



SCUOLA
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Forecasting upcoming 21cm SKA observations with 21cmFAST

Daniela Breitman¹

Scuola Normale Superiore

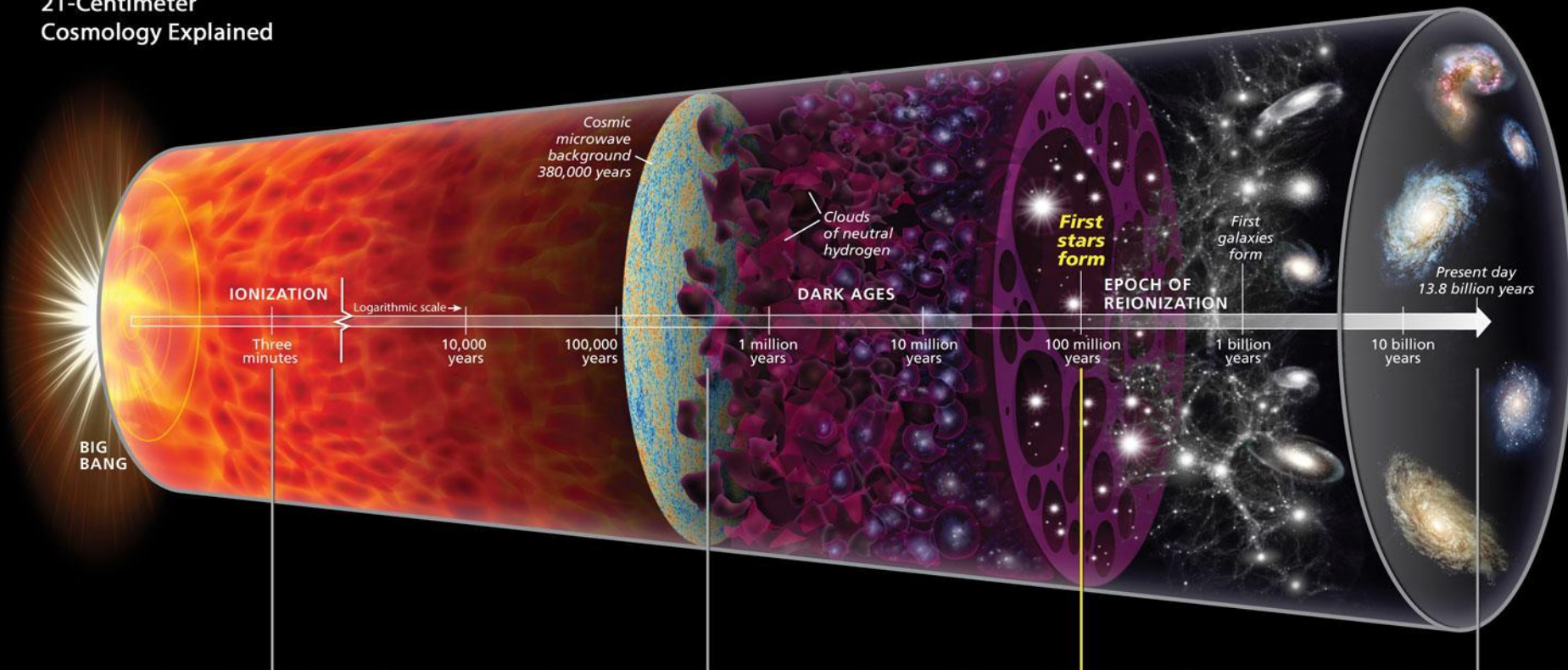
In collaboration with Prof. Andrei Mesinger

5th SKA Workshop - Bologna

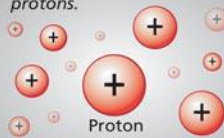
November 25, 2025

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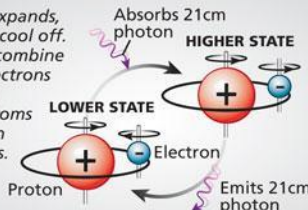
21-Centimeter Cosmology Explained



After the Big Bang, the universe fills with ionized hydrogen, single positive protons.



As the universe expands, hydrogen clouds cool off. Positive protons combine with negative electrons to create neutral hydrogen. The atoms can shift between two energy states.



Due to ultraviolet radiation from the first stars, neutral hydrogen atoms lose their electrons and become positively charged again.



Radio telescopes detect the 21cm emissions, now stretched out by the universe's expansion. Whenever they no longer appear, the first stars have formed.

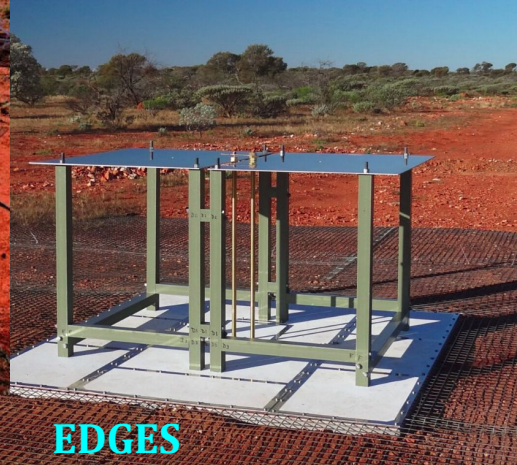




HST



MWA



EDGES



VLT



SKA-low



HERA



JWST



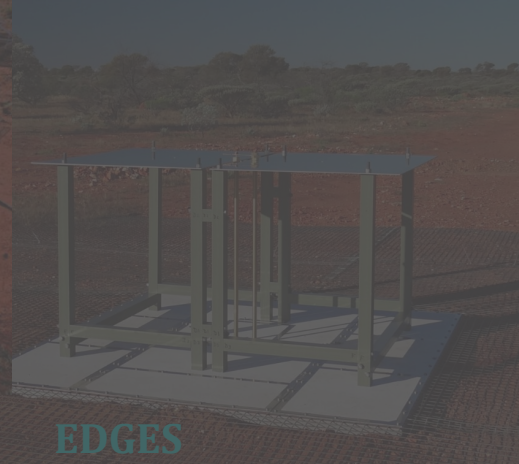
LOFAR



HST



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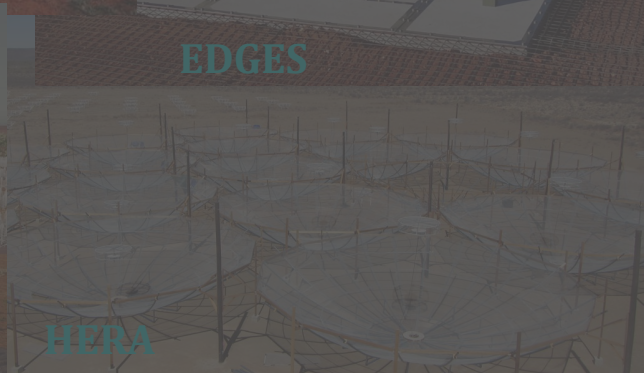
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LOFAR



HST

A detailed 3D rendering of the Hubble Space Telescope, showing its cylindrical body, solar panels, and the large circular primary mirror.



MWA

A photograph of the Murchison Widefield Array (MWA) in Australia, showing a grid of blue and black radio telescope antennas on a red dirt landscape.



EDGES

A photograph of the Edges of the Universe (EDGES) experiment, showing a green metal frame structure on a red dirt landscape.



VLT

A photograph of the Very Large Telescope (VLT) in Chile, showing four large telescopes mounted on a hillside.



HERA

A photograph of the Herion Array (HERA) in South Africa, showing several large radio telescope dishes.



JWST

A photograph of the James Webb Space Telescope (JWST) in space, showing its large gold-colored sunshield and the primary mirror.



SKA-low

A photograph of the SKA-low (Square Kilometer Array-low) in South Africa, showing a large array of radio telescope antennas.



LOFAR

A photograph of the LOFAR (Low Frequency Array) in the Netherlands, showing a large array of radio telescope antennas in a green landscape.



HST

A detailed 3D rendering of the Hubble Space Telescope, showing its cylindrical body, solar panels, and the large circular mirror at the rear.



MWA

An aerial view of the Murchison Widefield Array (MWA) in a dry, red landscape. It features a grid of low-frequency radio antennas, each with a complex metal support structure.



EDGES

A 3D architectural rendering of the EDGES (Experiment to Detect the Global Epoch of Reionization Signature) instrument. It shows a large, rectangular metal frame structure on a flat, light-colored base.



VLT

A 3D rendering of the Very Large Telescope (VLT) facility. It shows several large, box-like telescope enclosures (dome structures) arranged in a row on a dark, flat surface.



HERA

A 3D rendering of the HERA (Hydrogen Epoch of Reionization Array) radio telescope. It shows a large, circular dish antenna with a complex support structure, set against a dark background.



JWST

A 3D rendering of the James Webb Space Telescope (JWST) in space. It shows the large, gold-colored primary mirror and the complex support structure, with a bright light source in the background.



