Intergalactic Medium Properties from 21-cm Observations

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On behalf of the LOFAR EoR team

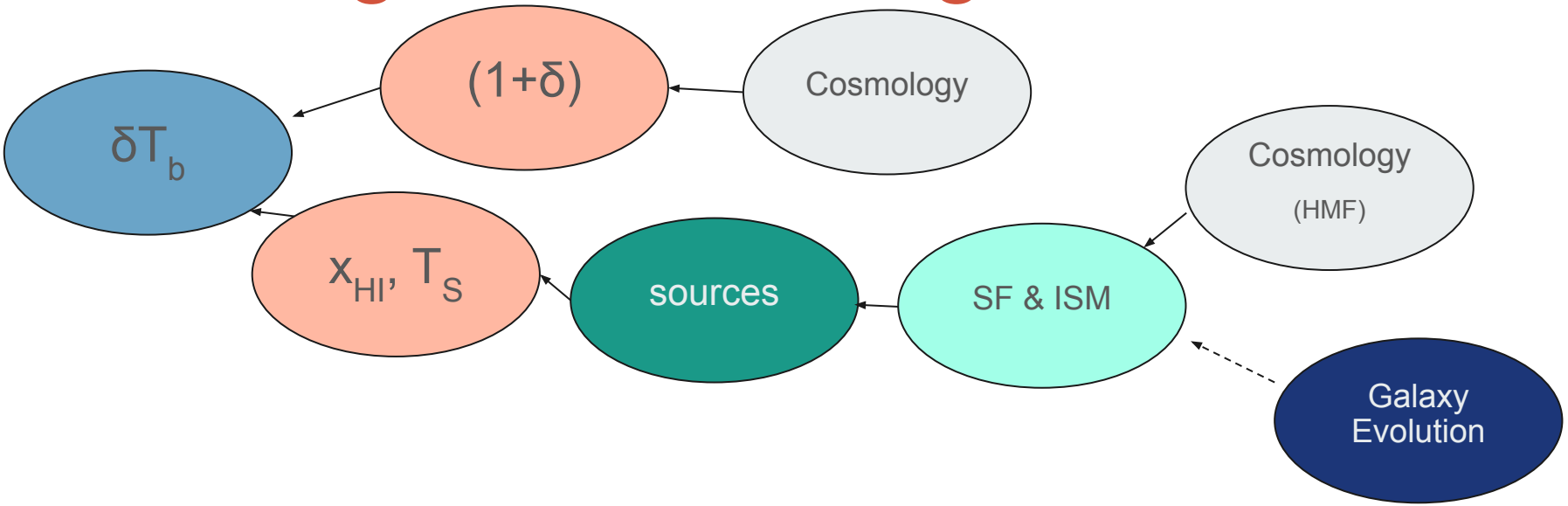
Thanks to

Raghu Ghara, Ivelin Georgiev, Sambit Giri, Benedetta Ciardi, Saleem Zaroubi

Content

- Redshifted 21-cm signal, connection to sources and IGM
- IGM framework for 21-cm power spectrum
- Physical interpretation of framework parameters
- Summary & conclusions

Modelling the 21-cm signal



- Model parameters: mainly SF & ISM recipes parameters.
- Different redshifts connected through assumed source model.
- Inference on parameters of SF & ISM recipes.

Inference on IGM parameters?

- Measured 21-cm signal depends on IGM properties, *not* on source properties.

- Philosophy used in Ghara et al. (2020) for single redshift (z=9.1); see also Mirocha et al. (2022).

- Two issues:
  - Choice of priors? (cf. HERA collaboration 2023)
  - How to handle multi-redshift data?

Inference on IGM parameters?

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  - **How to handle multi-redshift data?**

Parametrization of Δ_{21} Evolution

- Ghara et al. (2024): 8 parameter universal model for $T_S \gg T_{CMB}$ case.

