# 5σ TENSION BETWEEN CMB AND LY-α FOREST AND HINT OF PHYSICS BEYOND ΛCDM

*ArXiv: 2311.16377*

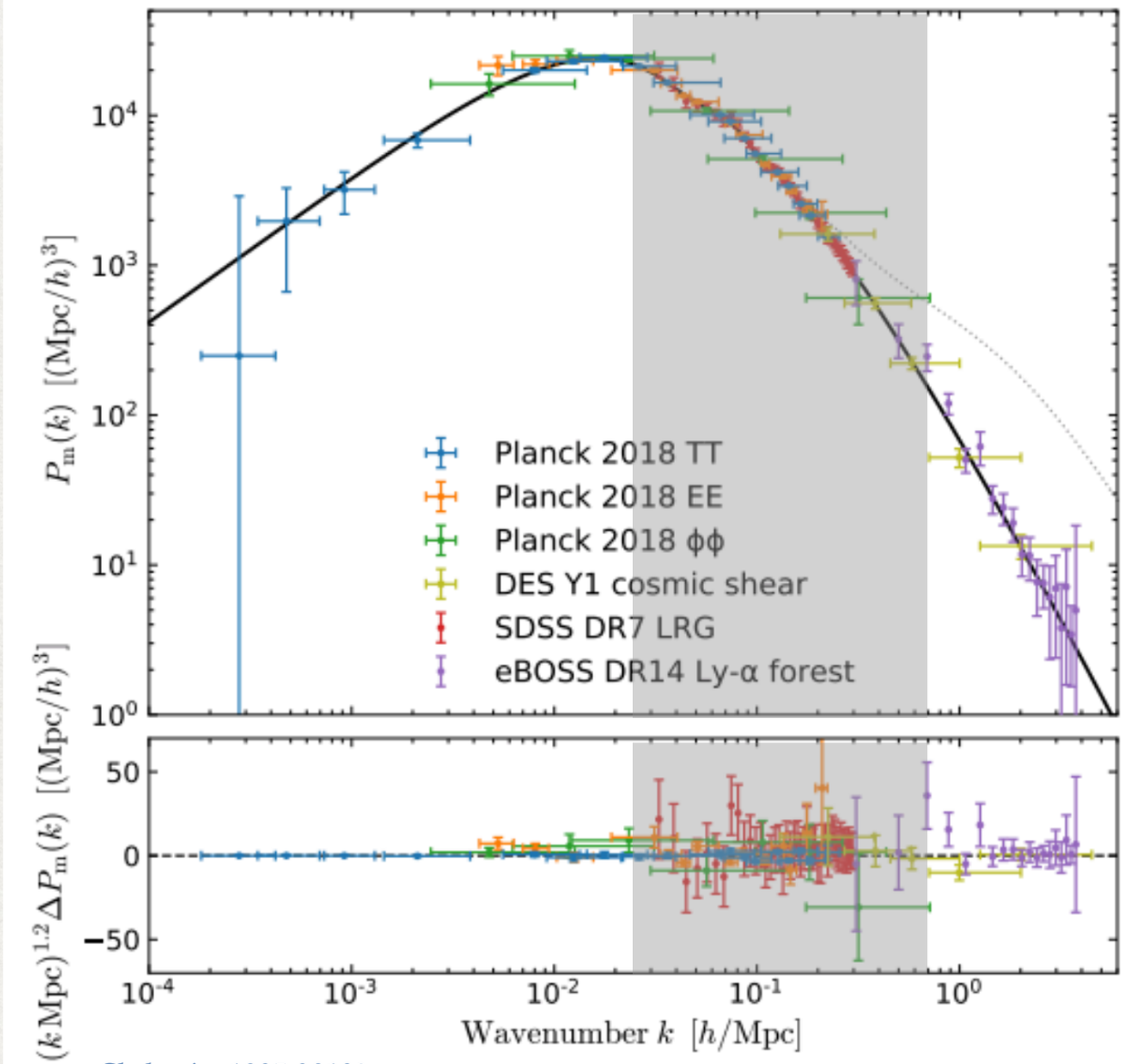

**Vivian Poulin**

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier


*In collaboration with Keir K. Rogers (U. Toronto)*

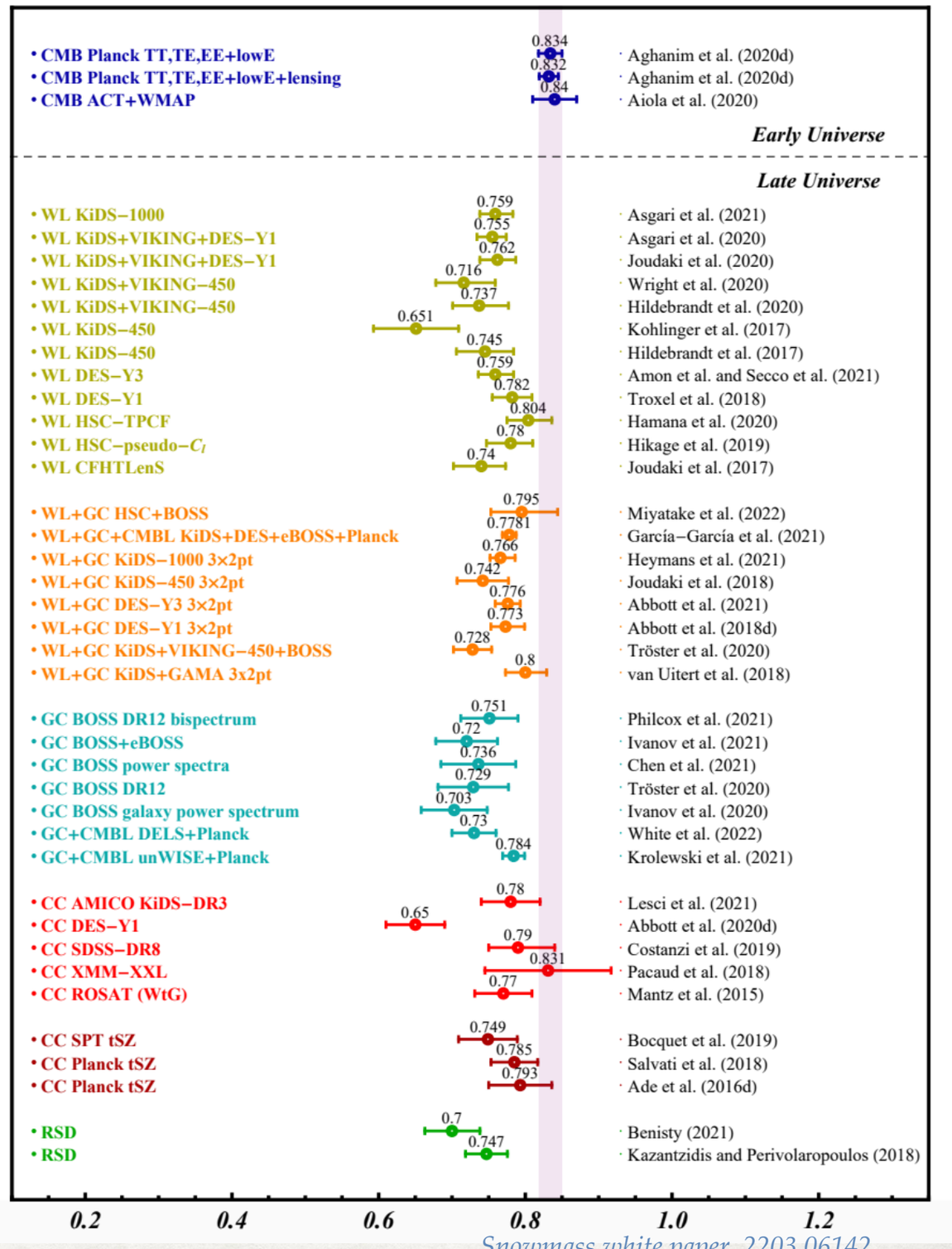
GDR CoPhy episode 2
May, 21st 2024

# The $S_8$ tension: hint about the nature of the dark sector?



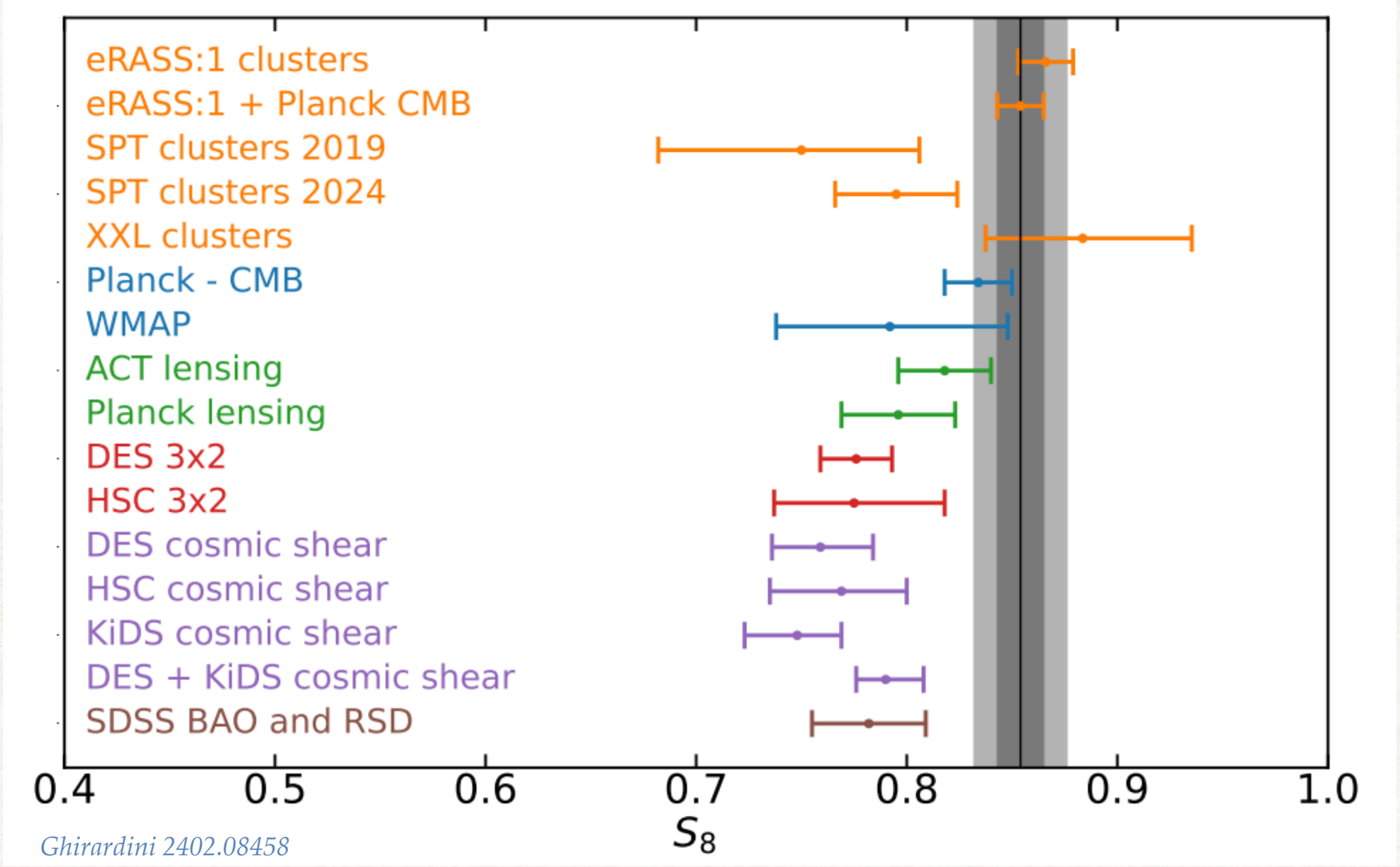

*Chabanier 1905.08103*

$$S_8 \equiv \sigma_8 \left( \frac{\Omega_m}{0.3} \right)^{0.5}$$




*Snowmass white paper 2203.06142*

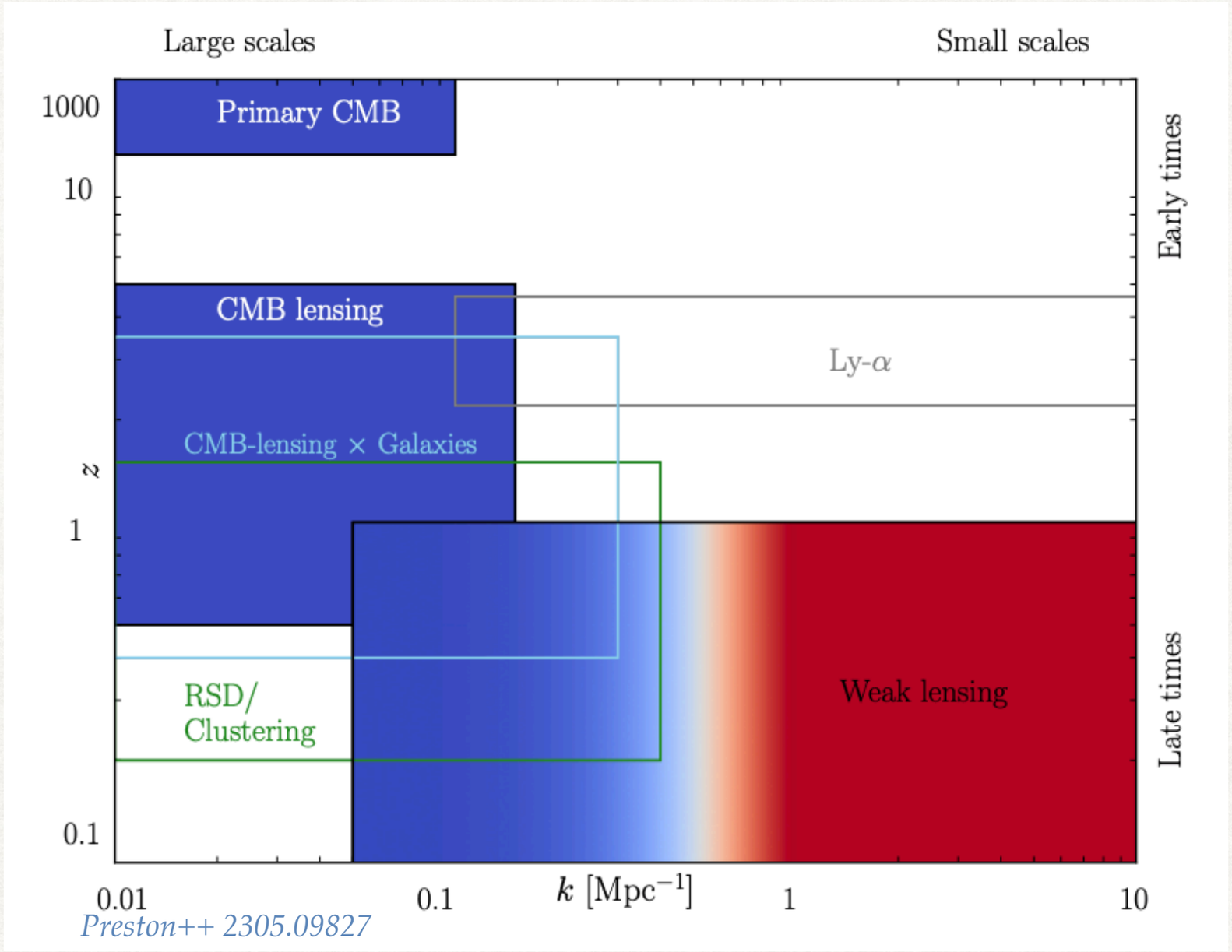
