ASKAP = Australian SKA Pathfinder

- 36 12-m dishes, each with 192-pixel phased-array feed (PAF), giving a 30 sq deg. field of view
- All dishes built, antennas being equipped with PAFs
- Science observing expected to start early 2015
- Generates 70 PB/year – cant afford to keep all of that!
- Driven by 2 key science projects (EMU & WALLABY) plus 8 second-tier projects
- All primary data in (VO) public domain after quality control

EMU & WALLABY

EMU=Evolutionary Map of the Universe

- Continuum survey: ike NVSS but 45 times deeper
- Will catalog 70 million galaxies
  (c.f. ~2.5 million radio sources currently known)
- Key Science goal: evolution of galaxies and AGN over cosmic time
- Secondary goals: cosmology, Galactic, serendipity (WTF)

WALLABY

- HI survey
- Will detect ~ 500,000 galaxies up to z=0.5
- (more redshifts than SDSS!)
- Key Science goal: evolution of galaxies since z=0.5
- Secondary goals: cosmology, star formation, etc.

EMU DATA

Primary data to be served using VO protocols from ASKAP server in Perth, WA (Catalogs, images, cut-outs, etc)

Secondary (value-added) data will include:

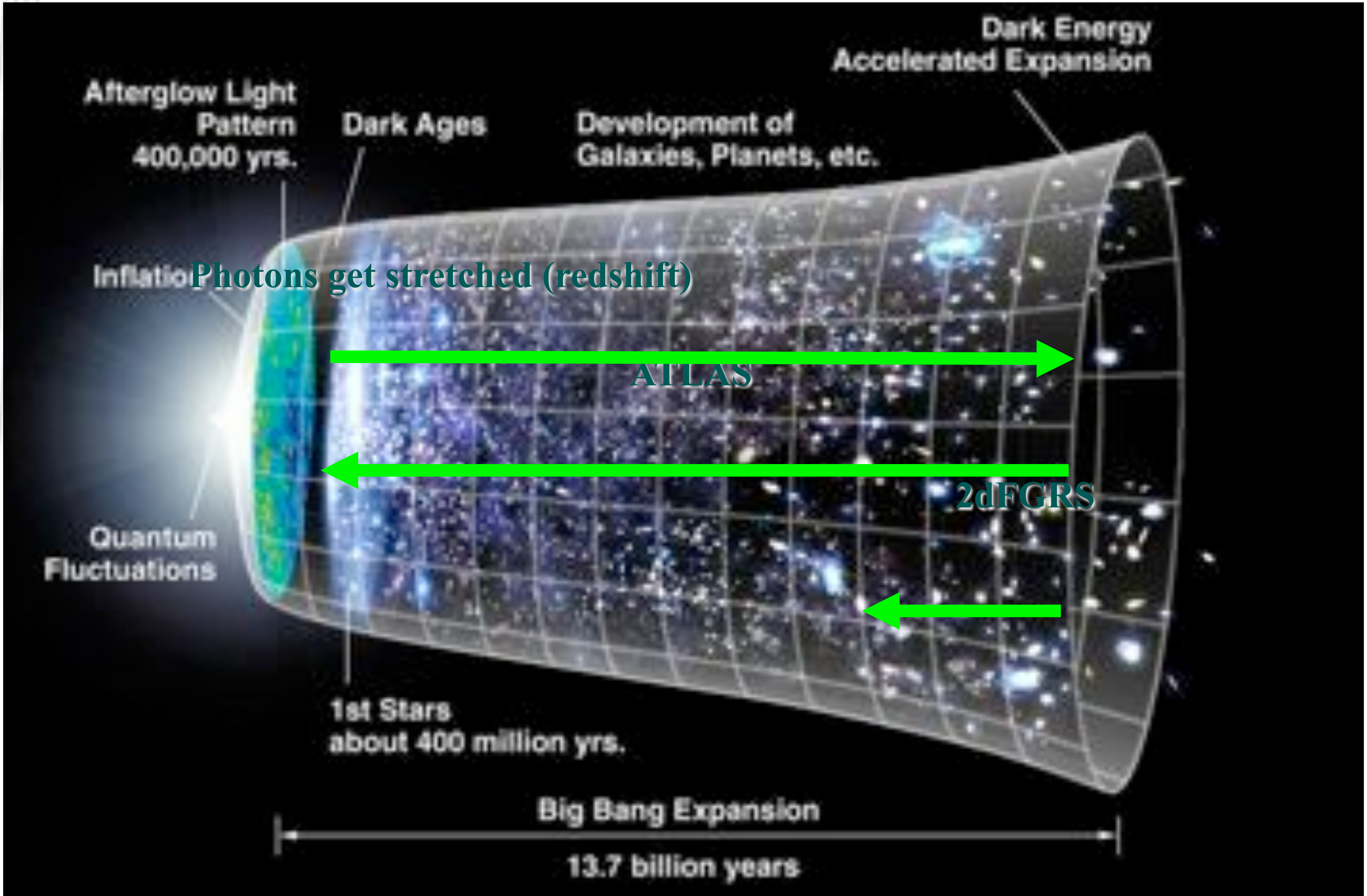
- **Cross-ids with optical/IR catalogs**
- **Classifications where possible**

Hosting of secondary data TBD (possibly CDS or Perth)

Challenges:

- **Calibration/uniformity/sidelobes**
- **Data volumes**
- **Source finding**
- **Cross-identification**
- **Stacking**
- **Redshifts**
- **Data mining/Compute-intensive projects/WTF**

Using redshift to see back in time



Using deep surveys to understand galaxy evolution

- **Find a patch of dark sky free from bright stars, dust clouds, etc**
- **Make deep images at several different wavelengths**
- **Make a census of all galaxies within it**
- **Sequence in age (= redshift)**
- **Identify**
  - different evolutionary tracks
  - rare but important transitional stages

The Hubble Deep Field South

SKA Pathfinders

- **Pioneer potential SKA technology**
- **Are powerful science-driven observatories**
- **Examples:**
  - ASKAP (Australia)
  - MWA (Australia)
  - MeerKAT (South Africa)
  - LOFAR (Netherlands)
  - Apertif (Netherlands)
  - EVLA (USA)
  - eMERLIN (UK)
  - eEVN (Europe)

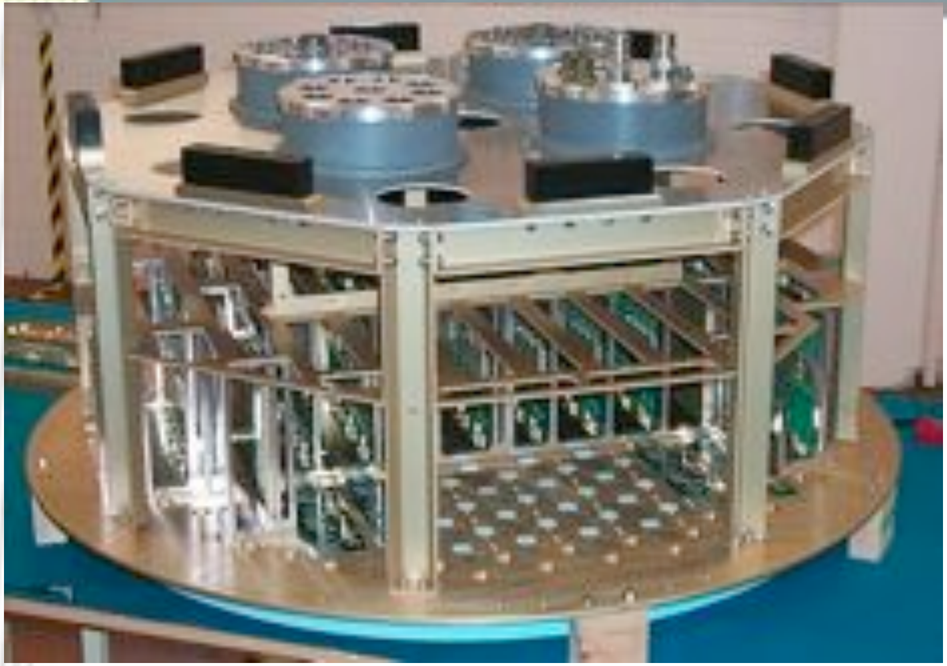
This is a

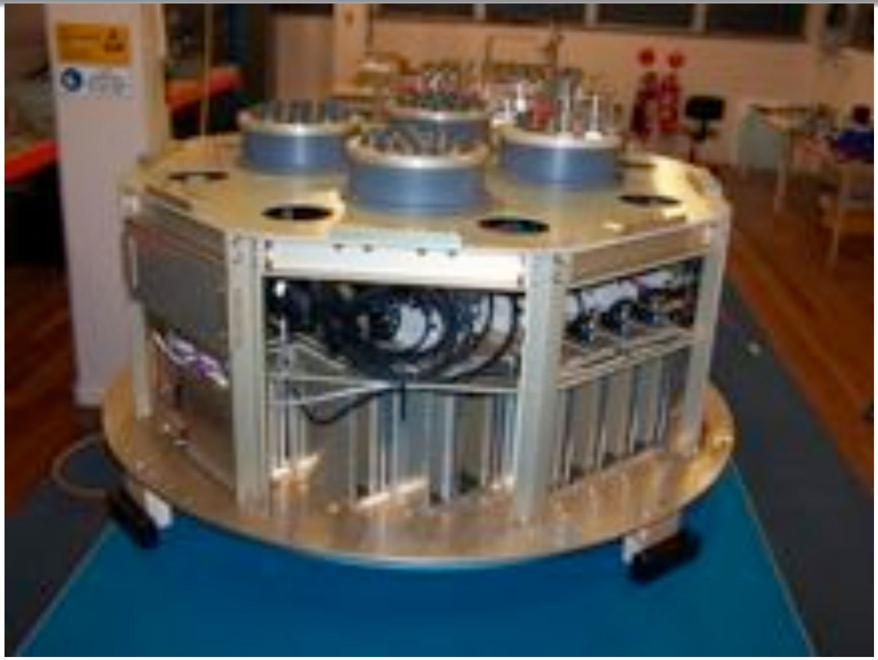
y migrated

ASKAP Design Specifications

• Number of antennas	36 (630 baselines)
• Antenna diameter	12 m (3 axis)
• Maximum baseline	6 km
• Cont. Angular resolution	10 arcsec
• Sensitivity	65 m^2/K
• Frequency range	700 – 1800 MHz
• Focal plane phased array	188 elements (92 dual pol)
• Field of view	30 deg^2
• Processed bandwidth	300 MHz
• Number of channels	16 384

