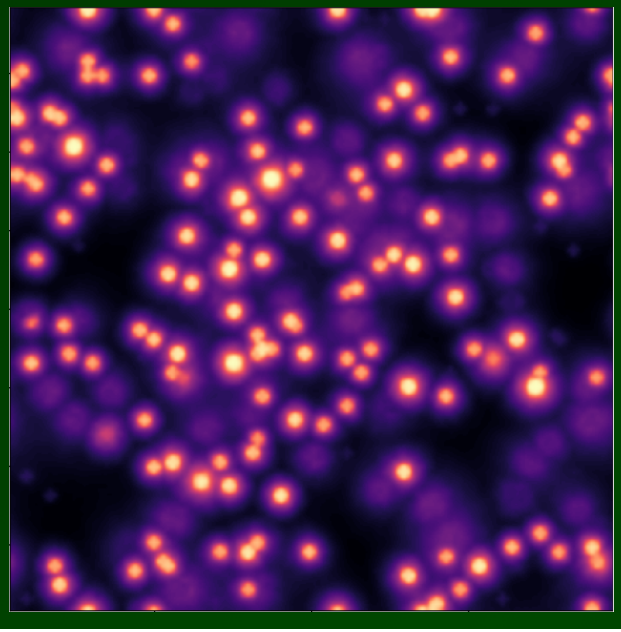
21-cm cosmology at a crossroads

Rennan Barkana

רנן ברקנא

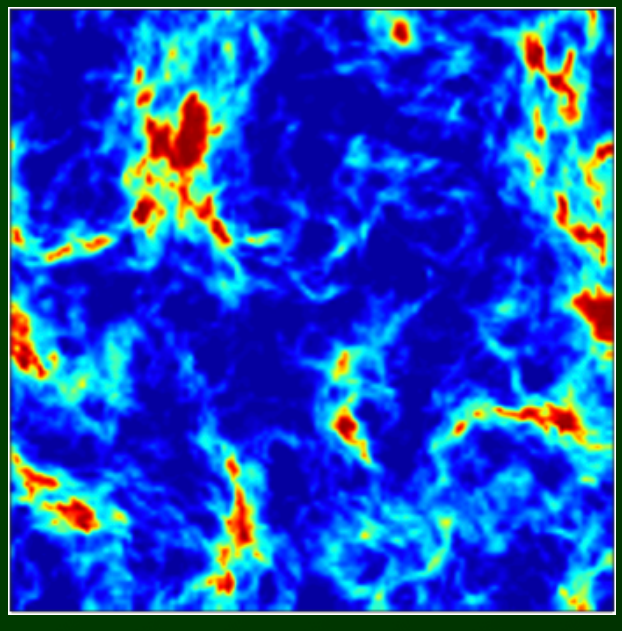
TEL AVIV UNIVERSITY

אוניברסיטת תל-אביב

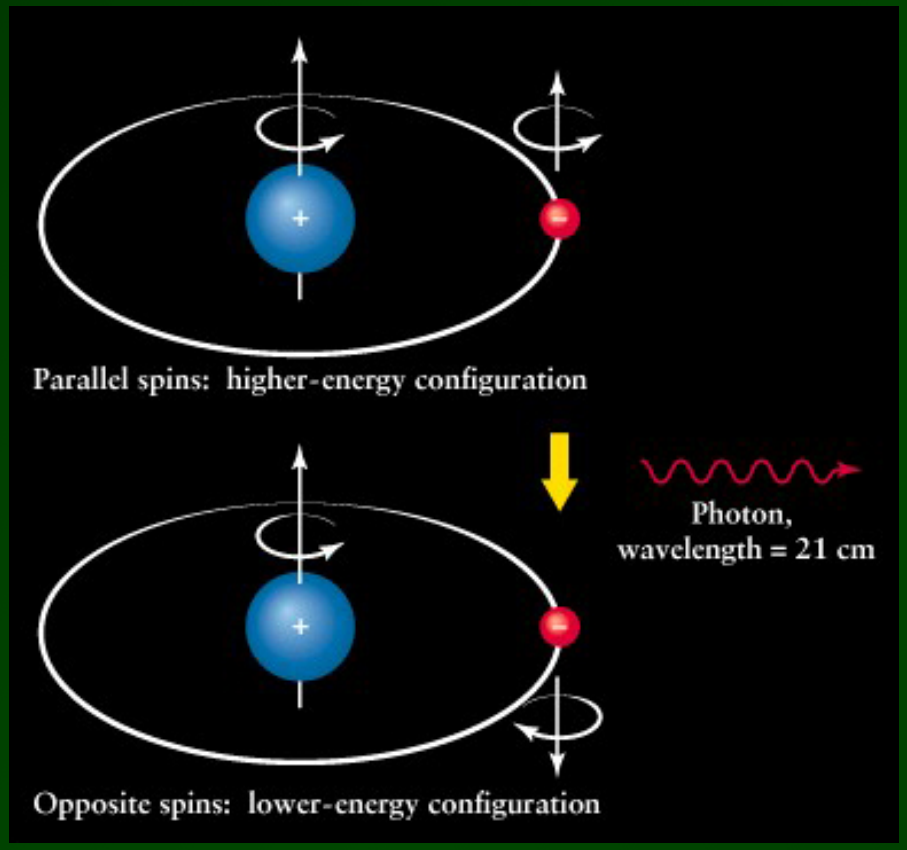


Some of this work is from recent Sabbatical at:

