The predictions of cross-power spectrum between 21cm emission and galaxy from the hierarchical galaxy formation model

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- Hierarchical galaxy formation model
- Cross-power spectrum, correlation function
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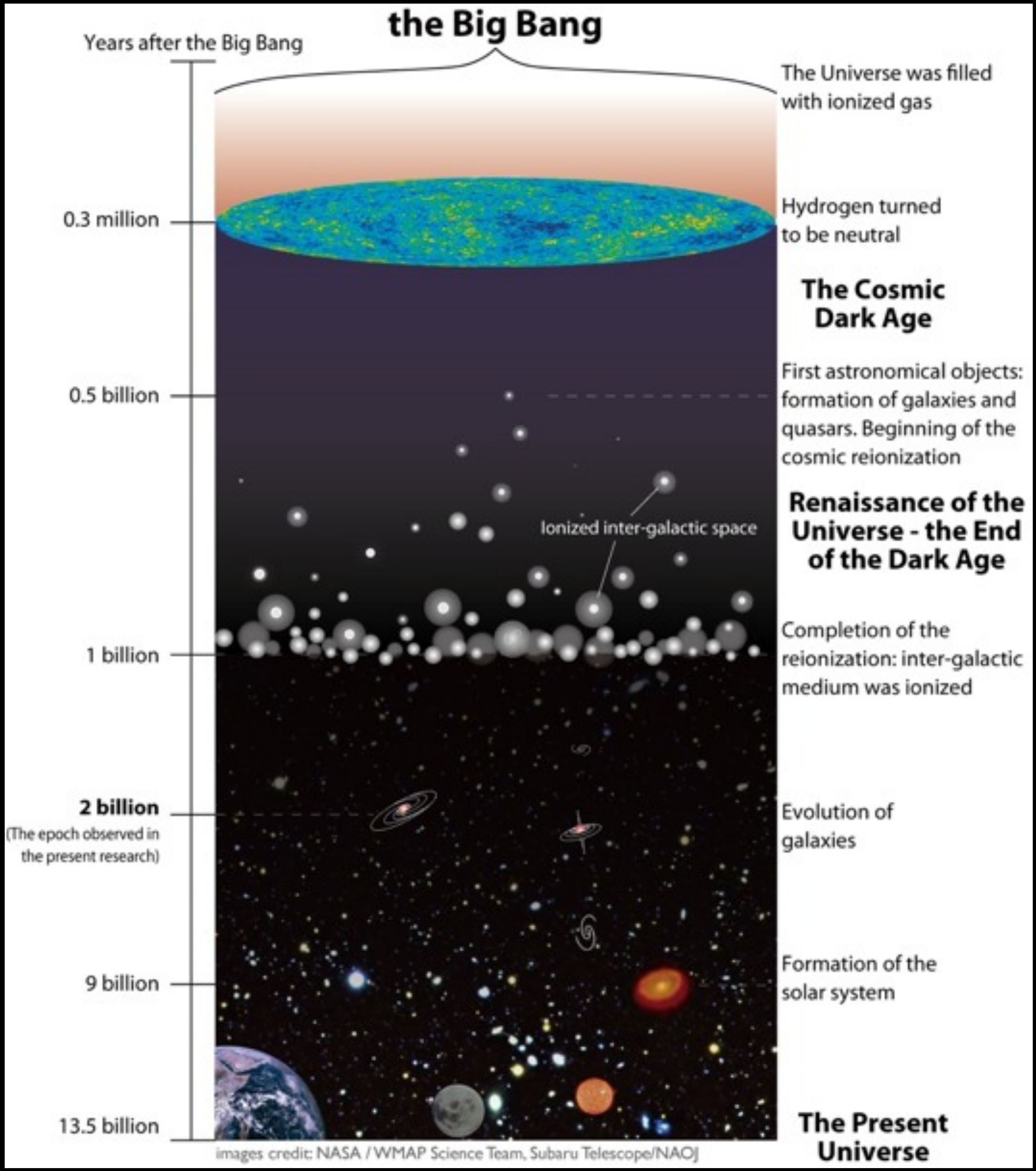
Epoch of Reionization (EoR)



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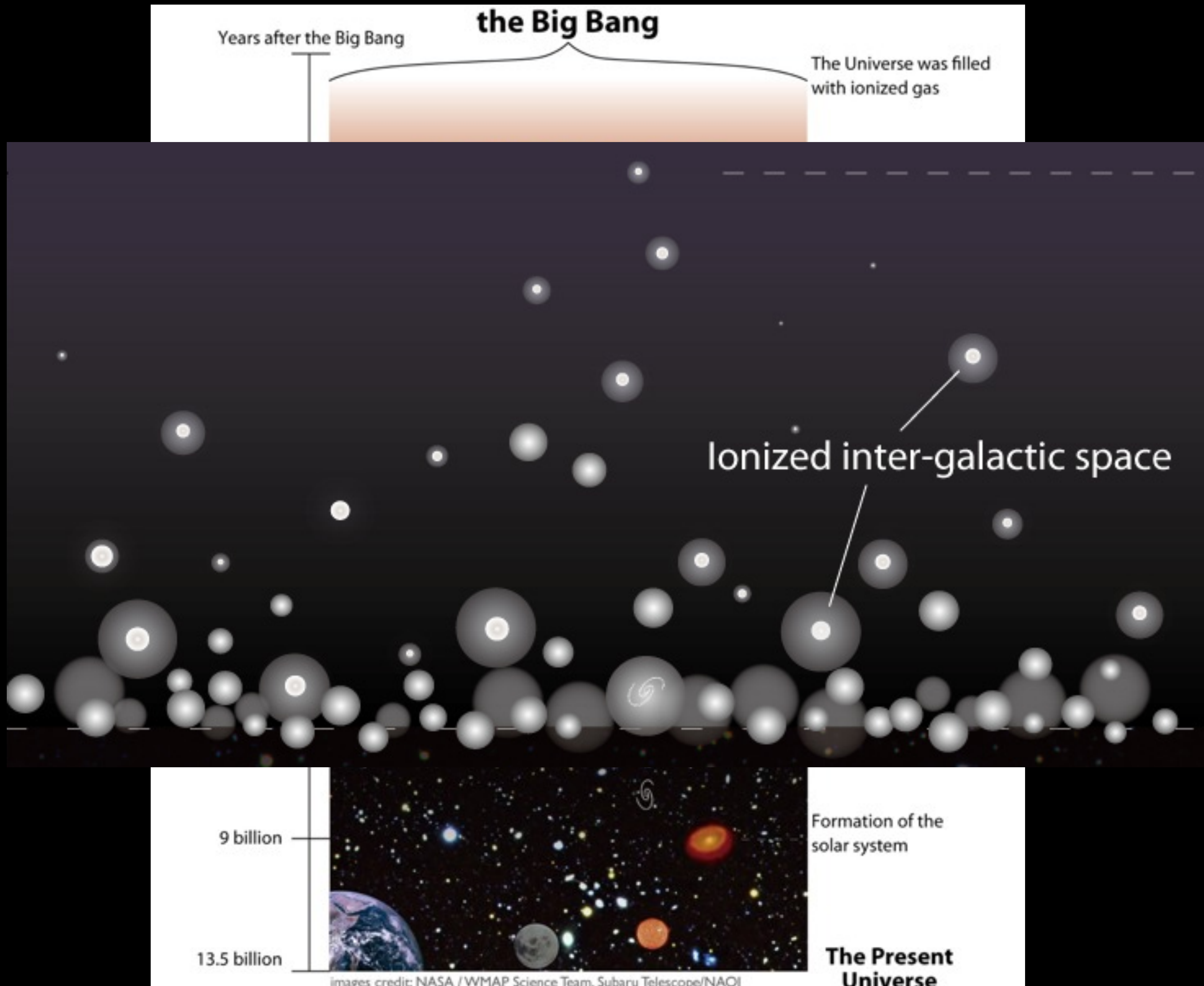
Epoch of Reionization (EoR)



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EoR- Why is the EoR important?

