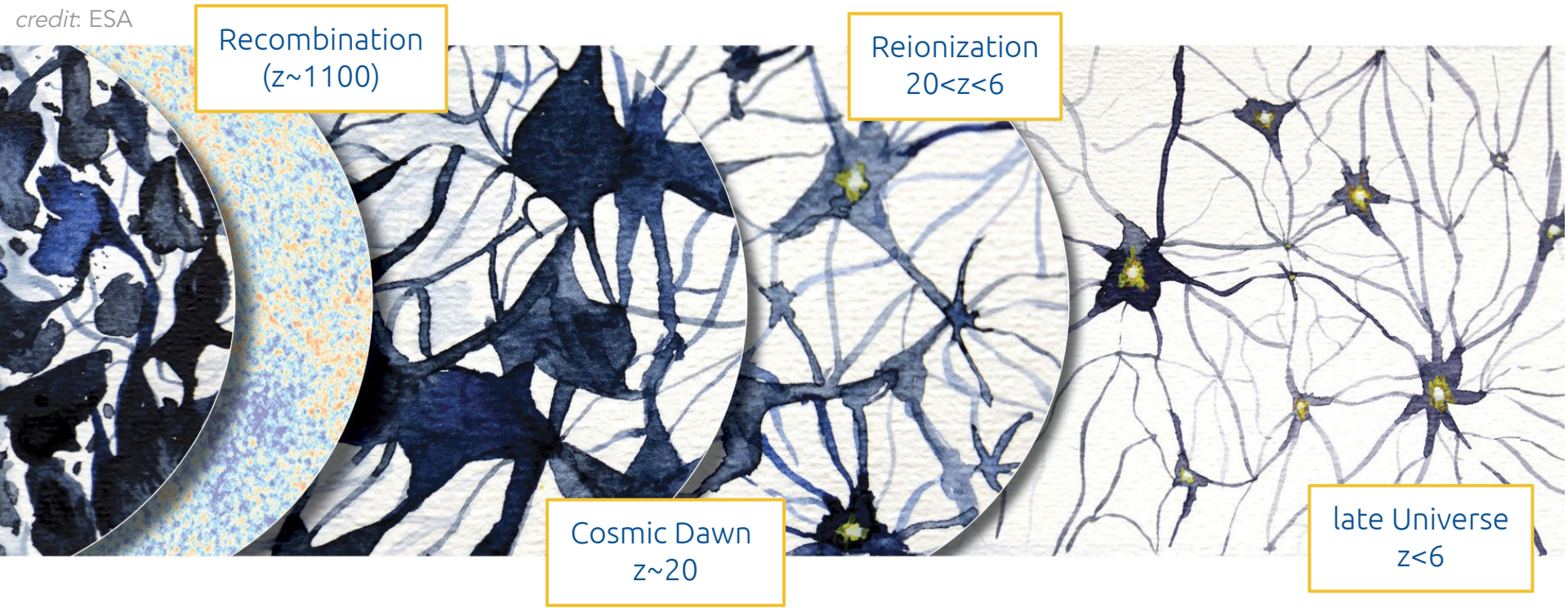
GAEA for SKA Cosmology

Marta Spinelli

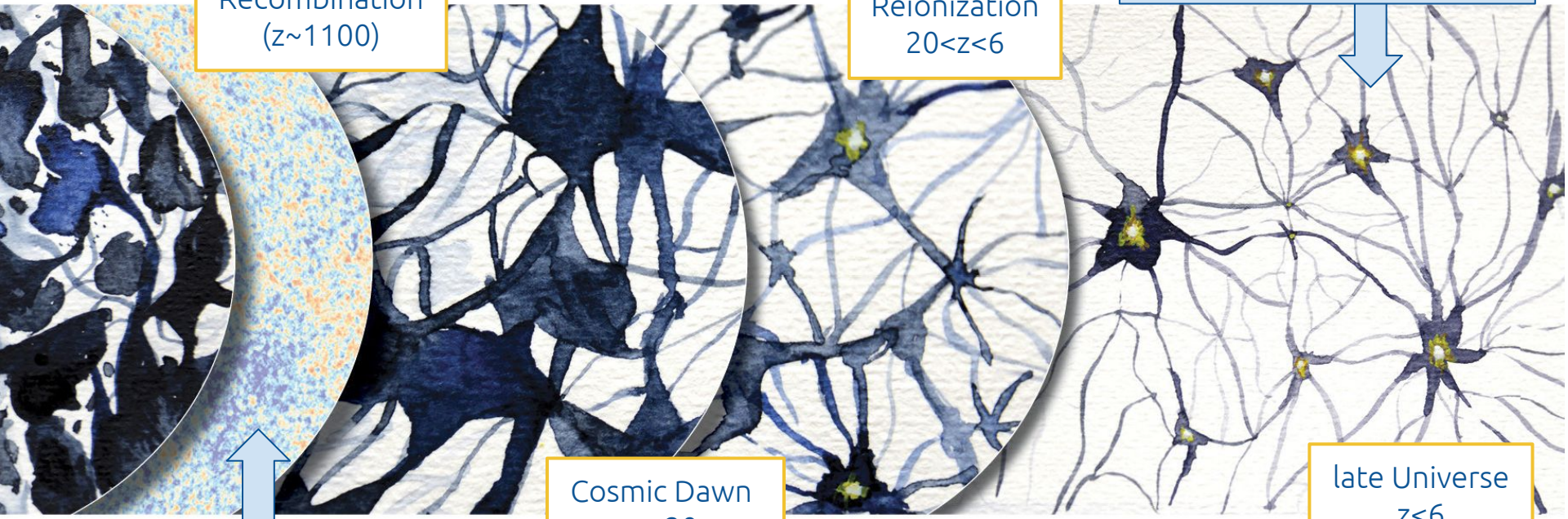
08/06/23

GAEA@IFPU

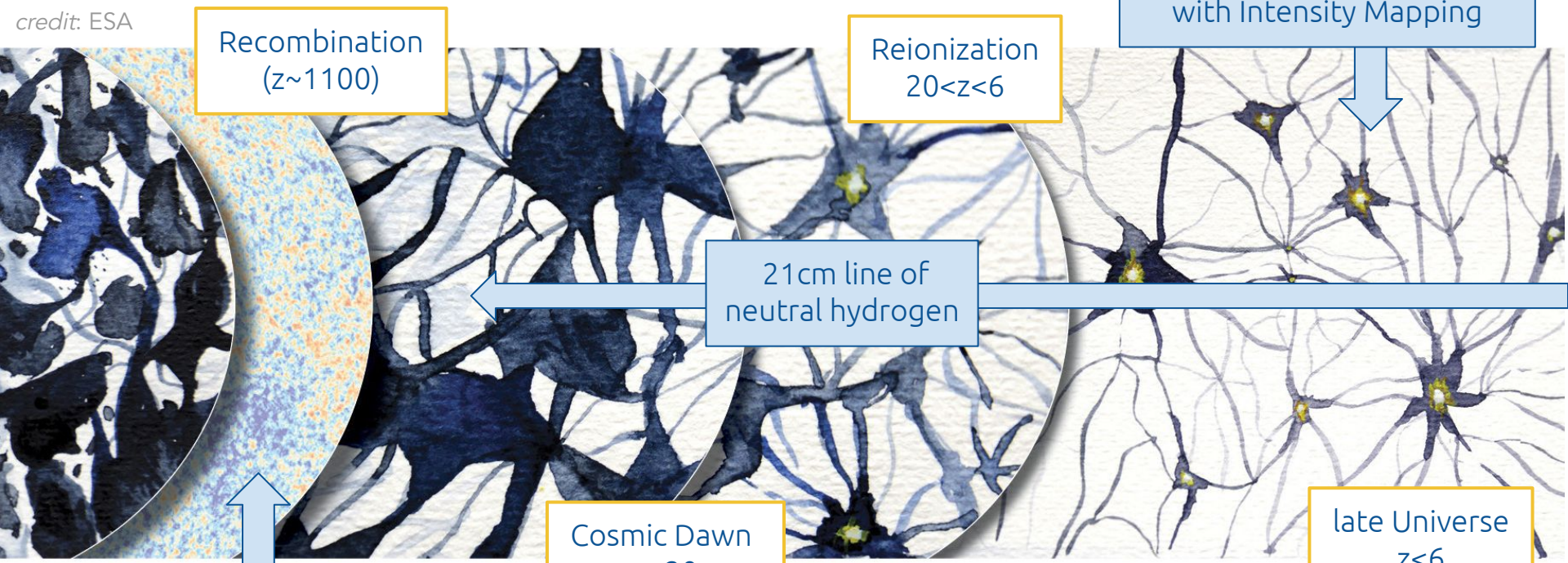
Hydrogen in cosmic history



Hydrogen in cosmic history

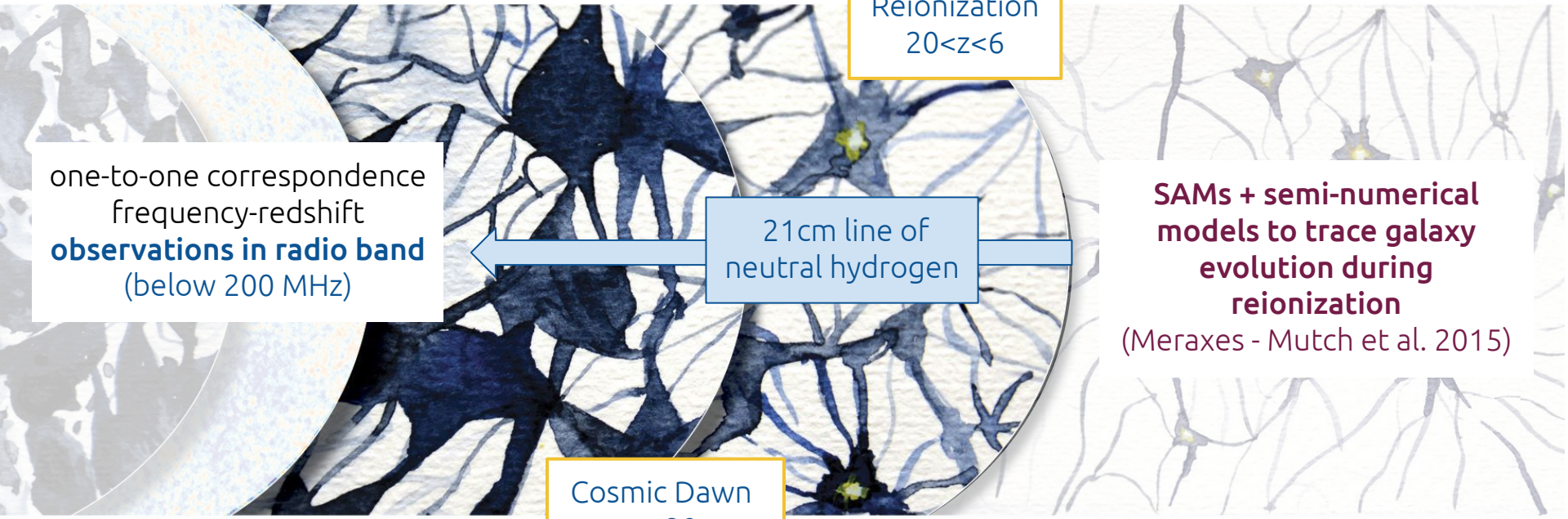


Hydrogen in cosmic history



High-redshift

credit: ESA



Reionization
20<z<6

one-to-one correspondence
frequency-redshift
observations in radio band
(below 200 MHz)

21cm line of
