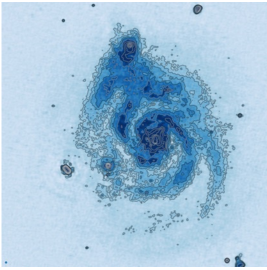
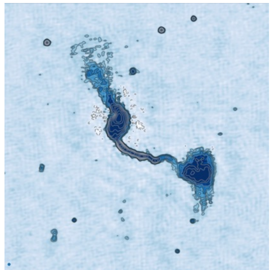
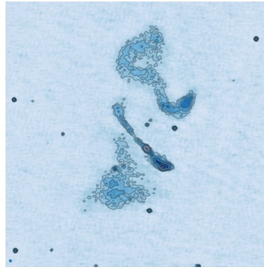
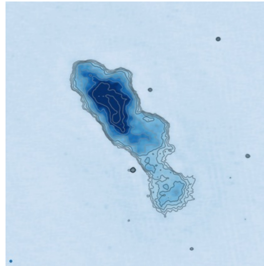
Images from Shimwell+ 2019

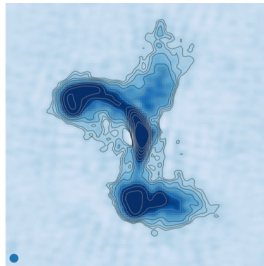


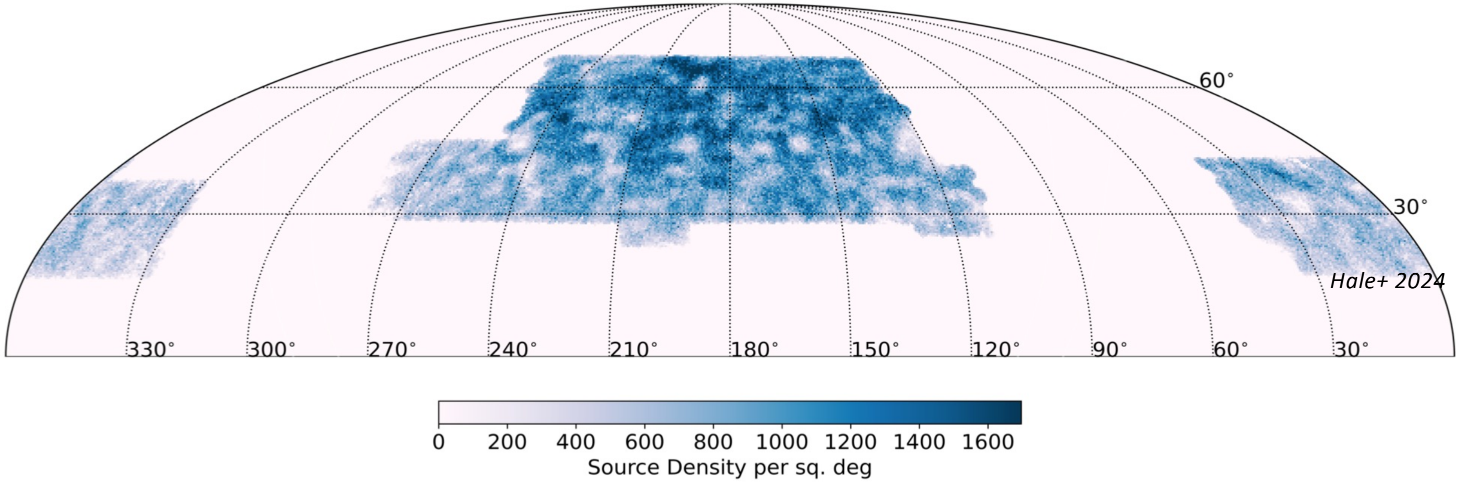


Cosmological Studies with the LOFAR Two-metre Sky Surveys









Catherine Hale

University of Oxford

*On behalf of members in the LOFAR Surveys Cosmology Team**

**Notably:*
S. Nakoneczny,
L. Böhme,
J. Zheng,
M. Pashapour-Ahmadabadi

THE UNIVERSITY of EDINBURGH

LEVERHULME TRUST

UNIVERSITY OF OXFORD

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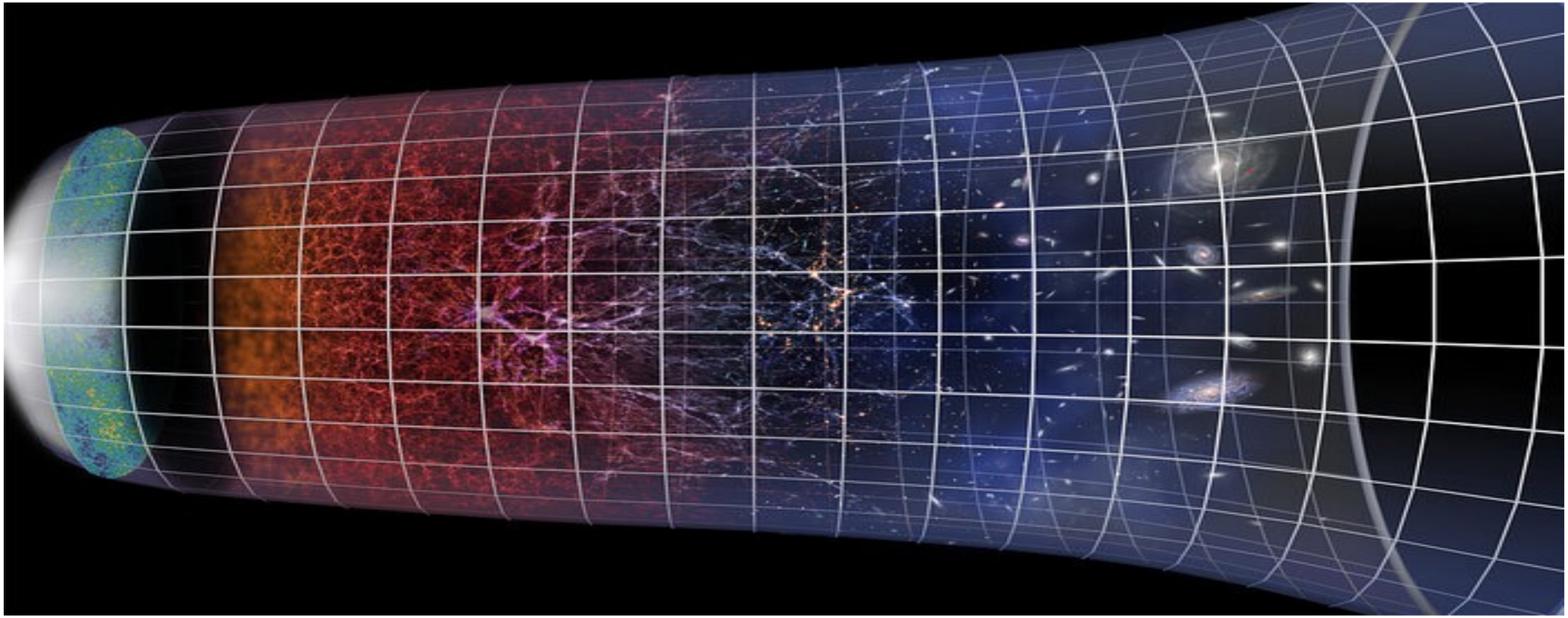
LOFAR Family Meeting, Leiden 2024

Overview

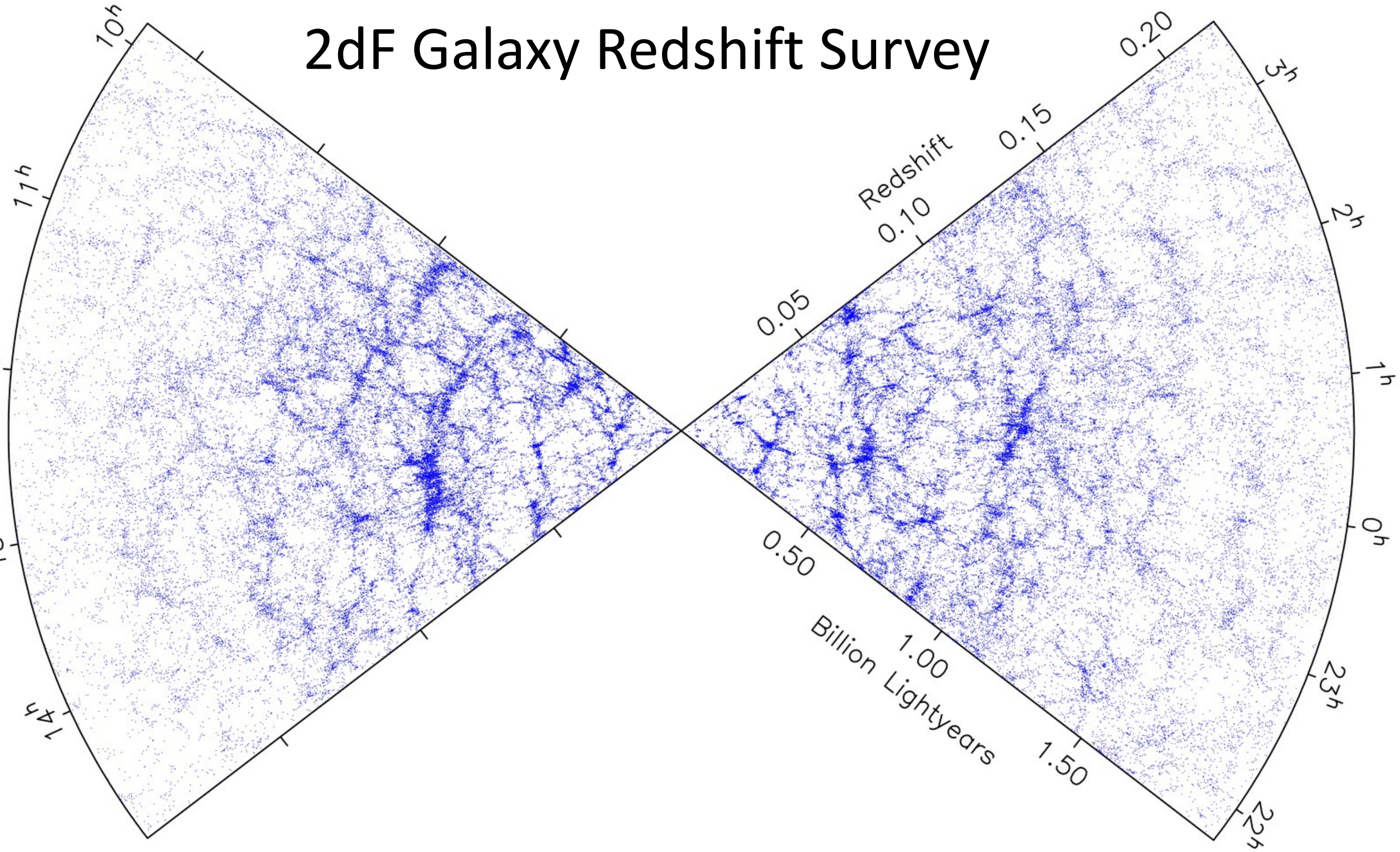
- Tracing Large Scale Structure with galaxy surveys
- LOFAR surveys: Systematics and observational biases
- Cosmology with LoTSS-DR2:
  - Angular Clustering (*Hale et. al 2024*)
  - One-Point statistics (Pashapour-Ahmadabadi et al. in prep)
  - Cosmic Dipole (Böhme et al. in prep)
  - Cross-Correlation with CMB (Nakoneczny et al. 2024) and eBOSS (Zheng et al. in prep)
  - Flux dependent Clustering (Bhardwaj+ in press)
- Bias evolution of AGN and SFGs in the LOFAR Deep Fields
  - *Hale et al. in prep*
- Future for cosmology studies with LOFAR

Tracing Large Scale Structure with galaxy surveys



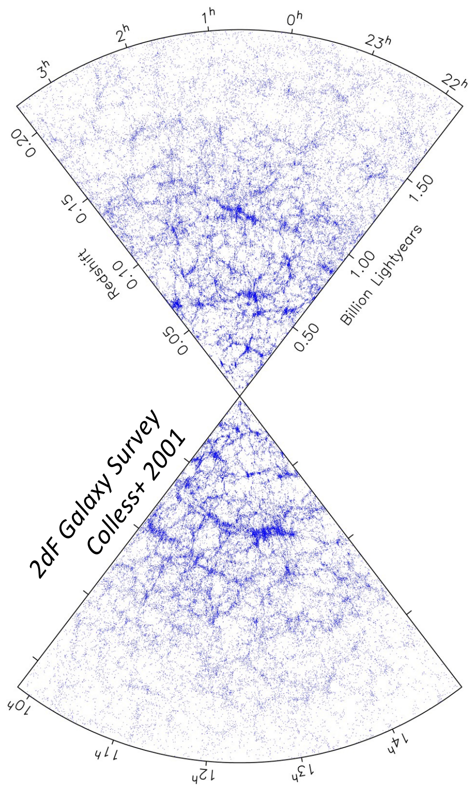
Credit: ESO/M. Kornmesser

Large-Scale Structure of the Universe



2dF Galaxy Survey; Colless+ 2001

Tracing Large Scale Structure with galaxy surveys



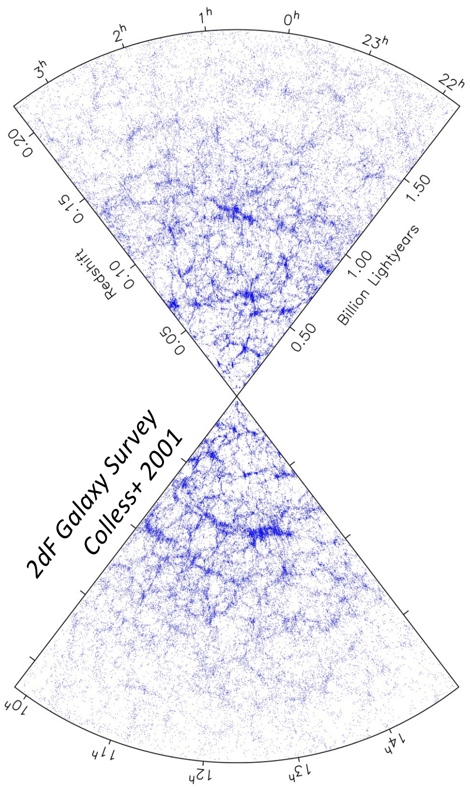
Large **spectroscopic surveys** provide an **excellent opportunity** to trace the **large-scale structure** of the Universe
See e.g. 2dFGS (Colless+ 2001), SDSS (York+ 2000), GAMA (Driver+ 2011)

Using accurate redshifts allows **precise observation** of the **location** of galaxies and to **observe clusters, filaments and voids**

One way to quantify the large-scale structure is by tracing **how clustered** galaxies appear in the survey at **different scales** compared to if there was no large-scale structure

This can be quantified by the **two-point correlation function**
See e.g. Hauser & Peebles 1980, Peebles+ 1980, Davis & Peebles 1983

