Multi-Beaming And Calibration

Multi Beaming And Calibration

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

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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 [are] boldly going where no man has gone before
  - A lot of this thanks to Arnold

- Result: we live in interesting times

Radio Interferometer...

(In celebration of the passing of an extremely lame but blissfully short-lived internet meme)
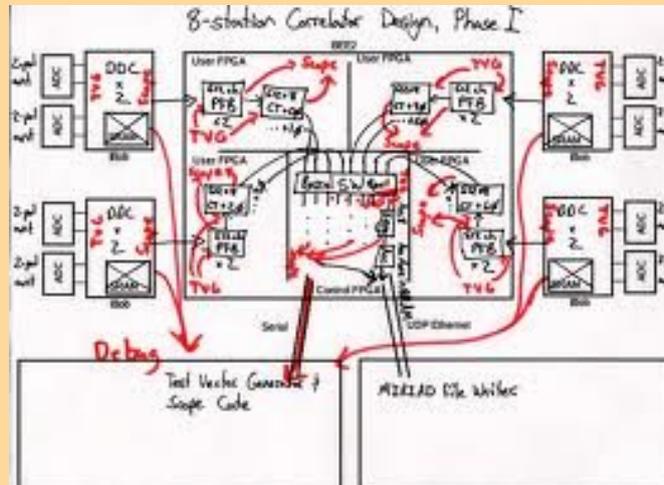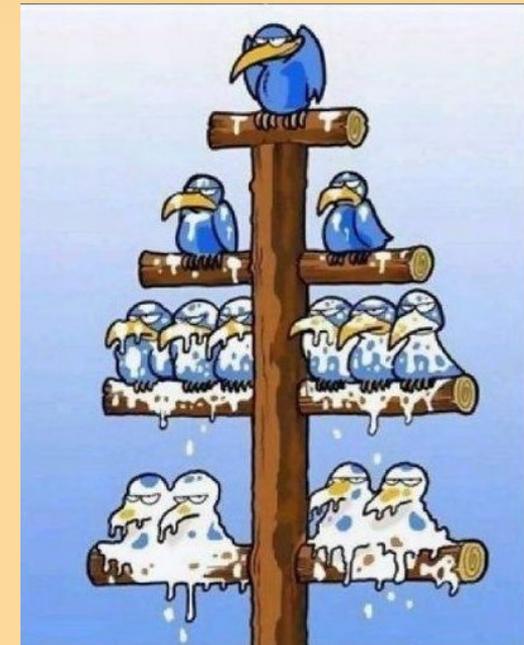

What lay people think I do
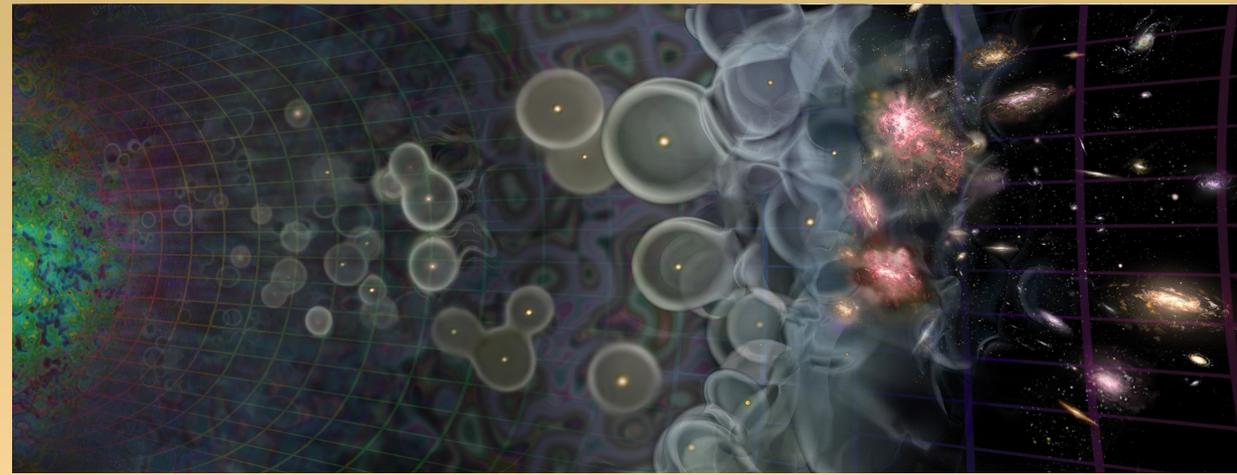
What funding agencies think I do

What cosmologists & astrophysicists think I do

What my engineers think I do

What I actually do

The Four Horsemen
of interferometer limitations

Well-understood (?)

- Thermal noise
  - lucky if we can reach it
- Classical confusion
  - (i.e. depth limited by resolution)

- Residual calibration and deconvolution artefacts (& calibration "noise")

this talk

- Dr. Sidelobes
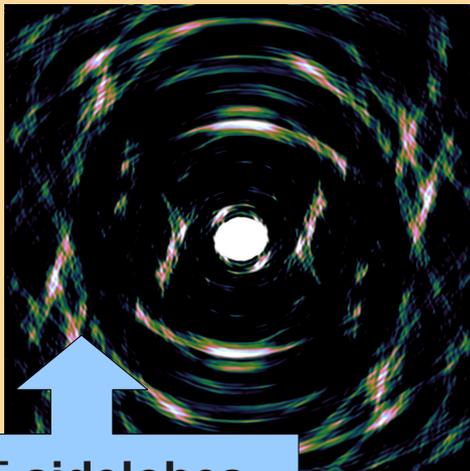
Dr Sidelobes: Missing Information

PSF of WSRT. The regular rings are due to the regular spacing of its antennas in the East-West direction.
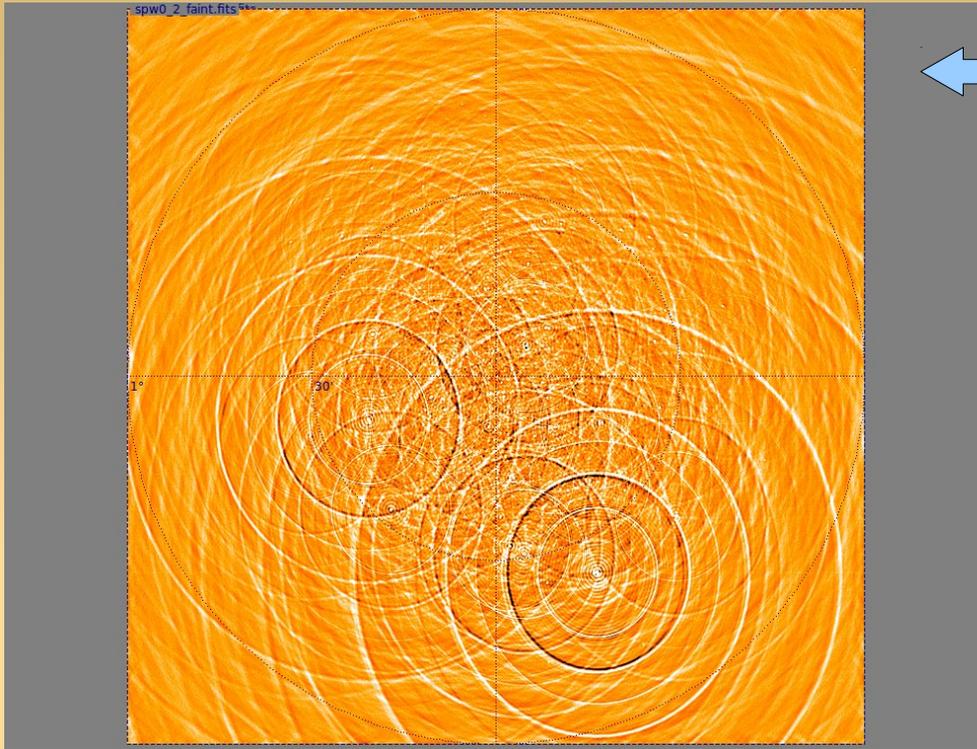
PSF of MeerKAT

PSF **sidelobes** extend over the entire sky

- Response to a point source: Point Spread Function (PSF)

- PSF = FT(uv-coverage)

- Observed "dirty image" is *convolved* with the PSF

- Structure in the PSF = uncertainty in the flux distribution (corresponding to missing data in the *uv*-plane)

4π 2π

Why Is This Bad?

spw0_2_faint.fits
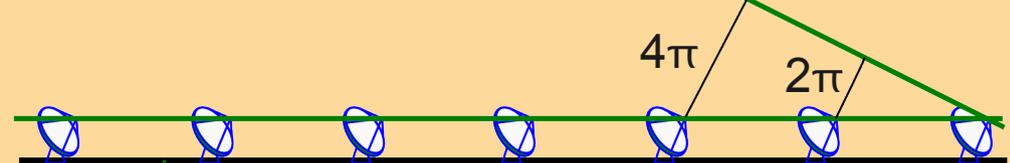
← Real-life WSRT dirty image

- Dirty image dominated by PSF sidelobes from the stronger sources

- *Deconvolution* required to get at the faint stuff underneath.

- A whole continuum of skies fits the dirty image (pick any value for the missing *uv*-components)

- Deconvolution picks one = interpolates the missing info from extra assumptions (e.g.: "sources are point-like").

Good News First

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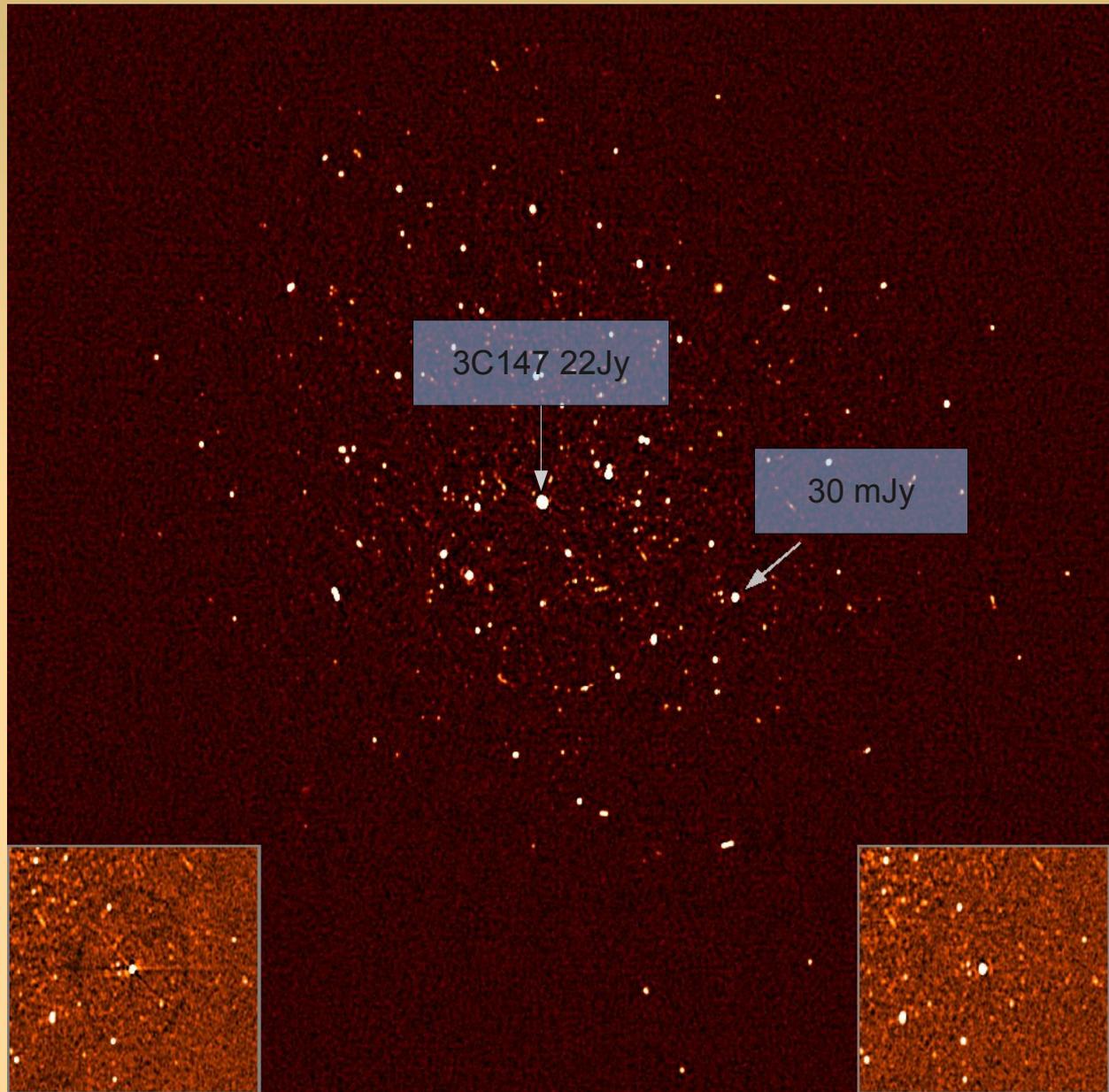160 MHz bandwidth

