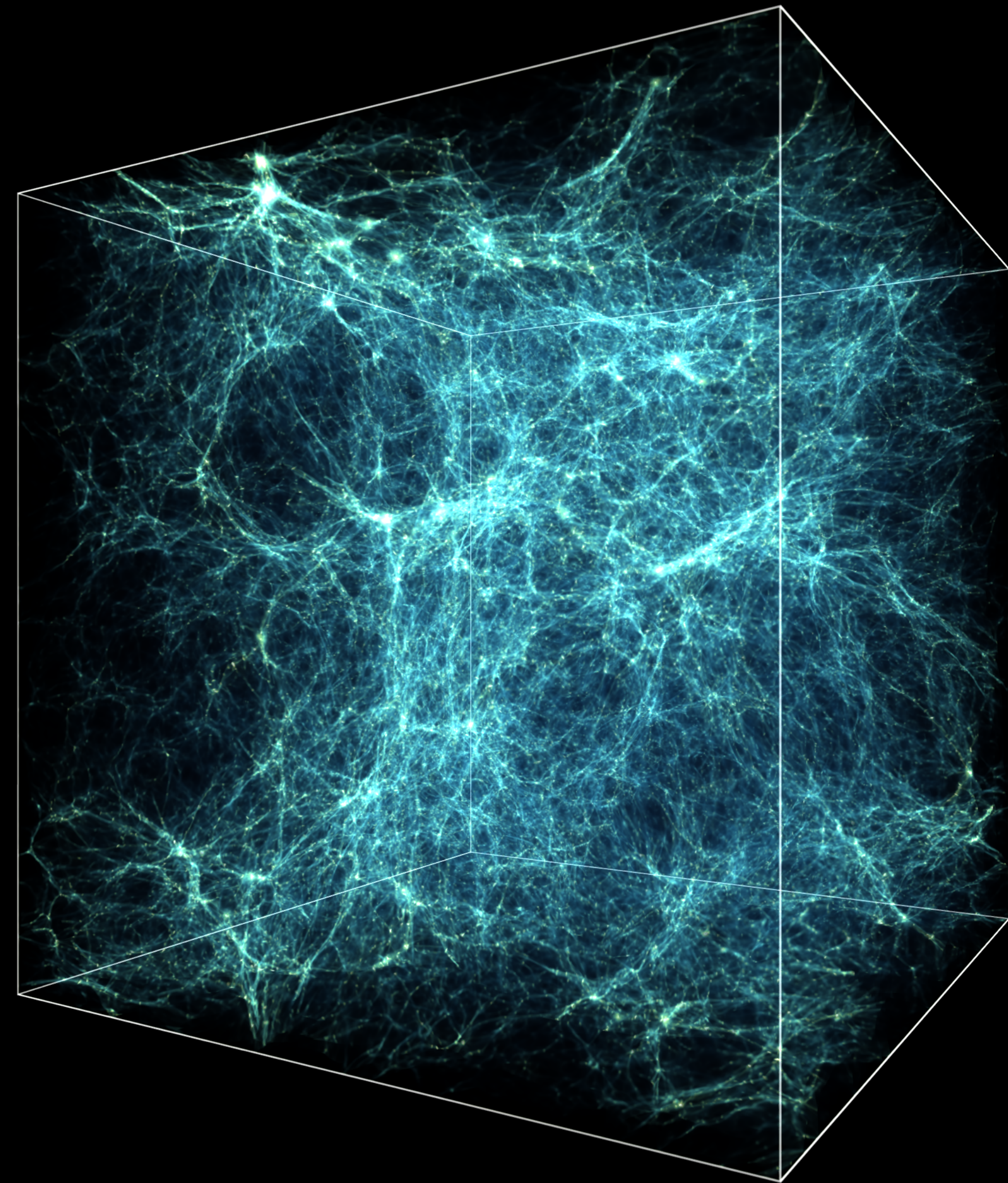


Exploring the Lyman-Alpha Forest in a Dynamical Dark Energy Cosmology using Cholla

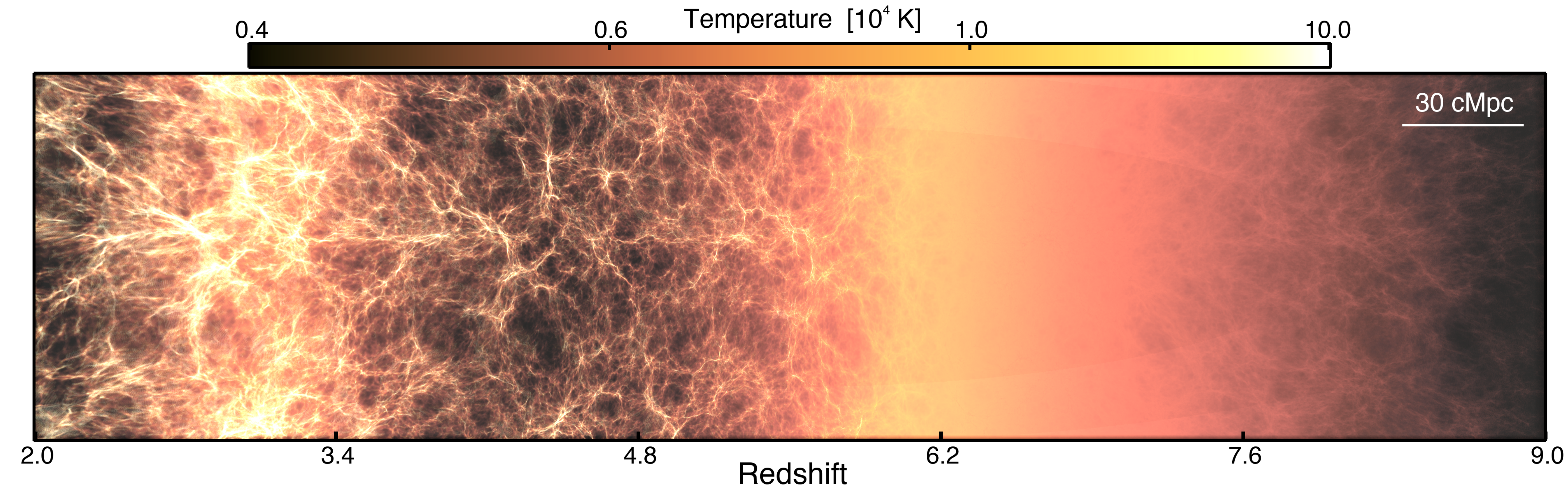
Diego Garza
(UC Santa Cruz)



Brant Robertson (UCSC), Piero Madau (UCSC), Nick Gnedin (Chicago), Matt Abruzzo (Pitt), Evan Schneider (Pitt), Reuben Budiardja (ORNL), Trey White (ORNL), Robert Caddy (Princeton), Bruno Villaseñor (AMD)

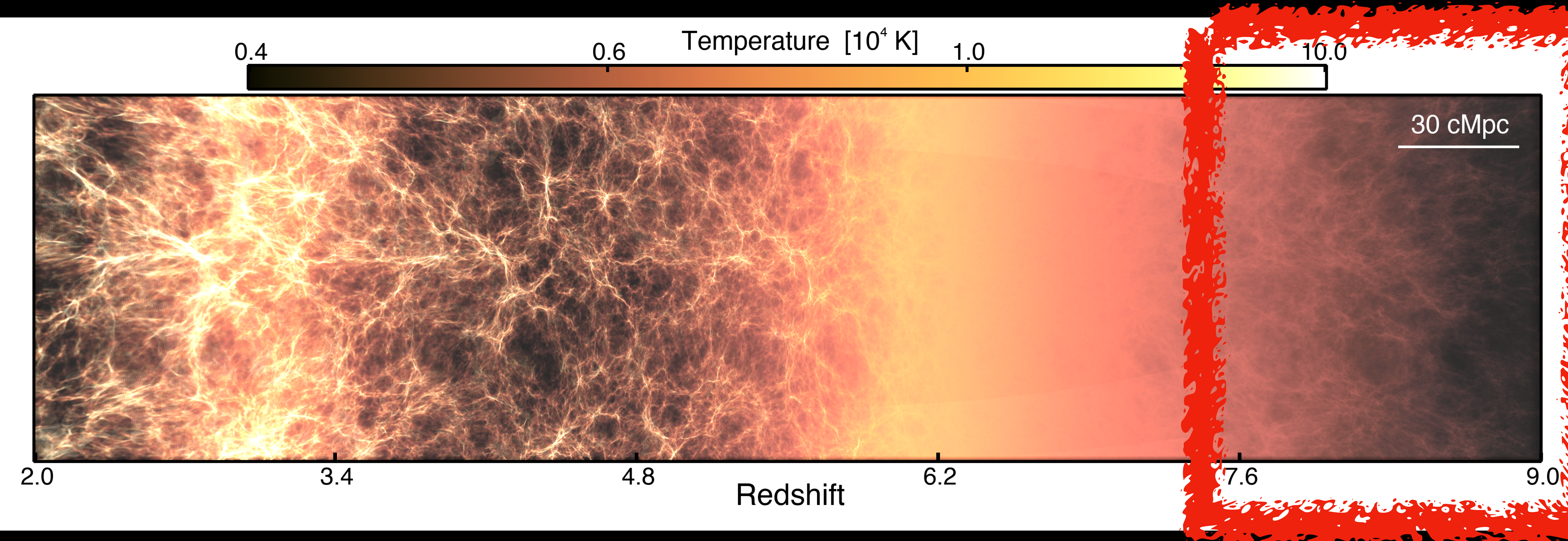


Expansion History Impacting IGM May Change $\text{Ly}\alpha$ Forest Structure



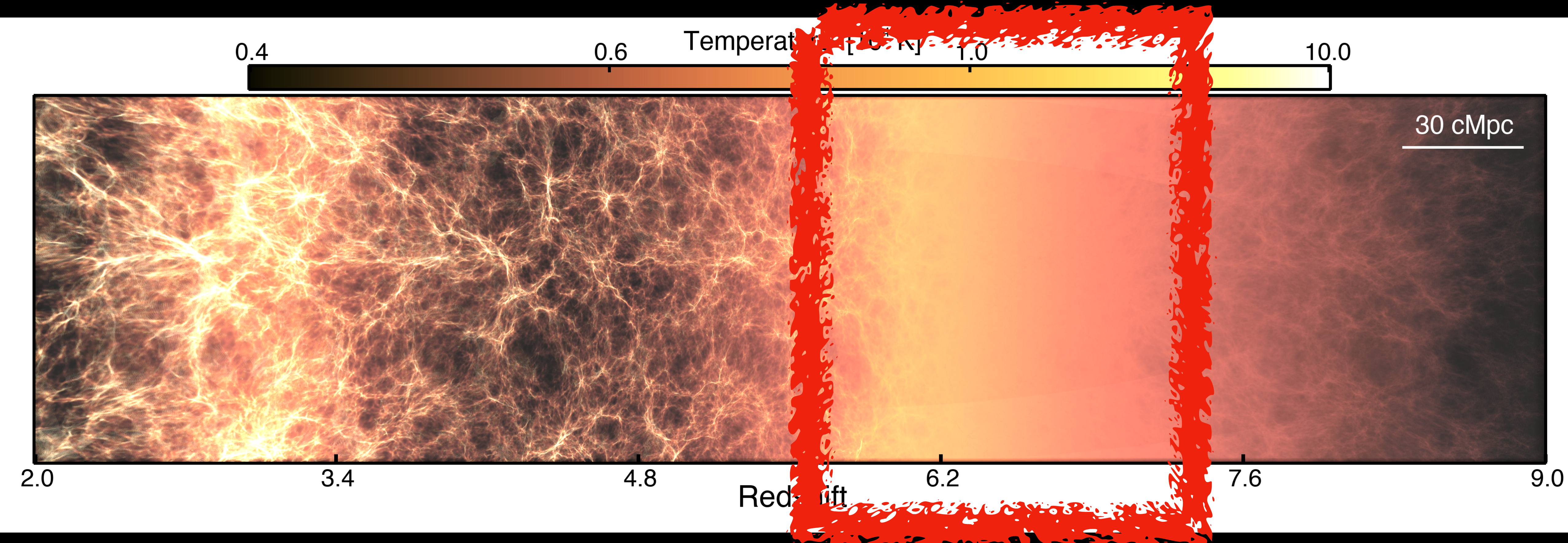
Villaseñor, et al, ApJ, 933, 59 (2022) Thermal history of the IGM.
From right to left: Hydrogen Ionization, Adiabatic Cooling, Helium Ionization, Adiabatic Cooling

