Effects of the Sources of Reionization on 21cm Redshift Space Distortions

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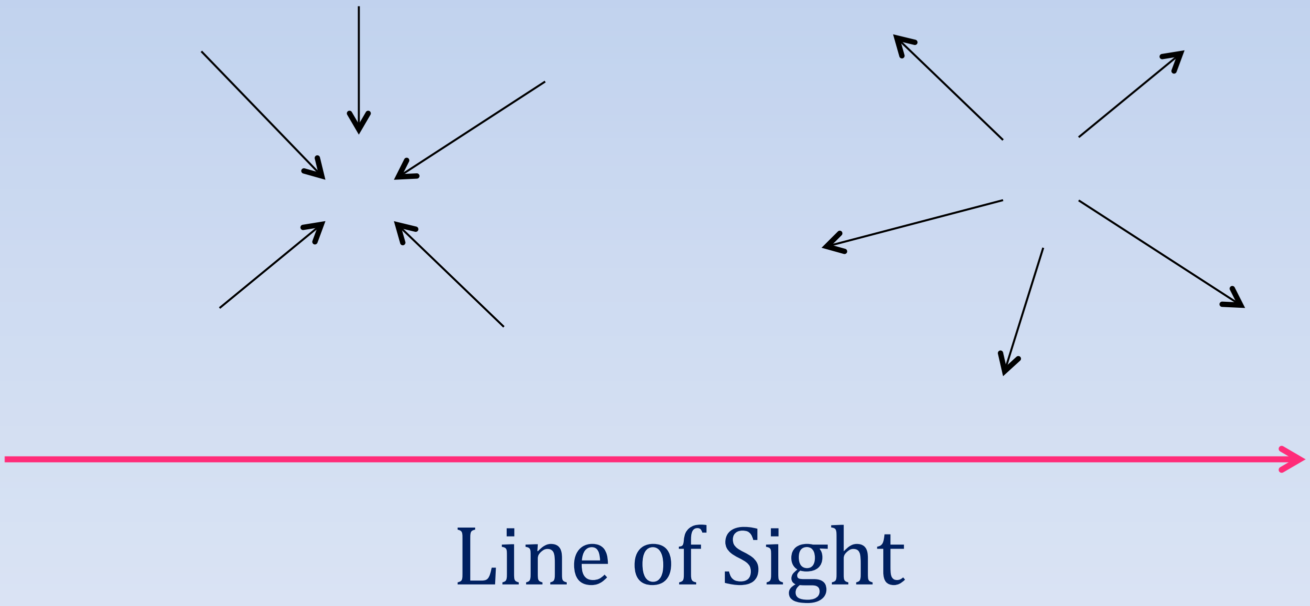
Filipe Abdalla, Ilian Iliev, Kanan Datta …………………..

Main Anisotropies along the LoS

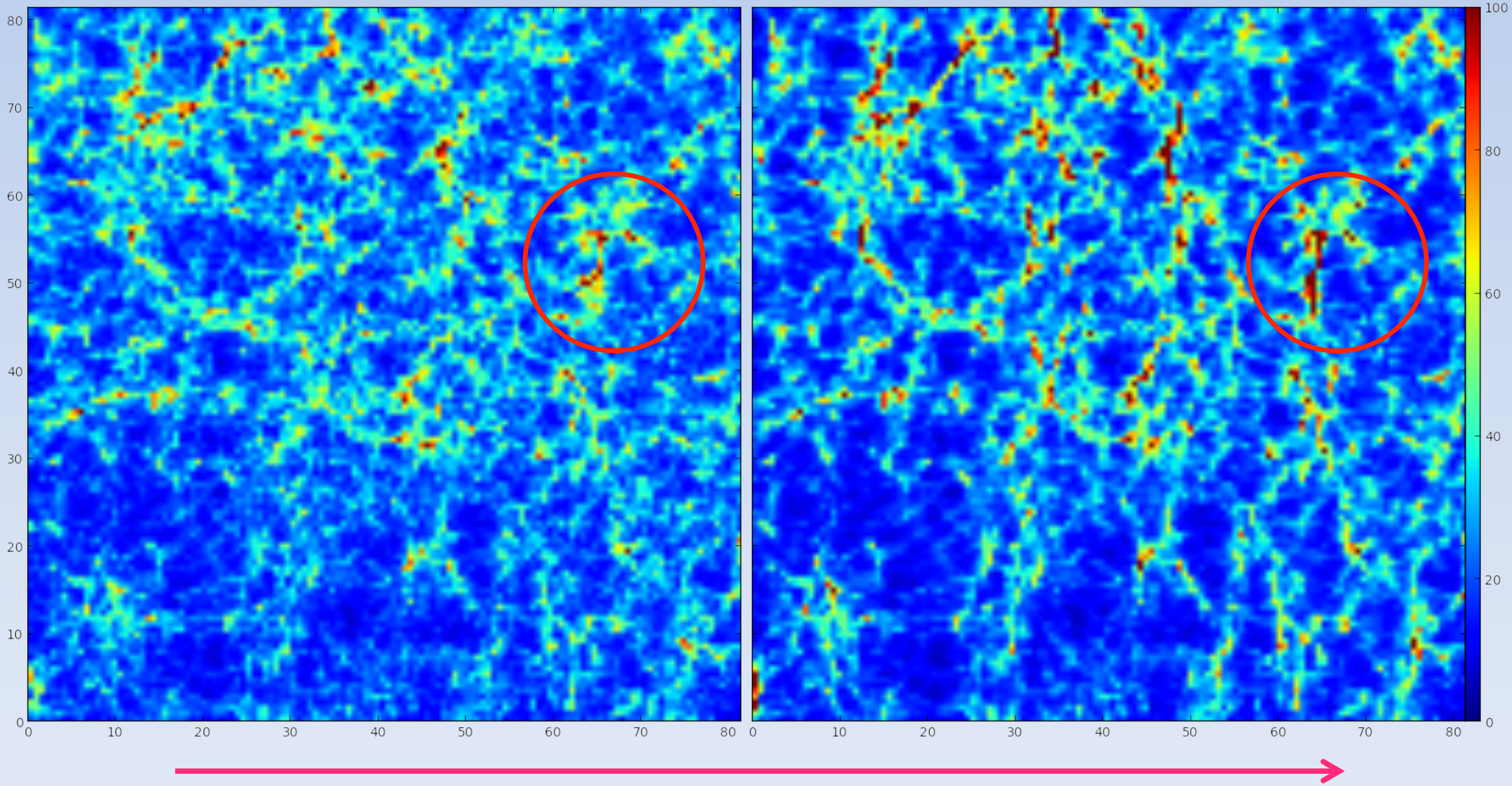
- Redshift Space Distortions.
- Effect of the Finite Light Travel Time (Light Cone Effect).

Redshift Space Distortion



Redshift Space Distortion

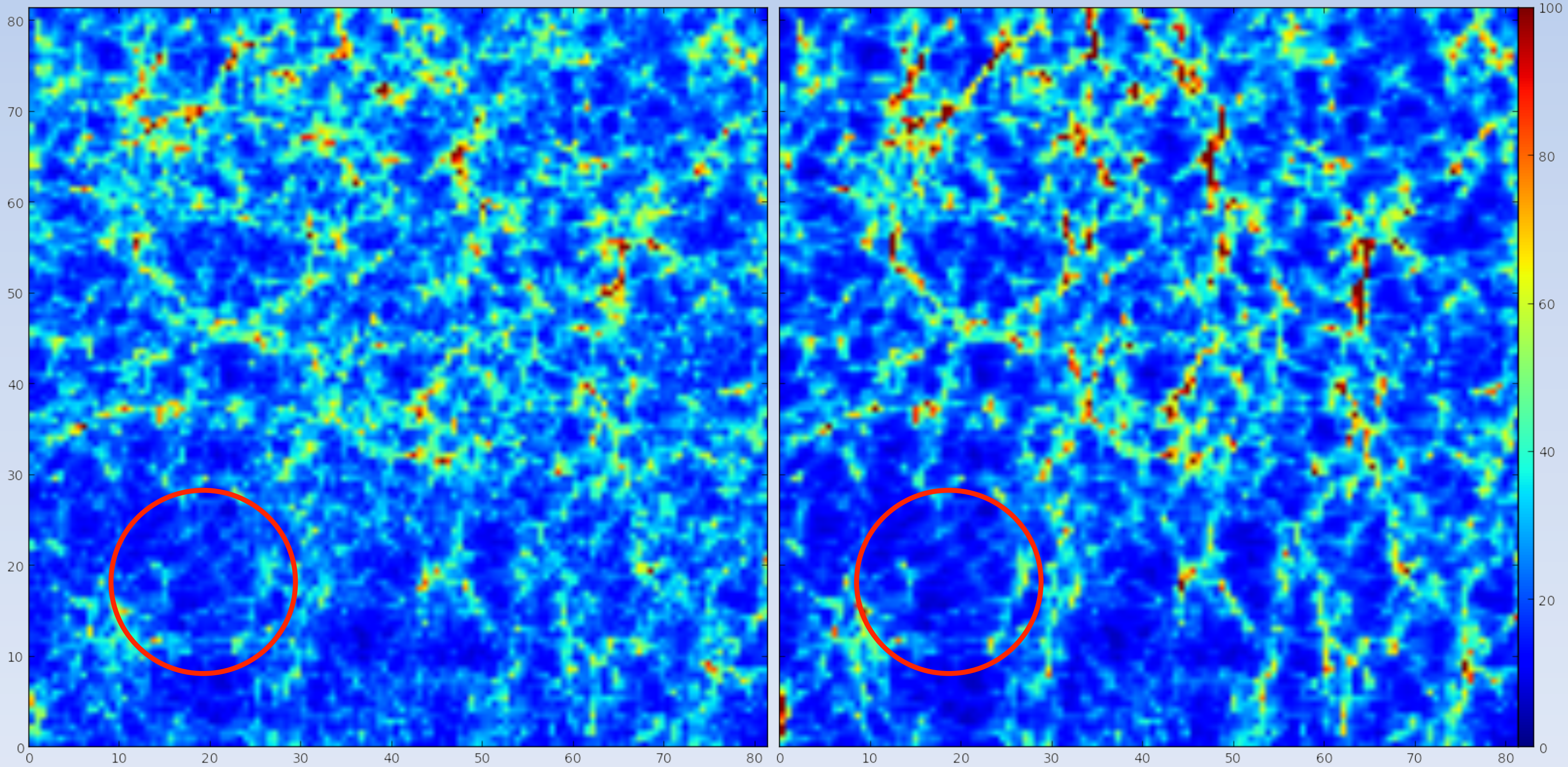
Real Space | Redshift Space



Line of Sight

Redshift Space Distortion

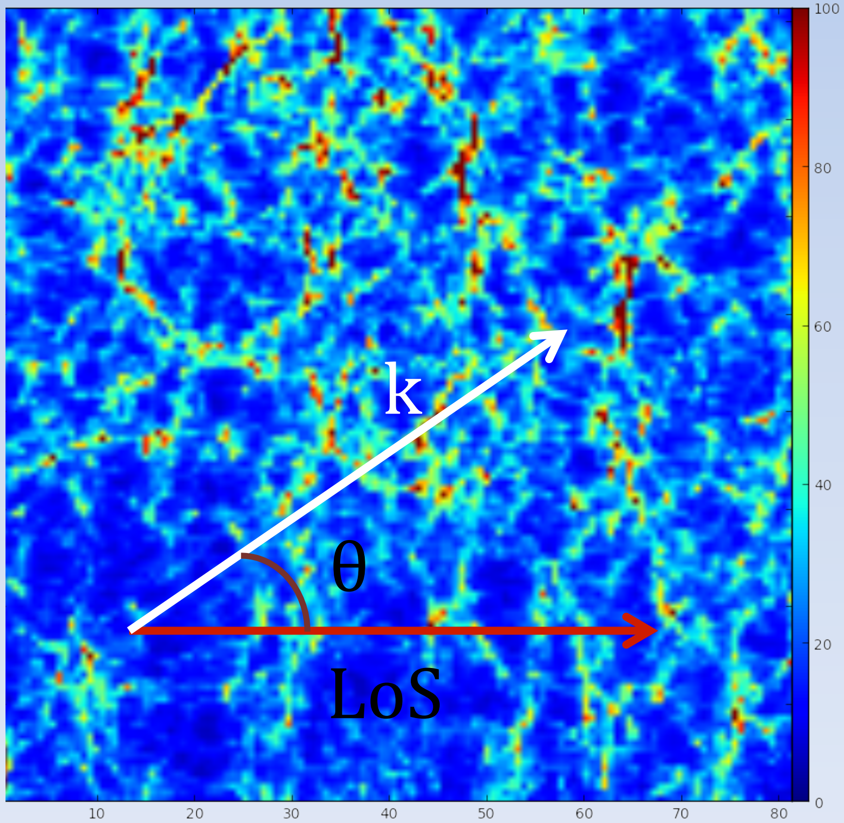
Real Space   Redshift Space



Line of Sight

Power Spectrum in Redshift Space

Observed power spectrum will be "anisotropic"
(or LoS dependent)