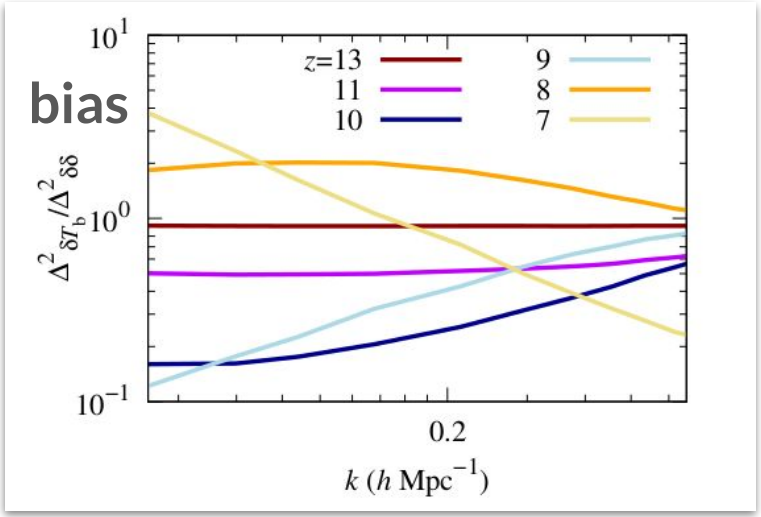
- Derived from set of 24 GRIZZLY simulations.

- Based on the 21-cm scale-dependent bias $b_{21}^2 = \frac{\Delta_{21}^2(k)}{\Delta_{\rm m}^2(k)}$

21-cm Bias

- The 21-cm bias follows relatively simple shapes.
- Two regimes in x_{HI}:
  - $> x_{HI,min}$ (single rising power law)
  - $< x_{HI,min}$ (double falling power law)
- Allows for three parameter fit:

$$\Delta^2_{\delta T_b} = \begin{cases} \Delta^2_{\delta\delta} A \dfrac{\left(\frac{k}{0.05}\right)^\gamma}{1+\left(\frac{k}{0.3}\right)^{1.5}}, & \text{if } \bar{x}_{HI} \lesssim \bar{x}_{HI,min}. \\ \Delta^2_{\delta\delta} A \left(\dfrac{k}{0.05}\right)^\gamma, & \text{otherwise.} \end{cases}$$



Ghara et al. (2024)

21-cm Bias Evolution

Ghara et al. (2024)

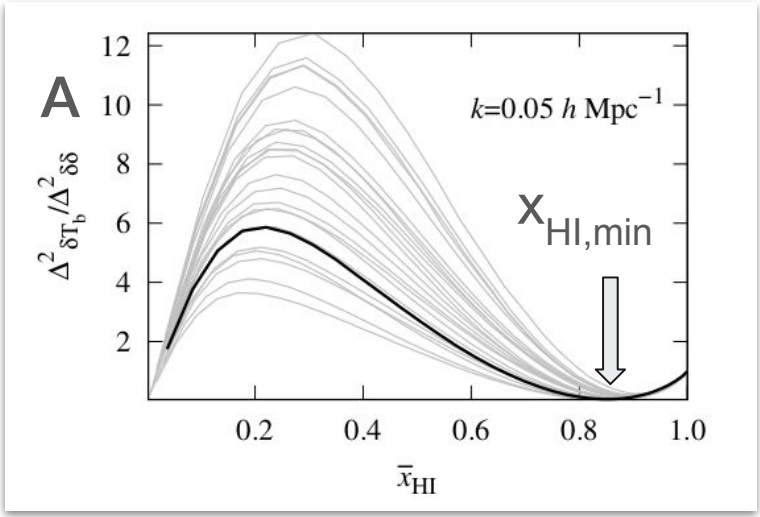
- Evolution of A and γ follow regular shapes as function of x_{HI}