# Is there a $S_8$ tension after all?




*Ghirardini 2402.08458*

- Latest $S_8$ from galaxy cluster number counts by eROSITA is not in tension with Planck
- A potential systematic in WL surveys was already pointed out: intrinsic alignements, non-linear modeling, baryonic feedback could play a role. *Amon& Efstathiou 2206.11794, Aricò++ 2303.05537, Abbott++ 2305.17173*

# How to resolve the tension about the $S_8$ tension



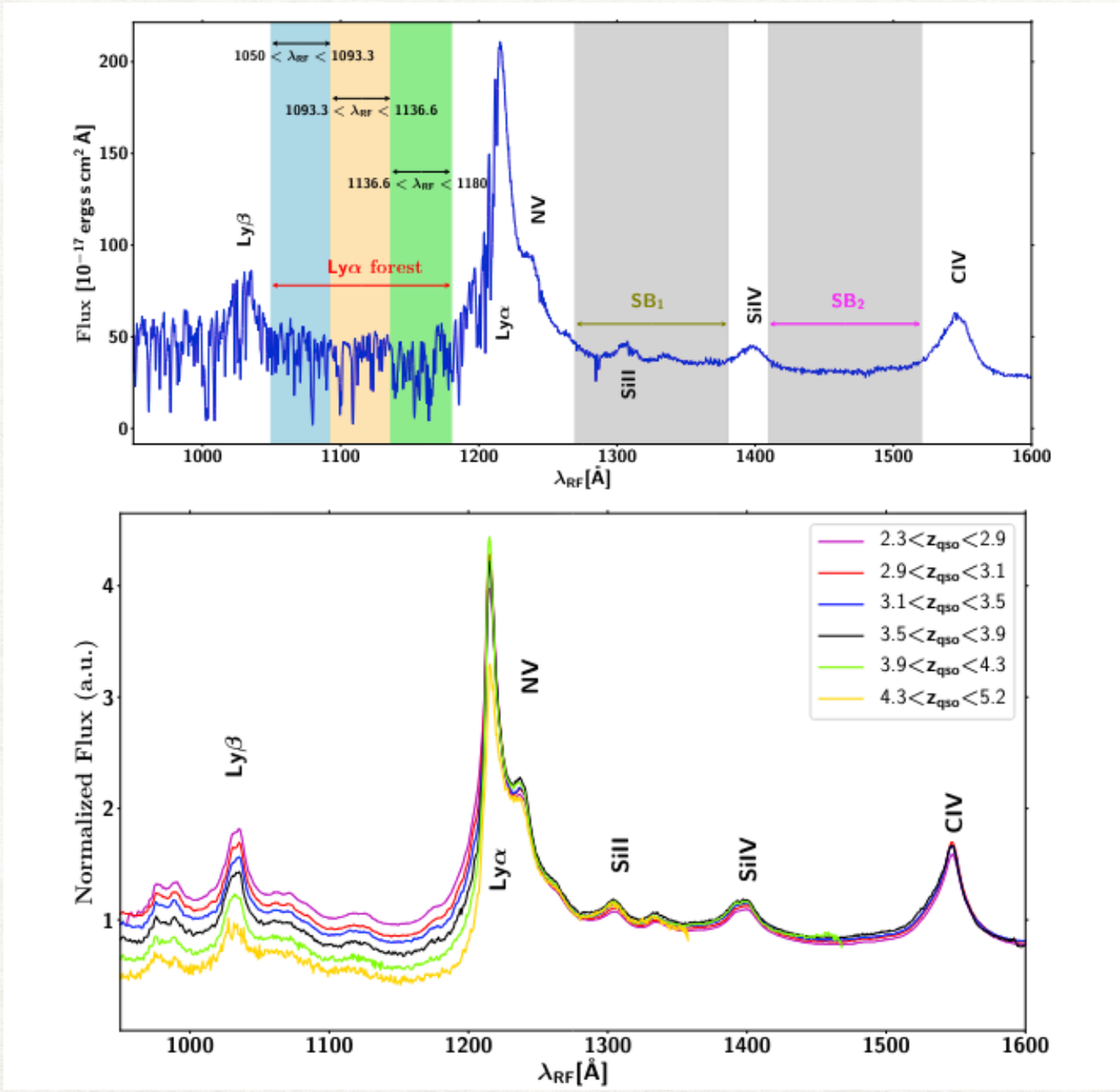

*Preston++ 2305.09827*

- KIDS/DES measure smaller scales than eROSITA & CMB lensing! Power suppression at $k \gtrsim 0.5$ h/Mpc?
- Lyman-$\alpha$ data can arbitrate whether there is a small scale tension!

