CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Australian National University

Gerfeest
EoR & MWA
Data Reduction

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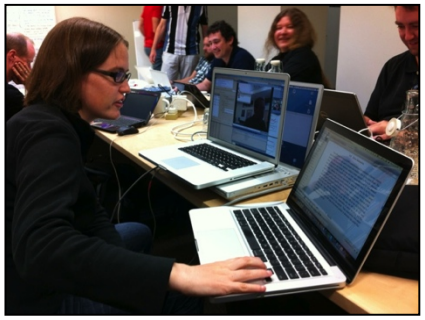
ANU Mt Stromlo Observatory / CAASTRO

www.caastro.org



Swinburne; CSIRO / Swinburne; NASA / ESA

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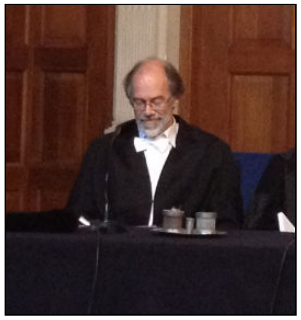

The MWA EoR project

- **Aim:**
  - 9 sigma detection after 1.5 years (~900 hours observing, Beardsley et al., 2013)
- **Status:**
  - Half a year (35 observing nights, ~300 h) has been completed
  - Data mostly unprocessed but quality validated
  - Several processing pipelines available, being tested & compared.
- **Project members:** Adam Beardsley, Gianni Bernardi, Judd Bowman, Frank Briggs, Josh Dillon, Aaron Ewall-Wice, Lu Feng, Steve Furlanetto, Bryan Gaensler, Robert Goeke, Lincoln Greenhill, Bryna Hazelton, Lars Herquist, Jackie Hewitt, Danny Jacobs, Emil Lenc, Al Levine, Adrian Lu, Avi Loeb, Colin Lonsdale, Ben McKinley, Daniel Mitchell, Miguel Morales, Ed Morgan, Abraham Nebe, André Offringa, Sourabh Paul, Bart Pindor, Pietro Procopio, Ron Rimillard, Jenny Riding, Shiv Sethi, Udaya Shankar, Ravi Subrahmanyan, Ian Sullivan, Max Tegmark, Nithyanandan Thyagarajan, Steven Tingay, Cath Trott, Randall Wayth, Rachel Webster, Chris Williams, Stuart Wyithe.

