Probing Beyond ΛCDM Cosmologies with the 21cm Signal

Evolving Dark Energy and EFT Corrections

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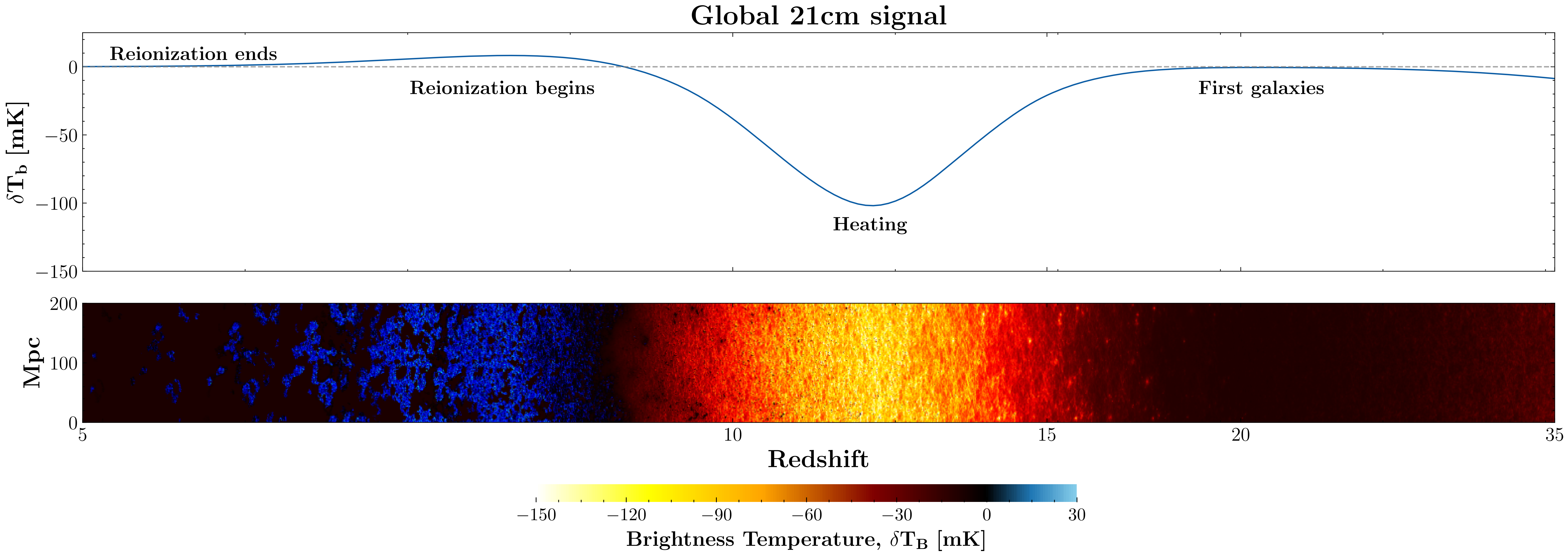
The 21cm Signal



- 21cm signal tracks evolution of structure formation and reionization
- Need simulations to connect future observations to theory
- Signal depends strongly on density field: $$\delta T_b(x, z) = \frac{T_S - T_\gamma}{1+z}(1 - e^{-\tau_{\nu_0}}) \propto x_{\mathrm{HI}}(1 + \delta_{\mathrm{nl}}) \left(\frac{H}{\mathrm{d}v_r/\mathrm{d}r + H} \right)$$

Figure: made with 21cmFAST

Questions

→ How does evolving dark energy affect the 21cm signal?

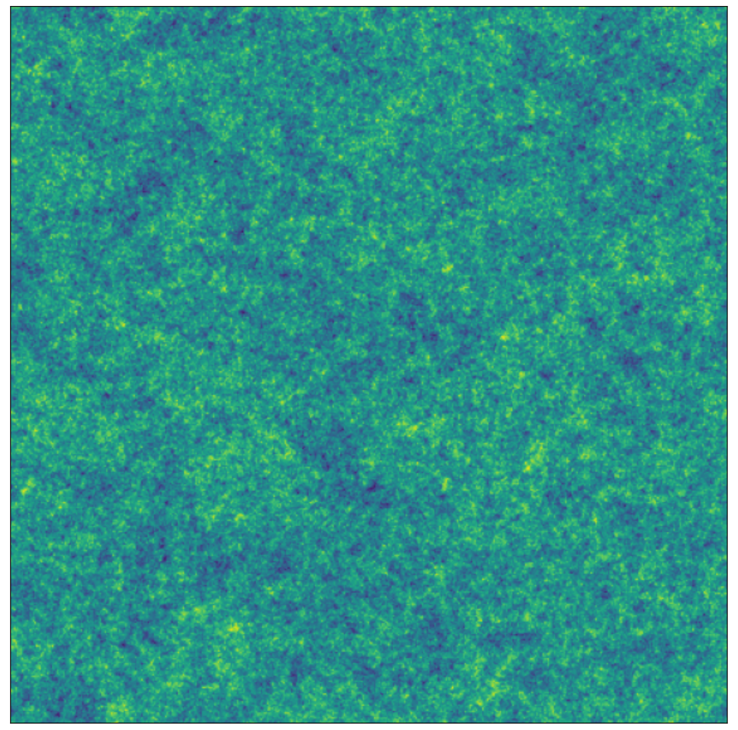
→ How do nonlinear corrections to the density field affect the 21cm signal?

→ Can we constrain beyond ΛCDM cosmological parameters from simulations via SBI?

→ Does extra information at nonlinear scales change inference performance?

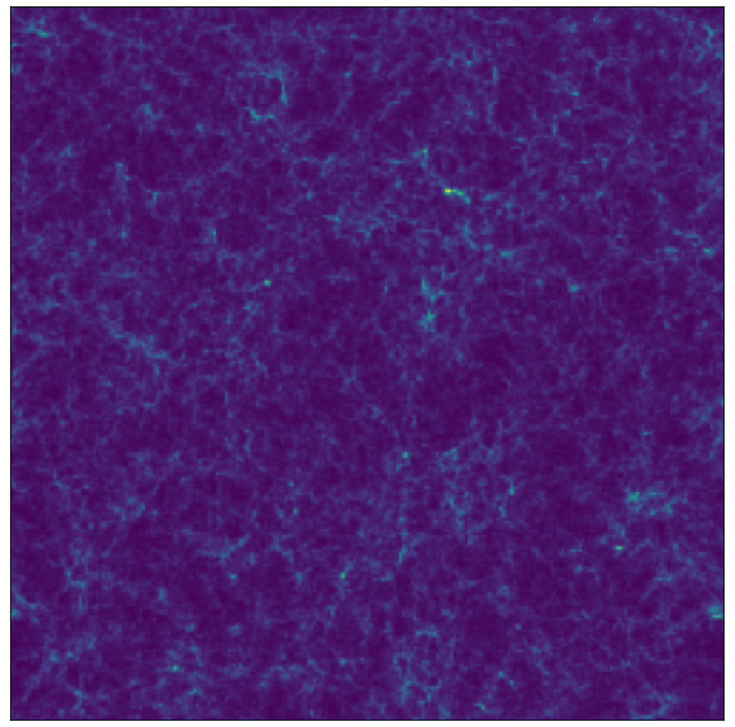
How to simulate the 21cm signal?

- **21cmFAST**:



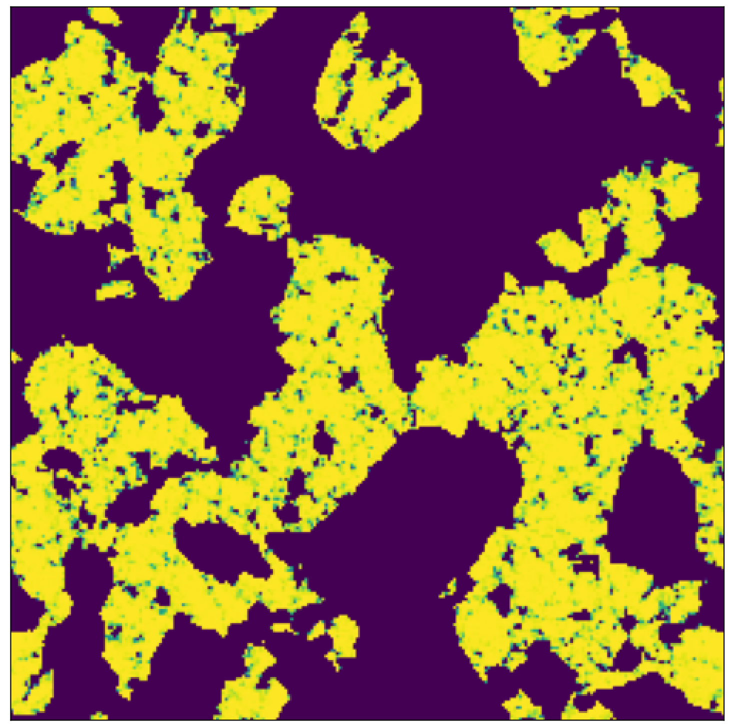
Gaussian random field

→



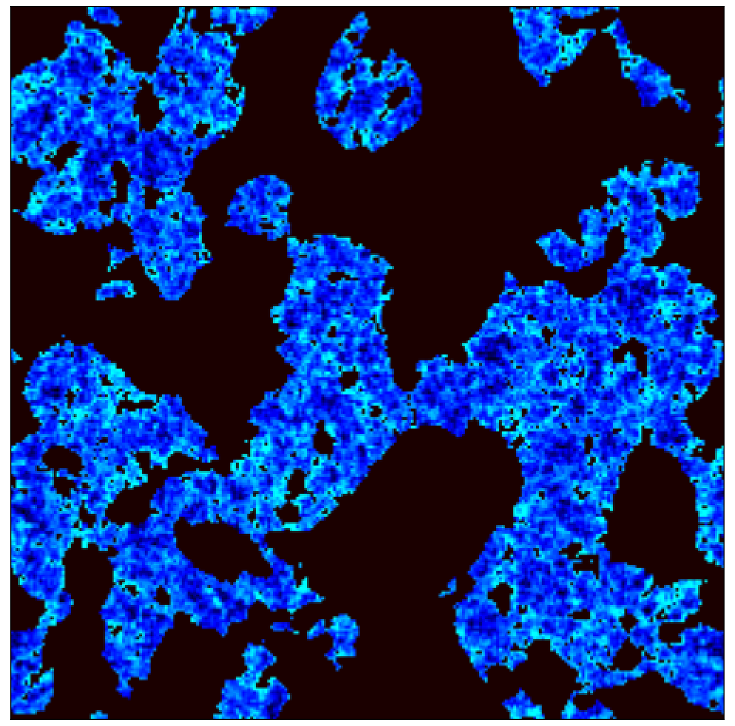
Perturbed density (2LPT)

→



Ionization field

→



Brightness temperature

- 2nd order perturbations, scaled to higher redshifts via $D(z)$

$$\delta T_b(x,z) = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau_{\nu_0}}\right)$$

$$\propto x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}})\left(\frac{H}{\mathrm{d}v_r/\mathrm{d}r + H}\right)$$

- Drawbacks:
    - Only ΛCDM cosmologies
    - 2nd order perturbation theory breaks down at nonlinear scales and low redshifts

