Implications of the z ~ 5 Ly-α Forest for the EoR 21-cm Power Spectrum

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State of the Universe Seminar

12th February, 2021

Outline

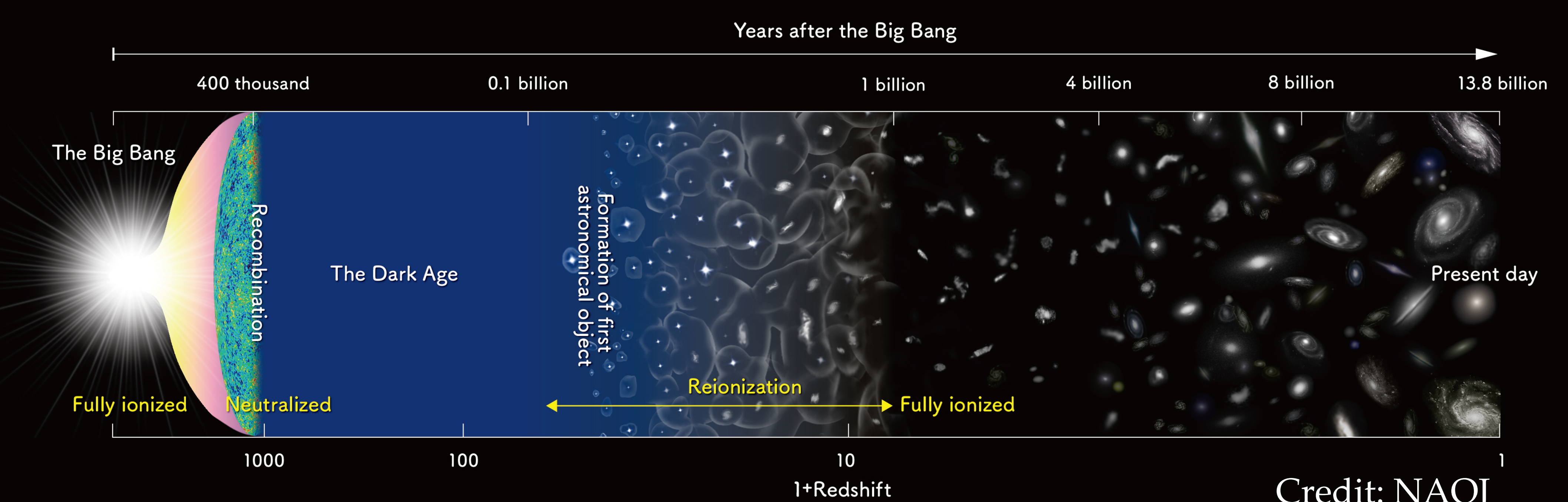
- Epoch of Reionization: Overview and probes

- Lyman-α forests in spectra of distant QSOs
- Late Reionization model: Kulkarni et al. 2019

- 21-cm signal from EoR
- Its observational prospects at $5.4 \lesssim z \lesssim 6$

Cosmic Dawn and Epoch of Reionization

- **Dark Ages**: Minimal interaction between matter and radiation
  Sources of radiation are not formed yet
- **Cosmic Dawn**: High-density regions collapse into structures
  Formation of first sources of radiations
- **Epoch of Reionization**: Ultraviolet (UV) photons ionize and heat surrounding neutral IGM
  With formation of more sources, ionization bubbles grow and merge



Credit: NAOJ

Epoch of Reionization: Uncertainties

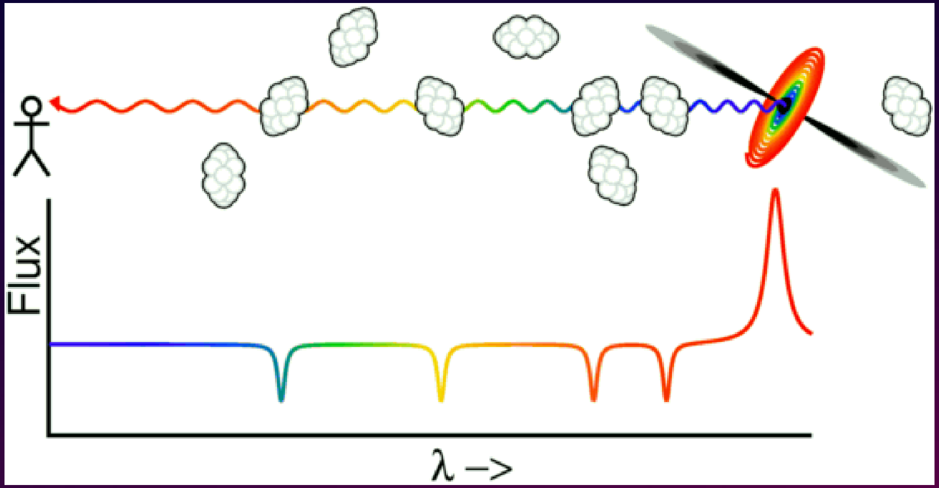
- What is the mass of collapsing halos?
  - Atomic or molecular cooling
  - Dark matter model for structure formation
- What are the heating and cooling mechanisms for IGM?
  - X-ray binaries (soft spectra), accretion around black holes (hard spectra)
  - Exotic physics (dark matter ?)
  - Lyman-α (?)
- What are the prominant sources of ionizing radiation? (AGN or galaxies?)
- What are the sinks of ionizing photons? (dense self-shielded regions)
  What is the escape fraction of photons?
- What feedback mechanisms are effective?
  - Metal enrichment by supernova explosions
  - Lyman-Werner feedback: Photodissossiation of H_2 molecules

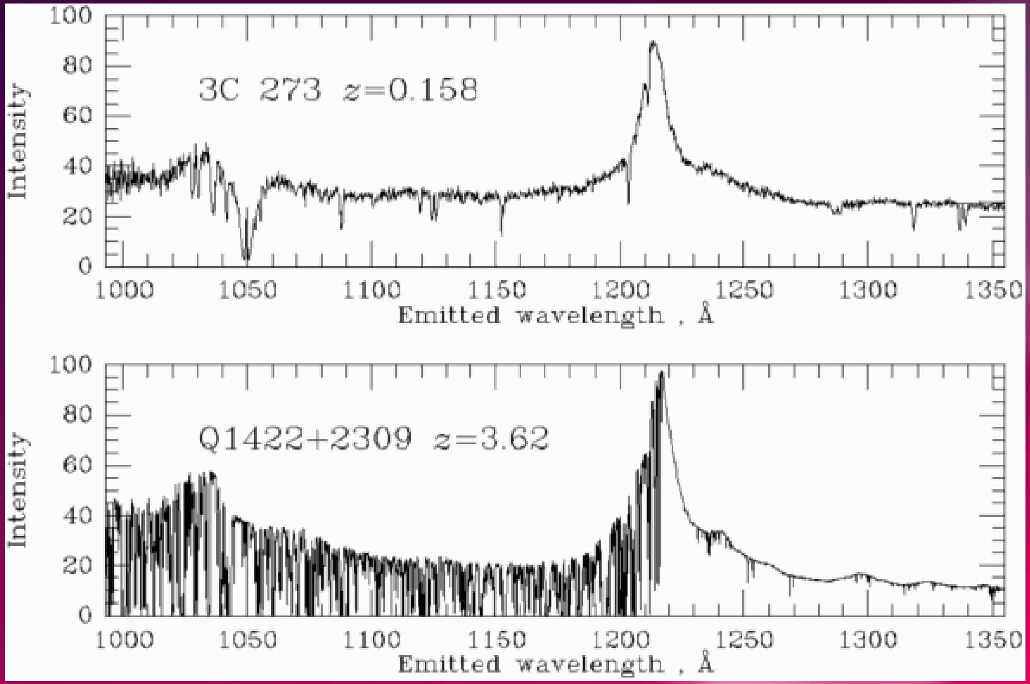
Observing the Reionization

- Direct detection: galaxies at high redshift
- Observing effect of electrons on CMB spectra:
  - Thomson scattering optical depth τ_{reion}
  - Sunyaev-Zeldovich effect
- H, He:
  - 21-cm hyperfine, 3-cm fine structure line of HI
  - HeII hyperfine line
  - Recombination lines
  - absorption of Lyman lines in QSO spectra
- Metal lines

Lyman-α forest of QSO spectra

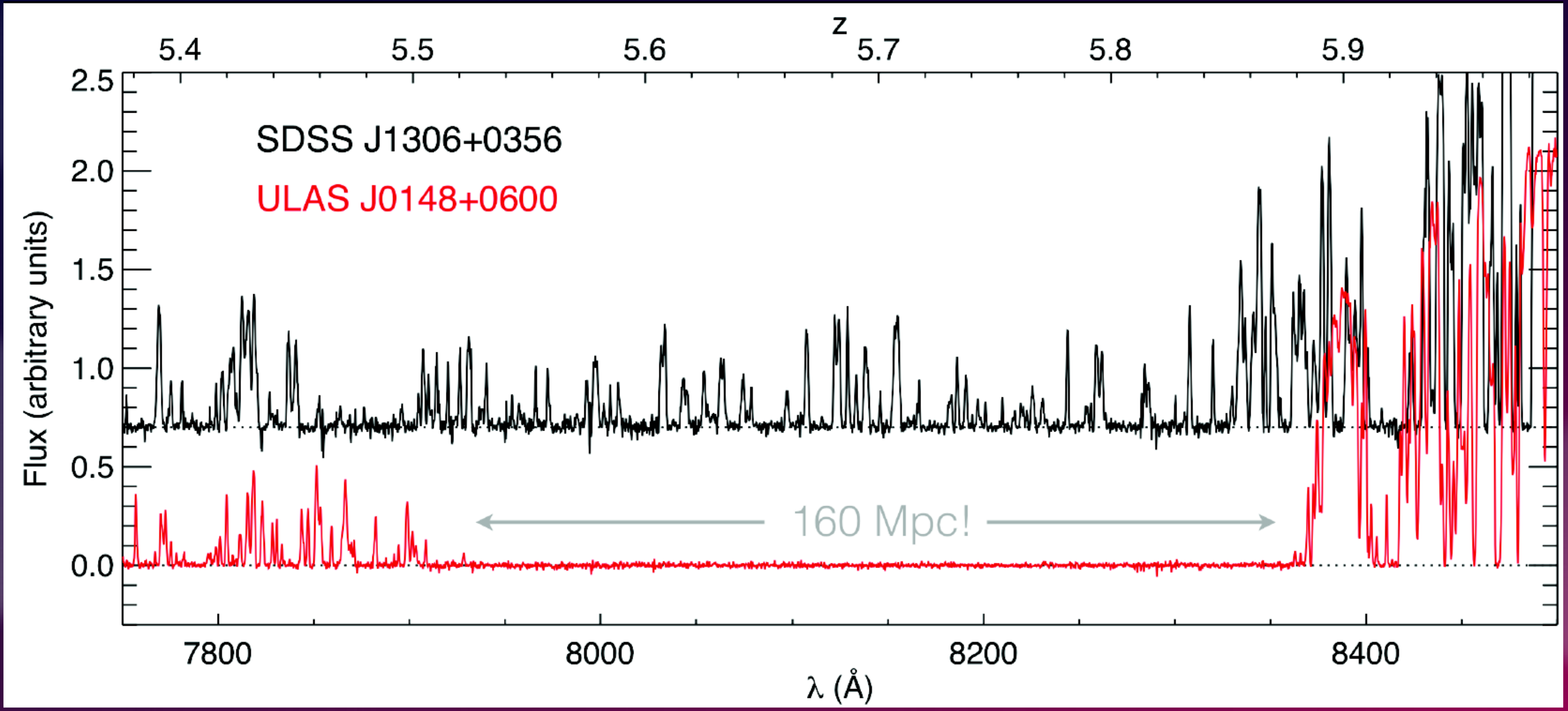
- Photons blueward of Lyman-α in QSO spectra is absorbed by HI in intermediate medium
- $x_{HI} \sim 10^{-4}$ in IGM can saturate Lyman-α absorption
- Extremely sensitive to detect presence of HI
- But only provides lower bound on x_{HI}





http://www.astro.ucla.edu/~wright/Lyman-alpha-forest.html

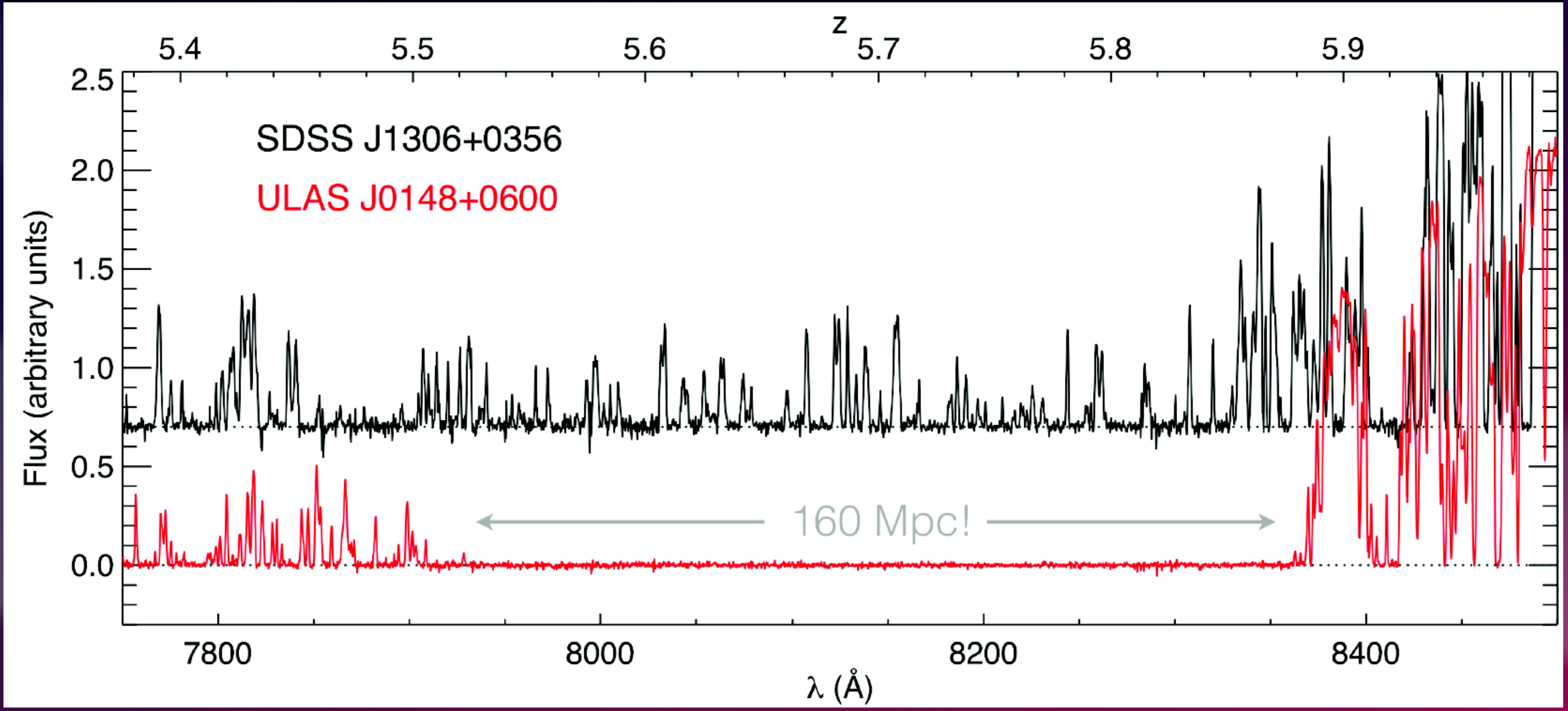
Large troughs in Lyman-α forest



Becker et al. (2015)

Two QSOs at z ~ 6 have absorption troughs of widely different widths

Lyman-α effective optical depth τ_{eff}



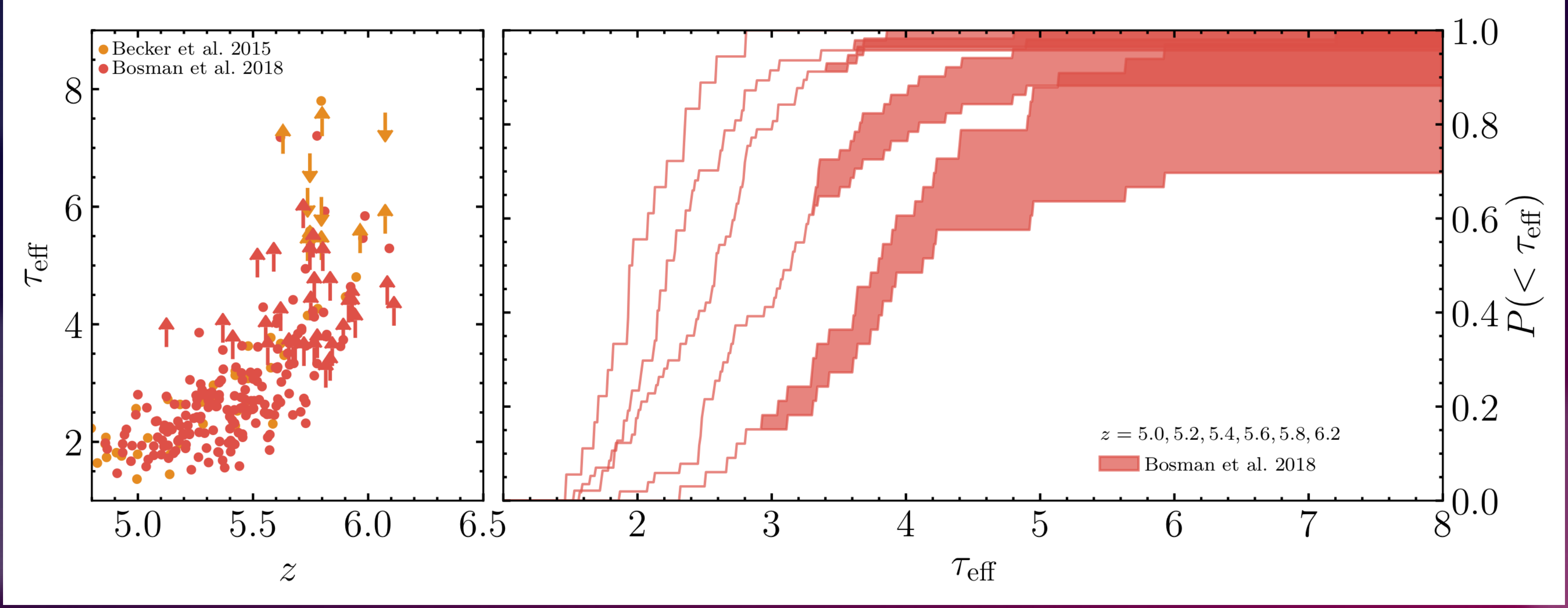
Becker et al. (2015)

$$\tau_{eff} = -\log \langle (F/F_0) \rangle$$

flux F is averaged over bins of 50 Mpc/h

F_0 is the unabsorbed continuum

Lyman-α τ_{eff} has large scatter



Kulkarni et al. (2019)

