EXTENDING the *EFFECTIVE FIELD THEORY* of *21CM RADIATION*

Wenzer Qin

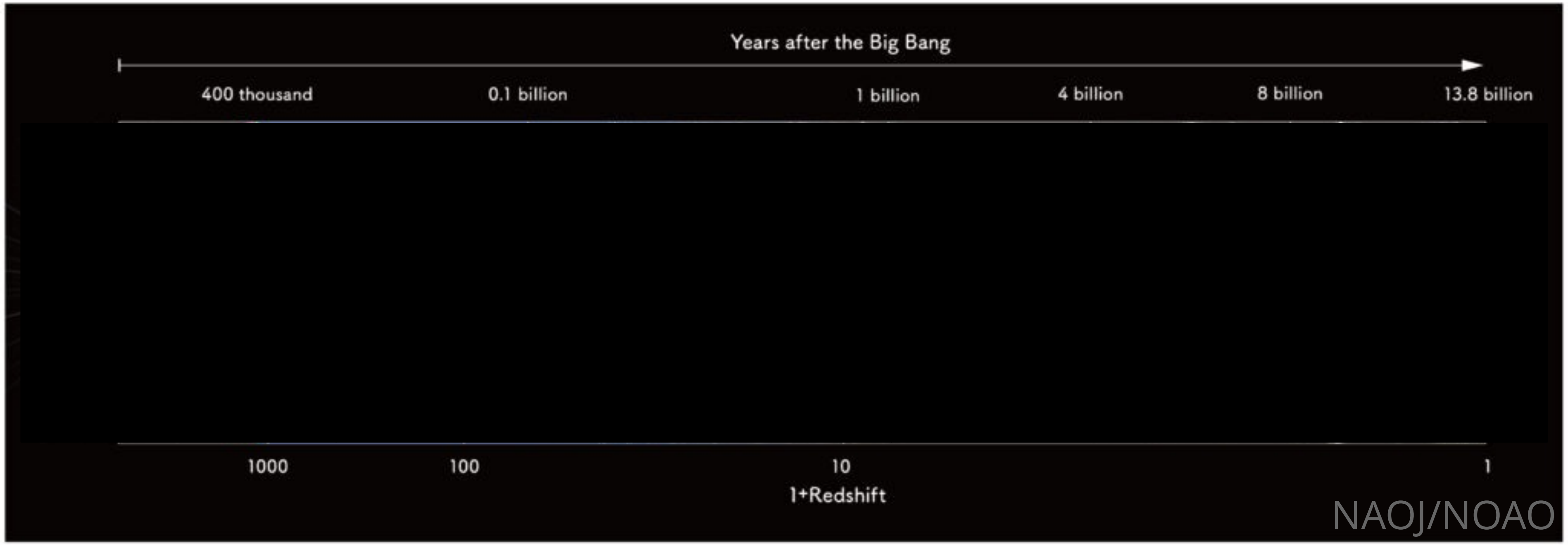
with Katelin Schutz, Aaron Smith,
Enrico Garaldi, Rahul Kannan
Tracy Slatyer, Mark Vogelsberger

based on 2205.06270

TeVPA
AUGUST 8TH , 2022

WHAT IS 21CM COSMOLOGY?

- What redshifts have we directly measured?



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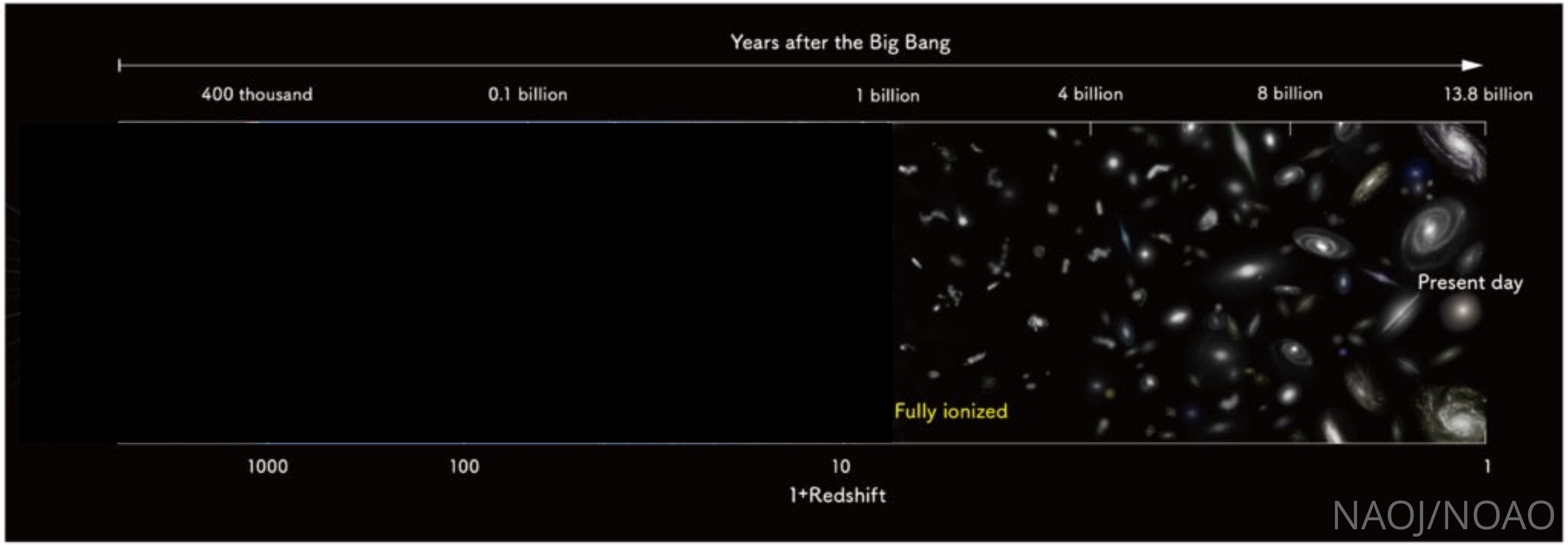
  - z~few: e.g. galaxy surveys



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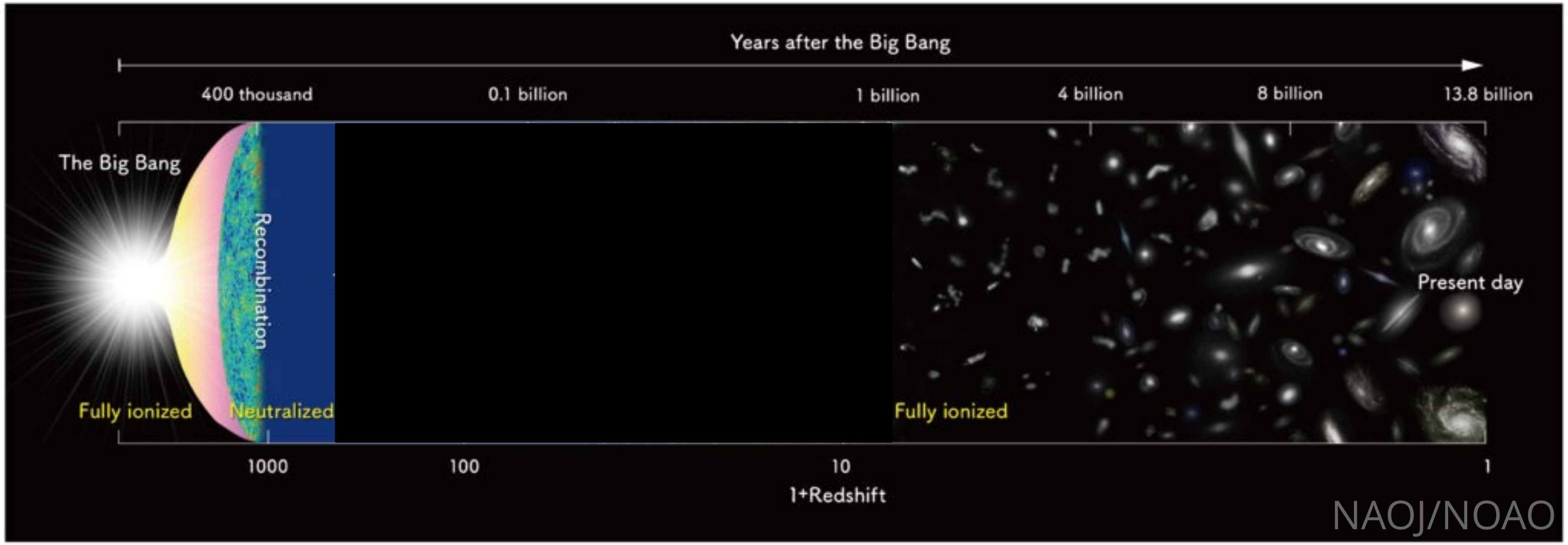
WHAT IS 21CM COSMOLOGY?