Expansion History Impacting IGM May Change $\text{Ly}\alpha$ Forest Structure



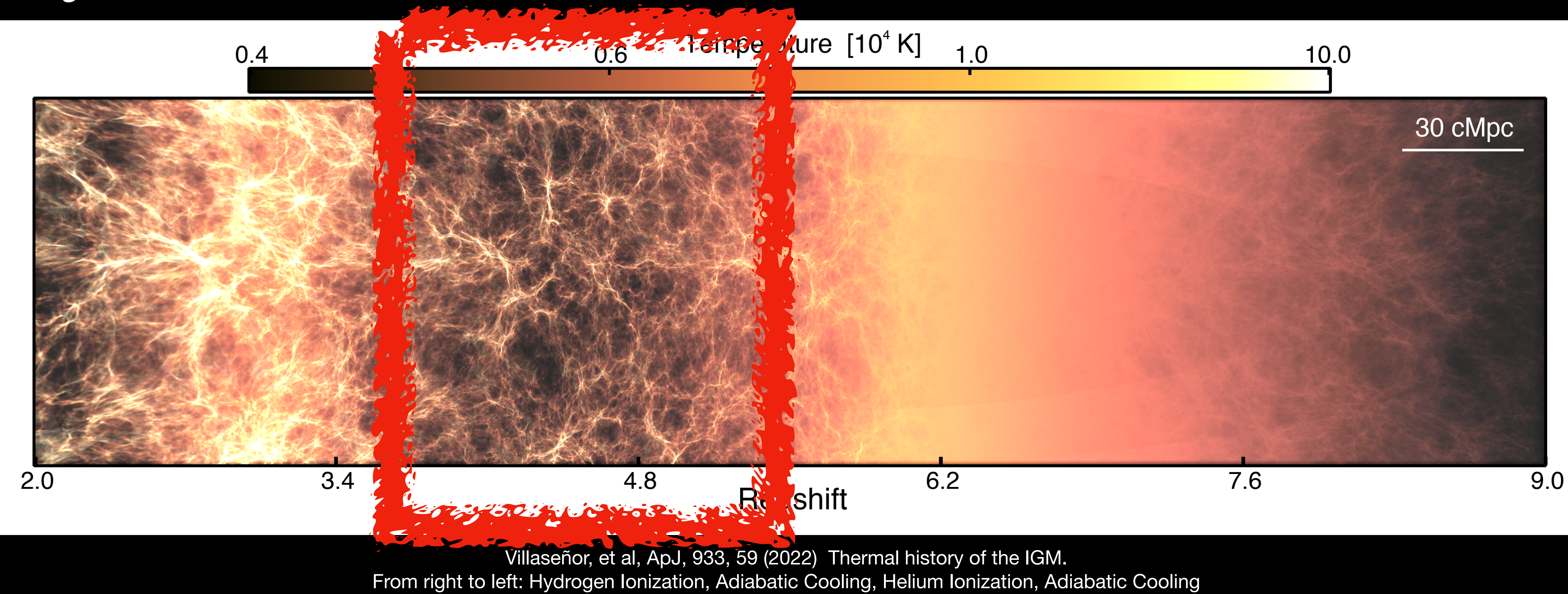
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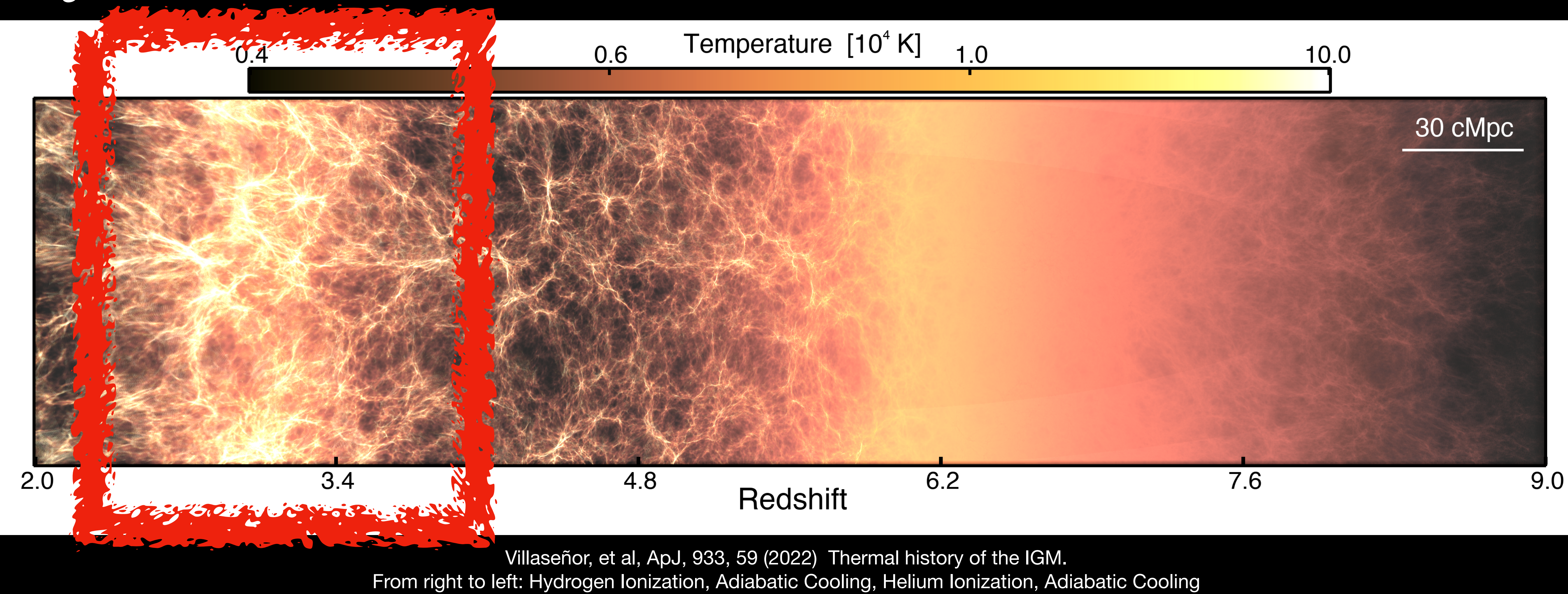


Villaseñor, et al, ApJ, 933, 59 (2022) Thermal history of the IGM.
From right to left: Hydrogen Ionization, Adiabatic Cooling, Helium Ionization, Adiabatic Cooling

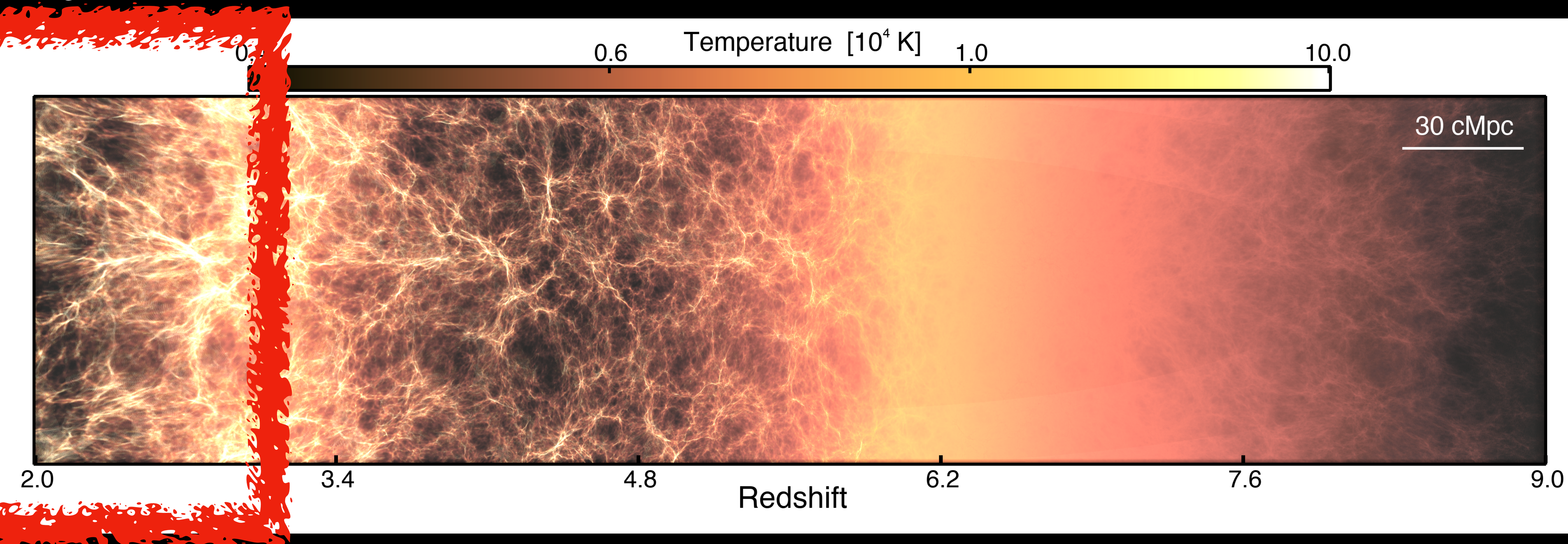
Expansion History Impacting IGM May Change $\text{Ly}\alpha$ Forest Structure



Expansion History Impacting IGM May Change $\text{Ly}\alpha$ Forest Structure



Expansion History Impacting IGM May Change $\text{Ly}\alpha$ Forest Structure



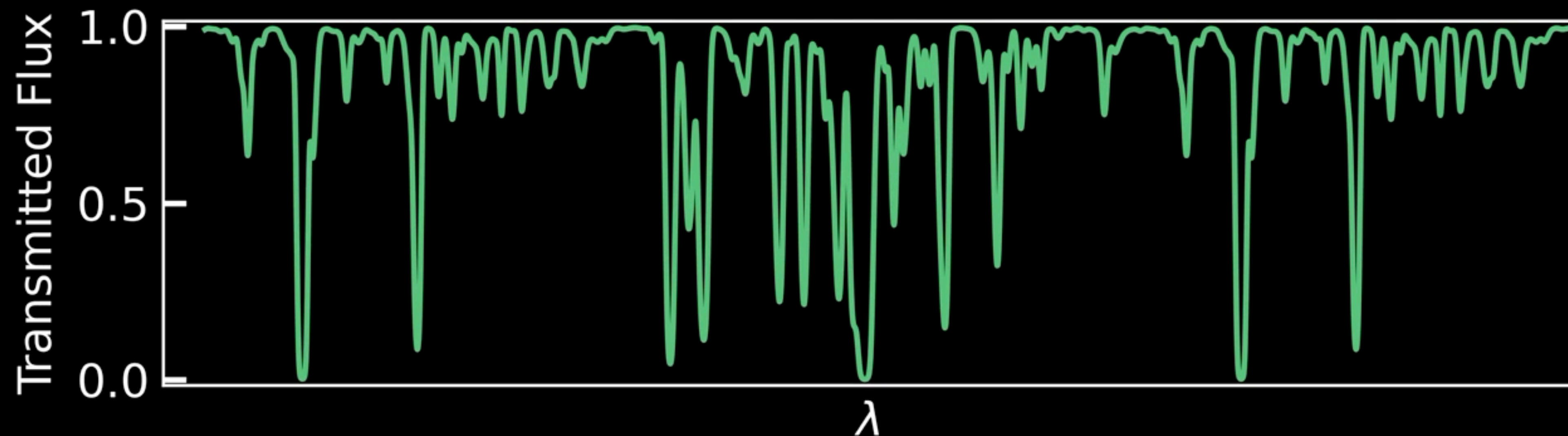
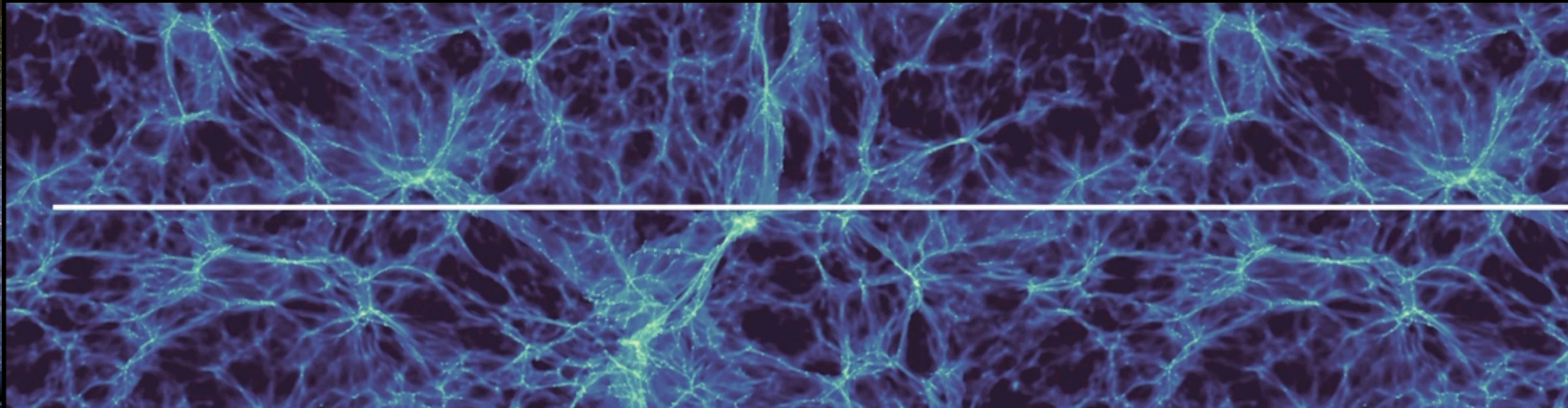
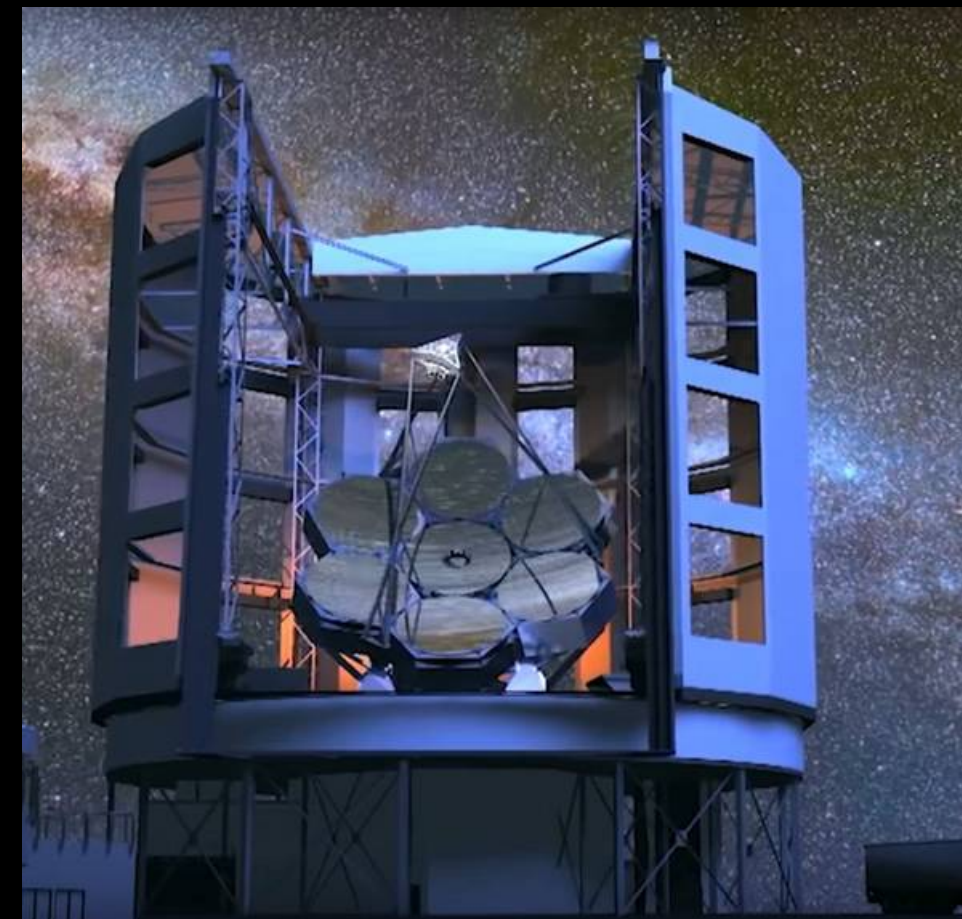
Villaseñor, et al, ApJ, 933, 59 (2022) Thermal history of the IGM.
From right to left: Hydrogen Ionization, Adiabatic Cooling, Helium Ionization, Adiabatic Cooling

