Neutral Hydrogen Intensity Mapping

as a cosmological tool

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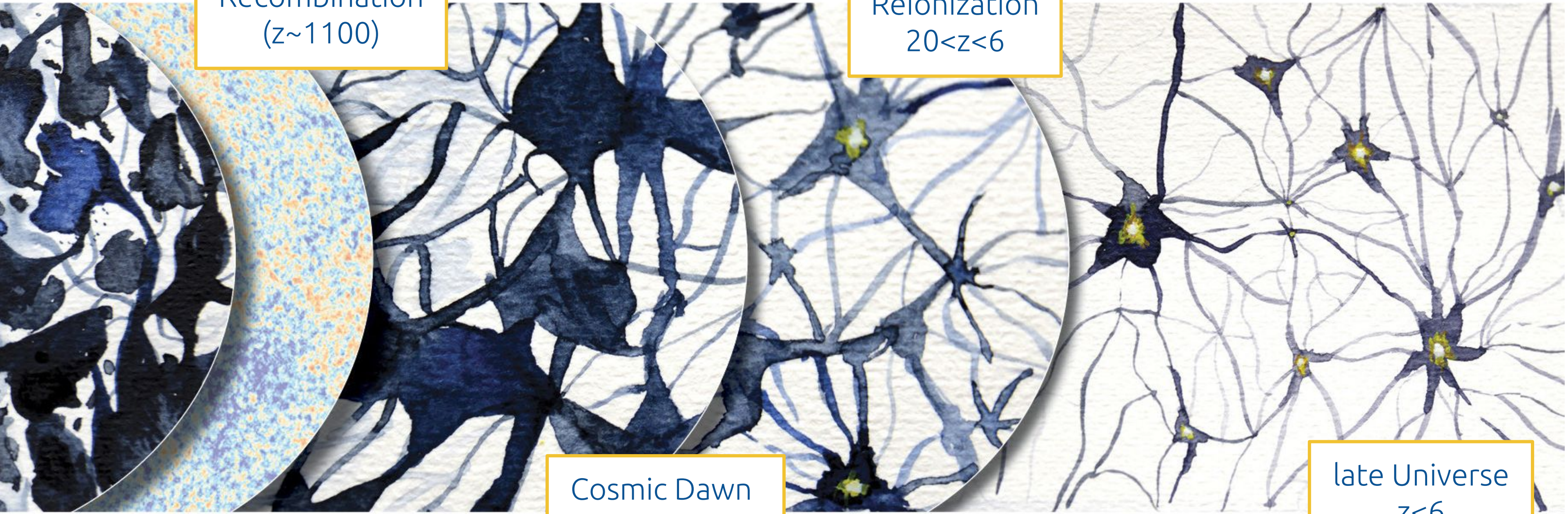
Observatoire de la Côte d'Azur

ModIC 2024

14 May 2024 - Trieste IFPU

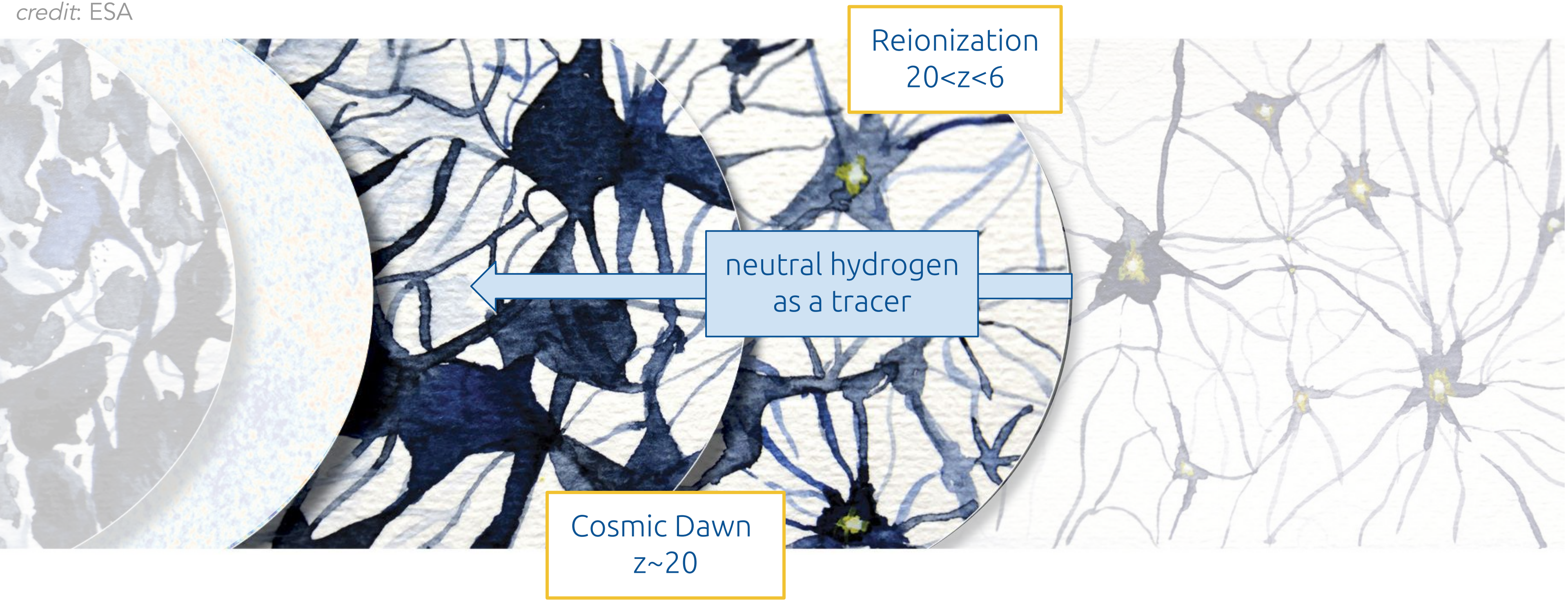
Hydrogen in cosmic history

credit: ESA

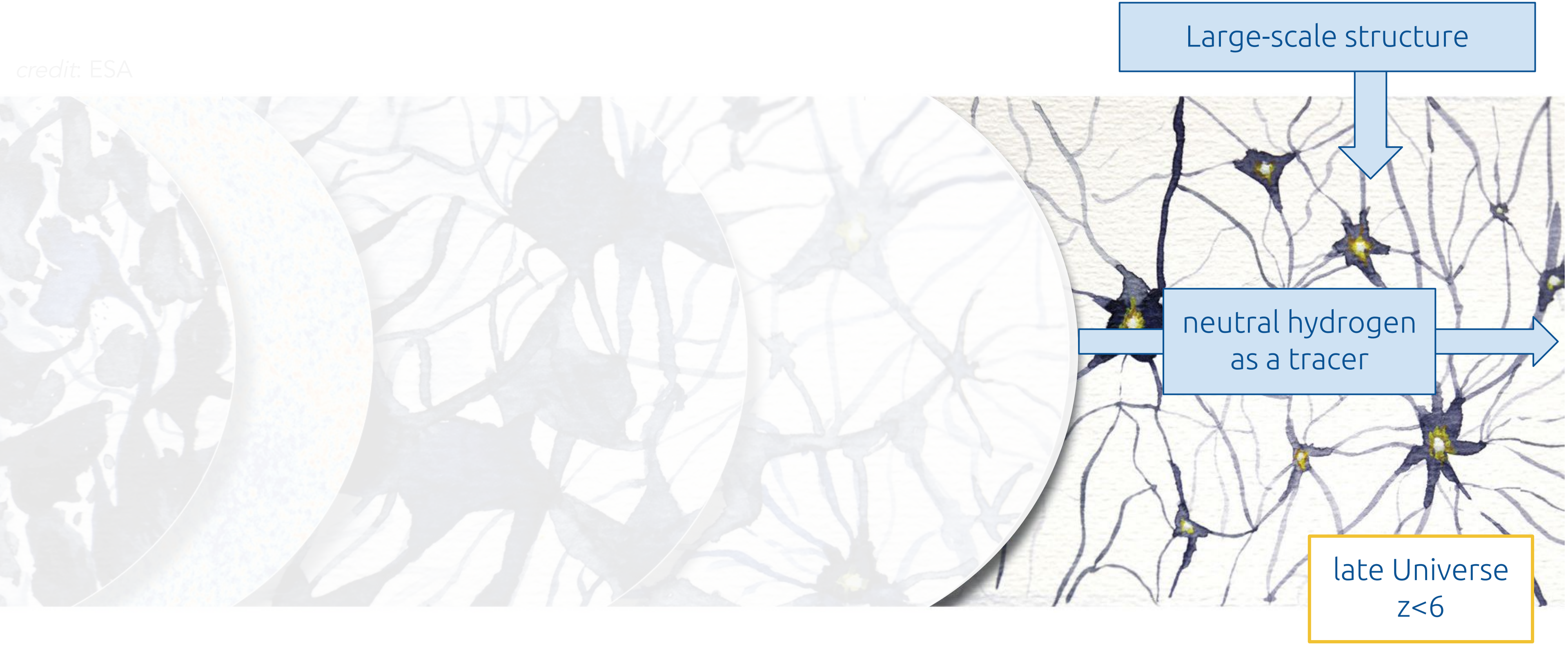


The **high** redshift universe

credit: ESA

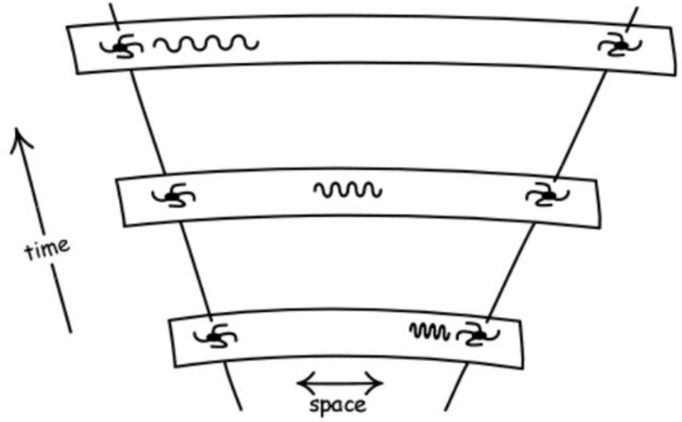


The **low** redshift Universe



Frequency and redshift for the 21cm line

$$z = \frac{(\nu_{\text{emitted}} - \nu_{\text{observed}})}{\nu_{\text{observed}}} \text{ with } \nu_{\text{emitted}} = 1420 \text{ MHz}$$



https://www.pitt.edu/~jdnorton/teaching/

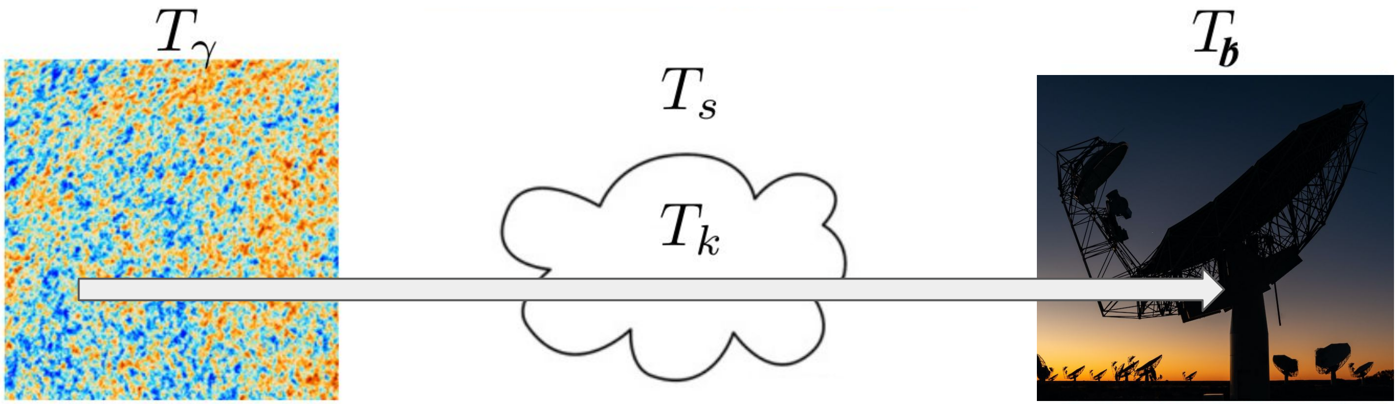
Examples:

ν_{observed} ~ 900 MHz
corresponds to z ~ 0.6: late Universe

ν_{observed} ~ 170 MHz
corresponds to z ~ 7: Epoch of Reionization

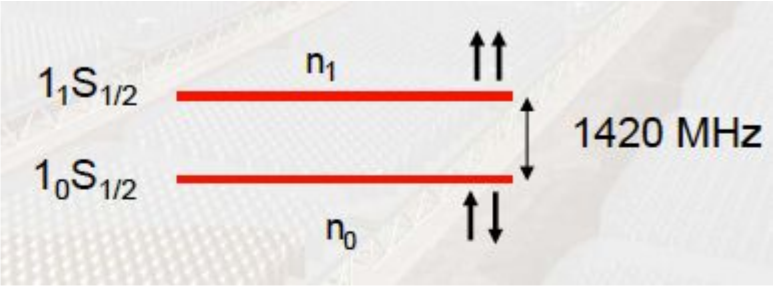
ν_{observed} ~ 70 MHz
corresponds to z ~ 20: Cosmic Dawn

The 21cm line



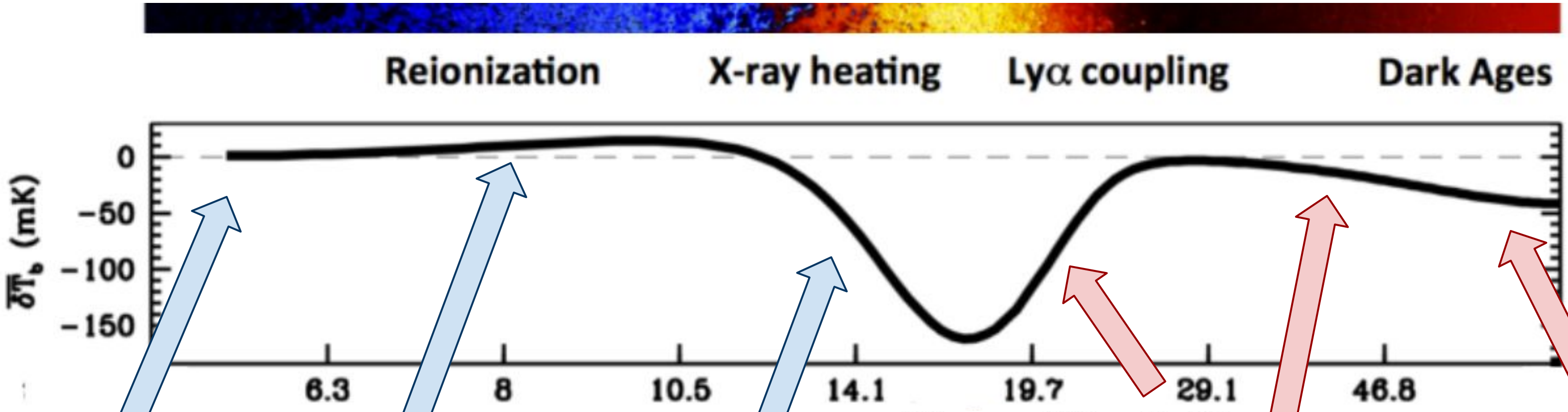
3 fundamental temperatures:

- Tγ the CMB temperature
- Tk the gas (IGM) temperature
- Ts the spin temperature: *sets the population of the hyperfine level with respect to the ground state*



21cm signal as the Universe evolves

$$\delta T_b \propto x_{HI}(1+\delta)(1-\frac{T_\gamma}{T_s})\ \mathrm{mK}$$



HI traces
the large-scale structure

Ionising source
fluctuations
dominated by x_HI

$T_k = T_s \gtrsim T_\gamma$

IGM hotter than CB:
emission ->absorption

$T_k \sim T_s \lesssim T_\gamma$

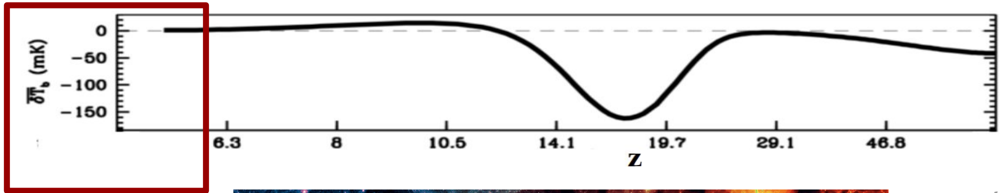
Universe expands,
IGM less dense
collisional decoupling

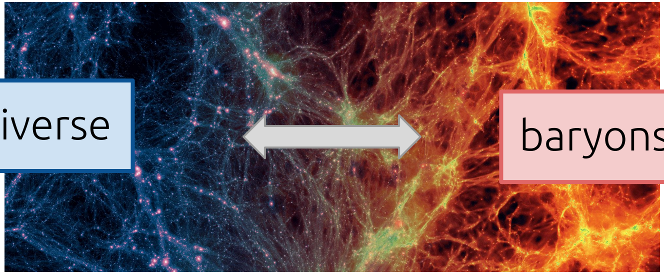
$T_k < T_s \lesssim T_\gamma$

$T_k = T_s \lesssim T_\gamma$

IGM dense:
collisional coupling

Late-time neutral hydrogen distribution





credit: Illustris

dark Universe

baryons: neutral Hydrogen (HI)

What is the nature of dark matter and dark energy?

how is dark matter distributed on large scales?

how does its distribution evolve with cosmic time?

what is the role of dark energy?

