Ghosts, Surprises & Simulations: Performance Limits Of Future Instruments

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Radio Interferometry 1970

- WSRT (Westerbork Synthesis Radio Telescope), The Netherlands
- **14**x25m dishes on an East-West line
- Max baseline 2.7km
- Completed 1970, upgraded since
- World record dynamic range, still

Radio Interferometry 2010

- Low Frequency Array (LOFAR)
- **36** stations (not dishes!) across The Netherlands
- **8** (and counting) international stations

Radio Interferometry 2016

- MeerKAT
- 64 dishes in the Karoo

Radio Interferometry 2020+

- SKA1 (2024?): 250 dishes
- SKA2: >2500 dishes?

And Design/Cost Trends

Problems are exacerbated by (financially inevitable) design trends...

1970: massive overengineering

2024: cheap junk

Introduction

- We're trying to design telescopes that are 1-2 orders of magnitude bigger than anything we've done before
- ...using novel technologies and approaches
- Existing intuition may be a poor guide
- We may need to worry about things we could ignore before (“the elephants in the room”)

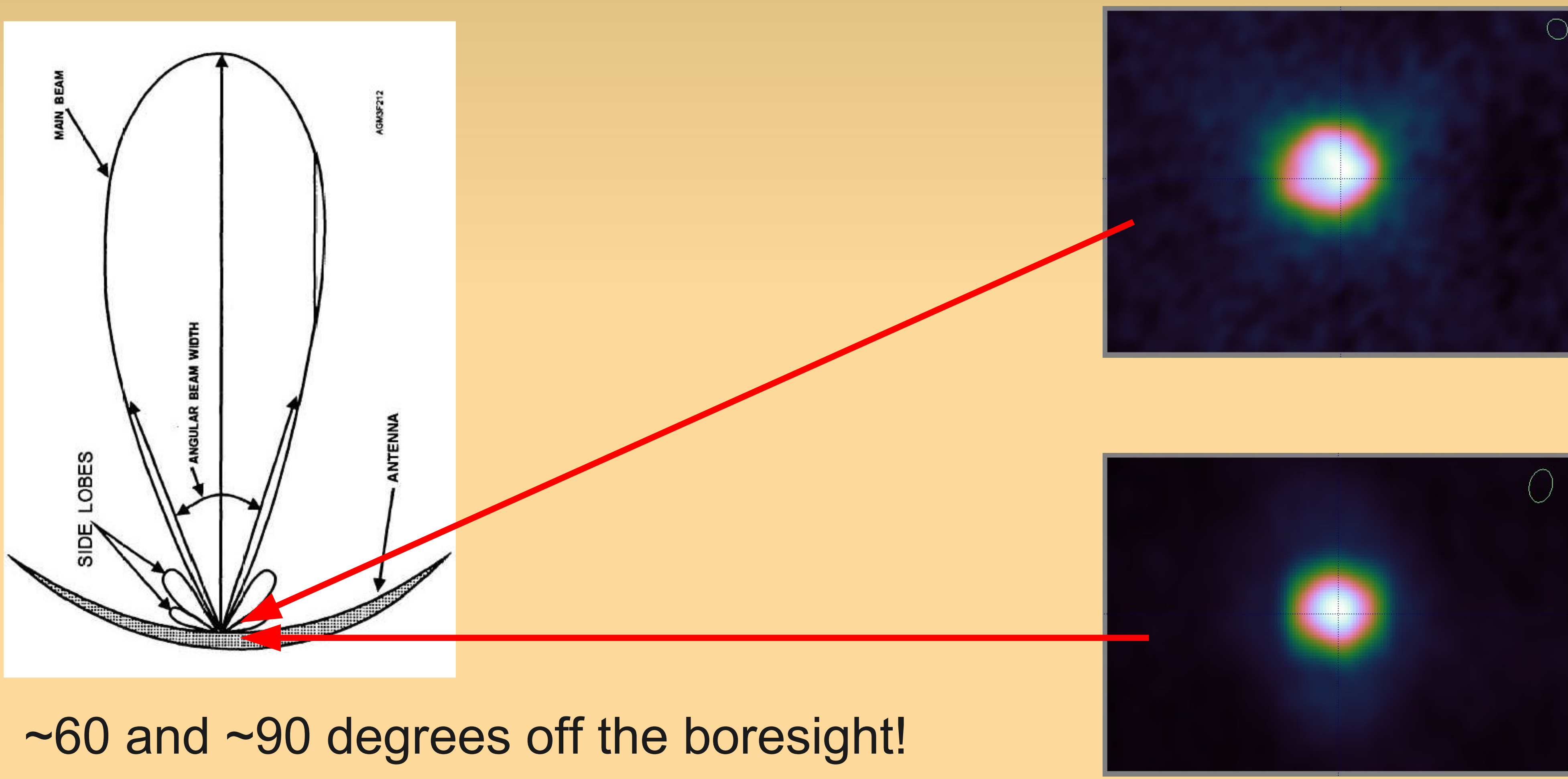
What Limits Dynamic Range?

- Thermal noise
  - lucky if we can reach it
- Classical confusion ← resolution
- Sidelobe confusion noise (SCN)
  - ← PB sidelobes
- Residual calibration artefacts (calibration "noise")
  - ← beamshape smoothness
  - ← other PB properties (?)
- Deconvolution

} this talk

Surprise 1: Sidelobes

- WSRT 300MHz maps of CygA and CasA



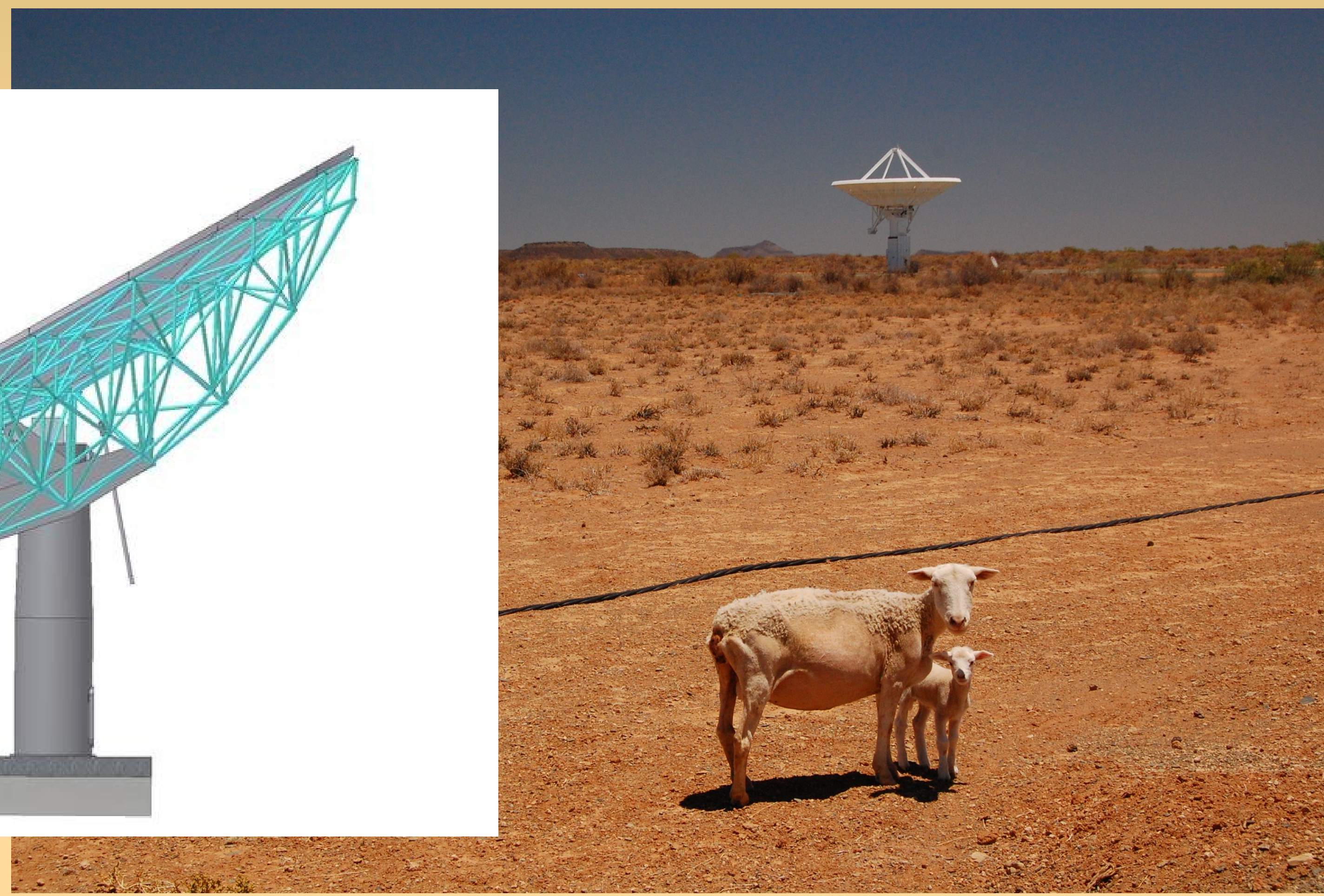
~60 and ~90 degrees off the boresight!

