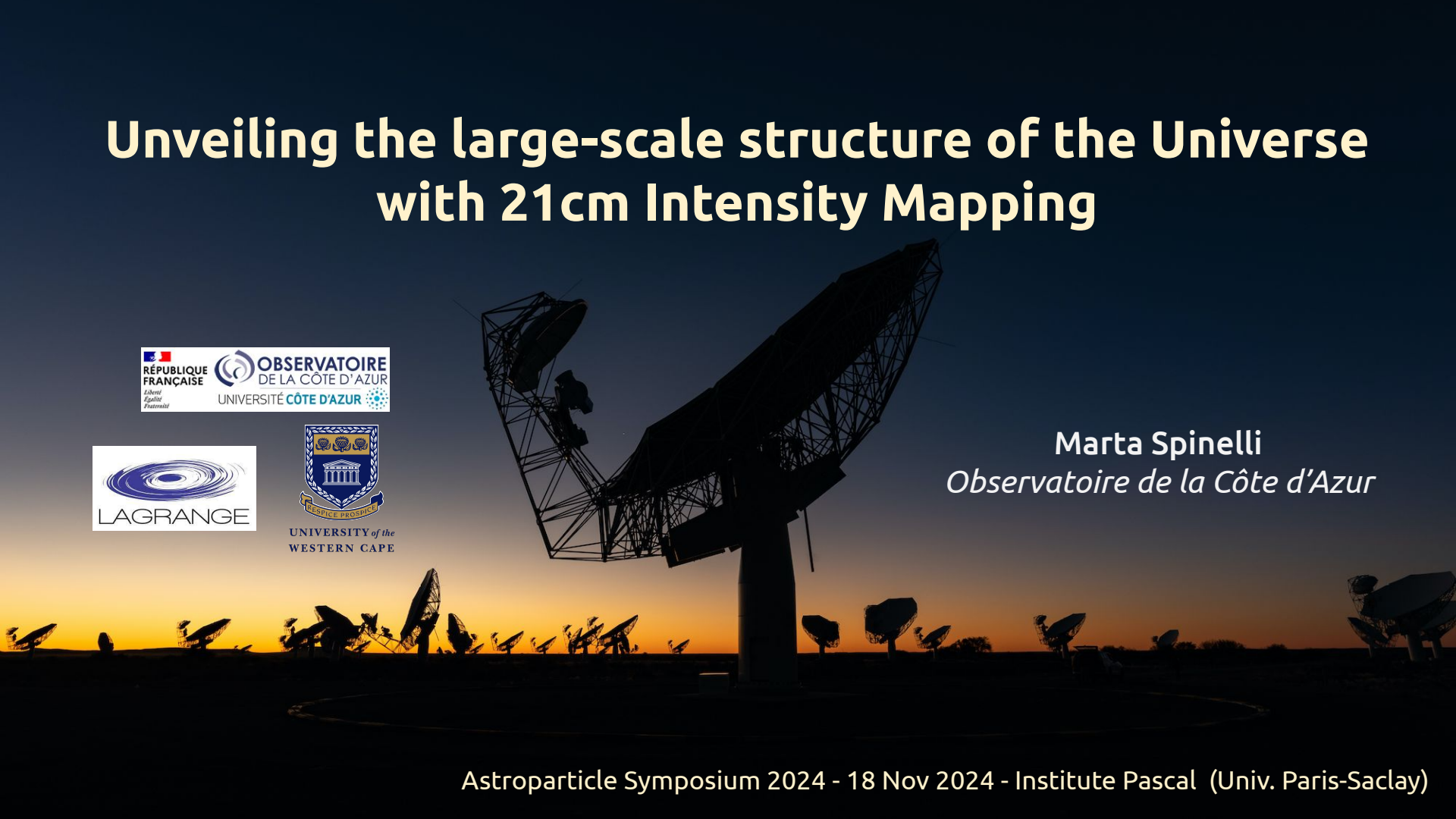
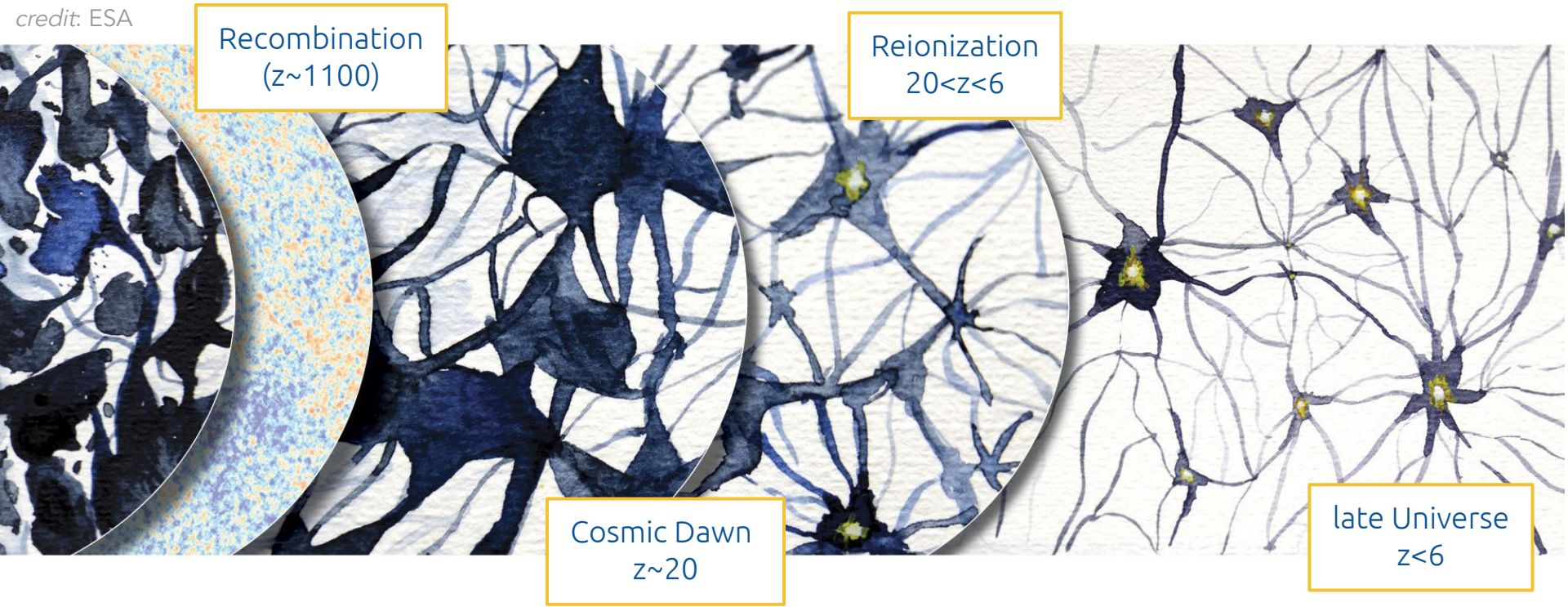
Unveiling the large-scale structure of the Universe with 21cm Intensity Mapping



Marta Spinelli
Observatoire de la Côte d'Azur

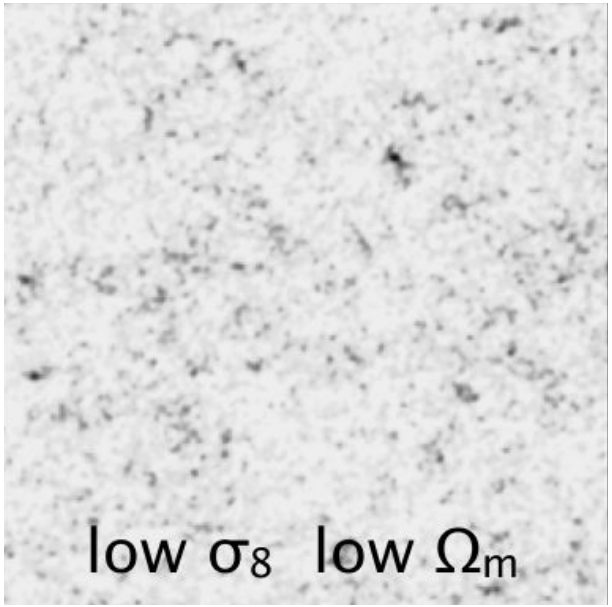
Astroparticle Symposium 2024 - 18 Nov 2024 - Institute Pascal (Univ. Paris-Saclay)

Hydrogen in cosmic history



The “**low**” redshift Universe

LSS with Neutral Hydrogen



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

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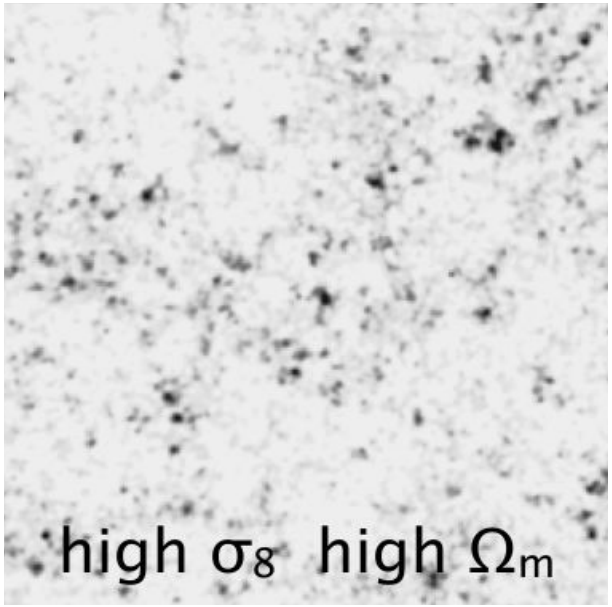

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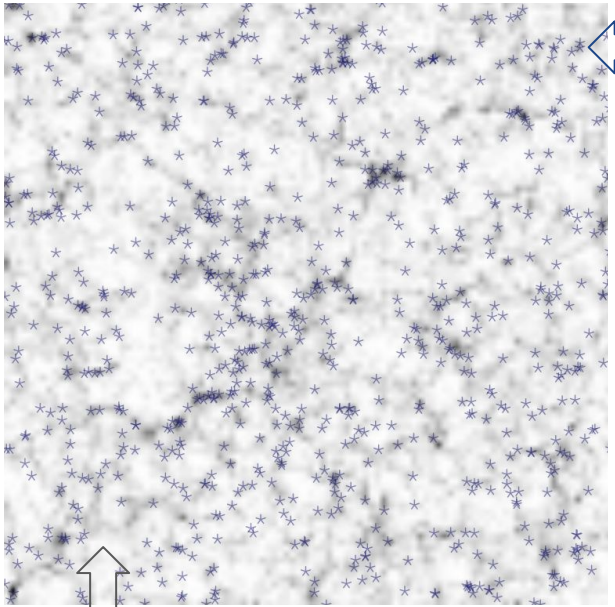
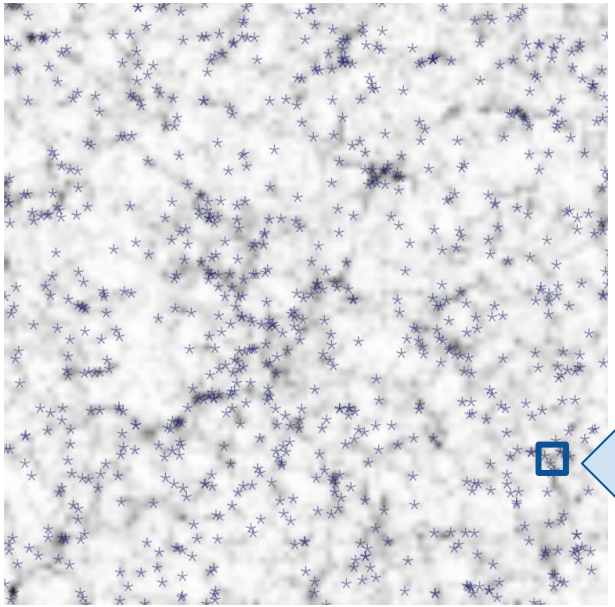


underlying matter distribution

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

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;
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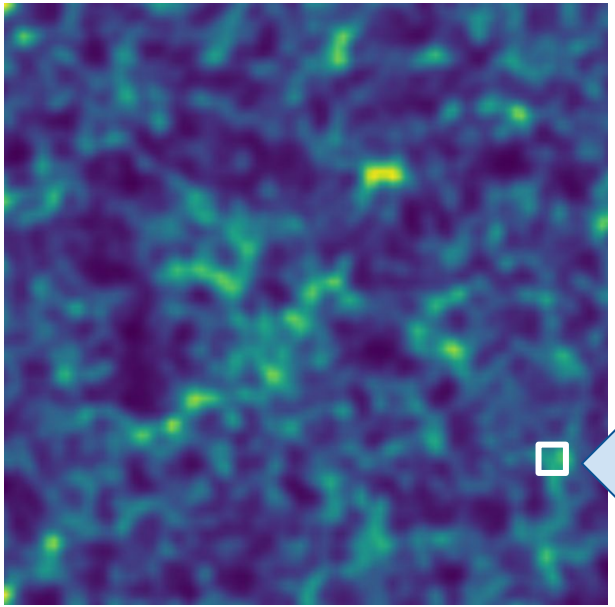

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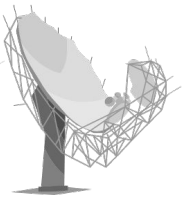

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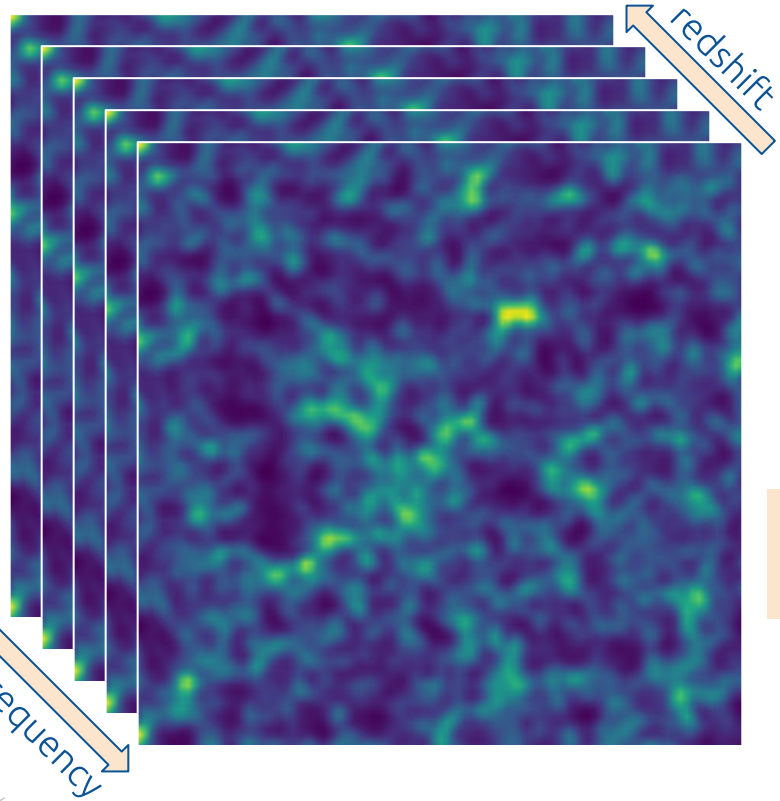


the distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**

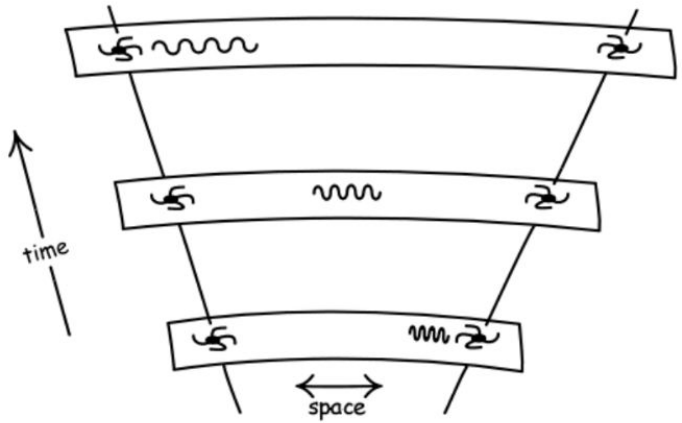
How can we efficiently observe
cosmological volumes?

