Mapping Neutral Hydrogen

opportunities and challenges on the road to the SKA Observatory

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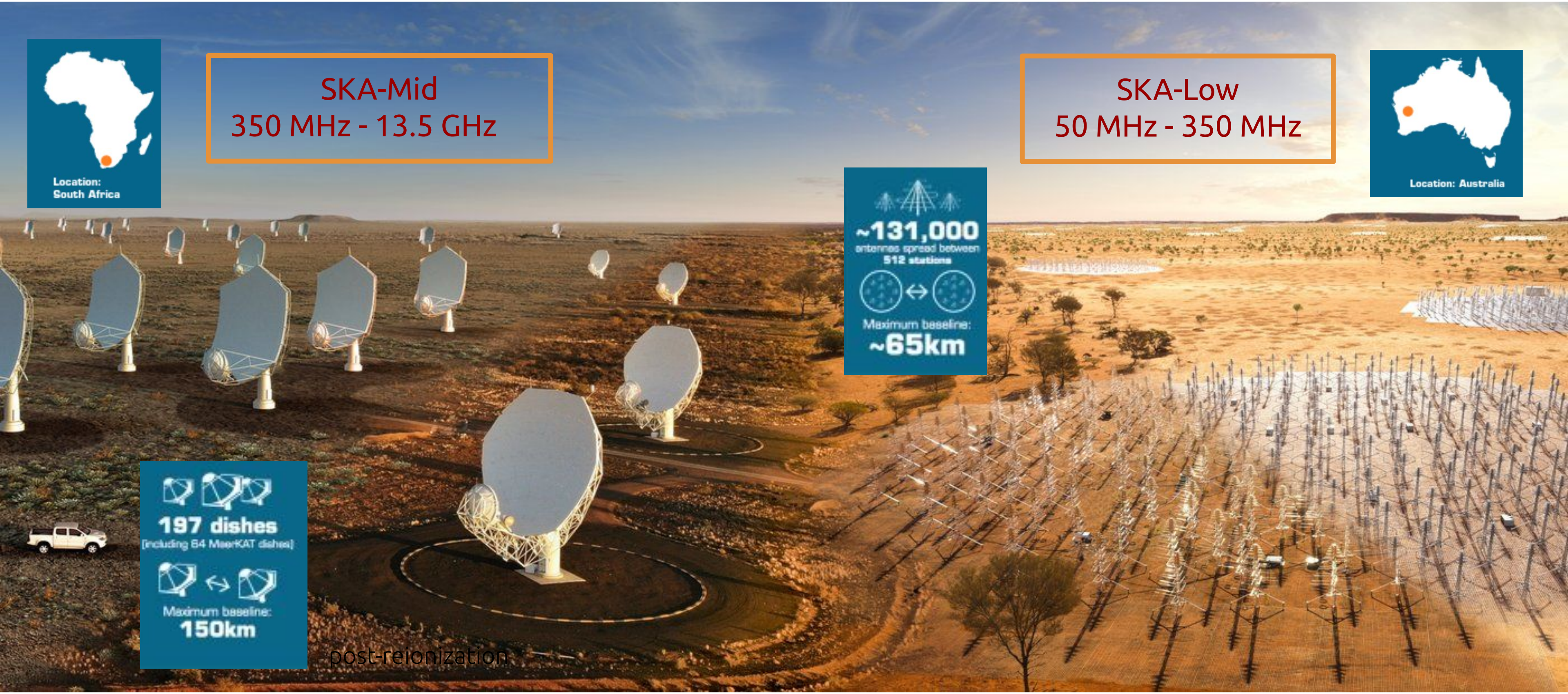
COLOURS

Colours - 12/06/2025 - Institute Pascal

The SKA Observatory

credit: skatelescope.org

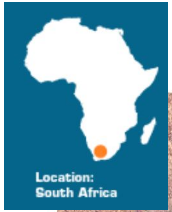


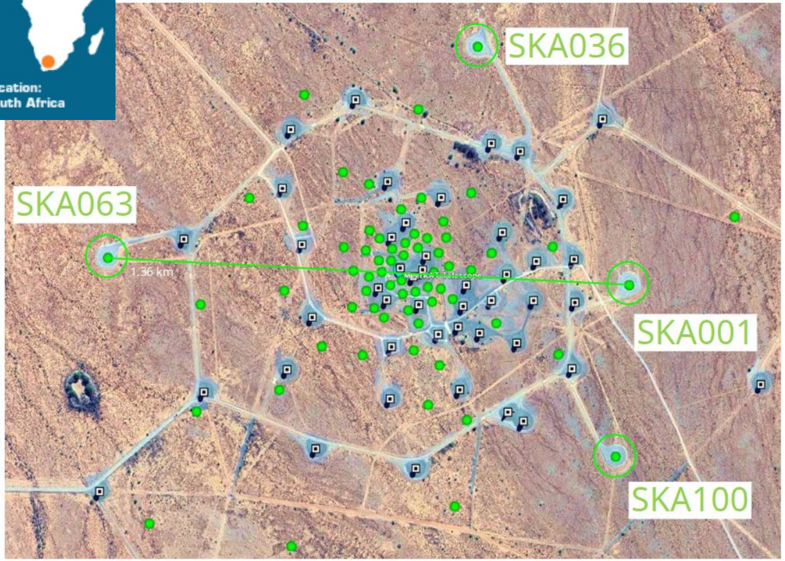
picture credit: SKAO

Construction Updates

Array Assembly phase AA0.5
to test architecture and
supply chain (ready by 2025)

SKA-Mid
350 MHz - 13.5 GHz



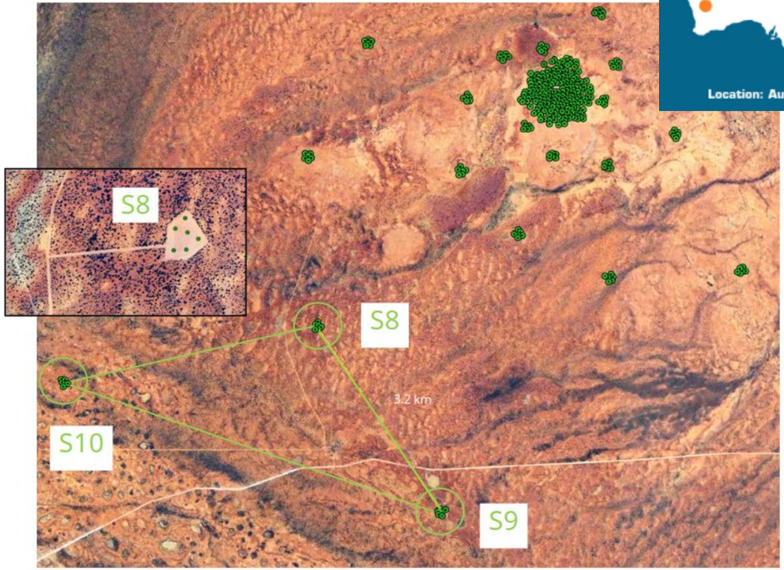


▣ MeerKAT

● SKA dish locations

First 4 dishes on site

SKA-Low
50 MHz - 350 MHz



First 4 stations on site

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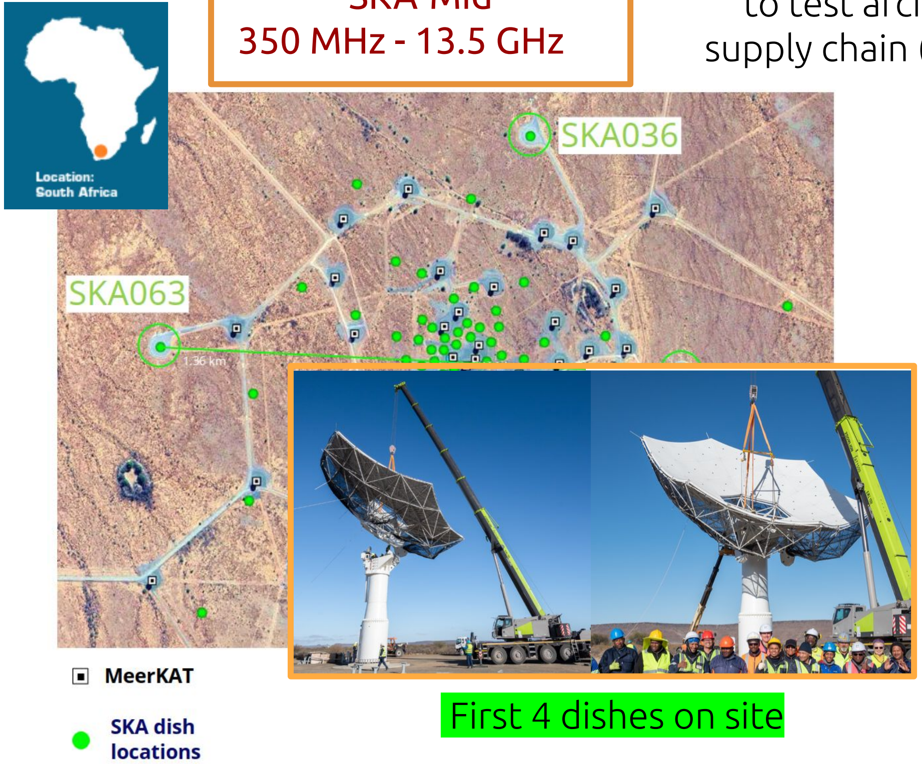
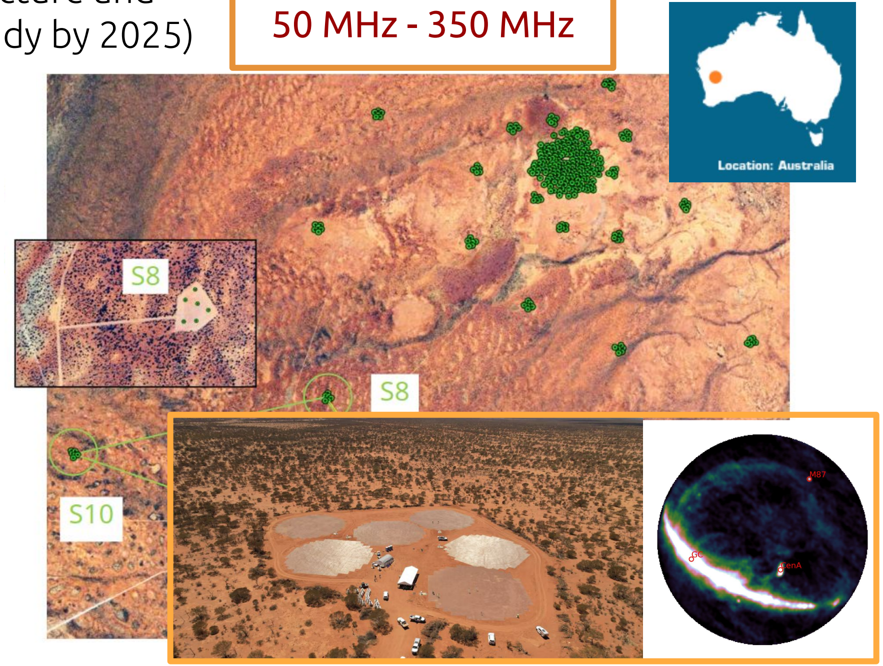


First 4 dishes on site



First 4 stations on site

The Radio Sky

credit: skatelescope.org

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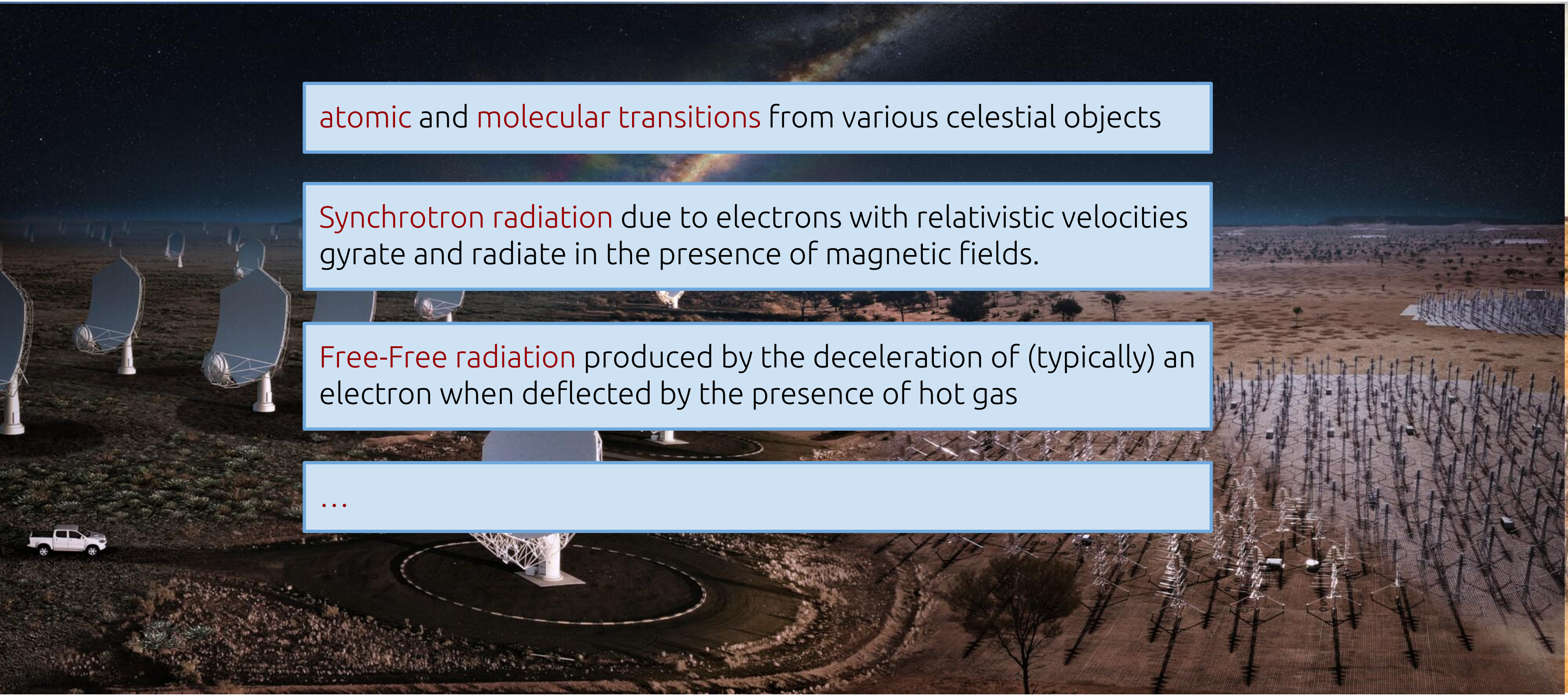


atomic and molecular transitions from various celestial objects

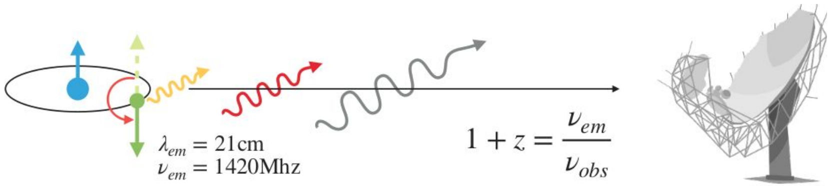
Synchrotron radiation due to electrons with relativistic velocities gyrate and radiate in the presence of magnetic fields.

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

…

Radio Cosmological Probes

HI

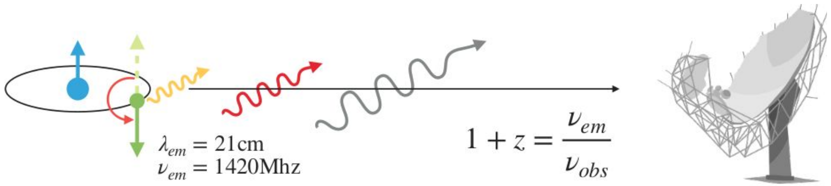


HI galaxies

Intensity Mapping

Radio Cosmological Probes

HI

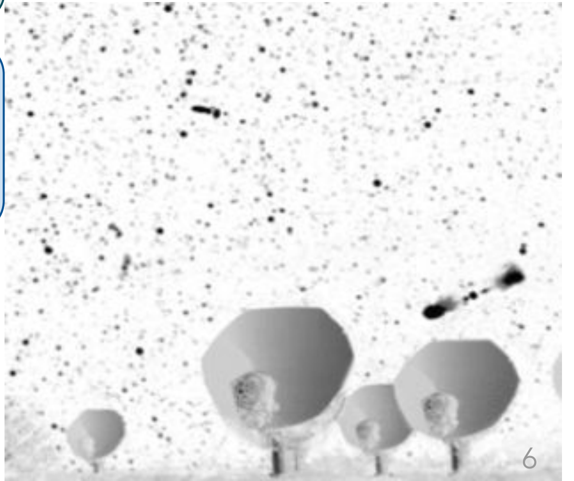


HI galaxies

Intensity Mapping

Weak lensing

Continuum



Radio Cosmological Probes

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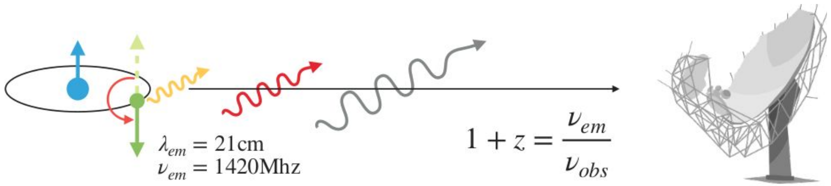
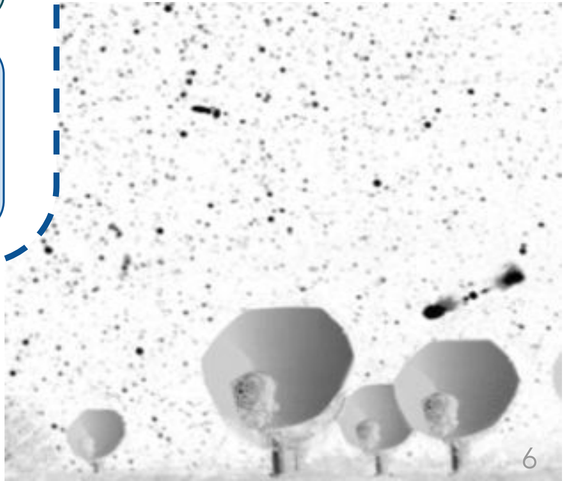


HI galaxies	Intensity Mapping
Weak lensing	Continuum

SKA Cosmology SWG



Radio Cosmological Probes

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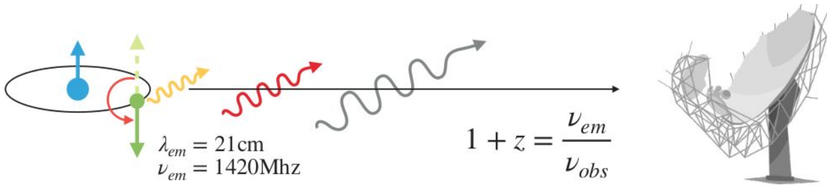
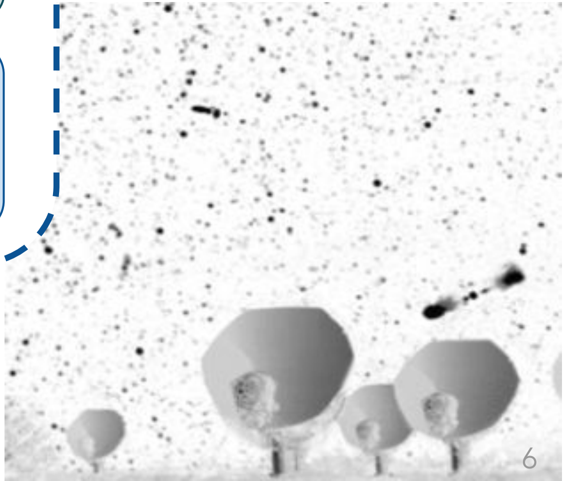


HI galaxies	Intensity Mapping
Weak lensing	Continuum

SKA Cosmology SWG

Available data
LOFAR
SuperCLASS (VLA)
ASKAP
MeerKAT
CHIME
Tianlai
...