Thermal History of IGM impacts $\text{Ly}\alpha$ Forest Structure

Observatory

Intergalactic Medium

Distant Quasar



CHOLLA

Computational Hydrodynamics On ParaLLeI Architectures



GPU-native, massively-parallel, grid-based simulation
code - <https://github.com/cholla-hydro/cholla>

State-of-the-art hydrodynamic algorithms (Precise
Riemann solvers, 3rd order spatial reconstruction, unsplit
integration, dual energy formalism)

Physics includes:

- Compressible hydrodynamics or ideal MHD
- Optically-thin radiative cooling and photoionization heating
- Gravity (FFT-based gas, static, particle-mesh)
- Cosmology (including time-variable dark energy)
- Scalar tracking

Schneider & Robertson, ApJS, 217, 24 (2015)

Schneider & Robertson, ApJ, 834, 114 (2017)

Villaseñor, et al, ApJ, 912, 138 (2021)

Villaseñor, et al, ApJ, 933, 59 (2022)

Garza, et al, PhysRevD (2025, submitted)

Isolating Dark Energy Impact on w_0w_a CDM models

Cosmology Name	$\Omega_{m,0}$	H_0	w_0	w_a
DESI+CMB+ Λ CDM	0.3069	67.97	-1.000	0.000
DESI+CMB+Pantheon	0.3085	68.03	-0.827	-0.750
DESI+CMB+Union3	0.3230	66.53	-0.650	-1.270
DESI+CMB+DESY5	0.3160	67.24	-0.727	-1.050

High resolution simulations of $(2048)^3$ cells, $V = (50\ h^{-1}\text{Mpc})^3$ required 512 GPUs

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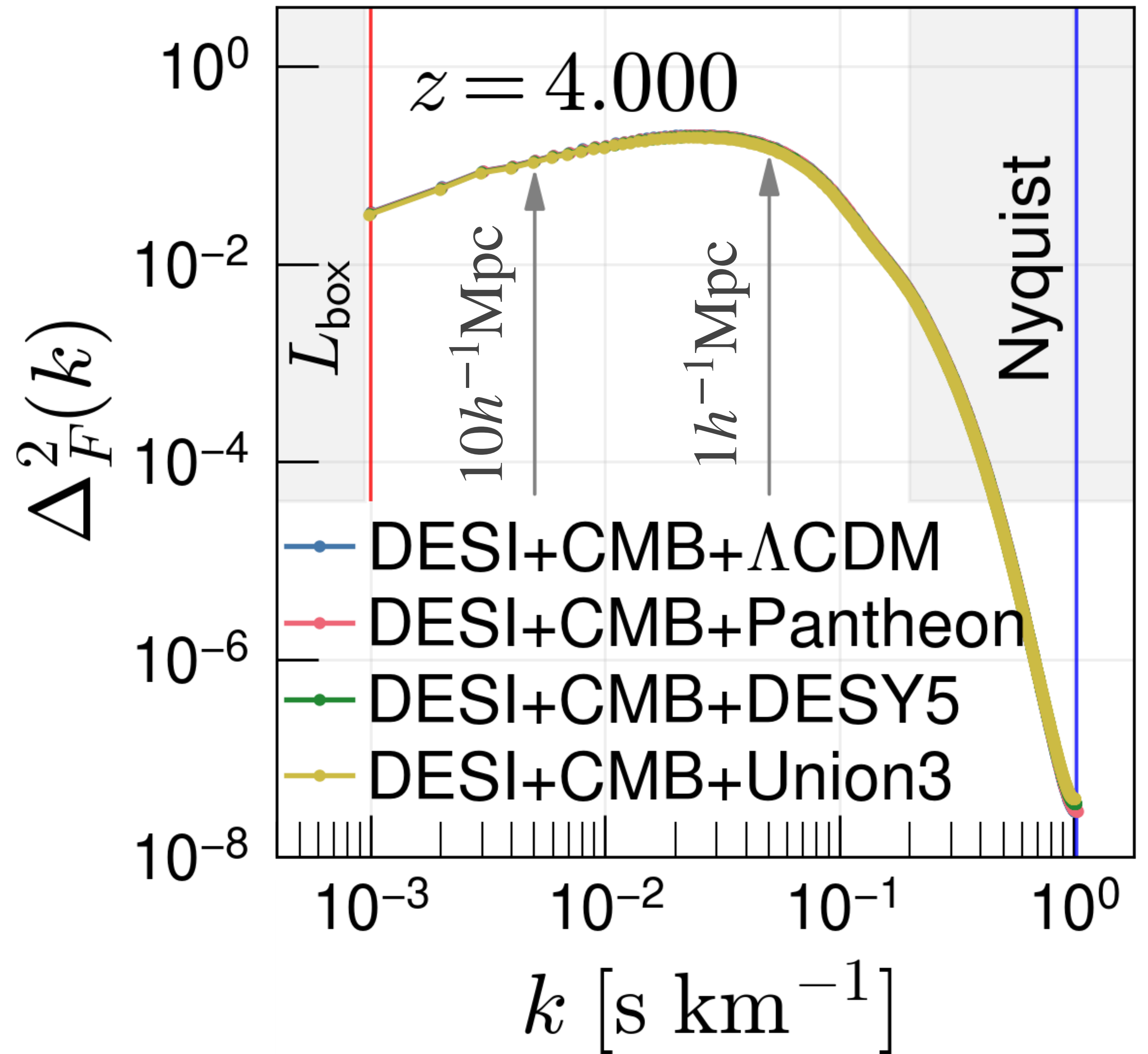
High resolution simulations of $(2048)^3$ cells, $V = (50 \ h^{-1}\text{Mpc})^3$ required 512 GPUs

Flux Power Spectrum Results

Dimensionless power spectrum:

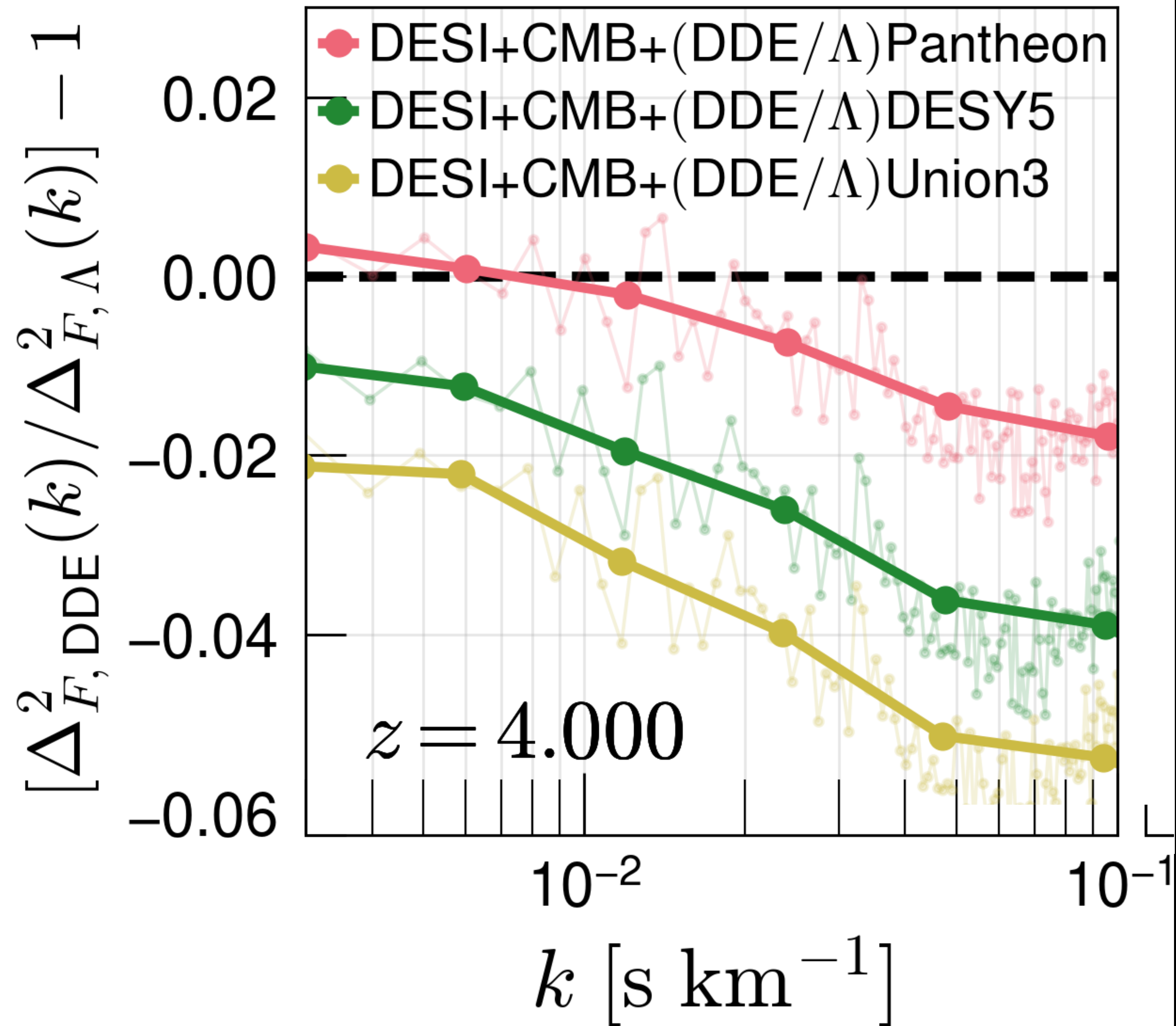
$$\Delta_F^2(k) = \frac{1}{\pi} k P(k)$$

Gray bands represent observational limits



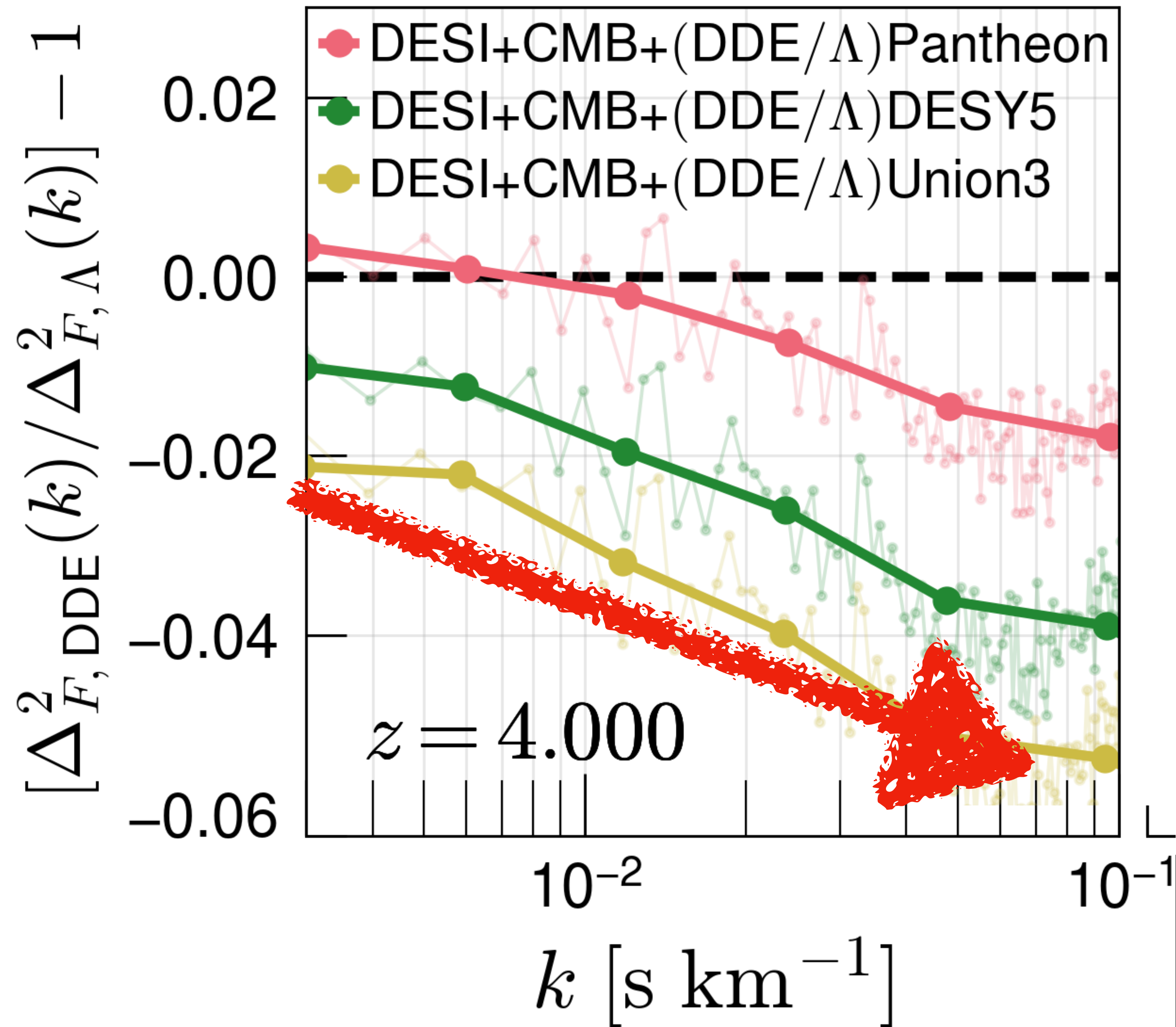
Flux Power Spectrum Results

Relative difference in power of HI flux fluctuations over different physical scales between a w_0w_a CDM model and its Λ CDM counterpart



Flux Power Spectrum Results

Relative difference in power of HI flux fluctuations over different physical scales between a w_0w_a CDM model and its Λ CDM counterpart