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

Key cosmological probe

Frequency and redshift for the 21cm line

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



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

Examples:

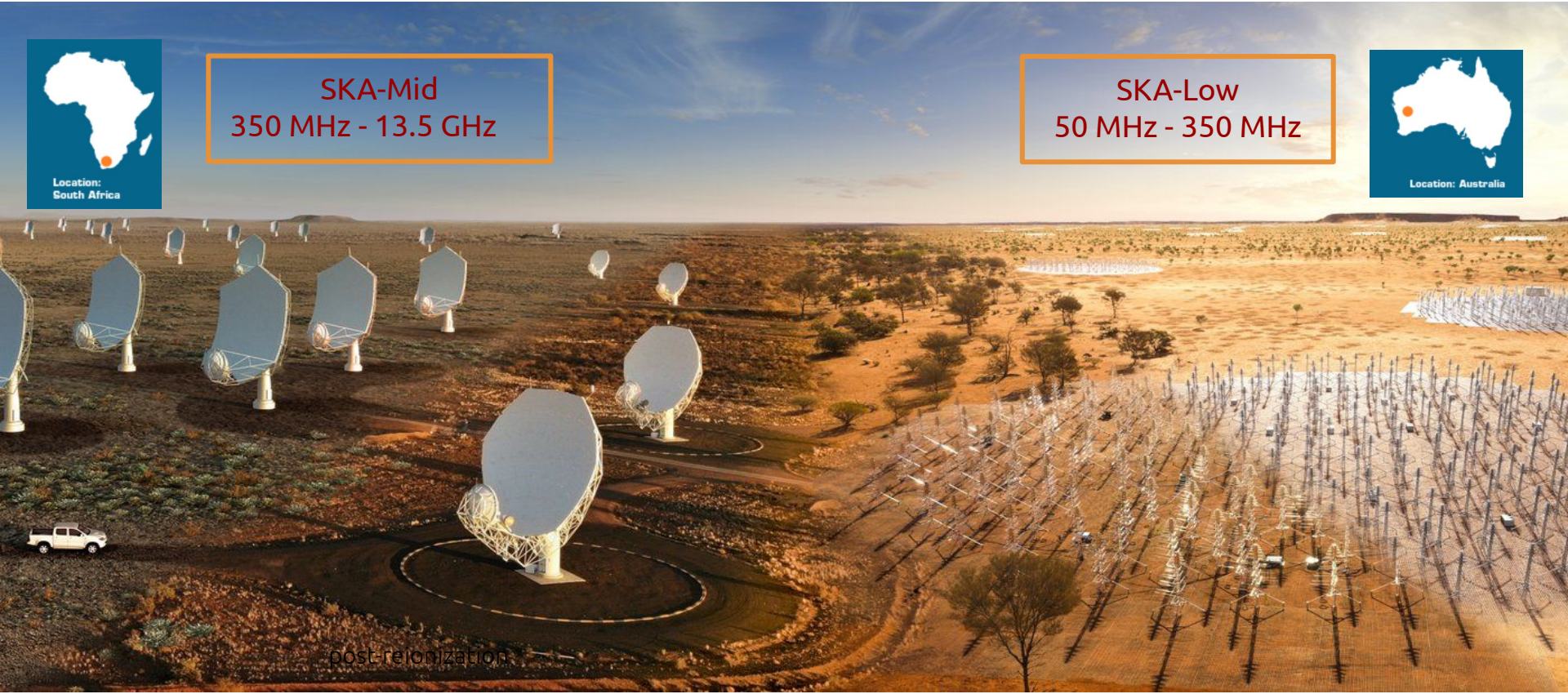
$\nu_{observed}$ ~ 900 MHz
corresponds to z ~ 0.6: late Universe

$\nu_{observed}$ ~ 170 MHz
corresponds to z ~ 7: Epoch of Reionization

$\nu_{observed}$ ~ 70 MHz
corresponds to z ~ 20: Cosmic Dawn

The SKA Observatory

credit: skatelescope.org



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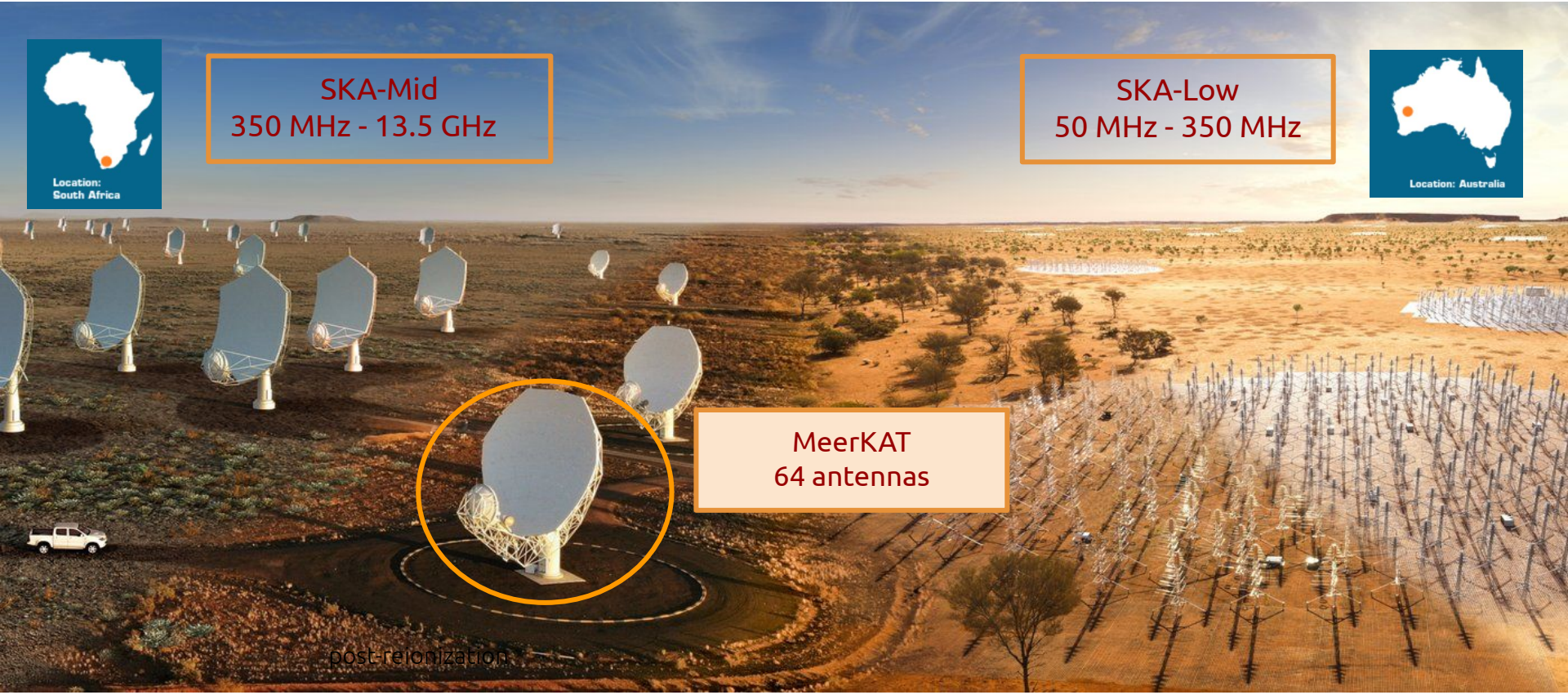