$$P^s(k, \mu)$$

Power spectrum in Redshift Space

$$P^s(k,\mu) = \sum_{l\ \mathrm{even}} \mathcal{P}_l(\mu) P_l^s(k)$$

- Kaiser, N., 1987, MNRAS, 227, 1
- Hamilton, A. J. S., 1992, APJL, 385, L5

Power spectrum in Redshift Space

$$P^s(k,\mu) = \sum_{l\ \mathrm{even}} \mathcal{P}_l(\mu) P_l^s(k)$$

Legendre Polynomial

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Angular Multipoles

- Kaiser, N., 1987, MNRAS, 227, 1
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Power spectrum in Redshift Space

$$P^s(k,\mu) = \sum_{l\,\mathrm{even}} \mathcal{P}_l(\mu) P^s_l(k)$$

$$P^s_l(k) = \frac{(2l+1)}{4\pi} \int \mathcal{P}_l(\mu)\, P^s(k)\, d\Omega$$

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Power spectrum in Redshift Space

$$P_l^s(k) = \frac{(2l+1)}{4\pi} \int \mathcal{P}_l(\mu)\, P^s(k)\, d\Omega$$

P_0^s	P_2^s	P_4^s
Monopole	Quadrupole	Hexadecapole

Power spectrum in Redshift Space

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- Majumdar, Bhardwaj & Choudhury, 2013, MNRAS, 434, 3
- Majumdar, Mellema, Datta et al., 2014, MNRAS, 443, 4

Model with Quasi-linear Approximations

$$P_0^s = \overline{\delta T_b}^2(z)\left[\frac{1}{5}P_{\rho_M\rho_M} + P_{\rho_{H\,I}\rho_{H\,I}} + \frac{2}{3}P_{\rho_{H\,I}\rho_M}\right]$$

$$P_2^s = 4\,\overline{\delta T_b}^2(z)\left[\frac{1}{7}P_{\rho_M\rho_M} + \frac{1}{3}P_{\rho_{H\,I}\rho_M}\right]$$

$$P_4^s = \frac{8}{35}\,\overline{\delta T_b}^2(z)\,P_{\rho_M\rho_M}$$ when $T_S >> T_{CMB}$

- Majumdar, Bhardwaj & Choudhury, 2013, MNRAS, 434, 3
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Model with Quasi-linear Approximations

$$P_0^s = \overline{\delta T_b}^2(z) \left[\frac{1}{5} P_{\rho_M \rho_M} + P_{\rho_{HI} \rho_{HI}} + \frac{2}{3} P_{\rho_{HI} \rho_M} \right]$$

Quadrupole Moment

$$P_2^s = 4\,\overline{\delta T_b}^2(z) \left[\frac{1}{7} P_{\rho_M \rho_M} + \frac{1}{3} P_{\rho_{HI} \rho_M} \right]$$

What happens to the quadrupole moment under different reionization source models?

- Majumdar, Bhardwaj & Choudhury, 2013, MNRAS, 434, 3
- Majumdar, Mellema, Datta et al., 2014, MNRAS, 443, 4

Effect of Spin Temperature Fluctuations

$$P_2^s = 4\,\overline{\delta T_b}^2(z)\left[\frac{1}{7}P_{\rho_M\rho_M} + \frac{1}{3}P_{\rho_{H\,I}\rho_M}\right]$$

$$P_2^s = 4\,\overline{\delta T_b}^2(z)\left[\frac{1}{7}P_{\rho_{\rm M},\rho_{\rm M}} + \frac{1}{3}P_{\rho_{\rm HI},\rho_{\rm M}} + \frac{1}{3}P_{\eta,\rho_{\rm M}}\right]$$

$$\eta(z,\mathbf{x}) = 1 - \frac{T_{\rm CMB}(z)}{T_{\rm S}(z,\mathbf{x})}$$

Majumdar, Jensen, Mellema et al., 2015, in prep.

Effect of Spin Temperature Fluctuations

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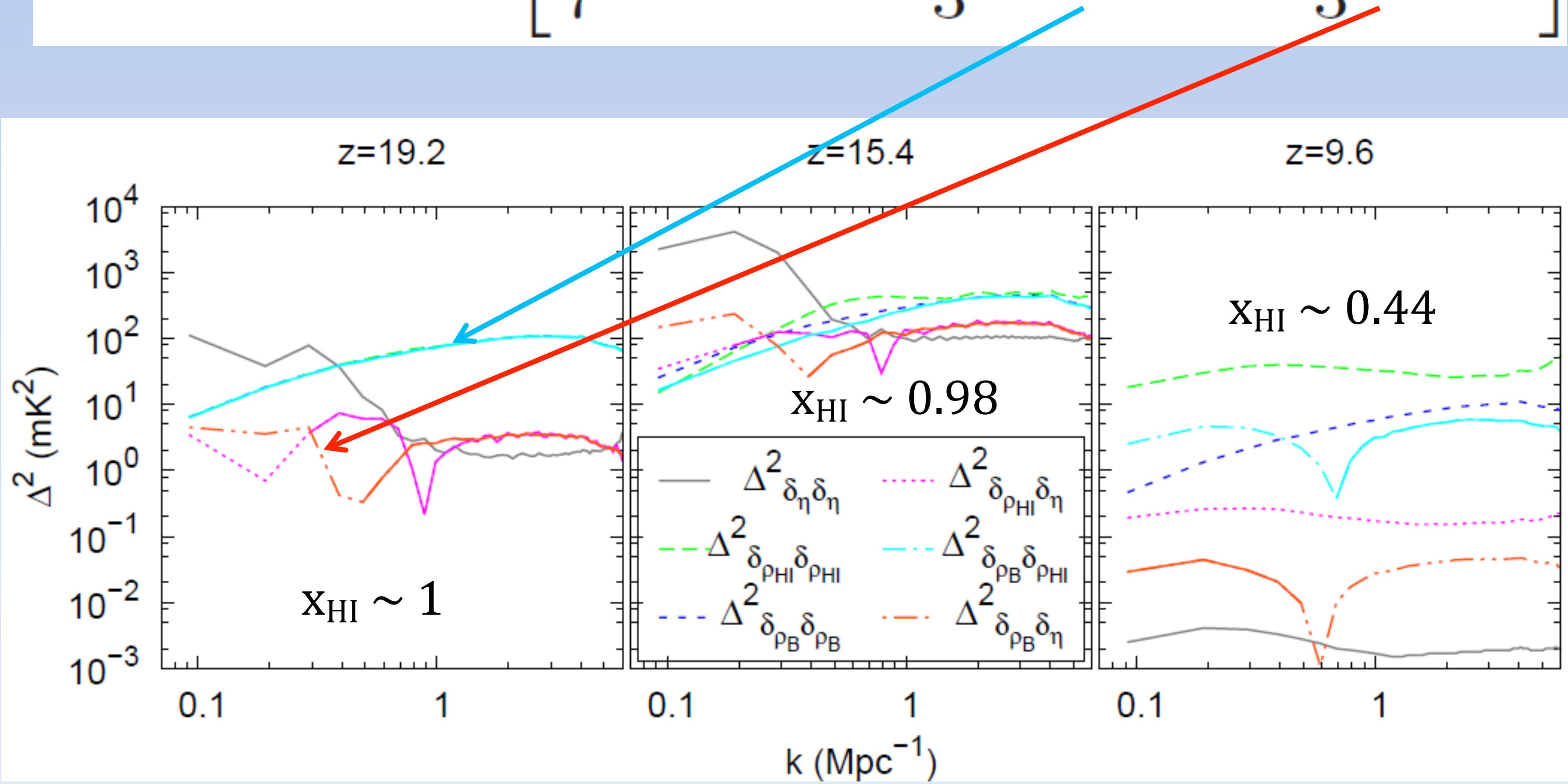

Ghara, Choudhury & Datta, 2015, MNRAS, 447, 2

Simulation

- DM distribution: P^3M N-body simulation (from PRACE4LOFAR project, Dixon et al. in prep.)
- Box size: $(714.28\ \mathrm{Mpc})^3$
- Minimum halo mass used: $2.0\times10^9\ M_{sun}$
- 21-cm brightness temperature fields: Excursion set based semi-numerical formalism (on a 600^3 grid)
- All source models are tuned to have same reionization history (i.e. x_{HI} vs z)

Majumdar, Jensen, Mellema et al., 2015, in prep.

Source Models

Reionization scenario	UV	UIB	SXR	PL n	Non-uniform recombination
Fiducial	100%	–	–	1.0	No
Clumping	100%	–	–	1.0	Yes
UIB dominated	20%	80%	–	1.0	No
SXR dominated	20%	–	80%	1.0	No
UV+SXR+UIB	50%	10%	40%	1.0	No
PL 2.0	–	–	–	2.0	No
PL 3.0	–	–	–	3.0	No

Majumdar, Jensen, Mellema et al., 2015, in prep.

Source Models

Uniform Ionization Background

Reionization scenario	UV	UIB	SXR	PL n	Non-uniform recombination
Fiducial	100%	–	–	1.0	No
Clumping	100%	–	–	1.0	Yes
UIB dominated	20%	80%	–	1.0	No
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PL 2.0	–	–	–	2.0	No
PL 3.0	–	–	–	3.0	No

Majumdar, Jensen, Mellema et al., 2015, in prep.

Source Models

Soft X-ray Photons

Reionization scenario	UV	UIB	SXR	PL n	Non-uniform recombination
Fiducial	100%	–	–	1.0	No
Clumping	100%	–	–	1.0	Yes
UIB dominated	20%	80%	–	1.0	No
SXR dominated	20%	–	80%	1.0	No
UV+SXR+UIB	50%	10%	40%	1.0	No
PL 2.0	–	–	–	2.0	No
PL 3.0	–	–	–	3.0	No

Majumdar, Jensen, Mellema et al., 2015, in prep.

