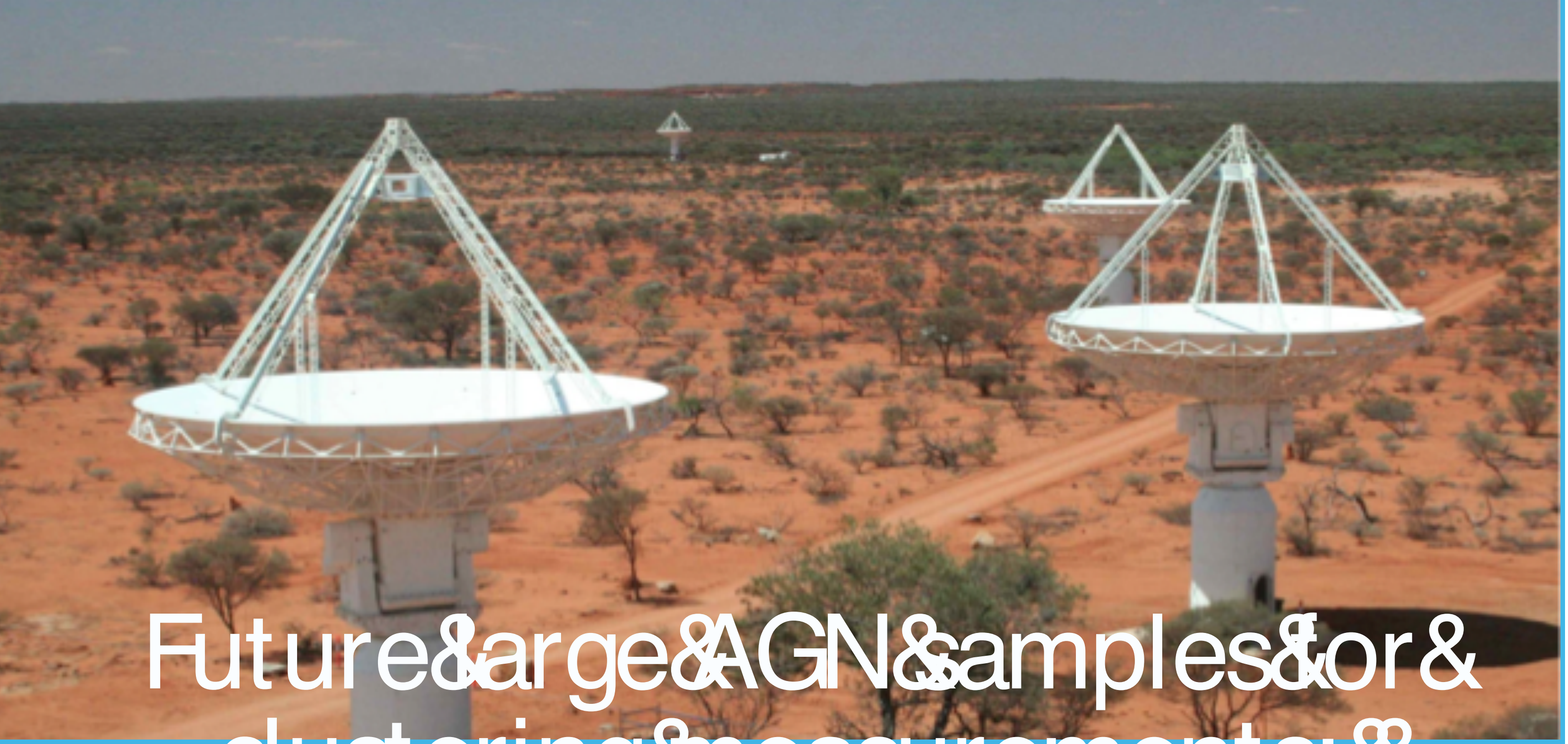


Future&large&AGN&samples&for& clustering&measurements:&& EMU&and&its&AGN&sample&

CSIRO&ASTRONOMY&AND&SPACE&SCIENCE&(CASS)&
www.csiro.au

Ray&Norris,&CSIRO&Astronomy&&&Space&Science&
June&2014&
!

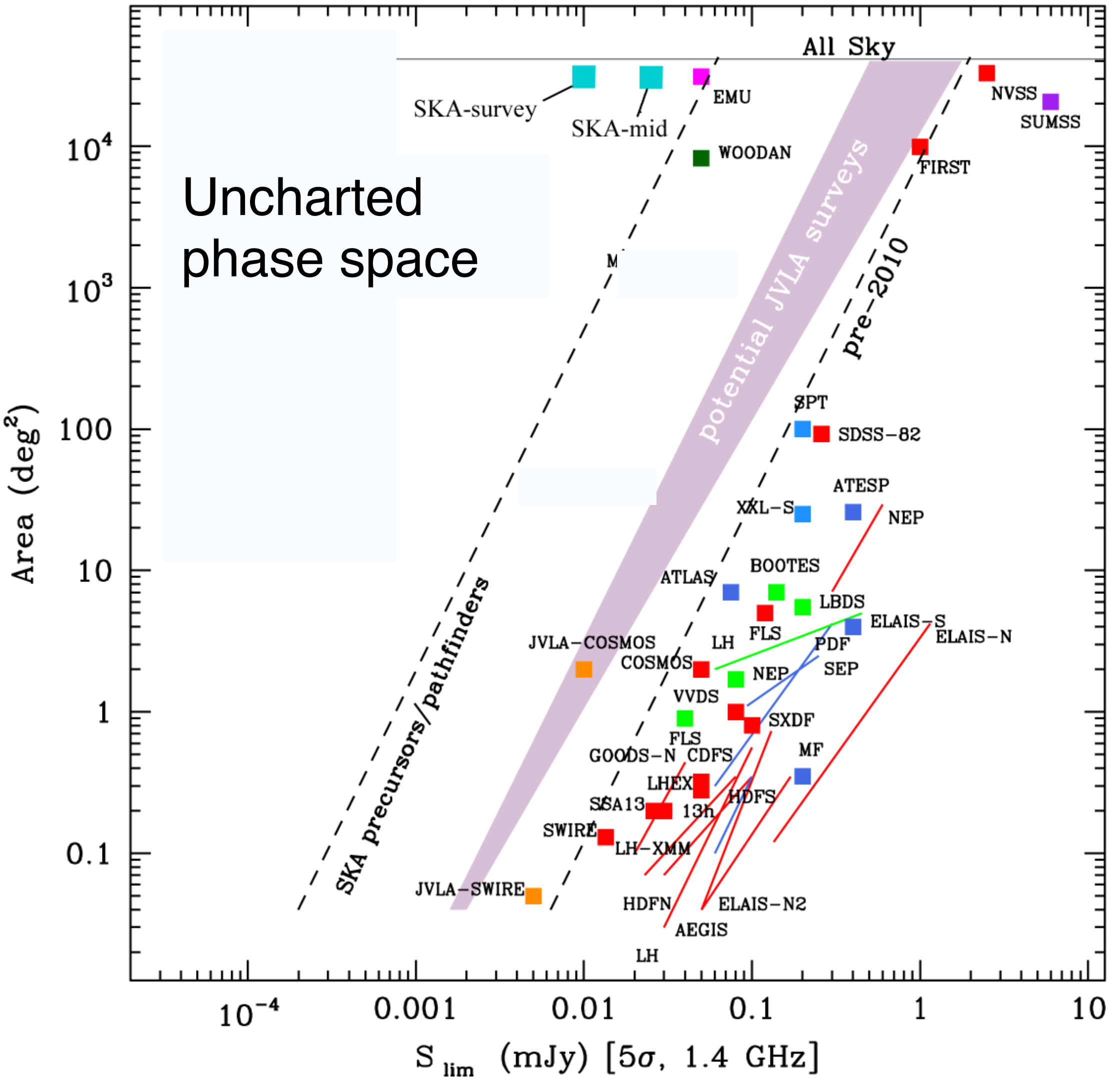


Diagram courtesy of Isabella Prandoni

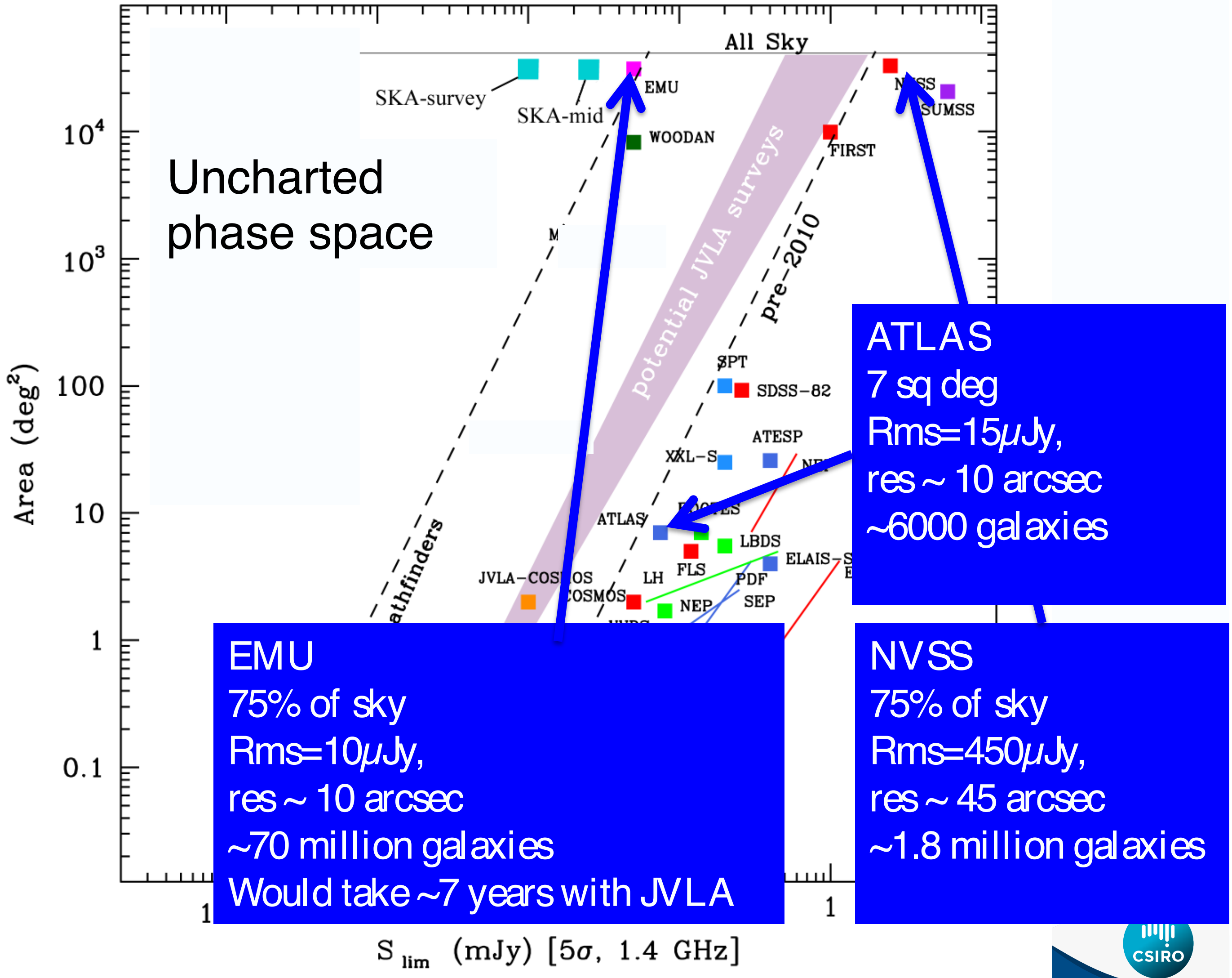


Diagram courtesy of Isabella Prandoni

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 – ATLAS - SPT
(2013-2015)
6 antennas single-pixel