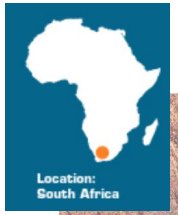
picture credit: SKAO

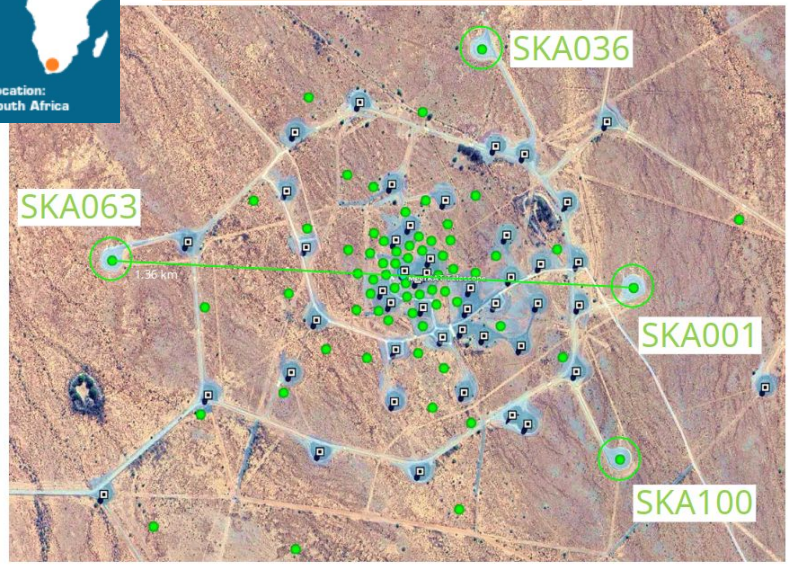
Construction Updates

SKA-Mid
350 MHz - 13.5 GHz

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

SKA-Low
50 MHz - 350 MHz

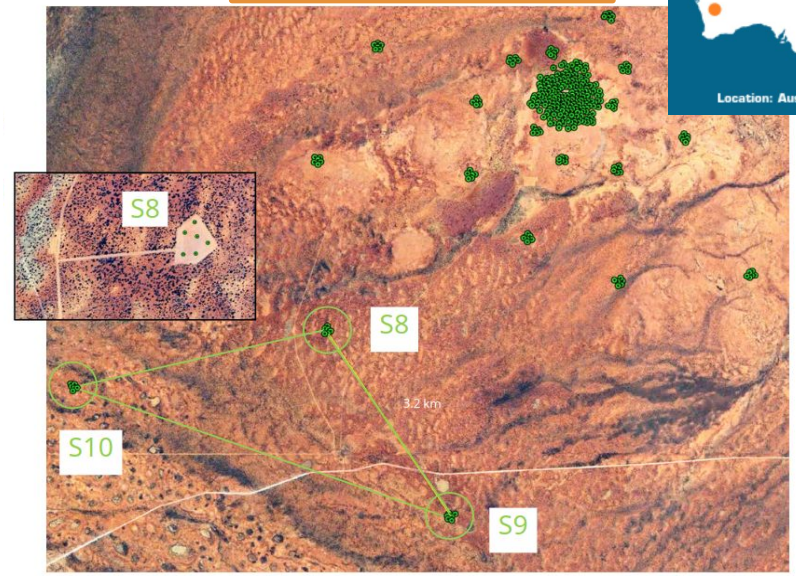




MeerKAT

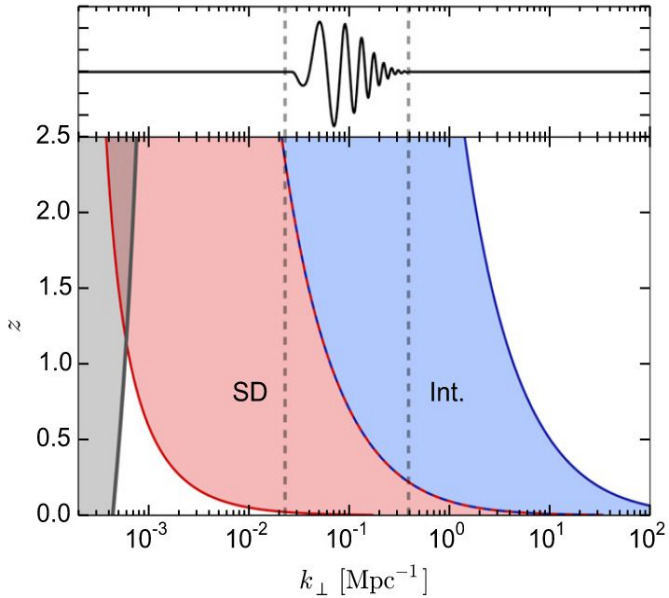
SKA dish locations

First 4 dishes on site



First 4 stations on site

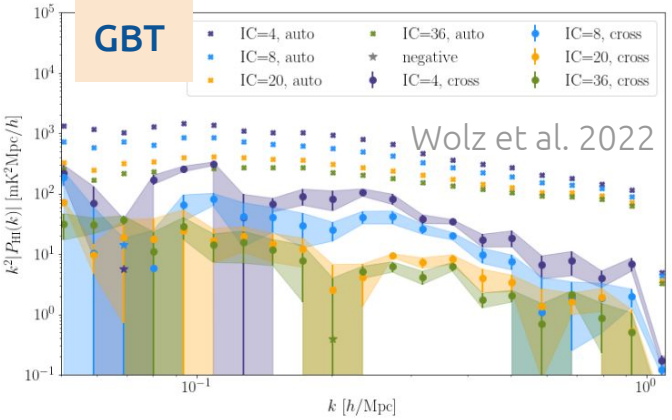
Single Dish vs Interferometry

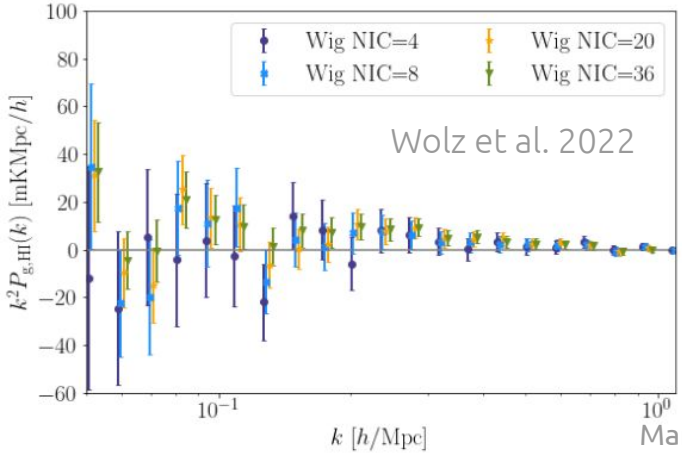


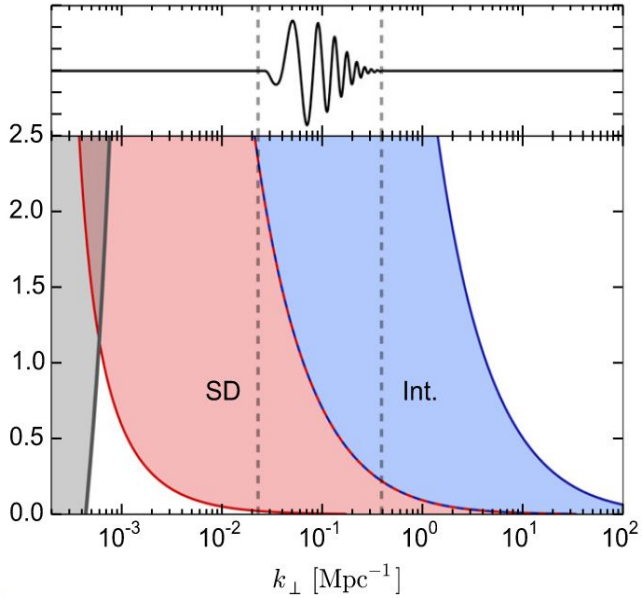
Bull et al. 2015

Single Dish vs Interferometry

GBT







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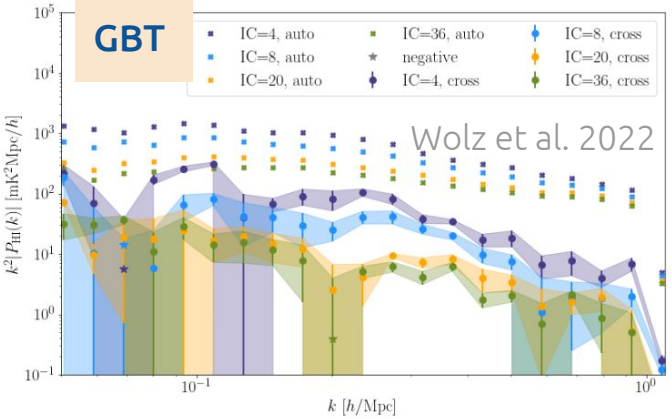
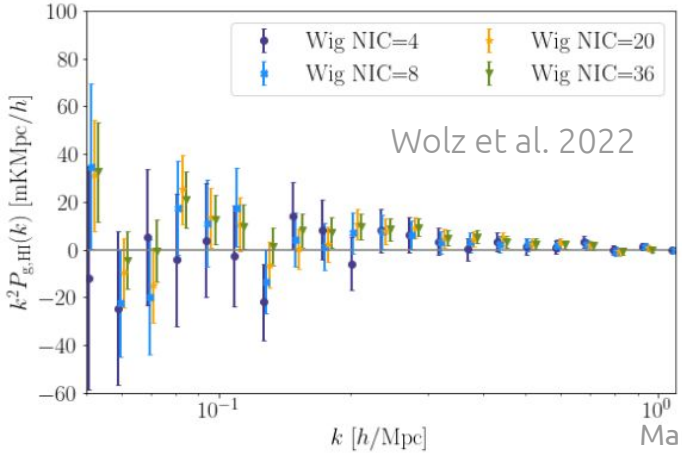
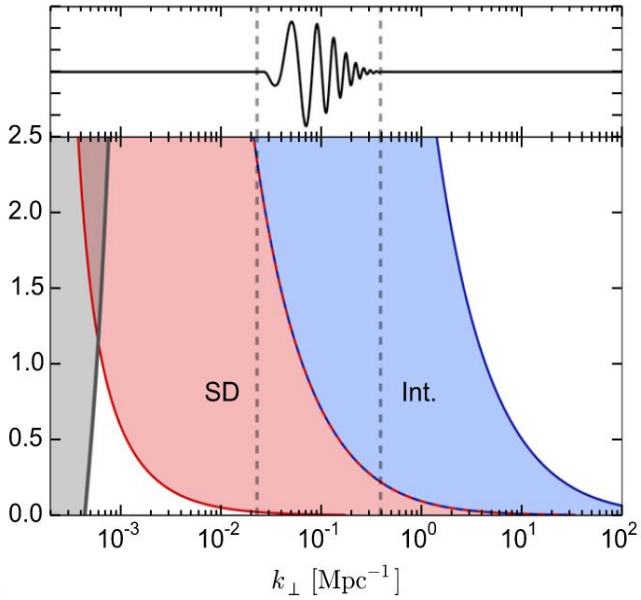
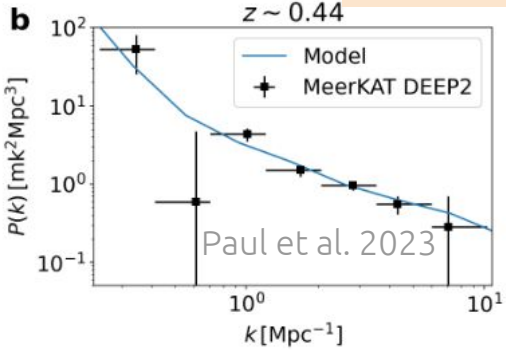






Bull et al. 2015

MeerKAT



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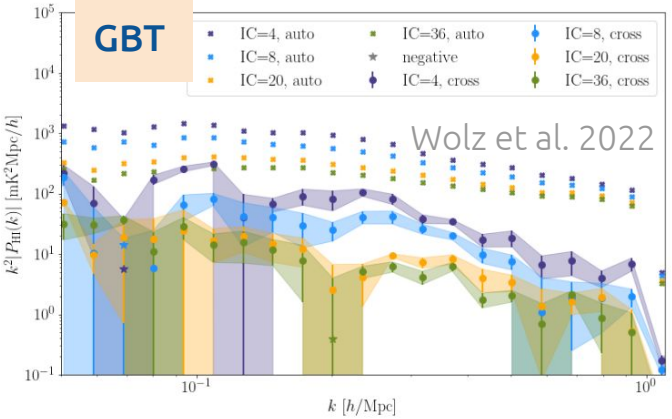

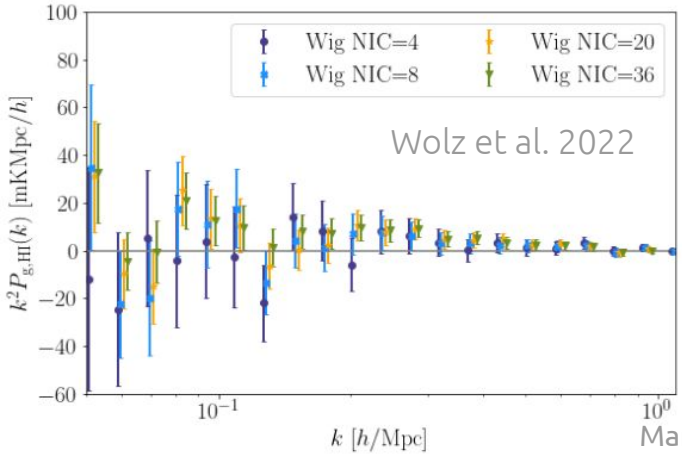

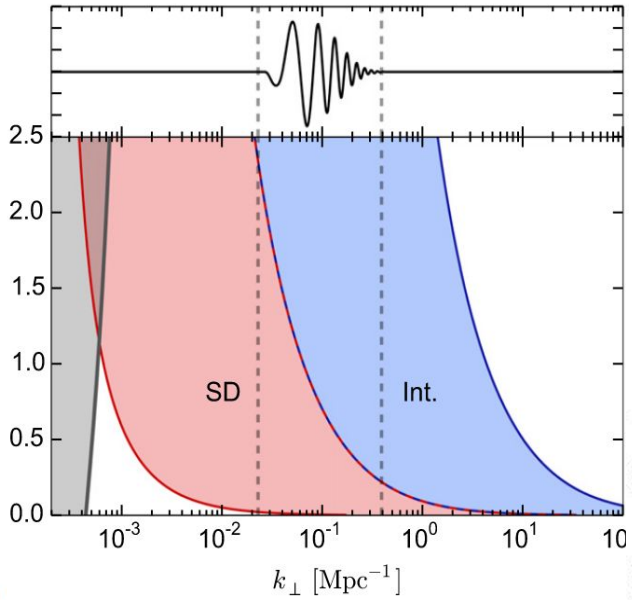

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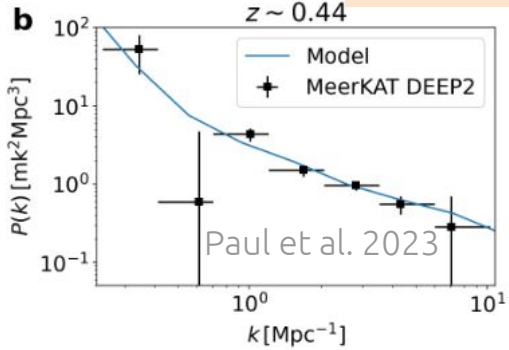
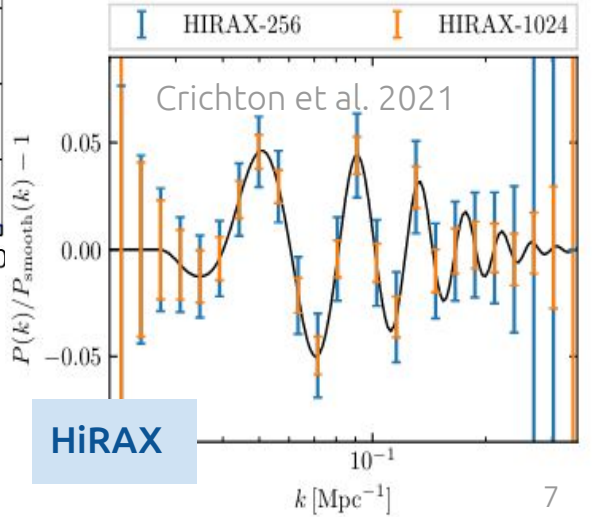
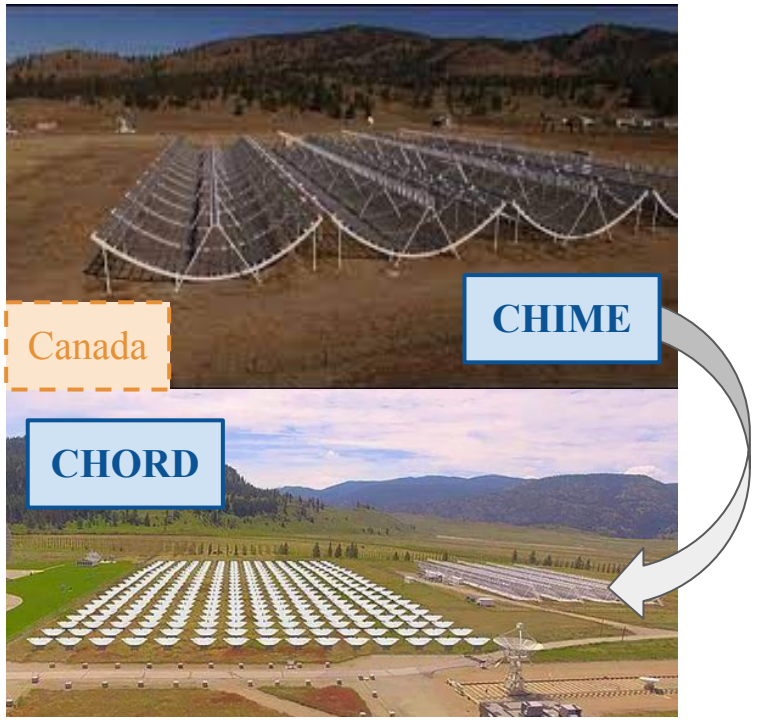




HiRAX

Interferometry for the BAO



SKAO forecasts

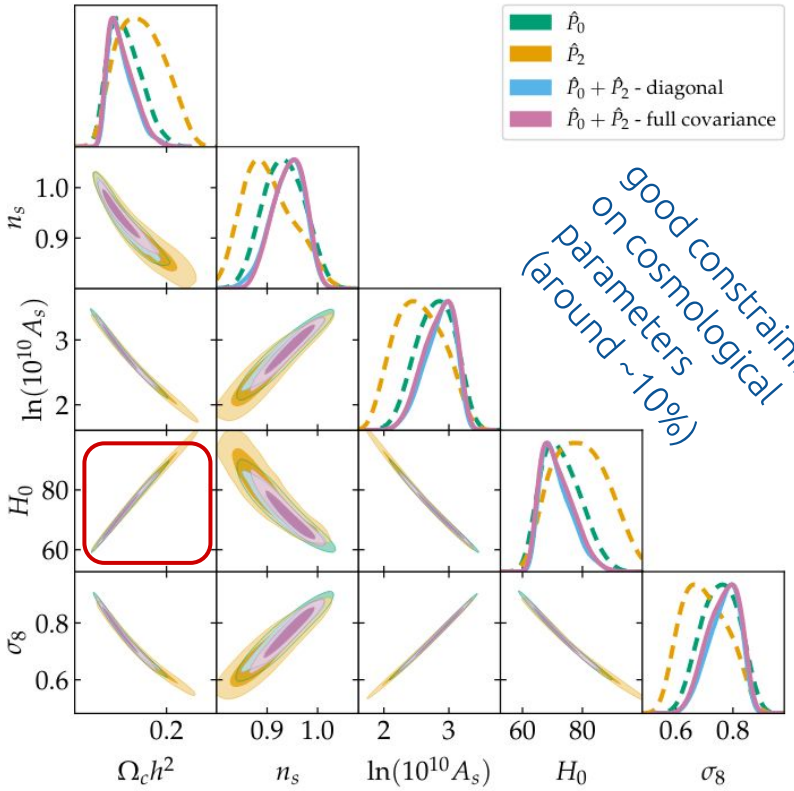
$$P_{21}(z,k,\mu) = \bar{T}_{\rm b}^2(z)\left[\, b_{\rm HI}(z) + f(z)\,\mu^2 \,\right]^2 P_{\rm m}(z,k)$$

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

- $\bar{T}_{\rm b}^2(z)$ 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

SKAO forecasts

Berti, MS, Viel (2023)



