VERY LARGE ARRAY SKY SURVEY

Survey Science: Galaxies through Cosmic Time

Mark Lacy, NRAO (for the extragalactic working group: chairs J. Hodge and G. Richards)

Galactic Center (Survey) Multiwavelength Image
Credit: X-ray: NASA/UMass/D.Wang et al., Radio: NRAO/AUI/NSF/NRL/N.Kassim, Mid-Infrared: MSX

Radio source populations

- Address the “Cosmic Dawn” theme of Astro2010
  - Formation of the first [stars], galaxies and black holes
- Specifically, radio is well-suited to studying the formation and evolution of massive galaxies and the close relationship with their central black holes, particularly feedback mechanisms.
- This talk:
  - Overview of the extragalactic radio source population
  - Science goals of the VLASS in galaxy evolution and mapping to requirements
  - Depth and resolution, simulations
  - Summary

High accretion rate, “cold mode” AGN

- Quasars, Seyferts and other high accretion rate (L/L_{Edd} >~0.1) are a major component of the radio source population at flux levels >1μJy, and dominate above 1mJy.
- In addition to the “radio-loud” (RL) AGN population that dominates at high flux densities, the “radio-quiet” (RQ) population is an important contributor at lower fluxes.
  - Radio emission mechanism from the RQ population still unclear (star formation vs thermal shocks vs low power radio jets)
- Both All-Sky and Deep components will have large numbers of cold-mode AGN sources (they will dominate the All-Sky survey).
- Rare, ultrapowerful RL radio sources such as those that will be found in the All-Sky survey are often found in dense protocluster environments (e.g. Wylezalek et al. 2014).
- Responsible for “prompt” or “quasar mode” feedback, where a short duration quasar event disrupts the ISM of its host galaxy.

VLA SKY SURVEY

Hot mode (advection-dominated) AGN

- Accretion rates <~0.01 L_{Edd}
- Radio-loud.
- Locally, the low excitation radio galaxy population (FRIs and low luminosity FRIIs), occurring in the most massive ellipticals.
- Crucial for "maintenance mode" feedback, i.e. stopping steady accretion of gas onto massive galaxies, as duty cycles can be high.
- Evolution seems to be tied closely to the massive tip of the galaxy luminosity function – they evolve the "wrong way" for AGN (Simpson et al. 2012)
- Again, likely to be tracers of protoclusters at high redshifts.
- Are there enough of these to stop galaxies growing? Low-z yes (e.g. Best et al. 2006), high-z not clear.

VLA SKY SURVEY

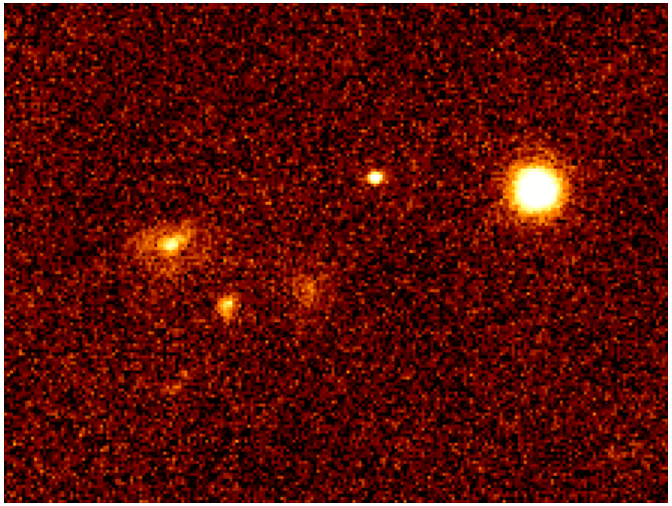
Starforming/submm galaxies

- Synchrotron emission powered by star formation - dominates the counts at ~1μJy.
- All-Sky sensitive to ULIRGS out to z~0.3
- Deep sensitive to ULIRGS out to z~2
- As these surveys are most sensitive to the higher-L objects, they also tend to find fairly massive galaxies, since star-forming galaxies tend to fall on a “main/mass sequence”.
- Use to obtain a dust-free estimate of the SF rate density of the Universe as a function of Cosmic time.

VLA SKY SURVEY

Hershel/Submm galaxies

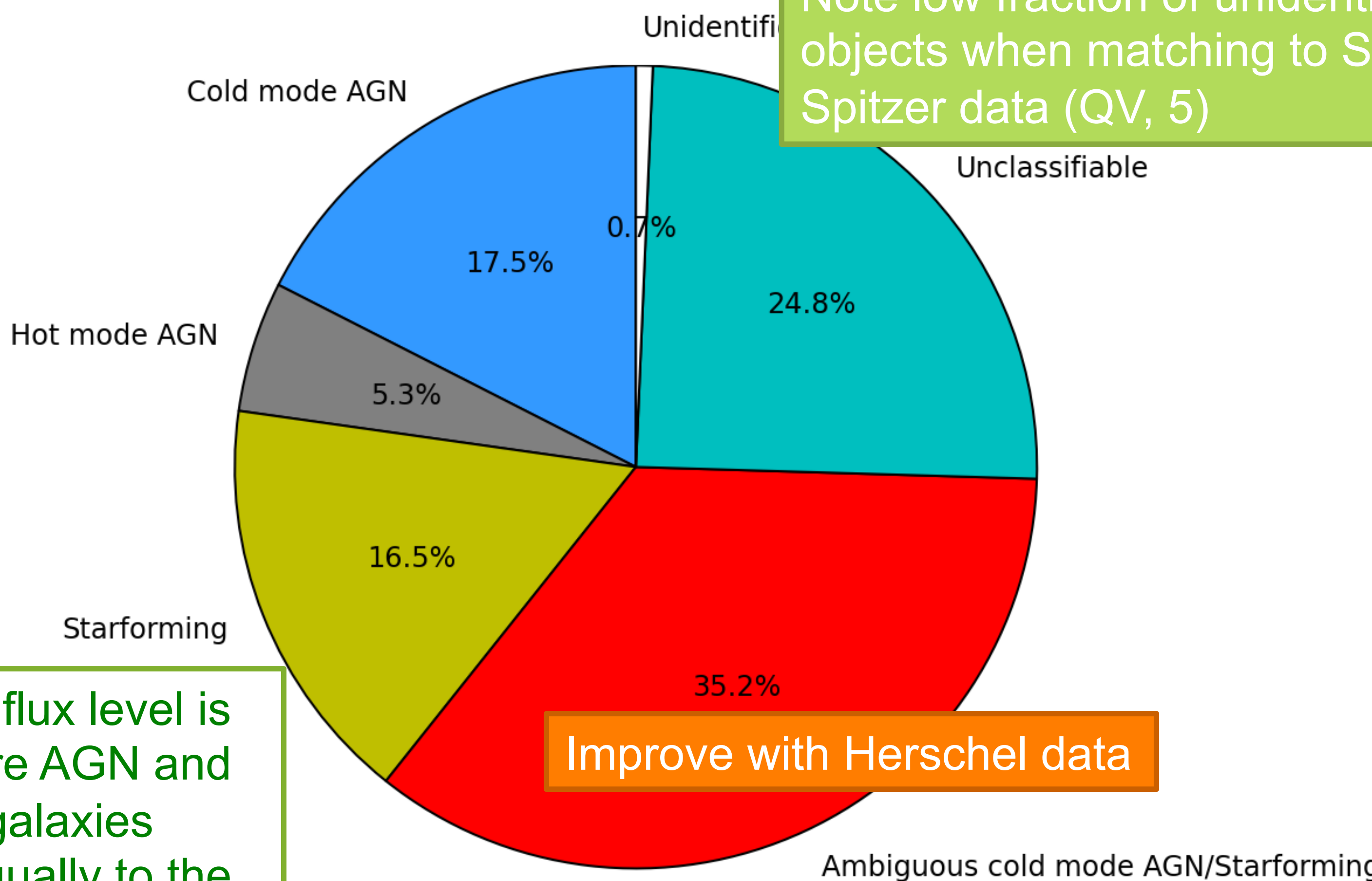
- Herschel surveys cover the entire area of VLASS Deep.
- Synergy with ALMA - reliably identify submm galaxies with ALMA (e.g. Hodge et al. 2013), then use radio emission to improve estimates of SFR, find/constrain AGN activity etc.



