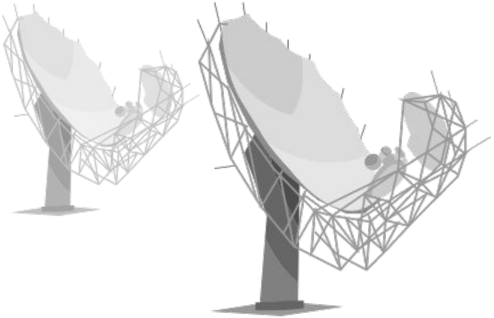
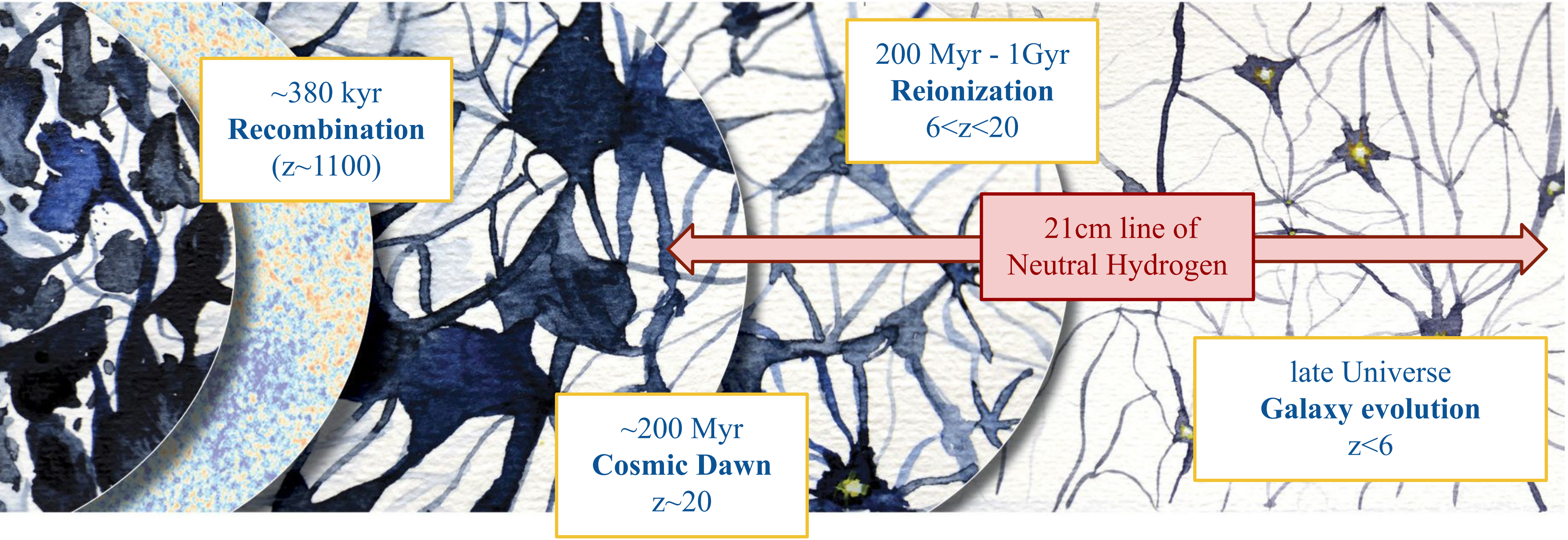
21cm Intensity Mapping: opportunities and challenges on the road to the SKA Observatory



Marta Spinelli

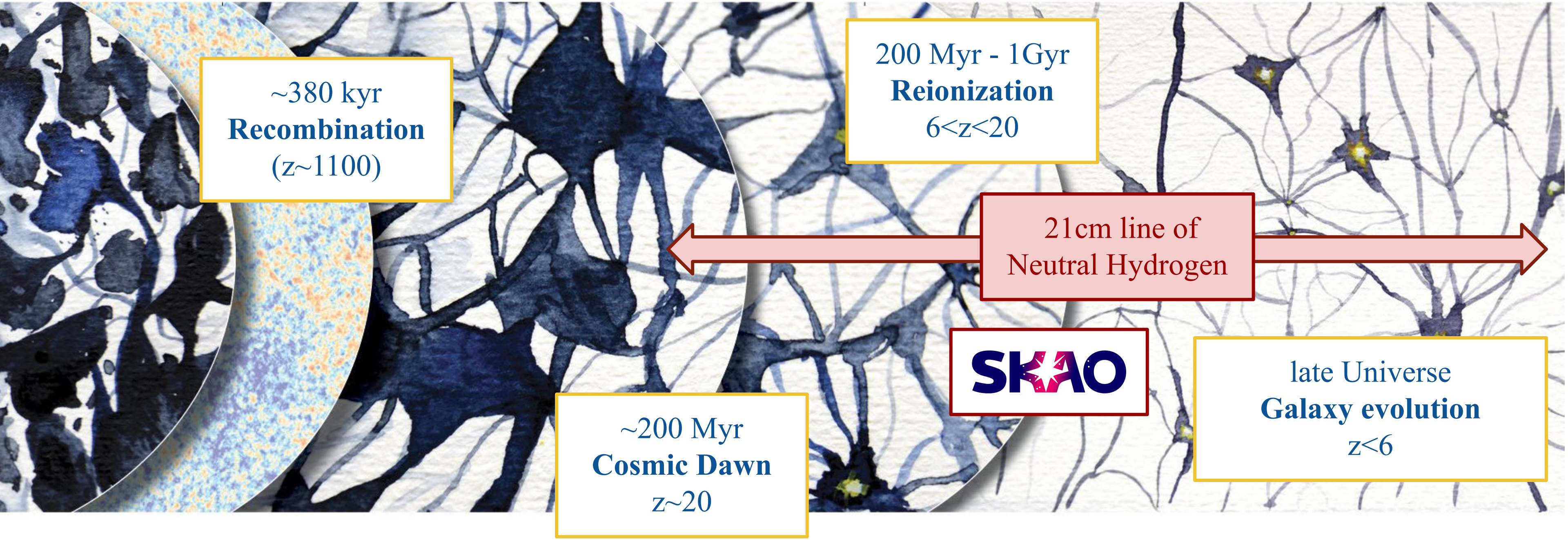
ETH zürich

Neutral hydrogen across time



credit: ESA

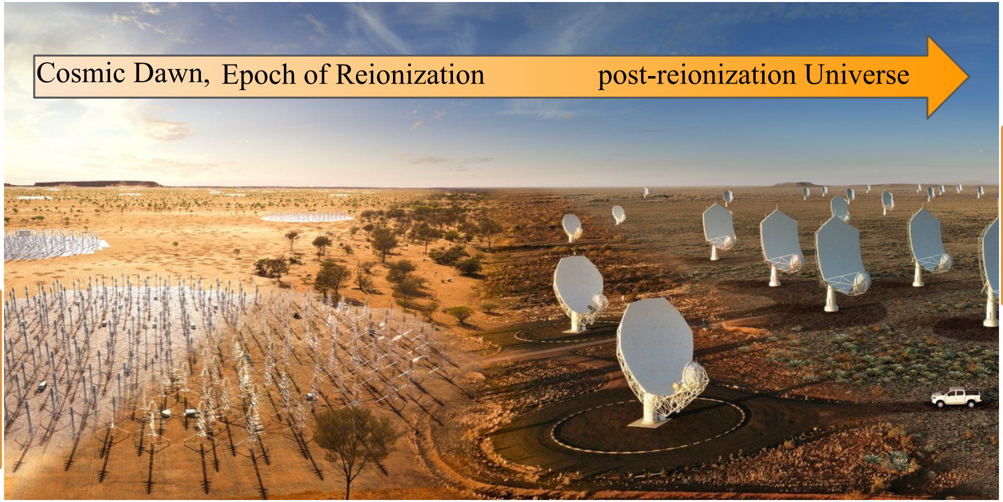
Neutral hydrogen across time



credit: ESA

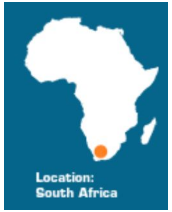
21cm Cosmology

SKA Observatory: cover **all the relevant frequencies** with unprecedented sensitivity



SKA-LOW
50 MHz - 350 MHz
30>z>3

SKA-MID
350 MHz - 13.5 GHz
3>z>0

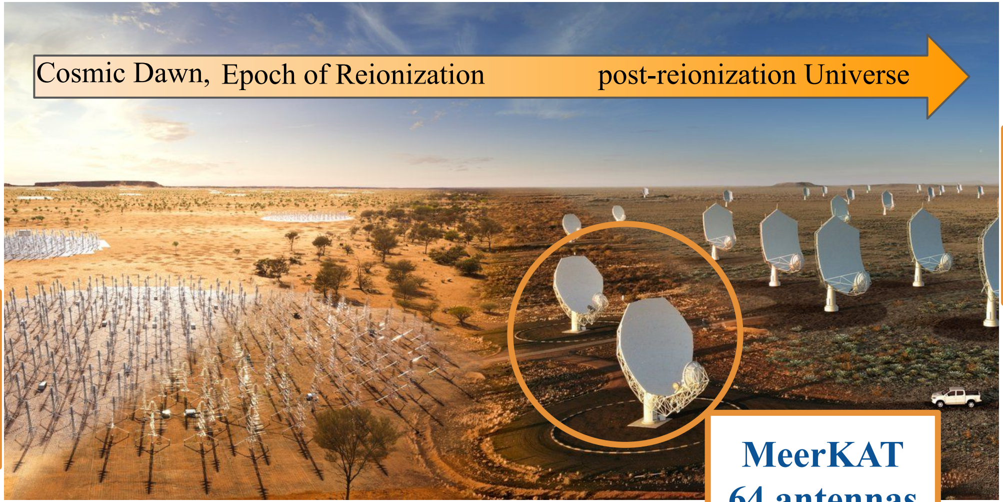


credit: skatelescope.org

21cm Cosmology

SKA Observatory: cover **all the relevant frequencies** with unprecedented sensitivity

