Evolution in the Bias of Faint Radio Sources

Sam Lindsay (University of Oxford/Hertfordshire)

+ Matt Jarvis (Oxford)
+ Mario Santos (Western Cape)
+ Kim McAlpine (Western Cape)

Clustering of Active Galactic Nuclei, 14th-18th July 2014

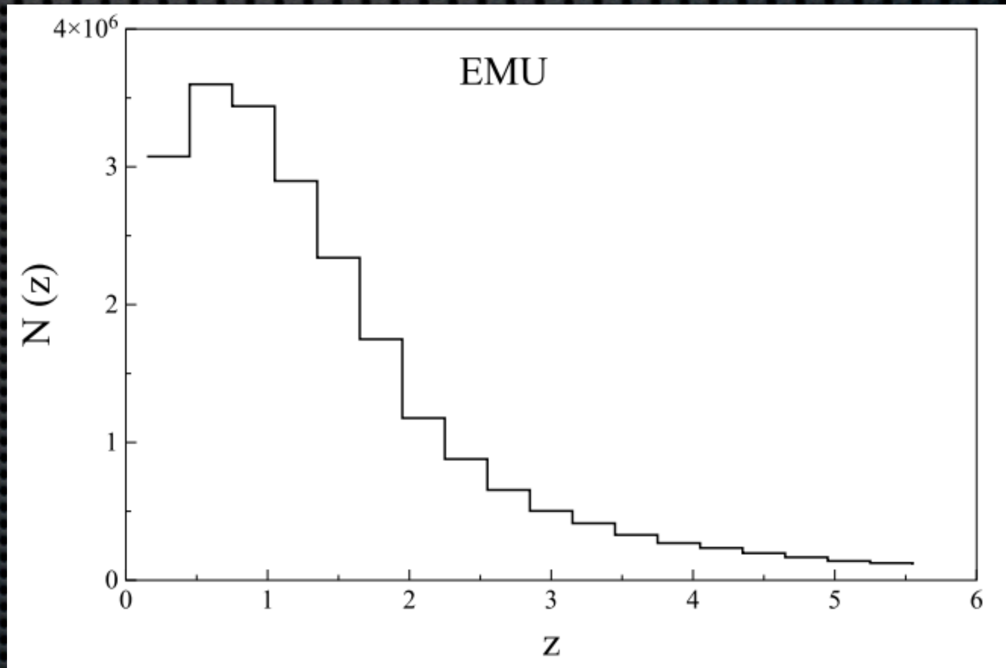
Outline

- Motivation: SKA ⟶ Cosmology
- Clustering of radio sources in GAMA survey area
  - 1 mJy to z~0.65 (z~1.54 if you cheat…)
- Deep, narrow cross-correlation analysis in VIDEO
  - 90 μJy to z~2.2
- Ongoing and future work

Radio Continuum with SKA

SKA1 (>2020)

- ~100 million galaxies
- 50 MHz - 24 GHz
  (6m - 12.5mm)
- Median z~1.1
- Need to actually measure redshifts...

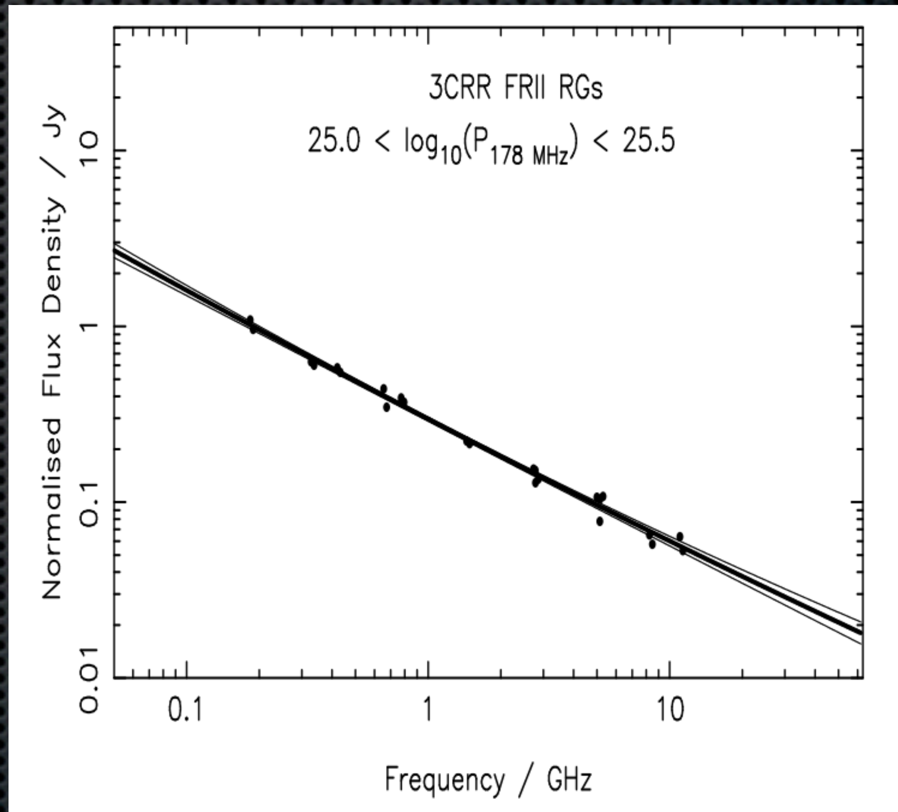


Raccanelli+12

Radio Continuum with SKA

SKA1 (>2020)

- ~100 million galaxies
- 50 MHz - 24 GHz
  (6m - 12.5mm)
- Median z~1.1
- Need to actually measure redshifts...

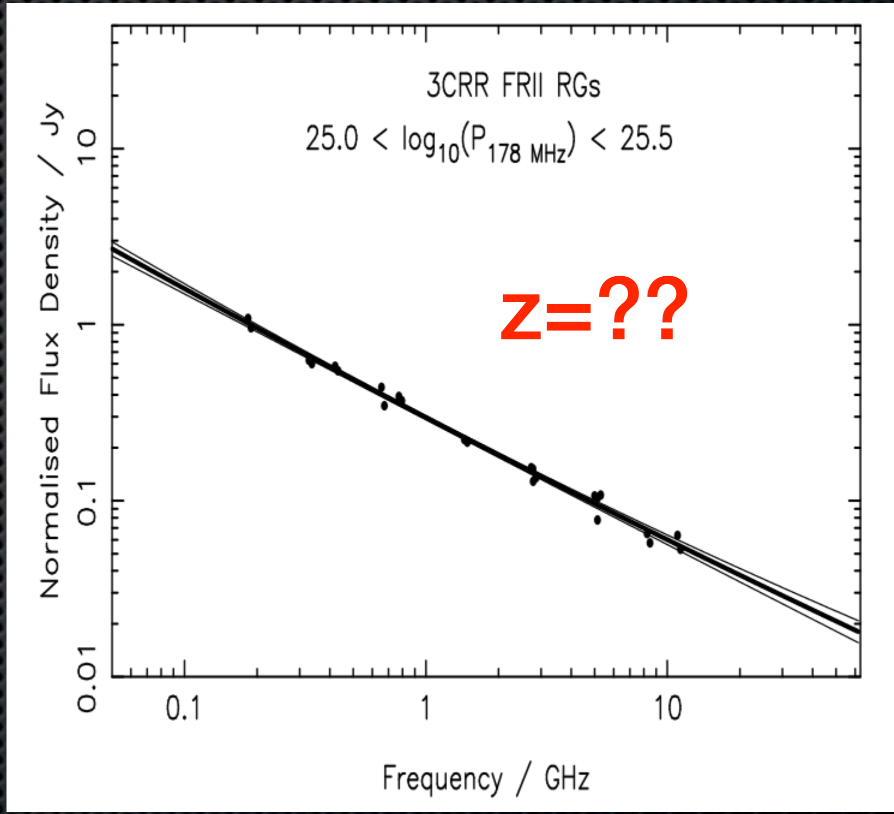


Jackson+Wall 01

Radio Continuum with SKA

SKA1 (>2020)

- ~100 million galaxies
- 50 MHz - 24 GHz
  (6m - 12.5mm)
- Median z~1.1
- Need to actually measure redshifts...



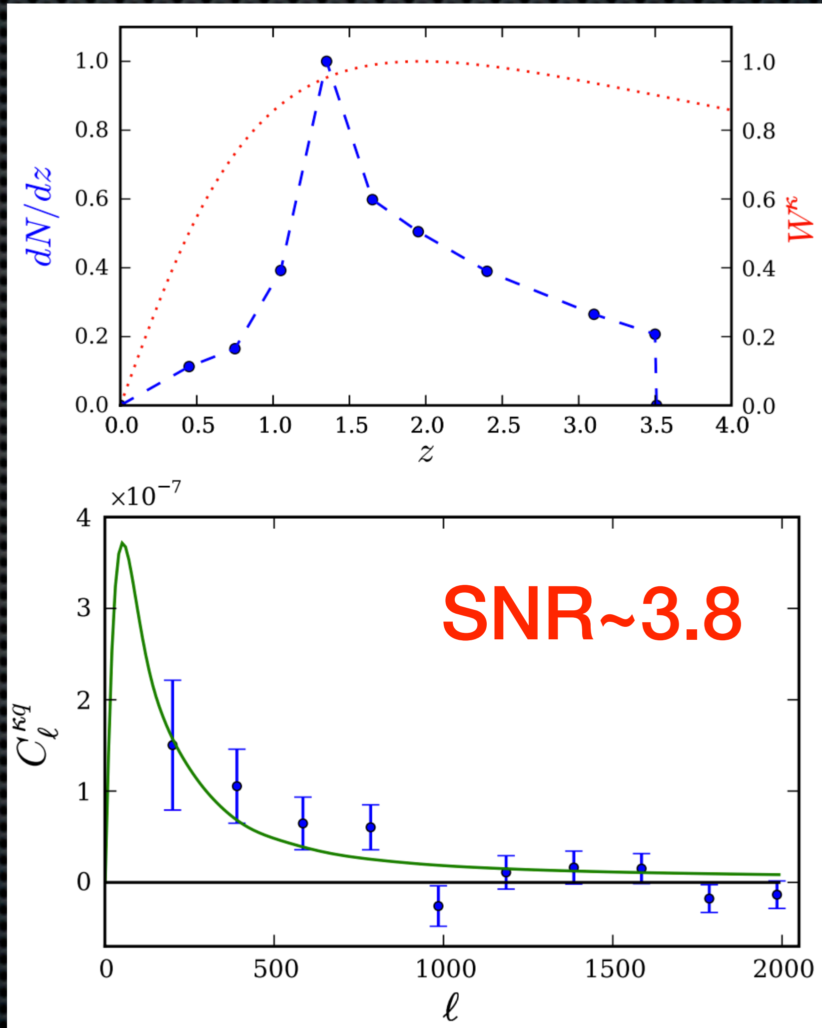
Jackson+Wall 01

Cosmology in the Radio

- Cosmic magnification
- Radio-CMB cross-correlation
  - Temperature (e.g. Giannantonio+08)
  - Lensing (e.g. Sherwin+13)
- Non-Gaussianity
- Weak lensing (yes, seriously…!)
- Baryon acoustic oscillations (BAO)
- Redshift-space distortions (RSD)

Cosmology in the Radio

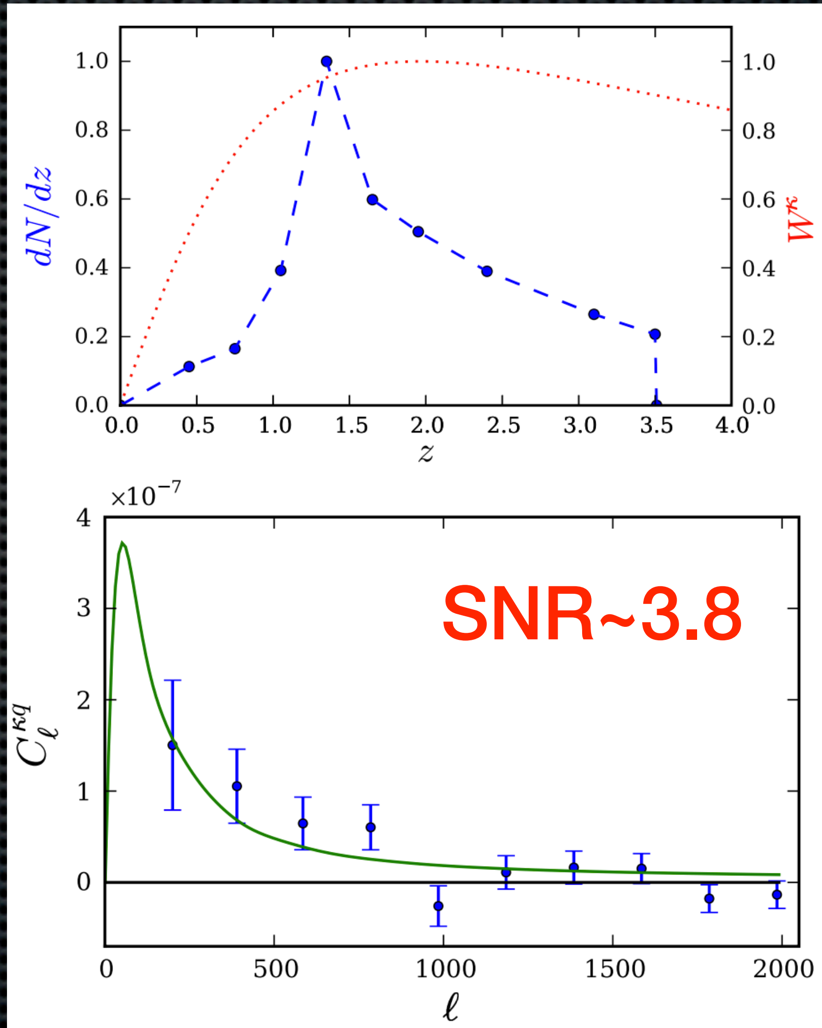
- Cosmic magnification
- Radio-CMB cross-correlation
  - Temperature (e.g. Giannantonio+08)
  - Lensing (e.g. Sherwin+13)
- Non-Gaussianity
- Weak lensing (yes, seriously…!)
- Baryon acoustic oscillations (BAO)
- Redshift-space distortions (RSD)



Sherwin+13

Cosmology in the Radio

- Cosmic magnification
- Radio-CMB cross-correlation
  - Temperature (e.g. Giannantonio+08)
  - Lensing (e.g. Sherwin+13)
- Non-Gaussianity
- Weak lensing (yes, seriously…!)
- Baryon acoustic oscillations (BAO)
- Redshift-space distortions (RSD)