Phased-Array Feeds (PAFs)





ASKAP Science

38 proposals submitted to ASKAP

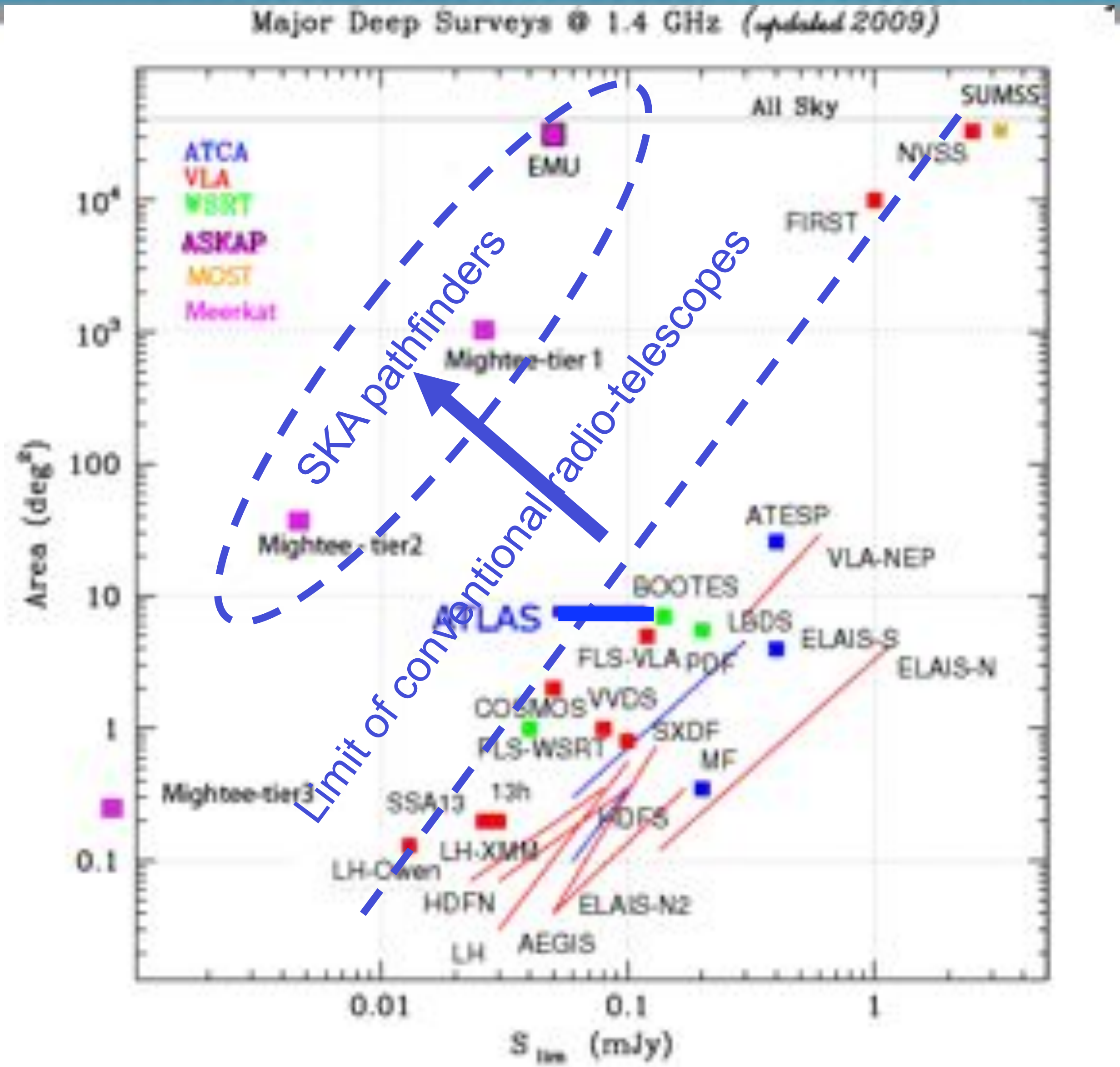
2 selected as being highest priority

- 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 major 20cm surveys

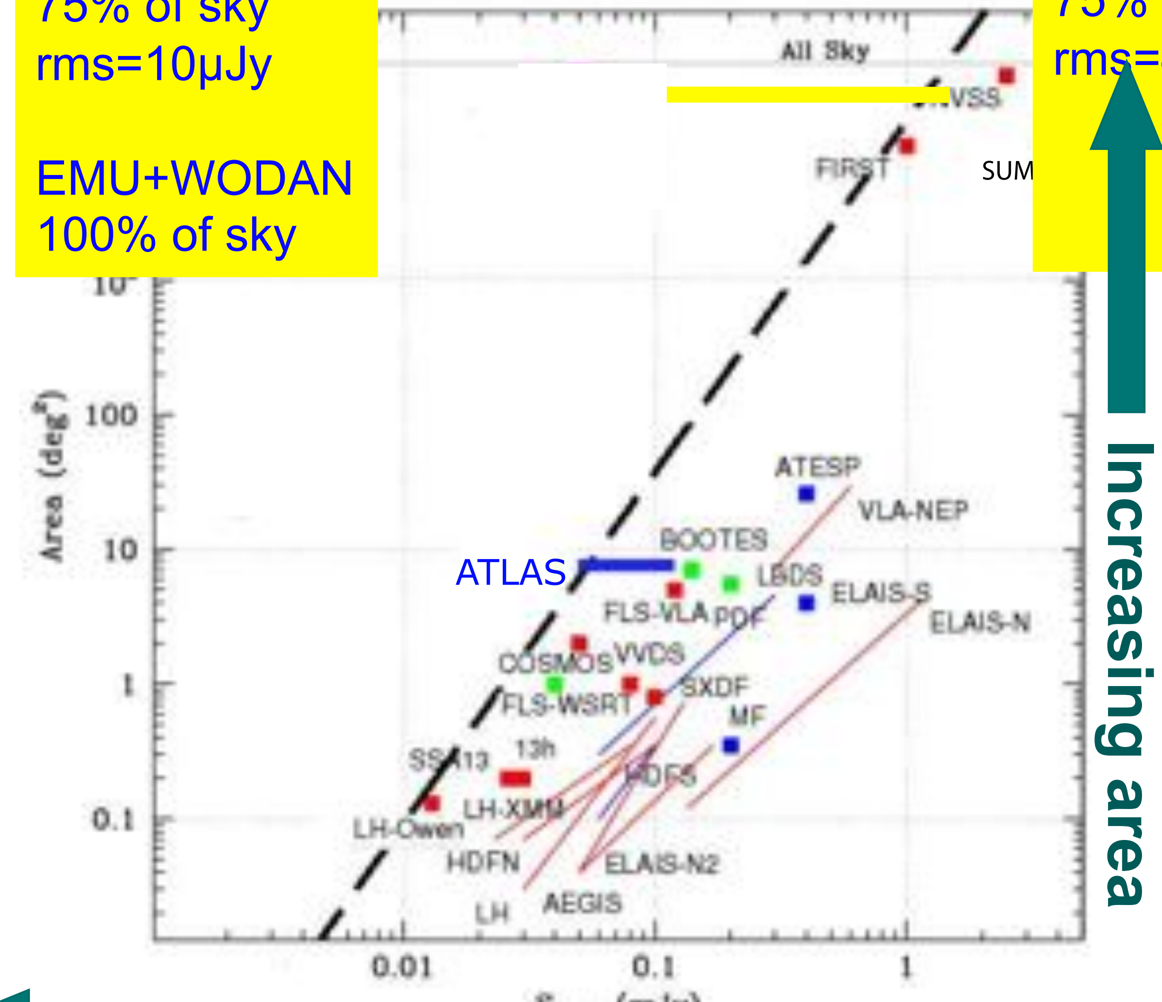


Current major 20cm surveys

EMU
75% of sky
rms=10μJy

EMU+WODAN
100% of sky

NVSS
75% of sky
rms=450μJy



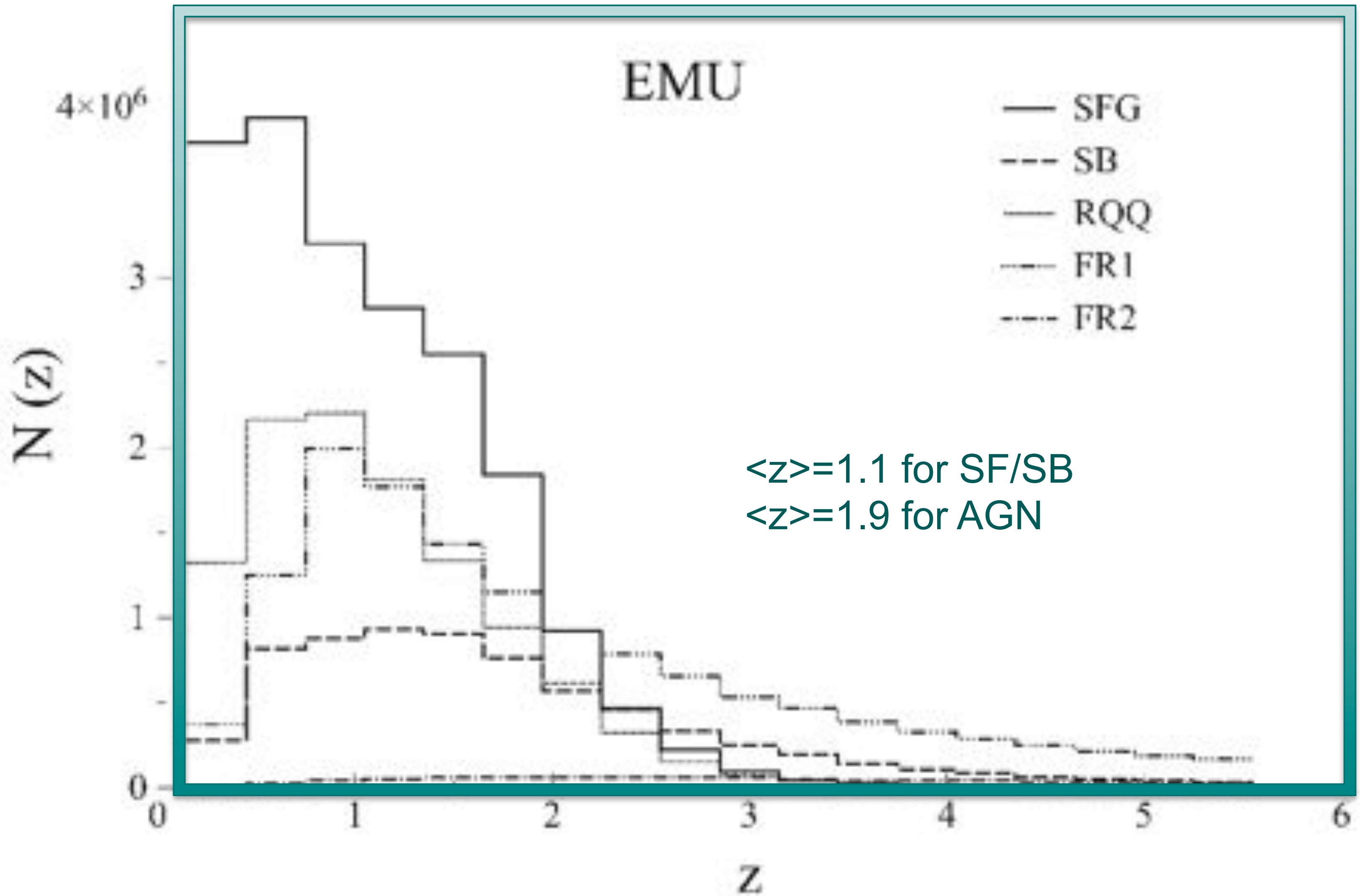
Increasing sensitivity

- **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 2014(?)**
- **Total integration time: ~1.5 years ?**

Complementary radio surveys

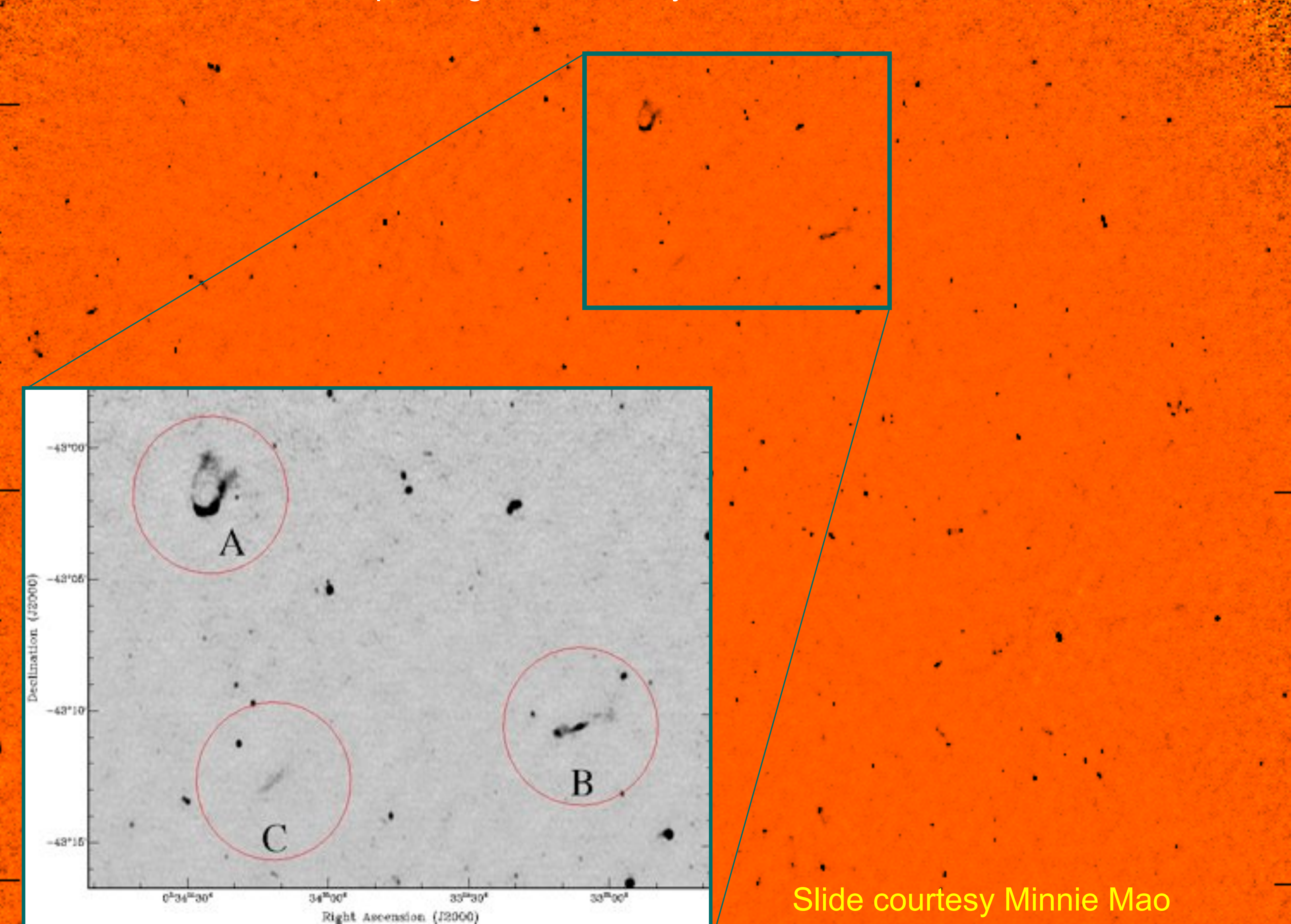
- **Westerbork-WODAN**
  - using Apertif PAF on Westerbork telescope
  - will achieve similar sensitivity to EMU
  - will observe northern quarter of sky ($\delta > +30°$)
  - well-matched to EMU
- **LOFAR continuum surveys**
  - lower frequency
  - covering Northern half(?) of sky
  - valuable because 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



Slide courtesy Minnie Mao

ATLAS =Australia Telescope Large Area Survey

- **covers 7 sq deg centred on CDFS and ELAIS-S1**
- **has the same rms sensitivity (10μJy) as EMU**
- **has the same resolution (10 arcsec) as EMU**
- **expect to catalogue 16000 galaxies**
- **Final data release early 2012 using EMU prototype tools**

Slide courtesy of Minnie Mao

How did galaxies form and evolve?