*Palanque-Delabrouille+ 1911.09073, Hooper&Lucca 2110.04024, Goldstein++ 2303.00746*

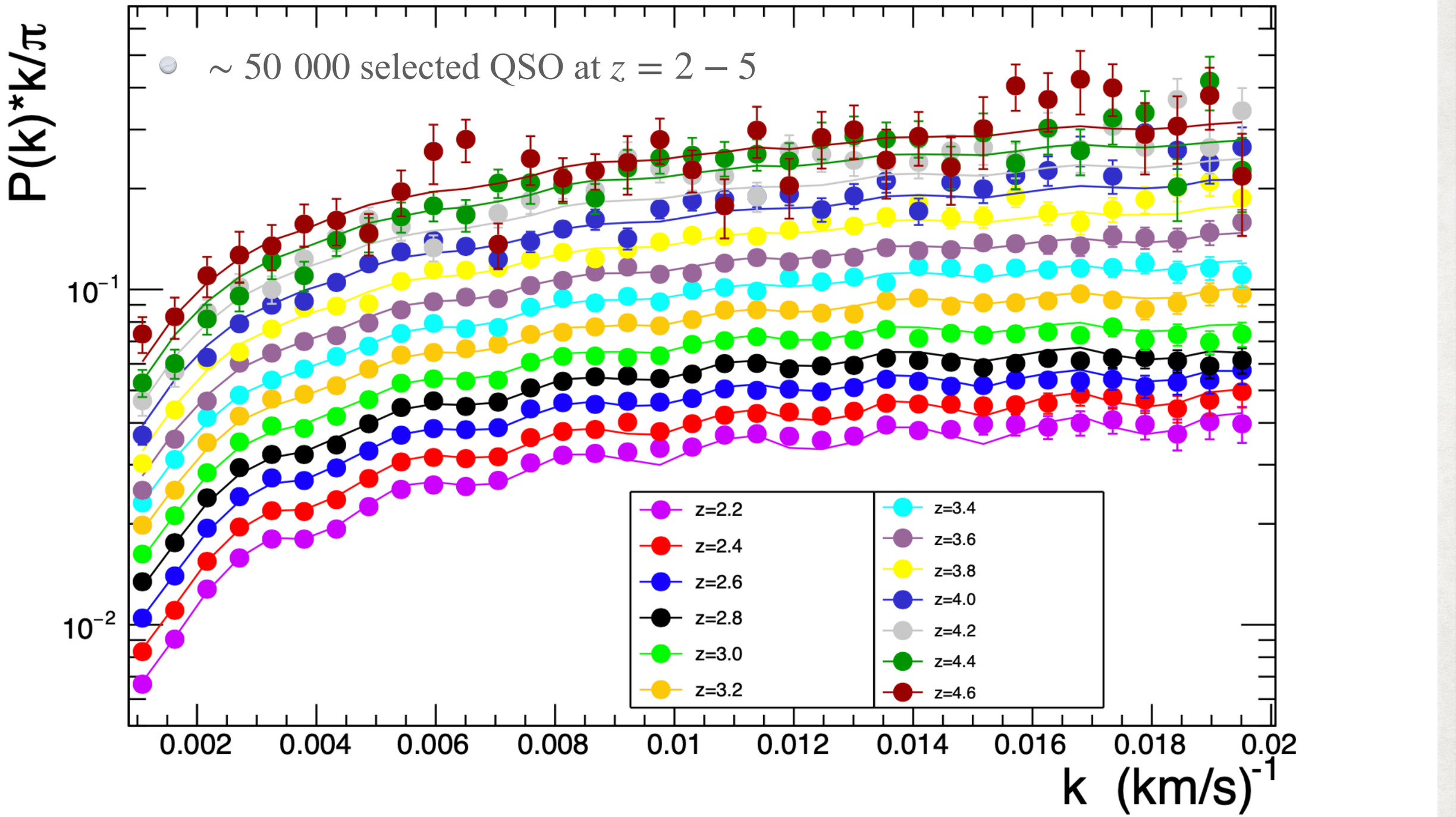
# The Lyman-$\alpha$ forest

- Ly-$\alpha$ forest: series of absorption features from neutral H observed in the spectra of high-redshift quasars




*Chabanier++1812.03554*

# eBOSS Ly-$\alpha$ flux power spectrum

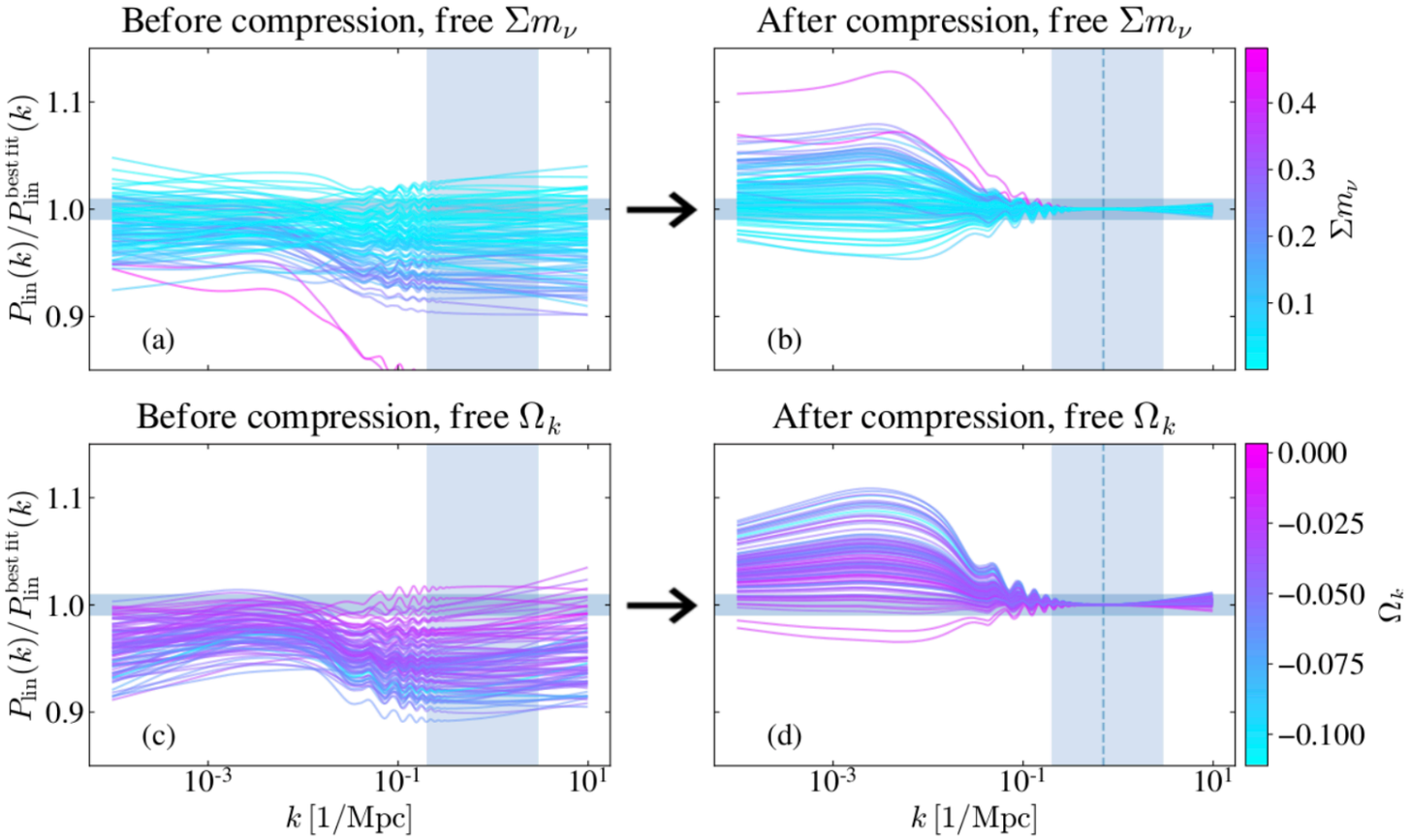



Chabanier et al. (2019)

# All the information in eBOSS Ly-$\alpha$ compressed to 2 parameters

- Modeling the Ly-$\alpha$ 1D PS is complicated: require hydrodynamical simulations to model non-linearities & baryonic effects, state of the IGM (ionization, temperature), emulators…

- For models with mild departure from Einstein-De Sitter & power-law $P(k)$: all the information can be compressed into matter power spectrum tilt $n_L$ & amplitude $\Delta^2_L$ at $z = 3$, $k_p \simeq 1h/\mathrm{Mpc}$