- The EoR is one of the landmark events in the early generations of structure formation.
    - identifying when first sources produce high energy photons to ionize neutral IGM
    - providing properties of first galaxies and stars

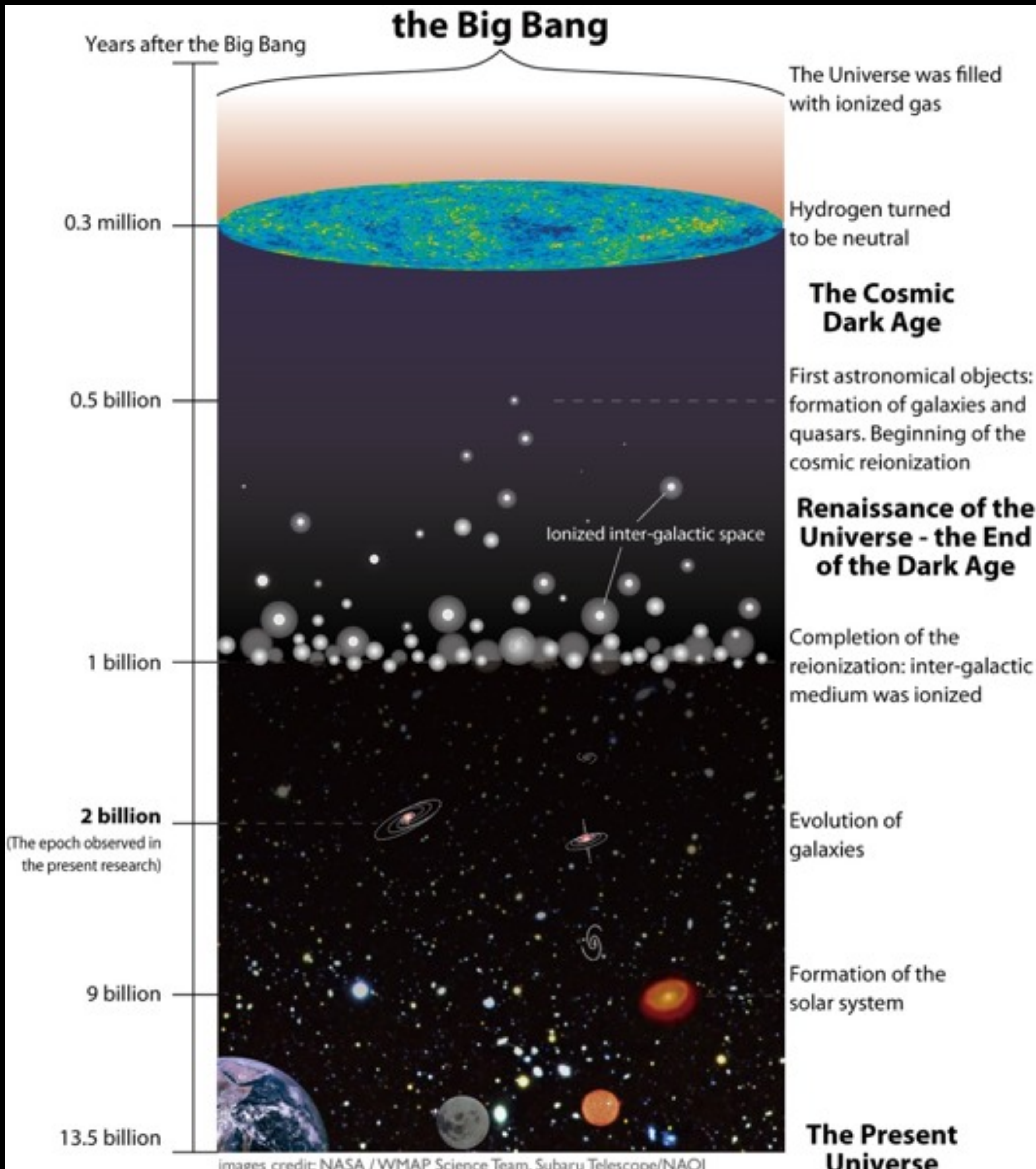
↓

- Early stage of structure formation.

EoR- Observation

- Thanks to advance of low-frequency instrumentation, several observations are being constructed.
  - Murchison Widefield Array (MWA)
  - The Low Frequency Array (LOFAR)
  - Precision Array to Probe Epoch of Reionization (PAPER)
  - The Square Kilometre Array (SKA)
- They will observe the 21cm signal from HI in IGM.

The hierarchical galaxy formation model



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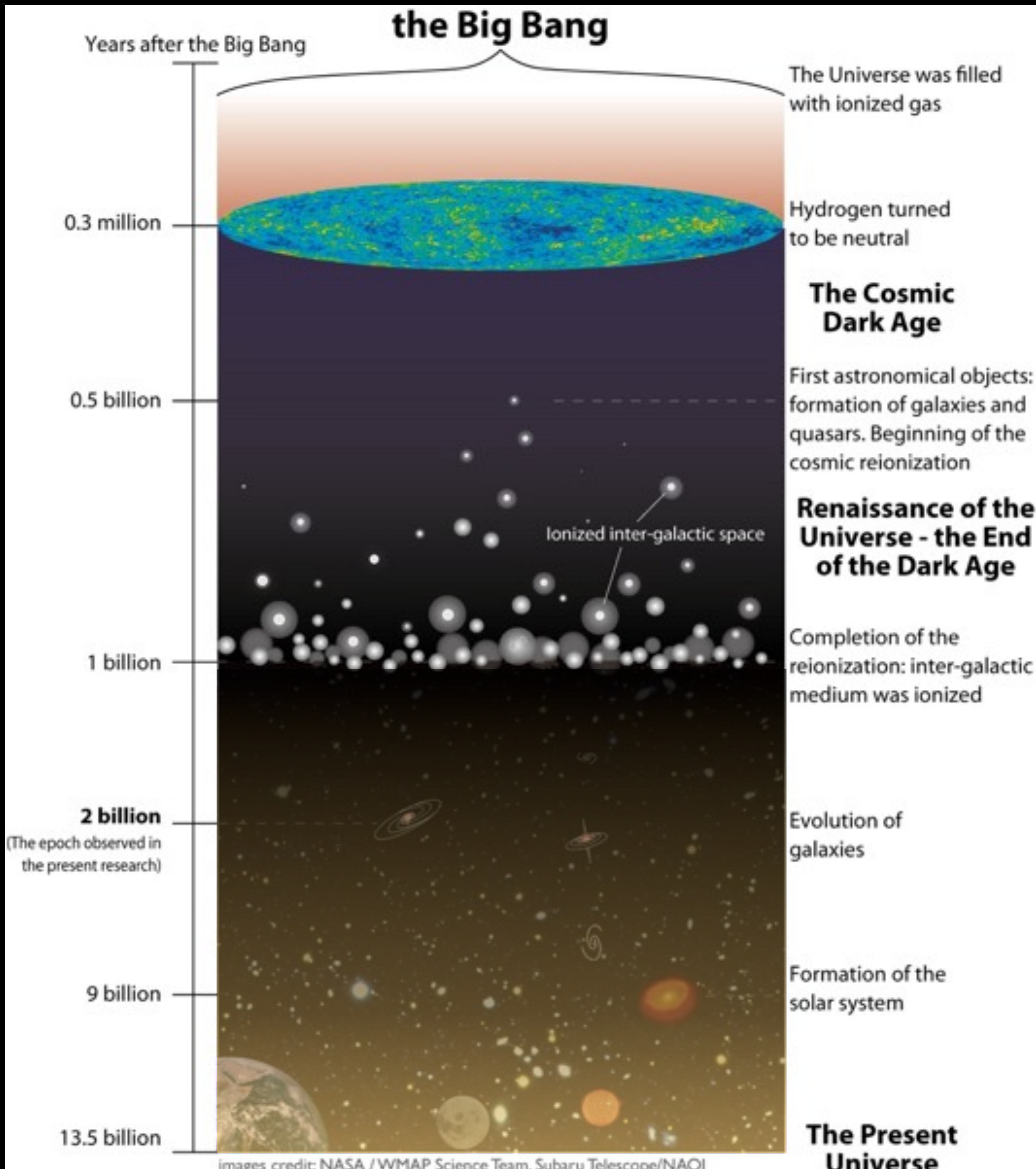
GALFORM
(Lagos et al. 2012)

AGN feedback
SNe feedback
Photoionization feedback

This simulation successfully describes the Universe.