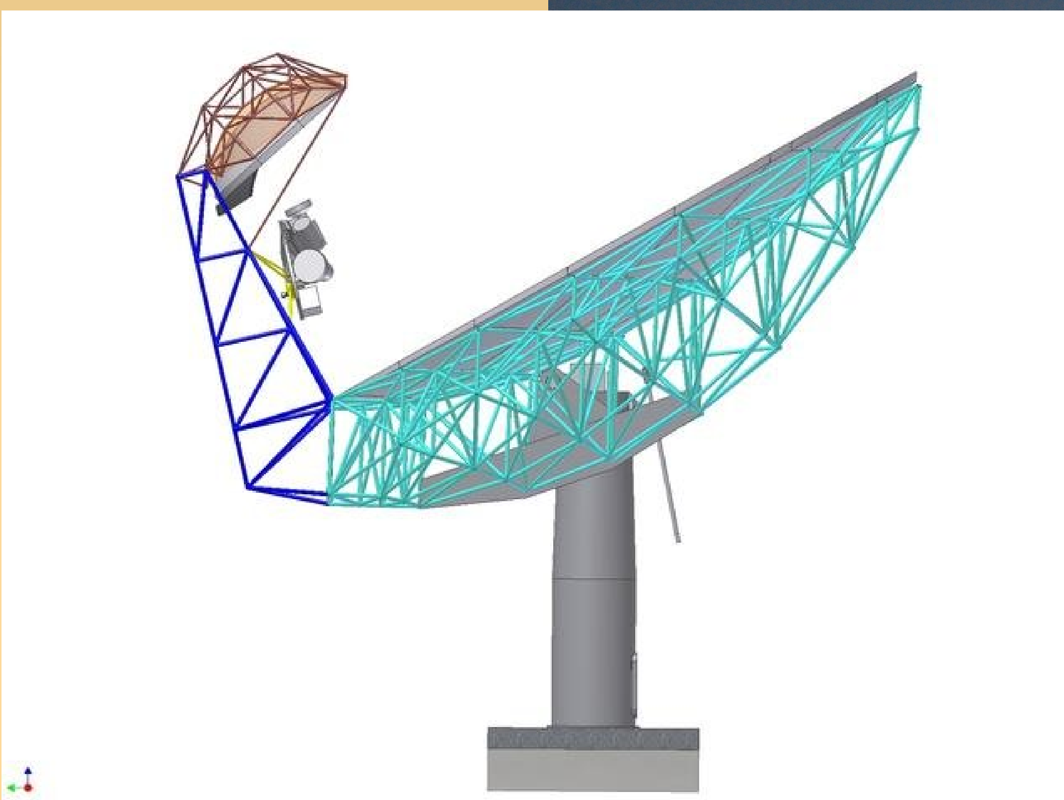
Sidelobe Confusion Noise

- Your dishes pick up radiation from the entire sky
  - Good news: it's attenuated by the primary beam
  - Bad news: the PSF spreads some of that signal everywhere, including over your target
- “A-team” sources can be suppressed individually
  - ...but there's a “sea” of fainter sources too
- This produces a fundamental “cosmological noise floor” which MeerKAT deep surveys will reach
  - Can drive this down by making bigger images
  - Which is expensive

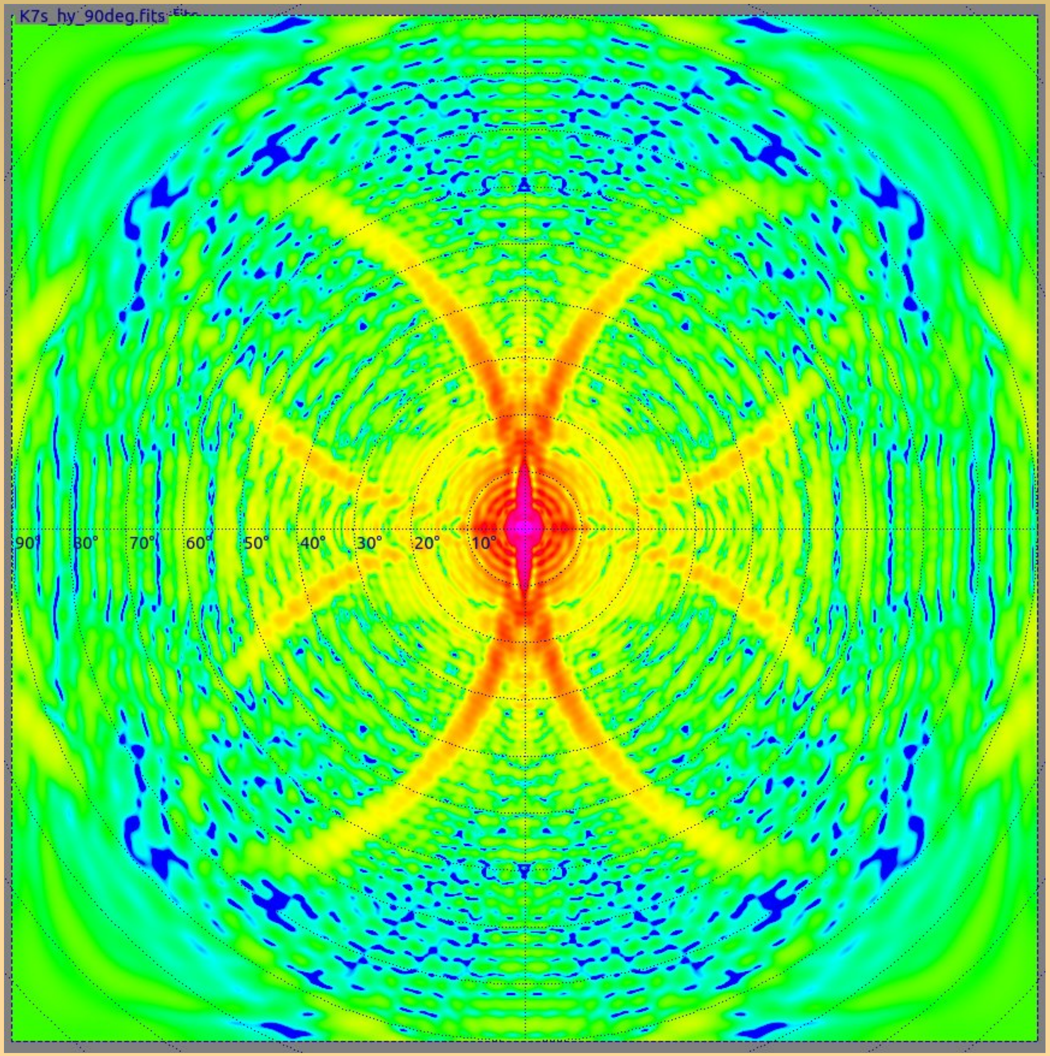
Case Study: PF vs OG

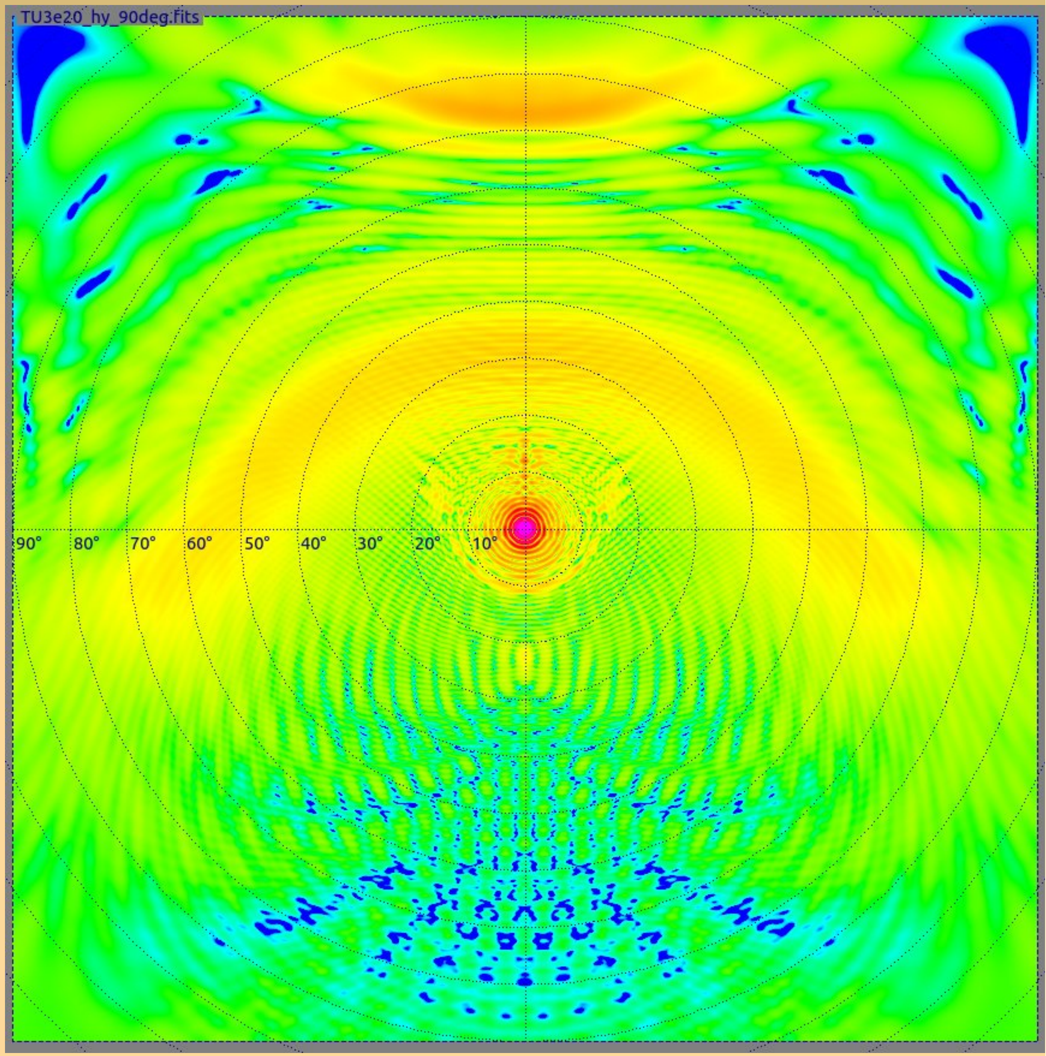
- Does choice of optics make a difference?