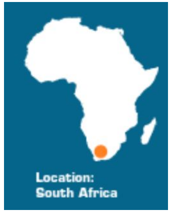
SKA-LOW
50 MHz - 350 MHz
30>z>3



credit: skatelescope.org

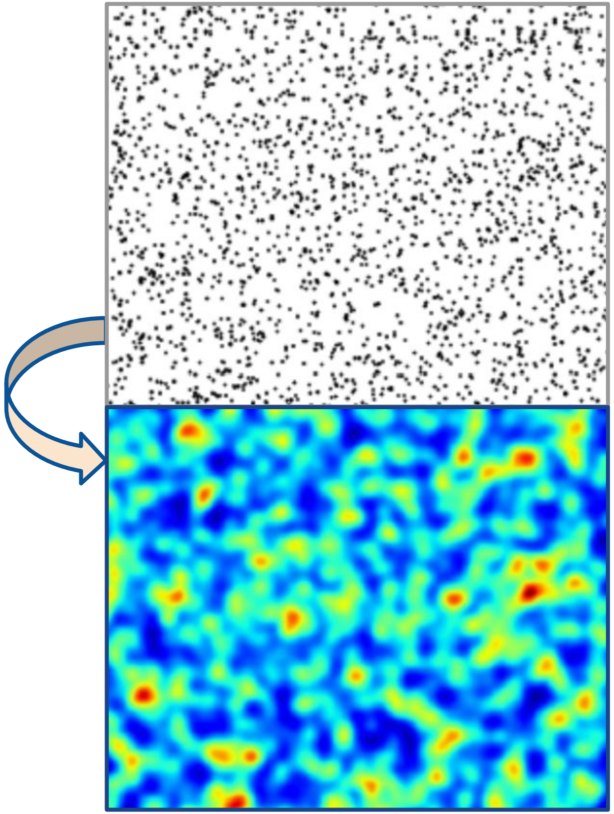
SKA-MID
350 MHz - 13.5 GHz
3>z>0

MeerKAT
64 antennas
1.5>z>0



Intensity Mapping

credit: A. Pourtsidou



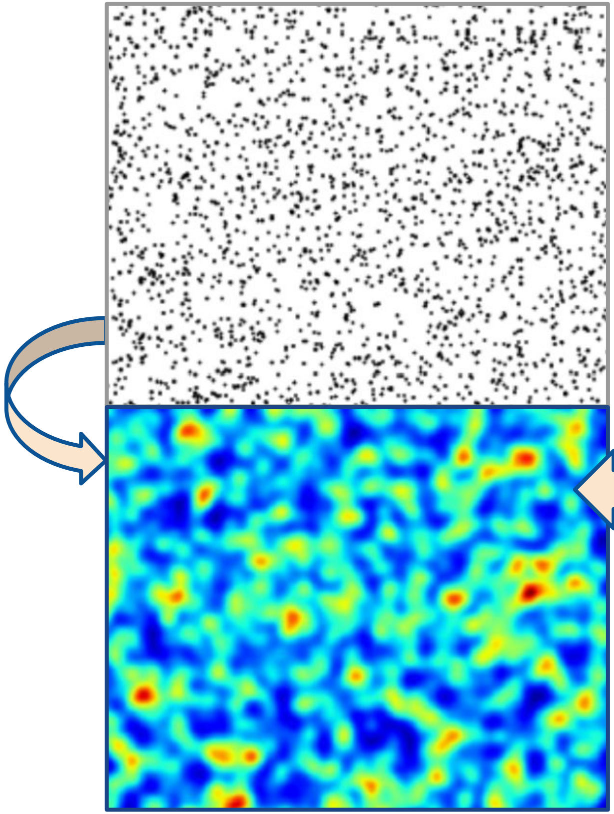
The distribution of **neutral Hydrogen** is a biased tracer of the **matter clustering** *similar to galaxy surveys*

In cosmology, **large scales** are fundamental

How can we efficiently observe cosmological volumes with an interferometer with not enough short baselines?

Intensity Mapping

credit: A. Pourtsidou



The distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**
similar to galaxy surveys

In cosmology, **large scales** are fundamental

How can we efficiently observe cosmological volumes with an interferometer with not enough short baselines?

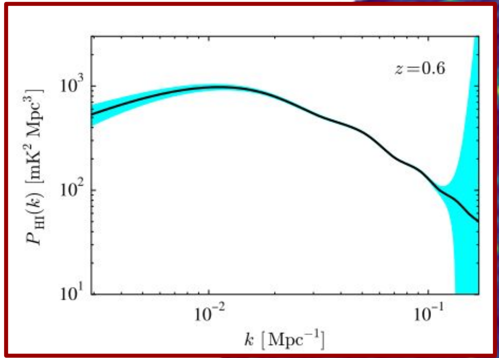
Single dish Intensity Mapping:
SKAO/MeerKAT as a collection of dishes

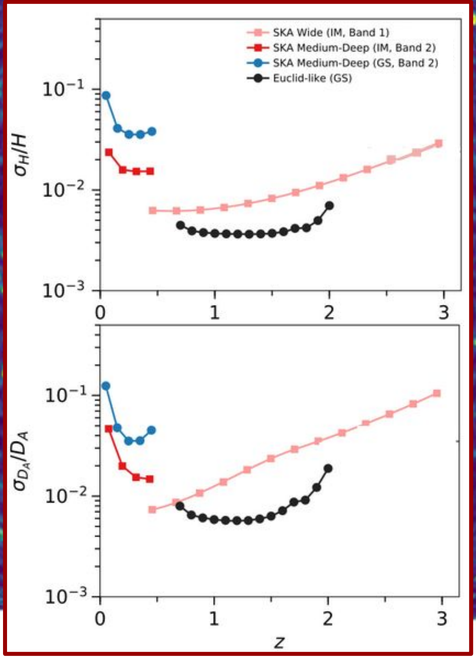
different frequencies, different z
high spectral resolution (tomography)

Key cosmological probe

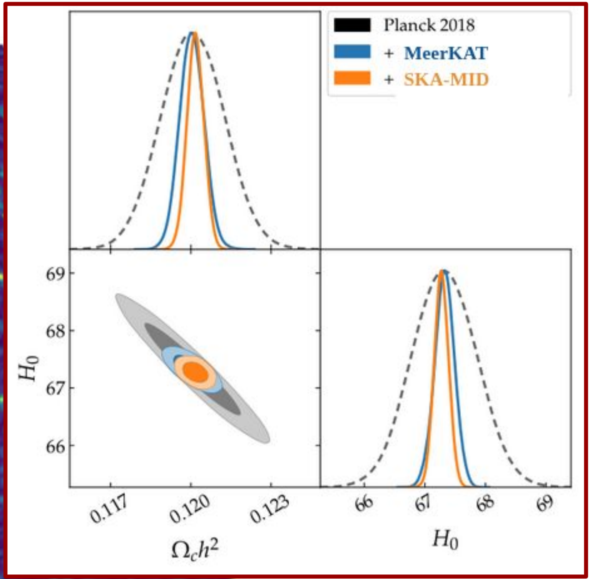
Key cosmological probe

SKA Red Book (2020)





SKA Red Book (2020)



