Radio continuum surveys five years from now: EMU and the synergy with optical surveys

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with

R.P. Norris (CSIRO), A. Hopkins (AAO), N. Seymour (CSIRO)
for the EMU team (of >200 members)

- several new radio observatories (interferometers & single dishes) being built
- many new deep radio surveys (spectral line & continuum) planned or carried out
- what is the motor behind these ?

The Square Kilometer Array (SKA)

- radio telescope with 1 km^2 collecting area, envisaged since ~1990, then called "Radio Schmidt telescope" cf. Workshop @ Penticton Oct. 1989, 1991ASPC...19..415D)
  (Grote Reber built 1-km^2 –area by himself inTasmania ~1960: dipoles for 2 MHz)
  real SKA : operate from ~200 MHz (λ ~1.5 m) to ~15 GHz (λ~2 cm)
- always conceived as a multi-nation effort for its huge cost (2012: ˜1.5 10^9 €)
- to be built in the southern hemisphere (to be able to observe Galactic Centre !) at a site with lowest human radio interference (the "Atacama for Radioastronomy")
- in 2005 bids received by 4 countries: Argentina, China, S. Africa, Australia
  Argentina eliminated for south atlantic anomaly, and China eliminated for being located in northern hemisphere (China still pursues "FAST": single, later multiple multiple 500-m dishes of Arecibo type in Karst regions
- 2006 – 2012: both S.Africa and Australia plan and build "SKA precursors" (worthy observatories of its own!) → see who's going to get the real SKA ??

- **June 2011: SKA Organization established its HQ at Jodrell Bank (Manchester, UK)**
- **May 2012: SKAO decides: both S.Africa (higher freq.) and Australia (lower freq.) will host the real SKA (extending to large parts of Africa and to New Zealand)**
- **SKA consists of filled-aperture central parts and stations out to ~3000 km from both centers: the Karoo in S.Africa, and the Murchison Rad.Obs., West Australia**
- **expected full science operations in 2020/2024 for full SKA phase 1/2 , resp.**

but ... the SKA can't be built "from scratch". . . (too risky)

→ "SKA pathfinders", designed to ...

- ❑ **pioneer the potential SKA technology**
- ❑ **be powerful science-driven observatories**

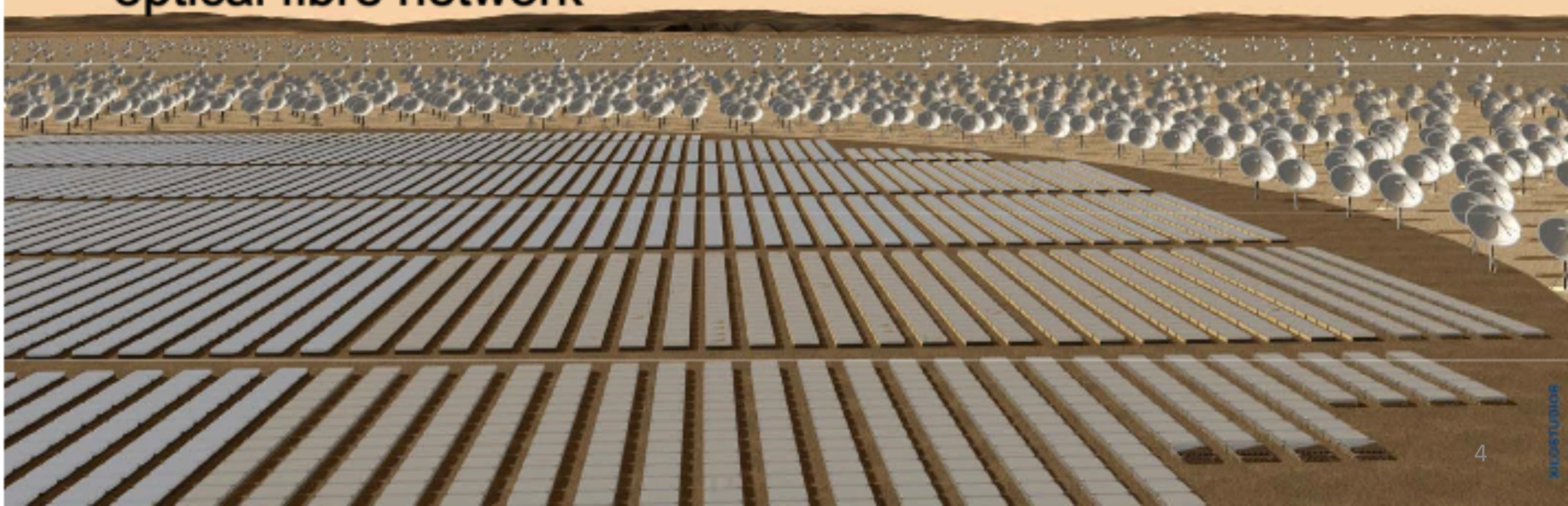
Examples:

- **ASKAP** = Australian SKA Pathfinder (Australia)
- **MWA** = Murchison Wide-Field Array (Australia)
- **MeerKAT** = extended Karoo-Array Telescope (South Africa)
- **LOFAR** = Low-Frequency Array (no moving parts!) (Netherlands + Europe)
- **Apertif** phased array feed on the "old WSRT" (Netherlands)
- **EVLA**: extended VLA = Karl G. Jansky Very Large Array (USA)
- **eMERLIN** (UK) & eEVN (Europe): linked via fast internet

The Square Kilometre Array (SKA)

1000- 1500 dishes (15m) in the central 5 km
2000-3000 total
+
dense and/or sparse aperture arrays

connected to a massive data processor by an
optical fibre network



In this talk: a representative for avalanche of radio data within ~5 years:

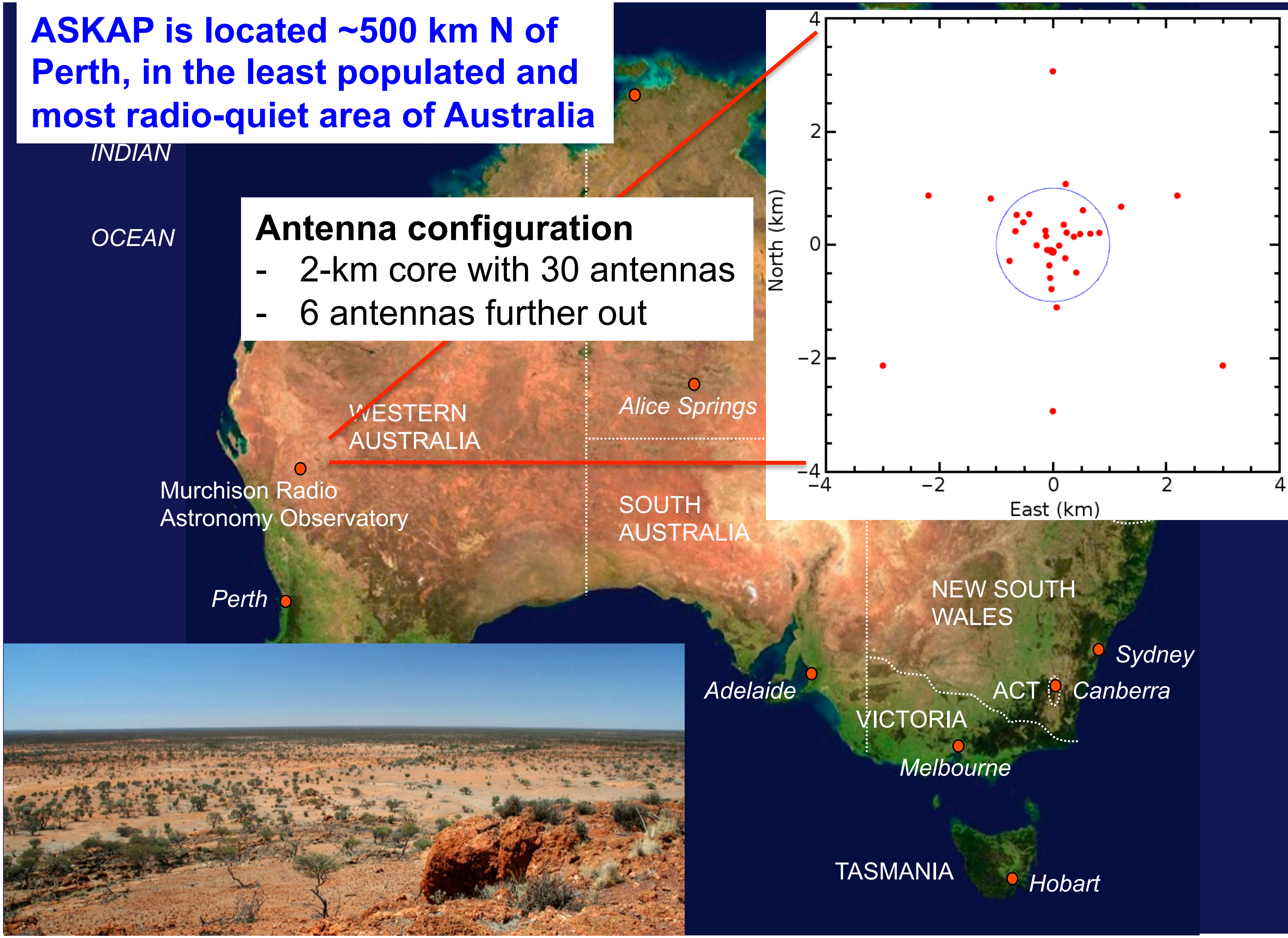
EMU on ASKAP = Australian SKA Pathfinder

- A$ 200 m (€ 140m) project under construction in Western Australia
- uses 36 12-m antennas, spread over ~6 km wide area, already in place
- antenna FoV ~ 1 deg^2 @ 1.4 GHz, but each will be equipped with a 192-pixel phased array feed (PAF) → "squint" provides 30 deg^2 FOV !
- Chinese-made antennas, surface proved good up to ~20 GHz
- Completion expected early 2014

ASKAP is located ~500 km N of Perth, in the least populated and most radio-quiet area of Australia

Antenna configuration

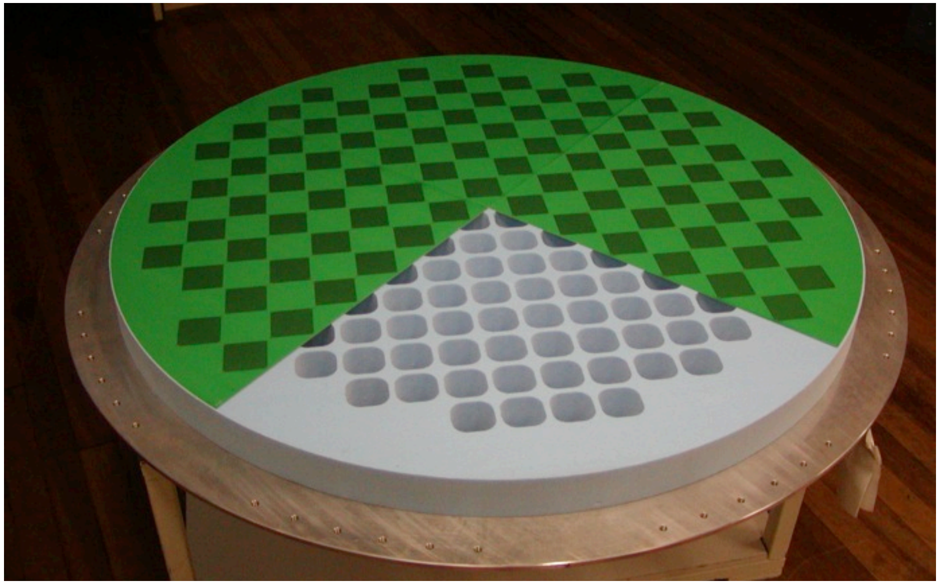
- 2-km core with 30 antennas
- 6 antennas further out

