Framework for the Physical Interpretation of HI Power Spectrum Measurement with CHIME

Albin Joseph
CHIME Collaboration

Framework for physical interpretation

$$P^{(obs)}_{21cm}(k; \overrightarrow{\Theta})$$

CHIME Data

Framework for physical interpretation

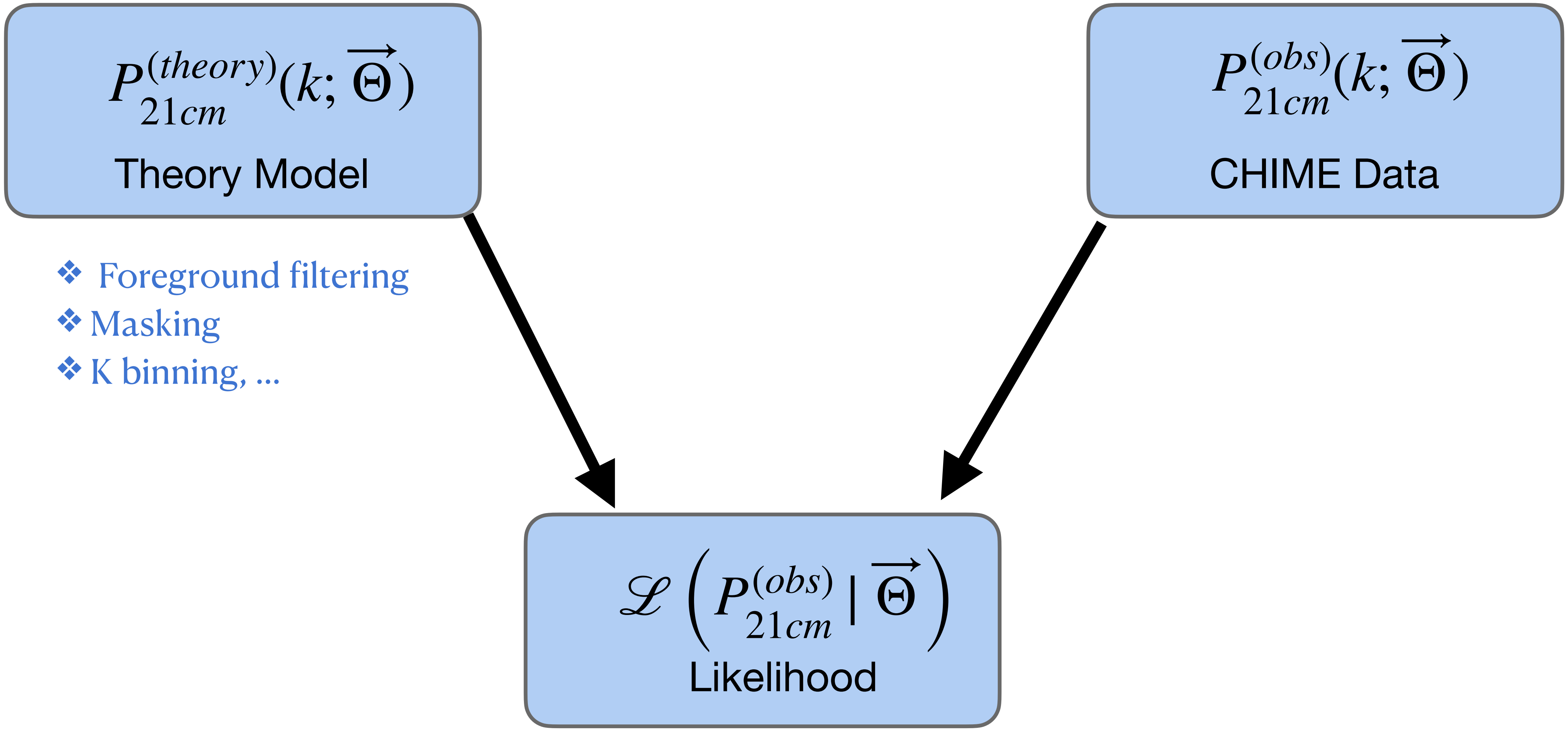
$$P_{21cm}^{(theory)}(k;\vec{\Theta})$$

Theory Model

$$P_{21cm}^{(obs)}(k;\vec{\Theta})$$

CHIME Data

Framework for physical interpretation



Framework for physical interpretation

$$P_{21cm}^{(theory)}(k; \vec{\Theta})$$

Theory Model

- Foreground filtering
- Masking
- K binning, ...

