Tsinghua Center for Astrophysics
(Beijing)

Signatures of Cosmic Reionization on the 21cm 3-Point Correlation

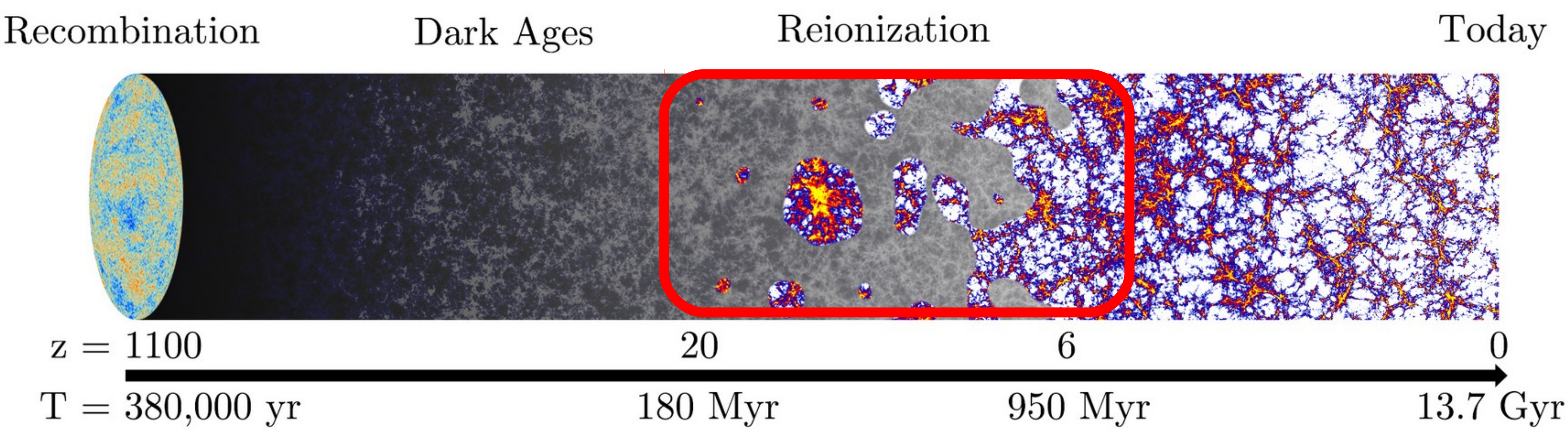
Kai Hoffmann

collaborators:
Yi Mao, Houjun Mo, Benjamin D. Wandelt

Motivation

21cm clustering statistics can constrain

- Reionization models *(Shimabukuro et al. 2017, 1608.00372)*
- possibly cosmological models at high z (see conclusions)



Credit: Kaurov

Motivation

21cm clustering statistics can constrain

- Reionization models *(Shimabukuro et al. 2017, 1608.00372)*
- possibly cosmological models at high z (see conclusions)

Why going beyond 2-point statistics?

21cm 2pc probes scale dependence of 21cm clustering, while 3pc is sensitive to additional information on shape of

- ionized regions
- matter fluctuations

→ tighter model constraints

(Suman Majumdar et al. 2017, arXiv:1708.08458)

Motivation

21cm clustering statistics can constrain

- Reionization models *(Shimabukuro et al. 2017, 1608.00372)*
- possibly cosmological models at high z (see conclusions)

Why going beyond 2-point statistics?

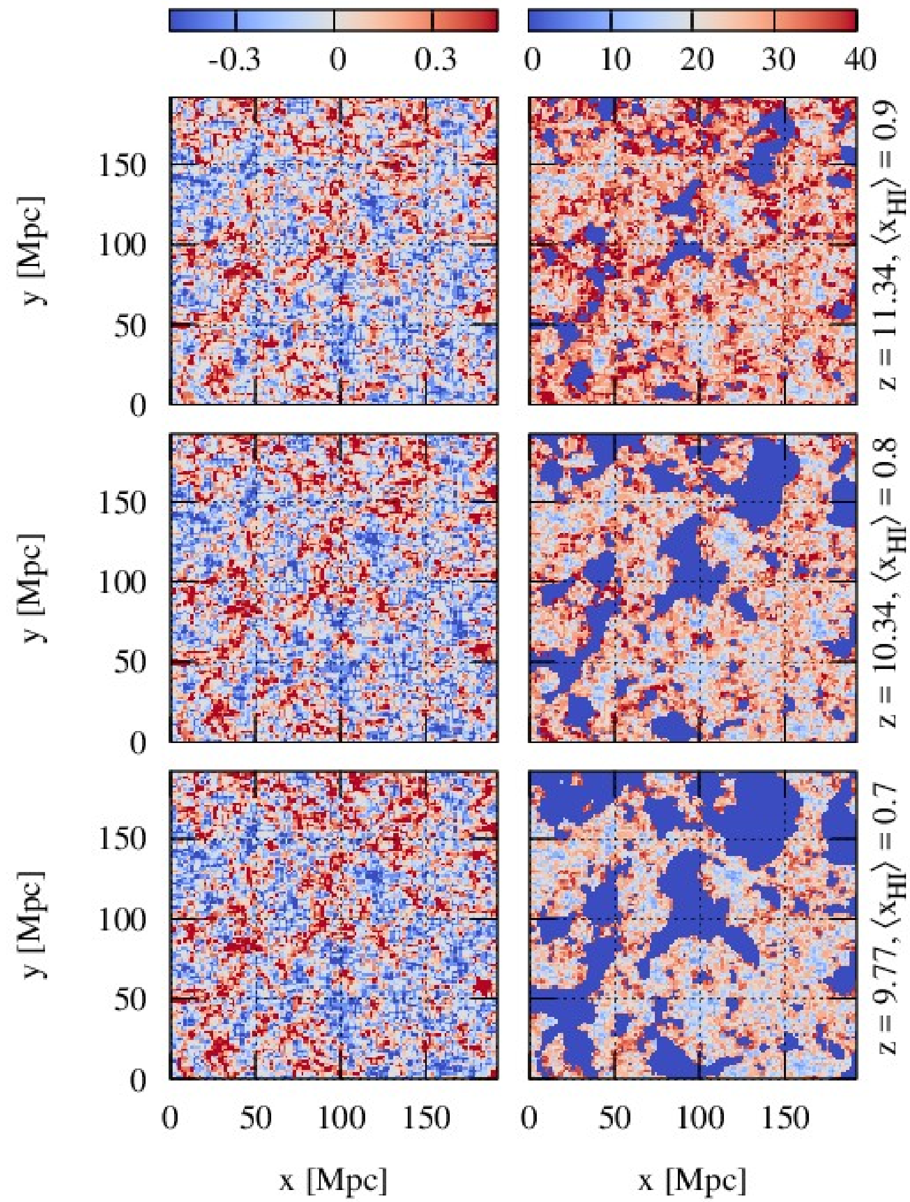
21cm 2pc probes scale dependence of 21cm clustering, while 3pc is sensitive to additional information on shape of

- ionized regions
- matter fluctuations

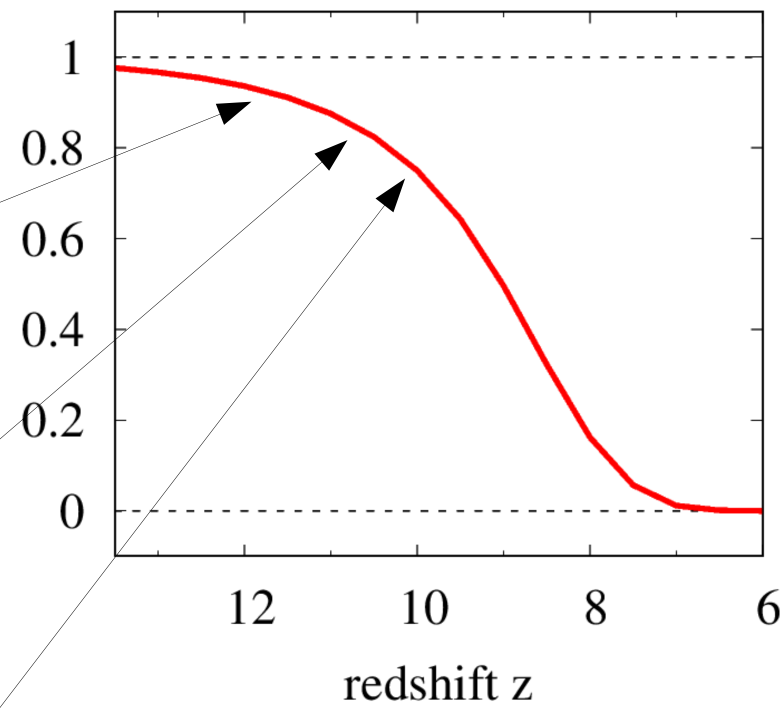
$\Rightarrow$ tighter model constraints

no theory model for the 21cm 3pc

21cmFast simulations



Global neutral fraction



- $(768\ \mathrm{Mpc})^3$ box
- 200 realizations

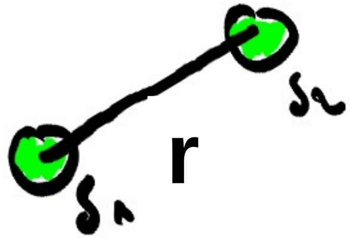
(21cmFAST: Mesinger et al. 2010)