**Rescaled to same amplitude and tilt at $k_{\rm pivot}$ = 1 h/Mpc, $z_{\rm pivot}$ = 3**

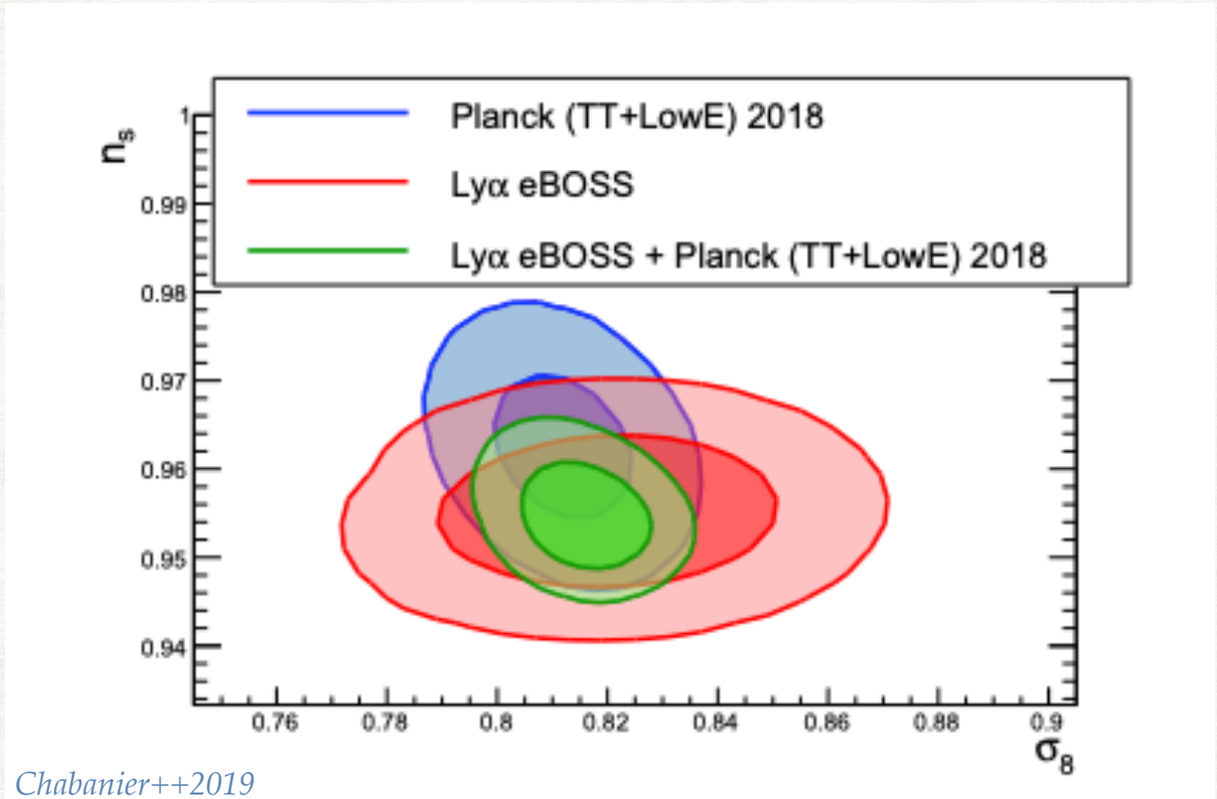
*Pedersen ++ 2011.15127*

*McDonald astro-ph/0407377,*
*Pedersen ++ 2209.09895,*
*Goldstein++ 2303.00746*

$$\Delta^2_p(z) = k^3 P_{\rm lin}(k,z)|_{k=k_p},$$

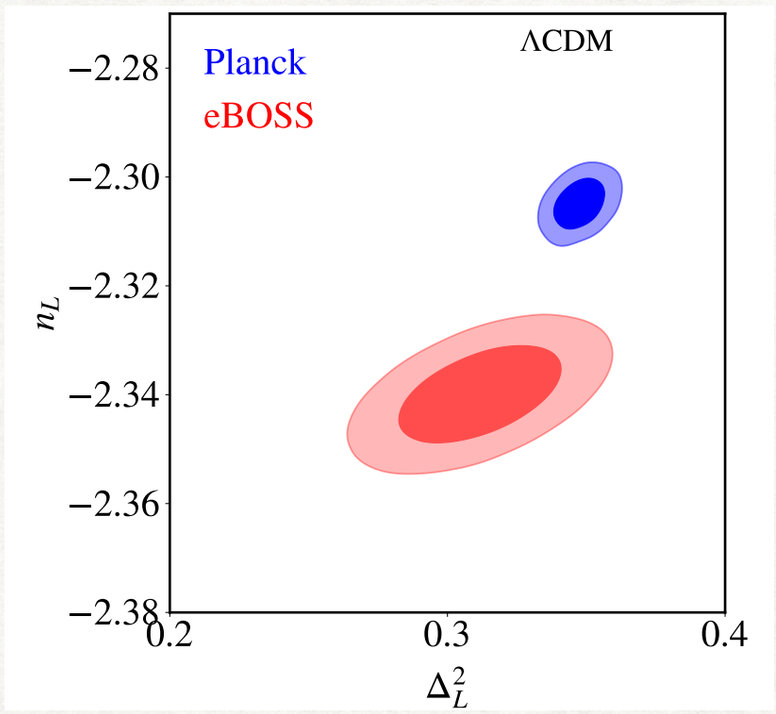
$$n_p(z) = {\rm dln}P_{\rm lin}(k,z)/{\rm dln}k|_{k=k_p},$$

# 5σ tension between Planck and eBOSS Lya?




*Chabanier++2019*

*Rogers & Poulin (arXiv: 2311.16377)*

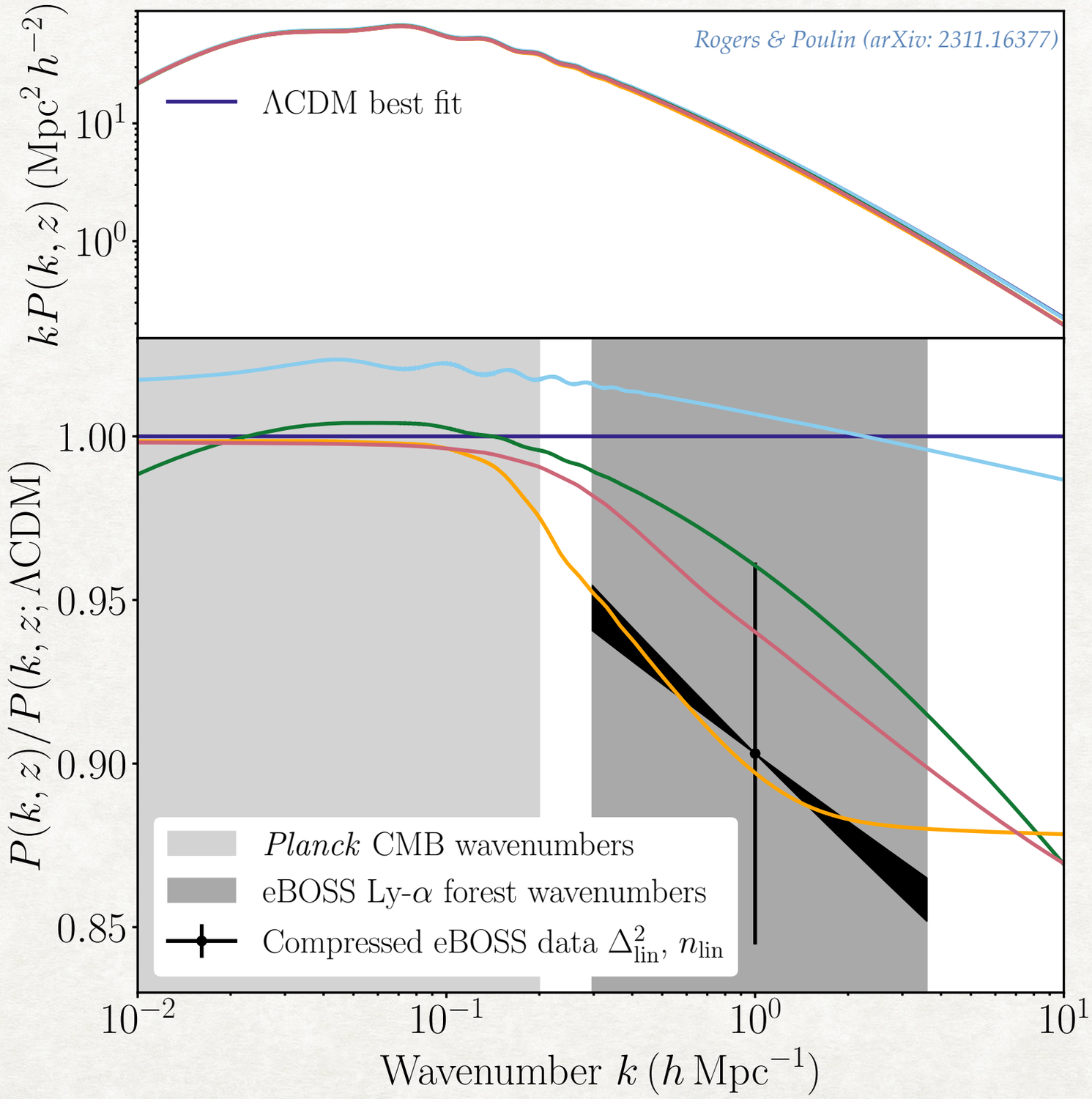



- ΛCDM + astrophysical parameters fit to eBOSS and Planck: good agreement?
- Apparent agreement between ΛCDM parameters but $4.8\sigma$ tension on $n_L$ & $\Delta_L^2$

*See also Palanque-Delabrouille+ 1911.09073*

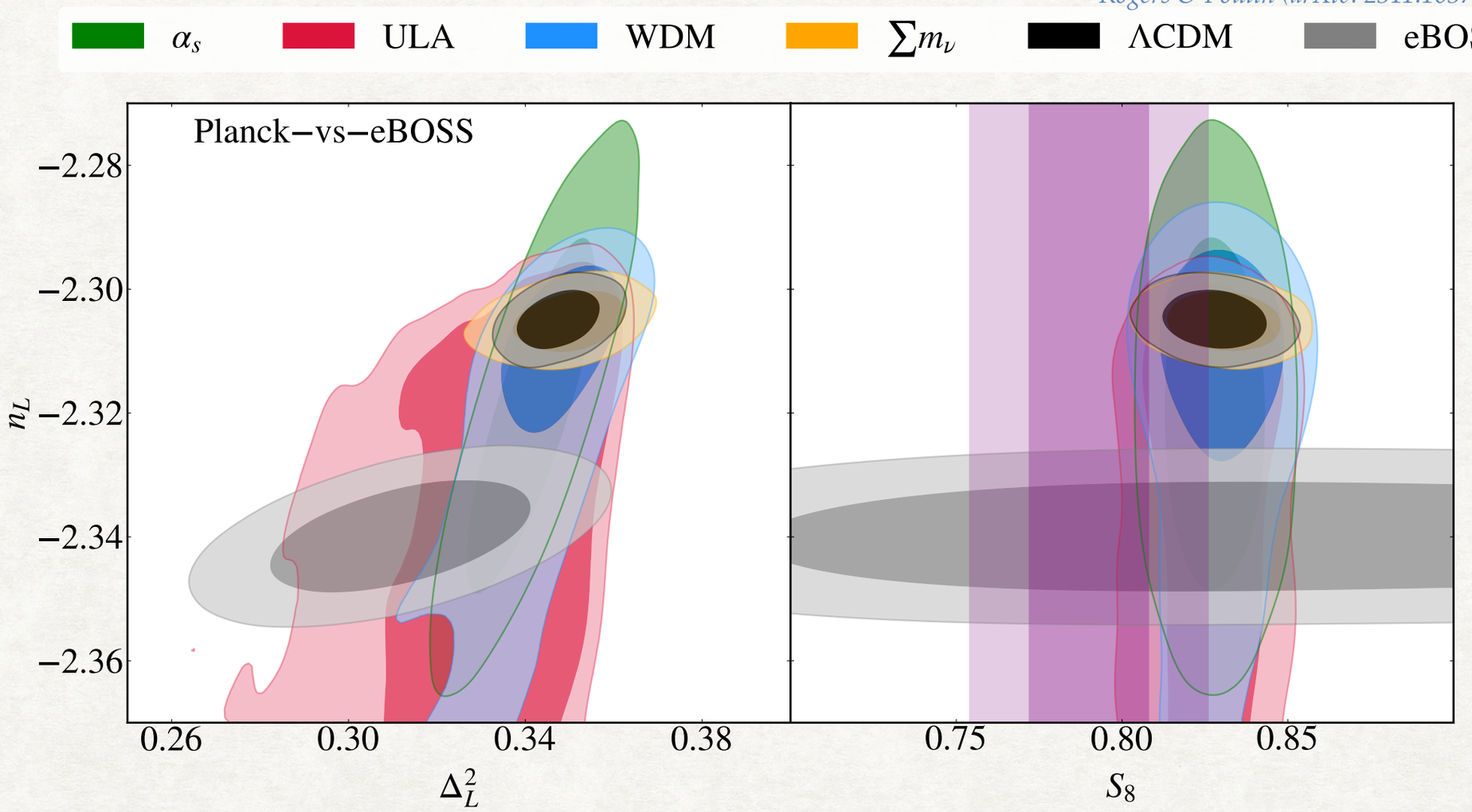
- Hint for model resolving $\sigma_8$ tension?
- Can it change bounds from Ly$\alpha$ on neutrino masses, WDM, ULA…?

