Cosmology with the SKA Observatory

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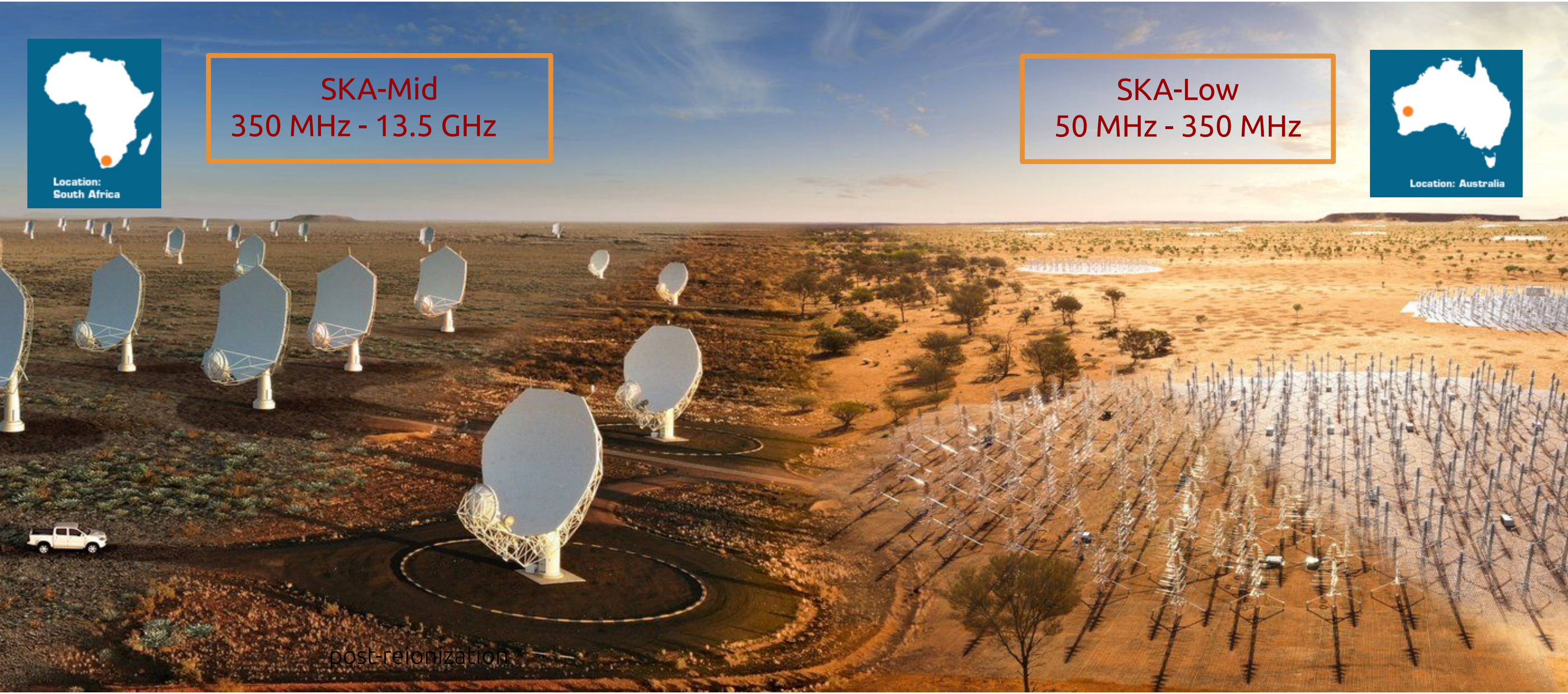
Observatoire de la Côte d'Azur

COSMO21

20 May 2024 - Chania

The SKA Observatory

credit: skatelescope.org



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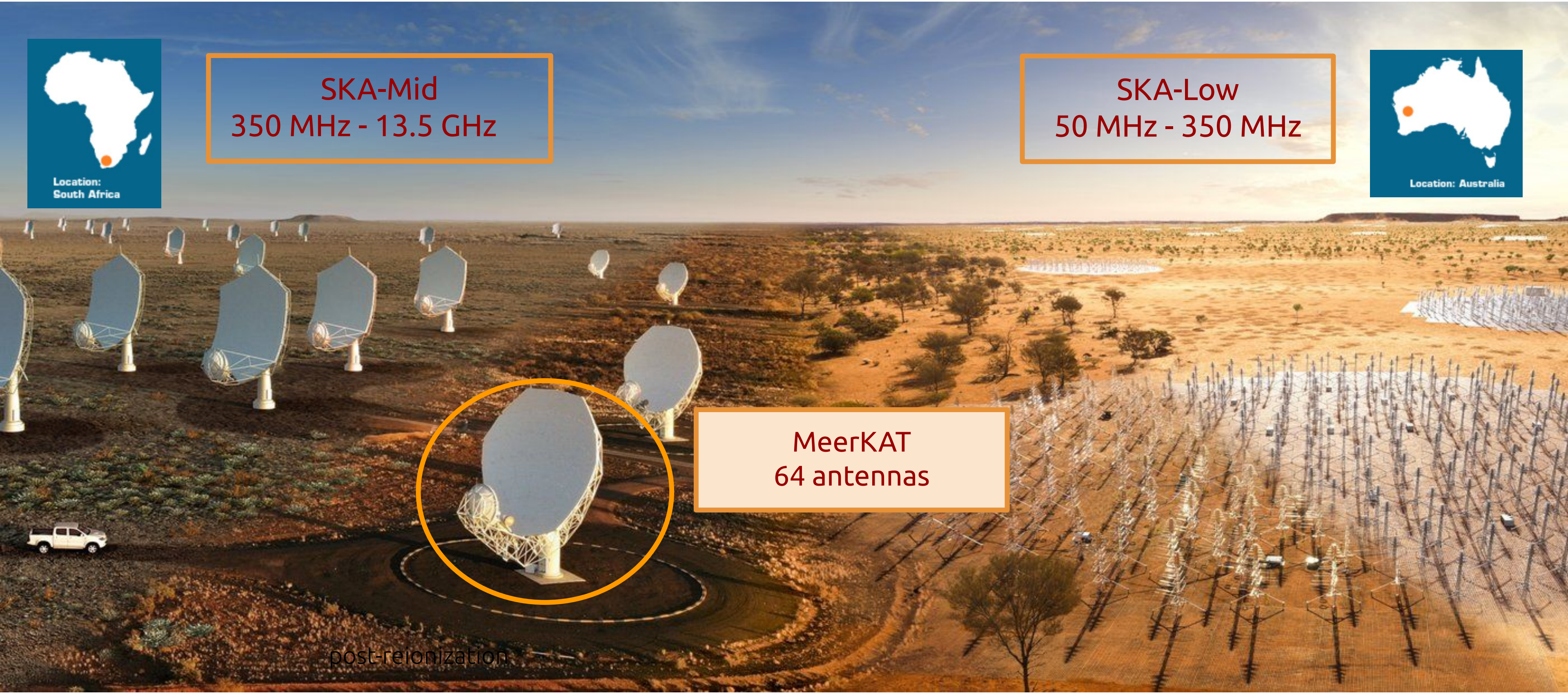
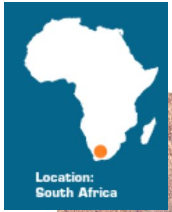
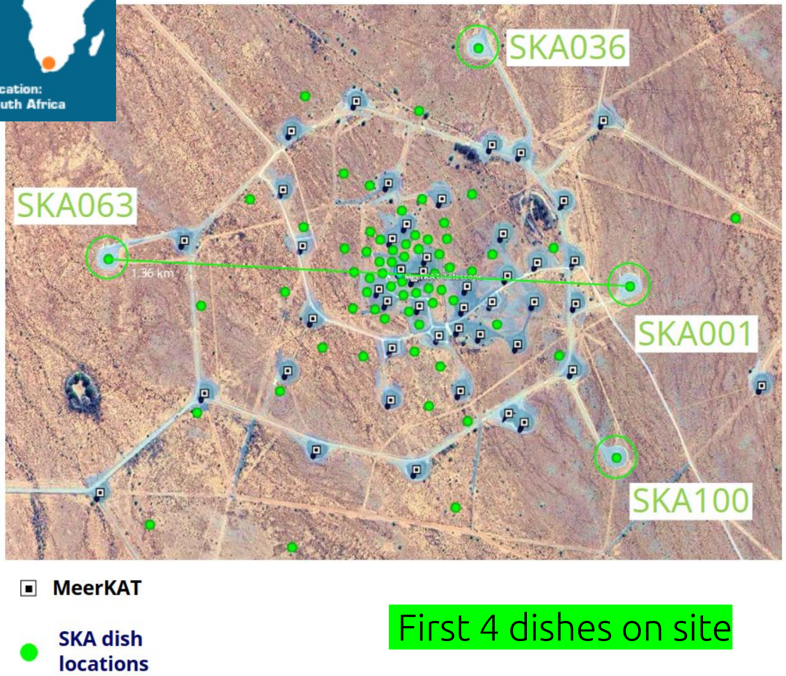


Construction Updates

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

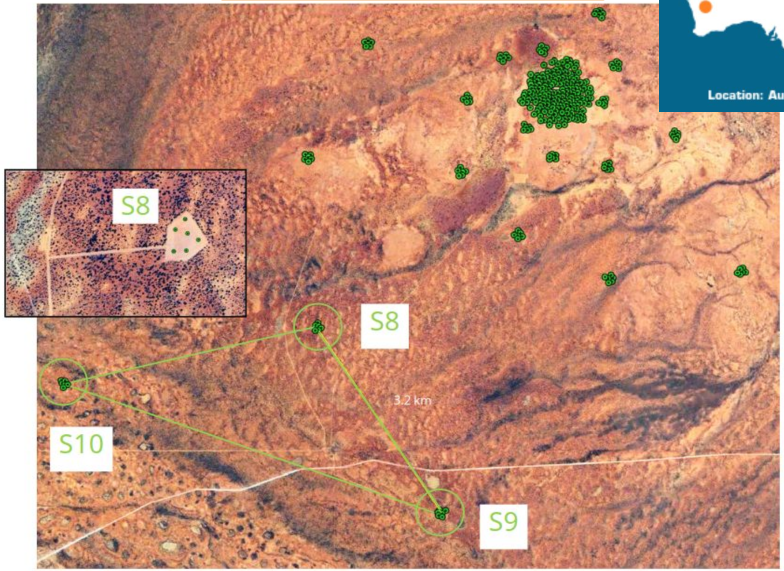
SKA-Mid
350 MHz - 13.5 GHz





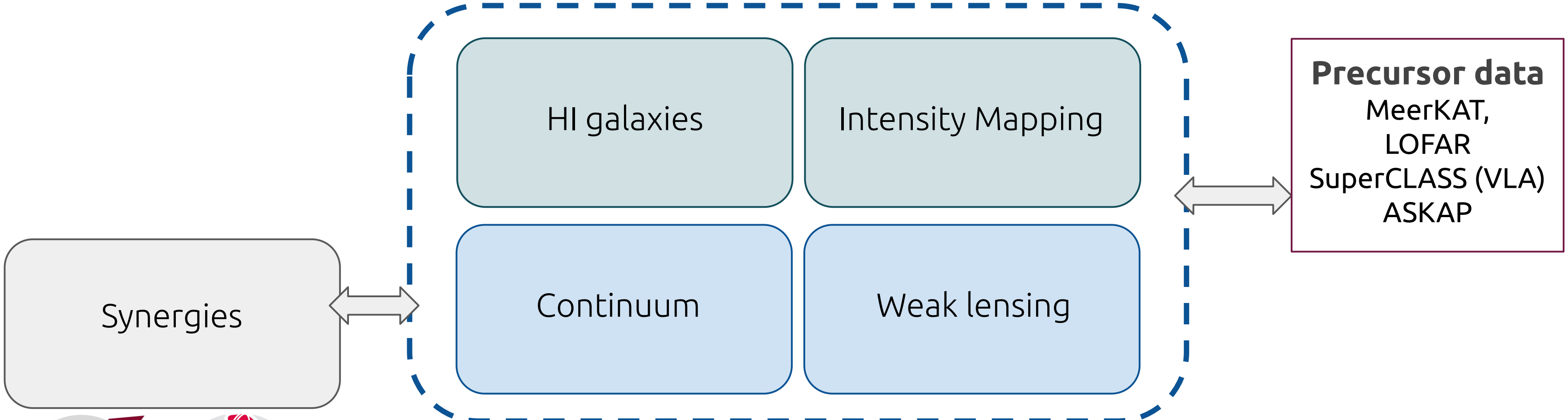
First 4 dishes on site

SKA-Low
50 MHz - 350 MHz



First 4 stations on site

SKA Cosmology *Science Goals*



structure of the Cosmology SWG

SKA Cosmology *Science Goals*

HI galaxies

Intensity Mapping

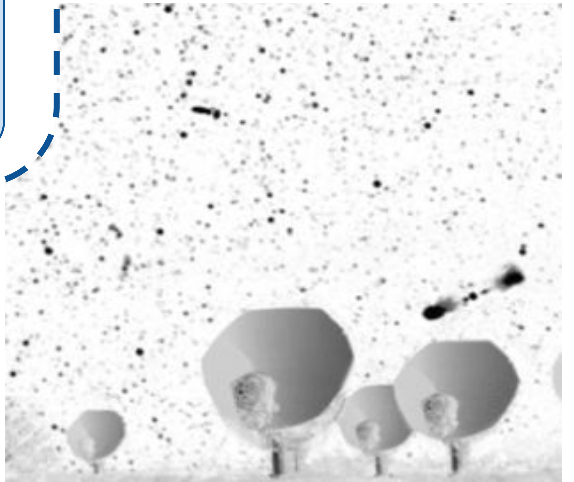
Continuum

Weak lensing

structure of the Cosmology SWG

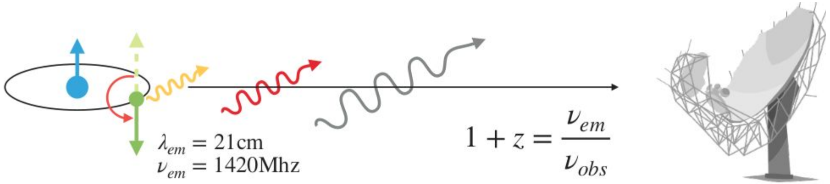
Synergies

Precursor data
LOFAR
SuperCLASS (VLA)
ASKAP
MeerKAT



SKA Cosmology *Science Goals*

HI



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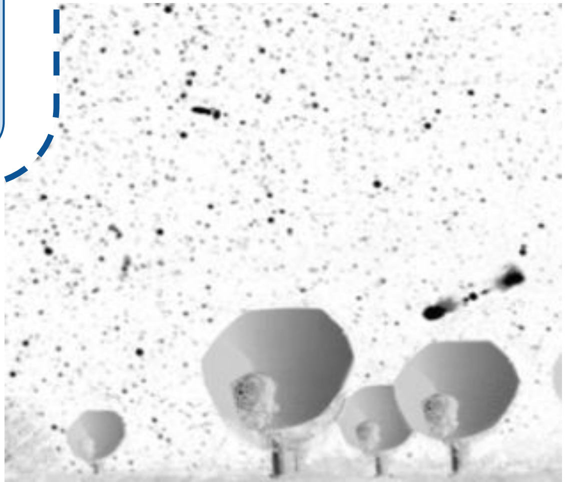

Continuum

FG leads: C. Hale & D. Parkinson

Angular clustering allows us to look at projected LSS but lots of systematics in radio data (source finder measurement/detection errors, sensitivity variations, etc.)

