Predicting the 21 cm Field with a Hybrid Perturbation Theory Approach

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Motivation

Many questions are yet to be answered in the field of cosmology and astrophysics. In cosmology for example, the nature of dark matter and dark energy is still unclear, while astrophysicists are still trying to understand when the first galaxies, stars, and supermassive black holes formed. The epoch of reionization is currently observationally underexplored, but it has the potential to yield information about both cosmology and astrophysics. The epoch of reionization is an astrophysically complex era in which the first sources of ionizing emissions ionized all of the neutral hydrogen in the universe (aside from the small fraction that lies within galaxies). Amongst the many benefits of using this epoch as a probe, cosmologists predict that better measurements of the reionization process would further constrain the properties of the ionizing sources, the abundance of small-scale structures that absorb many of the ionizing photons, and perhaps even cosmological parameters. The way to study the epoch of reionization is through the Hydrogen Epoch of Reionization Array (HERA), a radio telescope dedicated to observing large scale structure during and prior to the epoch of reionization. The most direct way to probe the neutral hydrogen in the universe is through the 21 cm field, which is caused by the hyperfine spin-flip transition that results in the emission of photons with a wavelength of 21 cm. In this project, we model the 21 cm field by using Lagrangian Perturbation Theory and show that this is a powerful tool for future experiments.

Theory

- The steps for our theoretical model are as follows:
  1. We use the initial conditions at z = 20 to calculate the 4 fields ($\delta_L, \delta_L^2, s_L^2, \nabla^2\delta_L$):
  2. We compute these fields on a cubic grid of size 1024^3 in Fourier space.
  3. At each snapshot, we evolve the initial condition fields linearly to some redshift of choice.
  4. We compute the advected bias operators $(1, \delta_L, \delta_L^2, s_L^2, \nabla^2\delta_L)$ by assigning each particle a weight given by the value of its position in the initial conditions.
  5. Finally, we store all the advected fields.
- We model our predicted matter distribution with the following equation:

$$1 + \Delta_{21,L} = 1 + b_1\delta_L + b_2\delta_L^2 + b_\nabla\nabla_L^2 + b_s s_L^2$$

- Given the final position ($\mathbf{x}$), the initial Lagrangian coordinates ($\mathbf{q}$), the Lagrangian displacement vector ($\mathbf{\Psi}$), we get:

$$1 + \Delta_{21}(\mathbf{x}) = \int d^3\mathbf{q}[1 - \Delta_{21,L}(\mathbf{q})]\delta^D((\mathbf{x}) - (\mathbf{q}) - \Psi(\mathbf{q}))$$

Methods

- We compare our theoretical model to the Thesan Project, a suite of large-volume cosmological radiation-magneto-hydrodynamic simulations of the Epoch of Reionization.

