Constraining cosmological models with the Effective Field Theory of Large-Scale Structures

Théo SIMON

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Based on arXiv:2210.14931

TS, Pierre Zhang and Vivian Poulin

[Cosmological inference from the EFTofLSS: the eBOSS QSO full-shape analysis]

IESC - 28/04/2023

The effective field theory of large-scale structures (EFTofLSS)

Main motivations

The galaxy power spectrum in the framework of the EFTofLSS:

$$P_g(k,\mu) \simeq \left[b_1 + f\mu^2\right]^2 P_m(k) = Z_1(\mu)^2 P_m(k)$$

We go from 1 to 10 free parameters

$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2 Z_1(\mu) P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm R}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm R}^2}\right)$$
$$+ 2\int \frac{d^3q}{(2\pi)^3}\, Z_2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}, \mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|) P_{11}(q) + 6 Z_1(\mu) P_{11}(k)\int \frac{d^3q}{(2\pi)^3}\, Z_3(\boldsymbol{q}, -\boldsymbol{q}, \boldsymbol{k}, \mu) P_{11}(q)$$
$$+ \frac{1}{\bar{n}_g}\left(c_{\epsilon,0} + c_\epsilon^{\rm mono}\frac{k^2}{k_{\rm M}^2} + 3c_\epsilon^{\rm quad}\left(\mu^2 - \frac{1}{3}\right)\frac{k^2}{k_{\rm M}^2}\right),$$

Carrasco++ [arXiv:1206.2926] ; Baumann++ [arXiv:1004.2488]
Senatore [arXiv:1406.7843] ; Perko++ [arXiv:1610.09321]

See also TS++ [arXiv:2208.05929]

See Emiliano Sefusatti's lecture

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$P_g(k,\mu)$ can be determined directly from $P_{11}(k) = P_m^{\rm lin}(k)$

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We go from 1 to 10 free parameters

$$\begin{aligned}P_g(k,\mu) &= Z_1(\mu)^2 P_{11}(k) + 2 Z_1(\mu) P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2 \frac{k^2}{k_{\rm R}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm R}^2}\right) \\ &+ 2\int \frac{d^3q}{(2\pi)^3} Z_2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q},\mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)P_{11}(q) + 6 Z_1(\mu) P_{11}(k)\int\frac{d^3q}{(2\pi)^3} Z_3(\boldsymbol{q},-\boldsymbol{q},\boldsymbol{k},\mu)P_{11}(q) \\ &+ \frac{1}{\bar{n}_g}\left(c_{\epsilon,0} + c_\epsilon^{\rm mono}\frac{k^2}{k_{\rm M}^2} + 3 c_\epsilon^{\rm quad}\left(\mu^2-\frac{1}{3}\right)\frac{k^2}{k_{\rm M}^2}\right),\end{aligned}$$

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10 parameters

4 parameters b_i $(i = 1,2,3,4)$ to describe the **galaxy bias** which arises from the one-loop contributions

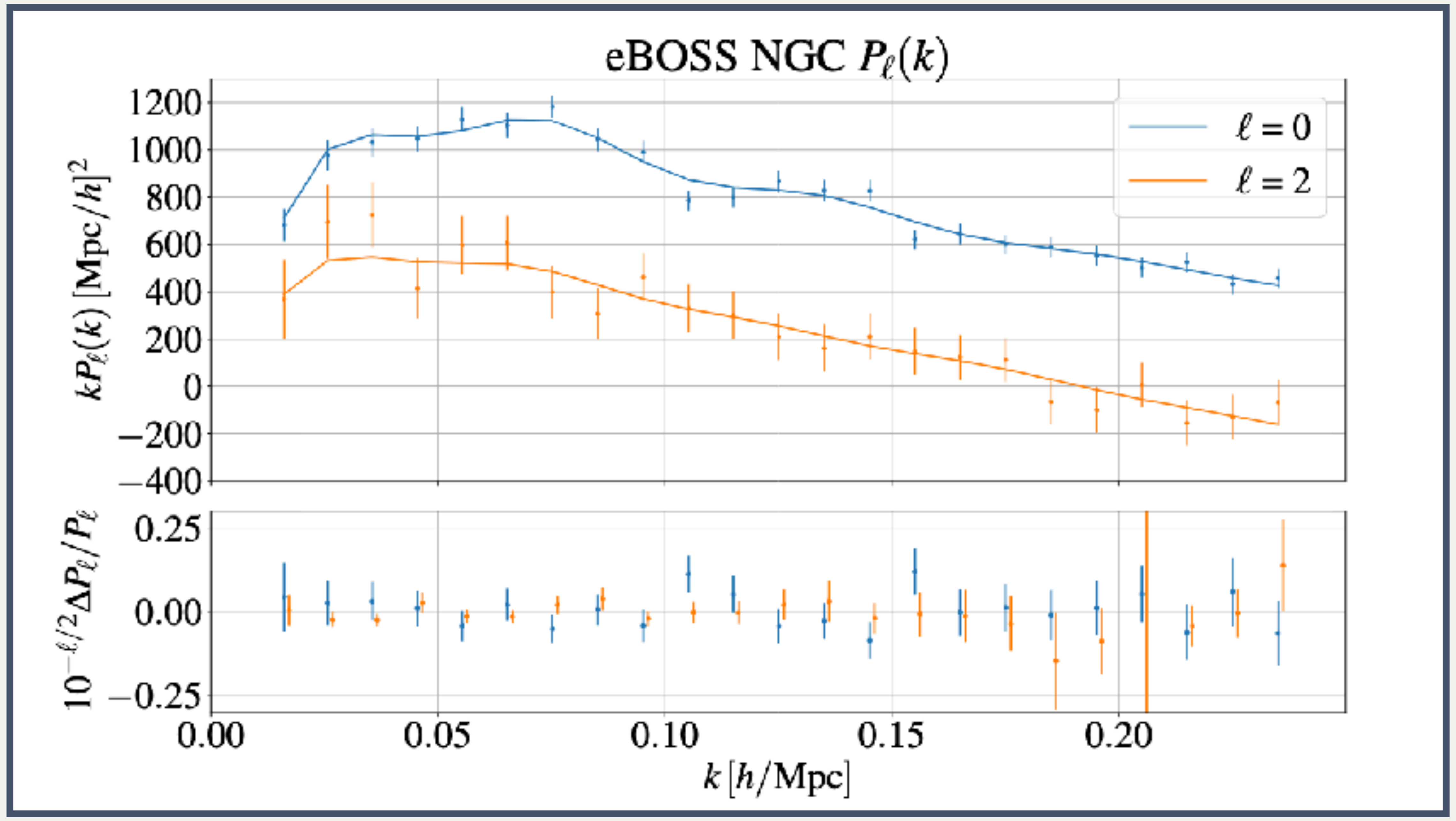
3 parameters corresponding to **counterterms** (c_{ct} linear combination of a higher derivative bias and the dark matter sound speed, while $c_{r,1}$ and $c_{r,2}$ are the redshift-space counterterms)