Small area: Bias evolution models for different source types

Large area: dipole, ISW, fNL, cross-corr, auto-corr

Continuum

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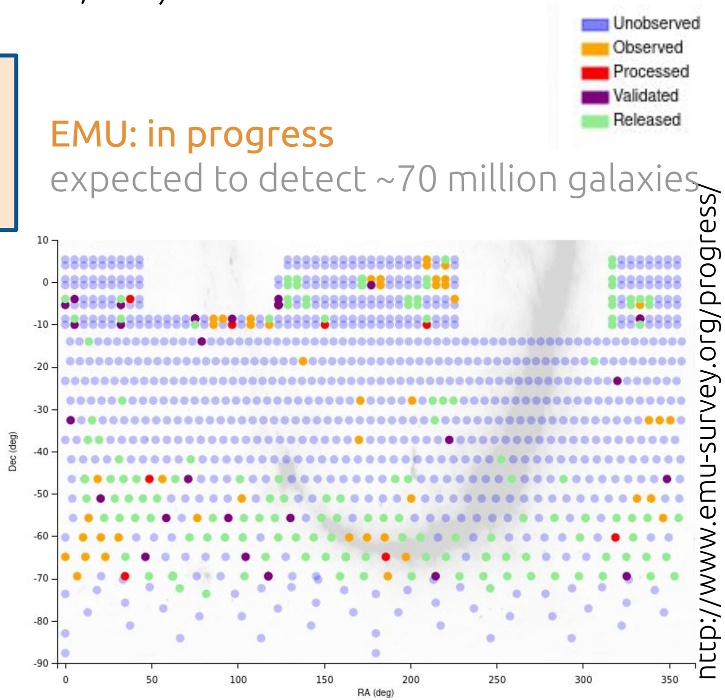
Large area: dipole, ISW, fNL, cross-corr, auto-corr

EMU: in progress

expected to detect ~70 million galaxies



http://www.emu-survey.org/progress/

LoTSS DR2:

- Angular clustering of radio sources Hale et al. (2023)
- cross-corr with CMB lensing (27σ detection and σ8) Nakoneczny et al (2023)
- cross-with eBOSS Zheng et al. (in prep)

Rapid ASKAP Continuum Survey data from Hale et al. (2021)

ISW studies Bahr-Kalus et al. (2022)

Continuum

FG leads: C. Hale & D. Parkinson

SKA-Mid in Band1 (350 MHz -1.05 GHz) - 20.000 deg2: *Wide Band*
SKA-Mid in Band2 (950 MHz - 1.75 GHz) - 5.000 deg2: *Medium-deep*

access to dark sector equation of state **w0-wa**

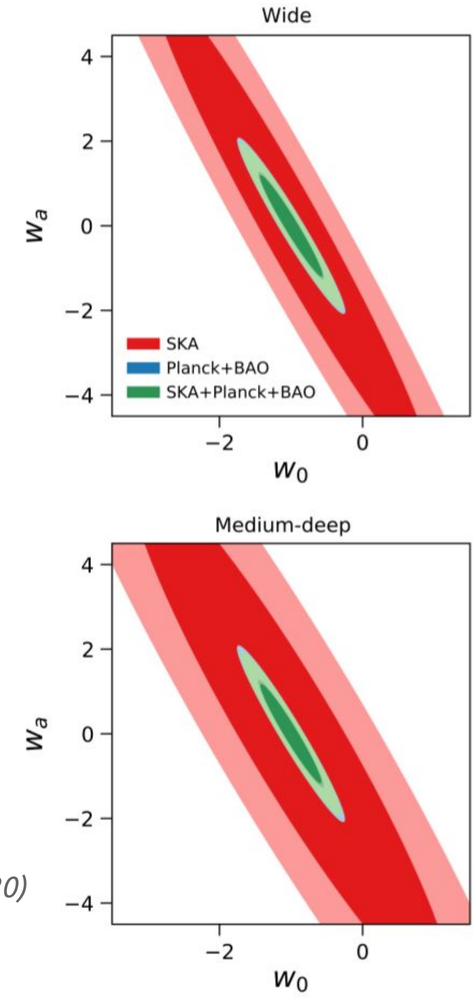
source population bias marginalised over: constraint will improve with better knowledge on the bias parameters

access to fNL

comparable with Planck
can do better with multi-tracer
e.g. Ferramacho et. al (2014)

dipole: test of cosmological principle

see talk D. Schwarz/L. Bohme

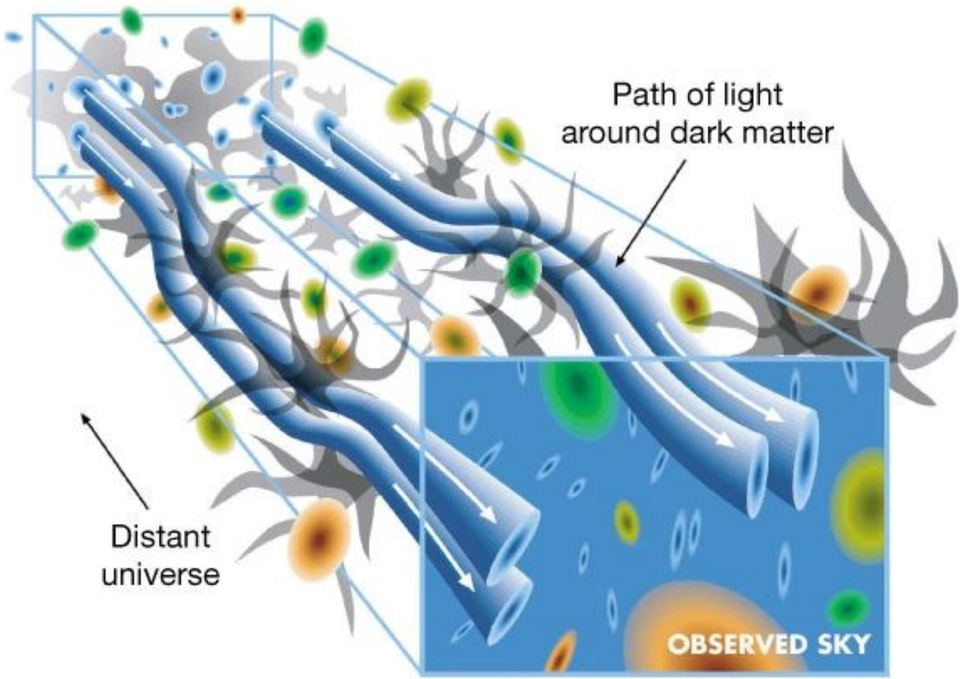


SKA Red Book (2020)

Radio weak lensing

FG lead: I. Harrison

Wittman et al. (2020)



probe of growth of cosmic structures
Dark matter & Dark energy

key observable in many current and future large optical/near-IR surveys

Requires shape measurement of ~billions of high redshift (z~1) galaxies

3.6σ detection in archival VLA FIRST
Chang, Refregier & Helfand (2004)

Unsuccessful measurements in too-noisy data (but a lot learnt)
Patel et al. (2010), Harrison et al. (2020)

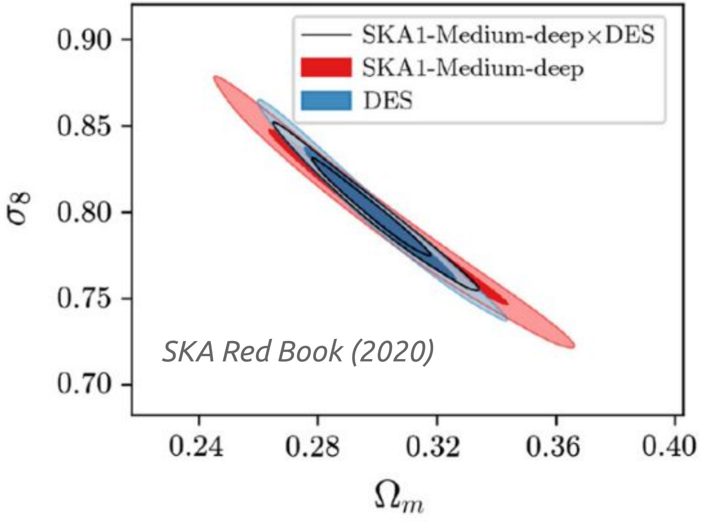
Successful detections of radio-optical correlations e.g. Hiller et al. (2019)

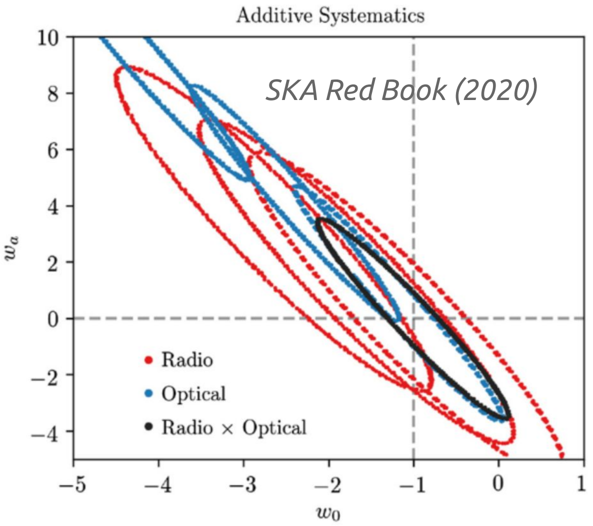
Radio weak lensing

FG lead: I. Harrison

SKAO SWG forecast assuming:
5,000 deg2 survey with **SKA-Mid**
Band 2 (950 MHz - 1.75 GHz) at 1 arcsec PSF

SKAO alone competitive
with completed Dark Energy Survey (DES)





cross-correlation retains almost all of the statistical power of individual experiments

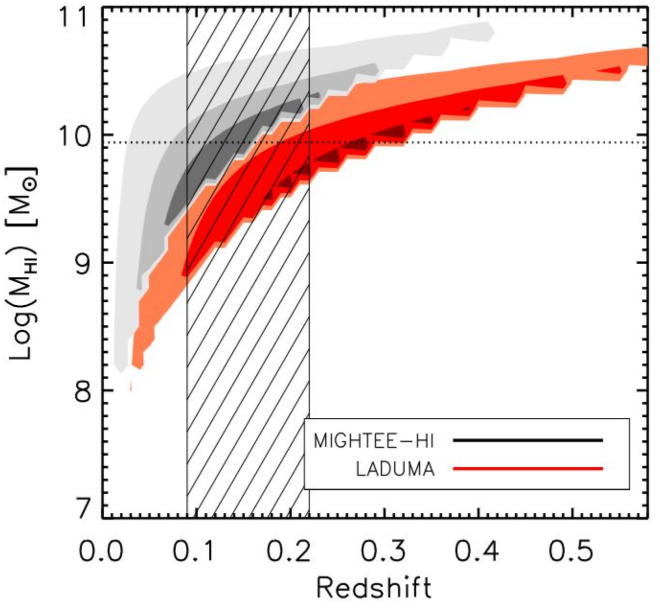
systematic errors on the measured weak lensing signal **uncorrelated** between the radio and the optical

caveat: radio shear measurement methods need improvements

HI galaxy surveys

FG leads: G. De Lucia & A. Ponomareva

Maddox et al. (2021)



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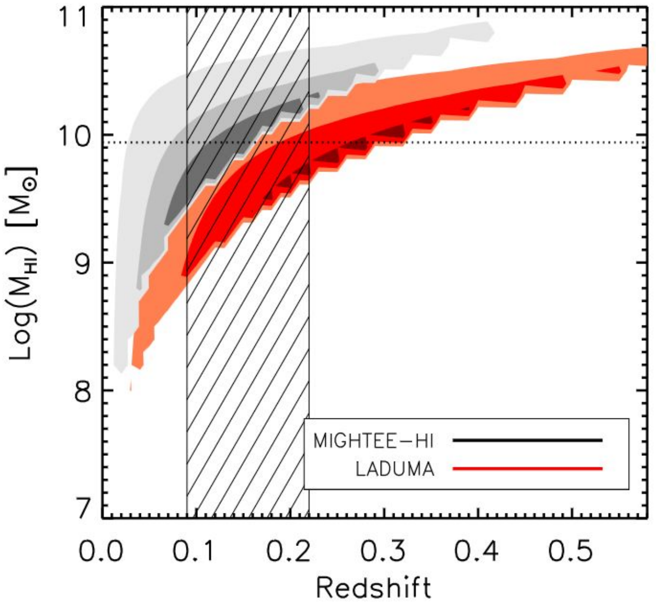

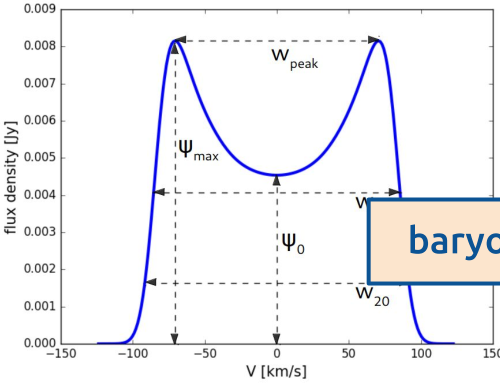

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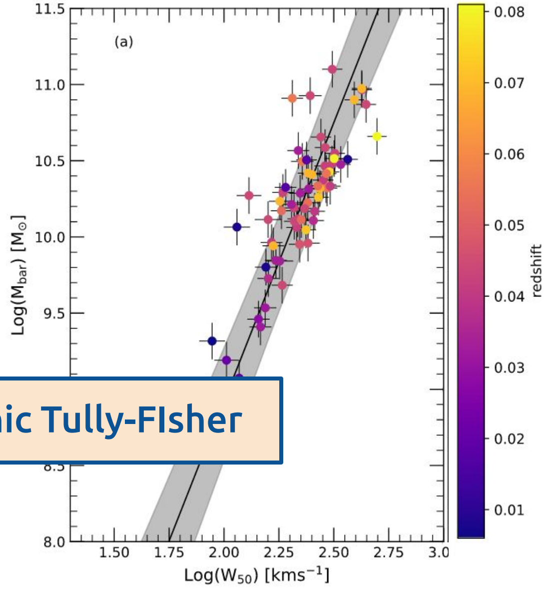

baryonic Tully-FIsher

direct peculiar velocity measurements

growth rate of structures
e.g. Koda et al. (2014)
probes of modified gravity

distance ladder

measurement of H0
e.g. Lelli et. al (2019), Schombert et al. (2020)

