The 21-cm signal from the epoch of reionization

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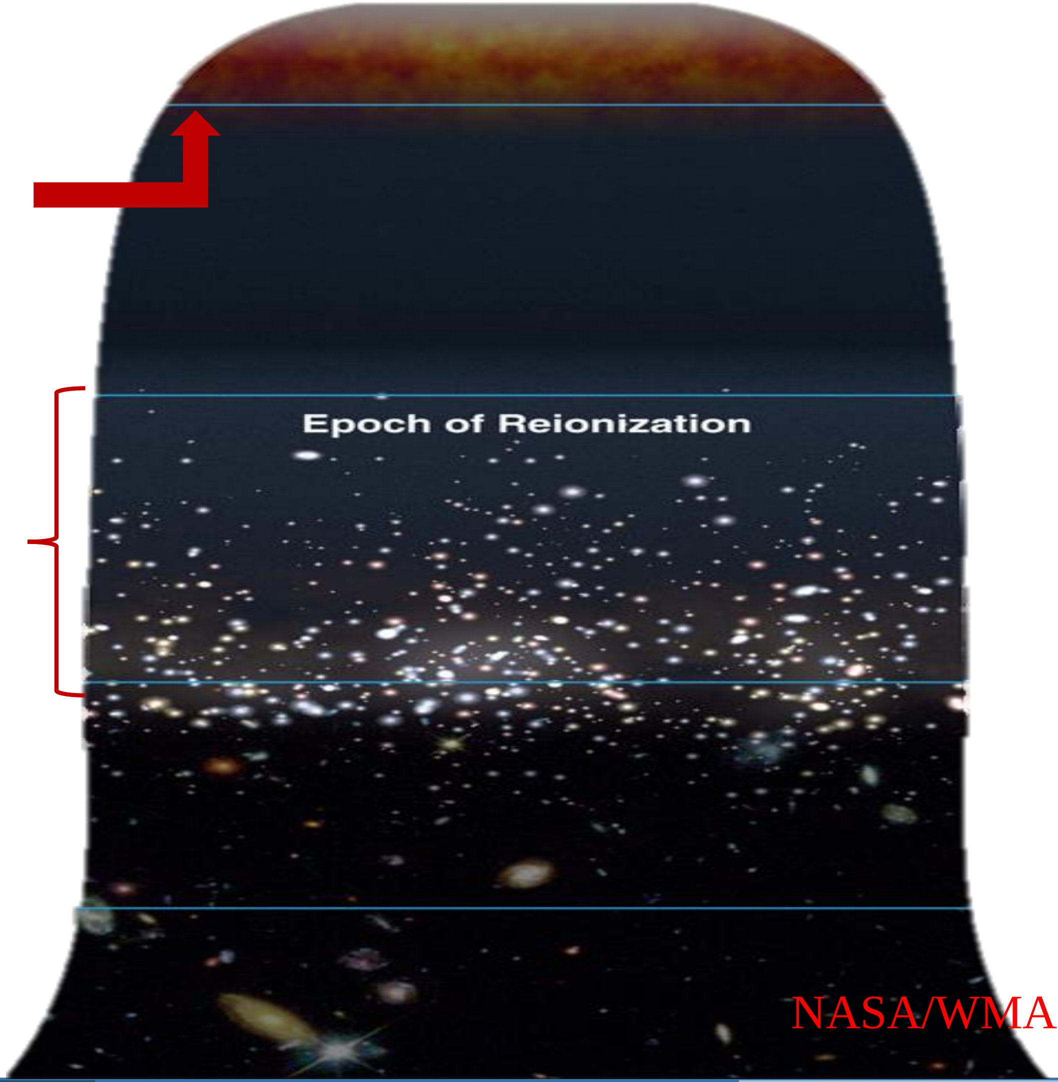
Outline

- Motivations
- Introduction
- Difficulties
- Semi-numerical approach
- N-body simulation
- Friends-of-friends (FoF) algorithm
- Generating the ionization field
- Discussion
- Future work plan

