# The structure of reionization in hierarchical galaxy formation models.

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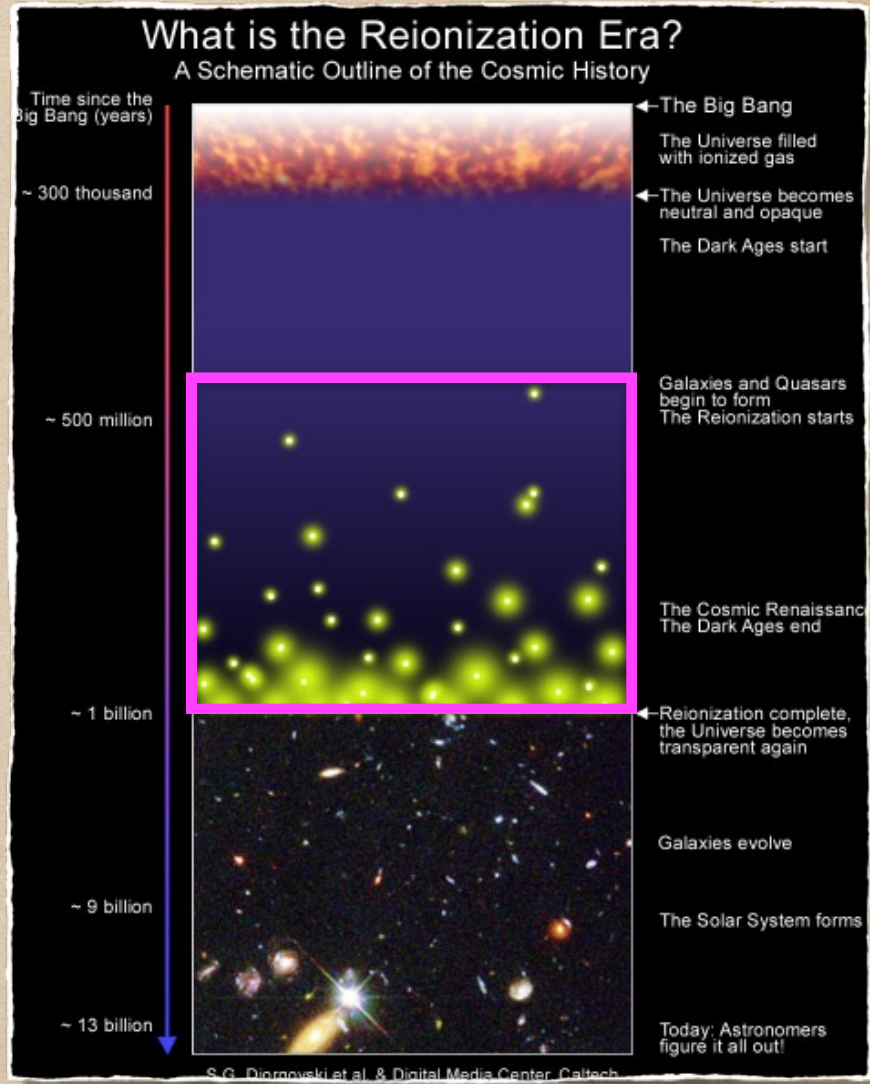
# Outline

- Hydrogen Reionization & Simulation
- Implications
- Summary

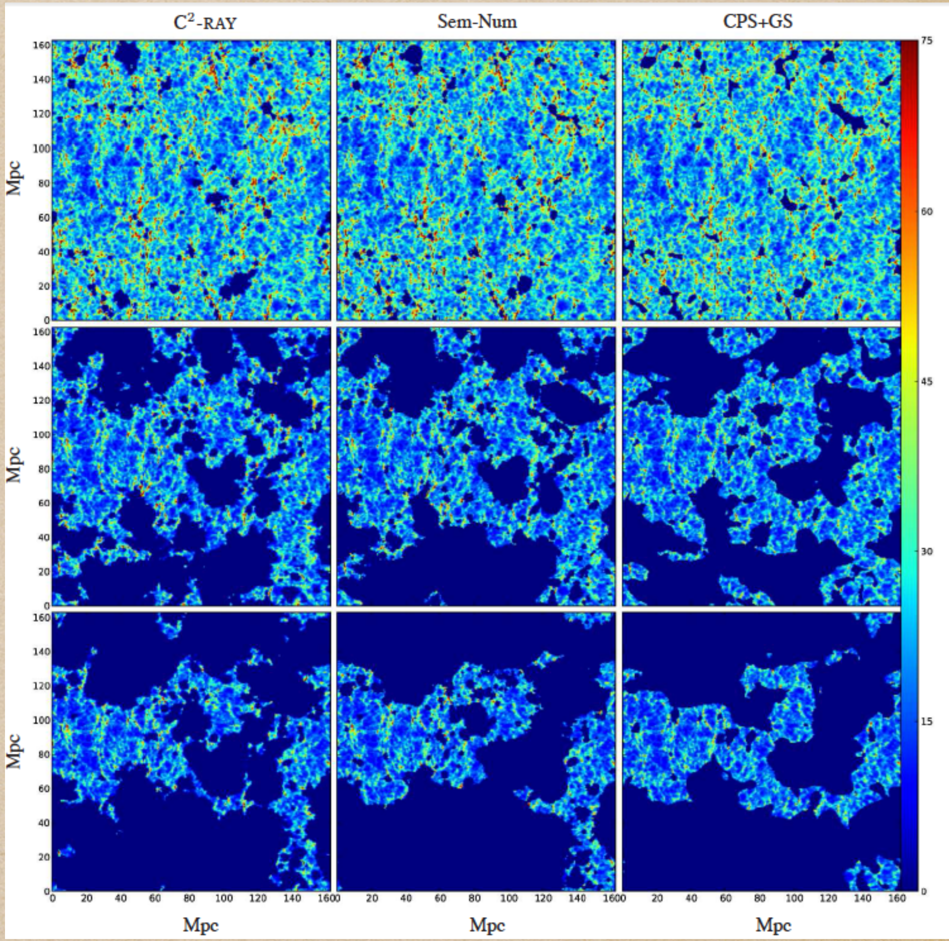
# Reionization

- Once first objects in early Universe that were emitting high enough energy to ionize neutral hydrogen.
- Important goal for modern cosmology.
- Sensitive to the astrophysical properties of the objects.
- Sensitive to the feedback processes.



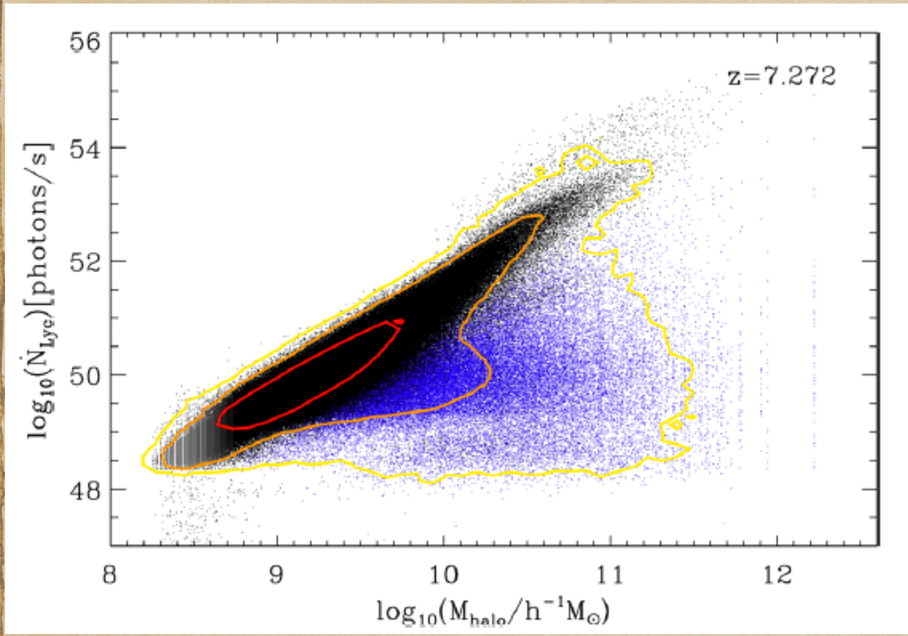
# Reionization Simulation

- Put ionising sources.
- Radiative transfer methods, or
- Semi-numerical scheme.
- Reionization structure, or 21cm power spectrum.