Many submm sources resolve into complex blends of objects at high angular resolution. Image shows the field of a Herschel source in Gemini GSAOI K-band observations (0.1” PSF) (Lacy et al. in prep). Image is 16”x8”.

Source population: Multiwavelength follow-up of 0.5deg^2 Ibar et al. VLA survey in Lockman (Luchsinger et al. 2015. submitted)

Similar analyses from COSMOS and UDS data (e.g. Simpson et al. 2012).

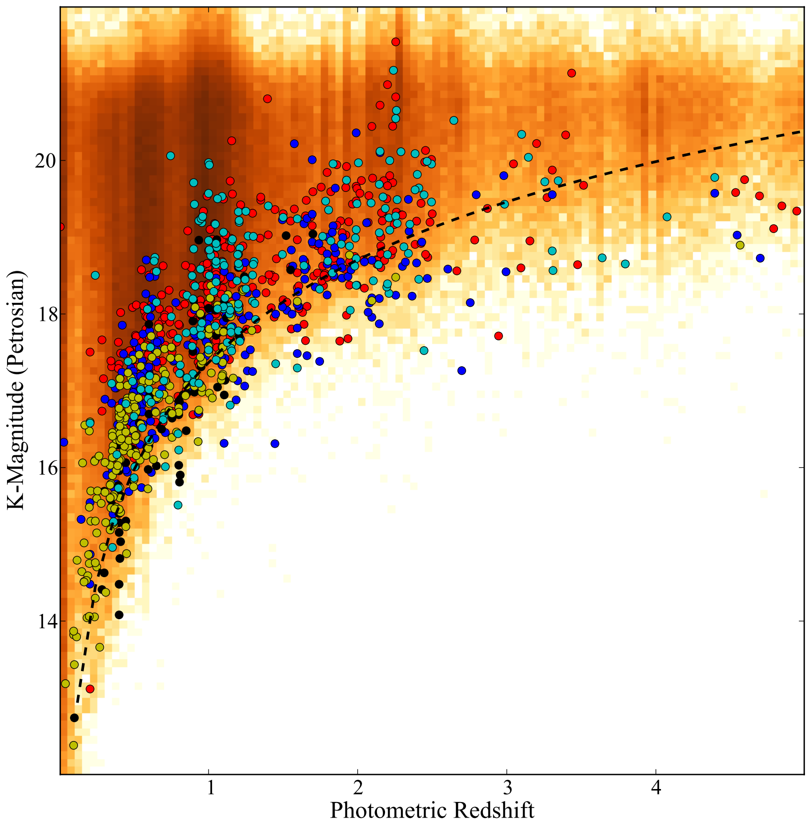


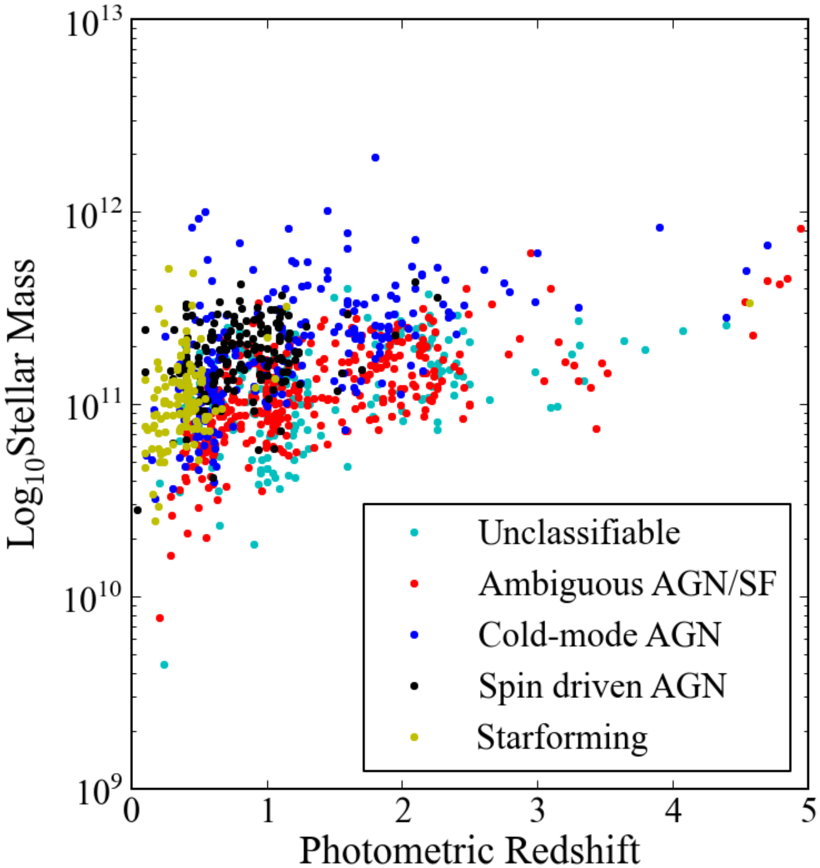
Note low fraction of unidentified objects when matching to SERVS Spitzer data (QV, 5)

Improve with Herschel data

This ~30μJy flux level is roughly where AGN and starforming galaxies contribute equally to the radio source population (QIV, 2)

Host galaxies





All submJy radio sources tend to be in massive hosts
(selection effect for SFG; black hole mass related for AGN)

Luchsinger et al. 2015, submitted

VLA SKY SURVEY

Three Galaxy Evolution Science Goals

- Do radio jets stop star formation? Are the majority of high redshift, $>10^{11}\ L_{\odot}$ galaxies radio loud? Aim to detect and identify large numbers of $L\sim10^{24}$ W/Hz radio AGN at the peak of massive galaxy formation, z~2-5 to help understand the role of radio jets in feedback.
- When did the first galaxy clusters form? Use luminous radio AGN as tracers of the first protoclusters to form at z~2-4.
- What is the evolutionary path of massive galaxies? Measure and compare the clustering of cold-mode AGN, hot-mode AGN and star-forming galaxies to constrain models for their relationships. Determine the radio properties of the hosts of Herschel and submm sources to better determine their SFR and AGN content.