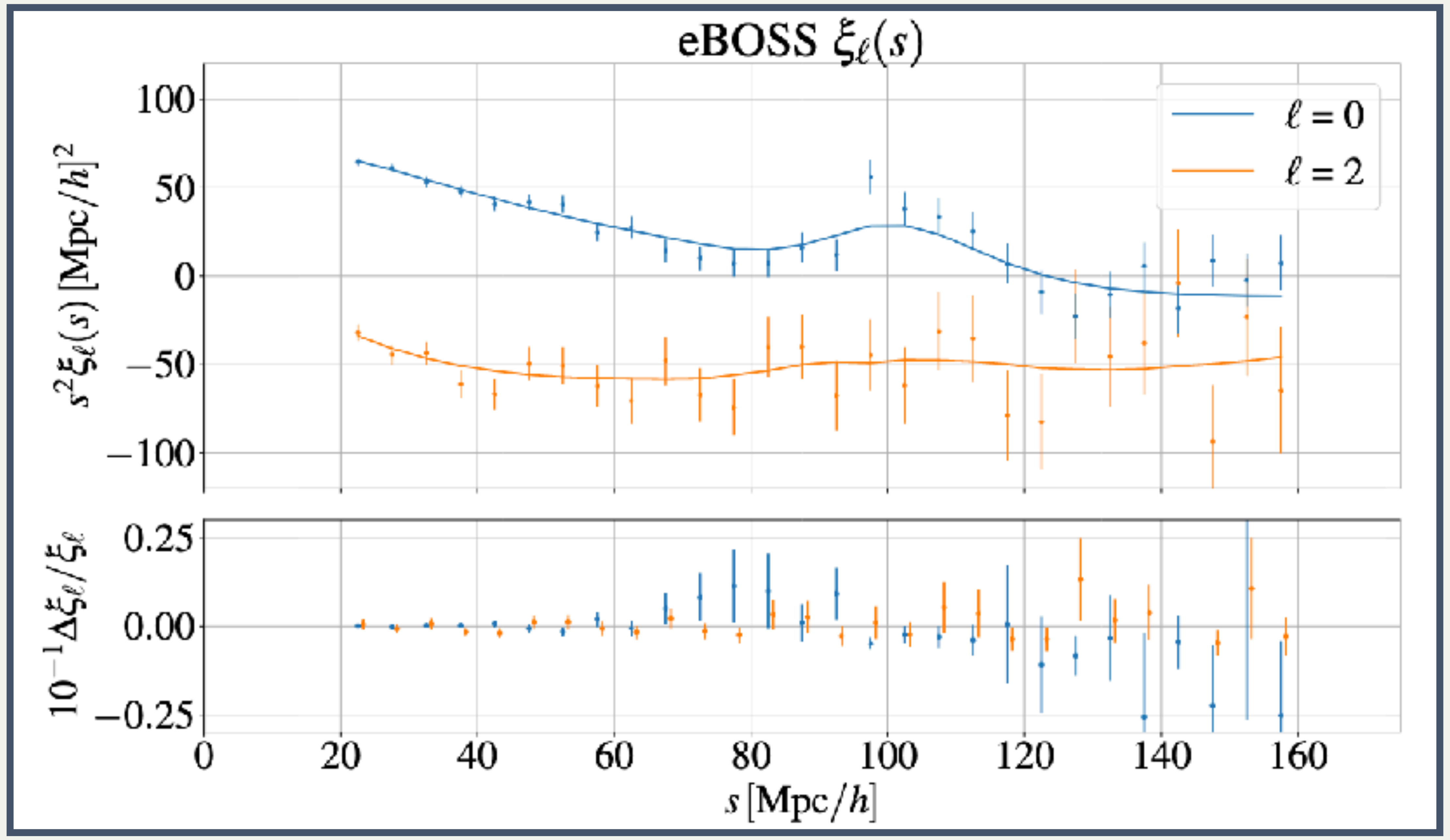
3 parameters which describe **stochastic** terms

EFTofLSS applied to eBOSS QSO data

- **343 708 quasars** selected in the redshift range $0.8 < z < 2.2$
- $z_{\text{eff}} = 1.5$
- 2 skycuts: NGC and SGC

eBOSS Collaboration [arXiv:2007.08991]





TS++ [arXiv:2210.14931]

Determination of the cut-off scale $k_{\rm max}$ of the one-loop prediction

The next-to-next-to-leading order (NNLO) terms

At **one-loop order**, the galaxy power spectrum reads:

$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2Z_1(\mu)P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm M}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm M}^2}\right)$$
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One can add the **NNLO terms** (*i.e.*, the dominant two-loop terms):

$$P_{\rm NNLO}(k,\mu) = \frac{1}{4}b_1\left(c_{r,4}b_1 + c_{r,6}\mu^2\right)\mu^4\frac{k^4}{k_{\rm R}^4}P_{11}(k)$$

Zhang++ [arXiv:2110.07539]

If the contribution of $P_{\rm NNLO}(k,\mu)$ becomes **too large,** the one-loop prediction is **not accurate enough** → this determines the **cut-off scale** $k_{\rm max}$ of the prediction

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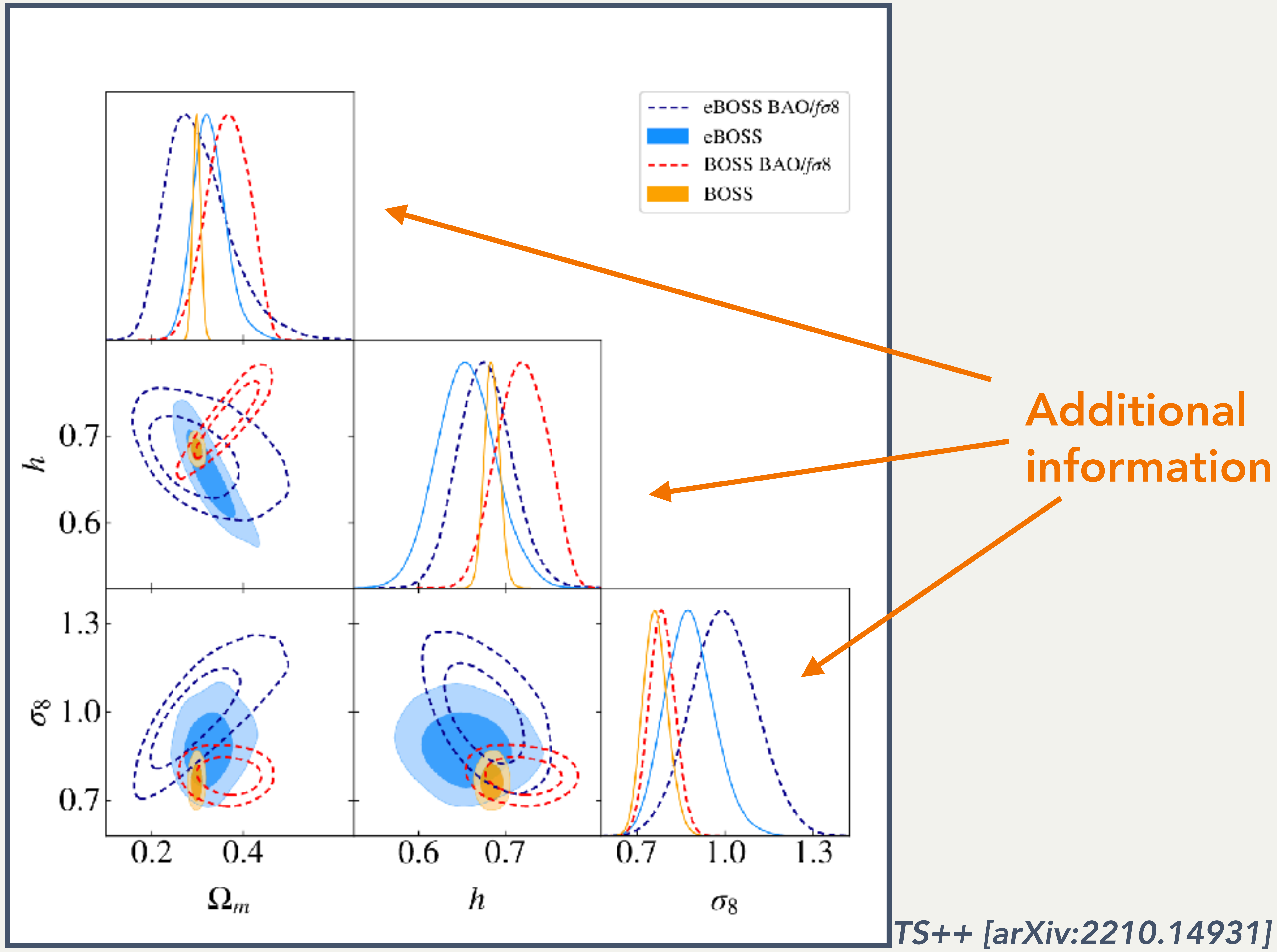
2 new EFT terms

If the contribution of $P_{\rm NNLO}(k,\mu)$ becomes **too large,** the one-loop prediction is **not accurate enough** → this determines the **cut-off scale** $k_{\max}$ of the prediction

