Title: First constraints on the high redshift 21-cm power spectrum from HERA

Speakers: Jordan Mirocha

Series: Cosmology & Gravitation

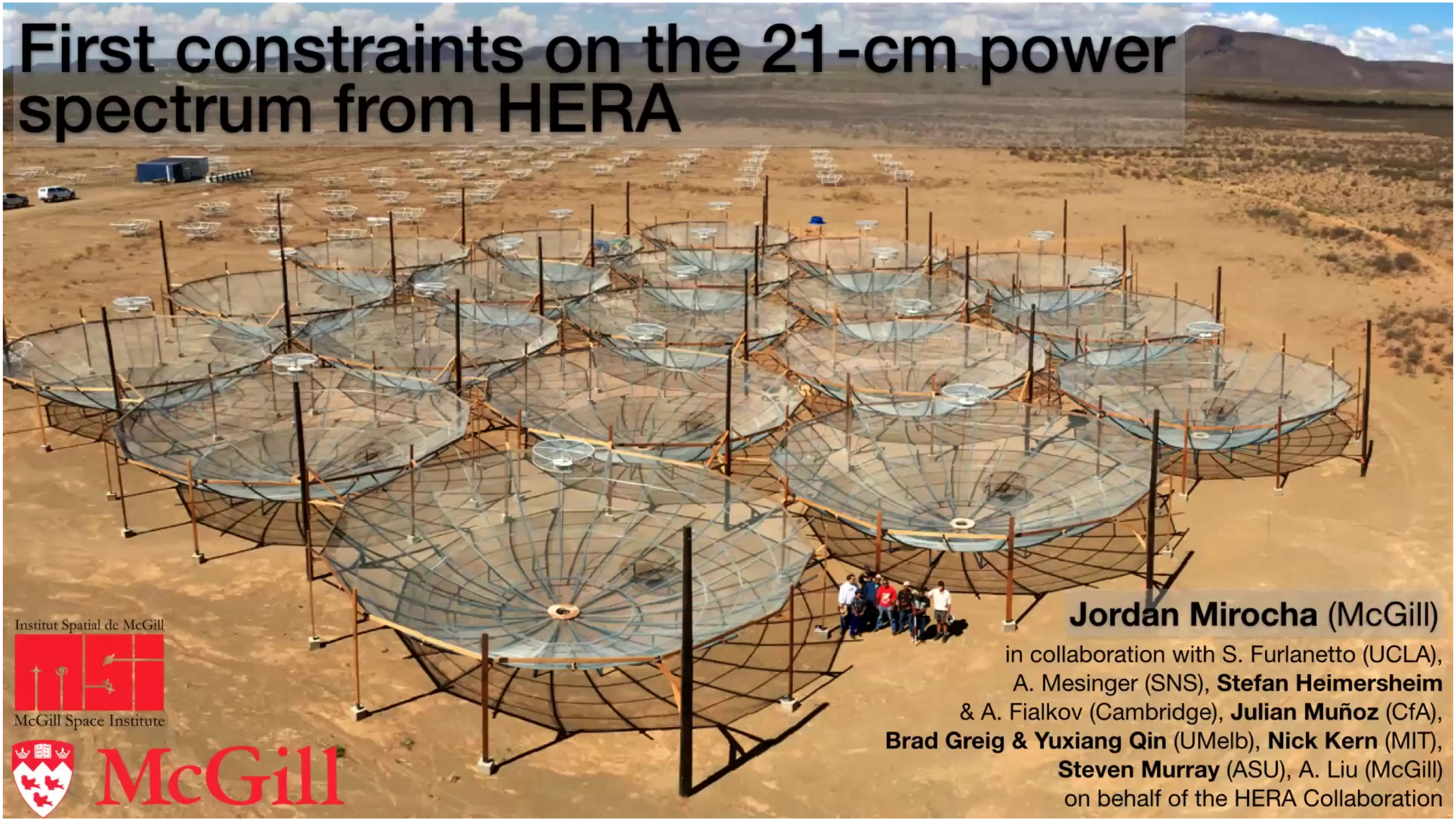
Date: March 01, 2022 - 11:00 AM

URL: https://pirsa.org/22030094

Abstract: 21-cm emission from neutral hydrogen atoms provides a unique window into galaxy formation and cosmology in the first billion years of cosmic history. As the first galaxies form after the Big Bang, they generate intense ultraviolet and X-ray radiation fields, which ionize and heat their otherwise neutral surroundings. The resulting modulations in the brightness of 21-cm emission relative to the background can be detected in principle by a single, well-calibrated dipole receiver, as features in the sky-averaged radio spectrum below ~200 MHz. Spatial fluctuations in the 21-cm background are expected also, and can in principle be detected statistically with the current generation of interferometers. In just the last few years, enormous progress has been made on both fronts. The sky-averaged 78 MHz feature reported by the EDGES collaboration in 2018 caused a flurry of activity, largely aimed at explaining its anomalous amplitude. Since then, the MWA, LOFAR, and HERA have all reported upper limits on the 21-cm power spectrum. In this talk, I will focus in particular on the first limits from HERA -- the most stringent limits reported to date -- and describe their implications for galaxy formation and cosmology. I will also discuss the ongoing EDGES controversy, and how JWST and SPHEREx can provide independent tests of astrophysical scenarios that produce EDGES-like 21-cm absorption troughs at frequencies below ~100 MHz.

Zoom Link: https://pitp.zoom.us/j/92616379096?pwd=eXNXQ0d5Z3IrUFdrY2hvY2daU2tMQT09

First constraints on the 21-cm power spectrum from HERA



Jordan Mirocha (McGill)

in collaboration with S. Furlanetto (UCLA), A. Mesinger (SNS), **Stefan Heimersheim** & A. Fialkov (Cambridge), **Julian Muñoz** (CfA), **Brad Greig & Yuxiang Qin** (UMelb), **Nick Kern** (MIT), **Steven Murray** (ASU), A. Liu (McGill) on behalf of the HERA Collaboration

Institut Spatial de McGill
McGill Space Institute
McGill

Outline

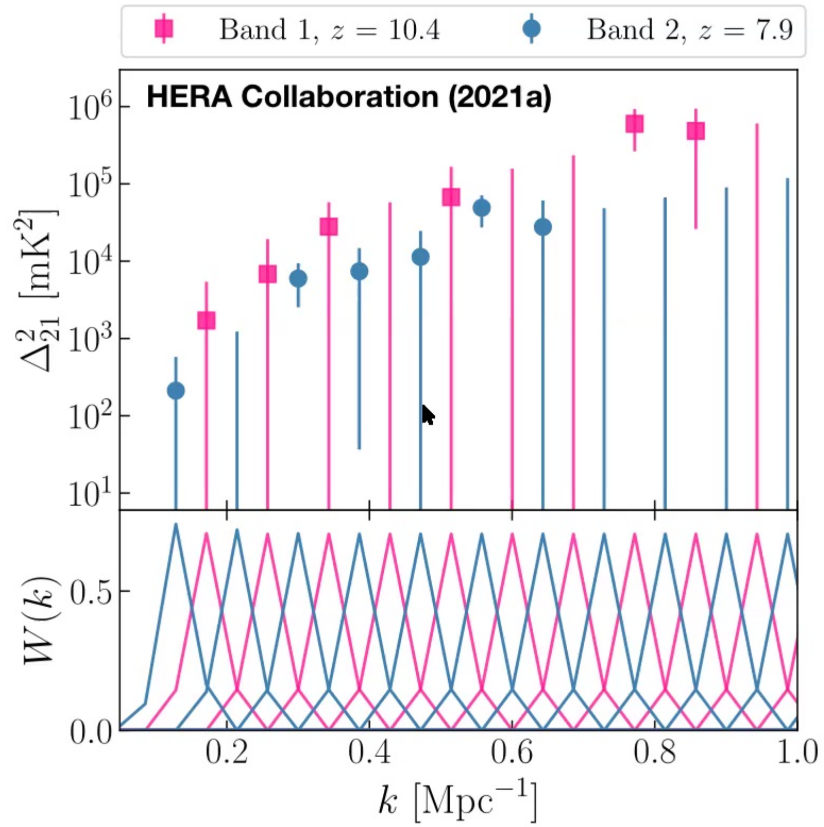
- What do HERA's first limits mean for galaxy formation and reionization?

  - Larger context: 21-cm intensity mapping, galaxy formation, reionization.

  - Recent updates to theoretical predictions.

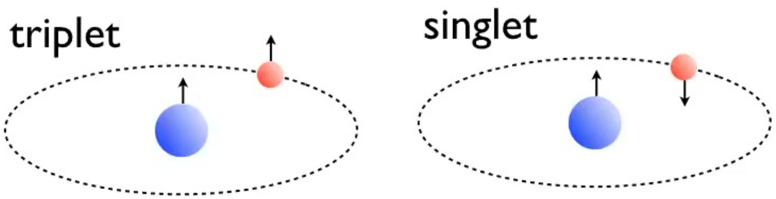
  - HERA's limits + interpretation.

  - Looking forward.

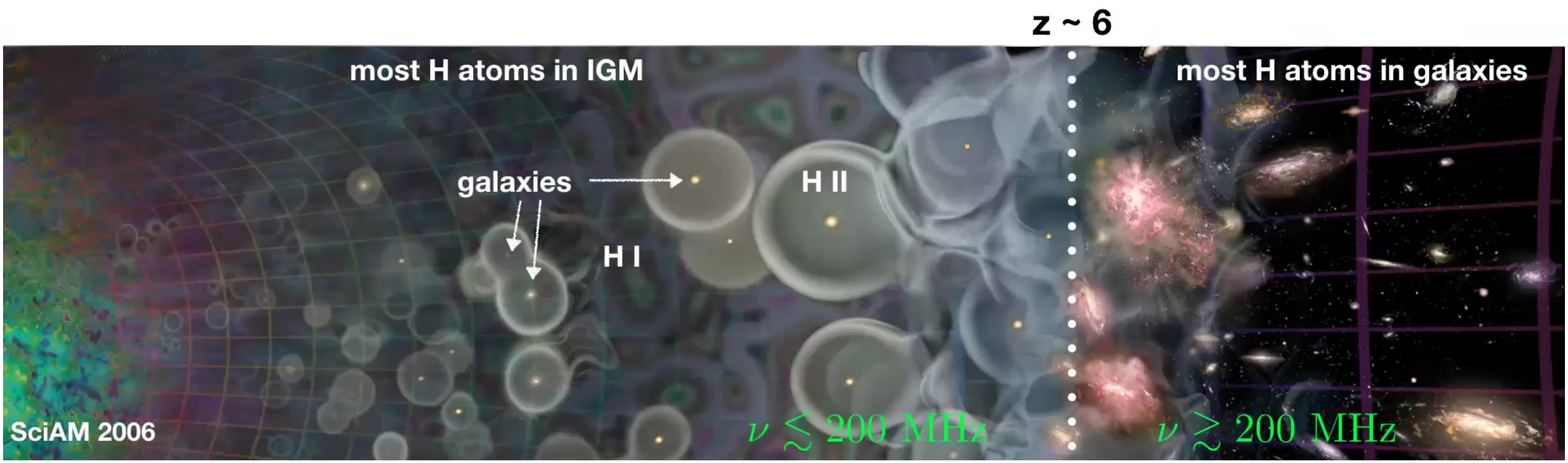


What is 21-cm cosmology?

Effort to constrain cosmology/astrophysics via observations of emission (or absorption) from H atoms:

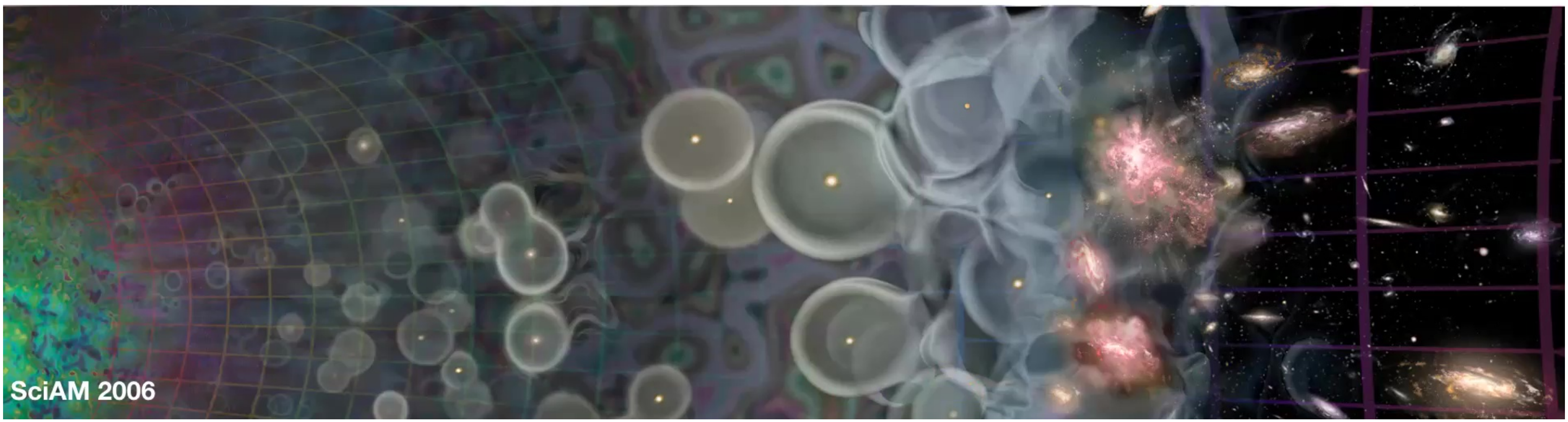


$$\nu_{\rm obs} = 1.4\ {\rm GHz}/(1+{\rm z})$$
$$\lambda_{\rm obs} = 21\ {\rm cm}(1+{\rm z})$$



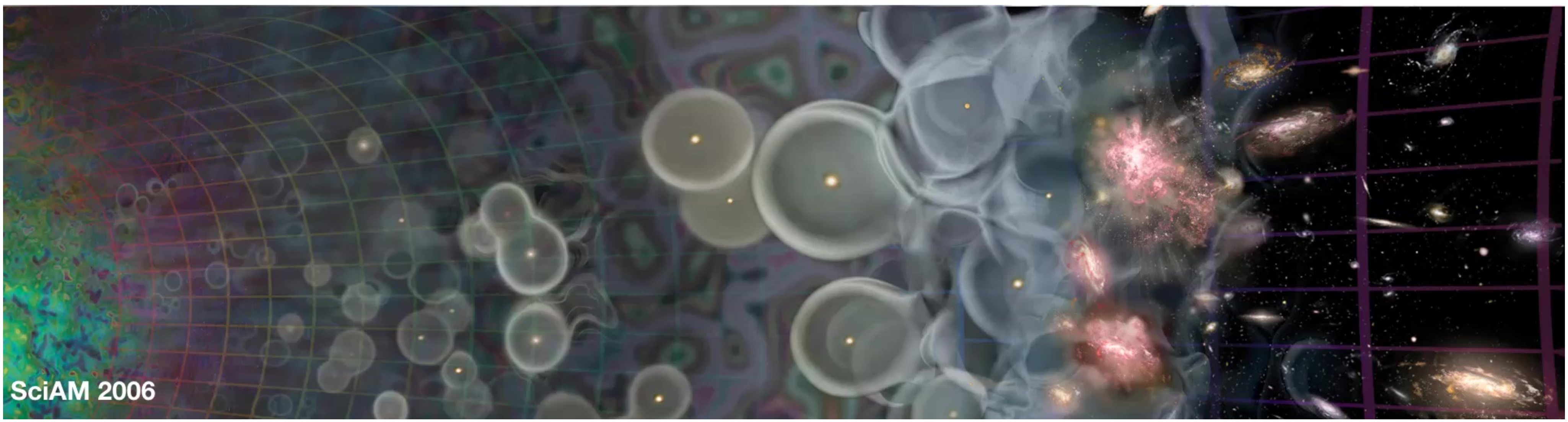
What's the point?

- What were the first stars like? BHs? Is galaxy formation self regulating? Reionization?



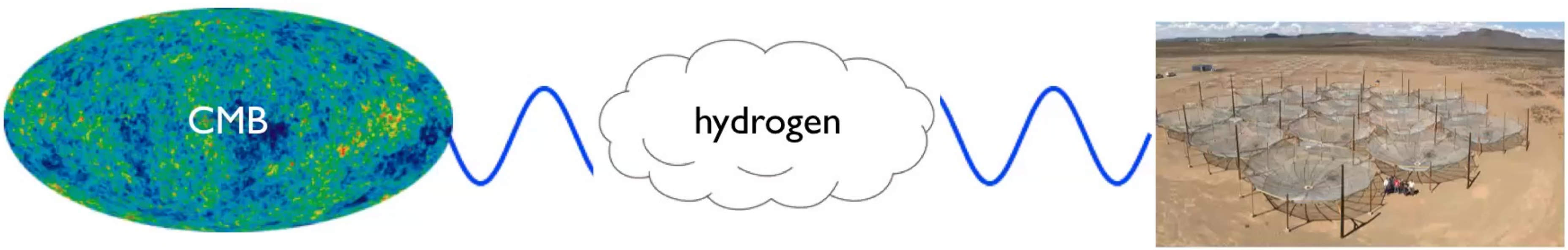
What's the point?

