How to mock a radio sky – empirical models with multiple populations for future SKAO surveys

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Cosmology in the Alps, 2026
Les Diablerets, March 20th

Preparatory science: “what do we 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 or synergies between experiments

Empirical methods
(not hydrodynamical nor semi-analytical)

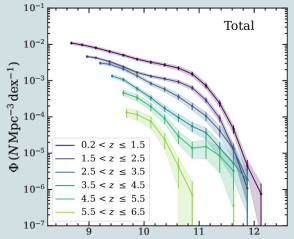
- **built on top of DM-only N-body sims**
- no explicit modelling of baryonic physics
- tuned on observational relations
- realistic (by construction) ⟶ forecasting results from obs.

How to cook an empirical sky simulation

Observation

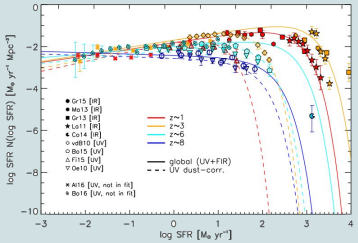
Observed Statistics

Image credits: Weaver et al., 2022



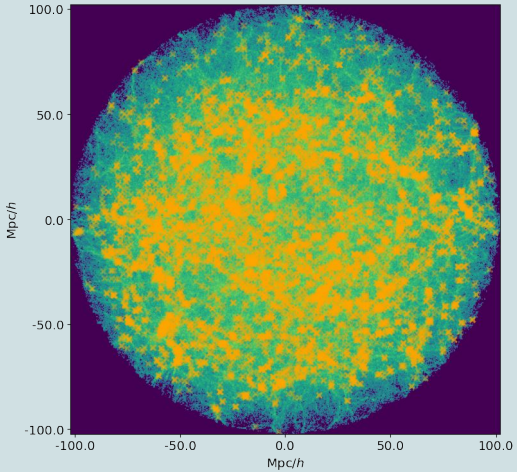
Analytical Relations

Image credits: Lapi+2017



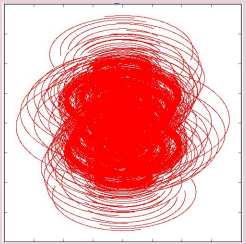
Tune the empirical model (HOD, SHAM, ML, ...)

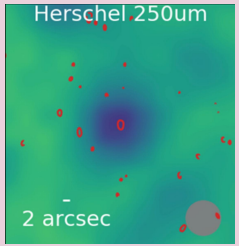
Extract a mock sample from the model



Add instrumental/observational effects

e.g.





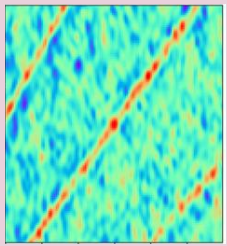


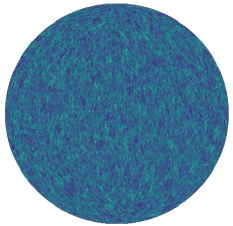
Image credits: Rivi+16 Amarantidis+23 Massardi, M. (pvt)

“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:

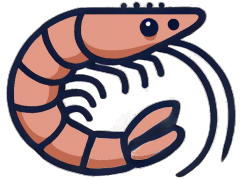
- Generate a **mock-catalogue of realistic sources**:
  - Active Galactic Nuclei
  - Star Forming Galaxies
  - HI Galaxies

⇨ **T-RECS**

BRUSH:

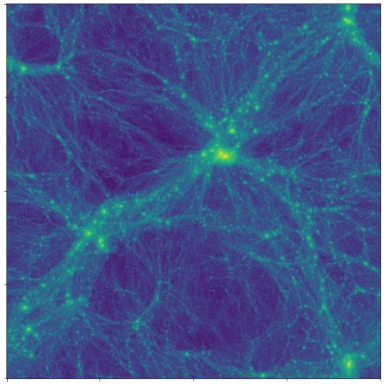
- **Link** the first to the second with **clustering properties from observations** (i.e. the spatial distribution of object has the same statistical properties of the observed sky)

