Title: Viewing the Cosmos Through the Highly Redshifted 21-cm Line

Speakers: Bobby Pascua

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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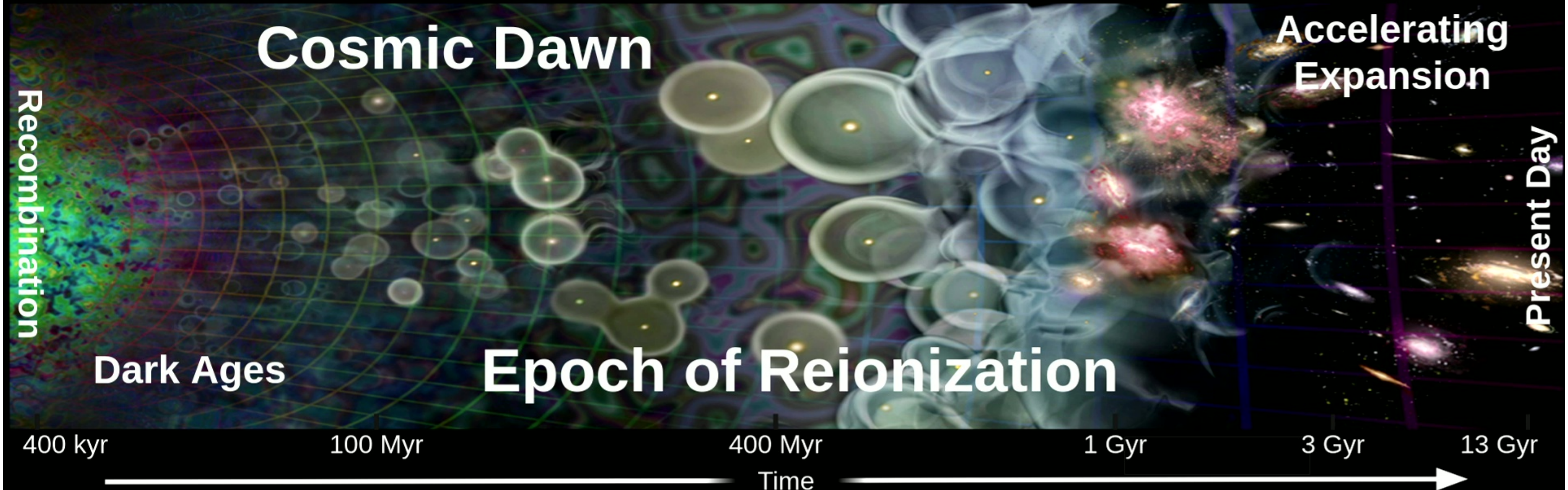
Abstract:

The 21-cm line from neutral hydrogen holds immense potential as a probe of early astrophysics and cosmic evolution. Realizing the potential of this observational probe, however, is limited by our ability to control systematic effects in the data and model the cosmological 21-cm signal. In this talk, I will provide an overview of the observational prospects made possible through the cosmic 21-cm signal and discuss the challenges confronting interferometric experiments that are targeting a high-redshift detection. I will focus on recent developments from the Hydrogen Epoch of Reionization Array (HERA), covering our latest upper limits on the 21-cm power spectrum and their implications for early X-ray heating of the intergalactic medium. I will additionally discuss our latest efforts to understand and mitigate mutual coupling, a complex systematic effect in the data that threatens to thwart our efforts to detect the cosmological 21-cm signal. I will conclude by discussing the path forward with HERA, with a preliminary view of what to expect from forthcoming analyses.


Viewing the Cosmos Through the Highly Redshifted 21-cm Line
Bobby Pascua
Perimeter Cosmology Seminar
robert.pascua@mail.mcgill.ca
21 Jan 2025
Photo: Dara Storer

21-cm Overview

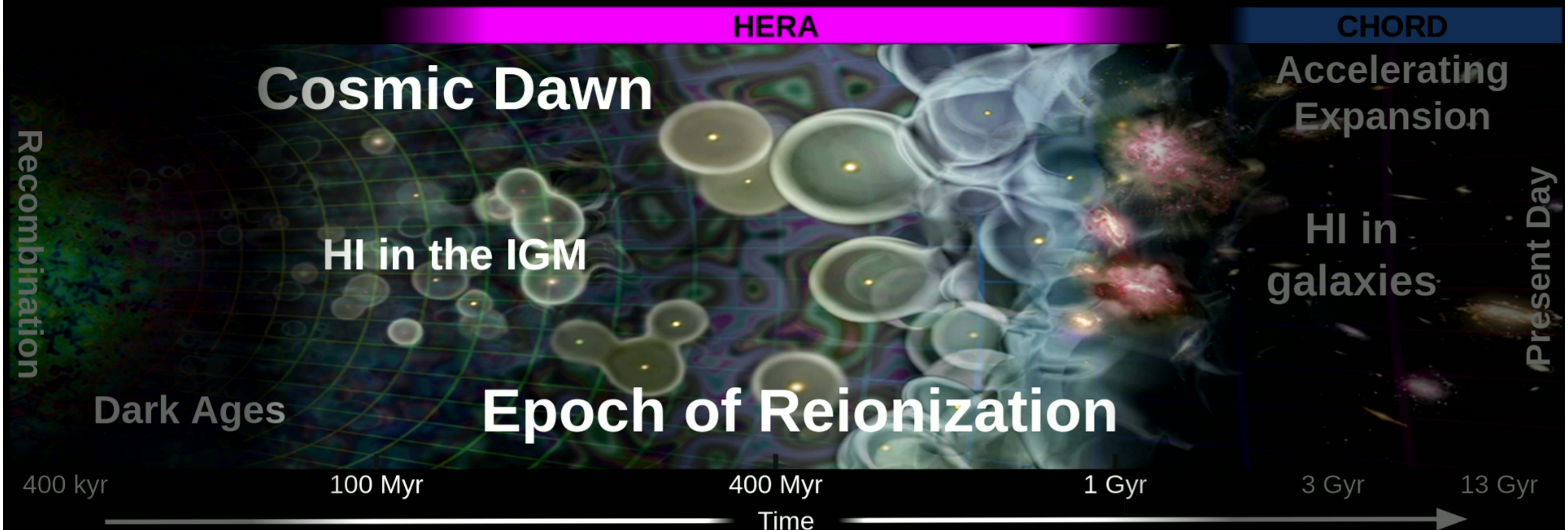
adapted from Loeb 2006
https://www.jstor.org/stable/26069038



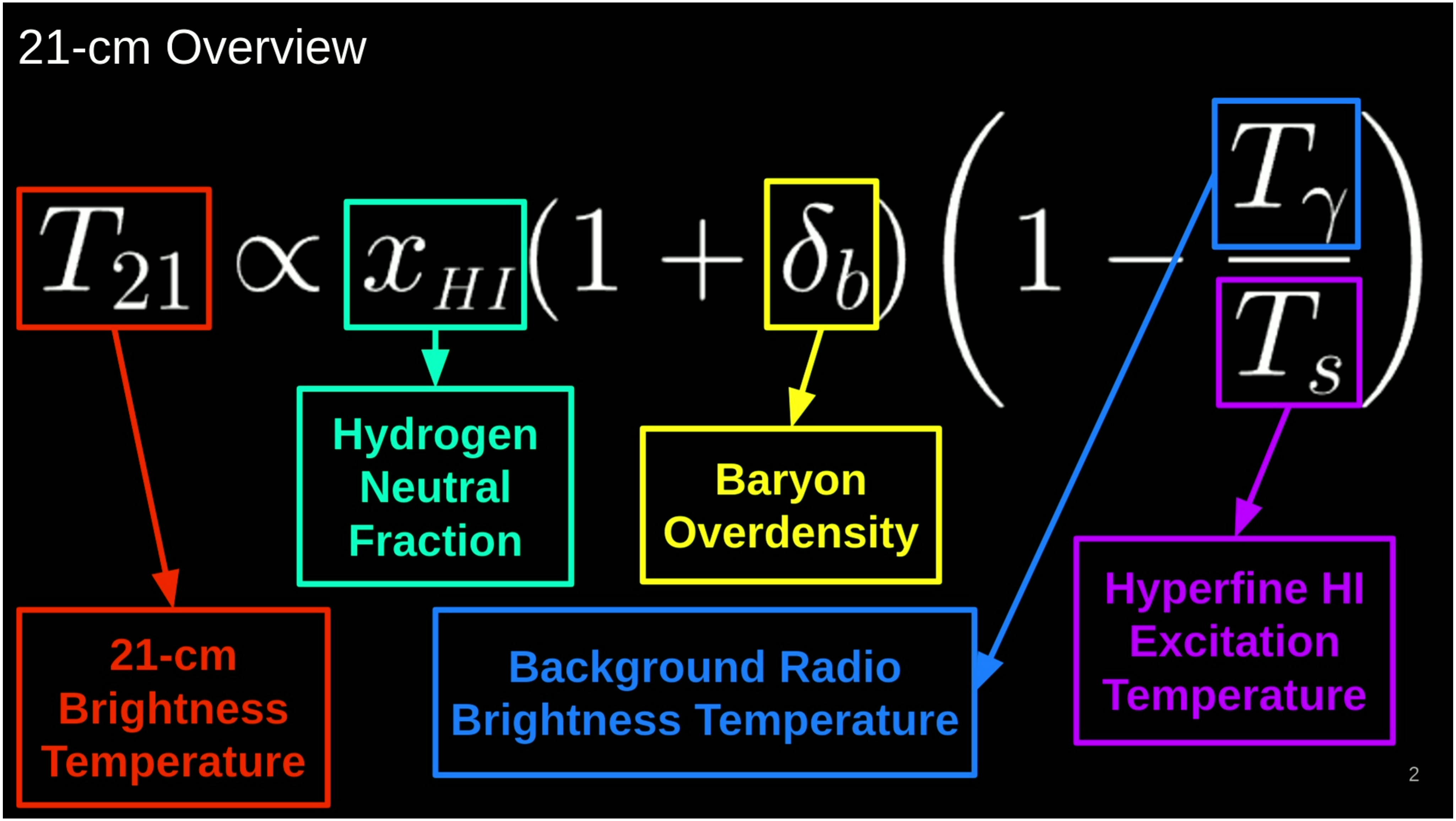
Constrain cosmology & astrophysics via 21-cm signal from HI

21-cm Overview

adapted from Loeb 2006
https://www.jstor.org/stable/26069038



Constrain cosmology & astrophysics via 21-cm signal from HI


21-cm Overview
$T_{21} \propto x_{HI}(1+\delta_b)\left(1-\frac{T_\gamma}{T_s}\right)$
21-cm Brightness Temperature
Hydrogen Neutral Fraction
Baryon Overdensity
Background Radio Brightness Temperature
Hyperfine HI Excitation Temperature
2

21-cm Overview

$$T_{21} \propto x_{HI}(1+\delta_b)\left(1-\frac{T_\gamma}{T_s}\right)$$

Reionization Astrophysics

Large-Scale Structure

Thermal Evolution + Astrophysics

3

21-cm Overview

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_c^{-1} + x_k T_k^{-1}}{1 + x_\alpha + x_k}$$

Coupling to Radio Background

Coupling to Lyman-α Radiation (Wouthuysen-Field Effect)

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21-cm Overview

$$T_{21} \propto x_{HI}(1+\delta_b)\left(1-\frac{T_\gamma}{T_s}\right)$$

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_c^{-1} + x_k T_k^{-1}}{1 + x_\alpha + x_k}$$

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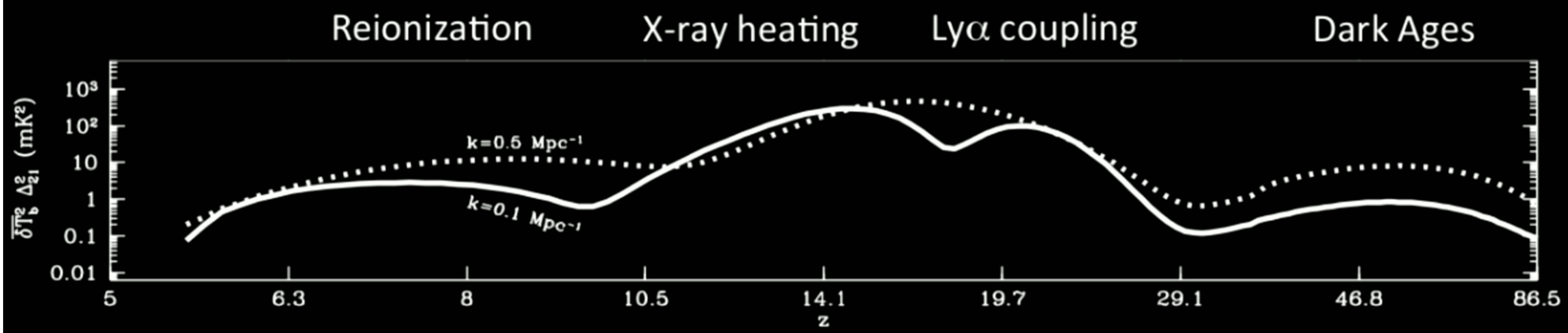
21-cm Overview

The Goal

Measure the statistics of fluctuations in the cosmologically-redshifted 21-cm signal.

$$\langle \tilde{T}(\boldsymbol{k})\tilde{T}(\boldsymbol{k}')^*\rangle = (2\pi)^3\delta^D(\boldsymbol{k}-\boldsymbol{k}')P(\boldsymbol{k})$$



Mesinger, Greig, Sobacchi 2016
doi: 10.1093/mnras/stw831

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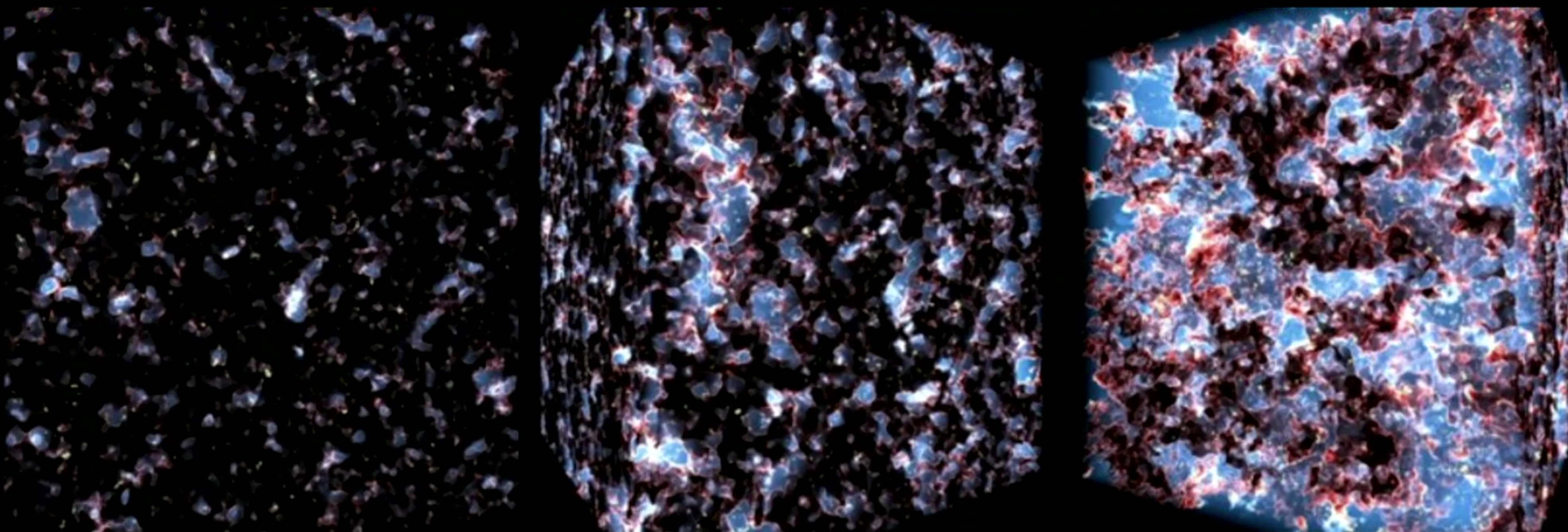
The Power of Fluctuations

