Evolutionary Map of the Universe: EMU cosmology

WESTERN SYDNEY UNIVERSITY

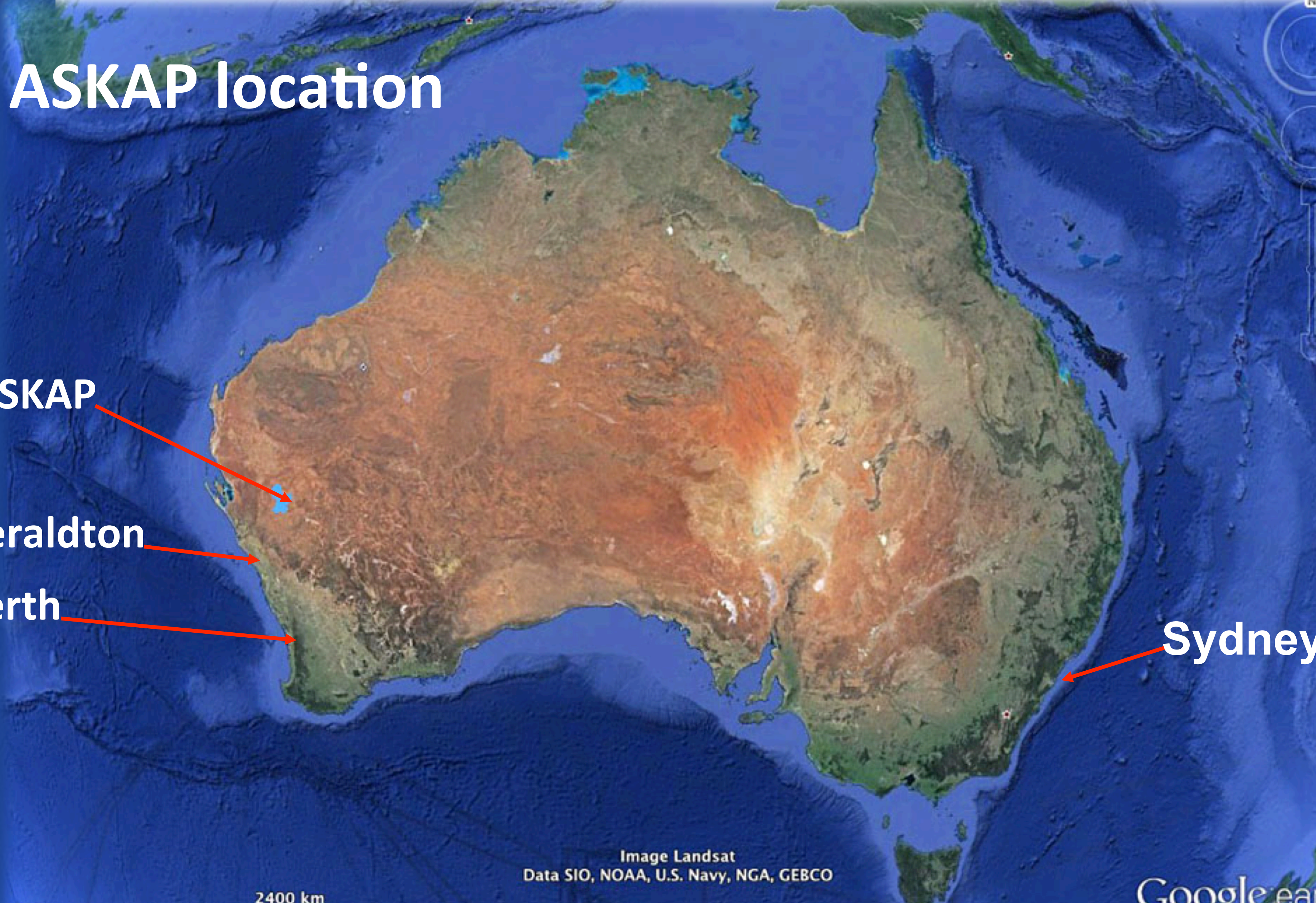
Ray Norris, Western Sydney University & CSIRO Astronomy & Space Science,

CSIRO

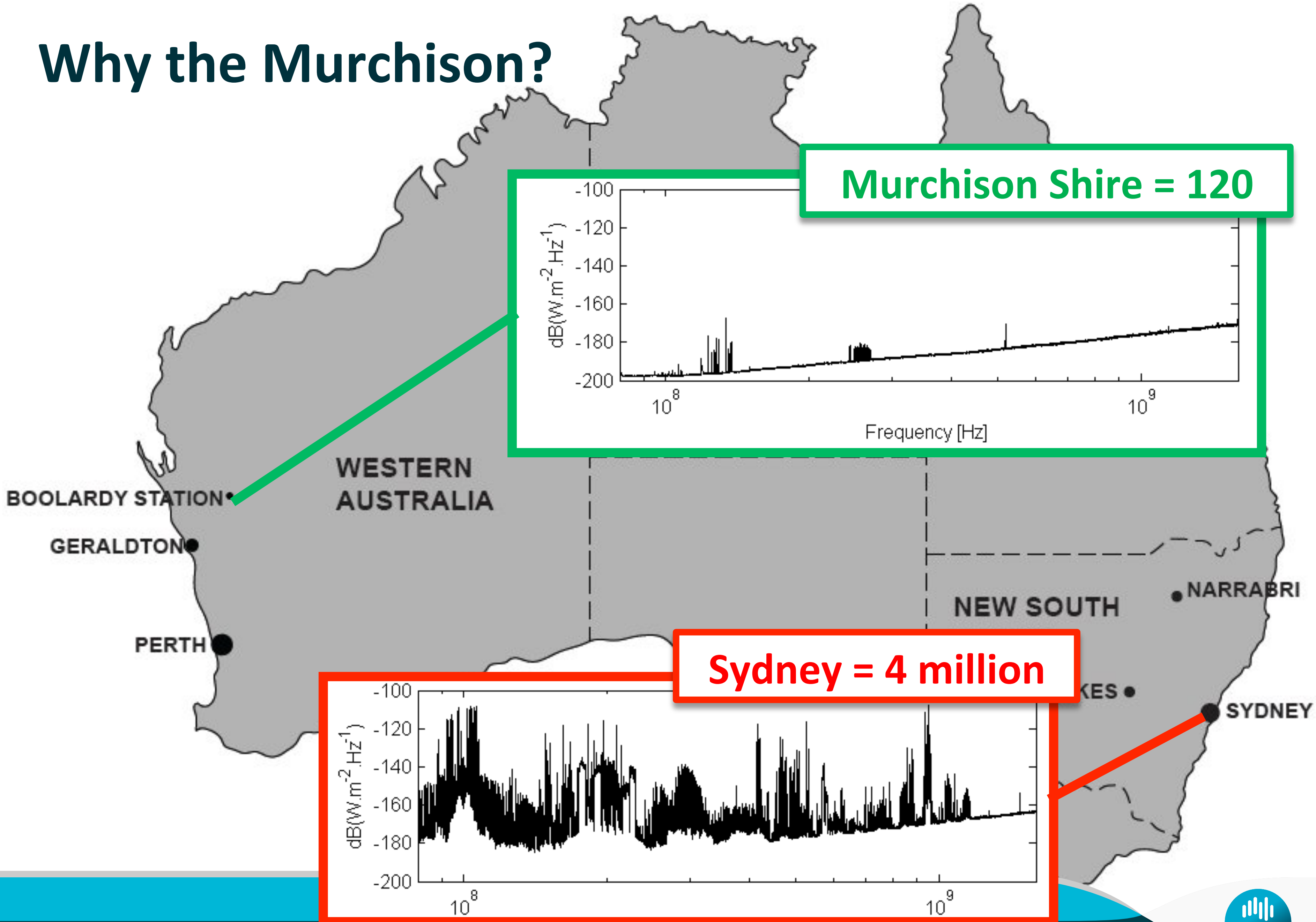

Overview

- ASKAP: the Australian SKA Pathfinder
- EMU: Evolutionary Map of the Universe
- EMU Cosmology

ASKAP location



Why the Murchison?

