Status of 21cm global signal measurements

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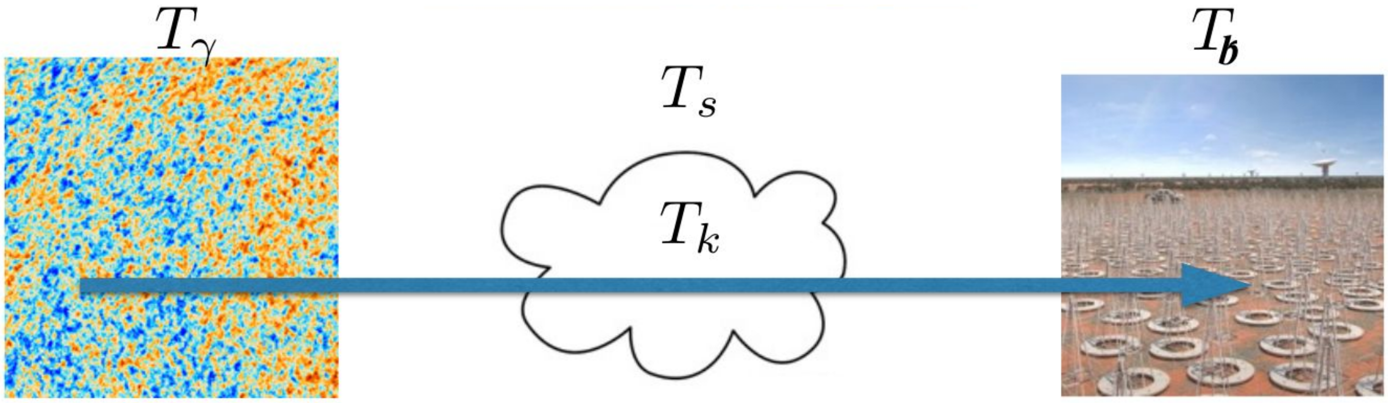
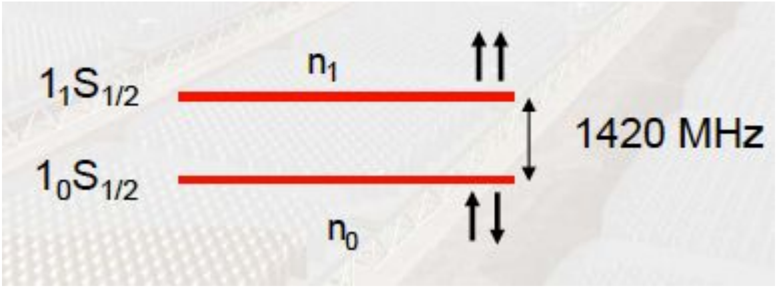
21cm signal



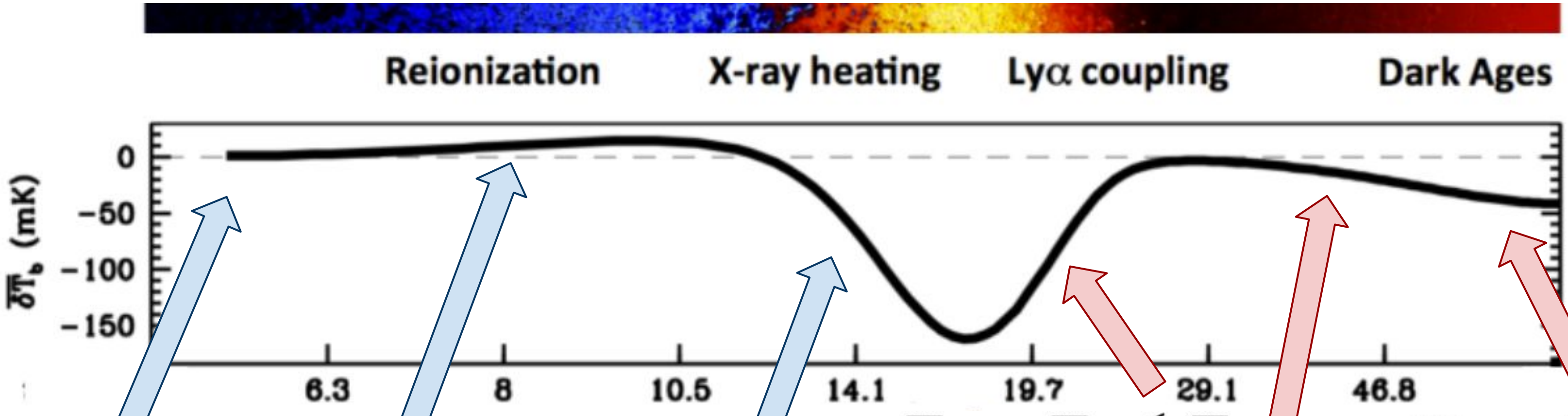
3 fundamental temperatures:

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



21cm signal as the Universe evolves

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



HI traces
the large-scale structure

Ionising source
fluctuations
dominated by x_HI

$T_k = T_s \gtrsim T_\gamma$

IGM hotter than CB:
emission ->absorption

$T_k \sim T_s \lesssim T_\gamma$

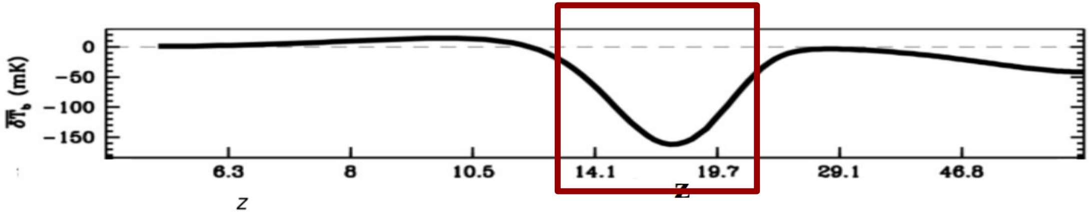
Universe expands,
IGM less dense
collisional decoupling

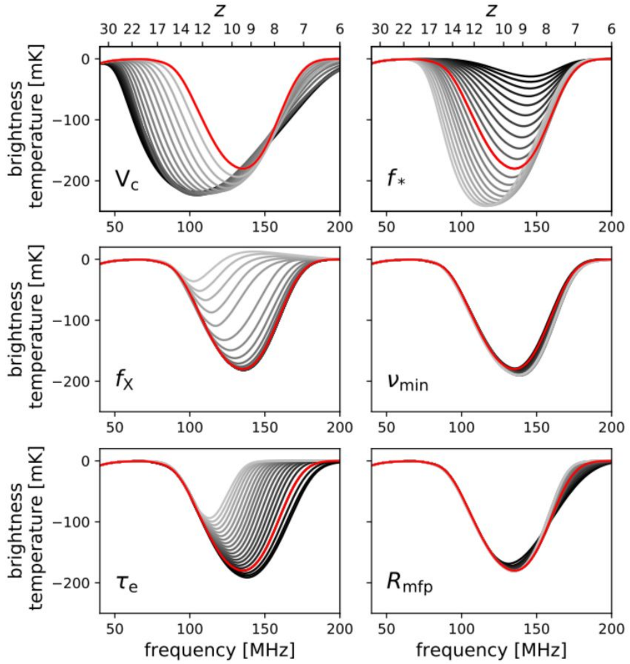
$T_k < T_s \lesssim T_\gamma$

$T_k = T_s \lesssim T_\gamma$

IGM dense:
collisional coupling

An absorption feature





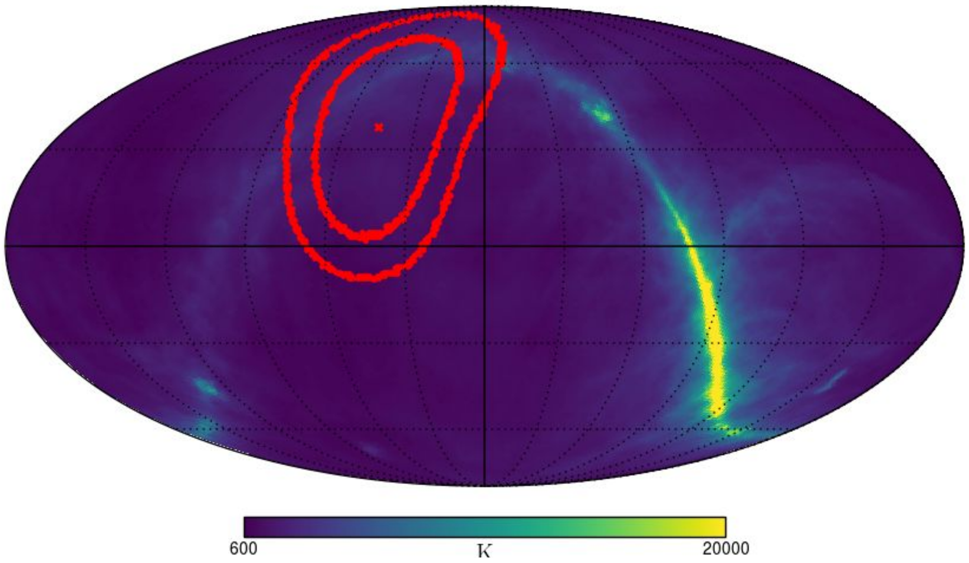
Monsalve et al. (2019)