VLA SKY SURVEY

Galaxy evolution requirements

- Need to be able to classify radio sources using multiwavelength criteria

  - Deep needs to be in well-studied fields with extensive multi-wavelength data. (All-Sky will have WISE all-sky, some SDSS.)
- Deep must be deep enough to find “moderately-luminous” ($L_{1.4GHz}$ ~ 10^{24} W/Hz) radio sources out to z~3 and ULIRGs to z~2.
- Deep must be wide enough to find thousands of galaxies at z>2 to constrain luminosity functions with reduced sample variance, cover a wide range of environments and enable measurements of large-scale structure .
- All-Sky needs to cover large surveys e.g. SDSS at the very least, to enough depth to sample the radio luminosity function of both AGN and ULIRGs in the nearby (z~<0.3) Universe.

One survey, two tiers

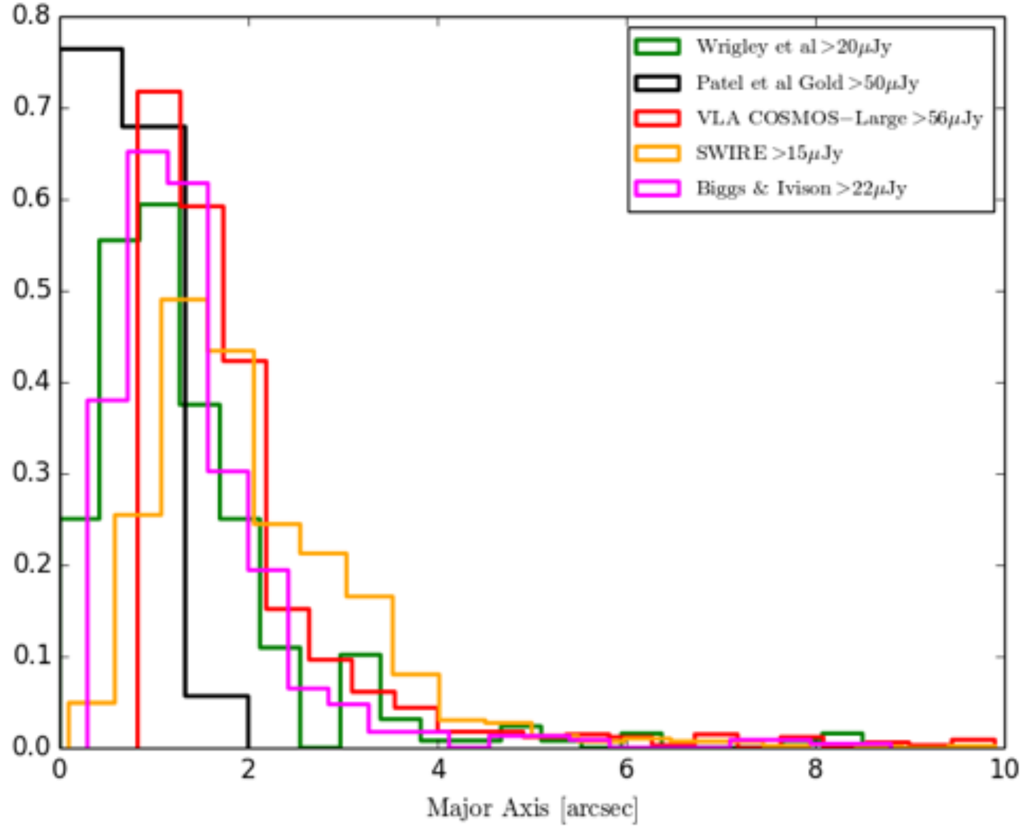
- “All-Sky” and “deep” can be thought of as a single survey with two tiers.
- Separate of redshift and luminosity dependent effects is essential to understanding the evolution of the radio source population e.g.
  - we can compare ULIRGs of similar luminosities at z~0.3 and z~2 to study their evolution, decoupled from trends of properties with luminosity, like AGN content.
  - we can compare the properties of quasars at a fixed redshift and optical luminosity, but with radio luminosities ranging from radio-loud to radio quiet.

VLA SKY SURVEY

Resolution and detectability (motivated by Condon 2015)

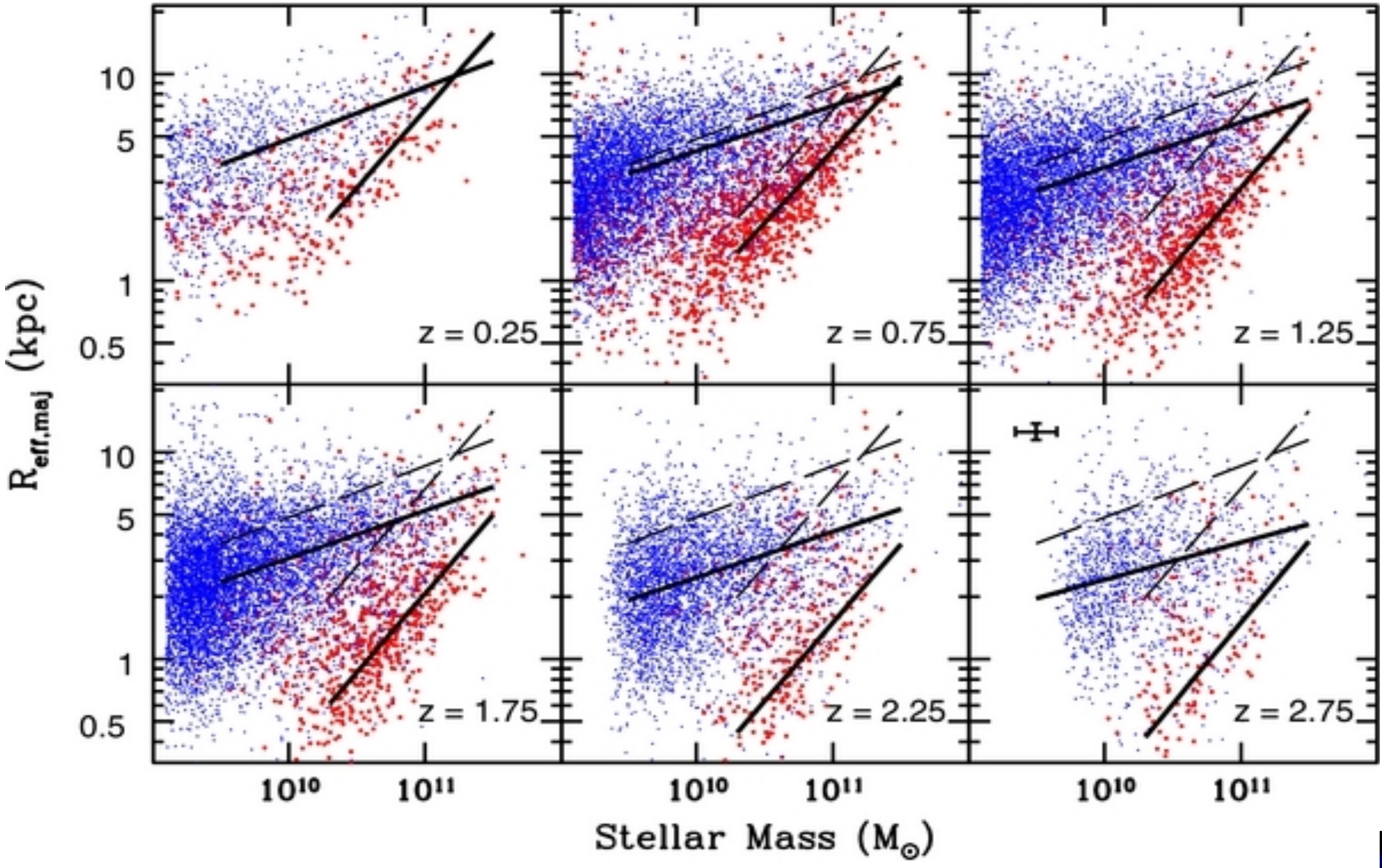
- Unlike optical, radio astronomers routinely adjust resolution to optimize surface brightness sensitivity (background not present in interferometric imaging).
- Ideally, match resolution to size of objects for maximum detectability while avoiding source confusion.
- VLASS does not do this – some science drivers require galaxies to be well resolved (e.g. weak lensing), so depth has to be sacrificed.
- SKA precursor surveys (EMU, MIGHTEE) will do a better job of the pure detection problem.
- The subarcsecond resolution of VLASS [deep], however, moves us from “radio” paradigm to “optical” paradigm for faint object characterization (modulo spatial filtering effects).
- Advantage for galaxy evolution studies is that we can perform “optical-like” studies e.g. morphologies, sizes, pair fraction, strong lens searches etc, in a dust-free way.