Suman Majumdar et al. 2014

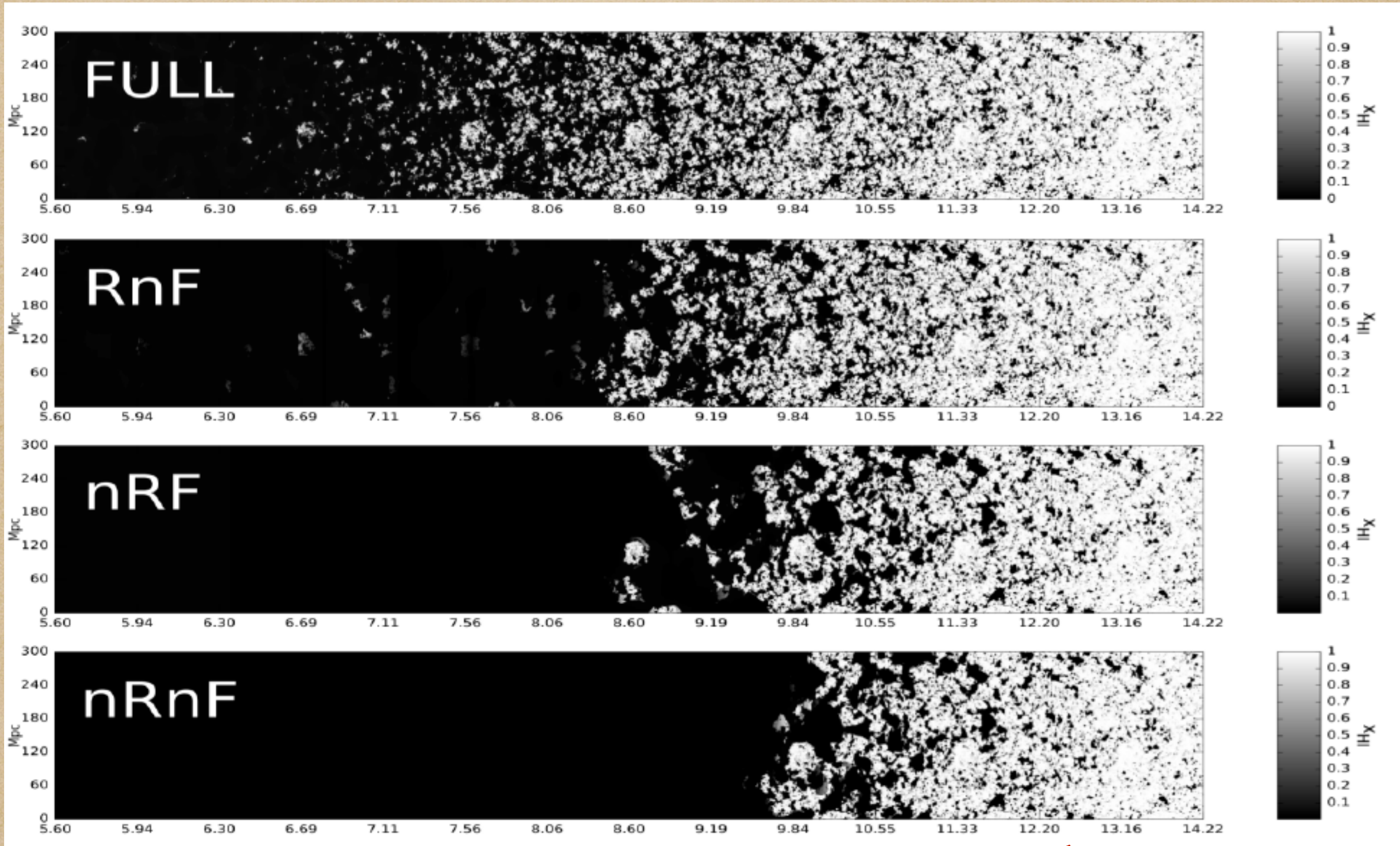
# 그러나..




Park et al. 2014

The luminosity of an ionizing source is not simply proportional to the host dark matter halo mass as if often assumed in reionization models.

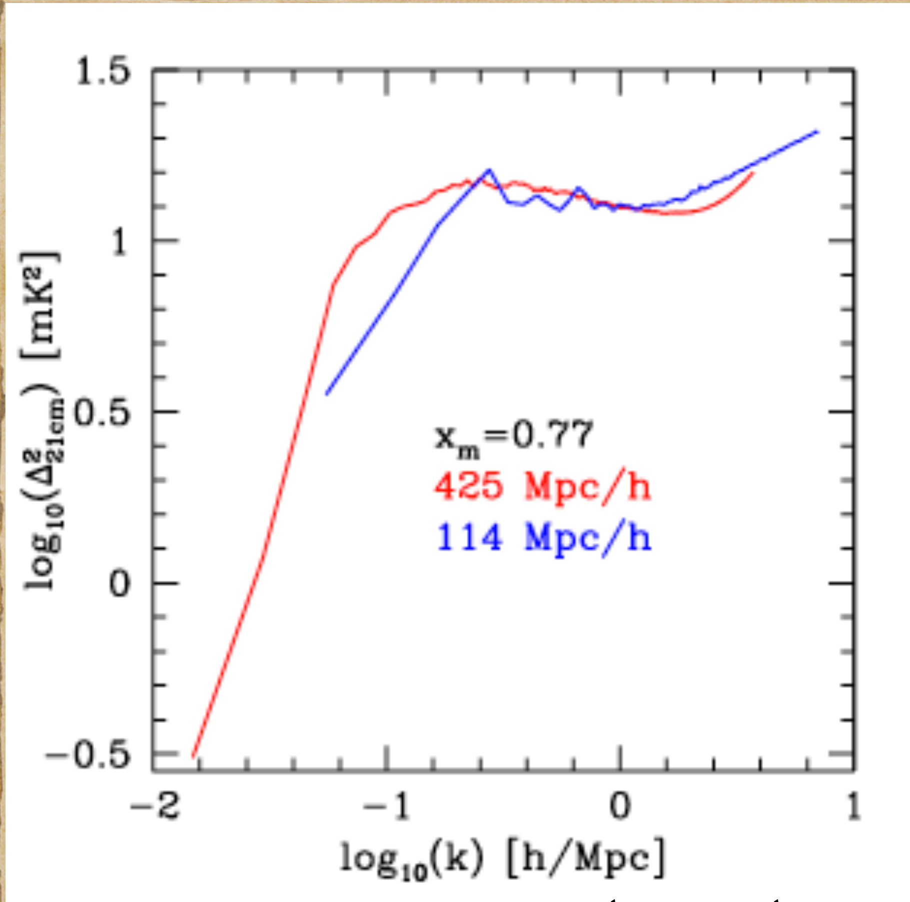
Physically motivated modelling for ionizing sources during the reionization should be included to understand the epoch of reionization.




Recombination (R)

UVB feedback (F)

Sobacchi&Mesinger (2014)




Iliev et al. 2014

Large scale power continues to increase as volume increases,

owing to the effect of large scale power on structure formation.

Furthermore, >Gpc volume reionization simulation needs to make mock observations for upcoming radio telescopes results.

# What we need are

- Galaxy formation model for ionizing sources and proper feedback processes.
- Large volume simulation (but has high resolution simulation information).
- Fast and easy to span parameter space of physical mechanism.