Science Goals

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

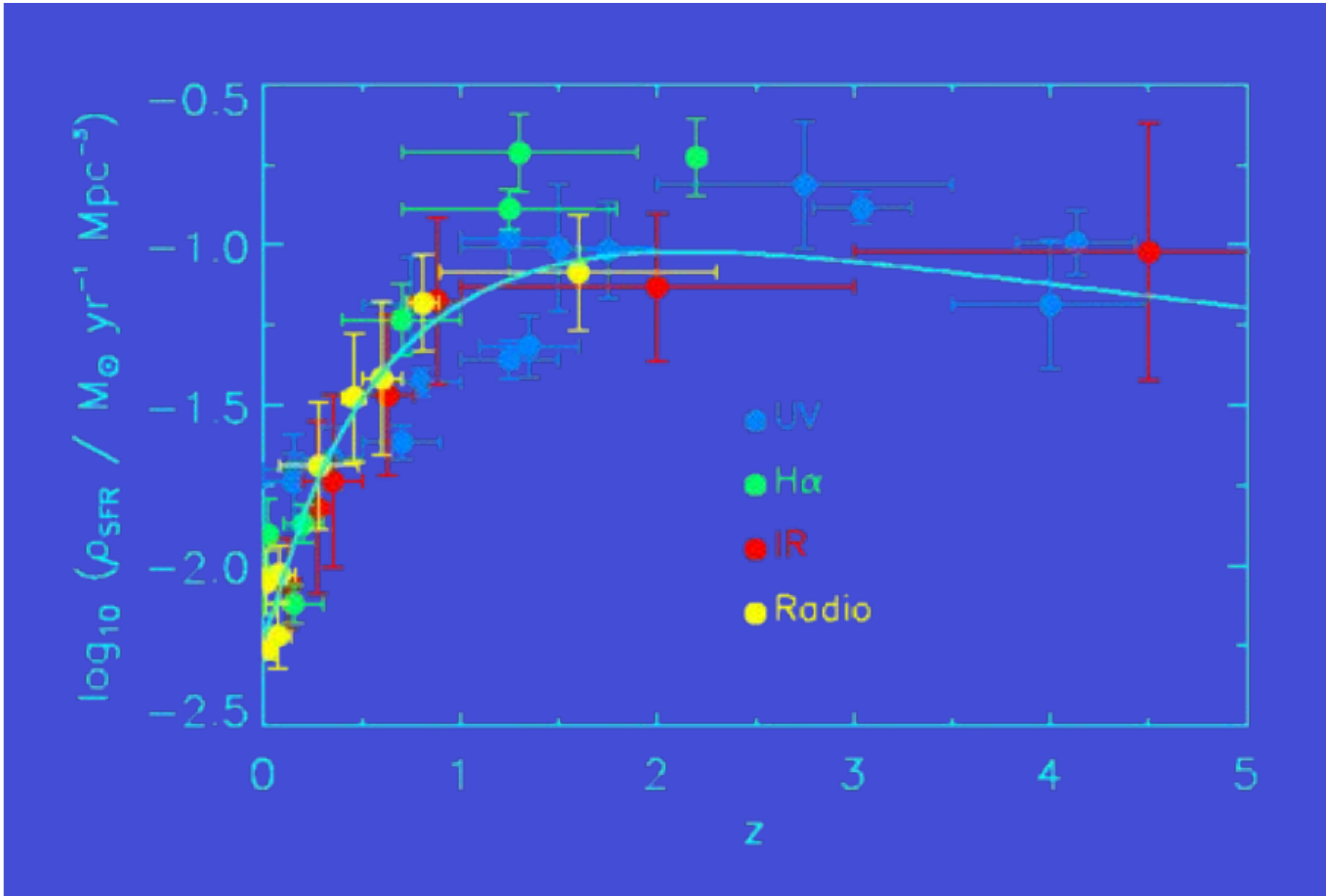
6) Generate an Atlas of the Galactic Plane

7) Create a legacy for surveys at all wavelengths (Herschel, JWST, ALMA, etc)

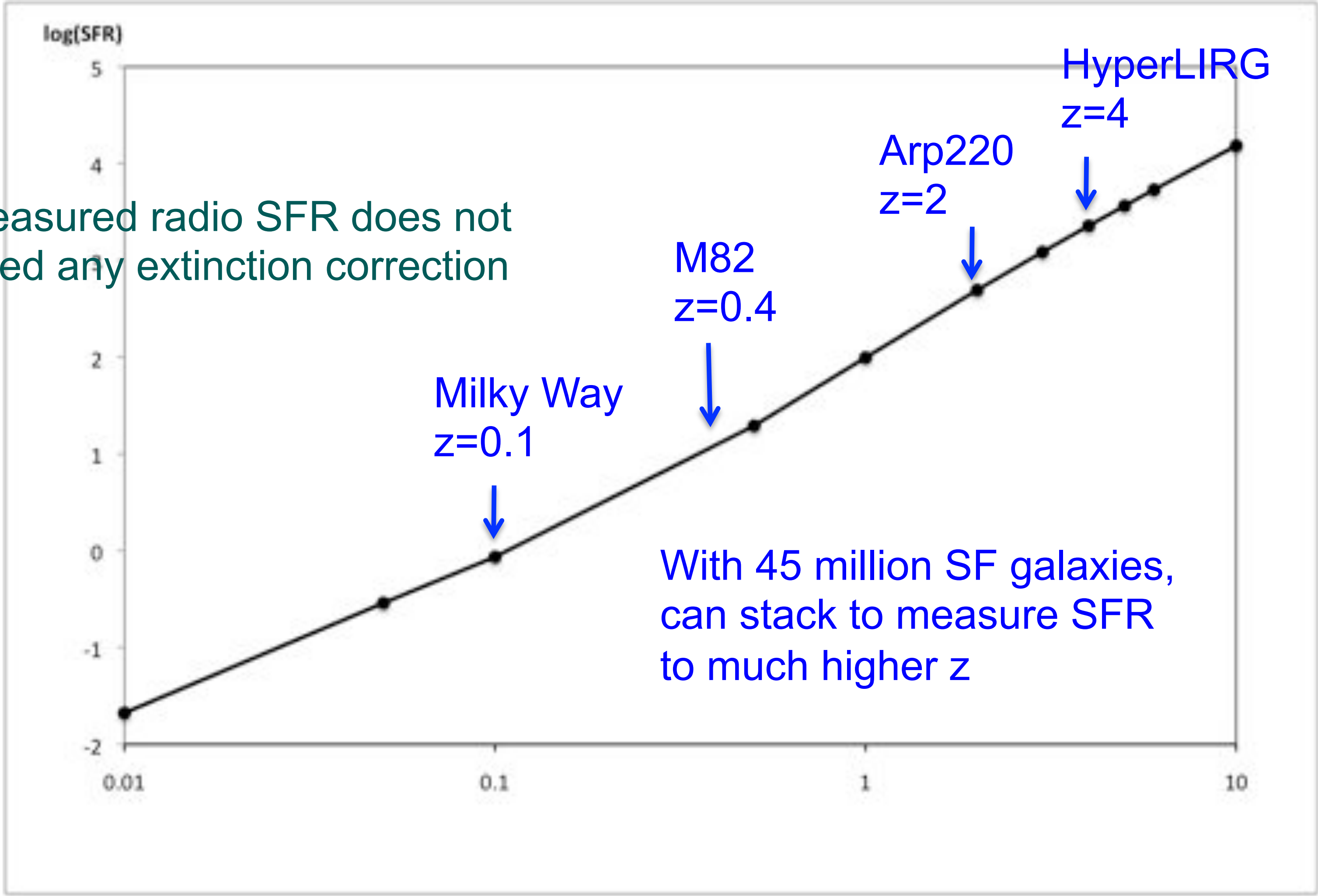
Science Goal 1:
measure SFR, unbiased by dust

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~2**
- **Can stack much higher**
- **Can measure SFR unbiased by extinction**