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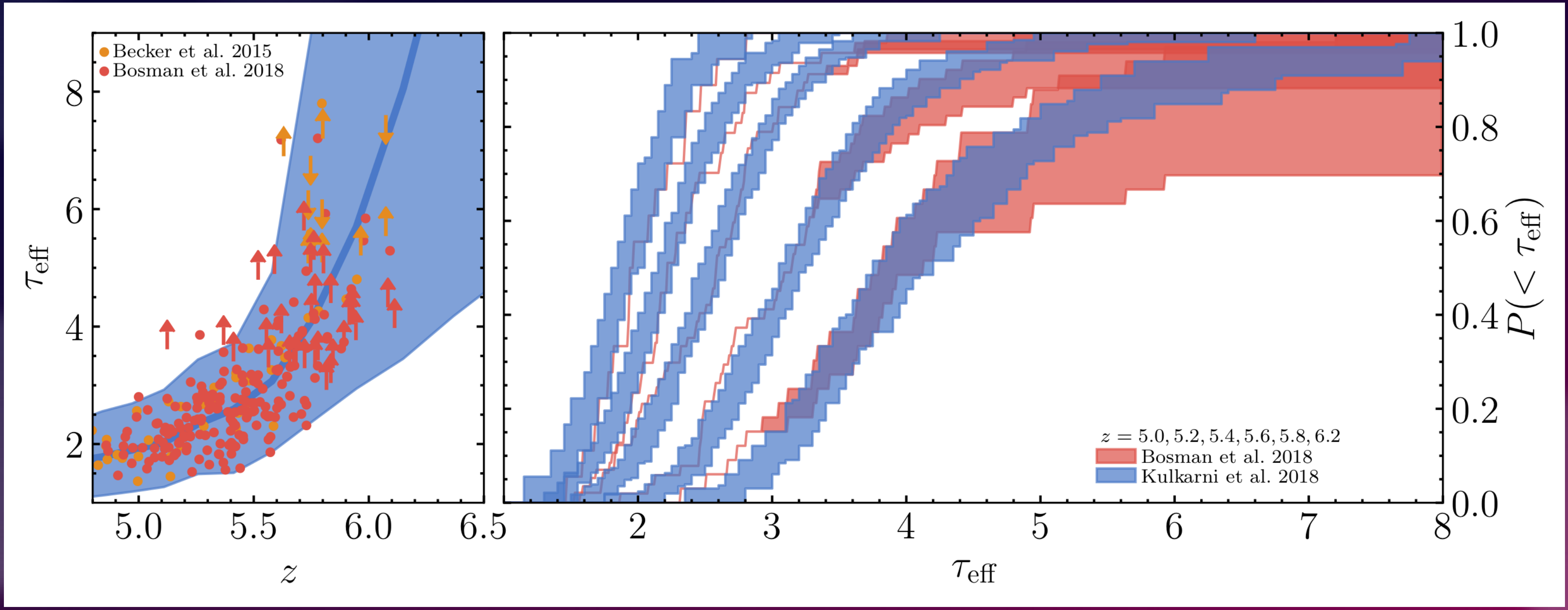
A Reionization model that fits Ly-α τ_{eff}



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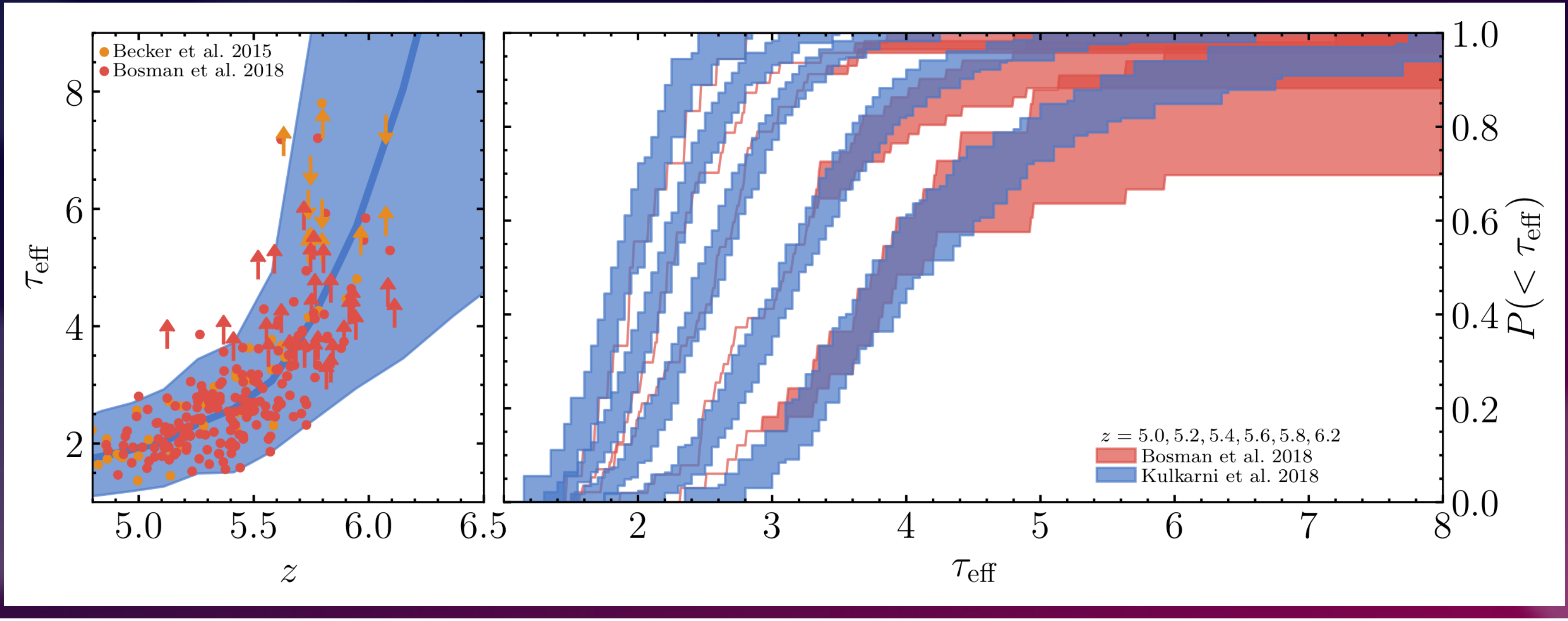

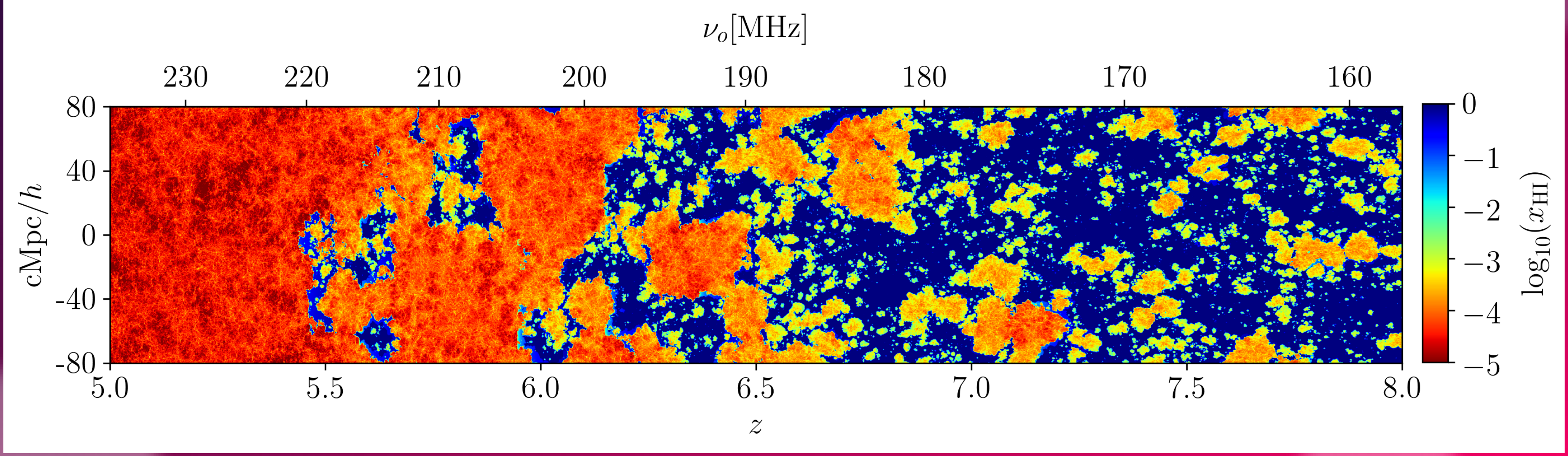

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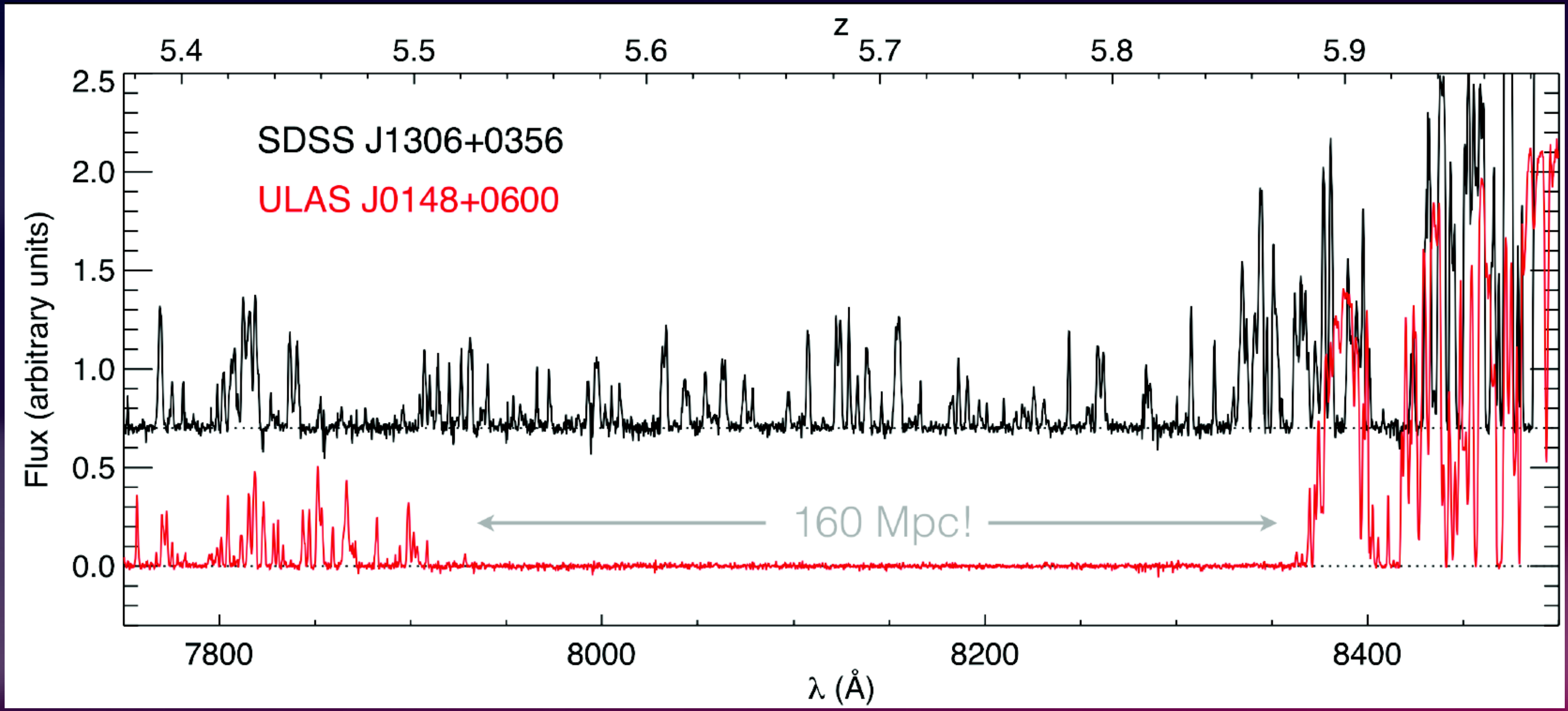

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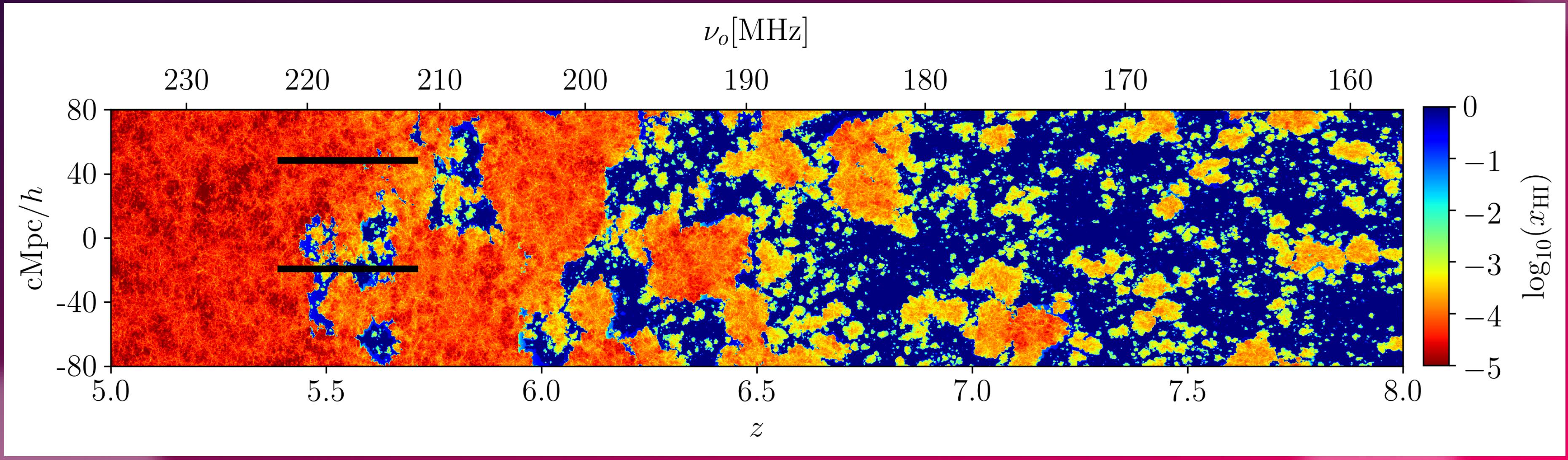
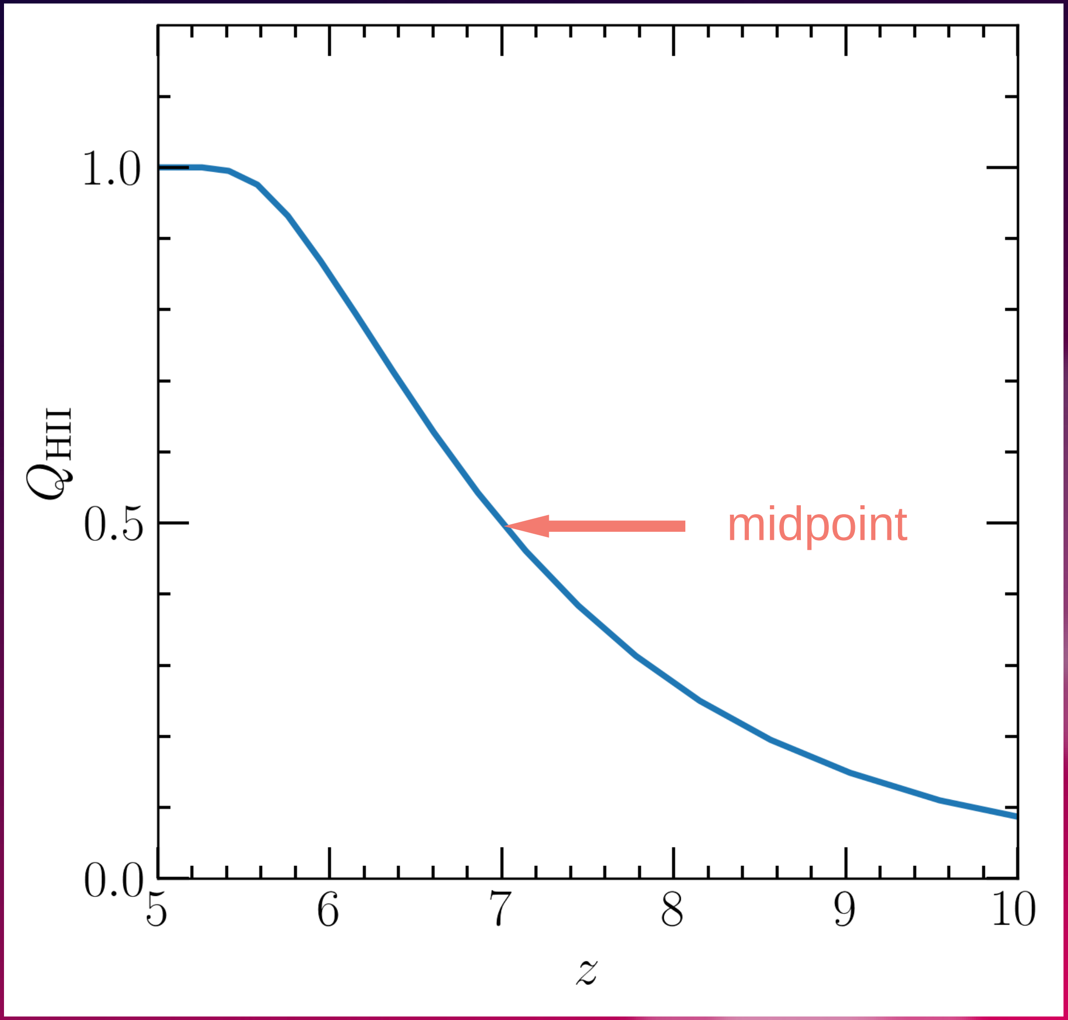


Simulation Setup

- Cosmological hydrodynamical simulation using the P-GADGET-3 code (Springel 2005)
- Large simulation with 2048^3 particles
- Dynamical range: 78.12 ckpc/h to 160 cMpc/h
- Starting at $z = 99$ to $z = 4$ (saved at 40 Myr intervals)
- Ionization and temperature field calculated with ATON (Aubert & Teyssier 2008, 2010)
- ATON uses moment-based algorithm along with M1 closure to solve cosmological raditive transfer
- This algorithm enables usages of GPUs

Reionization is delayed

- Reionization midpoint: $z \sim 7$



Raste et al. (2021)