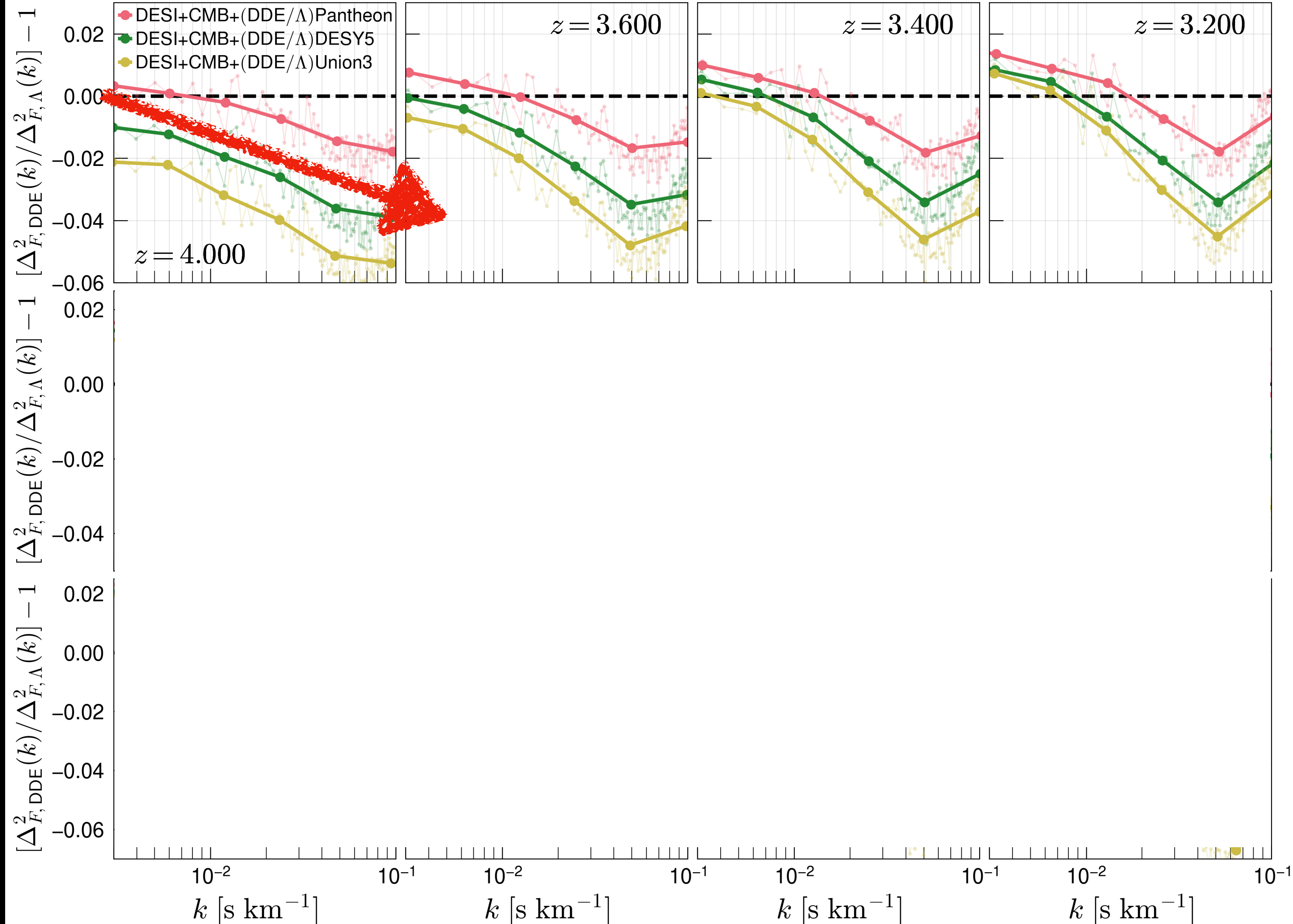


Flux Power Spectrum Results

$\Delta_F^2(k; z)$

Relative difference in power of HI flux fluctuations over different physical scales between a w_0w_a CDM model and its Λ CDM counterpart.

At lower redshifts, find more (less) relative power at large (small) scales.

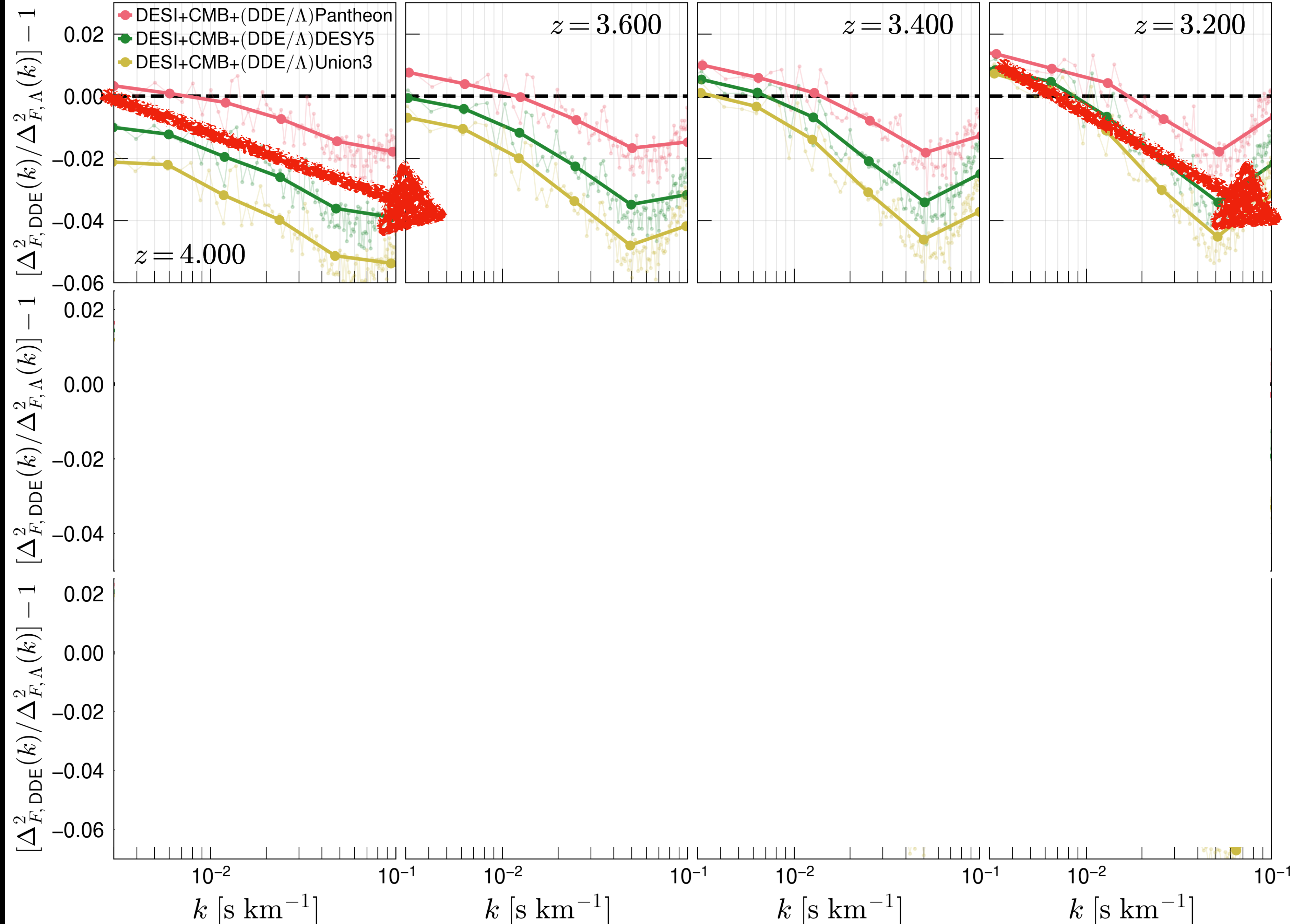


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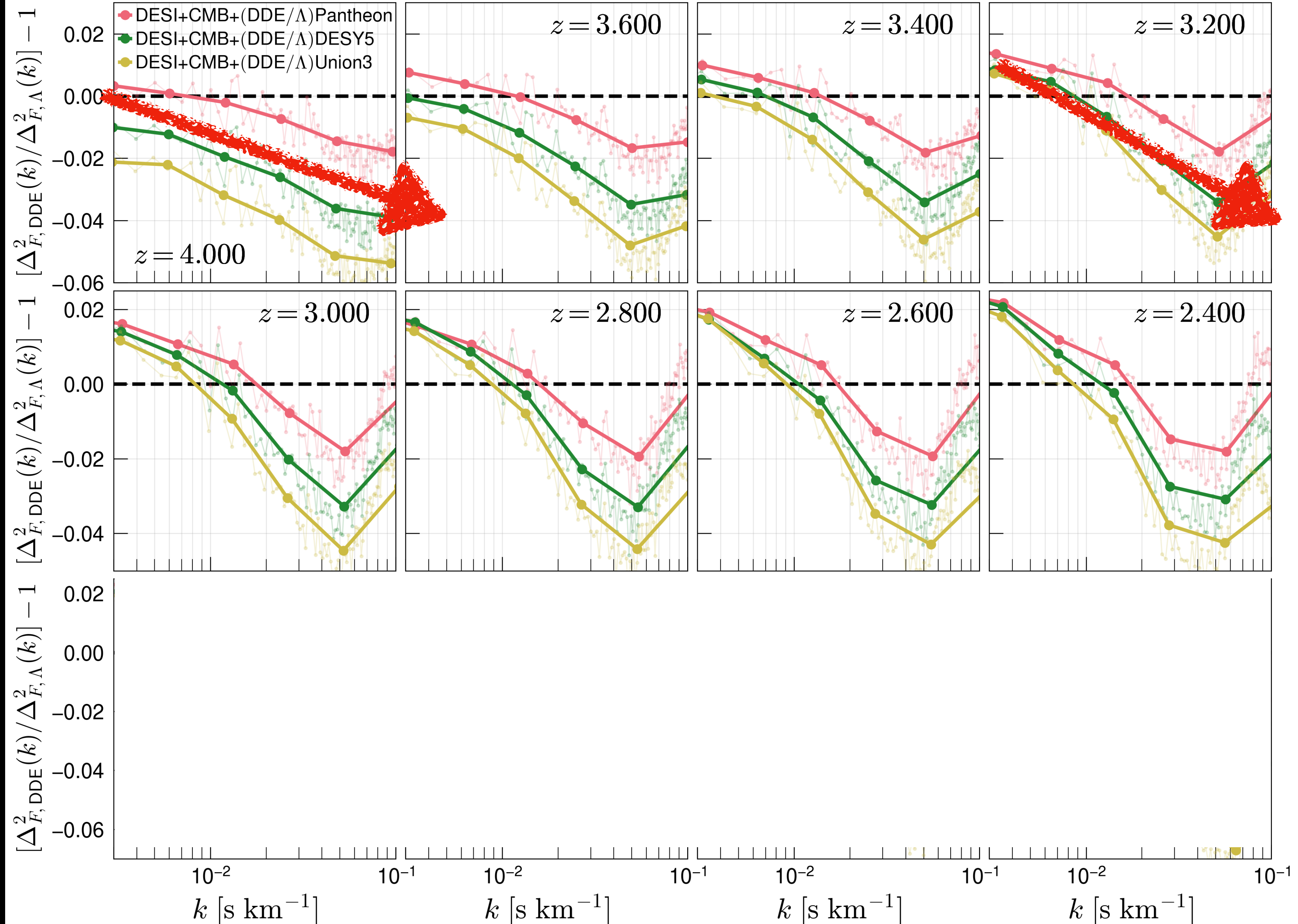


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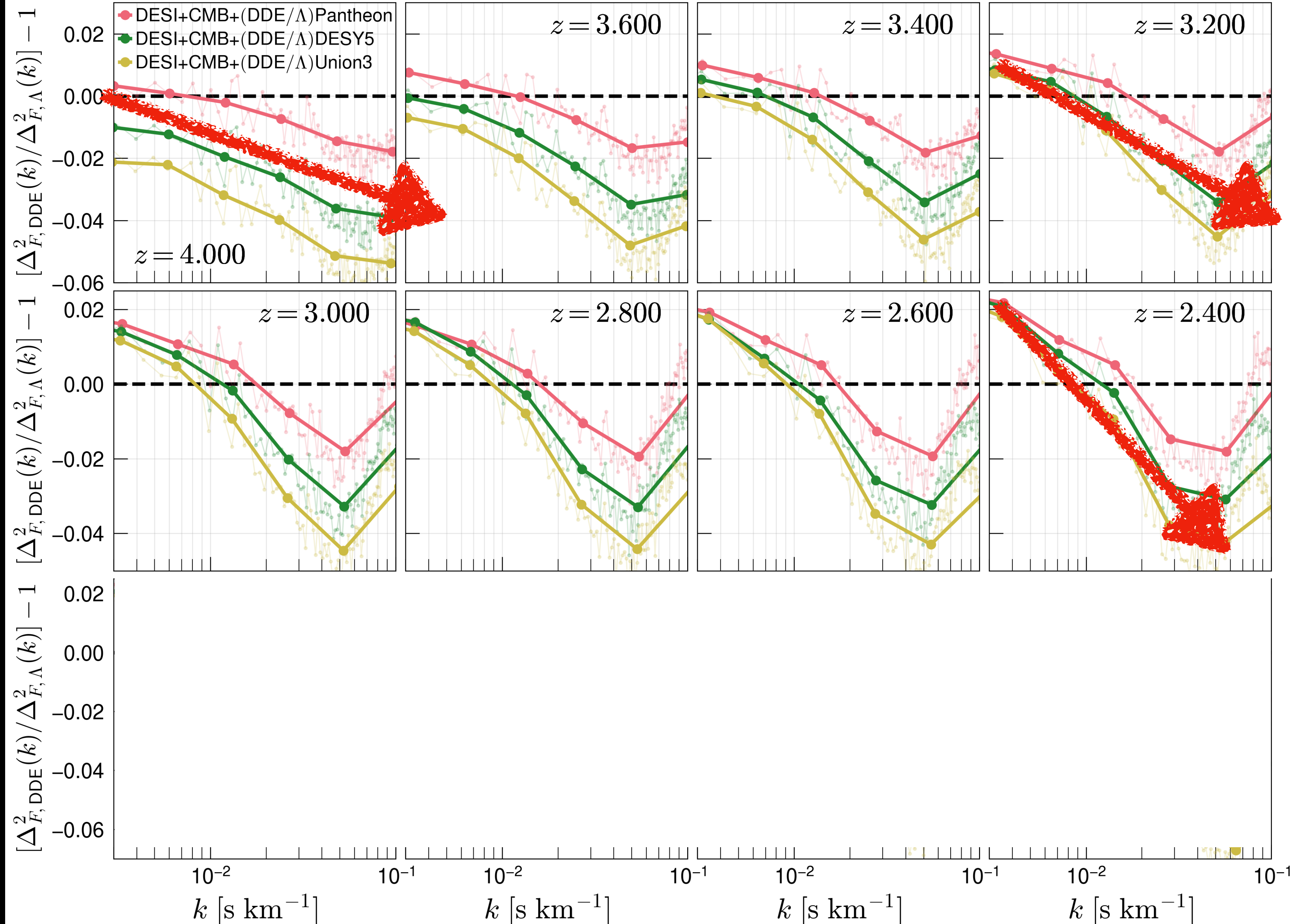