The hierarchical galaxy formation model



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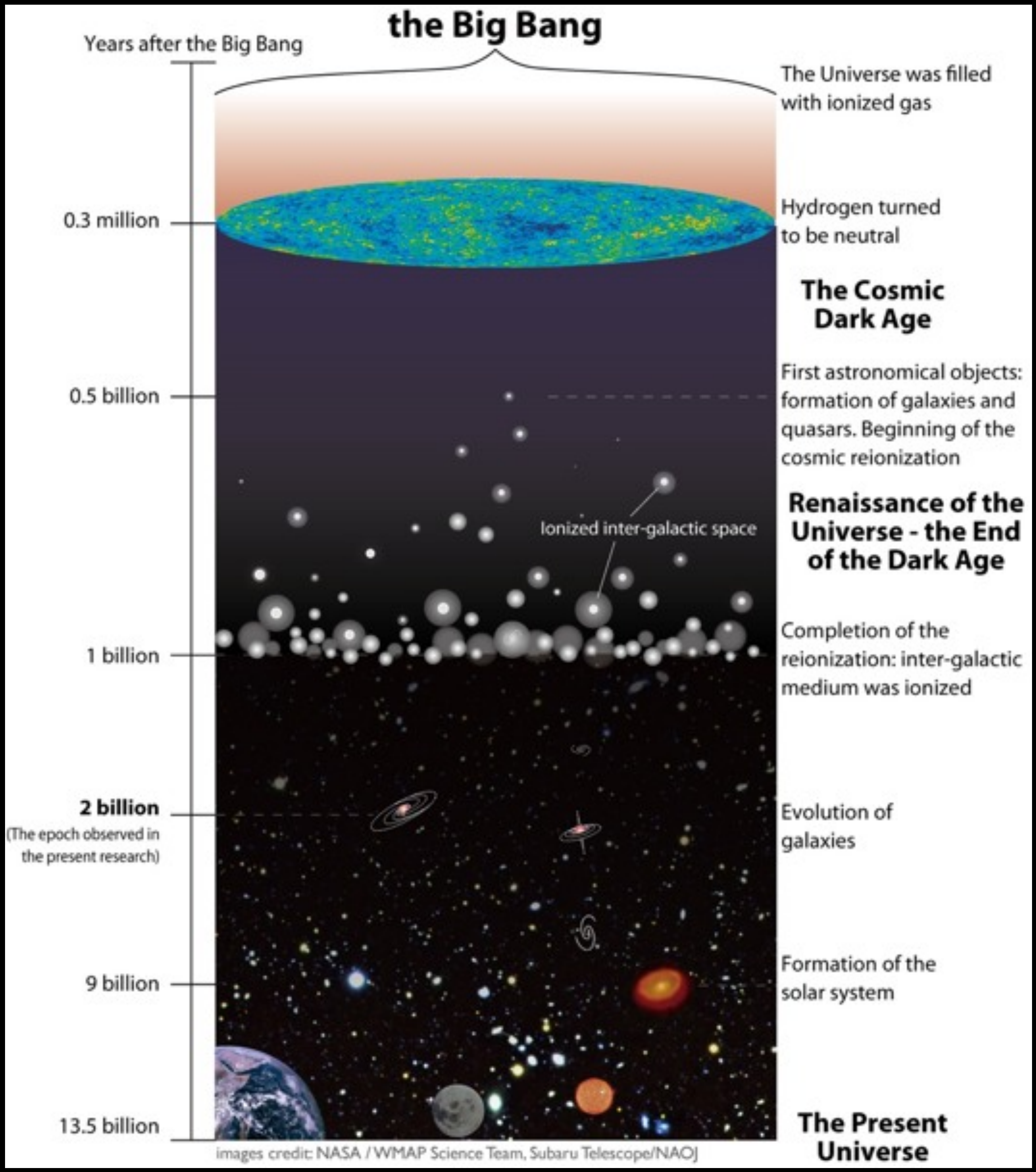

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+

Semi-Numerical scheme
(Kim et al. 2013)