Beyond ΛCDM cosmologies: evolving dark energy (CPL)

- **CPL model:** $w(a) = w_0 + w_a(1-a)$
- **Changes to 21cmFAST**: dynamically generate $P_{\rm lin}(k, z=0)$ using CLASS, calculate $D_{\rm CPL}(z)$

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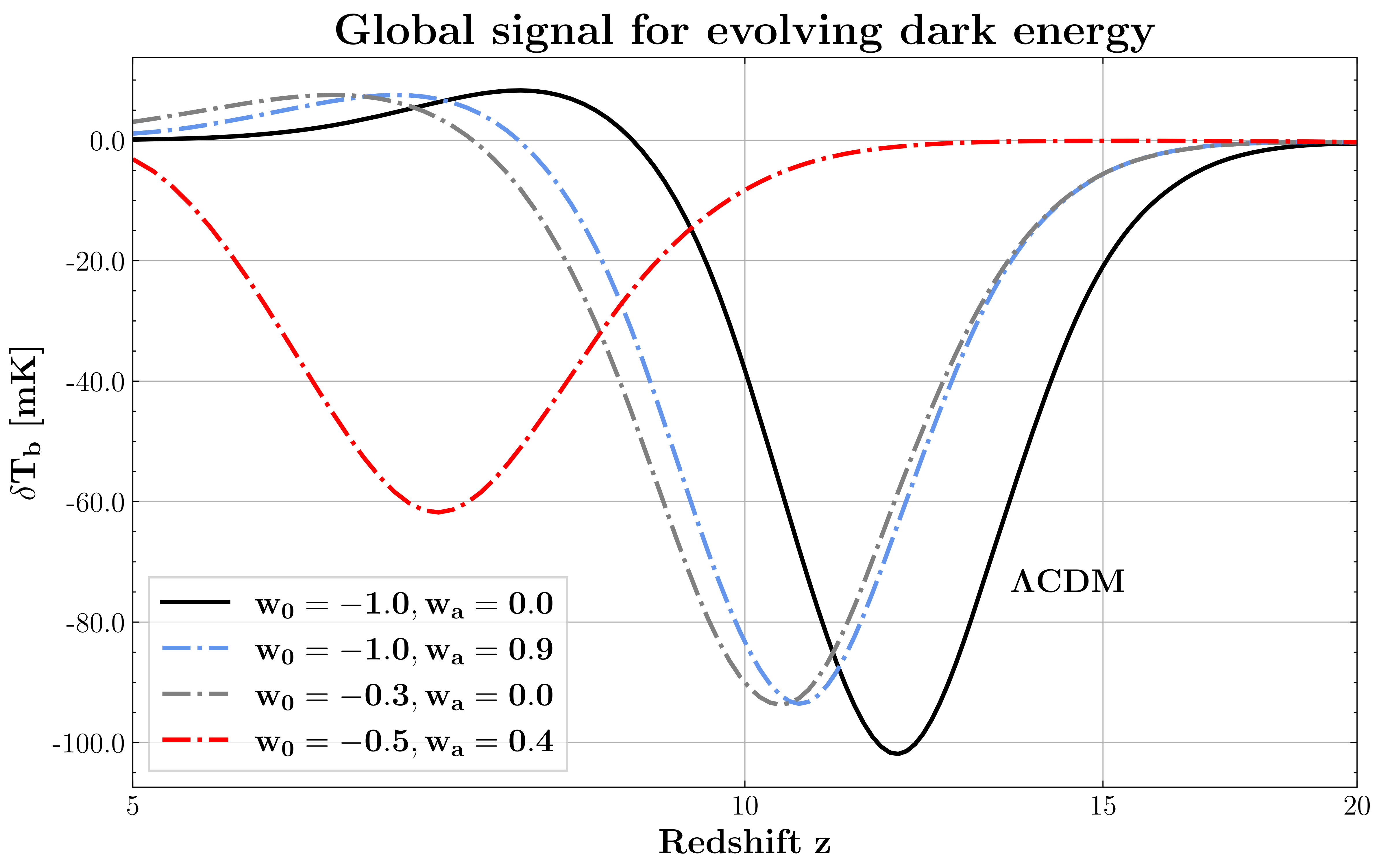
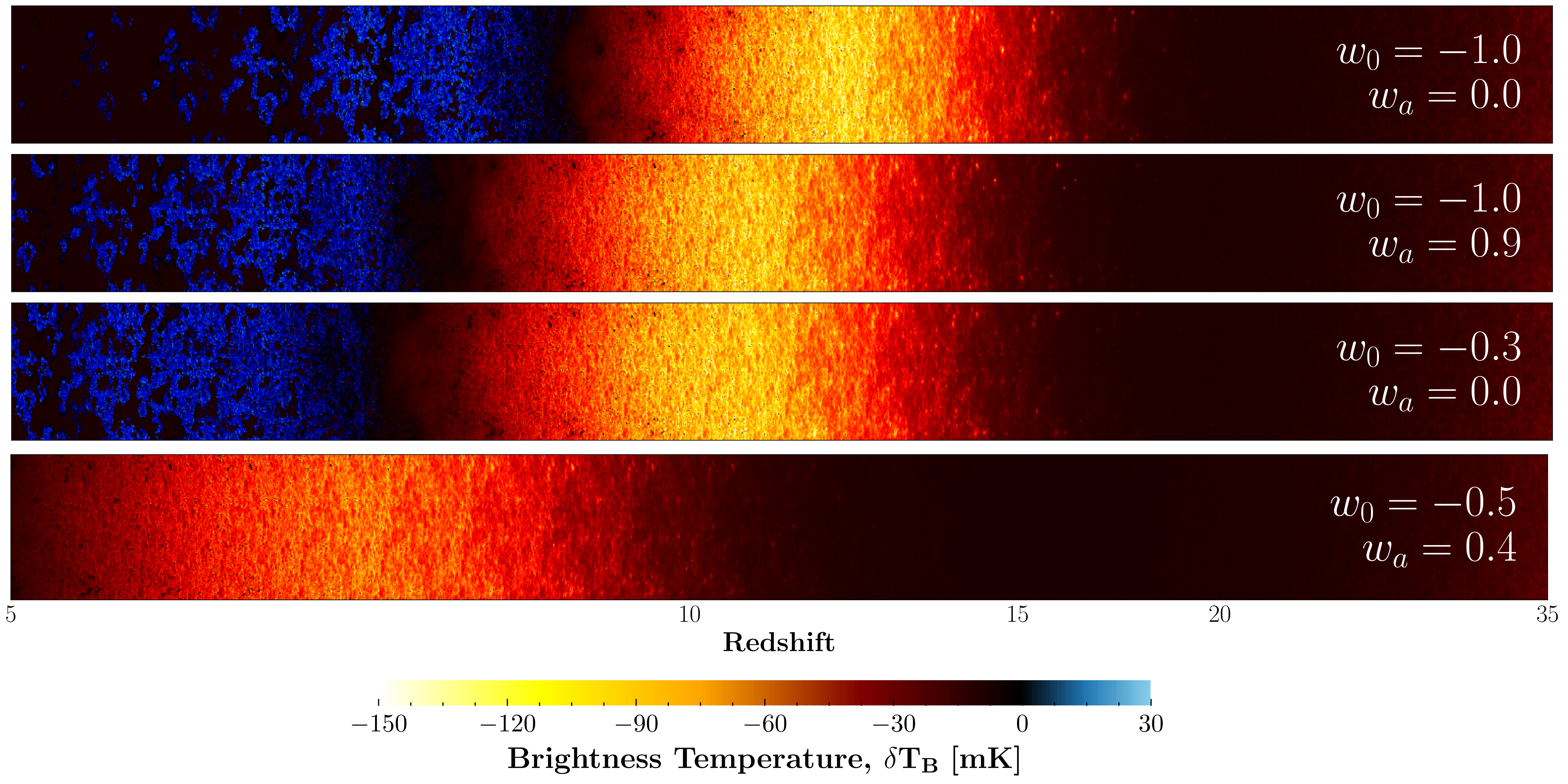




Figures: made with 21cmFAST

21cm at (slightly) nonlinear scales? - Effective Field Theory of LSS

- **EFTofLSS**: Standard perturbation theory + effective stress tensor (small scale physics)

$$\Rightarrow \quad P_{\rm EFT}^{1-{\rm loop}}(k,z) = \underbrace{P_{11}(k,z)}_{\rm tree} + \underbrace{P_{13}(k,z) + P_{22}(k,z)}_{\rm 1\text{-}loop} - \underbrace{2c_s^2(z)k^2 P_{11}(k,z)}_{\rm counter\ term}$$