Institute for Advanced Study, Princeton
UC Santa Cruz



21-cm Cosmology



$$\lambda = 21\,\mathrm{cm}$$

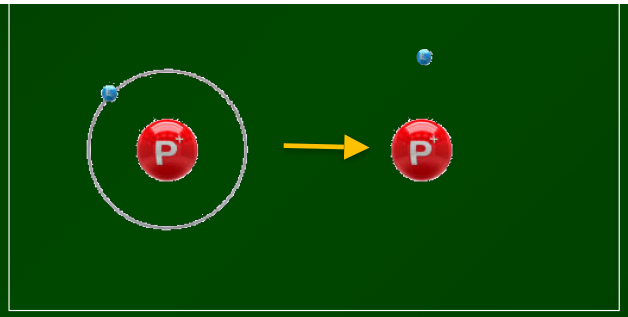
$$\nu = 1420\,\mathrm{MHz}$$

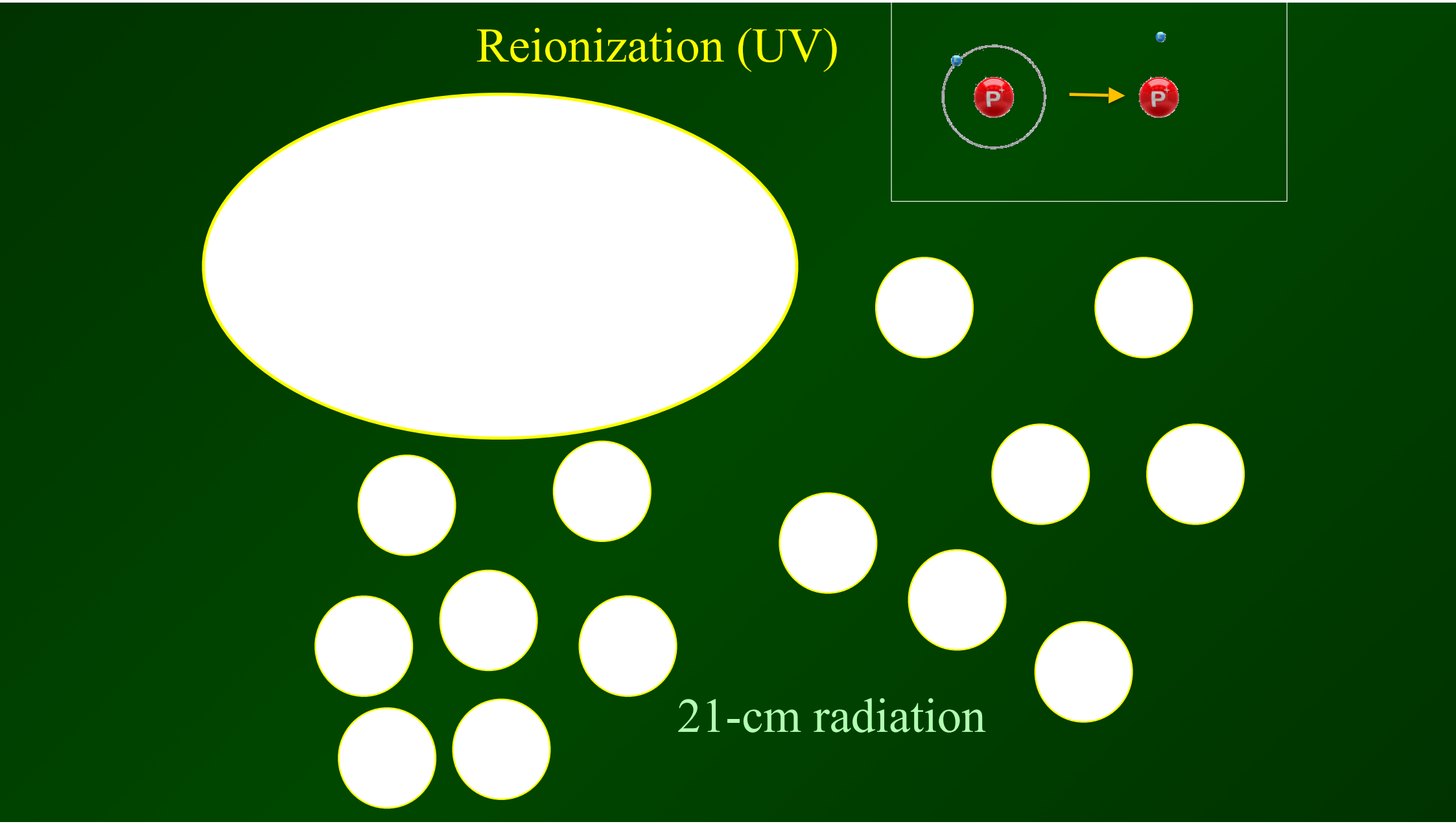
$$E = 5.9 \times 10^{-6}\,\mathrm{eV}$$

$$\frac{E}{k_B} = T_* = 0.068\,\mathrm{K}$$

$$\frac{n_1}{n_0} = 3\exp\left\{-\frac{T_*}{T_S}\right\}$$

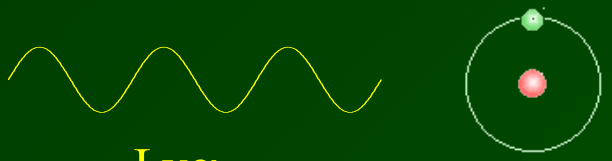
Reionization (UV)




Reionization (UV)
P+
P+
21-cm radiation

21-cm Cosmology

$$T_{21} \propto \frac{T_S - T_{\rm CMB}}{T_S}$$



Lyα

$T_S \rightarrow T_{\rm gas}$

Wouthuysen 1952
Field 1958

Madau, Meiksin & Rees 1997

Cosmic Dawn

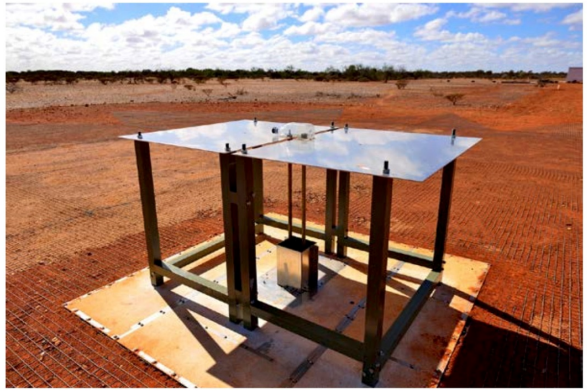
Lyα coupling
X-ray heating

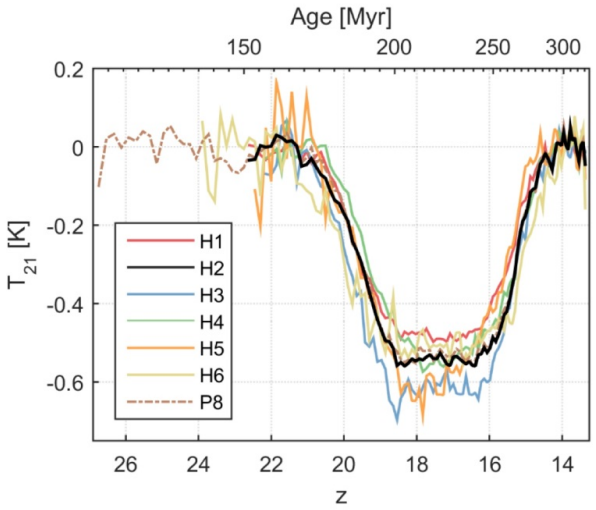
RB & Loeb 2005:
Ly-α fluctuations: z~20-30

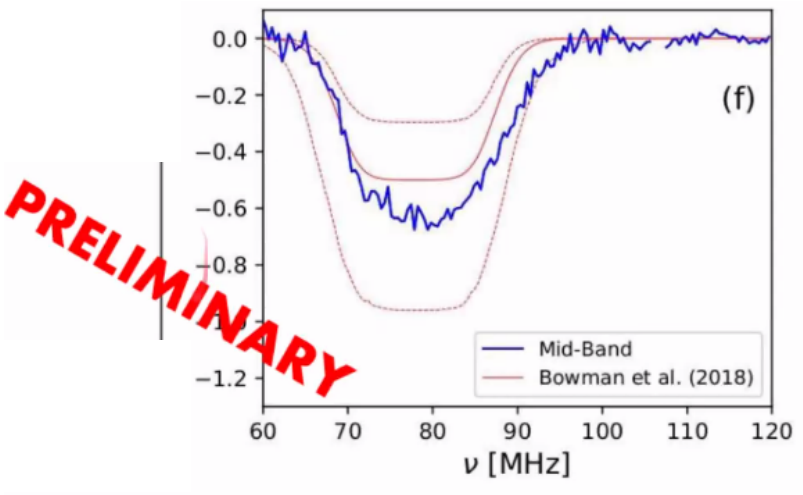
Pritchard & Furlanetto 2007:
Temperature fluctuations
(X-ray heating)

