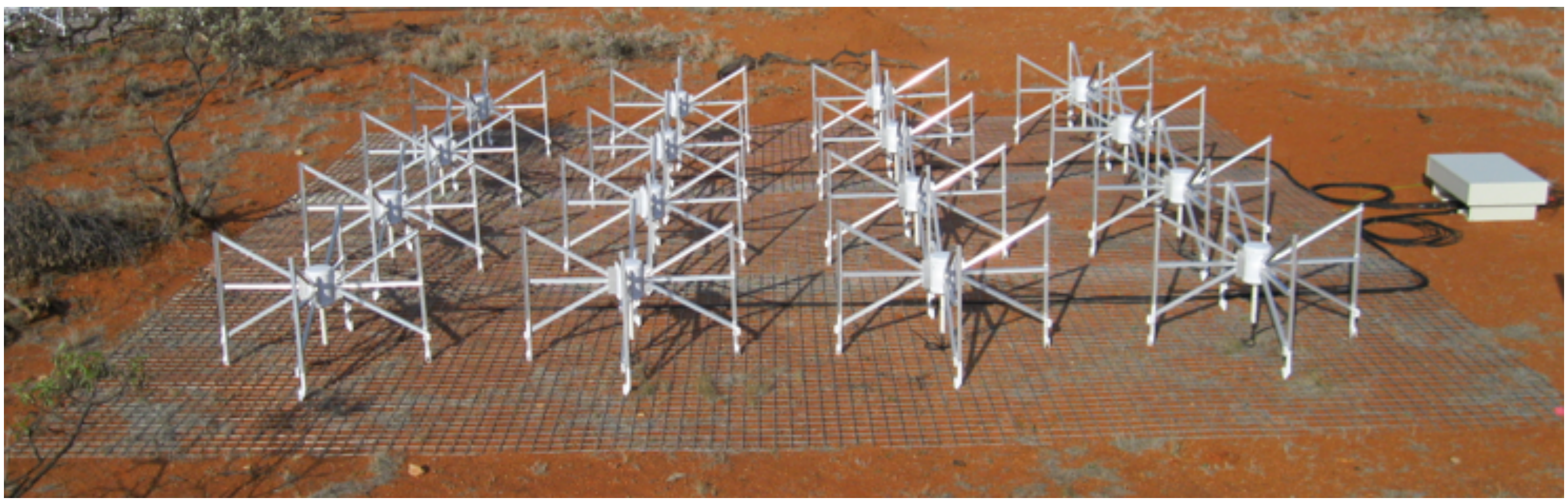
Murchison Widefield Array



Randall Wayth

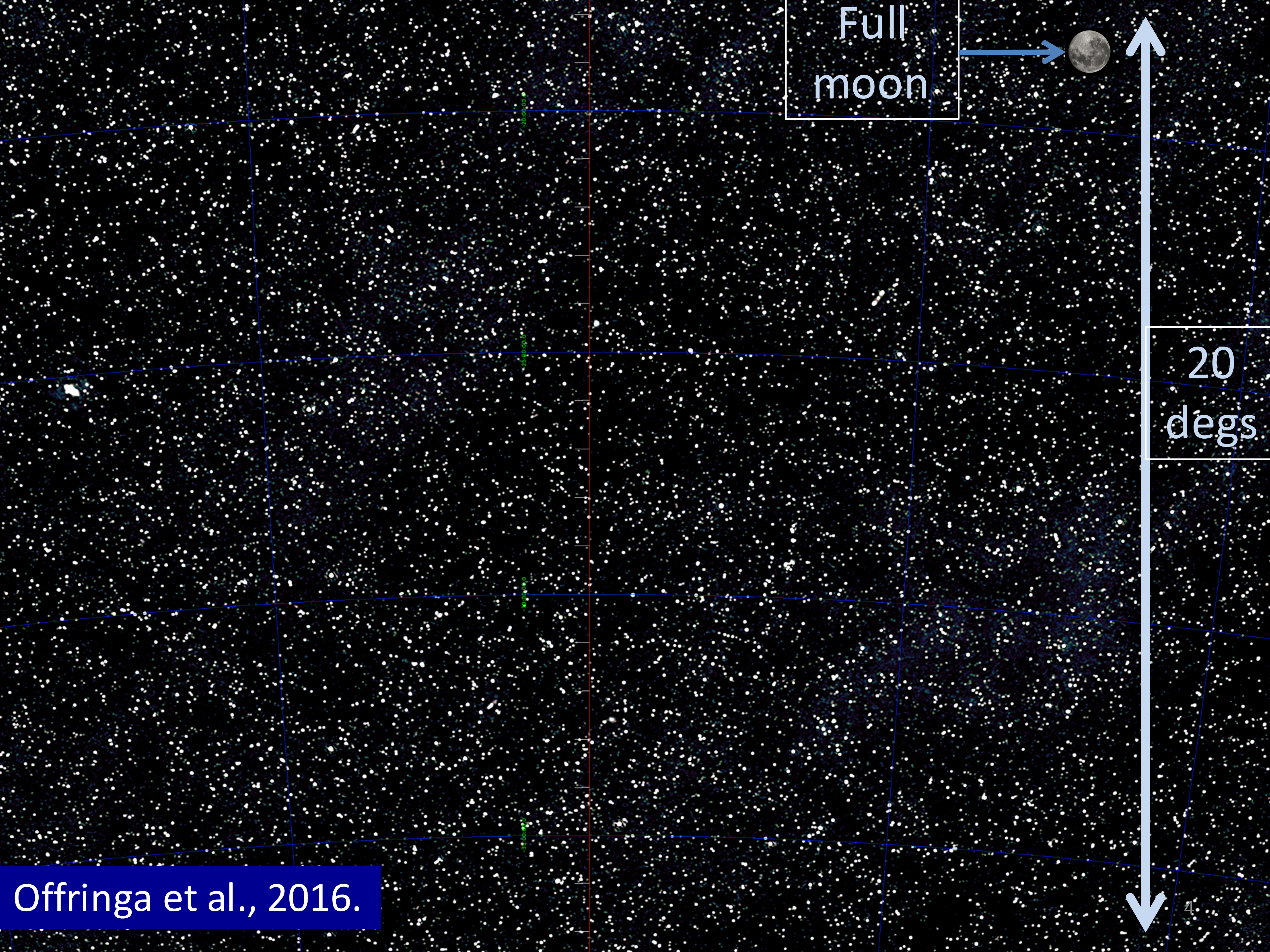
ICRAR – Curtin University

MWA: The SKA Low precursor

Current MWA: 128 tile system

- Antenna tiles: 128
- Operating frequency: 70-300 MHz
- Array diameter: 3 km
- Processed bandwidth: 30.72 MHz / 10 kHz
- Field of view: 30 degs @ 150 MHz

- Many small antennas -> huge field-of-view and excellent image fidelity
- 2016-2018: MWA phase 2 upgrade. Doubles number of antennas and array diameter

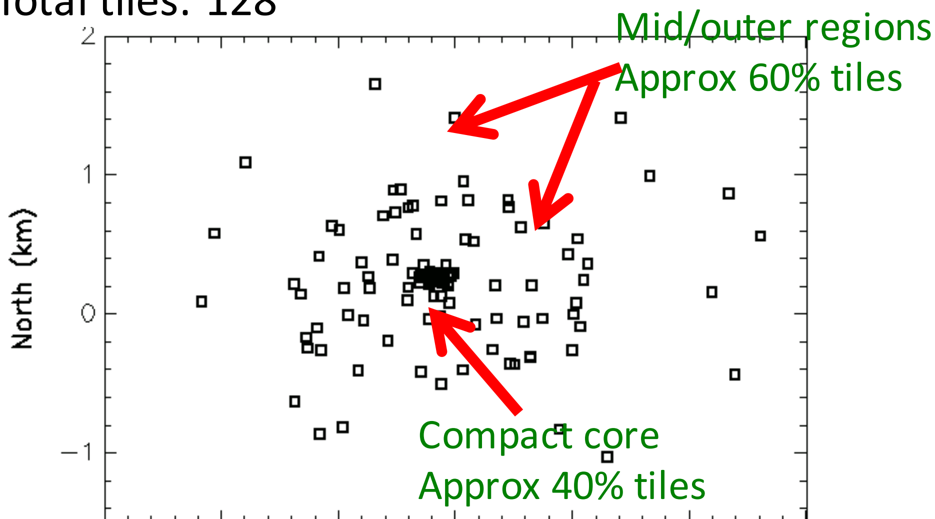

Full moon
20 degs
Offringa et al., 2016.

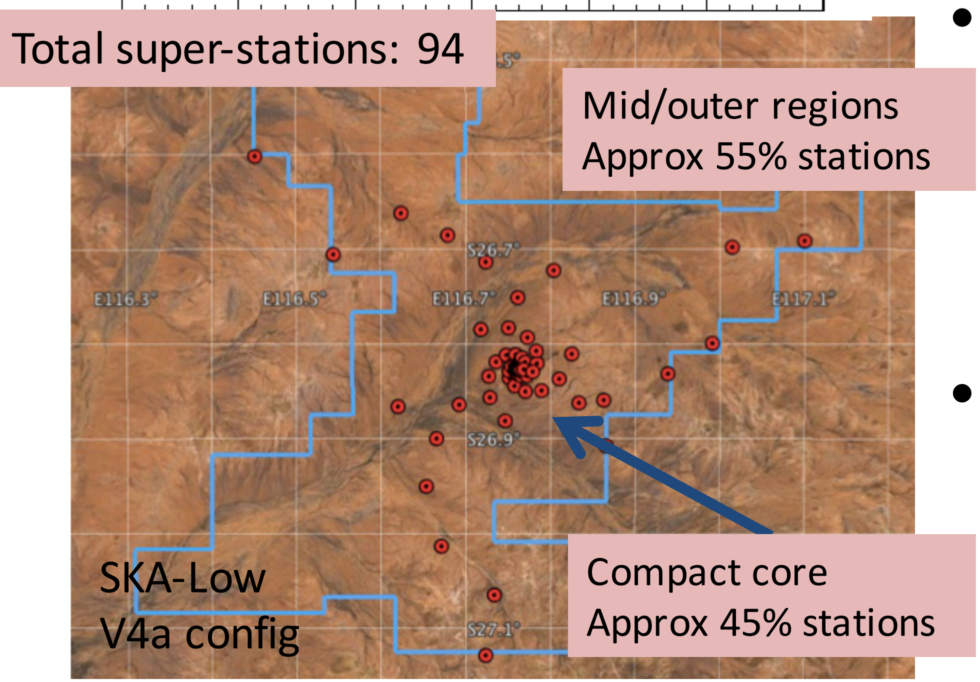
MWA -> SKA Low

- Key science
- Location
- Signal processing, calibration & imaging challenge
- Hosting and integrating SKA Low prototypes
- Training the next generation of radio astronomers
- Local Industry
- MWA phase 3

MWA: The SKA-Low precursor

Total tiles: 128



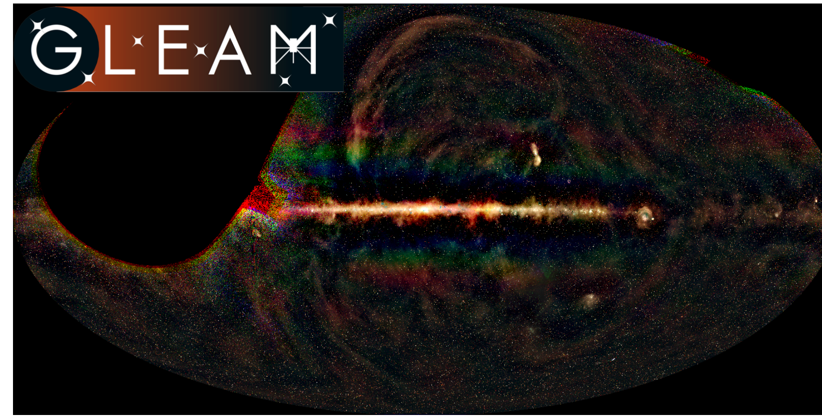


- MWA operating frequency & location same as SKA-Low
- Density distribution of antennas (core vs long baseline) very similar
- Scale of calibration/imaging problem (determined by station diameter / array diameter) is similar
- All MWA knowledge and experience is relevant to SKA-Low

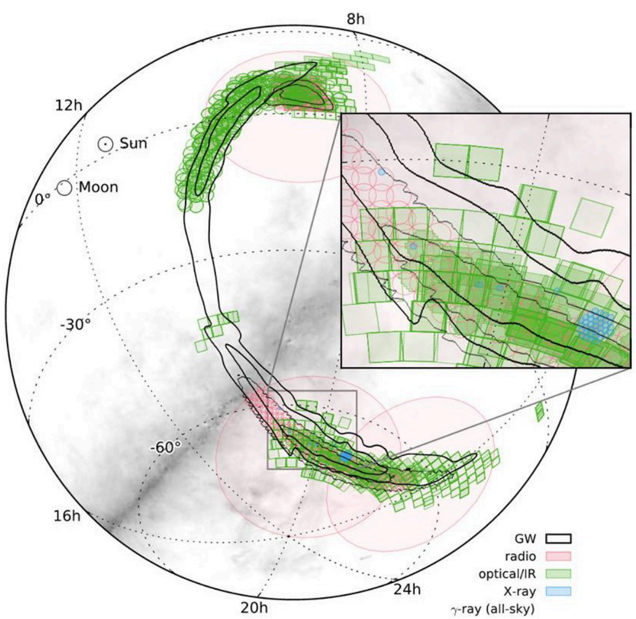
MWA Key science

Bowman et al, 2013.

