Mocking radio skies with realistic clustering
empirical full-sky simulations of SFG+AGN+HIG

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Preparatory science: what do you expect to see?

Models of the expected datasets are necessary

- to best **design surveys** that meet the various scientific objectives
- to **understand the computational and data analysis challenges** posed by the new observations
- to **test/demonstrate** the validity of ideas and **approaches being developed** for the specific experiment

***"ab initio"* approaches:**

Full-hydrodynamical simulations

- sub-grid modelling uncertain
- **HUGE** computational cost

Semi-analytical

- degeneracy of model parameters
- lots of fine-tuning

Empirical models

- no explicit modelling of baryon physics
- observed galaxy-simulated DM link is adjusted via tunable parameters
- tune ab initio models → help constrain relevant physical processes
- fast and realistic (by construction) → forecasting results from obs.

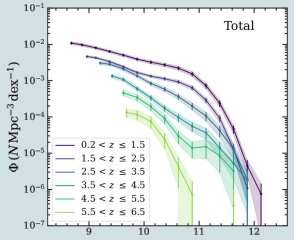
on top of DM-only N-body sims

How to cook an empirical sky simulation

Observation

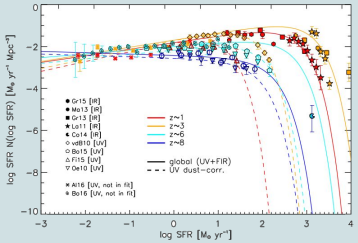
Observed Statistics

Image credits:
Weaver et al., 2022



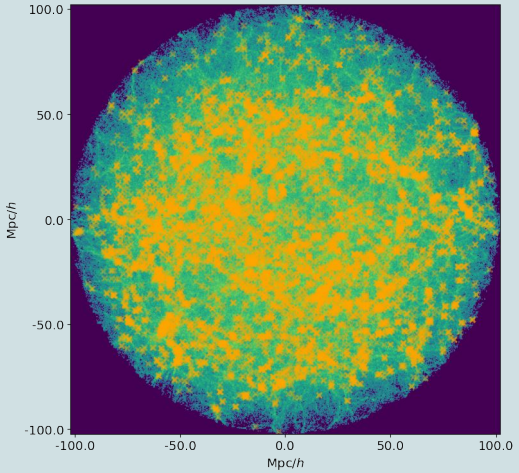
Analytical Relations

Image credits:
Lapi+2017



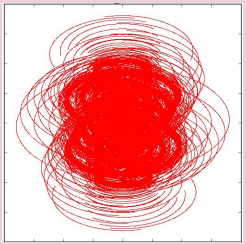
Tune the empirical model (HOD, SHAM, ML, ...)

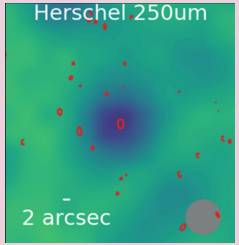
Extract a mock sample from the model



Add instrumental/observational effects

e.g.





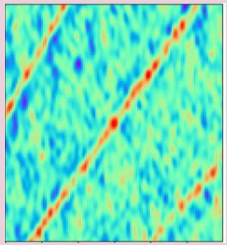


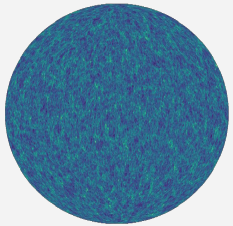
Image credits: Rivi+16 Amarantidis+23 Massardi, M. (pvt)

“Painting” empirical sources: the ingredients

CANVAS:

- Simulate a **Dark-Matter light-cone** (full-sky) z < 8
  - detect DM-haloes (i.e. hosts of clusters)
  - detect sub-haloes (i.e. hosts of galaxies)

⇨ **DEMNUNI**



PAINT:

- Generate a **mock-catalogue of realistic sources**:
  - Active Galactic Nuclei
  - Star Forming Galaxies
  - HI Galaxies