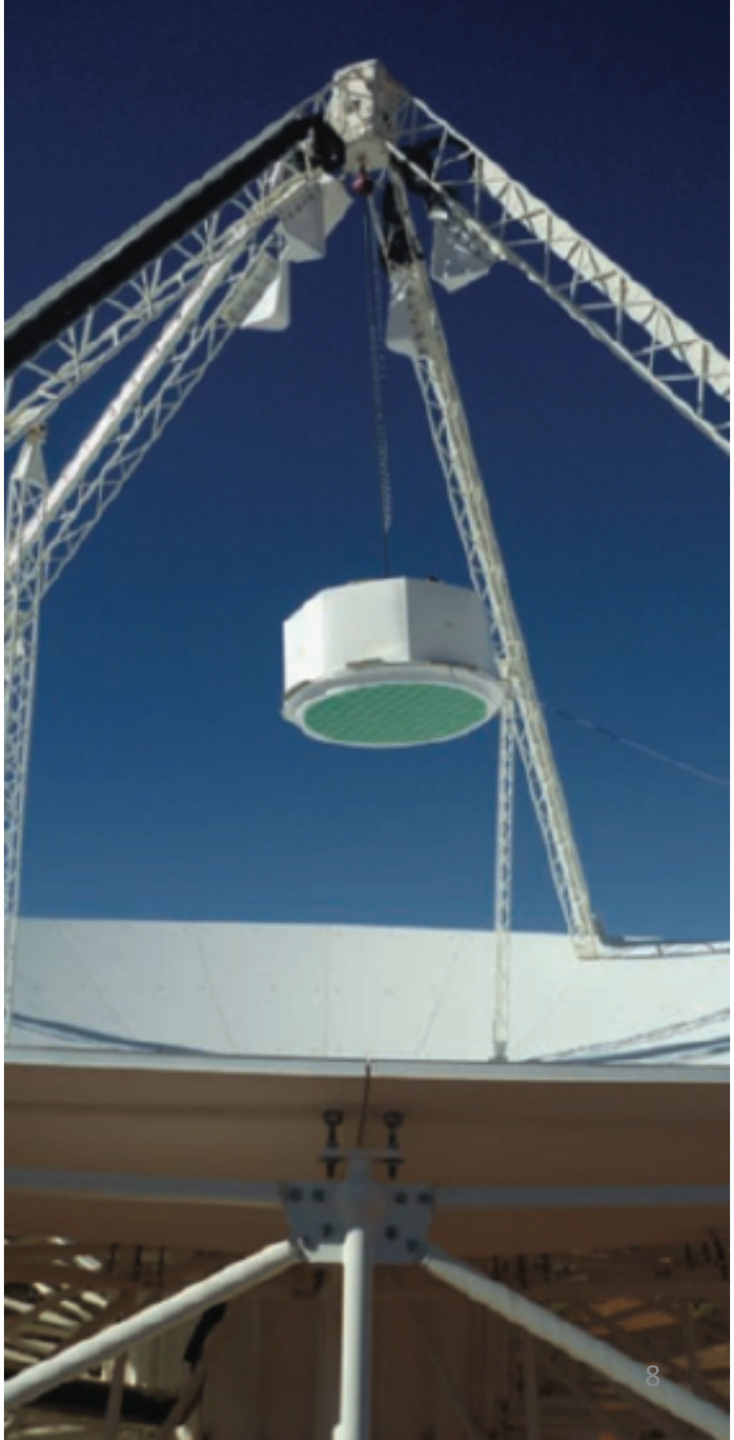


This is as significant a step as when optical astronomy migrated from single-pixel photometers to CCD's.

However: PAFs are also the main problem for cost & time to produce:

- 3 MkI PAFs now in place
  +3 more to be installed shortly
- MkI PAFs are less sensitive at 1.4 GHz
  → MkII PAFs remove this problem
- 6 MkII PAFs to be installed by March 2013
- another 6 MkII PAFs to be installed by late 2013?
- 18 PAFs in place by late 2013
- By late 2014? (funding permitting) 36 MkII PAFs installed.





Accepted Science Projects on ASKAP

2008: EoI's submitted (e.g. H.A. & O.B. Slee +16 CoI's: radio continuum processes in clusters of galaxies; ASKAP Science comm. recommends: join EMU !)

2009: 38 proposals submitted to ASKAP

2 selected as being of highest priority (together ~75% time)

- EMU all-sky continuum
  PI Norris +96 CoI's, 13 countries
- WALLABY all-sky HI
  PI Koribalski & Staveley-Smith

8 other projects are also supported

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

- **Deep radio image of 75% of the sky (declination ≤ +30°)**
- **Frequency range: 1100 − 1400 MHz**

  Largest/deepest radio survey to date: NRAO-VLA Sky Survey 1.4 GHz, covers Decl ≥ −40° (82% of sky); catalog of 1.8 million sources (NVSS)
- **40 x deeper than NVSS (σ ~10 μJy rms vs. 40 μJy for NVSS)**
- **4.5 x better resolution than NVSS (10" compared to 45")**
- **Better sensitivity to extended structures than NVSS**
- **Will detect and image ~70 million radio sources at S(1.4GHz) > 5 σ**
- **All data to be processed in pipeline**
- **Images, catalogues, cross-IDs, to be placed in public domain**
- **Survey starts 2014 (finishes 2017 or 2018)**
- **Total integration time: ~1.5 years**

Partial list of EMU's Science Goals

see 2011PASA...28..215Norris+ (arXiv:1106.3219) for details

- **Evolution of SF from z=2 to the present day,**
  - using a wavelength unbiased by dust or molecular emission.
- **Evolution of massive black holes**
  - and understand their relationship to star-formation.
- **Explore the large-scale structure and cosmological parameters of the Universe.**
  -- e.g., an independent measurement of dark energy evolution
- **Deepest radio continuum Atlas of the Galactic Plane ever**
  → e.g. increase the number of known radio stars by a factor of 10 − 100
- **Explore an uncharted region of observational parameter space**
  - almost certainly finding new classes of object.
- **Explore Diffuse low-surface-brightness radio objects**
- **Create a legacy for surveys at all wavelengths**
  - e.g. Herschel, JWST, ALMA, etc