Aim

- We want to understand the process by which the universe was ionizes

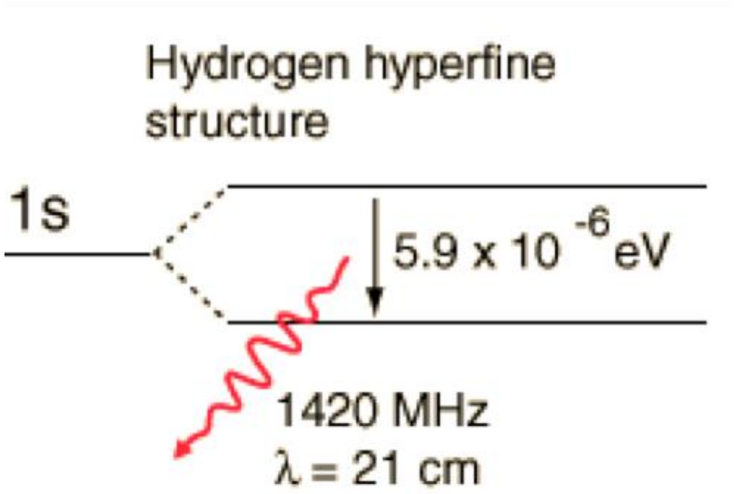


NASA/WMAP science Team

Motivation

- Unfortunately we have a very little knowledge about this event
- Many important questions such as the exact duration, properties of the first sources, thermal and ionization state of the IGM, feedback effect etc. are largely unknown

21-cm Signal



- The most favorable way
- Usually the 21-cm signal from neutral hydrogen is measured in terms of the brightness temperature which will be absorbed against the CMB radiation.
- The differential brightness temperature is proportional to

$$\delta T_b \propto x_{HI}(1+\delta_B)\left[1-\frac{T_{CMB}}{T_s}\right]$$

Sources

- To ionize H-atom, one need photons of energy > $13.6eV$
- So, the UV and X-ray photons are the candidate for that
- After ionization, the excess photon energy go to the IGM
- This process is called the IGM heating, which lead the T_s above the T_{CMB}
- Then the 21-cm signal will be in emission

Challenges

- But the strength of this signal very low

- Huge amount of foreground and noise associated with it, which has strength 4-5 order magnitude higher then the signal

- We statistically detect this signal i.e. by measuring the power spectrum

$$\langle \delta\hat{T}_b(k)\delta\hat{T}_b^*(k')\rangle = (2\pi)^3\delta_D(k-k')P(k)$$

- But, foreground removal challenge still remain there

Semi-numerical simulations

- So, one go for numerical simulation of this process, which play a crucial role in the modelling and prediction of 21-cm signal from the EoR.
- Full numerical simulations i.e. the radiative transfer simulations are computationally extremely expensive
- As an alternative to that, in a semi-numerical approach it is possible to achieve a reasonable accurate picture of the reionization
- Our Semi-numerical approach involve three main steps

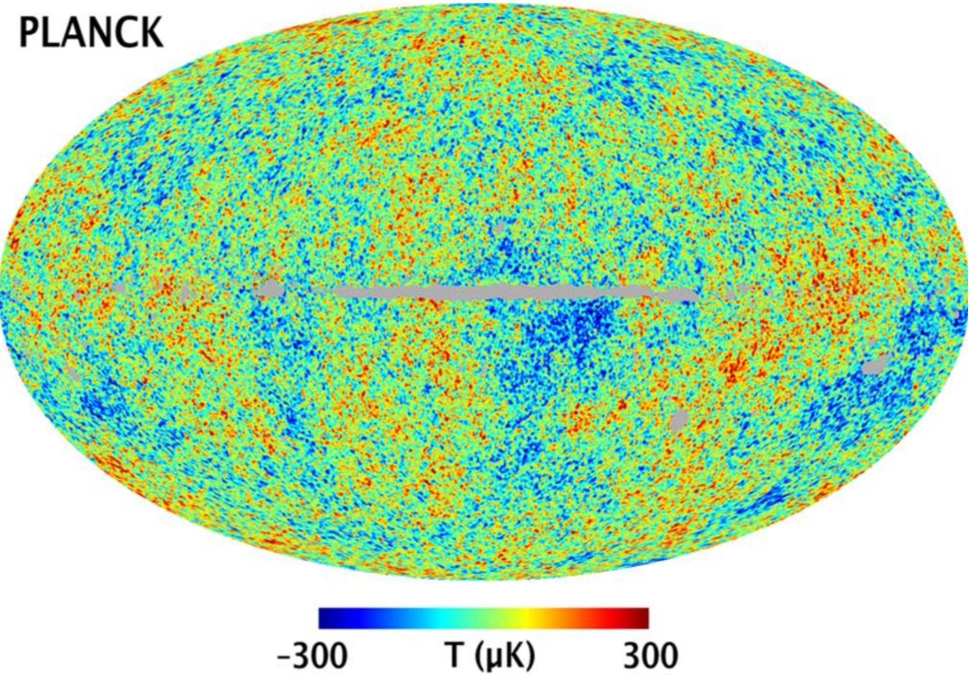
(i) N-body simulation (ii) FoF halo finder