KAT-7 vs. MeerKAT Beams





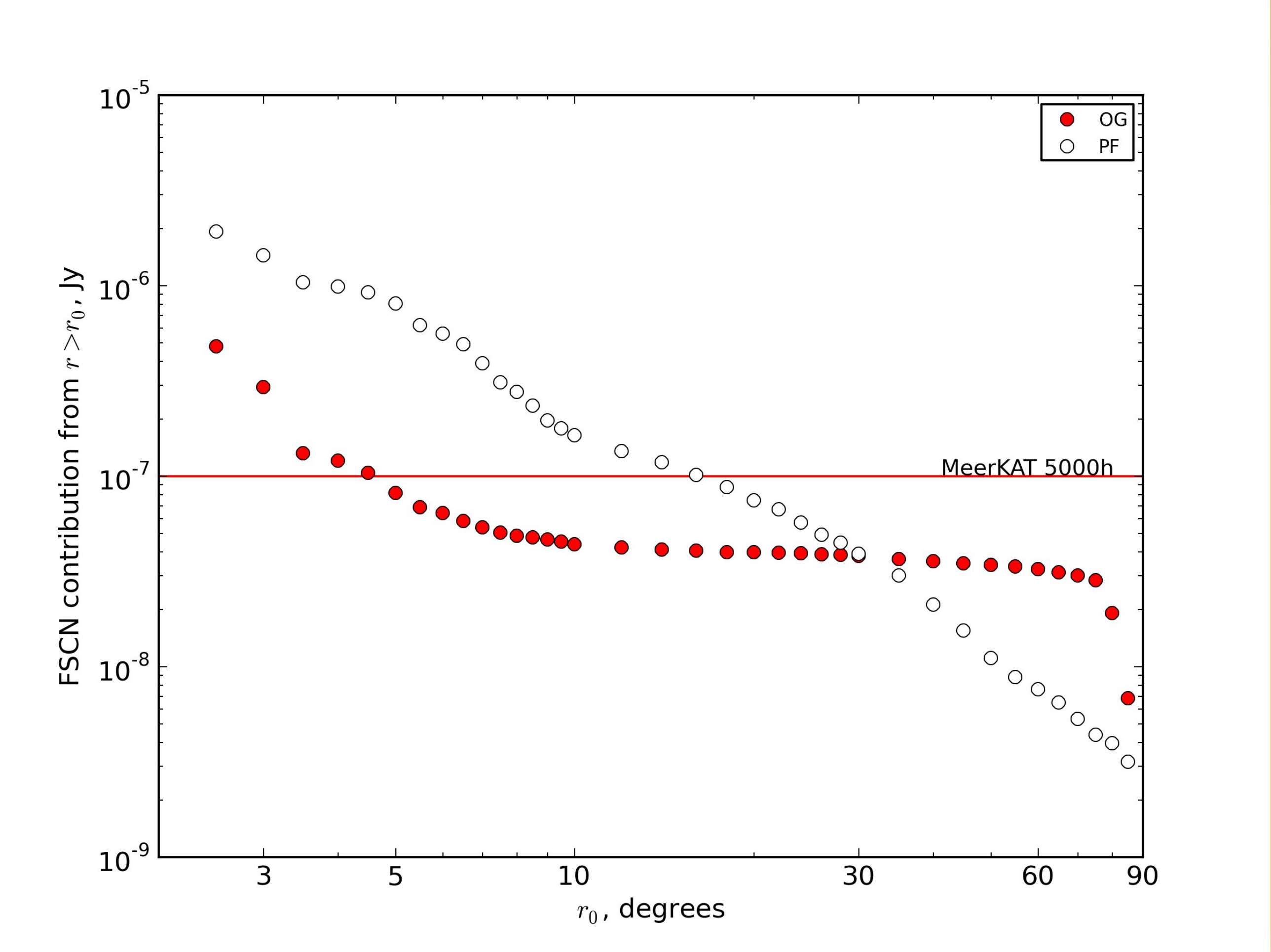
Pick your poison?

BeamSims

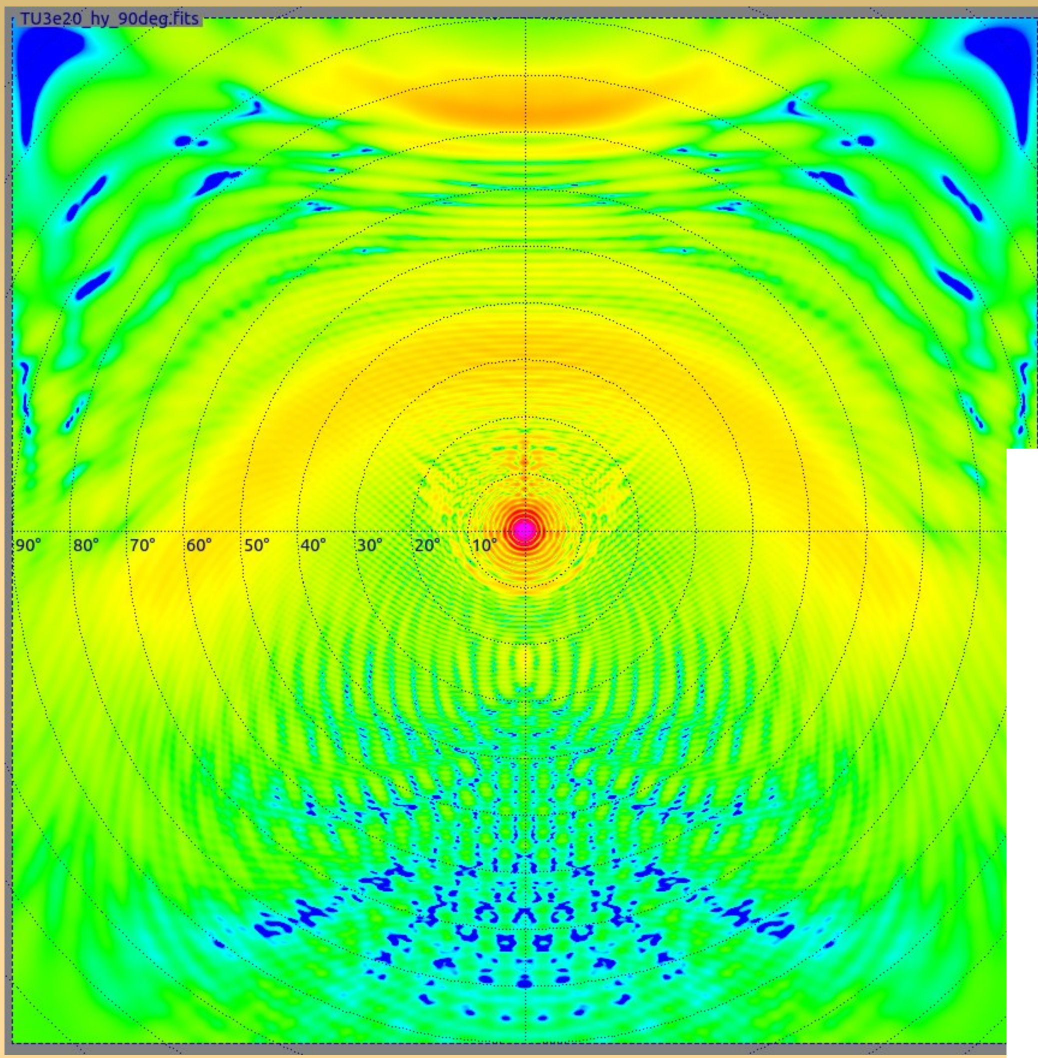
- Strategy: “brute force” interferometric simulation
- Use simulated primary beam patterns
  - full 2x2 complex voltage patterns, given as gridded “images” (in spherical coordinates)
- Make a realistic all-sky model
- Split it into “doughnuts”
- Simulate the sources within each doughnut of radius *r*, and image the nominally empty sky in the middle

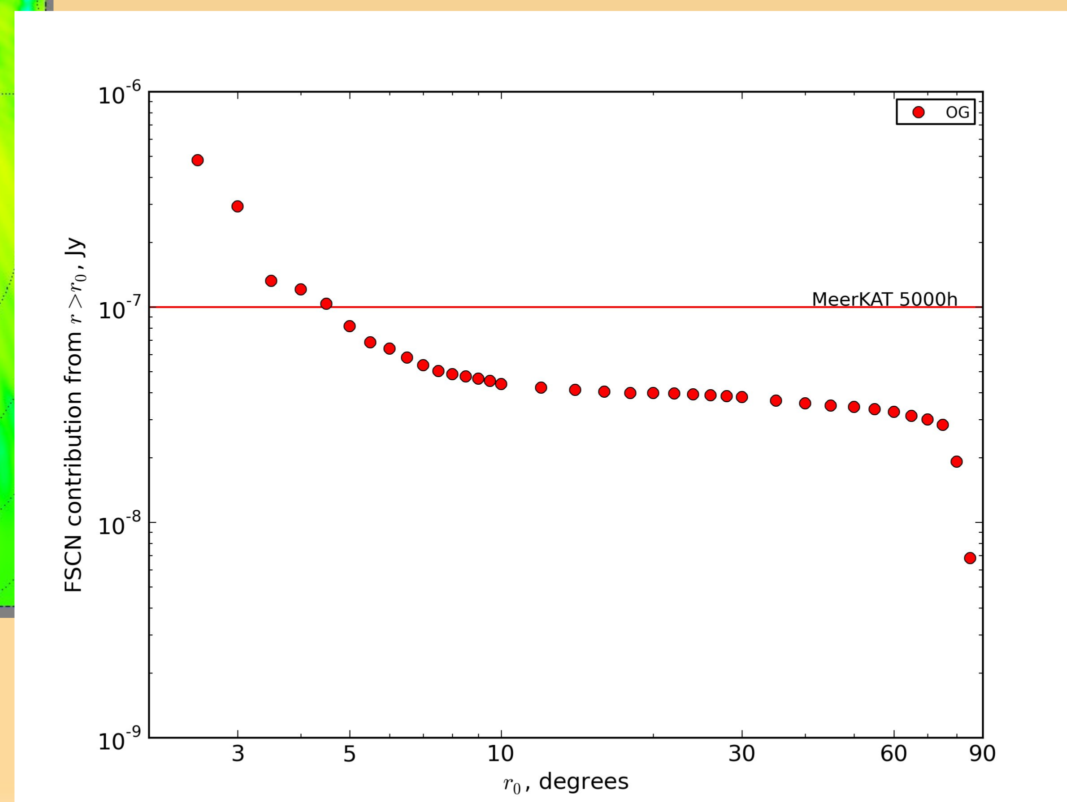
SCN Cost Curves

- This shows, as a function of r, the SCN contribution from sources $r \geq r_0$
- i.e. how far out do we have to image & deconvolve to drive SCN below a given level?

