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Radiative transfer of Lyα photons with realistic gas physics

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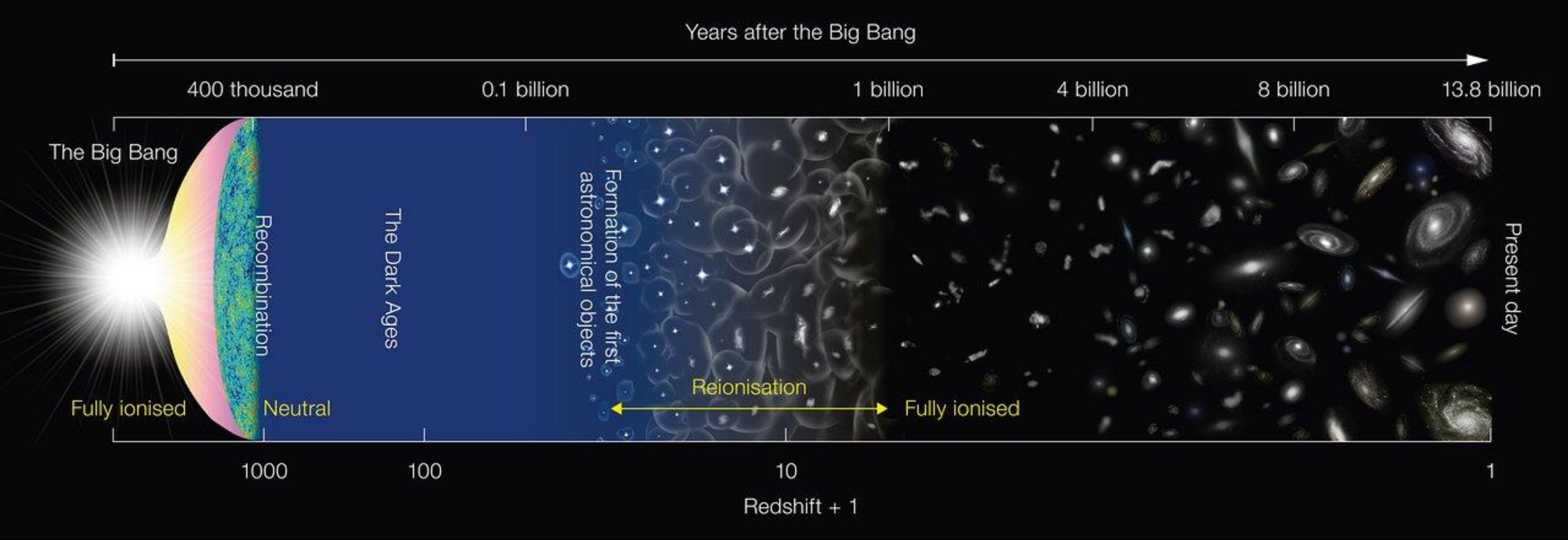
Advanced 21-cm Cosmology Workshop

