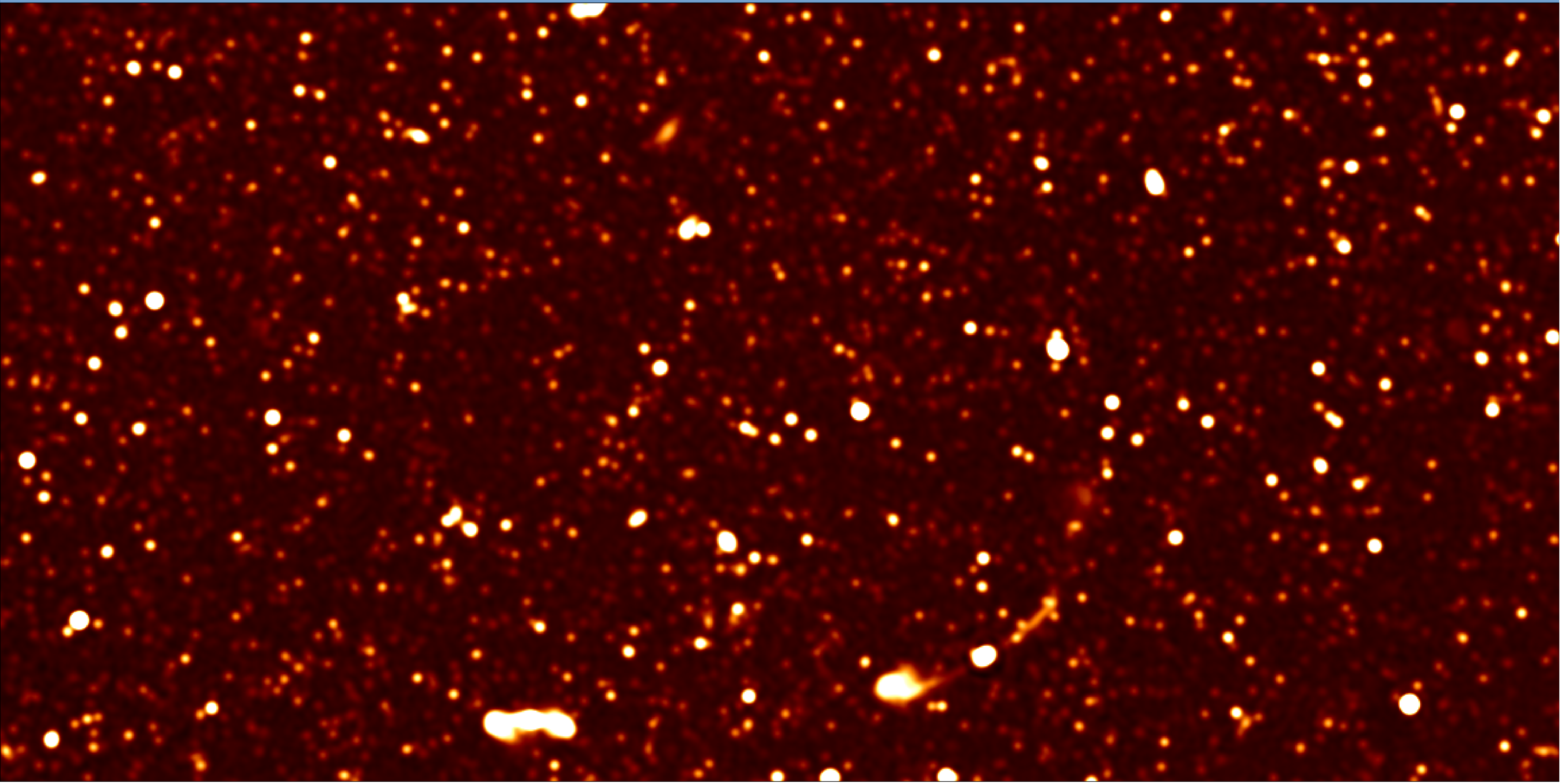
The MeerKAT DEEP Field



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Bill Cotton & Jim Condon (NRAO)
Allison Matthews (U Virginia)

The MeerKAT DEEP Field

- Comes from a requirement during the commissioning phase of MeerKAT that we have a field that is “easy” to image
  - As far south as possible so it’s observable at any time of day
  - Should have few bright sources in the field of view
- Such a field is useful for commissioning
  - Good for testing pipelines
  - Makes a nice looking ‘First Light’ image
- Can be used as a ‘ground truth’ reference for the performance of the telescope and other surveys (eg. ASKAP EMU)
- How far can we push sensitivity limit of the telescope?
- Scientific merit
  - Purely radio selected deep fields are few and far between, usually selection is made on the basis of available multiwavelength data
  - Radio equivalent of the Hubble Deep Field
  - P(D)

Field Selection

- Search SUMSS and NVSS to find field accessible to MeerKAT with fewest 'bright' sources in the primary beam.
- Demerit score (*D*) is the quadratic sum of expected gain variation due to pointing error (σ_p) and receiver gain error (σ_g) for every source in the field.