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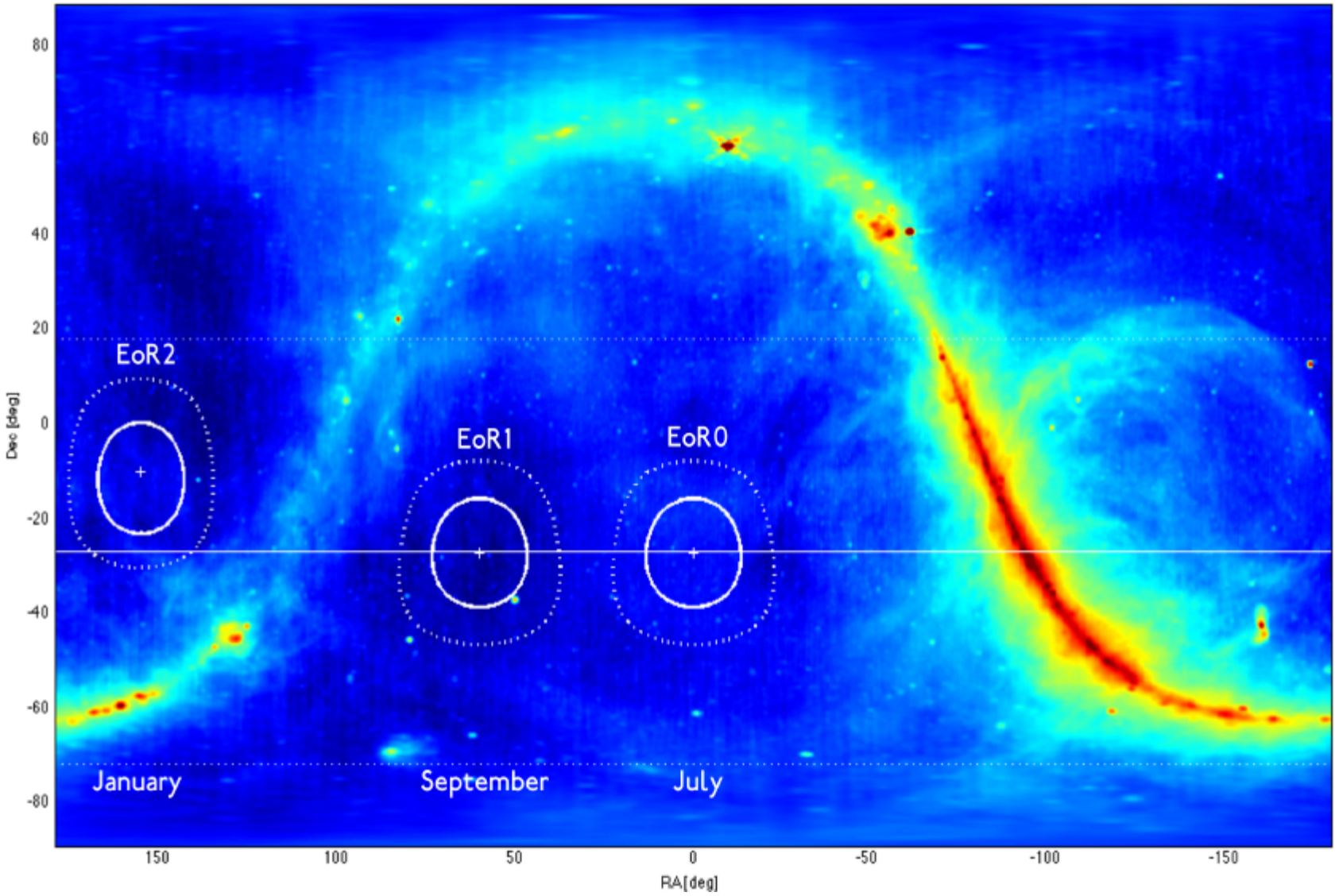
The MWA EoR project



MWA EoR observations

Several pipelines available:

- Real-Time System (RTS)
  - Performs full-Jones calibration, peeling, imaging & beam correction
  - GPU based “work horse”
- Fast Holographic Deconvolution (FHD, I. Sullivan et al., 2012)
- “Modular” pipeline, combining existing tasks
  - Verification pipeline
  - Also being used to measure extra-galactic foregrounds

- For “final” power spectra: see Cath Trott's talk on Thursday

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EoR modular pipeline

The modular pipeline has these steps:

- Pre-processing pipeline “Cotter”: flagging using AOFlagger, rephasing, calculate uvws, correct pass-bands, averaging, convert to MS.
- Calibration using Casa or custom full-polarization tool
- Optionally peeling and/or subtraction
- Imaging & deconvolution using Casa or WSClean
- Correct beam per snapshot
- (measure spectra, ...)

- Started by using Casa's tasks
- Over time, more and more tools were rewritten & improved