Berti et al. 2022

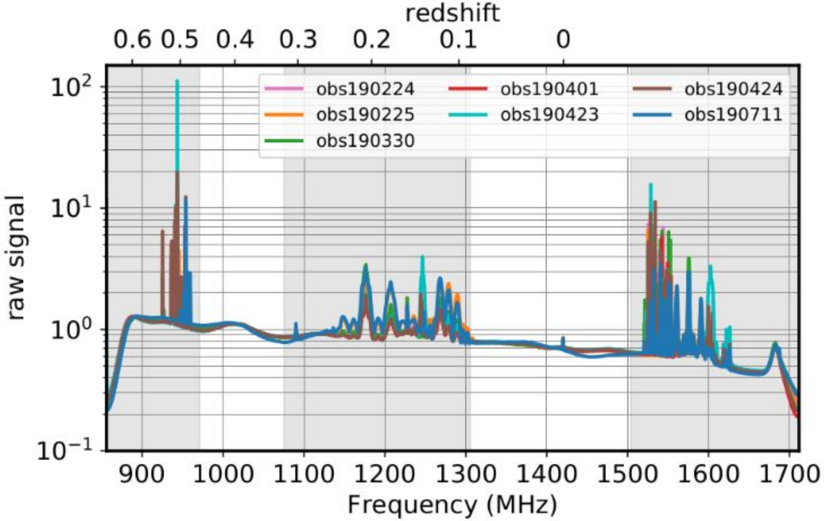
Intensity Mapping with MeerKAT

Science Verification Data

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

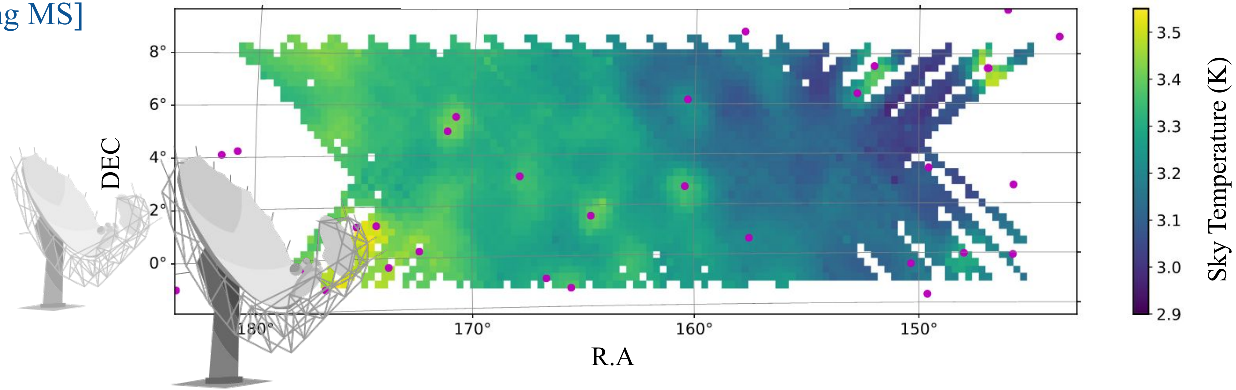
L-band

Wang et al. 2021 [including MS]



MeerKAT observations

Wang et al. 2021
[including MS]

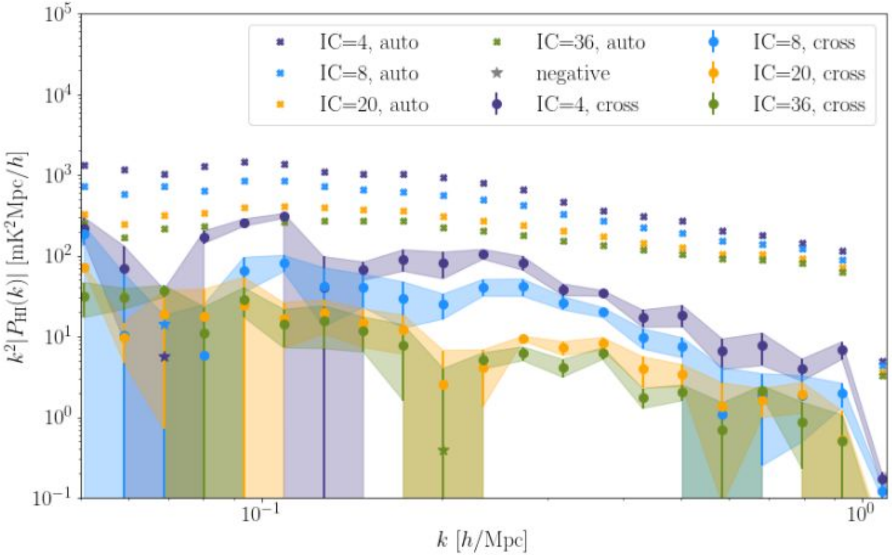


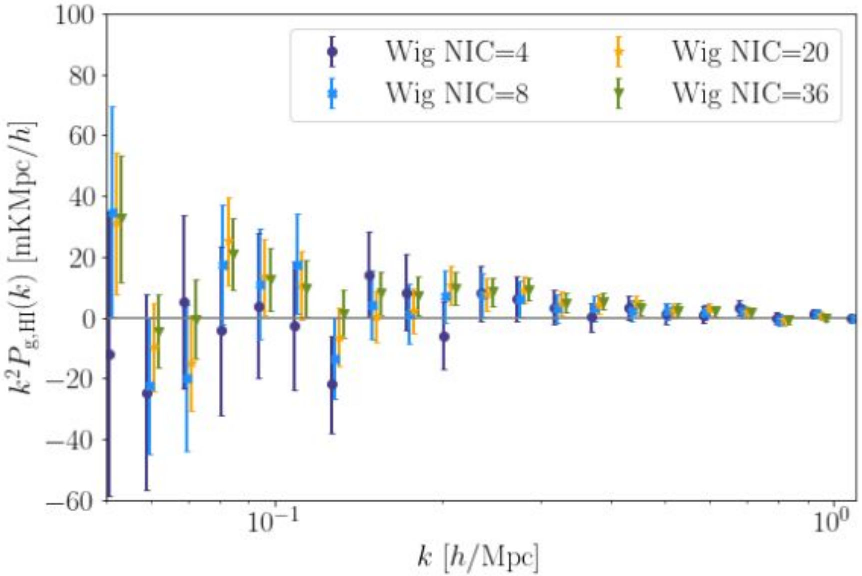
MeerKLASS: 64 MeerKAT antennas used in **single-dish mode**

- ❑ first successful calibration of **intensity mapping data from MeerKAT**
- ❑ multi-level RFI flagging
- ❑ two step calibration: tracking + scanning, with noise diode as relative reference

State of the Art (with GBT)

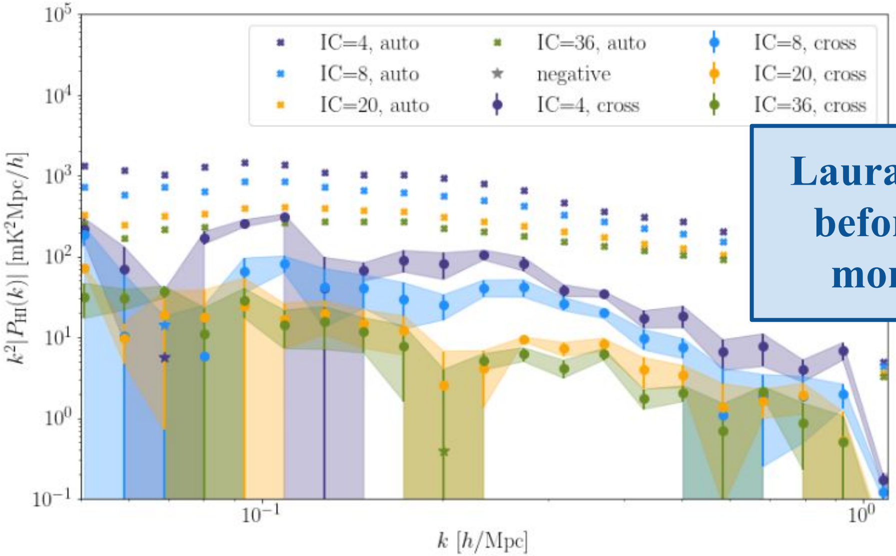
Wolz et al. 2022



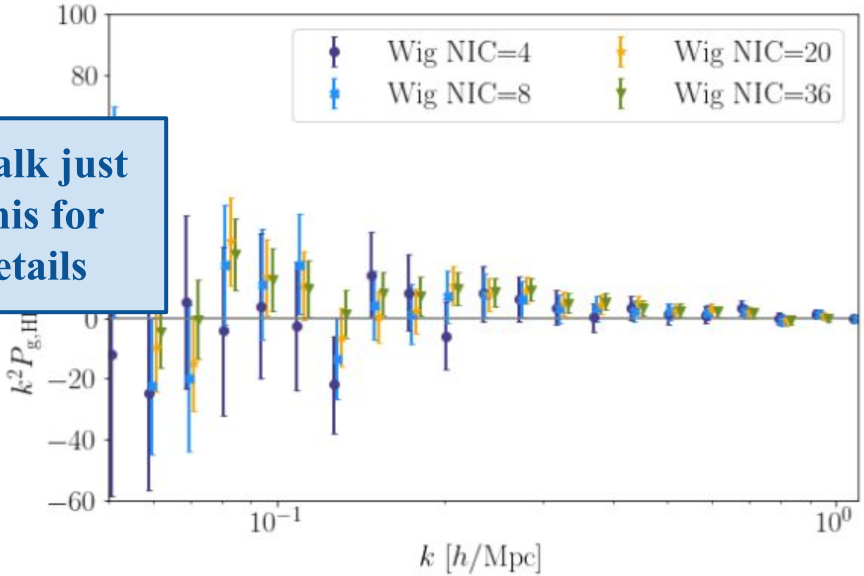


State of the Art (with GBT)