Self-consistent result

The hierarchical galaxy formation model

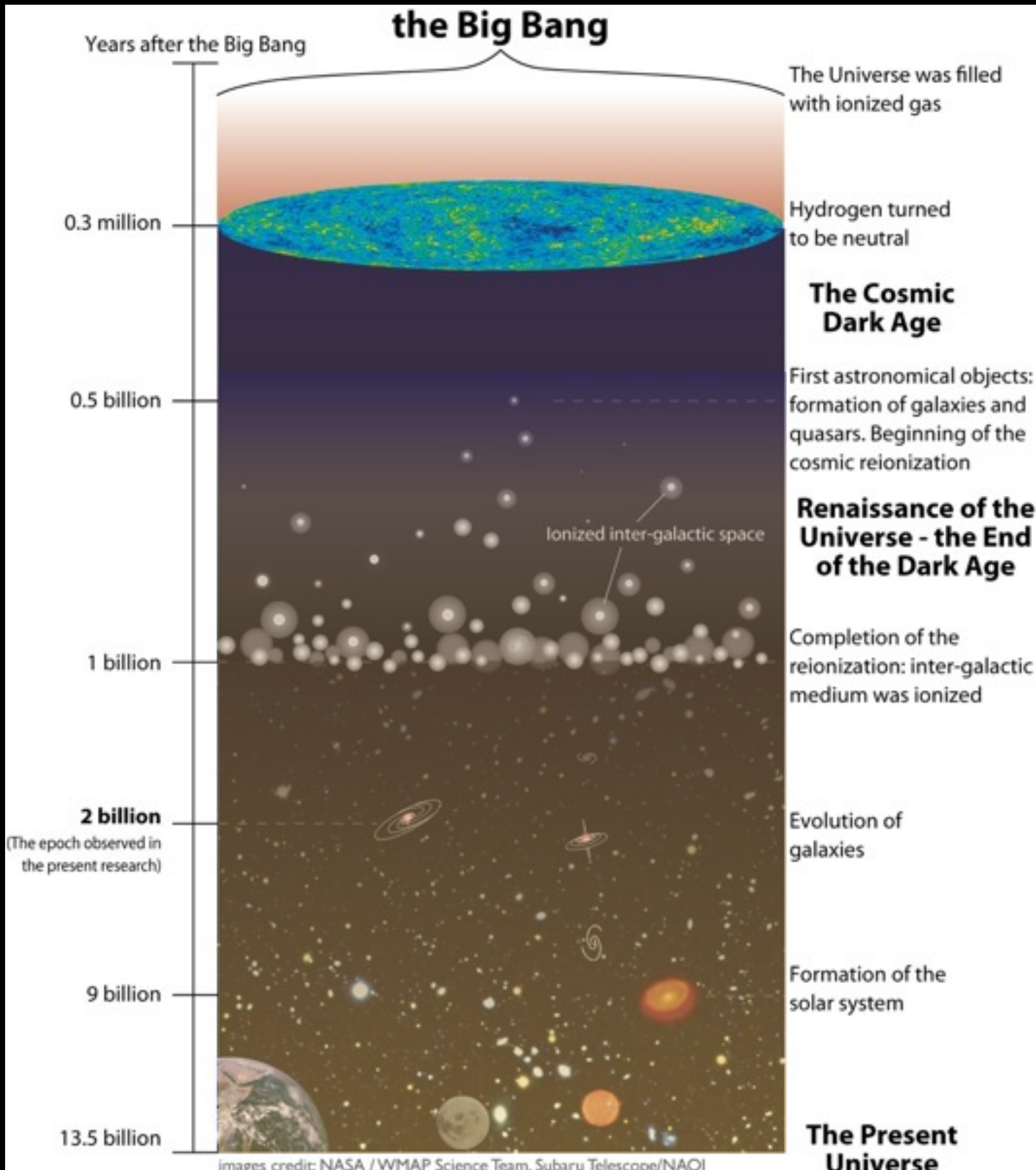

Image Credits: NASA/WMAP

GALFORM
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+

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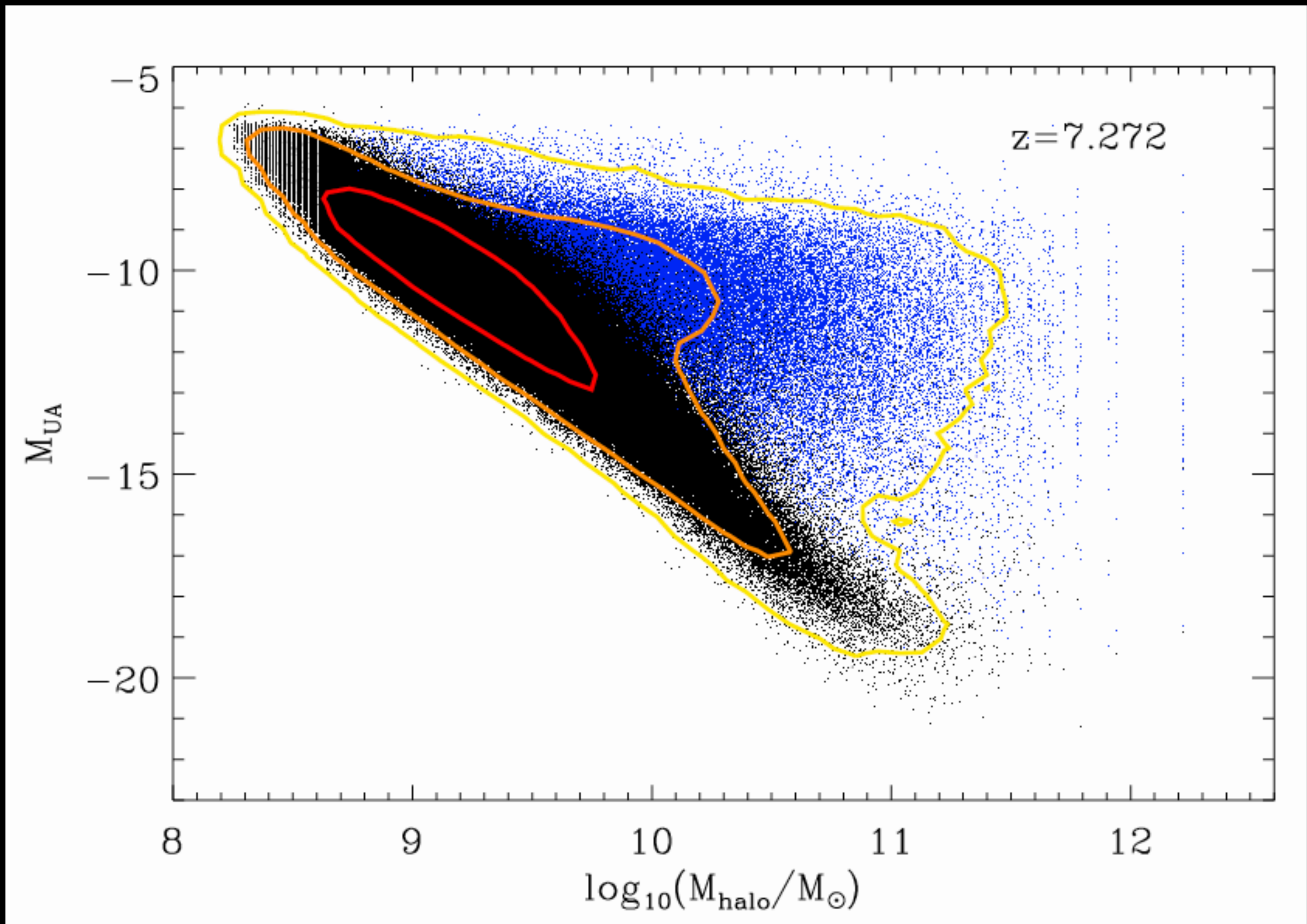
Self-consistent result

The hierarchical galaxy formation model

- Relation between UV magnitude and host halo mass



Luminosity is not simply proportional to dark matter halo mass.

Powerful method to probe EoR

- The observed cross-power spectrum between 21cm emission and galaxies and its evolution to be sensitive to the astrophysical properties such as...
    - the size of HII regions.
    - clumpiness of the IGM.
    - the nature of the ionizing sources.

Cross-power spectrum & cross-correlation function

21cm brightness temperature

$$\Delta T_{21} = T_0(z)[1-Q](1+\delta_{\rm DM,cell}),$$

$$\text{where } T_0(z) = 23.8\ \text{mK}\left(\frac{1+z}{10}\right)^{\frac{1}{2}}$$

Cross-power spectrum

$$\left\langle \hat{\delta}_{21}(\mathbf{k}_1)\hat{\delta}_{\rm gal}(\mathbf{k}_2)\right\rangle \equiv (2\pi)^3\delta_D(\mathbf{k}_1+\mathbf{k}_2)P_{21,\rm gal}(\mathbf{k}_1)$$

$$\Delta^2_{21,\rm gal}(k) = \frac{k^3}{(2\pi^2)}\frac{P_{21,\rm gal}(k)}{T_0^2(z)}$$

Cross-correlation function

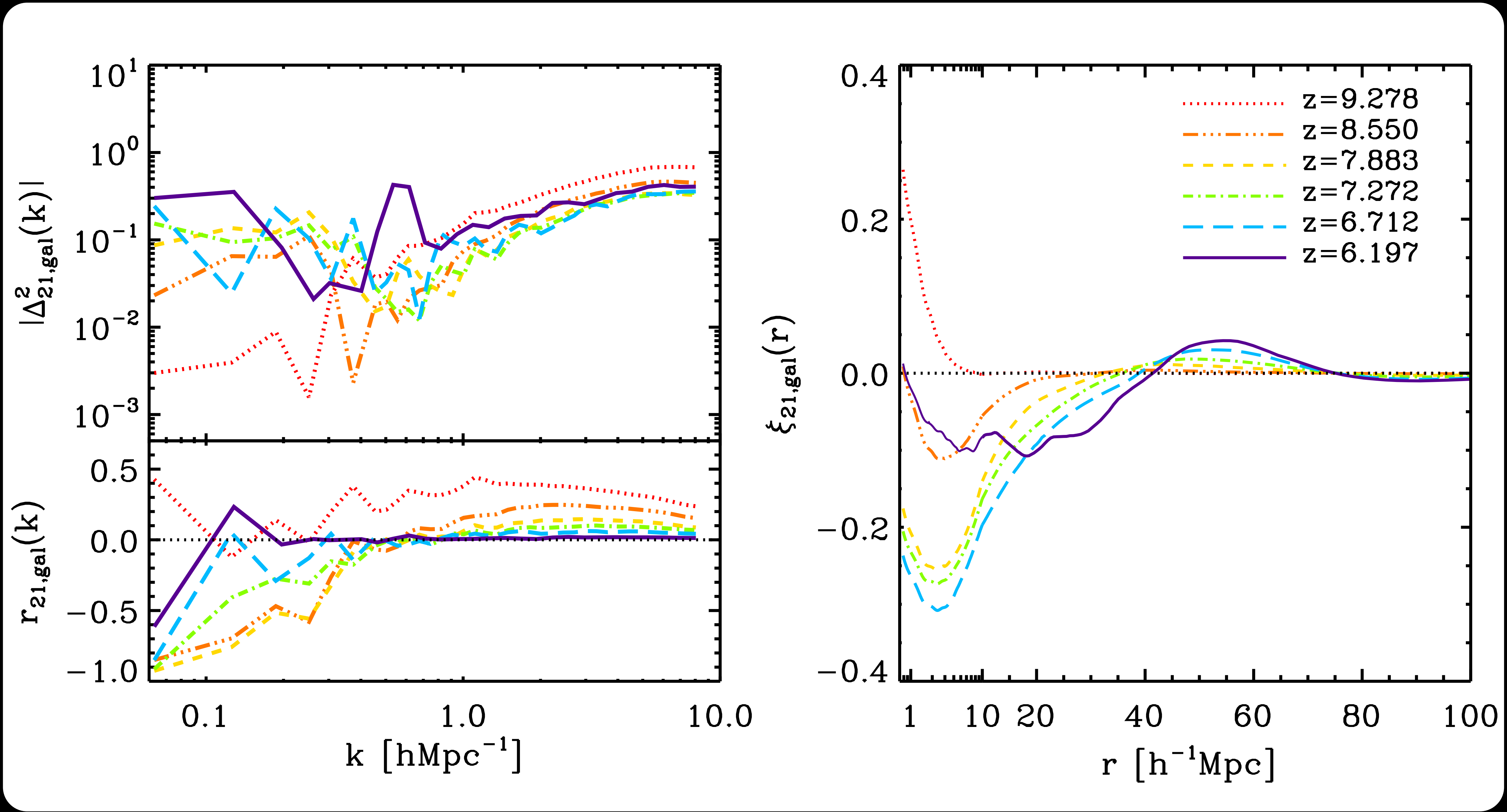
$$\xi_{1,2}(\mathbf{r}) = \langle \delta_1(\mathbf{x})\delta_2(\mathbf{x}+\mathbf{r})\rangle$$