Global 21-cm

EDGES 2018





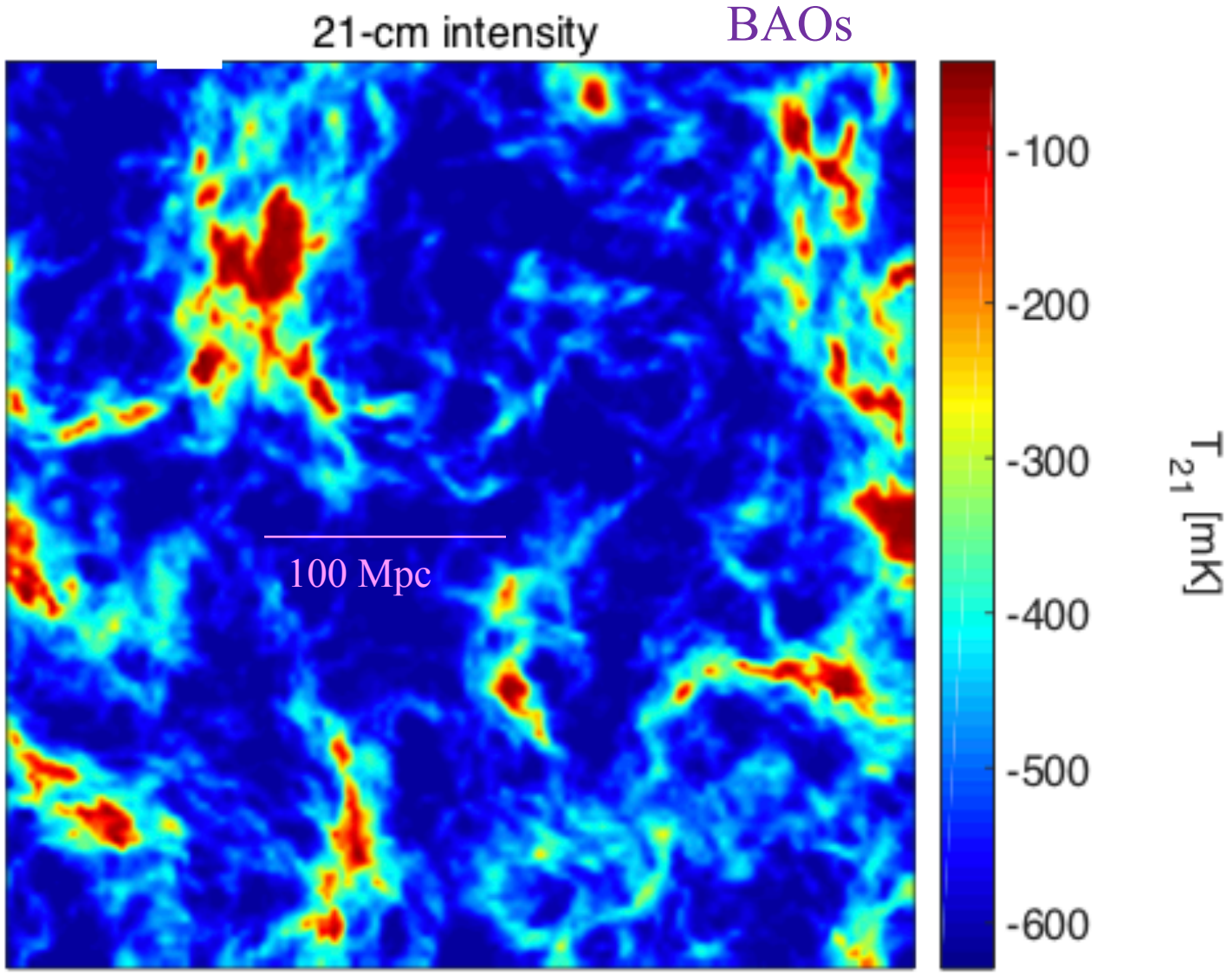


Bowman et al. 2018

$$T_{21} \propto \frac{T_S - T_{\rm CMB}}{T_S}$$

Cool the gas with a b-DM interaction

RB, Nature 2018



RB, Nature 2018

Millicharged DM

Muñoz & Loeb 2018

Interacting Millicharged DM

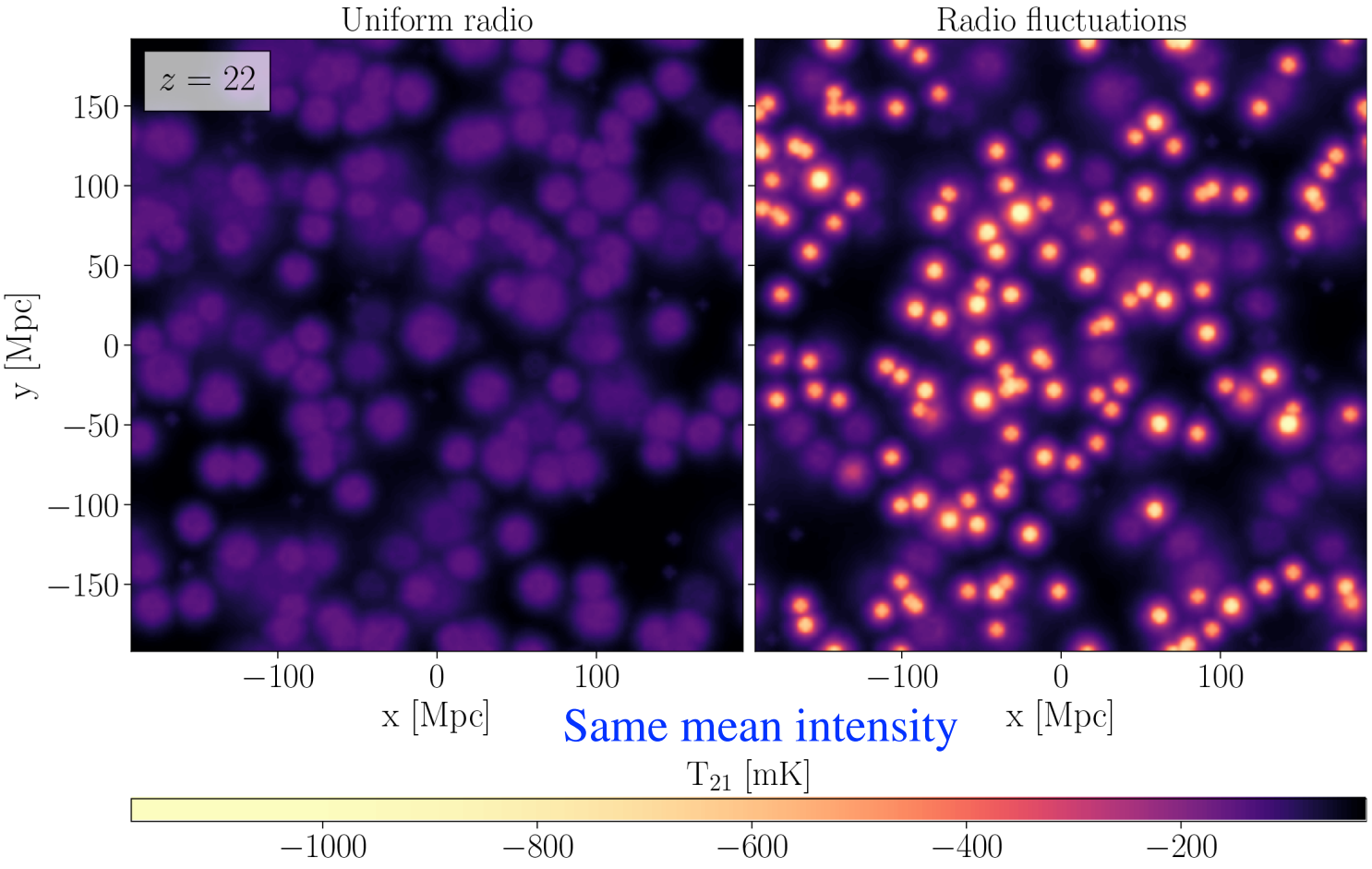
Liu, Outmezguine, Redigolo, Volansky 2019

Alternative explanation for EDGES

Early radio background

Bowman et al. 2018
Mirocha & Furlanetto 2018
Feng & Holder 2018
Fialkov & RB 2019

