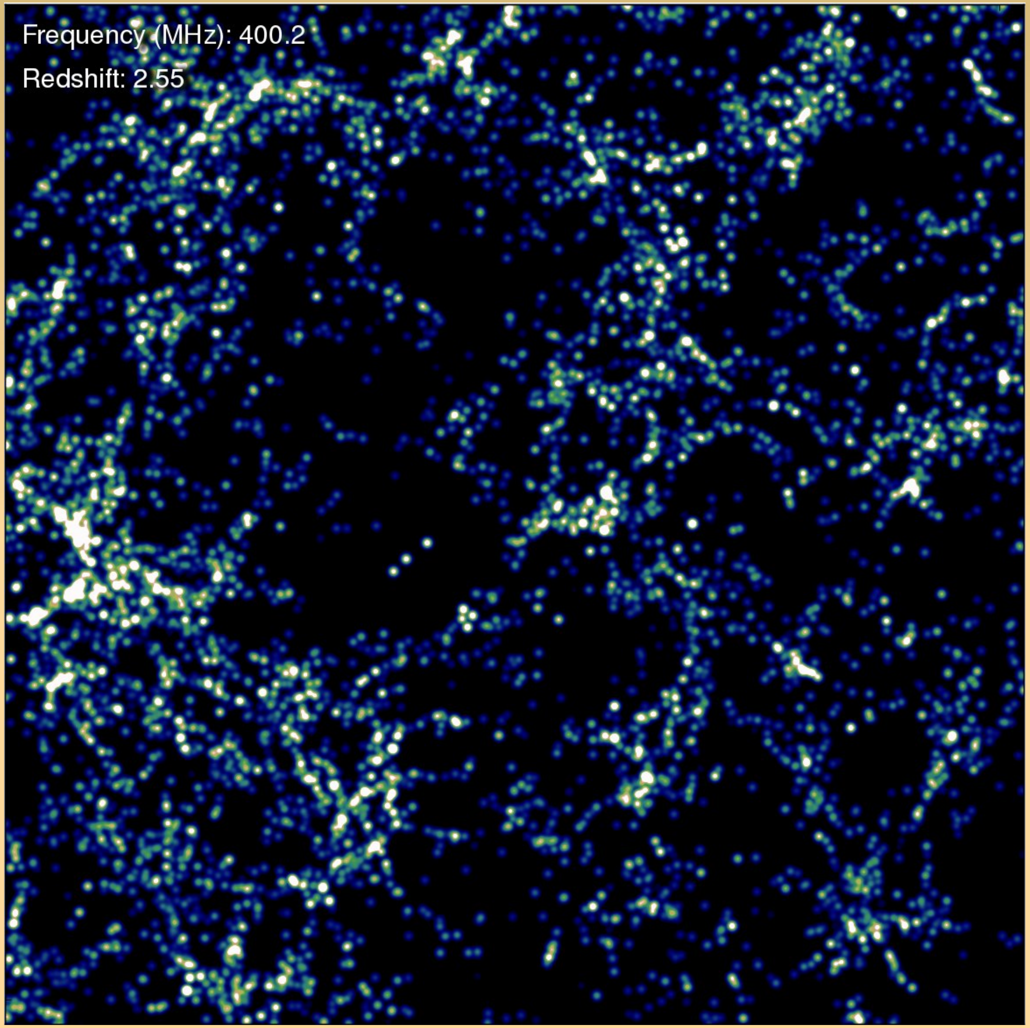
Interferometric HI Stacking:
The Ian “Bad News” Heywood Simulation I