2- and 3-point correlations

fluctuations: $\delta_m = \dfrac{\rho_m - \langle \rho_m \rangle}{\langle \rho_m \rangle}$ $\delta_{\delta T} = \dfrac{\delta T - \langle \delta T \rangle}{\langle \delta T \rangle}$

2-point correlation (2pc):

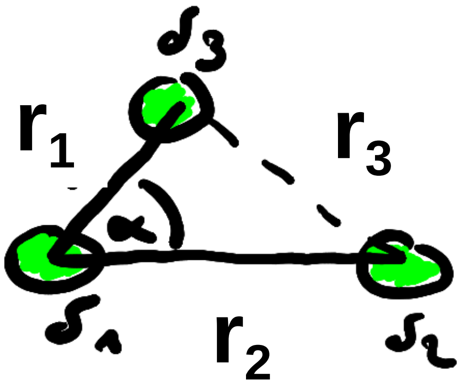
$$\xi^{(12)} \stackrel{\text{def}}{=} \langle \delta_1 \delta_2 \rangle (r)$$



- spherically symmetric $\rightarrow$ not sensitive to shape of fluctuations

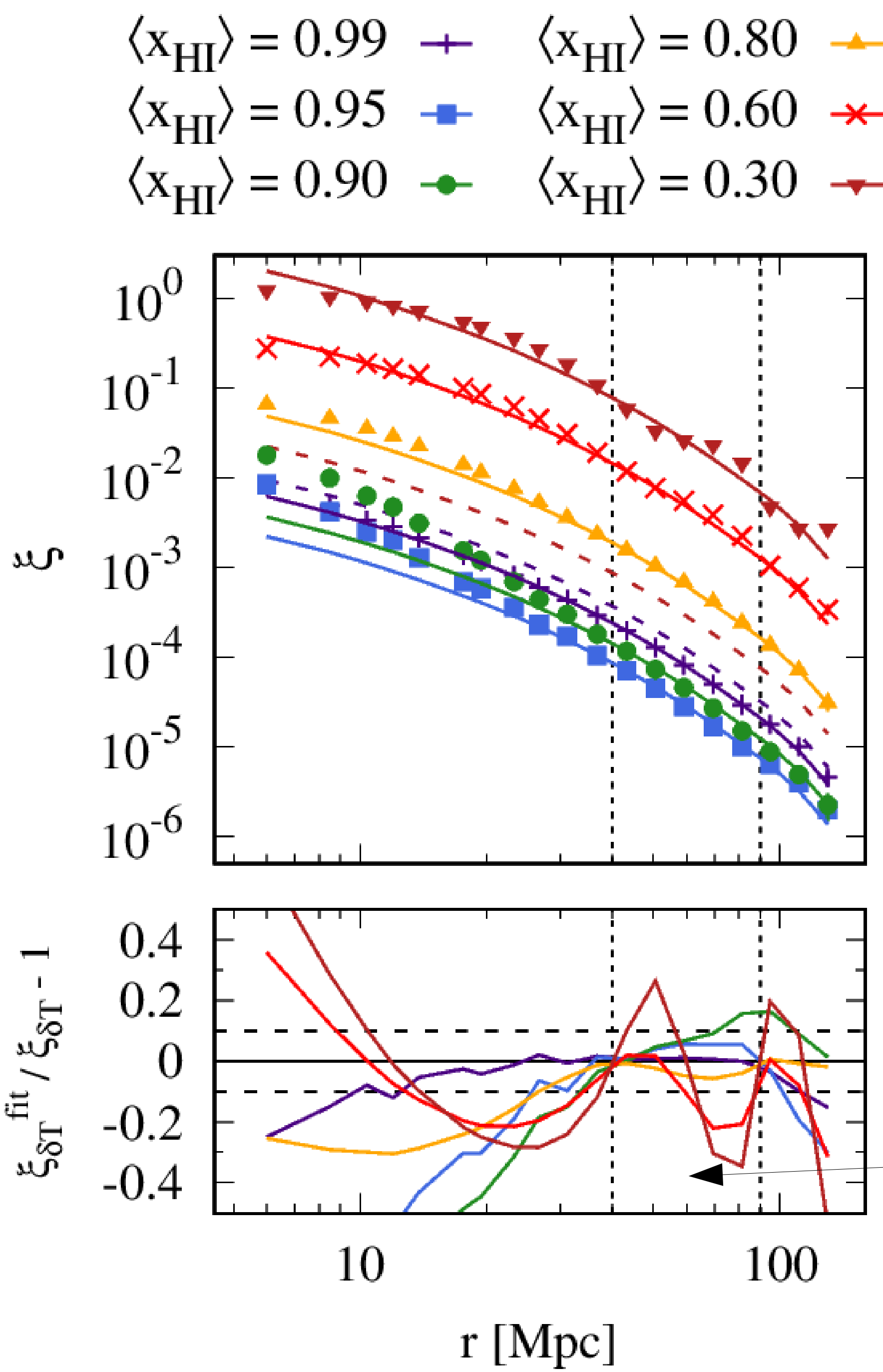
3-point correlation (3pc):

$$\zeta^{(123)} \stackrel{\text{def}}{=} \langle \delta_1 \delta_2 \delta_3 \rangle (r_{1,} r_{2,} r_3)$$



- provides additional shape info

2pc measurements



mean measurements
over 200 realizations

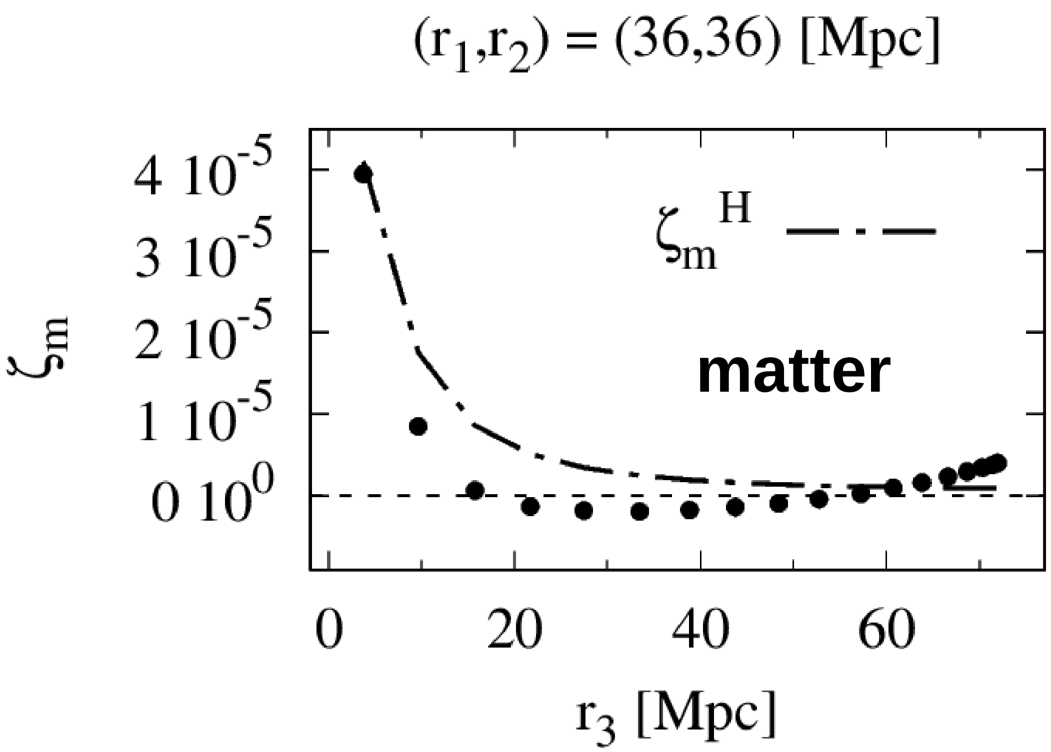
symbols:	21cm 2pc ($\xi_{\delta T}$)
dashed lines:	matter 2pc (ξ_m)
solid lines:	fits to bias model