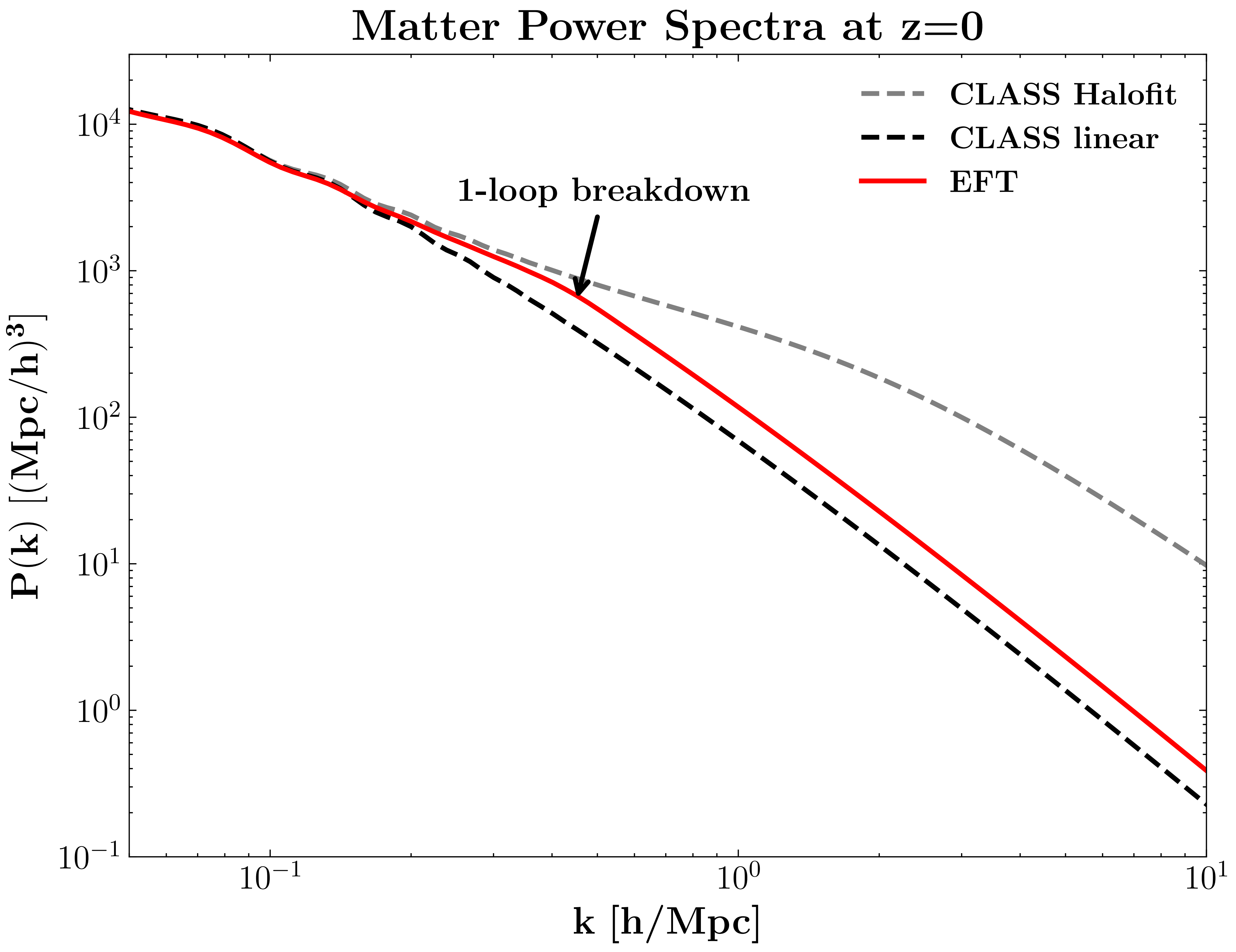
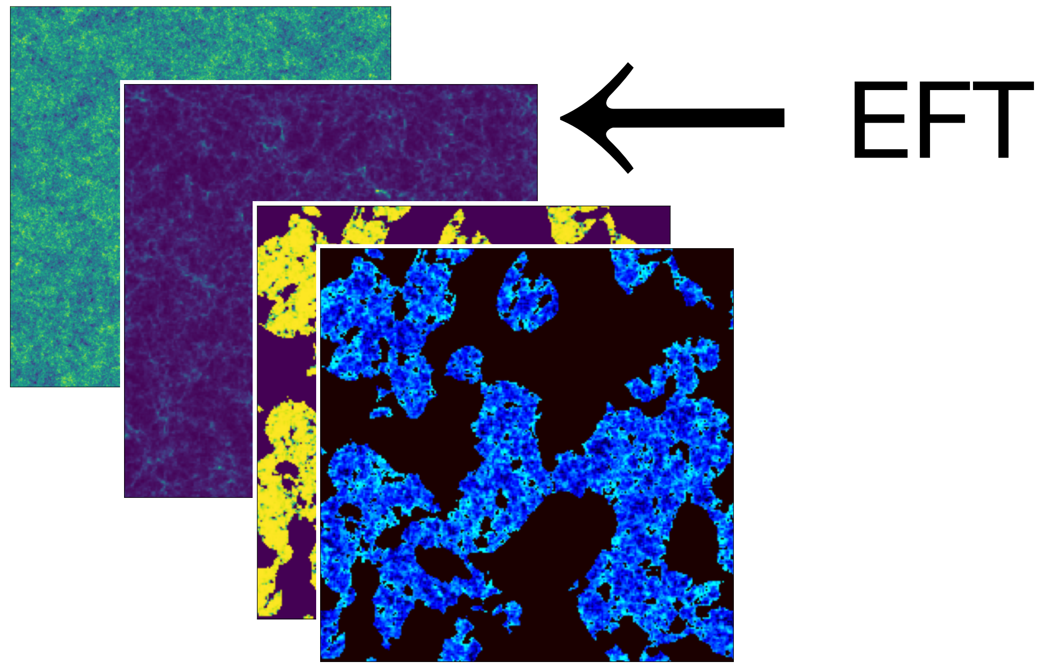


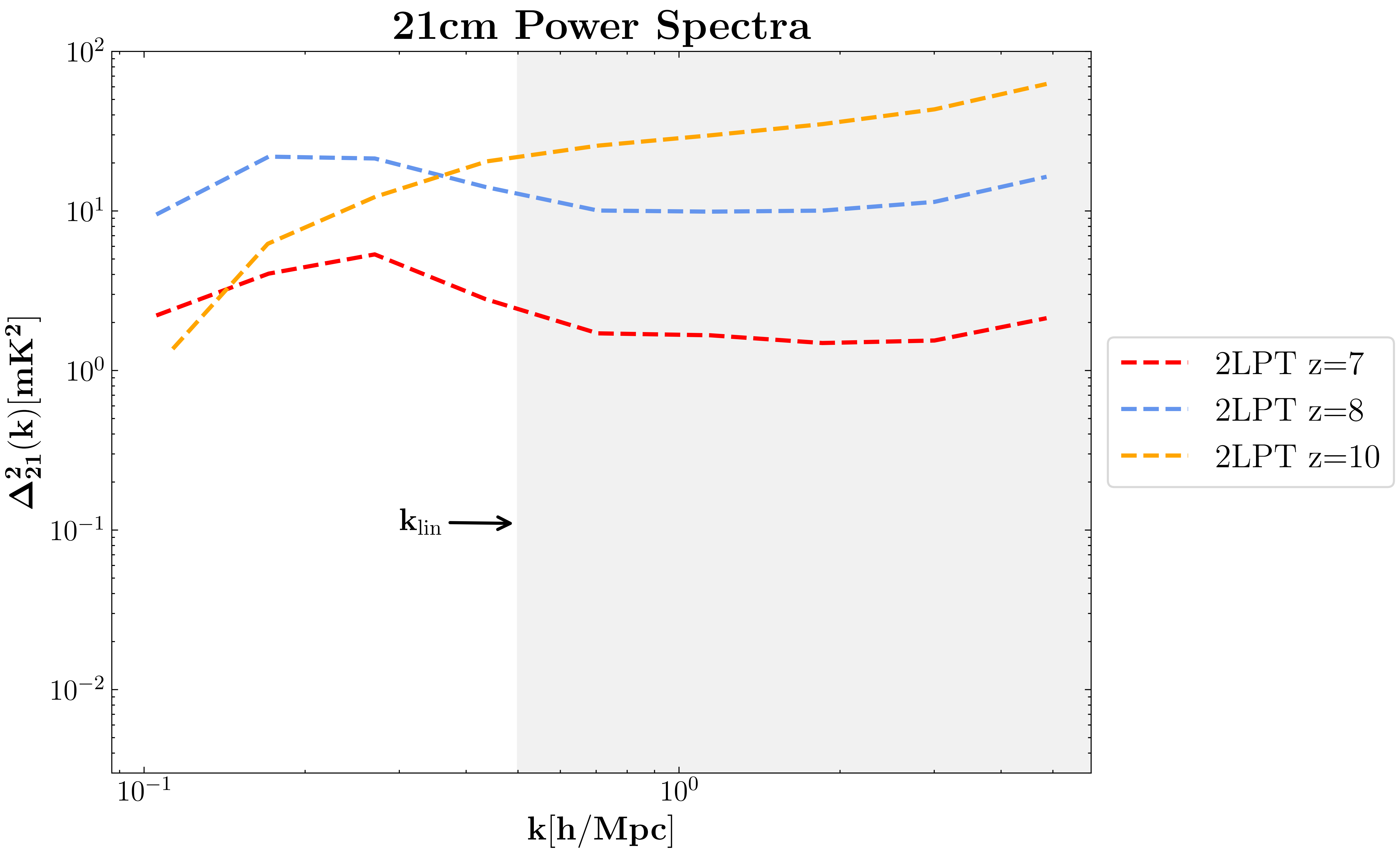
Figure: made with CLASS and CLASS-PT

EFT in 21cmFAST



- Implementation in 21cmFAST:

  → lognormal field with EFT 2-point statistics at each redshift (post heating)



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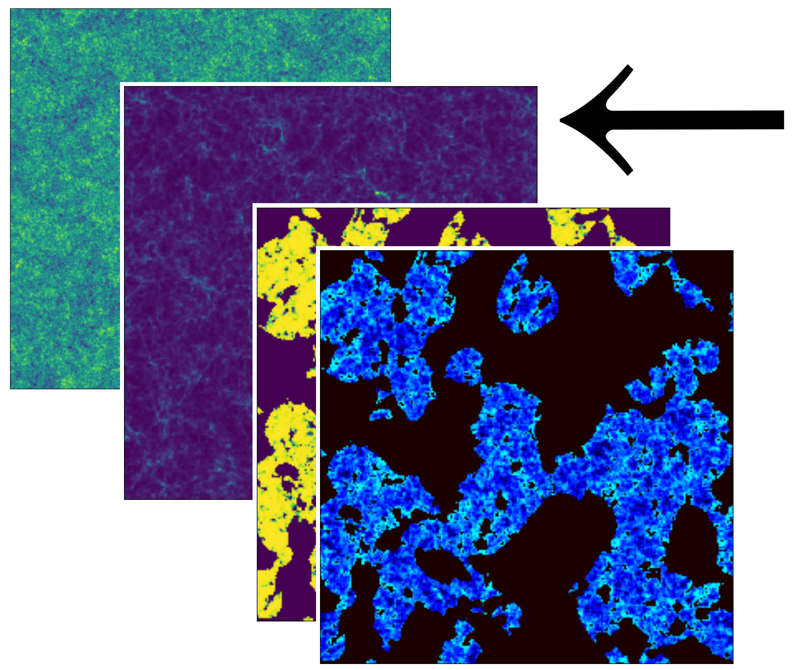