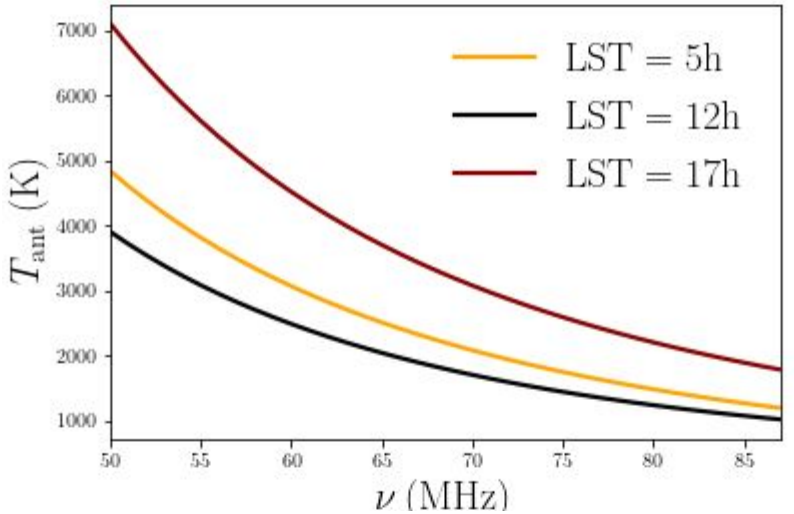
- interplay between Lyα coupling and X-ray heating
- regulated by cosmological and astrophysical parameters

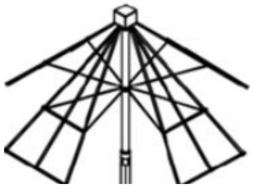
  interesting constraining power

- important input for power spectrum detection
  e.g. Gehlot et al. 2020, Mertens et al. 2023

Global signal observations



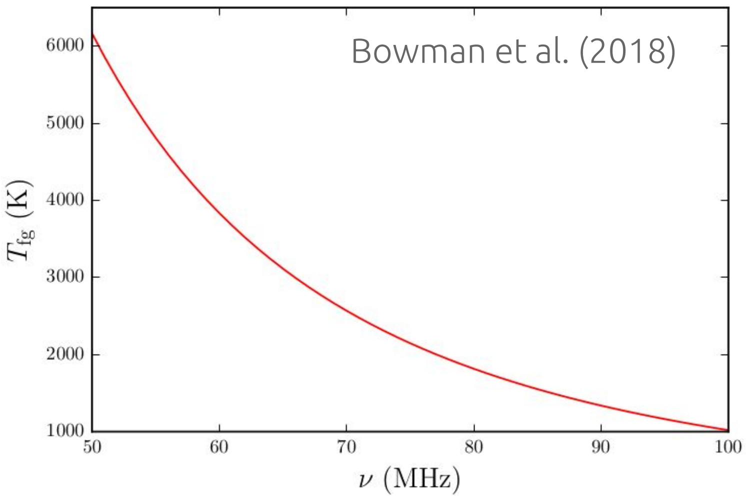


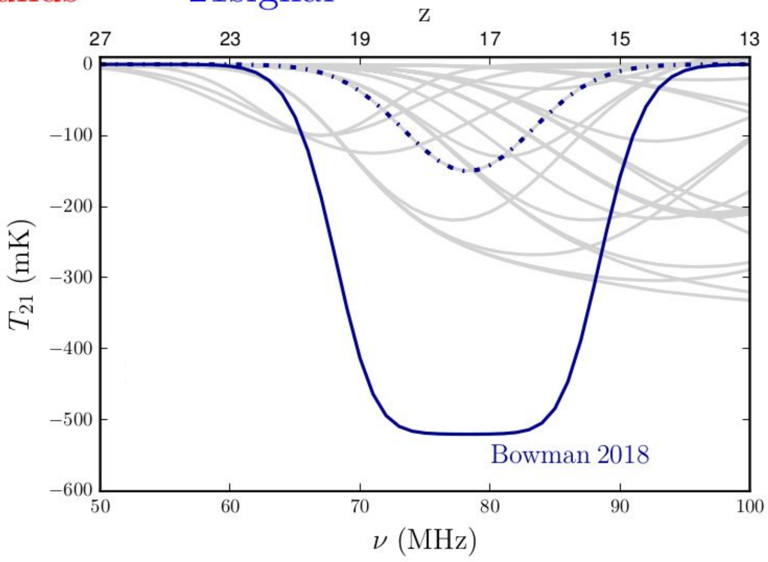


$$T_{\rm obs}(\nu) = \frac{\int_\Omega T_{\rm sky}(\nu,\Omega)B(\nu,\Omega)d\Omega}{\int_\Omega B(\nu,\Omega)d\Omega}$$

A (simple) sky model

$$T_{\mathrm{sky}} = T_{\mathrm{foregrounds}} + T_{\mathrm{21signal}}$$





foreground contamination
modeled with a n-term log pol

21cm signal
modeled as a (gaussian) absorption feature

A (simple) sky model

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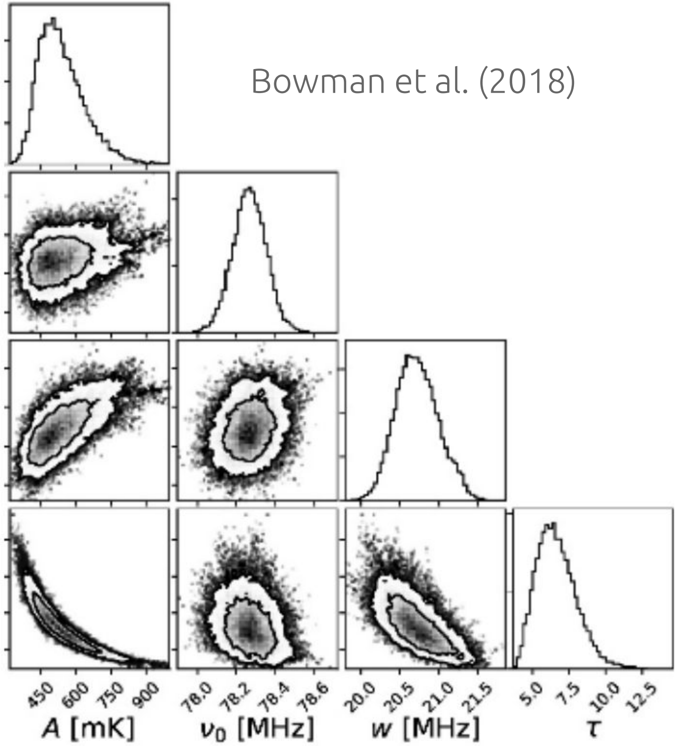
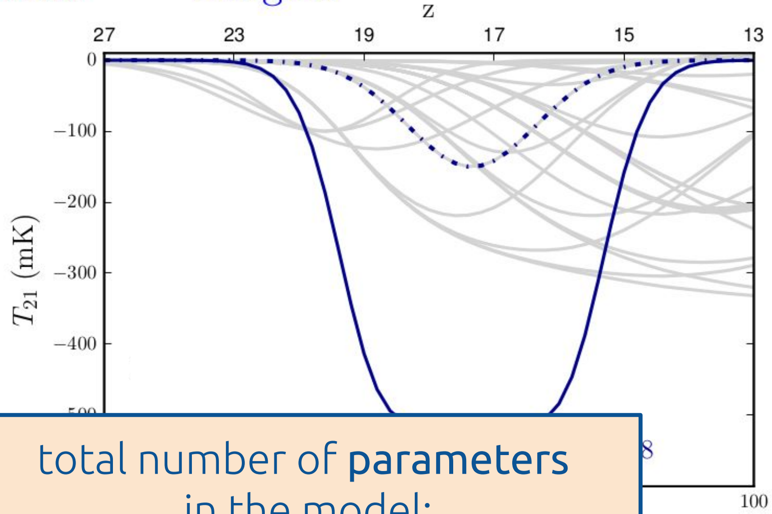


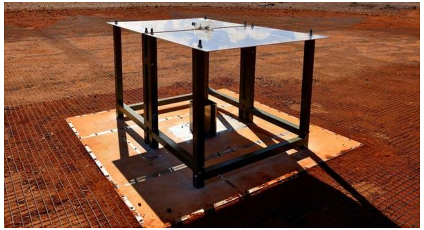
Bowman et al. (2018)

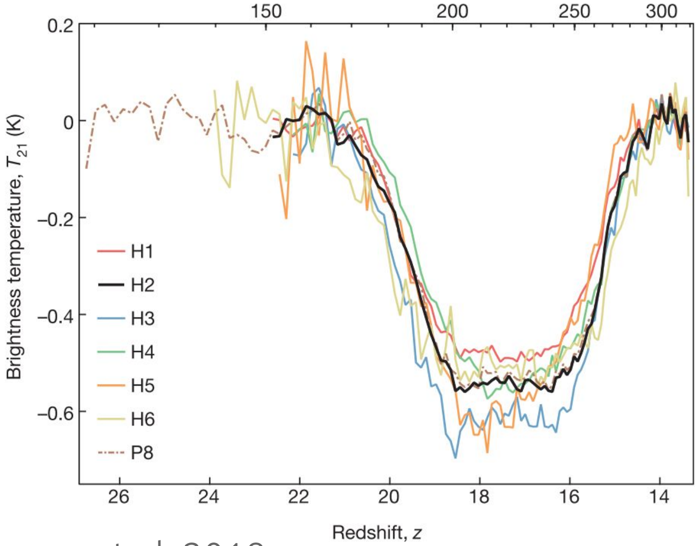


total number of **parameters**
in the model:
N (foregrounds, typically 5) +
3 or 4 (signal)