- What were the first stars like? BHs? Is galaxy formation self regulating? Reionization?
- D*irect* probe of ionization history, can then eliminate nuisance from in CMB analyses.
- Thermometer too, test of 'exotic' heating/cooling (DM annihilation/decay, RJ tail of CMB).



Key Physics

T_γ T_S δT_b



or CMB+???

e.g., HERA

"Differential brightness temperature":

$$\delta T_b \simeq 27\, \boxed{\overline{x}_{\mathrm{H\,I}}}(1 \boxed{+\,\delta)} \left(\frac{1+z}{10}\right)^{1/2} \left(1 - \frac{T_{\mathrm{CMB}}}{\boxed{T_{\mathrm{S}}}}\right) \text{ mK}$$

e.g., Furlanetto (2006)

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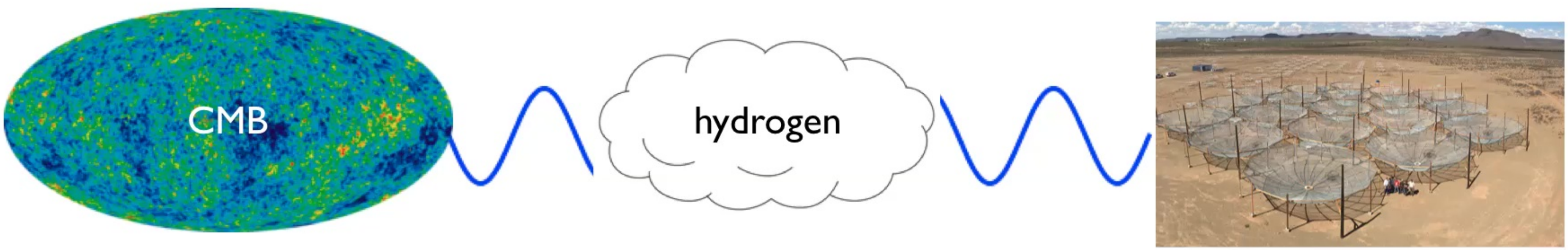

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$$\delta T_b \simeq 27\, \bar{x}_{\rm H\,I}(1+\delta)\left(\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)\ \mathrm{mK}$$

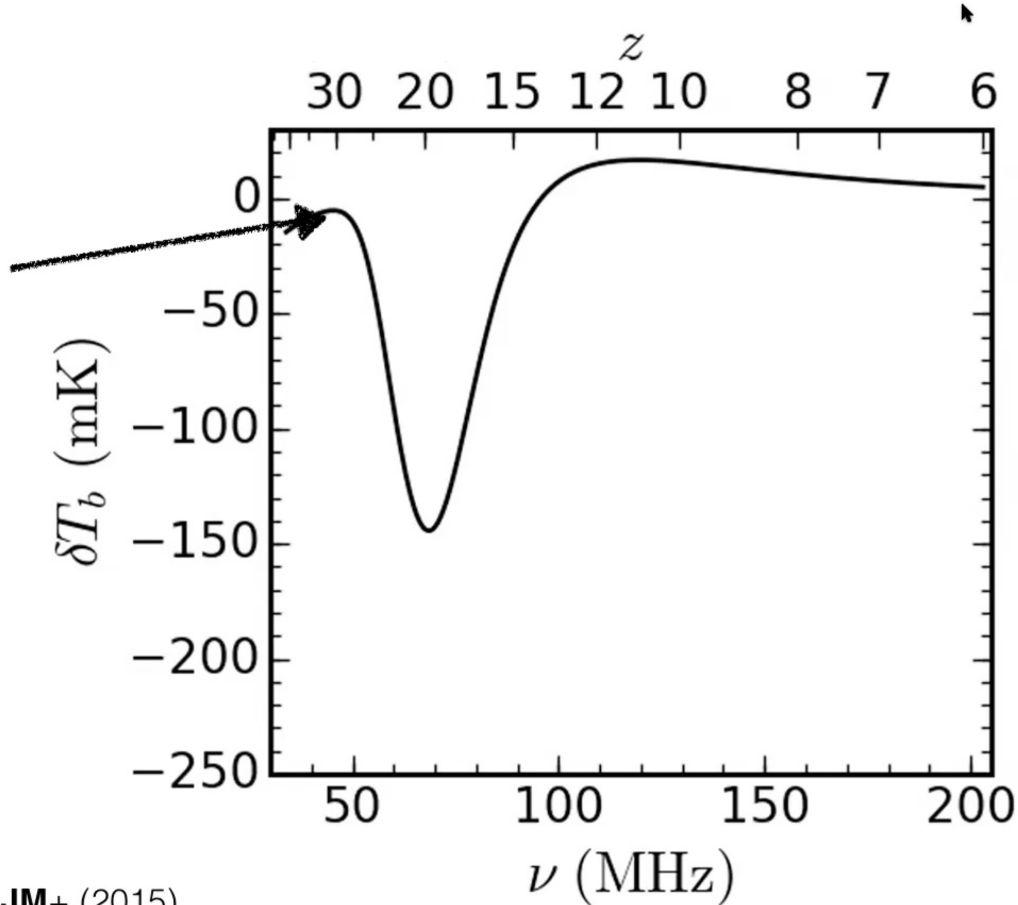
$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\left[-T_{21}/T_{\rm S}\right]$$

$$T_S = T_S(n_{\rm H}, n_e, T_K, T_\gamma, J_\alpha)$$

e.g., Furlanetto (2006)

Sky-averaged 21-cm Signal

- Key cosmic milestones:
  - First stars: Wouthuysen-Field coupling drives T_S to T_K, resulting in absorption signal.



e.g., Shaver+ (1999), Furlanetto (2006), **JM**+ (2015)

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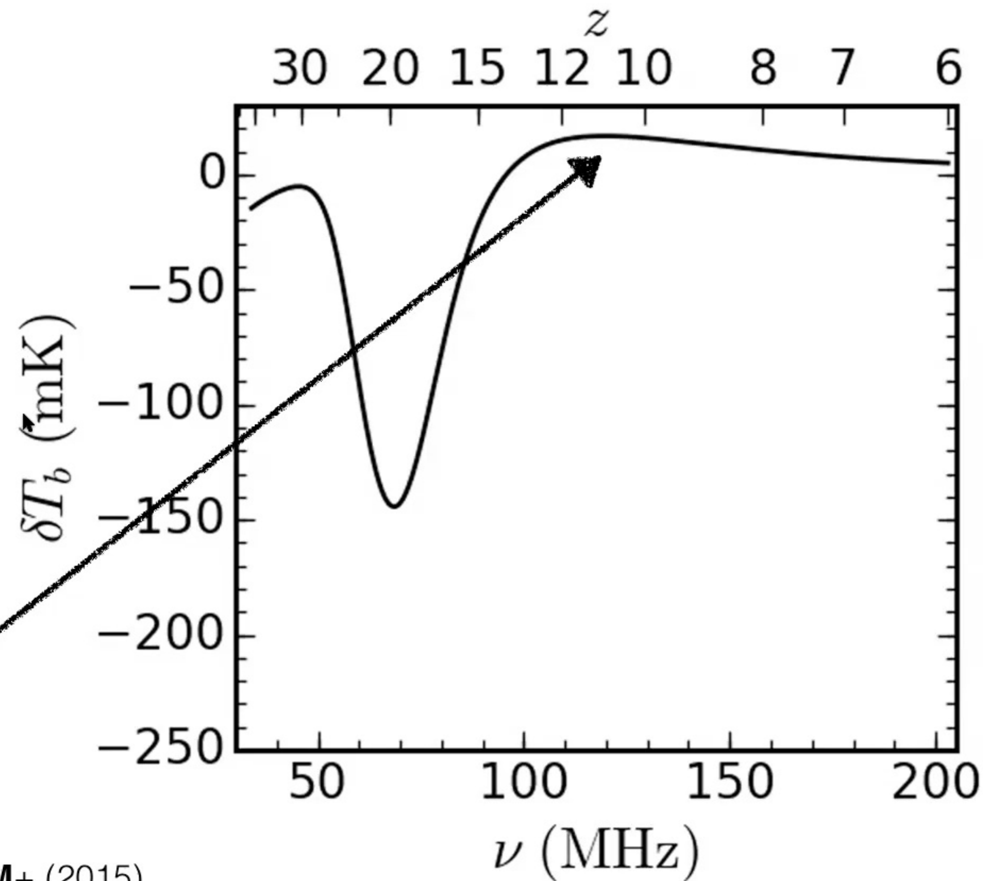

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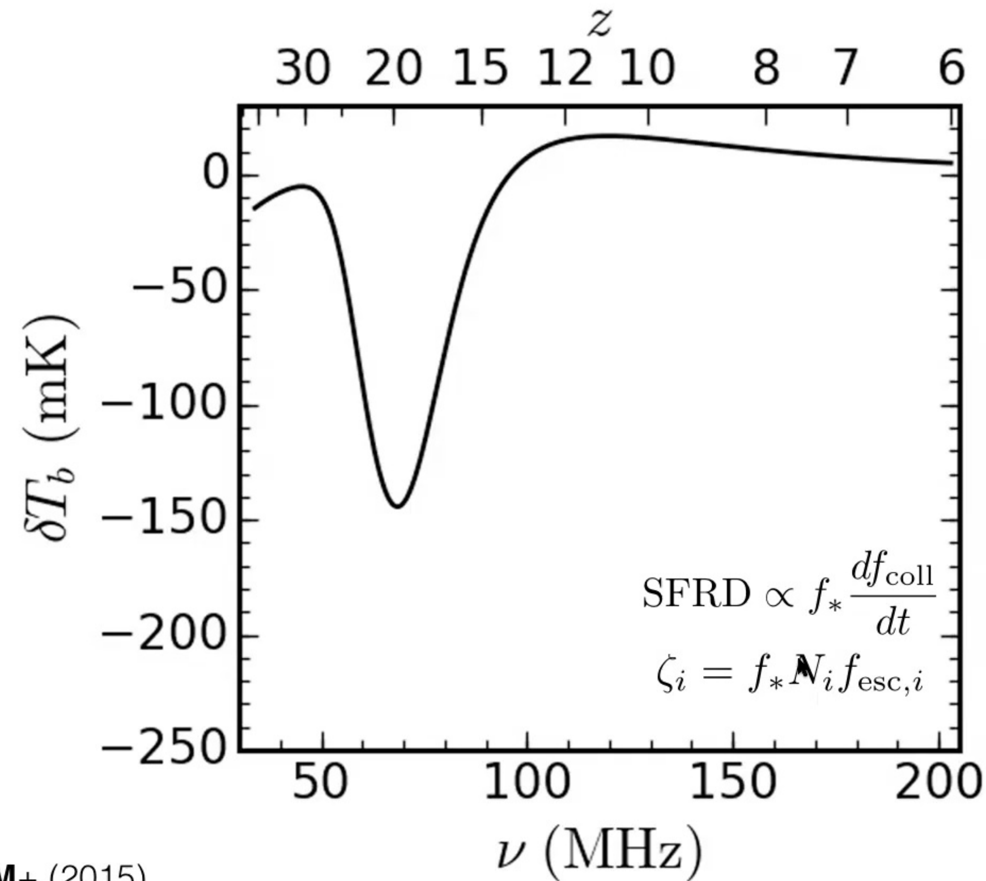

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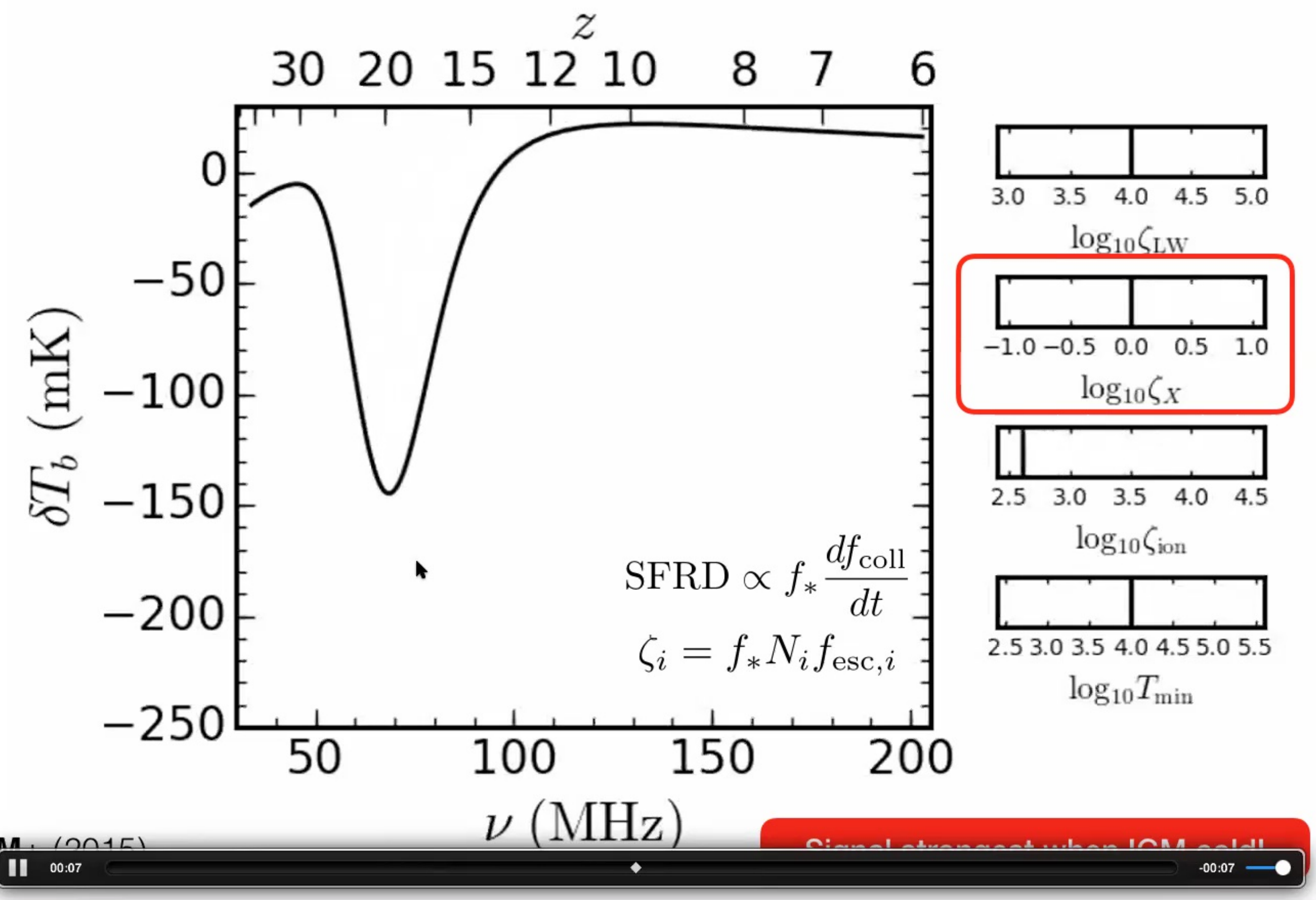
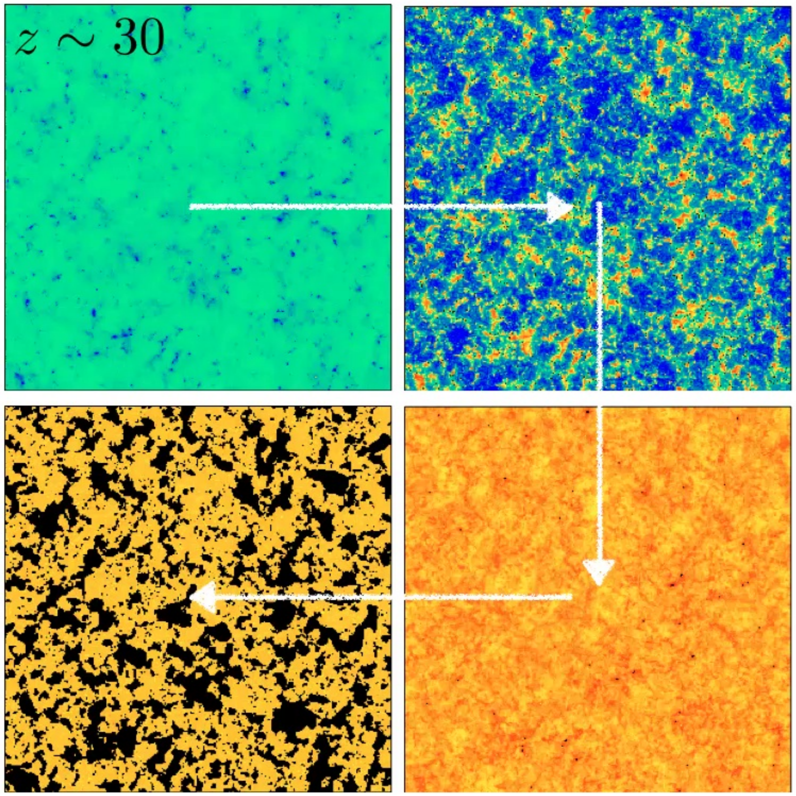