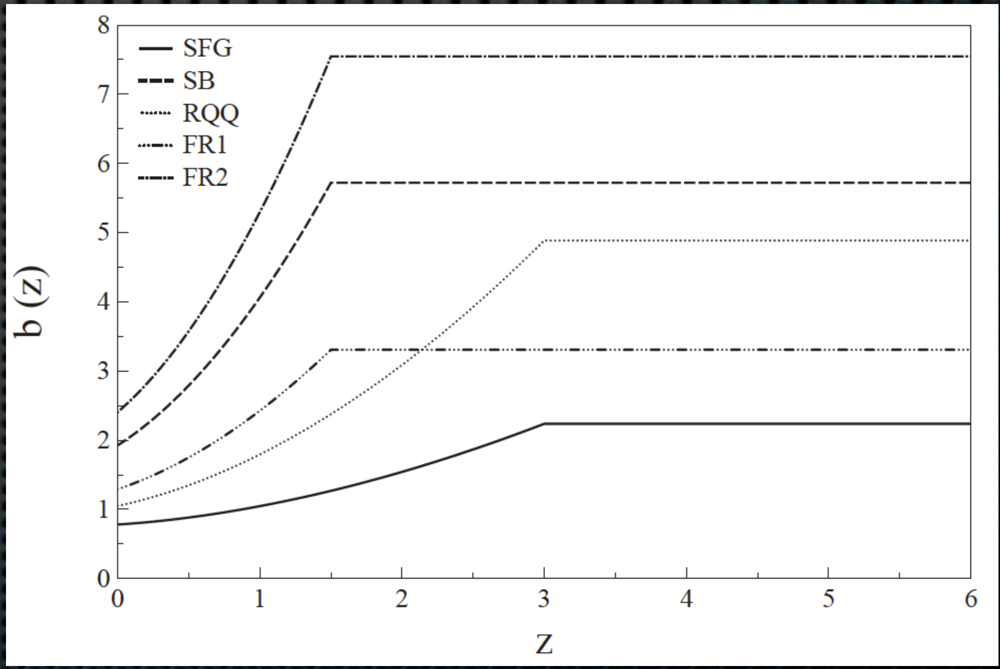
Sherwin+13

VLA Stripe82 ($S_{1.4}$>250 μJy) x ACT → **SNR~5**

Cosmology in the Radio

- Cosmic magnification
- Radio-CMB cross-correlation
  - Temperature (e.g. Giannantonio+08)
  - Lensing (e.g. Sherwin+13)
- Non-Gaussianity
- Weak lensing
- Baryon acoustic oscillations (BAO)
- Redshift-space distortions (RSD)

Many of these require a model bias evolution

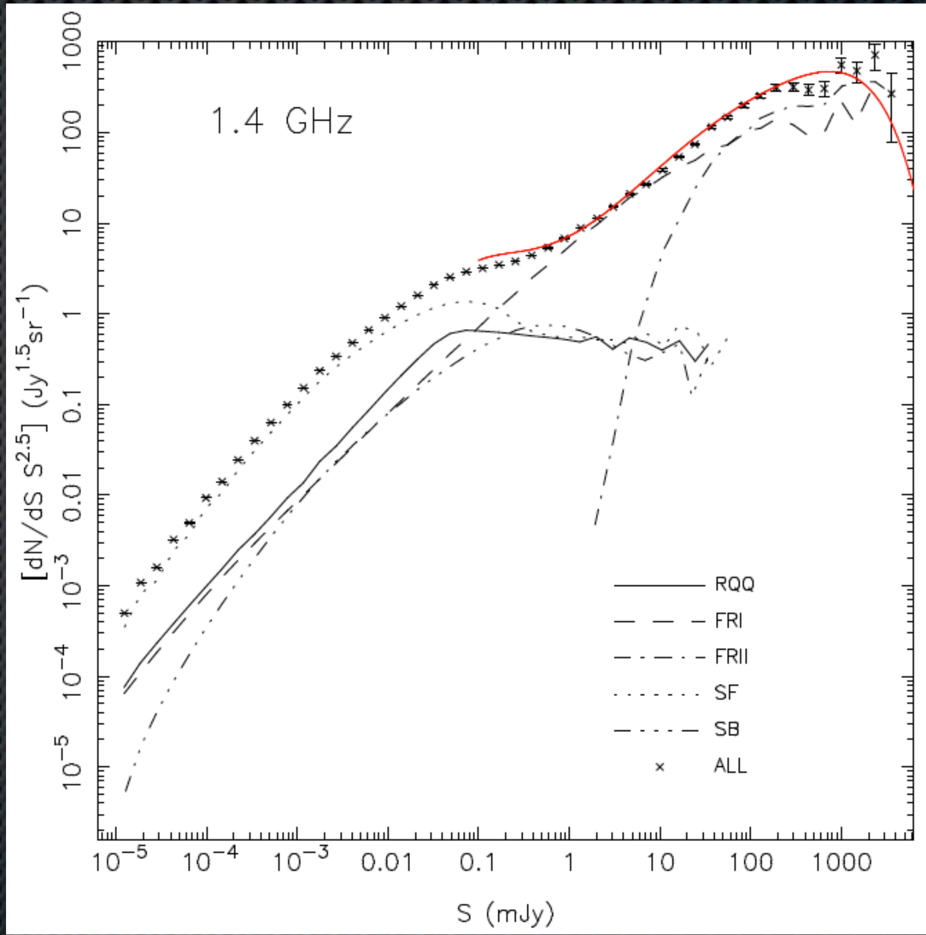


Raccanelli+12

SKADS Simulated Skies (S^3)

Semi-empirical radio continuum simulation by Wilman et al. (2008)

- 400 deg^2 to z<20
- S>10 nJy in 5 bands (150 MHz - 18 GHz)
- 5 radio populations:
  - LFs (extrapolated)
  - Fixed halo mass each, with corresponding bias from Mo & White (1996)

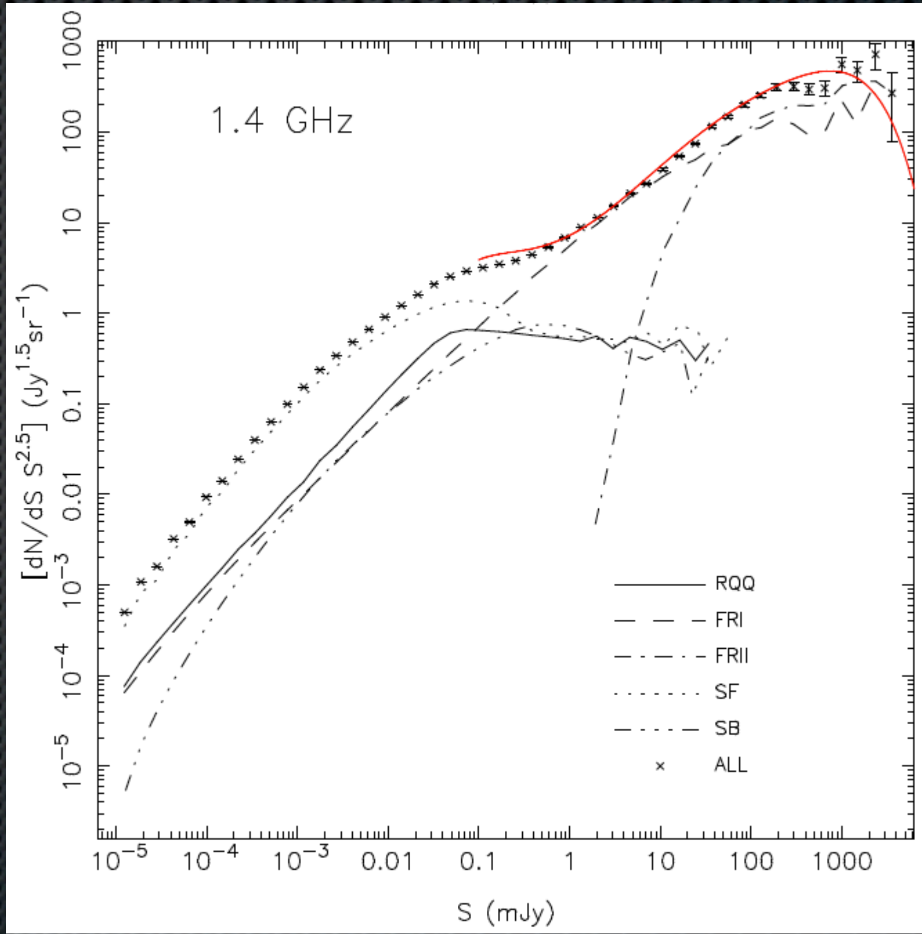


Wilman+08

SKADS Simulated Skies (S^3)

Semi-empirical radio continuum simulation by Wilman et al. (2008)

- 400 deg^2 to z<20
- S>10 nJy in 5 bands (150 MHz - 18 GHz)
- 5 radio populations:
  - LFs (extrapolated)
  - Fixed halo mass each, with corresponding bias from Mo & White (1996)



Wilman+08

Note: Updated simulations in preparation, incorporating more realistic clustering etc.

Redshift Surveys

Spectroscopic

Galaxy and Mass Assembly (GAMA; Phase 1)

- 3.9m Anglo-Australian Telescope (AAT) + AAOmega spectrograph
- 3720-8850 Å with 3.5 Å (blue) and 5.5 Å (red) resolution
- Three equatorial fields covering 144 deg^2 (98% complete at $r < 19.4$)
- **~140,000 redshifts**

Photometric

Sloan Digital Sky Survey (SDSS)

- 2.5m Sloan telescope @ Apache Point Observatory, New Mexico
- ~10,000 deg^2 in *ugriz* bands ($r < 22$)

UKIRT Infra-red Deep Sky Survey (UKIDSS) Large Area Survey (LAS)

- 3.8m UK Infra-Red Telescope (UKIRT) @ Mauna Kea, Hawaii
- ~2,000 deg^2 in *YJHK* bands ($K < 18.4$)

- **~1,000,000 redshifts per GAMA field**

Radio Data

Faint Images of the Radio Sky at Twenty-cm (FIRST)

- 1.4 GHz VLA survey in B-configuration
- 5.4” resolution, 1 mJy detection limit
- >10,000 deg^2 sky coverage (~25%)
- ~950,000 sources

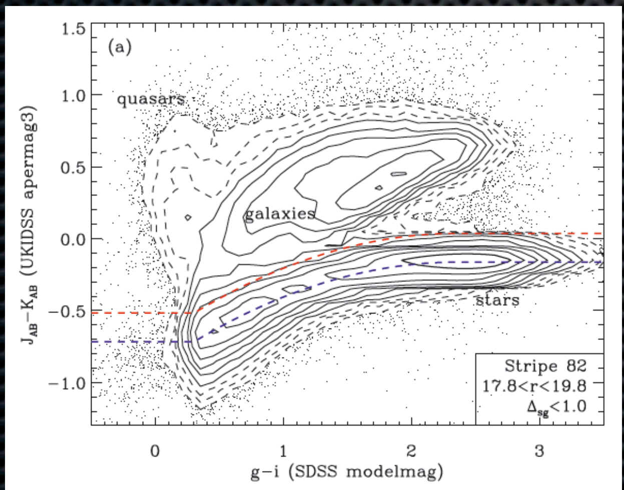
Baldry+10

Radio Data

Faint Images of the Radio Sky at Twenty-cm (FIRST)

- 1.4 GHz VLA survey in B-configuration
- 5.4” resolution, 1 mJy detection limit
- >10,000 deg^2 sky coverage (~25%)
- ~950,000 sources

Remove stars



Baldry+10

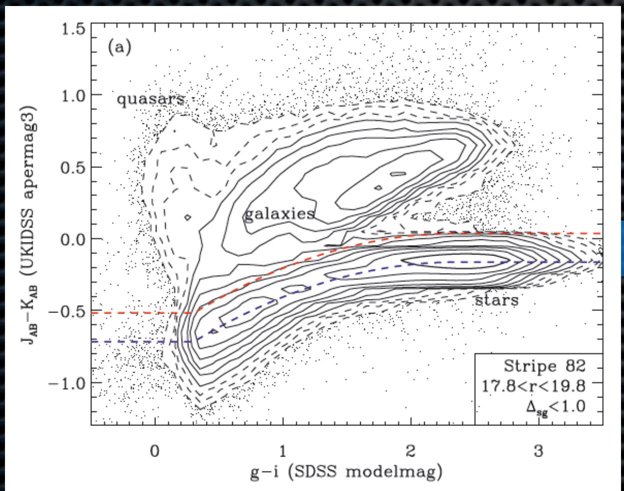
Radio Data

Faint Images of the Radio Sky at Twenty-cm (FIRST)

- 1.4 GHz VLA survey in B-configuration
- 5.4” resolution, 1 mJy detection limit
- >10,000 deg^2 sky coverage (~25%)
- ~950,000 sources

Remove stars

Collapse multiple radio sources within 72”



Baldry+10

Radio Data

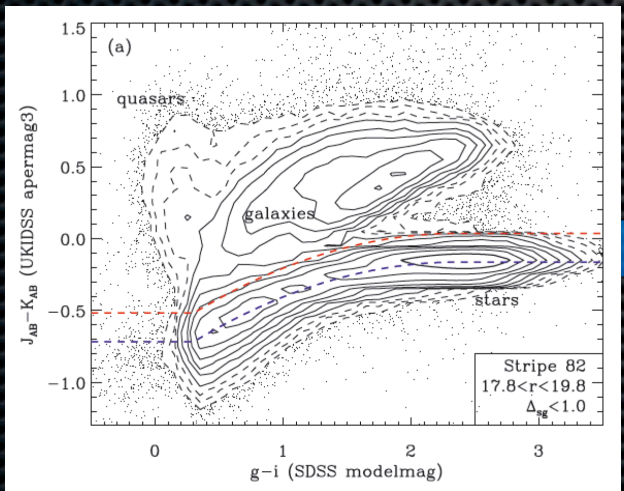
Faint Images of the Radio Sky at Twenty-cm (FIRST)