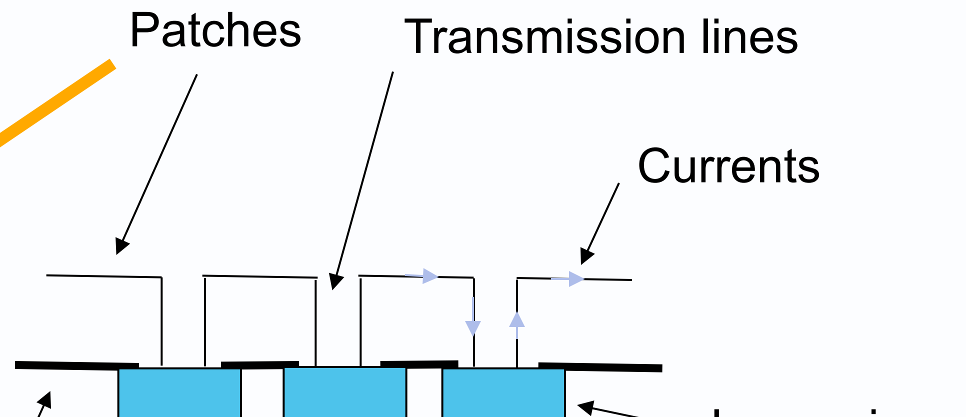


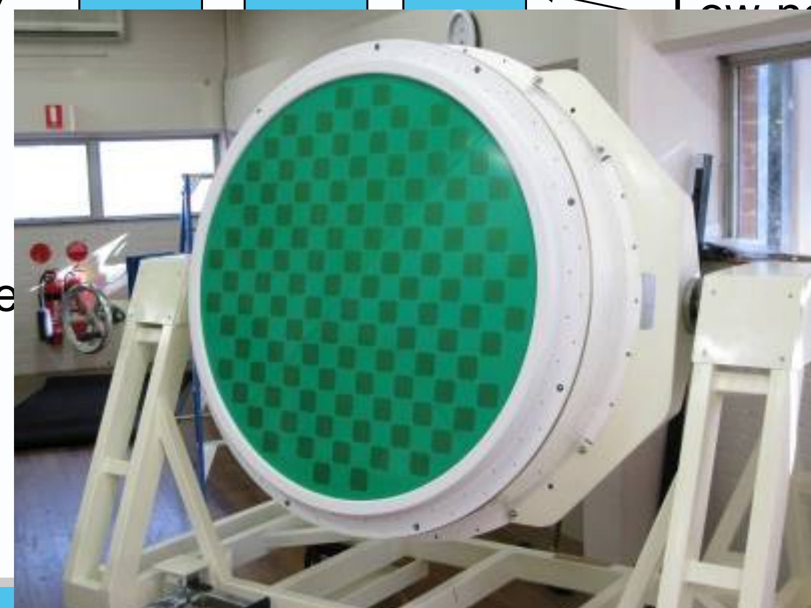
MRO power station

- Provide 850 kW (peak 1.1 MW)
- 4 diesel generators
- 5280 solar panels, 1.6 MW capacity
- 2.5 MWHr Lithium ion battery (largest in Australia

Slide courtesy of Antony Schinkel

ASKAP 188-element Phased Array Feed, or “PAF”





- Connected checkerboard array
- Operating range defined by electromagnetics and LNA
    - 1800-700MHz
- LNA - High-impedance, differential

PAFs -> Big Data

Data Rate to correlator = 100 Tbit/s
= 3000 Blu-ray disks/second
= 62km tall stack of disks per day
= world internet bandwidth in June 2012

Processed data volume = 70 PB/year

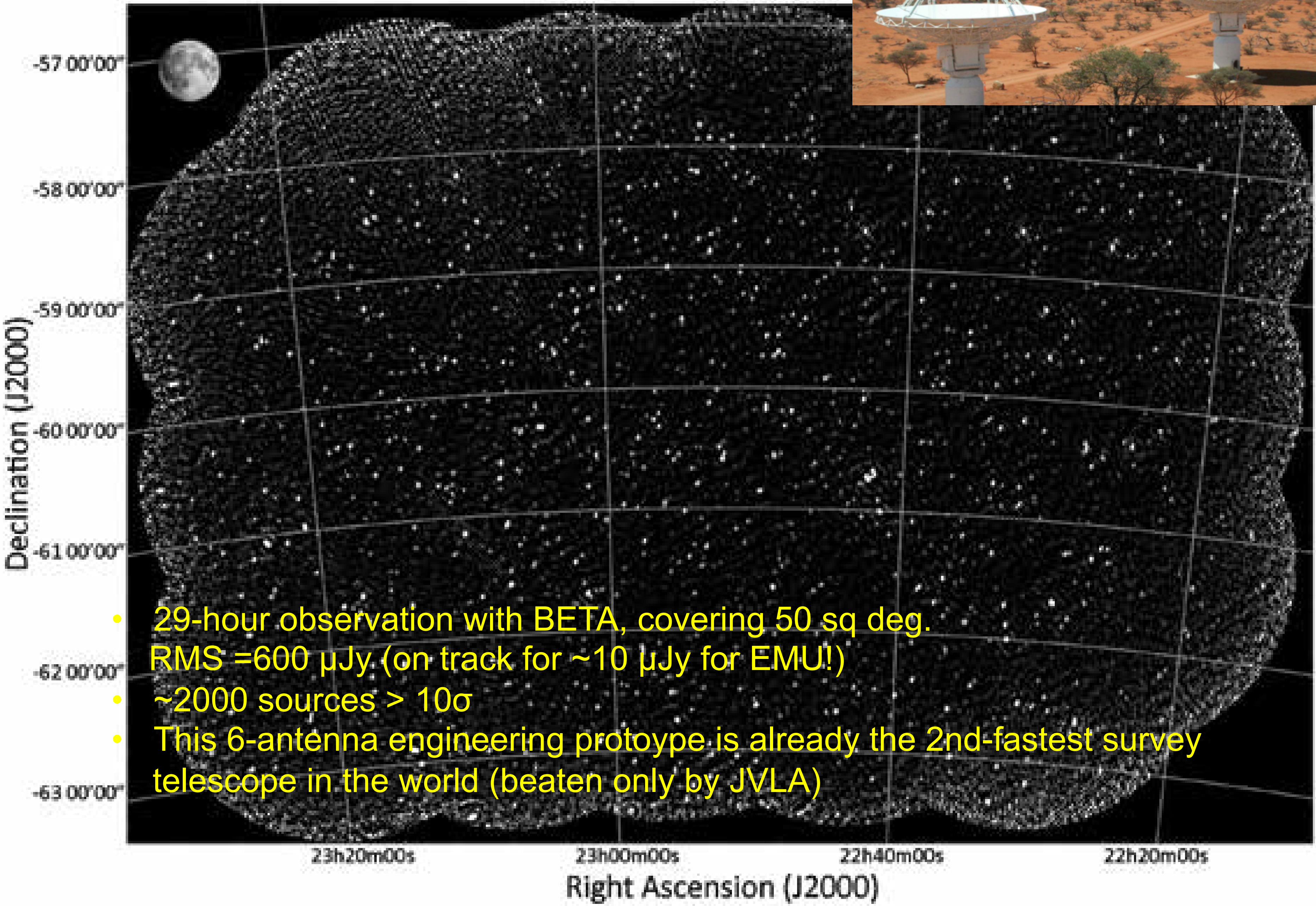
ASKAP Science Data Processor Platform

- The *galaxy* system at Pawsey
- 472 x Cray XC30 Compute Nodes
  - 200 TFlop/s Peak
- Cray Aries (Dragonfly topology)
- Cray Sonexion Lustre Storage
  - 1.4 PB usable
  - 480 x 4TB Disk Drives, RAID 6 + Hot Spares
  - Peak I/O performance: 30 GByte/s

ASKAP status & planned schedule

- All 36 antennas and infrastructure completed,
- Funding in place for all 36 PAFs
- **ASKAP-BETA 2015-2016:**
  - Engineering prototype array used prototype PAFs on 6 antennas giving 9 beams

PAFs work (even with only 6 antennas)!