National Institute of Science Education and Research, Bhubaneswar

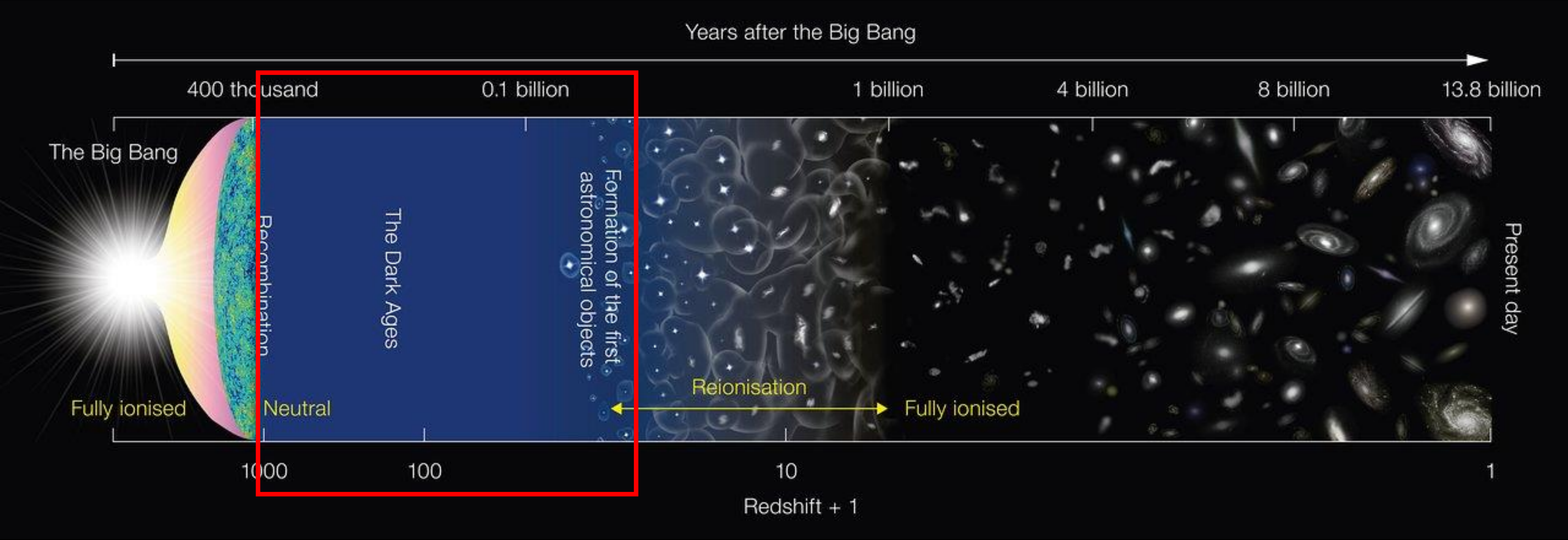
Outline

- Context and Motivation
- Methodology
- Results

Milestones in the history of the Universe

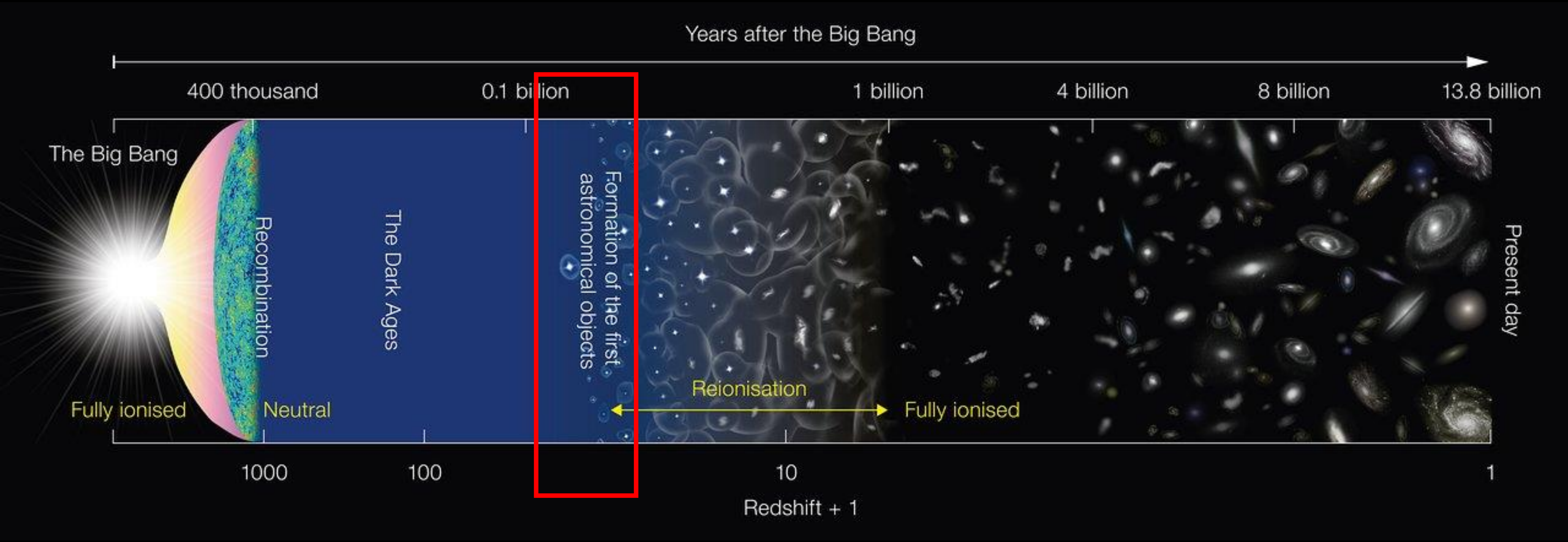


21-cm signal can probe dark ages and cosmic dawn



Dark ages + cosmic dawn

We will focus on cosmic dawn



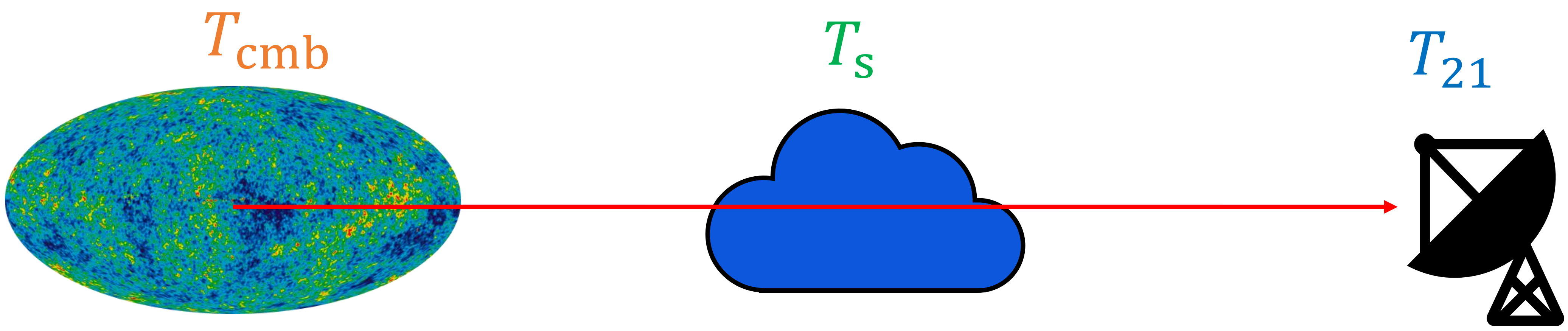
cosmic dawn

21-cm experiments are targeting cosmic dawn

- EDGES (Judd Bowman, ASU): They made the first detection in 2018
- SARAS (Saurabh Singh, RRI): Reject EDGES measurement
- **REACH** (Eloy de Lera Acedo, University of Cambridge)
    1. Radio Experiment for the Analysis of Cosmic Hydrogen
    2. Will cover $28 > z > 7.5$
    3. Karoo radio reserve in South Africa
    4. Funded by Kavli Foundation and Stellenbosch University
    5. Data expected in early 2024

MIST, PRIzM, ALBATROS, PRATUSH, ROLSES and more in development

The 21-cm signal

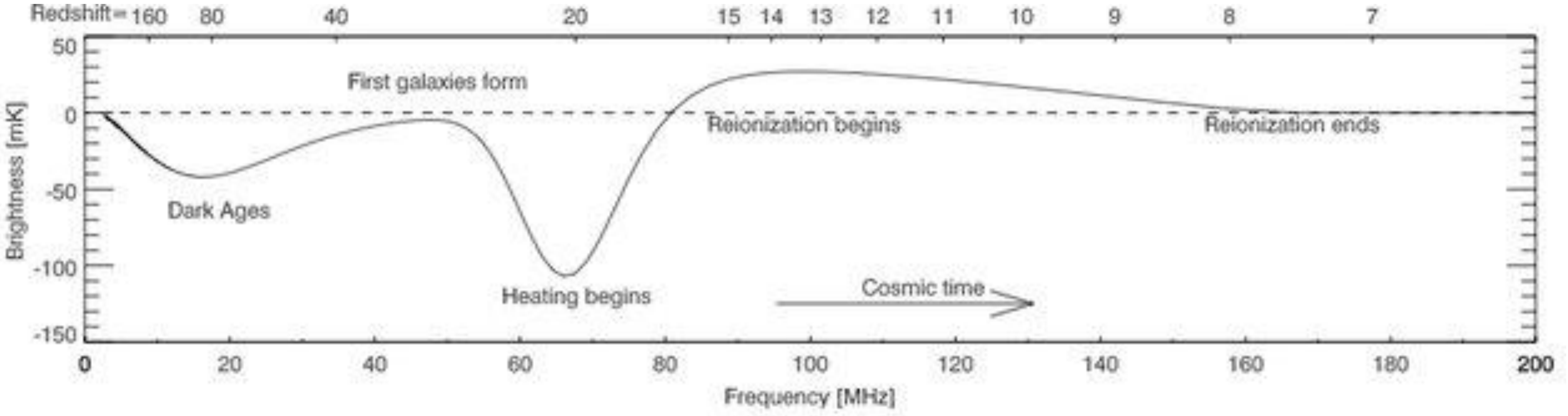


Our observable is the 21-cm brightness temperature relative to the background (CMB) temperature:

$$T_{21} = 27 x_{\mathrm{HI}} \left(\frac{1 - Y_{\mathrm{P}}}{0.76}\right) \left(\frac{\Omega_{\mathrm{B}} h^2}{0.023}\right) (1 + \delta) \sqrt{\frac{0.15}{\Omega_{\mathrm{m}} h^2} \frac{1 + z}{10}} \left(1 - \frac{T_{\mathrm{cmb}}}{T_{\mathrm{s}}}\right) \mathrm{mK}$$

Madau et al. (1997), Furlanetto (2006)

An example of the 21-cm signal evolution



Pritchard & Loeb (2012)

Lyα coupling is a critical ingredient deciding the strength of cosmic dawn 21-cm signal

$$T_{\mathrm{s}}^{-1} \approx \frac{T_{\mathrm{cmb}}^{-1} + x_\alpha T_{\mathrm{k}}^{-1}}{1 + x_\alpha}$$

T_{k} = Gas temperature

x_α = Ly α coupling

Wouthuysen (1952); Field (1958); Madau et al. (1997)

x_α quantifies the scattering rate of Lyman-α photons

Meiksin (2000), Loeb & Rybicki (2008)

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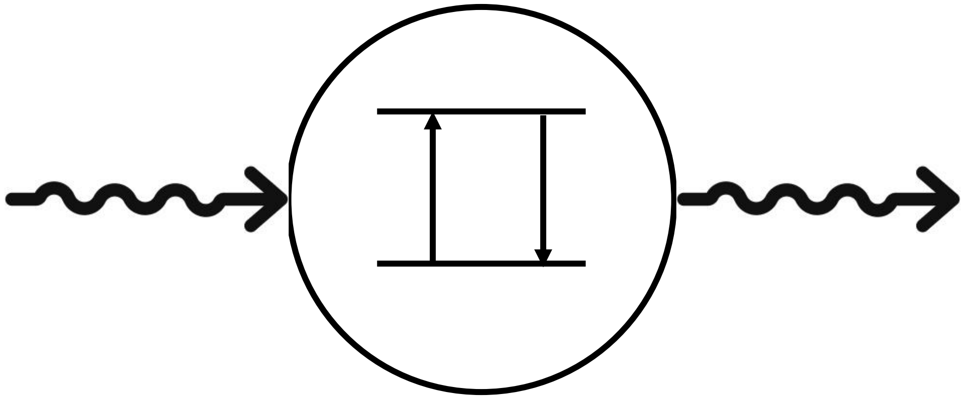

Lyα photons can indirectly cause a 21-cm (hyperfine) transition

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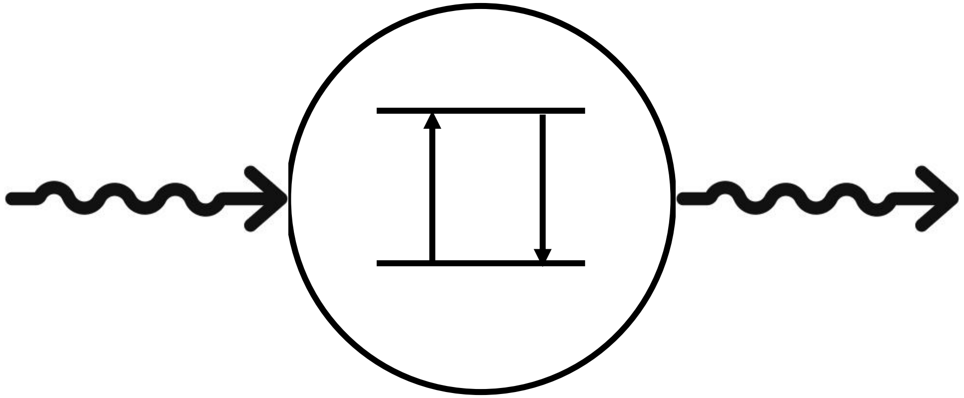