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

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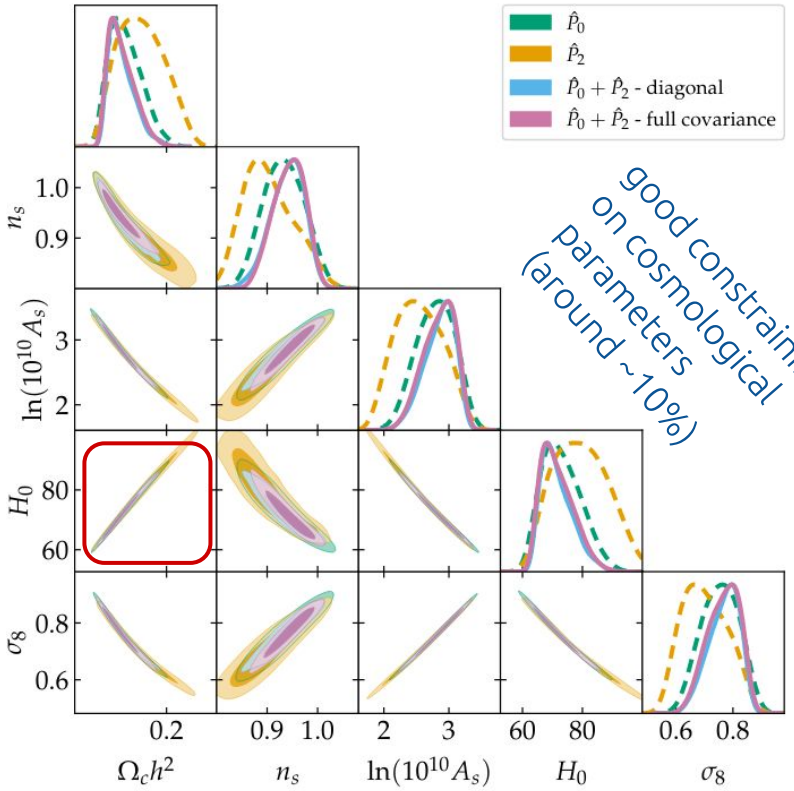

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$$P_{21,g}(z,k,\mu) = \bar{T}_b\left(b_{\rm HI} + f\mu^2\right)\left(b_g + f\mu^2\right)P_{\rm m}(z,k,\mu)$$

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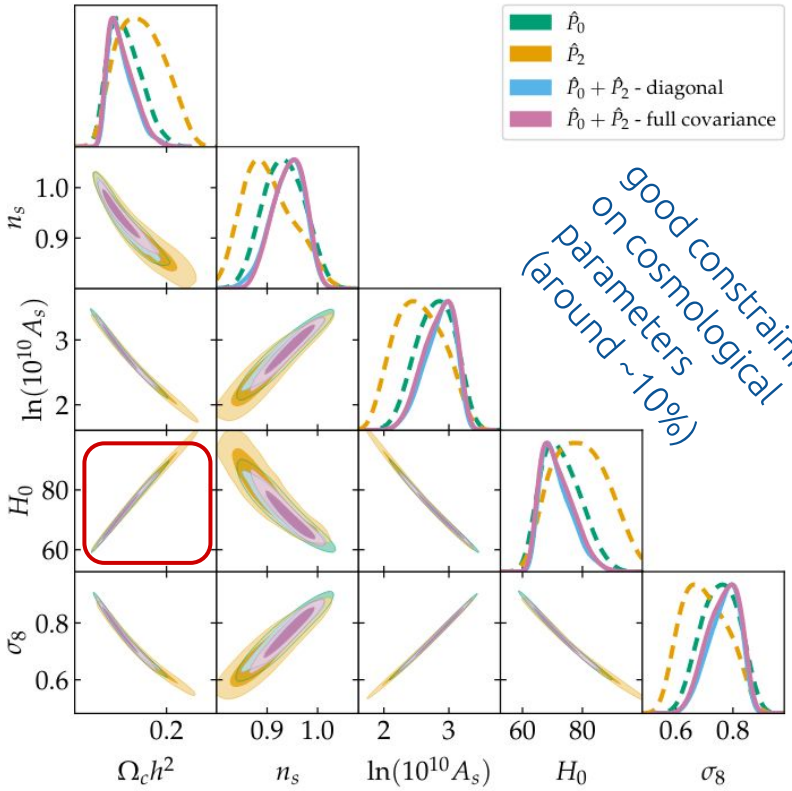

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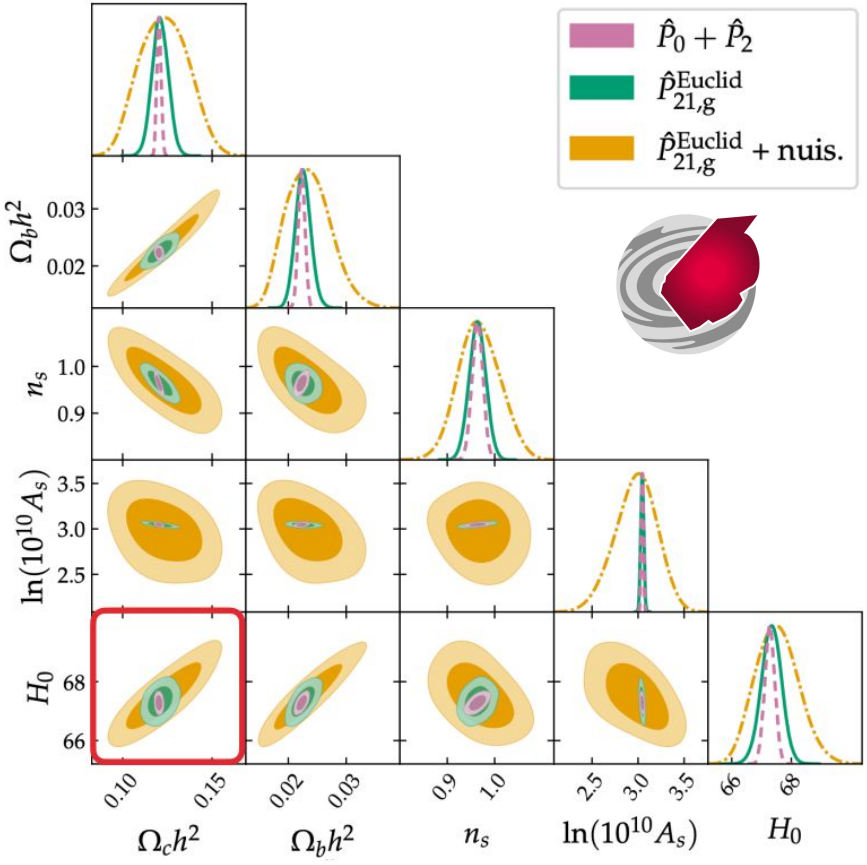

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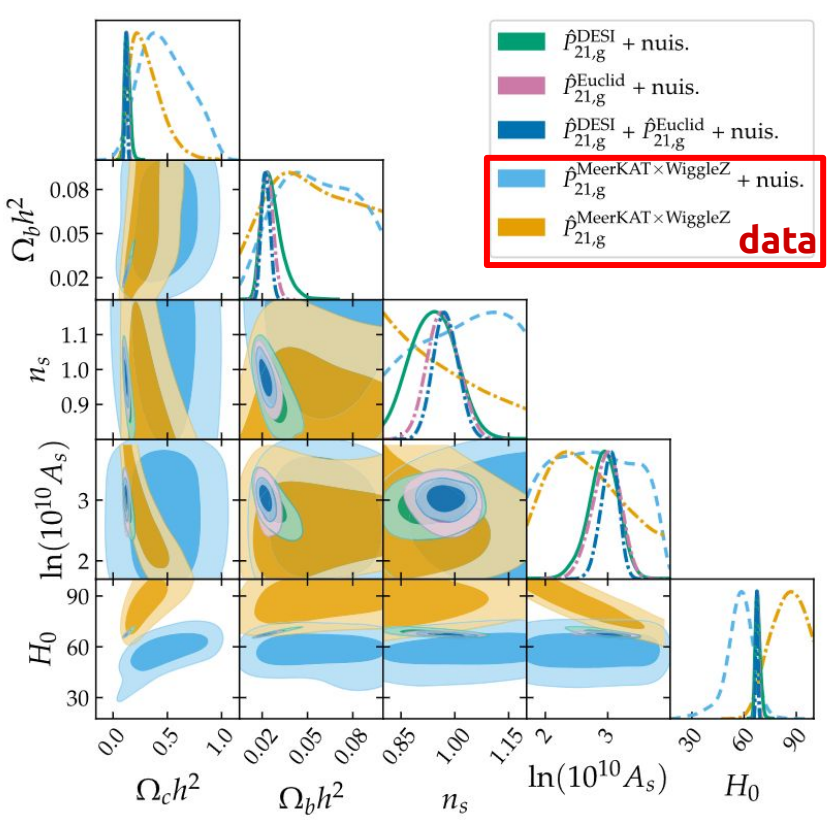
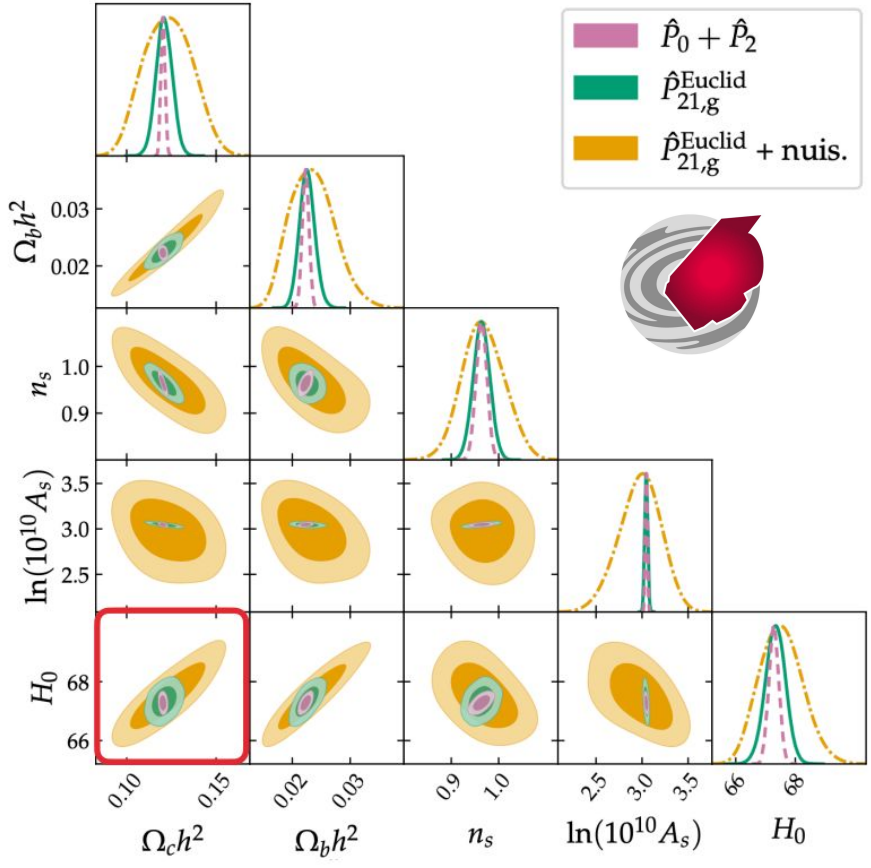
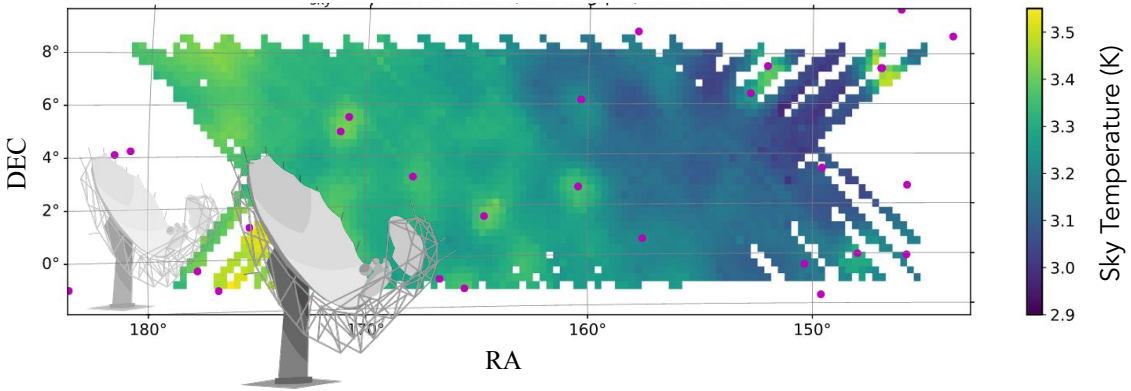




Intensity Mapping Observations

MeerKLASS: cosmological survey with MeerKAT 64 antennas

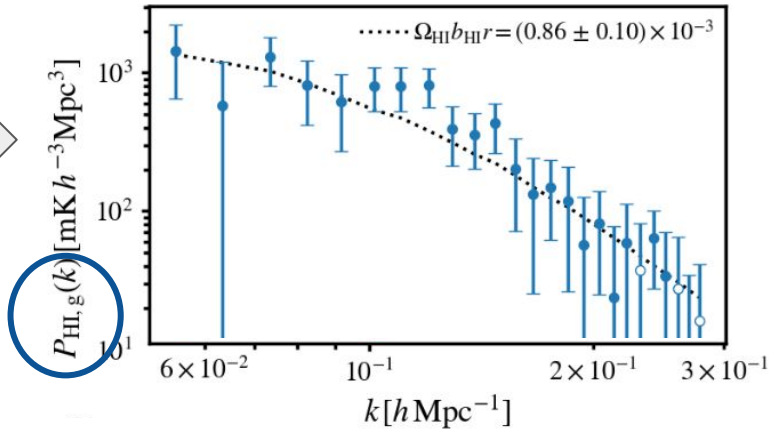


Wang et al. 2021

2019 calibrated sky map!

21cm signal detection achieved at redshift 0.4
in **cross-correlation with WiggleZ**
Cunnington et al. 2022

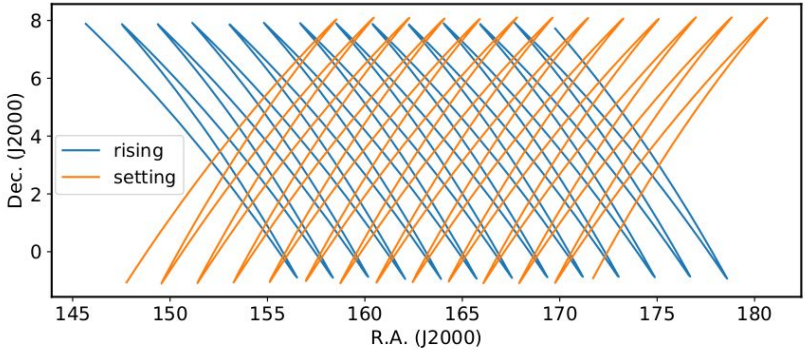
complex analysis pipeline
Need for RFI flagging, **foreground cleaning**, etc.