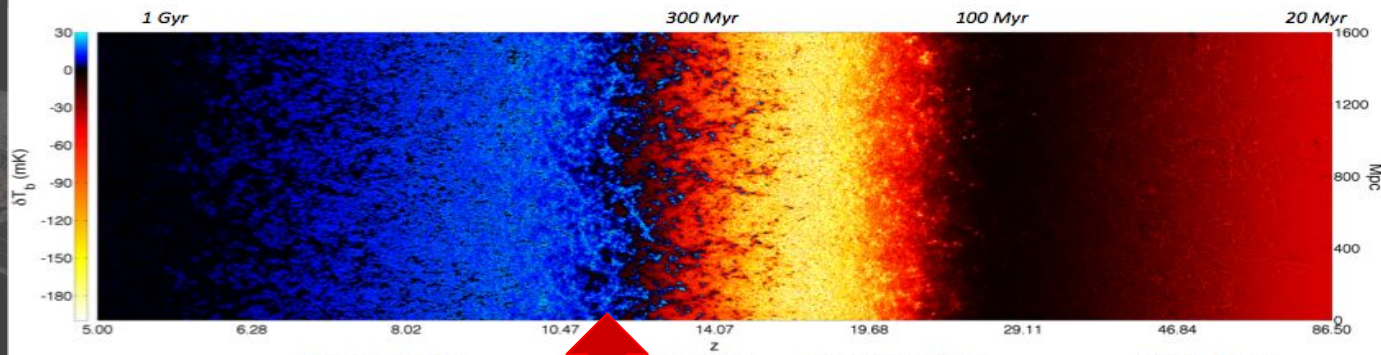
SKA-low

A wide-angle aerial photograph of the SKA-low (Square Kilometer Array-low) radio telescope. It shows a vast field of numerous small, white, conical antennas arranged in a grid across a dry, red landscape.



LOFAR

A 3D rendering of the LOFAR (Low Frequency Array) radio telescope. It shows a large, circular dish antenna with a complex support structure, set against a dark background.



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A 3D rendering of the Hubble Space Telescope, showing its cylindrical body, solar panels, and the large circular mirror at the rear.



MWA

A 3D rendering of the Murchison Widefield Array (MWA) radio telescope, showing a large number of small, identical antenna elements arranged in a grid on a flat, arid landscape.



EDGES

A 3D rendering of the Edge Length Experiment (EDGES) radio telescope, showing a large, rectangular metal frame structure on a flat, arid landscape.



VLT

A 3D rendering of the Very Large Telescope (VLT) at Paranal Observatory, showing four large, rectangular telescope structures on a flat, arid landscape.



HERA

A 3D rendering of the HERA radio telescope, showing a large, circular antenna structure with a complex, multi-lobed design.



JWST

A 3D rendering of the James Webb Space Telescope (JWST), showing its large, gold-colored primary mirror and the complex, multi-lobed secondary mirror structure.



SKA-low

A 3D rendering of the SKA-low radio telescope, showing a large number of small, identical antenna elements arranged in a grid on a flat, arid landscape.

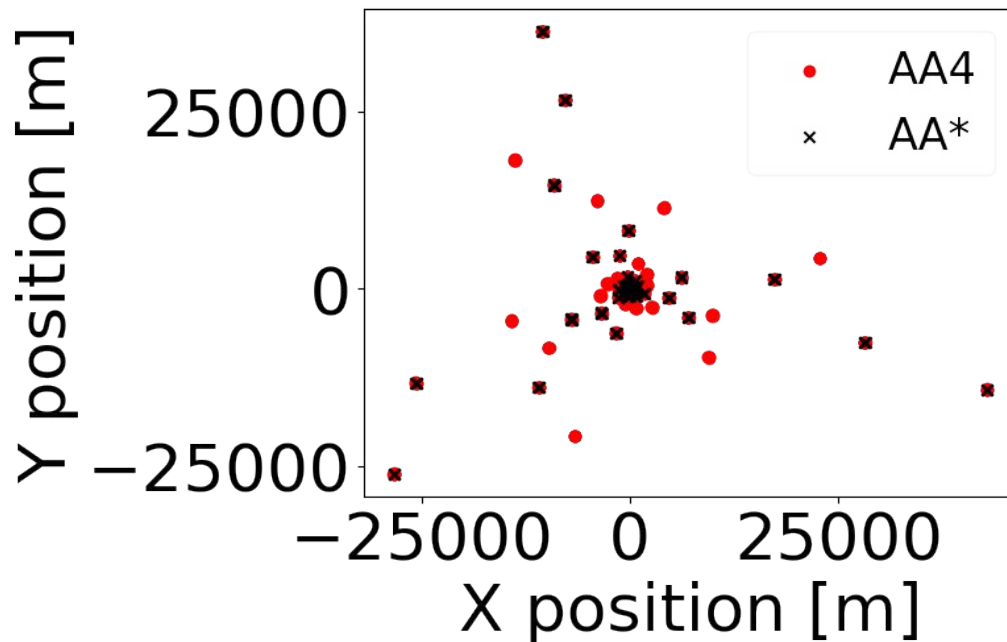


LOFAR

A 3D rendering of the LOFAR radio telescope, showing a large, circular antenna structure with a complex, multi-lobed design.

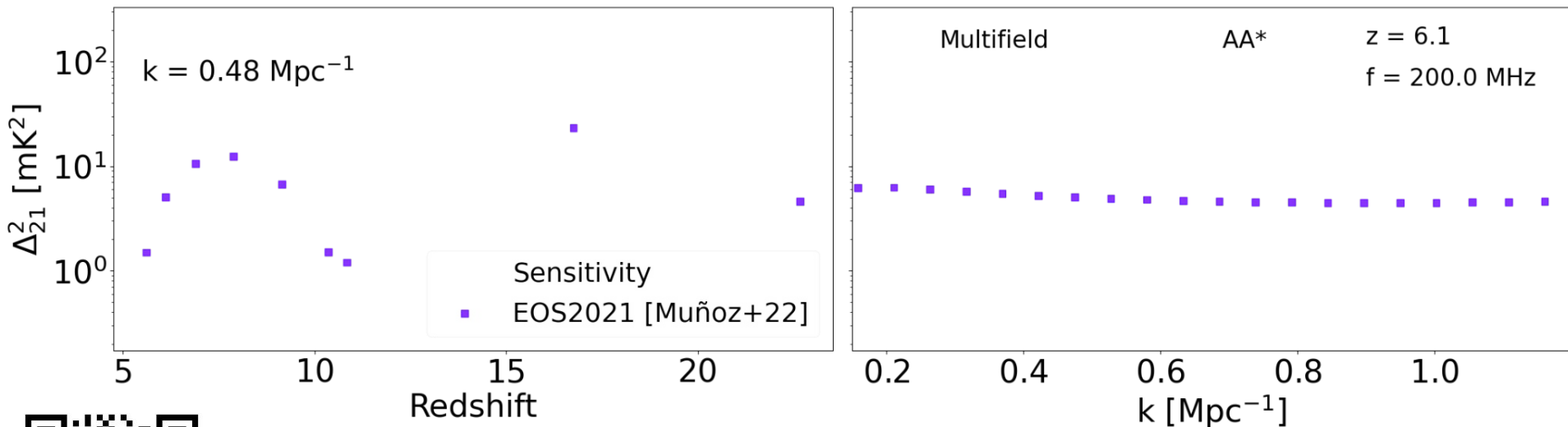
Forecast SKA 21 cm observation

Use 21cmSense [Murray+18, Pober+14] to forecast SKA observations:



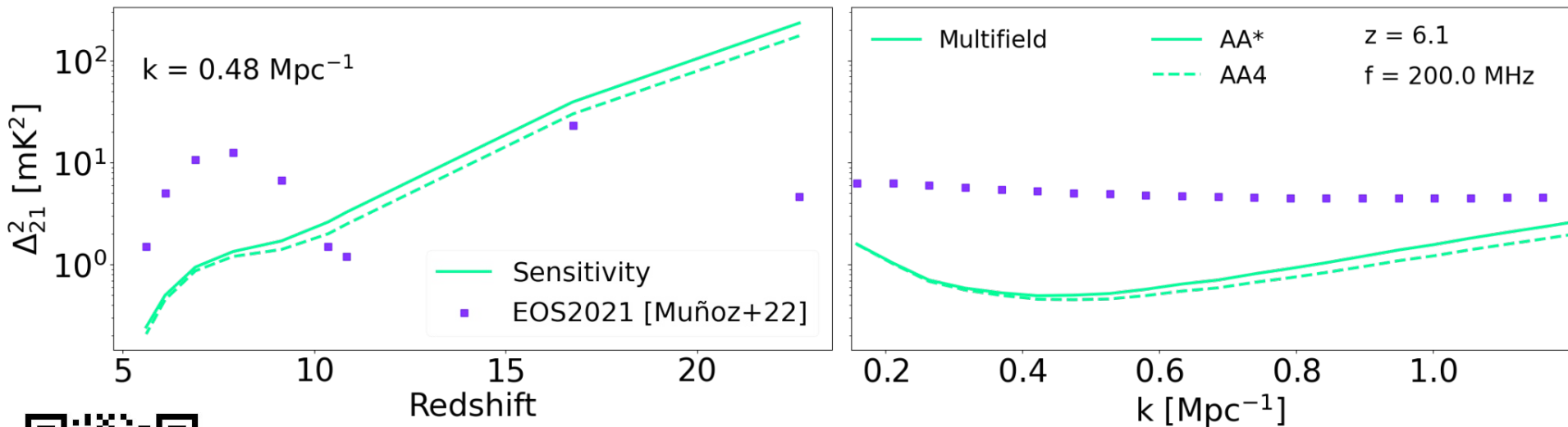
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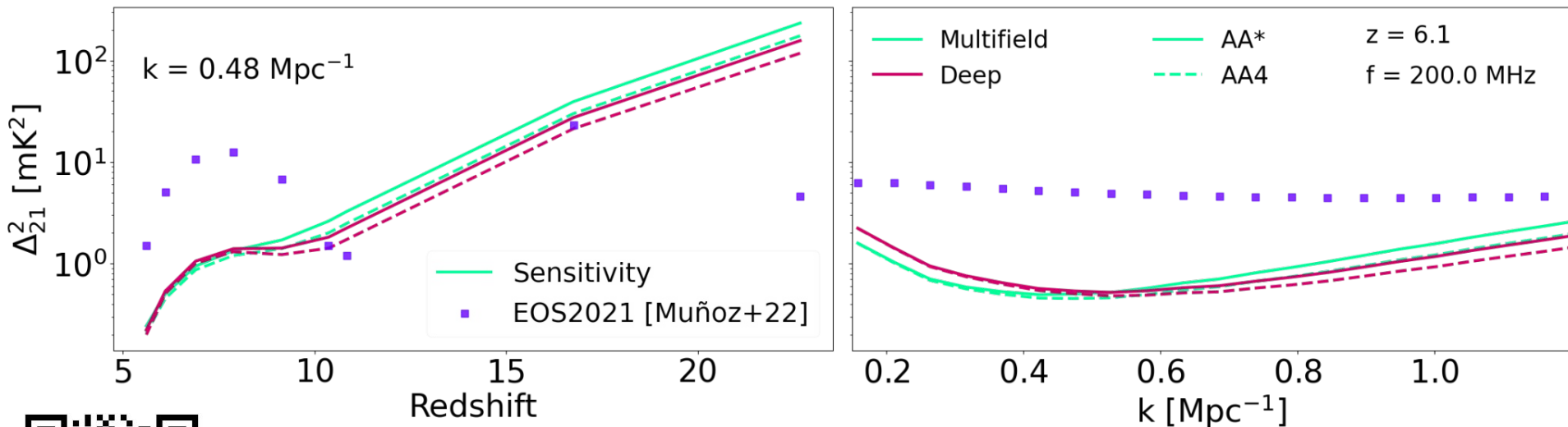
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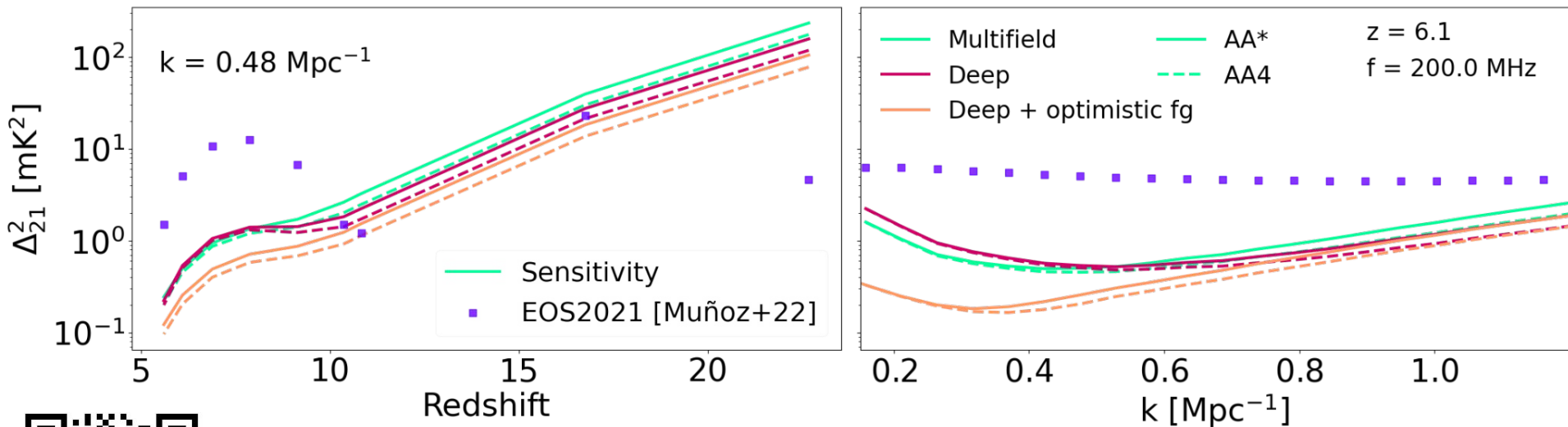
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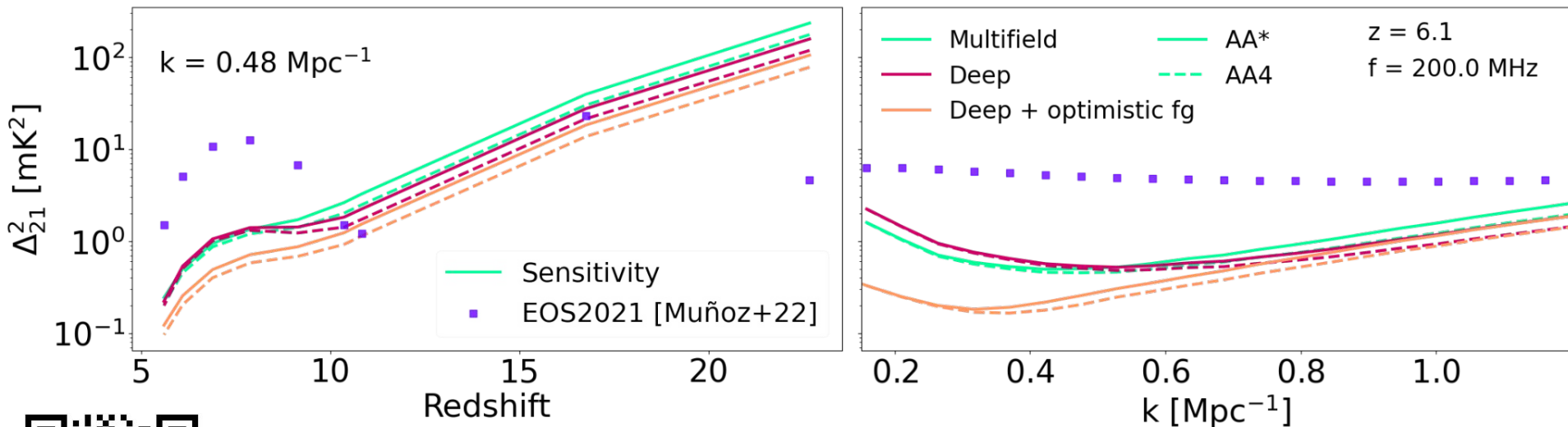
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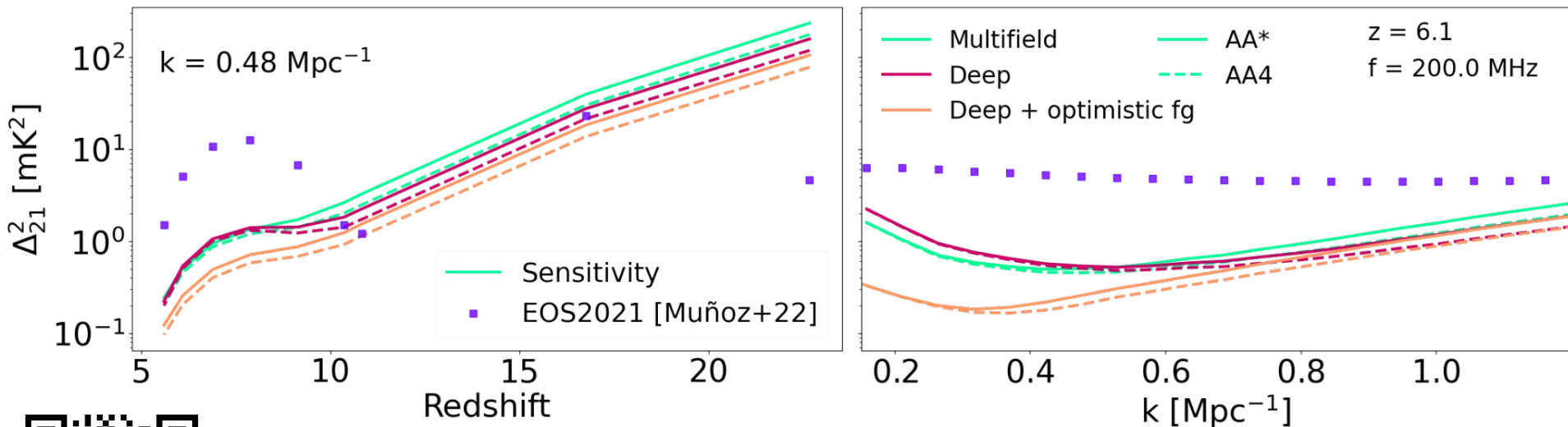


How can we learn from 21 cm SKA-low observations?