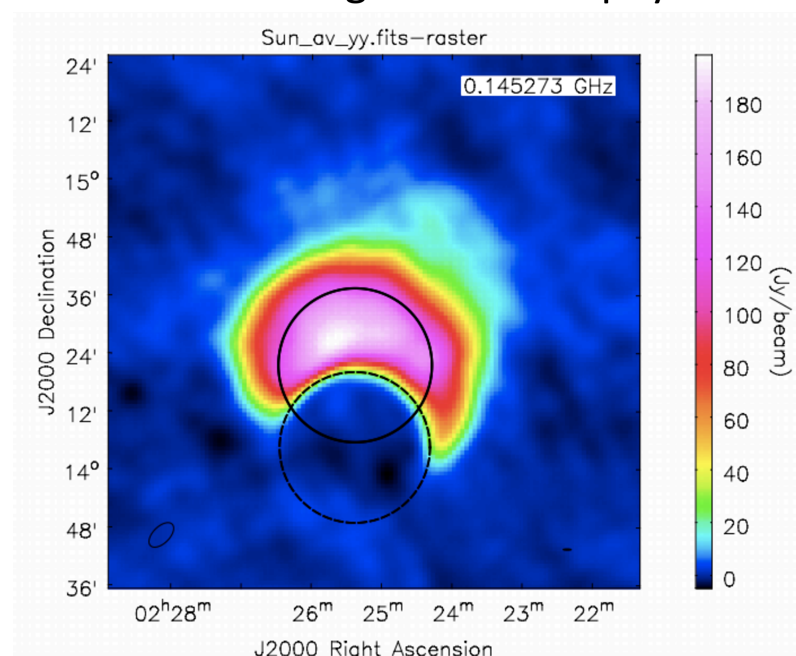
The Epoch of Reionisation



Galactic & extragalactic astrophysics

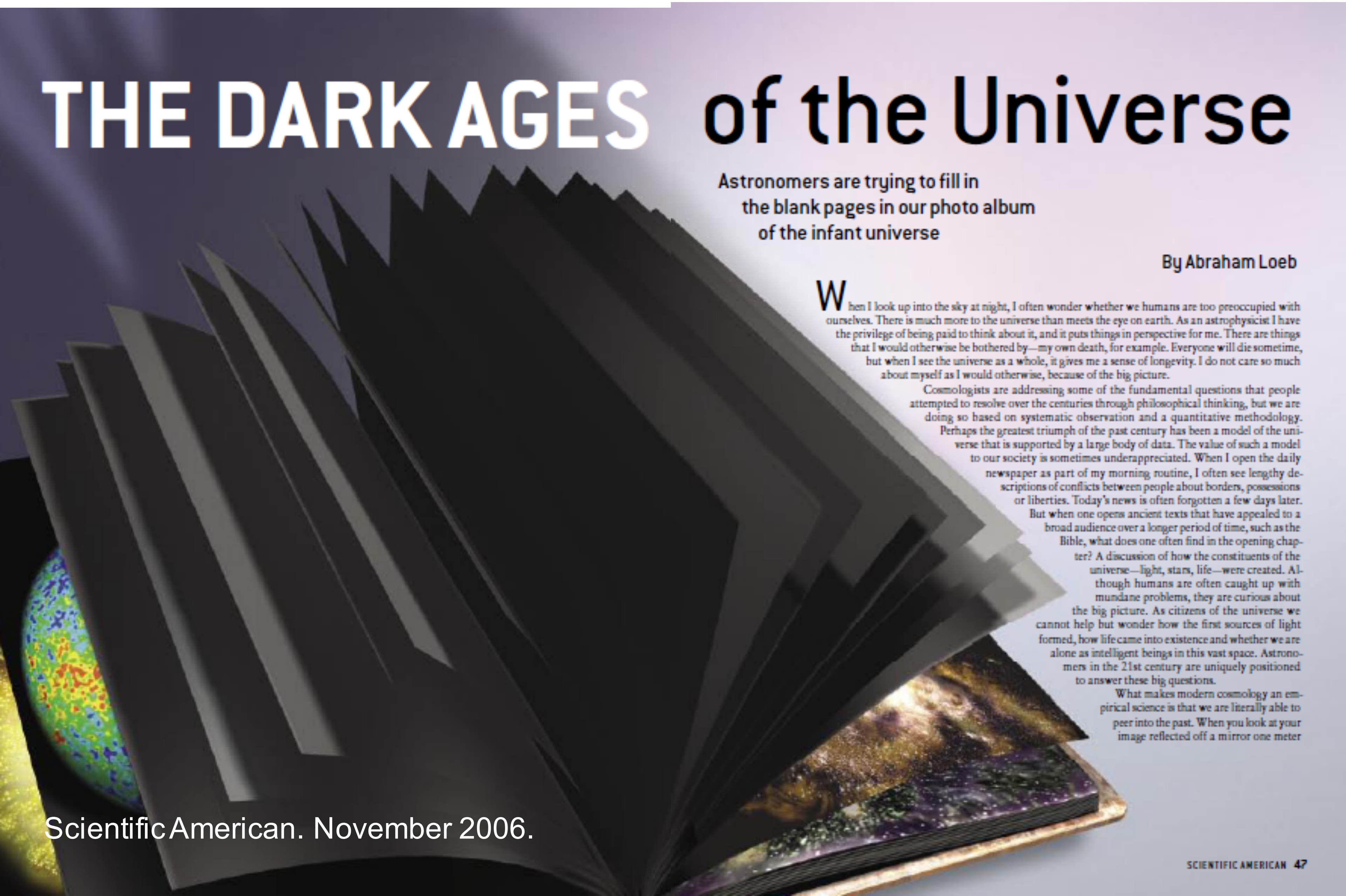


Transient & variable universe



Solar & heliospheric science

Key Science – Epoch of Reionisation



THE DARK AGES of the Universe

Astronomers are trying to fill in the blank pages in our photo album of the infant universe

By Abraham Loeb

When I look up into the sky at night, I often wonder whether we humans are too preoccupied with ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I have the privilege of being paid to think about it, and it puts things in perspective for me. There are things that I would otherwise be bothered by—my own death, for example. Everyone will die sometime, but when I see the universe as a whole, it gives me a sense of longevity. I do not care so much about myself as I would otherwise, because of the big picture.

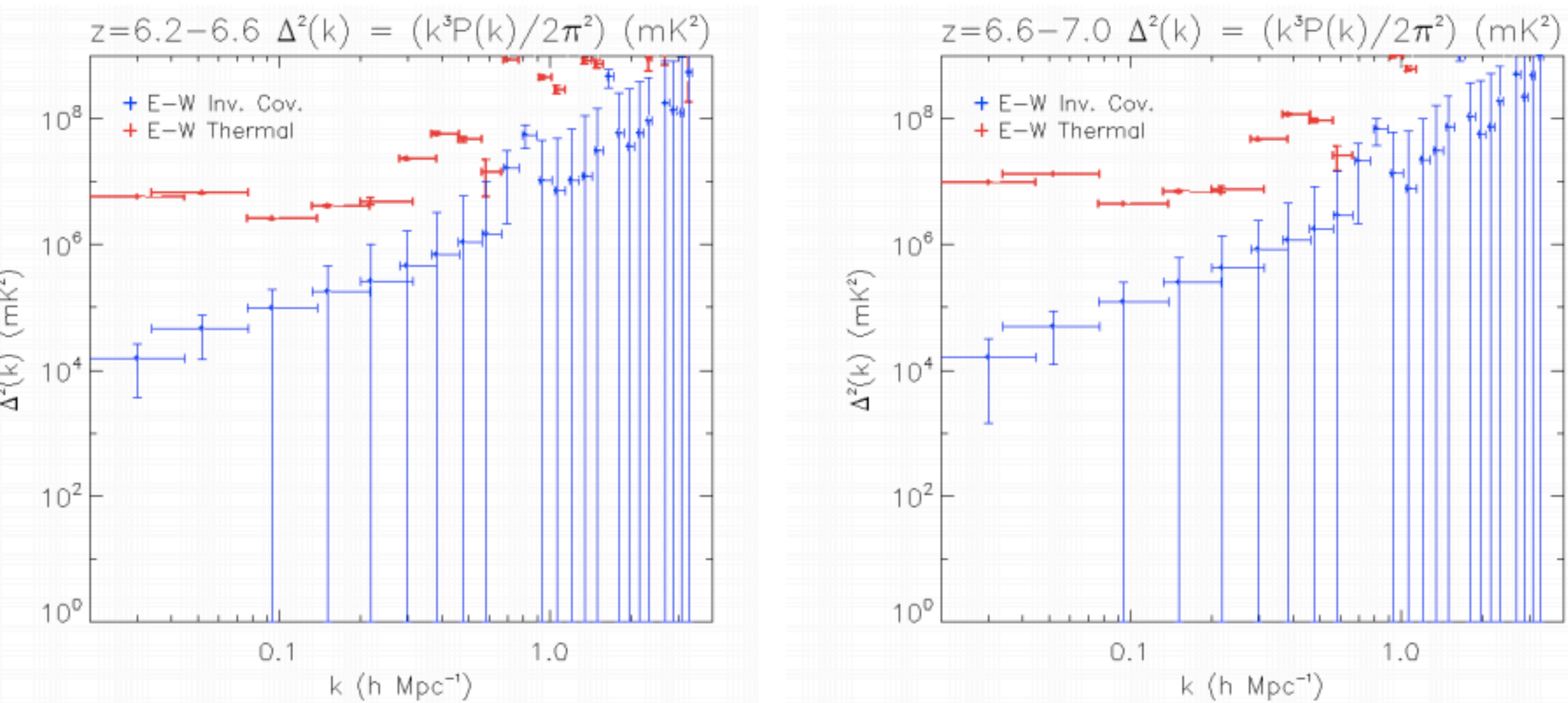
Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observation and a quantitative methodology. Perhaps the greatest triumph of the past century has been a model of the universe that is supported by a large body of data. The value of such a model to our society is sometimes underappreciated. When I open the daily newspaper as part of my morning routine, I often see lengthy descriptions of conflicts between people about borders, possessions or liberties. Today's news is often forgotten a few days later. But when one opens ancient texts that have appealed to a broad audience over a longer period of time, such as the Bible, what does one often find in the opening chapter? A discussion of how the constituents of the universe—light, stars, life—were created. Although humans are often caught up with mundane problems, they are curious about the big picture. As citizens of the universe we cannot help but wonder how the first sources of light formed, how life came into existence and whether we are alone as intelligent beings in this vast space. Astronomers in the 21st century are uniquely positioned to answer these big questions.

What makes modern cosmology an empirical science is that we are literally able to peer into the past. When you look at your image reflected off a mirror one meter

Scientific American. November 2006.

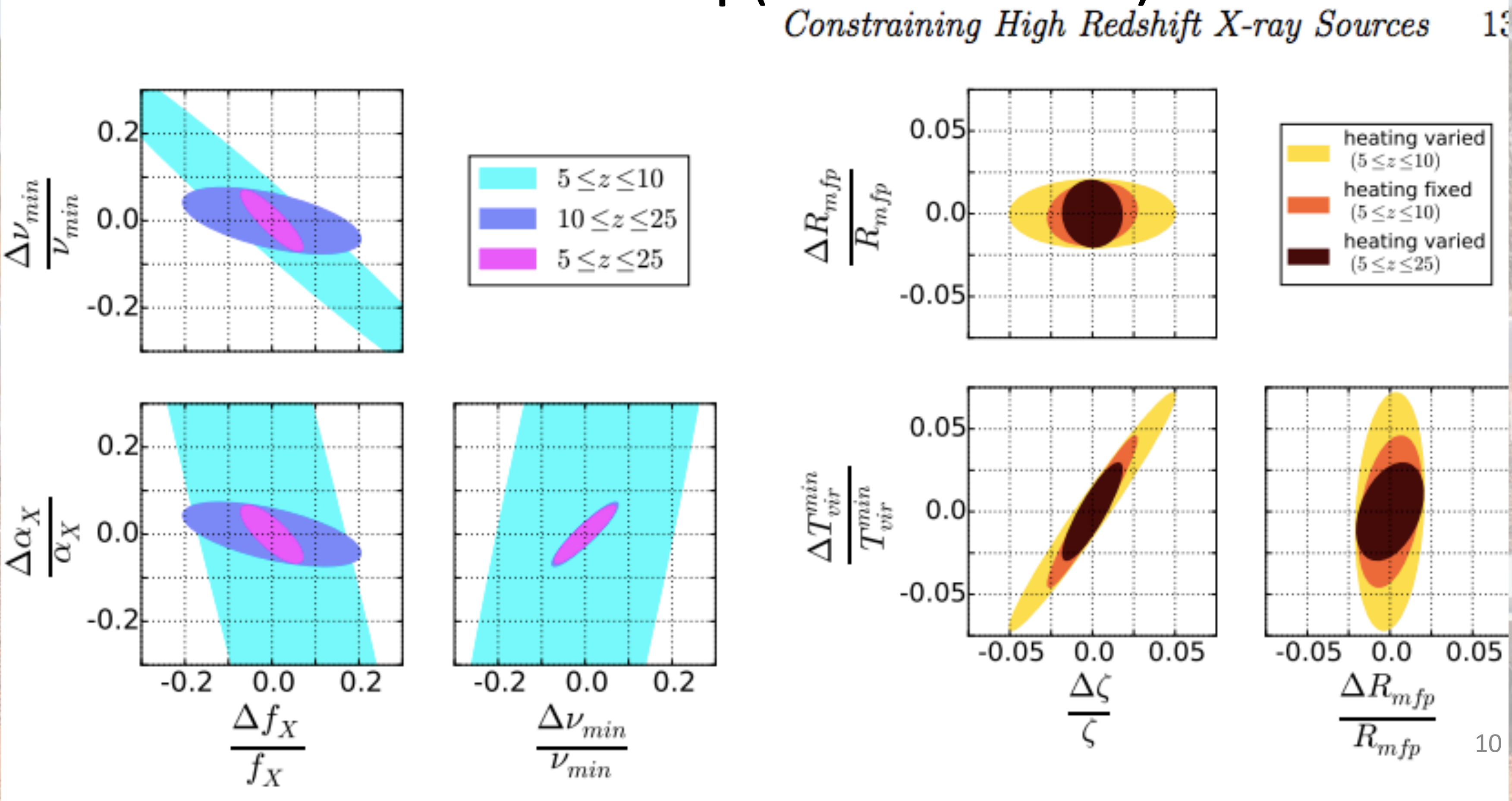
MWA EoR: current status

- Trott et al. 2016: CHIPS (one of two pipelines)