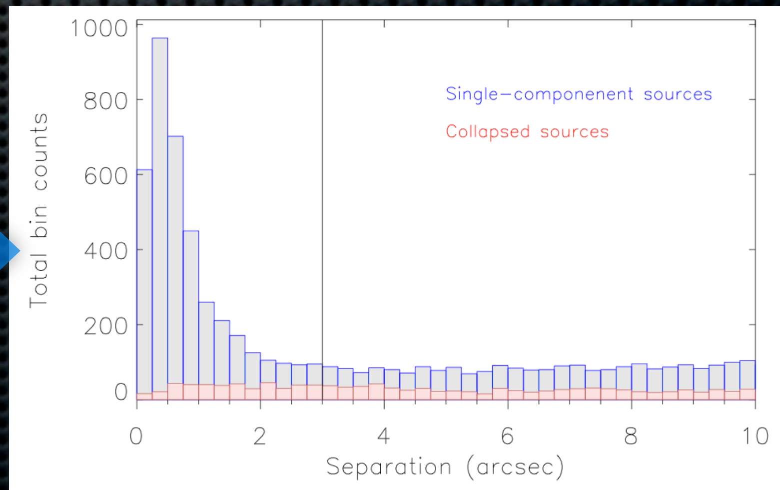
- 1.4 GHz VLA survey in B-configuration
- 5.4” resolution, 1 mJy detection limit
- >10,000 deg^2 sky coverage (~25%)
- ~950,000 sources

Remove stars

Collapse multiple radio sources within 72”

Find nearest radio-optical matches within 3”



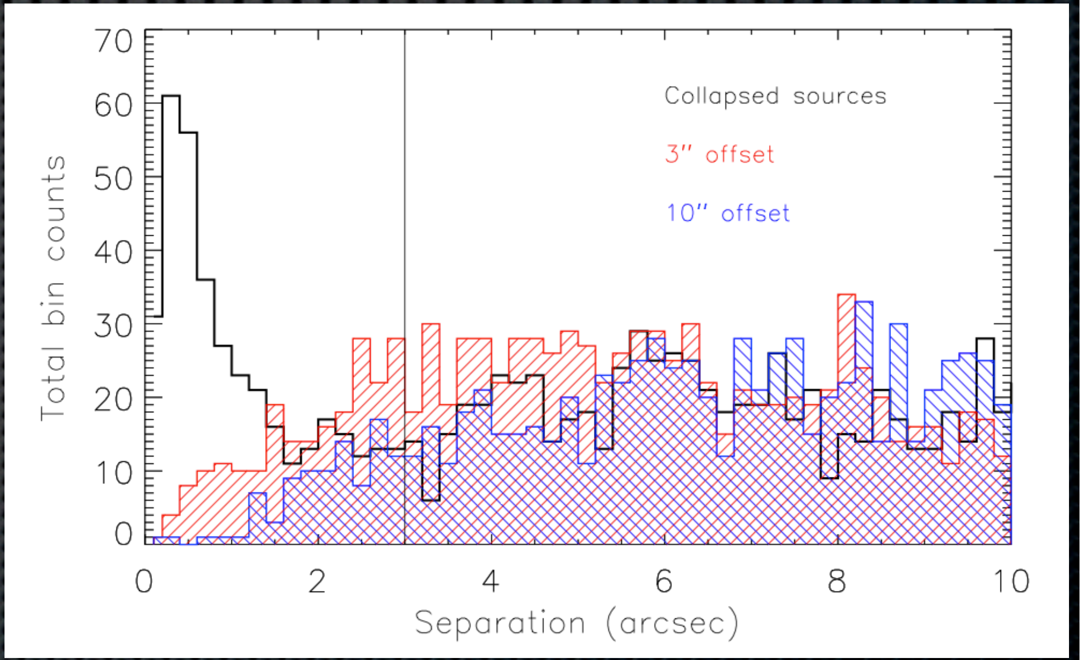


Baldry+10

Cross-matching

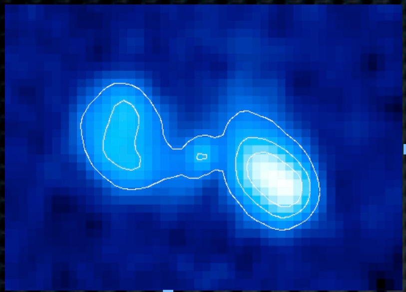
Does the collapsing procedure reliably locate the host galaxy position?

Randomly shift expected positions of radio galaxy cores by 3” and 10” and repeat nearest neighbour match with optical catalogue

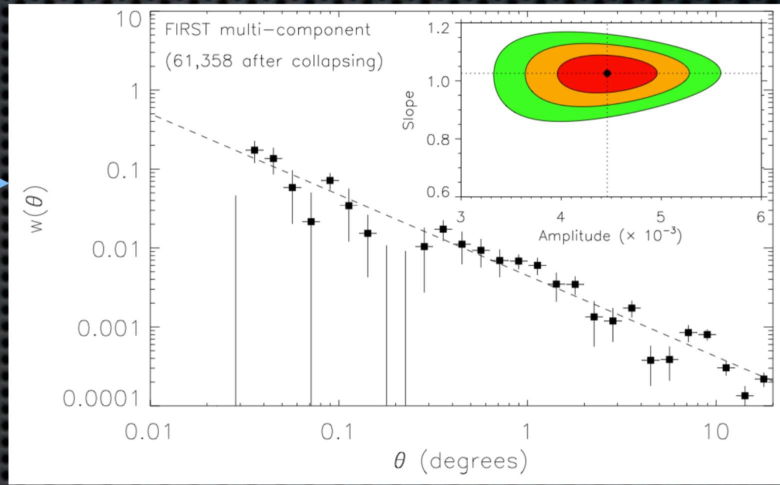


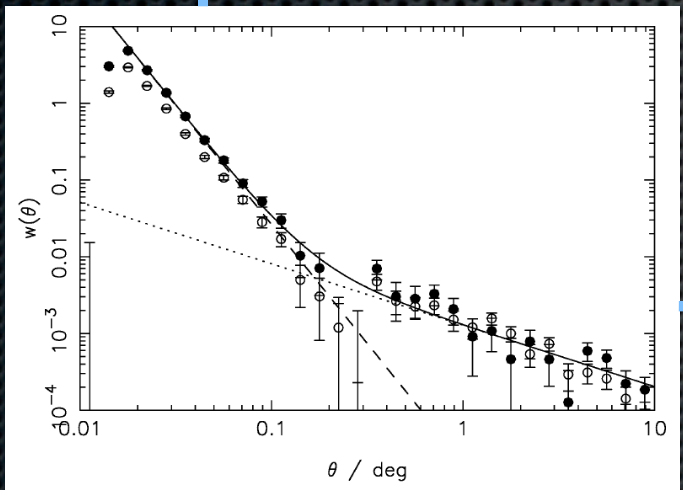
Majority of <3” matches appear not to be coincidental

Cross-matching

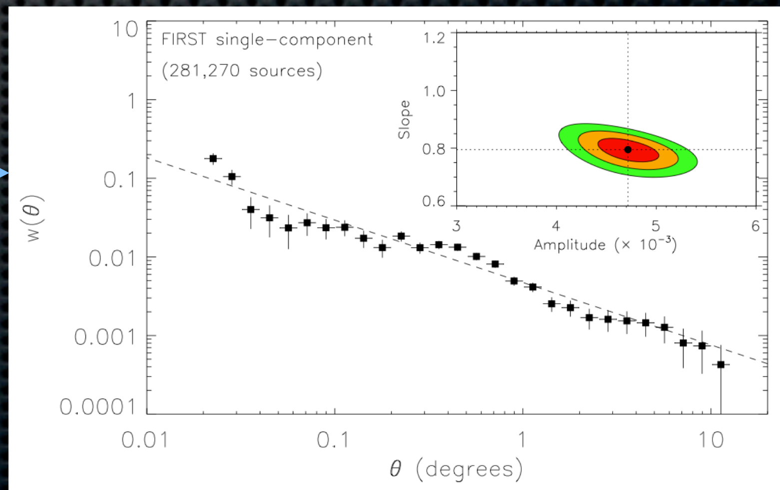


Collapse groups of sources within 72”

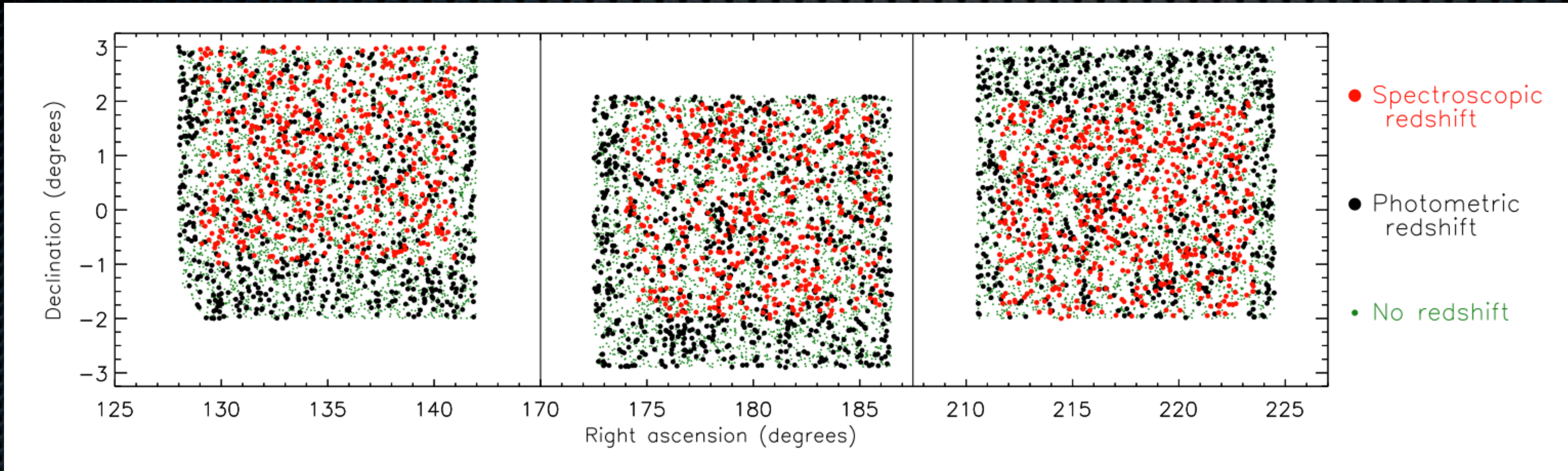




Blake+Wall 2002b



FIRST/GAMA/SDSS Samples



FIRST galaxies ($S_{1.4}$ > 1 mJy) : *13,346*
Optical IDs (within 3") : *3,886*

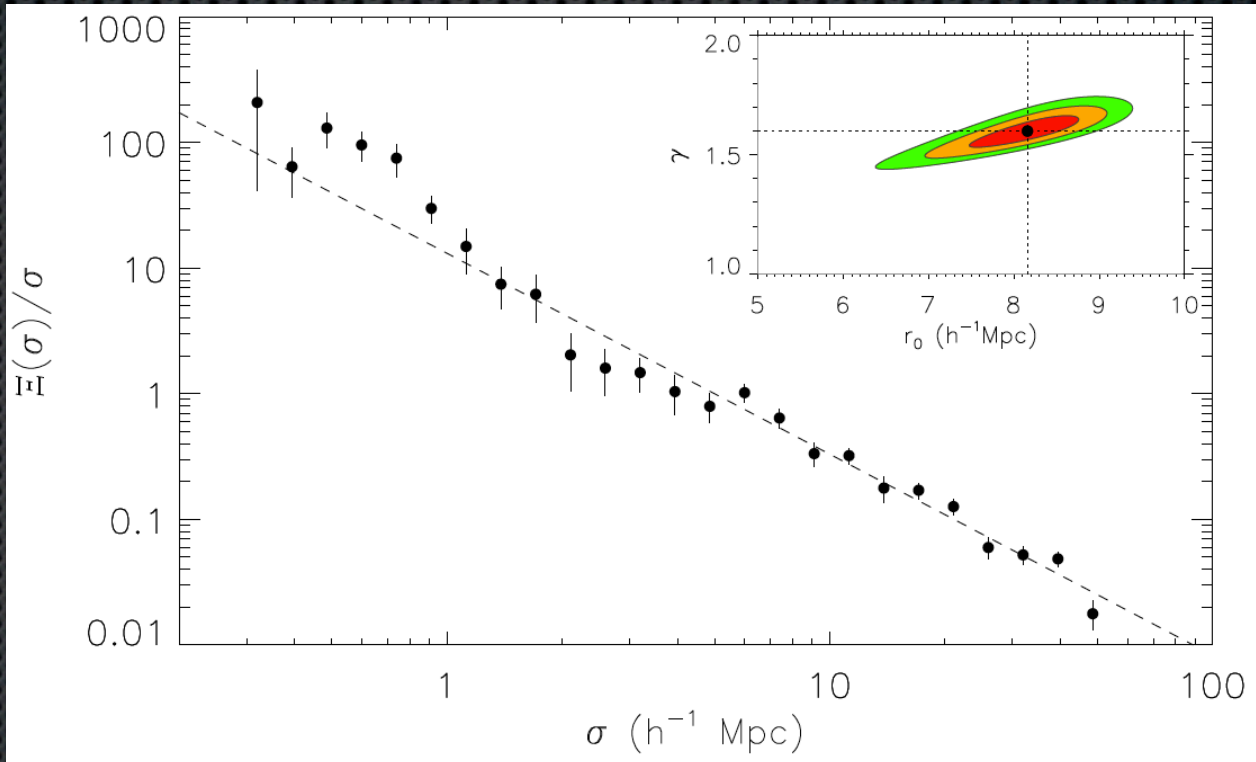
Of these matches 1,635 have spec-z's, 422 are collapsed multiple sources and ~78 are matched due to chance alignments of unrelated sources