Template Method

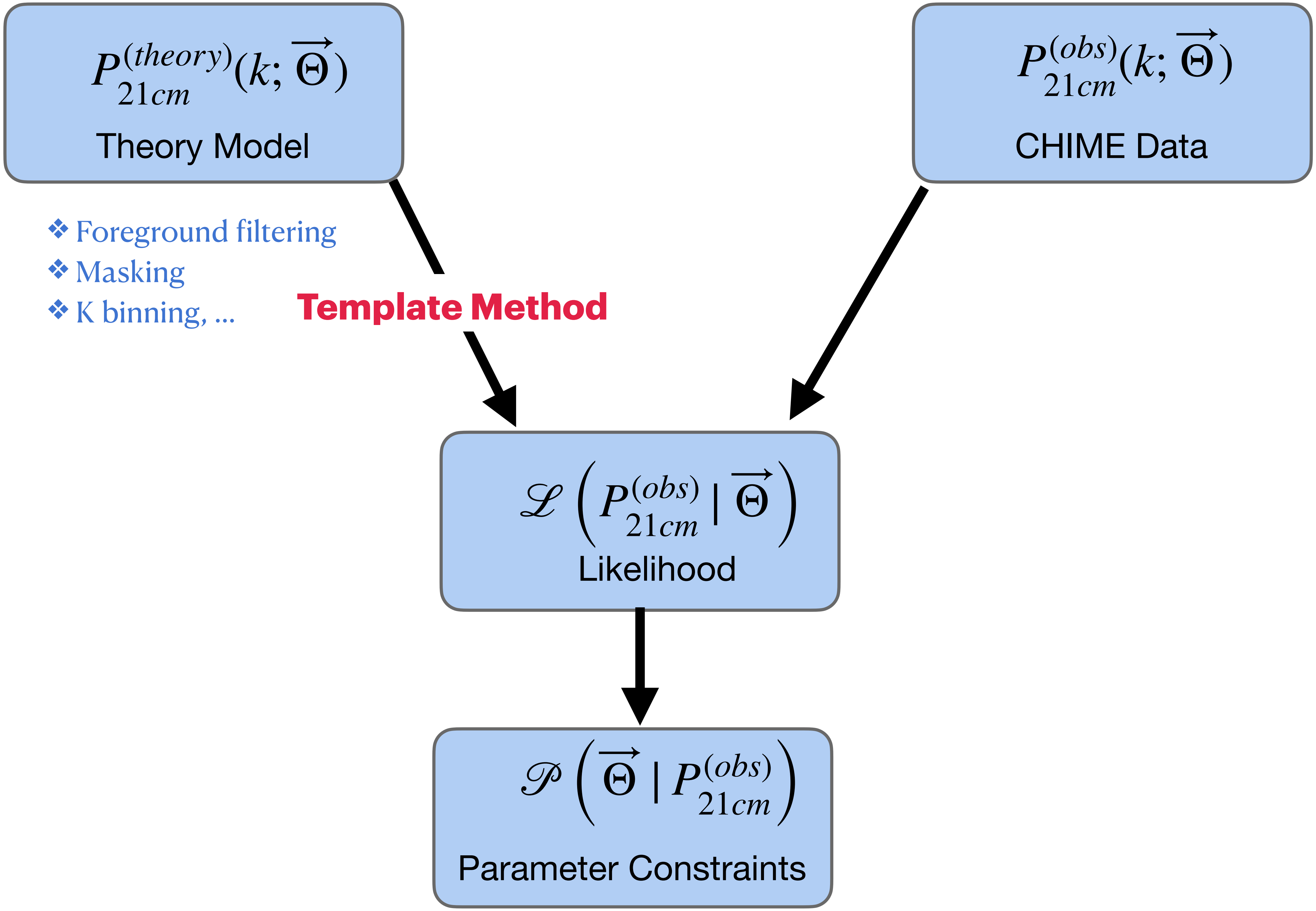
$$P_{21cm}^{(obs)}(k; \vec{\Theta})$$

CHIME Data

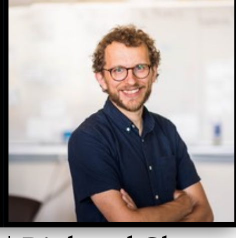
$$\mathscr{L}\left(P_{21cm}^{(obs)} \mid \vec{\Theta}\right)$$

Likelihood

Framework for physical interpretation



Template method

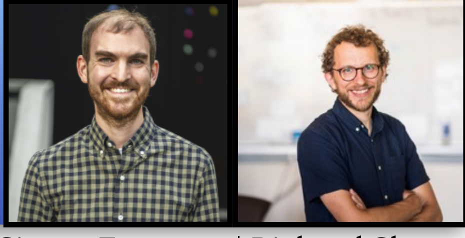


Simon Foreman | Richard Shaw

1. *Choose* $P_{\text{signal}}^{(\text{theory})}$ model with simple (linear, quadratic) dependence on model parameters, e.g.

$$P_{\text{signal}}^{(\text{theory})}(k, \mu, z; \vec{\Theta}) = \sum_i \theta_i \underline{P_i^{(\text{theory})}(k, \mu, z)}$$

theory templates

Template method



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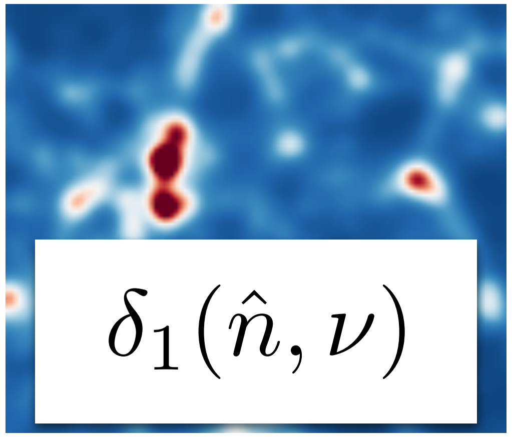
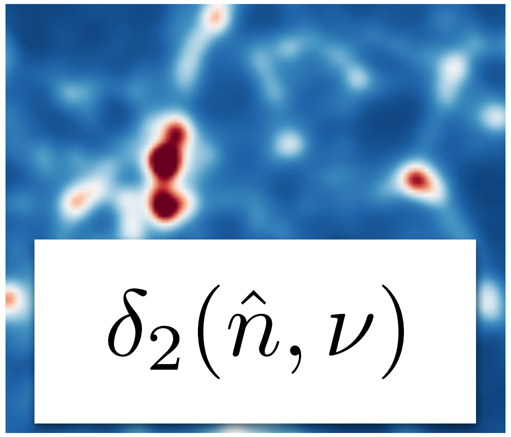
theory templates

2. Simulate sky maps from each theory template





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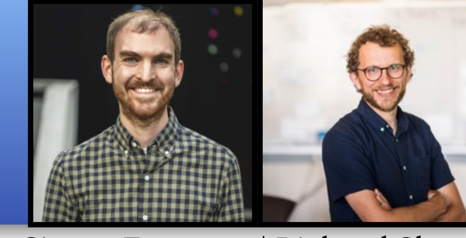
Template method



