

Recovering Cosmic Structure with a Simple Physical Constraint

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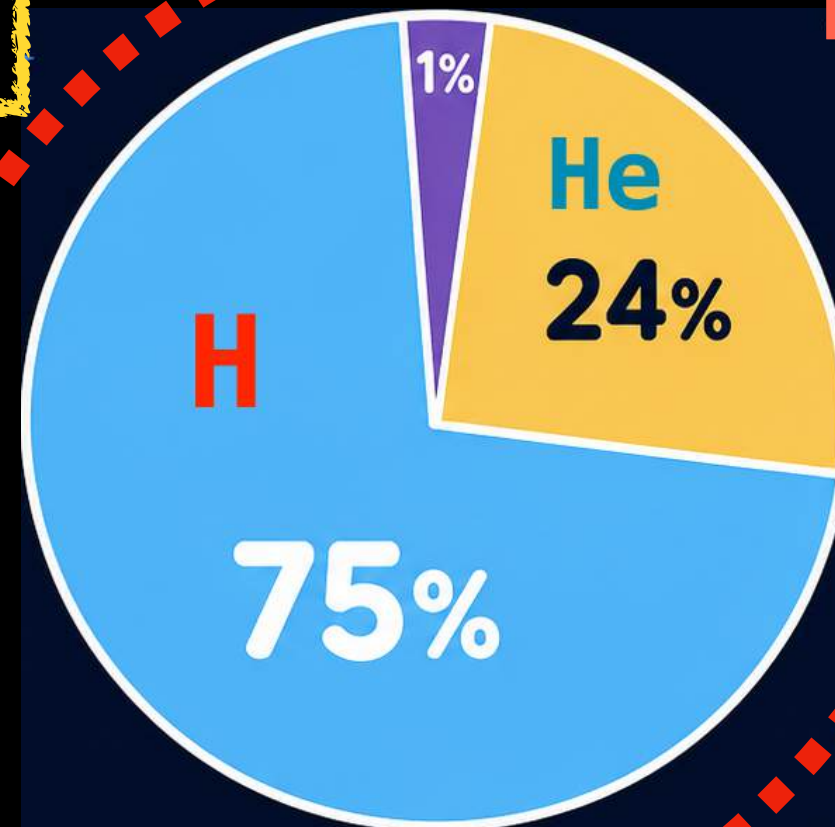
2026.5.24