# Suppression in the power spectrum at small scales



# New physics in eBOSS data?

*Rogers & Poulin (arXiv: 2311.16377)*




- Models with power suppression: running $\alpha_s$, fraction of WDM and ULA all favored

  *See also Palanque-Delabrouille+ 1911.09073*

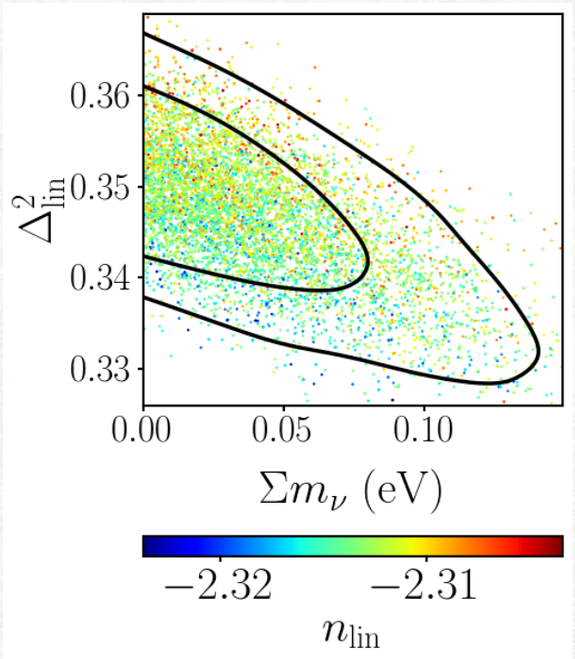
- Compatible with BOSS galaxy power spectrum, CMB lensing, etc.

  *Rogers++ 2301.08361*

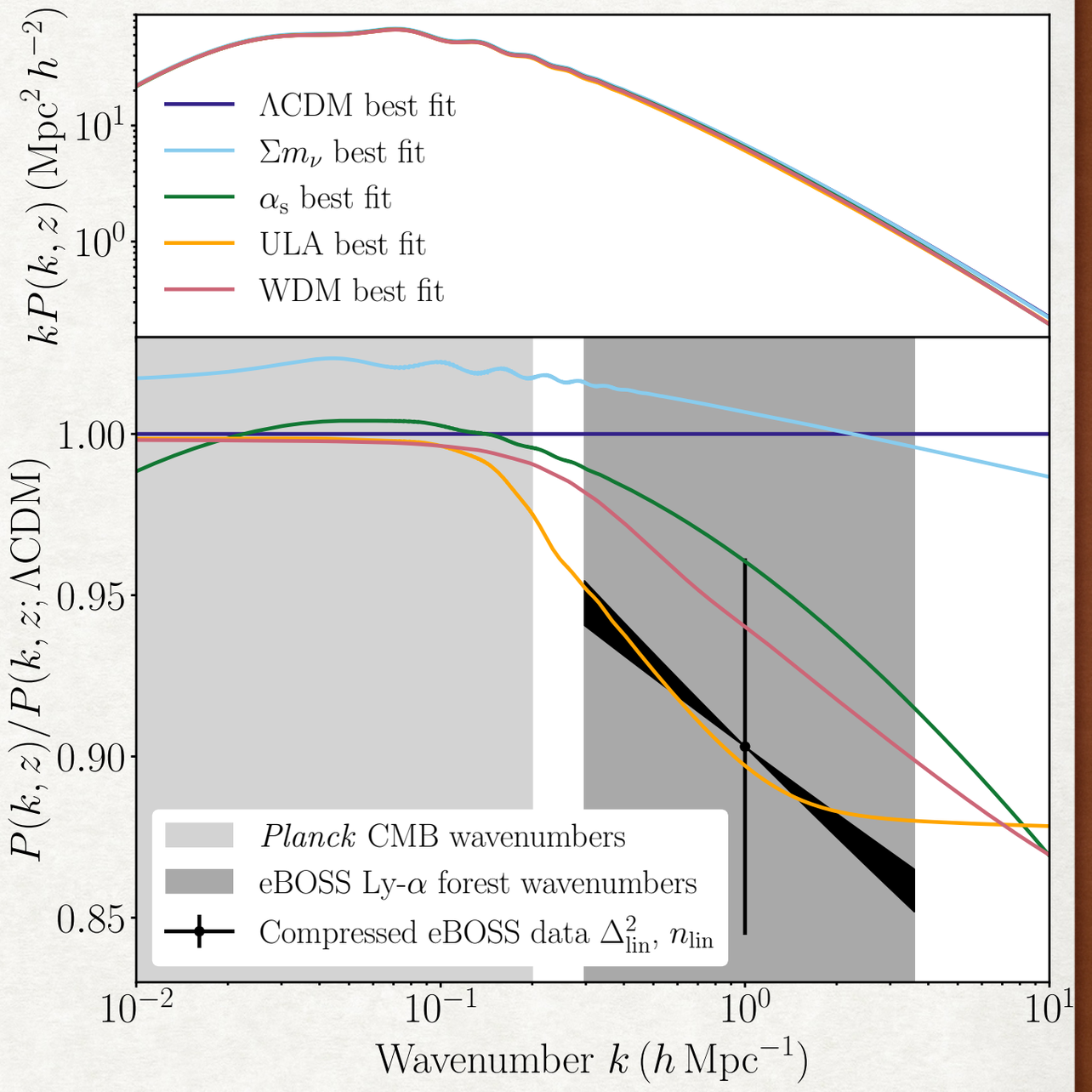
- Impact for $S_8$ is minor… but should be checked against actual weak lensing data.

# New physics in eBOSS data?

- $\sum m_\nu$ excluded as a solution



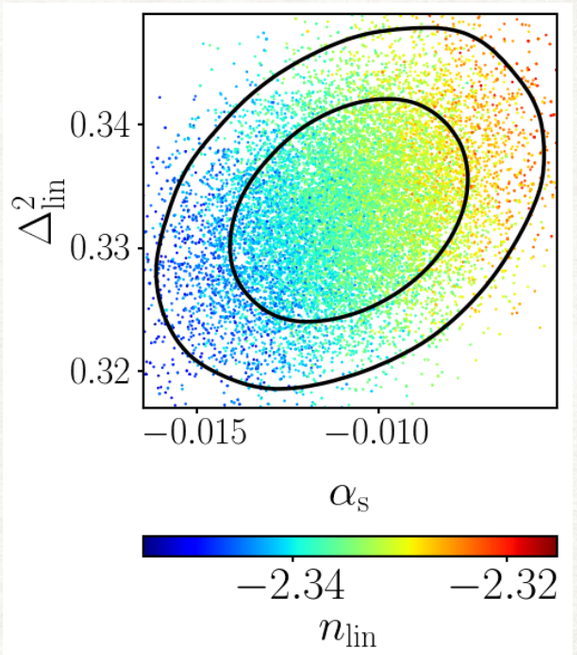

| Model | Tension ($\sigma$) | $\Delta\chi^2$ | Parameter constraints |
|---|---|---|---|
| $\Lambda$CDM | 4.90 | – | – |
| $\Sigma m_\nu$ | 4.80 | -1.9 | $\Sigma m_\nu < 0.110\,\mathrm{eV}$ |