MWA EoR: current status

- Trott et al. 2016: CHIPS (one of two pipelines)
- Ewall-wice et al 2016: first x-ray heating epoch results from low freq (70-100 MHz) data



MWA EoR: current status

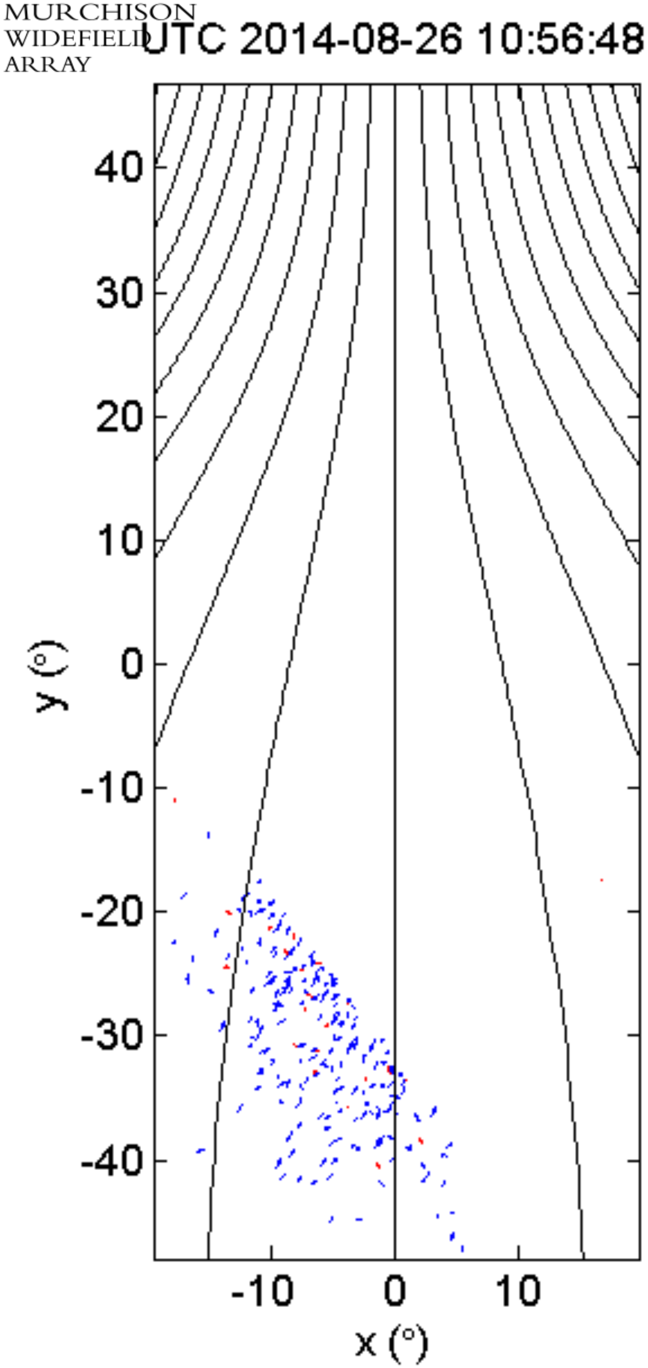
- Trott et al. 2016: CHIPS (one of two pipelines)
- Ewall-wice et al 2016: first x-ray heating epoch results

Also:

- Jacobs et al.: (submitted) (full MWA dual-pipeline overview paper)
- Beardsley et al (in prep): 100 night results

MWA EoR: spinoffs

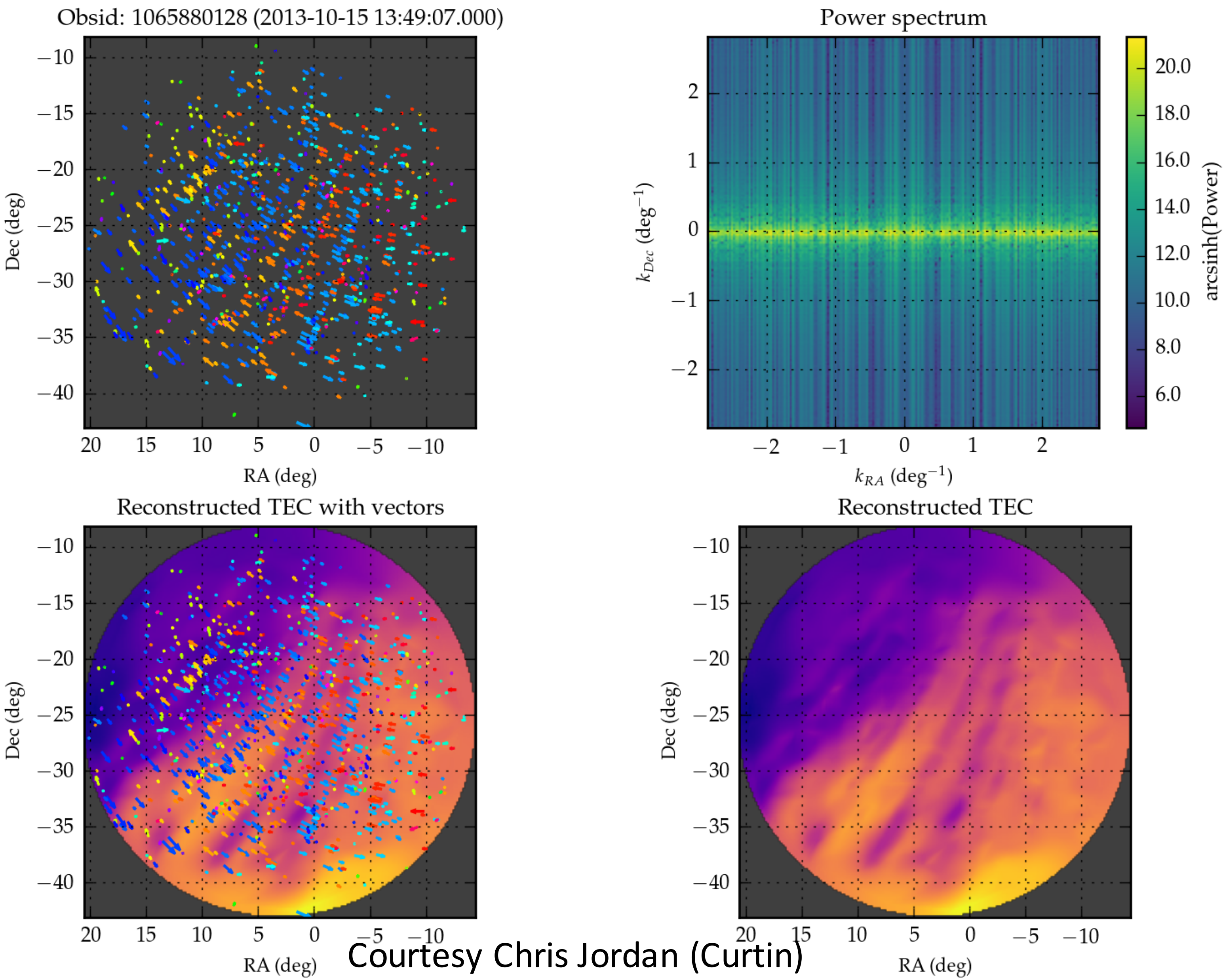
- Trott & Wayth 2016: Spectral smoothness
- Loi et al. 2015,2016: monitoring the ionosphere, discovery of plasma tubes
- Offringa et al. 2015, Franzen 2016: deep images and radio source counts
- Tingay et al. 2016, Rowlinson et al. 2016: limits on FRBs in EoR field(s)



Unexpected discoveries

- MWA confirms existence of ionsopheric plasma ducts Loi et al 2015.
- The movie shows formation of ducts aligned with B fields (lines) after passage of travelling ionospheric disturbance.
- Small vectors indicate direction of local gradients in ionospheric density (blue=left, red=right)

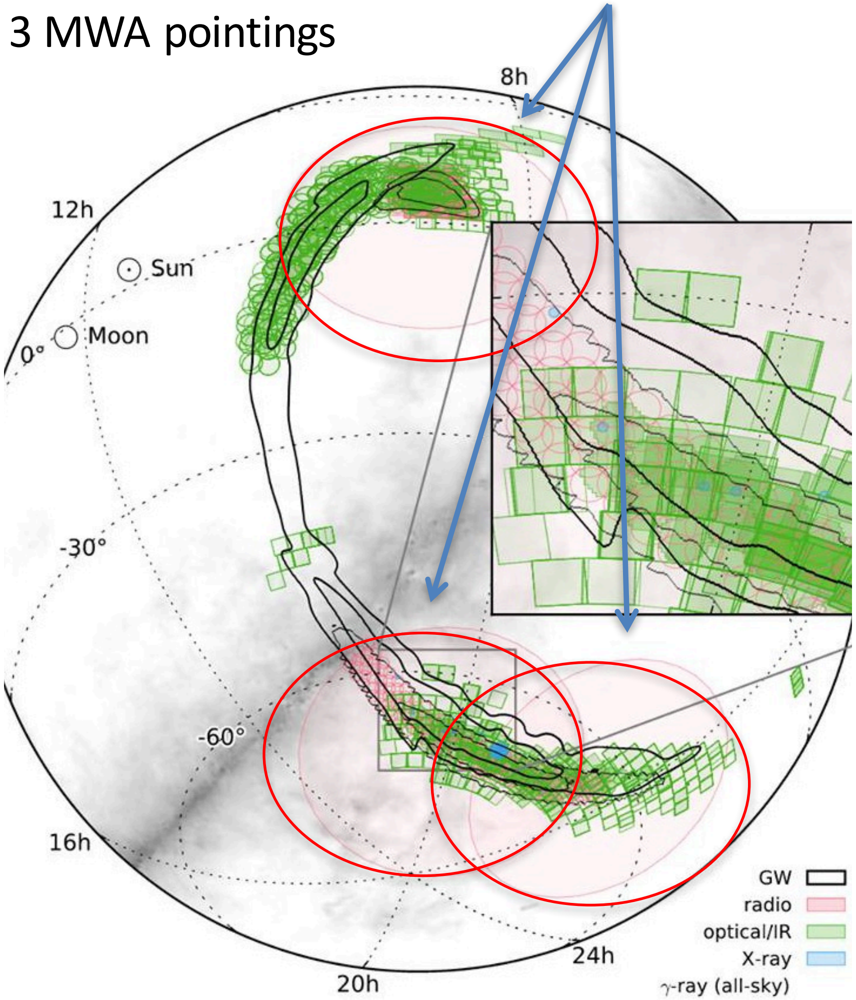
MWA EoR: spinoffs



Courtesy Chris Jordan (Curtin)

MWA: A sky monitoring machine

Bulk of GW error region covered
in 3 MWA pointings



Follow-up fields for the first GW event
http://arxiv.org/abs/1602.08492

- MWA was the first radio telescope to follow-up the GW event
- Sky coverage of MWA dwarfs others
- Frequently re-visiting sky: detailed time domain data
- Serendipitous observations of ANTARES neutrino events (Croft et al 2016)