arXiv: 2503.20434



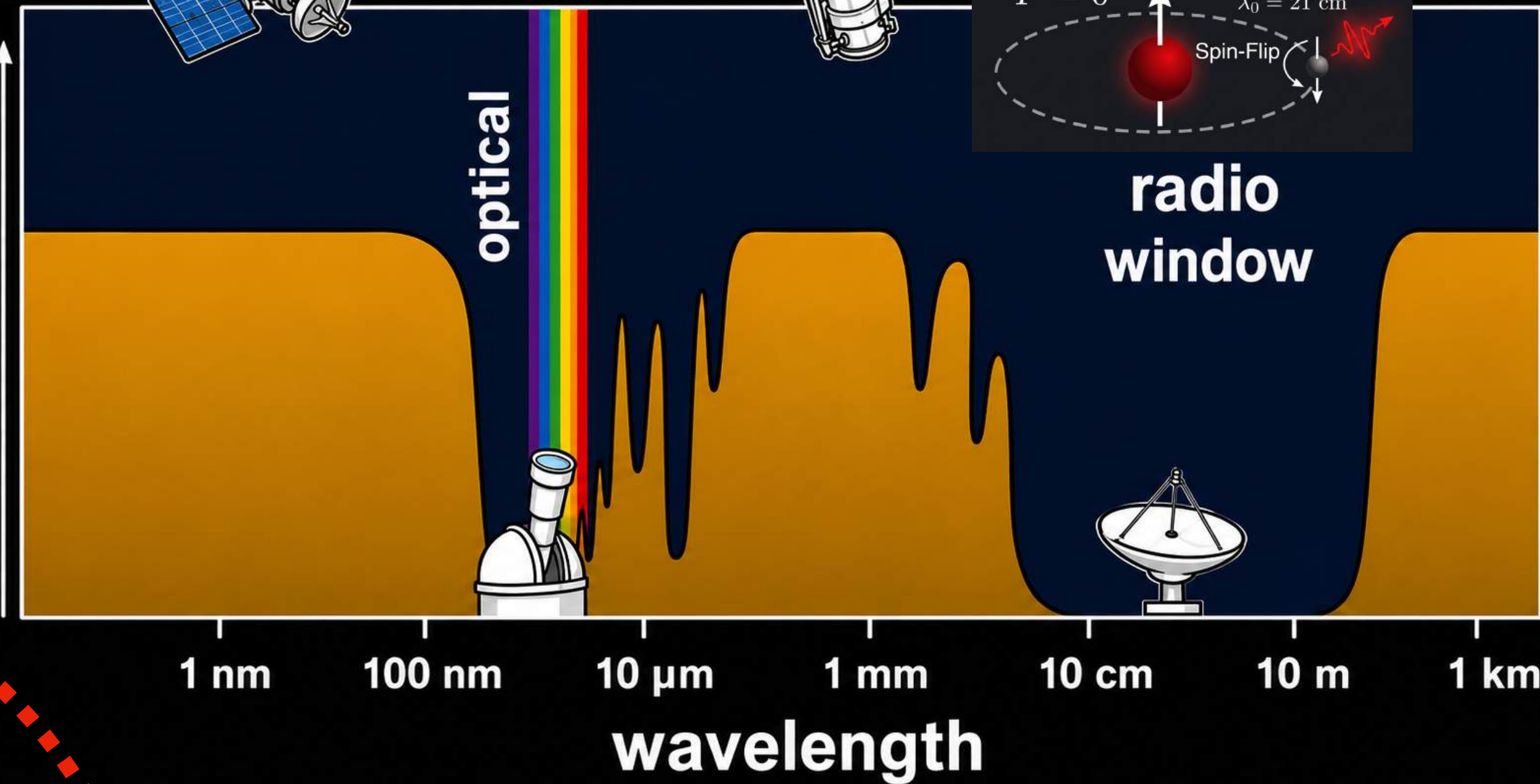
HI Cosmology Ambitions

1. Abundant

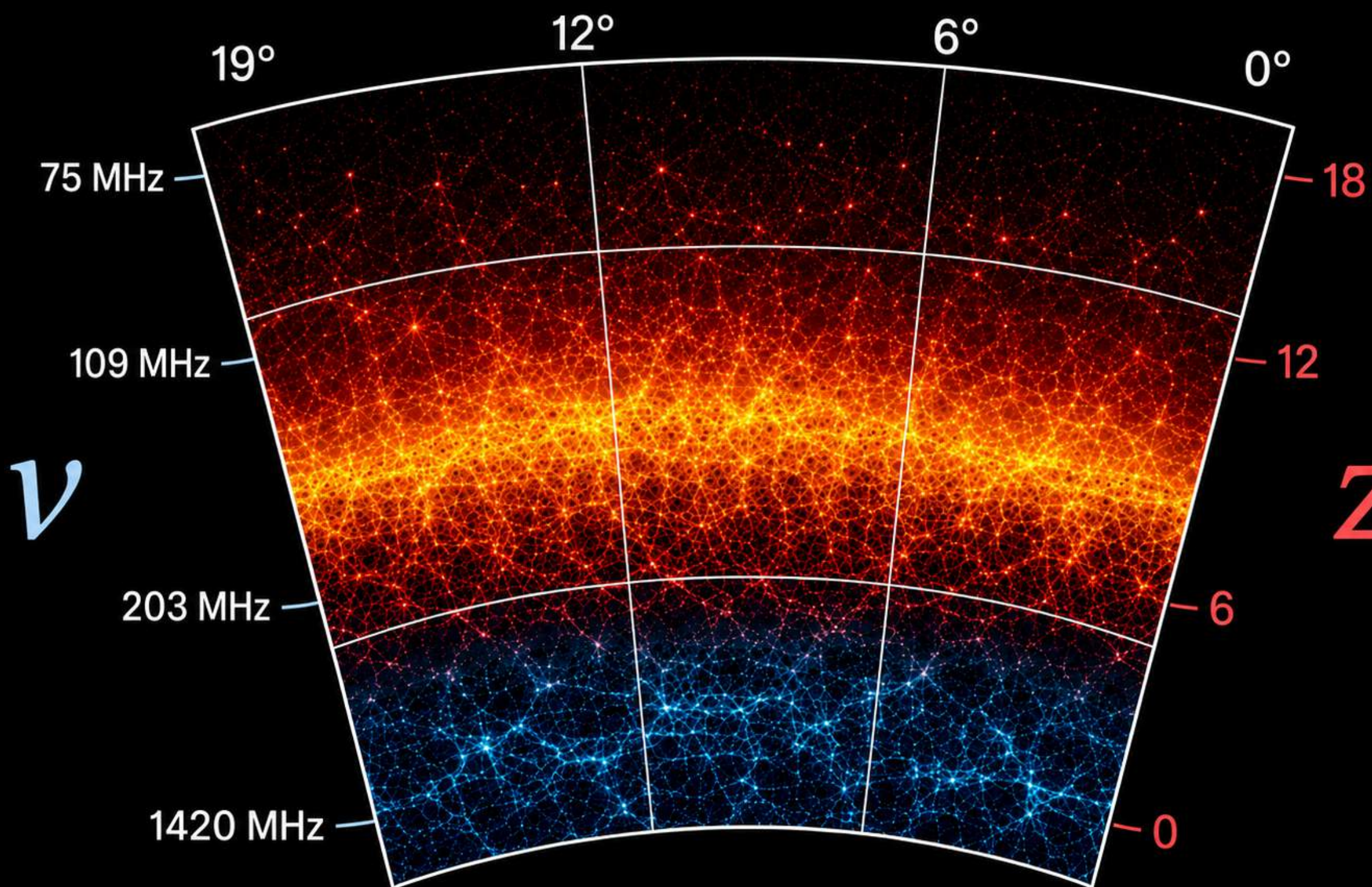


2. Ground Obs. window

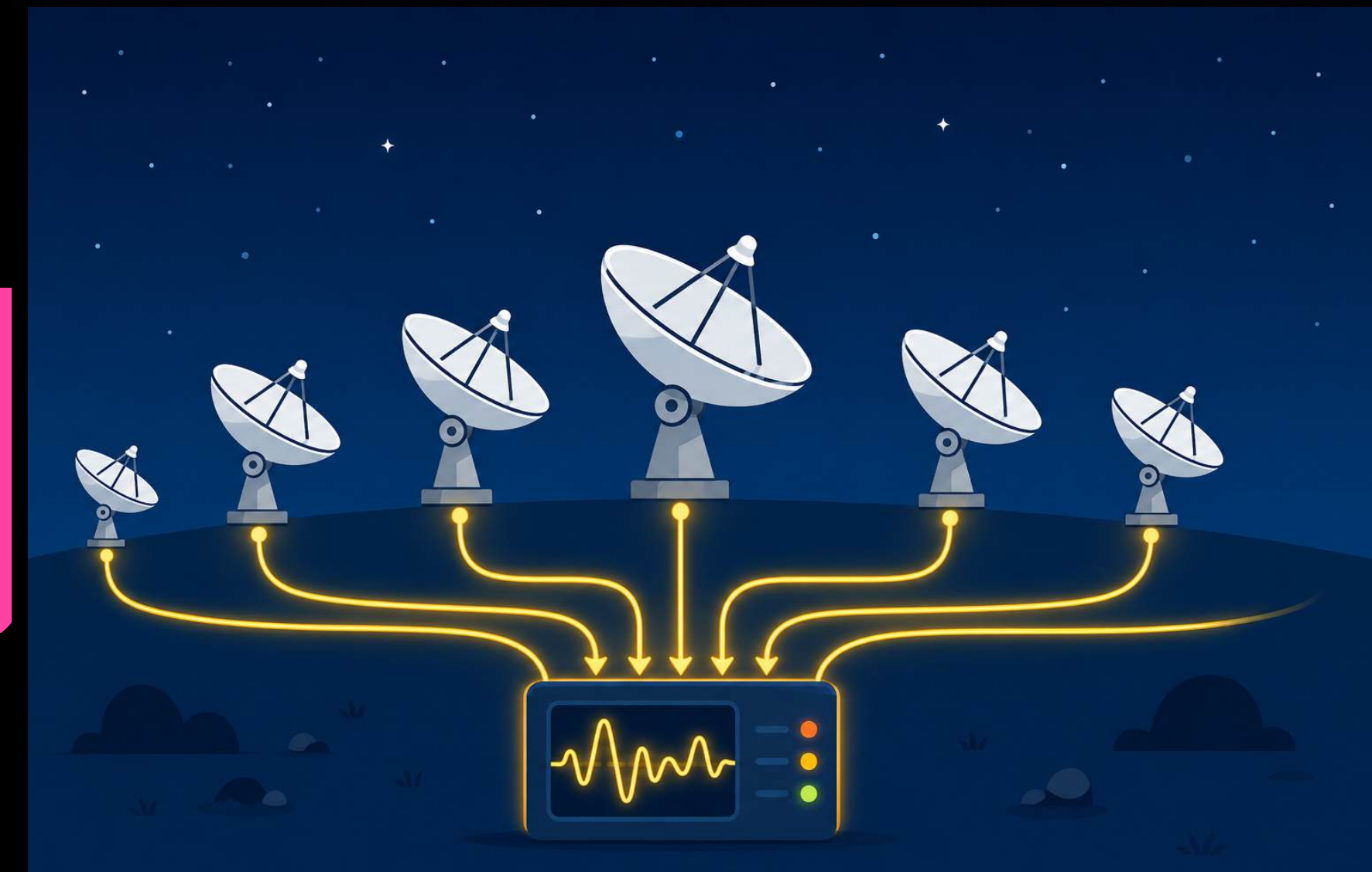
atmospheric opacity



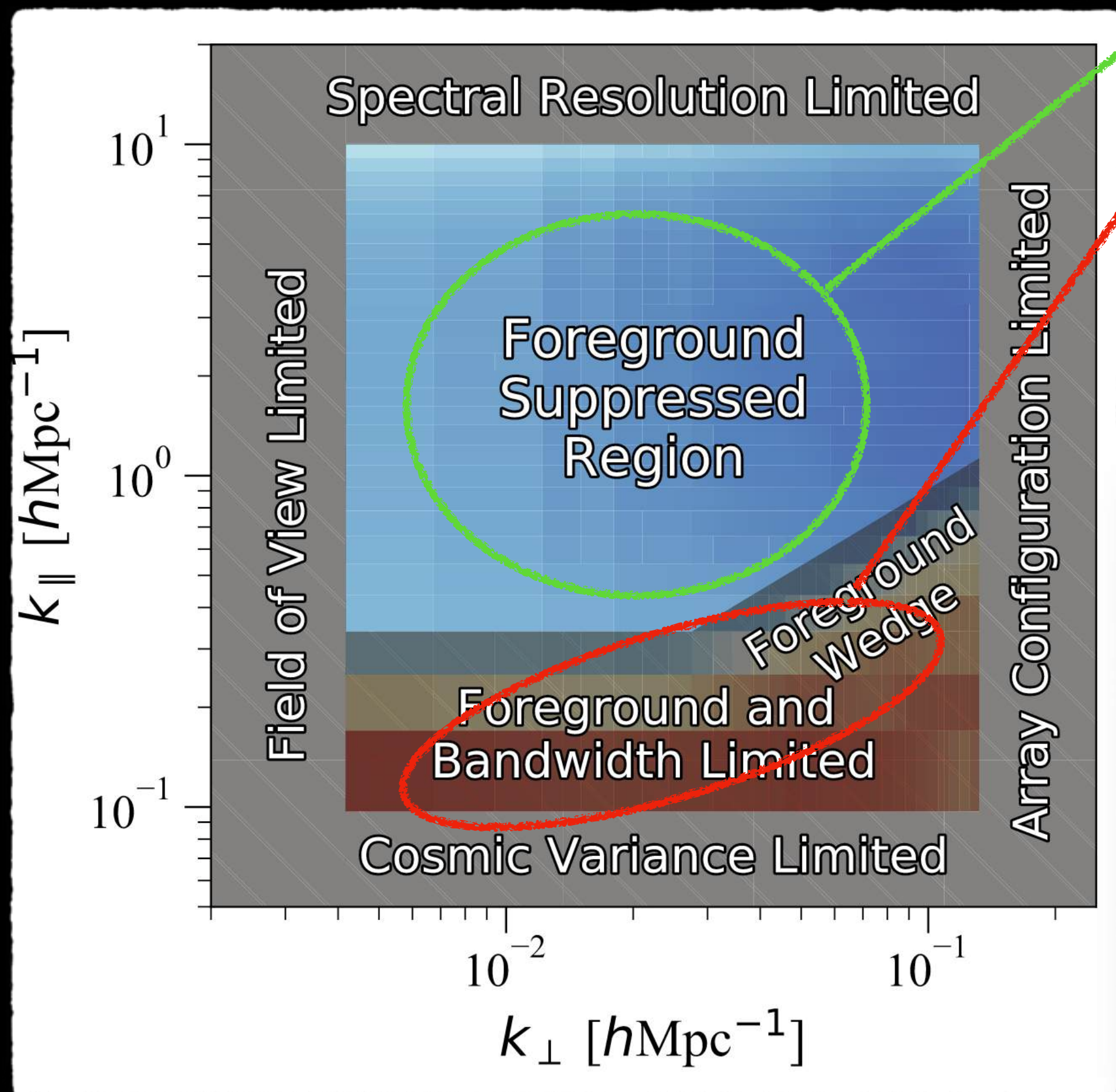
3. Efficient 3D Mapping



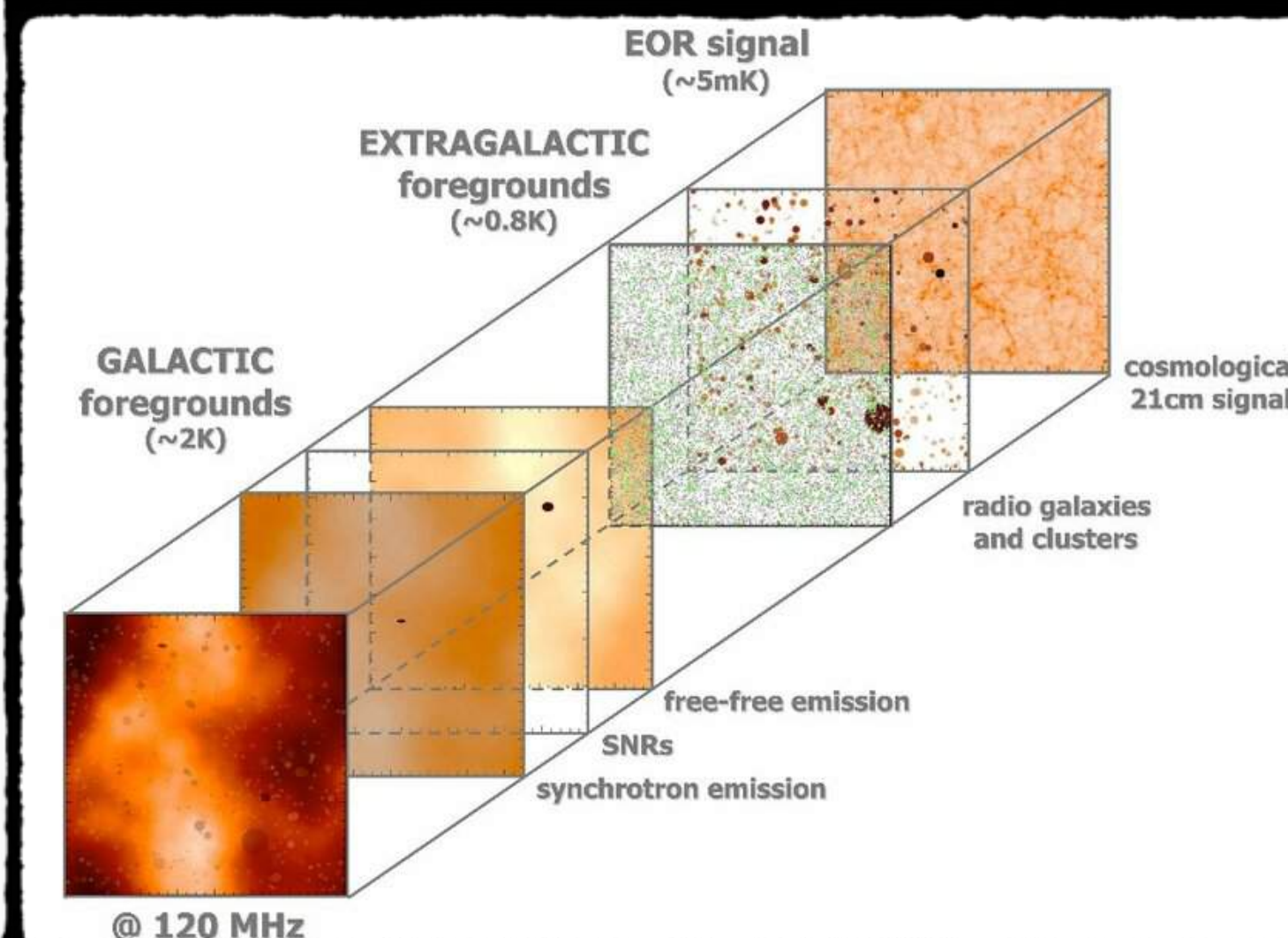
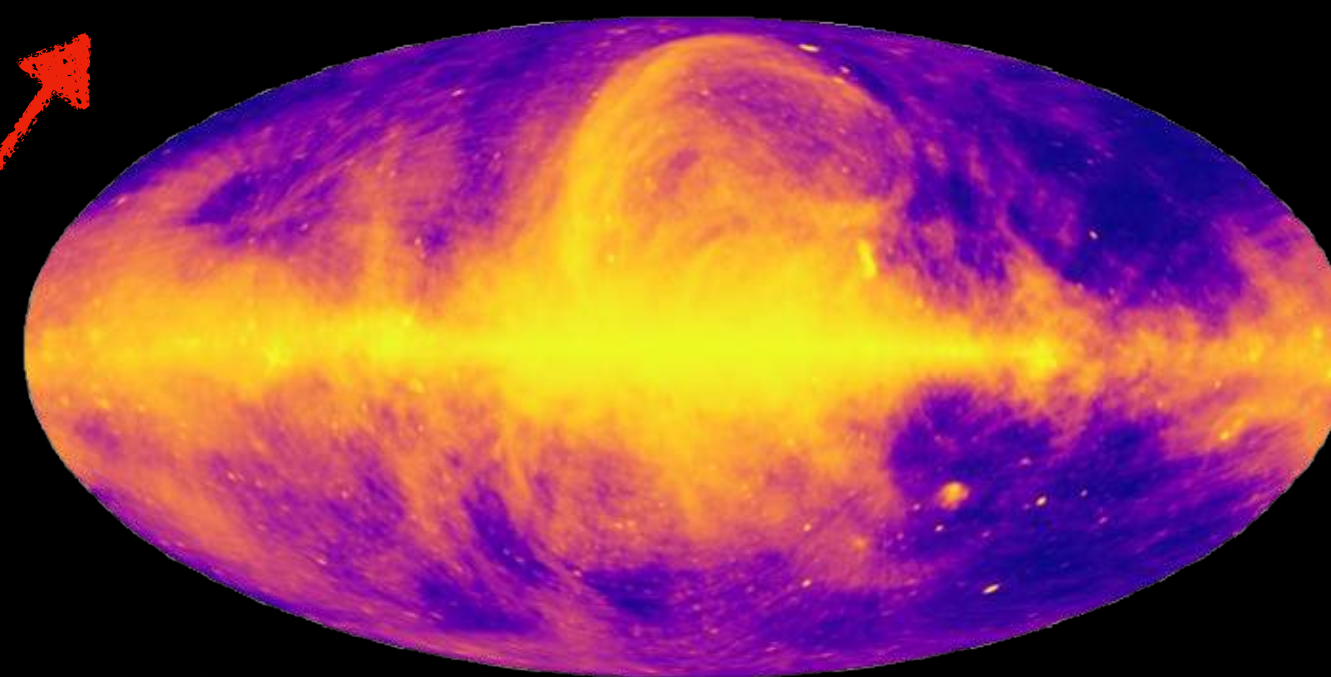
4. Interference
High-res