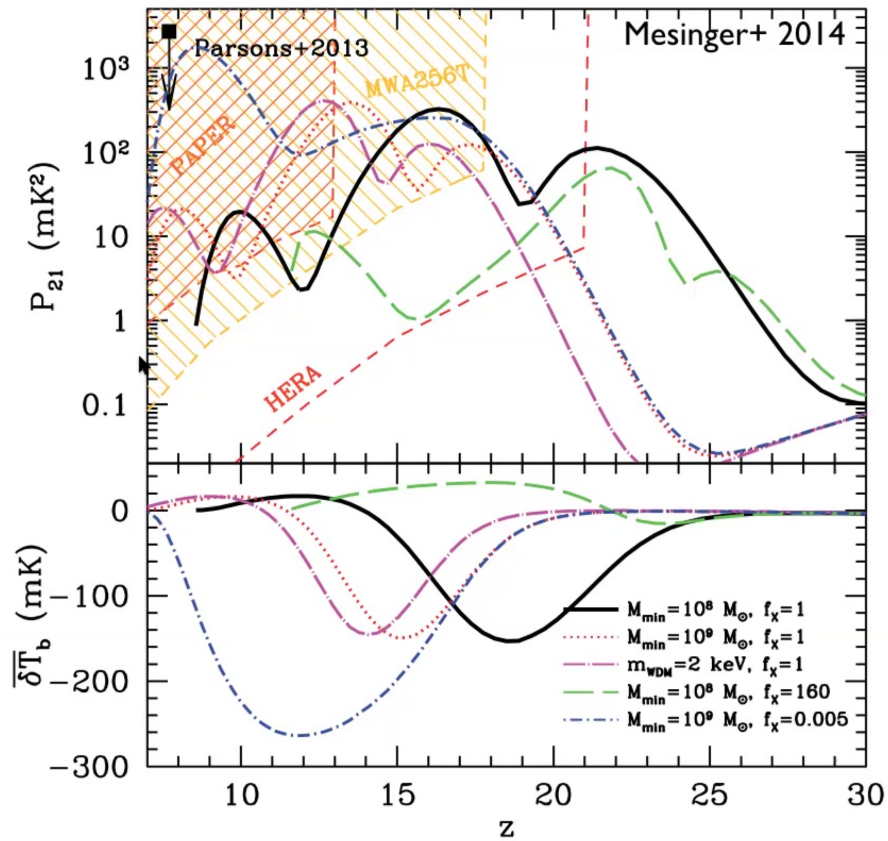
e.g., Shaver+ (1999), Furlanetto (2006), **JM**...

21-cm fluctuations

Heating and ionization drive fluctuations, too!

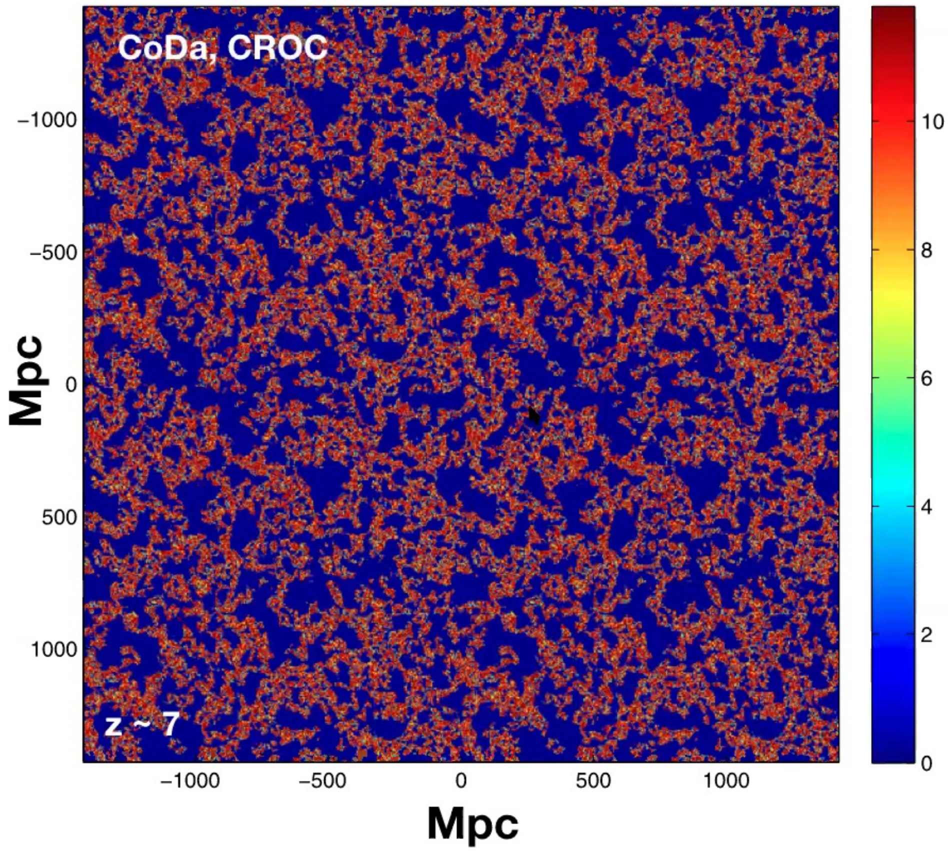


from Mesinger+ 2011; 21cmFAST



Modeling non-trivial in general!

Beardsley+ 2015; 21-cm mock generated w/ 21cmFAST



- Huge dynamic range problem:
  - Star forming regions ~ 10^0 pc
  - Typical bubble sizes ~ 10^7 pc
  - Volume probed by survey ~ $(10^9 \text{ pc})^3$
- Galaxies are messy: gas, dust, star formation, BHs, radiation.
- Non-trivial fraction (~50%?) of photons emitted by galaxies too faint to detect directly.

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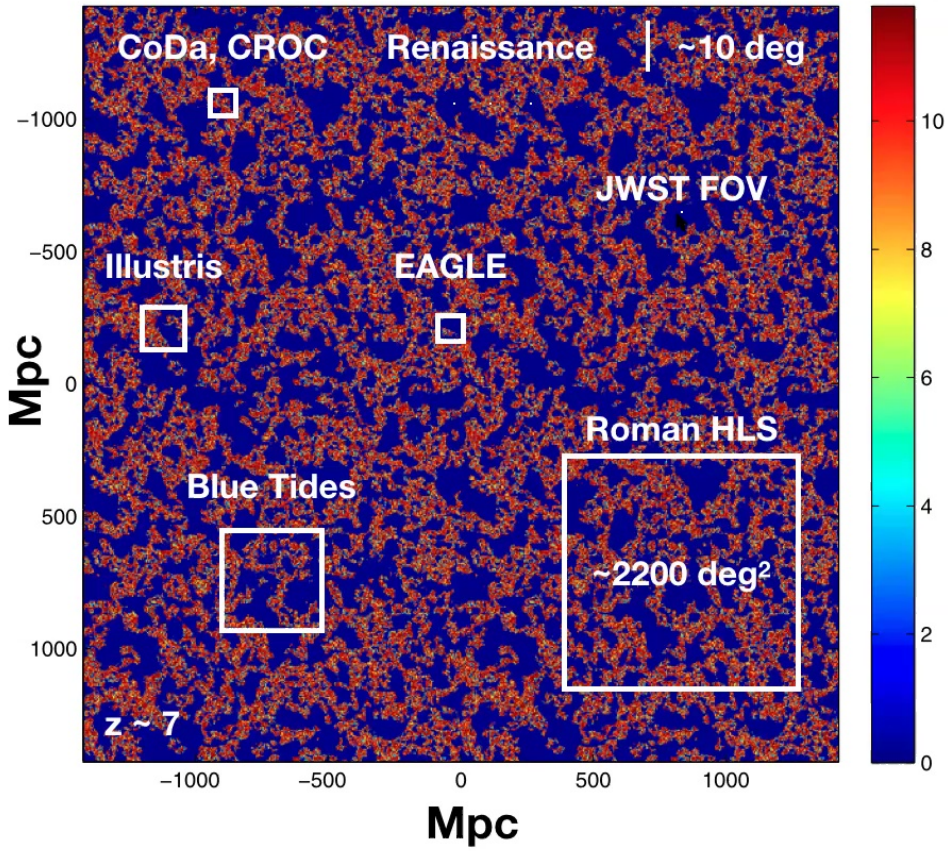

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Diverse landscape of models

Analytic models

FZH04, Barkana & Loeb (2005),
Pritchard & Furlanetto (2007), McQuinn & D'Aloisio (2018),
Raste+ (2018,2020), Schneider, Giri, & **JM** (2021), **JM**+ (2022)

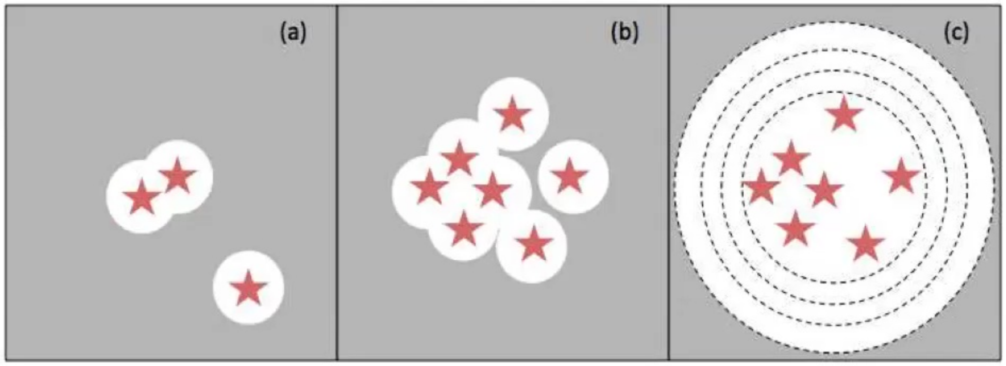
Excursion set + pert. theory for density and vel.

Mesinger & Furlanetto 2007, Mesinger+ (2011),
Santos+ (2011), Fialkov+ (2013)

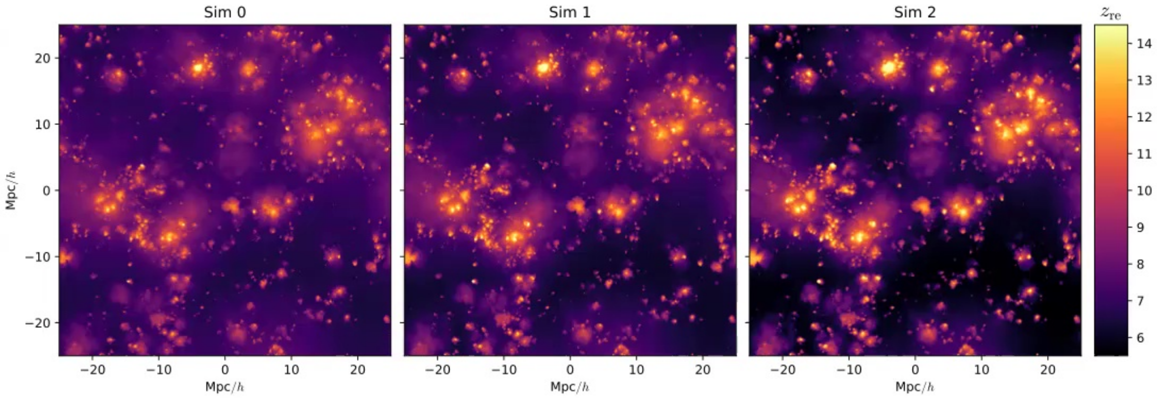
Excursion set on N-body simulations

Mutch+ (2016), Hutter+ (2018), Mondal+, Giri+, **JM**+ (2021)

The excursion set approach from Loeb & Furlanetto (2013)



also: Bond+ (1991), Furlanetto, Zaldarriaga, & Hernquist (2004; FZH04)



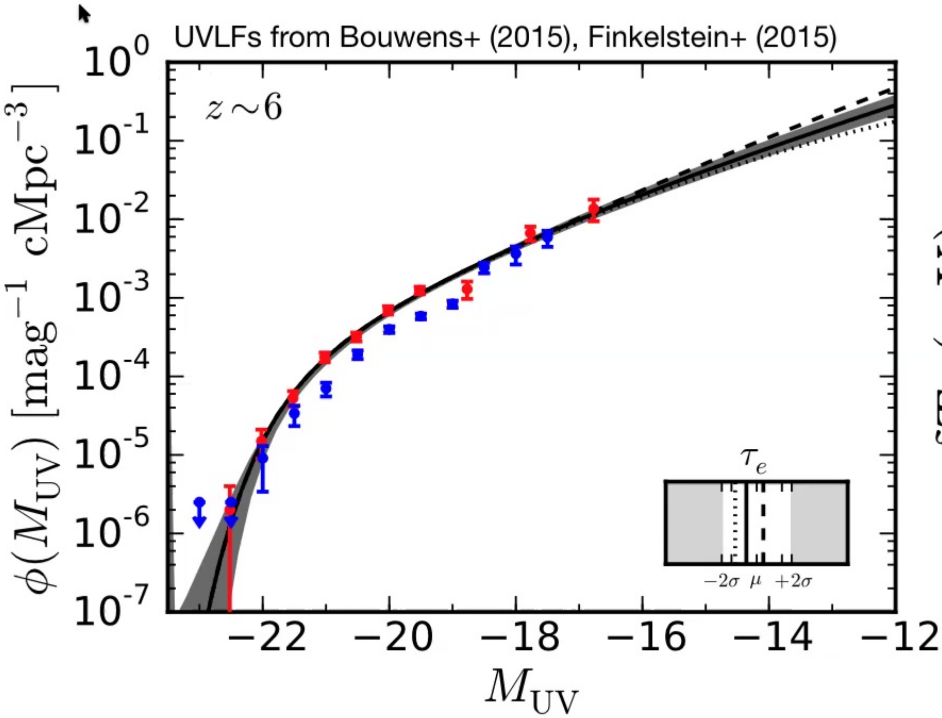
Models calibrated to radiative transfer sims

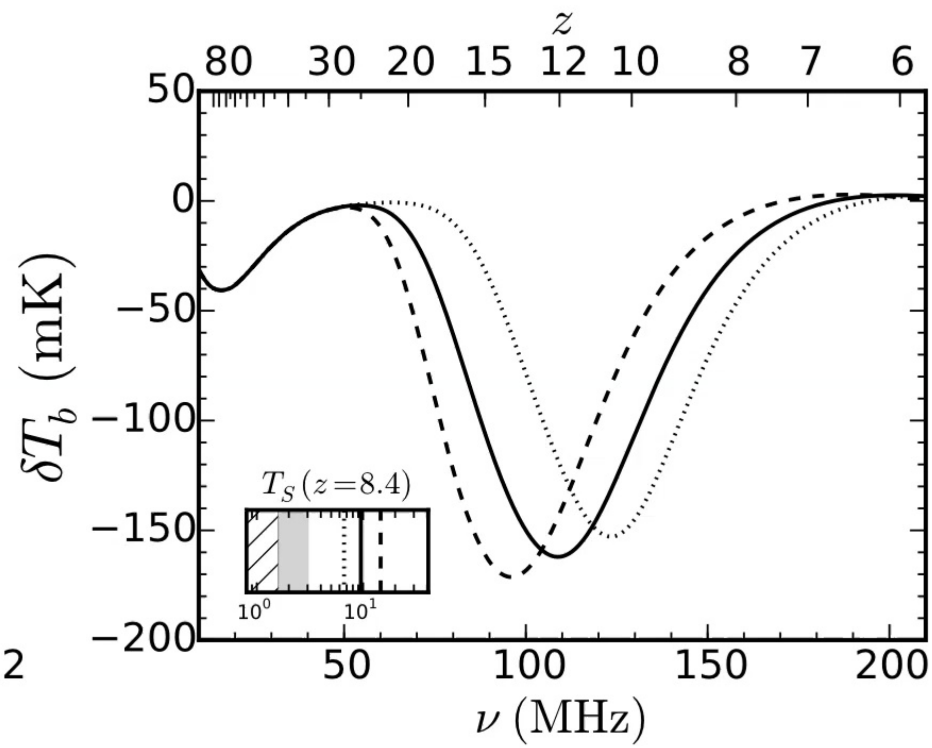
Battaglia+ (2013), Trac+ (2109.10375; left)