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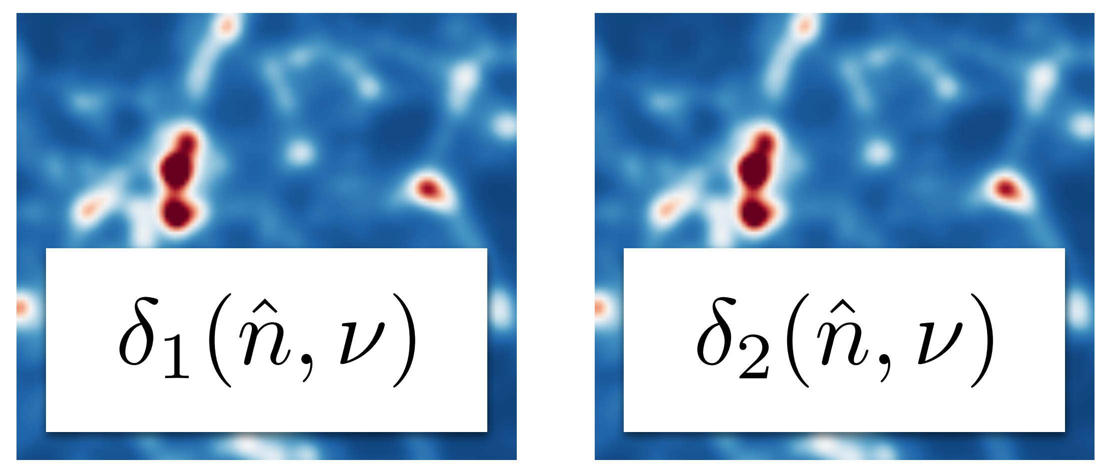
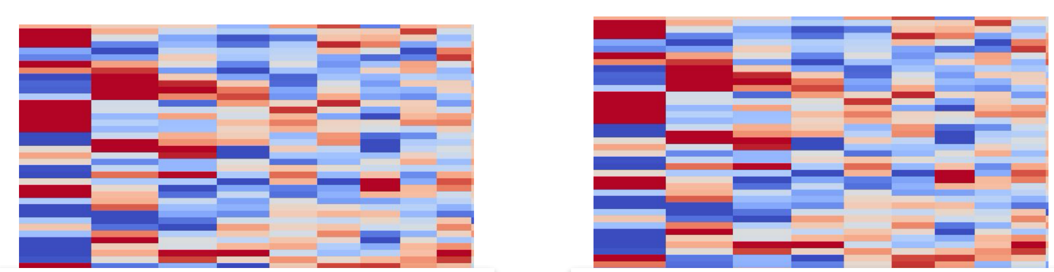


$\delta_1(\hat{n},\nu)$ $\delta_2(\hat{n},\nu)$ …

3. Propagate maps through sim+analysis pipelines, to obtain ***obs. templates***



$P_1^{(\mathrm{obs})}(k,\mu)$ $P_2^{(\mathrm{obs})}(k,\mu)$ …

NB: Pipeline must be linear!

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Template method

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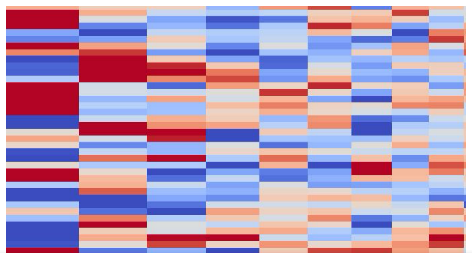
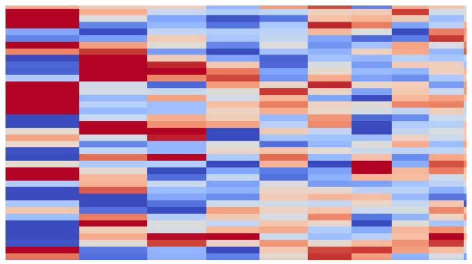


$P_1^{(\mathrm{obs})}(k,\mu)$



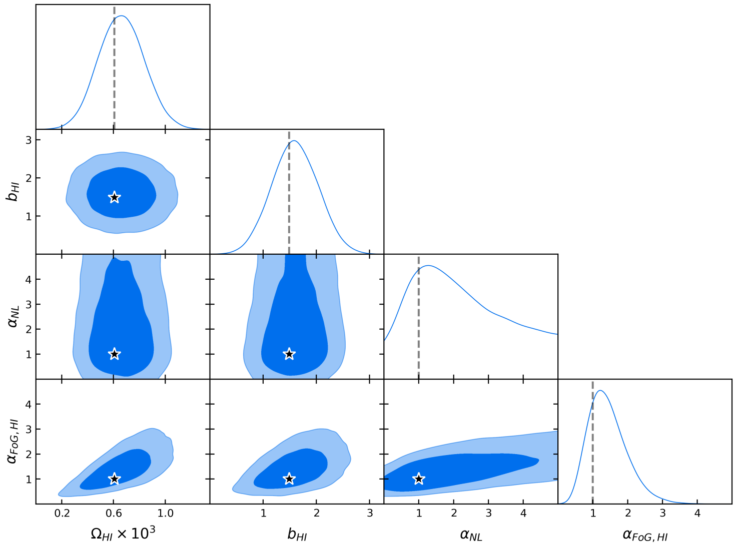
$P_2^{(\mathrm{obs})}(k,\mu)$

...

4. Observed power spectrum is linear combination of obs. templates

$$P^{(\mathrm{obs})}_{\text{signal}}(k,\mu;\vec{\Theta}) = \sum_i \theta_i P_i^{(\mathrm{obs})}(k,\mu)$$

5. Sample likelihood to obtain posterior for $\vec{\Theta}$



$P_{21cm}^{(theory)}$ Model

$$P_{21cm}^{(theory)}(k,\mu,z) = T_b(z)^2 \left[b_{HI}(z) + f\mu^2\right]^2 D_{FoG}(k\mu,z)^2$$

$$\times \left[\alpha_{NL} P_m^{(nonlin)}(k,z) + (1-\alpha_{NL}) P_m^{(lin)}(k,z)\right]$$

Matter power spectrum; α_{NL} interpolates between linear and nonlinear models (at fixed cosmology)

b_{HI} = linear HI bias

$f\mu^2$ = redshift-space distortions on large scales ("kaiser")

D_{FoG} = RSD on small scales ("Finger of God") $\longrightarrow \dfrac{1}{1+\frac{1}{2}k^2\mu^2\sigma_{FoG}^2}$