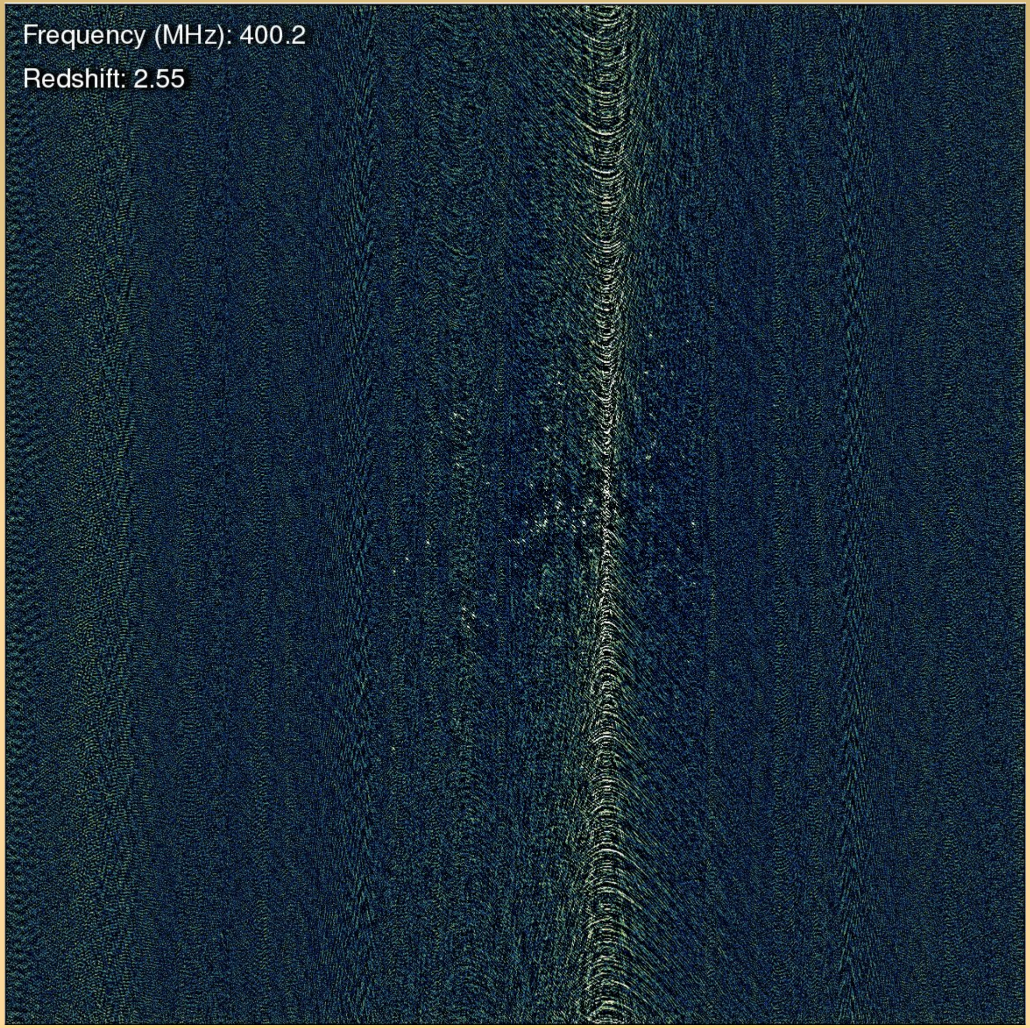
- Simulated HI emission (S^3-SAX)
- Pure sky model
- **No** noise
- **No** continuum
- **No** interferometer response
- So, what happens when Dr. Sidelobes shows up?

Stacking On The Celestial Equator?... Ouch!

- **No** noise
- **No** continuum
- **No** calibration or deconvolution residuals
- SKA-Mid sim
- Equatorial field: high N-S sidelobes

True vs. Observed



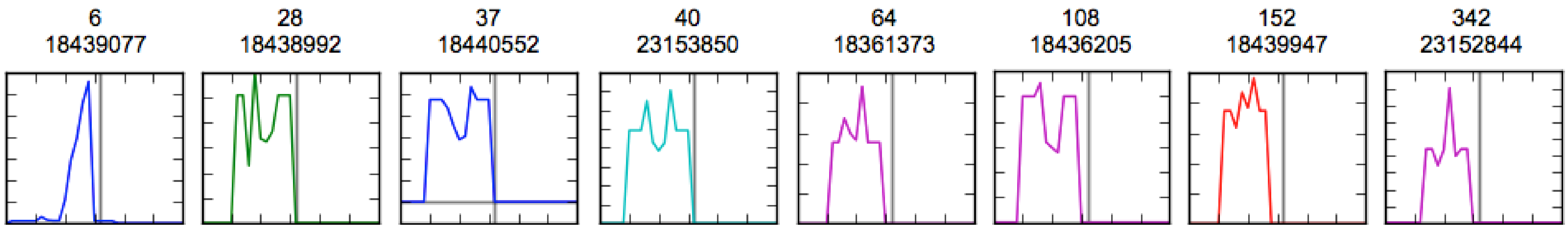


- How many of these galaxies will stack up coherently?