Source Models

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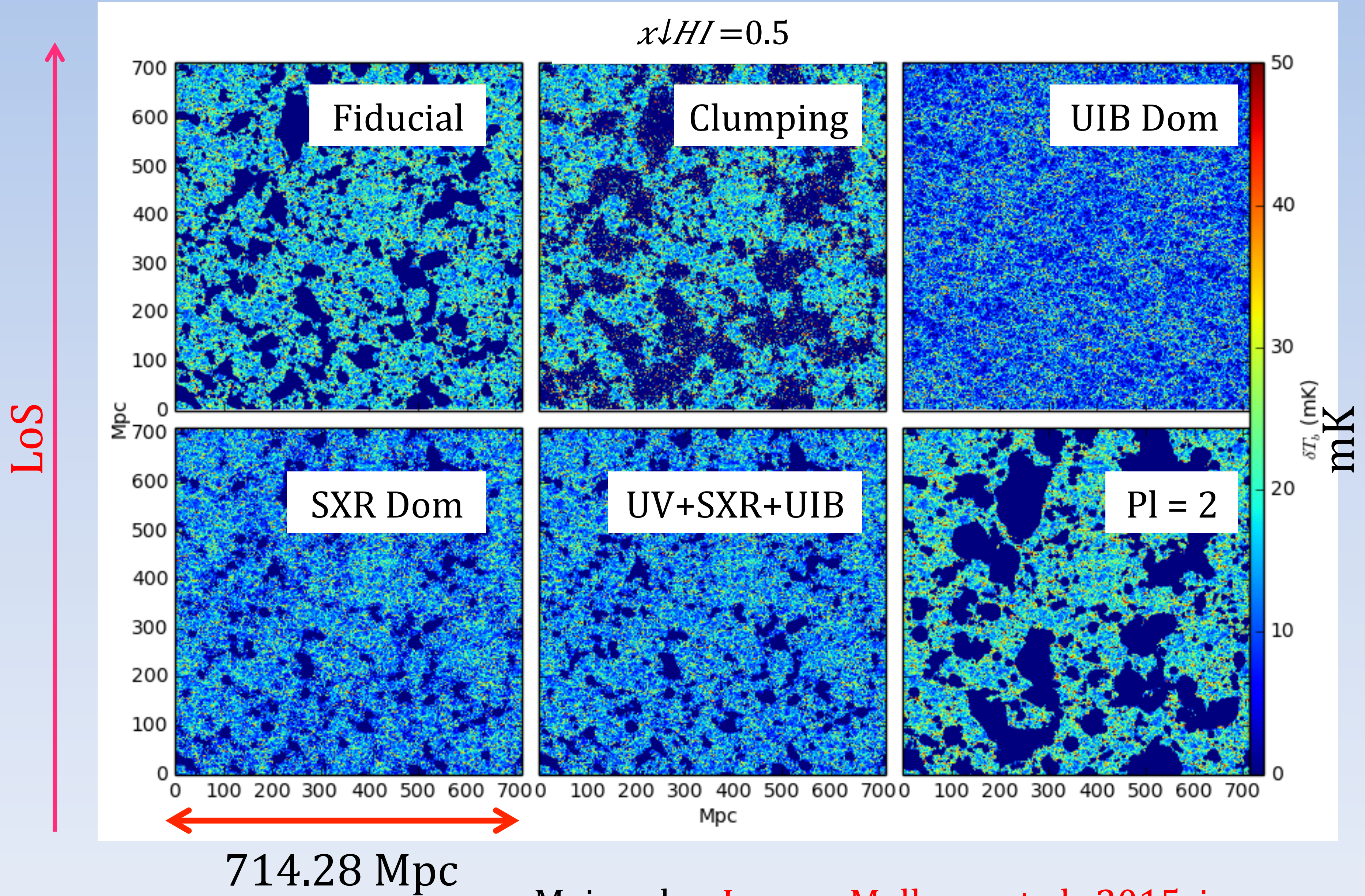
PL 3.0	–	–	–	3.0	No

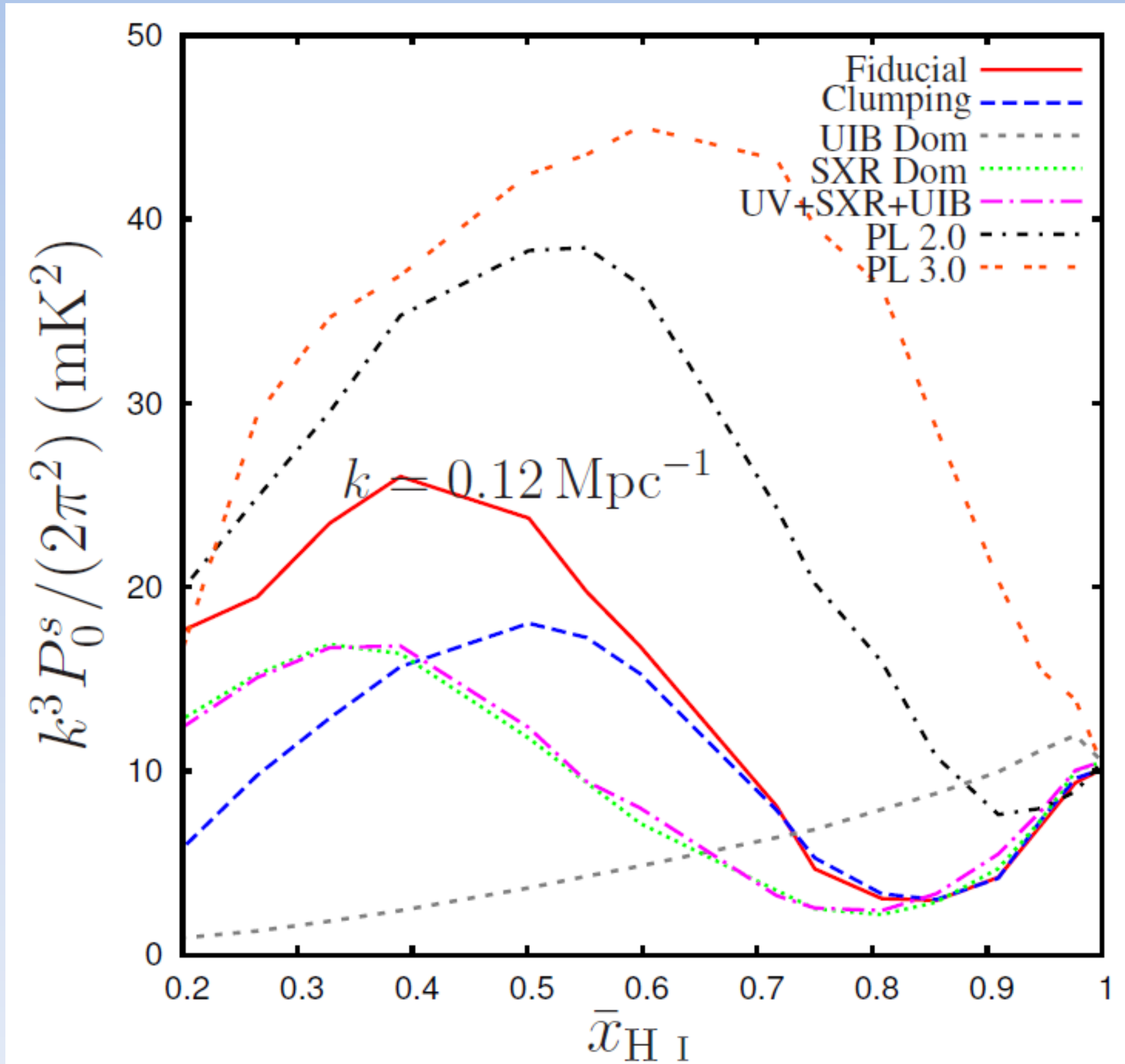
No. of photons $\propto$ (halo mass)^n

21-cm Maps in Redshift Space



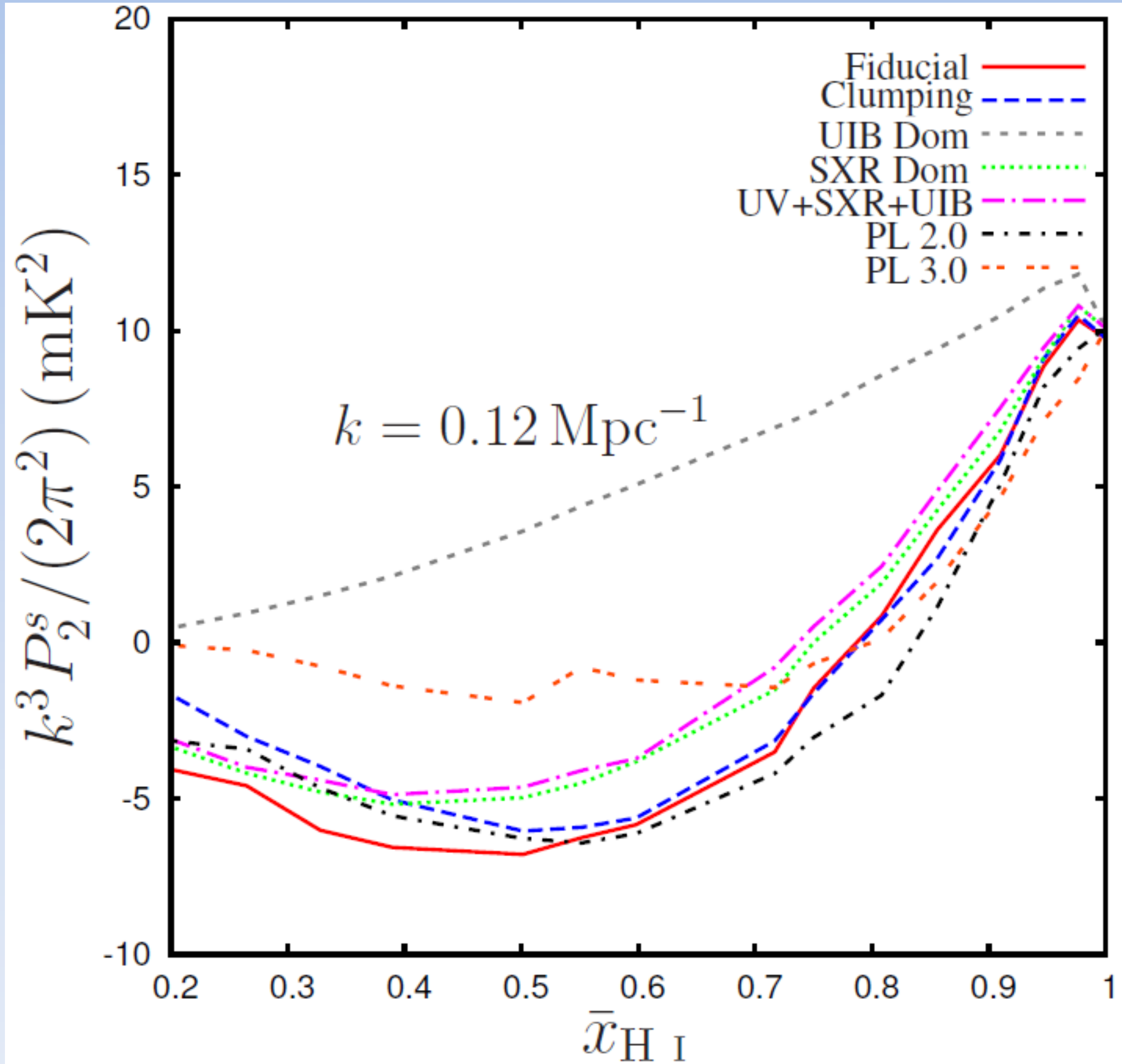
Majumdar, Jensen, Mellema et al., 2015, in prep.

Monopole Moment



Majumdar, Jensen, Mellema et al., 2015, in prep.

Quadrupole Moment



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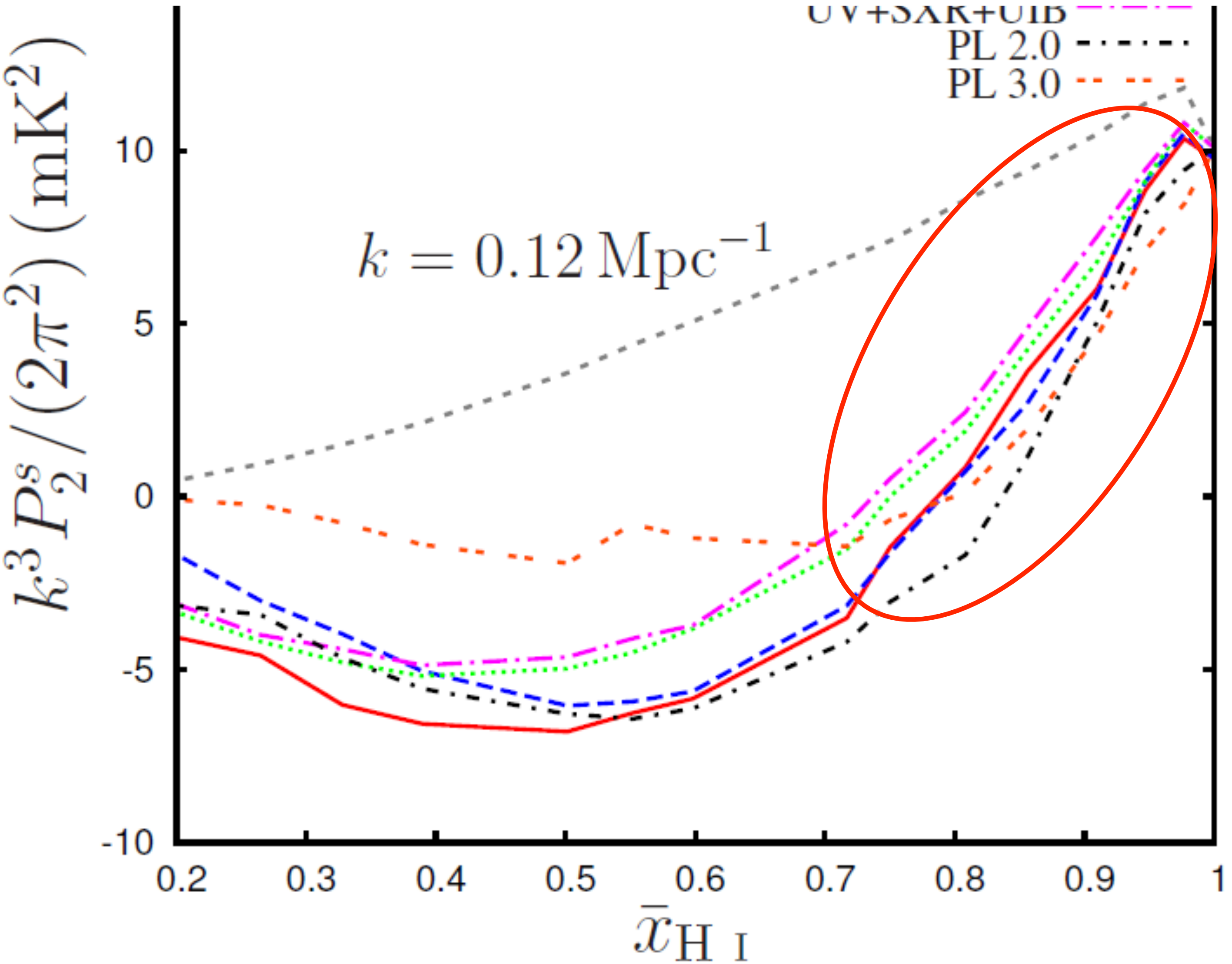