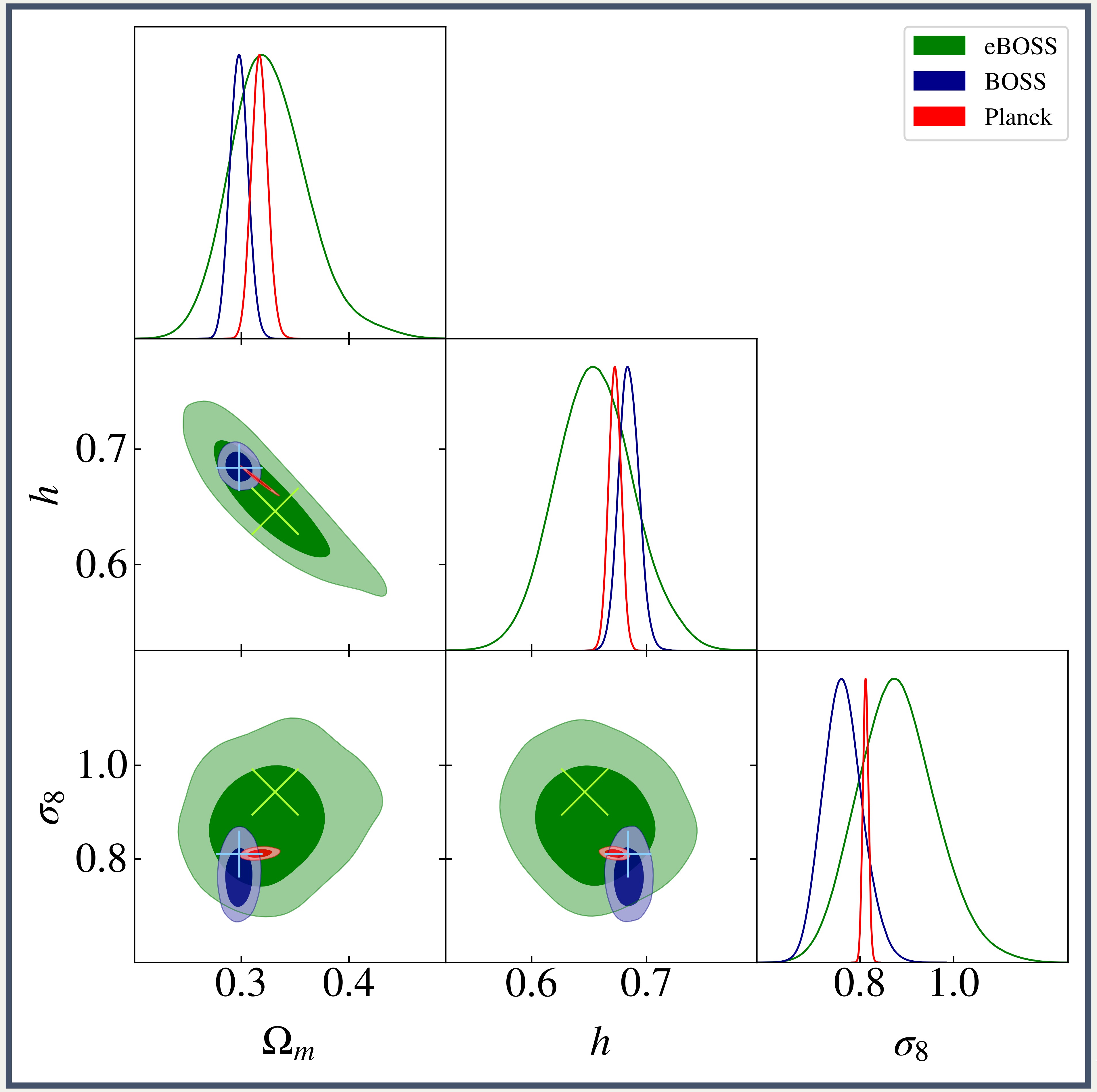
BAO/$f\sigma_8$ vs EFTofLSS



TS++ [arXiv:2210.14931]

- For **eBOSS**, the error bars of Ω_m and σ_8 are reduced by a factor ~ 2.0 and ~ 1.3
- For **BOSS**, the error bars of Ω_m and h are reduced by a factor ~ 5.4 and ~ 3.2

LSS data vs Planck

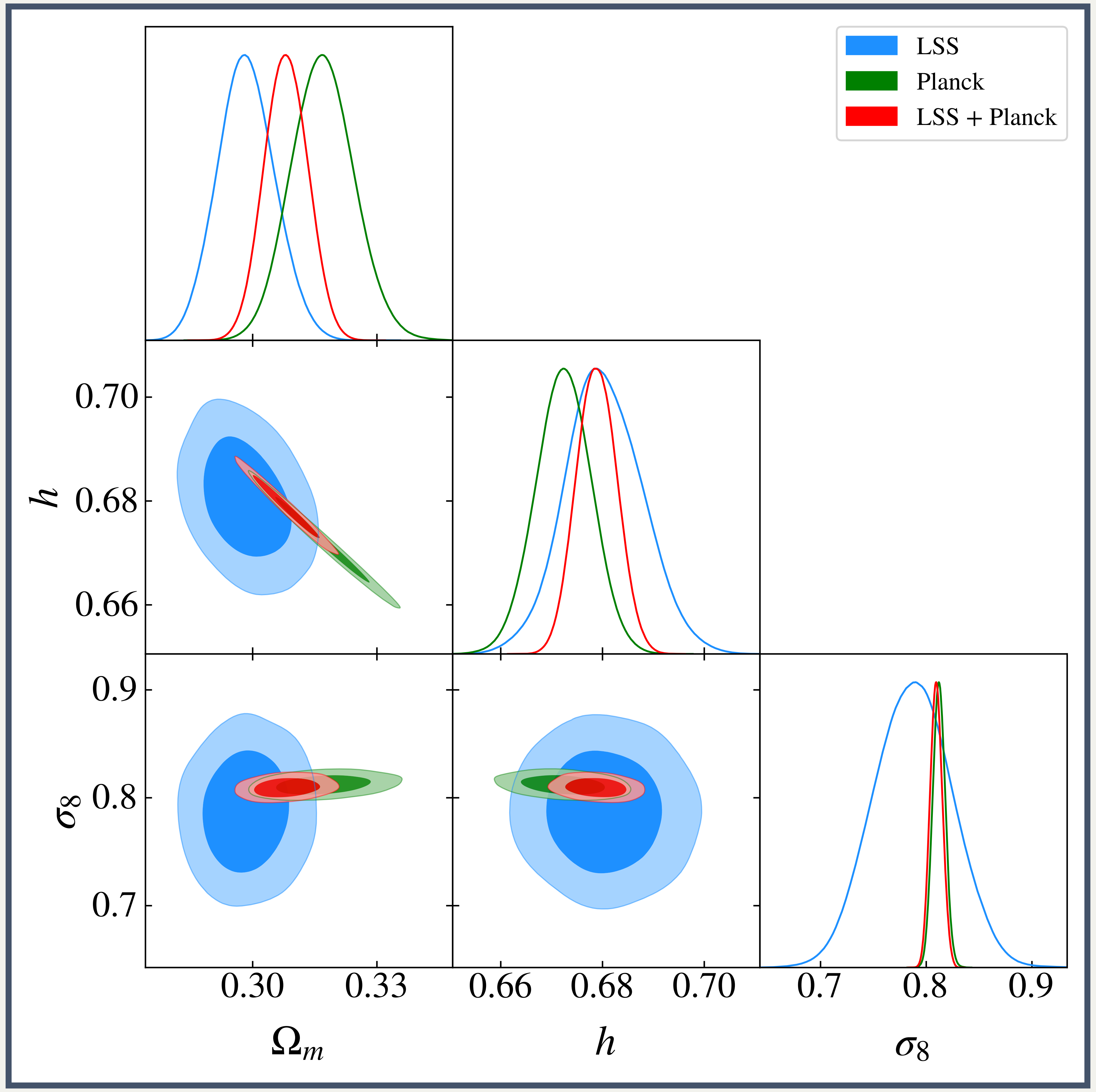


TS++ [arXiv:2210.14931]

- **eBOSS, BOSS and Planck are consistent** at $\lesssim 1.8\sigma$ on all cosmological parameters
- h is $\sim 1\sigma$ lower for eBOSS than for BOSS, while σ_8 is $\sim 1.5\sigma$ higher
- The h and σ_8 Planck values are in-between those of BOSS and eBOSS

→ **there is no tension between Planck and BOSS/eBOSS**

LSS data combined with Planck



LSS: eBOSS + BOSS + ext-BAO + Pantheon

- **Compared to Planck alone**, the constraints on Ω_m and h are **improved by** $\sim 30\,\%$
- σ_8 and A_s are not significantly impacted

TS++ [arXiv:2210.14931]

Extensions to ΛCDM: total neutrino mass $\sum m_\nu$

- The LSS constraint derived in this work is **only** $\sim 10\,\%$ **weaker than the Planck constraint** ($\sum m_\nu = 0.241 eV$)
- The EFT analysis **significantly improves the constraints** on $\sum m_\nu$ (by a factor of ~ 18) over the conventional BAO/$f\sigma_8$ analysis ($\sum m_\nu = 4.84 eV$)