Leading-order bias model

$$\xi_{\delta T} = b_1^2 \xi_m$$

fitting range: 40 < r < 90 Mpc

3pc measurements

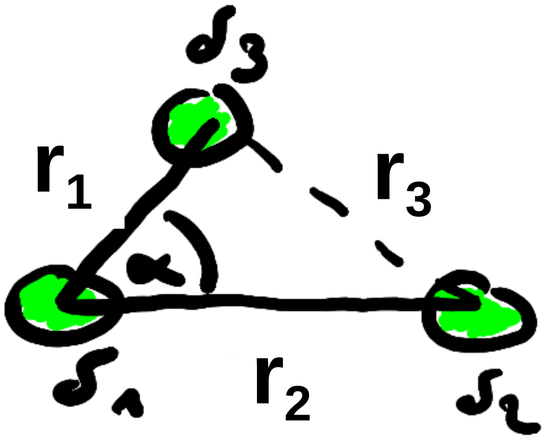


dots: 3pc

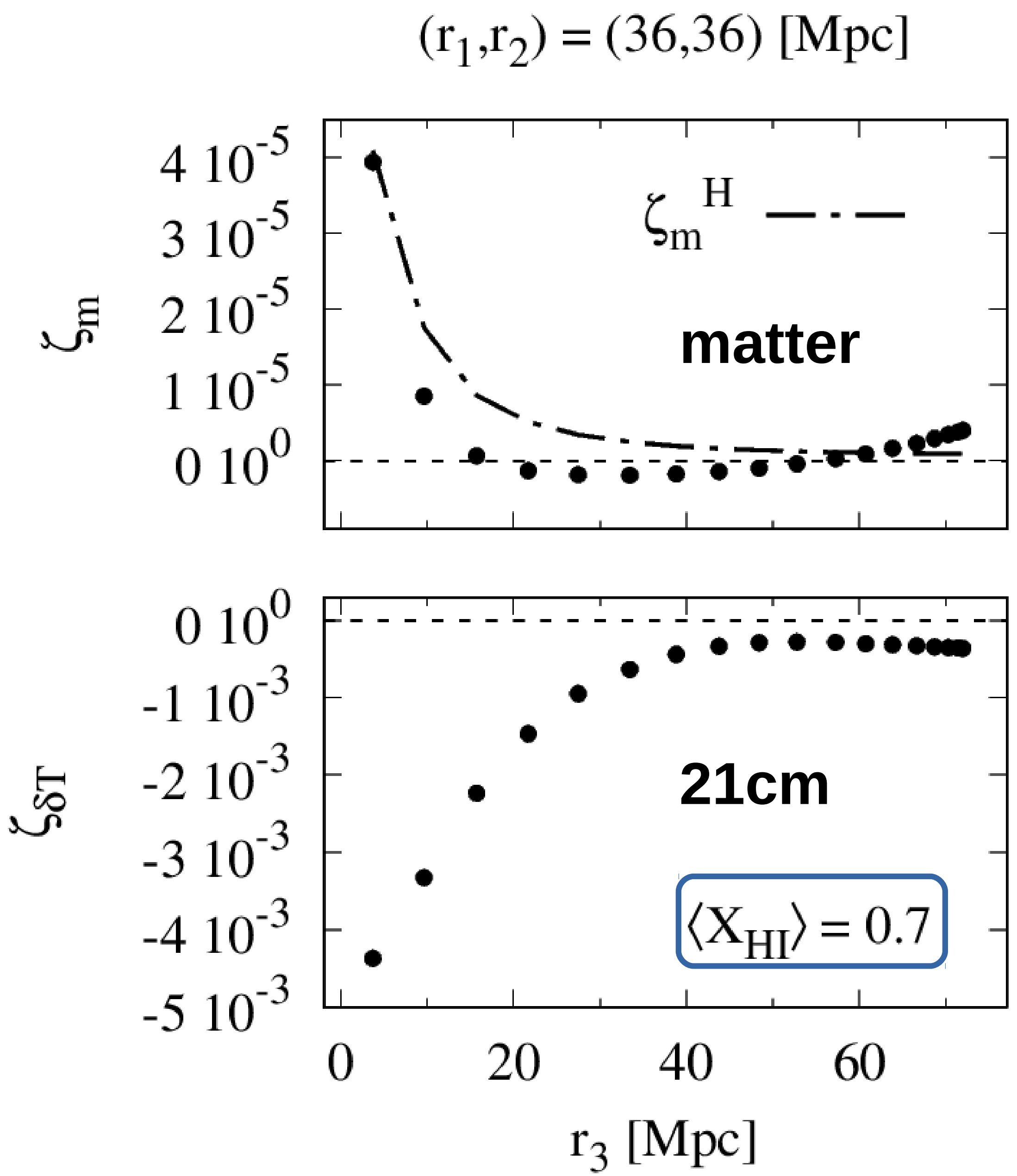
$$\zeta \overset{\text{def}}{=} \langle \delta_1 \delta_2 \delta_3 \rangle$$

line: hierarchical 3pc

$$\zeta^H \overset{\text{def}}{=} (\xi_m^{(12)} \xi_m^{(13)} + 2\, perm.)$$



3pc measurements

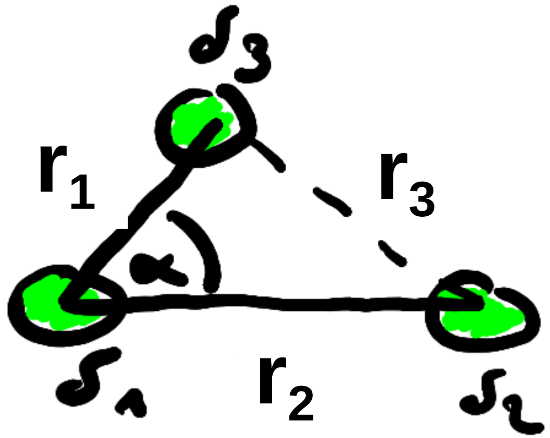


dots: 3pc

$$\zeta \stackrel{\text{def}}{=} \langle \delta_1 \delta_2 \delta_3 \rangle$$

line: hierarchical 3pc

$$\zeta^H \stackrel{\text{def}}{=} (\xi_m^{(12)} \xi_m^{(13)} + 2\, perm.)$$



quadratic bias model

Assumption: 21cm brightness temperature is deterministic function of underlying matter density

$$\delta_{\delta T} = F(\delta_m) \approx \sum_{n=0}^{N} b_n \frac{\delta_m^n}{n!}$$

(Taylor expansion of F around $\delta_m \approx 0$)

quadratic bias model

Assumption: 21cm brightness temperature is deterministic function of underlying matter density

$$\delta_{\delta T} = F(\delta_m) \approx \sum_{n=0}^{N} b_n \frac{\delta_m^n}{n!}$$

(Taylor expansion of F around $\delta_m \approx 0$)

Leading-order approximations for biased correlation functions

2pc $$\xi_{\delta T} \approx b_1^2 \xi_m$$

3pc $$\zeta_{\delta T} \approx b_1^3 \zeta_m + b_1^2 b_2 \zeta_m^H$$

(Fry & Gaztanaga 93)

quadratic bias model

Assumption: 21cm brightness temperature is deterministic function of underlying matter density

$$\delta_{\delta T} = F(\delta_m) \approx \sum_{n=0}^{N} b_n \frac{\delta_m^n}{n!}$$

(Taylor expansion of F around

$$Q_{\delta T} \approx \frac{1}{b_1}\left(Q_m + \frac{b_2}{b_1}\right)$$

with $Q \stackrel{\text{def}}{=} \zeta/\zeta^H$

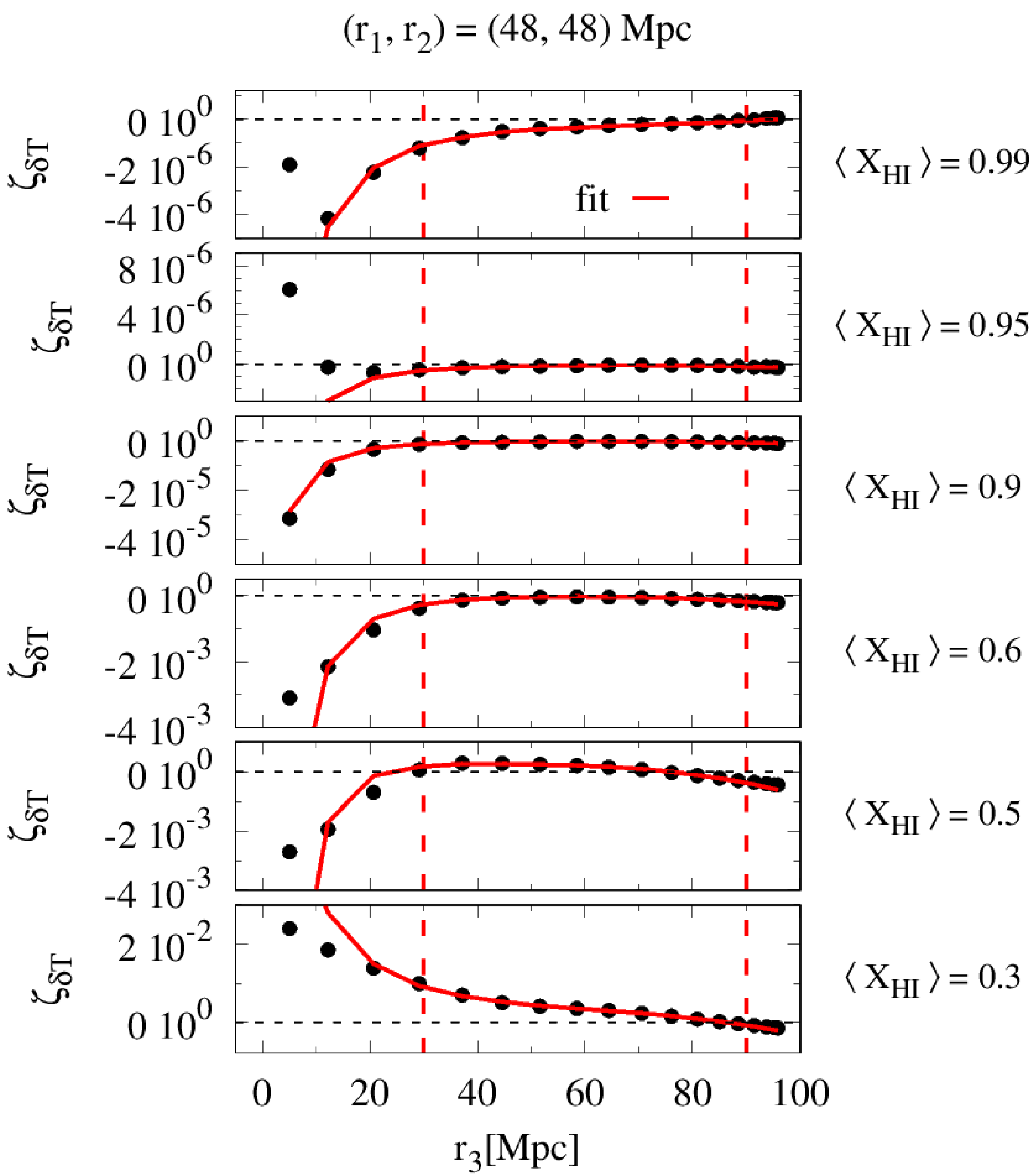
Leading-order approximations for biased s