Alvarez+ 2009
doi: 10.1088/0004-637X/703/2/L167

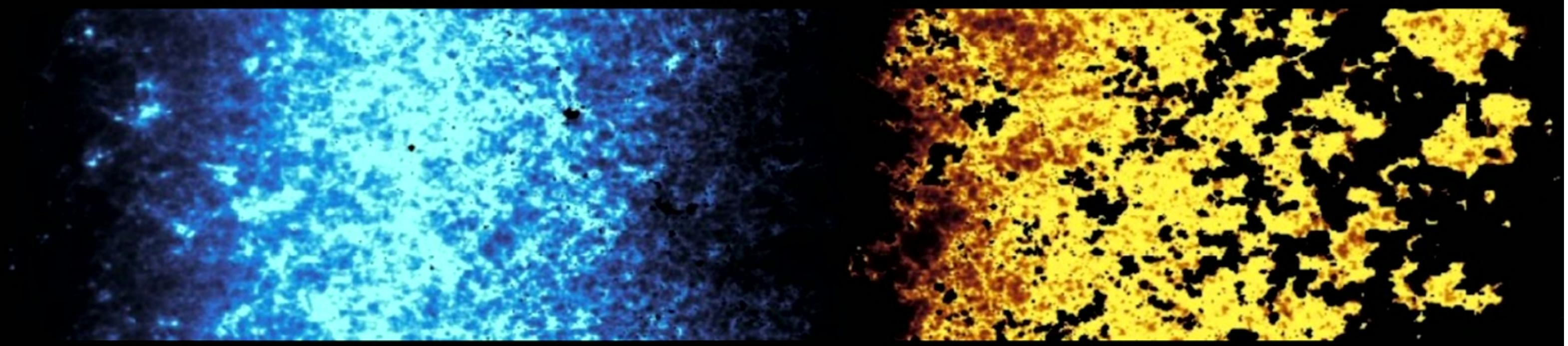
Early Reionization | Mid Reionization | Late Reionization



The Power of Fluctuations

Schaeffer+ 2023
doi: 10.1093/mnras/stad2937

“Usual” astrophysical picture

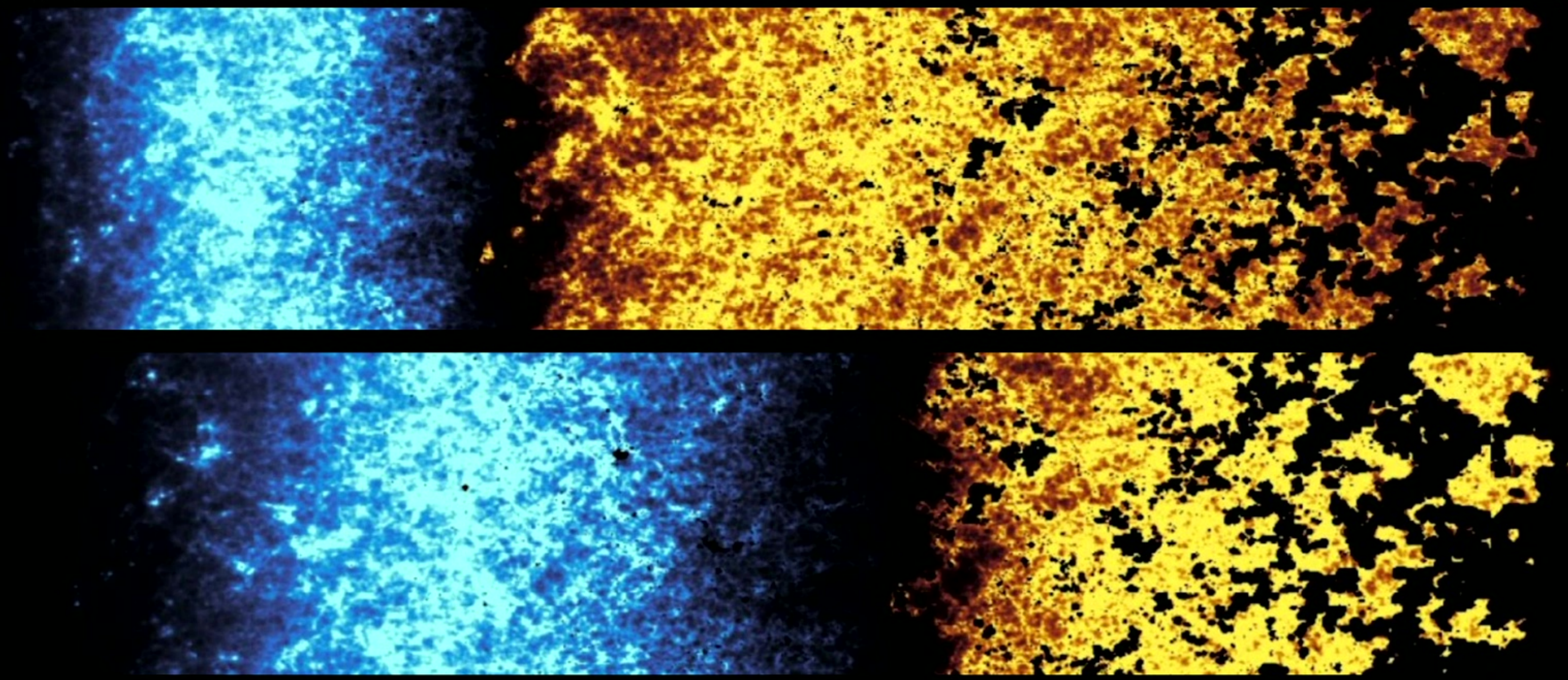


The Power of Fluctuations

Schaeffer+ 2023
doi: 10.1093/mnras/stad2937

Efficient early star formation

“Usual” astrophysical picture



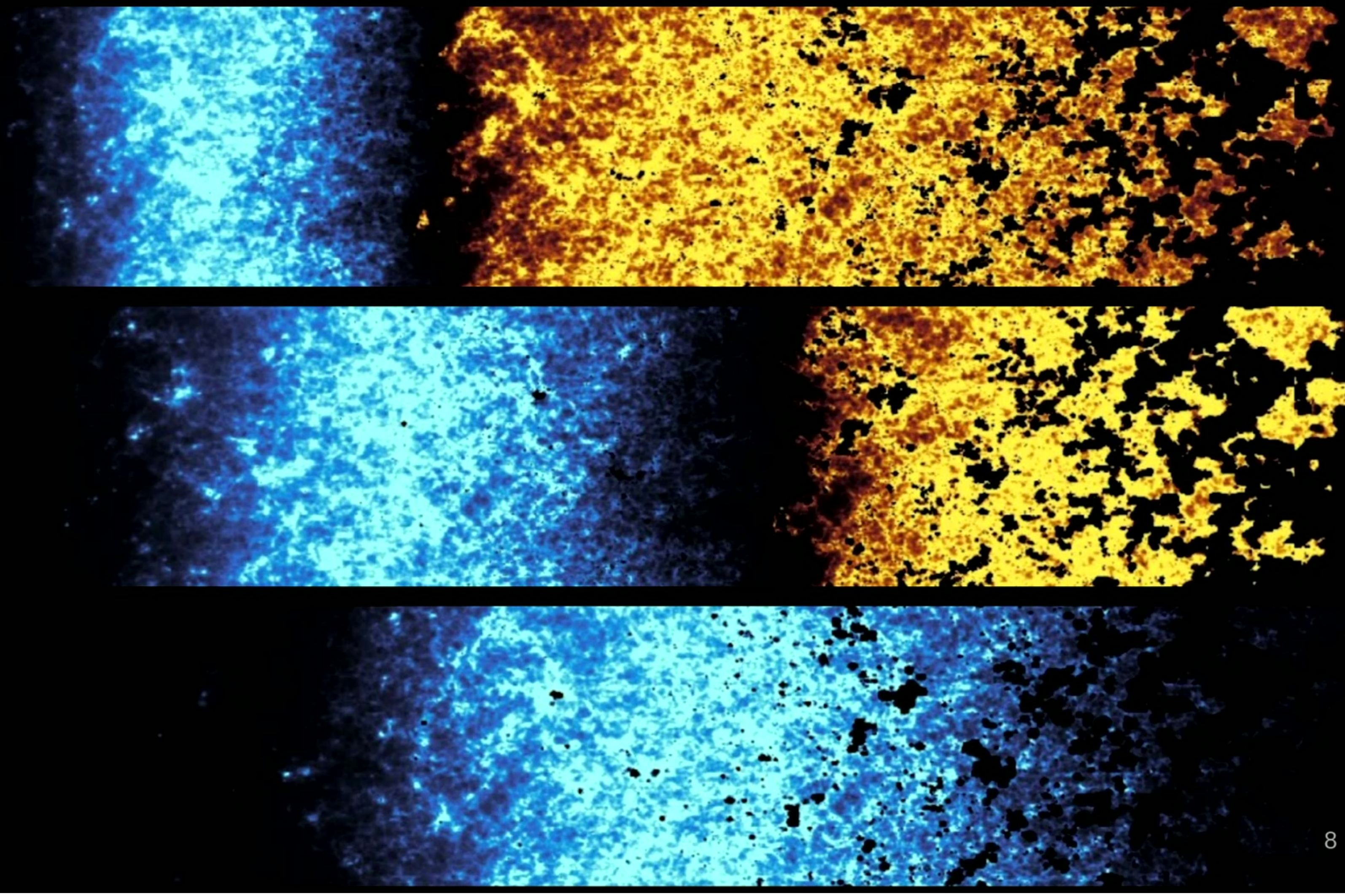
The Power of Fluctuations

Schaeffer+ 2023
doi: 10.1093/mnras/stad2937

Efficient early star formation

"Usual" astrophysical picture

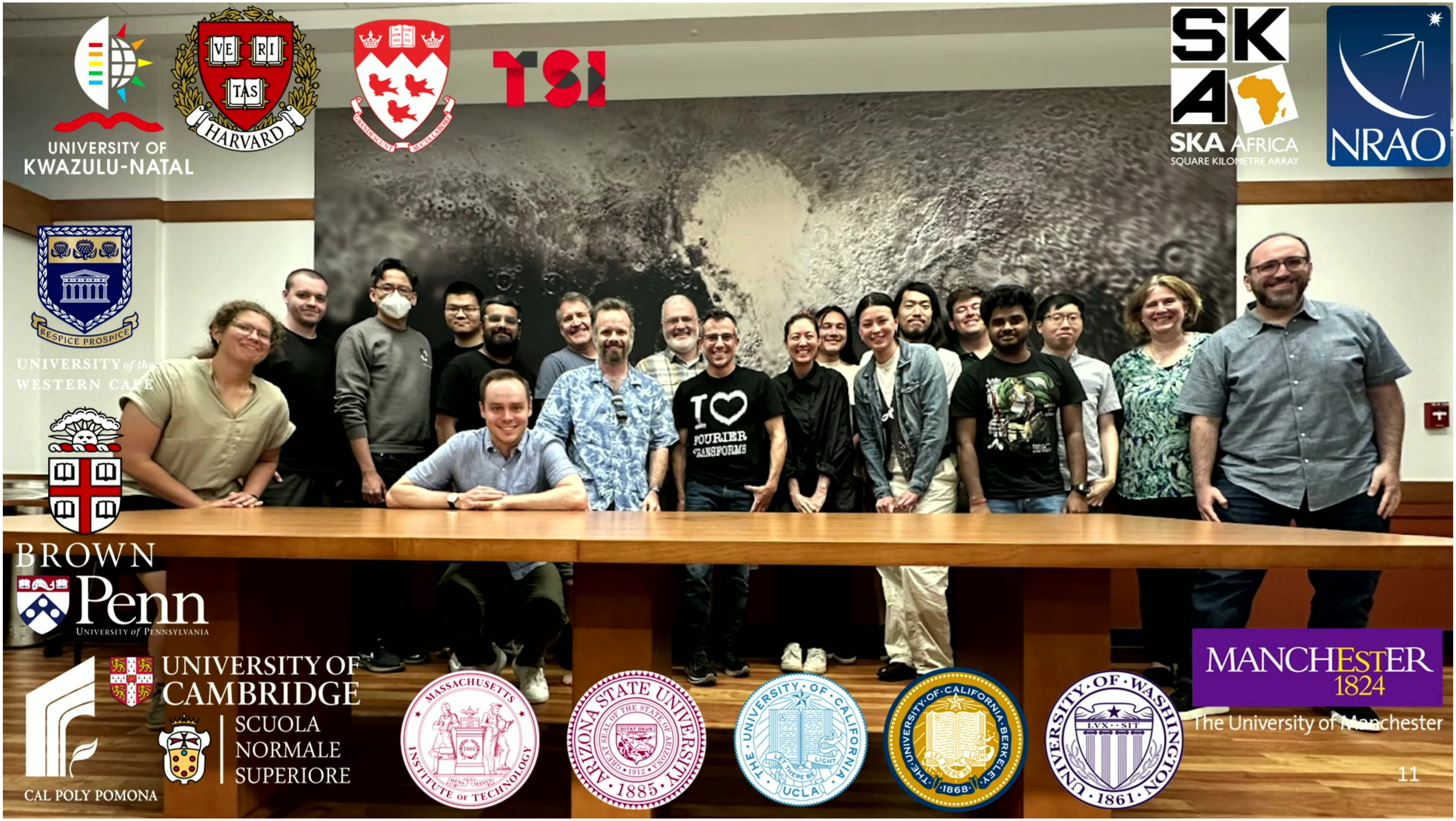
Stars only form in big galaxies



21-cm Overview

What were the first stars and galaxies like?

How did Reionization unfold?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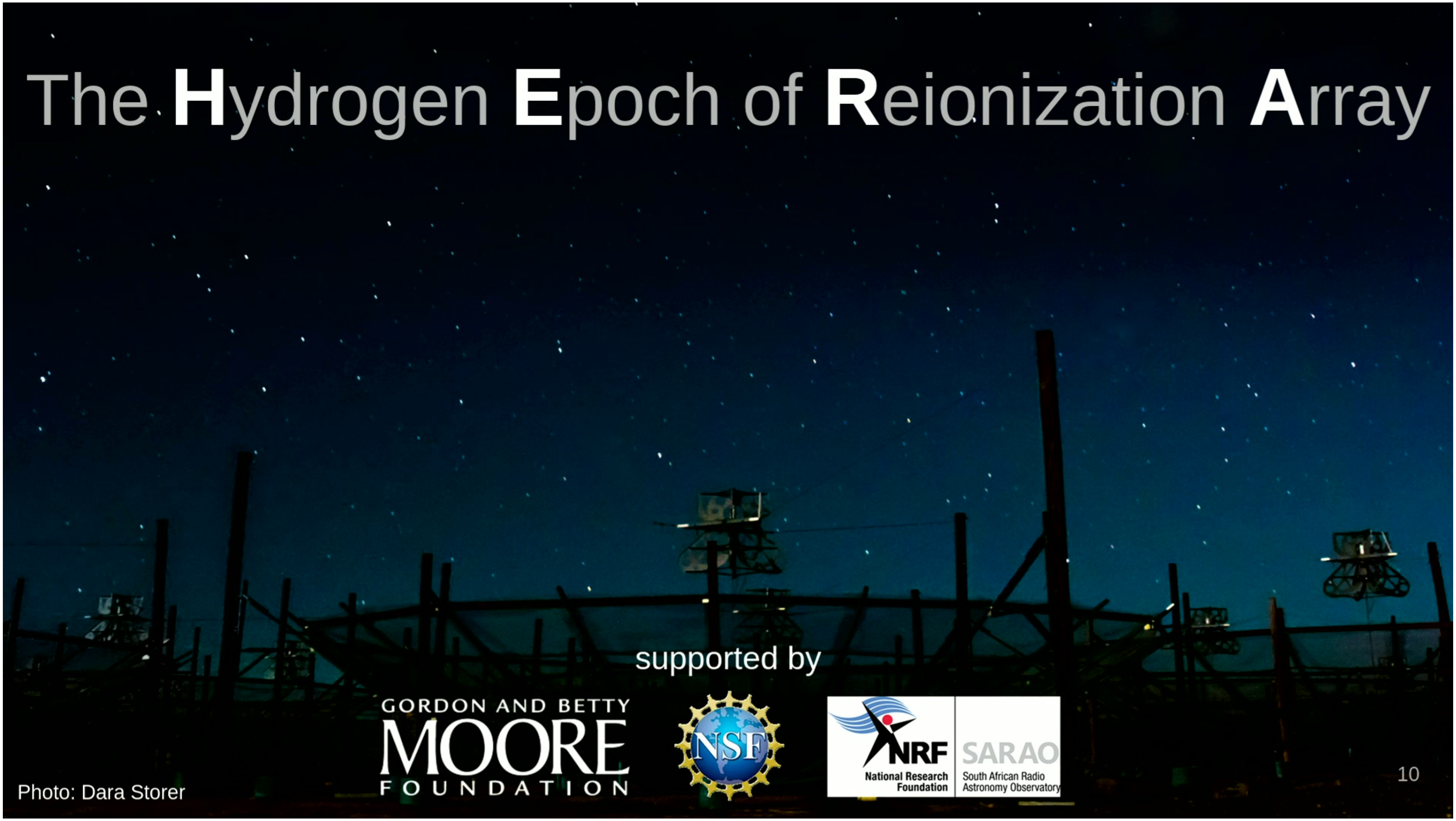
KWAZULU-NATAL
HARVARD
TSI
SKA AFRICA
SQUARE KILOMETRE ARRAY
NRAO
RESPICE PROSPICE
UNIVERSITY of the
WESTERN CAPE
BROWN
Penn
UNIVERSITY of PENNSYLVANIA
UNIVERSITY OF
CAMBRIDGE
SCUOLA
NORMALE
SUPERIORE
CAL POLY POMONA
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ARIZONA STATE UNIVERSITY
1885
THE UNIVERSITY OF CALIFORNIA
UCLA
THE UNIVERSITY OF CALIFORNIA BERKELEY
1868
UNIVERSITY OF WASHINGTON
1861
MANCHESTER
1824
The University of Manchester
FOURIER
TRANSFORMS
11


