# Improving HI cosmology analysis:

# Fisher forecasts & Machine Learning

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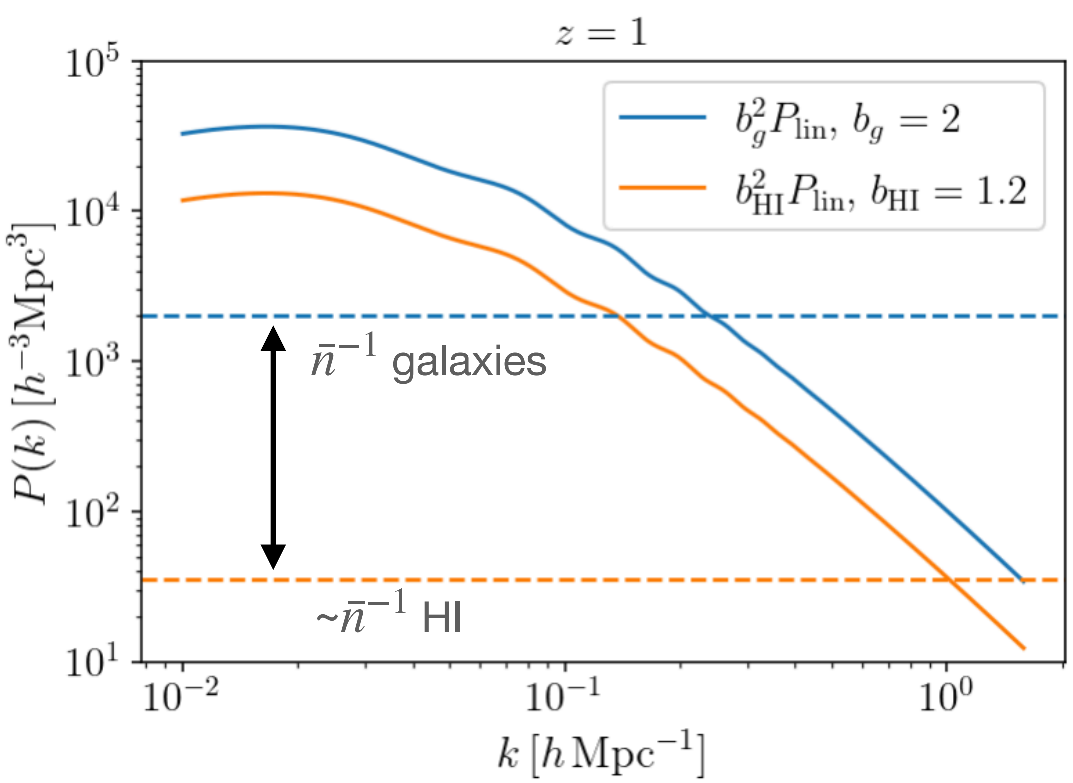
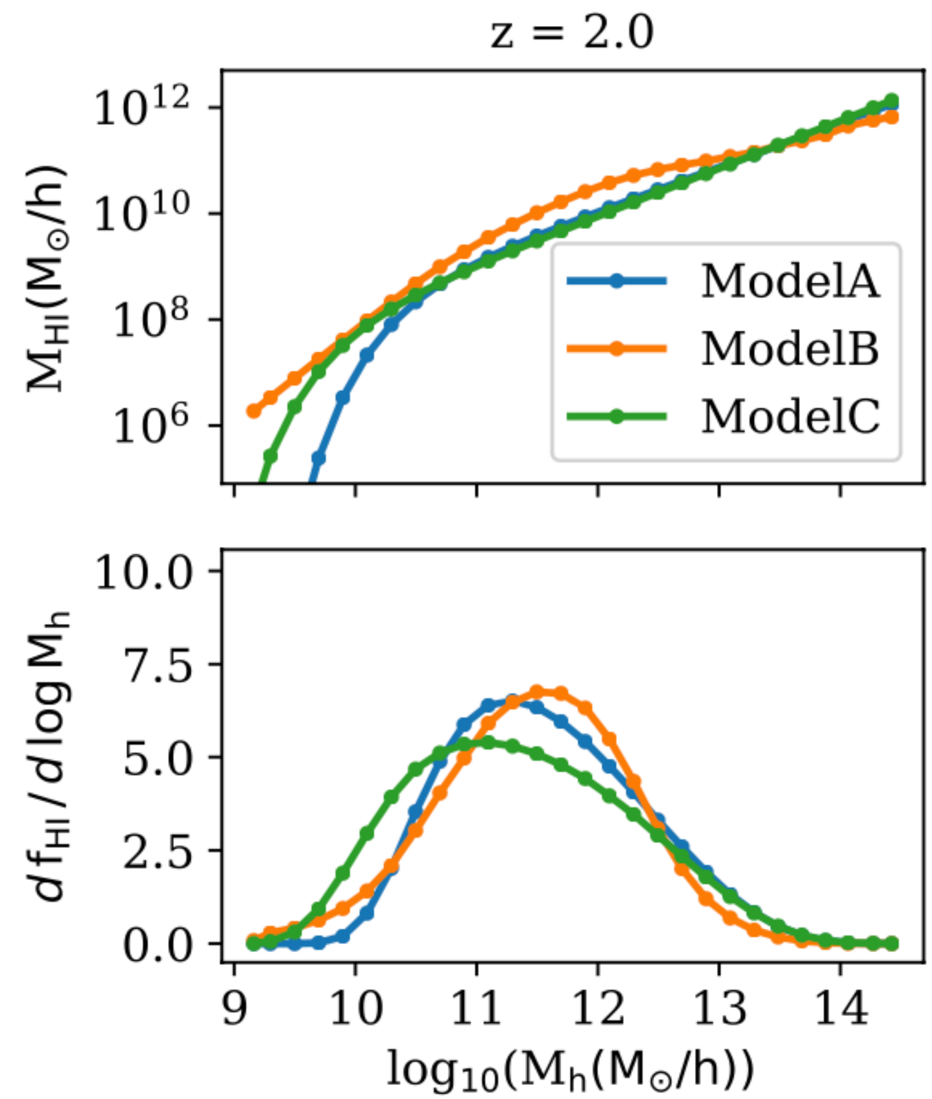
w/ S. Foreman, M. Simonović, F. Villaescusa-Navarro et al.

# Why is HI great for cosmology?

- HI signal from numerous lower halo masses ~$10^{11}$Ms/h
- Low sampling noise / shot-noise!
- Shot-noise limiting factor for galaxy clustering (Kobayashi+22)