neutral hydrogen

SAMs + semi-numerical models to trace galaxy evolution during reionization
(Meraxes - Mutch et al. 2015)

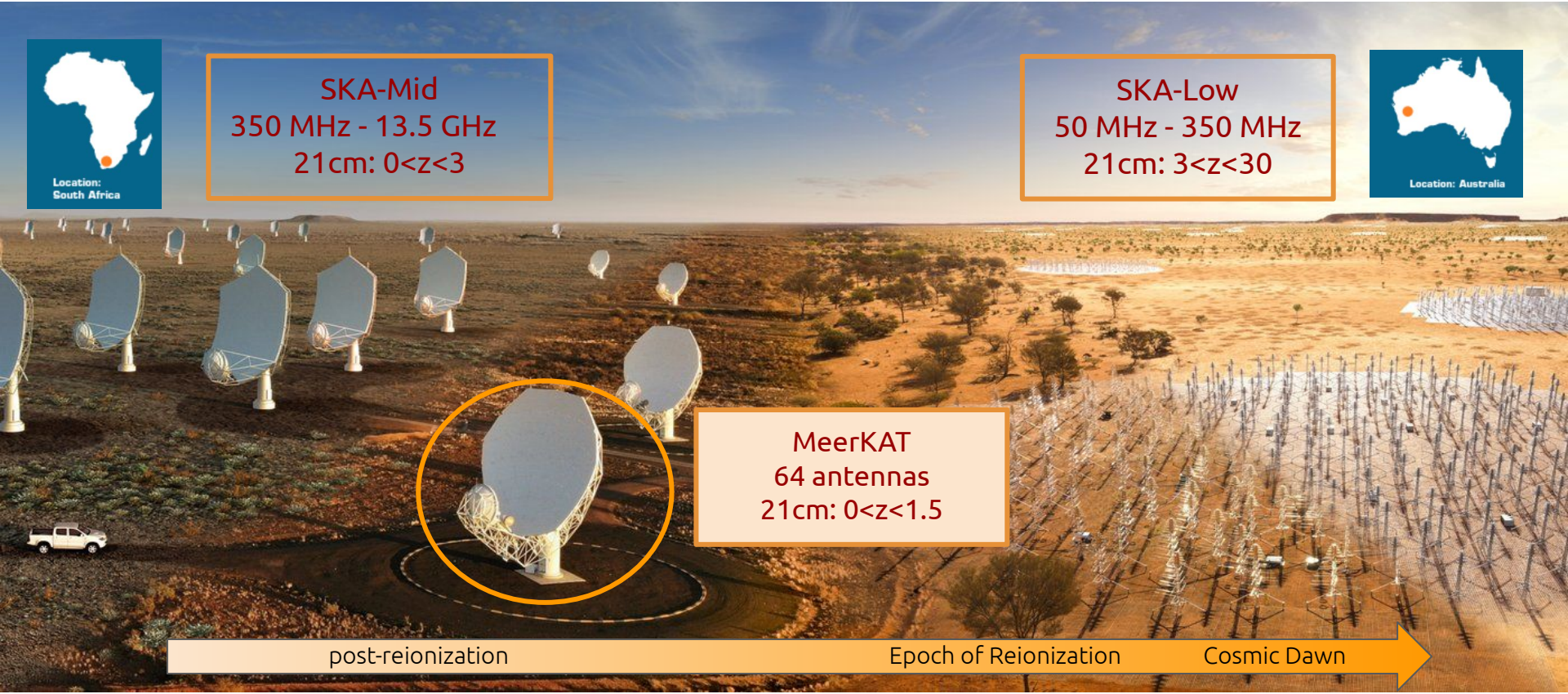
Cosmic Dawn
z~20

Low-redshift

credit: ESA

The SKA Observatory

credit: skatelescope.org



The SKA telescope: details

SKA-MID: a dish array in South Africa
133 -15m dishes
Band 1: 350-1050 MHz ⇒ $0.35 < z < 3$
(MeerKAT UHF-band only down to 580 MHz)
Band 2: 950-1075 MHz ⇒ $0 < z < 0.5$
(similar to MeerKAT L-band)