⇨ **T-RECS**

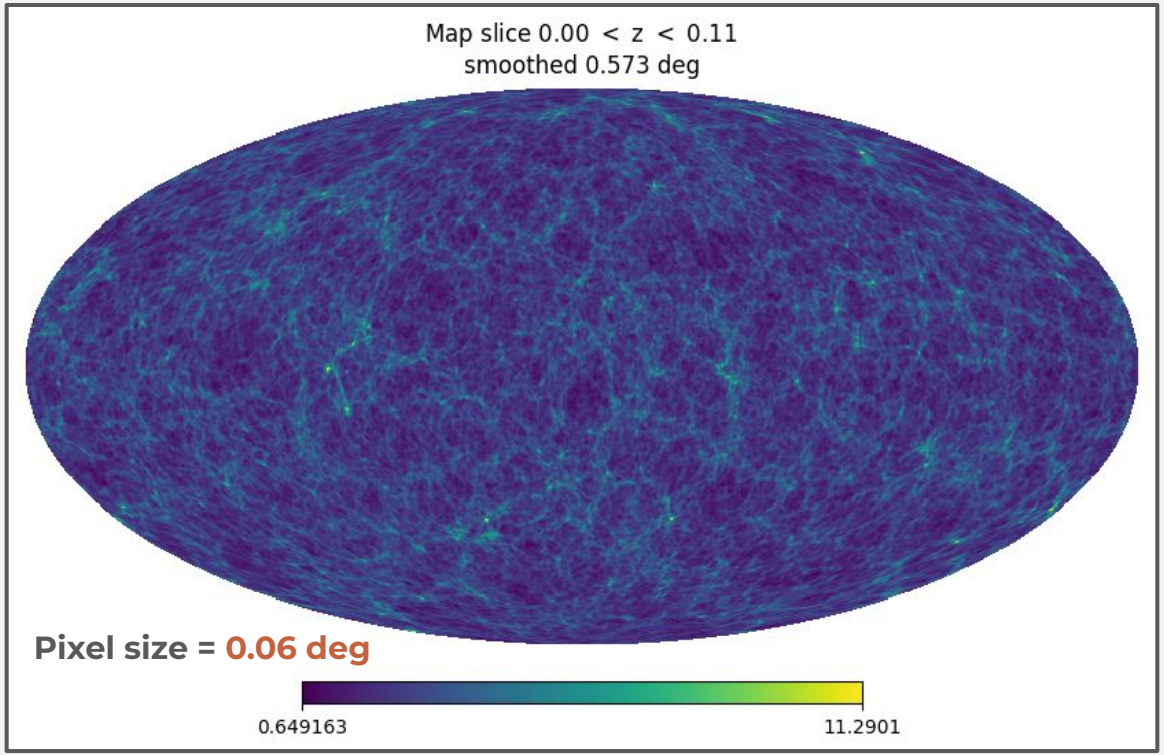
BRUSH:

- **Link** the first to the second with **clustering properties from observations** (i.e. the spatial distribution of object has the same statistical properties of the observed sky)

⇨ **SCAMPy**

DEMNUni full-sky light-cone

= Dark Energy and Massive Neutrino Universe



- **DEMNUni** (Carbone et al., 2016 Parimbelli et al., 2022)
  - 2 Gpc/h box-side length
  - $2x2048^3$ particles ($M_{DM} \sim 10^{10}\ M_\odot$)
  - Minimum halo mass: $\sim 10^{12}\ M_\odot$
- **DEMNUni High Resolution** (Hernández-Molinero et al., 2023, Verza, Carbone et al.,2024)
  - 500 Mpc/h box-side length
  - $2x2048^3$ particles ($M_{DM} \sim 10^{8}\ M_\odot$)
  - Minimum halo mass: $\sim 10^{10}\ M_\odot$
- Note that we need both
  - **Haloes** (to apply the HOD on)
  - **Sub-haloes** (hosting single galaxies)
  - the hierarchy among those

Final Light-cone:
Redshift: $0 < z < 8$
(i.e. $t_{age} \sim 400$ Myr)