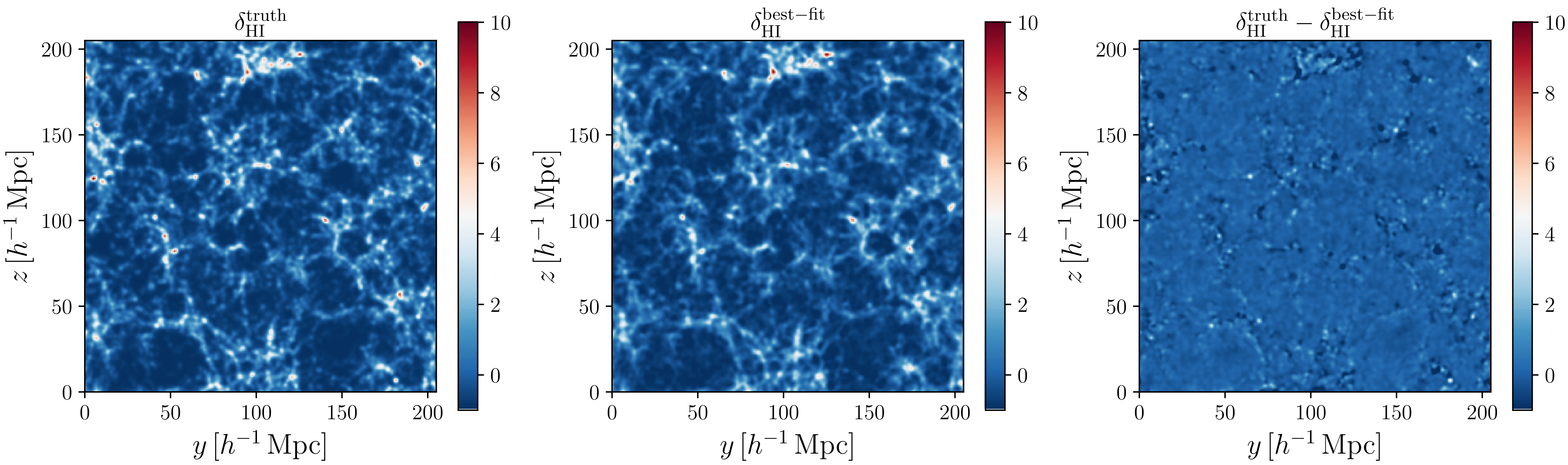



Modi+19

# HI: simulations vs theoretical model

$$\delta_{\rm HI}(\mathbf{k}) = \beta_1(k)\tilde{\delta}_1(\mathbf{k}) + \beta_2(k)\tilde{\delta}_2^{\perp}(\mathbf{k}) + \beta_{\mathcal{G}_2}(k)\tilde{\mathcal{G}}_2^{\perp}(\mathbf{k}) + \beta_3(k)\tilde{\delta}_3^{\perp}(\mathbf{k}) + \ldots + \text{noise}$$

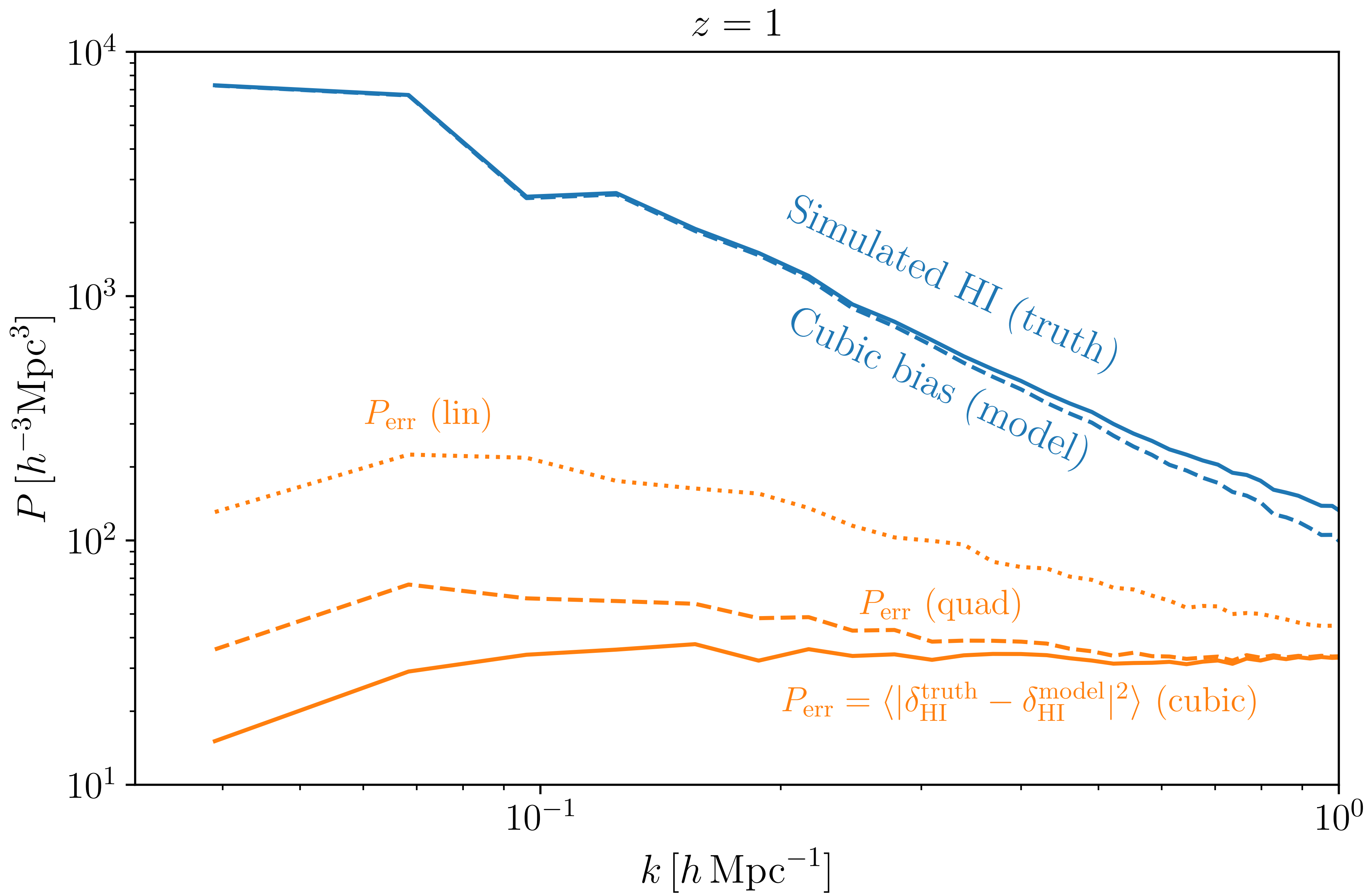



Slice depth 20 Mpc/h, smoothed 1 Mpc/h Gaussian

AO+2207.12398

# Simulated HI vs theoretical model

$$\delta_{\rm HI}(\mathbf{k}) = \beta_1(k)\tilde{\delta}_1(\mathbf{k}) + \beta_2(k)\tilde{\delta}_2^{\perp}(\mathbf{k}) + \beta_{\mathcal{G}_2}(k)\tilde{\mathcal{G}}_2^{\perp}(\mathbf{k}) + \beta_3(k)\tilde{\delta}_3^{\perp}(\mathbf{k}) + \ldots + \text{noise}$$