⇨ **SCAMPy**



DEMNUni full-sky light-cone

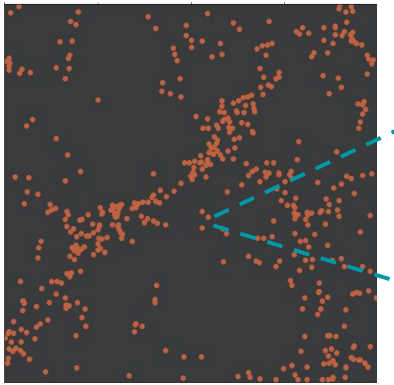
DEMNUni DM Field



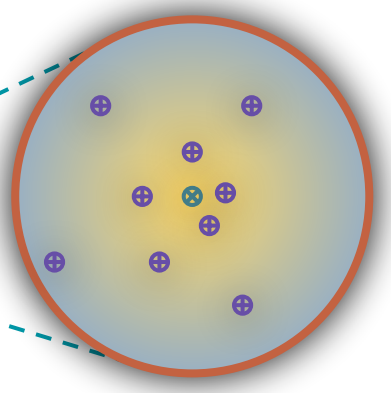
flat ΛCDM with
Planck 2013 parameters

group the particles

DM Haloes

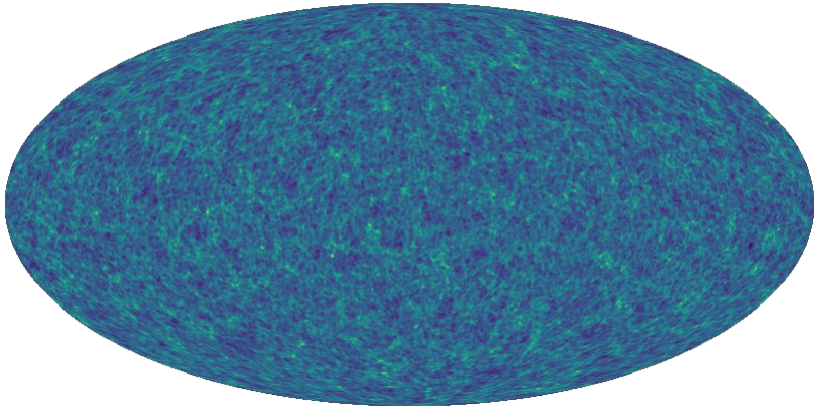


Sub-Haloes



Periodicity allows box tiling

full-sky light-cone



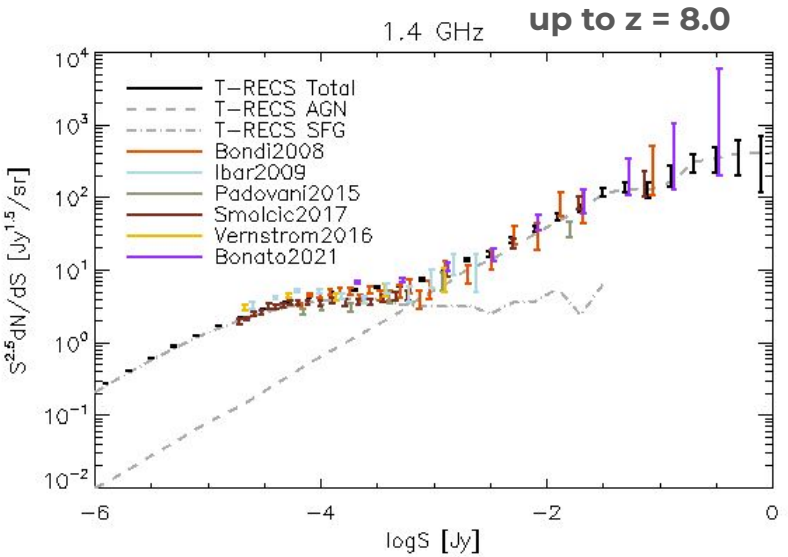
- **Redshift:** $0 < z < 8$
- $\mathbf{N_{haloes}} \sim 39 \times 10^9$
- $\mathbf{N_{subhaloes}} \sim 44 \times 10^9$
- **radius** ~ 6 cGpc/h
- $\mathbf{M_{halo}} > 10^{10}\ M_\odot/h$

[e.g. Parimbelli, et al., 2022, Verza et al., 2024]

T-RECS: mocking extragalactic radio sources

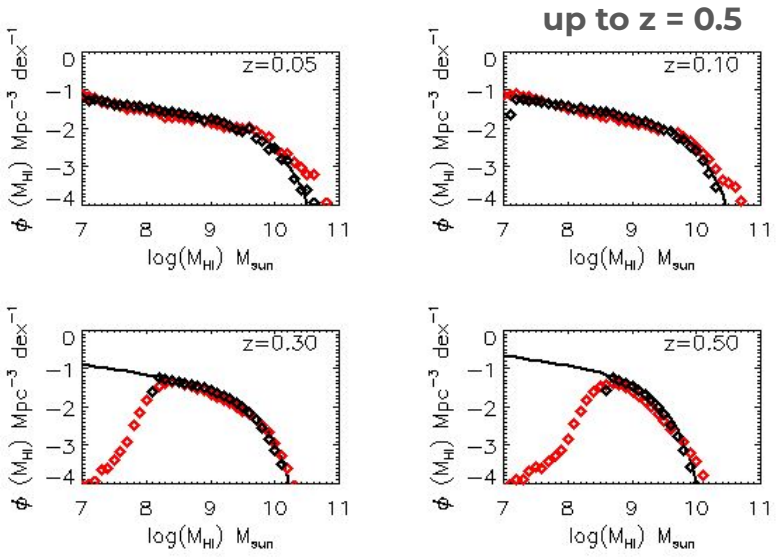
- **Radio Continuum**

  from 150 MHz to 15 GHz



- **HI galaxies**

theory TRECS HI gxys TRECS cross.