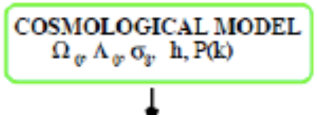
# Semi-analytic galaxy formation model

$$\dot{N}_{\mathrm{Lyc},i}(t) = f_{\mathrm{esc}} \int_{\nu_{\mathrm{thresh}}}^{\infty} \frac{L_{\nu,i}(t)}{h\nu}\,\mathrm{d}\nu,$$

$$\dot{N}_{\mathrm{Lyc,cell}}(t) = \sum_{i=1}^{N_{\mathrm{cell}}} \dot{N}_{\mathrm{Lyc},i}(t),$$

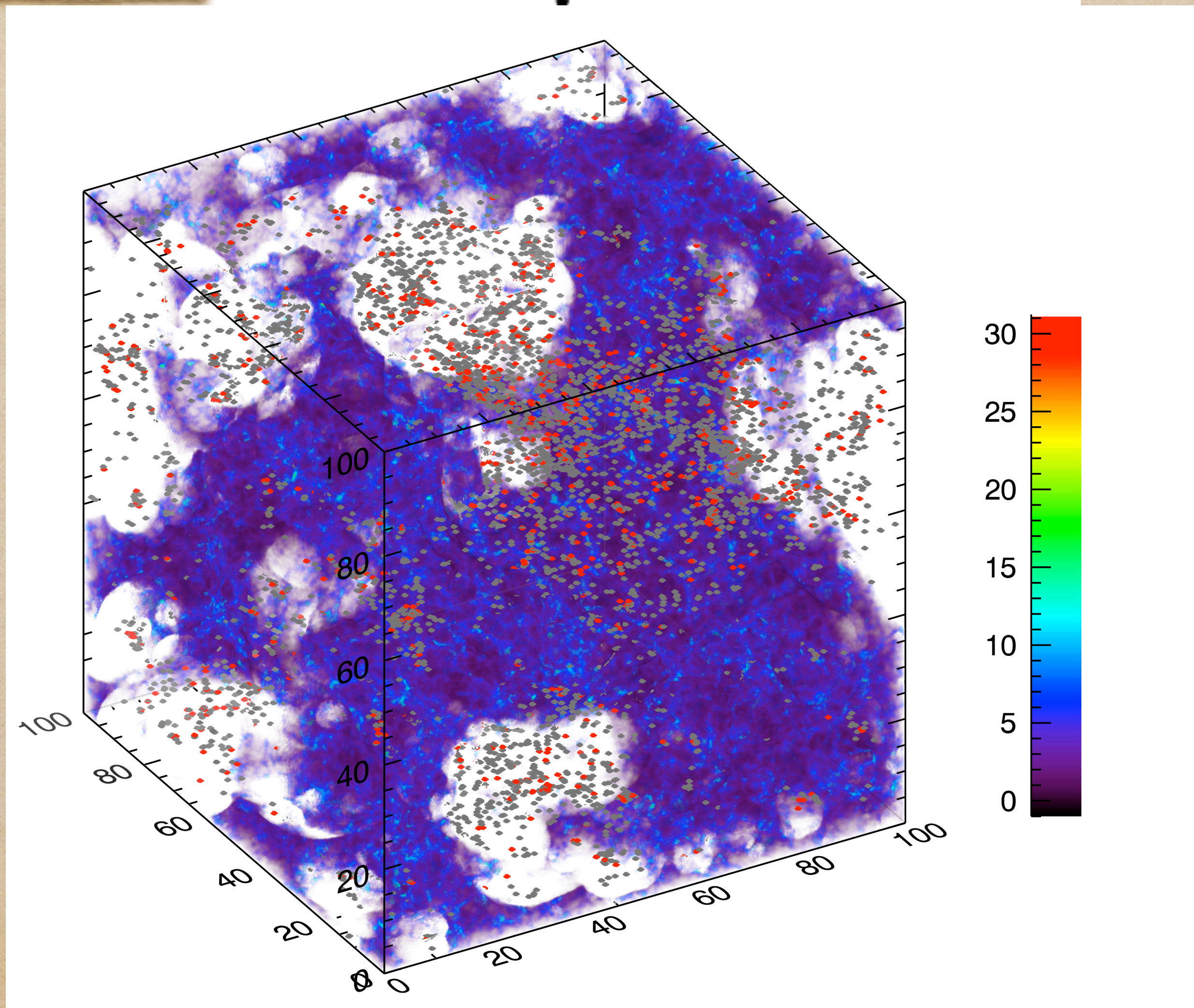
$$N_{\gamma,\mathrm{cell}} = \int_0^{t_z} \dot{N}_{\mathrm{Lyc,cell}}(t)\,\mathrm{d}t$$

$$N_{\mathrm{H\,I,cell}} = n_{\mathrm{H\,I}}(\delta_{\mathrm{DM,cell}} + 1)V_{\mathrm{cell}}$$




cell

$N_{\mathrm{H\,I,cell}}$ ]