- Also need a parametrized reionization history $x_{HI}(z)$:

$$\bar{x}_{\rm HI}(z_0, \alpha_0, \Delta z, z) = \frac{1}{2}\left[1 - \tanh\left\{\frac{y(z_0) - y(z)}{\Delta y}\right\}\right],$$

where $y(z) = (1+z)^{\alpha_0}$,

and $\Delta y = \alpha_0 (1+z)^{\alpha_0 - 1} \times \Delta z.$



Evolution of A and γ: 5 parameters

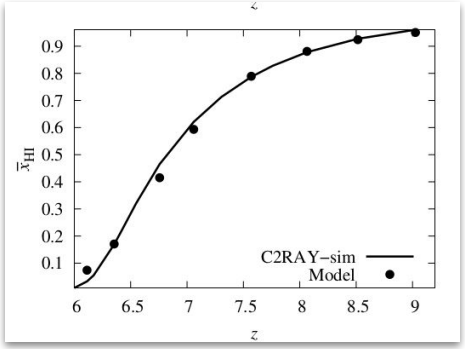
Reionization history: 3 parameters

Framework parameters

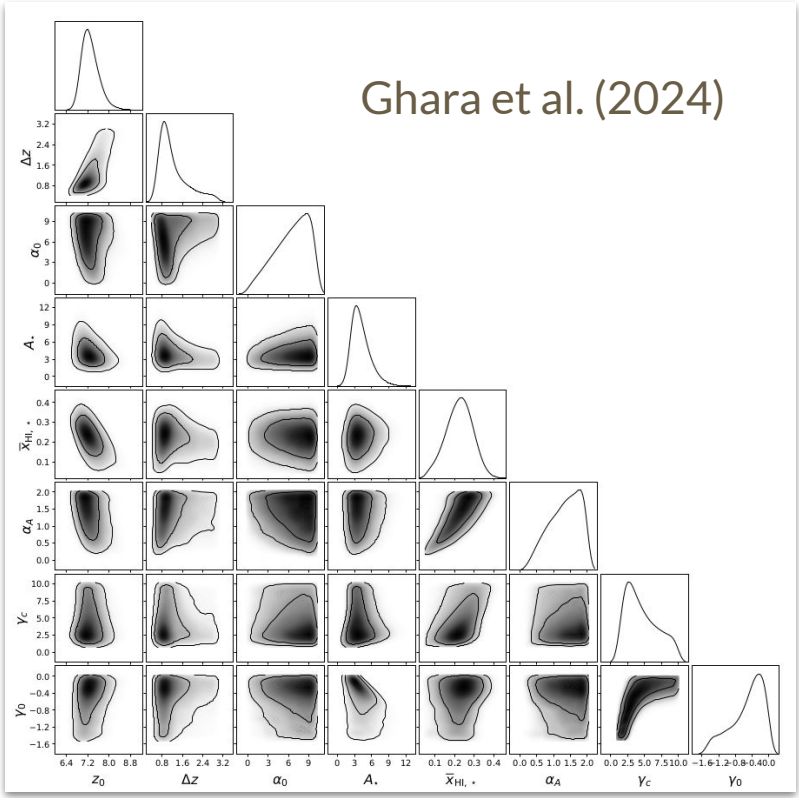
Parameters		Description
z_0	reionization history	Redshift corresponding to $\bar{x}_{\rm HI} = 0.5$.
Δz		Redshift range of reionization in a tanh model.
α_0		Asymmetry parameter around $\bar{x}_{\rm HI} = 0.5$ in the redshift evolution of $\bar{x}_{\rm HI}$.
$A_\star$	21-cm bias	Maximum value of the bias at $k = 0.05\,h\,{\rm Mpc}^{-1}$.
$\bar{x}_{\rm HI,\star}$		Mean neutral fraction at the redshift when the bias at $k = 0.05\,h\,{\rm Mpc}^{-1}$ gets the maxima.
α_A		Power-law index on $\bar{x}_{\rm HI}$ which accounts for the change of bias as a function of $\bar{x}_{\rm HI}$ at $k = 0.05\,h\,{\rm Mpc}^{-1}$.
γ_c		Account for the change in scale-dependence of bias with $\bar{x}_{\rm HI}$.
γ_0		Account for the all-scale feature of bias in addition to small-scale feature $1/[1 + (k/0.3)^{1.5}]$ at stages with $\bar{x}_{\rm HI} \to 0$.