Reionization is delayed

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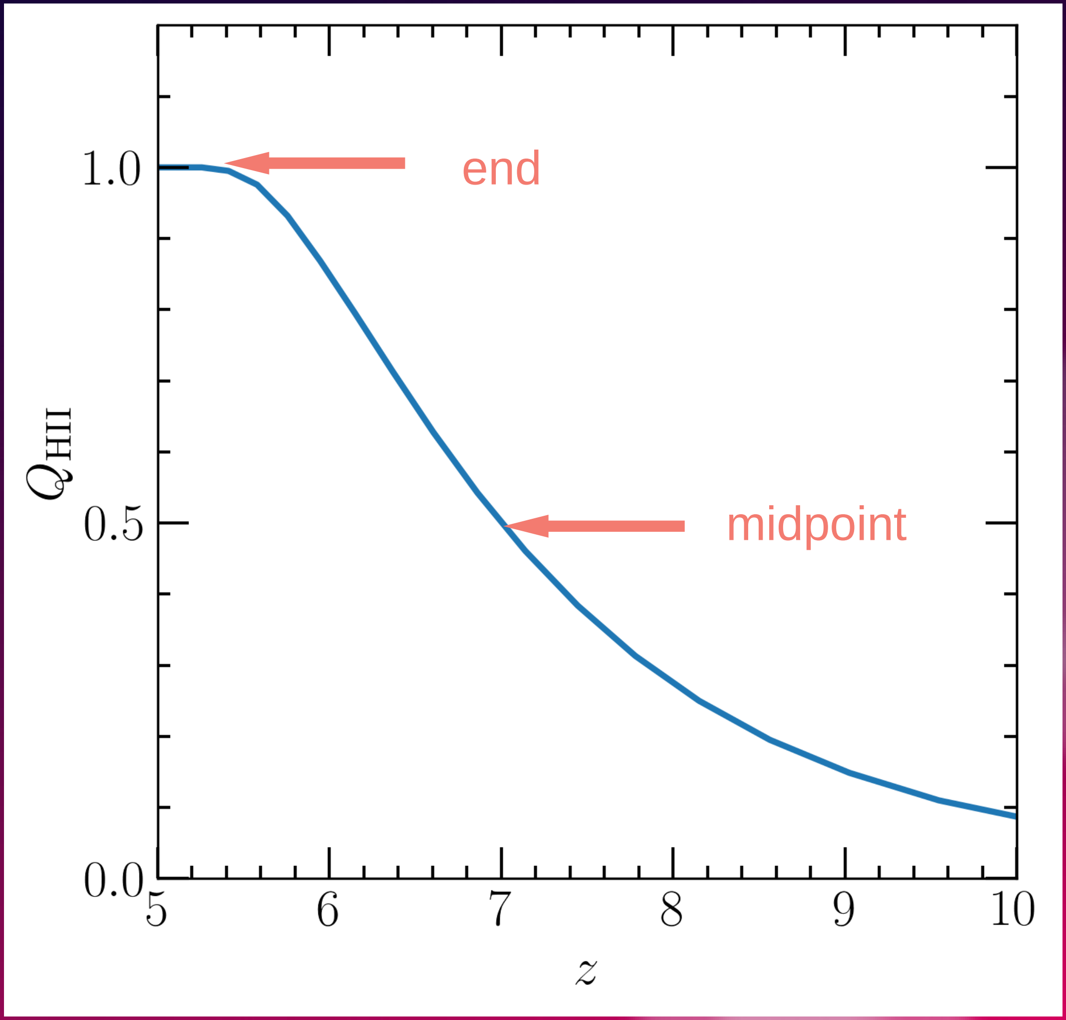
- Reionization completed: $z \sim 5.3$



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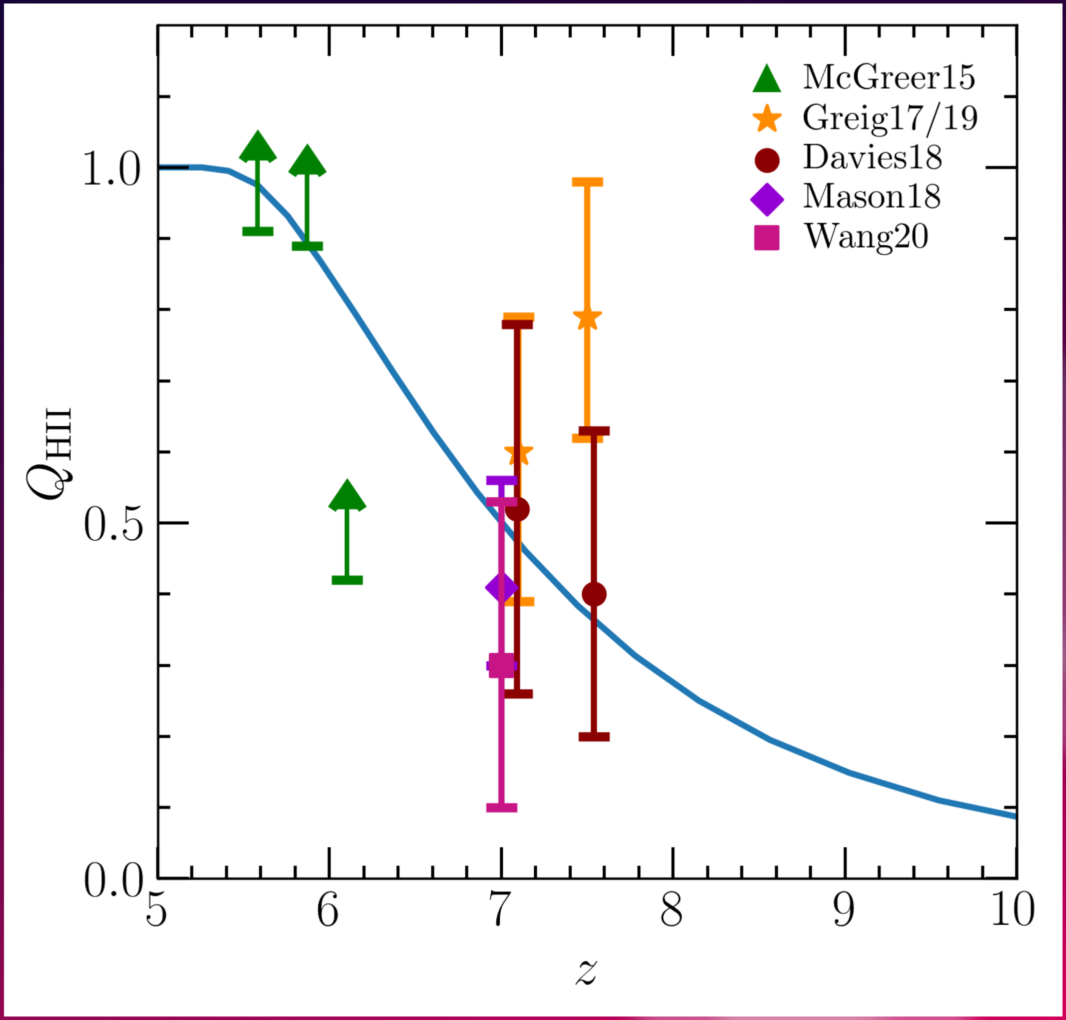

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Reionization is delayed

- Reionization midpoint: $z \sim 7$
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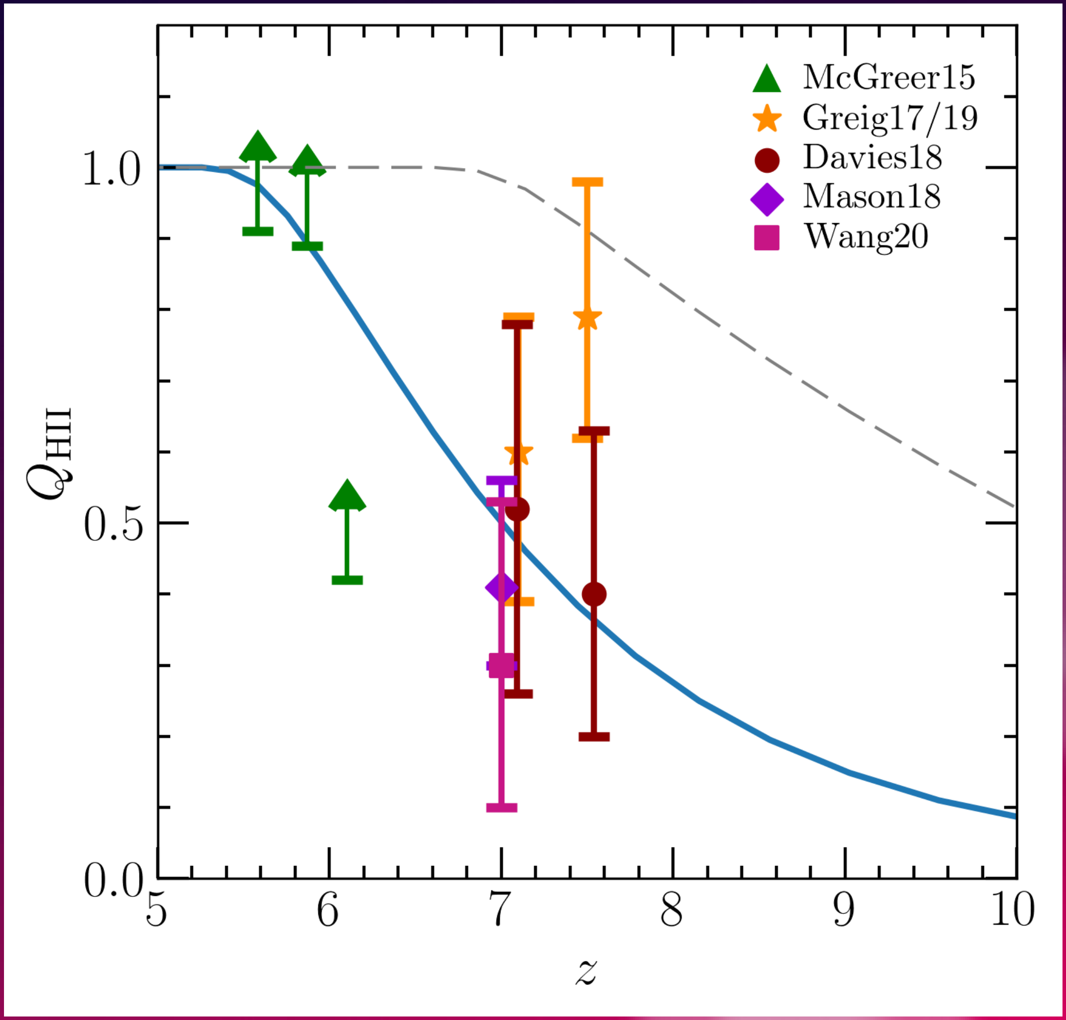
- Haardt and Madau (2012): reionization at $z \sim 6.7$

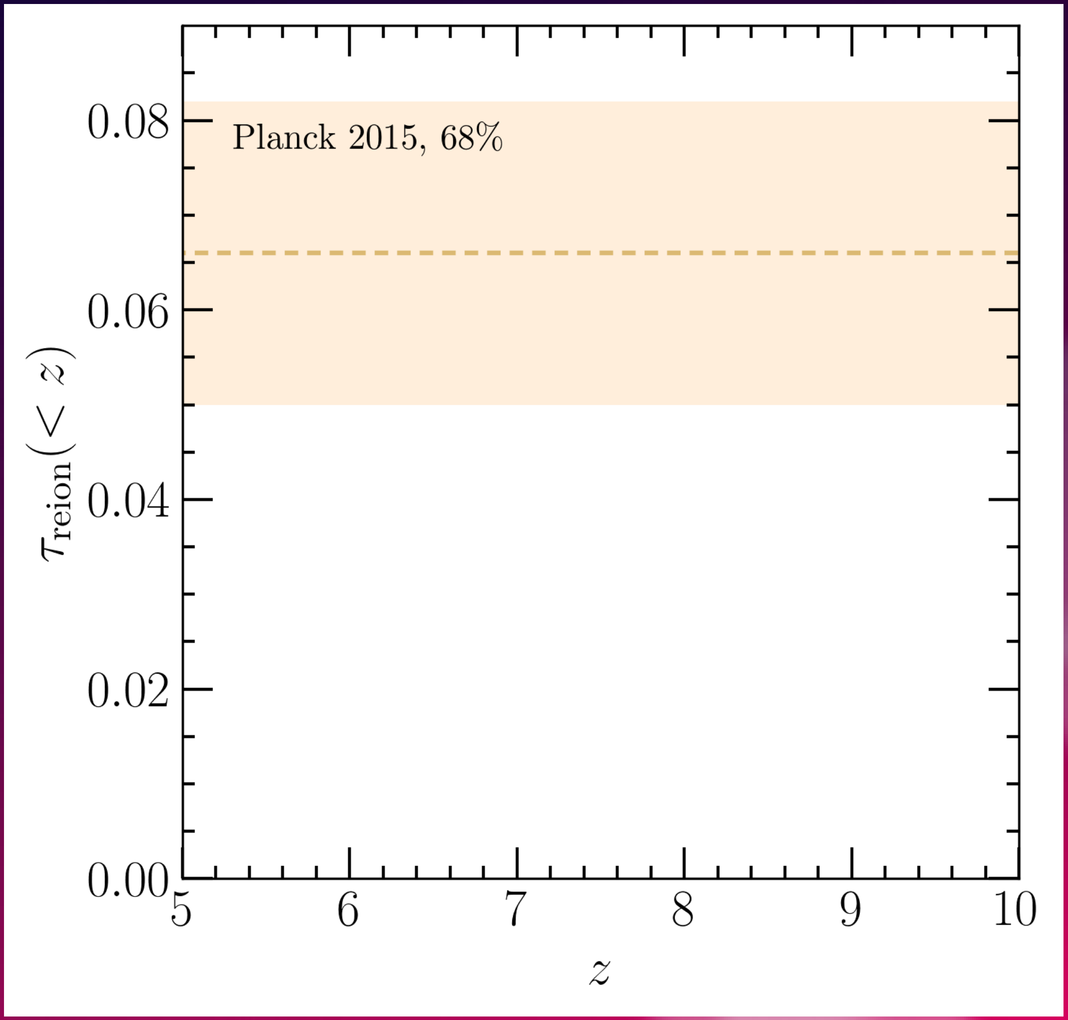


Raste et al. (2021)

τ_{reion} predicts Late Reionization

Planck Collab. (2015) :

$\tau_{reion} = 0.066 \pm 0.016$



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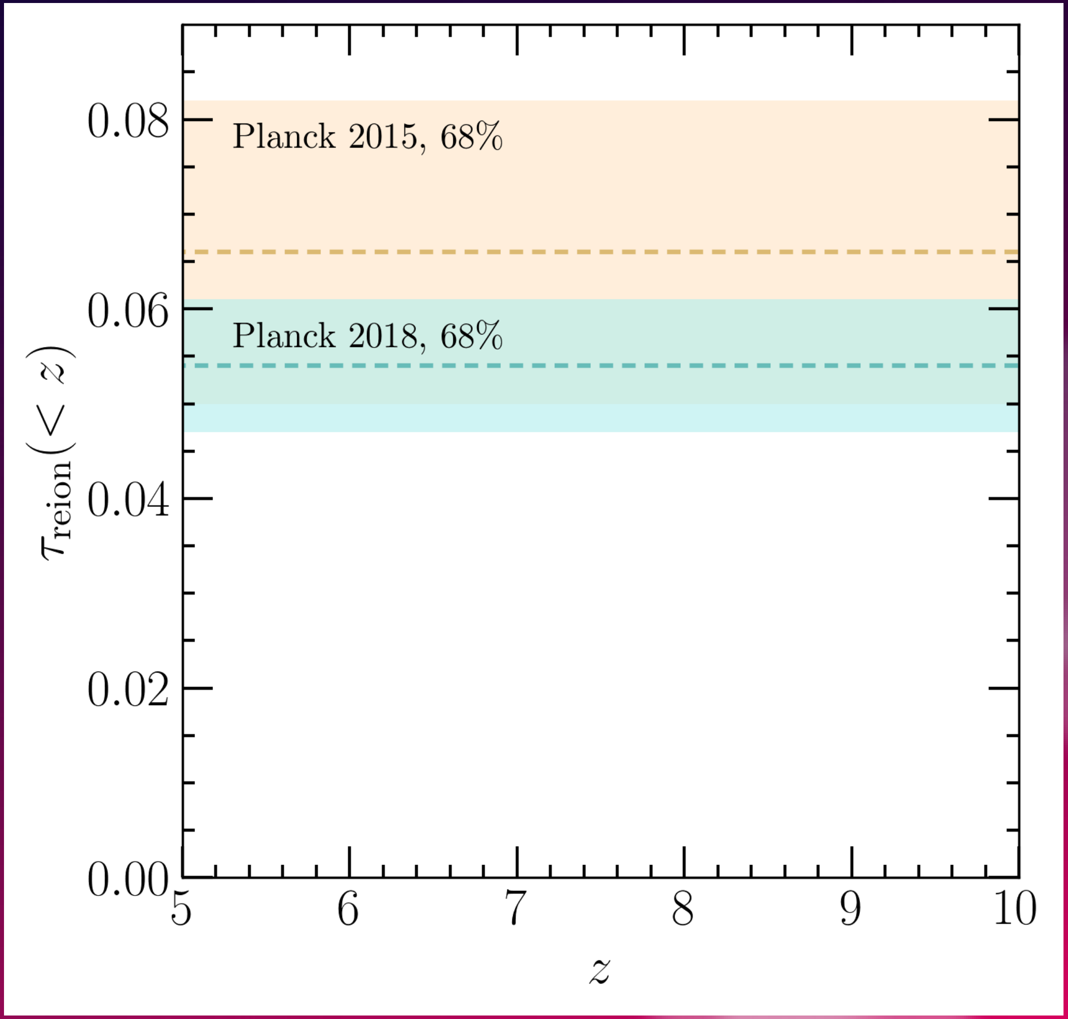