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

ASKAP – EMU early
(2015-2016)
12 antennas MkII PAF

1000 sq deg
Rms=30 μJy
0.5 million galaxies

ASKAP – EMU
(2016-2018)
30-36 antennas MkII PAF

3π sr
Rms=10 μJy
70 million galaxies

SKA1-SURVEY
(2022-????)
96 antennas MkIII PAF

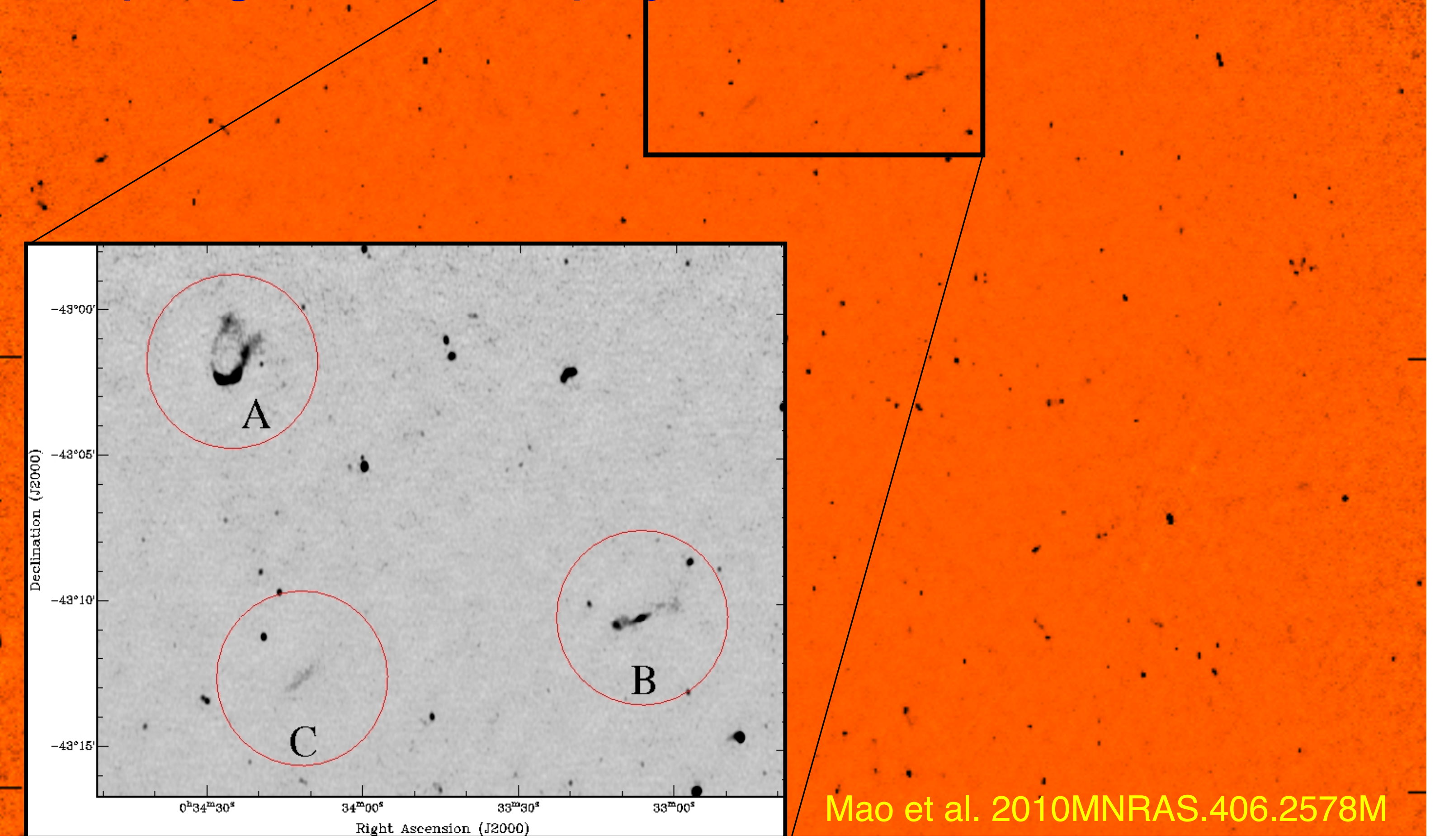
3π sr
Rms=2 μJy
500? million galaxies

7 sq deg in CDFS, ELAIS-S1 SWIRE fields
15 uJy rms, plus polarisation, spectral index, etc.
Deep coverage from SWIRE, SERVS, Hermes, VIDEO, etc
Also spectroscopy, photometry, etc

Data Release 1: Norris et al. 2006, Middelberg et al. 2008
Data Release 2: Hales et al. 2013
Data Release 3: Franzen et al 2014, Banfield et al. 2014
Other multiwavelength follow-up, VLBI, etc.
Collaborations with Hermes, VIDEO, DES, etc.

Science:
Galaxy evolution (Lilly-Madau diagram, luminosity function, etc)
AGN evolution (CSS, GPS, IFRS, Hi-z AGN, etc)
AGN feedback & environment
Clusters, etc

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



Mao et al. 2010MNRAS.406.2578M

ASKAP
Australian SKA Pathfinder

A$170M (=€120m) project now under construction in Western Australia

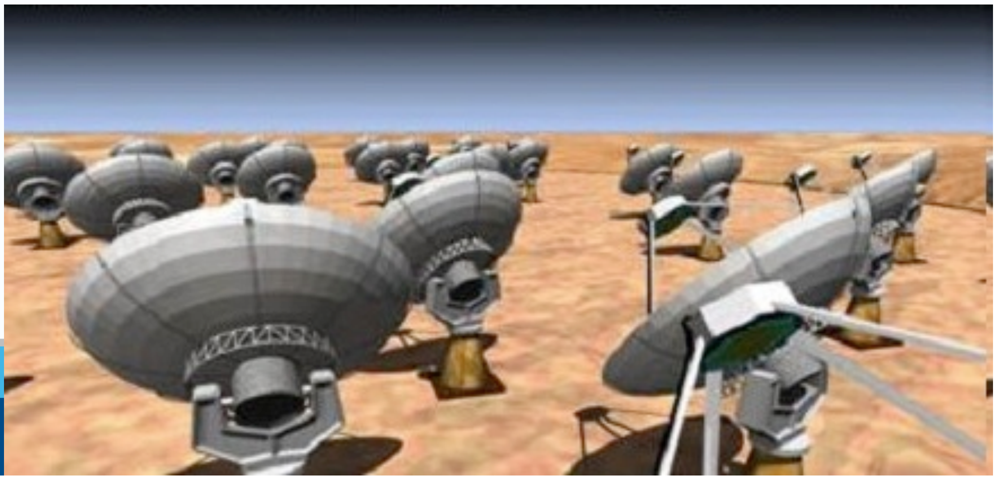
First shared-risk science (with 12 antennas) ~ mid-2015

Completion 2016-7?

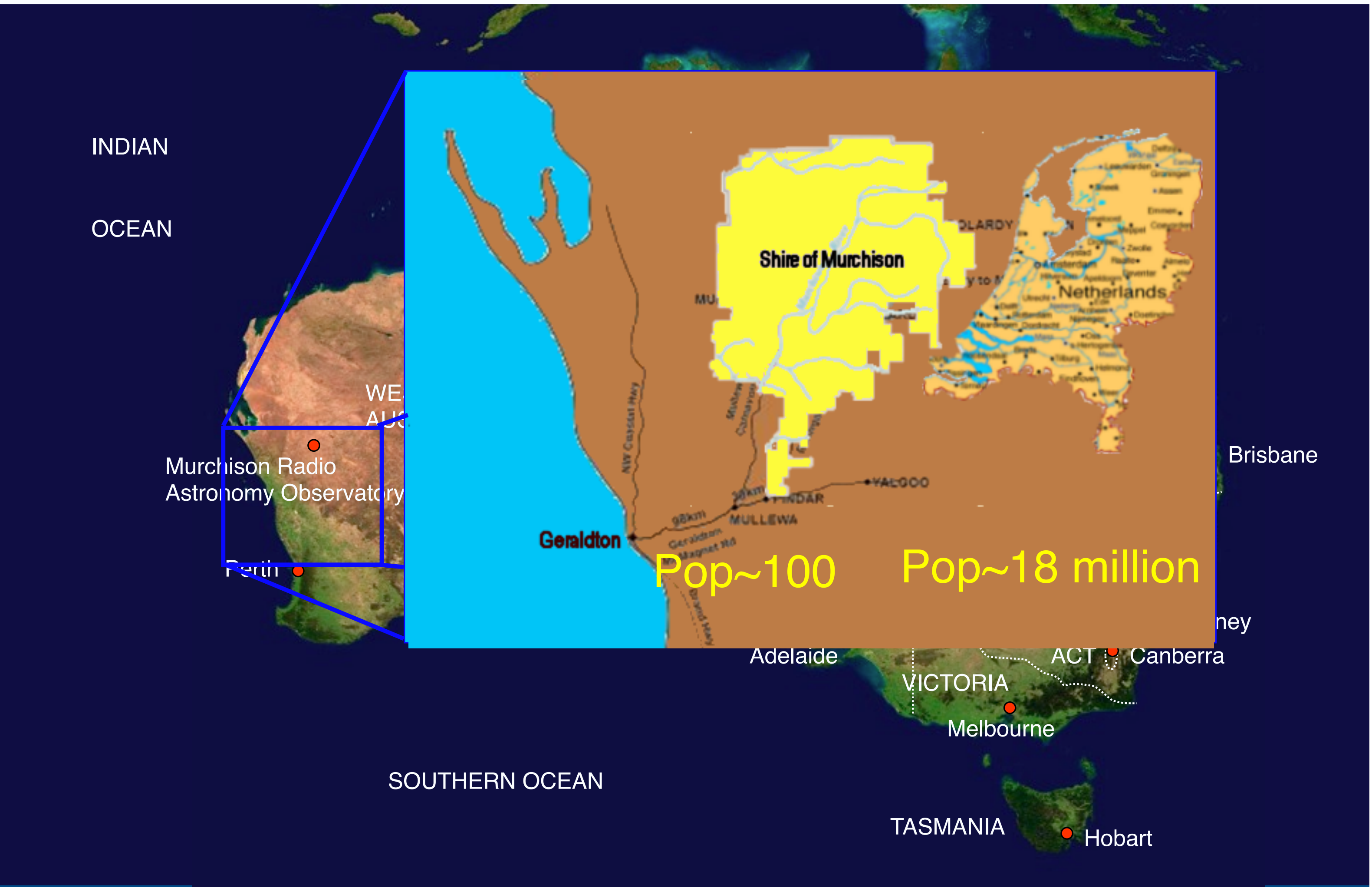
36*12m antennas

Antennas have a 192-pixel phased array feed (PAF)

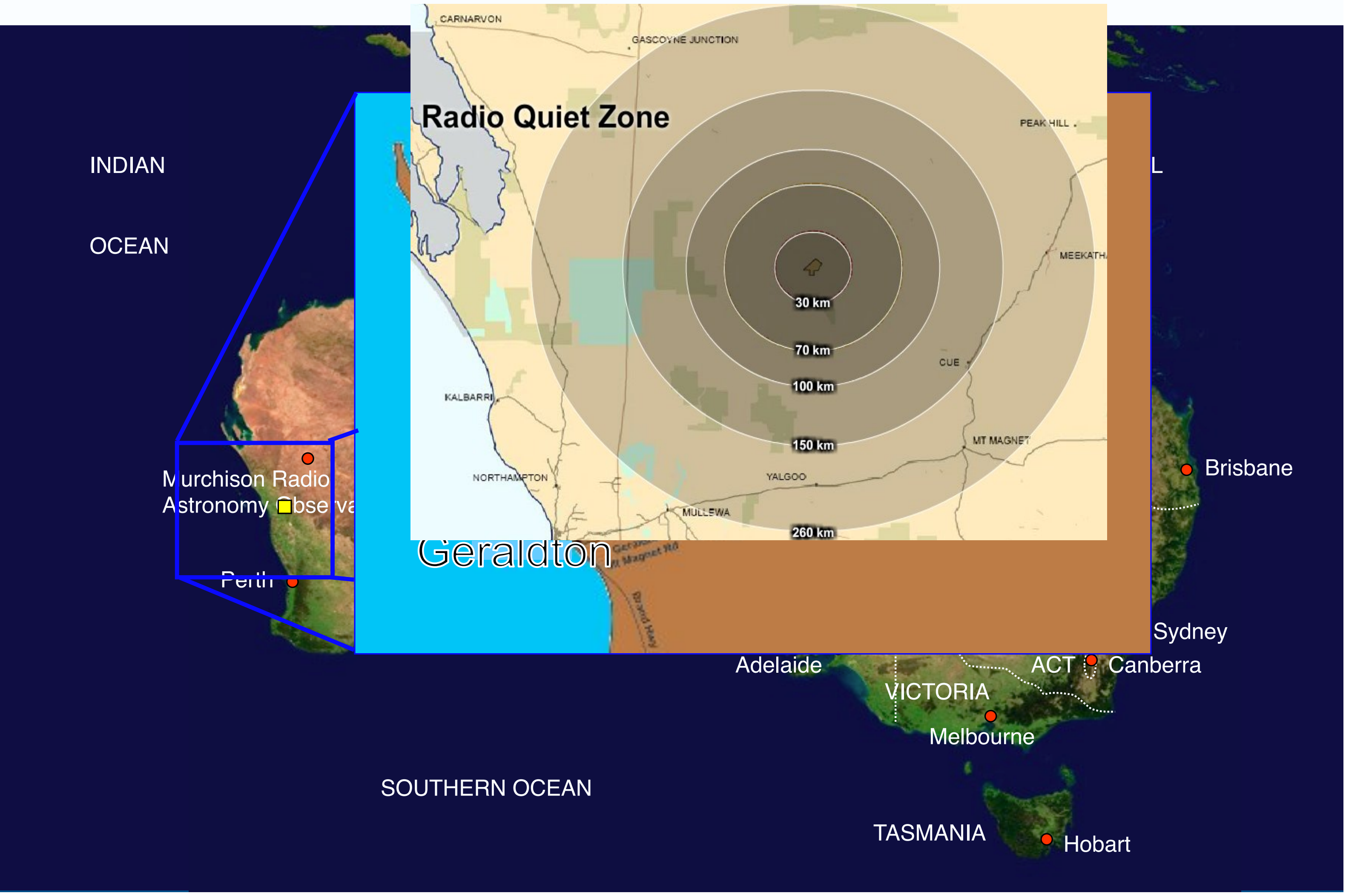
30 sq. deg FOV!