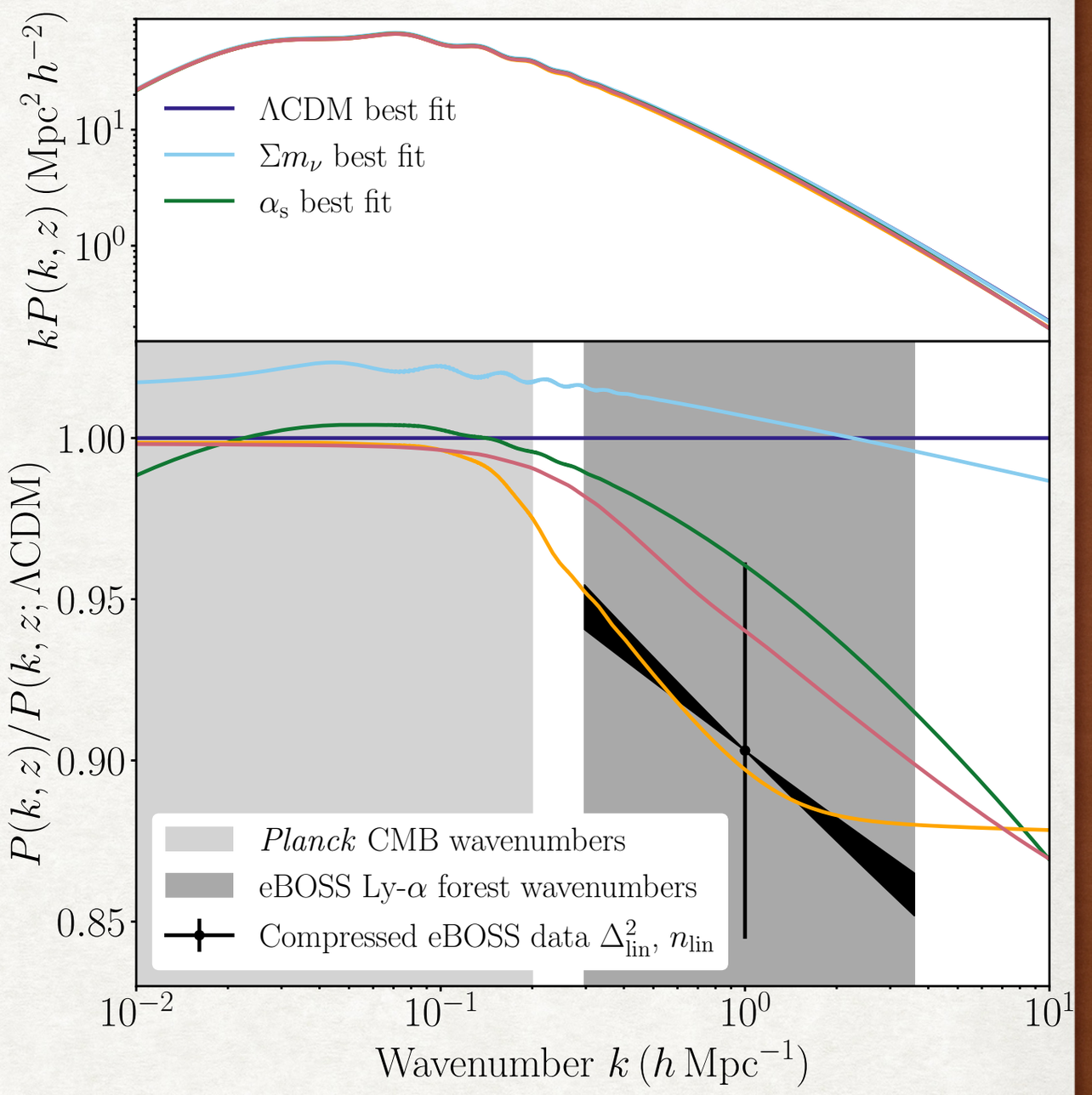

*See also Palanque-Delabrouille++ 1911.09073*

# New physics in eBOSS data?

- Running $\alpha_s$ is favored



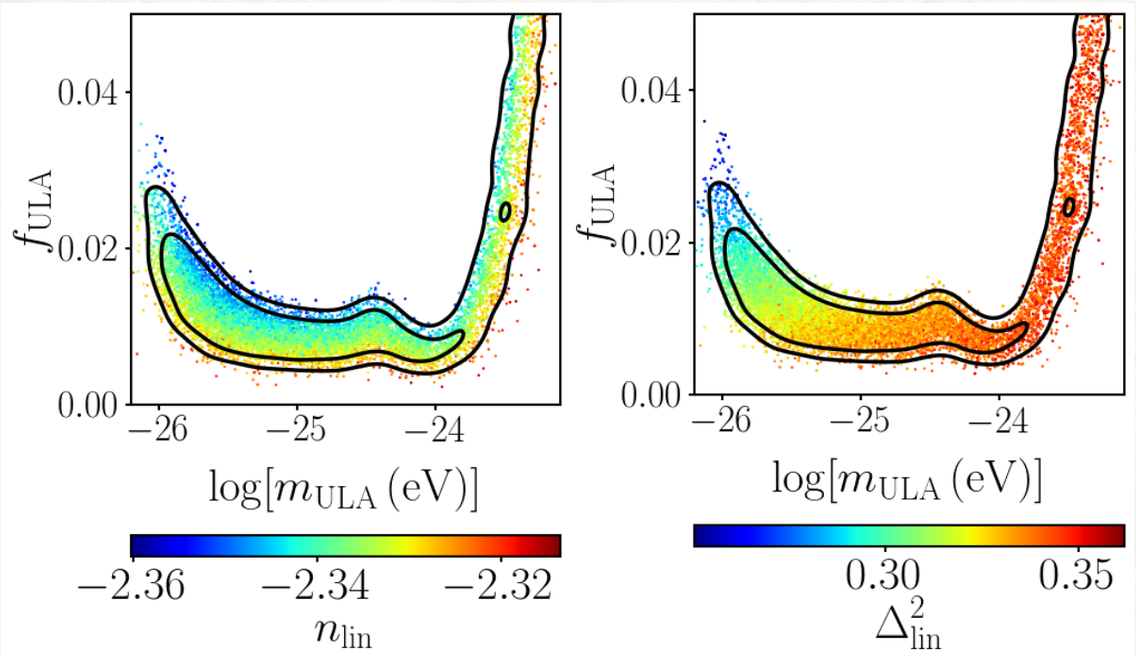

| Model | Tension ($\sigma$) | $\Delta\chi^2$ | Parameter constraints |
|---|---|---|---|
| $\Lambda$CDM | 4.90 | – | – |
| $\Sigma m_\nu$ | 4.80 | -1.9 | $\Sigma m_\nu < 0.110\,\mathrm{eV}$ |
| $\alpha_{\rm s} \equiv \frac{\mathrm{d}n_{\rm s}}{\mathrm{d}\ln k}$ | 0.92 | -25.61 | $\alpha_{\rm s} = -0.0108 \pm 0.0022$ |