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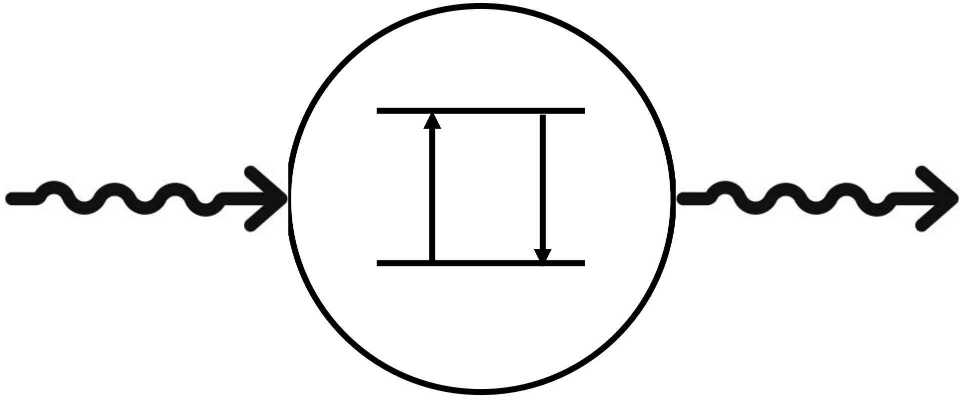

Lyα photons can indirectly cause a 21-cm (hyperfine) transition

$$x_\alpha \propto \boldsymbol{P_\alpha} = 4\pi \int J(\nu)\sigma(\nu)\,\mathrm{d}\nu$$

$J(\nu)$ - specific intensity at frequency ν

$\sigma(\nu)$ - cross-section of Lyα- HI interaction at frequency ν

Meiksin (2000), Loeb & Rybicki (2008)

Modelling of J (or τ) is computationally expensive

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- The simplest approach is to assume a negligible optical depth, $\tau = 0$. So that

$$J(\nu) = \frac{c}{4\pi}(1+z)^2 \int \frac{\epsilon(\nu', z')}{H(z')} e^{-\tau} \mathrm{d}z'$$

$$\approx \frac{c}{4\pi}(1+z)^2 \int \frac{\epsilon(\nu', z')}{H(z')} \mathrm{d}z' \, .$$

Furlanetto (2006), Mesinger et al (2011)

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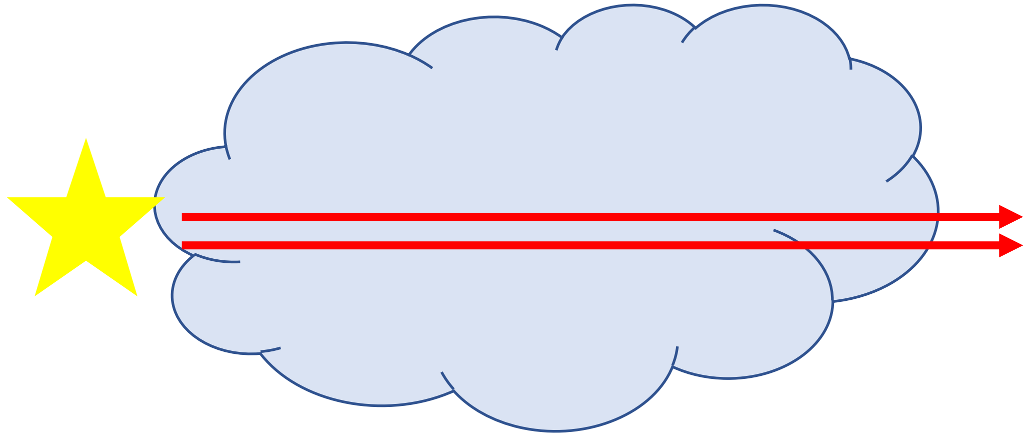
Another interpretation of the above: cross-section, $\sigma(\nu)$, is assumed to be a delta function.

Popular 21-cm codes like `21cmFAST` (Mesinger et al 2011) use this.

Furlanetto (2006), Mesinger et al (2011)

Ignoring $e^{-\tau}$ implies ignoring the random motion and medium inhomogeneities

Approximate



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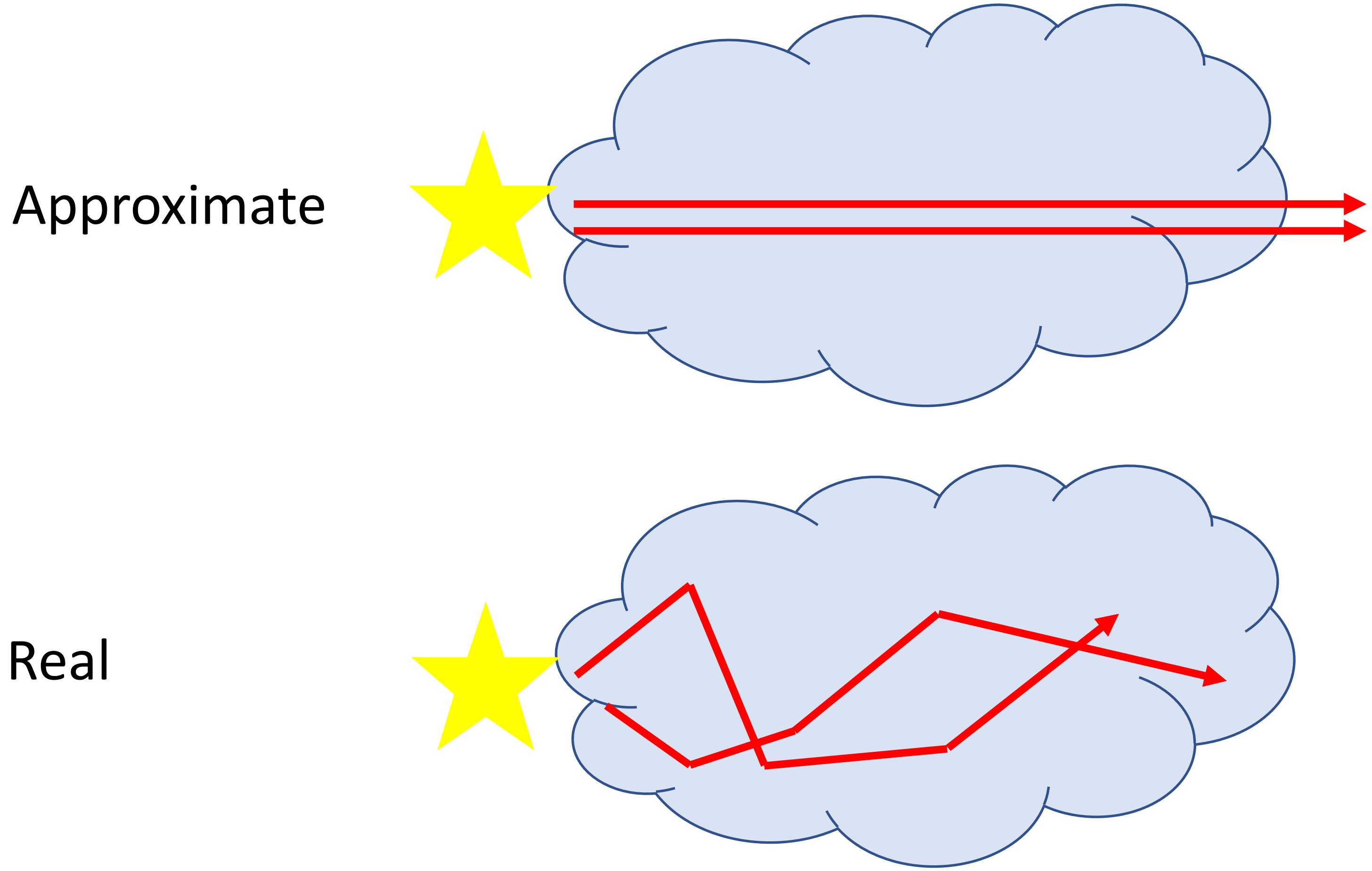

Methodology

We use a Monte Carlo approach for radiative transfer

Michel-Dansac et al (2020), Reis et al (2021), Semelin et al (2023)

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Do the full procedure for a large number of Monte Carlo photons.