Forecast SKA 21 cm PS observation

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How can we learn from 21 cm SKA-low observations?
Bayesian inference



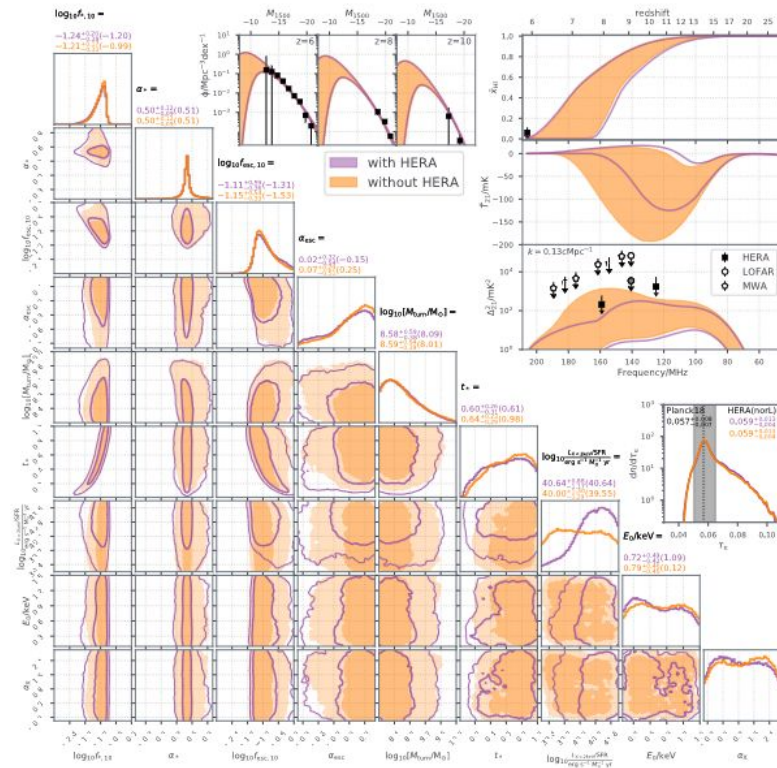
Bayesian Inference

- $P(\theta)$ = prior knowledge on model parameters θ
- **Forward model** $P(d|\theta)$ = probability of reproducing observation d with model parameters θ
- **What we want** $P(\theta|d)$ = updated knowledge on θ provided an observation d

$$P(\theta|d) = \frac{P(d|\theta)P(\theta)}{P(d)}$$

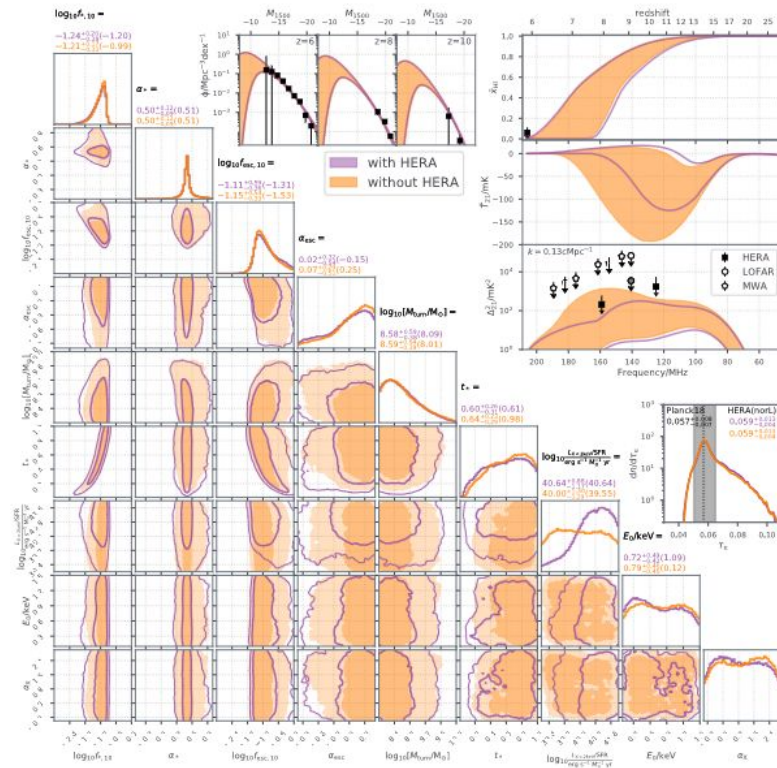
Bayesian Inference

- **Expensive:** requires $\sim 300k$ forward model evaluations



Bayesian Inference

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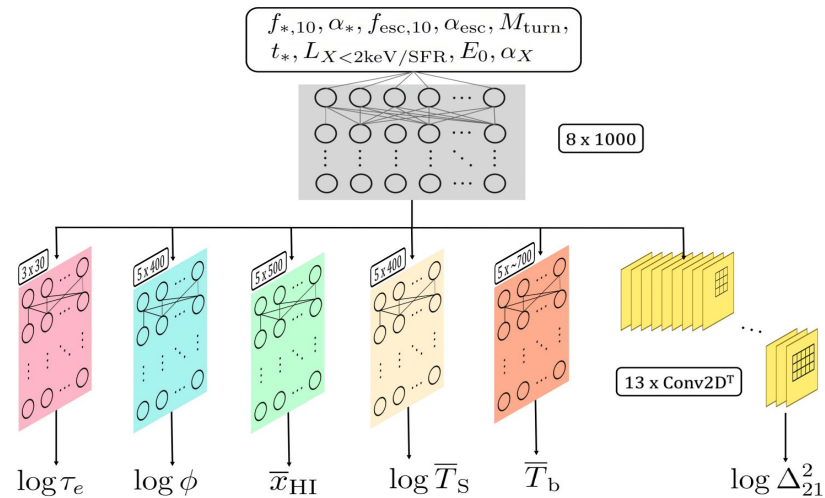
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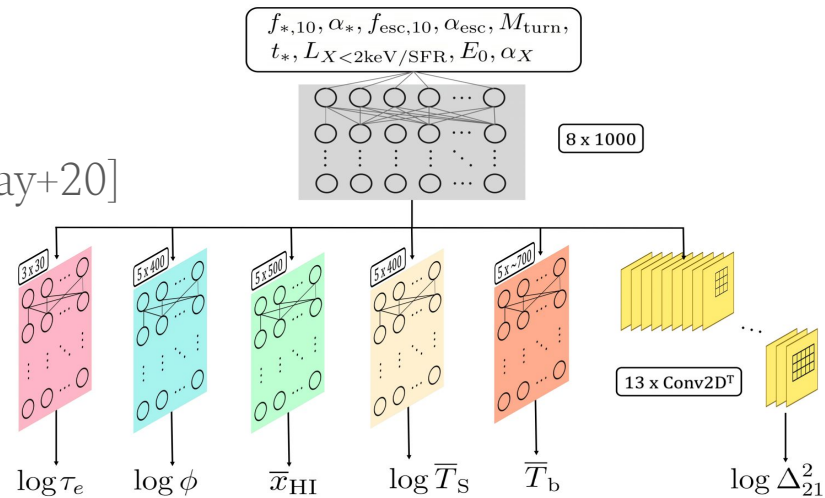
21cmEMUv1

- Input: nine astrophysical parameters



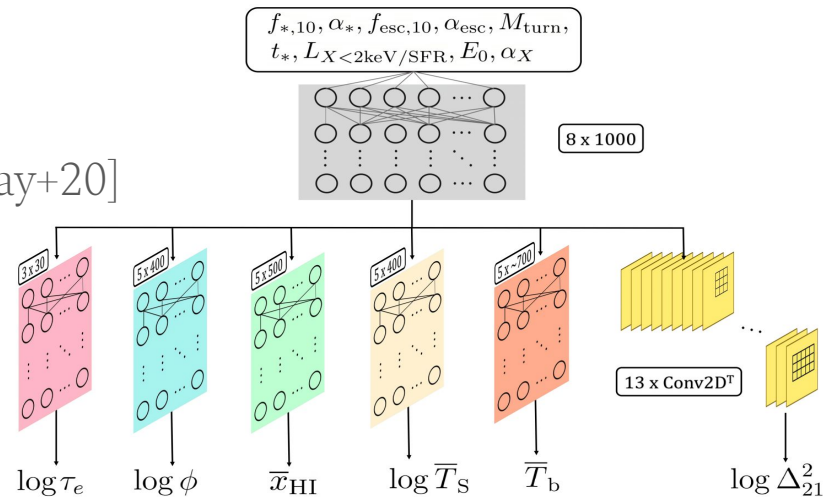
21cmEMUv1

- Input: nine astrophysical parameters
- Model: 21cmFASTv3 [Mesinger+07,11, Murray+20]