- What redshifts have we directly measured?
  - z~few: e.g. galaxy surveys
  - z=1100: cosmic microwave background



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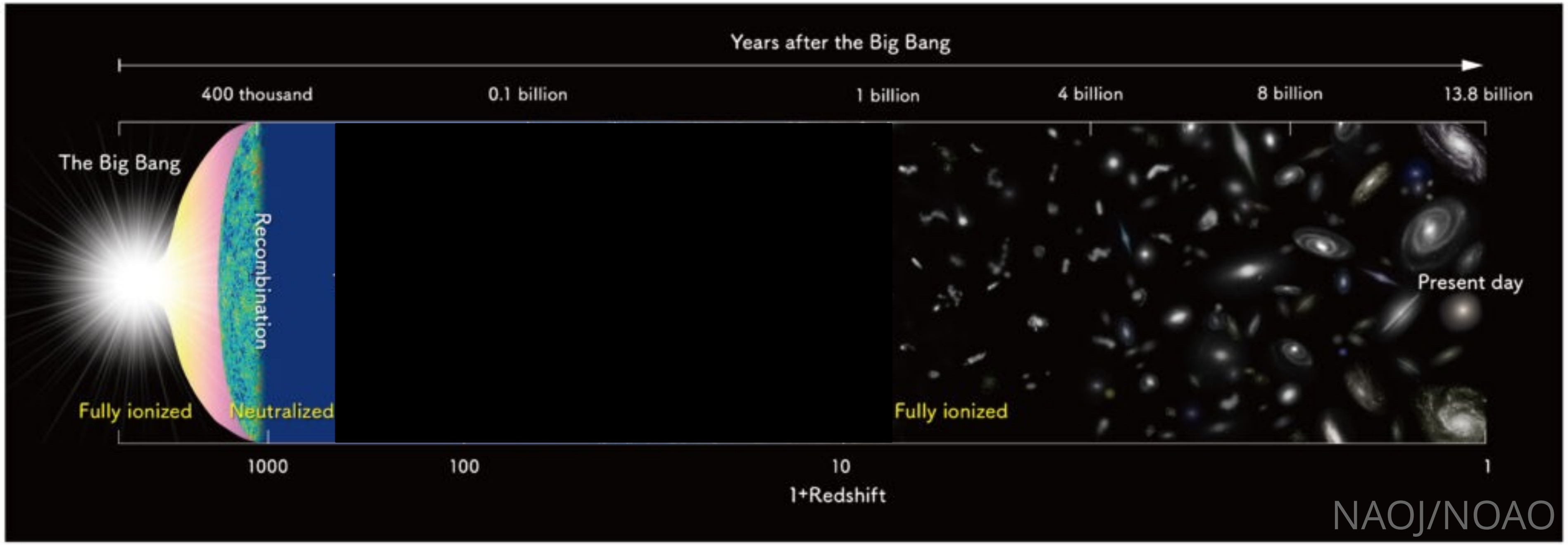
WHAT IS 21CM COSMOLOGY?

- In between, there are few stars/galaxies, only diffuse hydrogen



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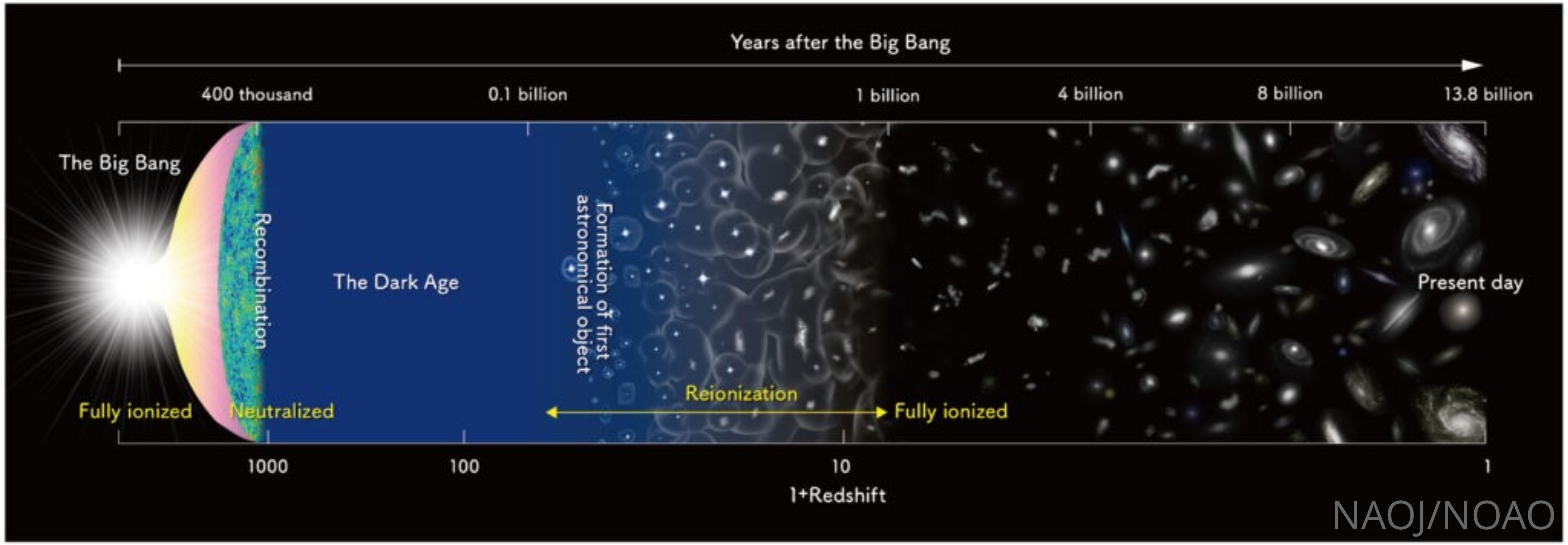
WHAT IS 21CM COSMOLOGY?

- In between, there are few stars/galaxies, only diffuse hydrogen
  - Search for the hyperfine transition of neutral hydrogen → 21cm



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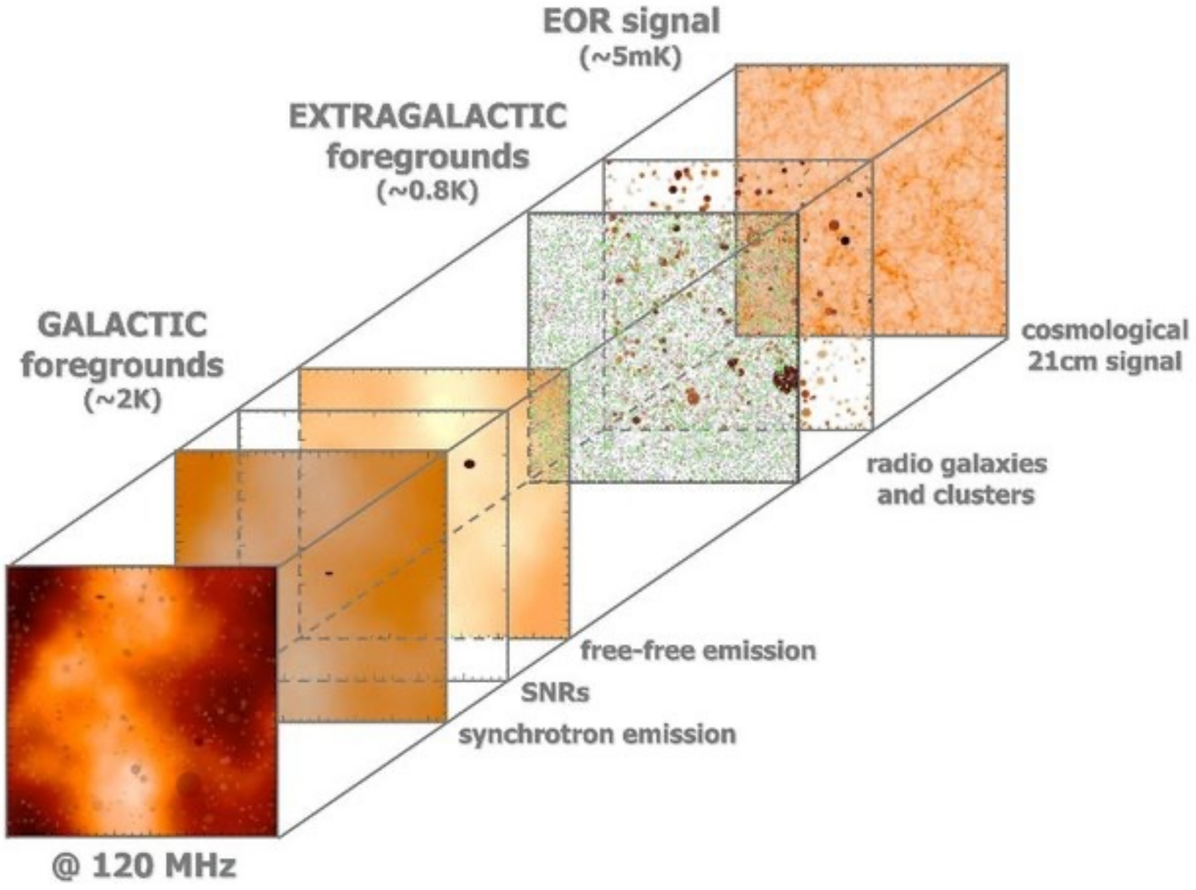
WHAT'S THE CATCH?

- Experimentally: huge foregrounds, e.g. synchrotron radiation



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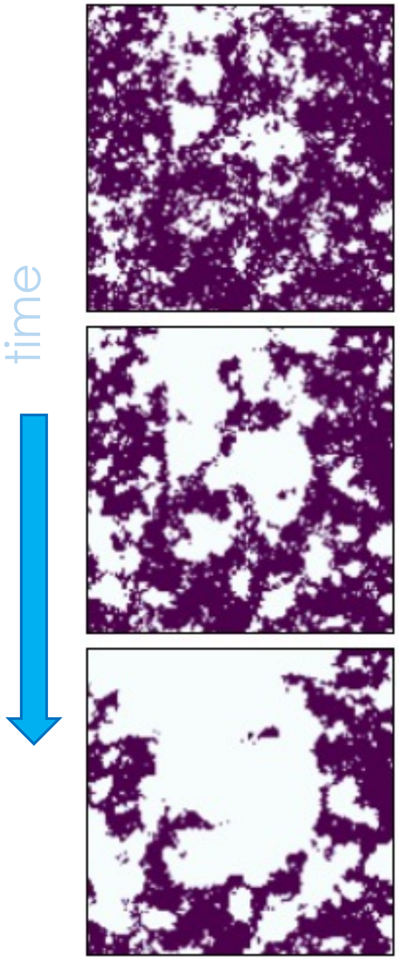
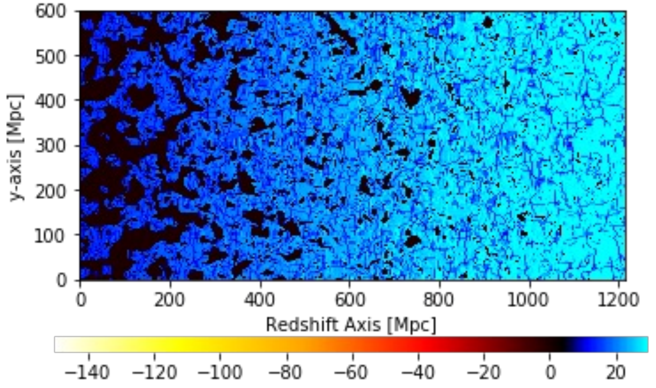
WHAT'S THE CATCH?