Radio Cosmological Probes

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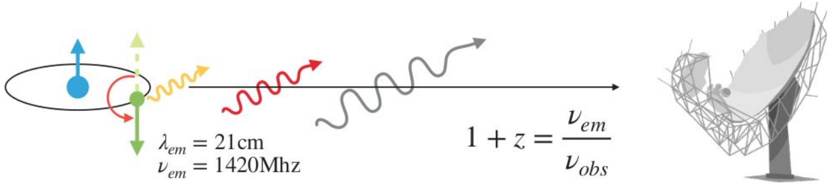

Available data
LOFAR
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CHIME
Tianlai
...

HI galaxies

Intensity Mapping

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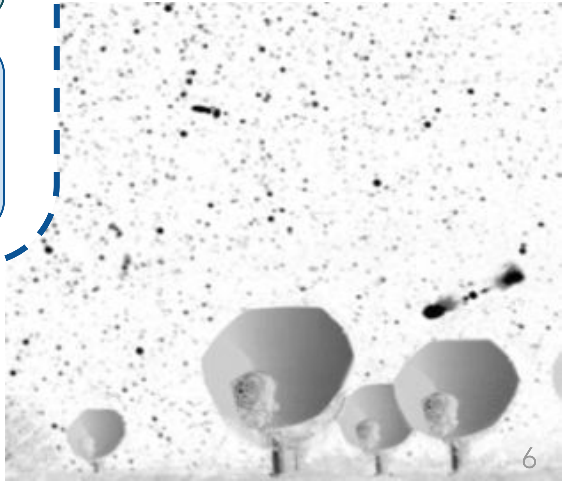
Continuum

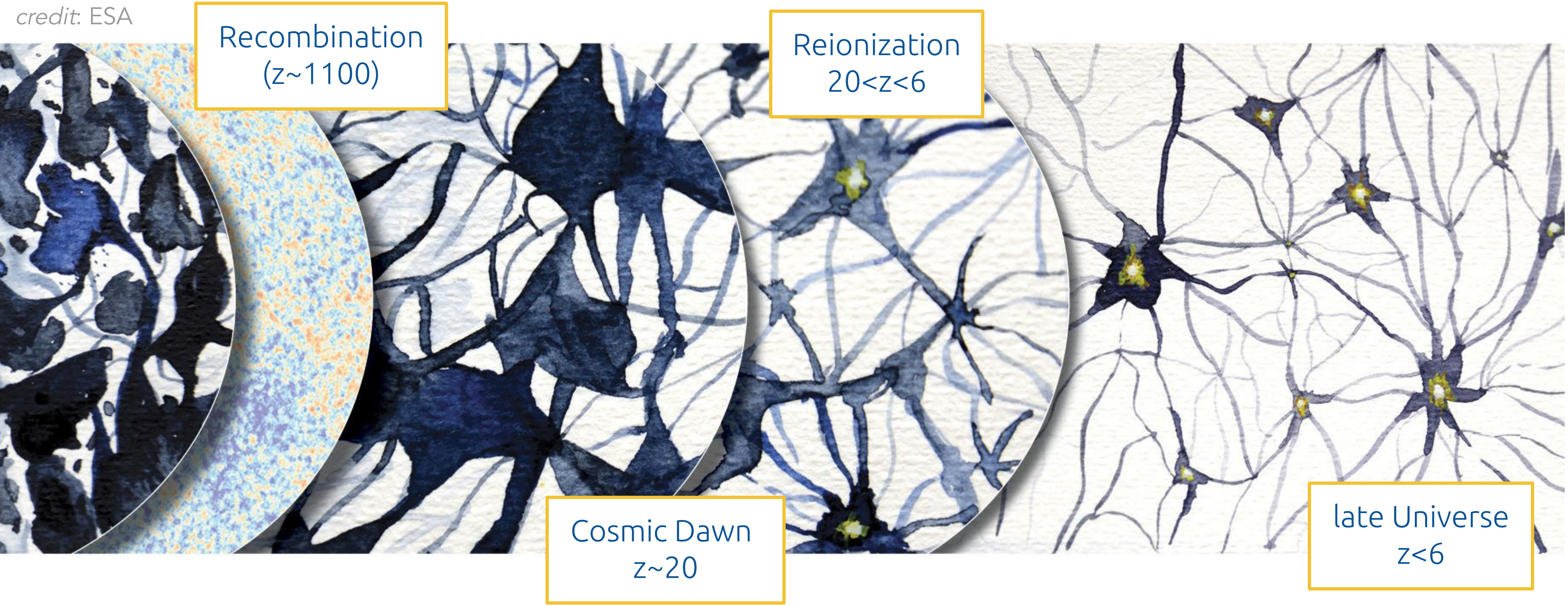
Synergies

SKA Cosmology SWG



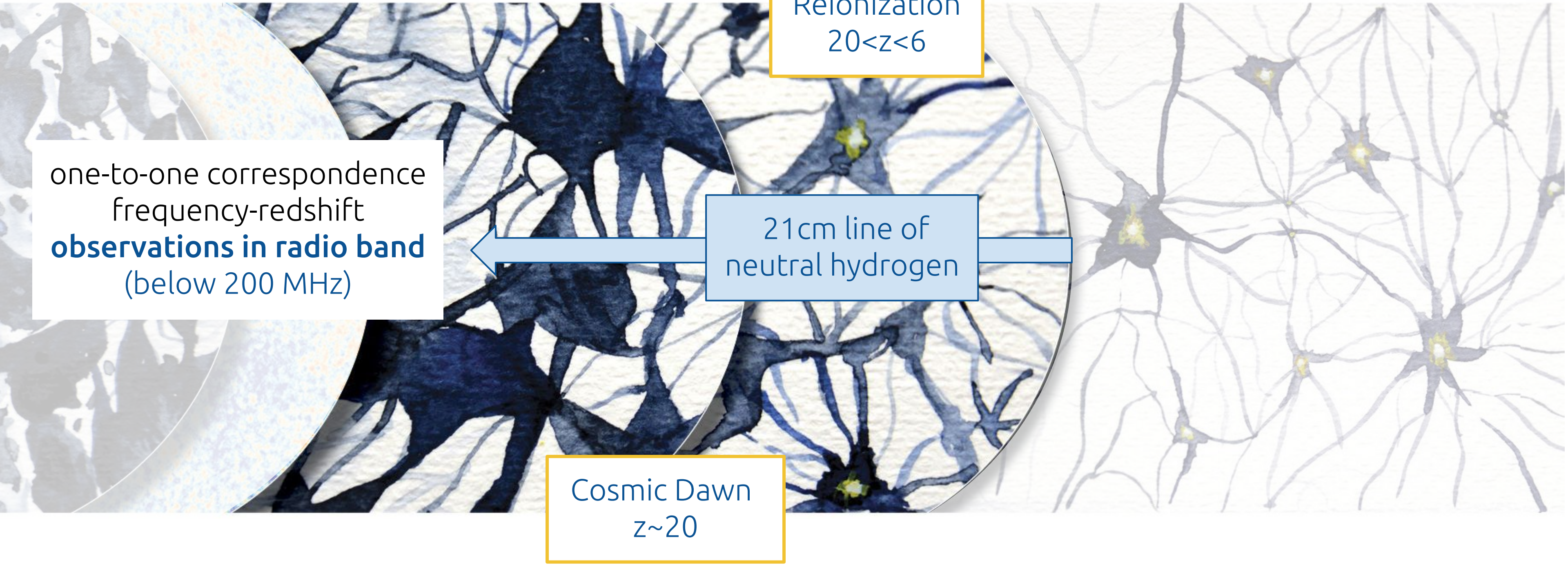
Hydrogen in cosmic history

credit: ESA



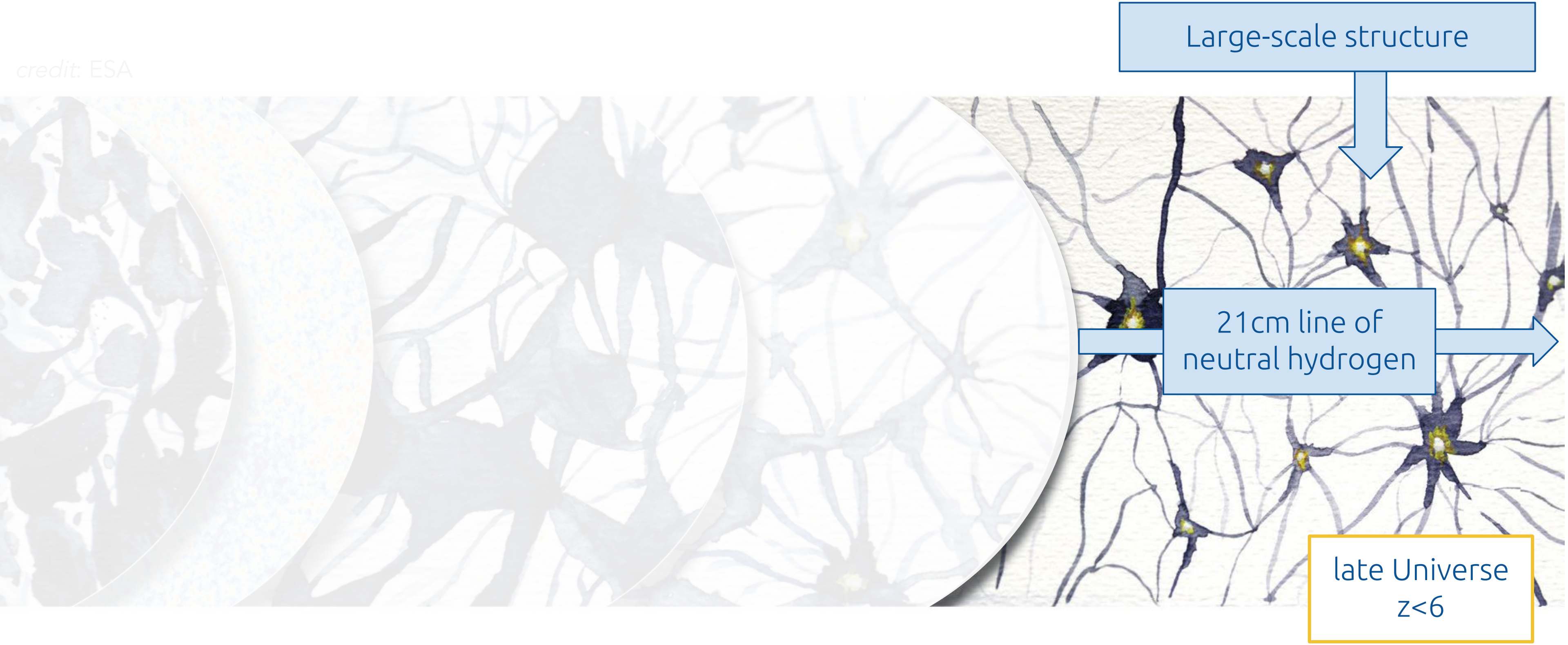
The “**high**” redshift Universe

credit: ESA

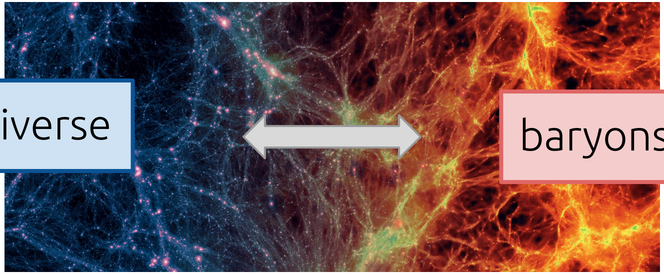


The “**low**” redshift Universe

credit: ESA



Late-time neutral hydrogen distribution



credit: Illustris

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?

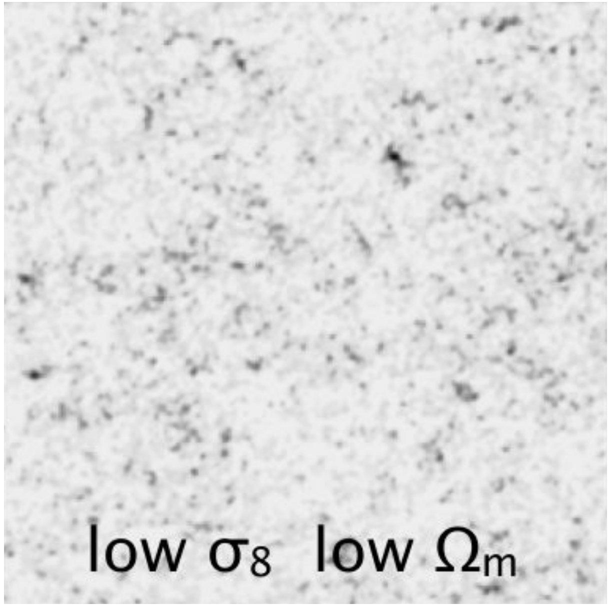
How do baryons trace dark matter?

what is the link between galaxies and dark matter halos?

how are HI galaxies distributed in the cosmic web?

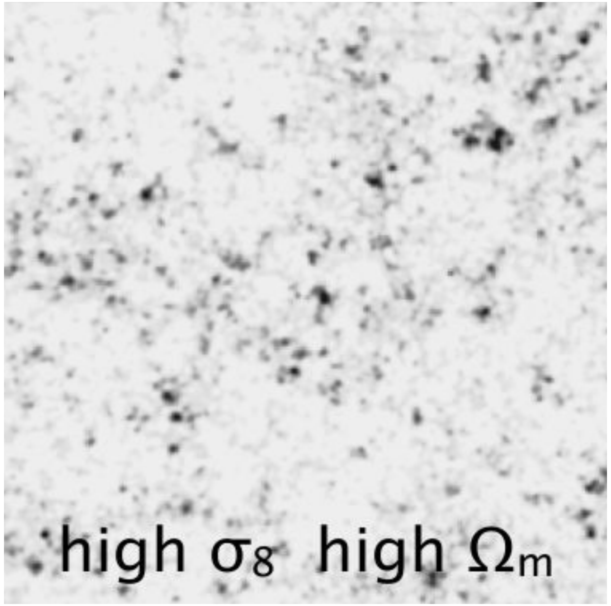
how does the total cosmic HI evolve with redshift?

LSS with Neutral Hydrogen



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

LSS with Neutral Hydrogen



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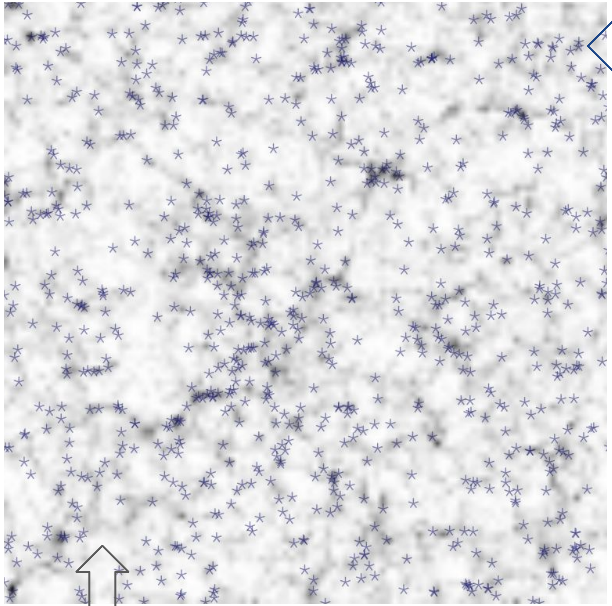
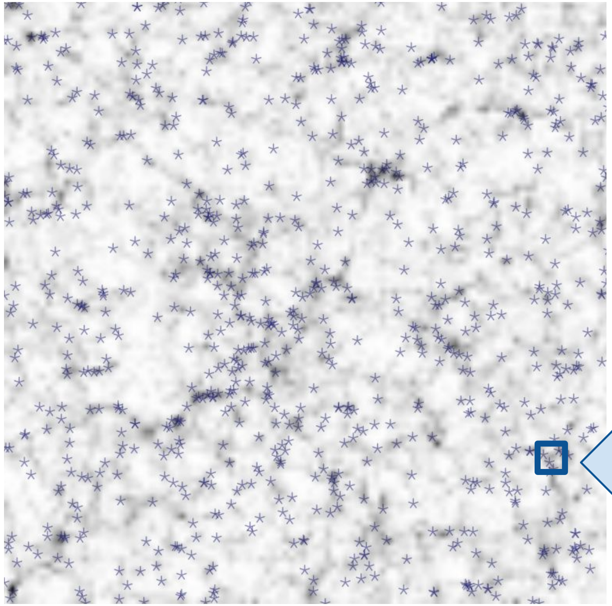


the distribution of **neutral Hydrogen** is a biased tracer of the **matter clustering**

underlying matter distribution

How can we efficiently observe cosmological volumes?

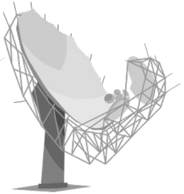
LSS with Neutral Hydrogen



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

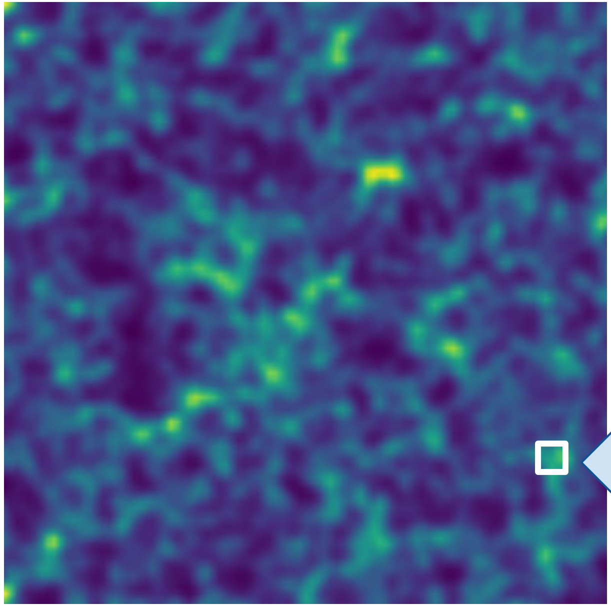
How can we efficiently observe
cosmological volumes?