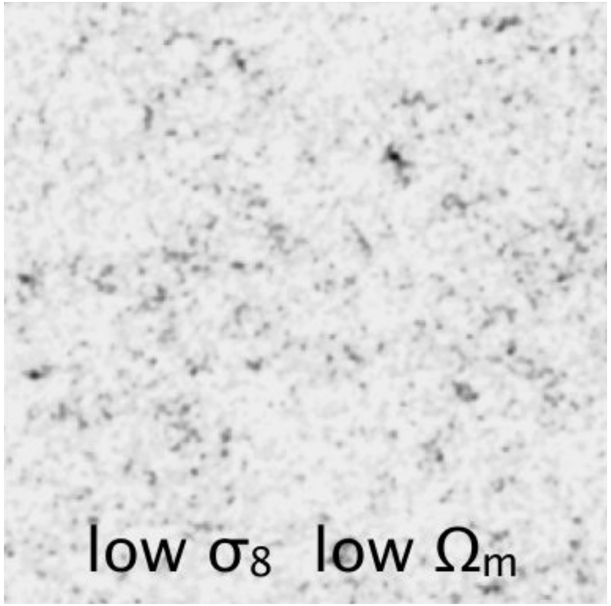
How do baryons trace dark matter?

what is the link between galaxies and dark matter halos?

how are HI galaxies distributed in the cosmic web?

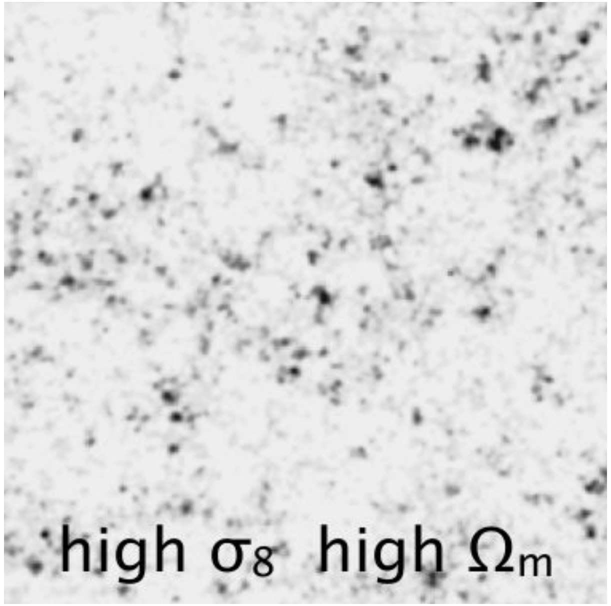
how does the total cosmic HI evolve with redshift?

LSS with Neutral Hydrogen



matter clustering contains a wealth of **cosmological information**

LSS with Neutral Hydrogen



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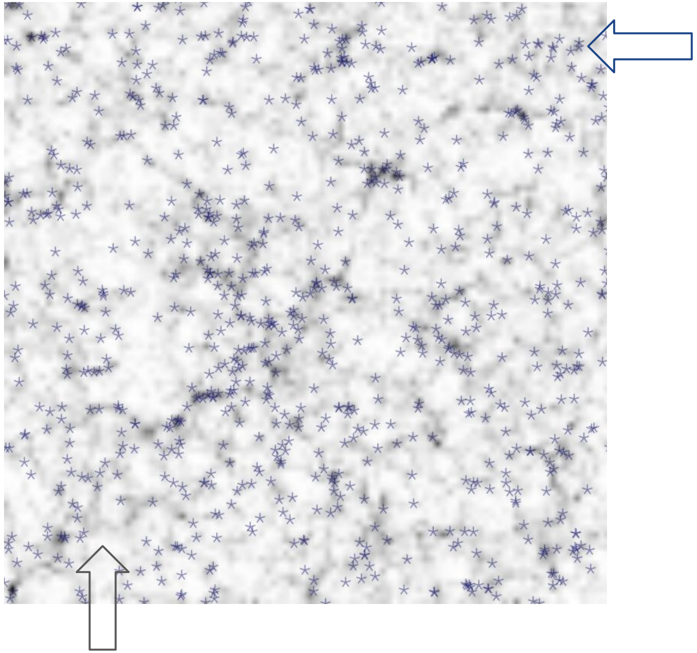
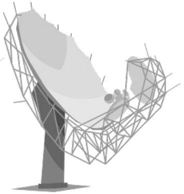


the distribution of **neutral Hydrogen** is a biased tracer of the **matter clustering**

underlying matter distribution

How can we efficiently observe cosmological volumes?



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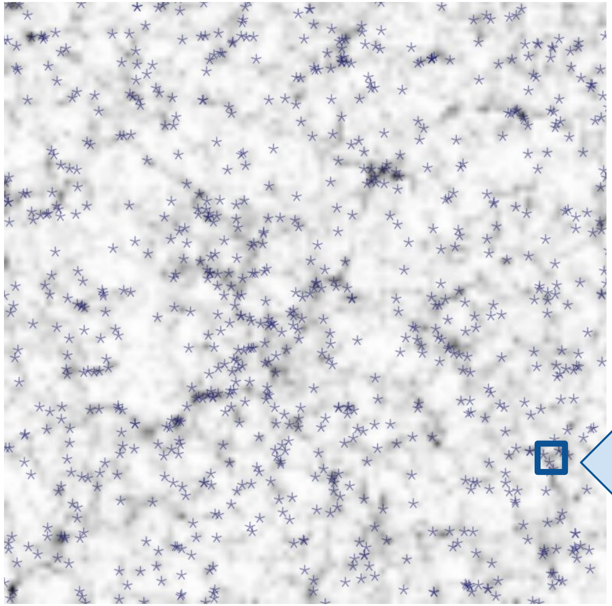


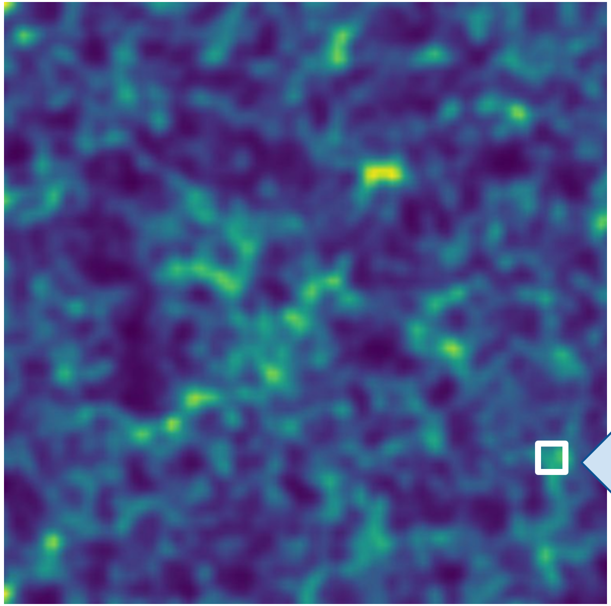
the distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**

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

E.g. Bharadwaj et al. 2001;
Battye et al. 2004; Wyithe et al. 2008;
Chang et al. 2008



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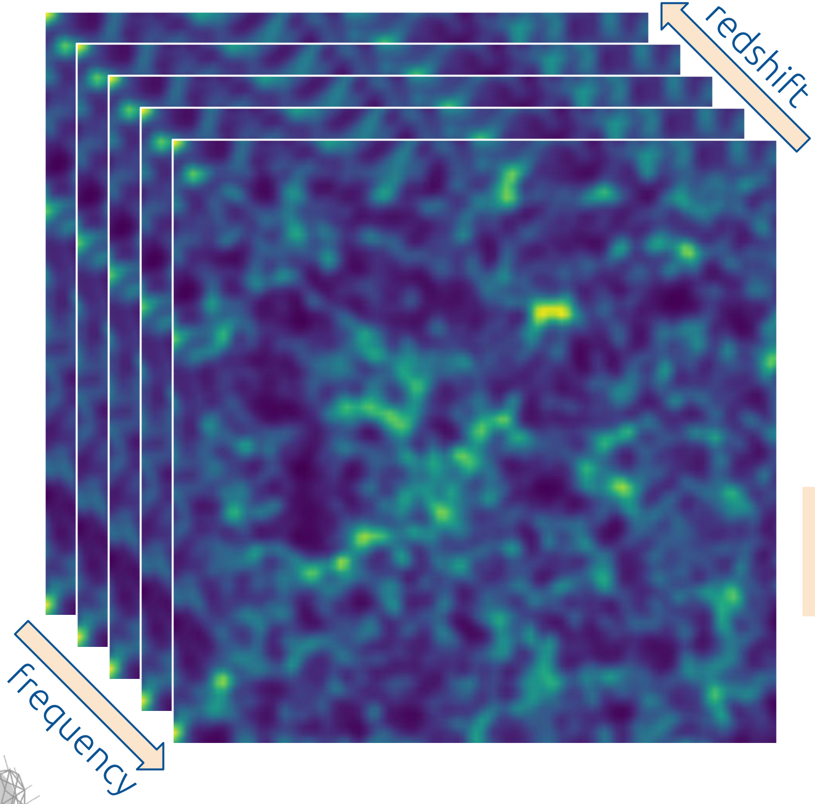
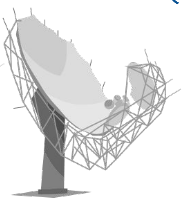




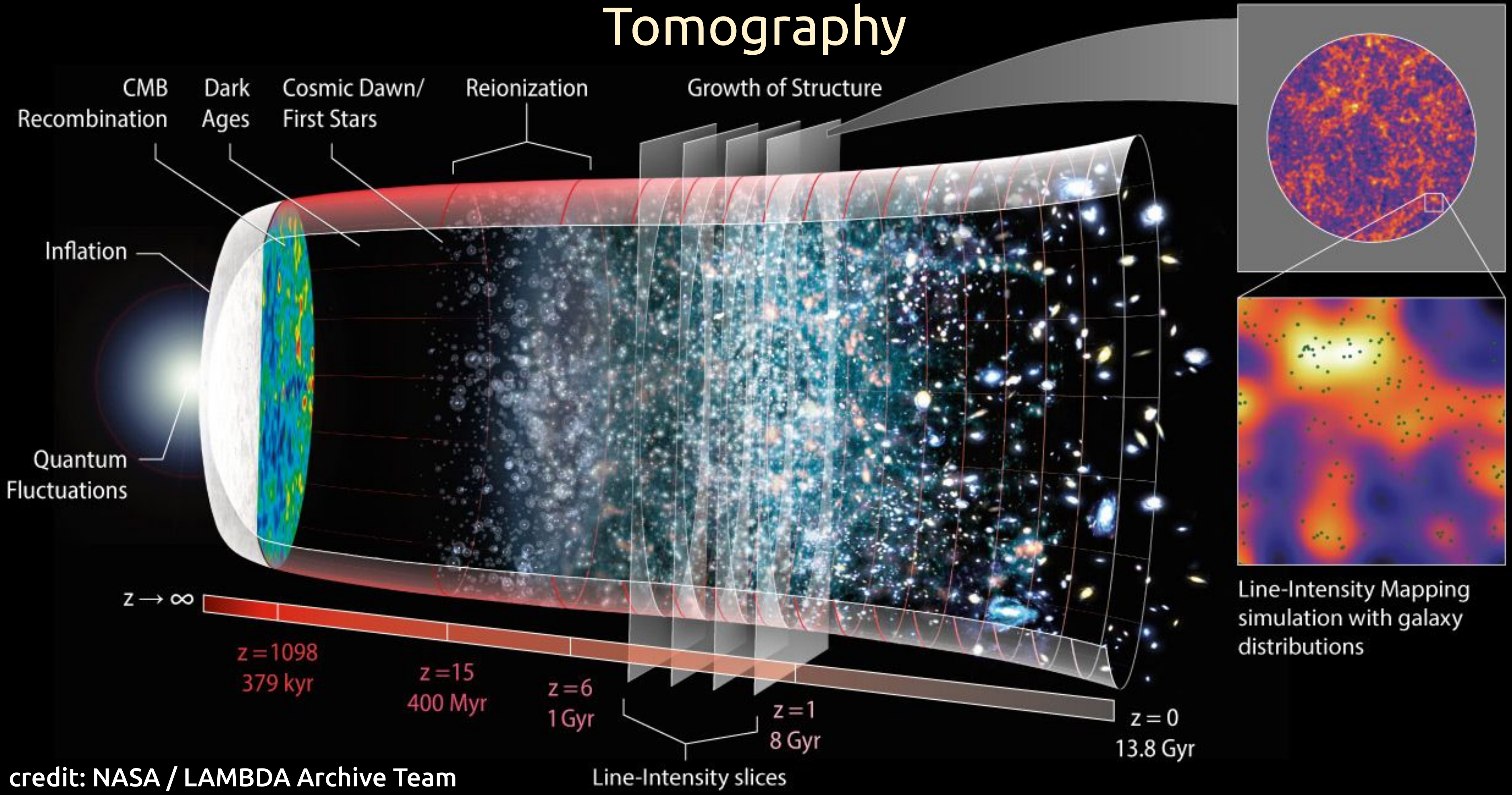
the distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**

How can we efficiently observe
cosmological volumes?