- 29-hour observation with BETA, covering 50 sq deg.
  RMS =600 μJy (on track for ~10 μJy for EMU!)
- ~2000 sources > 10σ
- This 6-antenna engineering protoype is already the 2nd-fastest survey telescope in the world (beaten only by JVLA)

ASKAP status & planned schedule

- All 36 antennas and infrastructure completed,
- Funding in place for all 36 PAFs
- **ASKAP-BETA 2015-2016:**
  - Engineering prototype array used prototype PAFs on 6 antennas giving 9 beams
  - Now shut down ready for the next stage
- **ASKAP Early Science 2016-17**
  - Early Science uses 12 fully-equipped antennas

First 36-beam ASKAP image (using 9 antennas)

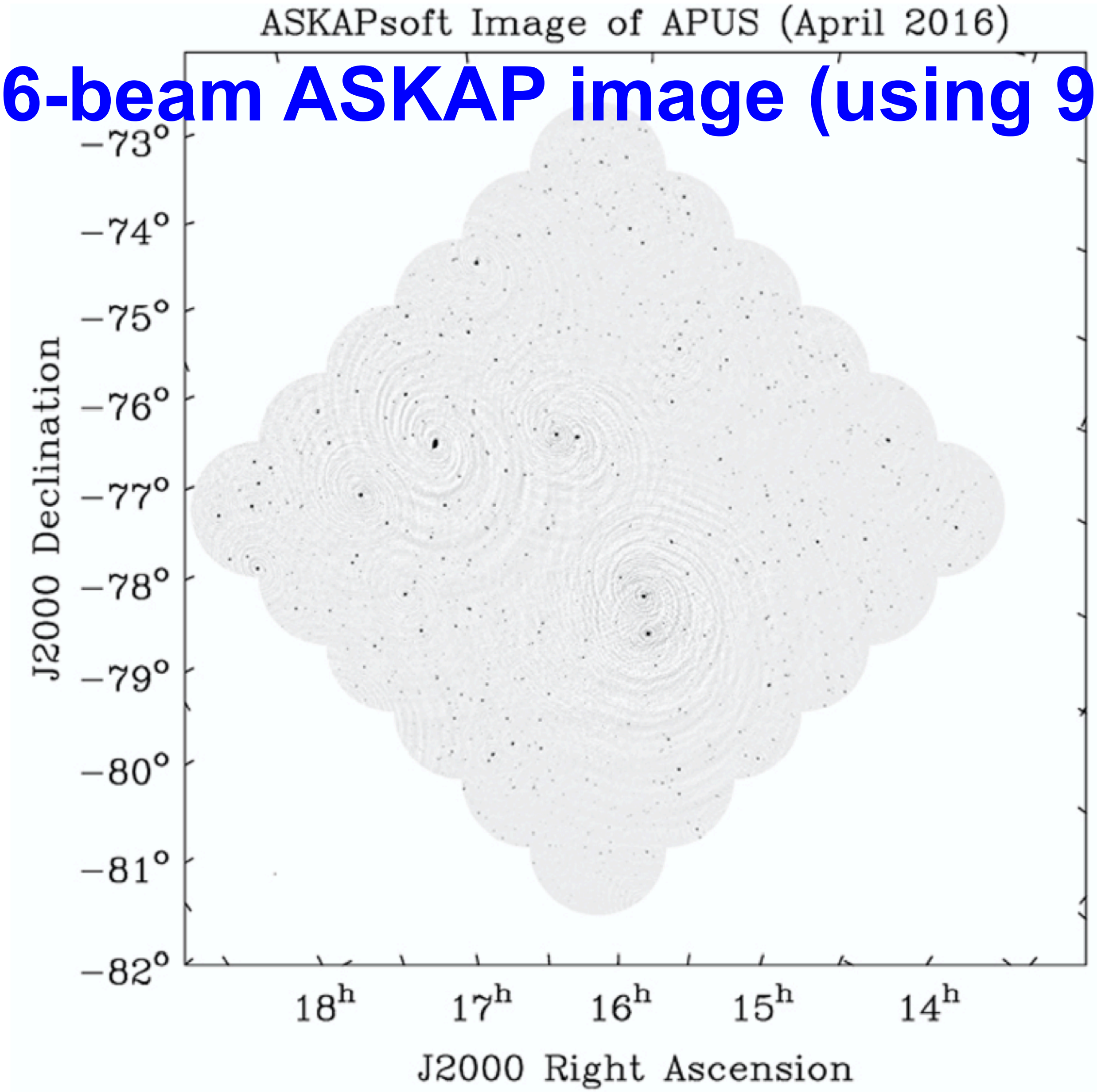


Figure 5. The continuum image, produced with ASKAPsoft, has an rms of around 300 uJy/beam and a field of view of 30 square degrees. It contains over 1300 sources. Image Credit: ASKAP Commissioning and Early Science (ACES) team

ASKAP status & planned schedule

- All 36 antennas and infrastructure completed,
- Funding in place for all 36 PAFs
- **ASKAP-BETA 2015-2016:**
  - Engineering prototype array used prototype PAFs on 6 antennas giving 9 beams
  - Now shut down ready for the next stage
- **ASKAP Early Science 2016-2017**
  - Early Science uses 12 fully-equipped antennas in "shared risk" mode
  - 12 PAFS installed June 2016
- **ASKAP Survey Science**
  - All PAFs installed by late-2016?
  - Late 2017: Full EMU/WALLABY surveys start ??????

CSIRO

Recent Developments

- ASKAP developments – now 12 antennas with PAFS – 36 by early next year!
- Fisrt 36-beam image
- Early Science expected to start Sept 2016
- ASKAP Tsys/η about 20% worse than expected - integrate longer or reduce sensitivity?
- Development towards an EMU "hub" at Western Sydney University
- Development of machine learning projects as part of WTF
  - E.g. source classification, cross-matching

ASKAP Science

38 proposals submitted to ASKAP

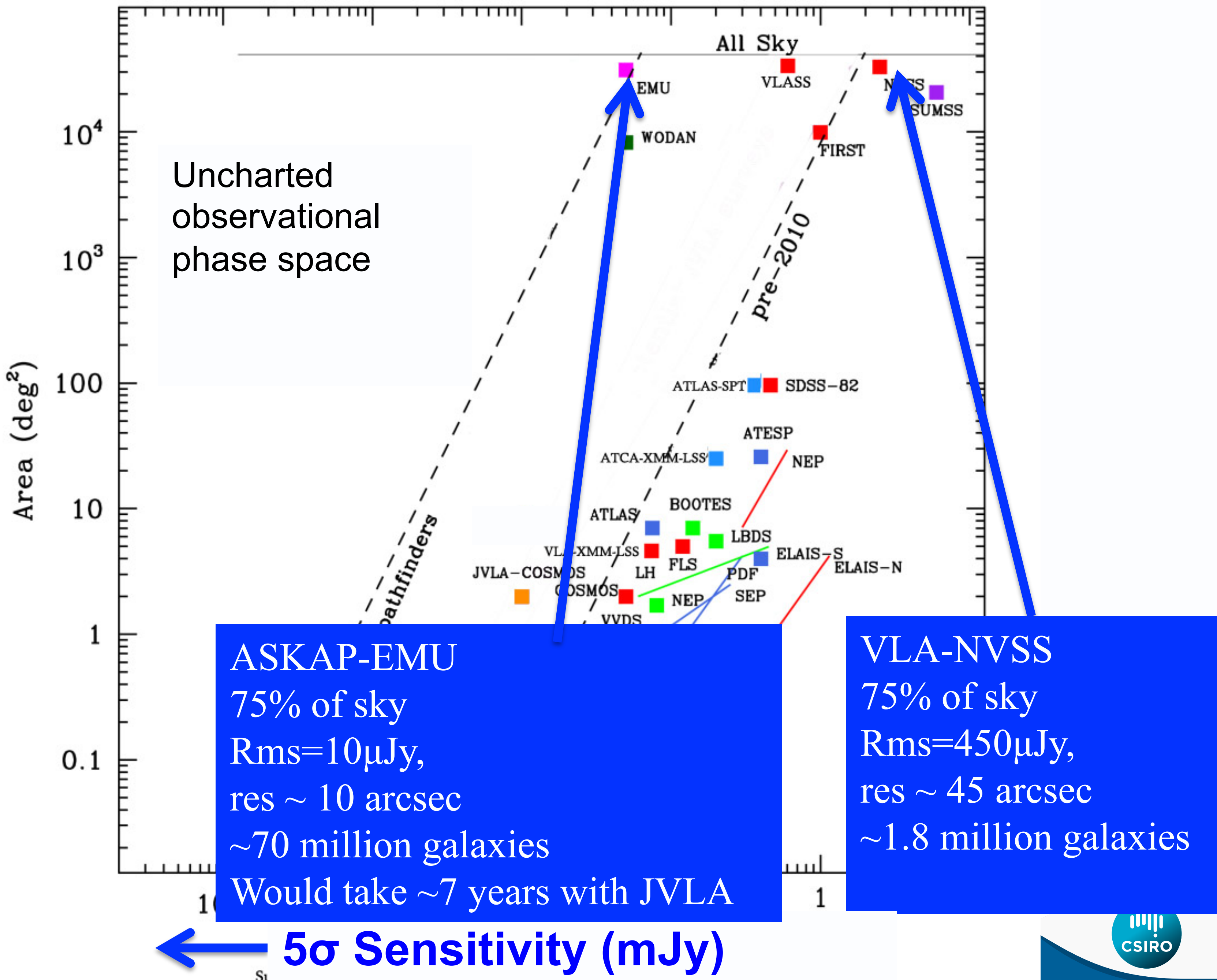
2 selected as being highest priority

- EMU all-sky continuum (PI Norris)
- WALLABY all-sky HI (PI Koribalski & Staveley-Smith)