Cross-correlation coefficient

$$r(k) = \frac{P_{21,\rm gal}(k)}{\sqrt{P_{21}(k)P_{\rm gal}(k)}} \equiv \frac{A(k)}{\sqrt{B(k)C(k)}}$$

Cross-power spectrum & cross-correlation function

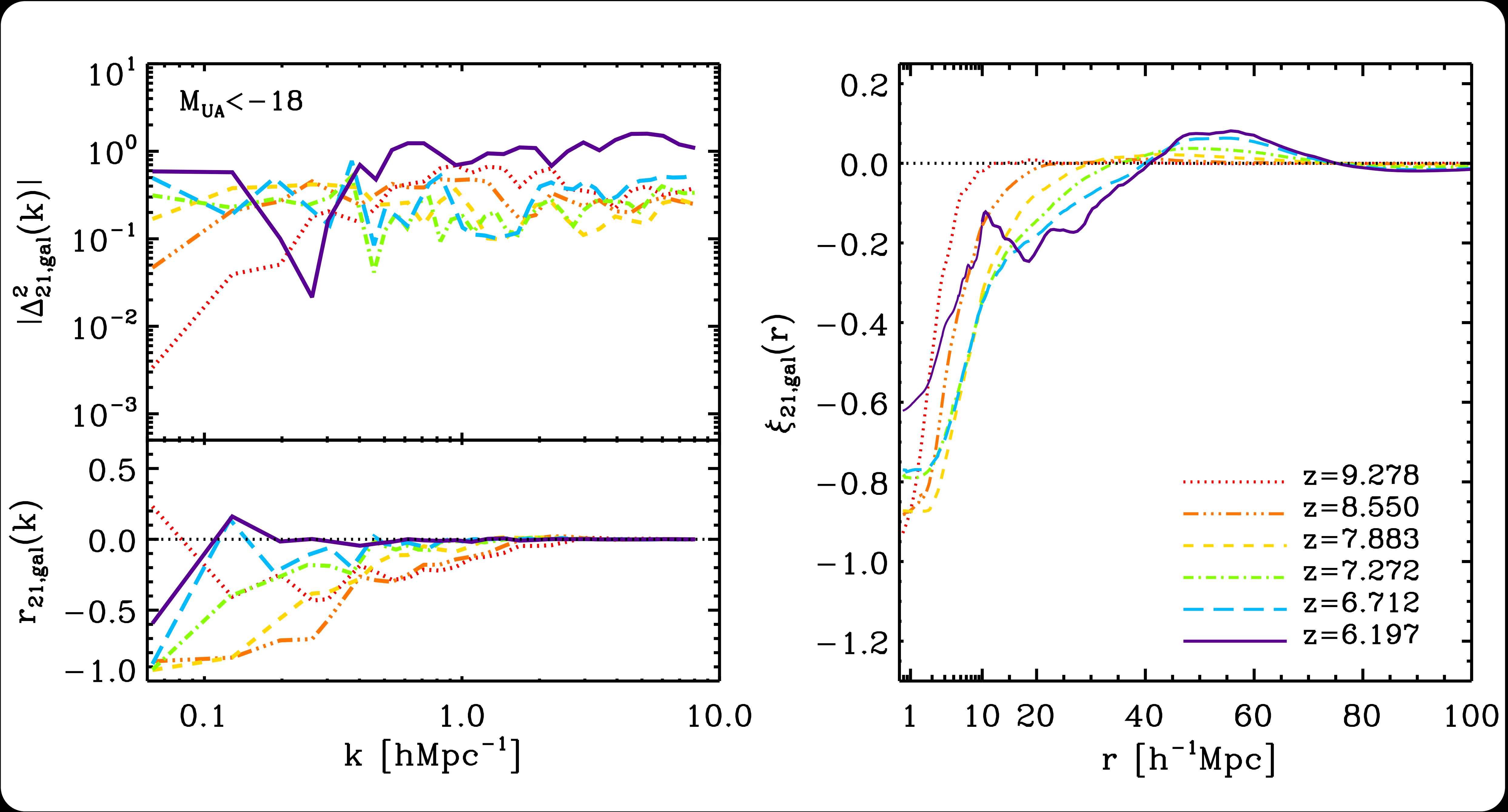
- Redshift evolution of cross-power spectra



The turnover scales imply HII bubble size.

Cross-power spectrum & cross-correlation function

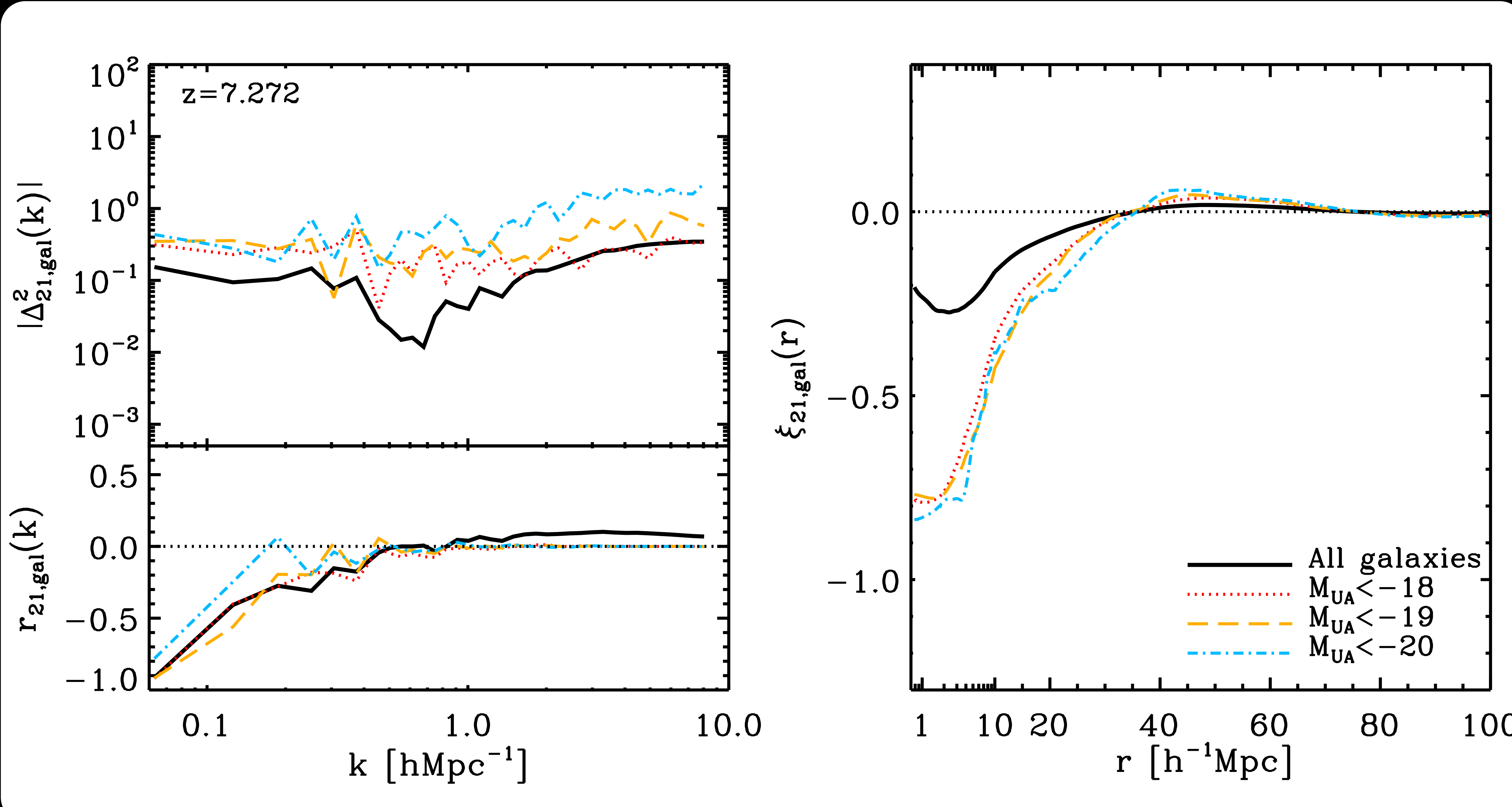
- Redshift evolution of cross-power spectra



Luminous galaxies have strong anti-correlation.