Michel-Dansac et al (2020), Reis et al (2021), Semelin et al (2023)

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- σ_{V} – Voigt line profile (convolution of natural & thermal)

Mittal et al (2023)

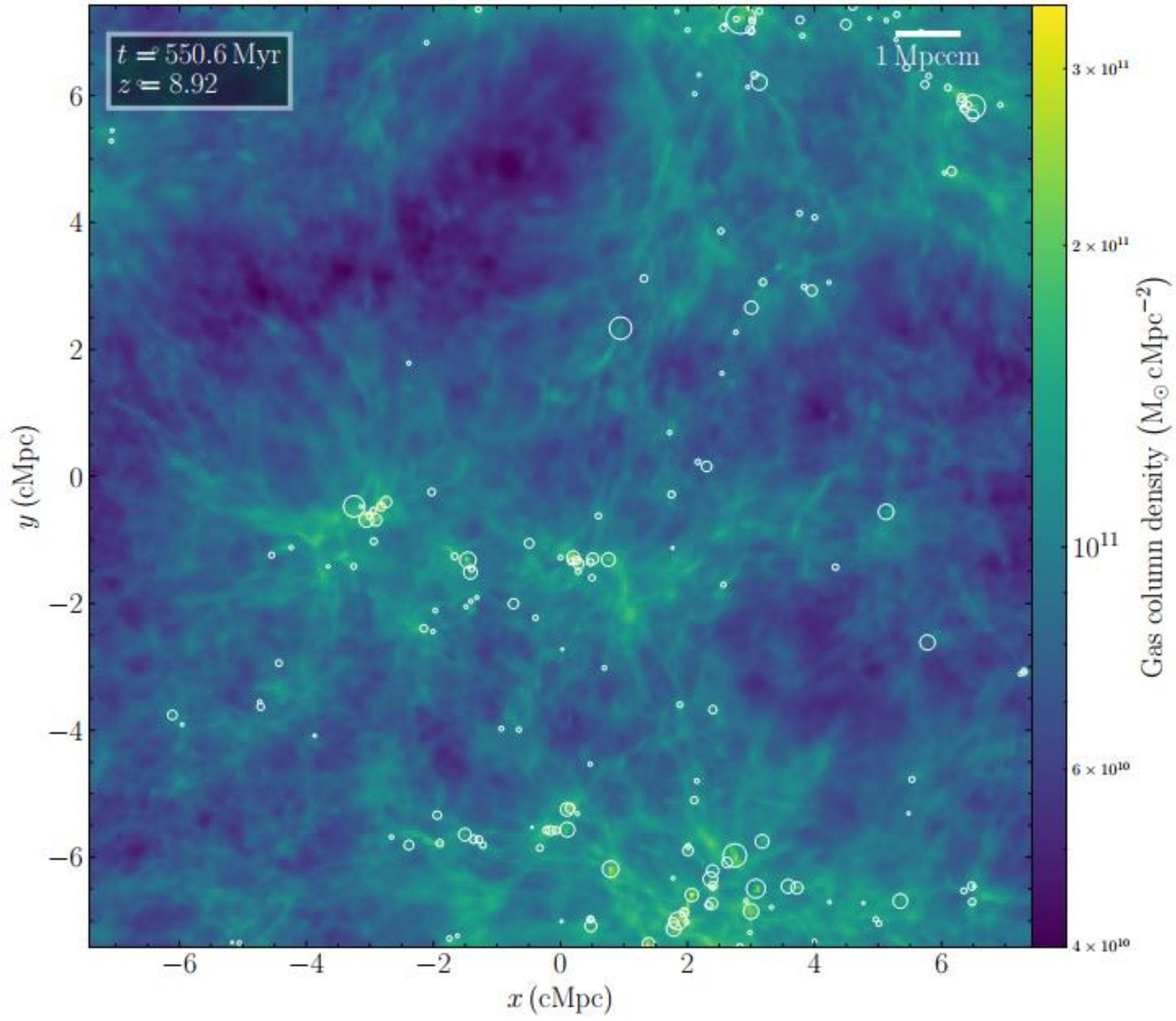
Results

We use an Eulerian based approach to prepare our cosmological box

RAMSES, Teyssier (2002)

We use an Eulerian based approach to prepare our cosmological box

- Box size $10\ h^{-1}\mathrm{cMpc}$



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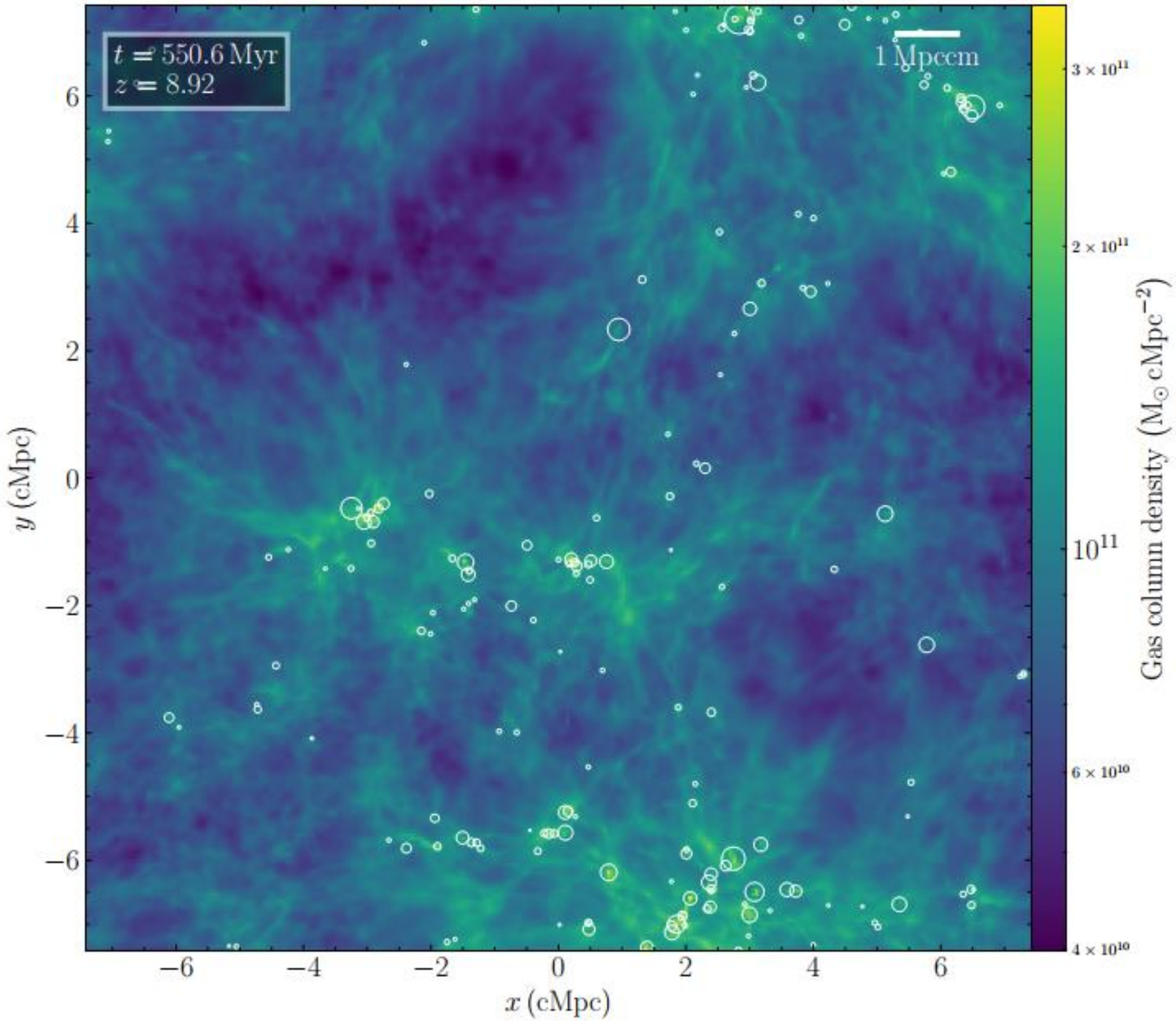