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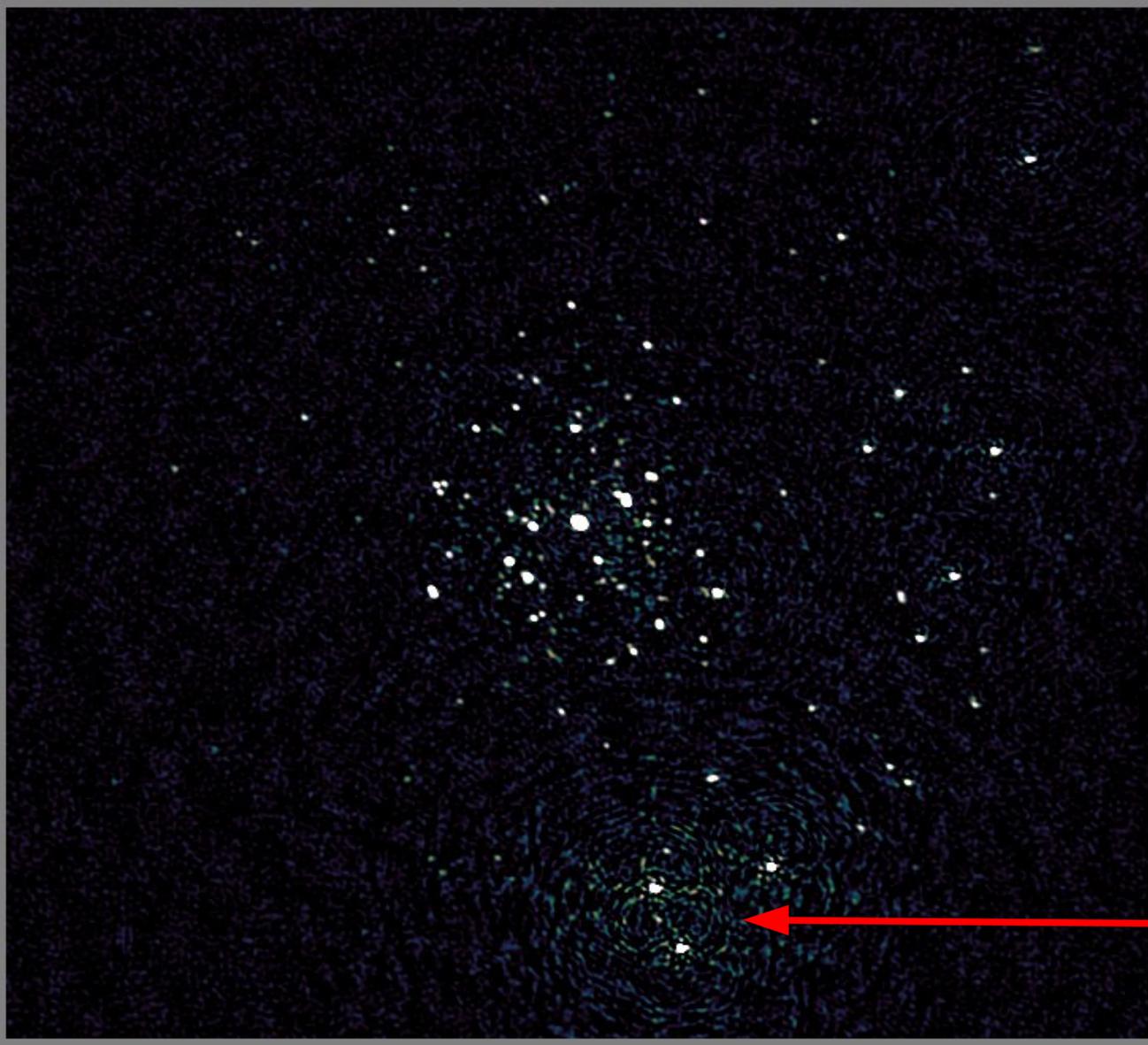**1,600,000:1 DR**
thermal noise-limited

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 Can Do It Too

- Recent result from 3GC3 workshop

- 3C147

- JVLA-D @1.4 GHz
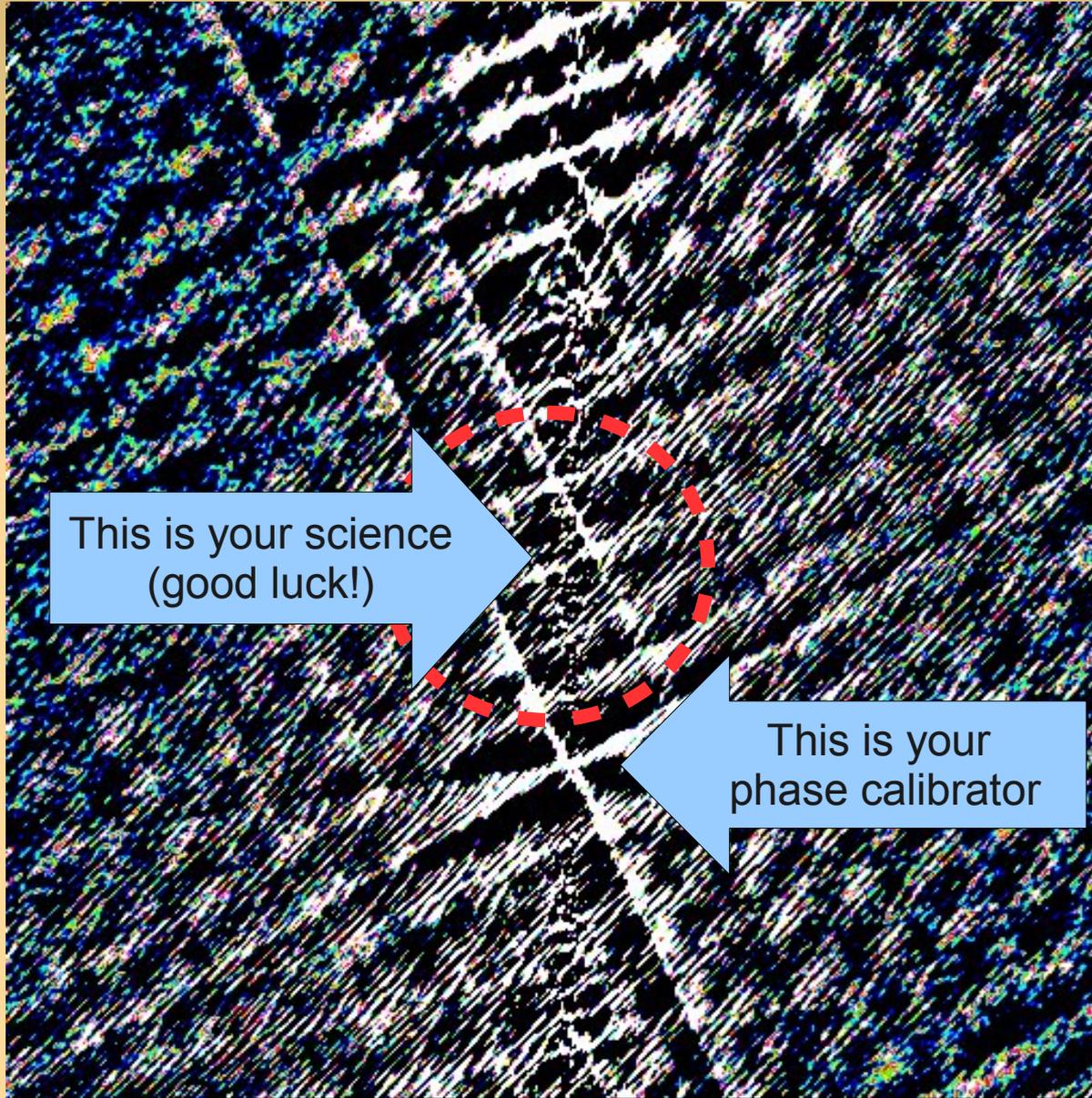
- Best image after regular selfcal

JVLA Can Do It Too II

- Recent result from 3GC3 workshop

- 3C147

- JVLA-D @1.4 GHz

- Best image after regular selfcal

- ...and direction-dependent (DD) calibration on a few sources

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

This is your science (good luck!)
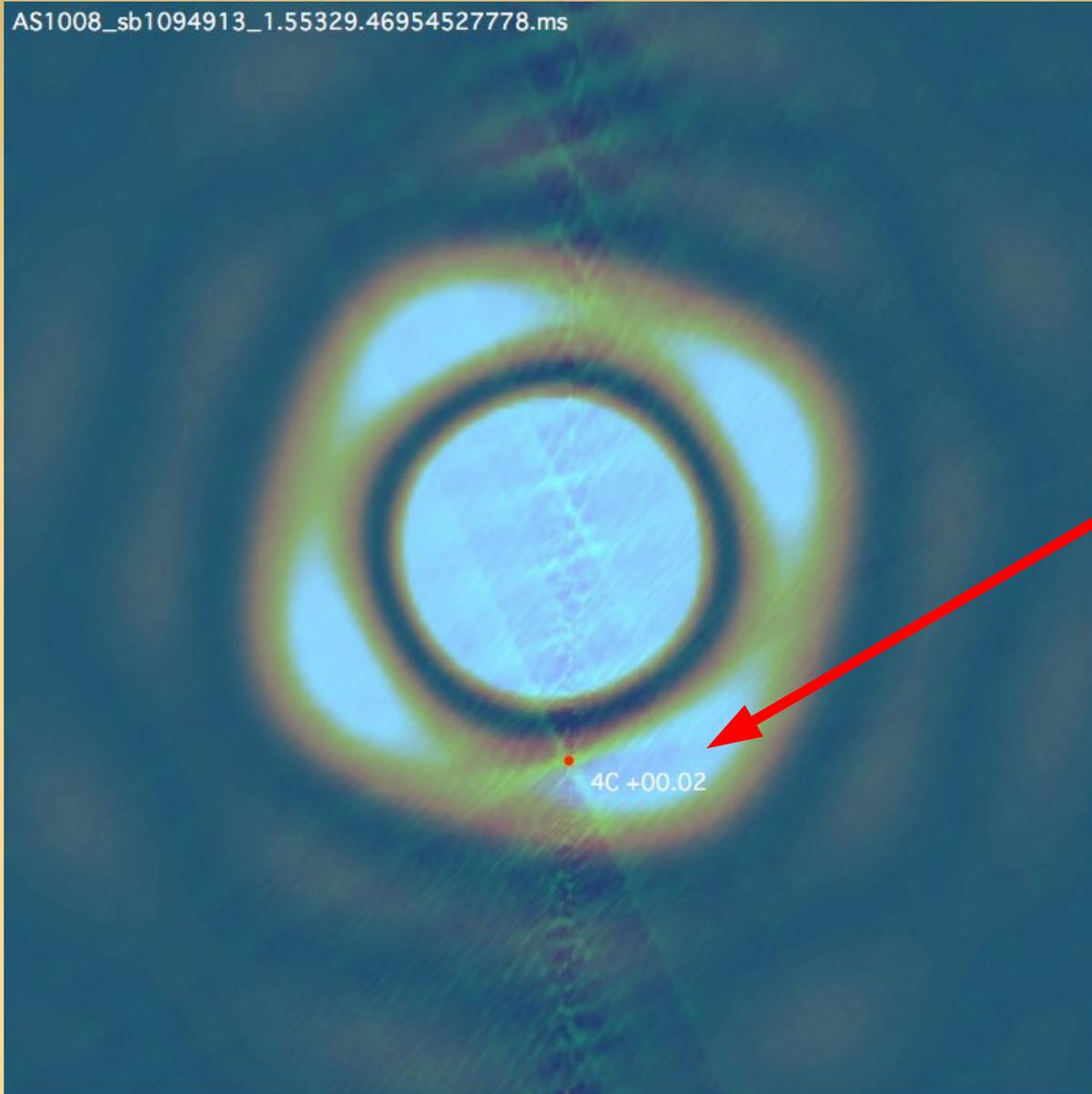
This is your phase calibrator

EVLA 8 GHz: Looking for sub-mm galaxies and QSOs in the William Herschel Deep Field.