$$T_{21} \propto \frac{T_S - T_{\rm CMB}}{T_S}$$

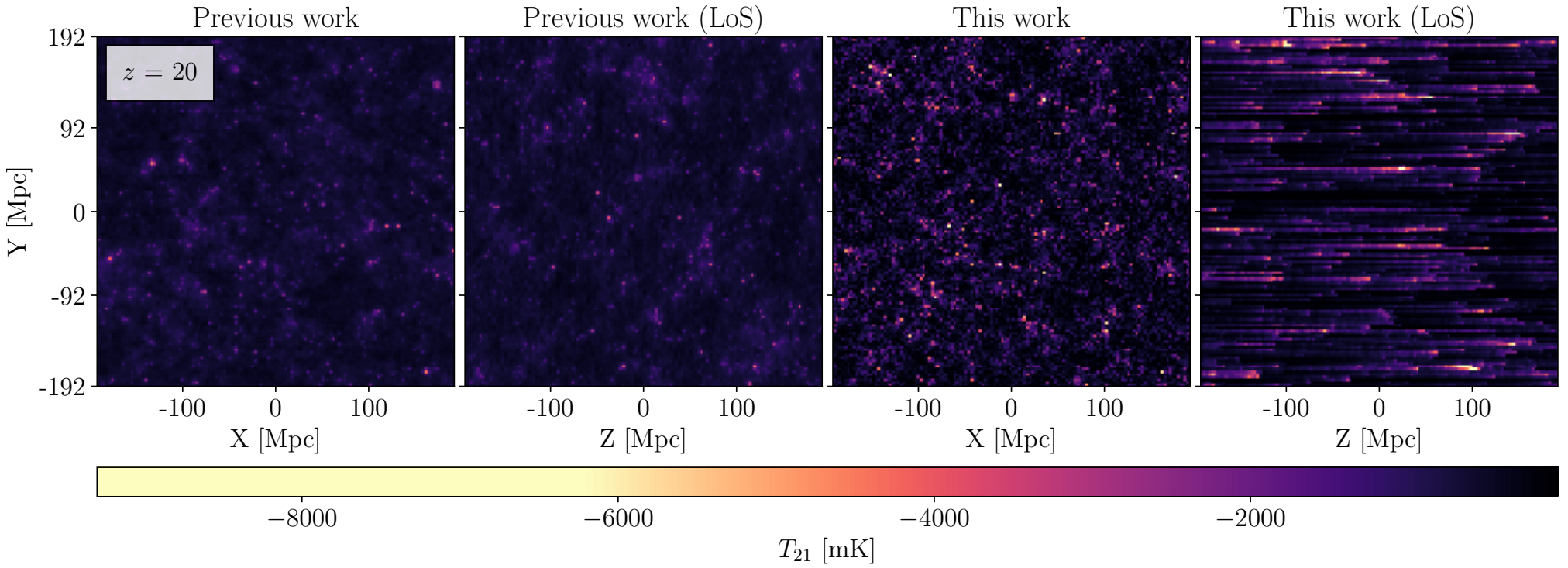


$$M_{\rm min} = 3 \times 10^8\ M_\odot$$

$$V_c = 35\ {\rm km\ s^{-1}}, f_* = 0.4, f_{\rm Radio} = 1000$$

Reis, Fialkov & RB 2020

Early radio background: Line-of-sight effect

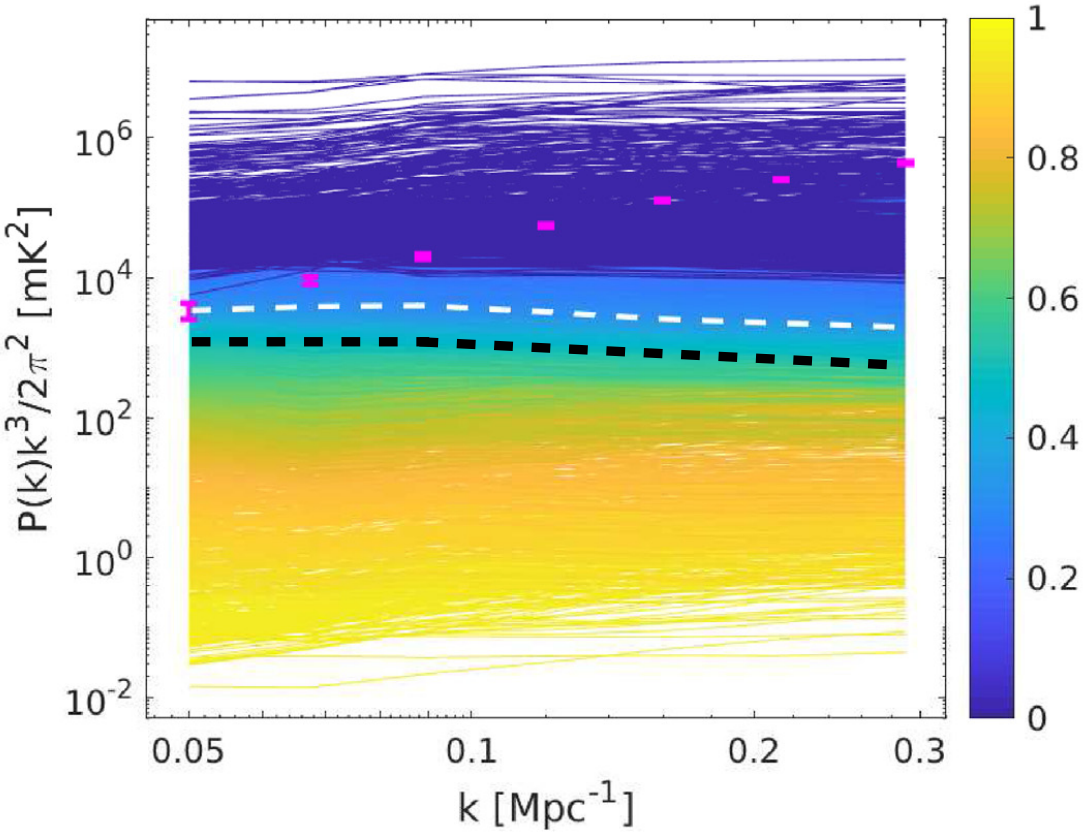


$V_c = 16.5$ km s^{-1}, $f_* = 0.1$, $f_{\rm Radio} = 3000$

Sikder, Reis, RB & Fialkov 2022

21-cm Fluctuations

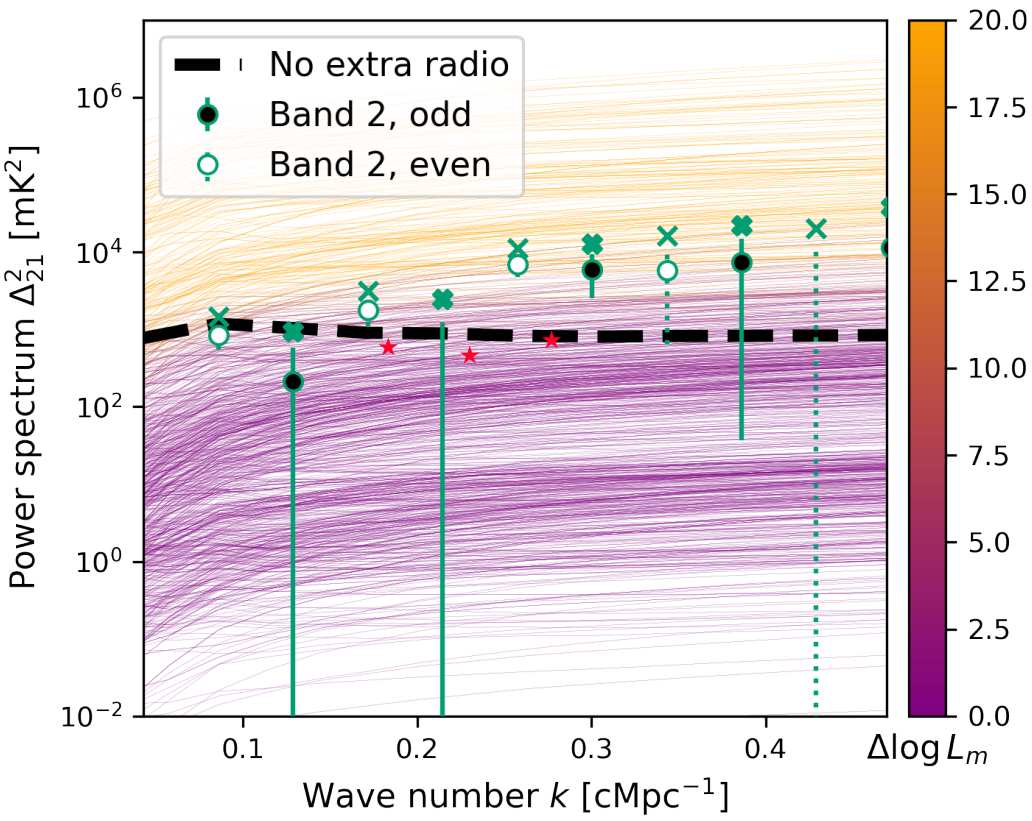