Emitted by: **Ionized Gas**
Traces: **SF**, **Nuclear Accretion**

⟺ **Modelled separately!**

Emitted by: **Neutral Gas**
Traces: **Gas Reservoir to SF & AGN**

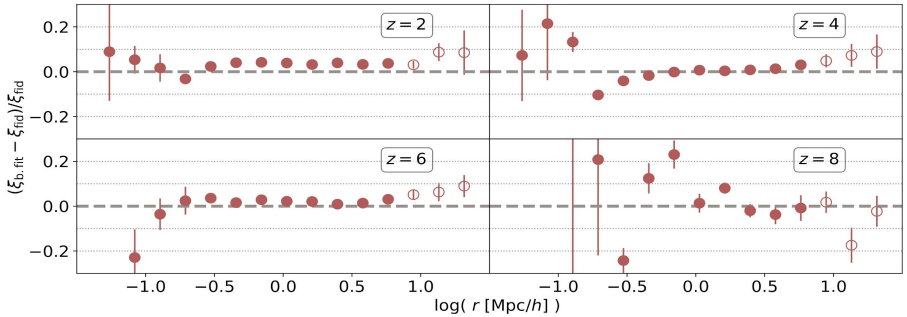
[Bonaldi et al., 2019; 2023, including **TR,** 2023]

The SCAMPy toolkit

Designed for:
Subhalo Clustering & Abundance Matching (SCAM)

Tuned on: 1- & 2-point statistics of target population:

- **First Step: HOD** ⇒ Clustering properties matched



- **Second Step: SHAM** ⇒ Observational property matched

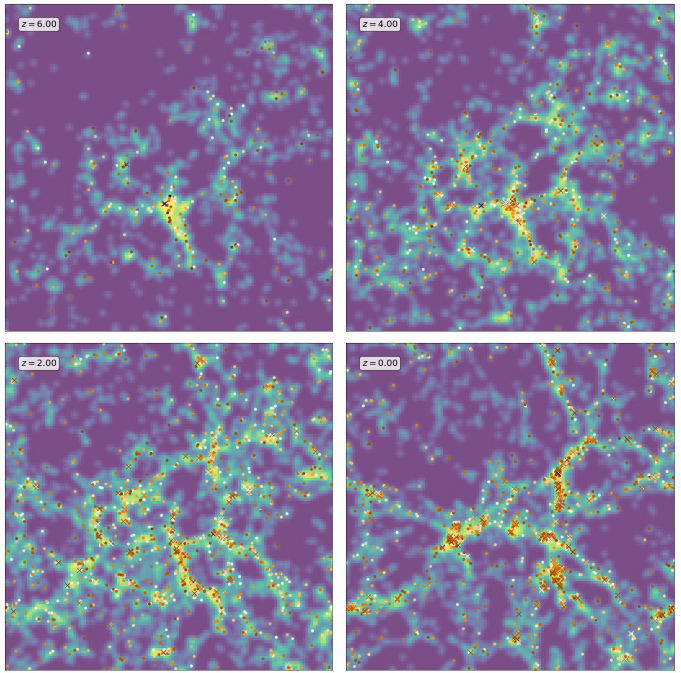
✔ Add unlimited number of baryonic properties

✔ Very fast!

❌ Scatter added "by-hand"

❌ Properties un-correlated

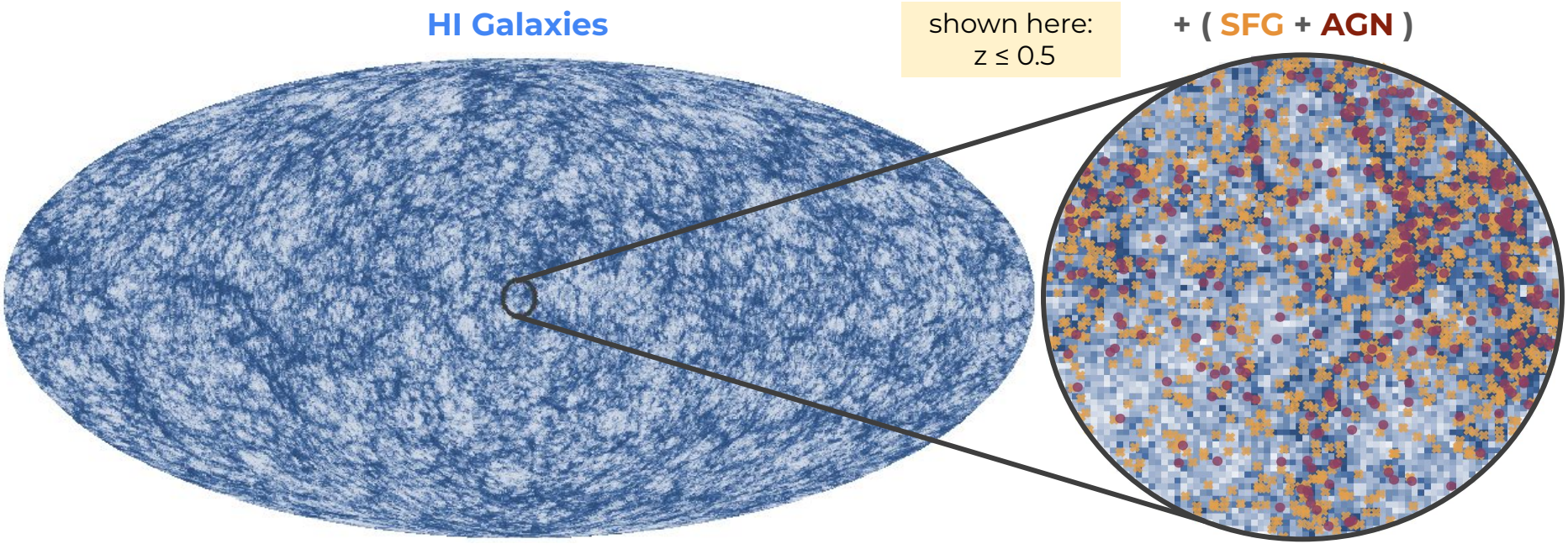
Resulting Catalogues



Public library on GitHub + docs on RTD (Ronconi et al., 2020, **v2.0** in α-testing)