The Hydrogen Epoch of Reionization Array
supported by
GORDON AND BETTY MOORE FOUNDATION
NSF
NRF National Research Foundation
SARAO South African Radio Astronomy Observatory
Photo: Dara Storer
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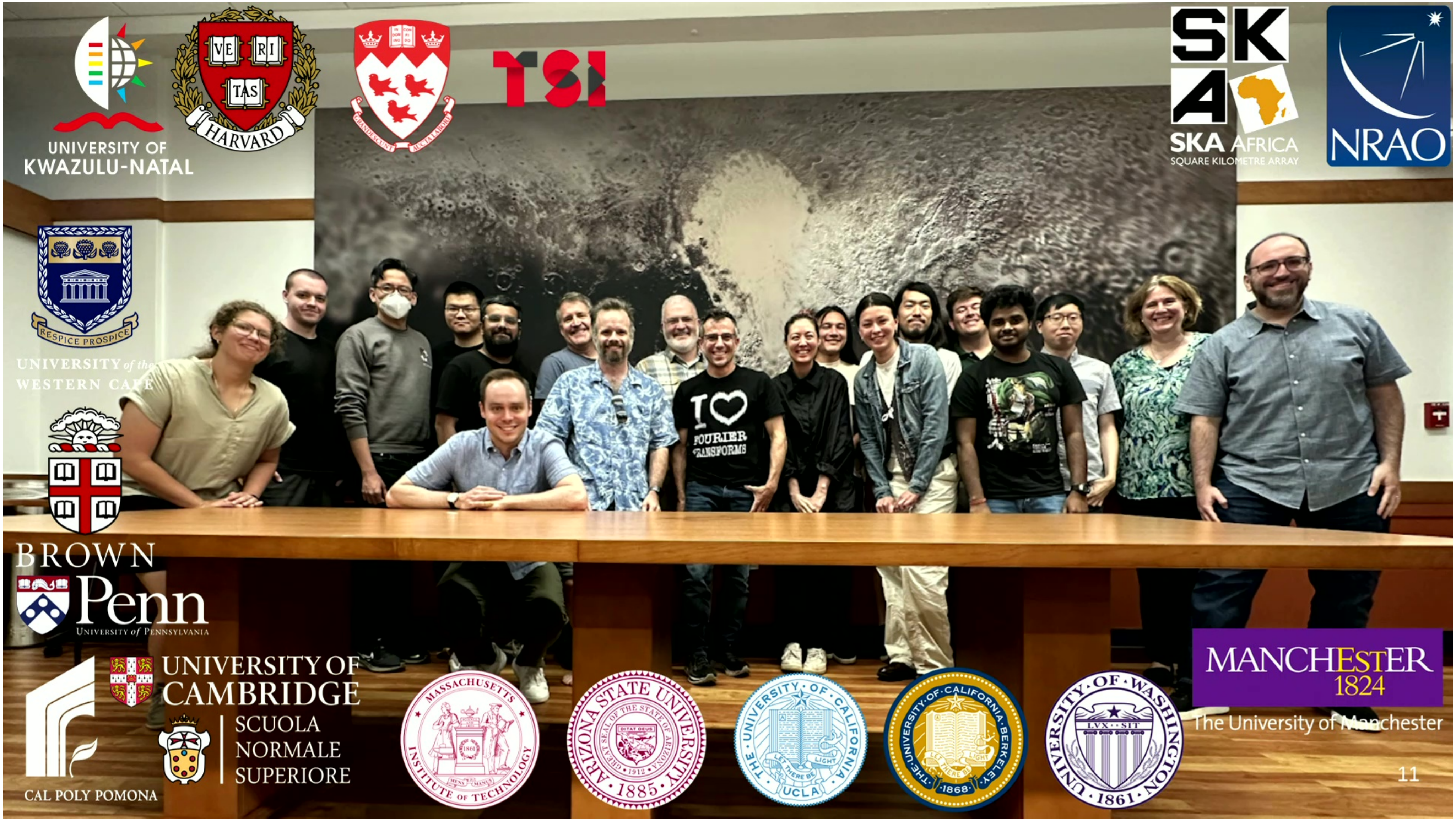
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SQUARE KILOMETRE ARRAY
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CAMBRIDGE
SCUOLA
NORMALE
SUPERIORE
CAL POLY POMONA
MANCHESTER
1824
The University of Manchester
I ♥ FOURIER TRANSFORMS
11


HERA
HERA
HARDER
BETTER
FASTER
STRONGER
12

HERA Overview

Google Maps

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HERA Overview

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Interferometry Overview

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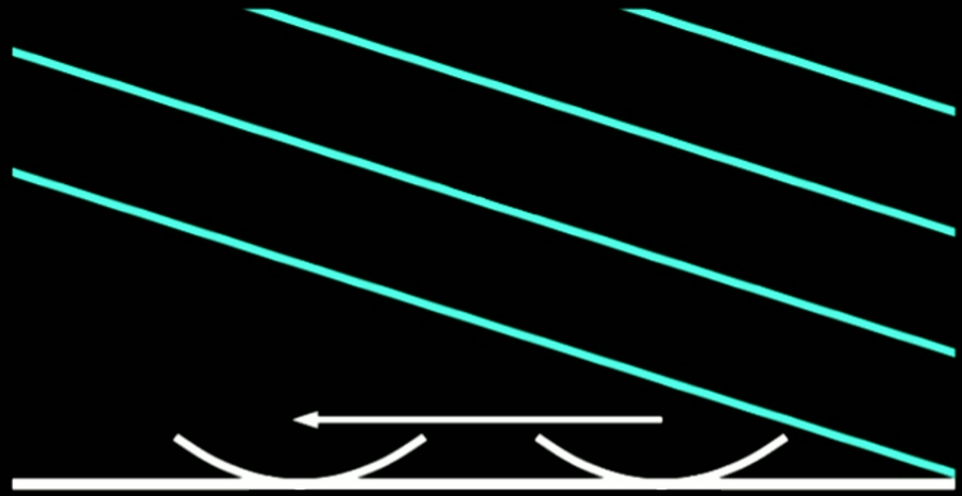
Interferometry Overview



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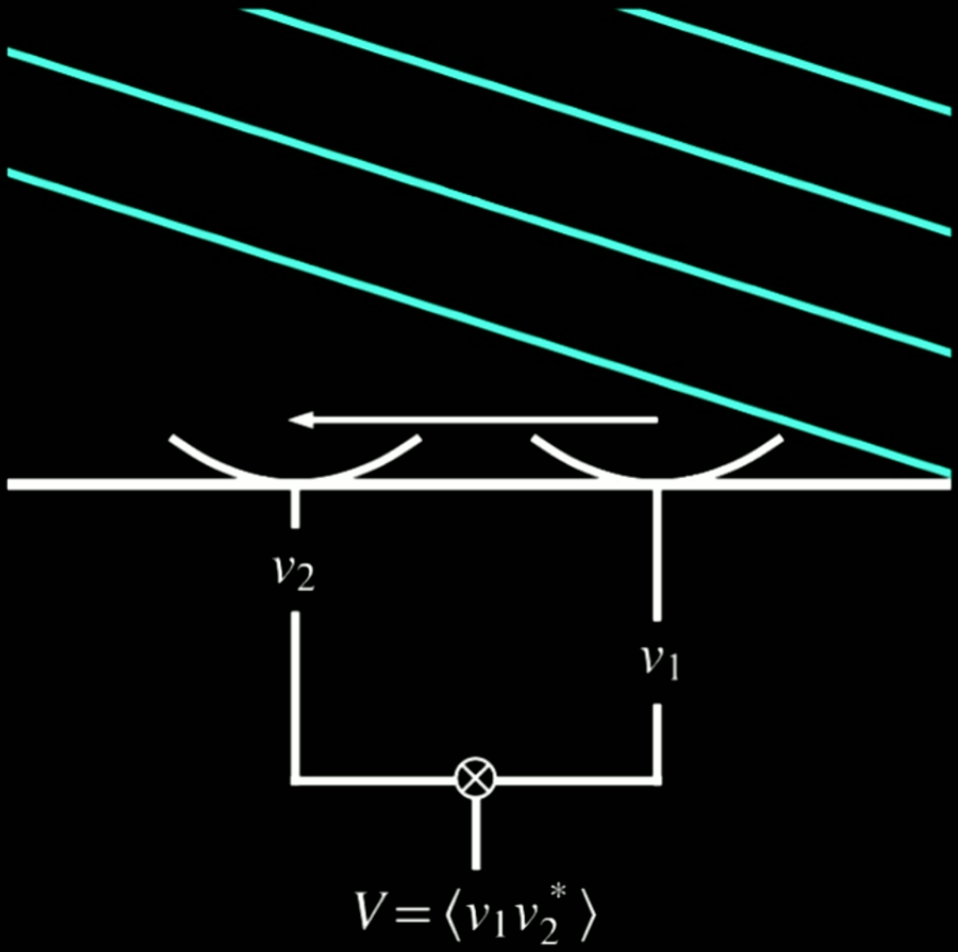
Interferometry Overview



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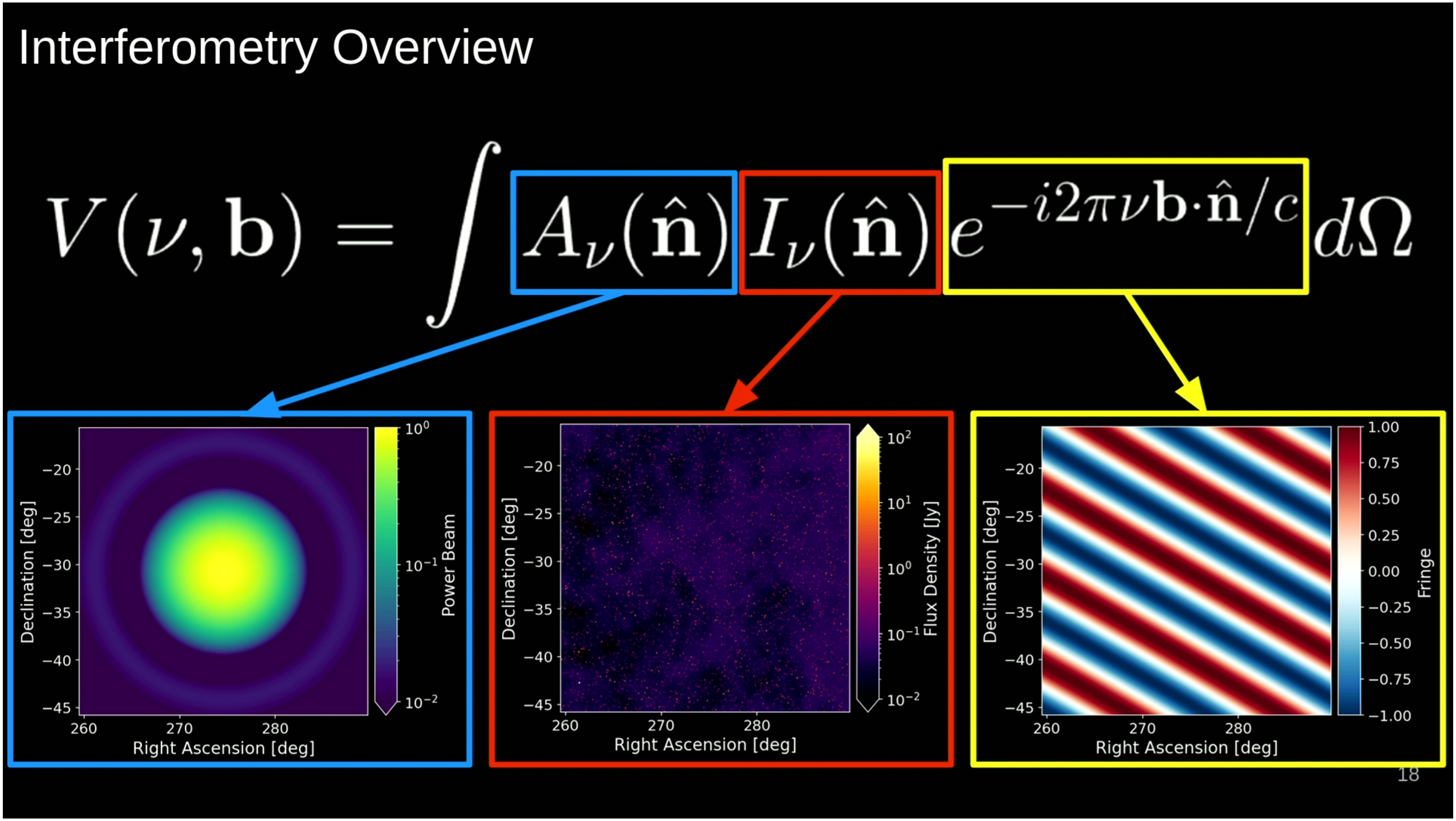

Interferometry Overview
$$V(\nu, \mathbf{b}) = \int A_\nu(\hat{\mathbf{n}}) I_\nu(\hat{\mathbf{n}}) e^{-i2\pi\nu\mathbf{b}\cdot\hat{\mathbf{n}}/c} d\Omega$$
Declination [deg]
Right Ascension [deg]
Power Beam
Flux Density [Jy]
Fringe
18

Interferometry Overview

“Flat sky” limit

$$V(\nu, \mathbf{b}) \approx \int A_\nu(l, m)\, I_\nu(l, m)\, e^{-i2\pi(ul+vm)}\, dl dm$$

$$\Downarrow$$

$$V(\nu, \mathbf{b}) \approx \int \tilde{A}_\nu(\mathbf{u}) \tilde{I}_\nu(\mathbf{u} - \nu \mathbf{b}/c) du dv$$