Angular sizes of faint radio sources (M. Brown)



Wide range from surveys at a few tens of μJy. Much of the spread is probably due to different analysis methods (FWHM vs isophotal size vs Gaussian sigma), however.

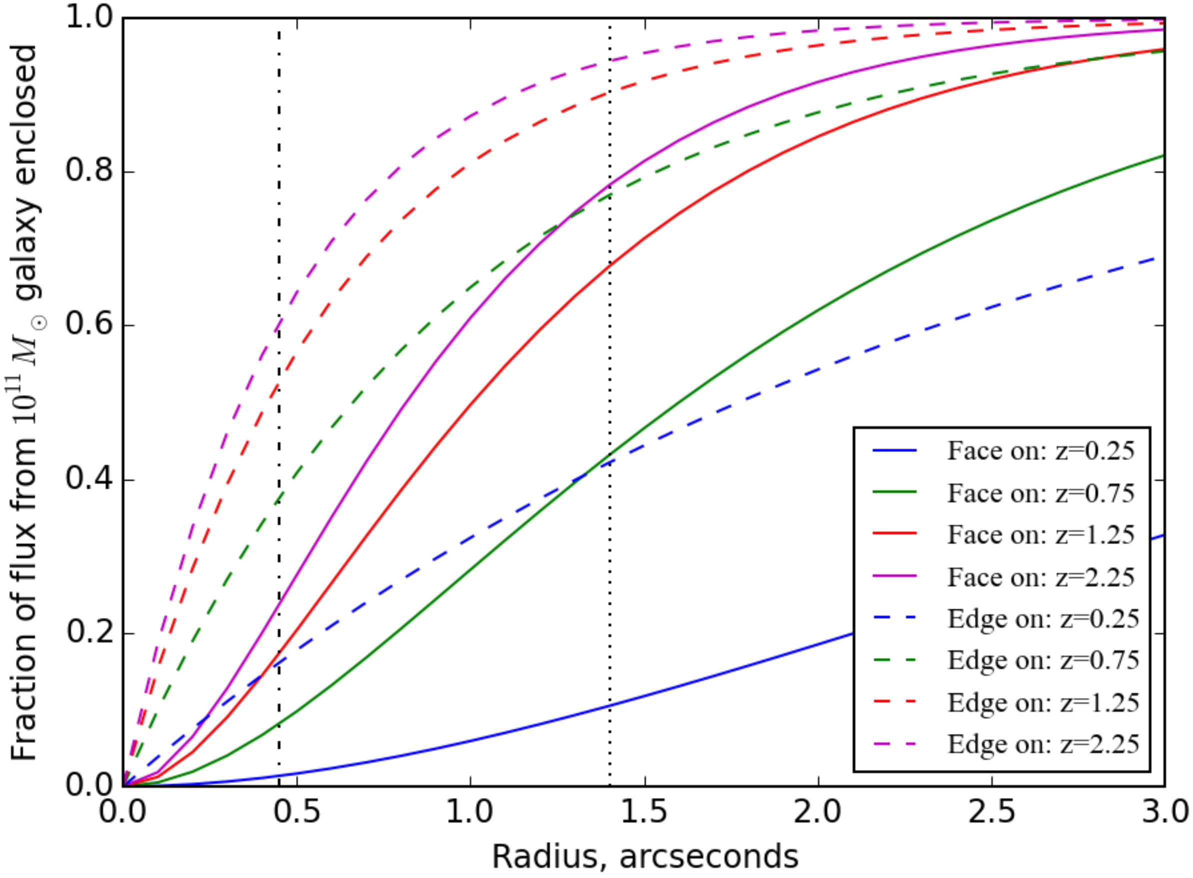
Galaxy sizes in the UV (van der Wel+14)



Sizes of disk galaxies

- UV/blue light from galaxies dominated by star-forming regions
- So sizes of blue galaxies in HST should be very similar to their sizes in the radio
- At z~1, we might expect blue galaxies to have typical effective radii r_{eff}~5kpc (0.6”).