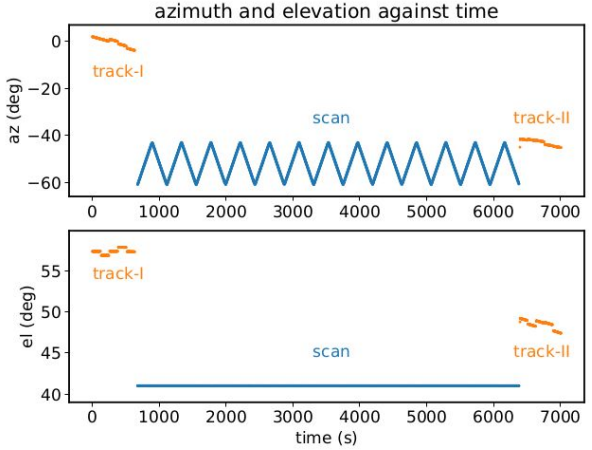


Intensity Mapping with MeerKAT

MeerKLASS: 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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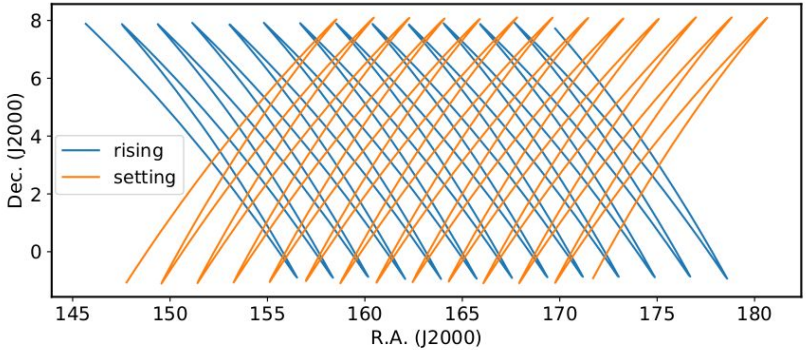
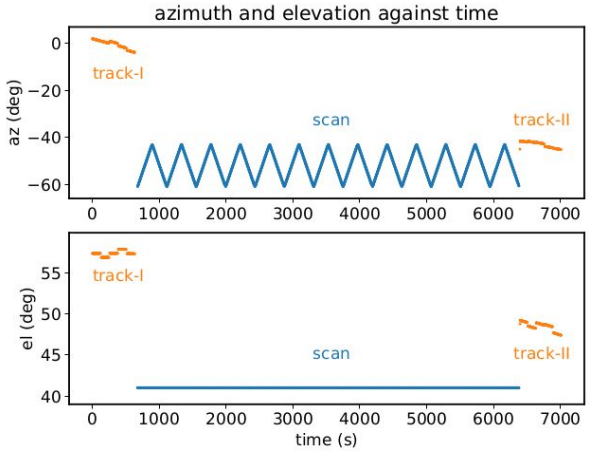


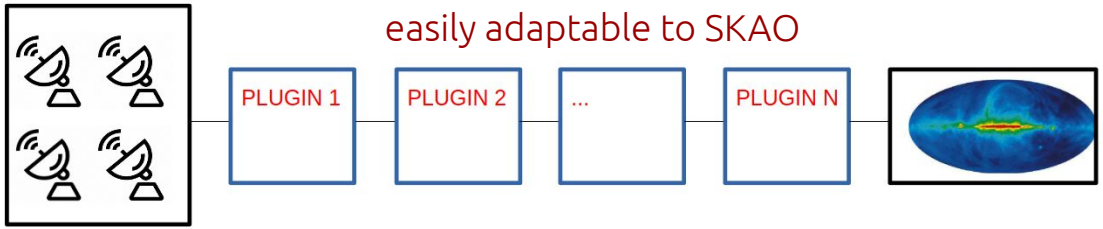


MeerKLASS ongoing

New calibration pipeline(s):

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

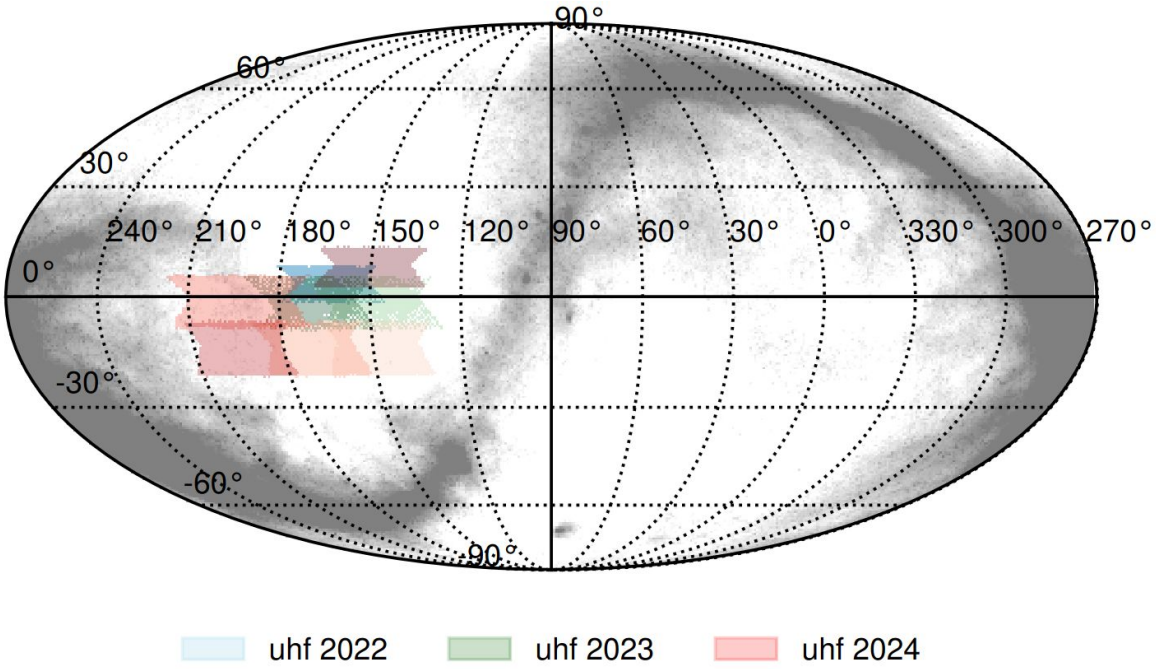
Ivory/MuSEEK: new improved modular plugin-based architecture **(main developers: A. Wild, W. Hu)**



L-band 2019: 7x1.5h scans	Improved cleaning/comparison **Carucci et al. in prep**
L-band 2021: 41x1.5h scans	Split data to reduce systematics cross-correlating different blocks Cross-correlation detection with GAMA **MeerKLASS collab papers in prep & arxiv**
UHF-band: 90x1.5h scans	Better RFI environment - deeper redshift coverage - 1600 deg2 **MeerKLASS collab paper in prep**

(more) Intensity Mapping Observations

MeerKLASS: cosmological survey with MeerKAT 64 antennas



UHF band:

580 MHz-1015 MHz (0.40 < z < 1.45)

~ 120 hours observed

MeerKAT proposal submitted

2,500 hours over 10,000 deg2

(continuum: 25 uJy rms, 13'')

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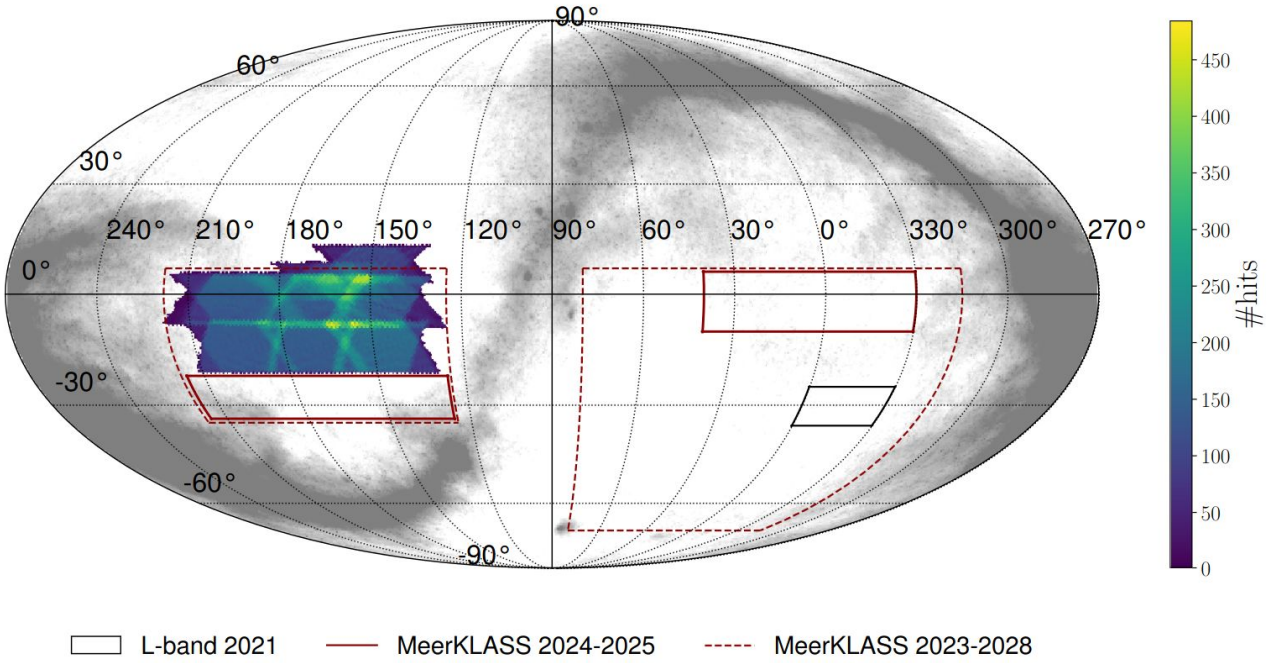

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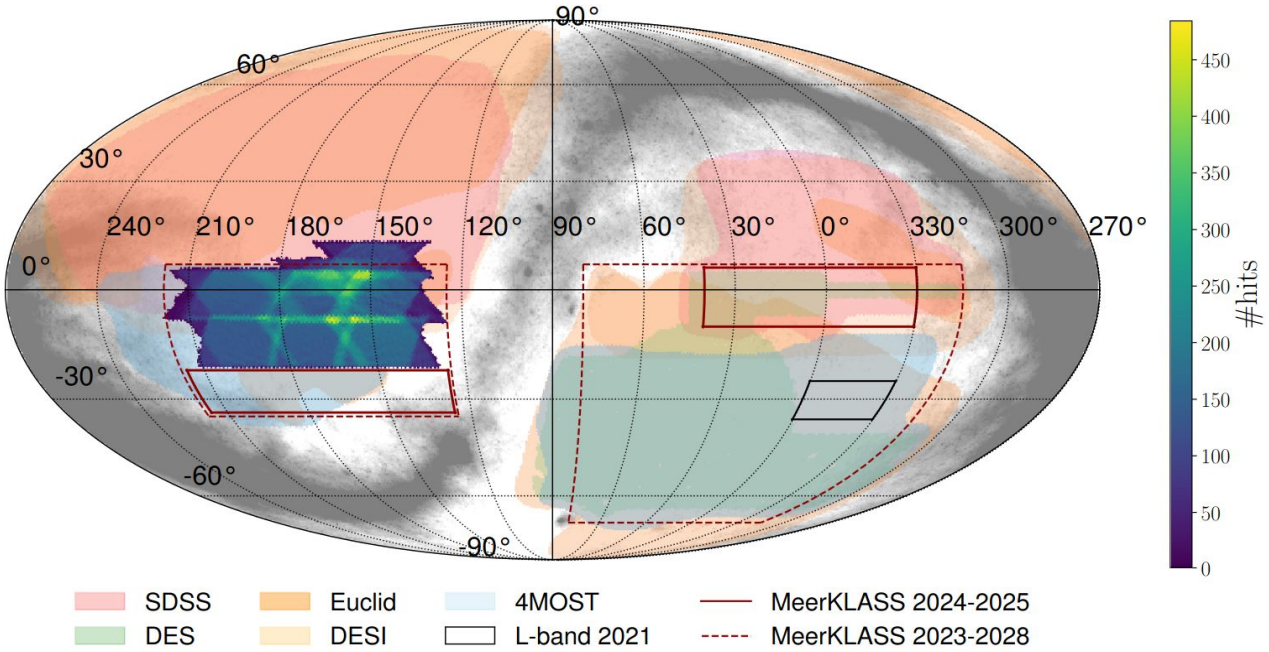

UHF band:

580 MHz-1015 MHz (0.40 < z < 1.45)

~ 120 hours observed

MeerKAT proposal submitted

2,500 hours over 10,000 deg2

(continuum: 25 uJy rms, 13'')

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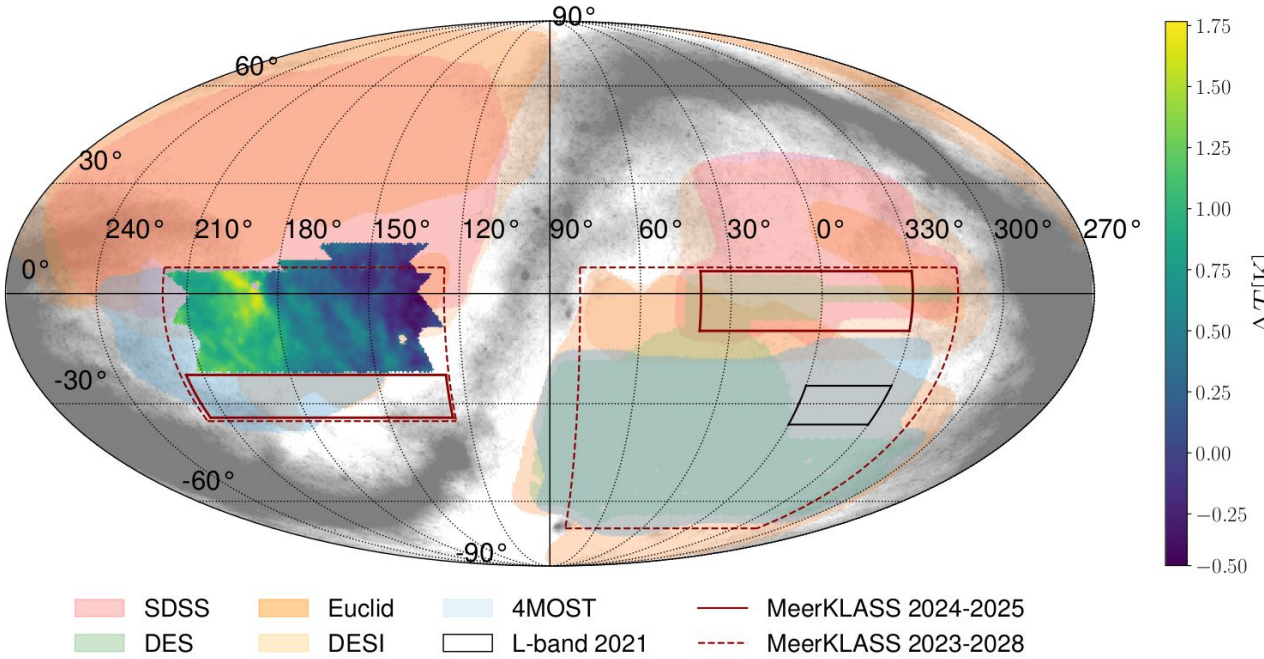