Complementary radio surveys

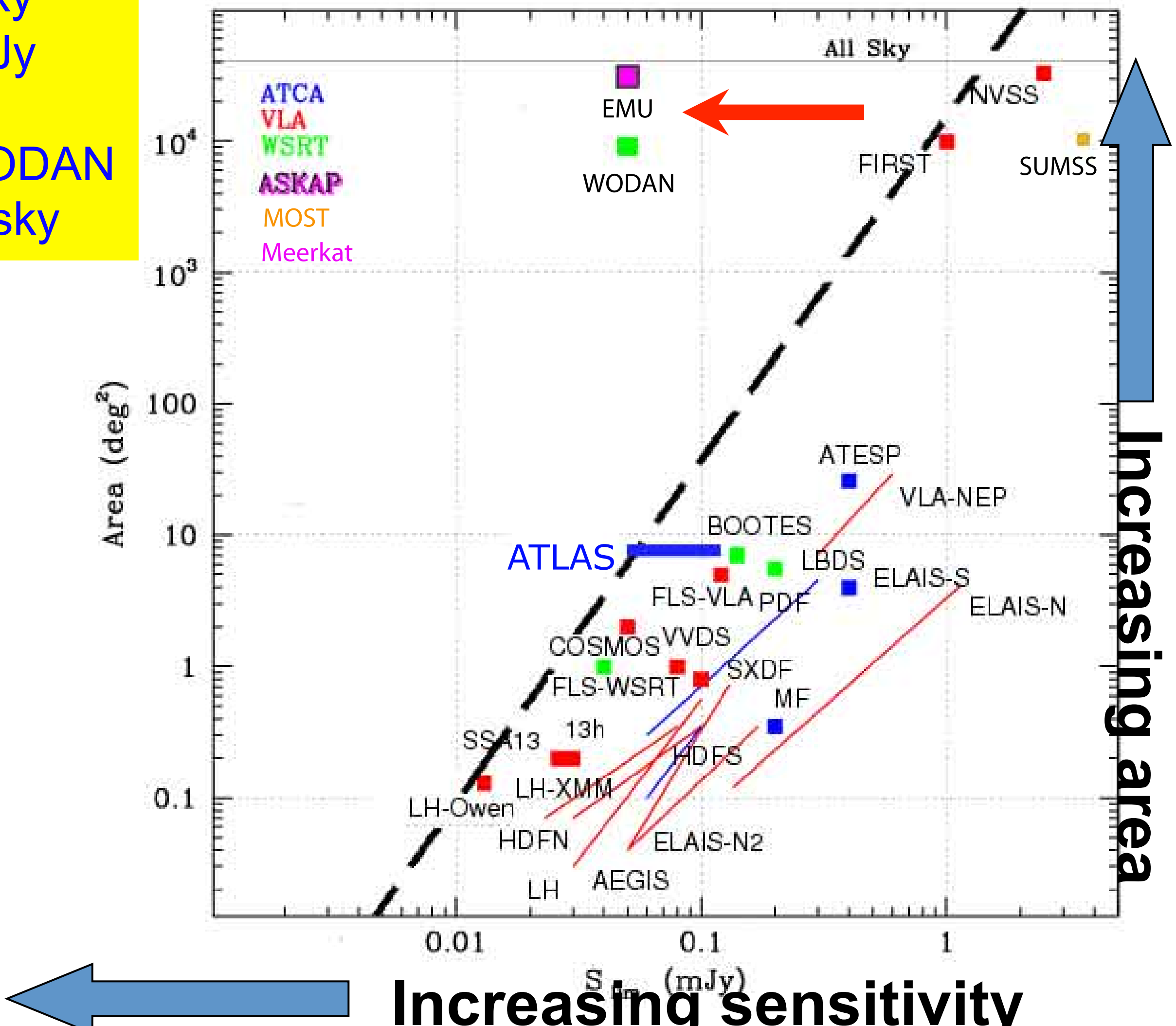
- Westerbork-WODAN
  - using Apertif PAFs on Westerbork telescope
  - will achieve similar sensitivity to EMU
  - will observe the northern quarter of sky ($\delta > +30°$)
  - is well-matched to EMU in angular resolution & sensitivity
- LOFAR continuum surveys ("LOw Frequency ARray")
  - observs at lower frequency (30 − 240 MHz)
  - covering Northern half(?) of sky
  - valuable because yields spectral index ("radio color")
- Meerkat-MIGHTEE
  - Potentially deeper over smaller area, but will be limited by confusion until Meerkat Phase II (2016?)

Current major 20-cm surveys

EMU
75% of sky
rms=10μJy

EMU+WODAN
100% of sky

NVSS
75% of sky
rms=450μJy

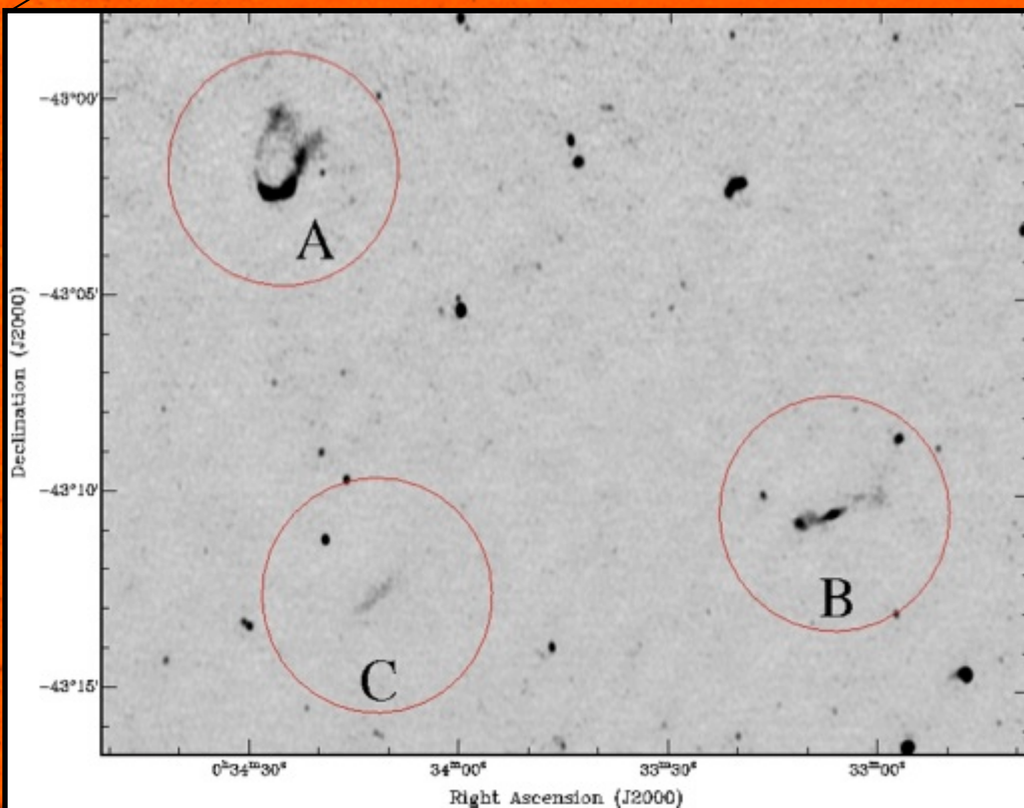


ATLAS = Australia Telescope Large Area Survey

comprises 2 deep fieds:

CDFS & ELAIS-S1

here: ELAIS-S1
at σ ~ 30 μJy
ctsy of Minnie Mao



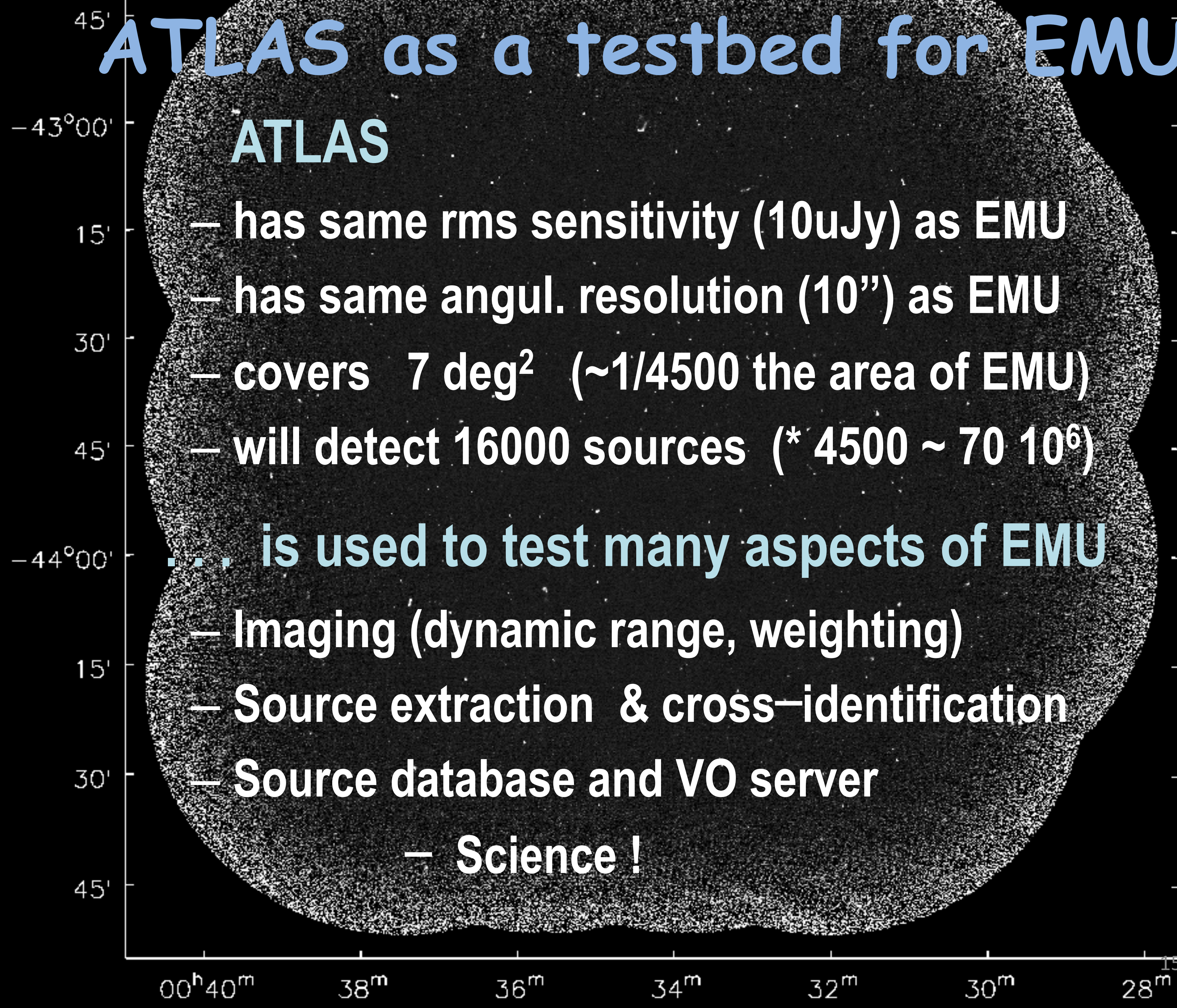
ATLAS as a testbed for EMU

ATLAS

- has same rms sensitivity (10uJy) as EMU
- has same angul. resolution (10”) as EMU
- covers 7 deg^2 (~1/4500 the area of EMU)
- will detect 16000 sources (* 4500 ~ 70 10^6)

… is used to test many aspects of EMU

- Imaging (dynamic range, weighting)
- Source extraction & cross–identification
- Source database and VO server
- Science !



EMU as of October 2012

- Team of 215 from 17 countries
- Split into ~15 working groups
- Cross-linkages with other major multiwavelength surveys

- Project Leader: Ray Norris
- Project Scientists:

  Andrew Hopkins, Nick Seymour

- Several new PhD/postdoc positions
  - Work within smaller group
  - Have ownership of an area

Radio
- LOFAR
- NVSS
- SUMSS
- MWA
- ATLAS
- South Pole Telescope
- GMRT-Herschel-ATLAS

Optical/IR
- SDSS
- LSST
- Pan-STARRS
- 2MASS
- HLA
- VISTA/VIKING/VHS/VIDEO
- GAMA
- VST/KIDS
- UKIDSS
- Herschel ATLAS/HerMES
- WISE
- SkyMapper

X-Ray
- eROSITA
- IXO

So what are we going to do with 70 million radio sources ?