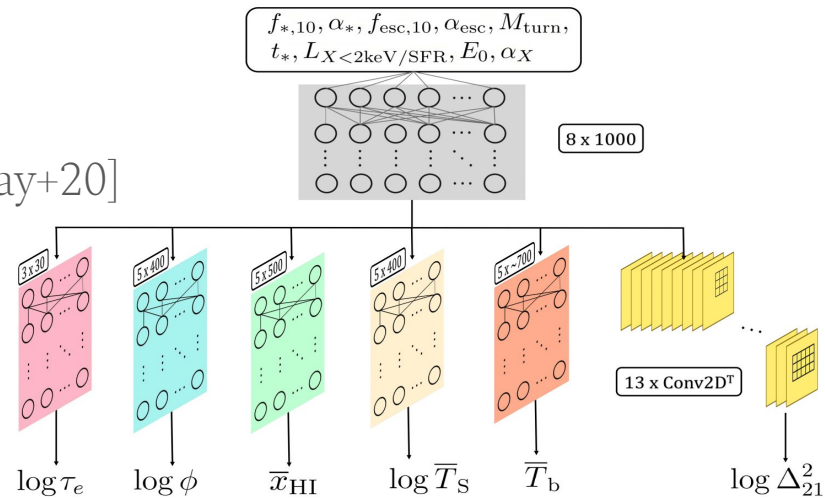
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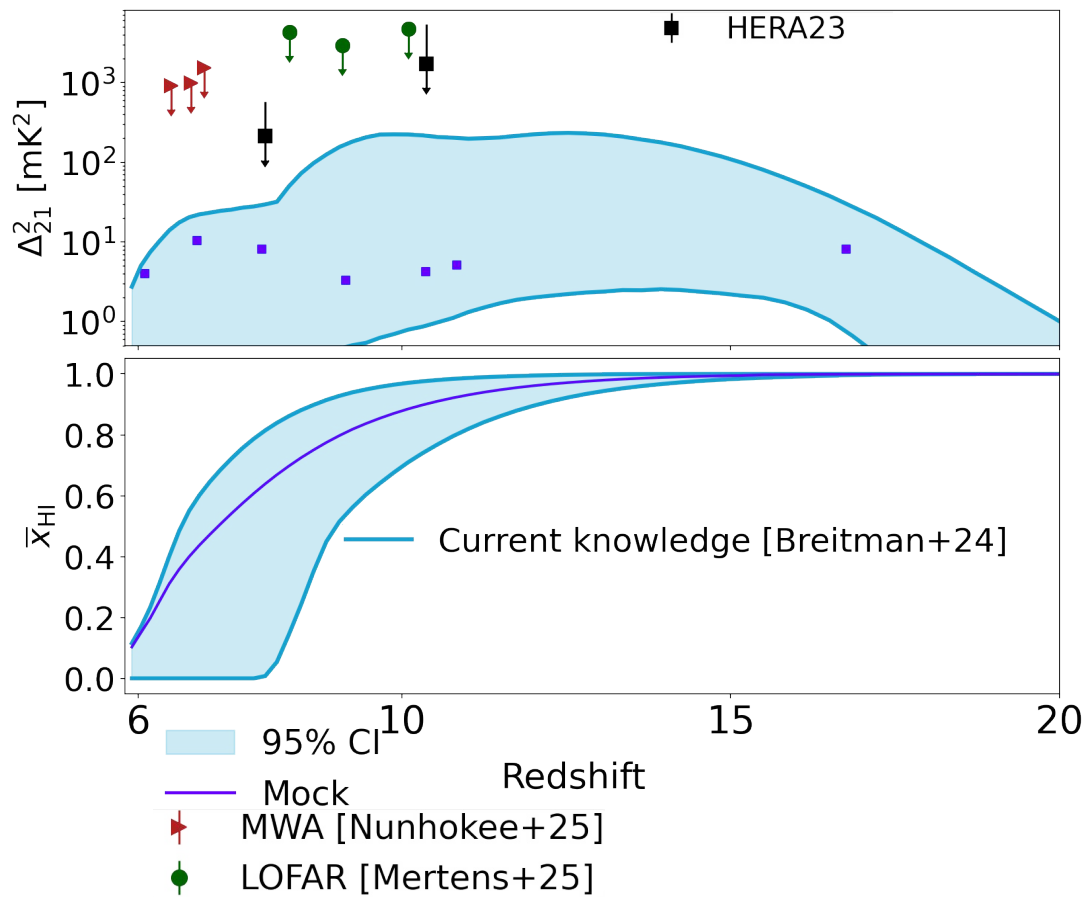
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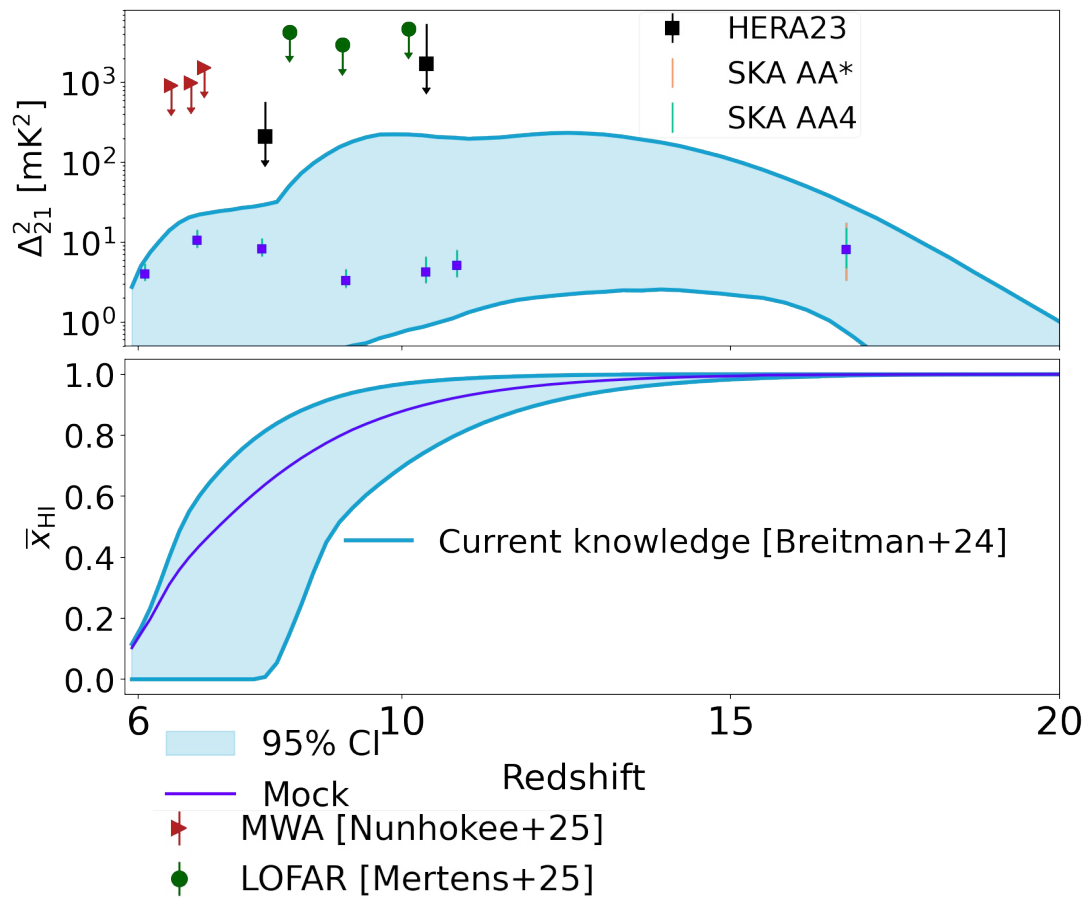