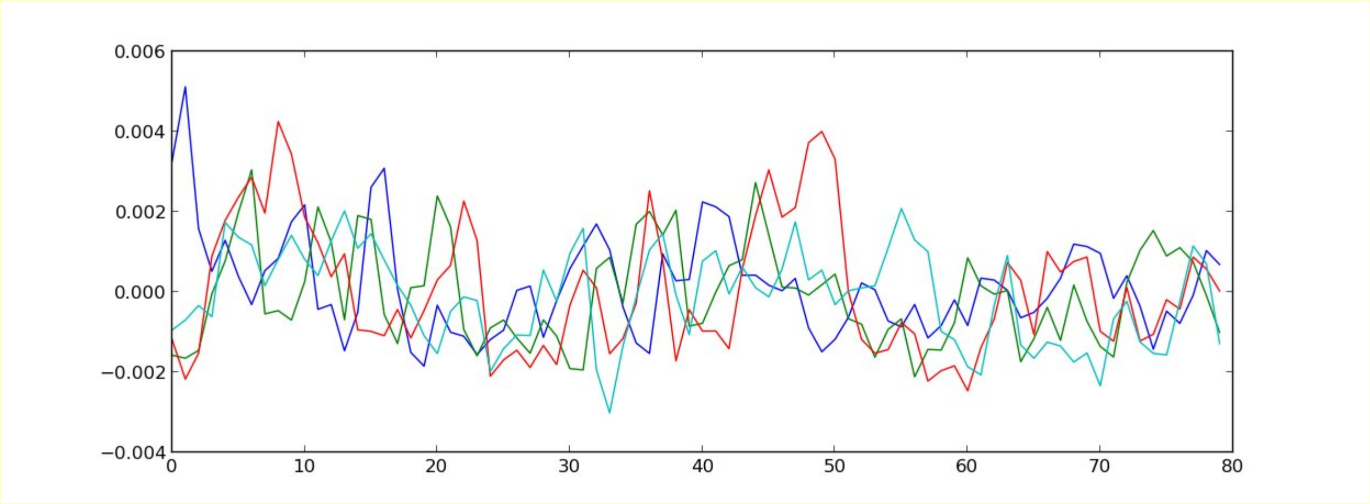
LADUMA Stacking Sim

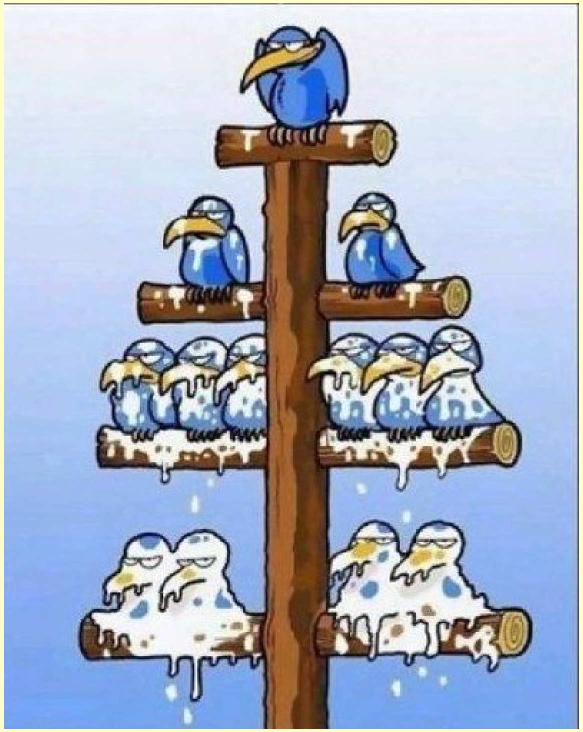
- **No** noise
- **No** continuum
- **No** calibration or deconvolution residuals
- MeerKAT sim
- (... with *some* YouTube artefacts...)