Flux enclosed as a function of radius



Simulations

- The problem is too complex to easily solve analytically.
- So did some simulations of the Deep survey using the CASA simulator:
  - Take F606W HST CANDELS 8x8 arcmin image in COSMOS, remove very red objects (ellipticals) by ratioing to F814W image, threshold at about 3-sigma. Also mask out bright stars. Left with blue (rest-frame UV) galaxies with median z~1.
  - This is still a factor of a few deeper in equivalent surface brightness sensitivity to star formation than Deep will get. (Very crudely, 1 e^-/s rest-frame UV in HST/ACS ~0.1μJy in radio.)
  - Simulate A, B and C-array observations, 4hr at transit clean ~50000 iterations.
  - "Noise" is from the dynamic range limit
  - Get 10 galaxies/arcmin^2 (high end of SKA predictions, which are ~3/arcmin^2)
  - Run Sextractor on the results

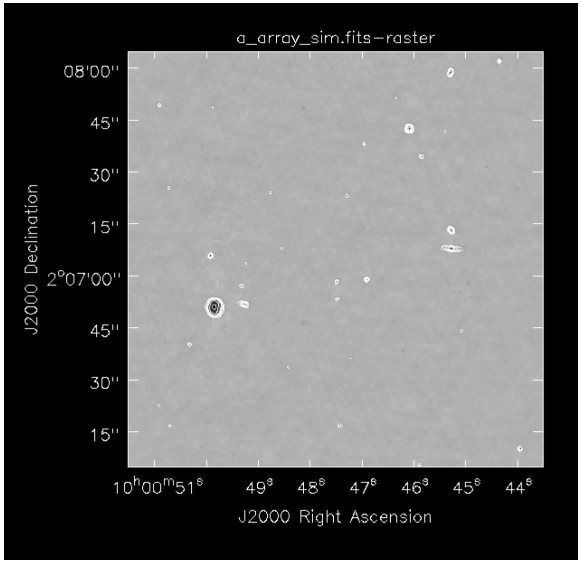
VLA SKY SURVEY

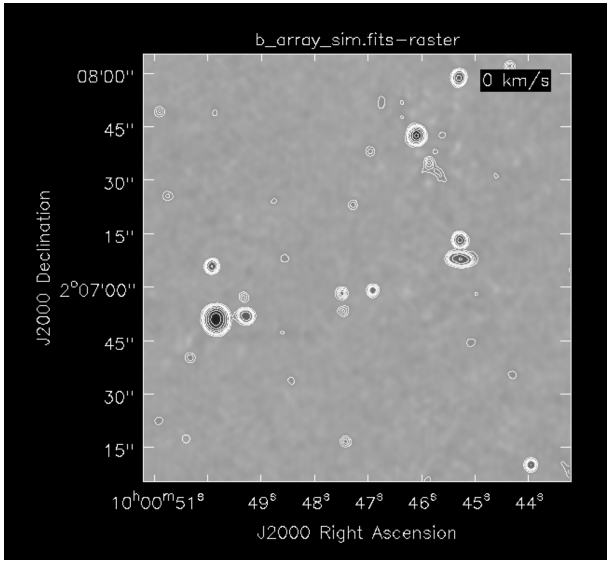
Results

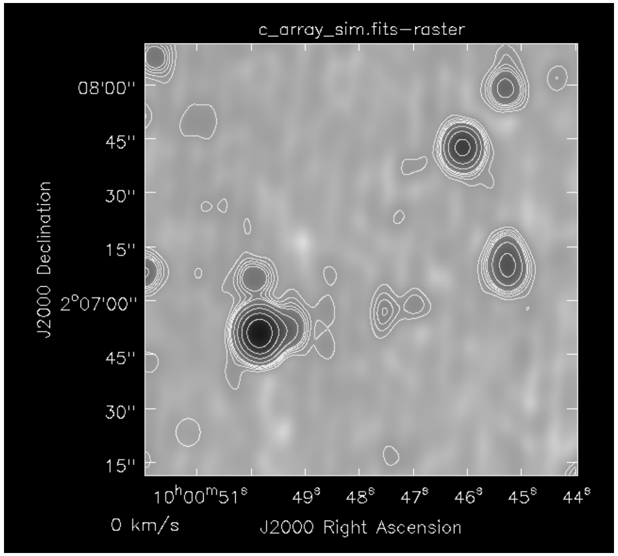
- C-array observations (7” beam) are heavily limited by confusion noise, even at 12 beams/source.
- B-array observations (2” beam) suffer from mild source confusion issues (mainly sidelobes in a crowded field). Also blends close galaxy pairs.
- A-array does quite well, but (as expected) is less complete than B when the counts are plotted. Although it will still be less sensitive to low SB sources than B-array, faint galaxies tend to be smaller in size, improving the situation. Inspection suggests A-array is detecting as many sources to a given S:N/beam threshold in Sextractor, but flux measurements are less accurate at the faint end.
- A-array objects also marginally resolved, allowing for weak lensing studies (as expected based on optical experience).

VLA SKY SURVEY

A (0.8”):B (2”):C(7”)