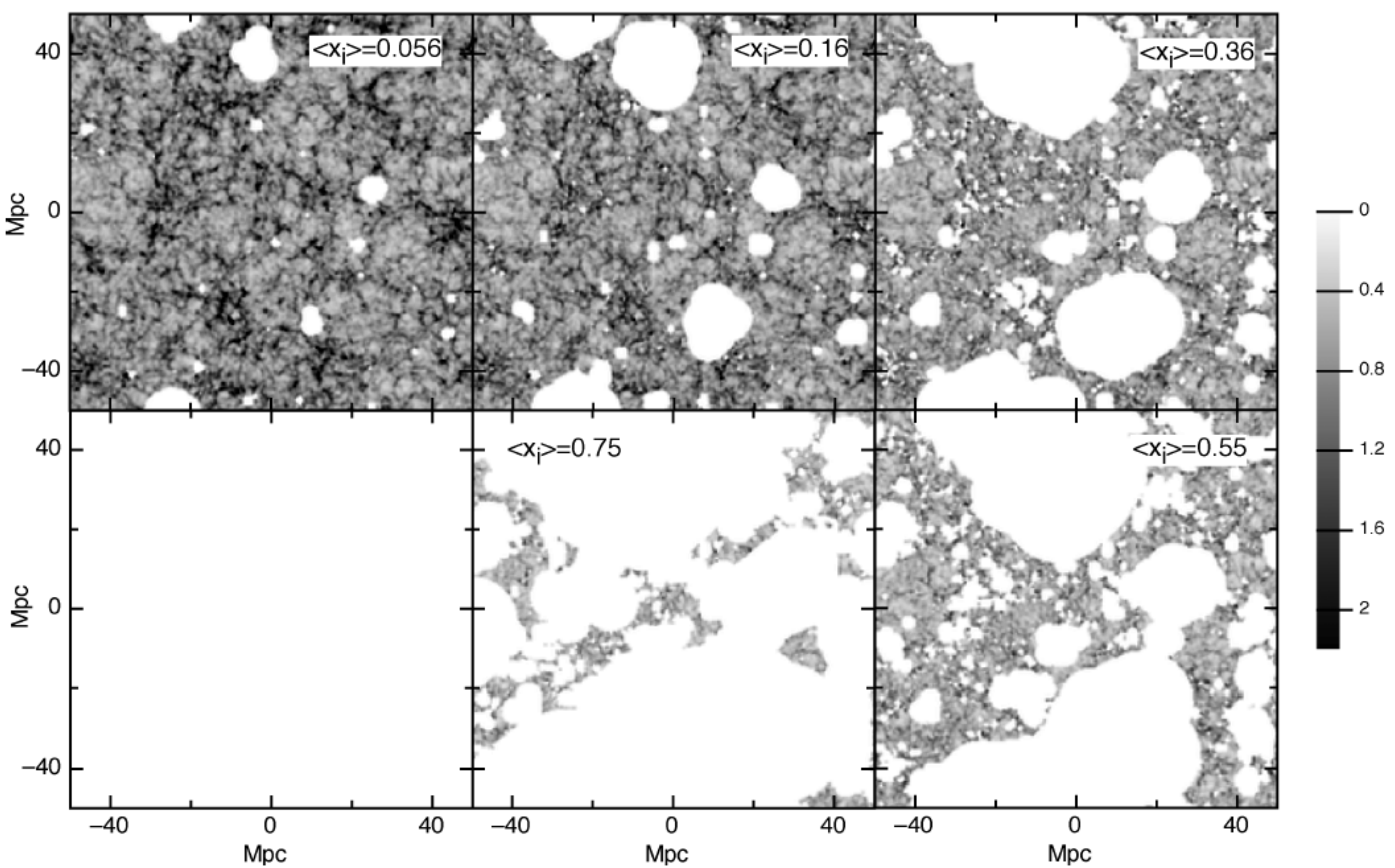

l by photons

ng cell

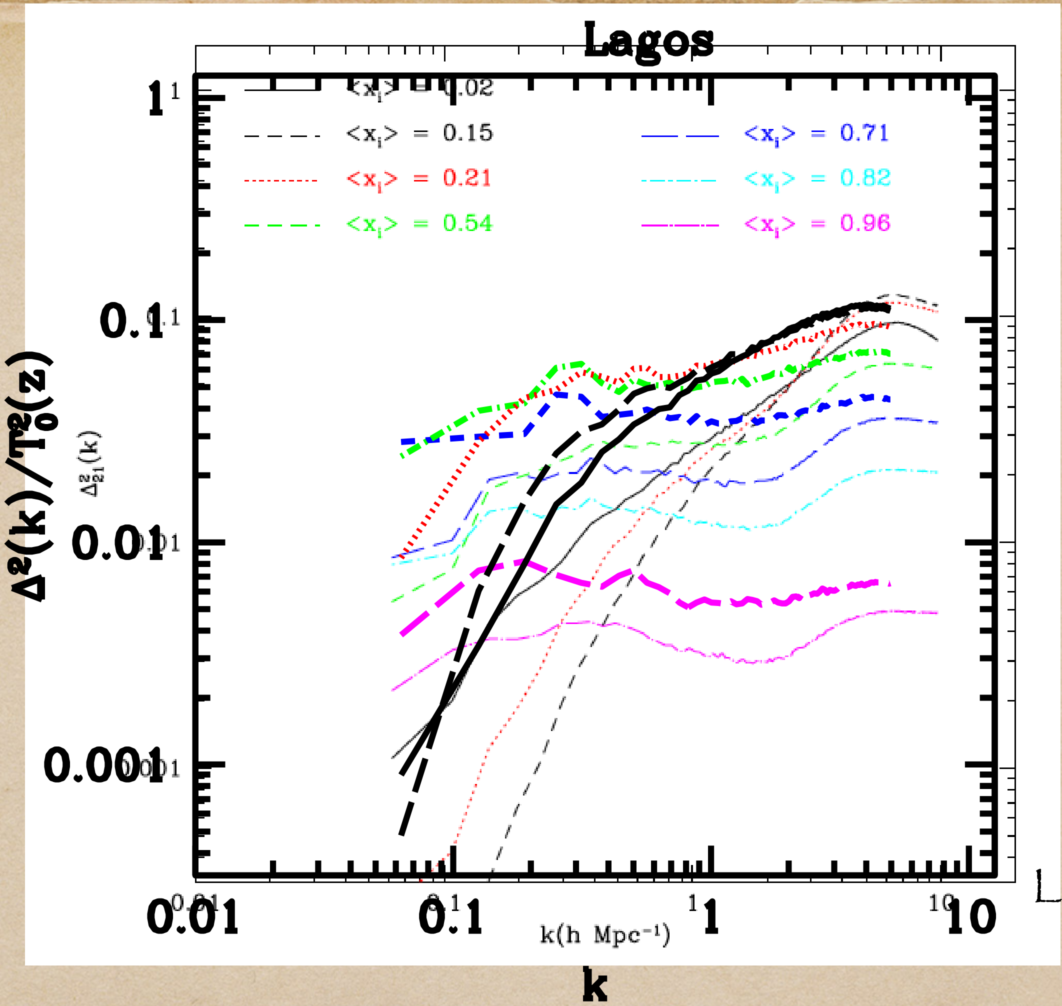
nized regions

space

et al. 2013




Kim et al. 2013




Lidz et al. 2008

- Amplitude of 21cm power spectrum predictions higher than Lidz et al. 2008 predictions.
- Prescriptions of galaxy formation physics in the model important to predict amplitude of 21cm power spectrum.

# Large volume simulation

- The size of individual HII bubbles > 10cMpc at highly ionized epoch.
- Overlapped regions are bigger than few times individual bubble size.
- Not enough to understand large scale fluctuation using ~100Mpc volume simulation.

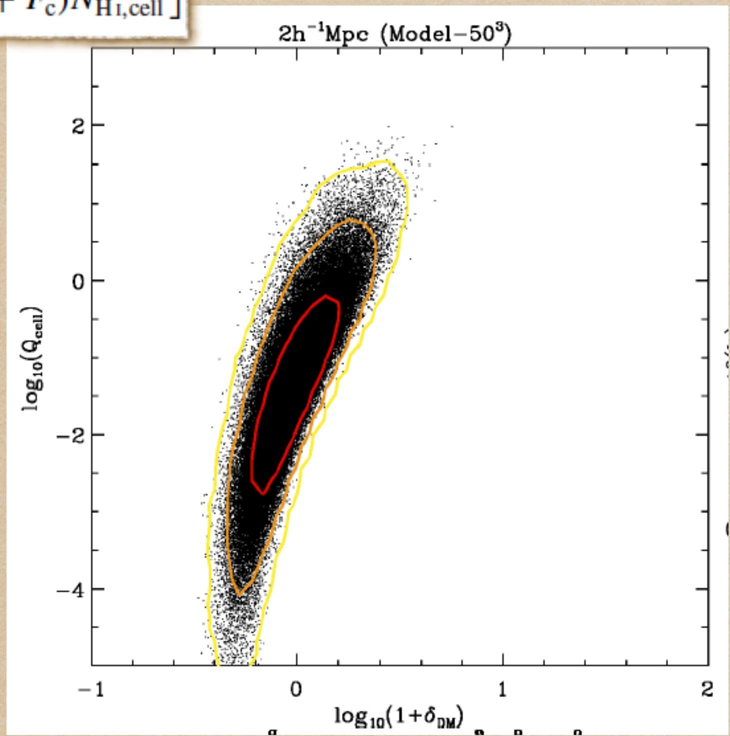
Resolution of Minimum dark halo mass should down to ~10^{8} solar mass to include small galaxies which are dominant at early Universe.

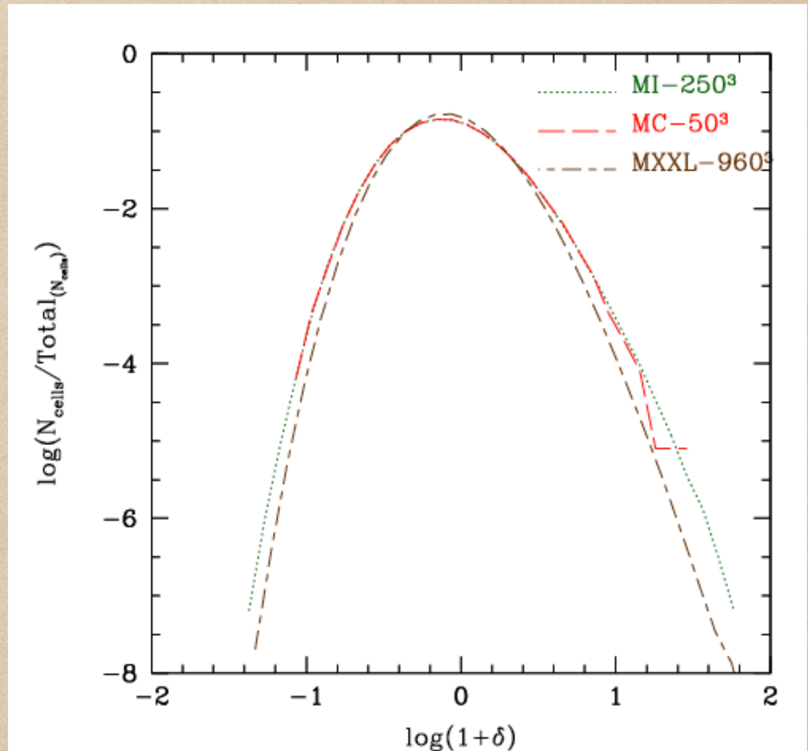
Large volume simulation needs more than Gpc volume

Dark matter halo resolution of Millennium-XXL (3Gpc/h) is ~10^{12} solar mass

# Qvalue Dark matter overdensity Occupation Distribution

$$Q_{\rm cell} = \left[ \frac{N_{\gamma,\rm cell}}{(1+F_{\rm c})N_{\rm H\,I,cell}} \right]$$