- Experimentally: huge foregrounds, e.g. synchrotron radiation
- Theoretically: Prevailing view is that analytic/perturbative methods won't work
  - Reionization is very patchy/nonlinear
  - Instead rely on computationally expensive simulations

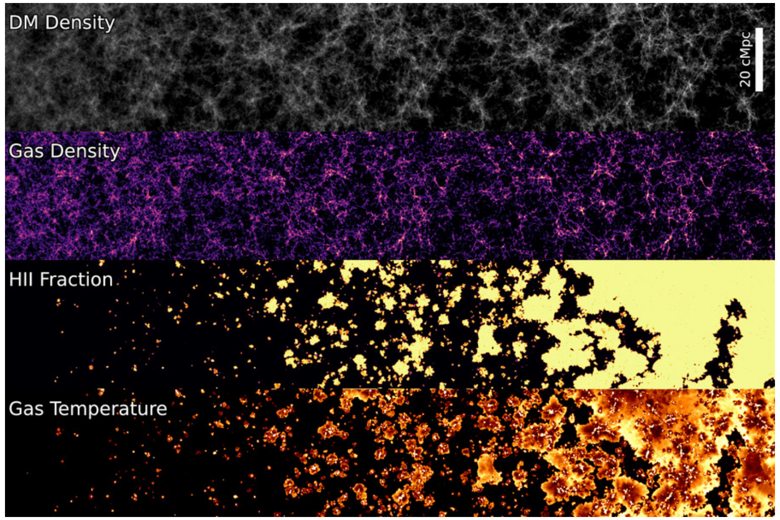


McQuinn & D'Aloisio, 2018.

21cmFAST



THESAN



21CM SIGNAL IS PERTURBATIVE

- McQuinn & D'Aloisio 2018 showed effective field theory (EFT) methods work on observable scales
- Steps in building up our EFT:
  - Relating 21cm to matter density?
  - Dealing with small nonlinear scales?
  - Redshift space distortions?

FROM DENSITY TO 21CM

- Evolution of matter density/large scale structure is well understood
- To study other quantities, we use ***local bias expansions***
  - E.g. galaxies are biased tracers of matter, form preferentially in overdensities

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  - E.g. galaxies are biased tracers of matter, form preferentially in overdensities
- 21cm brightness temperature is a biased tracer of the matter density field
- Include all operators that respect homogeneity and isotropy

$$\delta_{21} = b_1\delta - b_{\nabla 2}k^2\delta + b_2\delta^2 + \cdots$$

SMALL SCALE NONLINEARITIES?

- Small scale modes become nonlinear first → smooth over these

$$\delta_{\rm long}(\boldsymbol{x}) = \int d^3x' W_\Lambda(\boldsymbol{x}-\boldsymbol{x}')\delta(\boldsymbol{x}')$$

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$\boldsymbol{\Lambda}$ is the UV cutoff

- Terms with more than one field are still sensitive to small scale modes
  - E.g. using a sharp cutoff…

$$\left[\delta^2(\boldsymbol{k})\right]_{\rm long} = \int_0^\Lambda \frac{dq}{2\pi^2}\delta(\boldsymbol{q})\delta(\boldsymbol{k}-\boldsymbol{q}) \neq \left[\delta_{\rm long}(\boldsymbol{k})\right]^2$$

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  - Remove the dependence on Λ by *renormalization*

REDSHIFT SPACE DISTORTIONS

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REDSHIFT SPACE DISTORTIONS

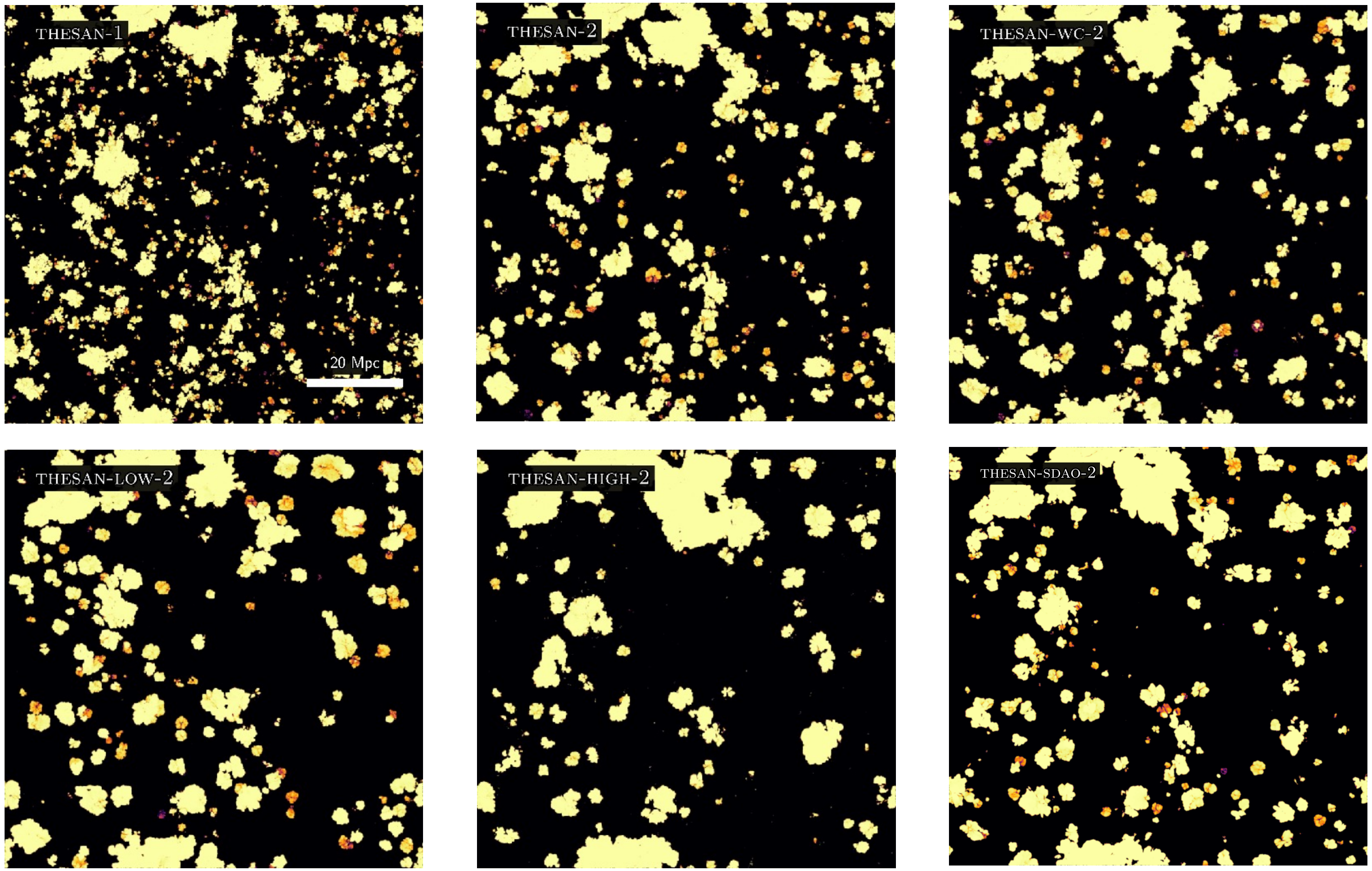
- 21cm signal is radiation
- Frequency is redshifted because sources have peculiar velocities
- Occurs along the line of sight, where interferometers are most sensitive
- Need to include redshift space distortions in perturbative treatments
  - Expand in small kv/H

$$\delta_r = \delta(\vec{k}) - i\frac{k_\parallel}{\mathcal{H}}v_\parallel(\vec{k}) - i\frac{k_\parallel}{\mathcal{H}}\delta v_\parallel(\vec{k}) - \frac{1}{2}\left(\frac{k_\parallel}{\mathcal{H}}\right)^2 v_\parallel^2(\vec{k}) - \frac{1}{2}\left(\frac{k_\parallel}{\mathcal{H}}\right)^2 \delta v_\parallel^2(\vec{k}) + \frac{i}{6}\left(\frac{k_\parallel}{\mathcal{H}}\right)^3 v_\parallel^3(\vec{k}) + \cdots$$