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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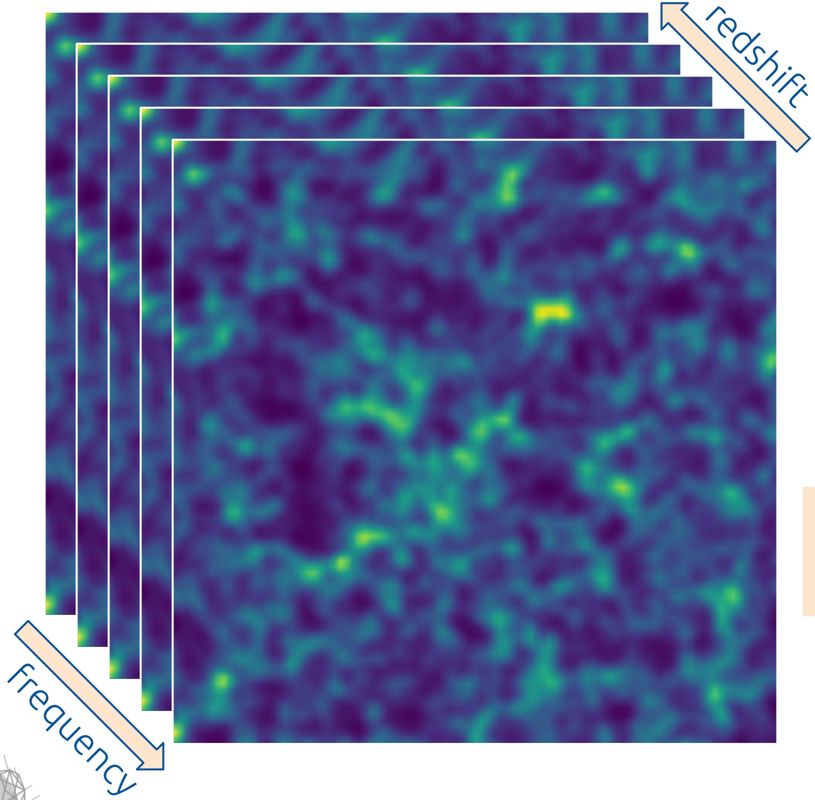
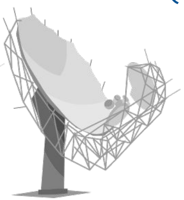


the distribution of **neutral Hydrogen** is a biased tracer of the **matter clustering**

How can we efficiently observe cosmological volumes?

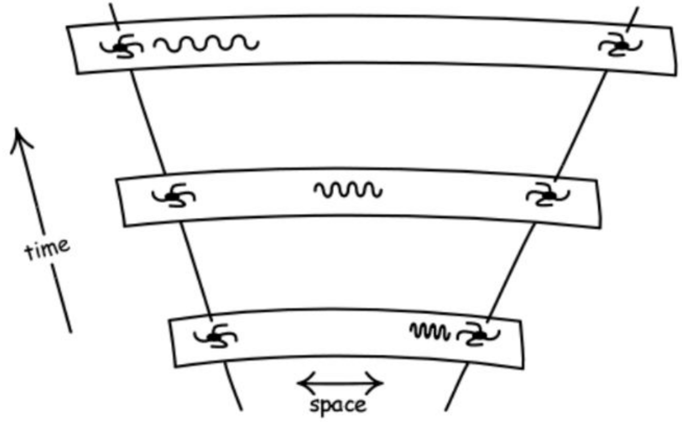
one-to-one correspondence frequency-redshift
high spectral resolution (tomography)

Key cosmological probe



Frequency and redshift for the 21cm line

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



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

Examples:

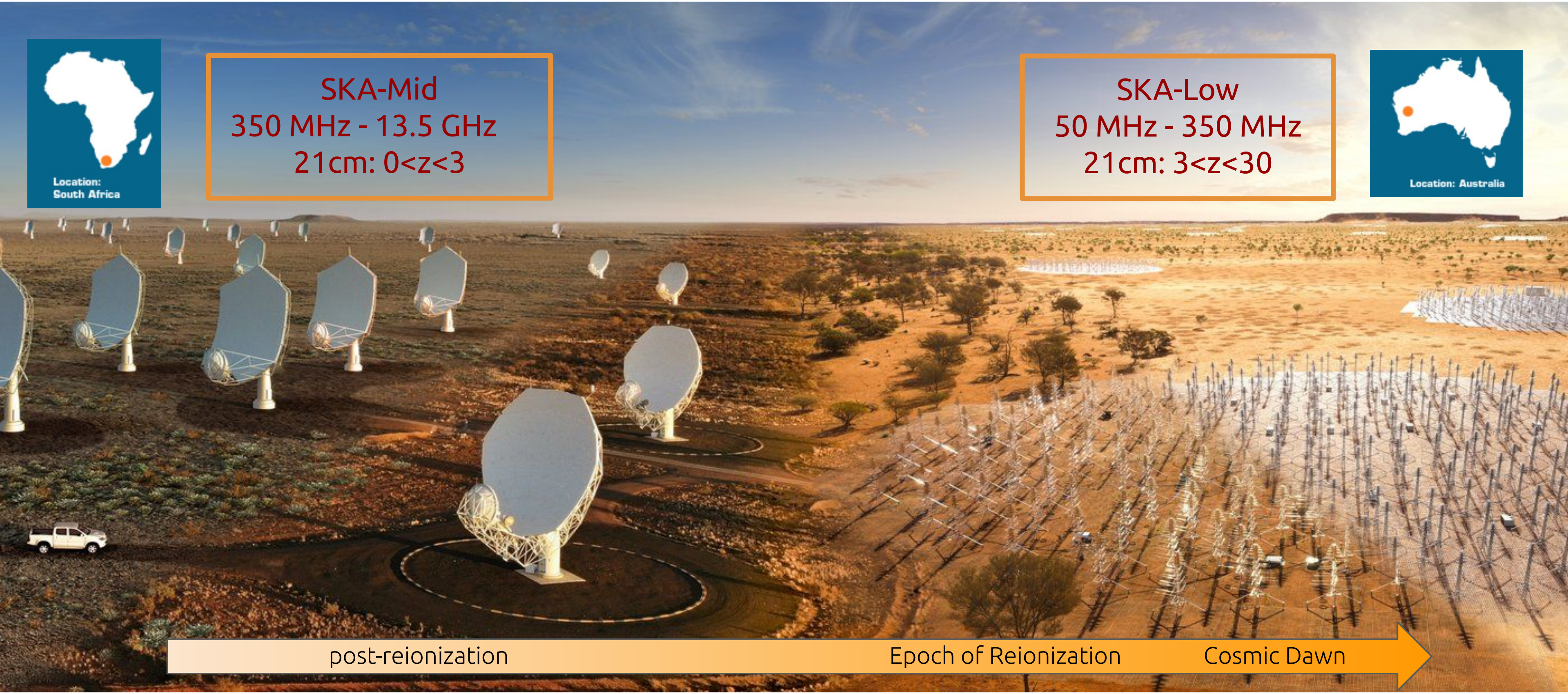
ν_{observed} ~ 900 MHz
corresponds to z ~ 0.6: late Universe

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

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

HI @ SKAO

credit: skatelescope.org



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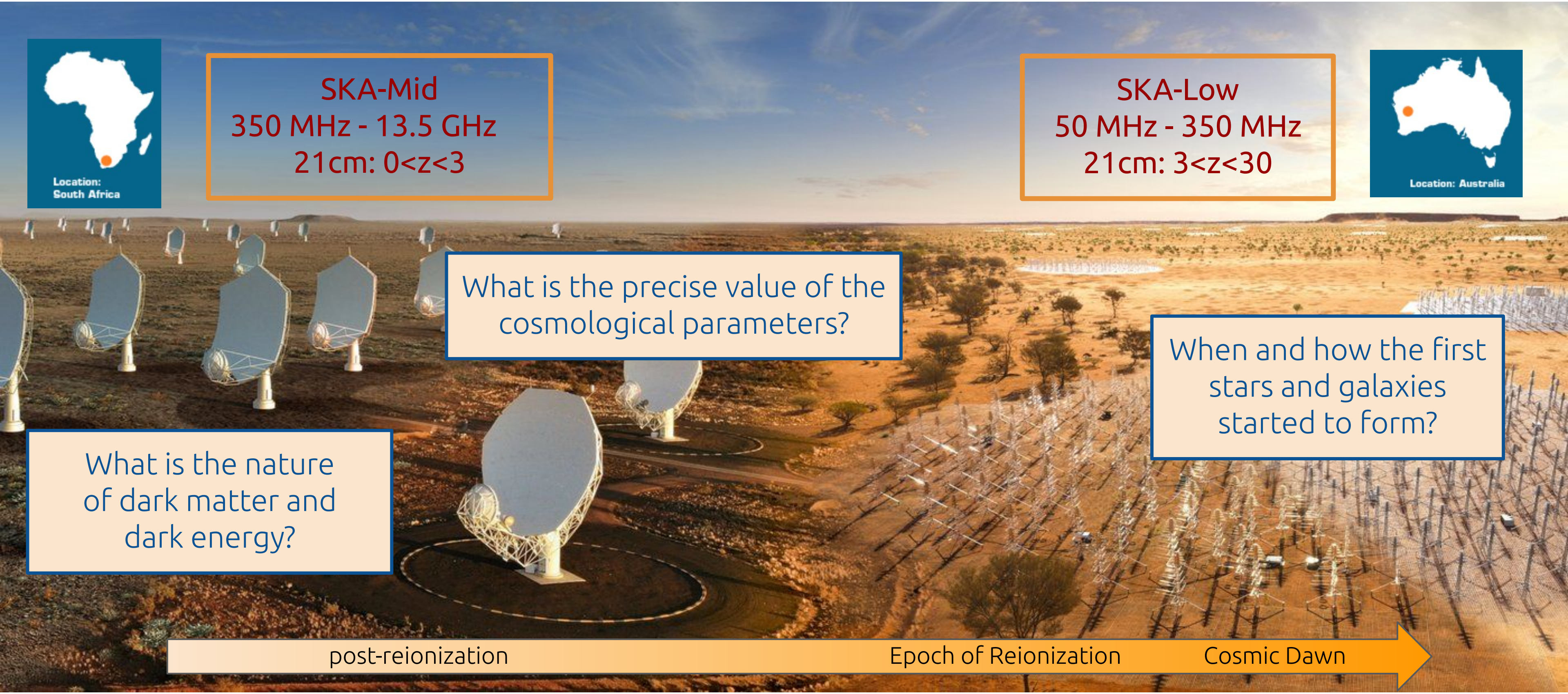

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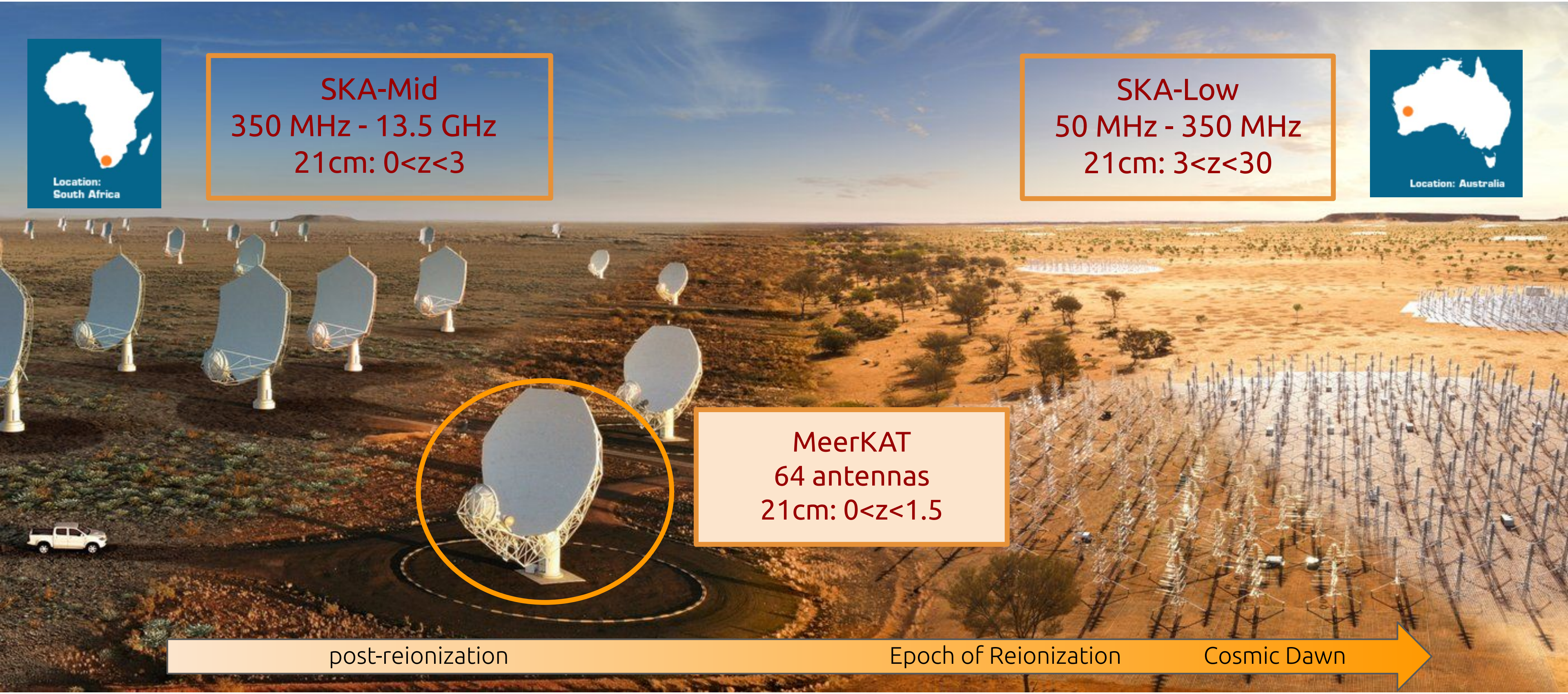
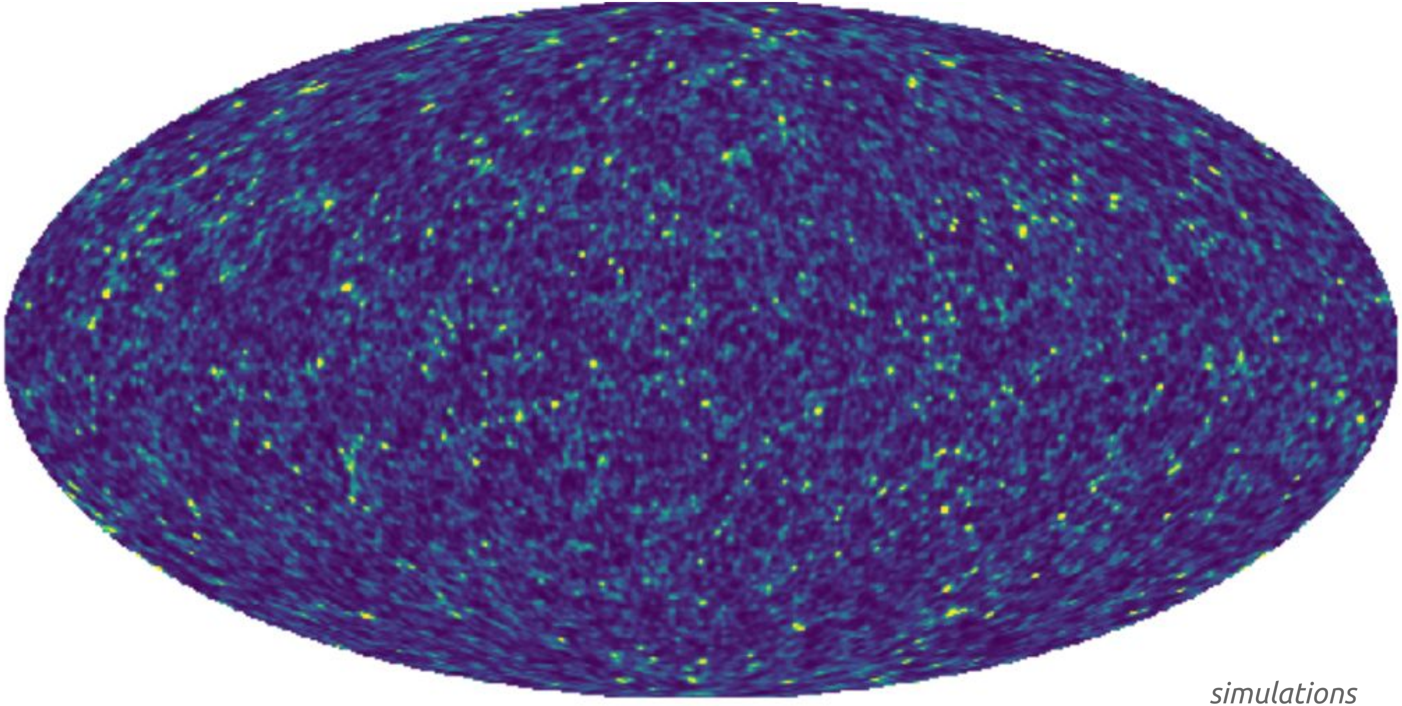


Hydrogen on cosmological scales



simulations
MS et al. 2021,2022

SKA-Mid 21cm forecasts

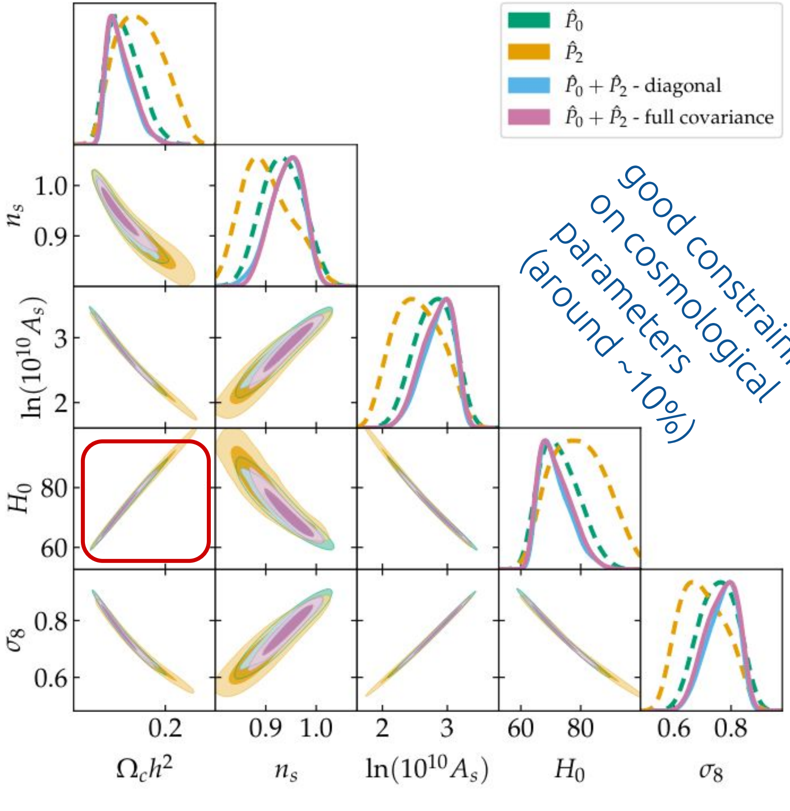
$$\boxed{P_{21}(z,k,\mu)} = \bar{T}_b^2(z)\left[\, b_{\rm HI}(z) + f(z)\,\mu^2 \,\right]^2 P_{\rm m}(z,k)$$

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

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

SKA-Mid 21cm forecasts

Berti, MS, Viel (2023)



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

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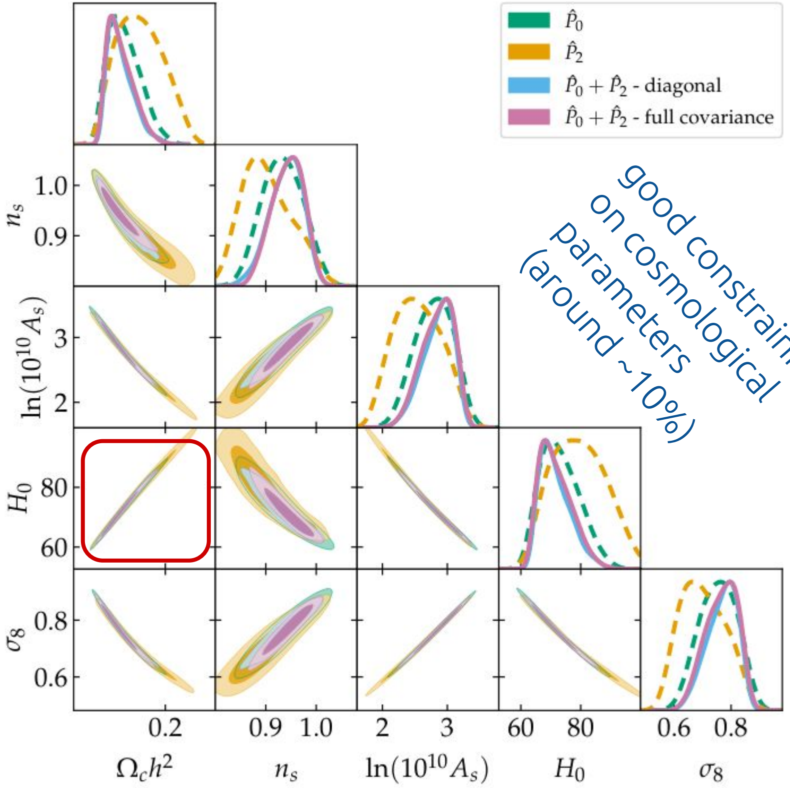