$$\Delta S_{\rm p}(\rho) \approx S_{\rm i} A(\rho) \epsilon(\rho)$$

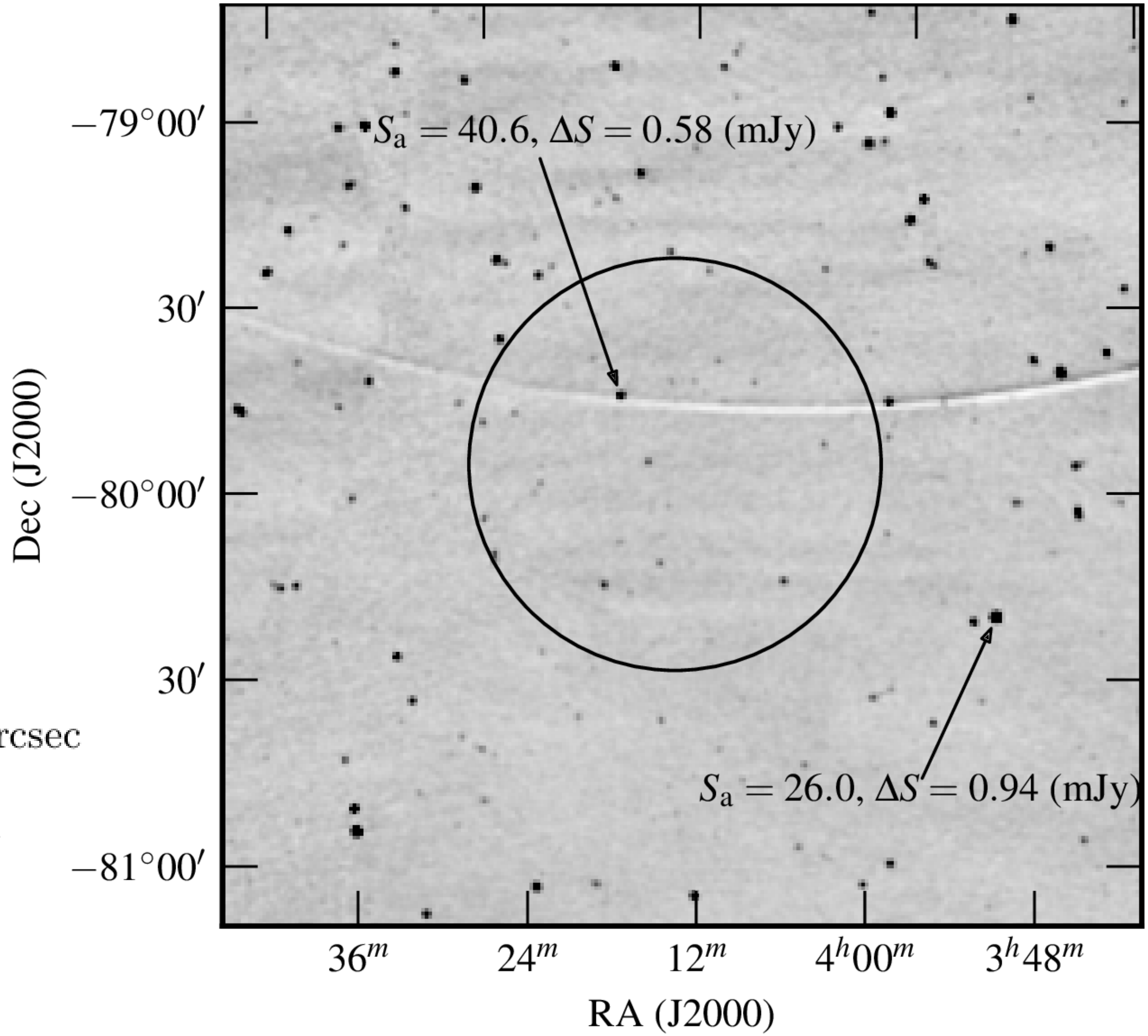
$$\Delta S_{\rm g}(\rho) = S_{\rm i} A(\rho) \sigma_{\rm g}$$

$$\epsilon(\rho) \approx \frac{8 \ln(2) \rho \sigma_{\rm p}}{\theta^2_{1/2}}$$

$$\sigma_{\rm p} = 30\,\text{arcsec}$$

$$\sigma_{\rm g} = 0.01$$

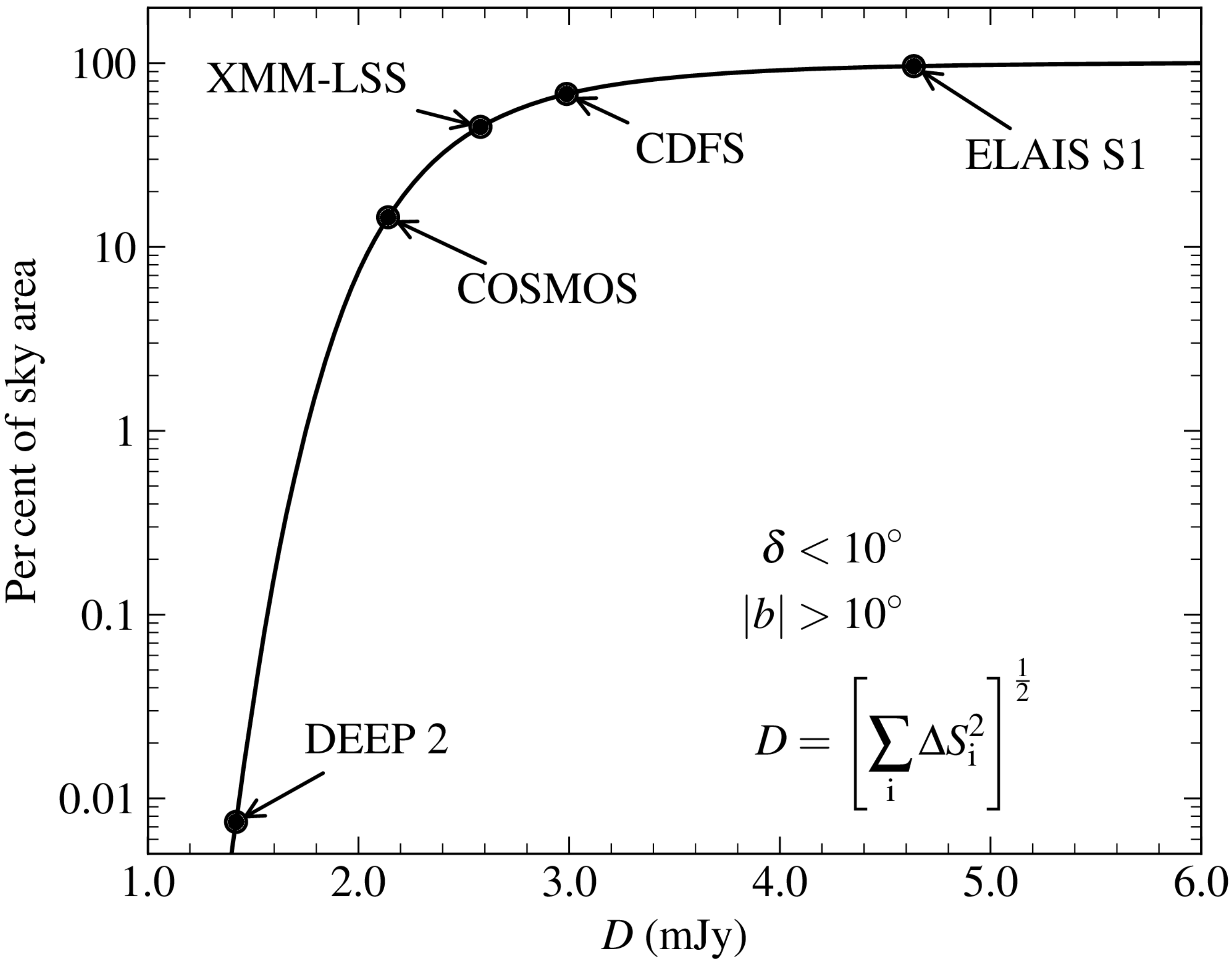
$$\Delta S = \sqrt{\Delta S_{\rm p}^2 + \Delta S_{\rm g}^2}.$$