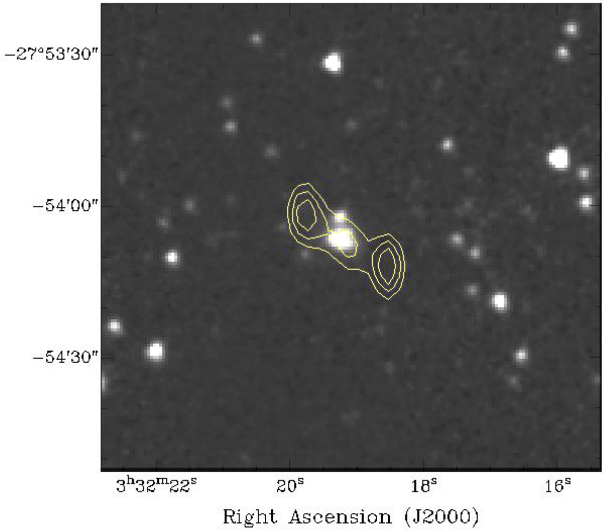
SFR measurable (5σ) by EMU

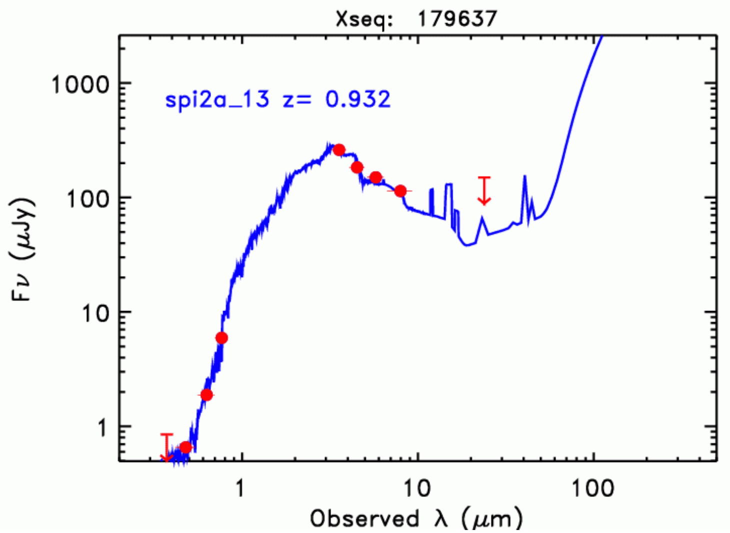


Measured radio SFR does not need any extinction correction

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



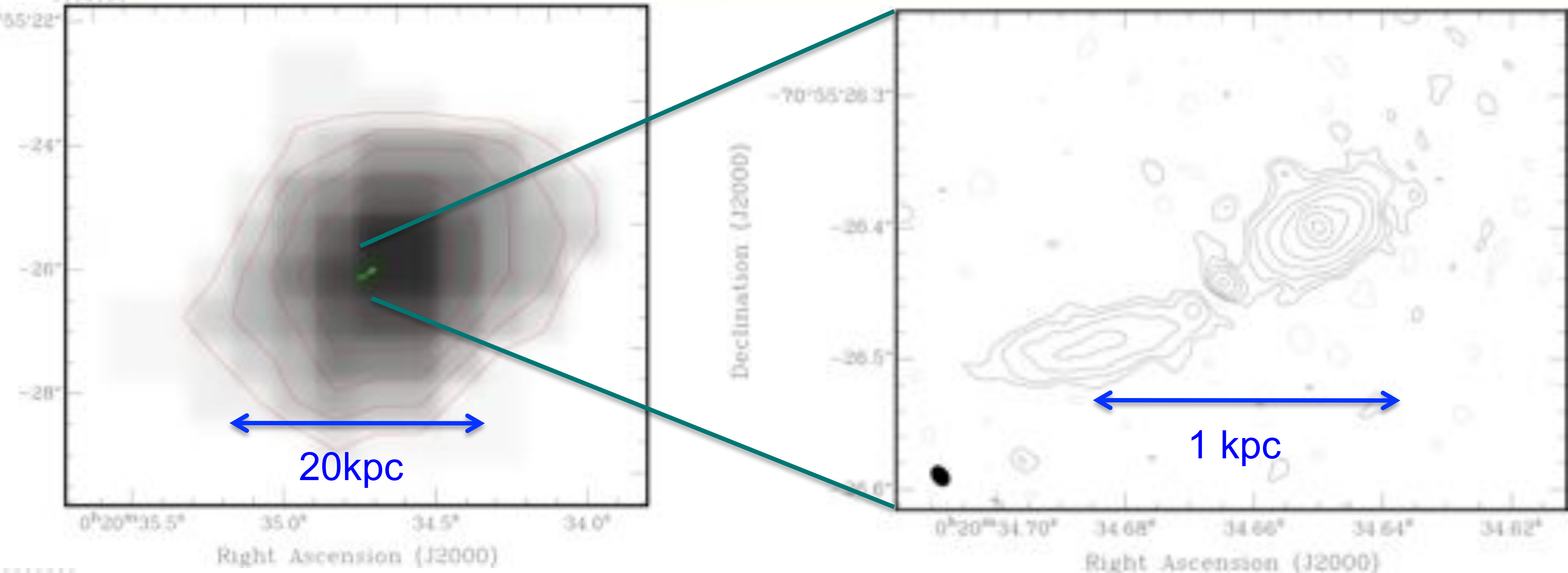


- *Norris et al. 2008, arXiv:0804.3998*
- S_{20cm} = 9mJy
- z = 0.932
- L_{20cm} = 4 x 10^{25} WHz^{-1}

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 $L=9.10^{12}\ L_o$)



z=0.327

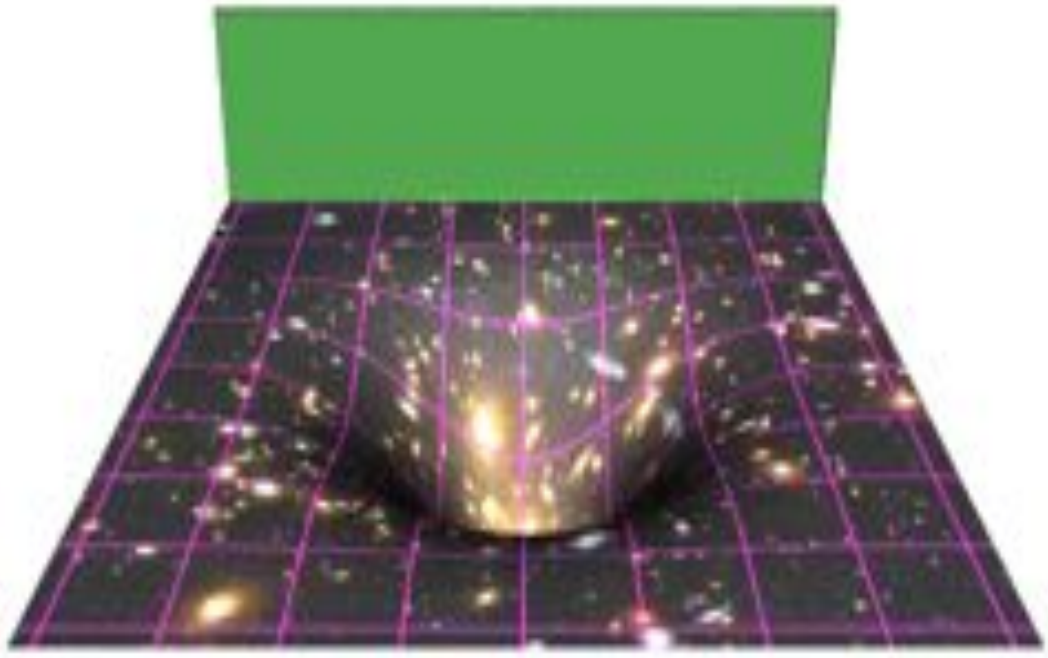
P=6.10^{25} W/Hz

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 optica/IR wavelengths**
- **see Norris et al. arXiv:1107.3895**

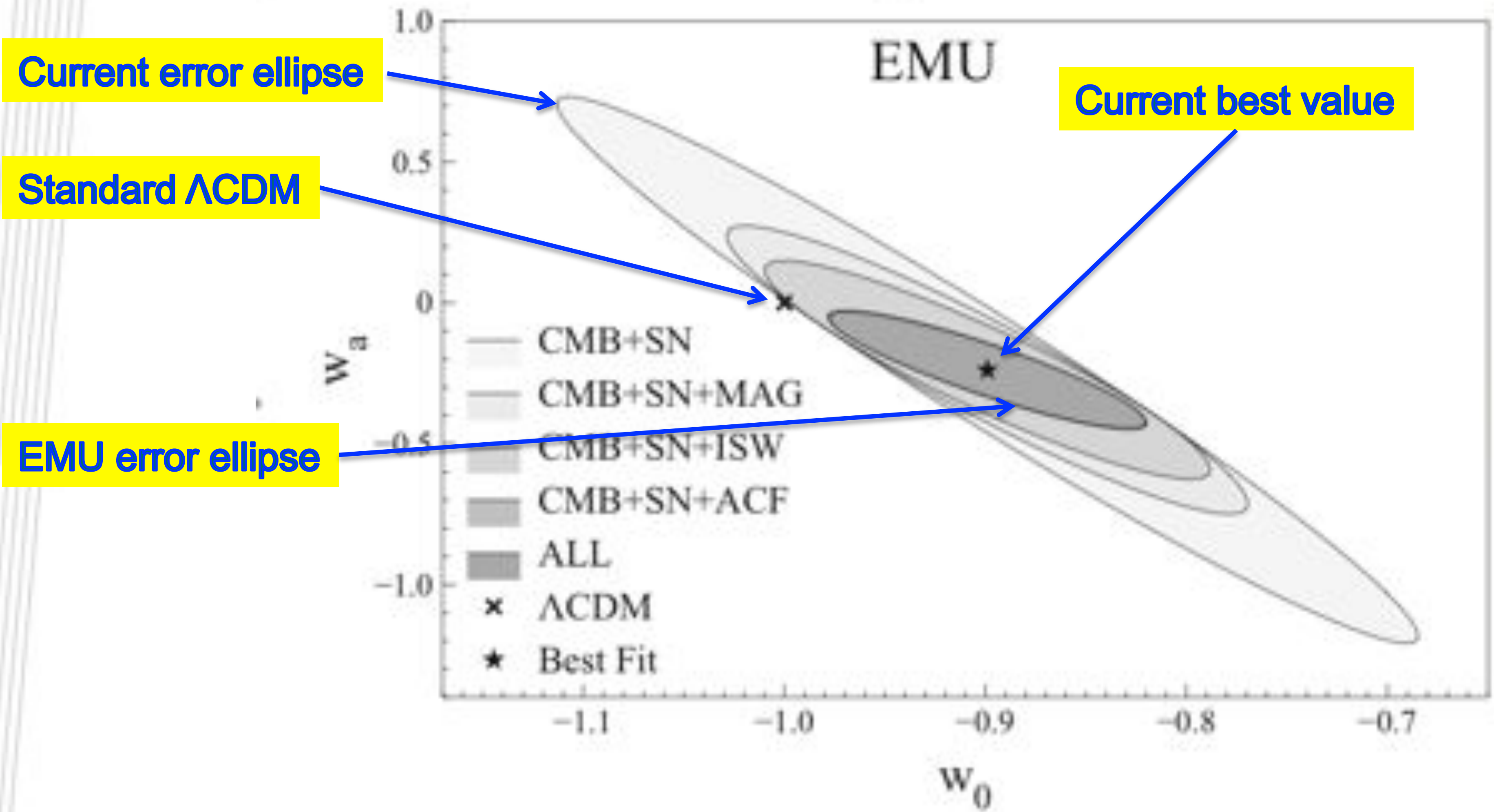
Measurement 2: Integrated Sachs-Wolfe Effect