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

(This also has a horrible PSF, being an equatorial field.)
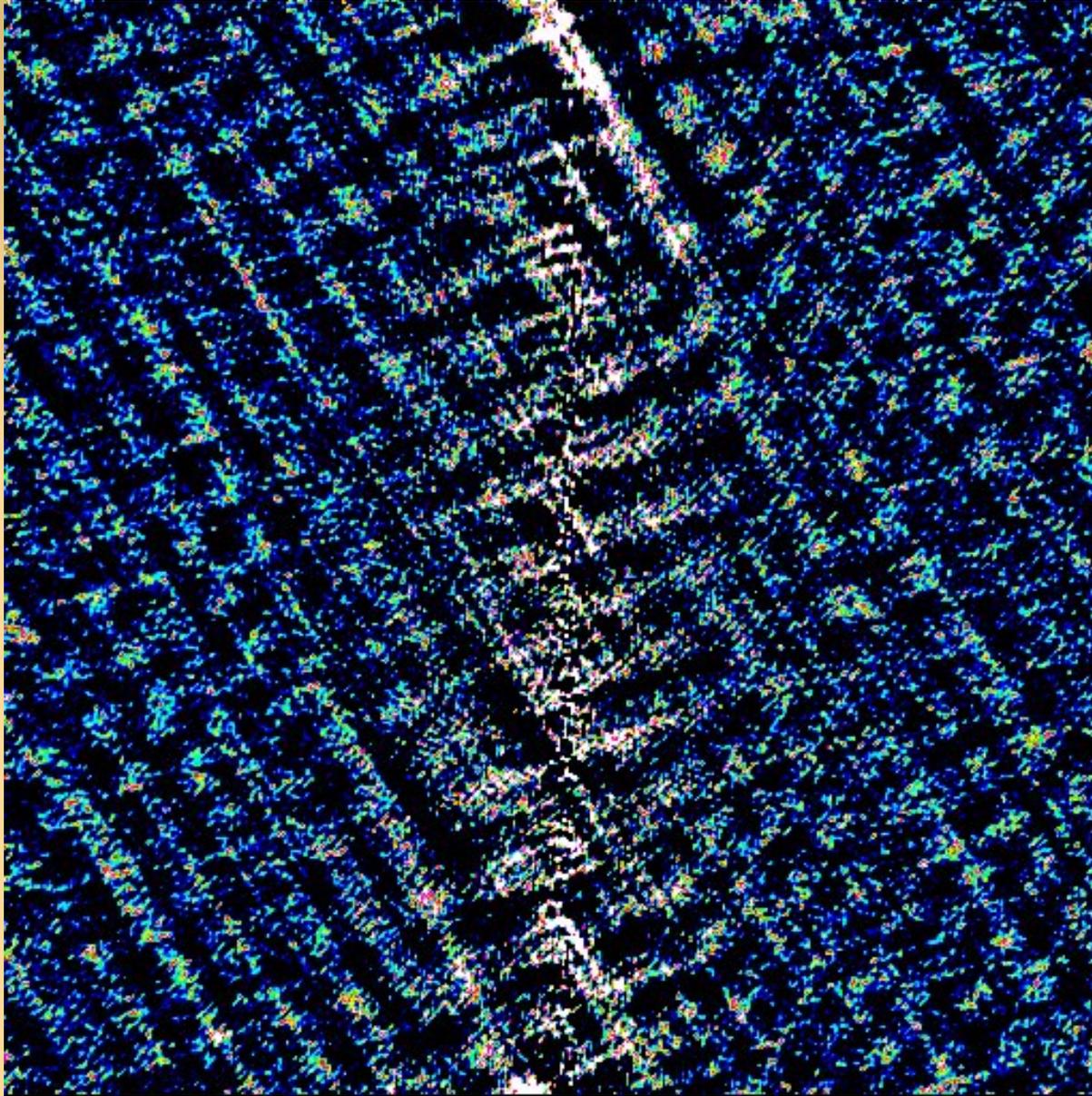
Brightness scale 0~50μJy

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.

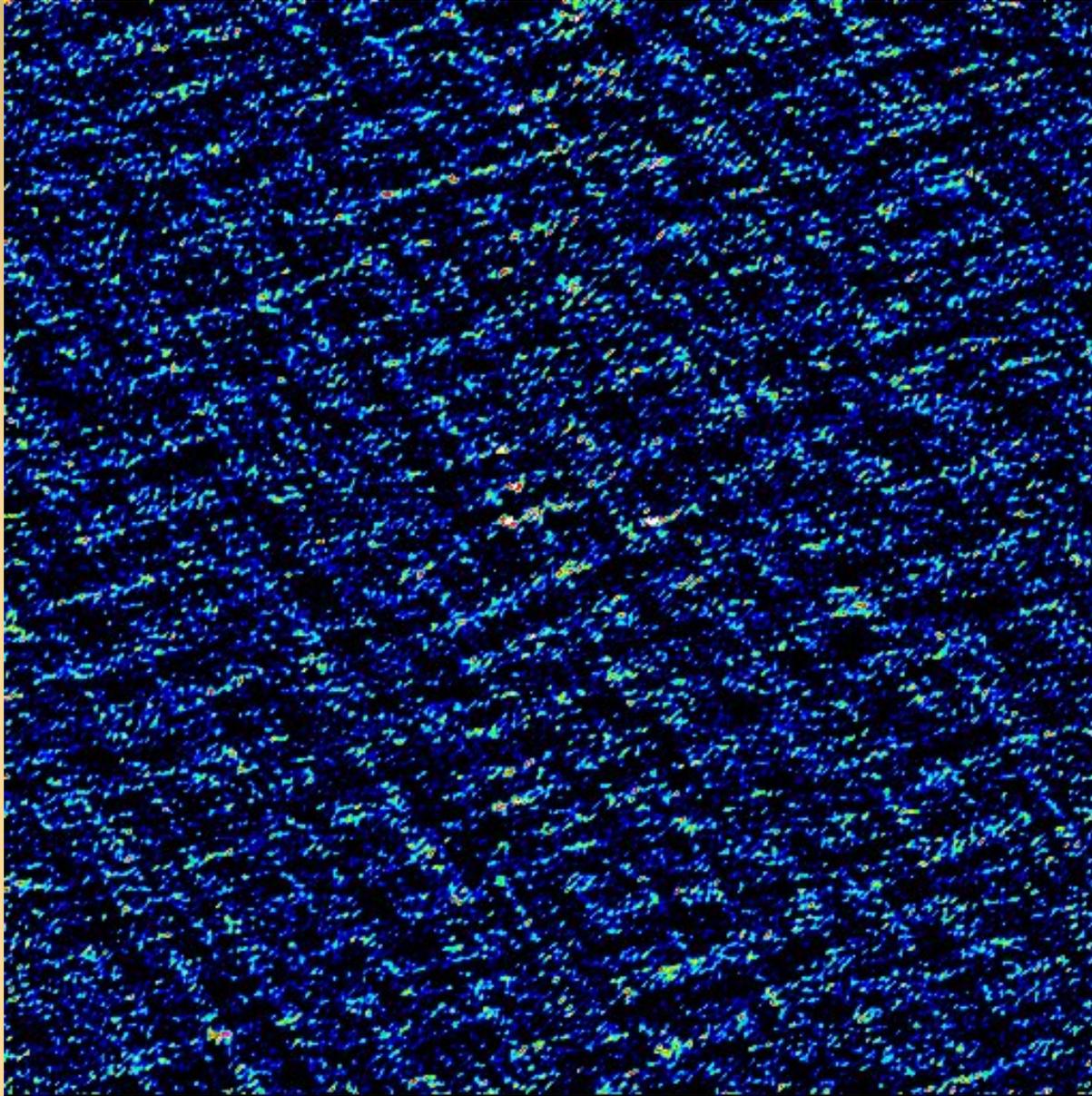(Brightness scale 0~50μJy)

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.

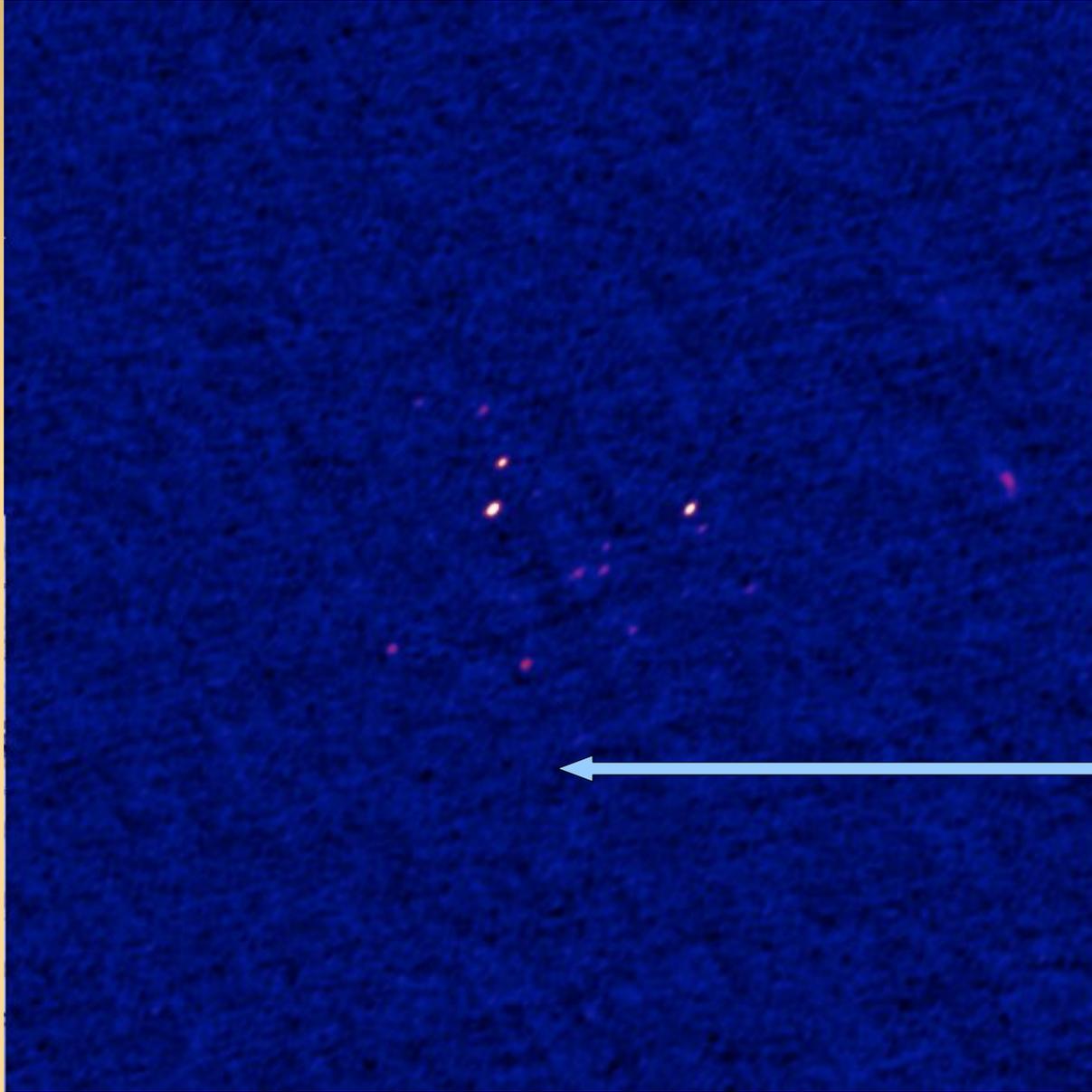But we did address them via differential gains...