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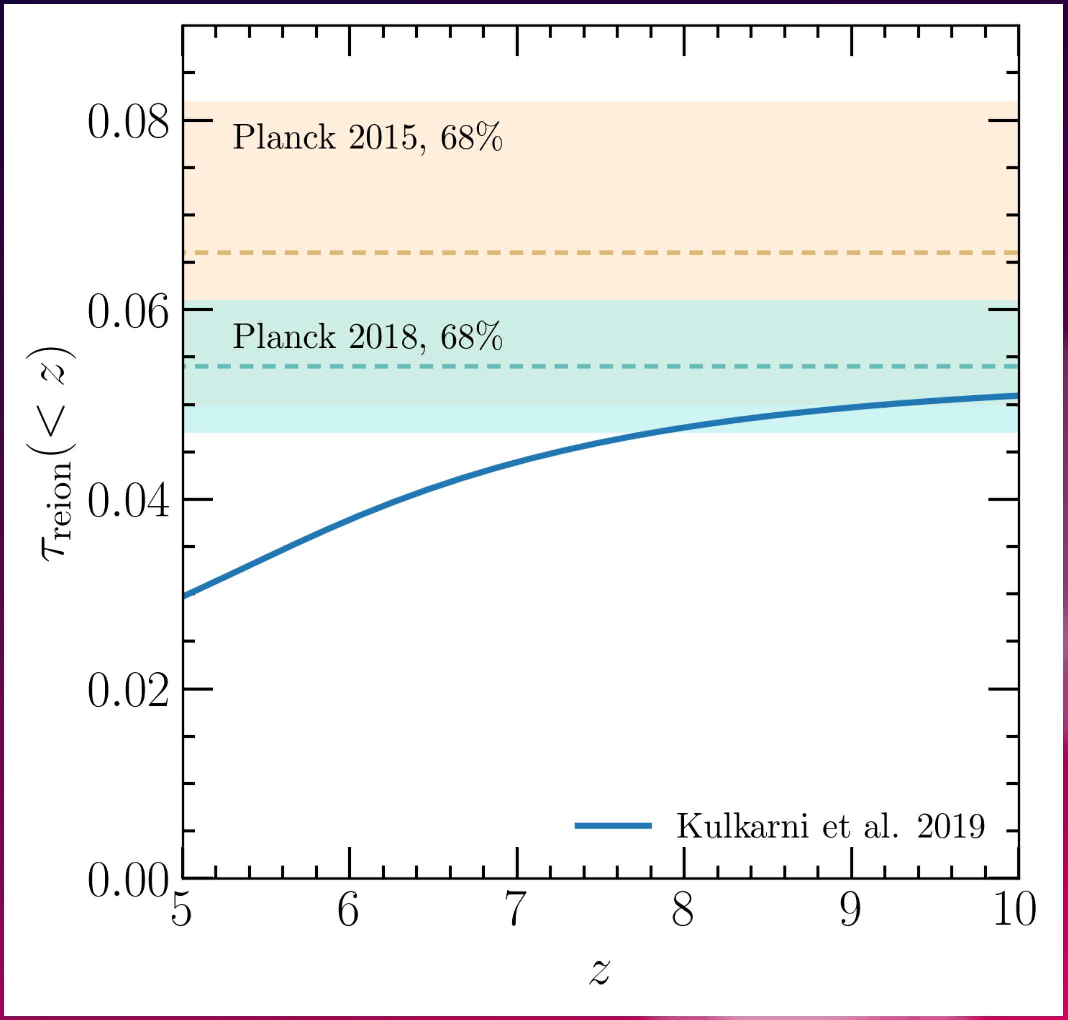

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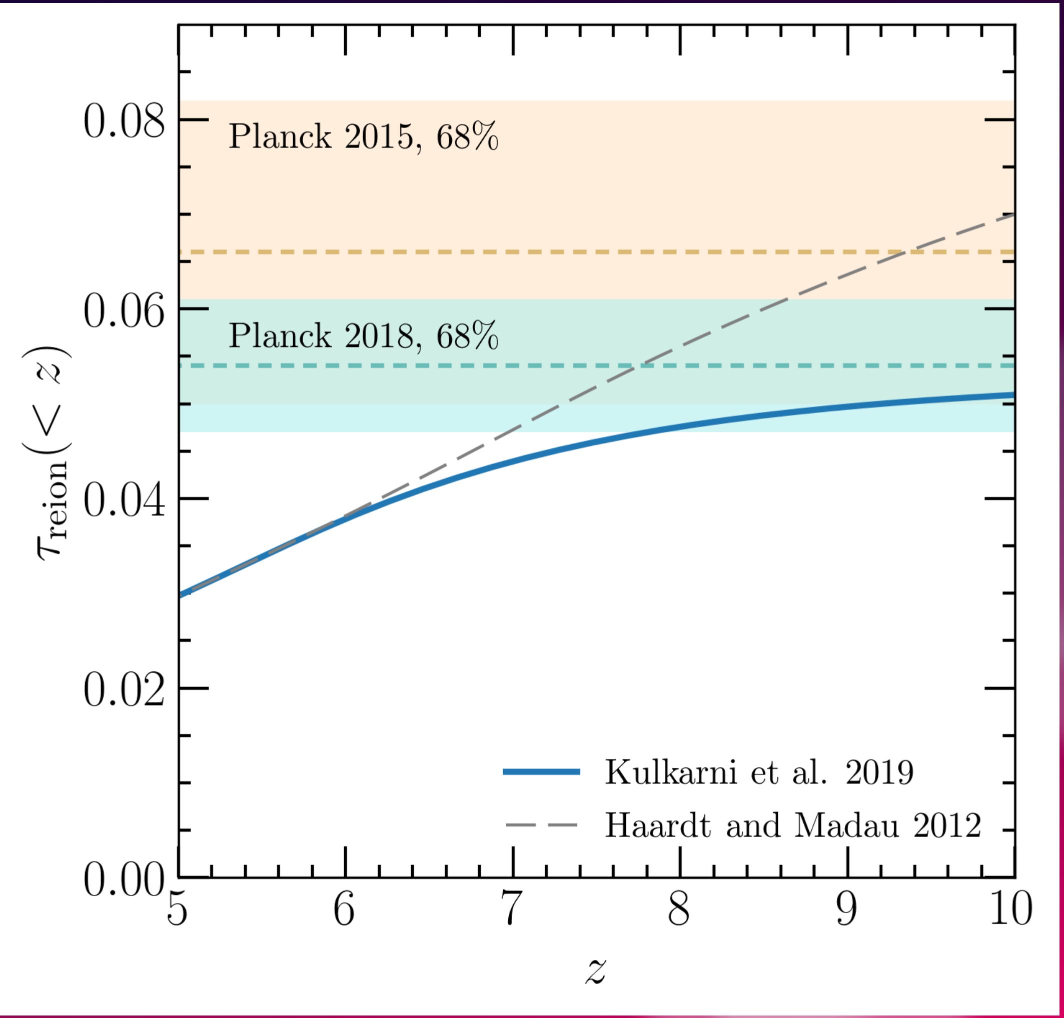
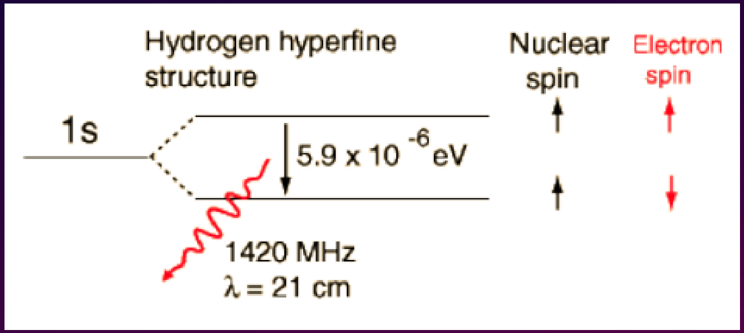


Raste et al. (2021)

Implications for 21-cm Signal

HI 21cm Signal from EoR

- Hyperfine splitting of HI ground state emits radiation of $\lambda = 21.1$ cm
- Spin temperature:

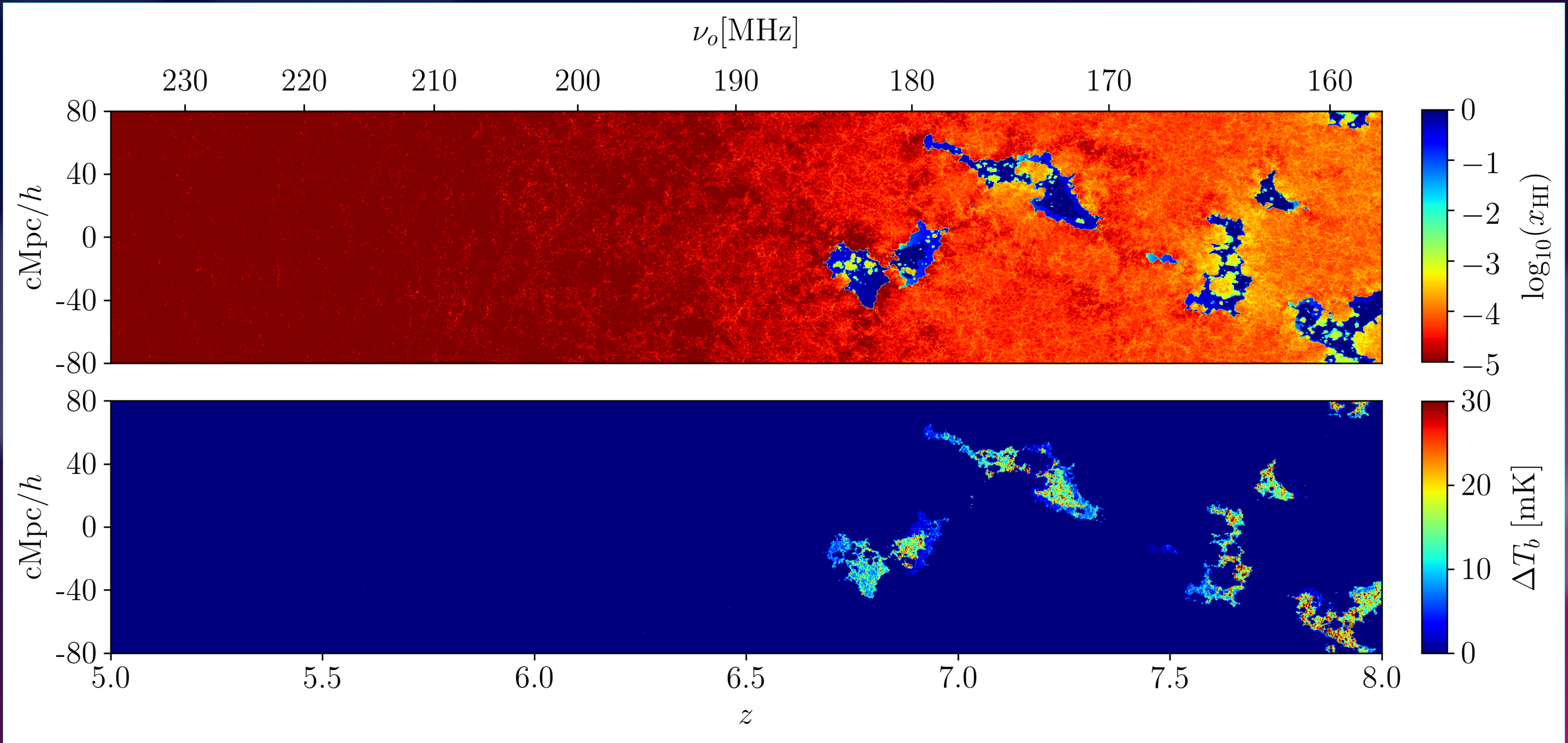


$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{h_p \nu_{21}}{kT_S}\right)$$

- Lyman-α photons and collisions couple T_S to T_K (Field 1958)
- When CMB radiations pass through a cloud of HI gas,
  - 21 cm photons are absorbed ($T_S < T_{CMB}$) from
  - or emitted ($T_S > T_{CMB}$) into it
- Change in observed brightness temperature of CMB:

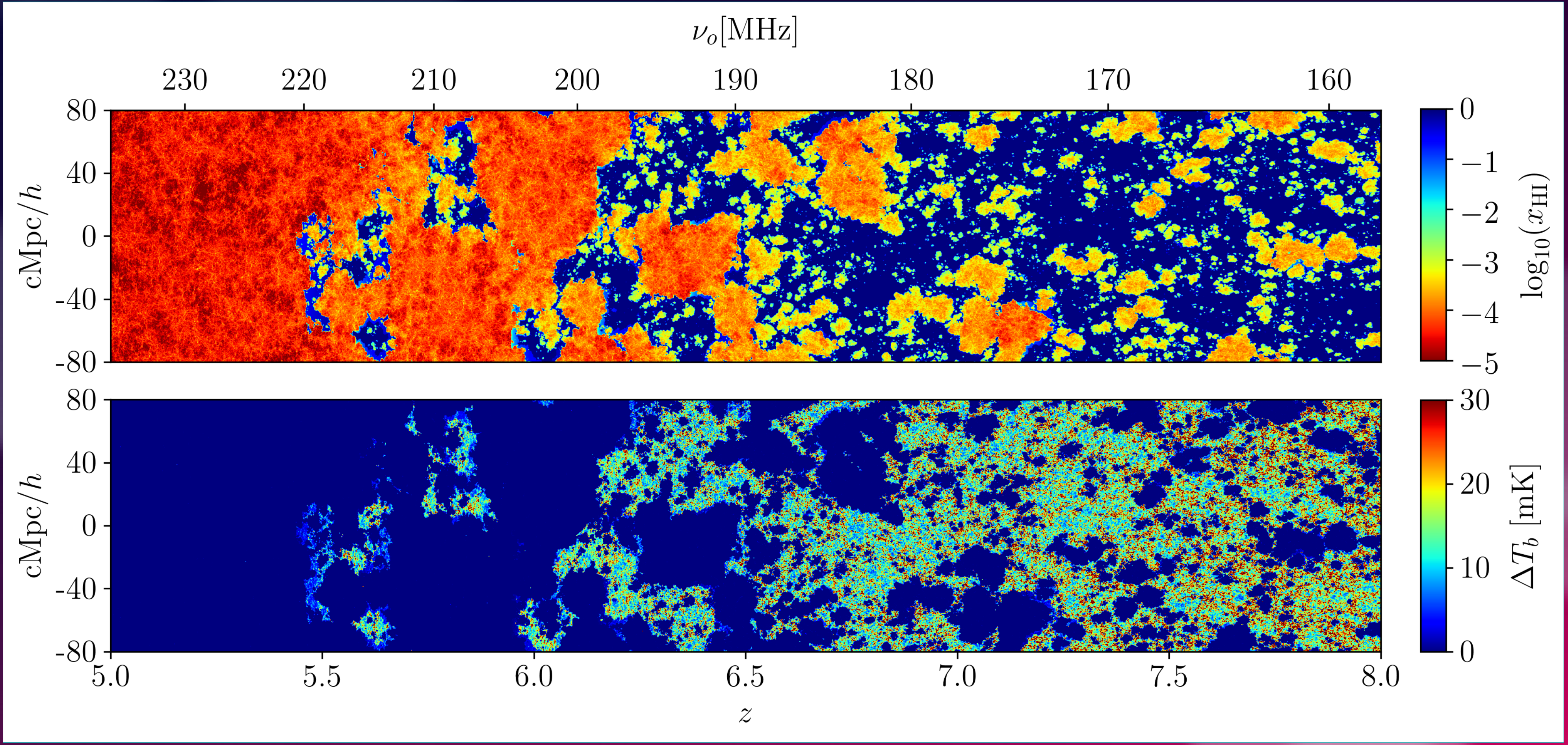
$$\Delta T_B \simeq 27 \text{ mK } x_{\rm HI}(1+\delta)\left(1-\frac{T_{\rm CMB}}{T_S}\right)\left(1+\frac{1}{H}\frac{{\rm d}v_p}{{\rm d}s}\right)^{-1}\left(\frac{1+z}{10}\right)^{\frac{1}{2}}\left(\frac{0.14}{\Omega_m h^2}\right)^{\frac{1}{2}}\left(\frac{\Omega_b h^2}{0.022}\right)$$

Early Reionization at z ~ 6.7



Raste et al. (2021)

Late Reionization at z ~ 5.3: 21-cm brightness temperature is large



Raste et al. (2021)

21-cm global signal is enhanced

$$\Delta T_B \simeq 27\ \mathrm{mK}\ x_{\mathrm{HI}}(1+\delta)\left(1-\frac{T_{\mathrm{CMB}}}{T_S}\right)\left(1+\frac{1}{H}\frac{\mathrm{d}v_p}{\mathrm{d}s}\right)^{-1}\left(\frac{1+z}{10}\right)^{\frac{1}{2}}\left(\frac{0.14}{\Omega_m h^2}\right)^{\frac{1}{2}}\left(\frac{\Omega_b h^2}{0.022}\right)$$

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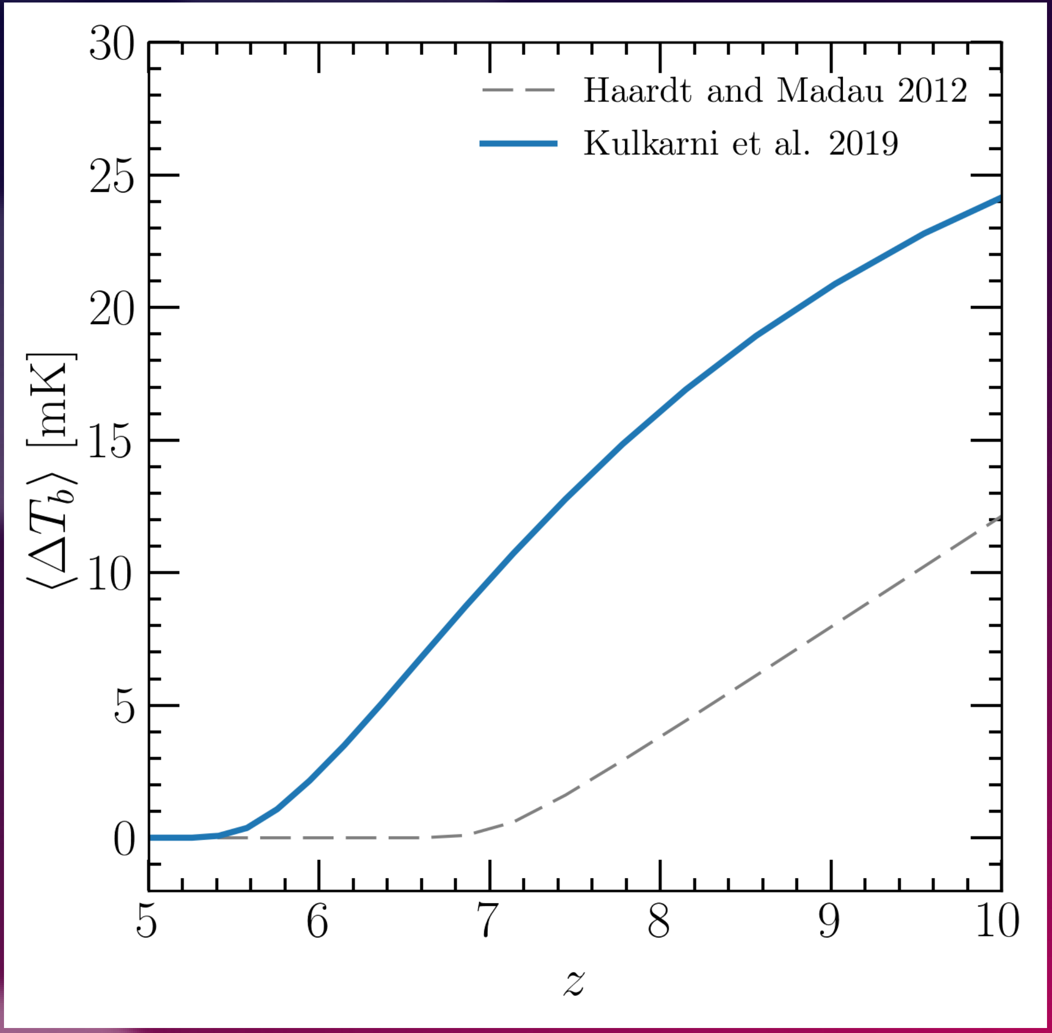


Approximation :
$T_S \gg T_{CMB}$ at $z < 10$

Therefore,

$0\ \mathrm{mK} \leqslant \langle \Delta T_b \rangle < 28.3\ \mathrm{mK}$

at $z < 10$

Power Spectrum

Brightness temperature power spectrum:

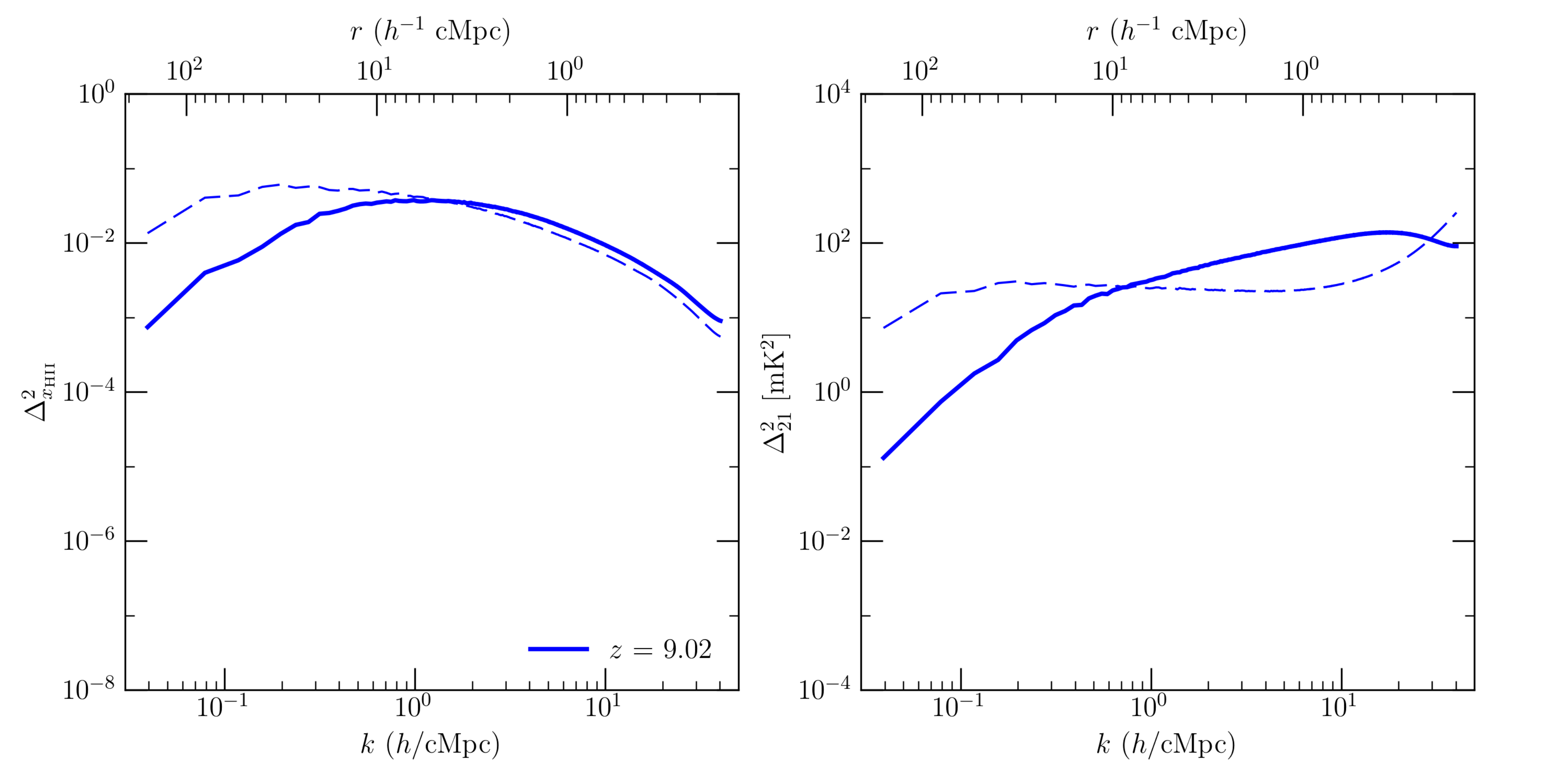
$$\langle \tilde{T}_B(k_1)\tilde{T}_B(k_2)\rangle = (2\pi)^2\delta_D(k_1 + k_2)P_{21}(k_1)$$

$$T_B \overset{\text{FT}}{\Longleftrightarrow} \tilde{T}_B$$

Dimensionless power spectrum:

$$\Delta^2_{21}(k) = \frac{k^3}{2\pi^2}P_{21}(k)$$

Power spectrum of 21-cm Signal



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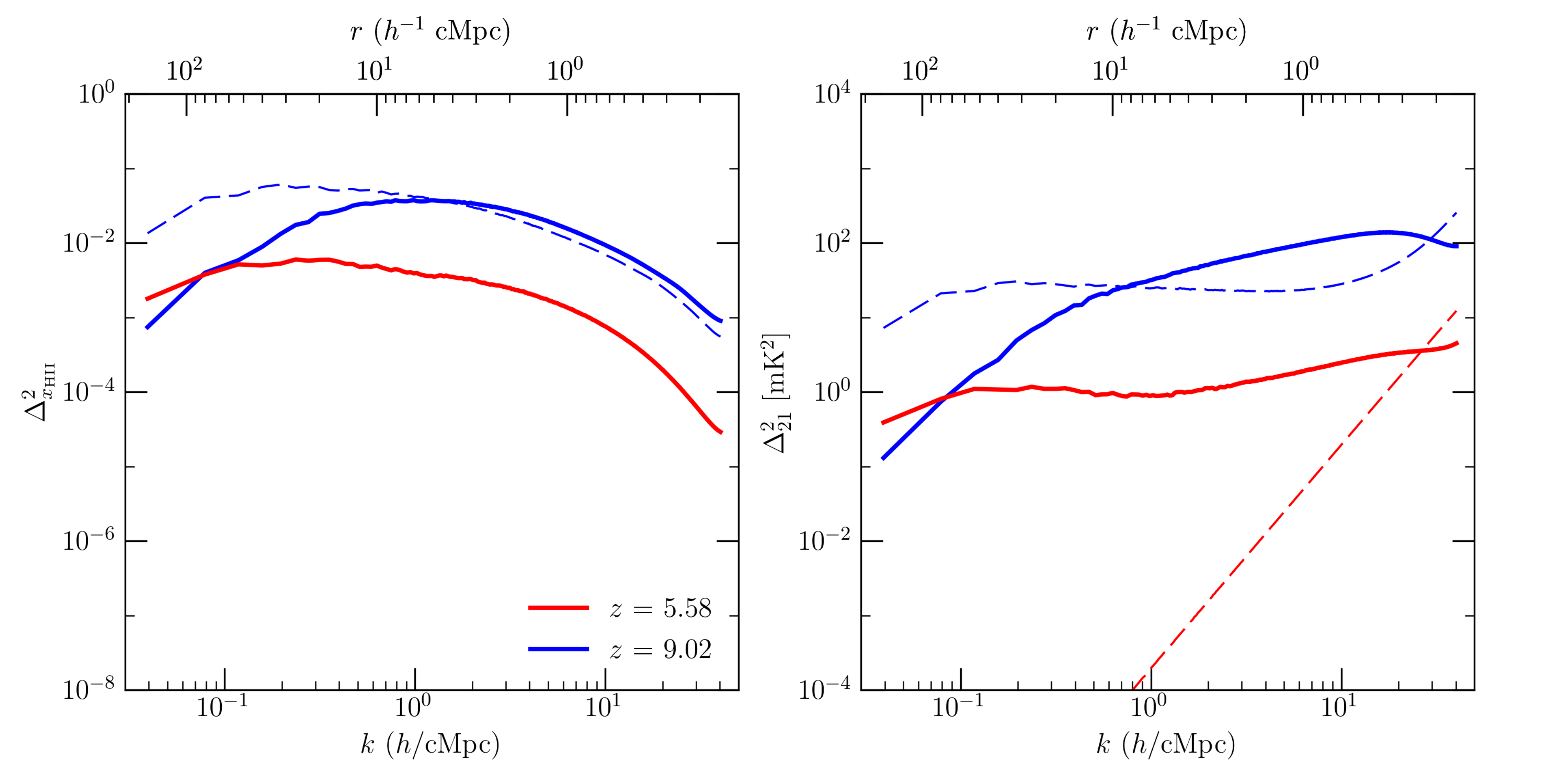
Orders of magnitude enhancement in Power



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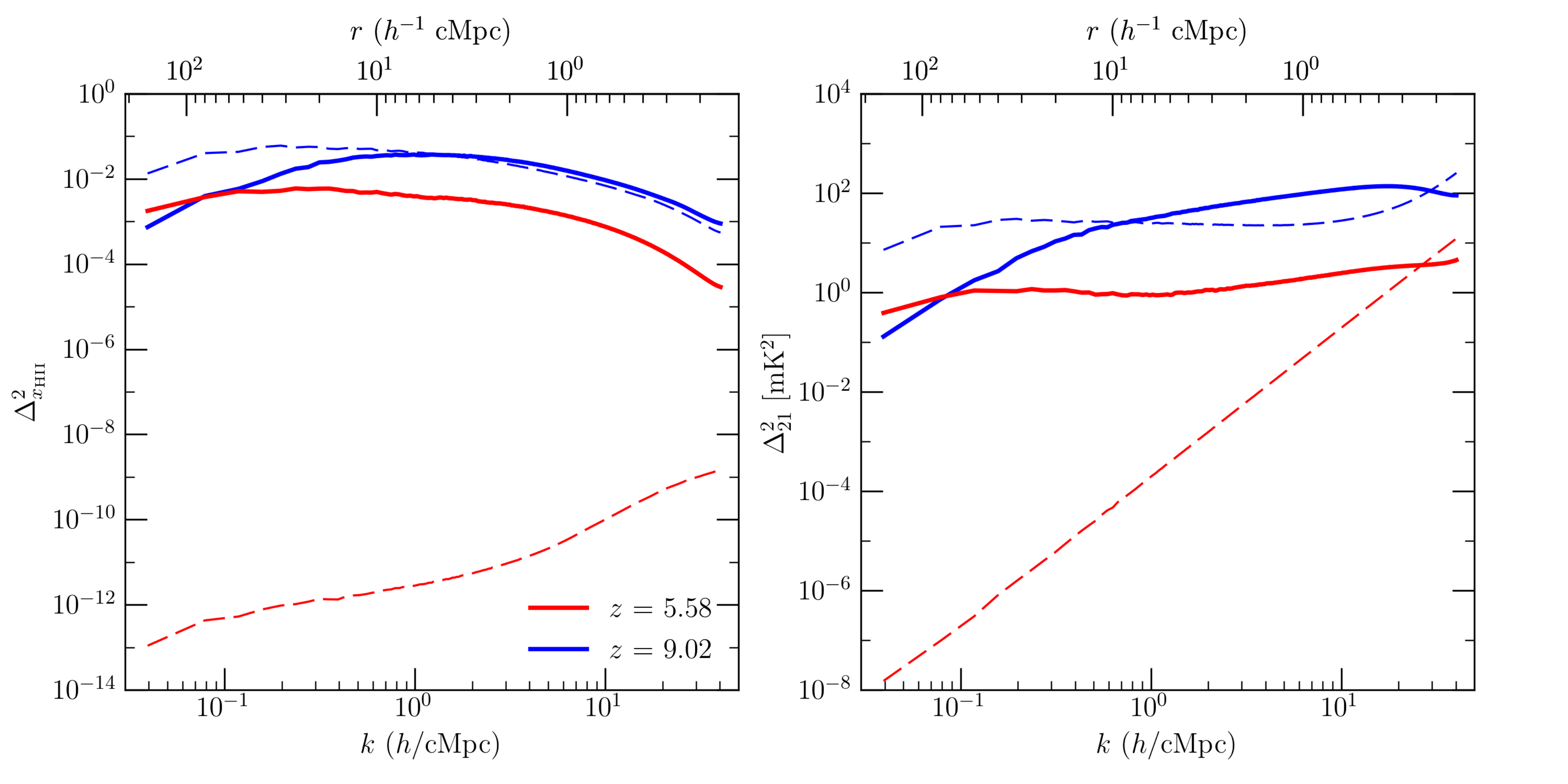

Raste et al. (2021)

Observational Prospects at $5.4 \lesssim z \lesssim 6$ (203 – 222 MHz)

- Contaminants: galactic synchrotron radition, extra-galactic point sources, Earth atmosphere, ionosphere, RFI, instrument system noise, ...
- Synchrotron foreground are weaker at higher frequency:

$$T \propto \nu^{-2.55}$$

- Radio Interferometers:
  - MWA [observing]
  - LOFAR [observing]
  - HERA [building, observing]
  - SKA1-LOW [upcoming]

Murchison Widefield Array (MWA)

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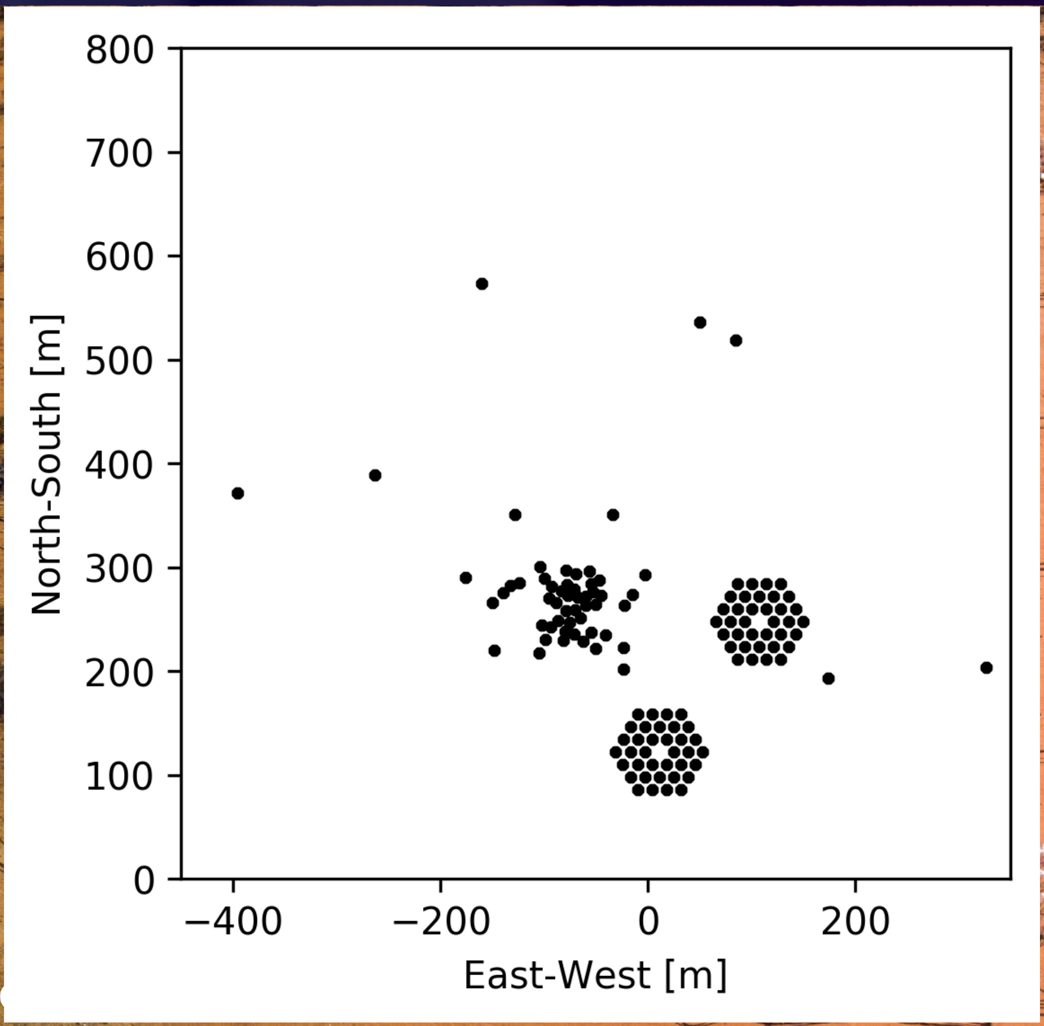

