



www.csiro.au

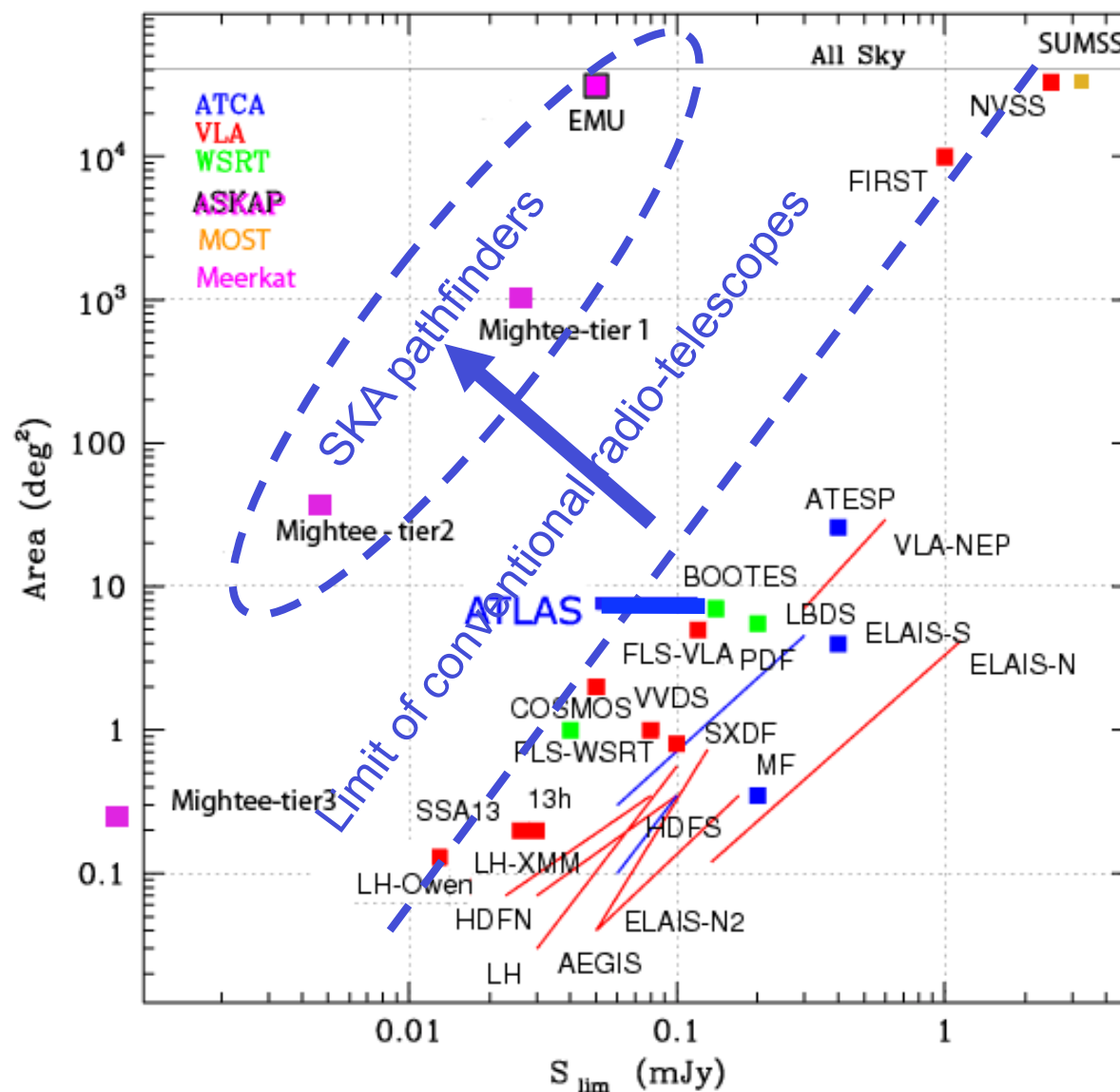
EMU: Evolutionary Map of The Universe

Ray Norris
IAU GA Beijing August 2012



Current major 20cm surveys

Major Deep Surveys @ 1.4 GHz (updated 2009)