Wolz et al. 2022

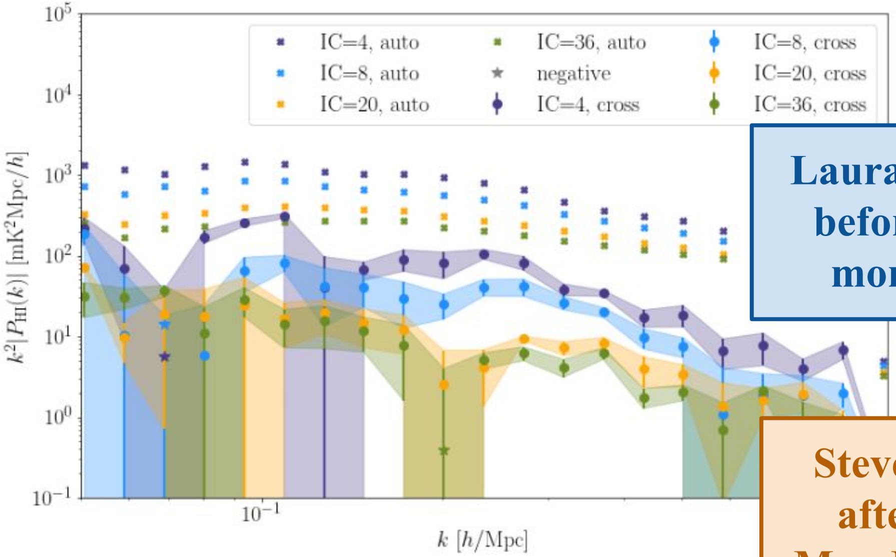


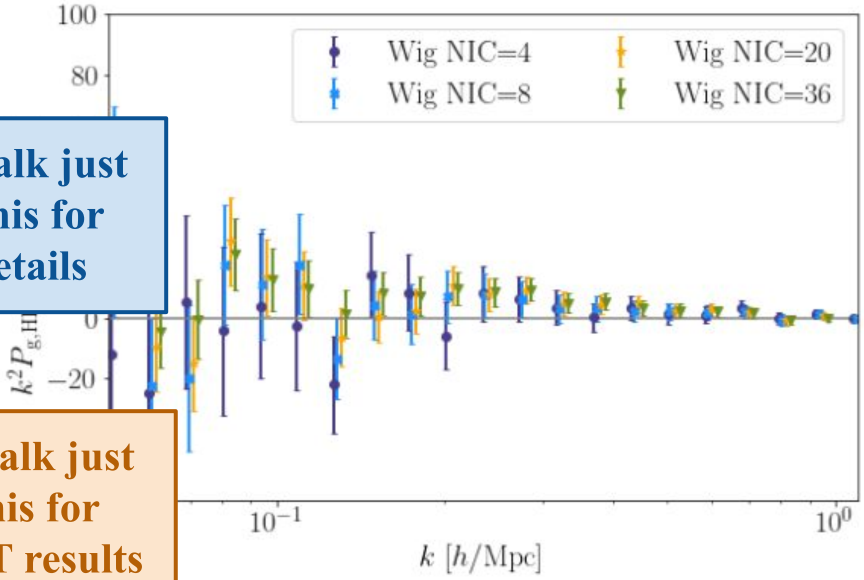
Laura's talk just before this for more details



State of the Art (with GBT)

Wolz et al. 2022



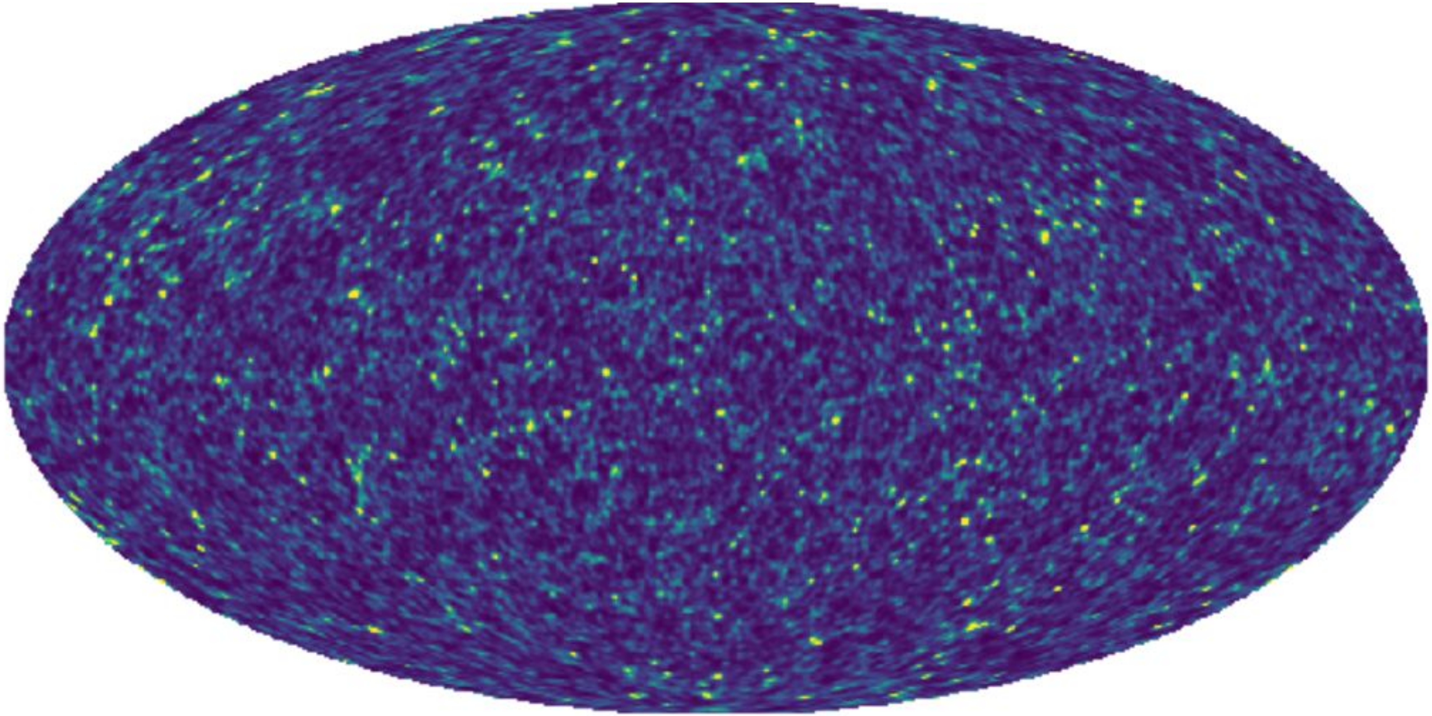


Laura's talk just before this for more details

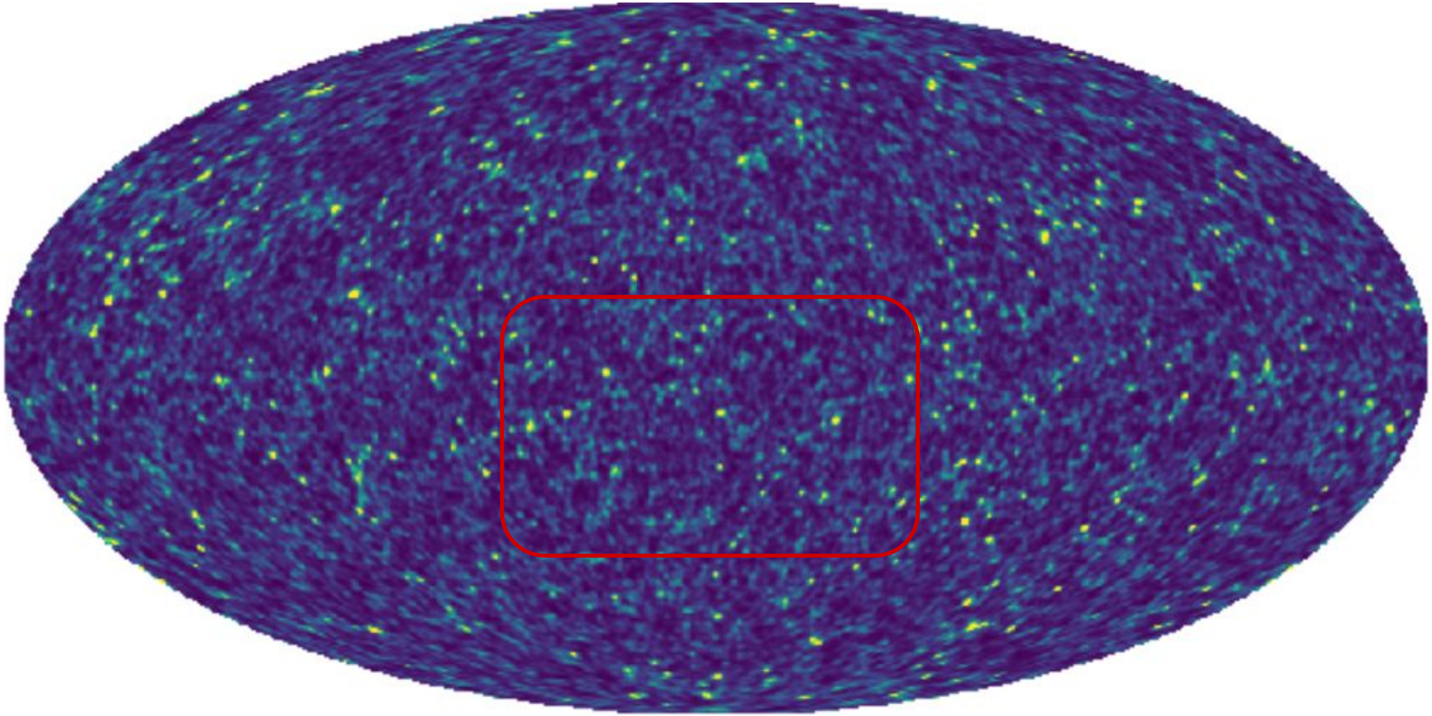
Steve's talk just after this for MeerKAT results