Tracing Large Scale Structure with galaxy surveys



See e.g. Peebles+ 1980

Two-Point Correlation Function

$$dP = n[1 + \xi(r)]dV$$

Probability to observe galaxy pairs at a given separation

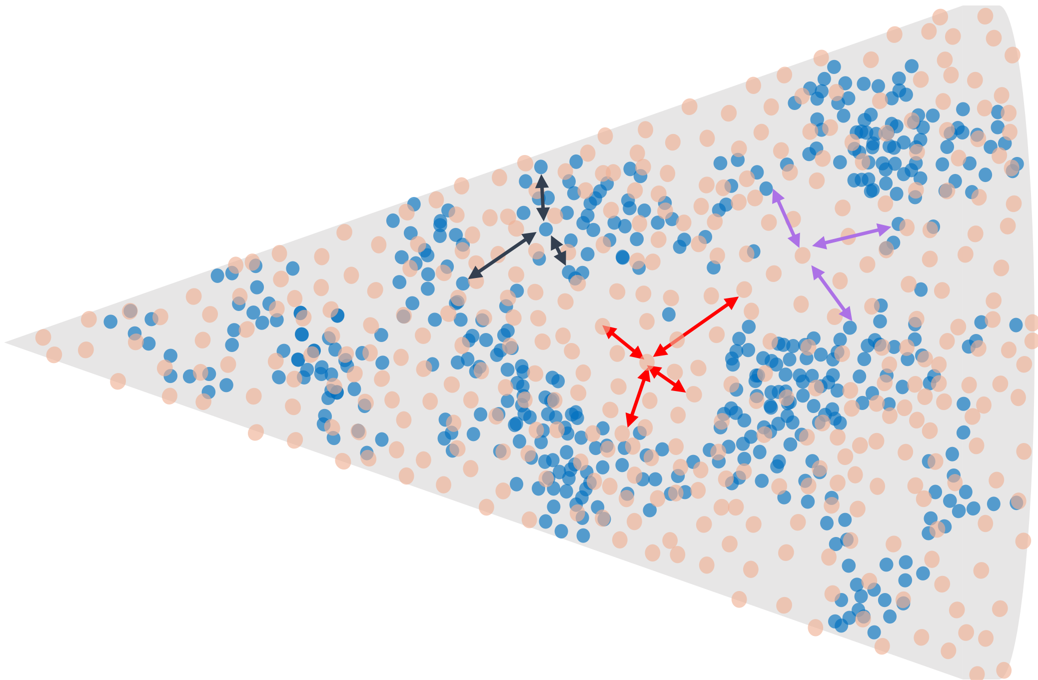
Mean number density

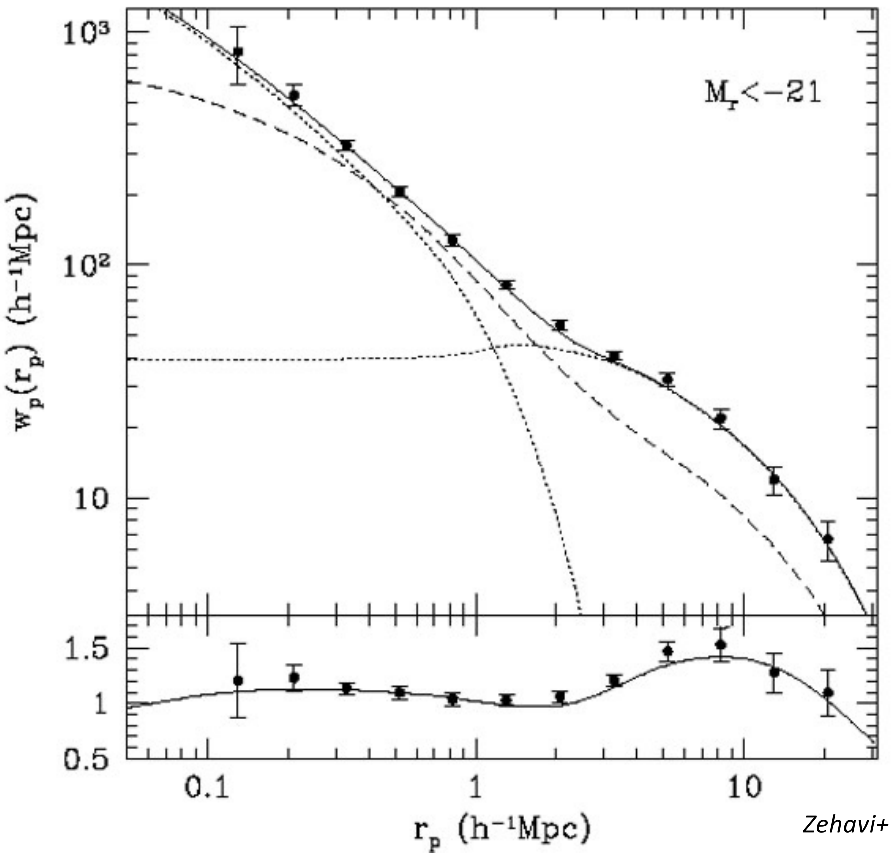
Spatial two-point correlation function

Volume element

If we measure $\xi(r)$ then we quantify the excess probability to observe galaxies at a given separation.

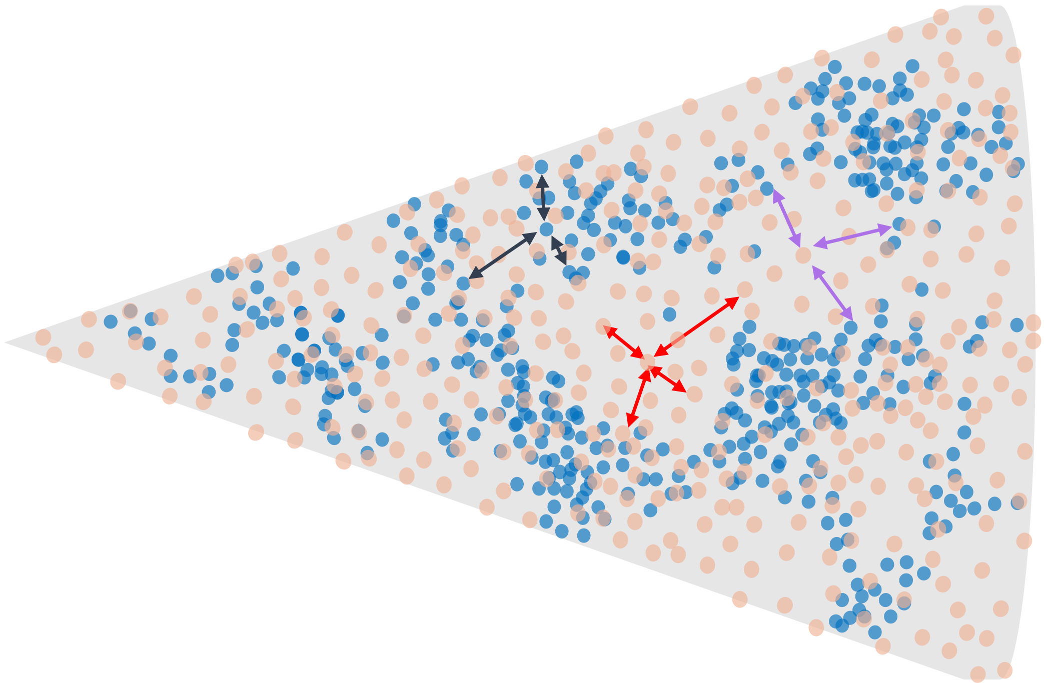
Large-Scale structure of the Universe

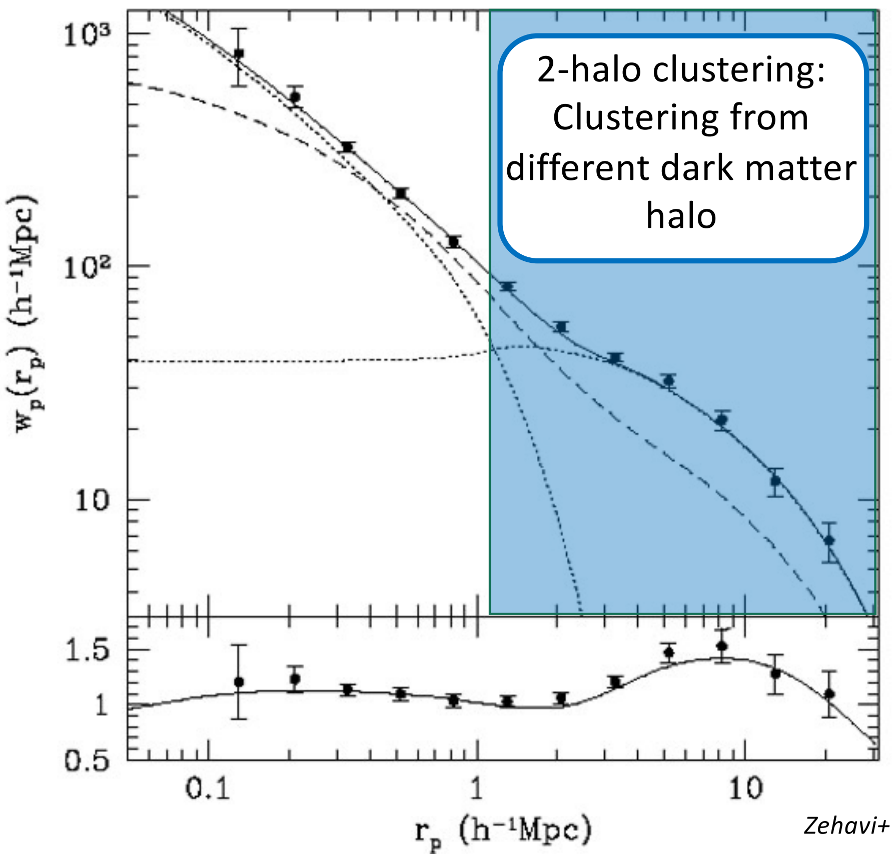




Zehavi+ 2004

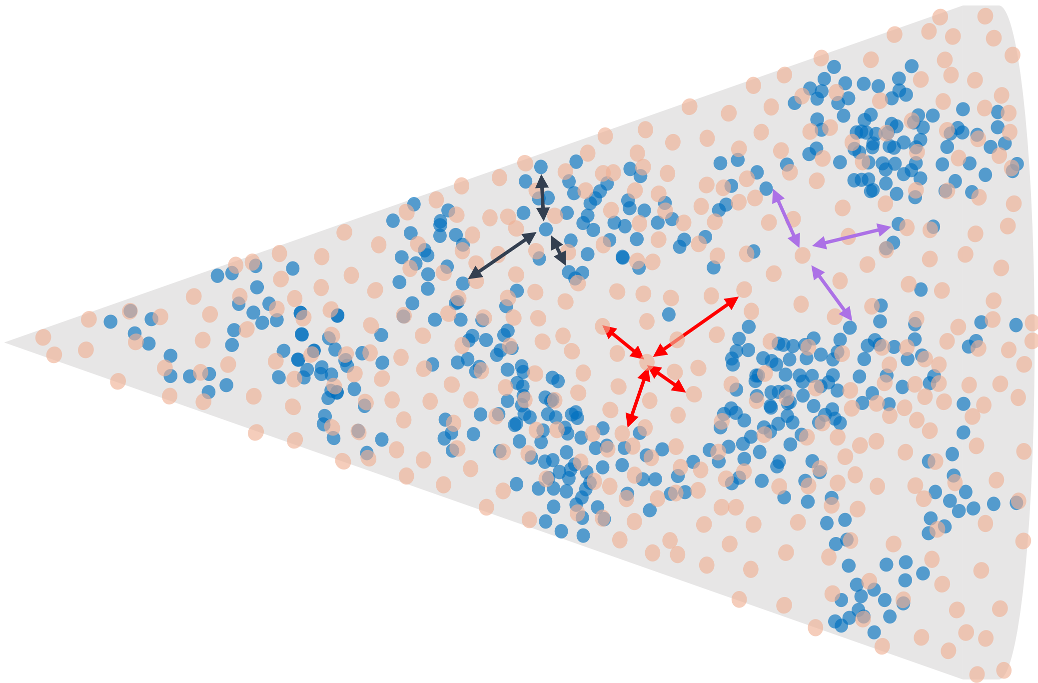
Large-Scale structure of the Universe

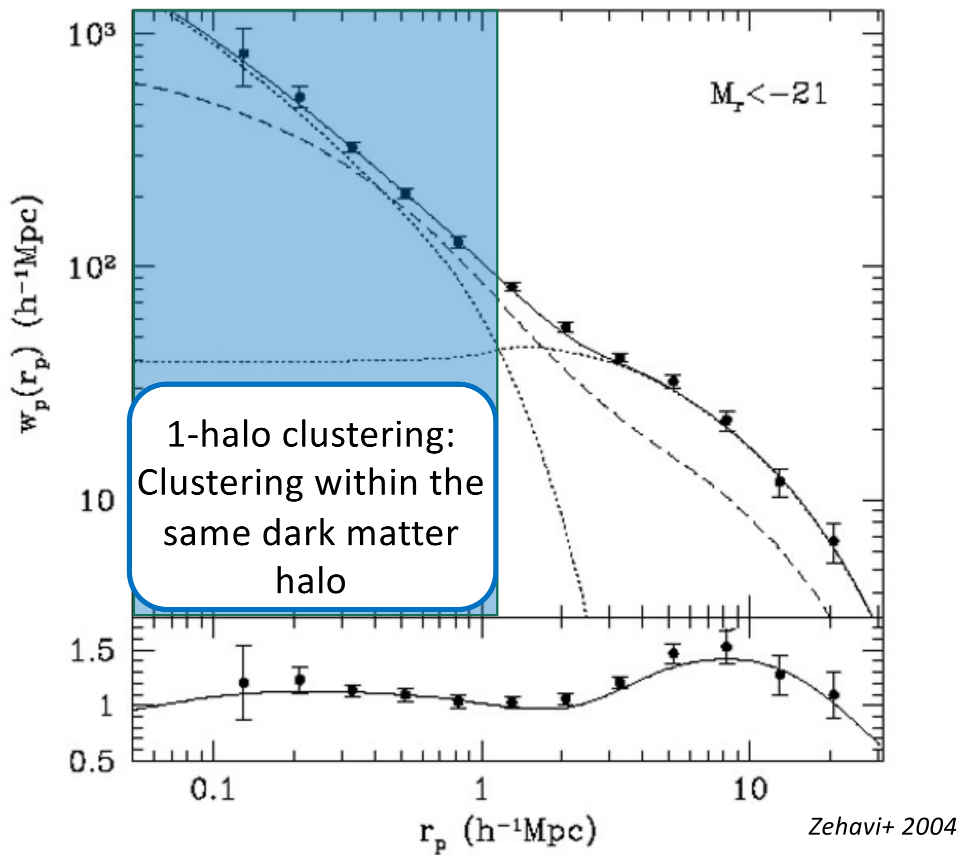




Zehavi+ 2004

Large-Scale structure of the Universe





Zehavi+ 2004

Large-Scale structure of the Universe

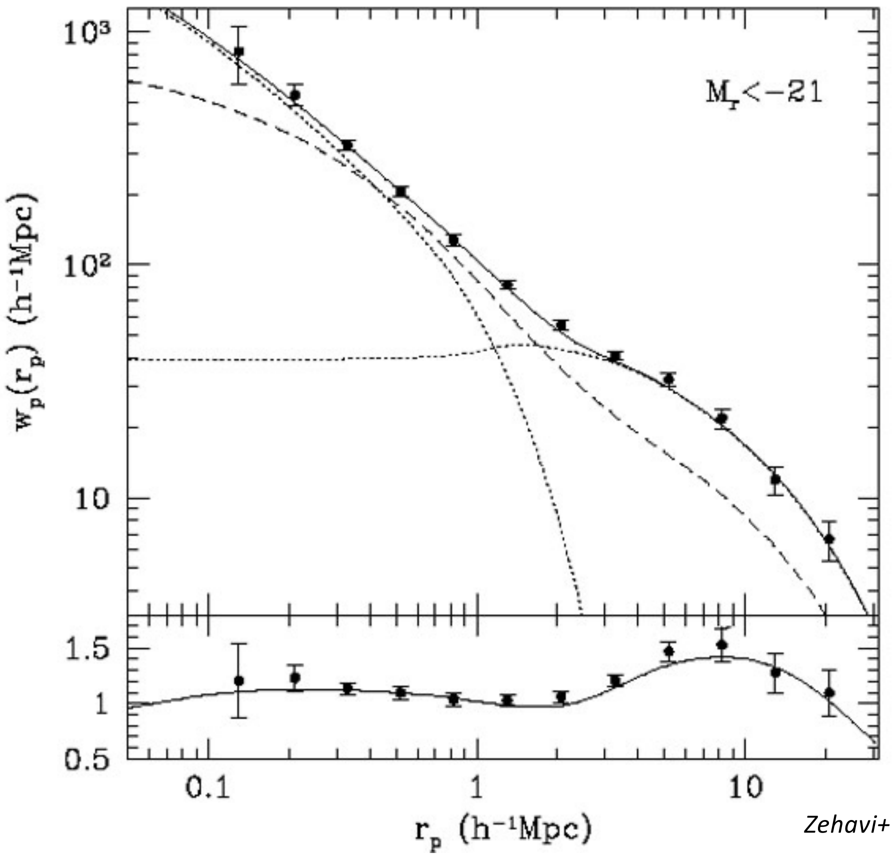
- Galaxies form in **dark matter haloes** and are "**biased**" tracers of the underlying matter (Kaiser+ 1984)

- Can quantify **galaxy bias** by looking at **two-point correlation function** of galaxies and compare to that for the **underlying matter**

Galaxy bias, $b_g = \frac{\delta_g}{\delta_M} = \sqrt{\frac{\xi_g}{\xi_M}}$

Ratio of mean mass density of galaxies c.f. underlying dark matter field

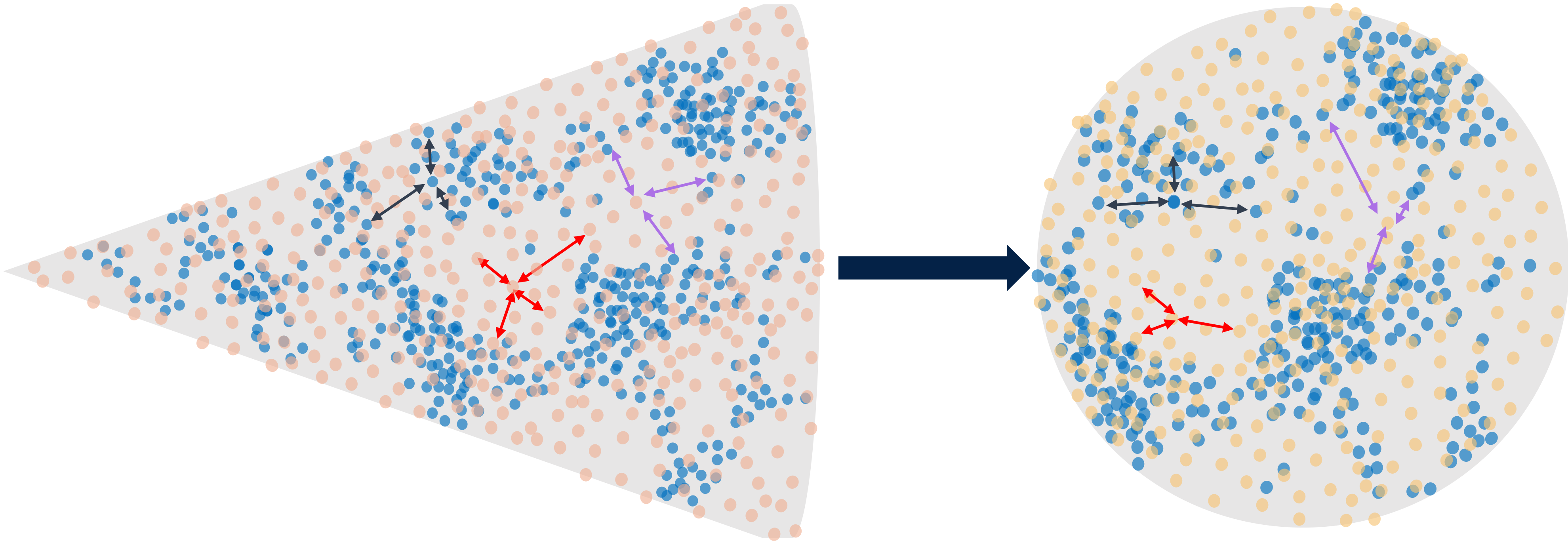
Relates to spatial clustering of galaxies