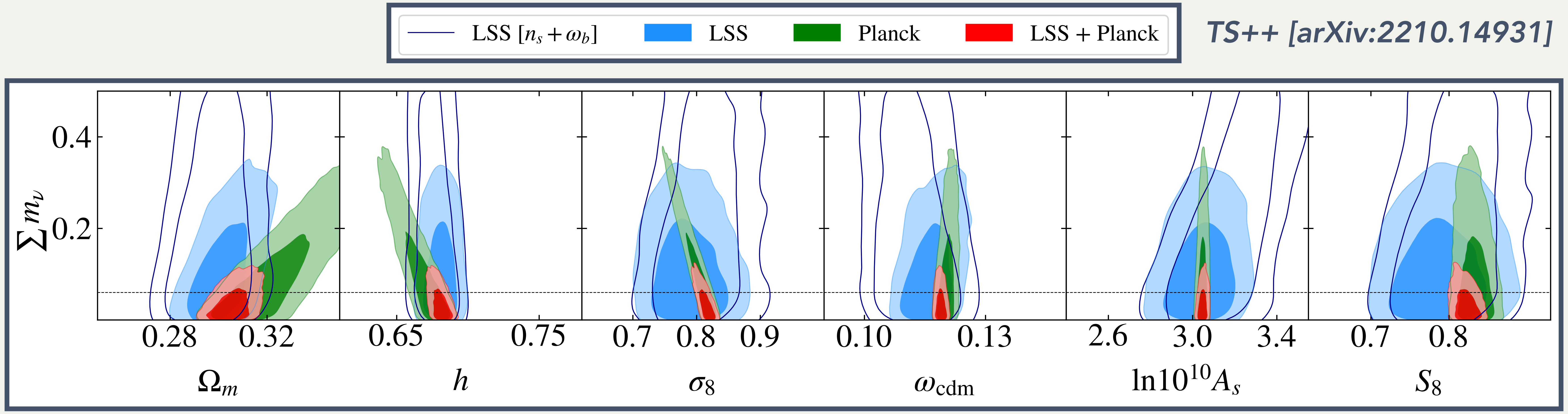
Palanque-Delabrouille++ [arXiv:1911.09073]

- This analysis **disfavors the inverse hierarchy** at $\sim 2.2\sigma$ & is **competitive to the Lyman-α constraints**

LSS:
$\sum m_\nu < 0.274 eV$

LSS+Planck:
$\sum m_\nu < 0.093 eV$

TS++ [arXiv:2210.14931]



Conclusions

- EFTofLSS allows to highlight that **there is no tension** between current BOSS/eBOSS data and Planck data (but not in tension with weak lensing neither)

- Data are consistent with ΛCDM at $\lesssim 1.3\sigma \rightarrow$ Strong constraints on canonical extensions to ΛCDM
  e.g. LSS+Planck: $\sum m_\nu < 0.093 e$V

- EFTofLSS provides **interesting constraints on non-trivial extensions** of the ΛCDM model:
  → see [TS et al. '22, arXiv:2203.07440] for **Decaying Cold Dark Matter**
  → see [TS et al. '22, arXiv:2208.05930] for **Early Dark Energy**

Thanks for your attention

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The effective field theory of large-scale structures (EFTofLSS)

Application to BOSS data

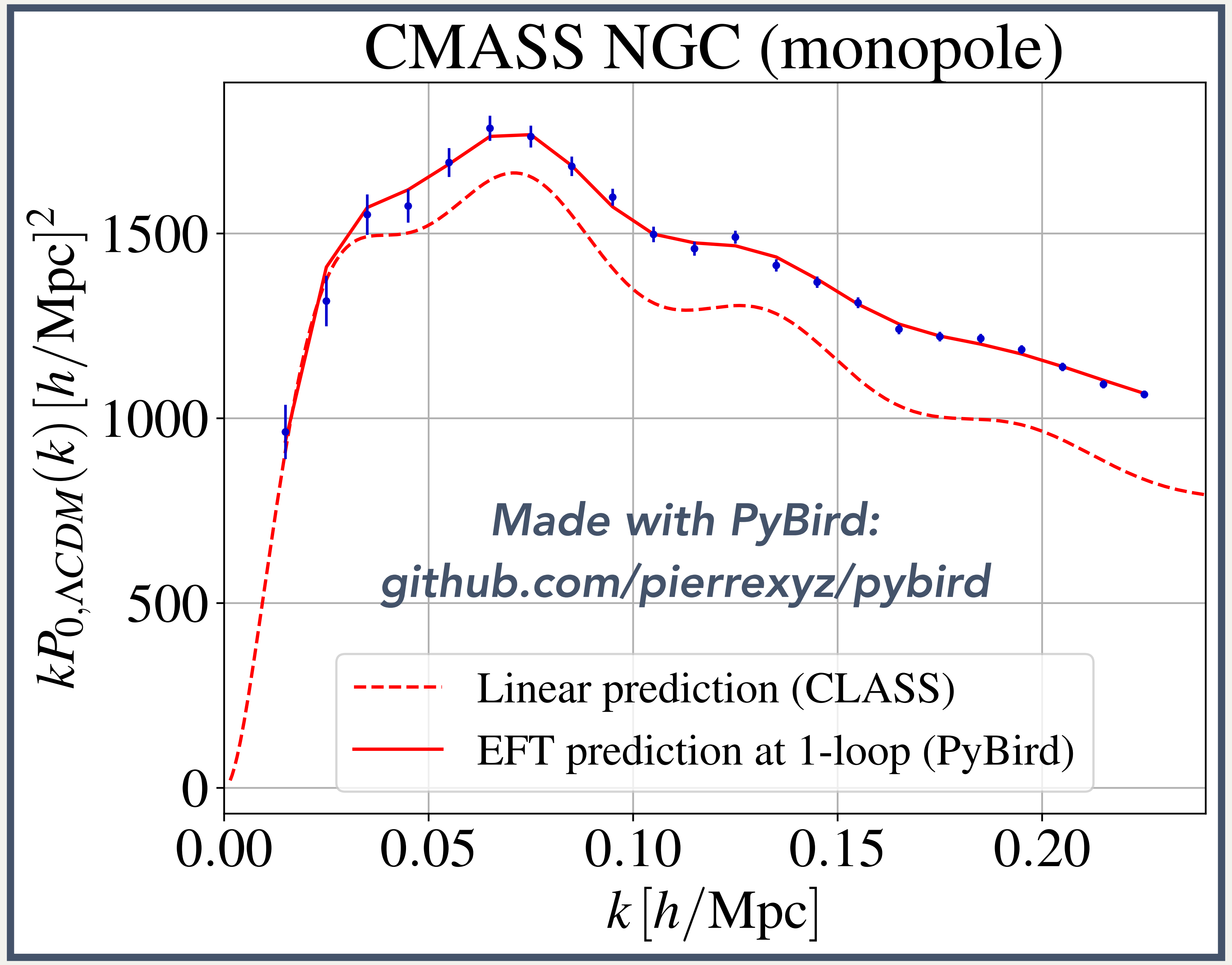
Galaxies selected in two redshift ranges:
→ LOWZ (SGC/NGC): $0.2 < z < 0.43$ ($z_{\rm eff} = 0.32$)
→ CMASS (SGC/NGC): $0.43 < z < 0.7$ ($z_{\rm eff} = 0.57$)