Current status in a nutshell

EDGES

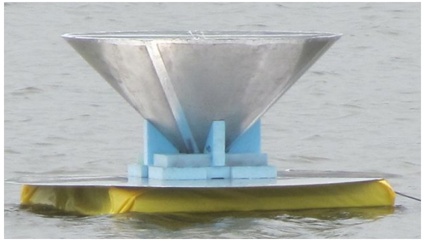


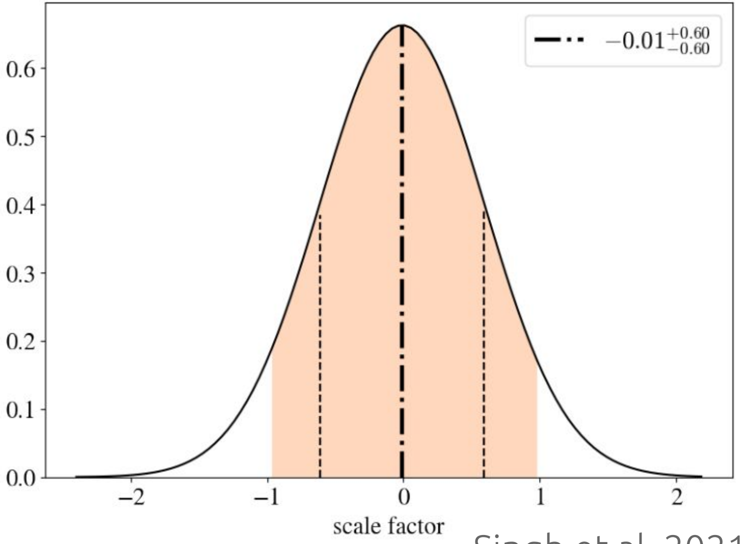


Bowman et al. 2018

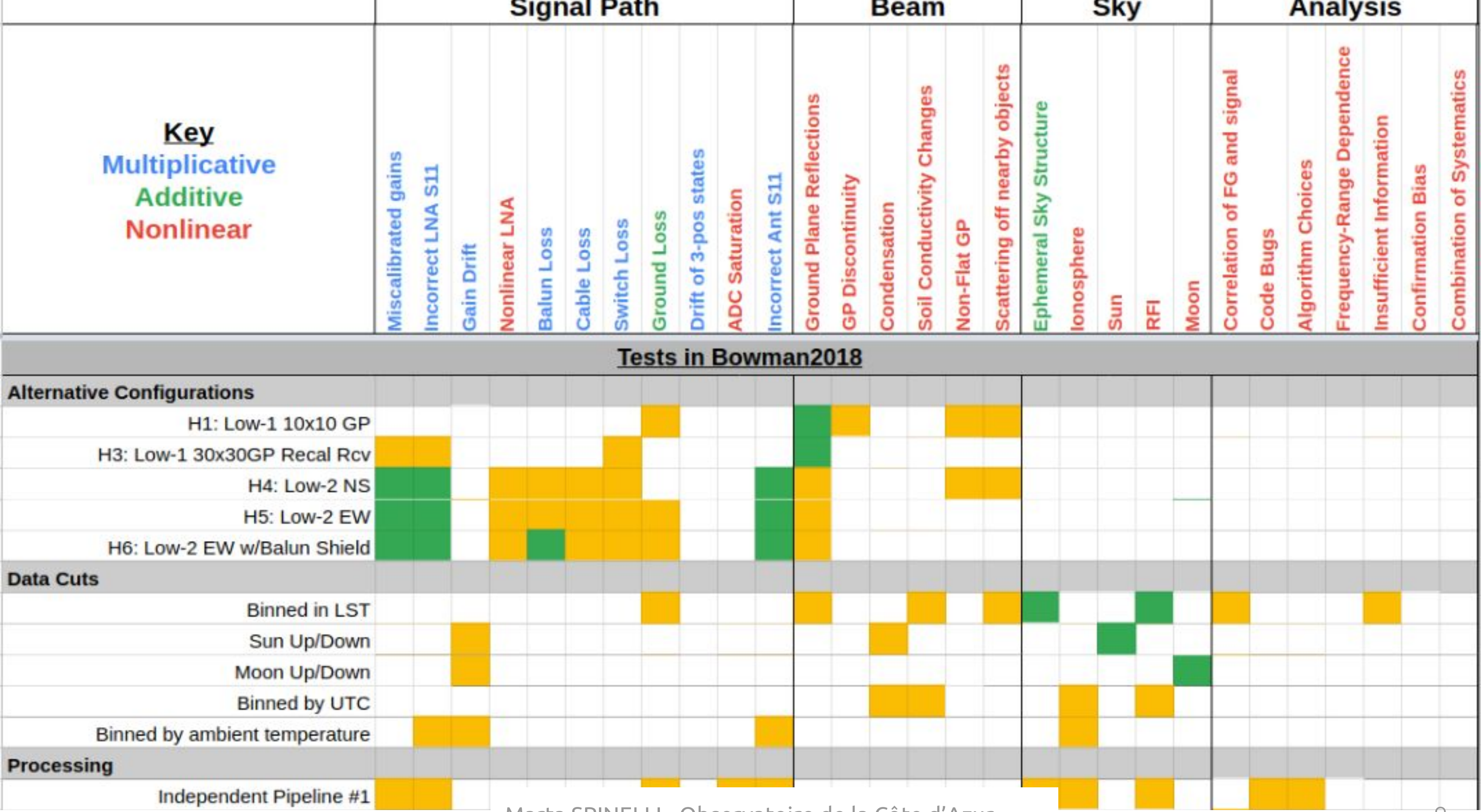
VS.

SARAS3





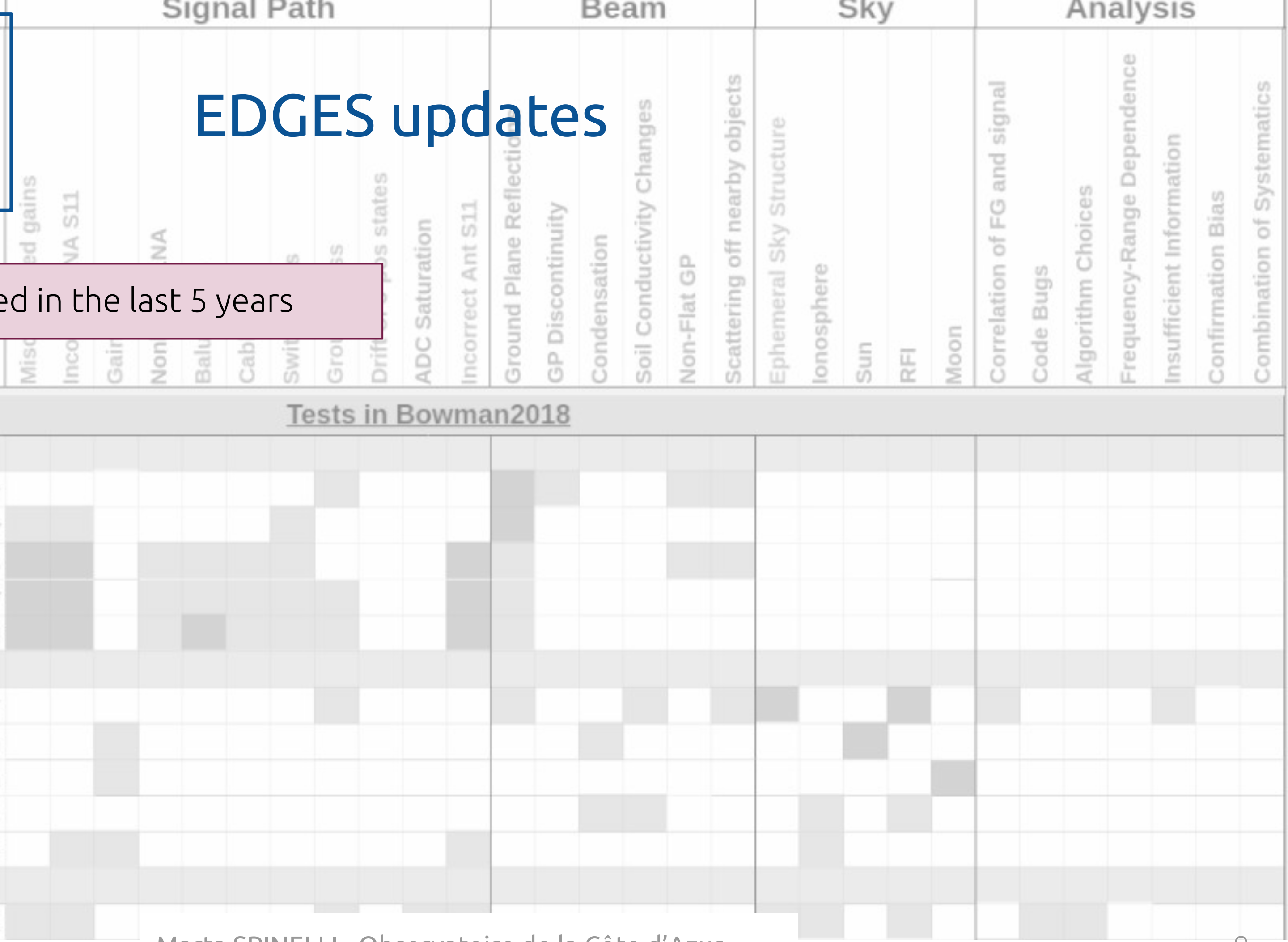
Singh et al. 2021


Signal Path
Beam
Sky
Analysis
Key
Multiplicative
Additive
Nonlinear
Miscalibrated gains
Incorrect LNA S11
Gain Drift
Nonlinear LNA
Balun Loss
Cable Loss
Switch Loss
Ground Loss
Drift of 3-pos states
ADC Saturation
Incorrect Ant S11
Ground Plane Reflections
GP Discontinuity
Condensation
Soil Conductivity Changes
Non-Flat GP
Scattering off nearby objects
Ephemeral Sky Structure
Ionosphere
Sun
RFI
Moon
Correlation of FG and signal
Code Bugs
Algorithm Choices
Frequency-Range Dependence
Insufficient Information
Confirmation Bias
Combination of Systematics
Tests in Bowman2018
Alternative Configurations
H1: Low-1 10x10 GP
H3: Low-1 30x30GP Recal Rcv
H4: Low-2 NS
H5: Low-2 EW
H6: Low-2 EW w/Balun Shield
Data Cuts
Binned in LST
Sun Up/Down
Moon Up/Down
Binned by UTC
Binned by ambient temperature
Processing
Independent Pipeline #1