GLEAM – a legacy dataset of the MWA

Wayth et al. 2015, PASA

Extragalactic catalogue: mid 2016
Hurley-Walker et al. 2016, in prep

300,000+ sources
72-230 MHz, 19 freq sub-bands
δ<+25, |b| > 10

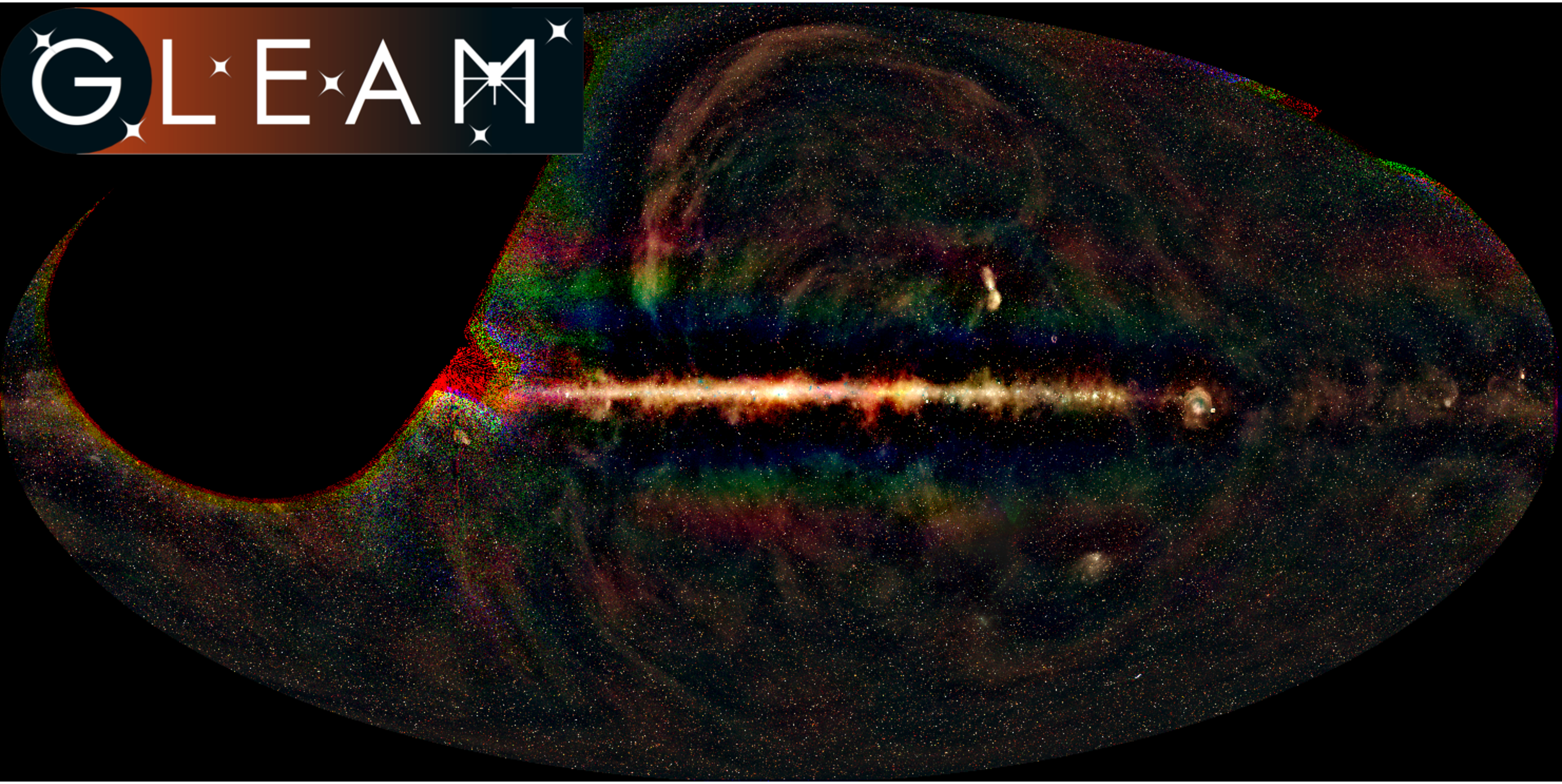
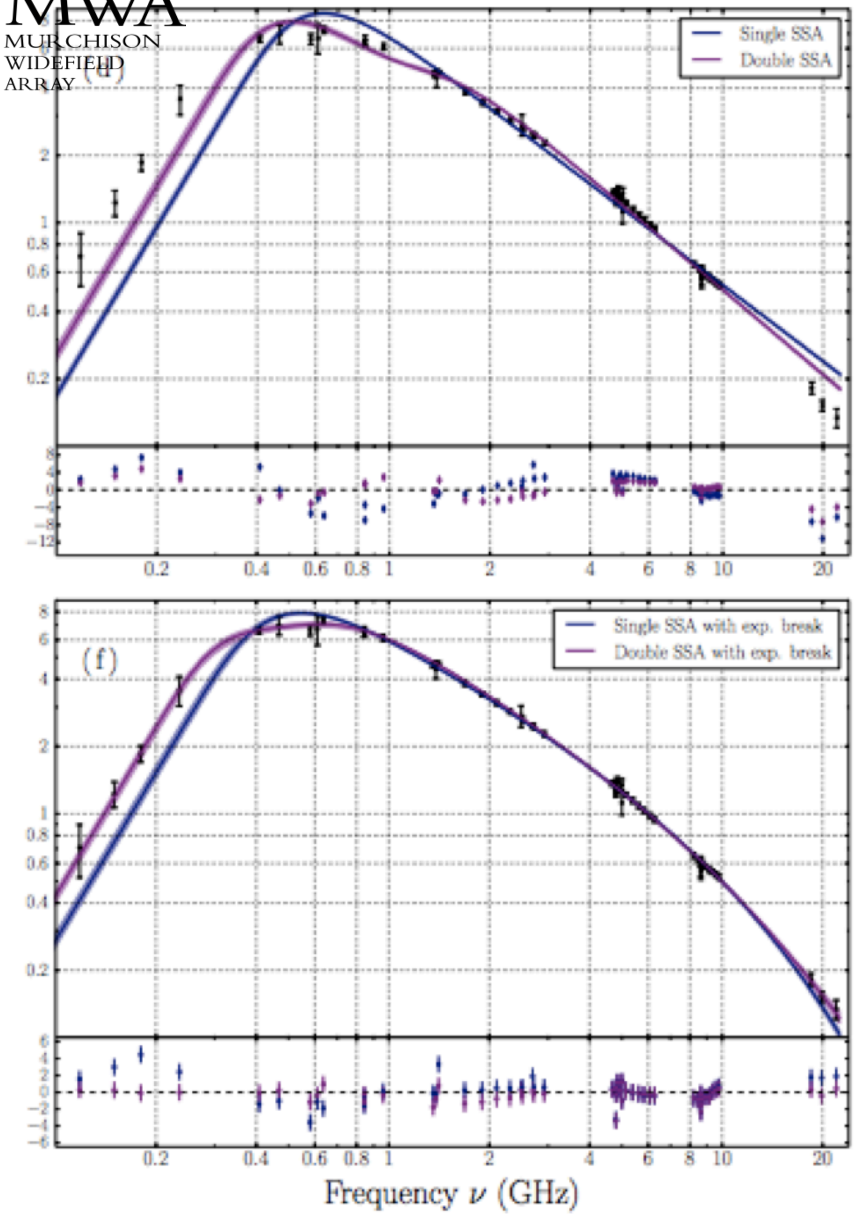
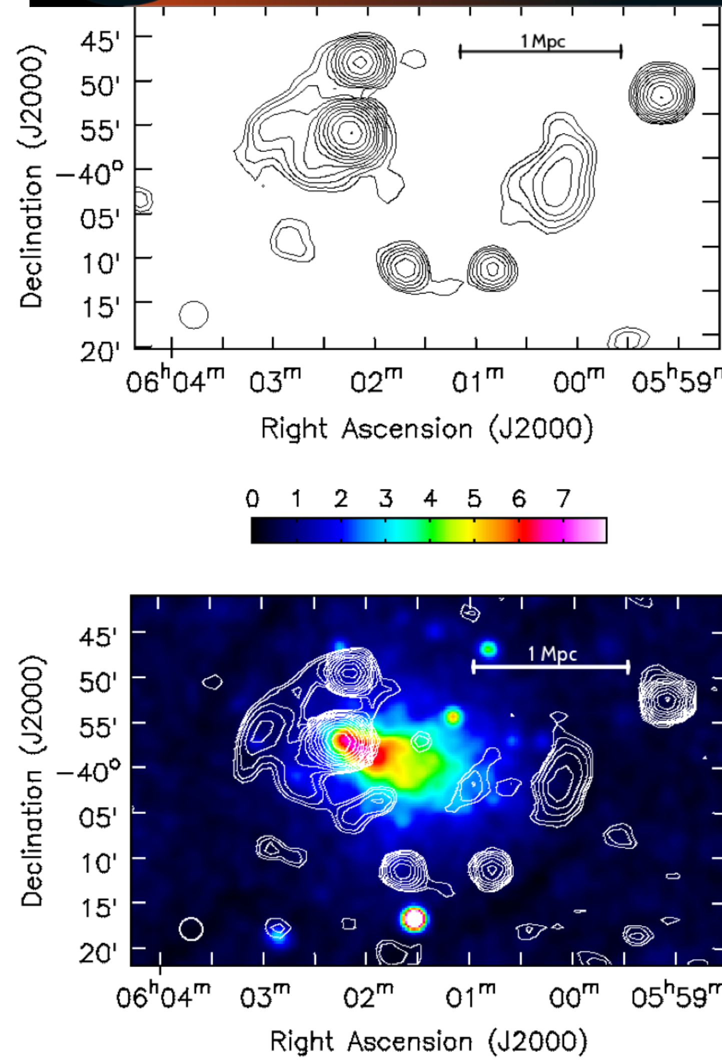


Image: Natasha Hurley-Walker

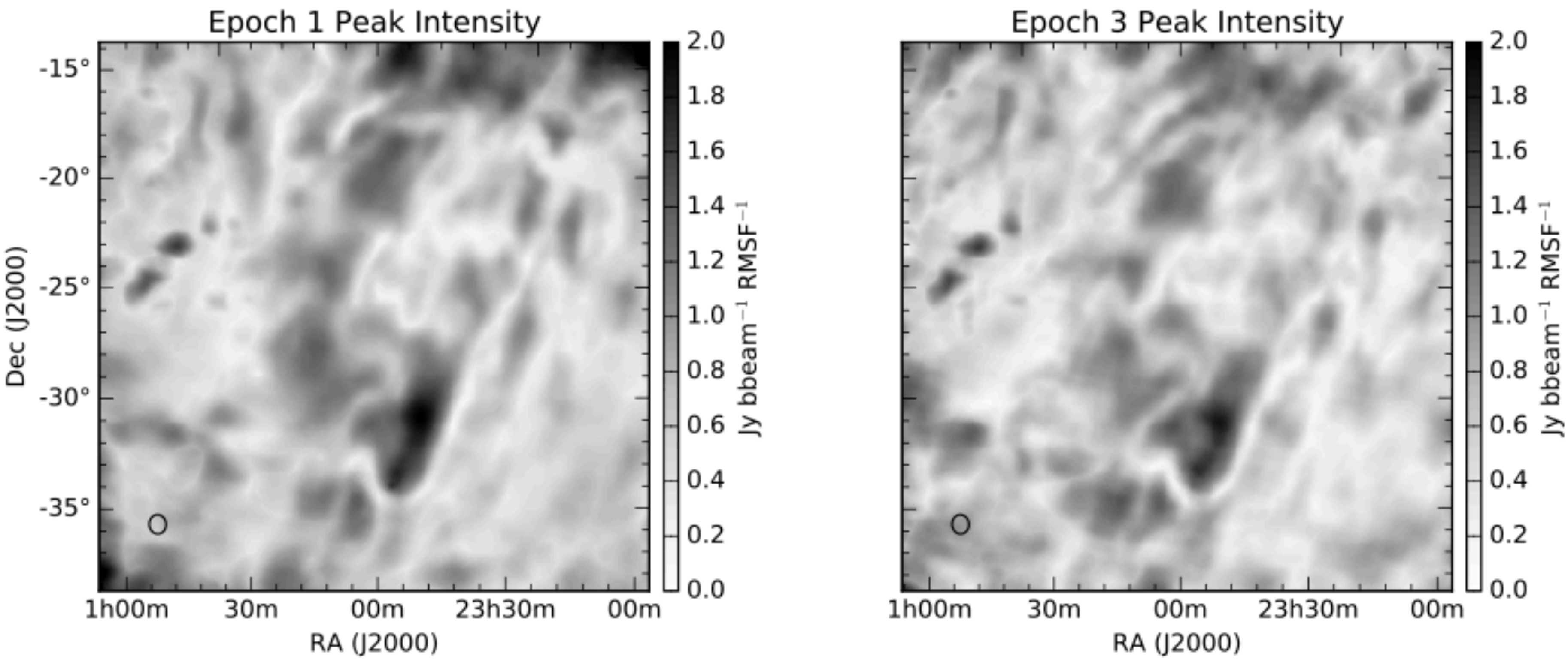


THE EXTREME GIGAHERTZ-PEAKED SPECTRUM RADIO SOURCE PKS B0008-421: Callingham et al. 2015 ApJ 809 168C



