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Forecasting upcoming 21cm SKA observations with 21cmFAST

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In collaboration with Prof. Andrei Mesinger

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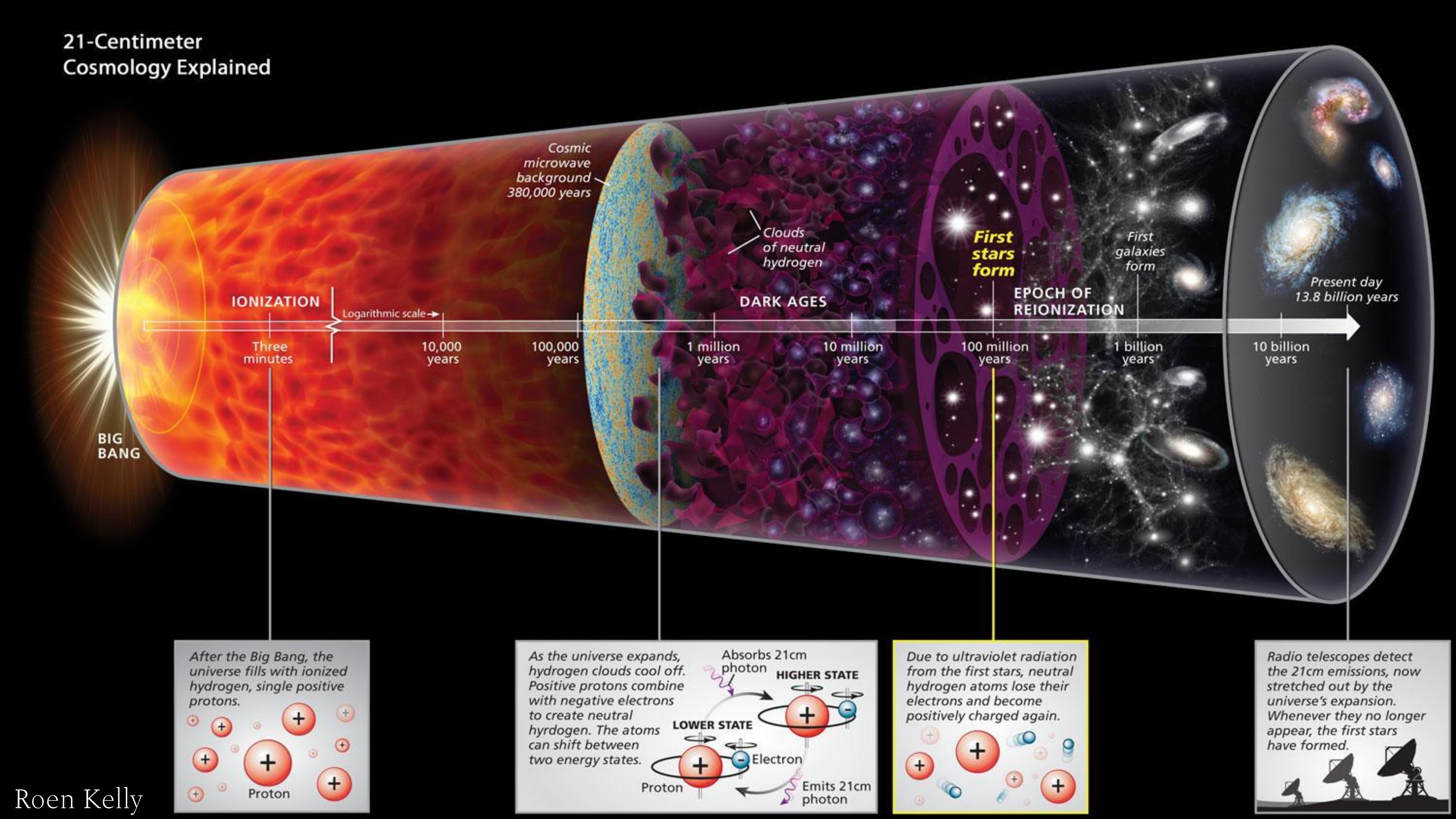
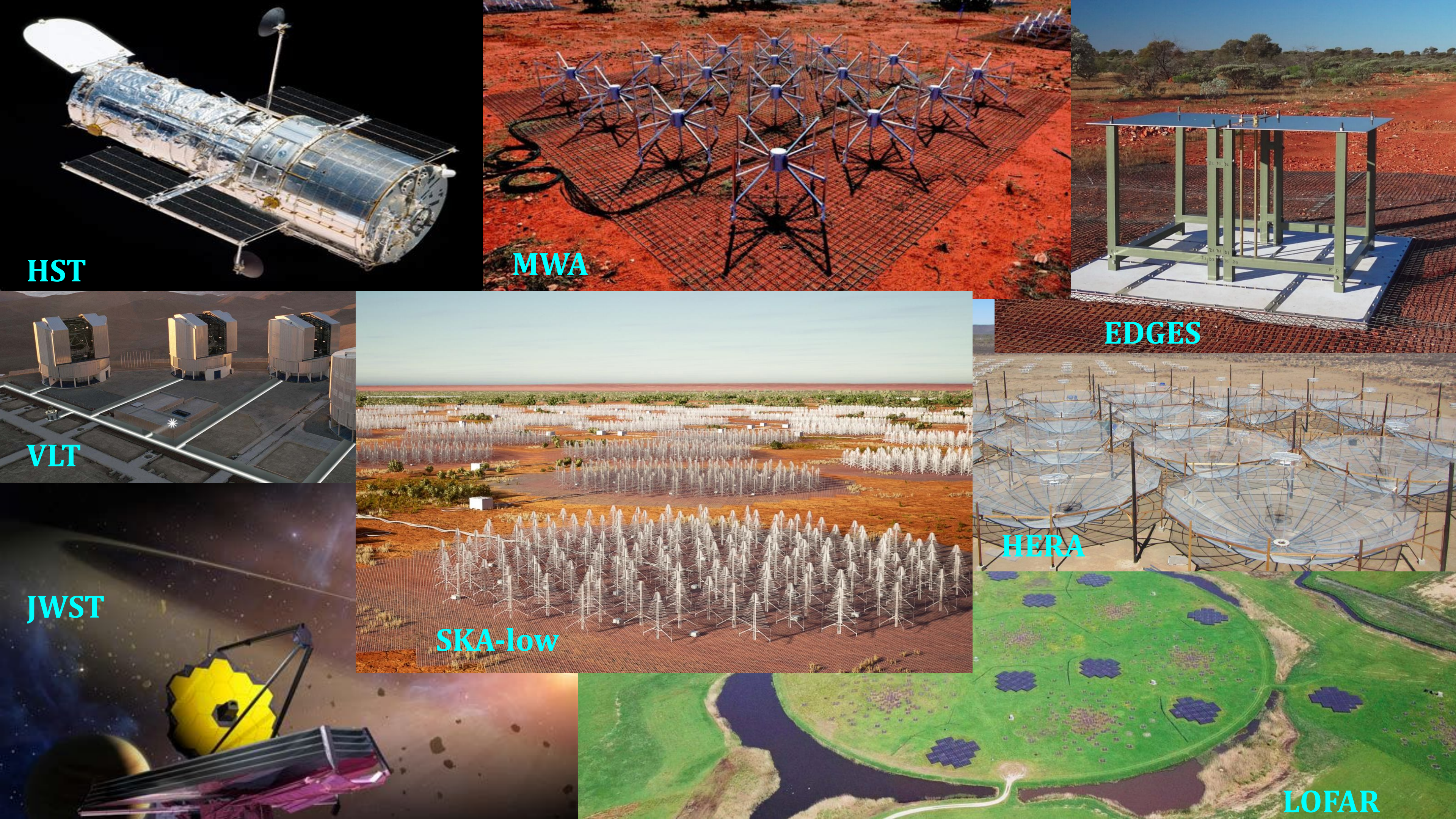


21-Centimeter Cosmology Explained
Cosmic microwave background 380,000 years
Clouds of neutral hydrogen
First stars form
First galaxies form
Present day 13.8 billion years
BIG BANG
IONIZATION
Logarithmic scale
DARK AGES
EPOCH OF REIONIZATION
Three minutes
10,000 years
100,000 years
1 million years
10 million years
100 million years
1 billion years
10 billion years
After the Big Bang, the universe fills with ionized hydrogen, single positive protons.
Proton
As the universe expands, hydrogen clouds cool off. Positive protons combine with negative electrons to create neutral hyrdogen. The atoms can shift between two energy states.
Absorbs 21cm photon
HIGHER STATE
LOWER STATE
Electron
Proton
Emits 21cm photon
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.

