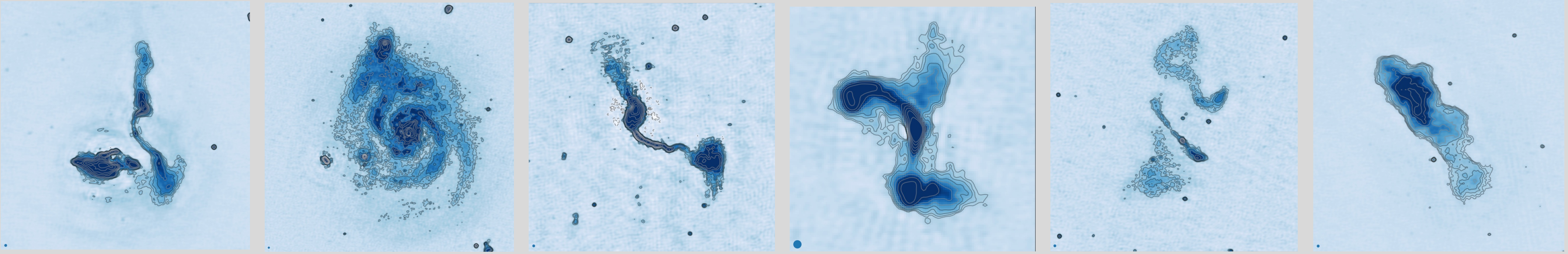
Images from Shimwell+ 2019

Cosmology with the LOFAR 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

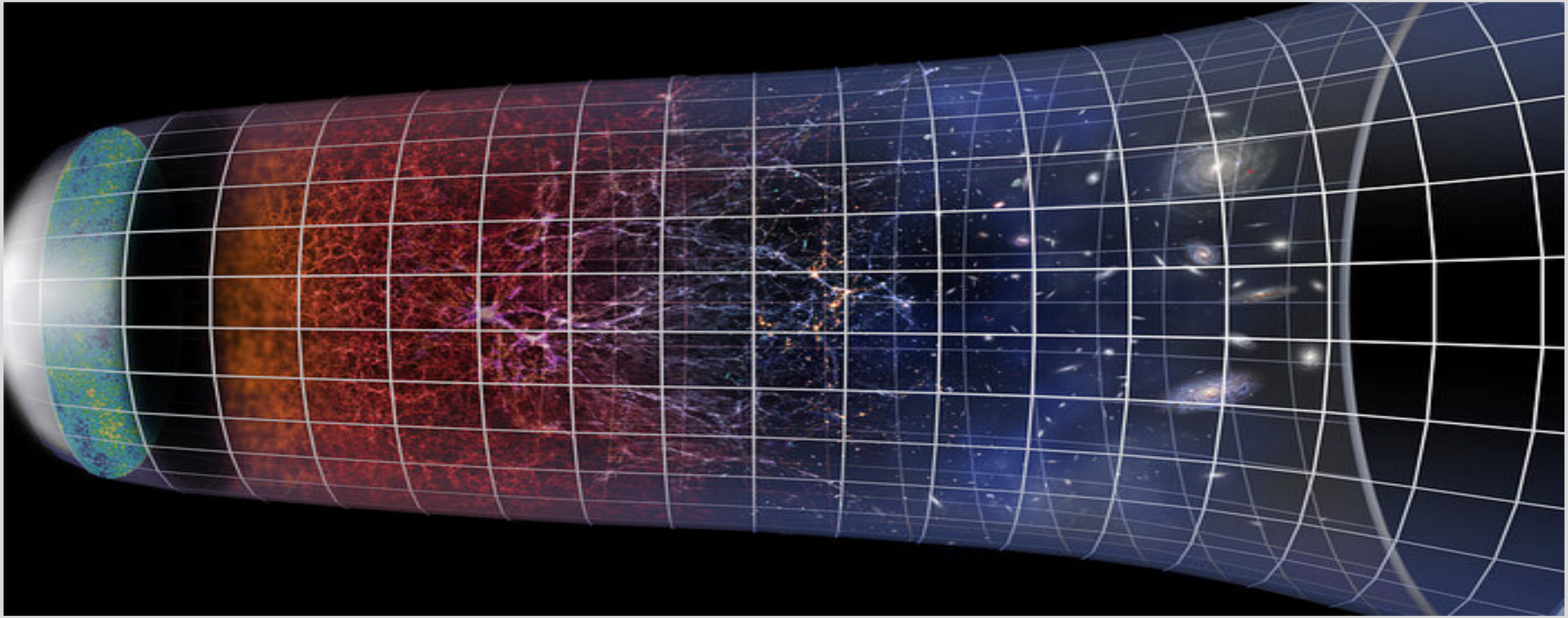
LEVERHULME TRUST

UNIVERSITY OF OXFORD

Overview

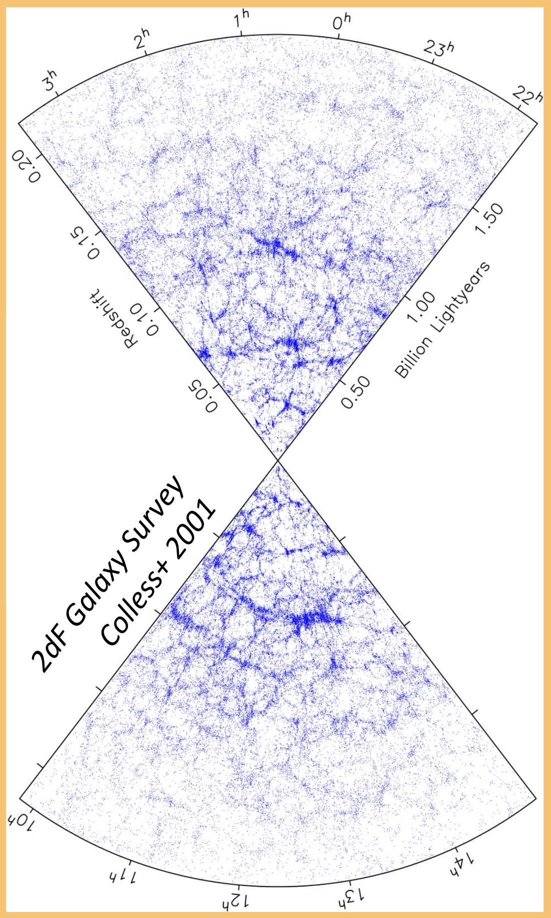
- Tracing Large Scale Structure with galaxy surveys
- LOFAR surveys: plans and status
- Cosmology with LoTSS-DR2:
  - Systematics and observational biases
  - Angular Clustering (*Hale et. al 2024*)
  - One-Point statistics (Pashapour-Ahmadabadi et al. in prep)
  - Cosmic Dipole (Böhme et al. in prep)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

Tracing Large Scale Structure with galaxy surveys



Credit: ESO/M. Kornmesser

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)

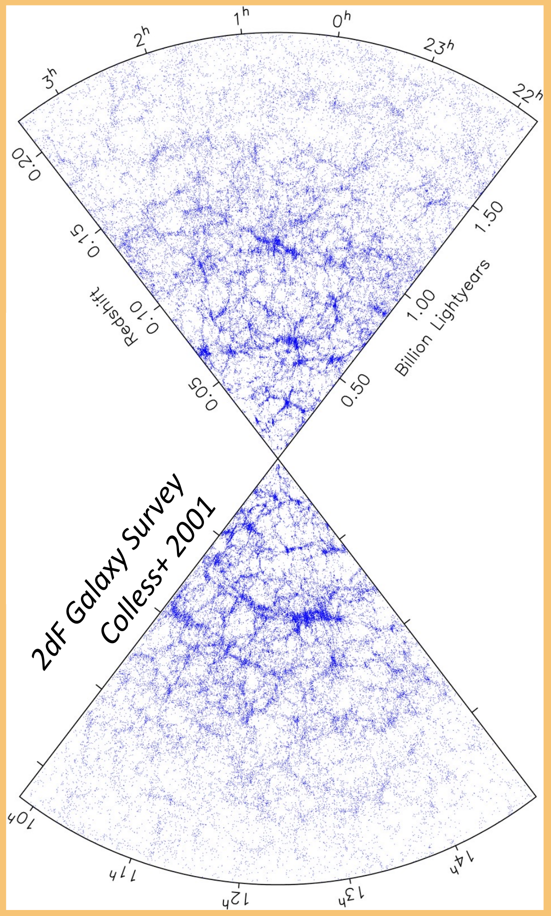
Using accurate redshifts allows **precise observation** of the **location** of galaxies and to **observe clusters, filaments and voids**