Each baseline measures a Fourier mode in the plane of the sky

Interferometry Overview

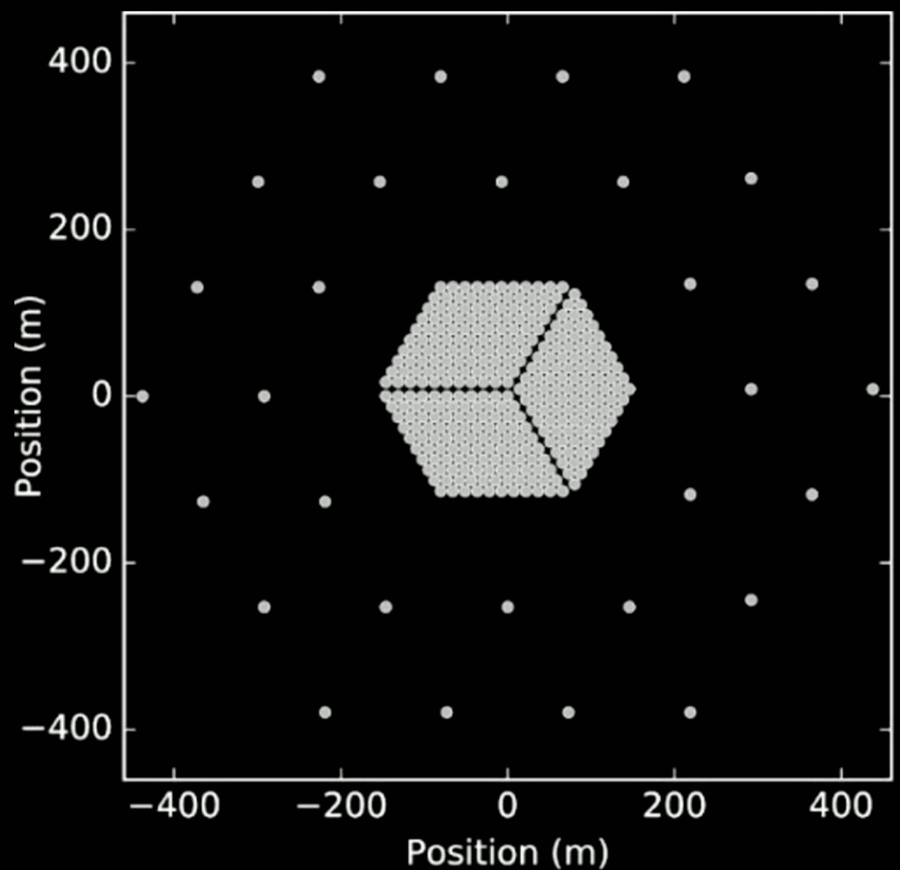
$$V(\nu, \mathbf{b}) \sim \tilde{I}_\nu(\mathbf{k}_\perp)$$

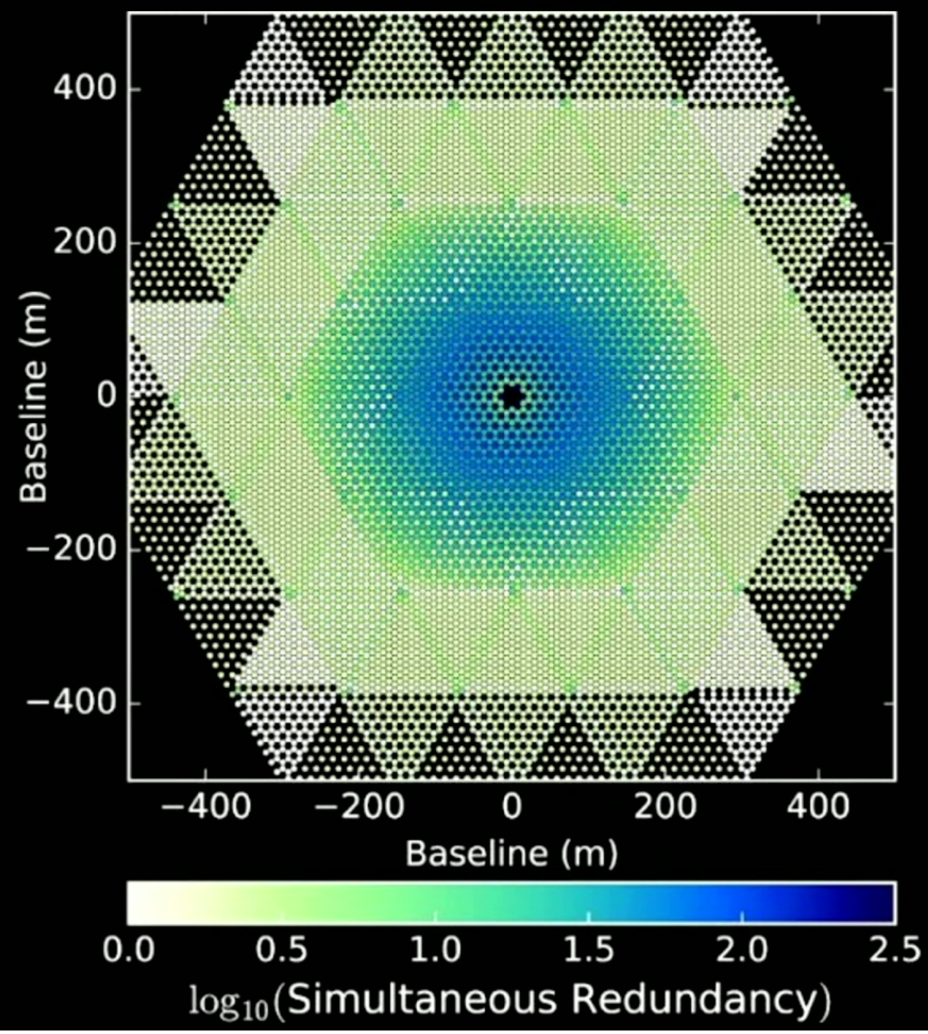
$$\Downarrow$$

$$\tilde{V}(\tau, \mathbf{b}) \sim \tilde{T}_{21}(k_\parallel, \mathbf{k}_\perp)$$

“Delay-transformed” visibilities directly probe cosmological 21-cm Fourier modes.

Observation Strategy





DeBoer+ 2017
doi: 10.1088/1538-3873/129/974/045001

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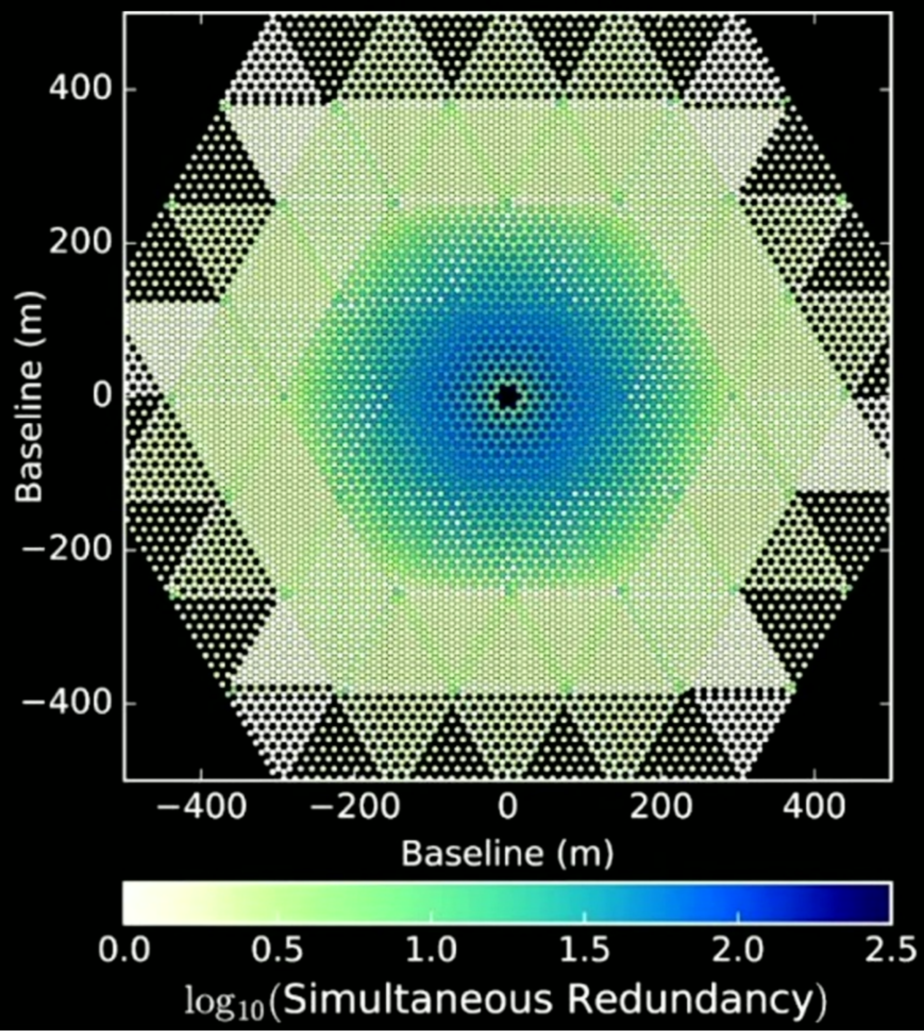
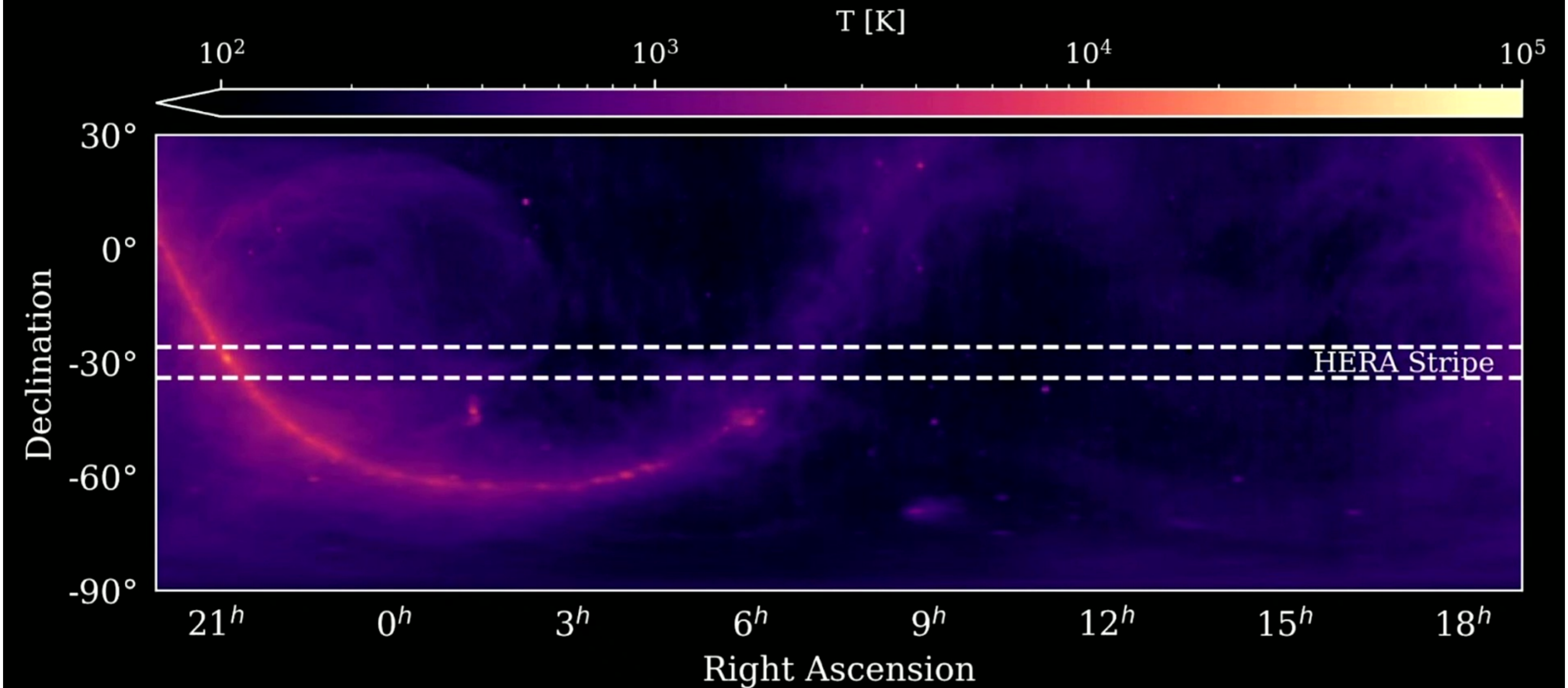
Observation Strategy

Improve instantaneous sensitivity through redundancy

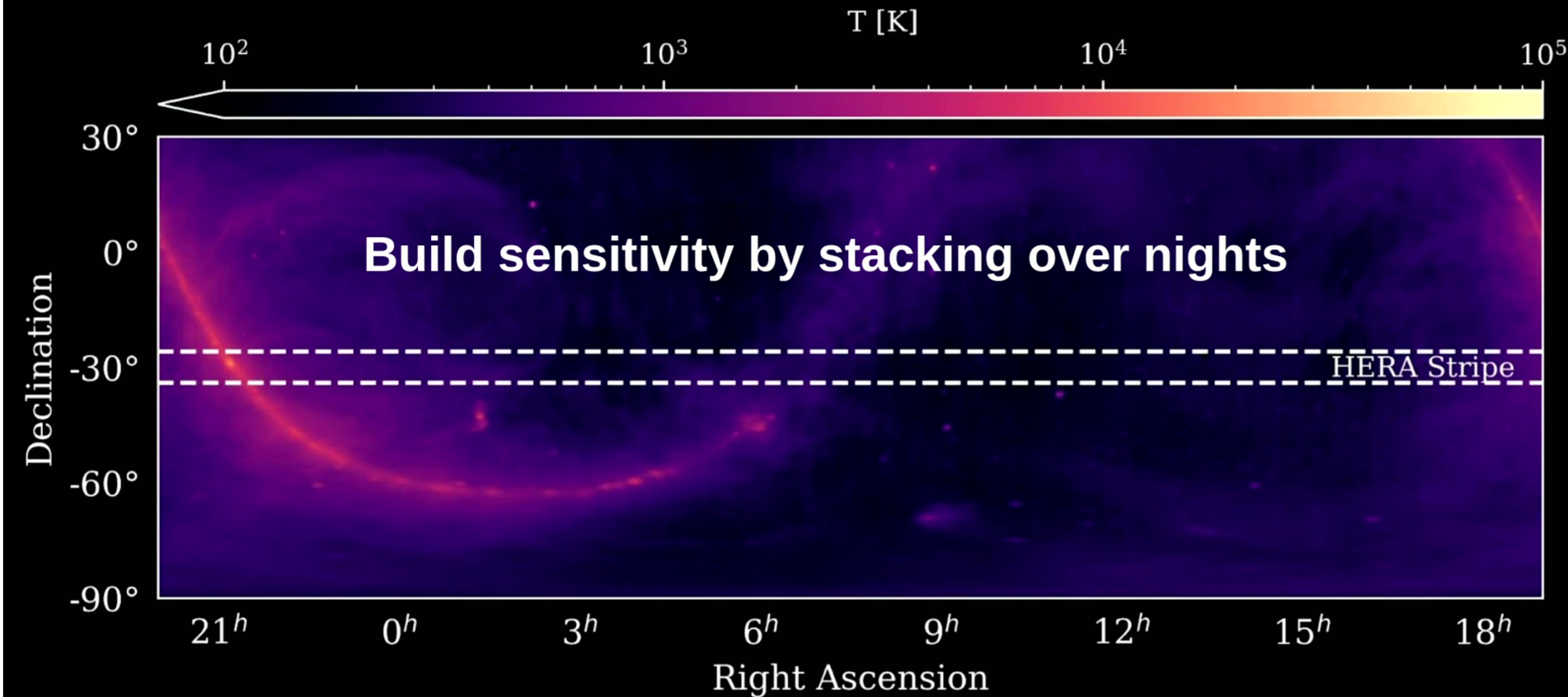


DeBoer+ 2017
doi: 10.1088/1538-3873/129/974/045001

Observation Strategy



Observation Strategy



Mutual Coupling

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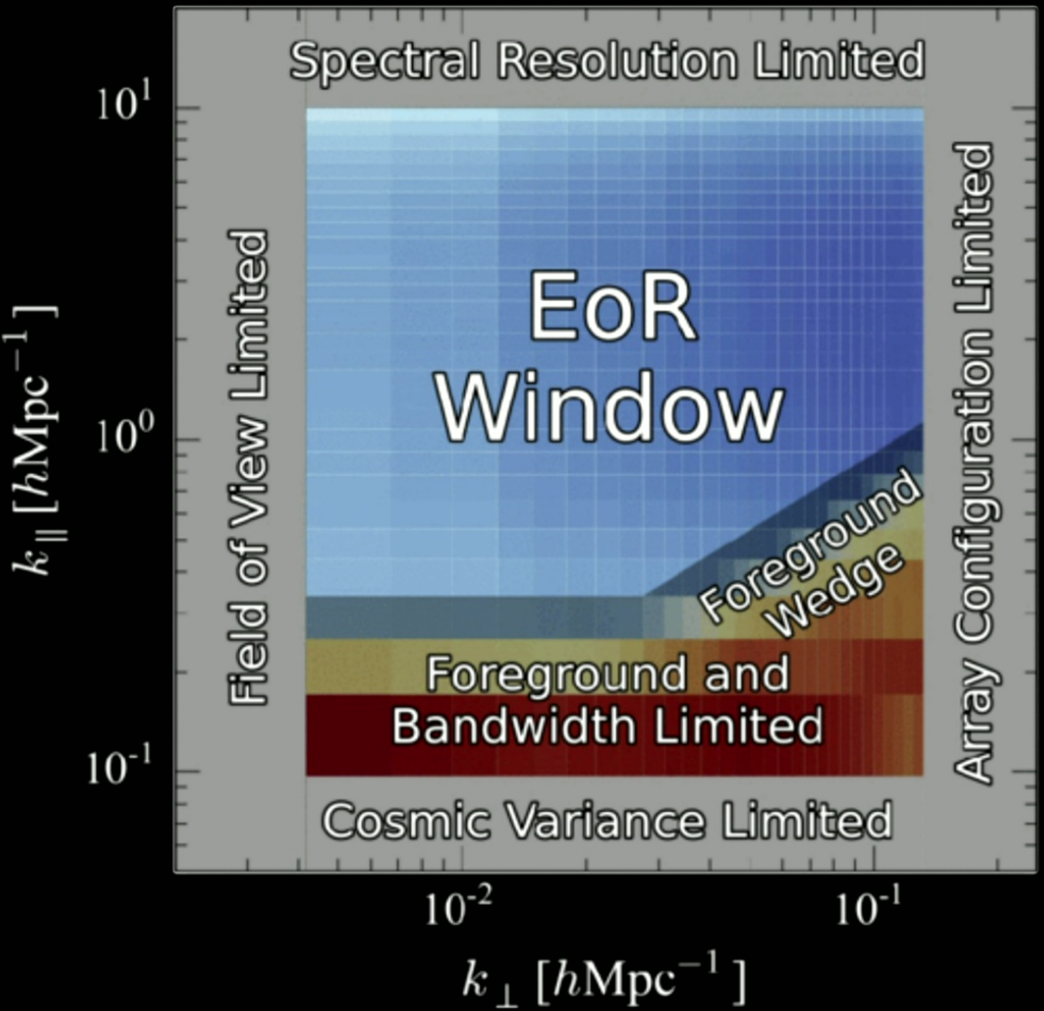
Observation Strategy