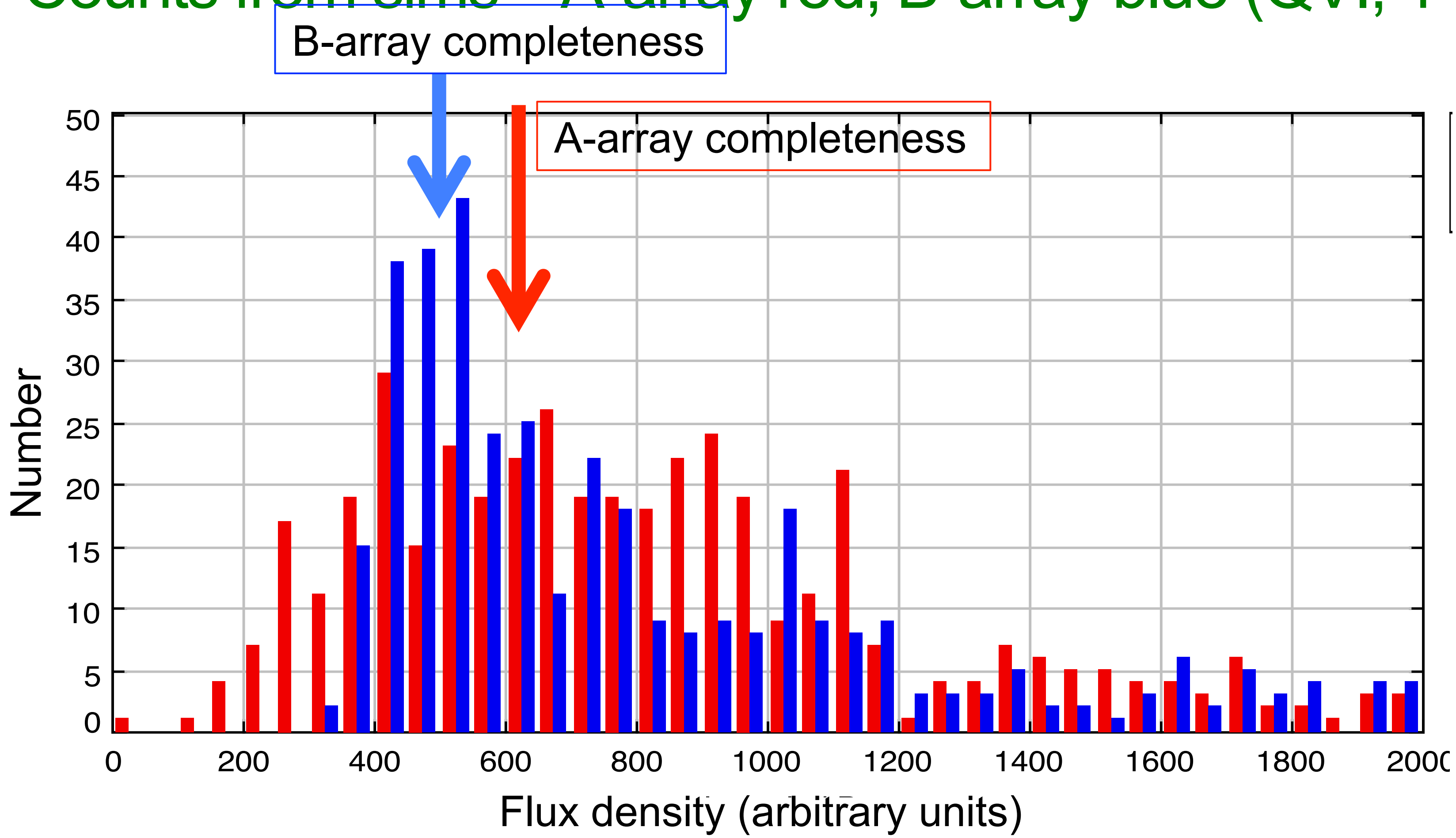






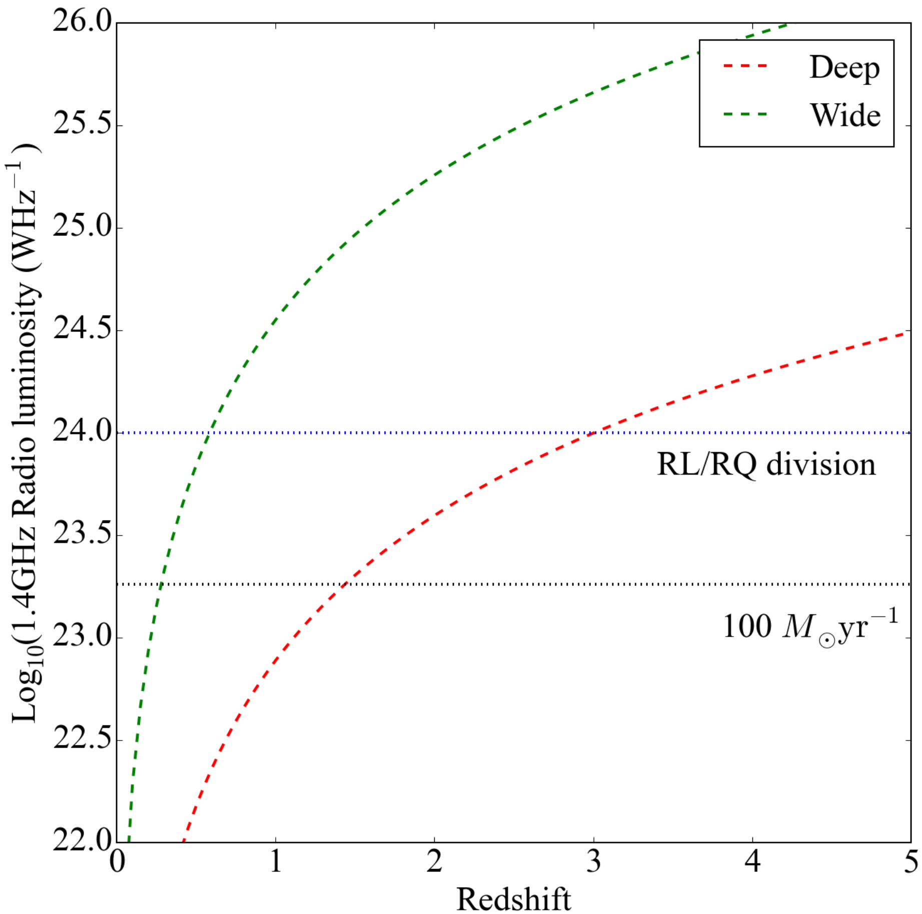
VLA SKY SURVEY

Counts from sims – A-array red, B-array blue (QVI, 14).



Suggests A-array 10-20% less deep than B-array.
For 15μJy RMS, 5-sigma 7.5μJy, allowing for this factor, true depth to ~80% completeness ~10μJy