EDGES updates

Steve Murray (SNS -MSCA) the expert in the room

A lot of stress-tests passed in the last 5 years



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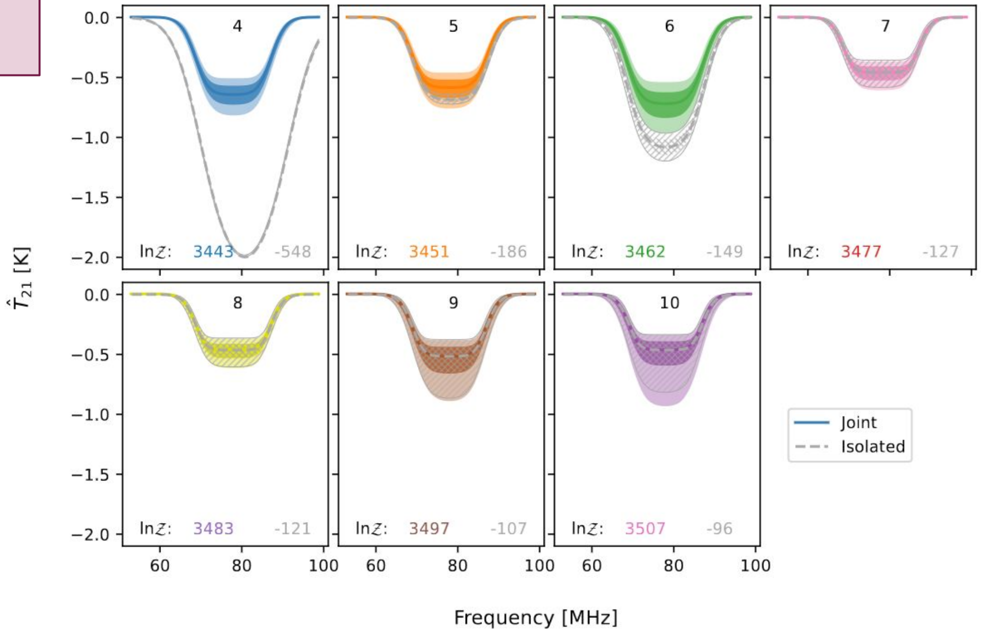
EDGES updates

A lot of stress-tests passed in the last 5 years

Bayesian Receiver Calibration (>50 parameters)
Murray et al. 2022
NOT dominant contribution to uncertainties

new, open-source data processing pipeline
validated on Bowman et al. 2018 data
Murray&Mahesh

Scattering from nearby objects
Rogers et al. 2022



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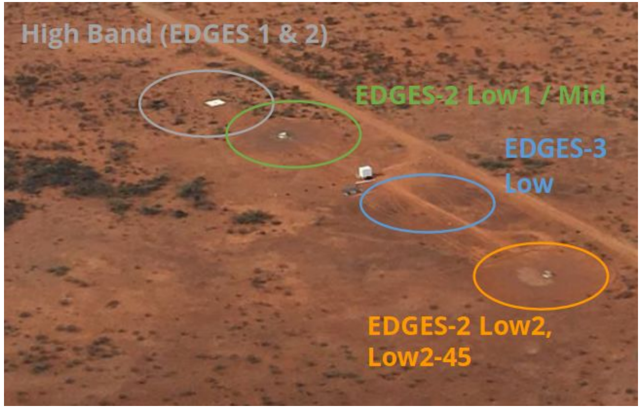
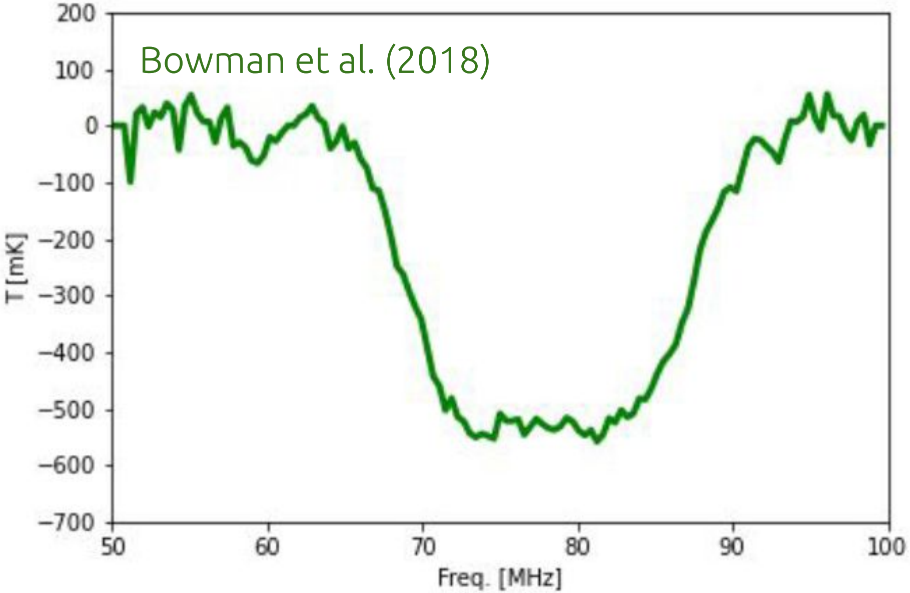
EDGES-3





- Less chromatic beam (50x50m ground plane)
- Changes in design
- In-situ, regular, calibration
- Larger usable bandwidth
- More portable design

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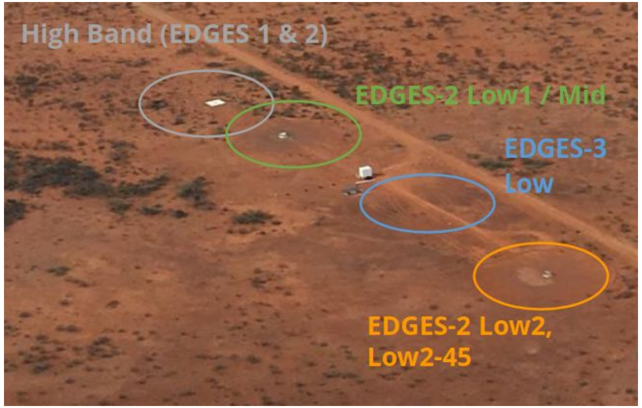
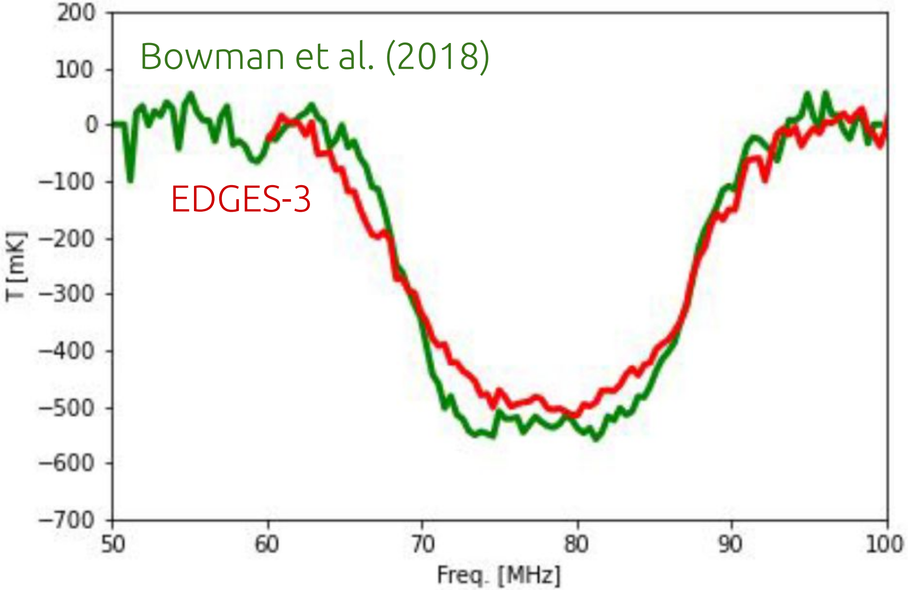
EDGES-3





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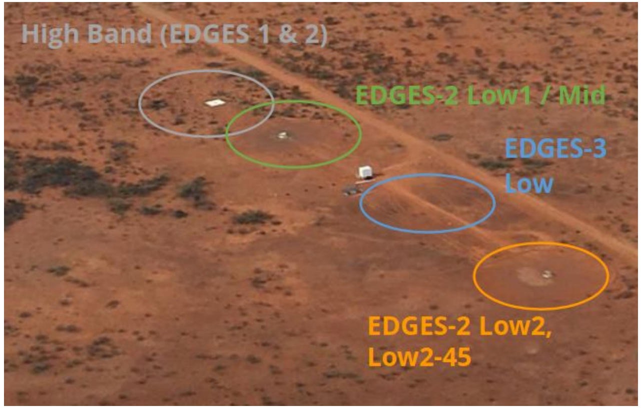

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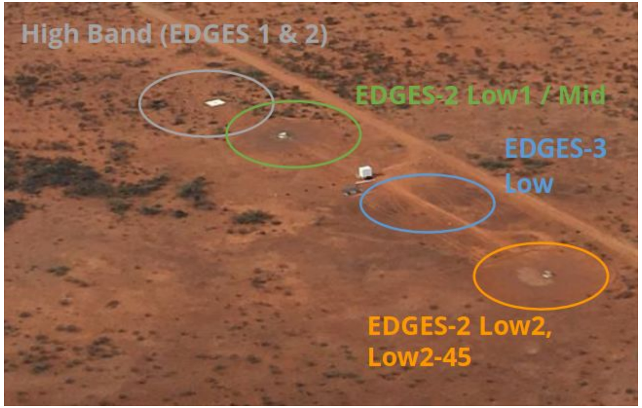