8 others supported at a lower priority

- COAST pulsars etc
- CRAFT fast variability
- DINGO deep HI
- FLASH HI absorption
- GASKAP Galactic
- POSSUM polarisation
- VAST slow variability
- VLBI

The EMU project consists of about
300 scientists in 21 countries
http://askap.pbworks.com/TeamMembers
It’s an open collaboration – email me to join


All Sky
EMU
VLASS
SUMSS
WODAN
FIRST
Uncharted observational phase space
pre-2010
pathfinders
Area (deg^2)
10^4
10^3
100
10
1
0.1
ATLAS-SPT
SDSS-82
ATESP
ATCA-XMM-LSS
NEP
BOOTES
ATLAS
LBDS
FLS
ELAIS-S
ELAIS-N
JVLA-COSMOS
COSMOS
LH
PDF
SEP
NEP
VVDS
1
ASKAP-EMU
75% of sky
Rms=10µJy,
res ~ 10 arcsec
~70 million galaxies
Would take ~7 years with JVLA
VLA-NVSS
75% of sky
Rms=450µJy,
res ~ 45 arcsec
~1.8 million galaxies
5σ Sensitivity (mJy)

EMU Overview

Deep radio image of 75% of the sky (to declination +30°)

Frequency range: 1100-1400 MHz

40 x deeper than NVSS (the largest existing radio survey)
- 10 μJy rms across the sky

5 x better resolution than NVSS (10 arcsec)

Better sensitivity to extended structures than NVSS

Will detect and image ~70 million galaxies at 20cm

c.f. 2.5 million detected over the entire history of radio-astronomy so far

All data to be processed in pipeline

Images, catalogues, cross-IDs, to be placed in public domain

Survey starts 2017(?)

How does EMU differ from earlier surveys?

1. Scale – increases the number of known radio sources by a factor of ~30

2. Will not be dominated by AGN – about half the galaxies will be normal SF galaxies

3. Ambition – includes:

- Cross-identification with optical/IR catalogues
- Ancillary data (redshifts etc)
- Key science projects as an integral part of the project

4. Uses "Large-n astronomy" techniques

5. Explicitly includes "discovering the unexpected"

EMU and its pathfinders

Comparison: NVSS
3π sr, rms=450 μJy
1.8 million galaxies

ATCA – ATLAS
(2006-2013)
6 antennas single-pixel

7 sq deg
Rms=15 μJy
6000 galaxies

ATCA - SCORPIO
(2014-2016)
6 antennas single-pixel
Galactic (b=0)

4 sq deg
Rms=30 μJy
Hundreds of
Galactic objects

ATCA – ATLAS - SPT
(2013-2016)
6 antennas single-pixel

100 sq deg
Rms=40 μJy
30,000 galaxies
300 clusters?

ASKAP – early science
(2016)
12 antennas MkII PAF

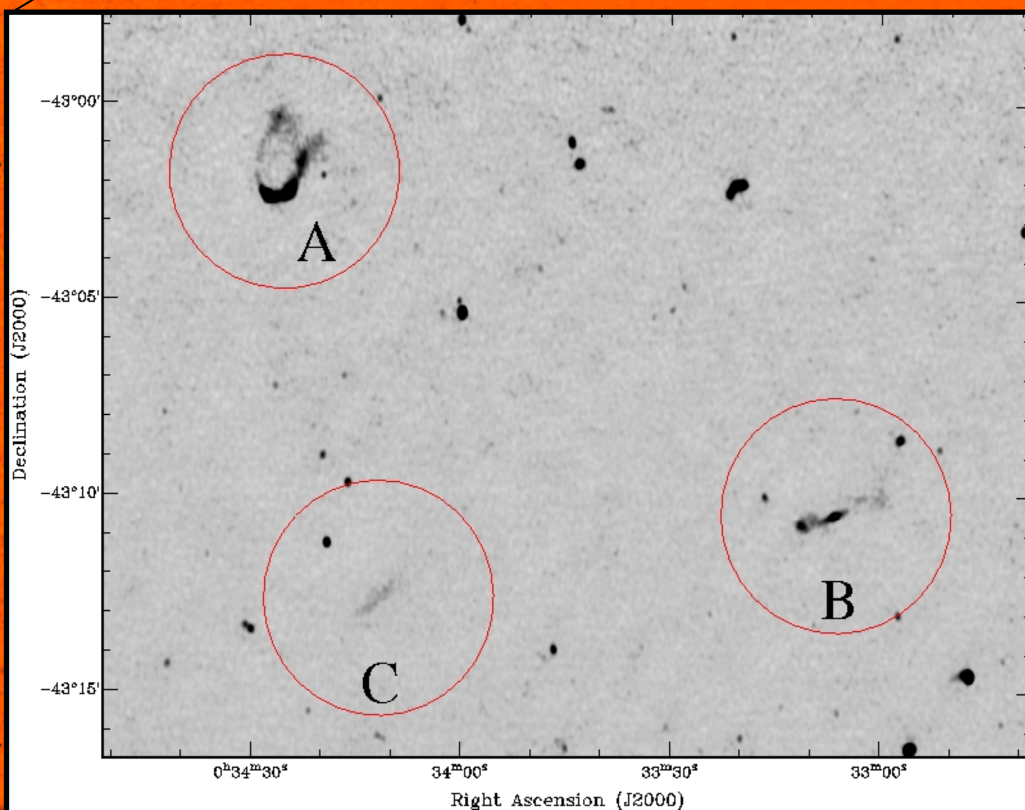
1000 sq deg
Rms=30 μJy
0.5 million galaxies