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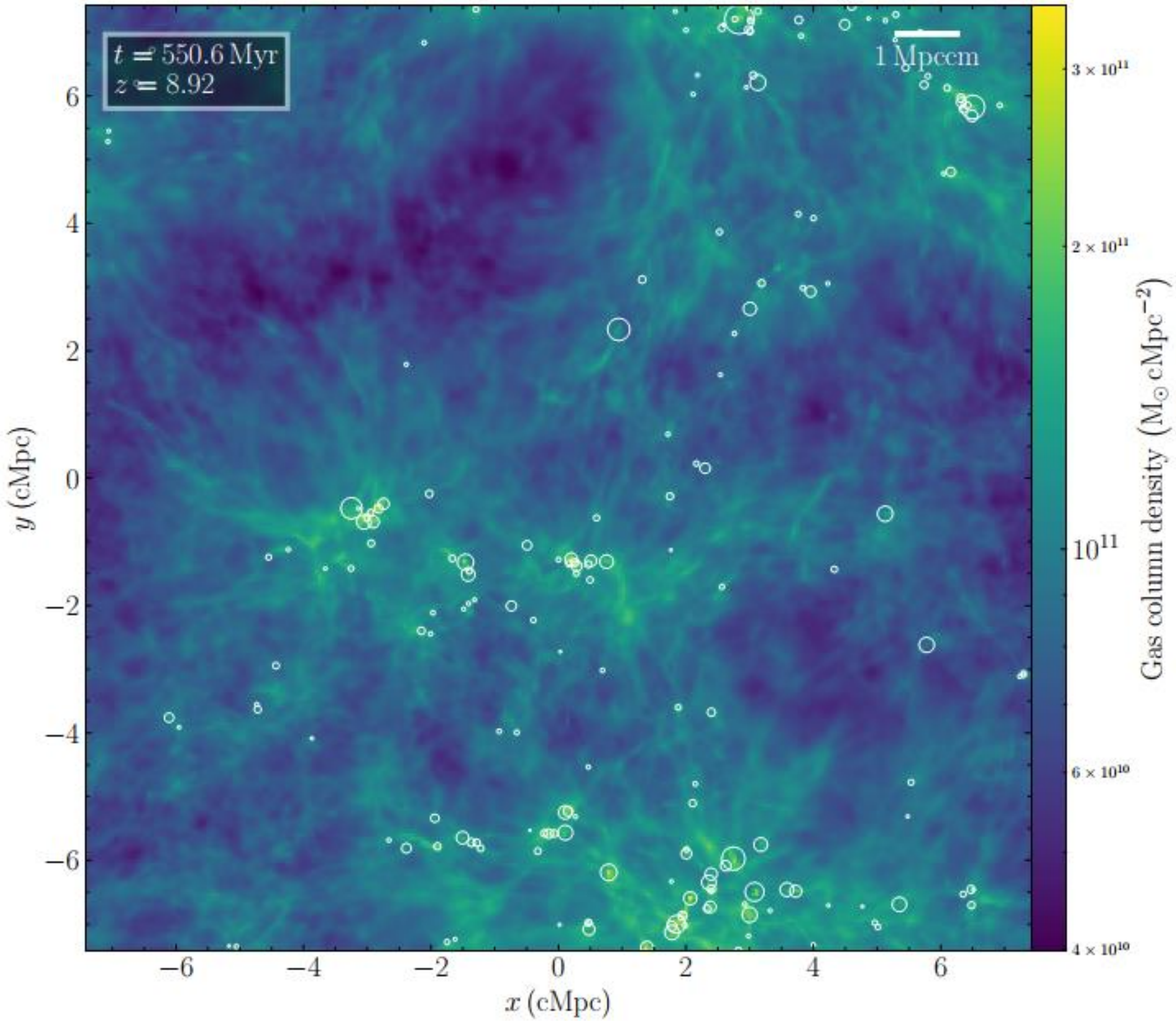
We use an Eulerian based approach to prepare our cosmological box

- Box size $10\ h^{-1}\mathrm{cMpc}$
- 256^3 cells
- White circles — DM haloes



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Mittal et al (2023)

Lyα coupling with and without multiple scatterings

With multiple scatterings
This work

Without multiple scatterings
Traditional

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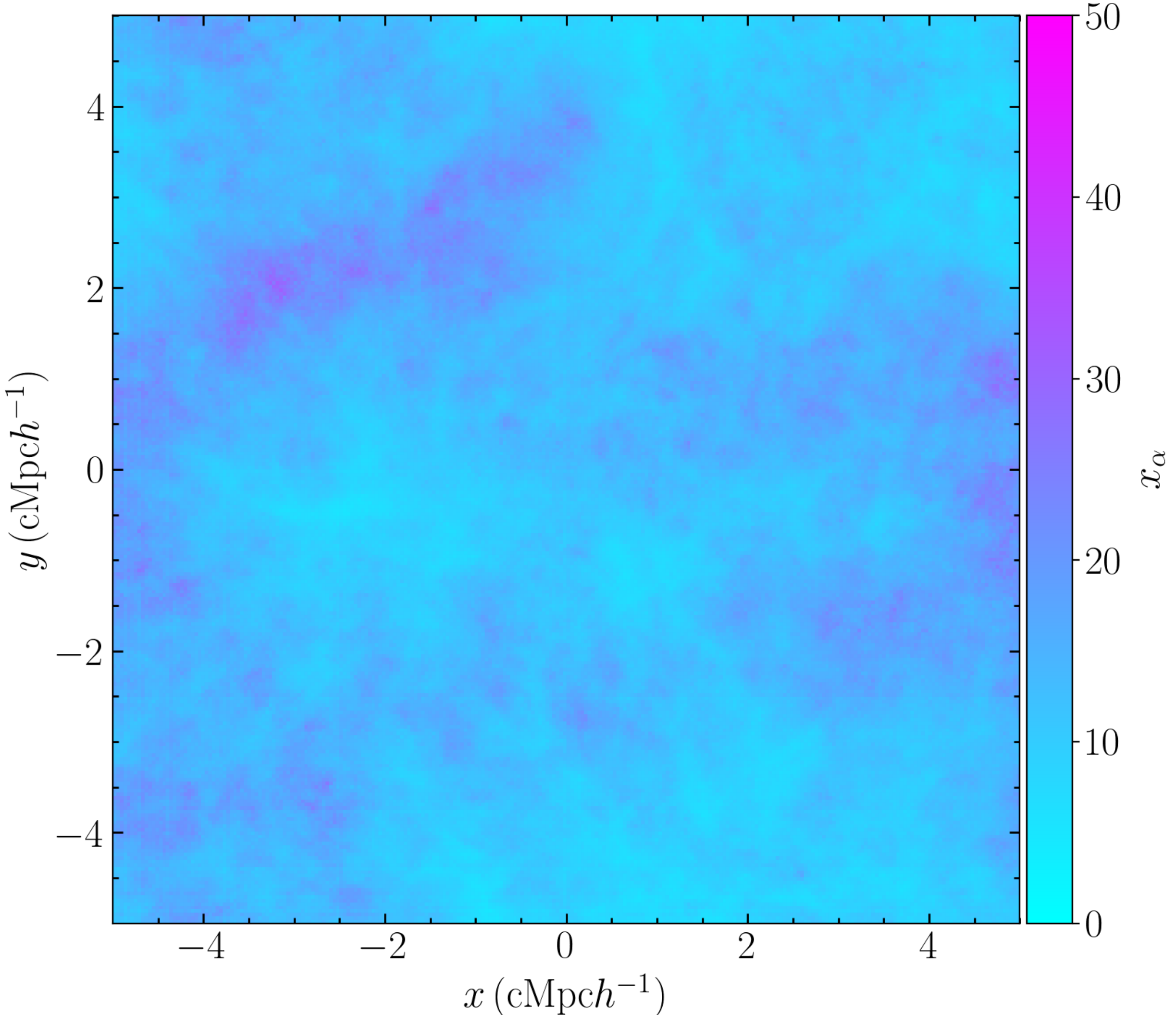