$N_{haloes} \sim 39 \times 10^9$

$N_{subhaloes} \sim 44 \times 10^9$
(of course > N_{haloes})

T-RECS: mocking extragalactic radio sources

TRECS

Github:
https://github.com/abonaldi/TRECS.git

Logo credit: E. Casetta

- Presented in
  - T-RECS I: Bonaldi et al., 2019
  - T-RECS II: Bonaldi et al., including **TR**, 2023
- Generates catalogues of **radio galaxies** using radio **evolutionary models**
- Analytical models for **a range of galaxy properties**
- **HI line emission**
- Continuum X HI
- Source populations proportion, flux, size, shape etc. distributions consistent with data

Mock catalogues of
AGNs, SFGs & HI galaxies

Modelled separately!
(i.e. mocks can be selected in either population of sources)

The SCAMPy toolkit

Designed for:
Subhalo Clustering & Abundance Matching (SCAM)
Tuned on: 1- & 2-point statistics of target

- **First Step: HOD**
  Halo Occupation Distribution ⟹ Clustering properties matched
- **Second Step: SHAM**
  Sub-Halo Abundance Matching ⟹ Observational property matched

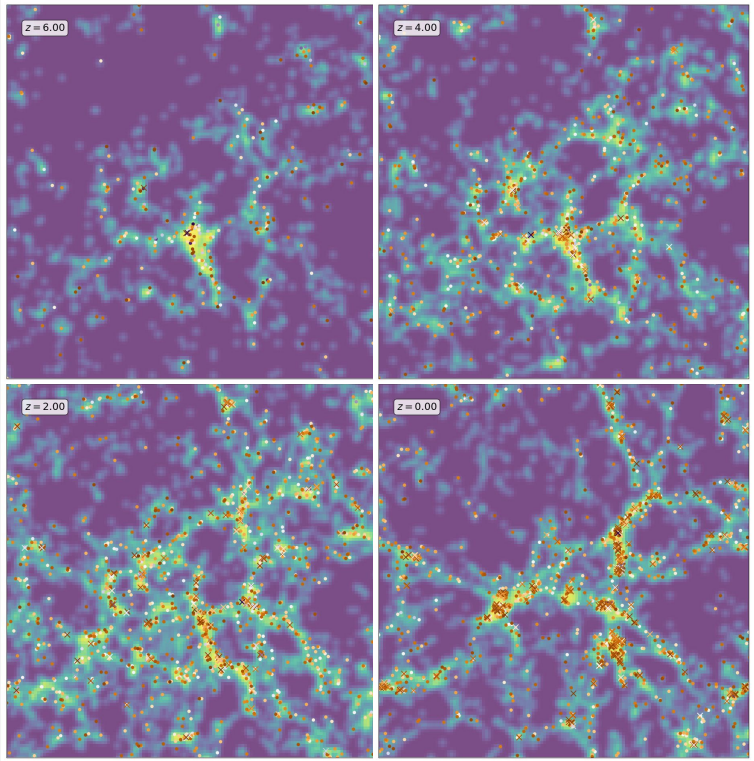
✔ Add unlimited number of baryonic properties
✔ Very fast!

❌ Scatter added by-hand
❌ Properties un-correlated

Additionally, instruments for

- Cosmological modelling (+ implementation of halo-model)
- DM halo/sub-halo catalogues treatment
- Light-cone construction and coordinates transformation
- Implementation of several recipes for HOD/SHAM

Resulting Catalogues



Public library on GitHub + docs on RTD (Ronconi+2020)
Version 2.0 under development

TRECS x SCAMPy x DEMNuni: Current results

1. TRECS → **mock radio sources**
2. **HOD tuning** on real data
   - abundances (1-point)
   - clustering (2-point)

   (separately for HI & cont.)
3. SCAMPy → **paint sources on lightcones**

Observables used in SCAMPy: clustering data

Datasets for tuning HOD:

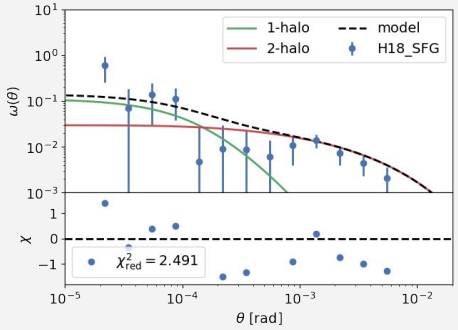
Continuum: Hale et al., 2018

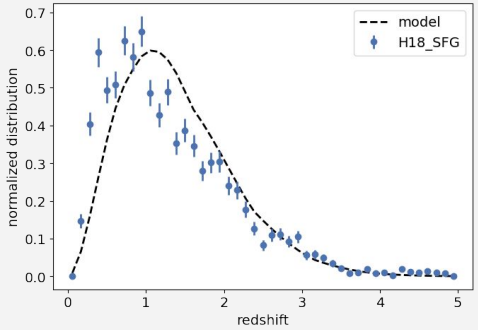
we separate between AGNs & SFGs

HI gxys: Martin et al., 2012

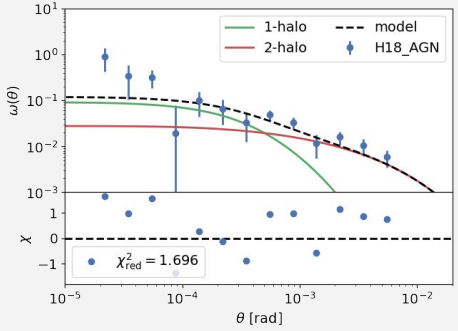
has a precise measurement of redshift

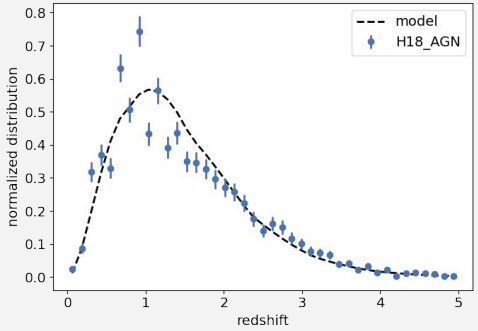
Active Galactic Nuclei

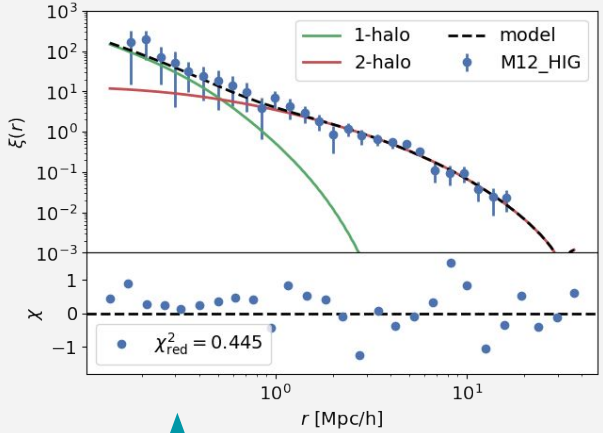




Star Forming Galaxies





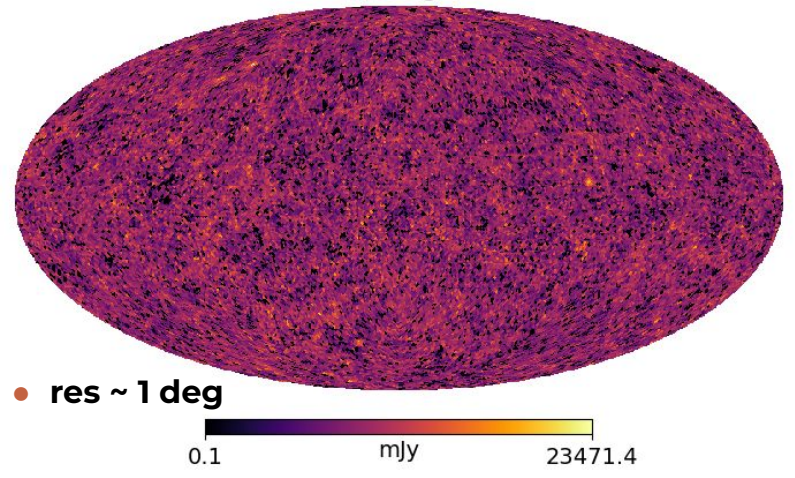


from 40% ALFALFA survey (Arecibo)

from the COSMOS field (VLA)