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The MWA EoR0 field

1 h data, 200 s subtracted, 7 mJy noise, few h on 10 nodes

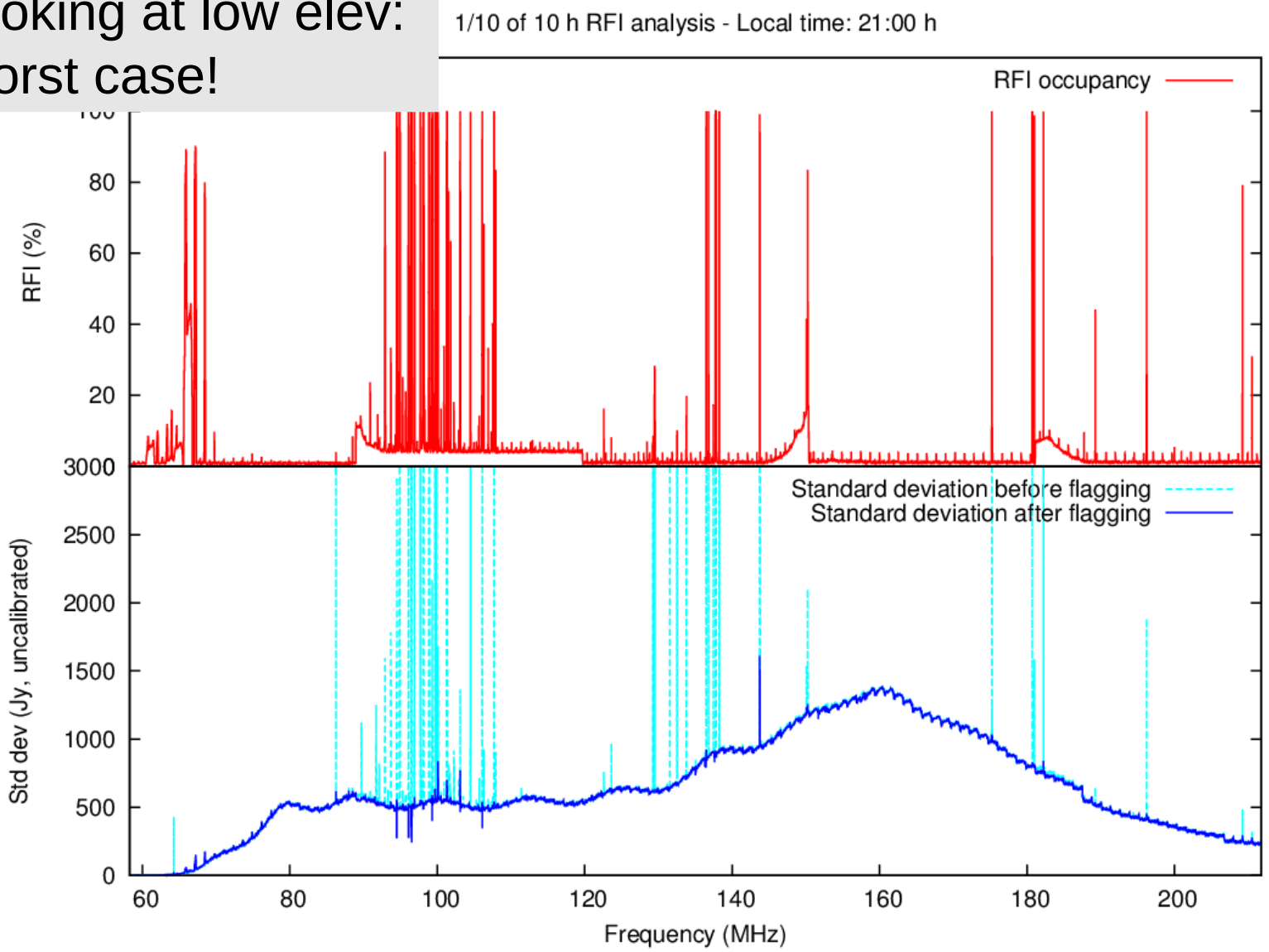
EoR modular pipeline

Pre-processing pipeline “Cotter”: flagging using AOFlagger, rephasing, calculate uvws, correct pass-bands, averaging, convert to MS.

- Can be compared to LOFAR's NDPPP
- Sees all data at highest res (400MB/s): performance important, technologically challenging because of memory constraints
- Can output Casa measurement sets, UVFits files and flag files for input into the RTS
- Runs about 5x slower than real time on one node, full 30 MHz band-width.