- Similar to situation for γ–ray sources (R. Mignani, this conf.)
- For 70 years radio sources were notoriously difficult to identify optically
- It took 35 years to identify the last of ~300 3CR sources (originally published in 1962 !)
- Radio galaxies often are extended/distorted
  → not obvious where to look for parent galaxy

PKS 0326-288
z = 0.1088
R = 17.6 AGN

ATLAS 1.4 GHz CDFS at σ ~ 30 μJy

Some examples of quantitative identification rates

NED: currently there is a bug in parameter queries like
"extract all radio sources that are also seen in a non-radio band"
via priv. comm. with NED → as of Oct. 2012:

- NED has 2,200,000 radio sources (~50% of published radio sources)
- ~9% are visual sources (G, QSO, ...) and ~5% are IR sources

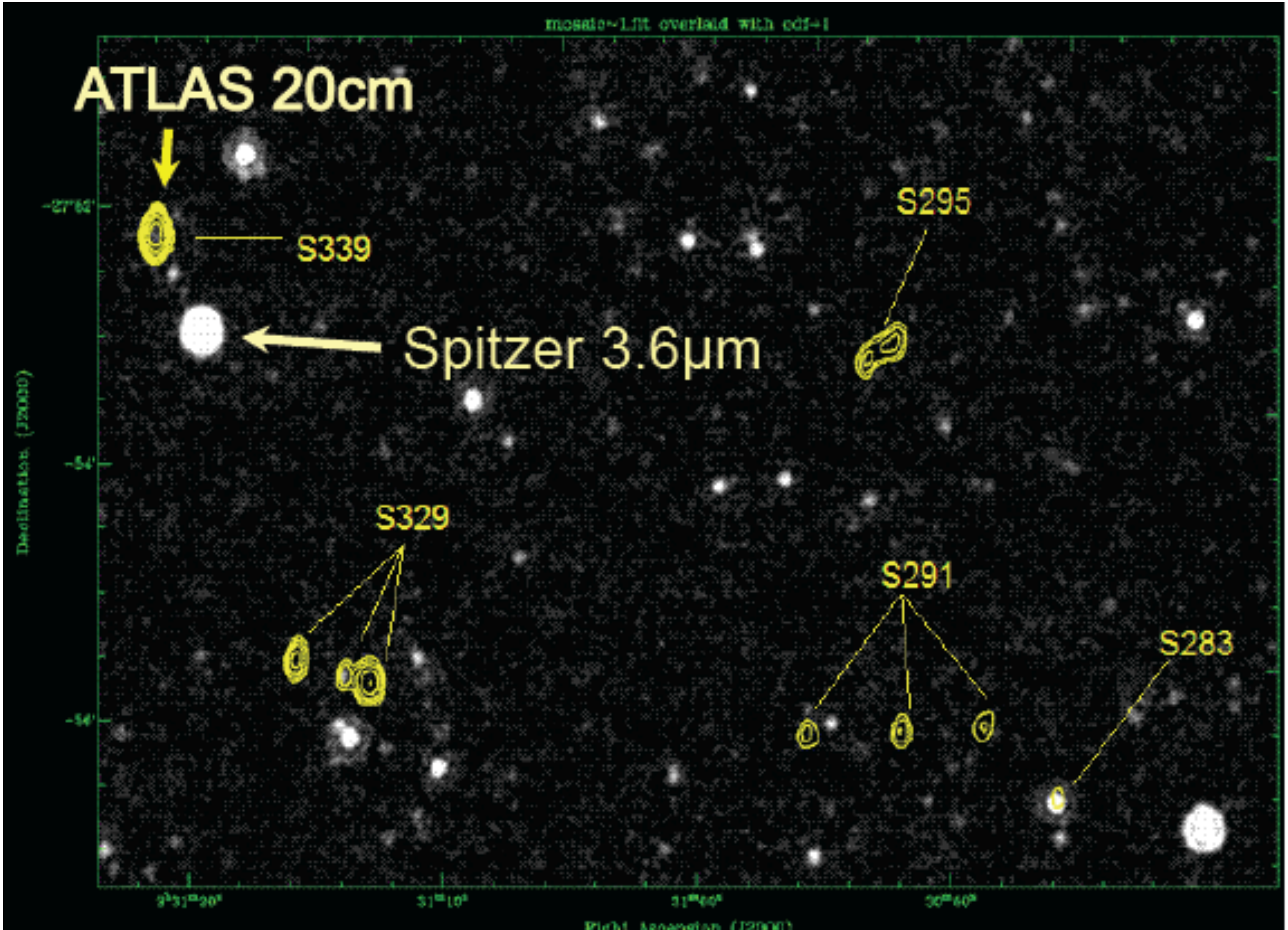
SIMBAD: the above query is not accessible for general users
→ priv. comm. with CDS:

- 480,000 radio sources of which ~7% have also a non-radio object type
- extrapolating to ~4 million radio sources known (90% not in Simbad)
  → perhaps only ~1% have known optical counterparts

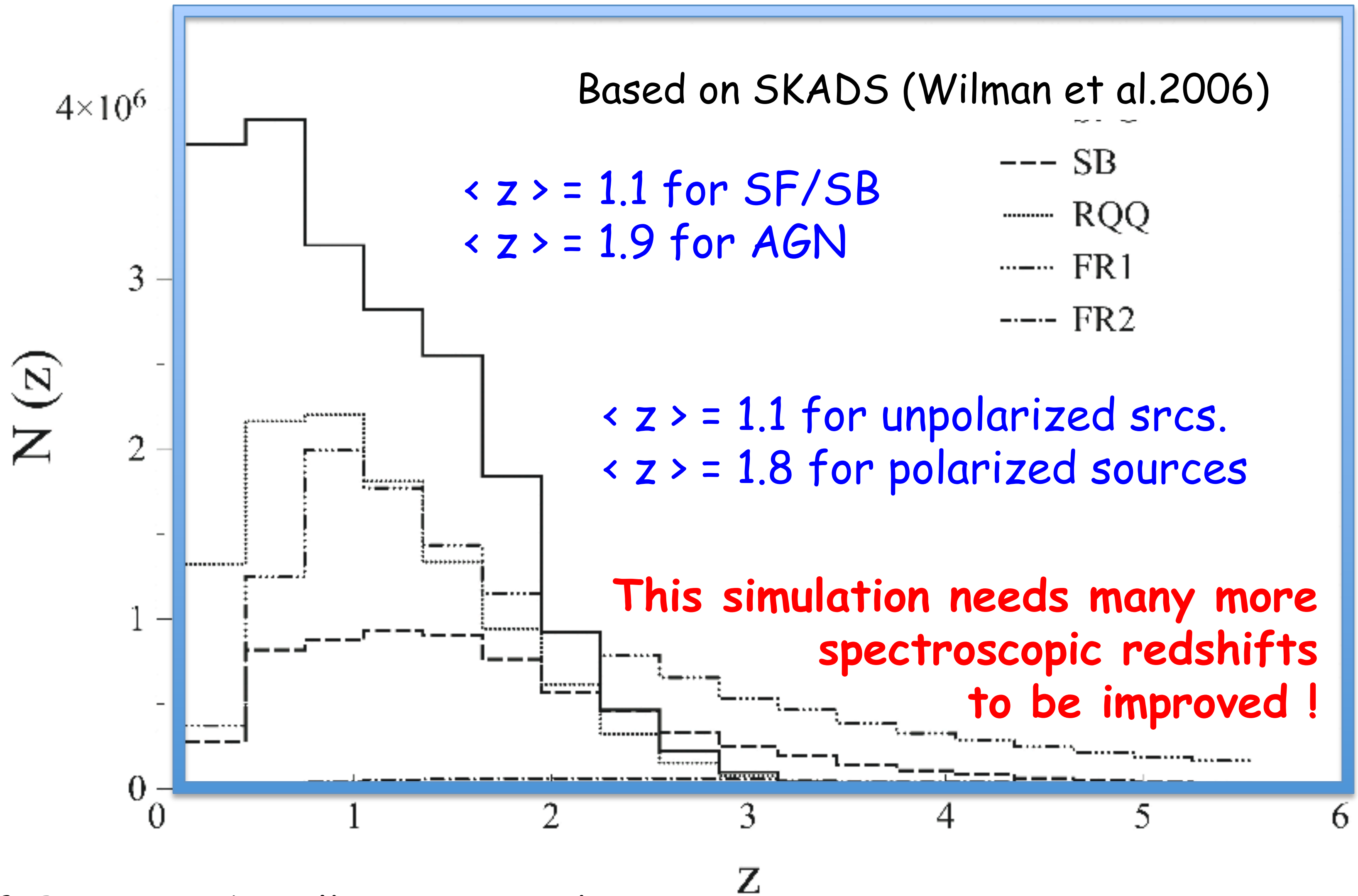
Only in deep fields the identification rate is more favorable:

e.g. CDFS-ATLAS: ~780 sources S(1.4GHz) > 150 μJy :
97.5% have opt. IDs with u,g,r,i < 25 Vega mag.
~200 opt. IDs bright enough to yield z with AAO 4-m tel.
but: EMU survey will yield 3 x weaker sources over 3/4 of sky !

Radio continuum (contours) overlaid on Spitzer 3.6 μm image



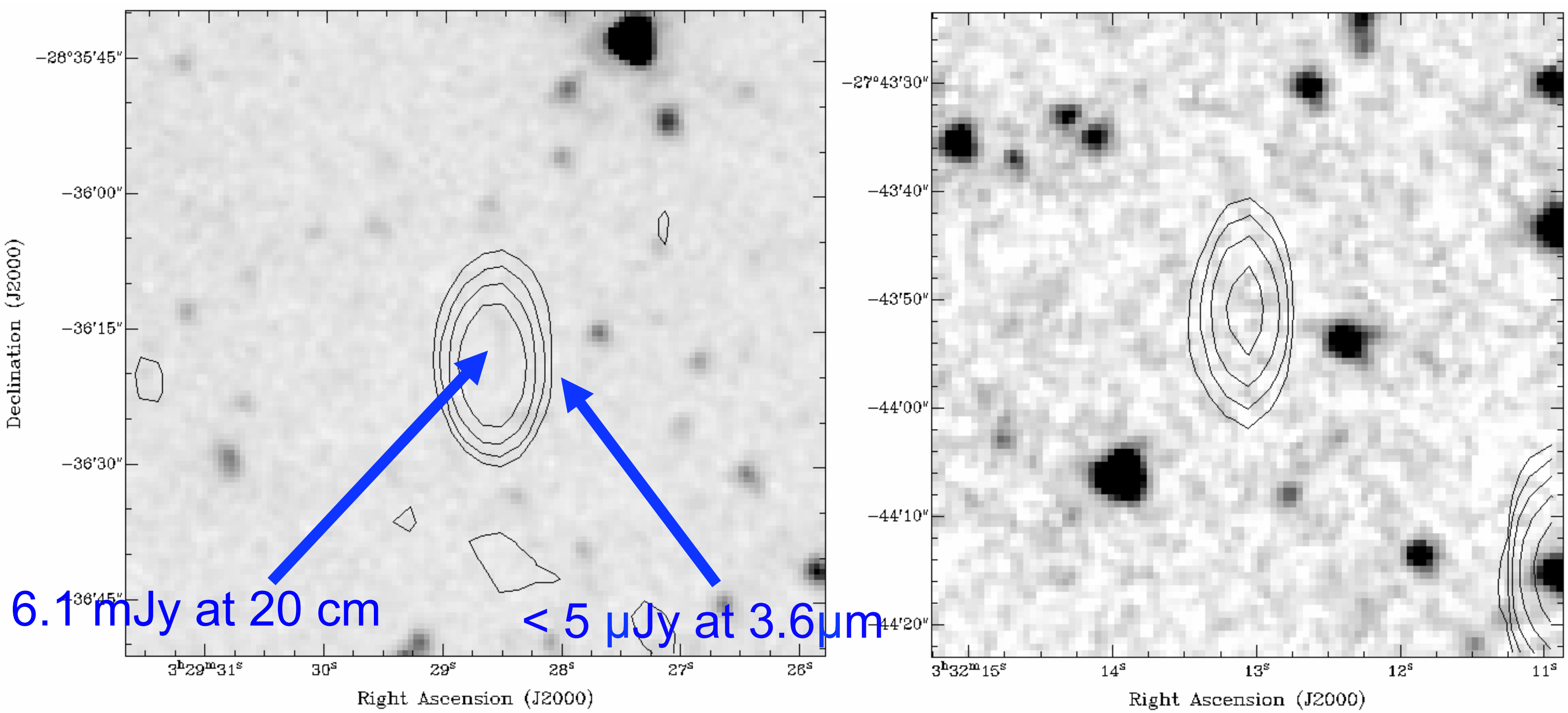
Distribution of "statistical redshifts" of EMU sources



cf. P.-C. Zinn's talk tomorrow !

Explore an uncharted region of observational parameter space → certainly finding new classes of object.

Here: so-called Infrared-Faint Radio Sources (IFRS)
(ATLAS 1.4 GHz vs. Spitzer)



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

Cross-Identifications with other wavelengths

A list of surveys with which EMU sources will be cross-identified
(present ESO workshop has shown there are quite a few more !)

to its 5 σ limit. The survey matched column is the fraction of EMU sources in the previous column which are in the area of sky covered by the multi-wavelength survey. The sensitivity shown for the WISE survey is for the 3.4 μm band. The final column indicates the estimated release date of the data after survey completion.