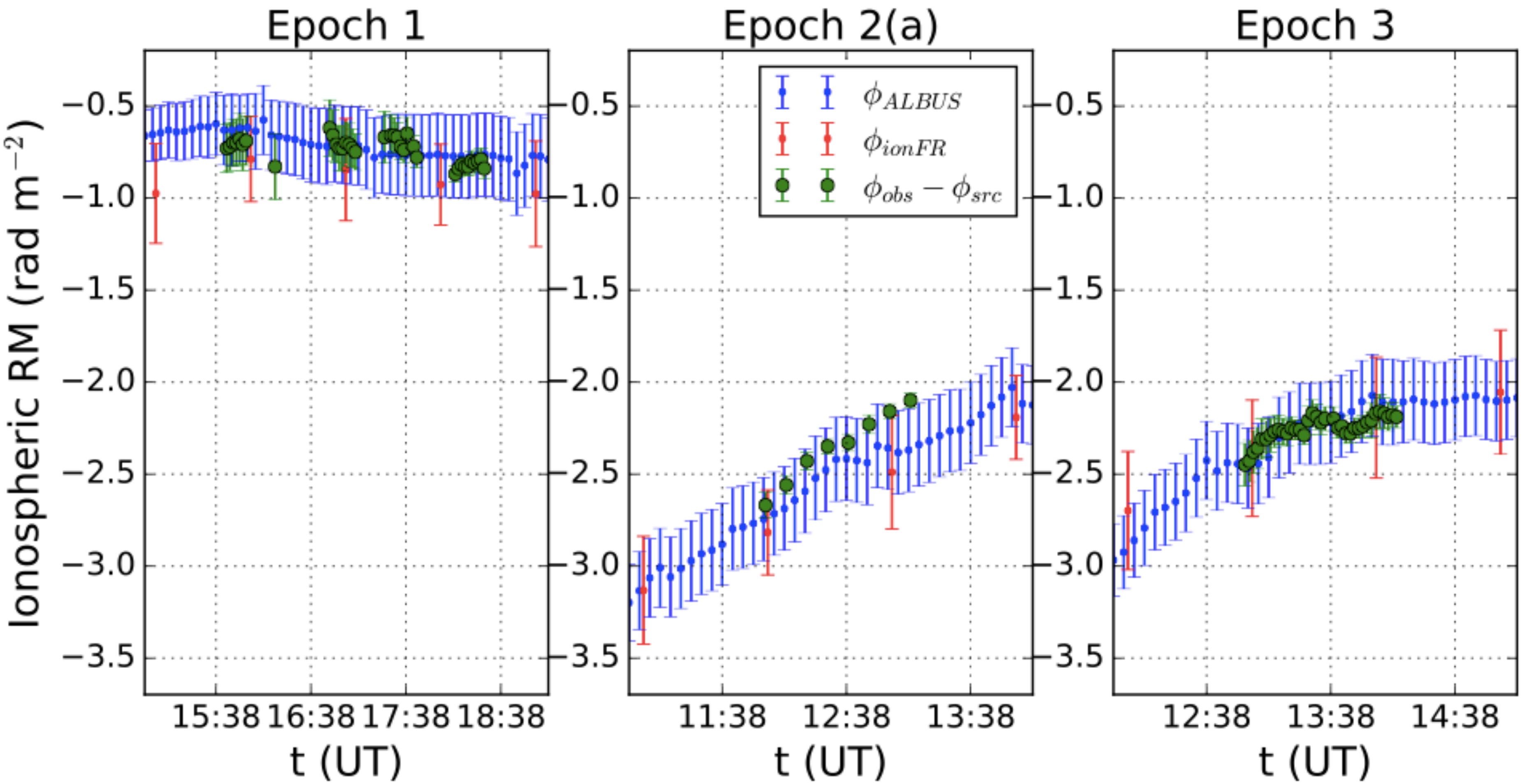
Halo and relic radio emission from Abell 3376: George et al. 2015

GLEAM: Polarised diffuse emission



From Lenc et al 2016 (in prep)

GLEAM: Polarised diffuse emission

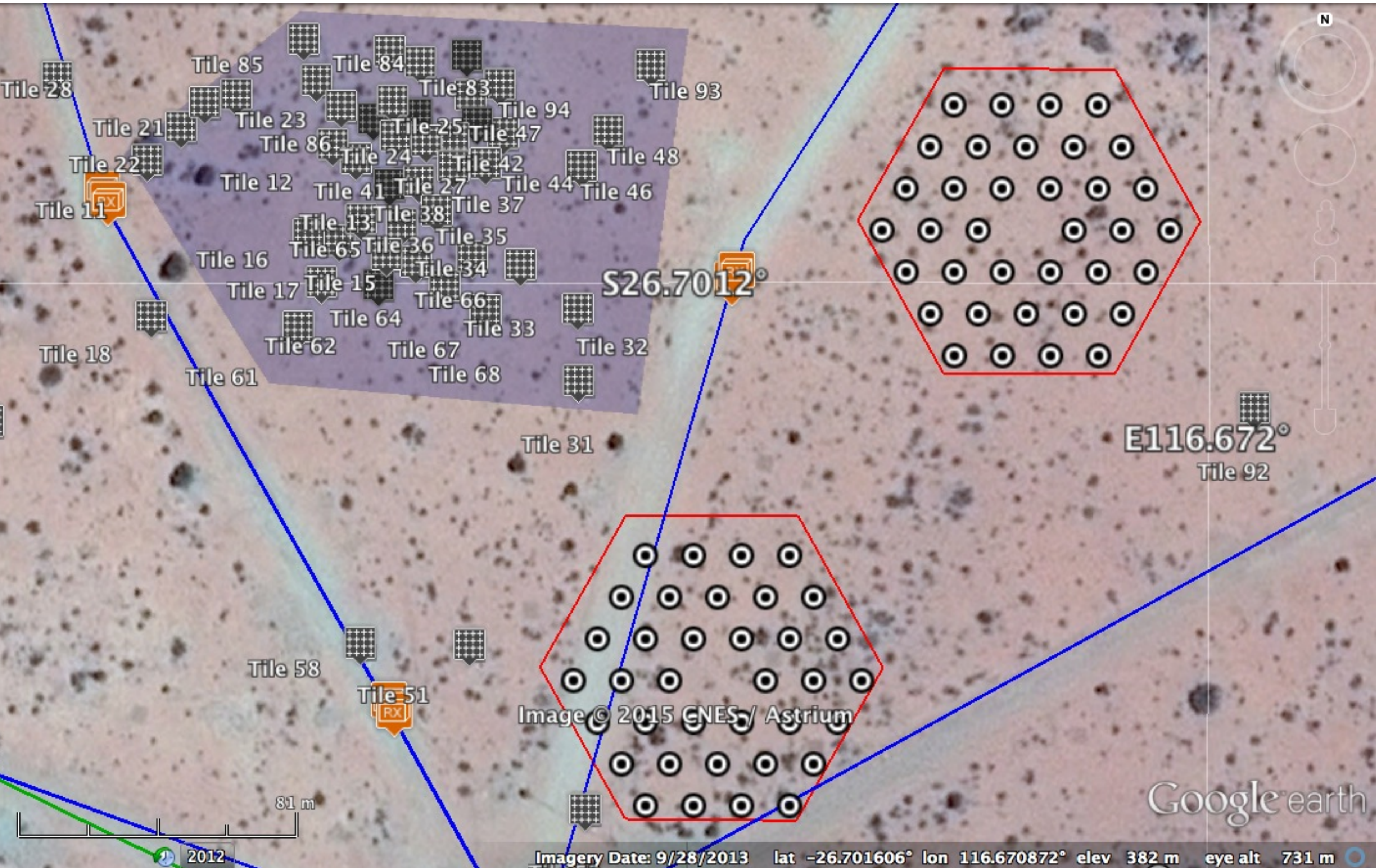


From Lenc et al 2016 (in prep)

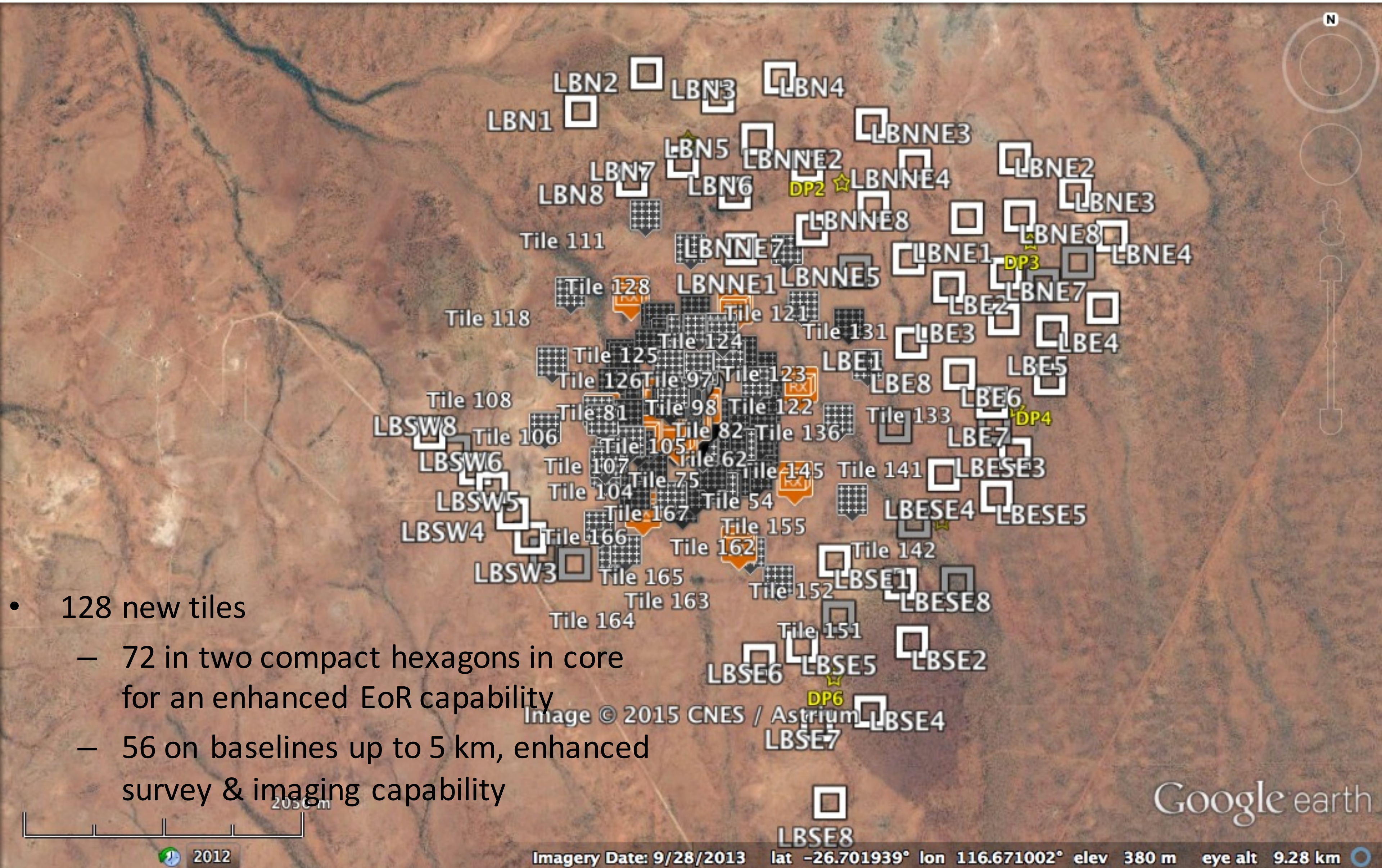
Past, present, future

- Phase 1: 2013-2016
  - 128 antennas, 2.5 km max baseline
- Phase 2: 2016-2018
  - Expand with additional 128 antennas, comprised of
    - 72 closely spaced in 2x hexagonal grids approx 100m size
    - 56 new long baseline antennas to double max baseline to 5km
  - Only 128 antennas used at any time: reconfigure for
    - ‘EoR array’ (existing core tiles plus new hexes)
    - ‘Long baseline array’ (existing non-core tiles + new long baseline tiles)
  - Same correlator, receivers: reconfigure by manual re-plugging of tiles into receivers
- Phase 3: 2018+(?)
  - All 256 tiles correlated
  - Increased frequency range and instantaneous bandwidth, resolution
  - Requires replacement of post-beamformer analogue and digital hardware

MWA phase 2: core region



MWA phase2 – long baselines



- 128 new tiles
  - 72 in two compact hexagons in core for an enhanced EoR capability
  - 56 on baselines up to 5 km, enhanced survey & imaging capability

MWA phase 3

- Vision
  - All 256 tiles correlated simultaneously
  - Increased instantaneous bandwidth to ~100 MHz
  - Coarse channel aliasing fixed
  - Improved dynamic range
  - More flexible correlation options:
    - Spectral resolution, time averaging etc
- Requires:
  - Replacement of existing digital hardware: receivers, PFBs, correlator