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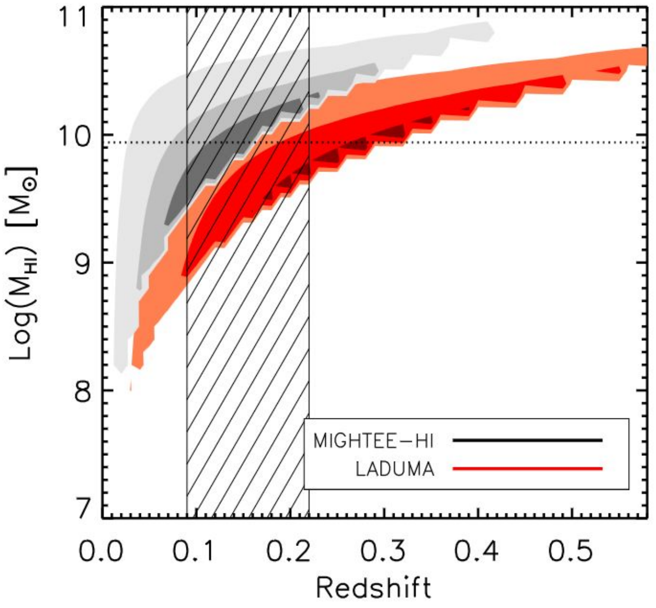
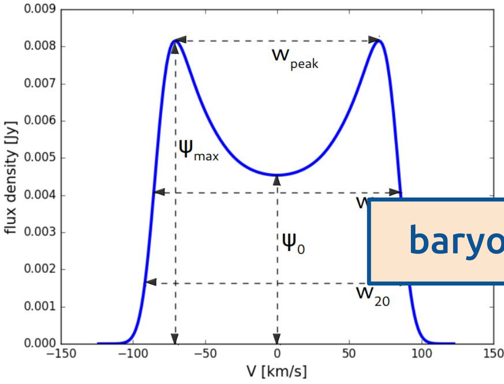
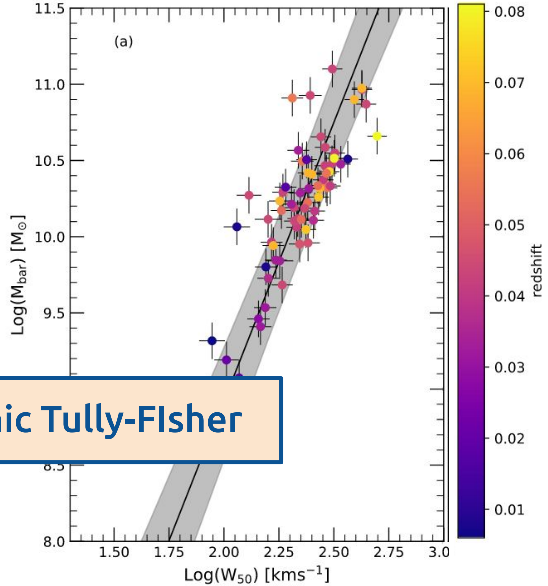


Baryon Acoustic Oscillations out to redshift 0.4



Ponomareva et al. (2021)



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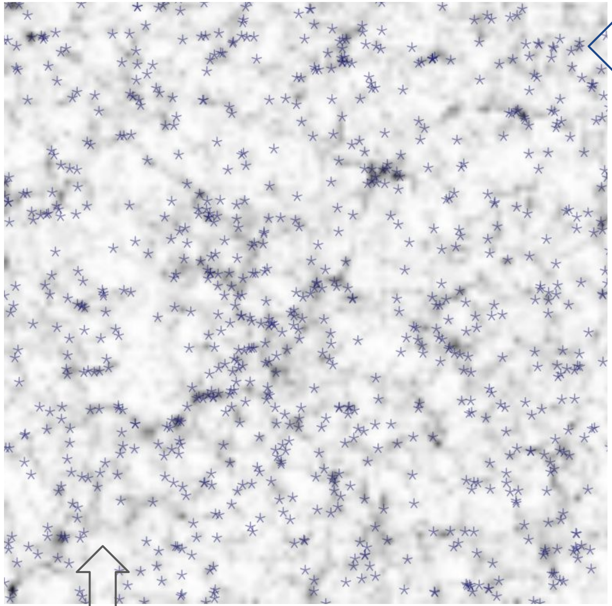
LSS with Neutral Hydrogen

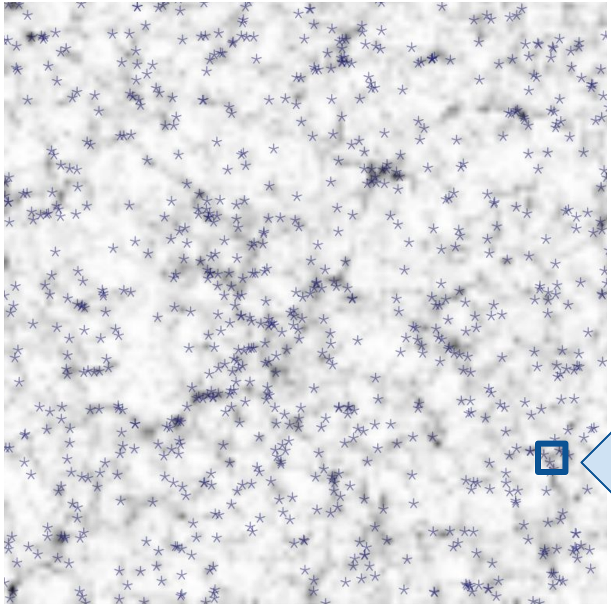


the distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**

underlying matter distribution

How can we efficiently observe
cosmological volumes?

LSS with Neutral Hydrogen



the distribution of **neutral Hydrogen**
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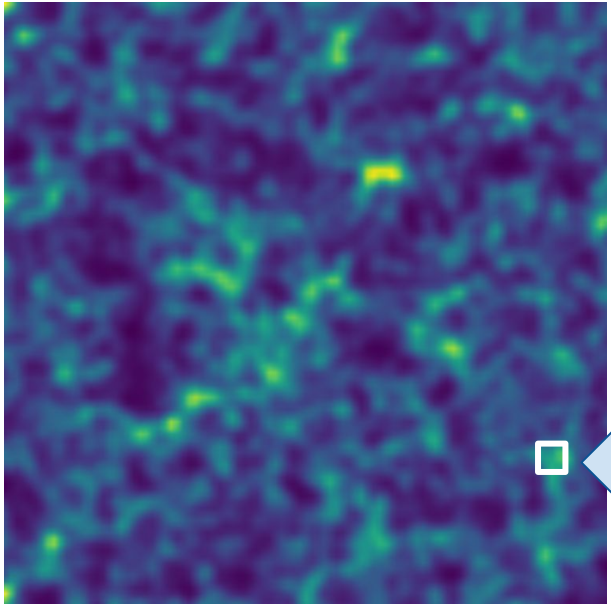
How can we efficiently observe
cosmological volumes?

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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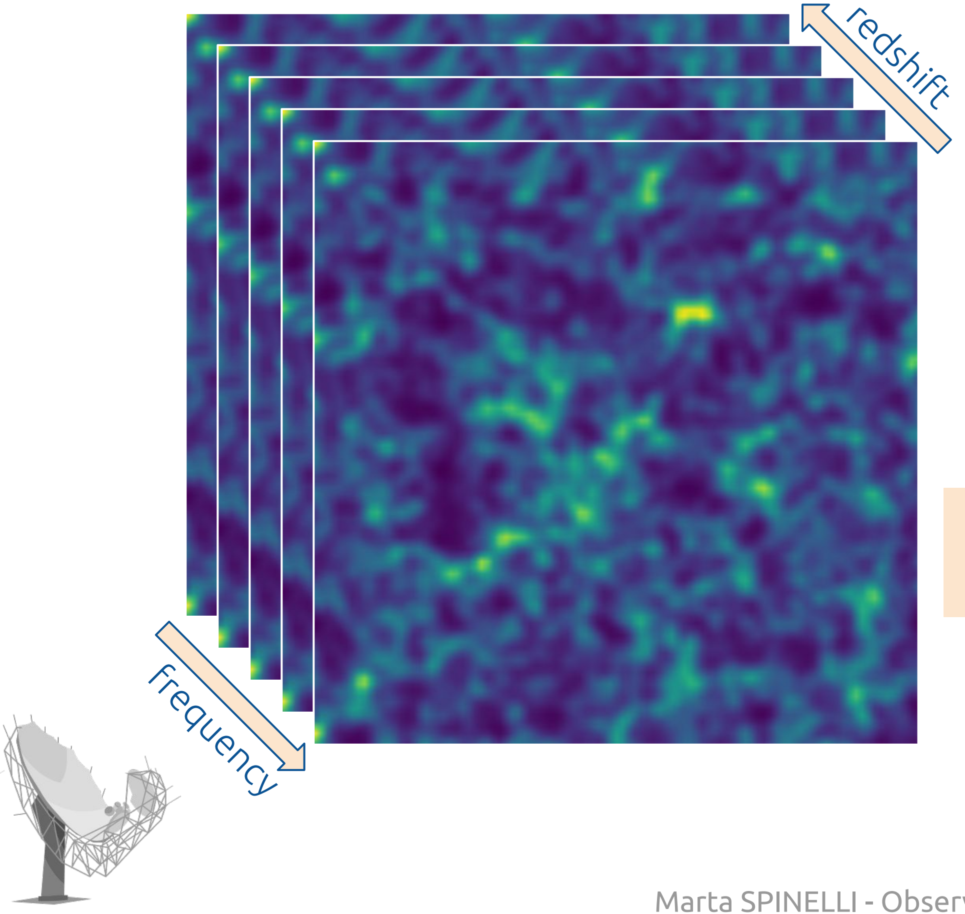

the distribution of **neutral Hydrogen**
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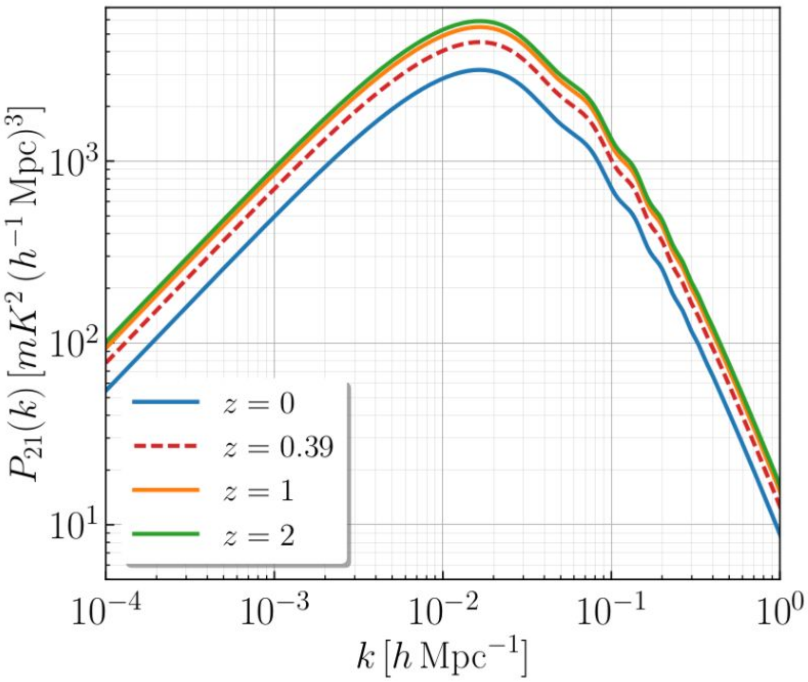
How can we efficiently observe
cosmological volumes?