Spatial Correlation Function

1,635 sources with GAMA spec-z:

r_0 = 8.2 +/- 0.4 h^{-1}Mpc

b(z~0.3) = 1.9 +/- 0.1

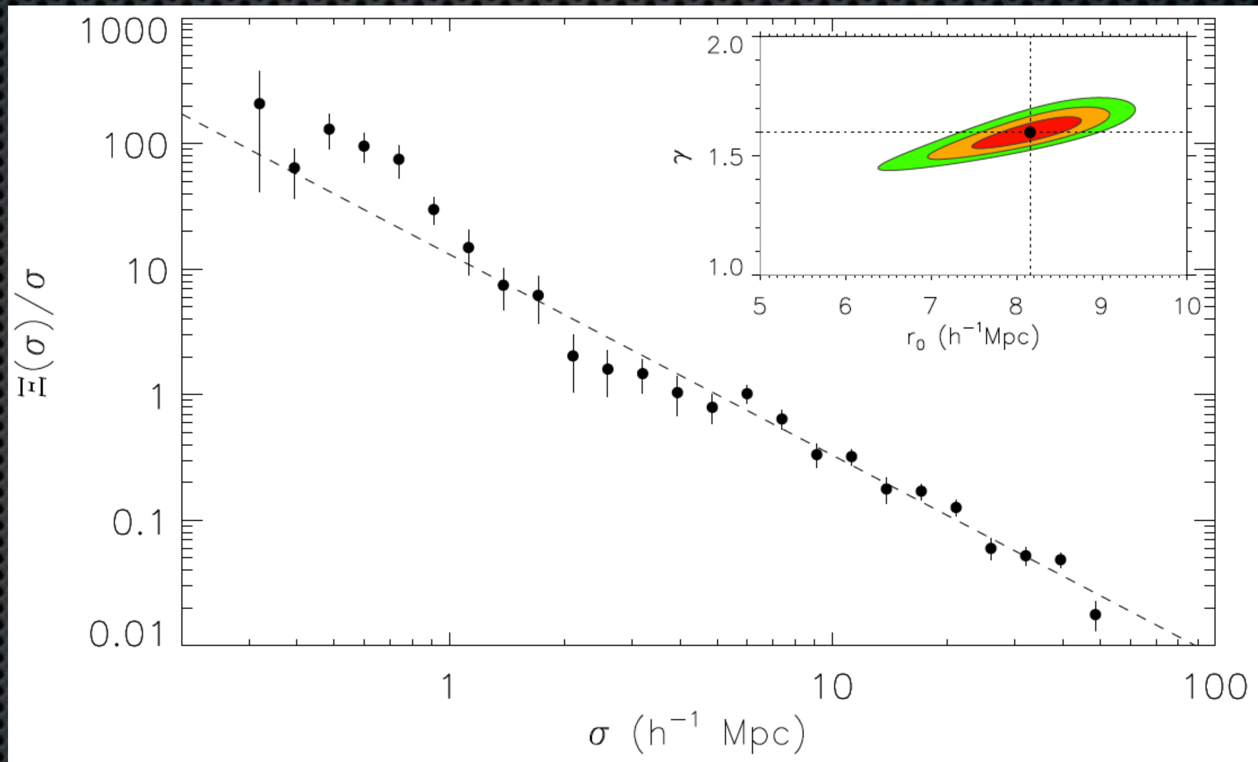


Spatial Correlation Function

1,635 sources with GAMA spec-z:

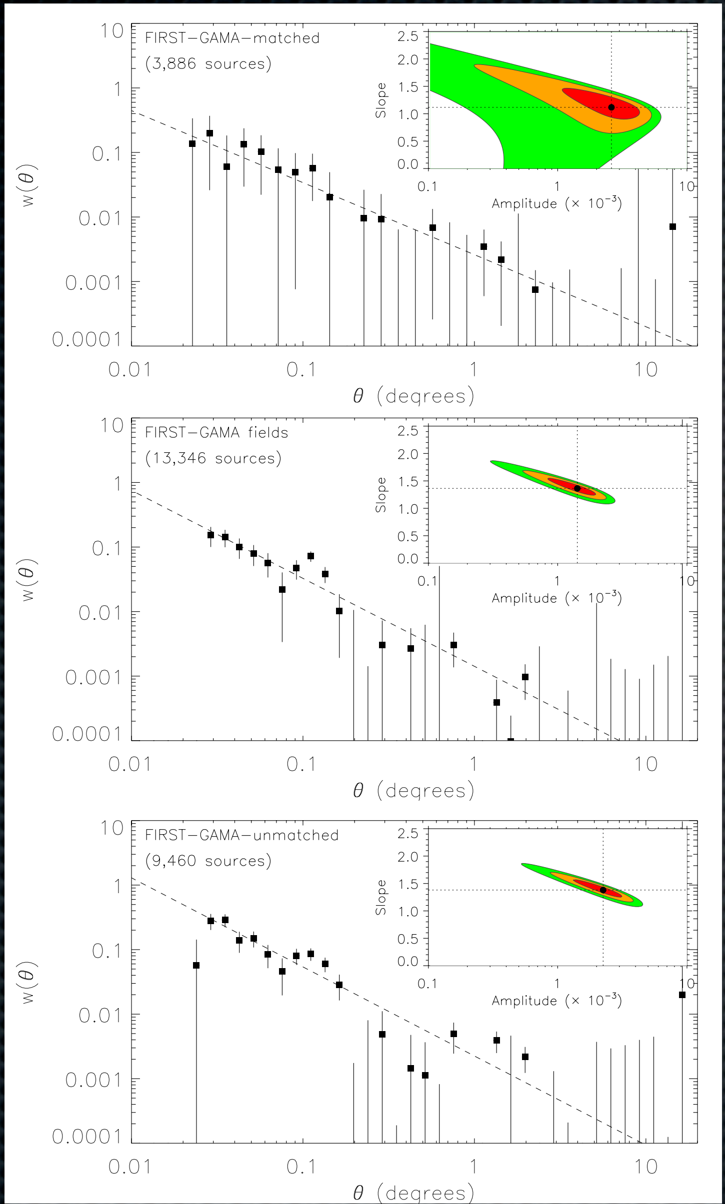
$r_0 = 8.2 \pm 0.4\ h^{-1}$Mpc

$b(z \sim 0.3) = 1.9 \pm 0.1$



...and this is where spec-z's and spatial c.f.s check out, for now.

Angular Correlation Function



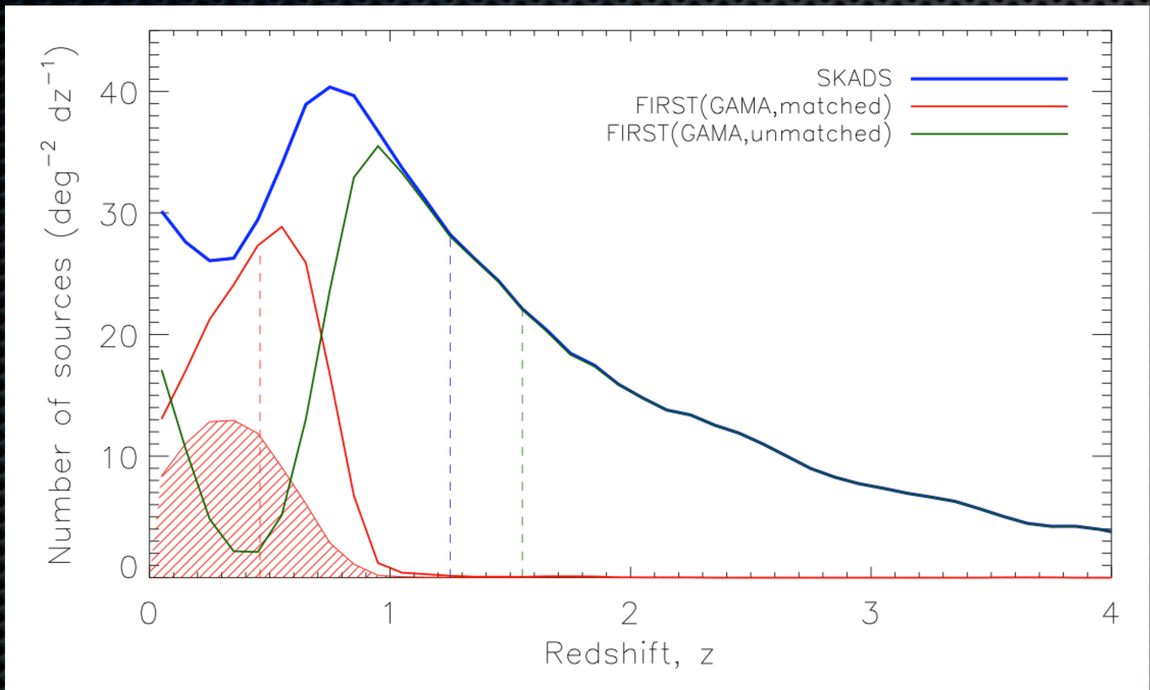
Matched sources (3,886)
z~0.5 (observed spec/phot redshifts)

Full sample (13,346)
z~1.2 (SKADS model distribution)

Unmatched sources (9,460)
z~1.5 (SKADS minus observed)

Redshift Distributions

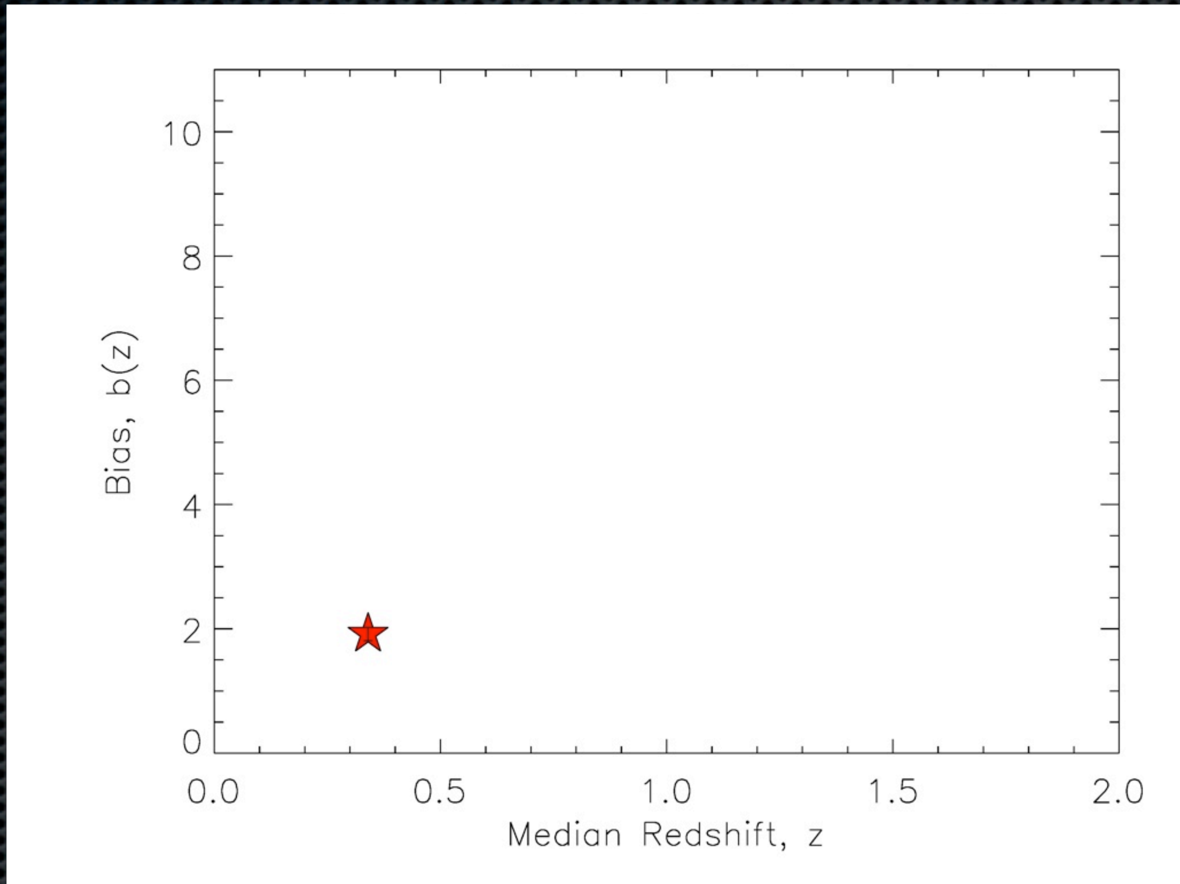
SKADS simulations (Wilman+ 2008) provide a simulated radio catalogue which we can cut at 1 mJy to roughly emulate the expected *N(z)* of FIRST radio sources.



FIRST sources with optical IDs from GAMA/SDSS have associated redshifts, giving a directly observed *N(z)*.

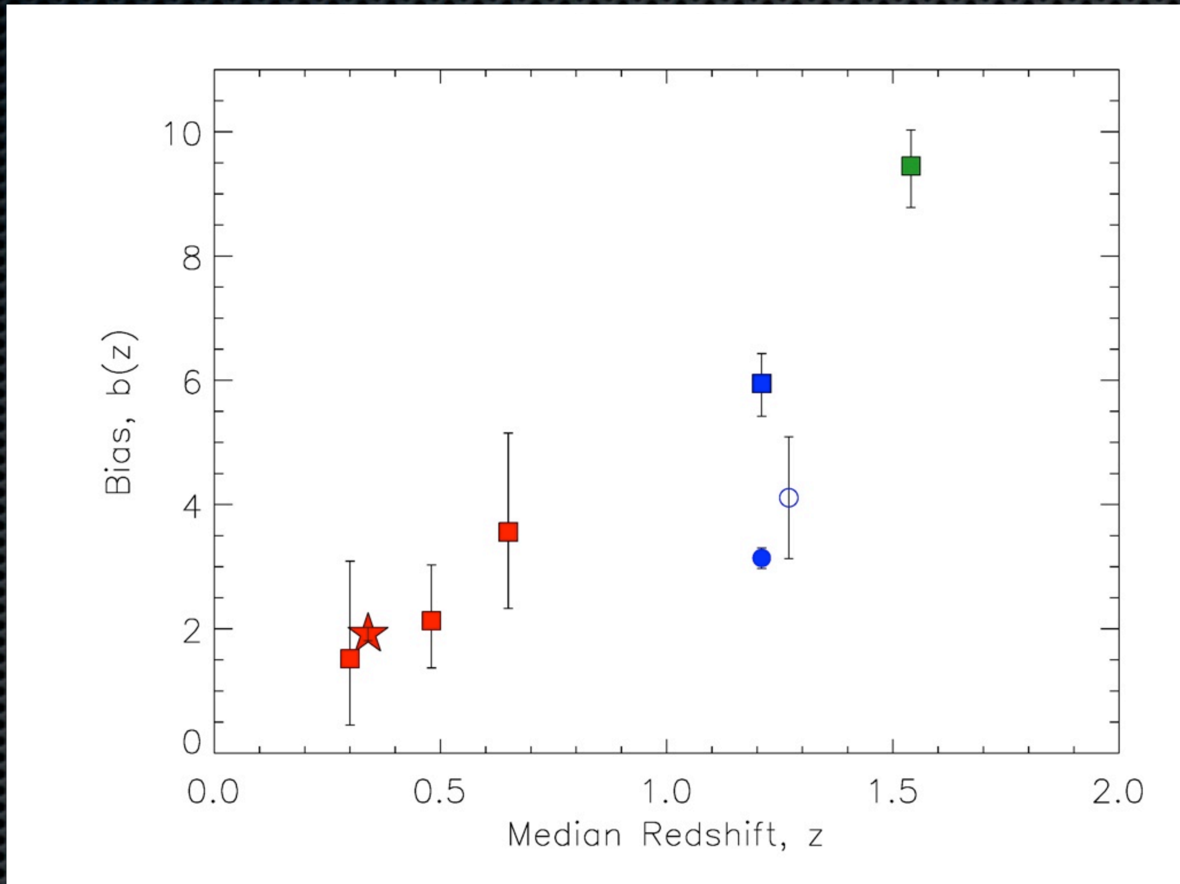
By assuming the SKADS distribution for FIRST, we subtract the observed *N(z)* for the matched sources to obtain one for those remaining sources without optical IDs.