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

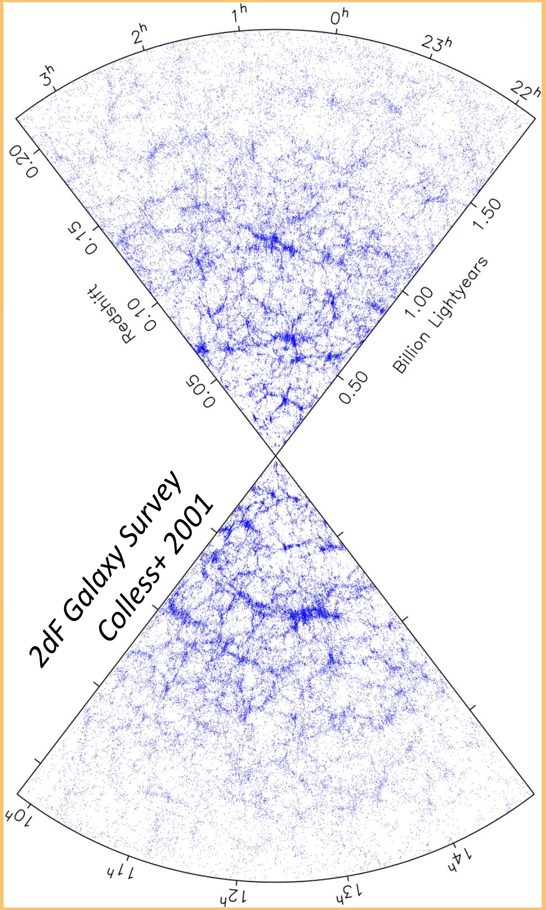
Mean number density

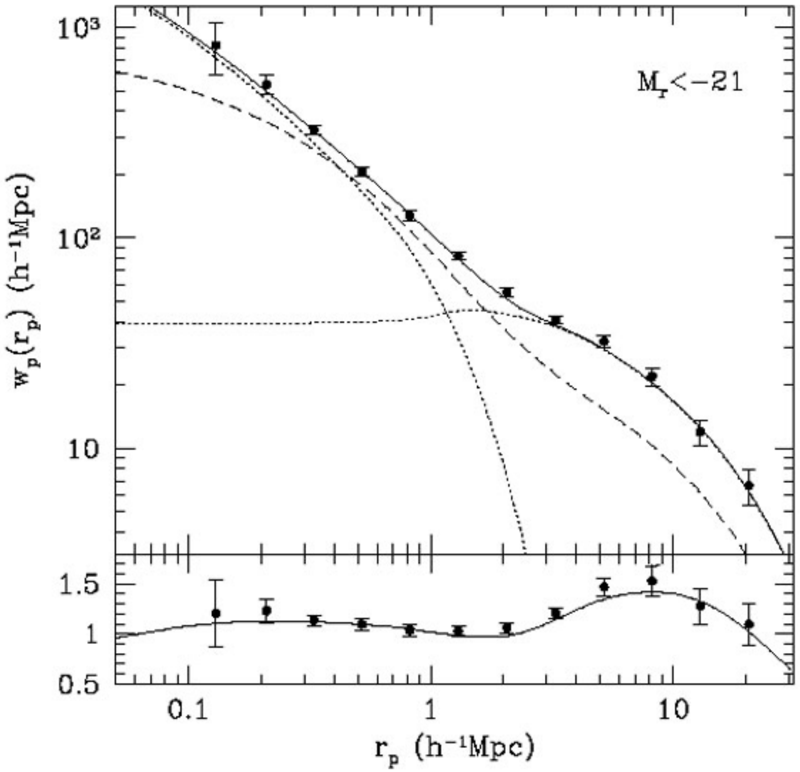
Spatial two-point correlation function

Volume element

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

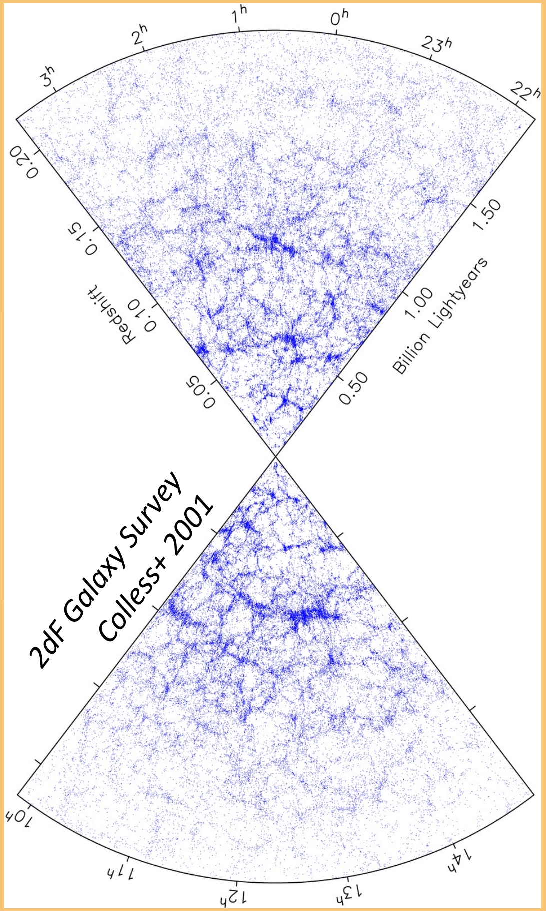
Large-Scale structure of the Universe



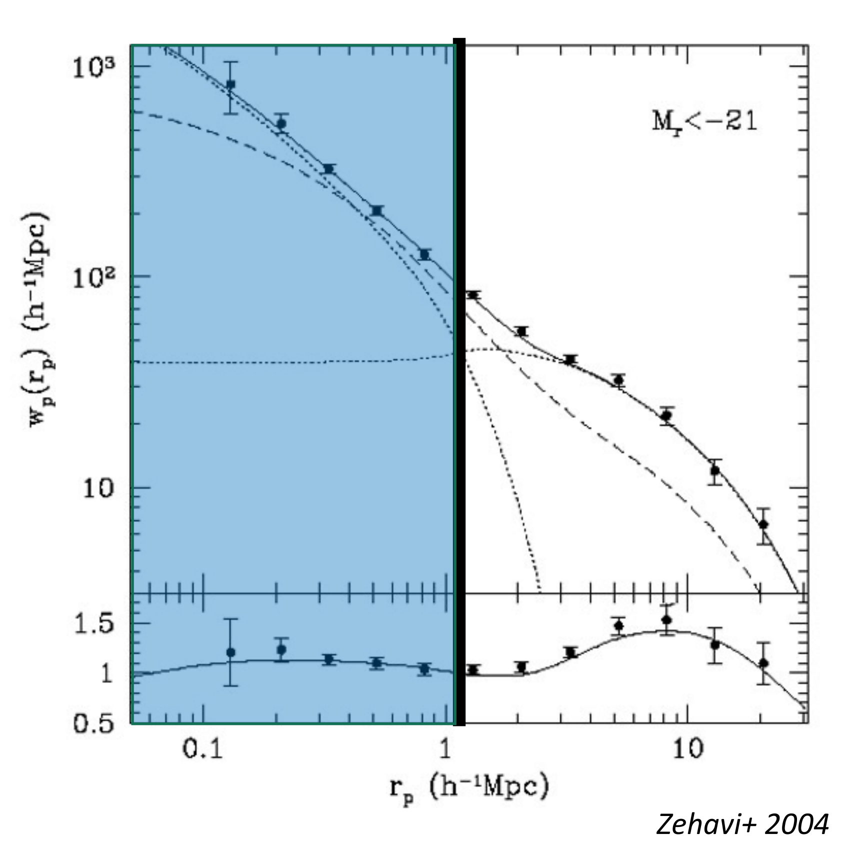


Zehavi+ 2004

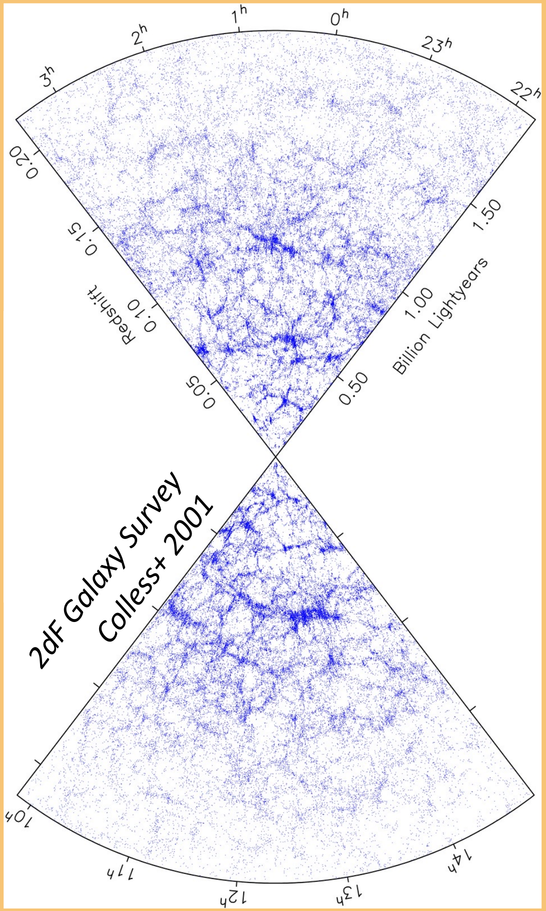
Large-Scale structure of the Universe



1-halo clustering:
Clustering within the same dark matter halo

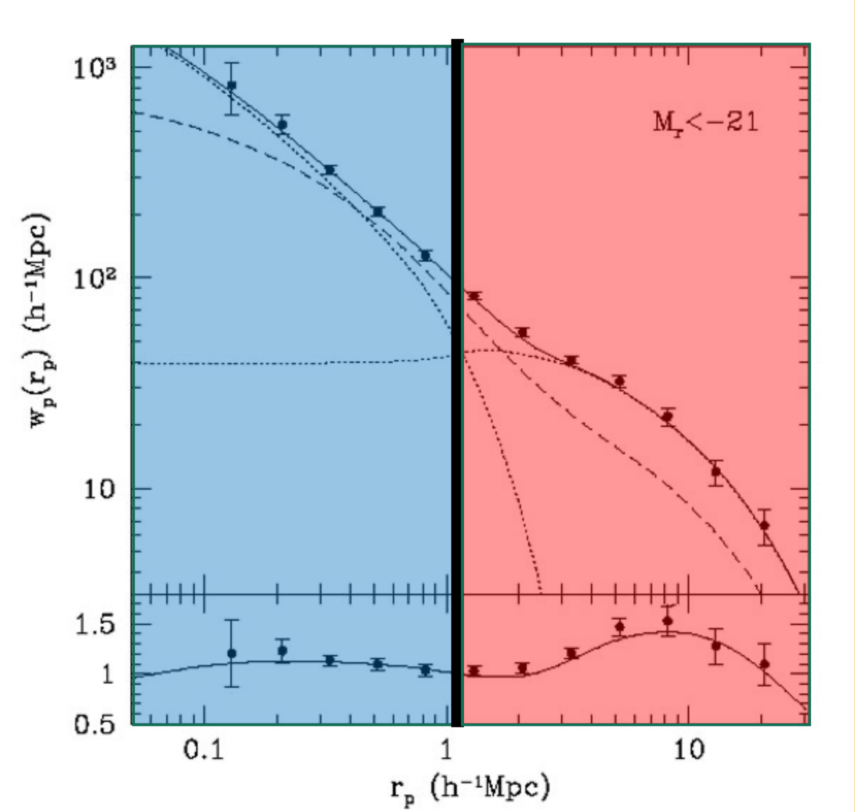


Large-Scale structure of the Universe



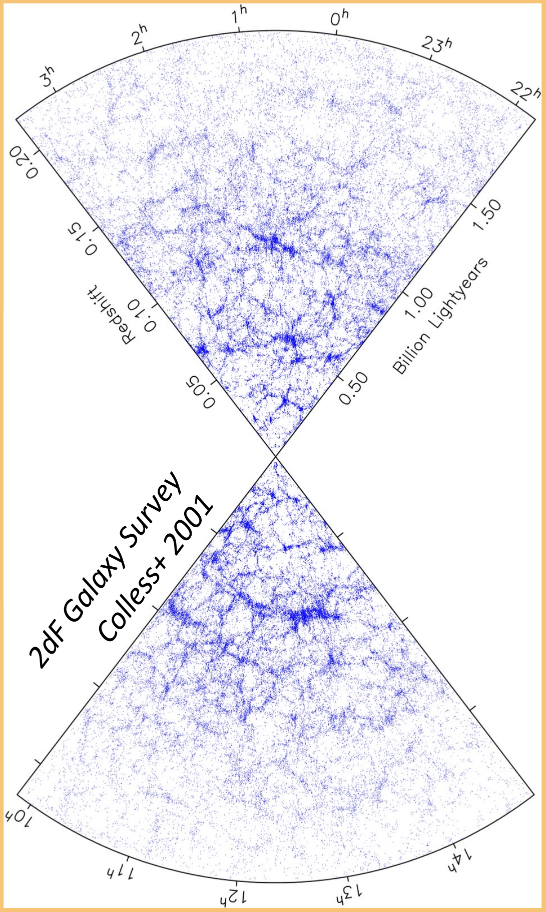
1-halo clustering:
Clustering within the same dark matter halo

2-halo clustering:
Clustering from different dark matter haloes



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

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 Two-Point Correlation Function

Excess probability to observe galaxies in a given angular scale compared to if no large-scale structure

To calculate this we use:

Landy & Szalay 1993

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

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.

Angular Two-Point Correlation Function

Excess probability to observe galaxies in a given angular scale compared to if no large-scale structure

To calculate this we use:

Landy & Szalay 1993

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

Creating accurate random catalogues are crucial to this work!

LOFAR Surveys: Plans and Status

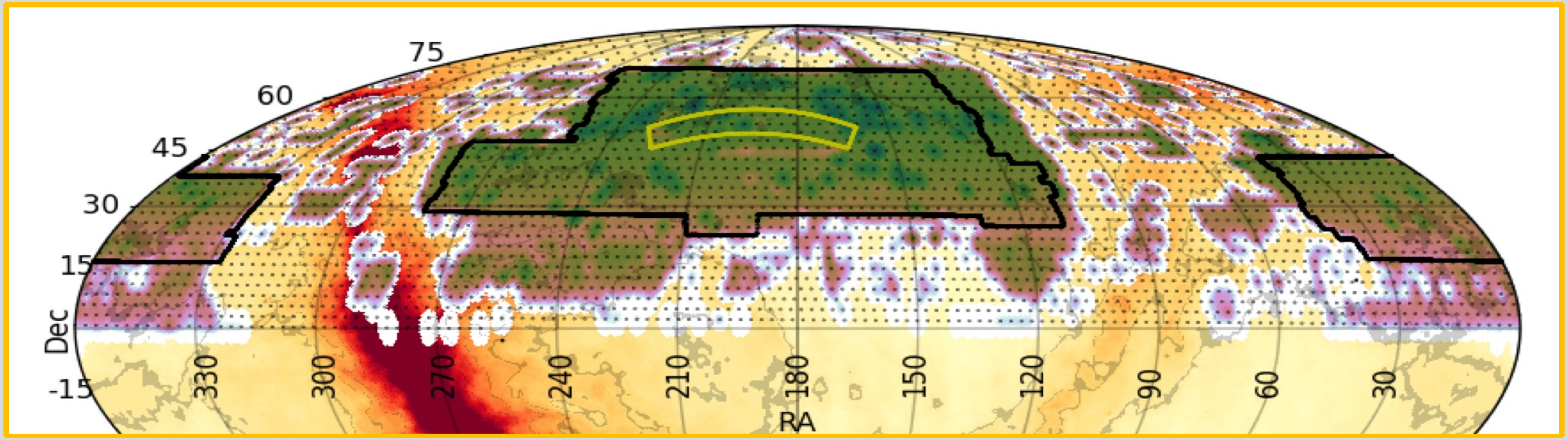
LOFAR Two-metre Sky Survey (LoTSS) Wide Area

Aim: Observe the northern sky with LOFAR

Data Release 2 (Shimwell+ 2022):

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

- 144 MHz observations
- 6" resolution
- ~8 hour pointings



Shimwell+ 2022

LOFAR Two-metre Sky Survey (LoTSS) Wide Area

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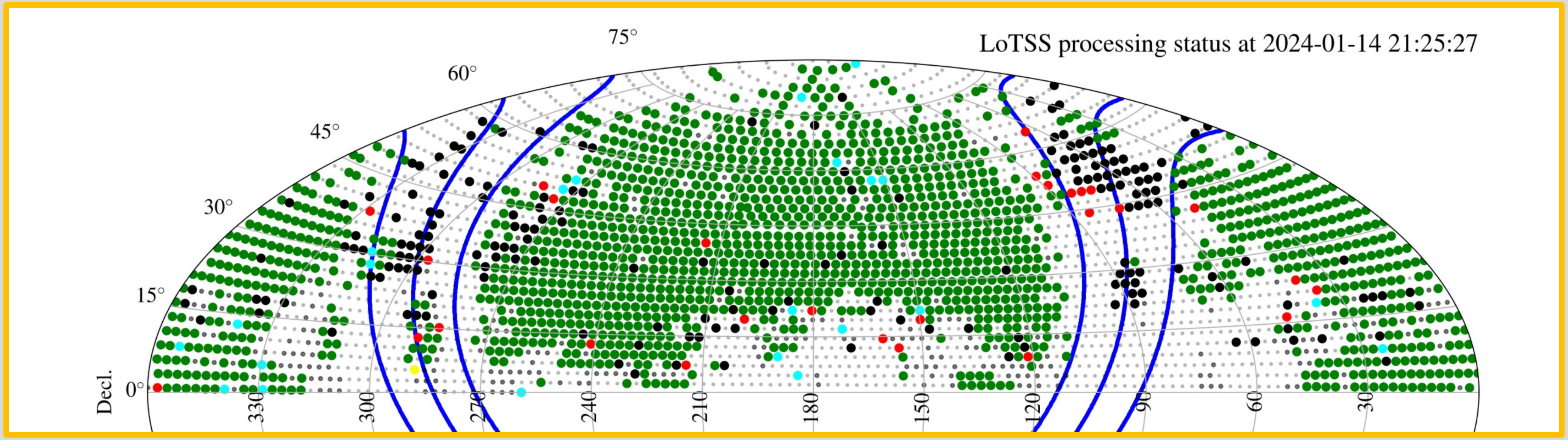
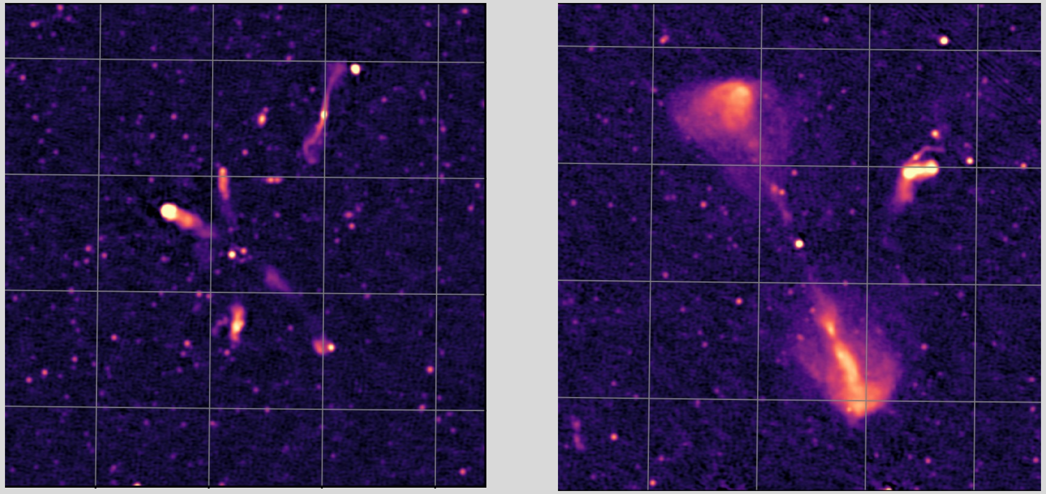
Current Observation Status:



See https://lofar-surveys.org/status.html

LOFAR Two-metre Sky Survey (LoTSS) Deep Fields

Aim: Observe four deep fields with LOFAR



- 144 MHz observations
- 6” resolution
- Boötes, Lockman Hole (Tasse+ 2021), ELAIS-N1 (Sabater+ 2021), North Ecliptic Pole (Bondi+ 2023)

Field	Obs. Time (hr)	$\mathrm{Area}^{\mathrm{full}}$ (deg^2)	N_S^{raw}	$\sigma_{\mathrm{med}}^{\mathrm{full}}$ (μJy beam^{-1})
LH	112	25.0	50112	42
Boo	80	26.5	36767	60
EN1	164	24.3	69954	33

Table from Mandal+ 2021, Images from Sabater+ 2021

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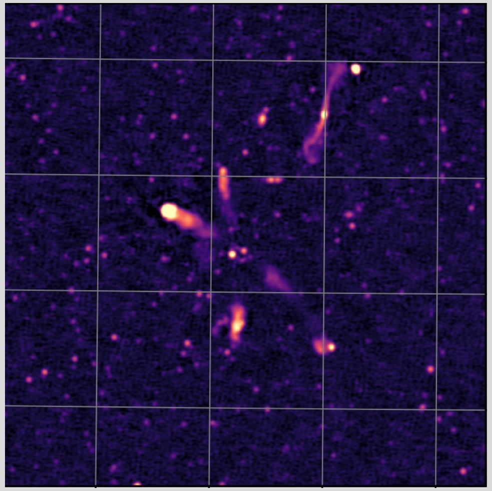

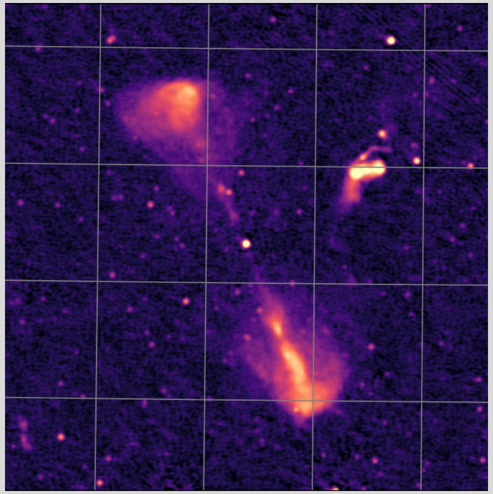

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- 144 MHz observations
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- Boötes, Lockman Hole (Tasse+ 2021), ELAIS-N1 (Sabater+ 2021), North Ecliptic Pole (Bondi+ 2023)

+ **Cross-matching** to **host galaxies** through likelihood ratios and Galaxy Zoo (Kondapally+ 2021)

+ **Redshifts** from photometric template fitting and machine learning (Duncan+ 2021)

+ **Source Classification** into source types (Best+ 2023)

All fields except for NEP

Cosmology from the Wide Area LOFAR Survey

LOFAR Two-metre Sky Survey (LoTSS) Wide Area

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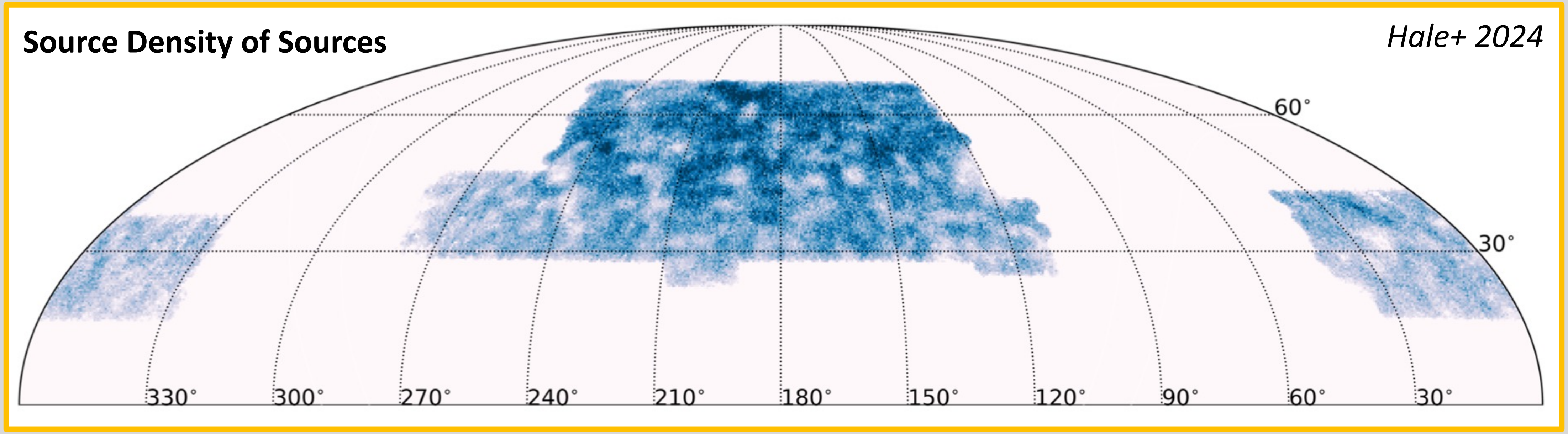