SKA-LOW: array of dipole antennas in Australia
512 (224 core) stations with 256 dipoles
350 MHz down to 50 MHz

Publications of the Astronomical Society of Australia (2020), **37**, e007, 31 pages
doi:10.1017/pasa.2019.51

CAMBRIDGE
UNIVERSITY PRESS

Research Paper

Cosmology with Phase 1 of the Square Kilometre Array Red Book 2018: Technical specifications and performance forecasts

Square Kilometre Array Cosmology Science Working Group: David J. Bacon [1], Richard A. Battye [2], Philip Bull [3], Stefano Camera [2,4,5,6], Pedro G. Ferreira [7], Ian Harrison [2,7], David Parkinson [8], Alkistis Pourtsidou [3], Mário G. Santos [9,10,11], Laura Wolz [12], Filipe Abdalla [13,14], Yashar Akrami [15,16], David Alonso [7], Sambatra Andrianomena [9,10,17], Mario Ballardini [9,18], José Luis Bernal [19,20], Daniele Bertacca [21,22], Carlos A. P. Bengaly [9], Anna Bonaldi [23], Camille Bonvin [24], Michael L. Brown [2], Emma Chapman [25], Song Chen [9], Xuelei Chen [26], Steven Cunnington [1], Tamara M. Davis [27], Clive Dickinson [2], José Fonseca [9,22], Keith Grainge [2], Stuart Harper [2], Matt J. Jarvis [7,9], Roy Maartens [1,9], Natasha Maddox [28], Hamsa Padmanabhan [29], Jonathan R. Pritchard [25], Alvise Raccanelli [19], Marzia Rivi [13,18], Sambit Roychowdhury [2], Martin Sahlén [30], Dominik J. Schwarz [31], Thilo M. Siewert [31], Matteo Viel [32], Francisco Villaescusa-Navarro [33], Yidong Xu [26], Daisuke Yamauchi [34] and Joe Zuntz [35]

Cosmology Science Working Group

Simulations Coordination

Synergies

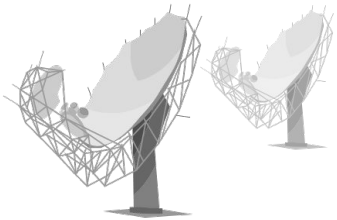
HI galaxies

Intensity Mapping

Continuum

Weak lensing

Precursor data
MeerKAT,
SuperCLASS (VLA)
ASKAP

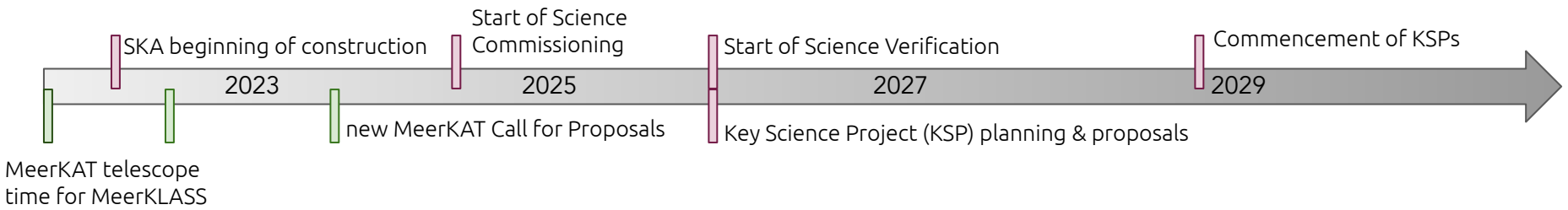


The SKA (Cosmology) timeline

21cm cosmology with the **SKA precursor MeerKAT**

Prepare a detailed scientific case for the **SKA cosmological surveys**

exploitation of the data collected with the **SKA cosmological surveys**



Proposed Cosmological Surveys

Medium Deep Band 2 with SKA-MID

5000 deg^2 and 10.000 h integration time
continuum weak leaning survey and HI galaxy survey out to $z \sim 0.4$

Wide Band 1 with SKA-MID

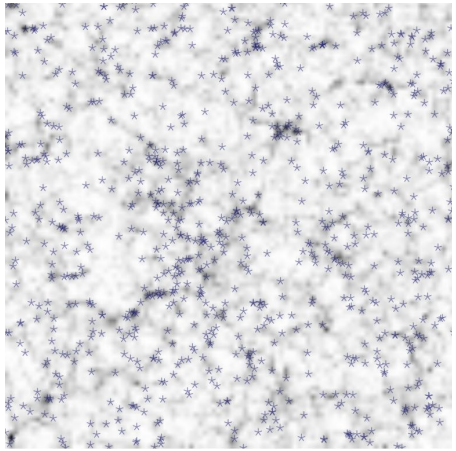
20000 deg^2 and 10.000 h integration time
continuum galaxy survey and HI Intensity Mapping out to $z \sim 3$

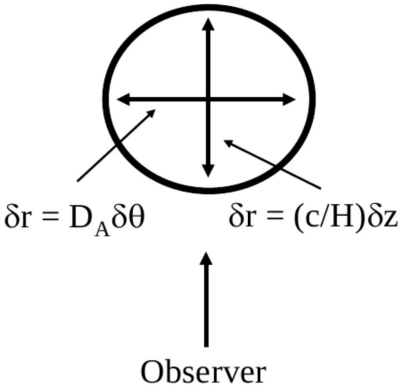
Deep SKA-LOW

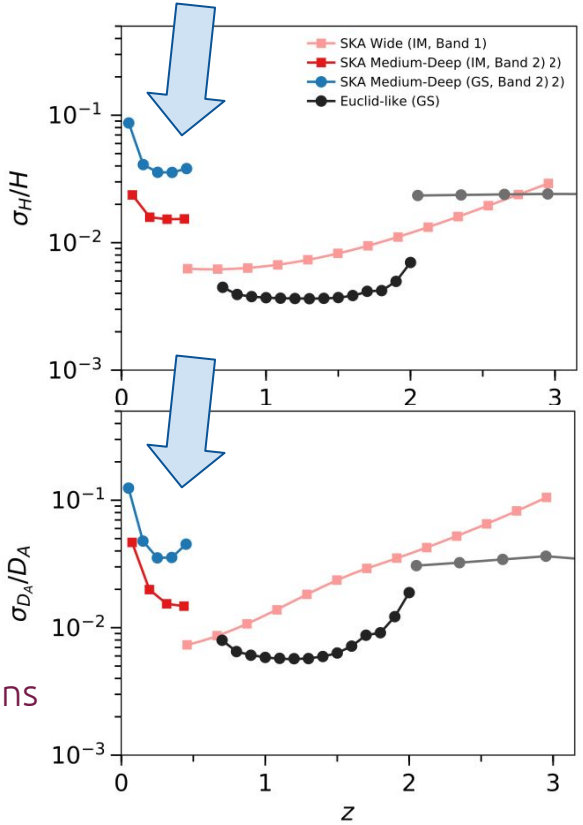
100 deg^2 and 5.000 h integration time
following the EoR survey strategy up to the end of Reionization.