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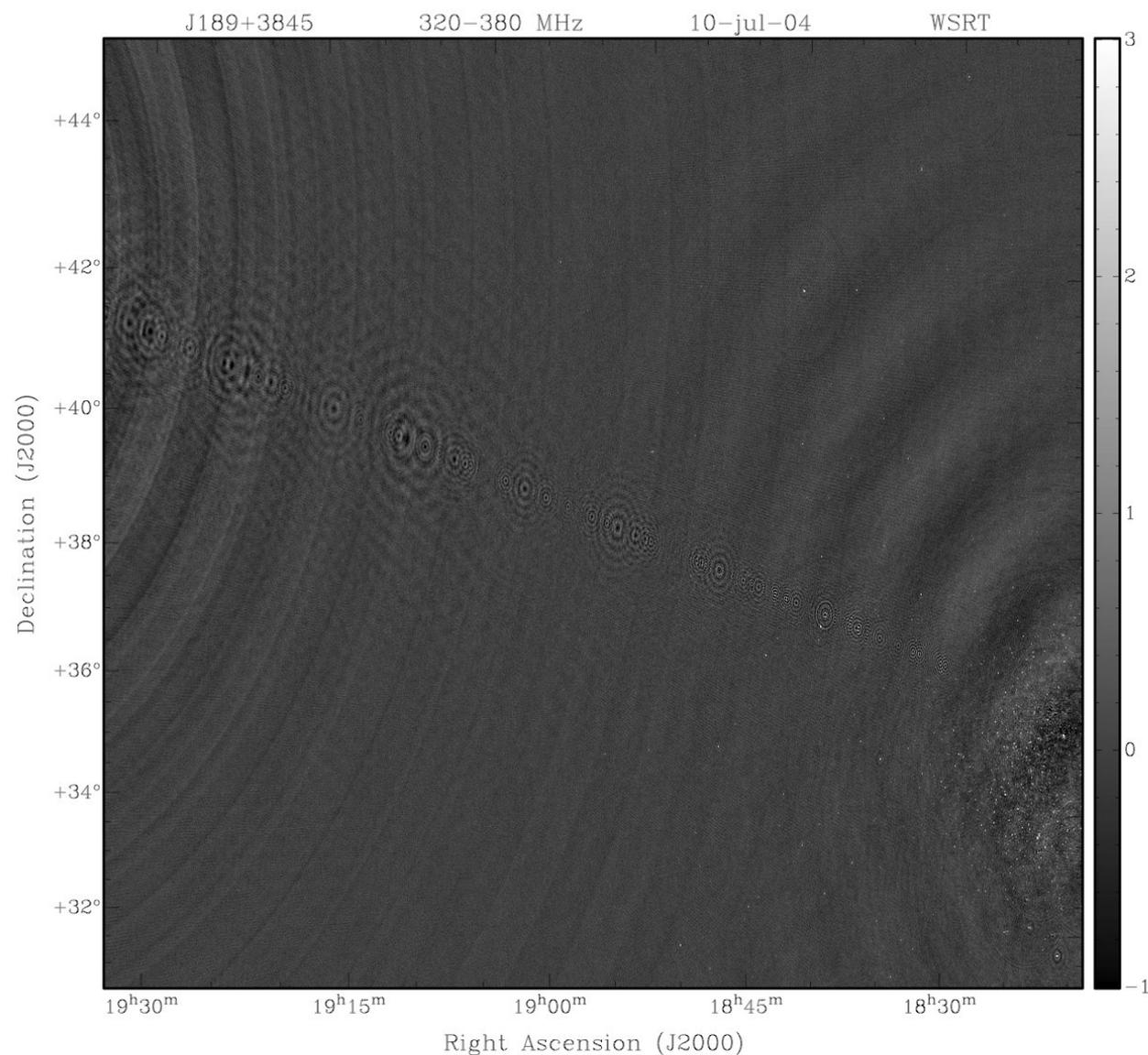
WSRT 92cm observation of J1819+3845 by Ger de Bruyn

- 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.)
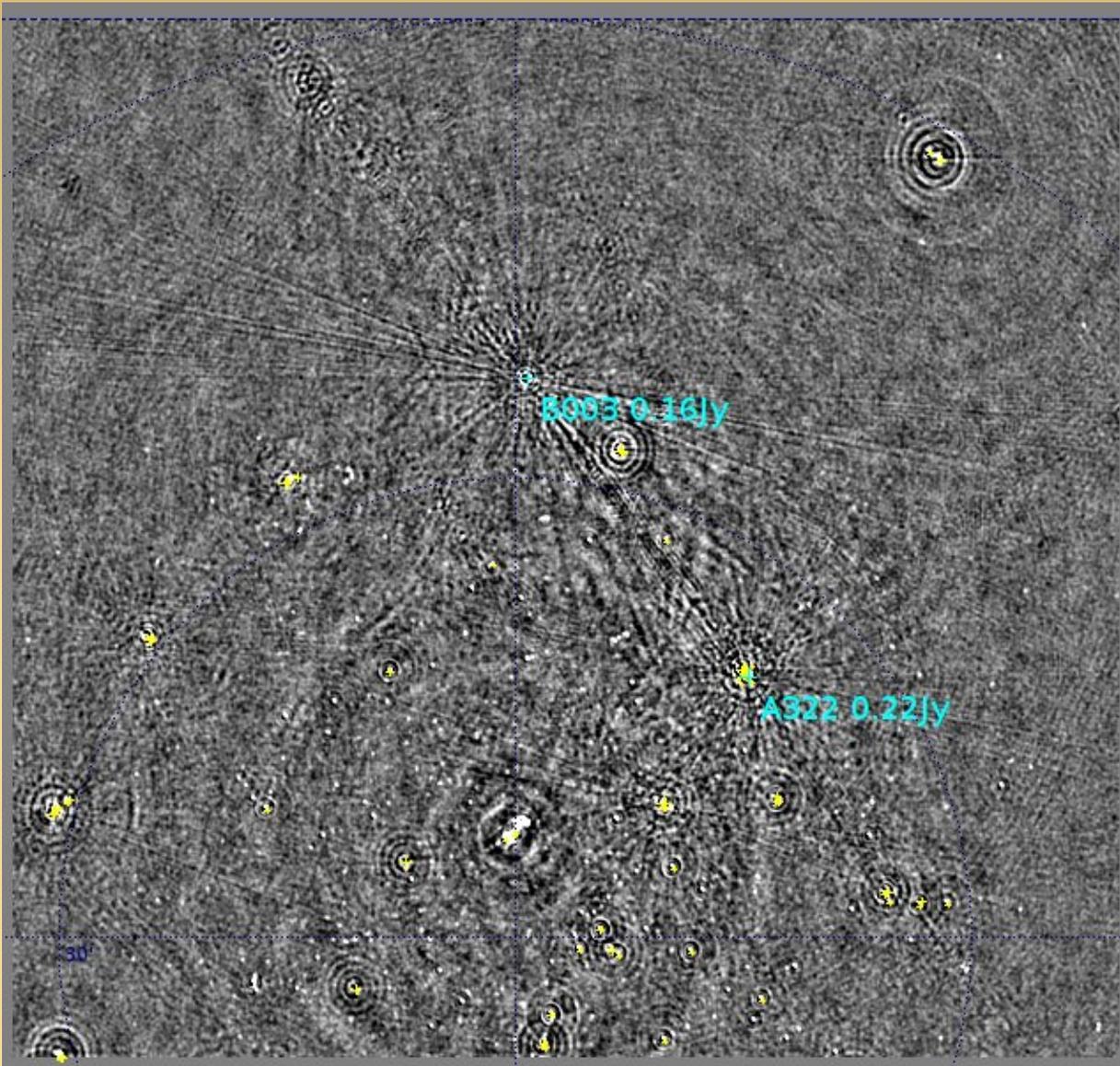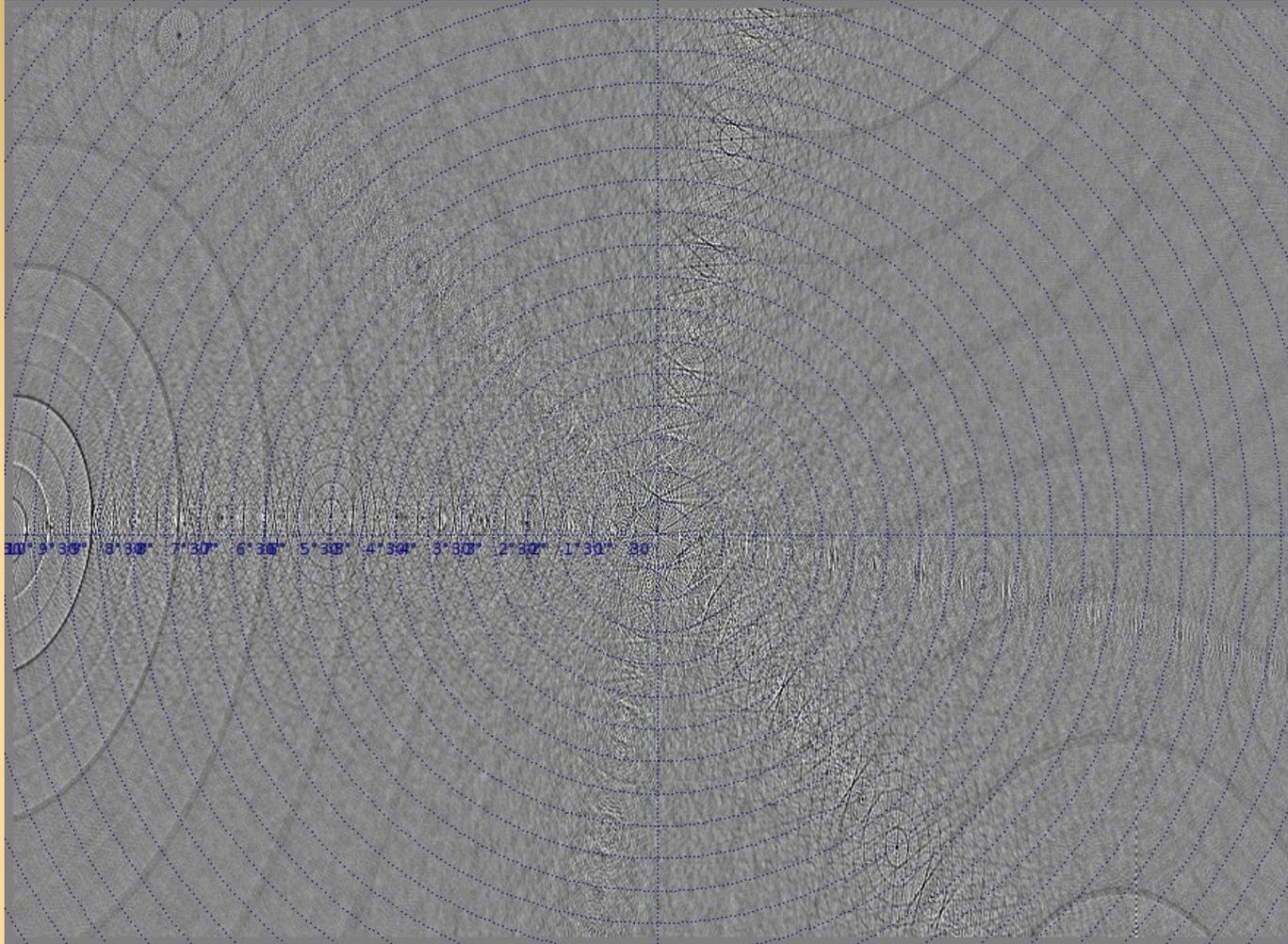
WSRT <u>21cm</u> observation

- ...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

Don't Mess With My L-Band!