Simulations

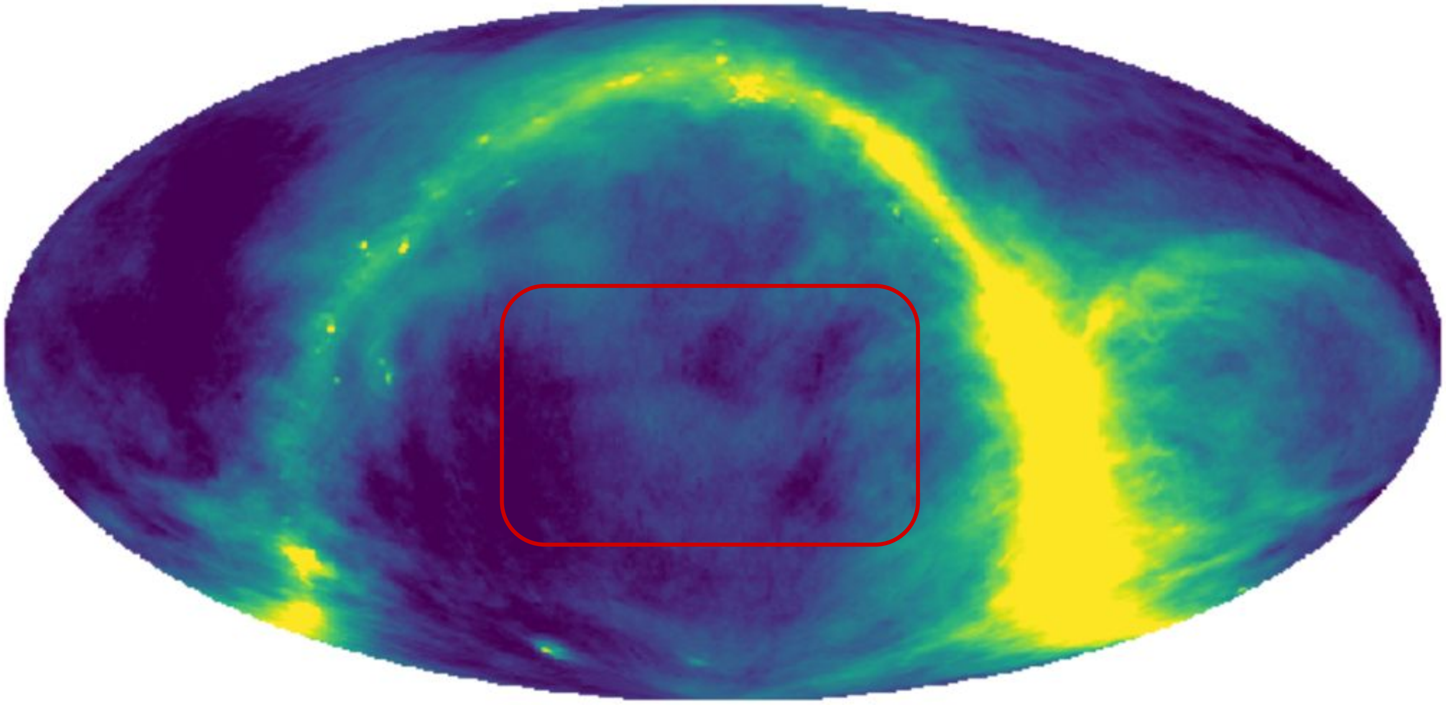
Simulations



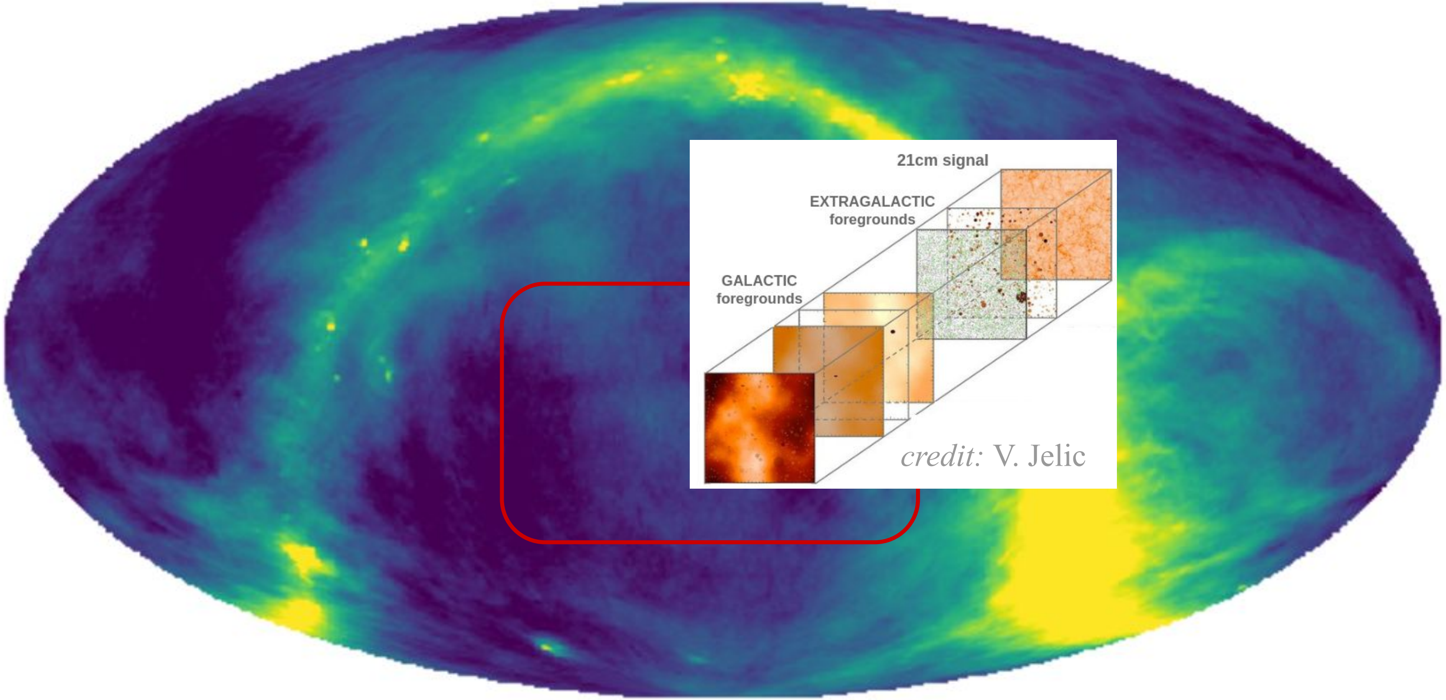
Simulations



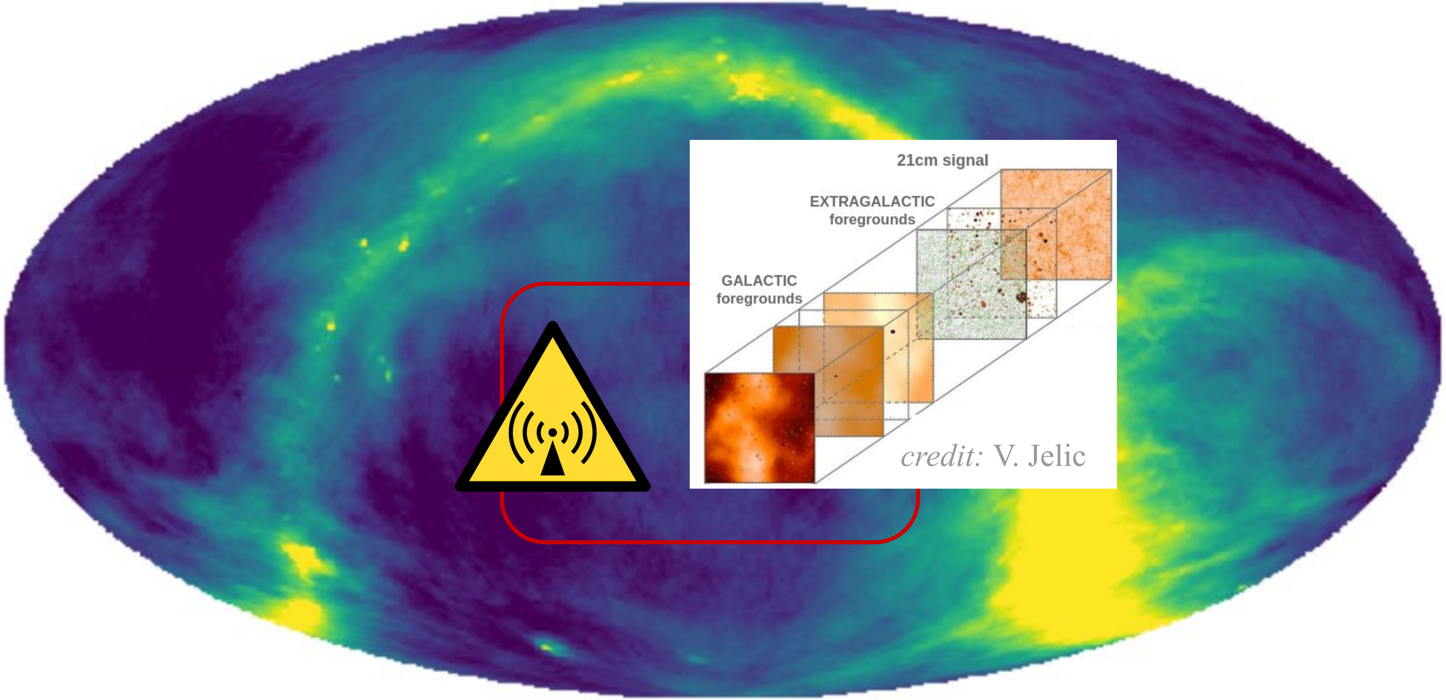
Simulations



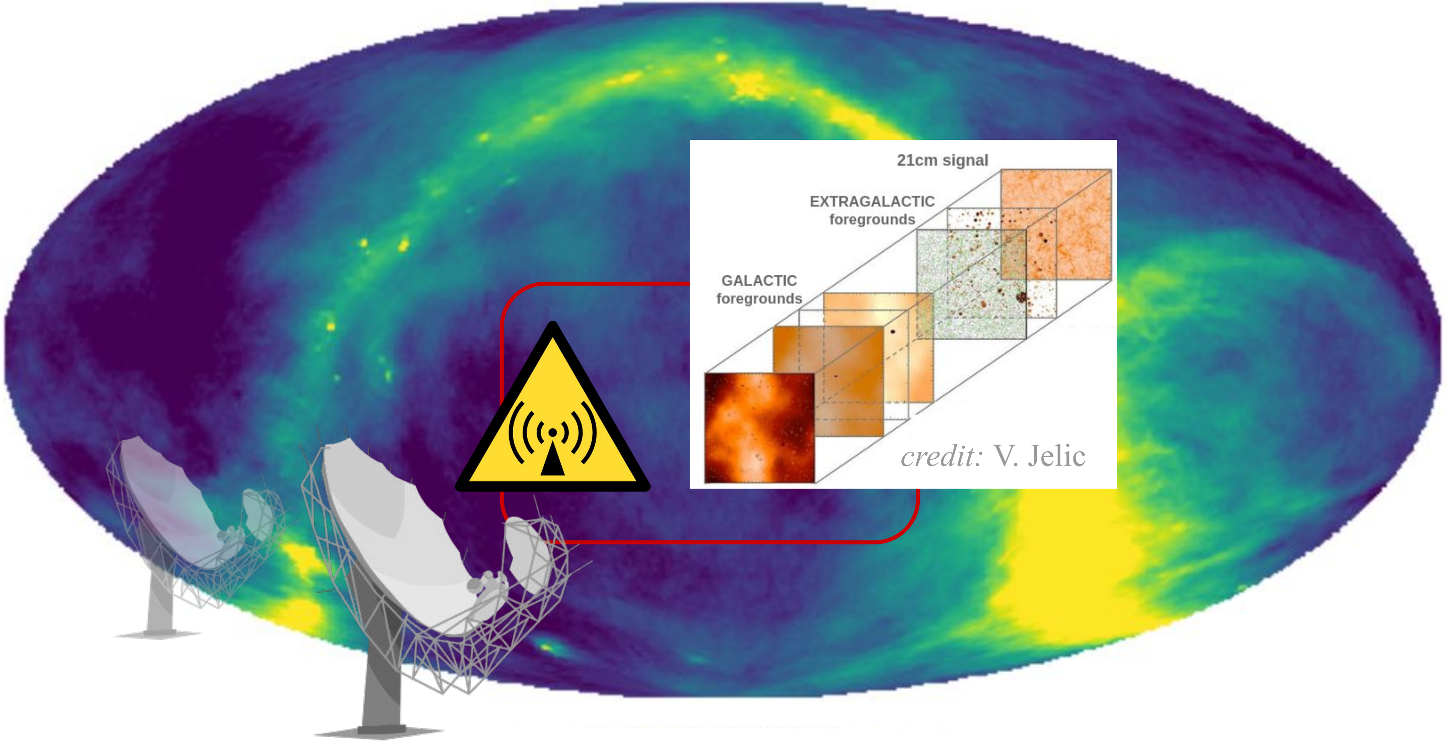
Simulations



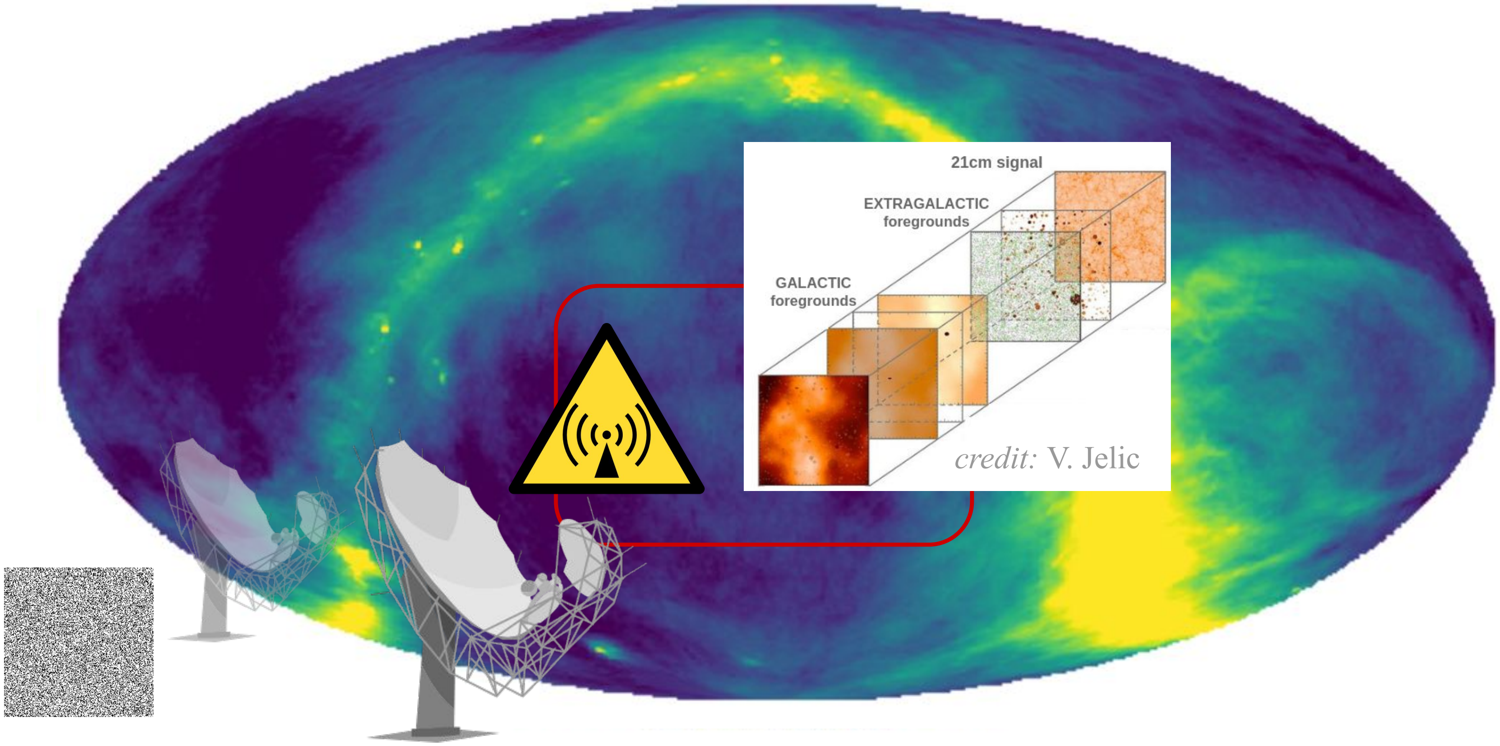
Simulations



Simulations

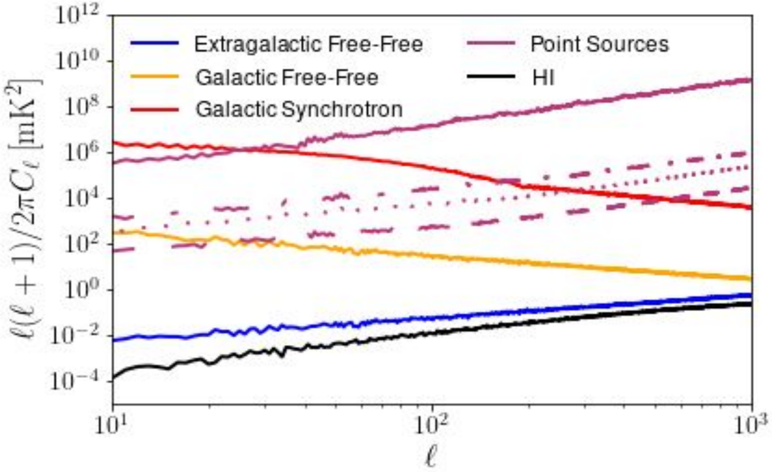


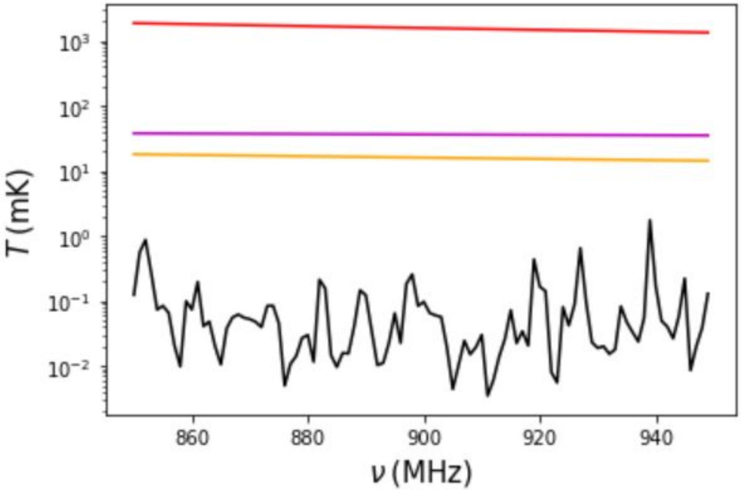
Simulations



Foregrounds

Matshawule, MS et al. 2021





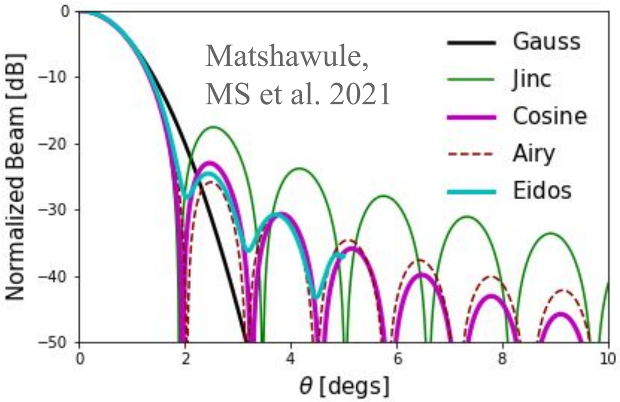
- ❑ orders of magnitude stronger than the 21cm signal and with their proper spatial structure
- ❑ possible improvements to the modeling