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

Key cosmological probe

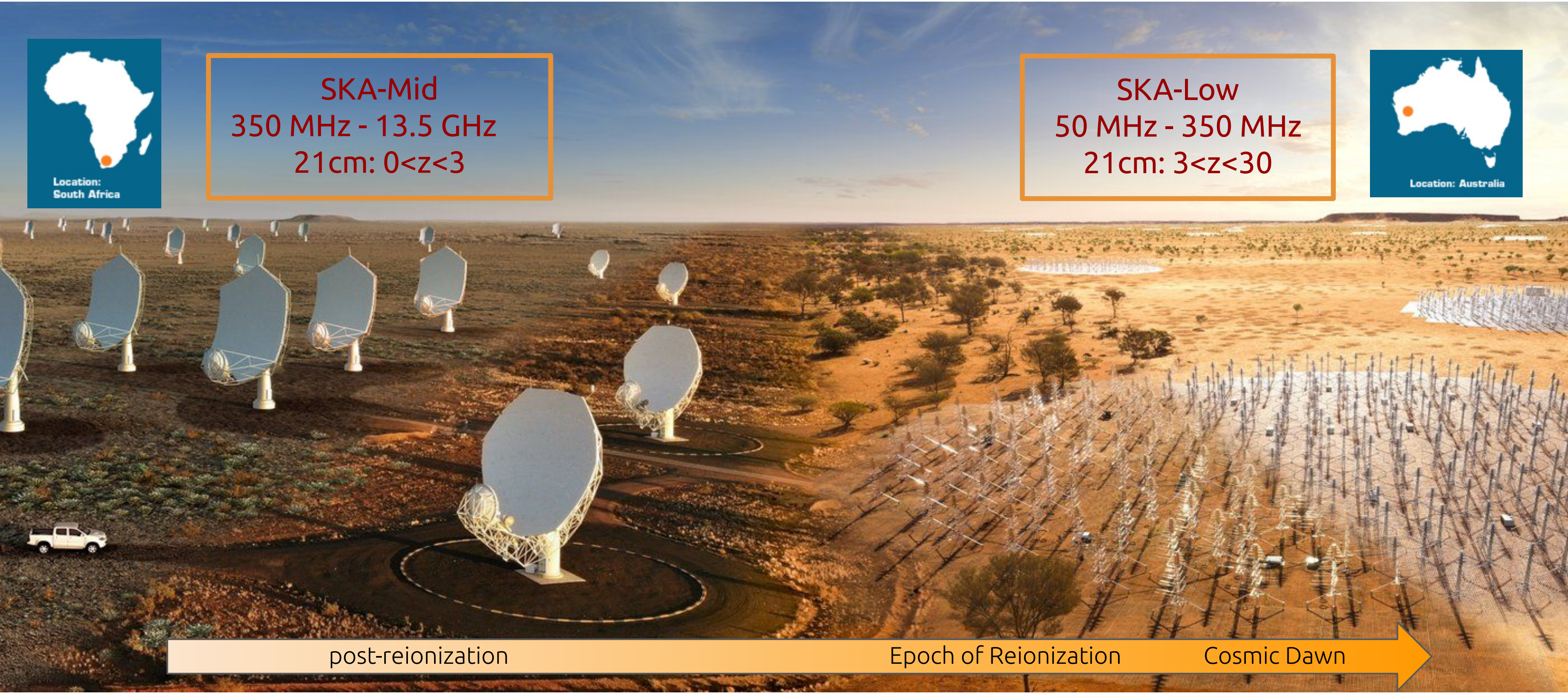
Tomography



credit: NASA / LAMBDA Archive Team

The SKA Observatory

credit: skatelescope.org



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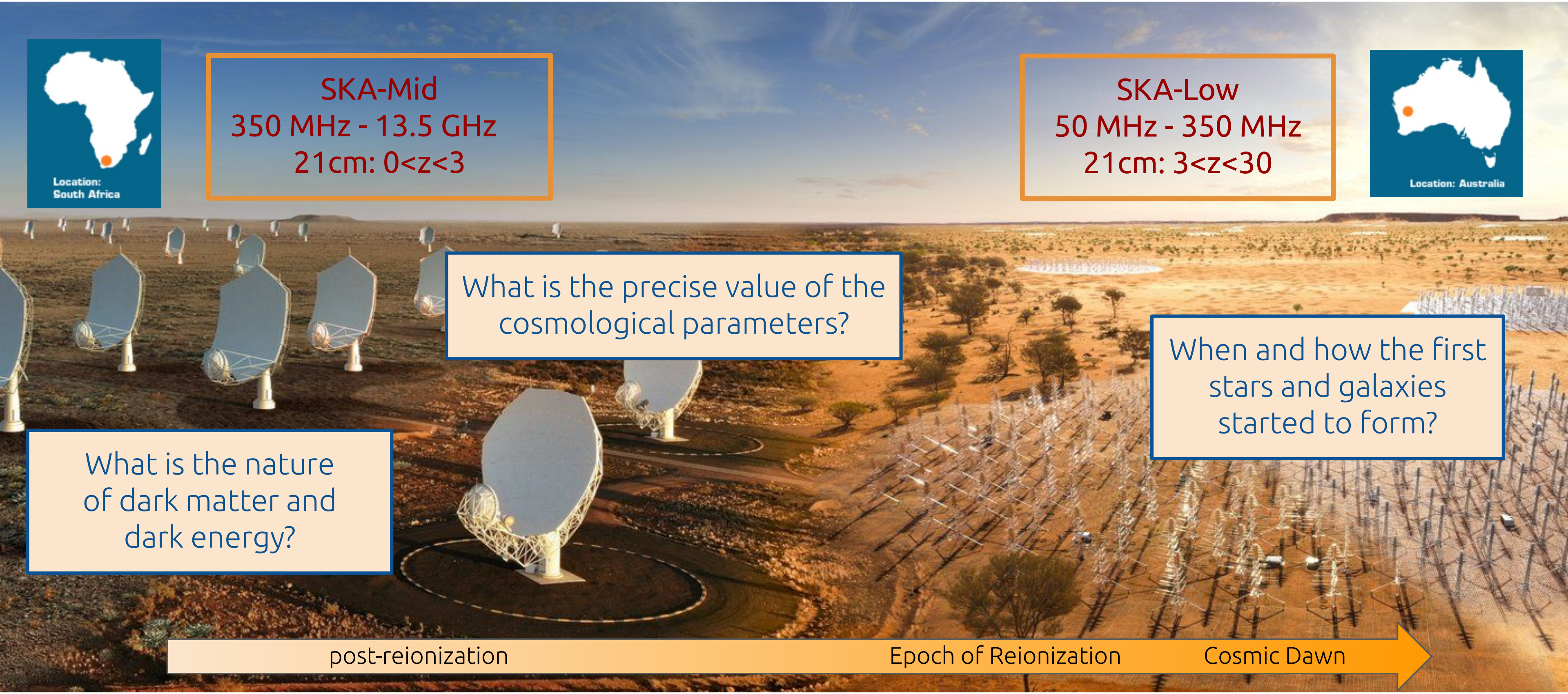
credit: skatelescope.org



SKA-Mid
350 MHz - 13.5 GHz
21cm: $0<z<3$

SKA-Low
50 MHz - 350 MHz
21cm: $3<z<30$

What is the precise value of the cosmological parameters?

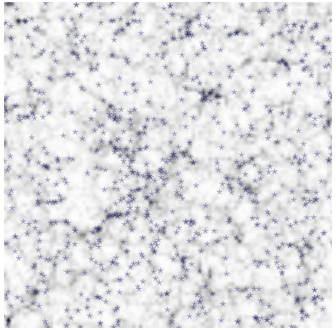
When and how the first stars and galaxies started to form?

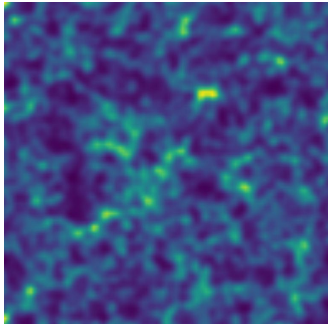
What is the nature of dark matter and dark energy?

post-reionization → Epoch of Reionization → Cosmic Dawn

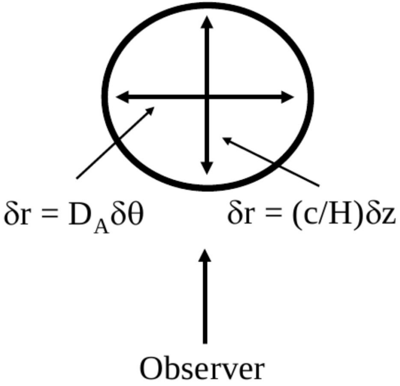
BAO at different redshift

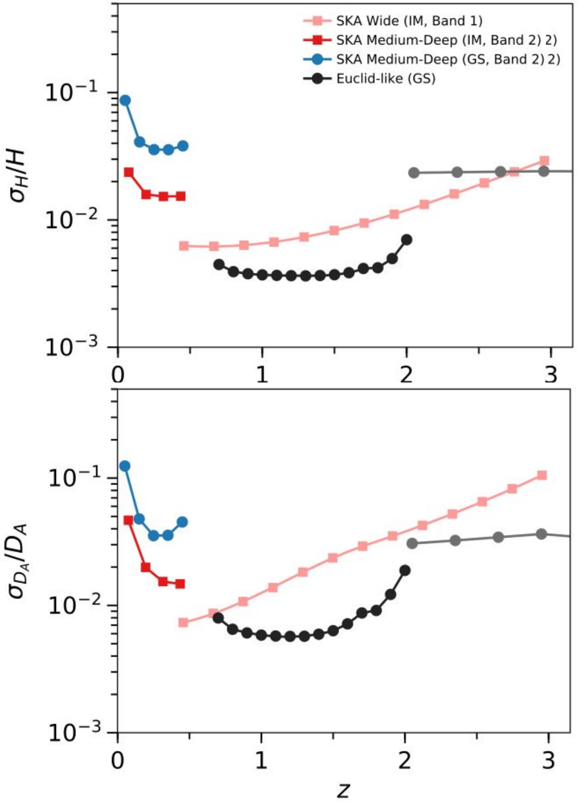
HI galaxies (GS) at low redshift





HI distribution (IM) at higher redshift

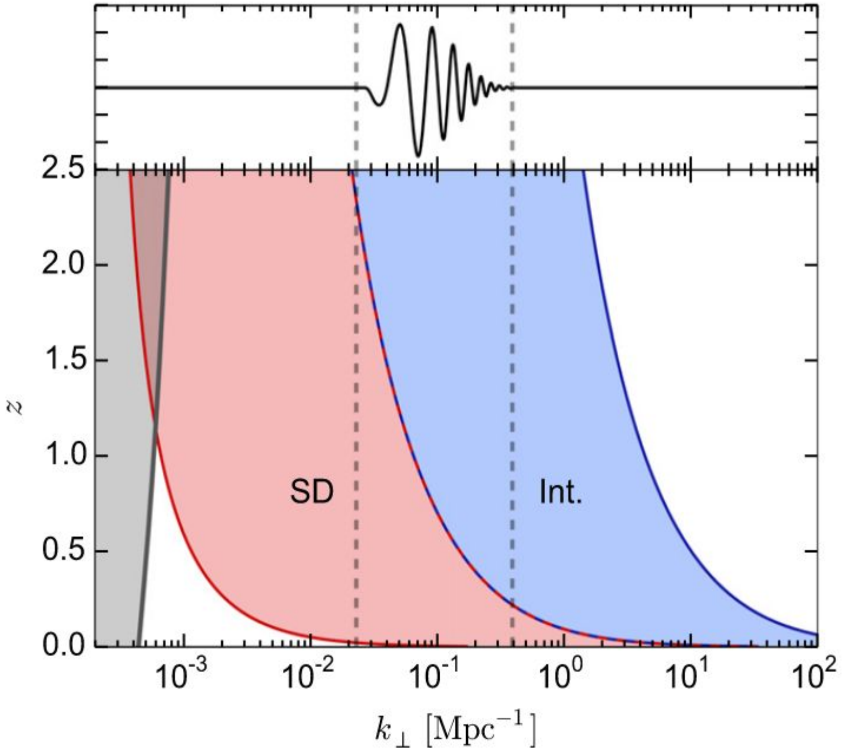




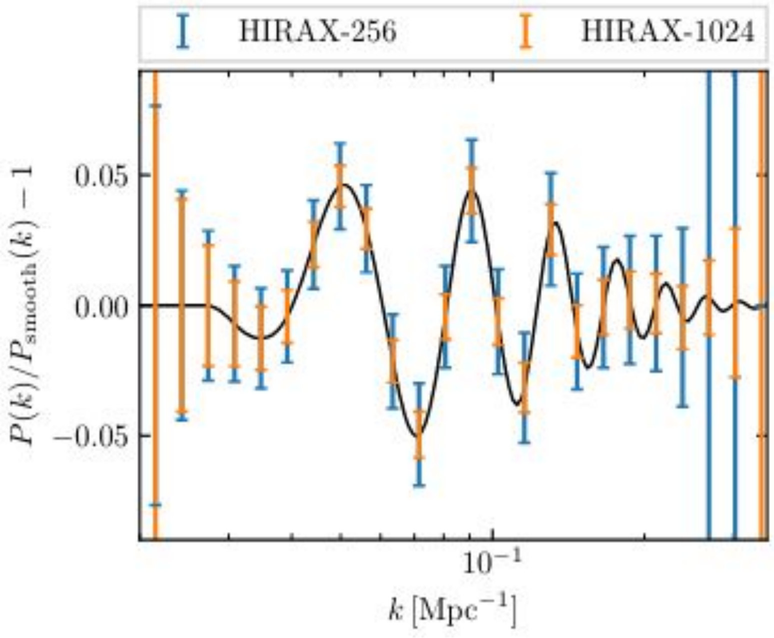
SKA Red Book (2020)

Beside the SKAO

Single Dish vs interferometry



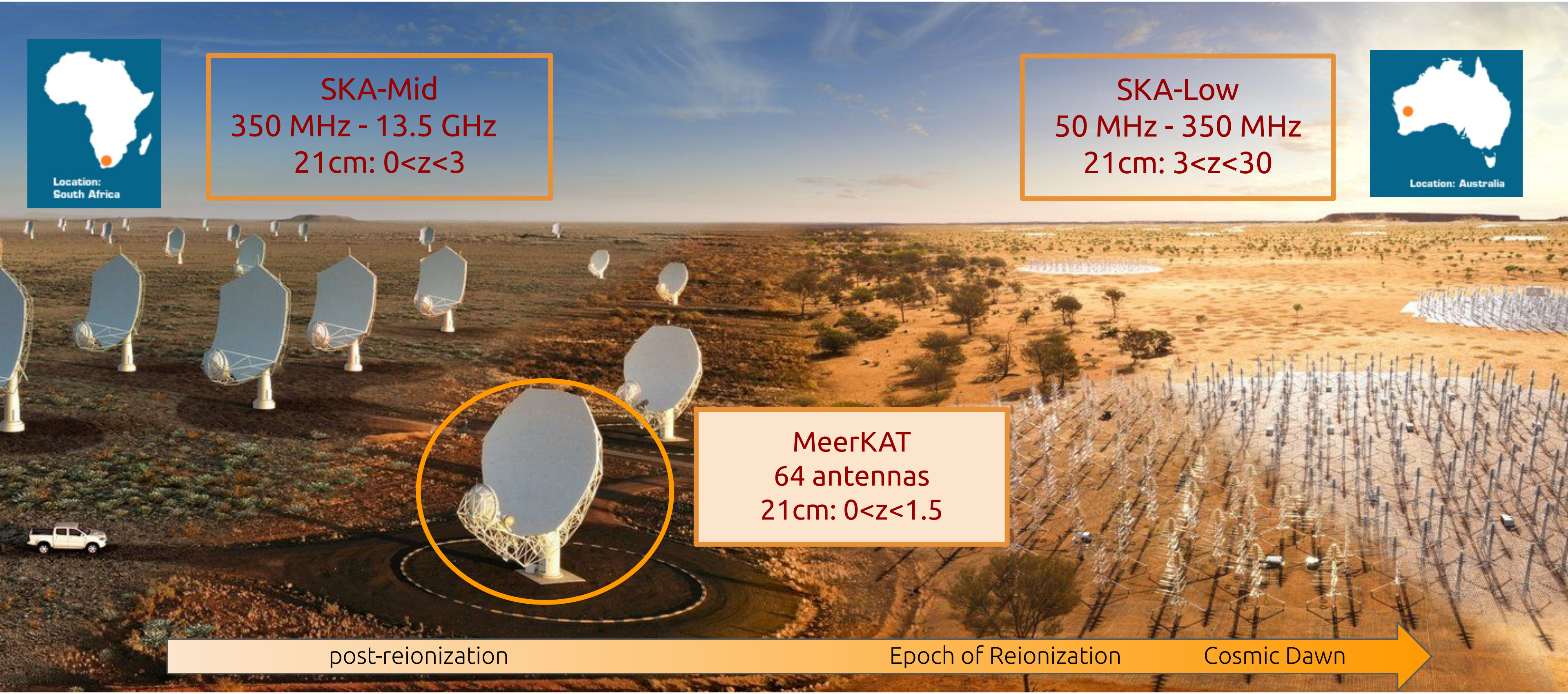
Bull et al. 2015



Crichton et al. 2021

The SKA Observatory

credit: skatelescope.org



The Radio Sky

credit: skatelescope.org

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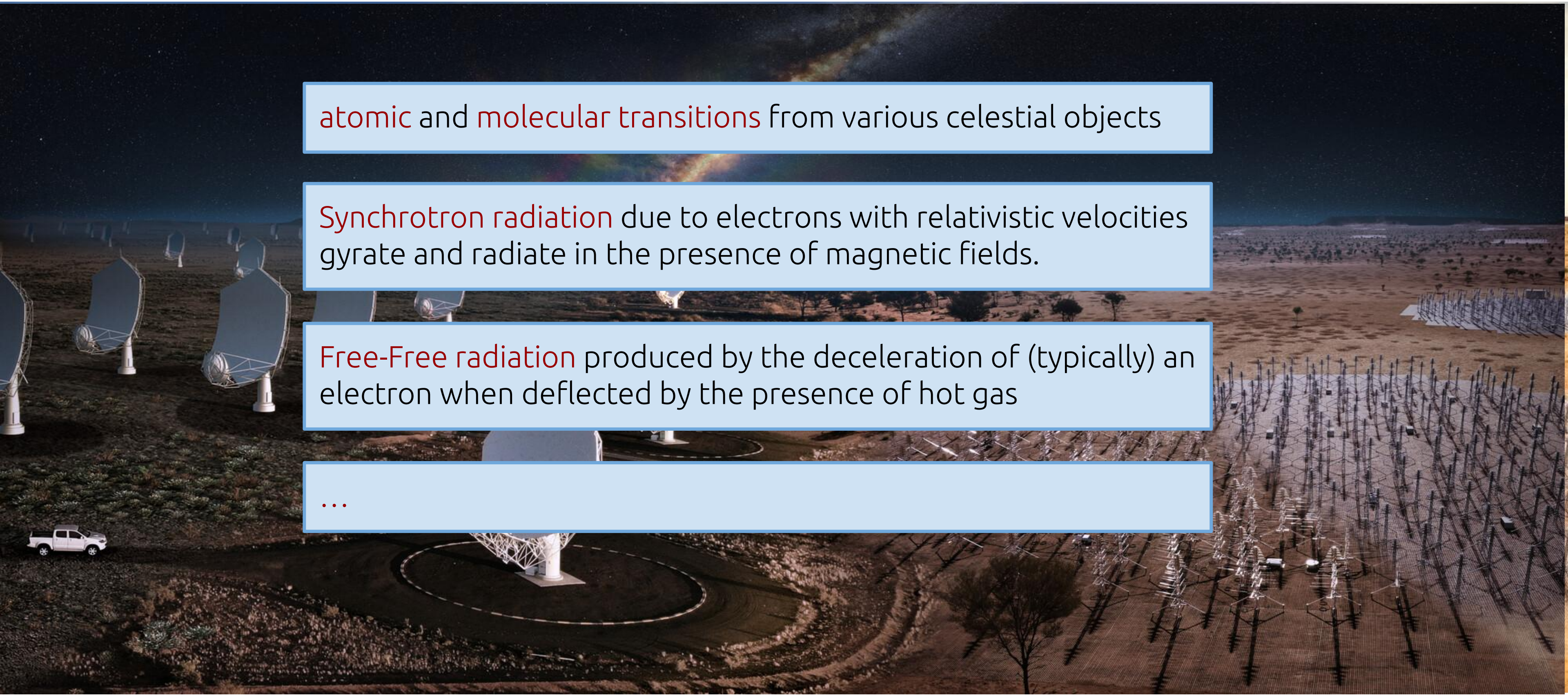