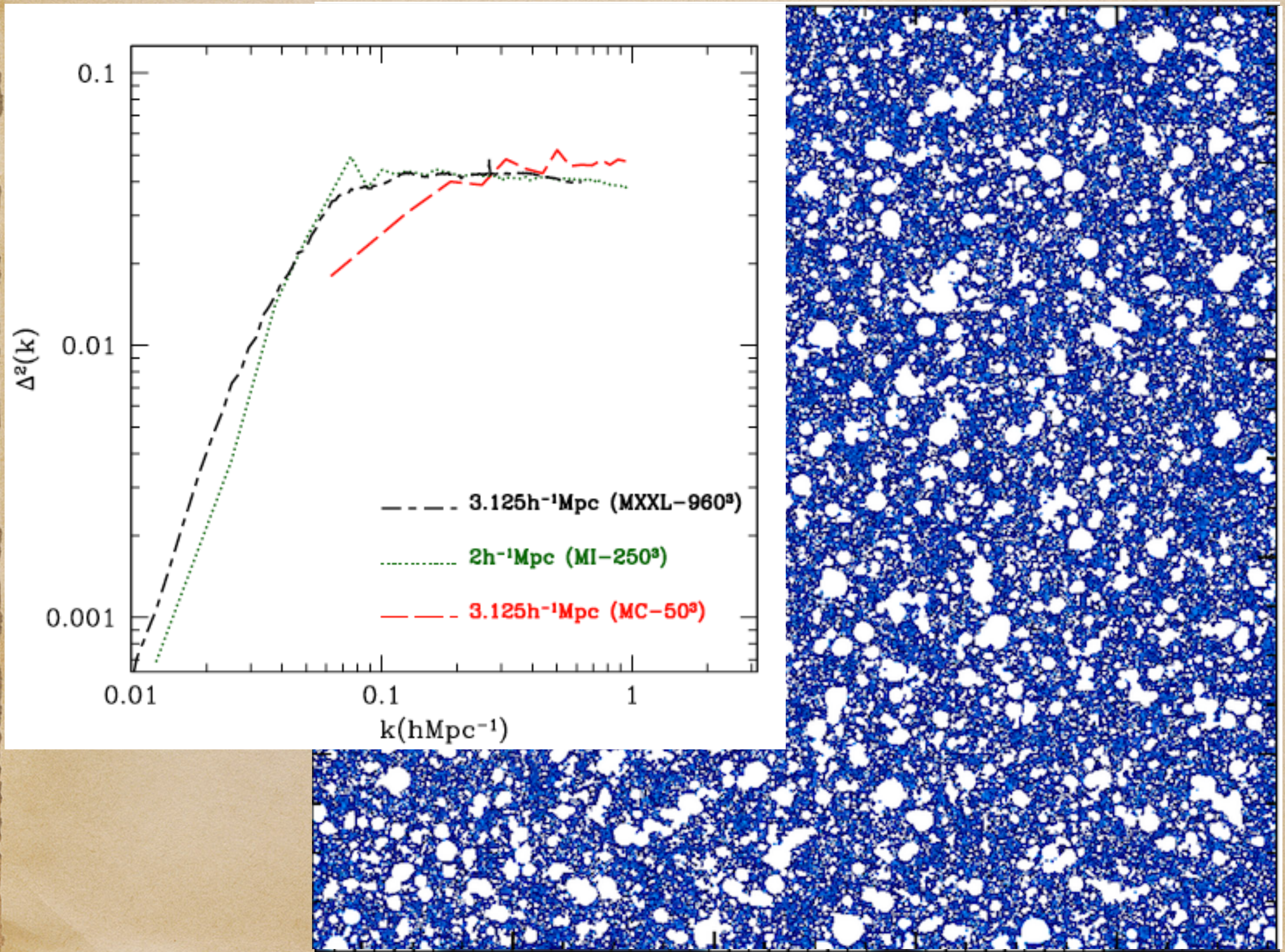



- To expand our calculations to larger volumes, it is convenient to increase the cell size. We have therefore smoothed the cell size from 0.39Mpc/h to 2Mpc/h.
- Dark matter overdensity distributions of different box size and resolution simulations based on same grid size are nearly same.
- The contribution of ionizing sources in the small grid model is all in the large grid size model.

# 21cm intensity maps & power spectra

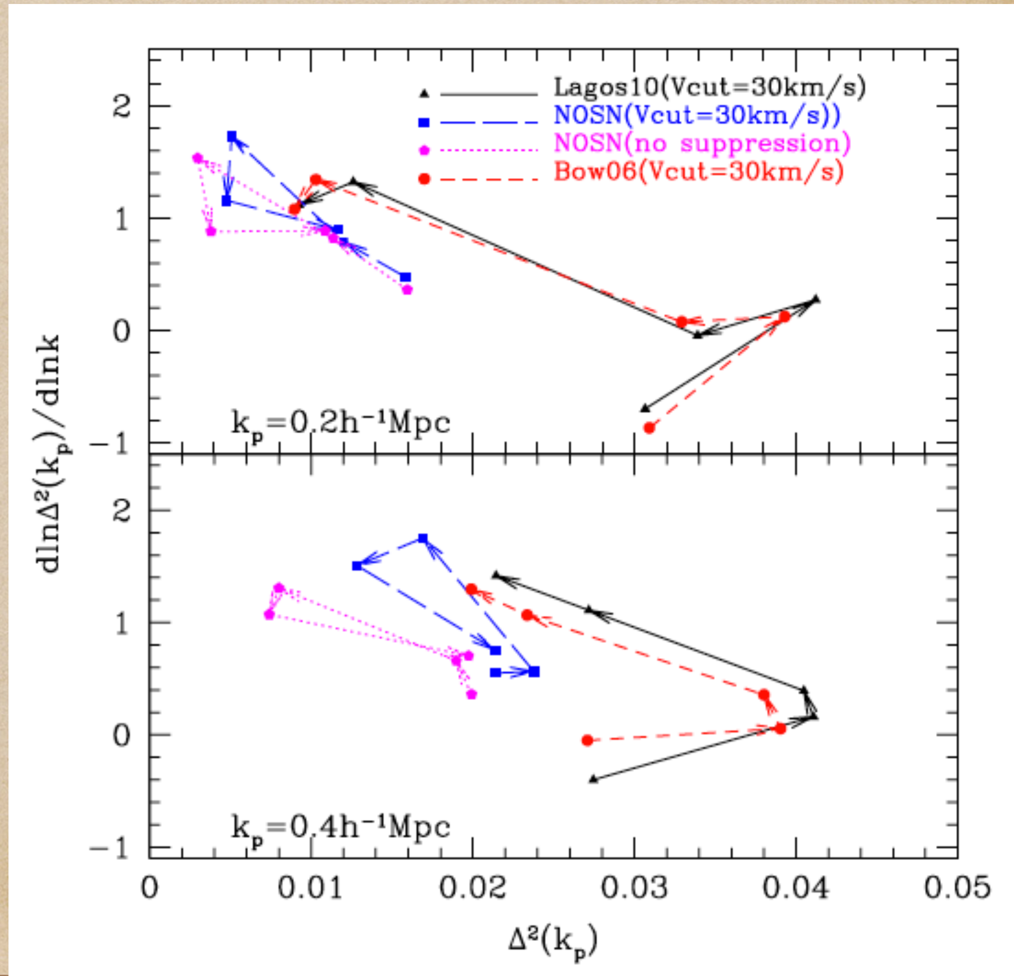
100Mpc/h 500Mpc/h 3000Mpc/h



# Amplitude .vs. slope of redshifted 21cm power spectrum

Galaxy formation physics

- Star formation recipe
- Minimum mass of halo
- (Photoionization feedback)
- SNe feedback



# Escape fraction of ionizing photons on 21cm power spectrum??

$$f_{\rm esc} = A\left(\frac{1+z}{7}\right)^{\alpha}\left(\log_{10}(M_{\rm halo}/h^{-1}\,{\rm M}_{\odot})/10\right)^{\beta}$$

Normarlization value to match 50% ionization fraction at z = 7.272

Redshift dependence

Halo mass dependence

- Redshift dependence
- Halo mass dependence
  - with supernovae feedback
  - without supernovae feedback

| With or without SNe feedback | Name | $A$ | $\alpha$ | $\beta$ |
|---|---|---|---|---|
| With | SN-0 | 0.5348 | 0 | 0 |
| With | SN-I | 0.1488 | 5 | 0 |
| With | SN-II | 1.6791 | −5 | 0 |
| With | SN-III | 0.3649 | 0 | 5 |
| With | SN-IV | 0.7358 | 0 | −5 |
| Without | NOSN-0 | 0.0319 | 0 | 0 |
| Without | NOSN-III | 0.0456 | 0 | 5 |
| Without | NOSN-IV | 0.0201 | 0 | −5 |