Bias at >1 mJy



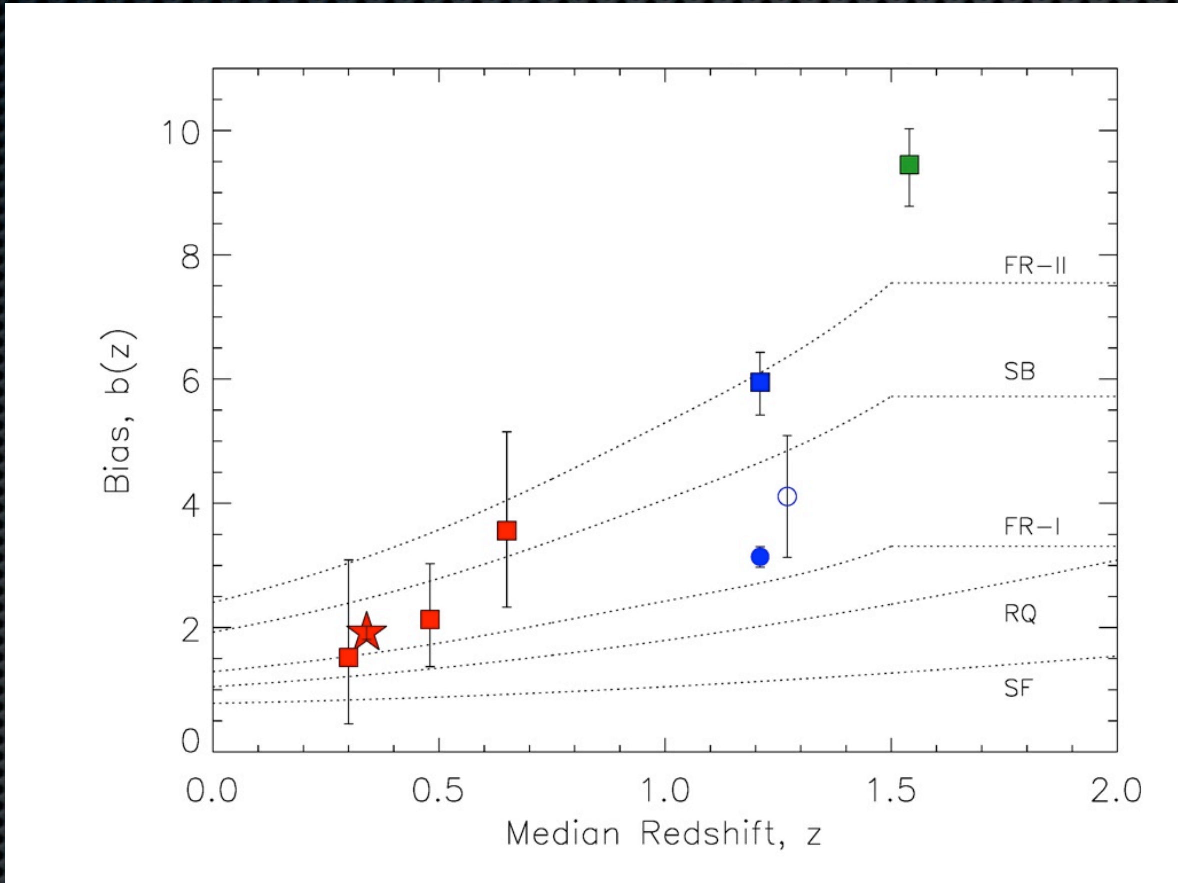
Lindsay, Jarvis, Santos+ 2014

Bias at >1 mJy



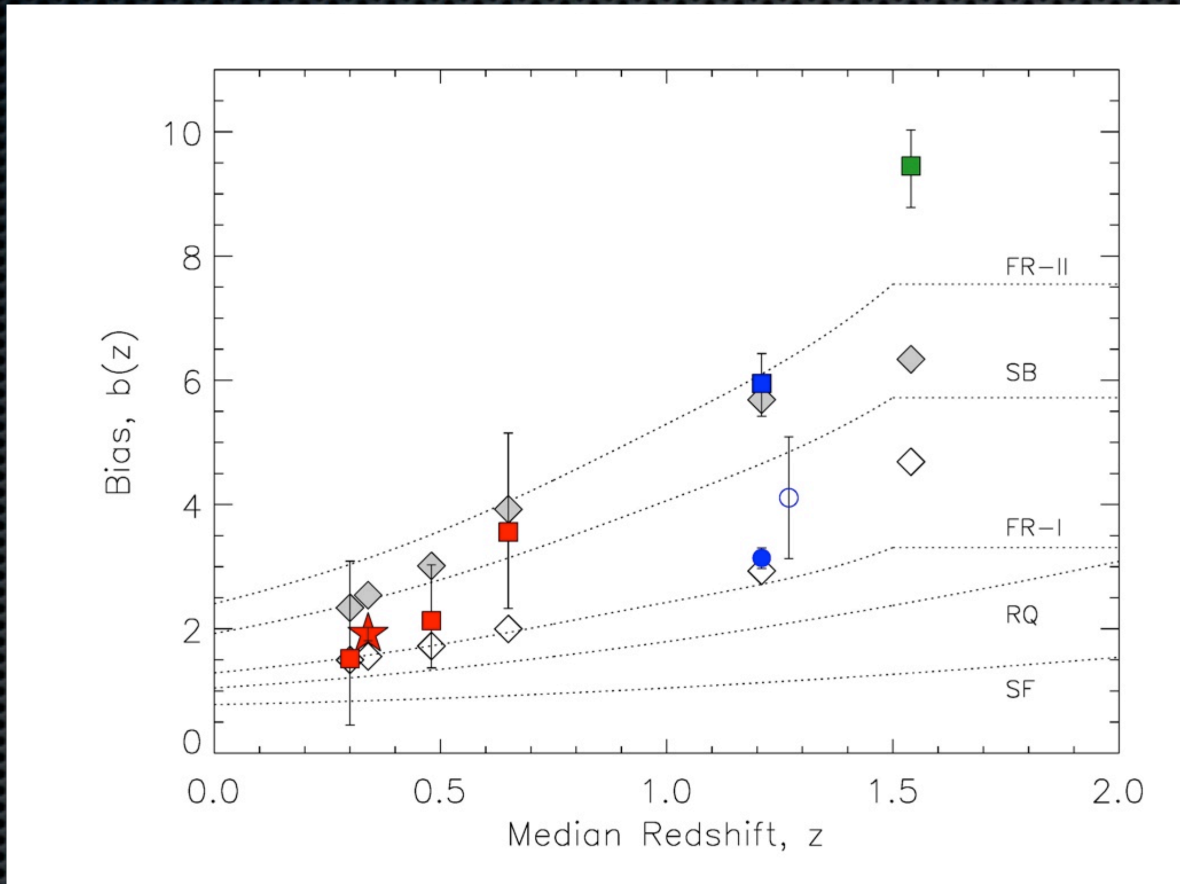
Lindsay, Jarvis, Santos+ 2014

Bias at >1 mJy



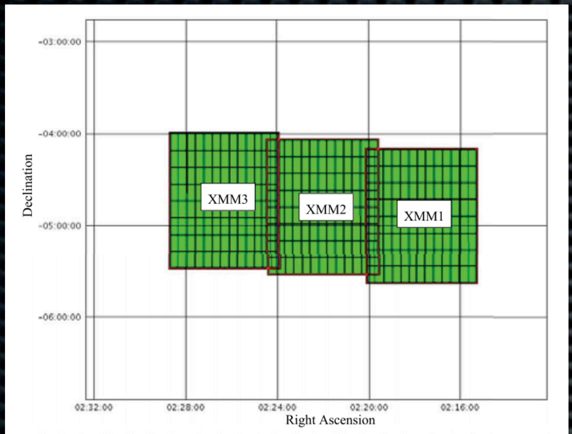
Lindsay, Jarvis, Santos+ 2014

Bias at >1 mJy



Lindsay, Jarvis, Santos+ 2014

Deep IR/Optical Data



Jarvis+ 2013

VISTA Deep Extragalactic Observations (VIDEO)

- 4.1m Visible Infrared Survey Telescope for Astronomy (VISTA)
- Three fields covering ~12 deg^2 in *zYJHK*$_s$ bands
- 5σ AB-magnitude depths of 25.7/24.5/24.4/24.1/23.8

Canada-France-Hawaii Telescope Legacy Survey (CFHTLS)

- 3.6m CFHT and MegaPrime wide-field camera
- Deep field 1 (D1) covers 1x1 deg in *u*griz* bands
- 80% complete to AB-magnitude depths of 26.3/26.0/25.6/25.4/25.0

>400,000 sources with photometric redshifts out to *z*~4 with 3% catastrophic outliers

Deep Radio Data

VLA VIRMOS Deep Survey (VVDS)

- 1.4 GHz VLA survey in B-configuration (6” resolution)
- Flux density limit of ~80 μJy over the full 1 deg^2
- Complete sample of 1,054 radio sources

	6 arcsec
r_{max} [arcsec]	3.6
Q_0	0.90
N(Rel>0.8)	915
$N_{no\ match}$	68
$N < r_{max}$	1274
N_{cont}	6.825
per cent Rel>0.8	88.7 per cent
per cent cont	0.74 per cent

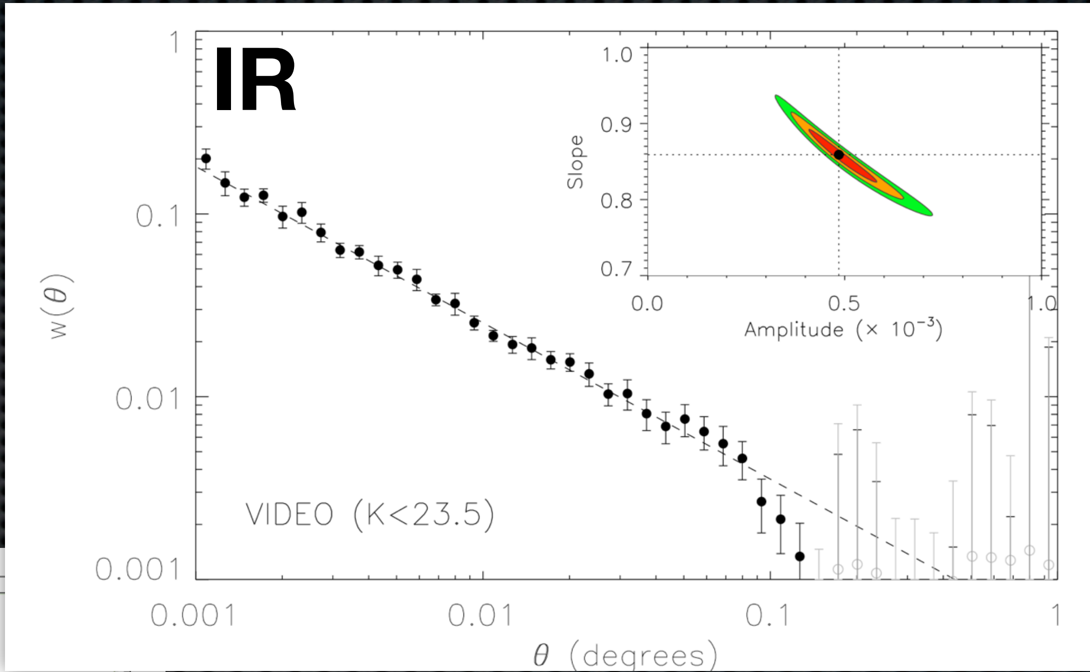
McAlpine+ 2012

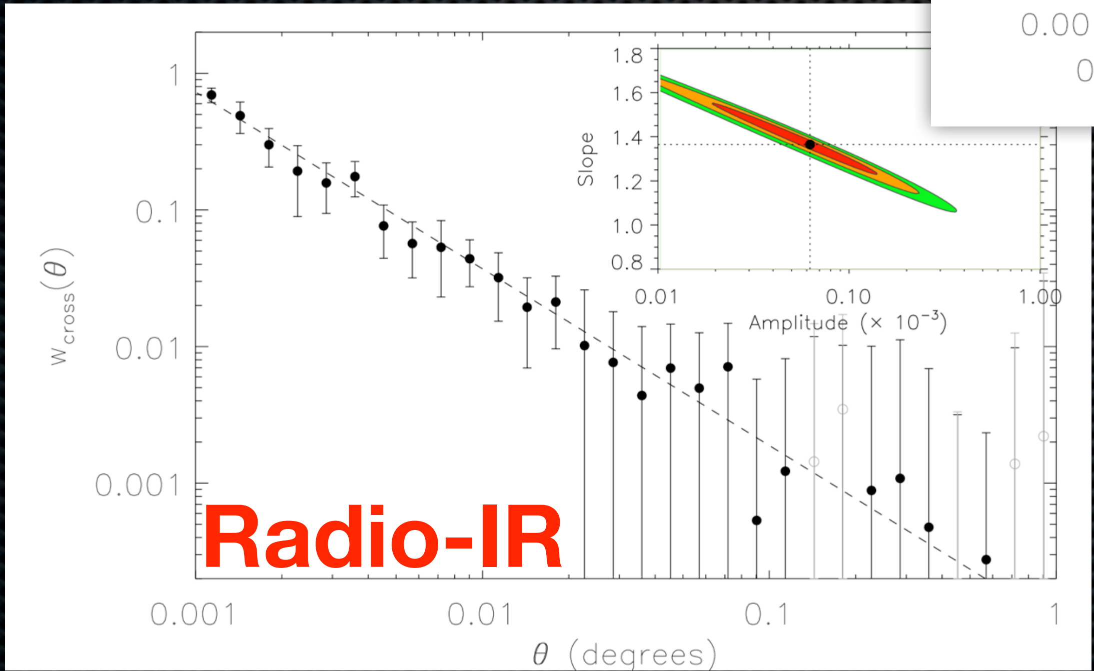
McAlpine et al. (2012) performed likelihood ratio technique to identify VIDEO/CFHTLS-D1 counterparts of these radio sources:

915 reliable (Rel>0.8) matches

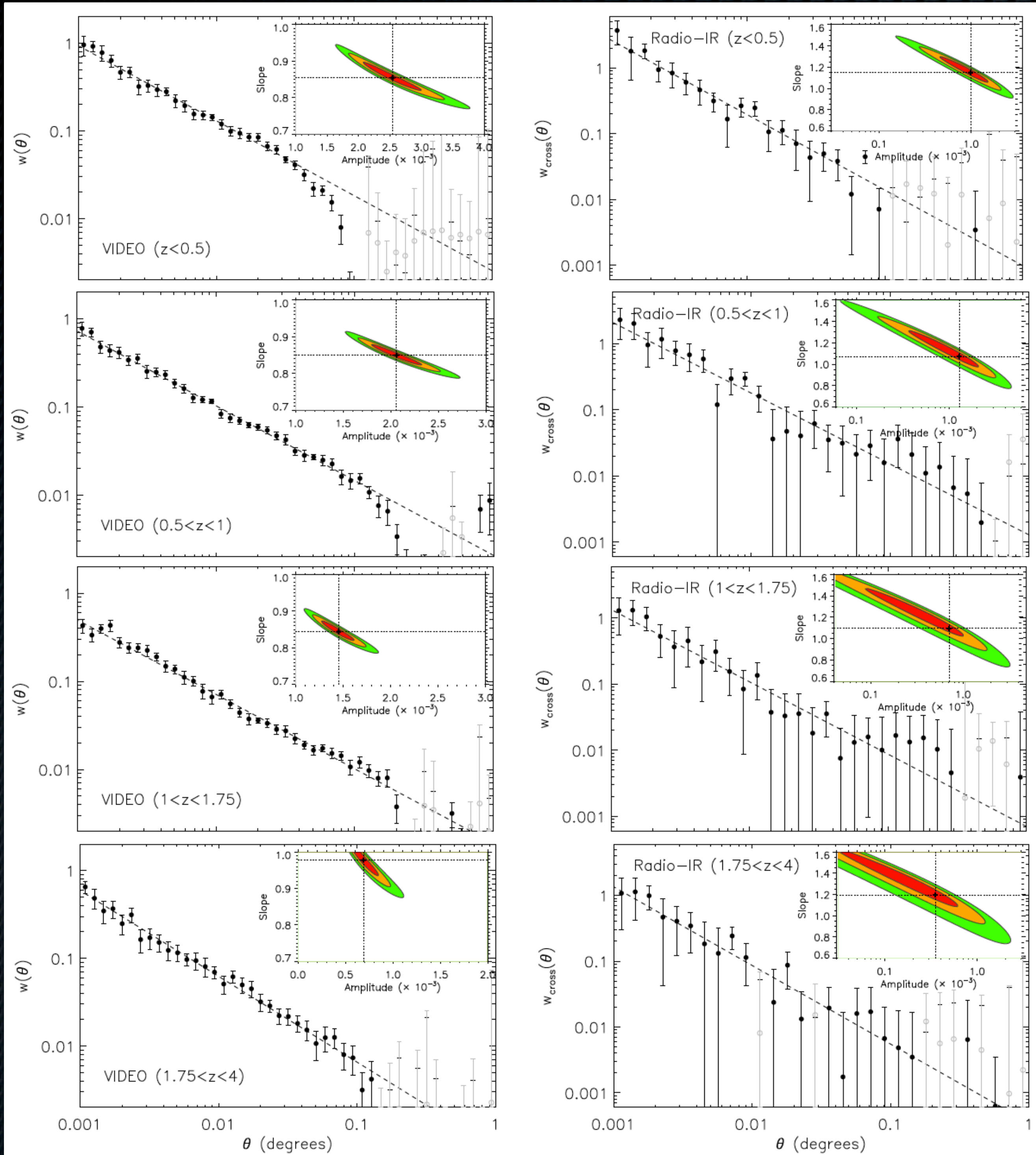
Angular Correlation Function

Auto-correlation function of K_S-selected sources is tightly constrained and well described by a power law function spanning almost two decades in θ.





Cross-correlation function of radio and IR sources describes the relative clustering of the two populations.



z < 0.5

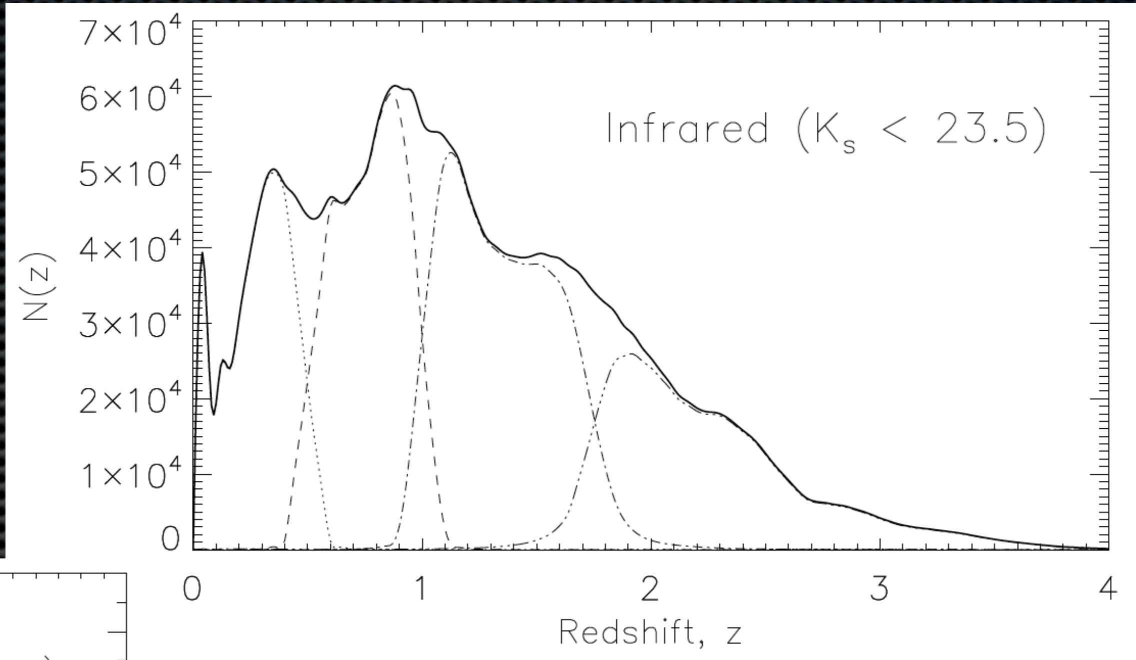
0.5 < z < 1

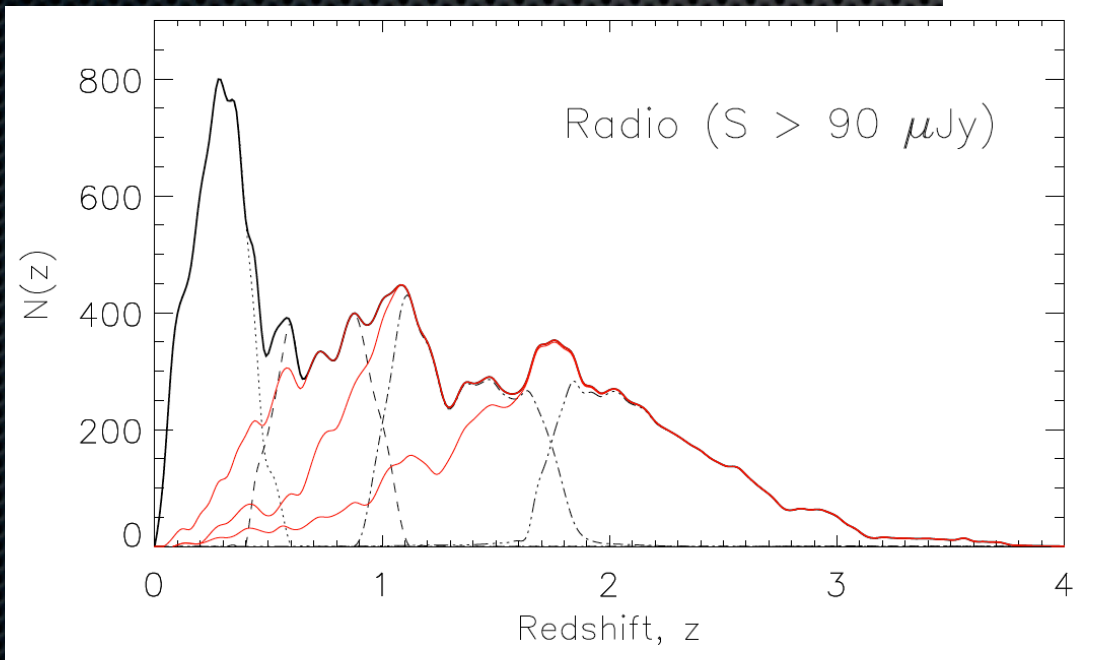
1 < z < 1.75

1.75 < z < 4

Redshift Distributions

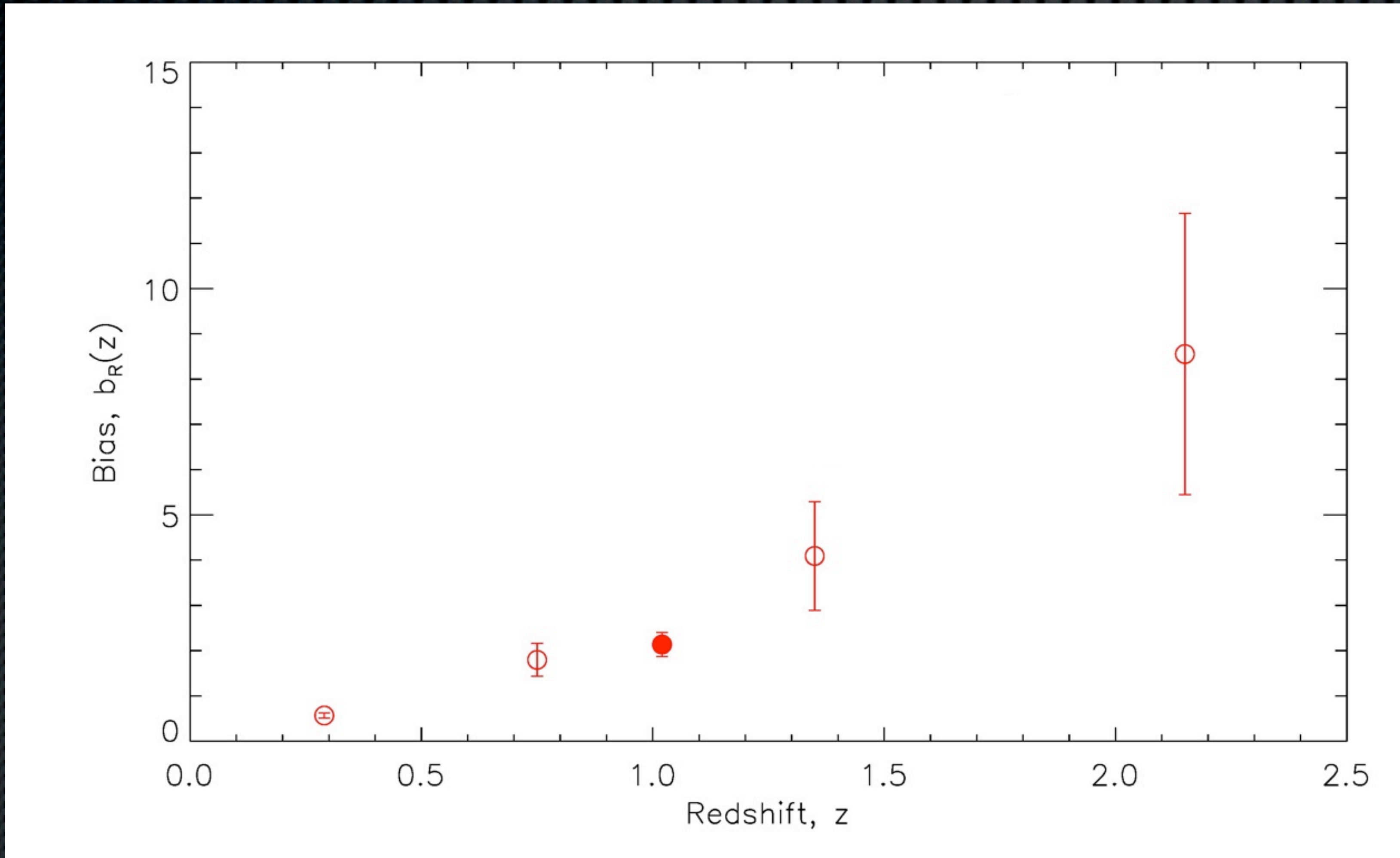
Sources binned by best-fit photometric redshift, but N(z) of neighbouring bins overlap after summing the individual redshift probability functions





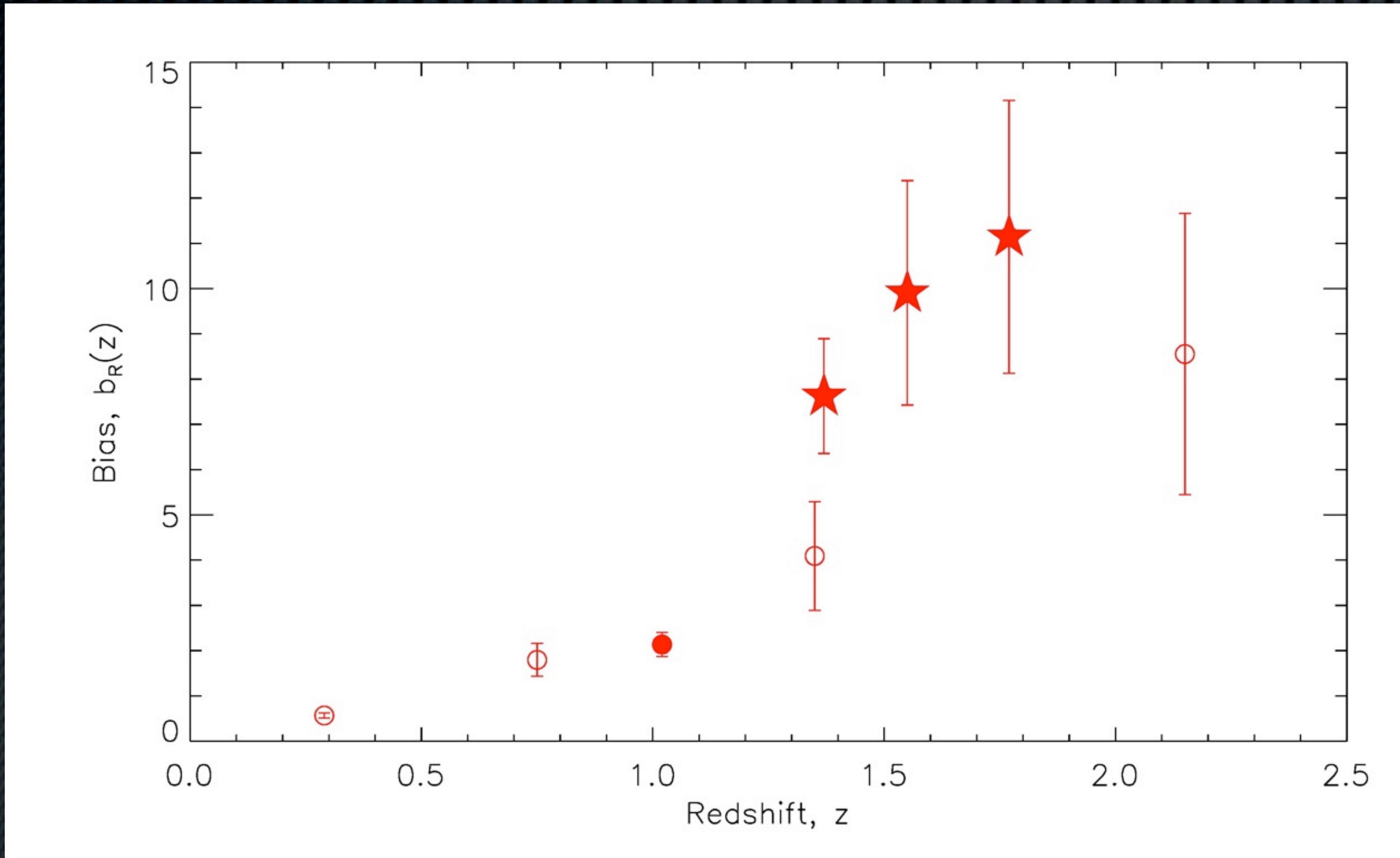
Additionally, select AGN subsamples with **radio luminosity cuts**