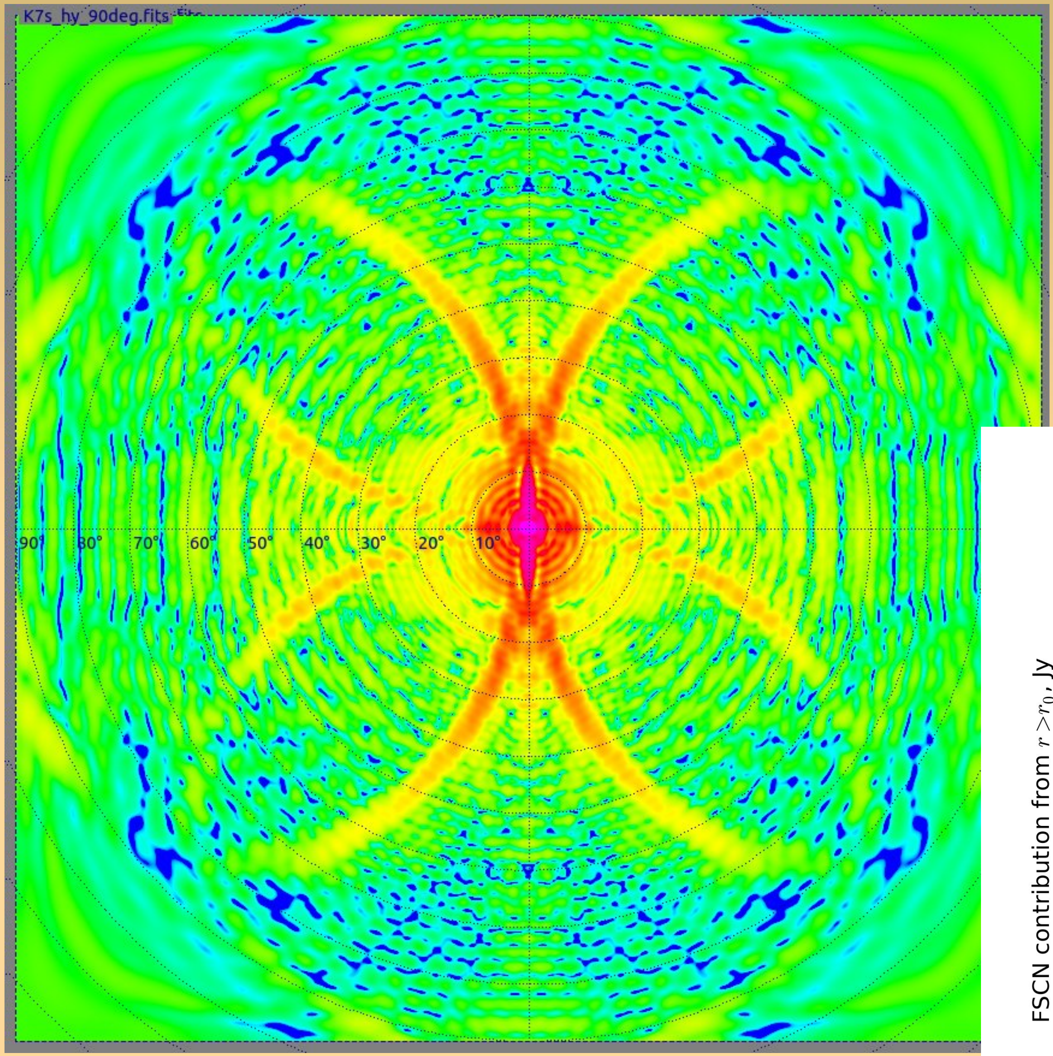


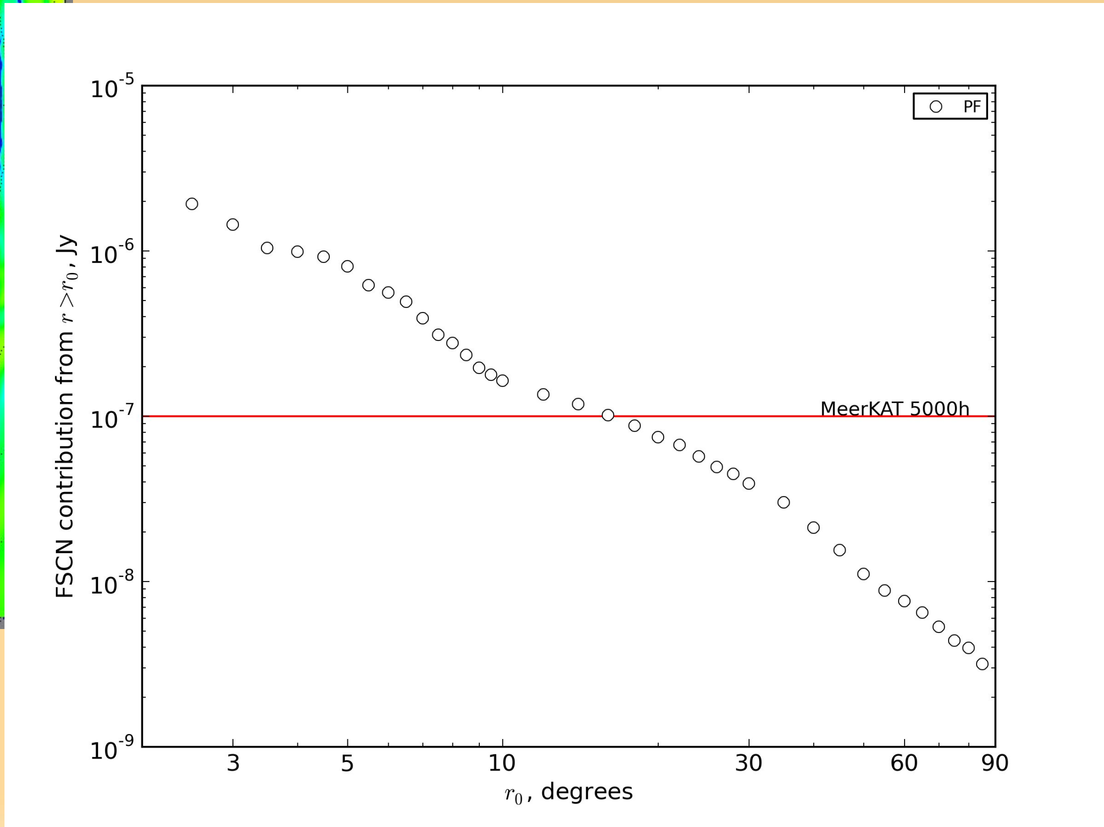
Cost Curve: Offset Gregorians



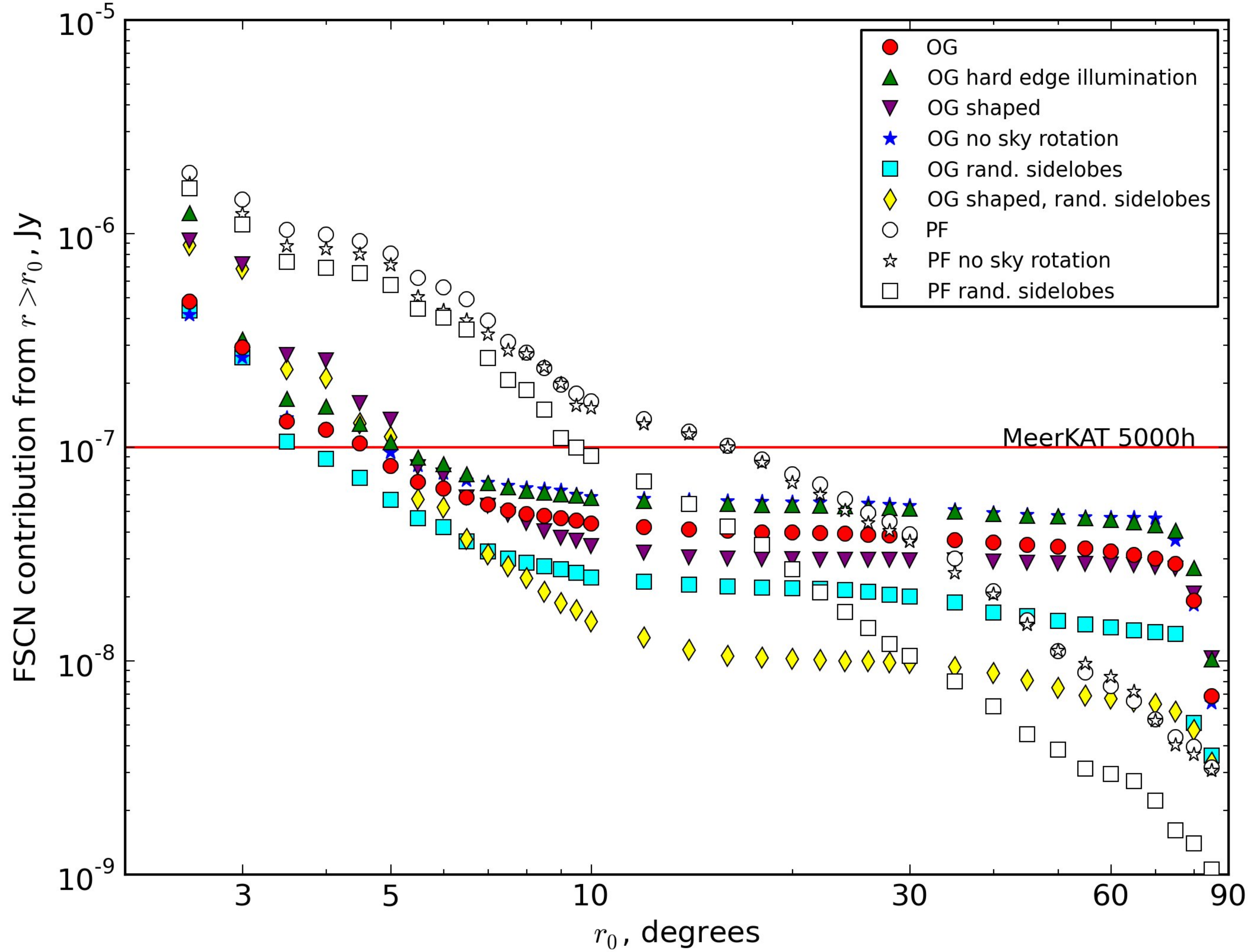


Cost Curve: Prime focus

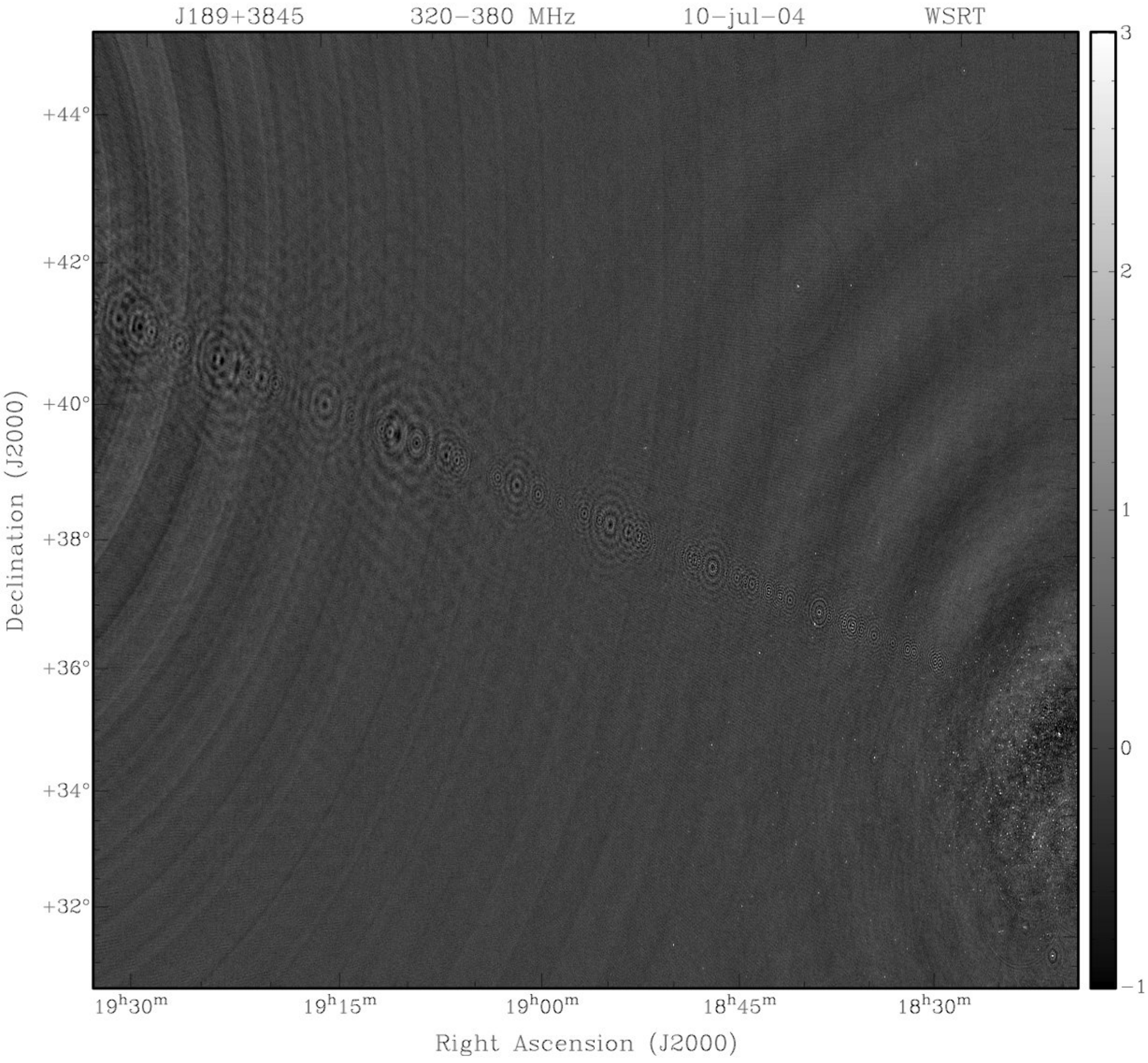




For Many Different Dishes