2pc $\xi_{\delta T} \approx b_1^2 \xi_m$

3pc $\zeta_{\delta T} \approx b_1^3 \zeta_m + b_1^2 b_2 \zeta_m^H$

(Fry & Gaztanaga 93)

21cm 3pc fits



dots: 21 3pc

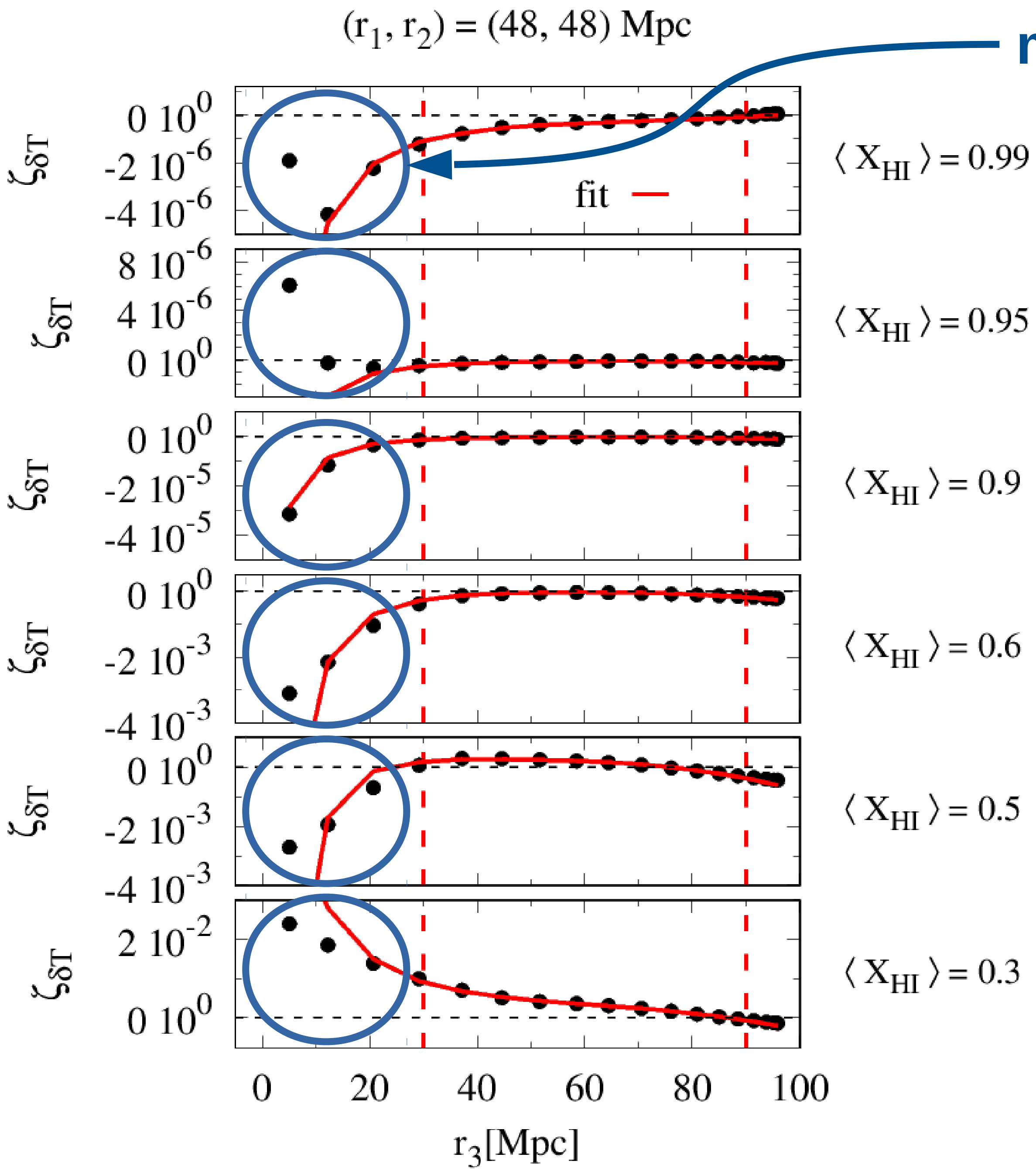
$$\zeta \stackrel{\text{def}}{=} \langle \delta_1 \delta_2 \delta_3 \rangle$$

lines: 3pc bias model fit

$$\zeta_{\delta T} \approx b_1^3 \zeta_m + b_1^2 b_2 \zeta_m^H$$

(fitting range: 30<r<90 Mpc)

21cm 3pc fits



dots: 21 3pc

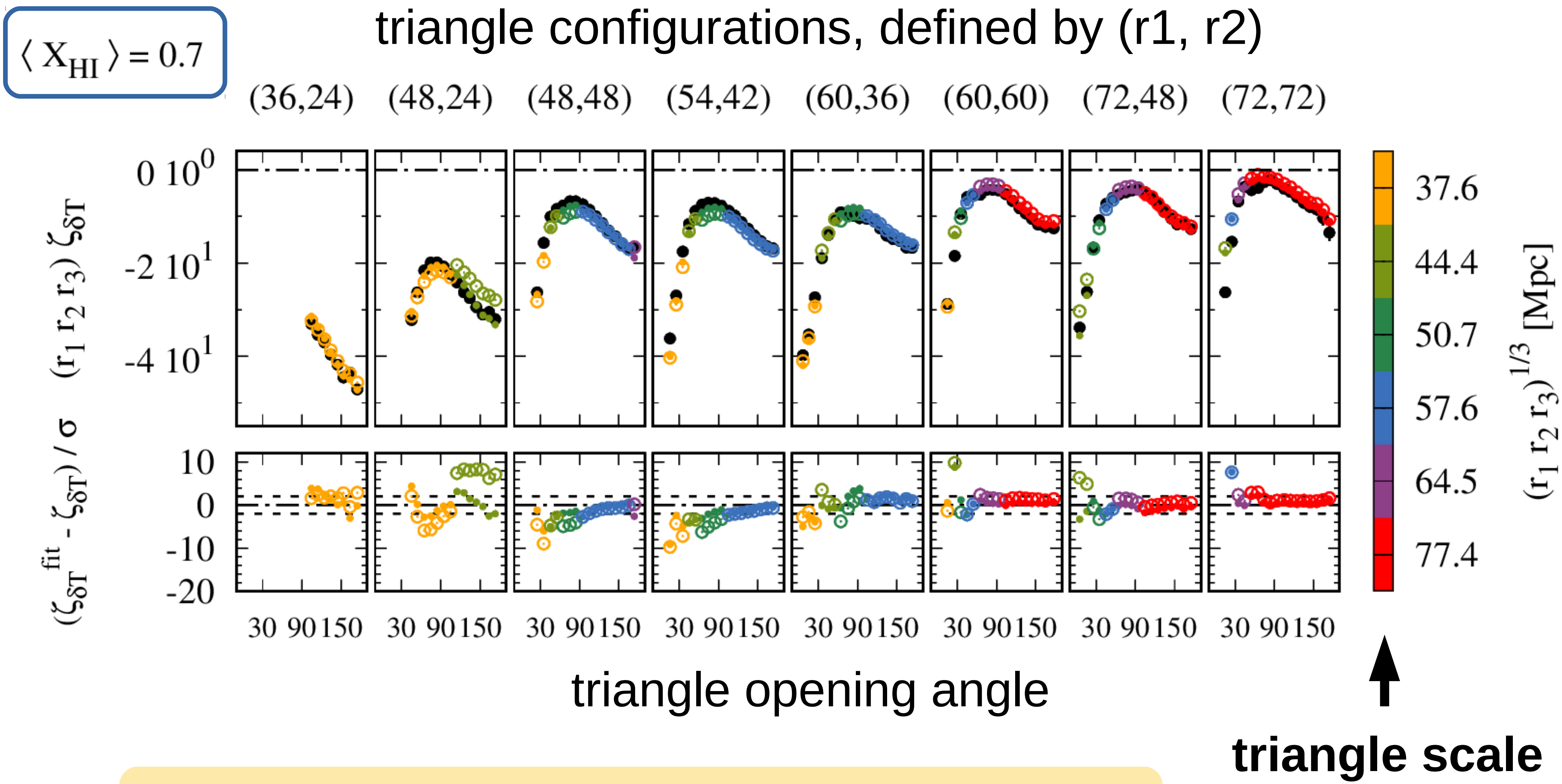
$$\zeta \stackrel{\text{def}}{=} \langle \delta_1 \delta_2 \delta_3 \rangle$$