Roen Kelly


HST
MWA
EDGES
VLT
SKA-low
HERA
JWST
LOFAR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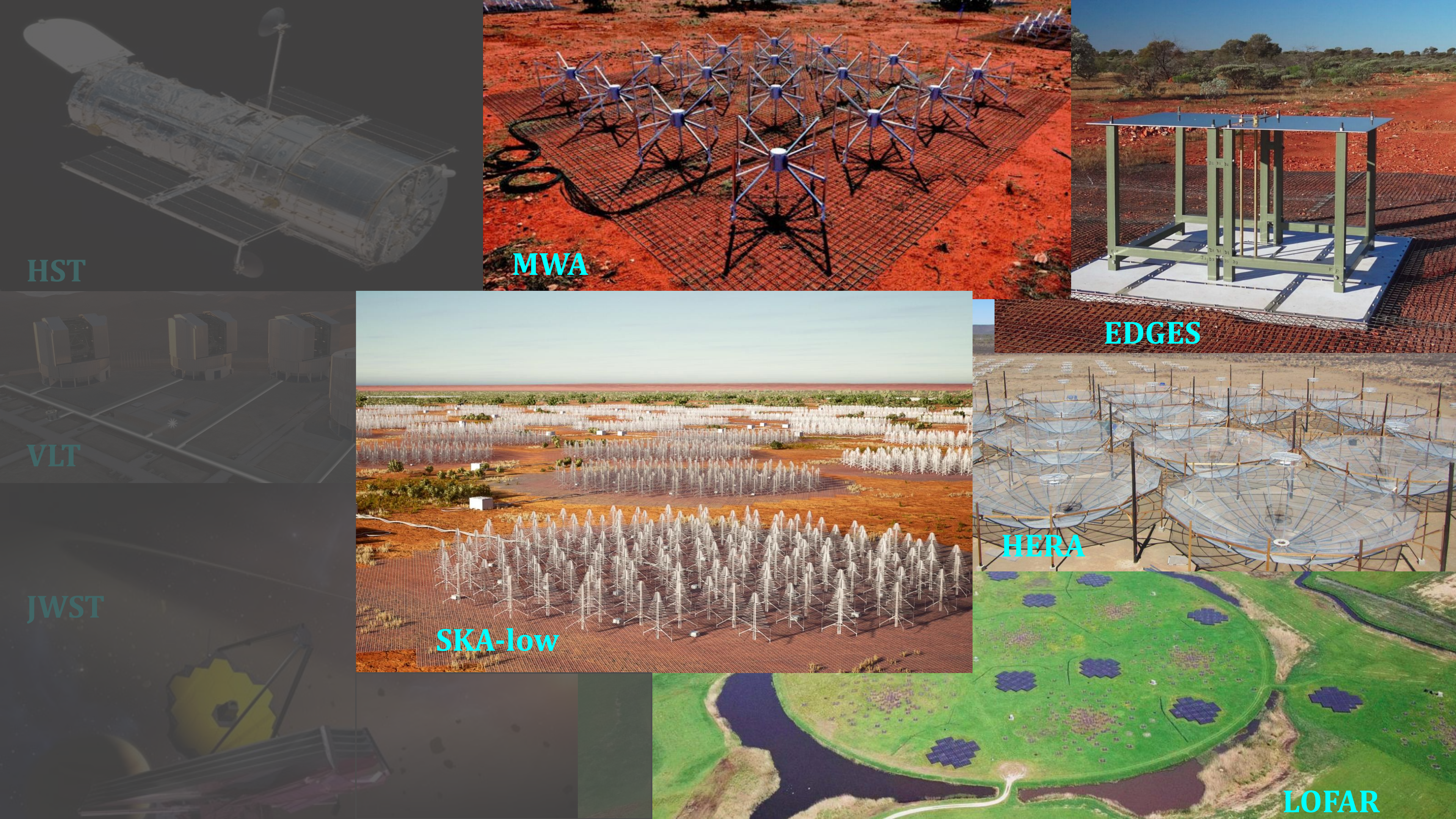
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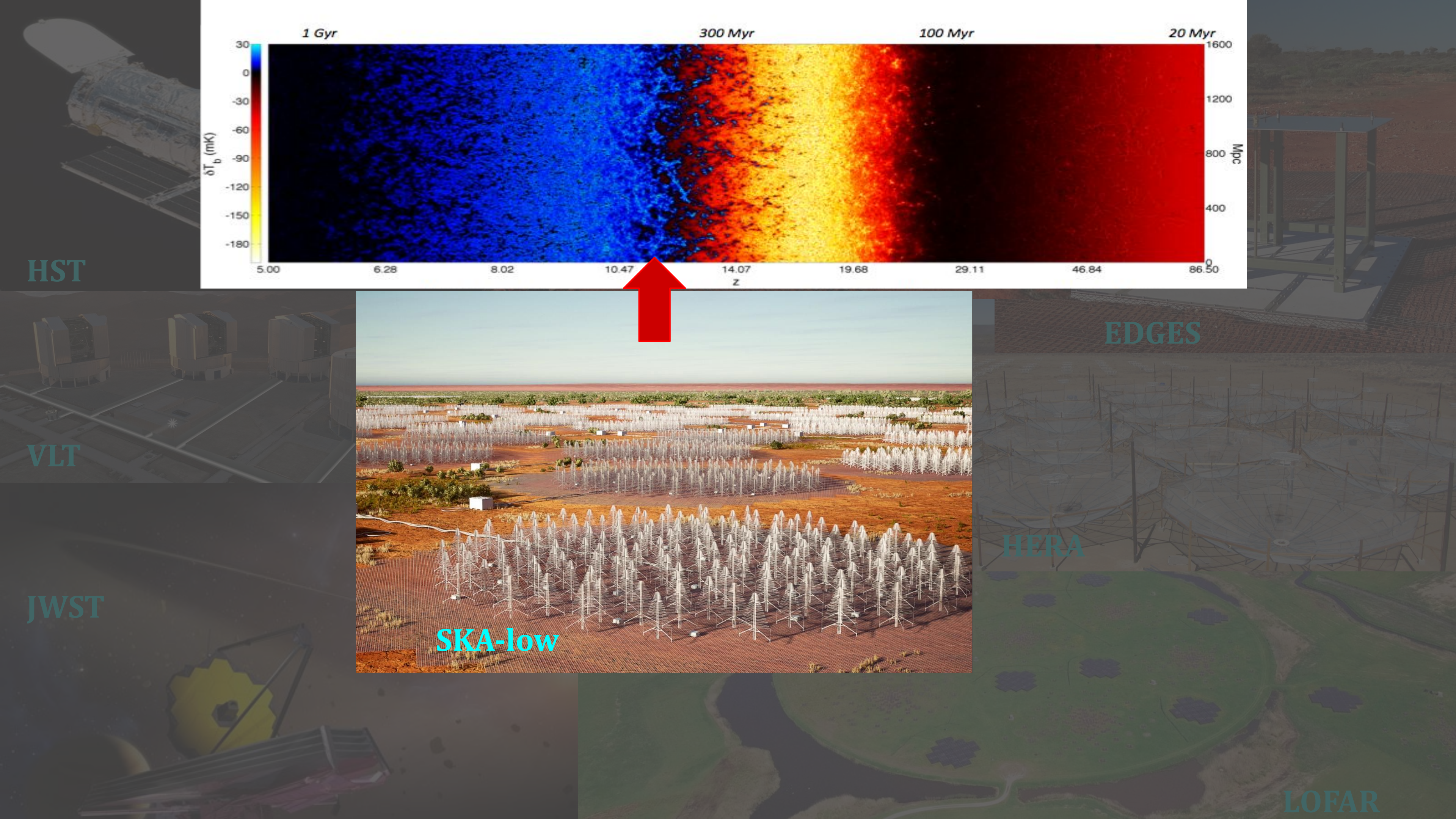
1 Gyr
300 Myr
100 Myr
20 Myr
δT_b (mK)
30
0
-30
-60
-90
-120
-150
-180
1600
1200
800
400
0
Mpc
5.00
6.28
8.02
10.47
14.07
19.68
29.11
46.84
86.50
z
HST
VLT
JWST
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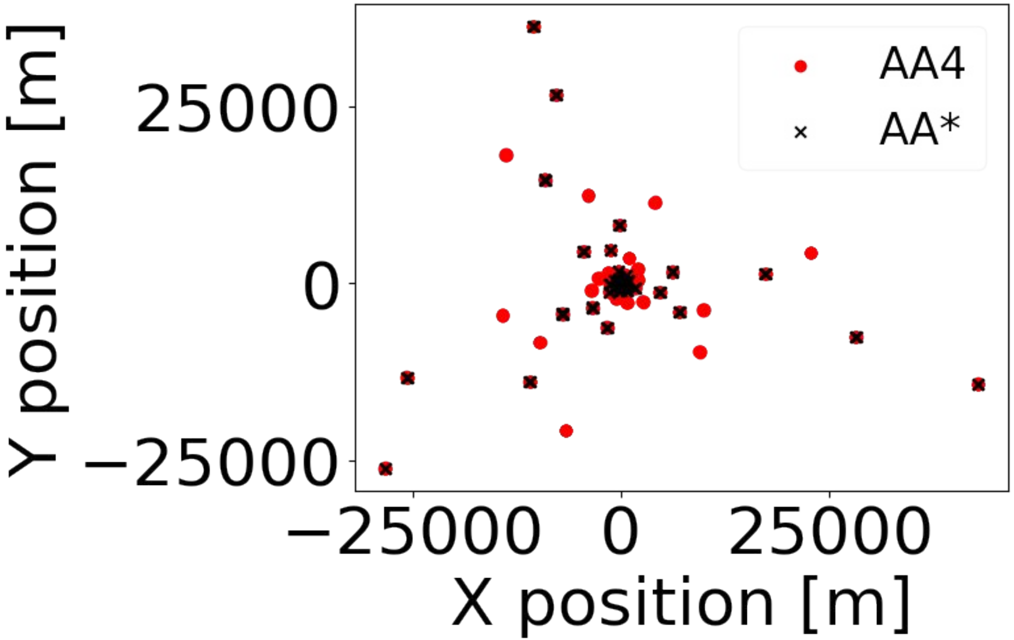
Forecast SKA 21 cm observation