LOFAR z=9.1



LOFAR, Mondal, Fialkov, RB, et al. 2020

HERA z=7.9

HERA



HERA, RB, Fialkov, Reis, Sikder, et al. 2022

Lyα coupling and 21-cm fluctuations

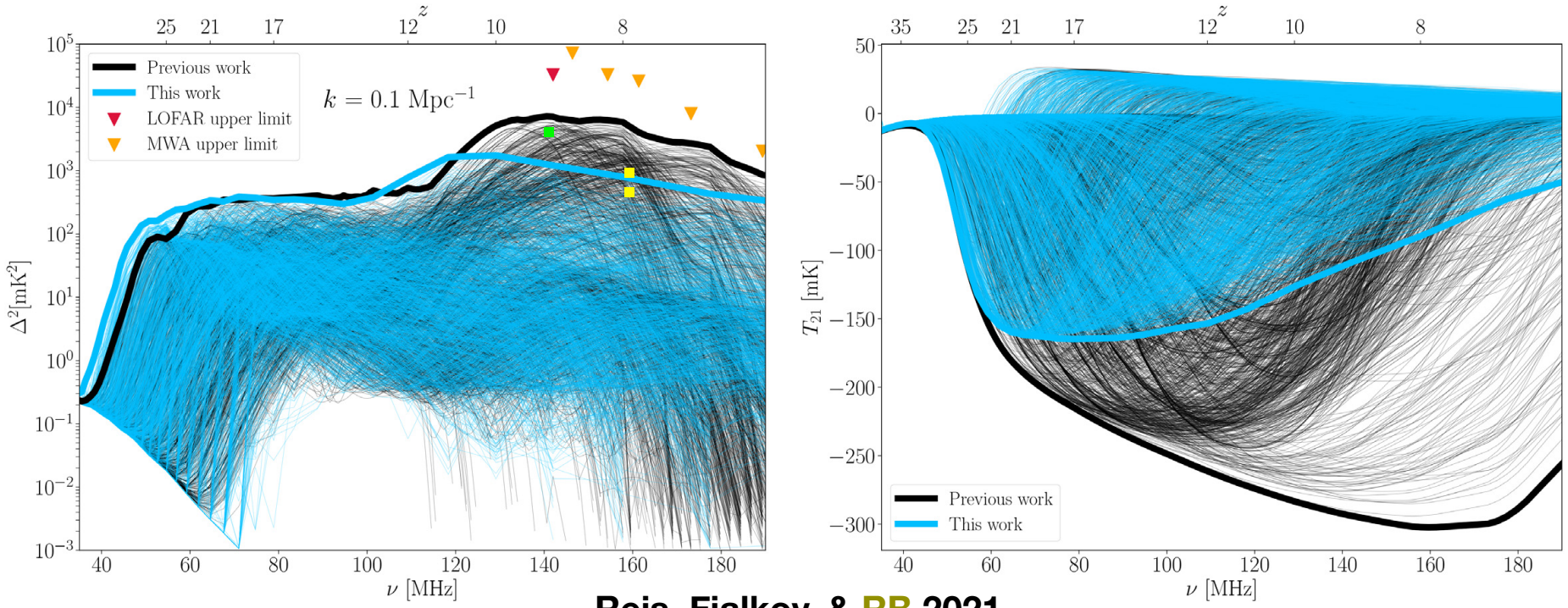
Madau, Meiksin, & Rees 1997

RB & Loeb 2005

Lyα/CMB Heating

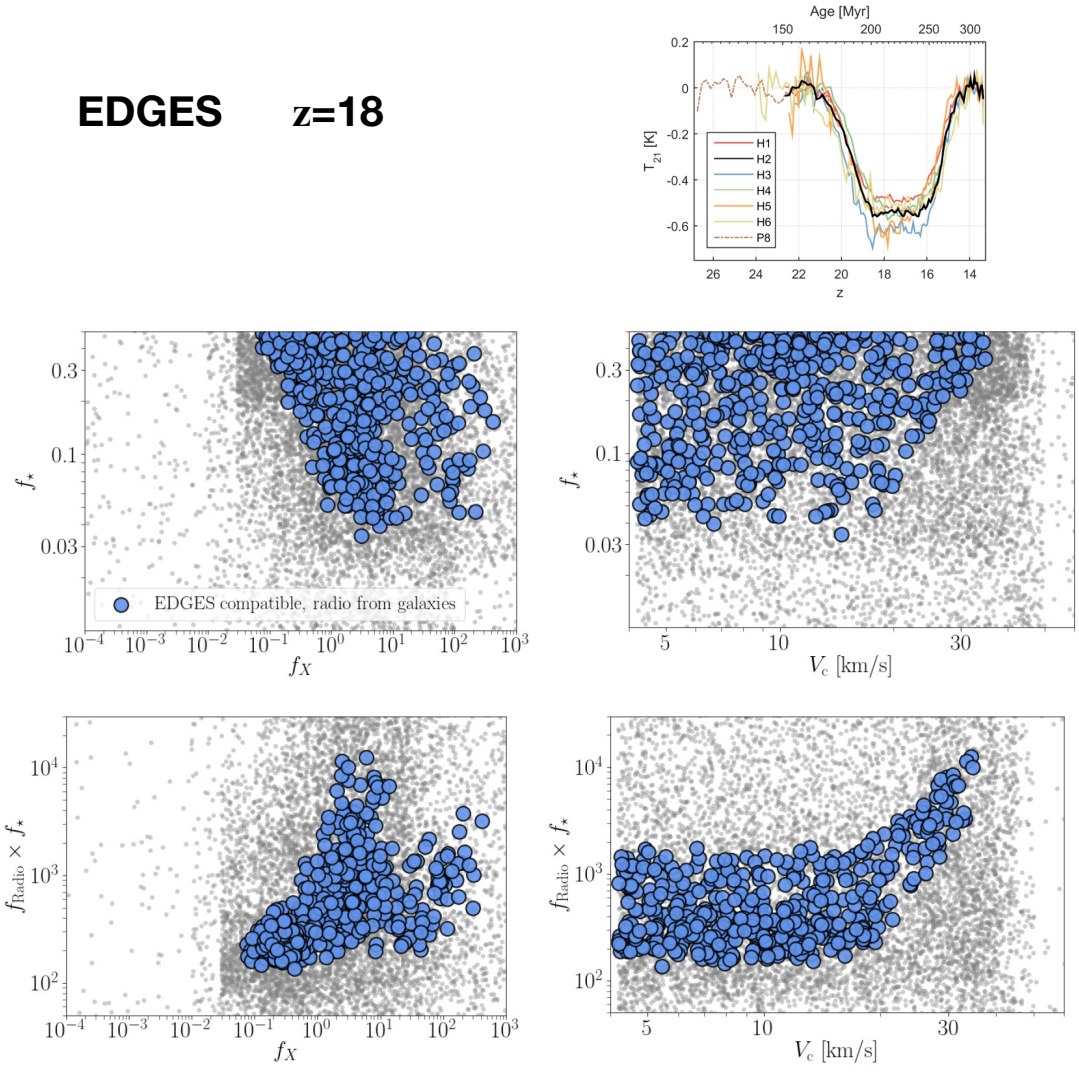
Madau et al. 1997; Chen & Miralda-Escudé 2004;
Chuzhoy & Shapiro 2006; Furlanetto & Pritchard 2006;
Chuzhoy & Shapiro 2007
Venumadhav et al. 2018