- 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
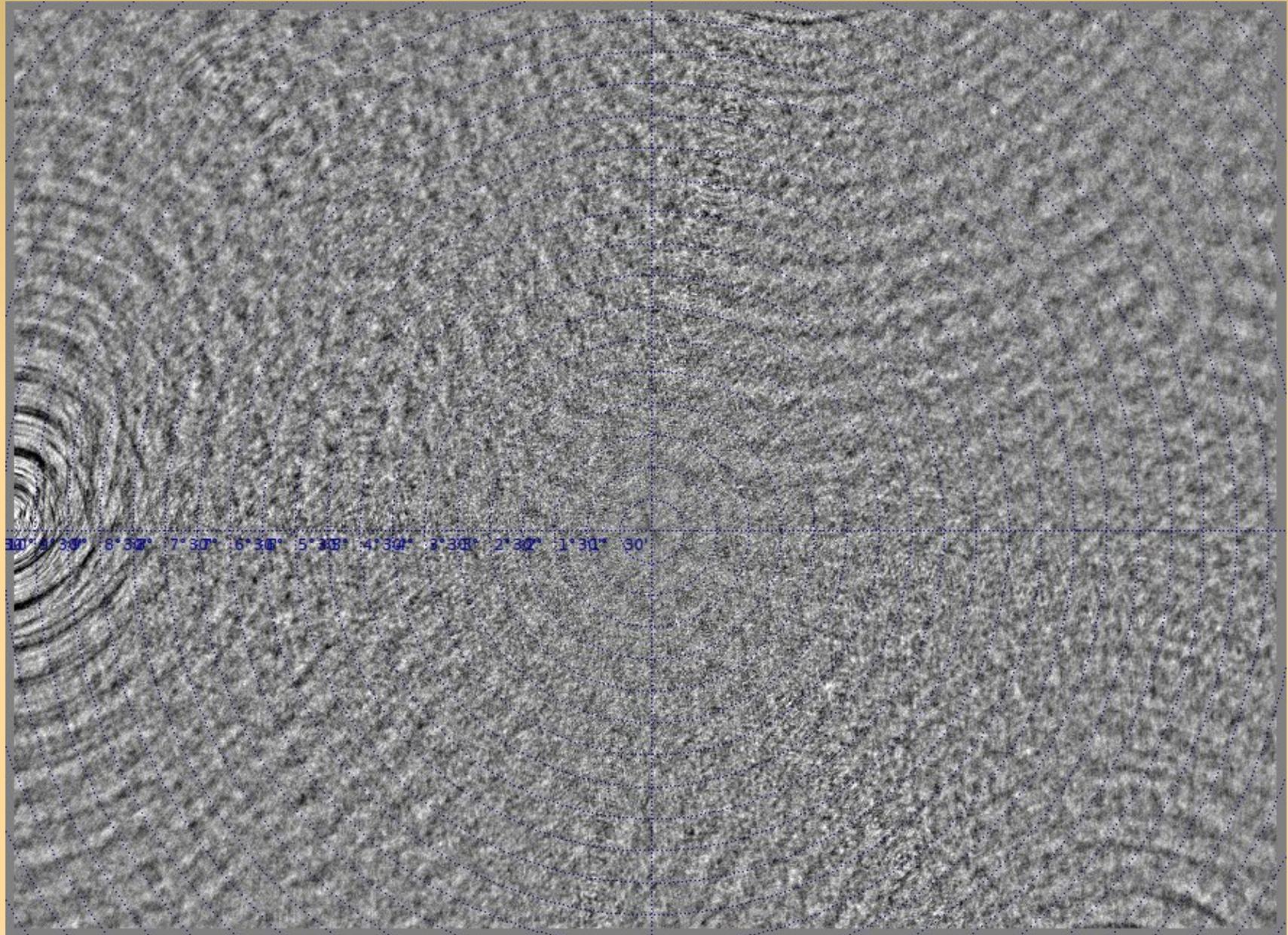
Ghastly Questions

- Does calibration 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.
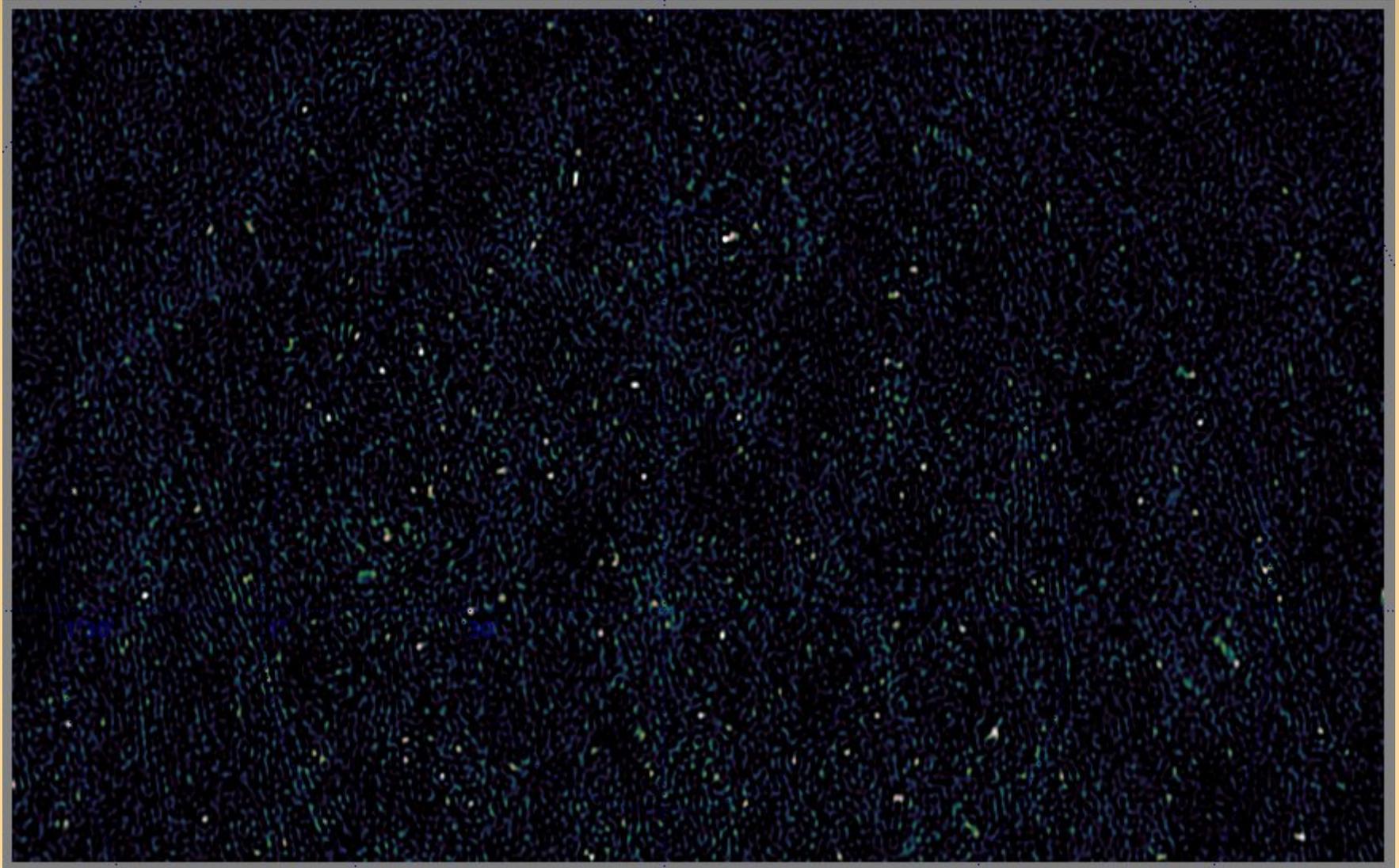- What else is that redistributed flux doing?

Ghosts, The Flip Side

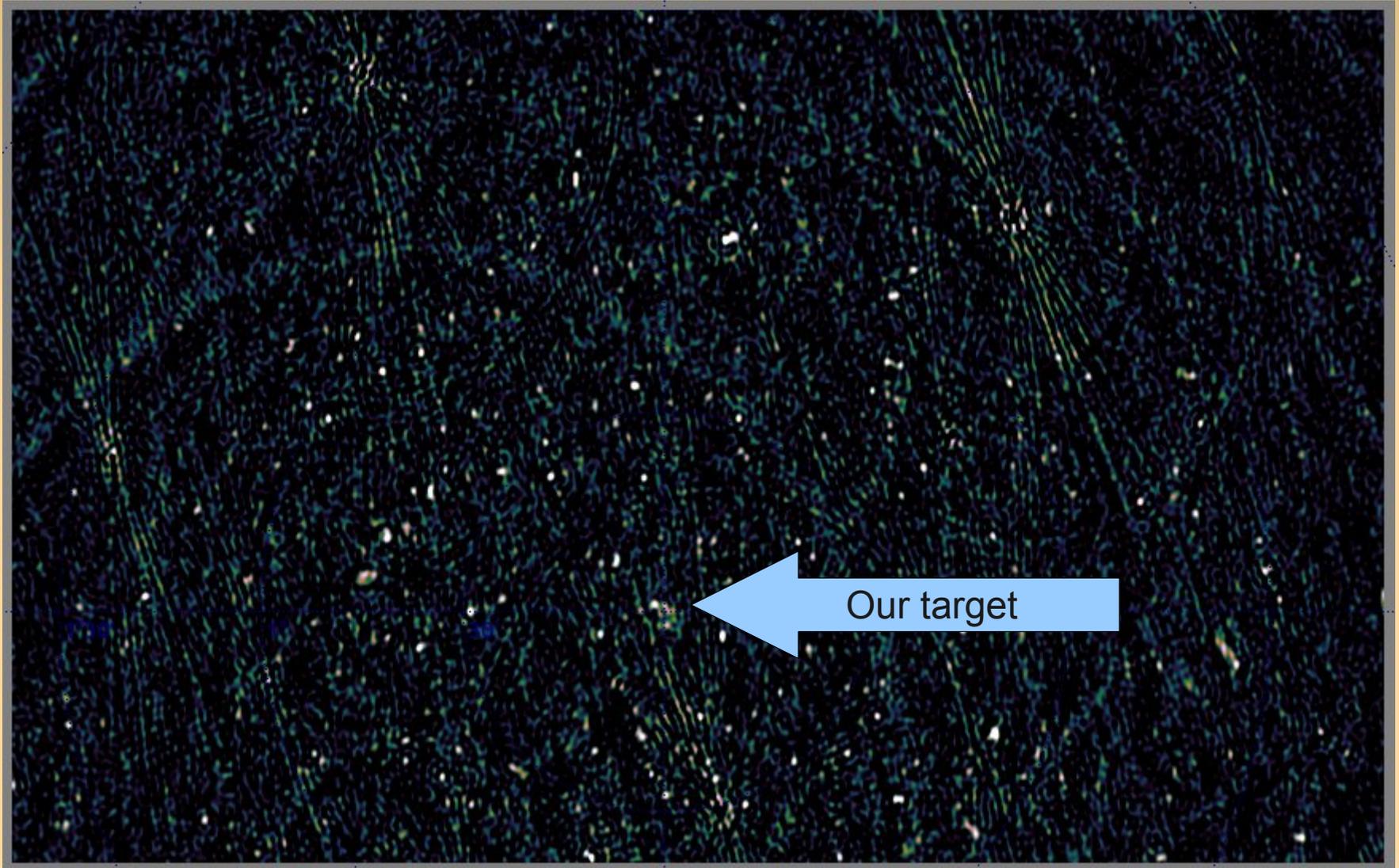- WSRT "Field From Hell" (Abell 773 @300 MHz), residual map
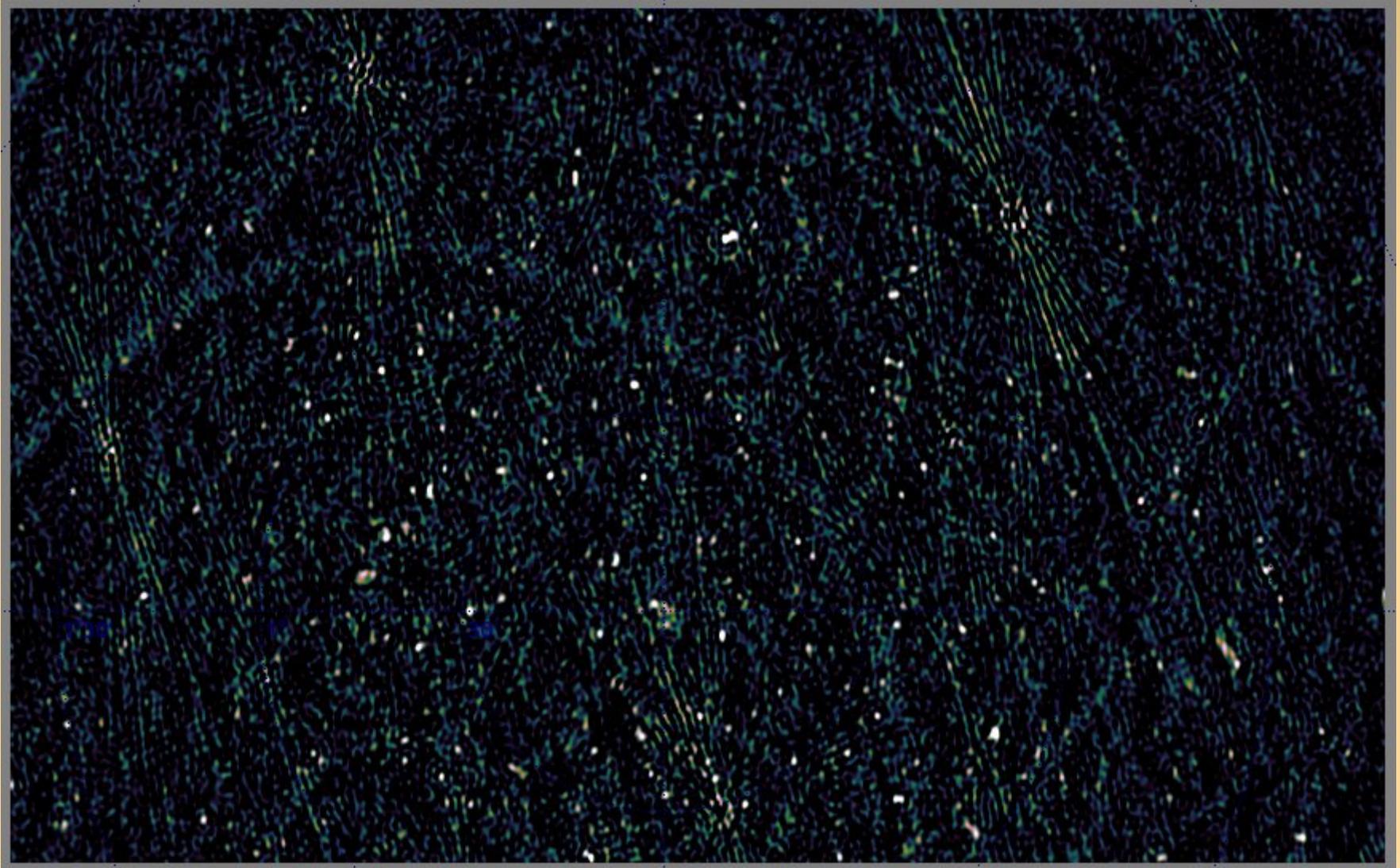
Getting There, Right?