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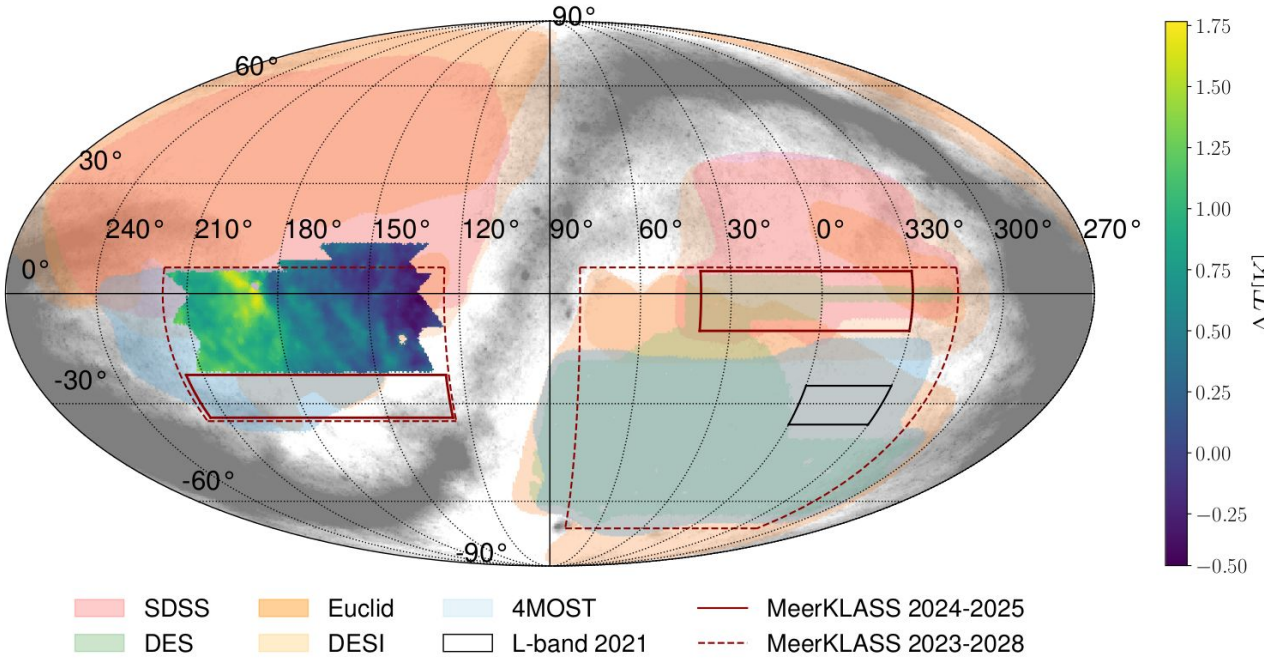

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580 MHz-1015 MHz (0.40 < z < 1.45)

~ 120 hours observed

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2,500 hours over 10,000 deg2

(continuum: 25 uJy rms, 13'')

L-band:

900-1670 MHz (z<0.58)

~ 100 hours observed

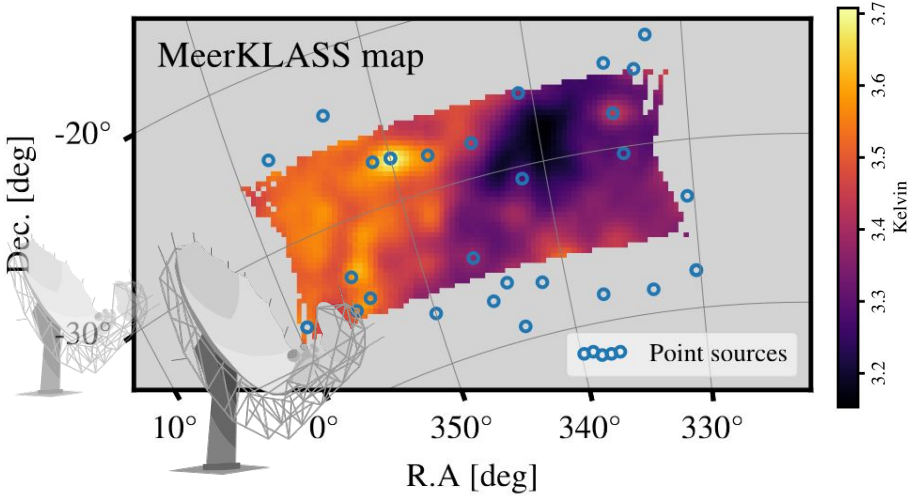
MeerKLASS+ proposal submitted

2,000 h over 5,000 deg2

(continuum: 9 uJy rms, 5'')

L-band 2021 latest 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)

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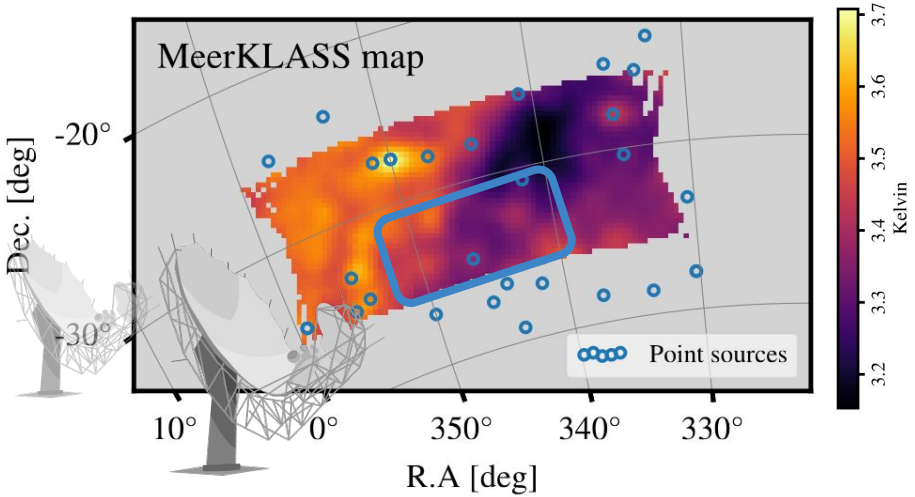

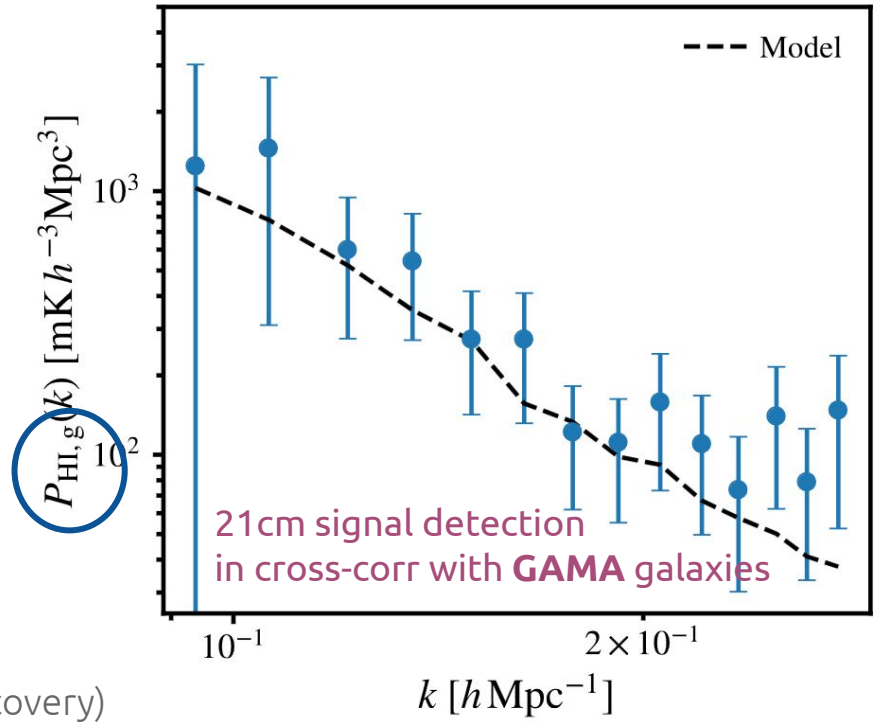

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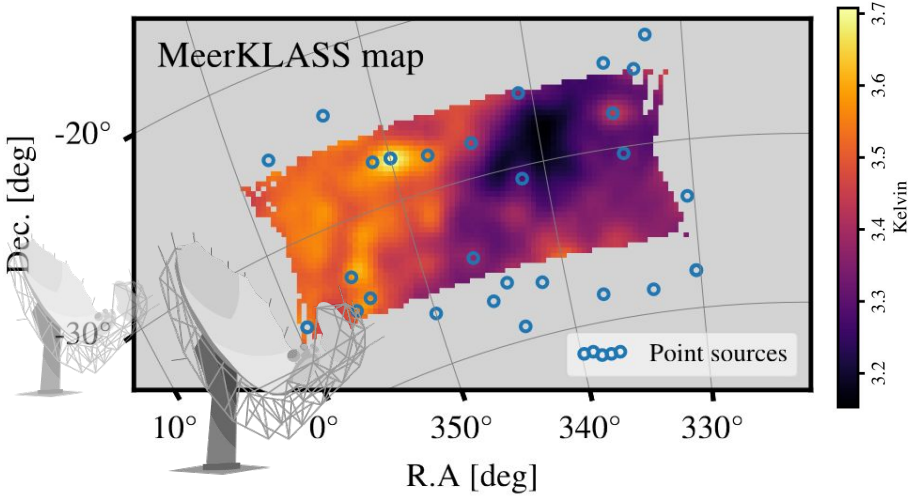

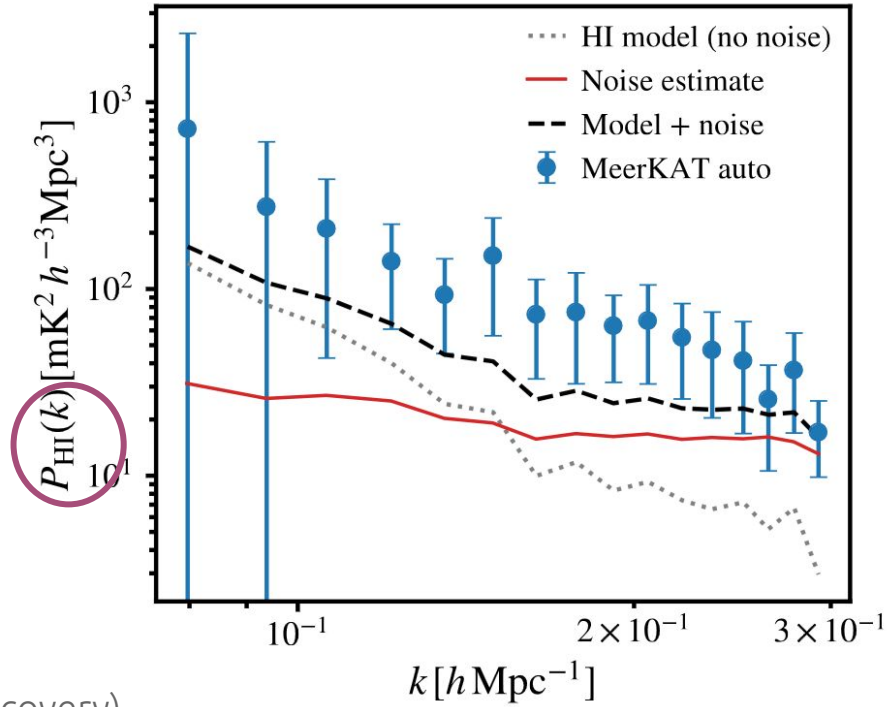

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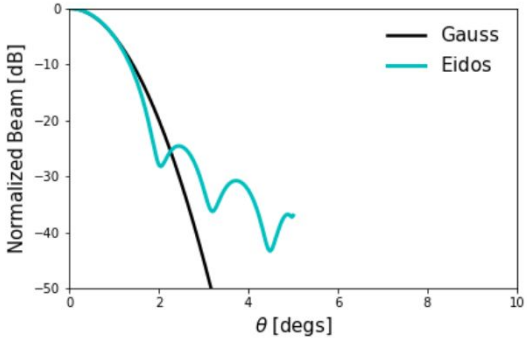
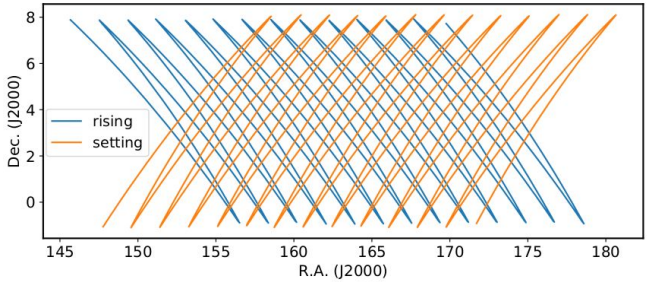
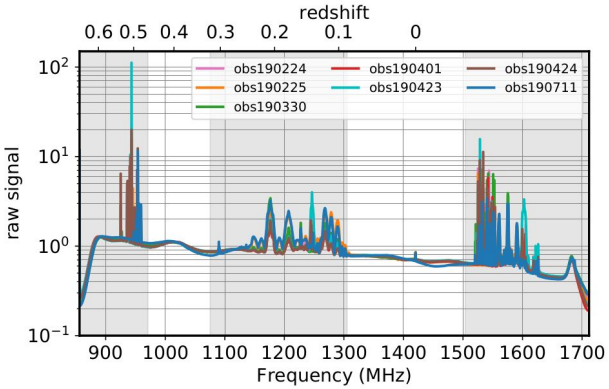
The devil is in the details







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. (2024)

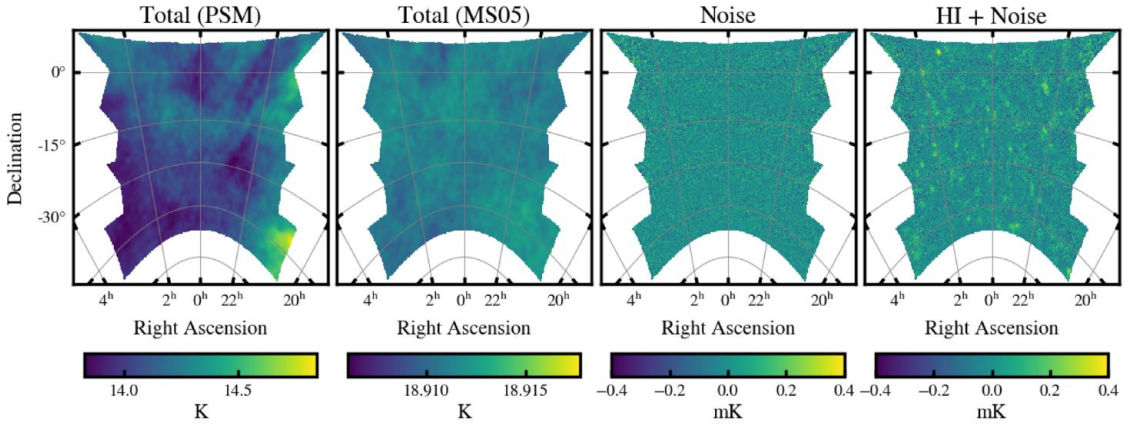
Foreground subtraction challenge

(subset) of the SKA Cosmo IM Focus Group and MeerKLASS members!