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



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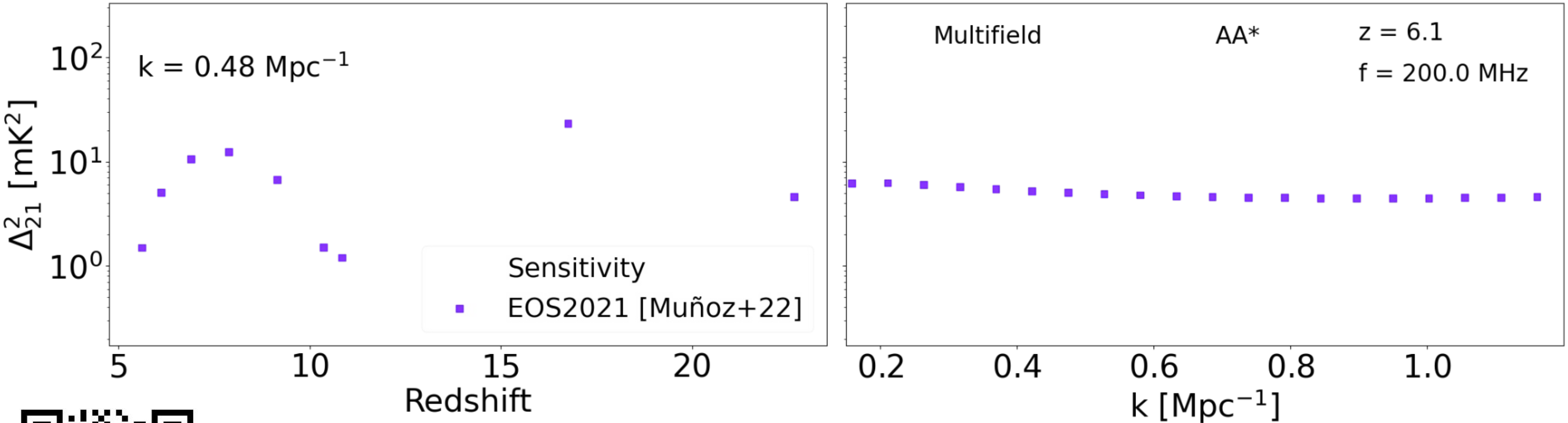

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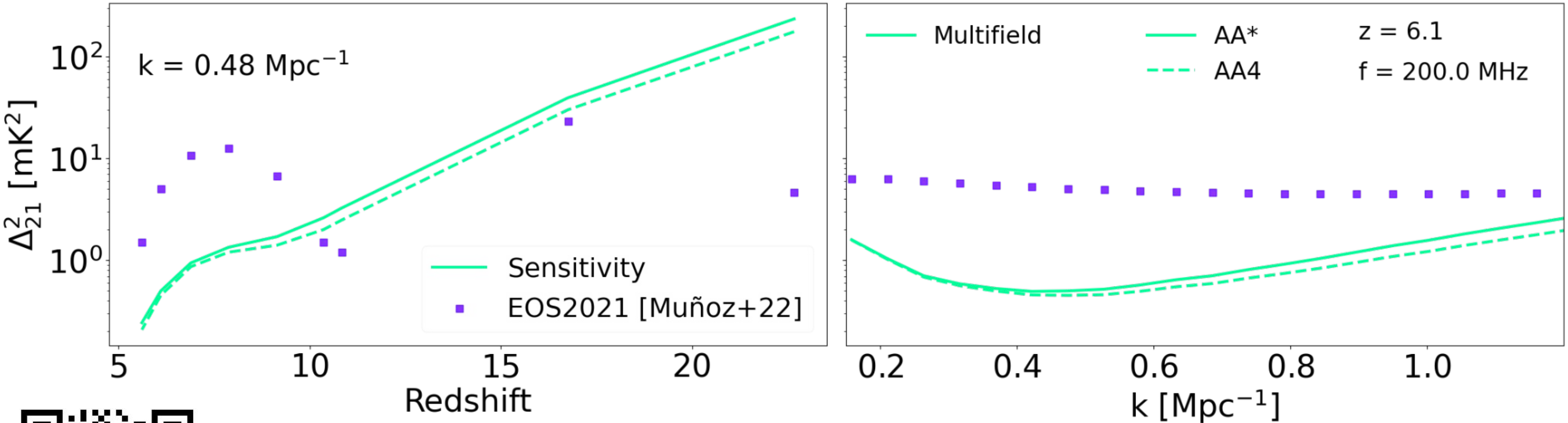

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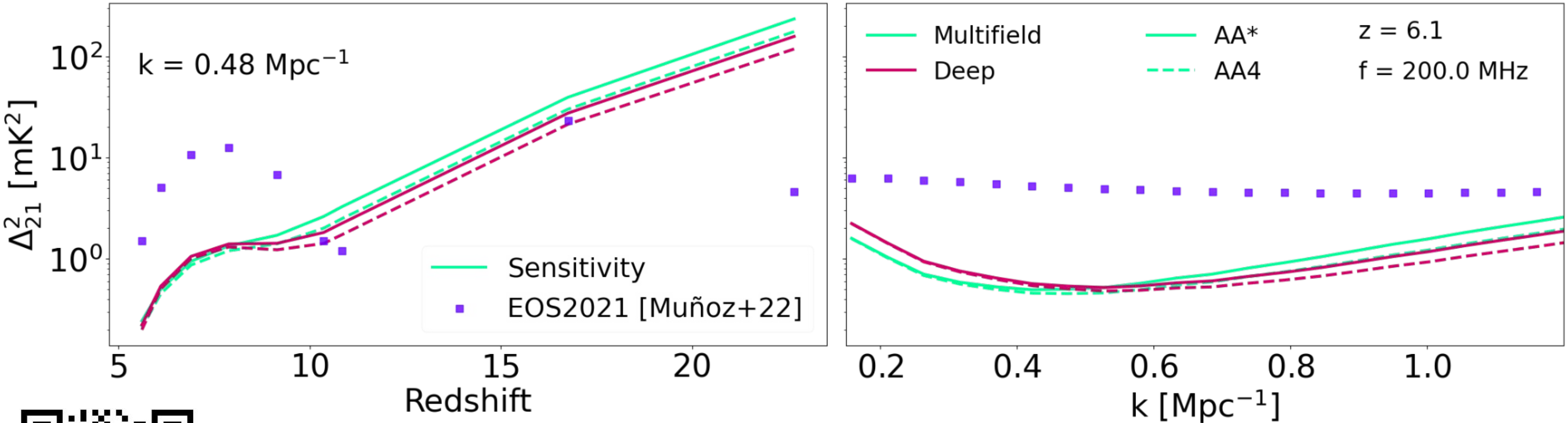

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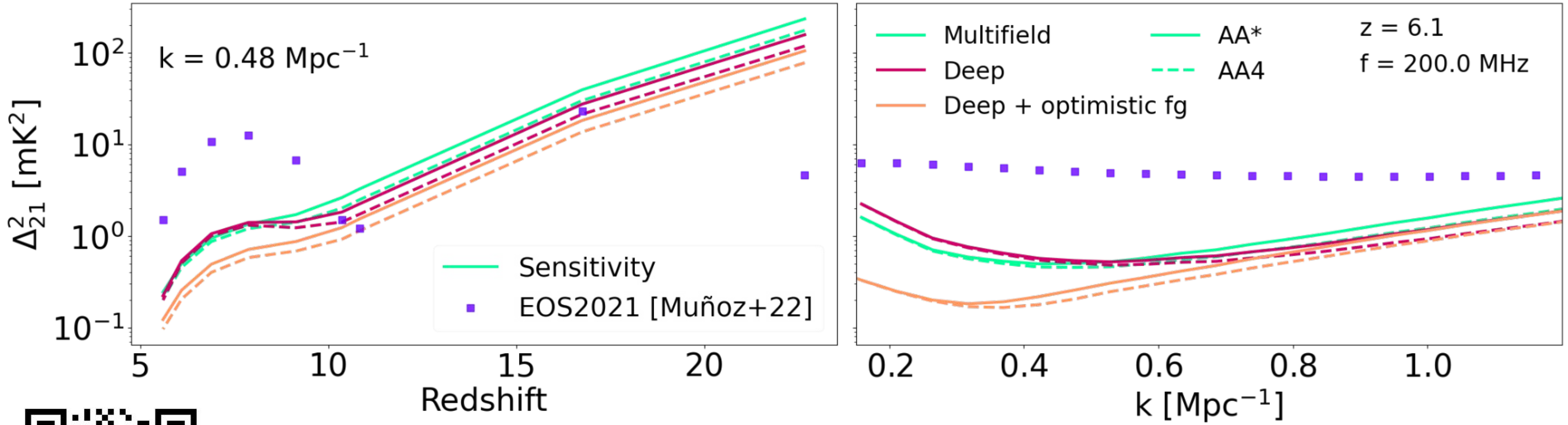