1-D RT "painted" onto N-body simulations

Thomas & Zaroubi (2009), Mondal+

Semi-empirical predictions

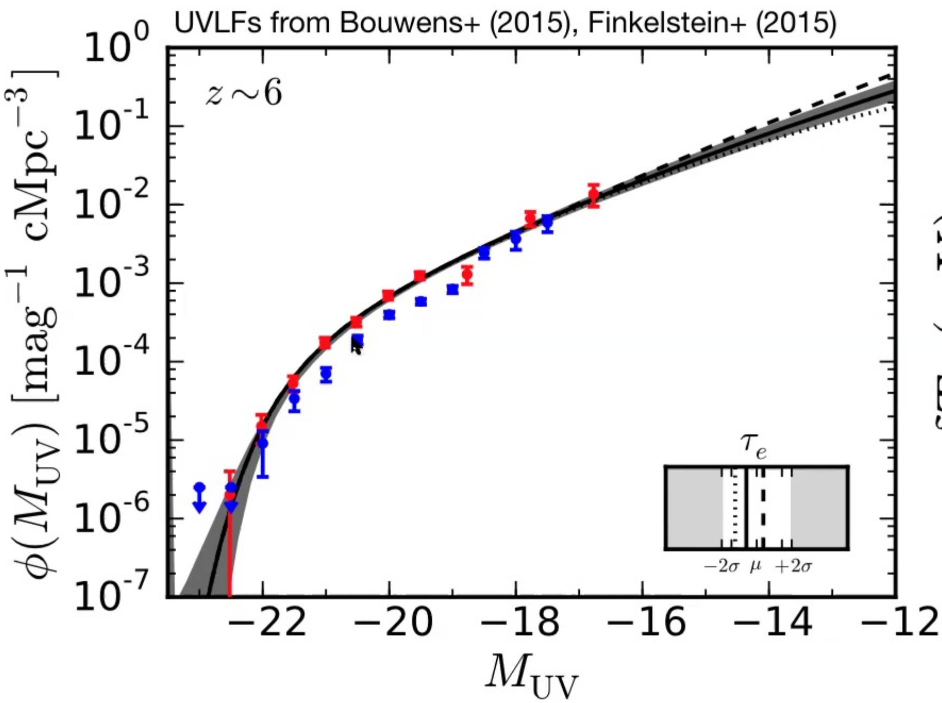


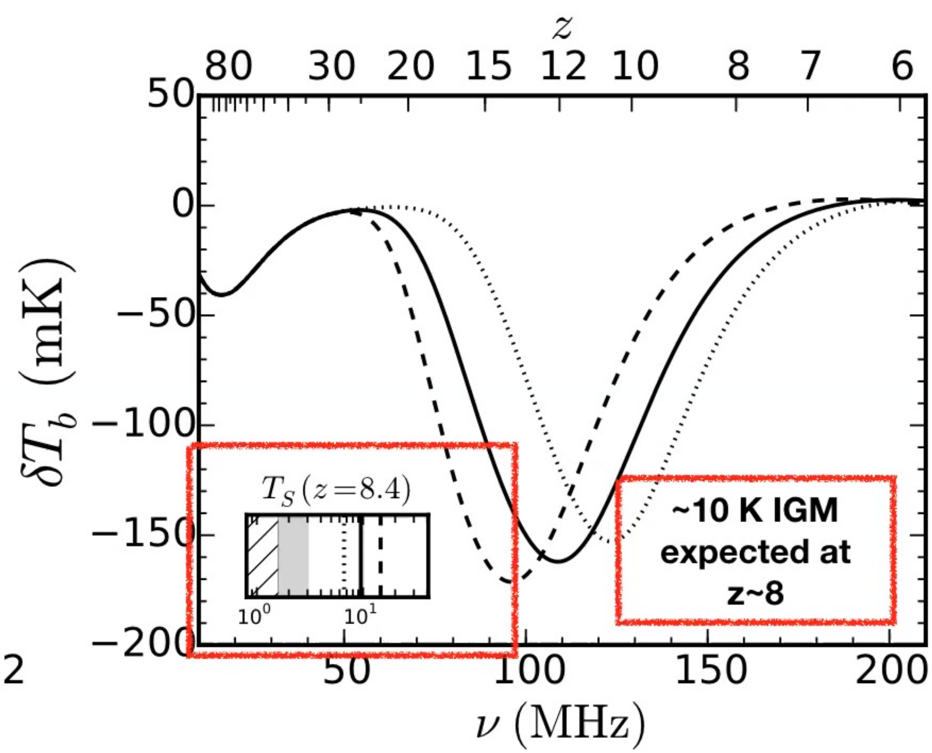


Star formation inefficient in low-mass halos, drives later heating and ionization than earlier models.

from **JM**, Furlanetto, & Sun (2017)
w/ `ARES` code (**JM** 2014)

Semi-empirical predictions





Star formation inefficient in low-mass halos, drives later heating and ionization than earlier models.

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Semi-Empirical Predictions

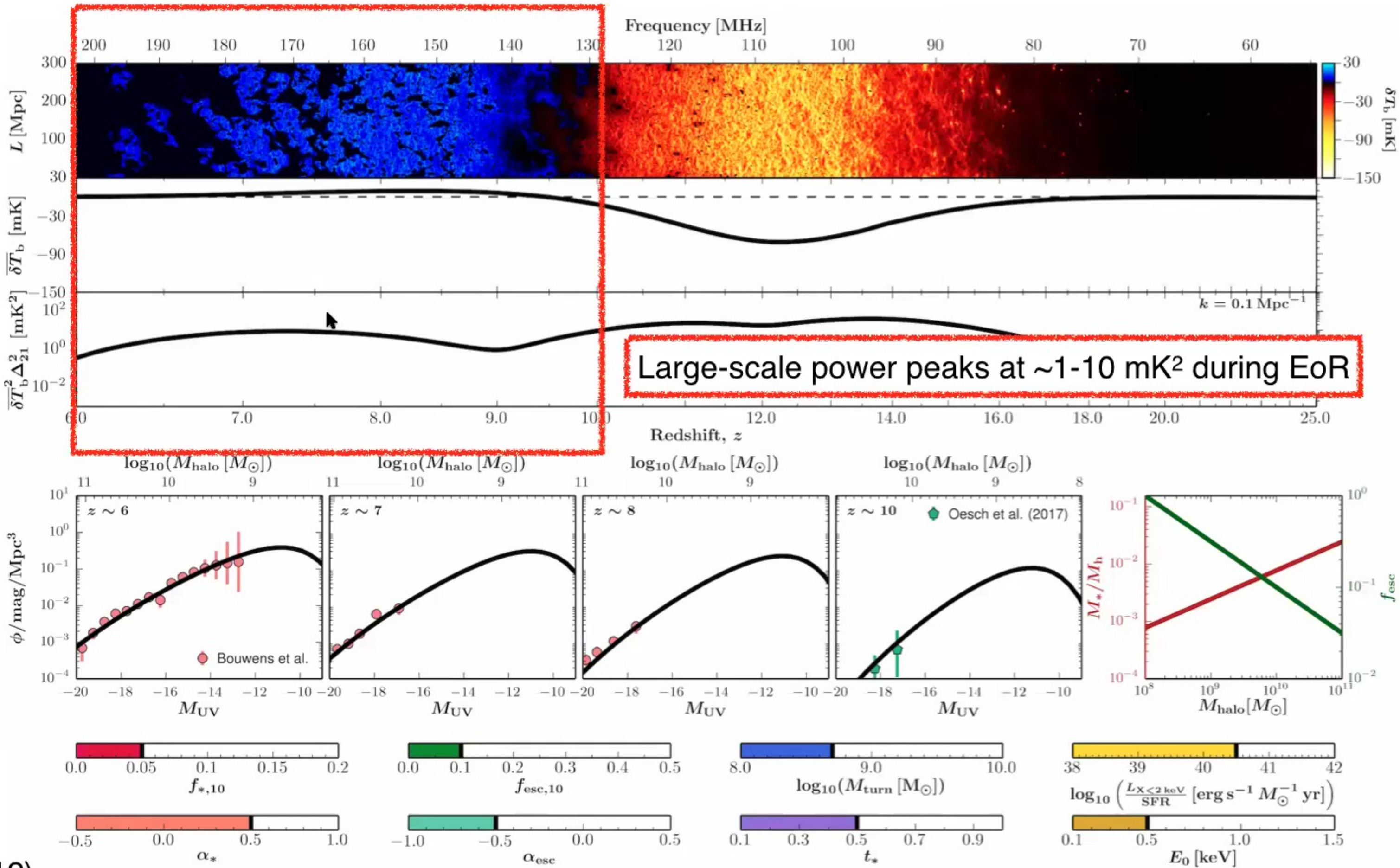
light cone

global signal

power spectrum

UVLFs

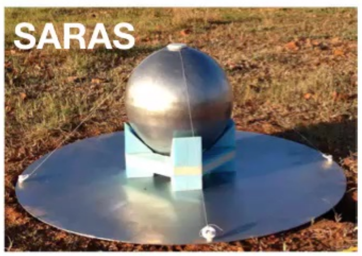
parameters



from **Park+** (2019)