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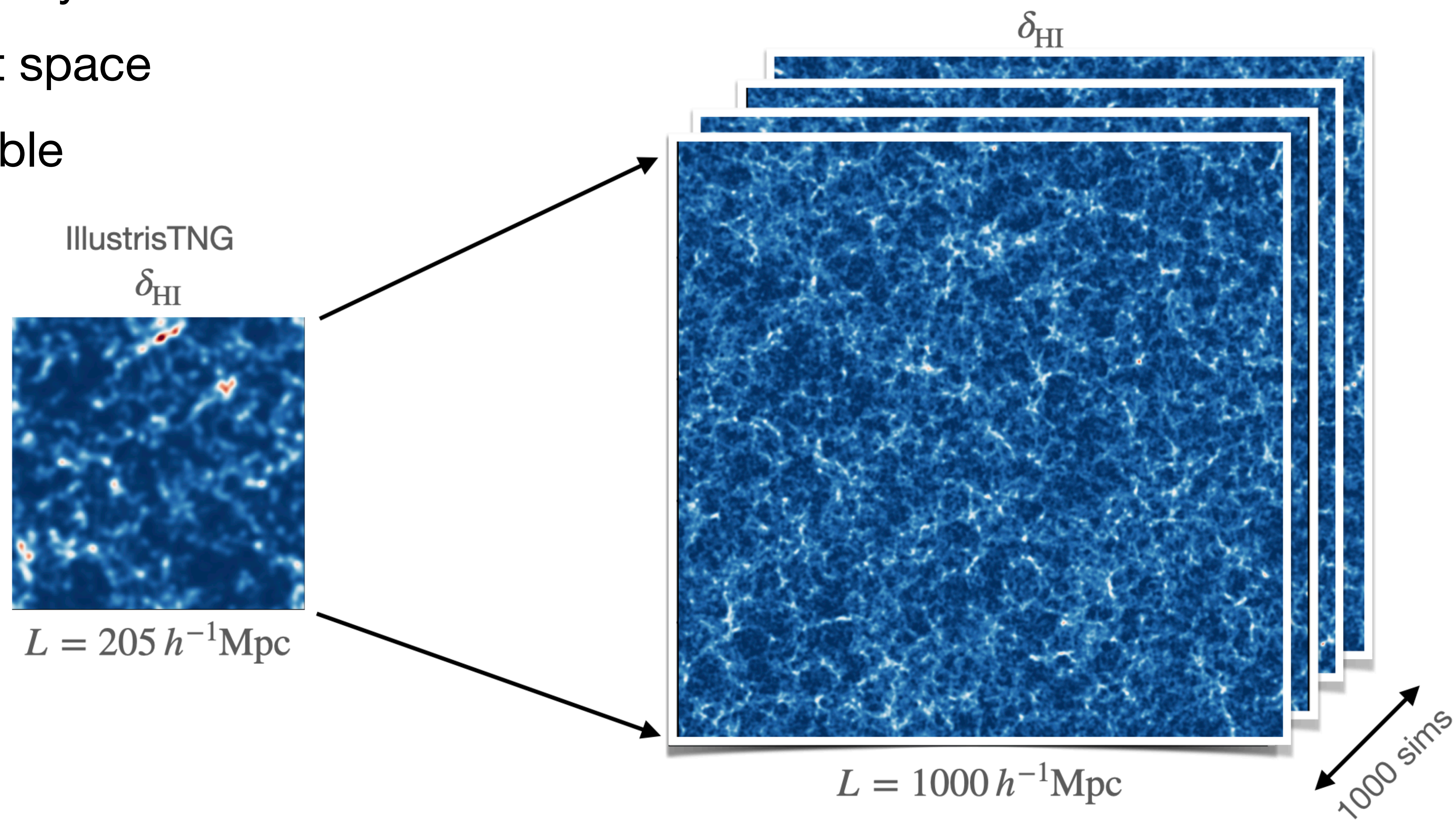
# Hi-Fi mocks

## https://github.com/andrejobuljen/Hi-Fi_mocks

- Generate fast 3D HI field-level mocks
- Tuned to TNG HI clustering at z=[0-5]
- Extendable to any volume!
- Real & redshift space
- Publicly available

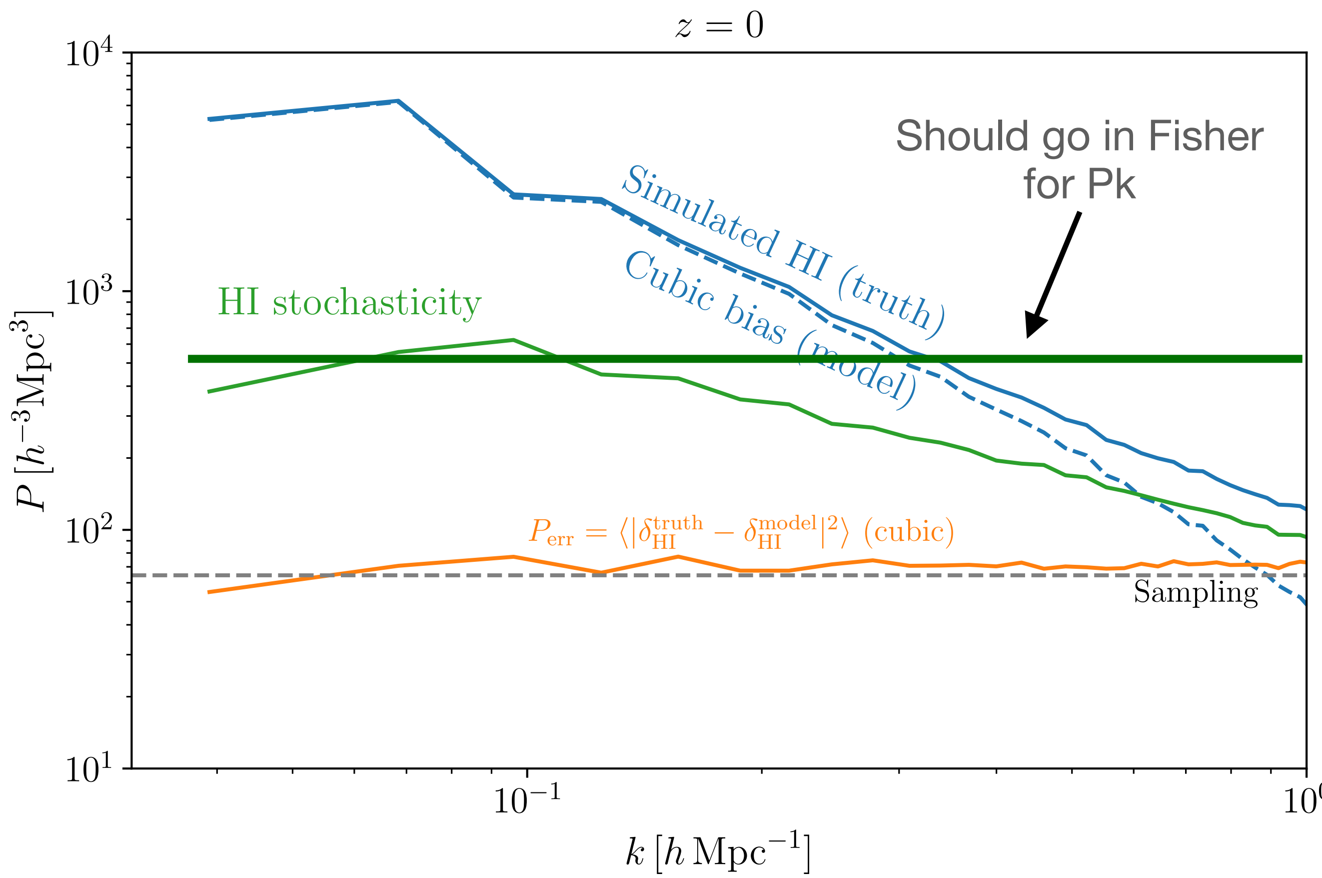


# HI noise properties

- HI stochasticity: $\langle \, | \, \delta_{\mathrm{HI}}^{\mathrm{truth}} - b_1 \delta_{\mathrm{m}} \, |^2 \, \rangle$
- Two contributions:

$$\delta_{\mathrm{HI}}(\mathbf{k}) - \beta_1 \tilde{\delta}_1(\mathbf{k}) = \beta_2 \tilde{\delta}_2^{\perp}(\mathbf{k}) + \beta_{\mathcal{G}_2} \tilde{\mathcal{G}}_2^{\perp}(\mathbf{k}) + \ldots + \epsilon$$

- In contrast to galaxies, higher order terms dominate sampling noise for HI
- Degenerate with sampling noise
- Fisher forecasts for Pk typically assume sampling noise (optimistic)
- Field-level may do better, even on linear scales!
- Improvement proportional to |b2|

