Semi-Numerical Simulations of EoR 21-cm Signal

Abinash Kumar Shaw

Epoch Of Reionization Workshop, 2016 (IIT Kgp)

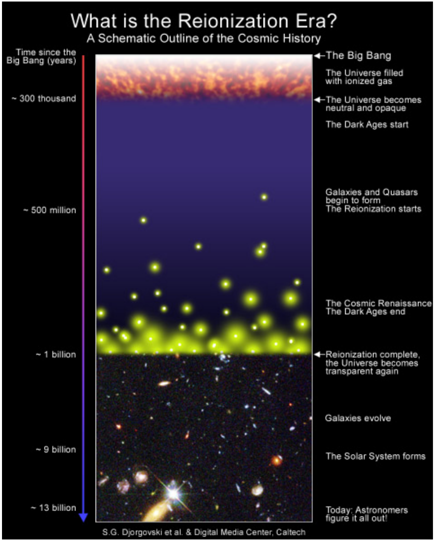
Department of Physics & Centre For Theoretical Studies
Indian Institute of Technology, Kharagpur

July 19, 2016

Introduction

What is Epoch Of Reionization (EoR)?

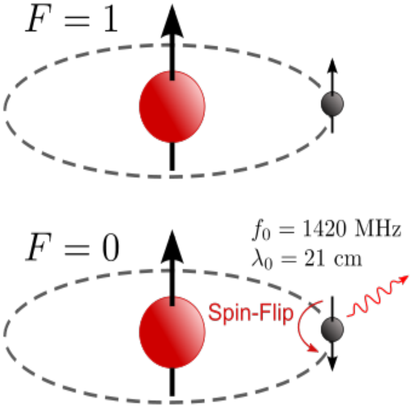
- Generation of First generation of luminous sources.
- Observations suggest range of the era $6 \leq z \leq 15$



Courtsey:www.haystack.mit.edu/ast/science/epoch/

HI 21-cm Cosmology

- Neutral atomic Hydrogen (HI) as probe.
- 21-cm radiation.
- Radio Interferrometric arrays (e.g. GMRT,uGMRT, OWFA, MWA,LOFAR, Mega project SKA) to detect signal.
- Challenges :
  * Astrophysical Foreground
  * Faint signal



Credit: www.astro.wisc.edu

Antenna


PC -- Abinash Kumar Shaw


PC -- Siddhartha Bhattacharya


www.skatelescope.org


www.mwatelescope.org/images

Motivation

- To study the formation of first sources and evolution of Universe.
- Model the expected 21-cm signal
- Quantitative prediction for detection using radio interferrometers.

Methodology

There are two most popular methods for simulating reionization map:

Methodology

There are two most popular methods for simulating reionization map:

1. Radiative transfer Method (Complete Numerical)
2. Semi-Numerical Models (Sem-Num)

Radiative Transfer Model

Features :

- Most accurate method.
- Incorporate all physical processes.
- Traces path of each ionizing photons in each direction in Inter Galactic Medium(IGM).

Radiative Transfer Model

Features :

- Most accurate method.
- Incorporate all physical processes.
- Traces path of each ionizing photons in each direction in Inter Galactic Medium(IGM).

Limitations:

- Computationally very expensive in context of resources and time.
- Limited in Dynamical range.

So, we need Sem-Num methods.

Semi-Numerical Methods

Features :

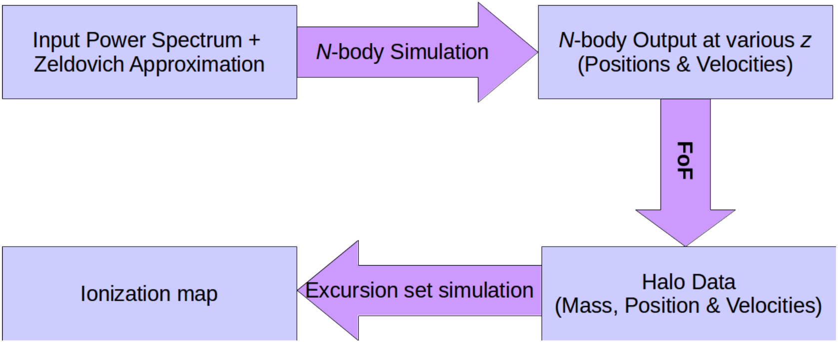
- Do not require huge computational efforts and are faster than Radiative Transfer methods.
- Produces ionization maps similar to the Radiative Transfer methods.
- Inside-out topology [Choudhury et al. (2009)]
- HI traces dark matter(DM) density distribution.
- Excursion-Set Fromalism to generate ionization map.