+ for EoR-people: toy-re-ionization morphologies (ask if interested)

The simulated radio sky: cross-catalogues for free



We made them in 2 flavours:

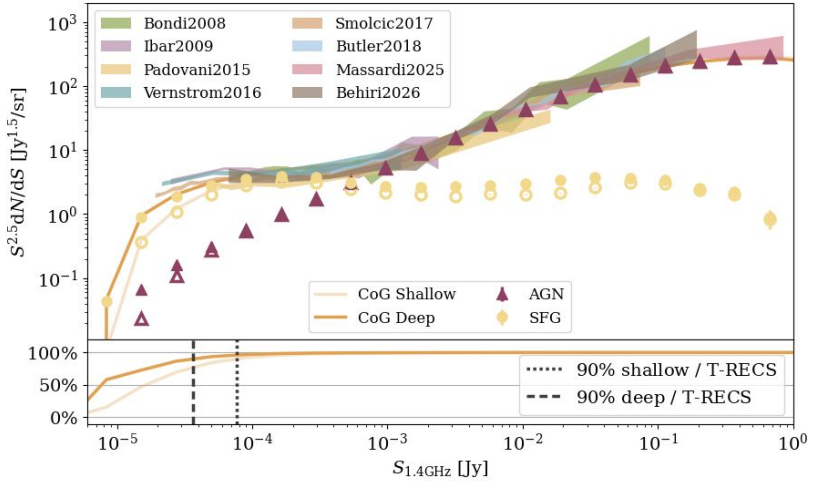
- **shallow:** constrained by observations (1+2 point from Hale+2018, Martin+2012)
- **deep:** extrapolated to SKA-Mid proposed surveys (see e.g. SKA Cosmology SWG, 2020)

This is the sky we would like to see:

✅ included: observational limits of the population

❌ not included: instrumental effects, systematics, foregrounds

Simulated sources number counts



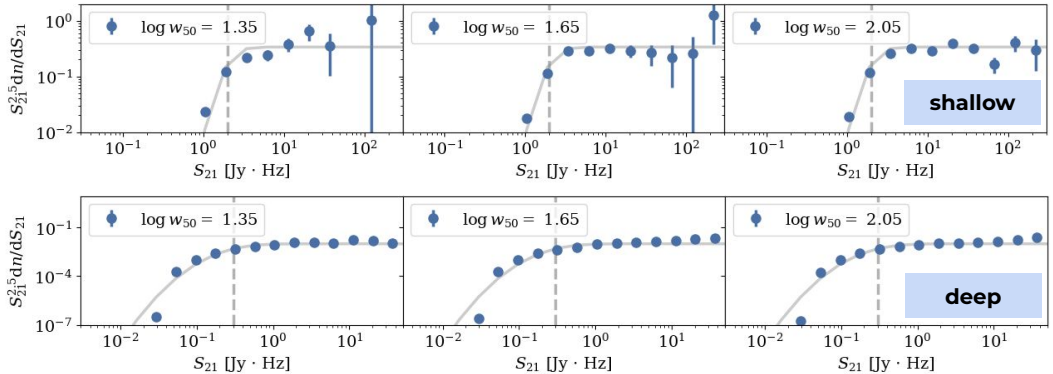
- **Continuum Galaxies**

  Surface density of sources per **flux** bin
  - ➜ shallow: $N_{tot}(z<5) \sim 2.2 \times 10^8$
  - ➜ deep: $N_{tot}(z<5) \sim 3.7 \times 10^8$

- **HI Galaxies**

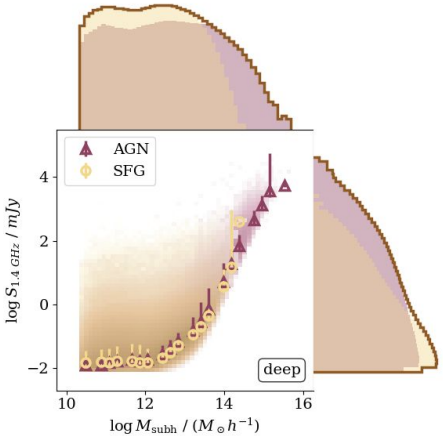
  Surface density of sources per **flux** bin per **linewidth** bin
  - ➜ shallow: $N_{tot}(z<0.5) \sim 5 \times 10^7$
  - ➜ deep: $N_{tot}(z<0.5) \sim 7.2 \times 10^8$

	limit $S_{1.4\ \mathrm{GHz}}$	limit $S_{21\ \mathrm{cm}}$
Shallow	8×10^{-5} Jy	2 Jy · Hz
Deep	4×10^{-5} Jy	0.3 Jy · Hz