FITTING TO THE *THESAN* SIMULATIONS

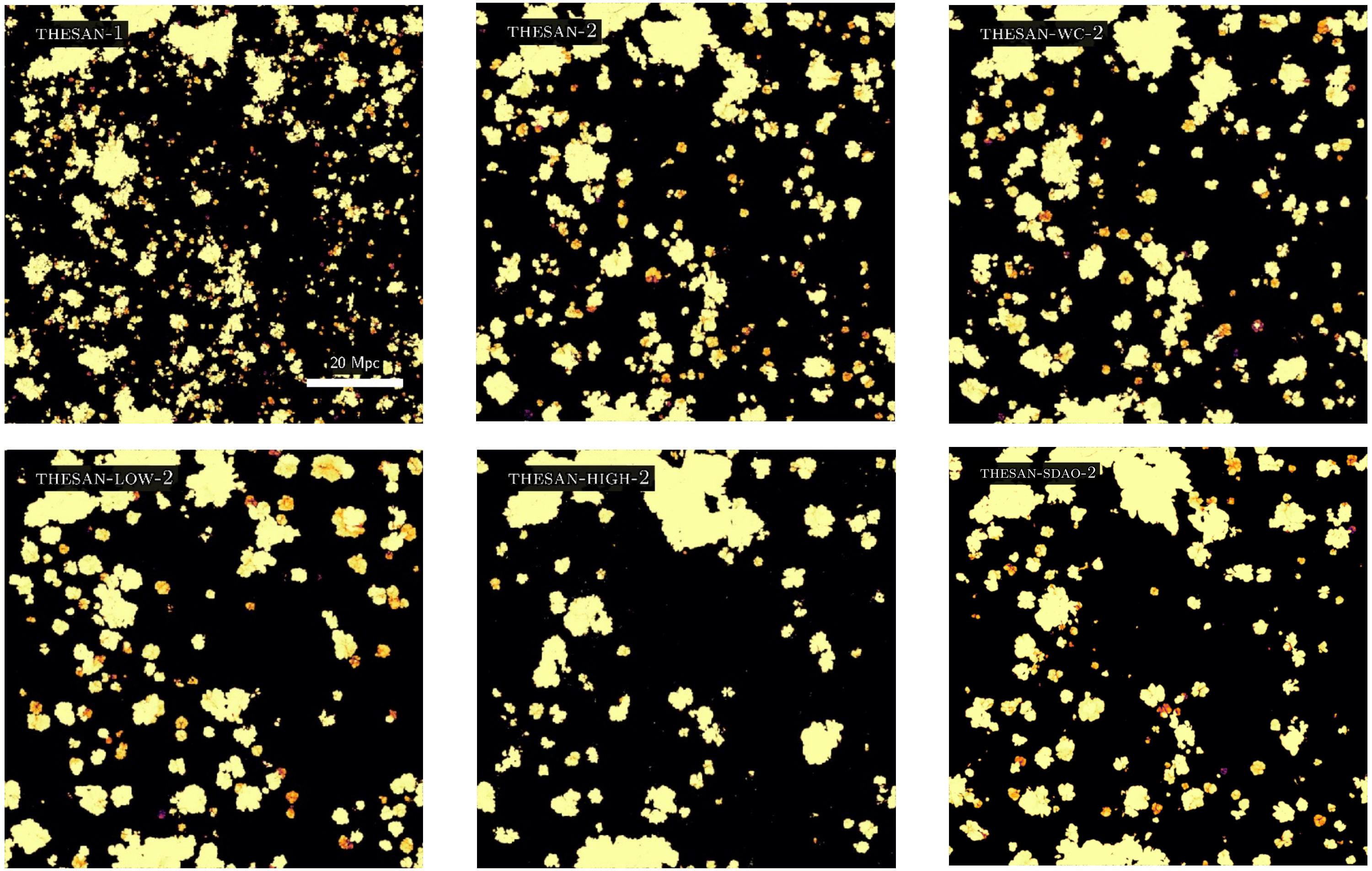
THESAN

- Neutral fraction is ~0.7 for each simulation shown



THESAN

- Thesan-1: High resolution
- Thesan-2: Medium resolution
- Thesan-WC-2: Compensates for lower star formation due to less resolution



THESAN

- Thesan-1: High resolution
- Thesan-2: Medium resolution
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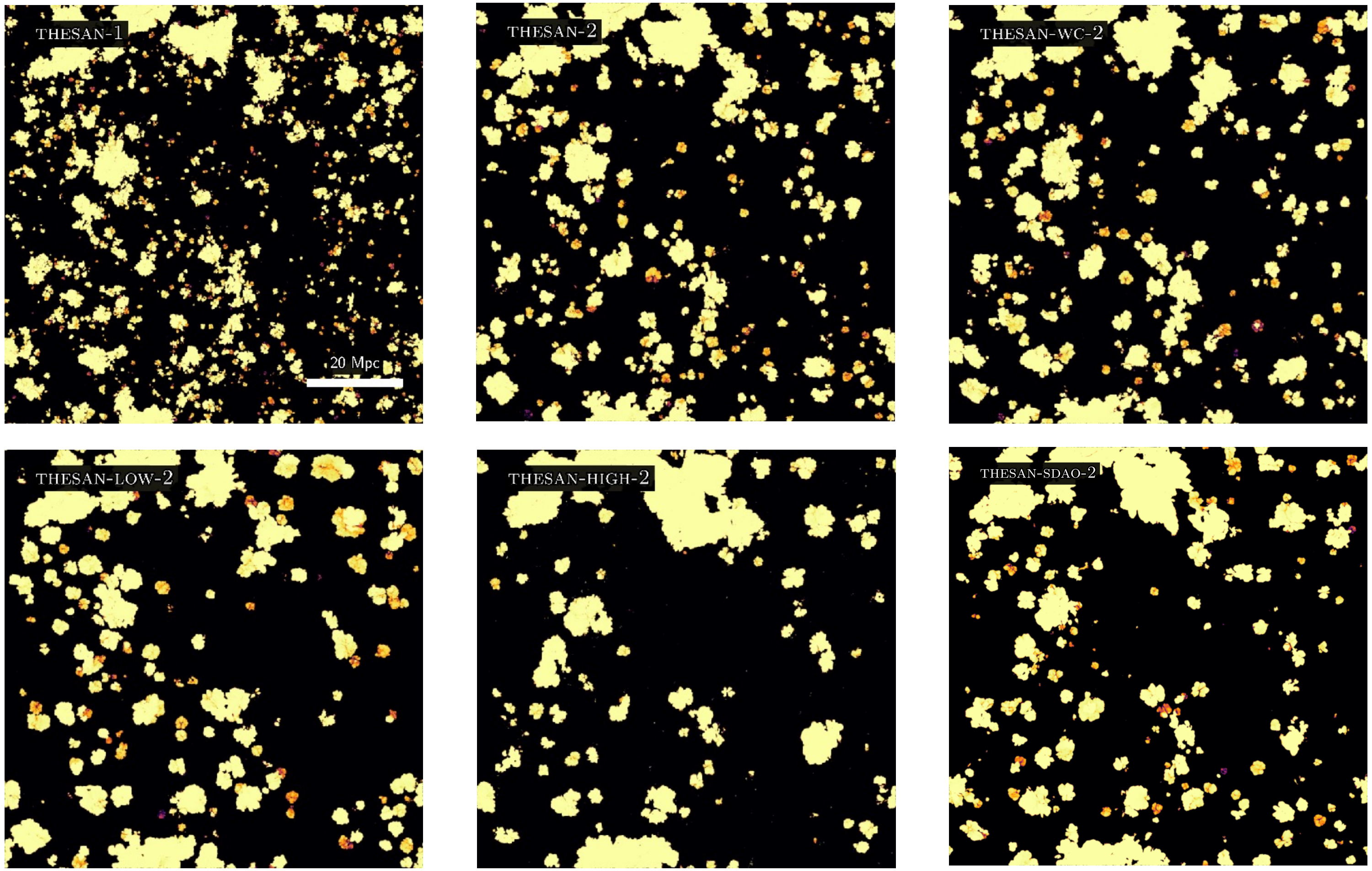
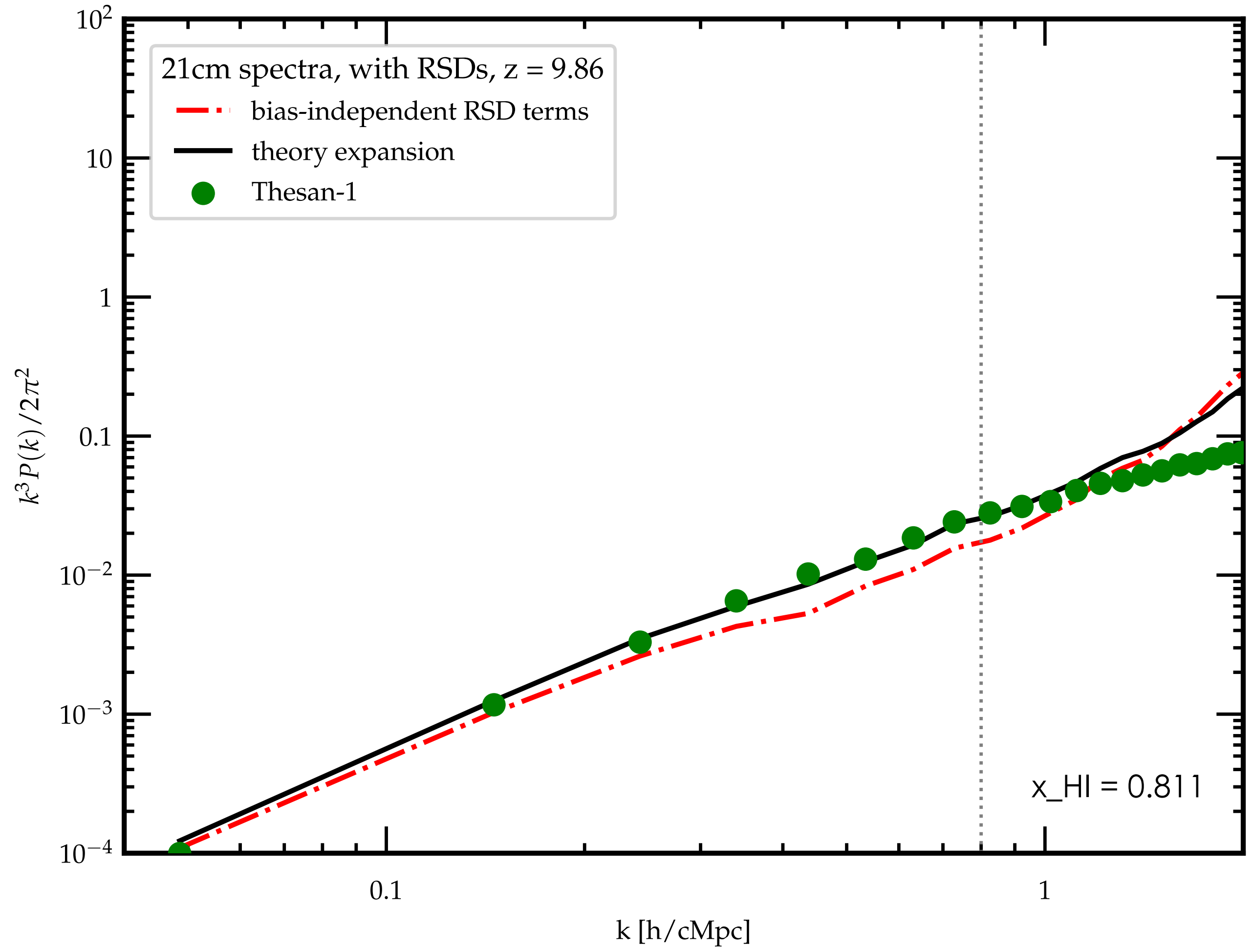
- Thesan-Low-2: Small haloes contribute to reionization
- Thesan-High-2: Large haloes contribute to reionization
- Thesan-SDAO-2: Non-standard dark matter model