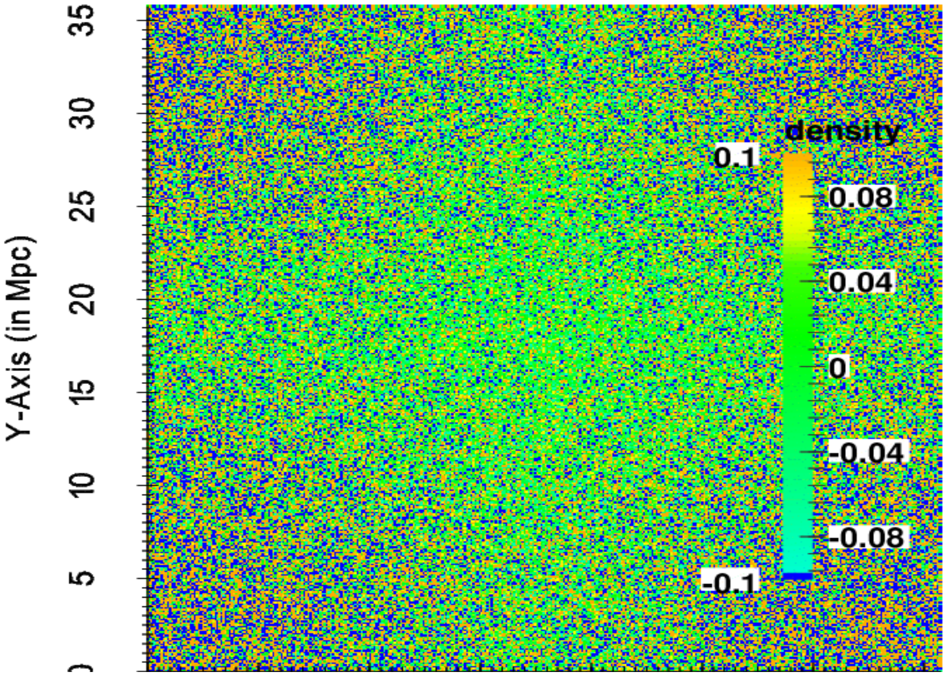
(iii) Ionization map generation

The N-body simulation

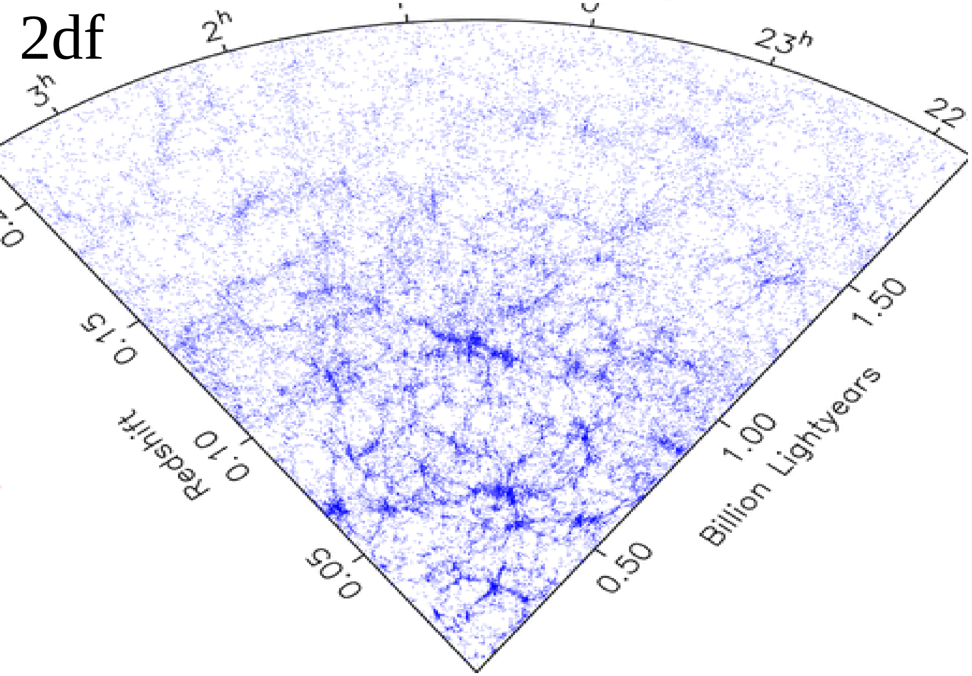
- The early universe was very homogeneous and density field is in linear regime (fig. 2)
- But, we can see the density field in our local universe is highly non-linear (fig. 3)
- From perturbation theory we know that this problem can be analytically solved only in linear regime
- The N-body simulations are used to compute the non-linear evolution of the dark matter distribution
- We have developed a efficient and parallelized particle mesh (PM) code for that purpose