Flux Power Spectrum Results

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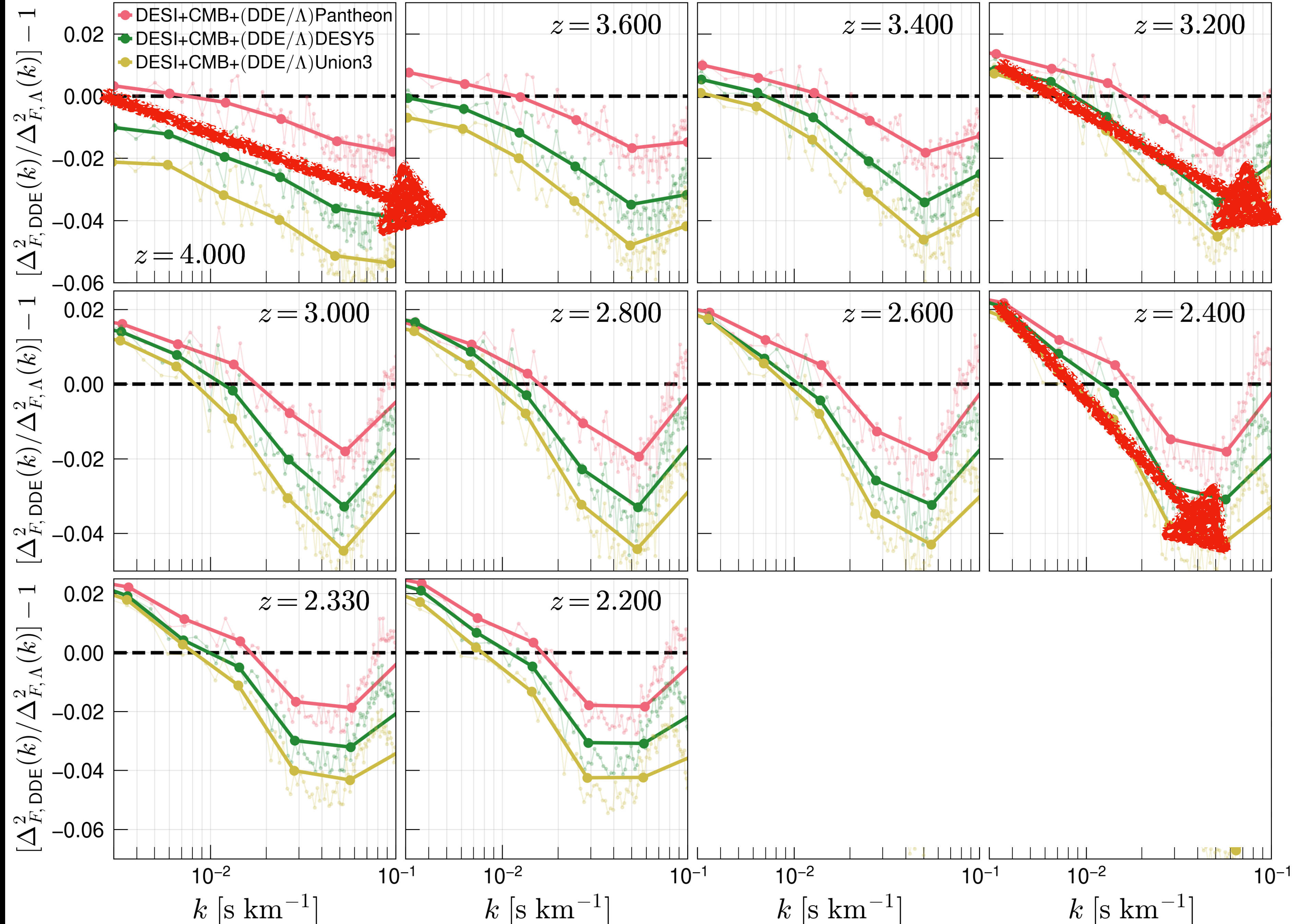


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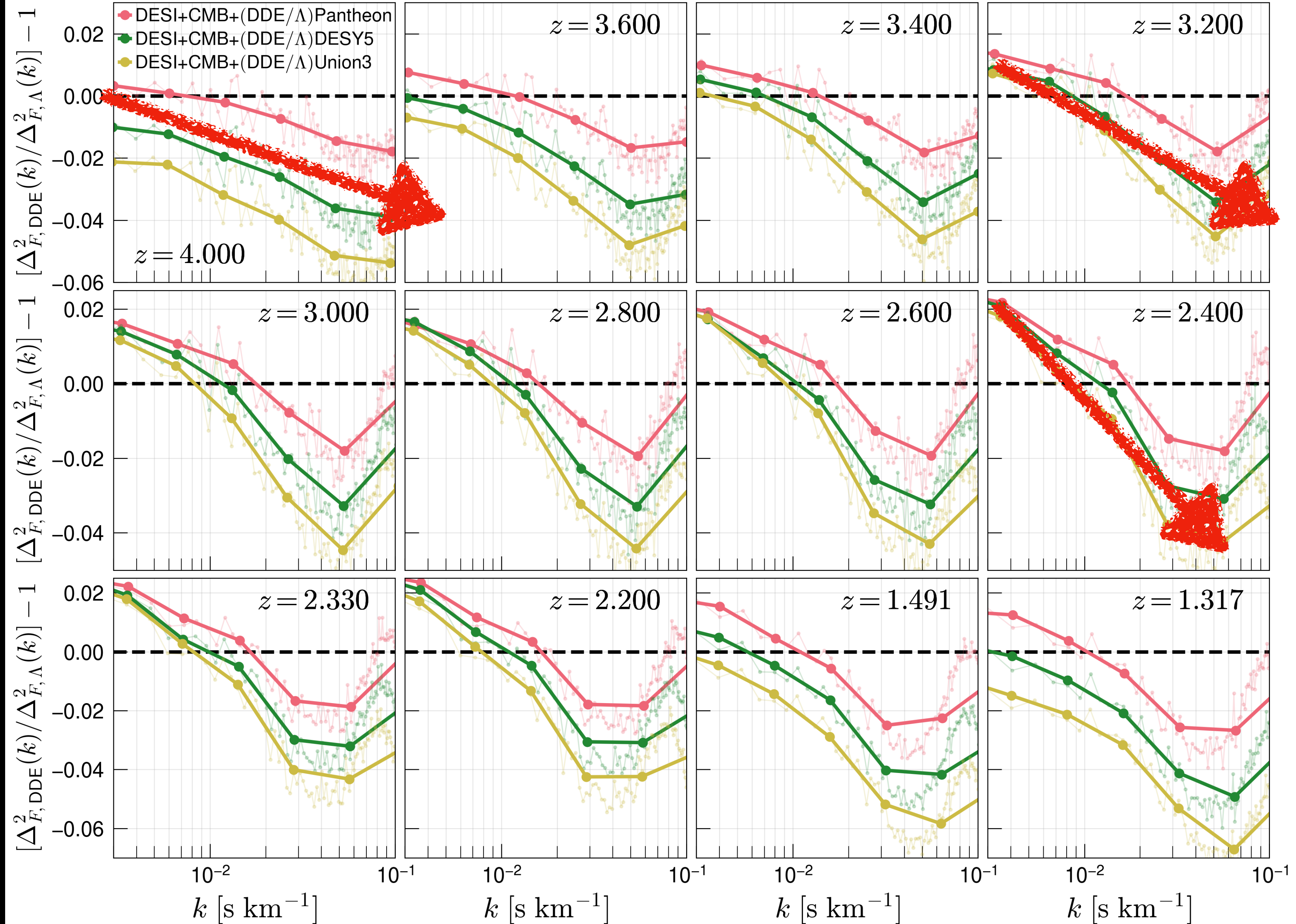


Flux Power Spectrum Results

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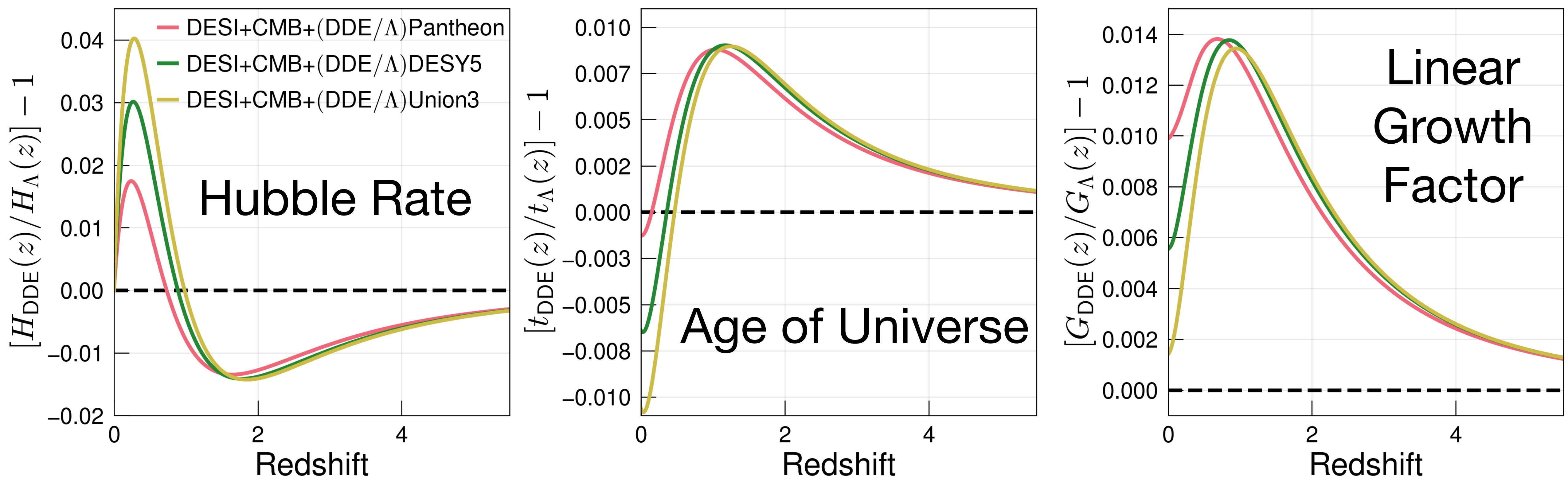


What do our simulations tell us about the **DESI Inferred w_0w_a CDM** cosmology compared to **Λ CDM**?

- All 3 **w_0w_a CDM** predict a +2% to -5% redshift-dependent Ly α Flux Power Spectra discrepancy
- All 3 **w_0w_a CDM** models predict a 0.8-1.5% warmer IGM, with the discrepancy larger at later times
- All 3 **w_0w_a CDM** models predict a 0.5-4.0% lower τ_{eff}
- Next Steps : Study covariance with temperature, $\Omega_m h^2$, n_s , & σ_8



More Results !