Australia – WA – Midwest – Murchison

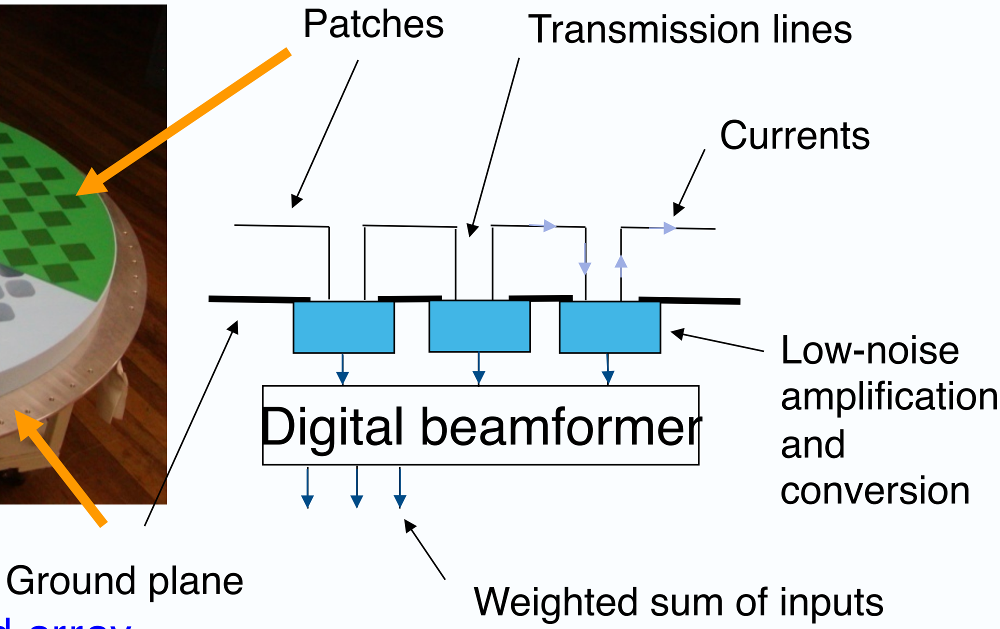


Australia – WA – Midwest – Murchison



Population density ~ 1 nanoperson m^{-2}

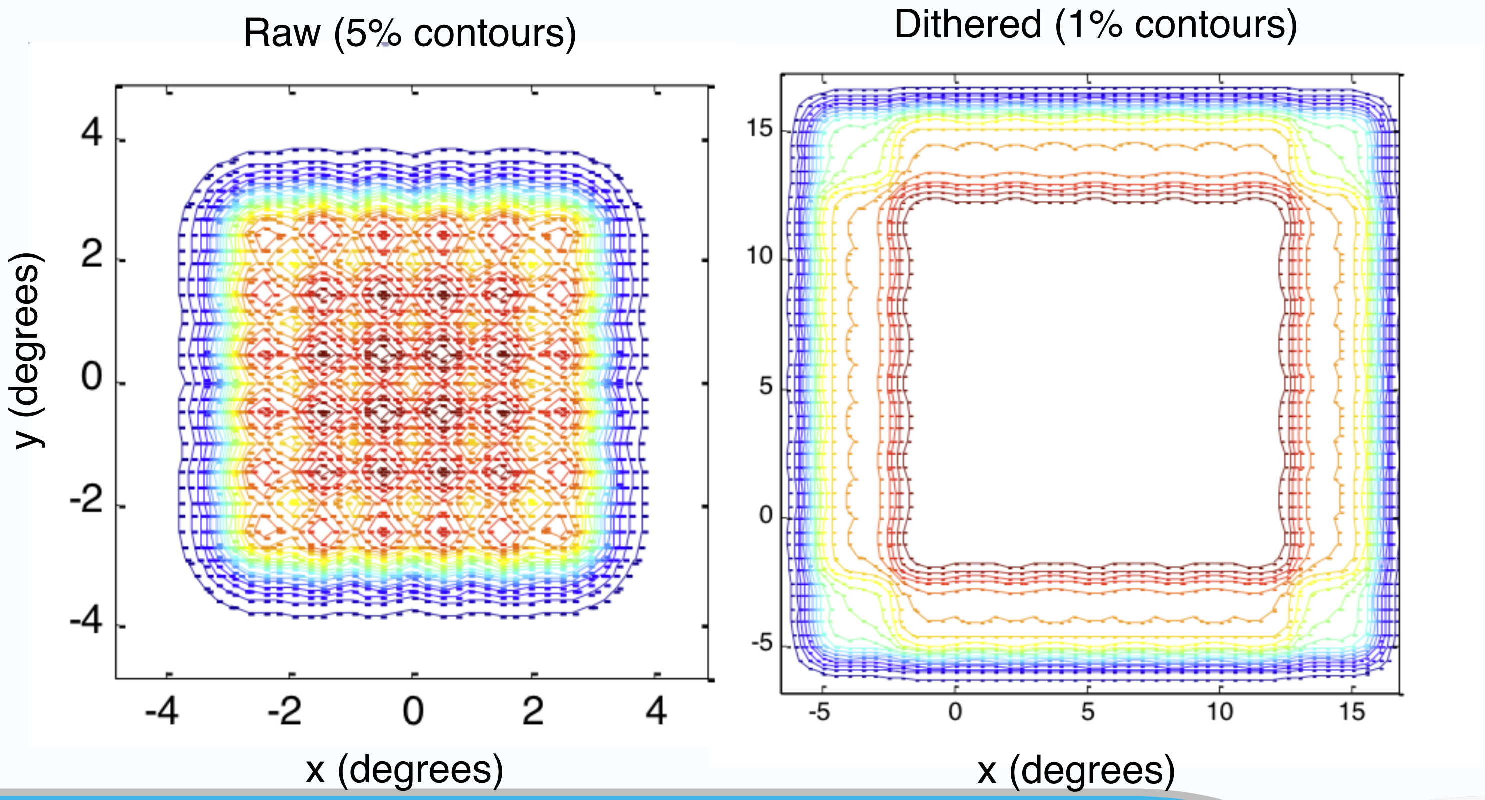
ASKAP 188-element Phased Array Feed



- Connected checkerboard array
- Self-complementary screen (Wide band - Babinet's principle)
- Operating range defined by electromagnetics and LNA
    - 700-1800 MHz

Total bandwidth = 2.1THz per antenna

ASKAP PAF footprint




ASKAP Opening October 2012
ASKAP Opening Ceremony
5 October 2012

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)

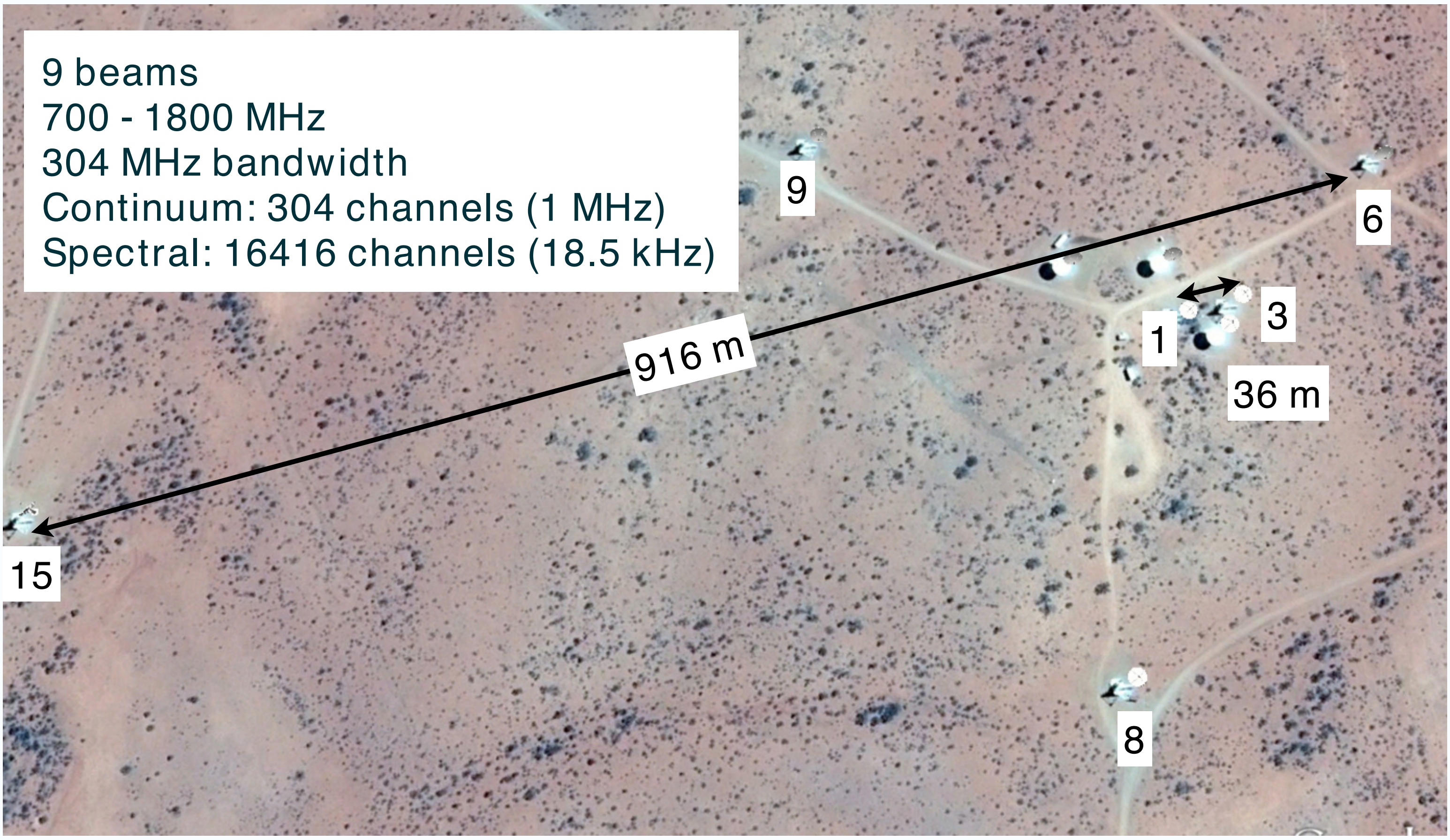
8 others at a slightly lower priority

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

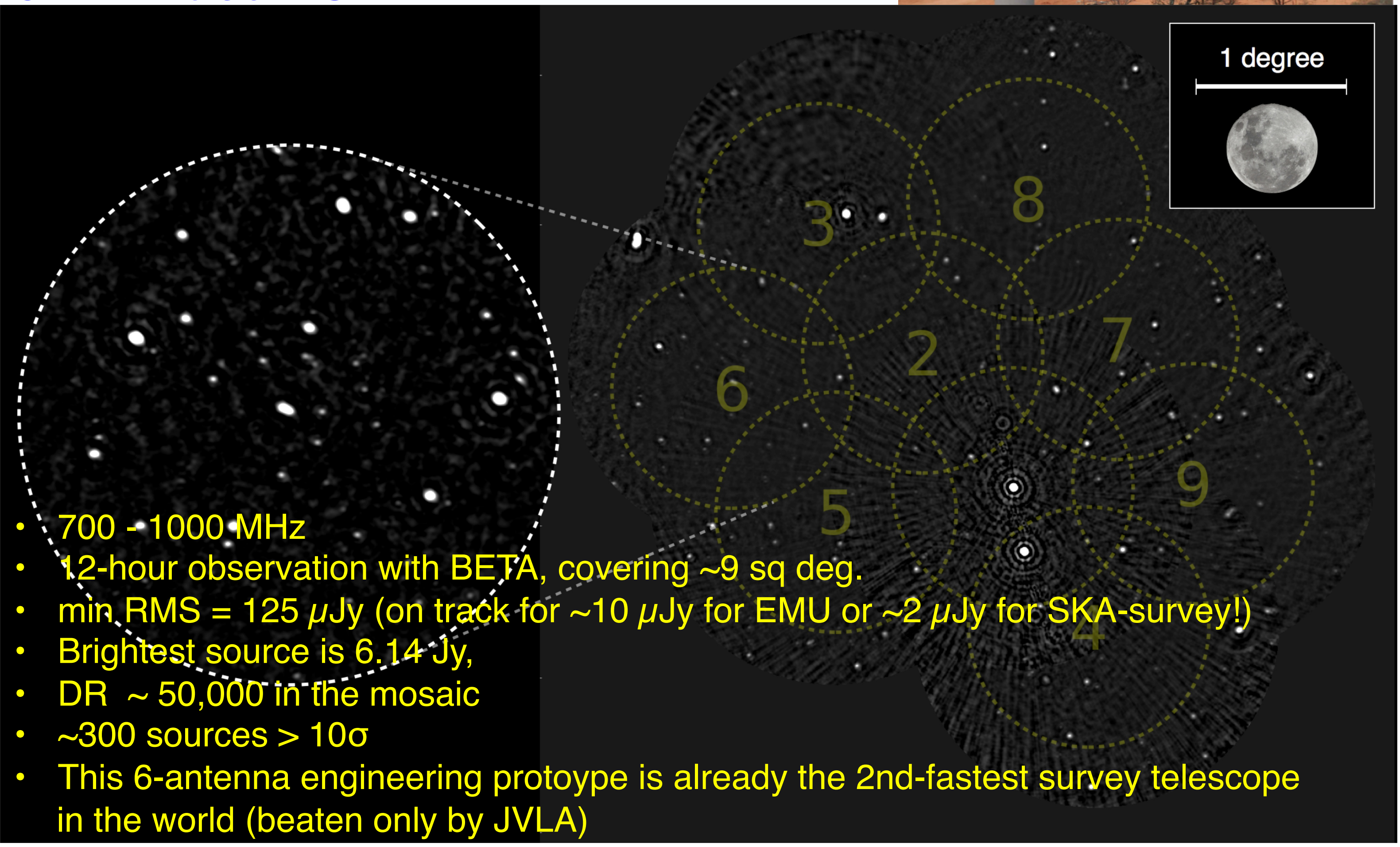
Current status

- All antennas and infrastructure completed
- 6-PAF-antenna BETA array currently operating with 9 beams
- Undergoing commissioning and debugging while final MkII (ADE) PAFs are being built
- Expect to have first MkII PAF at MRO in ~ July 2014
- Expect to have 8 MkII PAFS installed by ~Feb 2015
- Currently doing BETA science
- Mid 2015: “shared risk” ASKAP early science starts at night/ weekends
- Funding currently in hand for 30 ADE PAF’s
- 2016-7?????? Full ASKAP-36 available ??????