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

Key cosmological probe

Theoretical 21cm (linear) Power Spectrum



We model it as[1]

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

where

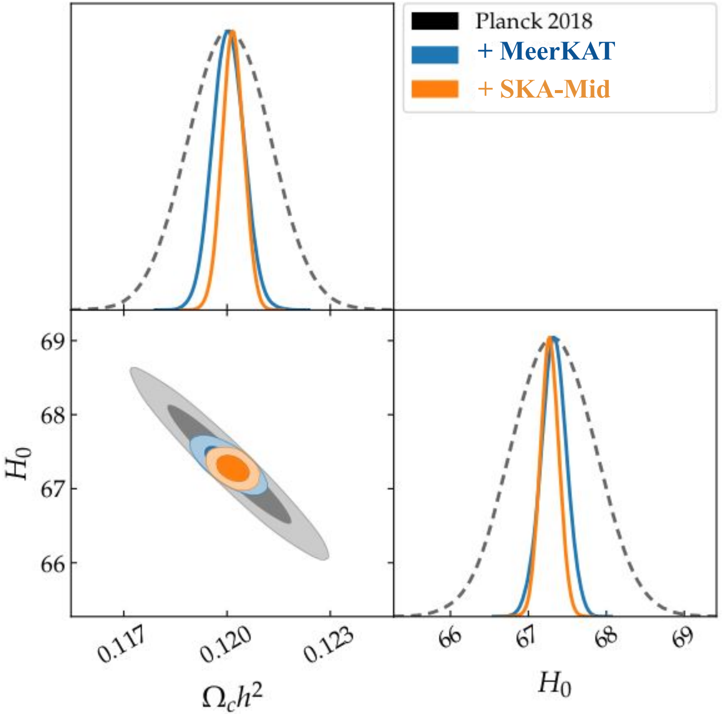
- $\bar{T}_b^2(z)$ is the mean brightness temperature
- $b_{\rm HI}(z)$ is the HI bias
- $f(z)$ is the growth rate
- $\mu = \hat{k} \cdot \hat{z}$
- $P_{\rm m}(z,k)$ is the matter power spectrum

✓ 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)

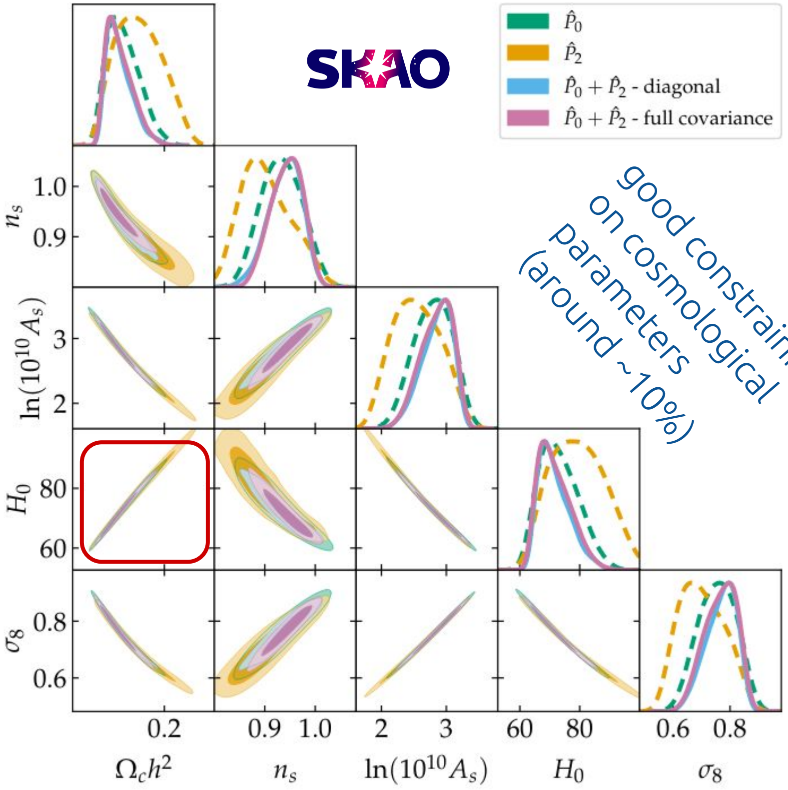
SKA-MID

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

P21 breaks parameter degeneracies

SKAO forecasts

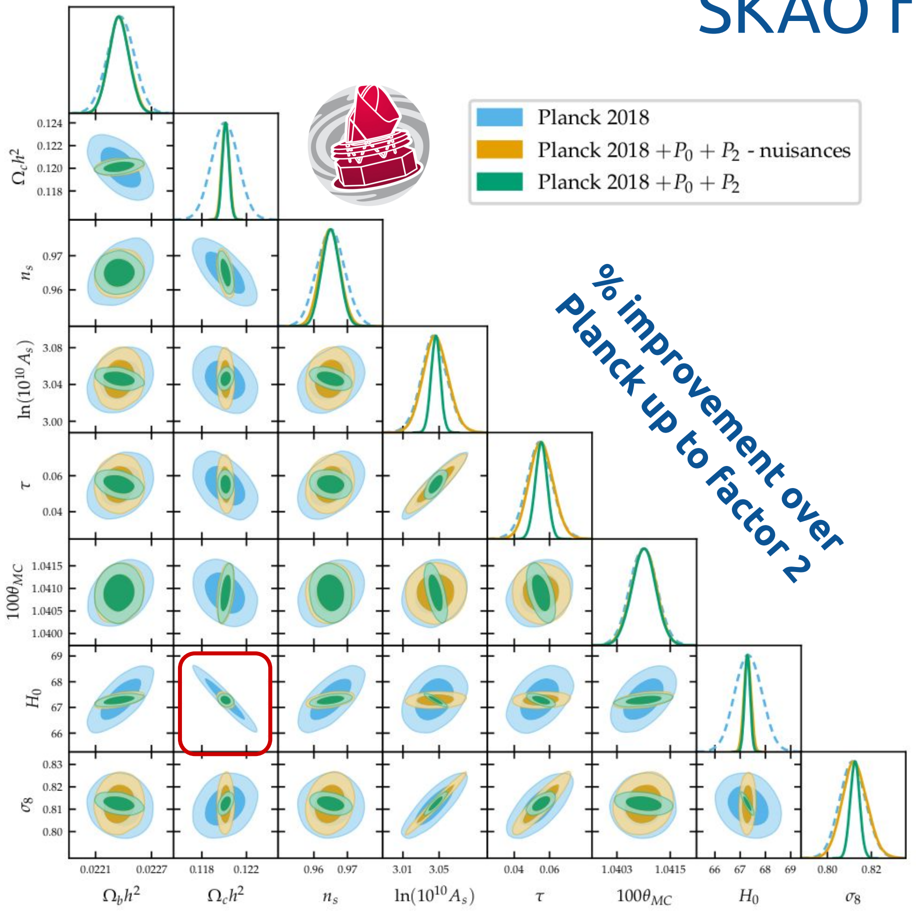
Berti, MS, Viel 2023a



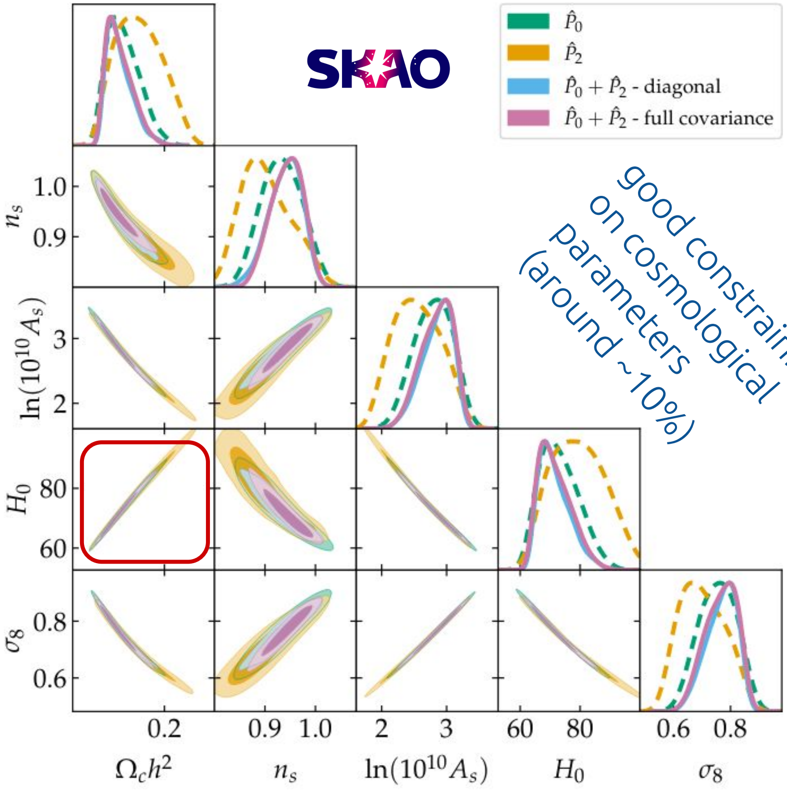
good constraining power on cosmological parameters (around ~10%)

SKAO forecasts

Berti, MS, Viel 2023a



% improvement over Planck up to factor 2



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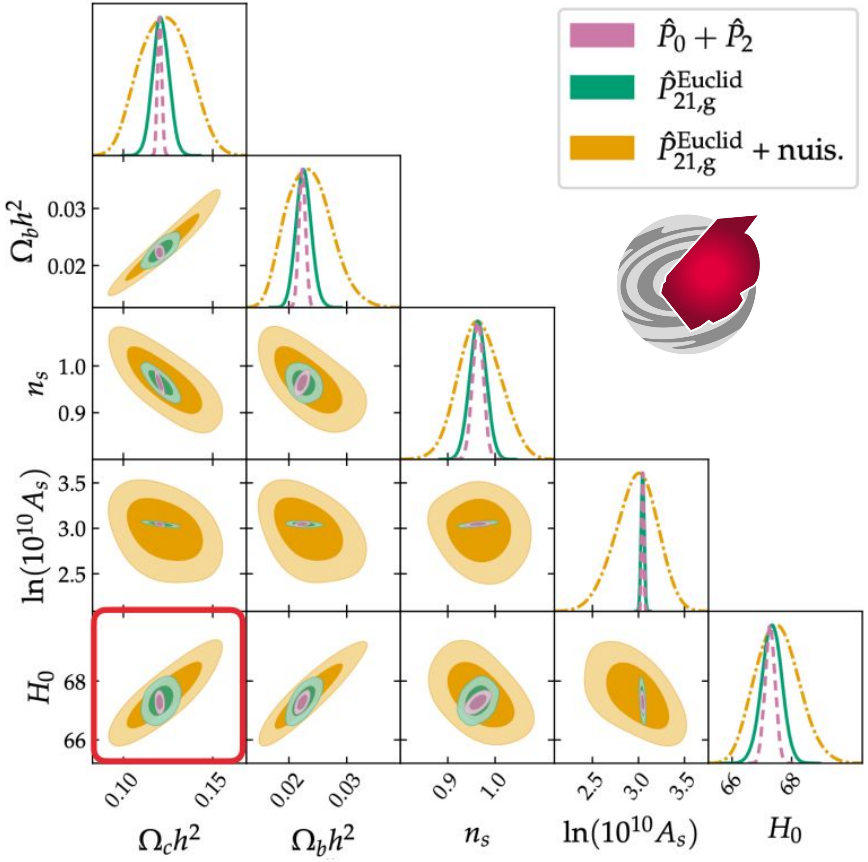
Berti, MS, Viel 2023b

SKAO forecasts: cross-correlation



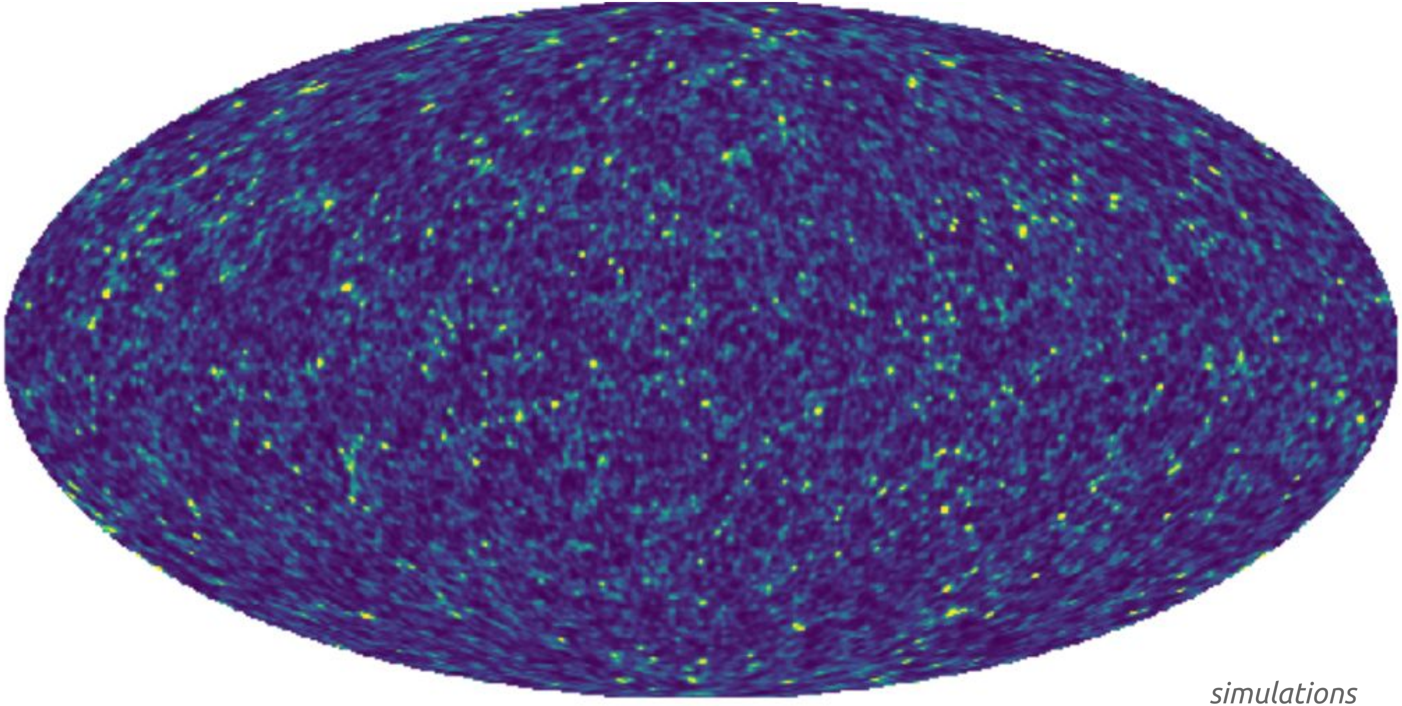
Power spectrum multipoles - 0< z <3

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

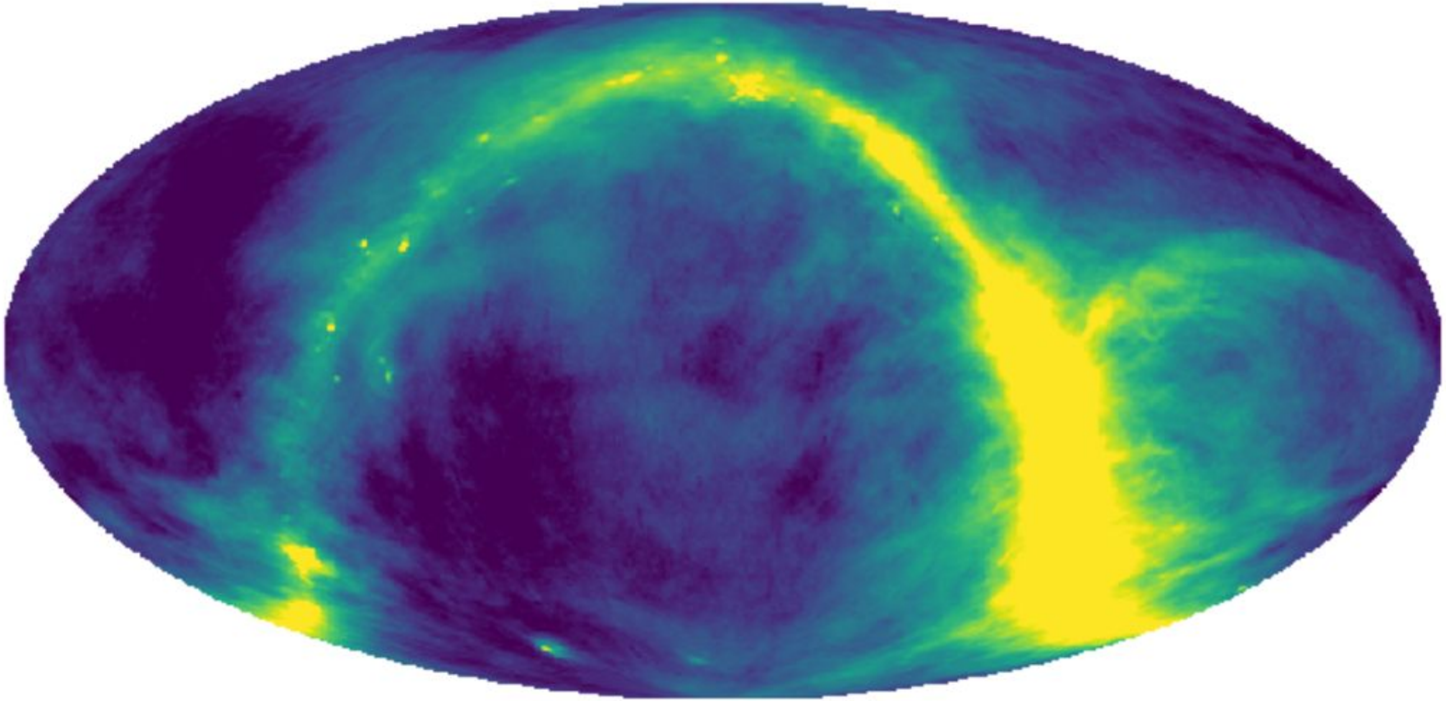
Broader constraints assuming no knowledge on HI bias (nuisances)