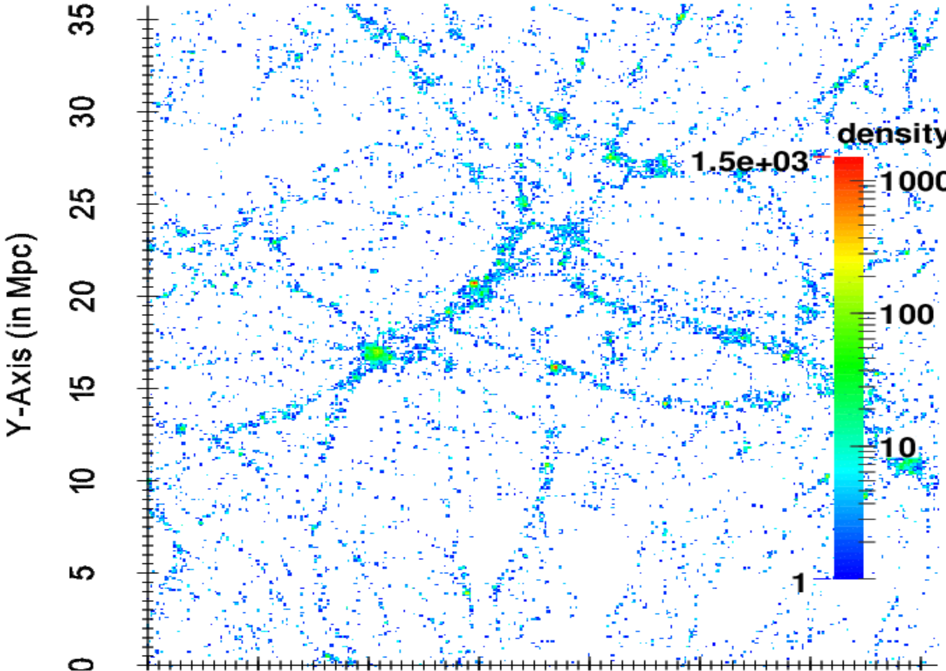
N-body simulation





2df





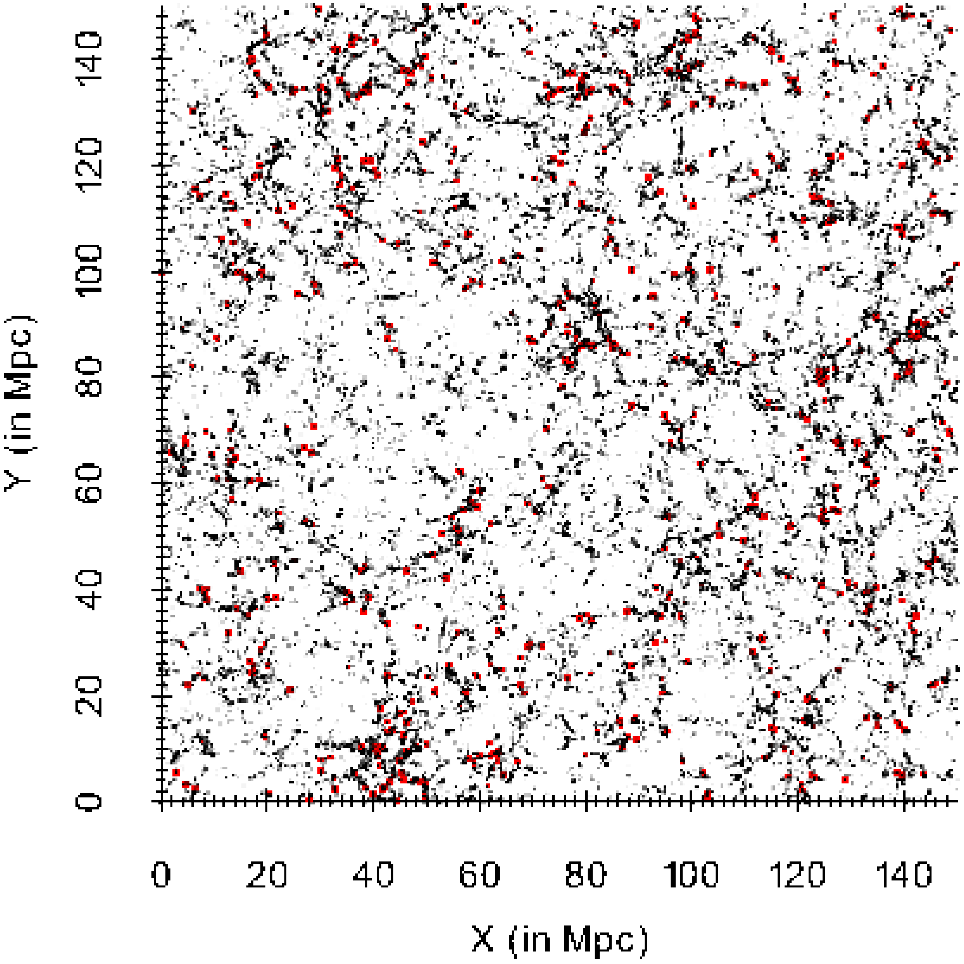
Friends-of-friends halo finder

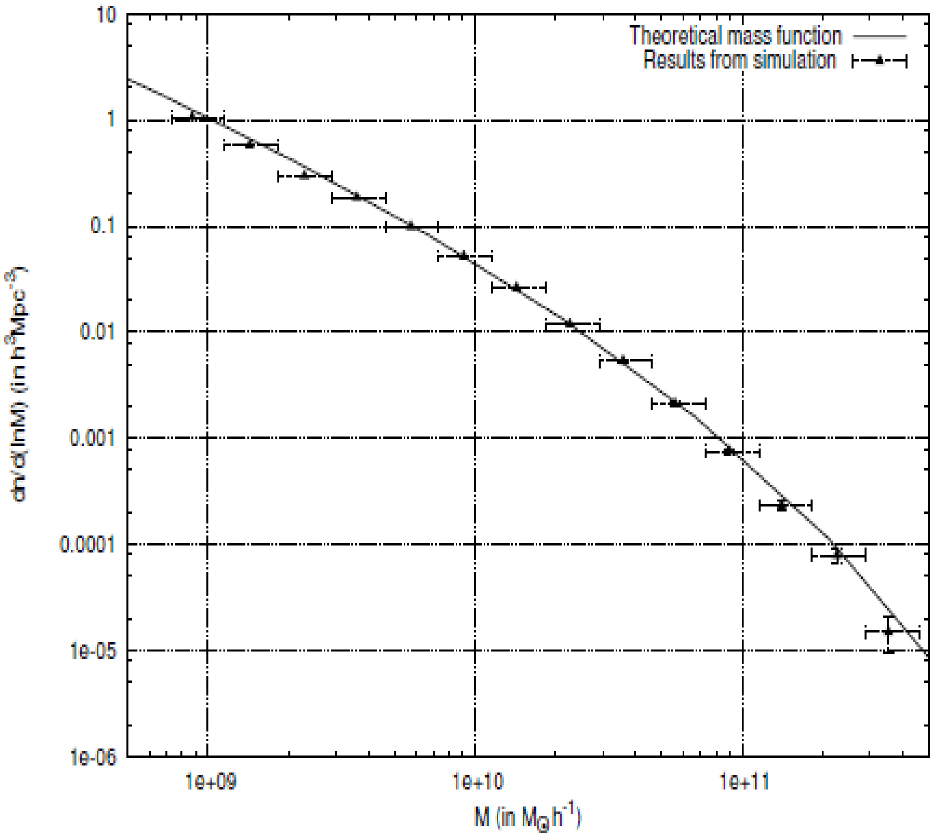
- The correct location and mass of the haloes are very important, because it is understood that first luminous objects were form inside those collapsed haloes

- To identify the dark matter haloes, we have written a code using standard Friends-of-friends (FoF) algorithm (fig. 6)

- The halo mass function calculated from our simulation is consistent with the theoretical mass function (fig. 7)