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



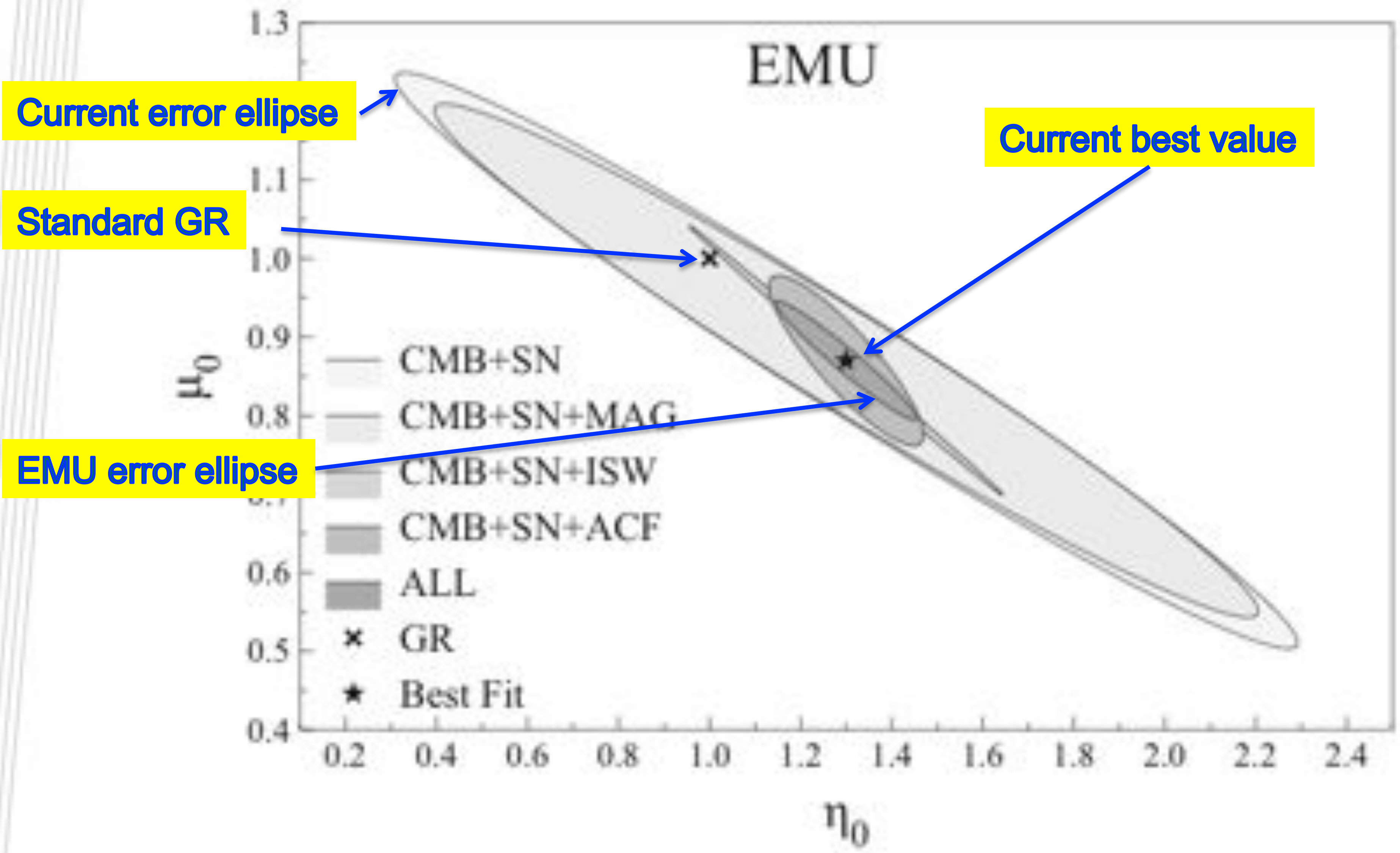
~10°

Dark Energy



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

Modified Gravity



How do Redshifts Help?

All those results made the conservative assumption that no redshifts are availablke for EMU sources (Raccanelli et al. arXiv 1108.0930)

But even imperfect photo-z's make a big difference (*Camera et al, arXiv 1205.1048)

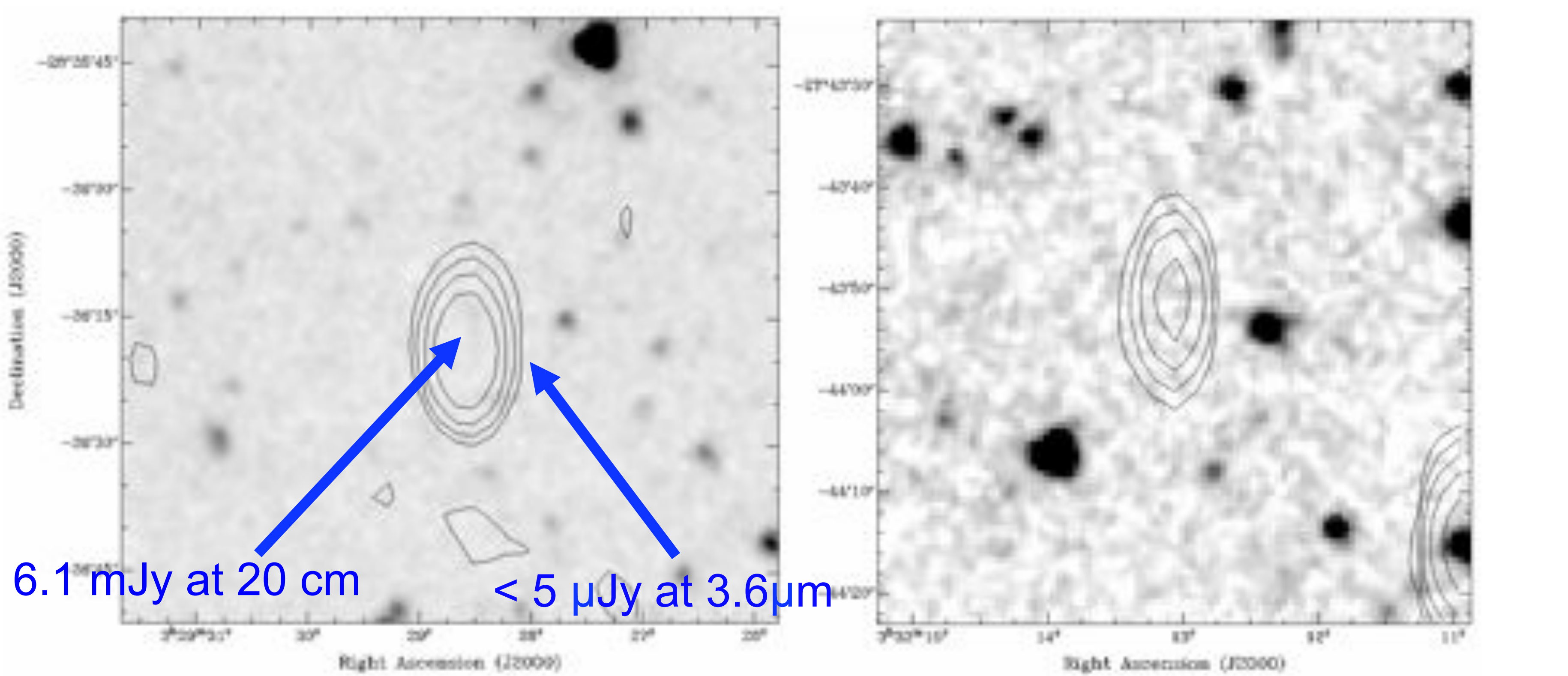
(e.g polarised sources have <z>=1.8, unpolarised sources have <z>=1.1)

Implications of statistical redshifts

1) **"tomographic cosmology"**
   - EMU samples much larger volume of space than DES etc

2) **Further reduce the error ellipses in all above tests**

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

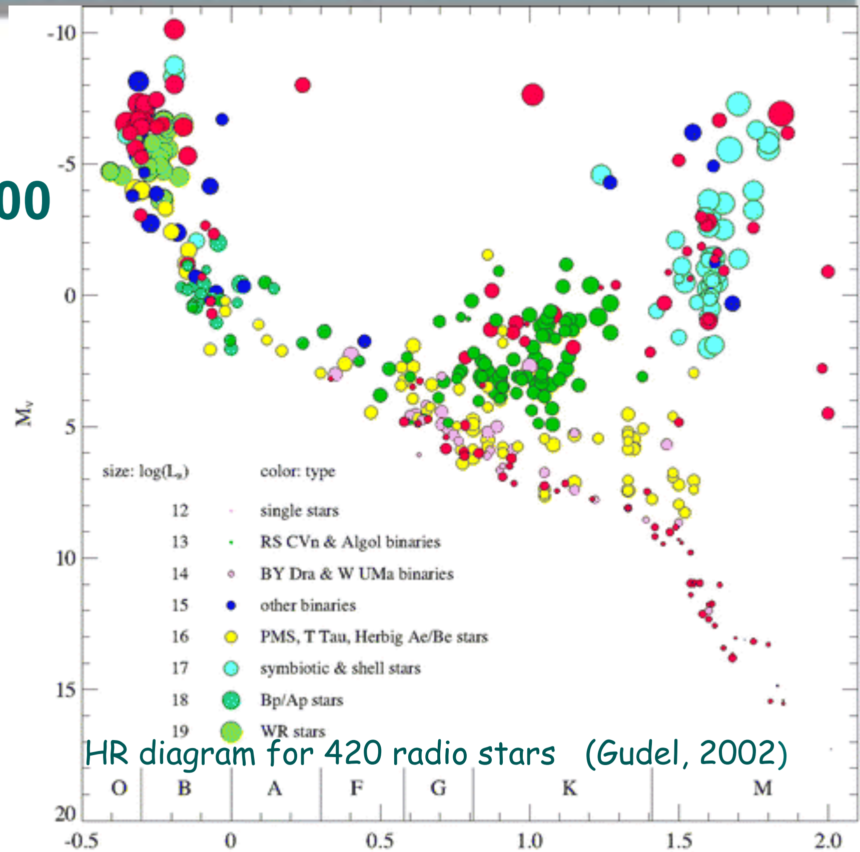
- decision tree
- cluster analysis
- kFN
- Bayesian