LOFAR Two-metre Sky Survey (LoTSS) Wide Area

Data Release 2 (Shimwell+ 2022):

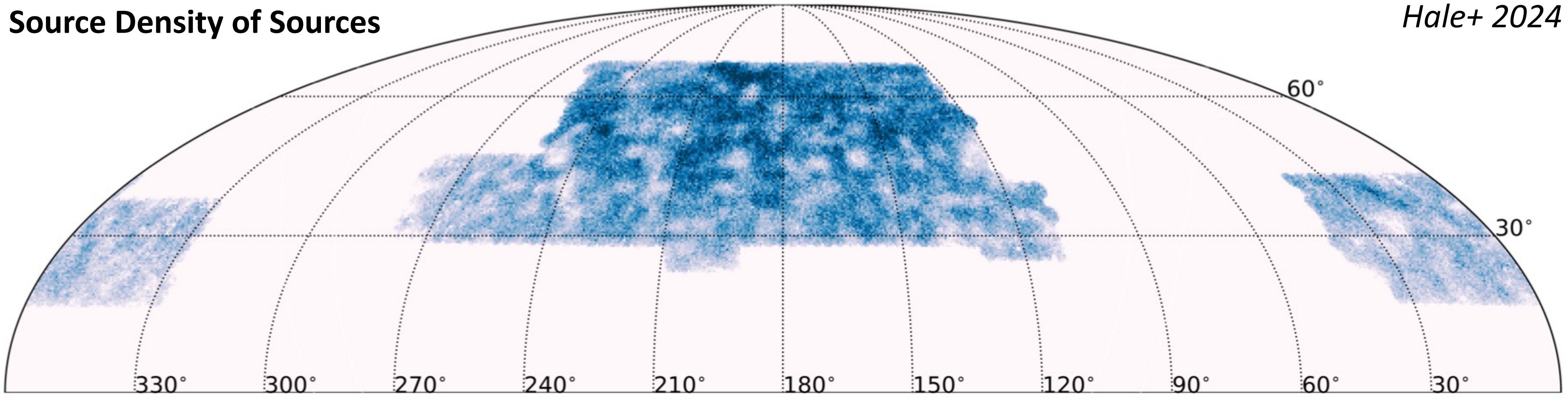
- 5600 sq. degrees
- ~4 million sources
- ~70-100uJy/beam rms

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

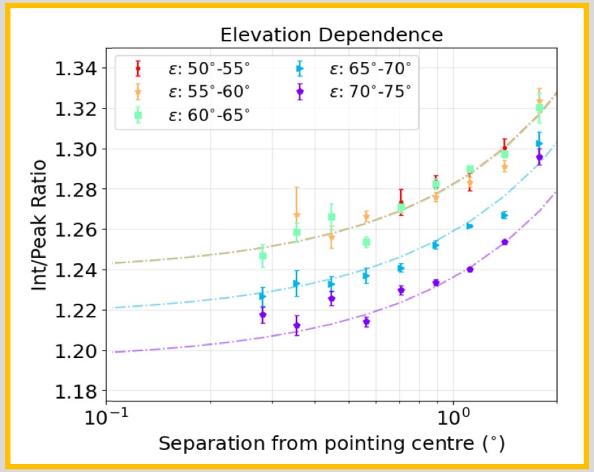
Hale+ 2024



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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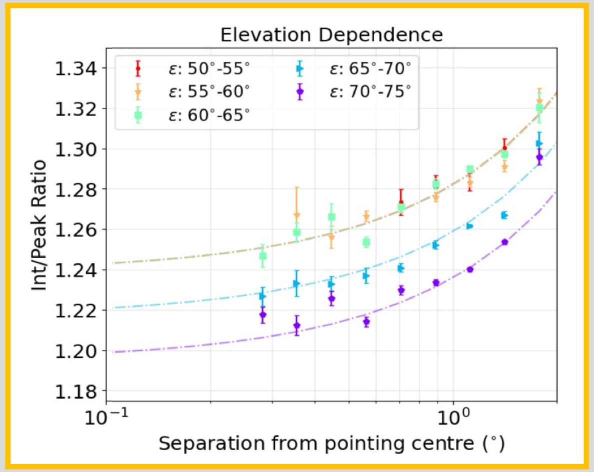
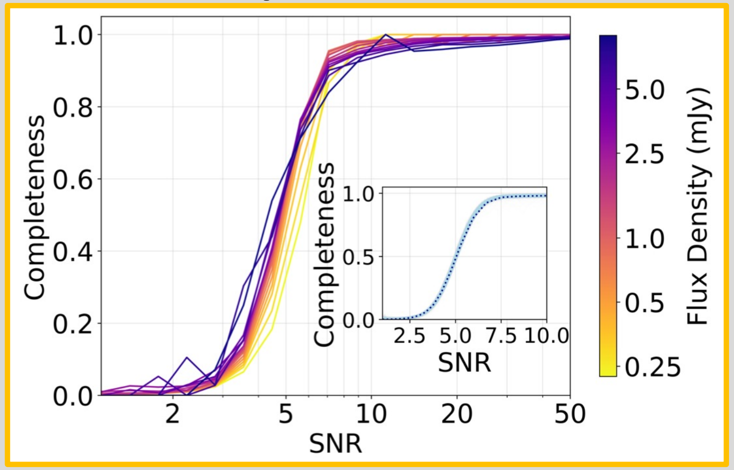
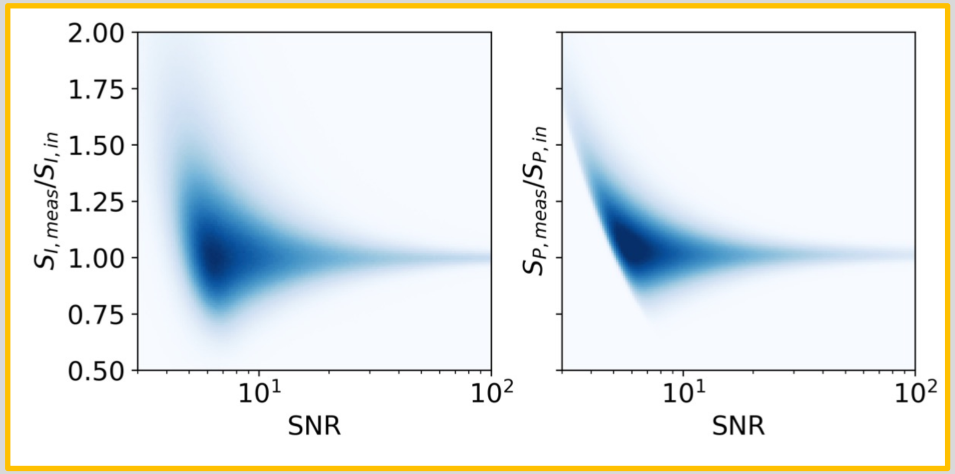


Incompleteness



Measurement Errors



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

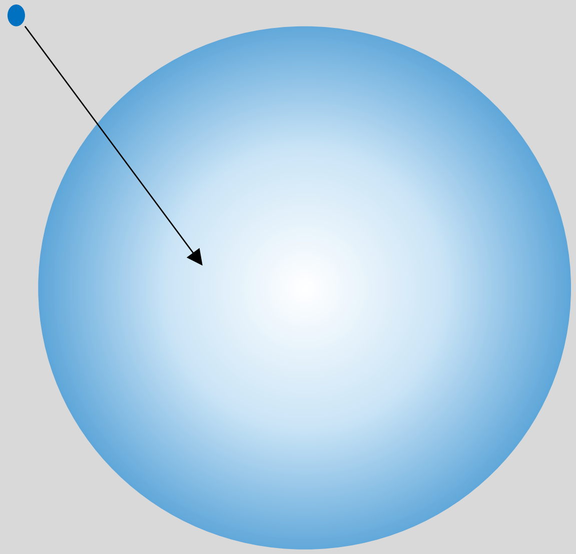
Use **simulations** from **Shimwell+ 2022** to investigate:
- **Incompleteness** (as a function of SNR)
- Differences between **simulated** and **measured** flux densities

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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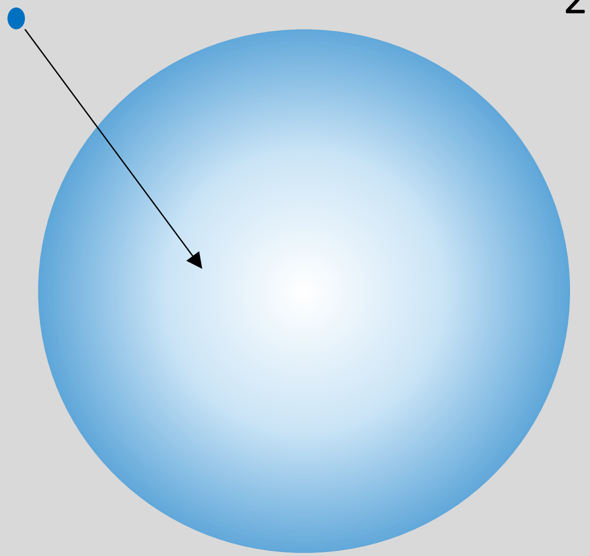

2) Apply **systematics**

- 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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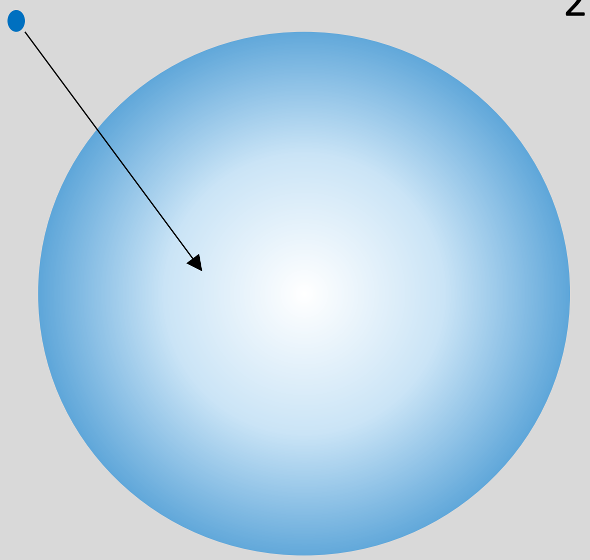

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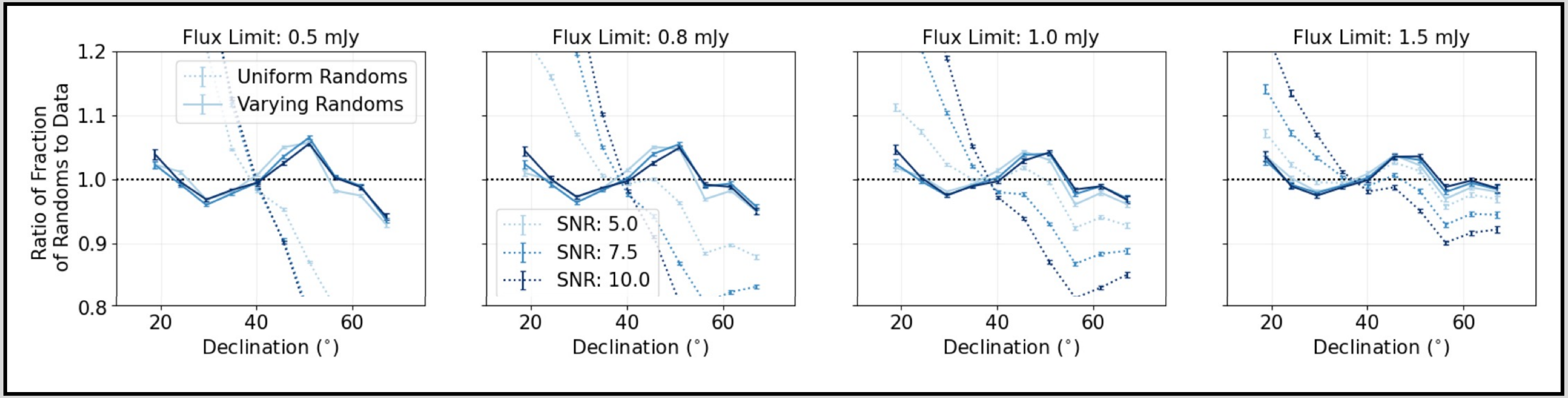
- Use this to obtain a **SNR** of the source
- Measure the **completeness** and sample to determine if the source is **detected**
- For detected sources determine the **measured** integrated and peak **flux densities**

3) Apply **additional** cuts

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

Simulated Random Catalogues



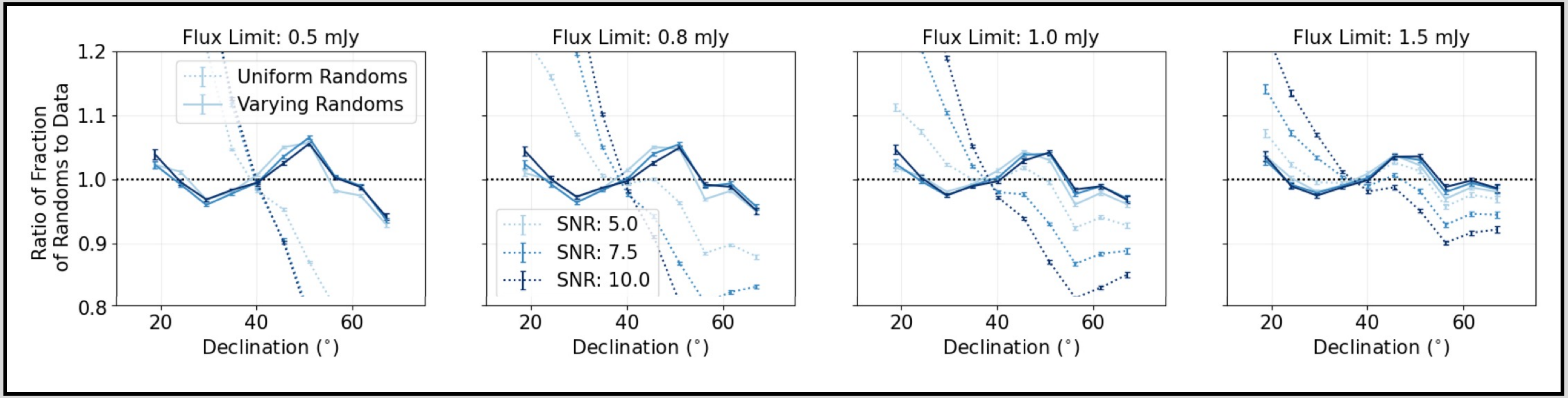
Dotted lines = Random sources uniformly distributed (i.e. not accounting for systematics)

Solid lines = Random sources accounting for systematics

Hale+ 2024

Simulated Random Catalogues

We are able to use this method to account for observational systematics and produce “random” catalogues which reflect the observational biases in the field