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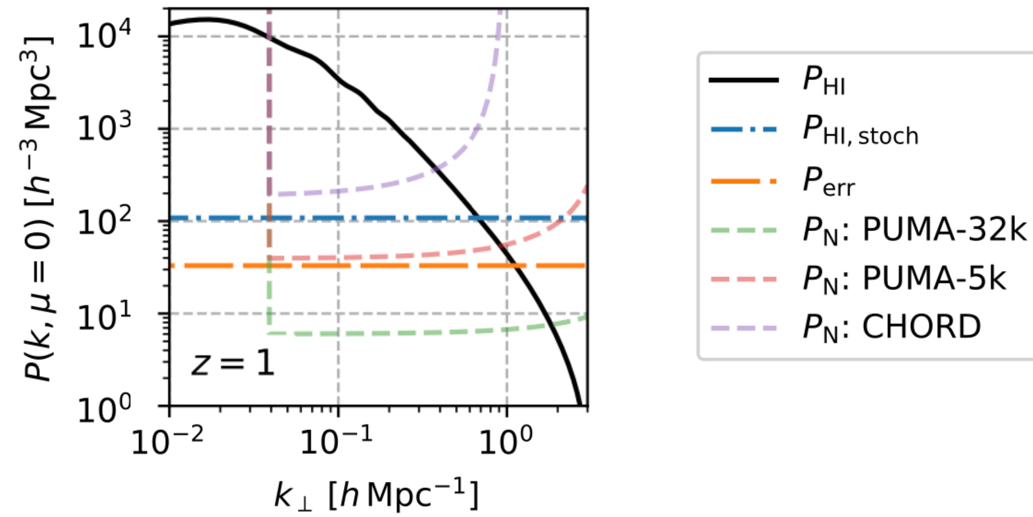
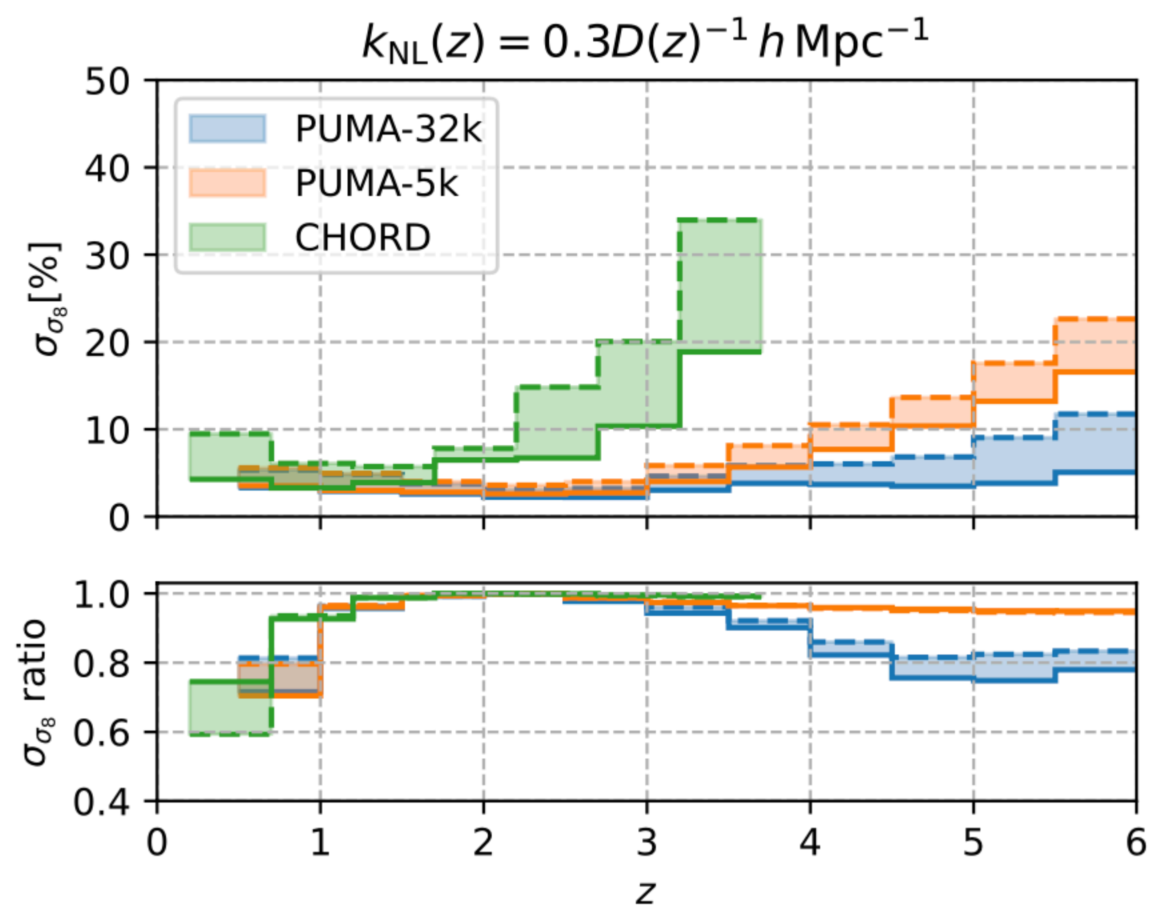
# Field-level vs Pk

## How big is the improvement?

w/ S. Foreman & M. Simonović 2405.18559

- Fisher forecasts with (un)realistic noise levels
- Two forecast sets:
  1. remove $< \delta^2 \delta^2 >$ from covariance
  2. keep it in the covariance
- Mimic FL vs Pk analysis on large scales
- **~20%** improvement on cosmological parameters given **current** thermal noise