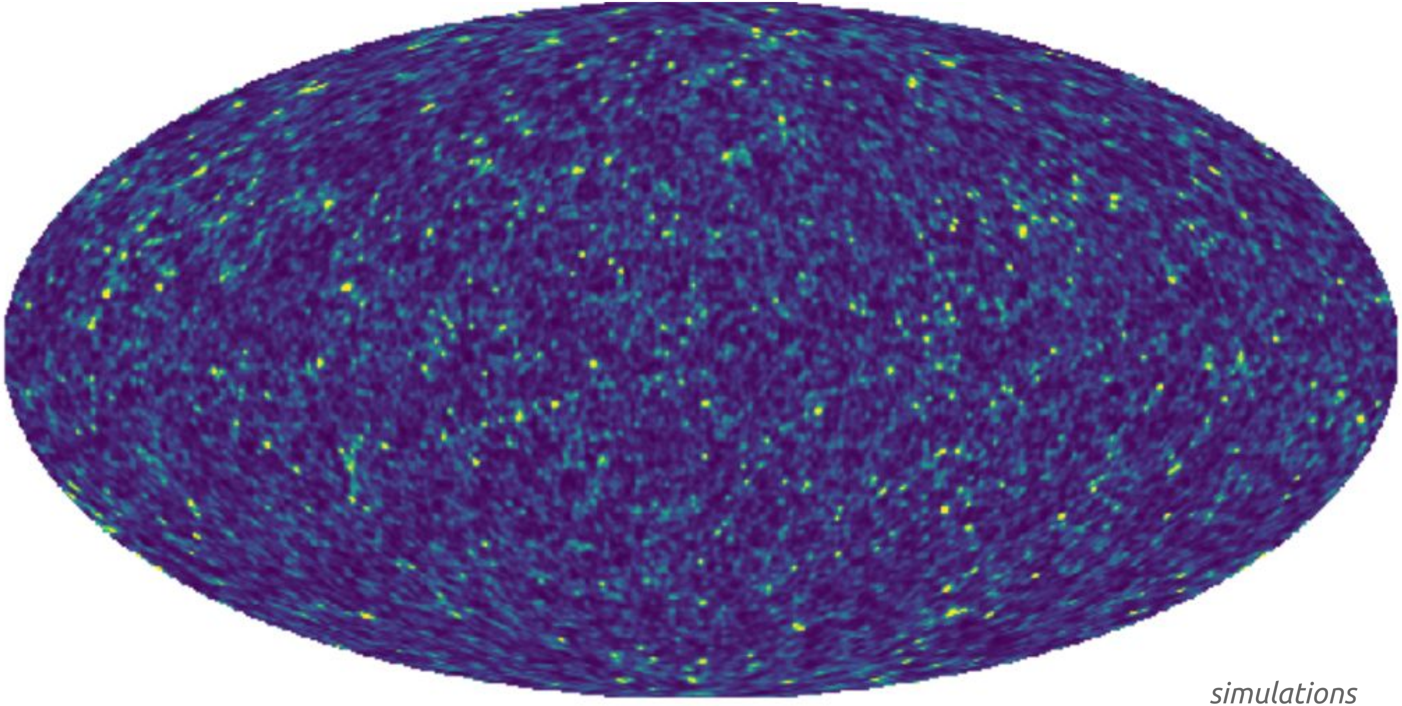
atomic and molecular transitions from various celestial objects

Synchrotron radiation due to electrons with relativistic velocities gyrate and radiate in the presence of magnetic fields.

Free-Free radiation produced by the deceleration of (typically) an electron when deflected by the presence of hot gas

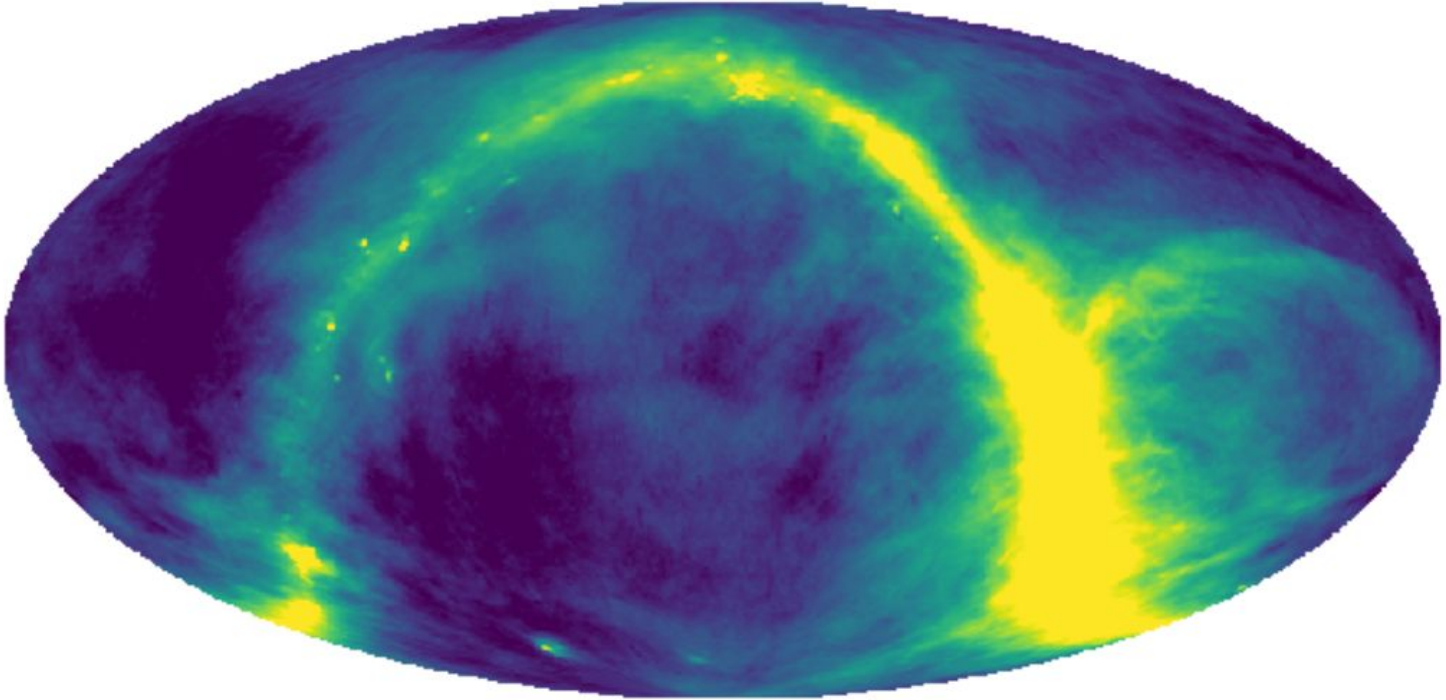
…

Hydrogen on cosmological scales



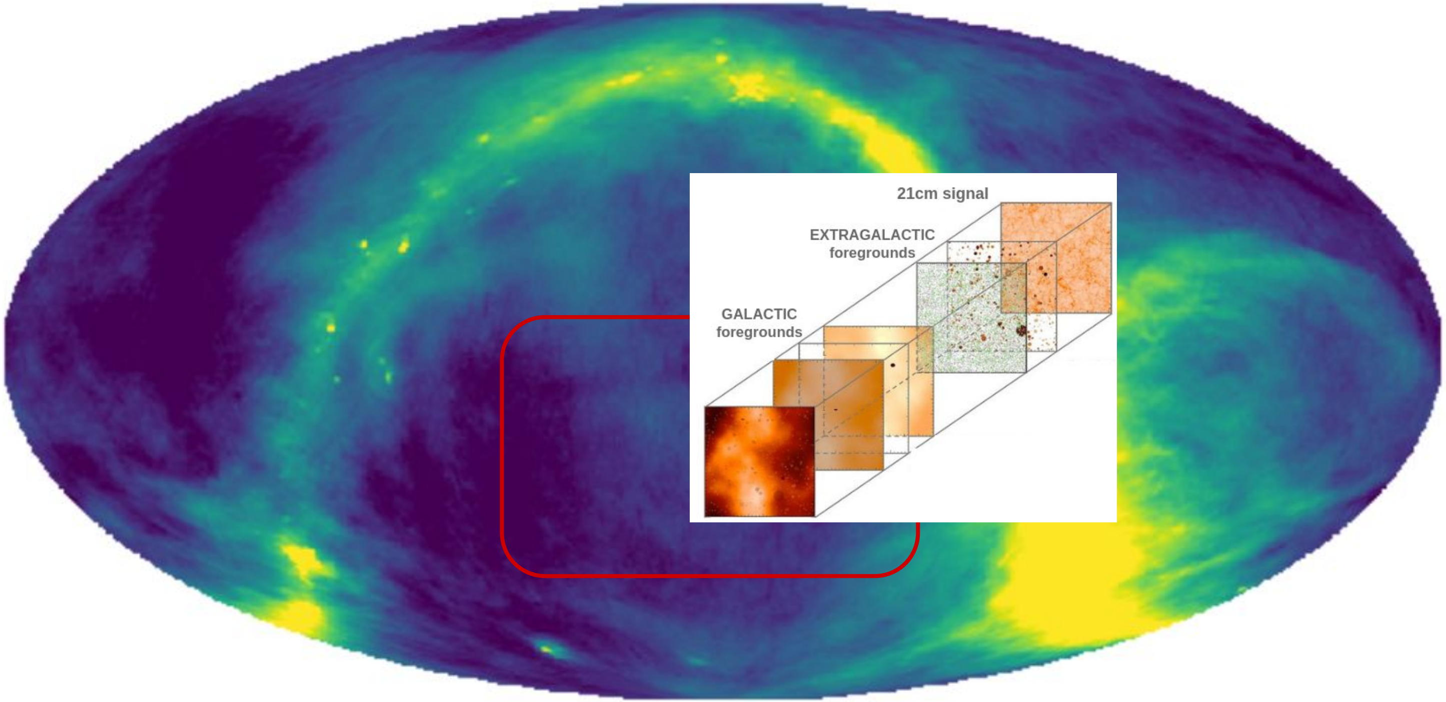
simulations
MS et al. 2021,2022

The challenge of foregrounds



Haslam et al. (1982)

The challenge of foregrounds



Haslam et al. (1982)

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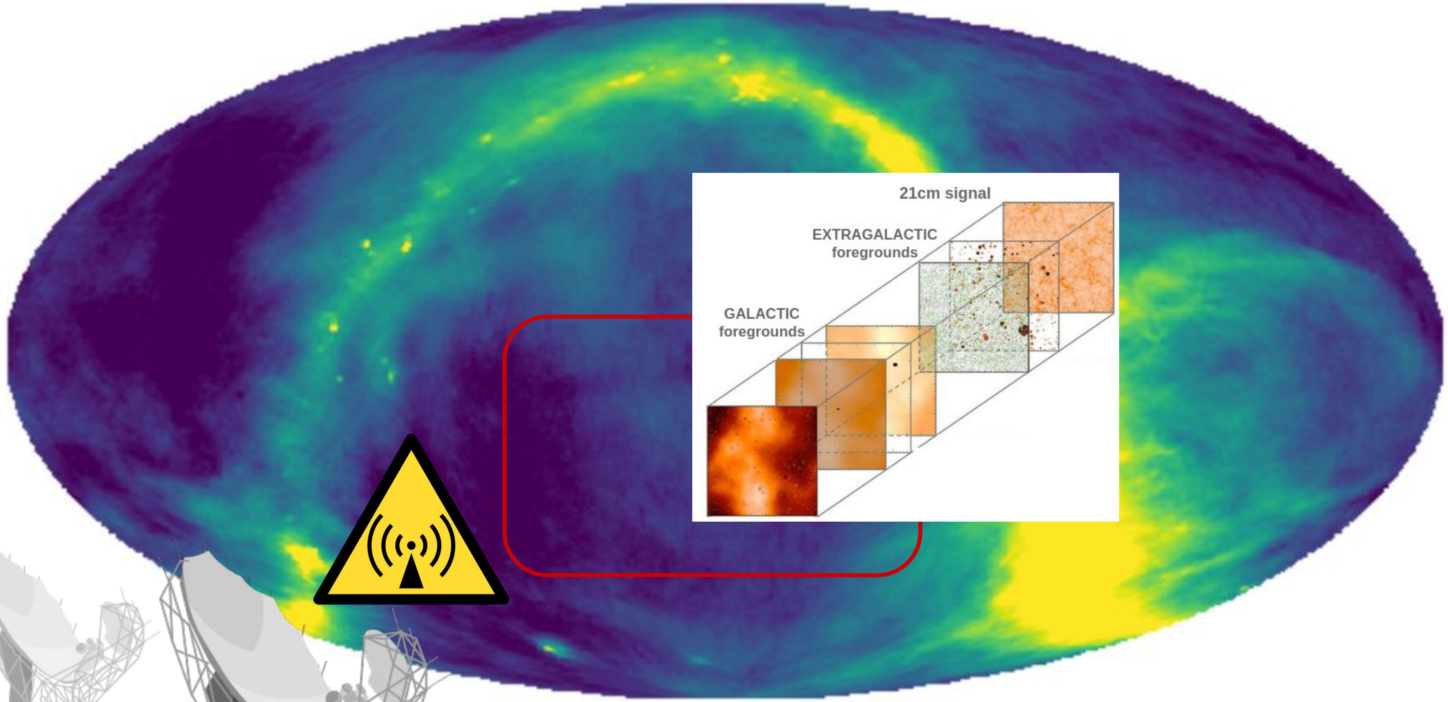
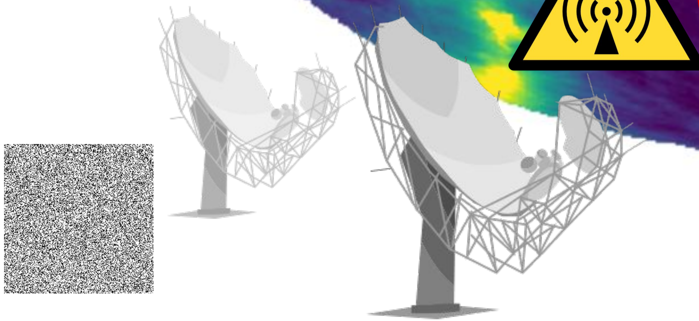
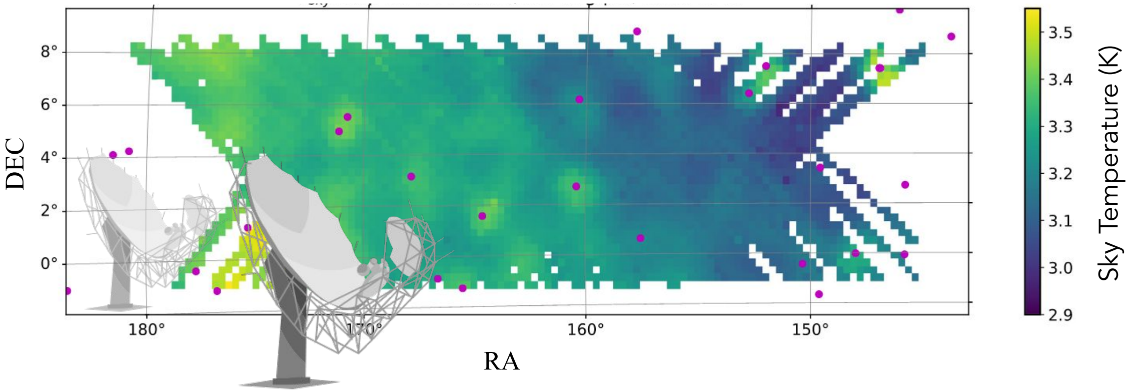




Haslam et al. (1982)

Intensity Mapping Observations

MeerKLASS: cosmological survey with MeerKAT 64 antennas

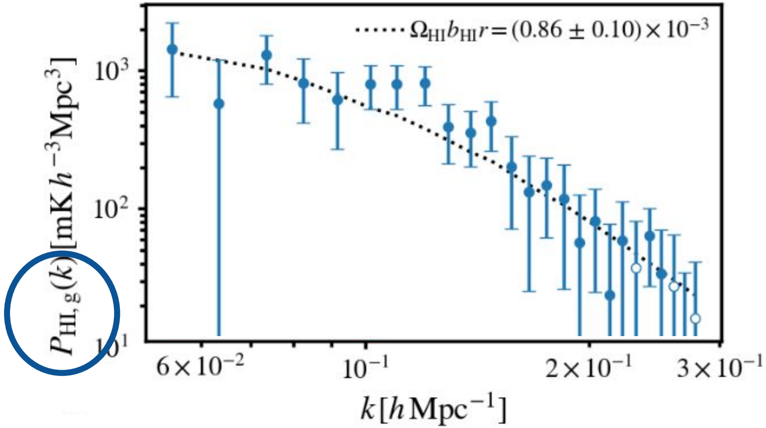


First calibrated sky map!