Zehavi+ 2004

But radio continuum surveys can’t provide redshifts, so we typically rely on photometric redshifts from multi-wavelength catalogues and measure the angular clustering

Angular Clustering

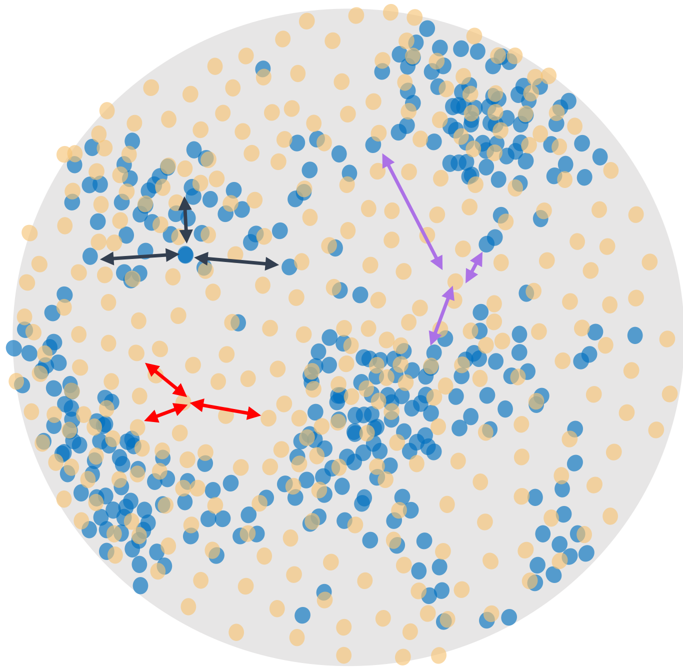


Angular Clustering

To calculate this we use:

$$\omega(\theta) = \frac{DD(\theta) + RR(\theta) - 2DR(\theta)}{RR(\theta)}$$

Landy & Szalay 1993



Normalised pairs of galaxies in the data (randoms or data-to-randoms) in an angular separation

To link angular clustering to galaxy bias we need to know redshift distribution and can use this to de-project the clustering.

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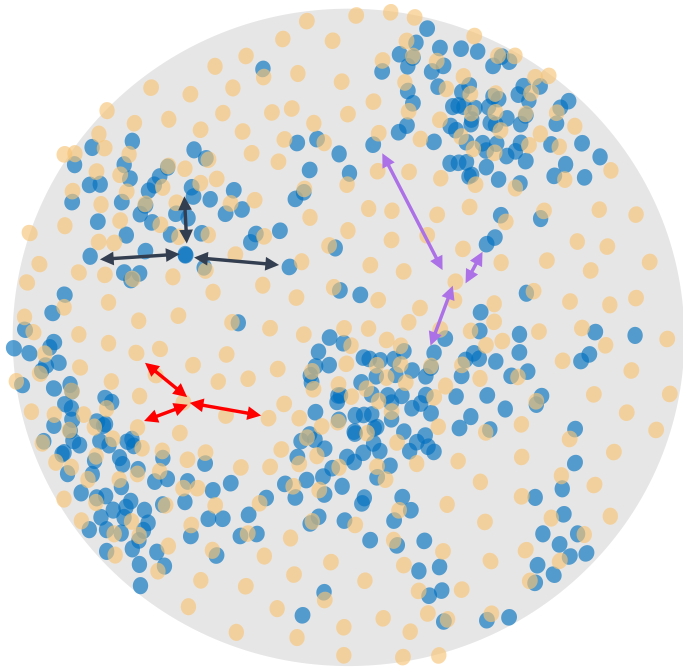
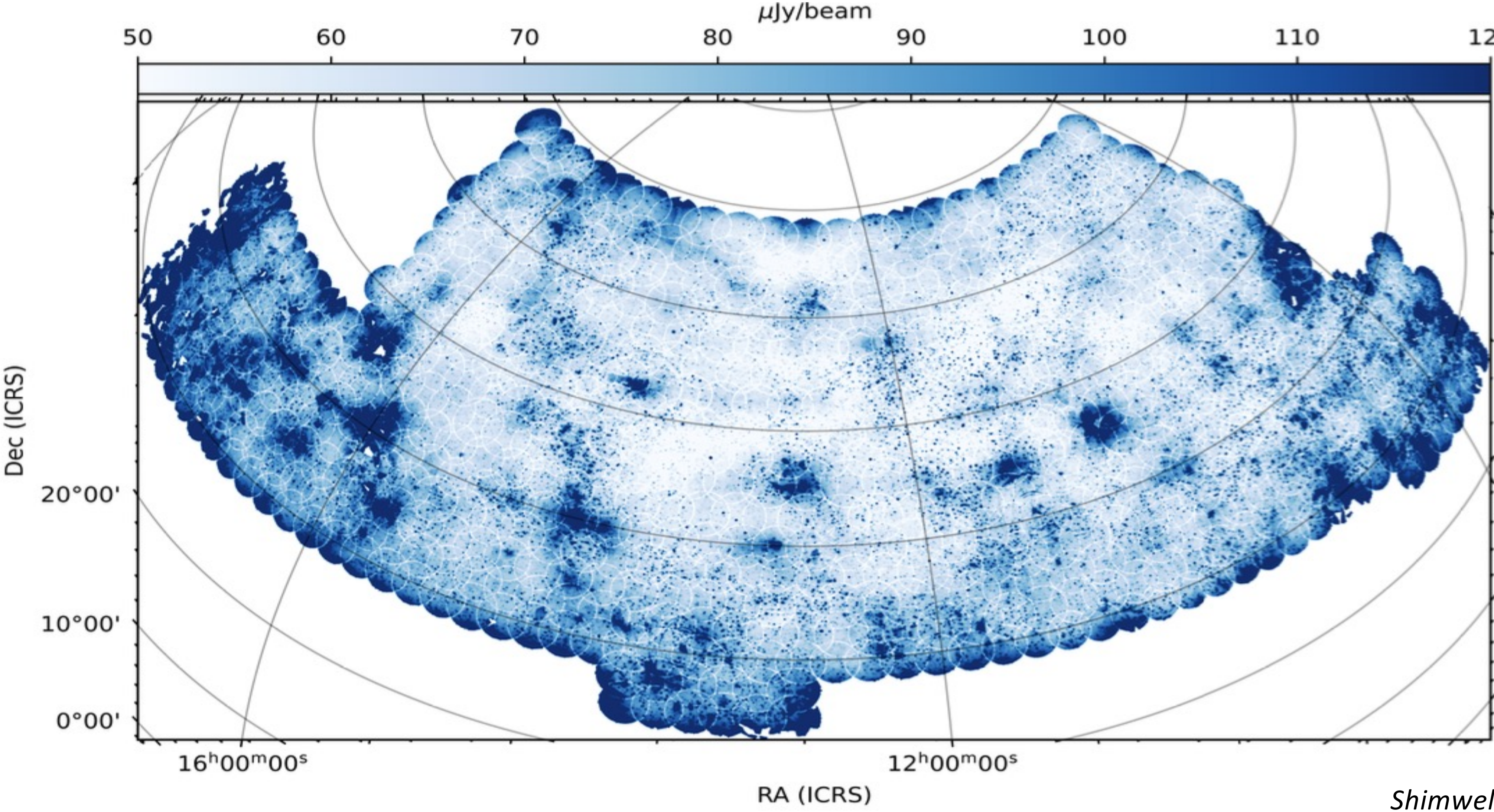


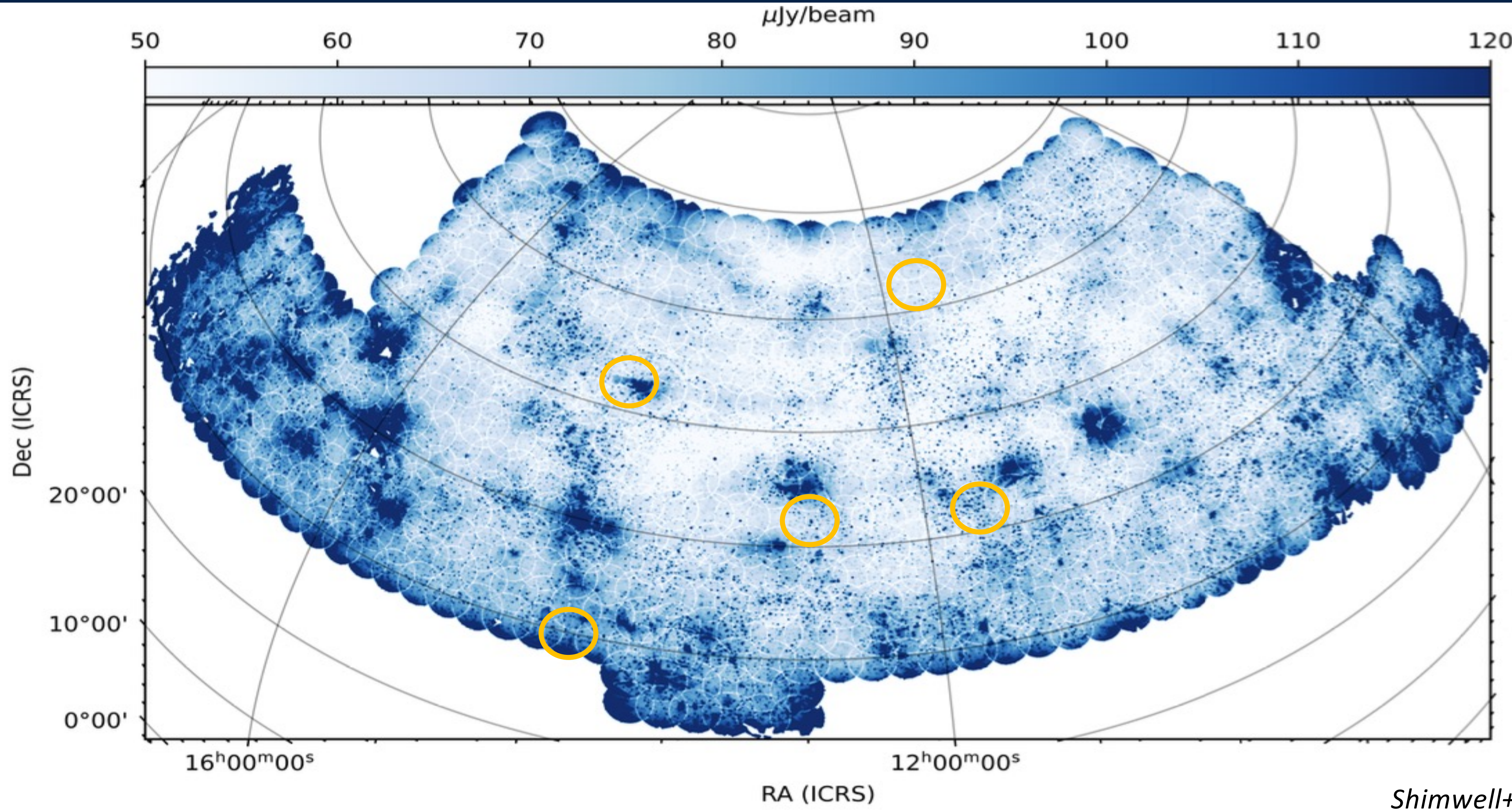
Normalised pairs of galaxies in the data (randoms or data-to-randoms) in an angular separation

To link angular clustering to galaxy bias we need to know redshift distribution and can use this to de-project the clustering.

Creating accurate random catalogues are crucial to this work!



Shimwell+ 2022



Shimwell+ 2022

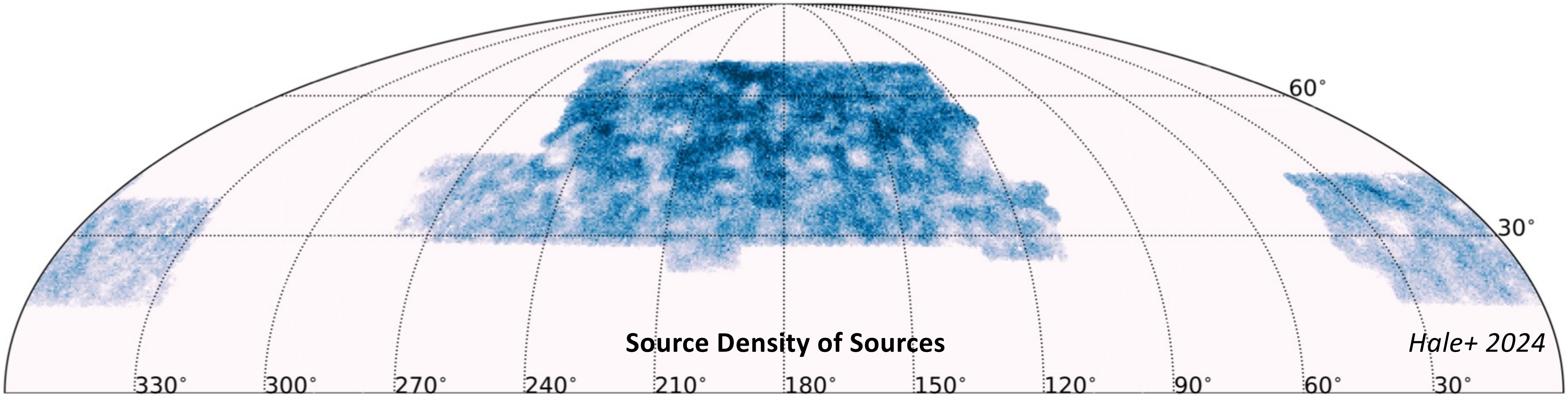
LOFAR Two-metre Sky Survey (LoTSS) Wide Area

Data Release 2 (Shimwell+ 2022):

- 5600 sq. degrees
- ~4 million sources
- ~70-100uJy/beam rms

Distribution of sources are very non-Uniform due to a combination of observational factors
e.g. loss of sensitivity with elevation, bright sources, mosaicking effects.