HI Galaxy surveys

the distribution of **HI galaxies**
is a biased tracer of the **matter clustering**



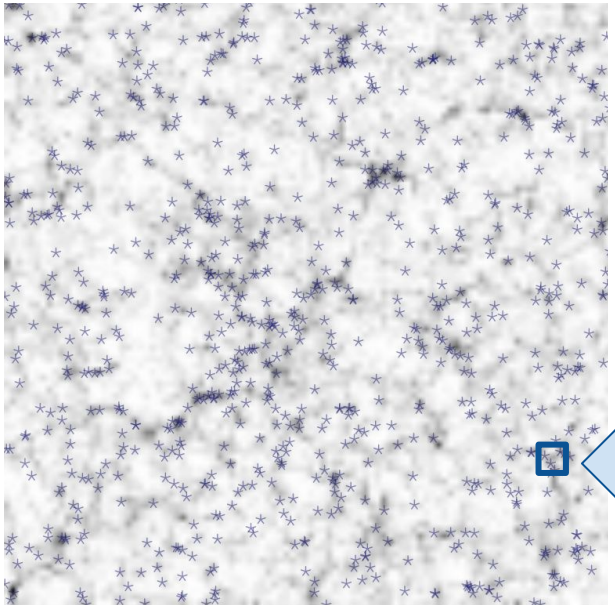




SKA Red Book (2020)

We can measure the Baryon Acoustic Oscillations

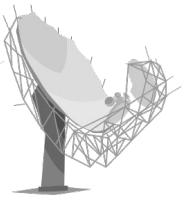
Intensity Mapping



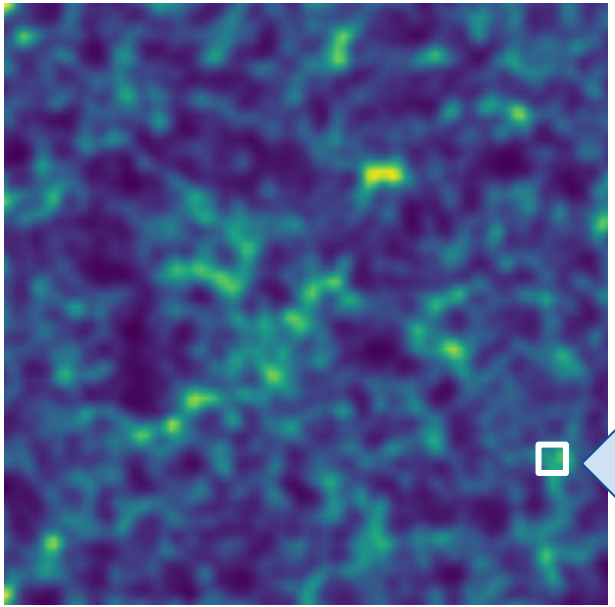
the distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**

How can we efficiently observe
cosmological volumes?

Intensity Mapping:
total intensity of the 21cm emission line
in a **large pixel** (low spatial resolution)



Intensity Mapping



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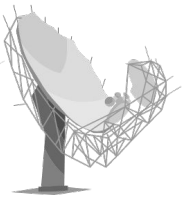
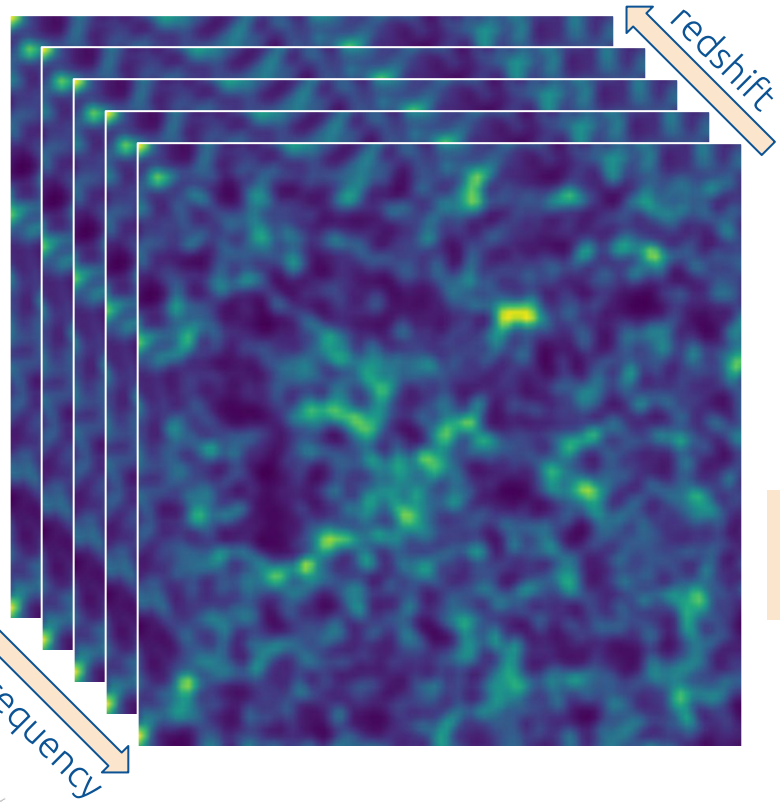


Intensity Mapping



the distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**

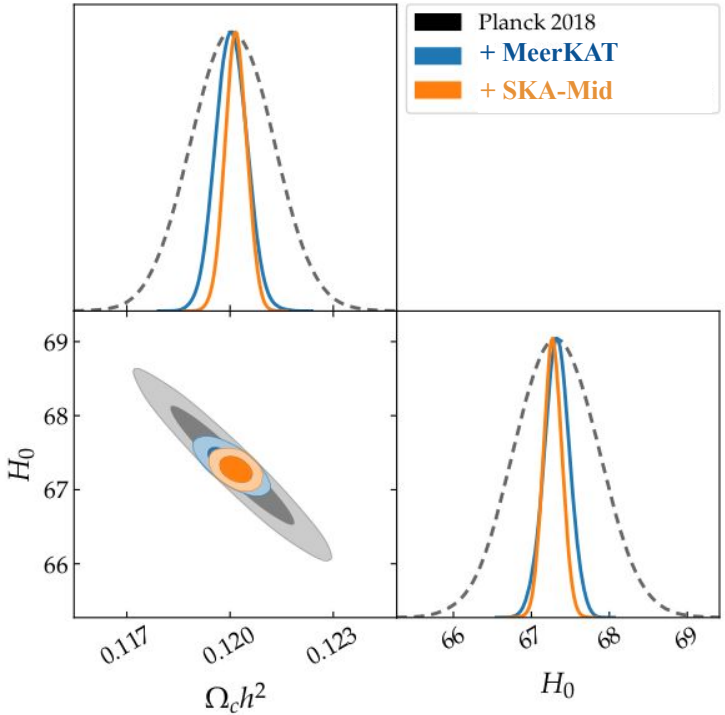
How can we efficiently observe
cosmological volumes?

one-to-one correspondence frequency-redshift
high spectral resolution (tomography)

Key cosmological probe

SKAO forecasts

Berti, **Spinelli** et al. 2022, 2023



$$P_{21}(z,k,\mu) = \bar{T}_b^2(z)\left[\, b_{HI}(z) + f(z)\,\mu^2 \,\right]^2 P_m(z,k)$$

$$P_\ell(z,k) = \frac{(2\ell+1)}{2}\,\bar{T}_b^2(z)\,P_m(z,k)\int_{-1}^{1} d\mu\,\mathcal{L}_\ell(\mu)\,\left[b_{HI}(z)+f(z)\,\mu^2\right]^2$$

MeerKAT

Gaussian beam (λ/D)
realistic noise level
2400h, 2000deg2 in L-band
(zeff~0.39)

SKA-MID

tomography up to z~3
20000 deg2, 10.000h
multipole expansion (P0+P2)