Hydrogen on cosmological scales



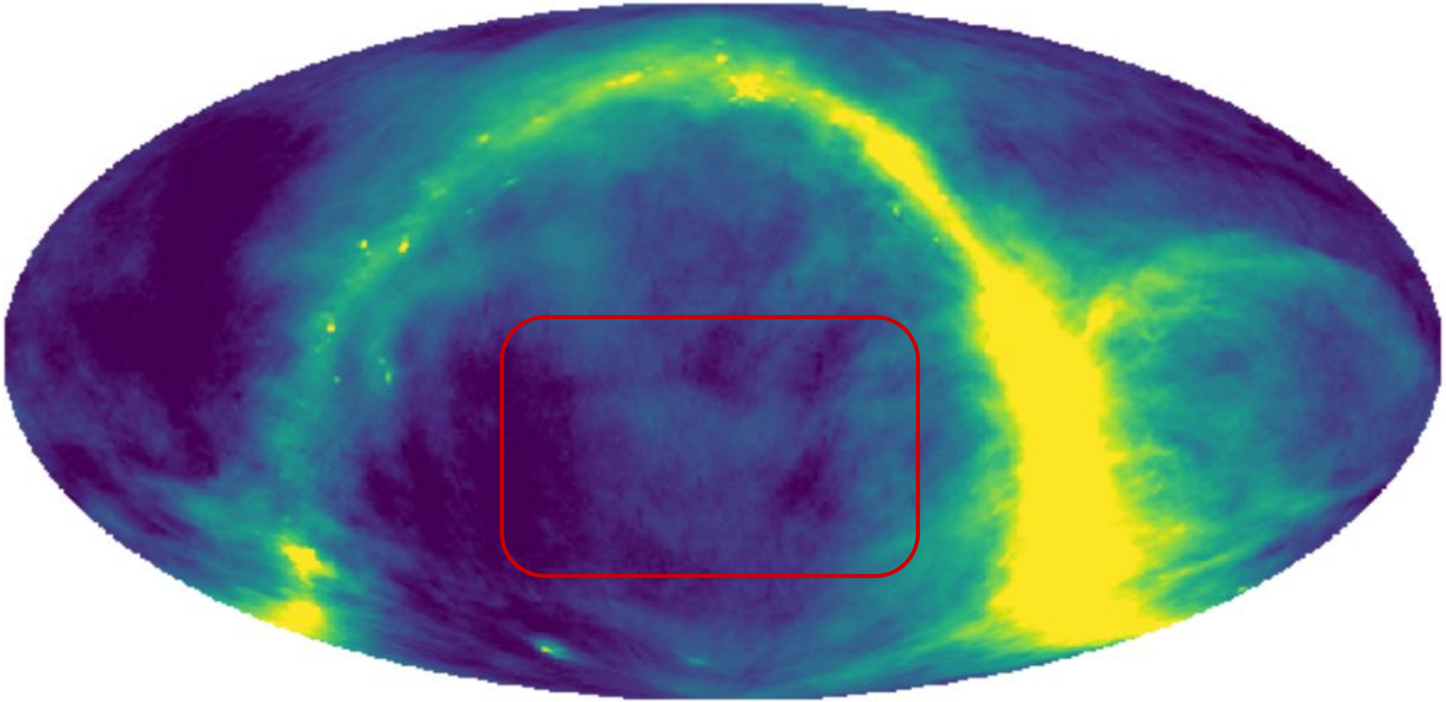
simulations
MS et al. 2021,2022

The challenge of foregrounds



Haslam et al. (1982)

The challenge of foregrounds



Haslam et al. (1982)

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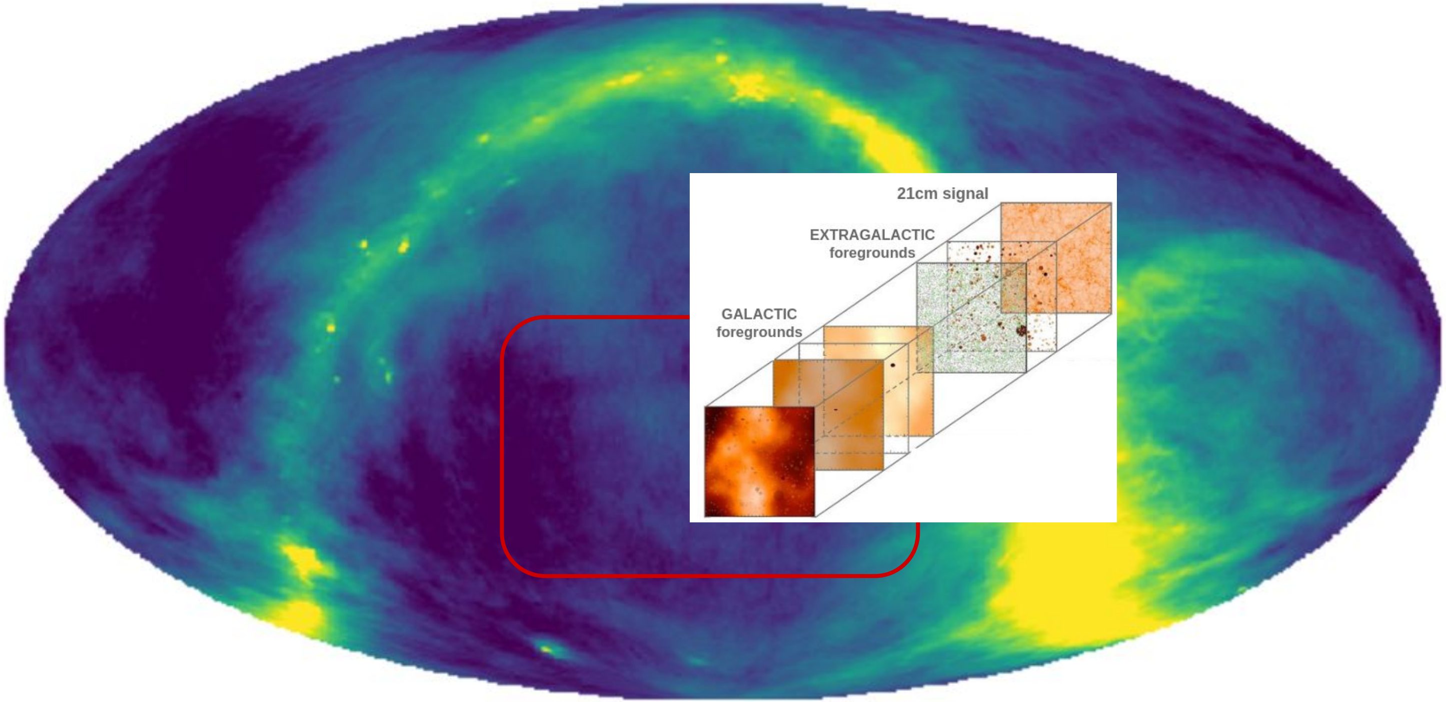

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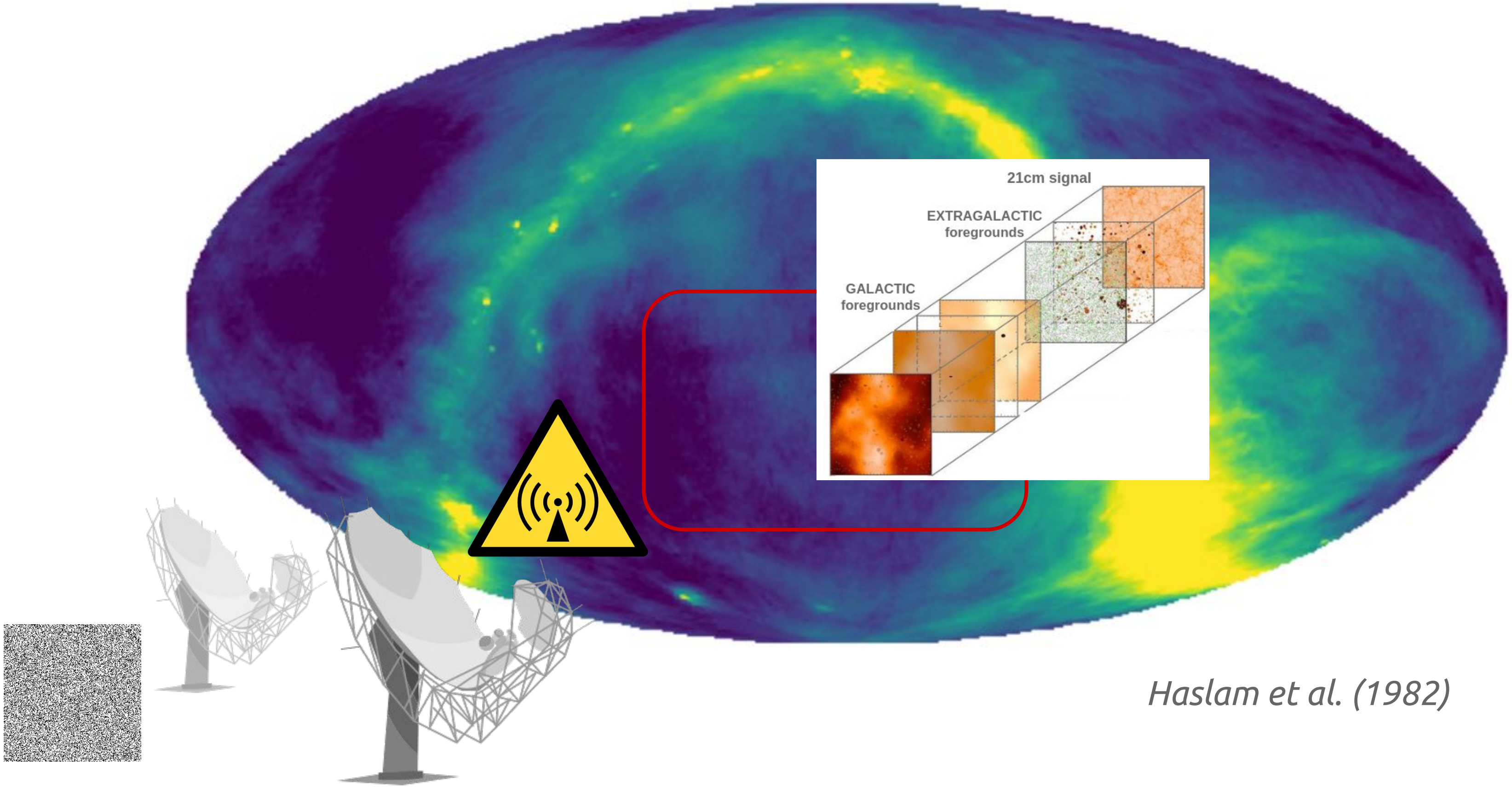
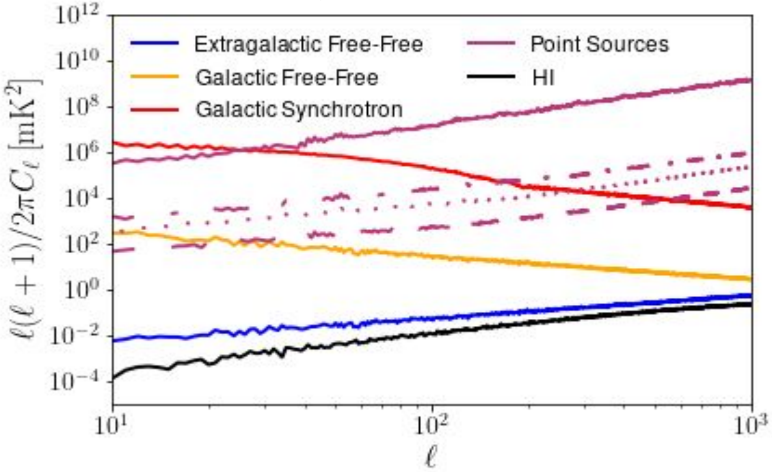
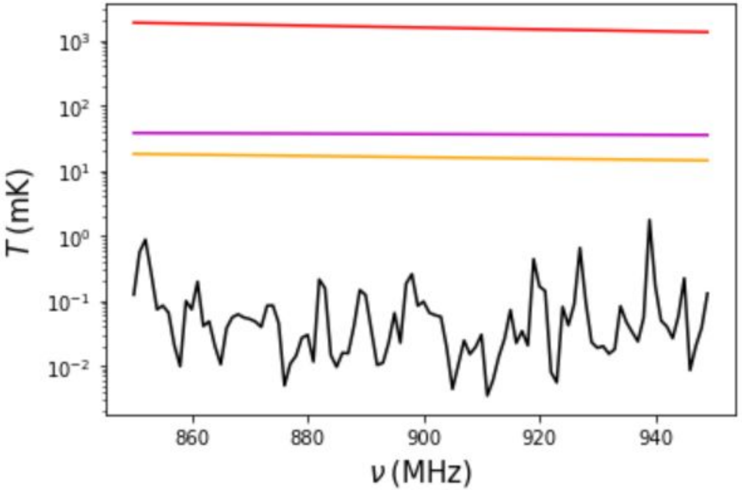


Haslam et al. (1982)

Properties of the foregrounds

Matshawule, MS et al. 2021





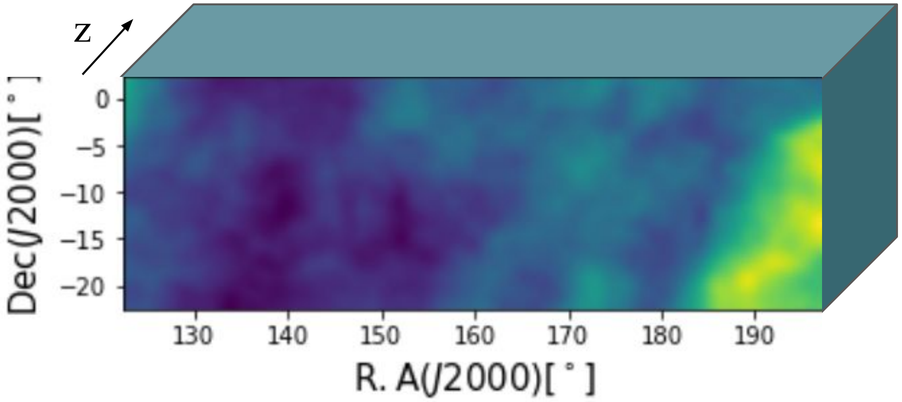
- ❏ foregrounds are orders of magnitude **stronger** than the 21cm signal
- ❏ they are **smooth in frequency** (highly correlated)

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,..)