Liu, Parsons, Trott 2014
doi: 10.1103/PhysRevD.90.023018



Detect the 21-cm signal by avoiding the foregrounds in cosmological Fourier space

Mutual Coupling

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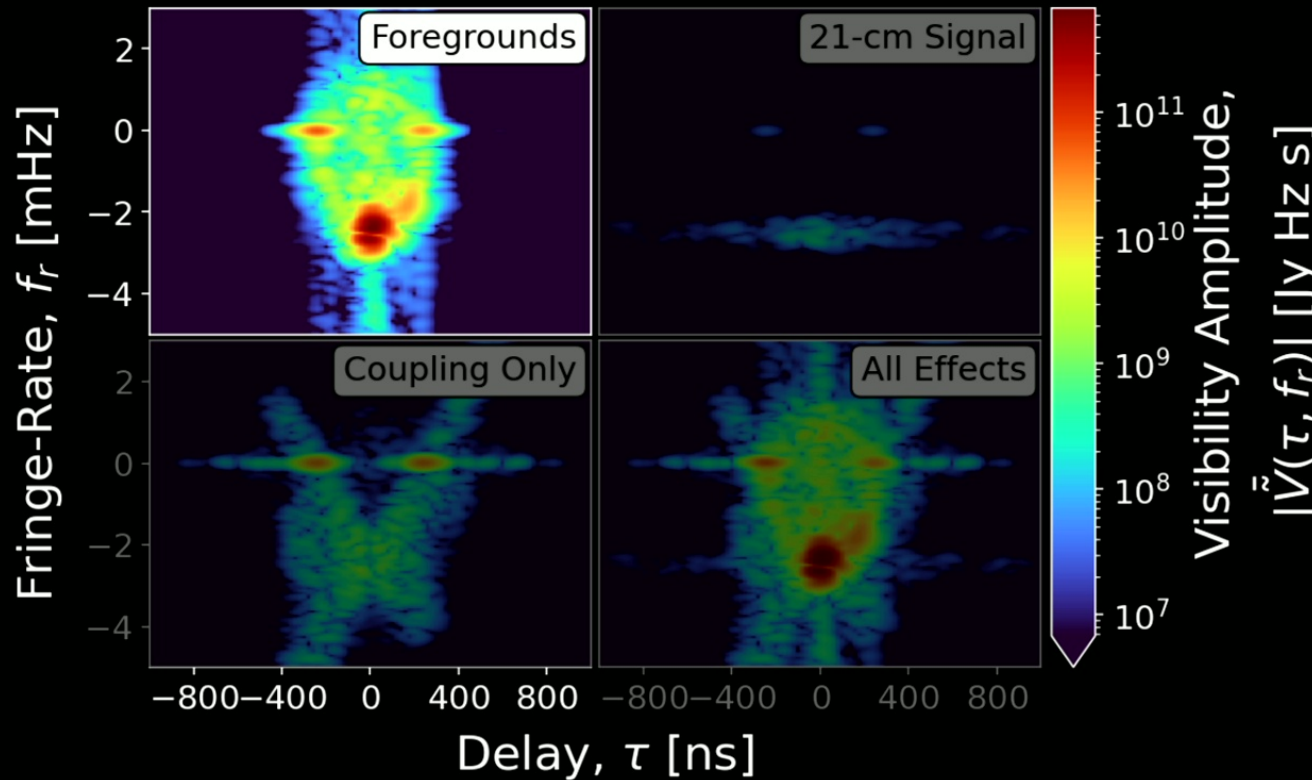
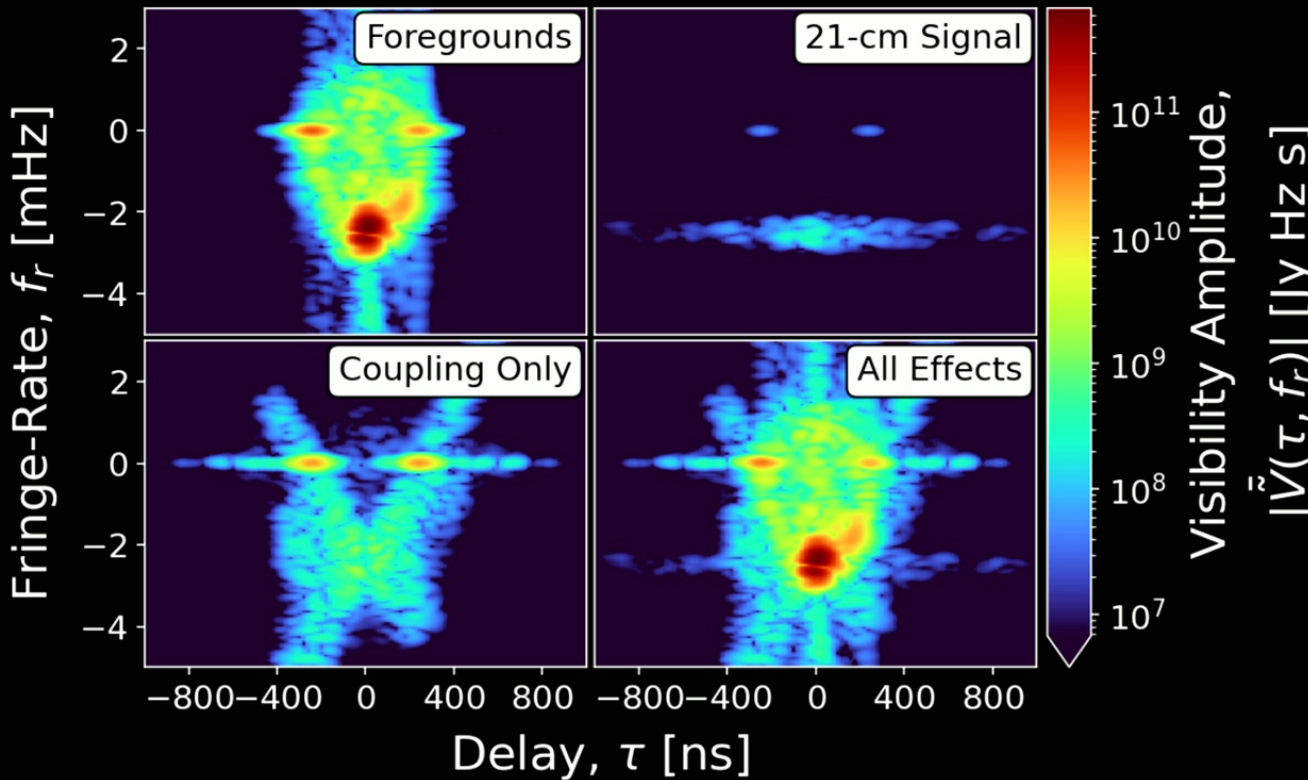
In Simulation

Foregrounds occupy a limited range of fringe-rate and delay modes.



In Simulation

Mutual coupling and foregrounds obscure the 21-cm signal.



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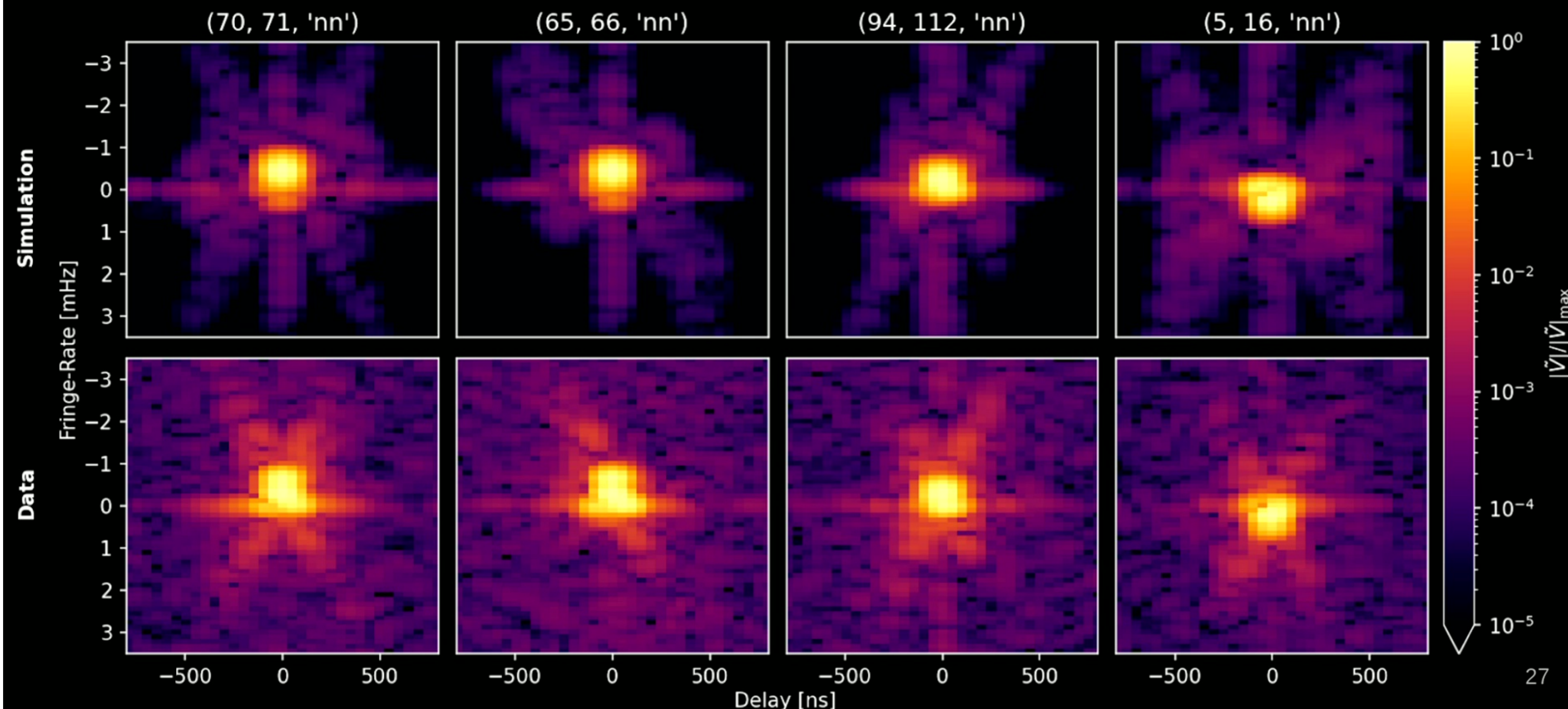
In Data

…which we can reproduce with mutual coupling simulations. (Rath & **Pascua**+ 2024)



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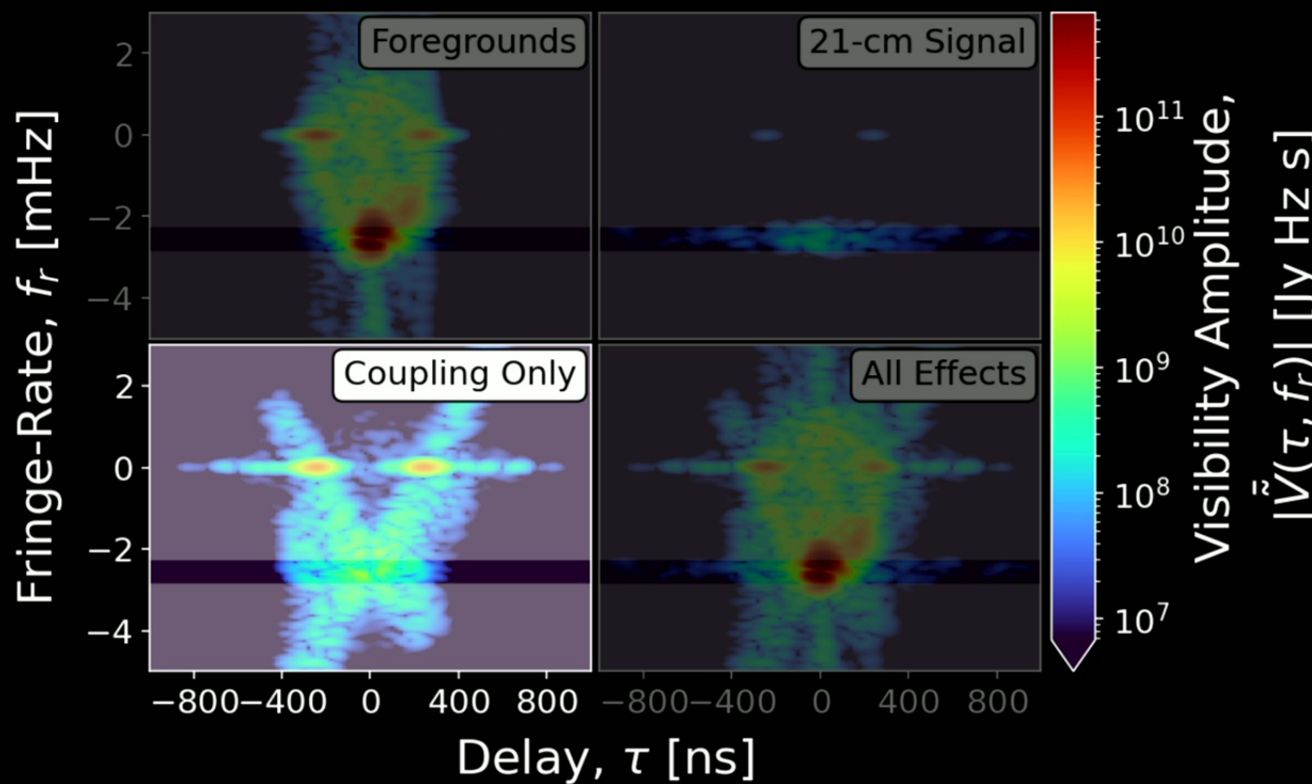
Mitigation via Filters

Some of the coupled signal will survive *any* fringe-rate filter.