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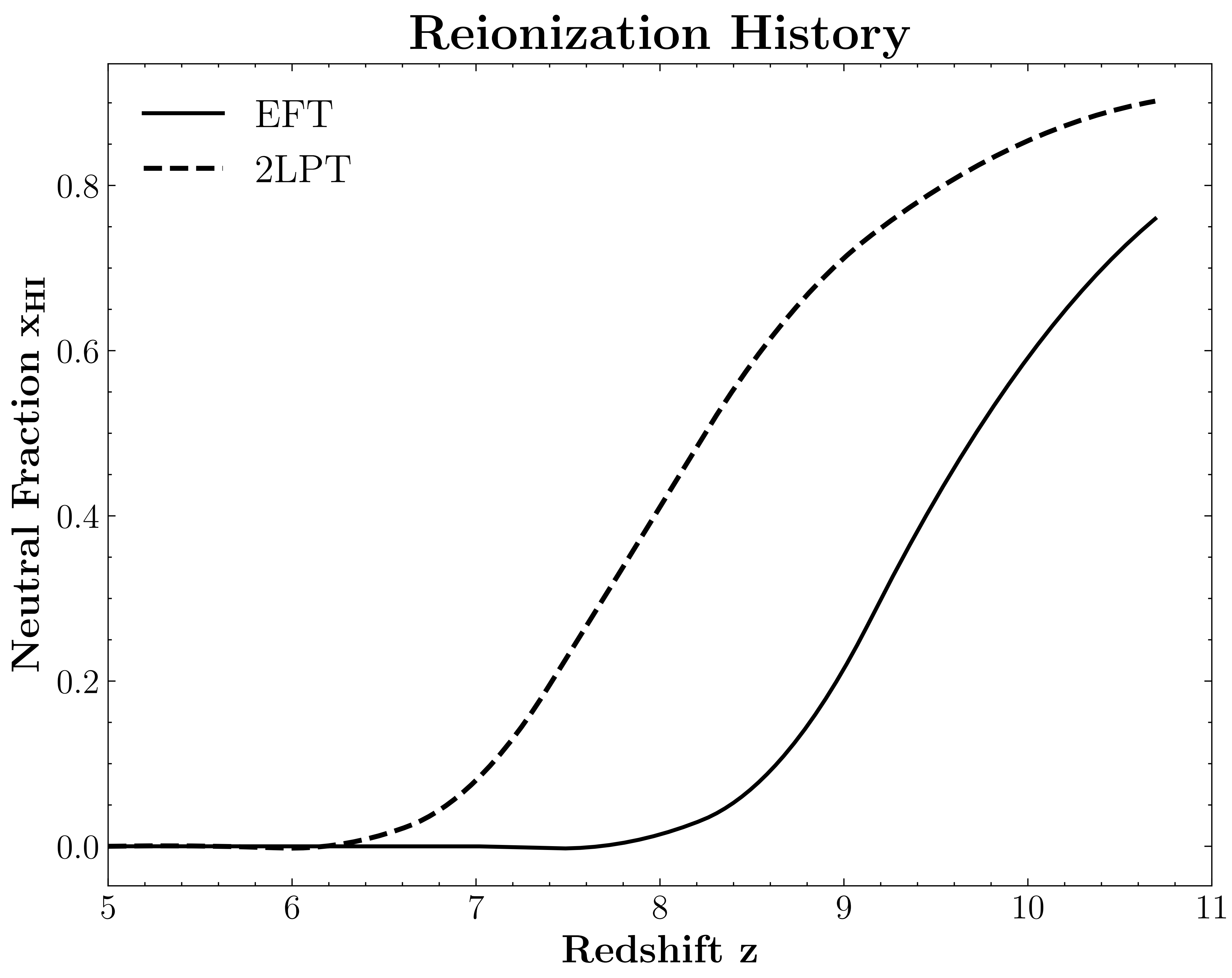
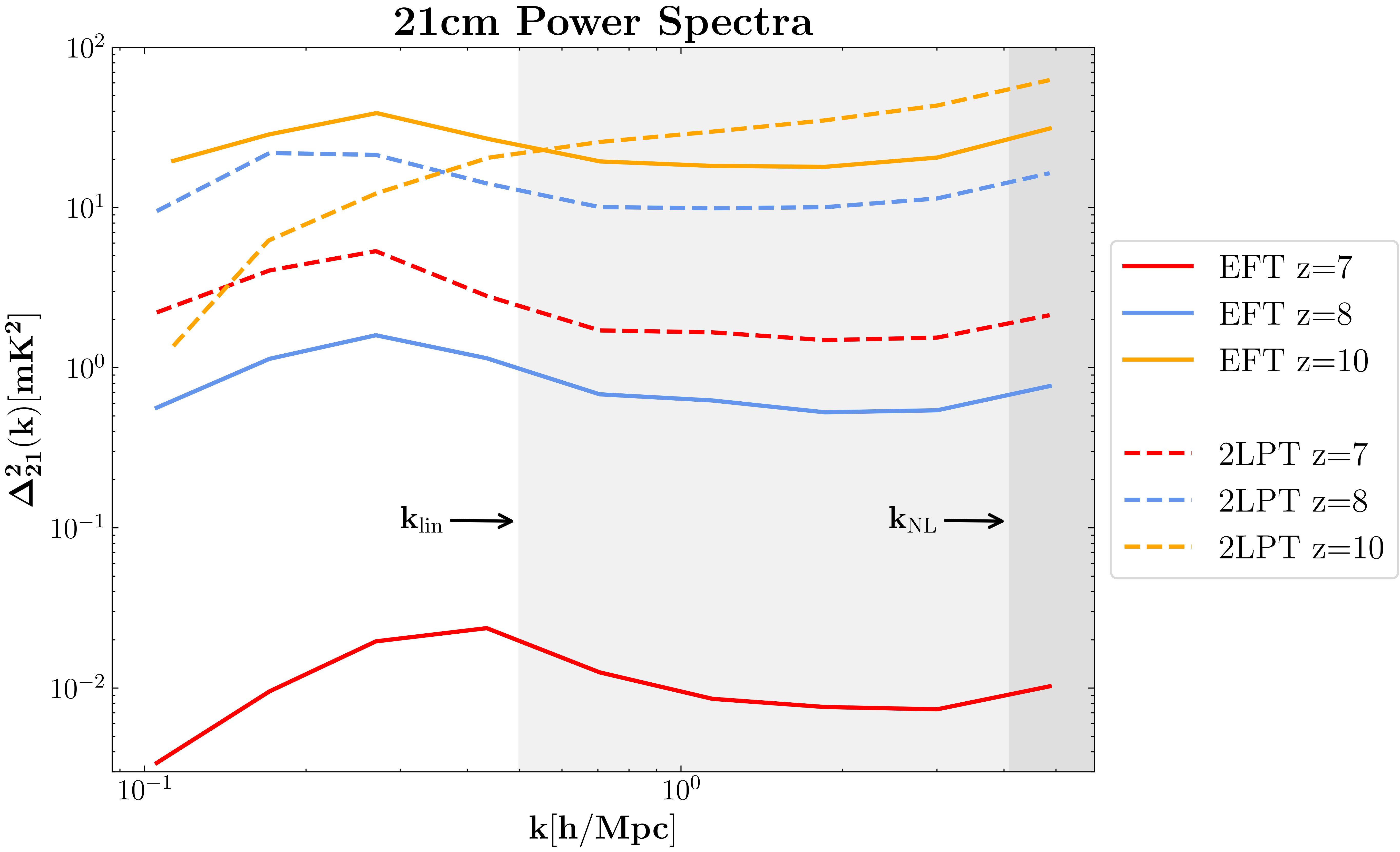
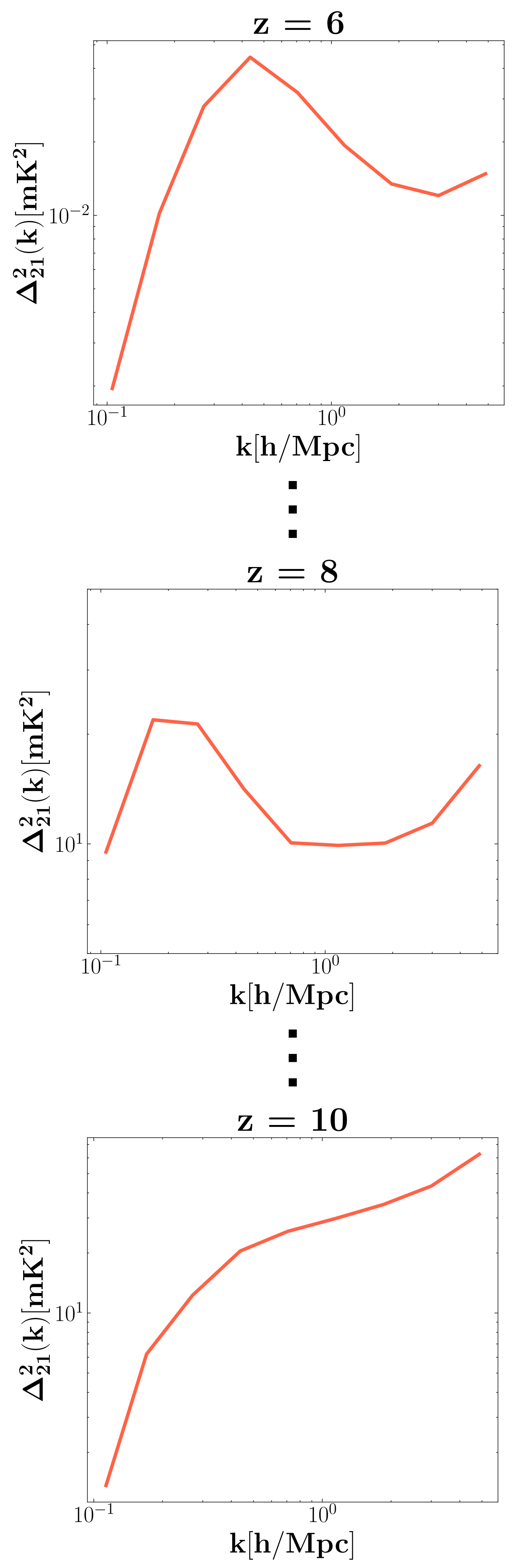




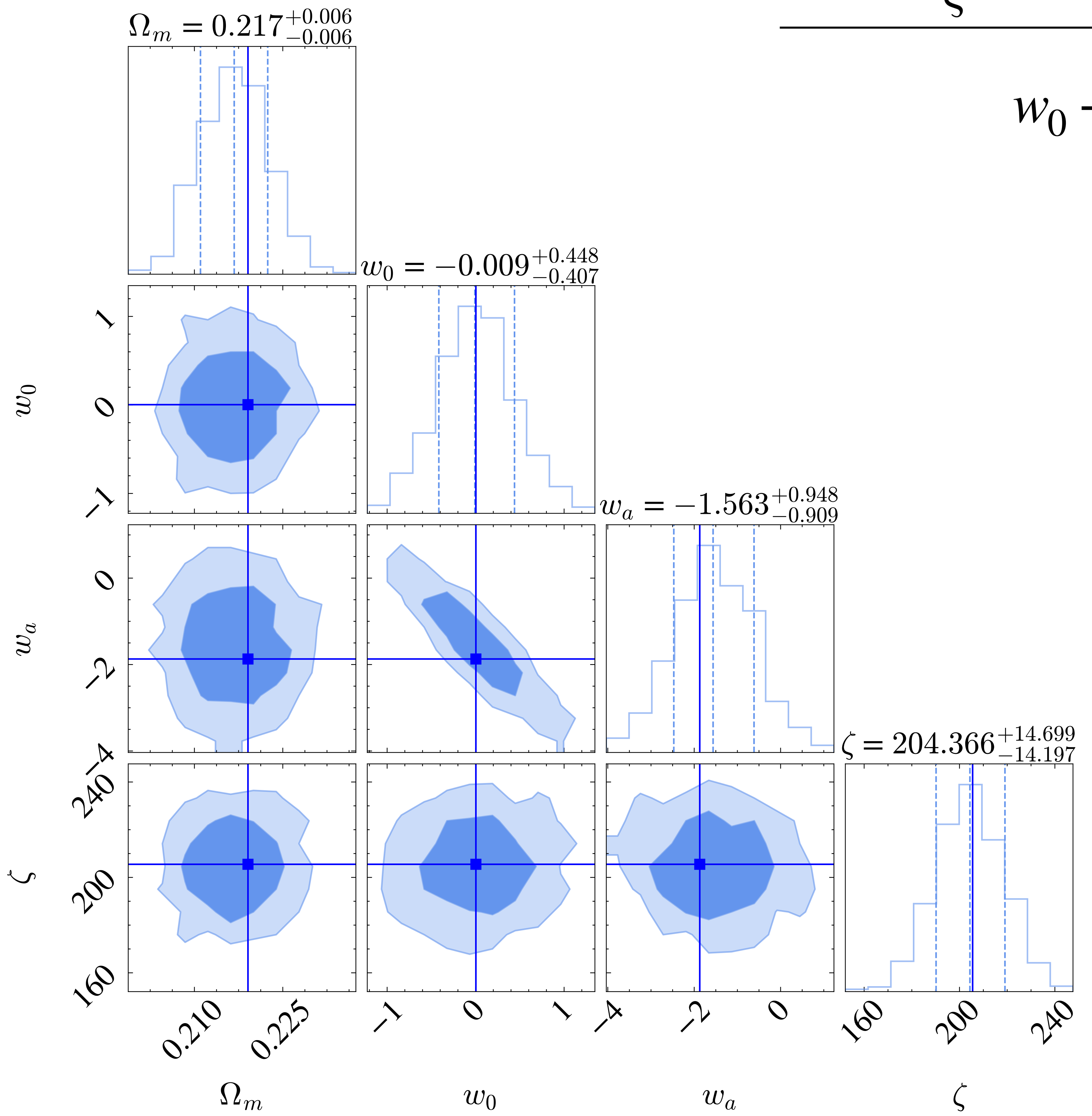
Simulation-based Inference (SBI)