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

How many sources?

N_{fg} need to be estimated/guessed

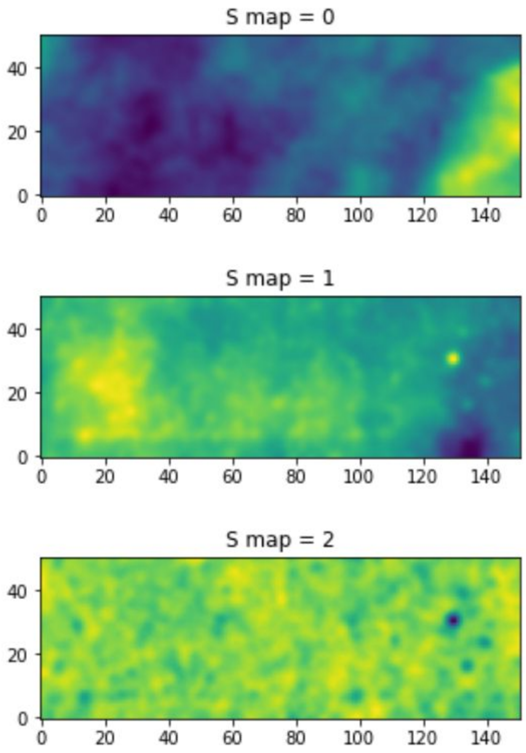
$$T = As + n + c$$

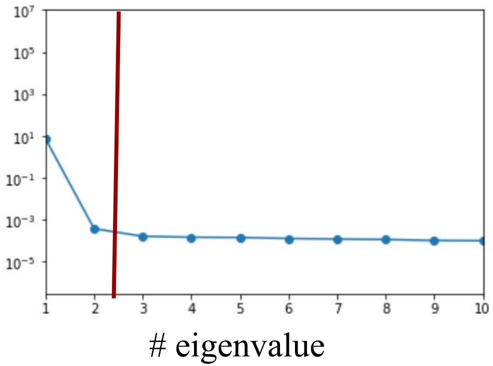
A mixing matrix of the foreground sources

noise

Cosmological signal

A cleaning example





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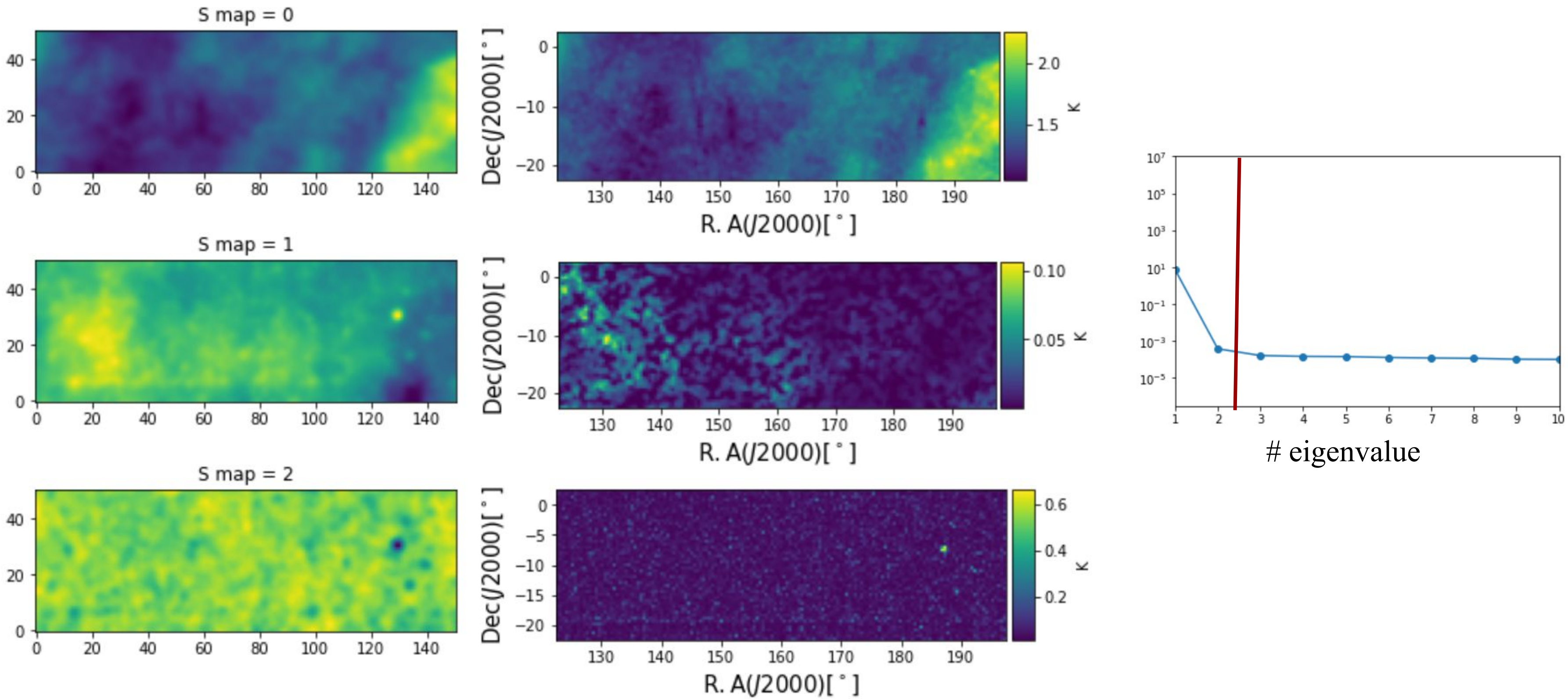
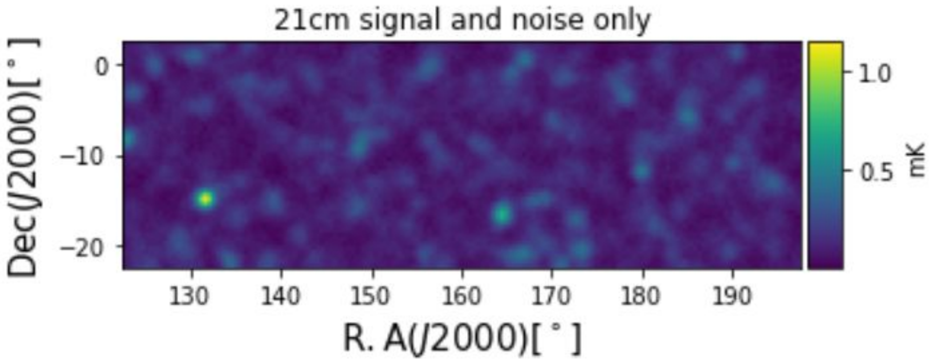
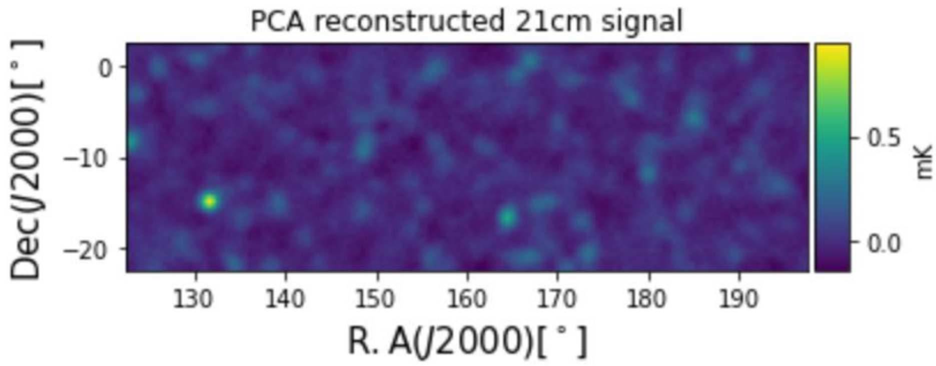


A cleaning example

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

A mixing matrix
including only the first
Nfg components





Foreground subtraction challenge

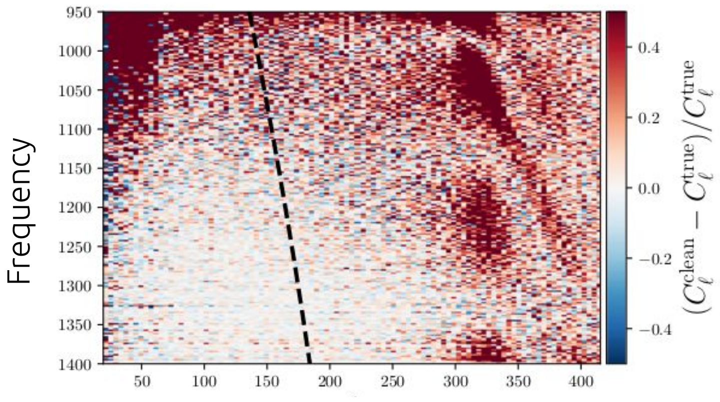
MS et al. 2022

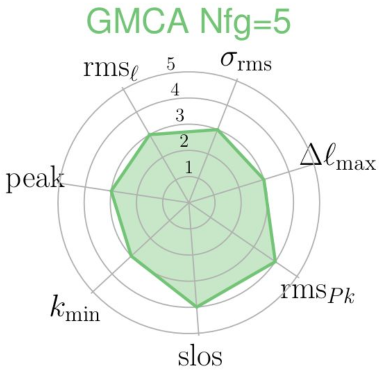
Project setup:

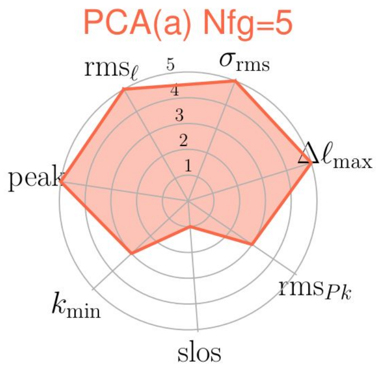
- ❑ various foreground models and realistic HI maps
- ❑ instrumental modeling MeerKAT-like and SKAO-like
- ❑ 9 different foreground removal methods (PCA, FastICA, …)

How much **instrument/foregrounds coupling** do impact the signal reconstruction?

Cleaning quality



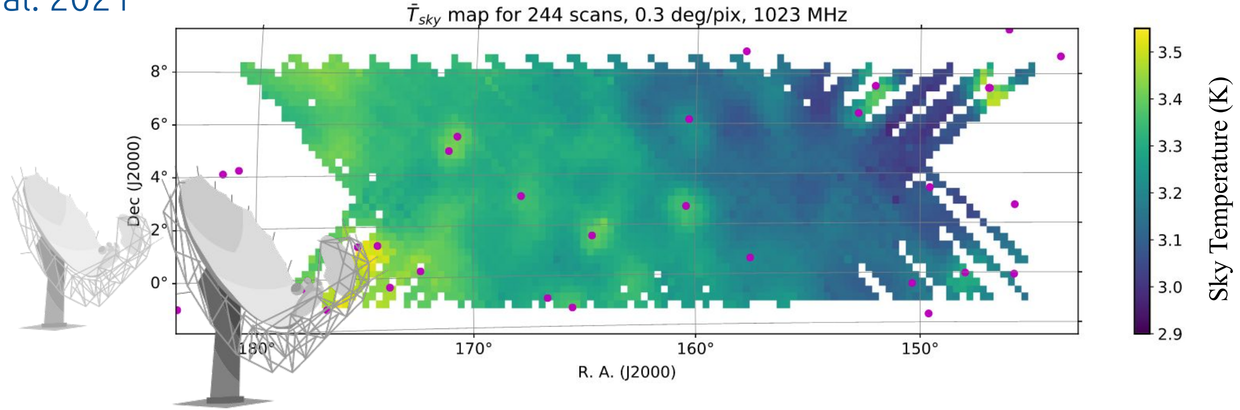




Realistic instrumental effects inevitably **complicate** the foreground cleaning

MeerKAT observations

Wang et al. 2021

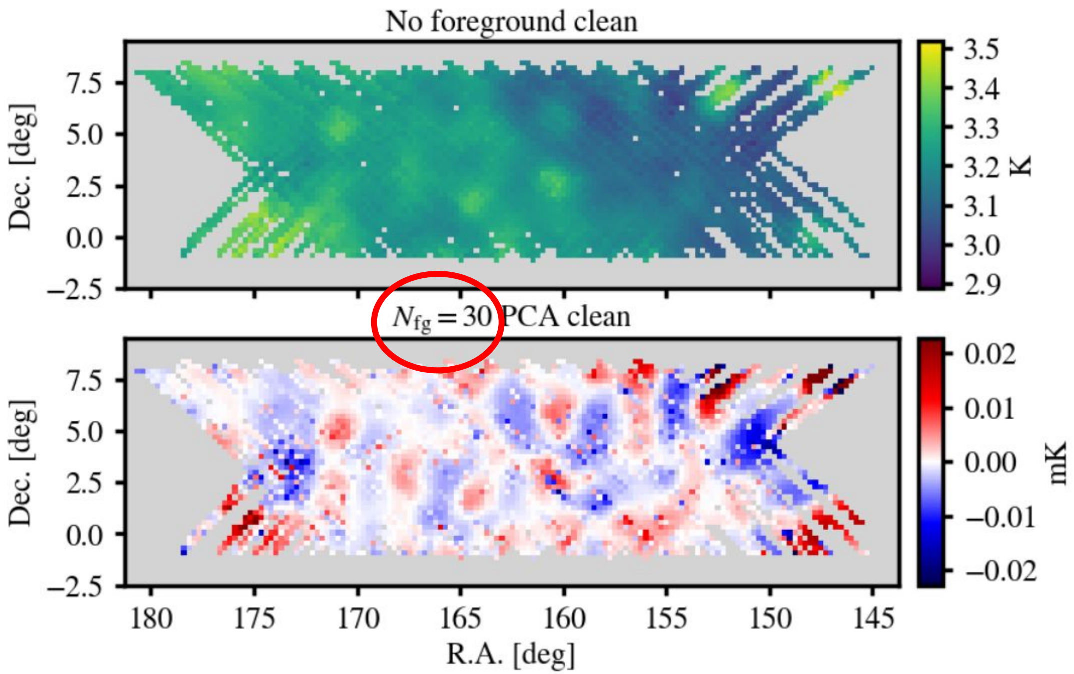


MeerKLASS: 64 MeerKAT antennas used in single-dish mode

PI: M. G. Santos (Santos et al. 2017)