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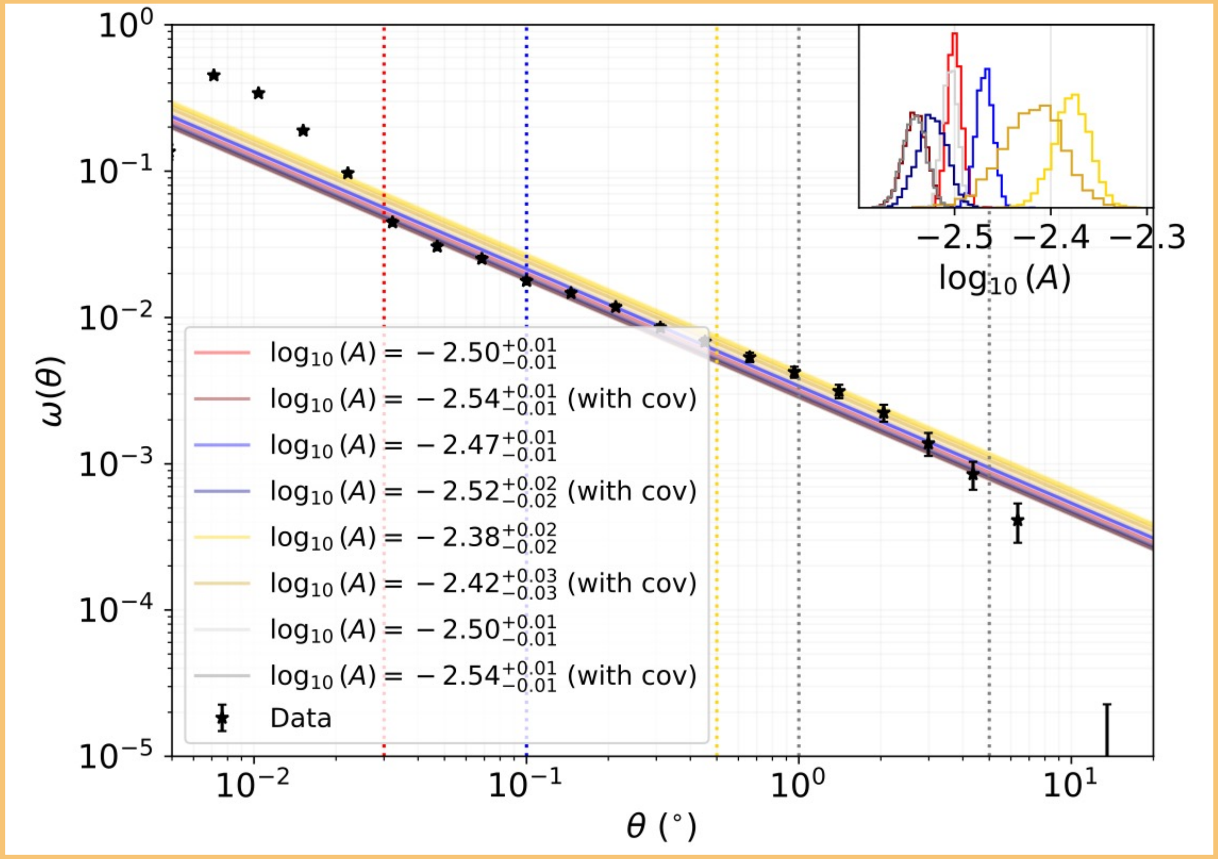
Hale+ 2024

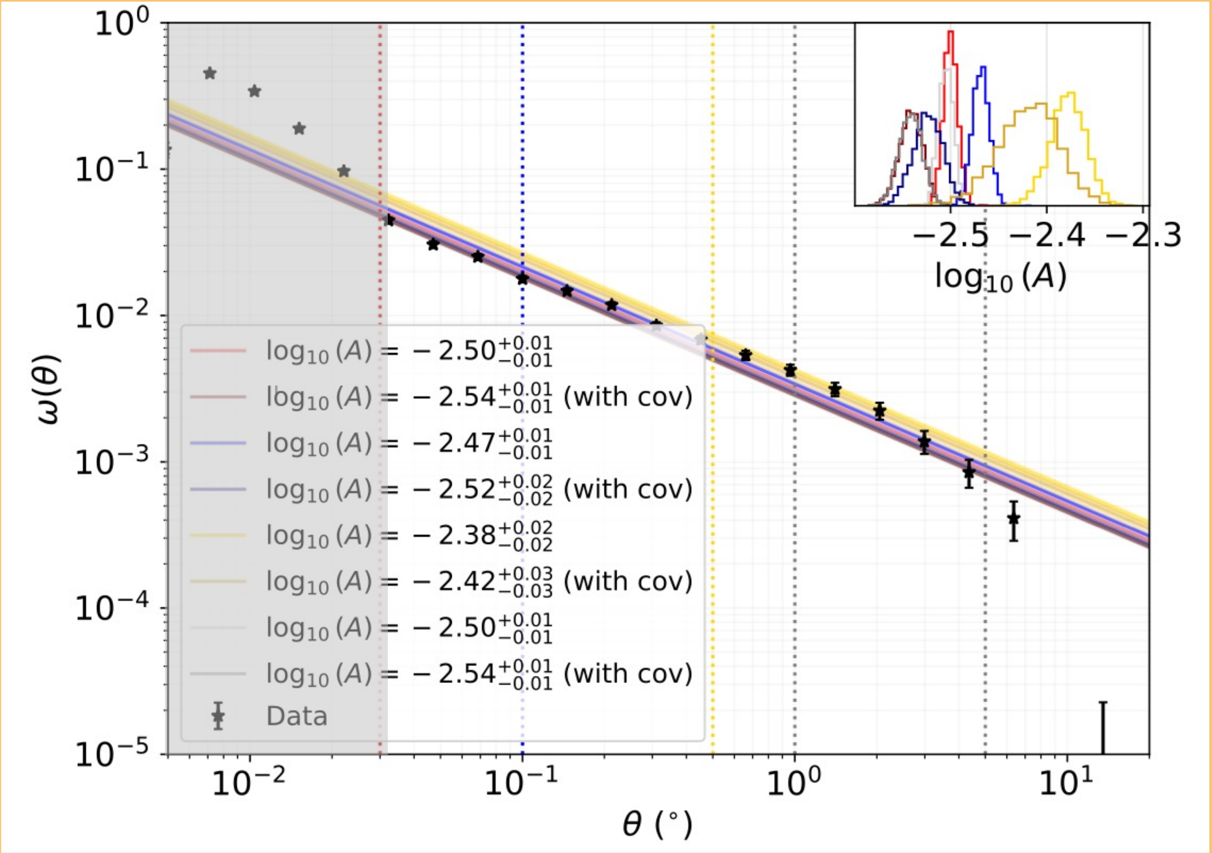
Angular Two-Point Correlation Function of LoTSS DR2



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

Hale+ 2024

Angular Two-Point Correlation Function of LoTSS DR2



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

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

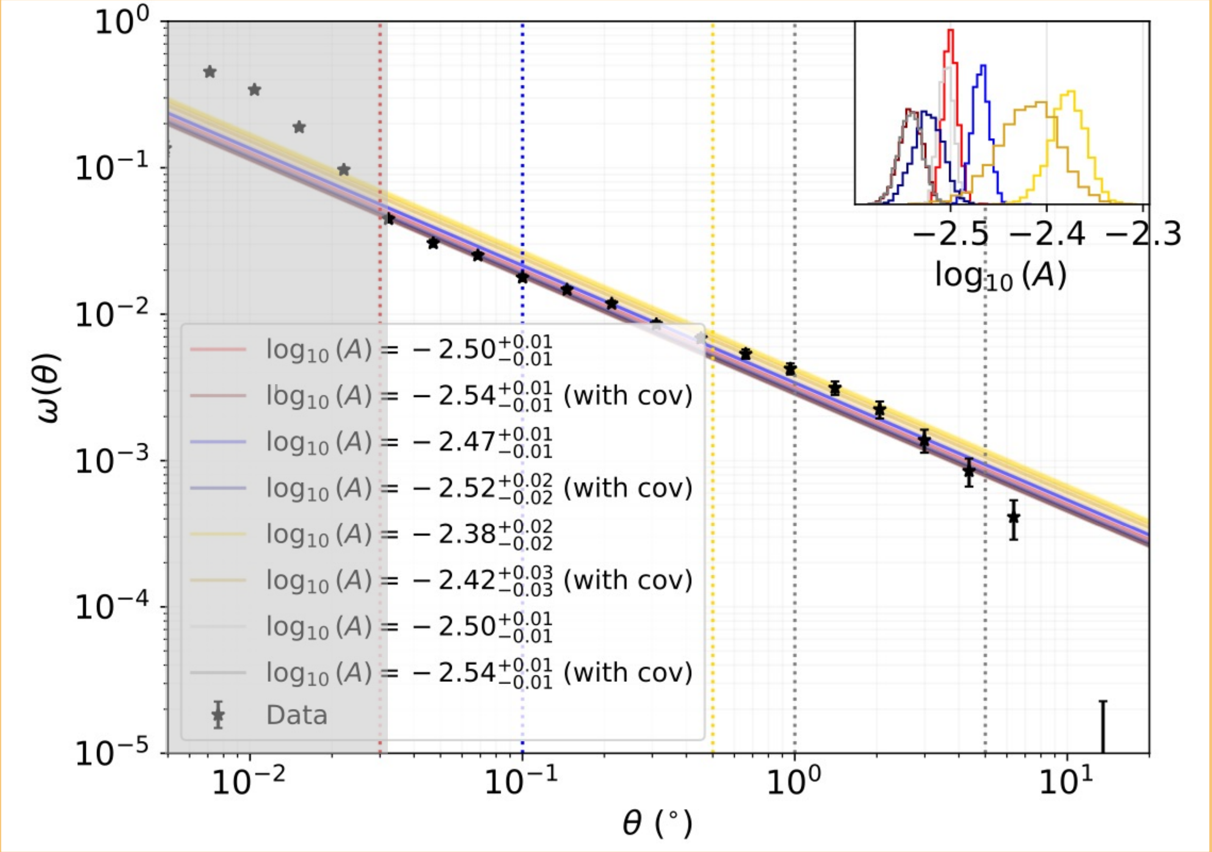
This likely has a significant contribution from multi-component radio sources.

Hardcastle+ 2023 create value added catalogues (i.e. with cross-matched multi-component sources) for >8 mJy sources.

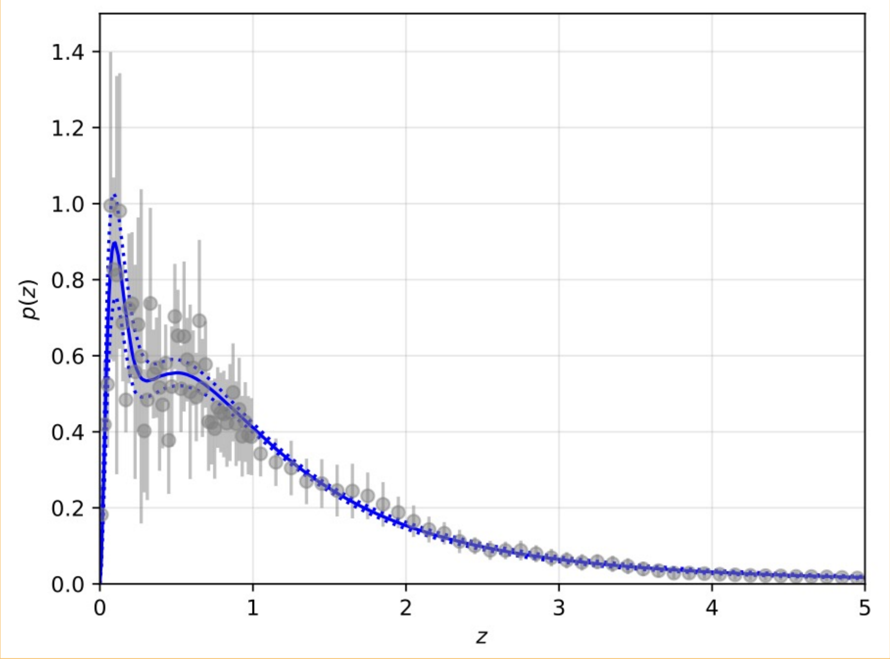
Therefore cannot fit below ~0.03 degree.

Hale+ 2024

Angular Two-Point Correlation Function of LoTSS DR2



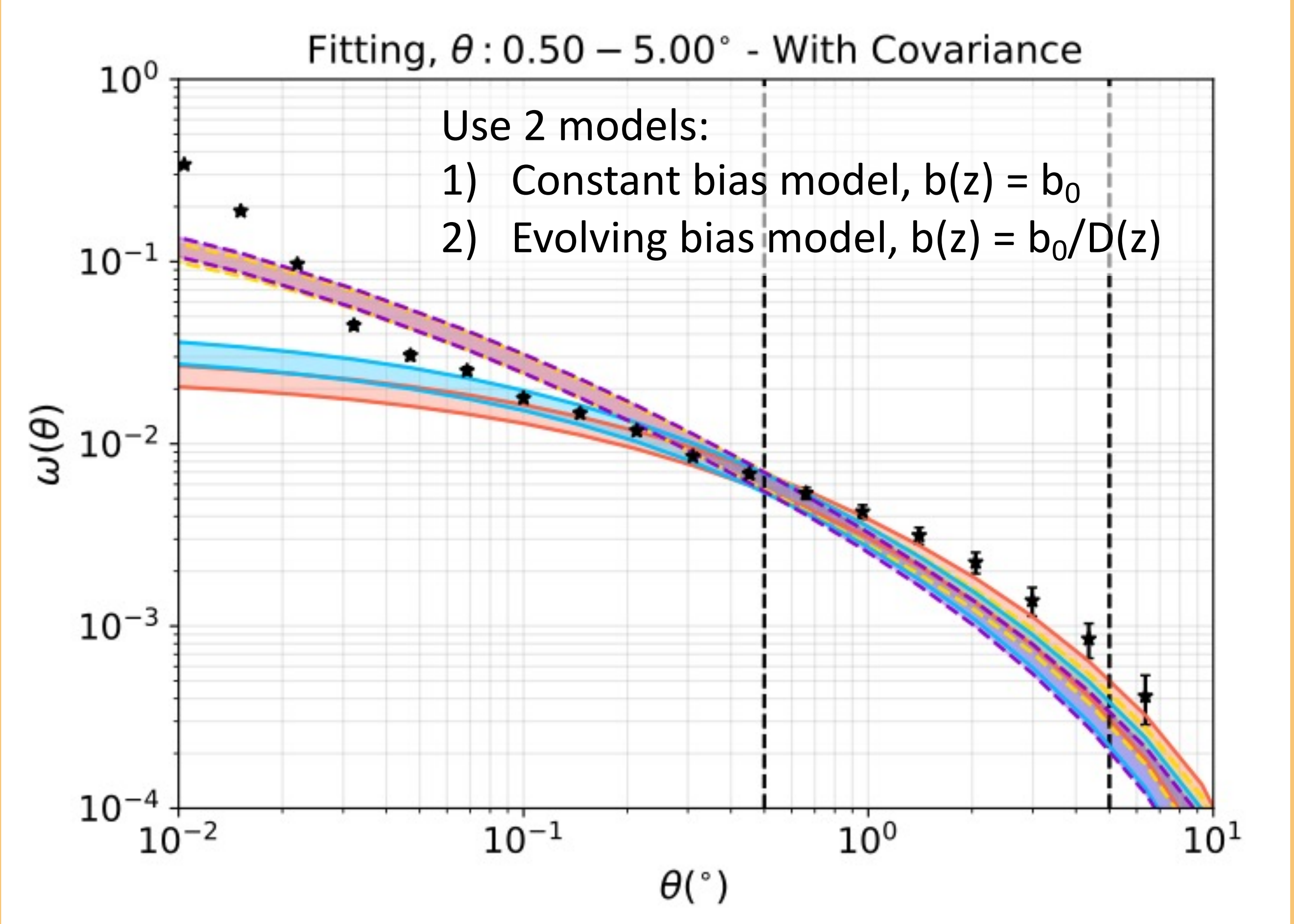
+ Use Redshift Distributions from LoTSS Deep Fields to model the clustering and infer galaxy bias using PyCCL (Chisari+ 2019)



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

Hale+ 2024

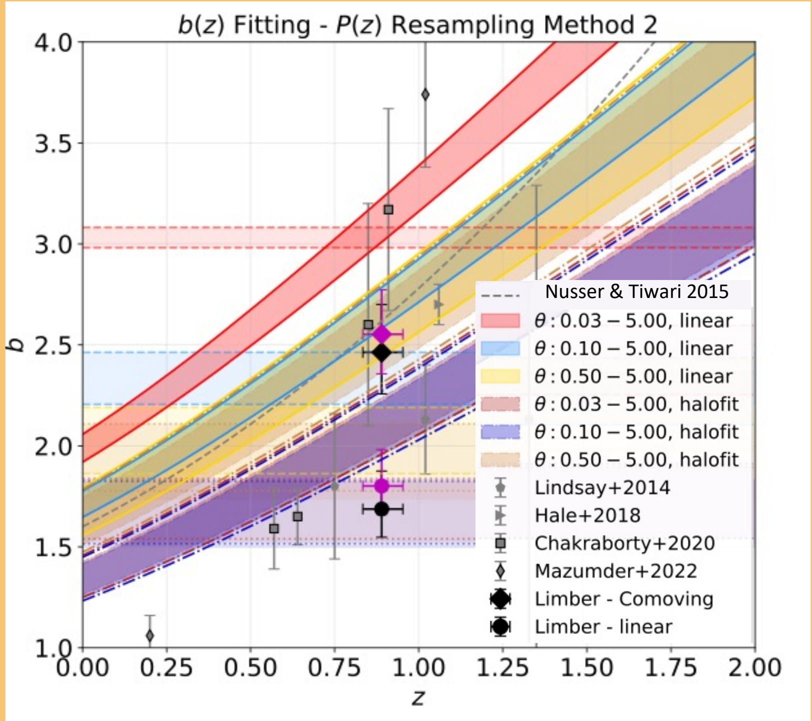
Modelling Galaxy Bias



Use 2 models:

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

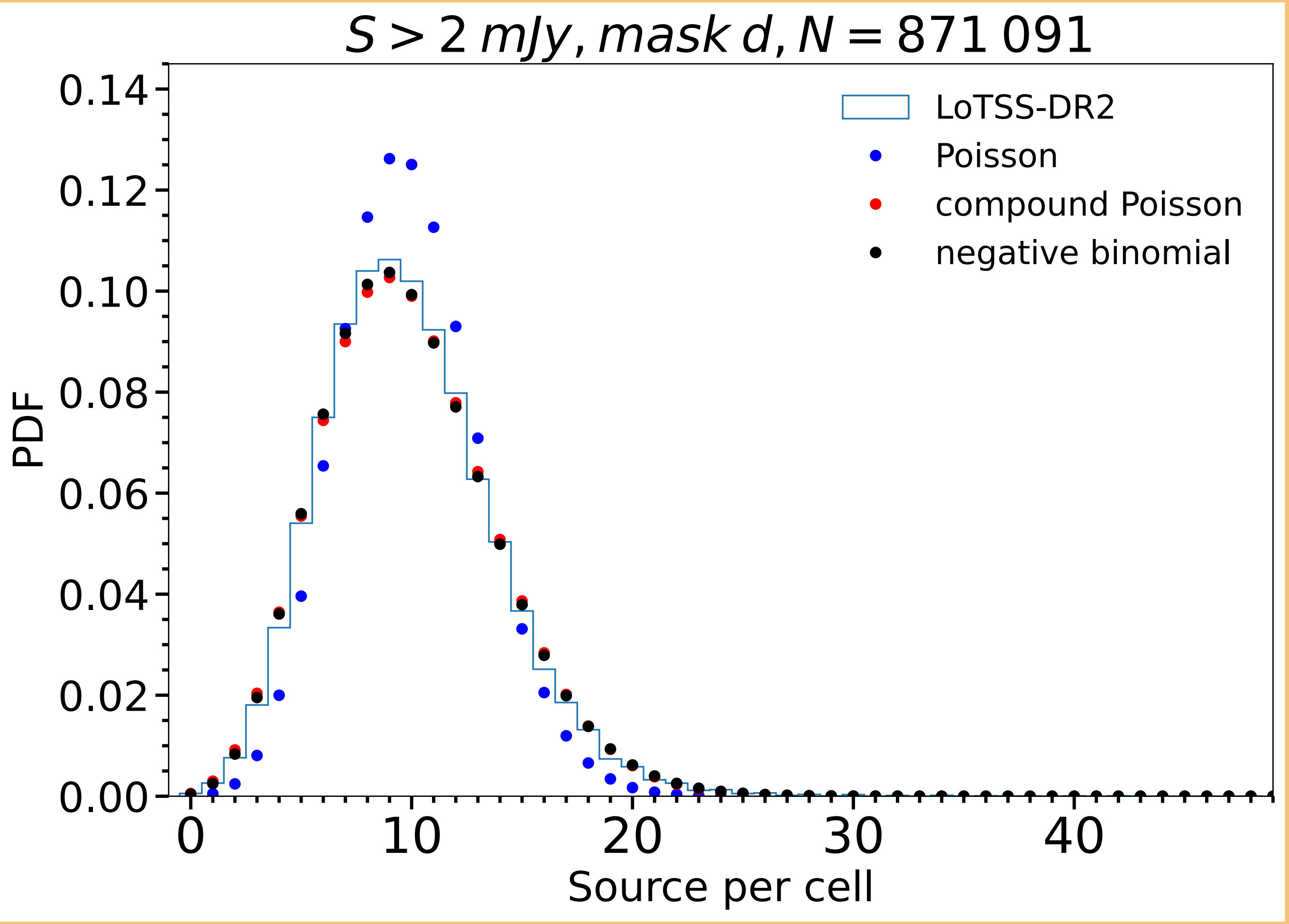
To agree with N(z) predictions from previous cross correlations with CMB (Alonso+ 2020) we must have evolving bias model



Other Cosmology Studies with LoTSS-DR2

Work in progress

One-point statistics (Pashapour-Ahmadabadi in prep)



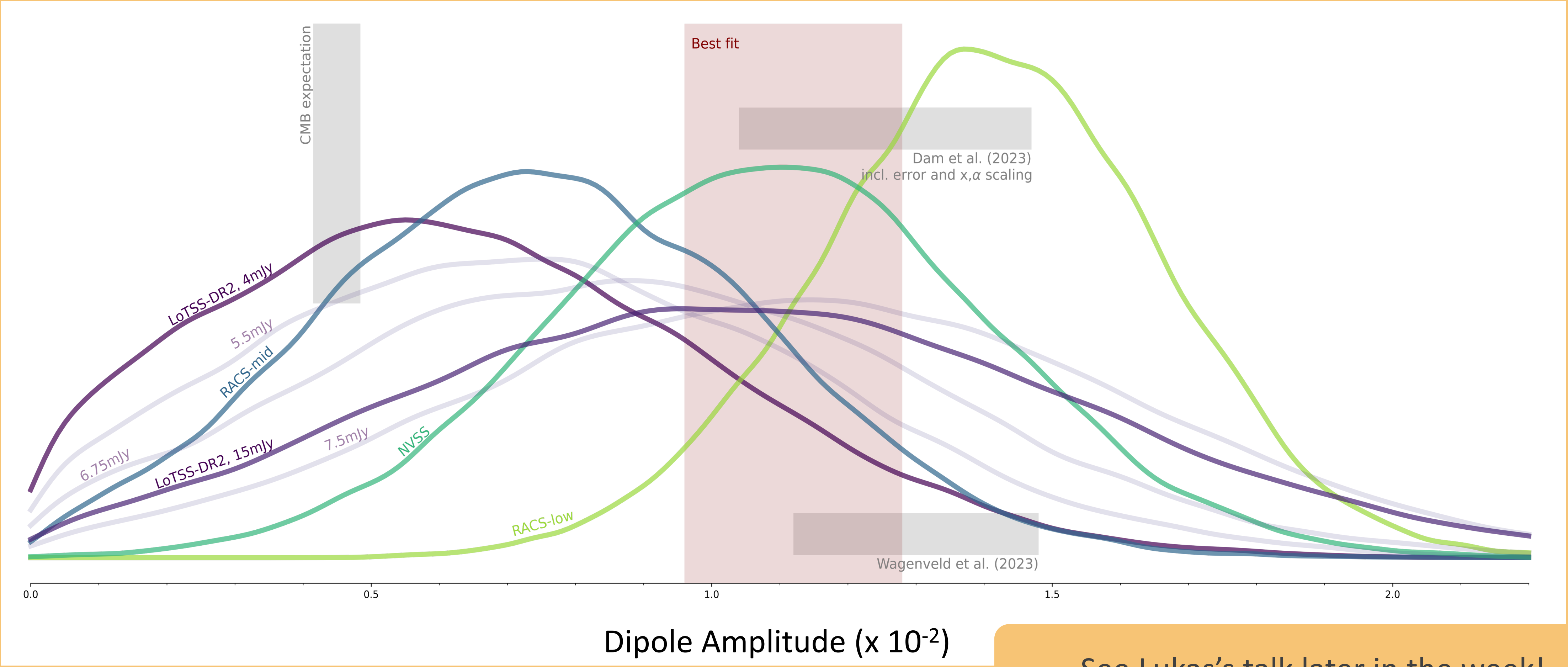
Use the counts of radio sources in cells to investigate the distribution of sources.

It is not well modelled by a Poisson process alone.

See Morteza's talk later in the week!

Work in progress

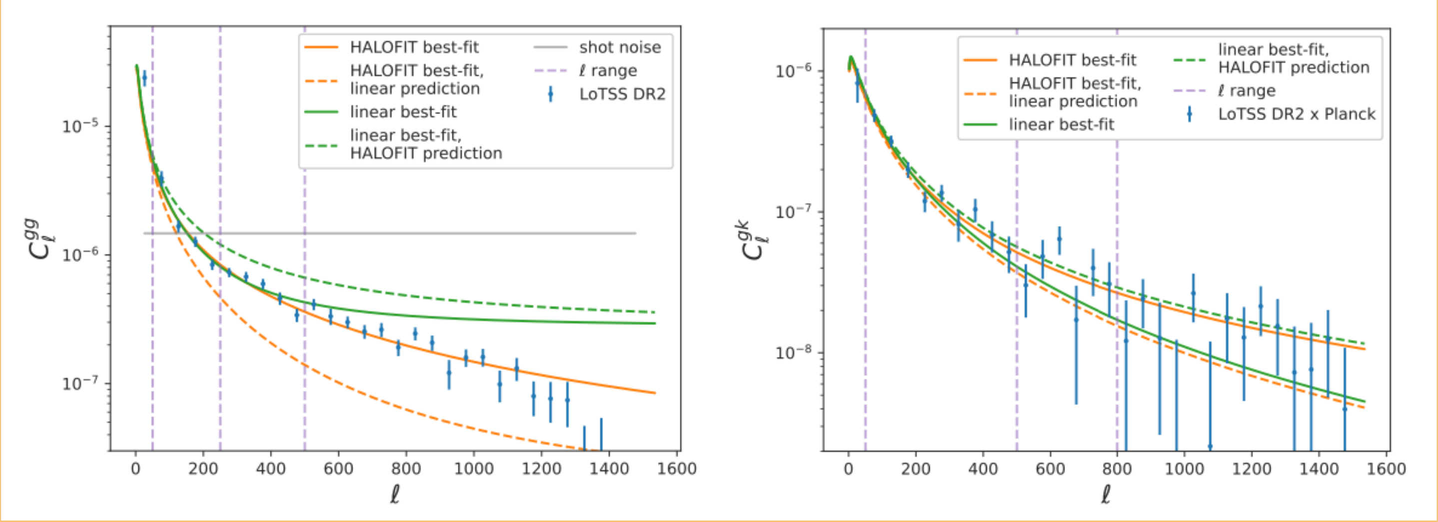
Radio Dipole (Böhme+ in prep)

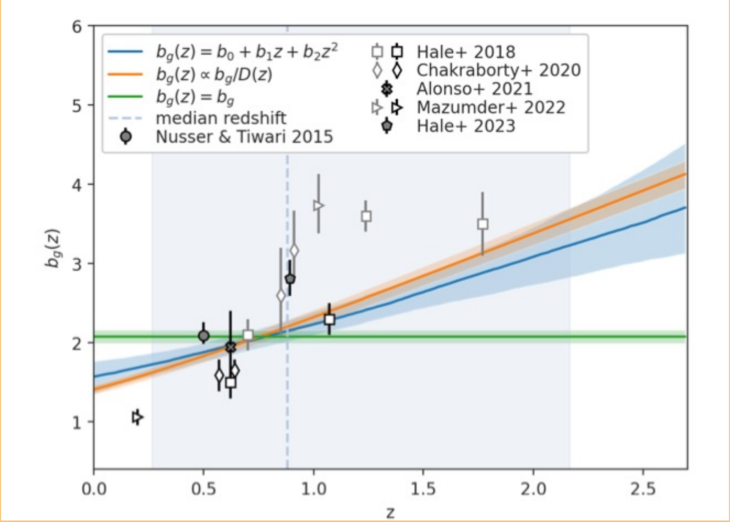


See Lukas's talk later in the week!

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 $\boldsymbol{\sigma_8}$

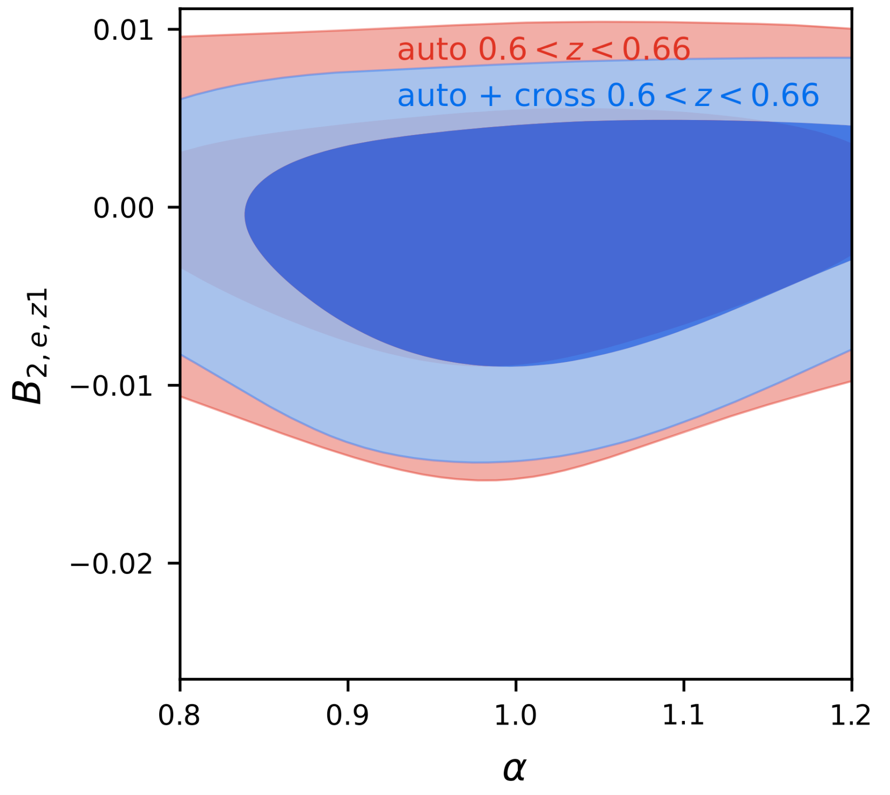




Work in progress

Cross-correlating with eBOSS (Zheng+ in prep)

(a nuisance parameter to do with the shape of the power spectrum)



(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**

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

See Jinglan's talk later in the week!