Location of the haloes and Mass function





Assigning ionizing luminosity

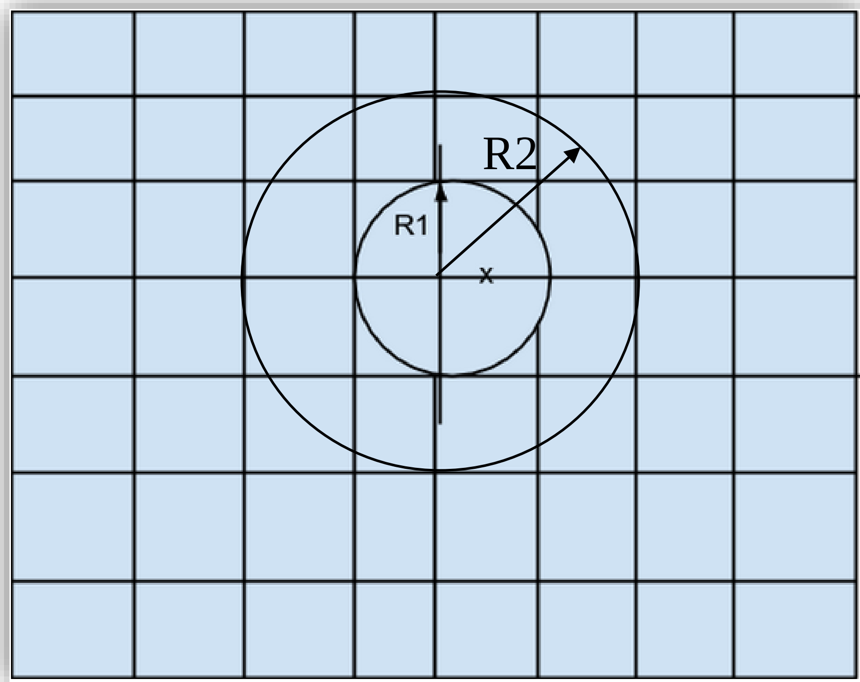
- Observationally it is not well established, how the ionizing luminosity varies with galaxy properties
- Generally it is assumed that the ionizing luminosity from galaxies is proportional to the halo mass
- Number of ionizing photons contributed by a halo of mass M_h

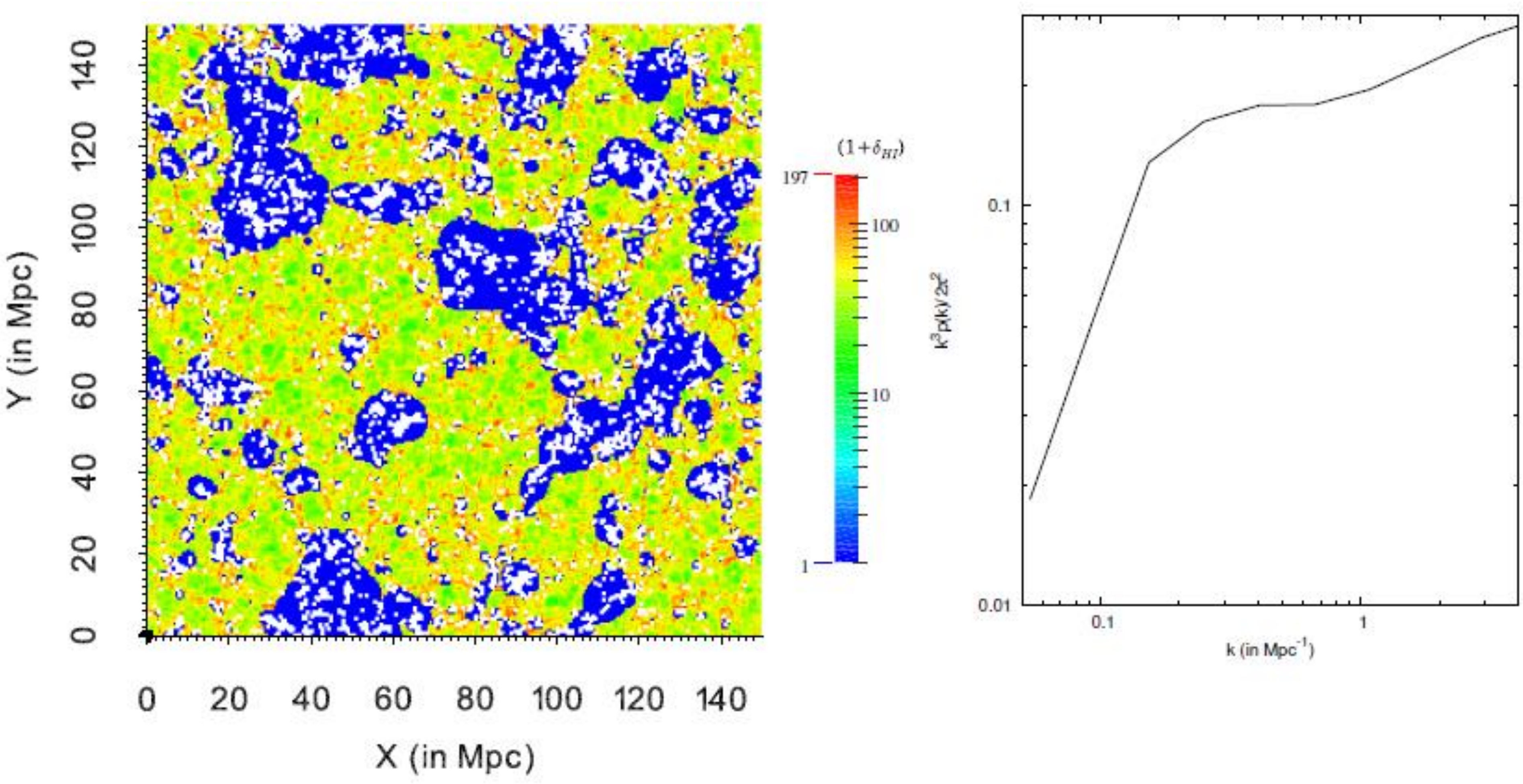
$$N_\gamma(M_h) = \frac{N_{ion} M_h}{m_H}$$