lines: 3pc bias model fit

$$\zeta_{\delta T} \approx b_1^3 \zeta_m + b_1^2 b_2 \zeta_m^H$$

(fitting range: 30<r<90 Mpc)

21cm 3pc fits

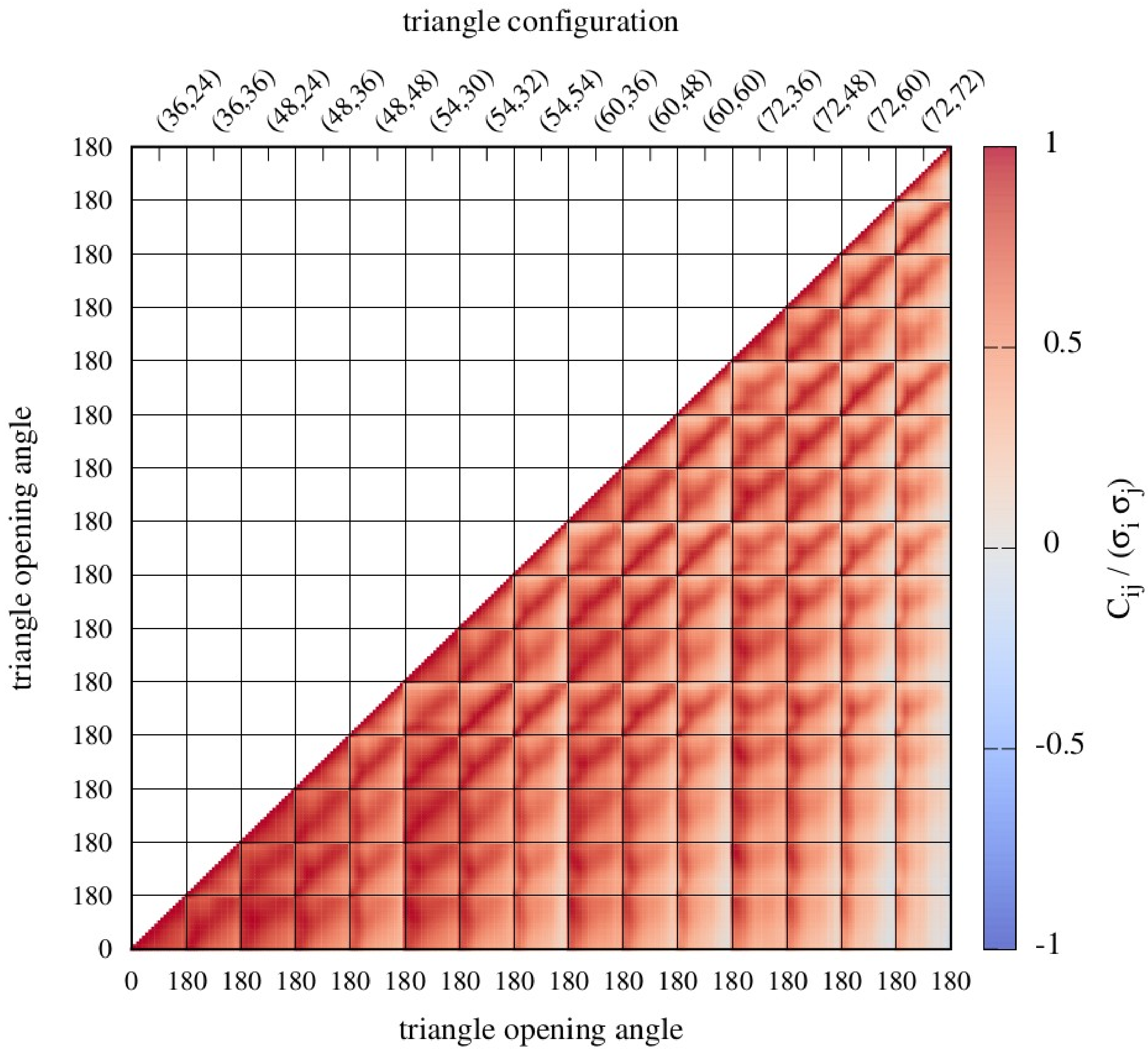


$(r_1 r_2 r_3)^{1/3}$

- **black dots:** 3pc measurements
- **colored dots:** fits to bias model prediction in triangle scale bins