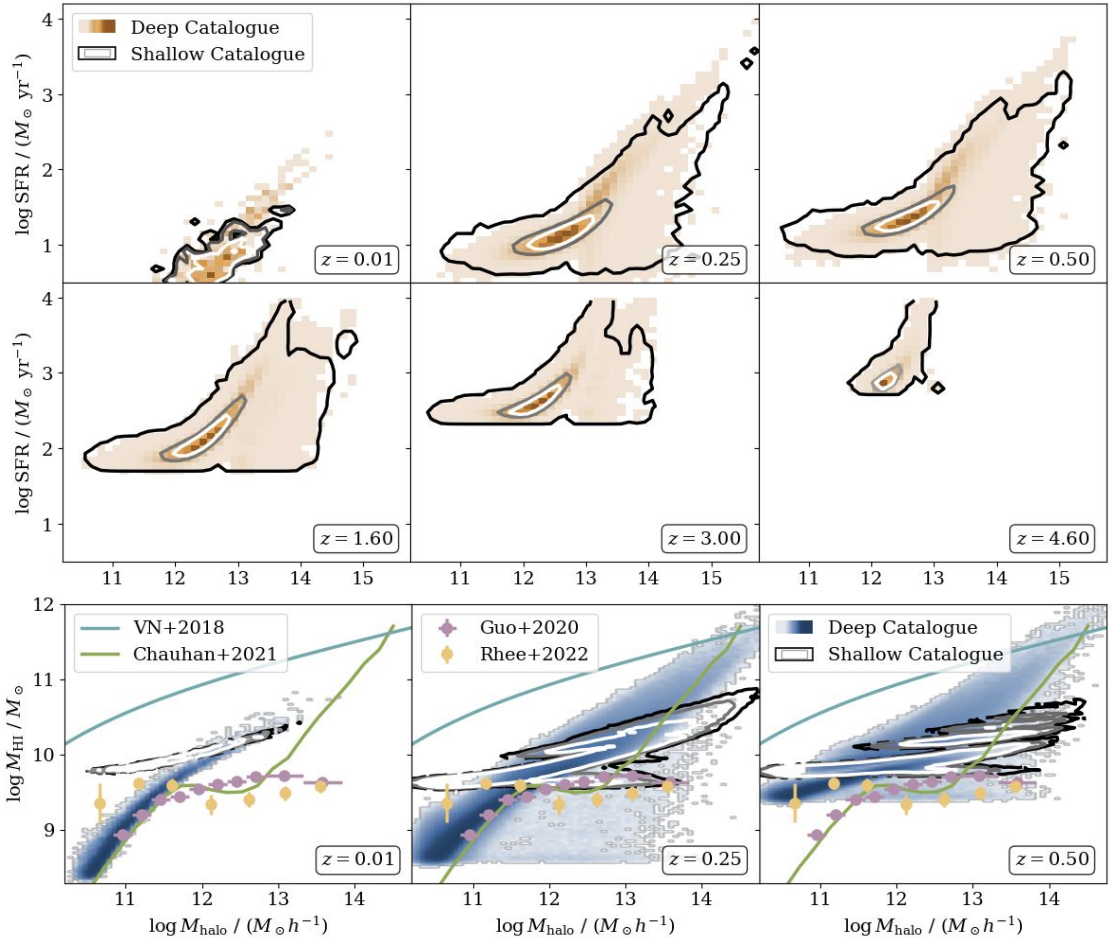


Baryonic VS Dark Properties

- **Continuum Galaxies**
  - ➜ SFR - M_{halo} relation
  - ➜ mass-segregation between **SFGs & AGNs**



- **HI Galaxies**
  - ➜ M_{HI} - M_{halo} relation
  - ➜ reasonable agreement at low z and low M_{halo} w.r.t. literature