Dr Sidelobes at Work



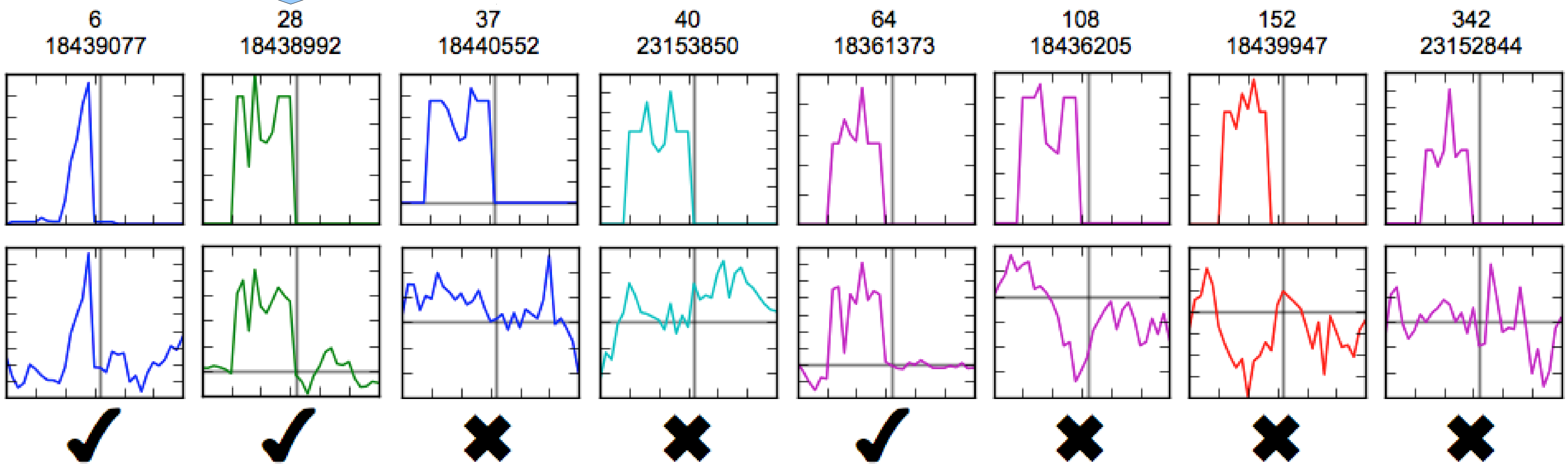
- TOP: A selection of individual galaxy spectra
- BOTTOM: A selection of "Dr. Sidelobes's spectra"