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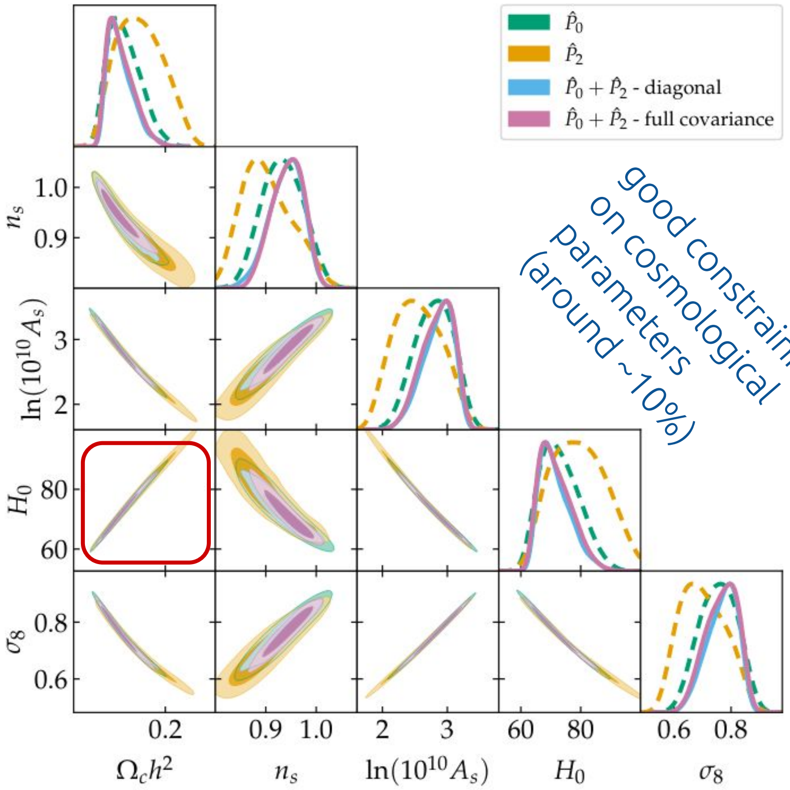
$$\boxed{P_{21,g}(z,k,\mu)} = \bar{T}_b\,\left(b_{HI} + f\mu^2\right)\left(b_g + f\mu^2\right) P_m(z,k,\mu)$$

SKA-Mid 21cm forecasts

Berti, MS, Viel (2023)



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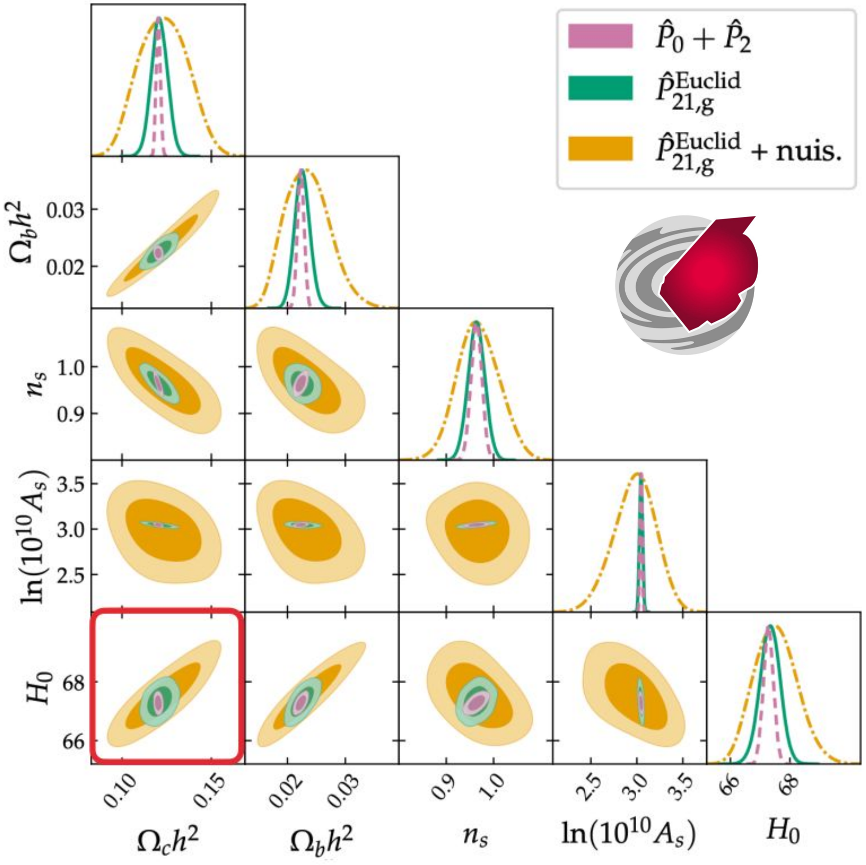
Berti, MS, Viel (2024)



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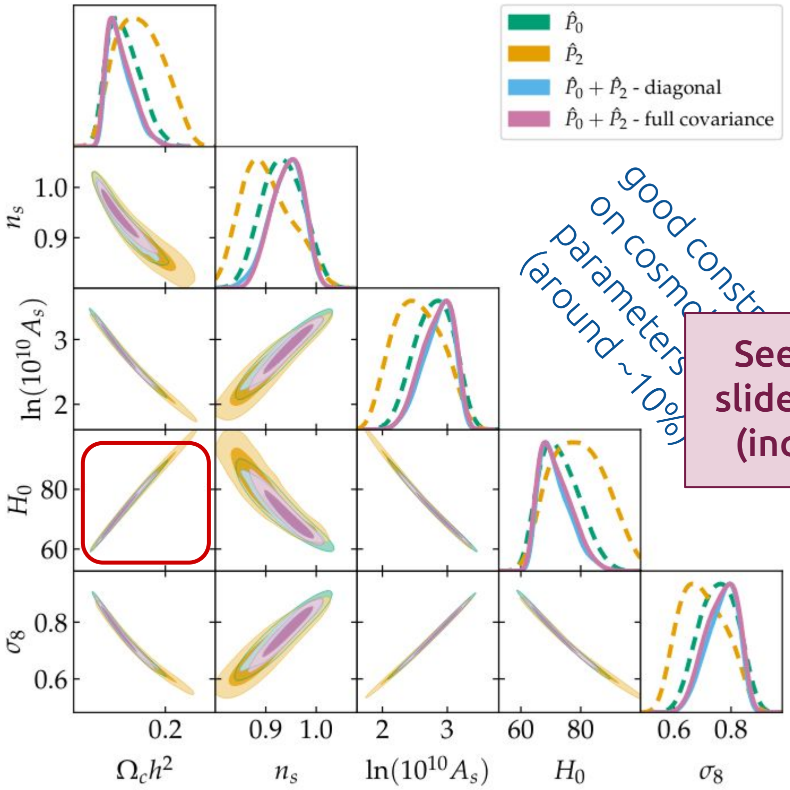
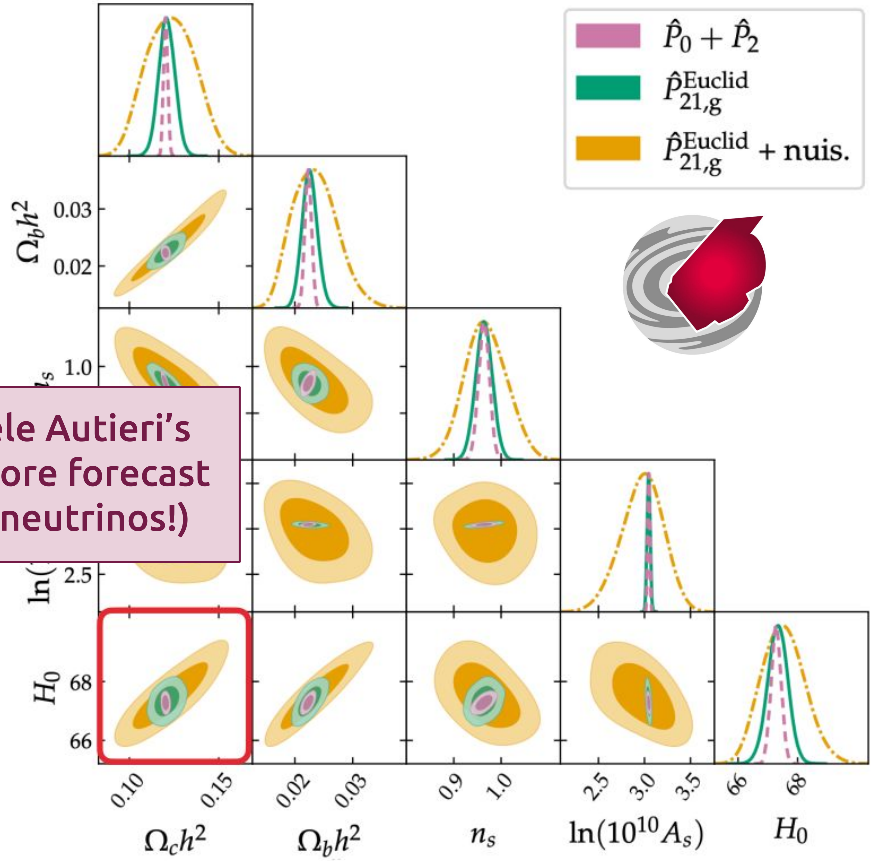
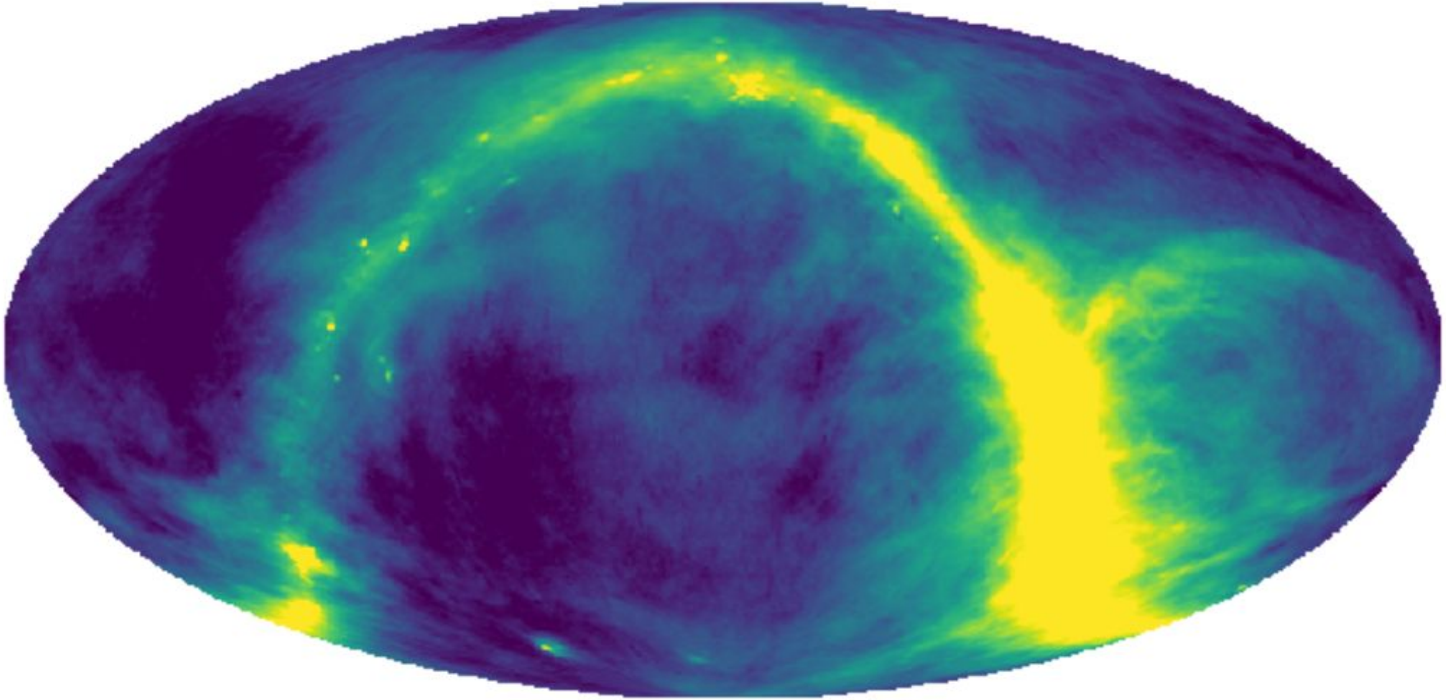


good constr
on cosmo
parameters
(around ~10%)



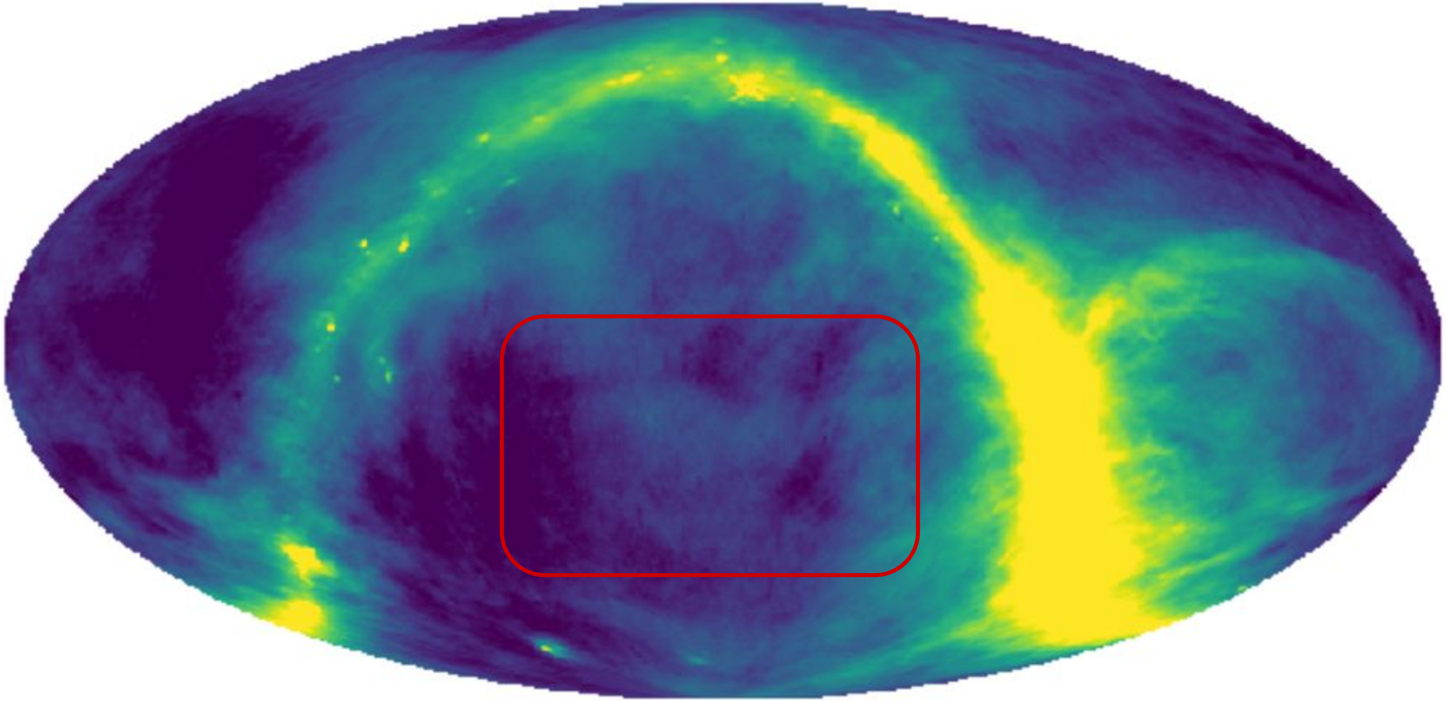
See Gabriele Autieri's slides for more forecast (including neutrinos!)

The challenge of foregrounds



Haslam et al. (1982)

The challenge of foregrounds



Haslam et al. (1982)

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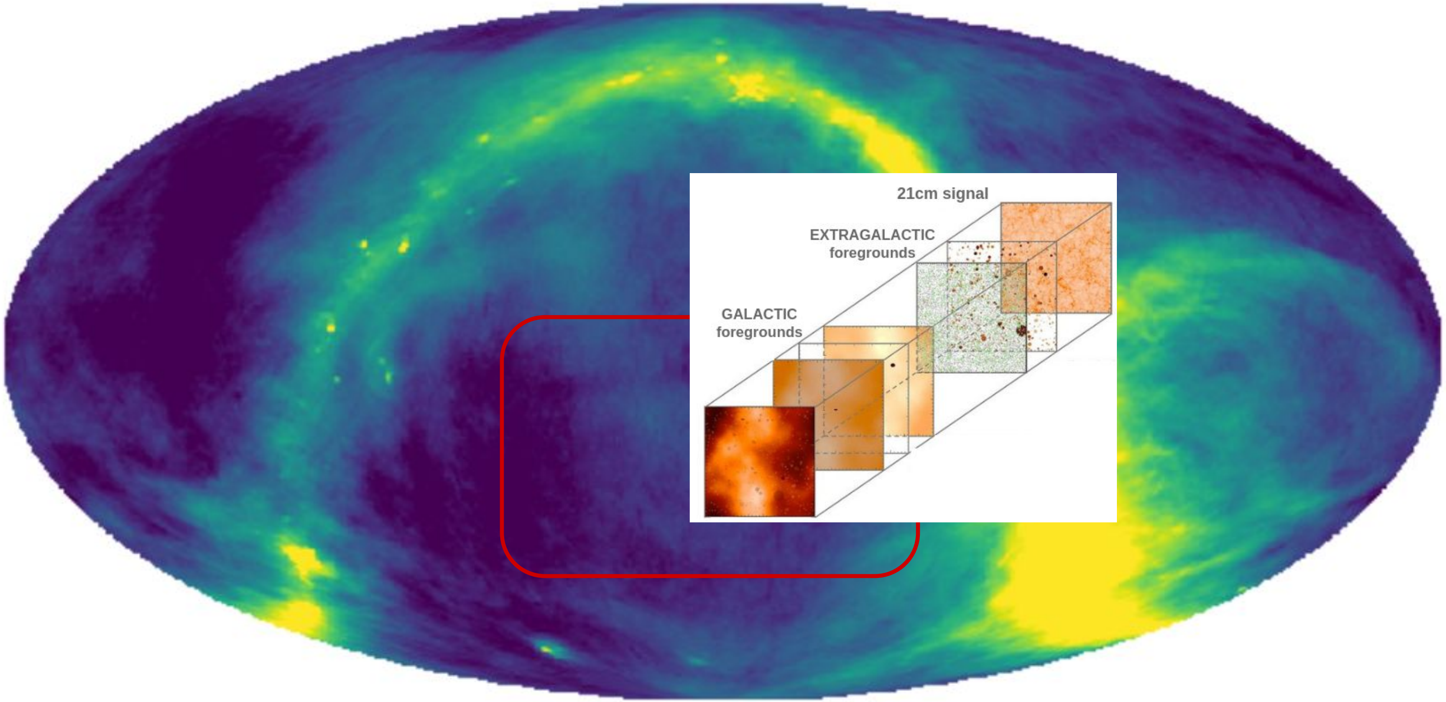