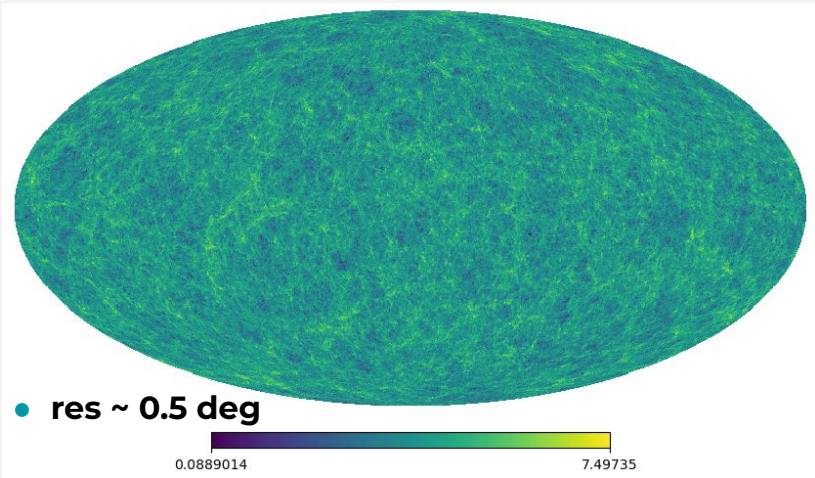
The simulated radio sky

- **Continuum Galaxies:**
  Flux in pixel



- **res ~ 1 deg**

- **HI galaxies:**
  log-number in pixel



- **res ~ 0.5 deg**

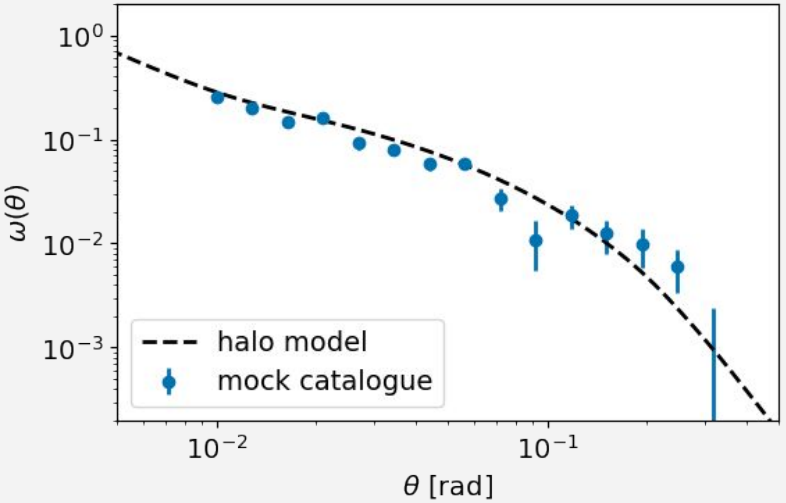
- **z <= 0.1**

➔ **Radius ~ 420 cMpc/h**

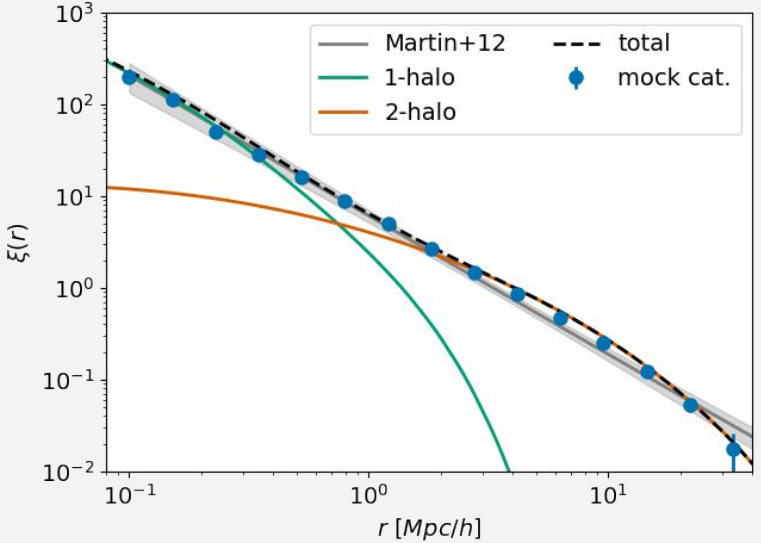