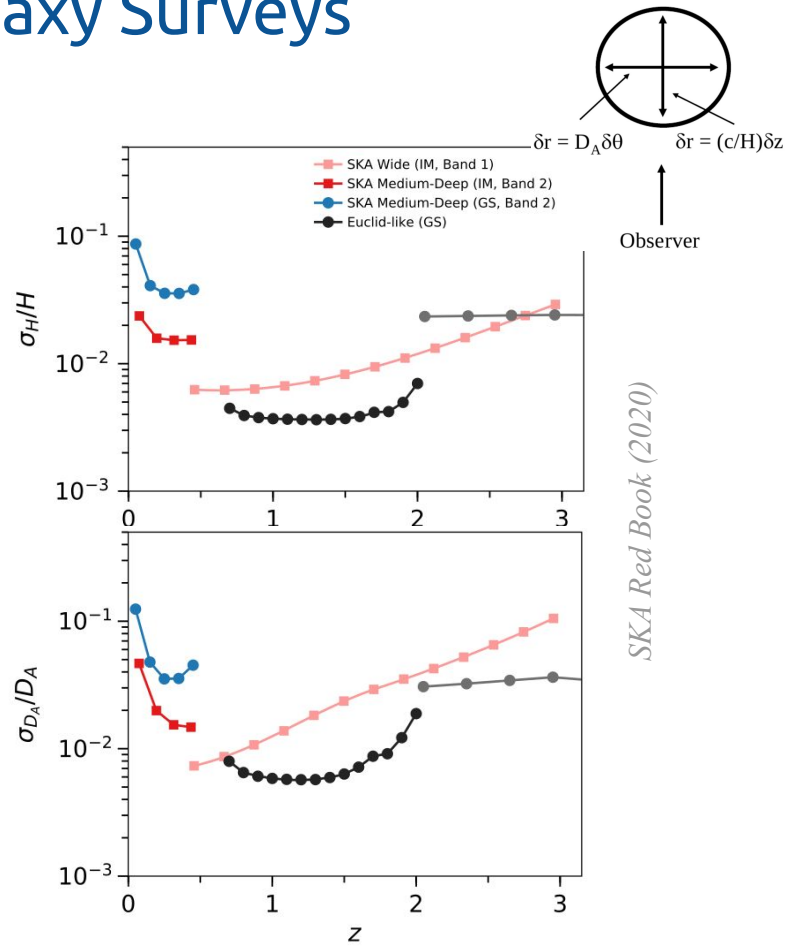
P21 breaks parameter degeneracies

Intensity Mapping & Galaxy Surveys

Complementarity to galaxy surveys
IM traces the LSS with a different bias and different systematics w.r.t. e.g. Euclid

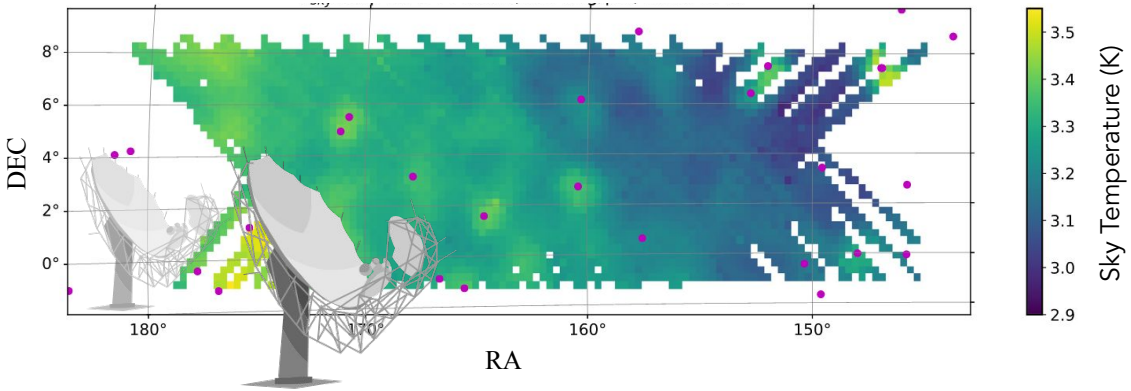
Broader redshift range
combining SKA-Mid and SKA-Low:
efficiently map cosmological volume up to high redshift (z~6)

Synergies
cross-correlation with CMB and/or galaxy surveys reduce the systematics and enhance the constraining power



Intensity Mapping Observations

MeerKLASS: cosmological survey with MeerKAT 64 antennas

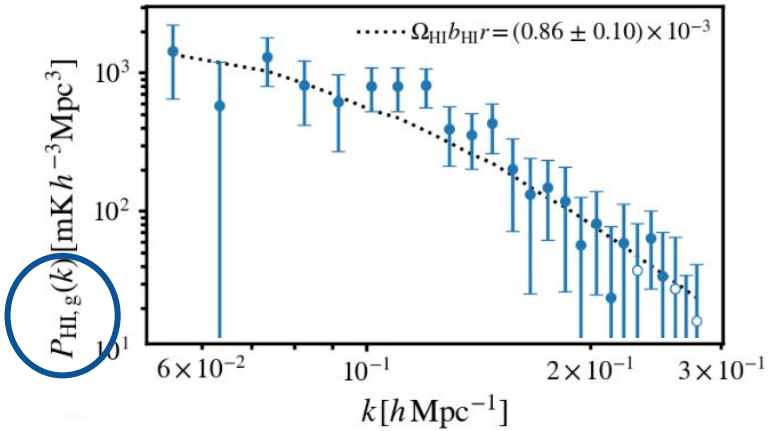


First calibrated sky map!

Wang et al. 2021 [including Spinelli]

complex analysis pipeline
Need for RFI flagging, foreground cleaning, etc.

21cm signal detection achieved at redshift 0.4
in **cross-correlation with galaxy surveys**
Cunnington et al. 2022 [including Spinelli]



End-to-end Simulations

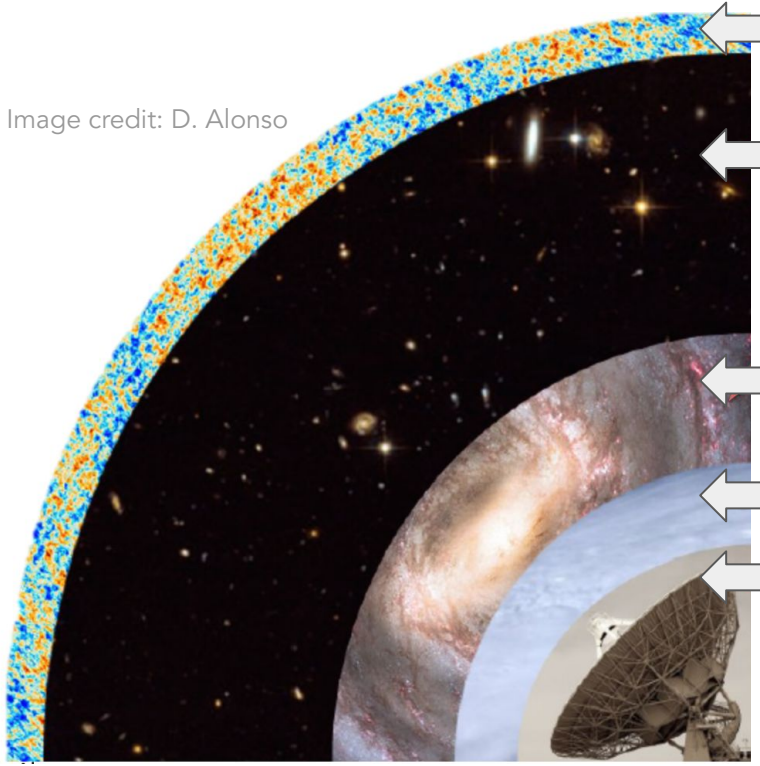


Image credit: D. Alonso

21cm signal maps

extra-galactic emission

Galactic emission

instrumental and systematic effects

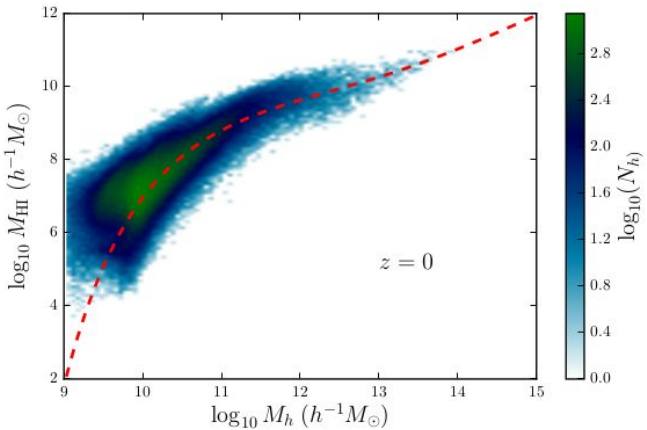
realistic mocks

analysis pipeline

power spectrum

cosmological parameter constraints

What we can do with GAEA



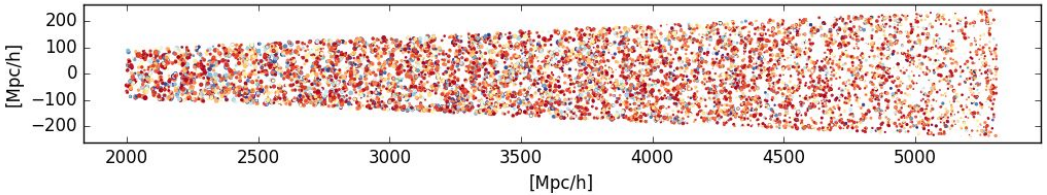
explicit treatment of cold gas partition in atomic (HI) and molecular (H2) (Xie et al. 2017)