1D PS [z=5-10]



EoRFlow

Posteriors

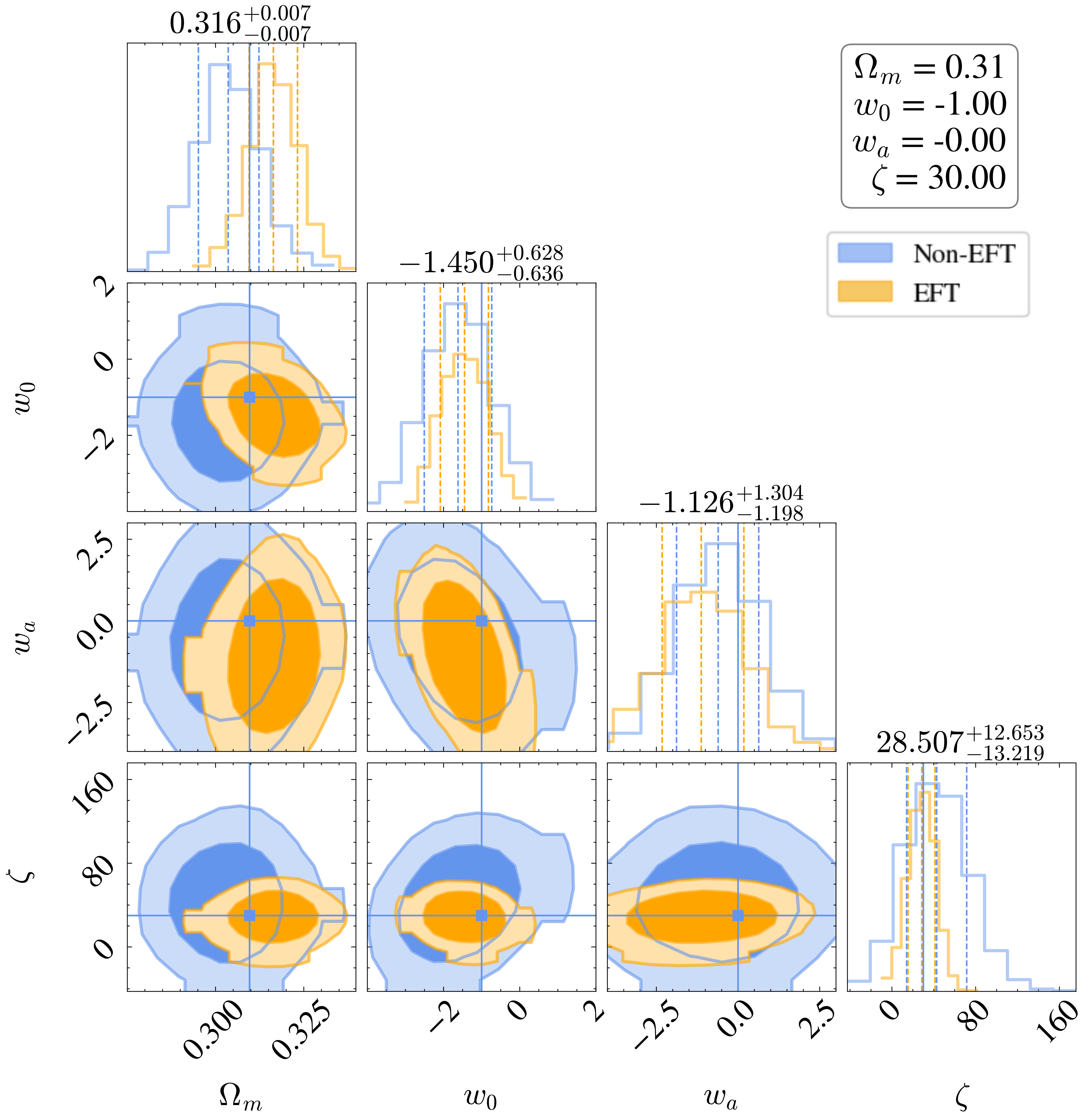


Parameter	Prior range
$\Omega_{m,0}$	$\mathcal{U}$[0.2, 0.4]
w_0	$\mathcal{U}$[-3.0, 1.0]
w_a	$\mathcal{U}$[-3.0, 2.0]
ζ	$\mathcal{U}$[10, 250]

$$w_0 + w_a < 0$$

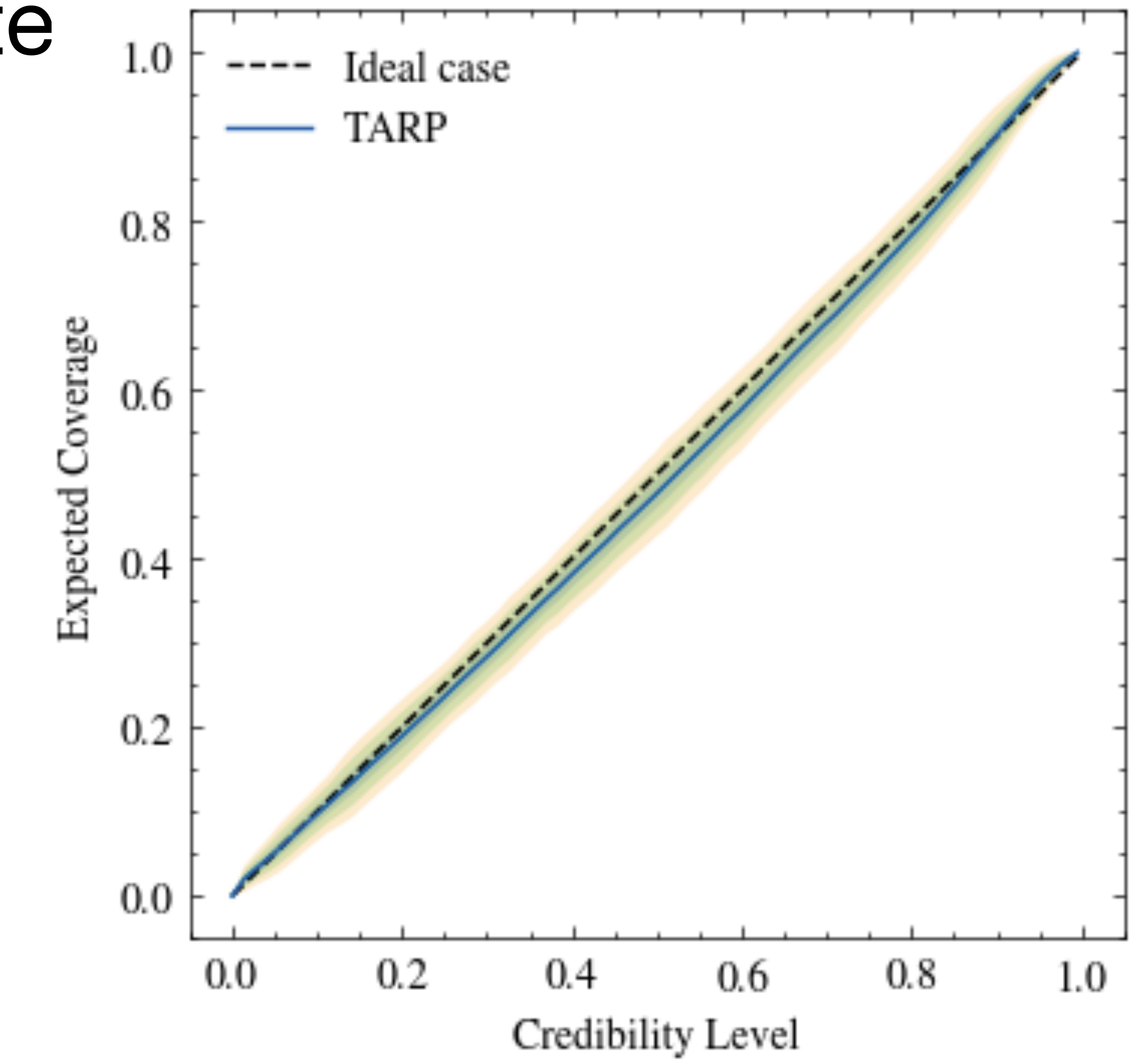
EoRFlow: Pietschke *et al* JCAP10(2025)039

SBI in beyond ΛCDM cosmologies



First results:

- EFT slightly more constrained, sims faster
- Posteriors: Ω_m, w_a similar for both models; w_0, ζ tighter for EFT
- $w_0 w_a$ degenerate



Conclusions

- **How does evolving dark energy affect the 21cm signal?**

  →

- **How do nonlinear corrections to the density field affect the 21cm signal?**

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- **Can we constrain beyond ΛCDM cosmological parameters from simulations via SBI?**

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- **Does extra information at nonlinear scales change inference performance?**

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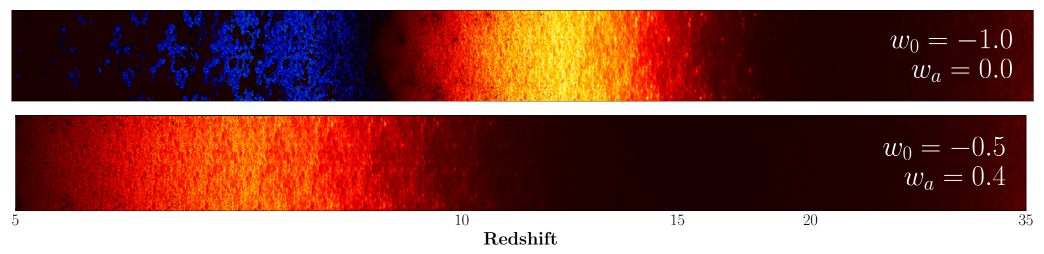

  → shifts global 21cm signal, time of reionization

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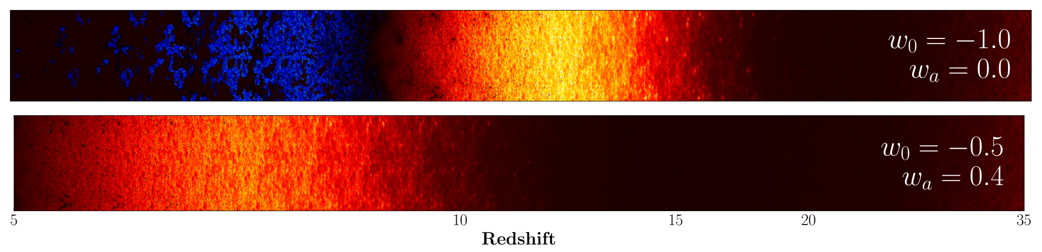