HI Cosmology Challenges: FOREGROUND



EoR Window
Foreground & Wedge



Solutions?

-> Foreground subtraction scheme

- Spectral smoothness

Model-dependent

- Principal Component Analysis (PCA)

Loss of vital info, subjective

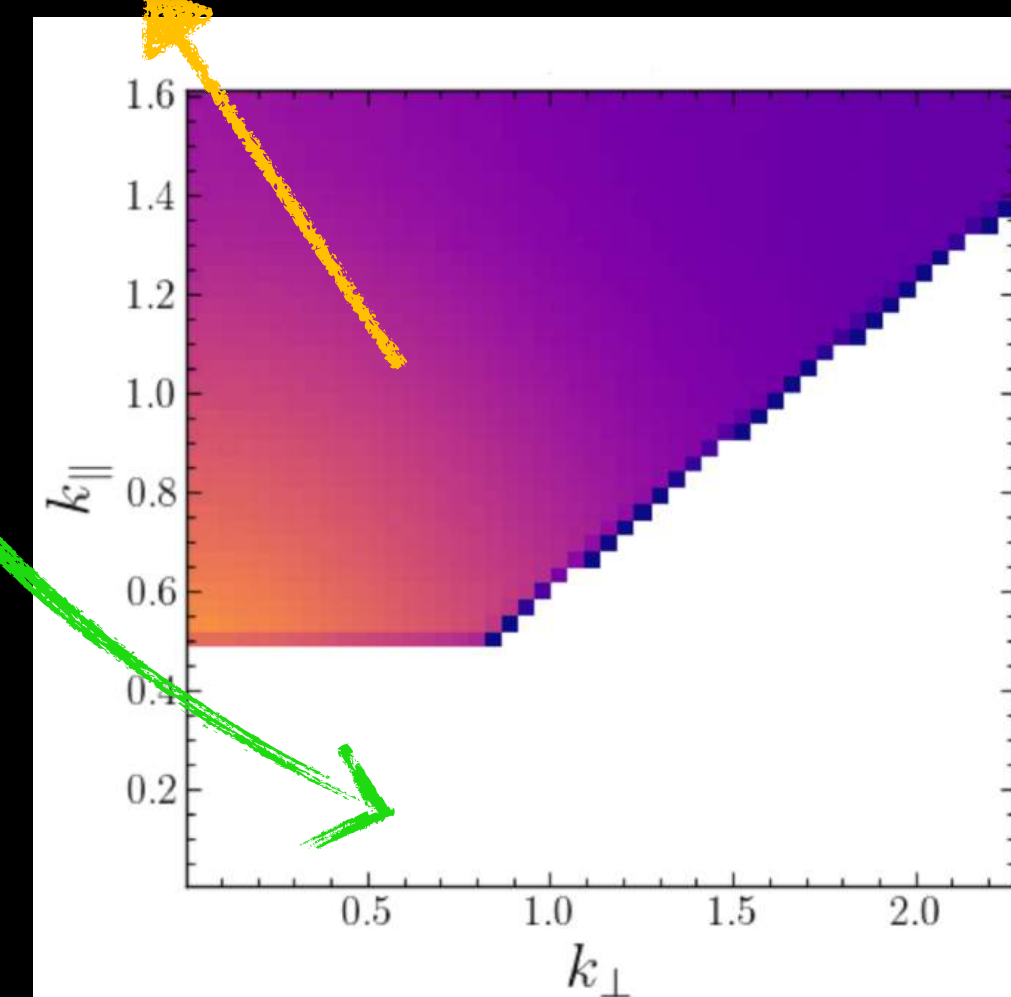
- Independent Component Analysis (ICA)

Model-dependent, complex

- Drop FG modes away...

Conservative

Extract LSS from SSS?



Biggest Challenge!