1 inference \approx GPUhr vs 10^6 CPUhrs

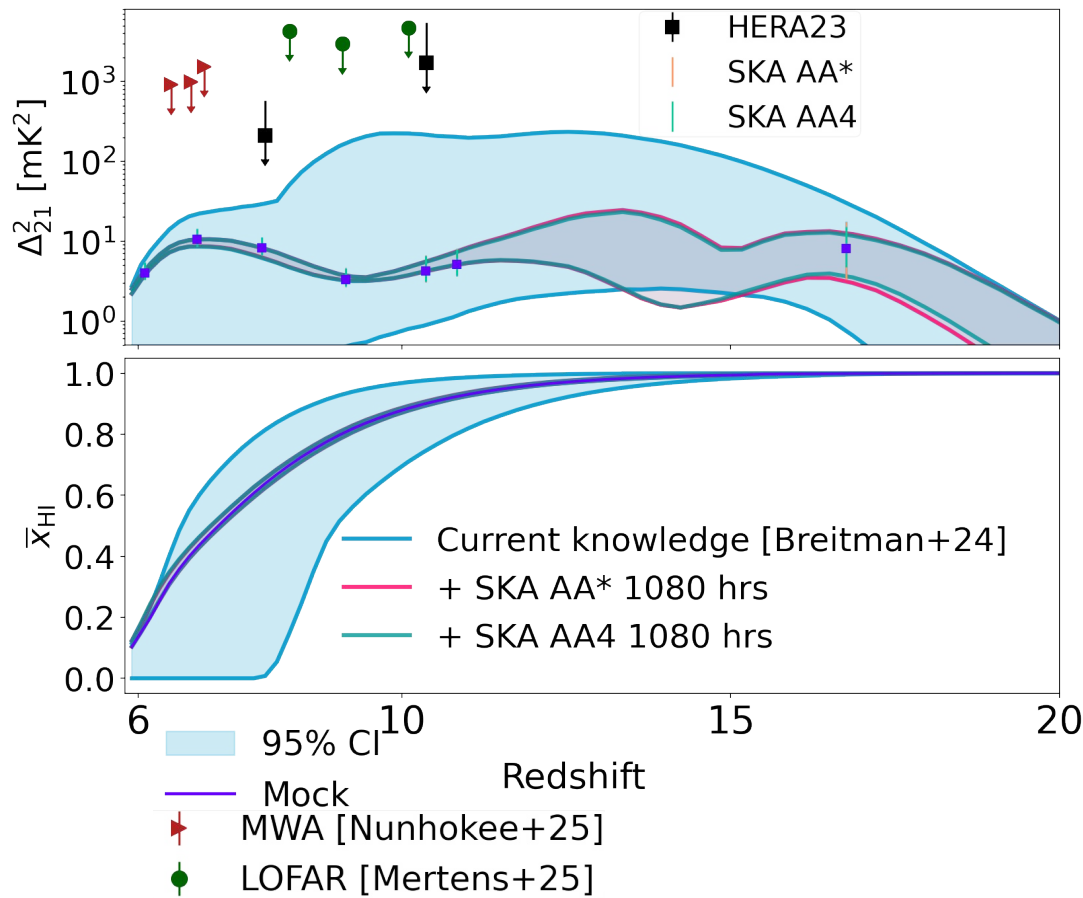
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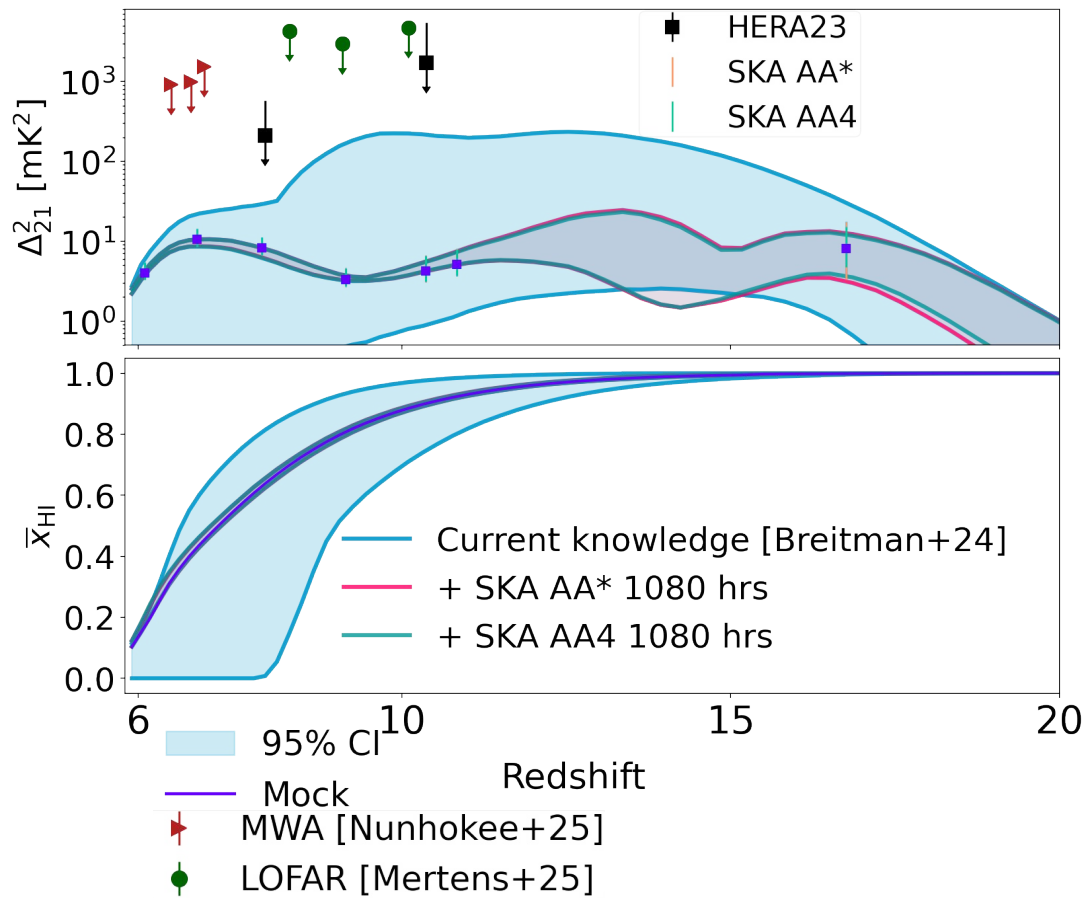


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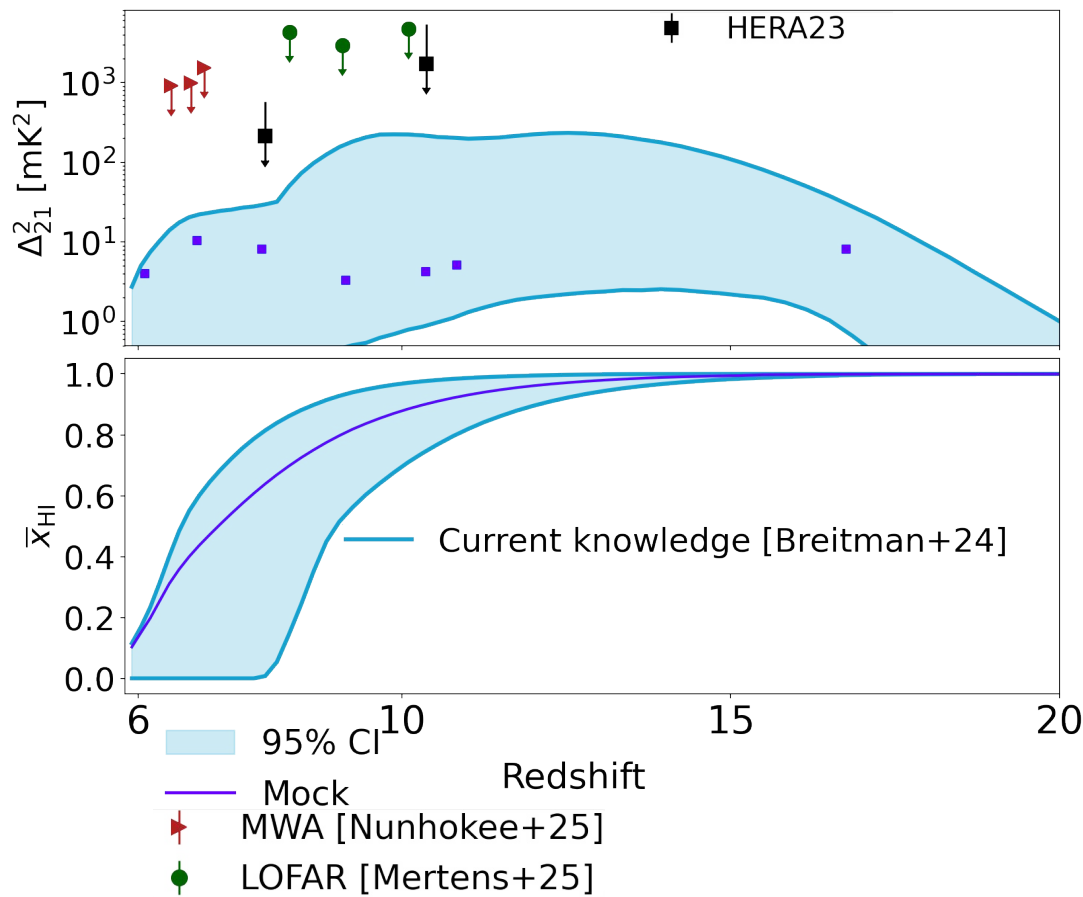
What can we learn from the 21 cm line with SKA-low?