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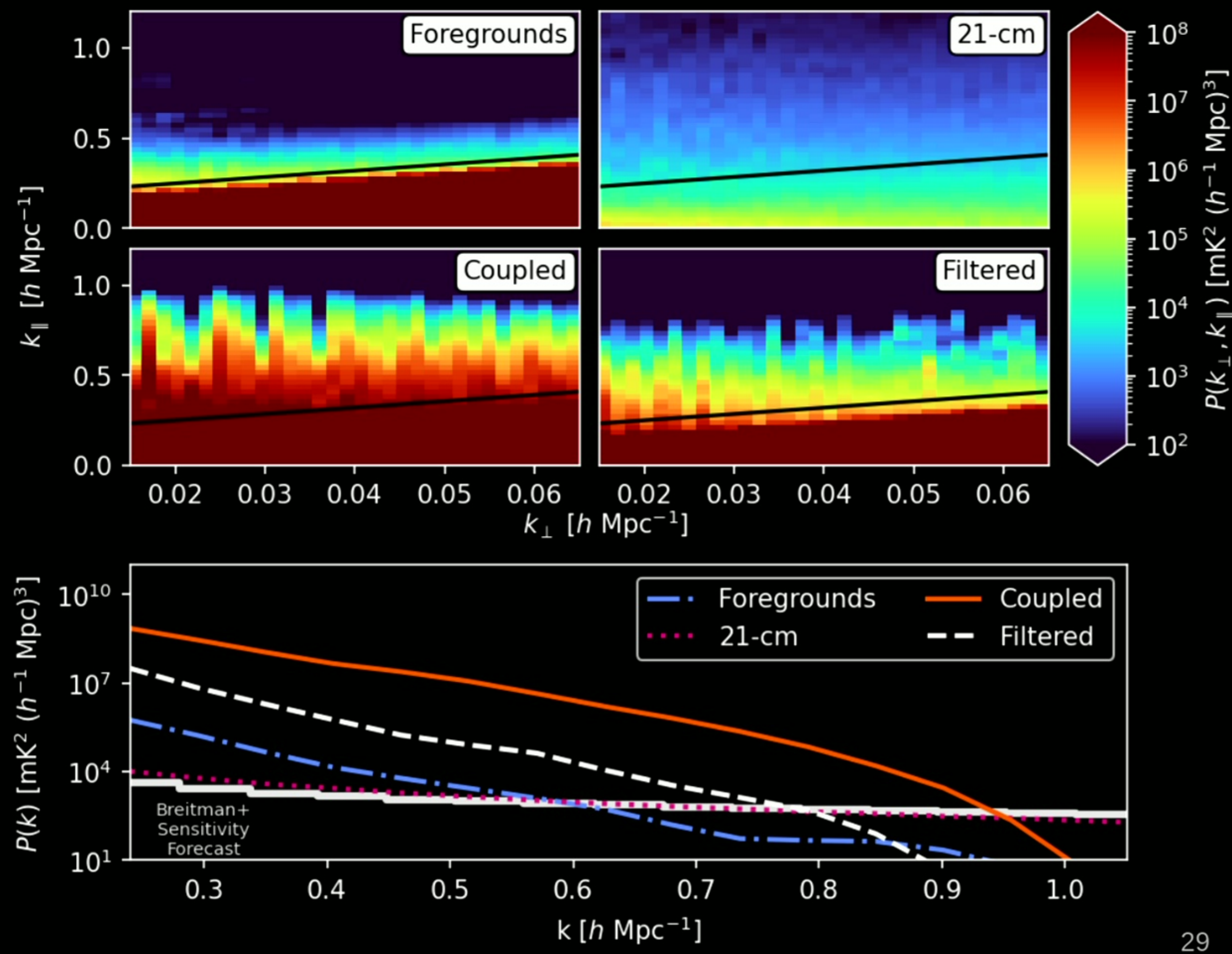
Mitigation via Filters

Fringe-rate filters do *not* go far enough.



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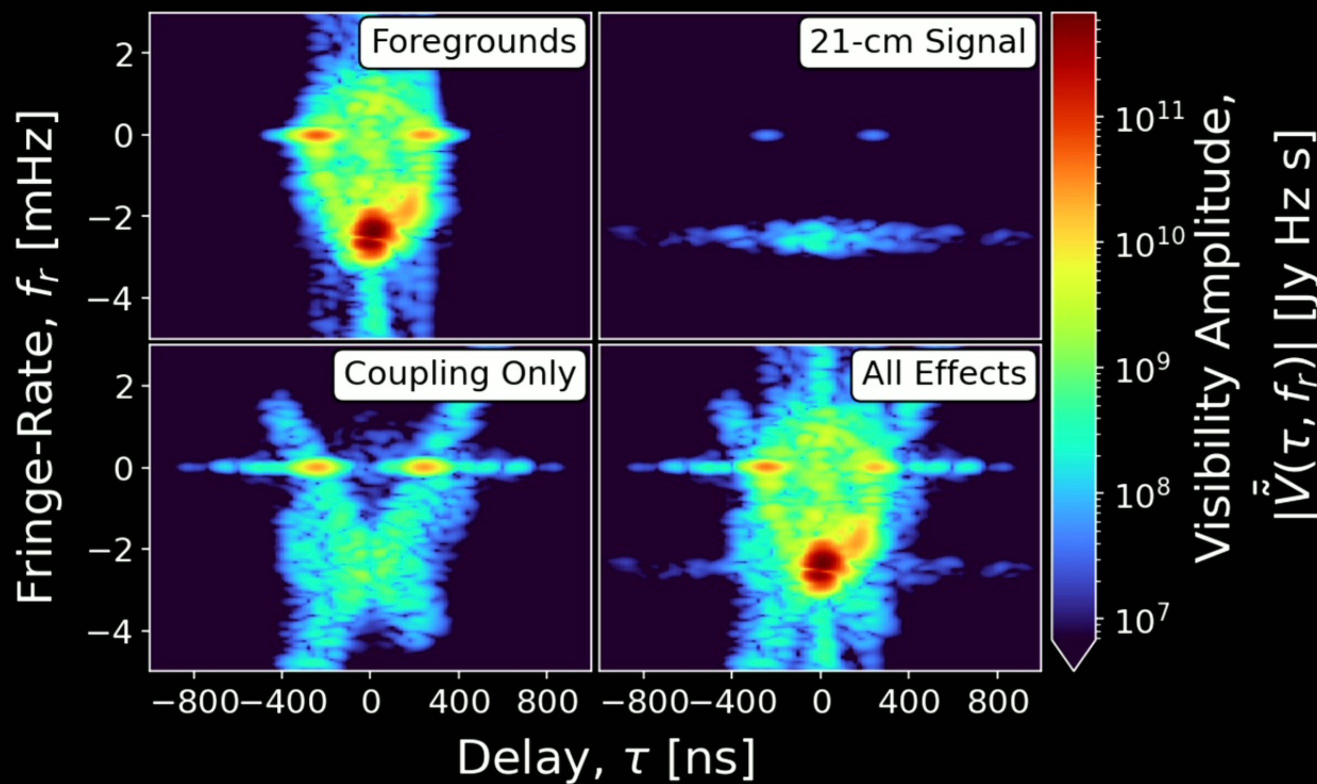
Latest Results

(HERA 2023)

doi:10.3847/1538-4357/acaf50

In Simulation

Mutual coupling and foregrounds obscure the 21-cm signal.



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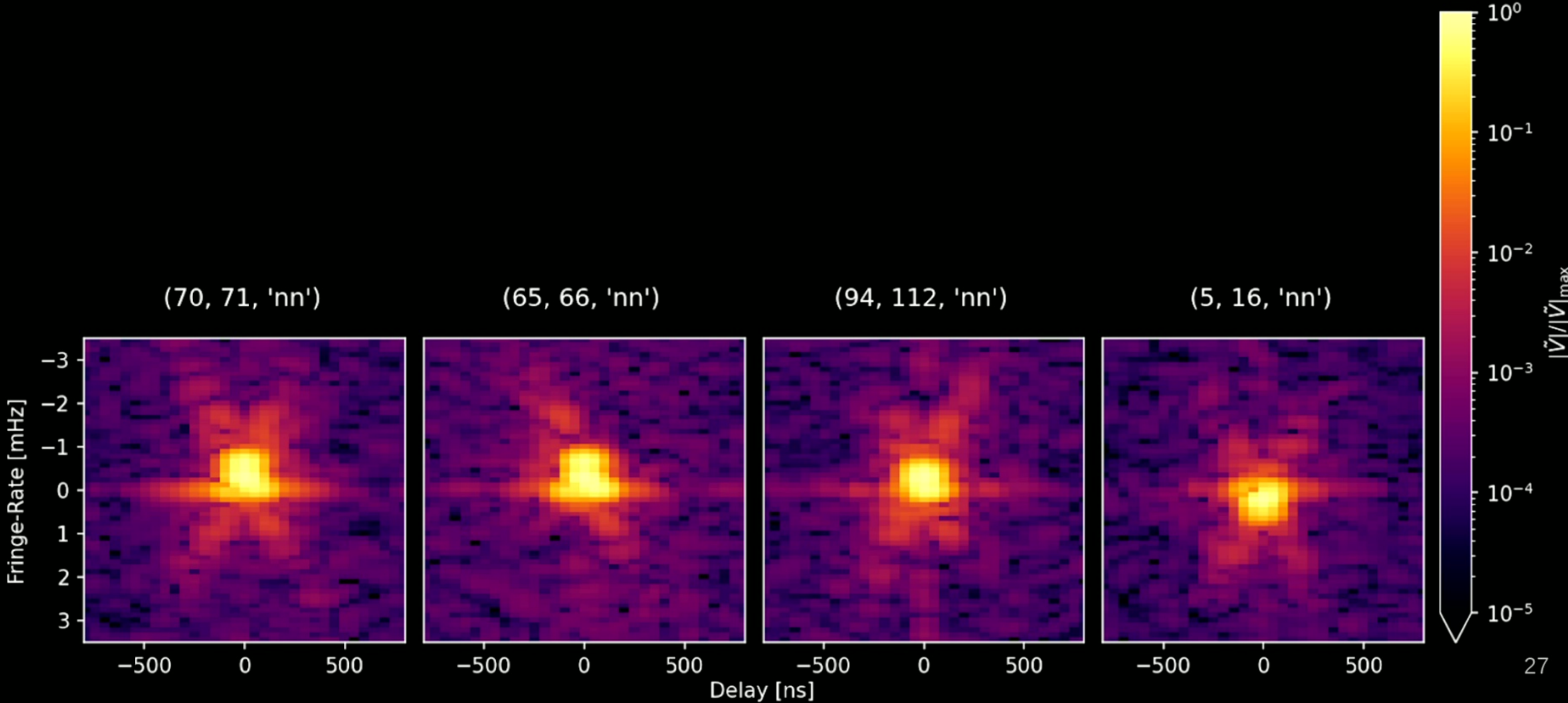
In Data

We see excess structure in the visibilities…



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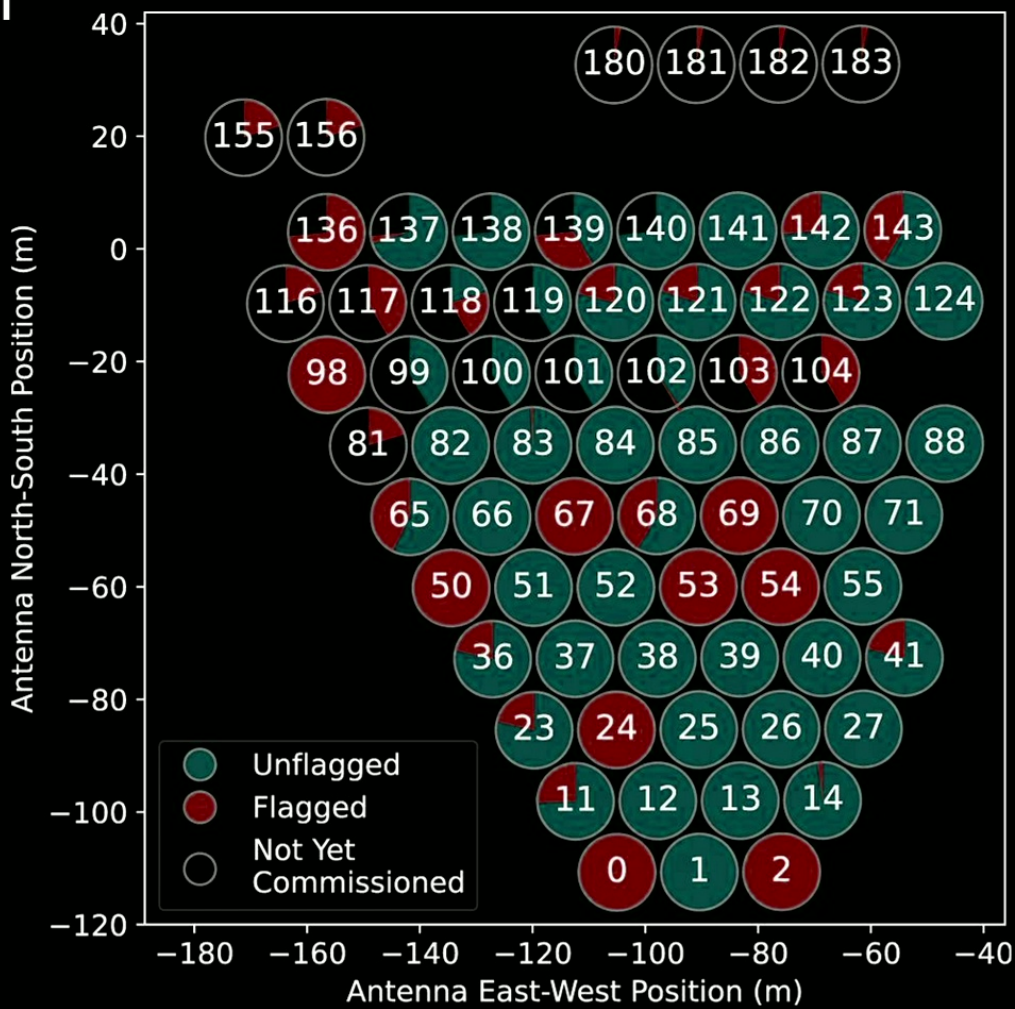
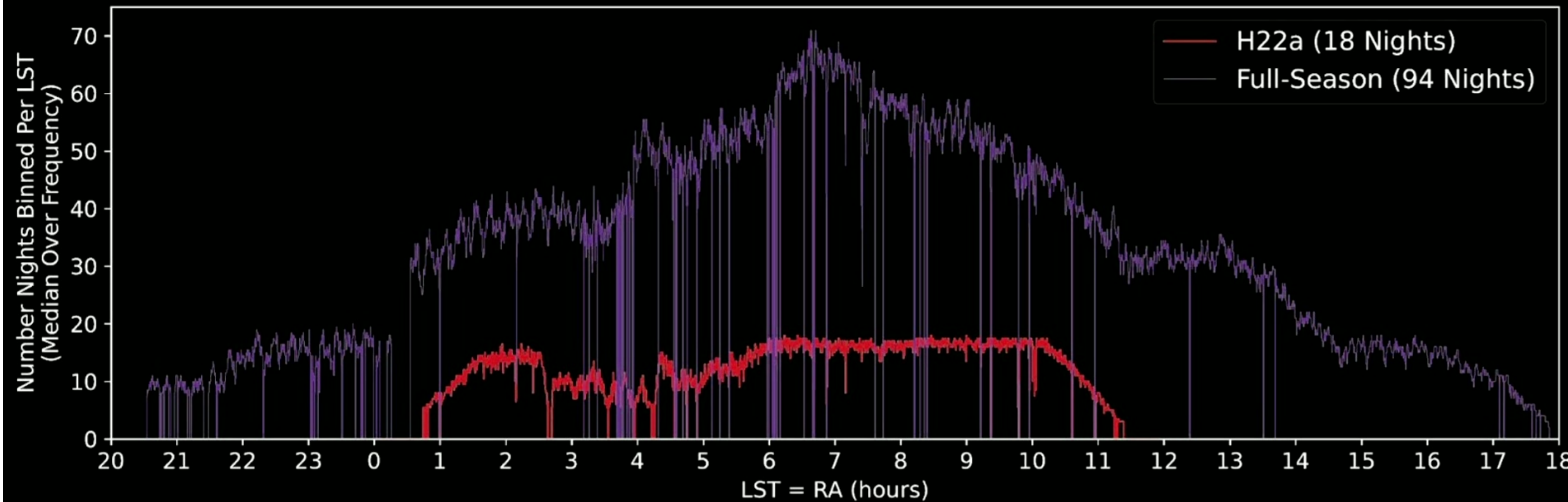
Data Description