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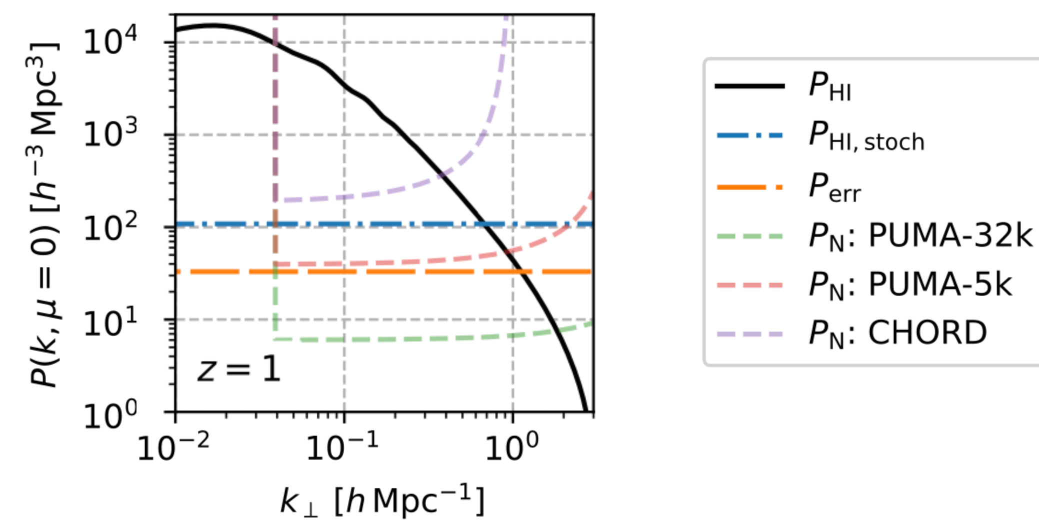
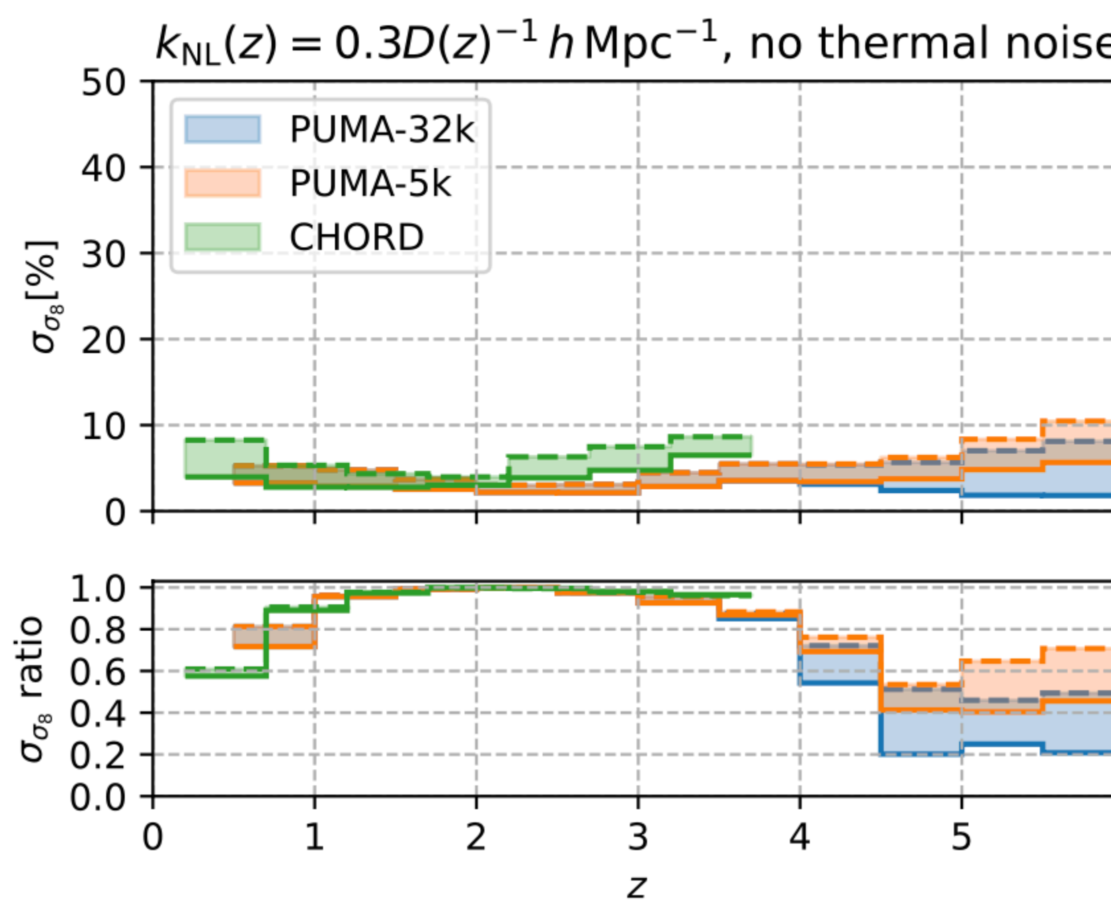
- Mimic FL vs Pk analysis on large scales
- **~50%** improvement on cosmological parameters given **no thermal** noise