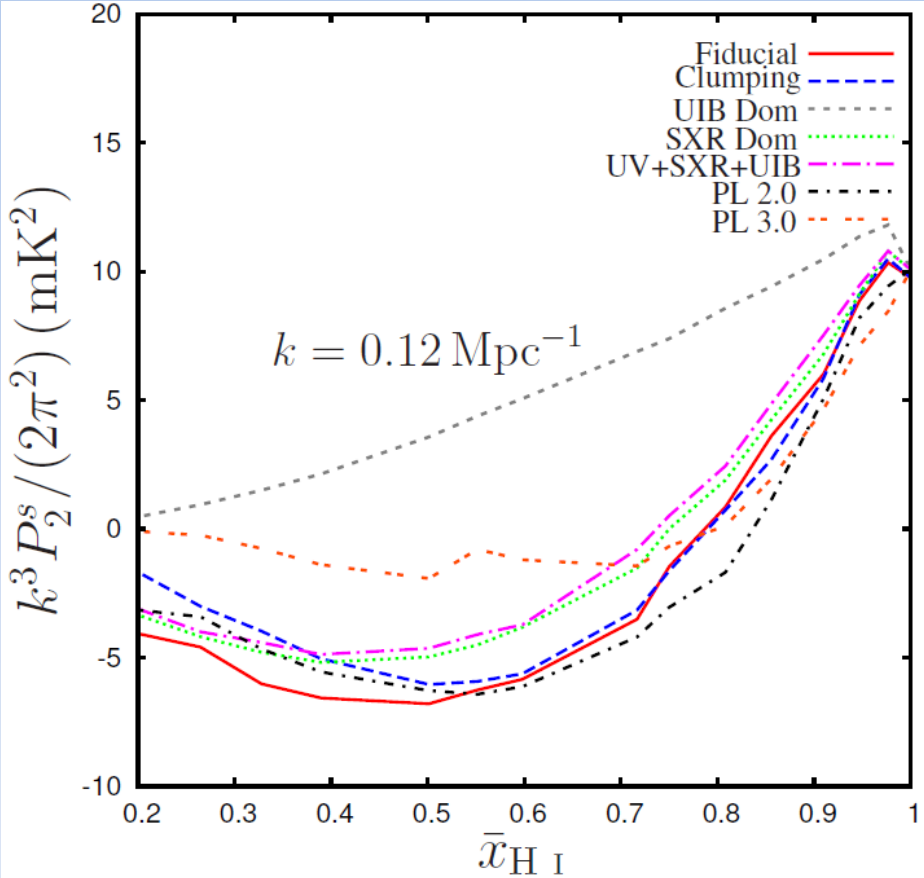
Cross-Correlation

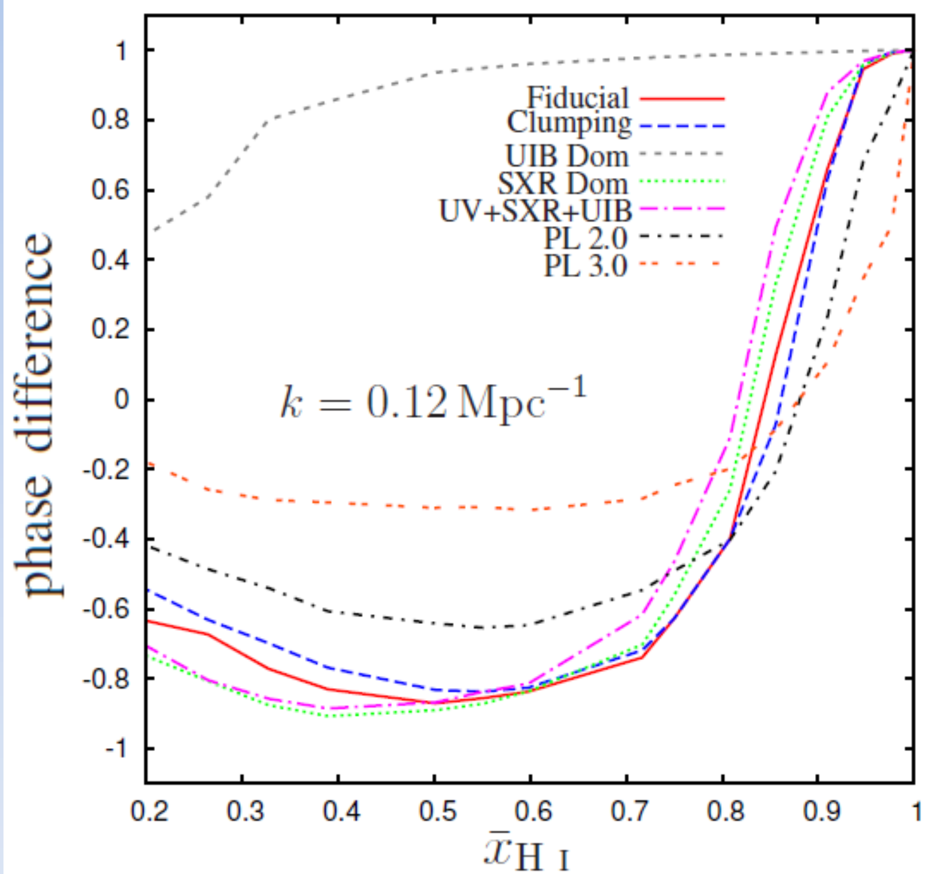
$X = Ae^{i\theta}$

$Y = Be^{i\varphi}$

$$P_{XY} = |A||B|\cos(\varphi - \theta)$$

Robustness of the Quadrupole Moment





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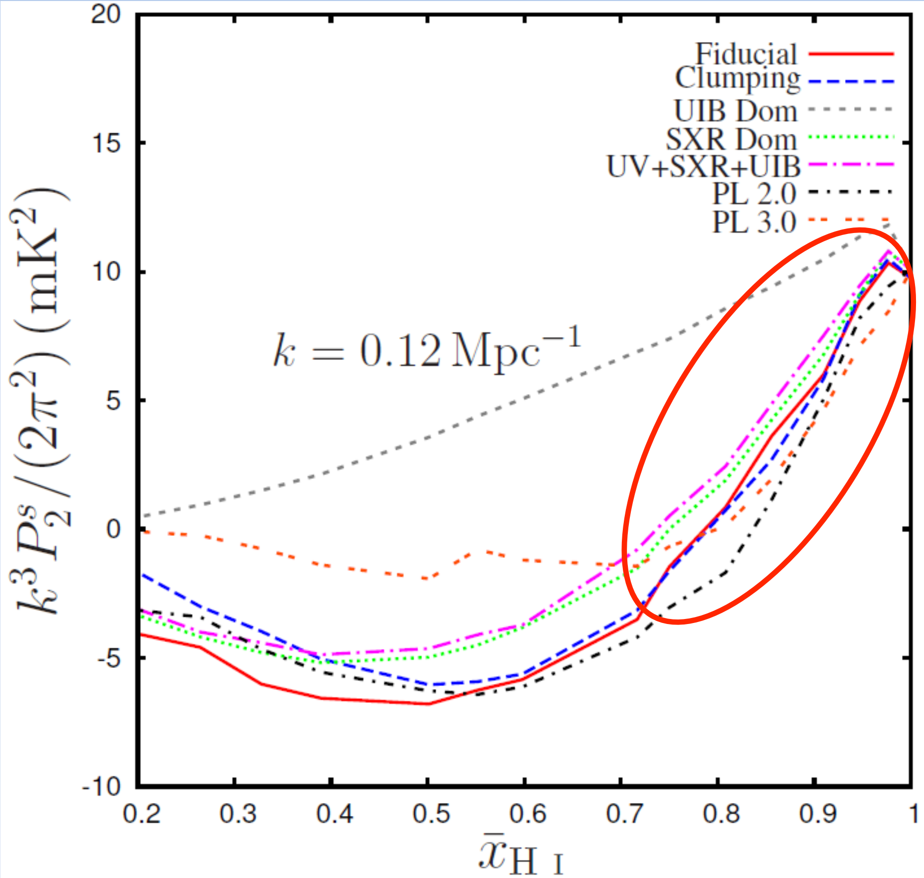
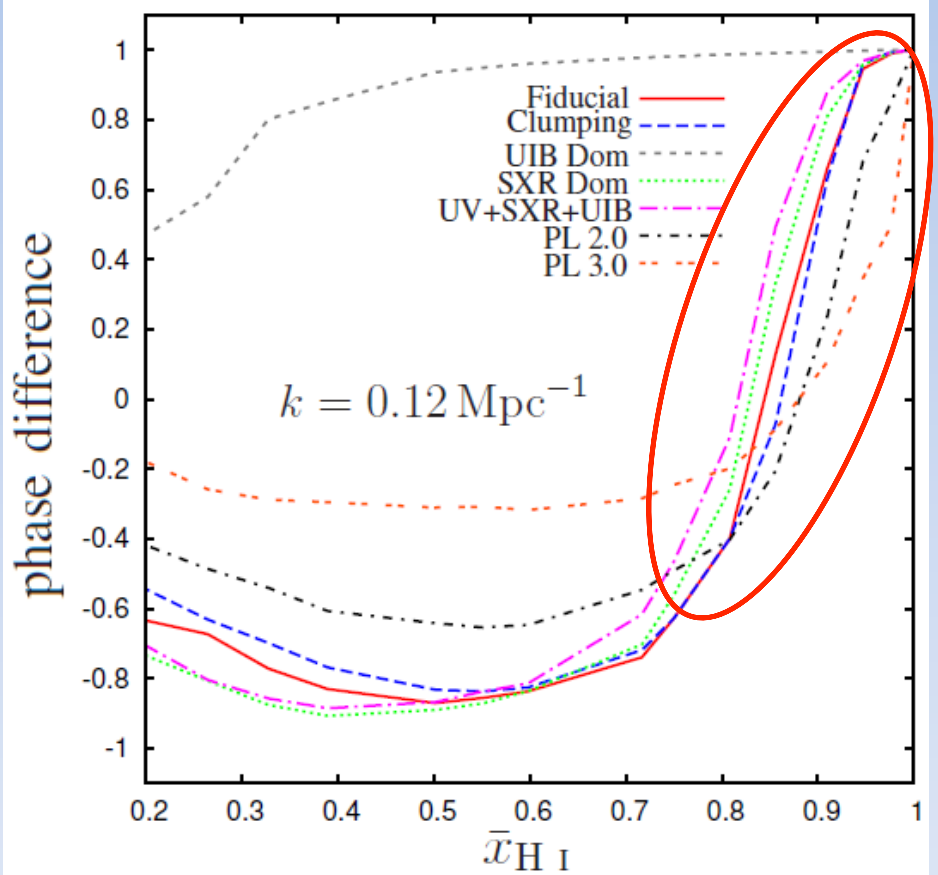
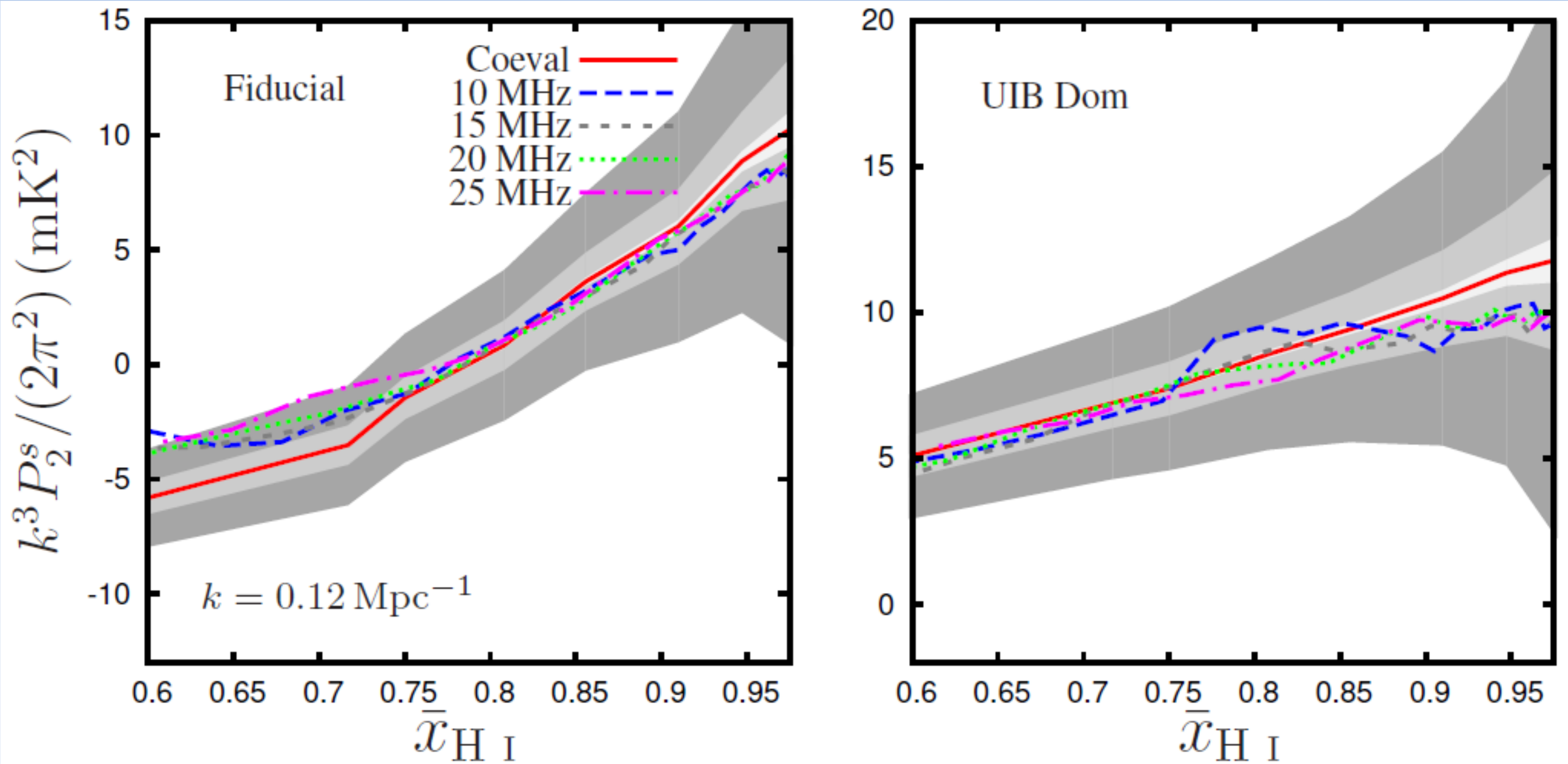