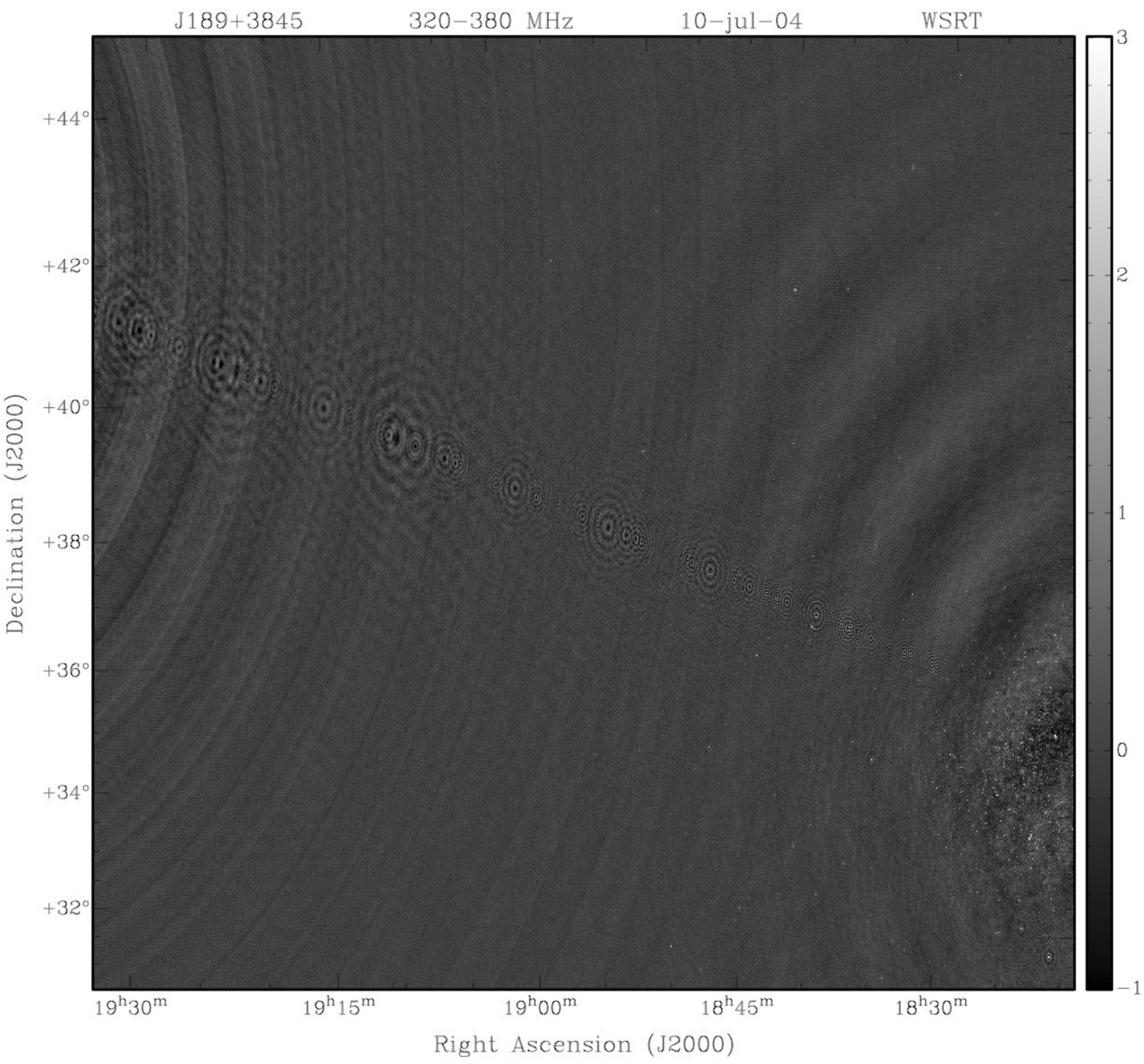
Surprise 2: Ghosts



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.)

Surprise 2: Ghosts 2004



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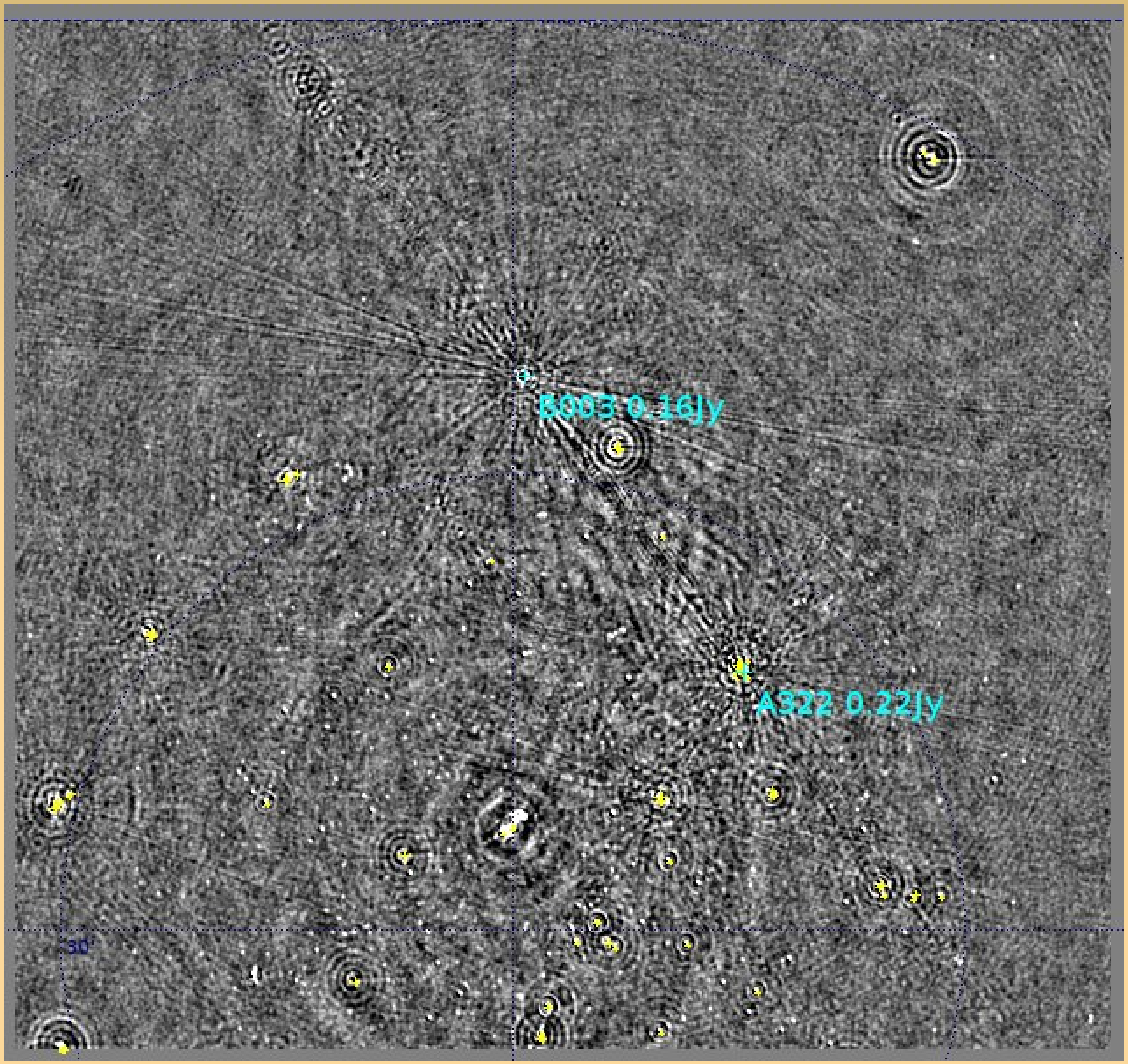
2010: Ghosts Return