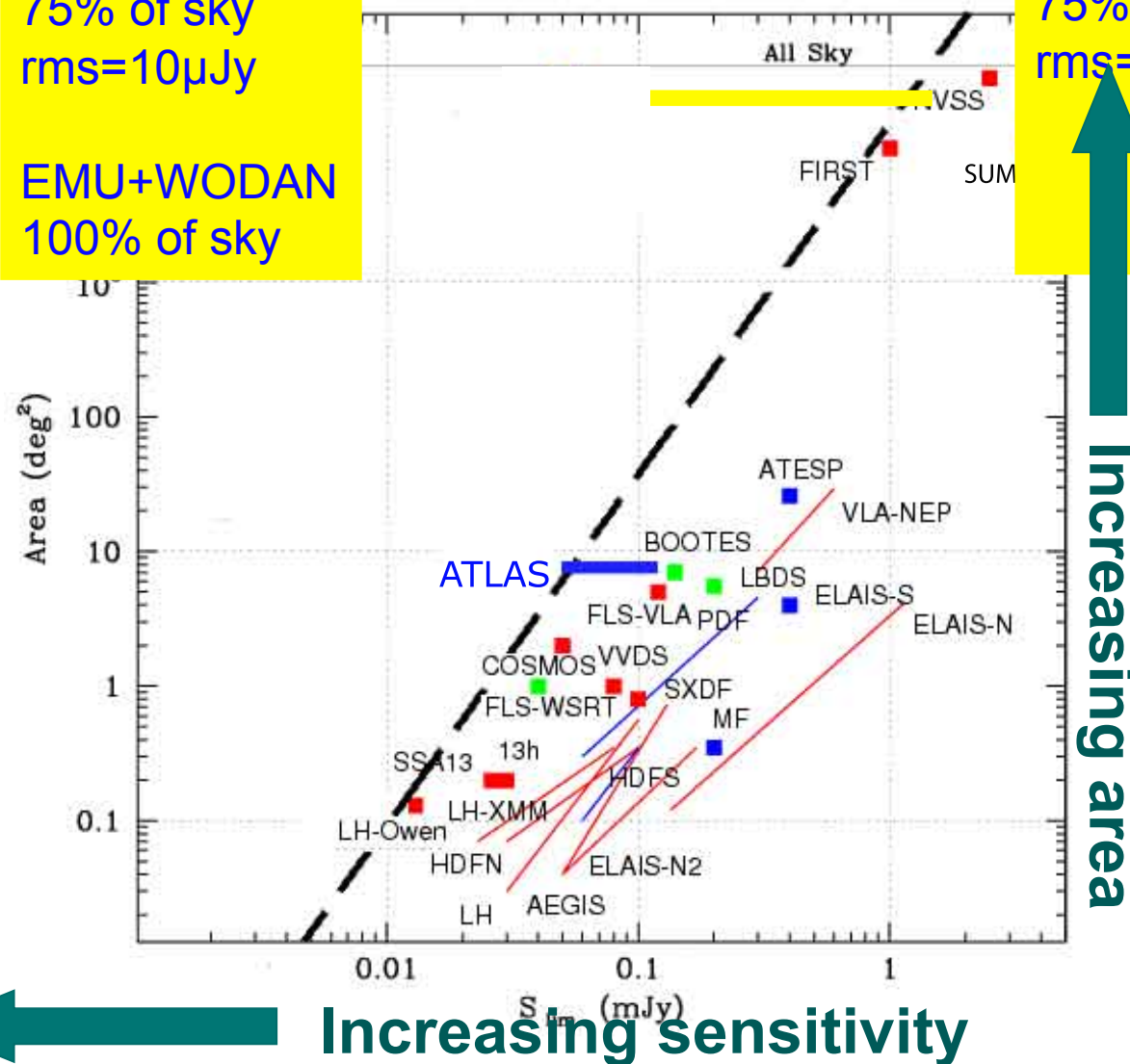


Current major 20cm surveys

EMU
75% of sky
rms=10 μ Jy

EMU+WODAN
100% of sky

NVSS
75% of sky
rms=450 μ Jy



The four phases of EMU

- **Phase 1: Design Study 2009-2012**
 - Develop process, software, design strategy, etc.
- **Phase 2: Commissioning 2012-2013**
 - Help make ASKAP work!
- **Phase 3: EMU early science with ASKAP-n 2013-2014?**
 - do real science with ASKAP-n ($11 < n < 36$)
- **Phase 4: EMU full survey 2014-2016?**
- **(Phase 5: EMU96?)**

ASKAP

EMU

Evolutionary Map of the Universe

- Deep radio image of 75% of the sky (to declination $+30^\circ$)
- Frequency range: 1100-1400 MHz
- 40 x deeper than NVSS
 - 10 μ Jy 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 2014(?)
- Total integration time: ~1.5 years ?

Complementary radio surveys

- **Westerbork-WODAN**

- using Apertif PAF on Westerbork telescope
- will achieve similar sensitivity to EMU
- will observe northern quarter of sky ($\delta > +30^\circ$)
- well-matched to EMU

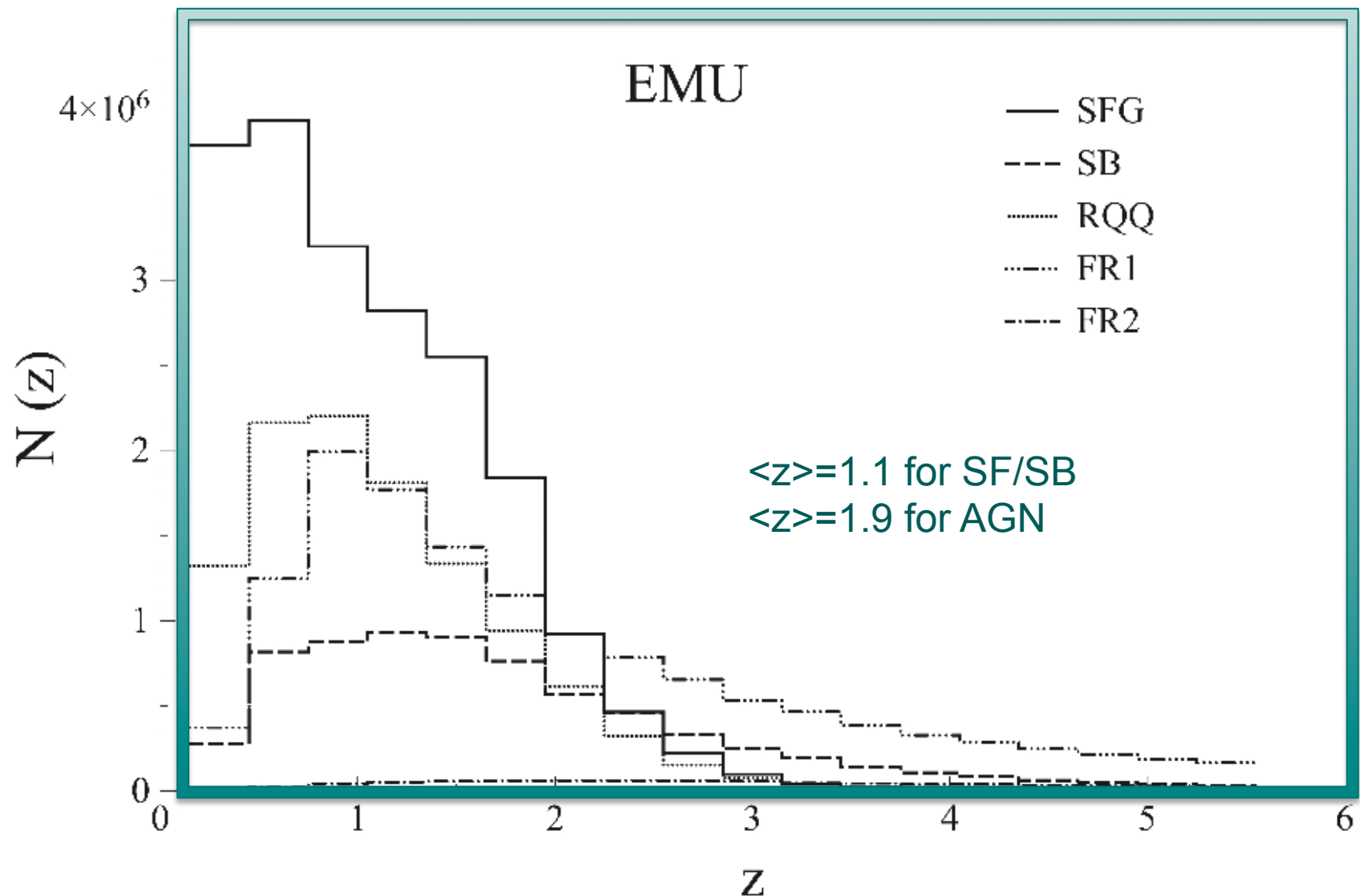
- **LOFAR continuum surveys**

- lower frequency
- covering Northern half(?) of sky
- valuable because yields spectral index