Need to account for such observational biases in the generation of random catalogues



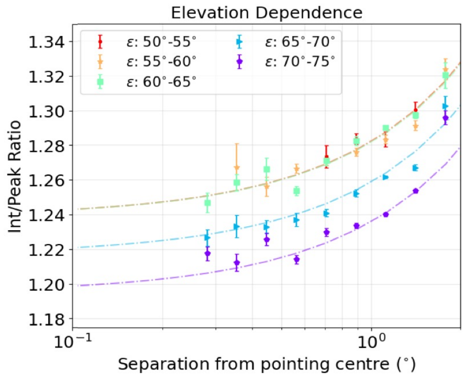
Source Density of Sources

Hale+ 2024

Systematics to Account For

Take **simulated** catalogues of radio sources and account for:

Smearing



Use comparisons with **FIRST** (Helfand+ 2015) to account for **smearing** in the sources as a function of **elevation**

Hale+ 2024

Systematics to Account For

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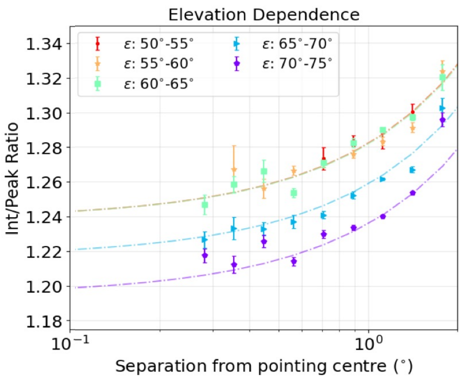
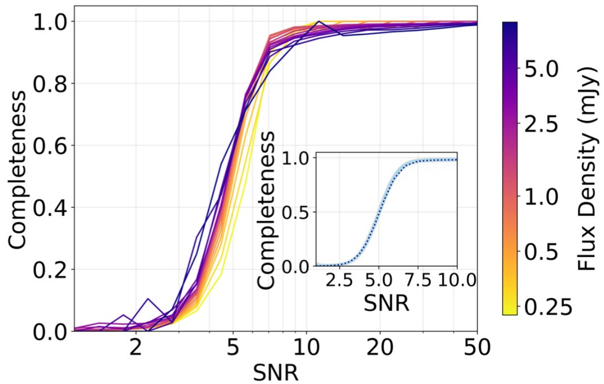
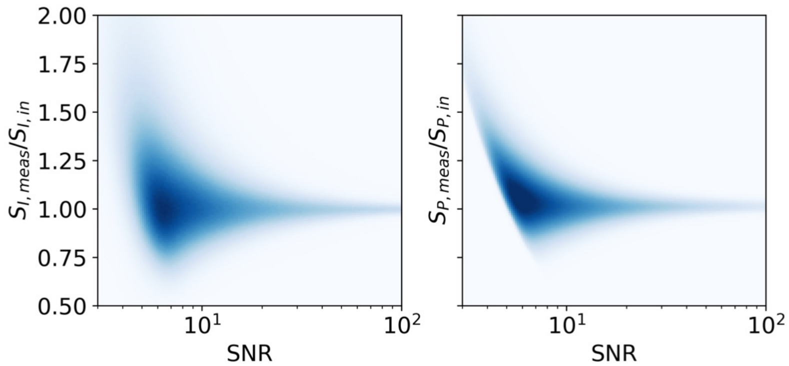


Incompleteness



Measurement Errors



Use comparisons with **FIRST** (Helfand+ 2015) to account for **smearing** in the sources as a function of **elevation**

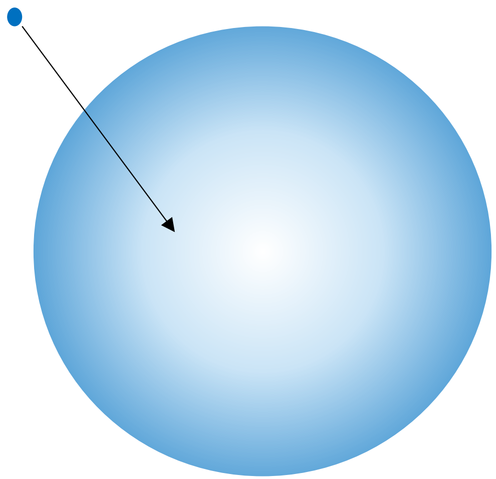
Use **simulations** from **Shimwell+ 2022** to investigate:
- **Incompleteness** (as a function of SNR)
- Differences between **simulated** and **measured** flux densities

Hale+ 2024

Generation of Randoms

1) **Simulated** radio source

- Integrated and peak **flux density** from Wilman+ 2008
- Assign **random position** in the DR2 area
- Obtain **rms** from **map**



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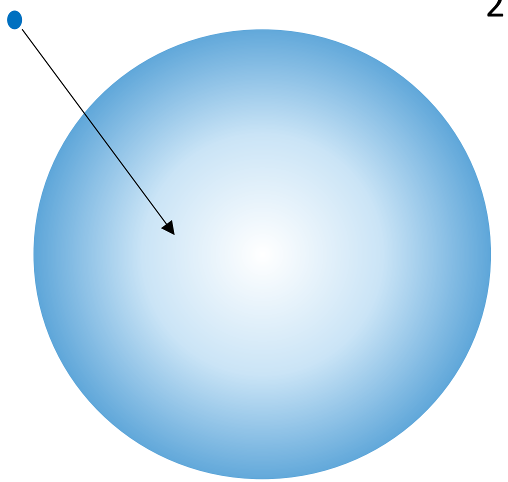

2) Apply **systematics**

- Use **smearing** vs **elevation** to determine the peak flux density of the source
- Use this to obtain a **SNR** of the source
- Measure the **completeness** and sample to determine if the source is **detected**
- For detected sources determine the **measured** integrated and peak **flux densities**

Generation of Randoms

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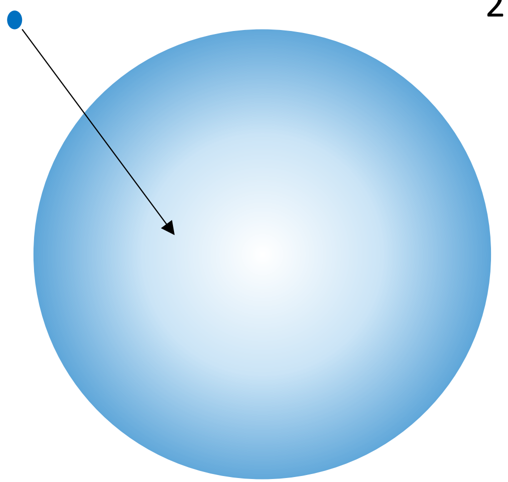

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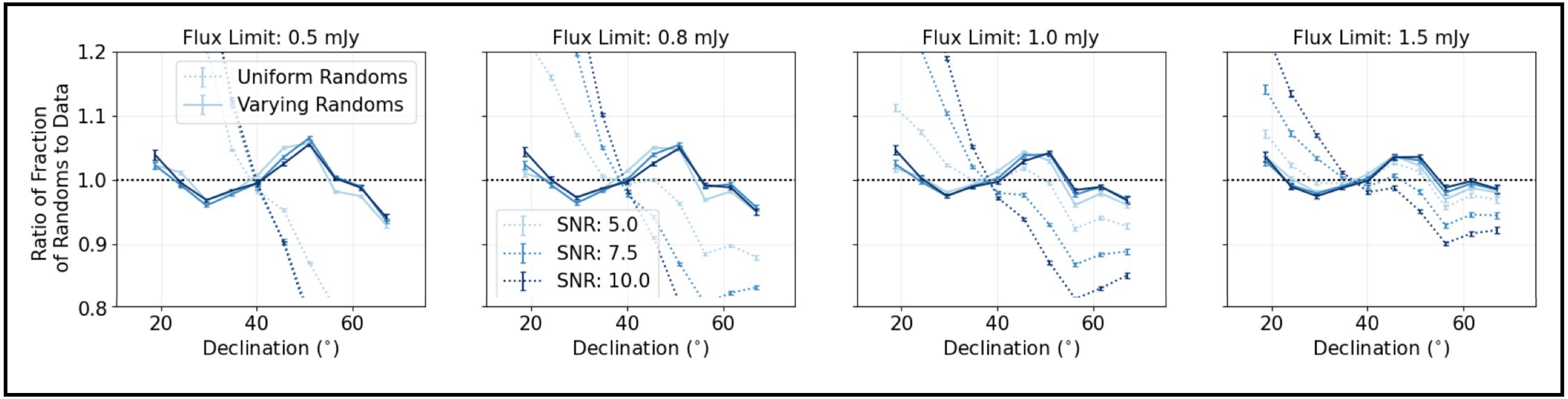
- Measure the **completeness** and sample to determine if the source is **detected**
- For detected sources determine the **measured** integrated and peak **flux densities**

3) Apply **additional** cuts

- Apply additional **SNR** and flux density cuts on the **measured properties** and the data

Simulated Random Catalogues

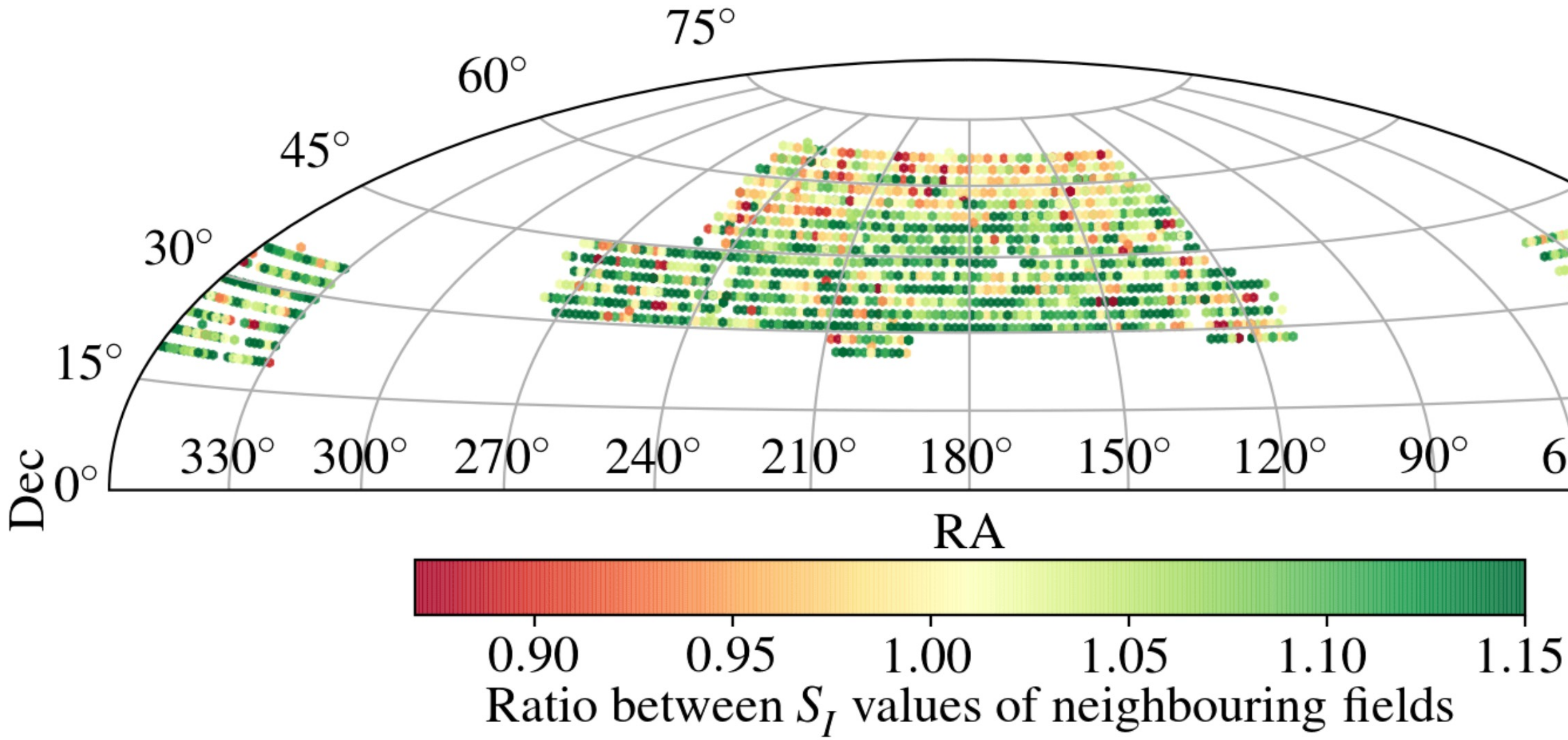


Dotted lines = Random sources uniformly distributed (i.e. not accounting for systematics)

Solid lines = Random sources accounting for systematics

Hale+ 2024

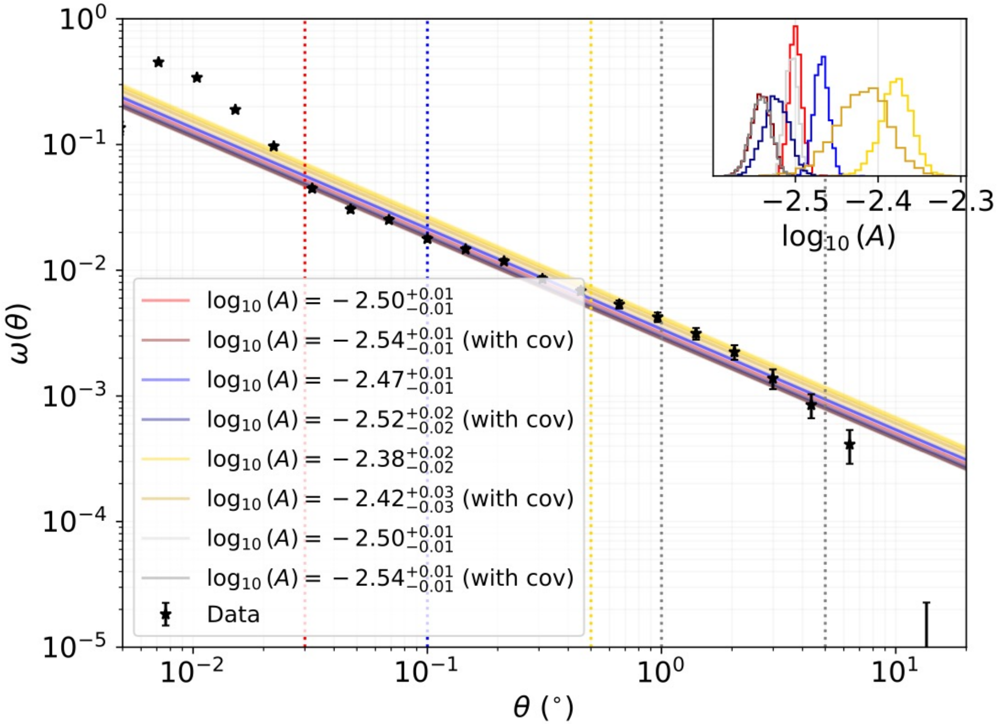
Flux Density Scale



Shimwell+ 2022

Cosmology Studies with LoTSS-DR2

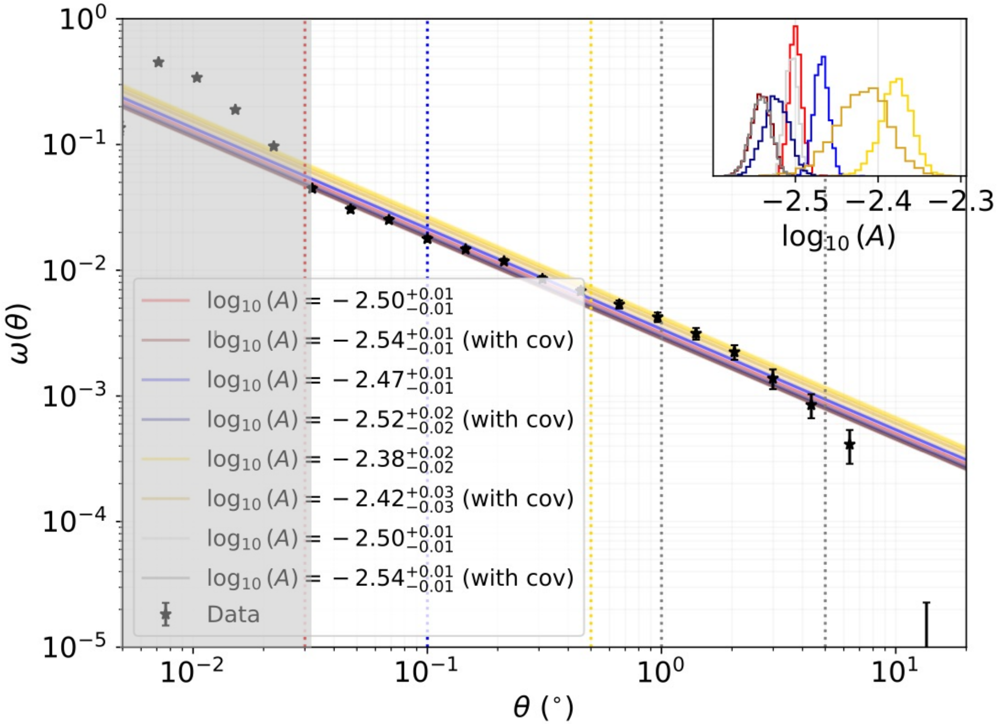
Angular Two-Point Correlation Function (Hale+ 2024)



$\geq$ 1.5 mJy, $\geq 7.5\sigma$

Hale+ 2024

Angular Two-Point Correlation Function (Hale+ 2024)



$\geq$ 1.5 mJy, $\geq 7.5\sigma$

At the smallest angular scales there is an uptick in the angular two-point correlation function

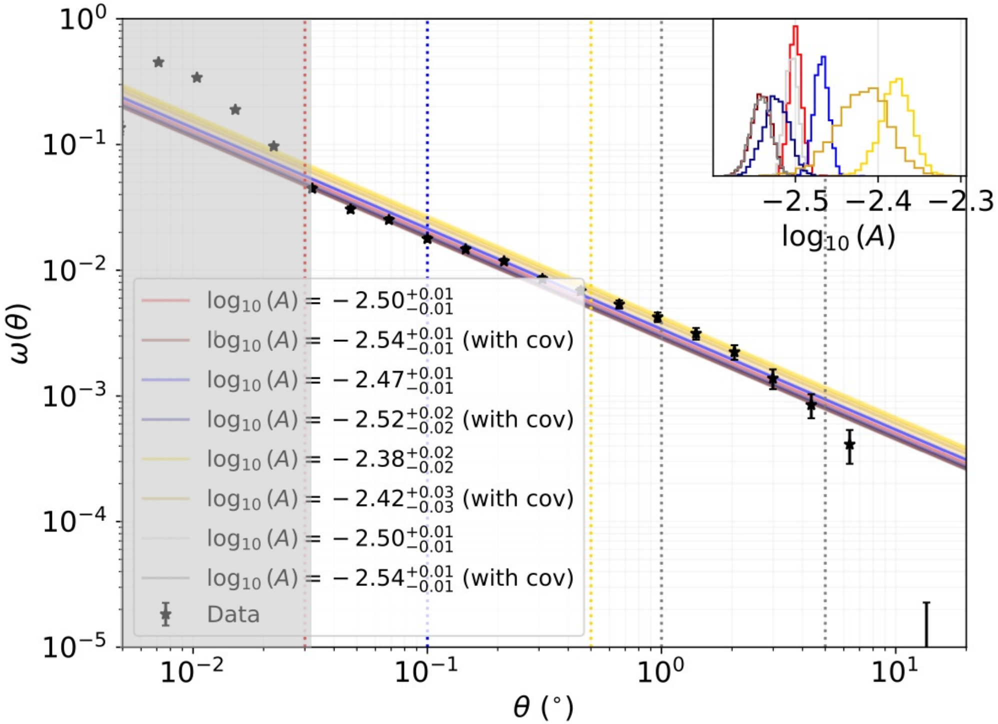
This likely has a significant contribution from multi-component radio sources.