Limitations :

- Based on simplified assumptions.
- Sources and sinks of ionizations are not properly taken into account.

Sem-Num Simulations

Our simulations mainly consists of three modules,



N-body : Overview

Purpose : Nonlinear evolution of DM density with redshift starting from Gaussian random matter distribution.

N-body : Overview

Purpose : Nonlinear evolution of DM density with redshift starting from Gaussian random matter distribution.

Technique : Parallelized Particle Mesh (PM)

N-body : Overview

Purpose : Nonlinear evolution of DM density with redshift starting from Gaussian random matter distribution.

Technique : Parallelized Particle Mesh (PM)

Periodic bounday conditions have been applied to remove surface effects.

PM Algorithm : Initialization

- Discretized Box ($N_1 \times N_2 \times N_3$) with constant grid separation (L)
- DM field is discretized to DM particle of equal masses(M_{part}) at grid points.
- Input power spectrum to generate density fluctuation $\Delta(\vec{k})$.

$$\Delta(\vec{k}) = \sqrt{\frac{VP(k)}{2}}[a(\vec{k}) + ib(\vec{k})]$$

where, $\langle a(\vec{k})a^*(\vec{k})\rangle = 1 = \langle b(\vec{k})b^*(\vec{k})\rangle$

PM Algorithm : Initialization cont...

- Zeldovich Approximation (ZA) to move particles from grids,

$$\vec{x} \rightarrow \vec{x} - \vec{\nabla}\nabla^{-2}\delta(\vec{x})$$

$$\vec{v} \rightarrow -aHf\vec{\nabla}\nabla^{-2}\delta(\vec{x})$$

  where, $f = \frac{d(lnD)}{d(lna)}$
- Cloud-in-Cell (CIC) algorithm calculate density at grid points from particle distribution.

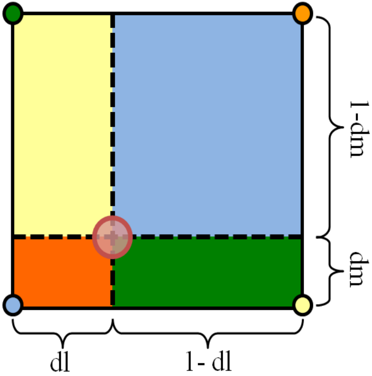
PM Algorithm : CIC

It calculates particle density distribution on grids given particle positions.

For a cell containing a particle at $\mathbf{x}$, weight to one of corner $\mathbf{a}_{i,j,k}$ is ,

$$W_{i,j,k} = \Pi_m(1 - |a_m - x_m|)$$

where, $m = 0, 1, 2$.



PM Algorithm : Force Calculation

- Calculate gravitational potential $\phi(\mathbf{x})$ at each grid points in fourier space.

$$\phi(\vec{k}) = -\frac{L^2}{4}\left[\sum_m sin^2\left(\frac{Lk_m}{2}\right)\right]^{-1}\Delta(\vec{k})$$

$$\phi(\mathbf{x}) = FFT(\phi(\vec{k}))$$

- Now forces at each grid is being calculated using central difference method.
- Force at particle poistion is now interpolated using same weight function as in CIC.
- Now velocity is updated using force and initialization is complete.