LOFAR | HERA



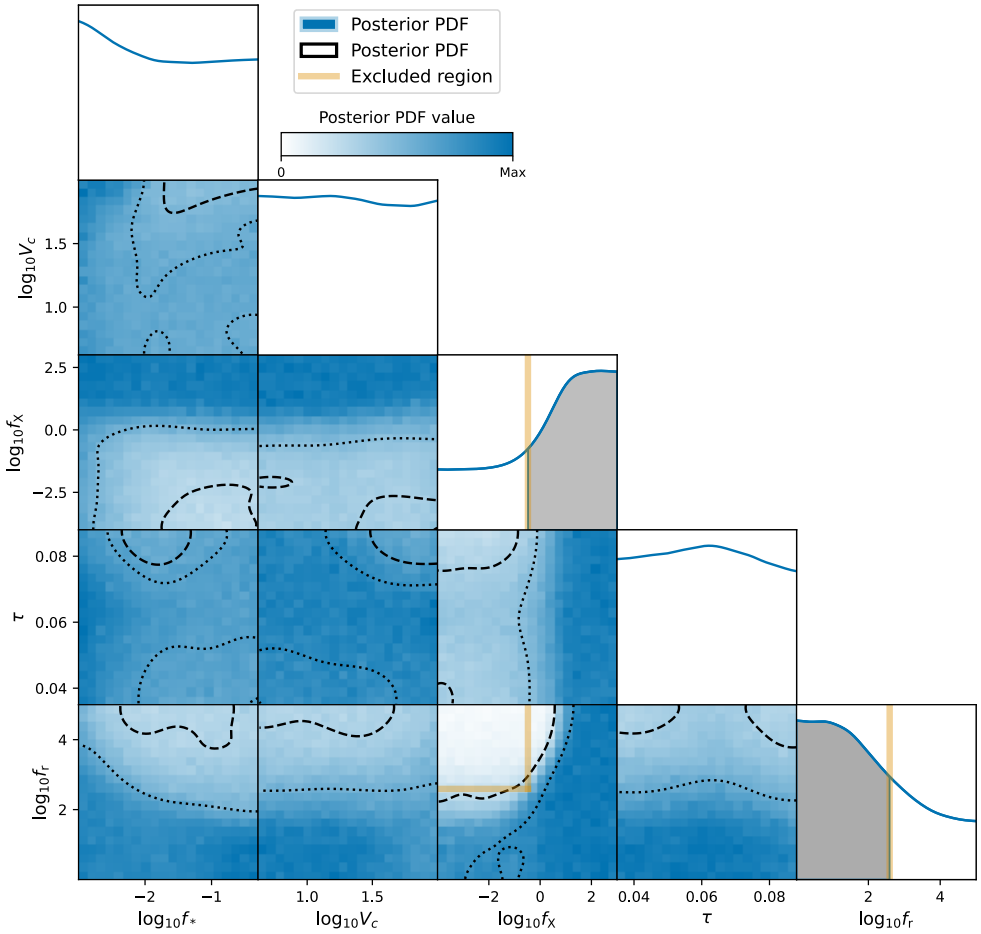
Reis, Fialkov, & RB 2021

EDGES z=18



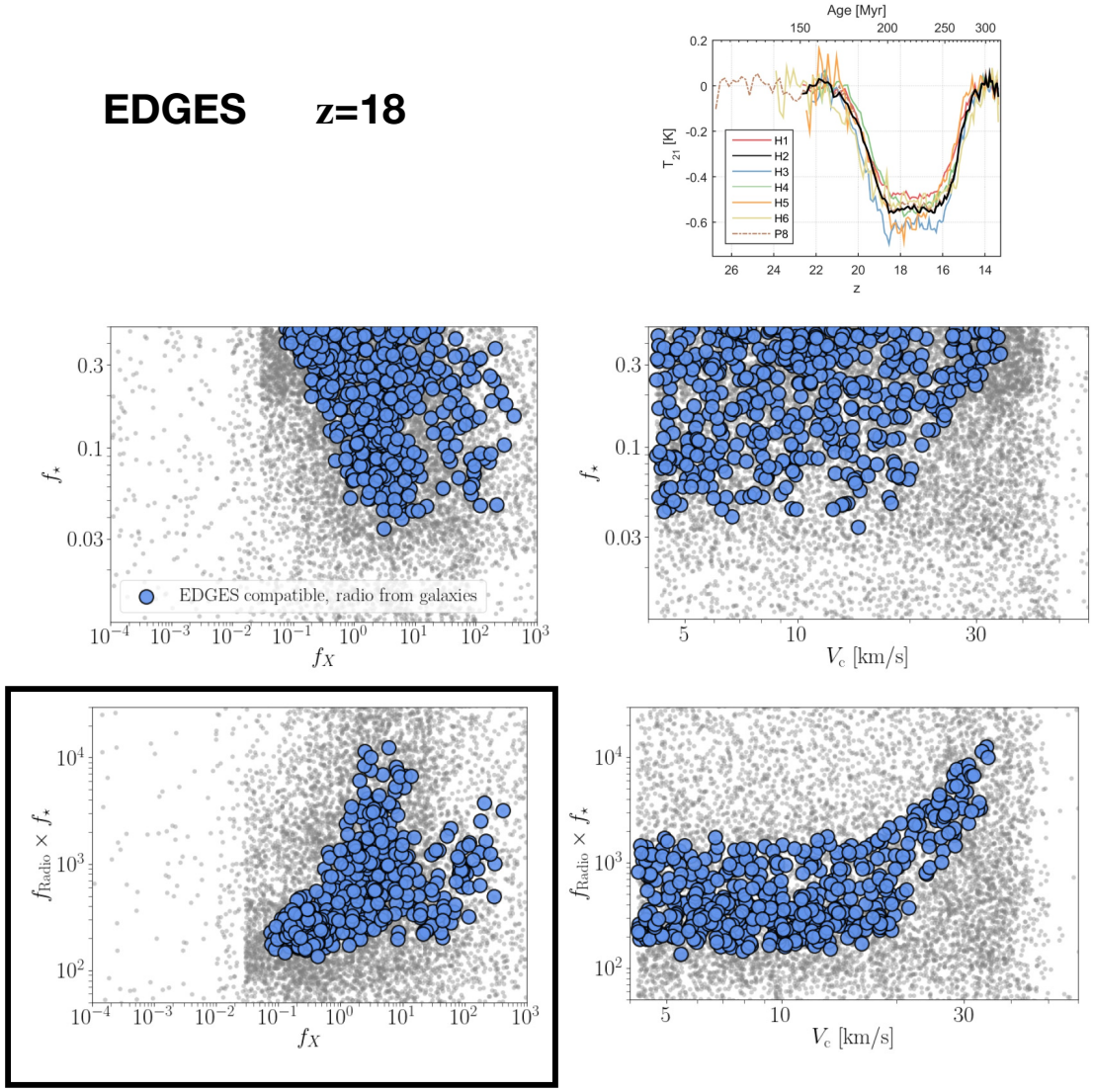
Reis, Fialkov, & RB 2020

HERA z=7.9



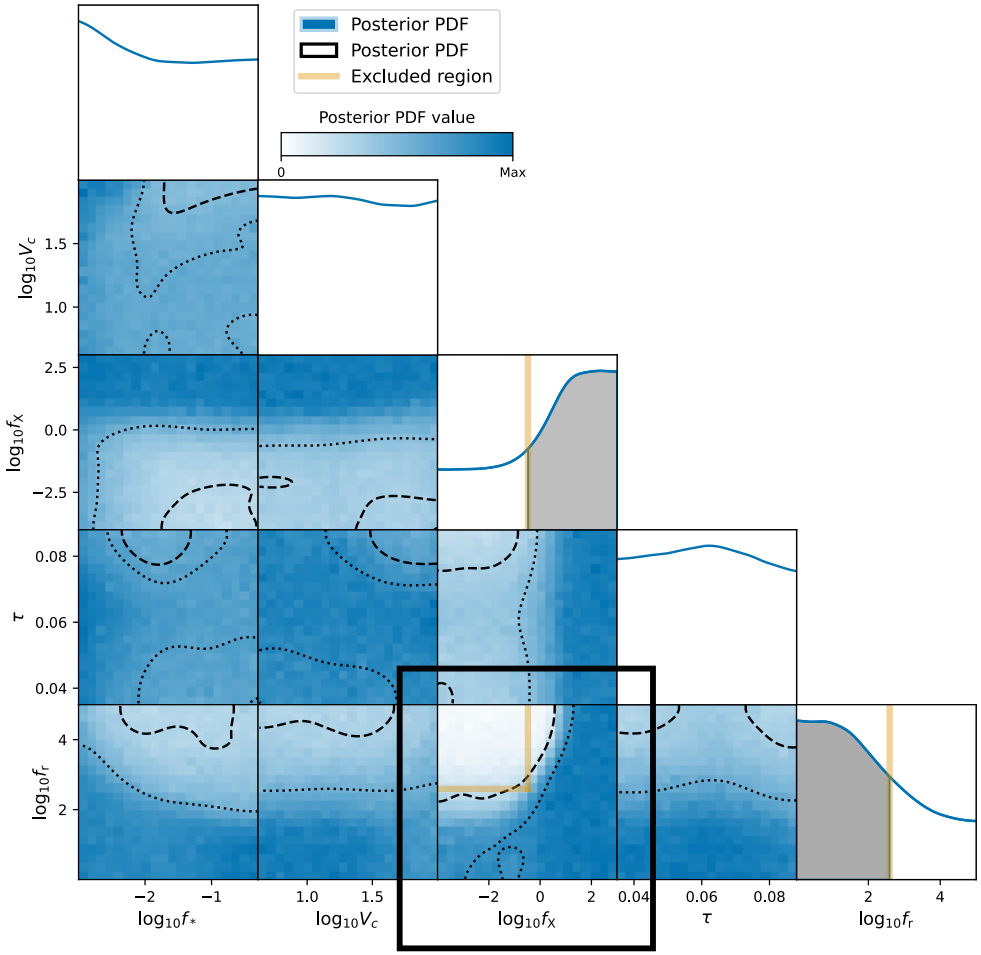
HERA, RB, Fialkov, Reis, Sikder, et al. 2021