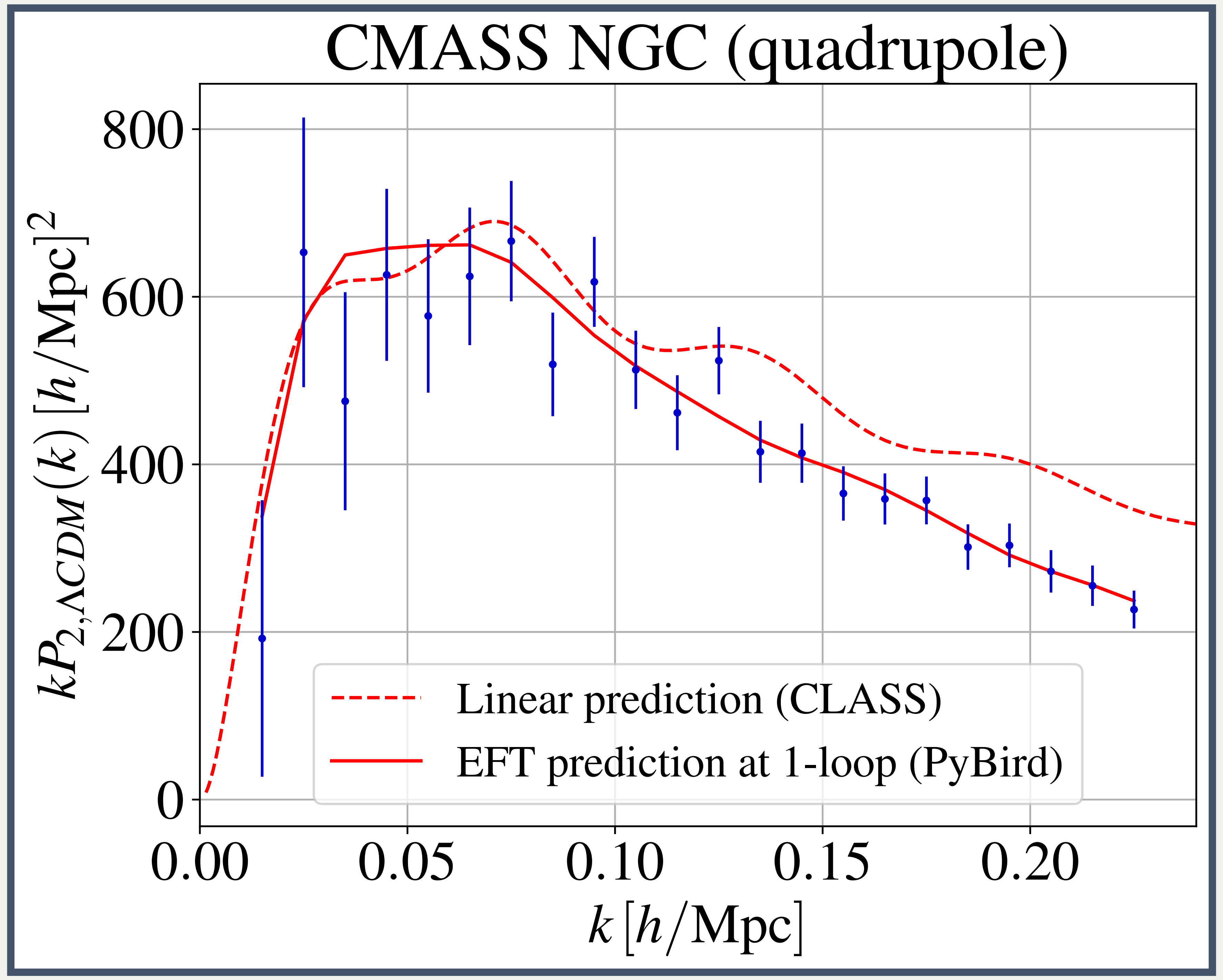
BOSS Collaboration [arXiv:1607.03155]

Multipoles of the galaxy power spectrum, obtained through a **Legendre** polynomials ($\mathscr{L}_\ell$) decomposition:

$$P_g(z,k,\mu) = \sum_{\ell \text{ even}} \mathscr{L}_\ell(\mu) P_\ell(z,k)$$

→ the two main contributions to $P_g(z,k,\mu)$ are the **monopole** ($\ell = 0$) and the **quadrupole** ($\ell = 2$)





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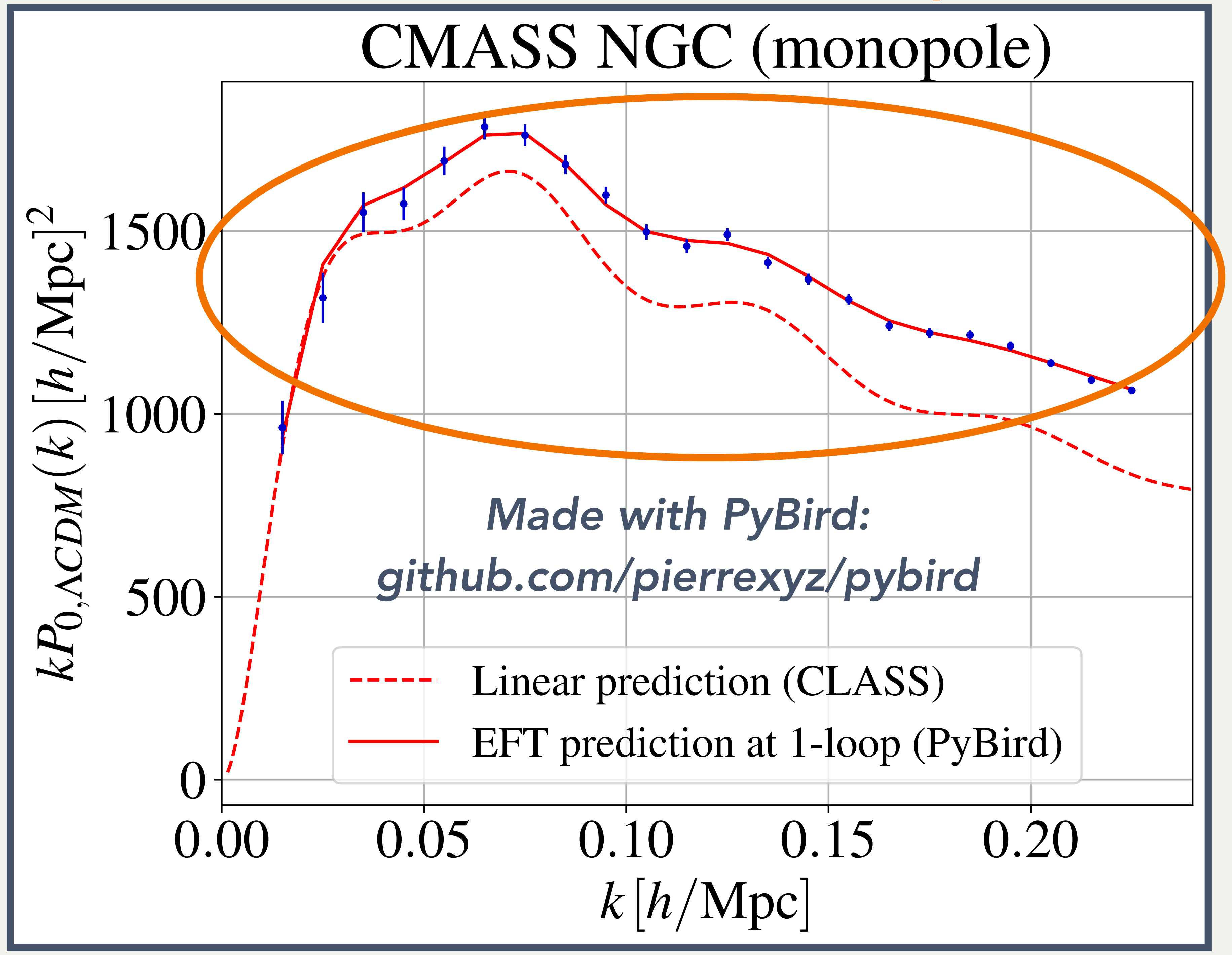
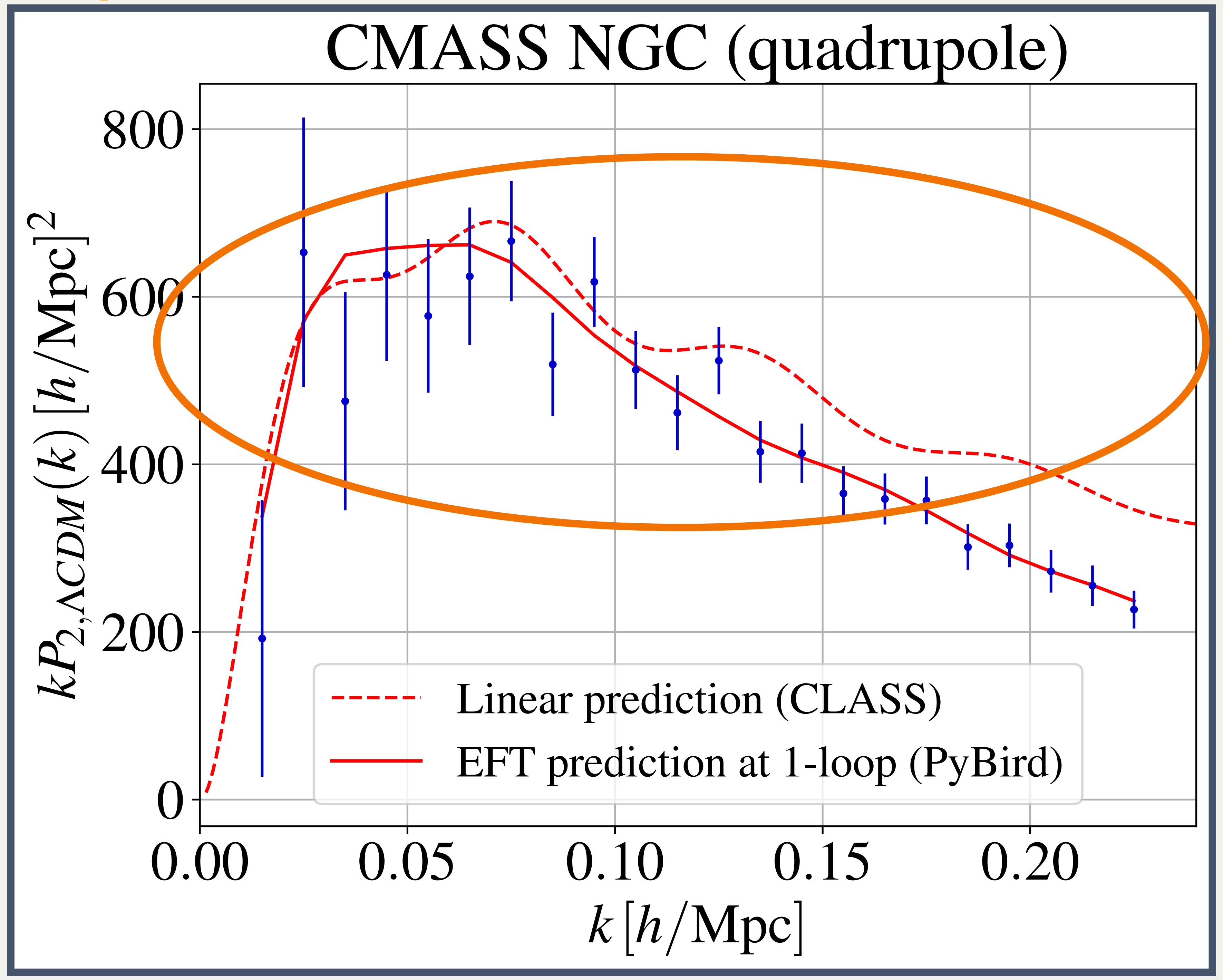
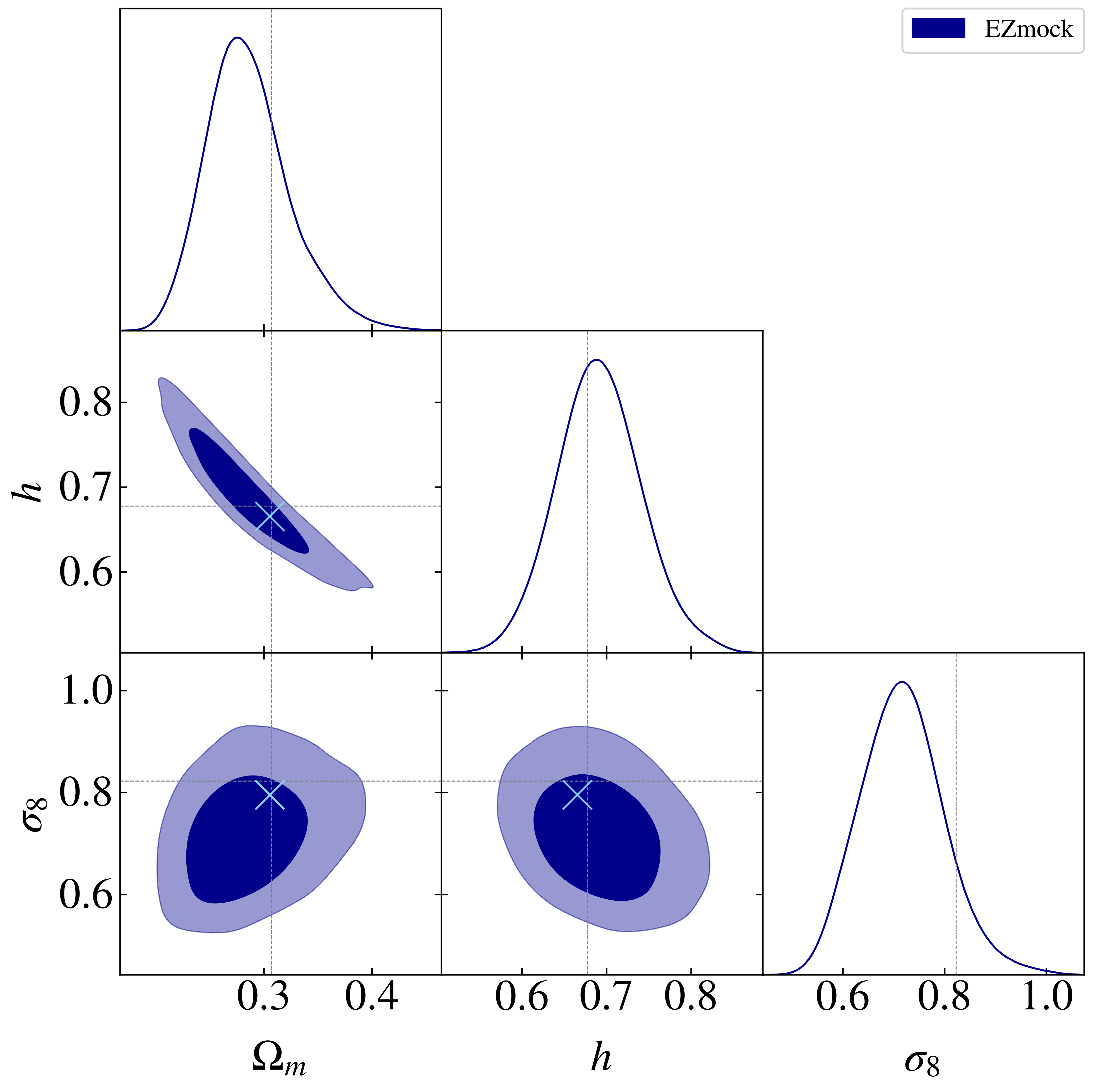
Improvement in precision!