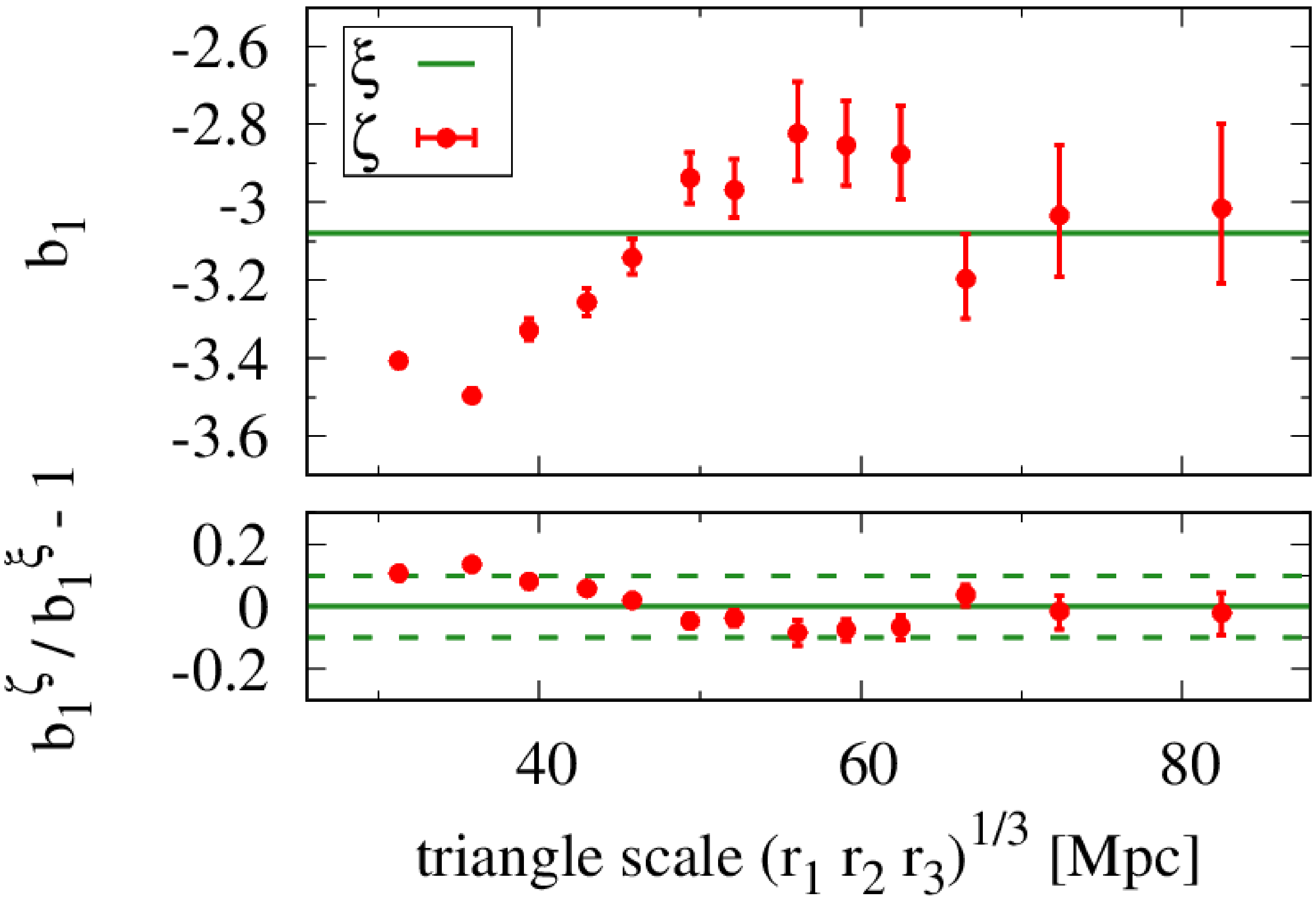
21cm 3pc covariance

15 configurations X
18 opening angles
= 270 triangles



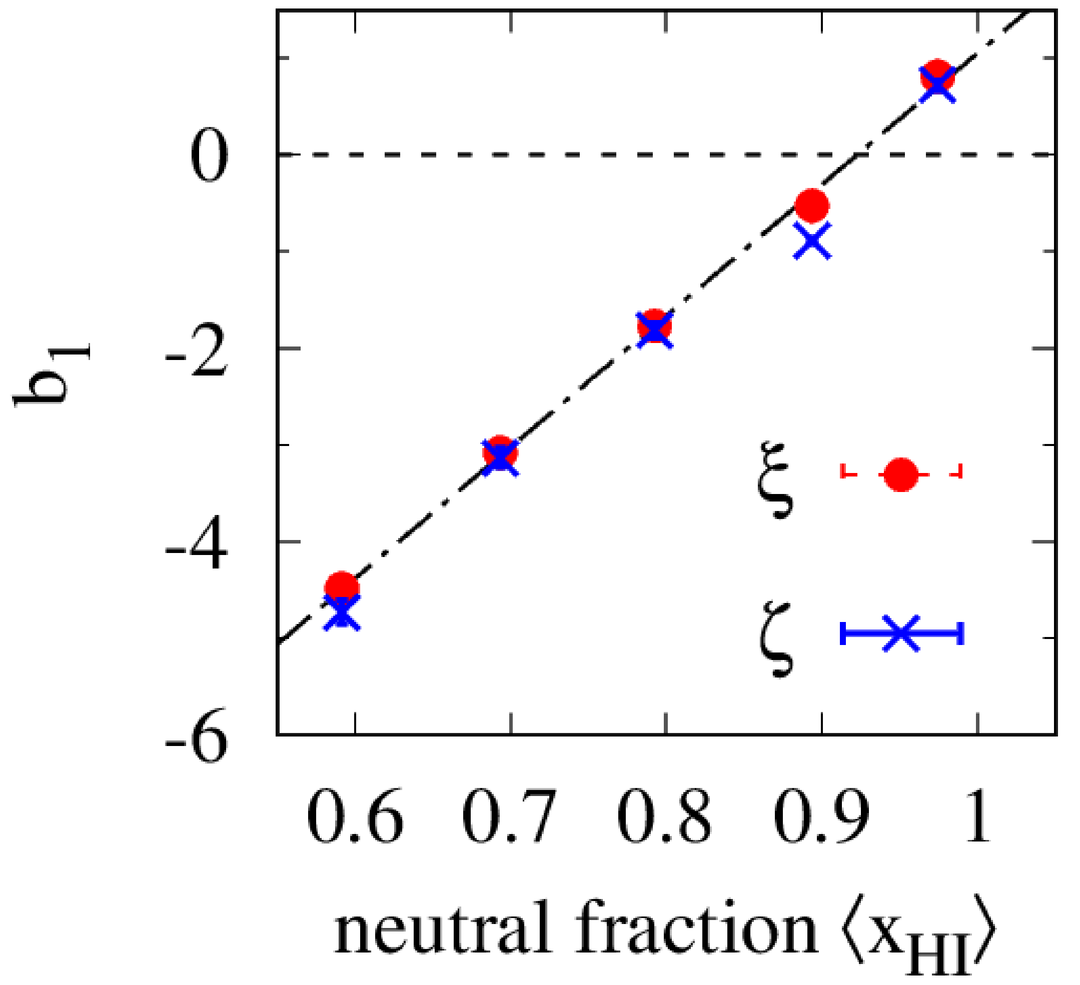
linear bias measurements

$\langle x_{HI} \rangle = 0.7$



~10% agreement between linear bias from 2pc and 3pc

Linear bias comparison with 2pc

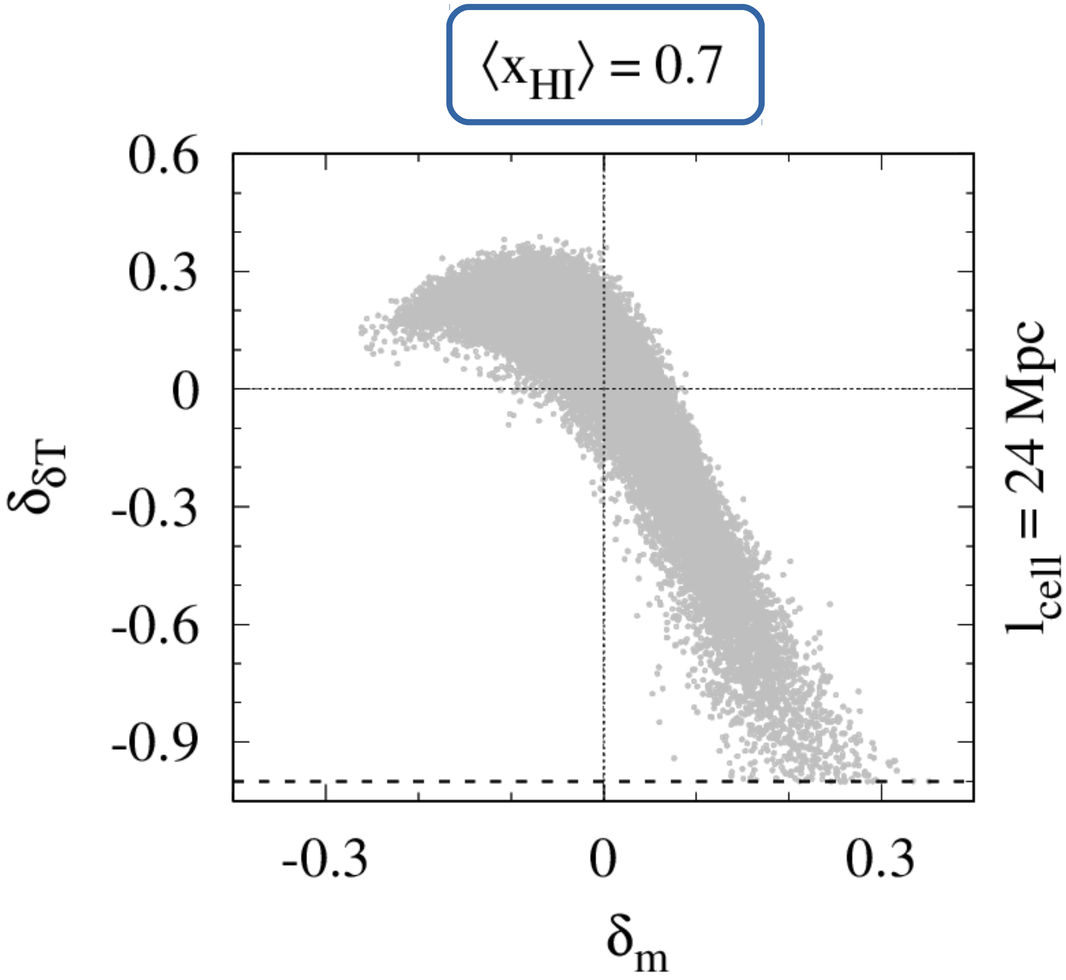


~10% agreement between linear bias from 2pc and 3pc

Bias model validation

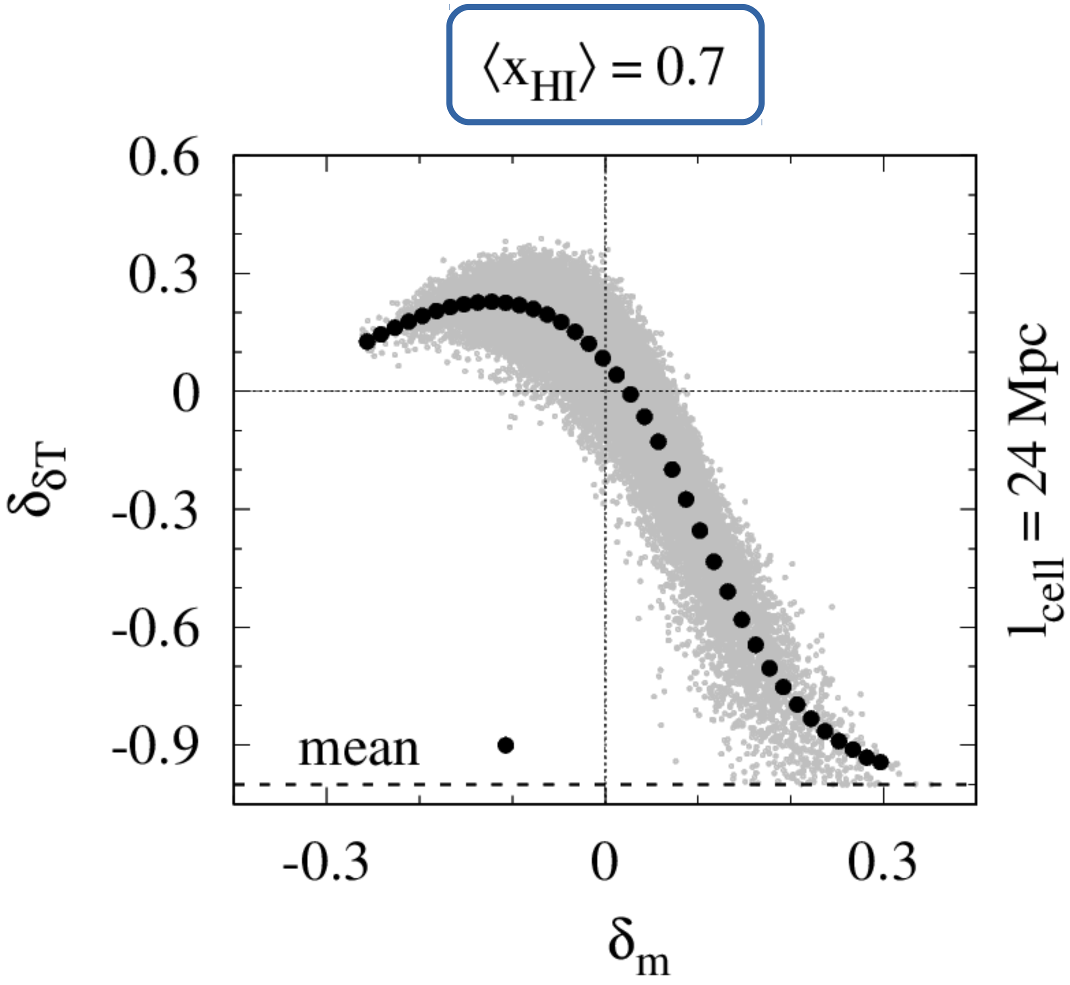
$$\delta_{\delta T} = F(\delta_m)?$$

Bias model validation



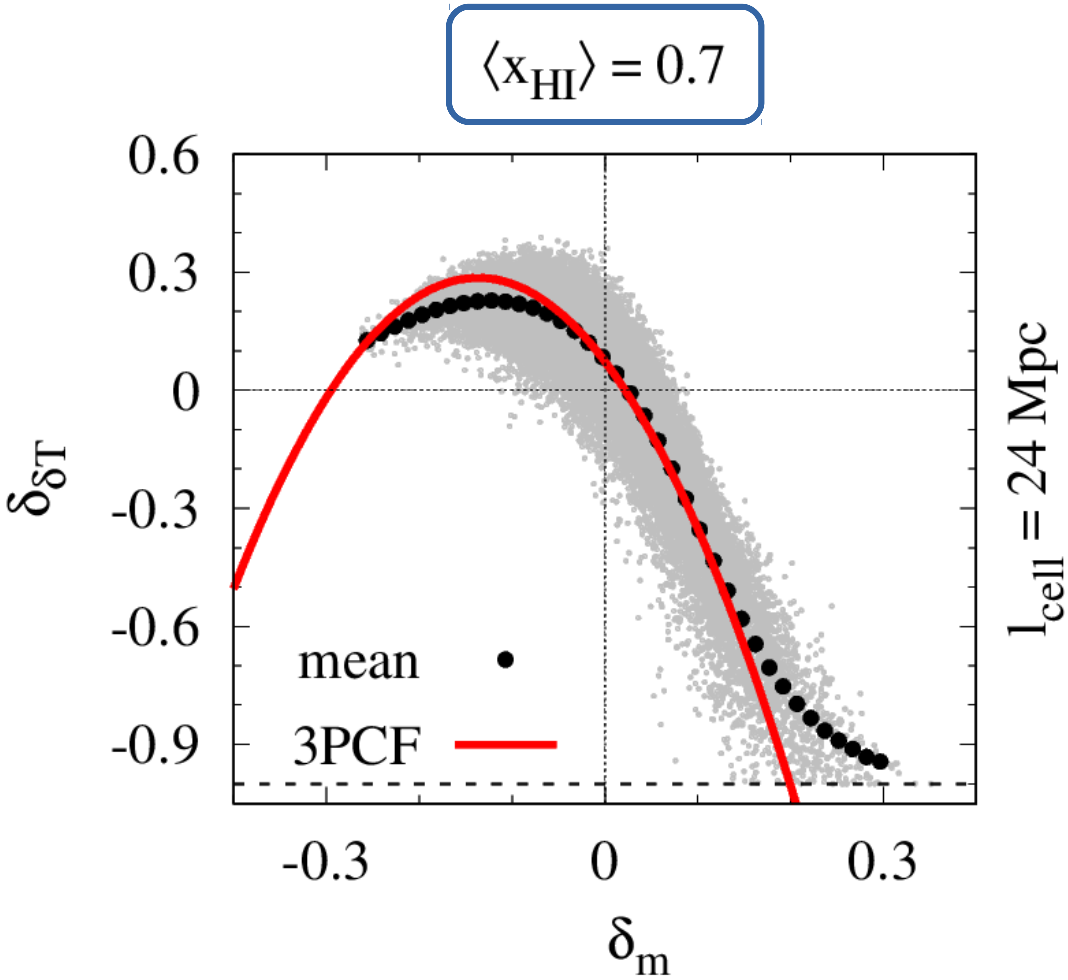
- **grey dots:** fluctuations in 24 Mpc cubical grid cells in one realization