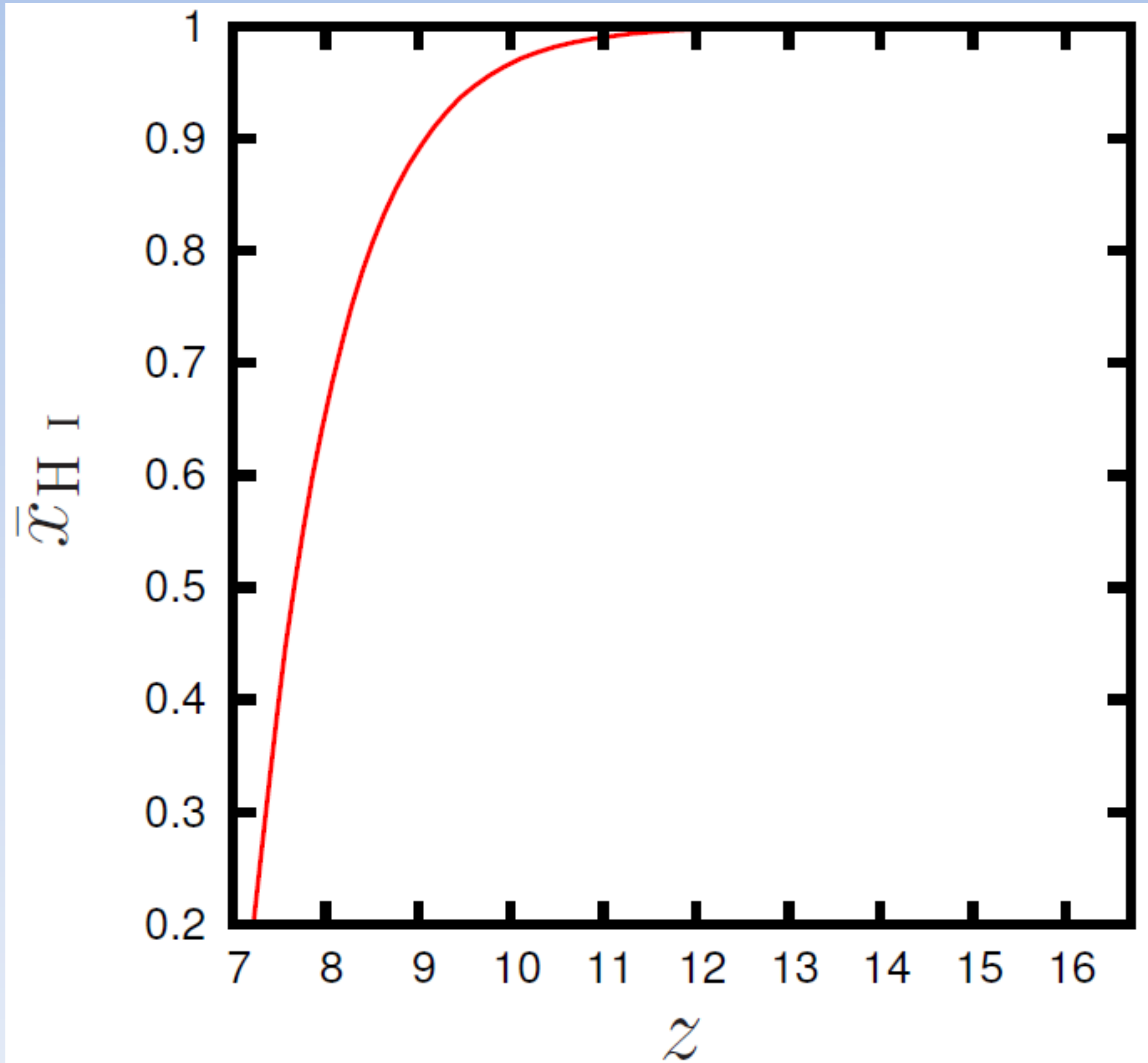
Majumdar, Jensen, Mellema et al., 2015, in prep.

Light Cone Effect on the Quadrupole Moment



Majumdar, Jensen, Mellema et al., 2015, in prep.

Robustness of the Quadrupole Moment & EoR History



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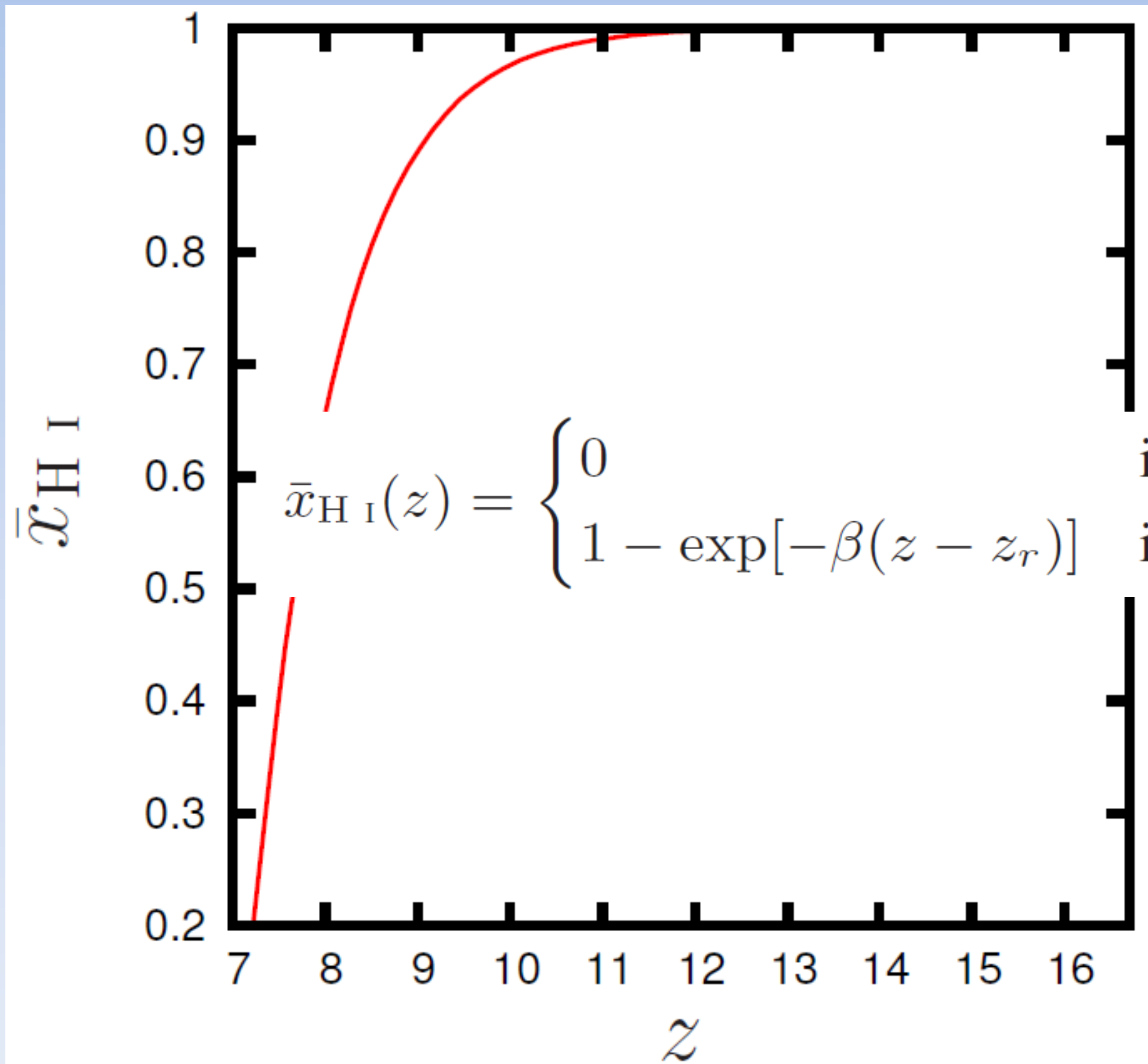


$$\bar{x}_{\mathrm{H\,I}}(z) = \begin{cases} 0 & \text{if } z < z_r \\ 1 - \exp[-\beta(z - z_r)] & \text{if } z \geq z_r \end{cases}$$

Majumdar, Jensen, Mellema et al., 2015, in prep.