ASKAP – EMU
(2017-2018)
30-36 antennas MkII PAF

3π sr
Rms=10 μJy
70 million galaxies

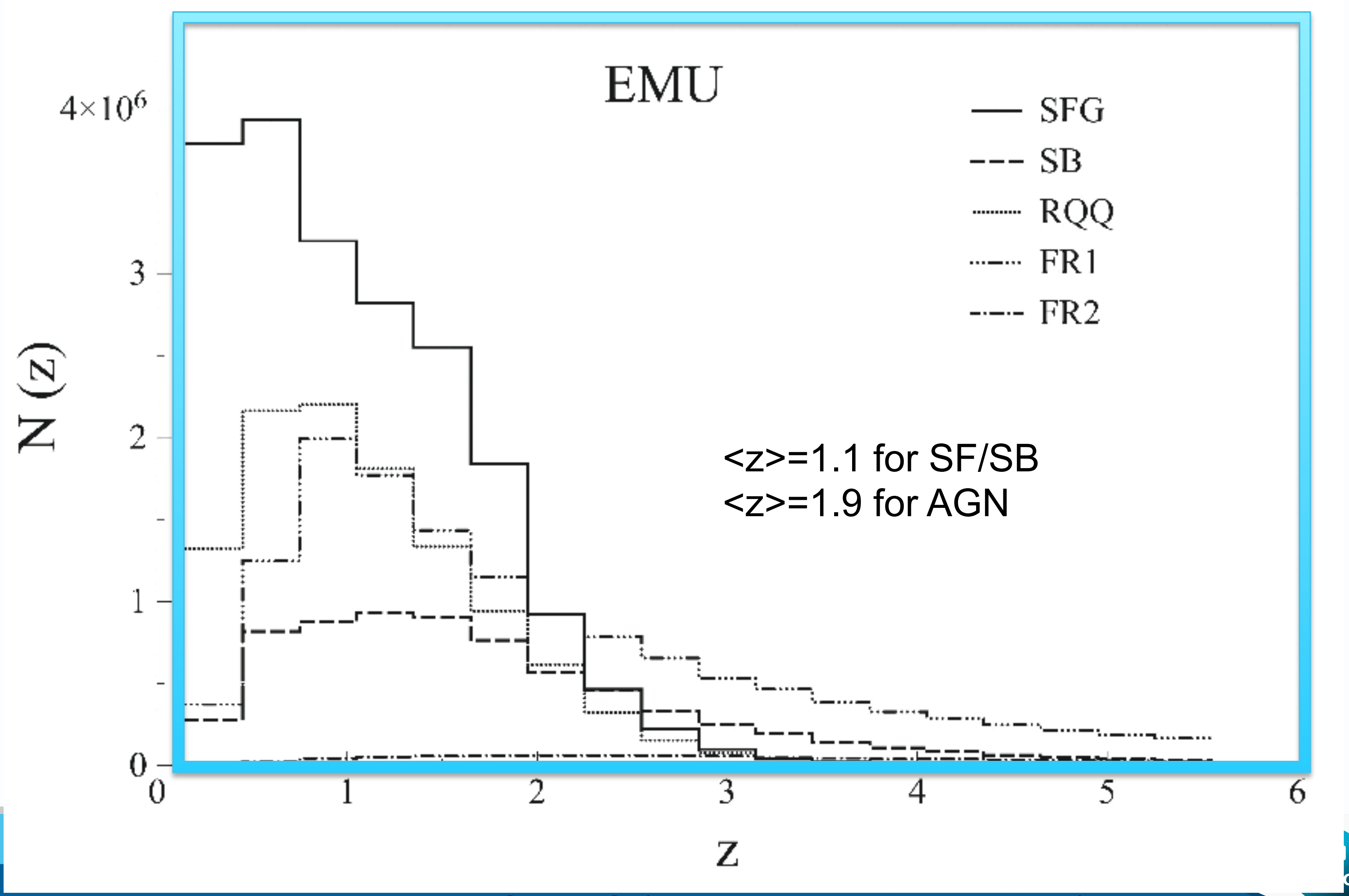
CSIRO

The EMU Pathfinder:
ATLAS=Australia Telescope Large Area Survey
7 sq deg to rms=15 μJy



Mao et al. 2010MNRAS.406.2578M

Redshift distribution of EMU sources



Based on SKADS (Wilman et al; 2006, 2008)

EMU Key Science Projects	Project Leaders
EMU Value-Added Catalogue	Nick Seymour
Characterising the Radio Sky	Ian Heywood
EMU Cosmology	David Parkinson
Cosmic Web	Shea Brown
Clusters of Galaxies	Melanie Johnston-Hollitt & Chiara Ferrari
Cosmic star formation history	Andrew Hopkins
Radio-loud AGN	Anna Kapinska
Radio AGN in the EoR	Jose Afonso
Radio-quiet AGN	Isabella Prandoni
Local Universe	Josh Marvil, Michael Brown
The Galactic Plane	Roland Kothes
SCORPIO: Radio Stars	Grazia Umana
WTF: Mining Data for the Unexpected	Ray Norris

EMU Key Science Projects

EMU Key Science Projects	Project Leaders
EMU Value-Added Catalogue	Nick Seymour
Characterising the Radio Sky	Ian Hey[illegible]
EMU Cosmology	Davi[illegible]
Cosmic Web	[illegible]
Clusters of Galaxies	[illegible]ie Johnston-Hollitt Chiara Ferrari
Cosmic star formation history	Andrew Hopkins
Radio-loud AGN	Anna Kapinska
Radio AGN in the EoR	Jose Afonso
Radio-quiet AGN	Isabella Prandoni
Local Univers[illegible]	Josh Marvil, Michael Brown
The Gal[illegible]e	Roland Kothes
SCO[illegible]dio Stars	Grazia Umana
[illegible]ning Data for the Unexpected	Ray Norris

How does the Universe evolve?

Examples of EMU Development Projects

Developers earn co-authorship on key science papers

- Ensure the EMU database satisfies our storage and access needs (both CASDA and value–added, and interactions with other data centres/VO)
- Develop, set up, and implement the data quality/validation process
- Ensure ASKAPSOFT imaging satisfies EMU needs
- See what special imaging is needed for the Galactic Plane
- Ensure ASKAPSOFT source extraction satisfies EMU needs

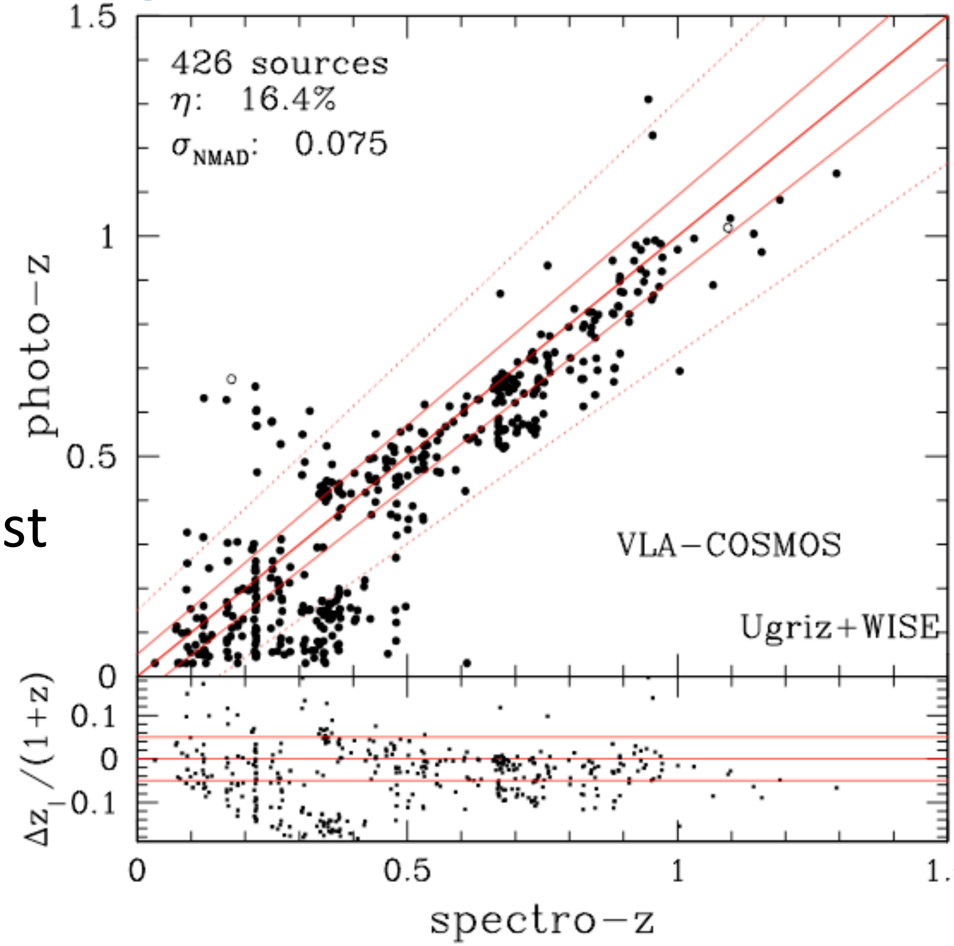
For Level 6 data

- Develop algorithms for extraction of diffuse emission
- Develop the self-ID and cross-ID algorithms
- Develop an "optimum photo-z algorithm" for all EMU and an optimum photo-z strategy for those smaller areas of EMU covered by other surveys such as DES
- Develop techniques for Statistical redshifts & Spatial Cross-correlation redshifts
- Explore other EMU ap[illegible]ne Learning

For Level 7 data

EMU (Statistical) Redshifts

- We will measure spectroscopic redshifts for only ~2% of EMU sources (WALLABY, TAIPAN, etc)
- Even photometric redshifts are hard to do well (SkyMapper)
  - But many of our science goals don't need accurate z's – they just need a redshift bin
- Several machine-learning algorithms are being tried (e.g. kNN, right)

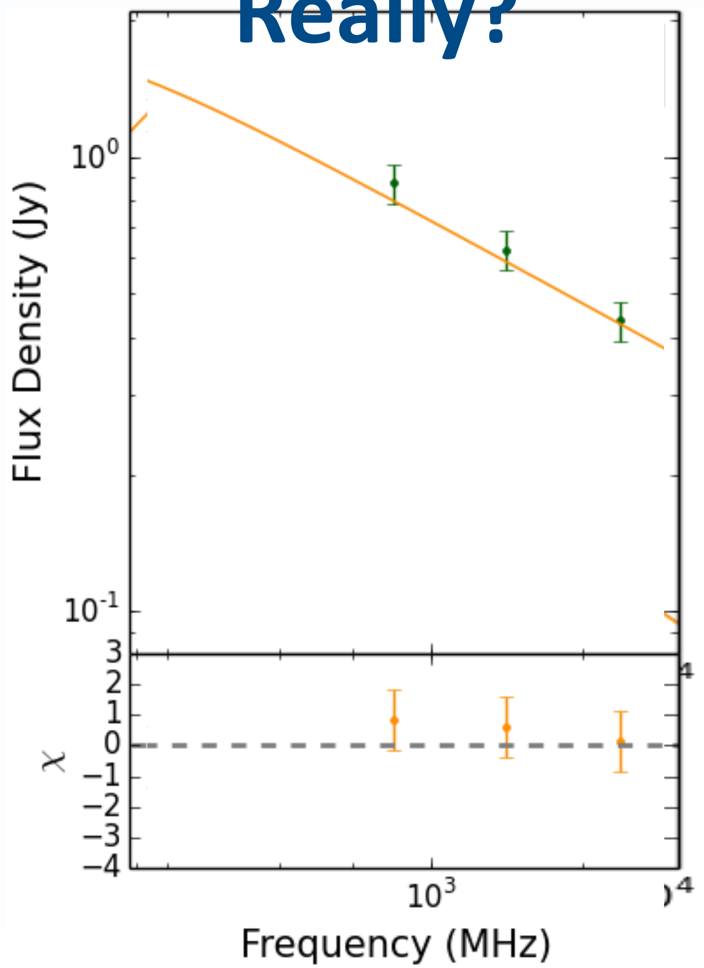


From Salvato, Zinn, ++ in preparation)

"There's nothing as useless as a radio source"

(Jim Condon, 2011)

Really?