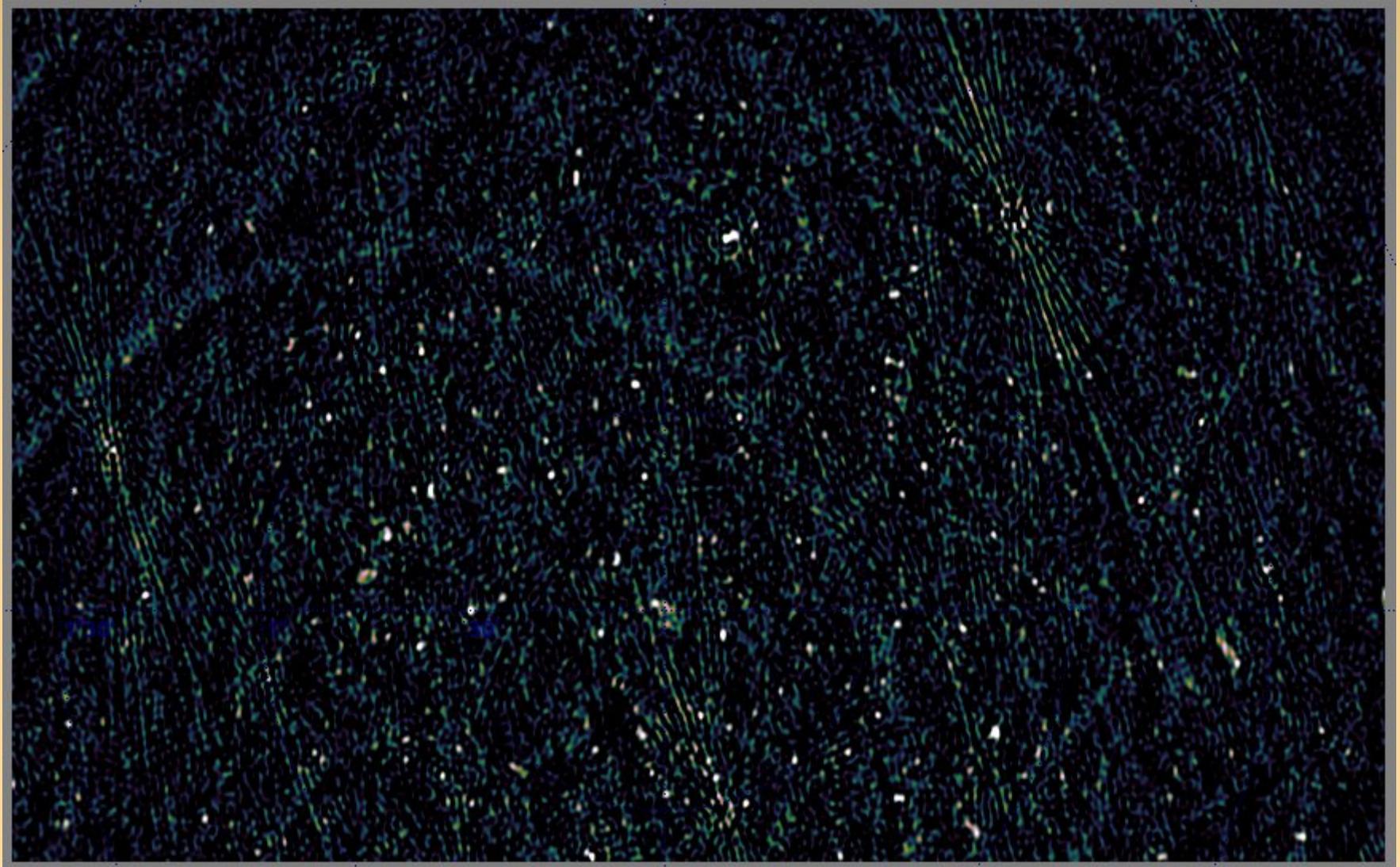- After diligent (direction-dependent) calibration

Noise-limited Is Not Always Good

- Suppression of non-model sources

Our target

The Dangers Of Direction-Dependent Solutions

- Suppression is less with more conservative calibration

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, 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 Arnold's enemies?"
– Anon., 3GC-II Workshop

(names and places changed to protect the guilty)

- Individual HI 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
- HI 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)
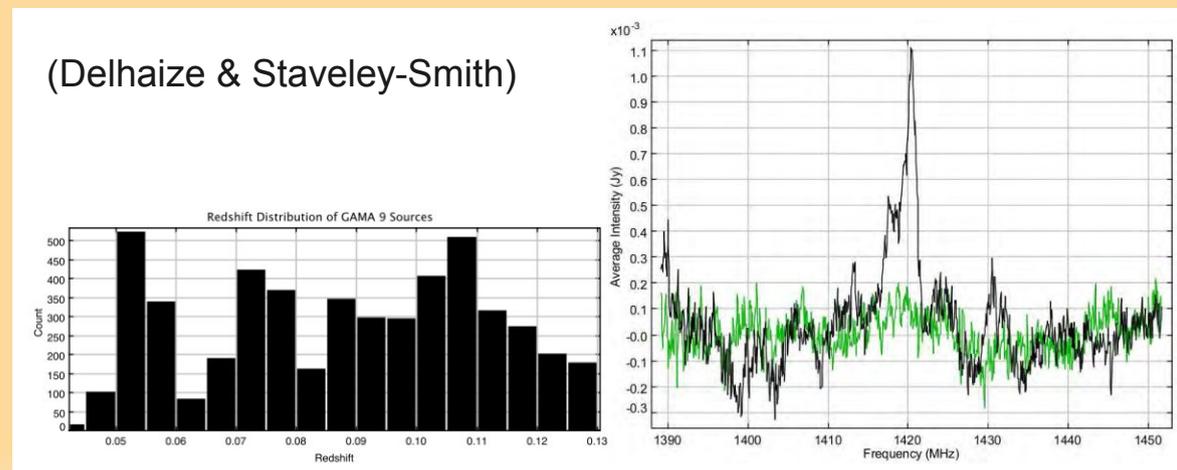
HI Stacking:
## The Ian "Bad News" Heywood Simulation I

- 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 experiment for high-z HI on the celestial equator? LOL!" – Anon.