Questions:

- ❑ To which extent the properties of the foregrounds can be used to separate them from the pristine **21cm signal**?
- ❑ **What if we add realism to our simulations?** (beam response,noise,RFI,..)

Improving simulations

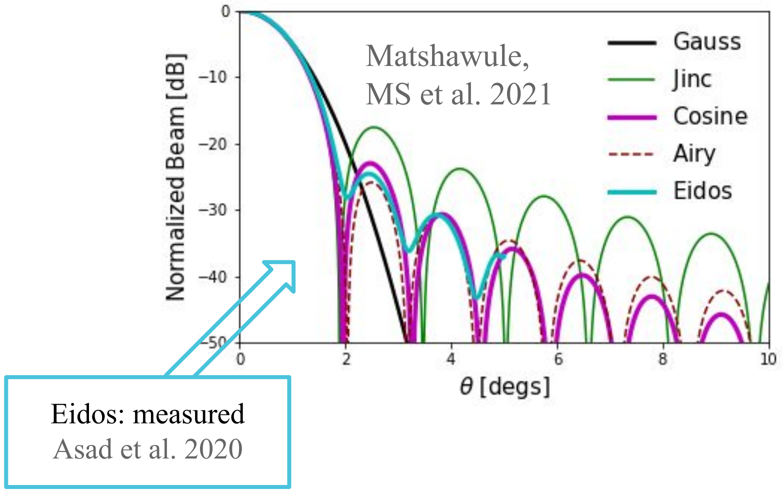
- MeerKAT beam has **side-lobes** (same for SKA-MID)
- a strong point source in the side-lobes contaminates the signal and can complicate the foreground subtraction



Improving simulations

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

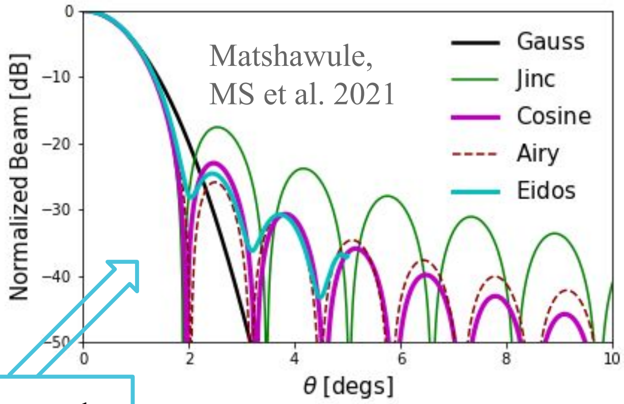