Limitations in bias constraints from LoTSS-DR2

The study into the angular clustering relies on a number of assumptions:

1) The bias evolves using one of the two models considered

2) The SFGs and AGN have similar bias evolution over time

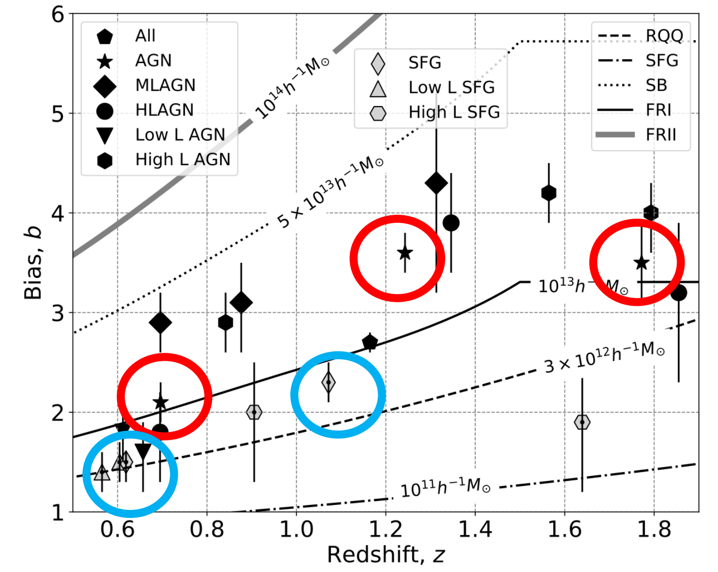
Limitations in bias constraints from LoTSS-DR2

The study into the angular clustering relies on a number of assumptions:

1) The bias evolves using one of the two models considered

2) The SFGs and AGN have similar bias evolution over time

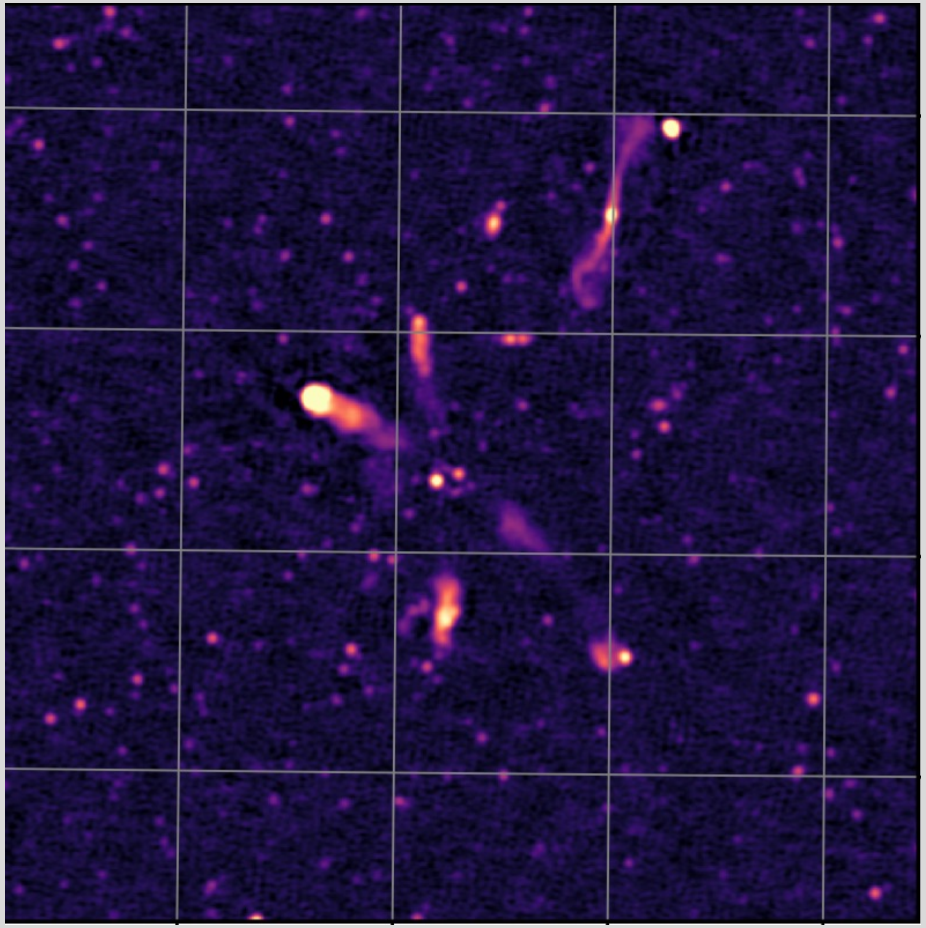
AGN vs **SFG**



Hale+ 2018

LOFAR Deep Fields

- Deep (~20-30 uJy/beam) observations over 3 deep fields: ELAIS-N1, Lockman Hole, Boötes (Sabater+ 2021, Tasse+ 2021)
- Source association presented in Kondapally+ 2021
- Redshifts/Stellar masses in Duncan+ 2021
- Source Classifications in Best+ 2023



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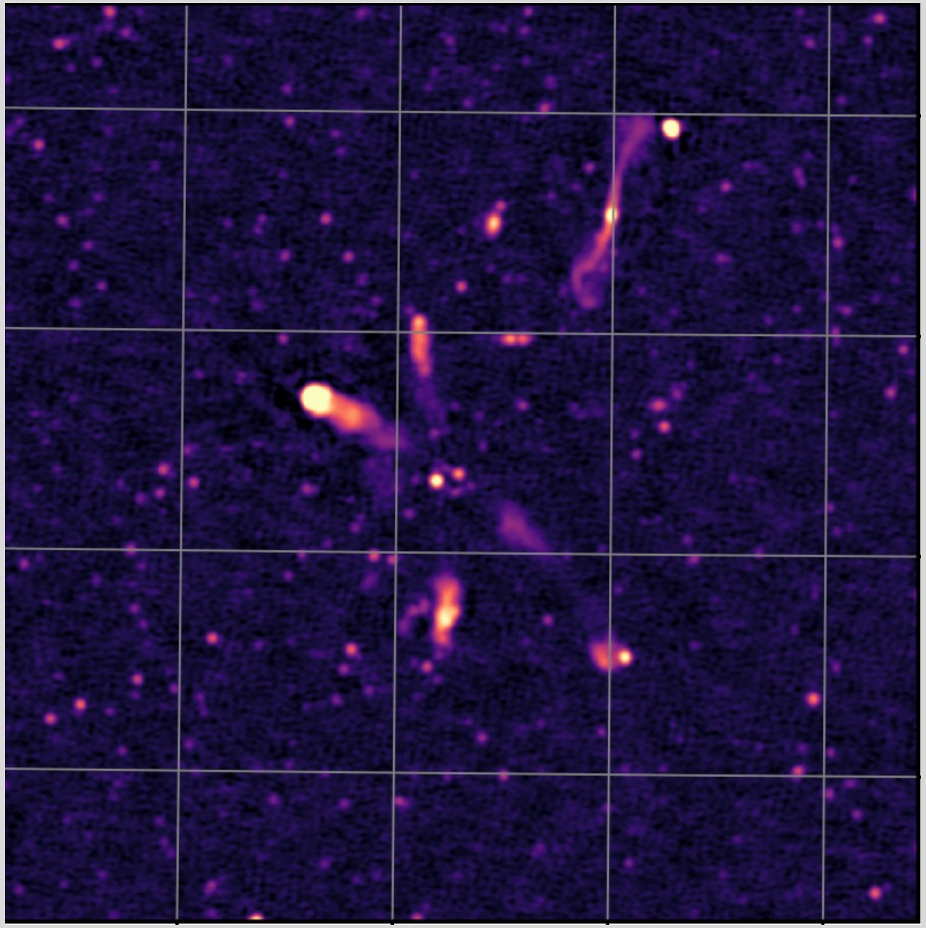
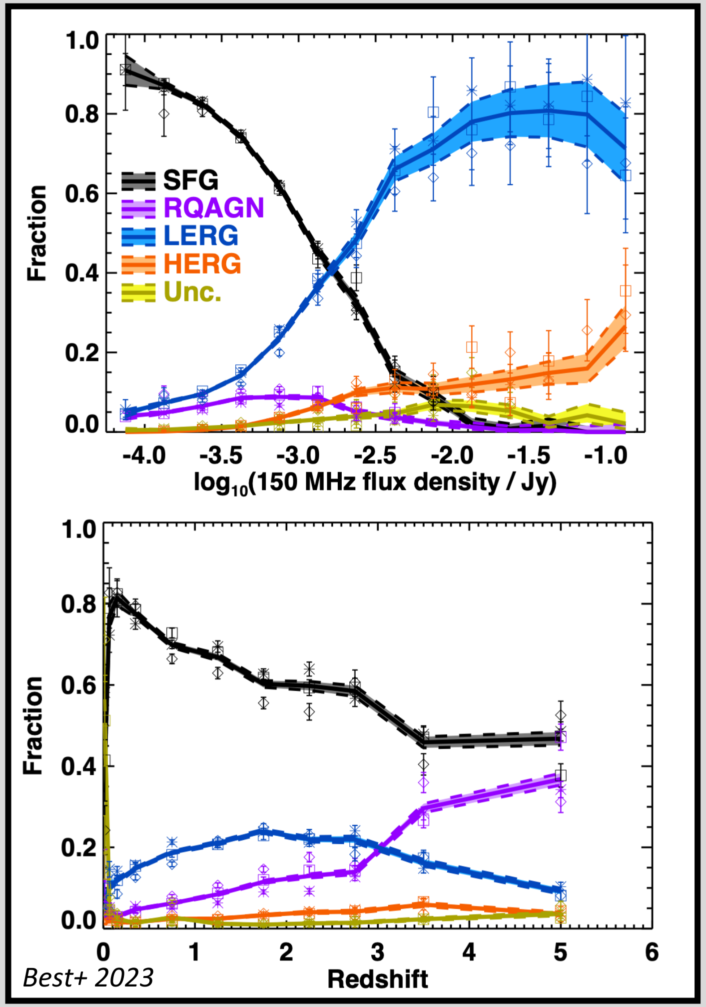
No small-scale clustering from multi-component sources, only 1-halo

Split source populations and investigate bias evolution

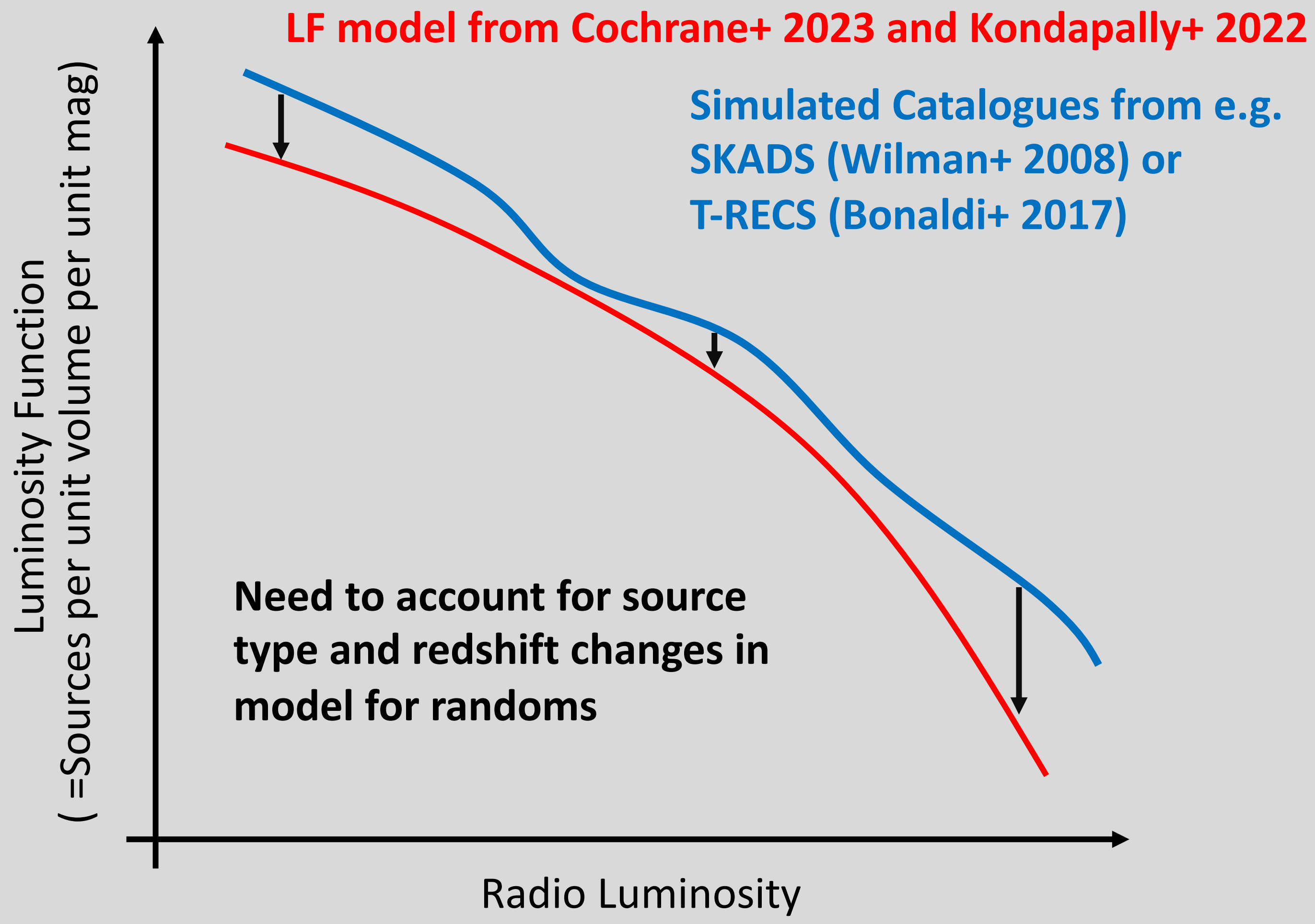


Hale+ in prep

Randoms Input for LoTSS Deep

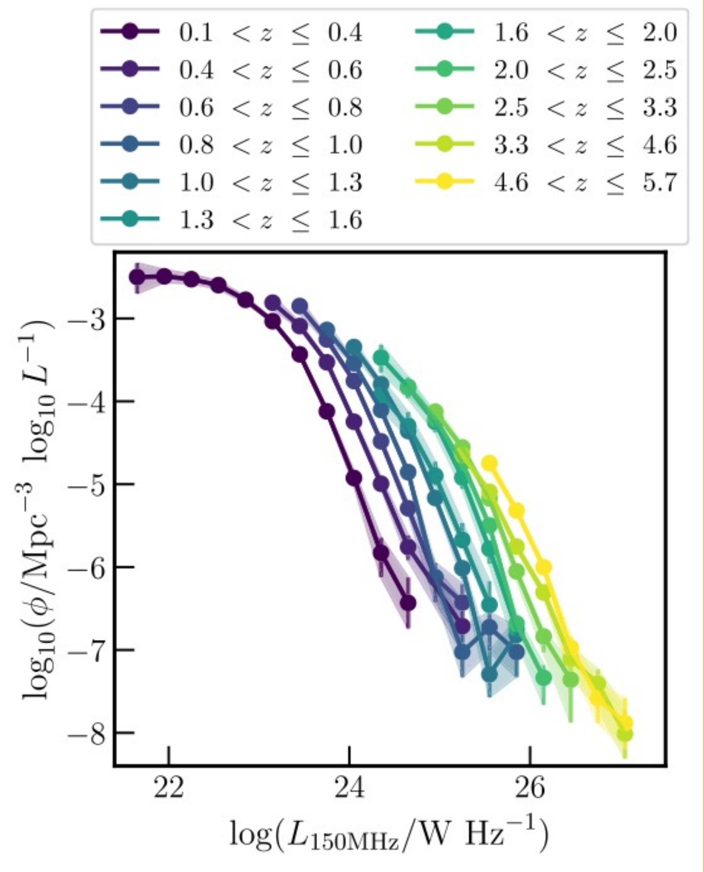


Best+ 2023



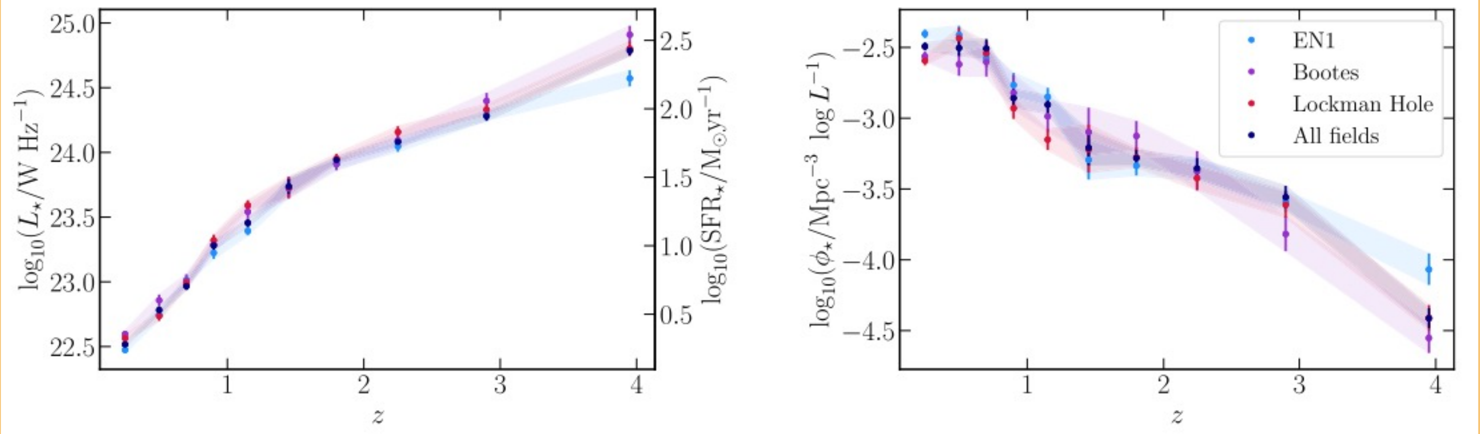
Randoms per Source Type

SFG Luminosity Function



Figures from Cochrane+ 2023

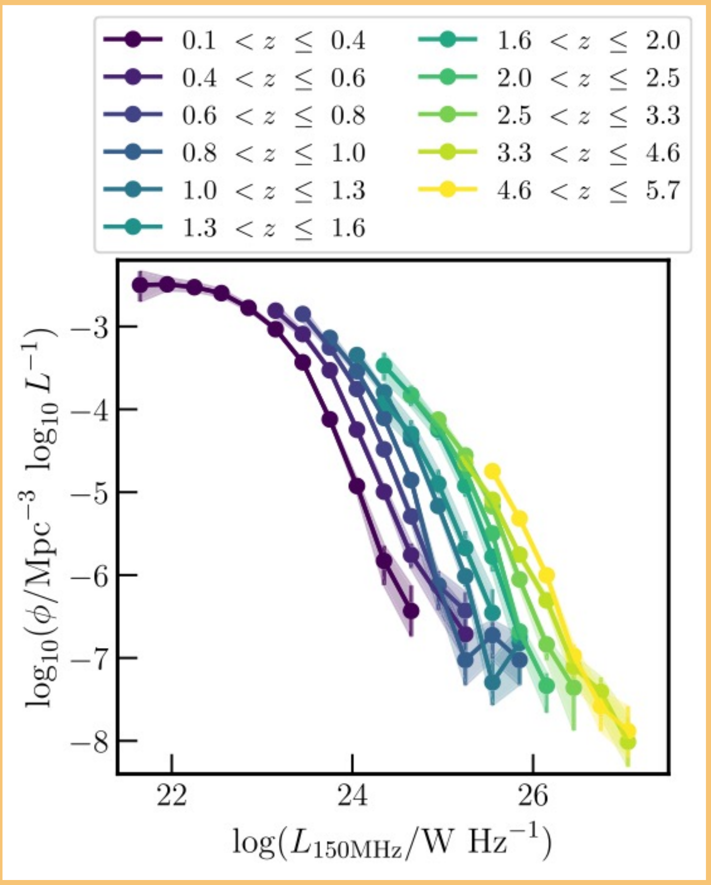
SFG Luminosity Function parameter evolution