Bias model validation



- **grey dots:** fluctuations in 24 Mpc cubical grid cells in one realization
- **black dots:** mean $\delta_{\delta T}$ over 200 realizations in δ_m bins

Bias model validation



- **grey dots:** fluctuations in 24 Mpc cubical grid cells in one realization
- **black dots:** mean $\delta_{\delta T}$ over 200 realizations in δ_m bins
- **red line:** quadratic bias model with b1 and b2 from 3pc measurements

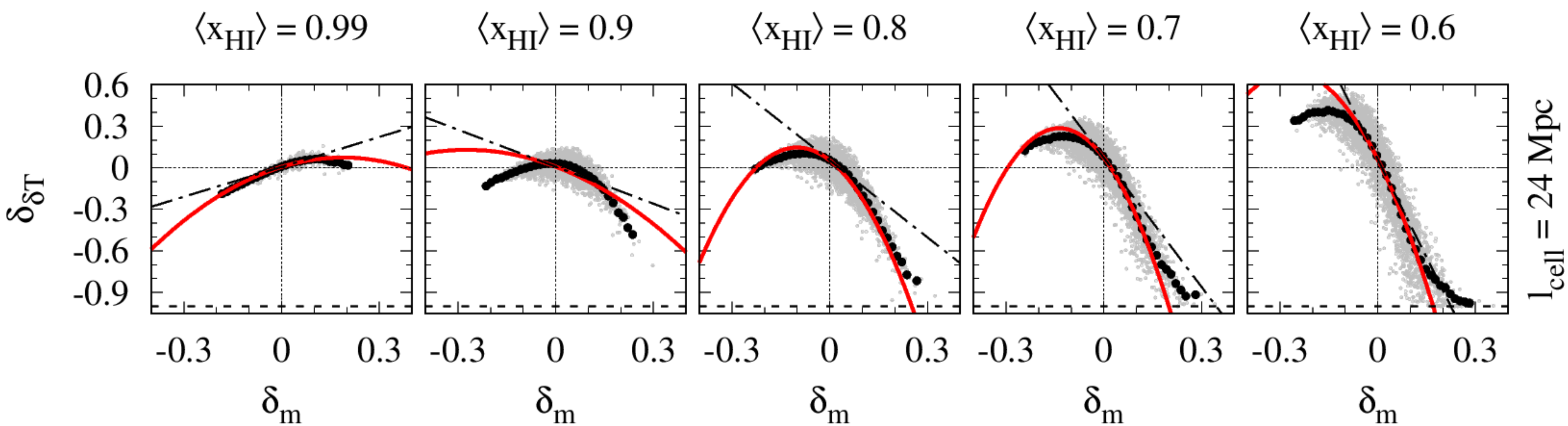
$$\delta_{\delta T} = b_0 + b_1 \delta_m + b_2 \delta_m^2$$

$$(\langle \delta_{\delta T} \rangle = 0 \rightarrow b_0 = -b_2 \langle \delta_m^2 \rangle)$$