- Where m_H is the hydrogen mass and N_{ion} is a constant which is basically the number of photon entering the IGM per baryon in collapsed object.

Generating the ionization field

- We estimate the mean number of photon $\langle n_\gamma(x)\rangle_R$ within a spherical region of radius R around a point x and compare it with the corresponding spherically-averaged hydrogen number density $\langle n_H(x)\rangle_R$.
- The condition for the point x (one pixel) to be ionized is that $\langle n_\gamma(x)\rangle_R \geq \langle n_H(x)\rangle_R(1+\bar{N}_{rec})$
- $\bar{N}_{rec}$ is the mean number of recombination in the IGM.





Left panel: The HI map with location of the haloes (white dots) for a mass averaged neutral hydrogen fraction $x_{HI} = 0.5$, of a slice through the centre of the simulation box. **Right panel**: The dimensionless power spectrum of HI fluctuations from the same simulated HI map.

Redshift space distortion

- 21-cm radiation can be mapped to a redshift space and thus to a position along the line of sight.
- As gas tends to move toward over dense regions, over/under dense regions will appear more over/under dense at large scales.
- the particle distribution is mapped to redshift space using

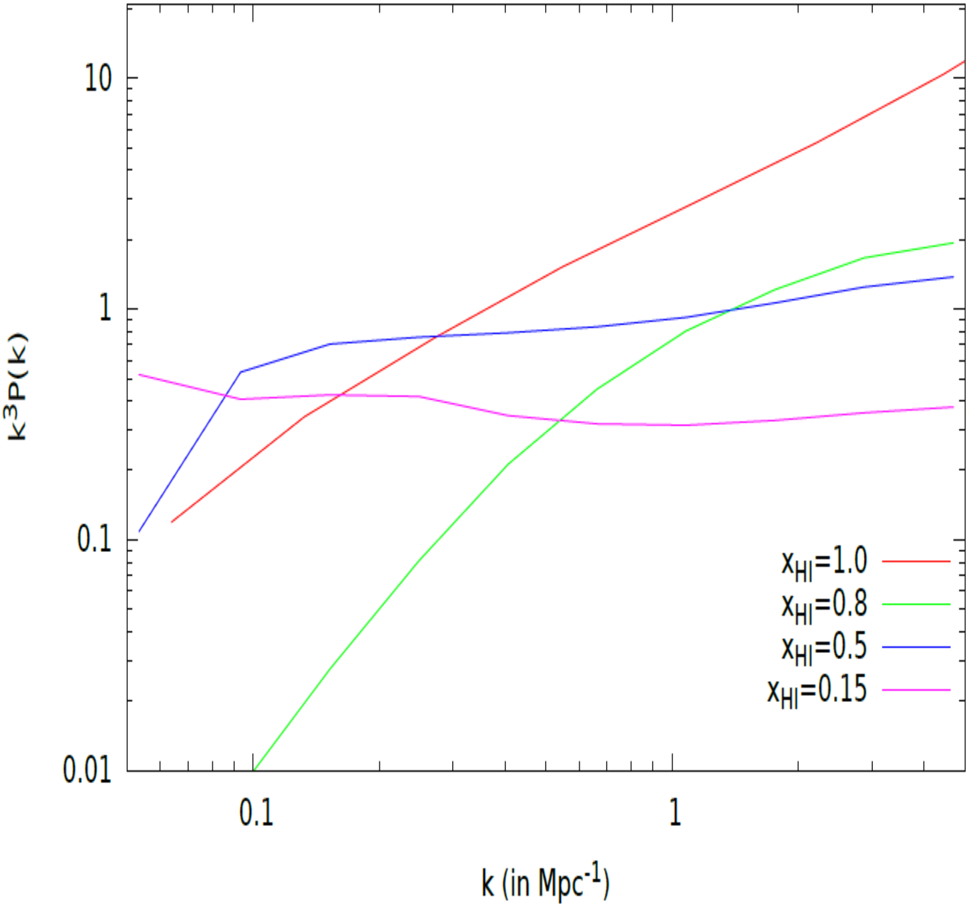
$$\mathbf{s} = \mathbf{x} + \hat{\mathrm{n}} \frac{\hat{\mathrm{n}} \cdot \mathbf{v}_p}{aH(a)}$$