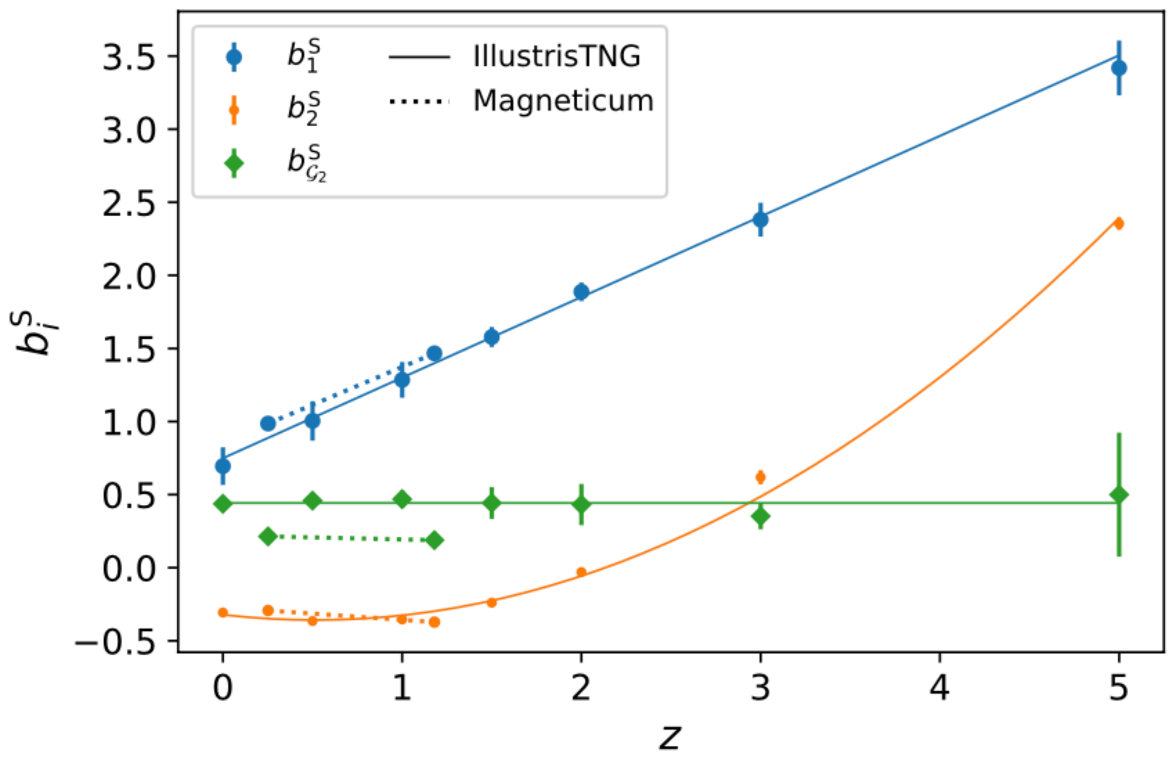




$\sigma_8$

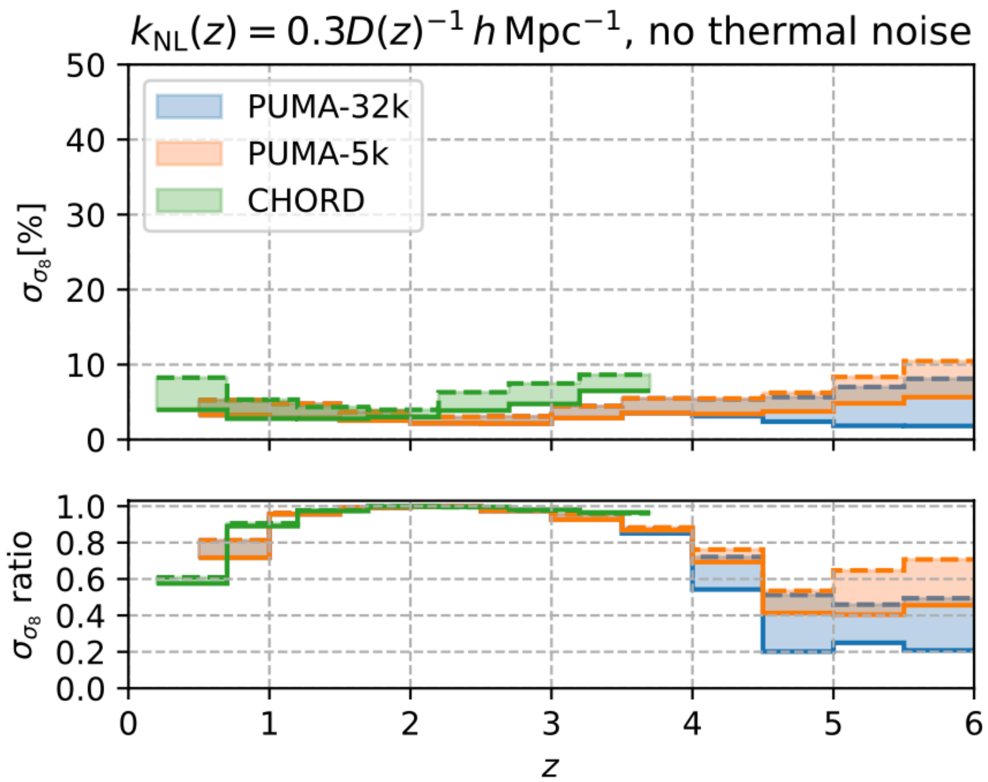
# Field-level vs Pk

## How big is the improvement?

- No improvement when $b_2 = 0$



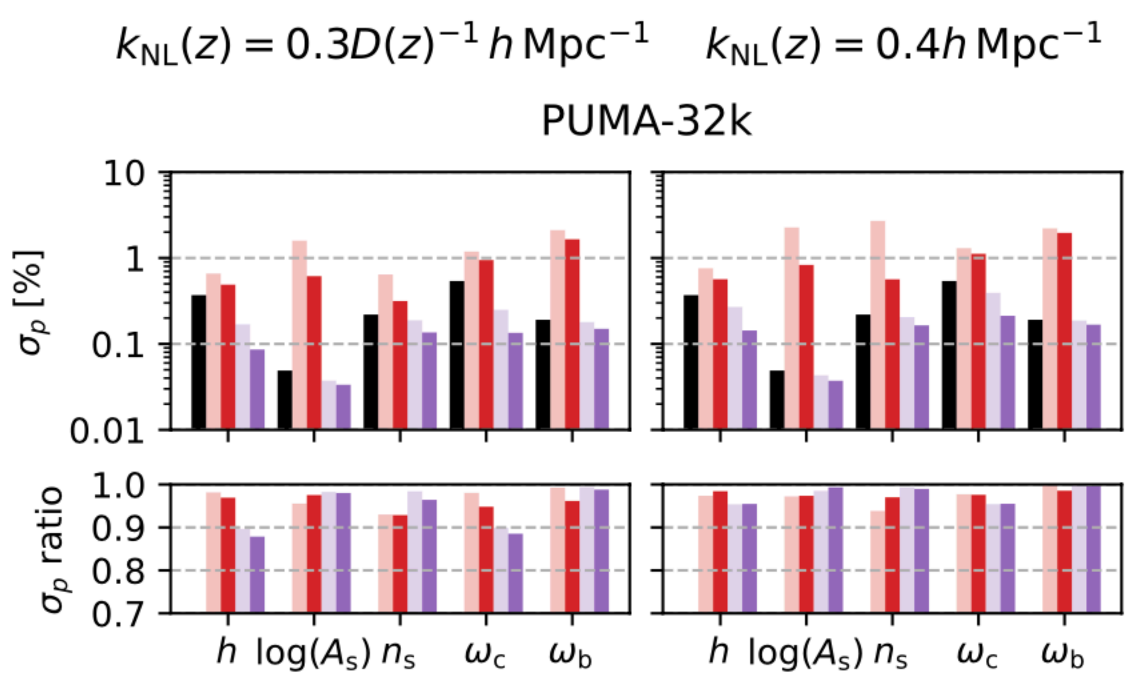

Constraints on $\sigma_8$



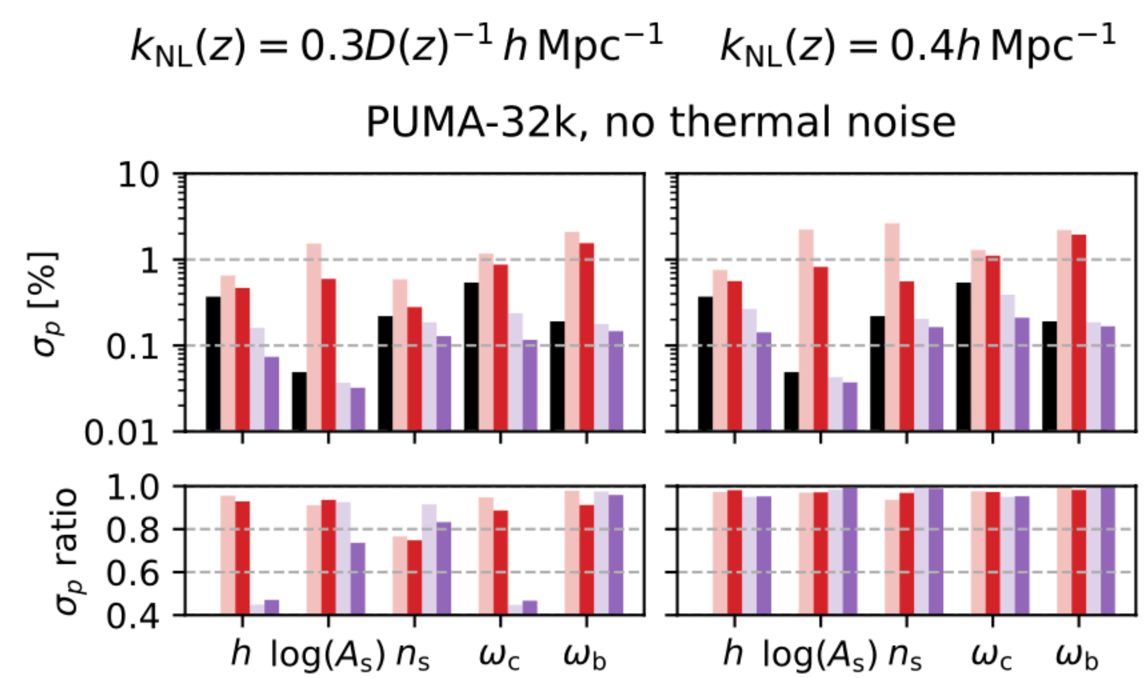
# Field-level vs Pk

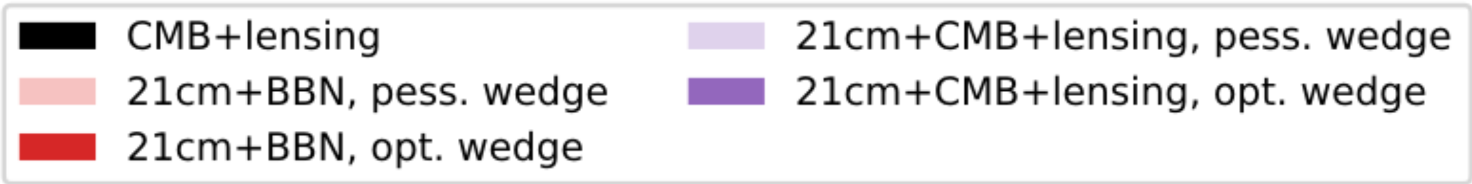
## How big is the total improvement?