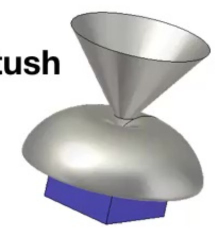
Diverse Landscape of Experiments

global signal

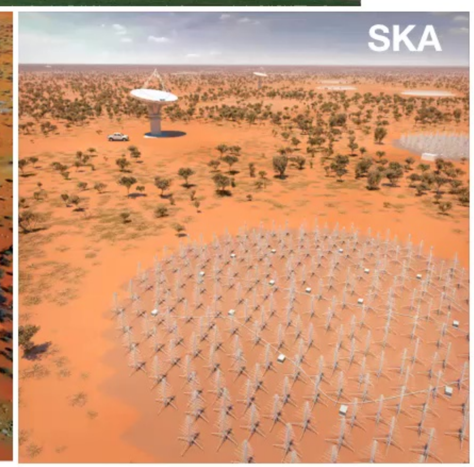


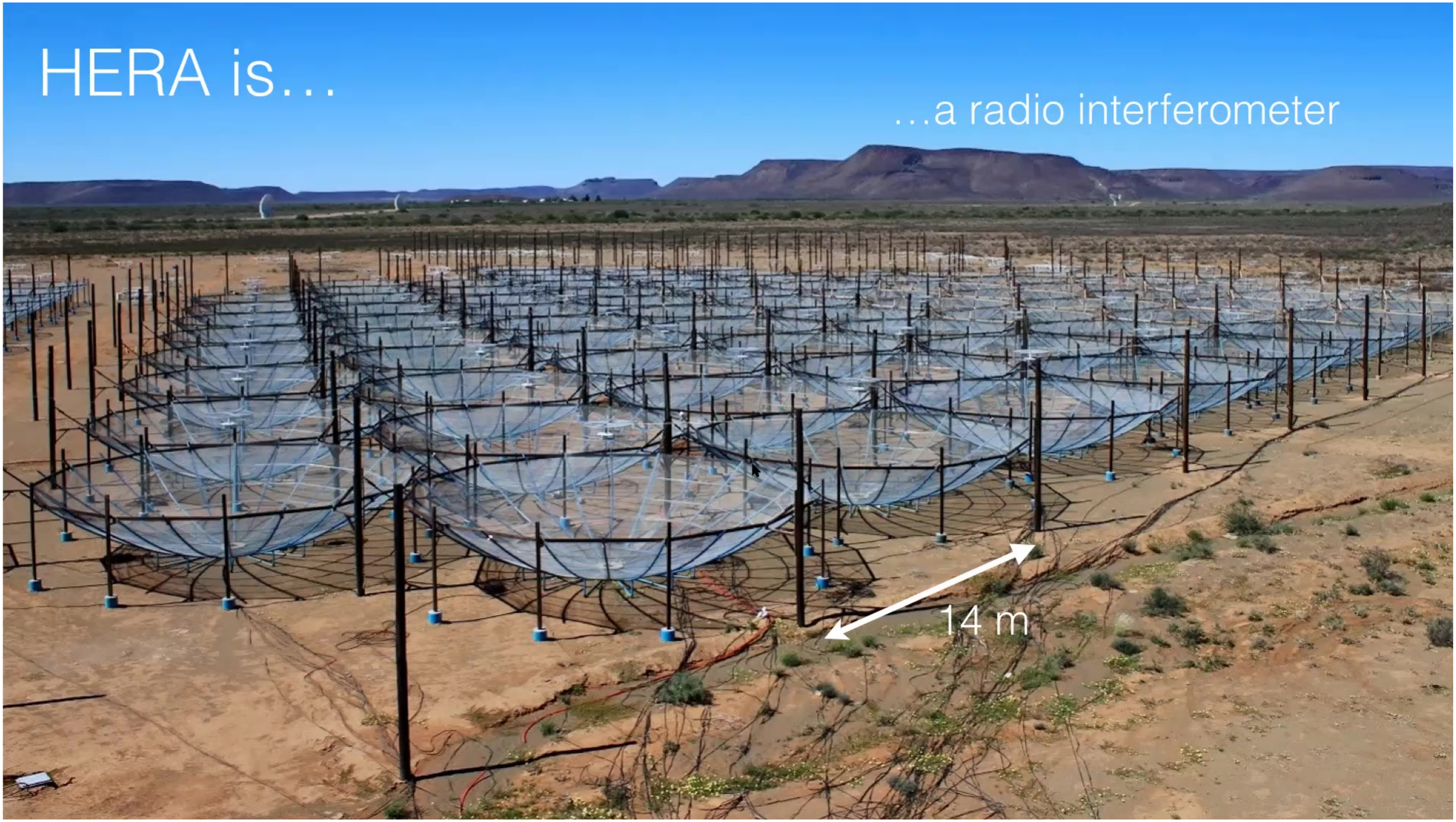
REACH

Pratush



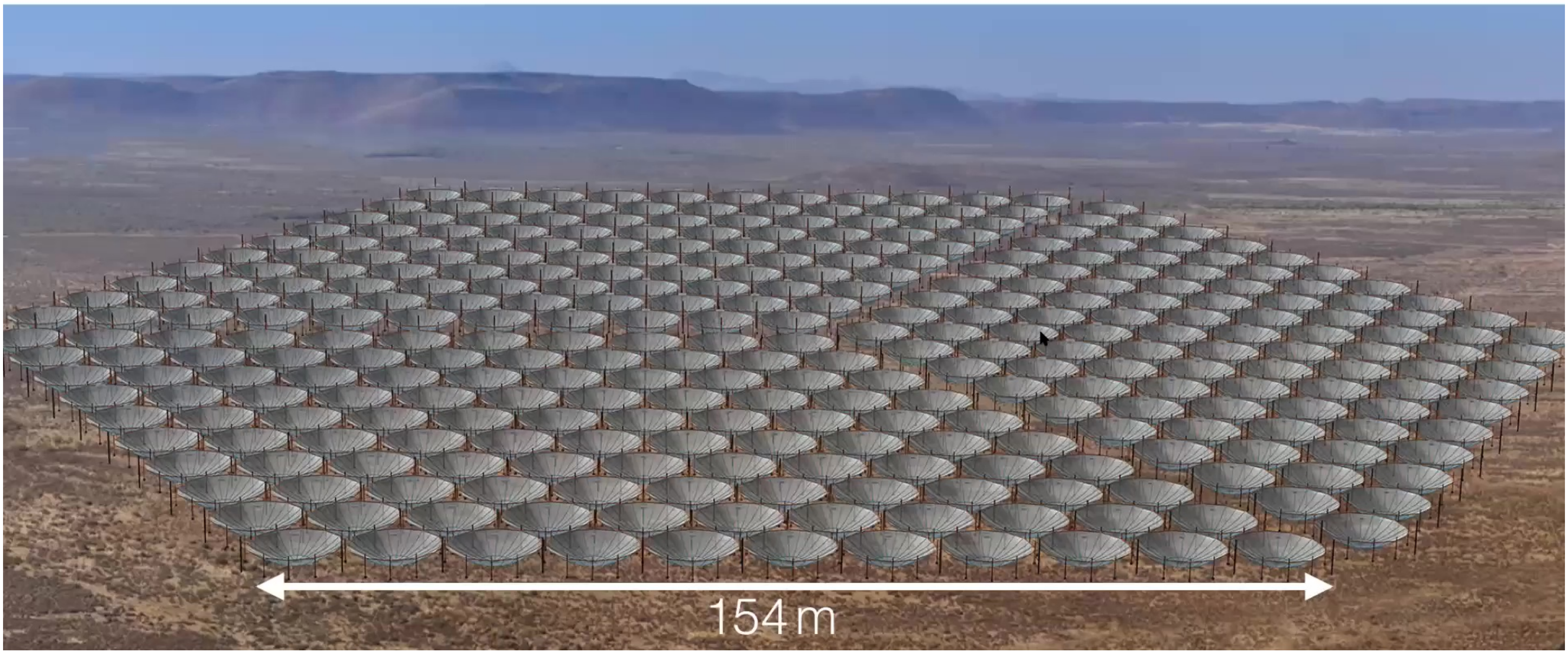
power spectrum & imaging



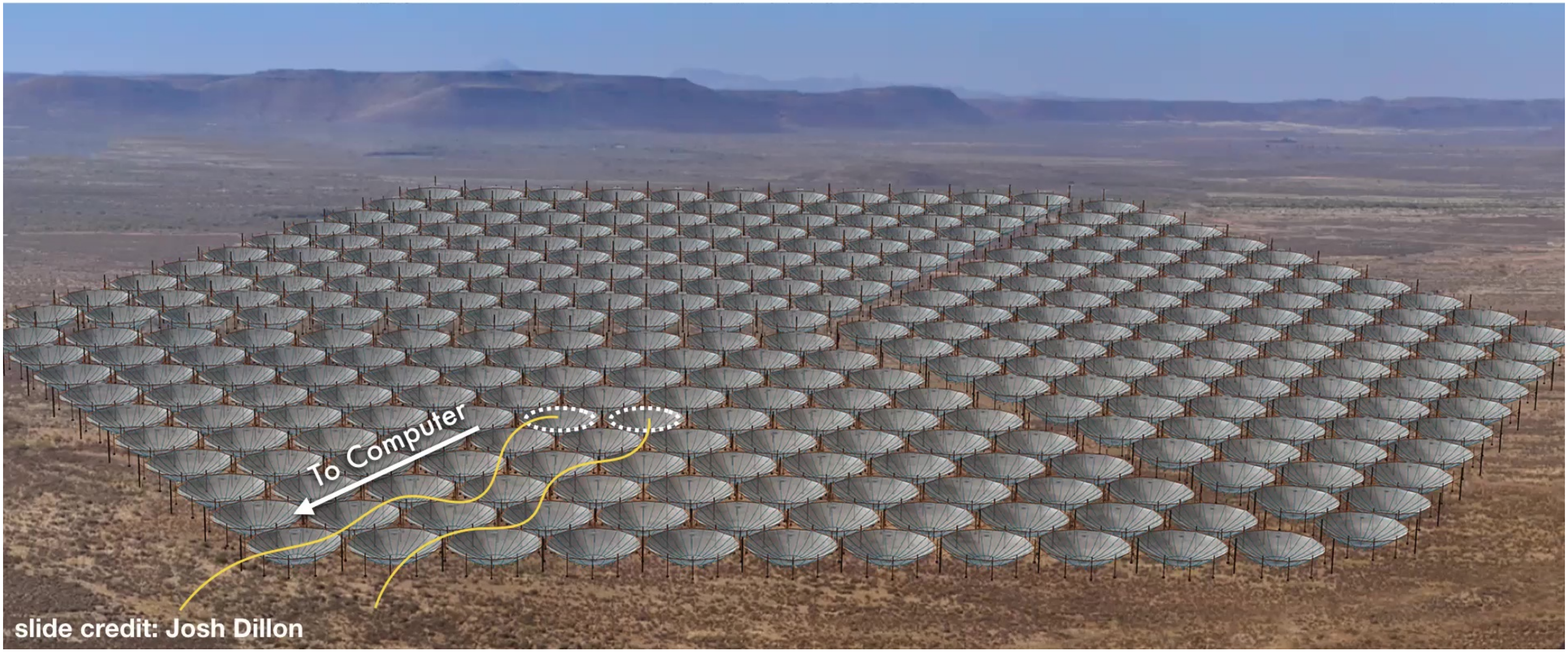

HERA is…
…a radio interferometer
14 m


HERA is…
…a drift-scan telescope that stares at zenith
No moving parts!

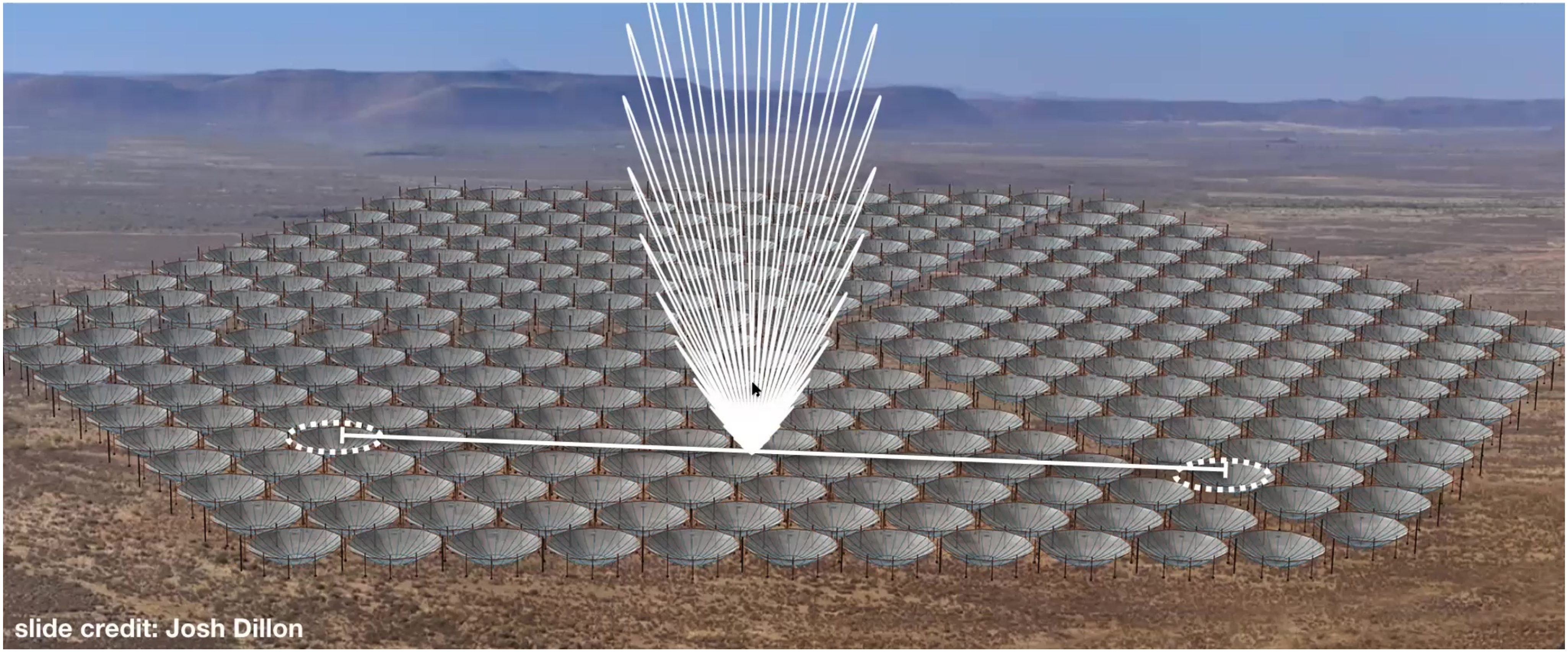
HERA will have 350 elements when complete!



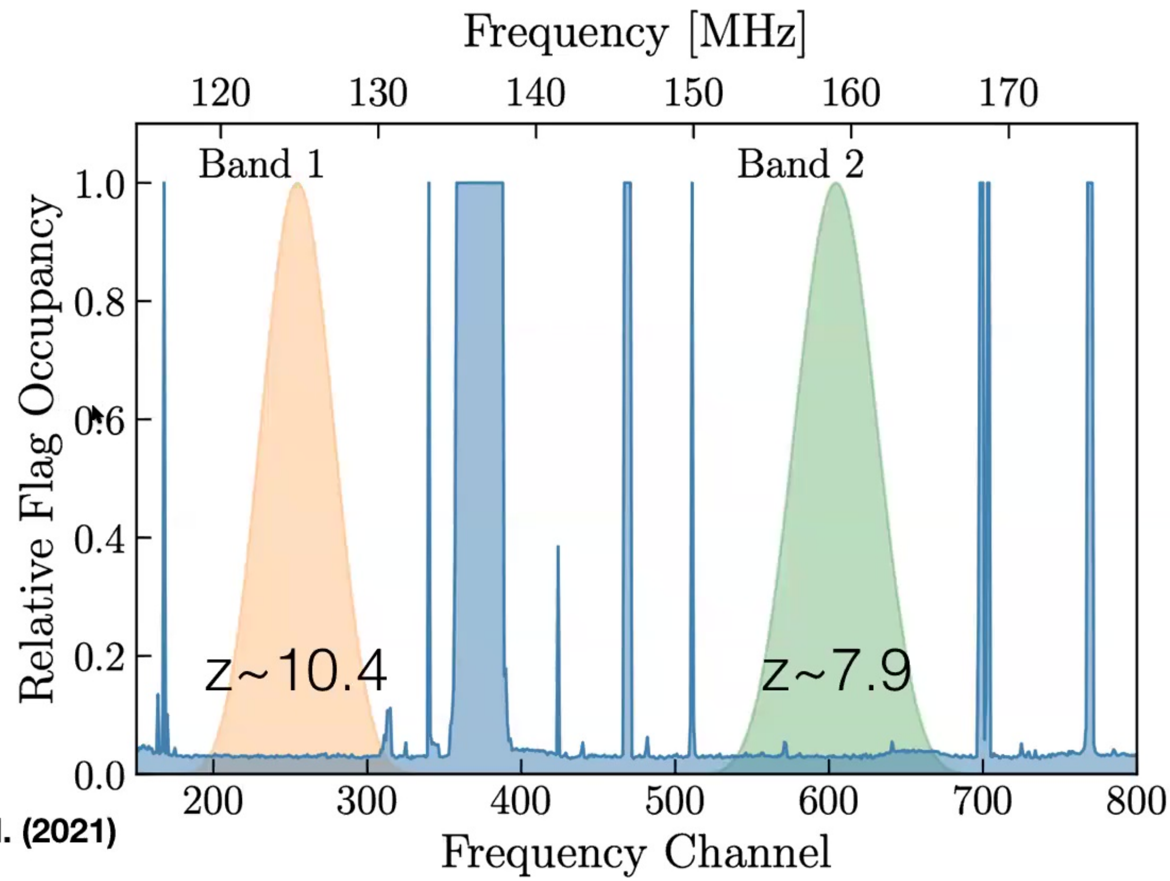
Signals from each pair of antennas are combined



Long baselines probe short wavelength modes

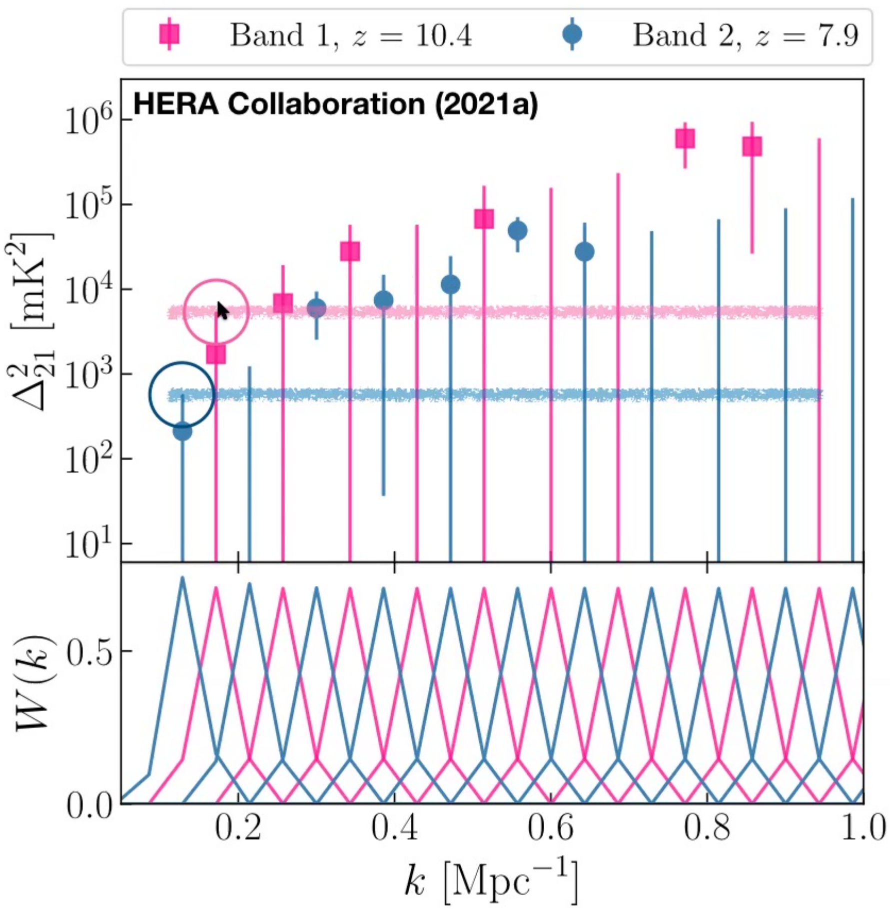


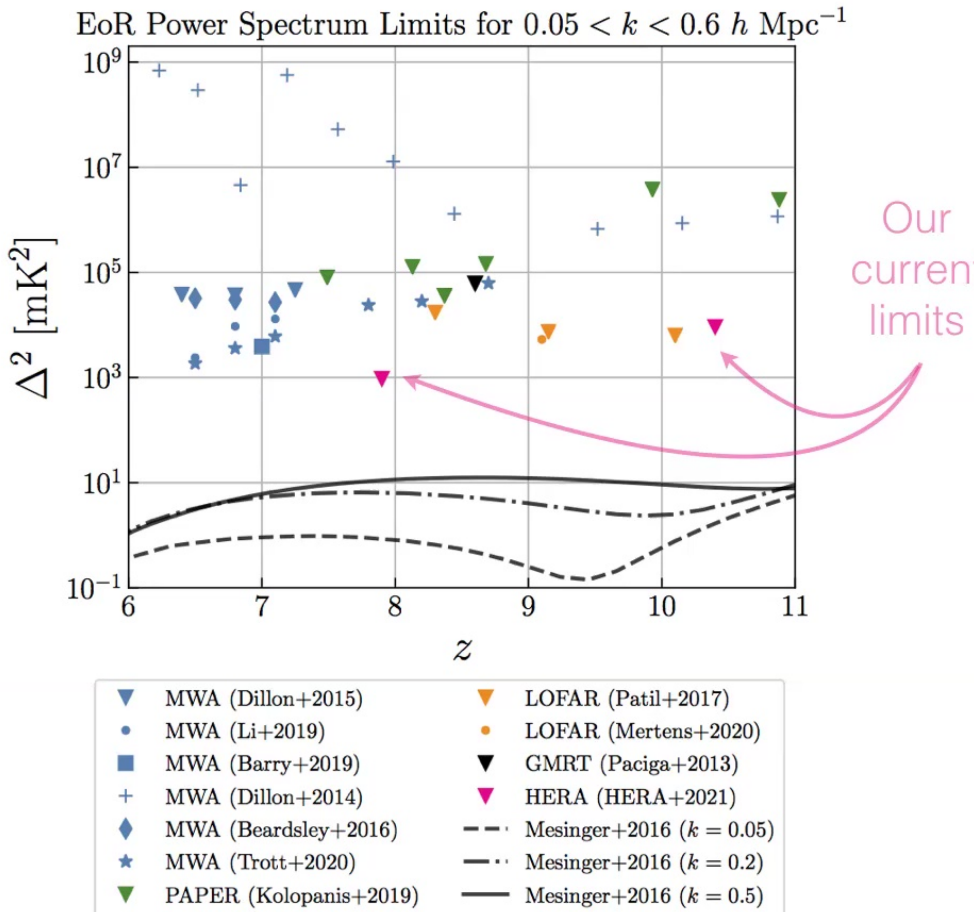
Nor is it the full frequency band



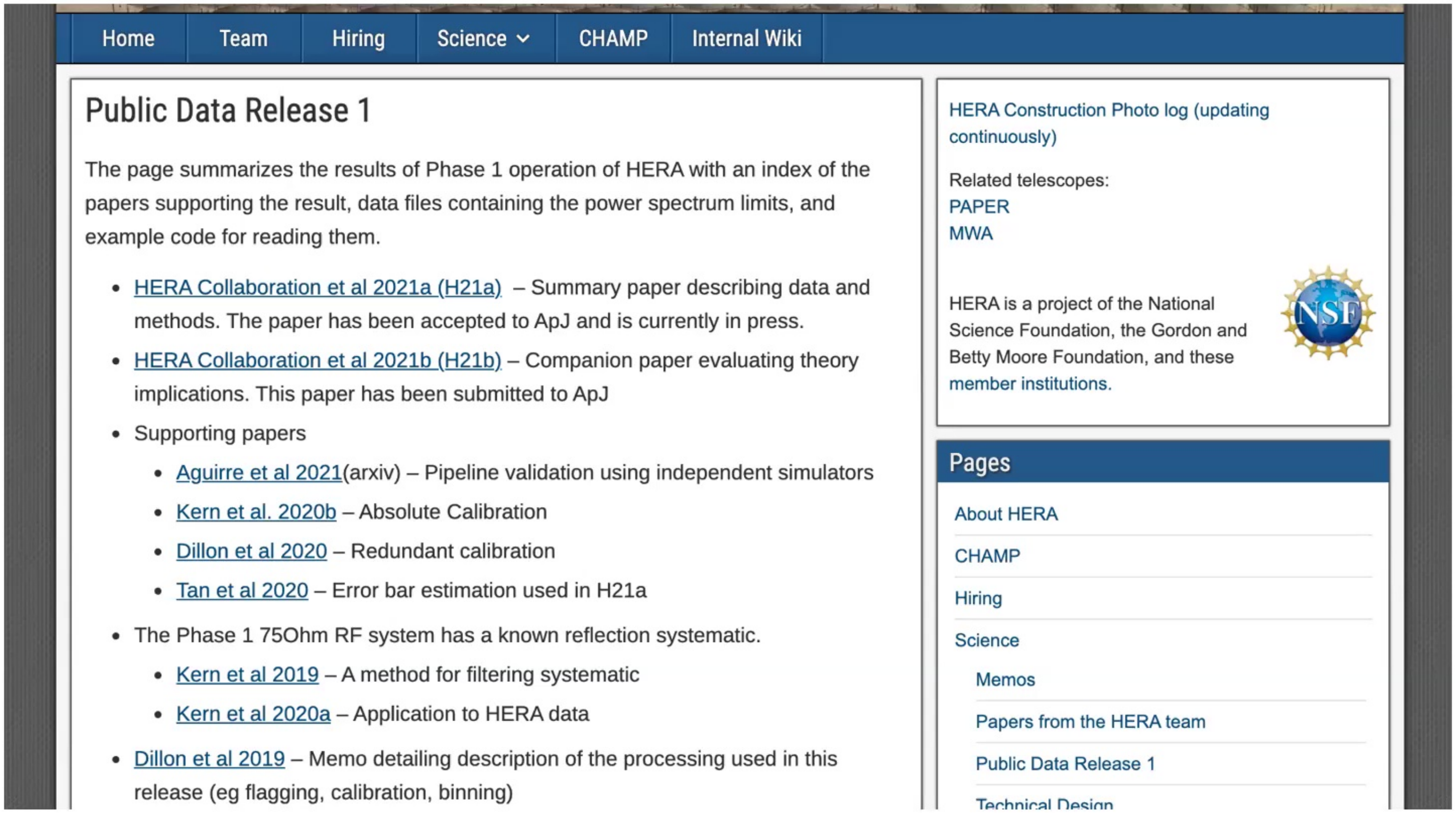
HERA Collaboration et al. (2021)
(2108.07282)

HERA Phase I Limits





This is the culmination of a lot of work!