- **Meerkat-MIGHTEE**

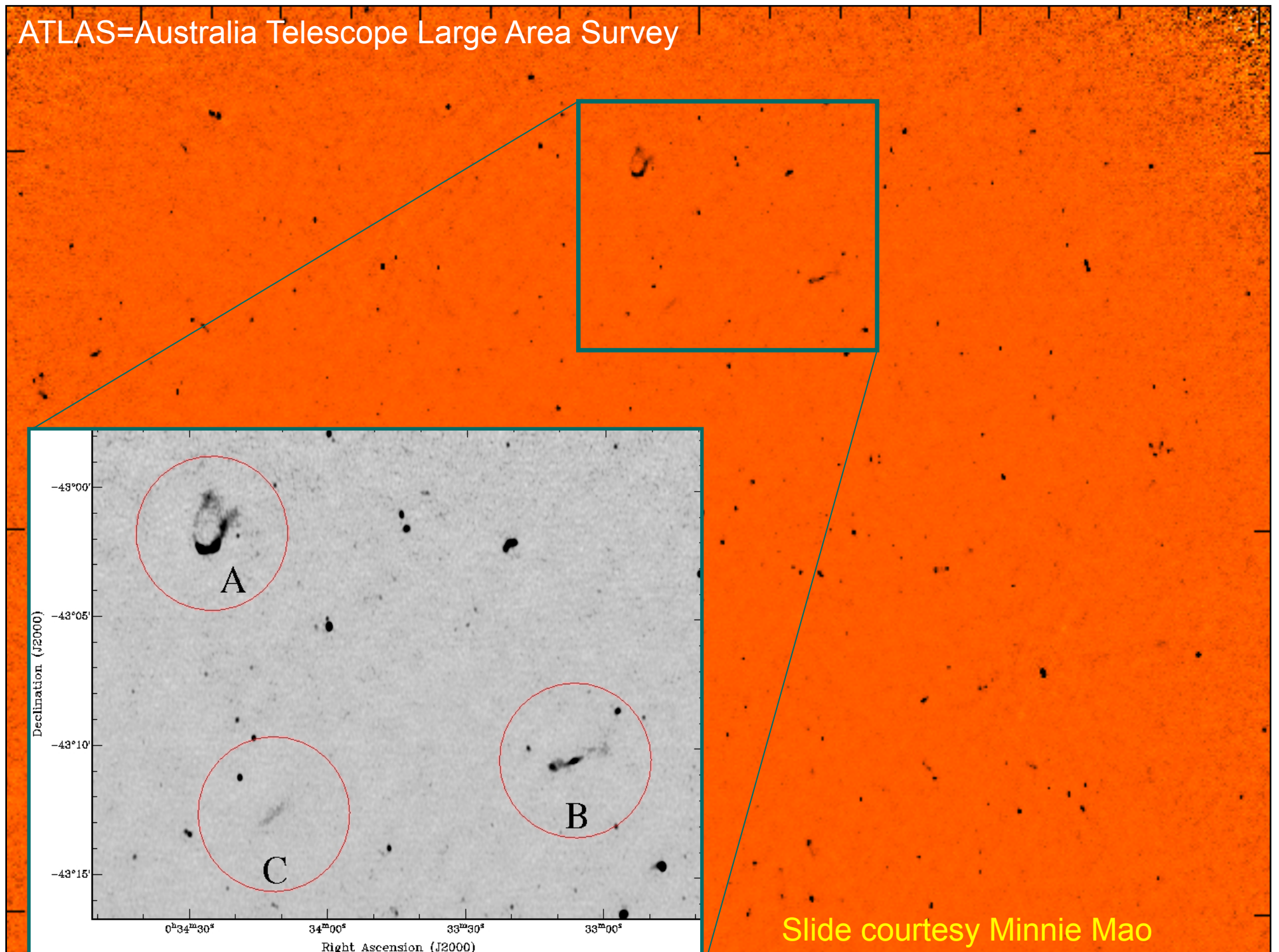
- Potentially deeper over smaller area, but will be limited by confusion until Meerkat Phase II (2016?)

Redshift distribution of EMU sources



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

ATLAS=Australia Telescope Large Area Survey



- 
- ATLAS =Australia Telescope Large Area Survey**
- covers 7 sq deg centred on CDFS and ELAIS-S1
 - has the same rms sensitivity ($10\mu\text{Jy}$) as EMU
 - has the same resolution (10 arcsec) as EMU
 - expect to catalogue 16000 galaxies
 - Final data release early 2012 using EMU prototype tools

ASKAP

EMU

Evolutionary Map of the Universe

Science Goals

How did galaxies form and evolve?