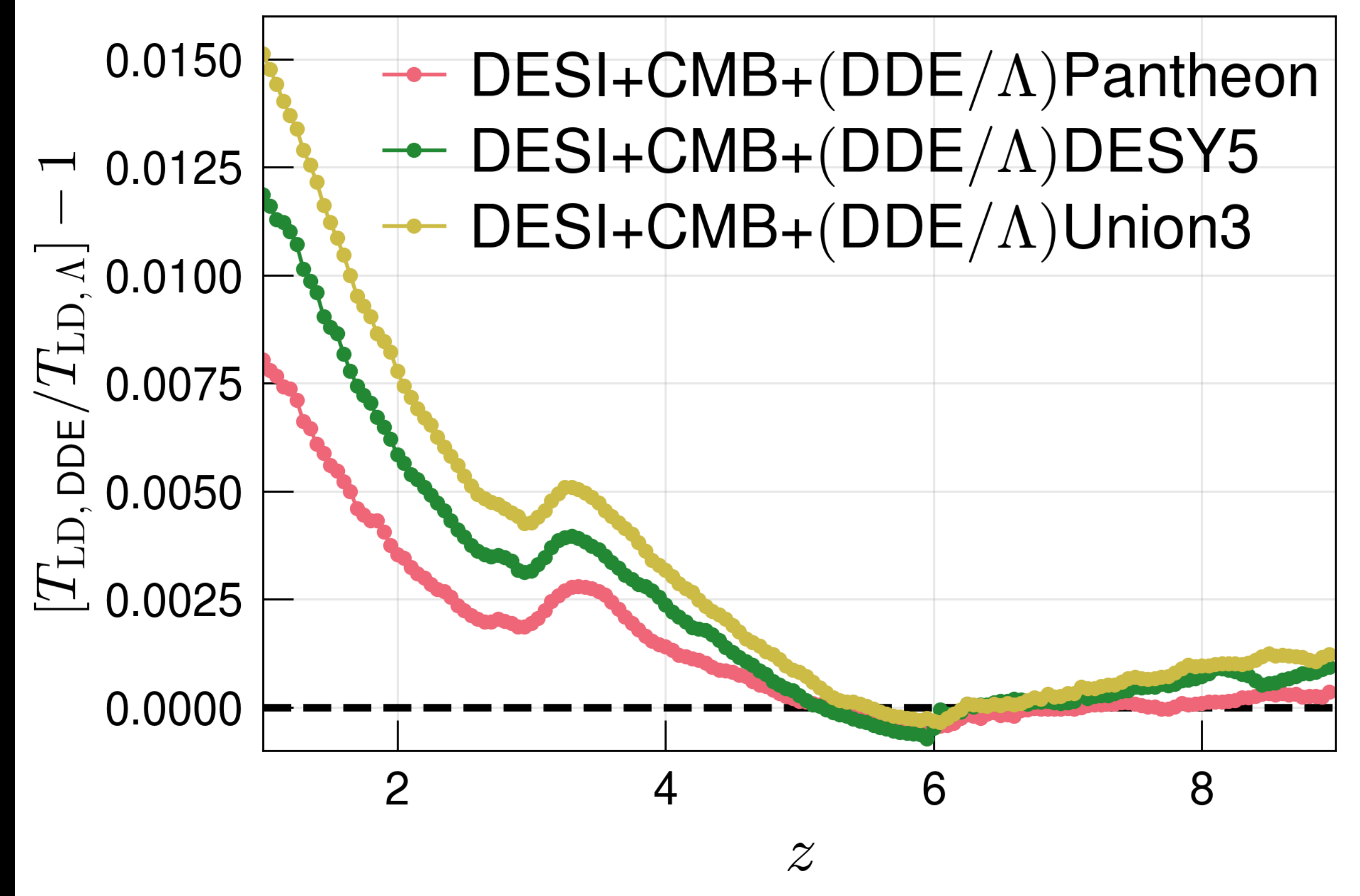
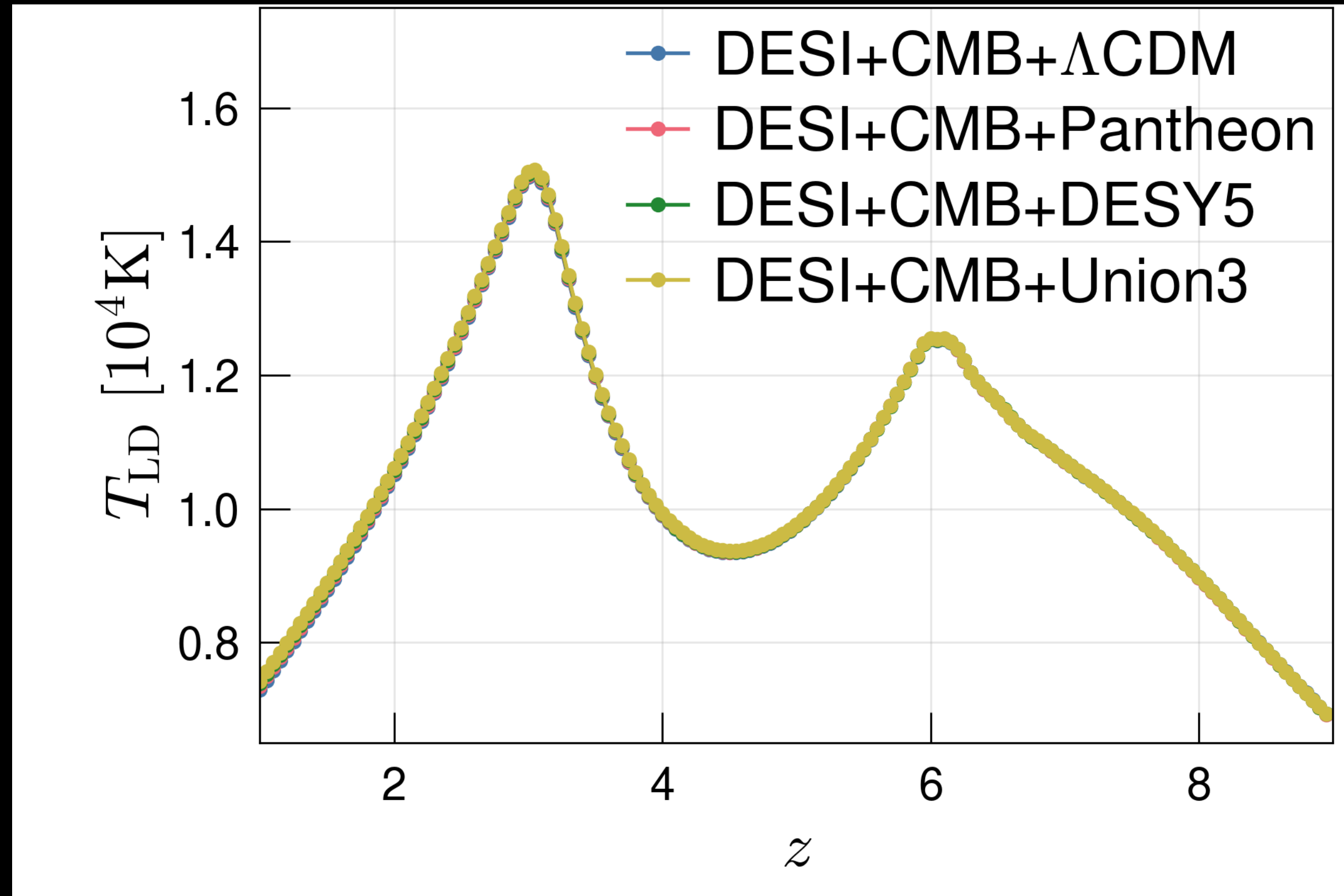


DESI Inferred

**w_0w_a CDM
Results**

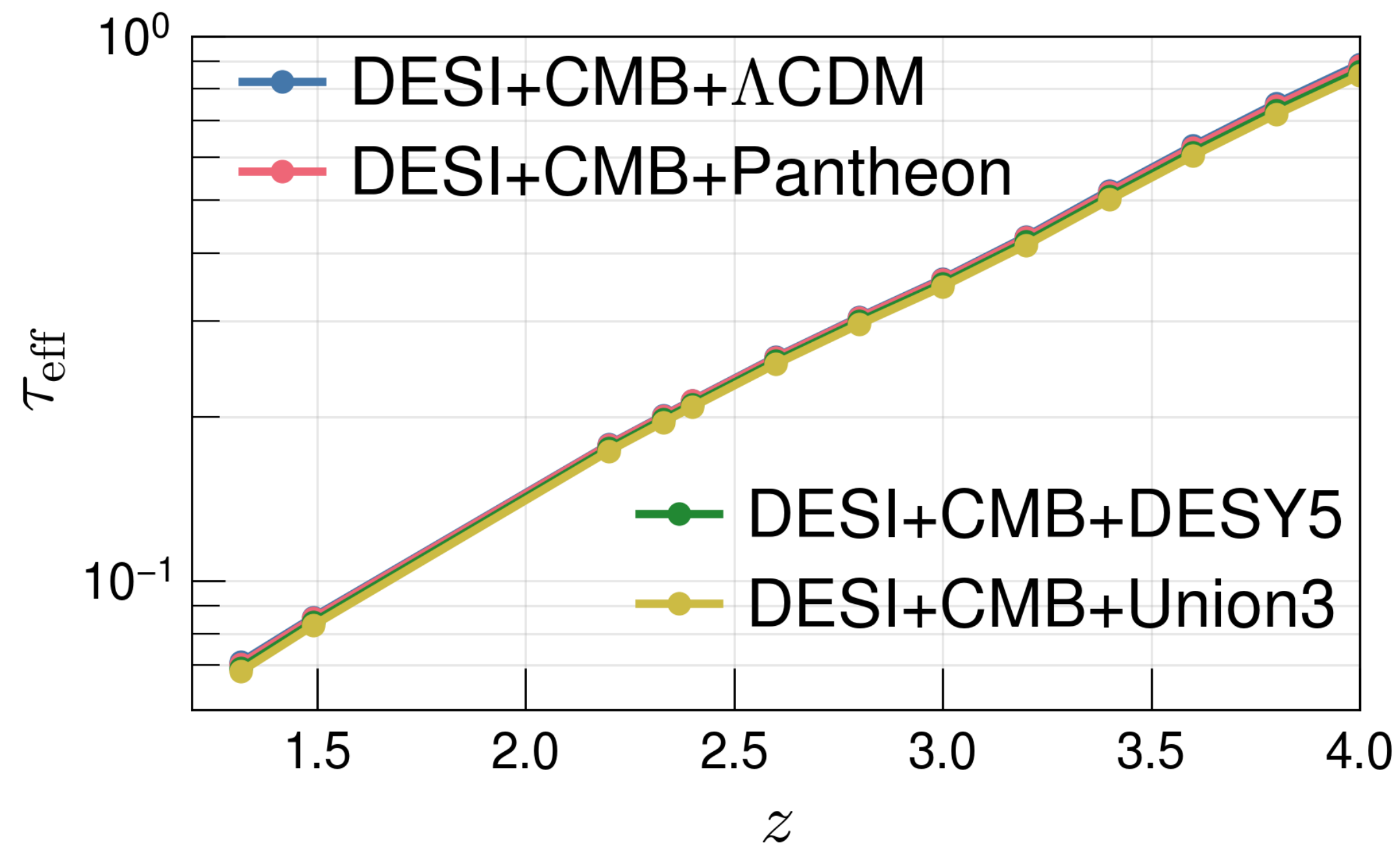
- In w_0w_a CDM models, diffuse gas undergoes slower adiabatic cooling, which tends to increase the Jeans mass.
- w_0w_a CDM models exhibit enhanced linear growth factor at all times, so we expect greater amplitude of large-scale structure

Temperature History of IGM w/Dynamical Dark Energy

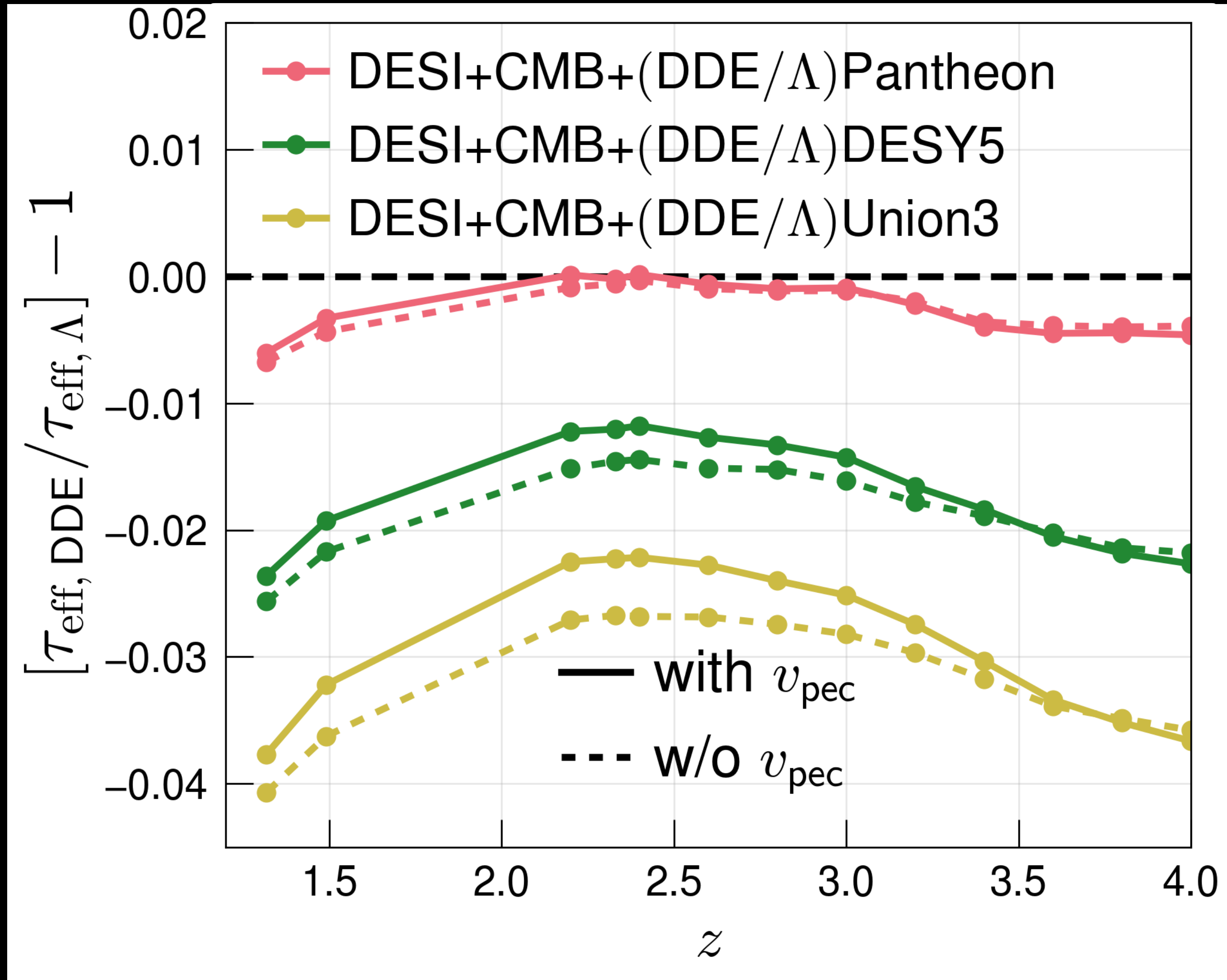


T_{LD} is the weighted average of temperature near cosmic mean density
 $-0.25 \leq \log_{10}(\rho/\bar{\rho}_b) \leq 0.25$ and cool $3 \leq \log_{10} T/K \leq 5$