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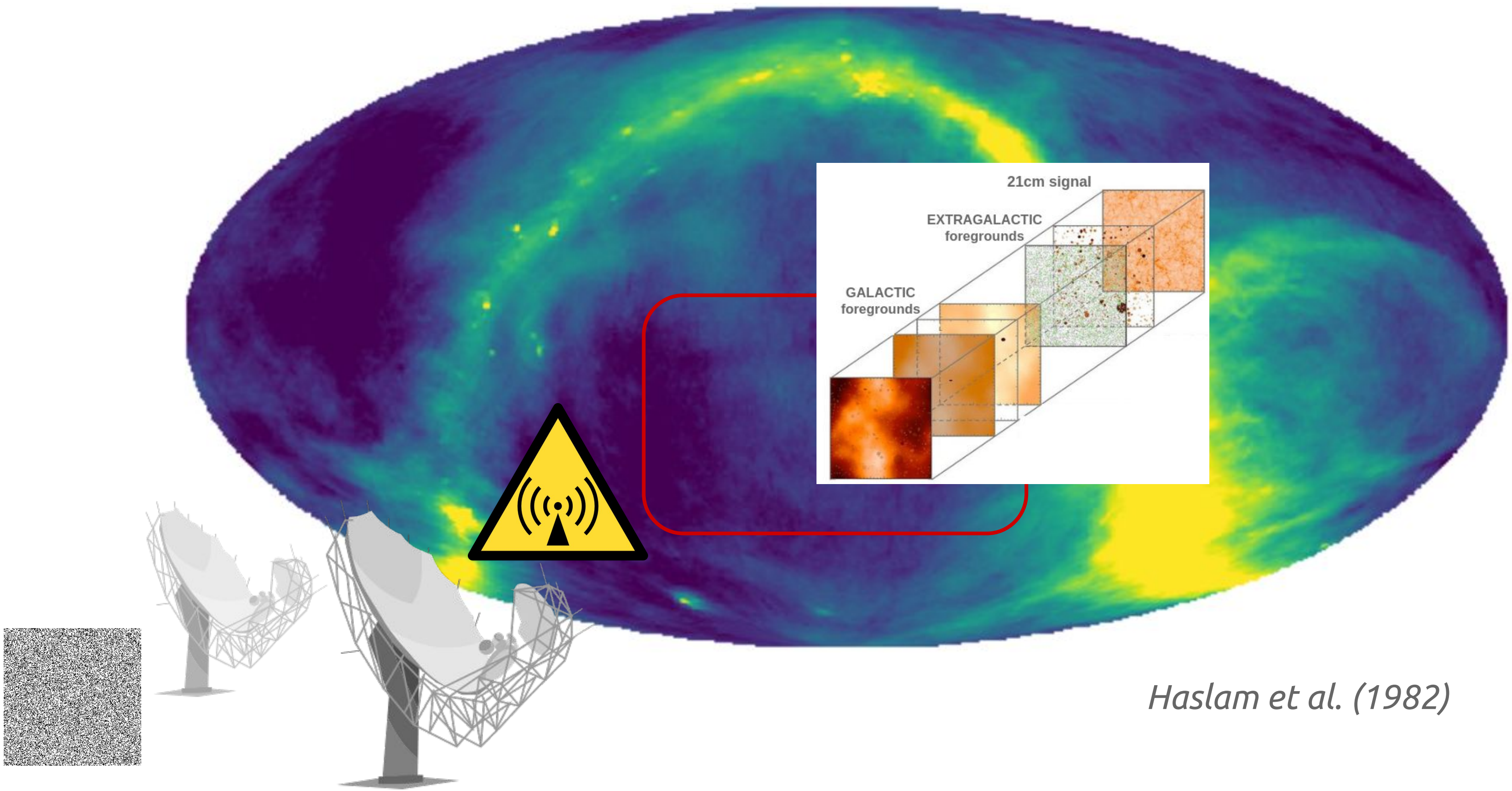
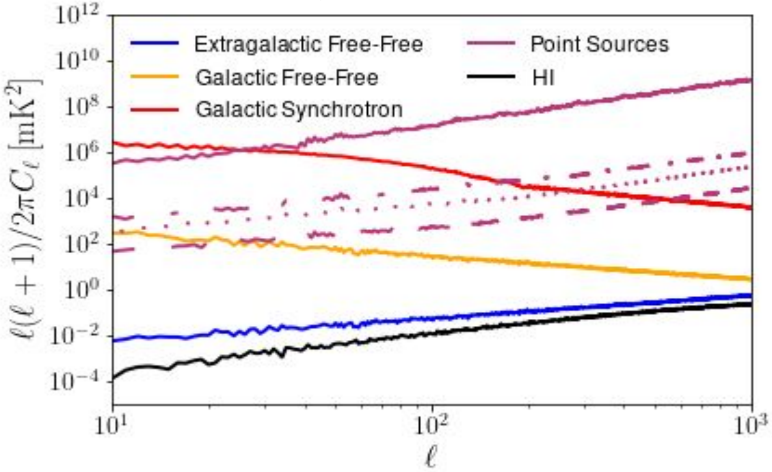
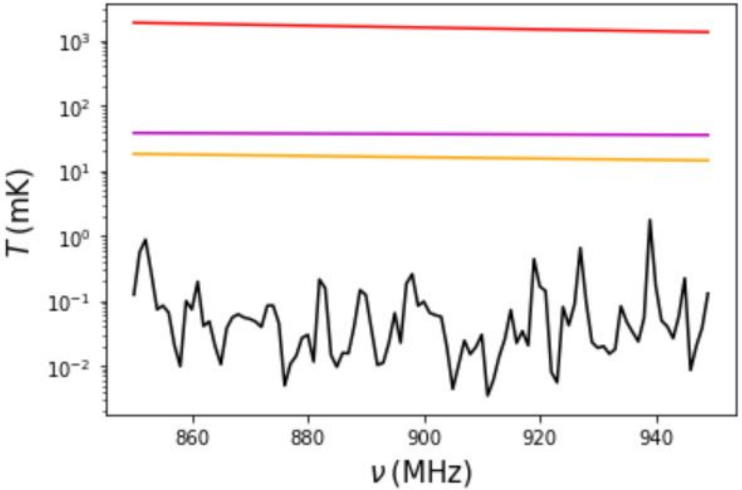


Haslam et al. (1982)

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)

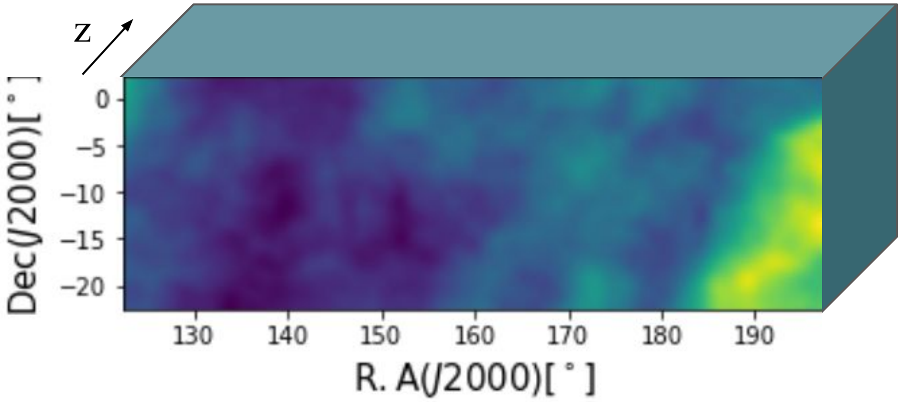
Questions:

- ❑ 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,..)

see also: Ansari et al. 2012; Wolz et al. 2014; Alonso et al. 2015; Shaw et al. 2015; Olivari et al. 2016; Carucci et al 2020; Fonseca & Liguori 2021; Makinen et al. 2021; Soares et al. 2021, MS et al. 2022 etc.

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

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

A mixing matrix of the foreground sources

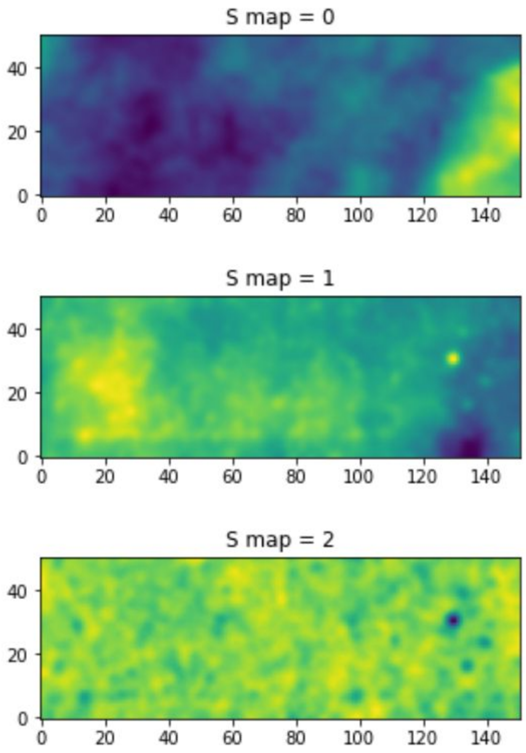
noise

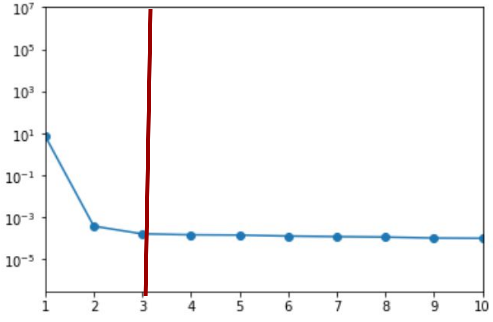
Cosmological signal

How many sources?

N$_{fg}$ need to be estimated/guessed

A cleaning example





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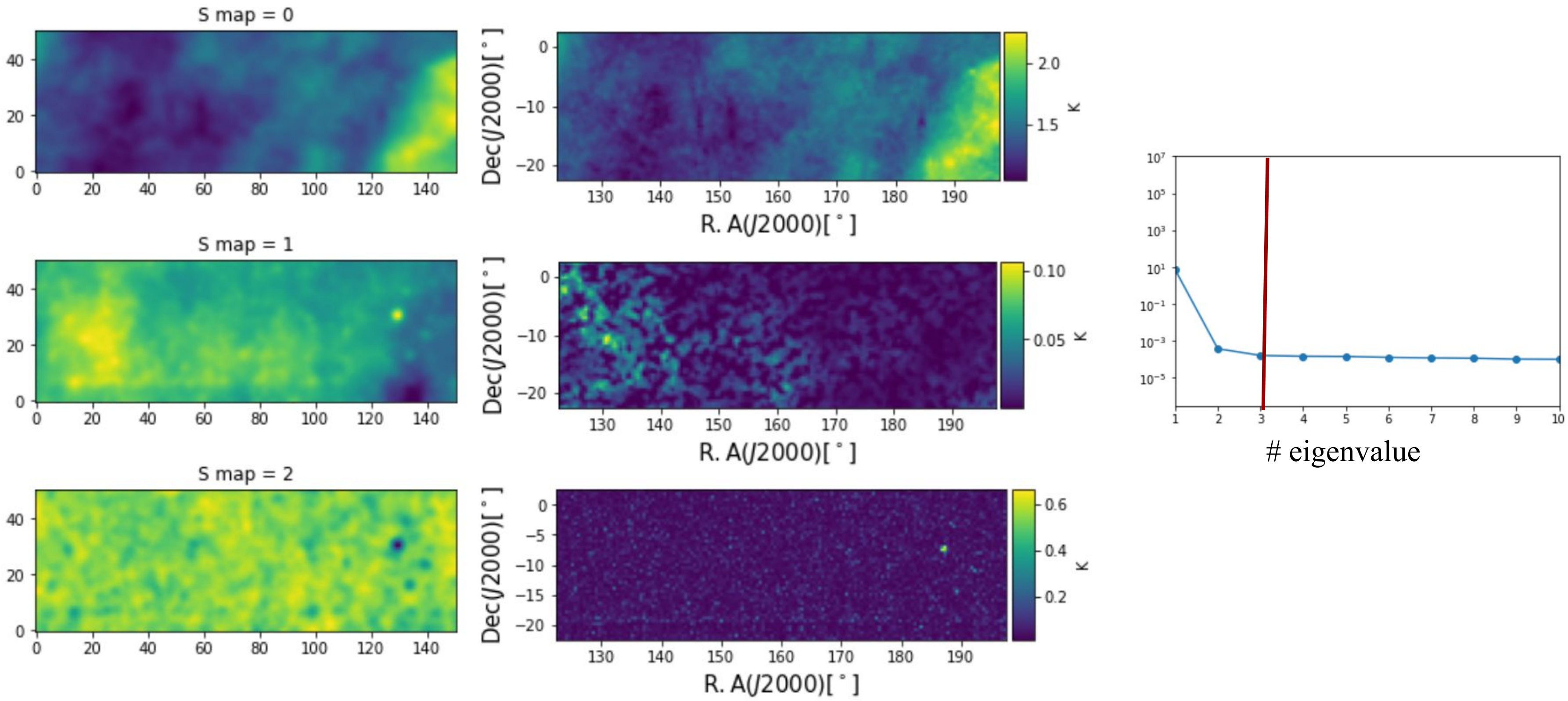
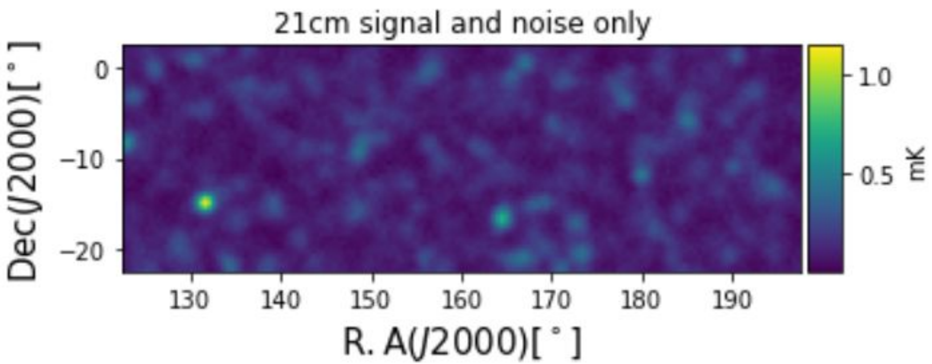
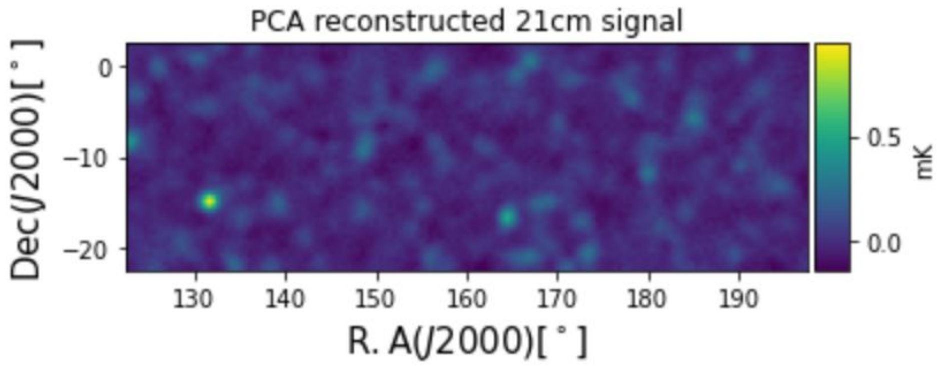


A cleaning example

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

A mixing matrix including only the first **Nfg** components



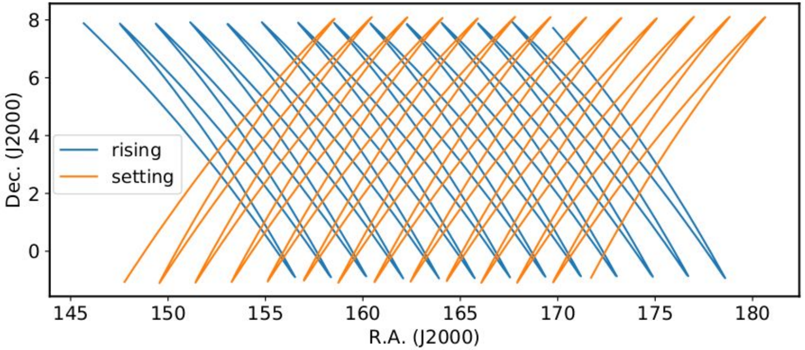


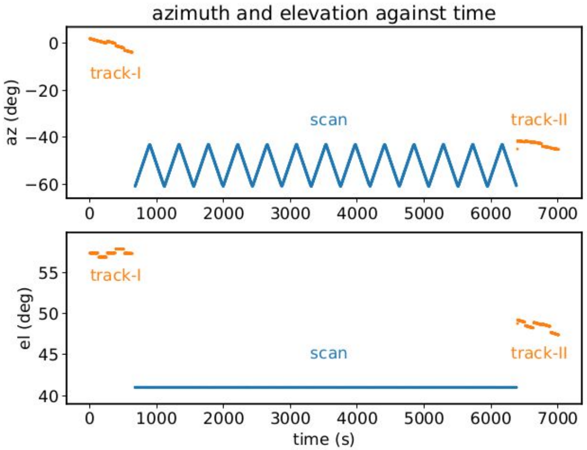
PI: Mario Santos (UWC)

Intensity Mapping with MeerKAT

Santos et al. 2017, Wang et al. 2021

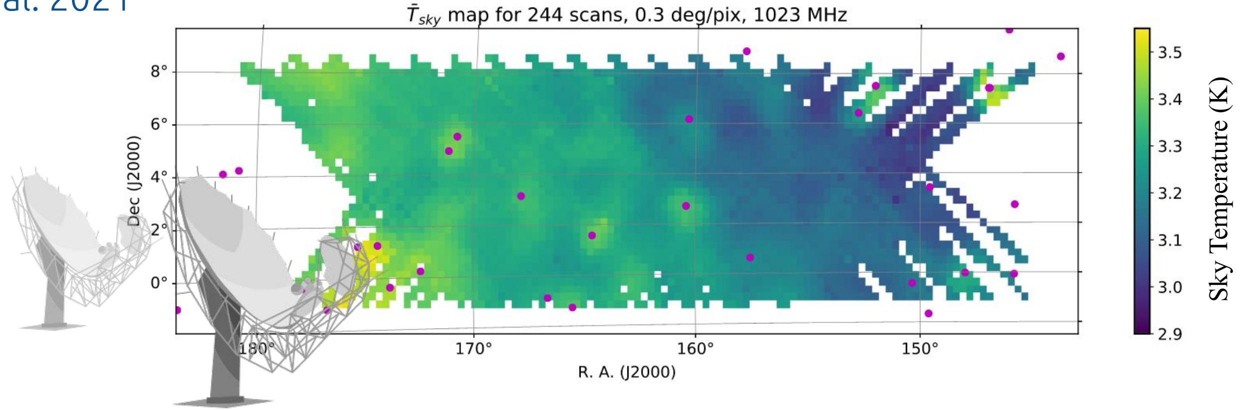
Antennas	All 64 MeerKAT dishes
Observation mode	Single-dish
Frequency range	0.856-1.712 GHz
Frequency resolution	0.2 MHz
Time resolution	2s
Exposure time	1.5hr x 7 scans
Target field	WiggleZ 11hr field ($10^\circ \times 30^\circ$)