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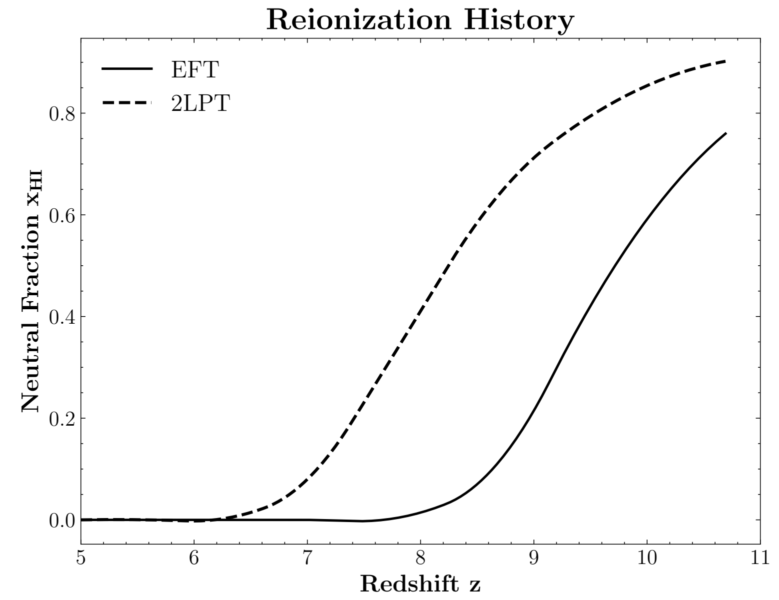

- **How do nonlinear corrections to the density field affect the 21cm signal?**

  → more power at small scales leads to earlier reionization

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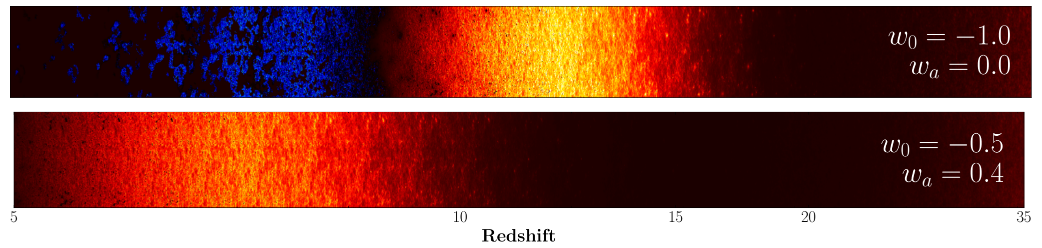

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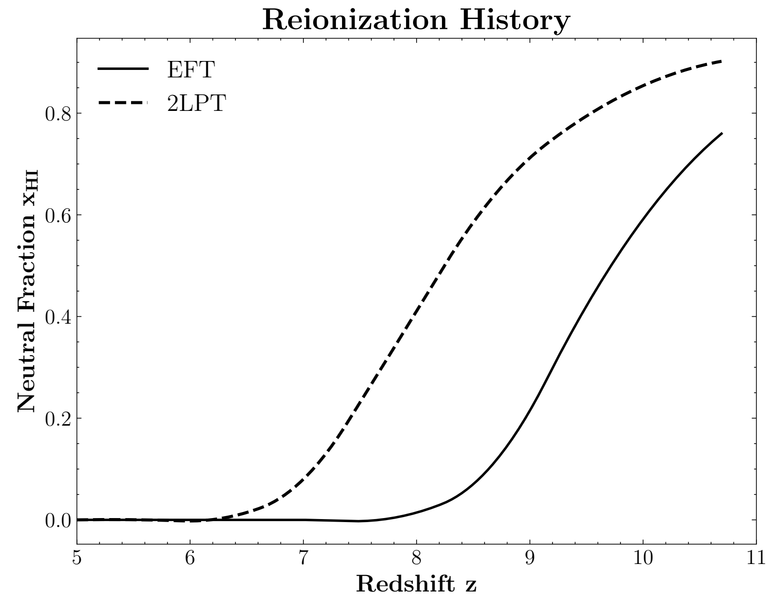

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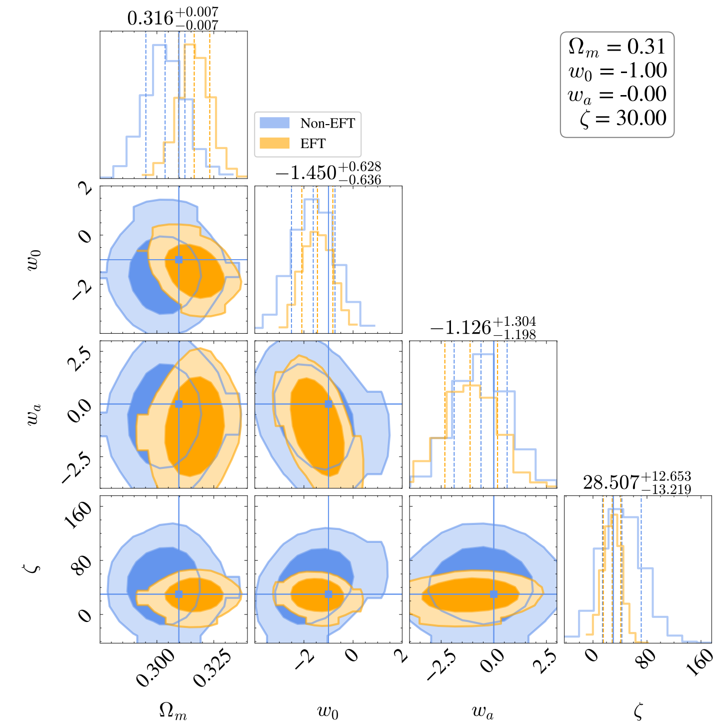

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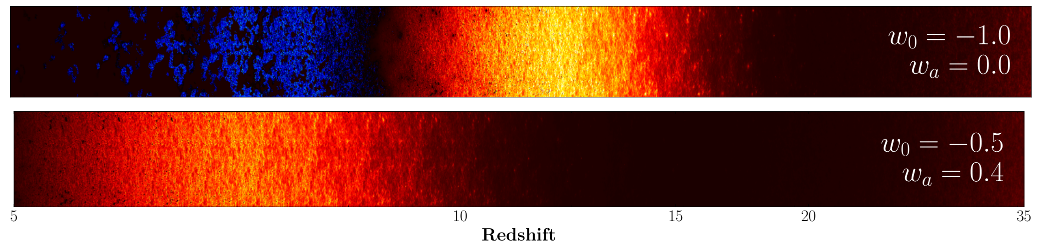

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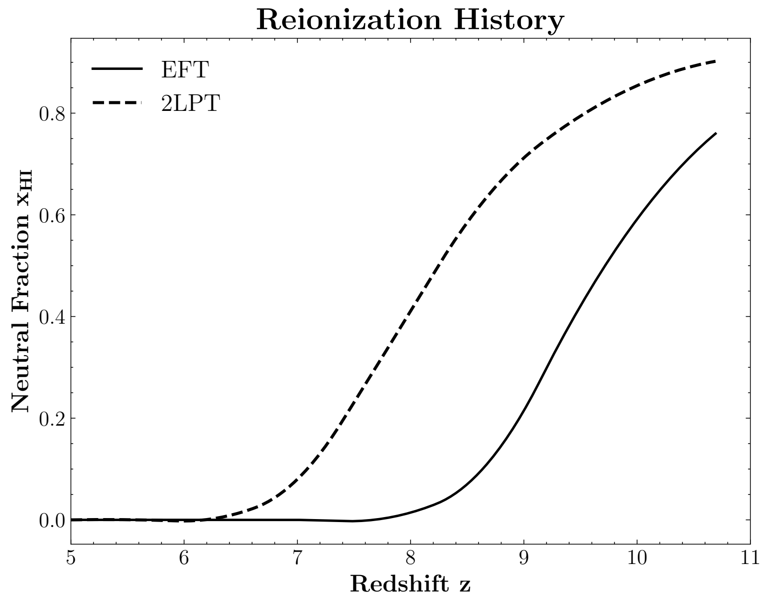

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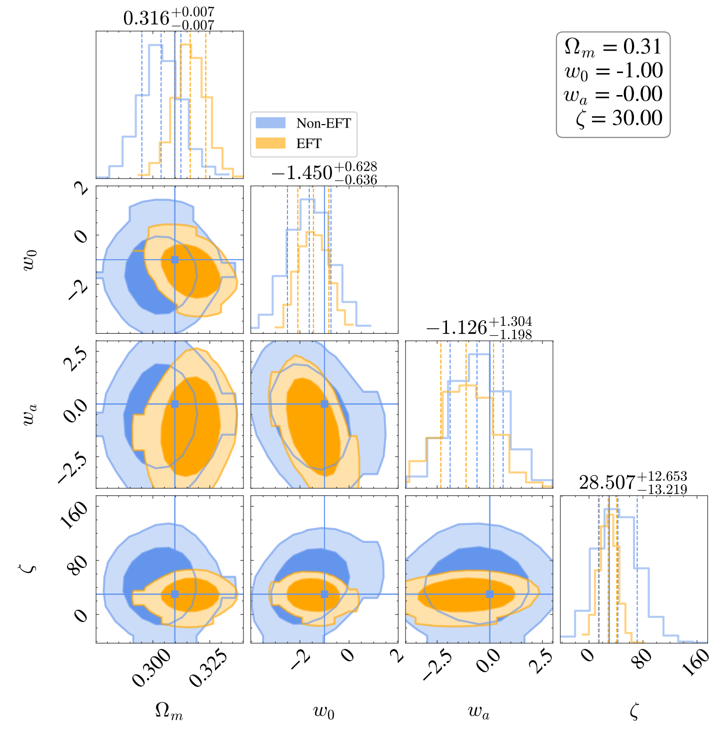

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- **Does extra information at nonlinear scales change inference performance?**

  → yes, tighter constraints for ζ and w_0

Thank you for listening!