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

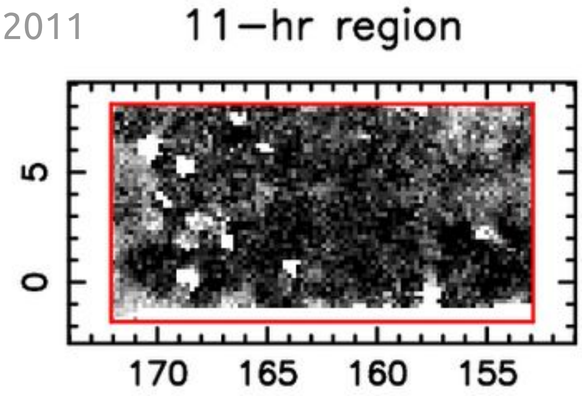
MeerKLASS observations

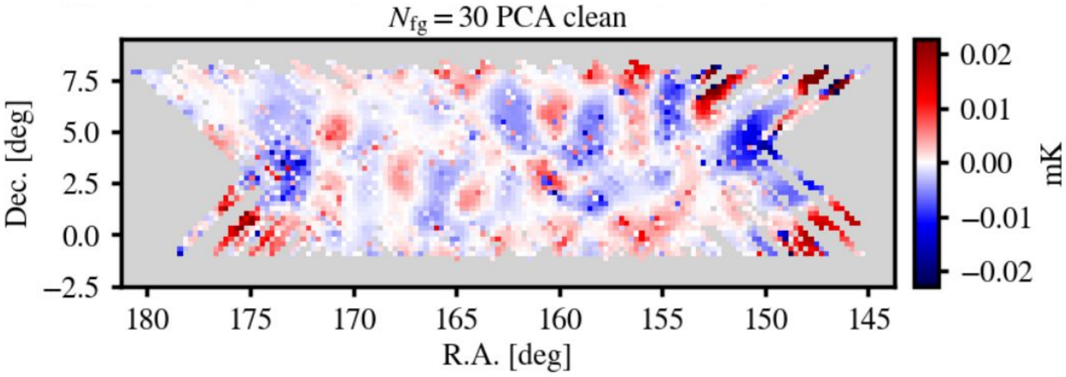


Cunnington et al. 2022

MeerKLASS results

Blake et al. 2011





Cunnington et al. 2022

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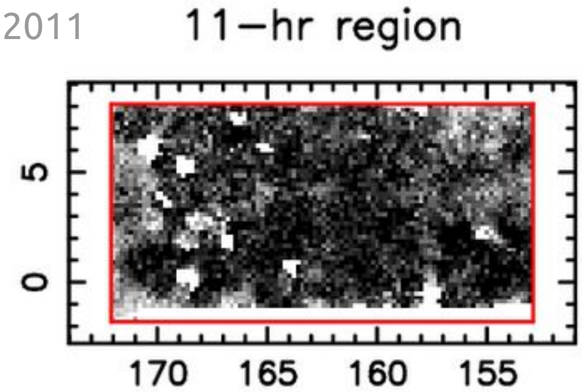

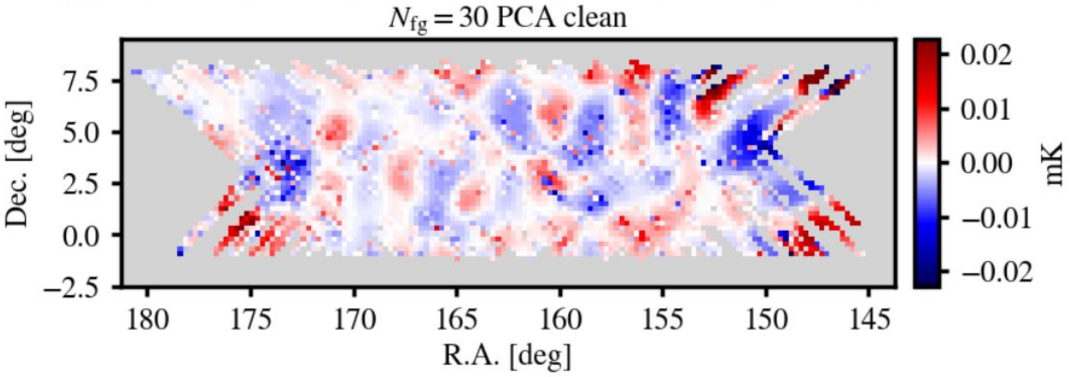

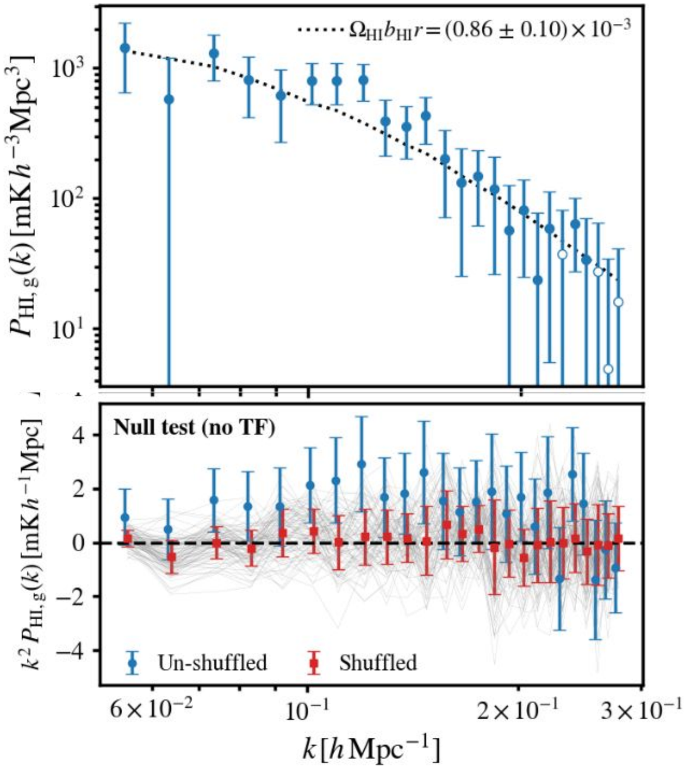

Cunnington et al. 2022

MeerKLASS results

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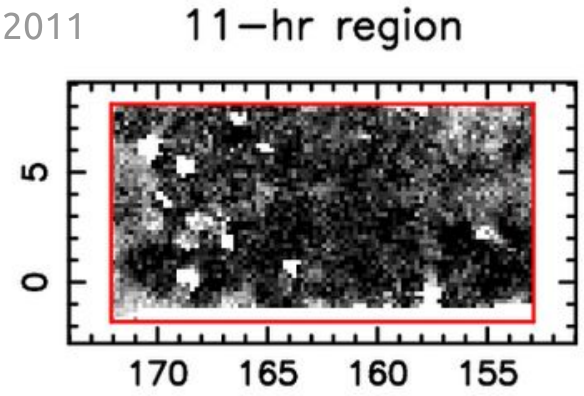
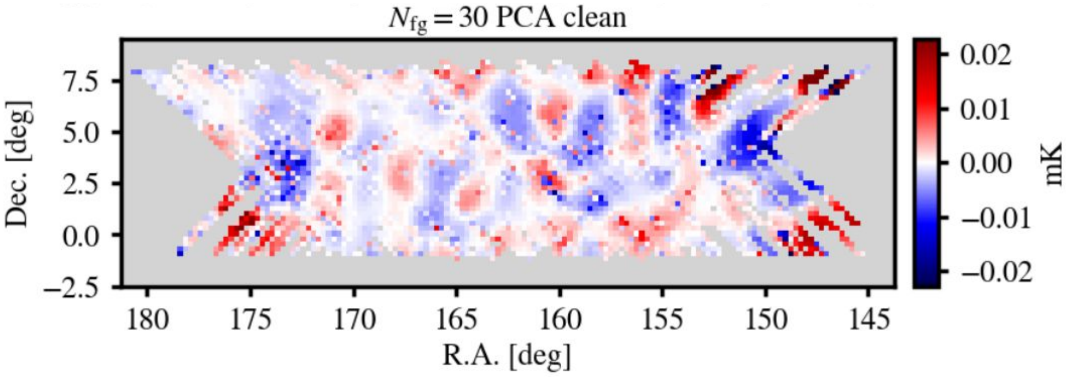
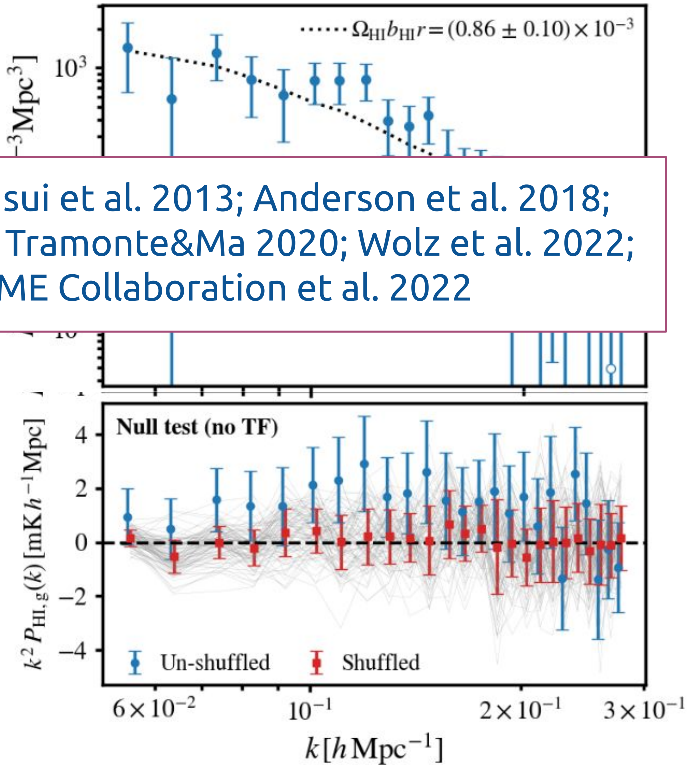




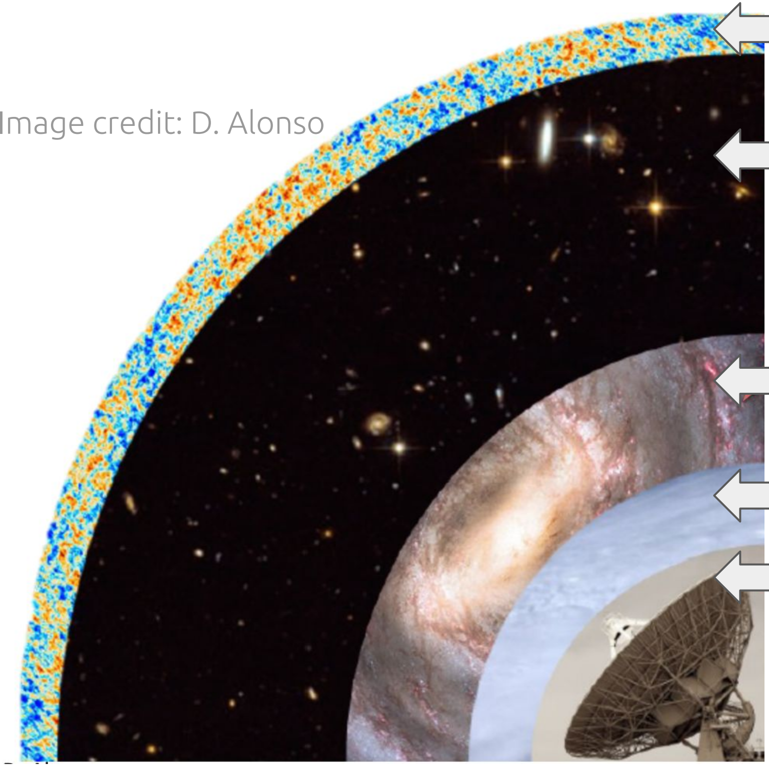


see also: Masui et al. 2013; Anderson et al. 2018;
Li et al. 2021; Tramonte&Ma 2020; Wolz et al. 2022;
CHIME Collaboration et al. 2022