Cross-power spectrum & cross-correlation function

- Luminosity dependance of cross-power spectra



Bright galaxies have stronger anti-correlation.

Detectability

We predict detectability of cross-power spectrum using cross-correlation coefficient error based on

- MWA specifications
  - 1000 hours total observing time
  - 800 sqdeg survey area
- Subaru-like galaxy survey &

  Futuristic galaxy survey
  - galaxy number density: 1.6 x 10^-4 h^3Mpc^-3

    1.6 x 10^-2 h^3Mpc^-3
  - redshift error: 0.01

Detectability

- Predictions of cross-correlation coefficient error

$$\frac{\sigma_r^2}{r^2}(k) = \frac{\sigma_A^2}{A^2}(k) + \frac{\sigma_B^2}{4B^2}(k) + \frac{\sigma_C^2}{4C^2}(k) - \frac{\sigma_{AB}^2}{AB}(k) - \frac{\sigma_{AC}^2}{AC}(k) + \frac{\sigma_{BC}^2}{2BC}(k)$$

$$\begin{aligned}
\sigma_A^2(k,\mu) &= \mathrm{var}[\mathrm{P}_{21,\mathrm{gal}}(\mathrm{k},\mu)] \\
&= \frac{1}{2}\left[P_{21,\mathrm{gal}}(k,\mu) + \sigma_B(k,\mu)\sigma_C(k,\mu)\right] \\
\sigma_B^2(k,\mu) &= \mathrm{var}[\mathrm{P}_{21}(\mathrm{k},\mu)] \\
&= \left[P_{21}(k,\mu) + \frac{T_{\mathrm{sys}}^2}{T_0^2}\frac{1}{Bt_{\mathrm{int}}}\frac{D^2\Delta D}{n(k_\perp)}\left(\frac{\lambda^2}{A_e}\right)^2\right]^2 \\
\sigma_C^2(k,\mu) &= \mathrm{var}[\mathrm{P}_{\mathrm{gal}}(\mathrm{k},\mu)] \\
&= \left[P_{\mathrm{gal}}(k,\mu) + n_{\mathrm{gal}}^{-1}e^{k_\parallel^2\sigma_\chi^2}\right]^2 \\
\sigma_{AB}^2(k,\mu) &= \mathrm{cov}[\mathrm{P}_{21,\mathrm{gal}}(\mathrm{k},\mu), \mathrm{P}_{21}(\mathrm{k},\mu)] \\
&= \left[P_{21,\mathrm{gal}}(k,\mu) + P_{21}(k,\mu)\right] \\
\sigma_{AC}^2(k,\mu) &= \mathrm{cov}[\mathrm{P}_{21,\mathrm{gal}}(\mathrm{k},\mu), \mathrm{P}_{\mathrm{gal}}(\mathrm{k},\mu)] \\
&= \left[P_{21,\mathrm{gal}}(k,\mu) + P_{\mathrm{gal}}(k,\mu)\right] \\
\sigma_{BC}^2(k,\mu) &= \mathrm{cov}[\mathrm{P}_{21}(\mathrm{k},\mu), \mathrm{P}_{\mathrm{gal}}(\mathrm{k},\mu)] \\
&= \left[P_{21}(k,\mu) + P_{\mathrm{gal}}(k,\mu)\right]
\end{aligned}$$

Murchison Widefield Array (MWA) specifications

- system temperature
- bandpass
- total observing time
- antenna array
- survey volume
- survey area

Subaru deep survey properties

- galaxy number density
- redshift error

Lidz et al., 2009, APJ

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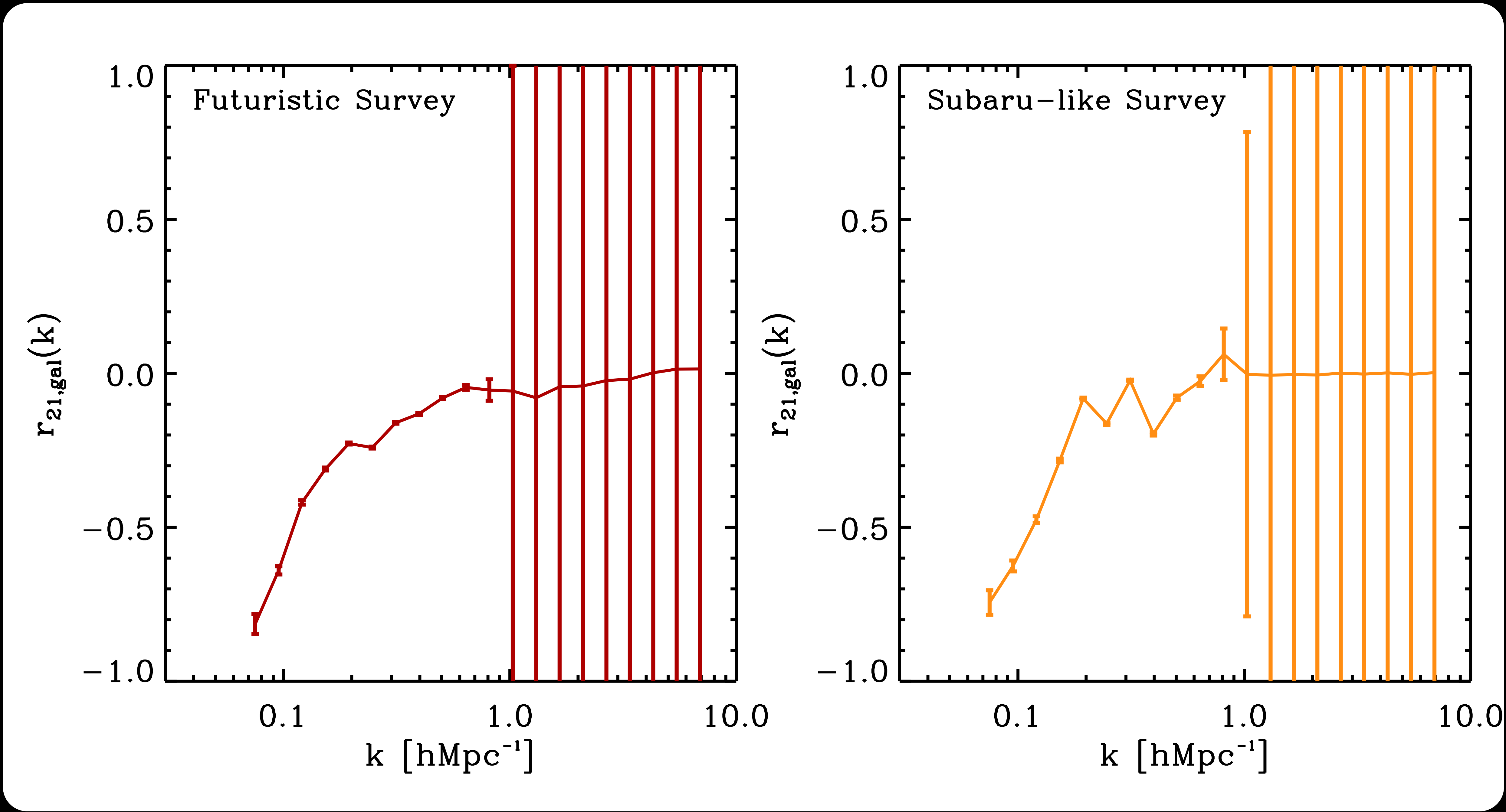
Detectability