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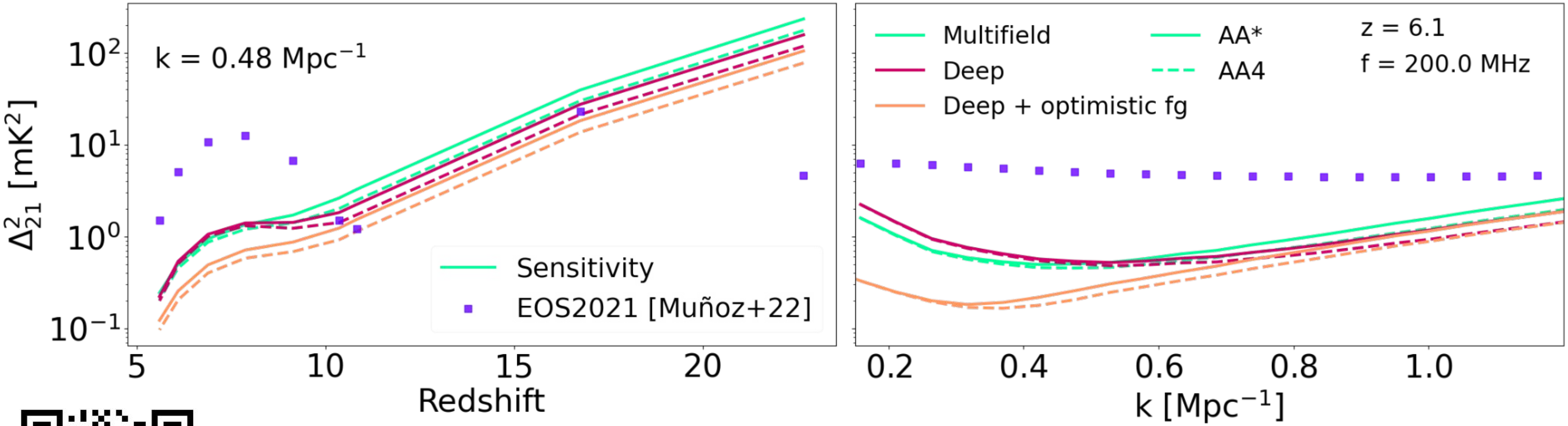

How can we learn from 21 cm SKA-low observations?

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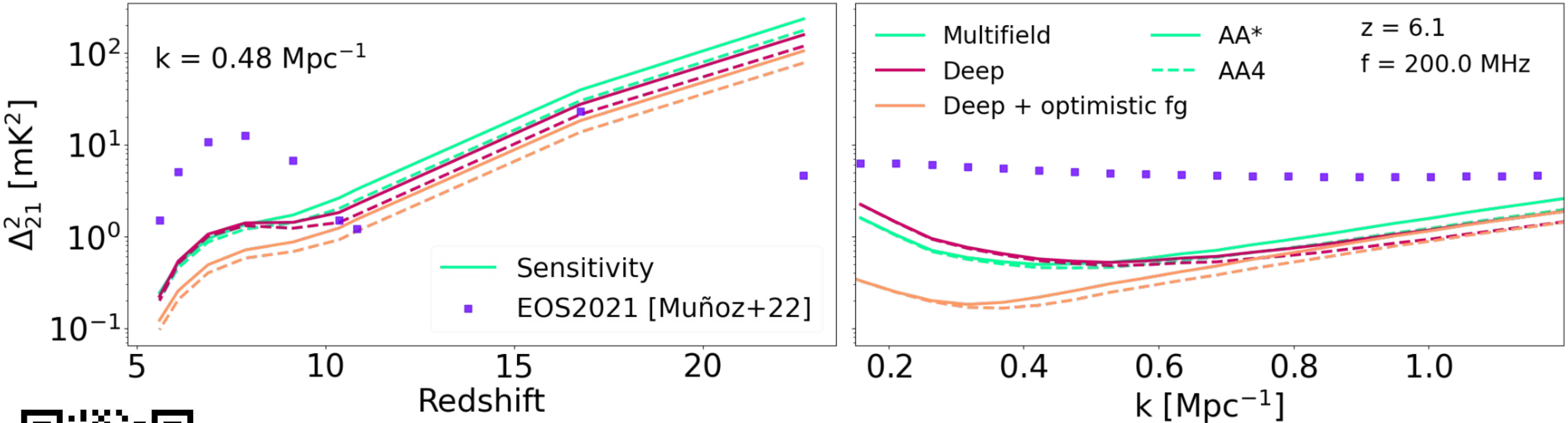


How can we learn from 21 cm SKA-low observations?

Bayesian inference

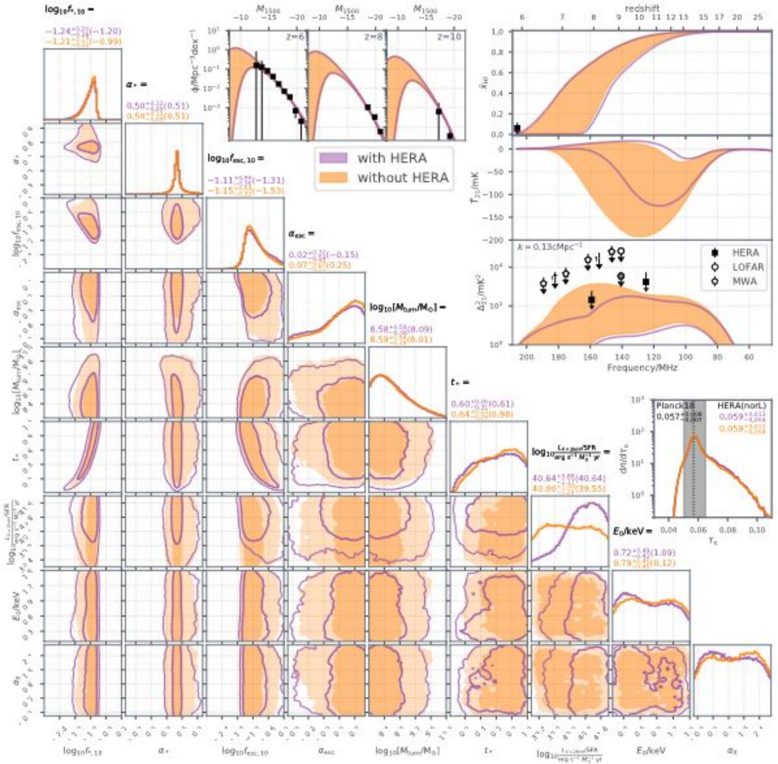
Bayesian Inference

- $P(\theta)$ = 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 ~ **300k** forward model evaluations



HERA23

Bayesian Inference

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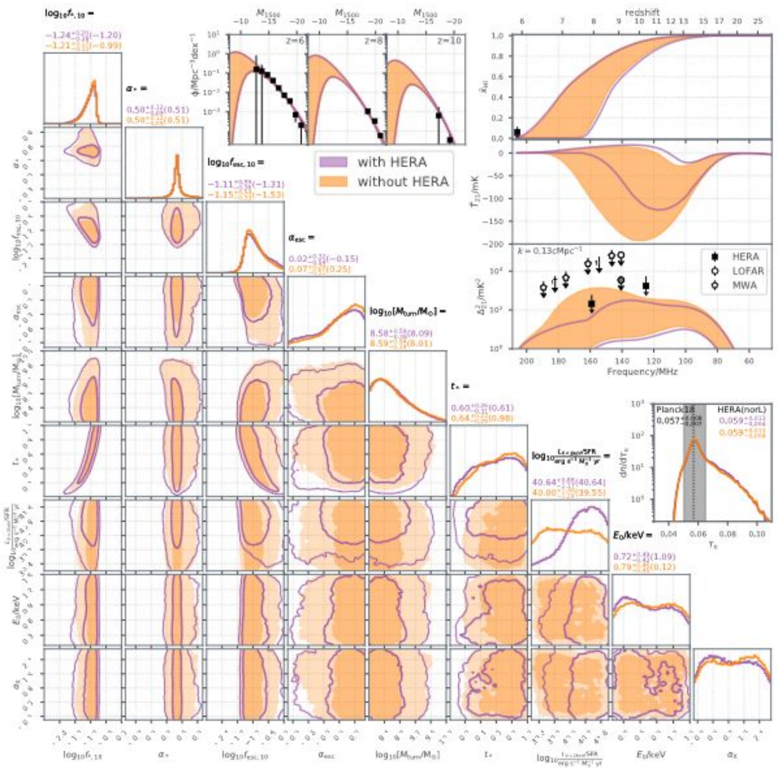

HERA23

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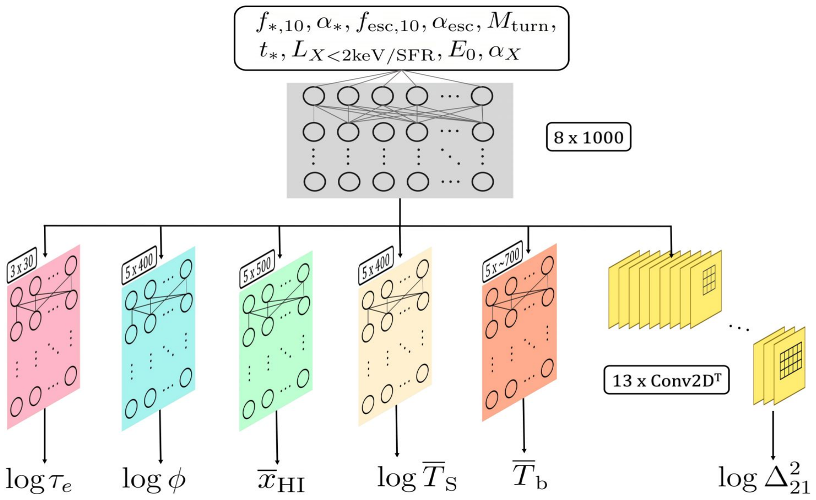
21cmEMUv1