Identified objects/regions will be either

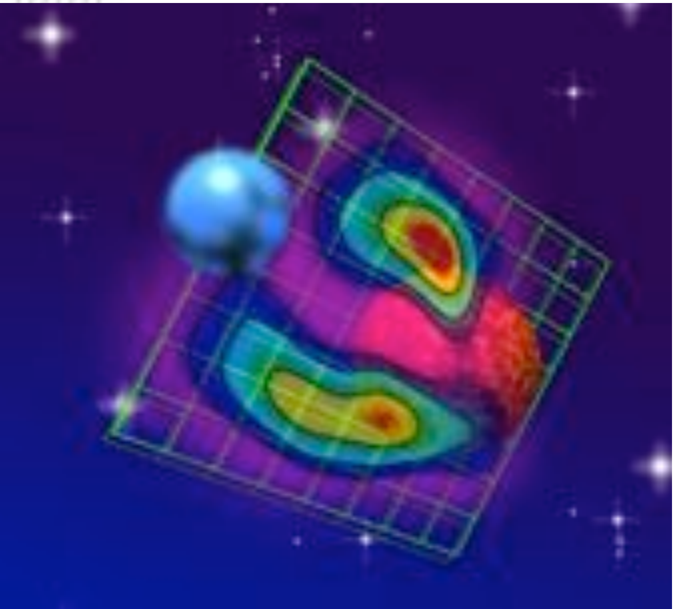
- processing artefacts (important for quality control)
- statistical outliers of known classes of object (interesting!)
- New classes of object (WTF)

Science goal 6: Generate an Atlas of the Galactic Plane, including increasing number of known radio stars by 10-100

- **Detect every UCHII region in the Galaxy**
- **Detect new SNR and PNe**
- **Increase # of known radio stars by 10-100**
- **Discover new types and define typical populations (unbiased)**
  - current samples too small



HR diagram for 420 radio stars (Gudel, 2002)

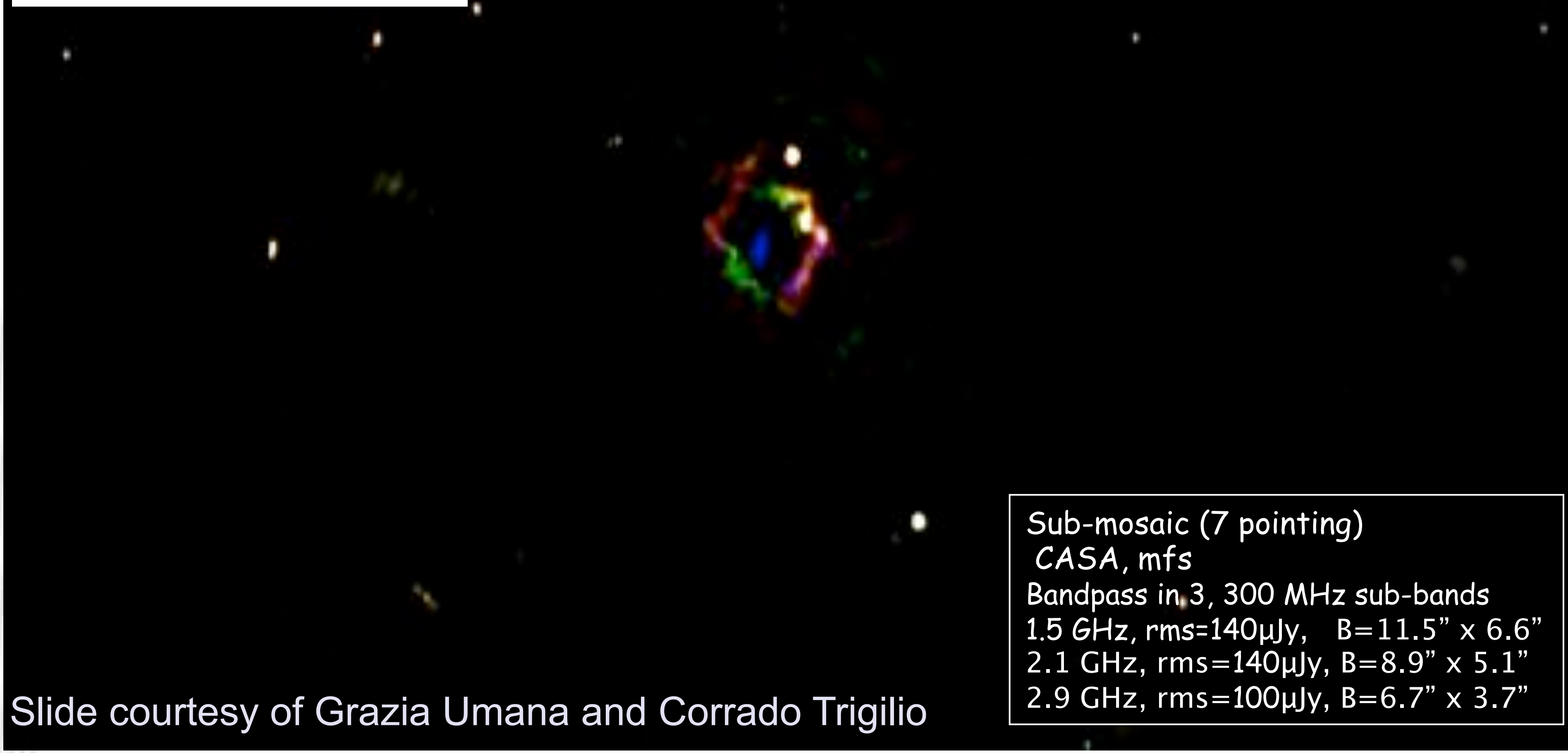


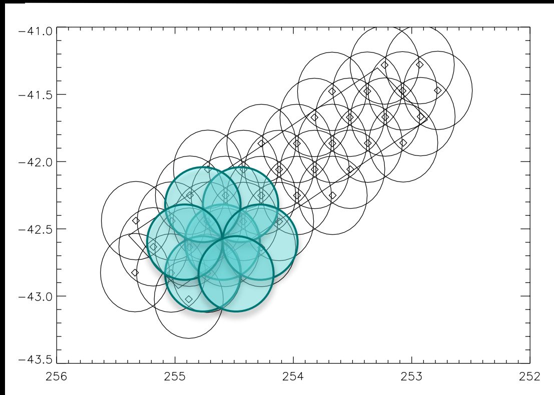
•Understand stellar magnetic activity

•Understand coherent emission mechanisms

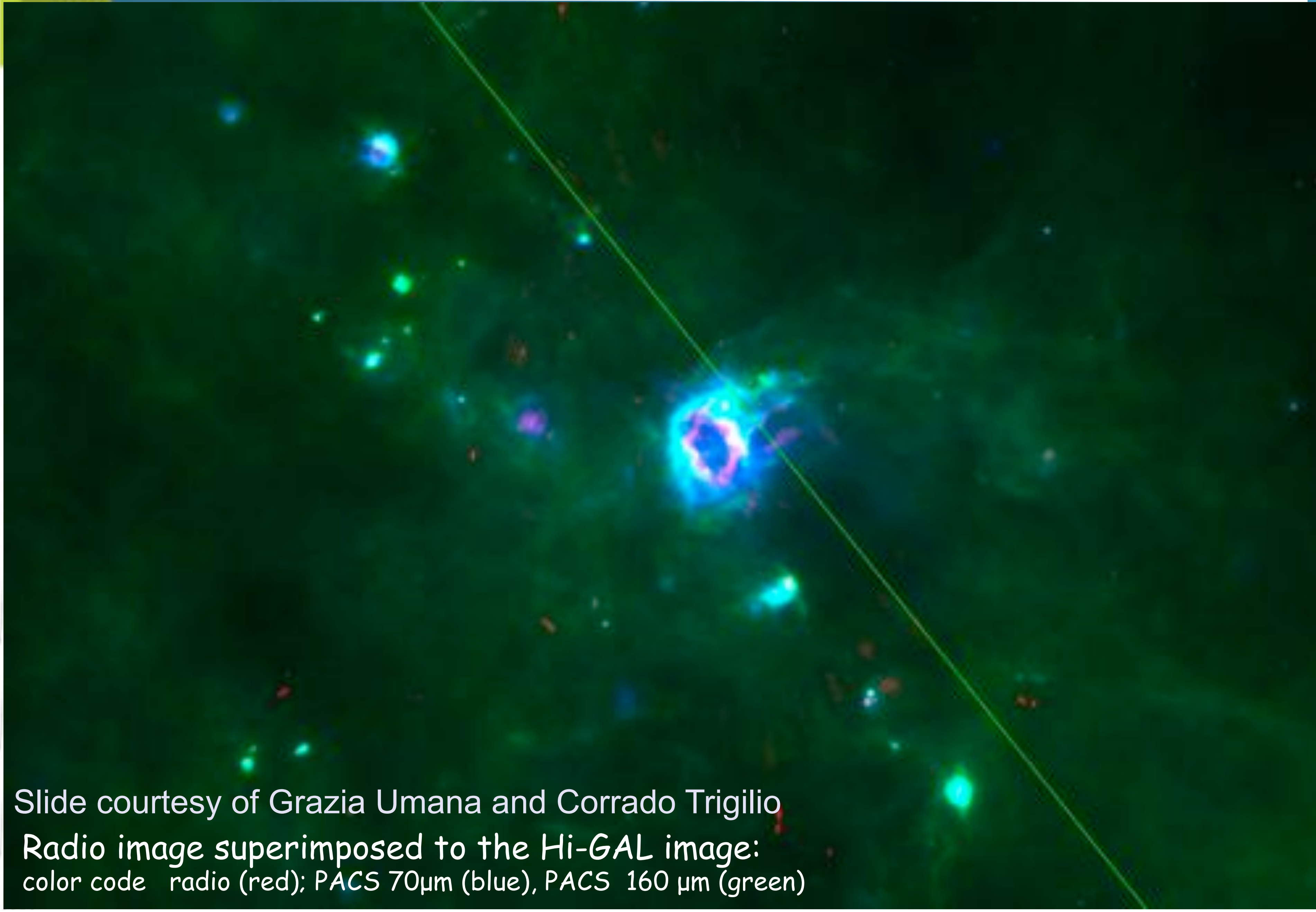
Algol: Mutel et al 2009

The pilot experiment: SCORPIO





Looking at the dust..