T_b = mean 21cm brightness temperature, $\propto \Omega_{HI}$

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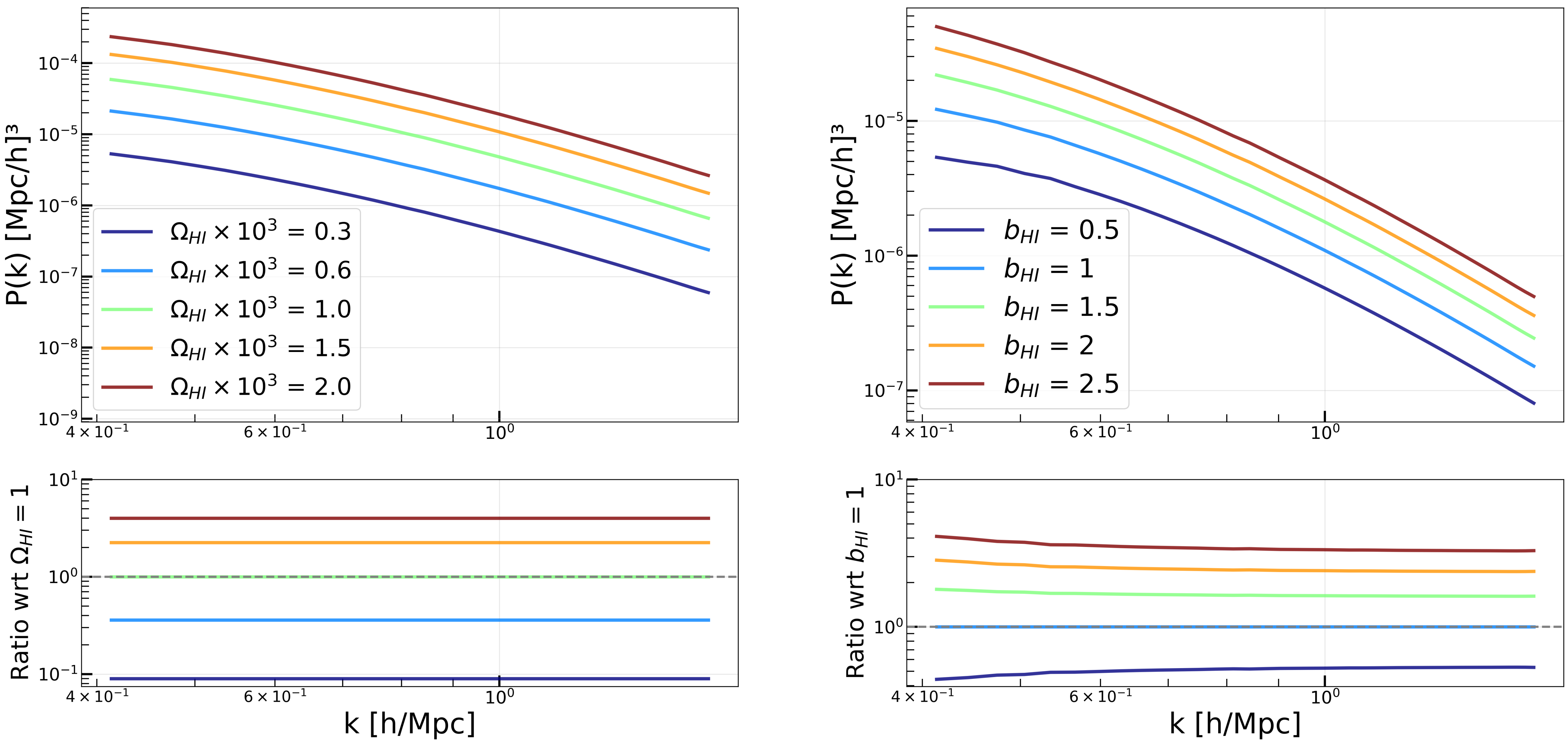
Parameter sensitivity: Ω_{HI} and b_{HI}