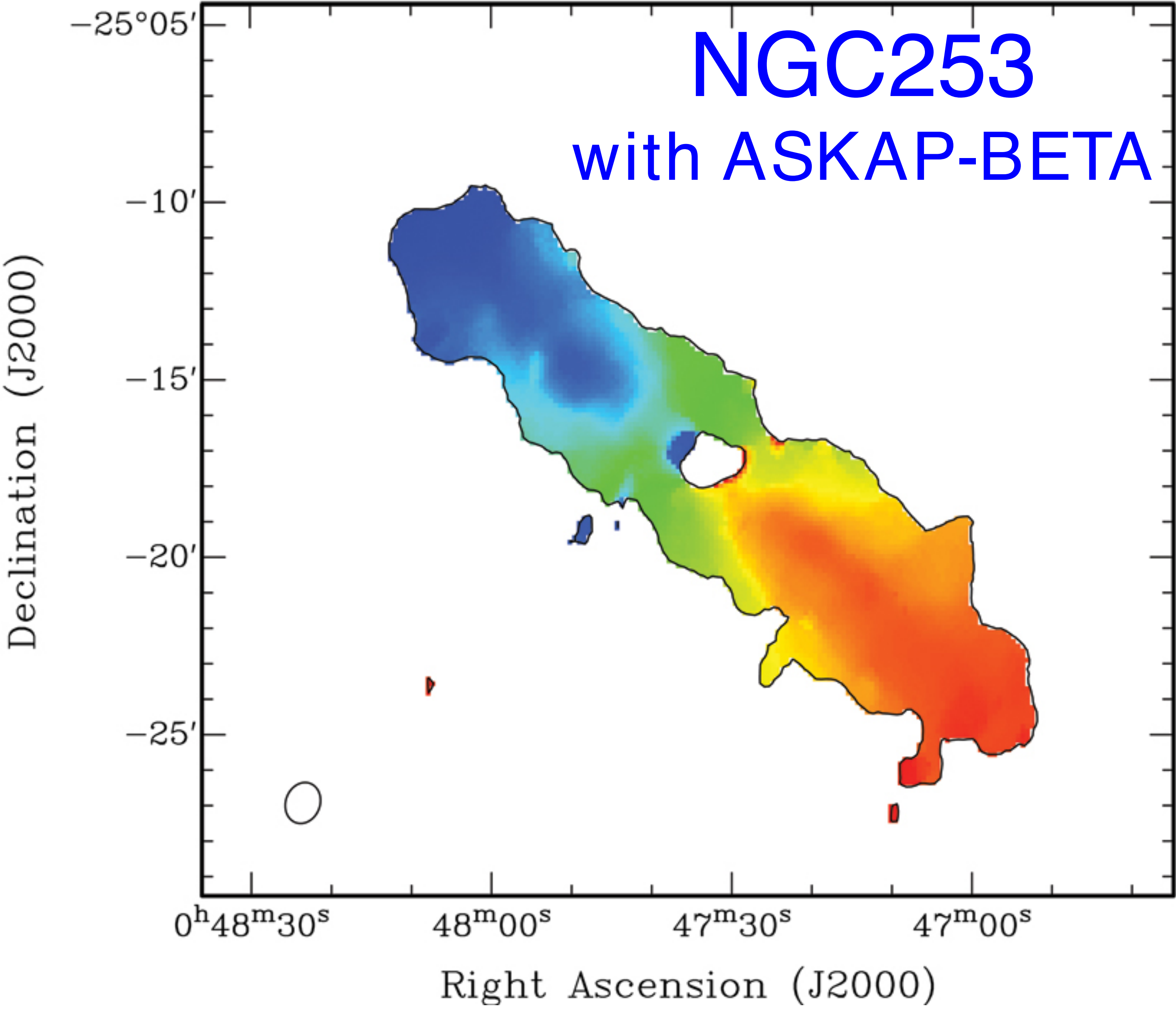
BETA%the%telescope



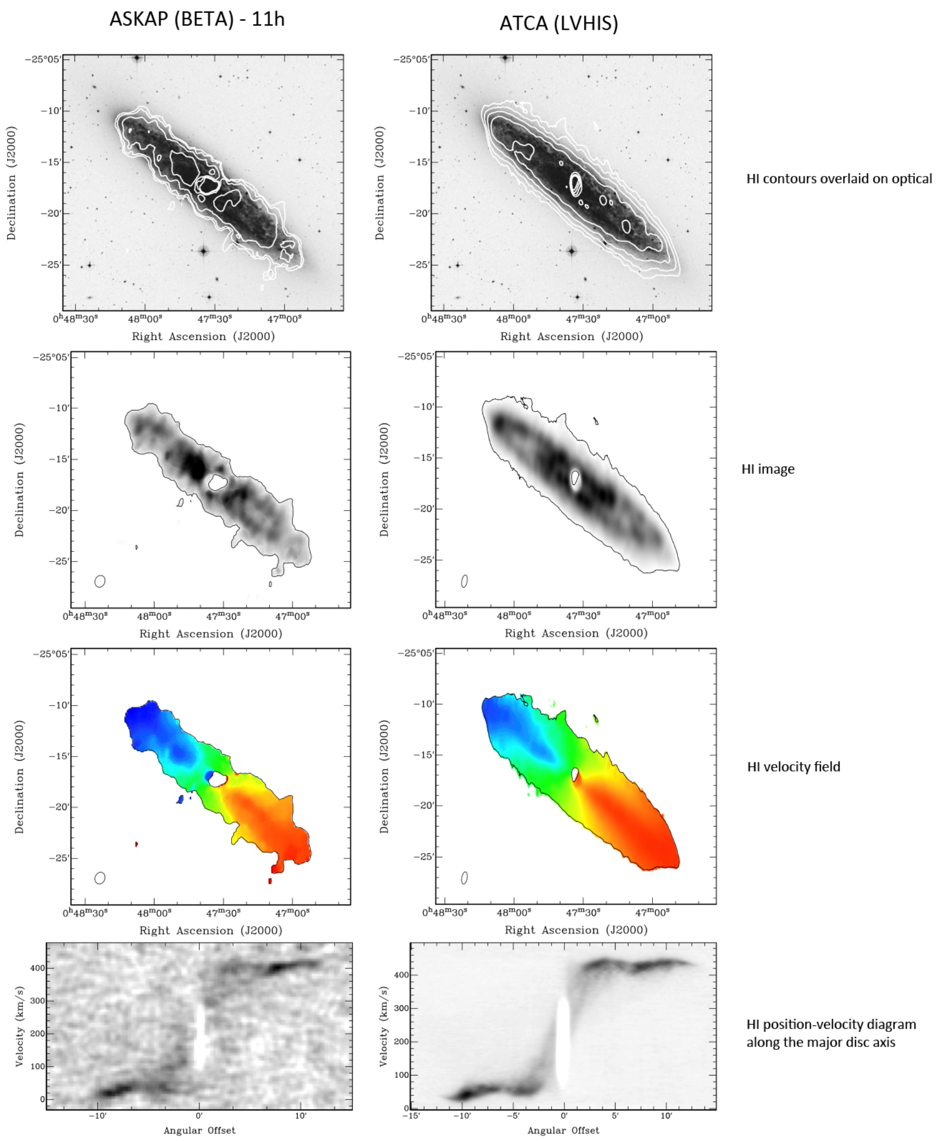
PAFs work!
6-antenna ASKAP-BETA with 9 PAF beams



- 700 - 1000 MHz
- 12-hour observation with BETA, covering ~9 sq deg.
- min RMS = 125 μJy (on track for ~10 μJy for EMU or ~2 μJy for SKA-survey!)
- Brightest source is 6.14 Jy,
- DR ~ 50,000 in the mosaic
- ~300 sources > 10σ
- This 6-antenna engineering protoype is already the 2nd-fastest survey telescope in the world (beaten only by JVLA)


NGC253
with ASKAP-BETA
−25°05′
−10′
−15′
−20′
−25′
Declination (J2000)
0ʰ48ᵐ30ˢ
48ᵐ00ˢ
47ᵐ30ˢ
47ᵐ00ˢ
Right Ascension (J2000)

NGC 253


ASKAP (BETA) - 11h
ATCA (LVHIS)
HI contours overlaid on optical
HI image
HI velocity field
HI position-velocity diagram along the major disc axis
Declination (J2000)
Right Ascension (J2000)
Velocity (km/s)
Angular Offset

EMU Overview

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

Frequency range: 1100-1400 MHz

40 x deeper than NVSS

- 10 μJy rms across the sky

5 x better resolution than NVSS (10 arcsec)

Better sensitivity to extended structures than NVSS

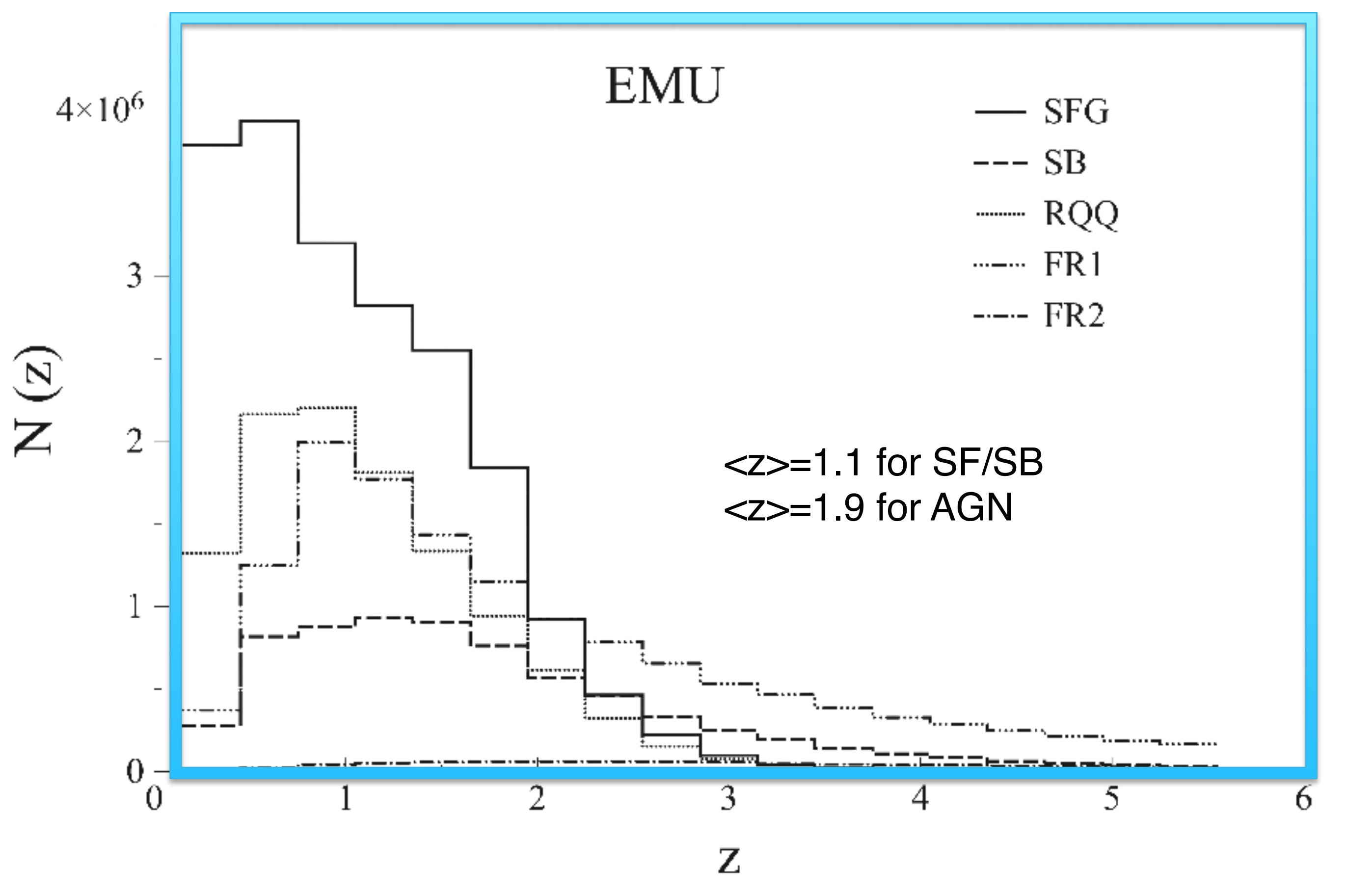
Will detect and image ~70 million galaxies at 20cm

All data to be processed in pipeline

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

Survey starts 2016(?)

Redshift distribution of EMU sources



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

Science Goals

1) Evolution of SF from z=2 to the present day,

- using a wavelength unbiased by dust or molecular emission

2) Evolution of massive black holes

- how come they arrived so early? How do binary MB
- what is their relationship to star-formation?

3) Explore the large-scale structure ological parameters of the Universe.

– E.g, Independent tests of da odels

4) Explore an uncharted observational parameter space

- almost certainly findi ses of object.

5) Explore Clu use low-surface-brightness radio objects

6) Genera of the Galactic Plane

7) Cr acy for surveys at all gths (Herschel, JWST, ALMA, etc)

How did galaxies form and evolve?

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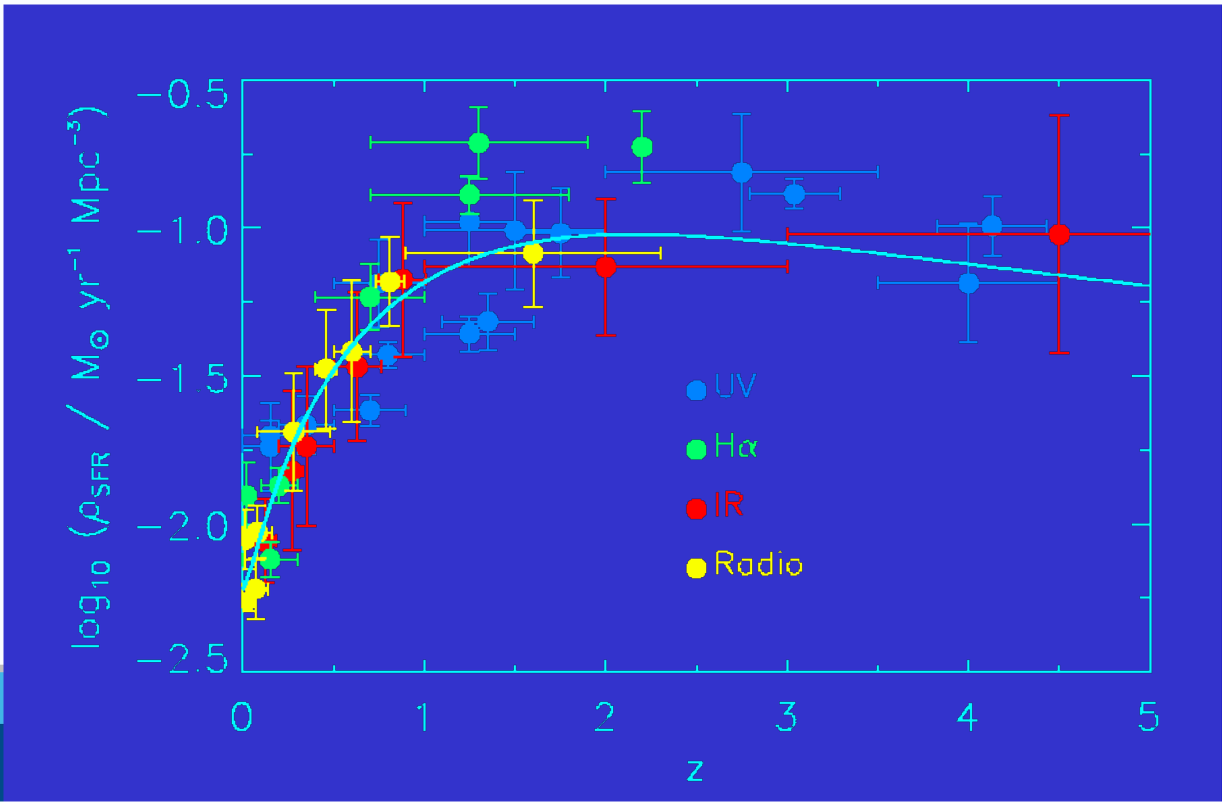
Science Goal 1: measure cosmic SFR, unbiased by dust

To trace the evolution of the dominant star-forming galaxies from z=5 to the present day, using a wavelength unbiased by dust or molecular emission.