Field Selection

- Search in region observable to MeerKAT (Dec. < 10 and |b| > 10 deg) using SUMSS and NVSS catalogues
- Calculate the Demerit score (*D*) in a grid of positions separated by 1'. Only include SUMSS/NVSS sources within 3 deg of each position.
- Our Chosen "DEEP 2" field has *D* = 1.4 mJy and is in a region with the 4th lowest demerit score in our search area

R.A. (J2000)	Dec. (J2000)	D mJy	Area ($D < 1.4$) $\deg^2$
03^h21^m	$-18°53'$	1.32	0.19
04^h22^m	$-80°15'$	1.35	0.22
16^h37^m	$-70°46'$	1.34	0.36
21^h04^m	$-54°25'$	1.36	0.25
22^h03^m	$-35°43'$	1.34	0.23



Radio fields selected for optical follow-up don't fare so well using our metric.

Observations

- Field was observed 12 times between April 2018 and January 2019
- L-band observation: 856-1712 MHz. 886-1682 MHz with 3.5% of each edge trimmed
- 155.2 total hours observing
- 128.8 hours on target
- 15% overheads for slewing etc.
- Always >58 antennas out of maximum 64
- Secondary calibrator J0252−7104 located 10 deg away was observed for 2 minutes every 15 minutes
- PKS1934-638 for 10 minutes every 3 hours

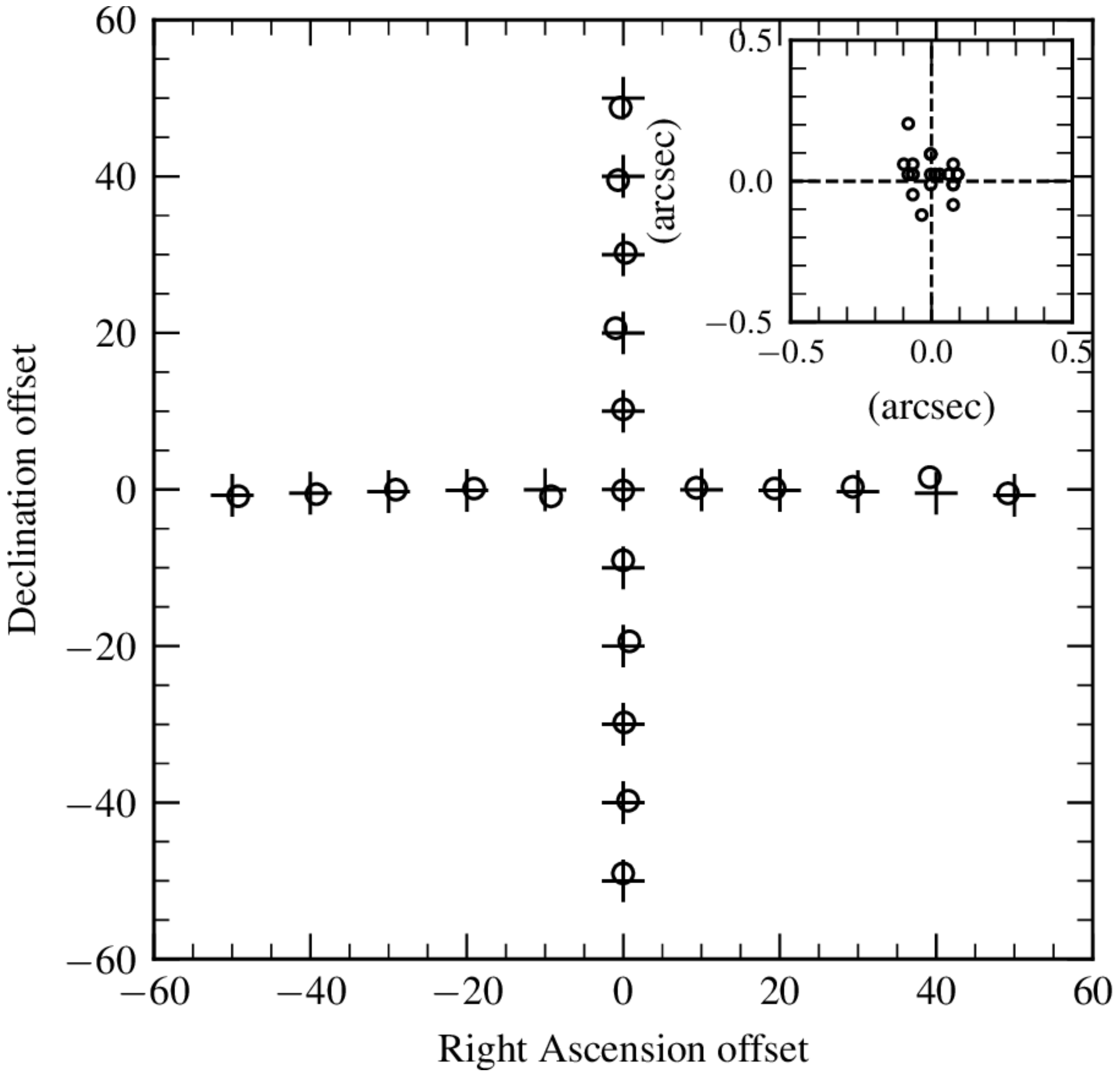
Date	Start Time UTC	τ_{Total} Hours	τ_{Target} Hours	N_{Ants}
2018 April 27	07:11	11.0	8.4	61
2018 June 30	23:00	16.2	12.6	60
2018 July 7	21:39	17.2	13.4	61
2018 July 16	21:37	8.0	6.0	61
2018 July 24	21:07	8.9	6.9	59
2018 July 25	21:01	9.0	7.6	58
2018 July 27	21:01	16.1	14.0	61
2018 July 28	20:51	16.2	14.1	60
2018 Oct 8	21:33	9.5	8.5	59
2018 Nov 4	14:37	16.2	14.2	62
2019 Jan 19	09:31	16.1	13.9	63
2019 Jan 20	09:41	10.8	9.2	63
Total		155.2	128.8	