Additional Slides

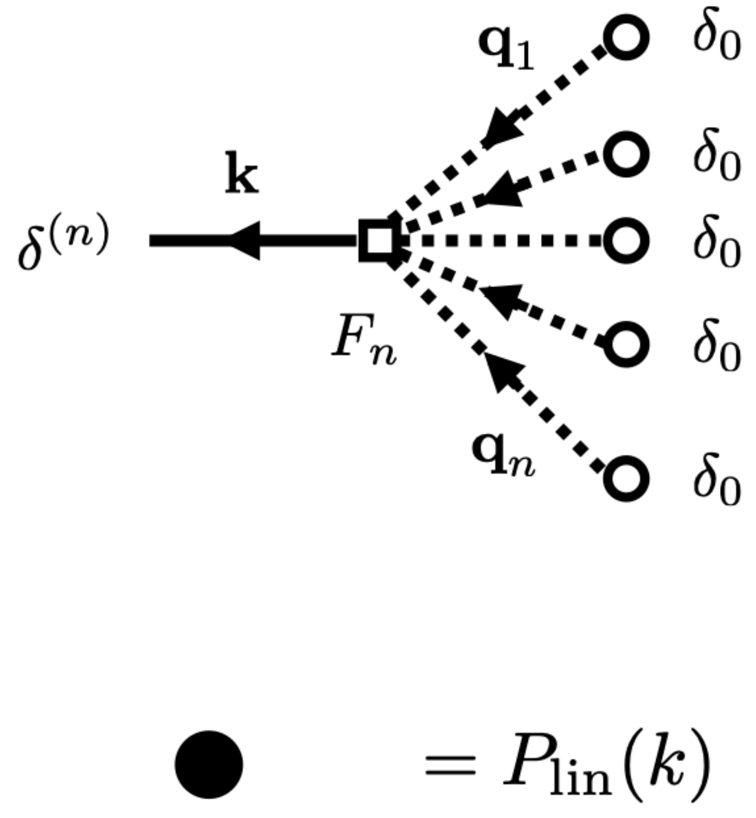
Effective Field Theory of Large Scale Structure

$$\delta^{(n)}(\mathbf{k}) = \left[\prod_{i=1}^{n}\int_{\mathbf{q}_i}\right]\delta_D^{(3)}(\mathbf{k}-\mathbf{q}_{1\ldots n})F_n(\mathbf{q}_1,\ldots,\mathbf{q}_n)\left[\prod_{i=1}^{n}\delta_0(\mathbf{q}_n)\right]$$

$$P_{22}(k) = \langle\delta_{\mathbf{k}}^{(2)}\delta_{\mathbf{k}'}^{(2)}\rangle' = 2\int_{\mathbf{q}}[F_2(\mathbf{q}-\mathbf{k},\mathbf{q})]^2 P_{11}(q)P_{11}(|\mathbf{k}-\mathbf{q}|)$$

$$P_{13}(k) = 2\langle\delta_{\mathbf{k}}^{(1)}\delta_{\mathbf{k}'}^{(2)}\rangle' = 6P_{11}(k)\int_{\mathbf{q}}F_3(\mathbf{k},\mathbf{q}-\mathbf{q})P_{11}(q)\,.$$

$$c_s^2 = -\frac{P_{\rm nl} - P_{11} - P_{\text{1-loop}}}{2k^2 P_{11}}$$



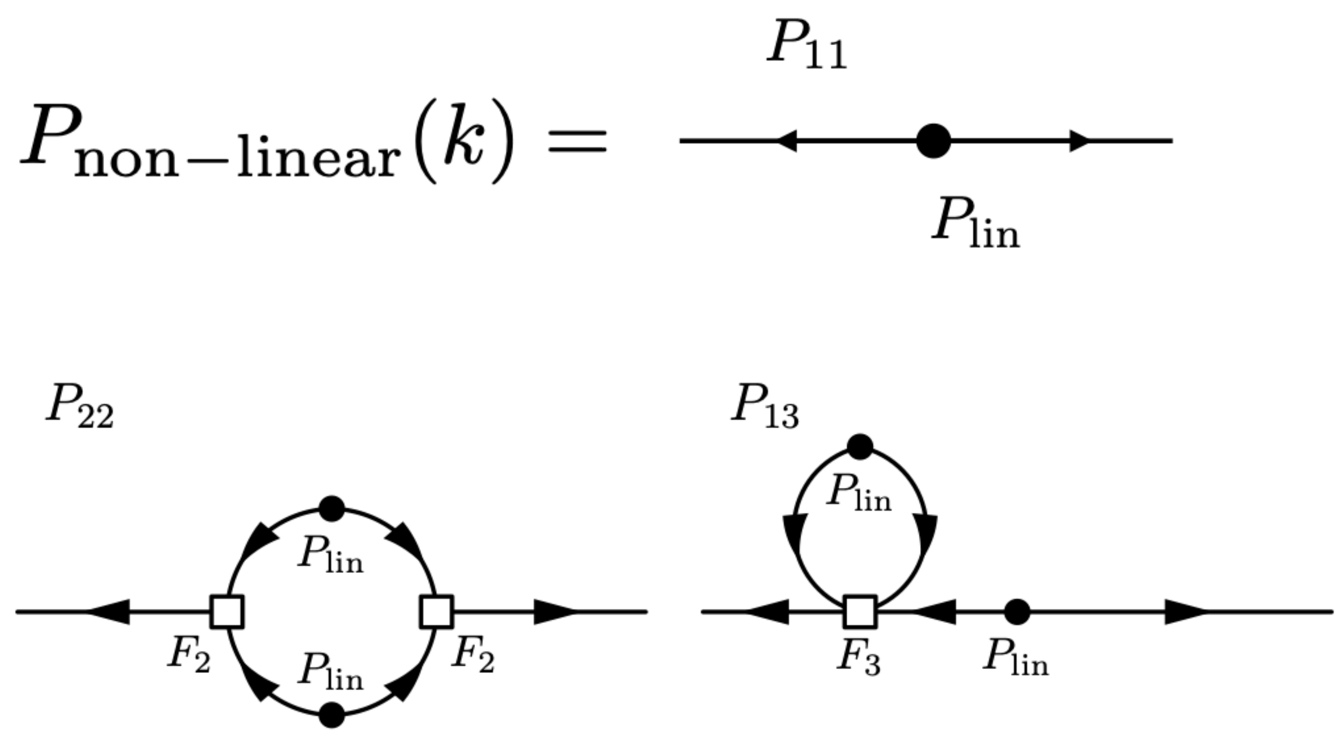


Figure: Ivanov, 2022 (arXiv:2212.08488)

Lognormal distribution

1. Correlation function: $\xi(r) = \frac{1}{V} \sum_k P(k) e^{ikr}$

2. Gaussian correlation function: $\xi_G(r) = \ln(1 + \xi(r)) \ \rightarrow P_G(k)$

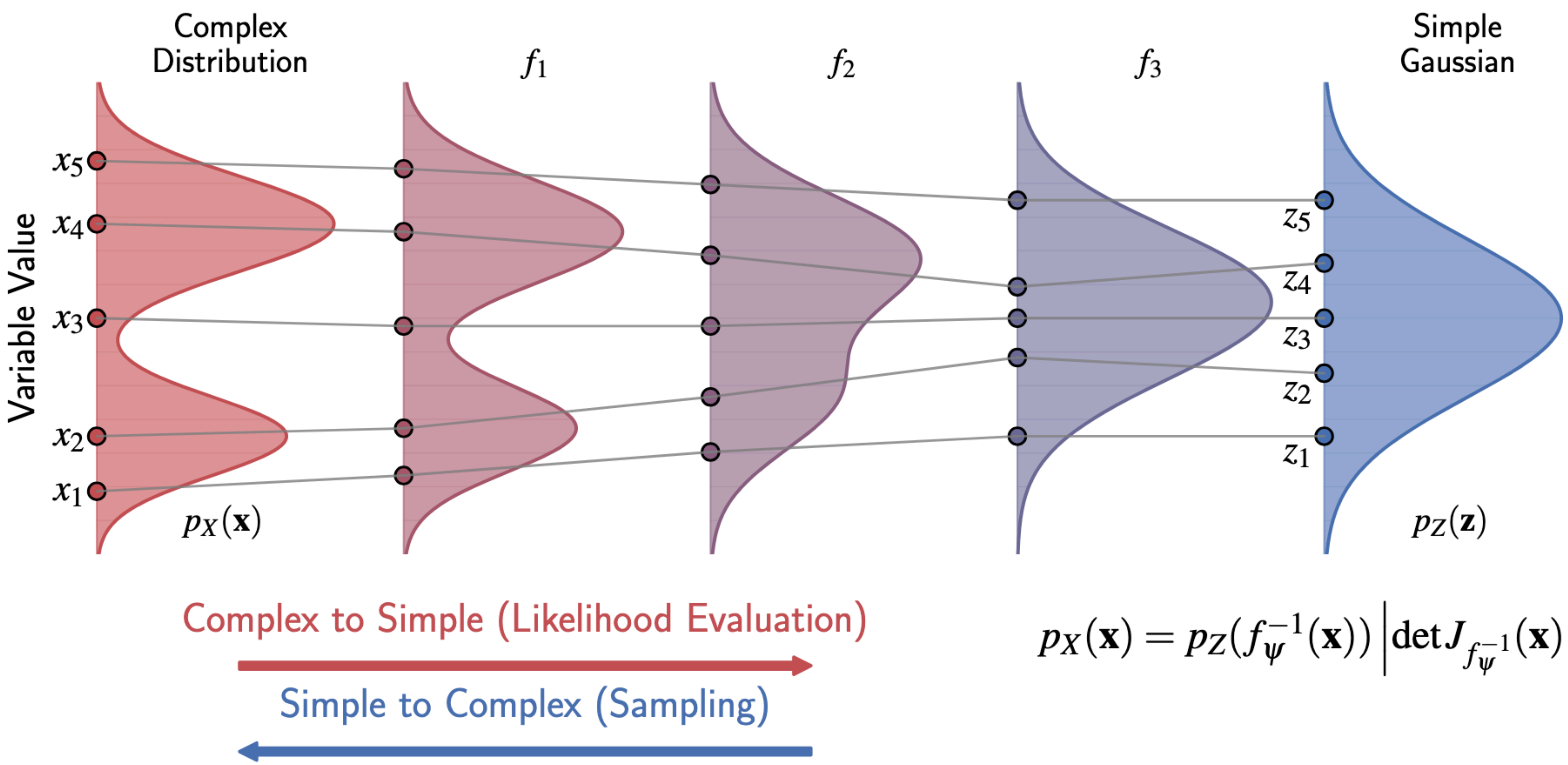
3. Generate gaussian random field with $P_G(k)$: $G(k) = \sqrt{\frac{P_G(k)V}{2}}(a_r + ia_i)$