The value-added catalogue (Hardcastle+ 2023, i.e. with cross-matched multi-component sources) is for >8 mJy sources.

Therefore, cannot fit below ~0.03 degree.

Hale+ 2024

Angular Two-Point Correlation Function (Hale+ 2024)

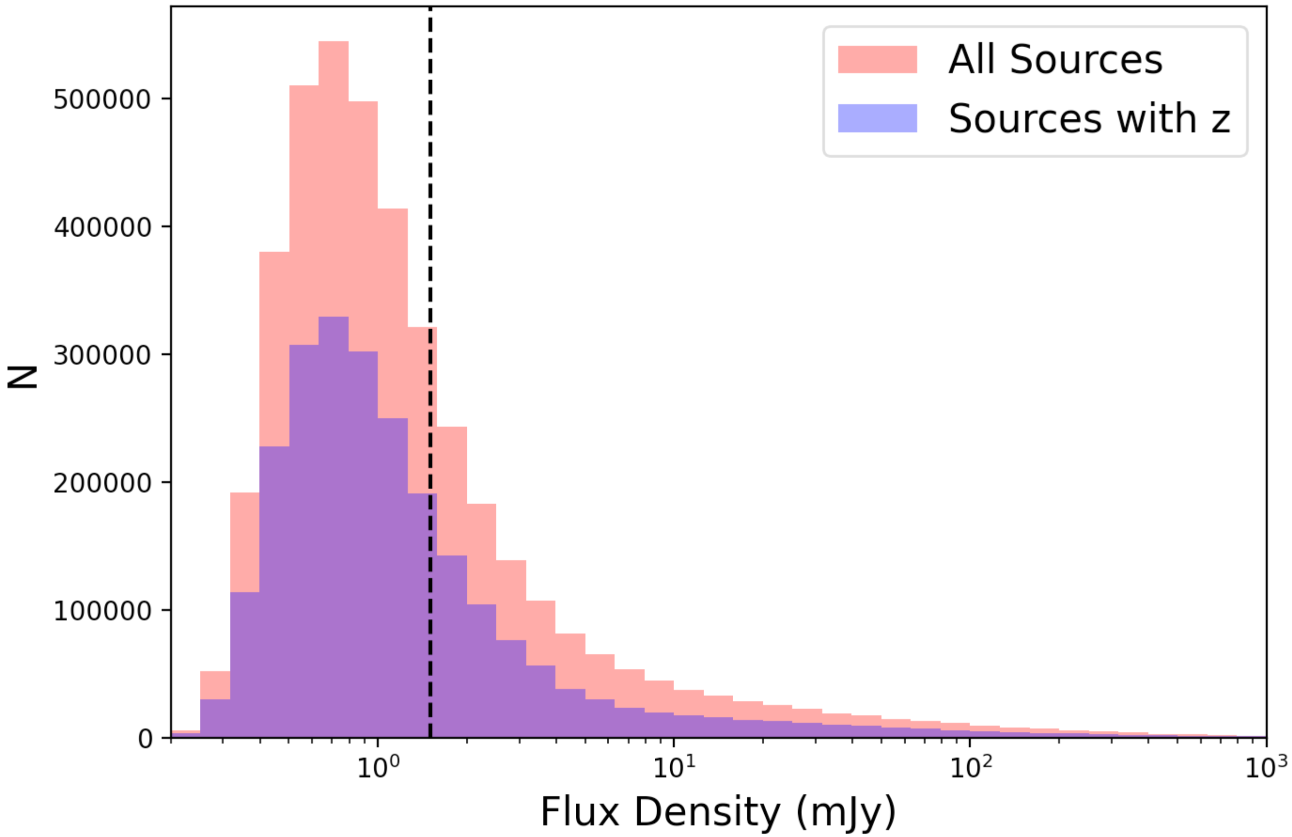


+ Use Redshift Distributions to model the clustering and infer galaxy bias using PyCCL (Chisari+ 2019)

$\geq$ 1.5 mJy, $\geq 7.5\sigma$

Hale+ 2024

Redshift Distribution of Sources



Cross-matched catalogue from Hardcastle+ 2023 provides host ID and redshifts for a large fraction of sources

40-50% of sources do not have redshifts

We don't know how these may be preferentially biased e.g. are we missing high redshift sources, or certain populations

We therefore use the more complete LOFAR Deep Fields data (Duncan+ 2022)

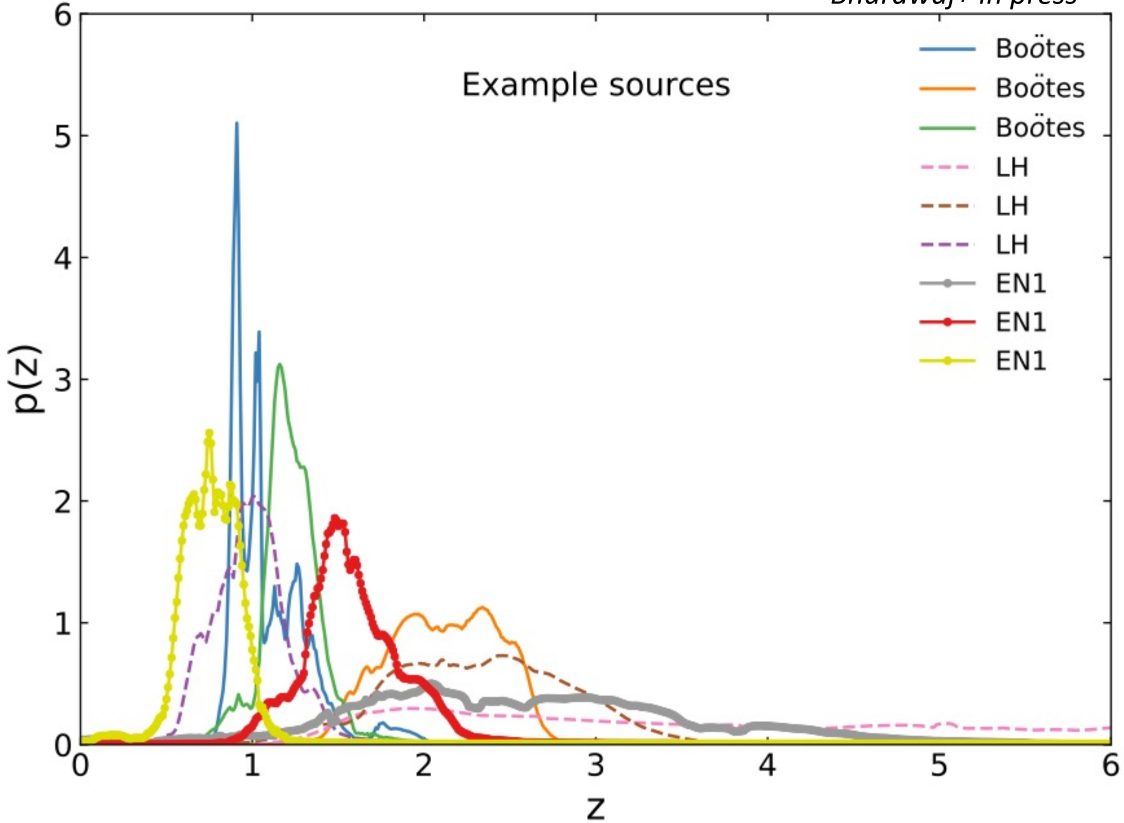
Redshift Distribution of Sources

Deep Fields data have **Z_Best** values in the catalogues but can have **wide ranging p(z)** distribution.

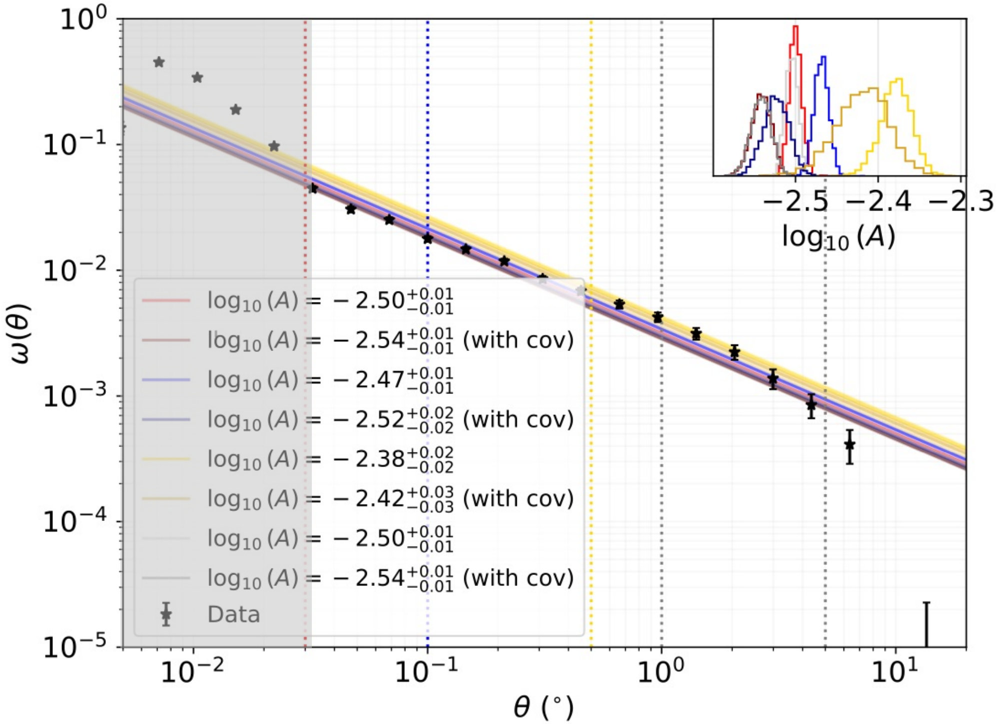
Therefore, we create **resampled full p(z)** by random sampling from the p(z) of the sources in the three fields which are above the flux limit being considered.

We **repeat** this numerous times and use the spread in the p(z) to give **uncertainties** to the p(z).

Bhardwaj+ in press



Angular Two-Point Correlation Function (Hale+ 2024)



$\geq$ 1.5 mJy, $\geq 7.5\sigma$

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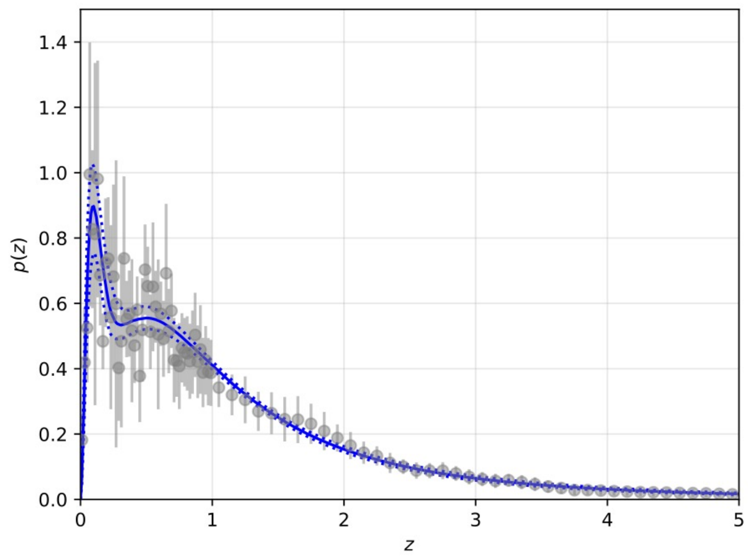

Hale+ 2024

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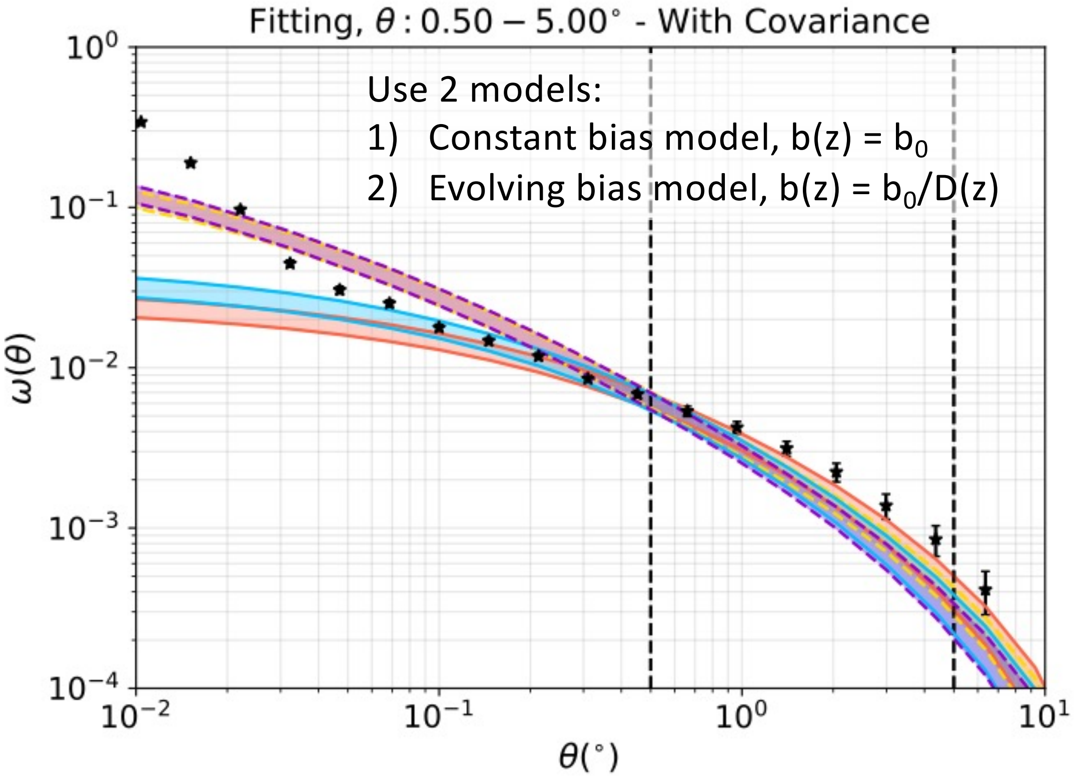
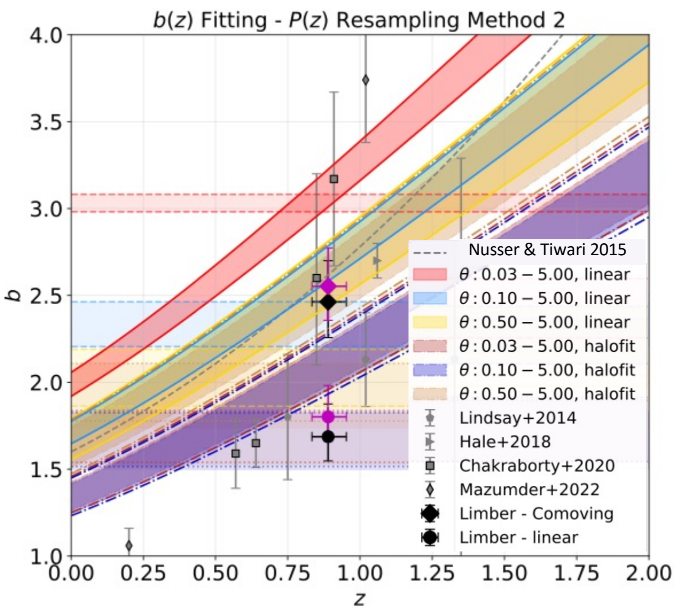


Use 2 models:

1) Constant bias model, $b(z) = b_0$
2) Evolving bias model, $b(z) = b_0/D(z)$

To agree with N(z) predictions from previous cross correlations with CMB (Alonso+ 2020) we must have evolving bias model