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

True vs. Observed

Frequency (MHz): 400.2
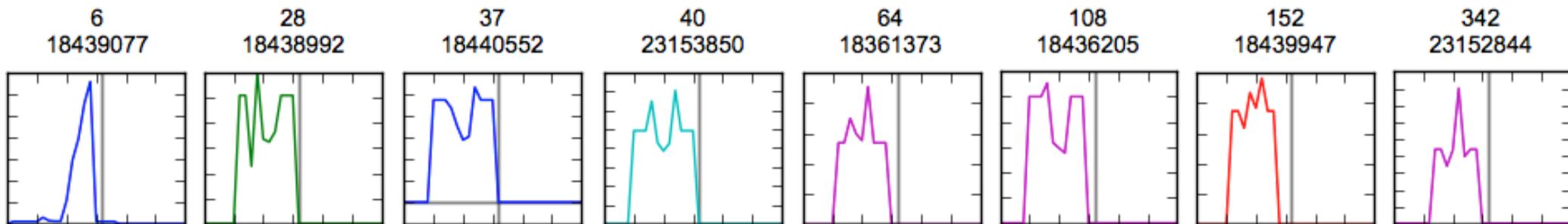Redshift: 2.55

Frequency (MHz): 400.2
Redshift: 2.55
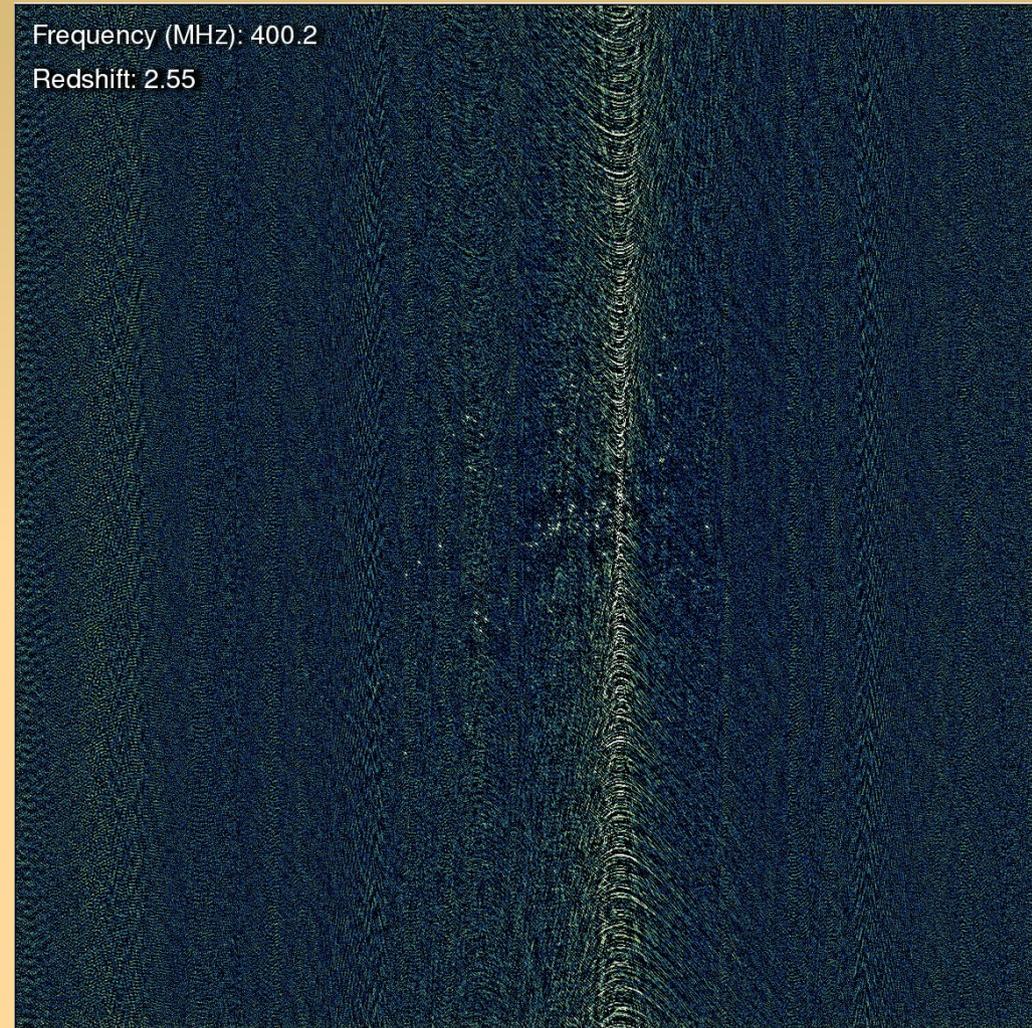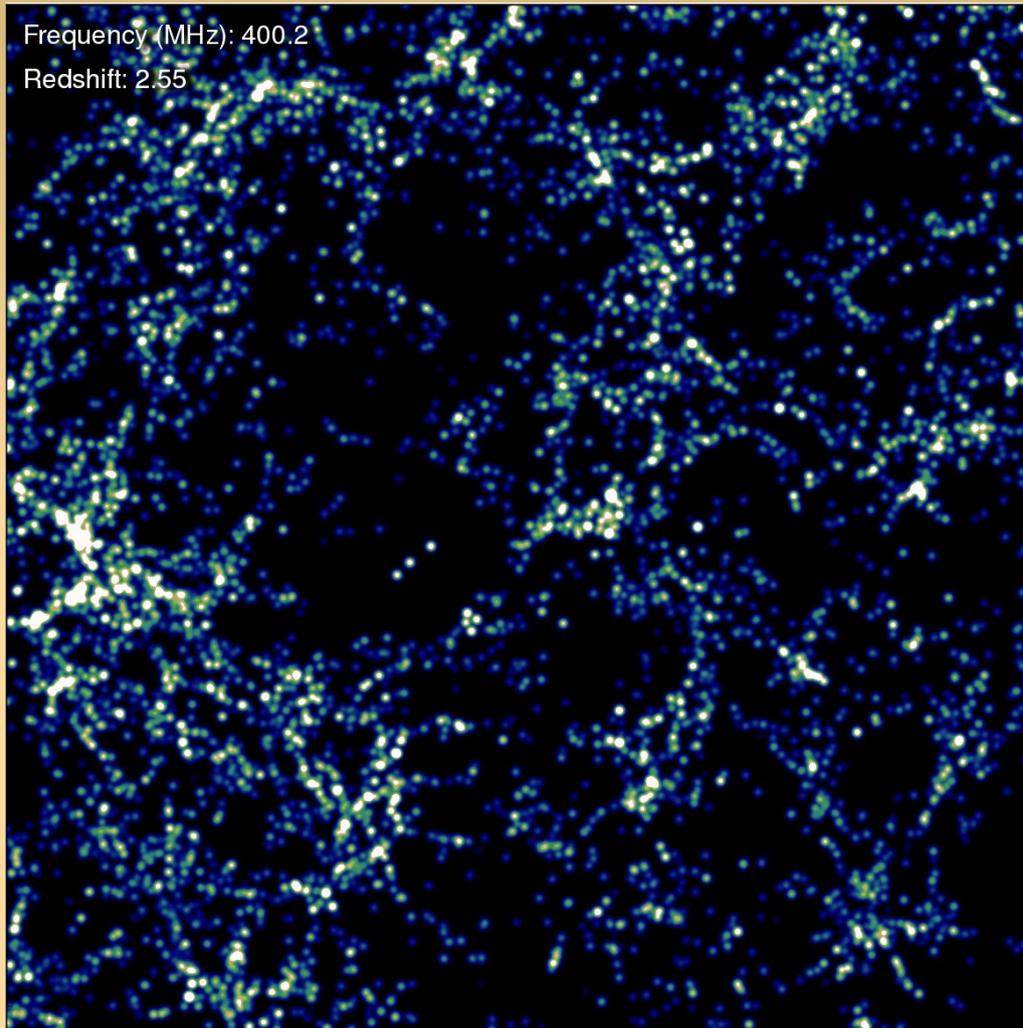
- How many of these galaxies will stack up coherently?
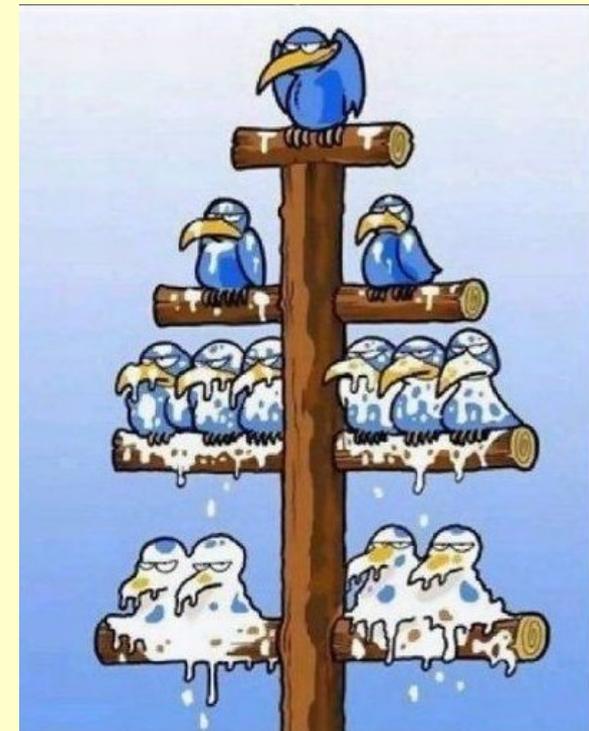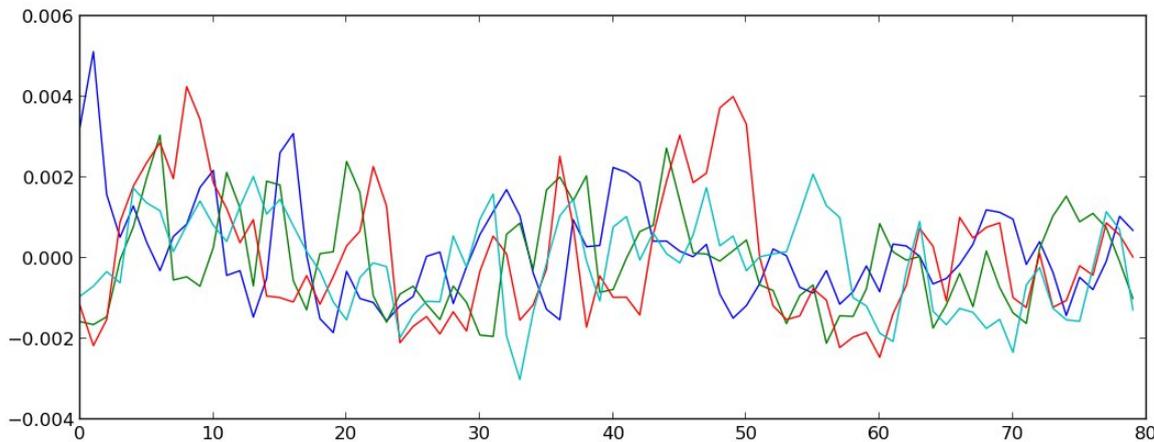
LADUMA Stacking Sim

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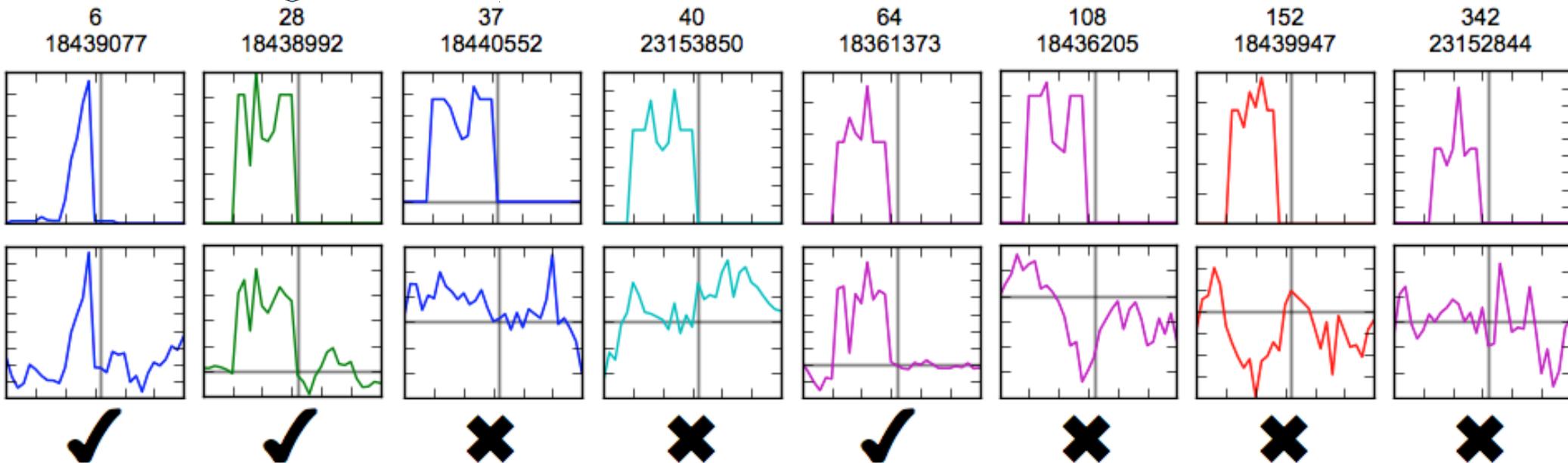- (... with *some* YouTube artefacts...)