POWER SPECTRUM



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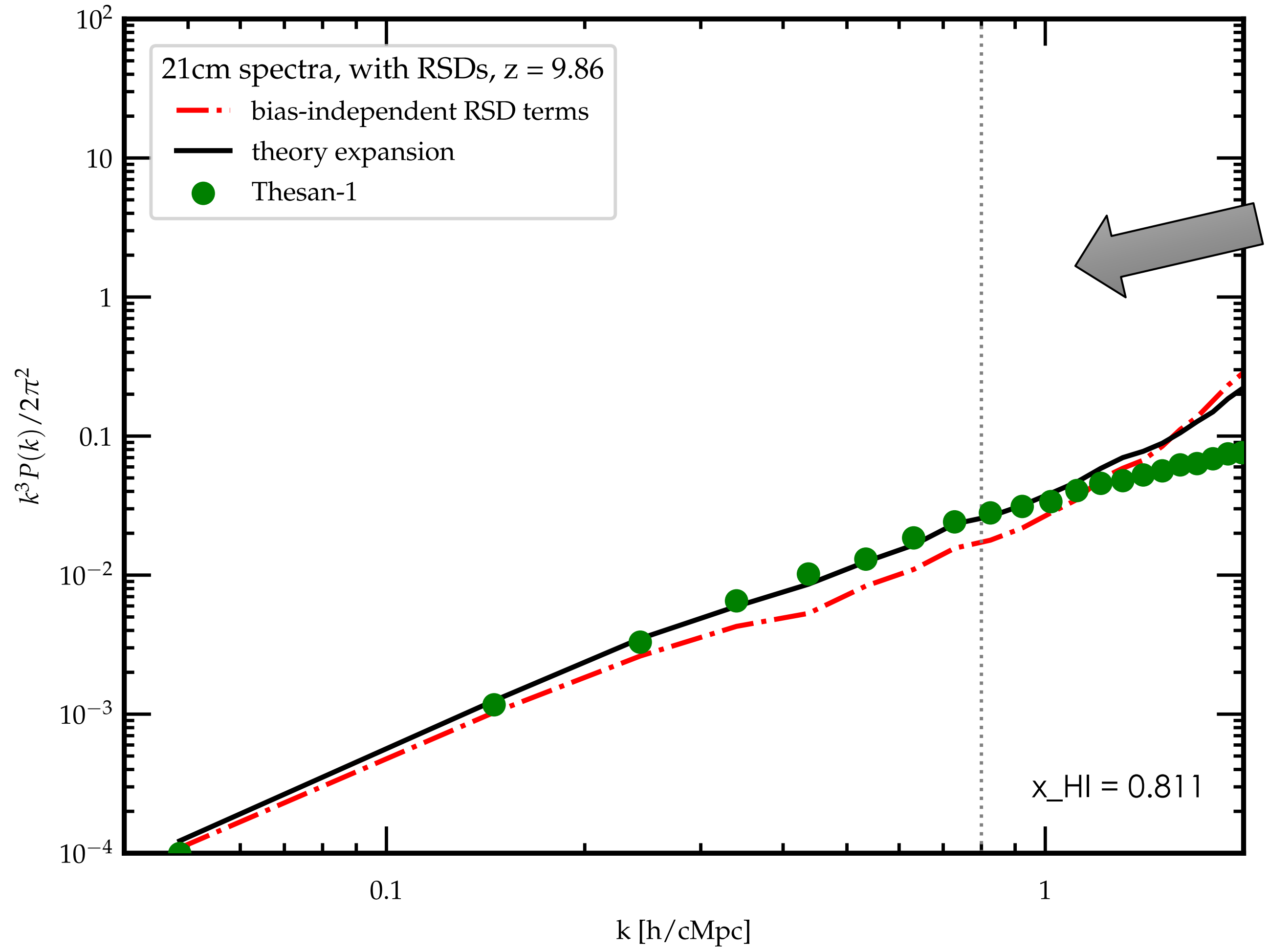
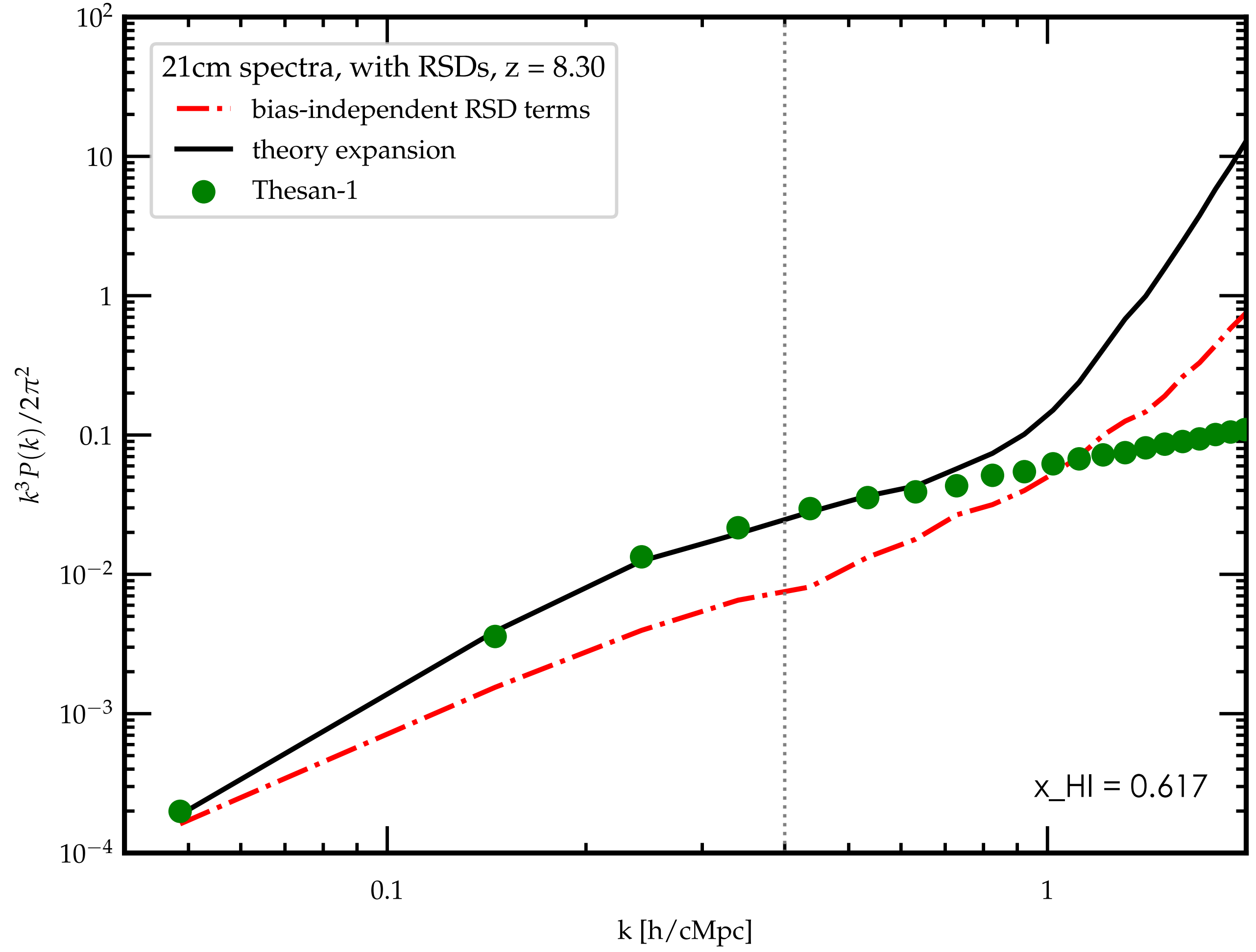