Bias at >90 μJy



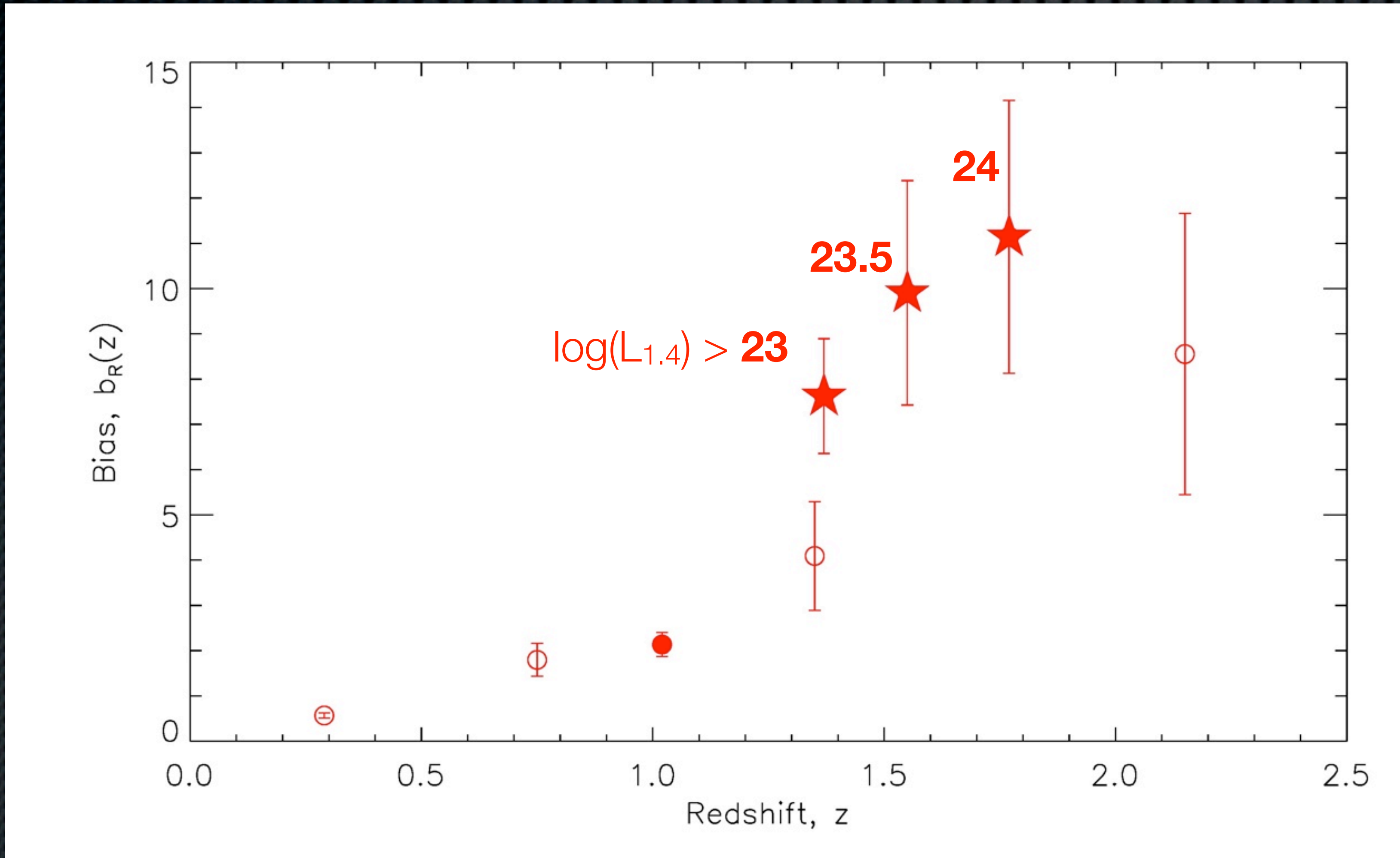
Lindsay, Jarvis & McAlpine, 2014

Bias at >90 μJy



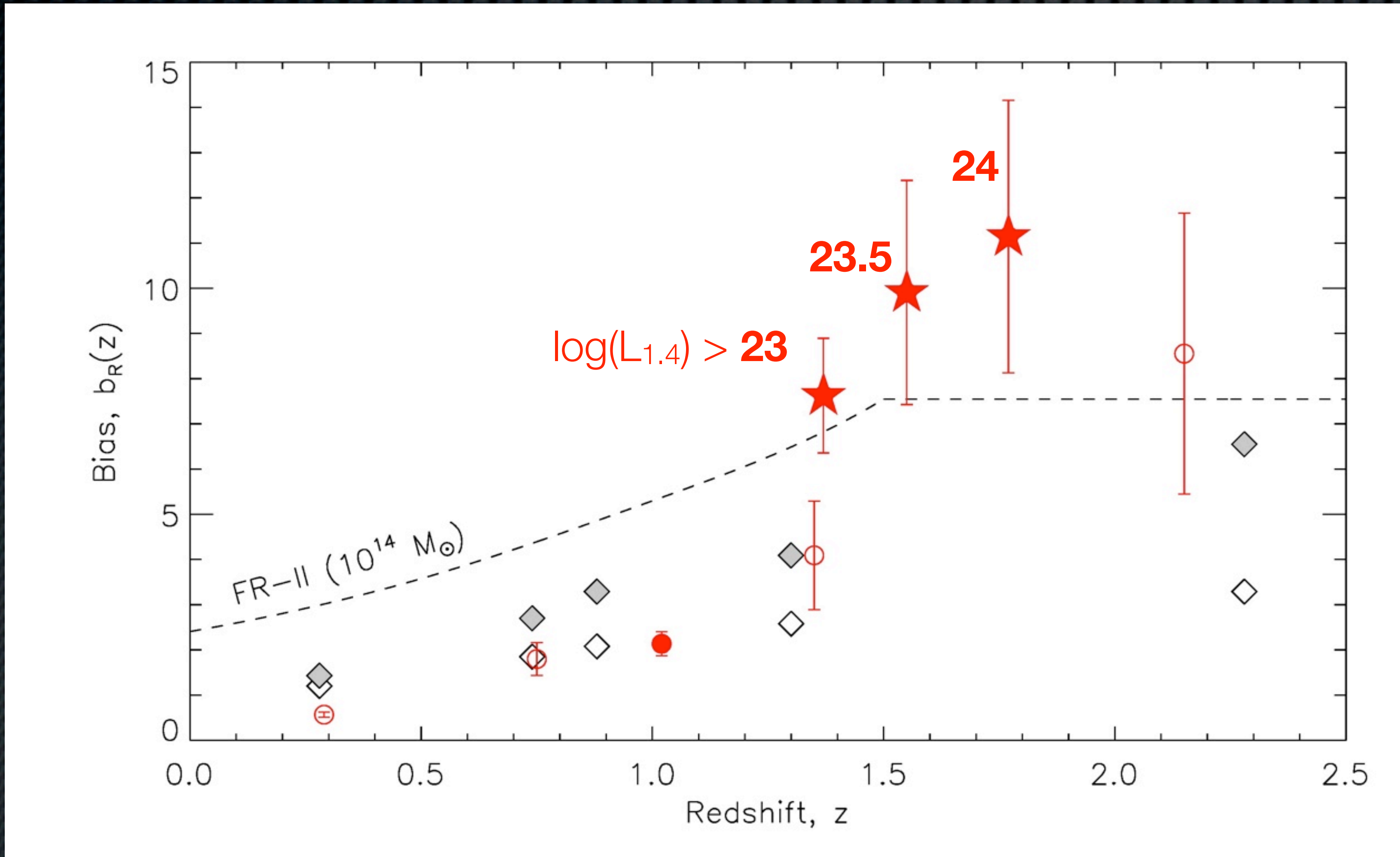
Lindsay, Jarvis & McAlpine, 2014

Bias at >90 μJy



Lindsay, Jarvis & McAlpine, 2014

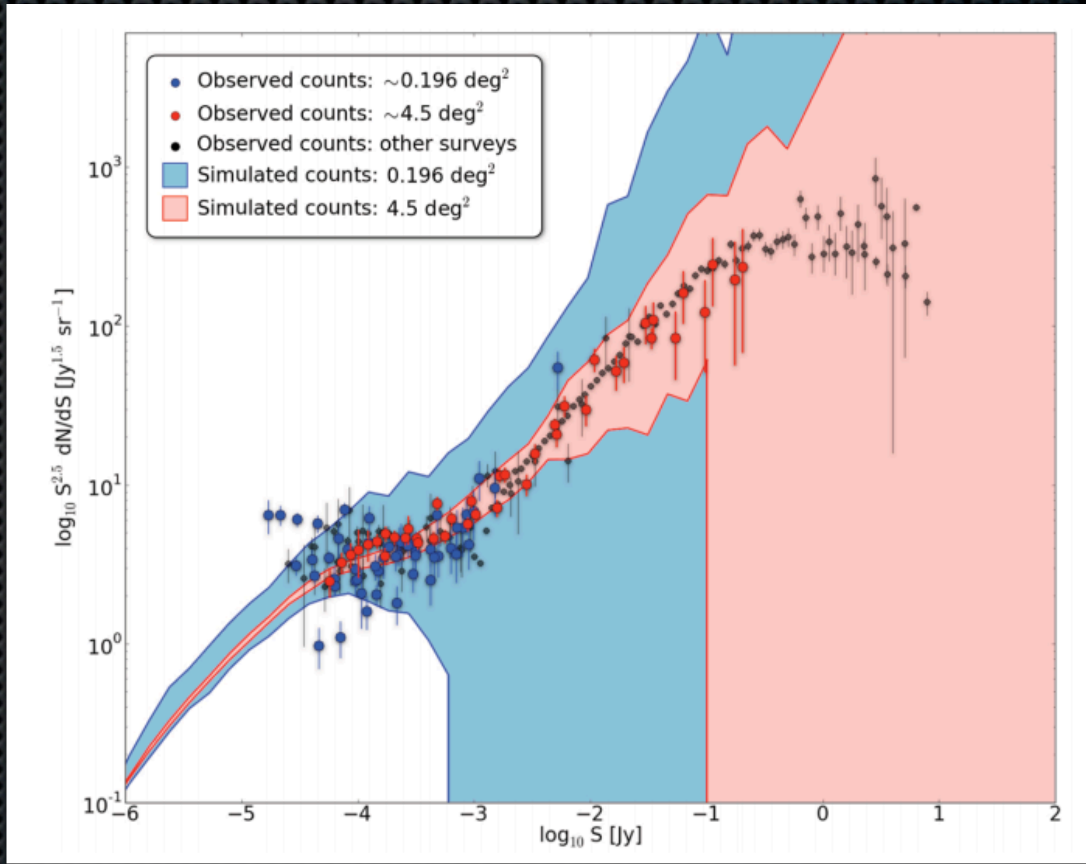
Bias at >90 µJy



Lindsay, Jarvis & McAlpine, 2014

Ongoing Work

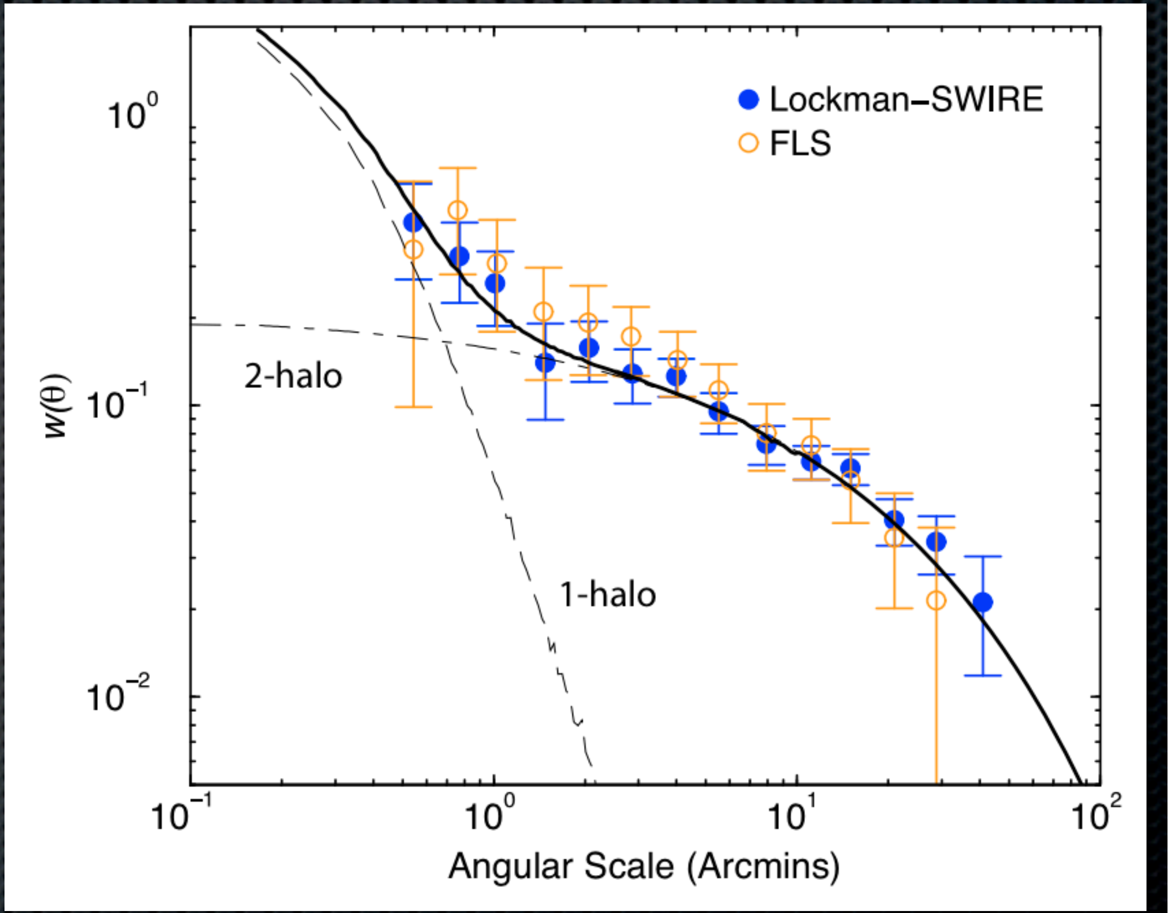
- Use SKADS simulations as a test bed to investigate clustering analyses on various depths and areas, looking for optimal deep survey to beat cosmic variance.
- Can test e.g. 400 x 1 deg^2, 100 x 4 deg^2, 40 x 10 deg^2 areas at flux density limits of e.g. 0.1, 10, 100 μJy flux limits.