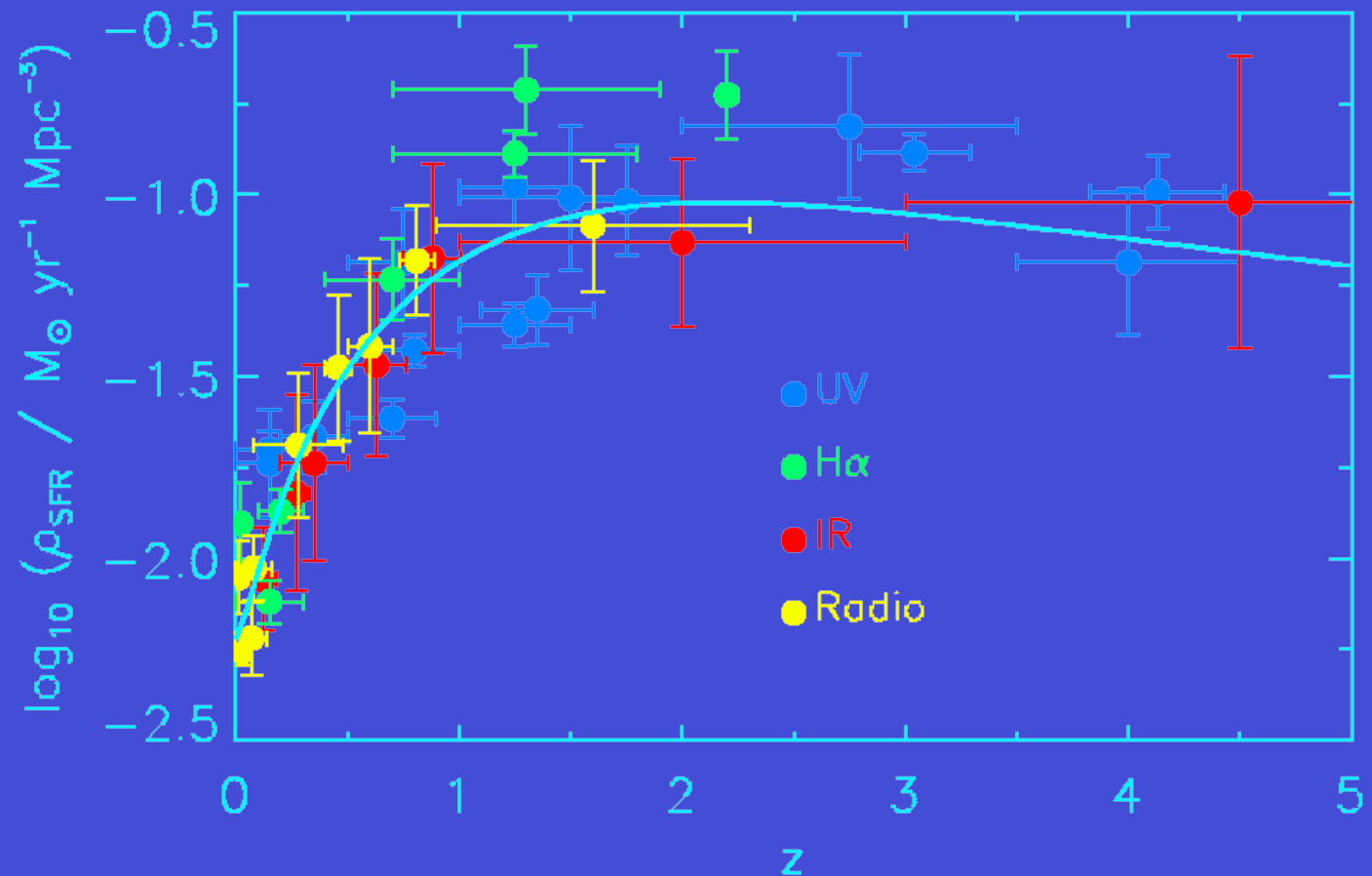
Science Goals

- 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 MBH merge?
 - what is their relationship to star-formation?
- 3) Explore the large-scale structure and cosmological parameters of the Universe.**
 - E.g, Independent tests of dark energy models
- 4) Explore an uncharted region of observational parameter space**
 - almost certainly finding new classes of object.
- 5) Explore Clusters & Diffuse low-surface-brightness radio objects**
- 6) Generate an Atlas of the Galactic Plane**
- 7) Create a legacy for surveys at all wavelengths (Herschel, JWST, ALMA, etc)**

Science Goal 1: measure SFR, unbiased by dust

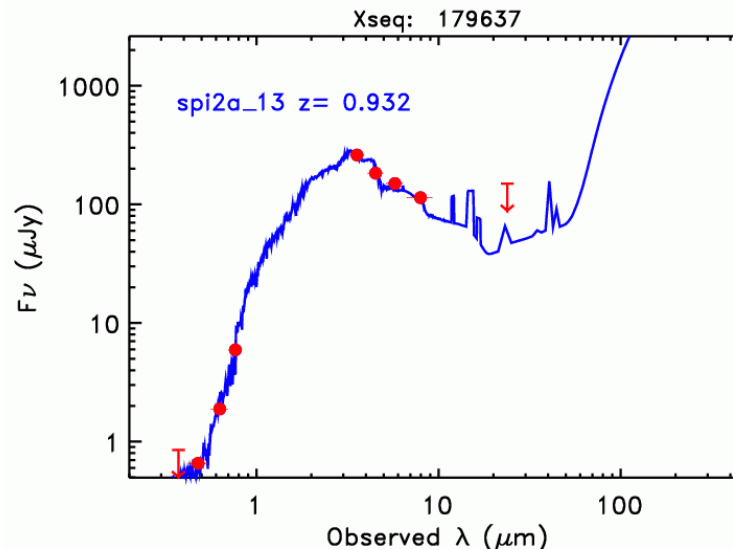
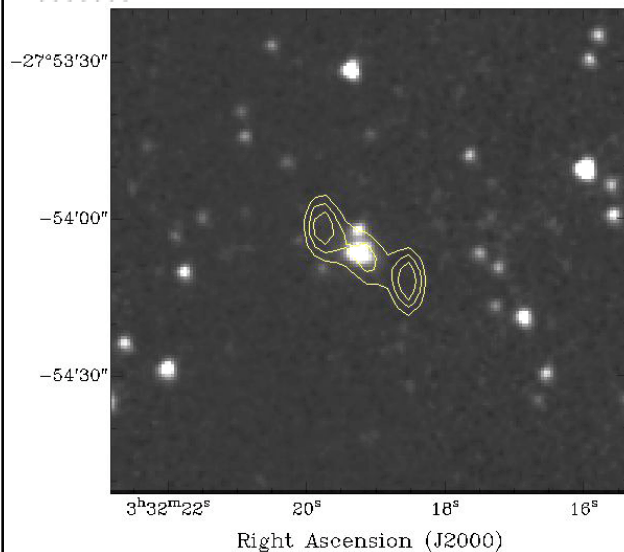
To trace the evolution of the dominant star-forming galaxies from $z=5$ to the present day, using a wavelength unbiased by dust or molecular emission.

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



Science goal 2: Trace the evolution of AGN

- EMU will detect 25 million AGN, including rare objects, such as
 - high- z AGN
 - composite AGN/SF galaxies
 - galaxies in brief transition phases

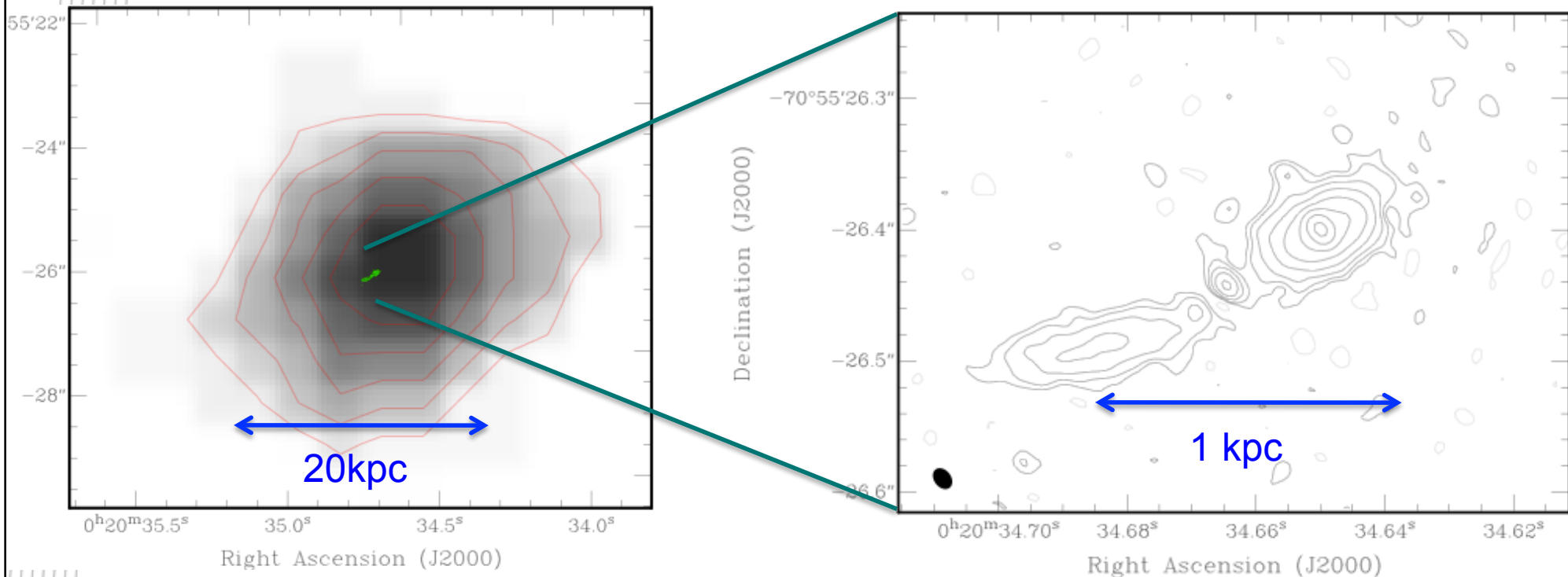


- Norris et al. 2008, [arXiv:0804.3998](#)
- $S_{20\text{cm}} = 9\text{mJy}$
- $z = 0.932$
- $L_{20\text{cm}} = 4 \times 10^{25} \text{ WHz}^{-1}$

Other questions:

- How much early activity is obscured from optical views?
- Can we use trace the evolution of MBH with z ?
- When did the first MBH form?
- How do binary MBH merge?