PM code : N-body loop

- Particle positions and velocities is being iterated in an N-body loop using **Particle Dynamics,**

$$\frac{d\vec{x}}{da} = \frac{\vec{v}}{a^3 H(a)}$$

$$\frac{d\vec{v}}{da} = -\vec{\nabla}\phi(\vec{x})$$

where,

$$\nabla^2\phi = \frac{3}{2}\frac{H_0^2\Omega_{m0}}{a^2 H(a)}\delta(\vec{x}, t)$$

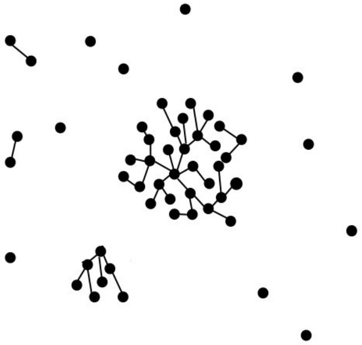
- Record paticle positions and velocities at desired redshifts.

Friends-Of-Friends (FoF)

- DM halos host ionizing sources
- Reionization starts inside halo then proceeds outwrads.

Hence it is important to identify halos.

- To identify halos we use FoF algorithm with a linking length $L_{fof} = 0.2\times$ Mean interparticle separation.
- Minimum halo mass ($M_{halo} = 10 M_{part}$) [Mondal et al. (2016)]
- Calculates mean position, mean velocity and masses of halos.

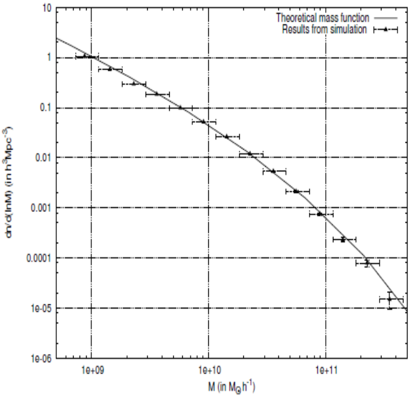


FoF : Mass function

- Comoving number density of halos per unit logarithmic mass

$$dn/d(lnM)$$

- Theoretical mass function from Sheth & Tormen (2002) with the fitting function from Jenkins et al. (2001)



Ionization Code :

Basic Idea :

- Reionization depednds upon many undetermined factors, e.g. Star forming rate and effiecieny within halos, HI bias within halos, photons produced per unit stellar mass, photn escape fraction, Helium weight fraction.
- Ionizing luminosity (N_γ) may depend upon Galaxy and Source properties.
- N_γ is a function of M_{halo}.

Sem-Num Model specifications:

- We assume that N_γ is linearly related with M_{halo}.

$$N_\gamma = N_{ion} \frac{M_{halo}}{m_H}$$

- N_{ion} is dimensionless parameter which take care of all physical processes mentioned above.
- All above dependencies have been taken care inside N_{ion} , which is number of ionizing photons per baryon into collapsed object.
- Another parameter in simulation is mean free path of ionizing photons R_{mfp}.
- We assume universe to be reionized by 50% at $z \sim 8$ and fully ionized around $z \sim 6$.
- $N_{ion} = 23.21$ and $R_{mfp} = 20$ Mpc [Mondal et al. (2016)]

Generating Ionization Field :

- Read N-body output and Halo catalogue
- Calculation of HI density (n_{HI}) using particle position from N-body output and photon density n_γ using Halo catalogue.
- Use Excursion set to ionize a pixel $\mathbf{x}$.

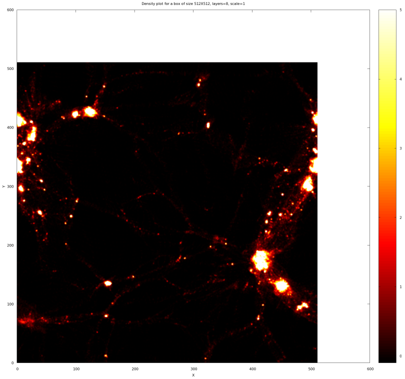
$$\langle n_\gamma(x)\rangle_R \geq \langle n_{HI}(x)\rangle_R$$