- Will detect about 45 million SF galaxies to z~2
- Can stack much higher
- Can measure SFR unbiased by extinction



EMU Science Goal 3: Cosmology

Four!sta6s6cal!measurements!!can!be!made!using!the!EMU!source! catalog:!

- CrossAcorrelate!galaxy!density!with!CMB!A>!ISW!effect!
- CrossAcorrelate!nearby!galaxies!with!distant!galaxies! !A>!lowAz!cosmic!magnifica6on!
- CrossAcorrelate!distant!galaxies!with!CMB! !A>!highAz!cosmic!magnifica6on!
- □utoAcorrelate!radio!

!

None!of!these!requires!morphology!

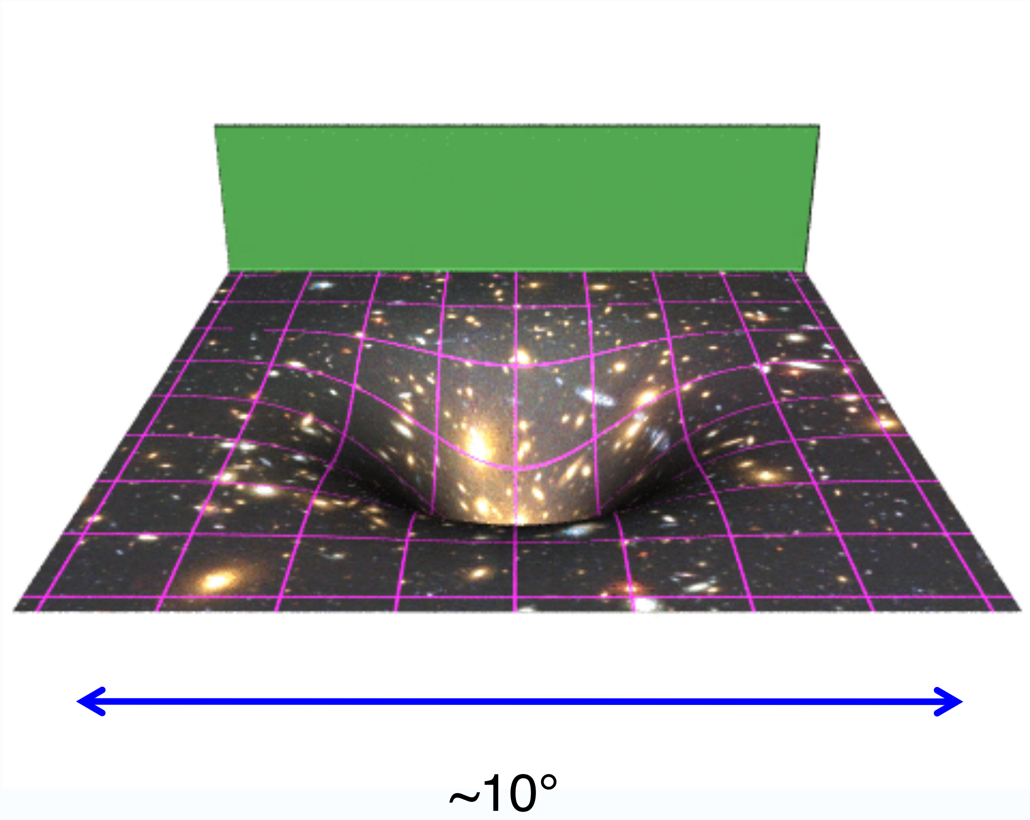
None!of!these!requires!redshiO!informa6on!

But!even!limited!redshiO!informa6on!improves!the!test!

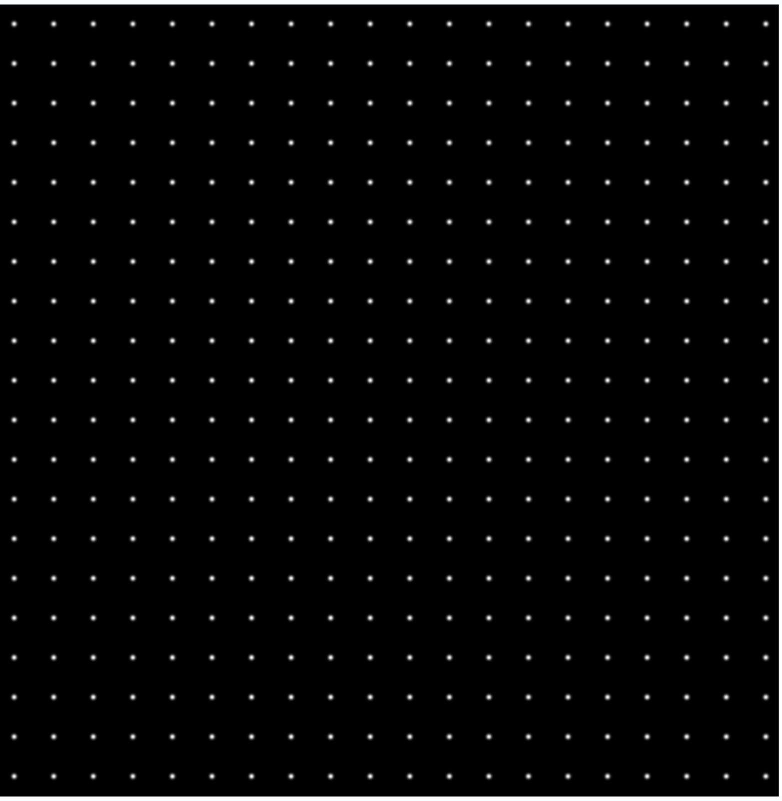
!

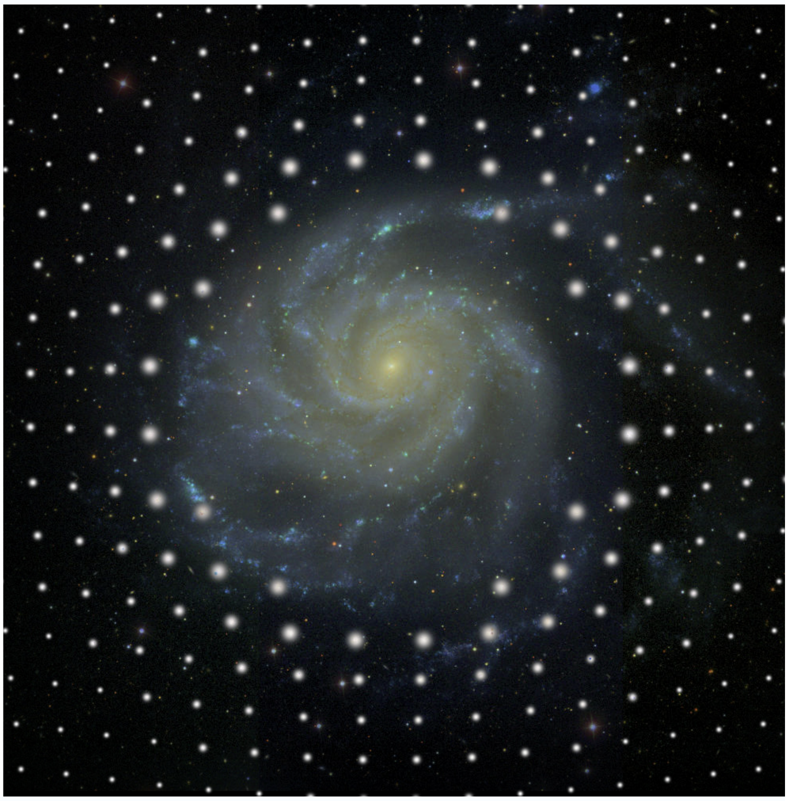
Integrated Sachs-Wolfe Effect

From http://ifa.hawaii.edu/cosmowave/supervoids/



Cosmic Magnification





Don’t need to know individual z’s, just 2 bins at different z

BUT do need to ensure there is no overlap between samples

The ecological niche of EMU Cosmology

1. (nearly) all sky
   - Uniform coverage over 3π steradians (or 4π with Westerbork-WODAN)

2. High redshift
   - $\langle z \rangle \sim 1.5$, or $\langle z \rangle(\mathrm{AGN}) \sim 1.9$

3. High space density
   - ~2000 sources per square degree, 70 million total

4. Low spatial resolution
   - $\theta \sim 10$ arcsec, so can't use cosmic shear

5. Incomplete redshift information
   - We don't have 70 million spec-z's!
   - But we do have significant statistical redshift information
   - Can divide EMU sources into redshift bins

The four probes of EMU Cosmology

1. Auto-correlations of radio data

- -> spatial power spectrum

2. Cross-correlation between ($z<0.5$) optical foreground galaxies and ($<z>\sim1.5$) EMU galaxies

- -> cosmic magnification at low z
- Only needs 2 redshift bins

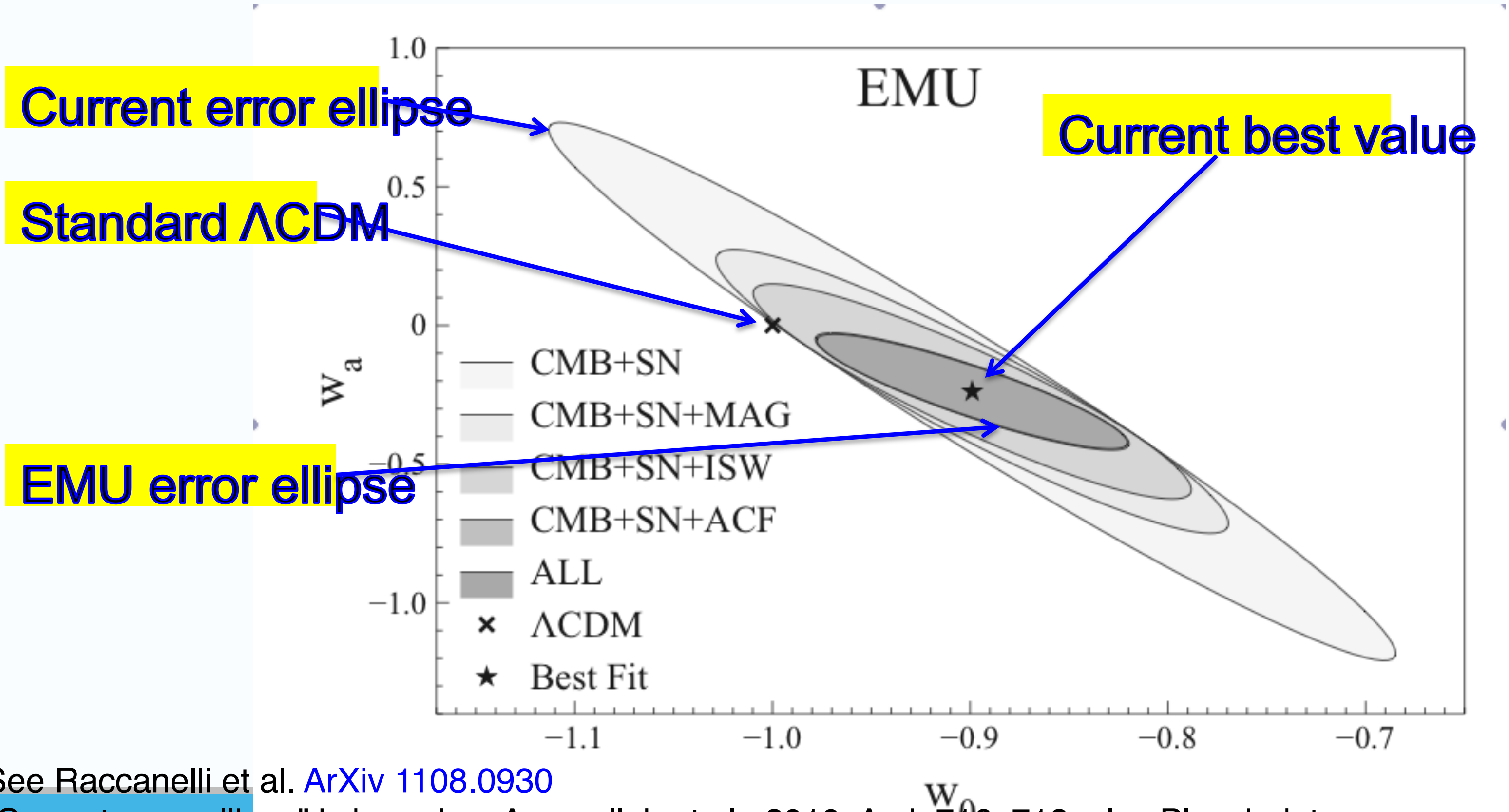
3. Cross-correlation between EMU galaxies and CMB ($\theta < 1°$)