HERA 2023

doi: 10.3847/1538-4357/acaf50

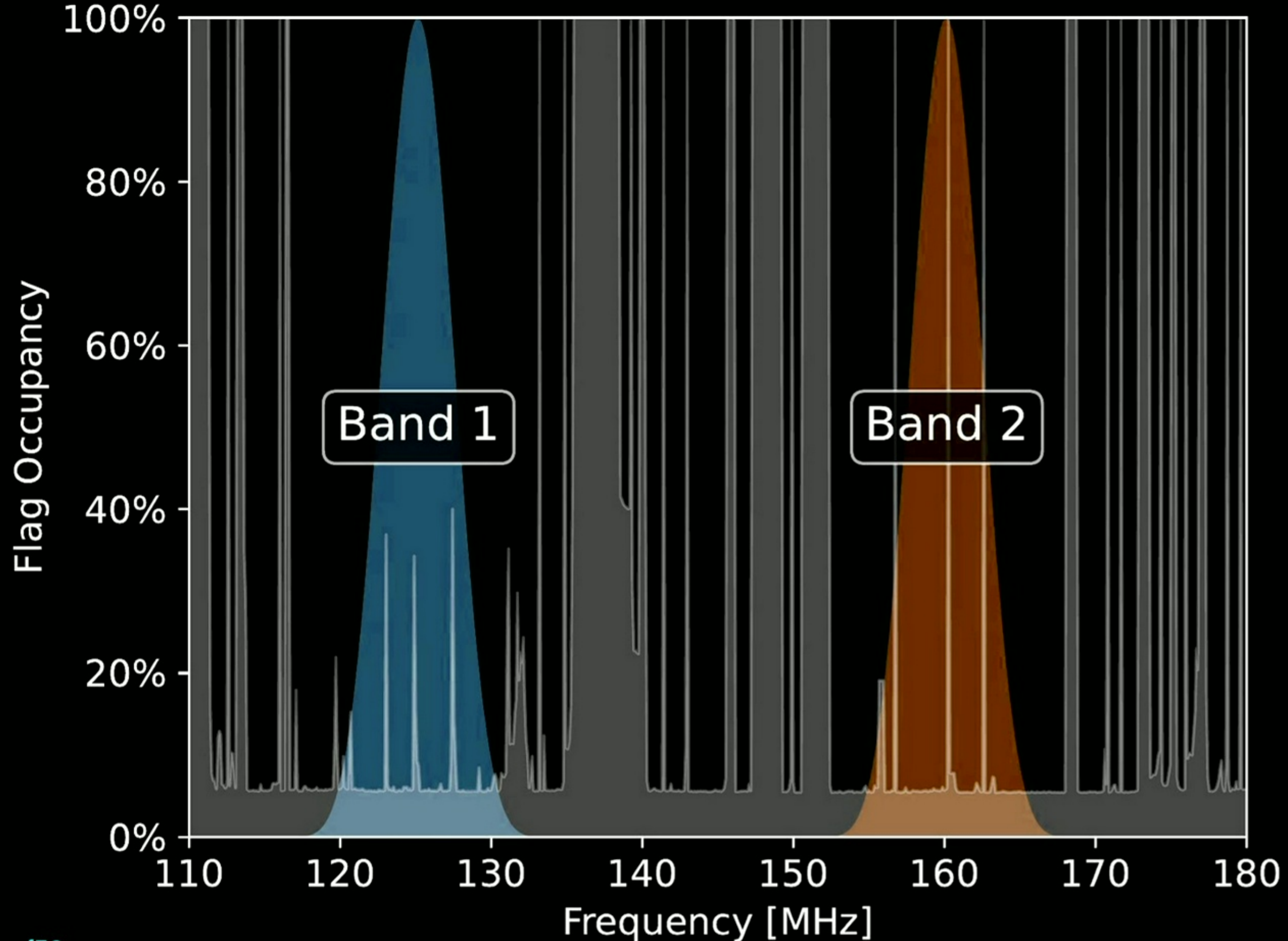
Data Description



HERA 2023
doi: 10.3847/1538-4357/acaf50

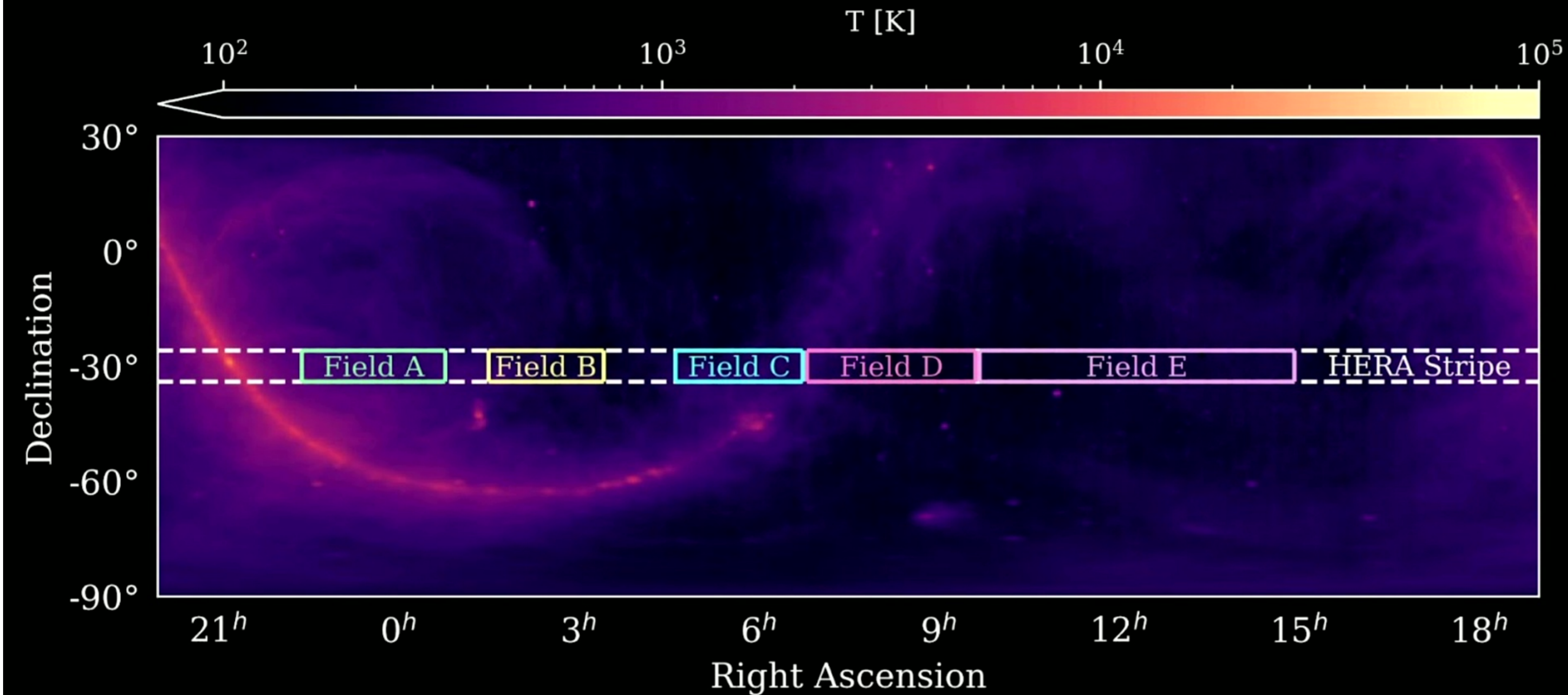
Data Description

$z \sim 10.4$ $z \sim 7.9$

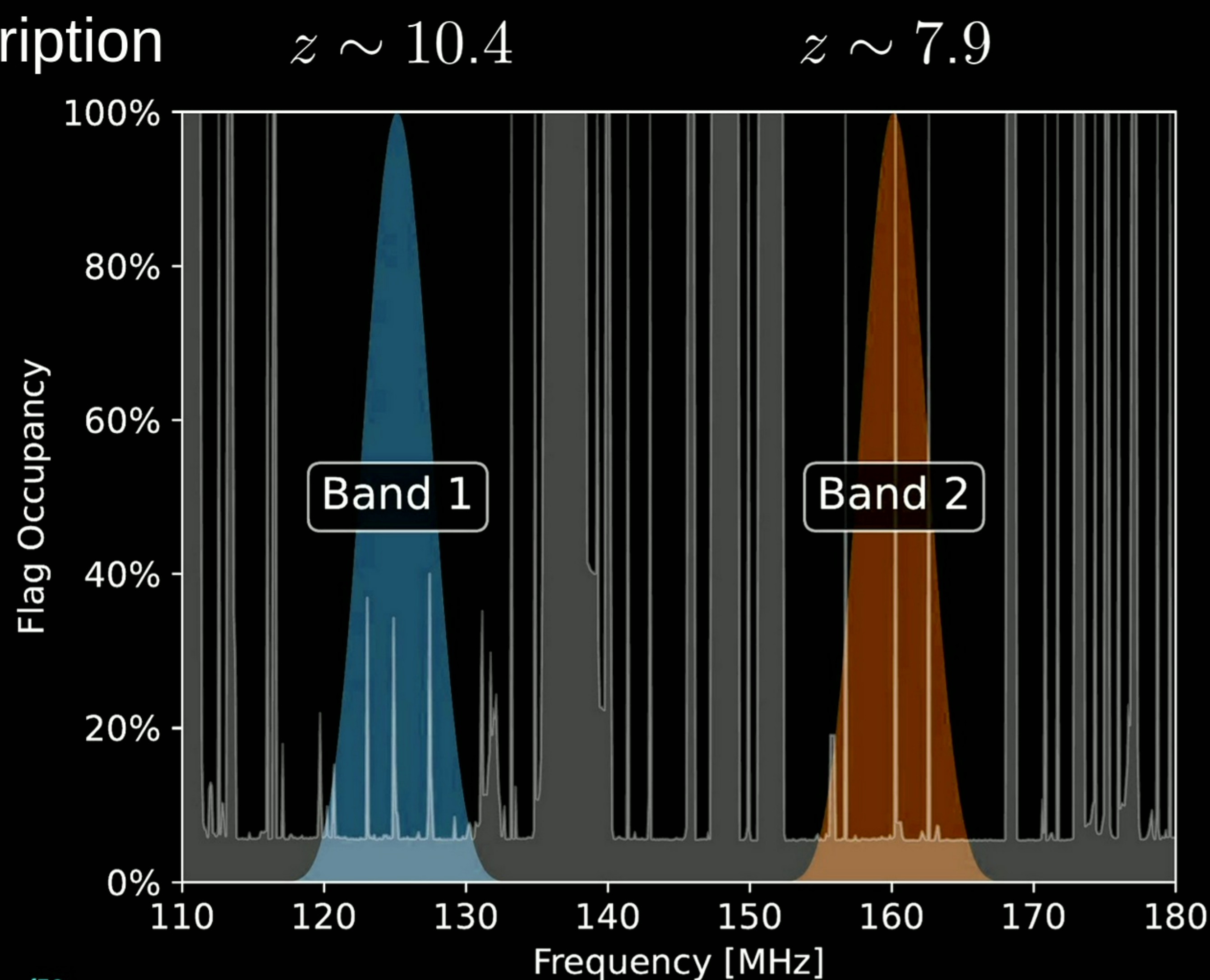


HERA 2023
doi: 10.3847/1538-4357/acaf50

Data Description

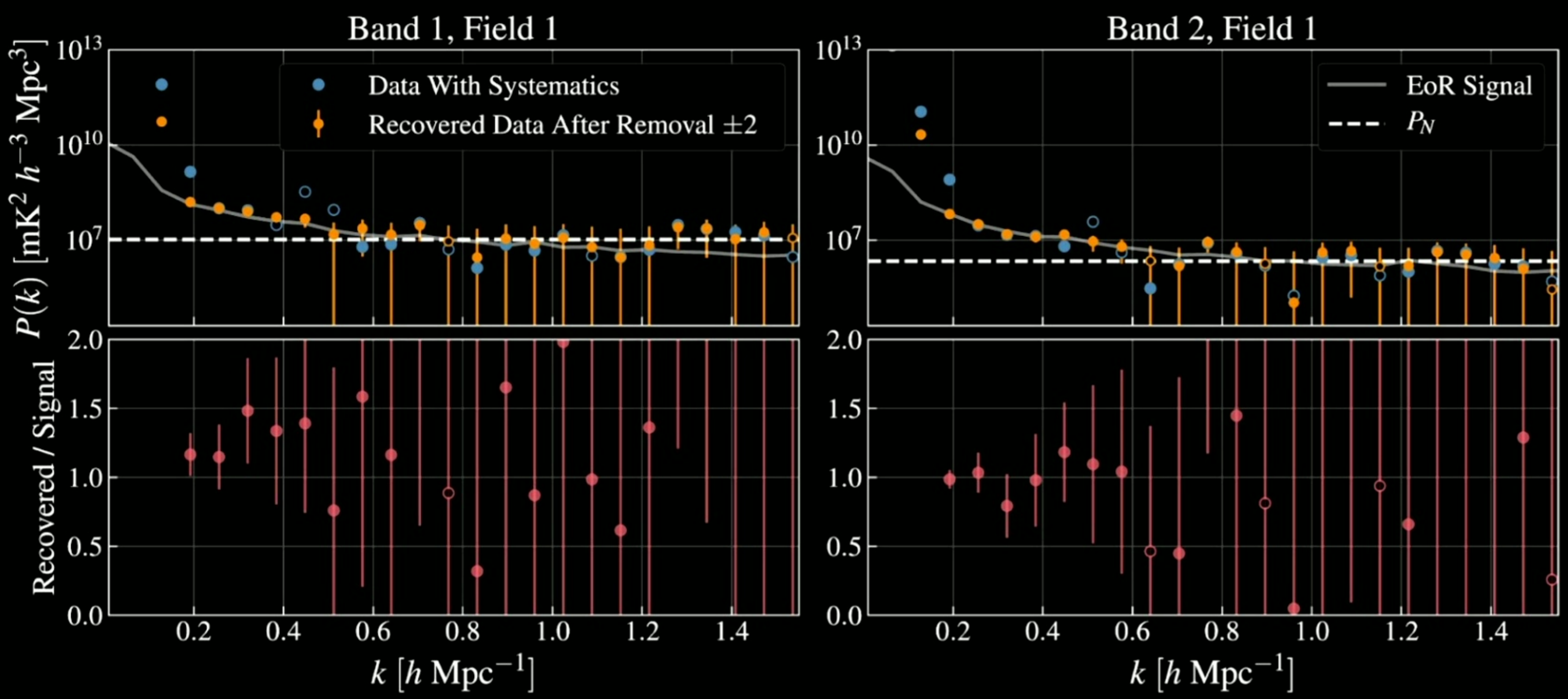


Data Description



HERA 2023
doi: 10.3847/1538-4357/acaf50

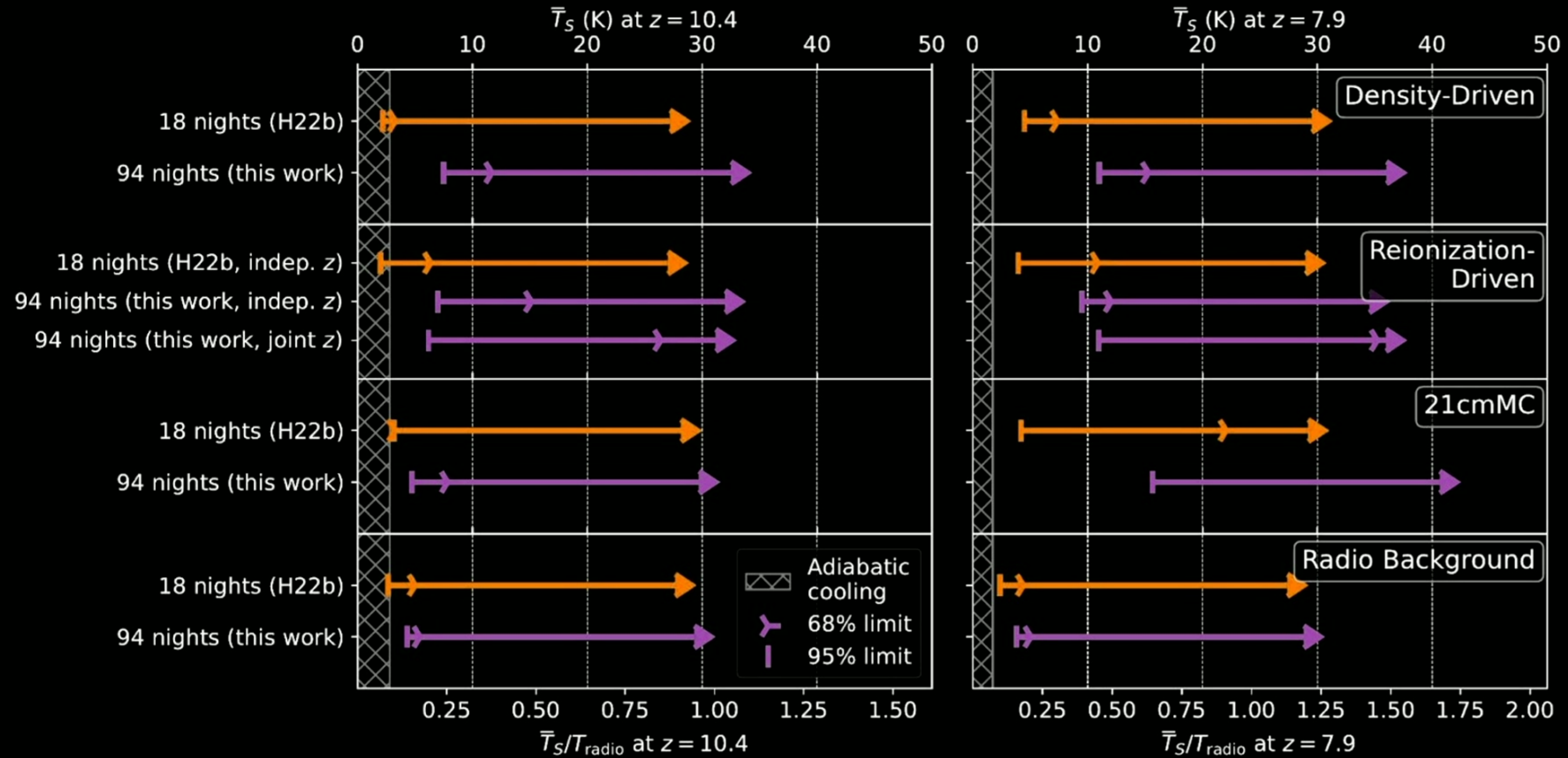
Validation



Aguirre, Murray, **RP**+ 2022

doi: 10.3847/1538-4357/ac32cd

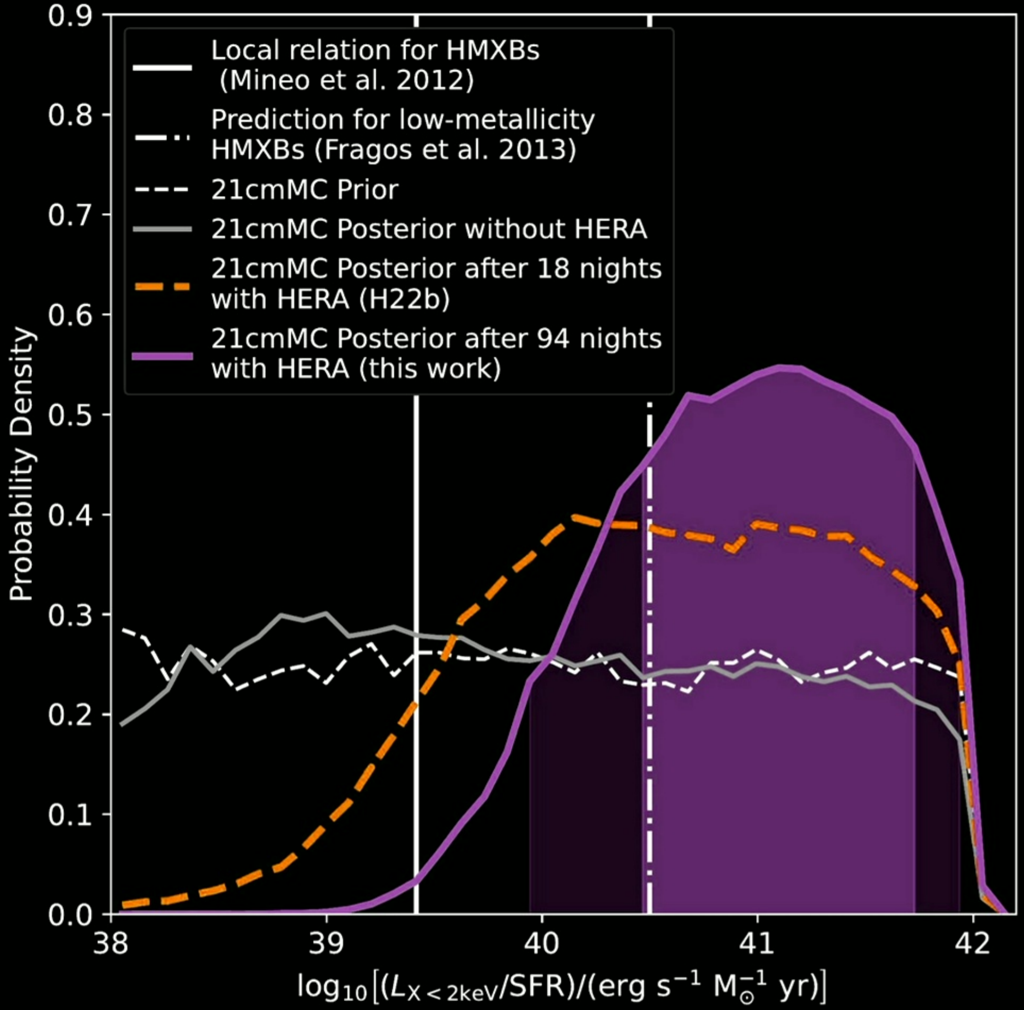
Astrophysical Constraints



HERA 2023
doi: 10.3847/1538-4357/acaf50

Astrophysical Constraints

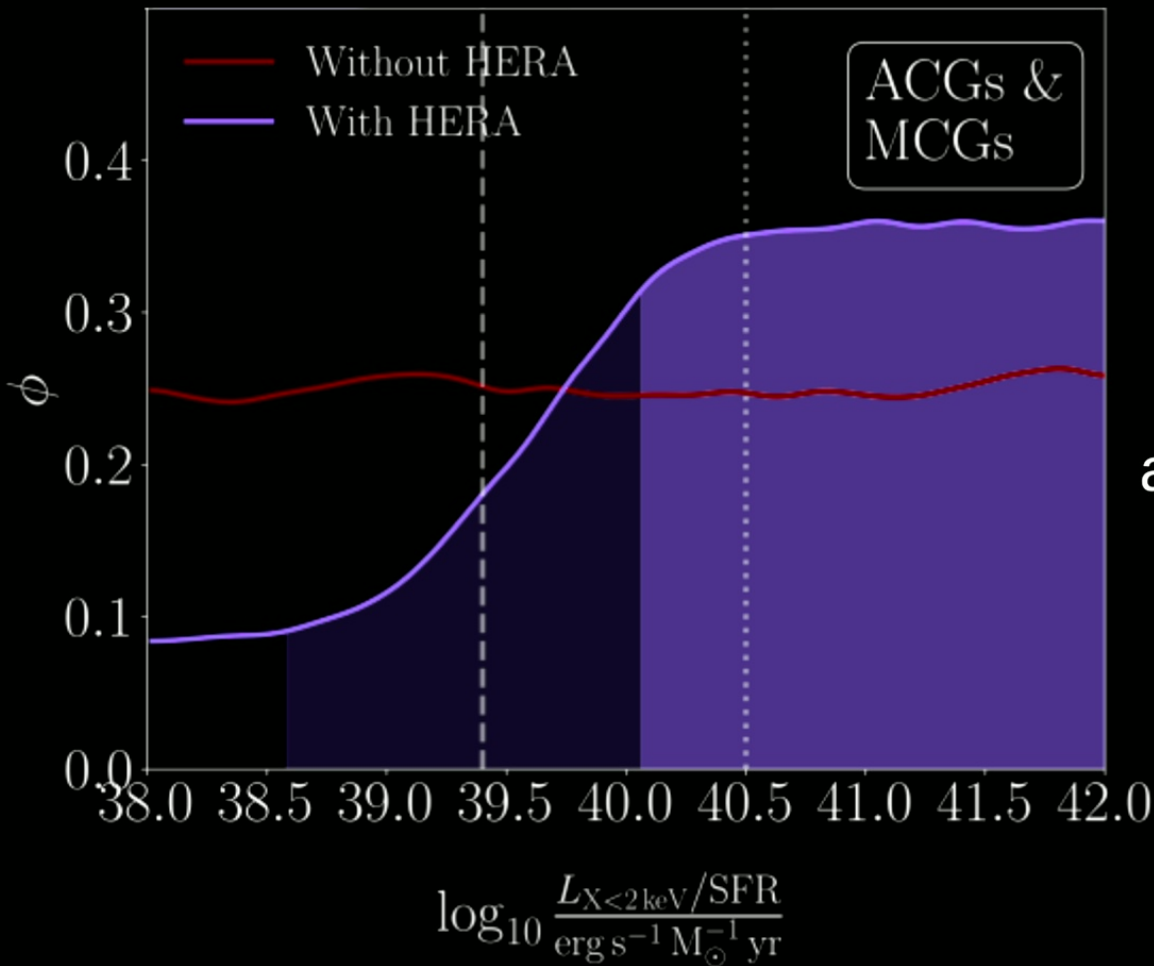
HERA 2023
doi: 10.3847/1538-4357/acaf50