MeerKLASS observations

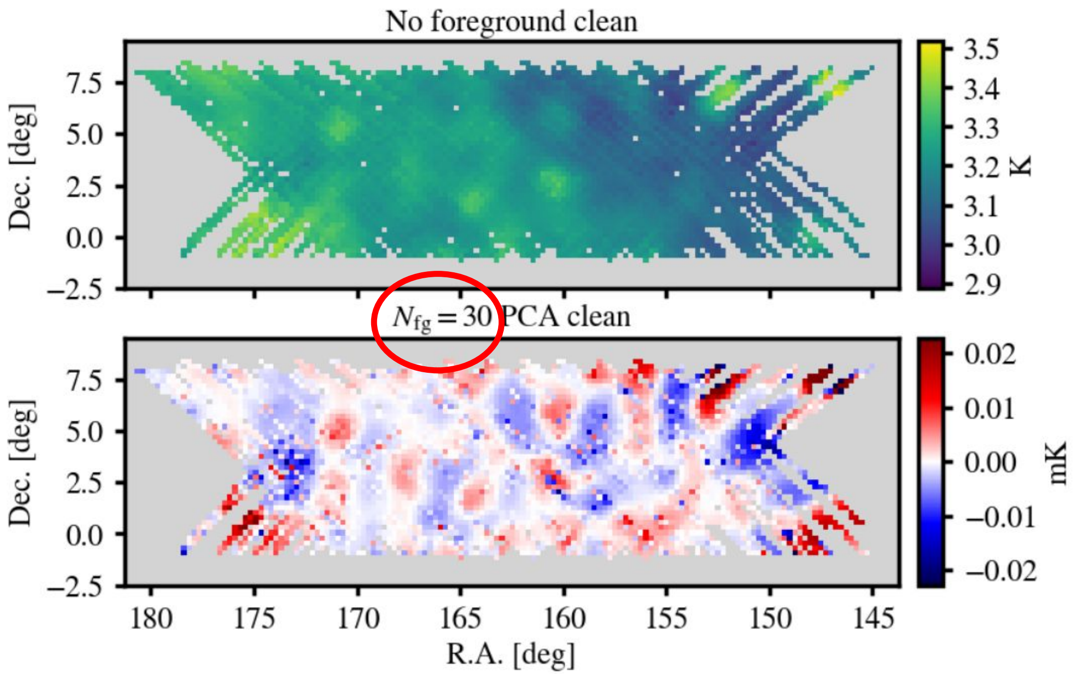
Wang et al. 2021



64 MeerKAT antennas used in single-dish mode *(Santos et al. 2017)*

- ❑ first successful calibration of intensity mapping data from MeerKAT
- ❑ L-band: 850-1700 MHz (4096 channels)

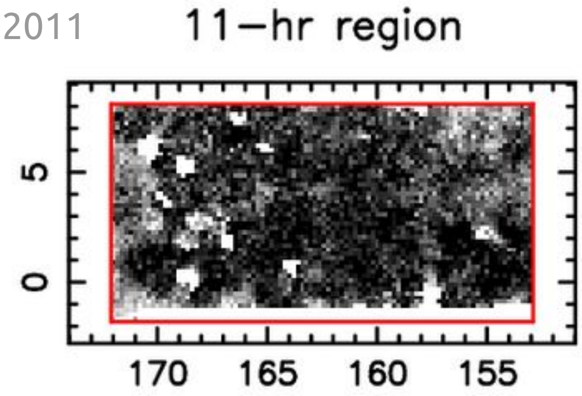
MeerKLASS observations

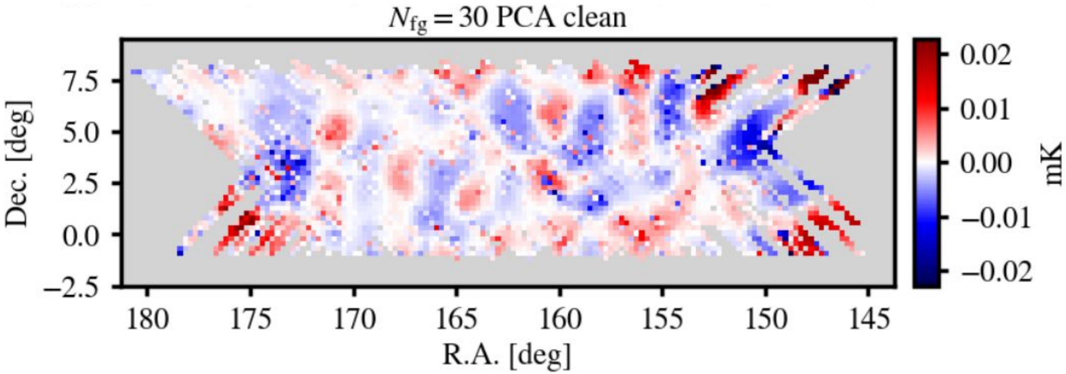


Cunnington et al. 2022

MeerKLASS results

Blake et al. 2011

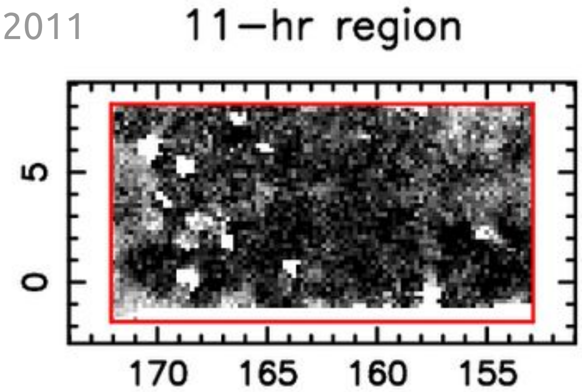


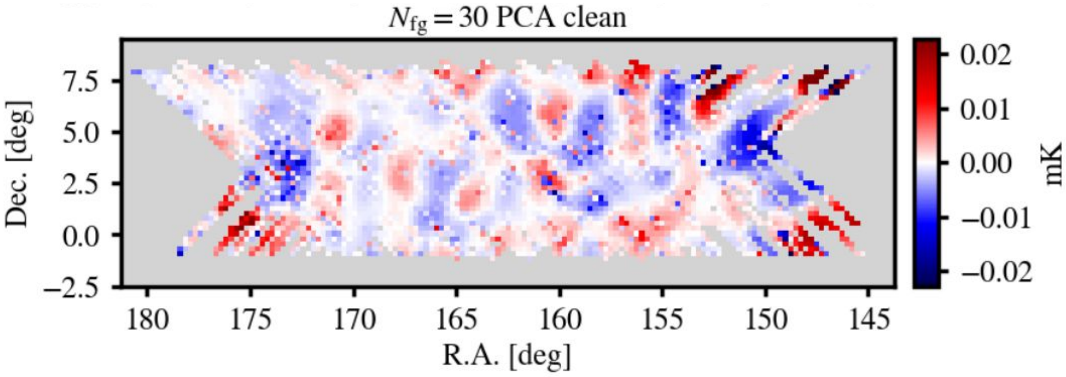


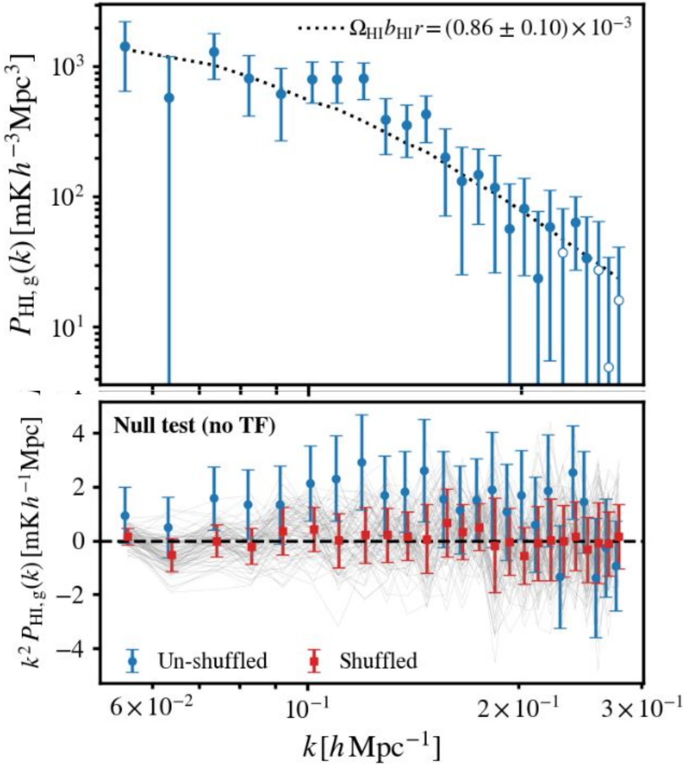
Cunnington et al. 2022

MeerKLASS results

Blake et al. 2011



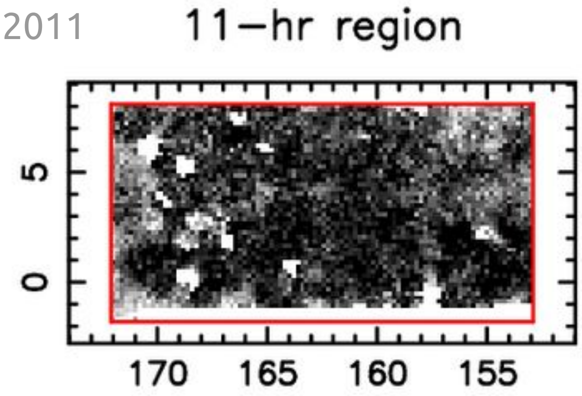


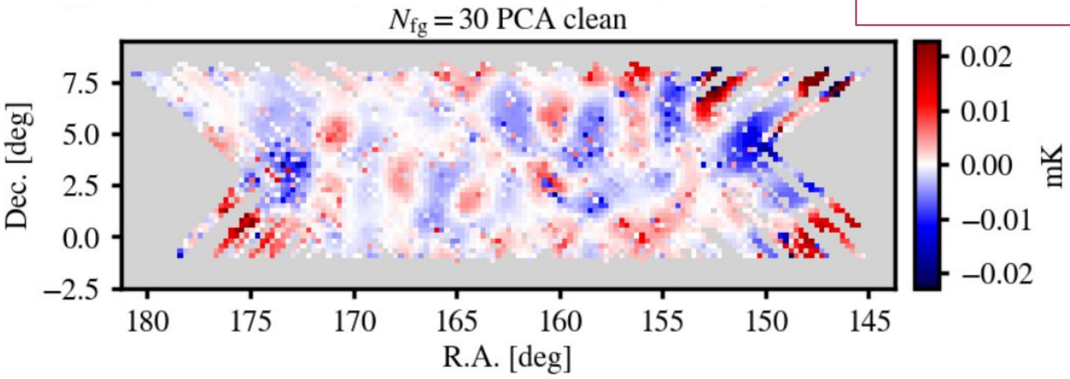


Cunnington et al. 2022

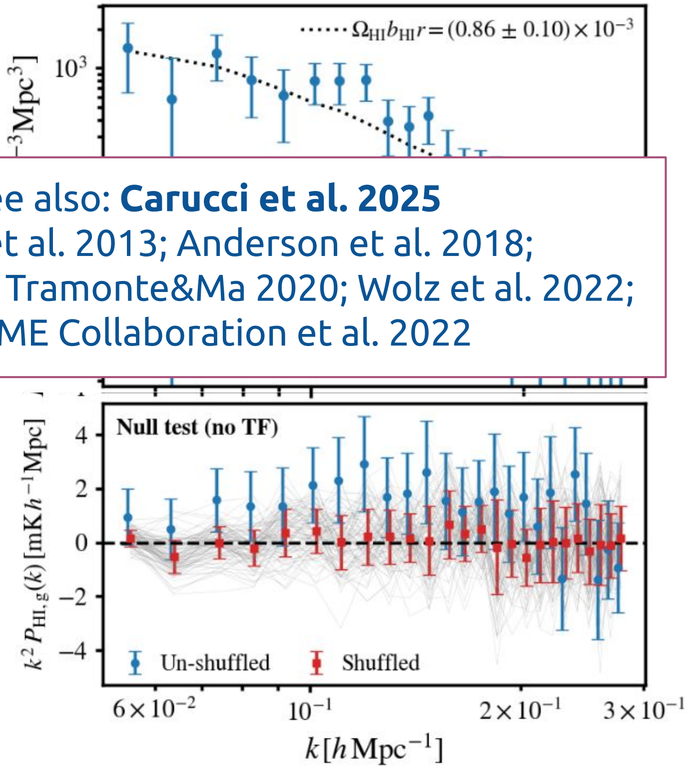
MeerKLASS results

Blake et al. 2011





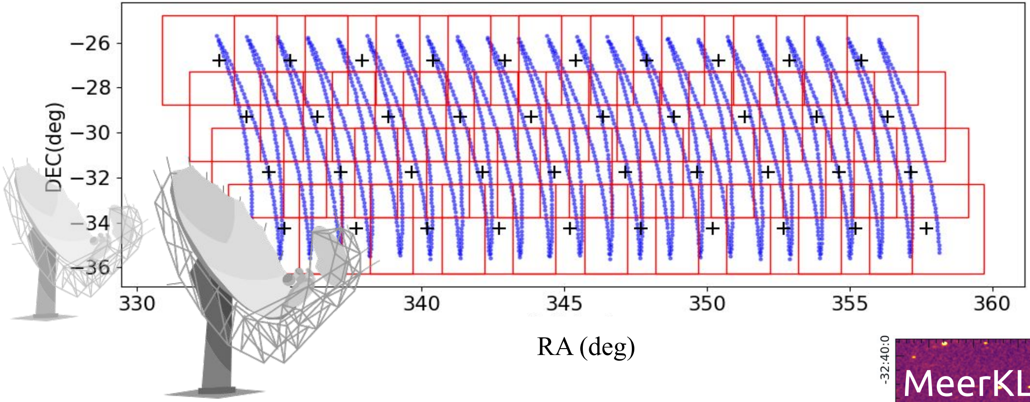
Cunnington et al. 2022



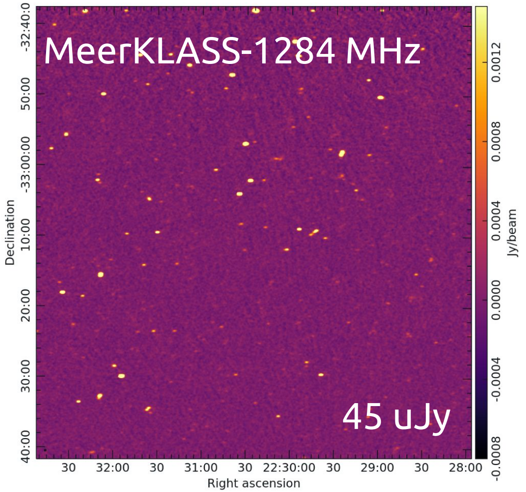
see also: **Carucci et al. 2025**
Masui et al. 2013; Anderson et al. 2018;
Li et al. 2021; Tramonte&Ma 2020; Wolz et al. 2022;
CHIME Collaboration et al. 2022

On-the-fly

MeerKLASS: MeerKAT Large Area Synoptic Survey



Chatterjee, Paul, Santos,Tasse, Mohr +

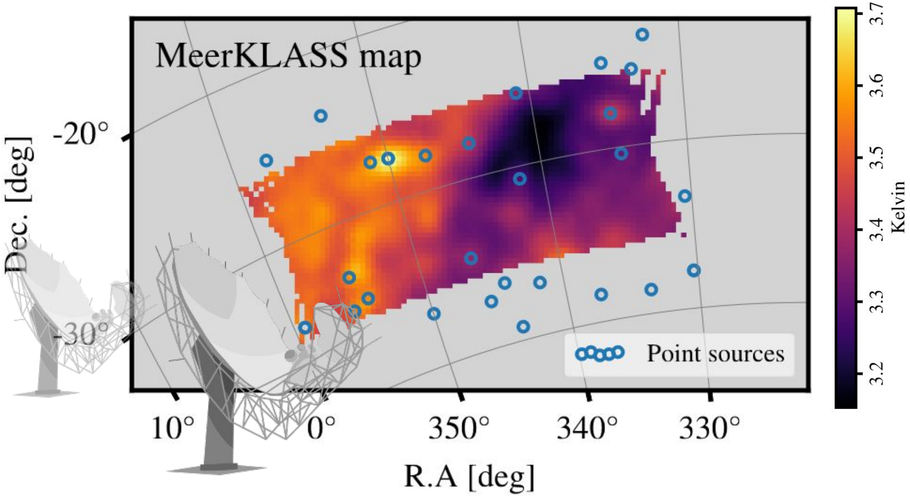


- OTF as a byproduct of IM observation
- 2s snapshot images ⟹ transient studies
- Large visibility mosaics produced using DDFacet

⟹ **continuum science**

L-band 2021 results

MeerKLASS collab (Cunnington & Wang corresponding authors) - arXiv:2407.21626

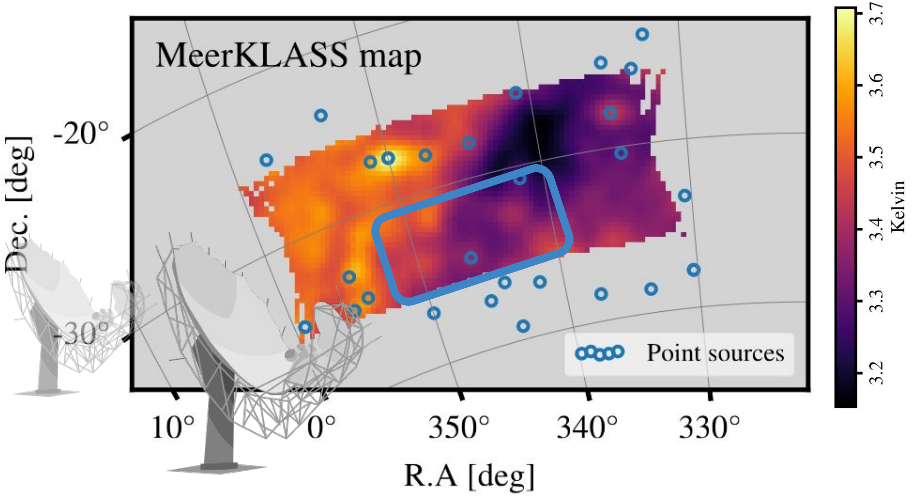


Freq range: 970 < ν < 1020 MHz (z~0.4)
41 blocks over 240 deg2
deepest single-dish Hi intensity maps to date

Improved Calibration strategy (better sky model)
Heavy RFI flagging (safe strategy but working on data recovery)