Testing the Bias Evolution Model

- Application to 8 outputs from a C^2-Ray simulation shows how the framework could be used.
- The best fit parameters reproduce the reionization history and power spectra from the simulation.



Reionization history



Ghara et al. (2024)

What's next?

- Include T_s fluctuations.
- Explore other fits (for reionization history or 21-cm bias)
- What do these parameters physically mean?

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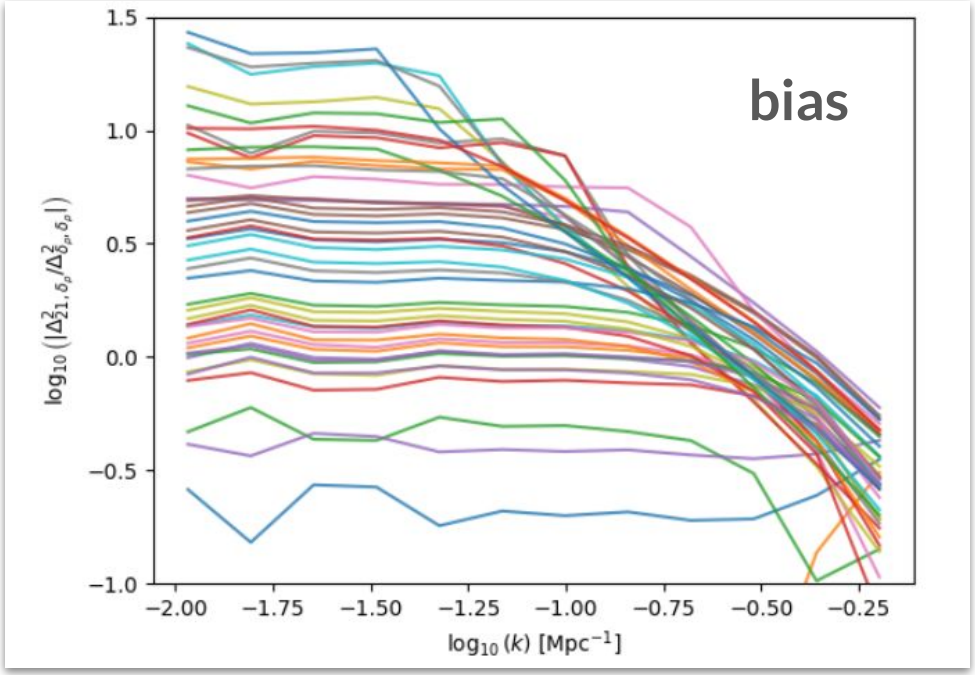
Understanding the 21-cm Bias

- For $x_{HI} < x_{HI,min}$ the 21-cm bias has characteristic shape:
  - ~linear large scale bias (b_0)
  - power-law fall-off beyond $k=k_{trans}$.
  - transition can be smooth or sharp.



Karin Kjellgren (2023)

Theoretical understanding

- Furlanetto et al. (2004) developed analytical model for 21-cm power spectrum.
- Its 21-cm bias shapes consistent with simulation results for low k and high k, bump at intermediate k **not** seen in simulations.
- What about Paranjape & Choudhury (2014)?

Furlanetto et al. (2004)