Effective HI Optical Depth History w/Dynamical Dark Energy



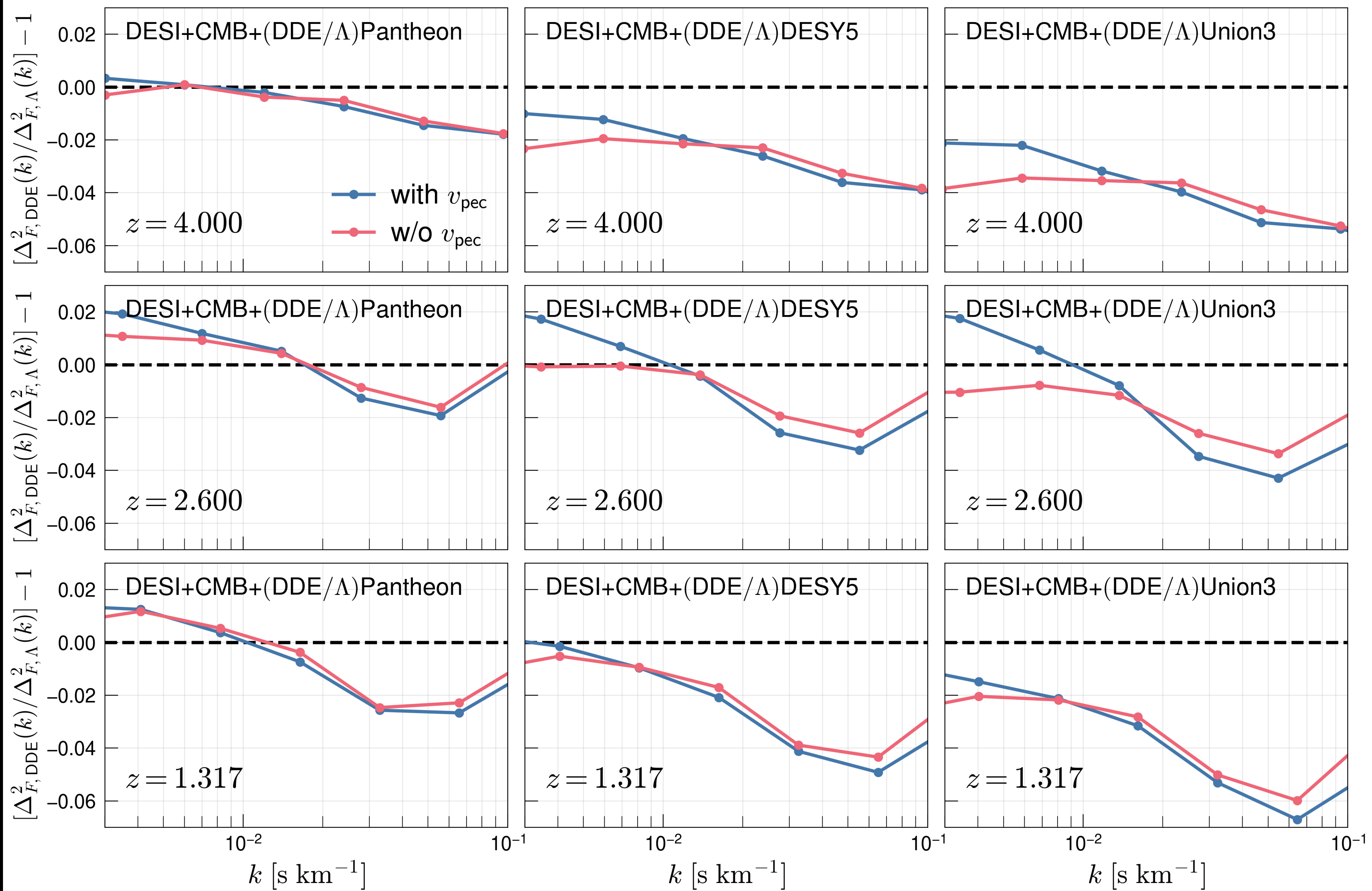
The IGM is more optically thin to HI in a w_0w_a CDM cosmology



Flux Power Spectrum Results

$$\Delta_F^2(k; z)$$

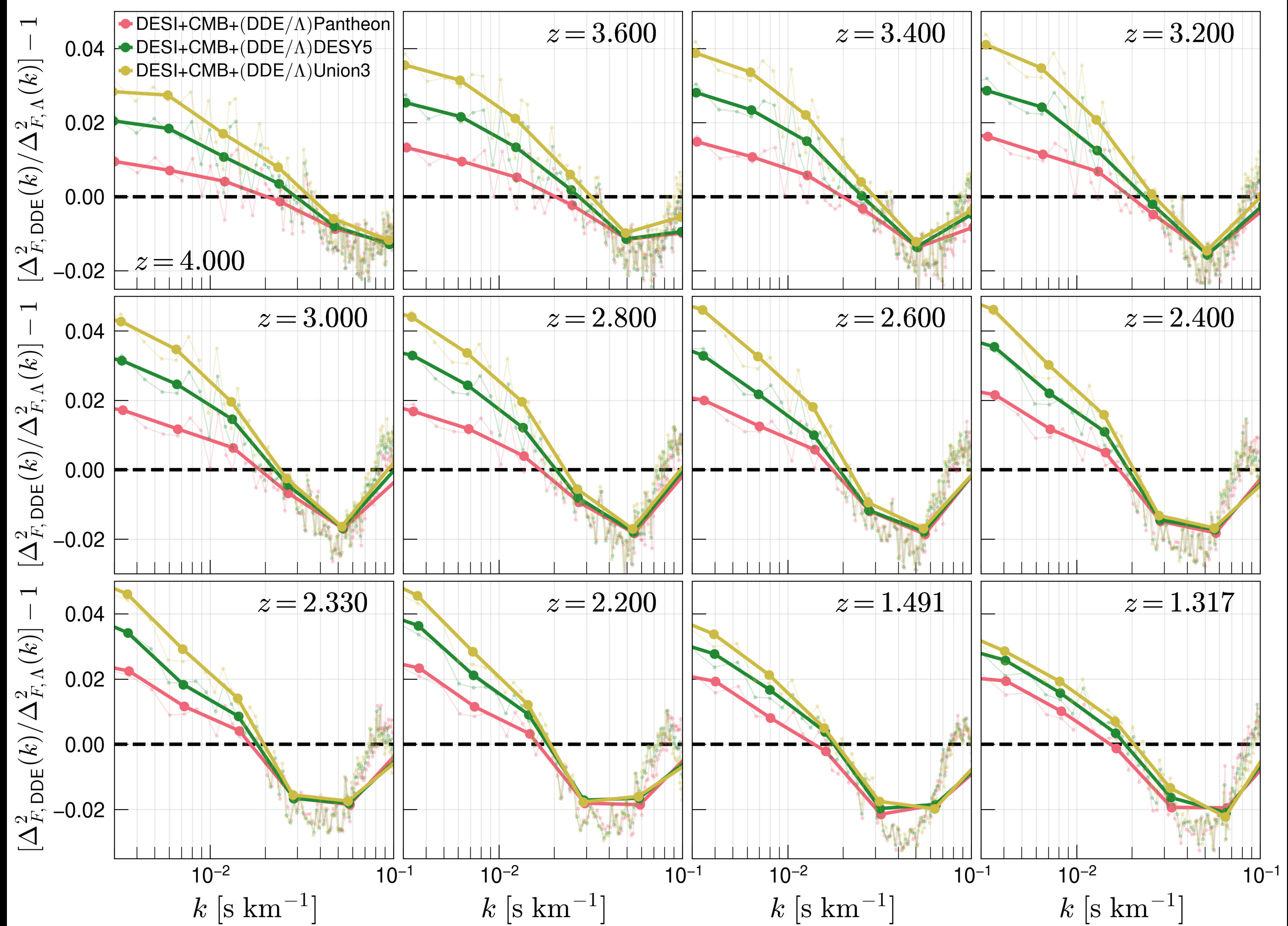
Removing
peculiar
velocities
mostly
impacts
large scales

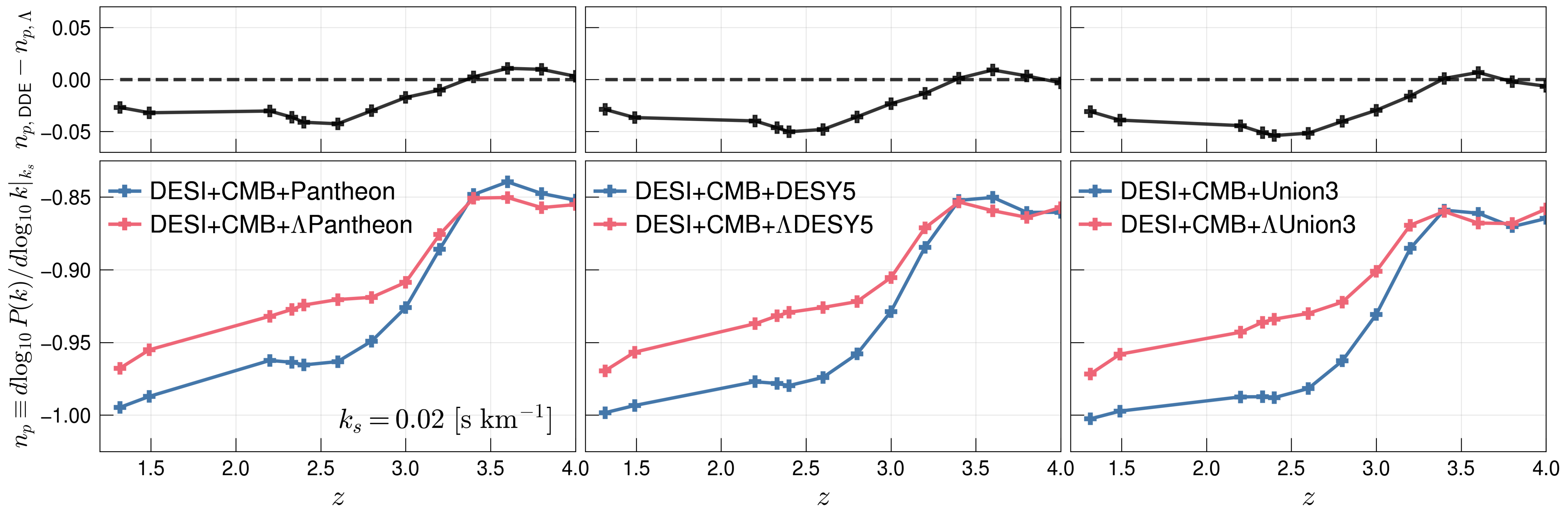


Flux Power Spectrum Results

$$\Delta_F^2(k; z)$$

Spectral tilt persists after matching τ_{eff}





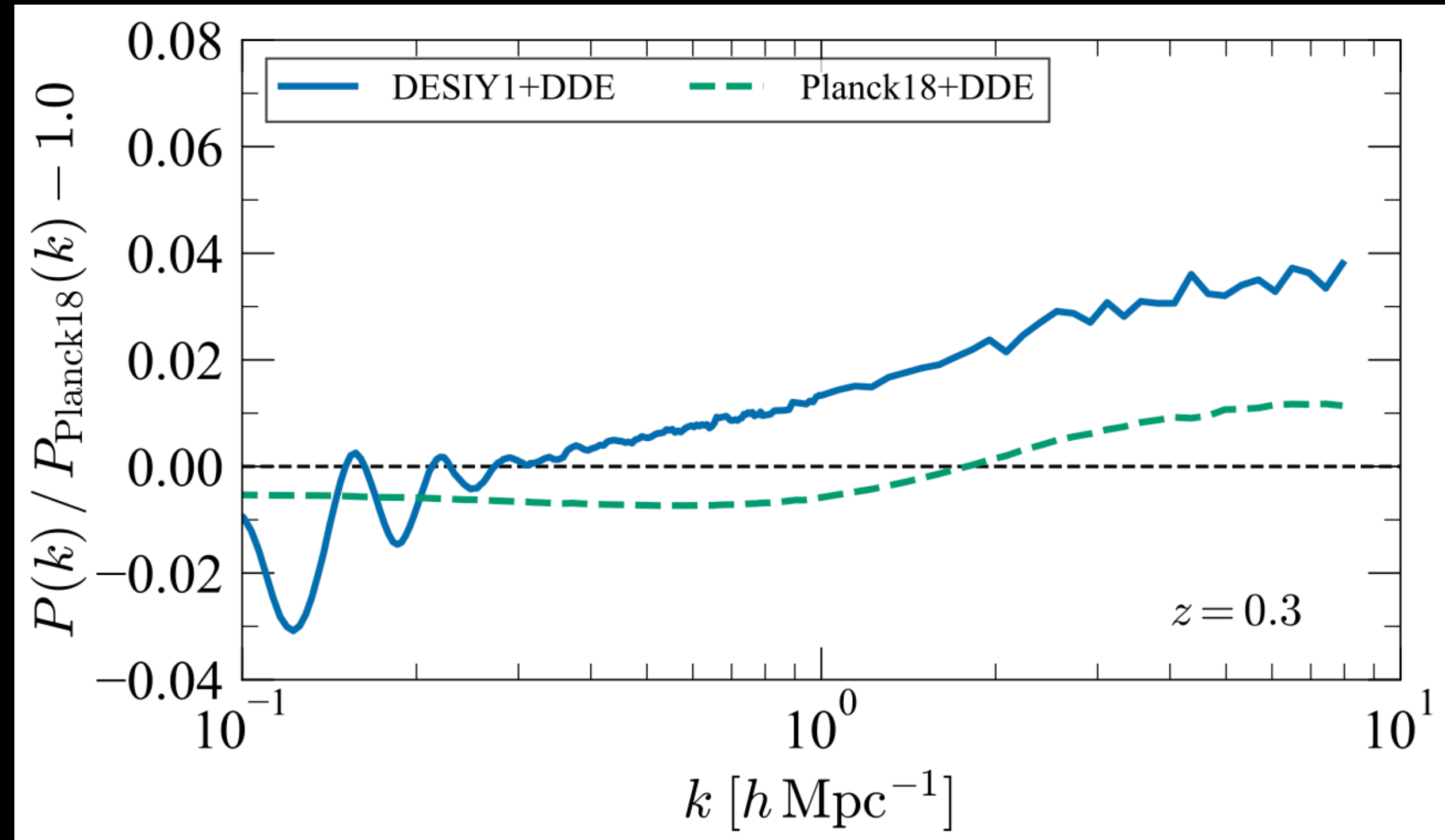
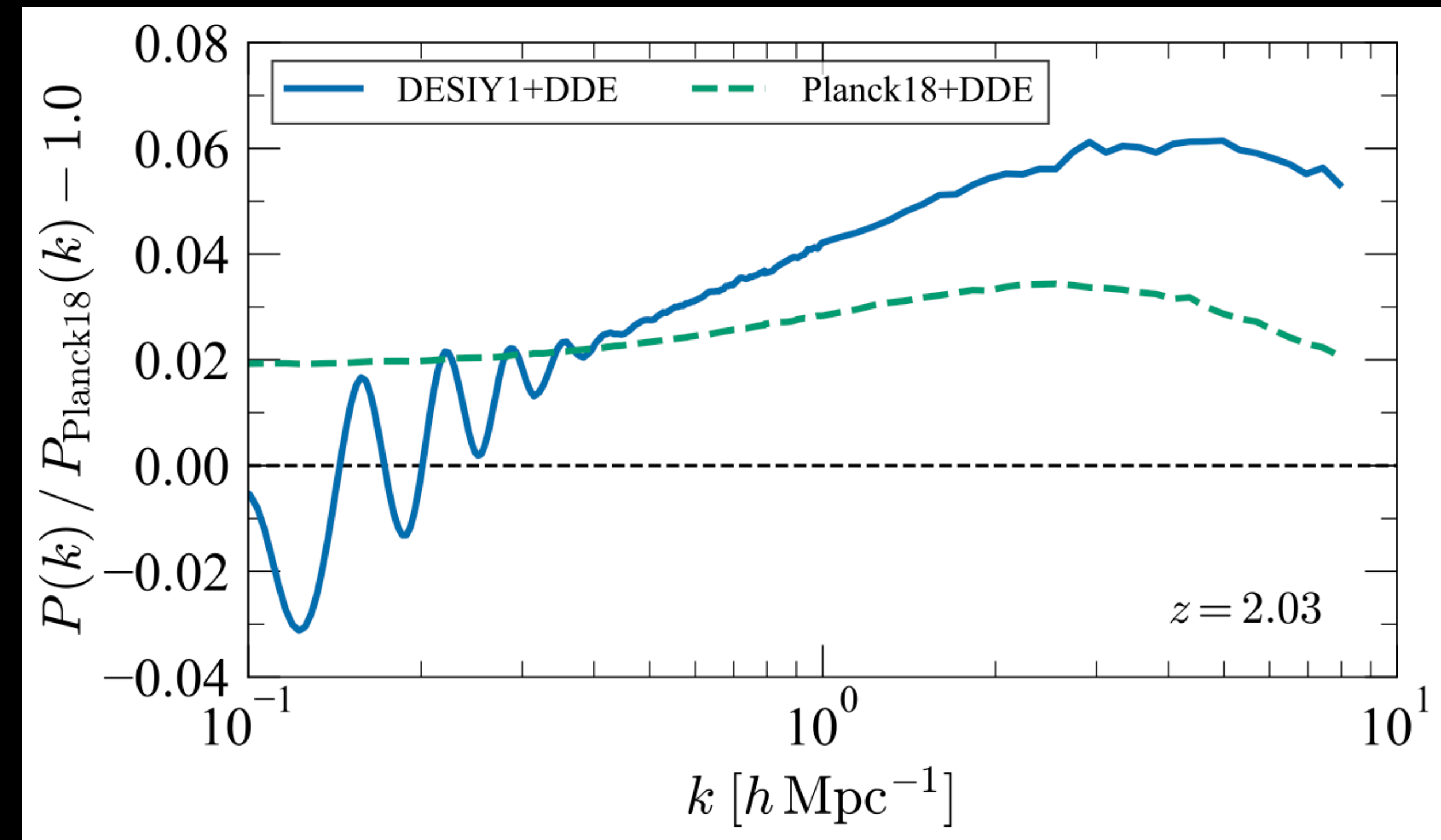
Flux Power Spectrum Results