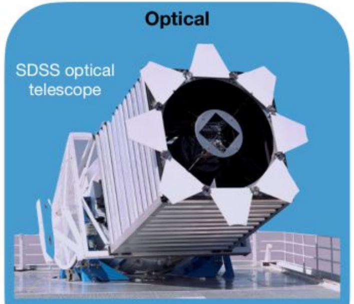
Wang et al. 2021 [including Spinelli]

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 + upcoming 2021 papers



Mitigating systematics with cross-correlation



$$\mathbf{X}_{\rm opt} = \mathbf{S}_{\rm opt} + \mathbf{N}_{\rm opt}$$

$$\mathbf{X}_{\rm rad} = \mathbf{S}_{\rm rad} + \mathbf{N}_{\rm rad}$$

Auto Correlation:

uncorrelated

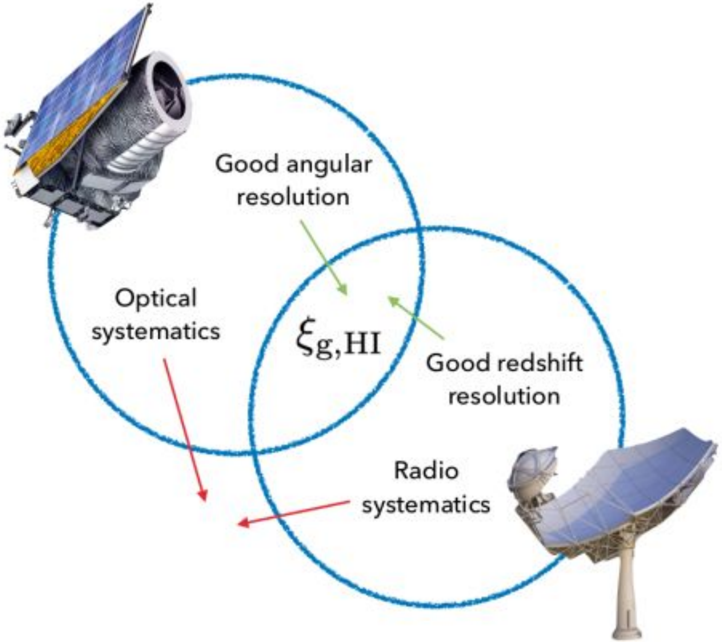
$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm opt}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm opt}\rangle + 2\langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm opt}\rangle + \langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm opt}\rangle$$

$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm opt}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm opt}\rangle + \langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm opt}\rangle$$

signal you want *noise you don't want*

Cross Correlation:

$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm rad}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm rad}\rangle + \langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm rad}\rangle + \langle \mathbf{S}_{\rm rad}\mathbf{N}_{\rm opt}\rangle + \langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm rad}\rangle$$



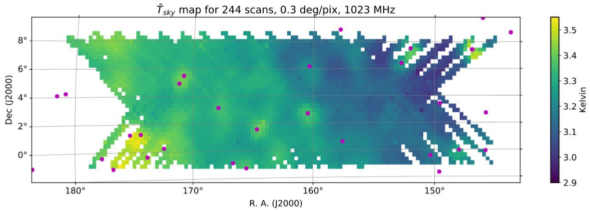
courtesy of Steve Cunnington

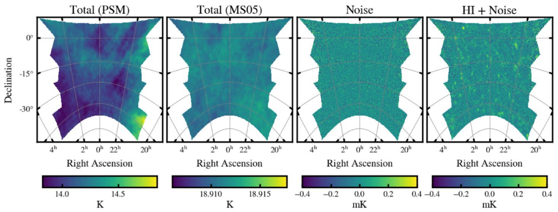
The SKA (Cosmology) timeline

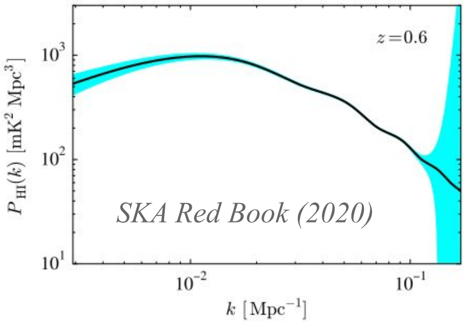
21cm cosmology with the **SKA precursor MeerKAT**

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

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







SKA beginning of construction

Start of Science Commissioning

Start of Science Verification

Commencement of KSPs

2023

2025

2027

2029

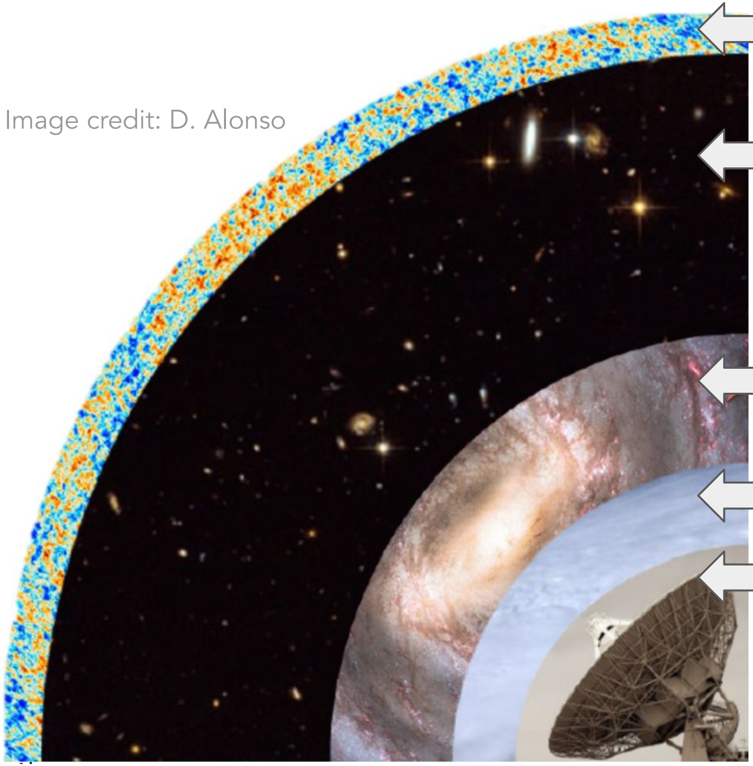
new MeerKAT Call for Proposals

Key Science Project (KSP) planning & proposals

MeerKAT telescope time for MeerKLASS

End-to-end Simulations

Image credit: D. Alonso



- 21cm signal maps
- extra-galactic emission
- Galactic emission
- instrumental and systematic effects

realistic mocks

↓

analysis pipeline

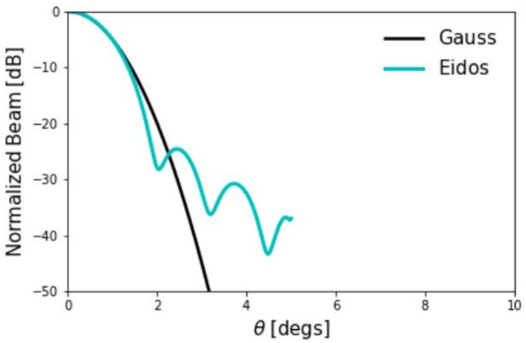
↓

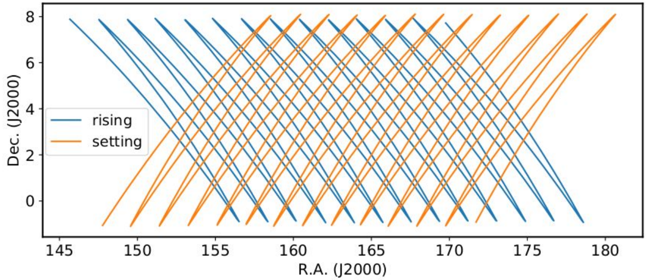
power spectrum

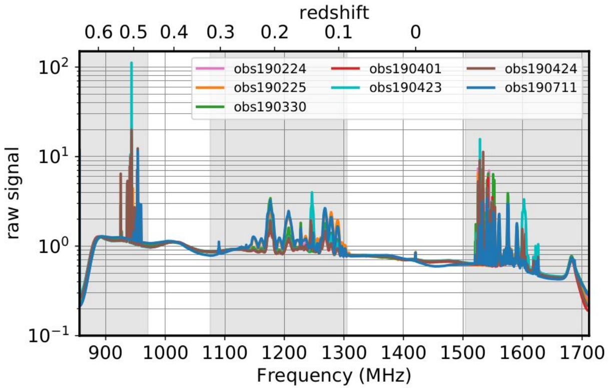
↓

cosmological parameter constraints

Getting to know the instrument







Need a realistic beam modeling
side-lobes, frequency evolution,
more accurate deconvolution

Matshwule et al. 2021,
MS et al. 2022

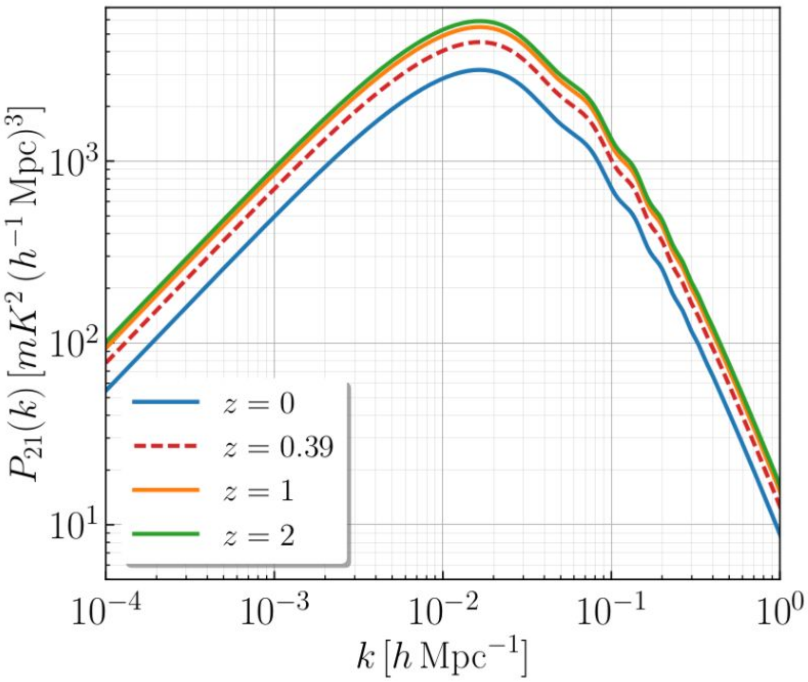
Scanning strategy
non homogeneous noise,
need for real space convolution,
polarization leakage

Harper et al. 2018
MS, Matshawule et al. (in prep)

Radio Frequency Interference (RFI)
impact on cleaning,
impact on signal interpretation

Harper et al. 2018
Engelbrecht et al. 2024

Theoretical 21cm (linear) Power Spectrum



We model it as[1]

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

where

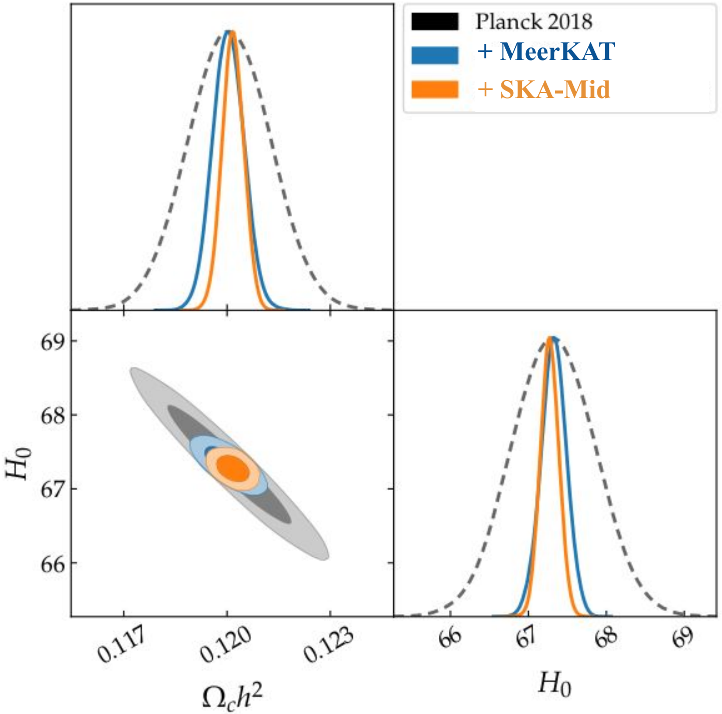
- $\bar{T}_b^2(z)$ is the mean brightness temperature
- $b_{HI}(z)$ is the HI bias
- $f(z)$ is the growth rate
- $\mu = \hat{k}\cdot\hat{z}$
- $P_m(z,k)$ is the matter power spectrum

✓ in good agreement with hydrodynamical simulations results (Villaescusa-Navarro et al. 2018)

[1] Kaiser (1987), Bacon et al. (2019)