Dr Sidelobes at Work

- TOP: A selection of individual galaxy spectra

- BOTTOM: A selection of "Dr. Sidelobes's spectra"
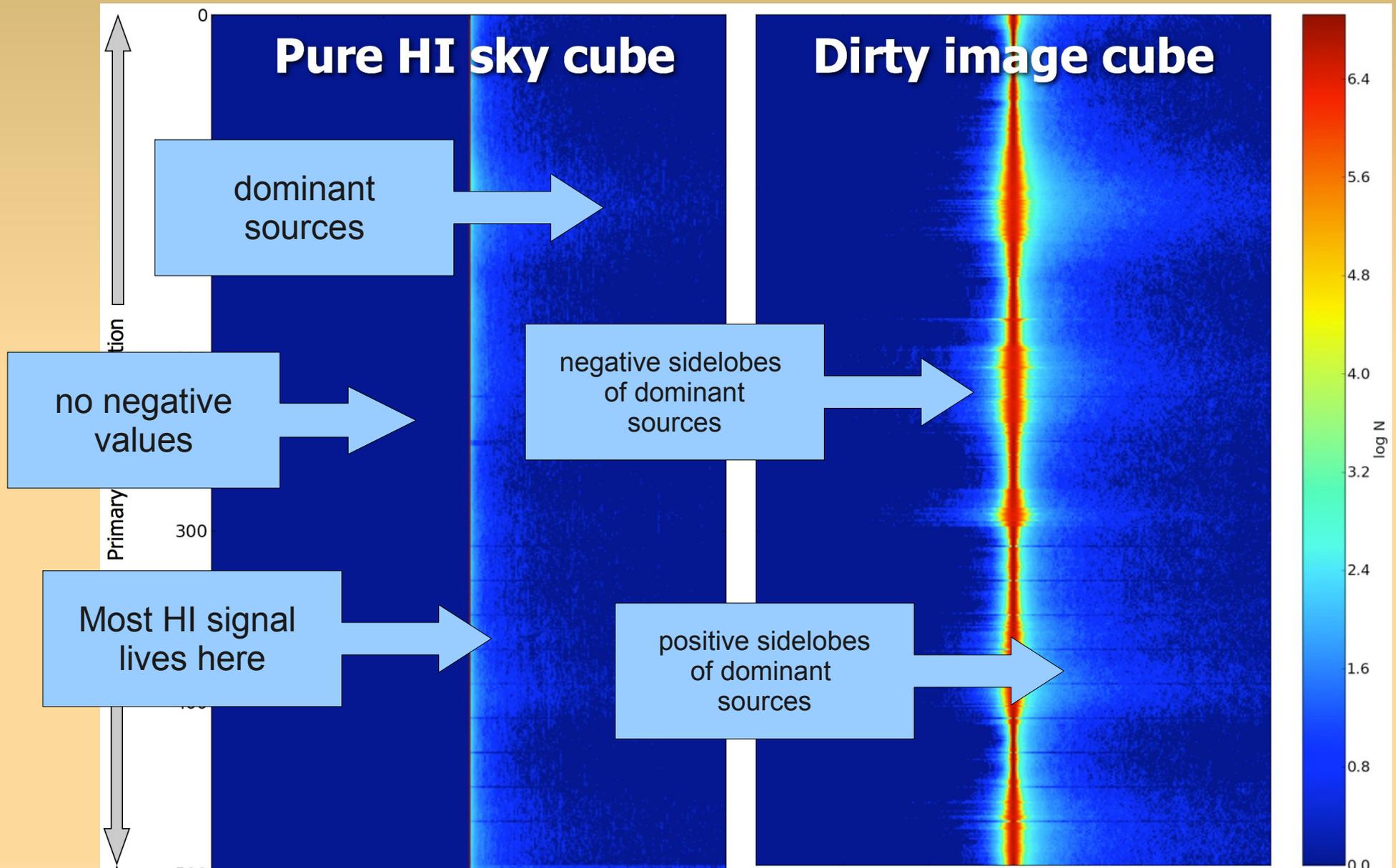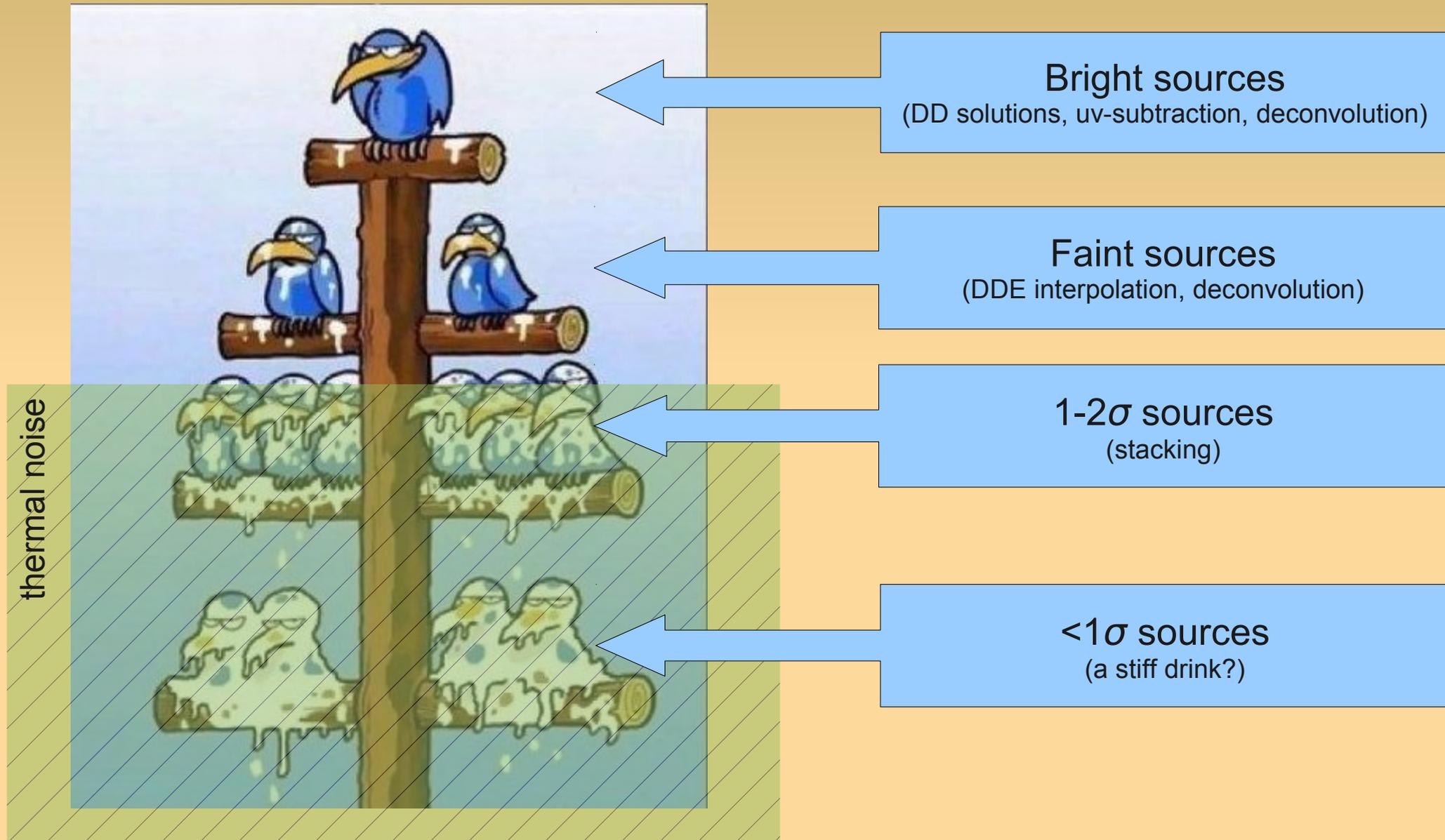
HI + Dr. Sidelobes

- ## TOP: original HI signal

- ## BOTTOM: HI + Dr. Sidelobes

  - ### ...most of which originate with *undetected* sources

75% of the top 500...

Pixel Values Histogram
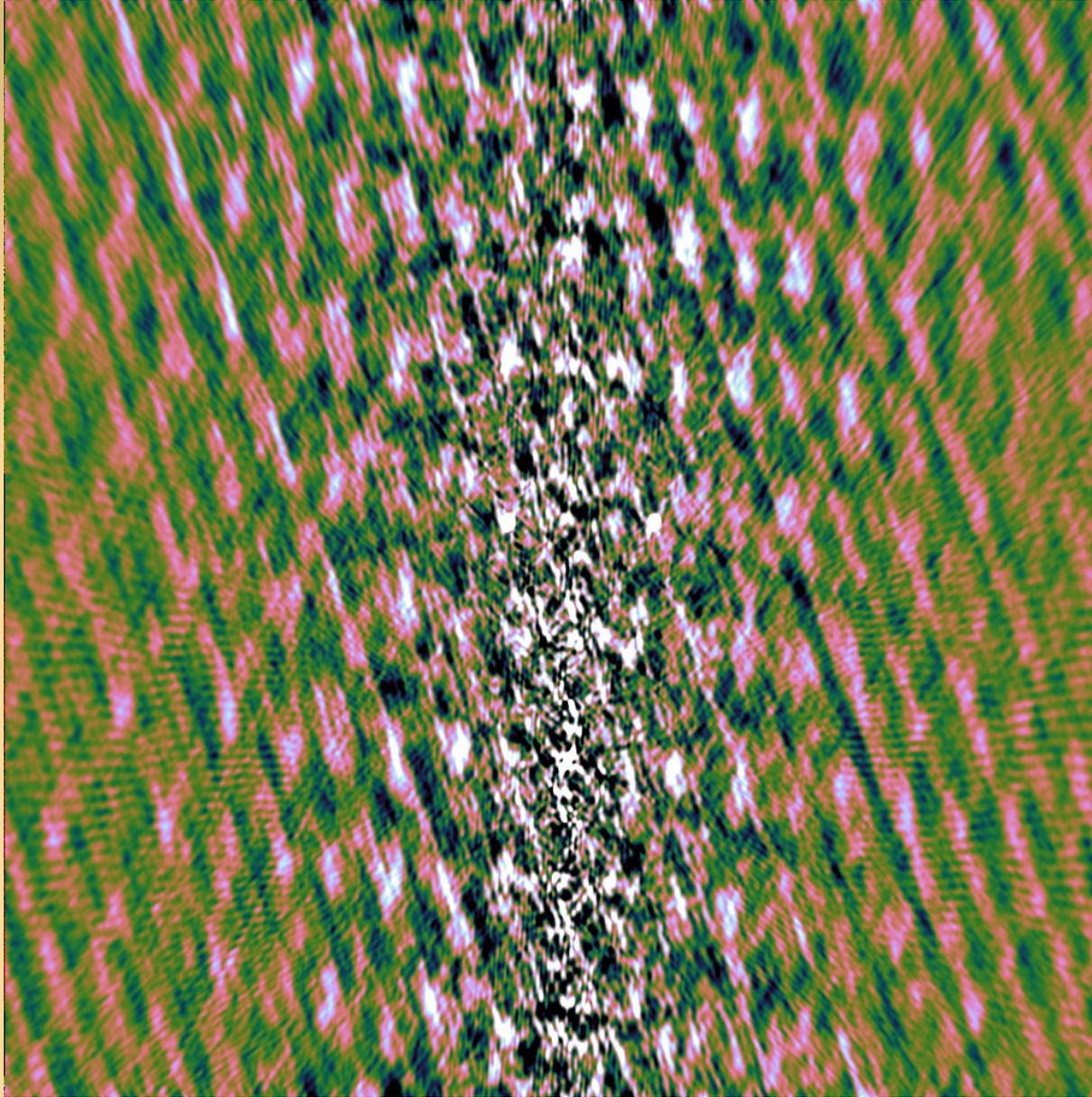
How Radio Interferometry *Really* Works

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

Faint sources
(DDE interpolation, deconvolution)

1-2σ sources
(stacking)

<1σ sources
(a stiff drink?)

thermal noise

Stacking In WHDF

Should have been possible: ~1700 optical positions available in this field.

Failed miserably.

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

Can simulate the whole thing...

And Things Can Only Get Worse...

- Radio interferometers of the past: simple machines built of beautiful, massively over-engineered components

- "Simple" experiments

The Future

- Complex machines built out of cheap junk
  - "We'll just solve it in software!"
- Increasingly subtle and elaborate experiments

Conclusion

- It's a brave new world that Arnold's had a hand in building

- And it's also full of surprises

- But we have the tools to discover them, and hopefully avoid the bad ones

- Another Golden Age in instrumental radio astronomy?