- a strong point source in the side-lobes contaminates the signal and can complicate the foreground subtraction



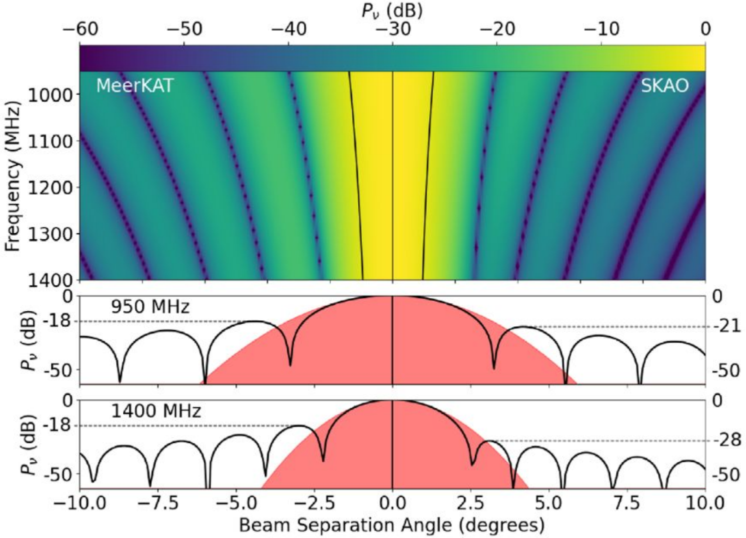
Improving simulations

Airy beam
Harper et al. (2018)

- ❑ MeerKAT beam has **side-lobes** (same for SKA-mid)
- ❑ a strong point source in the side-lobes contaminates the signal and can complicate the foreground subtraction



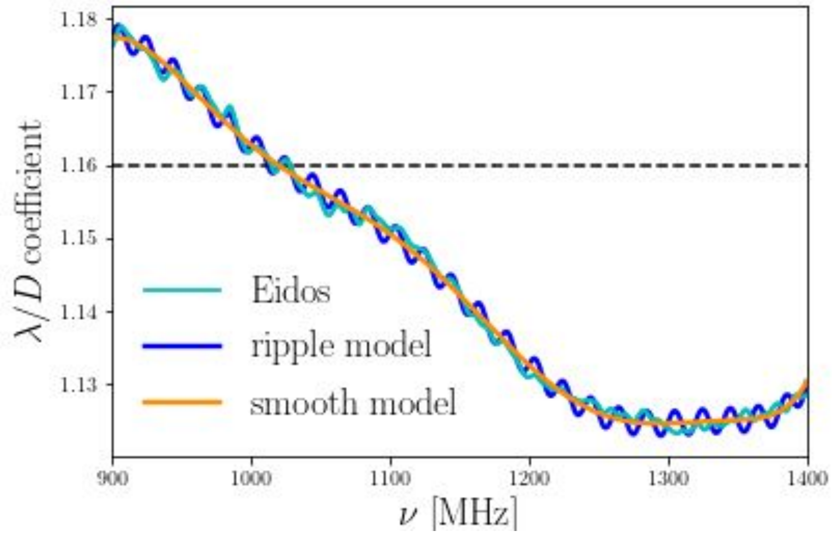
Eidos: measured
Asad et al. 2020



MS et al. 2022

The beam evolves with frequency

Effect of the telescope beam

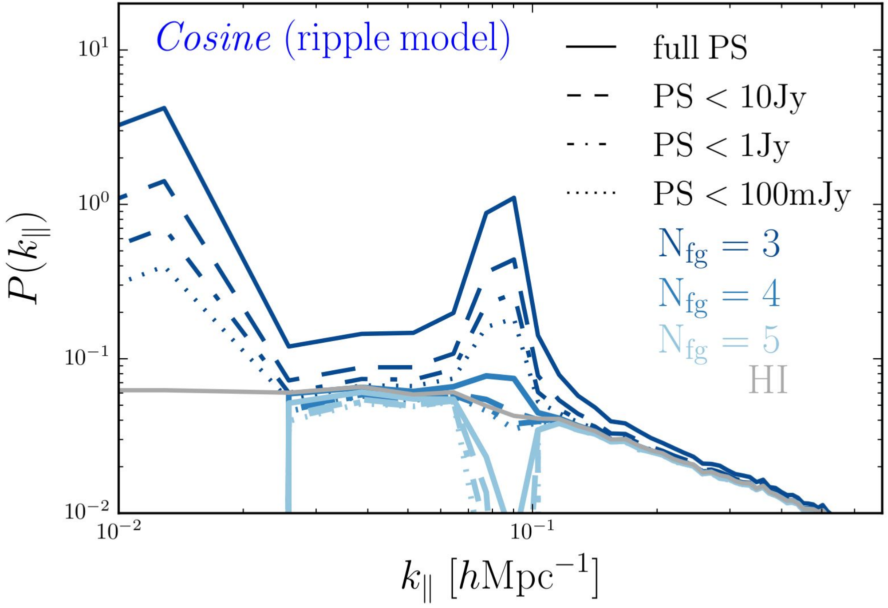


Matshawule, MS et al. 2021

MeerKAT (similarly SKAO):