Increases the overall amplitude

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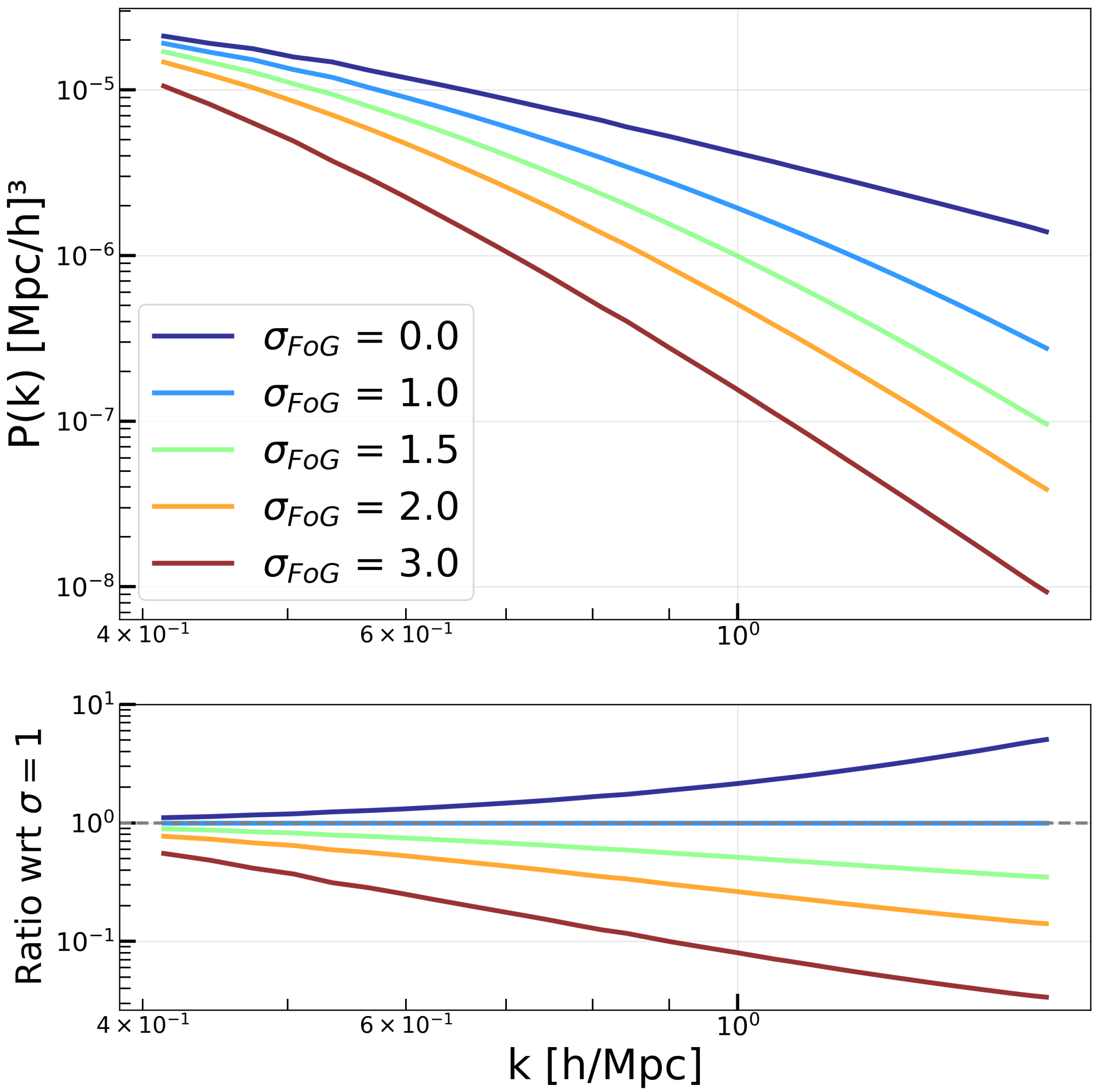
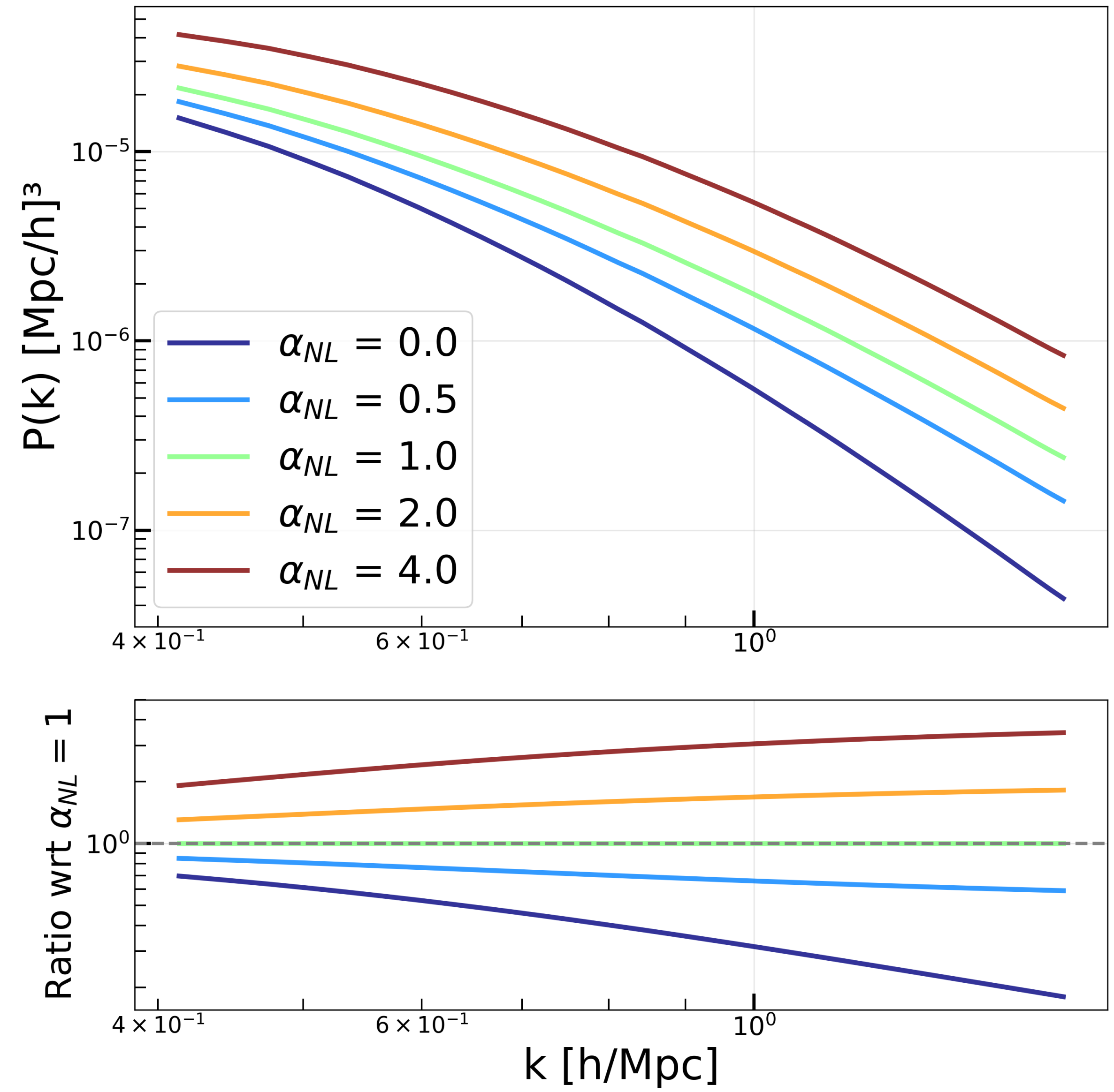
Parameter sensitivity: σ_{FoG} and α_{NL}





Scale dependence

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Parameter degeneracies

$$P_{21cm}^{(theory)} \propto \Omega_{HI}^2 [b_{HI} + f\mu^2]^2$$

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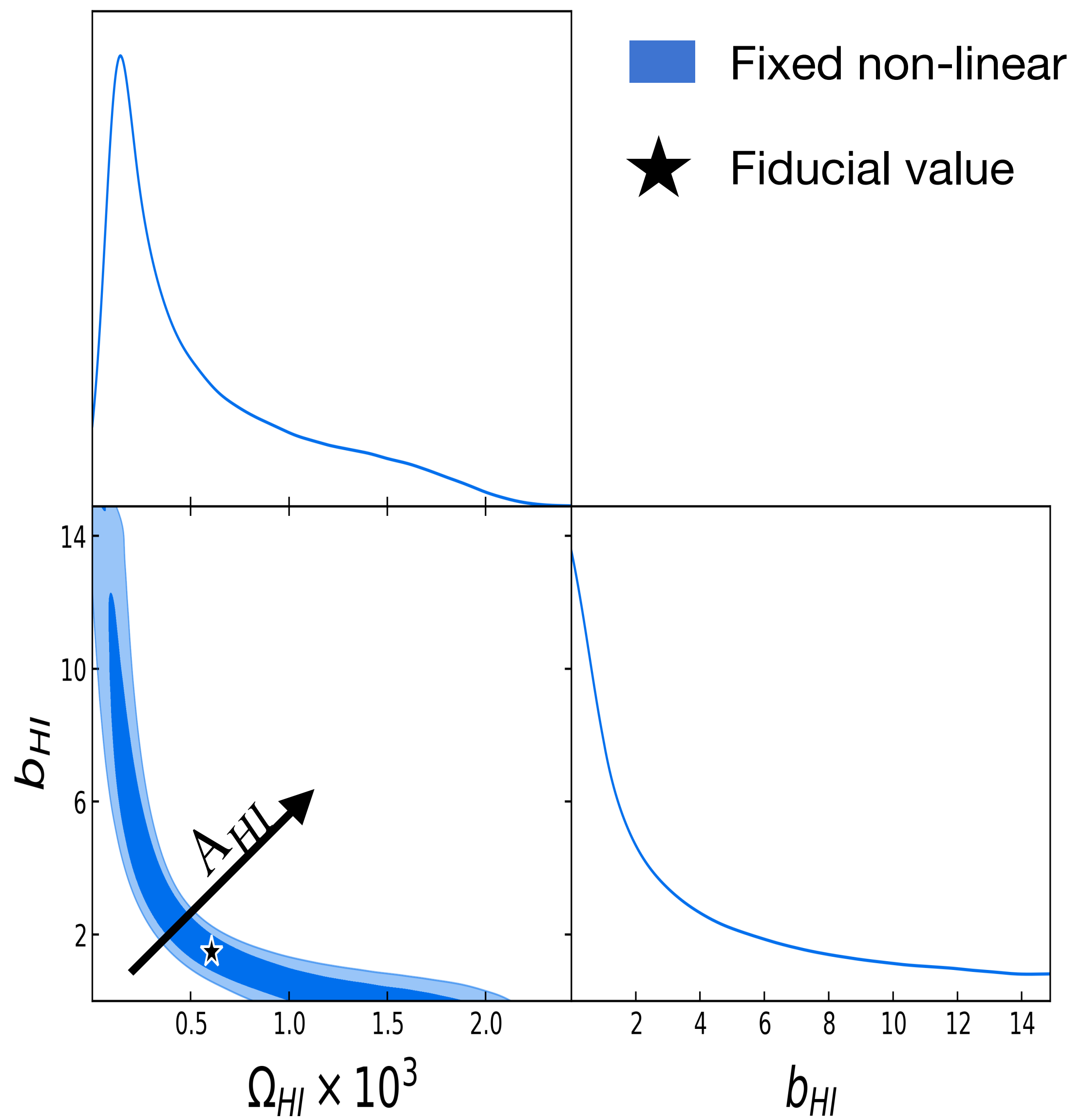