Solutions? -> From SSS to LSS

Lagrangian-to-Eulerian mapping

$$\mathbf{x} = \mathbf{q} + \Psi(\mathbf{q})$$

$$1 + \delta(\mathbf{x}) = \int d^3q \delta_D [\mathbf{x} - \mathbf{q} - \Psi(\mathbf{q})]$$

$\swarrow \mathcal{F}$

$$\delta(\mathbf{k}) = \int d^3q e^{-i\mathbf{k}\cdot\mathbf{q}} [e^{-i\mathbf{k}\cdot\Psi(\mathbf{q})} - 1]$$

$$= \int d^3q e^{-i\mathbf{k}\cdot\mathbf{q}} \left[-i\mathbf{k} \cdot \Psi - \frac{1}{2} (\mathbf{k} \cdot \Psi)^2 + \sum_{n=3}^{\infty} \frac{(-i)^n}{n!} (\mathbf{k} \cdot \Psi)^n \right]$$

$$\delta^{(2)}(\mathbf{k}) = -\frac{1}{2} \int \frac{d^3k_1}{(2\pi)^3} [\mathbf{k} \cdot \Psi(\mathbf{k}_1)] [\mathbf{k} \cdot \Psi(\mathbf{k} - \mathbf{k}_1)]$$

Mode coupling emerges

- Cosmic tidal reconstruction

Zhu et al., 2016, DOI: 10.1103/PhysRevD.93.103504



Quadratic
estimator

Rely on 2LPT

Complex

Sensitivity

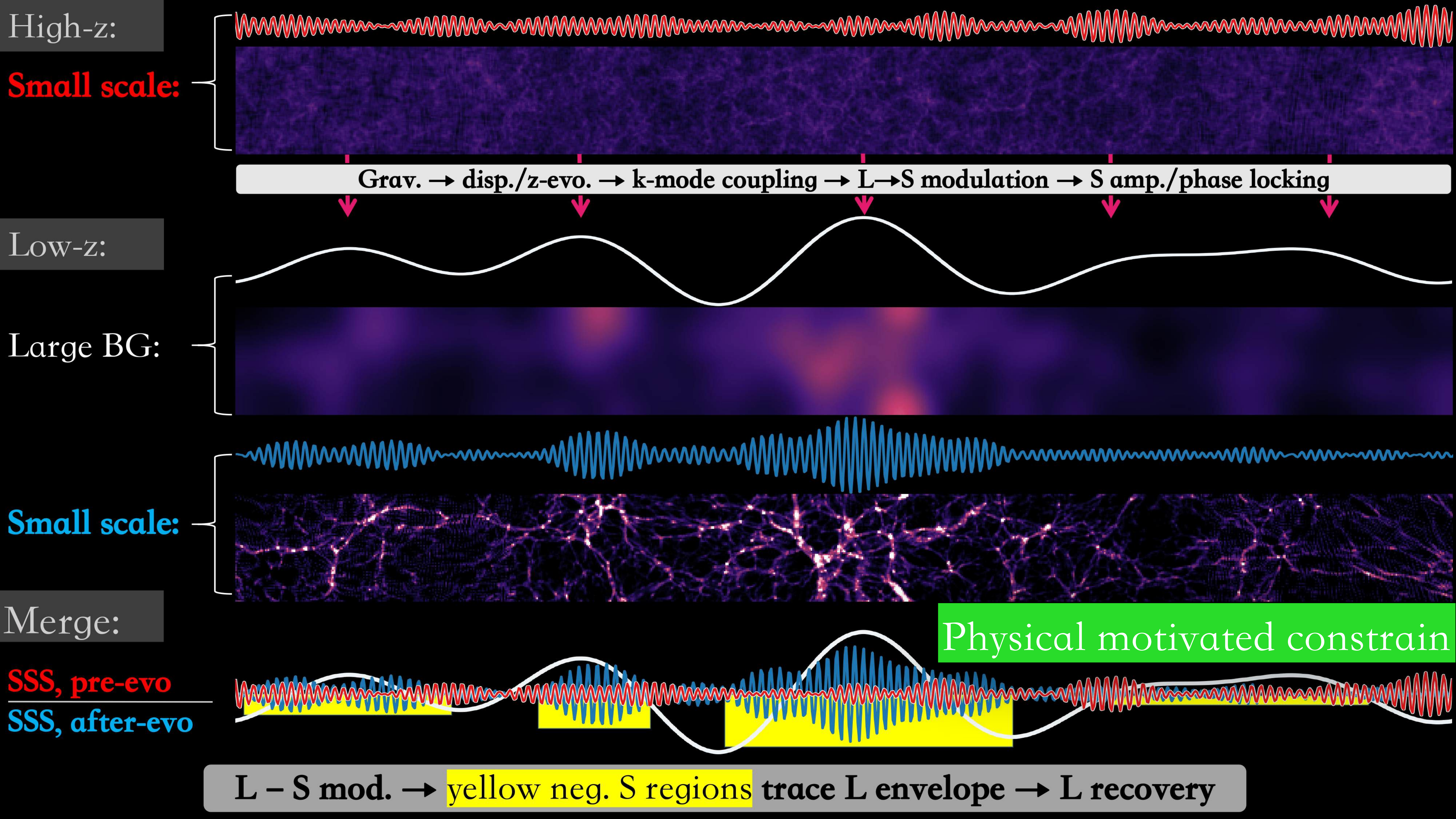
- Deep learning

Qian Li, XW, Xiaodong Li, TCL et al., 2025

Kaifeng Yu, XW et al., 2026

$$\mathcal{L}_\delta = \frac{1}{N} \sum_{i=1}^N \left[\delta_T^{\text{pred}}(\mathbf{x}_i) - \delta_T^{\text{true}}(\mathbf{x}_i) \right]^2$$

Capture higher order coupling



Toy Model illustration

Displacement potential: $\phi = A \sin(\nu_1 x + \Phi_1) + A \sin(\nu_2 x + \Phi_2)$

Positivization

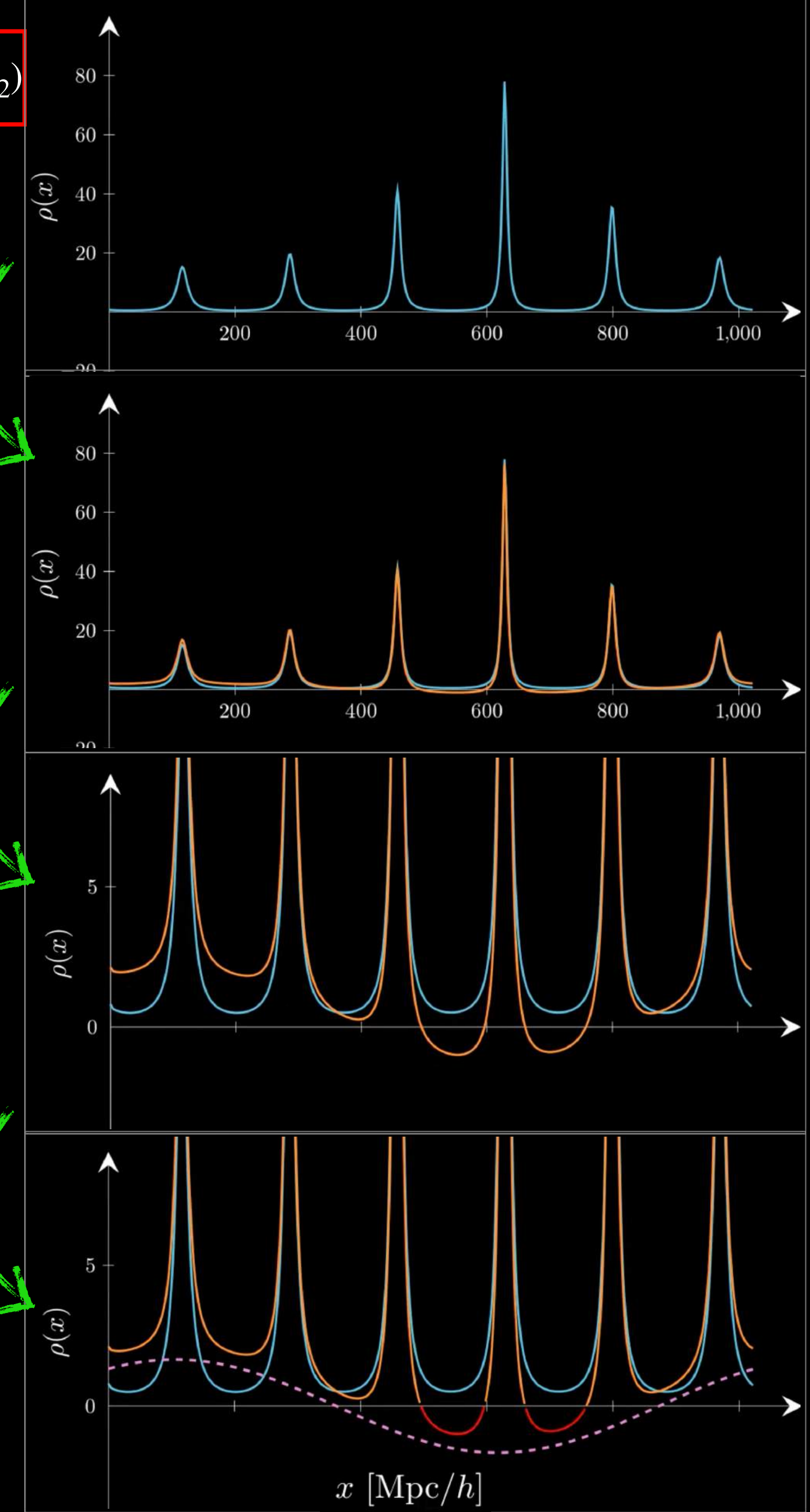
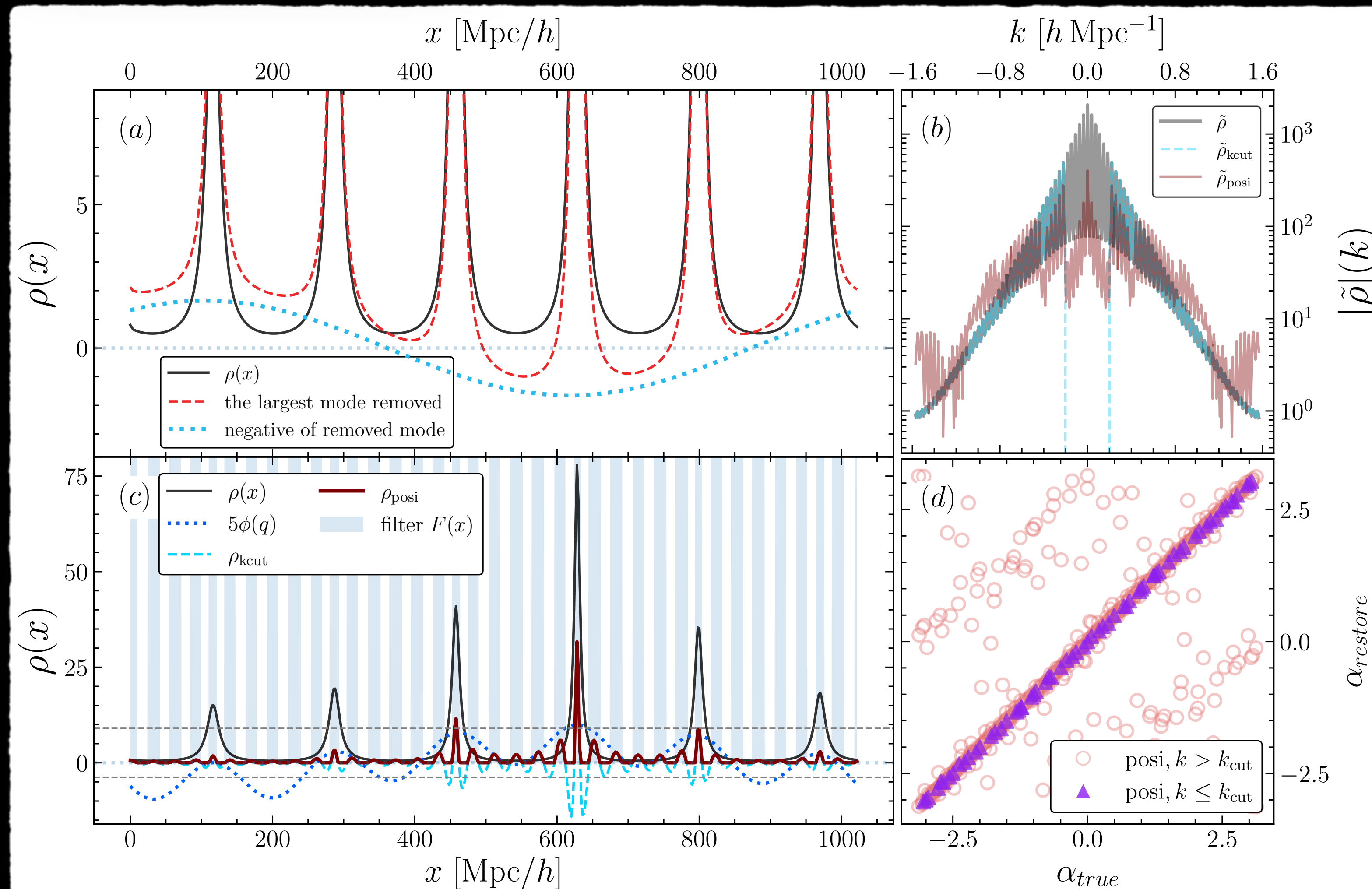
TCL, XW et al., 2025