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 μm	80 μJy	23	100	2012
PanSTARRS[2]	30000	g, r, i, z, y	$r < 24.0$	54	50	2020[b]
Wallaby[3,c]	30000	20 cm (HI)	1.6 mJy[d]	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
VISTA- VHS[6]	20000	Y, J, H, K	K< 20.5	49	66	2012
SDSS-III[7]	12000	u, g, r, i, z	$r < 22.2$	28	22	DR12 2014
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	2016
VST-KIDS[10]	1500	u, g, r, i	$r < 25.2$ (TBC)	70	5	2016
VISTA-Viking[10]	1500	Y, J, H, K	K< 21.5	68	5	2012
PanSTARRS Deep[2]	1200	$0.5 - 0.8$, g, r, i, z, y	$g < 27.0$	57	4	2020
eROSITA[11]	41000	$0.5 - 10$ keV	$\sim 10^{-14}$ $\mathrm{erg cm^{-2} s^{-1}}$	5	100	2018

A newly proposed redshift survey in Australia:

TAIPAN

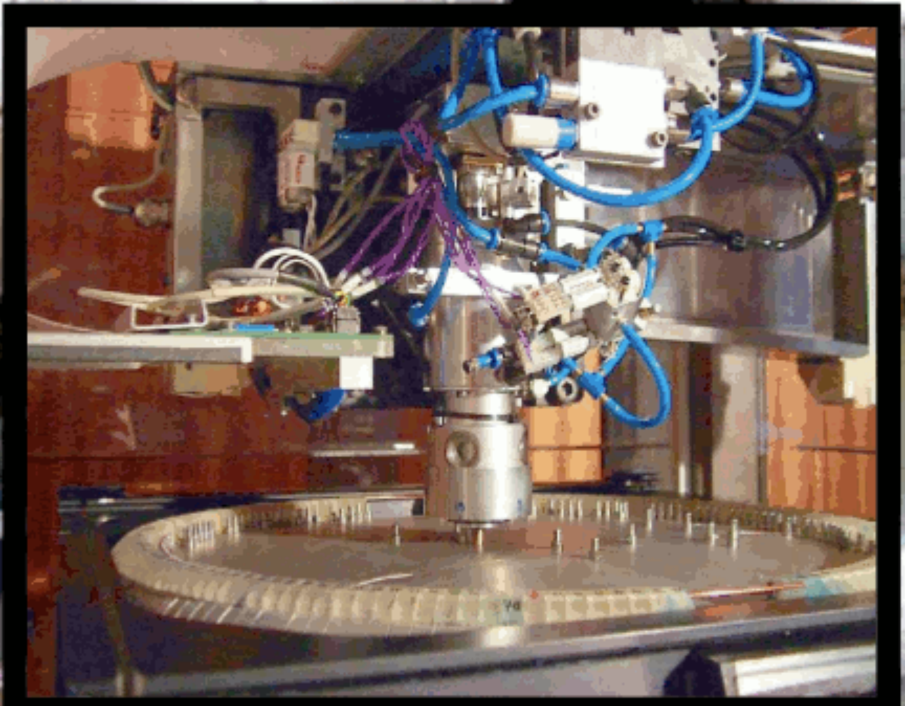
- **Transforming Astronomical Imaging-surveys through Polychromatic Analysis of Nebulae**

- **Survey with the UK Schmidt Telescope at Siding Spring, following in the footsteps of the 6dF Galaxy Survey (Jones et al., 2004, 2009)**
- **All southern sky multi-object spectroscopic survey, ~500000 galaxies**
- **30 authors on the original expression of interest to the AAO, but these are happy to have more people involved**

The 6-Degree Field instrument (6dF)

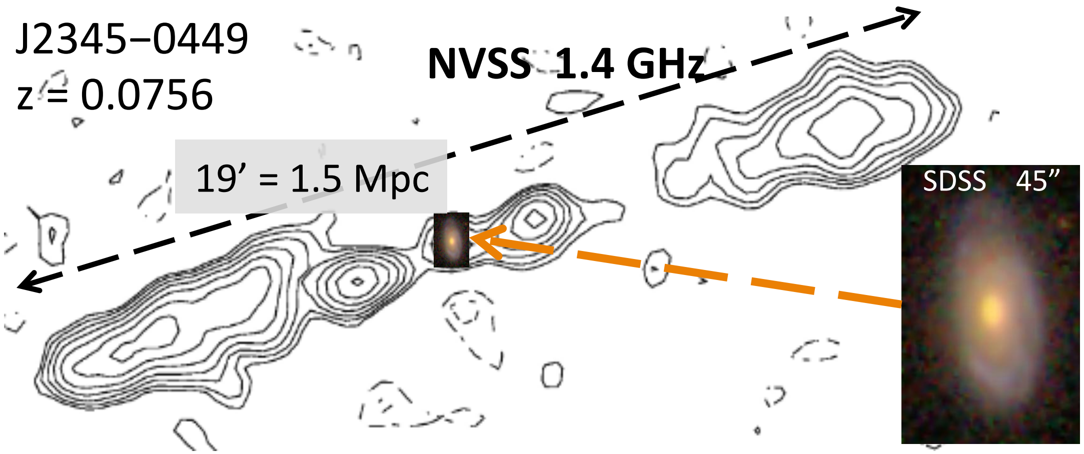
- The 6-Degree Field is a floor-mounted spectrograph for the AAO's UK Schmidt Telescope:
  - commissioned in 2001
  - 5.7º field (25.5 deg^2)
  - up to 150 objects at a time

- 6dF has *by far* the largest F.O.V. of any multi-object spectrograph in the southern hemisphere…
  - 6dFGS: 110,256 new galaxy redshifts (2001 – 2005)
  - RAVE: >500,000 stellar radial velocities (2005 – present)



Apart from image **depth**, image **quality** is also essential :

during a search for Giant Radio Galaxies (GRGs)
in Radio Surveys this object was found



The spiral arms of this galaxy were only recognized on SDSS,
not on the Digitized Sky Survey (DSS)

→ see poster session (no. 1)

Conclusions

A relief: The imaging and spectroscopic surveys needed for the upcoming radio surveys are actually being planned !

Only that "radio astronomers" and "optical astronomers" need to talk to each other ...

... otherwise the spectroscopic surveys won't put their fibres on the "right" targets