- Input: nine astrophysical parameters



Breitman+24

21cmEMUv1

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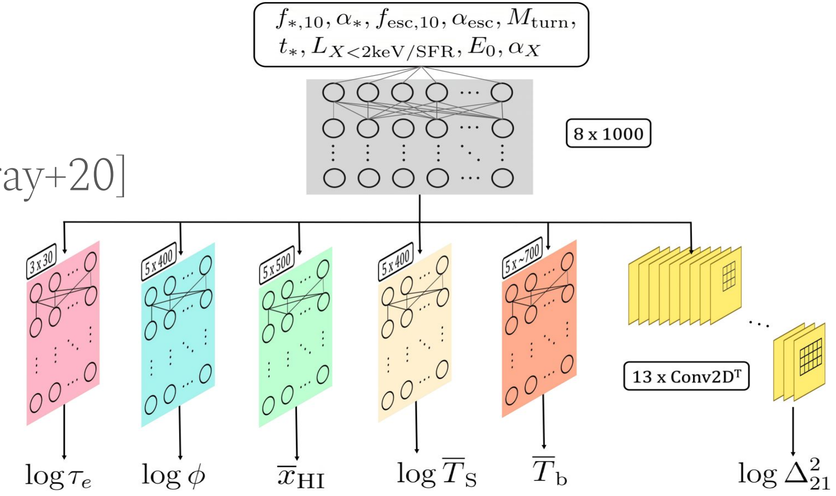
- Model: 21cmFASTv3 [Mesinger+07,11, Murray+20]



Breitman+24

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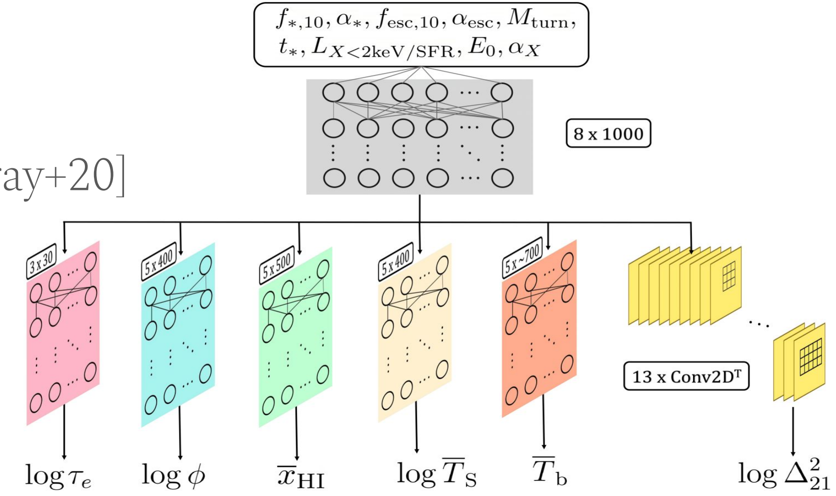

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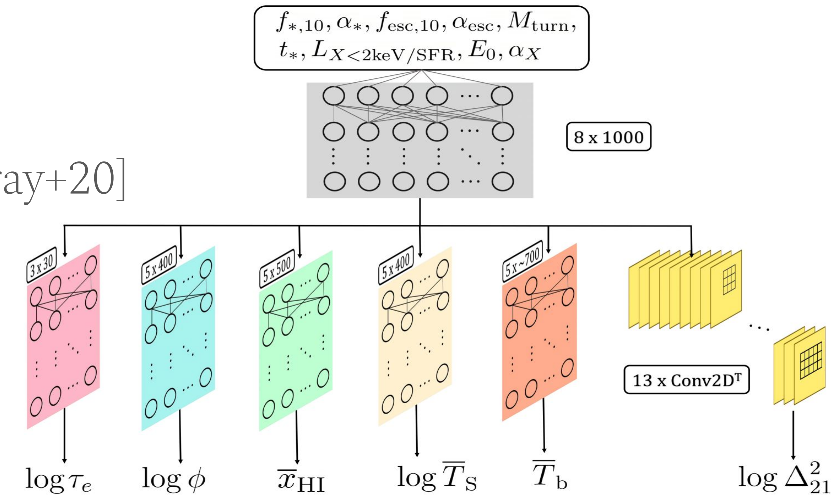
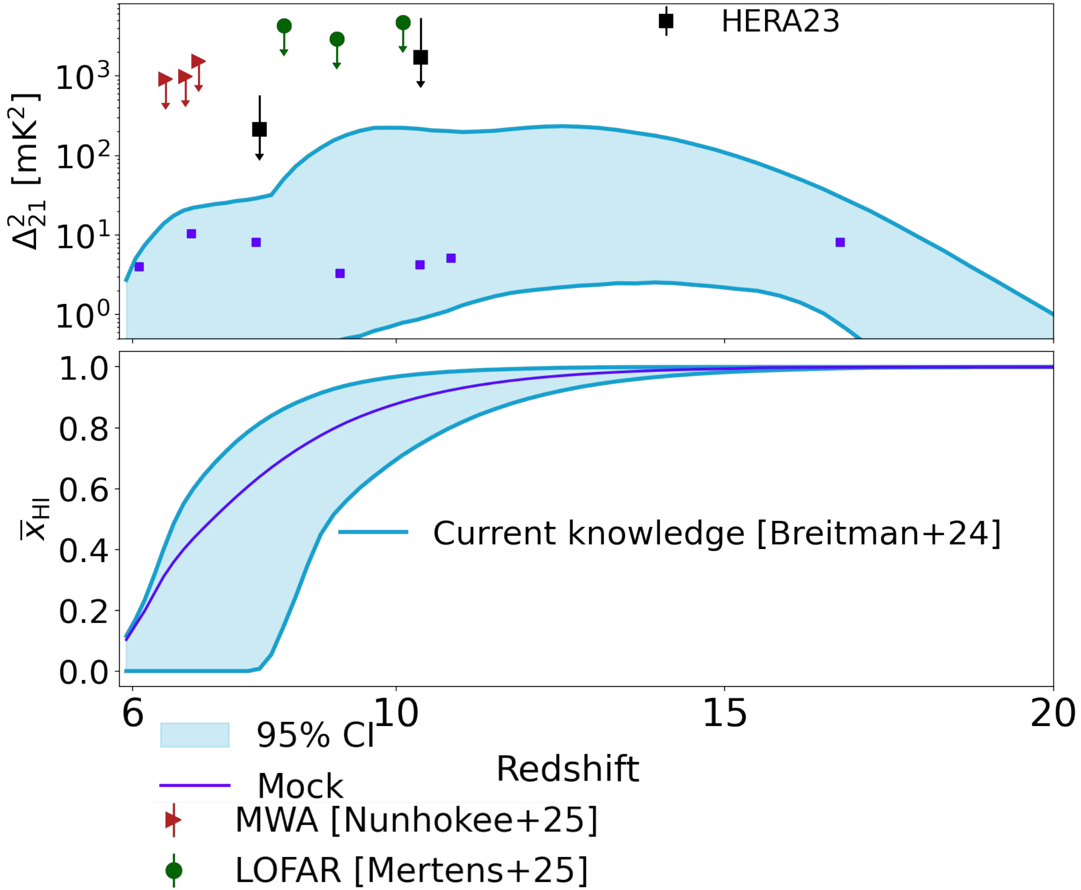