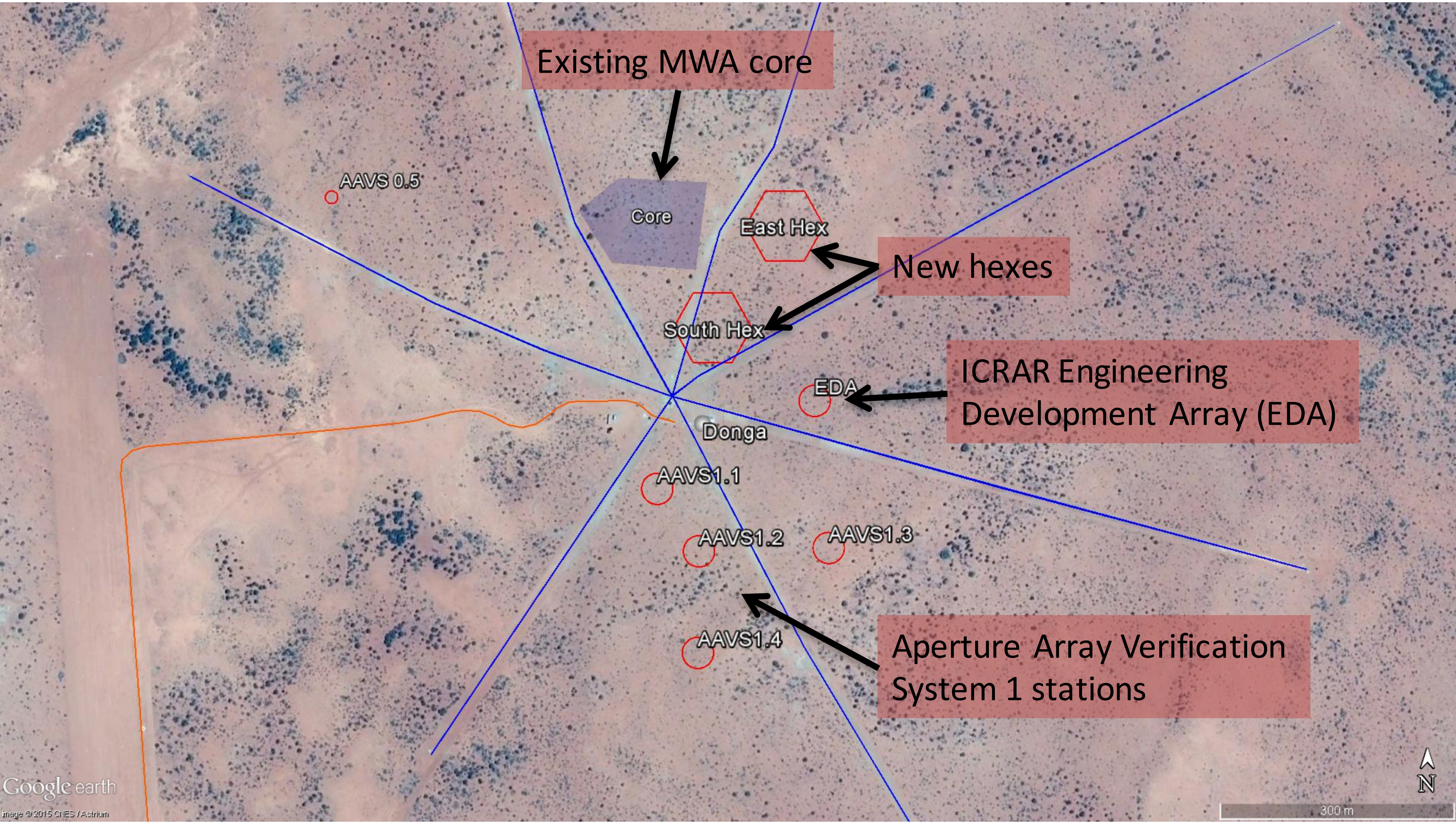
MWA Phase 3

Phase 2: 2016-2018
Phase 3: 2018 +

	MWA phase1, 2	MWA phase 3	SKA1 Low
Antennas correlated (x 2 pols)	128	256	564
Instantaneous BW (MHz)	30.72	~100	300
Bit/sample	4+4	8+8	8+8
Oversampling factor	1	1.25	1.25
Data rate per antenna (Mbps)	491.52	4000	12000
Data rate into correlator (Gbps)	62.91	1024	6768
Number of correlator boxes	24	~24	~100
Data rate per correlator box (Gbps)	2.62	42.67	67.68

MWA phase 3 is only a factor of 2 in stations and a factor of 3 in bandwidth from SKA Low

What else does MWA support?



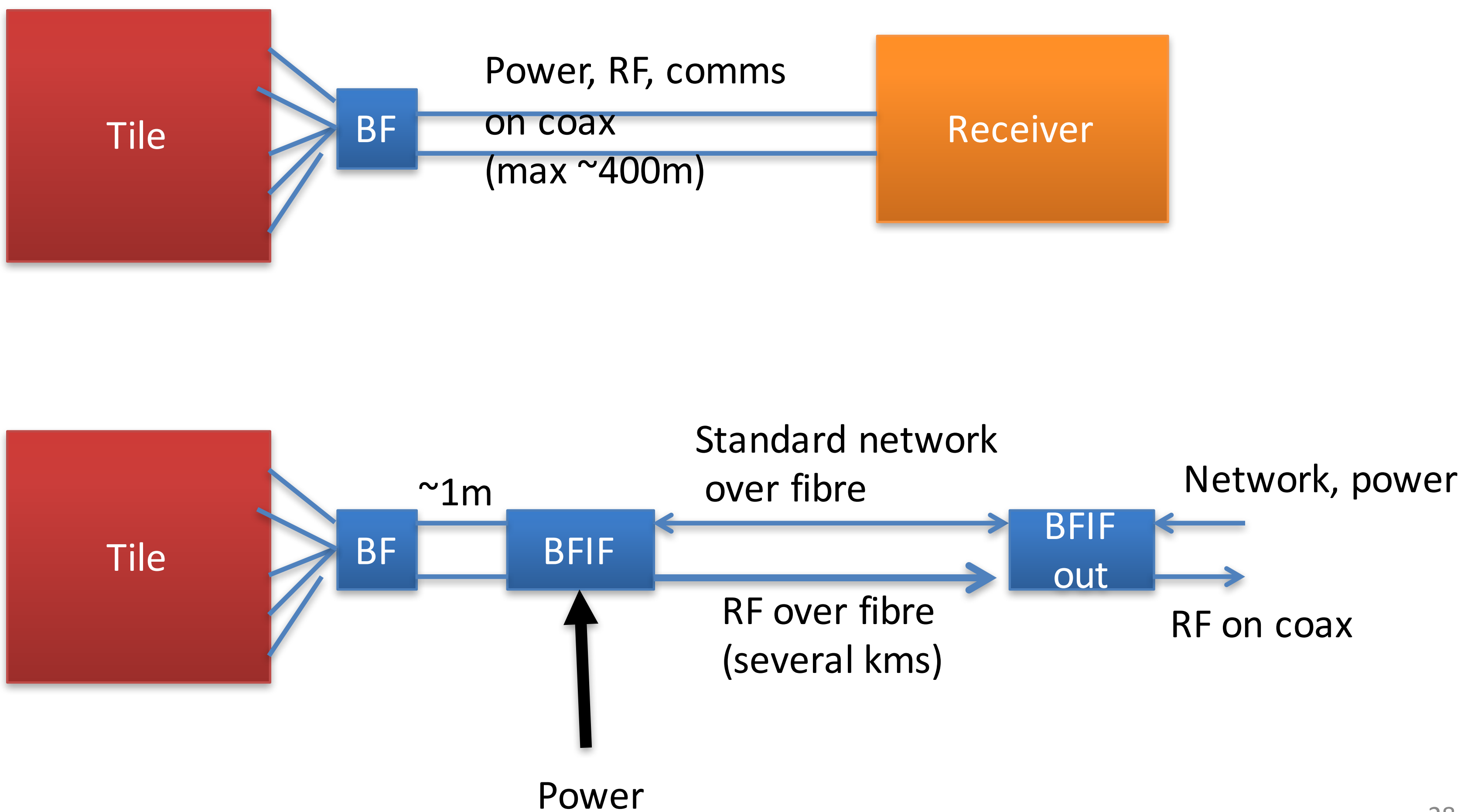
ICRAR Engineering Development Array (EDA)

- SKA-low sized station of MWA dipoles
- Prototype and test MWA and SKA equipment
- Integration of external instrument with MWA
- Risk mitigation for SKA-Low

Thanks!

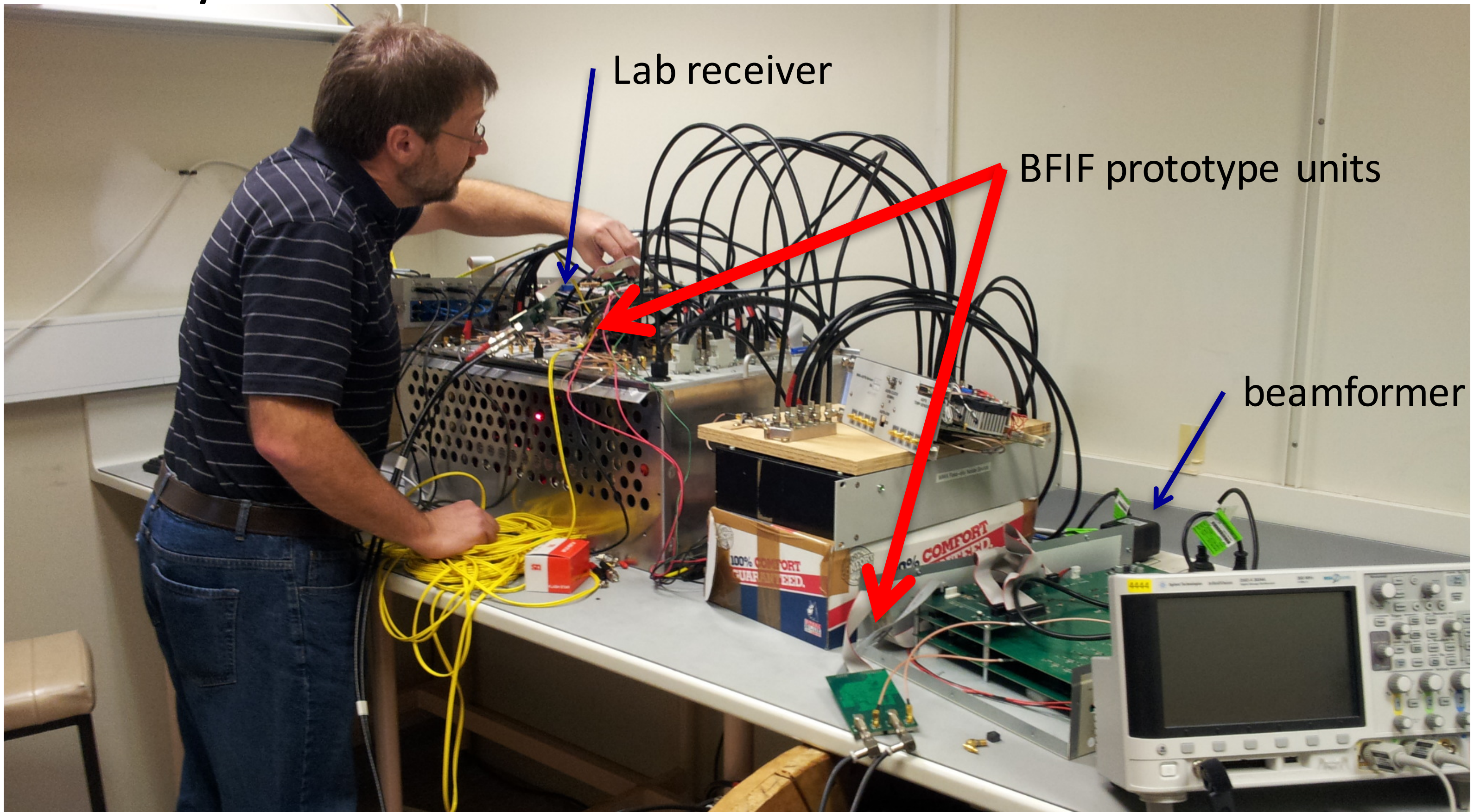
Beamformer interface (BFIF) units

- Long baselines supported by RF-over-fibre (RFoF) links from remote tiles to MWA hub region.