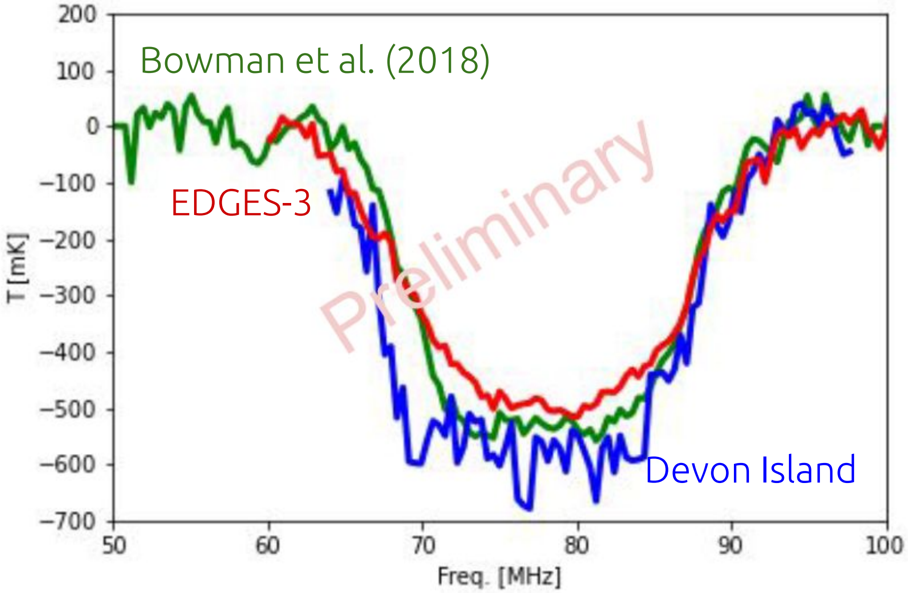

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Results in agreement with 2018 absorption feature!

SARAS updates

adapted from Yash Agrawal

87.5-175 MHz

110-200 MHz

40-110 MHz

SARAS team also introduced Maximally Smooth Polynomial

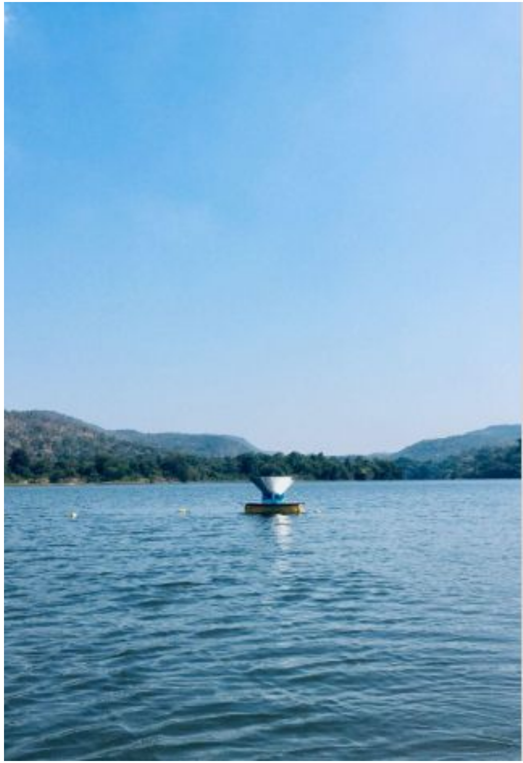
SARAS reanalysis of EDGES data with MSP - systematics in the data plus a reduced signal

Singh et al. (2020)

Singh et al. 2021

SARAS updates

adapted from Yash Agrawal



- foregrounds seems smooth (allowing for separation through modeling?)
- SARAS operating principle: “maintaining maximum smoothness in its systematics to preserve the spectral integrity of foregrounds”
- SARAS team says they can manage and control systematics
- new radio-quiet locations found after extensive site characterization and surveys for RFI
- EDGES absorption feature excluded in their data

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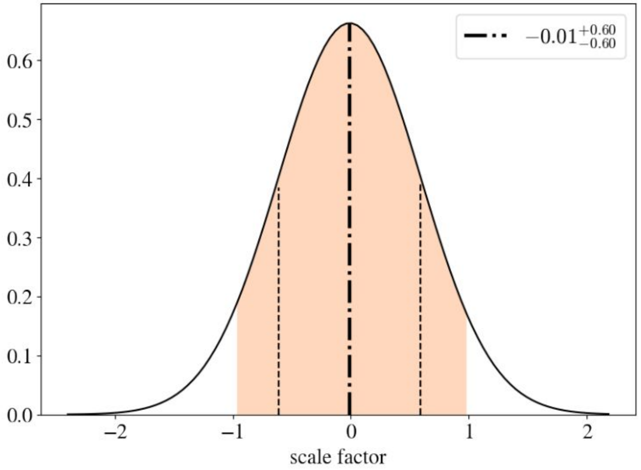
SARAS updates

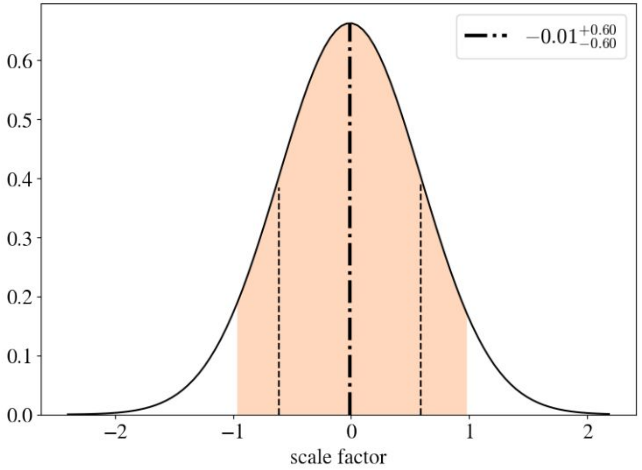
Singh et al. 2021



- EDGES absorption feature excluded in their data

SARAS updates

Singh et al. 2021



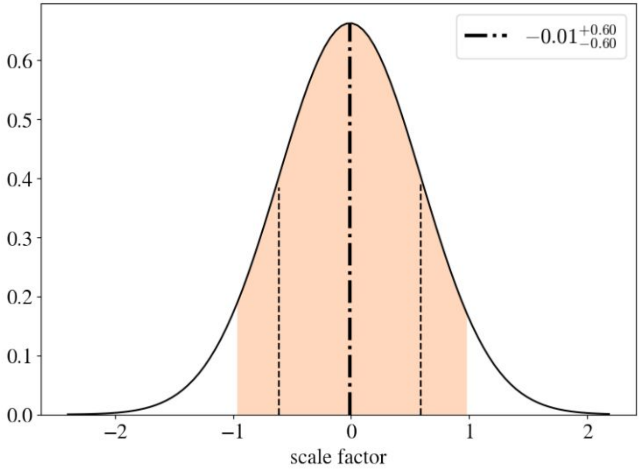
But what about a “generic” signal?

- EDGES absorption feature excluded in their data

Bevins et al. (2023)

SARAS updates

Singh et al. 2021



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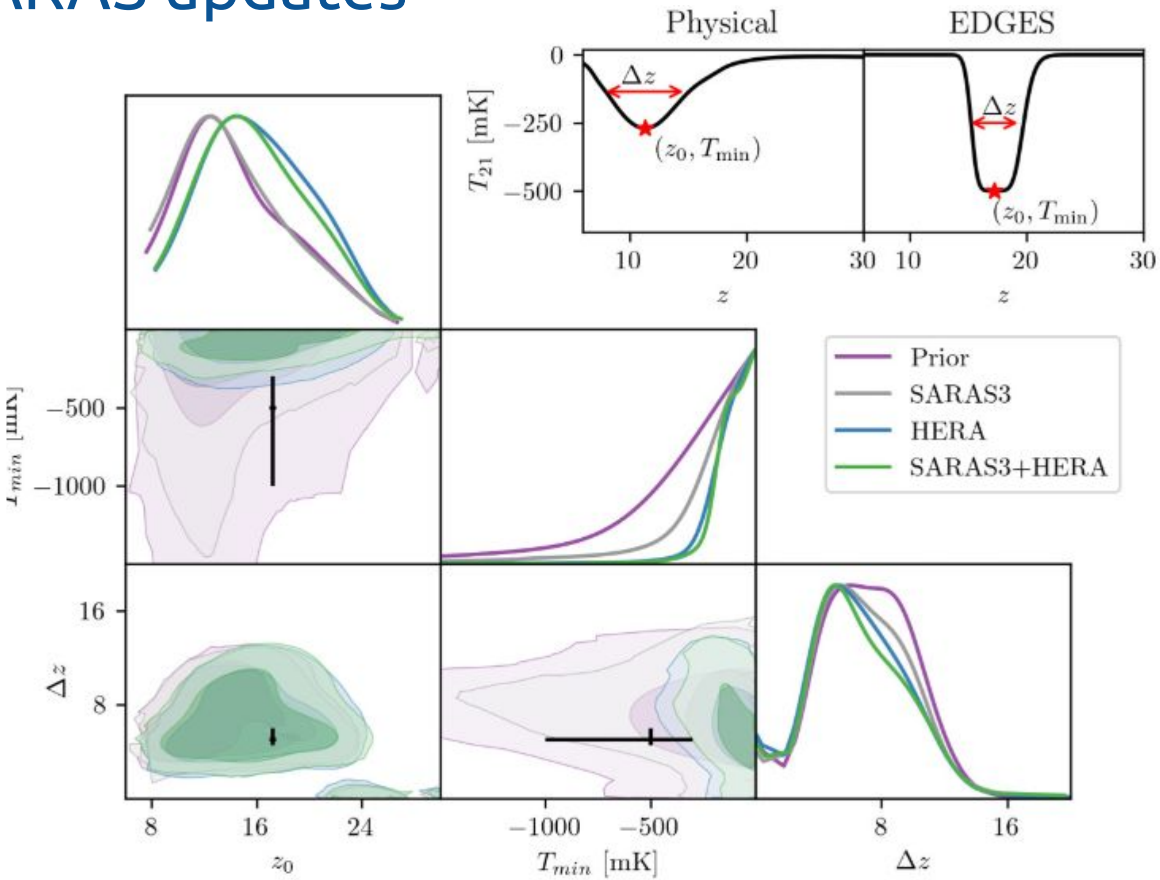
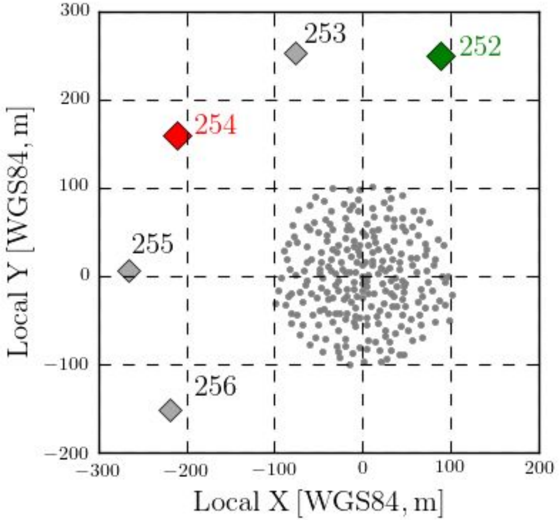