HI + Dr. Sidelobes

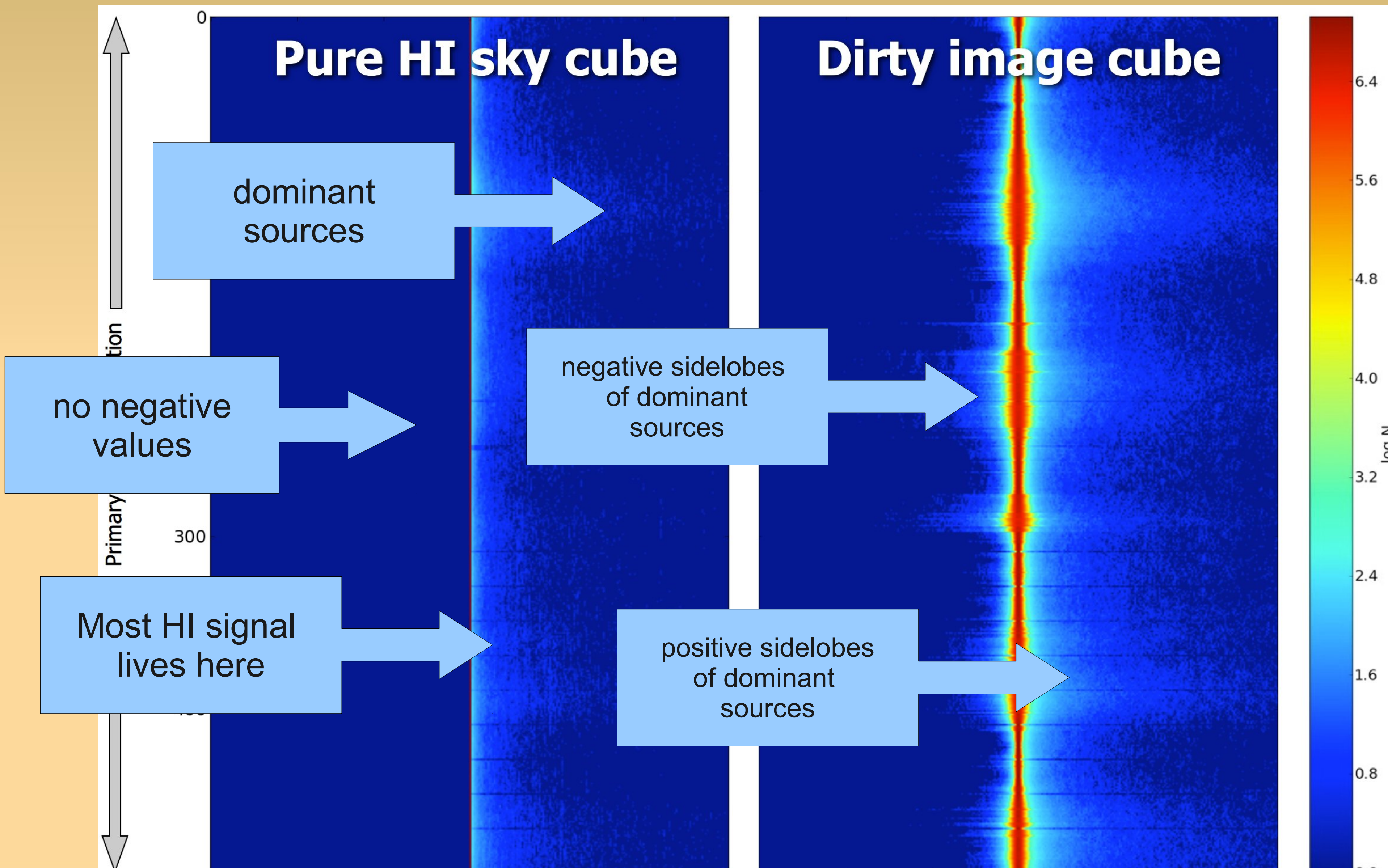
Ordinal number of galaxy
(in order of HI mass)