Zel'dovich Approximation:

$$\mathbf{x} = \mathbf{q} + A(t) \nabla \phi$$

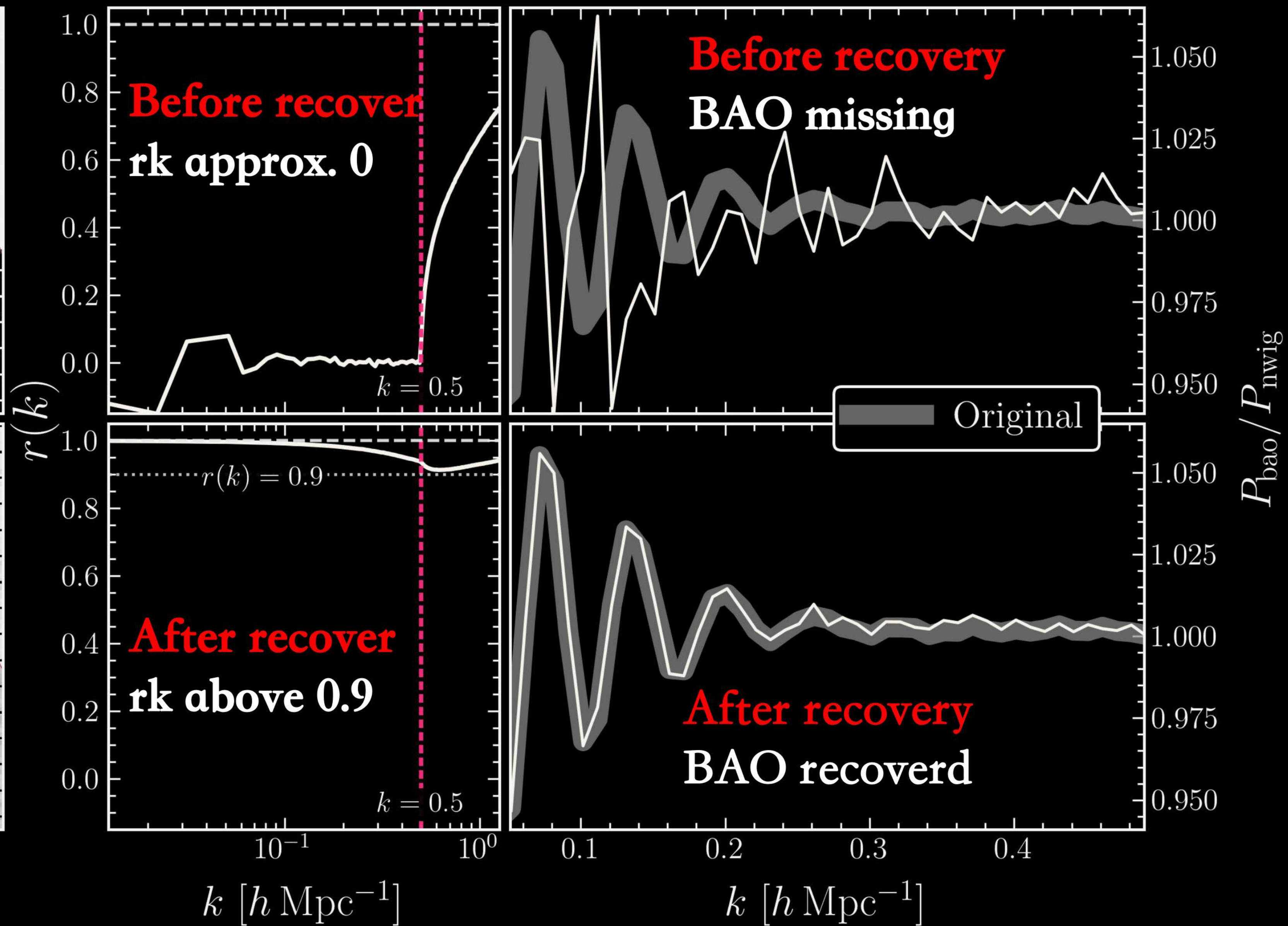
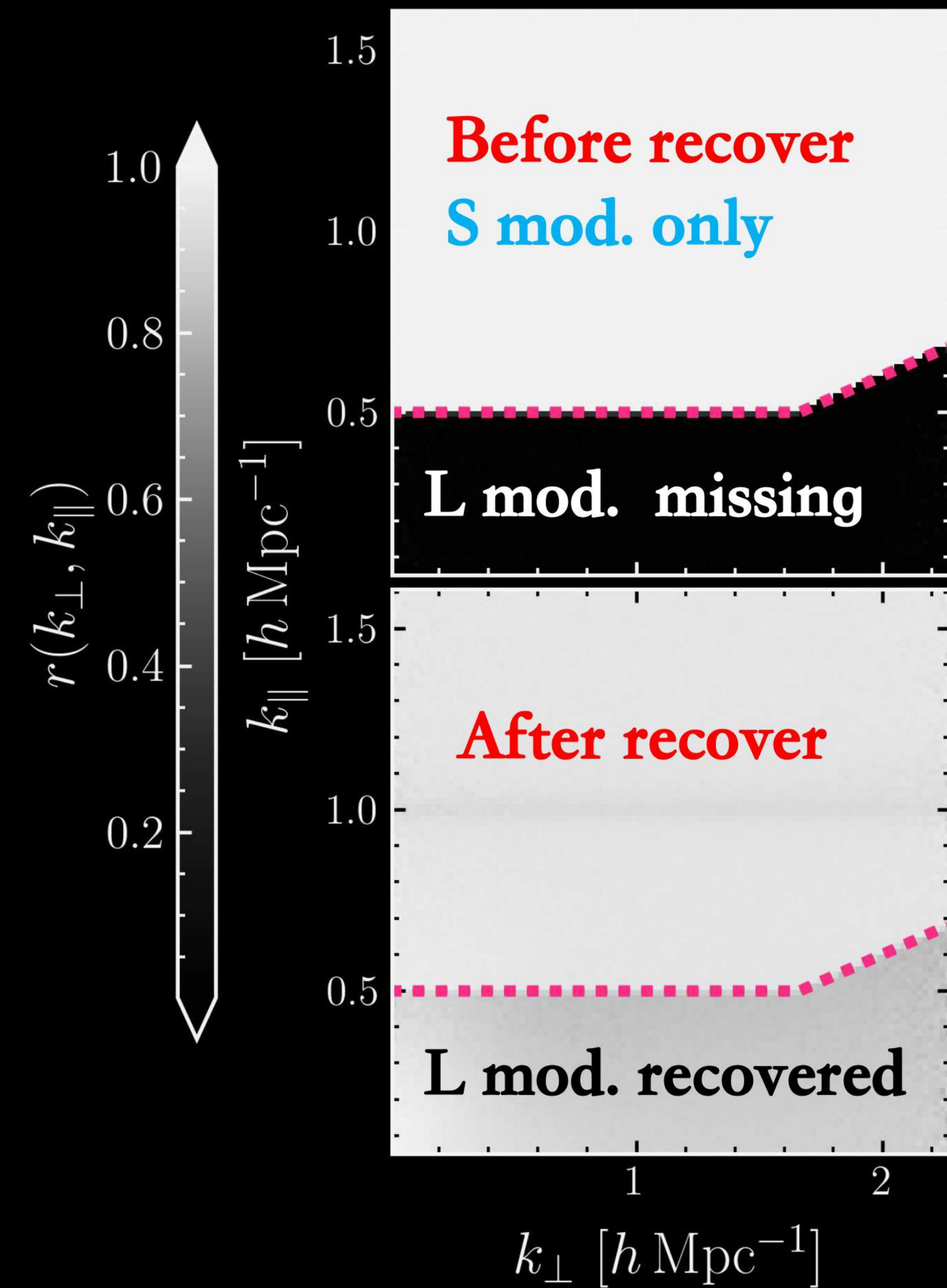
Evolved density:

$$\rho(\mathbf{x}) = \frac{1}{1 + A(t) \nabla^2 \phi}$$

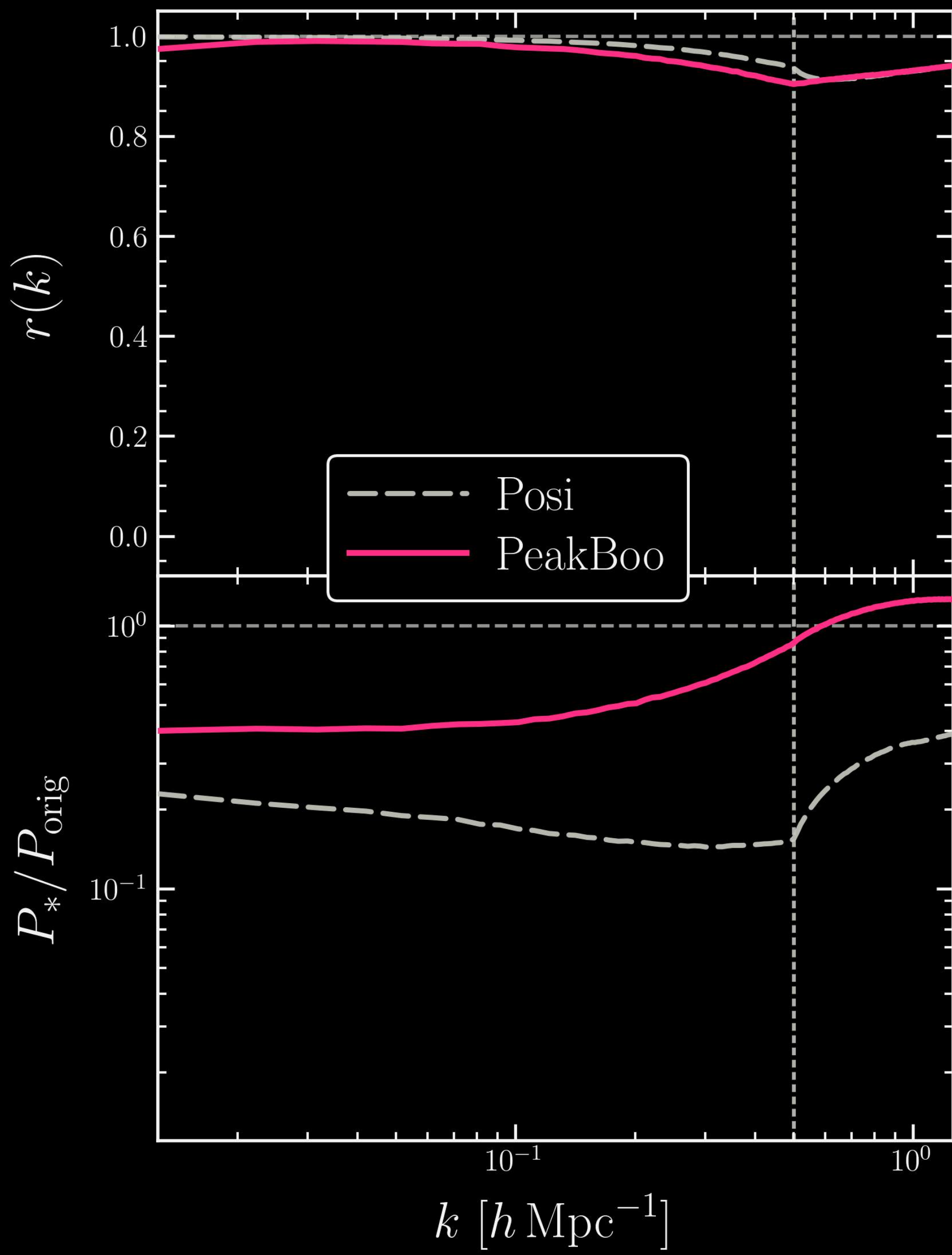


Positivization on 3D

Cross-correlation ratio: $r(k) = \frac{P_{12}}{\sqrt{P_1 P_2}}(k)$



Beyond Positivization