Positional Accuracy

- Observe PKS1934-638 at 21 positions in the primary beam
- Indicative of errors in (u,v,w) coordinates from time or frequency scaling
- Mean offsets and standard deviations in R.A. and Dec. are:

$$\langle\Delta\alpha\rangle = 0''.001, \qquad \sigma_{\Delta\alpha} = 0''.11$$
$$\langle\Delta\delta\rangle = 0''.02, \qquad \sigma_{\Delta\delta} = 0''.06.$$

- Radial scaling is 0.00004 and implies:
  $\Delta\nu = -36 \pm 44$ (kHz)
  $= -0.17 \pm 0.21$ channels
  << 1 channel



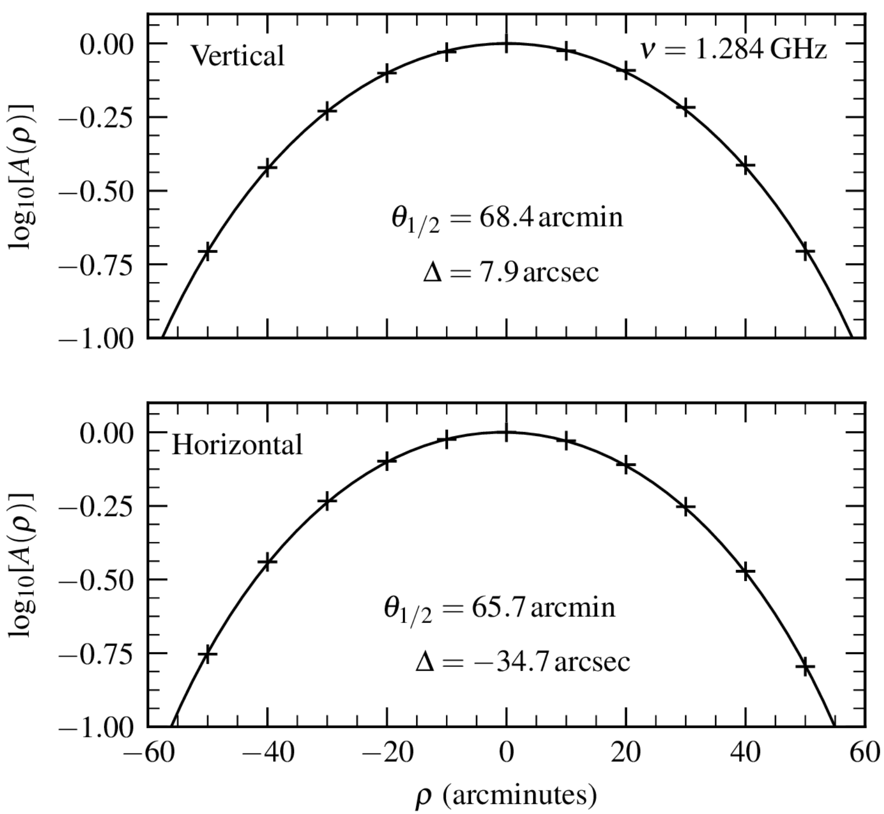
The Primary Beam

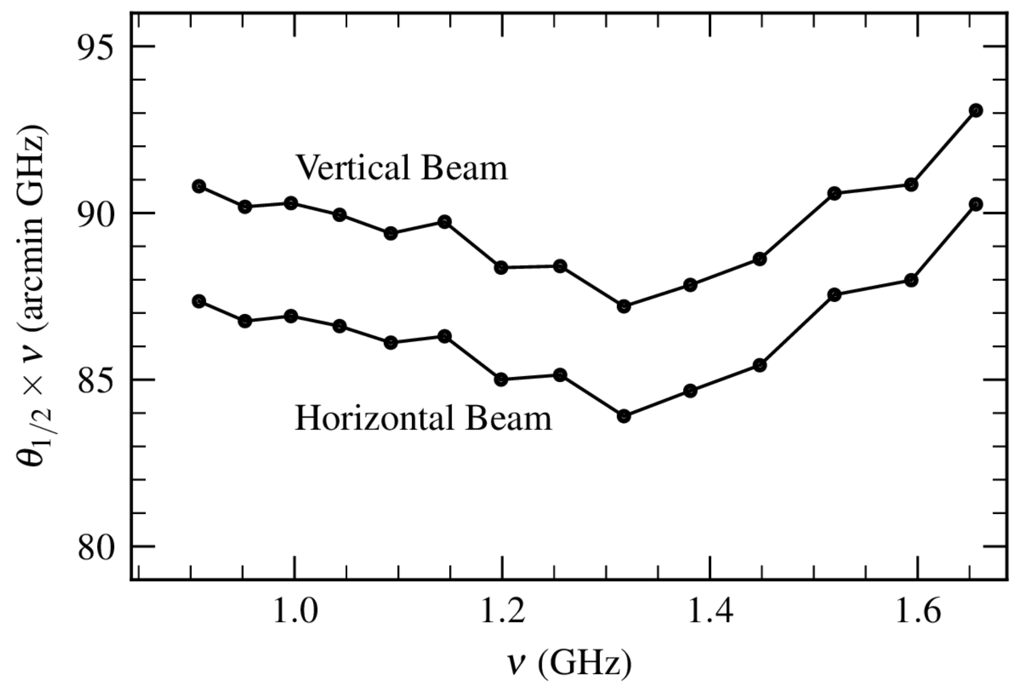
- Fit Jinc^2 pattern to attenuation of 1934-638
  - Fit pointing offset Δ and FWHM $\theta_{1/2}$
- $\theta_{1/2}$ x ν is within 3% constant in frequency
  - Increase at high frequency due to underillumination?