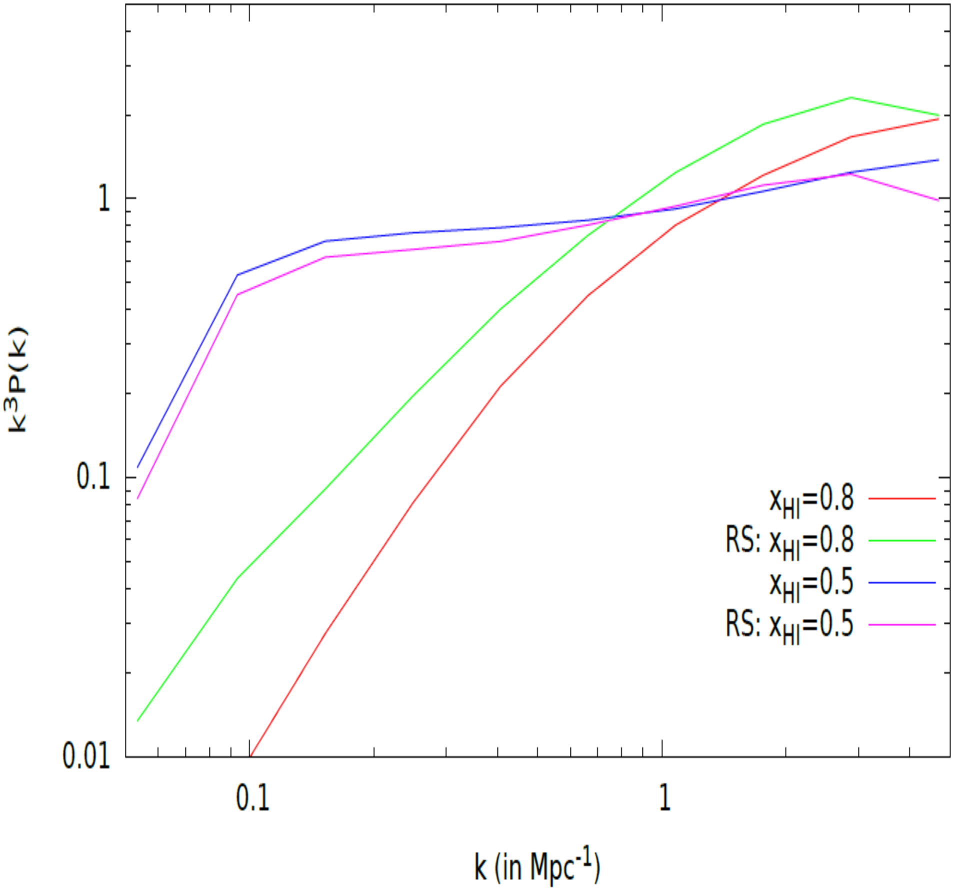
- The power spectrum in redshift space $P^s(k)$ depends on the direction of k. It is convenient to quantify this anisotropy in terms of angular momenta $P_l^s(k)$ as

$$P^s(\mu, k) = \sum p_l(\mu)\, P_l^s(k)$$

$\mu = \boldsymbol{k} \cdot \hat{n}/k$ which is the cosine of the angle between k and $\hat{n}$.

Power spectrum





For $x_{HI} = 0.9$: drop in power, but shape nearly same. The power as x_{HI} decrease. Become flat at low $x_{HI} < 0.4$

Conclusions

- Using PM N-body simulation and FoF halo finder, one can generate a high resolution ionization map for a extensive dynamic range
- Implementing some simple assumption on physical processes, we have got the reionization maps at the expanse of moderate computational resources.
- So, it possible to achieve a reasonably accurate picture of the reionization using this semi-numerical approach
- RSD introduce anisotropies in the signal and modify the amplitude of the power spectrum
- Our results are consistent with the result reported in earlier works

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Collaborators

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THANK YOU