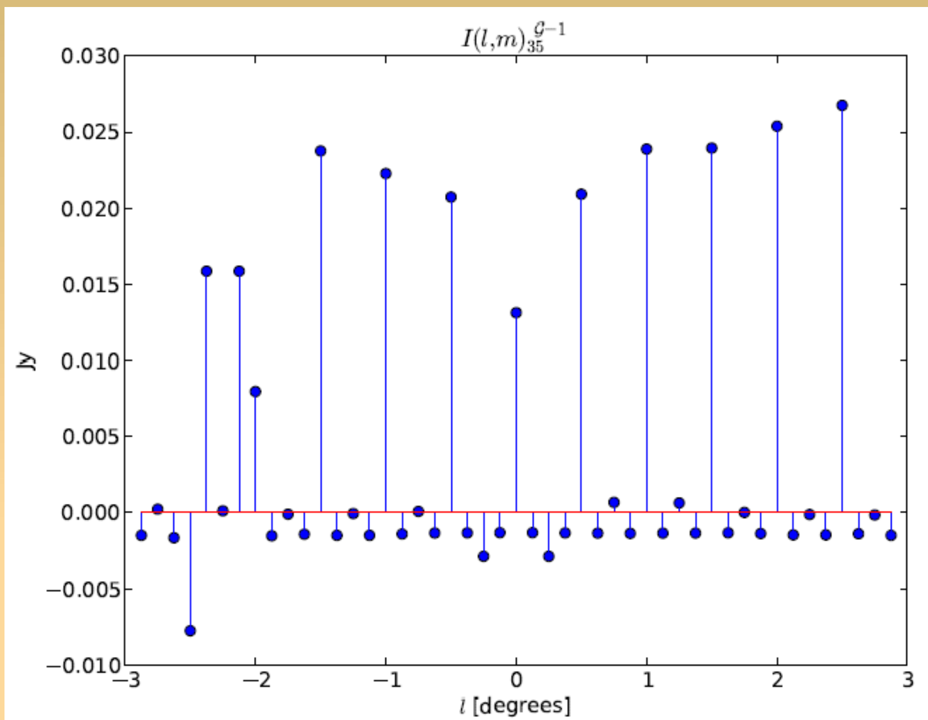
WSRT 21cm observation

- ...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

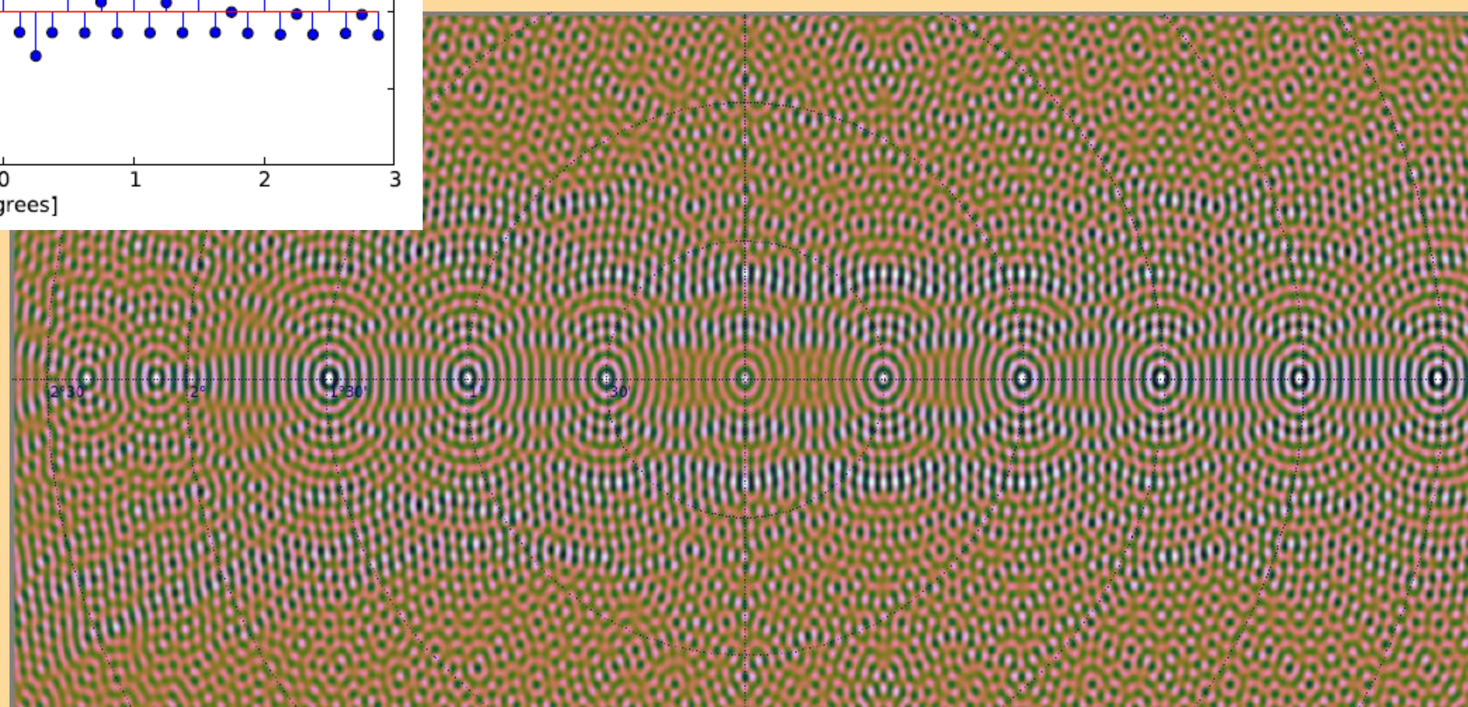
Ghastly Facts

- Grobler & Nunhokee (2013, in prep) have worked out the theoretical basis for ghosts
- Calibration with an incomplete sky model and DDEs will always introduce ghosts and suppress real sources
  - Geometric for WSRT, more noise-like for e.g. MeerKAT
- Why don't we always see them? A: Not enough sensitivity.
- Will they average out?
  - NO. Push the sensitivity, they pop out.
- How to fight them?
  - Build up a sufficiently deep & complete sky model iteratively, calibrate DDEs
  - This is expensive, so need to study how deep to go...

Ghosts (Grobler & Nunhokee)



Predicted (left) vs actual (bottom) patterns.



Surprise 3. Calibration "Noise"

- Imperfect calibration leaves residual artefacts
  - "Ghosts" or "calibration noise"
- We have been very successful at eliminating these via direction-dependent solutions
- And by "eliminating" we mean "driving below the (thermal) noise"
  - ...by which we really mean "sweeping under the carpet"
- So, how do we estimate what we have "swept", in case it comes back to haunt us?
  - ...and does this depend on primary beam choice?

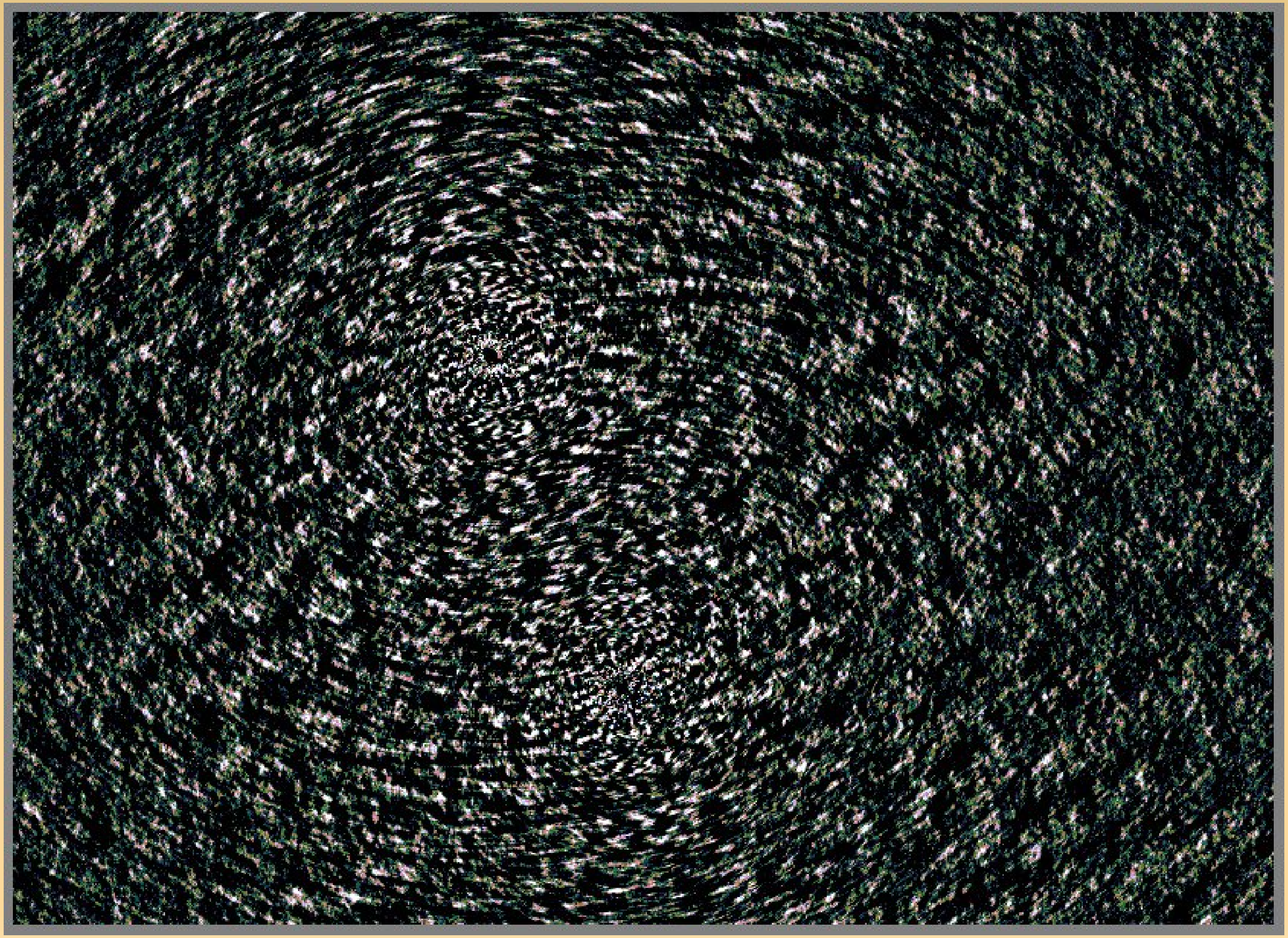
Distilling Out The Artefacts

- Simulate a full field that includes one or more bright sources ("contaminators"), errors (gain, pointing, ionosphere) and measurement noise: →"full data"
- Simulate the contaminators alone with the same errors, but no noise: →"contaminator data"
- Calibrate the full data
  - Residuals will contain unmodelled sources, artefacts and thermal noise
  - If these are noise-limited, this tells you very little about the other effects
- Apply the calibration solutions to contaminator data, and look at the residuals
  - Residuals are "distilled artefacts" associated with the contaminators

Example: Regular Selfcal

- Two "contaminators" with DDEs: this shows the resulting "calibration noise"
- Visible above thermal noise
- Here, rms 4.2 μJy

  (but very non-Gaussian)