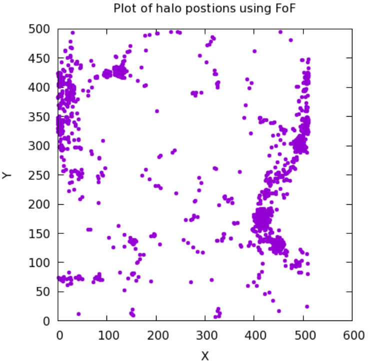
  where $R \in [L, R_{mfp}]$
- If not satisfied then assign ionization fraction at pixel,

$$Q_i(x) = \langle n_\gamma(x)\rangle_{R_{min}} / \langle n_{HI}(x)\rangle_{R_{min}}$$

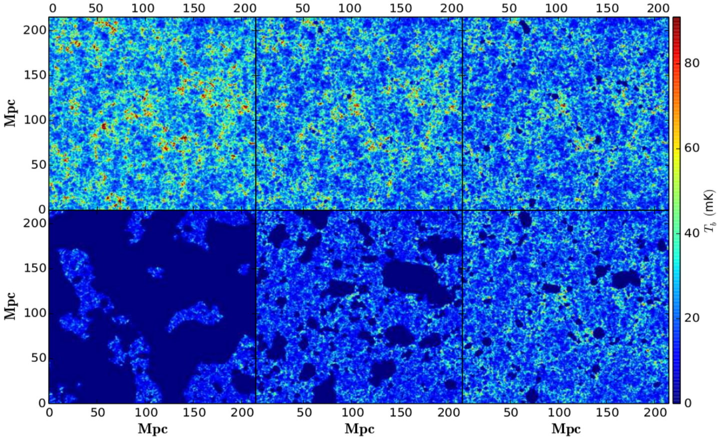
Results : Density Field & Halos

Size of box = $(512)^3$, No. Of particles = $(256)^3$, Slice thickness = 8 grid





Results : Ionization map

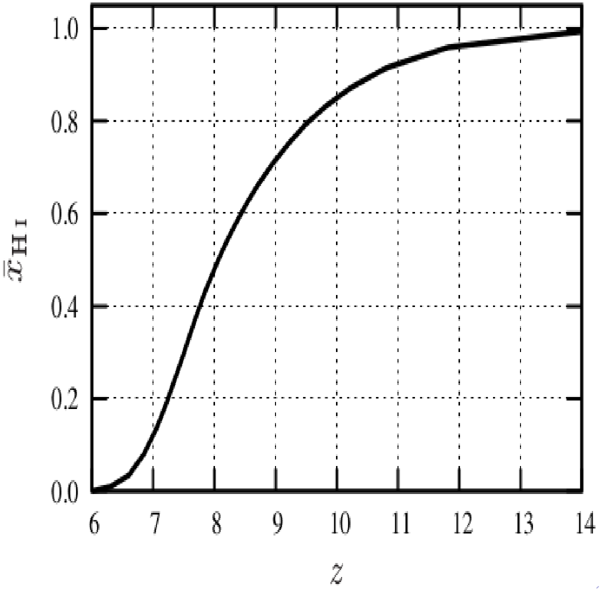


This shows one realization of the two dimensional sections through the simulated HI brightness temperature maps for the $[z, x_{HI}]$ values tabulated. In these panels, the value of x_{HI} decreases in the clockwise direction starting from the top-left panel. Volume of these simulation boxes are $[215 \text{ Mpc}]^3$. [Mondal et al. (2016)]

Results : $\bar{x}_{HI}$ vs z

z	$\bar{x}_{HI}$
13	0.98
11	0.93
10	0.86
9	0.73
8	0.50
7	0.15
6	0.00

Mondal et al.(2016)



Summary

- Semi-Numerical methods are bit faster than Radiative transfer techniques.
- Reionization of HI probe Reionization era and baryonic matter traces underlying DM.
- Paralellized Particle Mesh Code are used to simulate nonlinear evolution of matter density field.
- FoF algorithm is used to find halo which host ionizing sources.
- N_{ion} and R_{mfp} are two parameters in our reionization simulations.
- Photon luminosity is linearly proportional to M_{halo} and baryon density is with DM mass at grids.
- Ionization fraction at a pixel is decided by Excursion set fromalism.