EDGES z=18



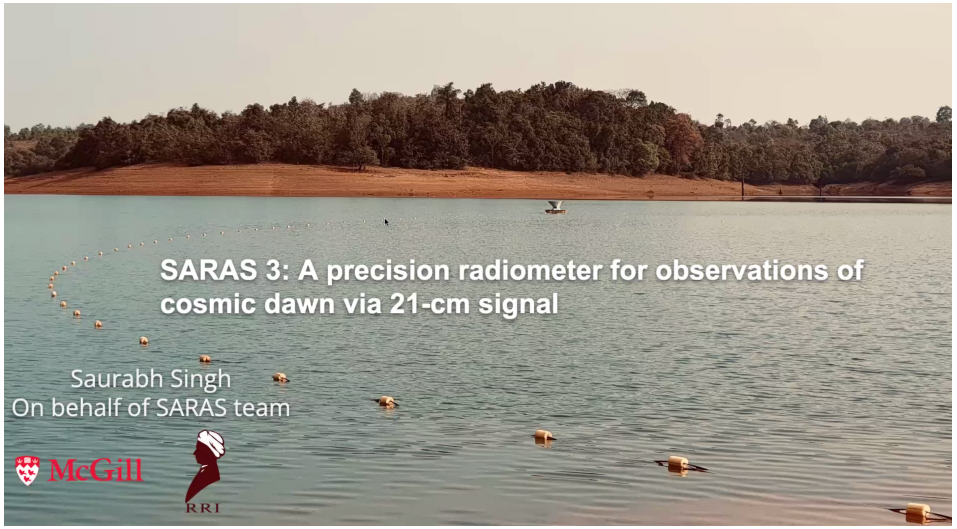
Reis, Fialkov, & RB 2020

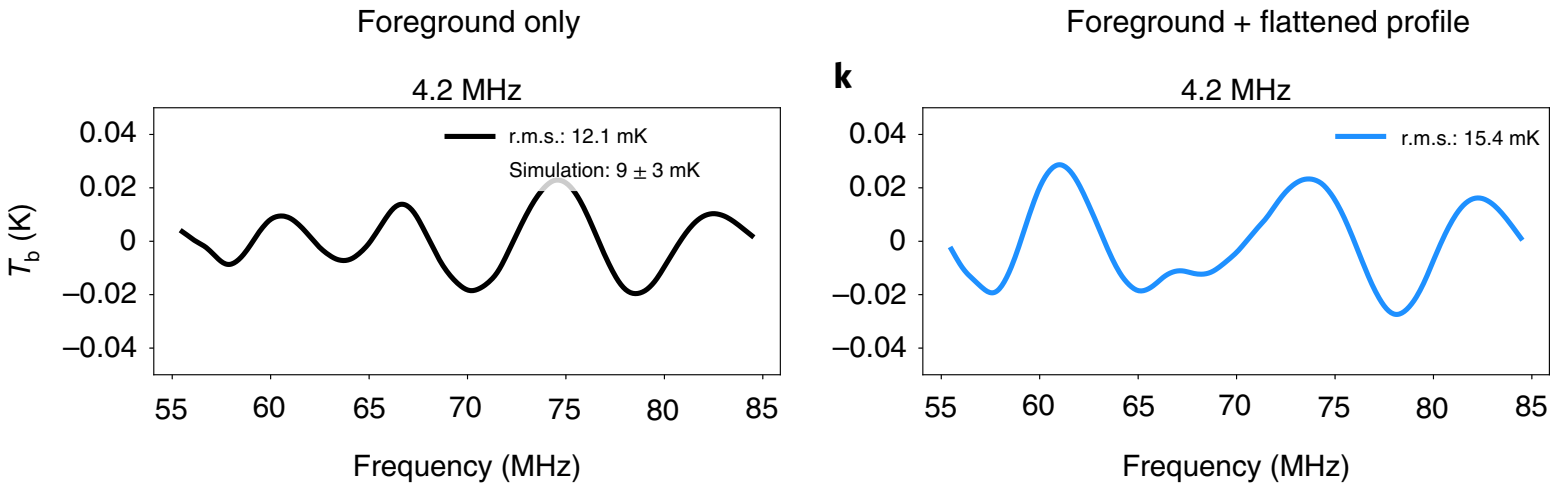
HERA z=7.9



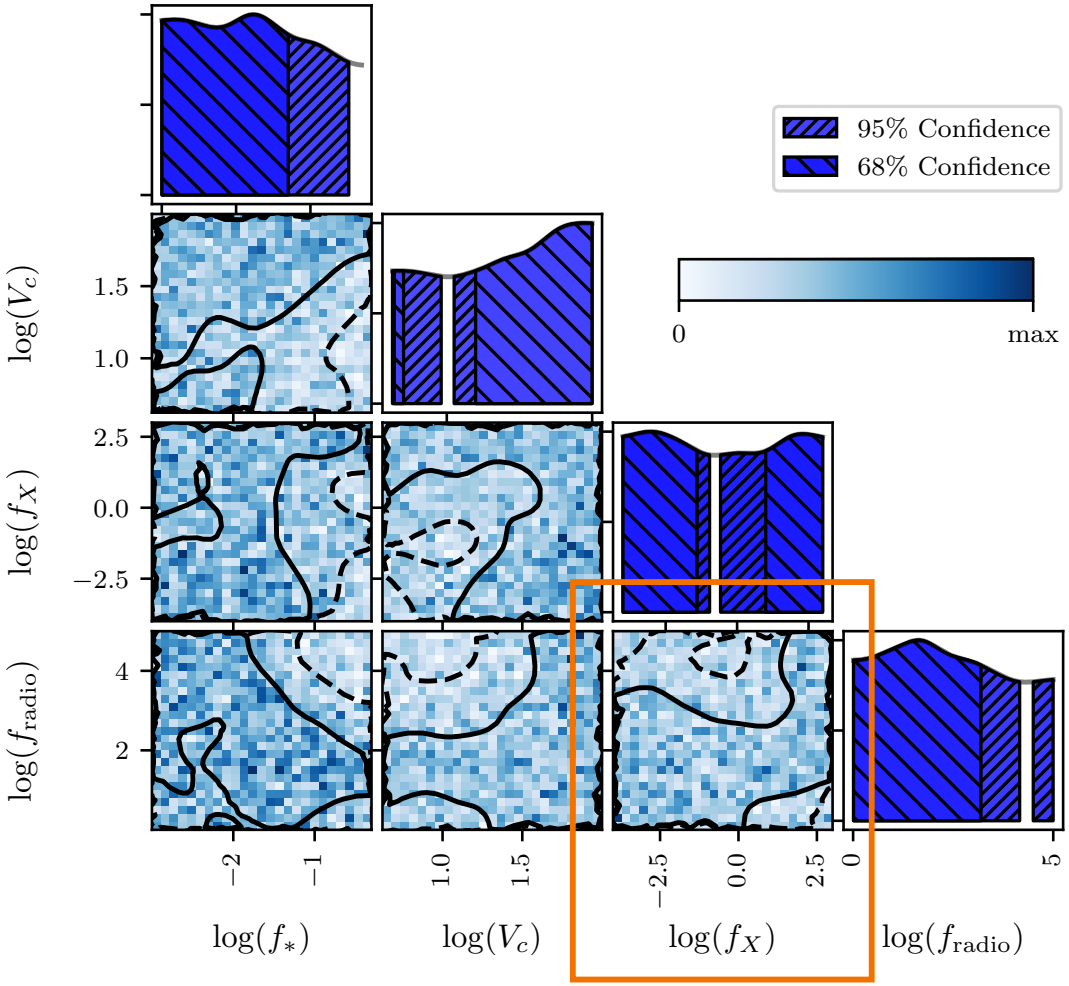
HERA, RB, Fialkov, Reis, Sikder, et al. 2021

SARAS, Singh et al. 2022

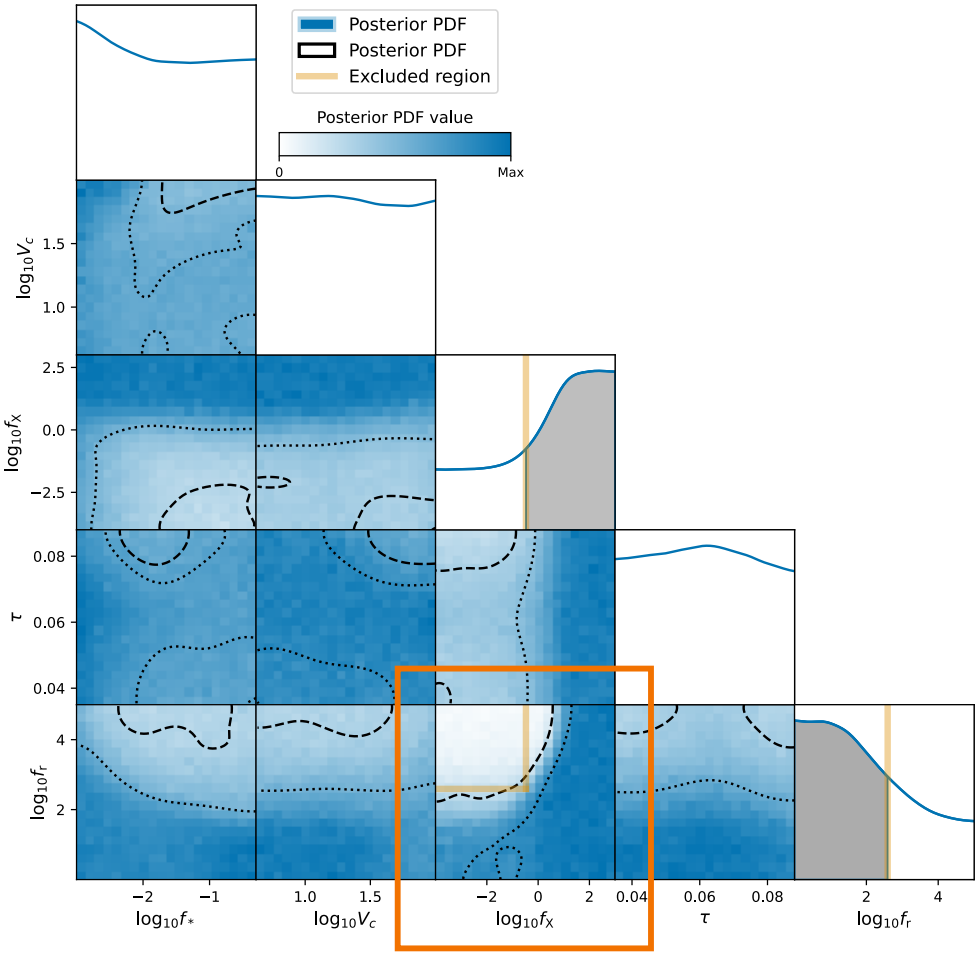




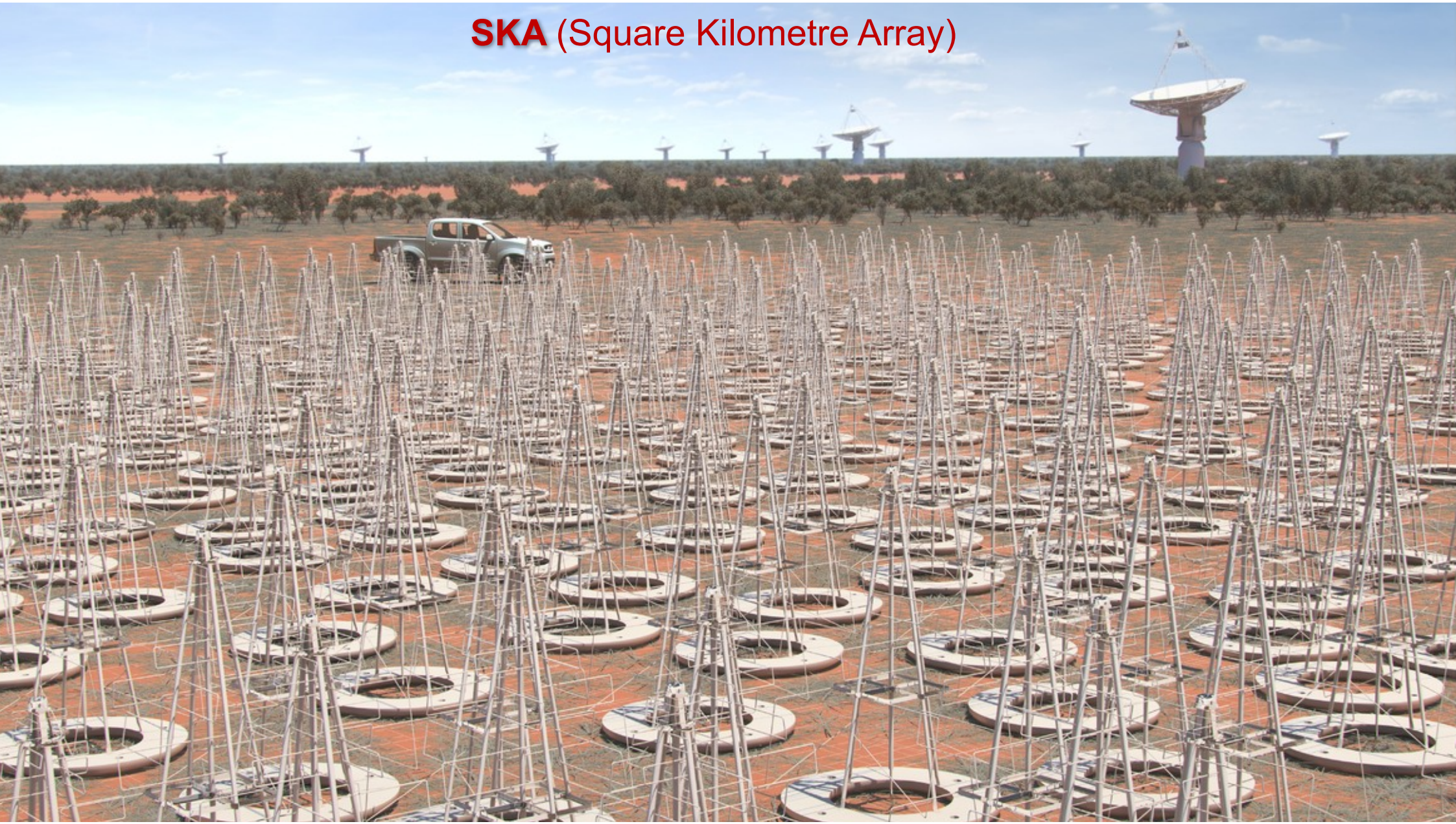
Bevins, SARAS, RB, et al., Nature Astro 2022



HERA z=7.9



SKA (Square Kilometre Array)