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Public Data Release 1

The page summarizes the results of Phase 1 operation of HERA with an index of the papers supporting the result, data files containing the power spectrum limits, and example code for reading them.

- HERA Collaboration et al 2021a (H21a) – Summary paper describing data and methods. The paper has been accepted to ApJ and is currently in press.
- HERA Collaboration et al 2021b (H21b) – Companion paper evaluating theory implications. This paper has been submitted to ApJ
- Supporting papers
  - Aguirre et al 2021(arxiv) – Pipeline validation using independent simulators
  - Kern et al. 2020b – Absolute Calibration
  - Dillon et al 2020 – Redundant calibration
  - Tan et al 2020 – Error bar estimation used in H21a
- The Phase 1 75Ohm RF system has a known reflection systematic.
  - Kern et al 2019 – A method for filtering systematic
  - Kern et al 2020a – Application to HERA data
- Dillon et al 2019 – Memo detailing description of the processing used in this release (eg flagging, calibration, binning)

HERA Construction Photo log (updating continuously)

Related telescopes:
PAPER
MWA

HERA is a project of the National Science Foundation, the Gordon and Betty Moore Foundation, and these member institutions.

NSF

Pages

About HERA
CHAMP
Hiring
Science
Memos
Papers from the HERA team
Public Data Release 1
Technical Design

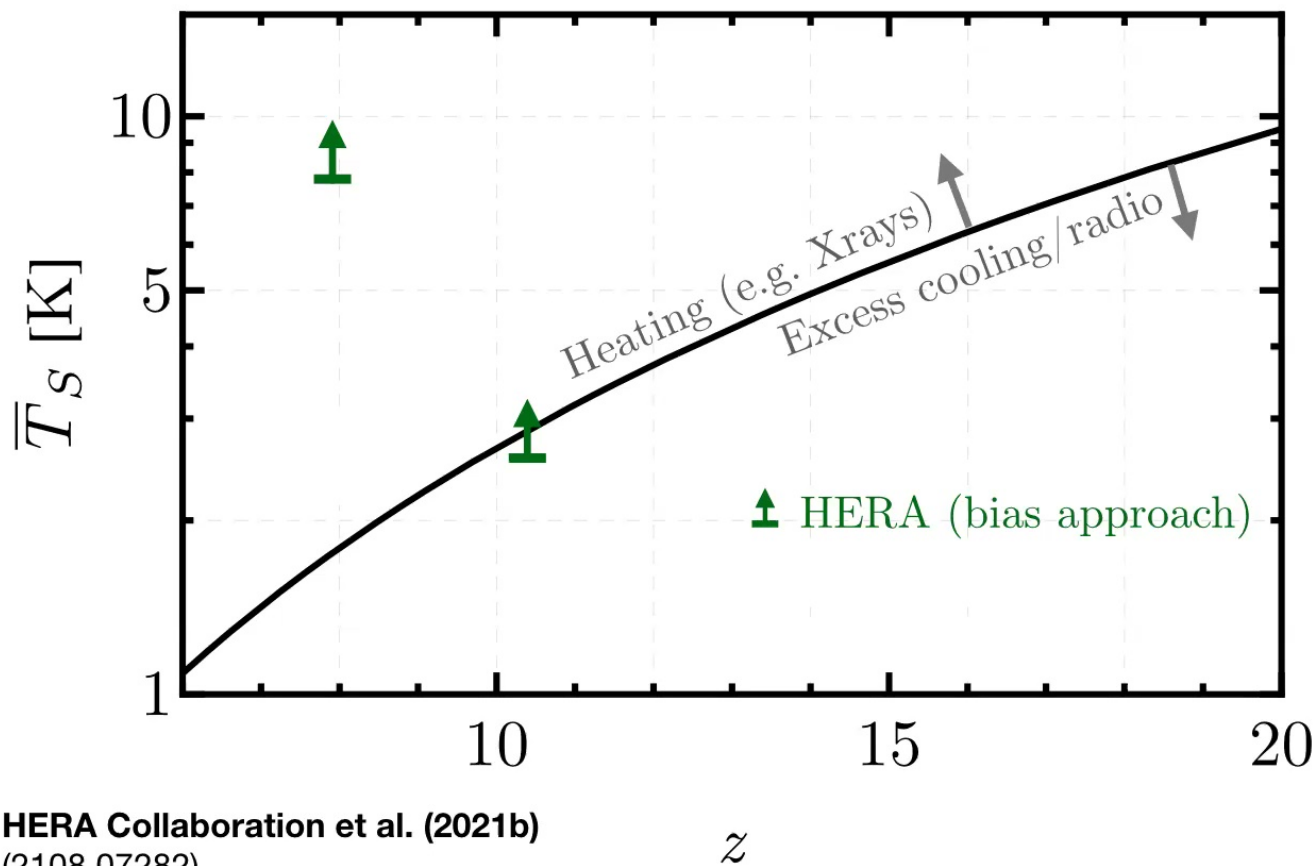
https://reionization.org/science/public-data-release-1/

What does it mean?

HERA results analyzed with four independently developed models!

1. Bias approach (analytic)
2. “Vanilla” 21cmFAST (semi-numeric)
3. Bubble model (analytic)
4. Radio background extension (semi-numeric)

1. Simplest approach: density fluctuations

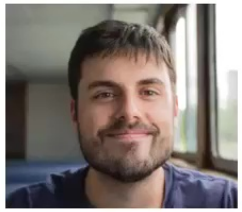


HERA Collaboration et al. (2021b)
(2108.07282)

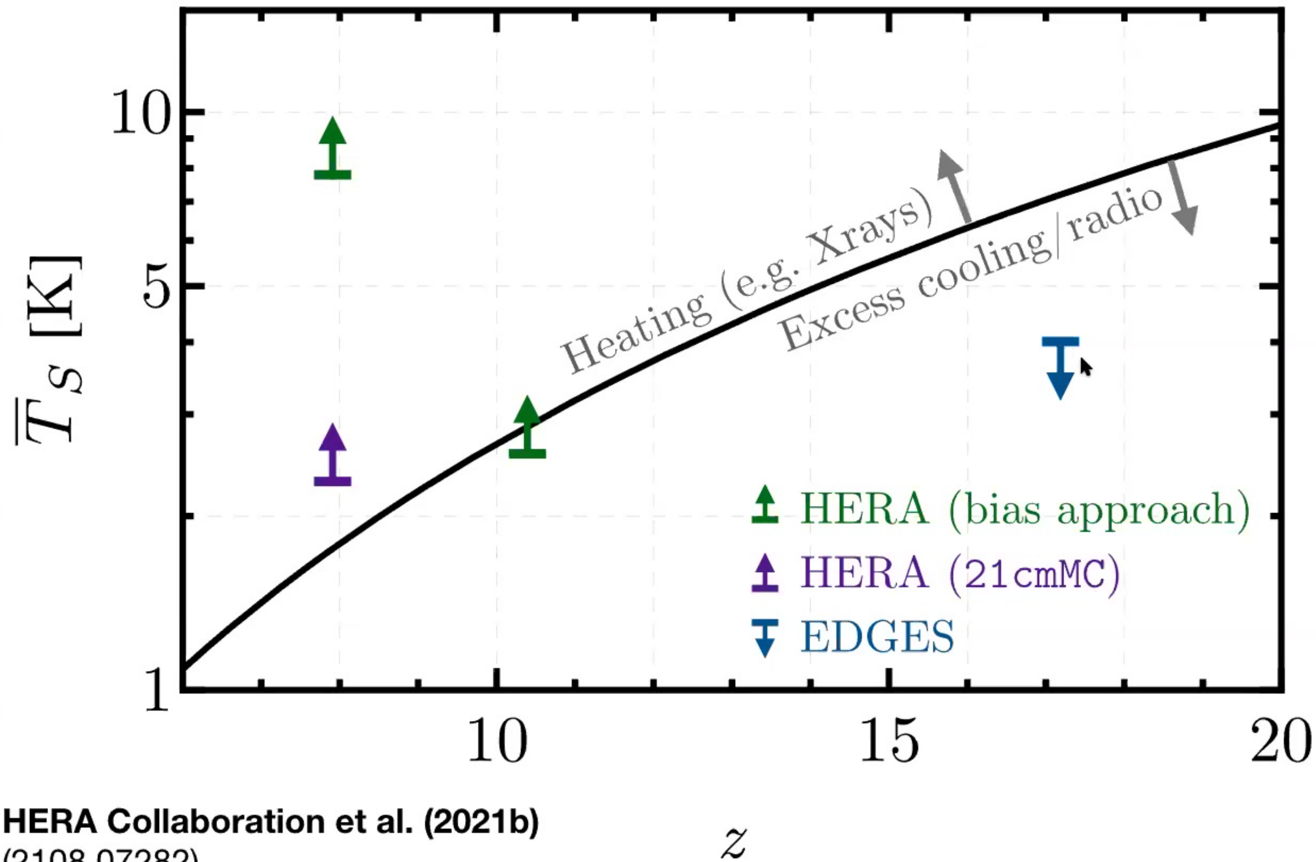
- Compute linear bias of 21-cm field from limits.
- Consider growth of density perturbations and preferential cooling of under-dense regions:

$$b = T_0 \left\{ (1+\mu) - \frac{T_R}{T_S} \left[(1+\mu) - C_T \right] \right\}$$

see Sec 4;
led by J. Muñoz



1. Simplest approach: density fluctuations



HERA Collaboration et al. (2021b)
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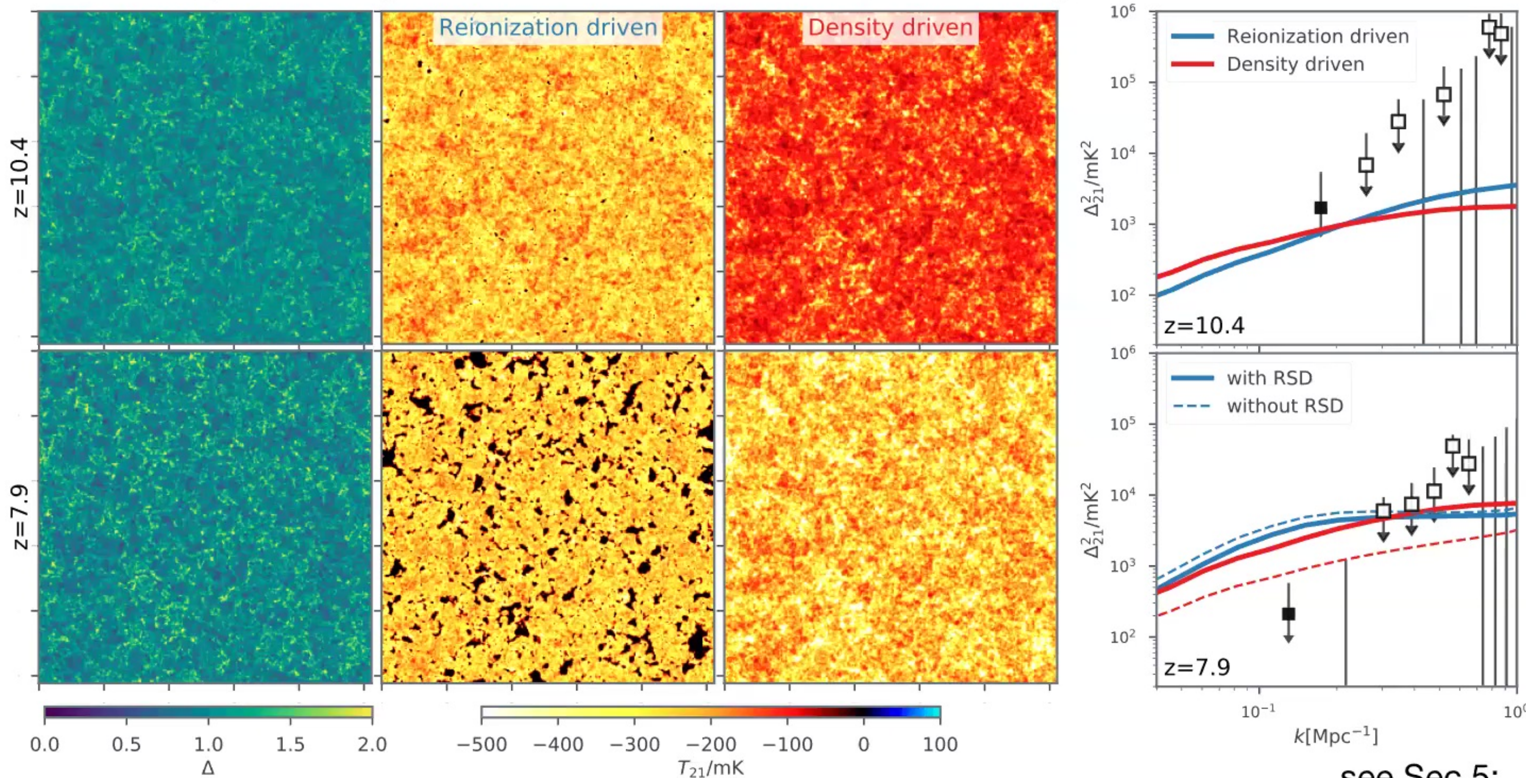
see Sec 4;
led by J. Muñoz

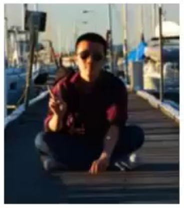
2. 21cmMC results

Two examples below; HERA disfavours models that have a very cold IGM at z ~ 8 and 10.