Available multiwavelength radio photometry of EMU sources in 2017-2018

Survey	% of EMU sources
MWA (low frequency) LOFAR (low frequency) POSSUM (polarisation) All others (GMRT,Meerkat, VLA etc)	10-20% 10-20% ~10% ~10%

Later: VLASS, etc
Eventually: SKA?

Available spectroscopy of EMU sources in 2017-2018

Survey	% of EMU sources
WALLABY HI spectroscopy TAIPAN optical spectroscopy All others (SDSS, 2dFGRS, DEEP2, etc)	1% 1% ~1%

Later: WAVES, 4MOST, etc, etc

Available multiwavelength optical/IR photometry of EMU sources in 2017-2018

Survey	% of EMU sources
WISE (IR) VHS (IR) Skymapper (optical) All others (SDSS, DES, etc)	50-70% 30-50% 30-50% ~20%

Later: LSST, Pan-Starrs, etc

Why are we exploring photo-z techniques? (Haven't the optical guys got it all sorted?)

- Instead of accurate z's, we want to place sources in redshift bins with high reliability (and known pdf)
- Only 70% of our sources will have optical/IR photometry – we want to use the non-detections
- Can also use radio properties – e.g. polarisation, morphology, and radio photometric data
- These are best handled using machine-learning techniques
- Expect to be able to place most EMU sources into redshift bins, but much more work needed
- Also using ML for classification and cross-ID

EMU C[illegible]ology
(leade[illegible]d Parkinson)

Warning: I am not a cosmologist!

The ecological niche of EMU Cosmology

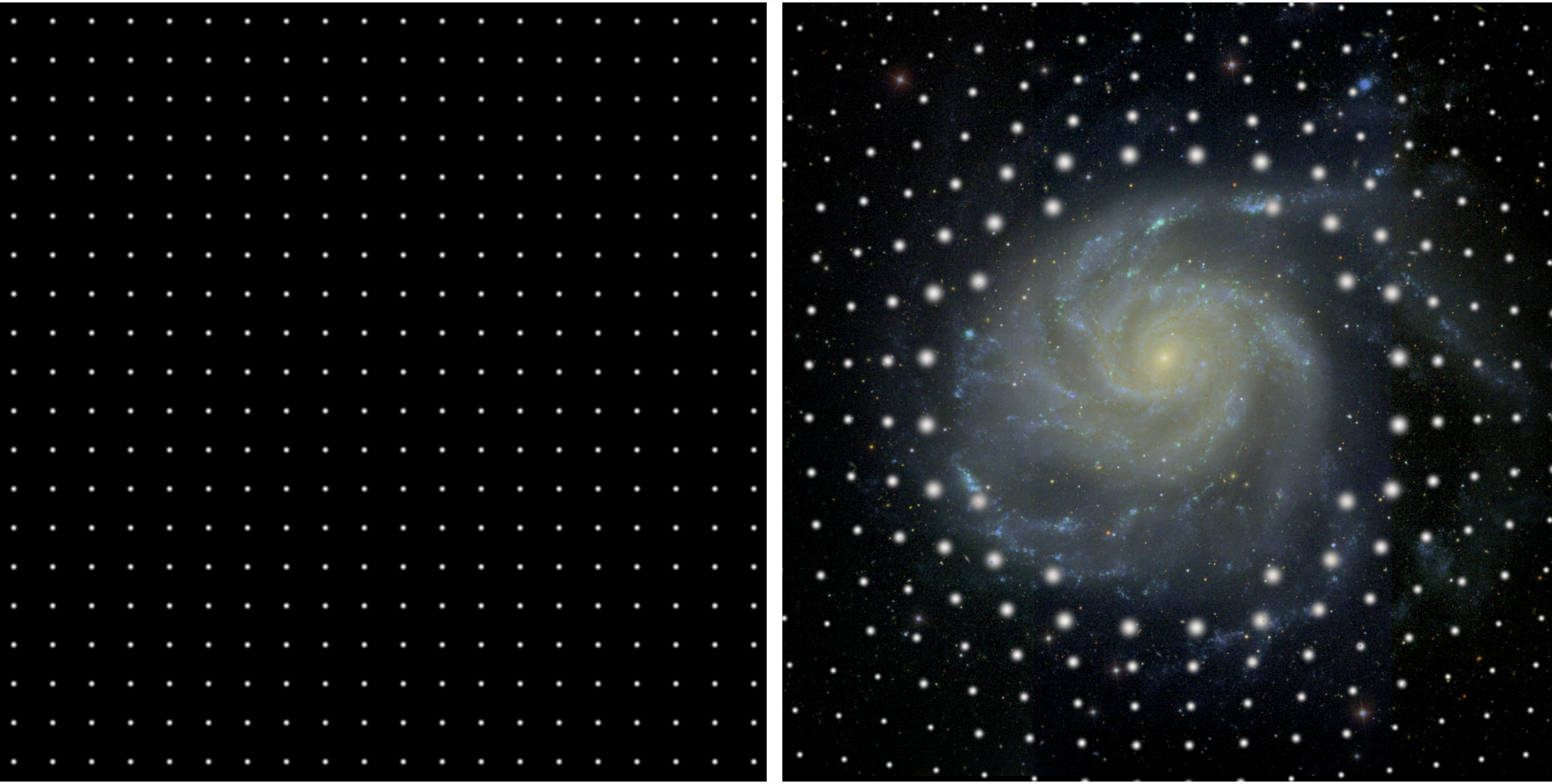
- **(nearly) all sky**
  - Uniform coverage over 3π steradians
  - (or 4π with Westerbork-WODAN)
- **High redshift**
  - <z>~1.5, or <z>(AGN)~1.8
- **High space density**
  - ~2000 sources per square degree, 70 million total
- **Provides <u>independent</u> measurement**
- **Low spatial resolution**
  - θ ~ 10 arcsec, so can't use cosmic shear
- **Incomplete redshift information**
  - We don't have 70 million spectroscopic redshifts!
  - But we do have significant statistical redshift information
  - Can divide EMU sources into redshift bins

Cosmological Observables

EMU can (in principle) measure four different cosmological observables:

1. **Angular correlation function of EMU galaxies**
2. **Cosmic Magnification of high-redshift EMU galaxies by low-redshift optical foreground galaxies**
   - **Cross correlation of EMU and (e.g. Skymapper or TAIPAN) sample**
3. **Cosmic Magnification of CMB by EMU galaxies**
   - **Cross-correlation between EMU density and CMB on small scales**
4. **Integrated Sachs-Wolfe effect**
   - **Cross-correlation between EMU density and CMB on large scales**