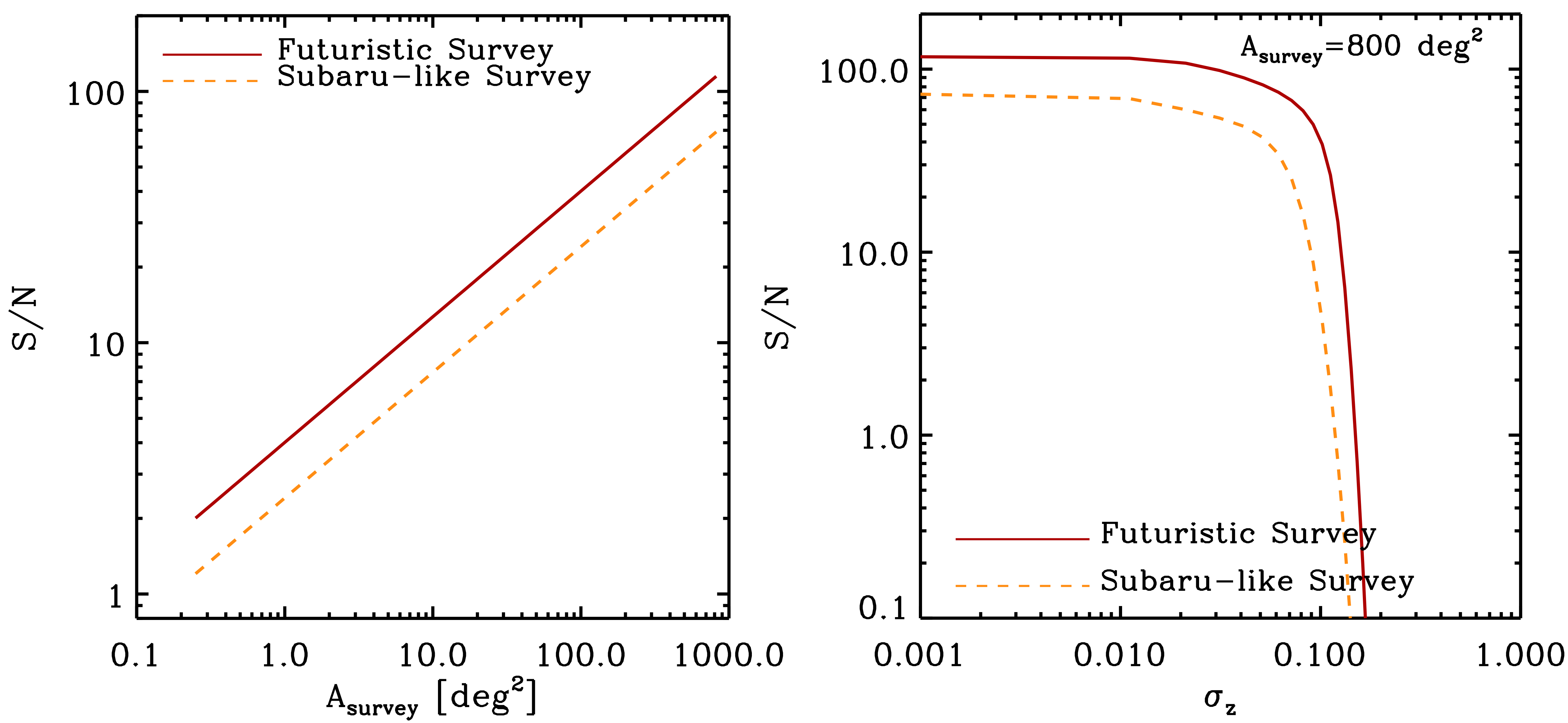
- Predictions of cross-correlation coefficient error



Cross-correlation could be detected at high significance.

Detectability

- S/N



Cross-correlation could be detected at high significance.

Effect of feedback process

- Our model (Lagos et al, 2012)
    - AGN feedback
    - SNe feedback
    - Photoionization feedback
- Modified Bow06 model (Bower et al, 2006)
    - AGN feedback
    - SNe feedback
    - Photoionization feedback
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  - ~~SNe feedback~~ NOSN
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Effect of feedback process

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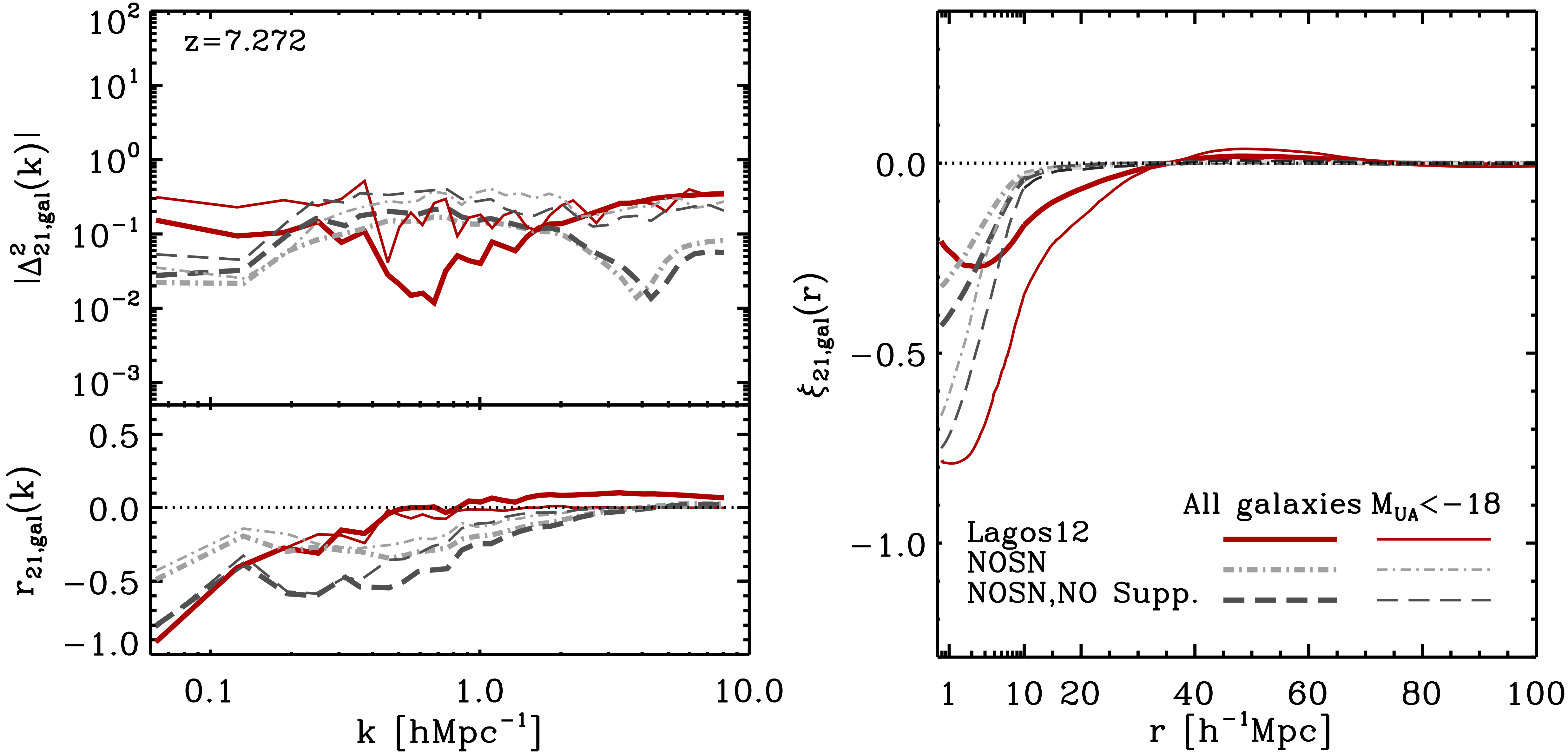
  - ~~SNe feedback~~ NOSN
  - Photoionization feedback
- Modified Bow06 model (Bower et al, 2006)
  - AGN feedback
  - ~~SNe feedback~~ NOSN
  - ~~Photoionization feedback~~ NO Suppression