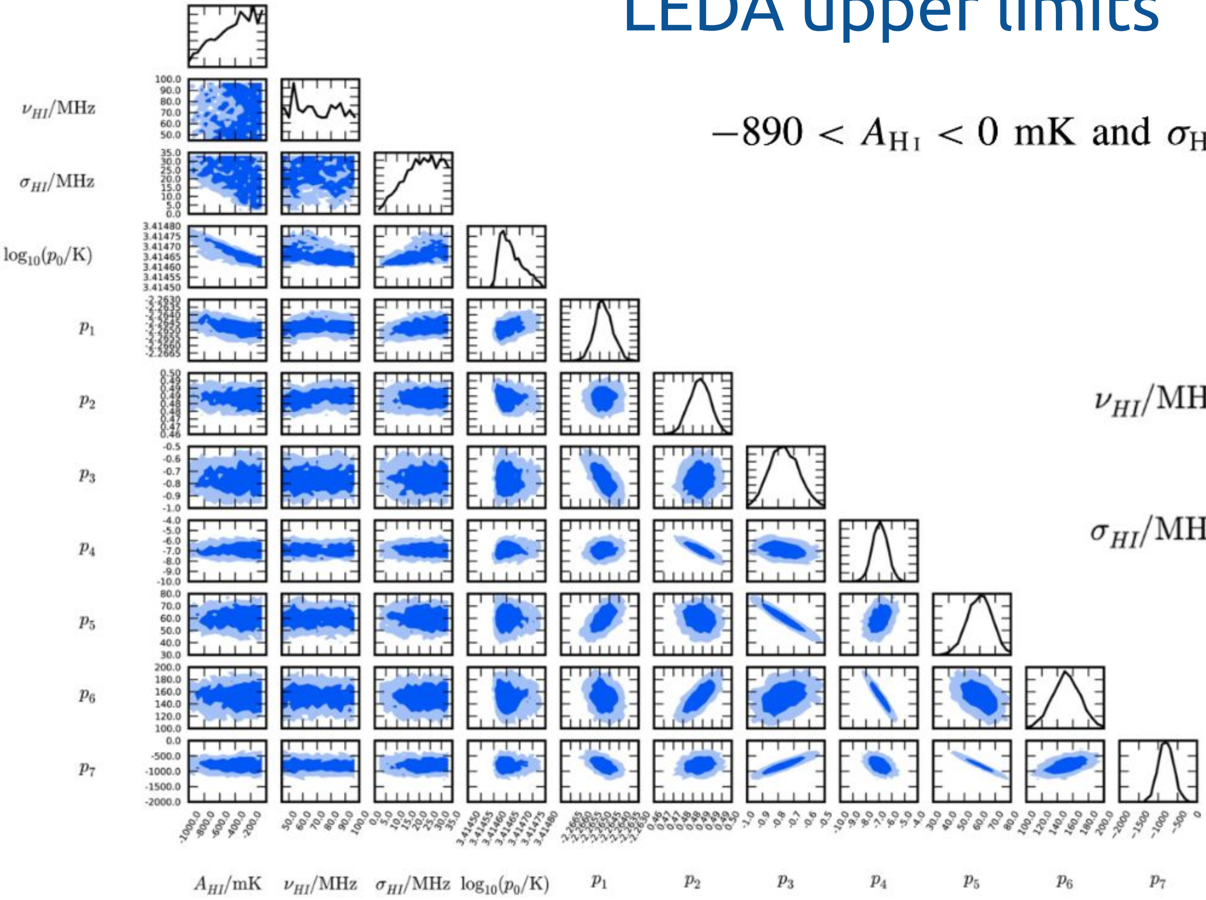
LEDA: **L**arge-aperture **E**xperiment to detect the **D**ark **A**ges

- outriggers of LWA stations at Owens Valley Radio Observatory
  simultaneous measurements with multiple antennas
- main analysis: 254 and 252 (E-W orientation)
- frequency range: 30-87 MHz
- instrument overview, RFI flagging and calibration:
  Price et al. (2018)

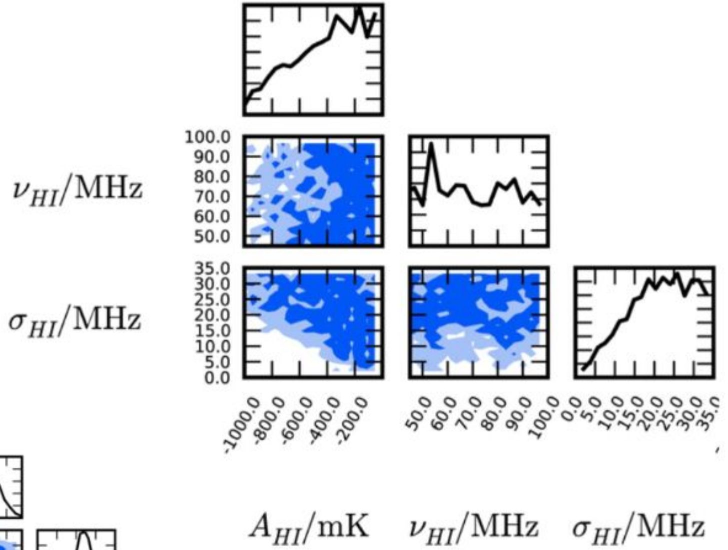


Bernardi et al. (2016)

LEDA upper limits



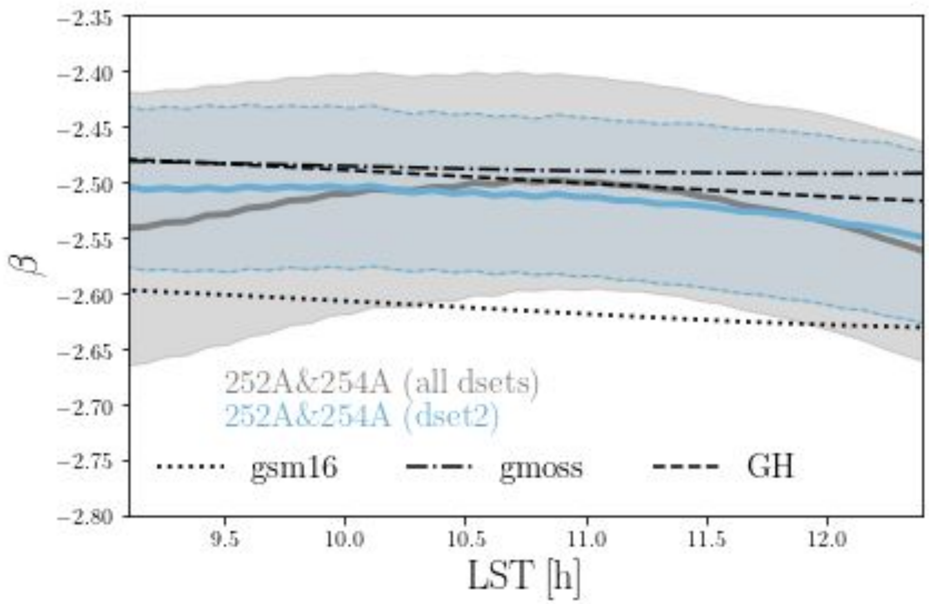
$$-890 < A_{\mathrm{H\,I}} < 0 \text{ mK and } \sigma_{\mathrm{H\,I}} > 6.5 \text{ MHz}$$



Synchrotron spectral index

- combined results from 254A and 252A
- compare with:
  - improved GSM Zheng et al. (2016)
  - GMOSS Sathyanarayana Rao et al. (2017)
  - $$\beta_{\mathrm{GH}}(\mathrm{lst}) = \ln \frac{\mathrm{T}_{45}}{\mathrm{T}_{408}} / \ln \frac{\nu_{45}}{\nu_{408}}$$

see also Mozdzen et al. (2017, 2019)