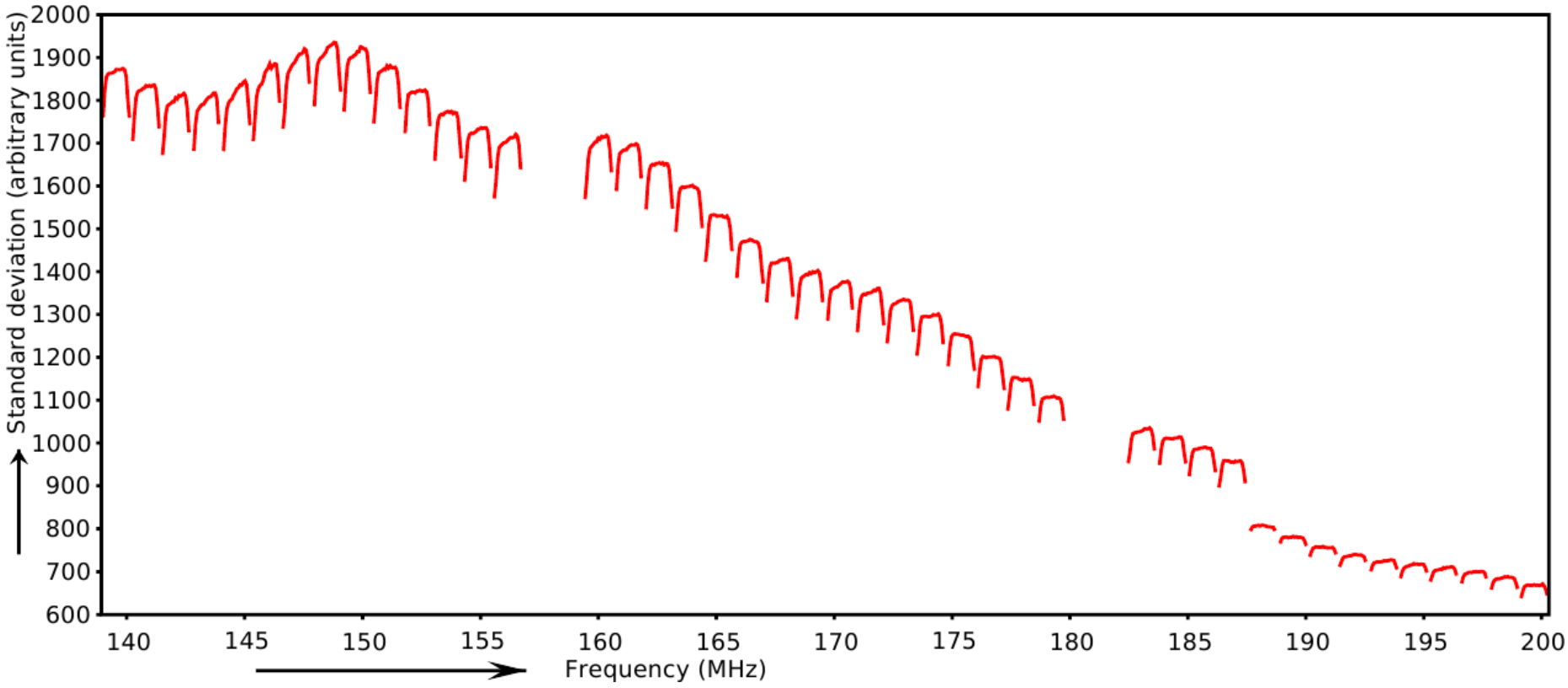
Some RFI results

Looking at low elev:
Worst case!



Some RFI results

- At higher elevation, almost no RFI observed
- EoR0 observations see ~1% RFI, which is accurately flagged:



Calibration

- Calibration:
  - Can use Casa, but Casa can't do proper full-polarization calibration
  - Using a simple calibration implementation based on Mitchel's RTS calibration to minimize:

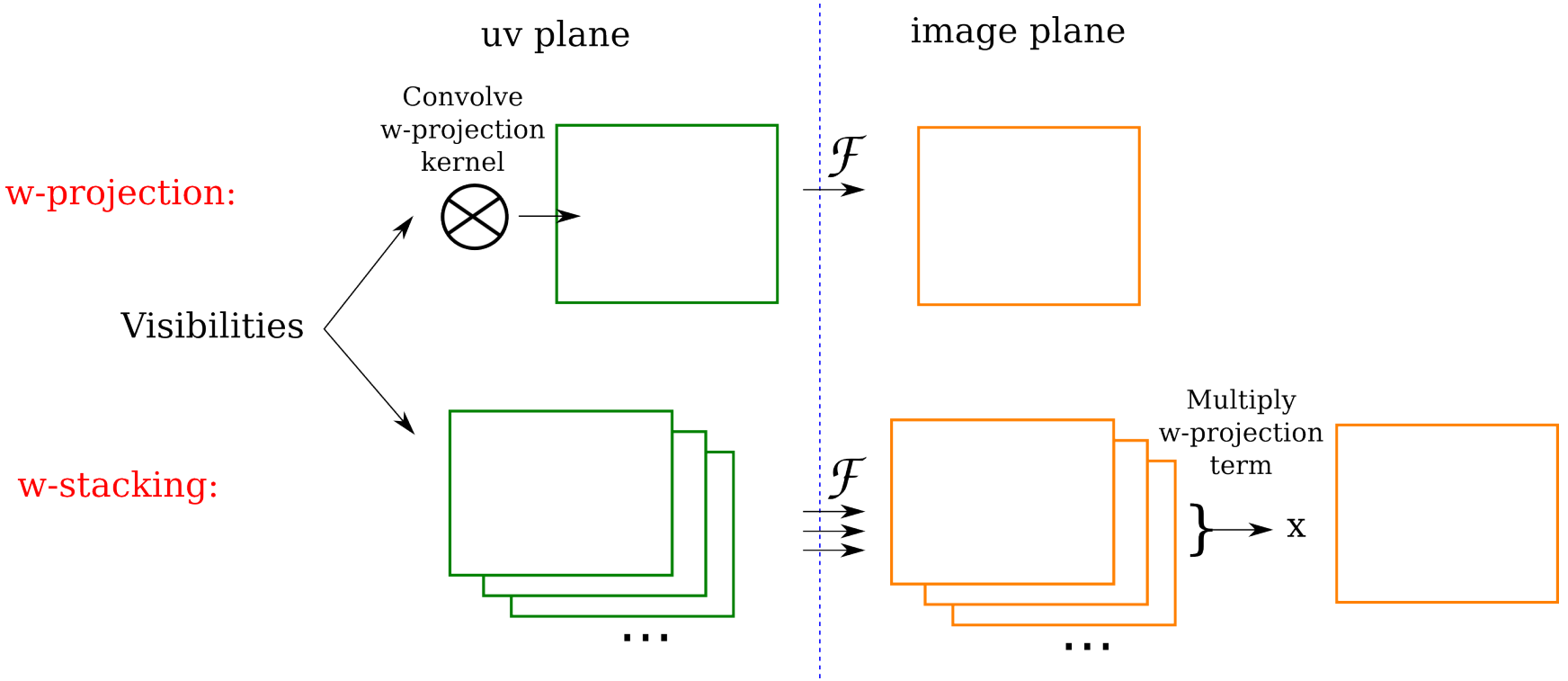
$$\sum_{j=1}^{N_a} \sum_{k,k\neq j}^{N_a} \left\| \mathbf{V}^{(K)}_{jk,c,f_0} - \mathbf{J}_{j,c,f_0} \, \widehat{\mathbf{P}}_{c,f_0} \, \mathbf{J}^{\dagger}_{k,c,f_0} \right\|^2_F$$

  - Implemented in C++, multi-threaded
  - Quite fast: one node can do a single direction per channel in ~real-time for MWA
  - Can be used for self-cal, peeling, clustered peeling
  - “Mitchcal” (Mitchel et al., 2008)

Wide-field Imaging

- Imaging with large w-terms is computationally very expensive
- Larger problem at low elevation:
  - MWA imaging with Casa w-projection, at ZA > 45 of 2 min obs can take 24 h (using one fast node with newest multi-threaded Casa clean)
- Faster algorithm required
- Many “SKA” algorithms suggested in T. J. Cornwell and M. A. Voronkov and B. Humphreys (2012)
- Decided to use a hybrid between w-stacking & snapshot imaging

Widefield Imaging



Widefield Imaging

- Result: a new imager, “WSClean”
- With equal nr. w-projection planes/layers, the stacking algorithm is equal or more accurate compared to w-projection
- Clean algorithm, including CS-like clean (goes back to visibilities)
- Multithreaded over gridding, FT-ing and cleaning

- Resulting implementation is in almost all MWA cases 10 x faster
  → Both at low and high zenith angles
- All operations are done with double precision (Casa uses single prec.)
- Can handle large images
- Also preliminary tested on GMRT observations