Wavenumber at which the density field becomes nonlinear

POWER SPECTRUM



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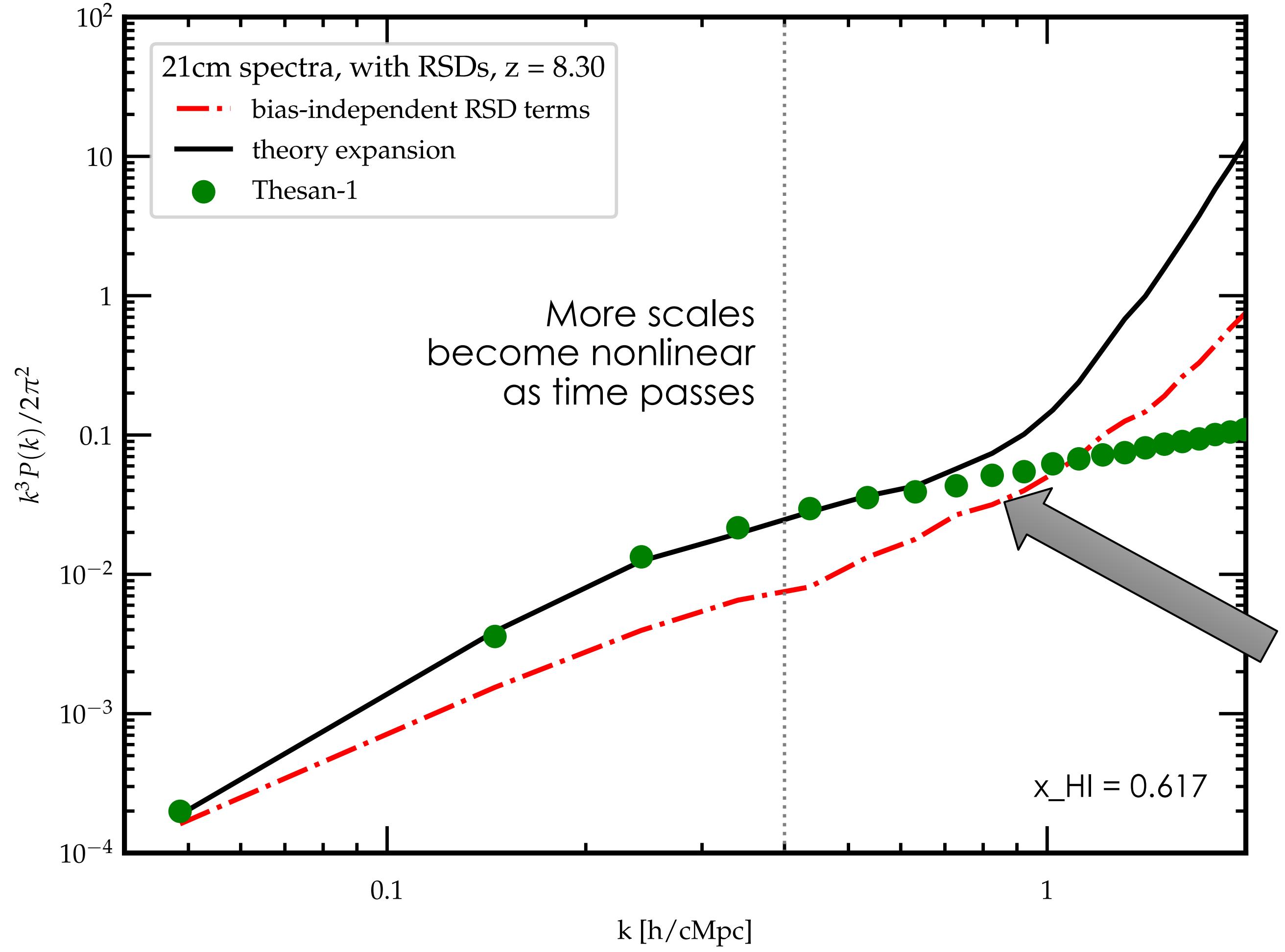
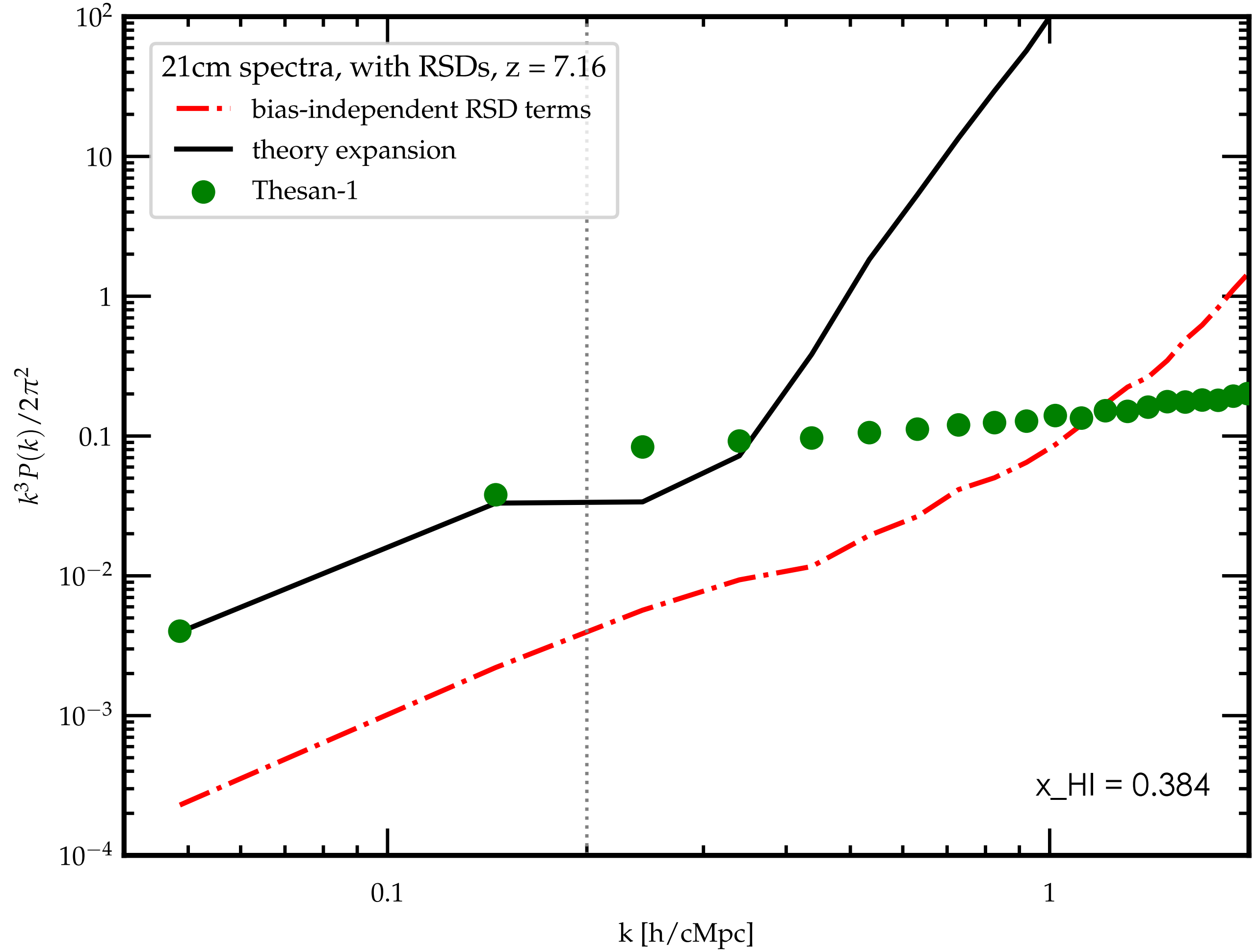