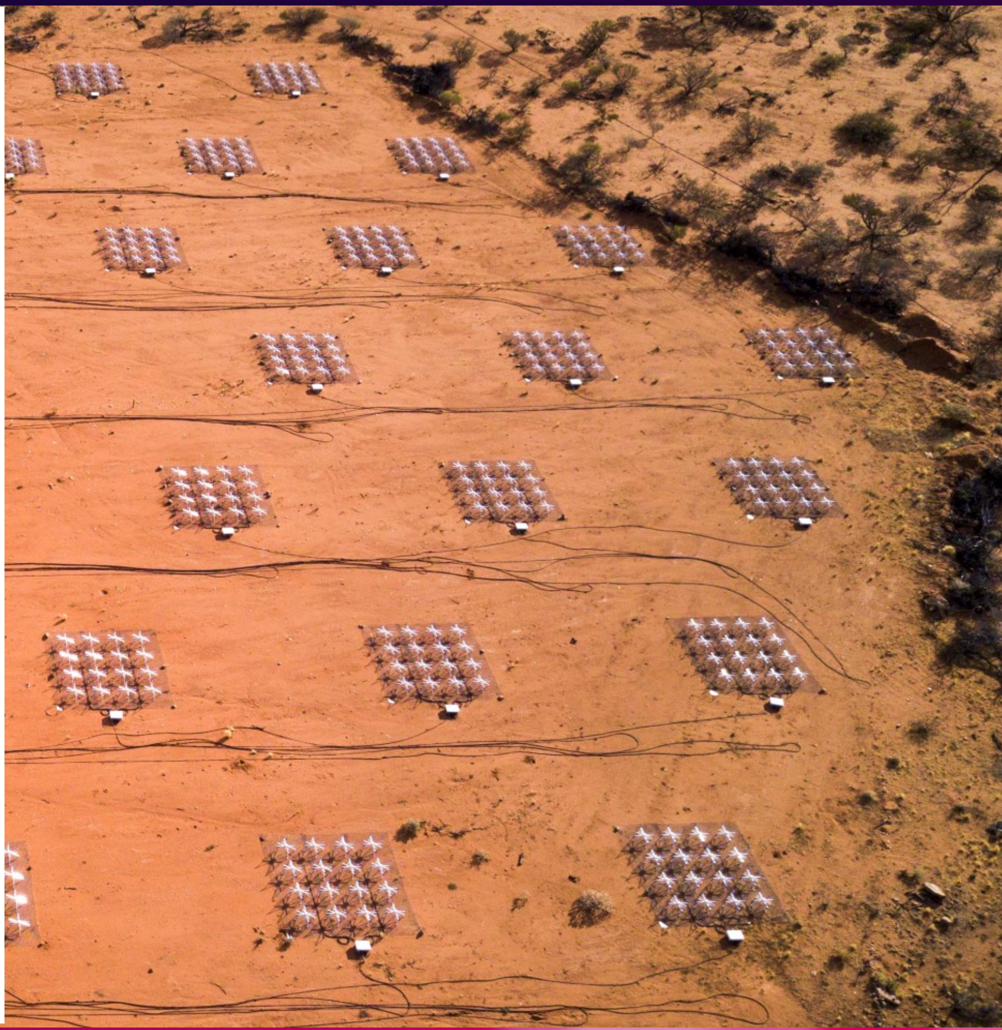

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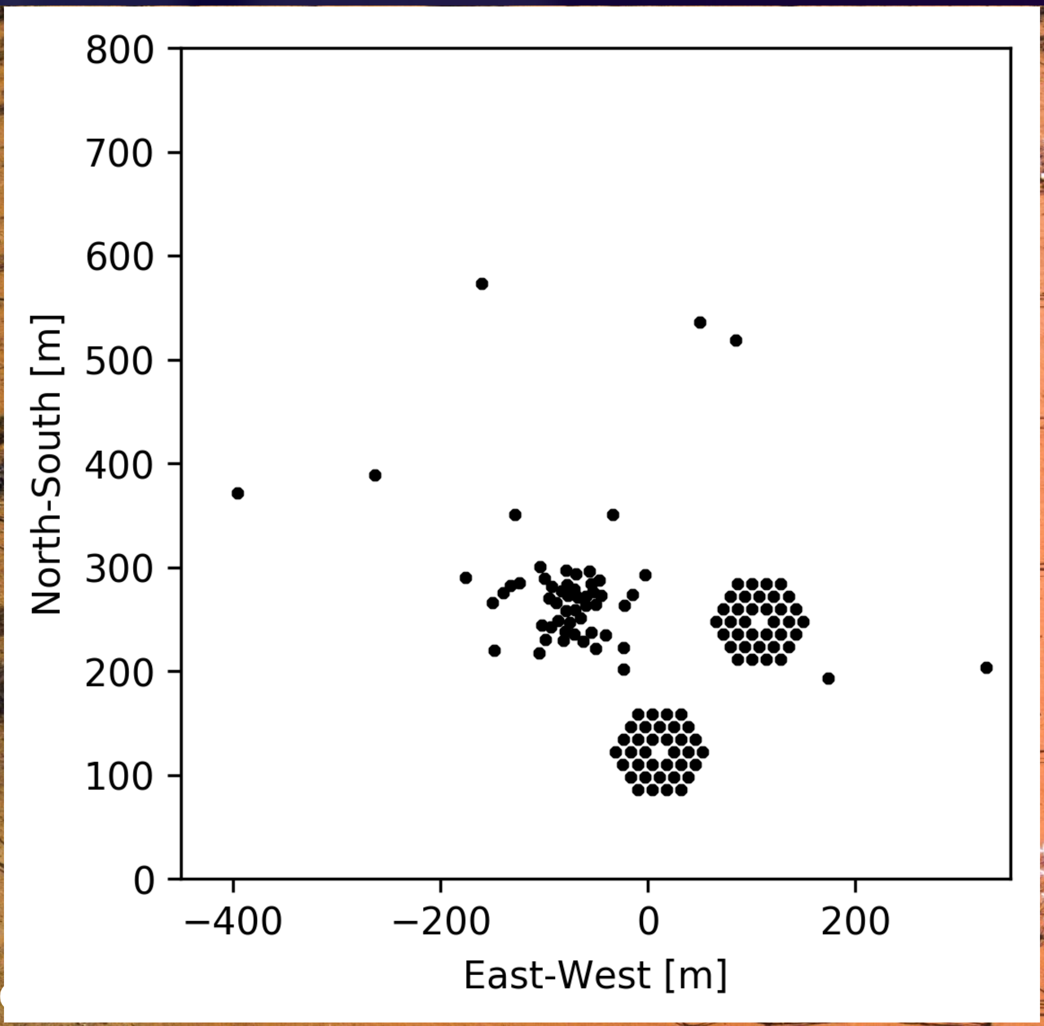
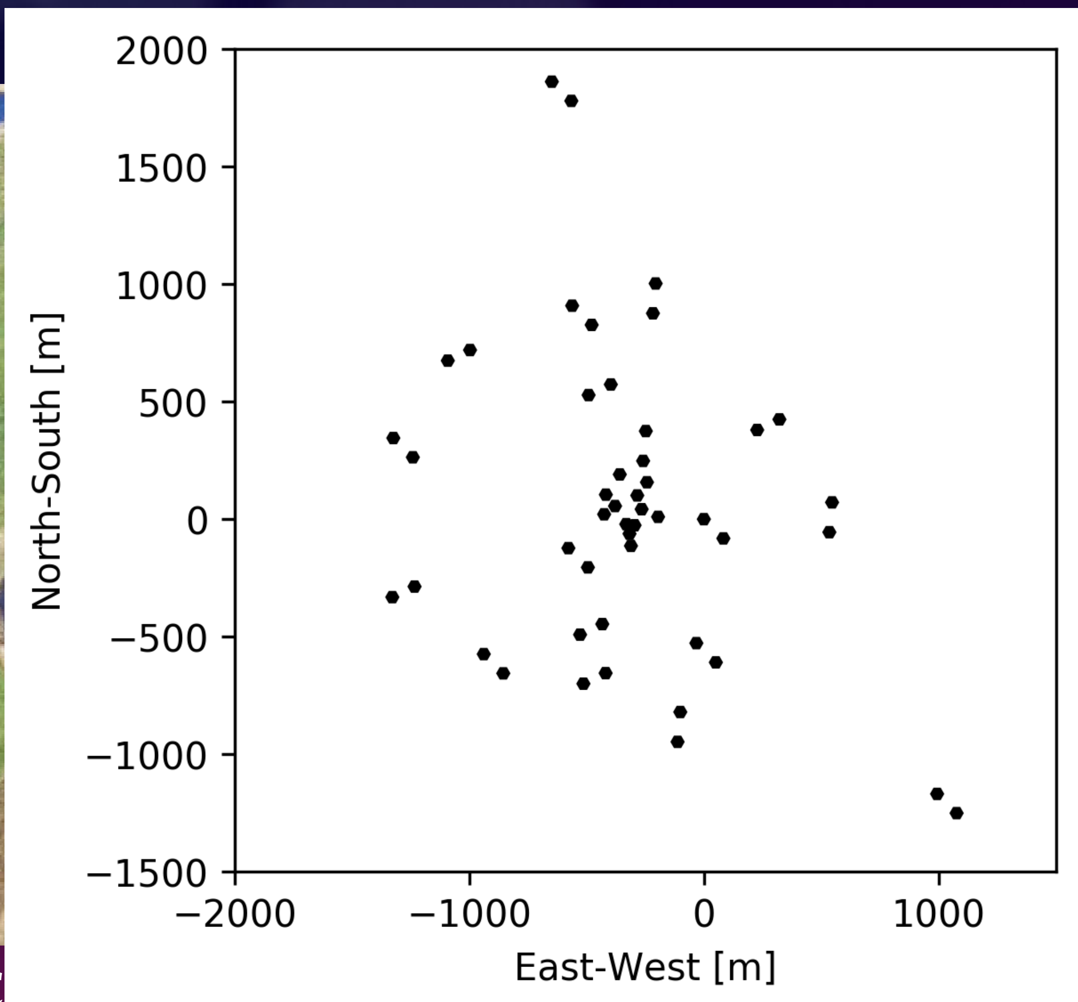


- Phase II Compact Configuration
- Antennas: 128
- Element size ≈ 4 m
- b_{min} ≈ 7.7 m
- b_{max} ≈ 740 m
- Freq. range ≈ 70–300 MHz (3.73 < z < 19.29)
- Freq. resolution ≈ 40 kHz
- Location: western Australia

Low-Frequency Array (LOFAR)

Credit: https://www.astron.nl/telescopes/lofar

Low-Frequency Array (LOFAR)



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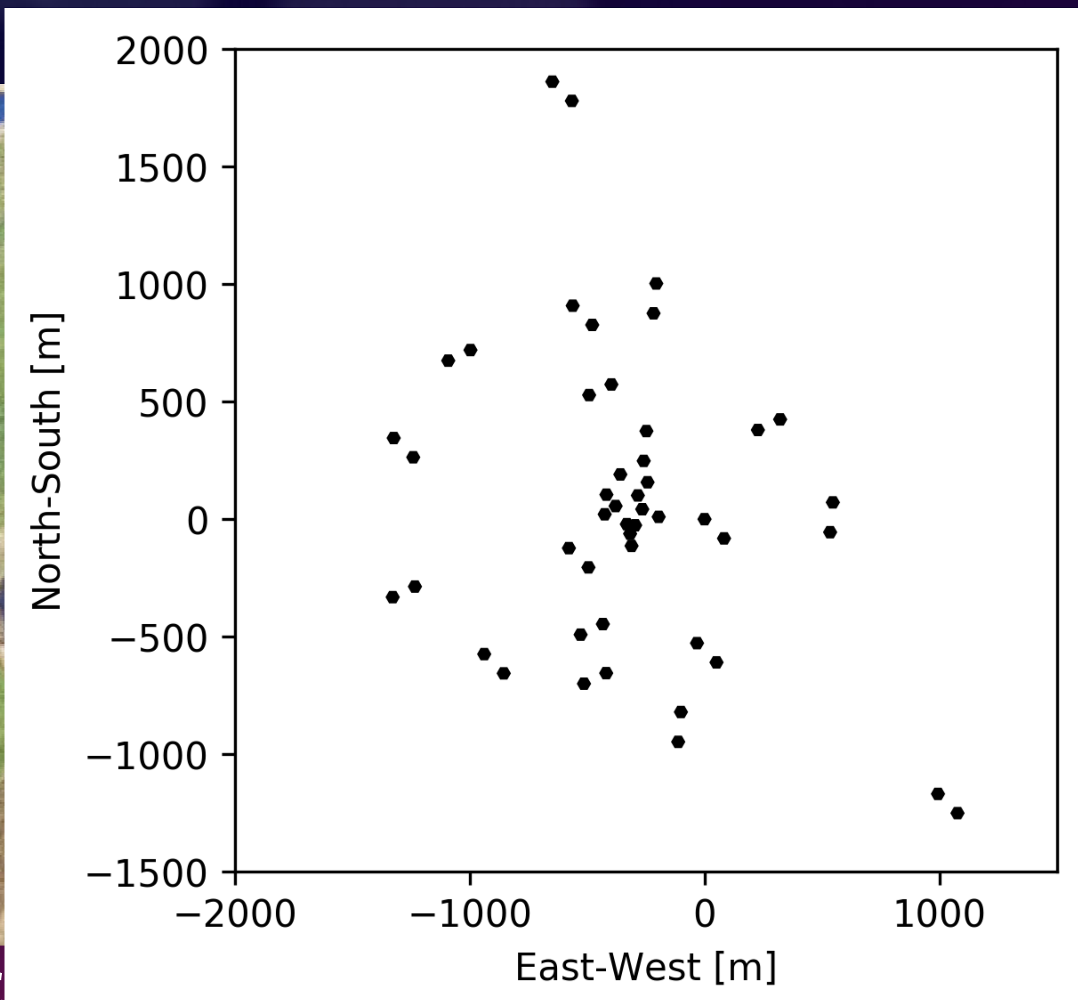

- High Band Antenna (HBA) Core Configuration
- Antennas (split-mode): 24 x 2
- Element size ≈ 30.75 m
- b_{min} ≈ 35.7 m
- b_{max} ≈ 3550 m
- Freq. range ≈ 120–240 MHz ($4.92 < z < 10.83$)
- Freq. resolution ≈ 61 kHz
- Location: Netherlands

Hydrogen Epoch of Reionization Array (HERA)

Credit: Daniel Jacobs

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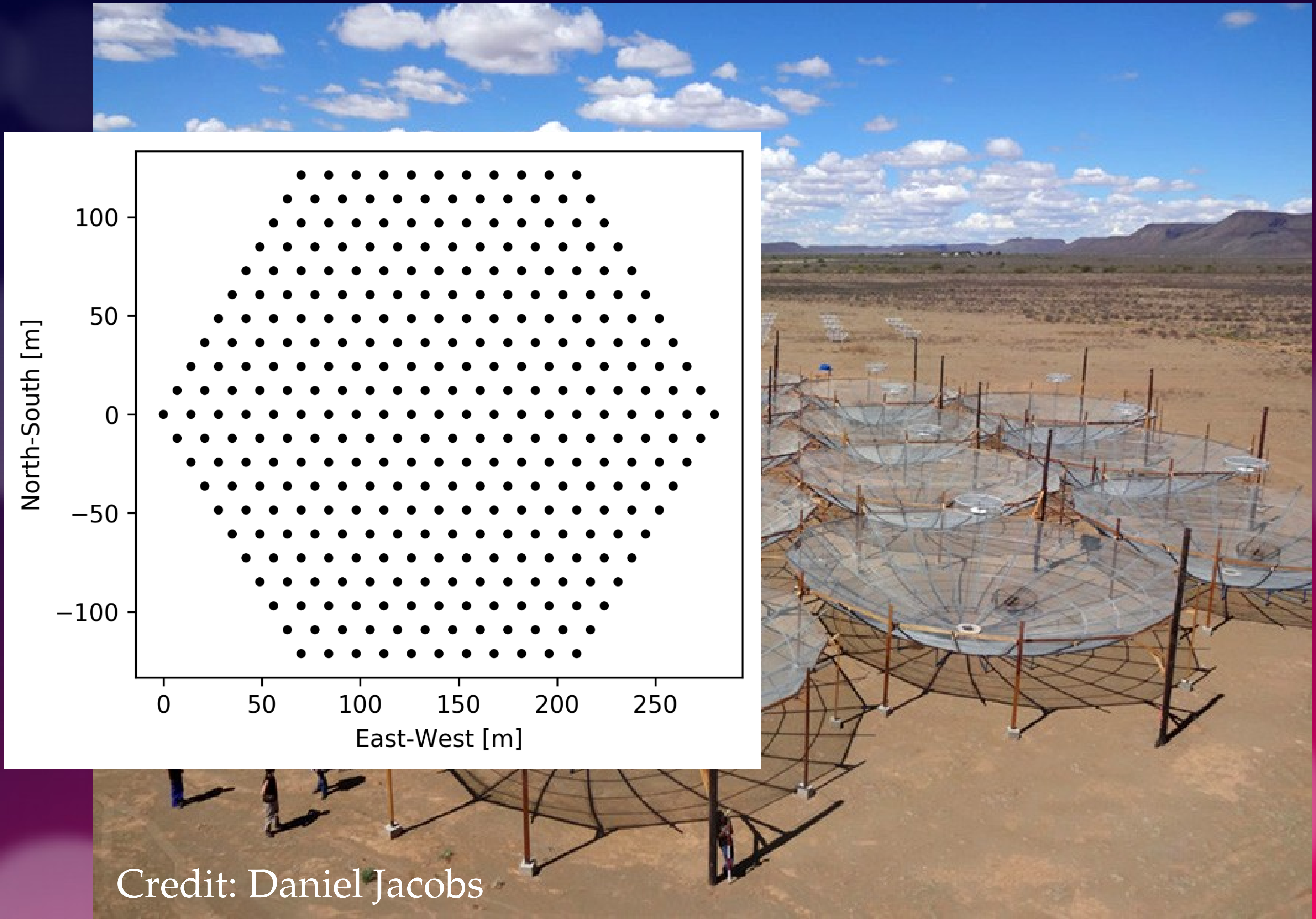

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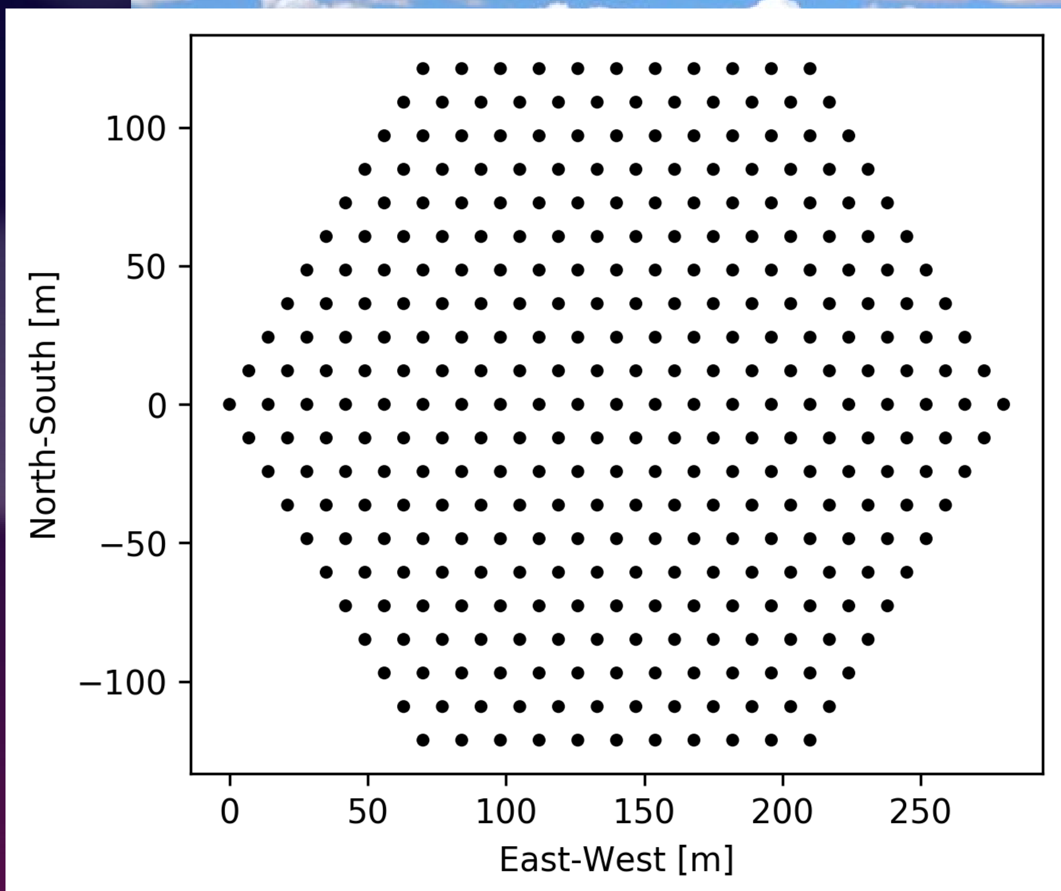
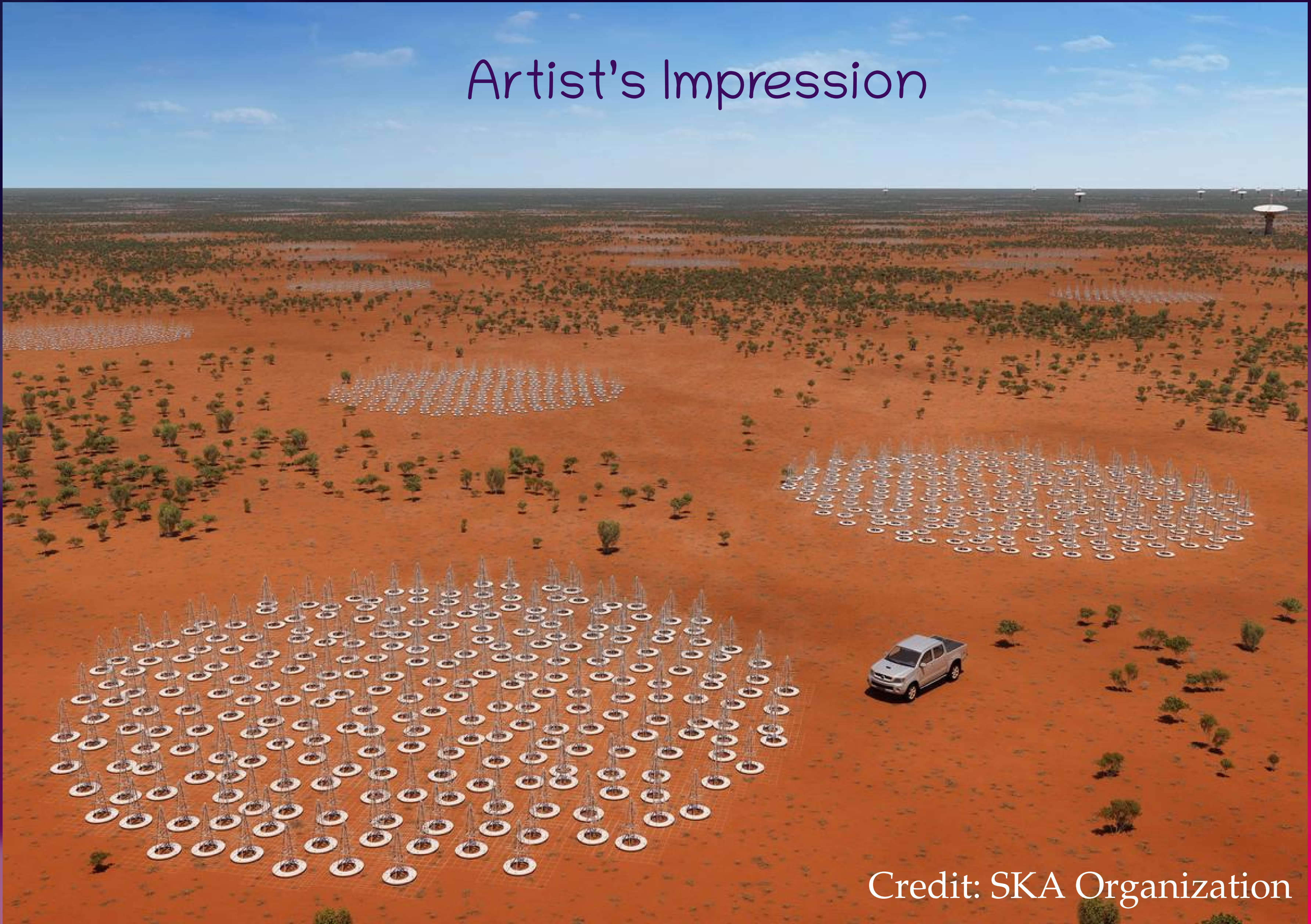