1 inference ≈ GPUhr vs 10^6 CPUhrs

Breitman+24

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



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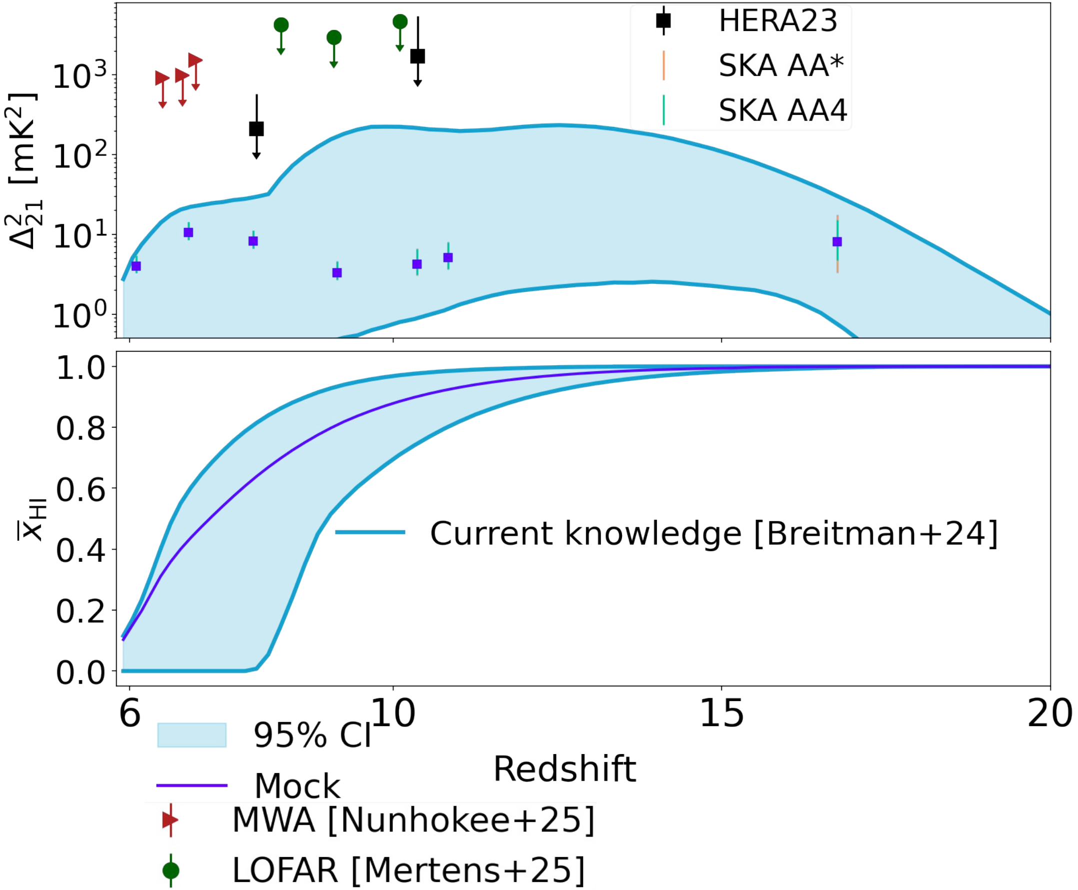

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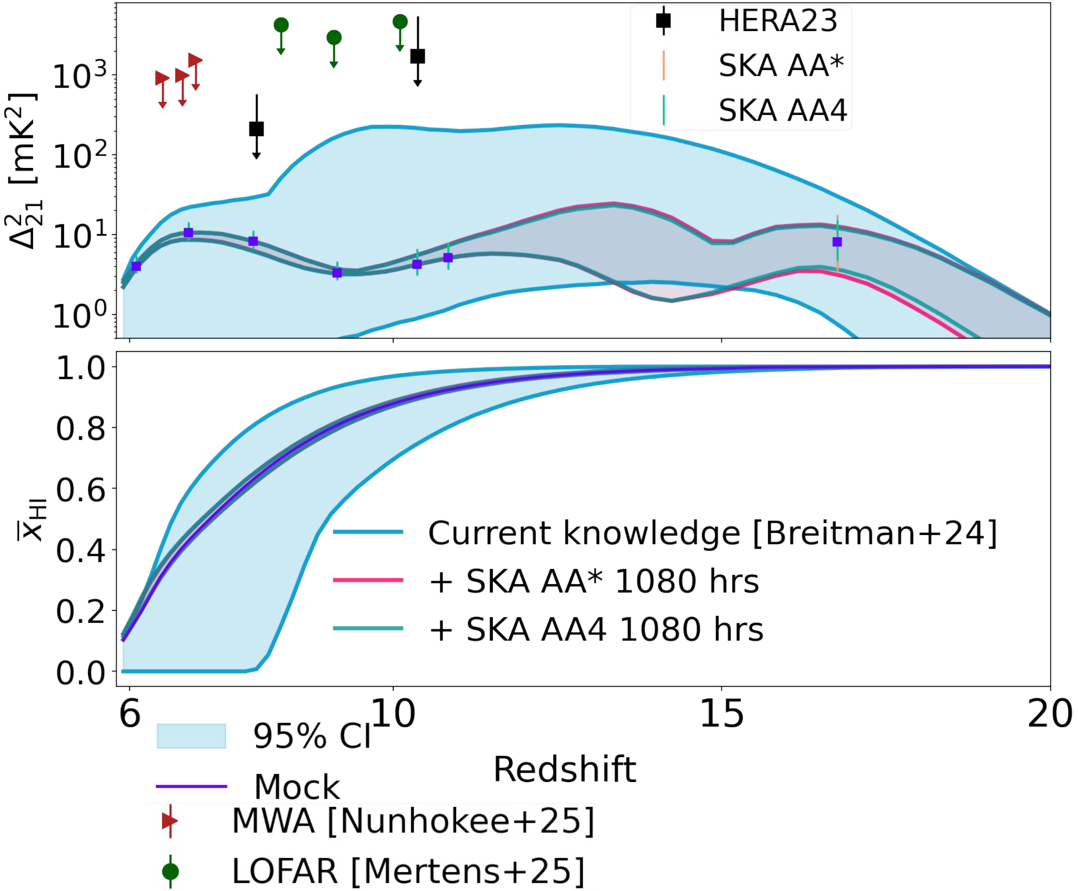
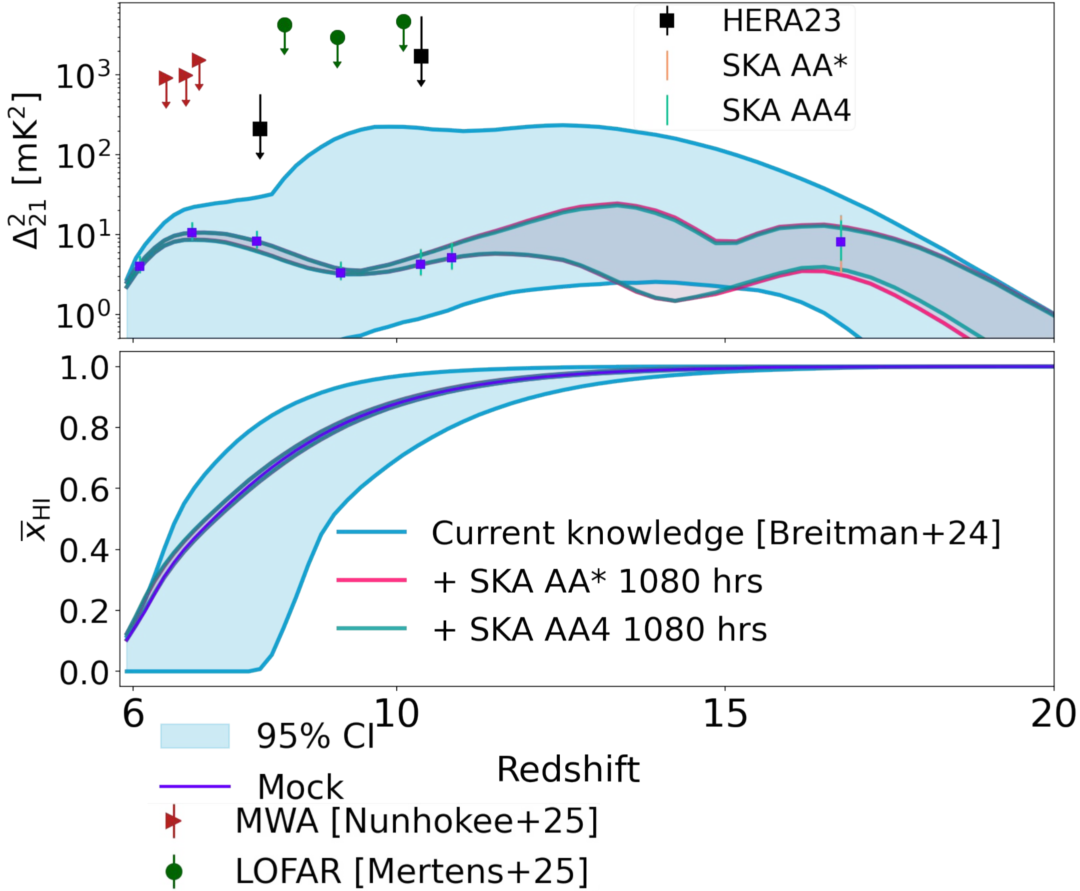


What can we learn from the 21 cm line with SKA-low?