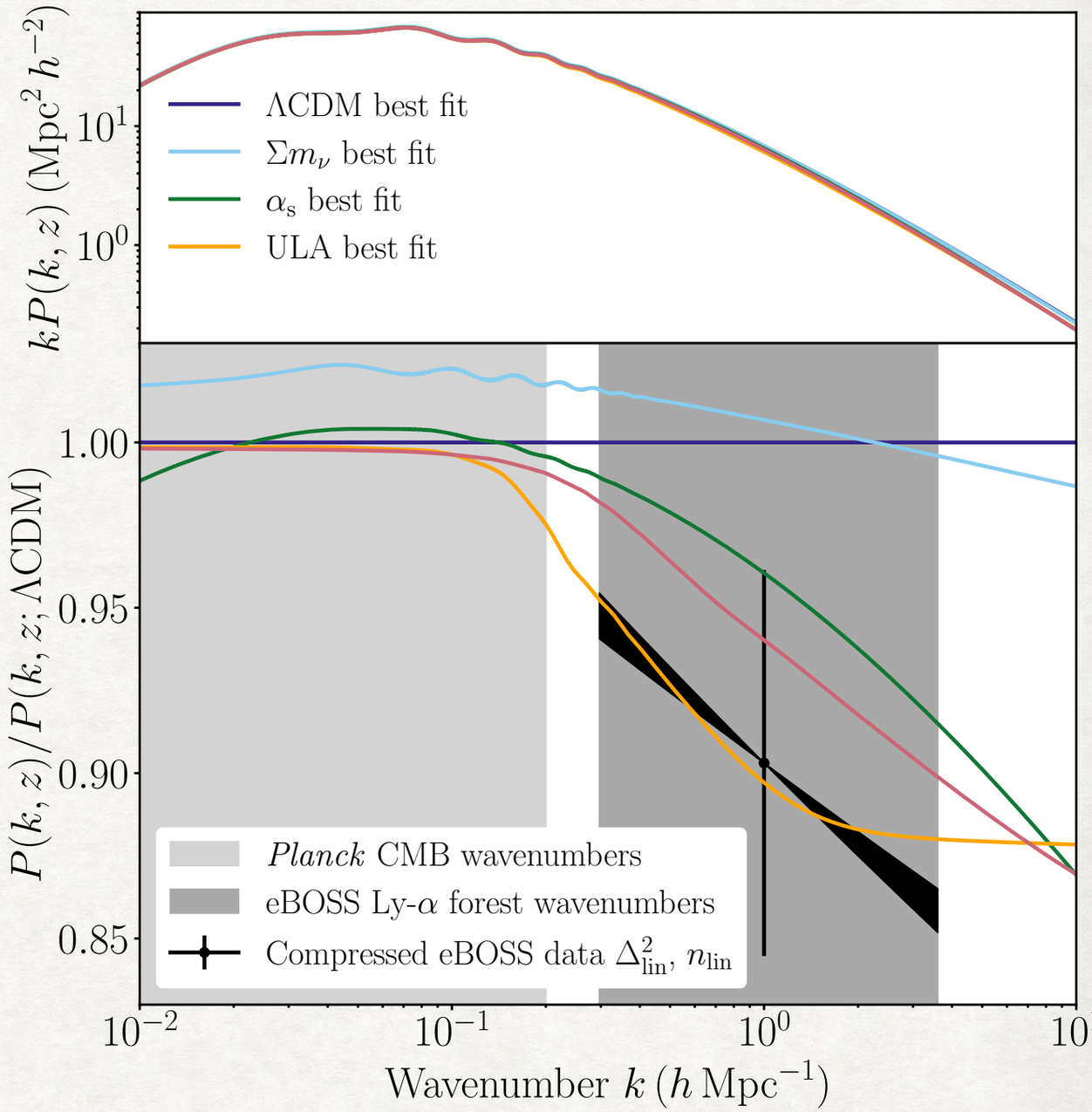

*See also Palanque-Delabrouille++ 1911.09073*

# New physics in eBOSS data?

- Ultra light axion fraction is favored



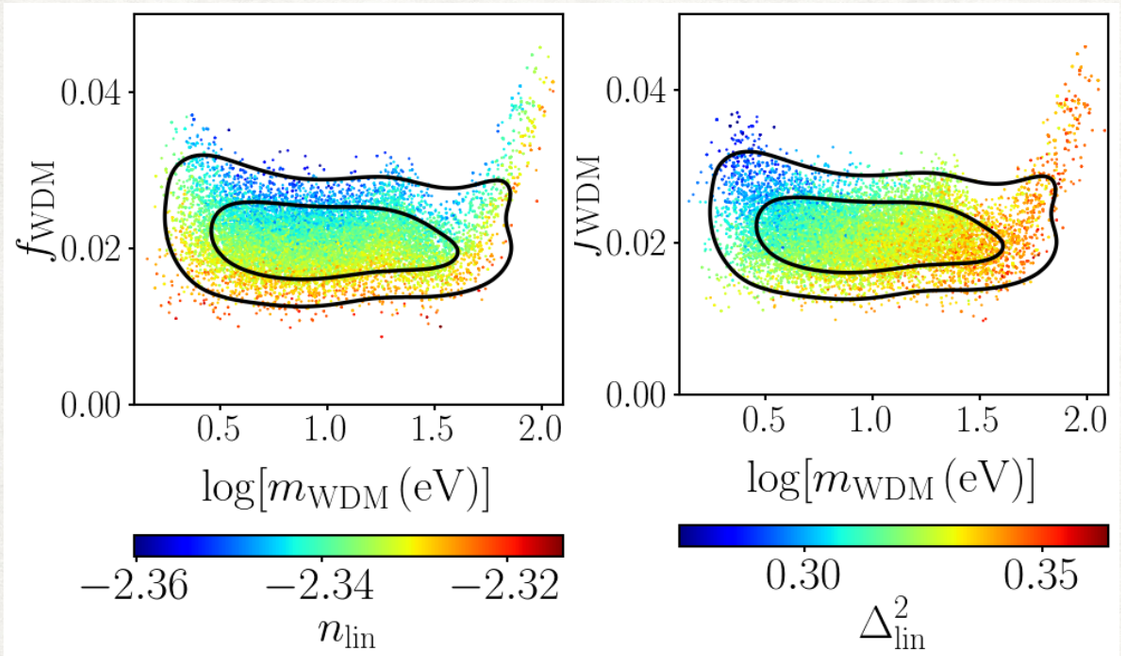

| Model | Tension ($\sigma$) | $\Delta\chi^2$ | Parameter constraints |
|---|---|---|---|
| $\Lambda$CDM | 4.90 | – | – |
| $\Sigma m_\nu$ | 4.80 | -1.9 | $\Sigma m_\nu < 0.110\,{\rm eV}$ |
| $\alpha_{\rm s} \equiv \frac{{\rm d}n_{\rm s}}{{\rm d}\ln k}$ | 0.92 | -25.61 | $\alpha_{\rm s} = -0.0108 \pm 0.0022$ |
| ULA | 0.56 | -27.58 | $\log[m_{\rm ULA}({\rm eV})] = -24.9^{+1.5}_{1.1}$<br>$f_{\rm ULA} = 0.0146^{+0.0014}_{0.0086}$ |



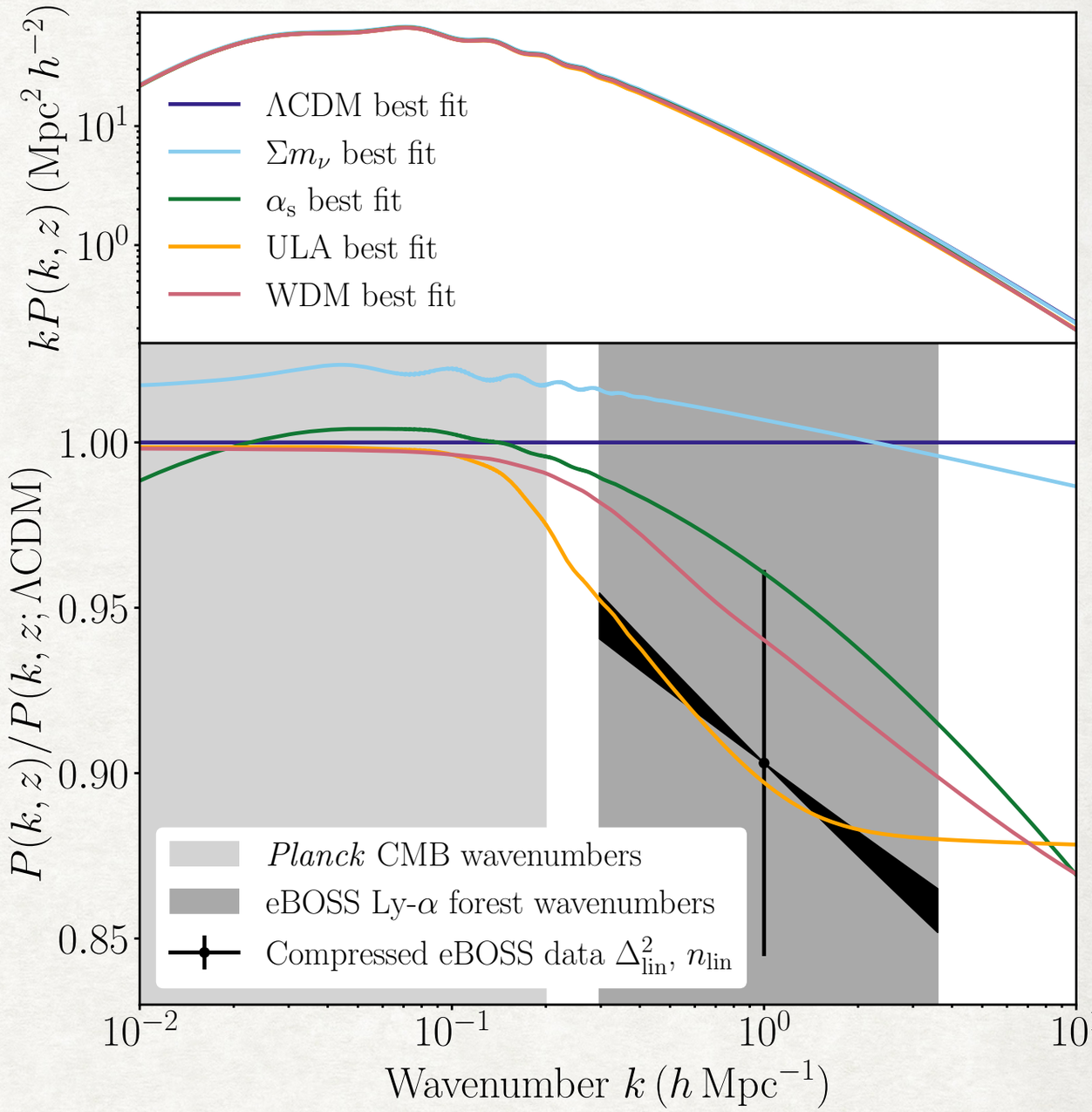

*See also Palanque-Delabrouille++ 1911.09073*

# New physics in eBOSS data?

- Warm Dark Matter fraction is favored




| Model | Tension ($\sigma$) | $\Delta\chi^2$ | Parameter constraints |
|---|---|---|---|
| $\Lambda$CDM | 4.90 | – | – |
| $\Sigma m_\nu$ | 4.80 | -1.9 | $\Sigma m_\nu < 0.110\,{\rm eV}$ |
| $\alpha_{\rm s} \equiv \frac{{\rm d}n_{\rm s}}{{\rm d}\ln k}$ | 0.92 | -25.61 | $\alpha_{\rm s} = -0.0108 \pm 0.0022$ |
| ULA | 0.56 | -27.58 | $\log[m_{\rm ULA}({\rm eV})] = -24.9\pm^{1.5}_{1.1}$<br>$f_{\rm ULA} = 0.0146\pm^{0.0014}_{0.0086}$ |
| WDM | 1.34 | -27.08 | $\log[m_{\rm WDM}({\rm eV})] = 1.01\pm^{0.30}_{0.44}$<br>$f_{\rm WDM} = 0.0219\pm^{0.0030}_{0.0042}$ |




*See also Palanque-Delabrouille++ 1911.09073*

# Conclusions

## Take-home message:

- eBOSS ly$\alpha$ tilt/amplitude of $P_m(k \simeq 1, z = 3)$ in tension with ΛCDM / Planck

  *Already hints from Palanque-Delabrouille++ 1911.09073*

- Important to compare the right scales / redshift not just ΛCDM parameters

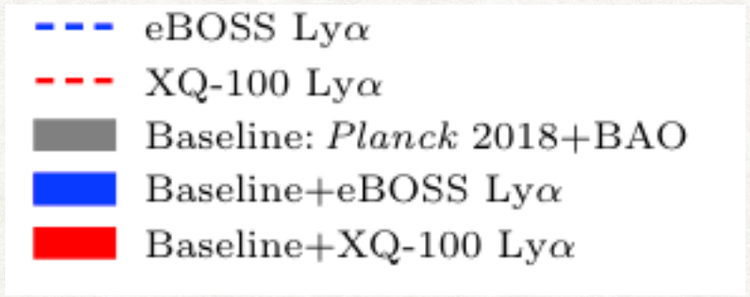
- Could be explained by $\alpha_s$, WDM, ULA…

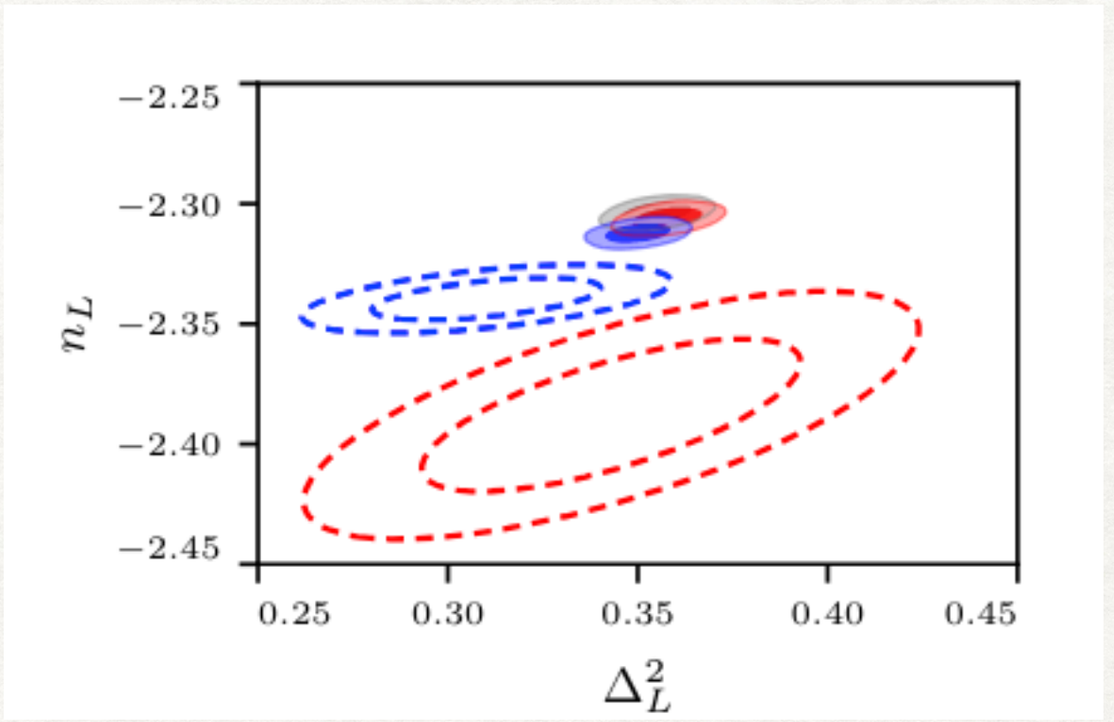
## What's next:

- Further improve data modeling, hydrodynamical simulations, emulators…
- DESI results to come soon! (Some early results already) ==> over 700 000 spectra!
- Joint analysis with high-resolution Lyman-alpha forest (MIKE/HIRES/XQ-100)
- Confront data with DES/KiDS/HSC weak lensing using non-linear model

# XQ100 Mike/Hires

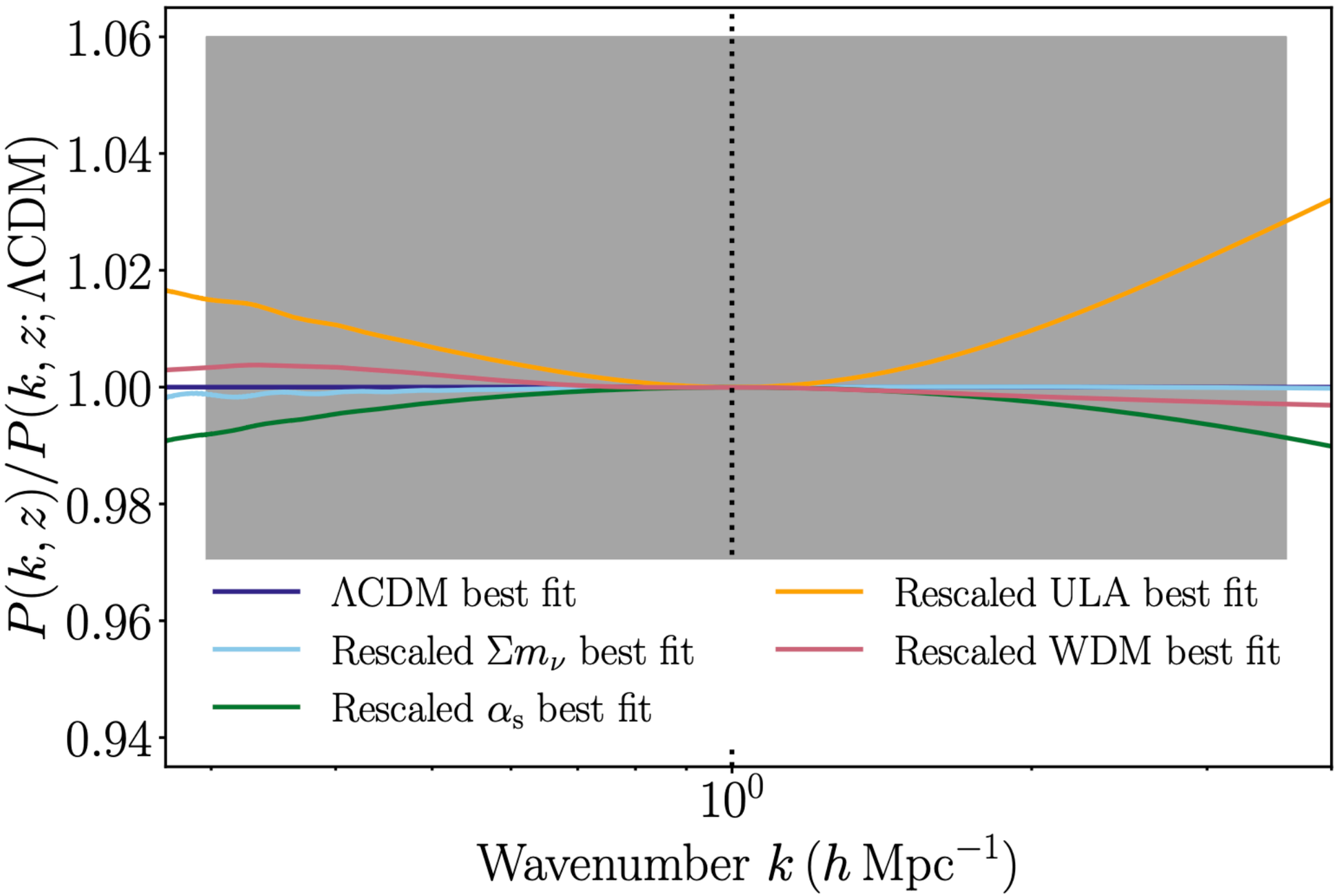
- XQ100 Mike/Hires == high-resolution ly-a measuring smaller scales than eBOSS




- Seems like XQ 100 also in tension with LCDM
- Discrepancy between eBOSS and XQ100 may come from evolution with scales

# The compression is valid for all models studied here




Rogers & Poulin (arXiv: 2311.16377)

# Systematics?

## 5 Systematic uncertainties

As we explained in the previous two sections, going from Eq. 2.4 (how $P^{\text{raw}}$ is derived from observational quantities) to the final measurement of $P^{\text{Ly}\alpha}$ requires selections and power spectrum corrections at several stages of the analysis. These corrections and the impact of the selections are each determined with their own degree of precision, from which we infer a $k$- and $z$-dependent systematic uncertainty on the measurement of $P^{\text{Ly}\alpha}$. We identify eight systematic uncertainties:

- Measurement of the quasar spectrum continuum
- Measurement of the quasar spectrum noise level
- Measurement of the spectrograph spectral resolution
- Measurement of the power spectrum in side bands
- Effect of masking of the sky emission lines
- Effect of masking of the DLA absorbers
- Effect of the completeness of the DLA catalog
- Effect of the completeness of the BAL catalog

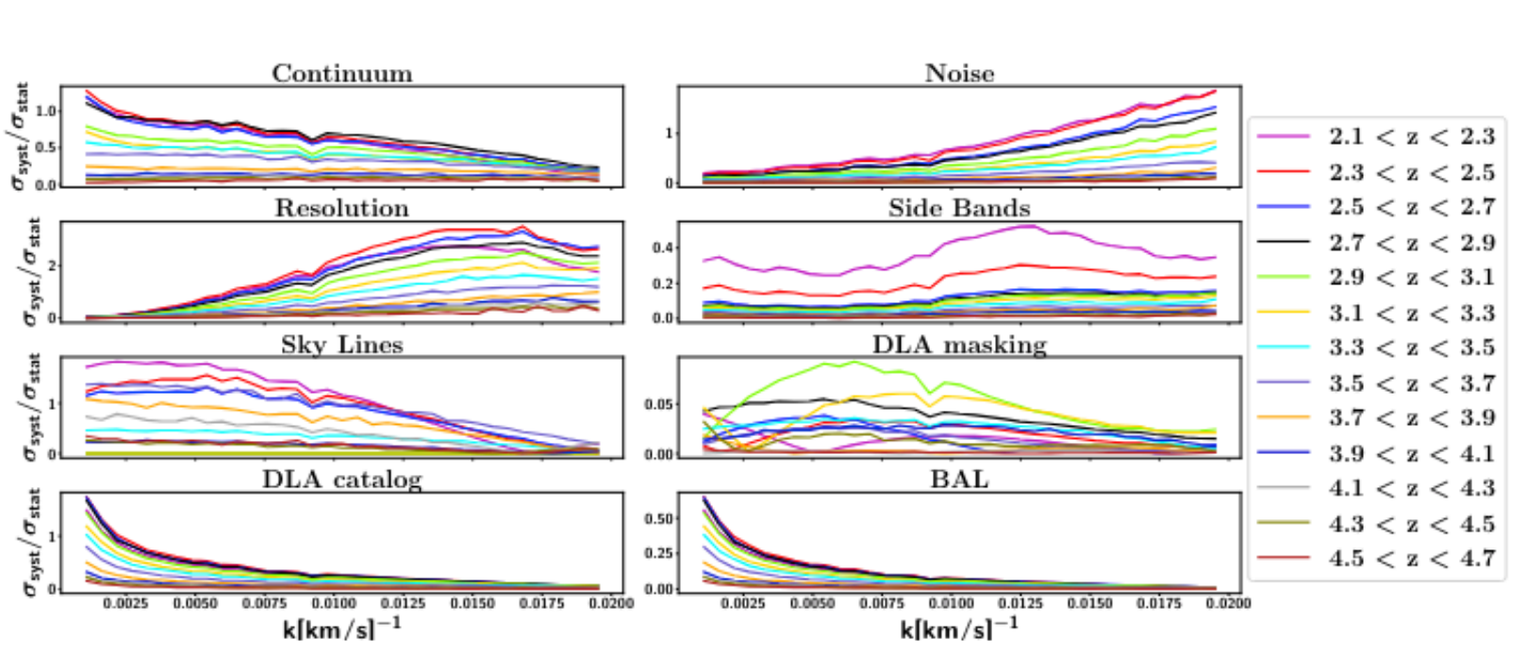



**Figure 10**: *Ratios of the systematic to the statistic uncertainties, as a function of redshift and wave number, for the eight identified sources. From left to right and top to bottom are illustrated the uncertainty ratios from the continuum estimation, the noise level, the spectral resolution, the side bands power spectra, the sky lines masking, the DLA masking, the DLA residual effects and the BAL features.*

# New analysis of eBOSS

- Claims a tension in the low-z bin

- Measures no tension in $n_s$ but strong tension in $\sigma_8 = 0.733 \pm 0.026$

*Fernandez, Bird, Ho 2309.03943*