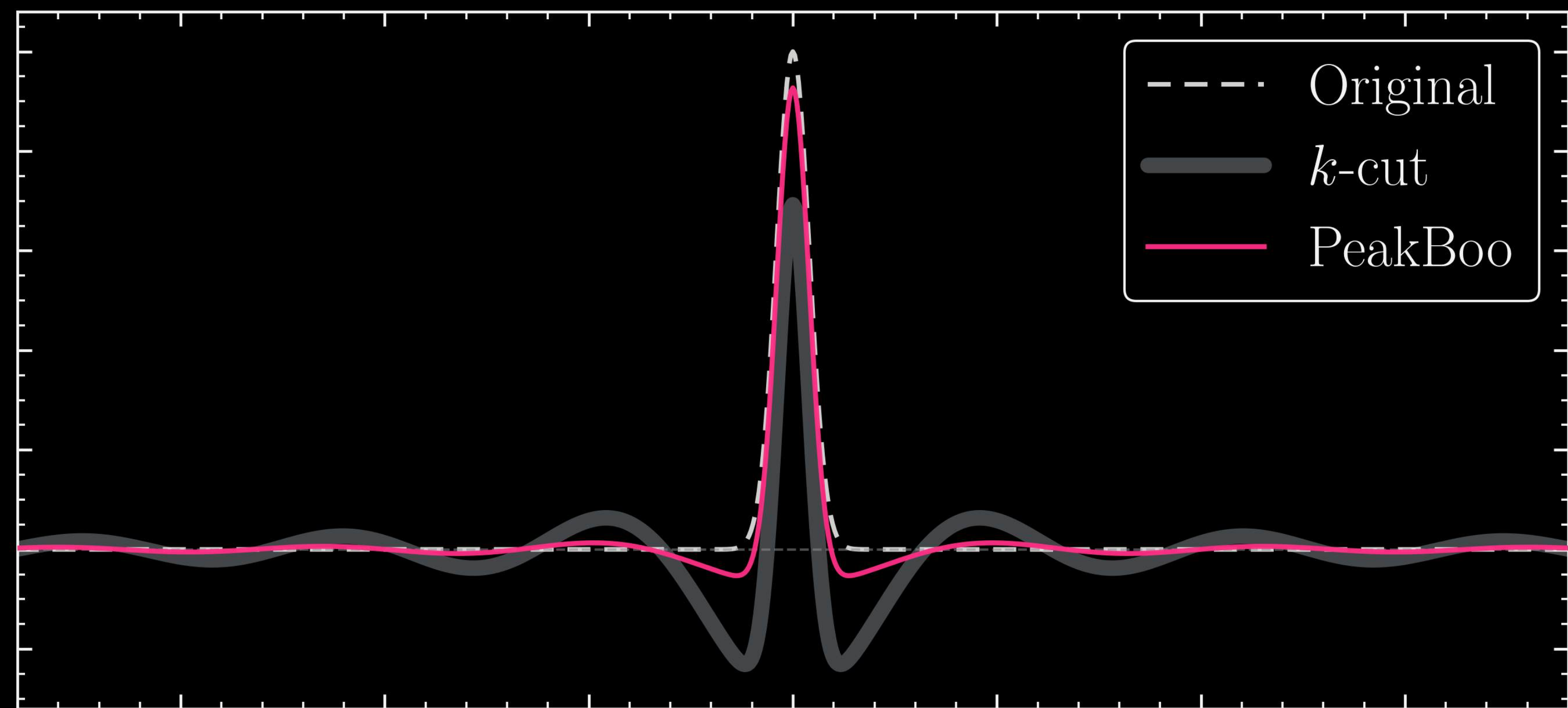
PeakBoo

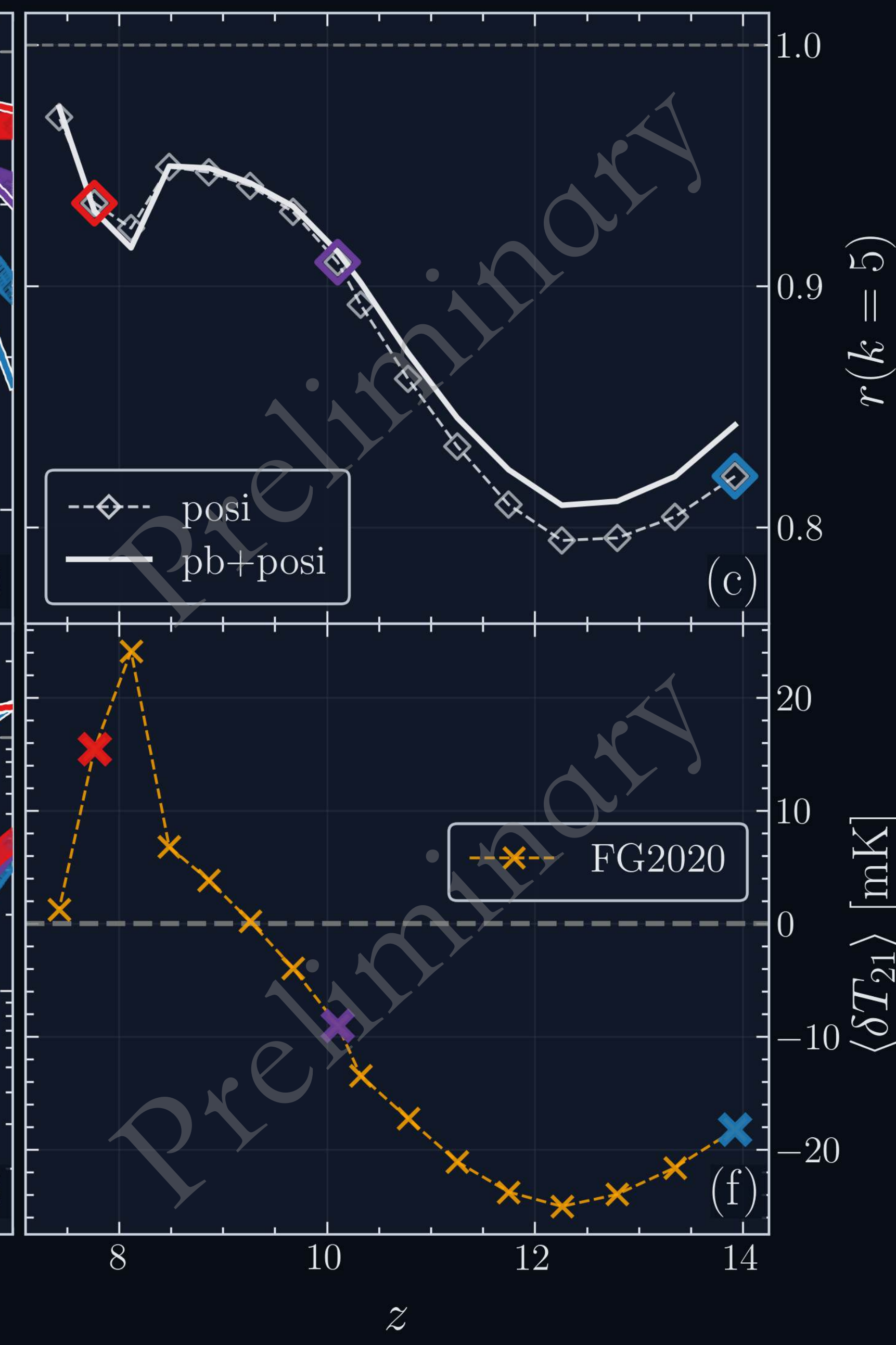
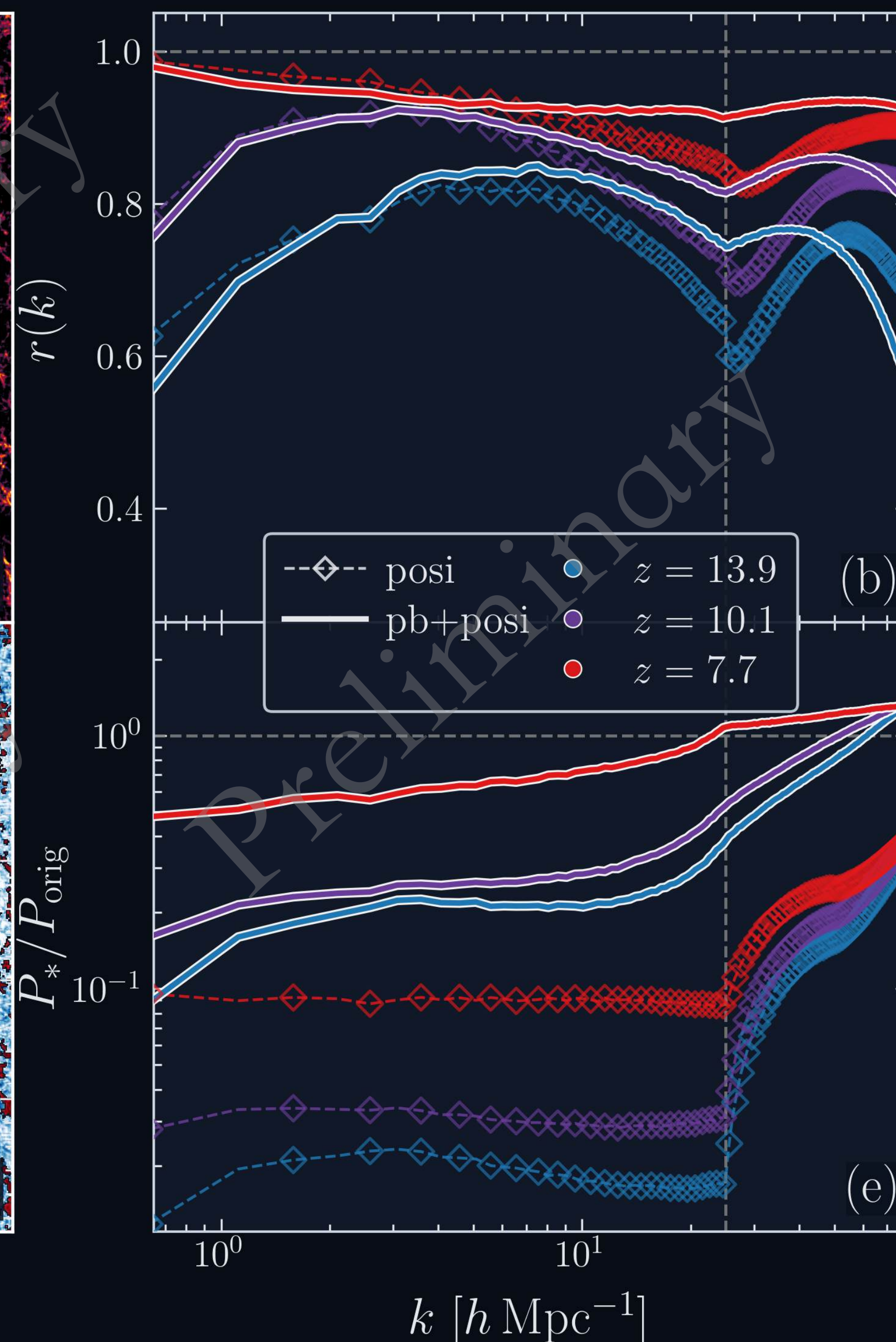
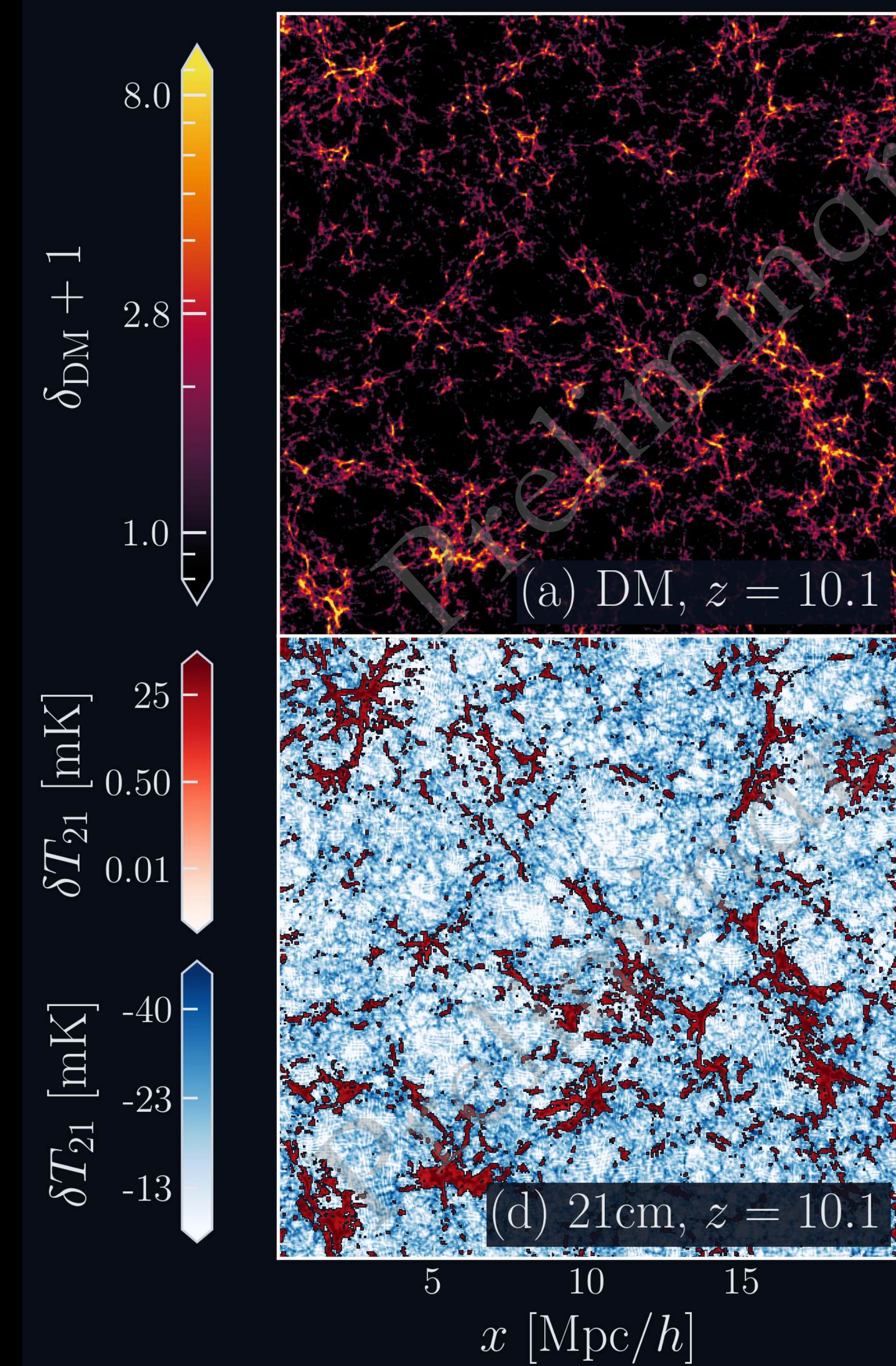
XW, TCL, in prep. 2026