Beamformer interface (BFIF) units

- Long baselines supported by RF-over-fibre (RFoF) links from remote tiles to MWA hub region.
- Prototype beamformer control unit working in ICRAR/Curtin lab

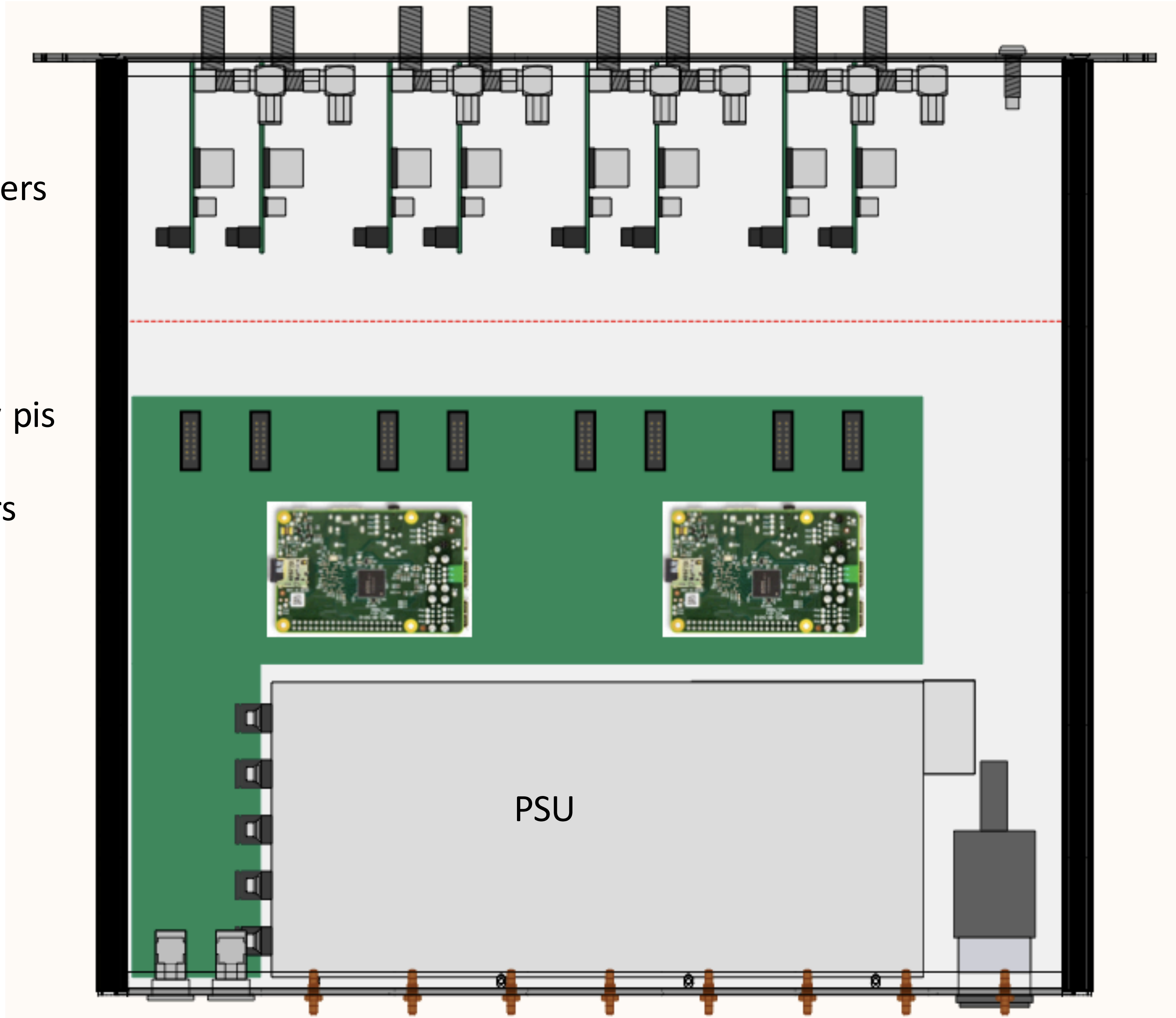


EDA beamformer controllers

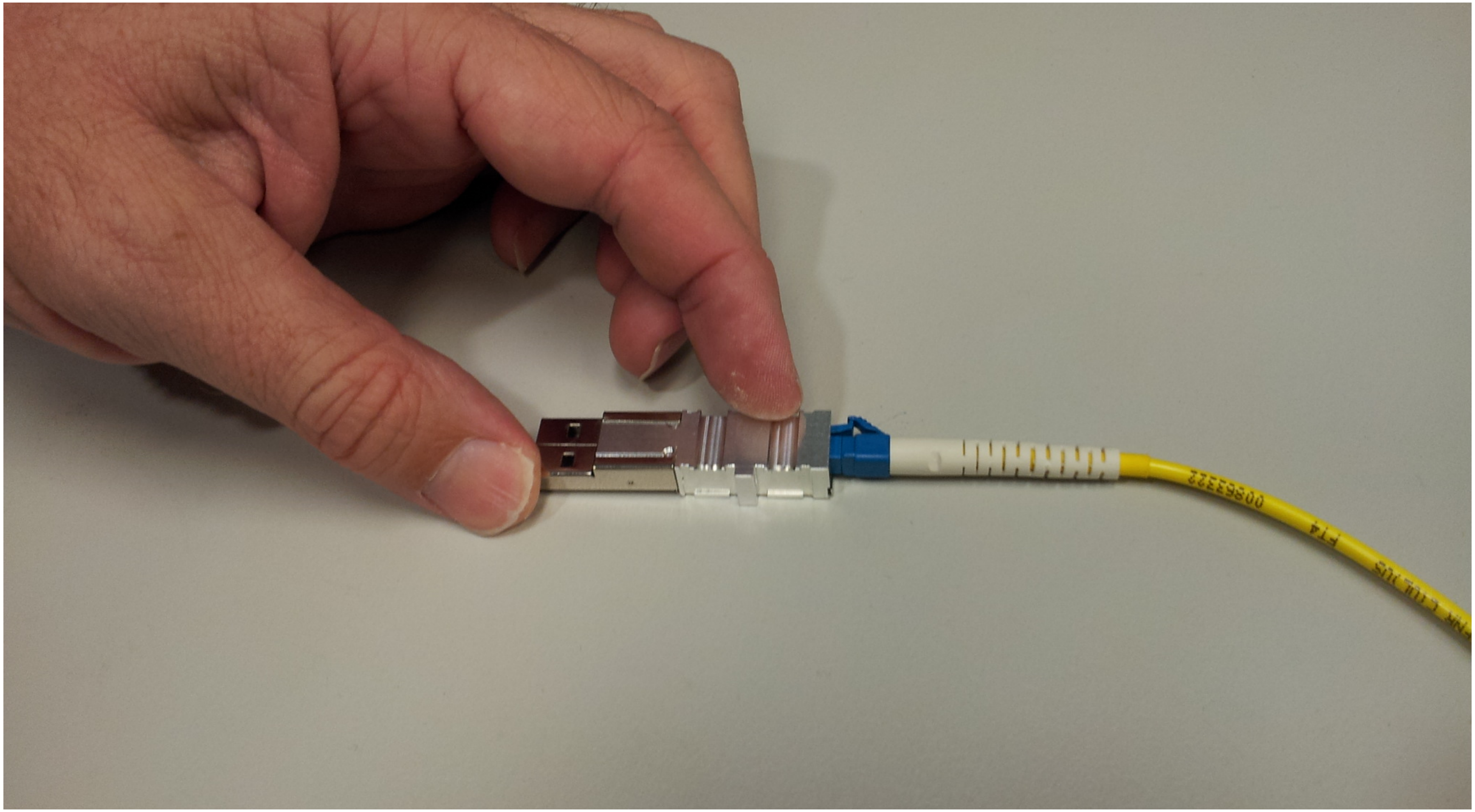
8x DoC units to beamformers

2x raspberry pis to control beamformers and power

Output RF



RF-over-fibre units



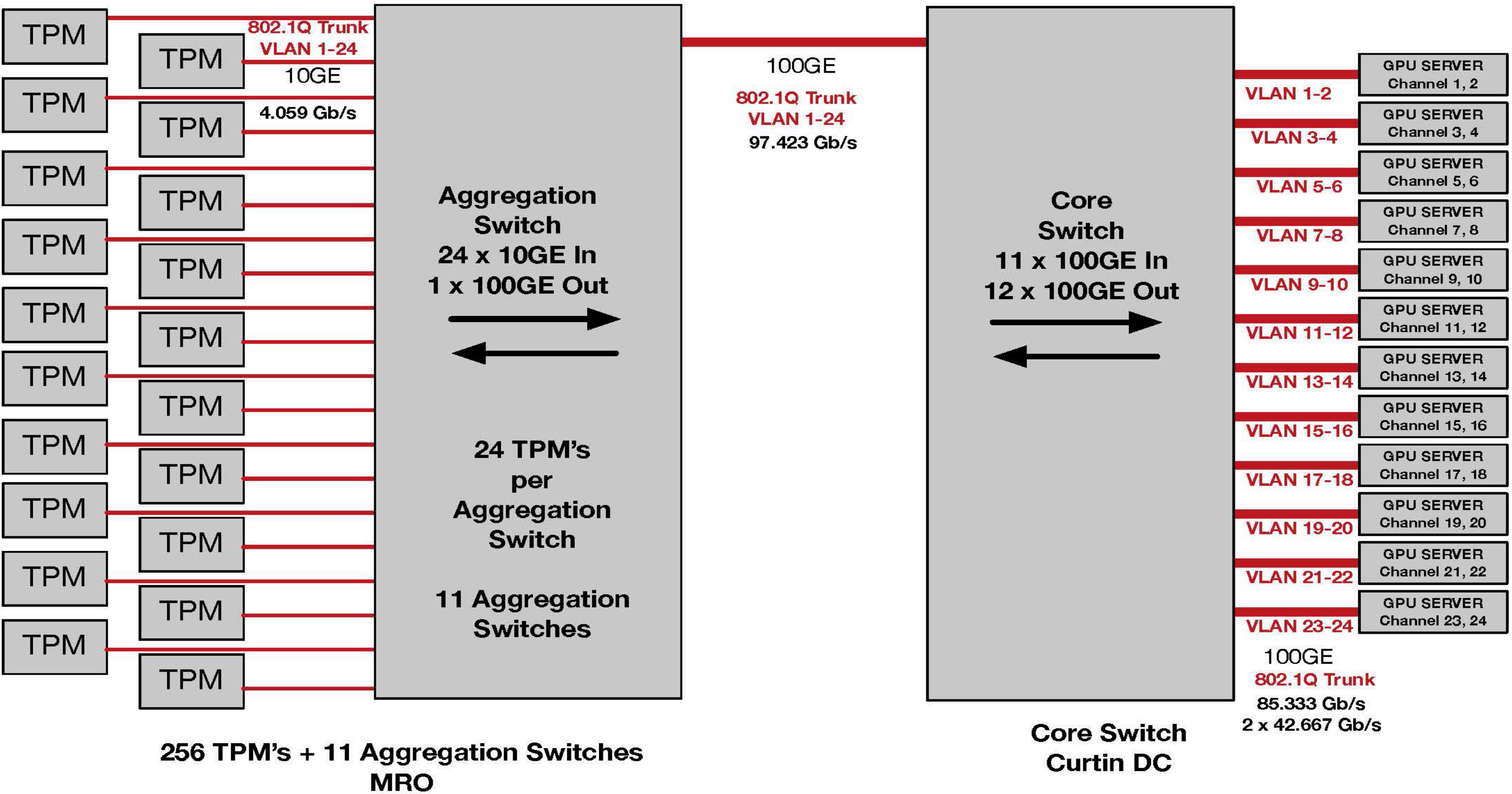
Potential digital receivers

- NI FlexRIO sampler/controller
  - **Standard** network, clock, RF interfaces
  - Built-in linux control computer
  - Extremely capable FPGA (no FPGA programming required!)

NI 5772 Digitiser, 12-bit resolution
2-CH 800MS/s per channel

NI 7935R FlexRIO controller
with Kintex-7 410T FPGA on board
and two built-in 10GbE SFP+ ports