SKAO forecasts

Berti, MS et al. 2022, 2023



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

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

MeerKAT

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

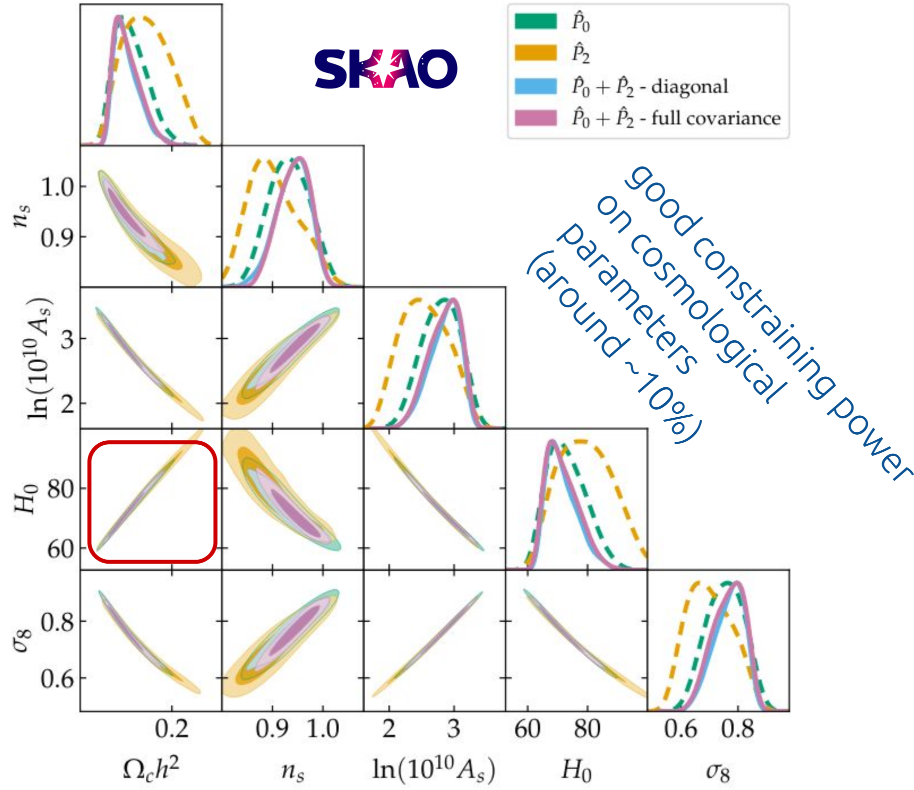
SKA-MID

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

P21 breaks parameter degeneracies

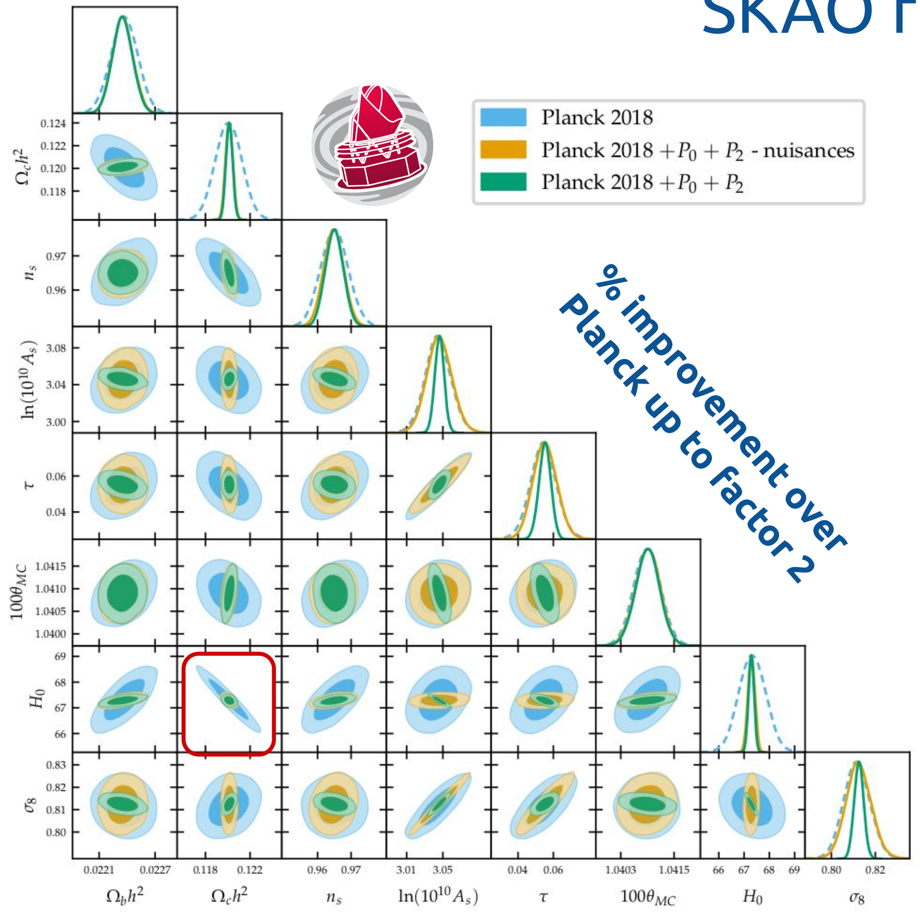
SKAO forecasts

***Berti**, MS, Viel 2023a*

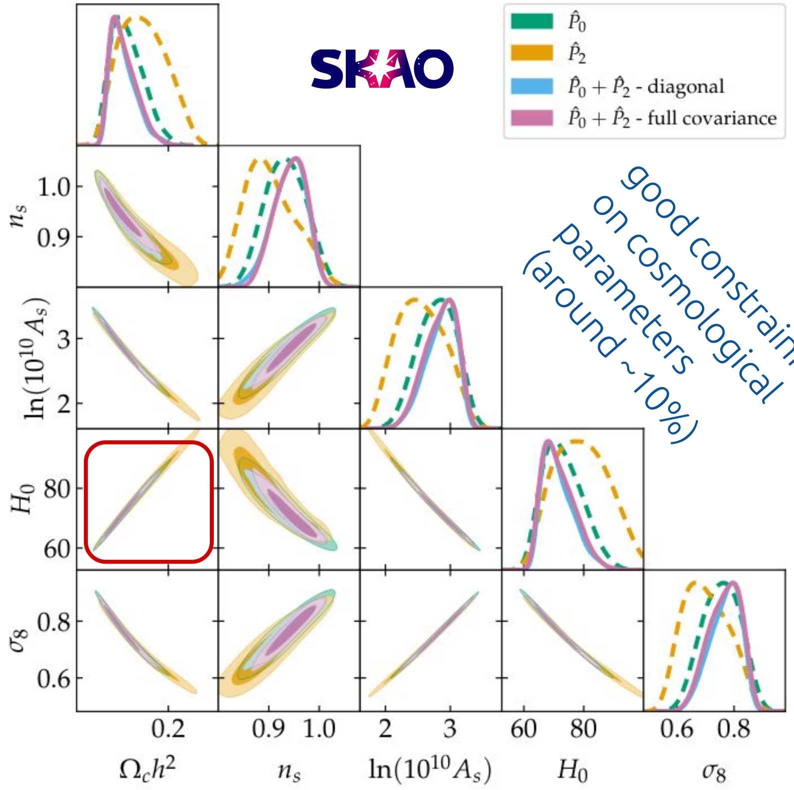


SKAO forecasts

Berti, MS, Viel 2023a



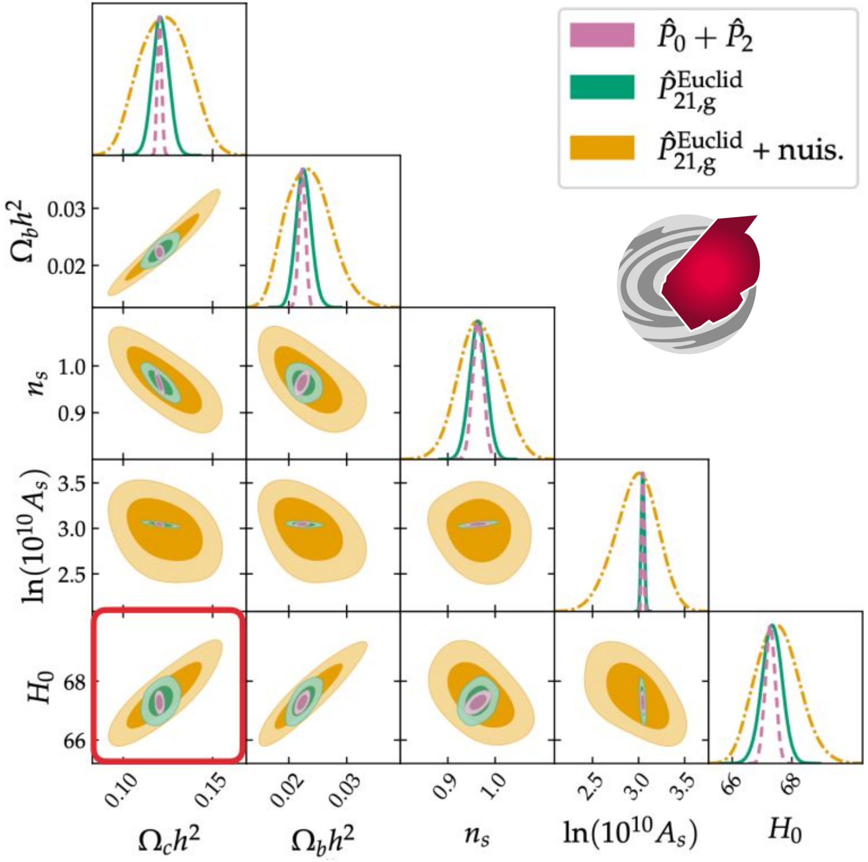
% improvement over Planck up to factor 2



good constraining power on cosmological parameters (around ~10%)

Berti, MS, Viel 2023b

SKAO forecasts: cross-correlation



Power spectrum multipoles - 0< z <3

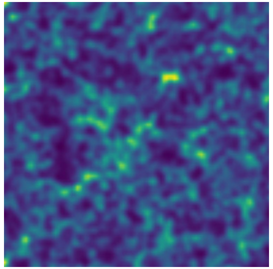
Parameter	$\hat{P}_0 + \hat{P}_2$	$\hat{P}^{\rm DESI}_{21,g}$	$\hat{P}^{\rm DESI}_{21,g}$ + nuis.	$\hat{P}^{\rm Euclid}_{21,g}$	$\hat{P}^{\rm Euclid}_{21,g}$ + nuis.
$\Omega_b h^2$	2.59%	6.43%	23.11%	5.78%	16.99%
$\Omega_c h^2$	0.99%	3.81%	16.63%	3.75%	11.87%
n_s	1.19%	2.43%	6.79%	1.82%	4.59%
$\ln(10^{10} A_s)$	0.37%	0.78%	8.08%	0.54%	7.62%
$100\theta_{MC}$	0.17%	0.39%	0.75%	0.30%	0.62%
H_0	0.25%	0.69%	1.96%	0.49%	1.07%
σ_8	0.29%	0.40%	9.41%	0.58%	10.03%

SKAOxEuclid and **SKAOxDESI** comparable constraining power

Broader constraints assuming no knowledge on HI bias (nuisances)

__Scelfo__, MS et al. (2022)

HI x GW



HI allows us to perform very fine tomography

21 cm line IM - SKAO

High z uncertainty without EM counterparts

GW resolved signals from BHBH mergers - Einstein Telescope

i) Can we calibrate the redshift distribution of GW events by looking at GW × IM?

ii) Can we use GW × IM to investigate Dark Energy?

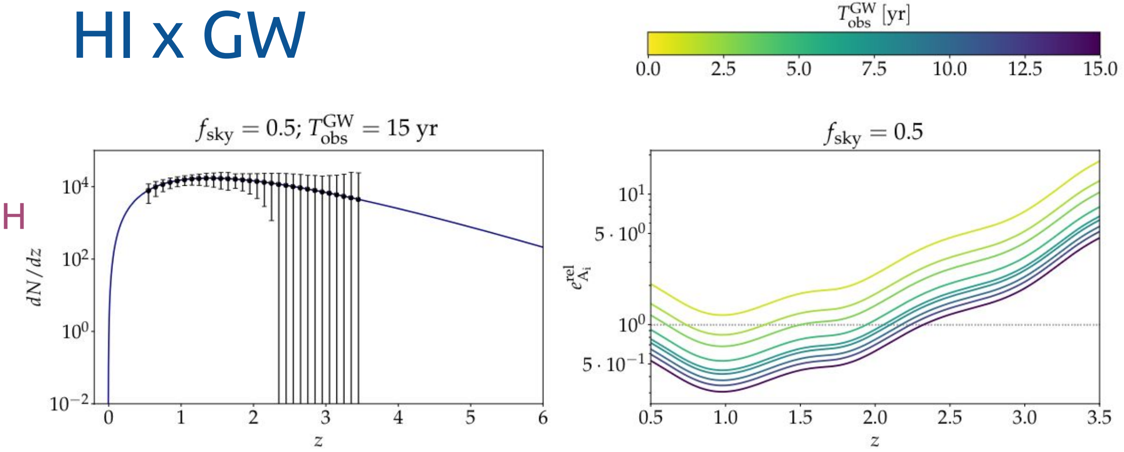
iii) Can we use GW × IM to detect imprints from a population of merging Primordial Black Hole binaries?

Tracer	GW (ET)	IM (SKAO)
z range	[0.5-3.5]	
N_{bins}	3	30
Δz	1.0	0.1

Multi CLASS: Bellomo et al. (2020), Bernal et al.(2020)
Fisher Forecasts

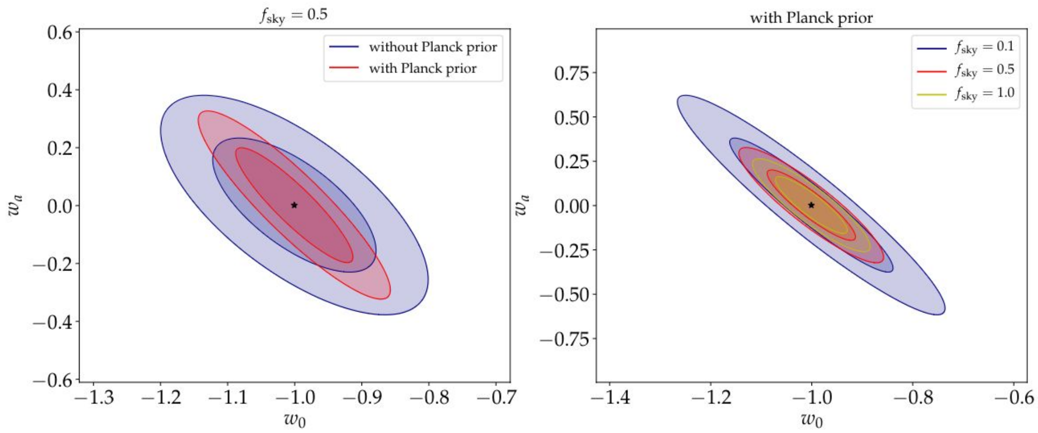
__Scelfo__, MS et al. (2022)

HI x GW



Clustering based Redshift estimation for BHBH
e.g. Alonso et al 2017 (Photo-z vs spectro-z)

assuming both HI and GW trace the LSS



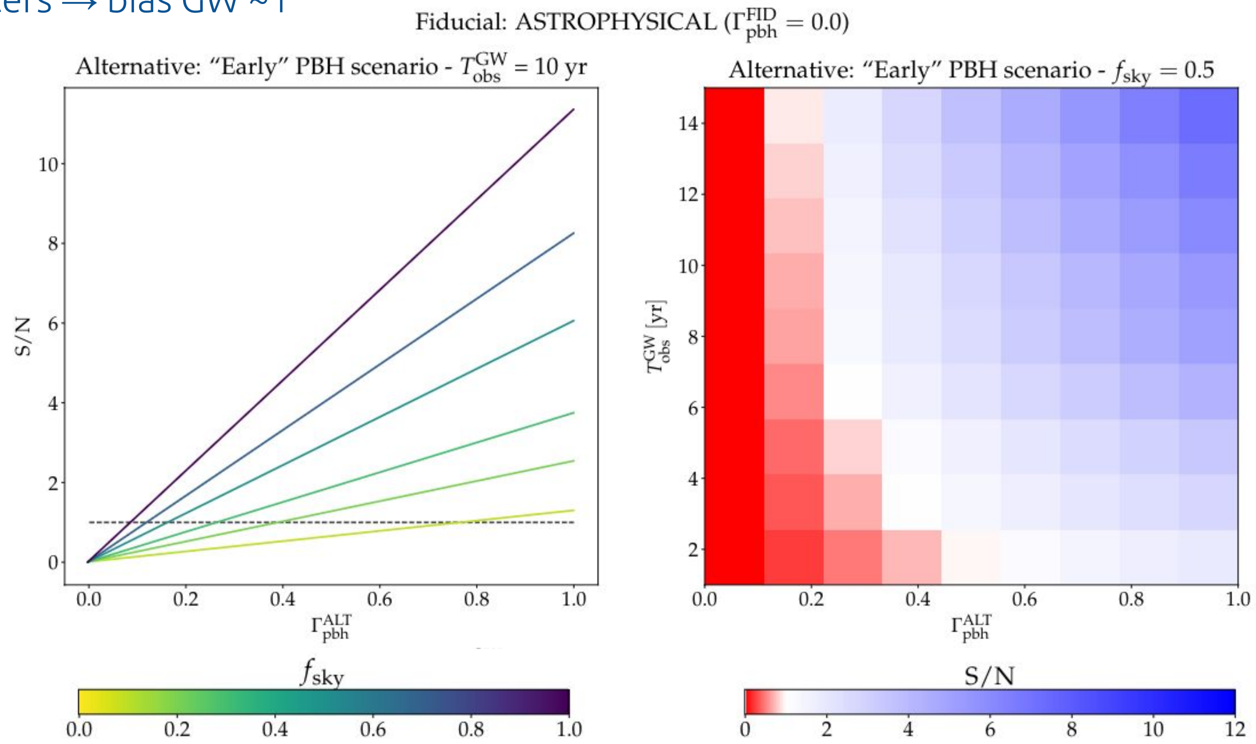
Dynamical Dark Energy
Constraints in agreement with IM only experiments [e.g. Bull+(2015)]

Cross-correlation GW × IM
can help in overcoming systematics

Scelfo, MS et al. (2022)

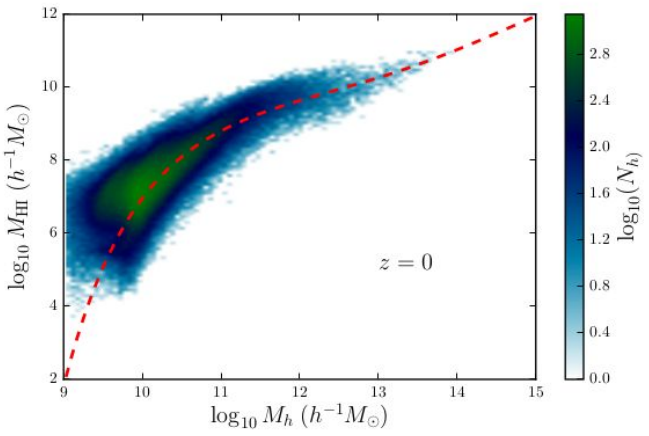
HI x GW

Astrophysical scenario: massive, highly star-forming halos → bias GW >1
"Early" primordial scenario: PBHs binaries form in the early universe → PBHs binaries good DM tracers → bias GW ~1



error on bGW small enough to distinguish between different scenarios

HI simulations



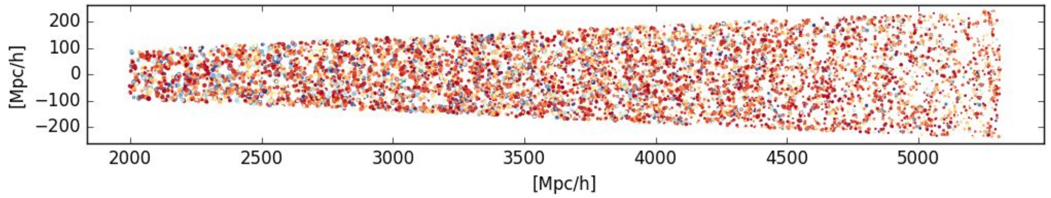
Semi-analytical model GAEA: explicit treatment of cold gas partition in atomic (HI) and molecular (H2) (Xie et al. 2017)

fast intensity map generation

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

Spinelli et al. 2020, 2022

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



Conclusions

21cm Cosmology still have to prove its full potential
but offers an incredible window into the evolution of the Universe

Intensity Mapping surveys are taking data (and new instrument are planned)

Detection in cross-correlation: e.g. MeerKLASS x galaxy survey (7.7 σ)

Analysing new data: effort in understanding the instrument
and developing better analysis pipelines

Keep improving the simulations:
both signal, foregrounds and
instrumental effects

Prepare for the SKAO era and its contribution to the knowledge of large-scale structures