Determination of the cut-off scale $k_{\max}$ of the one-loop prediction

The EZmock



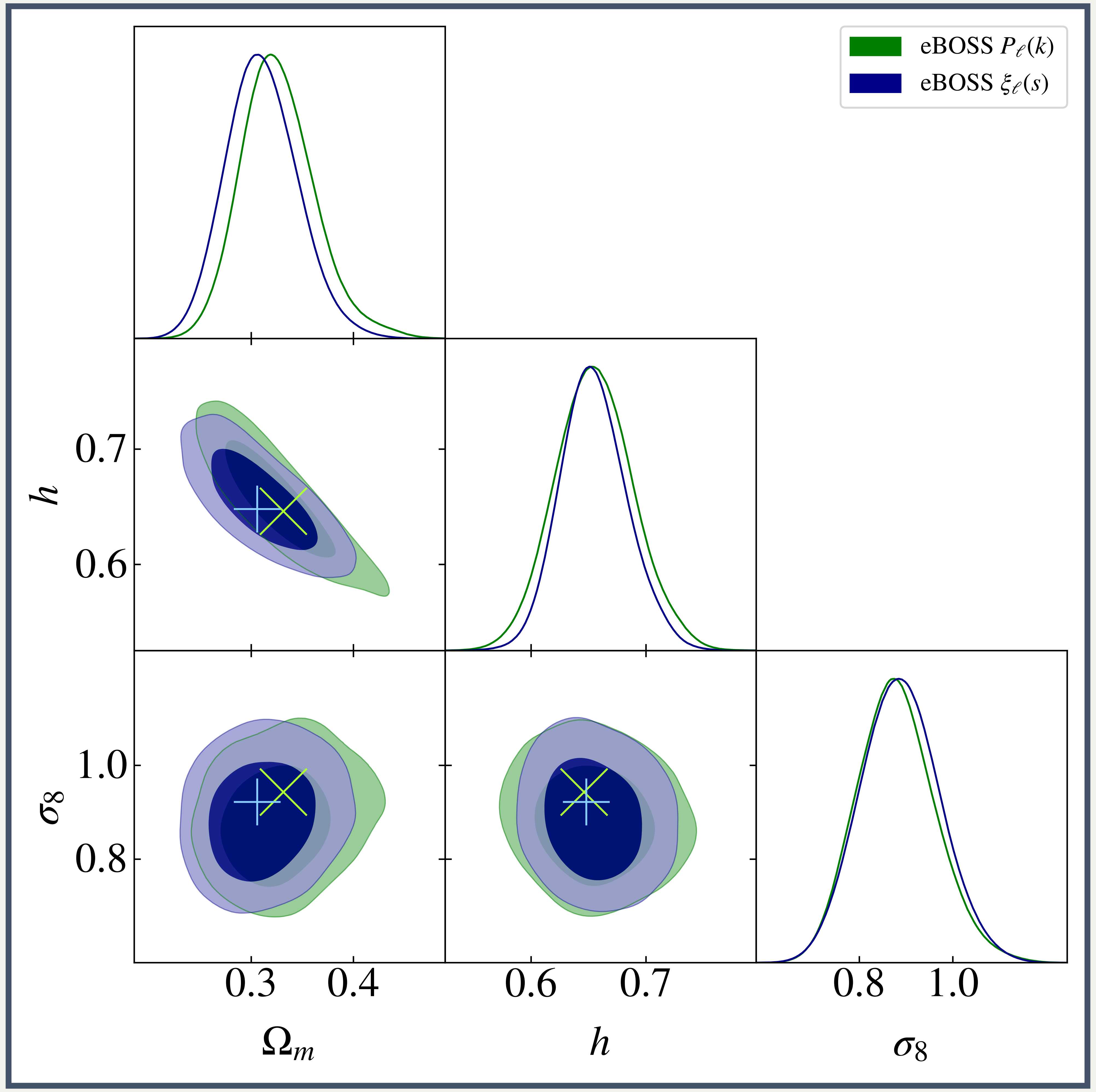
TS++ [arXiv:2210.14931]