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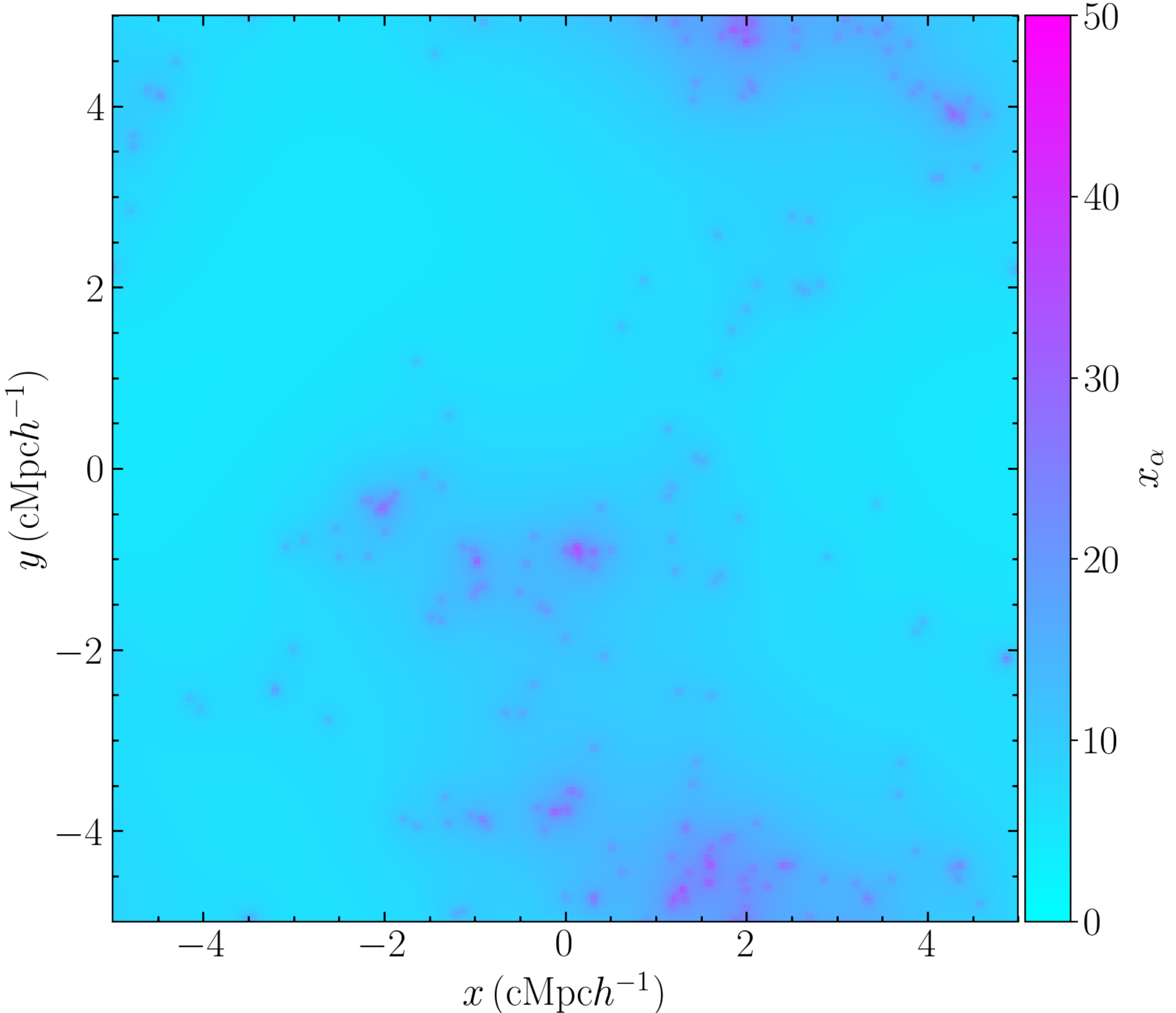


Mittal et al (2023)

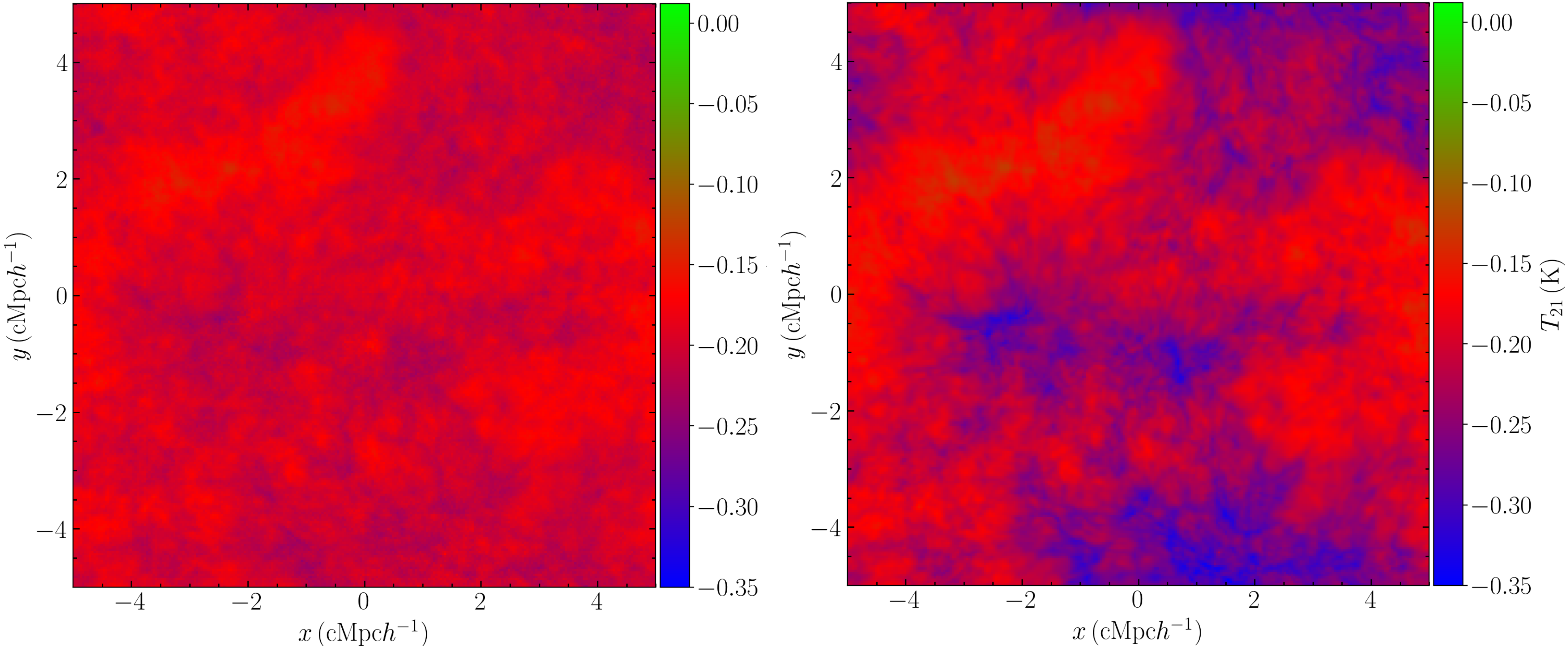
21-cm map with and without multiple scatterings

$\langle T_{21} \rangle = -196$ mK

This work

$\langle T_{21} \rangle = -216$ mK

Traditional



Comparison with a configuration like that of Reis et al (2021)

- $\sigma \rightarrow$ Lorentzian
- n_{HI} uniform
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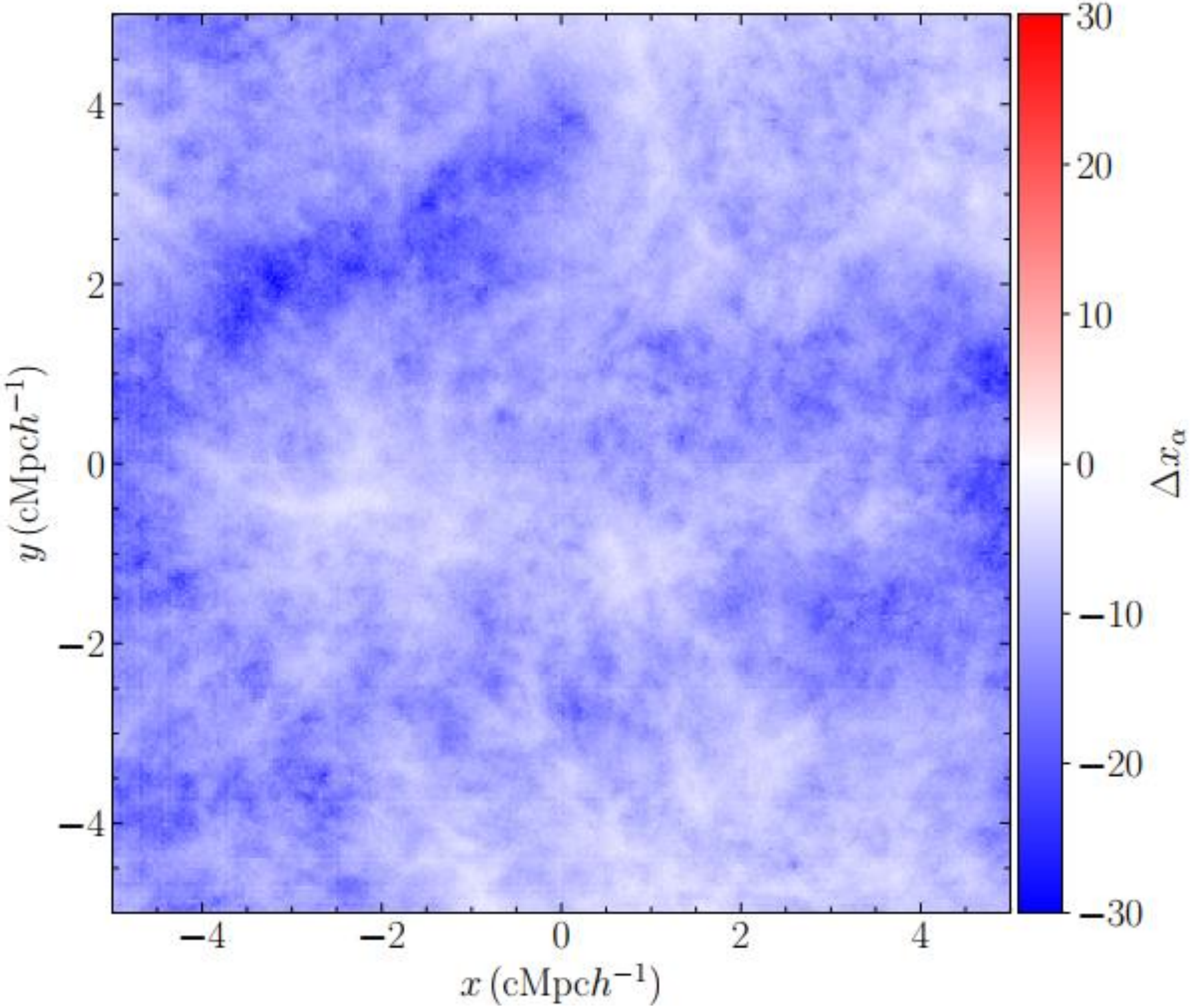
Plot shows:-
$(x_\alpha) - (x_\alpha)_{\text{this work}}$