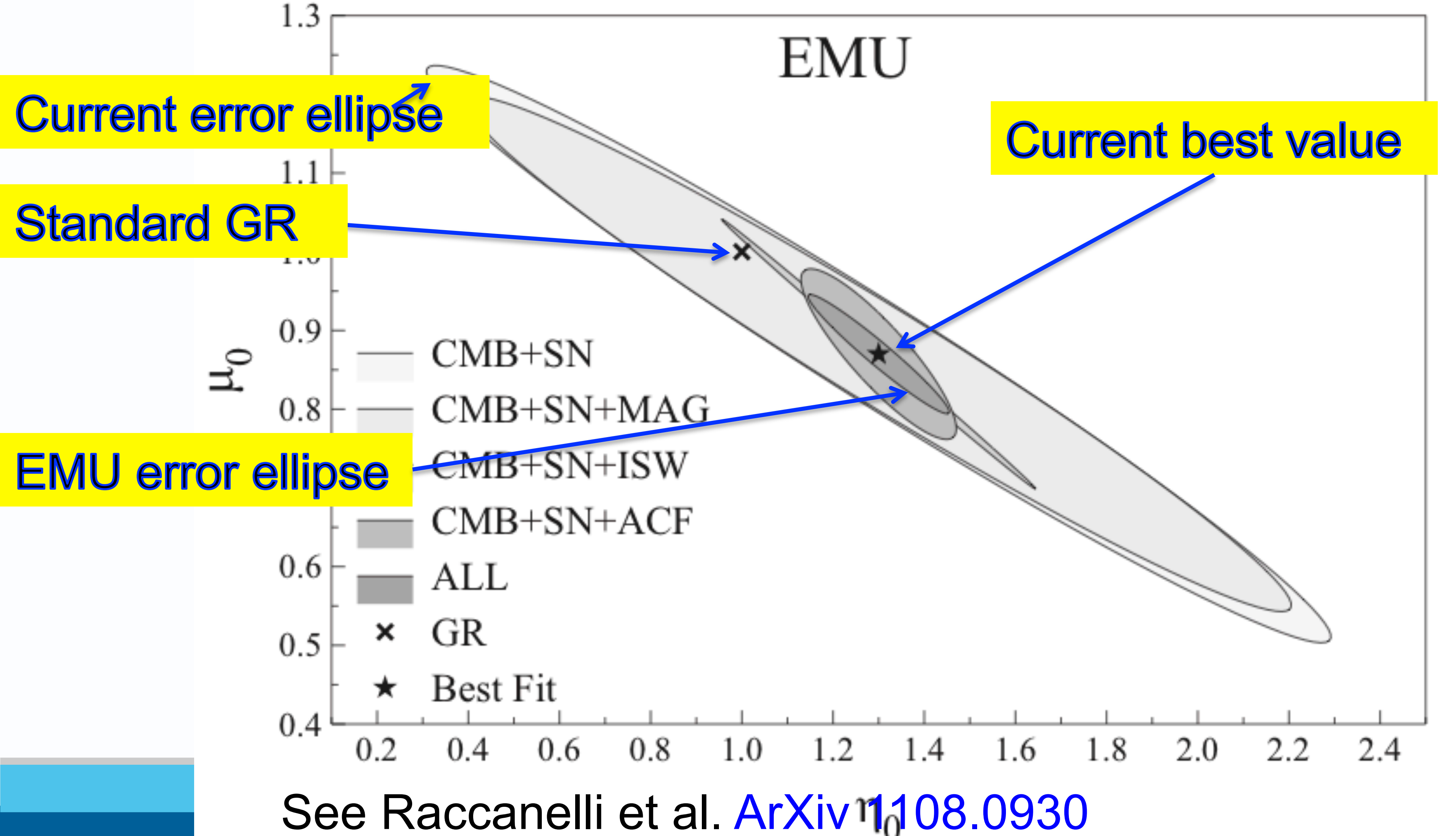
Cosmic Magnification



Don't need to know individual z's, just the z-distribution

BUT do need to ensure there is no overlap between samples

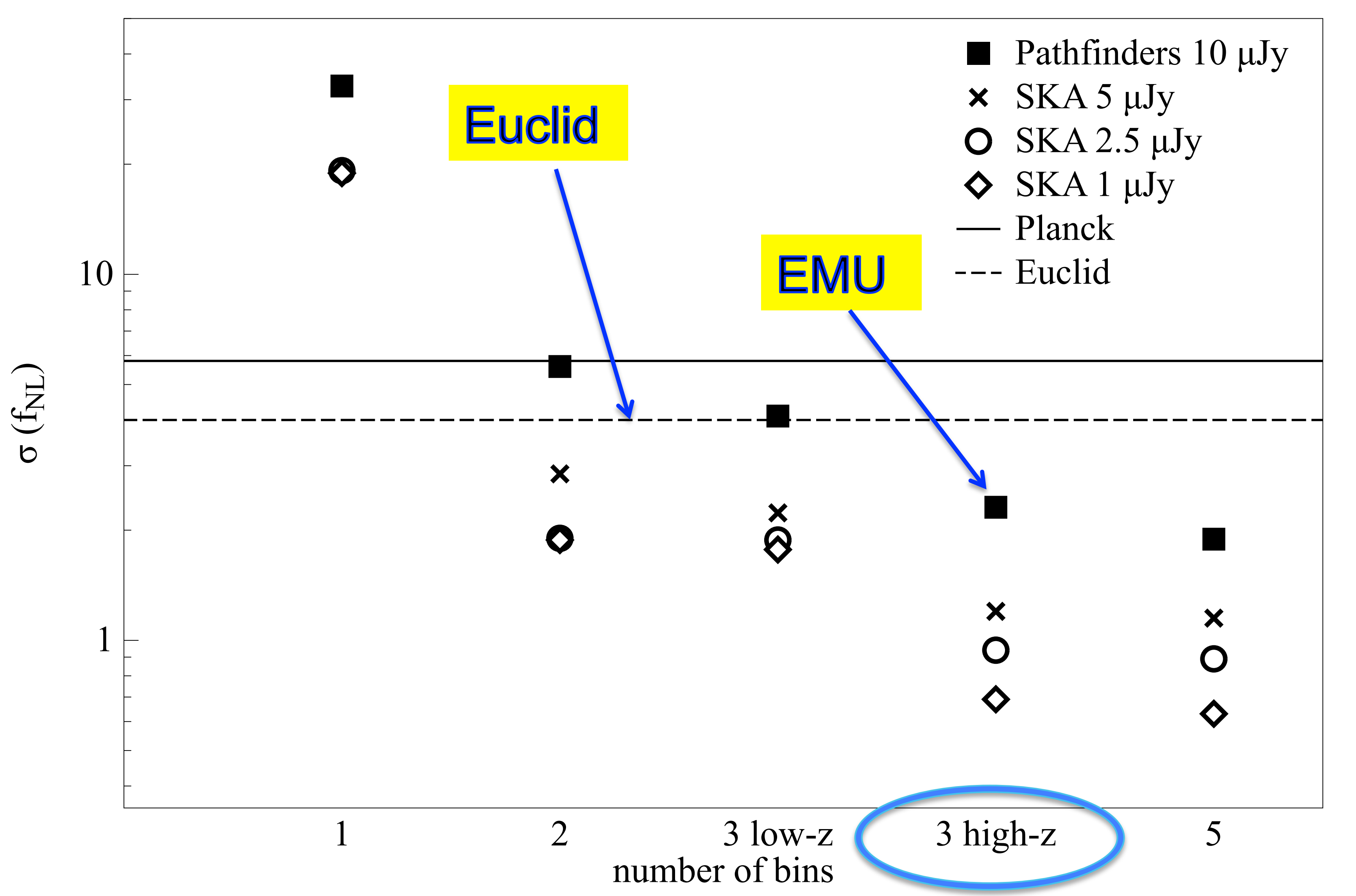
Modified Gravity from ISW (assuming no redshifts)