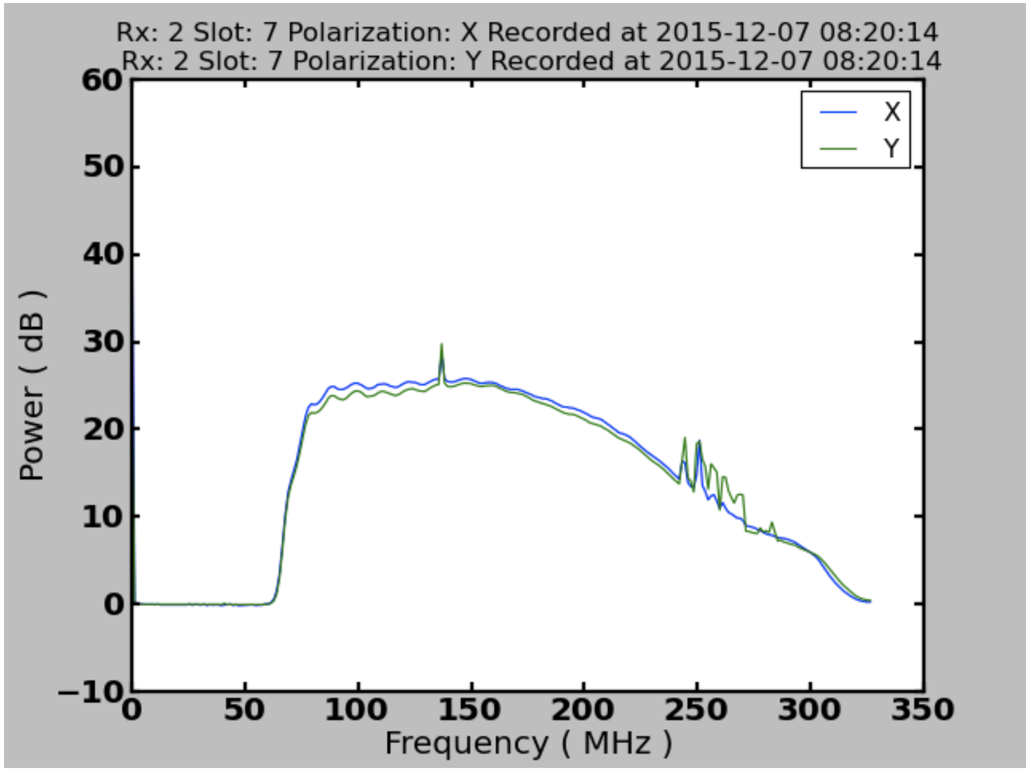
MWA Phase 3 Network Topology



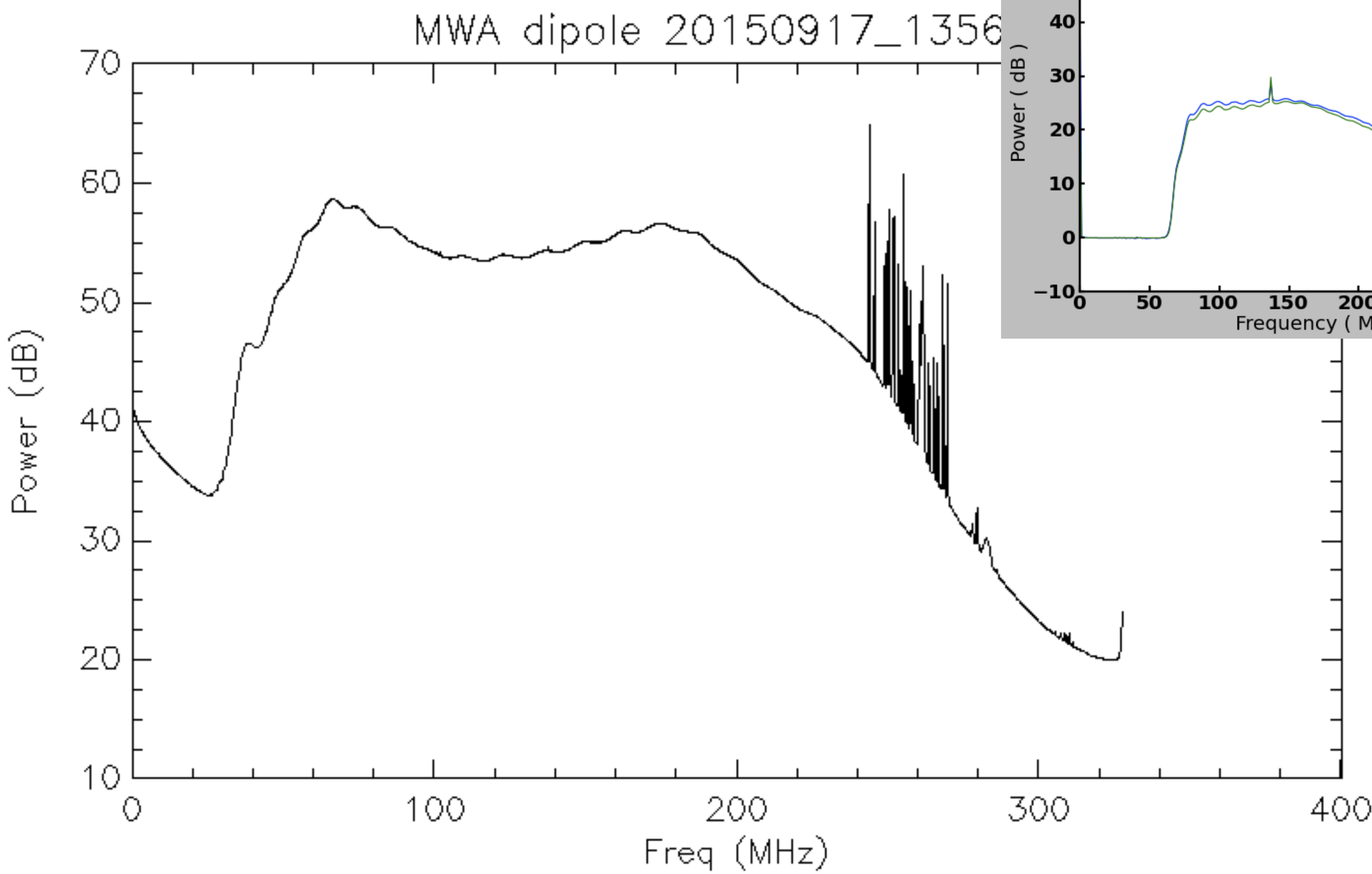
"TPM"=tile

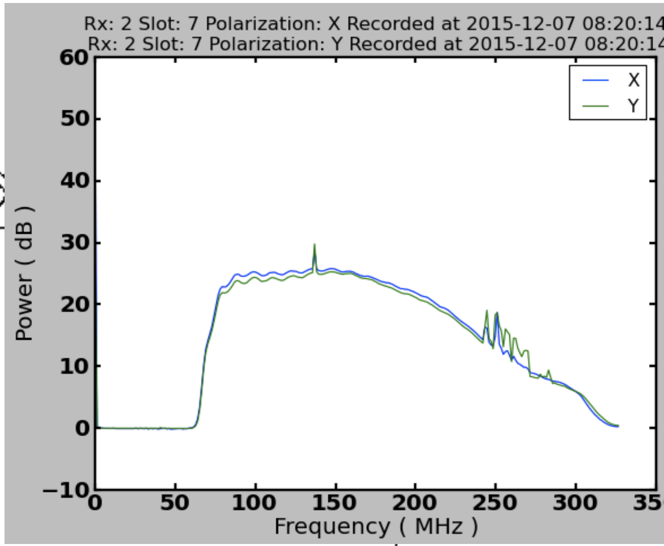
Array performance considerations

- Current performance > 250 MHz reduced by cable attenuation
- Signal > 300 MHz further attenuated by anti-aliasing filter
- RFoF link will preserve higher freq signals
- 800 MHz sampler means sky signals up to ~350 MHz are available (caveat dipole response)
- Coax cable reflections eliminated



Down to 50 MHz?

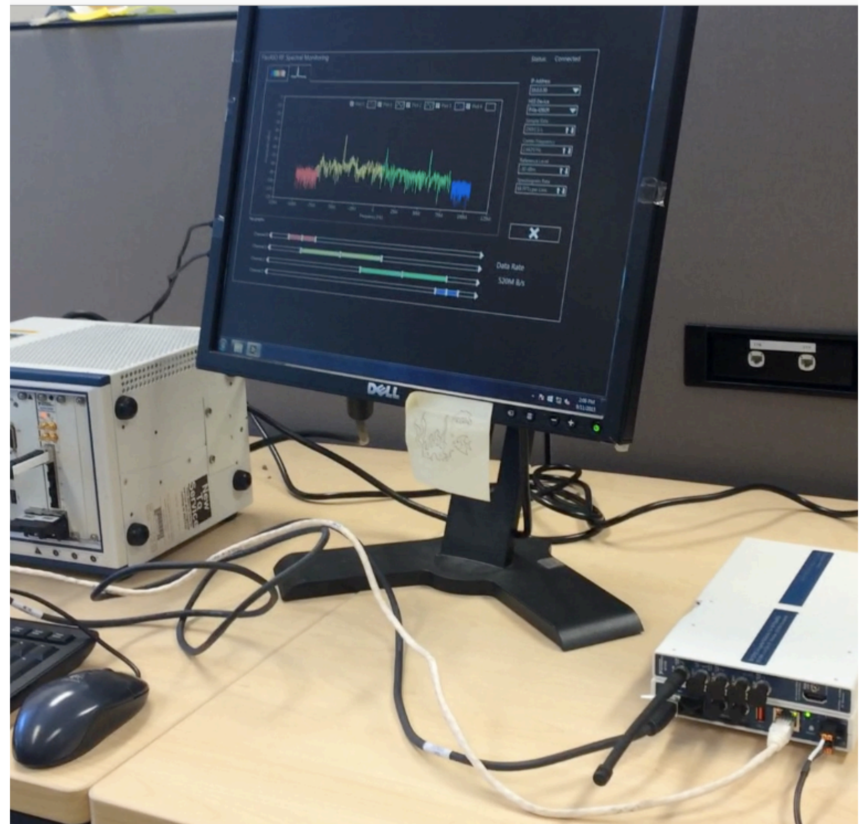




Data from standalone MWA dipole with modified LNA. High freqs have been attenuated by lowpass filter. EDA LNAs are modified to 50 MHz.

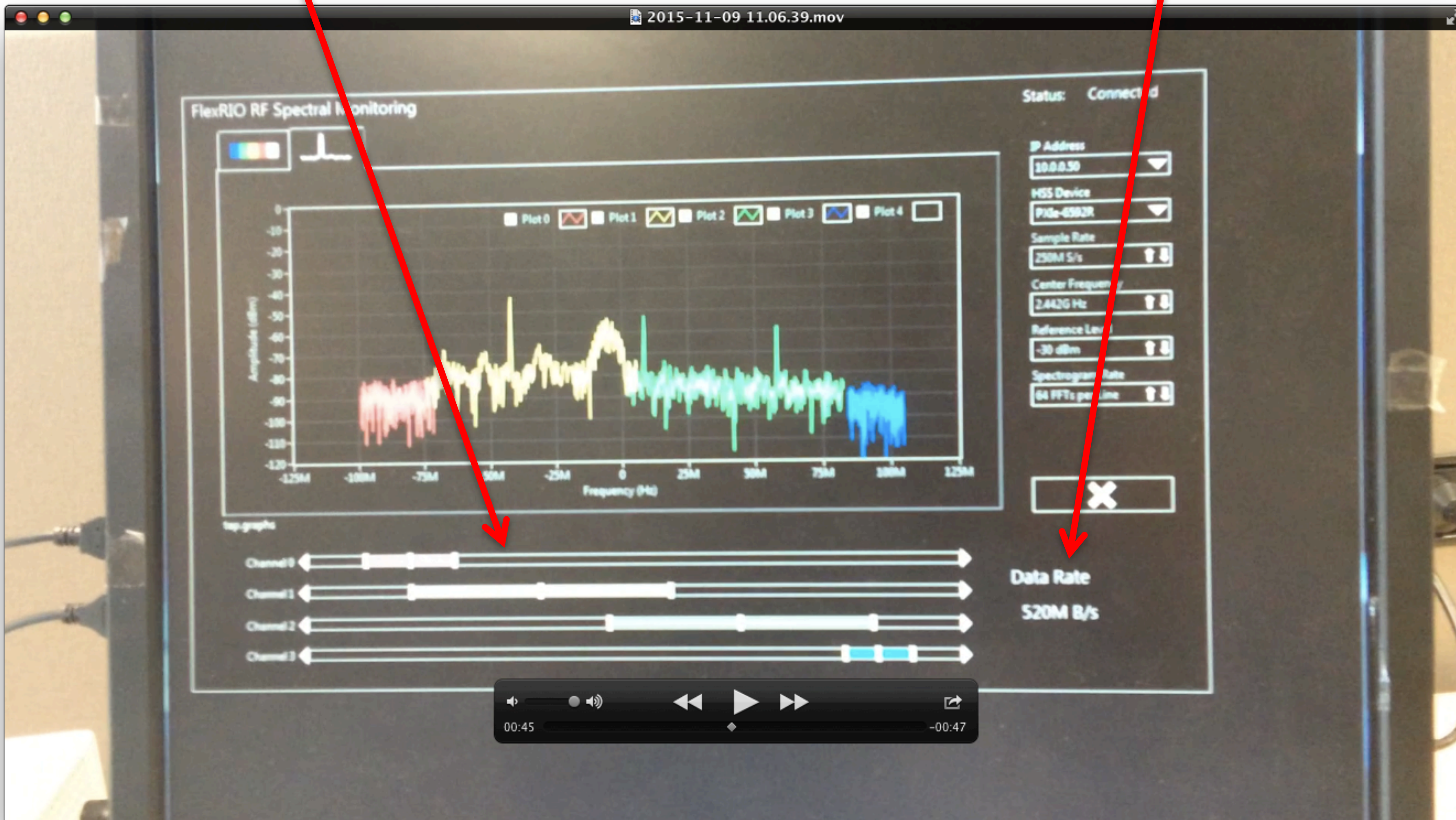
Potential Pulsar/VCS mode

- Pulsar astronomers want a large bandwidth unchannelised baseband voltage stream
- NI units offer “digital down conversion” (DDC) mode which selects one or more contiguous (large bandwidth) chunks of frequency as a baseband data stream



4 DDC channels
Different central freq, different BW, overlapping freq ranges

680 MB/s output over 10G



Expanded signal processing options

- Goals at Curtin are for core radio astronomy functionality: e.g. correlation with fixed spectral resolution
- Flexibility of receiver and software correlator offer potential for partner institutions to develop specialised modes, e.g:
  - Zoom modes
  - Pulsar binning mode
  - Sub-arrays, etc…
- Hardware and development environment is off-the-shelf. LabVIEW environment very popular in industry.

Phase 3 correlator: Number of server boxes

Numbers for 100 MHz bandwidth

Courtesy Charles Smith - Curtin

- 24 Channels @ 4.167MHz is the “sweet spot”
  - Allows 2 Channels @ 42.667 Gb/s to map onto a single 100GE Interface (this is reassuringly similar to the Swinburne UTMOST system)
  - Each of the 256 TPMs generates @ 0.167 Gb/s for each channel.
  - 8 coarse channels cannot fit onto a single 100GE.
  - 16 or 20 coarse channels require a 100GE per channel
  - If processing is insufficient the number of coarse channels can be increased with the number of GPU Servers.

Course Channels	MHz	TPM Channel	Server Channel	Chan Frames/s	Chan Gb/s
8	12.500	0.500	128.000	6992	0.508
16	6.250	0.250	64.000	3496	0.254
20	5.000	0.200	51.200	2797	0.203
24	4.167	0.167	42.667	2331	0.17
28	3.571	0.143	36.571	1998	0.145
32	3.125	0.125	32.000	1748	0.127
64	1.563	0.063	16.000	874	0.064

Scientific productivity

Professor Frank Briggs,
Dr Randall Wayth,
Professor Steven Tingay,
Professor Rachel Webster,
and Ms Kate Gunn

MWA instrument and scientists were recently recognised in the 2015 Thompson Reuters Citation and Innovation awards