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Plot shows:-

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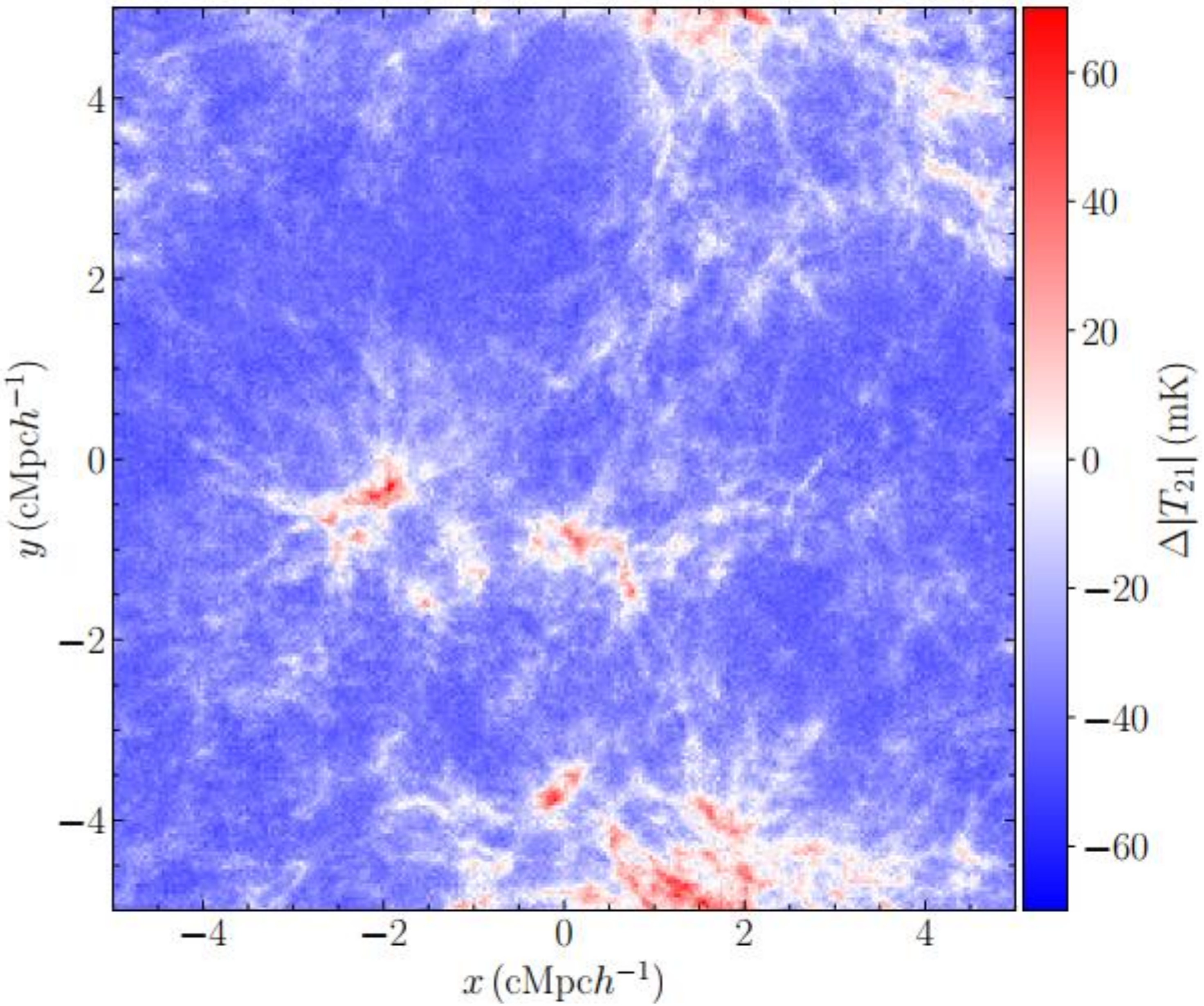
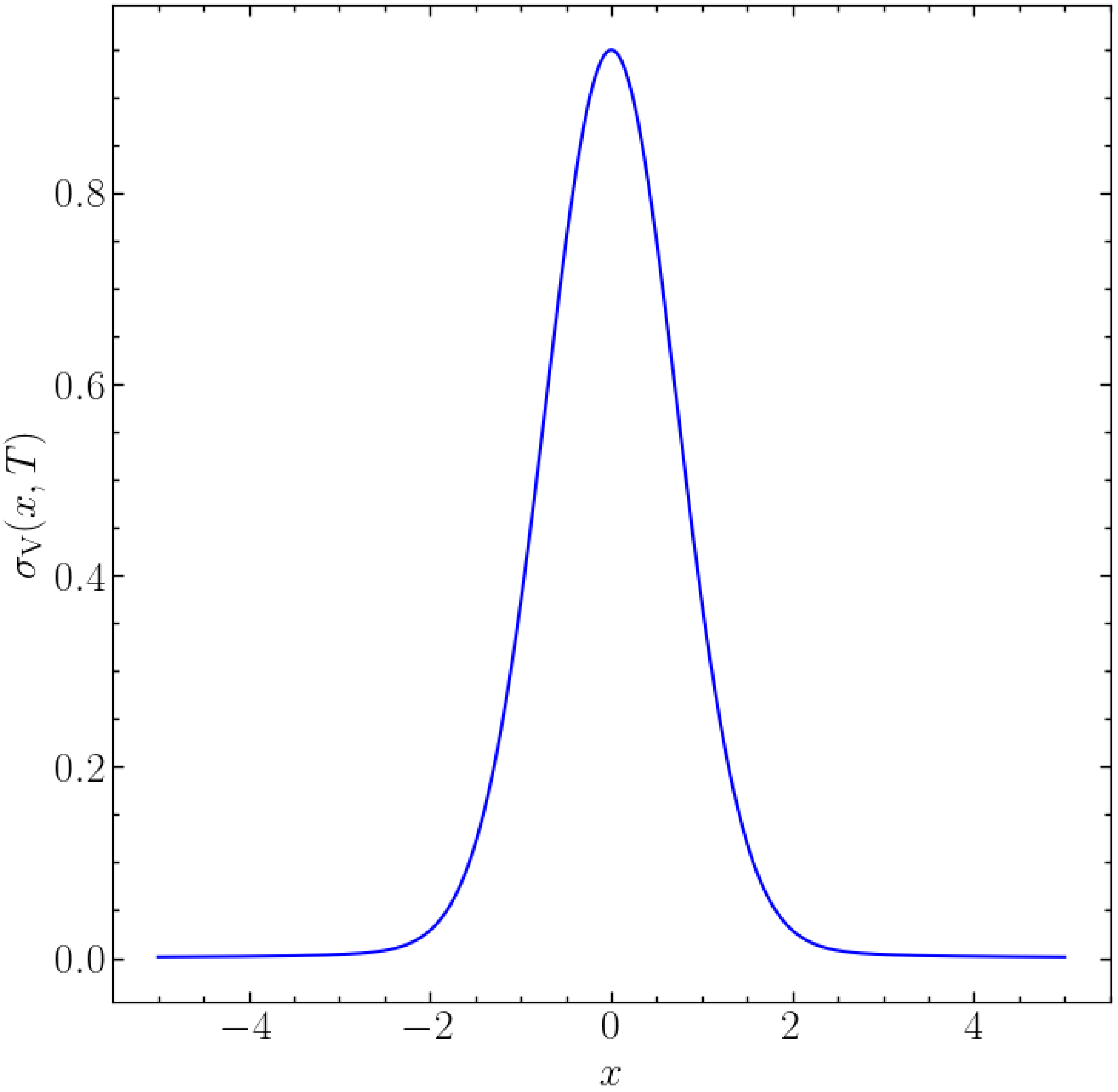
RMS difference is 39%