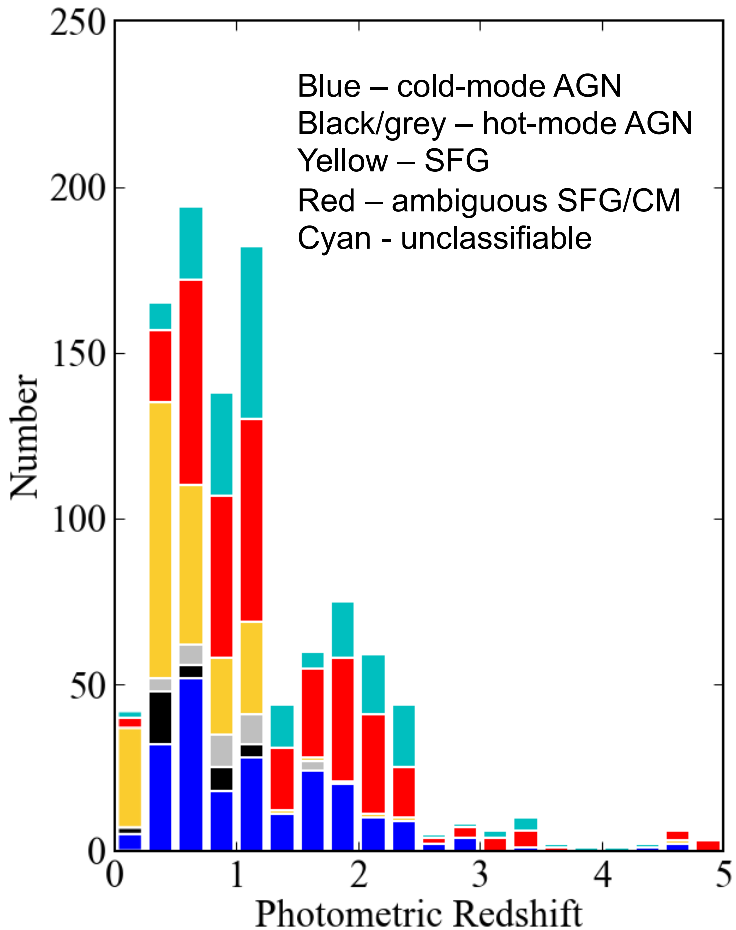
Luminosity-redshift plot

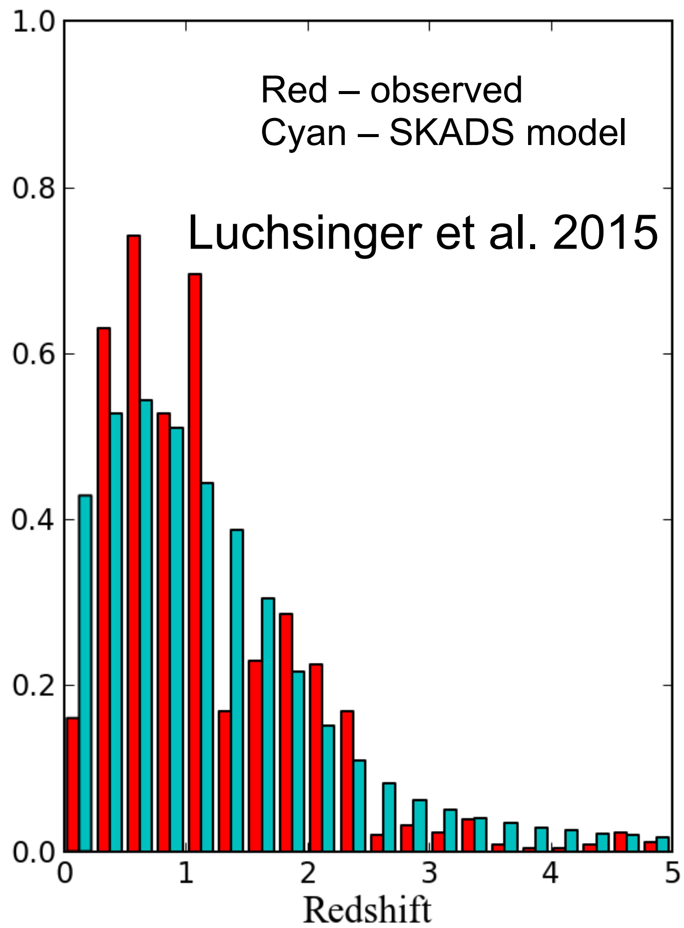


Assume spectral index of 0.8 to 1.4GHz, both surveys at 6.7-σ (5σ+20%) cuts.
Deep still comparable to, or slightly better than Herschel 250μm out to z~3 (Fig 12 of proposal)

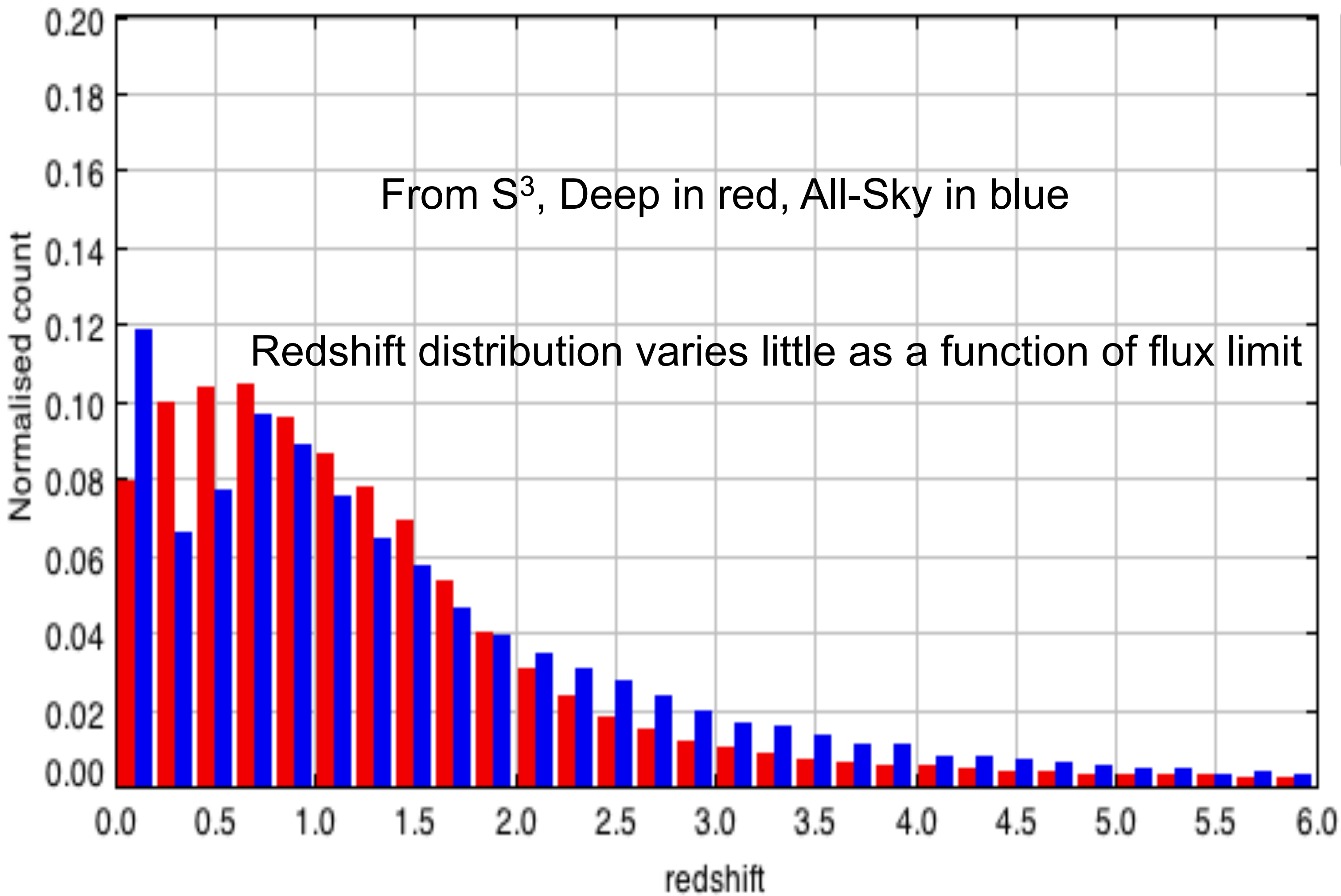
VLA SKY SURVEY

Redshift distribution





Predictions for All-Sky and Deep from SKA simulations (Wilman et al. 2008) (QIV 3).



RVEY

How many at high-z?

- Both the SKADs model and observations suggest about 15-20% of radio sources in Deep at z>2, 5-10% at z>3.
- Thus deep (~10^5 sources in total) will contain >15000 sources at z>2, >5000 at z>3.
- We can assume these are associated with a large fraction of the most massive galaxies at these redshifts, and thus also tracers of protogroup and protocluster environments.

VLA SKY SURVEY

Choice of fields for deep

- Surveying the entire sky to μJy sensitivity is not going to be practical until SKA-2.
- We therefore needed to pick ~10deg^2 with the best multi-wavelength data, constrained by the practicalities of doing the survey (RA coverage, RFI etc).
- Also above Dec~-30deg (rules out e.g. ELAIS-S1).