- ❑ realistic beam side-lobes
- ❑ a **non-trivial frequency evolution**:
  a **smooth** deviation from λ/D
  and a ~20 MHz **sinusoidal** trend

Effect of the telescope beam

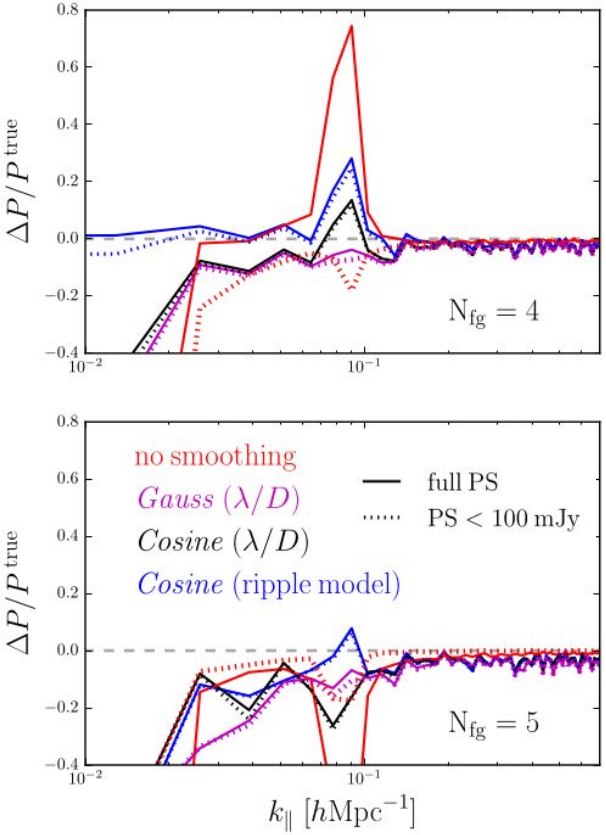


Matshawule, MS et al. 2021

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

- **point sources** and synchrotron spatial structures coupled with the beam **complicate the cleaning**
- residual foregrounds or overcleaning depending on the maximum flux of the PS and Nfg

Beam deconvolution



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

- ❑ Careful **beam-deconvolution** alleviates the problem
- ❑ need to be careful for precision cosmology

Matshawule, MS et al. 2021

Foreground subtraction challenge

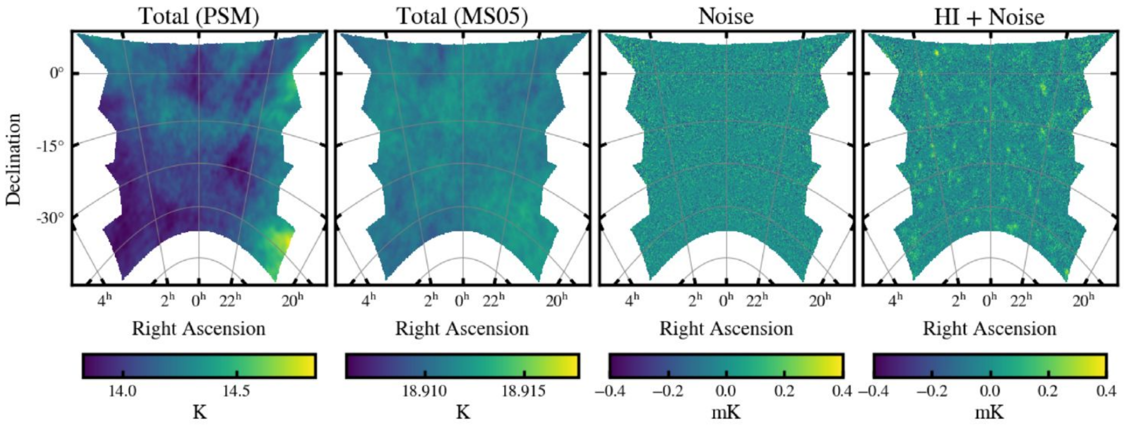
(subset of) **SKA IM Focus Group**

Isabella 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

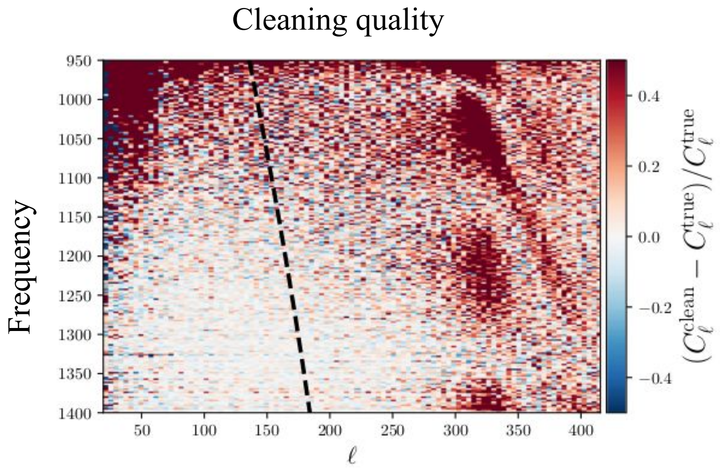


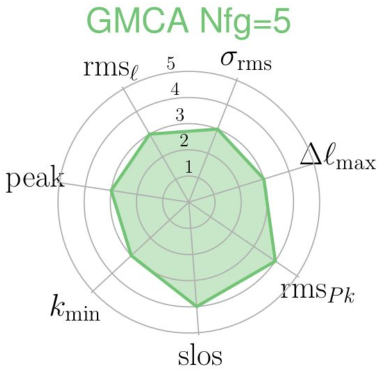
given IM data now, would your favorite method extract the cosmological signal?

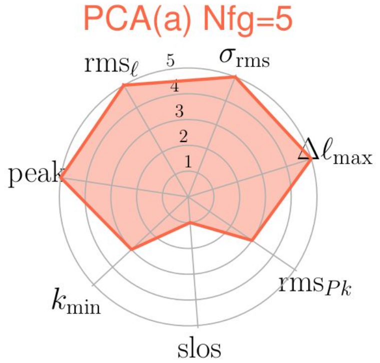
Foreground subtraction challenge

- 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

Towards the SKA Observatory

We have:

21cm intensity mapping signal detected only *in cross-correlation*

Simulations that are still not a very good representation of the data

Cleaning methods that have not been tested in realistic scenarios

We would like:

More and better data

More realistic simulations mimicking the data

More sophisticated cleaning methods tested on more realistic simulations

Final aim:

A 21cm **(auto) power spectrum detection** validated with realistic simulations and tested with various and robust cleaning methods

Towards the SKA Observatory

MeerKAT

- ❑ new L band data under analysis (41 x 1.5 h)
- ❑ UHF band available (could go to higher redshift)
- ❑ improving RFI flagging and calibration

Work in progress:

More and better data

More realistic simulations mimicking the data

More sophisticated cleaning methods tested on more realistic simulations

Towards the SKA Observatory

MeerKAT

- ❑ new L band data under analysis (41 x 1.5 h)
- ❑ UHF band available (could go to higher redshift)
- ❑ improving RFI flagging and calibration

Work in progress:

More and better data

More realistic simulations mimicking the data

- ❑ new 21cm signal sims
- ❑ asymmetries in the beam
- ❑ improved polarization leakage
- ❑ RFI flagging and calibration errors effects
- ❑ better PS model

More sophisticated cleaning methods tested on more realistic simulations

Towards the SKA Observatory

Work in progress:

MeerKAT

- ❑ new L band data under analysis (41 x 1.5 h)
- ❑ UHF band available (could go to higher redshift)
- ❑ improving RFI flagging and calibration

More and better data

More realistic simulations mimicking the data

- ❑ new 21cm signal sims
- ❑ asymmetries in the beam
- ❑ improved polarization leakage
- ❑ RFI flagging and calibration errors effects
- ❑ better PS model

More sophisticated cleaning methods tested on more realistic simulations

We are planning a new foreground cleaning challenge!