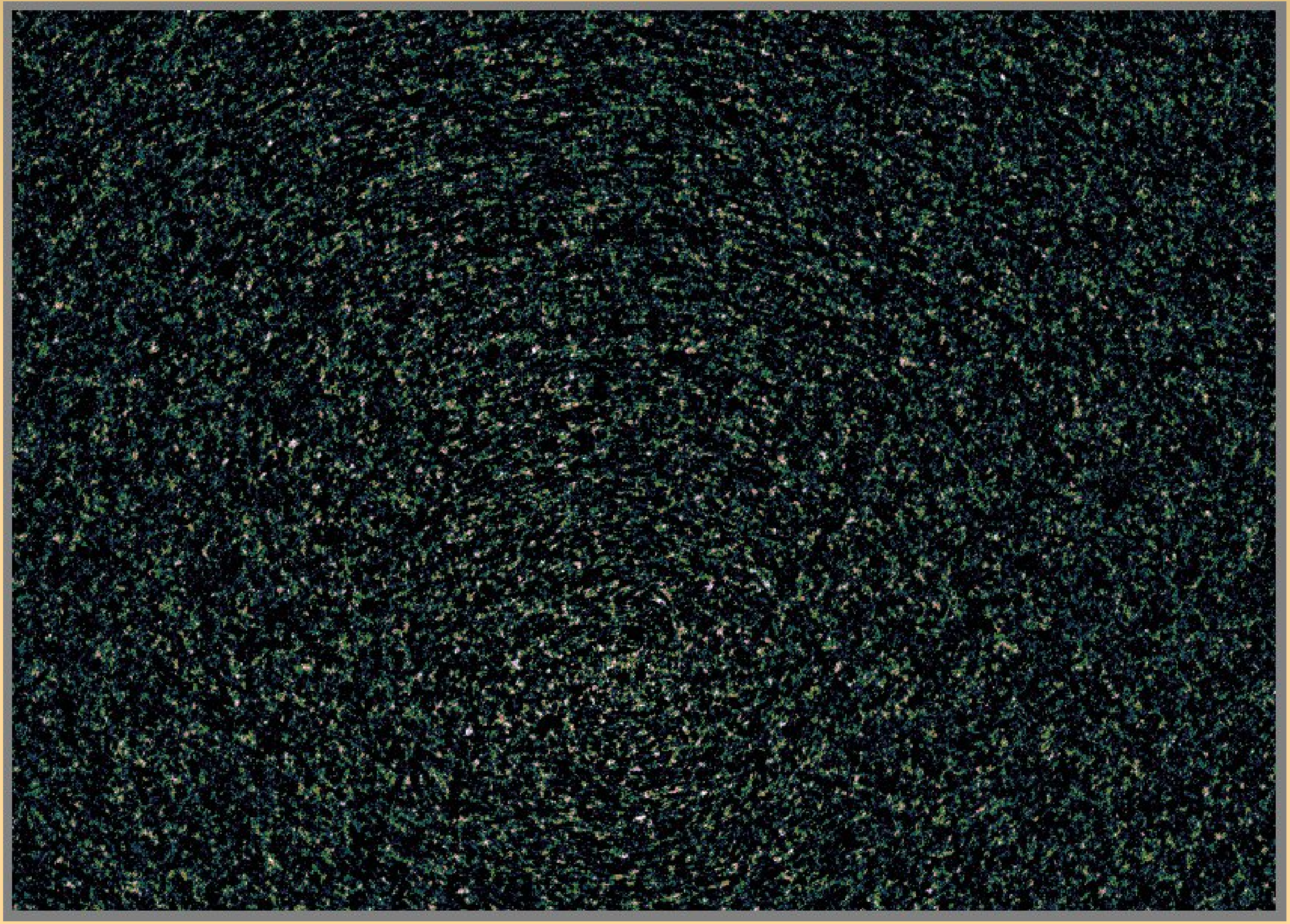


Distilling DDEs

- But nevermind, because direction-dependent solutions can take care of it, right?
- If we run a DD solution on the two contaminator sources, the resulting image (of the full residuals) becomes thermal noise limited; remaining artefacts are below the noise.
- But we can repeat the same distillation trick with DD calibration

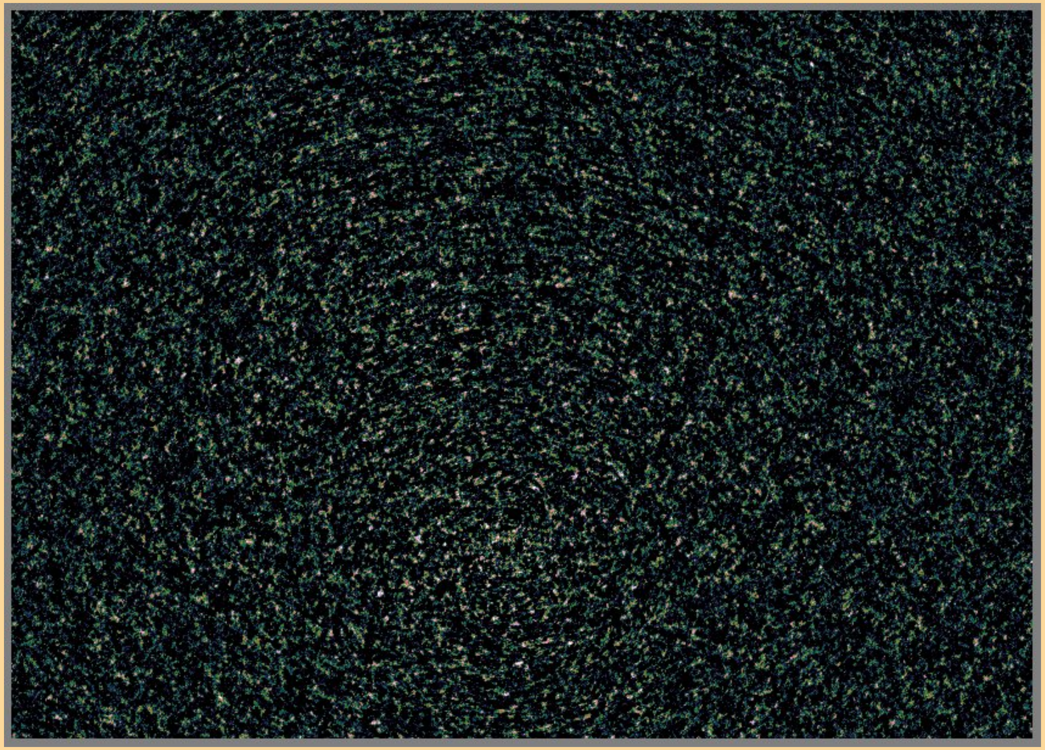
Calibration Noise (DD solutions)

- Here, rms 2.6 μJy, and far less spatially correlated and more noise-like



Why Do We Care?

- Just an extra noise-like contribution that's below the thermal noise, so what's the big deal?
- But it can be a big deal if its statistics are non-Gaussian



Scenario: Deep Survey

- Consider a deep survey where we obtain many pointings of the same field
  - MeerKAT MIGHTEE/LADUMA surveys: 5000 hours
- Each pointing must have independent DDE solutions
  - Beam stability, ionosphere, etc. always different
  - So for each pointing we leave an independent set of calibration artefacts buried in the thermal noise
- We now combine the pointings – thermal noise adds up as $\sqrt{n}$ (0.1 µJy after 5000 hours)
- How do the artefacts add up?

Distill, Rinse, Repeat

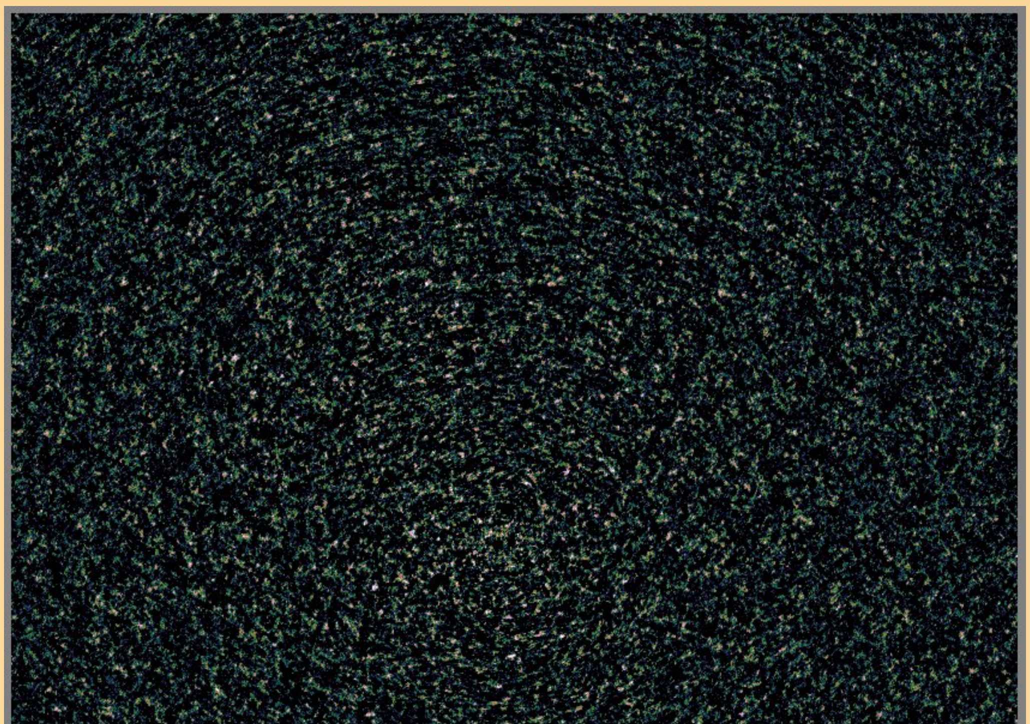
- We can repeat the distillation experiment multiple times, with different random realizations of errors
- ...and add up the “distilled” maps

Mean Of 10 DD-Distills

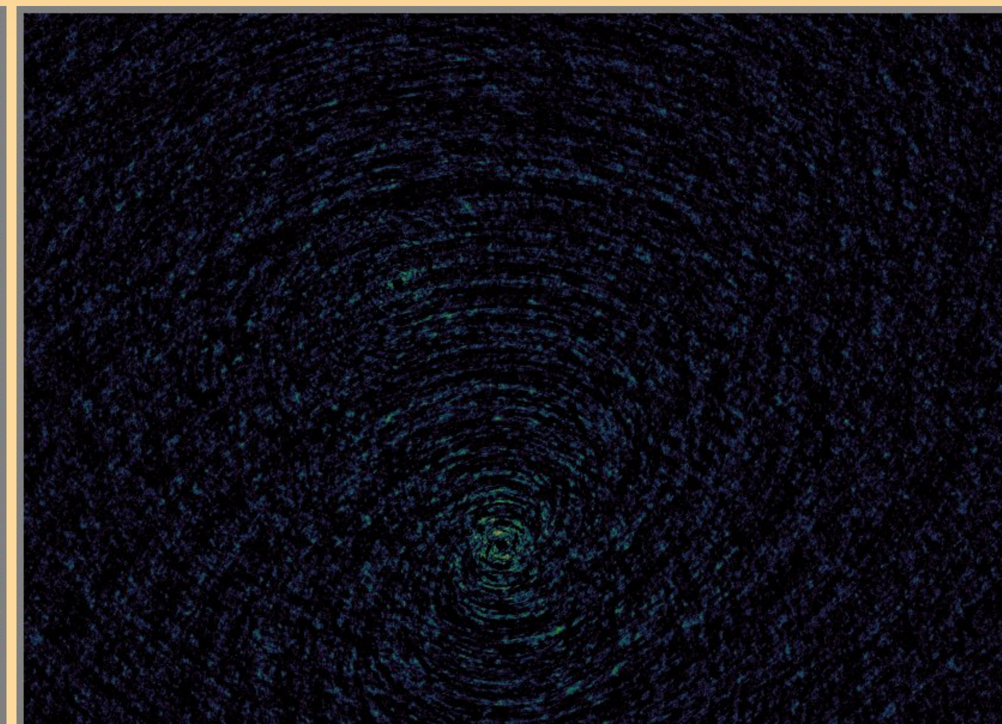
EXTREMELY PRELIMINARY!