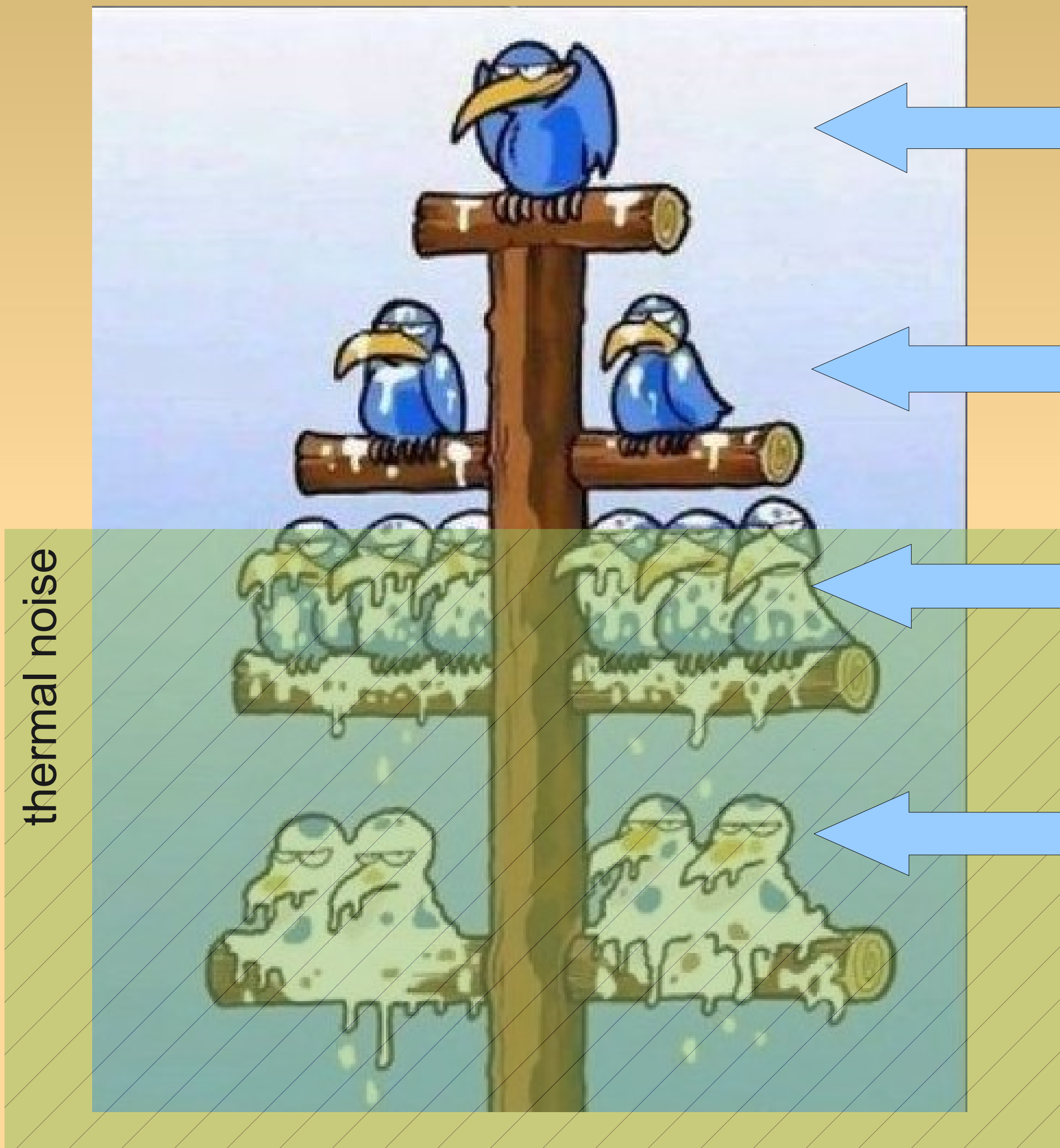
75% of the top 500...

- TOP: original HI signal
- BOTTOM: HI + Dr. Sidelobes
  - ...most of which originate with *undetected* sources

Pixel Values Histogram



How Radio Interferometry *Really* Works



Bright sources
(DD solutions, uv-subtraction, deconvolution)