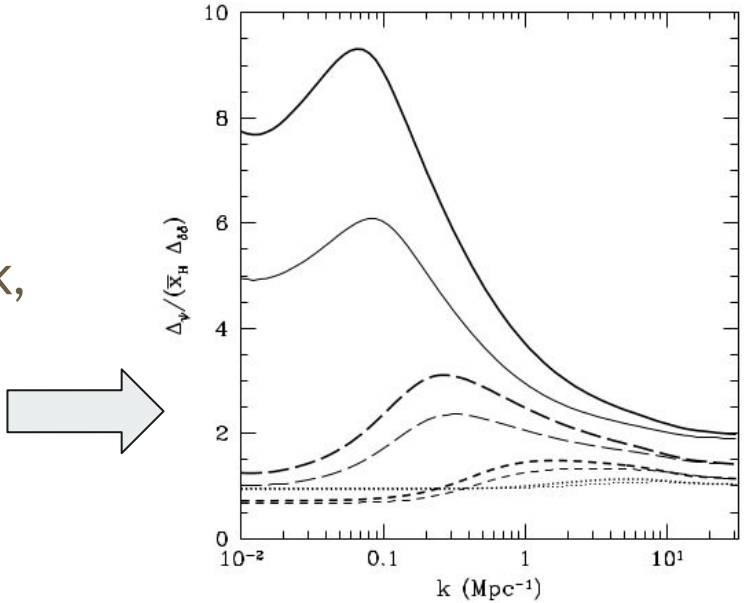
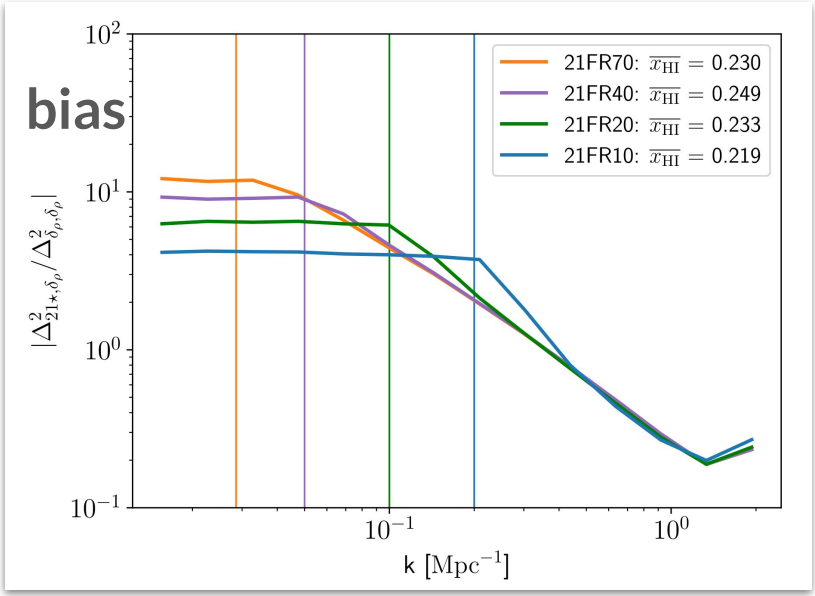


FIG. 9.—Redshift evolution of $\Delta_\psi/(\bar{x}_H\Delta_{\delta\delta})$ in the $\zeta = 12$ (*thin lines*) and $\zeta = 40$ (*thick lines*) models. The curves are for $\bar{x}_H = 0.96$ (*dotted*), $\bar{x}_H = 0.8$ (*short-dashed*), $\bar{x}_H = 0.5$ (*long-dashed*), and $\bar{x}_H = 0.26$ (*solid*). The redshifts in the two models differ. [*See the electronic edition of the Journal for a color version of this figure.*]