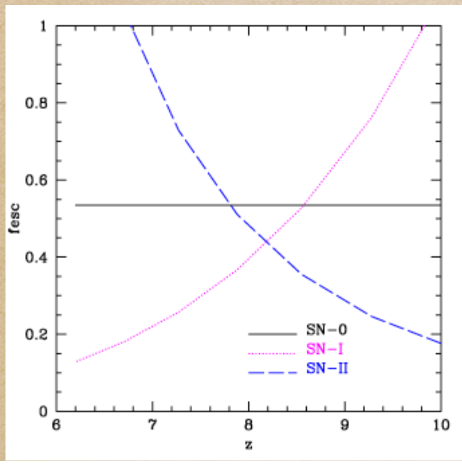
# Reionization history

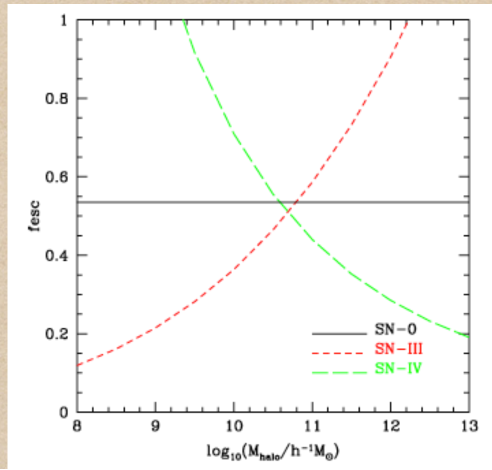
## Redshift dependence

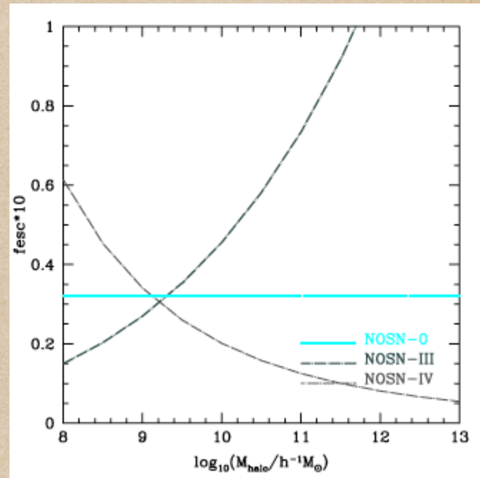
## Halo mass dependence

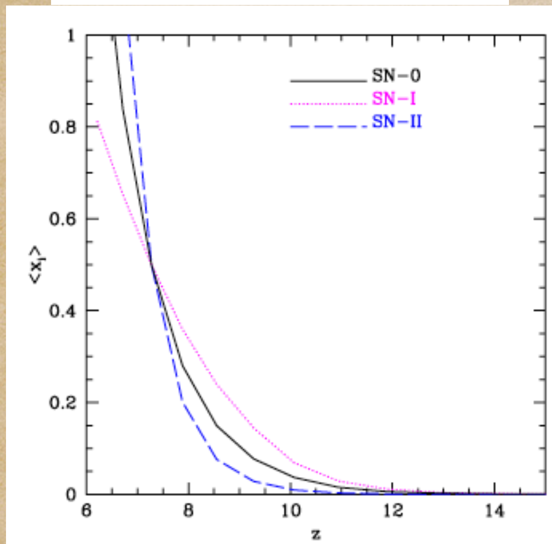
### With SNe

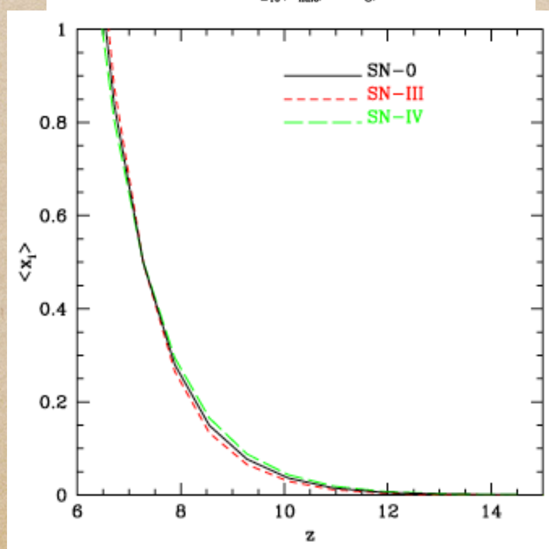
### Without SNe

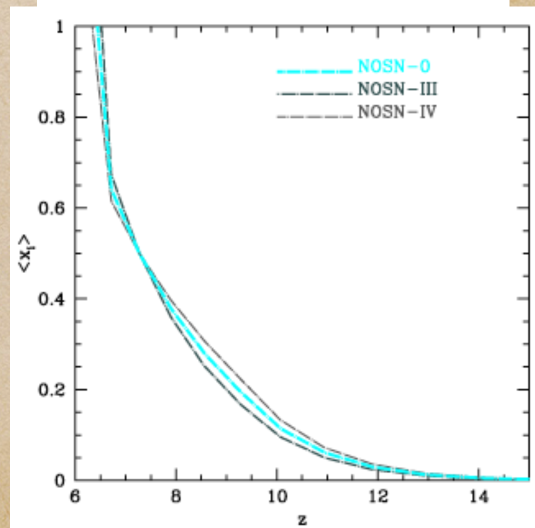


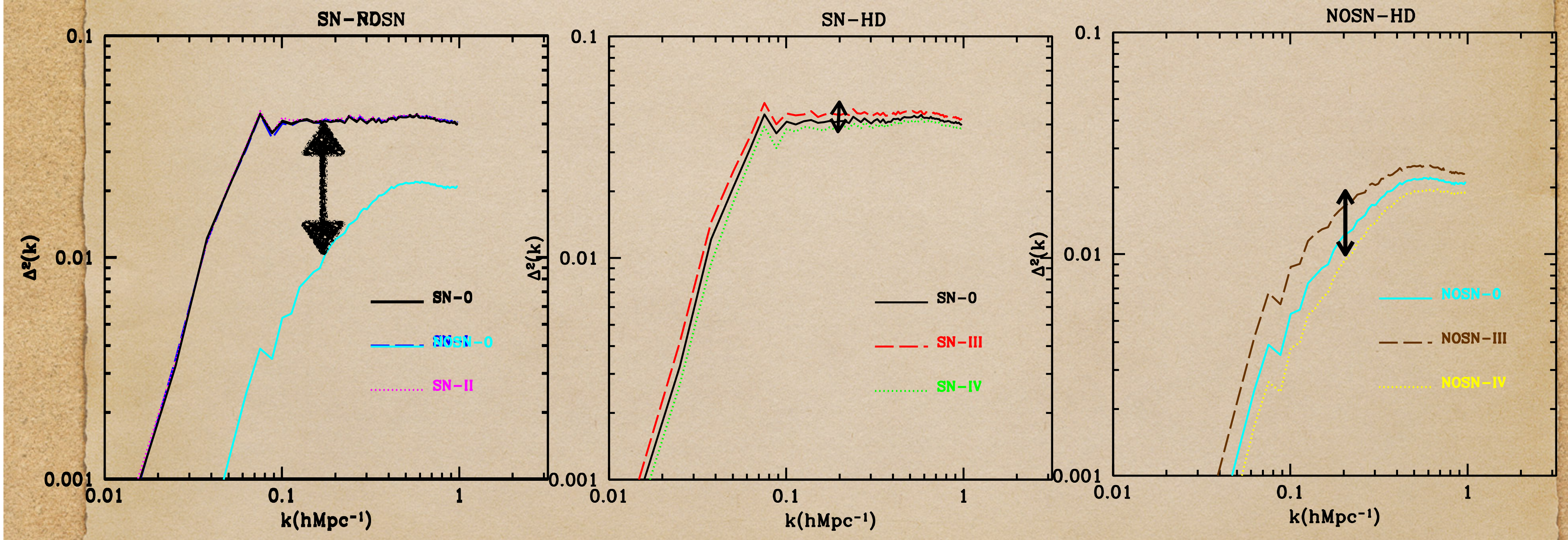



# 21-cm power spectrum

Redshift dependence | Halo mass dependence

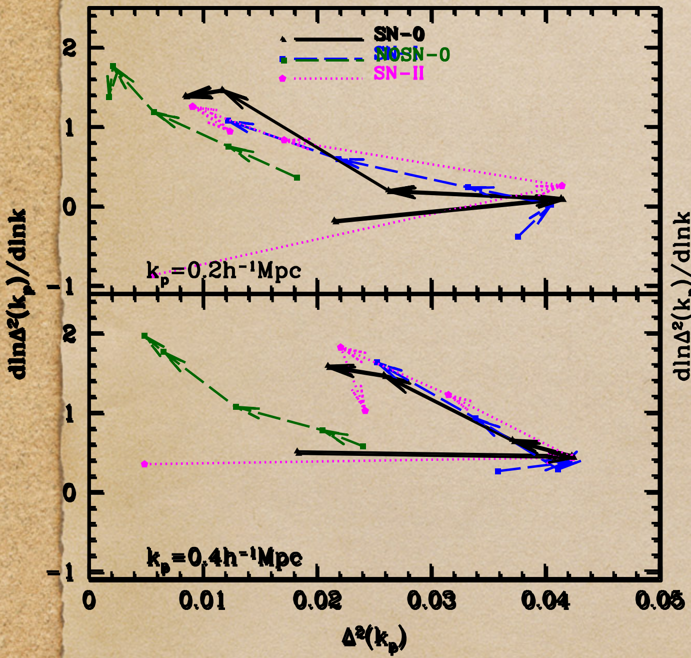
With SNe | Without SNe




at z=7.272, $\langle x_i \rangle$=0.5 using Millennium (500Mpc/h)