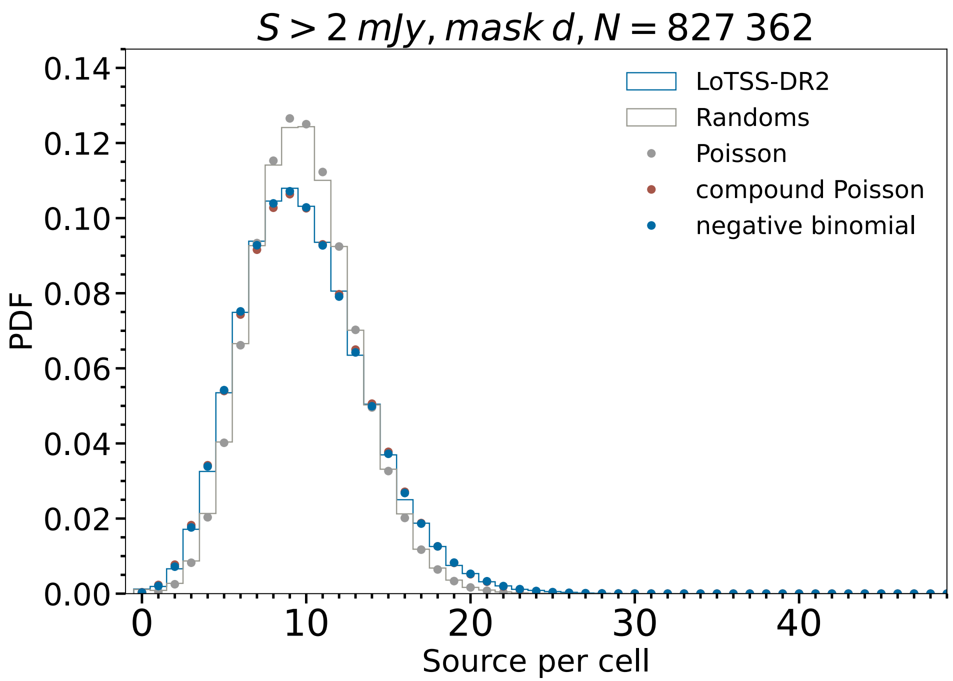
Work in progress

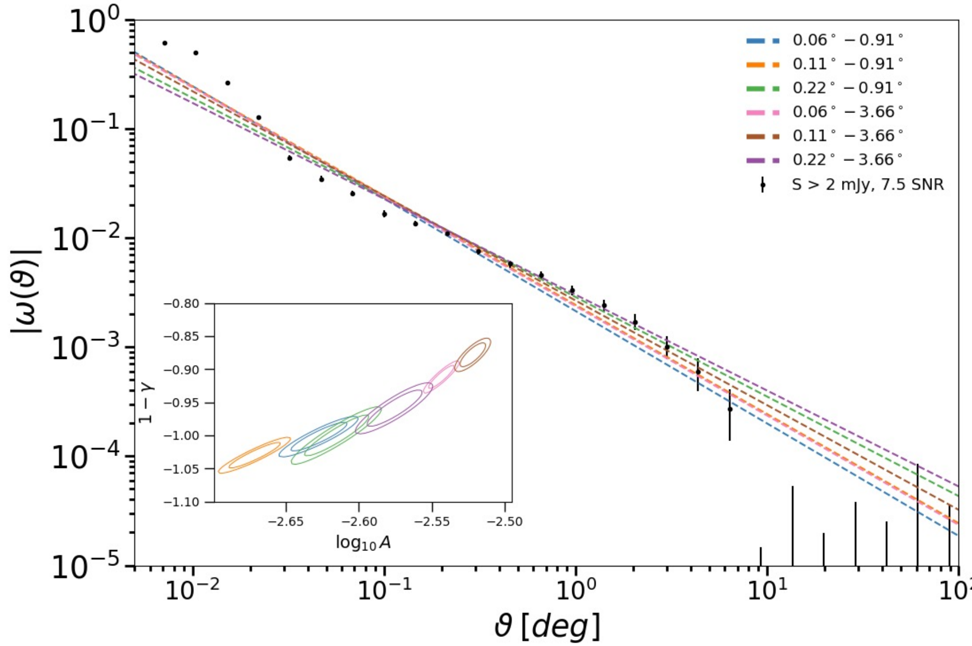
One-point statistics (Pashapour-Ahmadabadi et al. in prep)

Use the counts of radio sources in cells to investigate the distribution of sources and see it is not well modelled by a Poisson process alone.

Can use counts in cell to estimate the angular clustering, assuming a power law

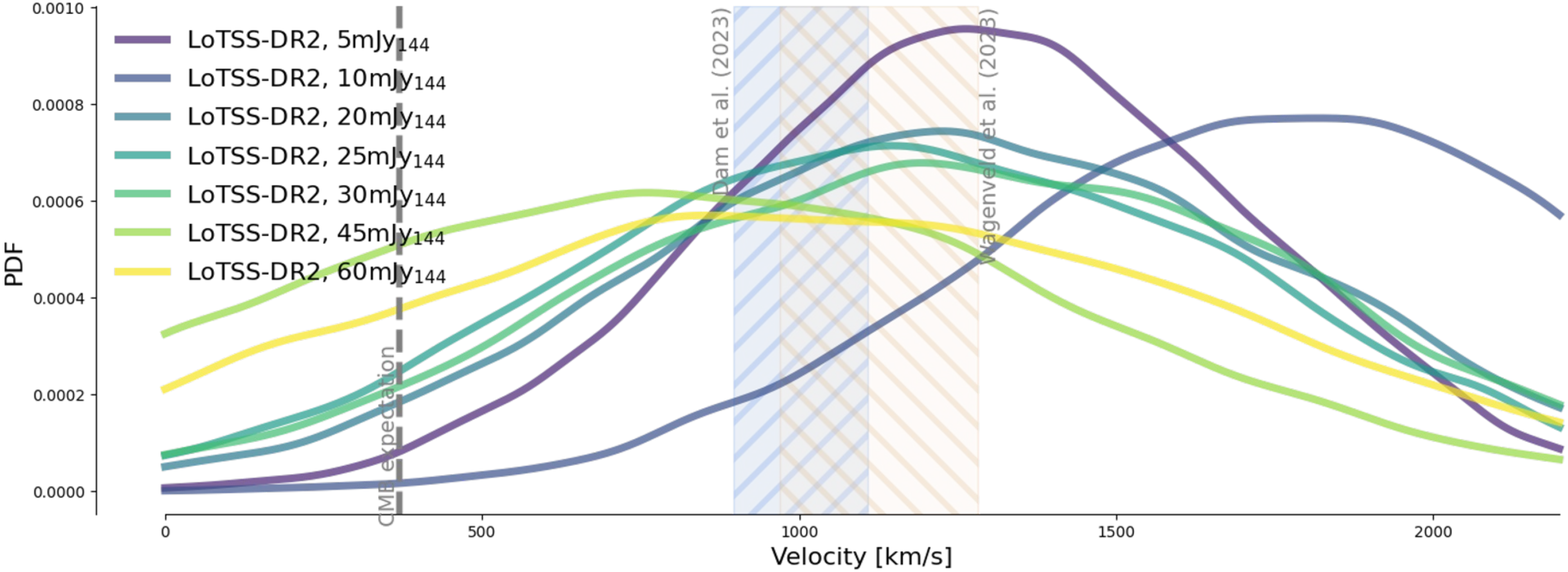
See Morteza's poster in the coffee/lunch breaks!





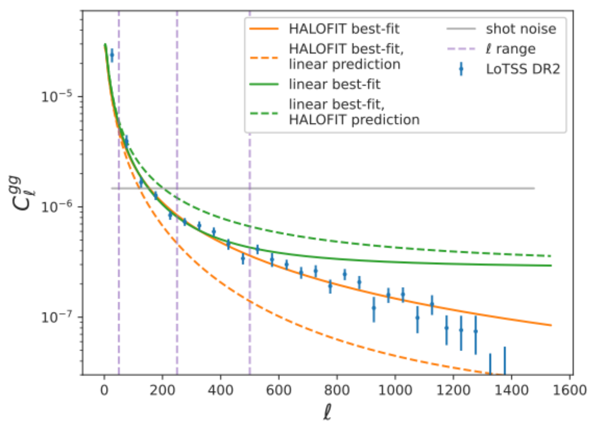
Work in progress

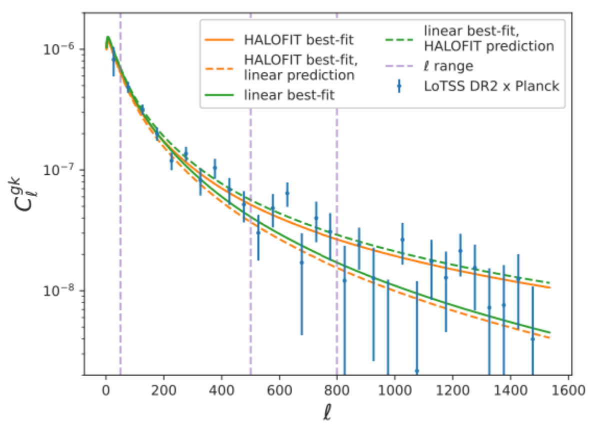
Radio Dipole (Böhme+ in prep)

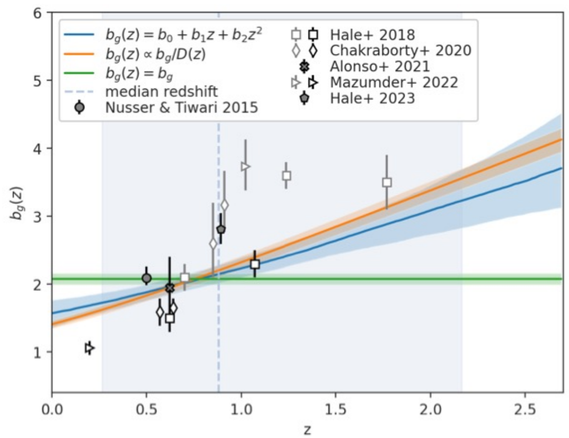


Cross-Correlation with CMB (Nakoneczny+ 2024)

- Combine LoTSS-DR2 with **CMB lensing maps** from Planck (Planck Collaboration+ 2020) to measure **power spectrum**
- Use this to place constraints on **bias evolution models** by using cross correlations helping to avoid any potential remaining systematics in the radio data.
- By fixing certain parameters, was also able to place constraints on $\boldsymbol{\sigma_8}$

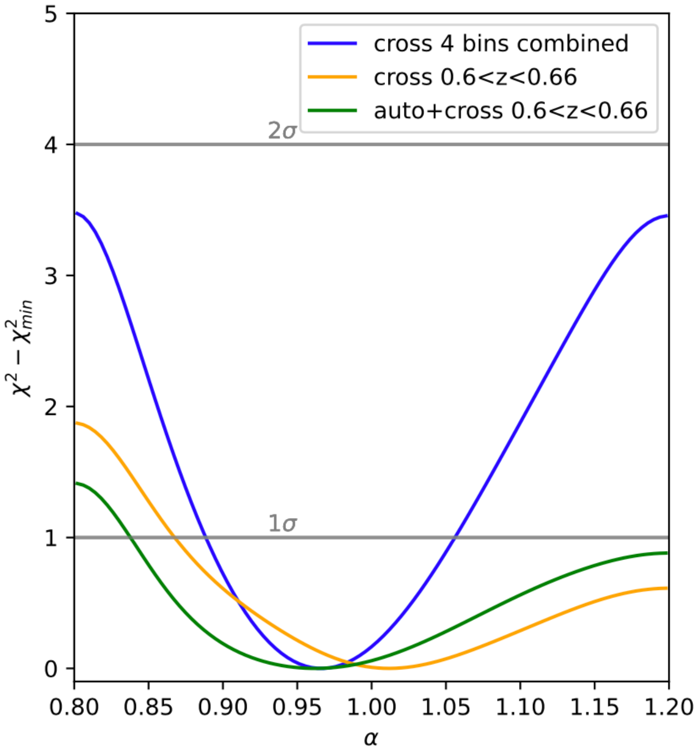






Work in progress

Cross-correlating with eBOSS (Zheng+ in prep)



(Represents how the BAO wiggles in the power spectrum shift with scale)

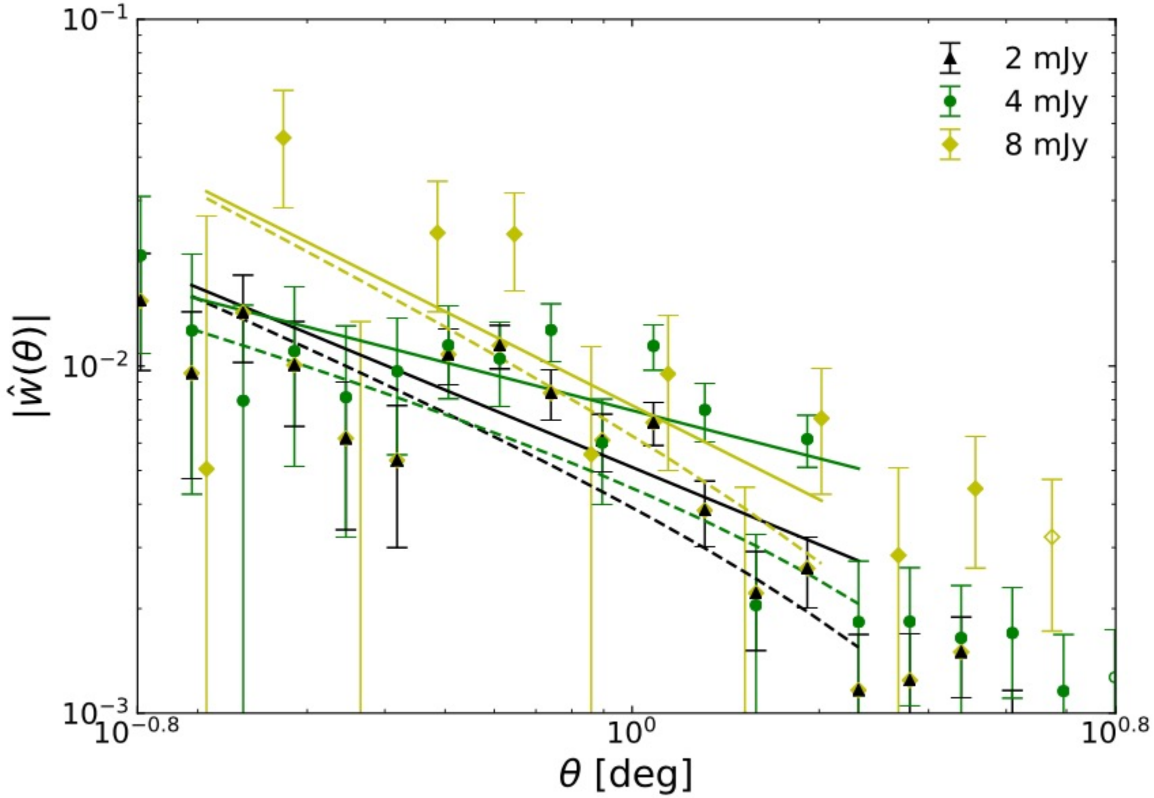
Cross-correlate **luminous red galaxies** from **eBOSS** (Ross+ 2020) with LoTSS-DR2 in different eBOSS redshift bins

Use this to put constraint on the **angular BAO parameter** ass **bias evolution**

Using cross-correlations helps **reduce systematics** in both fields and improve constraints on cosmological parameters

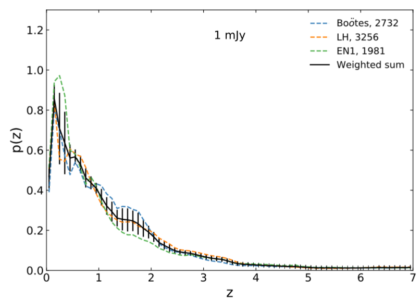
Jinglan presented this earlier in the week!

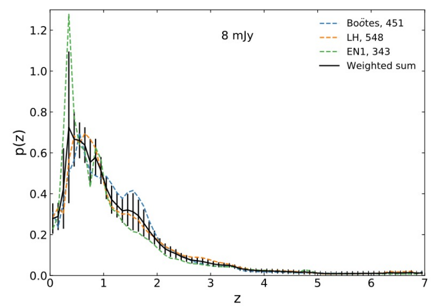
Flux Dependent Clustering (Bhardwaj+ in press)



Investigate the flux dependent clustering of LoTSS DR1 using the cosmological analysis of Siewert+ 2020.