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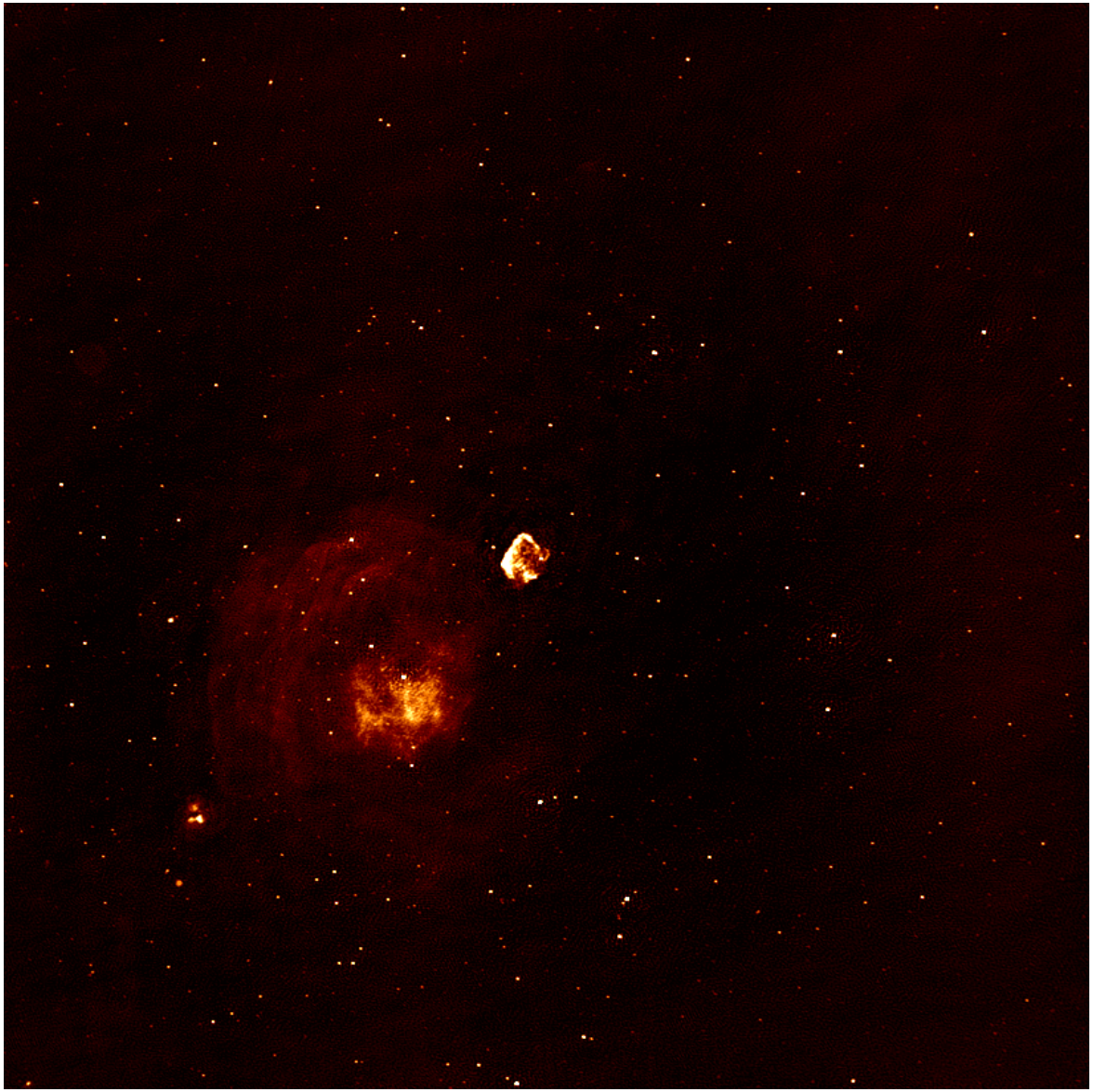
WSClean results