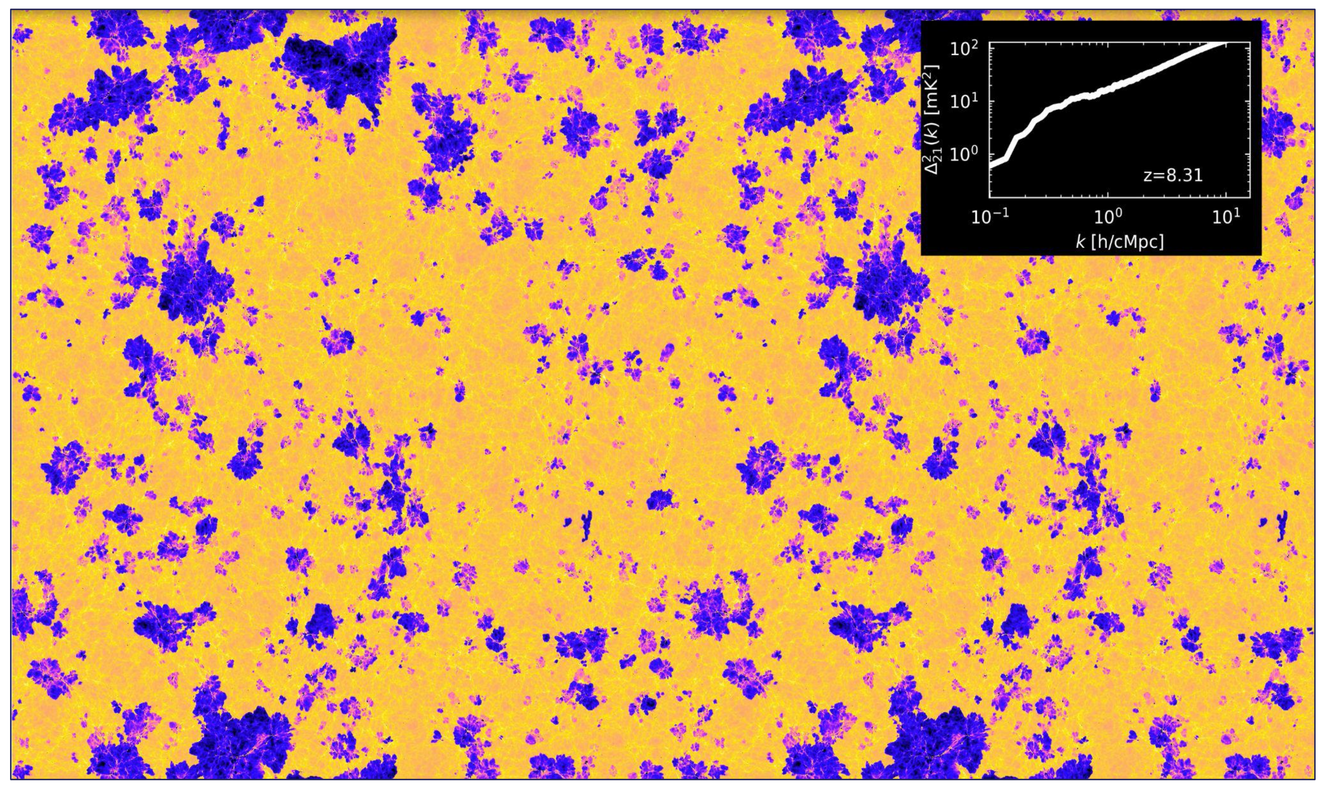
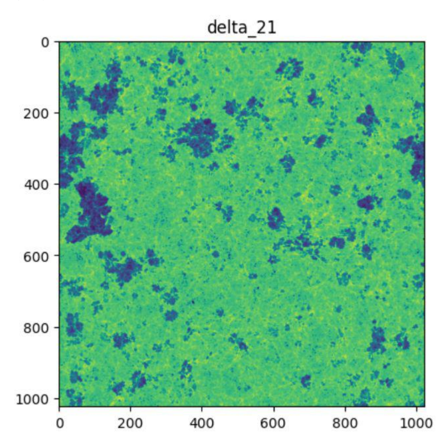


Figure (1): shows the 21 cm HI emission in a slice through the Thesan-1 simulation at z = 8.3. The panel in the top right corner shows the 21 cm field power spectrum at the same redshift.

- The figures below *(2-7)* show our observable, the 21 cm field, and the five advected bias fields that we use to model it:

(2)



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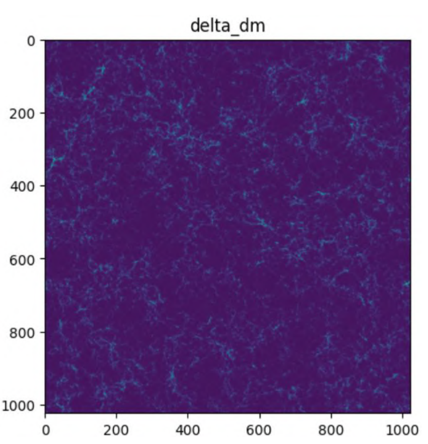

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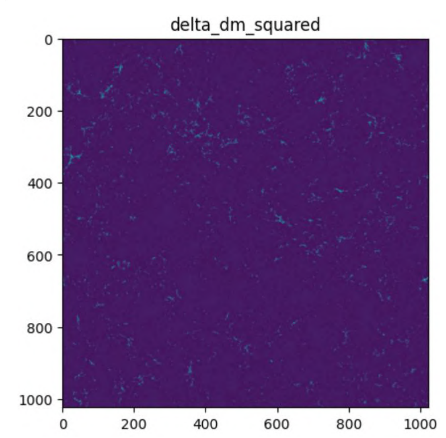

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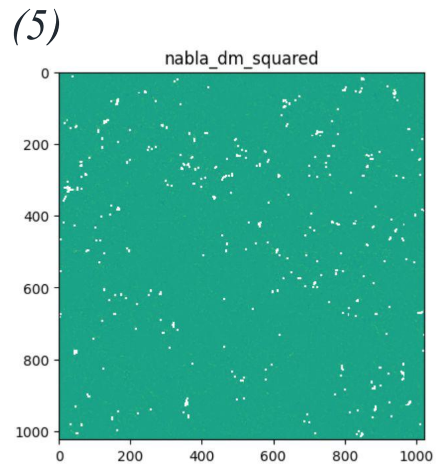