EFT still has predictive power past the wavenumbers that we fit

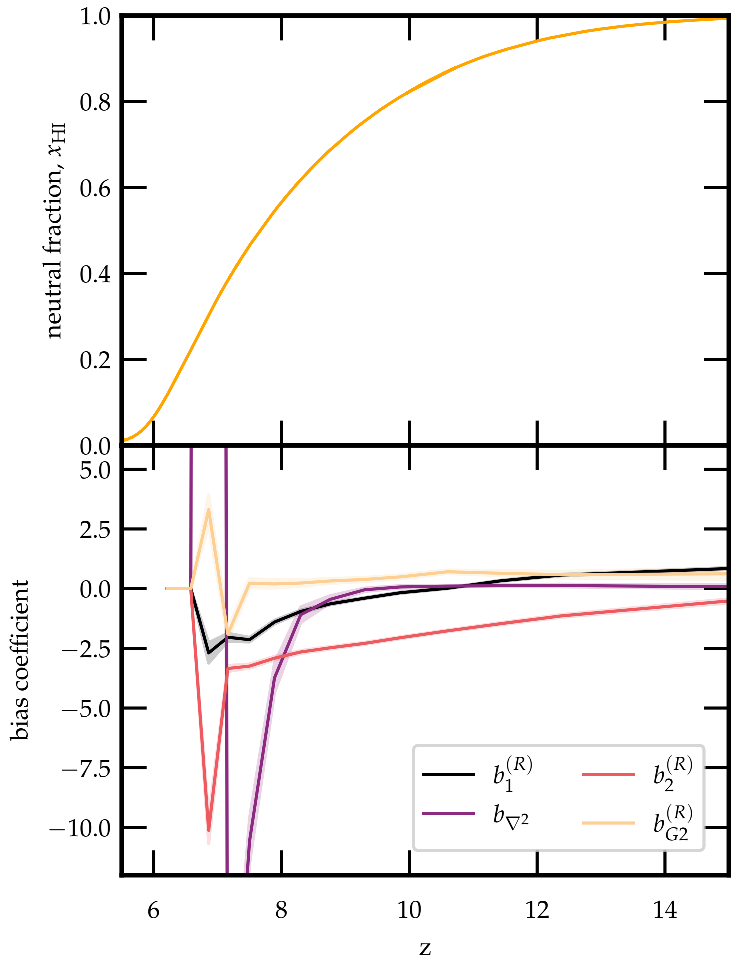
POWER SPECTRUM



At this level of ionization, perturbative theory breaks down

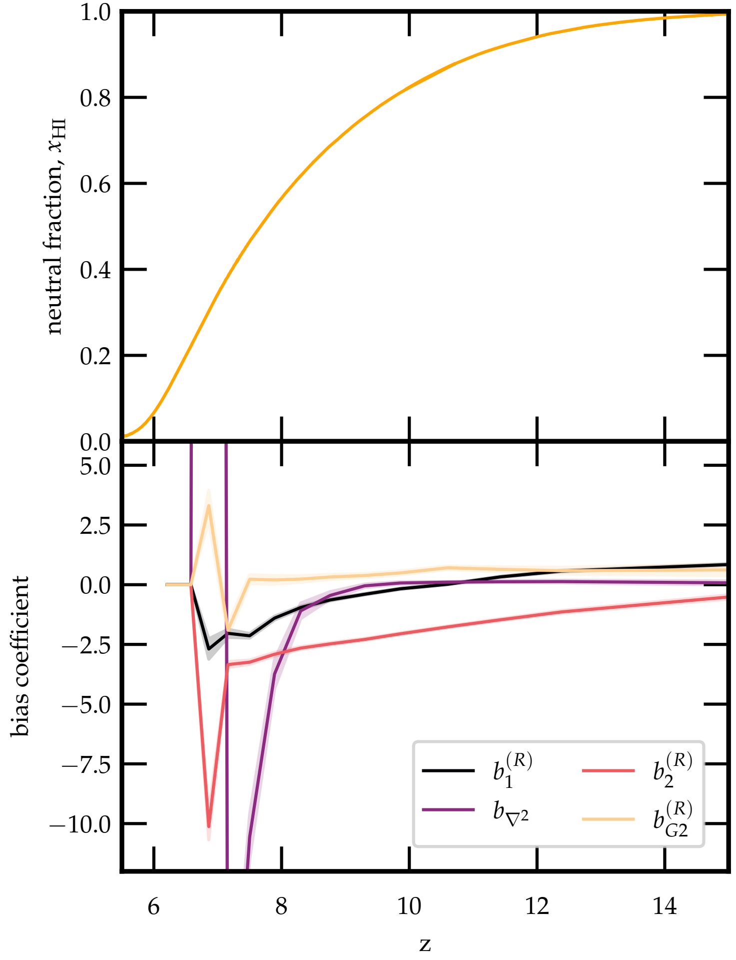
EVOLUTION OF COEFFICIENTS

- How do these coefficients evolve with time?
- Evolution becomes rapid/jagged after a certain time --- theory is breaking down
- At the end of reionization, 21cm signal vanishes

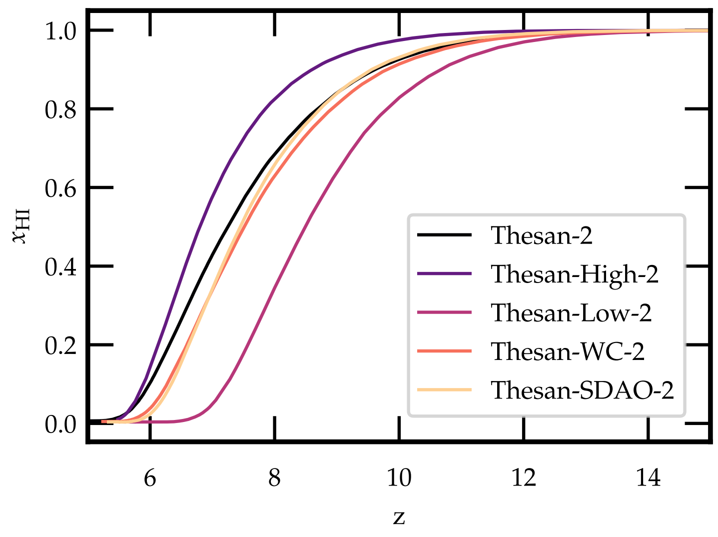


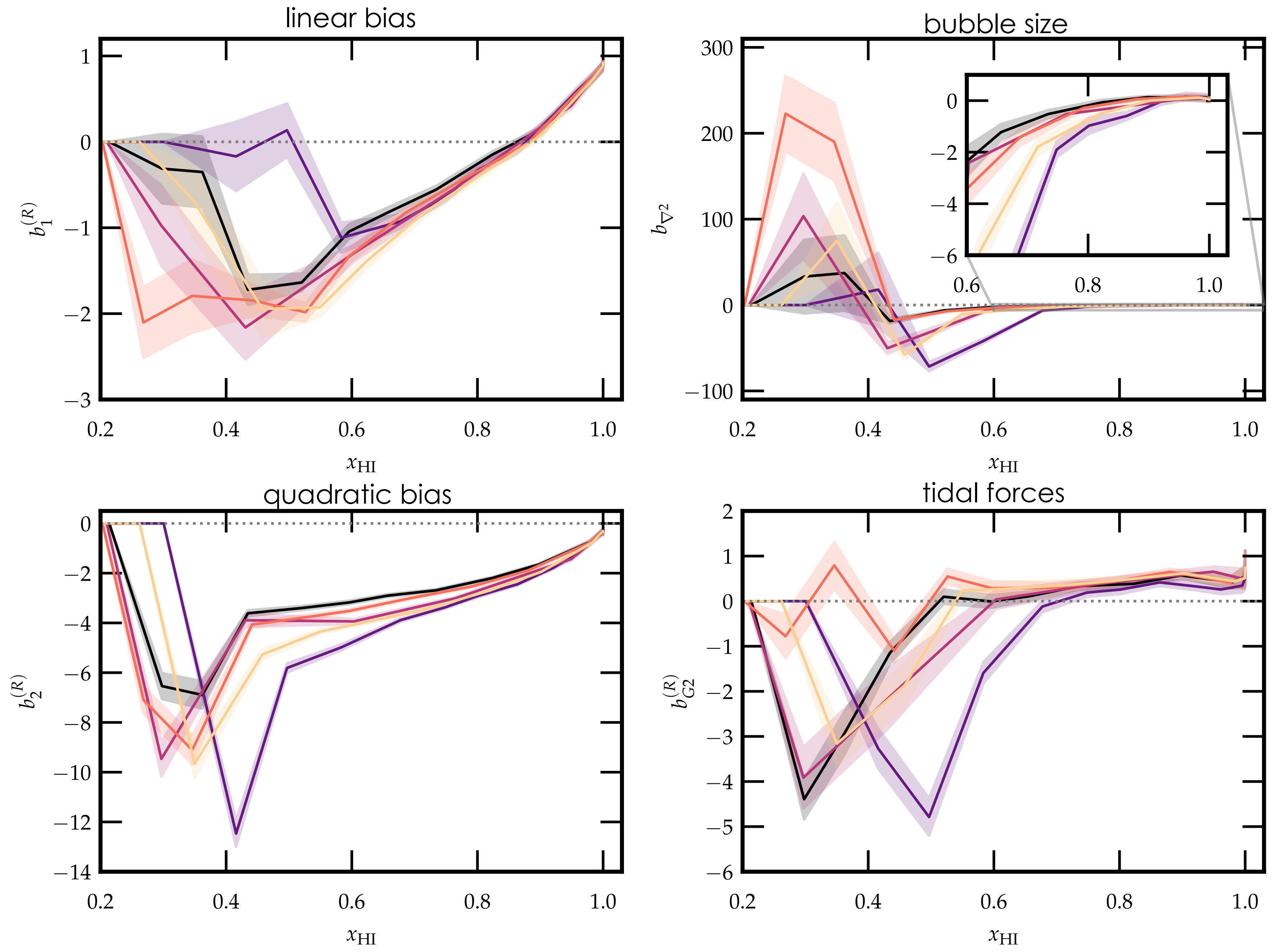
EVOLUTION OF COEFFICIENTS

- Physical interpretations:
  - $b_1^{(R)}$ is linear bias
  - $b_2^{(R)}$ is quadratic bias
  - b_{∇^2} is related to bubble size
  - $b_{G2}^{(R)}$ quantifies anisotropic stresses