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

Project setup:

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



Blind challenge to discover weaknesses and strengths of the various methods

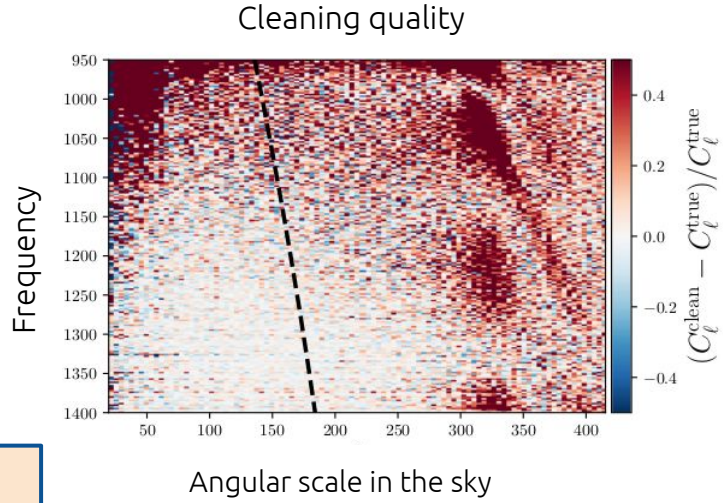
given IM “data”,
would your favorite method extract the cosmological signal?

MS et al. (2022)

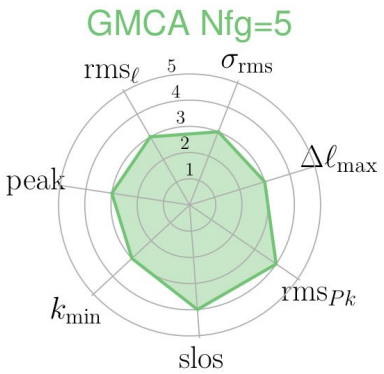
Foreground subtraction challenge

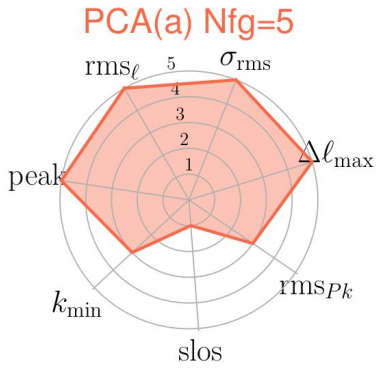
- How much can **instrument/foregrounds coupling** impact the signal reconstruction?
- definition of statistics and metrics to evaluate the relative performances

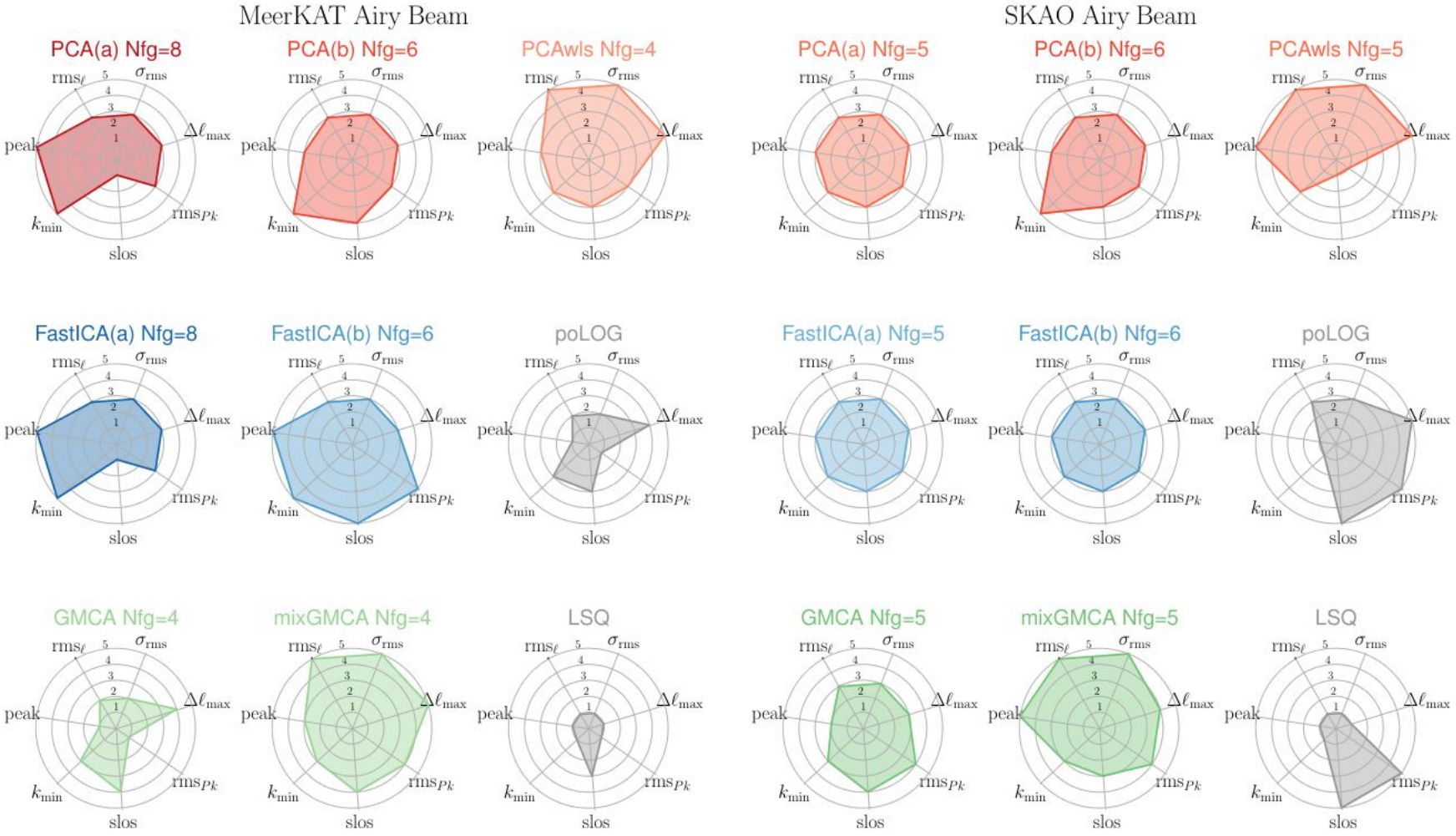
Realistic instrumental effects inevitably **complicate** the foreground cleaning



MS et al. (2022)



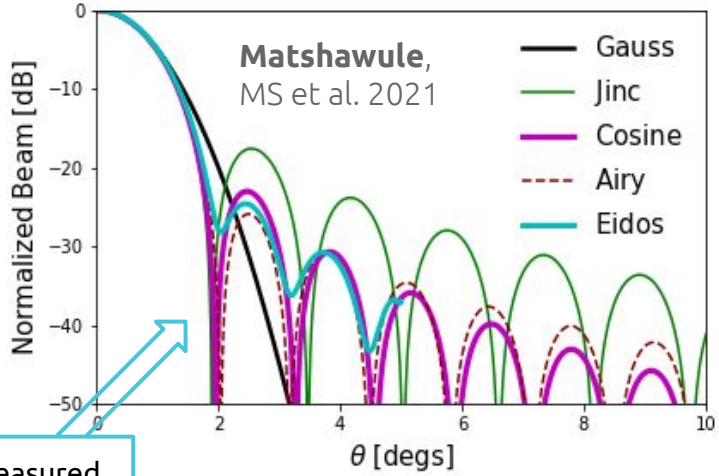



MeerKAT Airy Beam
SKAO Airy Beam
PCA(a) Nfg=8
PCA(b) Nfg=6
PCAwls Nfg=4
PCA(a) Nfg=5
PCA(b) Nfg=6
PCAwls Nfg=5
FastICA(a) Nfg=8
FastICA(b) Nfg=6
poLOG
FastICA(a) Nfg=5
FastICA(b) Nfg=6
poLOG
GMCA Nfg=4
mixGMCA Nfg=4
LSQ
GMCA Nfg=5
mixGMCA Nfg=5
LSQ
rms_ℓ
σ_{rms}
$\Delta\ell_{\max}$
rms_{Pk}
slos
$k_{\min}$
peak
1
2
3
4
5

Telescope beam

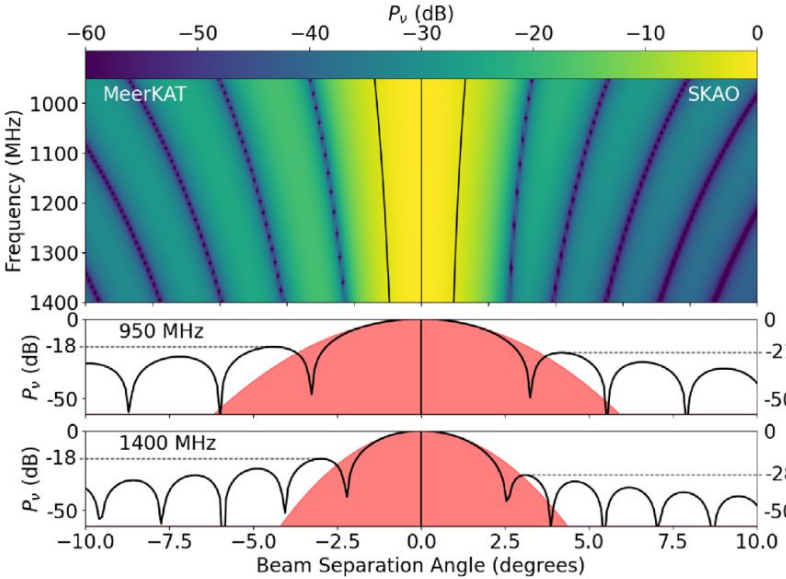
MeerKAT beam has **side-lobes** (same for SKA-MID)

a strong point source in the side-lobes:
contaminates the signal and
complicate the foreground subtraction



Eidos: measured
Asad et al. 2020

Airy beam
Harper et al. (2018)



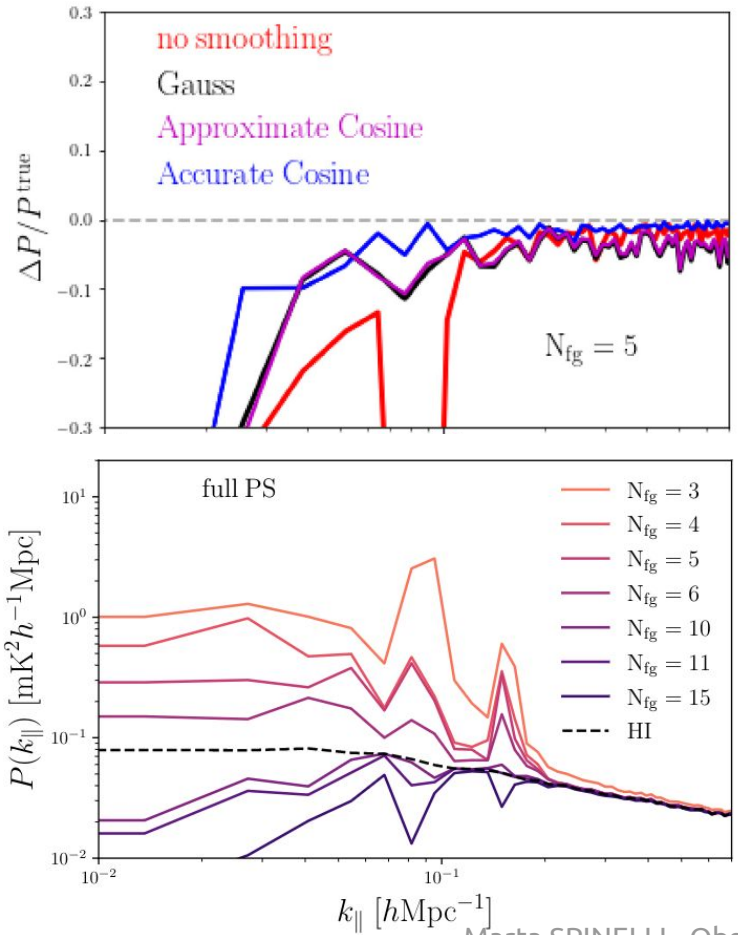
MS et al. 2022

The beam evolves with frequency

Effect of the telescope beam

Matshawule, MS et al. 2021

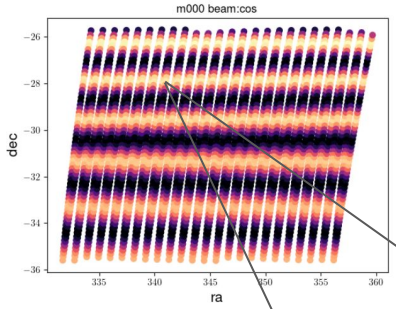
MS, Matshawule et al. in prep



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

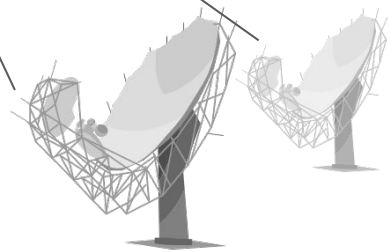
- **point sources** and synchrotron spatial structures coupled with the beam **complicate the cleaning**
- Careful **beam-deconvolution** alleviates the problem but need to be careful for precision cosmology
- What about the measured 2D beam?