**‘Planned’ thermal noise levels ~20%**




**No thermal noise ~50%**



# HI bias & stochasticity fitting functions

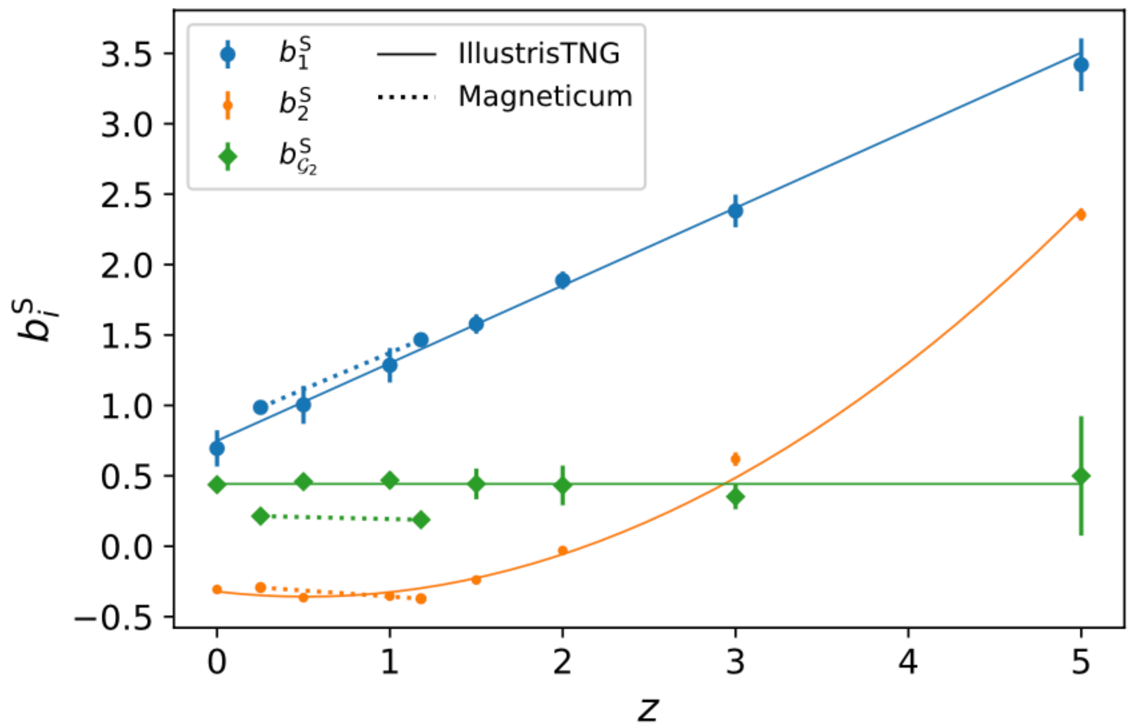
## arXiv:2405.18559

- HI biases:

$$b_1^{\rm E}(z) = 0.75 + 0.55z,$$
$$b_2^{\rm E}(z) = -0.64 - 0.28z + 0.28z^2,$$
$$b_{\mathcal{G}_2}^{\rm E}(z) = 0.23 - 0.16z,$$

- HI stochasticity:

$$P_{\rm stoch}^{(k\to 0)}(z) = \begin{cases} 471 - 485z + 132z^2, & \text{if } z \leq 2 \\ -33 + 31z, & \text{if } 2 < z \leq 5 \end{cases}$$



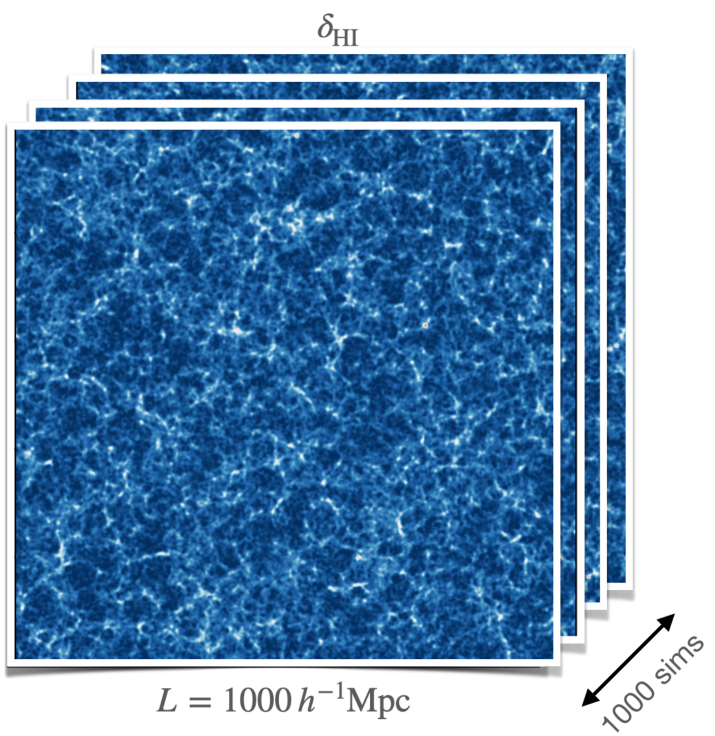
# Some messages

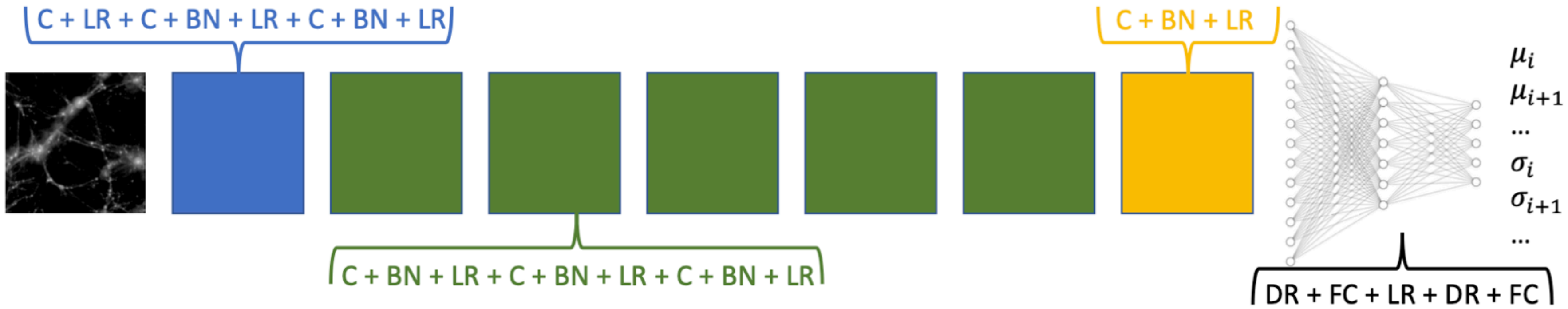
- Clear motivation to go beyond Pk, even on large scales
- Large gains from future surveys with more optimal data analysis
- For current surveys gains small due to large thermal noise…
- HI sampling noise is ideal thermal noise target, not stochasticity
- Our estimates conservative, field-level analysis will do better

# HI field-level inference with CNNs

## w/ F. Villaescusa-Navarro in prep.

- Likelihood-free inference using ML on large boxes
- Train convolutional neural networks on 1000 Hi-Fi mocks (L=1Gpc/h) following 2109.09747
- Dataset of 24000 HI maps, varying: cosmology, biases & initial conditions
- We test different scale cuts, different HI simulations and other redshifts
- We compare to Pk analysis




C = Convolutional layer
BN = Batchnorm layer
LR = LeakyReLU activation layer
DR = Dropout
FC = Fully connected layer