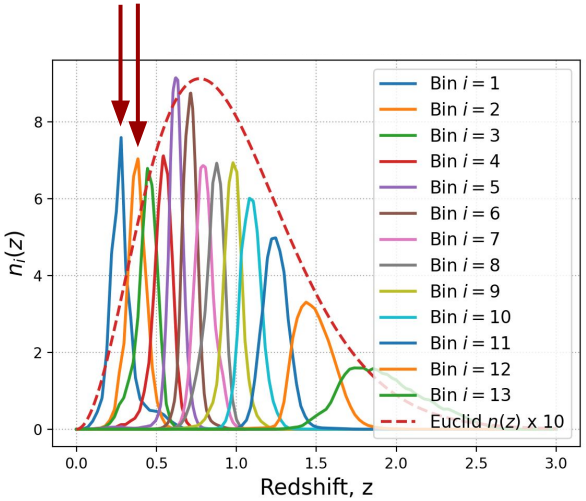


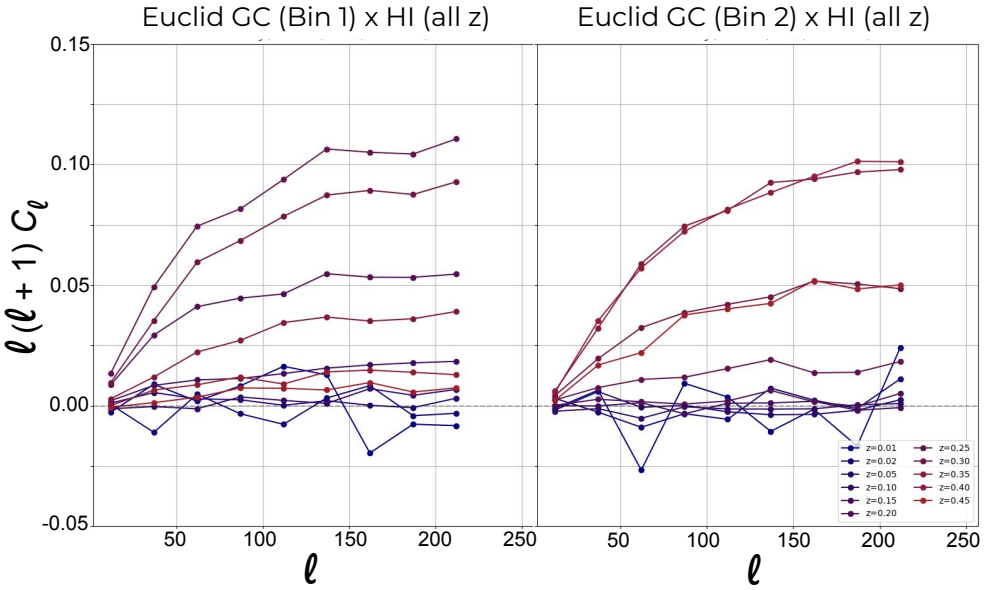
Synergies: Euclid DR3 (Preliminary)

- **Lead by Dr Bianca de Caro** (@ INAF-IASF, Milan)
  - ➜ compute the distribution of hydrogen from HIG maps integrated over redshift ($0 \leq z \leq 0.5$)
  - ➜ compute the distribution of galaxies in Euclid DR3 (expected ~2030)
  - ➜ derive the cross-power spectrum in different Euclid redshift bins

Euclid DR3 expected Redshift distribution:

2 overlapping photometric redshift bins:



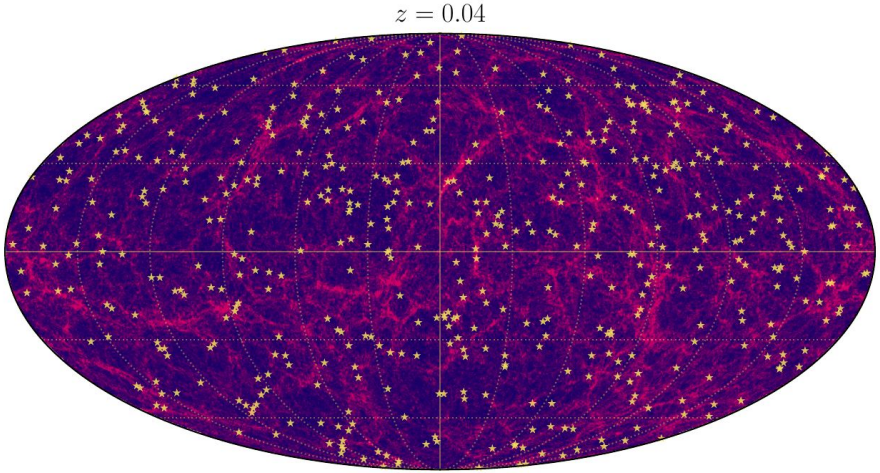


de Caro et al., including **TR** (expected 2026)

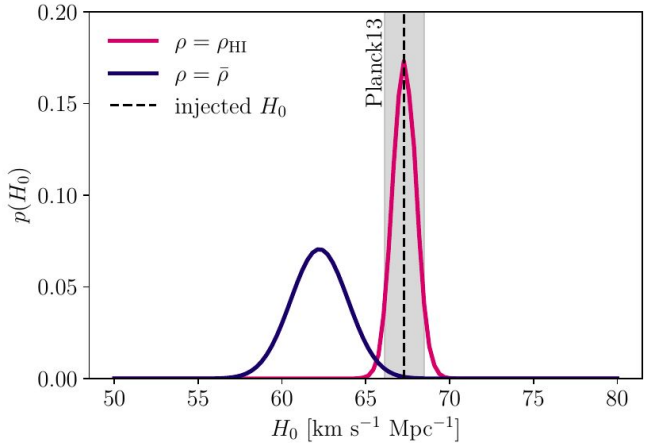
Synergies: Einstein Telescope (Preliminary)

- **Lead by Dr Ulyana Dupletsa** (@ INAF-IASF, Milan)
  - ➜ generate 21cm intensity maps from DM maps (tomographic up to z=3)
  - ➜ use the HI distribution **as a prior** to predict the GW distribution (Dupletsa+2023, 2025)
  - ➜ extract the GW population parameters (Hierarchical Bayesian Inference with **`icarogw`**, Mastrogiovanni+2021, 2023, 2024): including cosmological parameters!
  - ➜ tomographic info on source distribution ⟶ constraint on H_0 (**radio sirens method**)

Generated Intensity Map + simulated GW events:



Info on HI improves the constraint on H_0



AASKAII Chapter, including **TR** (2026)

Dupletsa et al., including **TR** (expected 2026)

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 applying the maps on synergy studies and extensions

Final Product:

➔ full-sky light-cone with all the sources up to redshift 5

➔ 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

➔ maps upon request

➔ **pre-print out (hopefully) before April!**

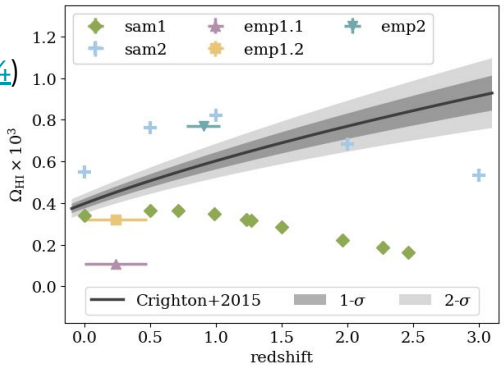
HI simulations Chapter @AASKA II (Cosmology SWG)

We compare different simulation models and approaches

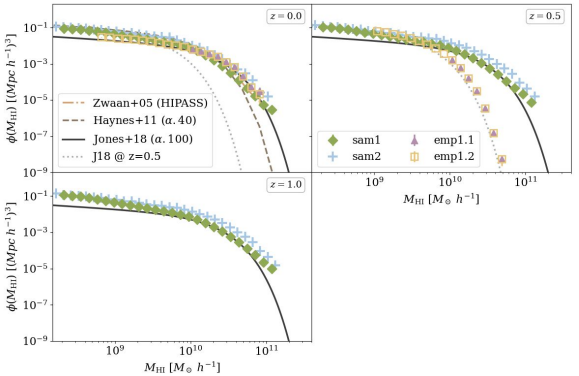
- **sam1**: GAEA
  (see **Mohammad**'s talk, deLucia+2024)
- **sam2**: L-Galaxies
  (e.g. Yates+2024)
- **emp1**: SCAM+T-RECS
  (this presentation)
- **emp2**: HI halo model
  (see **Pascal**'s talk, Hitz+2025)
- **emp3**: environment HIHM
  (e.g. Sinigaglia+2024)

- **Scatter** between the results (see **Catherine**'s talk)
  - there are no data!
  - all methods can be refined
- But also **agreement** in the well-studied regimes
- **Different methods for different applications**

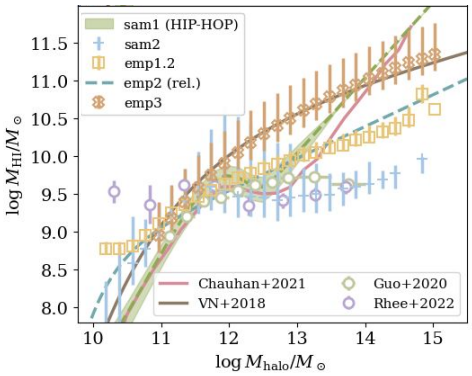
Density parameter



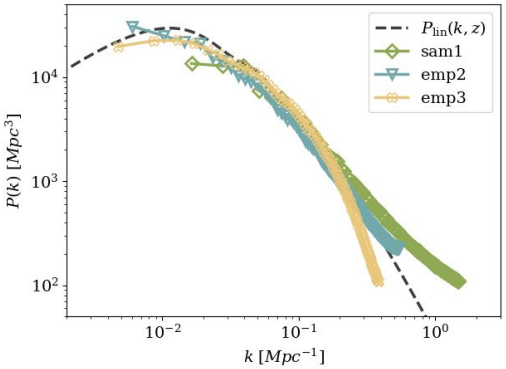
HI Mass Function



HIHM Relation



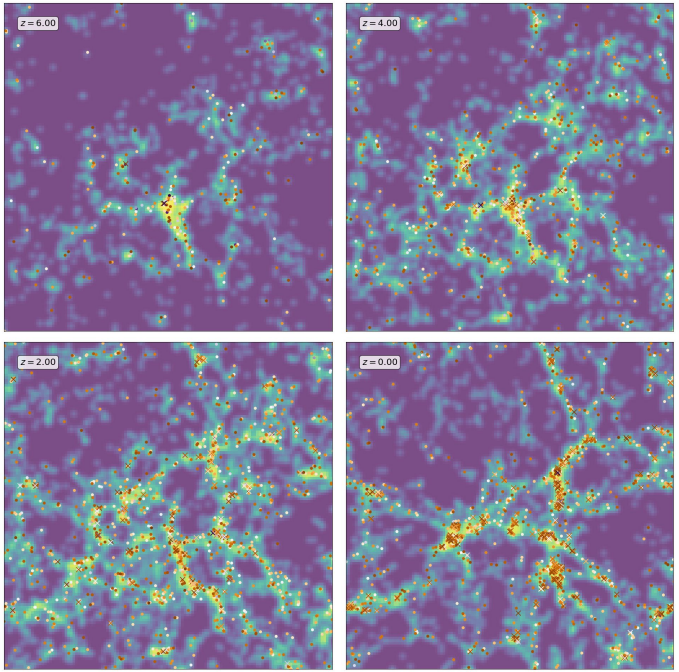
Power spectrum




... and this is my last slide, THANKS!