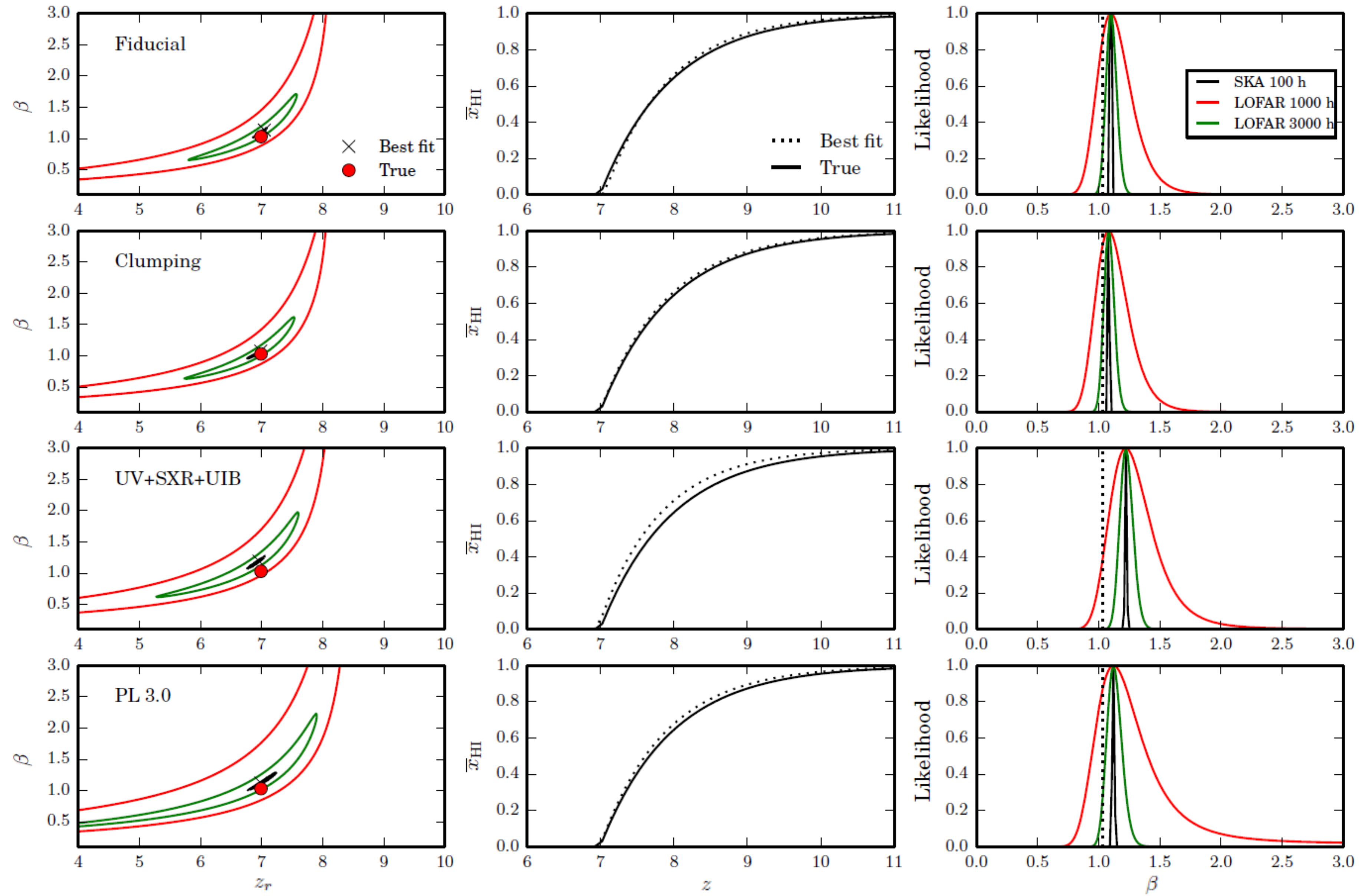
Robustness of the Quadrupole Moment & EoR History

$$\bar{x}_{\mathrm{H\,I}}(z) = \begin{cases} 0 & \text{if } z < z_r \\ 1 - \exp[-\beta(z - z_r)] & \text{if } z \geq z_r \end{cases}$$

$$\mathcal{L} = \prod_i \frac{1}{\sqrt{2\pi}\sigma} \exp\left[\frac{\left(P_{2,i}^{s,\mathrm{meas}} - P_{2,i}^{s,\mathrm{true}}\right)^2}{2\sigma^2} \right]$$

Majumdar, Jensen, Mellema et al., 2015, in prep.

Recovering the EoR History



Majumdar, Jensen, Mellema et al., 2015, in prep.

Summary

- The quadrupole moment of the power spectrum provides a very robust estimate of the EoR 21-cm signal compared to the monopole moment.

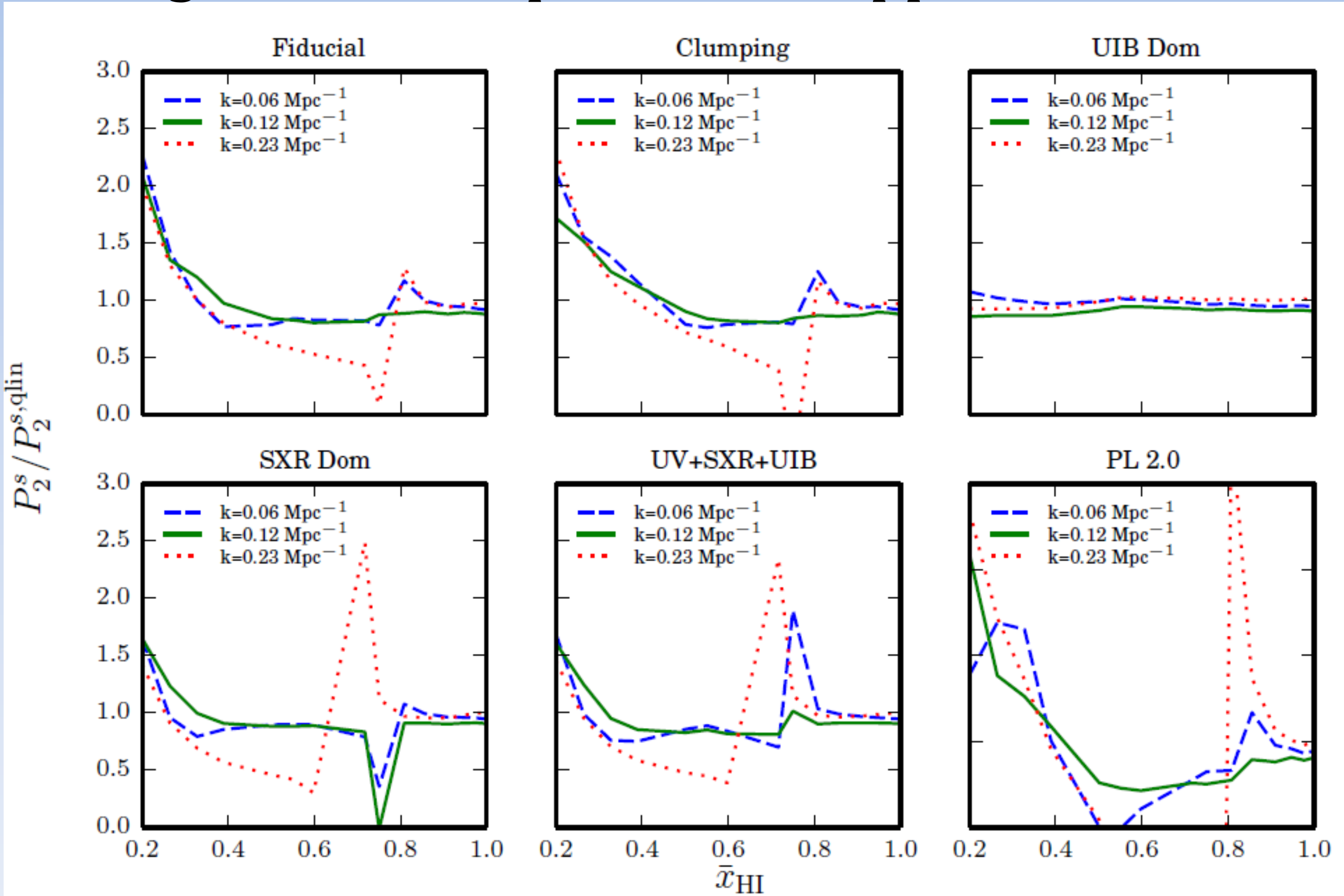
- It is very insensitive to the properties of the reionization sources (or ionization topology) as long as their spatial distribution is even loosely correlated to the distribution of collapsed bound structures.

- It is also expected to be less sensitive to the spin temperature fluctuations compared to the monopole moment.

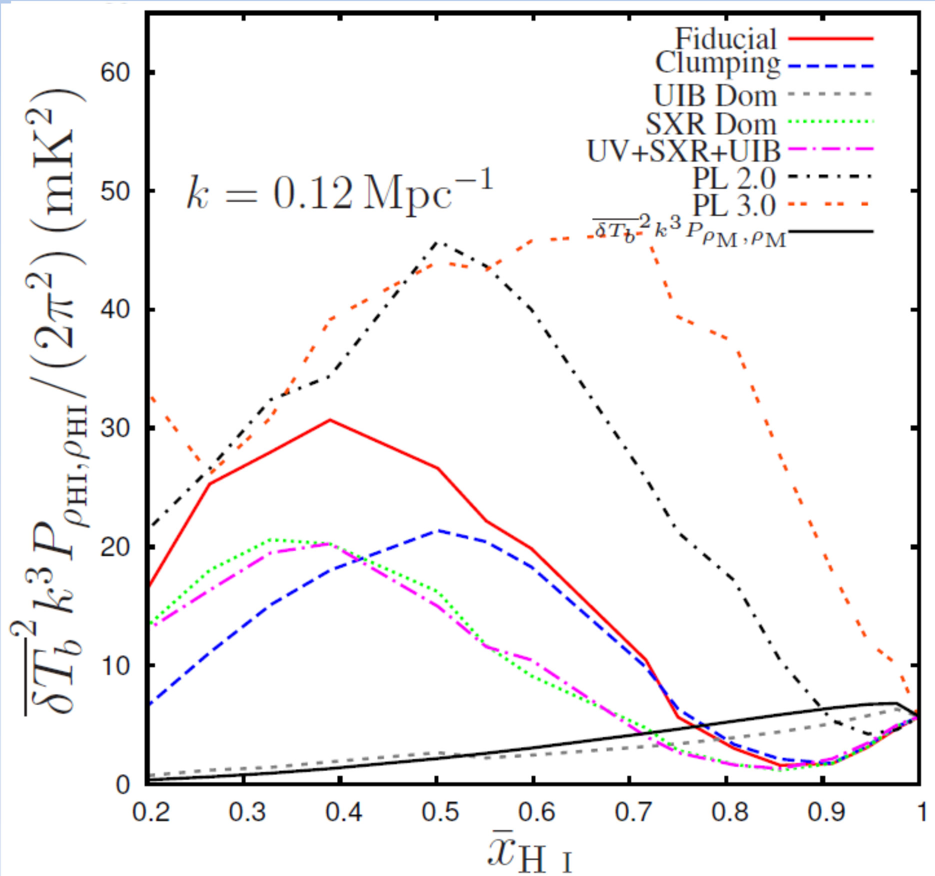
- This roboustness of the quadrupole moment can be used to extract the history of EoR very efficiently.