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

CAMBRIDGE
UNIVERSITY PRESS

Research Paper

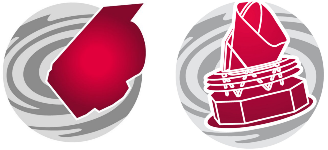
Cosmology with Phase 1 of the Square Kilometre Array Red Book 2018: Technical specifications and performance forecasts

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]

SKA Cosmology *Science Working Group*

Simulations Coordination

Synergies



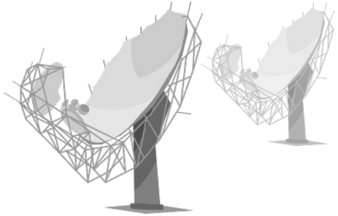
HI galaxies

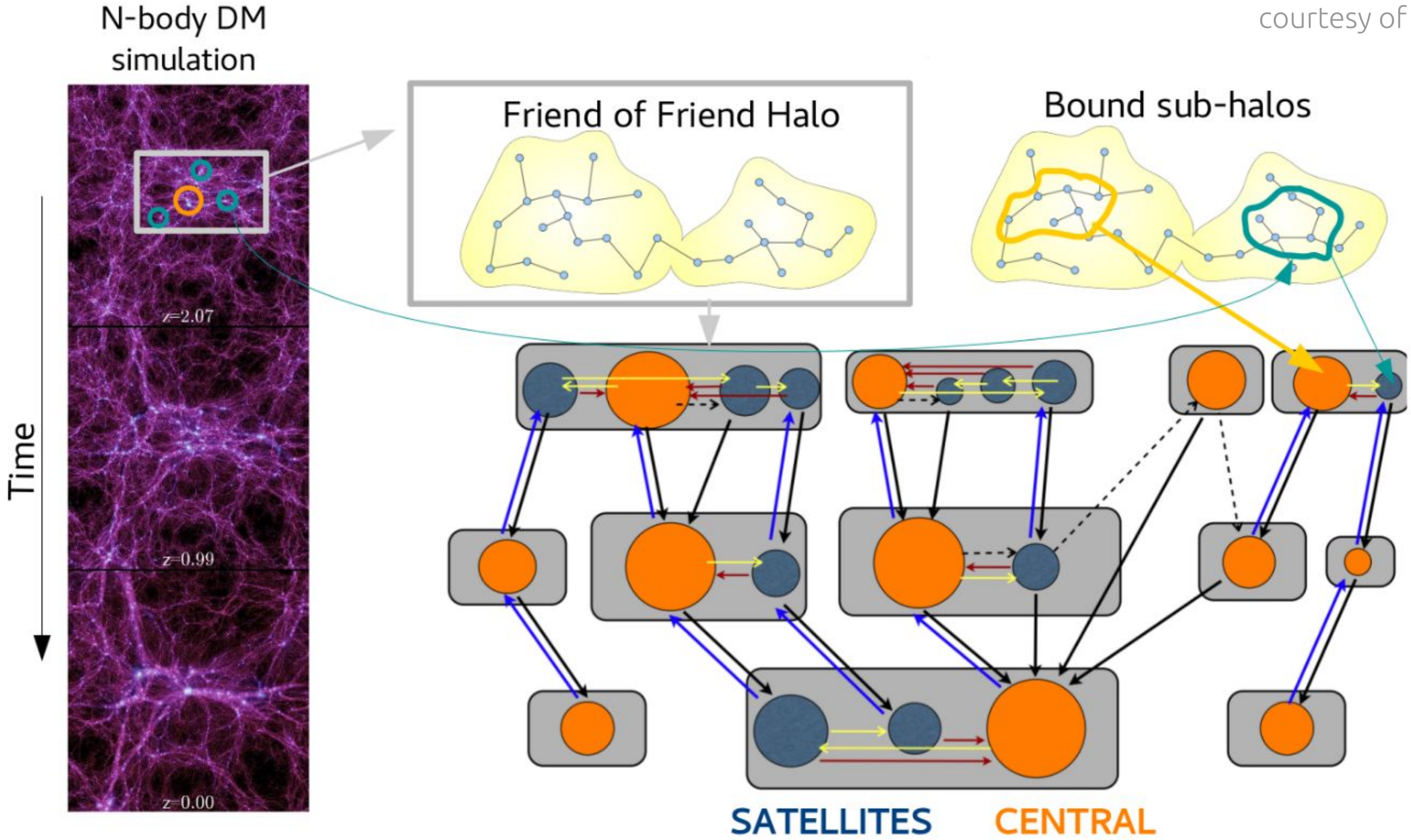
Intensity Mapping

Continuum

Weak lensing

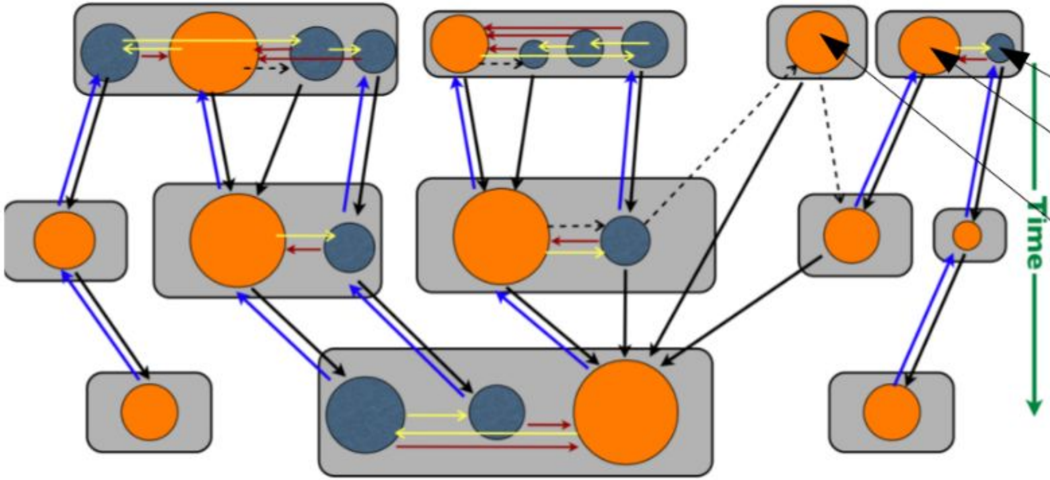
Precursor data
MeerKAT,
LOFAR
SuperCLASS (VLA)
ASKAP



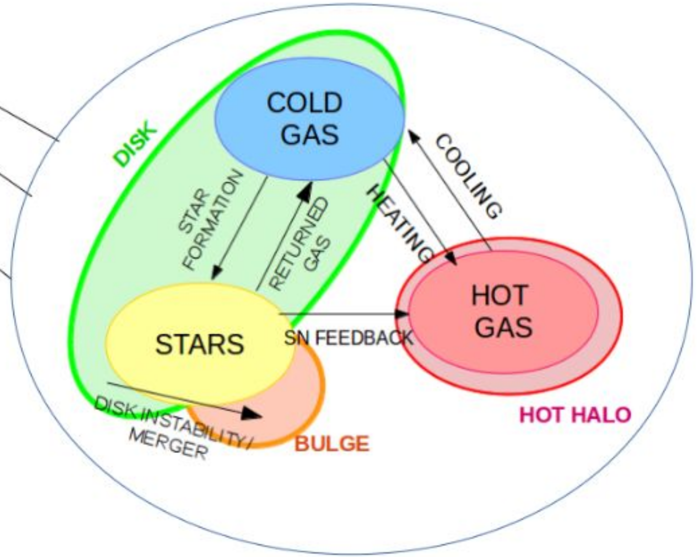

N-body DM
simulation
Time
z=2.07
z=0.99
z=0.00
Friend of Friend Halo
Bound sub-halos
SATELLITES
CENTRAL

courtesy of Anna Zoldan

N-body DM simulation:
Millennium Simulation (Springel et al. 2005)



Semi-analytic model

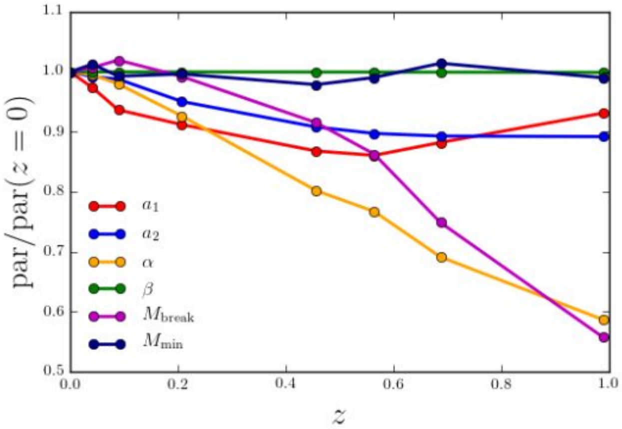


Sub-halo properties:

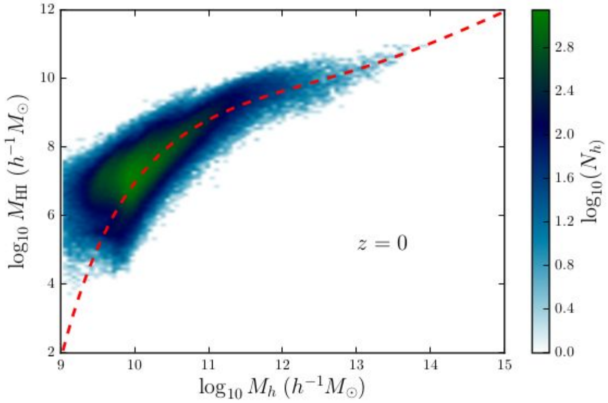
- M_{200};
- Spin;
- Rotational velocity;

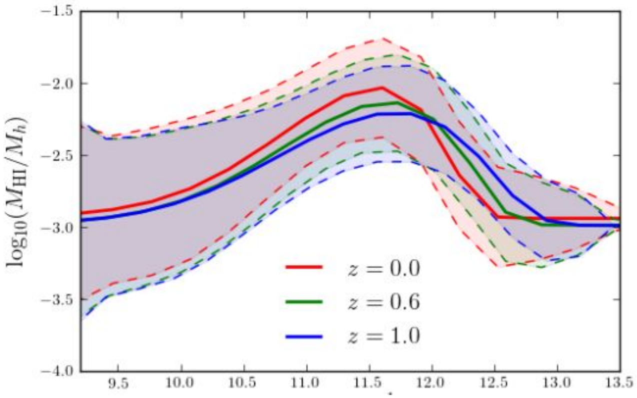
Hi-Probe POPulator (HiP-POP)

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



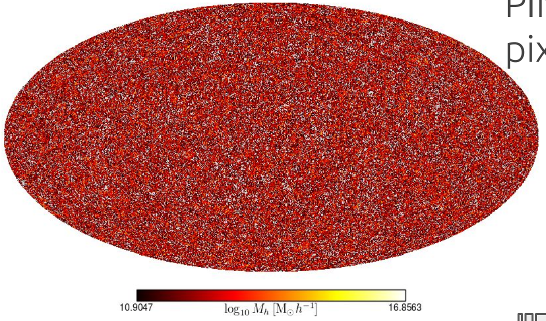
Fit the MHI-Mhalo relation at various GAEA snapshots and find a redshift trend

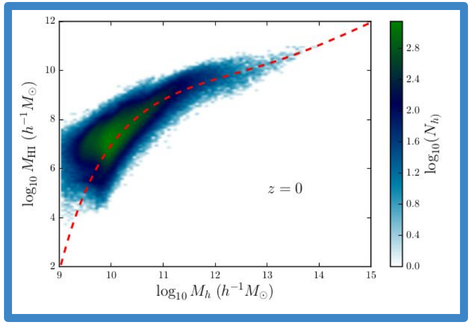


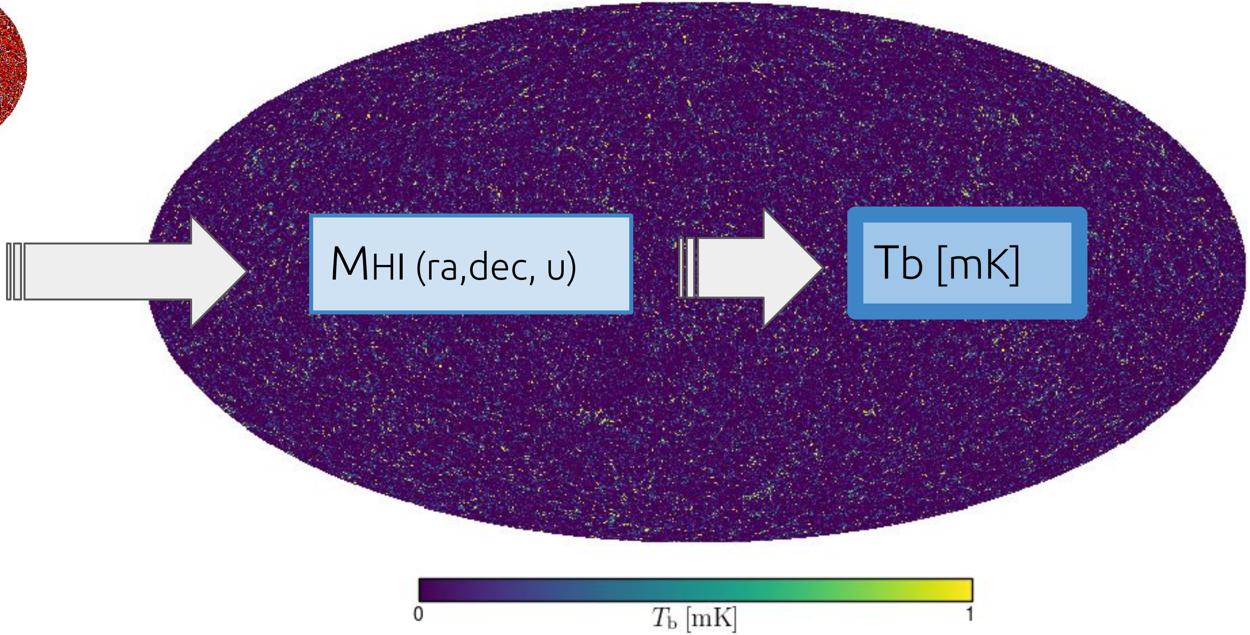


Hi-Probe POPulator (HiP-POP)

PINOCCHIO full sky light-cone
pixelized with Healpix



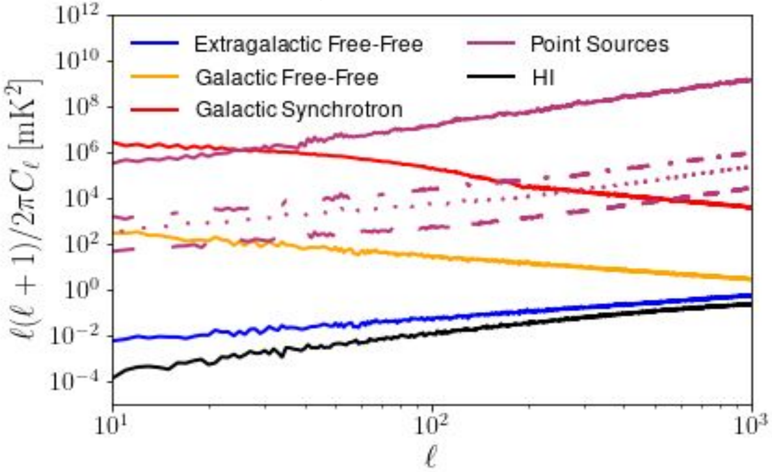


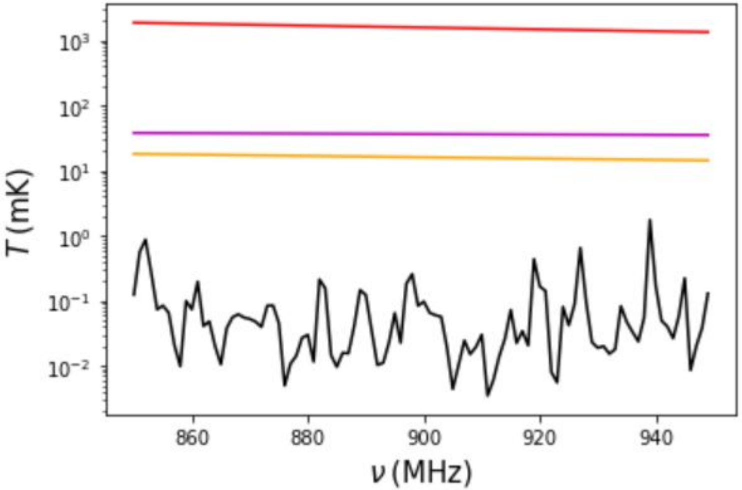


Too big halos “spread” with NFW in nearby pixels

Properties of the foregrounds

Matshawule, MS et al. 2021





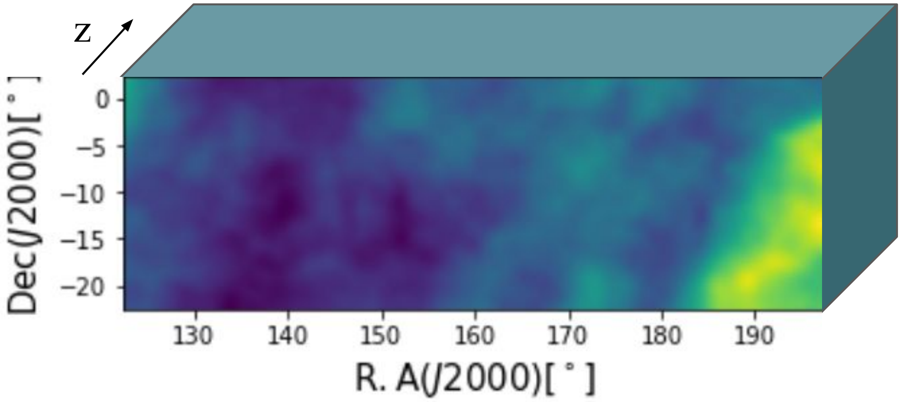
- ❏ foregrounds are orders of magnitude **stronger** than the 21cm signal
- ❏ they are **smooth in frequency** (highly correlated)

Questions:

- ❏ Can the **properties** of the foregrounds be used to separate them from the 21cm signal?
- ❏ Even if we add some **realism** to our simulations? (foregrounds,beam response,noise,RFI,..)