Transition scale ⇿ Mean free path

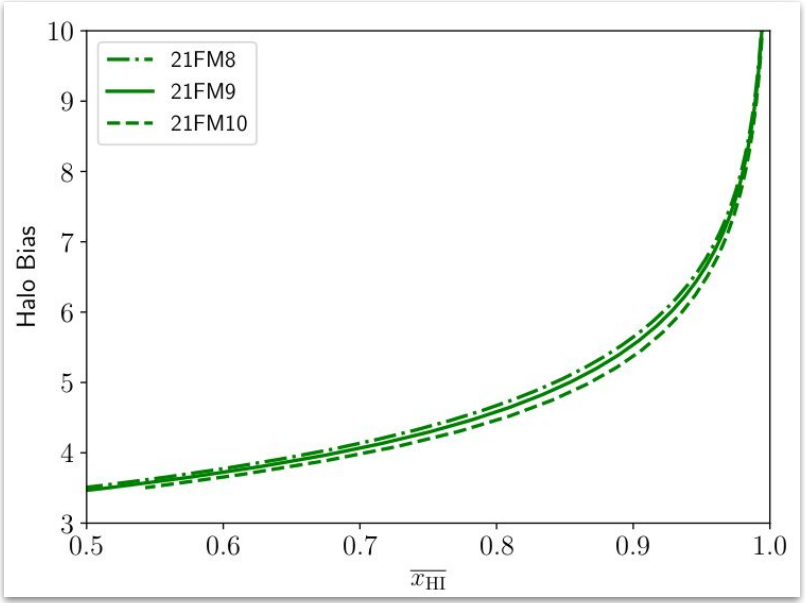
- 21cmFAST models with hard barrier on extent of source influence (R_{max}):
  - $k_{trans} \approx 2/R_{max}$ sharp (late)
  - $k_{trans} > 2/R_{max}$ smooth (early)
- Suggests: k_{trans} set by effective λ_{mfp} of ionizing photons, initially set by size of ionized bubbles, later by value of R_{max}.



Georgiev, GM et al. (2022)

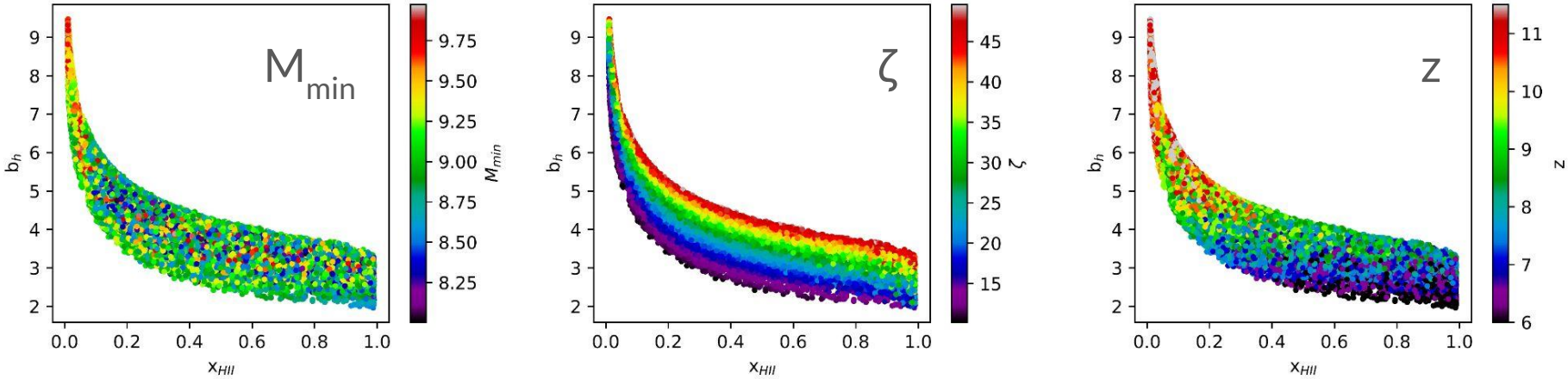
Role of source bias

- Previous work (Furlanetto et al. 2004; McQuinn & D'Aloisio 2018) suggests important role for source (halo) bias.
- Three 21cmFAST models with different minimum halo mass (M_{min}) show nearly identical b_h - x_{HI} relations.



Georgiev, GM et al. (2022)