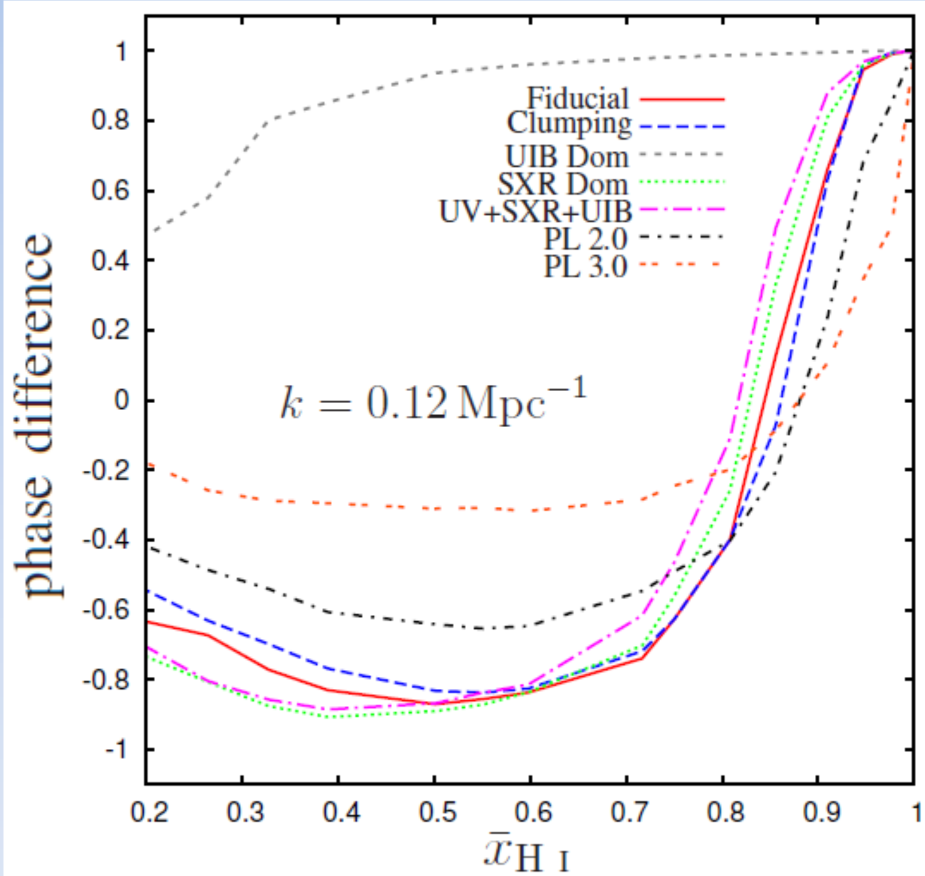
Thanks

How good are the quasi-linear approximations??



Robustness of the Quadrupole Moment





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Power Spectrum in Redshift Space

Considering the model with quasi-linear approximations ----

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when $T_S >> T_{CMB}$

Mao et al., 2013, MNRAS, 2012, 422, 2

Power Spectrum in Redshift Space

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Power Spectrum of total Matter Density Field

Mao et al., 2013, MNRAS, 2012, 422, 2

Power Spectrum in Redshift Space

Considering the model with quasi-linear approximations ----

$$P^s(k,\mu) = \overline{\delta T_b}^2(z)\left[P_{\rho_{H\,\mathrm{I}}\rho_{H\,\mathrm{I}}}(k) + 2\mu^2 P_{\rho_{H\,\mathrm{I}}\rho_M}(k) + \mu^4 P_{\rho_M\rho_M}(k)\right]$$

Power Spectrum
of
HI Density Field

Mao et al., 2013, MNRAS, 2012, 422, 2

Power Spectrum in Redshift Space

Considering the model with quasi-linear approximations ----

$$P^s(k,\mu) = \overline{\delta T_b}^2(z)\left[P_{\rho_{H\,\text{I}}\rho_{H\,\text{I}}}(k) + 2\mu^2 P_{\rho_{H\,\text{I}}\rho_M}(k) + \mu^4 P_{\rho_M\rho_M}(k)\right]$$

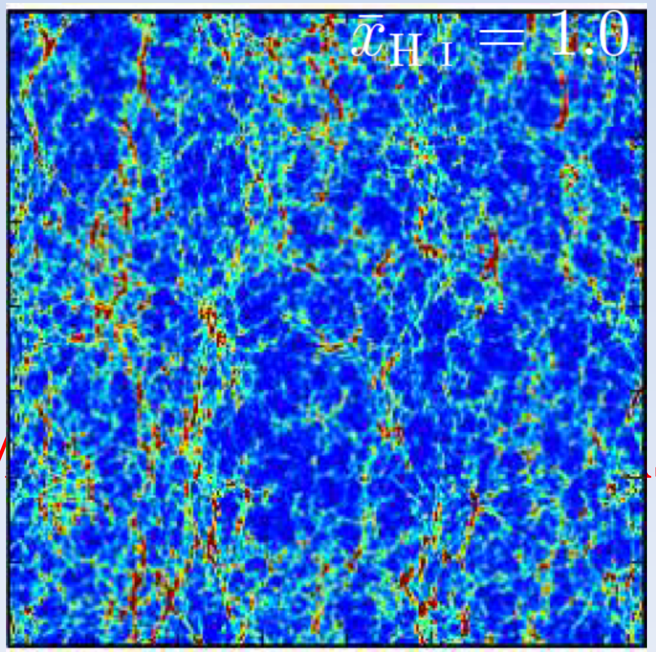
Cross-Power Spectrum
of
HI and Matter Density Fields

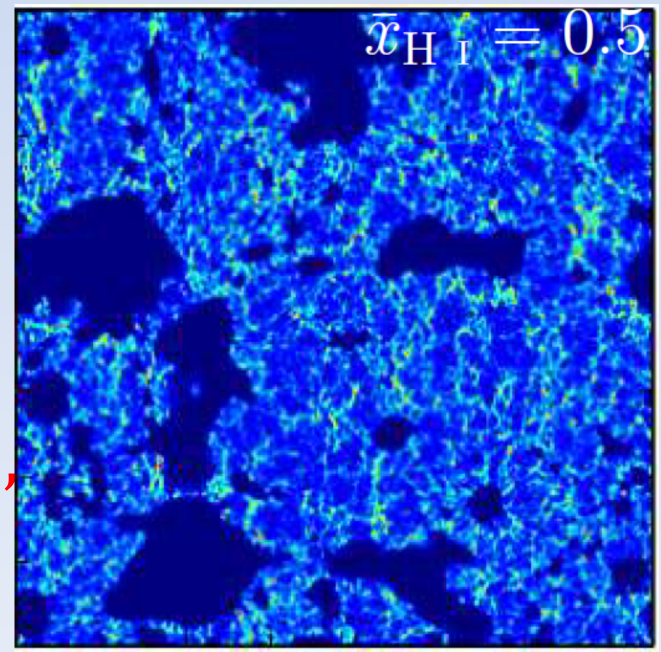
Mao et al., 2013, MNRAS, 2012, 422, 2

Power Spectrum in Redshift Space

Considering the model with quasi-linear approximations ----

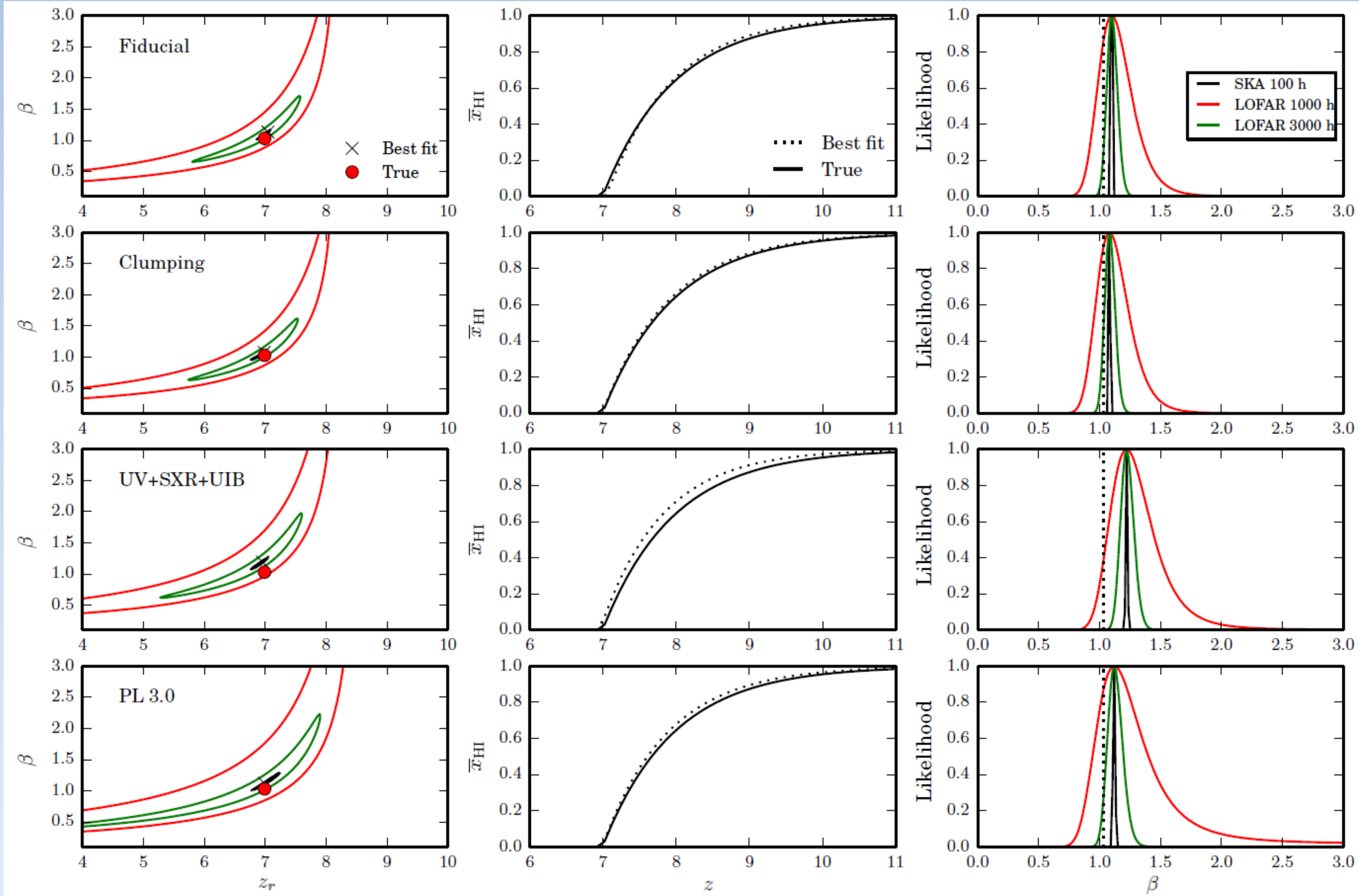
$$P^s(k,\mu) = \overline{\delta T_b}^2(z)\left[P_{\rho_{H\,I}\rho_{H\,I}}(k) + 2\mu^2 P_{\rho_{H\,I}\rho_M}(k) + \mu^4 P_{\rho_M\rho_M}(k)\right]$$