- **EZmock**: mocks that are built to simulate eBOSS observational characteristics

  Chuang++ [arXiv:1409.1124]

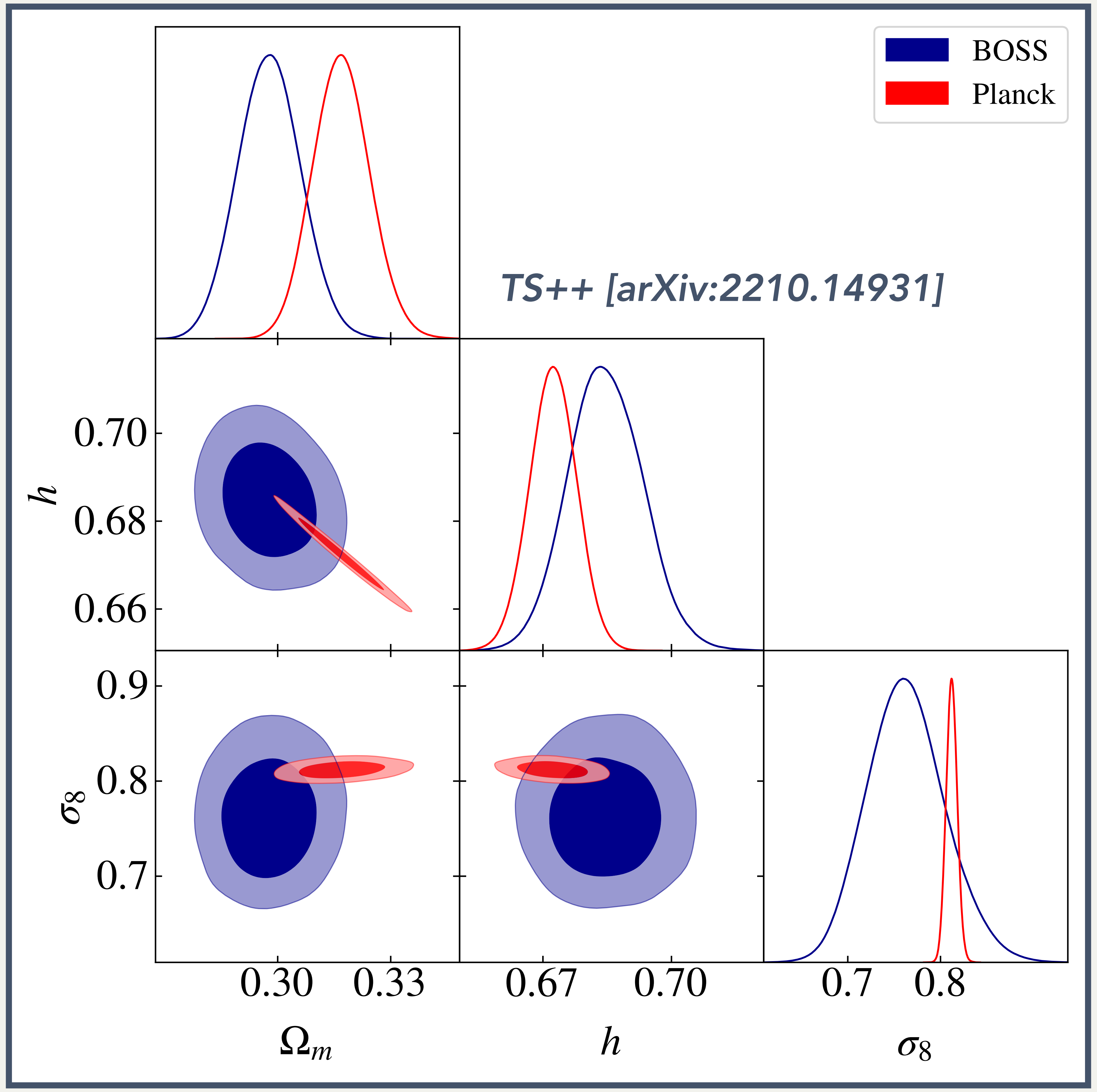
- Up to $k_{\max} = 0.24h\,\mathrm{Mpc}^{-1}$, the best-fit values of the cosmological parameters are shifted with respect to the truth of the simulations by $\lesssim 1/3 \cdot \sigma$

eBOSS $P_\ell(k)$ vs eBOSS $\xi_\ell(k)$



The effective field theory of large-scale structures (EFTofLSS)

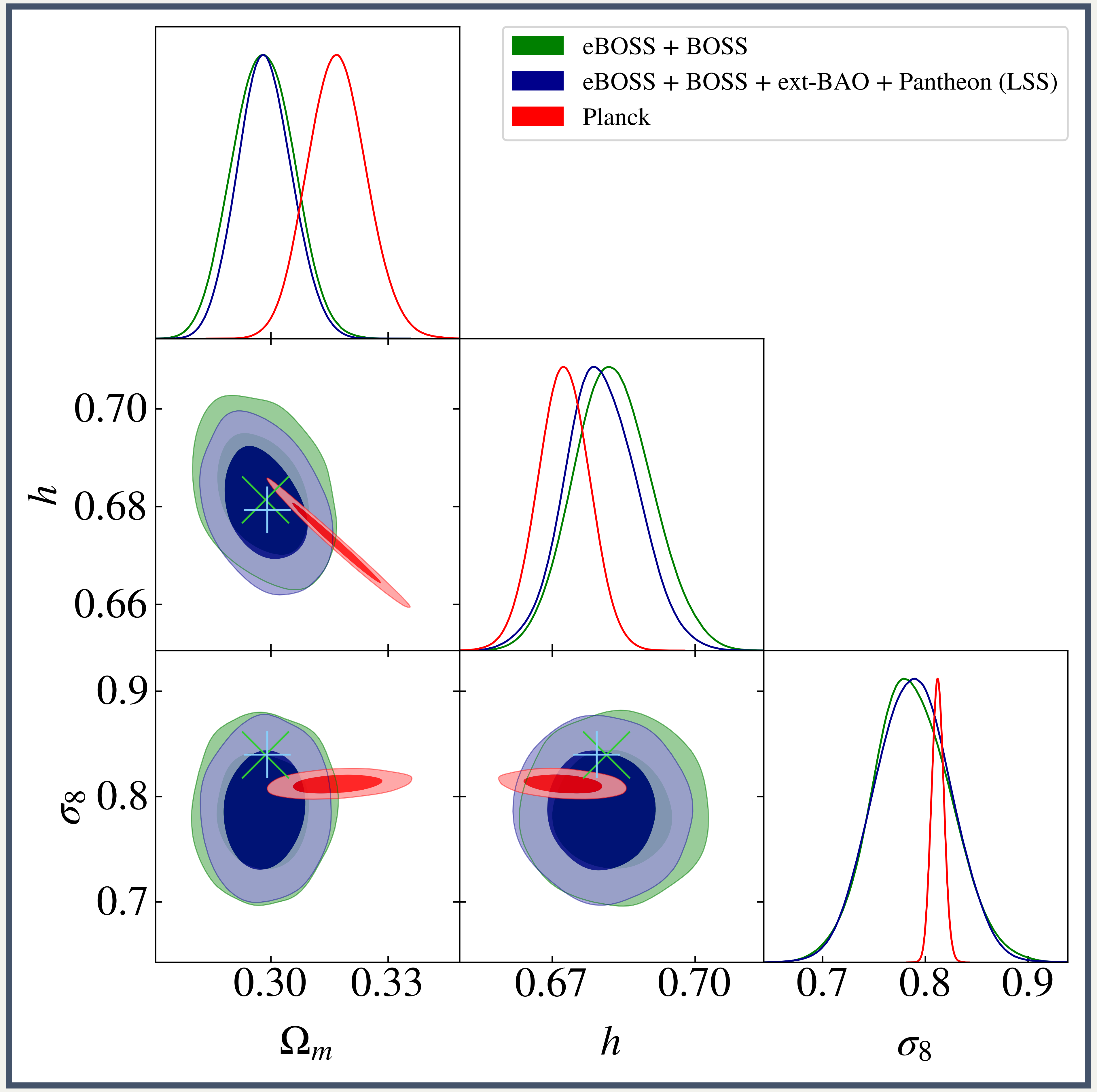
Application to BOSS data



The EFTofLSS analysis of BOSS data allows to determine Ω_m and h with a **precision of only** $10\,\%$ **and** $60\,\%$ lower than Planck