- Hexagon with side: 11
- Antennas: 331
- Element size ≈ 14 m
- b_{min} ≈ 14 m
- b_{max} ≈ 280 m
- Freq. range ≈ 50–250 MHz ($4.7 < z < 27.4$)
- Freq. resolution ≈ 97.8 kHz
- Location: South Africa

Credit: Daniel Jacobs

Square Kilometre Array SKA1-LOW



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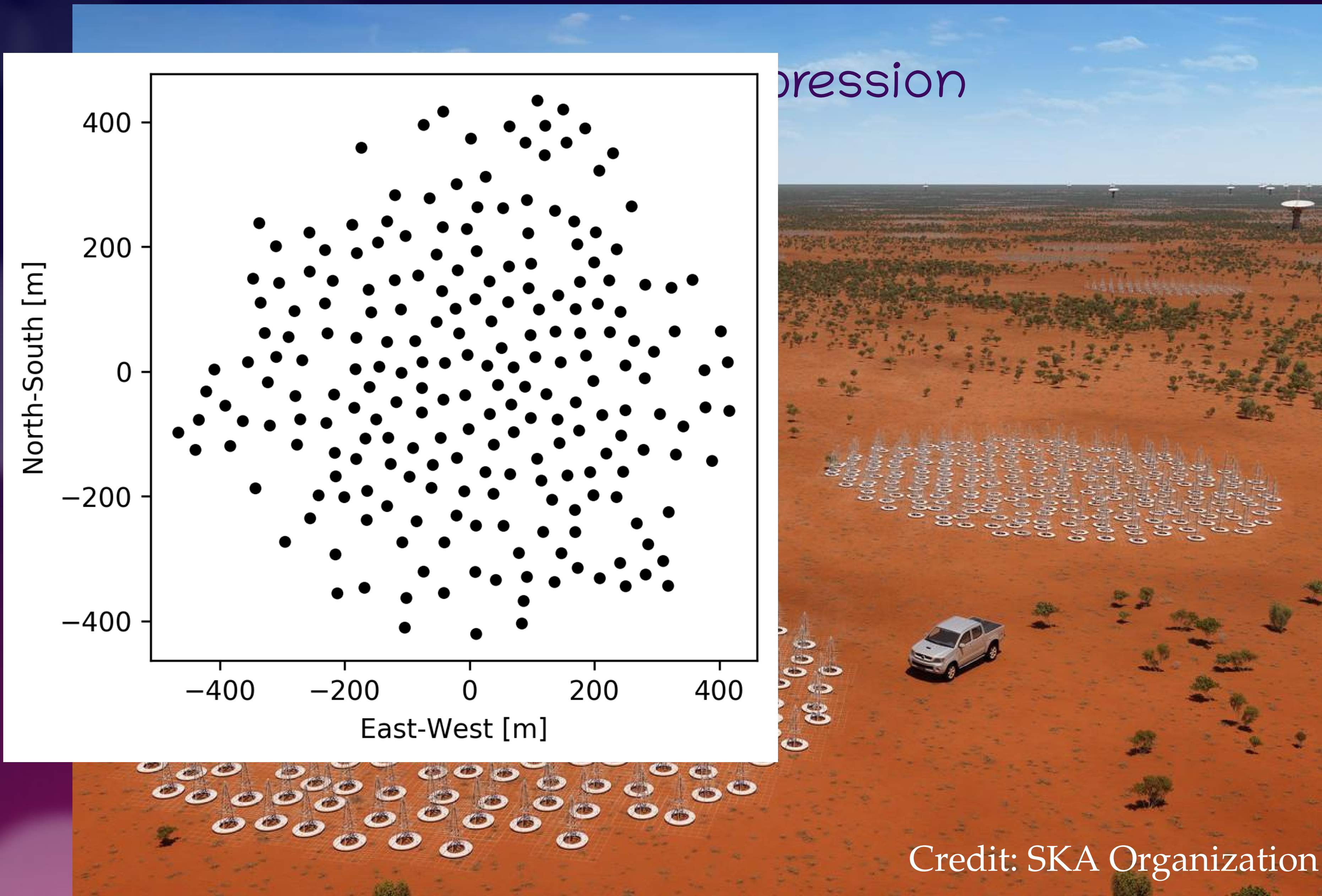

Credit: SKA Organization

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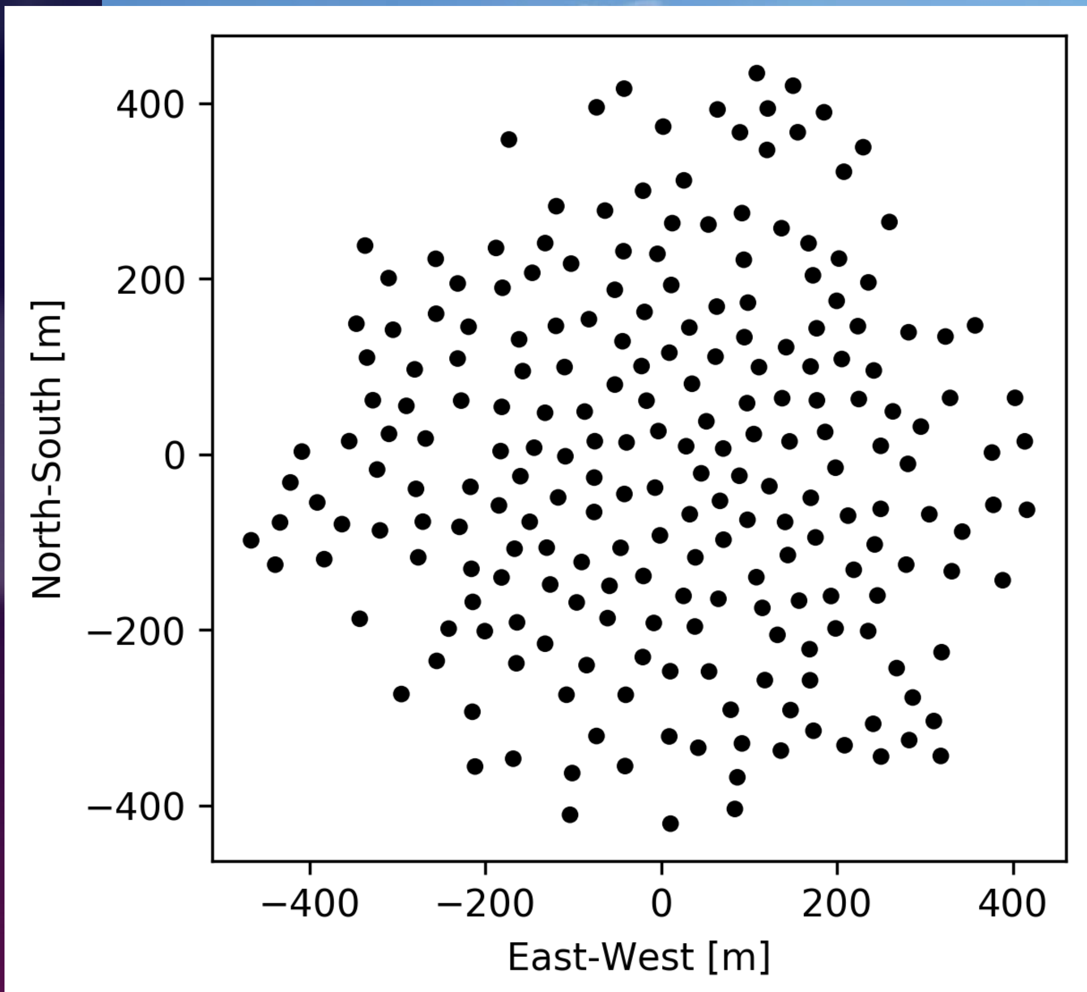


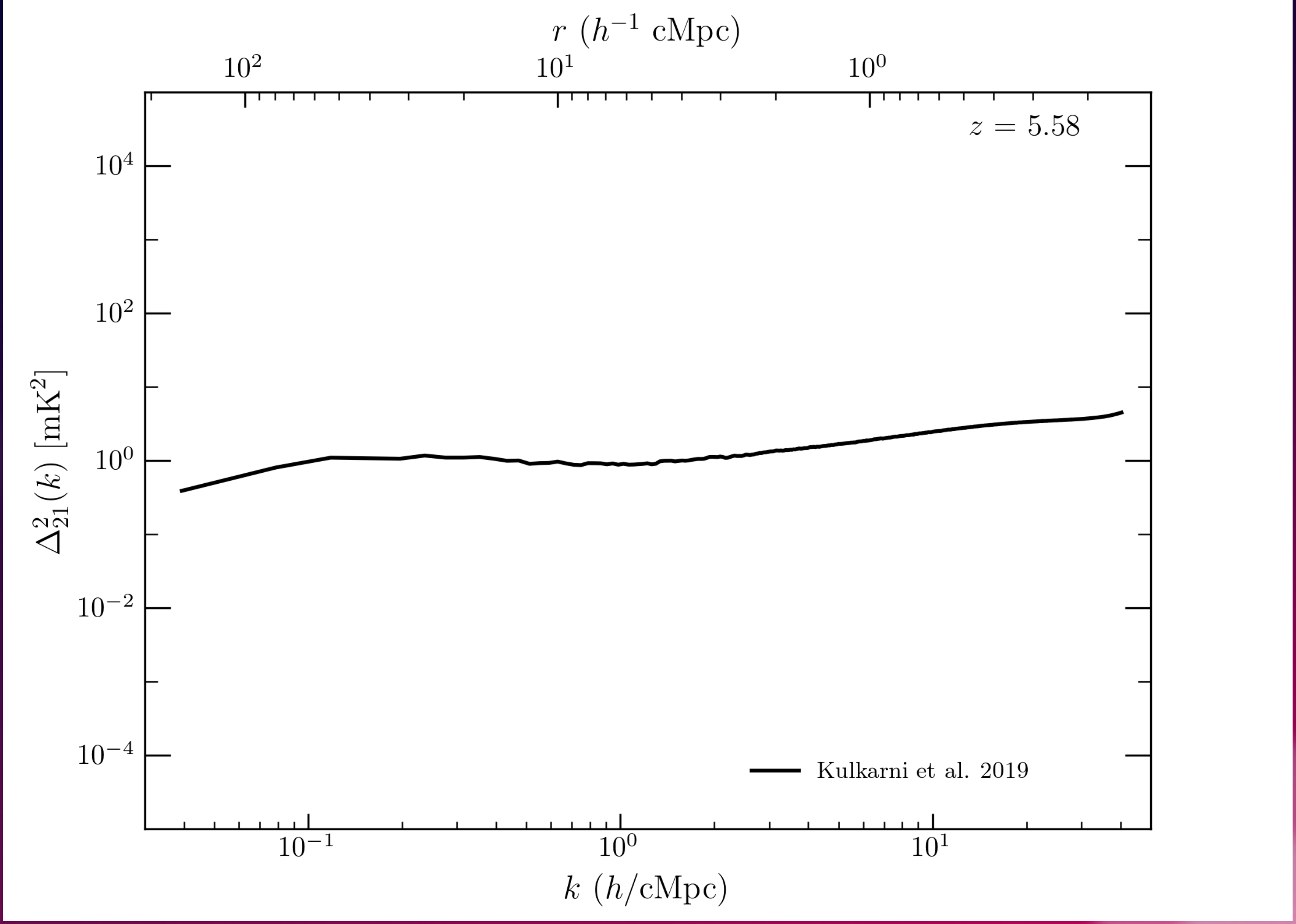
- Core Configuration
- Stations: 224
- Element size ≈ 35 m
- b_{min} ≈ 35.1 m
- b_{max} ≈ 887 m
- Freq. range ≈ 50–350 MHz (3.06 < z < 27.4)
- Freq. resolution ≈ 70 (?) kHz
- Location: Western Australia

Credit: SKA Organization

Sensitivity

- **Sensitivity**: Weakest signal that is detectable by the instrument
- We use `21cmSense` (Pober et al. 2013, 2014) to compute instrument sensitivities:
  - Tracking mode
  - Number of days of observation: 180
  - observation duration per day: 6 hr
  - Bandwidth: 8 MHz
  - Moderate foreground models

Can we detect 21-cm signal at z = 5.58?



Raste et al. (2021)

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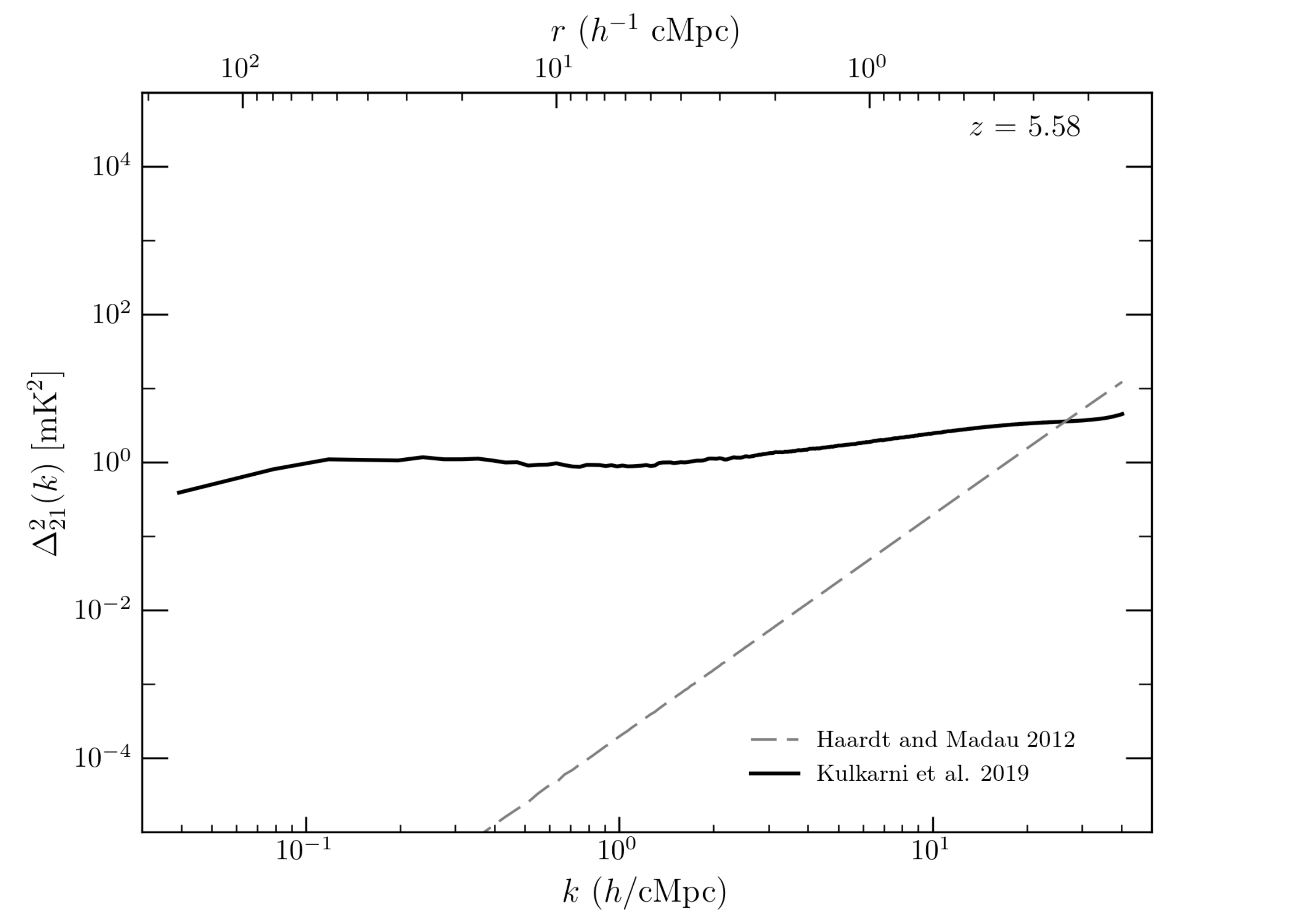