F00183-7111 (ULIRG with $L=9.10^{12} L_{\odot}$)



$z=0.327$

$P=6.10^{25} \text{ W/Hz}$

Merger of two cool spirals:

- SB just turned on - AGN just turned on
- radio jets already at full luminosity, boring out through the dust/gas
- Almost no sign of this at optical/IR wavelengths
- see Norris et al. [arXiv:1107.3895](https://arxiv.org/abs/1107.3895)

Science Goal 3: Cosmology

- To use the distribution of radio sources to explore the large-scale structure and cosmological parameters of the Universe, and test fundamental physics.

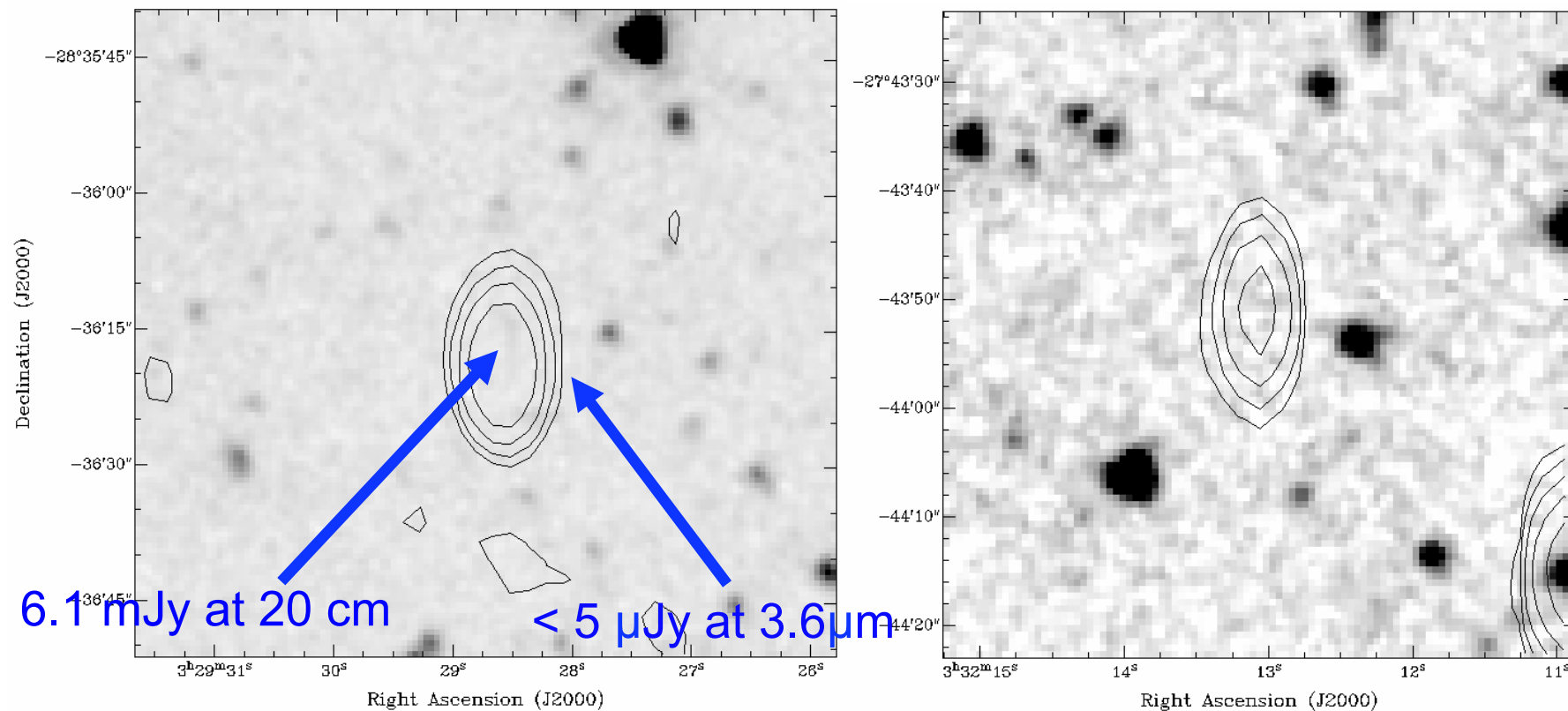
Nearly everything in this section is contained in two papers:

- Norris et al., <http://arxiv.org/abs/1106.3219>, “EMU: Evolutionary map of the Universe”
- Raccanelli et al., <http://arxiv.org/abs/1108.0930>, “Cosmological Measurements with Forthcoming Radio Continuum Surveys”

We can use EMU to make significant tests in three areas:

- Models of inflation
- Models of dark energy
- Models of modified gravity

Science Goal 4: To explore an uncharted region of observational parameter space, almost certainly finding new classes of object.



Norris et al 2007, MNRAS, 378, 1434; Middelberg et al 2008, AJ, 135, 1276; Garn & Alexander, 2008, MNRAS, 391, 1000; Huynh et al., 2010, ApJ, 710, 698; Norris et al. 2011, ApJ, in press

Science goal 4: Explore an uncharted region of observational parameter space

- Large volume of virgin phase space -> probability of unexpected discovery is high
- Because of data volume, probability of a person stumbling across a discovery is small
- Need to actively mine data, looking for things that don't conform to expectations of ordinary objects

WTF?