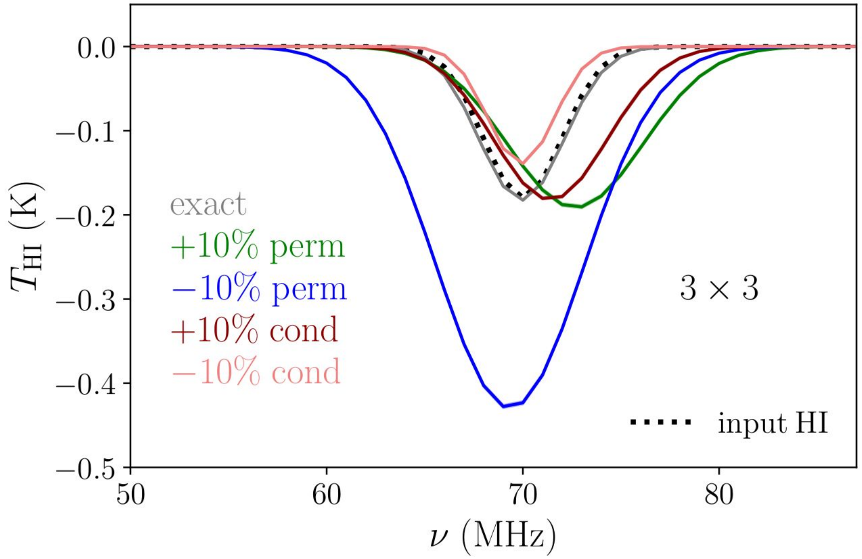


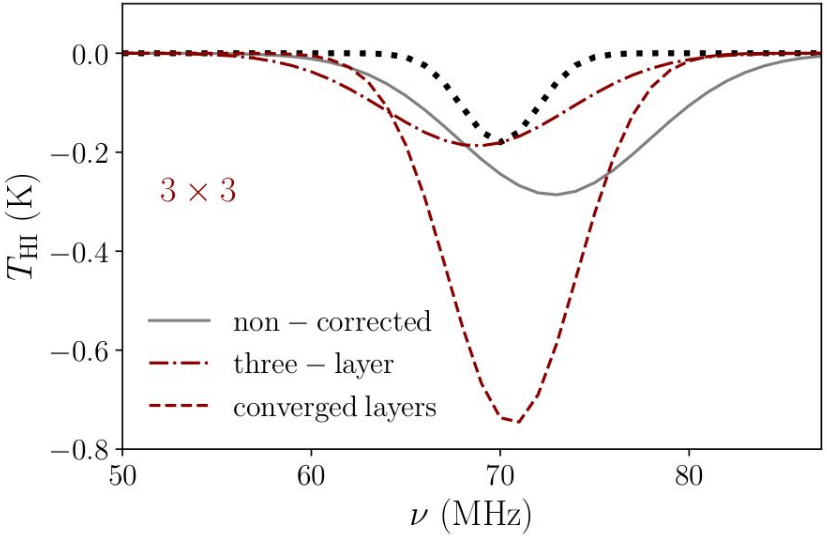
Spinelli et al. (2021)

Instrumental modelling

with the LEDA team + **G. Kyriakou** (Arcetri) and **P. Bolli** (Arcetri)

include the ground properties and ground plane geometry in the beam modelling using available measurements for both dry and wet conditions & simulate LEDA data taking assuming a “Haslam” sky



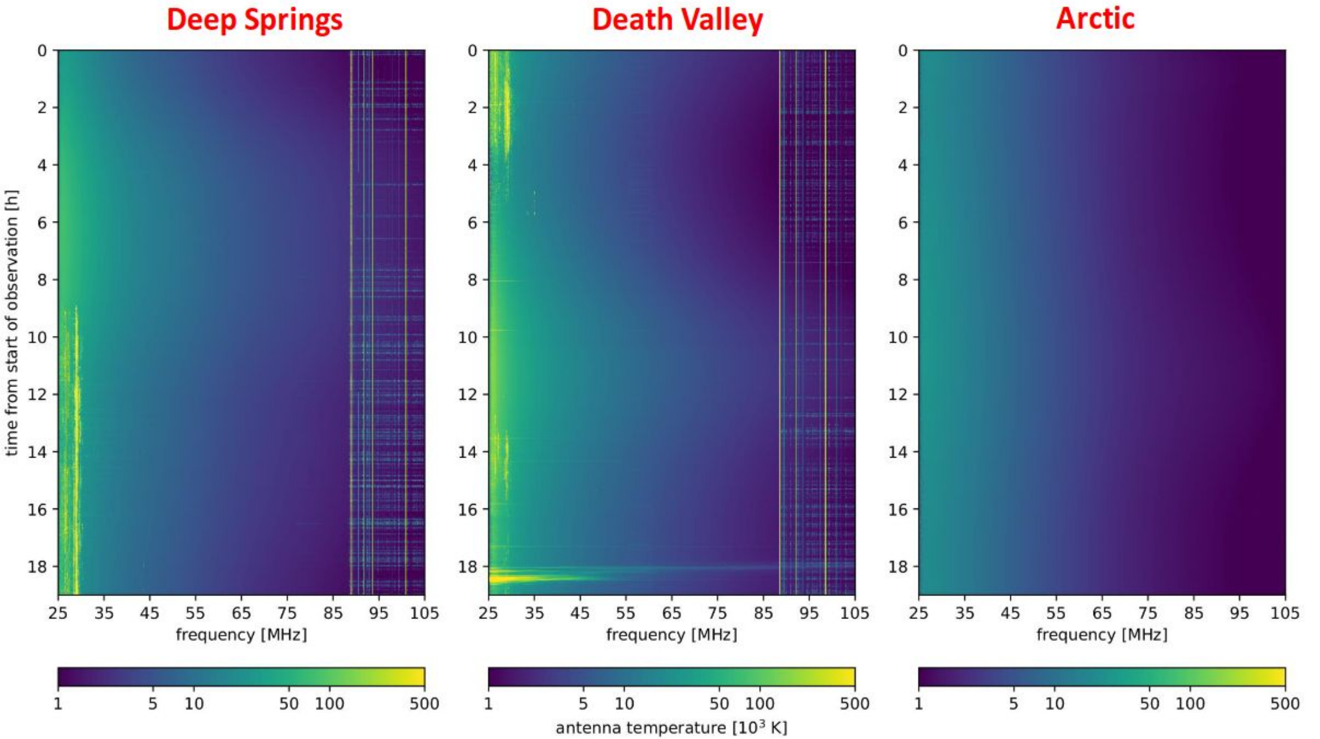


correcting for the beam chromaticity with a slightly off modelling wrt “base” model give a bias

MIST

Monsalve et al. (2023)

New approach: could be better to model directly the soil instead of complicating the modeling with an (imperfect) ground plane?

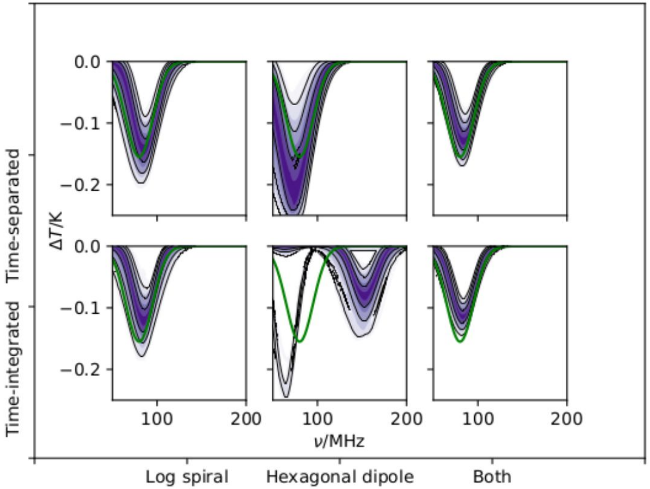


REACH

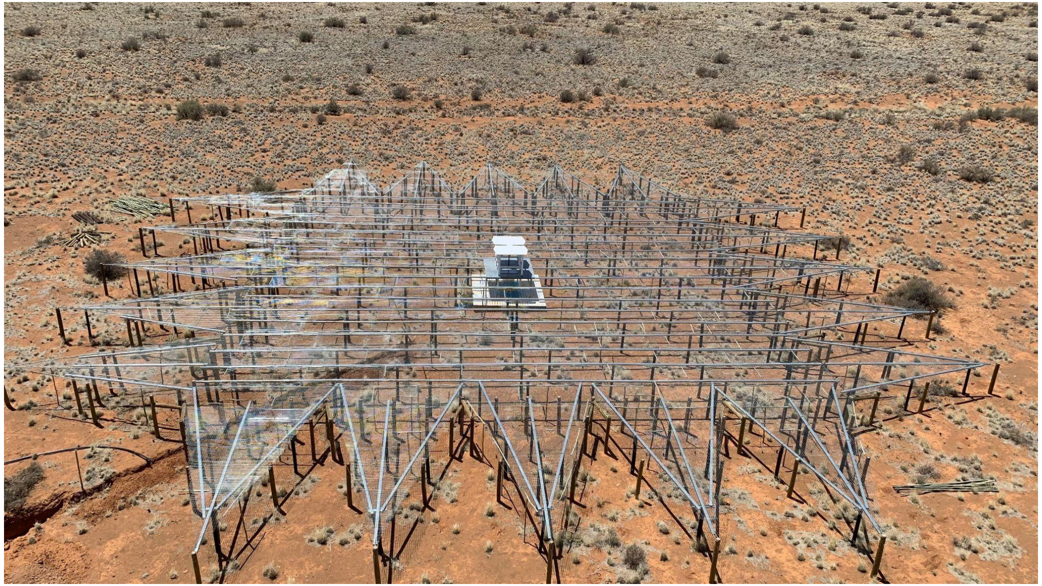
Cambridge & Stellenbosch - P.I.: E. de Lera Acedo

What about an elevated ground plane?