- For CD/EoR science, **AA*** is just as constraining as AA4



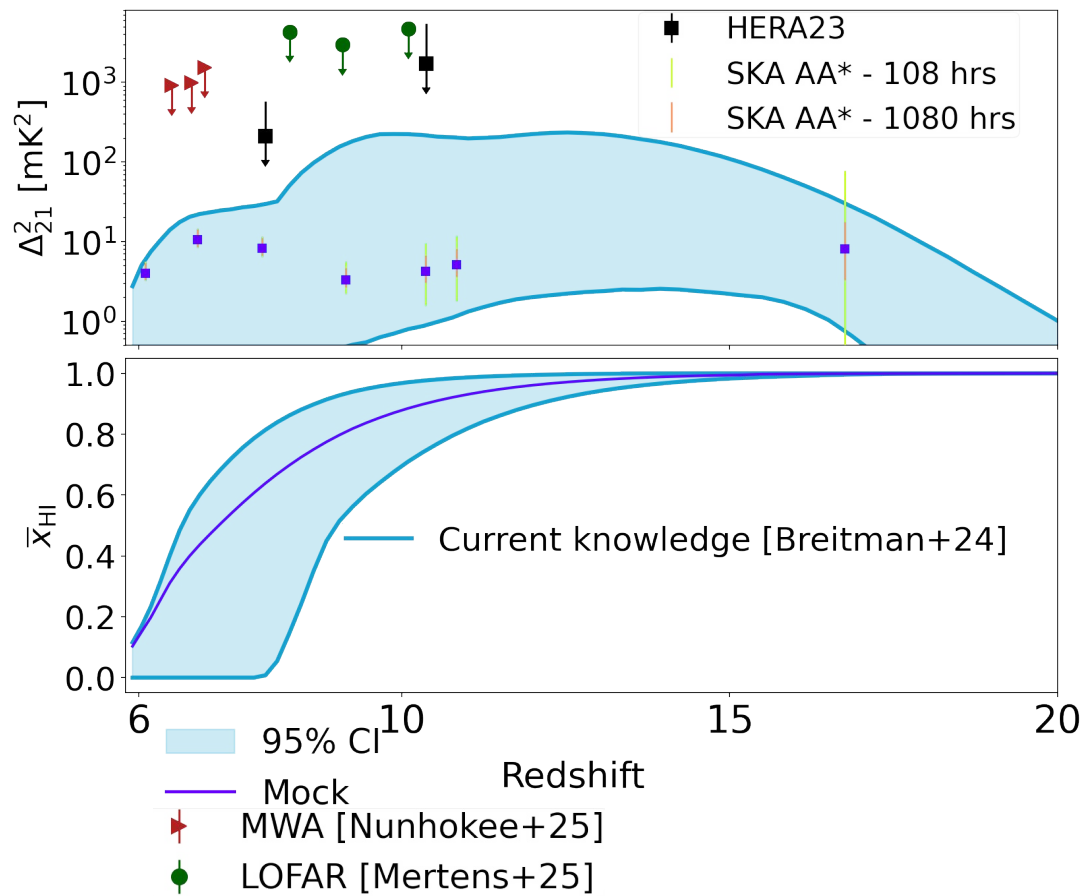
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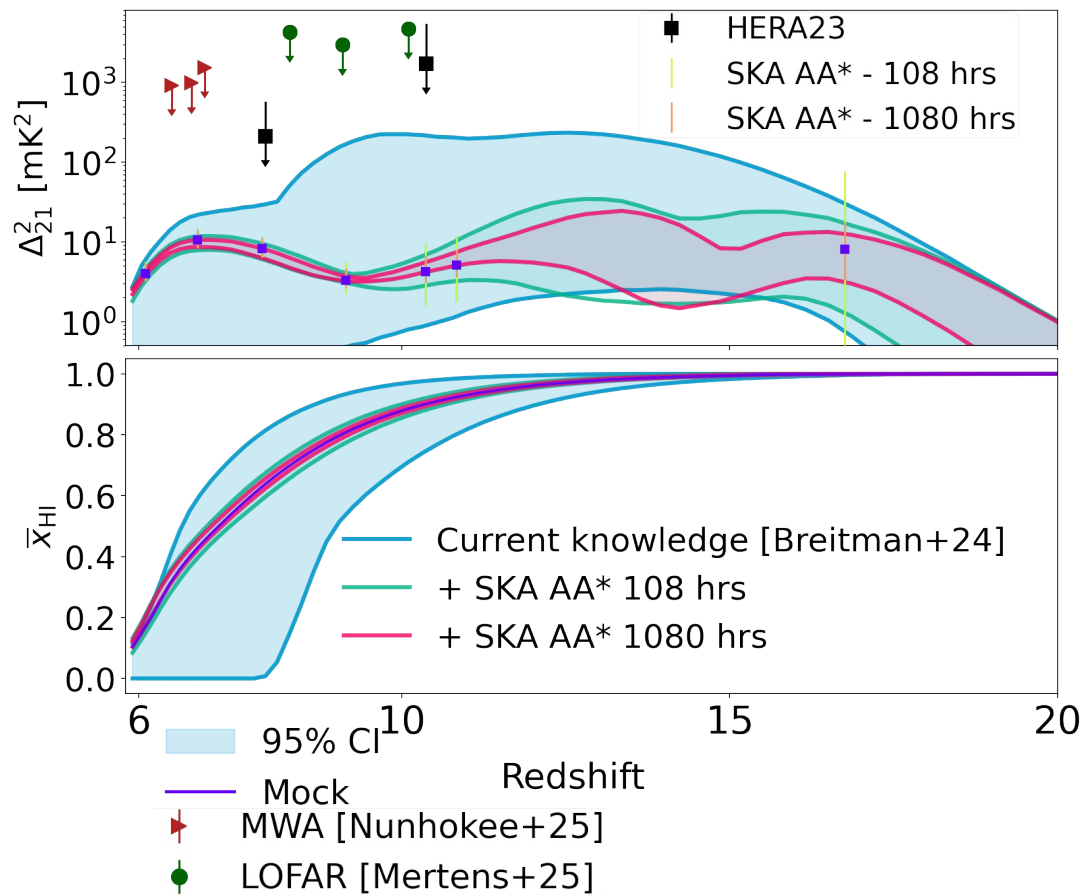
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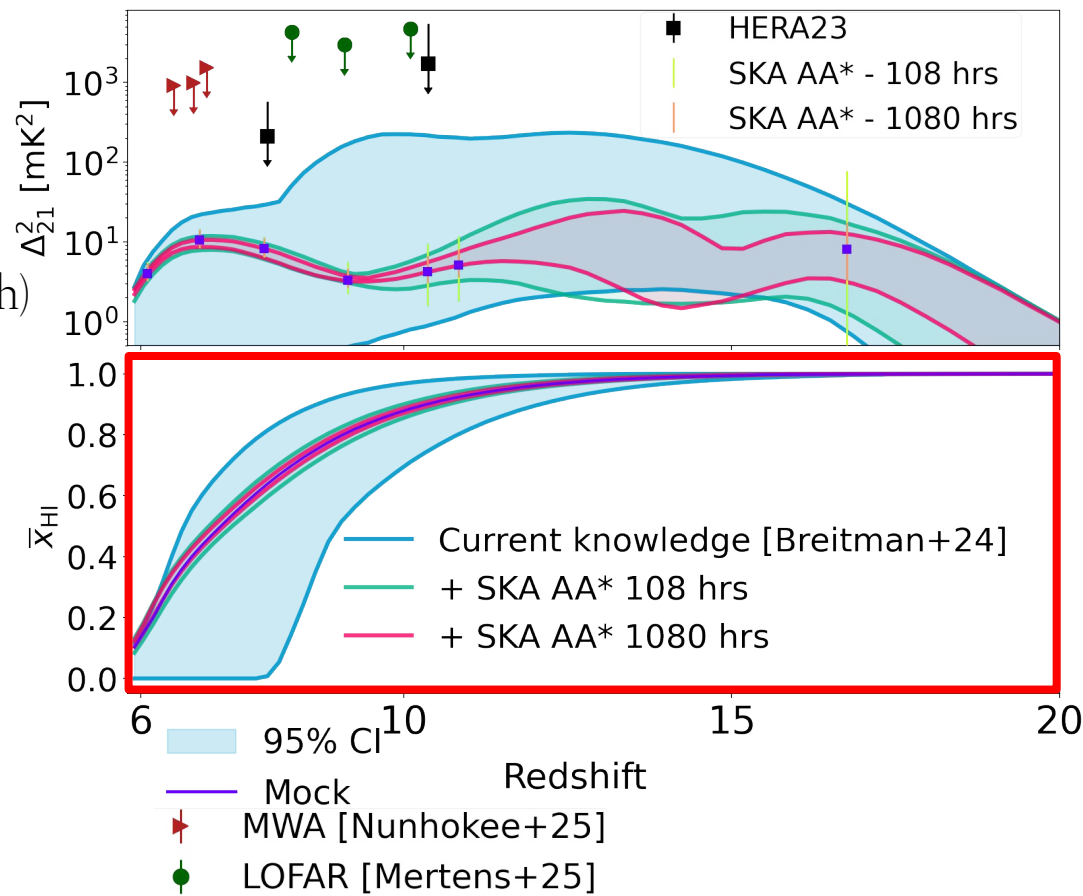
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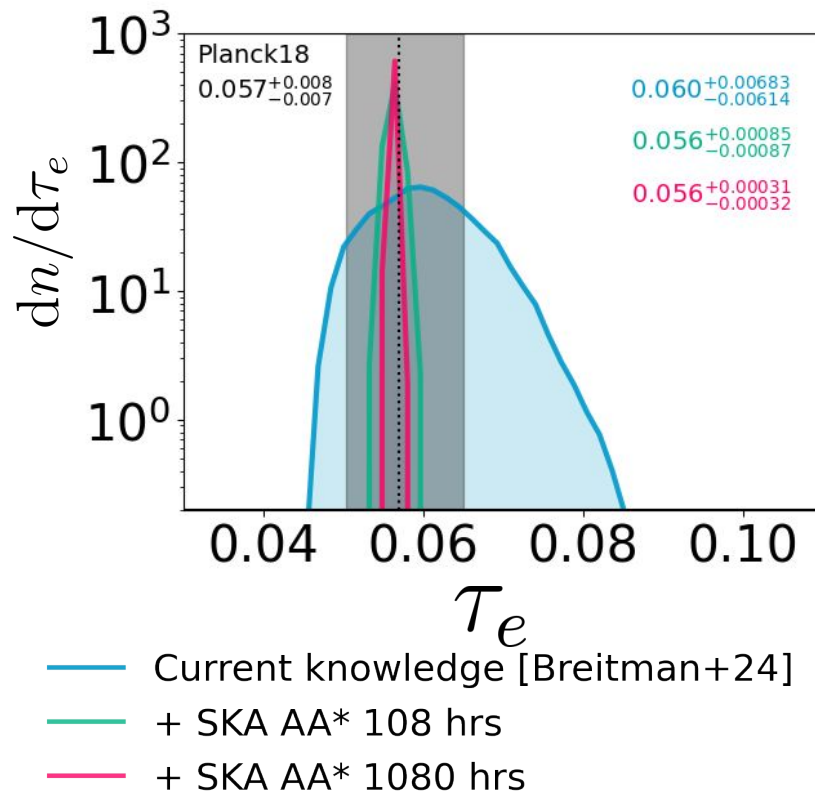
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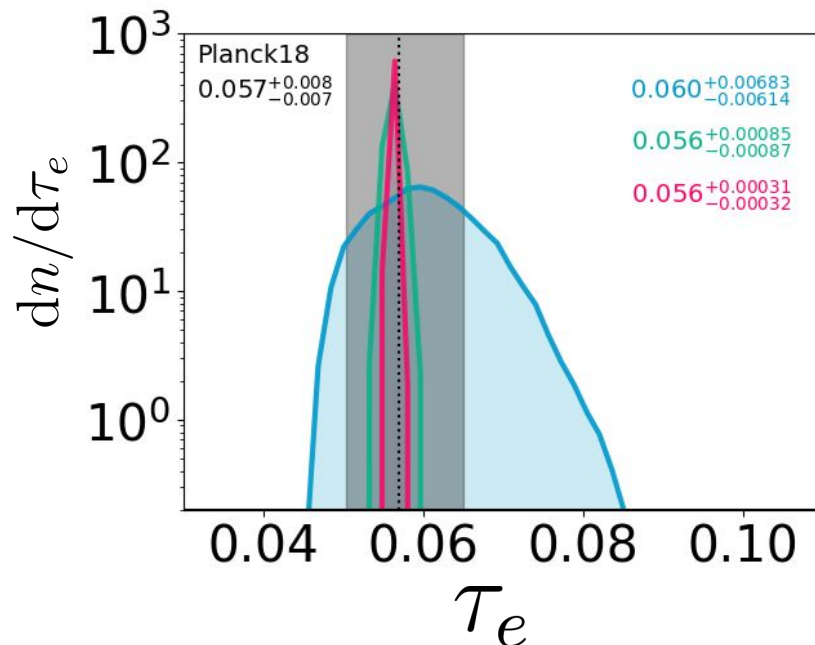
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What can we learn from the 21 cm line with SKA-low?