L-band 2021 results

MeerKLASS collab (Cunnington & Wang corresponding authors) - arXiv:2407.21626



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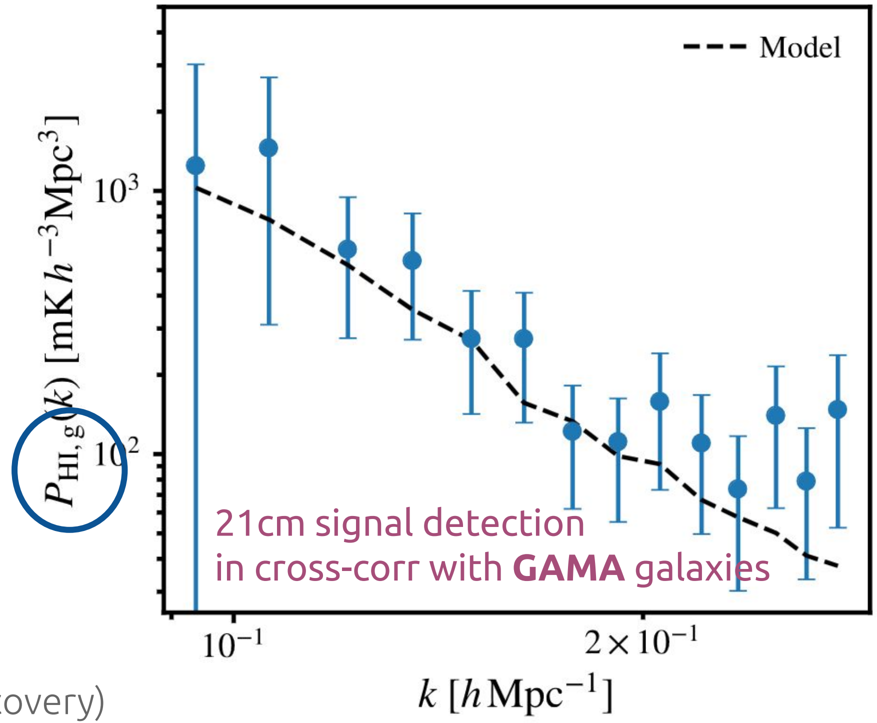
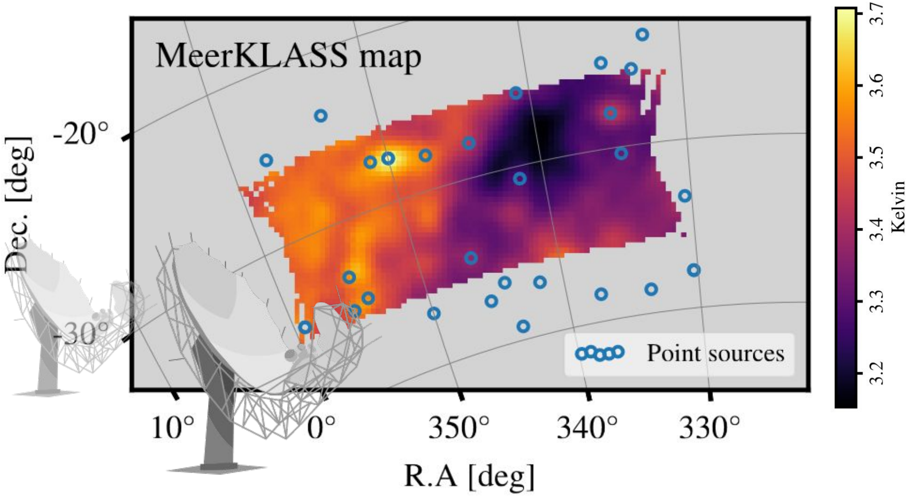
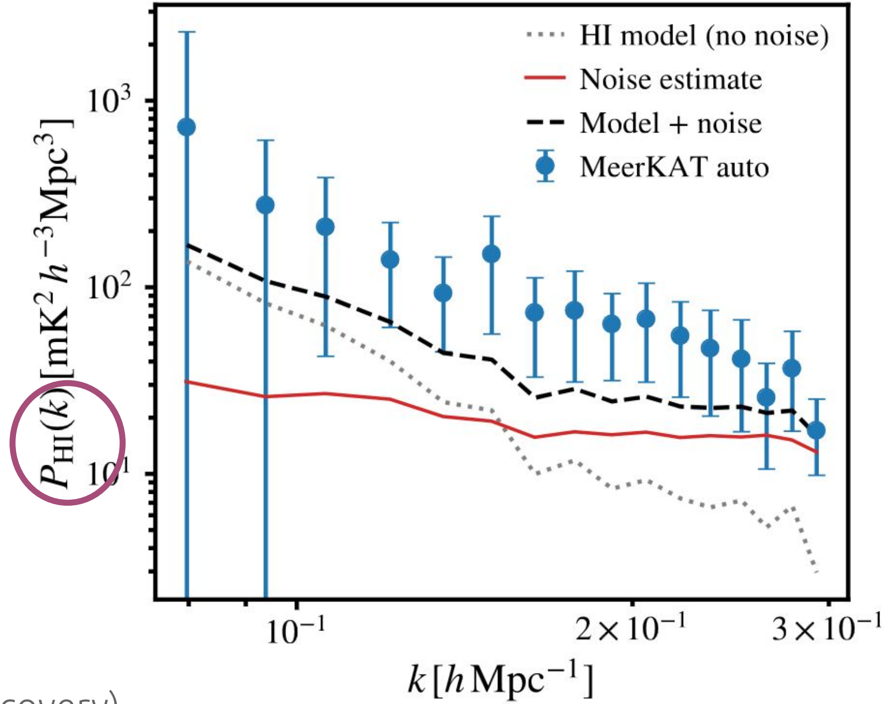


21cm signal detection
in cross-corr with **GAMA** galaxies

L-band 2021 results

MeerKLASS collab (Cunnington & Wang corresponding authors) - arXiv:2407.21626





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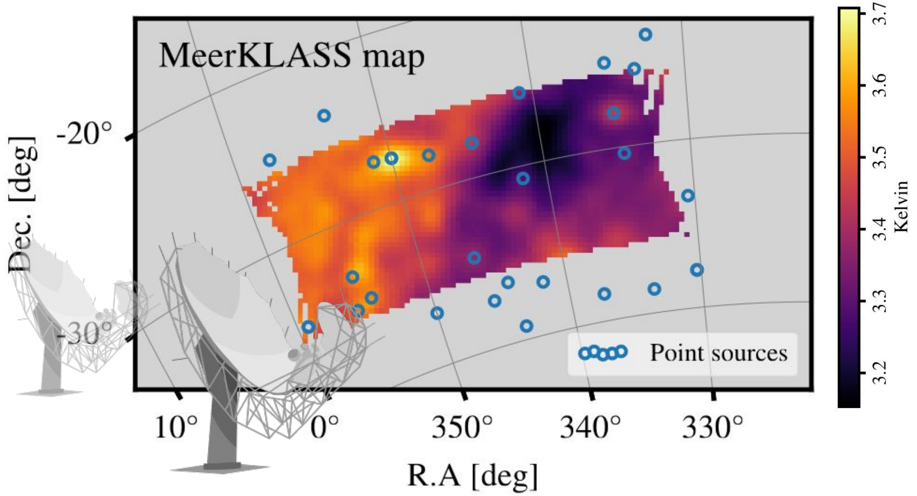
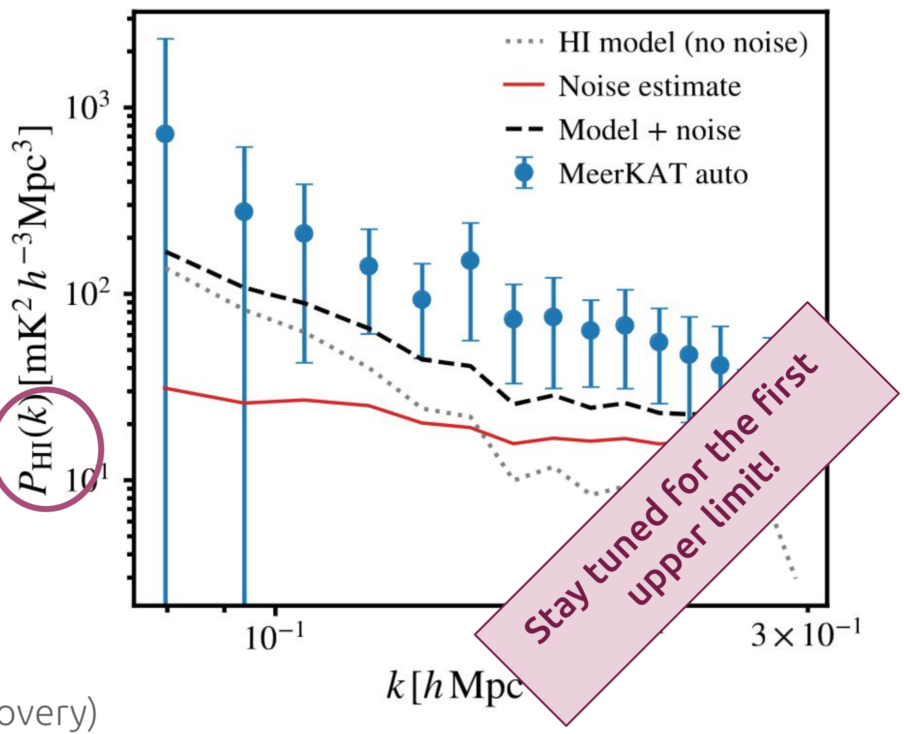




Freq range: $970 < \nu < 1020$ MHz (z~0.4)

41 blocks over 240 deg2

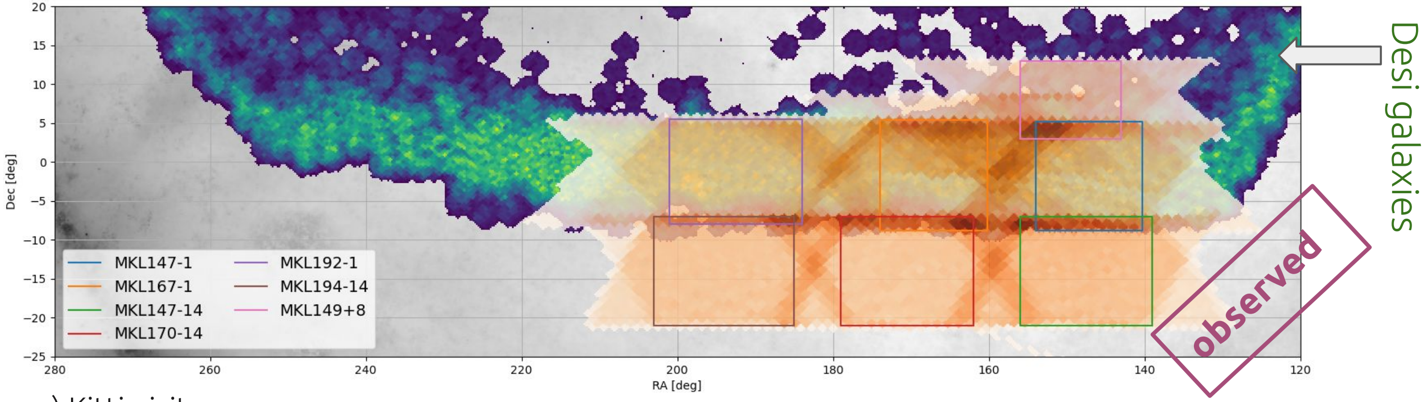
deepest single-dish Hi intensity maps to date

Improved Calibration strategy (better sky model)

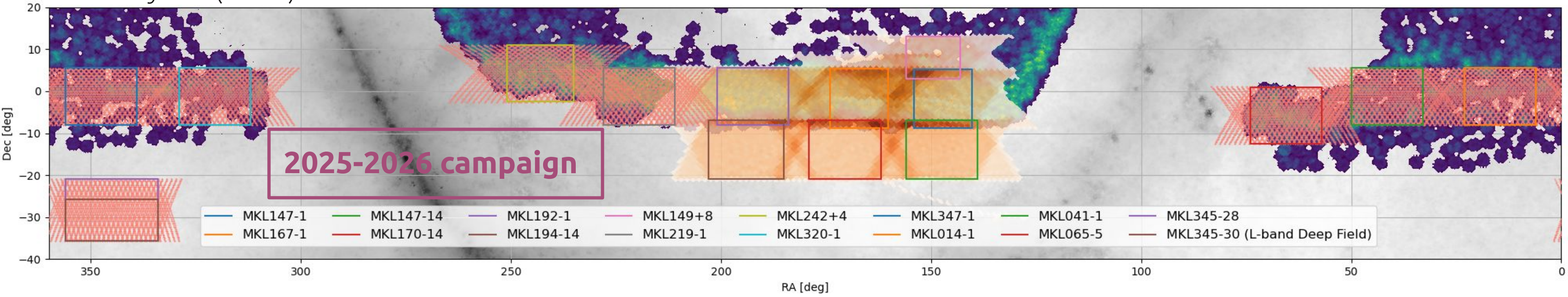
Heavy RFI flagging (safe strategy but working on data recovery)

(more) Intensity Mapping Observations

MeerKLASS: cosmological survey with MeerKAT 64 antennas

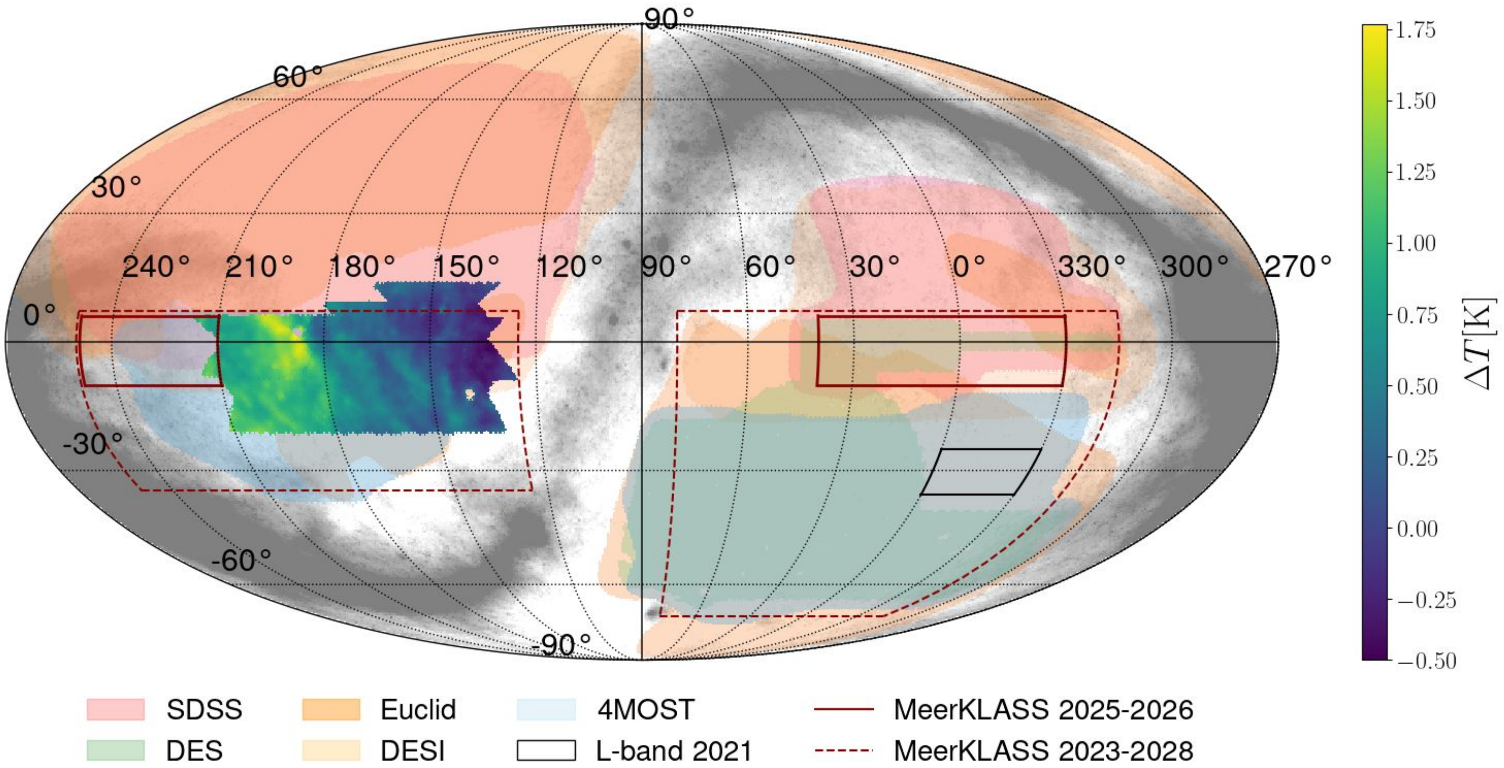


credit: Piyanat (Boom) Kittiwisit



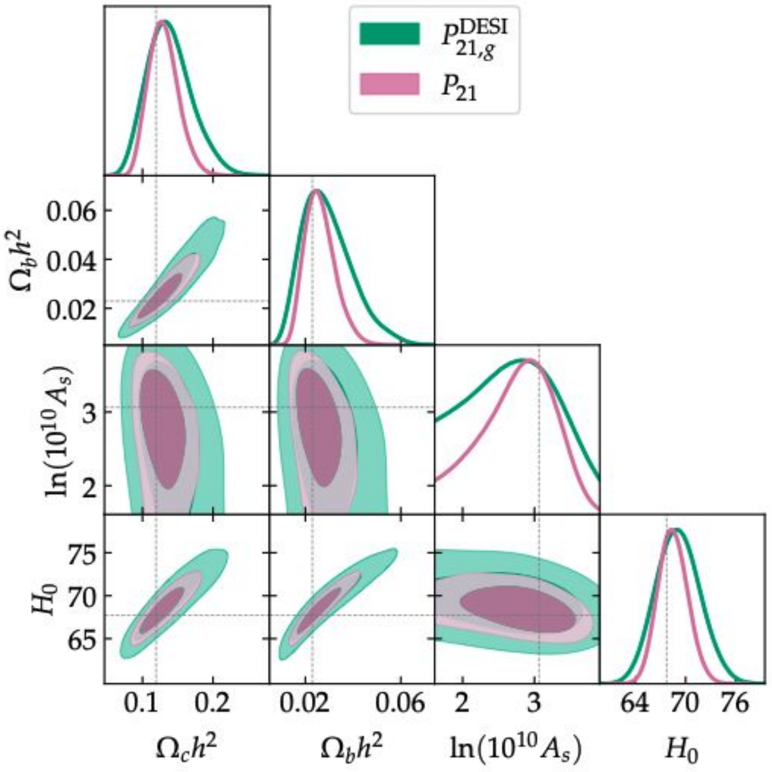
(more) Intensity Mapping Observations

MeerKLASS: cosmological survey with MeerKAT 64 antennas

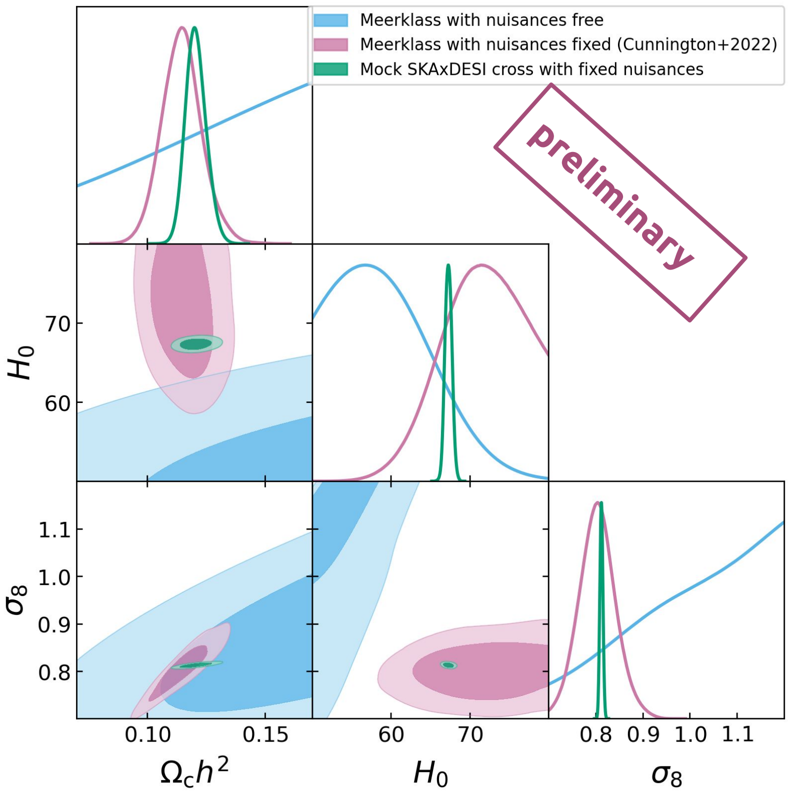


Forecasts and more

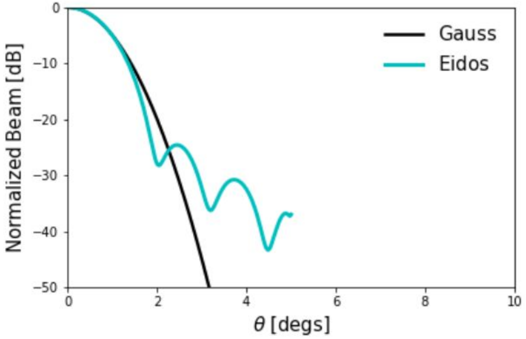
Berti, MS for the MeerKLASS collab

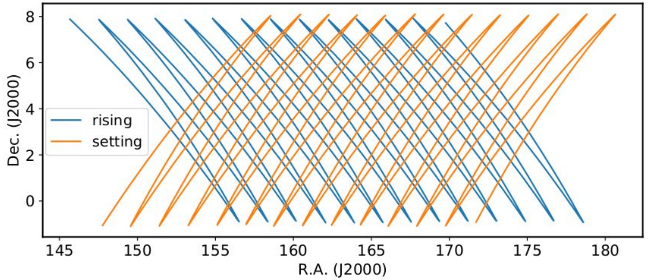


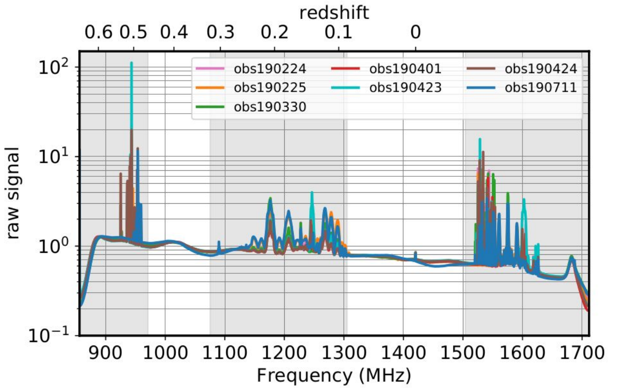
Berti, **Autieri**, MS, Santos +



Every detail counts







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 map space convolution?
polarization leakage?