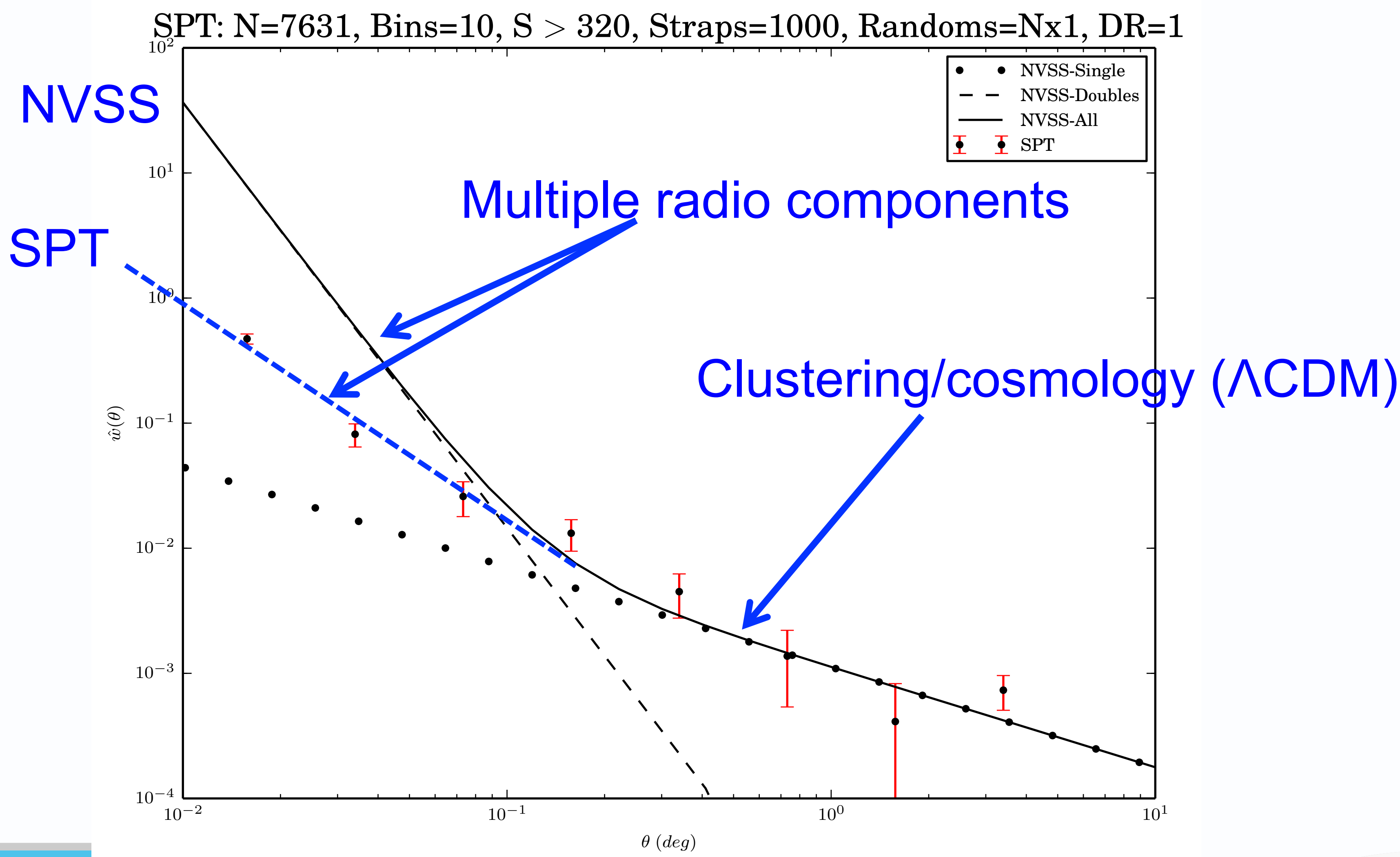
See Raccanelli et al. ArXiv 1108.0930

Non-gaussianity

Raccanelli et al., 2014, arXiv1406.0010



Progress report from PhD student Glen Rees
E.g Spatial autocorrelation function on ATLAS-SPT

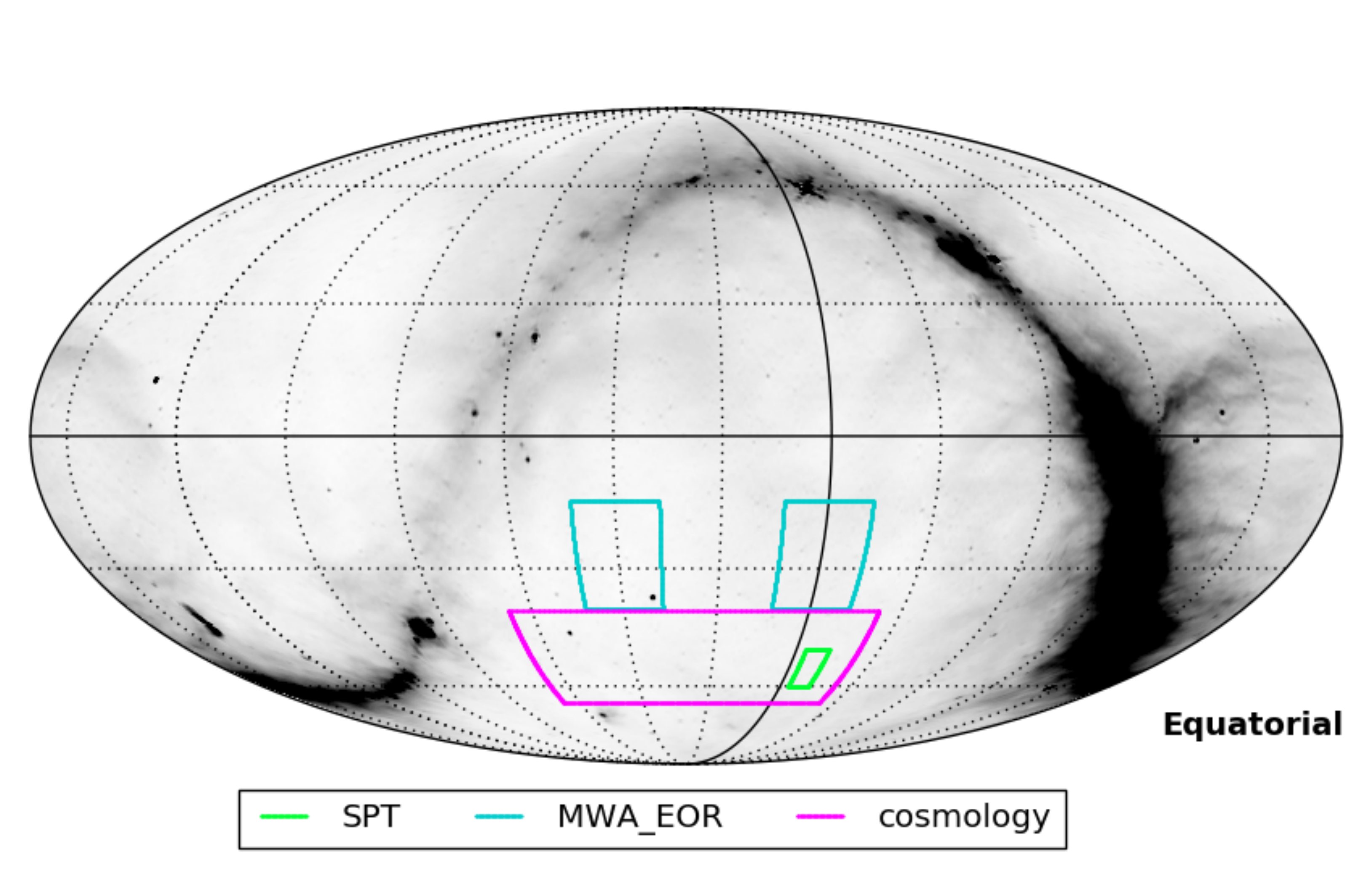


Cosmology in EMU Early Science (late 2016/early 2017)

Want widest, contiguous area with largest number of galaxies, and good overlap with other large-area surveys

- Area: 2000 sq. deg.
- Freq: 800-1100 MHz
- Rms: 80 uJy/bm
- Time: 200 hours
- Number density: 150 sources/deg^2
- Total Number of sources: ~300,000 sources

Proposed region



EMU Early Science
Cosmology Objectives

- Test/develop cosmology pipeline
- Characterize sample
- Cross-correlate with other surveys (CMB, optical)
- Early cosmology results (auto-correlation, cosmic magnification, bias measurement)
- Maybe even a competitive measurement

EMU Early Science
Cosmology Outcomes

Testing and development of analysis pipeline

Cosmological observables

- Auto-correlation function
- Cross-correlation with the CMB: to determine bias and characterise our sample.
- Cross-correlation with a low-redshift optical sample (either Skymapper or DES): to measure cosmic magnification

Conclusions – the positives

- EMU will increase # of radio sources from 2.5 million to 70 million
- EMU turns radio continuum into a powerful cosmological tool, giving uncertainties competitive with other techniques
- EMU will give you an <u>independent</u> measurement of cosmological parameters
- EMU probes a larger volume than most other tests
- EMU sources are at high-z, enabling new tests like (e.g.) cosmic magnification of CMB

CSIRO

Conclusions – the caveats

- We need to understand the bias for EMU sources
  - particularly radio-loud AGN
- We need to understand the effect of systematic errors
- EMU will be valuable without z's, but will be far more valuable with z's – we need to develop techniques
- We need to develop the EMU cosmology pipeline
  - it's "just" software!
- EMU sources are at high-z, enabling potential new tests
  - e.g. cosmic magnification of CMB
- We need help!

Conclusions – the caveats

- EMU will increase # of radio sources from 2.5 million to 70 million
- It is potentially a powerful cosmological tool for cosmology
- We will be able to test cosmological models using four different probes: the autocorrelation function, ISW effect, and cosmic magnification of high and low redshift sources

We acknowledge the Wajarri Yamaji people as the traditional owners of the ASKAP site

See our newsletter on http://tinyurl.com/emunews