Summary

- We have studied the radiative transfer of Lyα photons at cosmic dawn
- Previous work did not account for multiple scattering effects at all
- Those that improve upon this have ignored gas bulk motion, used Lorentzian line profile and assumed uniform gas density
- Our results suggest that Lyα coupling distribution is significantly different
- The box-averaged 21-cm signal differs from previous work by $\sim 40\%$

IGM is transparent when the photon is red enough



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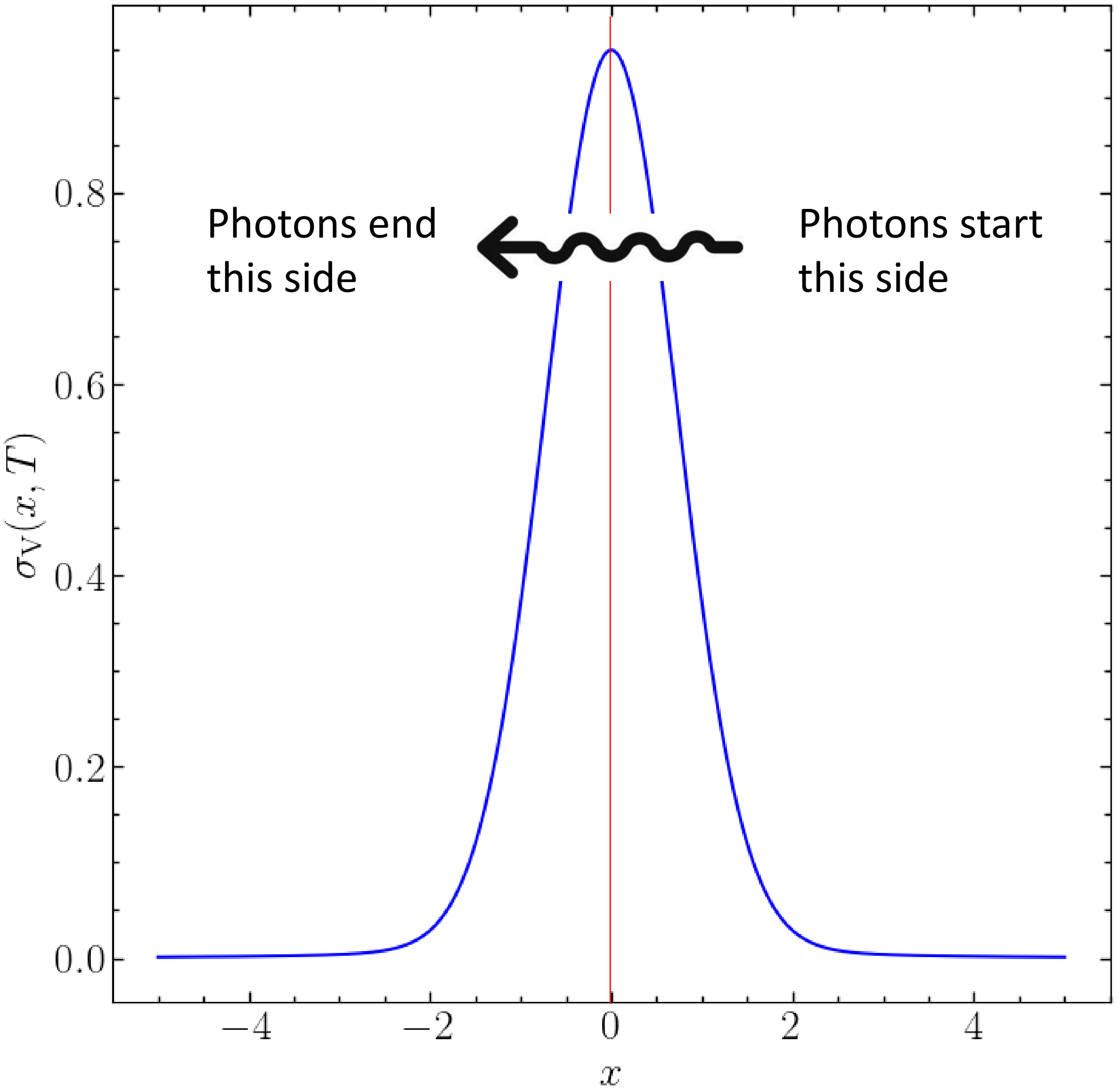
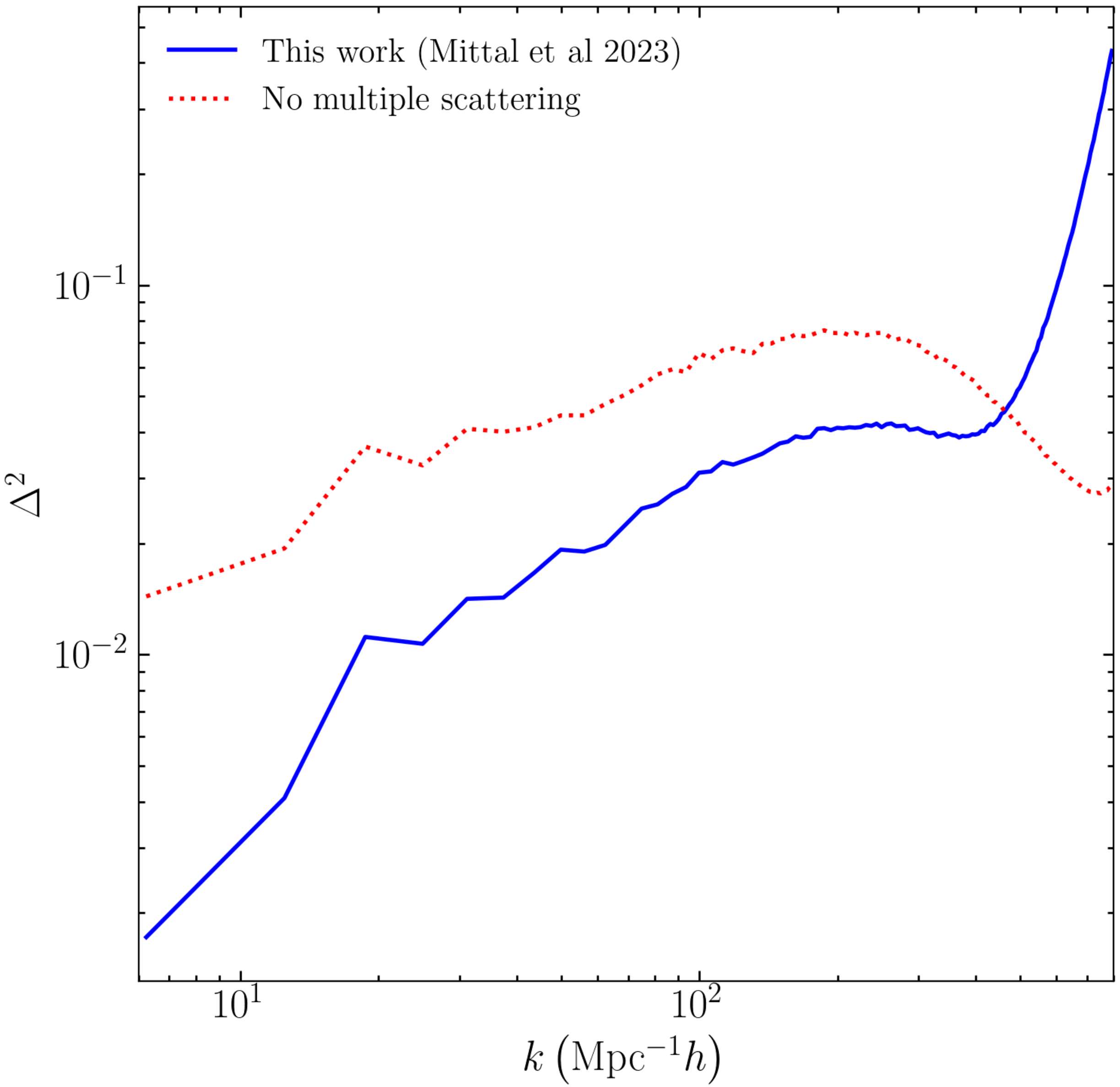
Quantitatively, when the following ratio is small enough

$$\frac{\sigma_V(x_{crit})}{\sigma_V(0)} \approx 10^{-4}, \text{ for } x_{crit} \sim -6$$

where $x = (\nu - \nu_0)/\Delta\nu_D$



21-cm power spectrum (normalised)



Comparison of line profiles at 1 K