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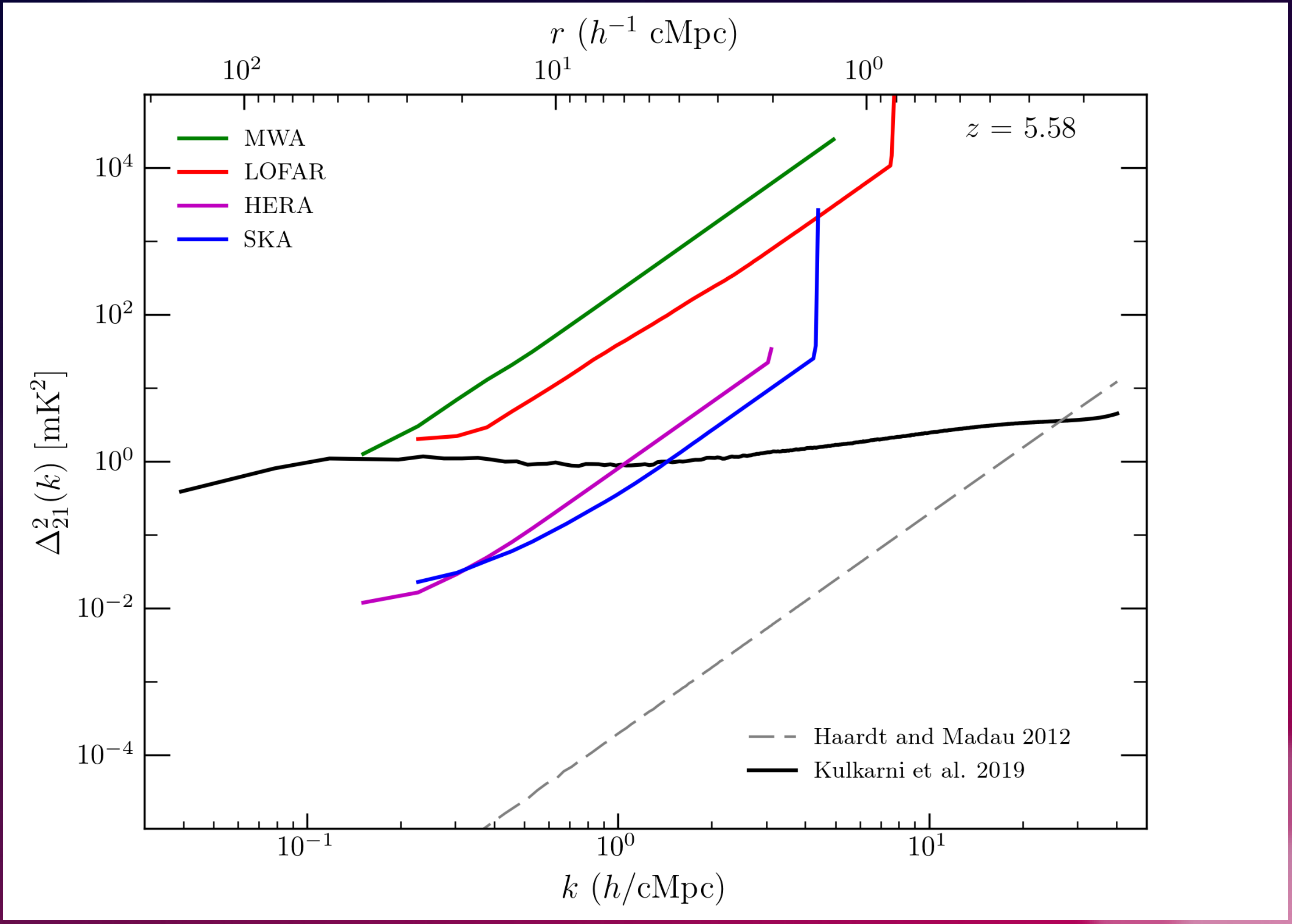
HERA and SKA1-LOW look promising !



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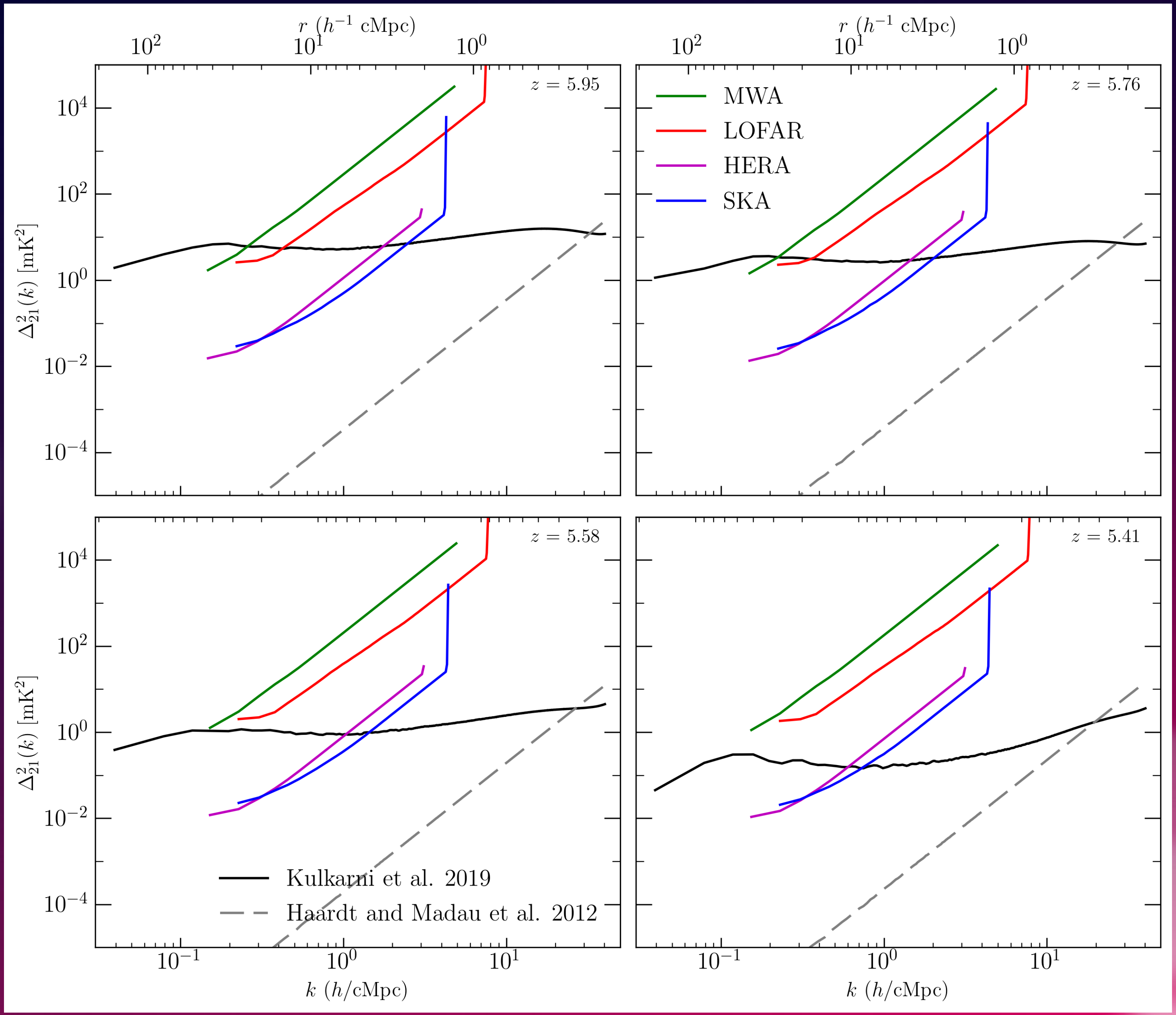

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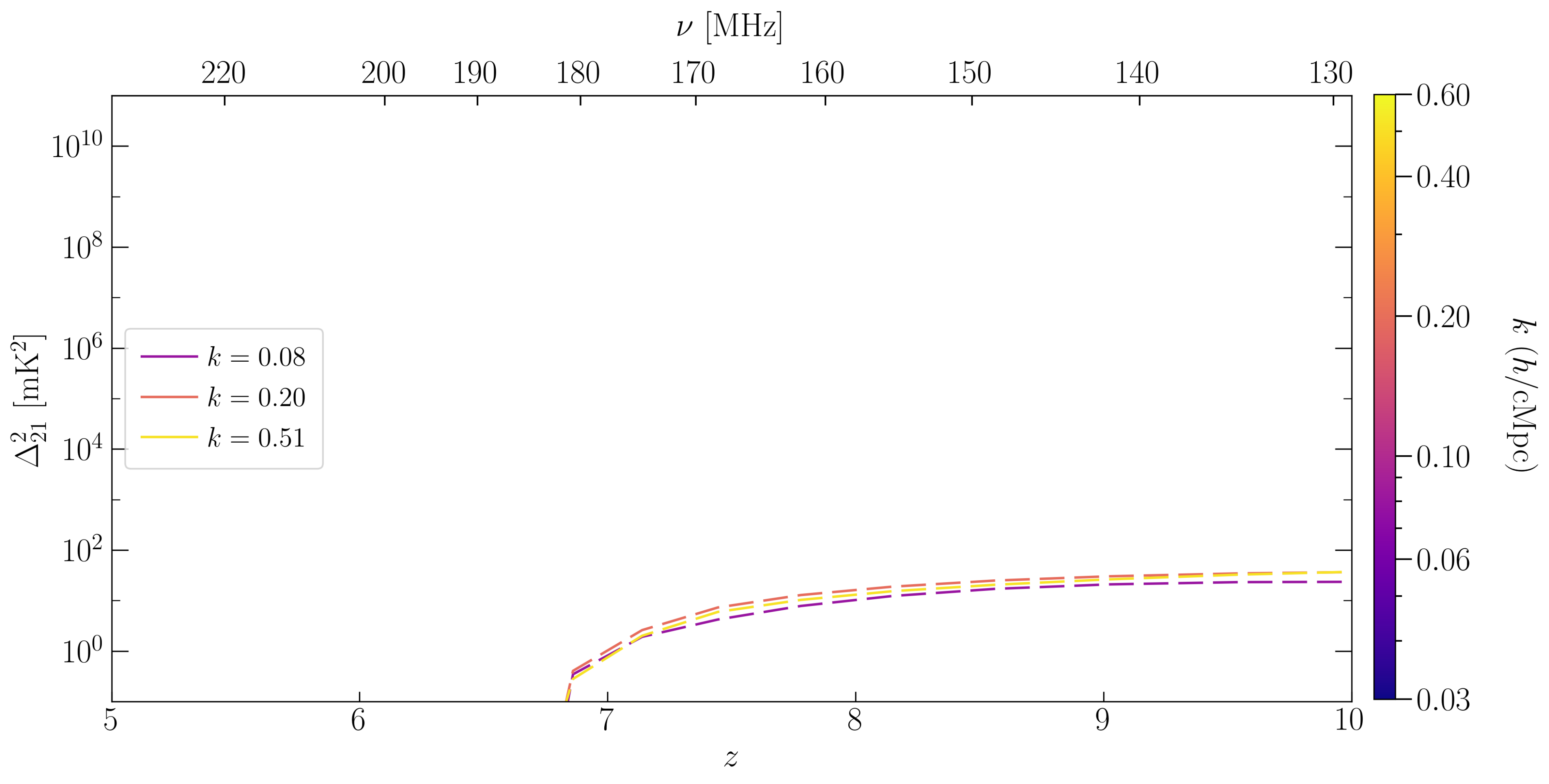
Evolution of power spectra $\Delta^2_{21}(k)$



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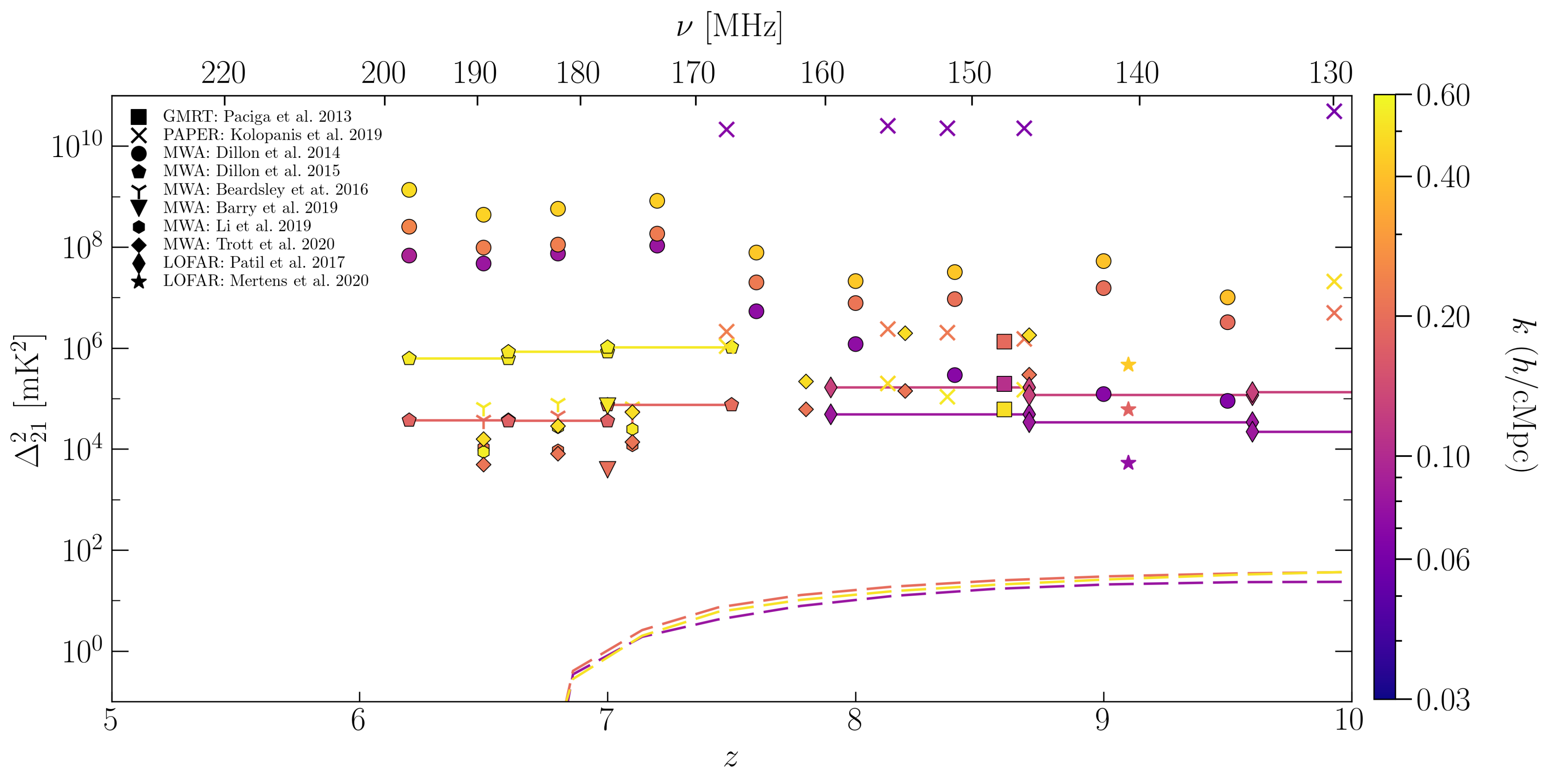
Δ^2_{21} upper limits have improved over years



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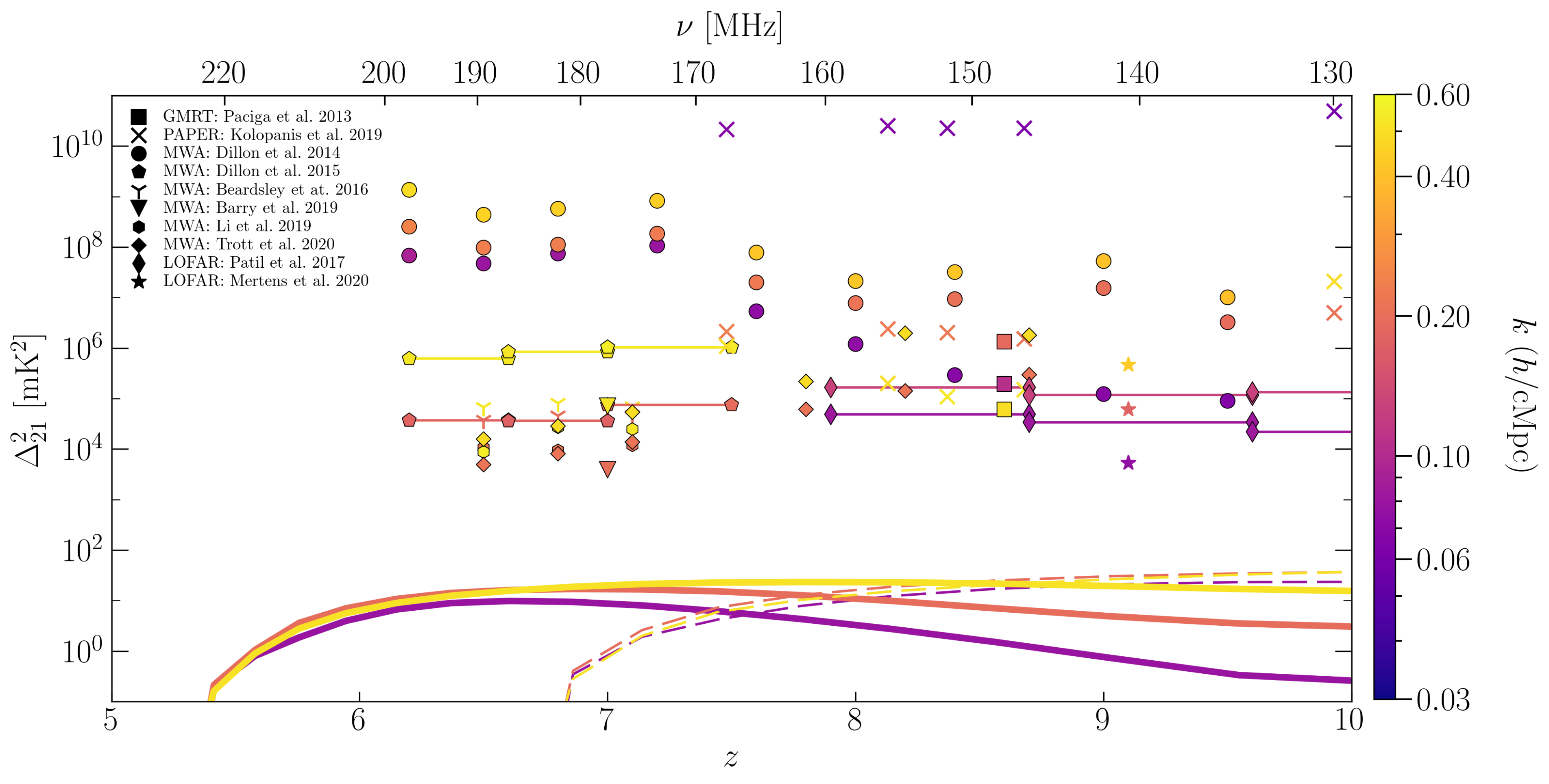

Raste et al. (2021)

Summary

- Spatial fluctuations of Ly-α forest $\tau_{\rm eff}$ imply that reionization is late and patchy. It ends at $z \sim 5.3$.

- 21-cm power spectra at $5.4 \lesssim z \lesssim 6$ are enhaced by orders of magnitude.

- Readily observed with SKA1-LOW and HERA for 1080 hr of observation assuming optimistic foreground models.