*"Signal-only **simulations** with realistic error bars"*

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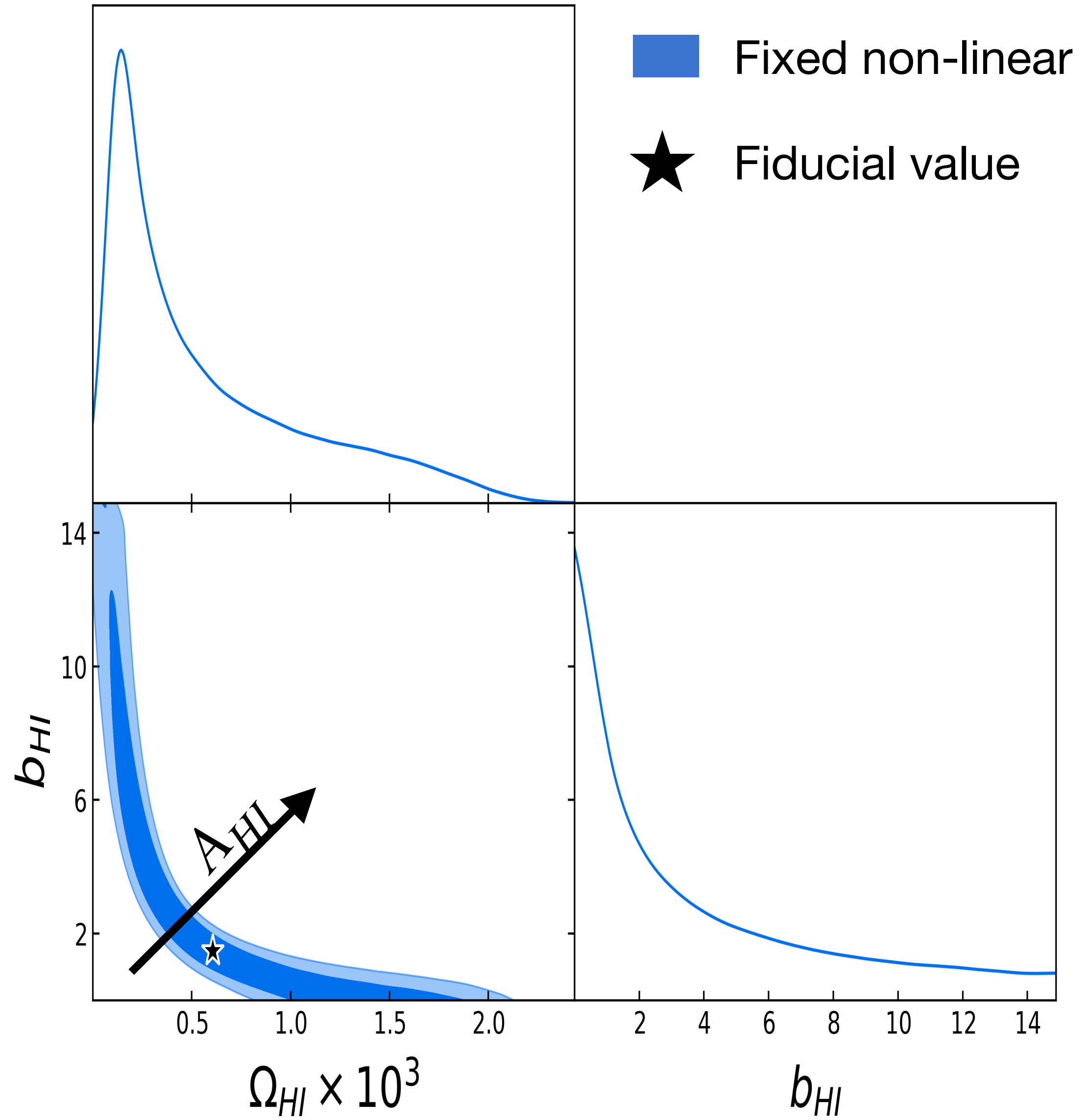
Parameter degeneracies

$$P_{21cm}^{(theory)} \propto \Omega_{HI}^2[b_{HI} + f\mu^2]^2$$

Degeneracy

Constrain $A_{HI} = 10^6\Omega_{HI}^2\left(b_{HI}^2 + 2b_{HI}\langle f\mu^2\rangle + \langle f^2\mu^4\rangle\right)$