$$A(\rho/\theta_{1/2}) = \left[\frac{2J_1(\rho/\theta_{1/2})}{\rho/\theta_{1/2}}\right]^2$$

$$\theta_{1/2} = 90'.1 \pm 0'.1 \left(\frac{\nu}{\mathrm{GHz}}\right)^{-1} \quad \text{(Vertical)}$$

$$\theta_{1/2} = 86'.8 \pm 0'.2 \left(\frac{\nu}{\mathrm{GHz}}\right)^{-1} \quad \text{(Horizontal)}$$

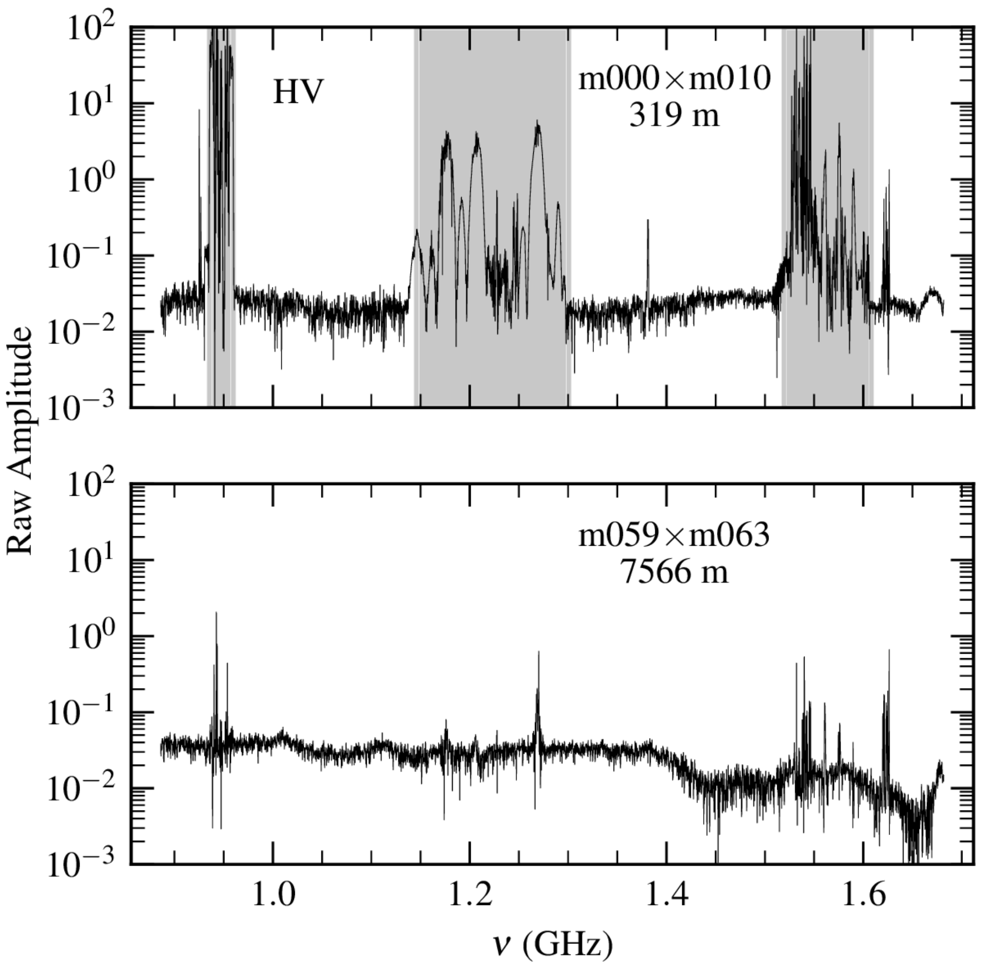




Calibration and Imaging

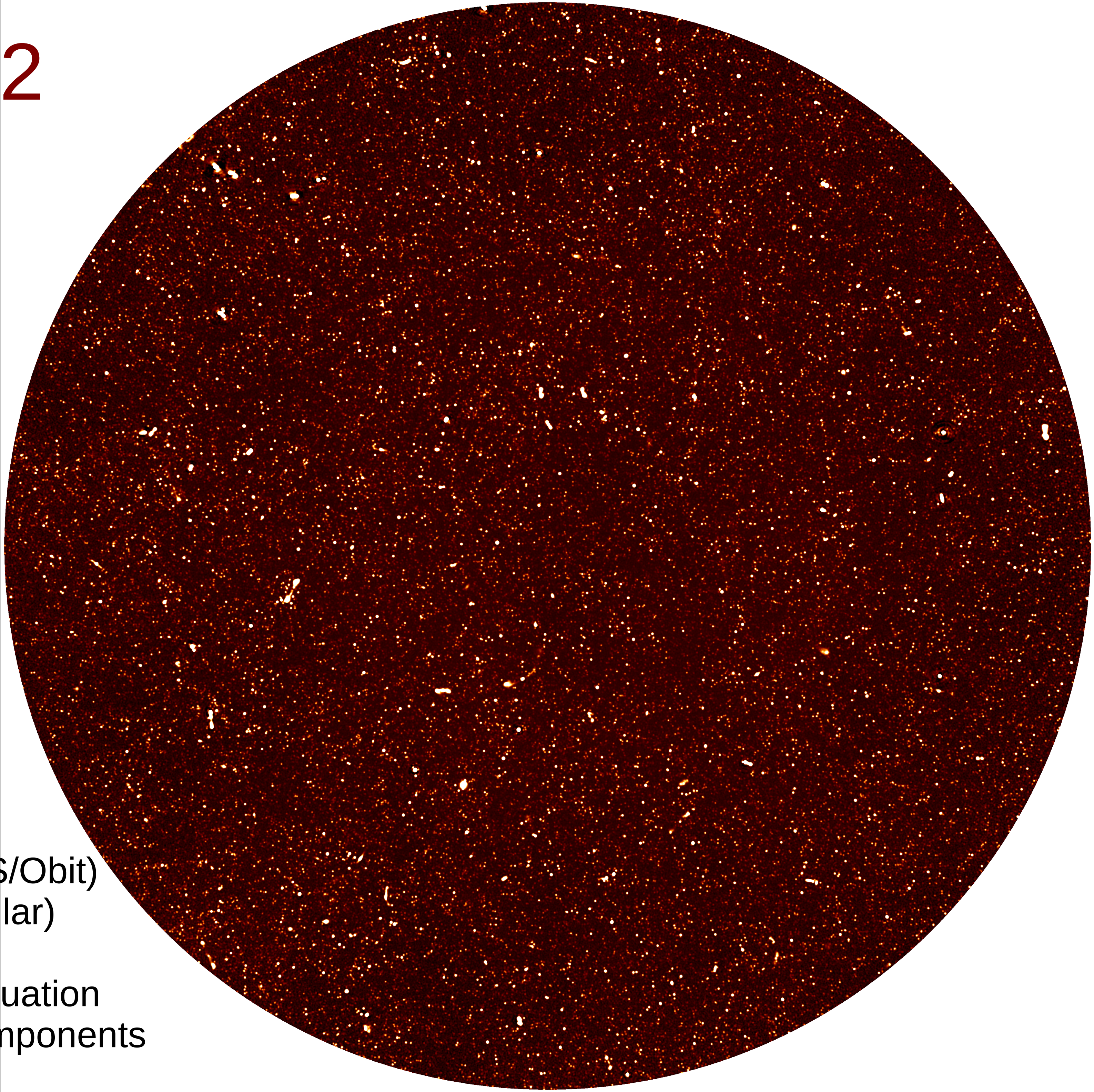
- Data were flagged/calibrated using a combination of Obit (for calibration) and MeerKAT software (for flagging, archive retrieval).
- Mask data on baselines shorter than 1000m (17% of the data), automatically flag the rest (35% of all data were flagged prior to imaging).
- Use a single observation as a model from which to ‘self’ calibrate the rest of the data and tighten astrometry over 9 months of observations.
- Joint deconvolution in 14 narrow ‘subbands’ with fractional bandwidth < 0.05
- Combine narrow subbands into wideband image with maximum SNR (α=-0.7):

$$\mathrm{SNR}^2 \propto \sum_{i=1}^{14} w_i (\nu_i^{\alpha}/\sigma_i)^2 \Bigg/ \sum_{i=1}^{14} w_i$$



Example average raw amplitude spectra from a 10 minute scan on PKS1934-638. Greyed regions show the RFI mask; 319m baseline (top), 7566m baseline (bottom).