intensity map generation

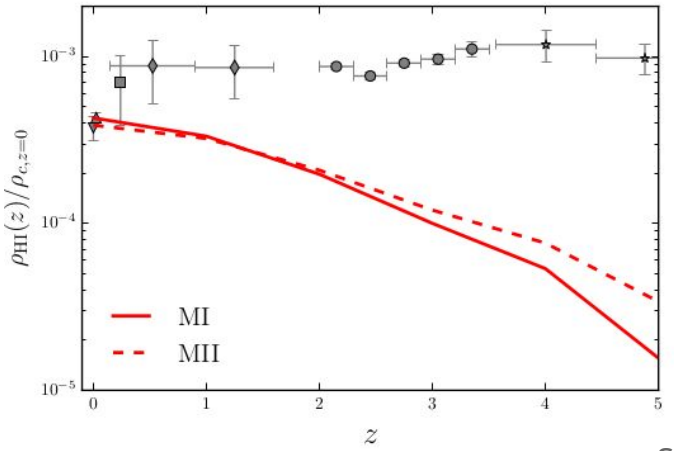
21cm line properties from semi-analytical models, Halo Occupation Distribution methods on fast halo catalogues

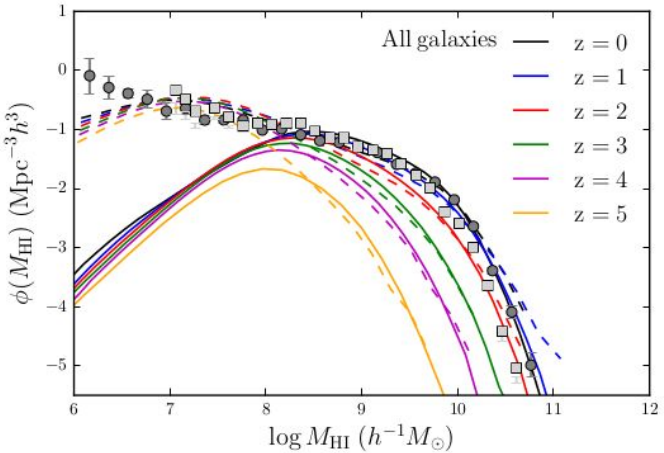
Spinelli et al. 2020, 2022

GAEA **light-cone construction** essential also for cross-correlation studies with **galaxy surveys**
code: Anna Zoldan



HI evolution with redshift





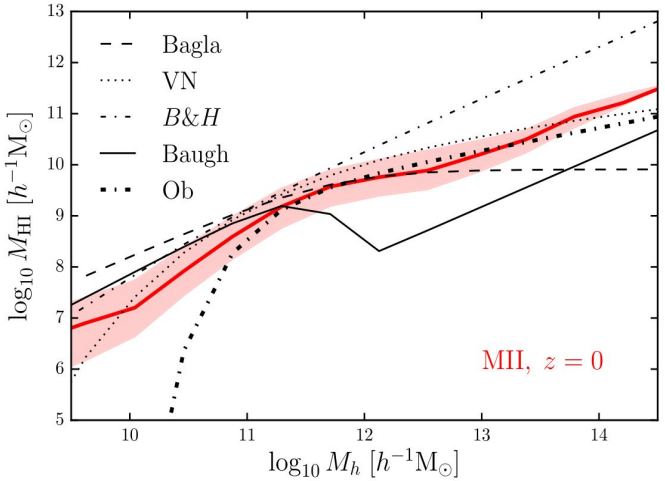
Spinelli et al. 2020

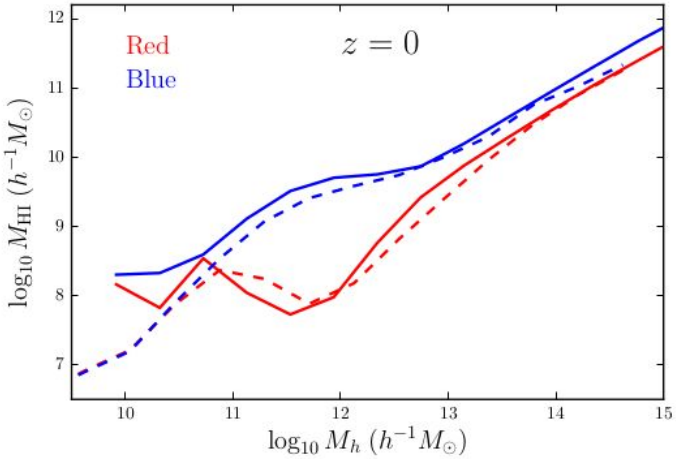
tuned to match ΩHI in the local universe

SAMs often predict decrease with redshift
Problem is not solved yet!

hierarchical growth of structures,
switch between z = 0 and z = 1
due to AGN feedback

MHI-Mhalo relation



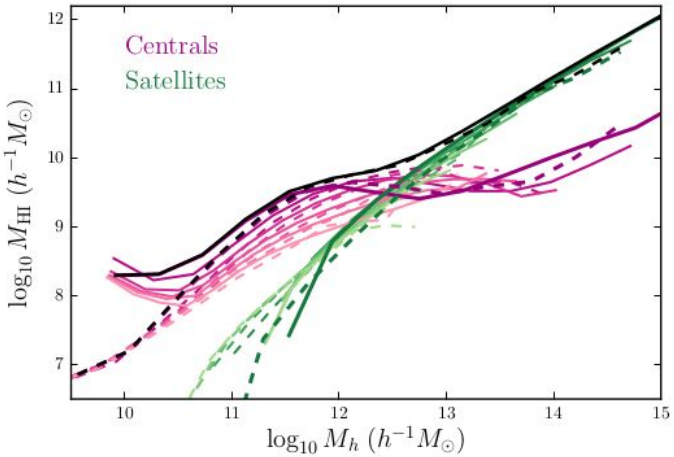


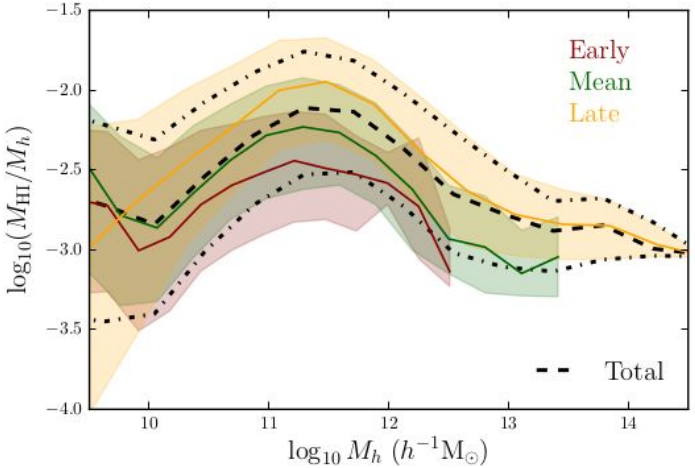
Red vs Blue with a cut in sSFR

Most satellites in massive halos are red galaxies

Blue star forming dominates HI content of medium mass haloes driving the clustering properties of all HI