WTF = Widefield ouTlier Finder

**Unlikely to stumble across new types of object,
Instead, systematically mine the EMU database,**

- discarding objects that already fit known classes of object

Approaches include

- decision tree
- cluster analysis
- kFN
- Bayesian

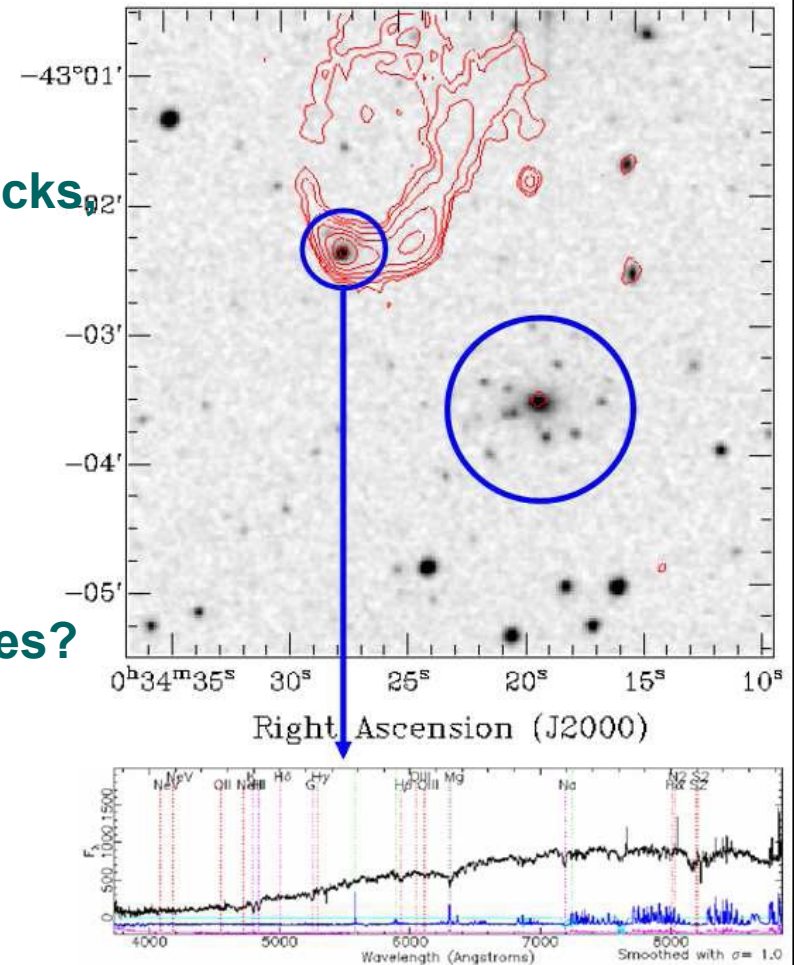
Identified objects/regions will be either

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

Science goal 5: Explore Clusters & Diffuse low-surface-brightness radio objects

Goals

- **Detect $\sim 10^5$ new clusters**
- **Determine luminosity function of relics & shocks**
 - how do they change with z ?
- **How do bent radio sources depend on environment?**
 - Can we use them to detect clustering at high z ?
- **How common are low luminosity radio galaxies?**
- **Do diffuse structures end at $z \sim 1$ because of inverse compton cooling? If not why not?**

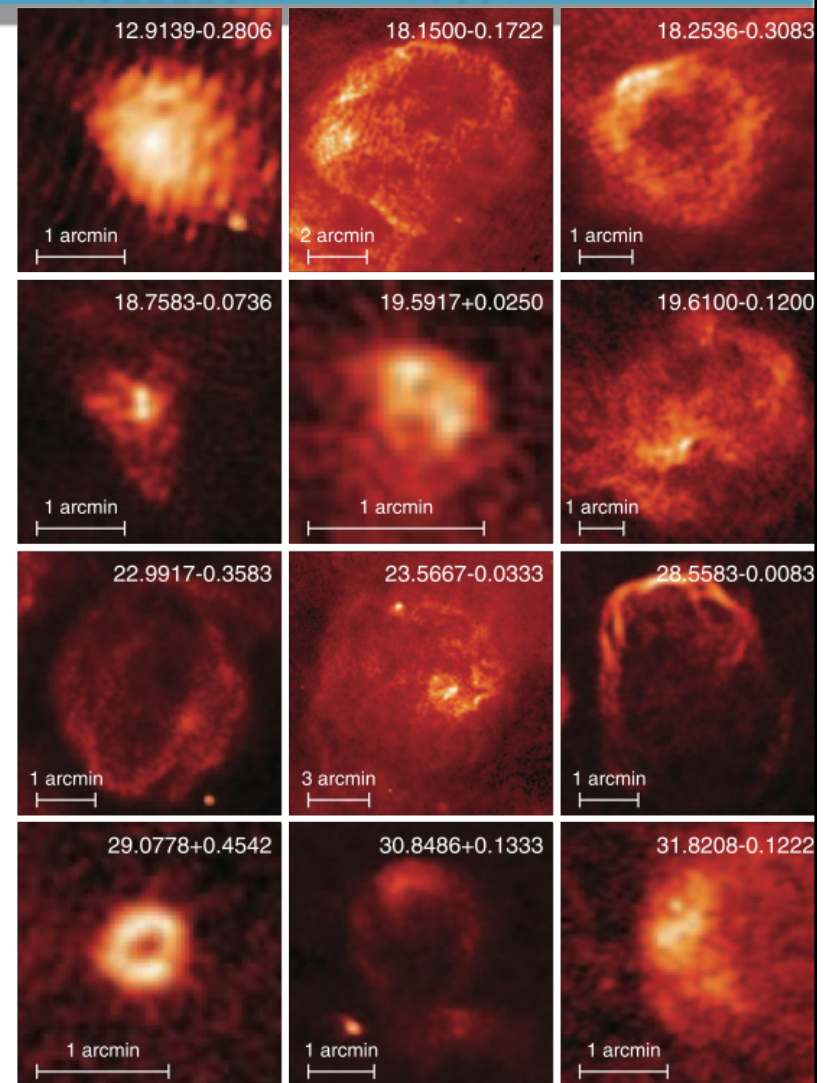


z=0.22. From Mao et al 2010, MNRAS, 406, 2578

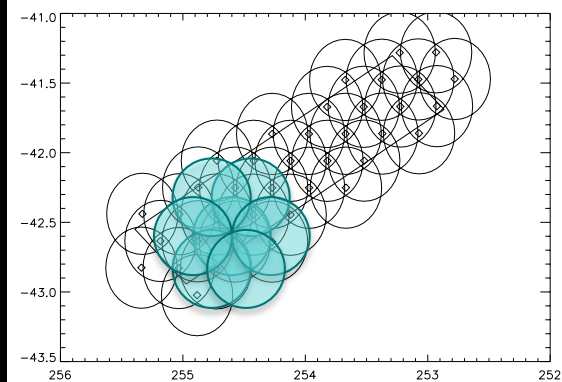
Science goal 6: Produce the most complete catalogue of the Galactic Plane to date.