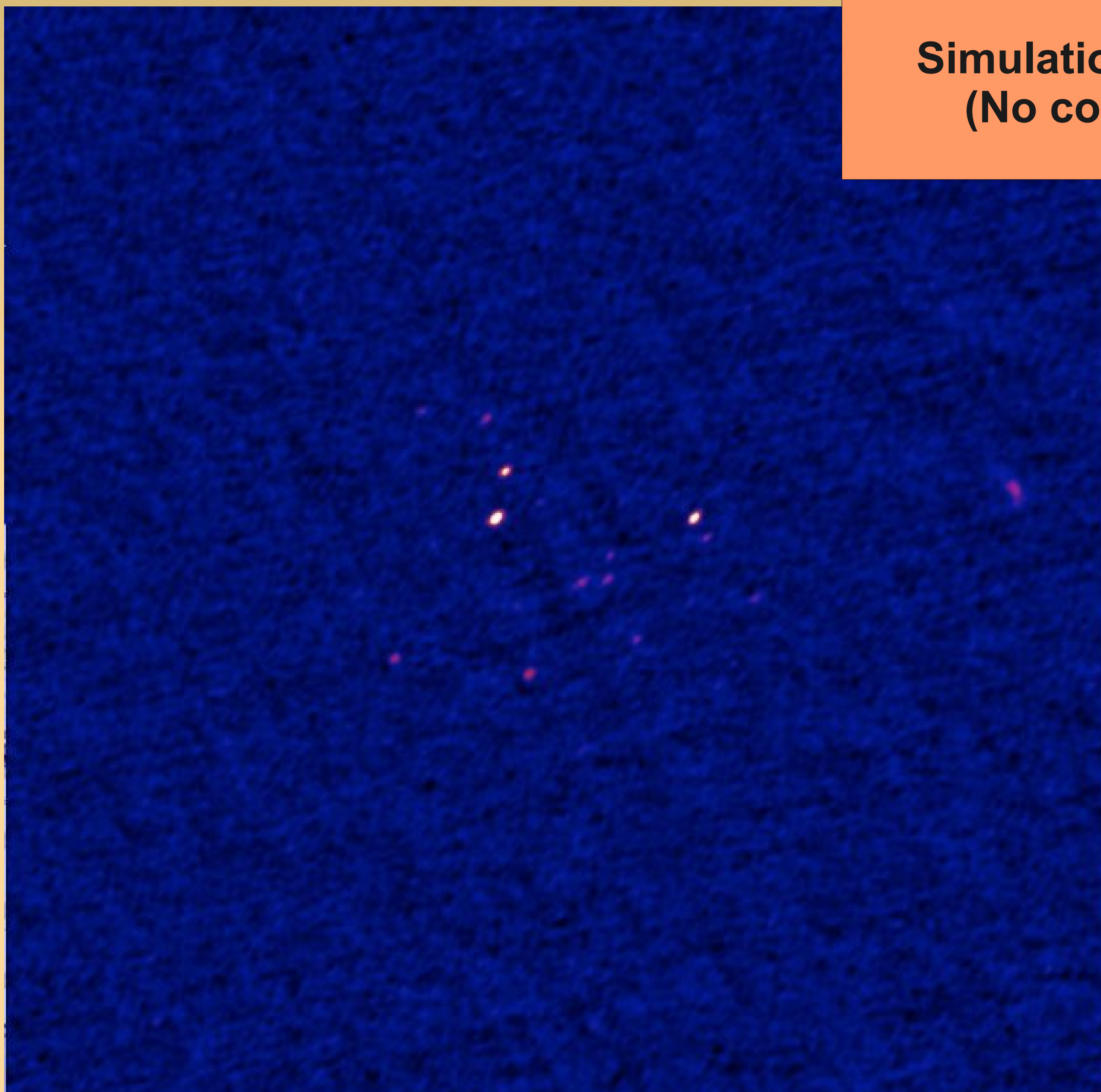
Faint sources
(DDE interpolation, deconvolution)

1-2σ sources
(stacking)

<1σ sources
(a stiff drink?)

Stacking In WHDF

Simulations were just the ideal scenario...
(No continuum, <u>no calibration errors</u>)