MWA 128T
~1 h of data
Imaged & jointly deconvolved with WSClean

Imaging processing time:
~3 h

WSClean results Fornax A

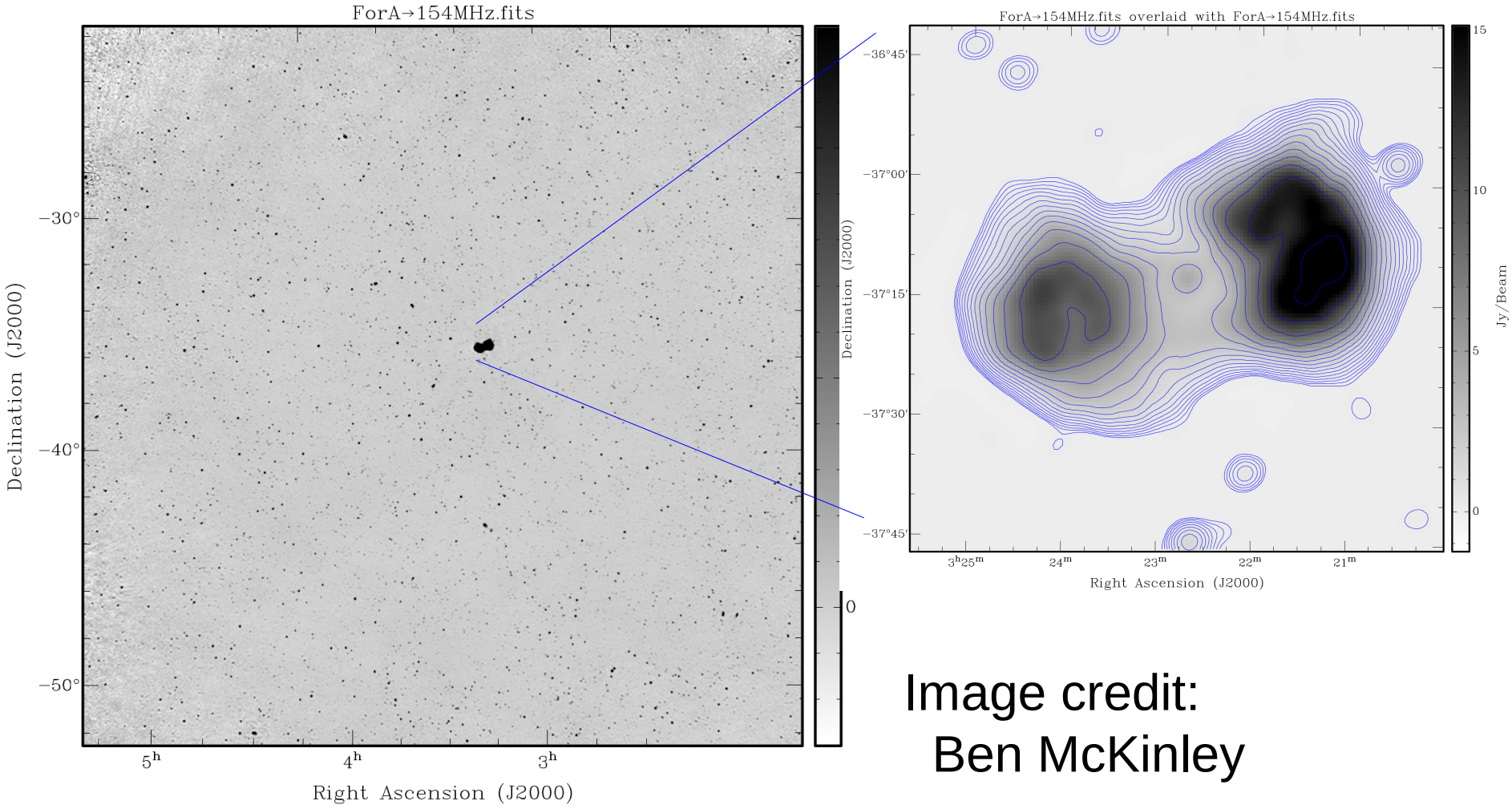


Image credit:
Ben McKinley

WSClean

- Speed still depending on size of w-term (& thus elevation)
- Full-sky imaging best done by rephasing to “minimal w-term direction” (directional orthogonal to best fitted antenna plane)
- MWA data are stored in 2-5 minute “snapshots”
  - → Hybrid between w-stacking & w-snapshot (Cornwell et al. 2012)
  - → No regridding required in image plane
- Timings: (using one heavy node)
  - 10k x 10k dirty image for 2 min obs takes a few minutes
  - 10k x 10k fully CS cleaned image ~ 35 minutes

WSClean full-sky image

GLEAM data

Full-sky image with WSClean

(Calibrated by Natasha)

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WSClean

- Exact speed benefit varies per situation and might be different for different telescopes
- Article in preparation to show more situations besides MWA MFS
- Source code will be published together with the article

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Questions?