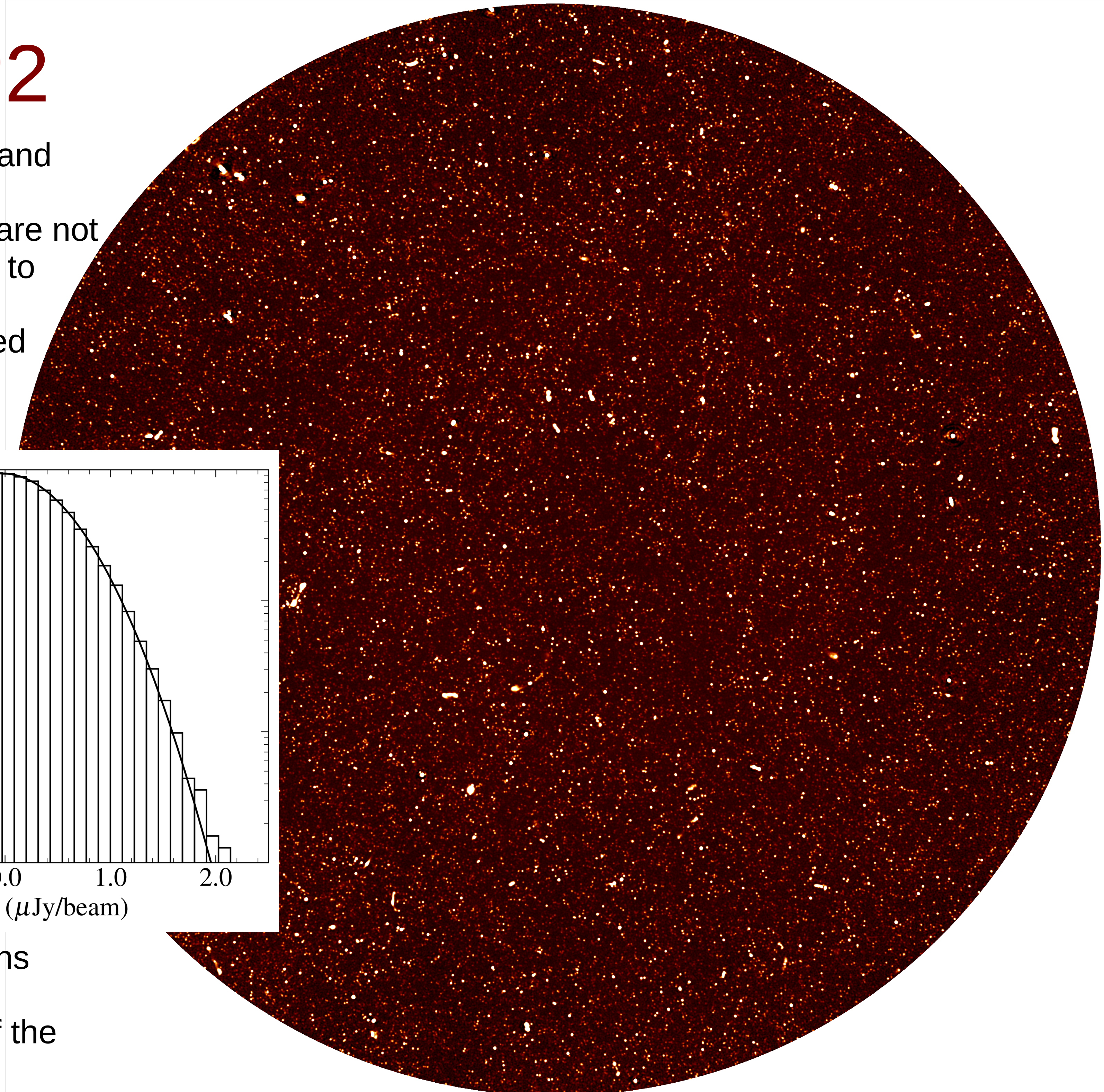
DEEP2

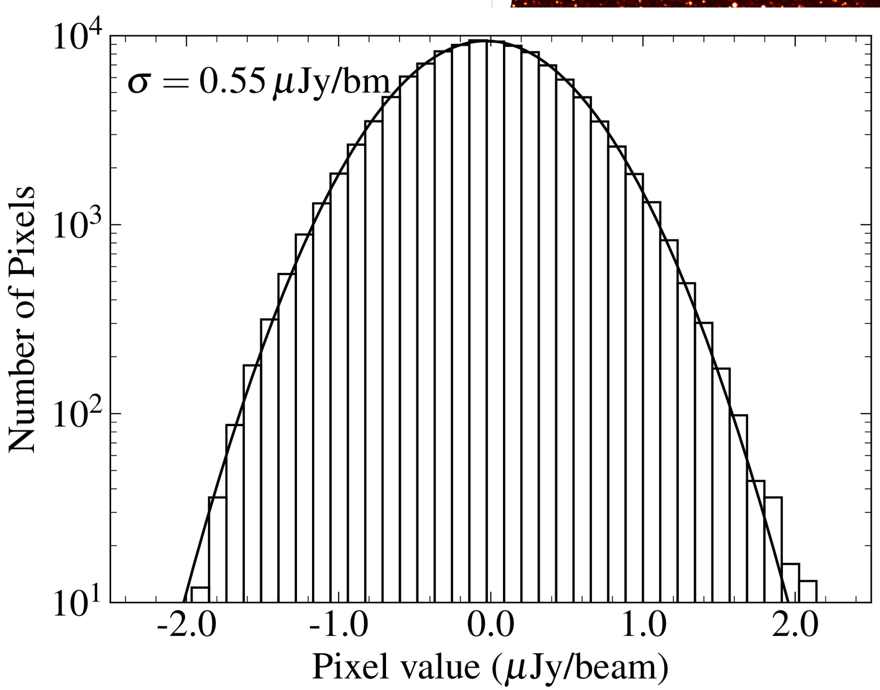


ROBUST: -1.3 (AIPS/Obit)
θ = 7.6 arcsec (circular)
Diameter ~1.6 deg.
to 25% PB attenuation
250,000 CLEAN components

DEEP2