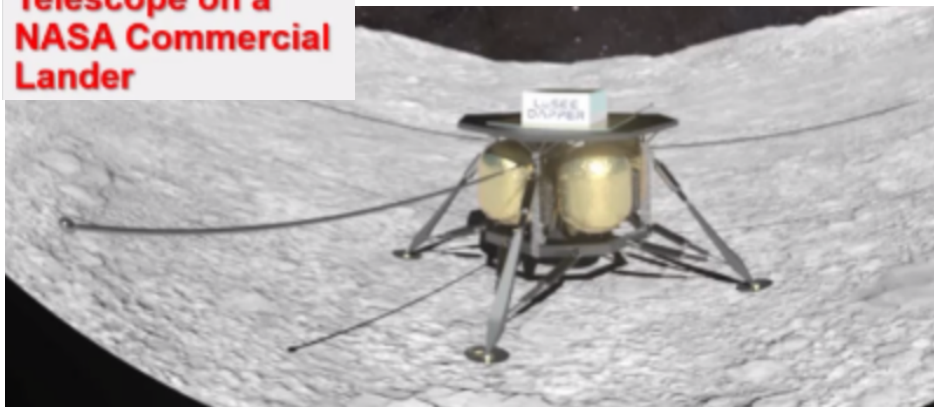


The Moon: The Dark Ages

ROLSES

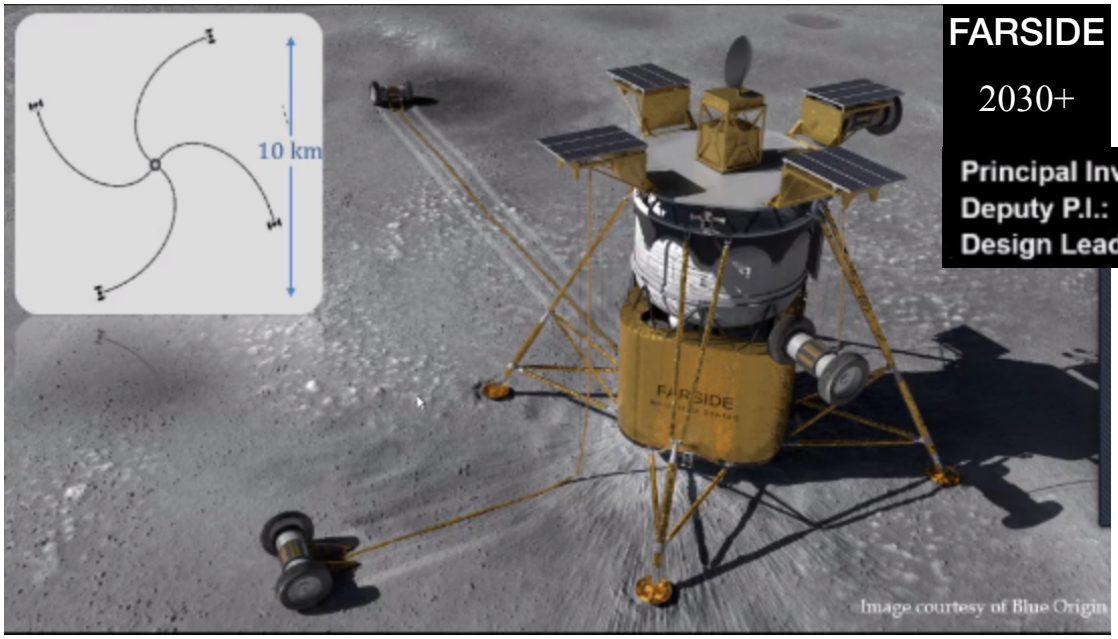
- Team: Robert MacDowall, William Farrell, Damon Bradley, Nat Gopalswamy, Michael Reiner, Ed Wollack, Jack Burns, David McGlone, Mike Choi, Scott Murphy, Rich Katz, Igor Kleyner.
- Status: Scheduled to land on lunar nearside in Spring 2023 using *Intuitive Machines Nova-C.*

Lunar Farside Low Frequency Radio Telescope on a NASA Commercial Lander



Team: S. Bale (UC Berkeley), J. Burns (Colorado), R. Bradley (NRAO).

Status: Landing in Schrödinger basin on lunar farside in 2025.

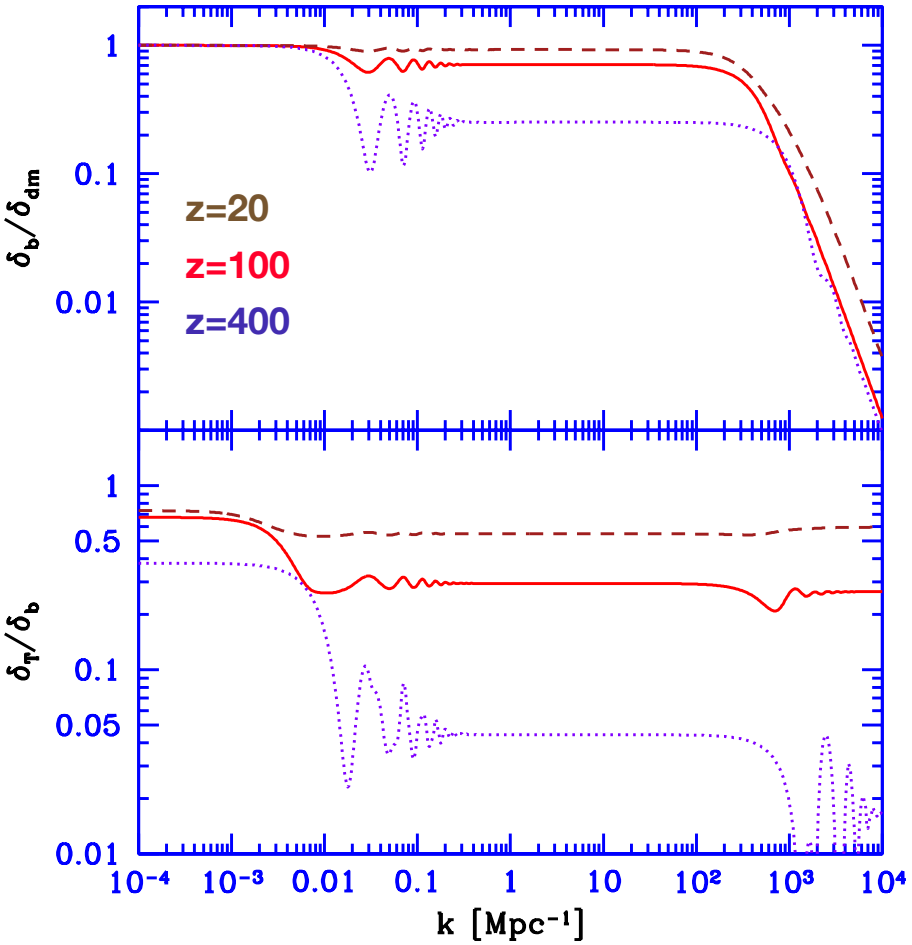


FARSIDE

2030+

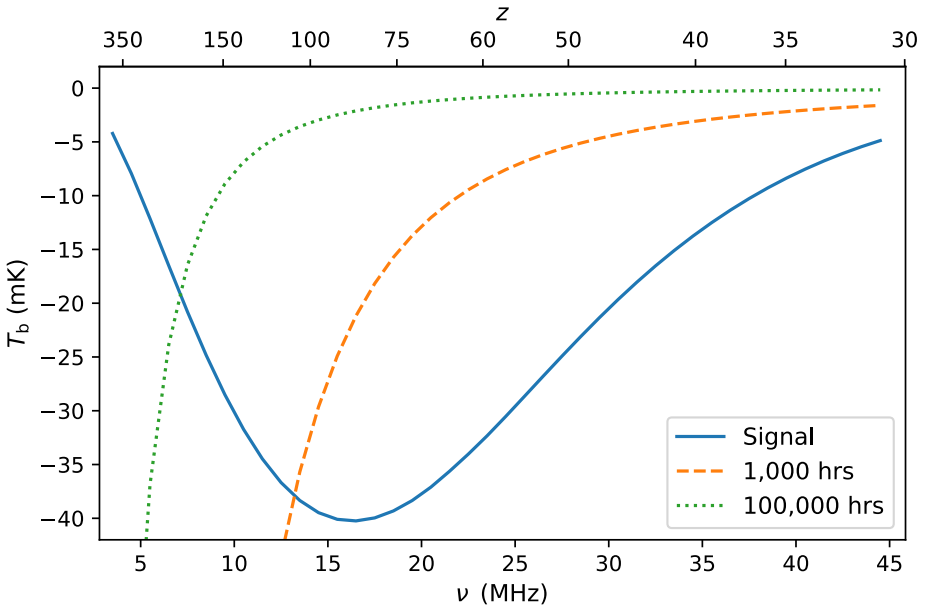
Principal Investigator: Jack Burns, University of Colorado
Deputy P.I.: Gregg Hallinan, Caltech
Design Lead: Lawrence Teitelbaum, JPL

The Moon: The Dark Ages



Naoz & RB 2005
RB & Loeb 2005

Baryon Infall



Mondal & RB 2022

Summary

- 21-cm Cosmology
  - Cosmic Reionization
  - Cosmic Dawn (first stars): Lyα, X-rays
  - Dark ages

- Theory
  - b-DM interaction or enhanced radio
  - Lyα heating
  - Baryon infall

- Observations
  - EDGES & SARAS, LOFAR & HERA
  - Future: High-z HERA, NenuFAR, SKA, Lunar telescopes