Hunting RFI details



gain non-linearities
(Wild, Grainge, Wolz, ..)

each antenna
az(timestamps)



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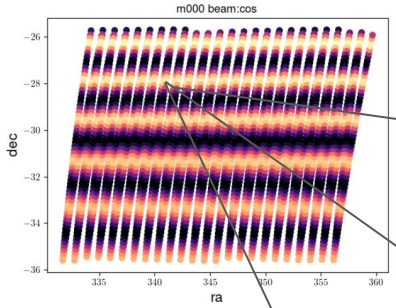

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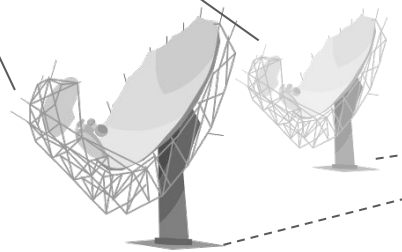
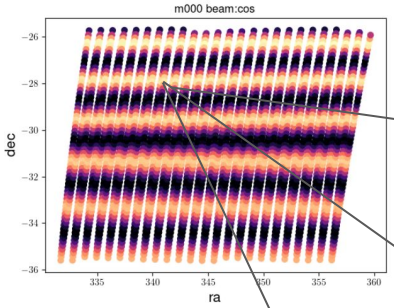


approx great circle distance

Vanwyksvlei

fixed az
of the tower

Hunting RFI details



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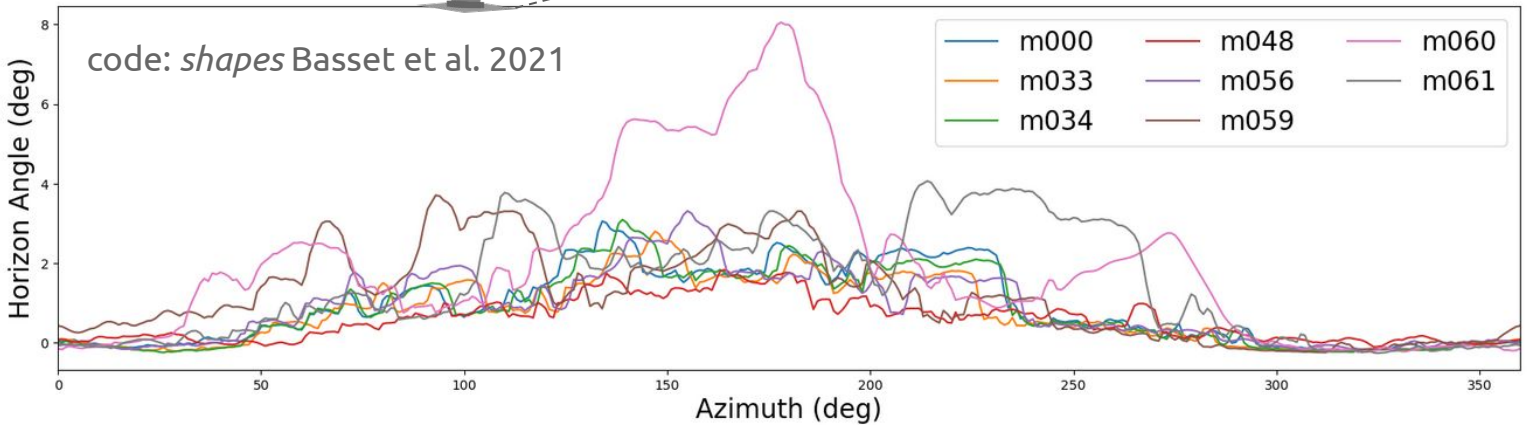
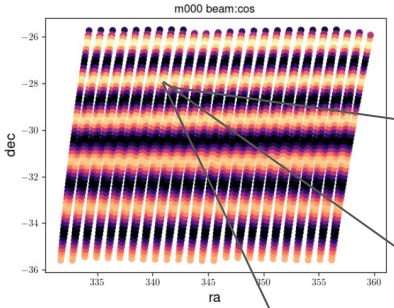


Hunting RFI details



gain non-linearities
(Wild, Grainge, Wolz, ..)

approx great circle distance

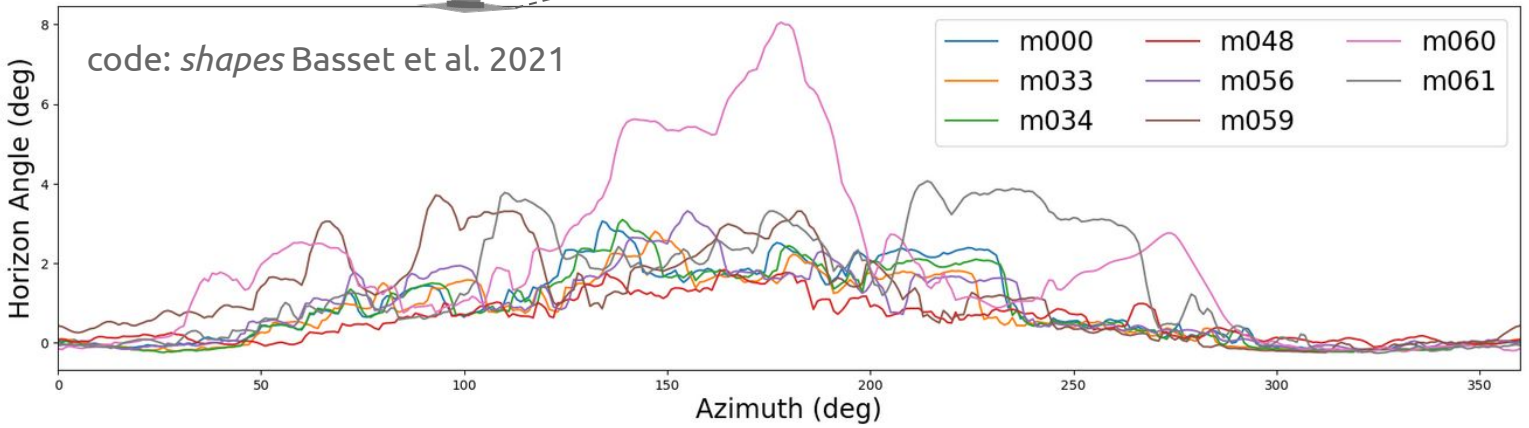
Vanwyksvlei

each antenna
az(timestamps)

fixed az
of the tower

simulation of RFI environment is tricky but useful to test the stability of the pipeline

e.g **Engelbrecht** et al. (2024)



Summary

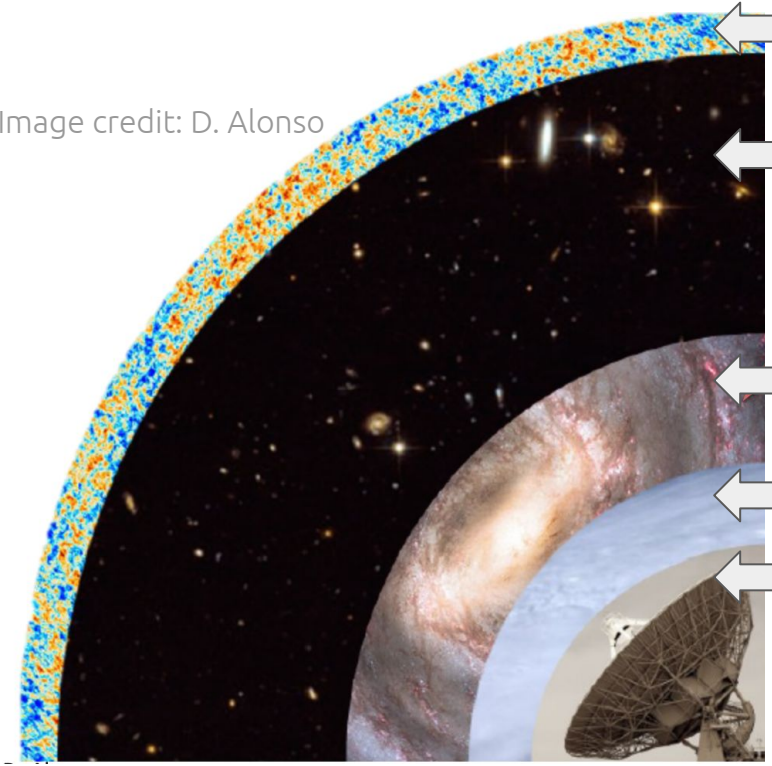


Image credit: D. Alonso

21cm signal

extra-galactic emission

Galactic emission

instrumental and systematic effects

analysis pipeline: TOD, beam, RFI flagging/treatment, calibration, …

Source separation

power spectrum

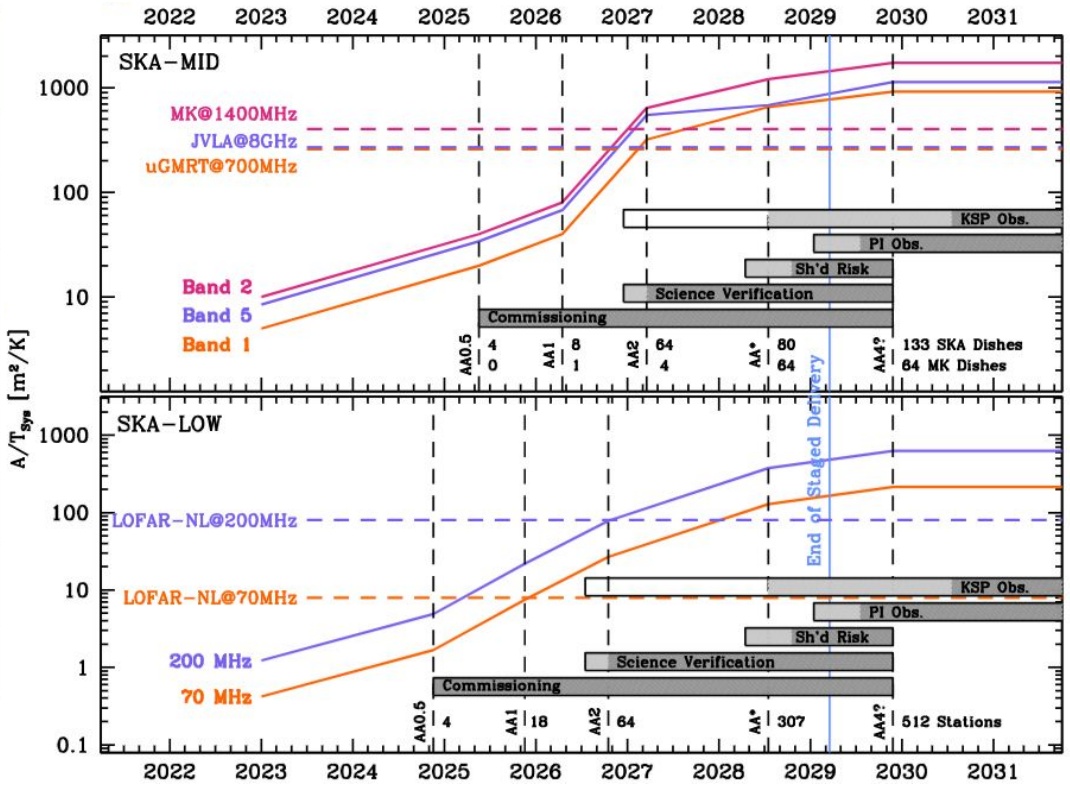
cosmological parameter constraints

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)

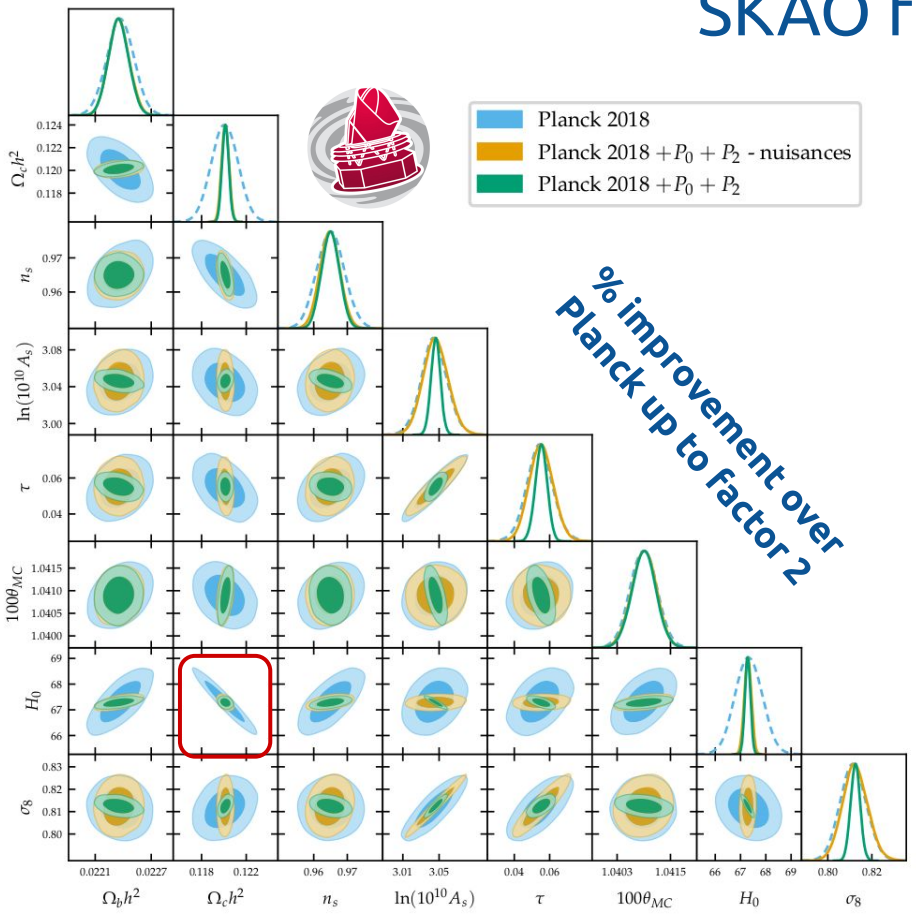
First data release to the community expected in 2026/27 (for science verification)



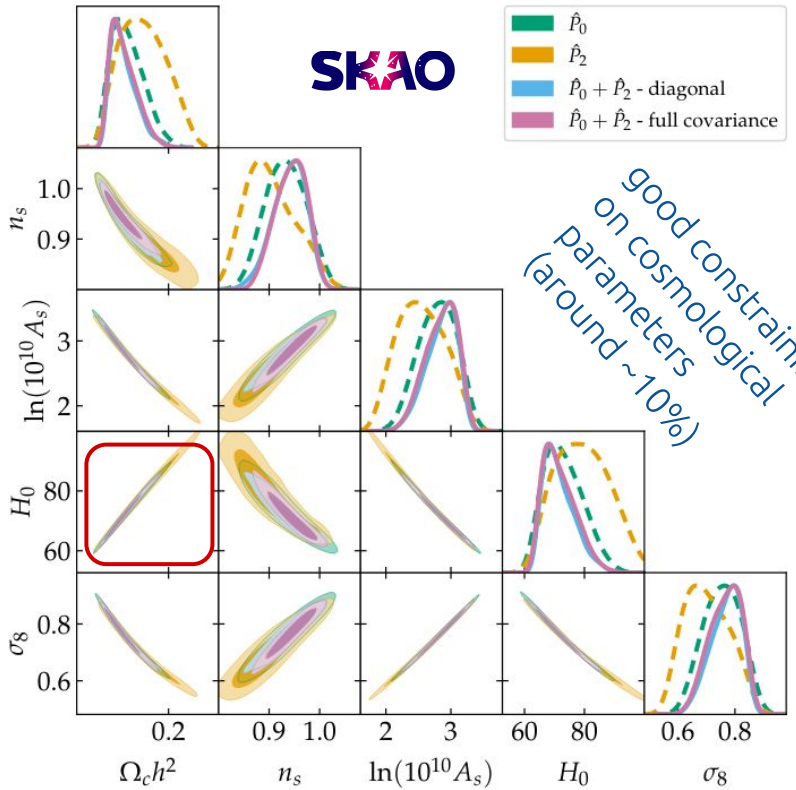
Backup

SKAO forecasts

Berti, MS, Viel 2023a



% improvement over Planck up to factor 2



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

Backup