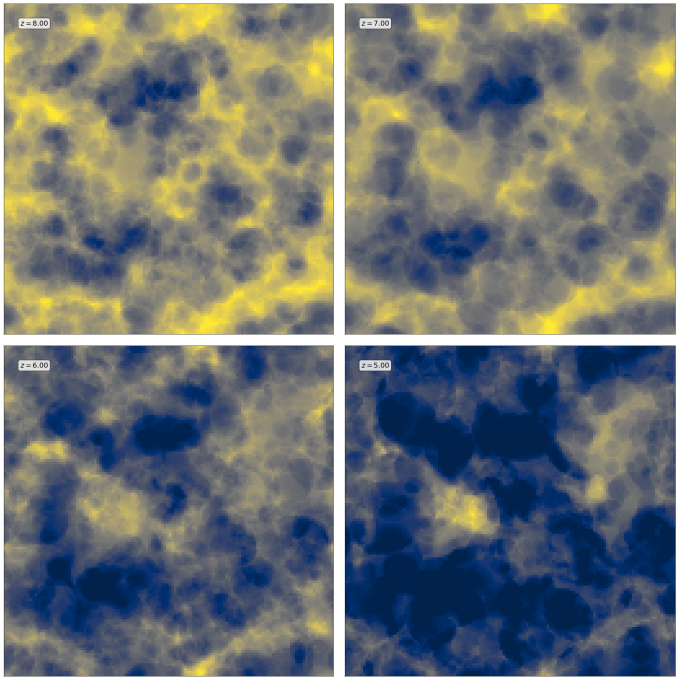
Detour (for the EoR people)

Mock galaxy catalogues



Empirical Relations

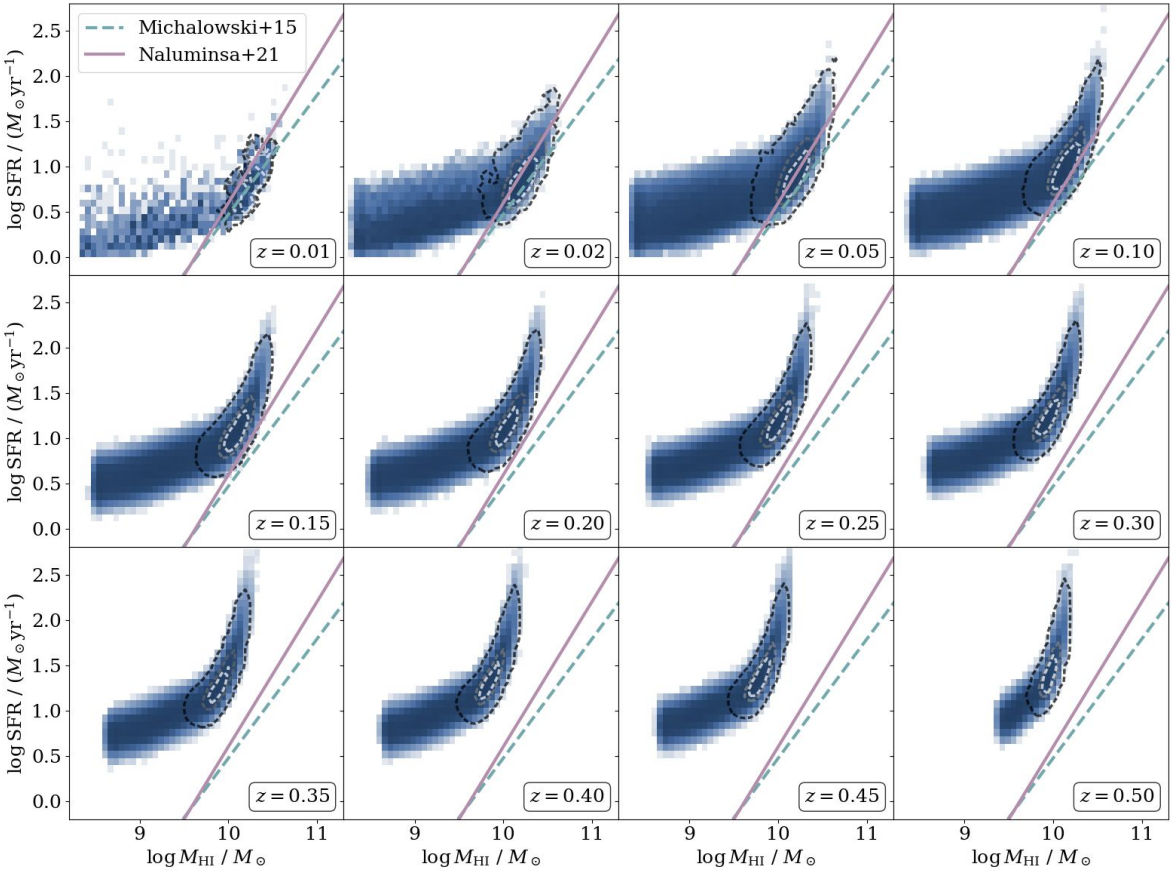
Toy re-ionization morphologies



- Generate Mock Catalogue of **Star Forming galaxies at high redshift**
  - Clustering from Harikane+16, 17
  - Luminosity from Bouwens+19

- **Empirical model of re-ionization**
  - ∀ redshift uniform HI field
  - SF-gxys produce ionizing photons
  - Stromgren spheres

Derived relations: HI vs Continuum Properties



- **CoG x HIG catalogues**
  - → results up to z ≤ 0.5
  - → HI mass VS SFR
  - → literature is tuned up to low redshift (z ≲ 0.02)
  - → our maps agree but predict a redshift evolution not observed (yet?)
  - → note there is a dependence on the HI mass model adopted
  - → the tail might be a numerical effect