Harper et al. 2018
Matshawule (2022)

Radio Frequency Interference (RFI)
new strategies for flagging,
impact on cleaning

Harper et al. 2018
Engelbrecht et al. (2024)
MS, Wang, et al (in prep)

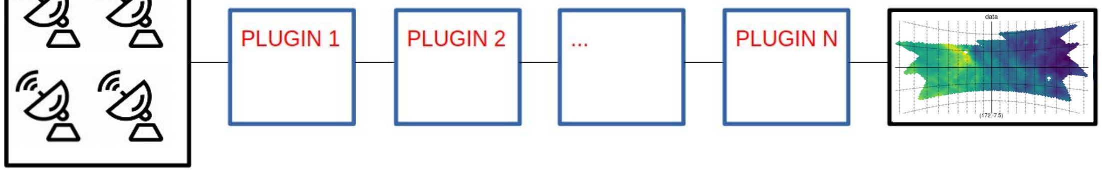
MeerKLASS ongoing

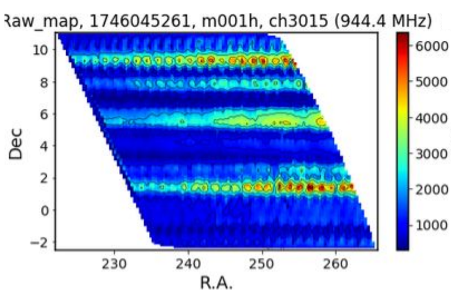
New calibration pipeline(s):

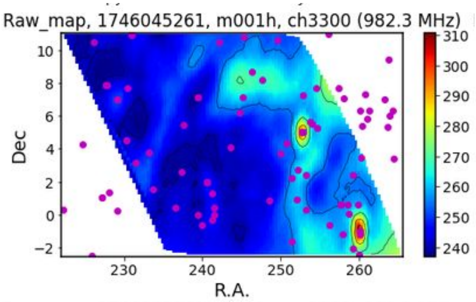
KATcali: improved RFI flagging, improved sky model with self-calibration
arXiv:2407.21626, **main developer: JY Wang**

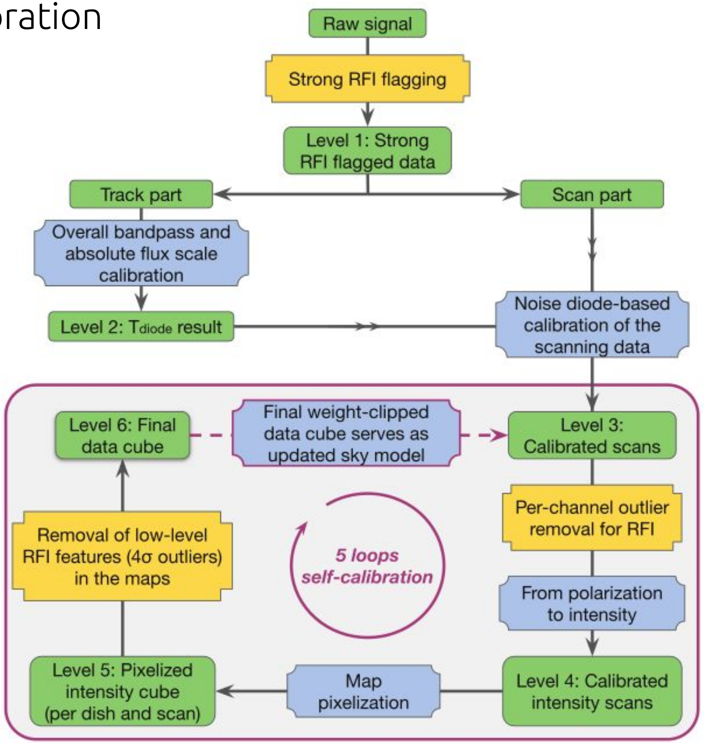
Ivory/MuSEEK: new improved modular plugin-based architecture
(main developers: W. Hu, A. Wild)

easily adaptable to SKAO

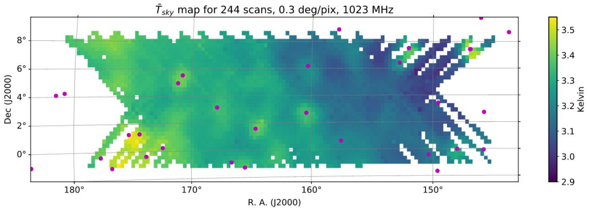


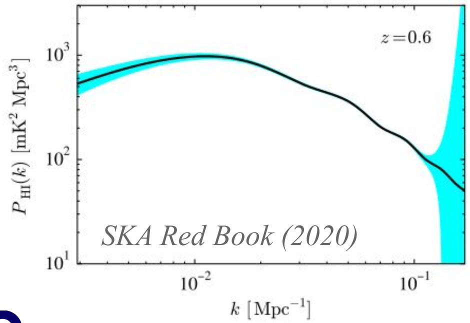






Moving forward





Radio cosmology with the **SKA precursors**
MeerKLASS

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

SKAO

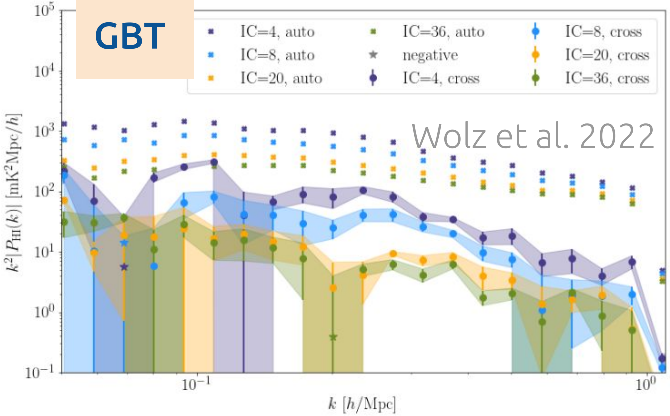
exploitation of the data collected with the **SKA cosmological surveys**

- MeerKAT telescope time for MeerKLASS
- SKA beginning of construction
- 2023
- 2025
- new MeerKAT campaign
- Start of Science Commissioning
- Start of Science Verification
- 2027
- Key Science Project (KSP) planning & proposals
- Commencement of KSPs
- 2029

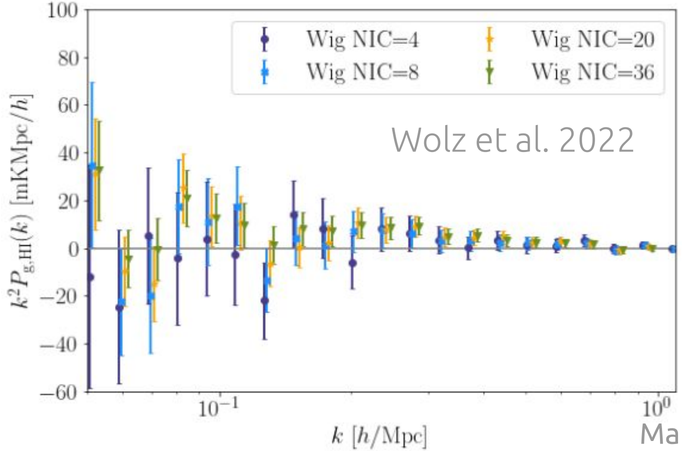
Backup

Single Dish vs Interferometry

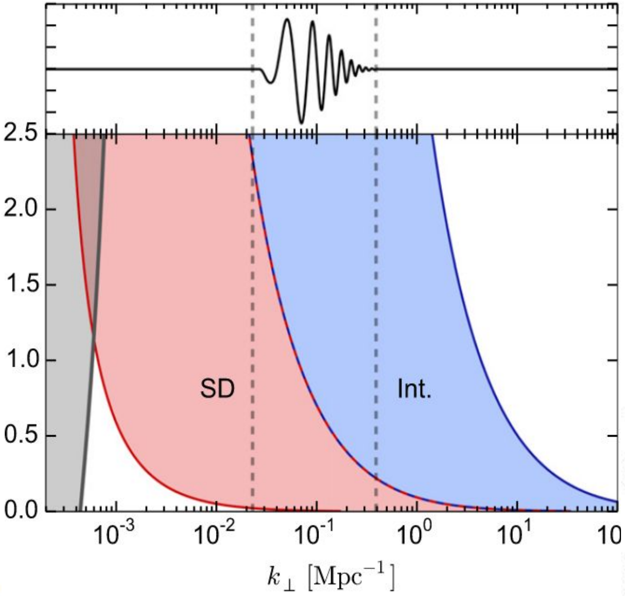
GBT



Wolz et al. 2022

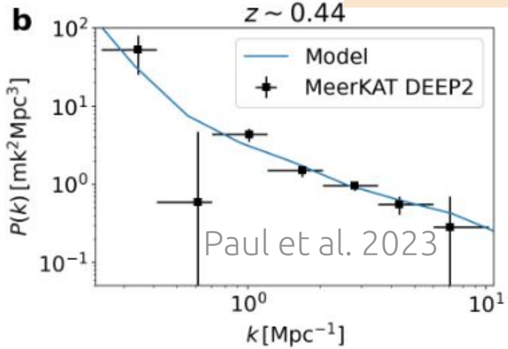


Wolz et al. 2022

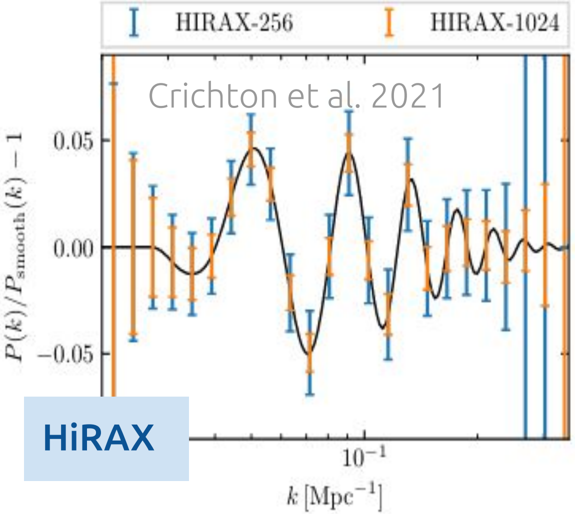


Bull et al. 2015

MeerKAT



Paul et al. 2023



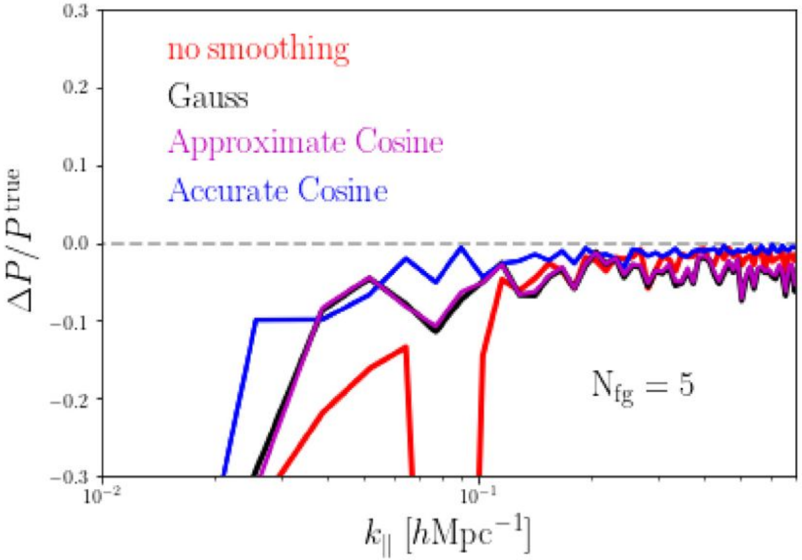
Crichton et al. 2021

HiRAX

Interferometry for the BAO

Effect of the telescope beam

Matshawule, MS, Santos et al. 2021



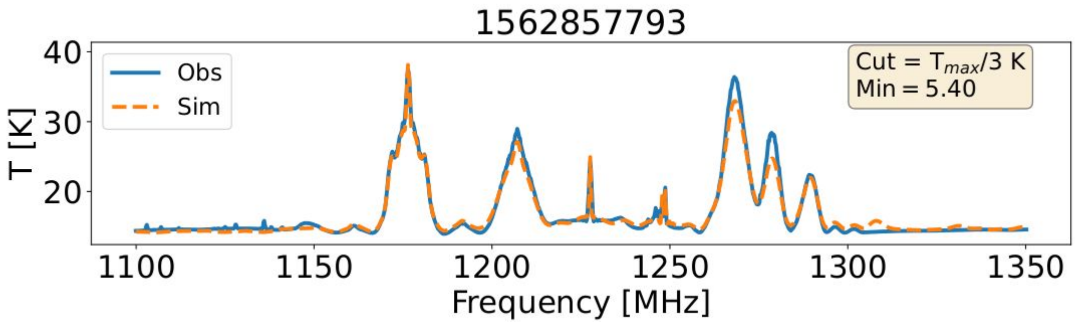
a realistic **MeerKAT** beam model:
side-lobes and a non-trivial frequency evolution

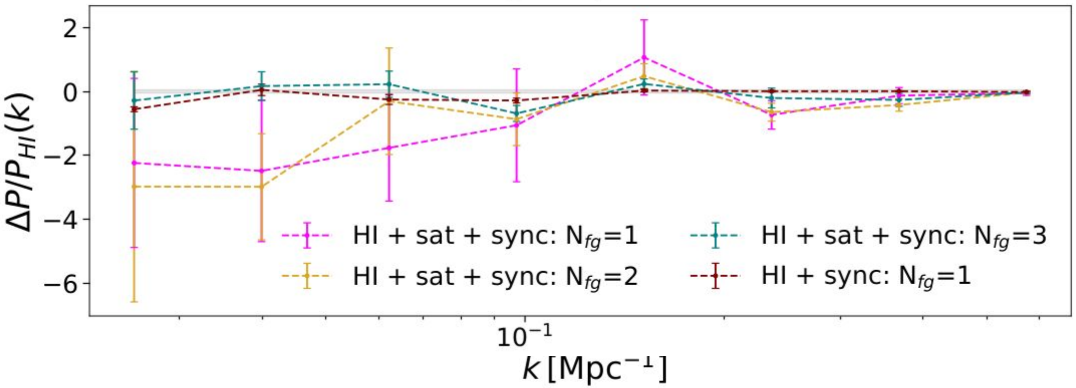
- **point sources** and synchrotron spatial structures coupled with the beam **complicate the separation of HI signal and foregrounds**
- careful **beam-deconvolution** alleviates the problem but need to be careful for precision cosmology
- Even more structure if using measured 2D beam

RFI from satellites

Engelbrecht et al. (2024)

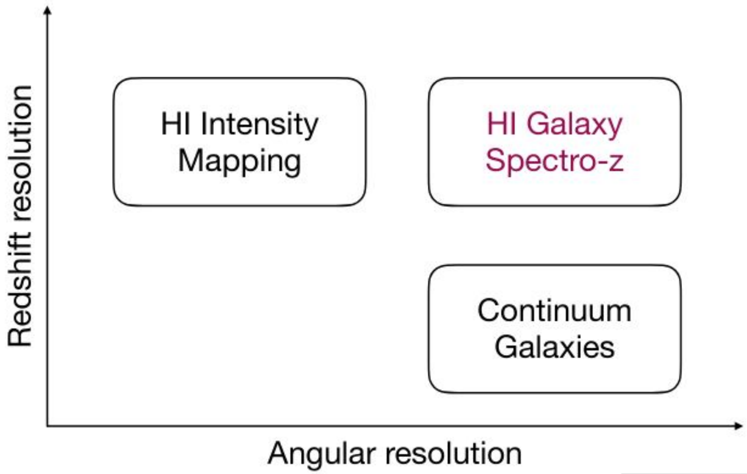
Radio Navigational Satellite System (RNSS)
modelled and calibrated on MeerKLASS data (1100-1350 MHz)





- recreate the satellite contamination with high accuracy around its peak frequencies in MeerKLASS data
- predicted signal below the noise in L-band cosmological window (970 - 1015 MHz)
- in simulations, we detect the signal in cross-correlations after mild foreground cleaning

HI galaxy surveys

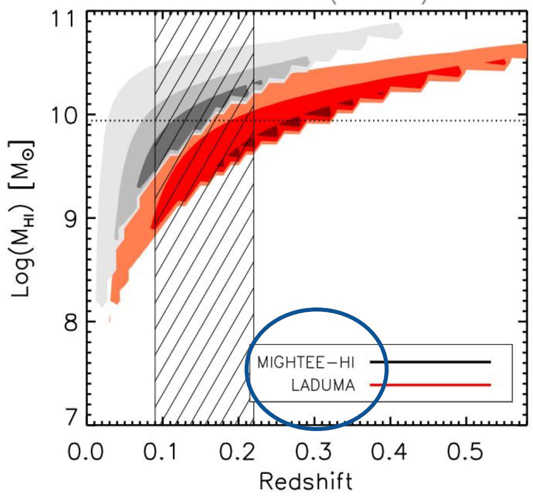


distance ladder

measurement of H0

e.g. Lelli et. al (2019), Schombert et al. (2020) Boubel et al. (2024)b

Maddox et al. (2021)



direct peculiar velocity measurements

growth rate of structures

e.g. Koda et al. (2014)

Boubel et al. (2024)a

probes of modified gravity

accurate galaxy positions in ra,dec,z

BAO detection at low z

e.g. SKA Red Book 2020