This is the sky we would like to see (do not include instrumental effects, systematics, observational limits)

Sanity check: clustering properties are recovered

- **Continuum Galaxies**
  (here clustering properties of AGN+SFG)



- **HI Galaxies**
  (here measured on a box)

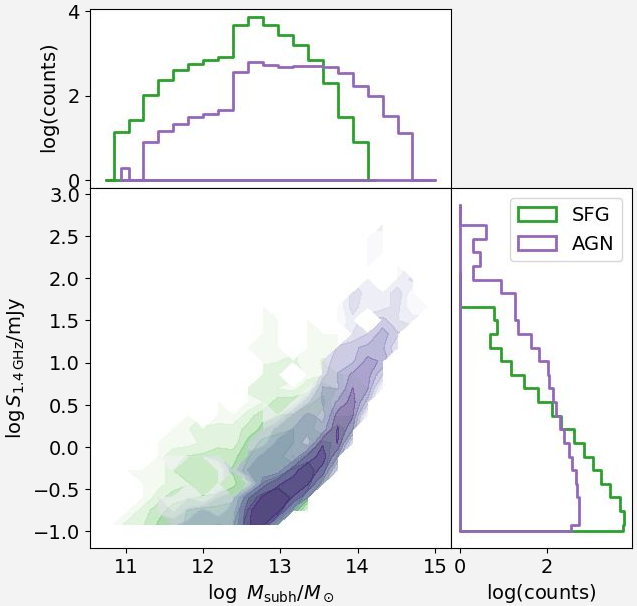


Ok good, this should work by construction and indeed it does

Some derived relations (what do we learn)