Effect of feedback process

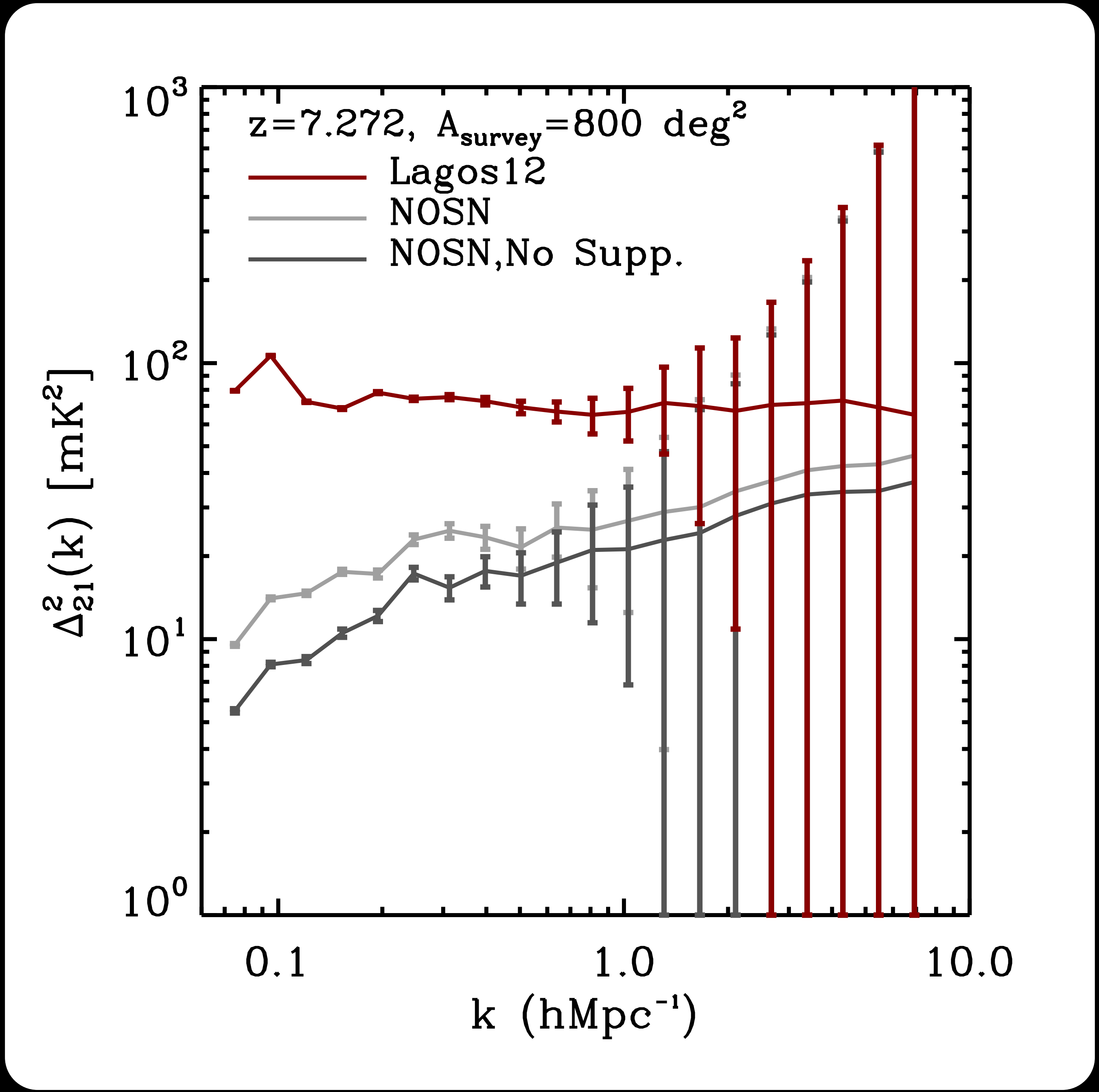
- The effect of feedback process on cross-power spectra



Different feedback processes show different turnover scale.

Effect of feedback process

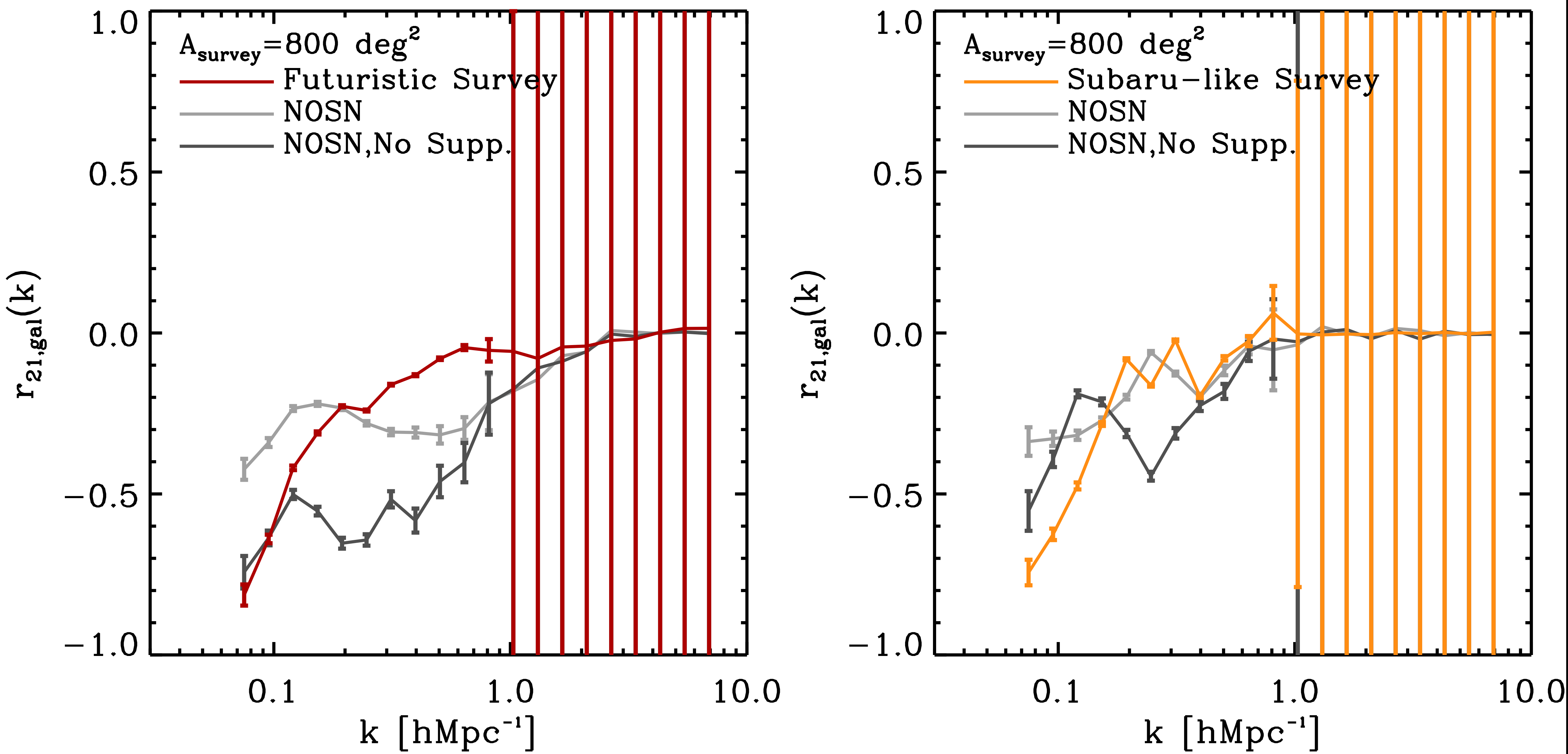
- The effect of feedback process on 21cm power spectra



Different feedback processes affect the shape and error of 21cm power spectra.

Effect of feedback process

- The effect of feedback process on the detectability



Different feedback processes affect the shape and error of cross-correlation coefficient.

Summary

- We calculated cross-power spectrum, cross-correlation function, and cross-correlation coefficient using Hierarchical galaxy formation model.
- We calculated observational uncertainties of cross-correlation based on MWA specifications and Subaru-like galaxy survey properties.
- We found that feedback processes make difference on cross-power spectra and estimated error. Thus, detailed modelling is required to predict accurate cross-correlation.

Thank you.