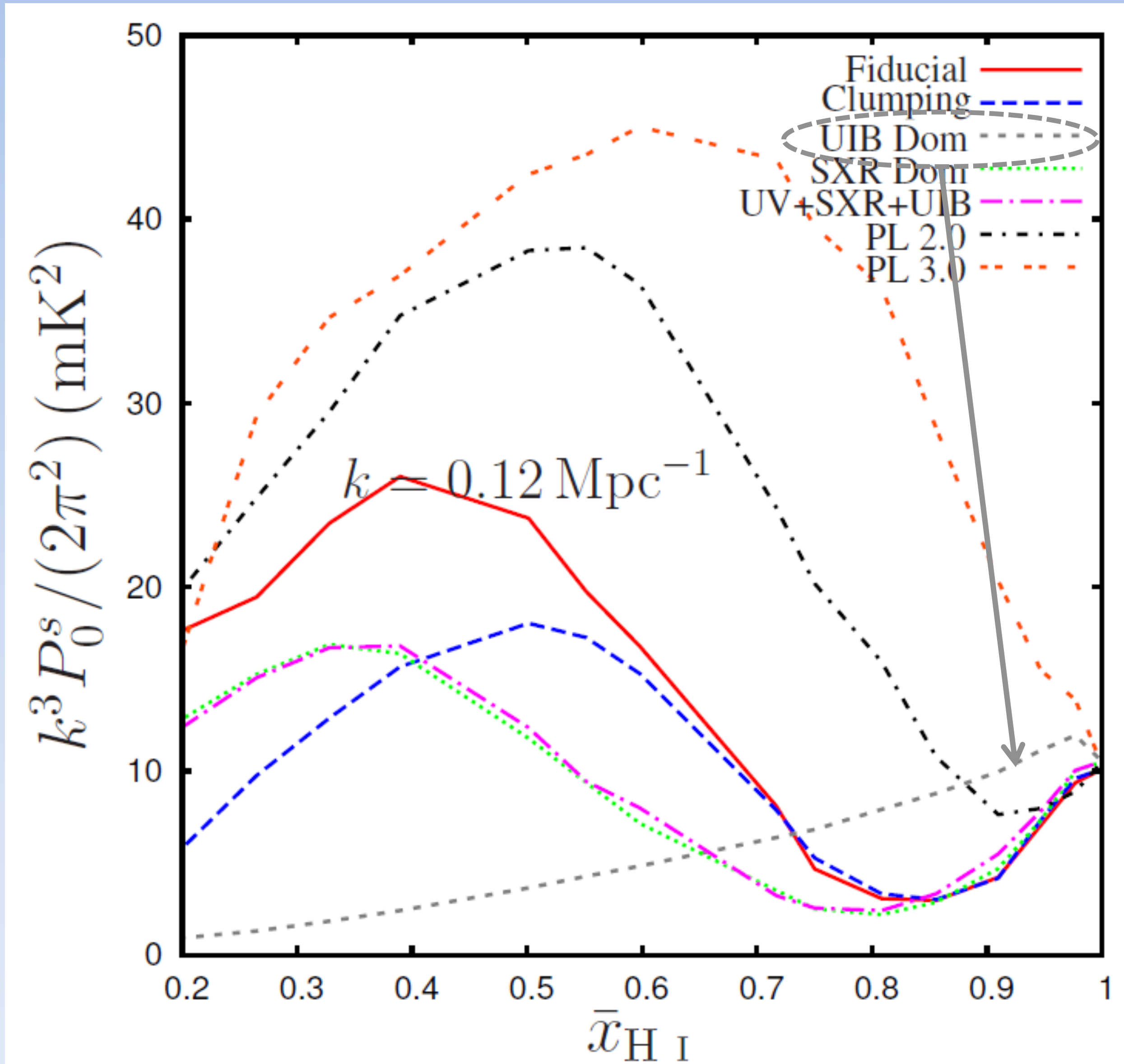
M S, 2012, 422,

Recovering the EoR History



Majumdar, Jensen, Mellema et al., 2015, in prep.

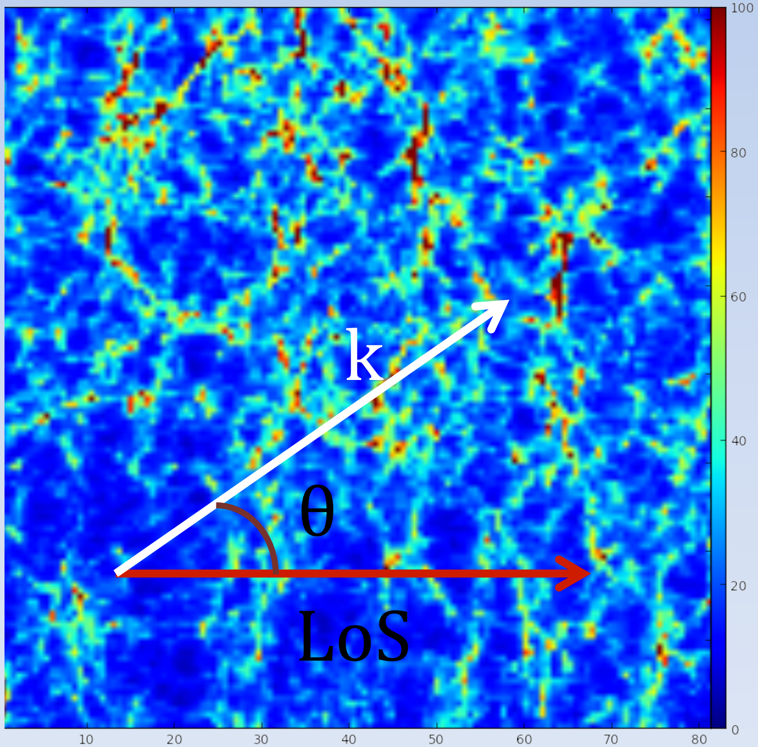
Monopole Moment



Majumdar, Jensen, Mellema et al., 2015, in prep.

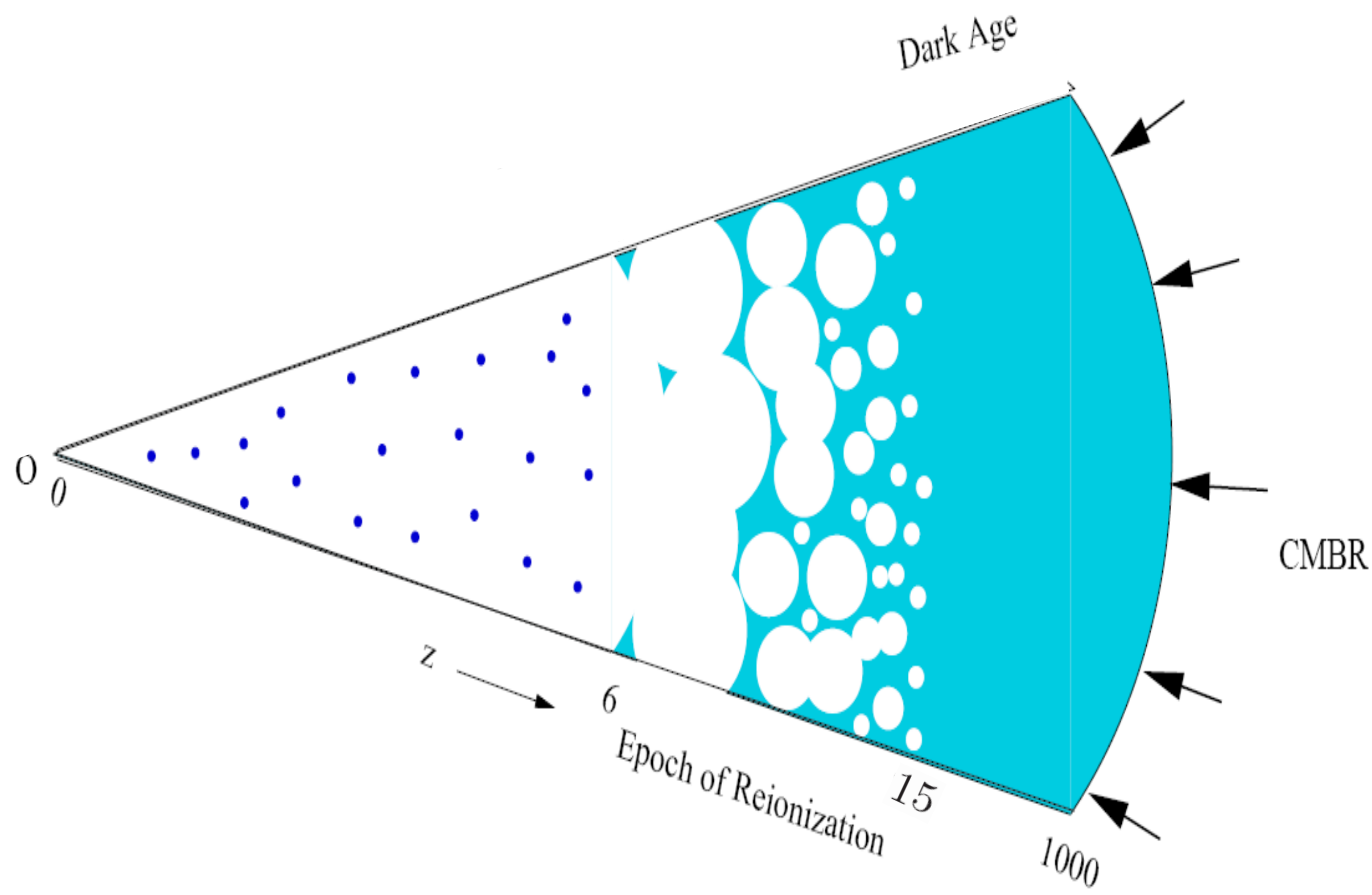
Power Spectrum in Redshift Space

Effect of this anisotropy on the 21-cm power spectrum will be significant.

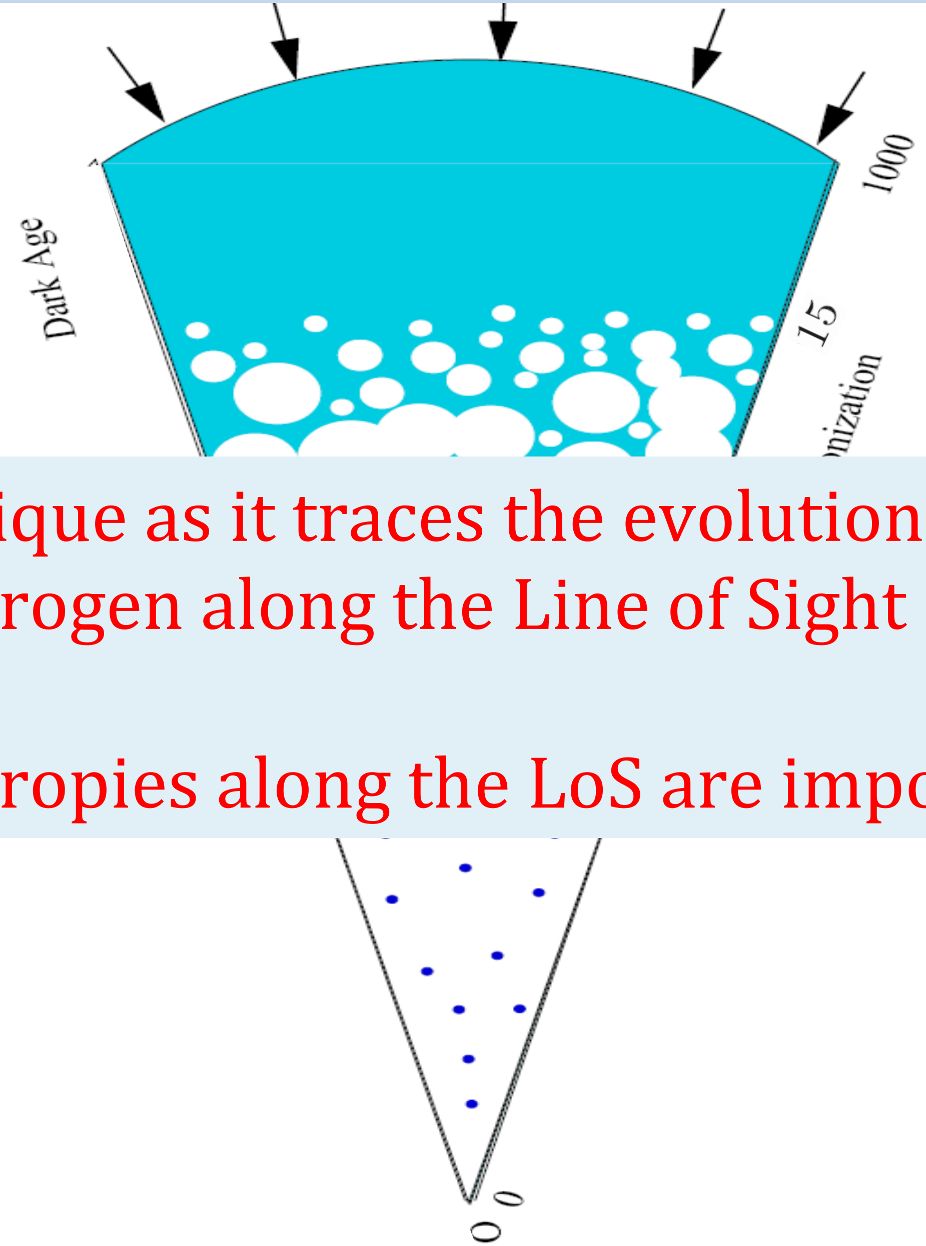


$$P^s(k, \mu)$$

- Bharadwaj & Ali, 2004, MNRAS, 352, 142
- Bharadwaj & Ali, 2005, MNRAS, 356, 4
- Barkana & Loeb, 2005, ApJL, 624, L65
- ....


Dark Age
CMBR
O
0
z
6
Epoch of Reionization
15
1000

!!Time Travel!!



21-cm is unique as it traces the evolution of the state of hydrogen along the Line of Sight (LoS).

Anisotropies along the LoS are important.

HI 21-cm Radiation