4. Lognormal field: $\delta(x) = \exp(G(x) - \frac{\sigma_G^2}{2}) - 1$

$\Rightarrow$ Resulting field has $\delta(x) \geq -1$

Normalizing Flows

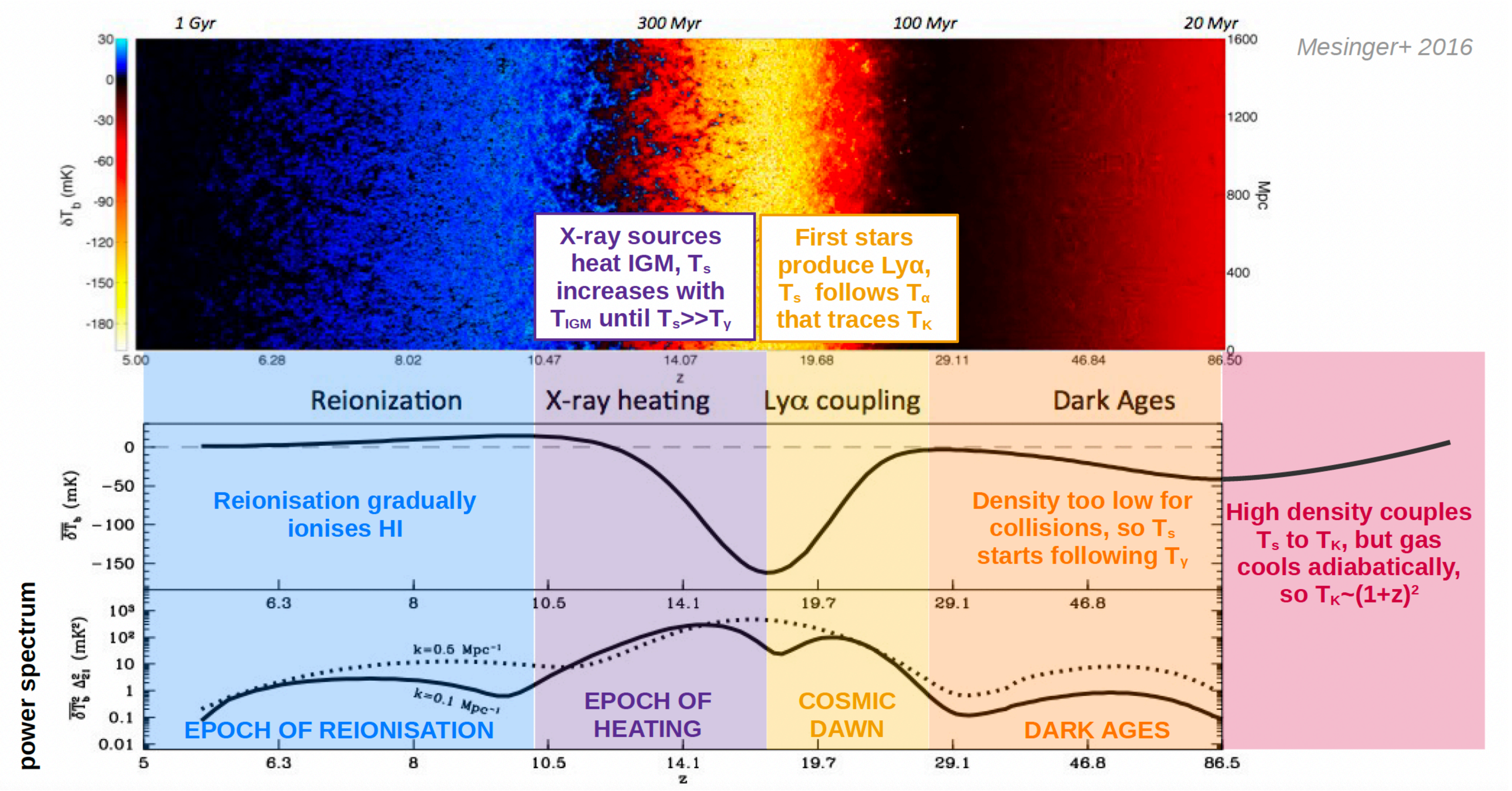
(a) Normalizing Flows: Direct Transformation Between Distributions



$$p_X(\mathbf{x}) = p_Z(f_\psi^{-1}(\mathbf{x})) \left| \det J_{f_\psi^{-1}}(\mathbf{x}) \right|$$

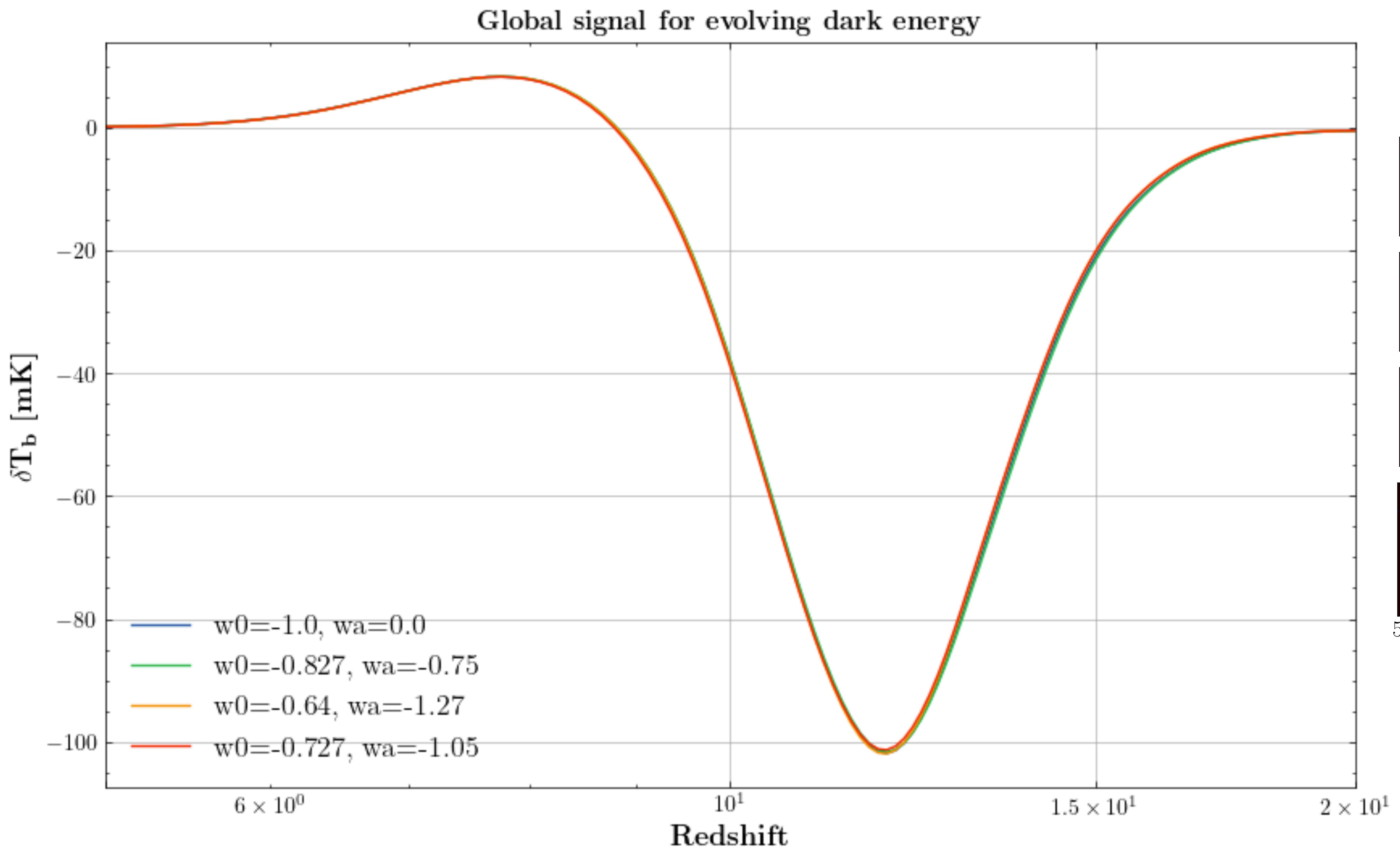
Image Credit: "Deep Learning in Astrophysics" Yuan-Sen Ting

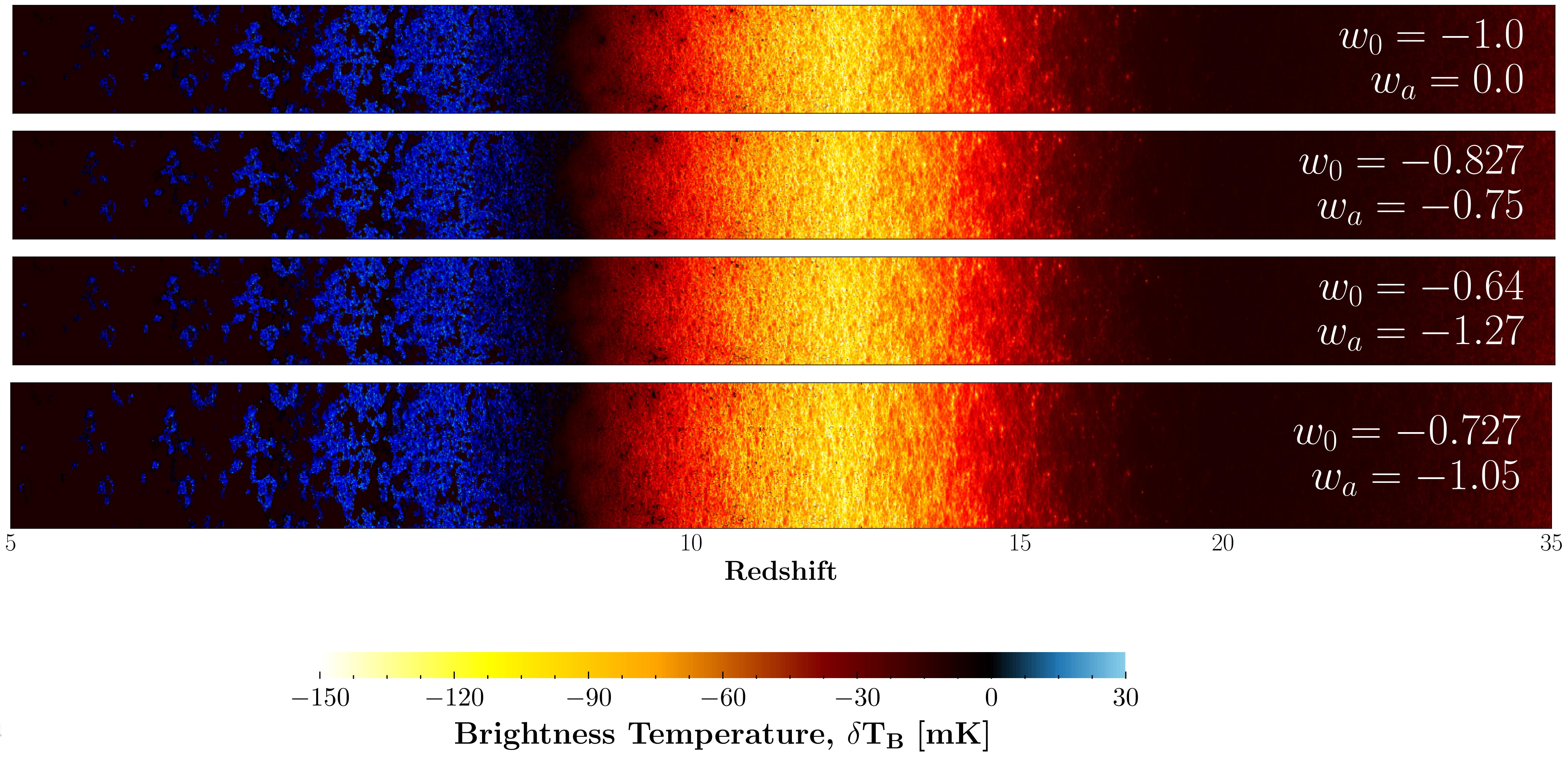
21cm signal evolution



DESI values in 21cmFAST

$$E^2(a) = \Omega_{m,0}a^{-3} + \Omega_{r,0}a^{-4} + \Omega_\Lambda a^{-3(1+w_0+w_a)}e^{-3w_a(1-a)}$$





$w_0 = -0.827 \pm 0.063$, $w_a = -0.75^{+0.29}_{-0.25}$, } DESI+CMB +PantheonPlus

$w_0 = -0.64 \pm 0.11$, $w_a = -1.27^{+0.40}_{-0.34}$, } DESI+CMB +Union3,

$w_0 = -0.727 \pm 0.067$, $w_a = -1.05^{+0.31}_{-0.27}$, } DESI+CMB +DESY5,