$\Delta_F^2(k; z)$

At redshifts $z < 3.4$, the slope of the power spectrum for $w_0 w_a \text{CDM}$ model is lower than its ΛCDM counterpart

Matter Power Spectrum $P(k; z)$

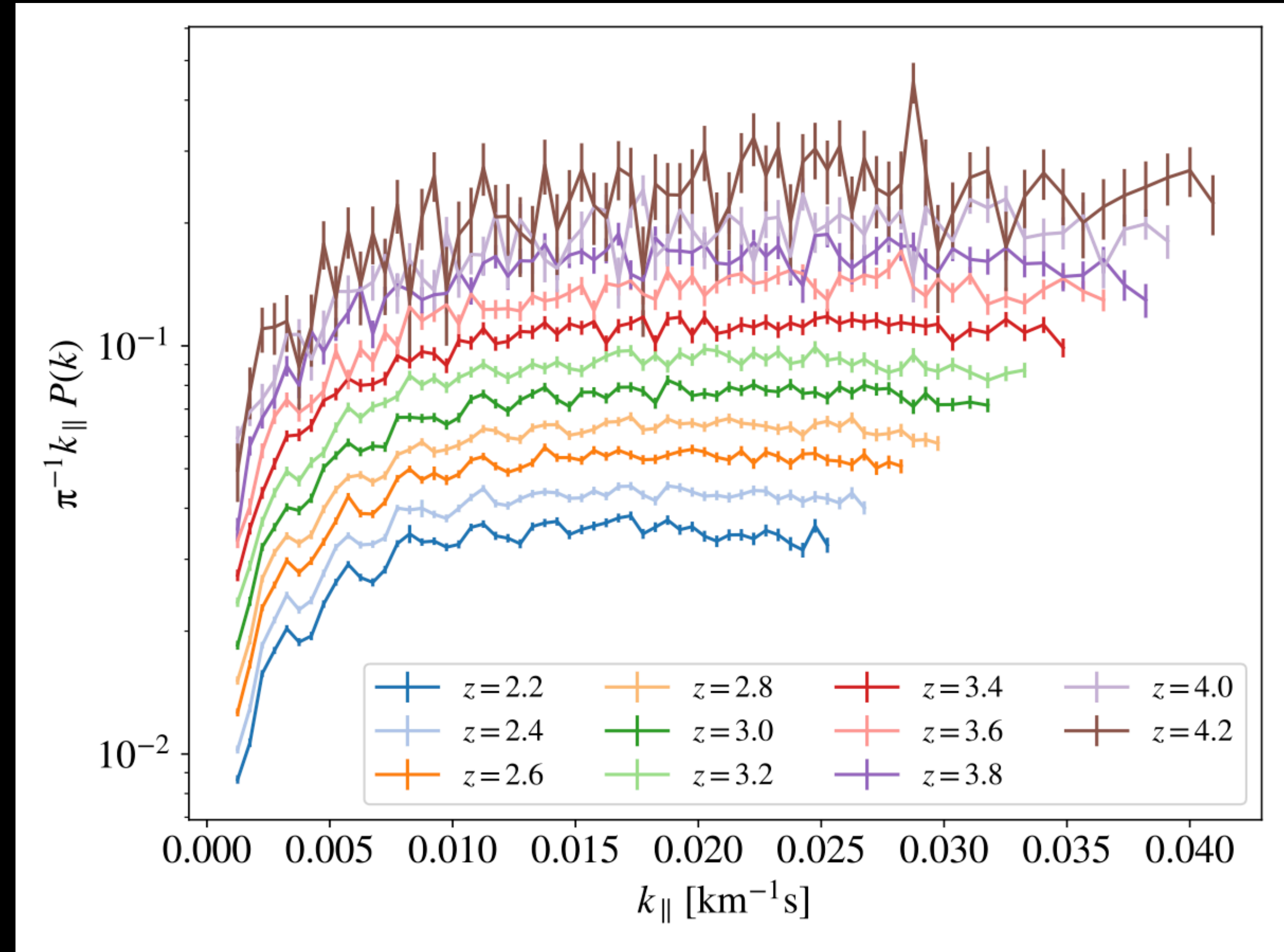
Relative difference in power of dark matter density fluctuations over different physical scales between a w_0w_a CDM and Λ CDM model



Ishiyama, et al. PhysRevD, 112, 4 (2025)

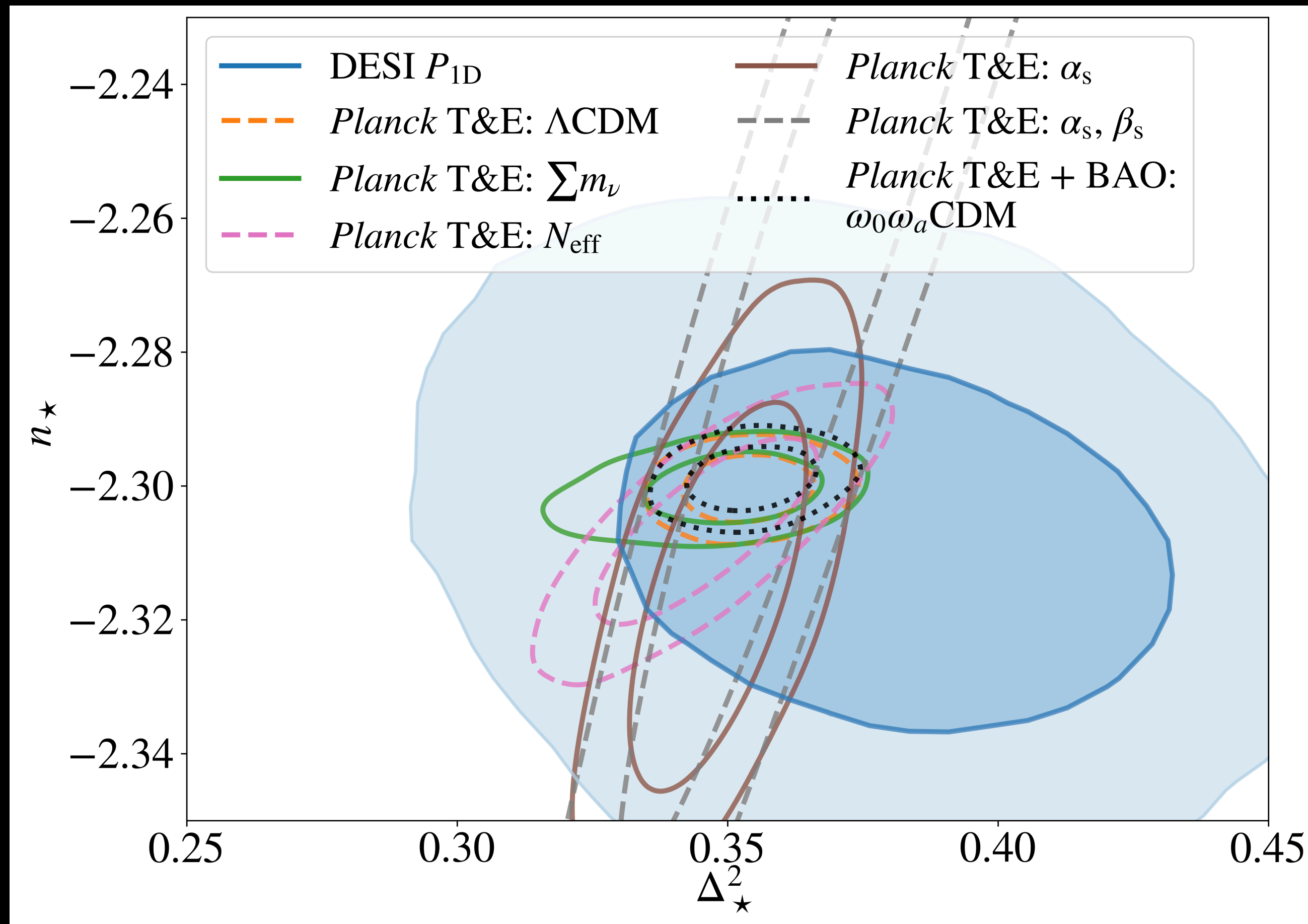
Placing Observational Constraints

- DESI DR1 included measurement of $\approx 500,000$ quasars with Flux Power Spectrum statistical uncertainties $\leq 10\%$ and absolute statistical uncertainties at $\leq 1\%$ for $z < 3.4$
- Systematic uncertainties dominated DR1 Flux Power Spectrum measurements
- High-resolution datasets for small-scale constraints: KODIAQ, SQUAD, and XQ-100. Archival Keck/HIRES, VLT/UVES datasets. We can utilize BOSS and eBOSS

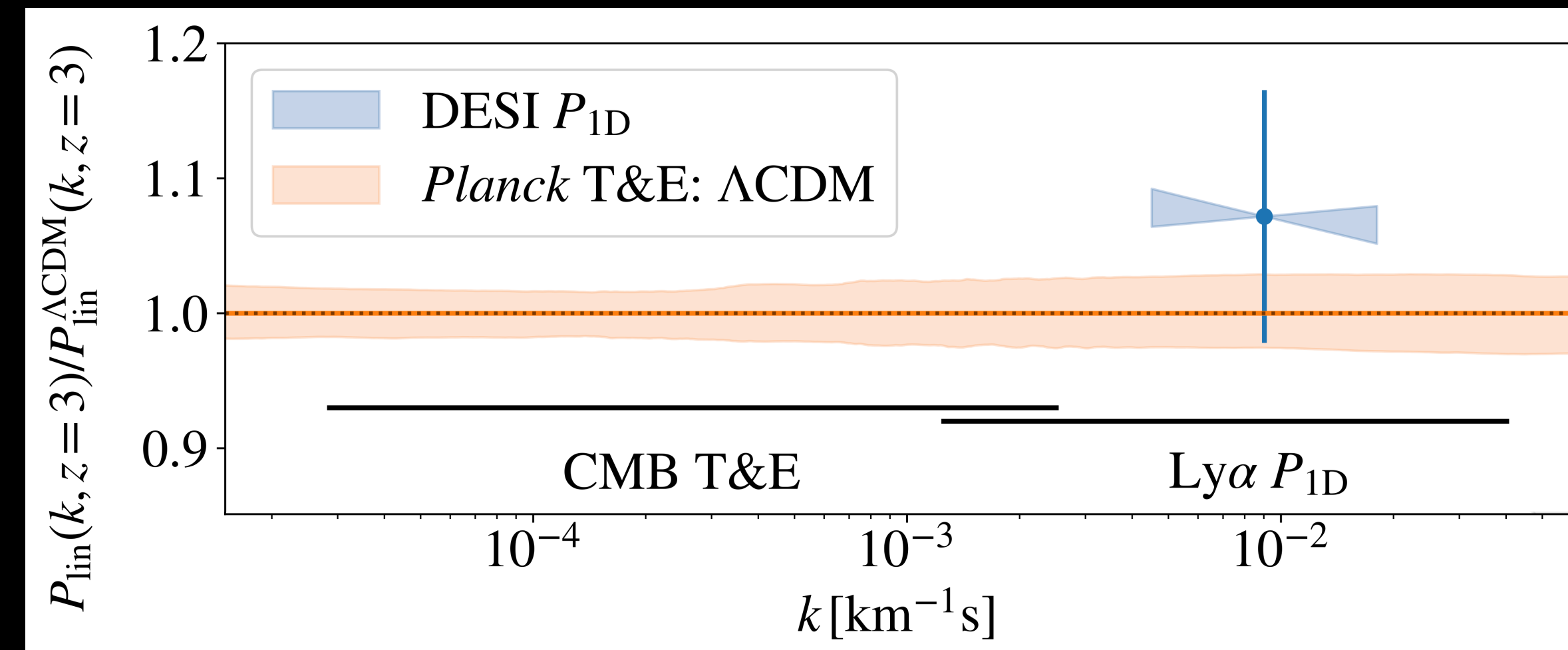


Chaves-Montero, et al, JCAP, accepted (2026)

Constraining power spectrum amplitude and slope at LyA scales



Chaves-Montero, et al, JCAP, accepted (2026)



Chaves-Montero, et al, JCAP, accepted (2026)