# HI field-level inference with CNNs

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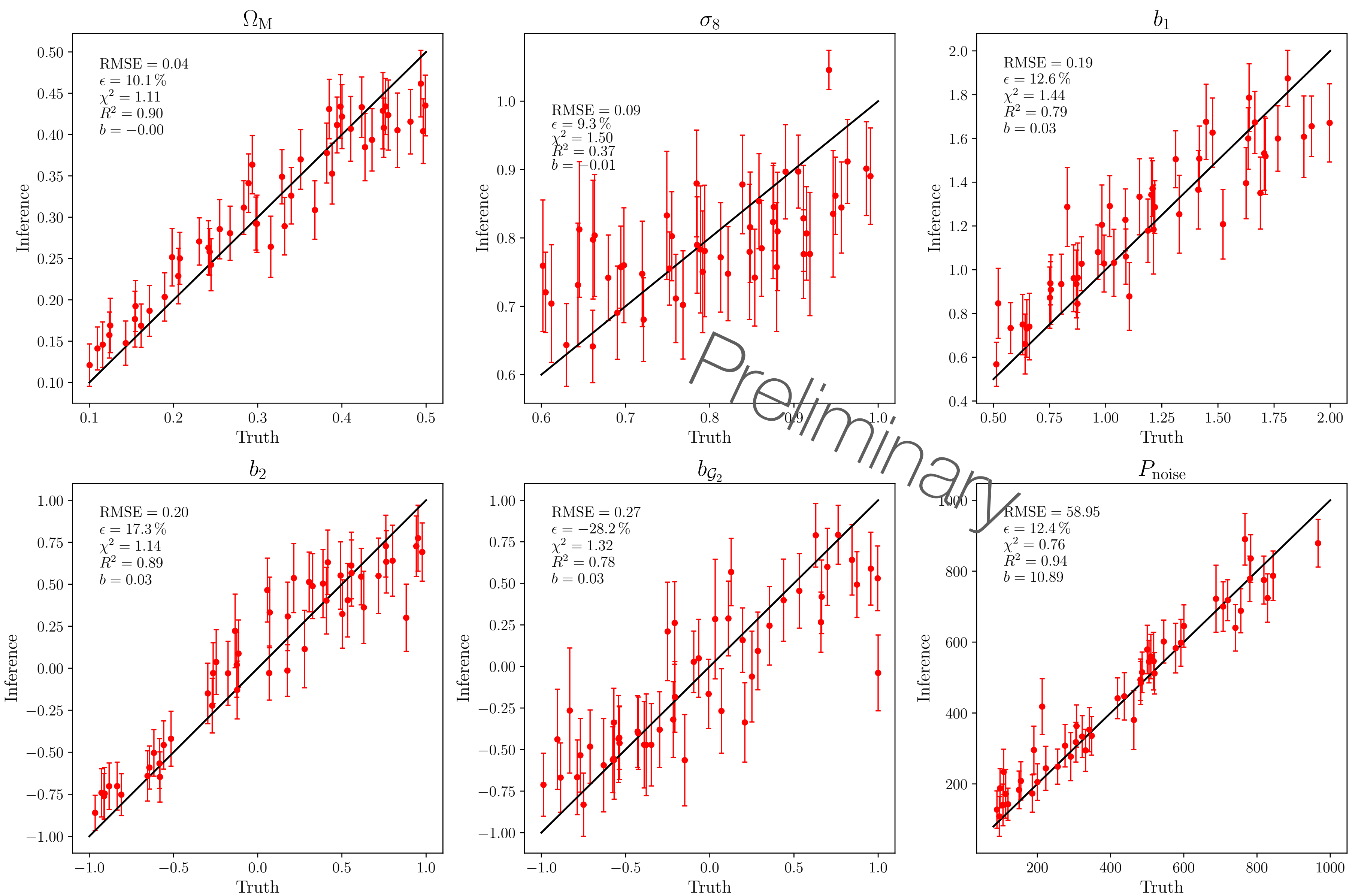
### Field-level




kmax=0.4 h/Mpc

# HI field-level inference with CNNs

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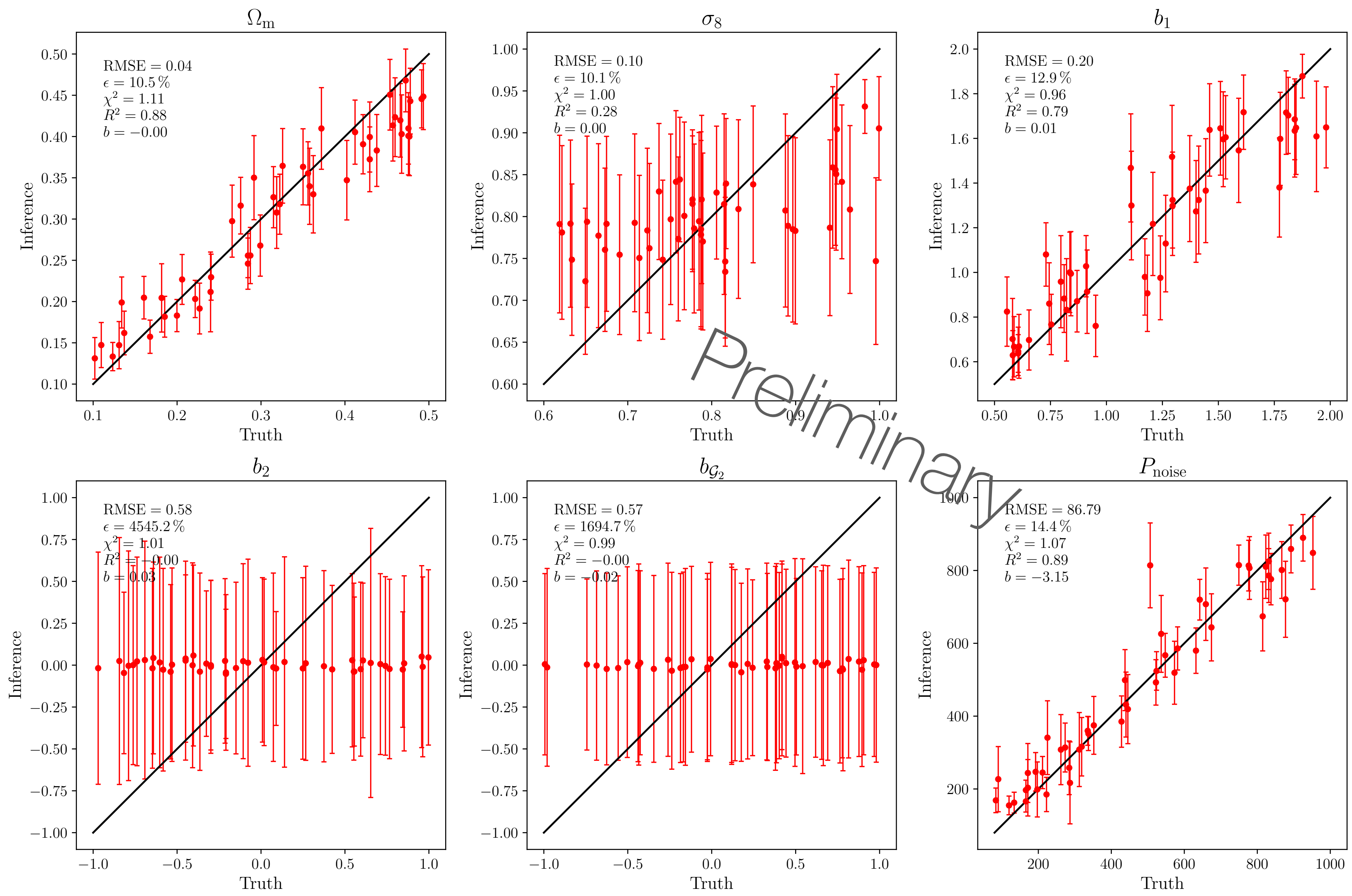
### Power spectrum




kmax=0.4 h/Mpc

# Conclusions

- HI dense tracer with very low sampling (shot) noise
- HI clustering well captured by perturbation theory
- We provide code to generate fast HI mocks (Hi-Fi mocks)
- For dense tracers like HI, power spectrum is suboptimal
- Field-level analysis breaks these degeneracies and provides better constraints on cosmology even on large scales!
- For ideal instruments, the improvement can be at least 50%