SIMULATION DIFFERENCES





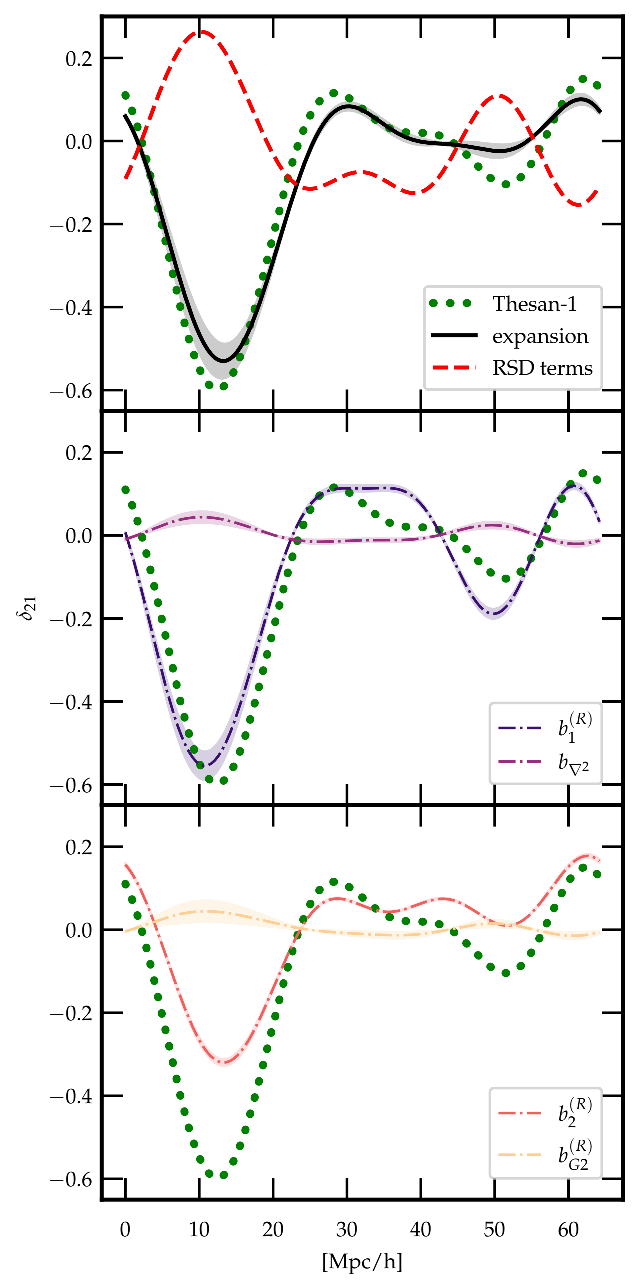
SUMMARY

- On observable scales, we can use perturbative methods
- We've extended these EFT methods, e.g. including RSDs
- Theory expansion is a good fit to simulations, at early enough redshifts and large length scales
- Evolution of coefficients reflects different physics

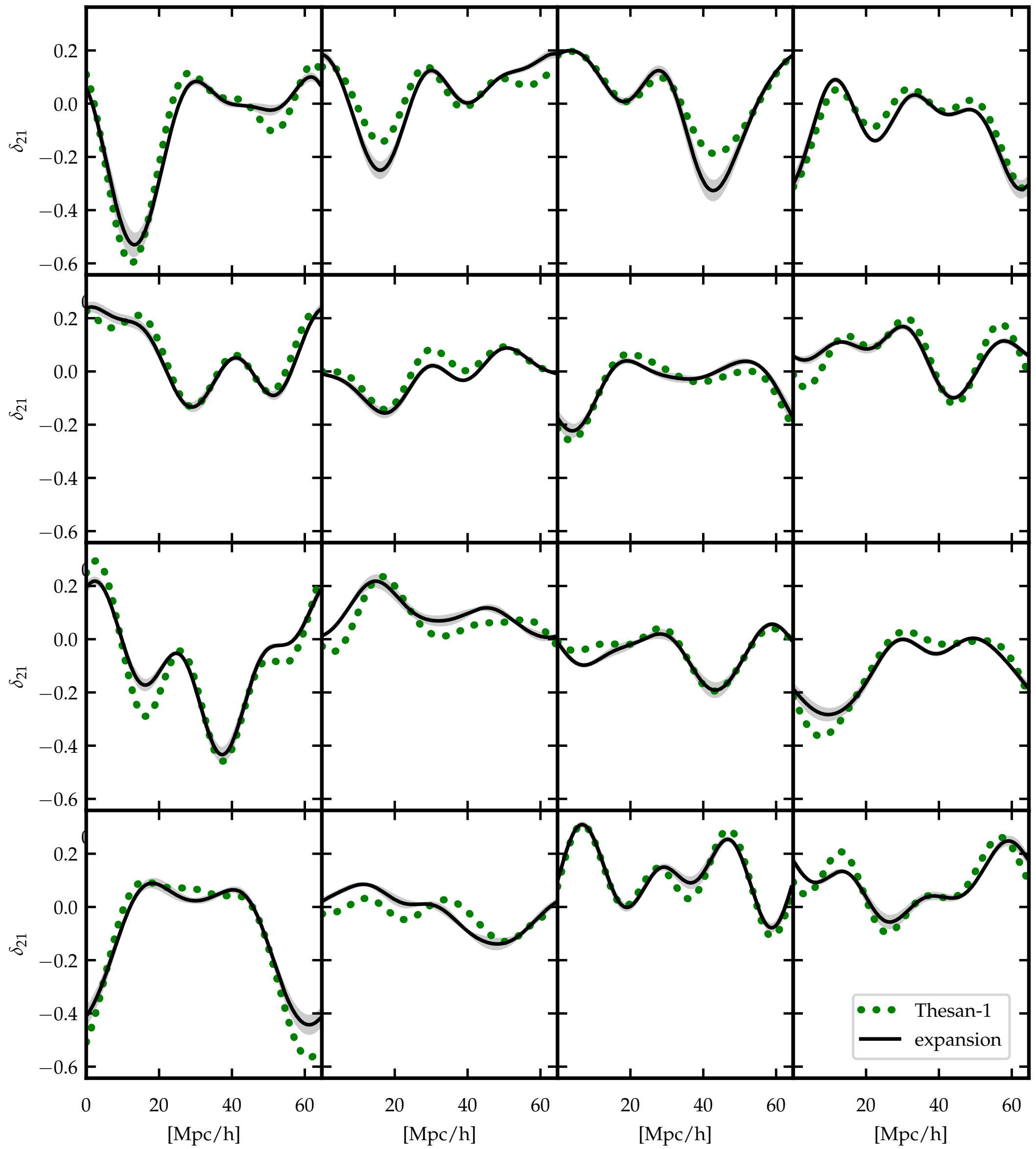
- Future steps:
  - Spin temperature fluctuations
  - Reconstructing modes in the foreground wedge

BACKUP

COMPARISON IN CONFIGURATION SPACE



- 1D slices of 21cm brightness temperature at z = 8.30, x_HI = 0.617
- Smoothed over k = 0.4 h/cMpc



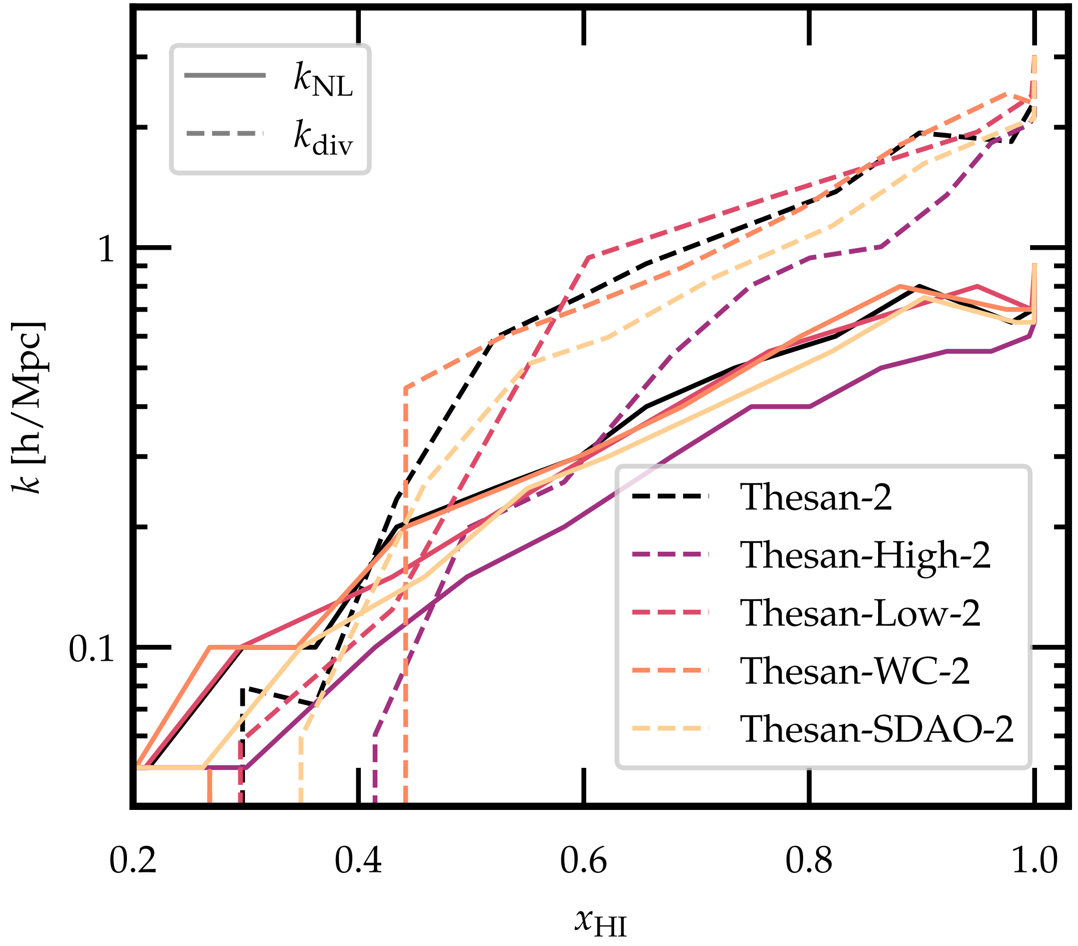
Thesan-1
expansion
δ_{21}
[Mpc/h]
0
20
40
60
0.2
0.0
−0.2
−0.4
−0.6

SMALL SCALE NONLINEARITIES?

- Use a systematic method to remove dependence of observables on small scales/cutoff → *renormalization*

$$[\delta^2] = \delta^2 - \sigma^2(\Lambda)\left(1 + \frac{68}{21}\delta + \frac{8126}{2205}\delta^2 + \frac{254}{2205}\mathcal{G}_2\right) + \cdots$$

WHEN PERTURBATIVITY BREAKS DOWN



EFT SHAPES AS FUNCTION OF ANGLE