QV, 4

Field	Area (deg^2)	X-ray	Optical (existing public)	Near-IR (1-5mu)	Mid-IR	Far-IR	RFI env.
~~Bootes~~	~~9~~	~~CXO (shallow)~~	~~NDWFS~~	~~NDWFS/ SDWFS~~	~~Bootes GTO~~	~~HerMES L5/L6~~	~~OK~~
ELAIS-N1	3.5	1deg^2 CXO	SWIRE/ INT	DXS/ SERVS (partial)	SWIRE	HerMES L5 (partial)	OK
ECDFS*	4.5	CXO 4Ms center only	SWIRE/ CTIO	VIDEO/ SERVS	SWIRE	HerMES L5	OK
~~Lockman~~	4	~~Partial CXO/ XMM~~	~~SWIRE/ INT~~	~~DXS/ SERVS~~	~~SWIRE~~	~~HerMES L3/L5~~	~~OK~~
COSMOS*	2	CXO+XMM	COSMOS	COSMOS	SCOSMOS	Hermes L4	OK
~~XMM-LSS*~~	~~4.5~~	~~XMM~~	~~CFHTLS~~	~~VIDEO/ SERVS~~	~~SWIRE~~	~~HerMES L4/L5~~	~~Clarke Belt~~
~~XFLS/NEP~~	~~3.8~~	~~Few pts only~~	~~XFLS~~	~~XFLS~~	~~XFLS~~	~~Hermes L6~~	~~OK~~

*LSST deep drilling field (XMM and ECDFS also DES DDFs)

Euclid, WFIRST yet to determine their deep fields

Key science goals - traceability

- Do radio jets stop star formation?
  - Deep component will deliver many hundreds of $L \sim 10^{24}$ radio sources in the critical range z~2-4, from the start to the peak of massive galaxy formation.
- When did the first galaxy clusters form?
  - Quasars and AGN from both All-Sky and deep components will trace the most massive galaxies, likely to be in the most massive structures, out to high-z.
- What is the evolutionary path of massive galaxies?
  - Deep component will inform on the physical properties of thousands of Herschel/submm galaxies.
  - Deep and All-Sky will construct a census of radio-loud/intermediate AGN, and, in conjunction with ancillary data, allow calculations of duty cycles for AGN and SF activity as a function of host galaxy mass.

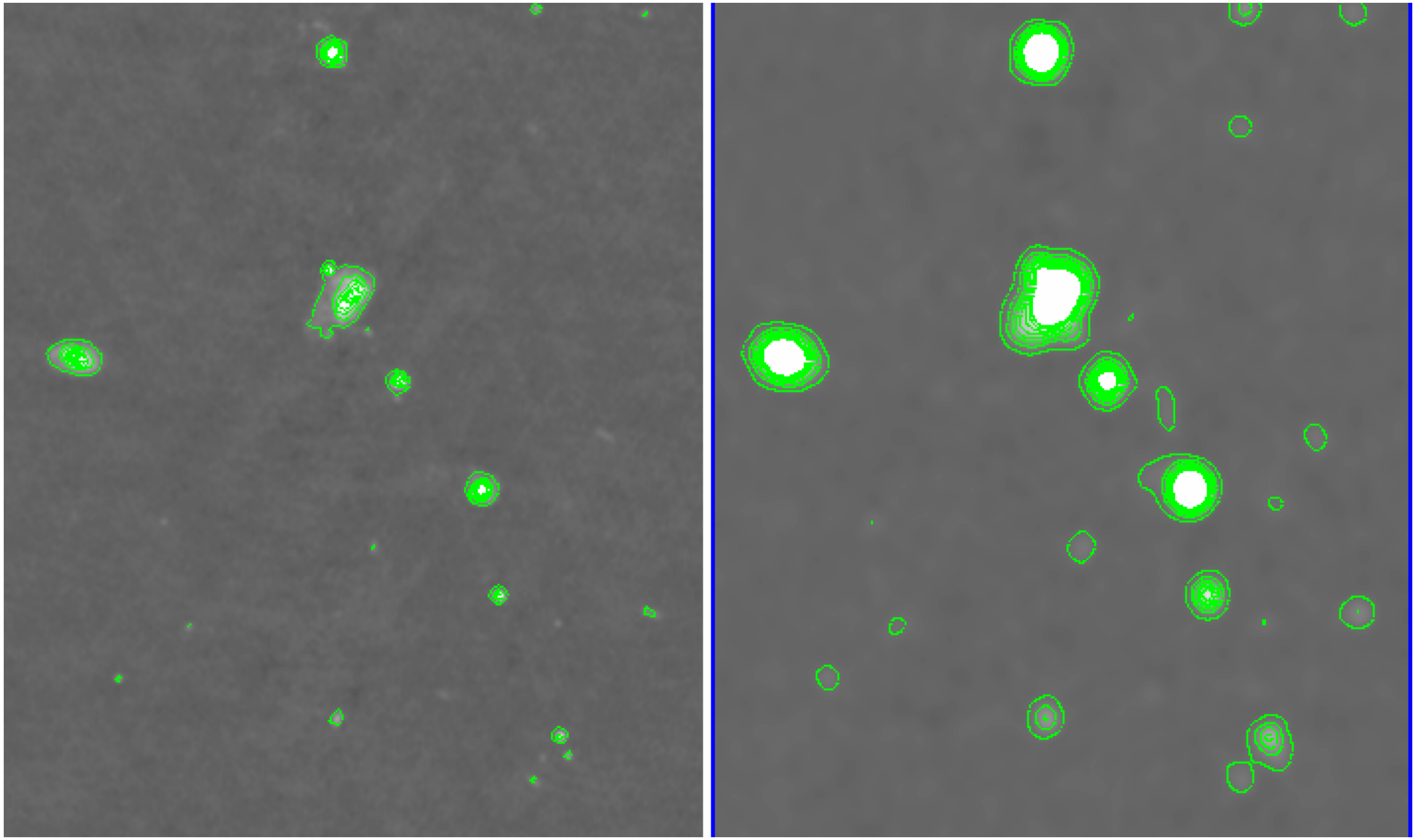
VLA SKY SURVEY

Summary

- The VLASS represents an opportunity to perform a transformational study of the evolution of massive galaxies in both starforming and AGN phases.
- Ancillary data is key, especially for Deep, to disentangle the radio source populations. Field choices dictated by this, plus scheduling considerations.
- Simulations of the Deep component suggest a significant penalty for A-array vs B-array (~20%-40% of observing time), but improved resolution of galaxy pairs/mergers, and sufficient resolution for weak lensing studies.
  - Comparable to a deep optical survey, but in the radio

Reserve slides

A and B comparison



VLA SKY SURVEY

Comment on resolution and identification

- Statistically, don't need great resolution to identify sources, likelihood ratio will tell you what fraction of IDs are real.
- Problem comes with false associations, especially in searches for rare objects.
  - e.g. looking in an optical survey for high-z radio source candidates – you want the things that are not optically-detected (or extremely faint), but it's human nature to assume that something is if there is anything in the error circle, even if it is not a real association.
- Also many galaxies blended/merging, so low resolution centroid won't help you understand which component is the radio source.

VLA SKY SURVEY