Much deeper and higher res than any other survey:

- CGPS: arcmin, few mJy, 73° of Northern plane
- SGPS: arcmin, 35 mJy, most of S plane
- MAGPIS: 6 arcsec, 1-2 mJy, 27° of N plane
- EMU: 10 arcsec, down to 50 μ Jy, most of plane
 - all of plane when linked to Apertif
- Build a complete census (and possibly discover new types of):
 - all phases of HII region evolution
 - the most compact and youngest supernova remnants
 - radio-emitting Planetary Nebulae to constrain galactic density and formation rate



The pilot experiment: SCORPIO



Use of the large bandpass to get spectral information

FOV $\approx 1^\circ \times 0.5^\circ$

Sub-mosaic (7 pointing)

CASA, mfs

Bandpass in 3, 300 MHz sub-bands

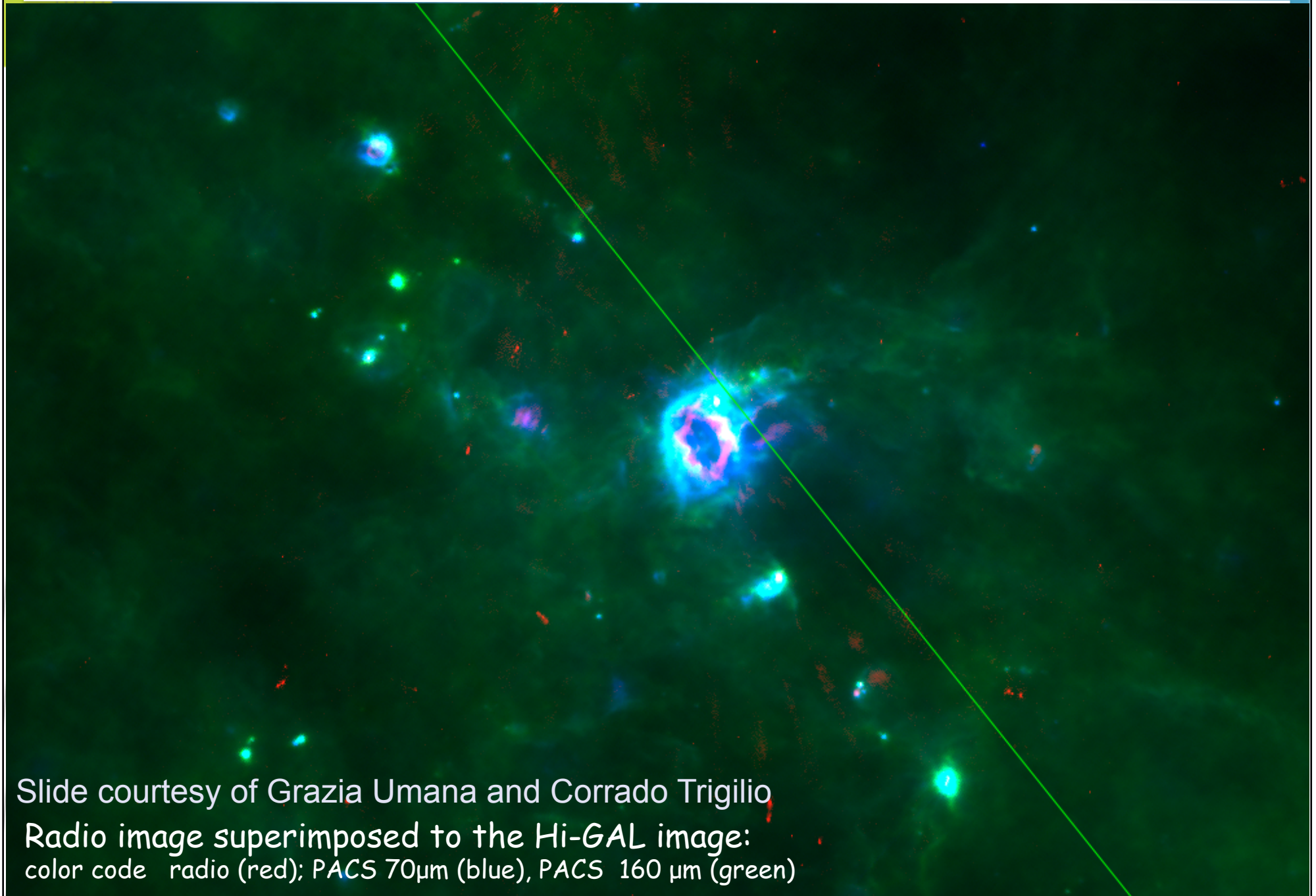
1.5 GHz, rms=140 μ Jy, B=11.5" x 6.6"

2.1 GHz, rms=140 μ Jy, B=8.9" x 5.1"

2.9 GHz, rms=100 μ Jy, B=6.7" x 3.7"

Slide courtesy of Grazia Umana and Corrado Trigilio

Looking at the dust..