Assuming the X-rays come from HMXBs in a single population of galaxies, X-rays were produced more efficiently in the past.

Astrophysical Constraints

Lazare+ 2024
doi: 10.1103/PhysRevD.109.043523

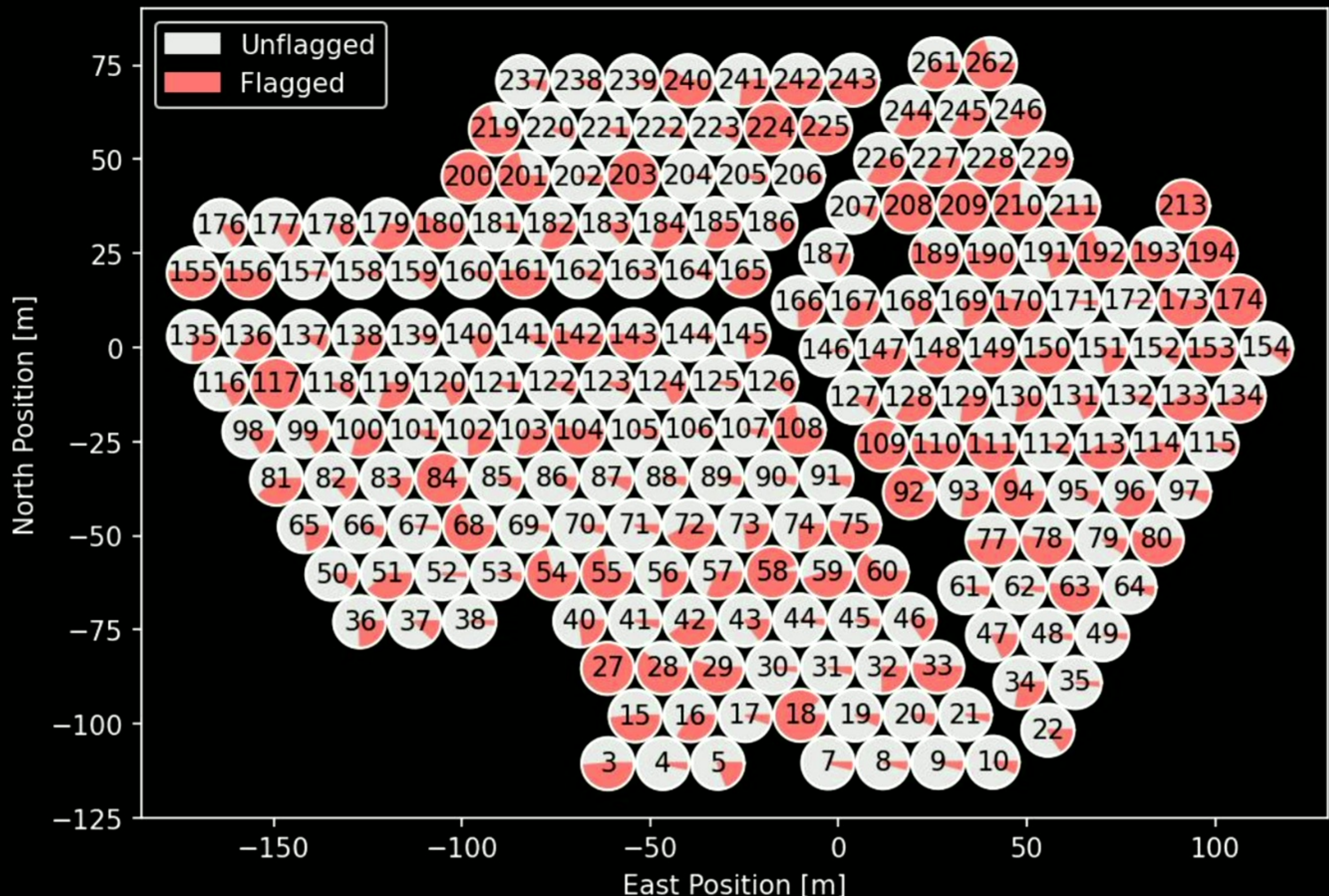


However, this constraint can be weakened by considering alternate heating mechanisms

Current Status

2022-2023 Season

- Up to ~140 nights (~1300 hours) of data
- Up to ~140 antennas with good data each night
- Currently analyzing 14 nights of data
- 2023-2024 season has similar sensitivity



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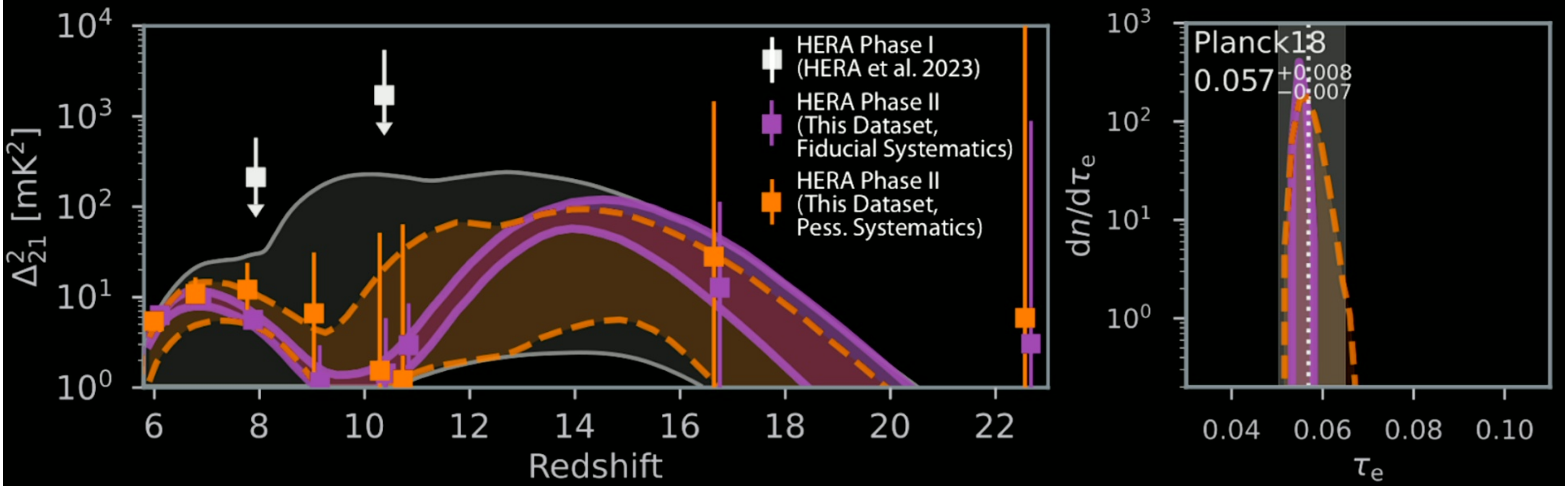
Current Status



A joint analysis of the 2022-2023 and 2023-2024 seasons could be sensitive enough to detect the 21-cm power spectrum and constrain τ better than Planck.

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