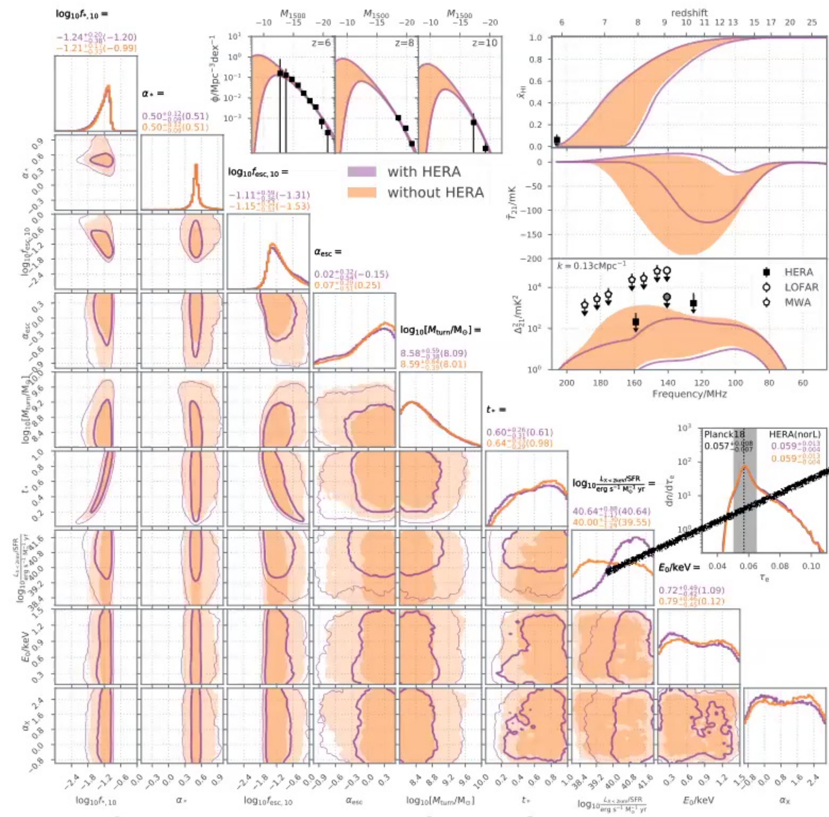
HERA Collaboration et al. (2021b)
(2108.07282)

see Sec 5;
led by Y. Qin

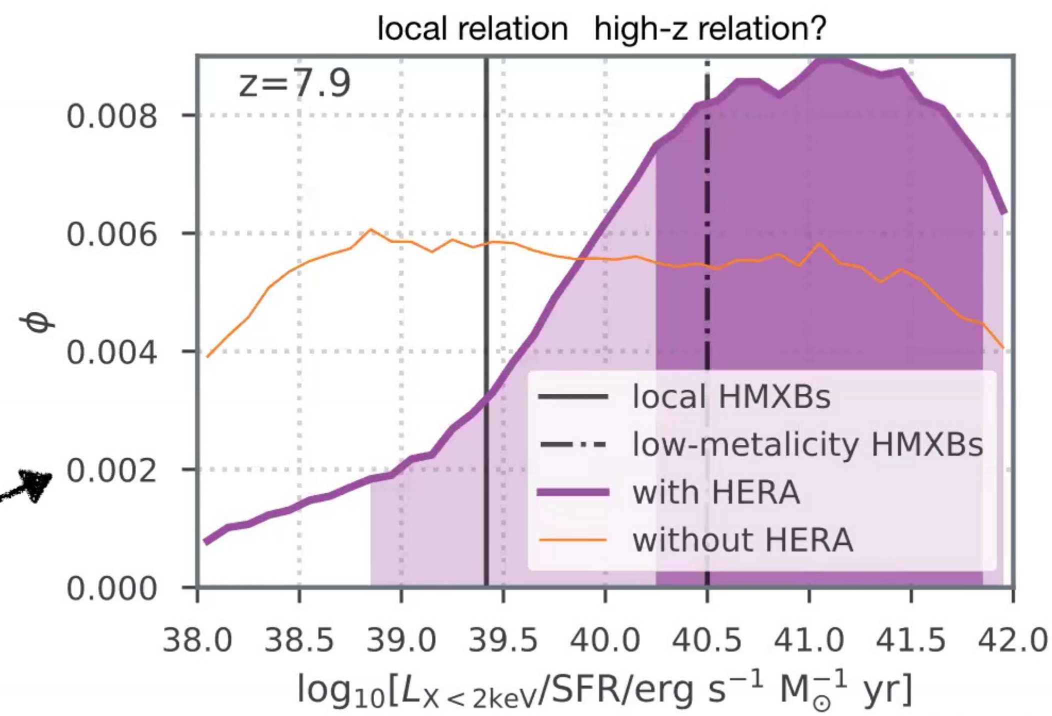


2. 21cmMC results

Full 9-D fit via `MultiNest:`

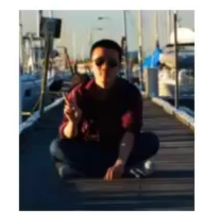


HERA Collaboration et al. (2021b)
(2108.07282)



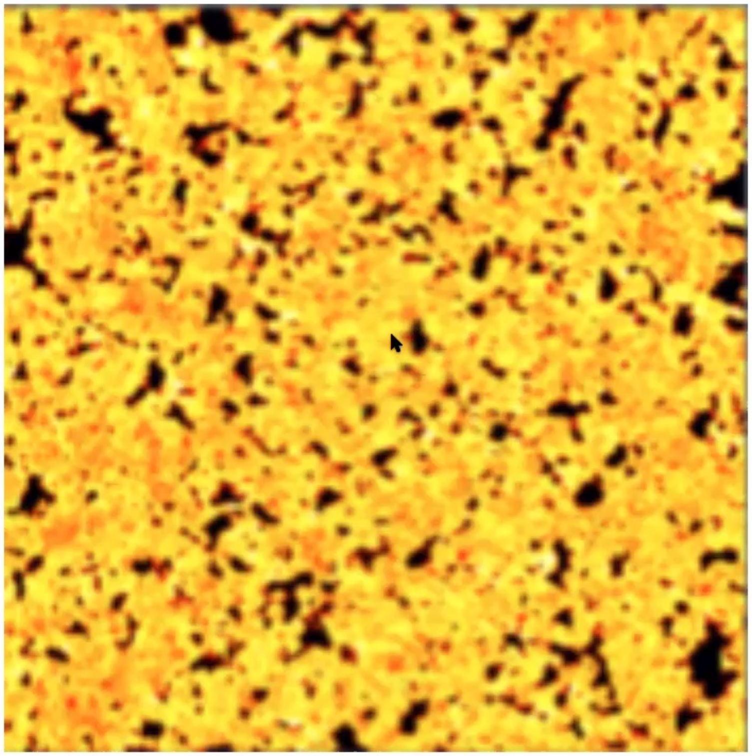
Fiducial X-ray heating disfavoured at 2 sigma.

see Sec 5;
led by Y. Qin



3. How to understand 21cmMC results?

21cmFAST slice



HERA Collaboration et al. (2021b)
(2108.07282)

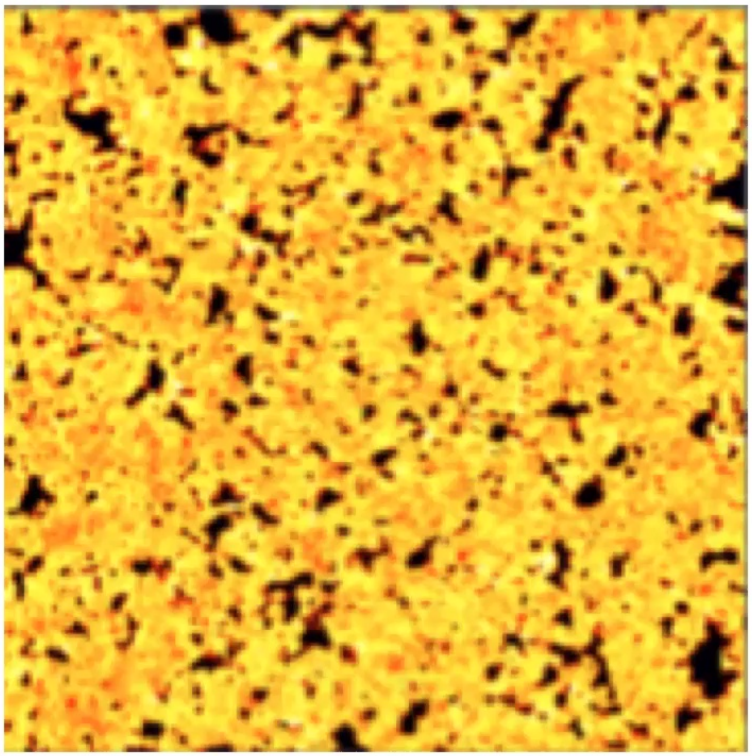
Key features:

- Fraction of volume that is ionized (black)
- Typical temperature of ~neutral IGM (orange).
- Typical size of ionized bubbles.
- Distribution of bubble sizes.

see also, e.g., Furlanetto, Zaldarriaga, & Hernquist (2004)

3. How to understand 21cmMC results?

21cmFAST slice



HERA Collaboration et al. (2021b)
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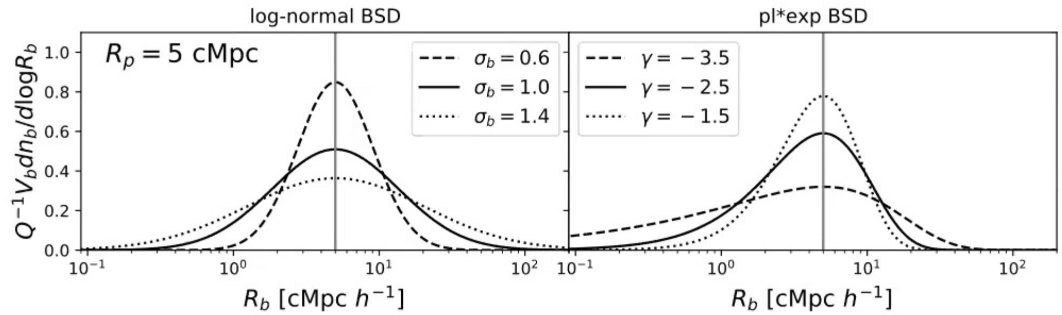
Let's try a four parameter model that works directly in terms of IGM properties. Can we constrain the ionized fraction, temperature, and bubble size distribution *without* explicit assumptions about galaxies?

see also, e.g., Furlanetto, Zaldarriaga, & Hernquist (2004)

3. How to understand 21cmMC results?

- We assume:
  - Binary ionization field.
  - Uniform temperature in IGM.
  - Spherical bubbles.
  - Log-normal size distribution.
  - Simple “abundance matching” inspired treatment of ioniz.-density cross-terms.

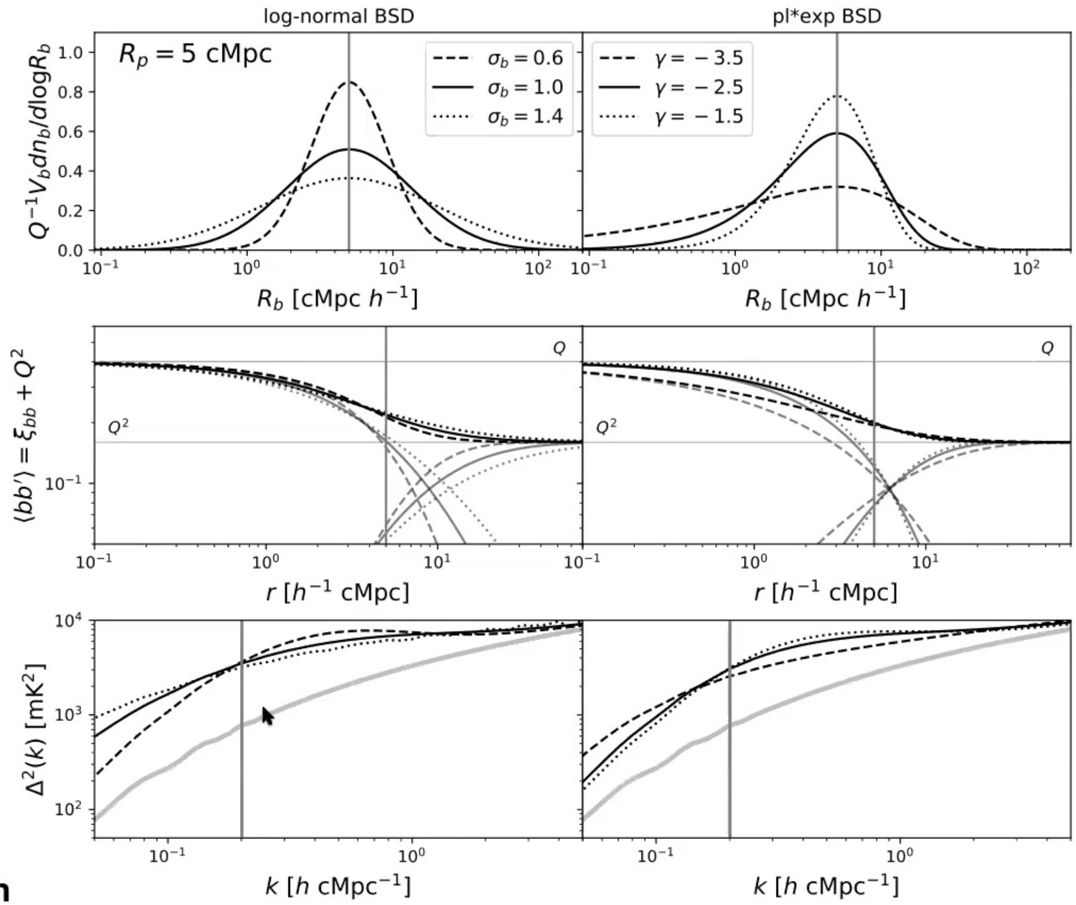


$$
\begin{aligned}
T_0^{-2}\xi_{21} = & \langle \delta\delta' \rangle + \langle xx' \rangle - \langle x \rangle^2 \\
& - 2\langle x\delta' \rangle + 2\langle xx'\delta \rangle - 2\langle x\delta\delta' \rangle + \langle xx'\delta\delta' \rangle \\
& - 2\langle x \rangle\langle x\delta \rangle - \langle x\delta \rangle^2
\end{aligned}
$$

JM, Muñoz et al. (submitted) **/mirochaj/micro21cm**

3. How to understand 21cmMC results?

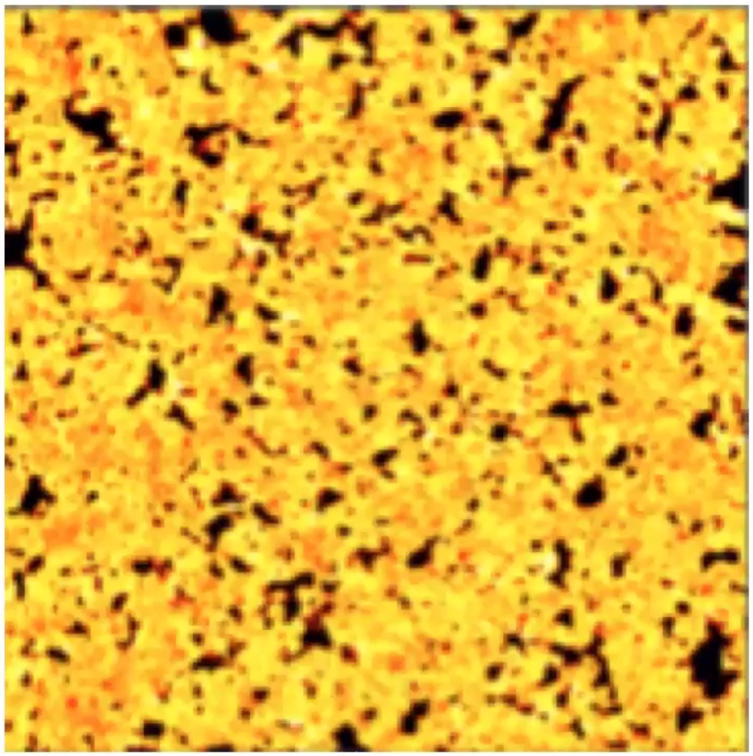
- We assume:
  - Binary ionization field.
  - Uniform temperature in IGM.
  - Spherical bubbles.
  - Log-normal size distribution.
  - Simple "abundance matching" inspired treatment of ioniz.-density cross-terms.