MHI-Mhalo relation

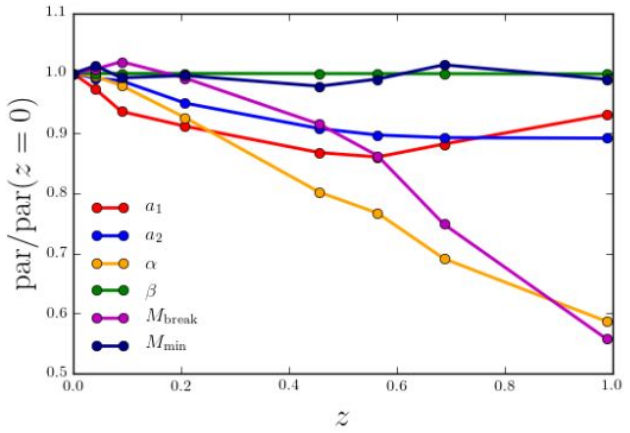


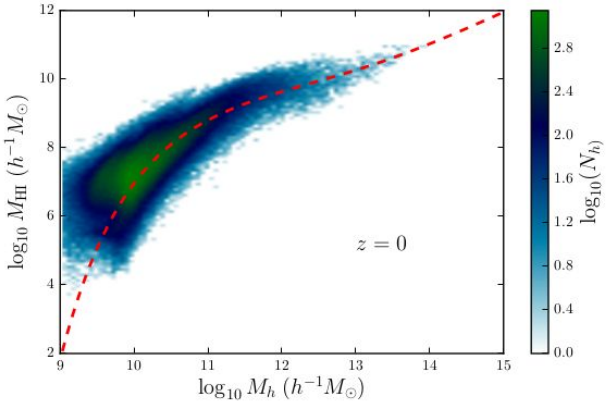


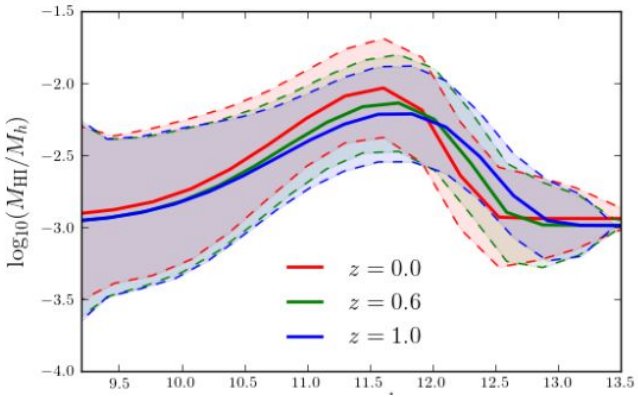
Hi-Probe POPulator (HiP-POP)

$$M_{\rm HI}(M_{\rm h}) = M_{\rm h}\left[a_1\left(\frac{M_{\rm h}}{10^{10}}\right)^{\beta} e^{-\left(\frac{M_{\rm h}}{M_{\rm break}}\right)^{\alpha}} + a_2\right] e^{-\left(\frac{M_{\rm min}}{M_{\rm h}}\right)^{\gamma}}$$

Fit the MHI-Mhalo relation at various GAEA snapshots and find a redshift trend

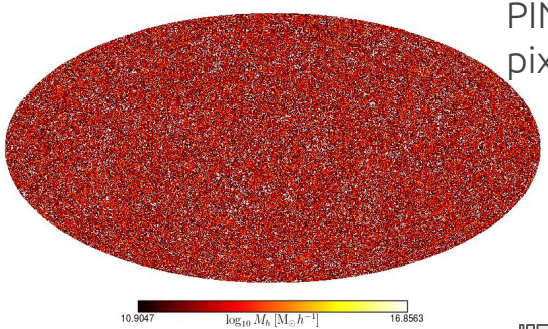


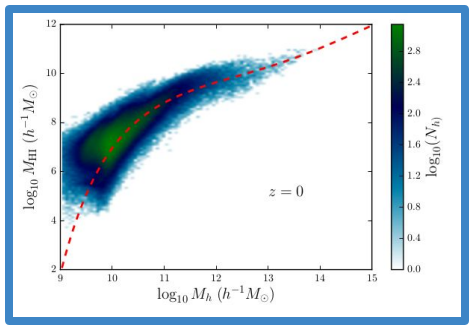




Hi-Probe POPulator (HiP-POP)

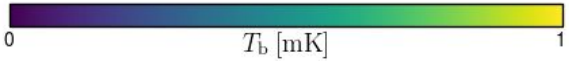
PINOCCHIO full sky light-cone
pixelized with Healpix





MHI (ra,dec, u)

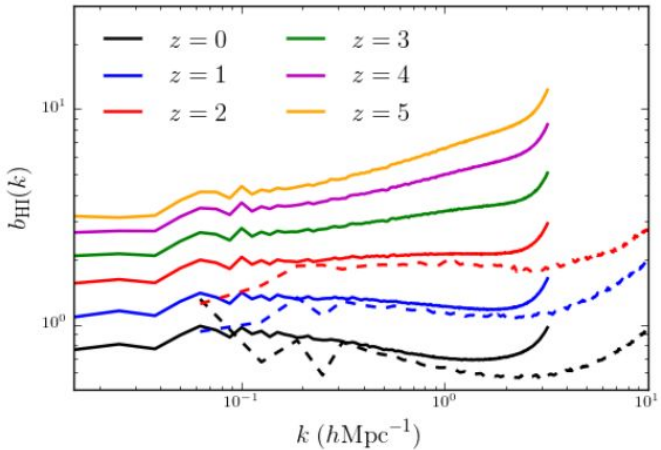
Tb [mK]