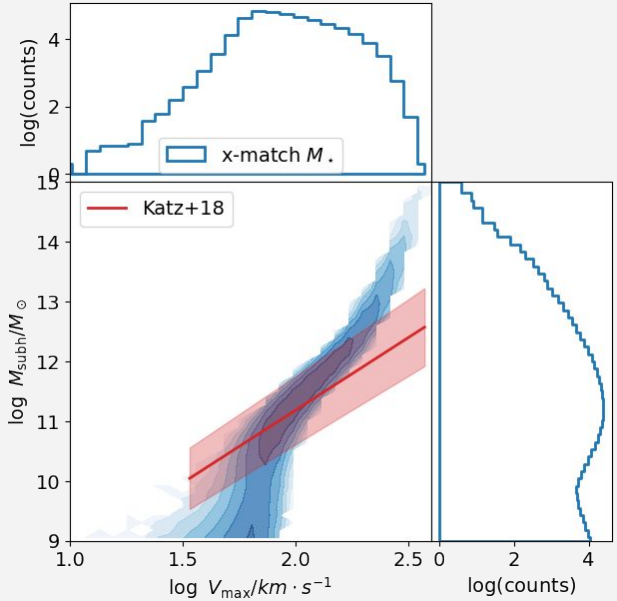
- **Continuum Galaxies**

➜ some hints of mass-segregation between **SFGs & AGNs**



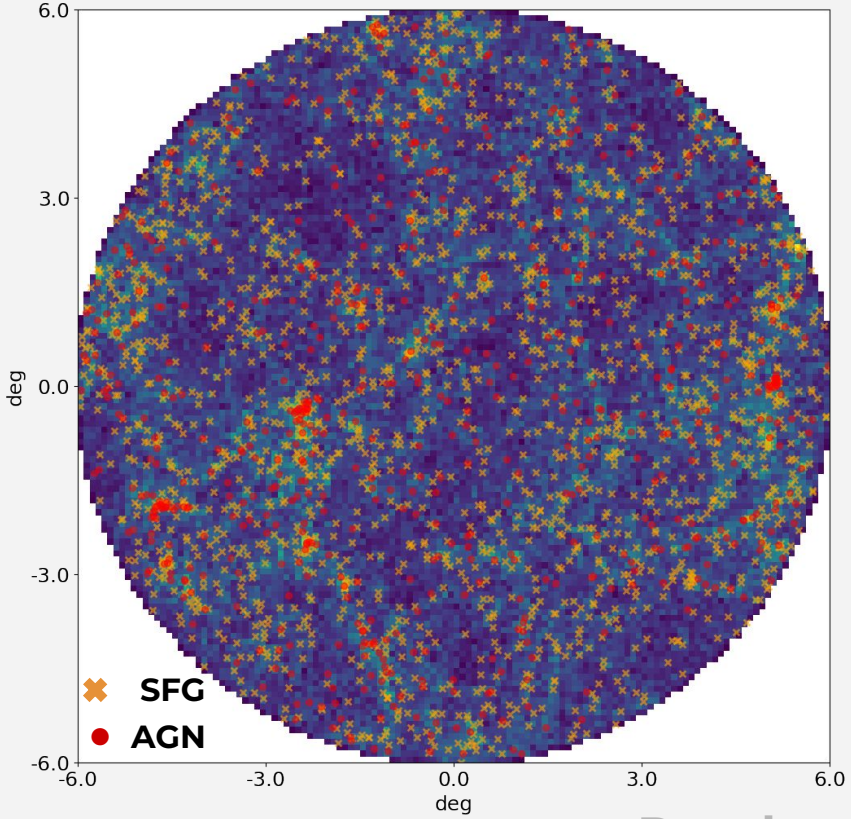
- **HI Galaxies**

➜ even though not instructed we recover independent results



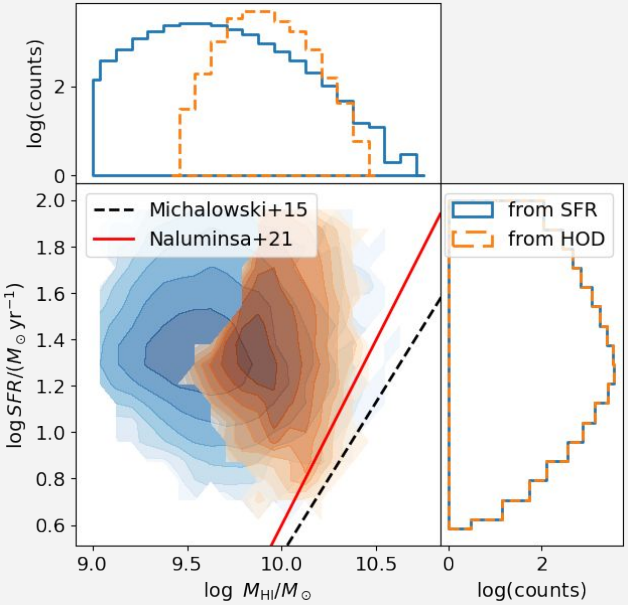
Not many other ways to investigate on the galaxy-halo connection

The final light-cone has all the 3 populations together



- **Continuum-HI cross catalogues**

➜ too soon to call probably
(but at least we are in the same region)