Heywood+2013

Ongoing Work

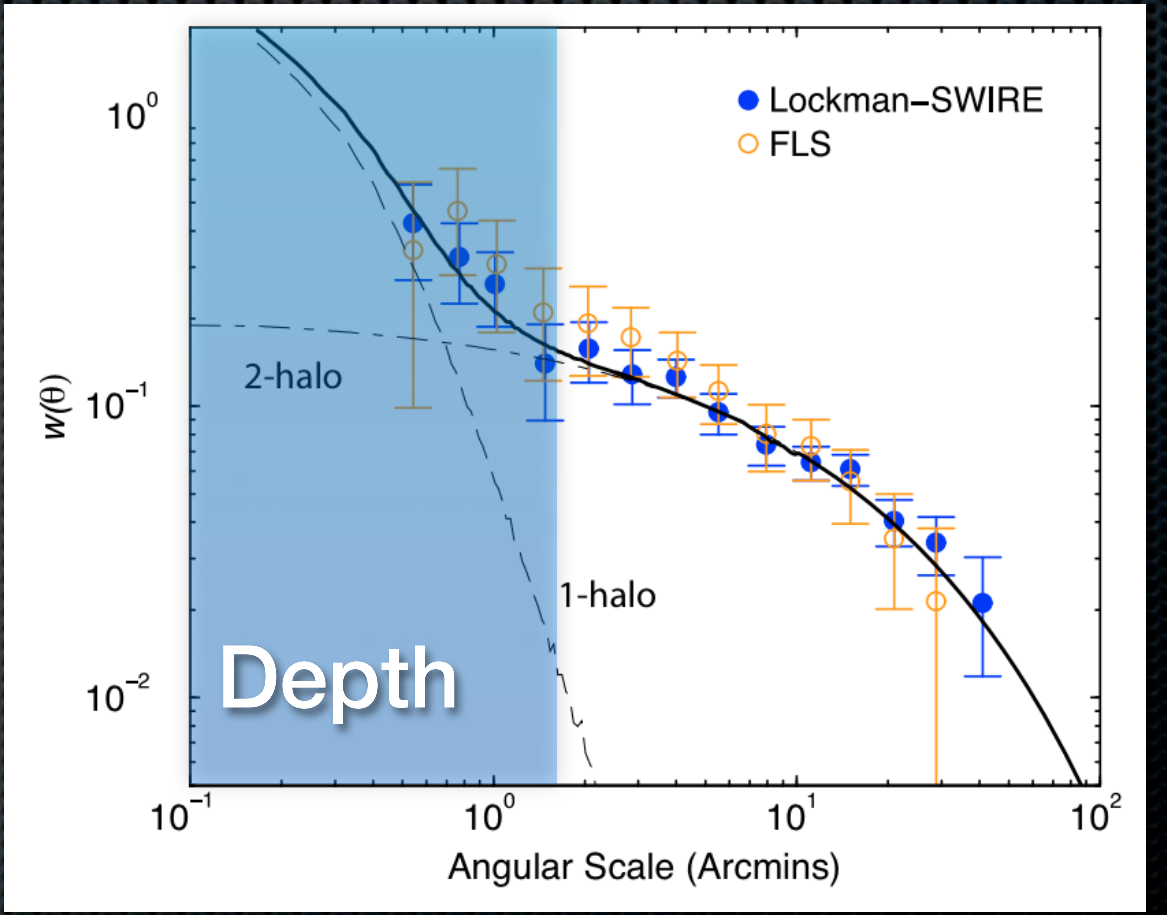
- Full HOD approach, rather than simple power law
  - More physical interpretation of clustering
- Full VIDEO survey (4.5 deg^2) + deeper VLA data (50 μJy)
  - Constrain both 1- and 2-halo terms



Cooray+ 2010

Ongoing Work

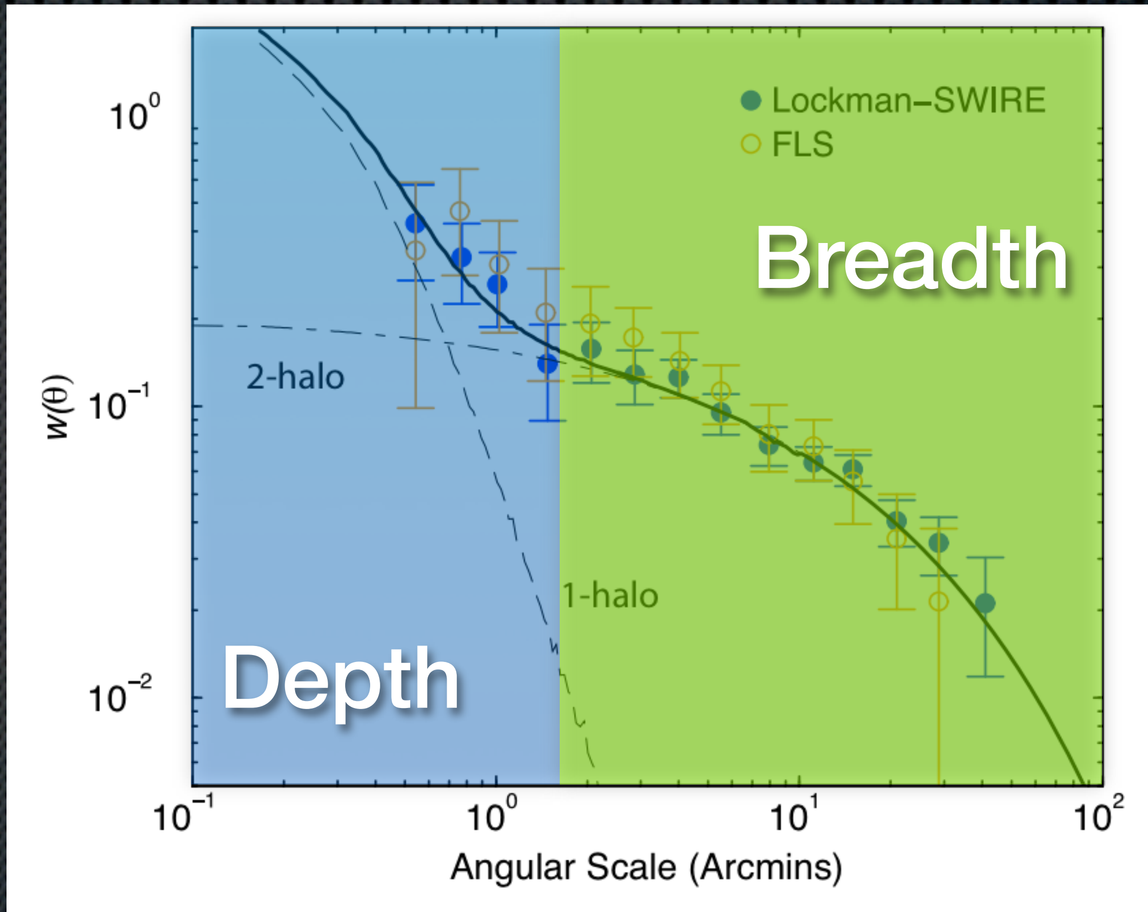
- Full HOD approach, rather than simple power law
  - More physical interpretation of clustering
- Full VIDEO survey (4.5 deg^2) + deeper VLA data (50 μJy)
  - Constrain both 1- and 2-halo terms



Cooray+ 2010

Ongoing Work

- Full HOD approach, rather than simple power law
  - More physical interpretation of clustering
- Full VIDEO survey (4.5 deg^2) + deeper VLA data (50 μJy)
  - Constrain both 1- and 2-halo terms



Cooray+ 2010

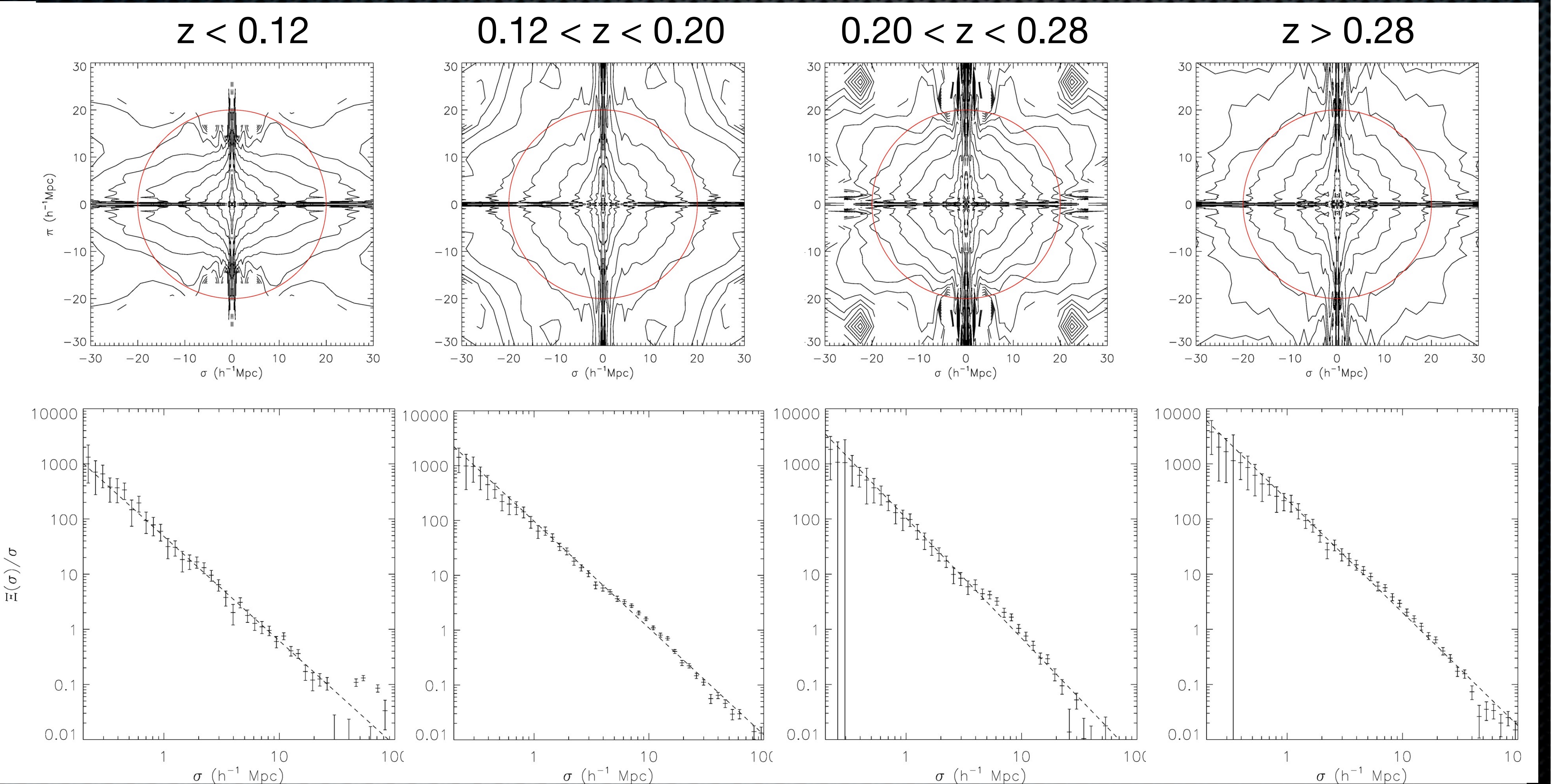
Future Surveys

	FIRST + SDSS/UKIDSS	VVDS + CFHTLS/VIDEO	SKA1 + LSST/Euclid
1.4 GHz flux limit	1 mJy	90 μJy	~1 μJy
Optical/IR mag limits	r~22 (SDSS)* K~18.5 (UKIDSS)	r~25 (CFHTLS-D1) K_s~23.5 (VIDEO)	r~24.7 (LSST) YJH~24 (Euclid)*
Area	~200 deg^2	1 deg^2	~10^5 deg^2
Radio sources with photo-z's	~4,000	~800	Millions!

* Also spec-z contribution from GAMA (r<19.8; z<0.6) and Euclid (0.7<z<2.0).

Ongoing Work

- GAMA cross-correlation: direct spatial clustering of ~1,600 x ~130,000 sources with spectra up to z~0.6



Summary

- Wide, shallow data -> bias at $z<0.6$ ($z\sim1.5$ by using model dN/dz)
  - 2D cross-correlation of GAMA radio/non-radio sources can improve estimates at low-z (in prep)
- Narrow, deep data -> bias out to $z>2$ due to photo-z's to z~4 and high S/N from cross-correlation
  - More up-to-date halo modelling approach should make our conclusions more robust
- Combination of depth and area of current and next generation of surveys brings the statistics to pin down finer bias evolution, feeding into direct cosmological probes.
- Working on cosmic variance; matching samples by stellar mass, colour, etc.; better low-z evolution with spec-z's; and better simulations.