A cleaning example

Mock observation **“cube”**



Simulation includes:

- ❑ 100 channels around redshift 0.5
- ❑ Foreground contamination: *Synchrotron, Free-free, point sources*
- ❑ Gaussian beam
- ❑ White noise

$$T = \mathbf{A}s + n + c$$

A mixing matrix of the foreground sources

noise

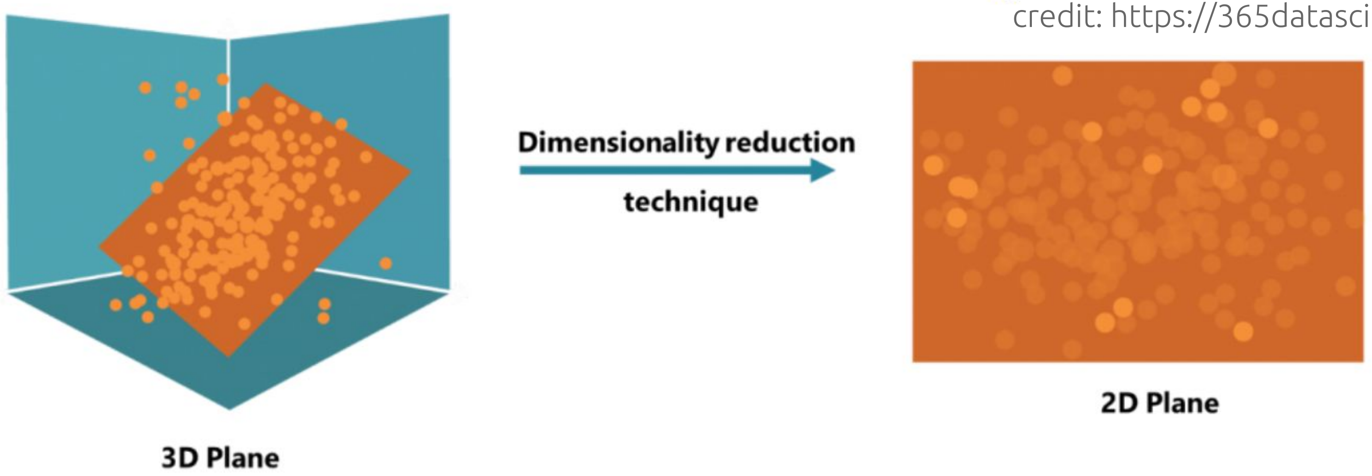
Cosmological signal

How many sources?

$\mathbf{N_{fg}}$ need to be estimated/guessed

Principal Component Analysis

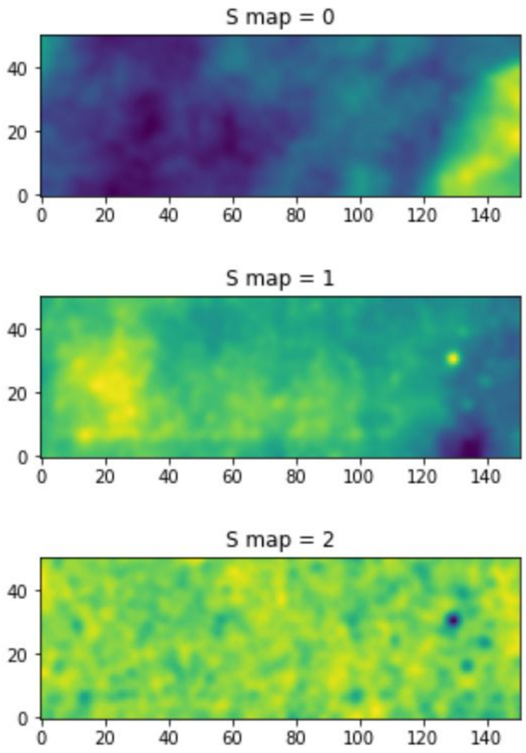
credit: https://365datascience.com/

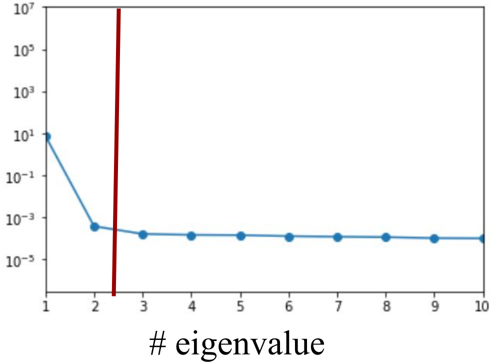


For our Intensity Mapping case:

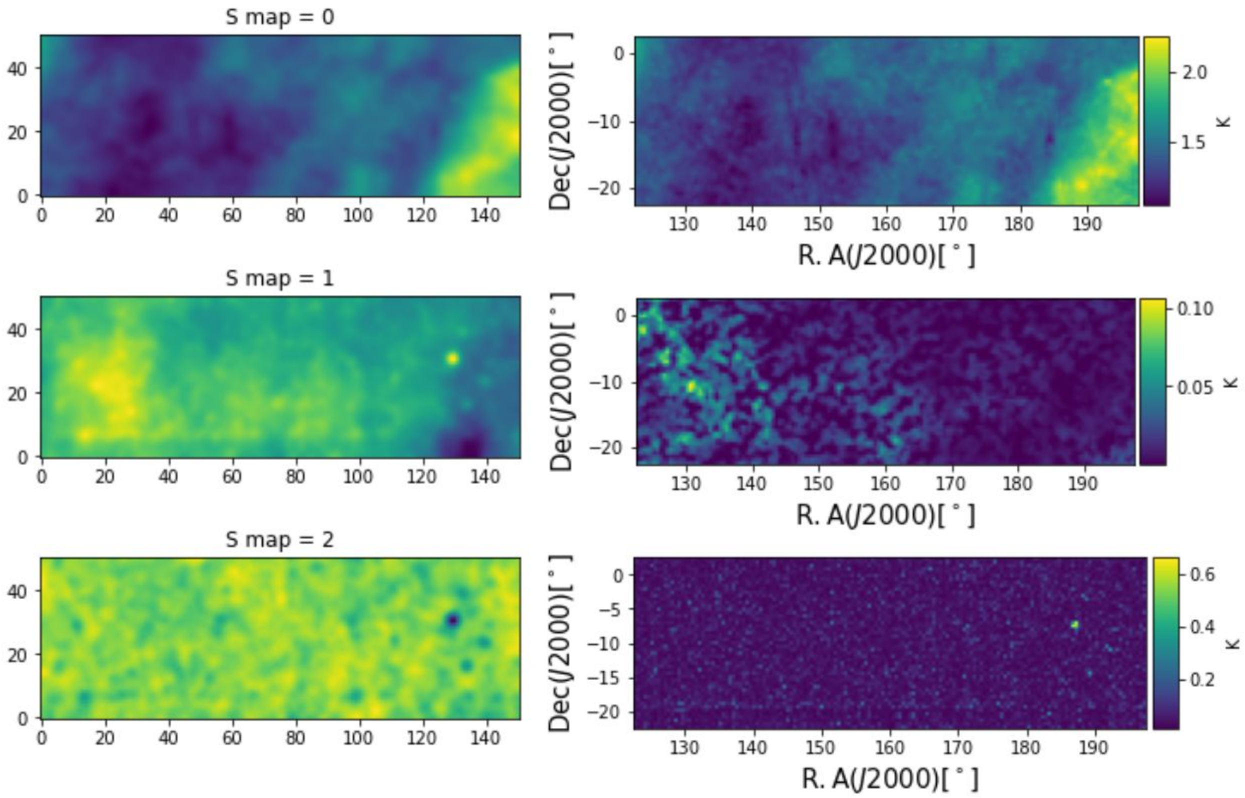
- from data-"cube" $(N_\nu \times N_{\hat{n}})$ one construct $C_{ij} = \frac{1}{N_{\hat{n}}} \sum_{p=1}^{N_{\hat{n}}} T(\nu_i, \hat{n}_p)\, T(\nu_j, \hat{n}_p)$
- compute eigenvectors and assume foregrounds can be described by the most important of them $(N_{\rm fg})$.

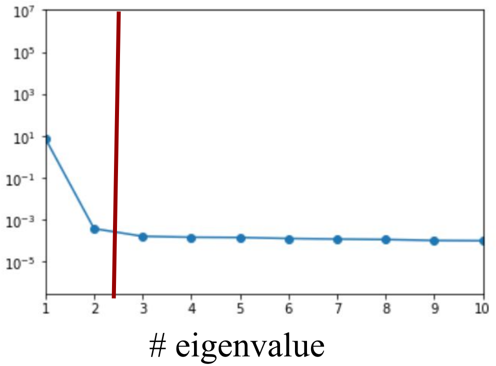
A cleaning example





A cleaning example

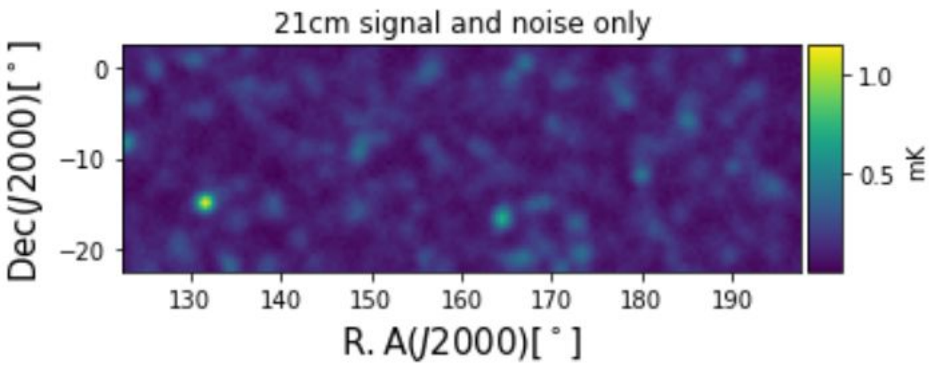


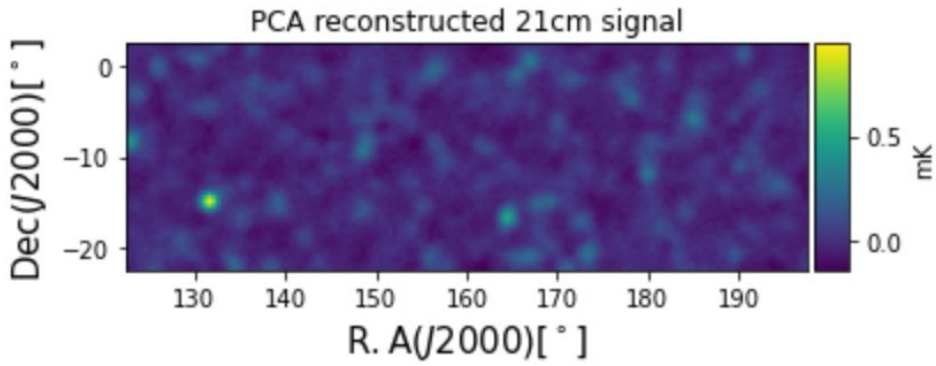


A cleaning example

$c+n = T - \mathbf{A}s$

A mixing matrix
including only the first
Nfg components



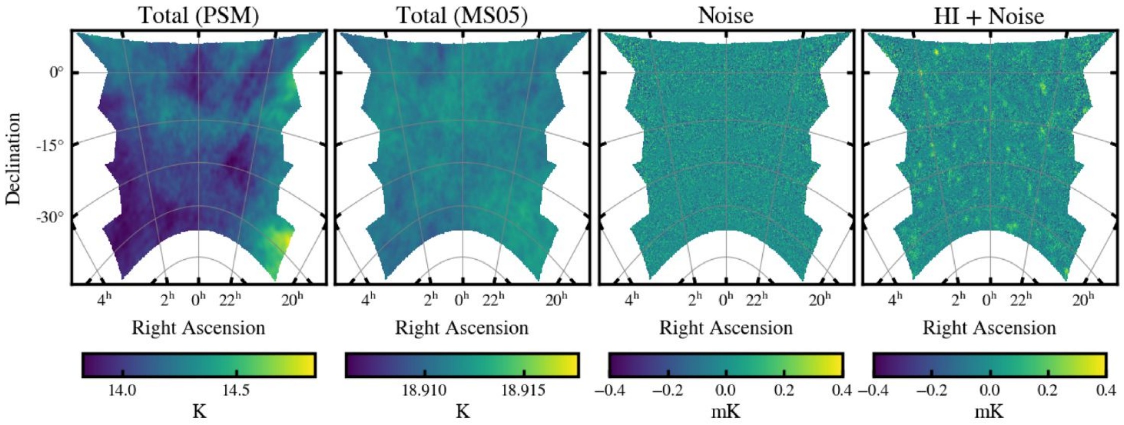


Foreground subtraction challenge

(subset) of the SKA Cosmo IM Focus Group

Project setup:
- various foreground models and realistic HI maps
- instrumental modeling MeerKAT-like and SKAO-like
- 9 different foreground removal methods (PCA, FastICA, …)

Isabella Carucci, Steve Cunnington, Ze Fonseca, Stuart Harper, Mel Irfan, Alkistis Pourtsidou, Marta Spinelli, Laura Wolz



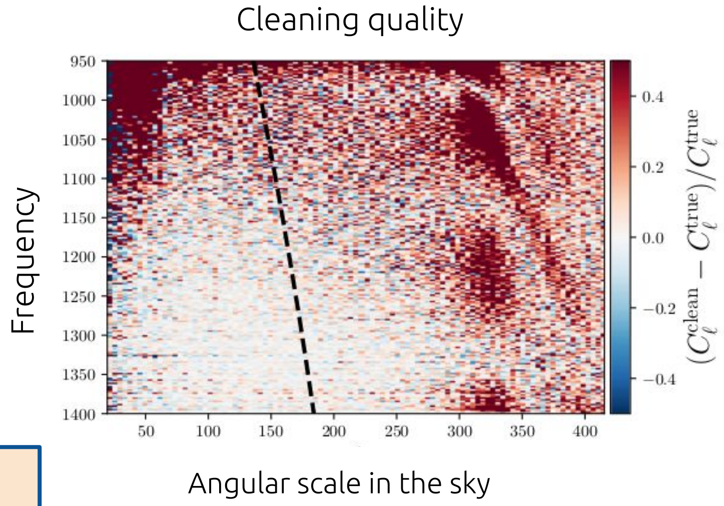
Blind challenge to discover weaknesses and strengths of the various methods

given IM "data",
would your favorite method extract the cosmological signal?

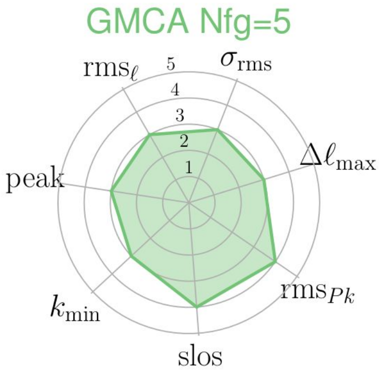
Foreground subtraction challenge

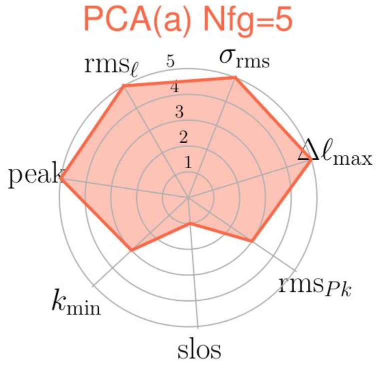
- How much can **instrument/foregrounds coupling** impact the signal reconstruction?
- definition of statistics and metrics to evaluate the relative performances

Realistic instrumental effects inevitably **complicate** the foreground cleaning



MS et al. 2022





Intensity Mapping with MeerKAT

Santos et al. 2017, Wang et al. 2021

Antennas	All 64 MeerKAT dishes
Observation mode	Single-dish
Frequency range	0.856-1.712 GHz
Frequency resolution	0.2 MHz
Time resolution	2s
Exposure time	1.5hr x 7 scans
Target field	WiggleZ 11hr field ($10^\circ \times 30^\circ$)