- -> cosmic magnification at high z
- Doesn't need redshifts
- Good match to EMU

4. Cross-correlation between EMU density and CMB ($\theta \sim 10°$)

  - Using Integrated Sachs-Wolfe effect
  - Standard ΛCDM predicts no high-z ISW
  - Massive neutrinos do predict high-z ISW

Dark Energy

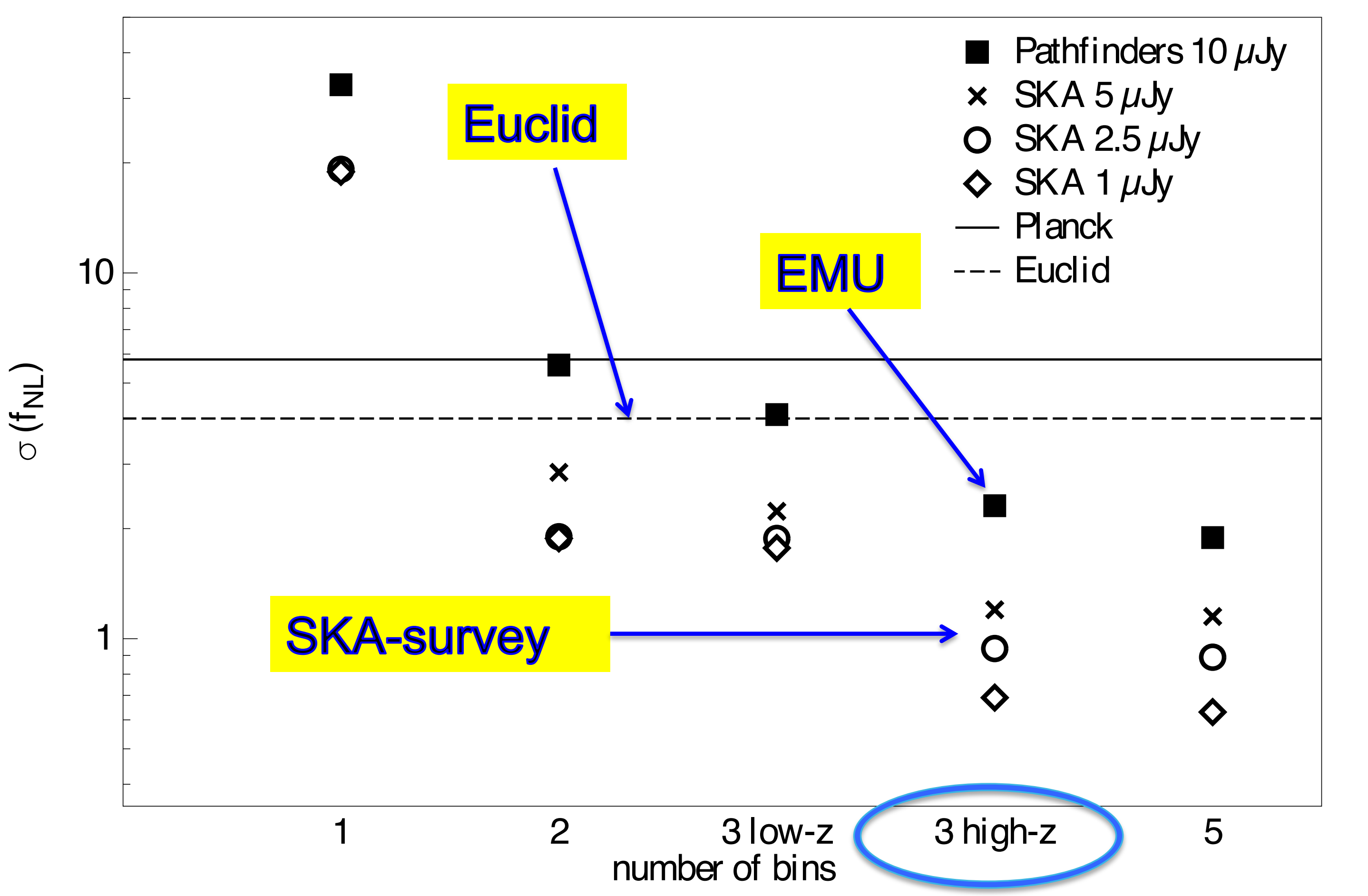


See Raccanelli et al. ArXiv 1108.0930

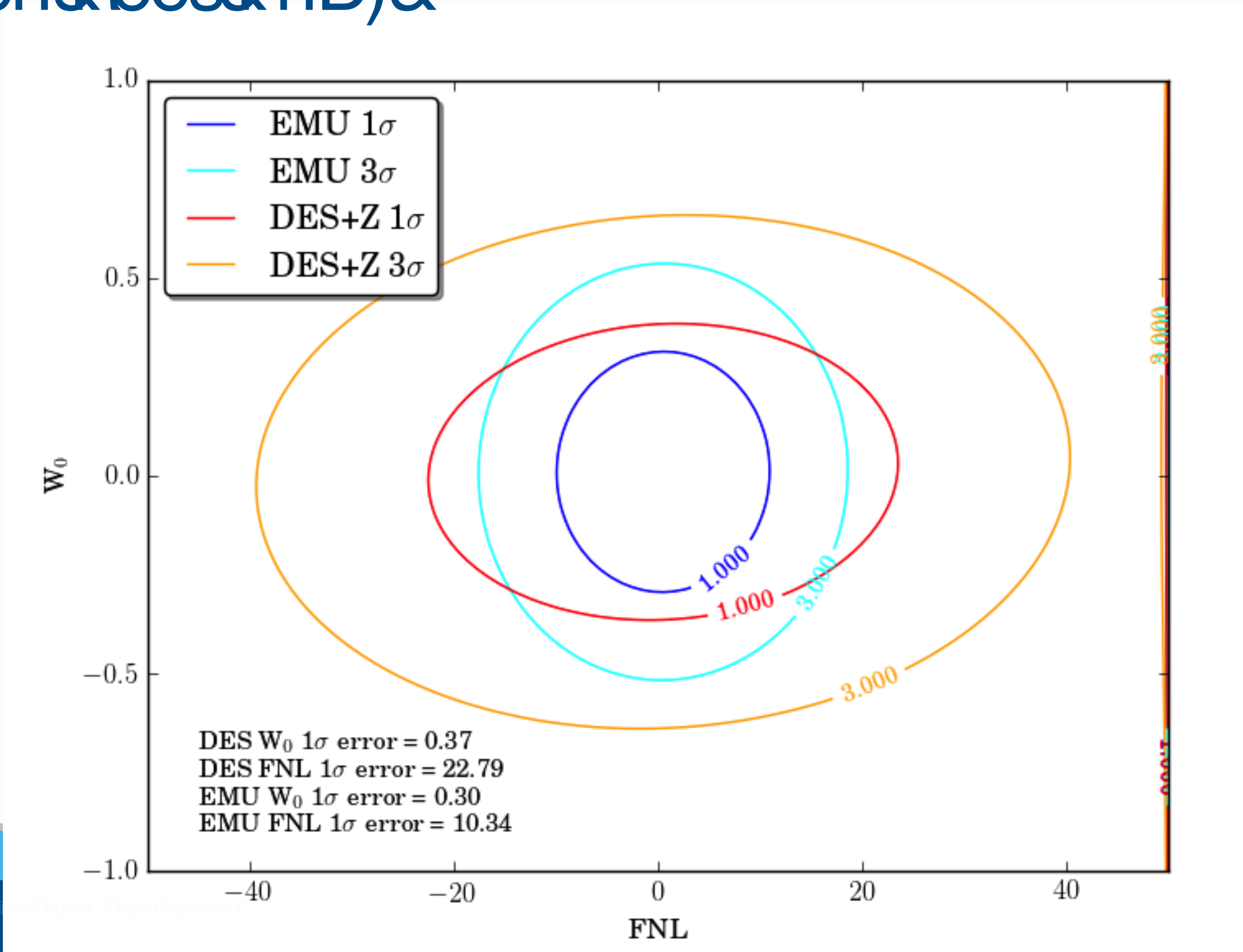
"Current error ellipse" is based on Amanullah et al., 2010, ApJ, 716, 712, plus Planck data

Non-gaussianity

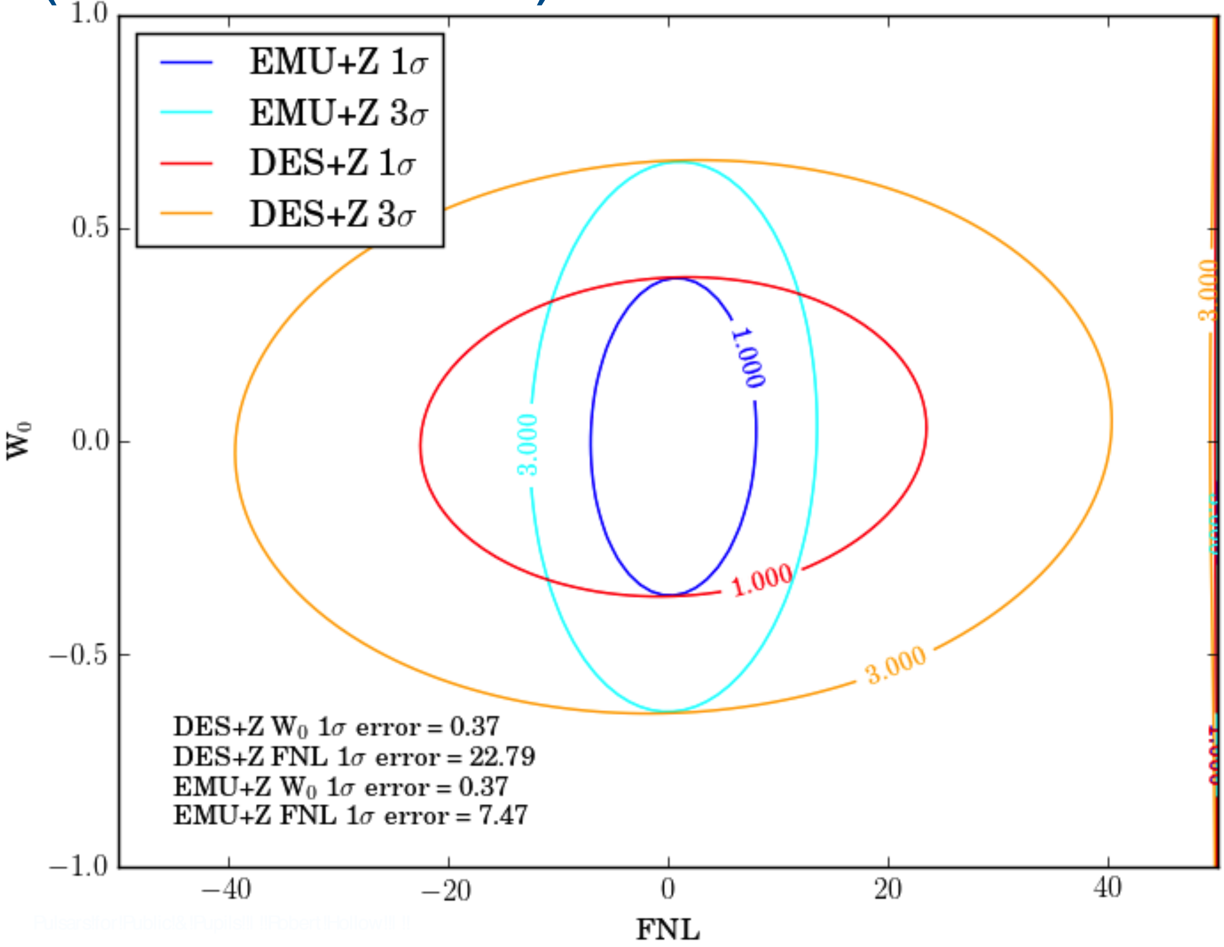
Raccanelli et al., 2014, arXiv1406.0010



EMU&with&no&edshi s&
(Glen&Rees&PhD)&



EMU with redshifts (Glen Rees PhD)



Limiting factors for EMU cosmology

We!need!to!include!the!effects!of:!

Uncertainty!in!bias!

Systema6c!data!errors:!

- Flux!calibra6on!
- Window!func6on!
- Lack!of!uniformity!
- Subtle!data!bias!(clean!bias,!!noise!bias,!etc)!
- ~~□strometry!~~

Errors!in!redshiO!distribu6ons!(where!used)!

Science goal 5: Clusters of Galaxies

~10 clusters per square degree Dehghan et al., 2014

In!4!sq!deg!of!the!□TL□S!CDFS!field,!we!find!

- 44!clusters!via!tailed!galaxies!(up!to!z~2)!
- 1!relic!
- 2!puta6ve!haloes!
- Needs!to!be!confirmed!but!Subrahmanyan et!al.!see!similar!numbers!in!□TLBS!

!

Scaling!this!up!to!EMU..!

- 300,000!clusters!detected!via!tailed!galaxie
- (maybe)!□0,000!haloes!

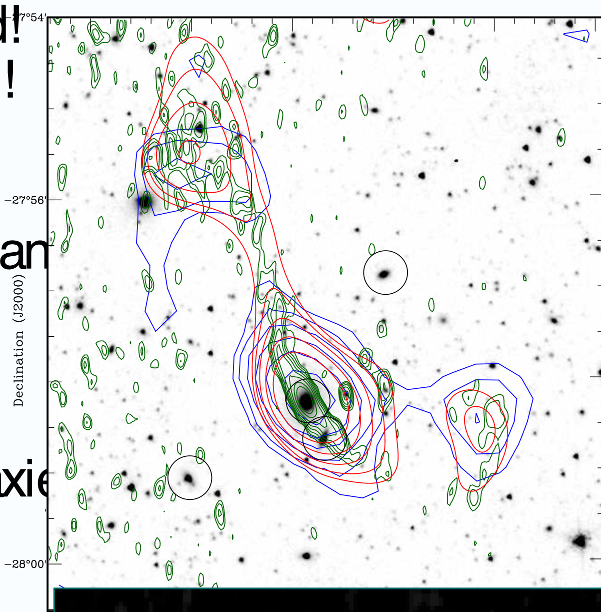
!