Using the method to obtain redshift distributions from resampling the p(z) this can see how spatial clustering models varies with flux density





Limitations in bias constraints from LoTSS-DR2

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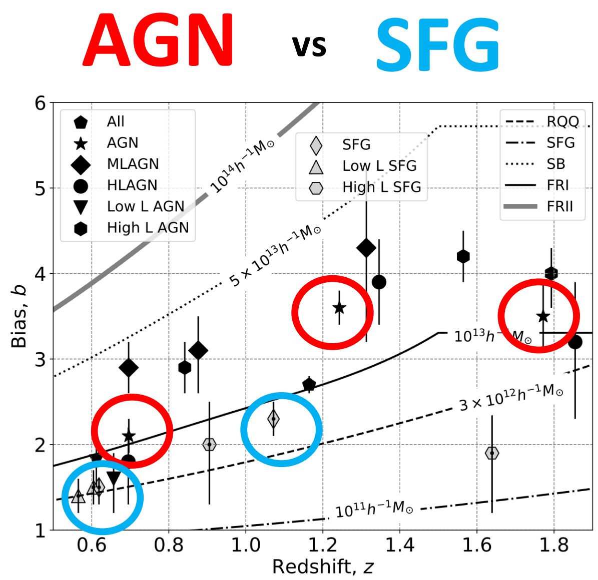

Hale+ 2018

LOFAR Deep Fields

- Deep (~20-30 uJy/beam) observations over 3 deep fields: ELAIS-N1, Lockman Hole, Boötes (Sabater+ 2021, Tasse+ 2021)
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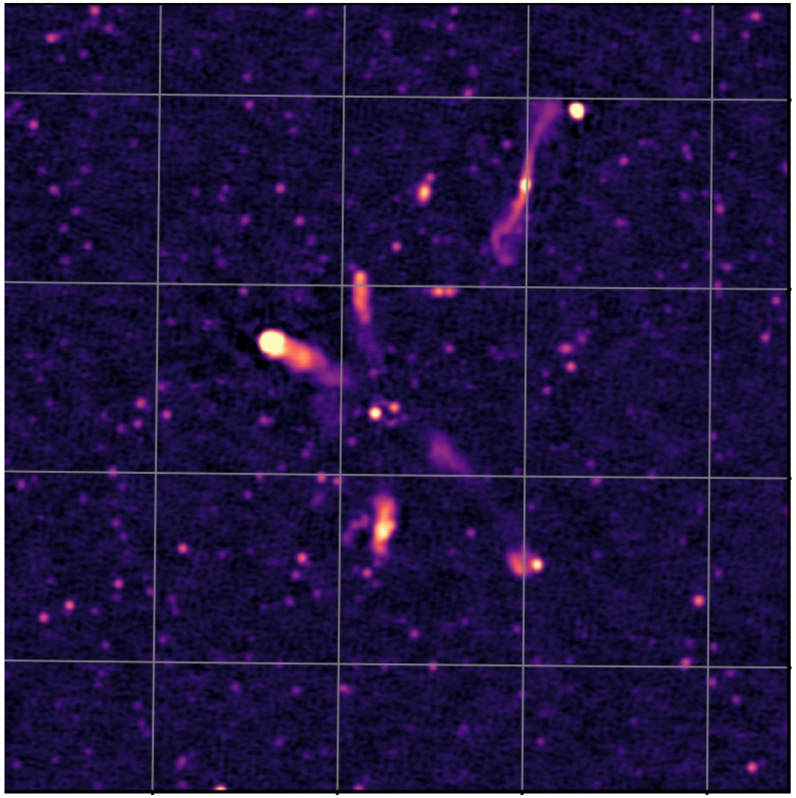

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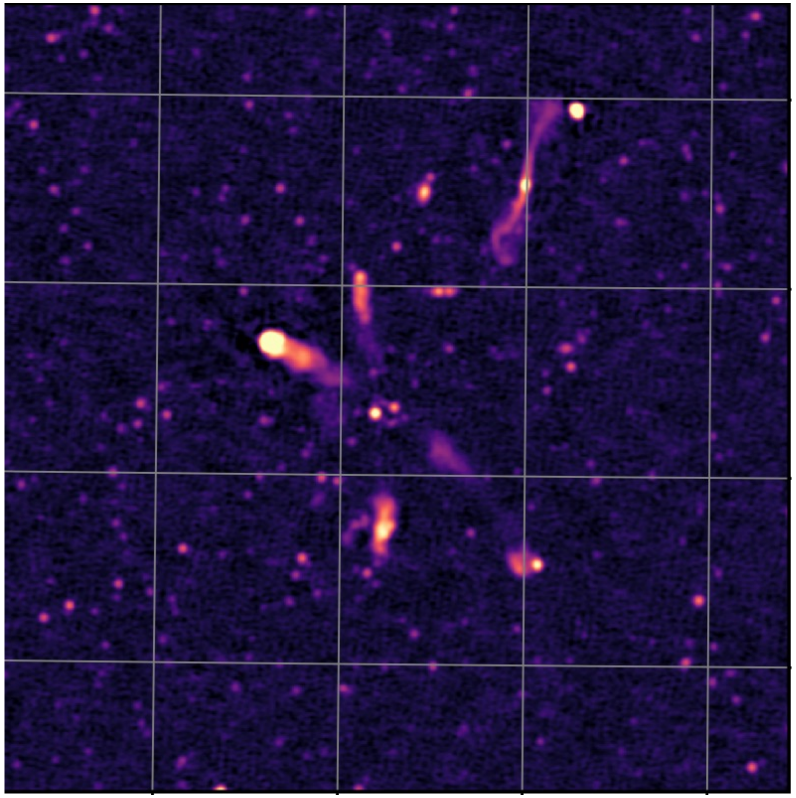
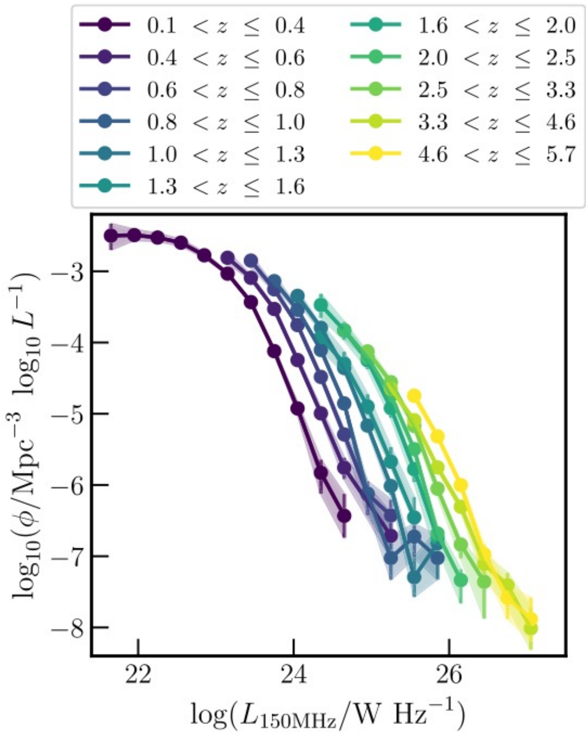
No small-scale clustering from multi-component sources, only 1-halo

Split source populations and investigate bias evolution

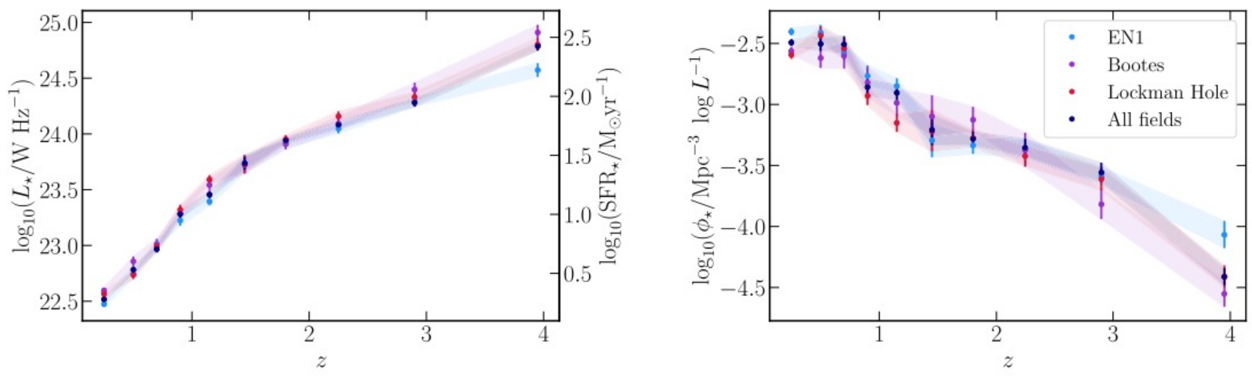


Randoms per Source Type

SFG Luminosity Function



SFG Luminosity Function parameter evolution



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Figures from Cochrane+ 2023

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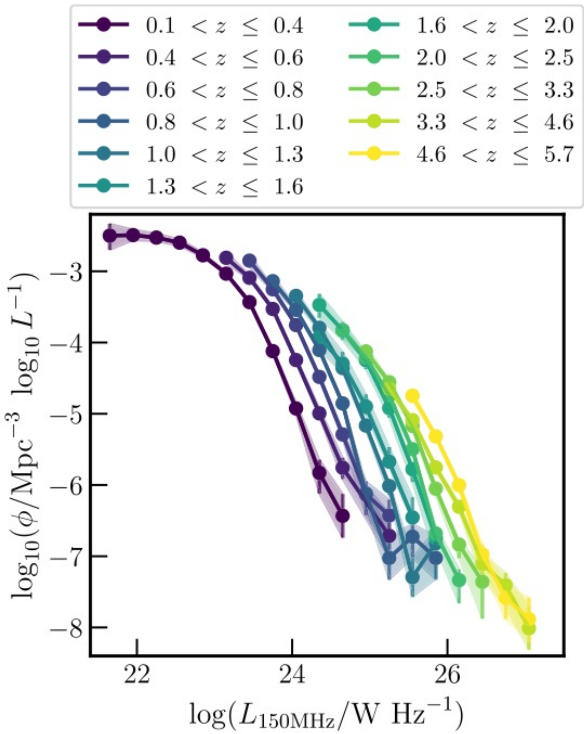

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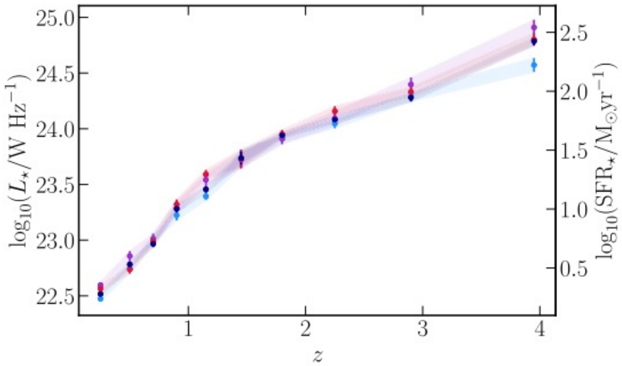

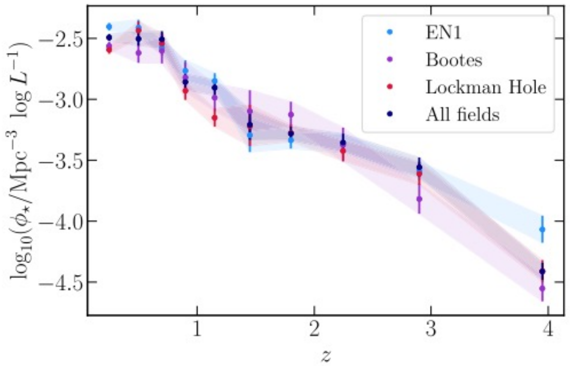

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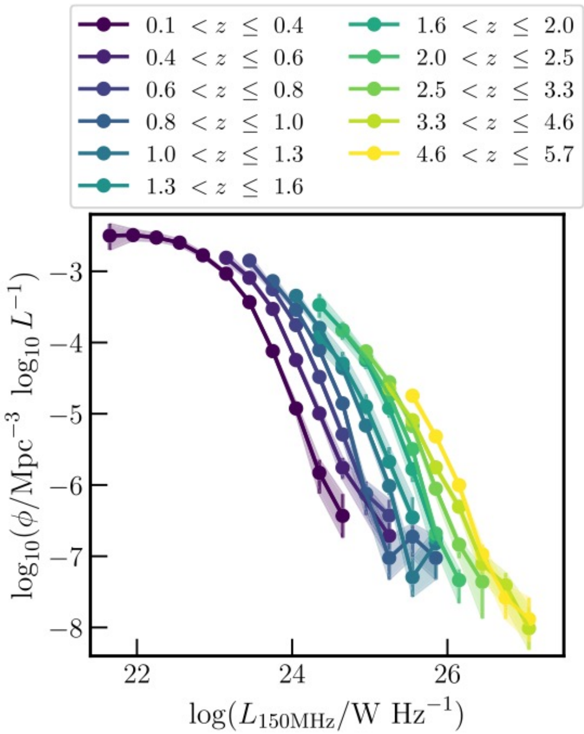

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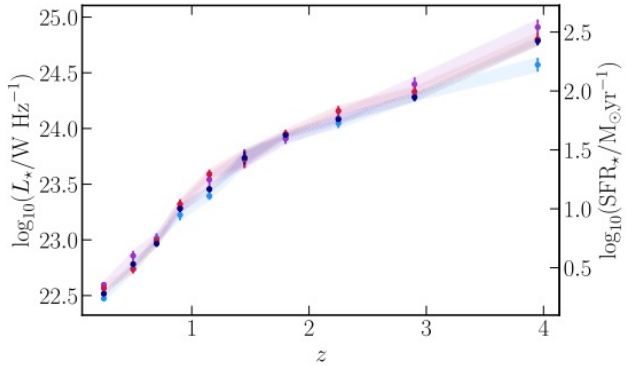

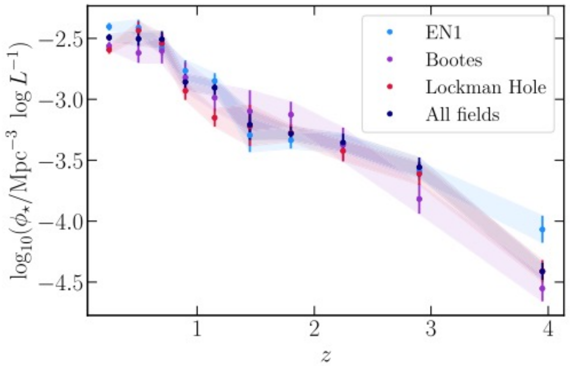

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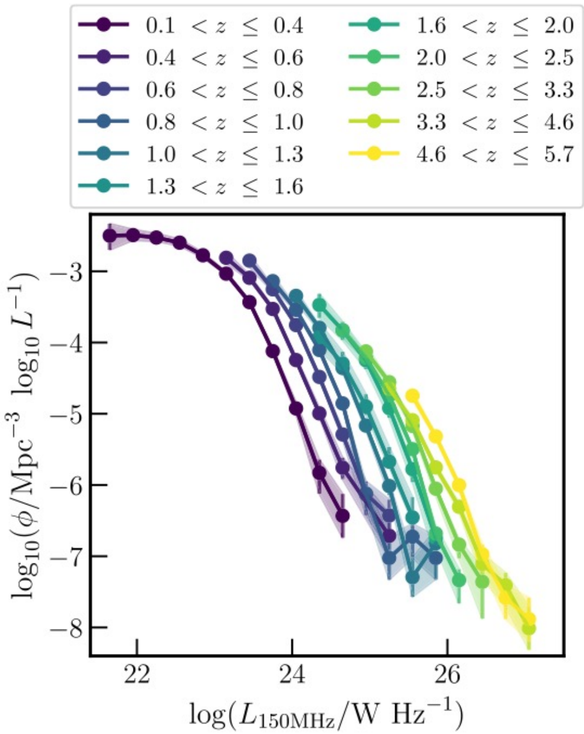

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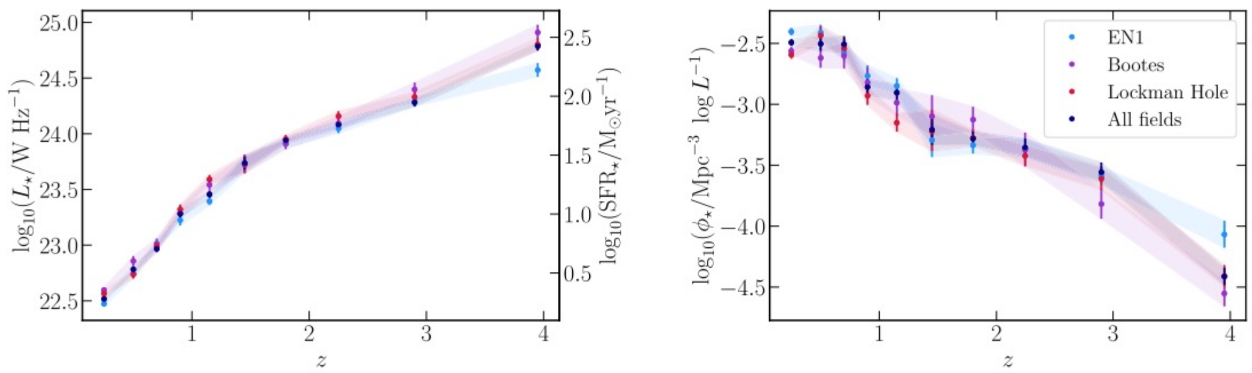

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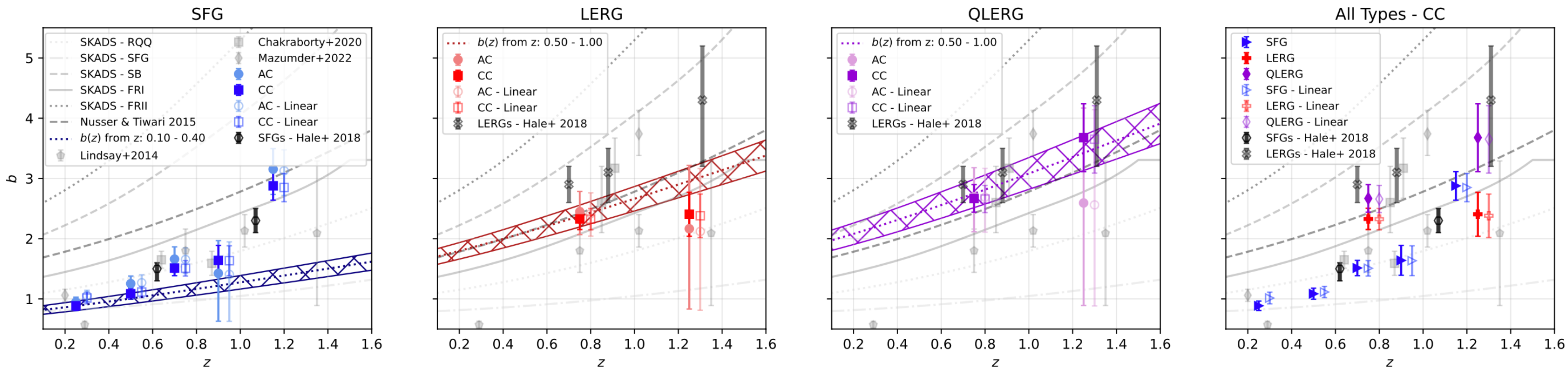
- Gives **input source distribution** with the **LF, n(z)** and **dN/dS** which matches the intrinsic distribution for the given source type in the z bin

Results



LERGs appear **more clustered** than **SFGs** and **quiescent LERGs more clustered** than **full LERG** population.