- Structure shows up
- Does not scale as a Gaussian

1 distill, rms 2.6 μJy



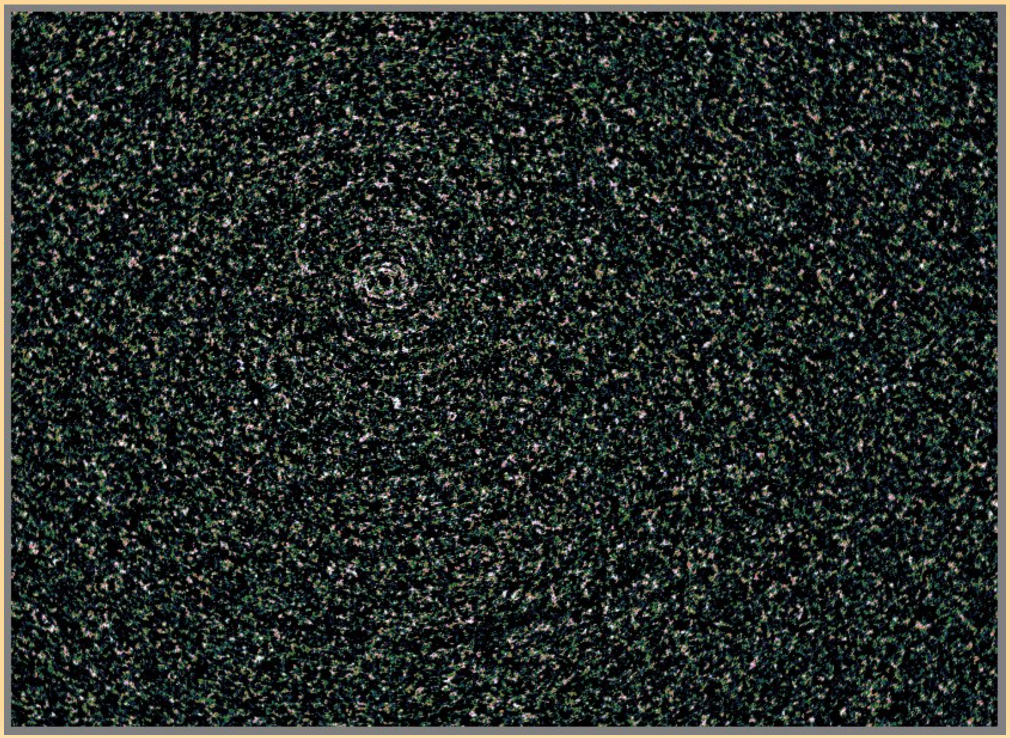
10 distills, rms 1.2 μJy



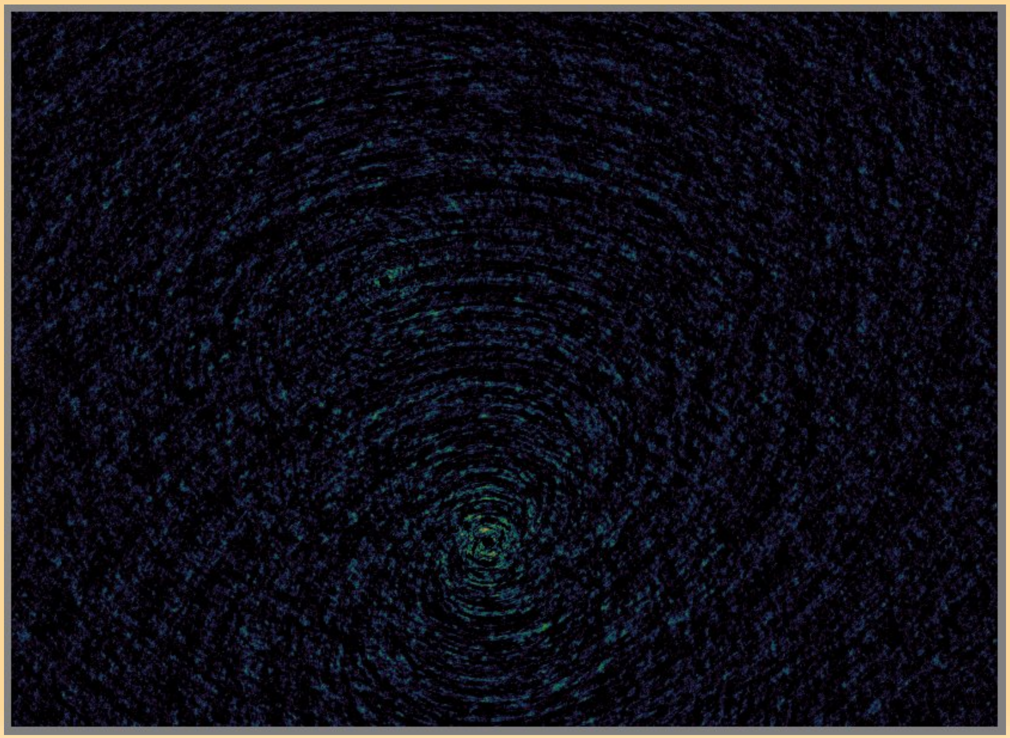
PF vs OG

- Repeat this experiment for PF and OG beam patterns
- Calibration “noise” for OG lower by a factor ~3

PF: rms 3.6 µJy

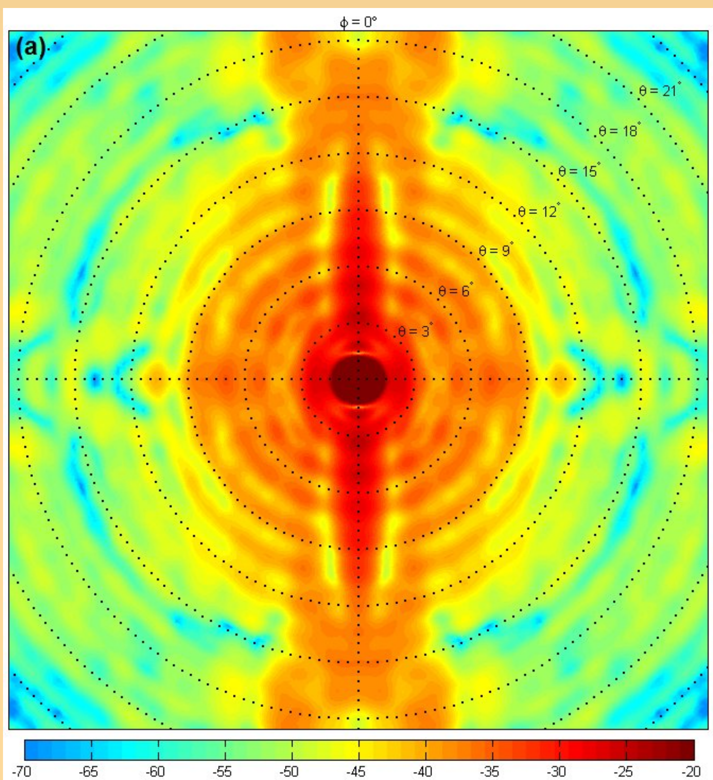


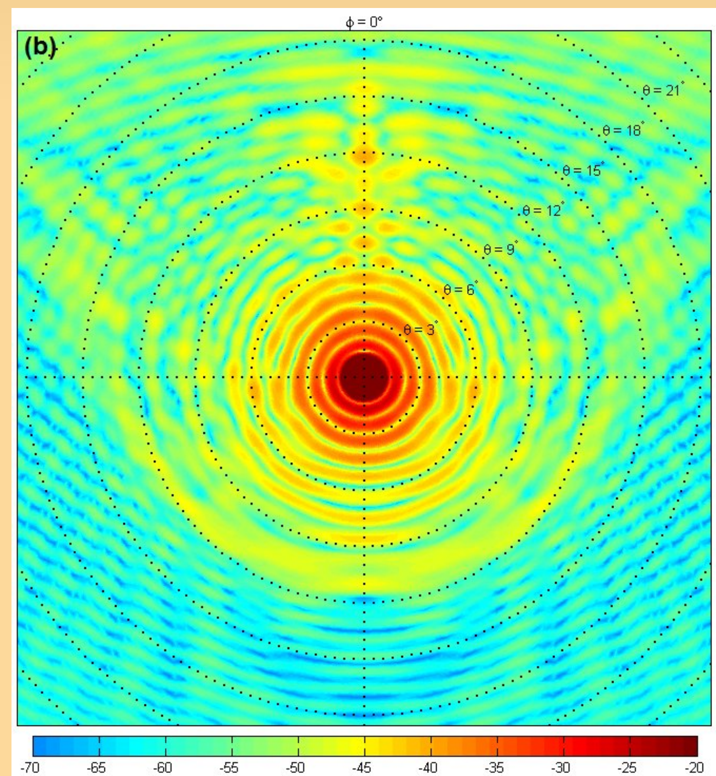
OG: rms 1.2 µJy



Why The Difference?

- Difference probably due to OG's smoother beam pattern
- same amount of pointing error causes more gain variation in the PF case





Conclusions

- Radio interferometry is hard and full of surprises
- High dynamic range is even harder
- This SKA idea is crazy
  - ...which is exactly why we should be building it
- Specific design decisions (such as choice of primary beam) can make things harder or easier in entirely non-obvious ways
  - But simulations (“design experiments”) can be a great help in understanding it