Cunnington et al. 2022

End-to-end Pipeline

Image credit: D. Alonso



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

realistic mocks

↓

analysis pipeline

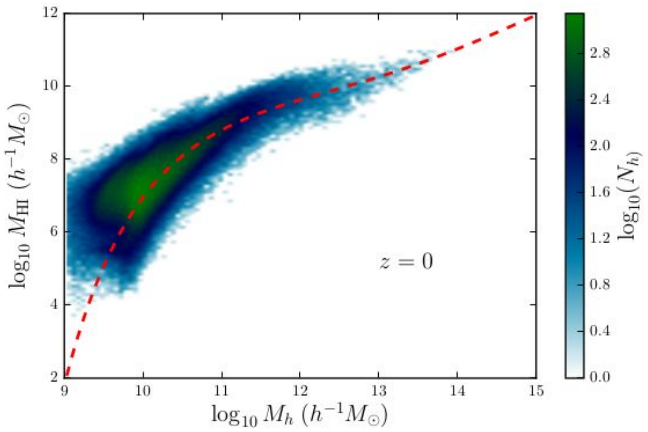
↓

power spectrum

↓

cosmological parameter constraints

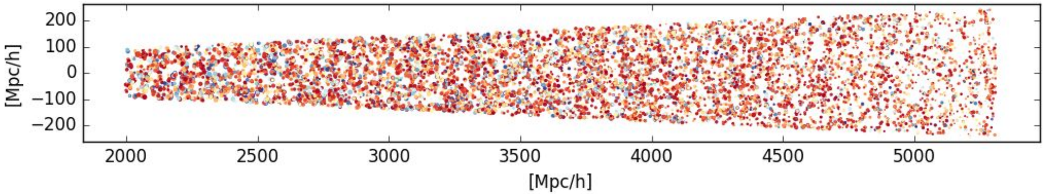
HI simulations



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

fast intensity map generation
Halo Occupation Distribution methods
on fast halo catalogues using the MHi-Mhalo relation
e.g. MS et al. 2020, 2022

light-cone with various properties for each galaxies
essential also for cross-correlation studies with **galaxy surveys**



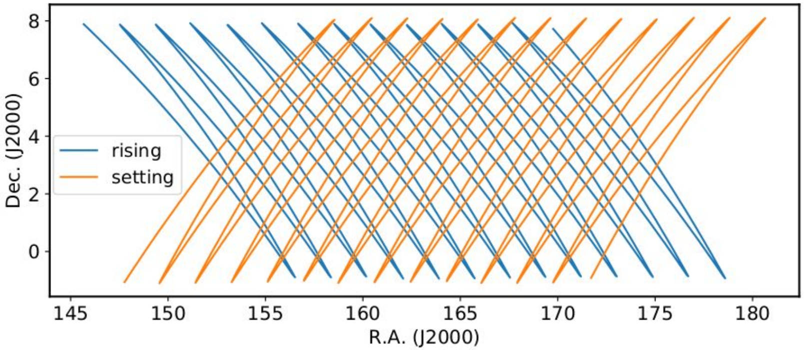
Need resolution, small scale physics and large volume

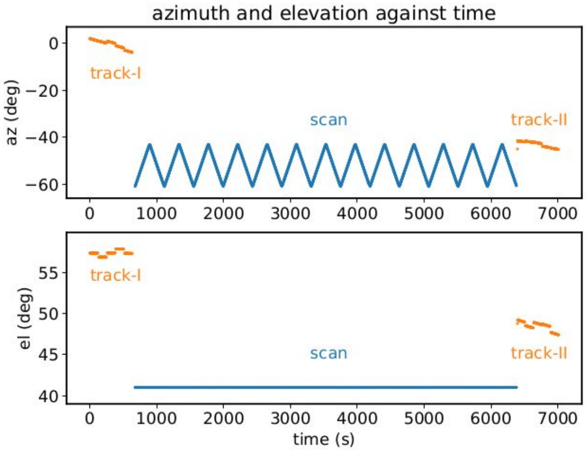
see also e.g. Villaescusa-Navarro et al. (2018), Obuljen et al. (2023)

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 ($10^\circ \times 30^\circ$)





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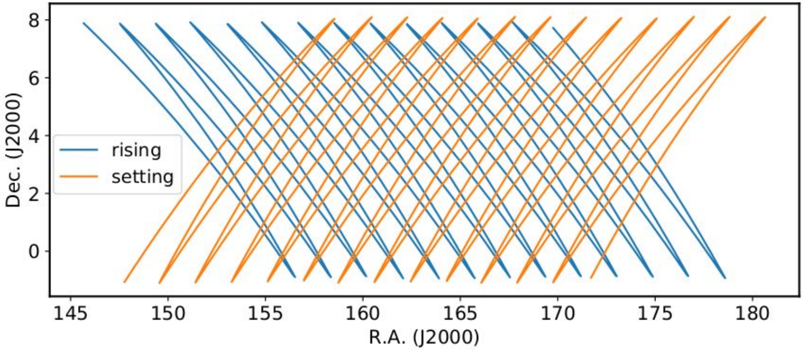
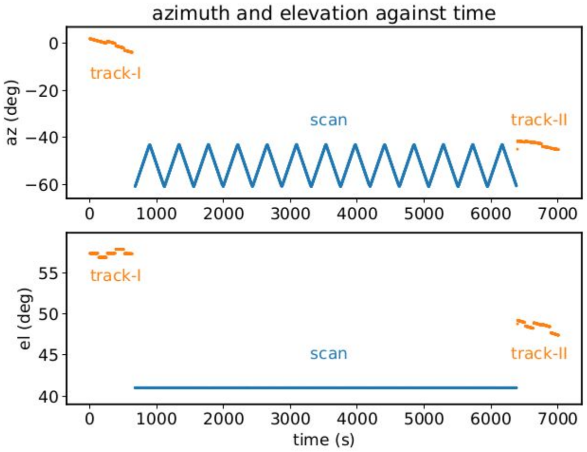




Intensity Mapping with MeerKAT

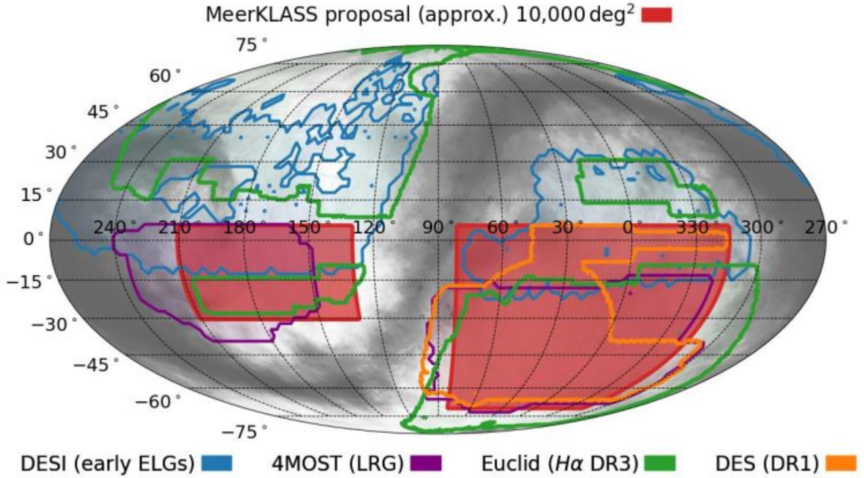
L-band:
900-1670 MHz (z<0.58)
~ 100 hours observed

MeerKLASS+ proposal submitted
2,000 h over 5,000 deg2
(continuum: 9 uJy rms, 5”)

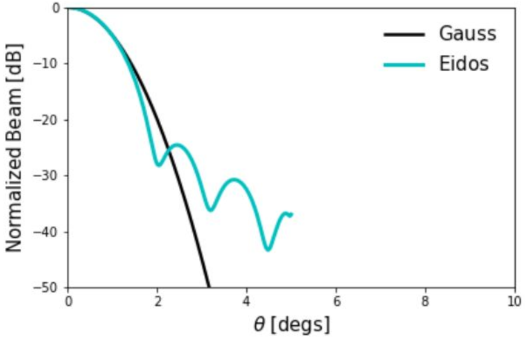
UHF band:
580 MHz-1015 MHz (0.40 < z < 1.45)
~ 120 hours observed

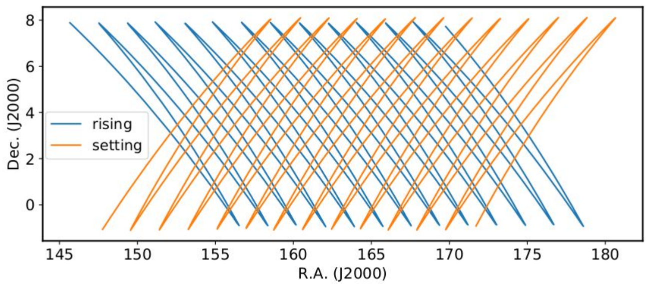
MeerKAT proposal “approved”
2,500 hours over 10,000 deg2
(continuum: 25 uJy rms, 13”)

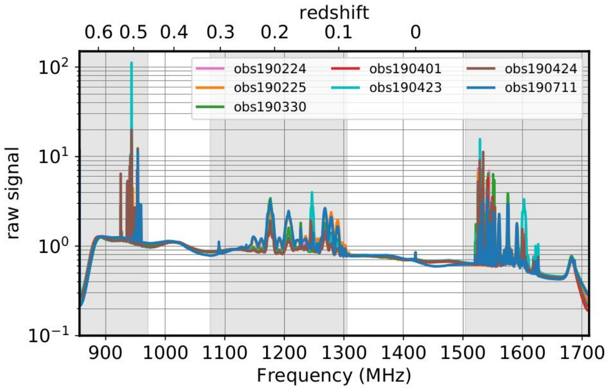
Antennas	All 64 MeerKAT dishes
Observation mode	Single-dish
Frequency range	0.856-1.712 GHz
Frequency resolution	0.2 MHz
Time resolution	2s
Exposure time	
Target field	



The devil is in the details







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

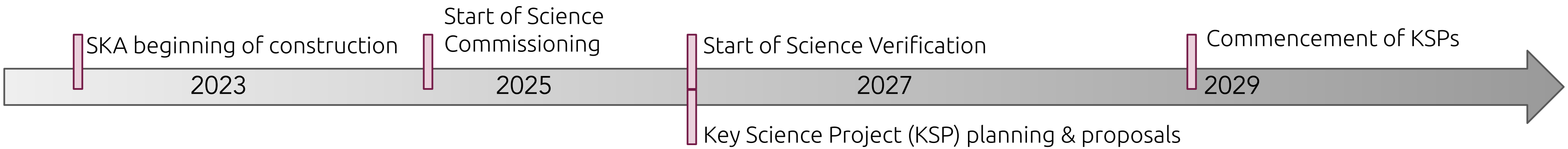
Harper et al. 2018
MS, Matshawule et al. (in prep)

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

Harper et al. 2018
Engelbrecht et al. (in prep)

Moving forward

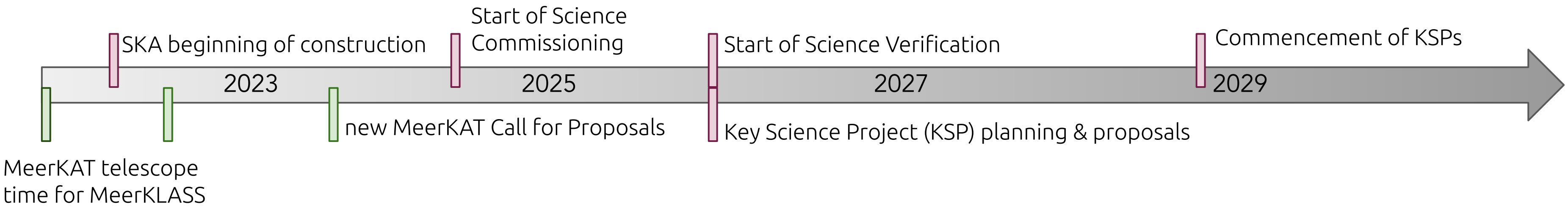
Prepare a detailed scientific case for the **SKA cosmological surveys**



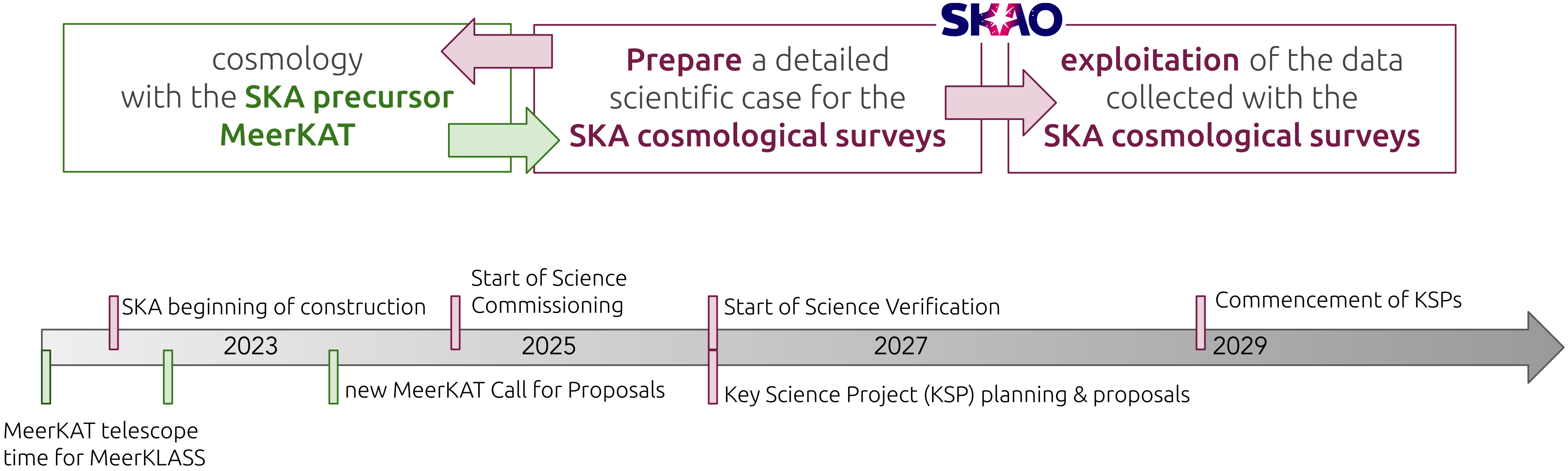
Moving forward

cosmology
with the **SKA precursor**
MeerKAT

Prepare a detailed
scientific case for the
SKA cosmological surveys



Moving forward



SKAO Timeline

Milestone Event (earliest)		SKA-Mid	SKA-Low
Construction Approval		2021 Jul	2021 Jul
AA0.5 AIV start	4(3) dishes 4 stations	2024 Nov	2024 Jul
AA0.5 end	4(3) dishes 4 stations	2025 May	2024 Nov
AA1 end	8 dishes 18 stations	2026 Apr	2025 Nov
AA2 end	64 dishes 64 stations	2027 Mar	2026 Oct
AA* end	144 dishes 307 stations	2027 Dec	2028 Jan
Operations Readiness Review		2028 Apr	2028 Apr
End of Staged Delivery programme		March 2029 Formal end of Construction Including Schedule Contingency	
AA4	197 dishes 512 stations	TBD	TBD

Dates from Jan 2024 Construction Report (not including contingency)

First data release to the community expected in 2026/27 (for science verification)