And more than one antenna type?



de Lera Acedo et al. (2022)



italian contribution:
G. Bernardi, MS

REACH

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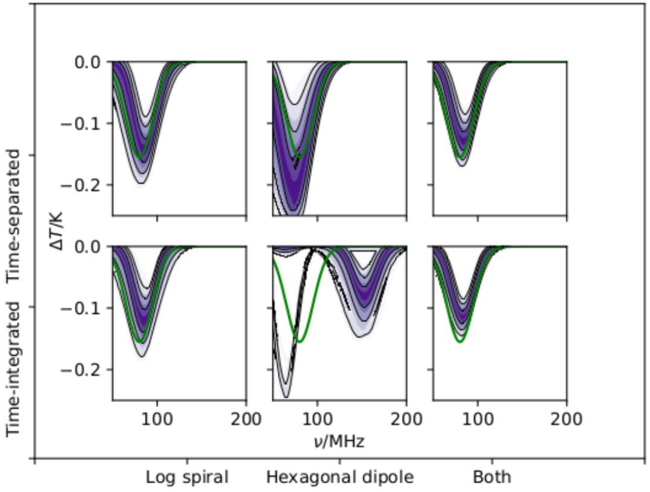

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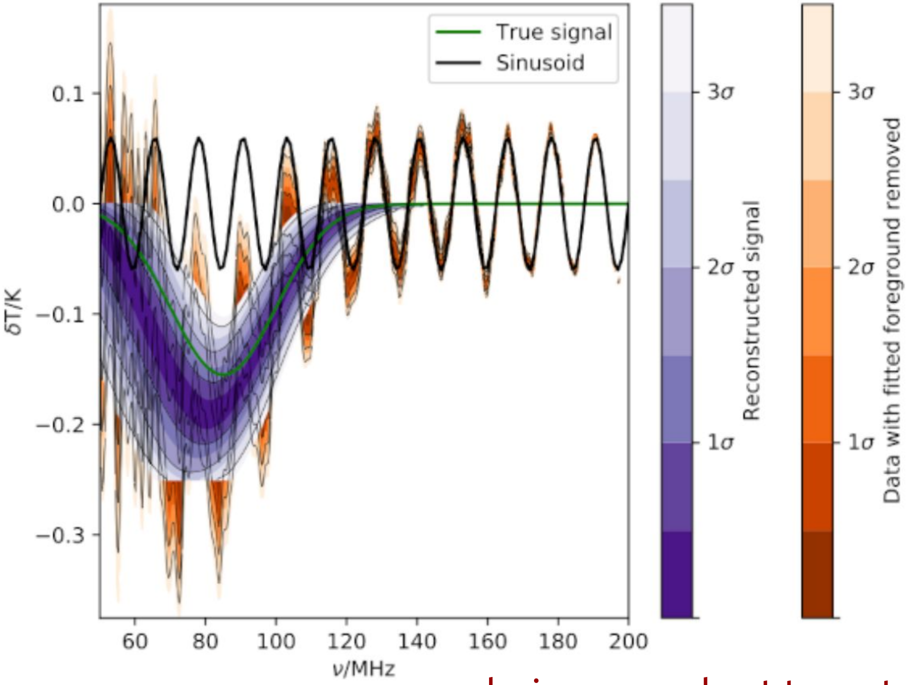


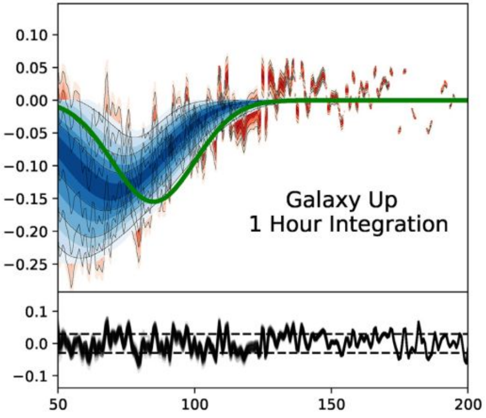
analysis more robust to systematics!

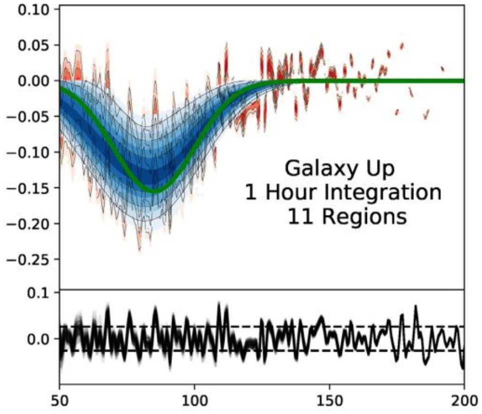
REACH

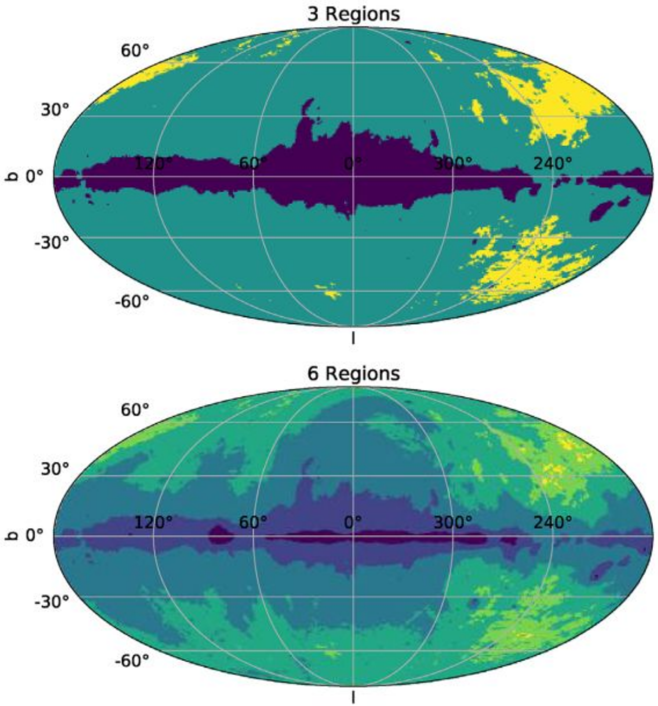
see also Taucher et al. (2021)
Basset et al. (2021)
Hibbard et al (2023)

How to make the analysis more robust to systematics?

- a more accurate sky model with spatially varying spectral index
- take into account the beam in a more consistent way
- bayesian exploration of the full parameter space
- a powerful tool also for instrument design



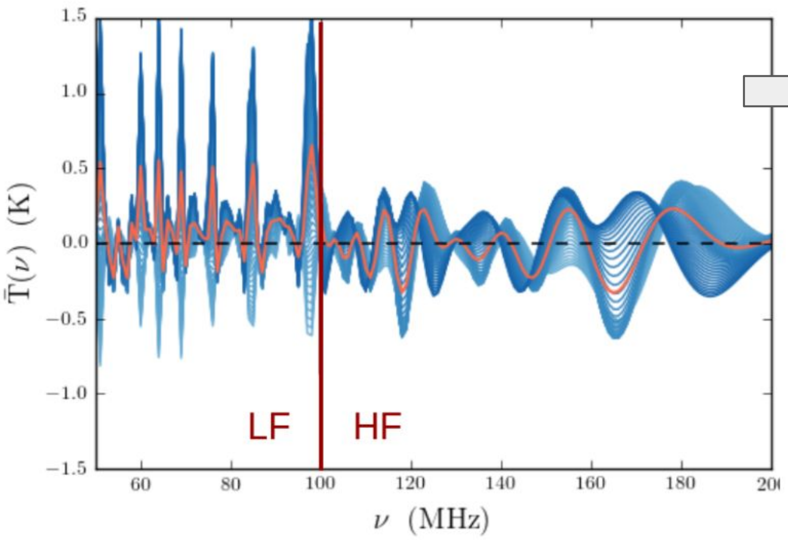


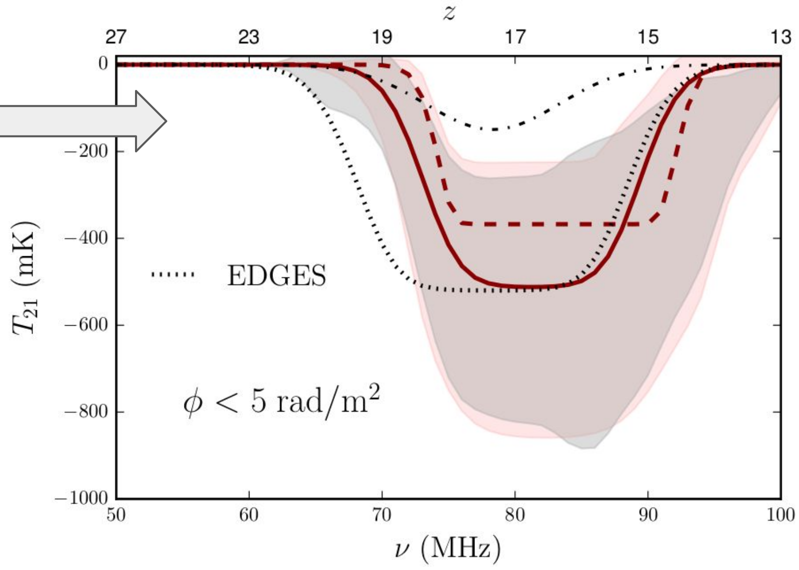


MS, Bernardi, Santos (2018, 2019)

italian contribution:
G. Bernardi, MS

REACH pipeline & polarization





Standard polynomial analysis gives **biased results** in presence of unmodelled polarized emission

REACH pipeline: results are stable wrt this type of systematics

Conclusions

- 21cm science crucial for understanding the high redshift universe
- Global signal is rich and should be accessible with (cheap) single dipole antennas
- the community has advance both from instrumental and analysis point of view
- EDGES vs SARAS results requires another independent measurement
- A lot of ongoing and planned instruments: EDGES3, SARAS3, LEDA, MIST, REACH, etc.
- Next stop, the moon! (or its orbit) (for Cosmic Dawn or even the Dark Ages)