*"Signal-only **simulations** with realistic error bars"*

Parameter degeneracies

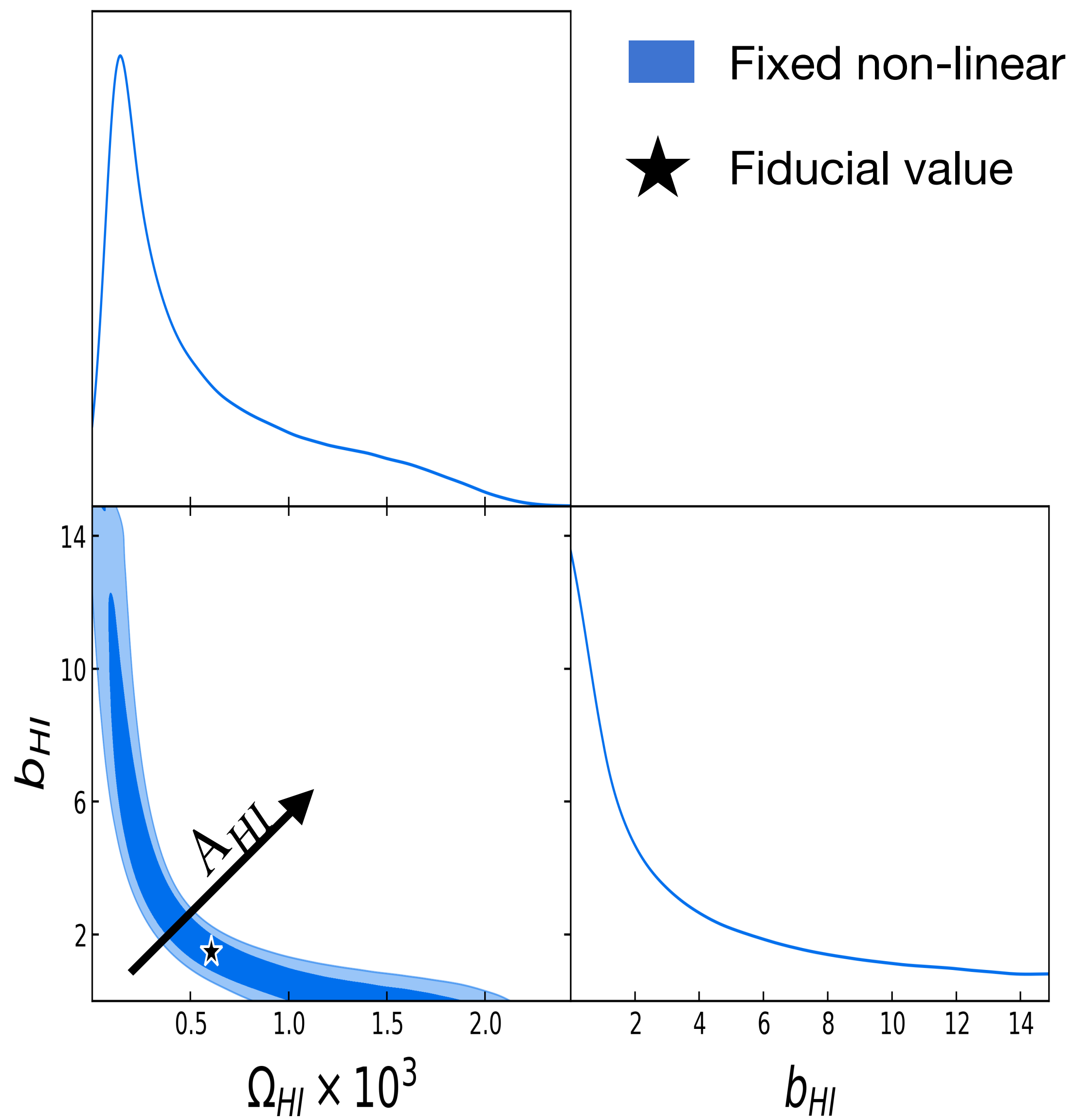
$$P^{(theory)}_{21cm} \propto \Omega^2_{HI}[b_{HI} + f\mu^2]^2$$

Degeneracy

Constrain $A_{HI} = 10^6\Omega^2_{HI}\left(b^2_{HI} + 2b_{HI}\langle f\mu^2\rangle + \langle f^2\mu^4\rangle\right)$

<u>Nuisance parameters</u>

α_{FoG} , α_{NL} where $\alpha_{FoG} = \dfrac{\sigma_{FoG}(z)}{\sigma^{fid}_{FoG}(z_{eff})}$



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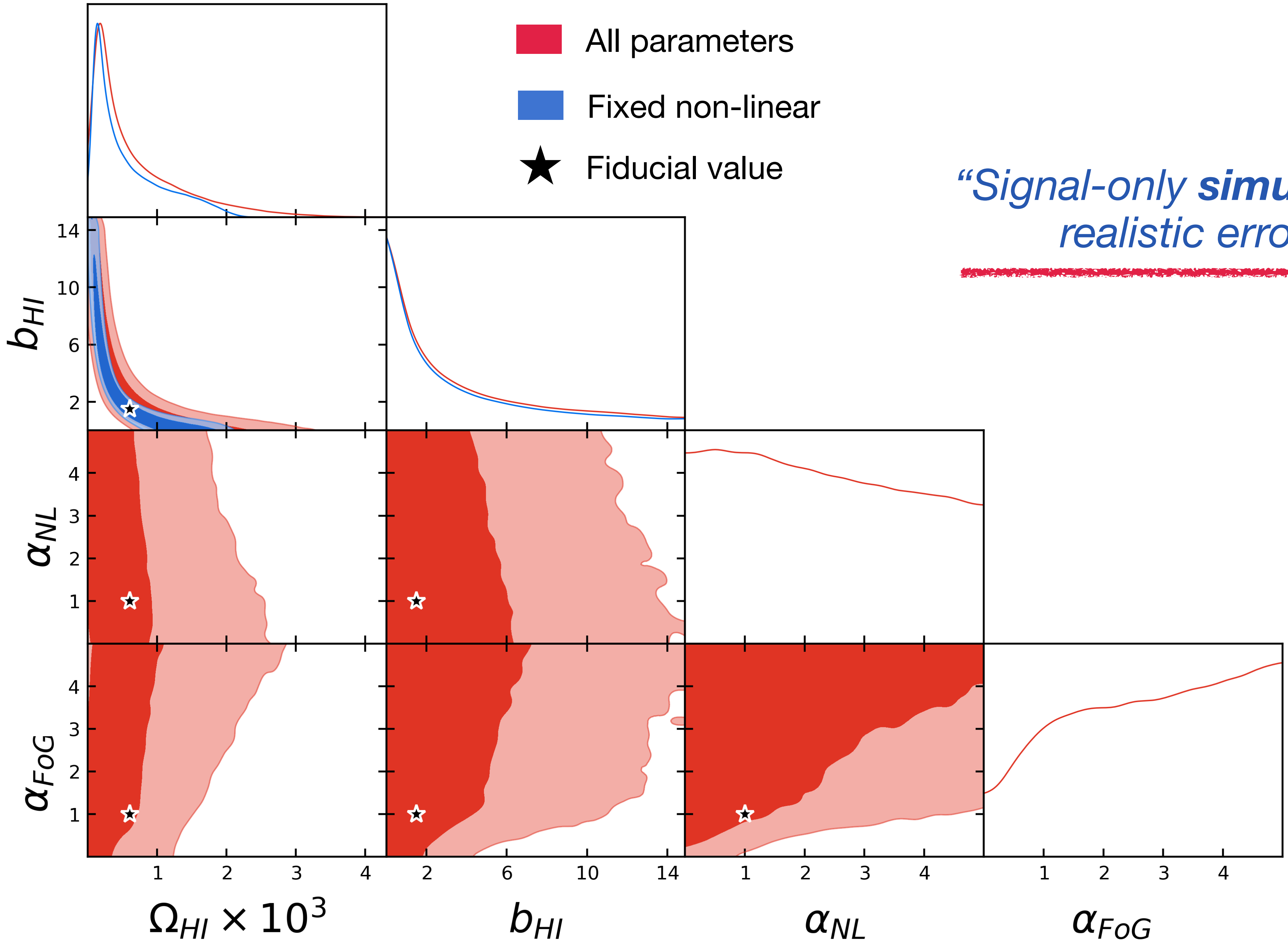