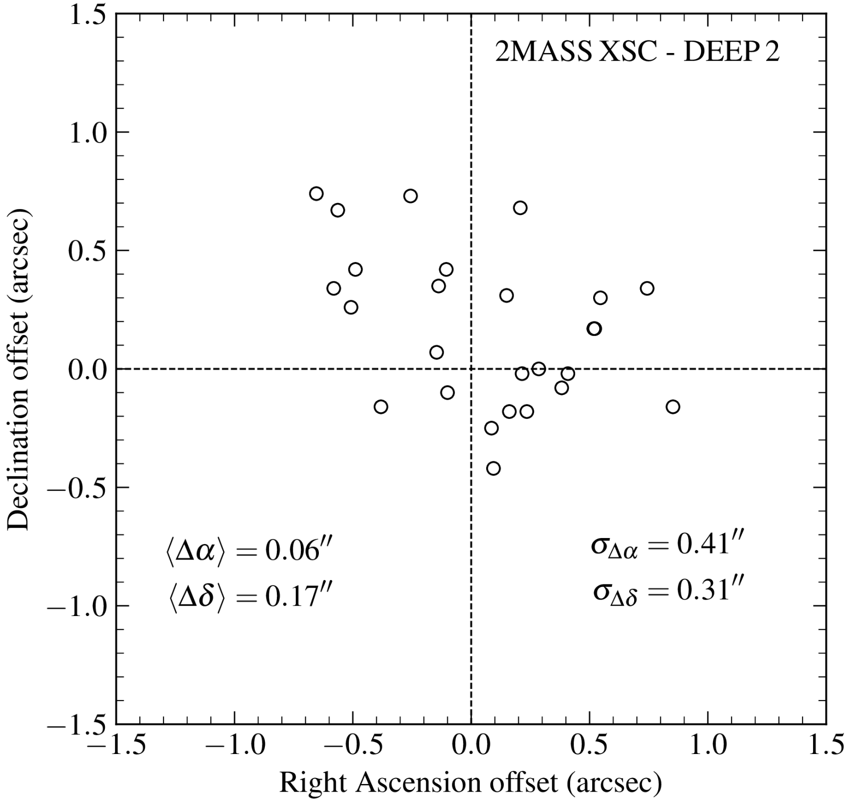
The most sensitive L-band image ever made?
Faint α = -0.7 sources are not seen at high frequency to an equivalent depth.
20,000 sources detected in one pointing ($10,000$ per deg^2).