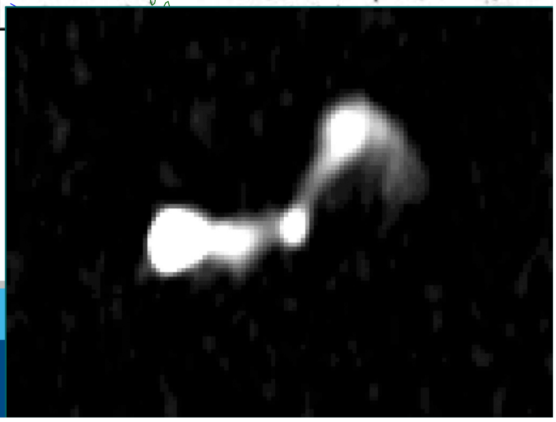
c.f.!eRosita!~100,000!expected!

!

- SK□_survey!will!see!~5!6mes!as!many?!
- Short!baselines!are!important□

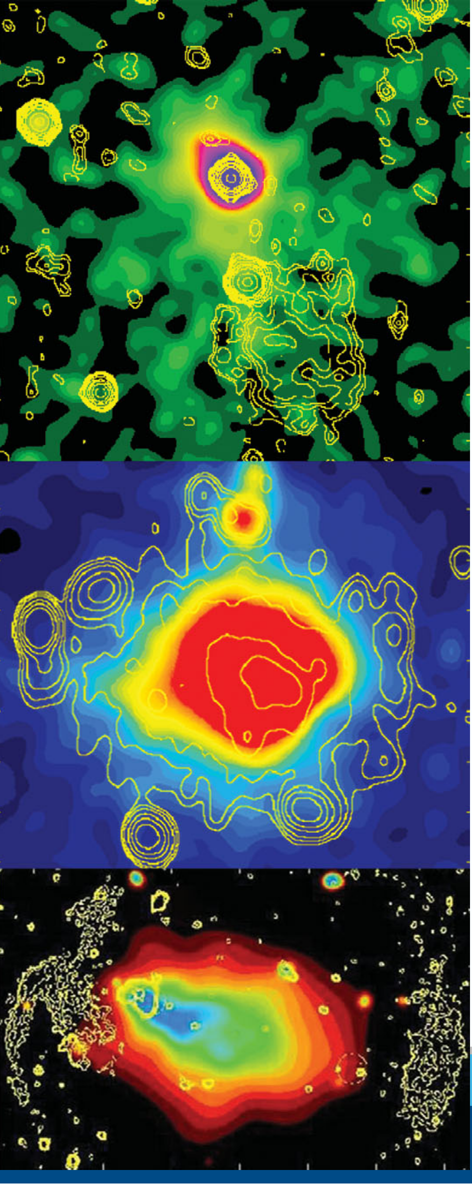
!

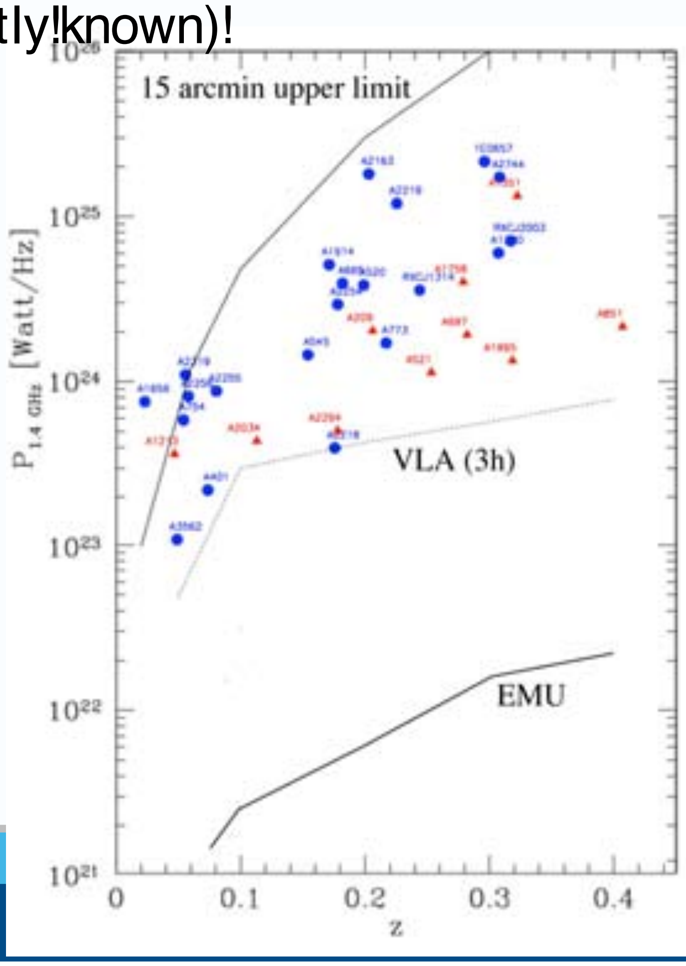




Detecting radio haloes with EMU

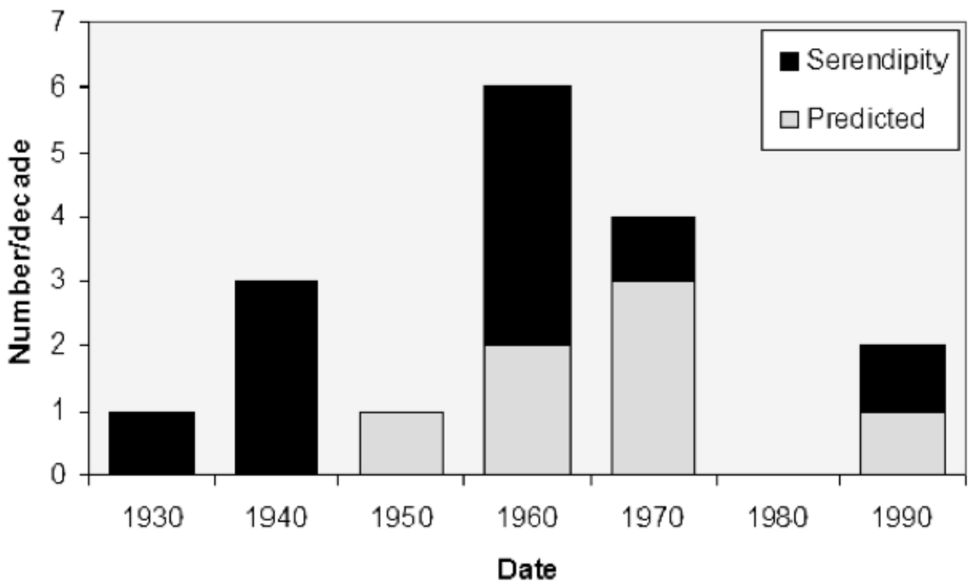
Expect to see ~□0,000 radio haloes
(cf ~50 currently known)





EMU&Science&Goal&4:&
Searching&for&the&unexpected&

What fraction of discoveries in astronomy were "planned"?



(b) Predicted v Serendipity

+1 for dark energy (2010)

Serendipity: 11
Predicted: 7

Discoveries&with&HST&(Lallo:!arXiv:1203.0002)!

Project&	Key& project&	Planned?&	Nat.& Geo.&top& ten?&	Highly& cited?&	Nobel& prize?&
Use!Cepheids!to!improve!value!of!H0!	✔ &	✔ &	✔ &	✔ &	
study!intergalac6c!medium!with! uv!spectroscopy!!!	✔ & !	✔ & !			
MediumAdeep!survey!	✔ &	✔ &			
Image!quasar!host!galaxies!		✔ &	✔ &		
Measure!SMBH!masses!		✔ &	✔ &		
Exoplanet!atmospheres!		✔ &	✔ &		
Planetary!Nebulae!		✔ &	✔ &		
Discover!Dark!Energy!			✔ &	✔ &	✔ &
Comet!ShoemakerALevy!			✔ &		
Deep!fields!(HDF,!HDFS,!UDF,!FF,!etc)!			✔ &	✔ &	
Proplyds!in!□rion!			✔ &		
GRB!Hosts!			✔ &		

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Discoveries with HST (Lallo: arXiv:1203.0002)

Project	Key	Planned?	Nat.	Highly	Nobel prize?
Use Cepheids to					
study intergalac uv spectroscopy					
Medium-deep s					
Image quasar ho					
Measure SMBH					
Exoplanet atmos					
Planetary Nebul					
Discover Dark E					✔
Comet Shoemak					
Deep fields (HDF					
Proplyds in Orion			✔		
GRB Hosts			✔		

Summary:

Of the "top ten" HST discoveries:

- 1 was a key project
- 4 were planned by astronomers but were not key projects
- 5 were totally unexpected (e.g. dark energy)

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The discovery of pulsars

Jocelyn Bell:

explored a new area of observational phase space

knew the instrument sufficiently well to distinguish interference from signal

observant enough to recognise a sidereal signature

open minded – prepared for discovery

within a supportive environment

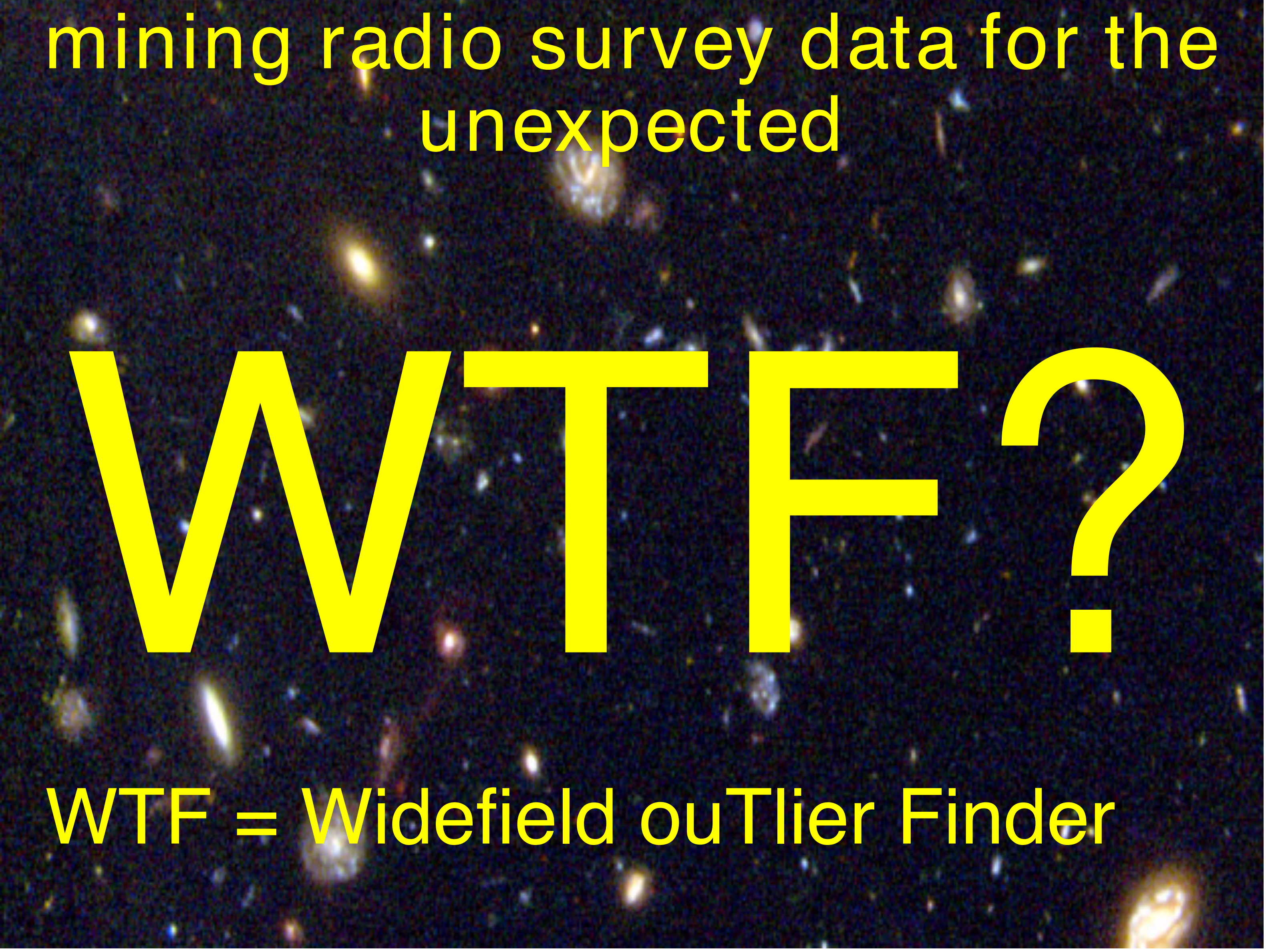
persistent

See Bell-Burnell (2009) PoS(sps5)014 for a personal perspective

Could Jocelyn Bell Discover the Unexpected in SKA data?

- Data volumes are huge – cannot sift by eye
- Instrument is complex – no single individual will be familiar with all possible artifacts
- Humans won't be able to find the "unknown unknowns"
- Can we mine data for the unexpected, by rejecting the expected?