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



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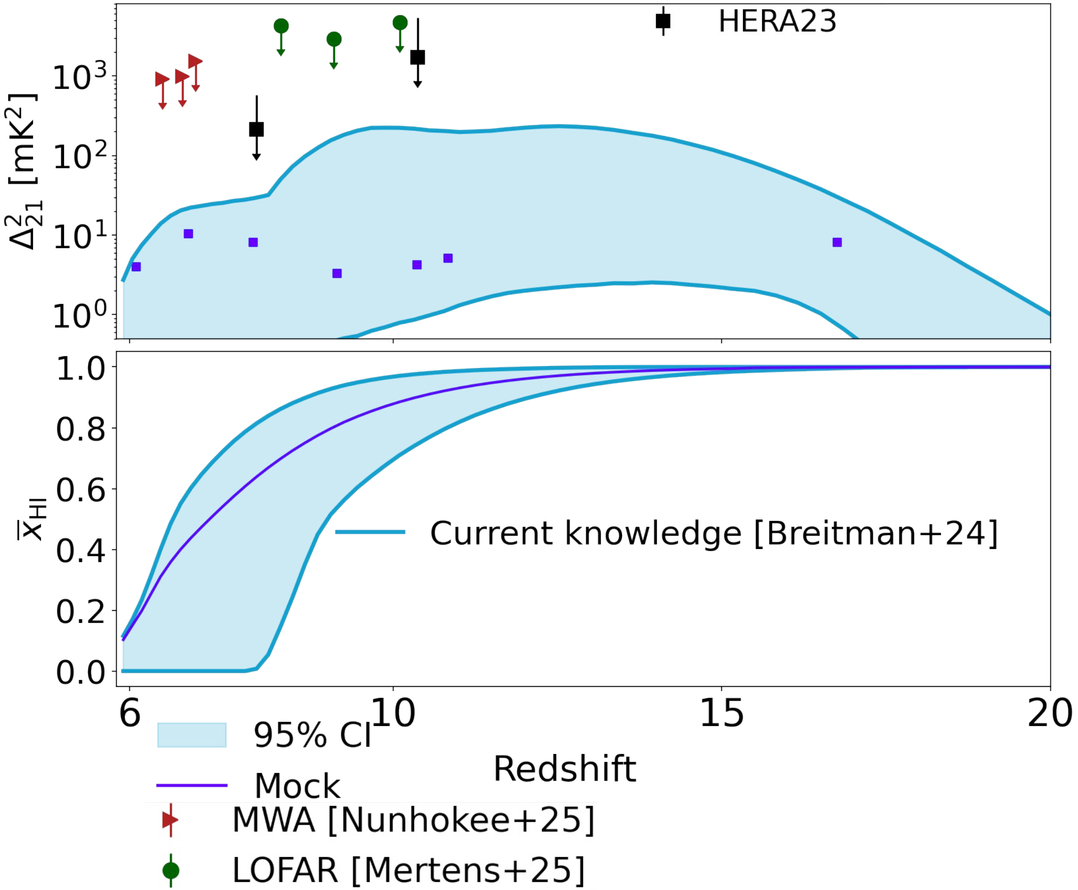

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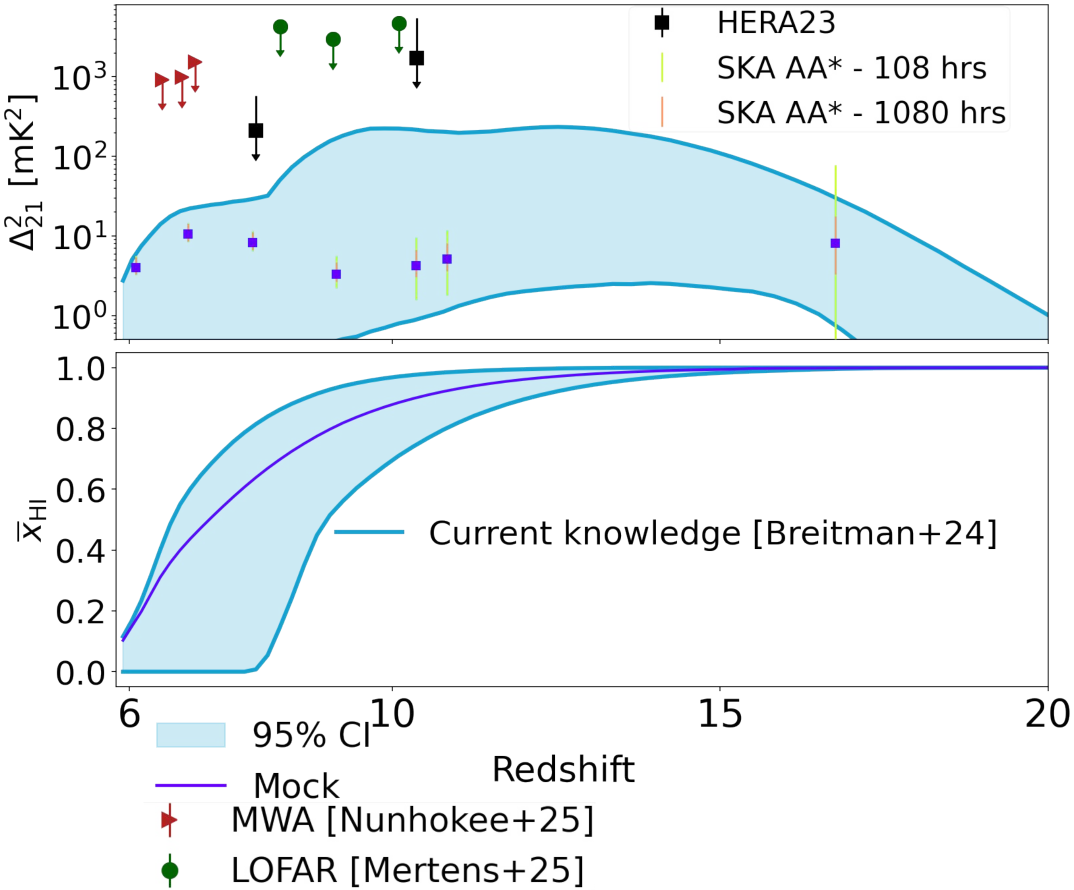

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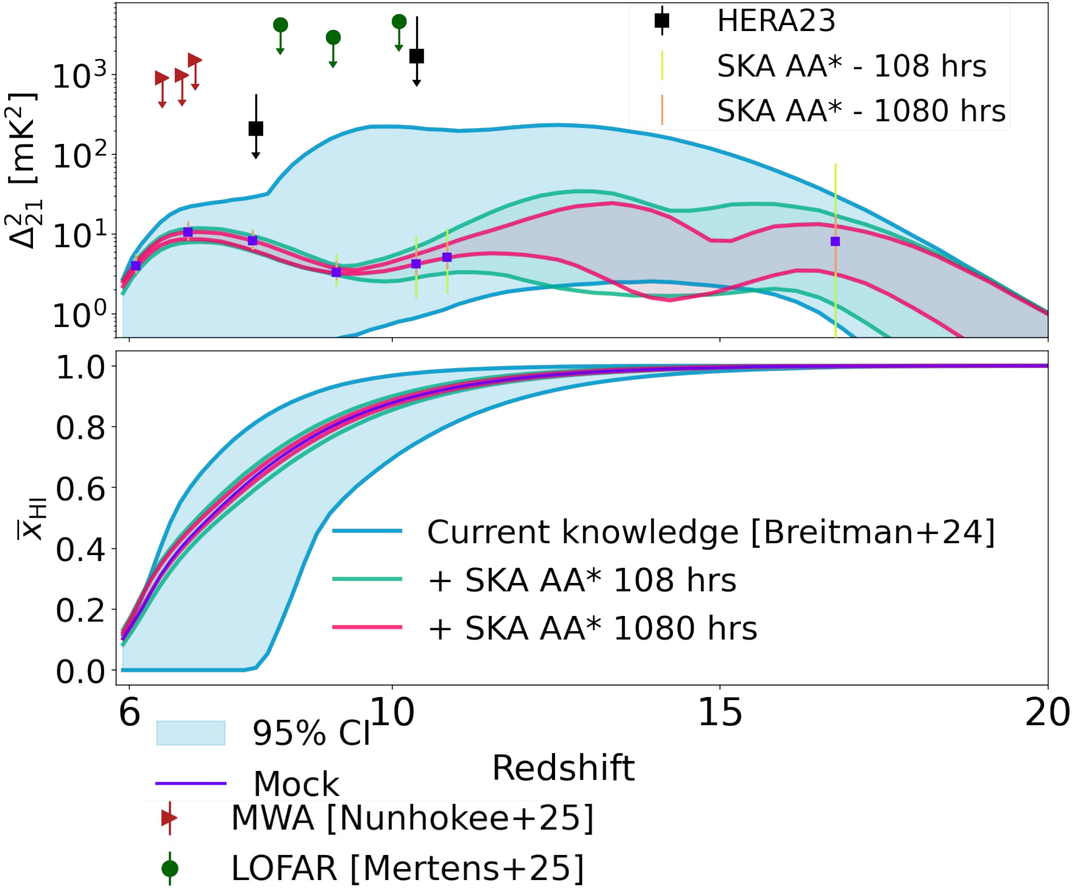

What can we learn from the 21 cm line with SKA-low?