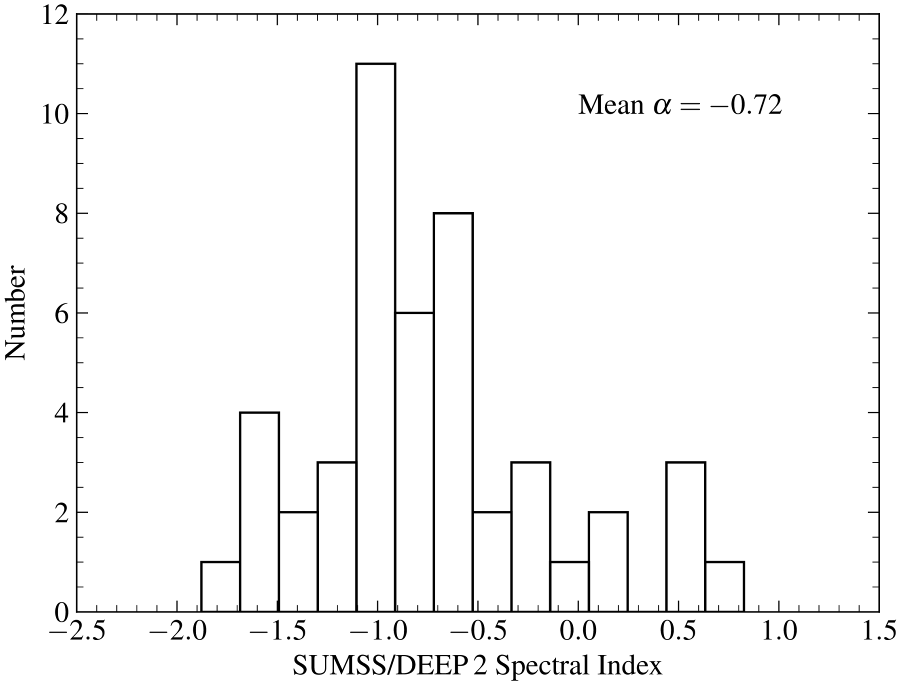




4 ‘source free’ regions with area ~150x150 pixels at the edge of the uncorrected image

DEEP 2 Position and Flux Density Accuracy





There is little ancillary data available but things line up nicely with what we have

MeerKAT Science Data Processor

Calibration is done in real time as observation progresses

Report showing results of calibration available in the archive immediately after observation.

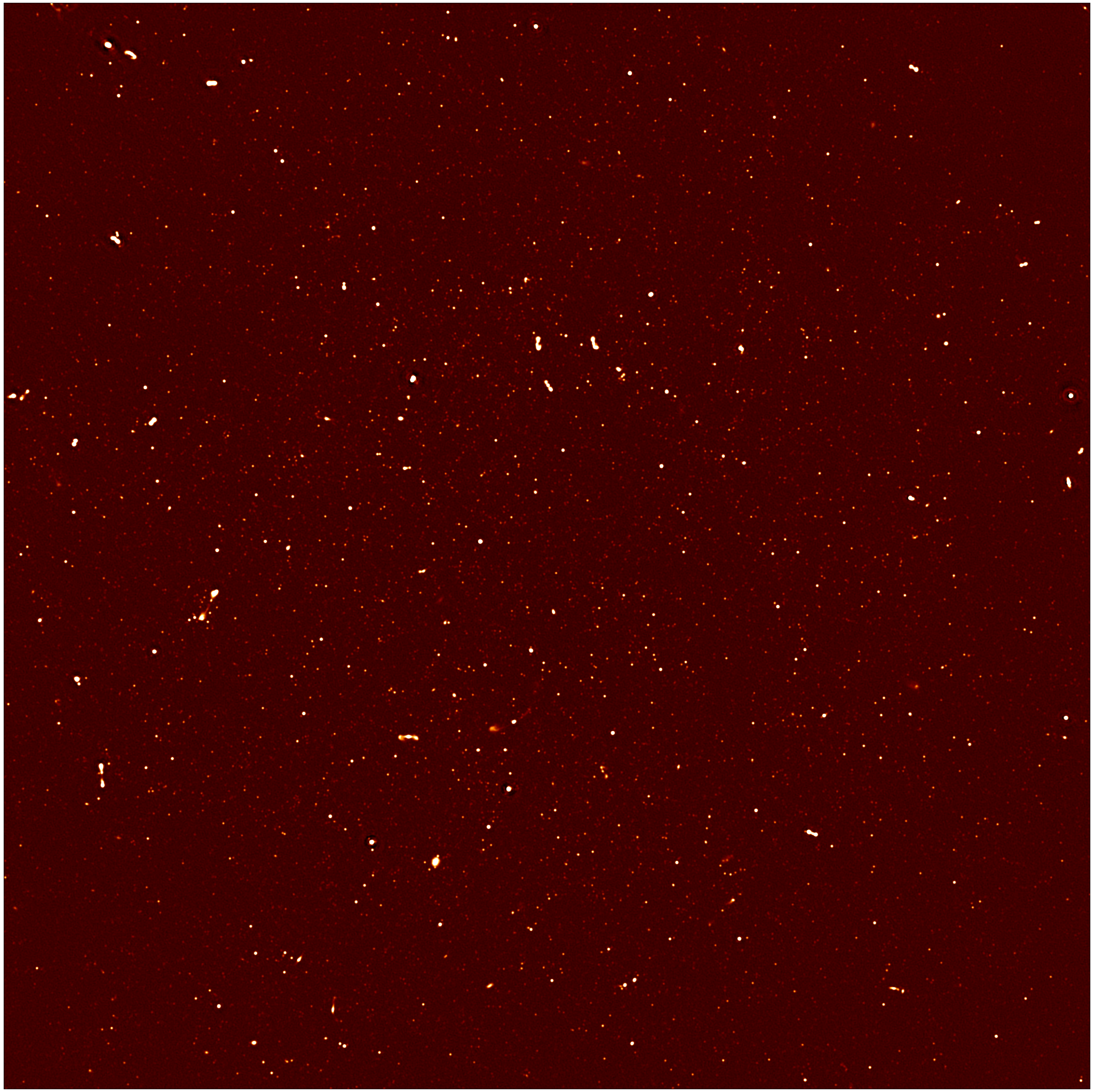
Automated imaging

Online calibration solutions can be applied as the data is read from the archive (‘applycal’)

Image on the right shows our first results from a test of the MeerKAT SDP pipeline on DEEP 2 data of July 2018.

Calibration / Self-calibration / Imaging within 6 hours of end of observation.

With the DEEP 2 field we can test our pipeline against combined ‘reference’ image.



And....

- Don't miss!
  - Jim Condon: "Confusion is a feature not a bug"
  - Allison Matthews: "The star-formation history of the Universe"
  - Bill Cotton: "Source Finding in Crowded Fields"
  - All exploiting DEEP 2 data.
  - Coming this Thursday to a lecture theatre near you!