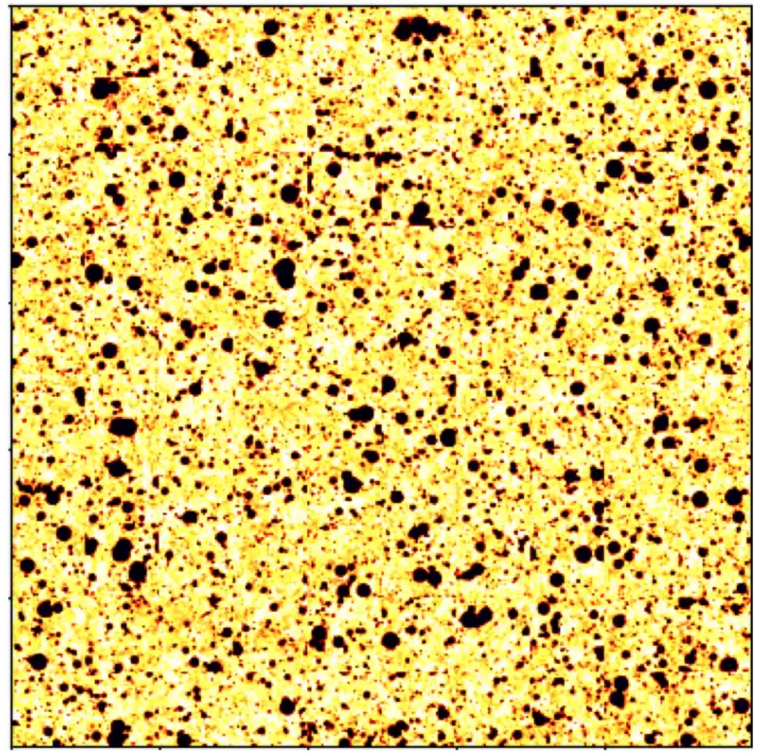
JM, Muñoz et al. (submitted) /mirochaj/micro21cm

3. How to understand 21cmMC results?

21cmFAST slice

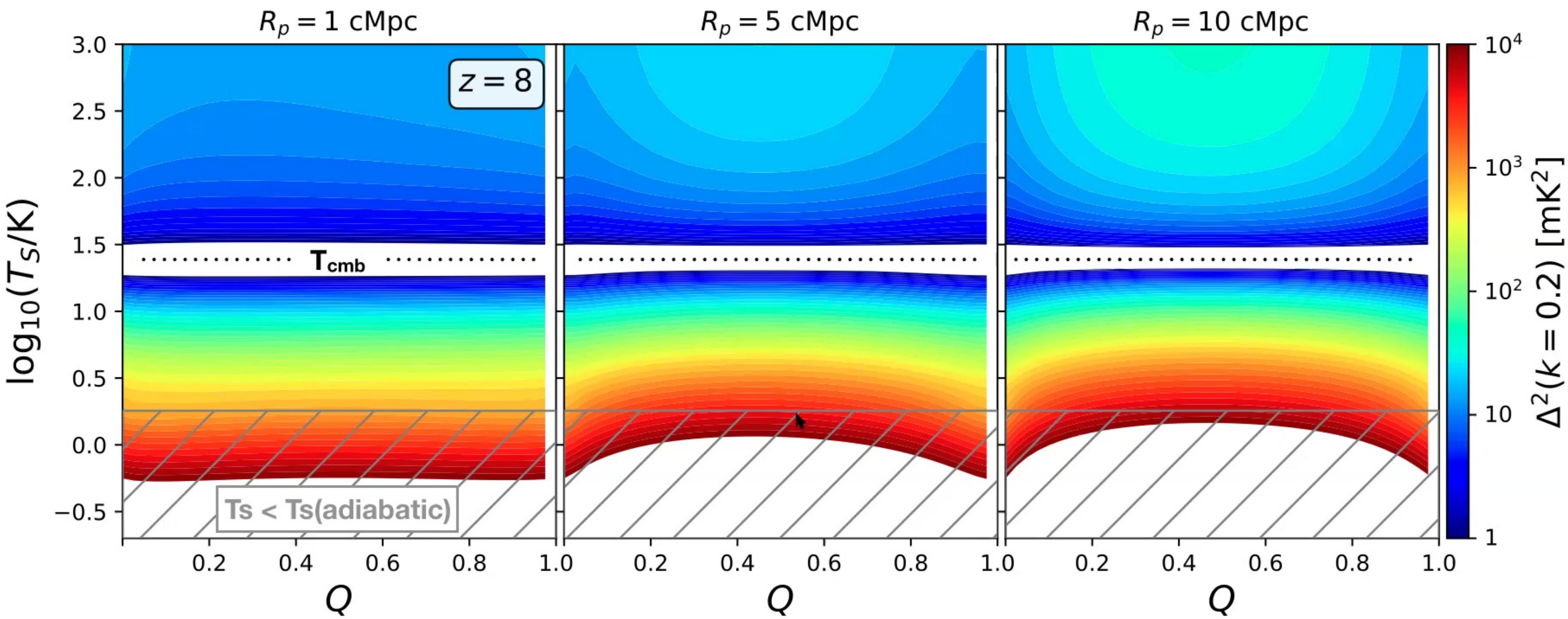


Visualization of analytic model; same x_{HI}, T_S



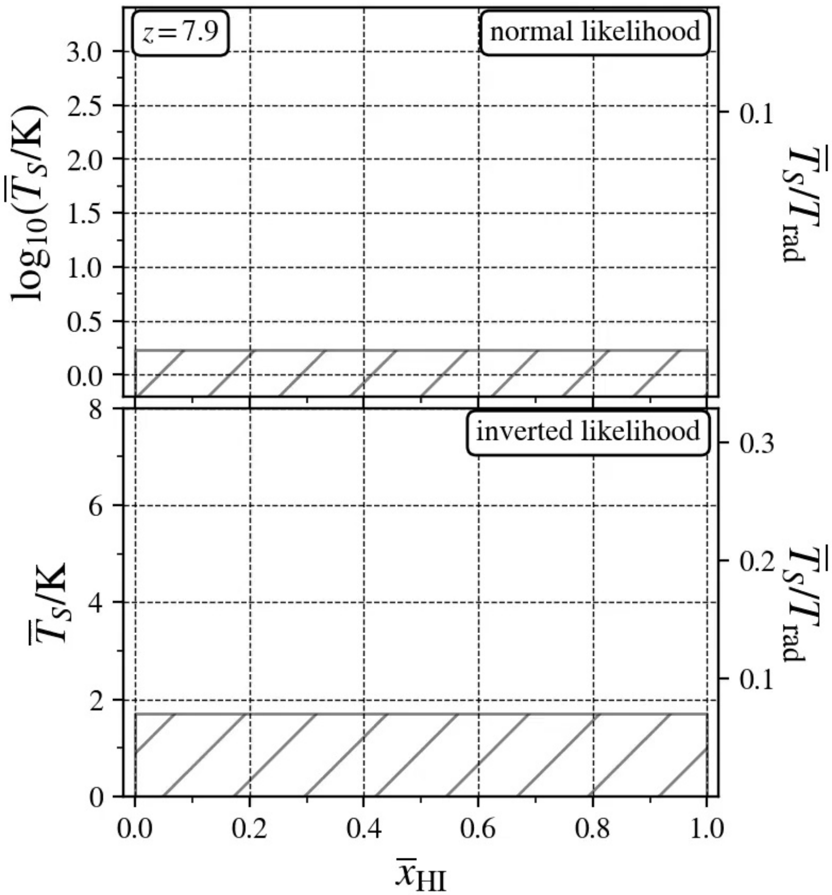
JM, Muñoz et al. (submitted) **/mirochaj/micro21cm**

3. How to understand 21cmFAST results?



JM, Muñoz et al. (submitted) /mirochaj/micro21cm

3. Bubble Model



Approach:

- Uninformative priors, e.g., T_S>0, allows us to explore exotic models without explicitly choosing one.
- Only four parameters, computation scales as N_k x N_z, MCMCs finish in a few hours on a cluster.
- Can avoid explicit parameterization of redshift dependences in principle.

see Sec 5;
led by **J. Mirocha**

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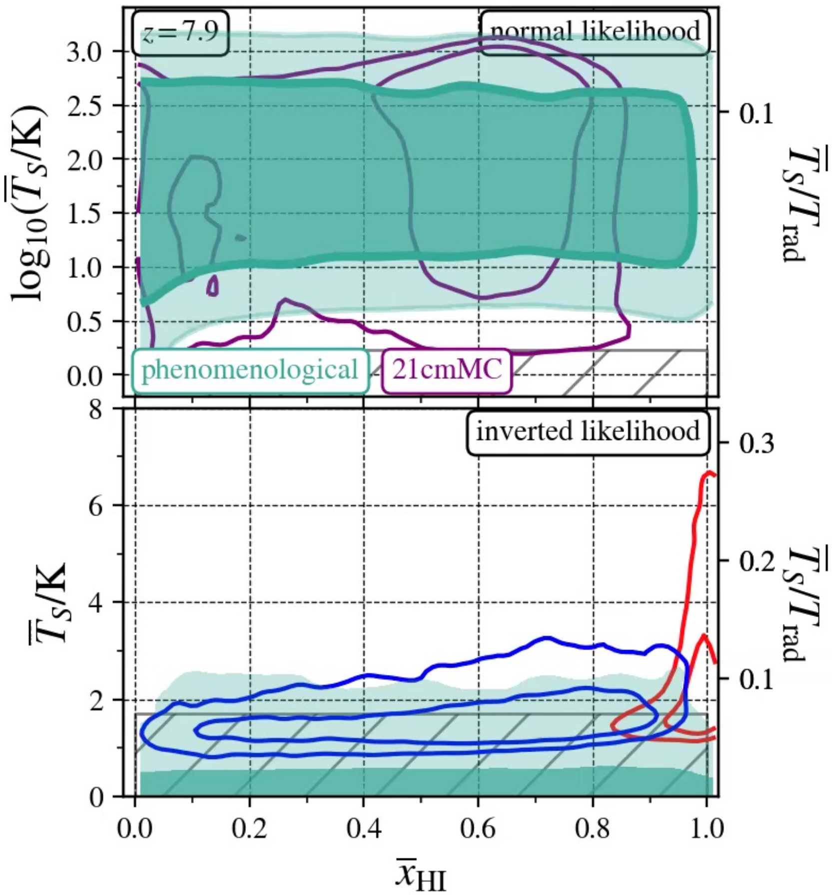
(2108.07282)

3. Bubble Model



Approach:

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see Sec 5;
led by **J. Mirocha**

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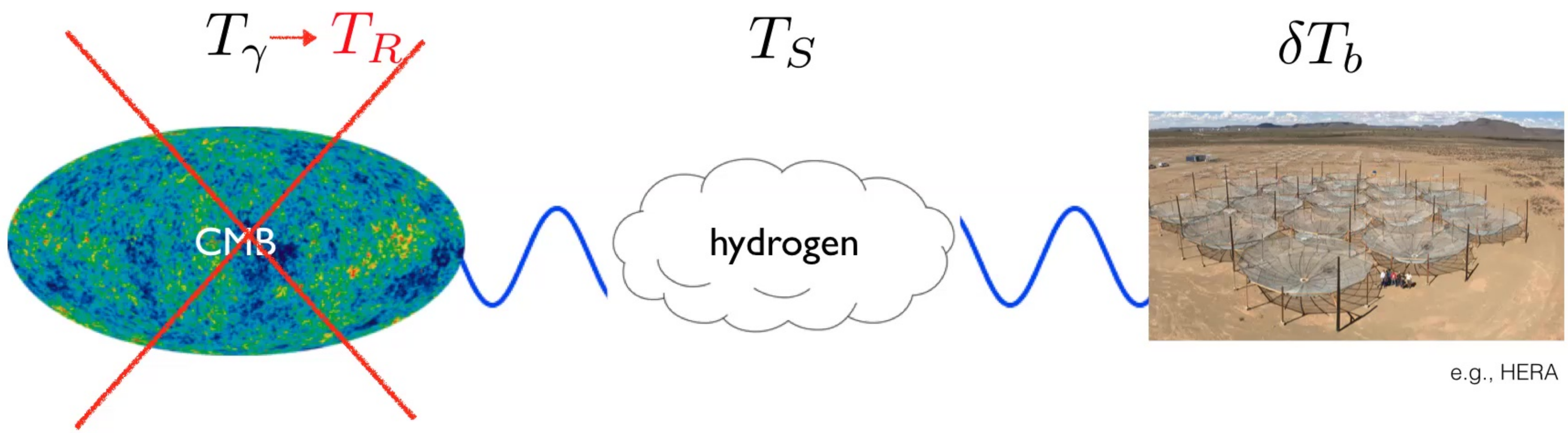
(2108.07282)

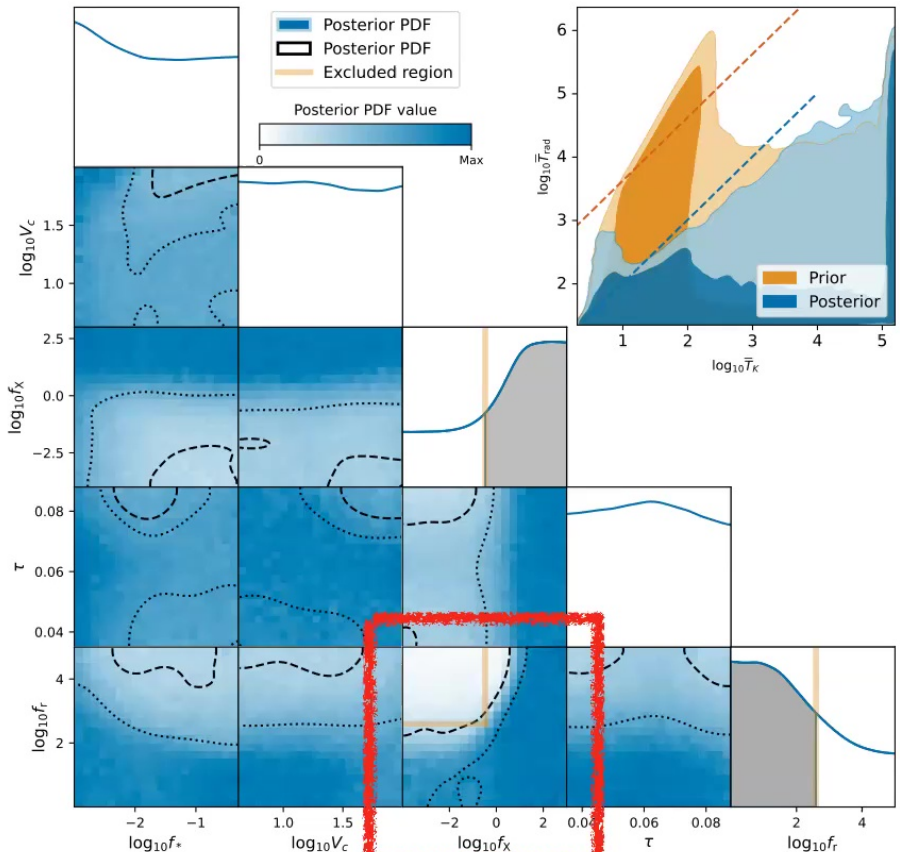
4. What if $T_R > T_{cmb}$?



Additional low-frequency backgrounds from…

Decaying particles?
Star-forming galaxies?
AGNs?
PBHs?

Radio backgrounds?



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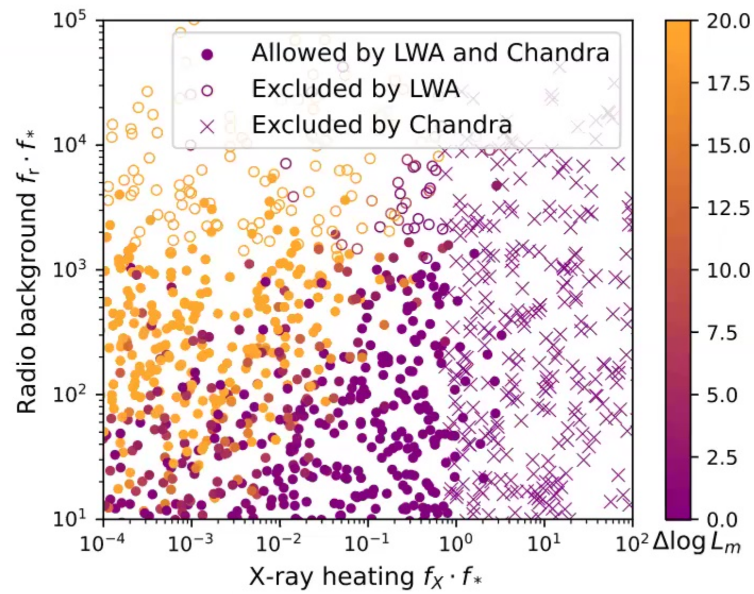
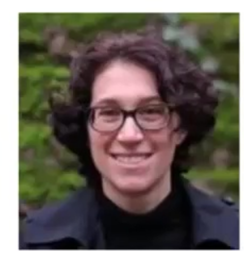
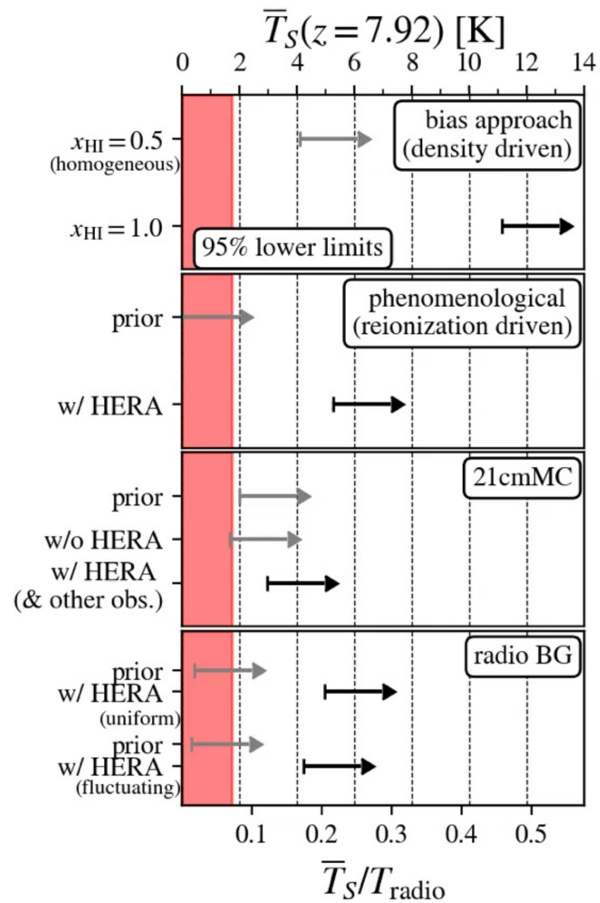


see Sec 9;
led by S. Heimersheim,
A. Fialkov



Do these models all agree?

- Different parameterizations, methods, priors, so we compare constraints on IGM temperature.
- Simplest model predicts the highest temperature.
- **Remaining models consistent with 95% lower limit on z~8 temperature of ~3-5 Kelvin, clearly above the adiabatic cooling limit (1.8 K at z=8).**



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