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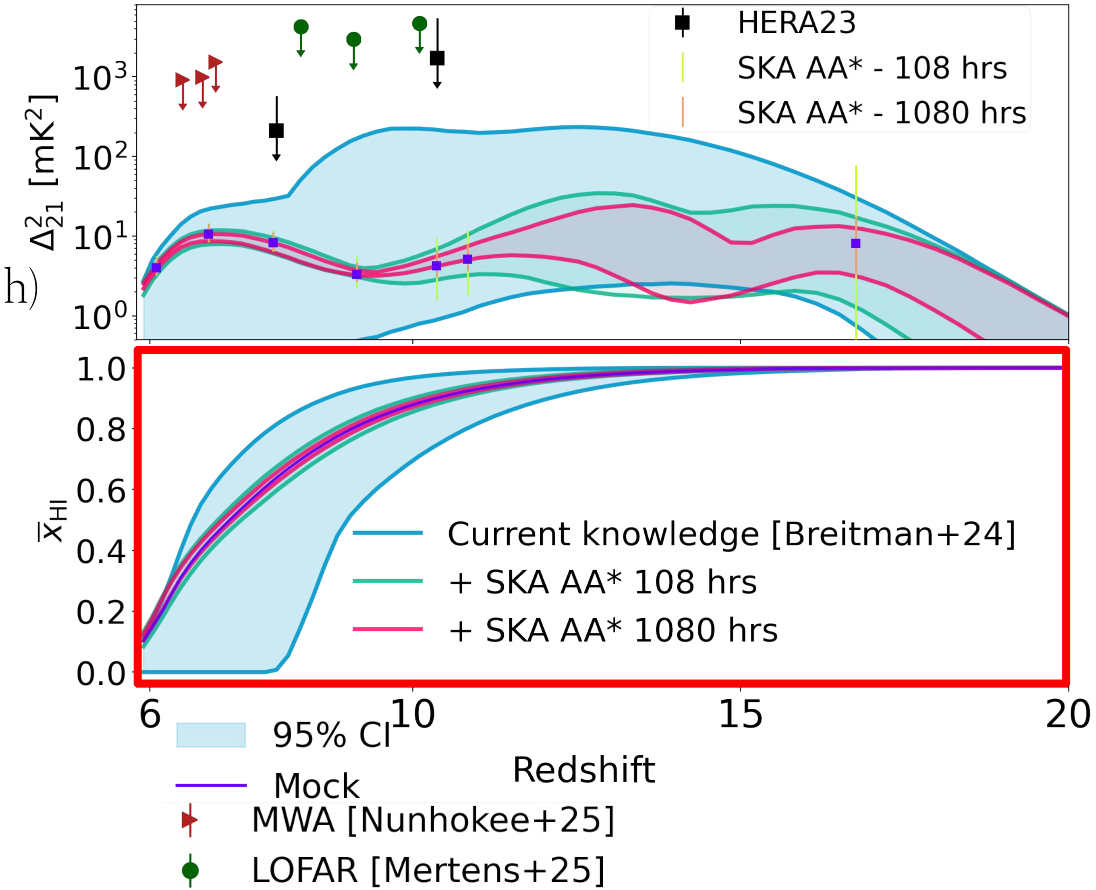
- **Percent-level EoR**: 1080h (108h) midpoint within ±0.04 (0.02)



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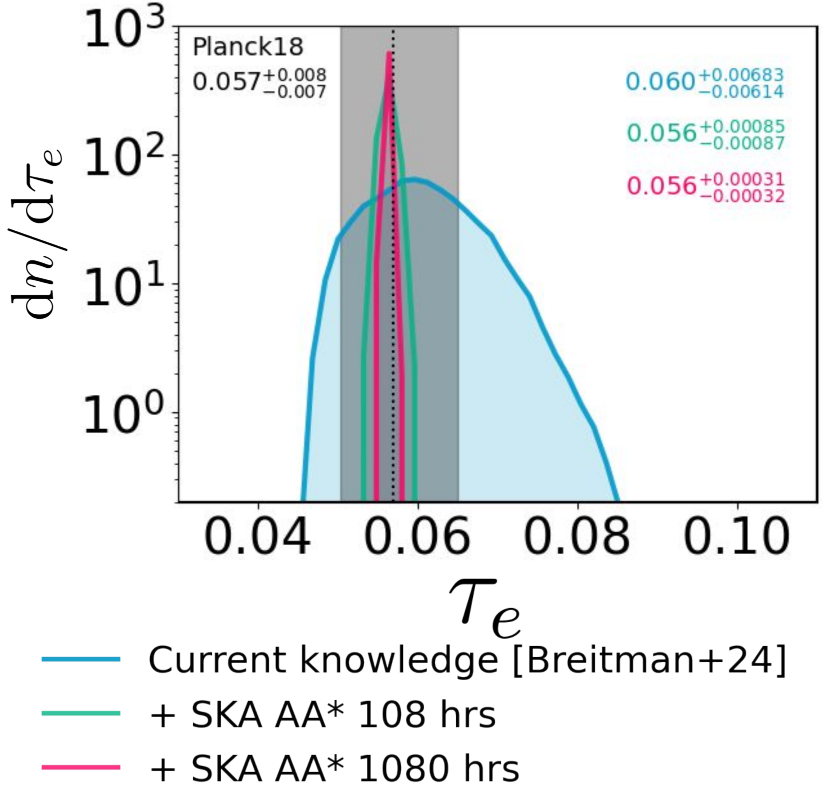
- **τ_e 1σ over 20x tighter than Planck18**



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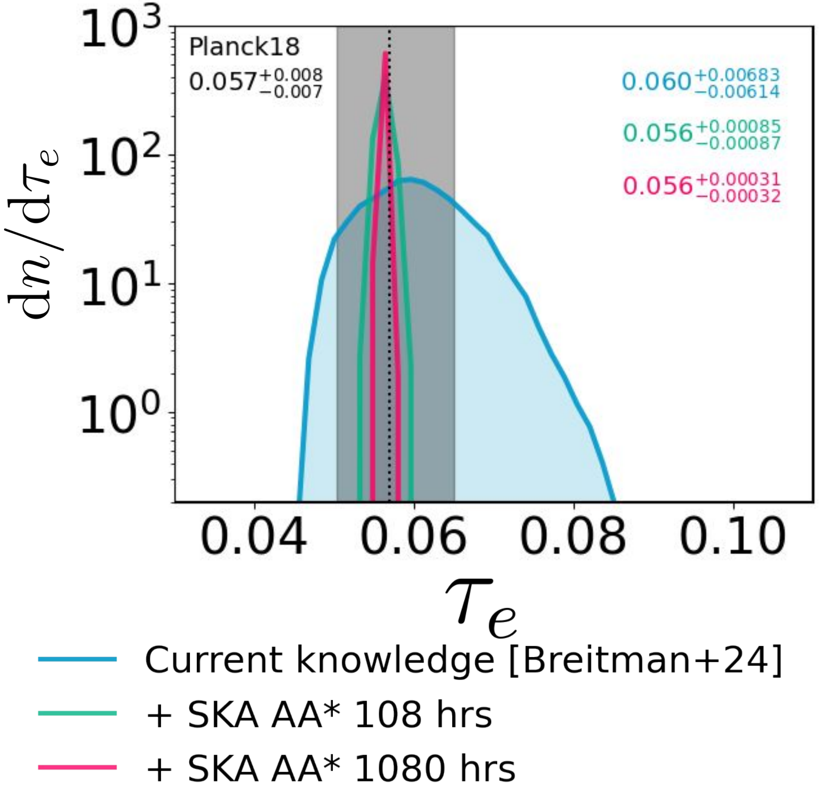
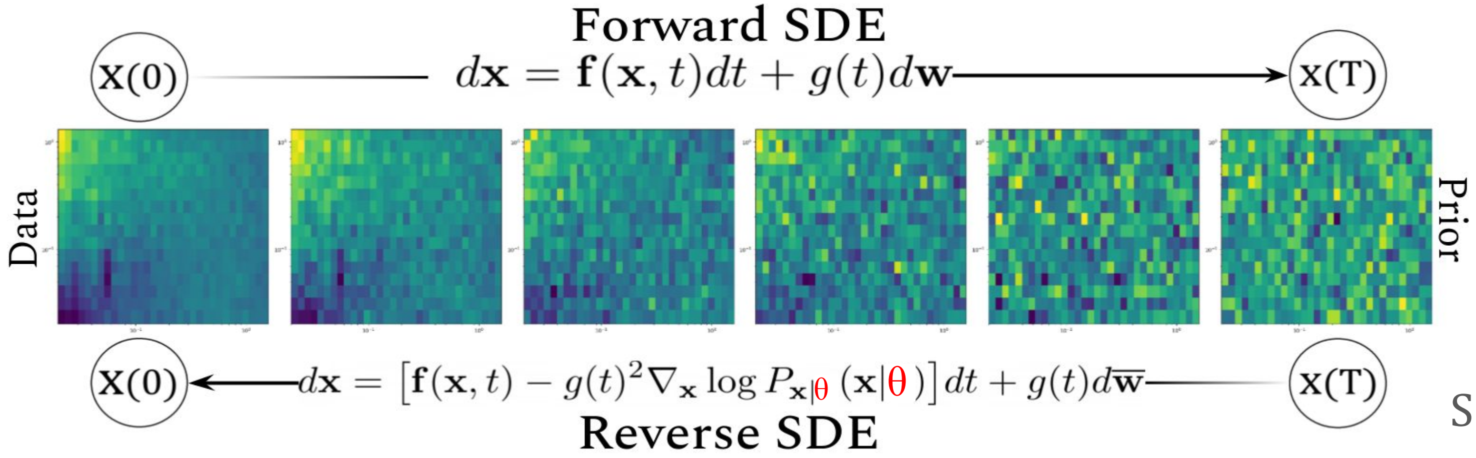


AA* is extremely informative for CD/EoR science even after only ~100 hrs of observation!

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



Song+20

Breitman+25 in prep

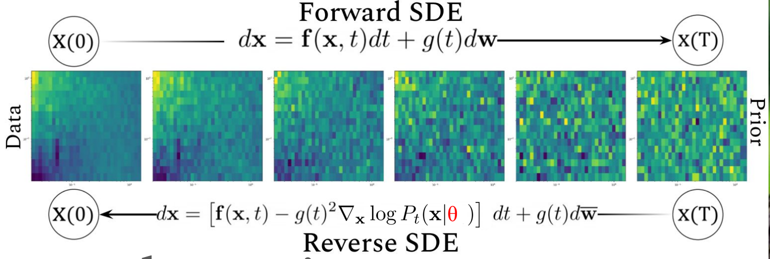
Now available!!

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 ≲ 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 1σ 20x tighter than Planck18**
  - **AA* is very constraining even after ~100 hrs**

21 cm