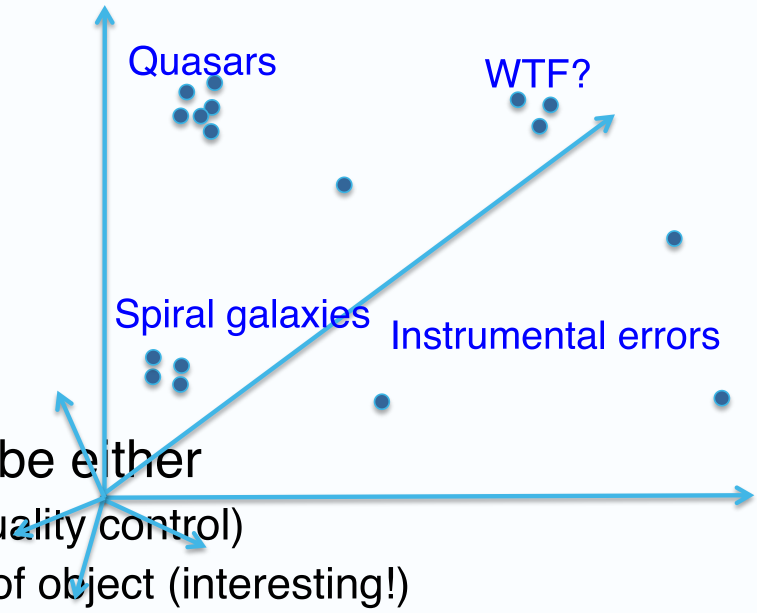
If not, SKA will not reach its full potential


mining radio survey data for the unexpected
WTF?
WTF = Widefield ouTlier Finder

Mining large data sets for the unexpected

WTF will work by searching the n-dimensional (large n) phase space of observables, using techniques such as

- Decision tree approach
- Zoo approach
- Cluster analysis
- k-nearest-neighbours
- self-organised maps
- Bayesian approach to combine all the above



Identified objects/regions will be either

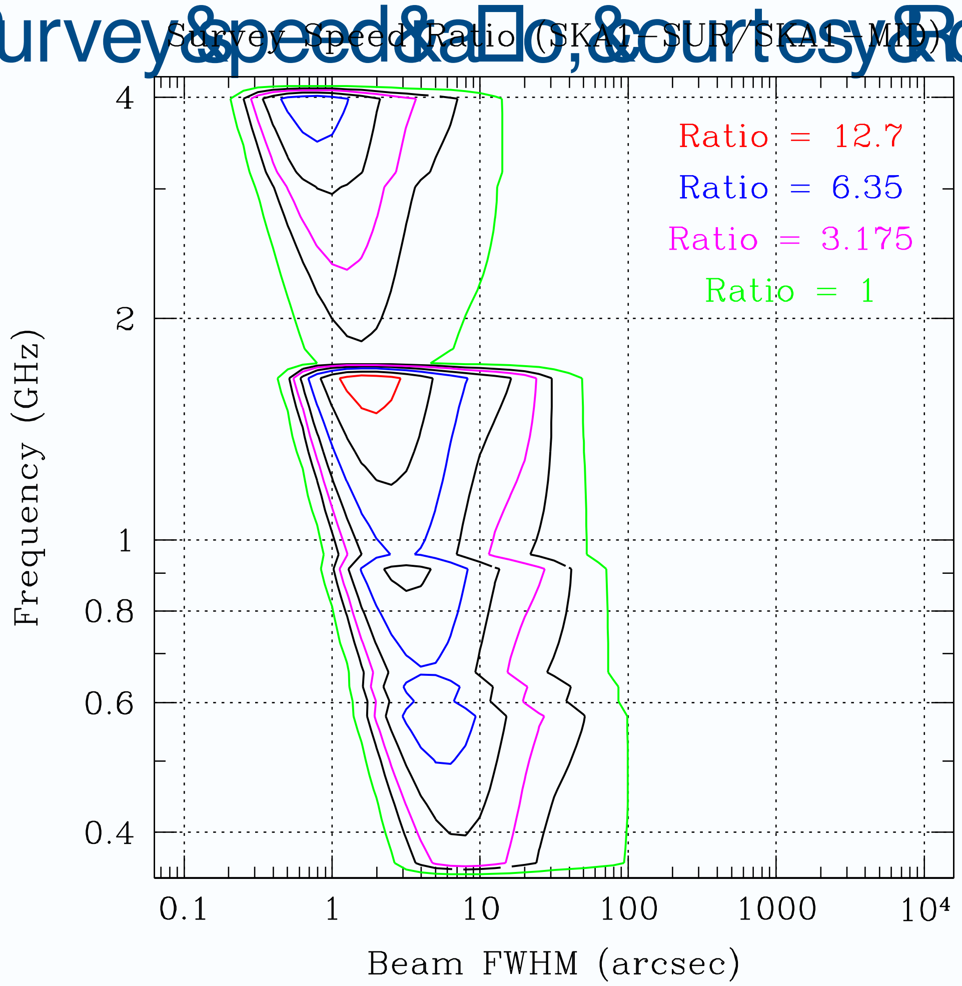
- processing artifacts (important for quality control)
- statistical outliers of known classes of object (interesting!)
- New classes of object (WTF)

What do surveys need to do to discover the unexpected?

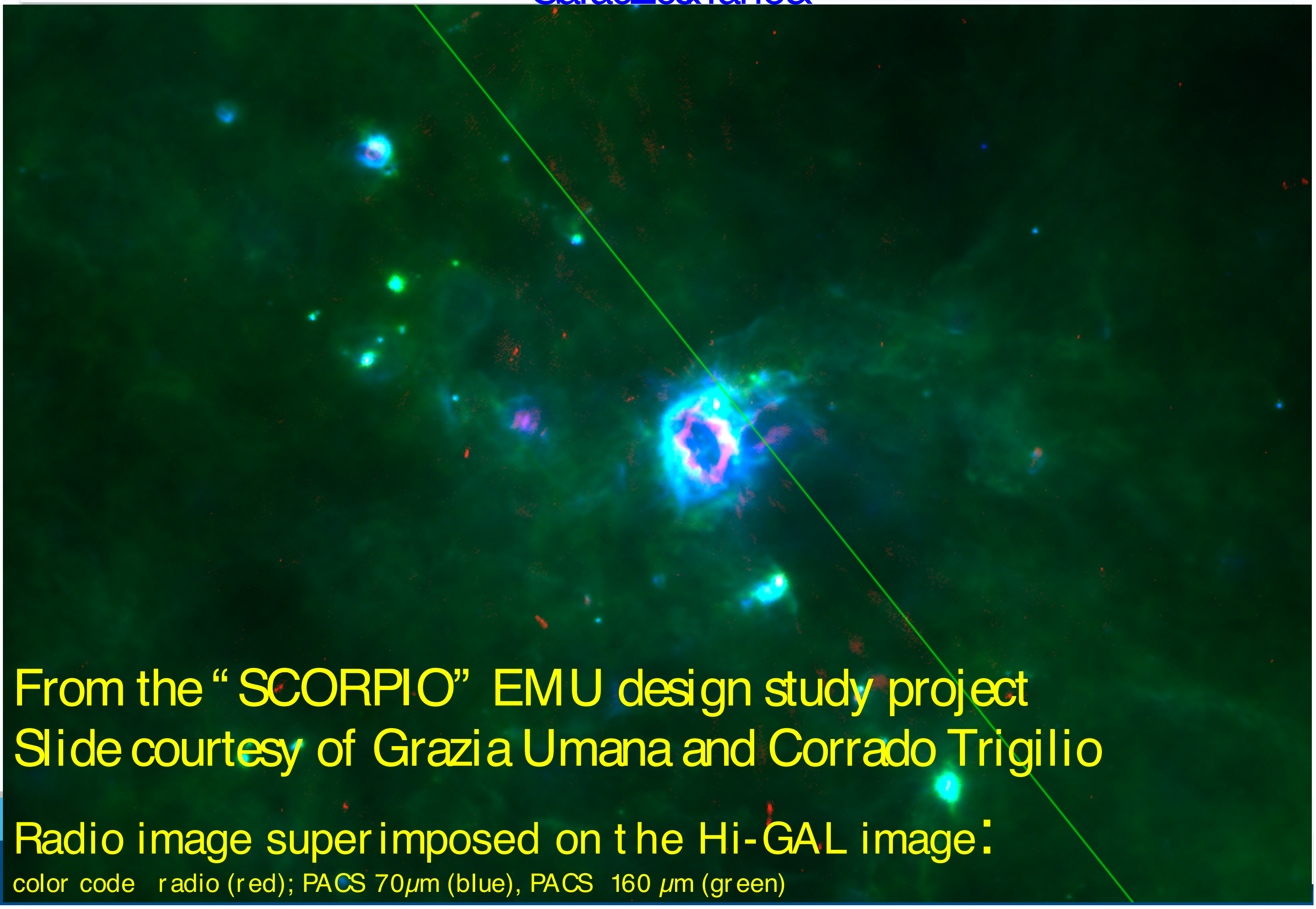
- Maximise the volume of new phase space
  - A good surrogate is to use # of known objects
  - Maximised by an all-sky survey
- Develop data mining software to search for the unexpected
- Retain flexibility


YOU ARE NOW LEAVING THE
MURCHISON RADIO-ASTRONOMY
OBSERVATORY
THANK YOU FOR BEING RADIO QUIET

Survey speed ratio, courtesy Robert Braun



EMU Science Goal 6: The deepest, highest resolution atlas yet of the Galactic Plane



Challenge: difficult to get redshifts, or even optical/IR photometry

Survey Name	Area (deg^2)	Wavelength Bands	Limiting Mag. or flux[a]	EMU Detected (%)	Survey Matched (%)	Data Relea Date
WISE[1]	40000	3.4, 4.6, 12, 22 μm	80 μJy	23	100	2012
Pan-Starrs[2]	30000	g, r, i, z, y	$r < 24.0$	54	50	2020
Wallaby[3,b]	30000	20 cm (HI)	1.6 mJy[c]	1	100	2013
LSST[4]	20000	u, g, r, i, z, y	$r < 27.5$	96	67	2020
Skymapper[5]	20000	u, v, g, r, i, z	$r < 22.6$	31	66	2015
VHS[6]	20000	Y, J, H, K	K< 20.5	49	66	2012
SDSS[7]	12000	u, g, r, i, z	$r < 22.2$	28	22	DR8
DES[8]	5000	g, r, i, z, y	$r < 25$	71	17	2017
VST-ATLAS[9]	4500	u, g, r, i, z	$r < 22.3$	30	15	2012?
Viking[10]	1500	Y, J, H, K	K< 21.5	68	5	2012
Pan-Starrs Deep[2]	1200	$0.5 - 0.8$, g, r, i, z, y	$g < 27.0$	57	4	2020

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The EMU Redshift WG

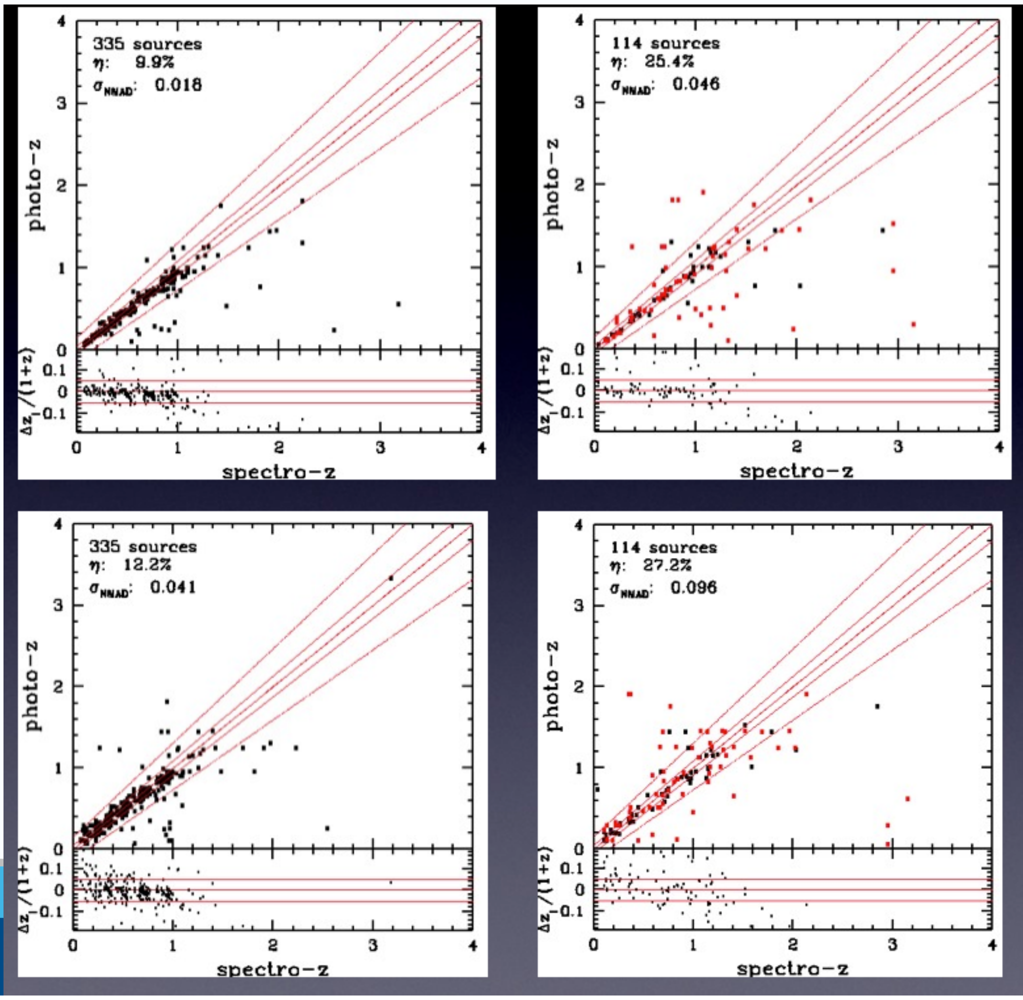
Only ~1% of EMU sources will have spectroscopic redshifts (most from WALLABY)

Generating photometric redshifts for AGNs is notoriously unreliable

EMU redshift group (Seymour, Salvato, Zinn, et al) exploring a number of different approaches:

- conventional template fitting
- kNN algorithms
- SoM algorithms
- etc

kNN does remarkably well!



Another alternative approach: Statistical Redshifts

Philosophy: Obtain the redshift distribution without necessarily measuring individual z's

1) Polarisation
- mean redshift of polarised sources ~1.9
- mean redshift of unpolarised sources ~1.1

2) Spectral index
- Steep spectrum sources have a higher redshift than moderate spectrum sources

3) Radio-k relation
- High values of $S_{20cm}/S_{2.2\mu m}$ have high z
- even a non-detection is useful

Combining all the above indicators (+others)
- Use a Bayesian approach to assign a probabilistic redshift distribution (=> statistical redshifts)

Using incomplete redshift data to test hypotheses