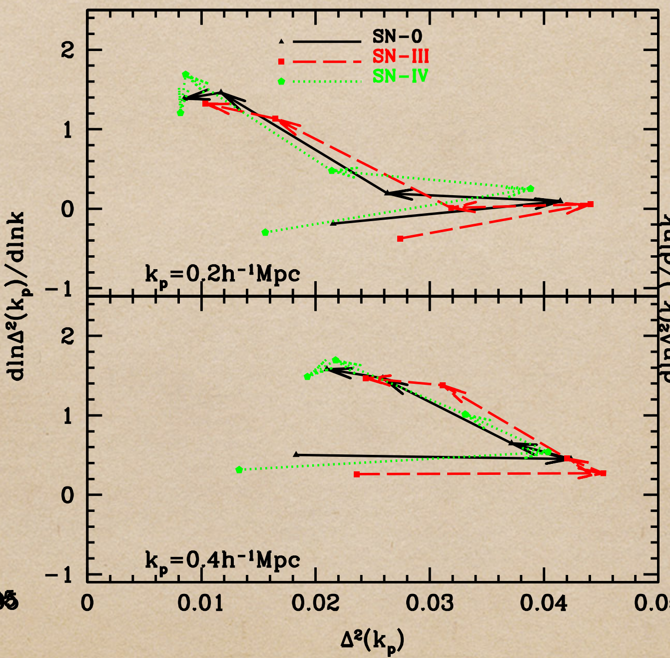
# Amplitude .vs. slope

## Redshift dependence

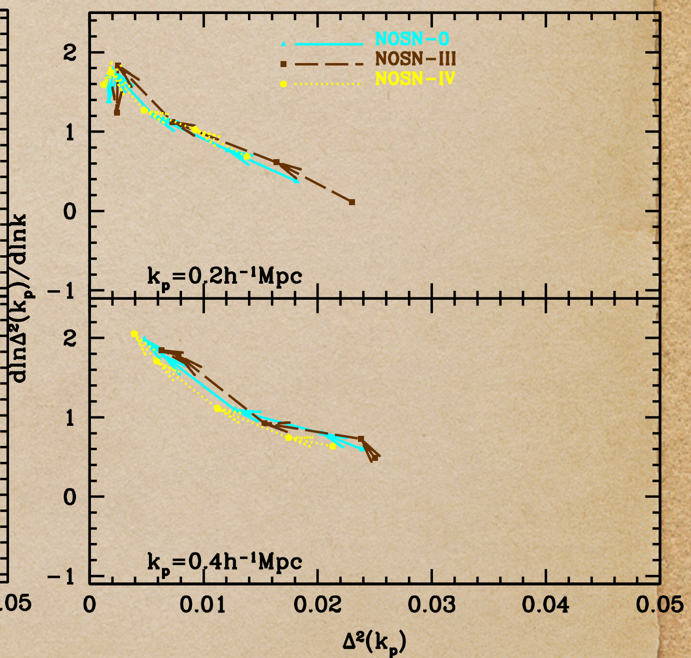



## Halo mass dependence

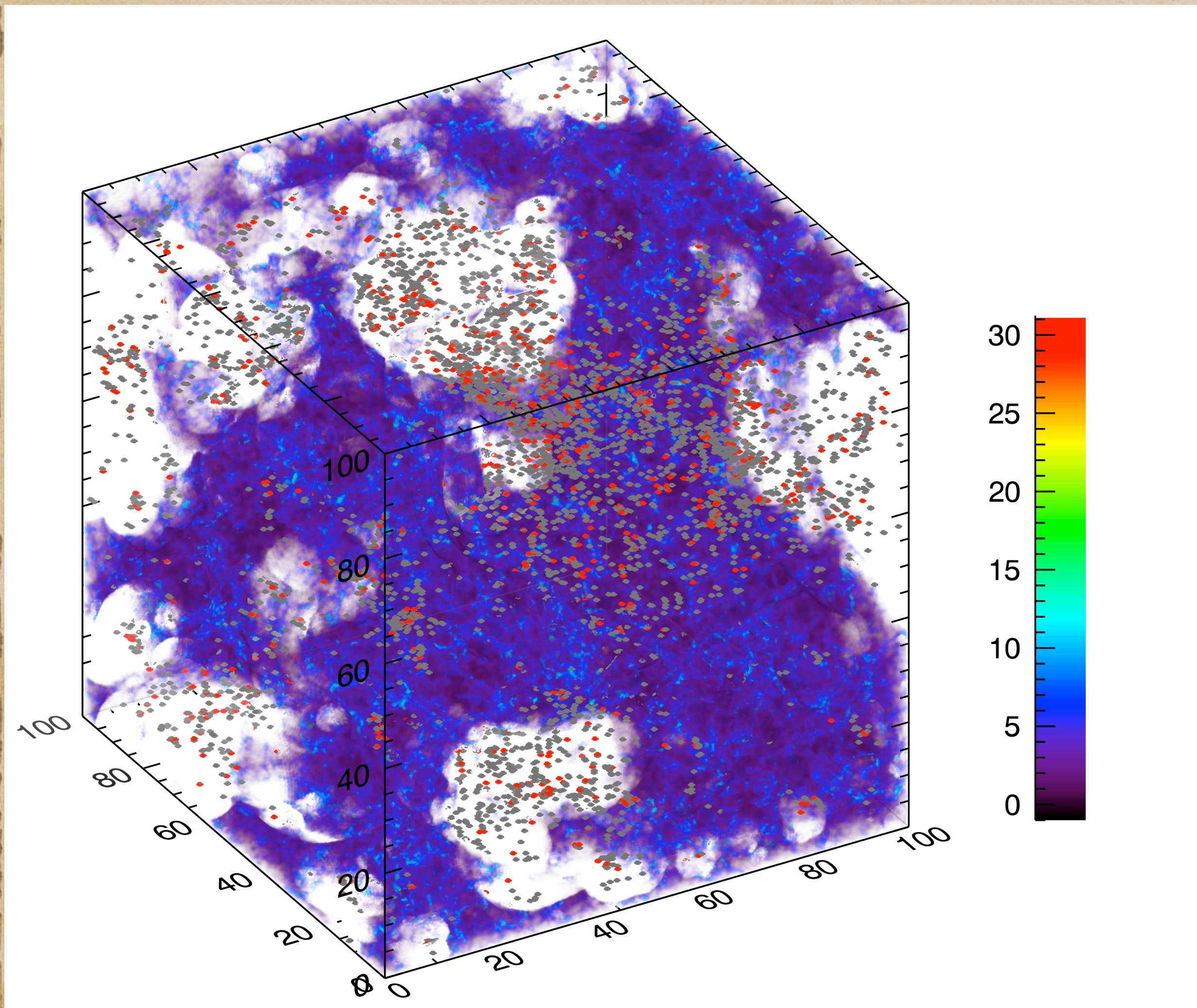
### With SNe




### Without SNe



# Cross-Correlation between 21cm and galaxy properties

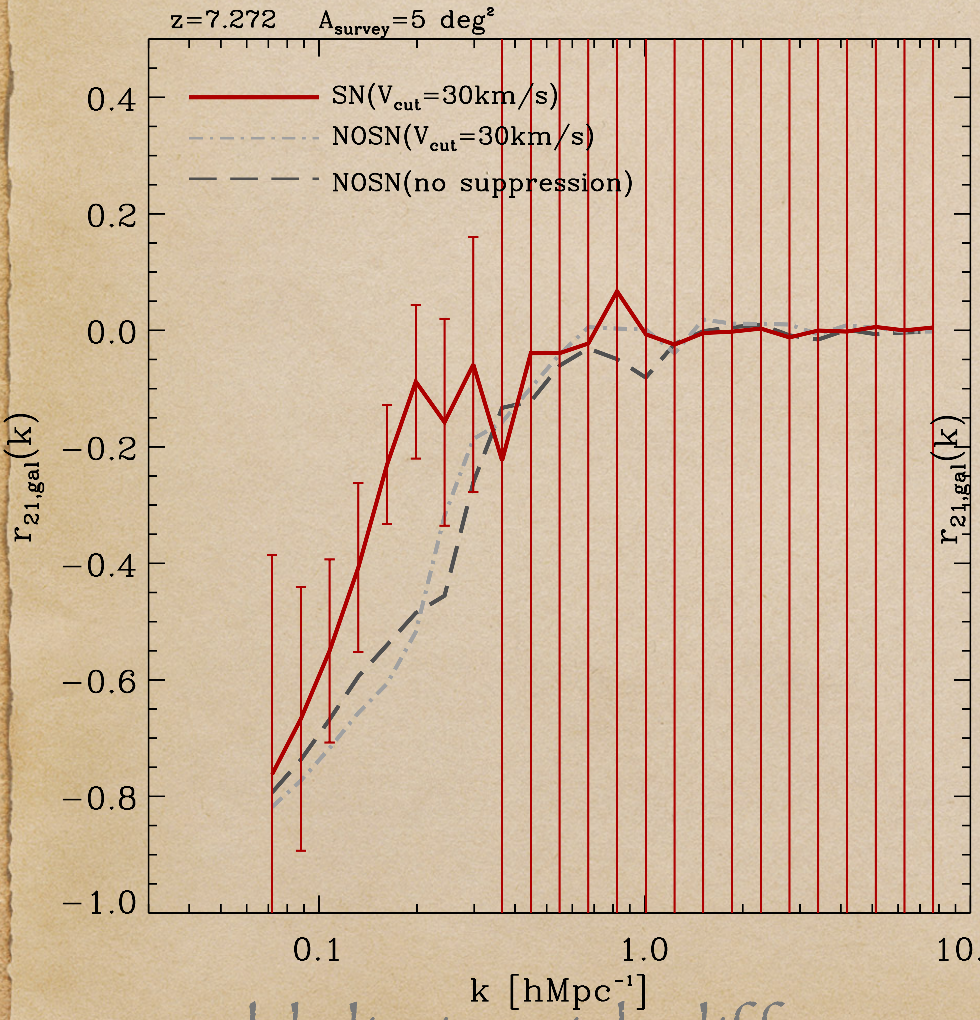


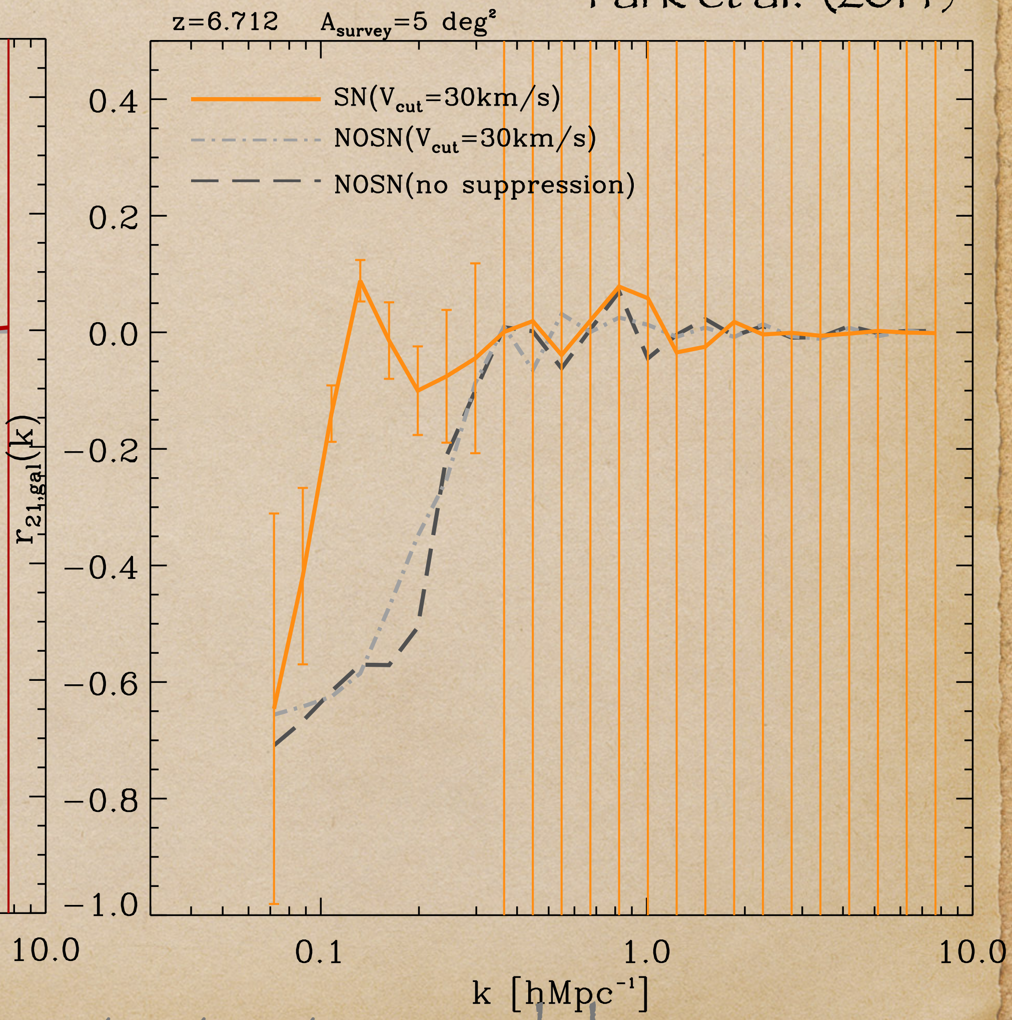

- Rapid exploration of the parameter space of galaxy formation physics.
- Large, statically useful samples.
- Wide range of properties, multi-wavebands.
- Well explain local and moderate redshift observations.

Self consistent

# Detectability of Predictions of cross-correlation coefficient error

Park et al. (2014)




We could distinguish different reionization models.

# Summary

- A hydrogen reionization model needs

A proper galaxy formation model

A large volume but should include ionizing sources' contribution of small galaxies within ~10^{8} solar mass dark matter haloes.

- Galaxy formation physics imprinted on the redshifted 21cm power spectrum or cross-correlation power spectrum btw 21cm and galaxy properties.

SNe feedback

Photoionization feedback

Star formation recipe

- Escape fraction dependence (halo mass or redshift) of ionizing photons from galaxies is less dominant than a galaxy formation physics.

- Unknown, Uncertainties =>> many things to do.

# 10 years ago


고등과학원 Korea Institute for Advanced Study (KIAS)
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