Slide courtesy of Grazia Umana and Corrado Trigilio

Radio image superimposed to the Hi-GAL image:

color code   radio (red); PACS 70μm (blue), PACS 160 μm (green)

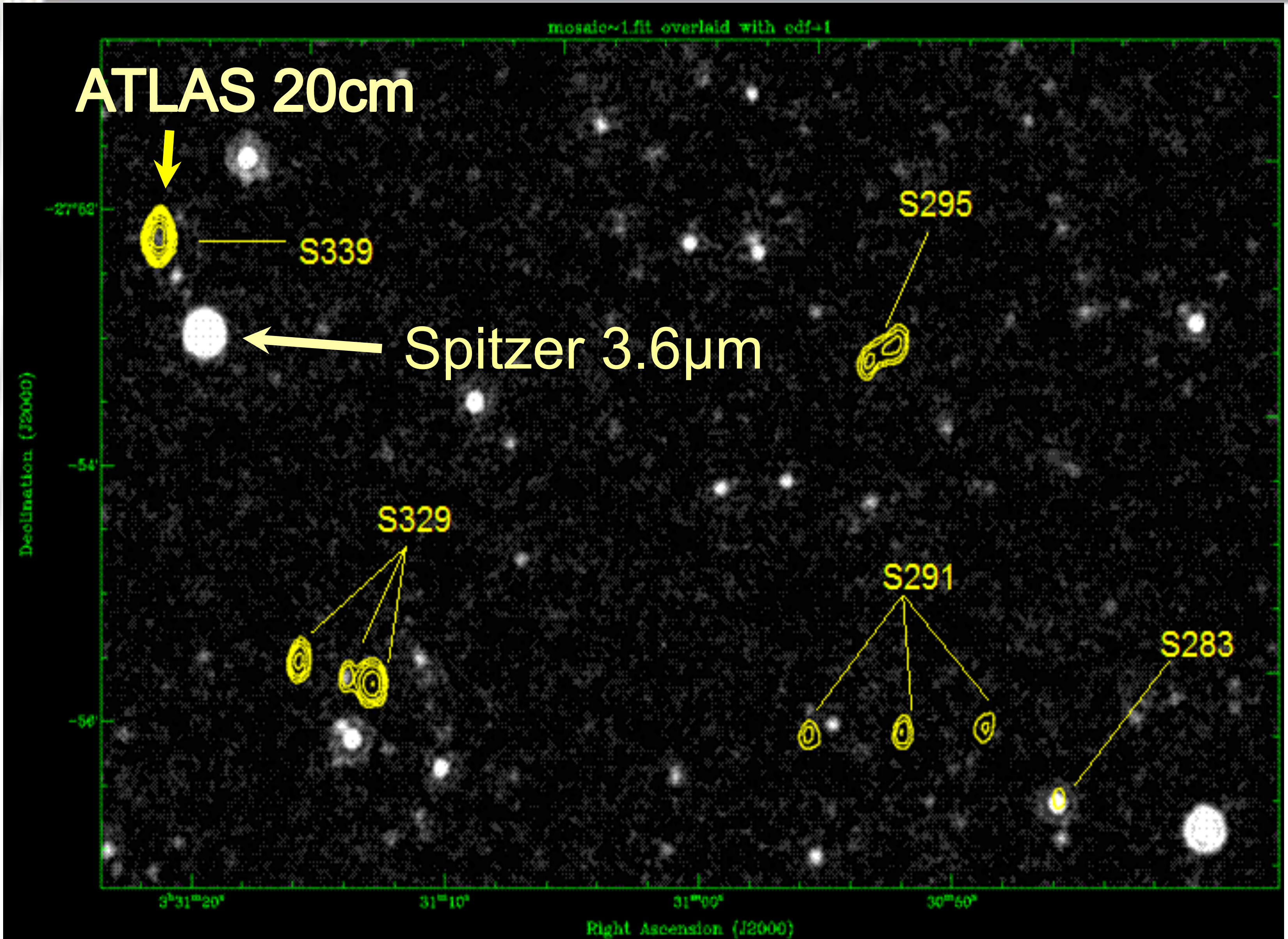
Technical Challenges

- **Survey Strategy**
- **Performance of PAF**
  - uniformity, poilarisation, 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



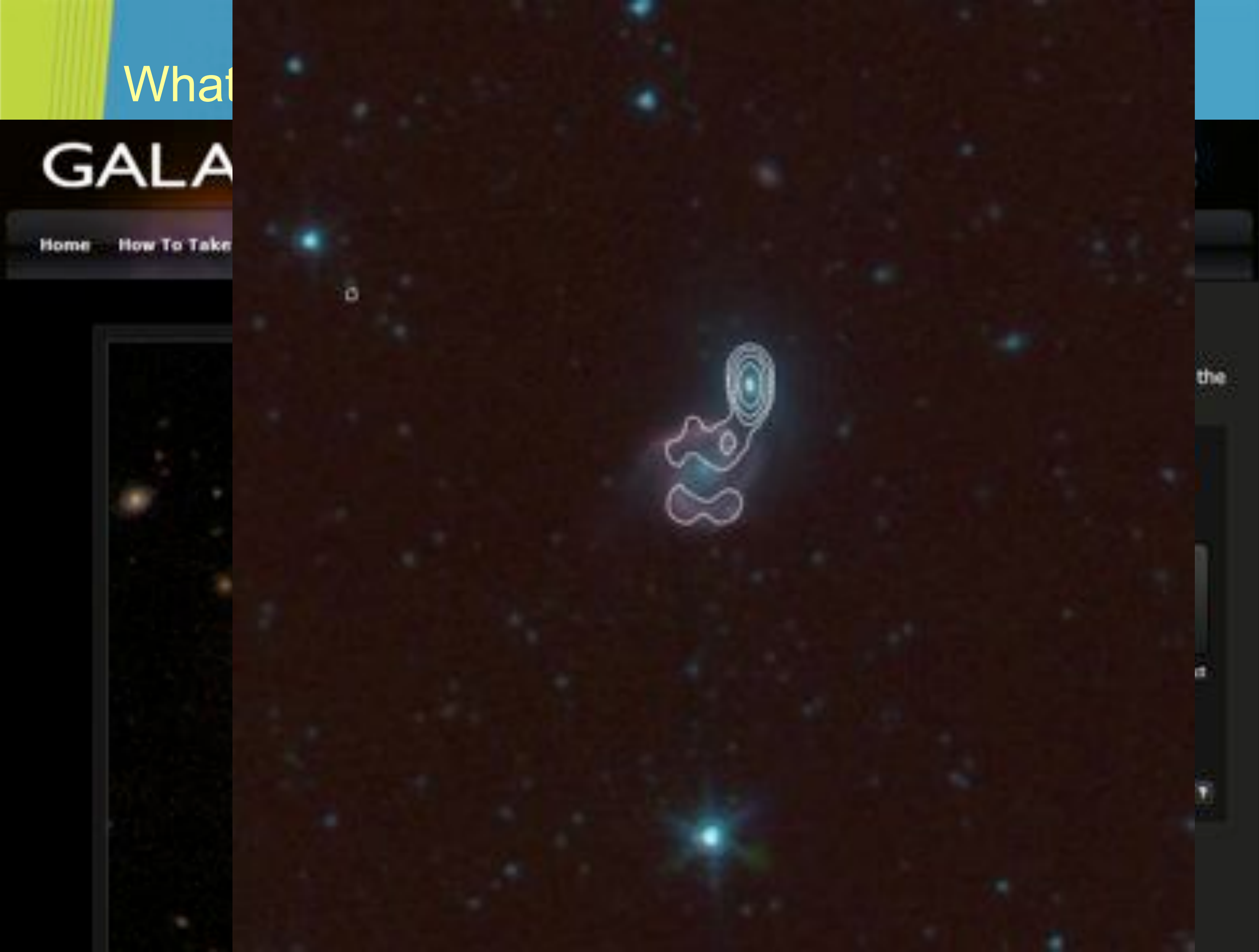
Challenge: difficult to get redshifts, or even optical/IR photometry

Survey Name	Area (deg^2)	Wavelength Bands	Limiting Mag. or flux[a]	EMU Detected (%)	Survey Matched (%)	Data 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

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



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 $S_{20cm}/S_{2.2\mu m}$ 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)

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. Norris[1], A. M. Hopkins[2], J. Afonso[3], S. Brown[1], J. J. Condon[4], L. Dunne[5], I. Feain[1], R. Hollow[1], M. Jarvis[6], M. Johnston-Hollitt[7], E. Lenc[1], E. Middelberg[8], P. Padovani[9], I. Prandoni[10], L. Rudnick[11], N. Seymour[12], G. Umana[13], H. Andernach[14], D. M. Alexander[21], P. N. Appleton[15], D.Bacon[16], J. Banfield[1], W. Becker[17], M. Brown[18], P. Ciliegi[19], C. Jackson[1], S. Eales[20], A. C. Edge[21], B.M. Gaensler[22], G. Giovannini[10], M.Y.Huynh[23], E. Ibar[24], R. Ivison[25], R. Kennicutt[26], Amy E. Kimball[4], A. M. Koekemoer[27], B. S. Koribalski[1], A. Lopez-Sanchez[2], M. Y. Mao[1,28], H. Messias[29], K. A. Pimbblet[18], A. Raccanelli[16], T. H. Reiprich[30], I. G. Roseboom[31] H. Rottgering[32], D.J. Saikia[33], R.G.Sharp[34], O.B.Slee[1], I.R. Smail[21], M. Thompson[6], J. S. Urquhart[1], J. V. Wall[35]

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 (∼10μJy rms) radio continuum survey of the entire Southern Sky, extending as far North as +30° 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-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