- Use modelling of **LOFAR luminosity function** (LF; Kondapally+ 2022, Cochrane+ 2023) parameters to construct LFs in small z bins (dz = 0.025)

Randoms per Source Type

SFG Luminosity Function



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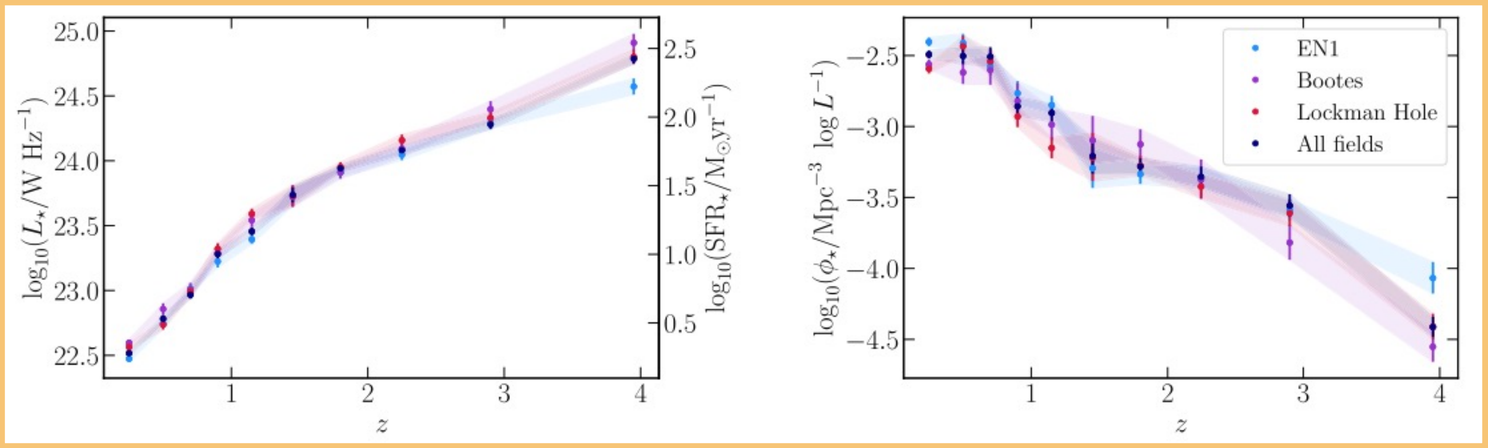

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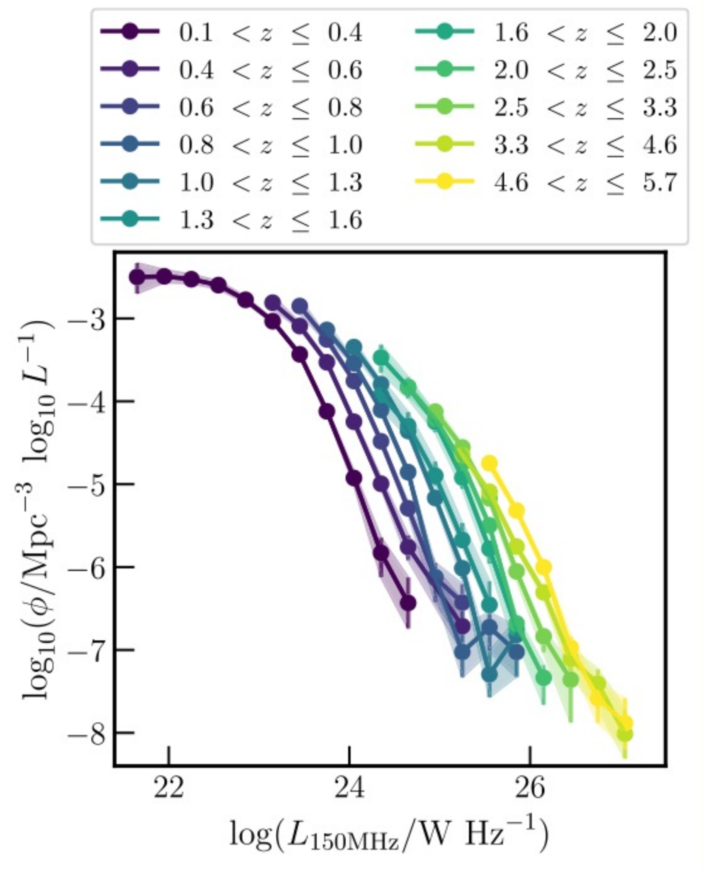
- **Down sample** the LF from the input random catalogue so they agree with **the model LF**

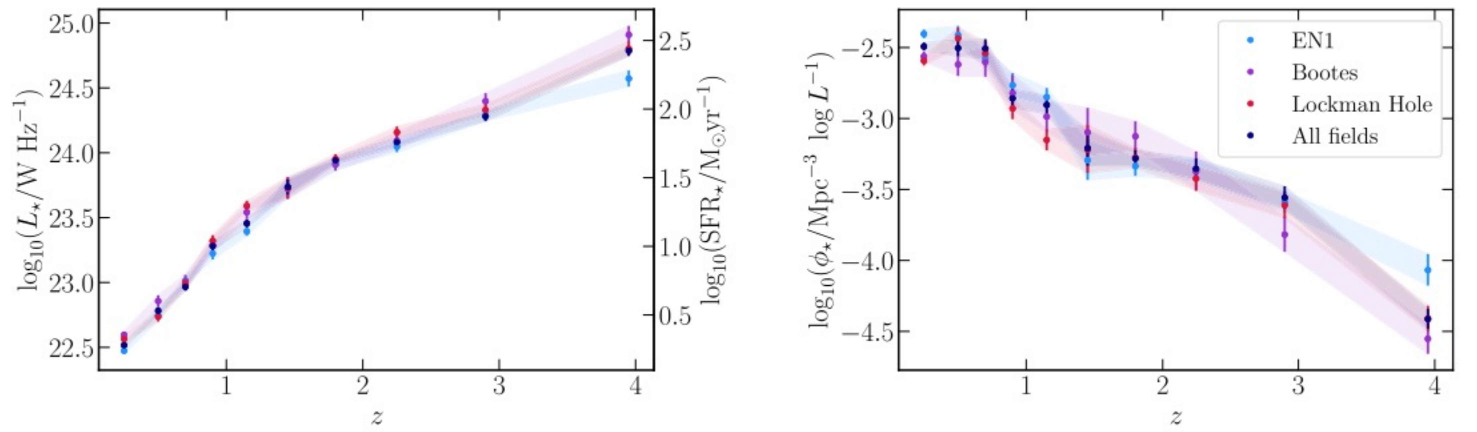
Figures from Cochrane+ 2023

Randoms per Source Type

SFG Luminosity Function



SFG Luminosity Function parameter evolution



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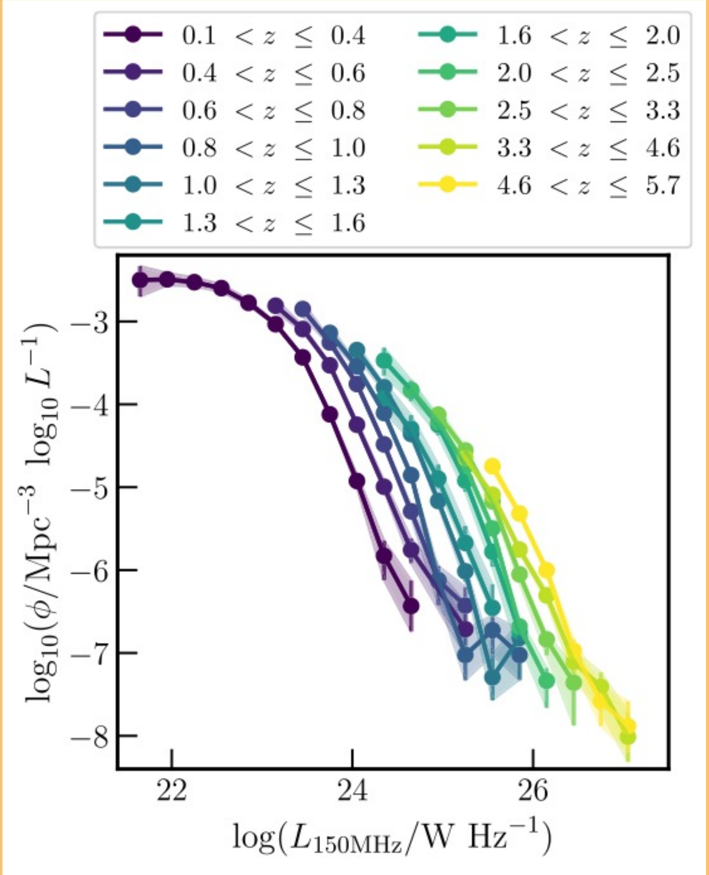
- **Combine** the z bins together to get randoms over the **full z range** (dz = 0.2-0.5 depending on source type)

Figures from Cochrane+ 2023

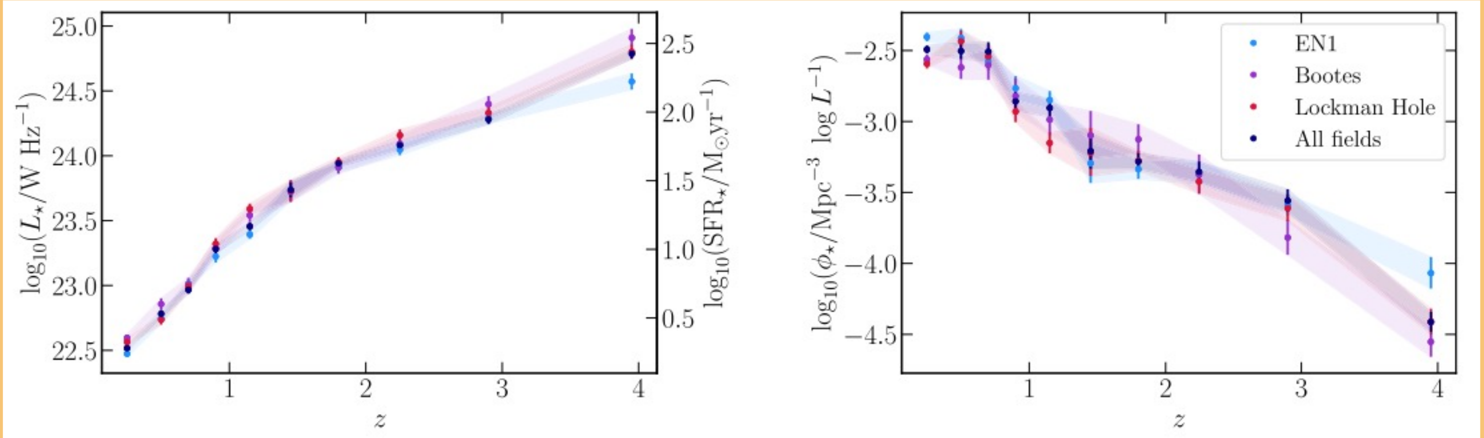
Randoms per Source Type

SFG Luminosity Function



Figures from Cochrane+ 2023

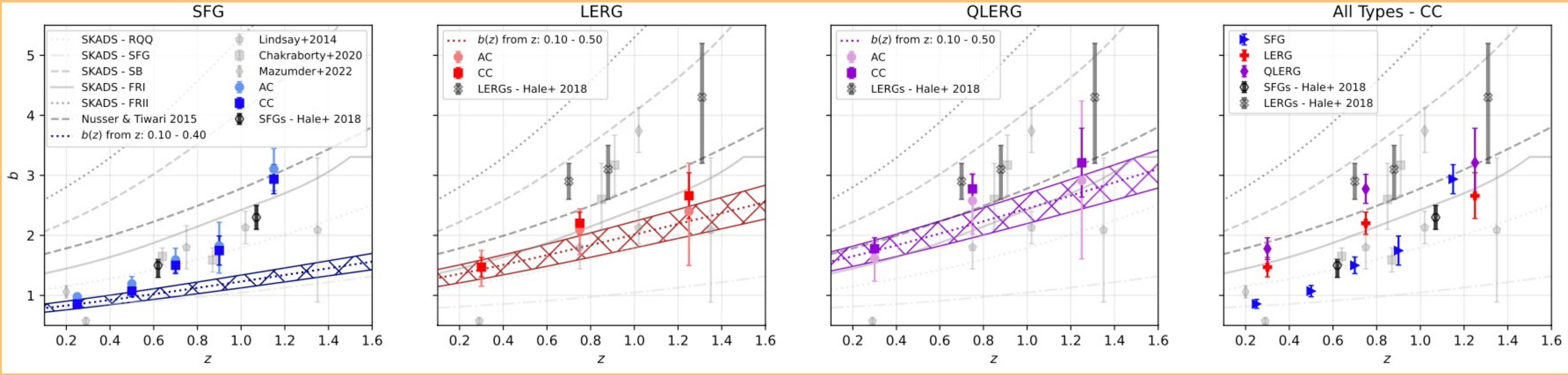
SFG Luminosity Function parameter evolution



- Use modelling of **LOFAR luminosity function** (LF; Kondapally+ 2022, Cochrane+ 2023) parameters to construct LFs in small z bins (dz = 0.025)
- **Down sample** the LF from the input random catalogue so they agree with **the model LF**
- **Combine** the z bins together to get randoms over the **full z range** (dz = 0.2-0.5 depending on source type)
- 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

Hale+ in prep

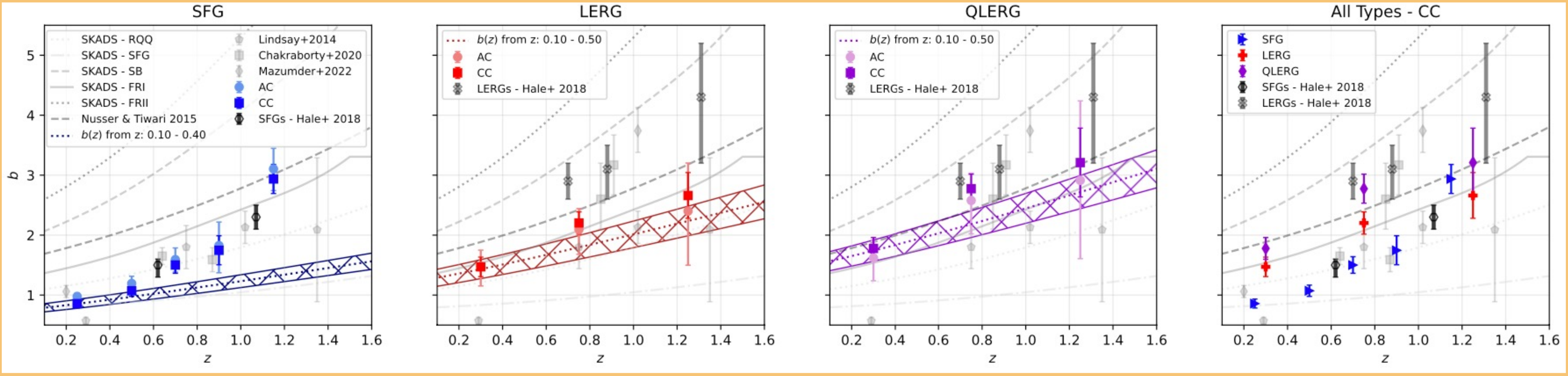
Results



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

Hale+ in prep

Results



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Good agreement between **Hale+ 2018** SFGs and **this work** and Hale+ 2018 LERGs and the QLERGs (which are more similar based on selection function used in Smolčic+ 2017)