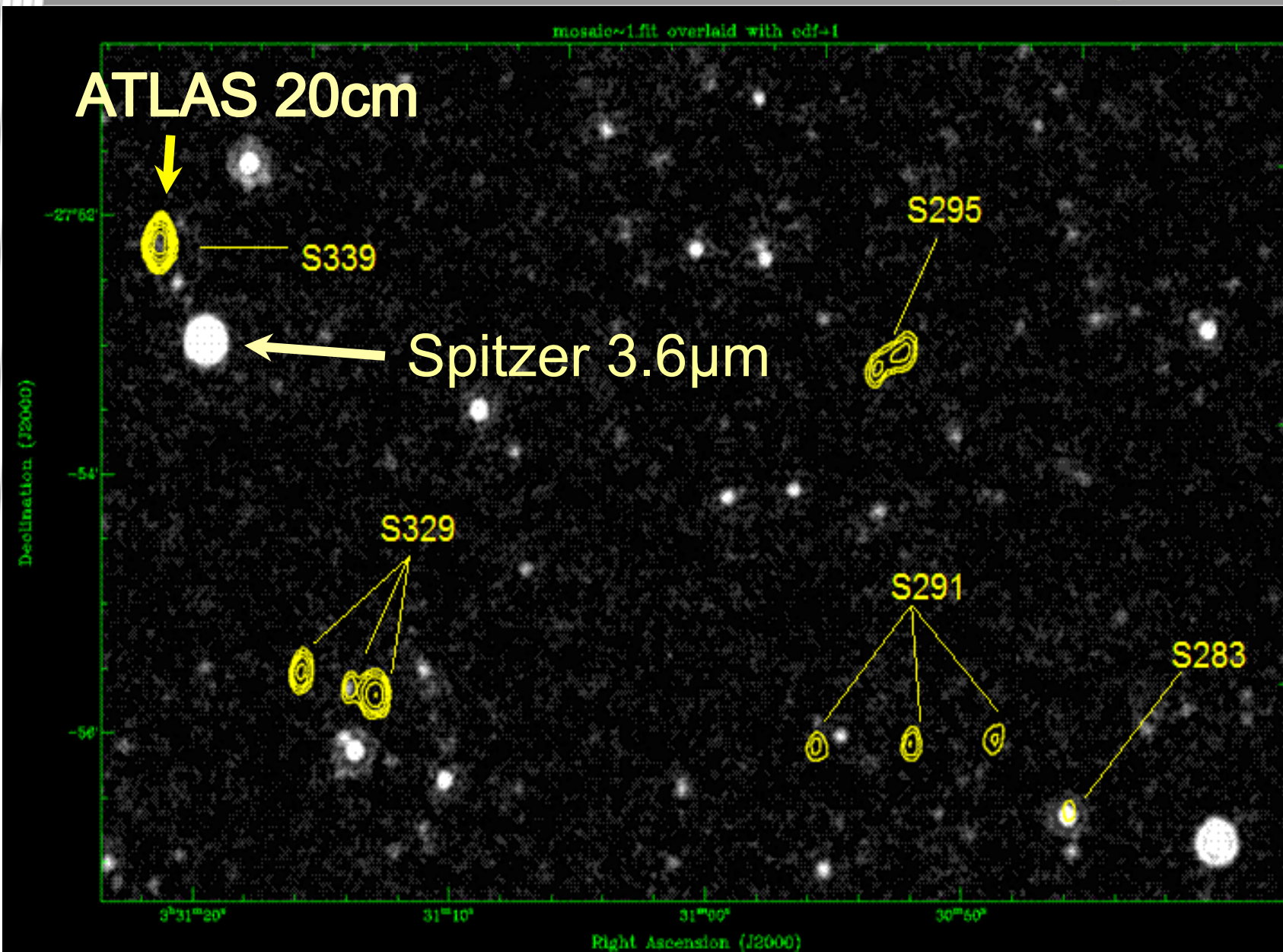
Technical Challenges

- **Survey Strategy**
- **Performance of PAF**
 - uniformity, polarisation, sidelobes, etc.
- **Image Processing**
 - Dynamic range, calibration, sensitivity as function of scale size, etc.
- **Source Extraction**
- **Cross-identification**
- **Redshifts**
- **Data delivery (Value-added catalogue/VO)**

Source Extraction

- **EMU source extraction team currently exploring available source finders (sExtractor, sfind, DuChamp, etc).**
- **None are yet optimum**
- **Will incorporate optimum algorithm into ASKAP processing pipeline**
- **See (e.g.)**
 - Compact continuum source finding for next generation radio surveys (Hancock, P.J., Murphy, T., Gaensler, B.M., Hopkins, A., & Curran, J.R. 2012, mnras, 422, 1812)
 - The completeness and reliability of threshold and false-discovery-rate source extraction algorithms for compact continuum sources (Huynh, M., Hopkins, A., Norris, R., et al. 2011, arXiv:1112.1168)
 - BLOBCAT: Software to Catalogue Flood-Filled Blobs in Radio Images of Total Intensity and Linear Polarization (Hales, C.A., Murphy, T., Curran, J.R., et al. 2012, arXiv:1205.5313)

Cross-identification with other wavelengths



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 Release Date
WISE ¹	40000	3.4, 4.6, 12, 22 μ m	80 μ Jy	23	100	2012
Pan-Starrs ²	30000	<i>g, r, i, z, y</i>	$r < 24.0$	54	50	2020
Wallaby ^{3,b}	30000	20 cm (HI)	1.6 mJy ^c	1	100	2013
LSST ⁴	20000	<i>u, g, r, i, z, y</i>	$r < 27.5$	96	67	2020
Skymapper ⁵	20000	<i>u, v, g, r, i, z</i>	$r < 22.6$	31	66	2015
VHS ⁶	20000	Y, J, H, K	$K < 20.5$	49	66	2012
SDSS ⁷	12000	<i>u, g, r, i, z</i>	$r < 22.2$	28	22	DR8
DES ⁸	5000	<i>g, r, i, z, y</i>	$r < 25$	71	17	2017
VST-ATLAS ⁹	4500	<i>u, g, r, i, z</i>	$r < 22.3$	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, <i>g, r, i, z, y</i>	$g < 27.0$	57	4	2020

Cross-Identification for EMU

(WG chair: Loretta Dunne, Canterbury Uni)

- **We plan to develop a pipeline to automate cross-IDS**
 - using intelligent criteria
 - not simple nearest-neighbour
 - working closely with other survey groups
 - use all available information (probably Bayesian algorithm)
- **Expect to be able to cross-ID 70% of the 70 million objects**
- **20% won't have optical/IR ID's**
- **What about the remaining 10% (7 million galaxies)?**

What

GALA

Home How To Take

the

ct

?

Redshifts

- **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:**
 - template fitting
 - kNN algorithms
 - SoM algorithms
 - etc

Statistical Redshifts

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 $S_{20\text{cm}}/S_{2.2\mu\text{m}}$ 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 ($\Rightarrow$ statistical redshifts)

EMU Survey Design Paper

(Norris et al., 2011, PASA, 28, 215, <http://arxiv.org/abs/1106.3219>)

EMU: Evolutionary Map of the Universe

Ray P. Norris¹, A. M. Hopkins², J. Afonso³, S. Brown¹, J. J. Condon⁴, L. Dunne⁵, I. Feain¹, R. Hollow¹, M. Jarvis⁶, M. Johnston-Hollitt⁷, E. Lenc¹, E. Middelberg⁸, P. Padovani⁹, I. Prandoni¹⁰, L. Rudnick¹¹, N. Seymour¹², G. Umana¹³, H. Andernach¹⁴, D. M. Alexander²¹, P. N. Appleton¹⁵, D. Bacon¹⁶, J. Banfield¹, W. Becker¹⁷, M. Brown¹⁸, P. Ciliegi¹⁹, C. Jackson¹, S. Eales²⁰, A. C. Edge²¹, B. M. Gaensler²², G. Giovannini¹⁰, M. Y. Huynh²³, E. Ibar²⁴, R. Ivison²⁵, R. Kennicutt²⁶, Amy E. Kimball⁴, A. M. Koekemoer²⁷, B. S. Koribalski¹, A. Lopez-Sanchez², M. Y. Mao^{1,28}, H. Messias²⁹, K. A. Pimbblet¹⁸, A. Raccanelli¹⁶, T. H. Reiprich³⁰, I. G. Roseboom³¹, H. Rottgering³², D. J. Saikia³³, R. G. Sharp³⁴, O. B. Slee¹, I. R. Smail²¹, M. Thompson⁶, J. S. Urquhart¹, J. V. Wall³⁵

Abstract: EMU is a wide-field radio continuum survey planned for the new Australian Square Kilometre Array Pathfinder (ASKAP) telescope. The primary goal of EMU is to make a deep ($\sim 10\mu\text{Jy}$ rms) radio continuum survey of the entire Southern Sky, extending as far North as $+30^\circ$ declination. EMU is expected to detect and catalog about 60 million galaxies, including typical star-forming galaxies up to $z=1$, powerful starbursts to even greater redshifts, AGNs to the edge of the Universe, and will undoubtedly discover new classes of object. This paper defines the science goals and parameters of the survey, and describes the development of techniques necessary to maximise the science return from EMU.

Keywords: methods: data analysis — telescopes — surveys — stars: activity — Galaxy: general — galaxies: evolution — galaxies: formation — cosmology: observations — radio continuum: general

1 Introduction

1.1 Background

Deep continuum surveys of the radio sky have a

vation (Owen & Morison 2008) in the lower left. All current surveys are bounded by a diagonal line that roughly marks the limit of available telescope time of current-generation radio telescopes. The region to the left of this line is currently unex-

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