Hale+ in prep

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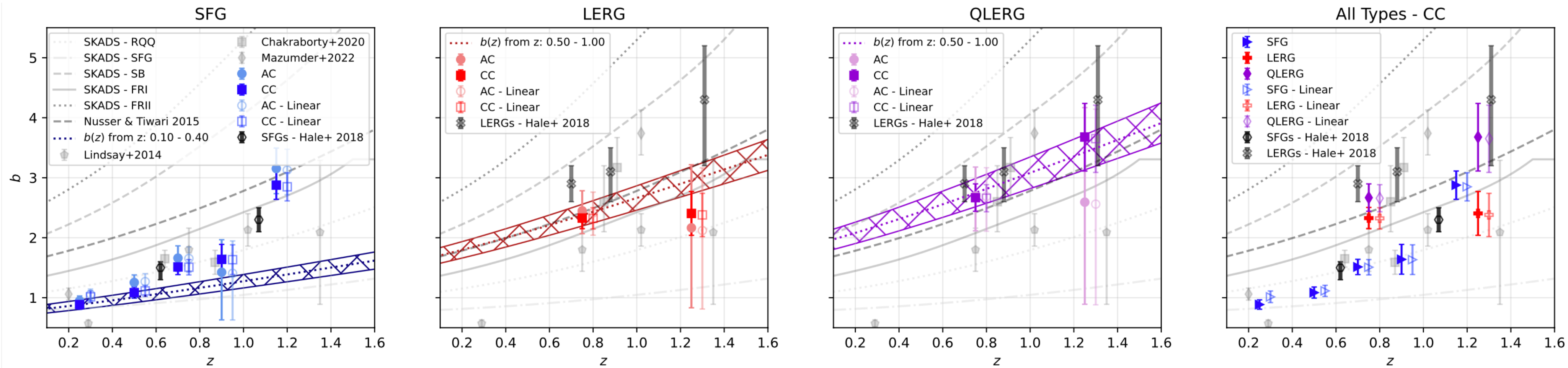

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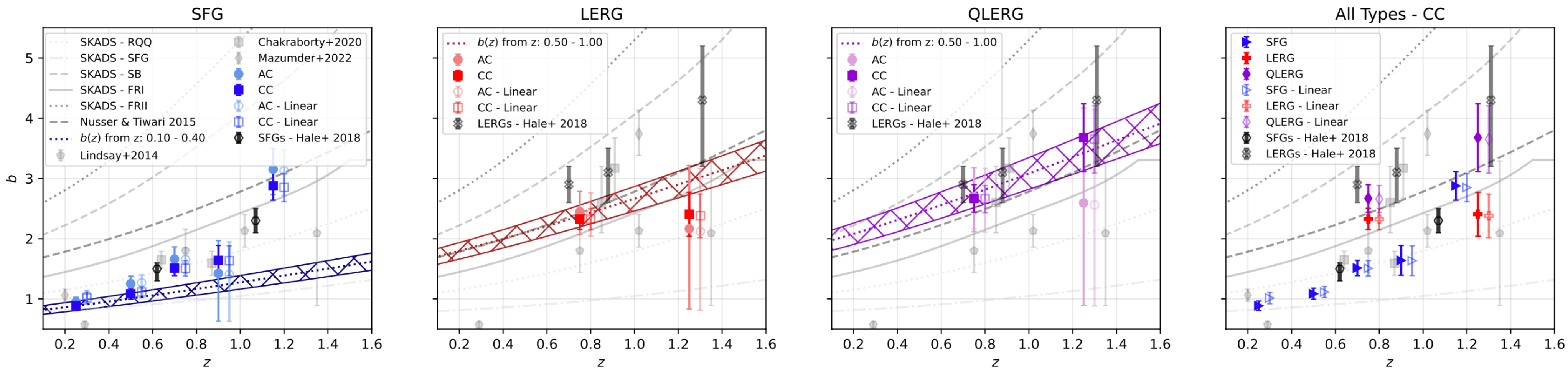

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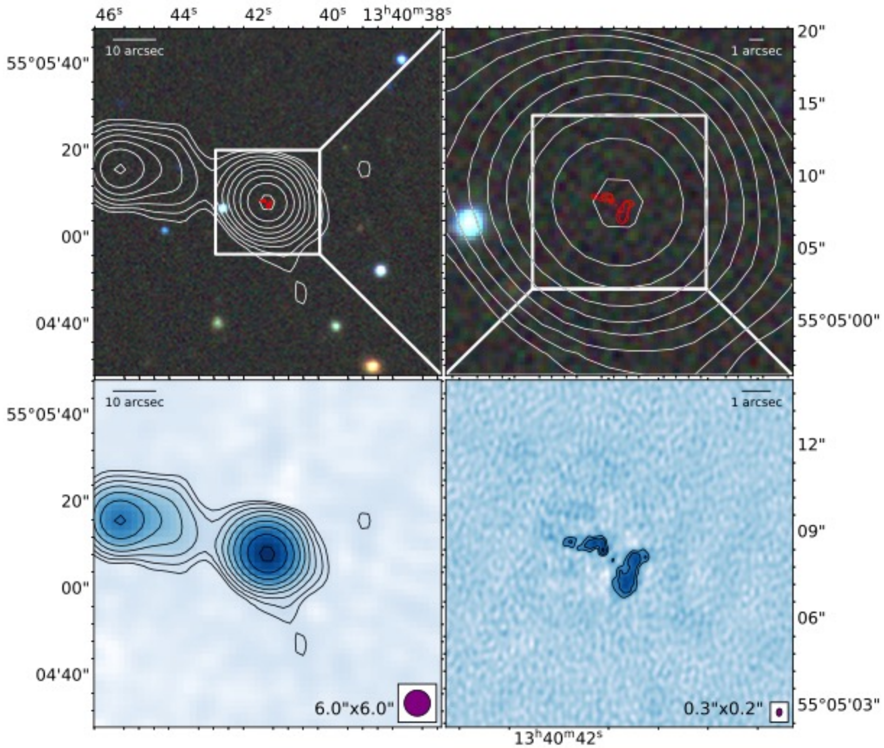
SFG bias evolution is **steeper** than the **evolving model** assumed for **LoTSS DR2** – but good approximation for LERGs

Future of Cosmological Studies with LOFAR

Future with LOFAR

LOFAR High Resolution



Morabito+ 2022

Future with LOFAR

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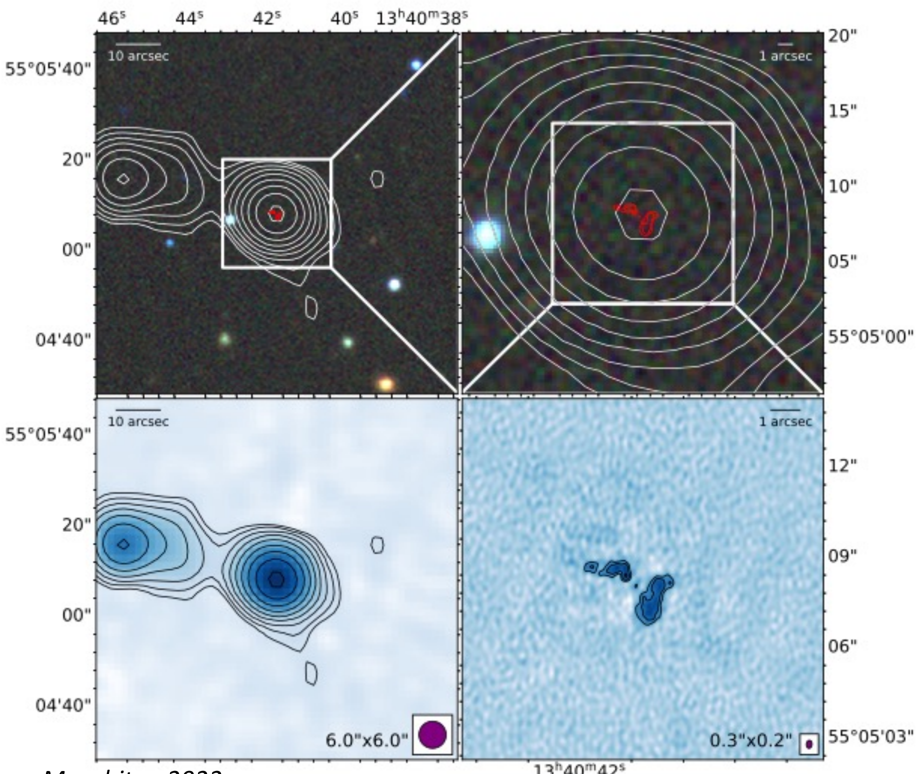
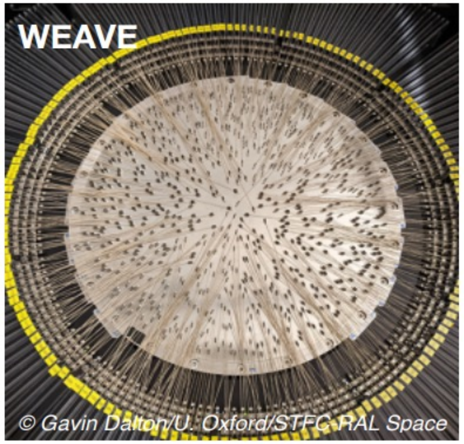
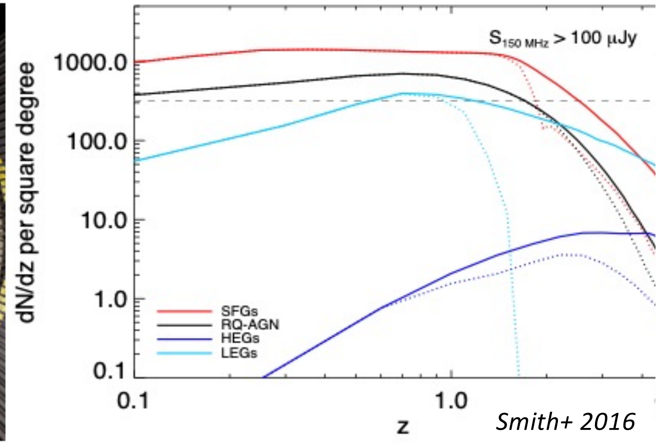


Morabito+ 2022

LOFAR Follow up Redshift Survey: WEAVE-LOFAR





Smith+ 2016

Future with LOFAR

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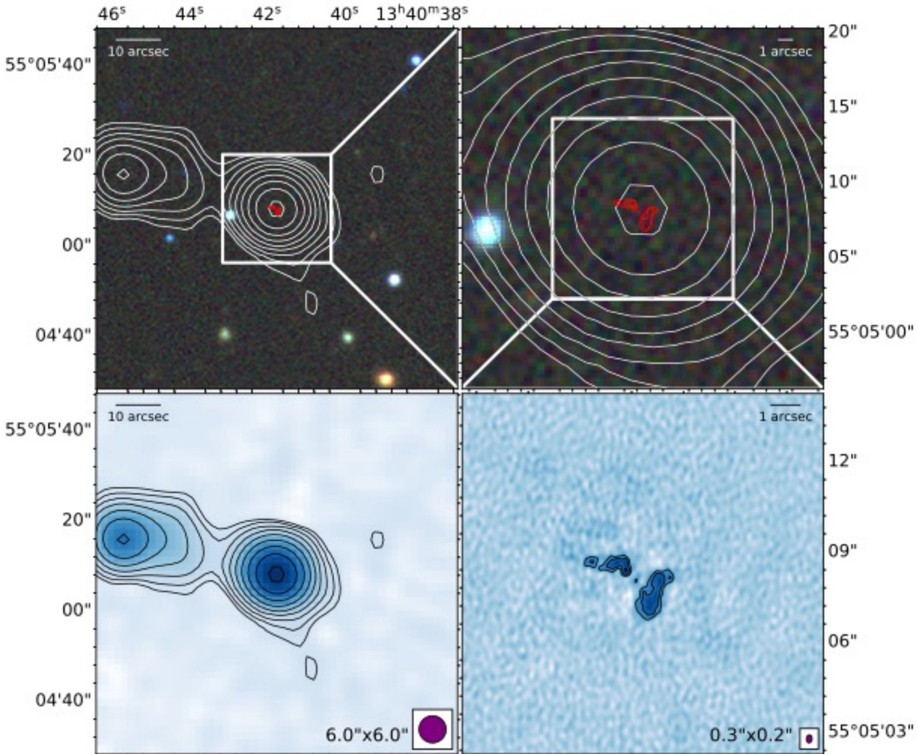

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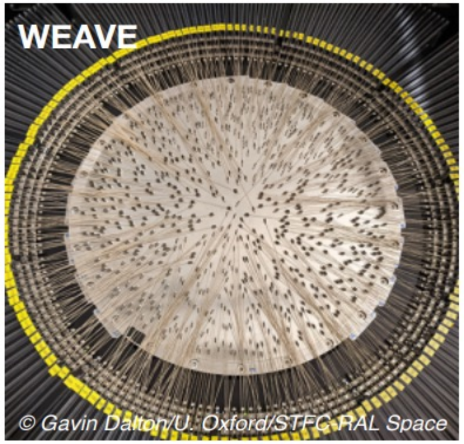
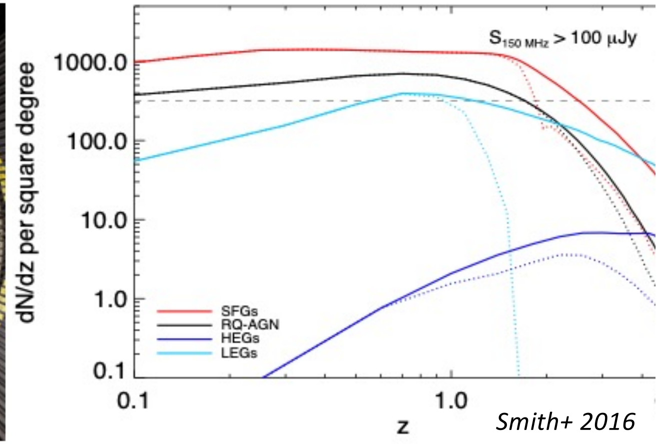
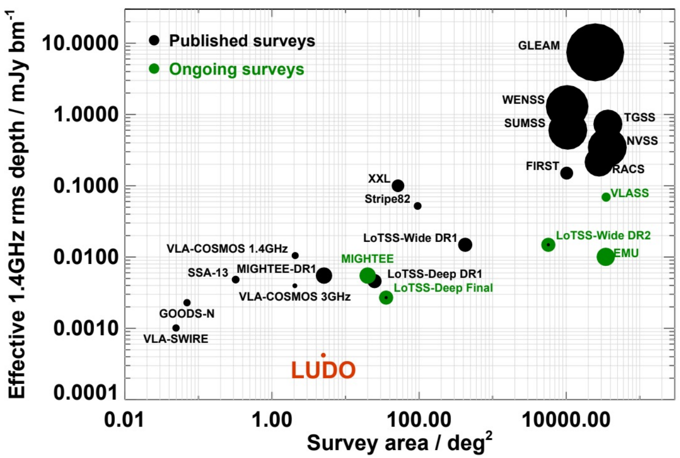




Smith+ 2016

Combining LOFAR 2.0 with other surveys



LUDO proposal, Best, Morabito et al.

ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi

Summary

- Radio Surveys with LOFAR are great for **cosmology** studies:
  - Combination of **large area** observations + **deep fields** with a **wealth of ancillary data**
- **Systematics** are **key** to understand to accurately trace the **large-scale structure**:
  - We use a combination of simulations and account for **systematic effects** e.g. incompleteness, smearing, measurement errors
- Numerous studies of the **evolving bias** in the **LoTSS DR2** wide area survey from the auto-correlation (**Hale+ 2024**) and cross-correlations (**Nakoneczny + 2024, Zheng+ in prep)** with other data to improve such measurements.
- The **deep fields** allow us to more accurately trace the **bias evolution** for different **populations (AGN vs SFGs)**.
- Future is exciting:
  - **Spectroscopic surveys** (i.e. **WEAVE-LOFAR**, Smith+ 2016) will allow us to **directly** measure **the spatial correlation function**, not use projected angular clustering
  - High resolution and LOFAR 2.0 will improve 1-halo studies and cross-correlating with optical/IR data