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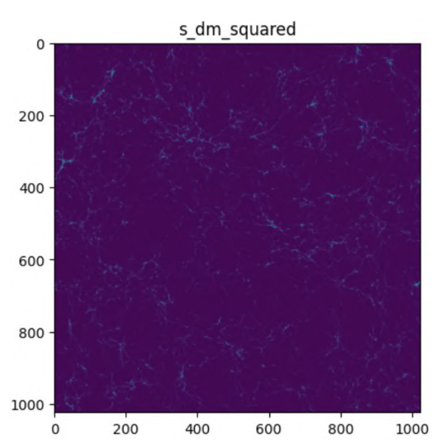

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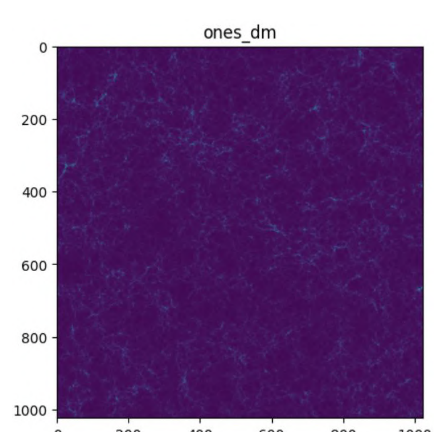

- We also minimize the squared difference to obtain the bias parameters ():

$$\sum_{|\mathbf{K}|<K_{\min}} \left(\delta_{21}(\vec{\mathbf{k}}) - \hat{\delta}_{21}(\vec{\mathbf{k}})\right)^2 \text{, where } K_{\min} = b_1, b_2, b_\nabla, b_s$$

Results

- The plot in *Figure (8)* shows that our model can capture the physics of the 21 cm field at large scales:

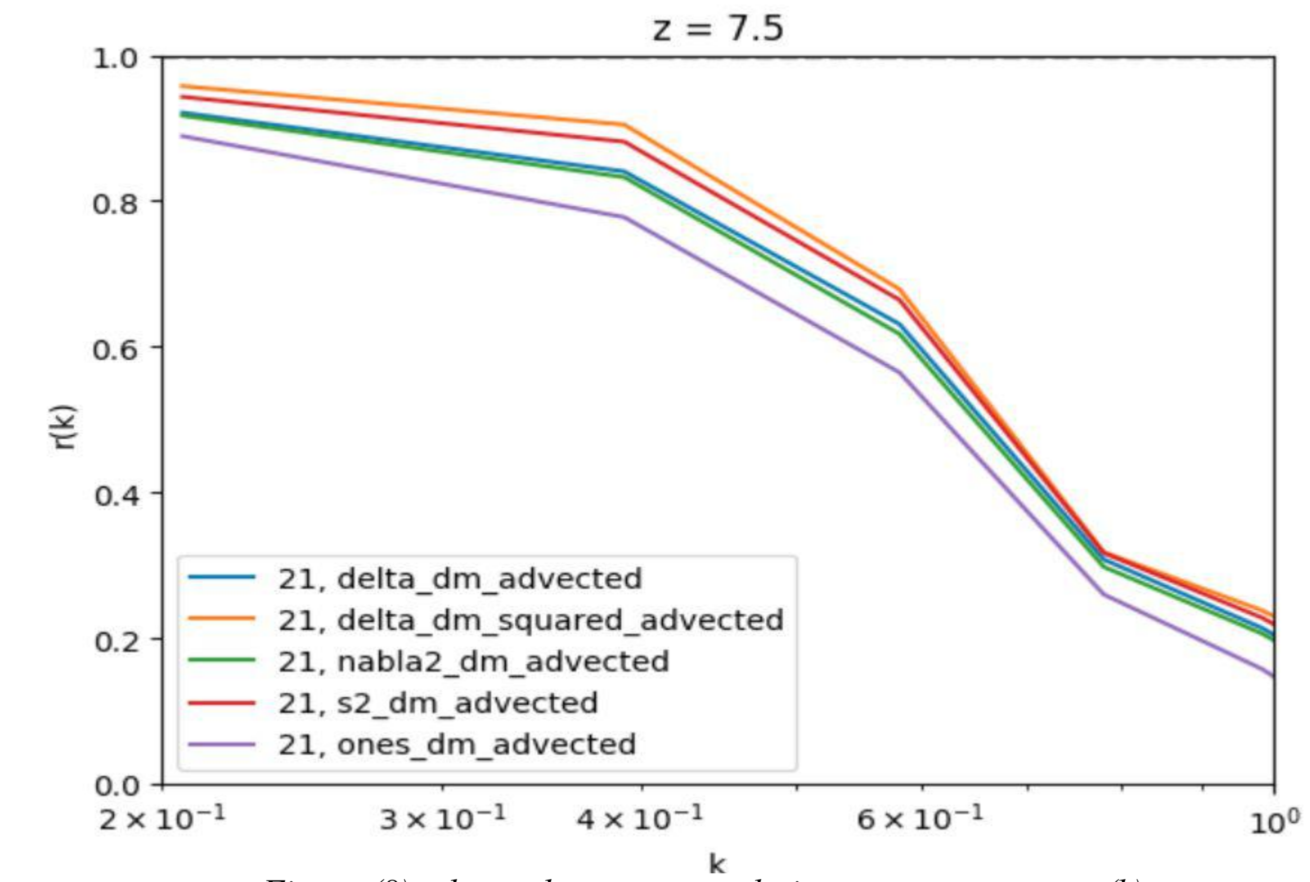

Figure (8): shows the cross-correlation power spectrum r(k) between the 21 cm field and each of the five advected fields as function of k at z = 7.5.

- The figure below *(9)* shows that our equation can successfully model the 21 cm field at the precision required by future requirements.

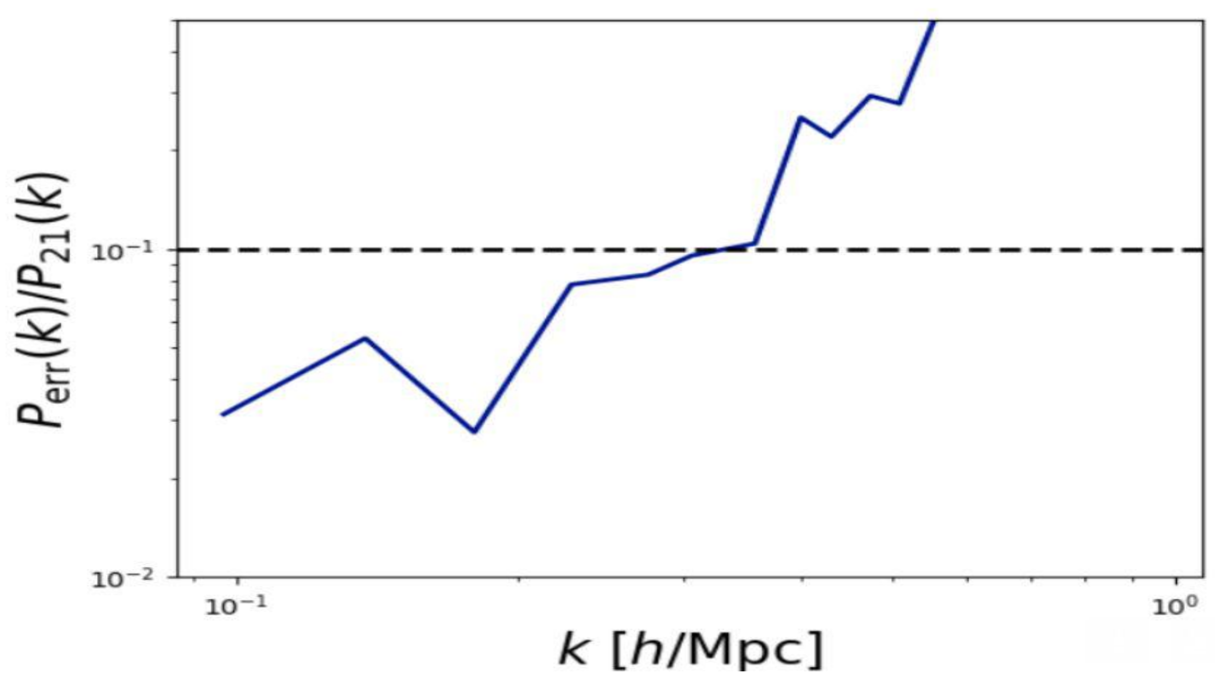

Figure (9): shows that our error is less than 10% on the scales of interest.

Conclusions

Our model works quite well up until k ≈ 0.4 *h*/Mpc, the scales at which future cosmological experiments have the most sensitivity. This implies that perturbation theory can be used to model the 21 cm signal, which can be very useful for future experiments. Indeed, perturbation theory is a mathematically robust model that allows us to connect the observables to the underlying cosmological parameters, giving us a way to interpret future results that are sensitive to both astrophysical and cosmological probes of interest.

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