Bias model validation

quadratic bias model with b1 and b2 from 21cm 3pc:

$$\delta_{\delta T} = b_1 \delta_m + b_2 (\delta_m^2 - \sigma_m^2)$$

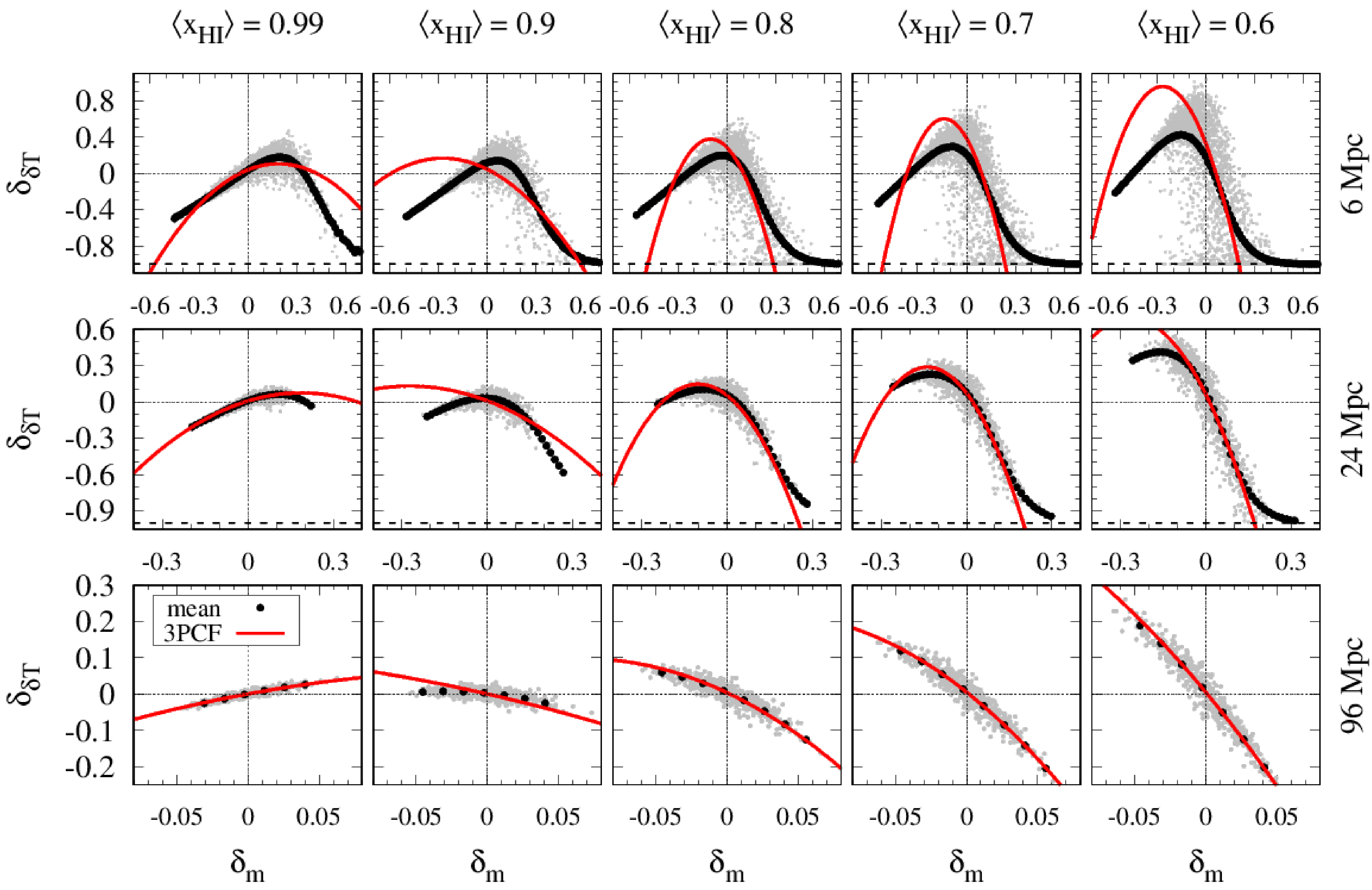


b1 = slope of $\delta_{\delta T}$ **at** $\delta_m = 0$

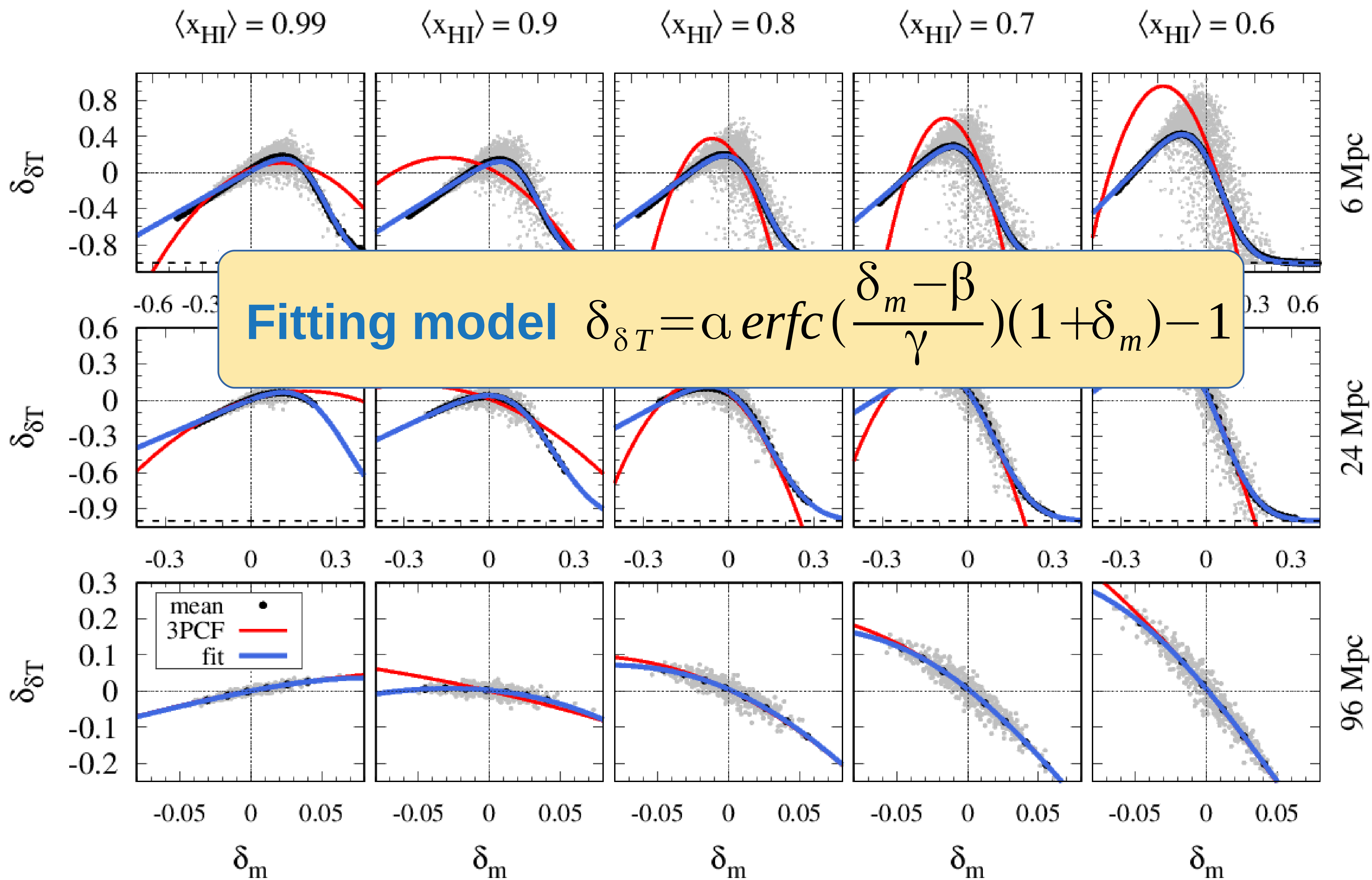
- positive at early times
- negative at late times

$$\delta T \propto \rho_{HI} \propto x_{HI} (1 + \delta_m)$$

Bias model validation



Bias model validation



Fitting model $$\delta_{\delta T} = \alpha\, erfc\left(\frac{\delta_m - \beta}{\gamma}\right)(1+\delta_m) - 1$$

conclusions

- Quadratic bias model explains shape of 21cm 2pc & 3pc at large scales and early times of reionization (neutral fraction > 60%, r> 20 Mpc)

- b1 from 2pc and 3pc consistent at 10% level

- b1 and b2 measurements might allow for extracting physical information on EoR from 21cm observations

- Combining 21cm 2pc & 3pc can break growth-bias degeneracy

$$\frac{\xi_{\delta T}(z)}{\xi_{\delta T}(z_0)} \propto \frac{D(z_0)^2}{D(z)^2} \frac{b_1(z_0)^2}{b_1(z)^2}$$

→ cosmological constraints from growth measurements at high z

arXiv:1802.02578

conclusions

- Quadratic bias model explains shape of 21cm 2pc & 3pc at large scales and early times of reionization (neutral fraction > 60%, r> 20 Mpc)

- b1 from 2pc and 3pc consistent at 10% level

- b1 and b2 measurements might allow for extracting physical information on EoR from 21cm observations

- Combining 21cm 2pc & 3pc can break growth-bias degeneracy

$$\frac{\xi_{\delta T}(z)}{\xi_{\delta T}(z_0)} \propto \frac{D(z_0)^2}{D(z)^2} \frac{b_1(z_0)^2}{b_1(z)^2}$$

→ cosmological constraints from growth measurements at high z

Thanks!

arXiv:1802.02578