$$\widetilde{W}_{k_c}(k) = \Theta(k_c - |k|) \quad W_{k_c}(x) \sim \text{sinc}(k_c x)$$

$$\mathcal{F} : \quad \tilde{T}_{\text{cut}} = \tilde{T}_{\text{orig}}(1 - \widetilde{W}_{k_c}) \quad \mathcal{R} : \quad T_{\text{cut}} = T_{\text{orig}} - T_{\text{orig}} * W_{k_c}$$

$$T_{\text{orig}}(x) \sim \sum_i A_i \delta_D(x - x_i) \quad T_{\text{orig}} * W_{k_c} \sim \sum_i A_i \text{sinc}[k_c(x - x_i)]$$





Summary

HI Cosmology

- Ambitions
- Challenges

Solutions?

- FG mitigation
- Recover (pre)
- Recover (our, physical constrained)

Ongoing

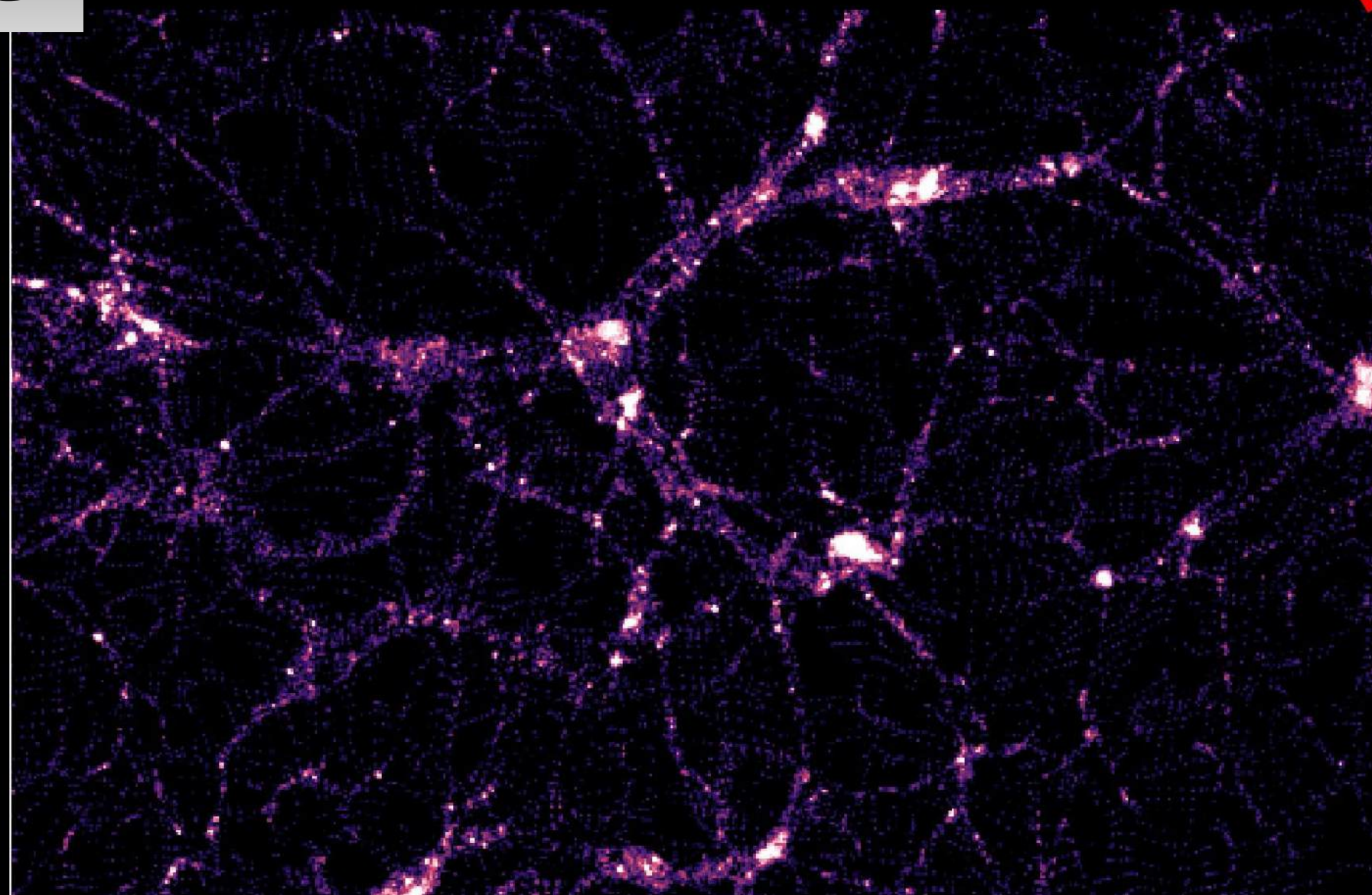
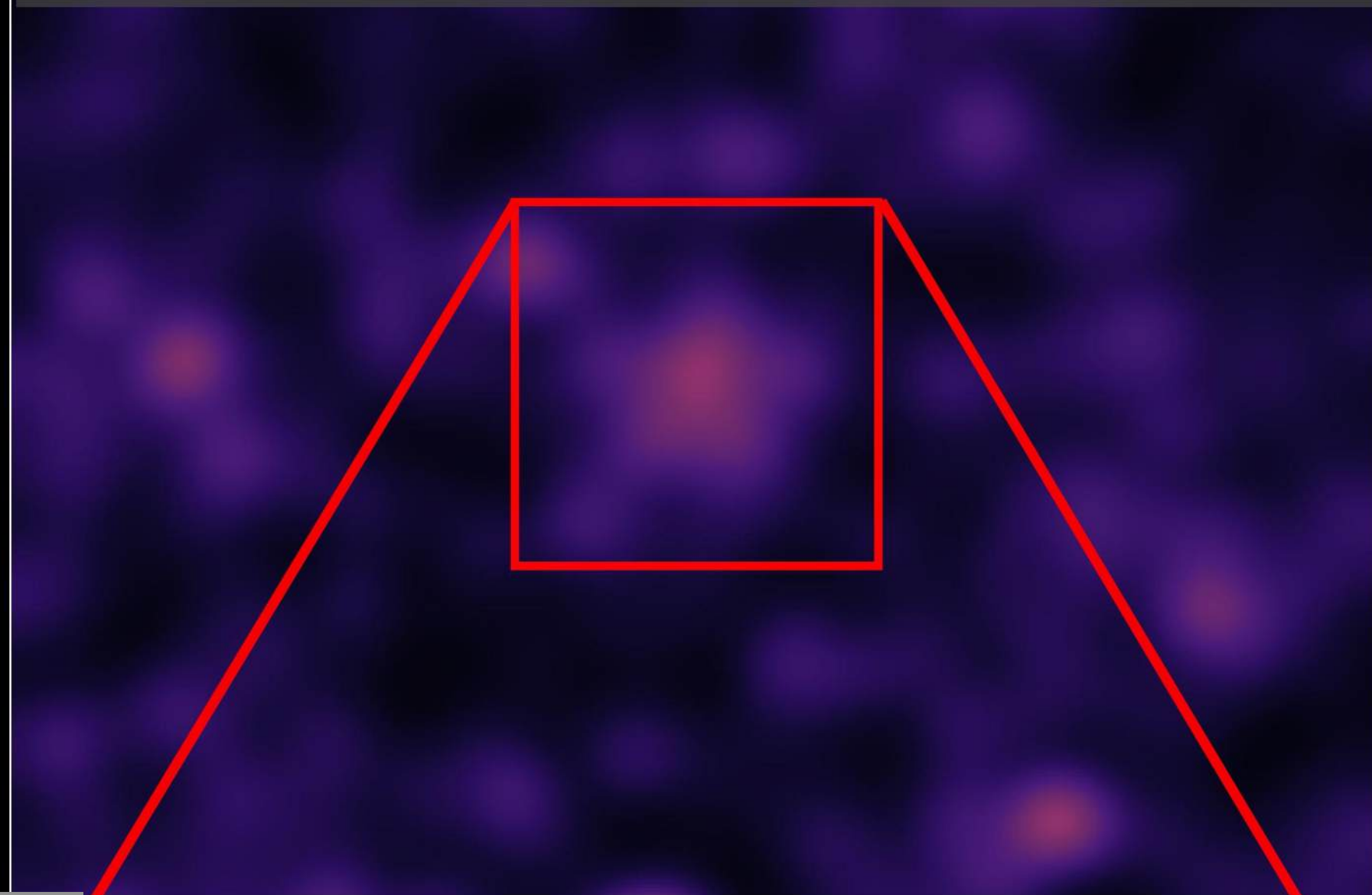
- Apply on obs
- Theory modeling

STAY TUNED 😊



ENCODING

Large scale background



Small scale fluctuation