Results up to z<0.5

Summary

- Built a full sky Dark Matter -only full sky light-cone (with haloes and sub-haloes)
- Generated realistic distribution of
  - Active Galactic Nuclei
  - Star Forming Galaxies
  - Neutral Hydrogen Galaxies
- Painted the sources on top of the light-cone
- We are currently performing sanity checks on reduced versions of the light-cones
  - in terms of depth (lower redshift)
  - in terms of Field Of View (not going full sky yet)

Final Product:

➔ full-sky light-cone with all the sources up to redshift 8

➔ public software code for the community to use in their applications

➔ reduced version of the DM-only light-cone to be used by the community

… and this is my last slide, THANKS!

T-RECS HI-catalogues

Tag Name	Units	Description
ID_HI		Numerical identifier for the source
MHI	$\log(M_\odot)$	HI mass
HI flux	mJY Hz	HI flux
Mh	$\log(M_\odot)$	Dark halo mass
Mstar	$\log(M_\odot)$	Stellar mass
x_coord	degs	First angular coordinate in the flat-sky approximation (see T-RECS I for more details)
y_coord	degs	Second angular coordinate in the flat-sky approximation (see T-RECS I for more details)
latitude	degs	Latitude spherical coordinate for a chosen centre of the field
longitude	degs	Longitude spherical coordinate for a chosen centre of the field
redshift		redshift
HI size	arcsec	Apparent size of the HI source
inclination	degs	galaxy inclination
axis ratio		galaxy axis ratio, defined as the ratio between major and minor axis
bmaj	arcsec	major axis
bmin	arcsec	minor axis
PA	degs	position angle
OptClass		Number identifying the optical type: 1 for elliptical, 2 for spiral

T-RECS continuum-catalogues

Tag Name	Units	Description
ID_cont		Numerical identifier for the source
Lum_{1400}	log(erg/s/Hz)	Luminosity at 1.4 GHz (AGN only)
logSFR	$\log(M_{\mathrm{sun}})$/yr	SFR (SFG only)
$\mathrm{I}_{\mathrm{freq}}$	mJy	Total intensity flux density of the source at frequency *freq* for each of a list of N_{freqs} frequencies as specified by the user.
$\mathrm{P}_{\mathrm{freq}}$	mJy	Polarized flux density of the source at frequency *freq* for each of a list of N_{freqs} frequencies as specified by the user. See T-RECS I for details of the polarization model.
Mh	$\log(M_{\mathrm{sun}})$	Dark halo mass
Mstar	$\log(M_{\mathrm{sun}})$	Stellar mass
MHI_pred	$\log(M_{\mathrm{sun}})$	HI mass proxy
x_coord	degs	First angular coordinate in the flat-sky approximation (see T-RECS I for more details)
y_coord	degs	Second angular coordinate in the flat-sky approximation (see T-RECS I for more details)
latitude	degs	Latitude spherical coordinate for a chosen centre of the field
longitude	degs	Longitude spherical coordinate for a chosen centre of the field
redshift		redshift
size	arcsec	Apparent size of the source. This is the maximum size of the core+jet emission for AGN, and the scale radius of a Sersic profile for SFG.
inclination	degs	galaxy inclination
axis ratio		galaxy axis ratio, defined as the ratio between major and minor axis
bmaj	arcsec	major axis
bmin	arcsec	minor axis
PA	degs	position angle
Rs		Ratio between the distance between the spots and the total size of the jets, for the FR I /FR II classification (steep-spectrum AGN only)
RadioClass		Number identifying the sub-population: 1 for late-type; 2 for spheroids; 3 for lensed spheroids; 4 for FSRQ, 5 for BL Lac and 6 for SS-AGN.
OptClass		Number identifying the optical type: 1 for elliptical, 2 for spiral.
$\mathrm{L}_{\mathrm{freq}}$	erg/s/Hz	OPTIONAL OUTPUT: Luminosity of the source at frequency *freq* for each of a list of N_{freqs} frequencies as specified by the user.