The b_h - x_{HI} relation



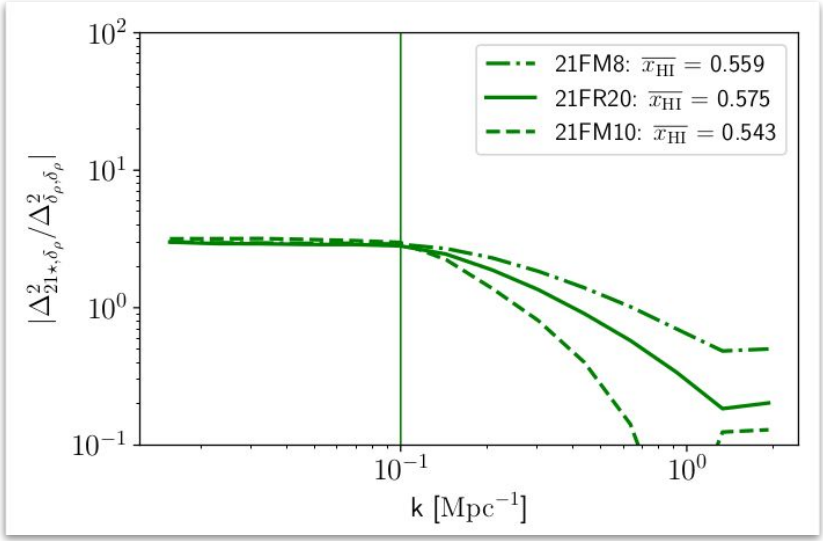
Larger sample of 21cmFAST models shows that b_h - x_{HI} relation

- does not depend on M_{min}
- *does* depend on source efficiency ζ.

Georgiev et al., in prep

Connection b_h to b_0

- Three 21cmFAST models which only differ in minimum halo mass (M_{min}) show the same b_0 at the same b_h and x_{HI}.
- Suggests a b_0 - b_h relation…



Georgiev, GM et al. (2022)

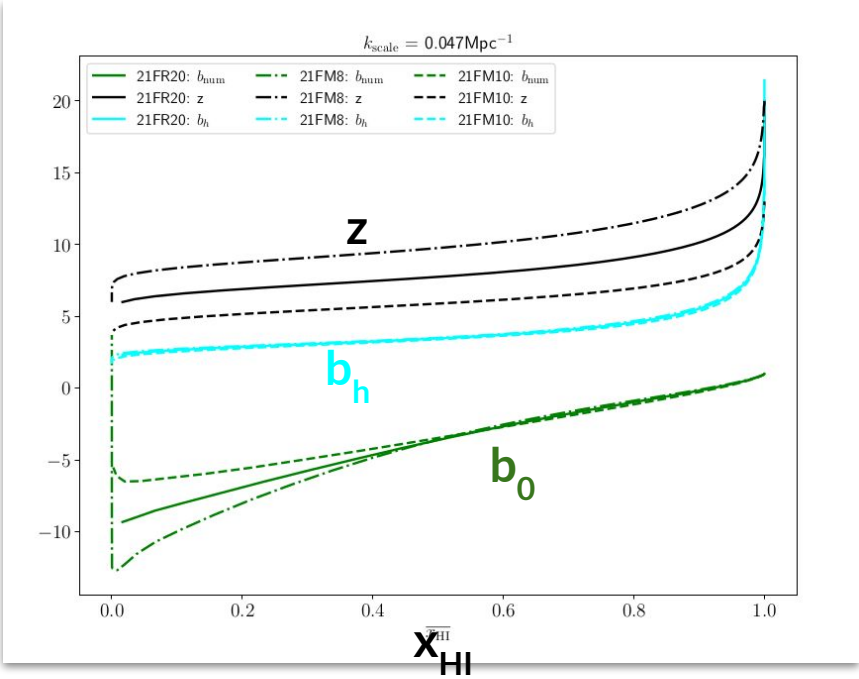
But it's not that simple…

The same three models show that for $x_{HI} \lesssim 0.5$:

- b_h - x_{HI} relation persists (----)
- b_0 values start to diverge (----)

Probably connected to level of overlap between ionized bubbles:

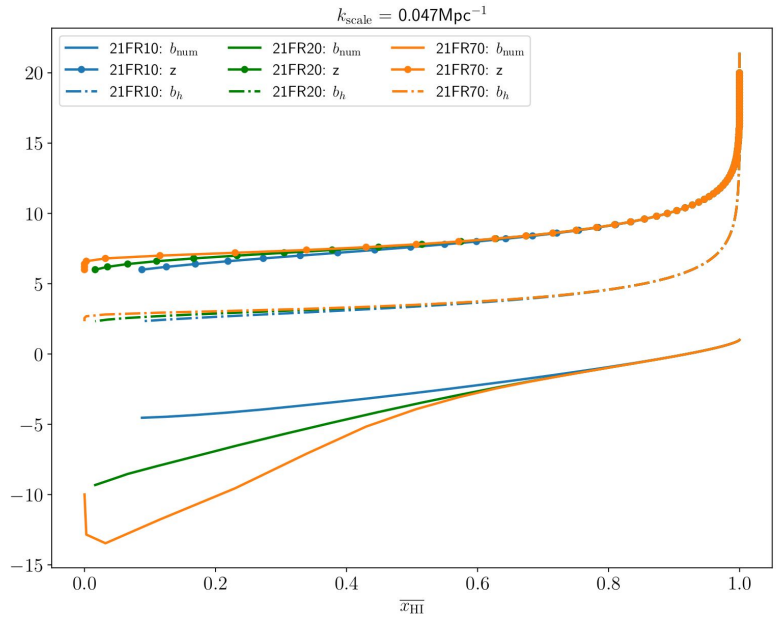
- More overlap increases amplitude of b_0.



Mean free path and b_0

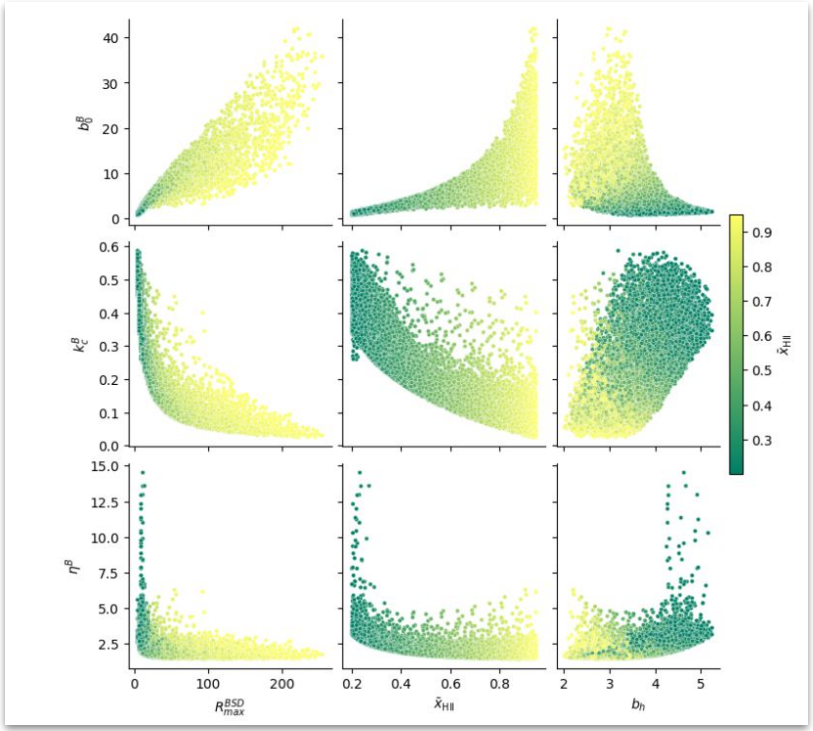
Three models which only differ in R_{max} show that

- For $x_{HI} > 0.7$ b_0 is the same in all models.
- For $x_{HI} < 0.7$ a larger mean free path boosts b_0 amplitude.
- Supports the correlation between overlap and b_0.



Work in progress

- Building a large sample of reionization models, exploring multidimensional correlations with key quantities.



Summary

- Parameter inference can be done on source parameters or IGM parameters. Both are useful.
- Current methodology for IGM parameters cannot really use multi-redshift data.
- The 21-cm bias appears to yield a parameterizable evolution which can be used for IGM inference in the future.
- The shape of the 21-cm bias curves connect to key physics (λ_{mfp}, b_h, x_{HI}) but needs further investigation.