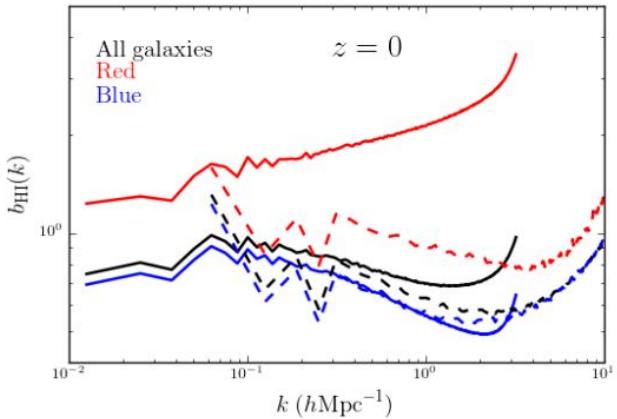


Too big halos “spread” with NFW in nearby pixels

Hi bias from GAEA

$$b_{\rm HI}(k) = \sqrt{\frac{(P_{\rm HI}(k) - P_{\rm SN})}{P_m(k)}}$$





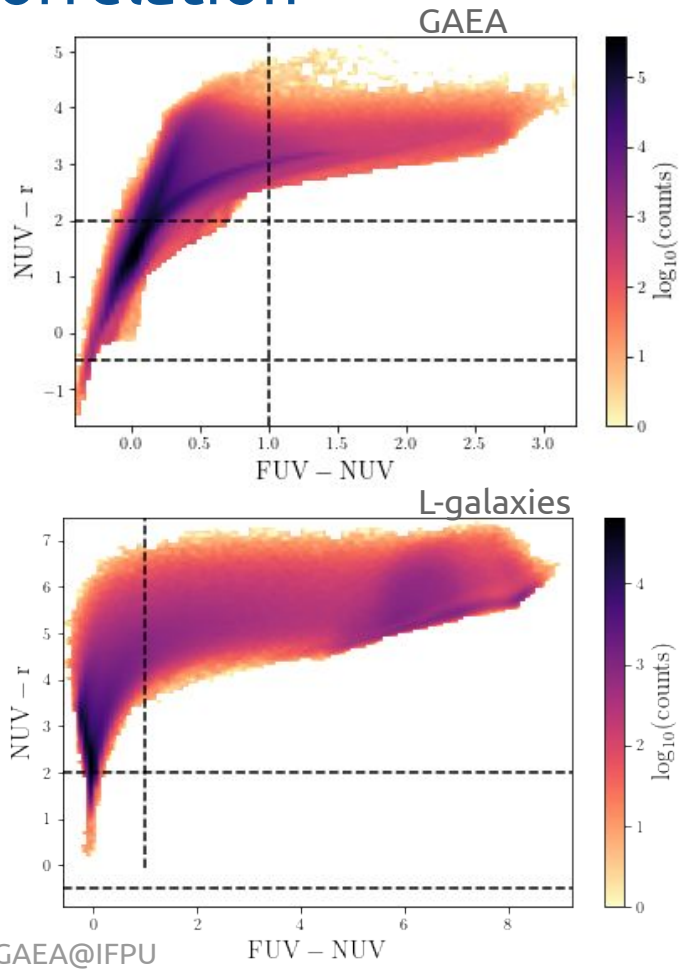
GAEA for cross correlation

We run GAEA **with galaxy survey of interest filters (e.g. WiggleZ)**

How much we can recover the observed properties?
Difficult to be accurate using selection criteria!

[snapshot level]

Possibly need to use other proxies (work in progress)

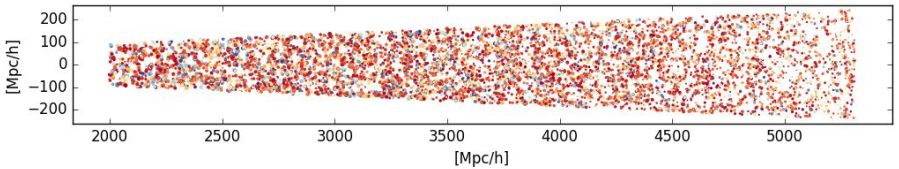


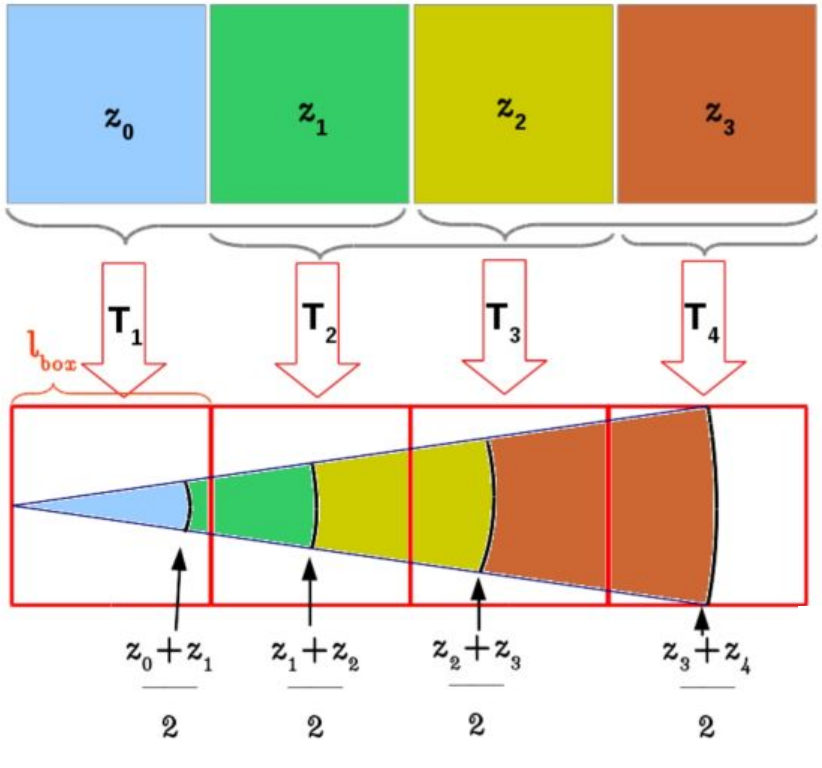
Light-cone construction

We run on GAEA **the python version of MOMAF code (Credit: Anna Zoldan)**
+ Fabio, Gabriella, Olga

For the moment “pencil beam” only working properly.

Work in progress on the “full-sky” light-cone (e.g. MeerKLASS at z~0.4 would already need 800 Mpc/h instead of 500)



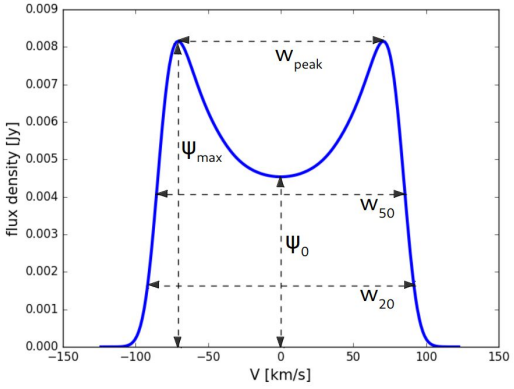


used for ***Euclid*** and **MOONS**

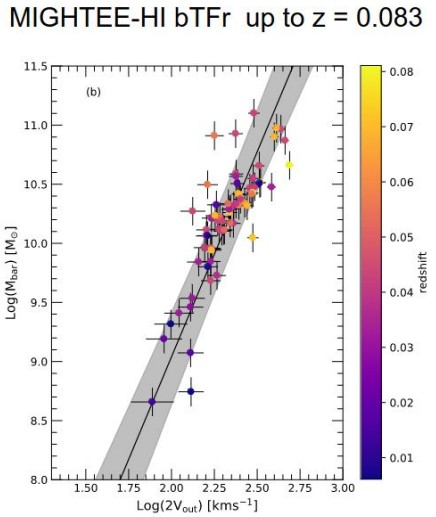
Peculiar velocities

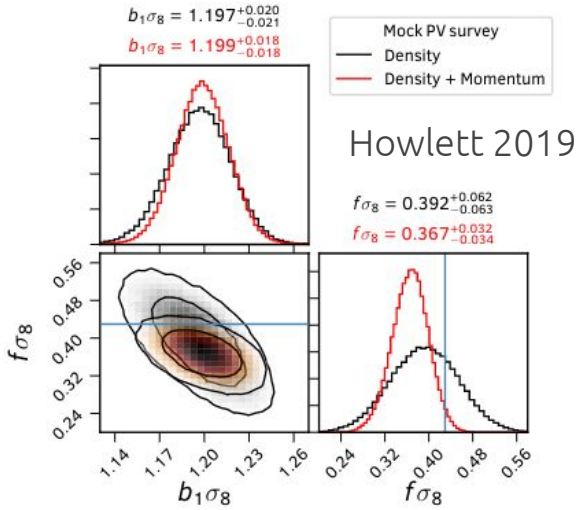
New project of the HI galaxies FG (Gabriella & Anastasia) (work staring now with input from HI SWG)

How to construct realistic mocks to simulate how SKAO will measure the bTF for peculiar velocities and then extract the cosmology?



Anna Zoldan's code for synthetic lines available!





Howlett 2019

Conclusions

SKAO and its precursors will be crucial for 21cm Cosmology

Various probes: HI galaxies, peculiar velocities, HI Intensity Mapping
(and correlation with galaxy surveys)

Need to prepare the Key Science Project case for Cosmology (soon!)

GAEA has most of the fundamental ingredients (HI mass, galaxy properties, …)

- We can study **clustering properties** of various galaxy surveys
  and their cross correlation with HI mass.
- For **HI intensity mapping** (large cosmological volumes) coupling with fast halo catalogues generation code (e.g. PINOCCHIO) is key.
  (but need proper HOD for galaxy property for correlation studies).
- **HI galaxy survey mock** can also be studied: add SKAO-like instrumental effects
- Forecasts on **peculiar velocities** just started!