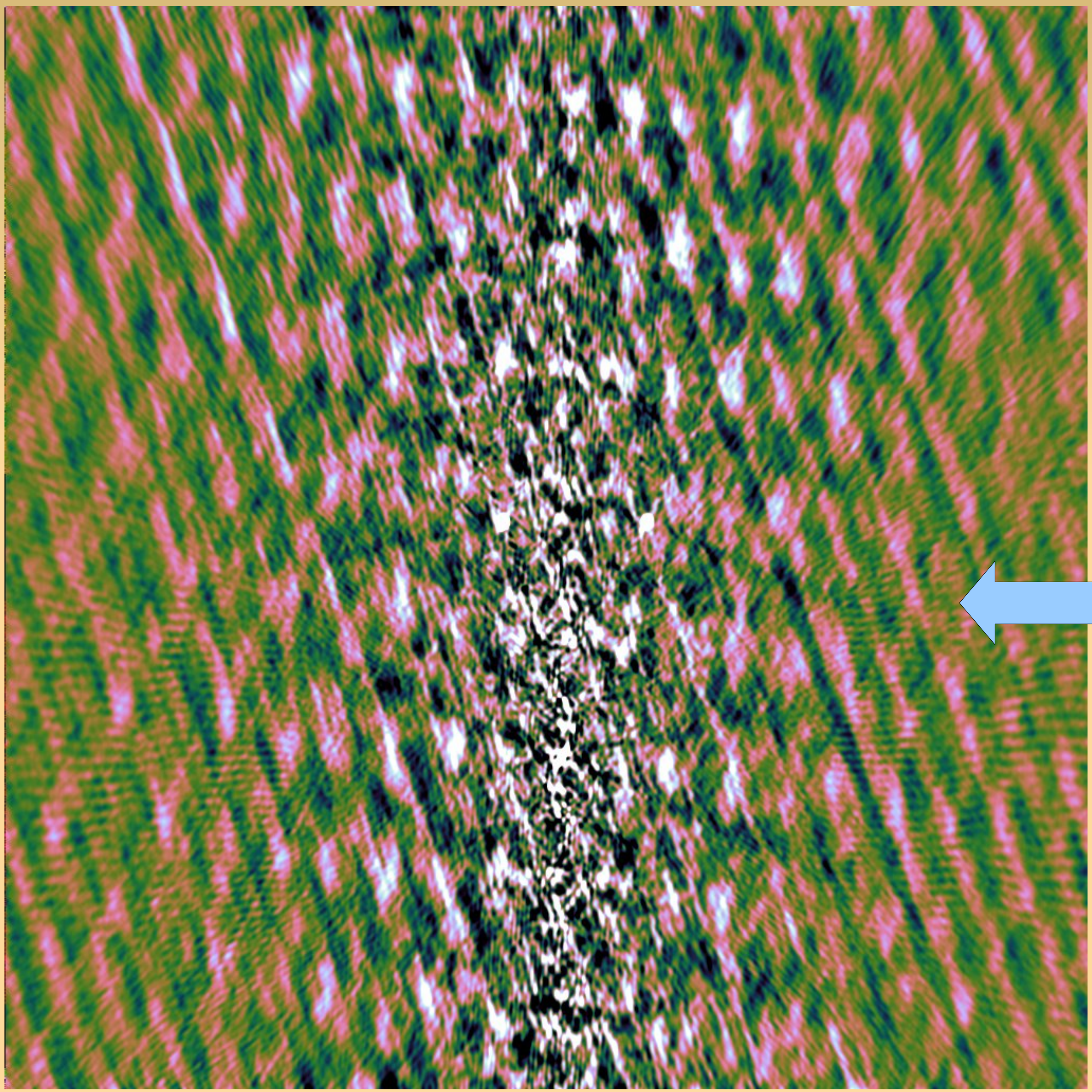
WHDF: should have been stackable: ~1700 optical positions available in this field.

<u>Miserable failure.</u>

Prime suspect: the bones of Jan's enemies left behind by the phase calibrator.

Can simulate the whole scenario...

Stacking In WHDF



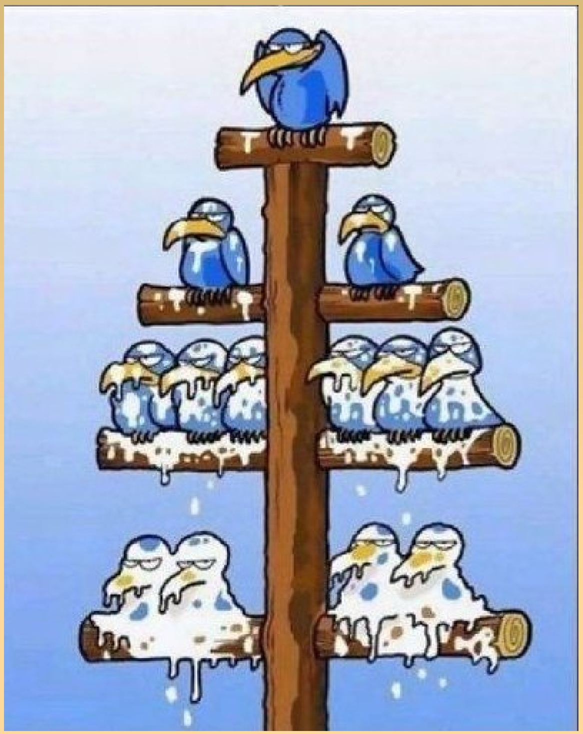
Simulated field (including calibrator), with beam rotation and pointing errors.

Calibrated and peeled off the calibrator.

Removed noise.

This is what lives in the noise.

Conclusions



- Interferometry is *counterintuitive*
- We're pushing the boundaries
- This leads to “surprises” (look up!)
- Simulations are coming of age
  - can be a powerful tool for discovering some of the surprises before they land on our heads...