"Signal-only ***simulations*** *with realistic error bars"*

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Reality check: Does our model hold up?

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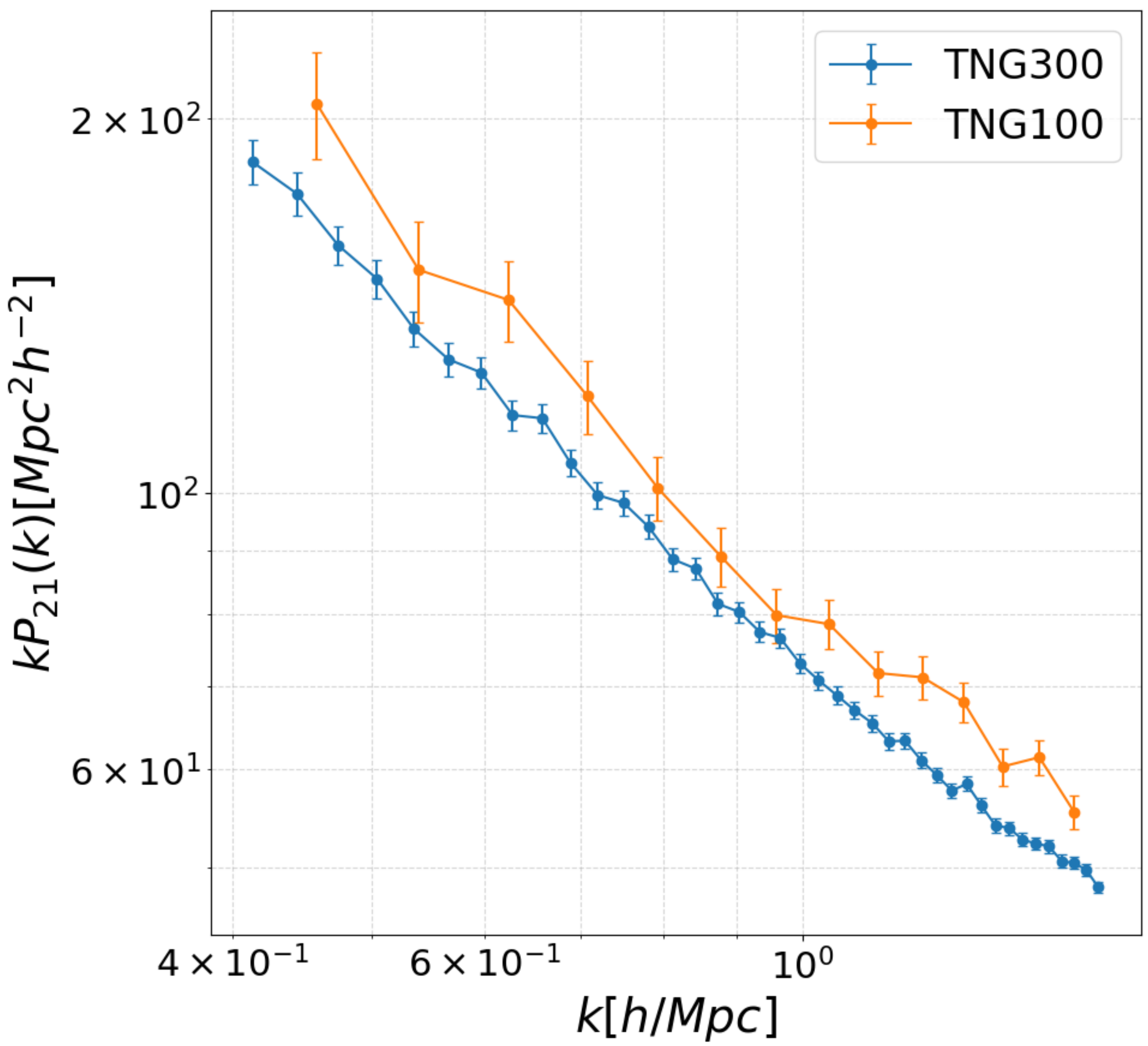
In progress...

- Verifying that 4-parameter model is flexible enough to fit **IllustrisTNG** HI power spectrum
- Verifying that TNG values of Ω_{HI}, b_{HI} are recovered from simulated parameter inference
- Ensuring that posteriors are unbiased if extended power spectrum model is used (e.g. including shot noise, FoG from intra-galaxy HI motions)



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- Villaescusa-Navarro et al. (2018)

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Summary

- We use simulation-based pipeline to bridge theoretical HI power spectrum model to CHIME observations
- Our model includes Ω_{HI}, b_{HI}, and nuisance parameters α_{FoG} and α_{NL} characterizing small-scale physics.
- Strong degeneracy exists between Ω_{HI} and b_{HI}, limiting individual parameter constraints.
- We address this by constraining the amplitude parameter A_{HI}, which remains well-determined.
- Model accuracy is verified through systematic validation against IllustrisTNG hydrodynamical simulations.

Thank You

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