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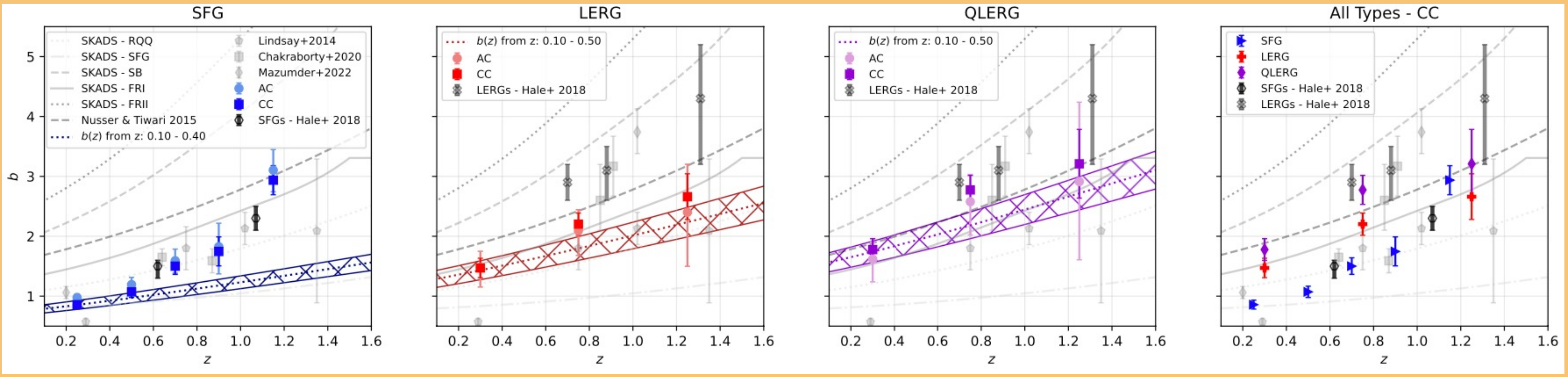

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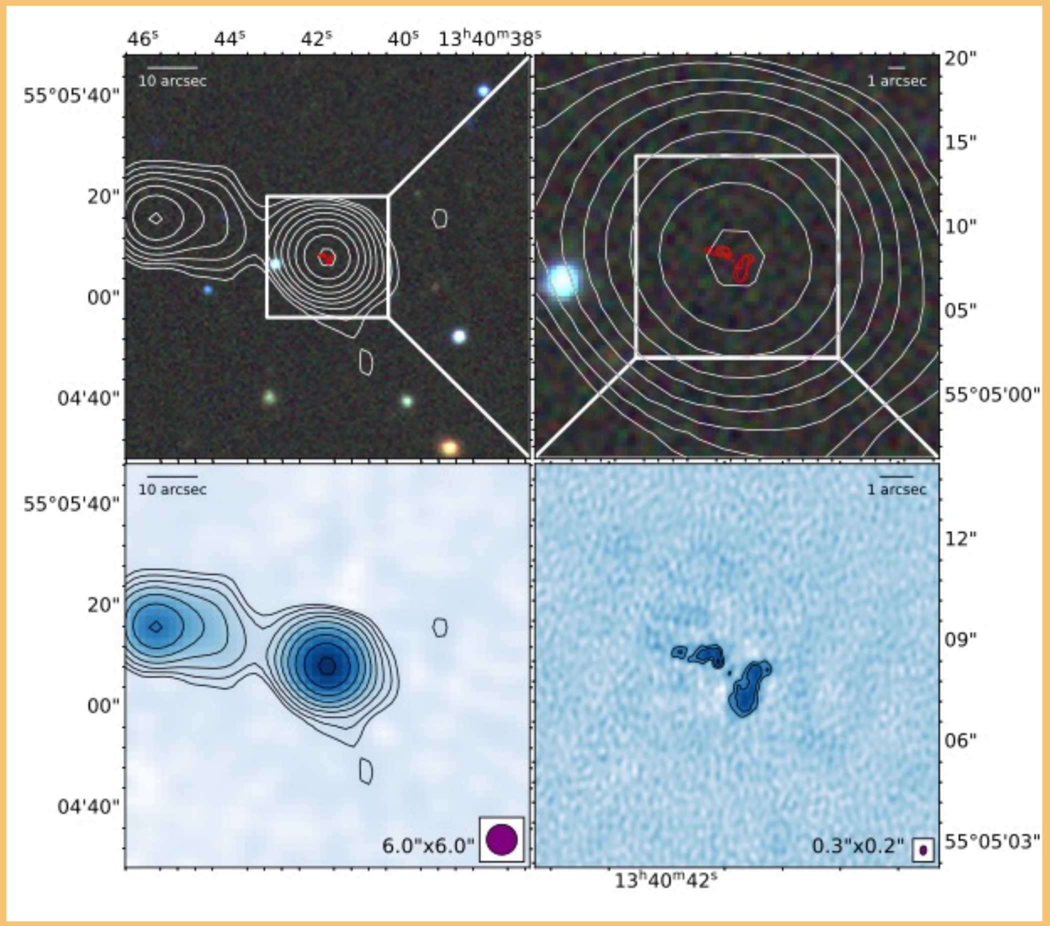
(which are more similar based on selection function used in Smolčic+ 2017)

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

Future with LOFAR

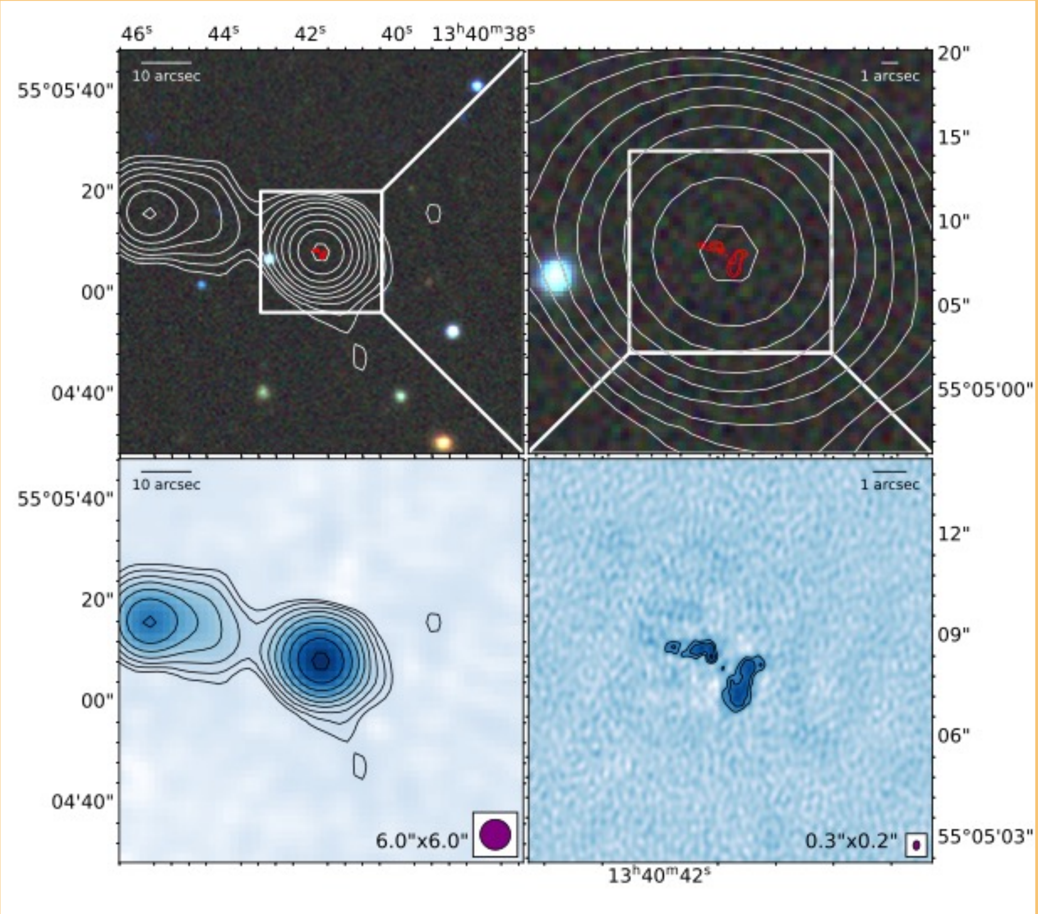
LOFAR High Resolution



Morabito+ 2022

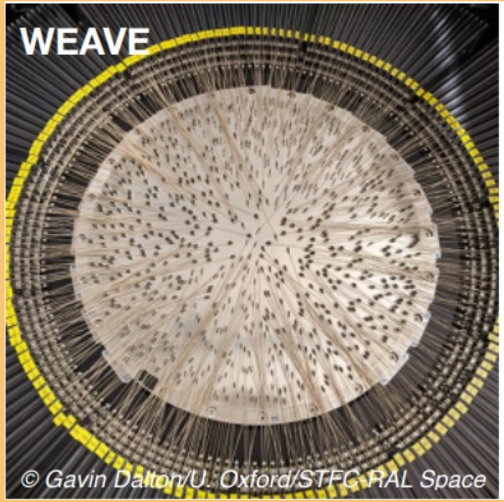
Future with LOFAR

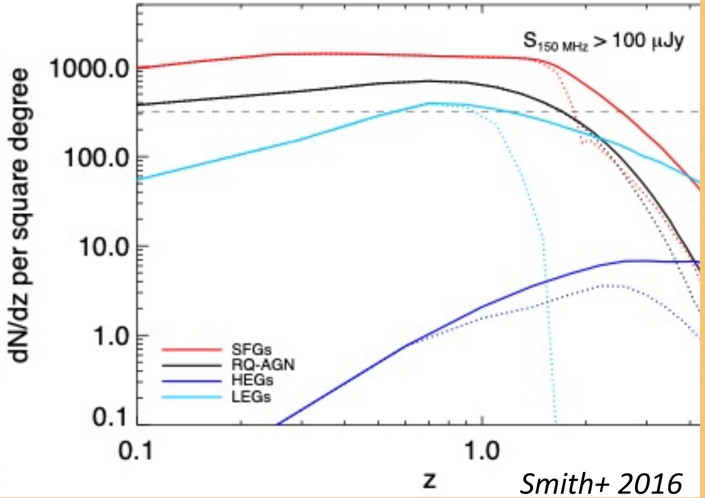
LOFAR High Resolution



Morabito+ 2022

LOFAR Follow up Redshift Survey: WEAVE-LOFAR





Smith+ 2016

Future with LOFAR

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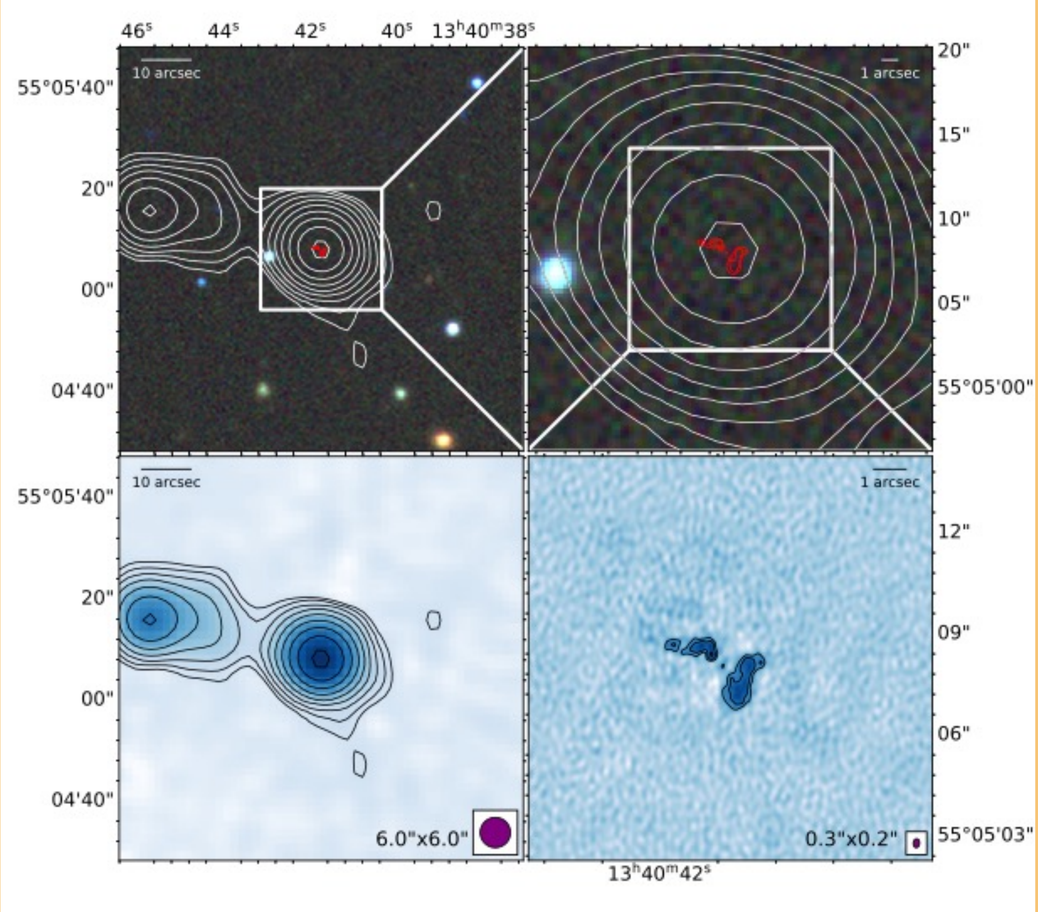

Morabito+ 2022

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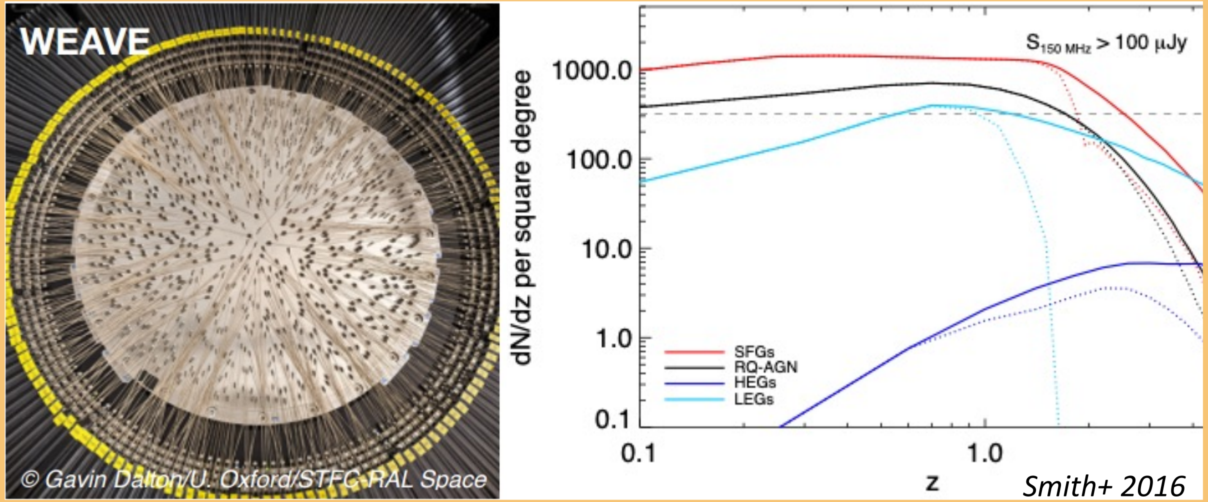

Smith+ 2016

Combination of **High-resolution** imaging (better classification + host galaxy association) and **redshifts** (no need for angular clustering) will be crucial in improving **cosmology** studies **with LOFAR** in the future.

+ **LOFAR 2.0** Upgrade (and associated surveys)

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
- **Hale et al. in press** has studied the **evolving bias** in the **LoTSS DR2** wide area survey and other works e.g. **Nakoneczny et al. in press** use **cross-correlations** 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** which target radio sources (e.g. **WEAVE-LOFAR**, Smith+ 2016, and **ORCHIDSS**, Duncan+2023) will allow us to **directly** measure **the spatial correlation function**, not use projected angular clustering