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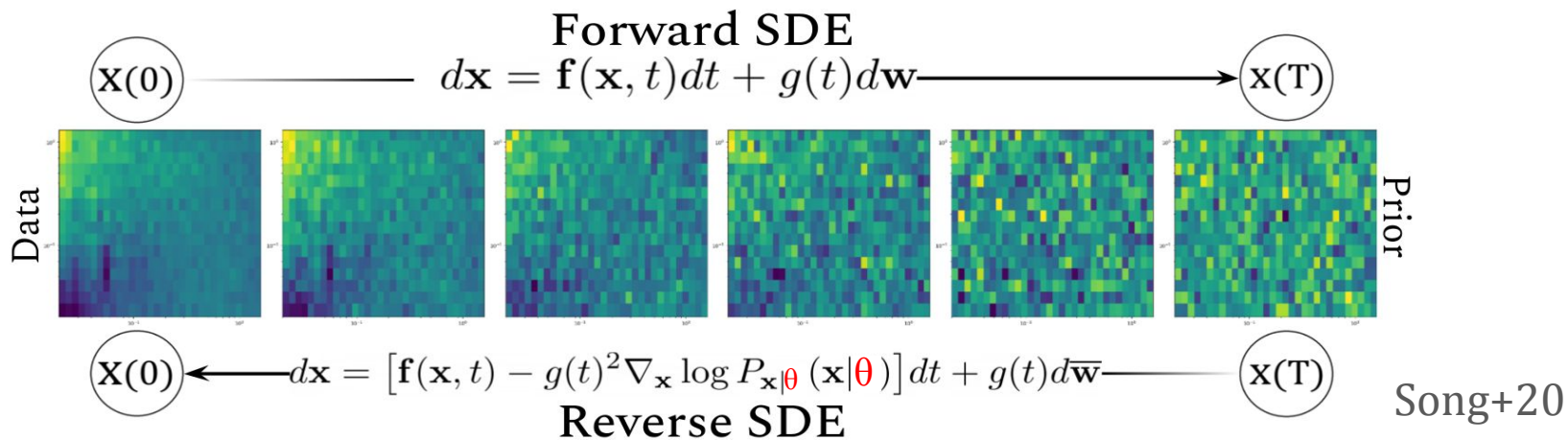


- Current knowledge [Breitman+24]
- + SKA AA* 108 hrs
- + SKA AA* 1080 hrs

AA* is extremely informative for CD/EoR science even after only ~100 hrs of observation!

21cmEMUv3

- First emulator of CD/EoR summary observables with **eleven** input parameters
- **First emulator of the 2D 21-cm PS**
- **First score-based generative emulator** of the PS



Now available!!

`pip install py21cmemu`

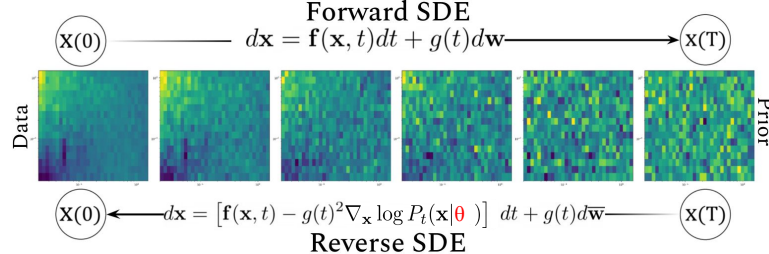
<https://github.com/21cmfast/21cmemu>



21 cm



Conclusions



- **Goal: Learn from 21-cm PS observations**
- **Method: Multi-tracer inference with 21-cm and other EoR/CD probes**
 - **Emulation makes these inferences computationally cheap**
- **New 21cmEMUv3:**
 - Astrophysical model including two galaxy populations: **ACGs and MCGs**
 - **First emulator** of CD/EoR summary observables **with eleven input parameters**
 - **First emulator of the 2D 21-cm PS**
 - **First score-based generative emulator of the PS**
 - **FE 68% CL \lesssim 5%** for all quantities
- **Forecasting SKA with 21cmSense:**
 - All SKA station and sub-station layouts available
 - **For CD/EoR, AA* is just as constraining as AA4**
 - **Percent-level EoR**
 - **τ 1 σ 20x tighter than Planck18**
 - **AA* is very constraining even after ~100 hrs**

21 cm