See also D'Amico++ [arXiv:1909.05271] ; Philcox++ [arXiv:2002.04035]

LSS data vs Planck

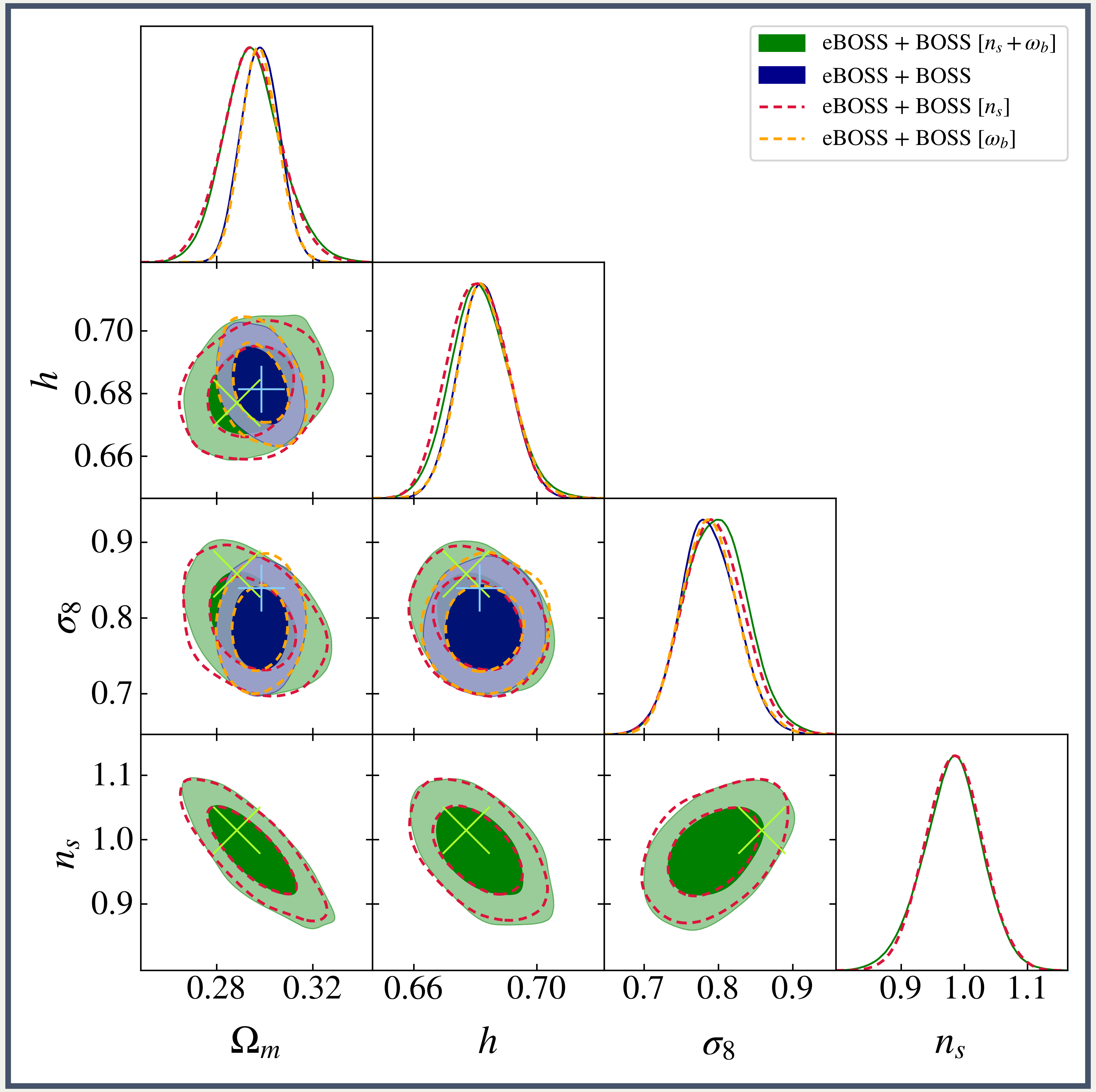


ext-BAO: 6dF & MGS (SDSS) data

TS++ [arXiv:2210.14931]

- The combination of eBOSS + BOSS allows to determine Ω_m and h at a **precision similar to Planck**
- The combination of LSS data remains consistent with Planck → **we can combine them!**

Variation of n_s and ω_b



- We impose a uninformative large flat prior on n_s, while we impose a BBN Gaussian prior on ω_b
- The variation of ω_b within the BBN prior has a negligible impact on the cosmological results: we have a relative shift of $\lesssim 0.04\sigma$
- The variation of n_s within a uninformative large flat prior leads to a relative shift $\lesssim 0.4\sigma$

Extensions to ΛCDM: curvature density fraction Ω_k

- With LSS data only, we find Ω_k **compatible with zero curvature at** 1.3σ
- The EFT analysis **significantly improves the constraints** on Ω_k by $\sim 50\,\%$ compared to the conventional BAO/$f\sigma_8$ analysis
- The combination of LSS and Planck leads to a **strong constraint** and excludes the (slightly favored) negative values of Ω_k

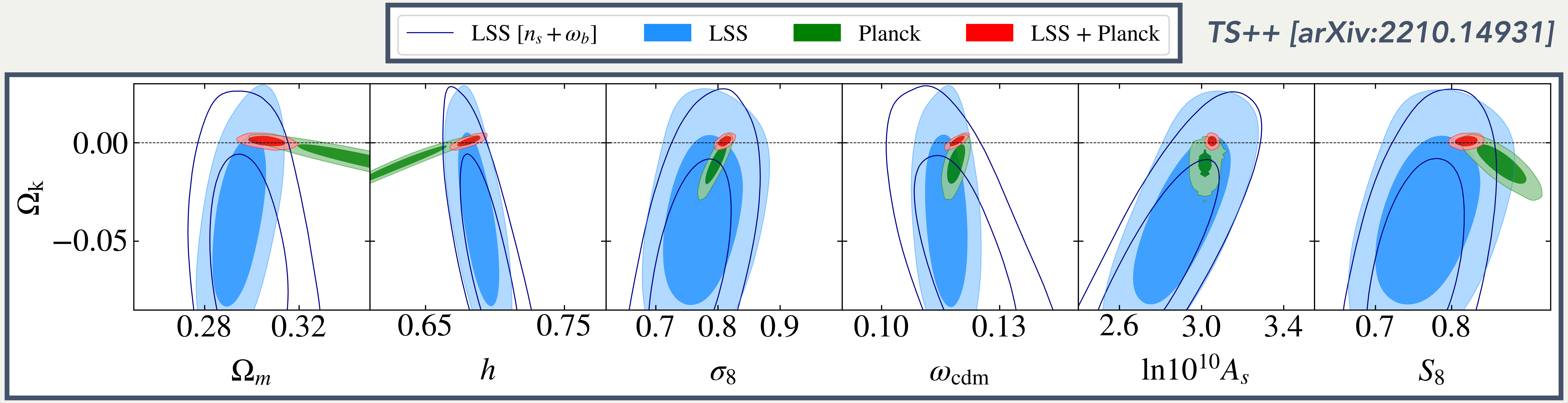
TS++ [arXiv:2210.14931]

LSS:

$$\Omega_k = -0.039^{+0.028}_{-0.029}$$

LSS+Planck:

$$\Omega_k = 0.0008^{+0.0018}_{-0.0017}$$



Extensions to ΛCDM: dark energy equation of state w_0

- With the LSS data only, we find **no evidence for a universe with** $w_0 \neq -1$
- The EFT analysis **improves the constraints** on w_0 by $\sim 20\,\%$ compared to the conventional BAO/$f\sigma_8$ analysis
- The addition of LSS data select values of w_0 close to -1, located in the 2σ region reconstructed from Planck data

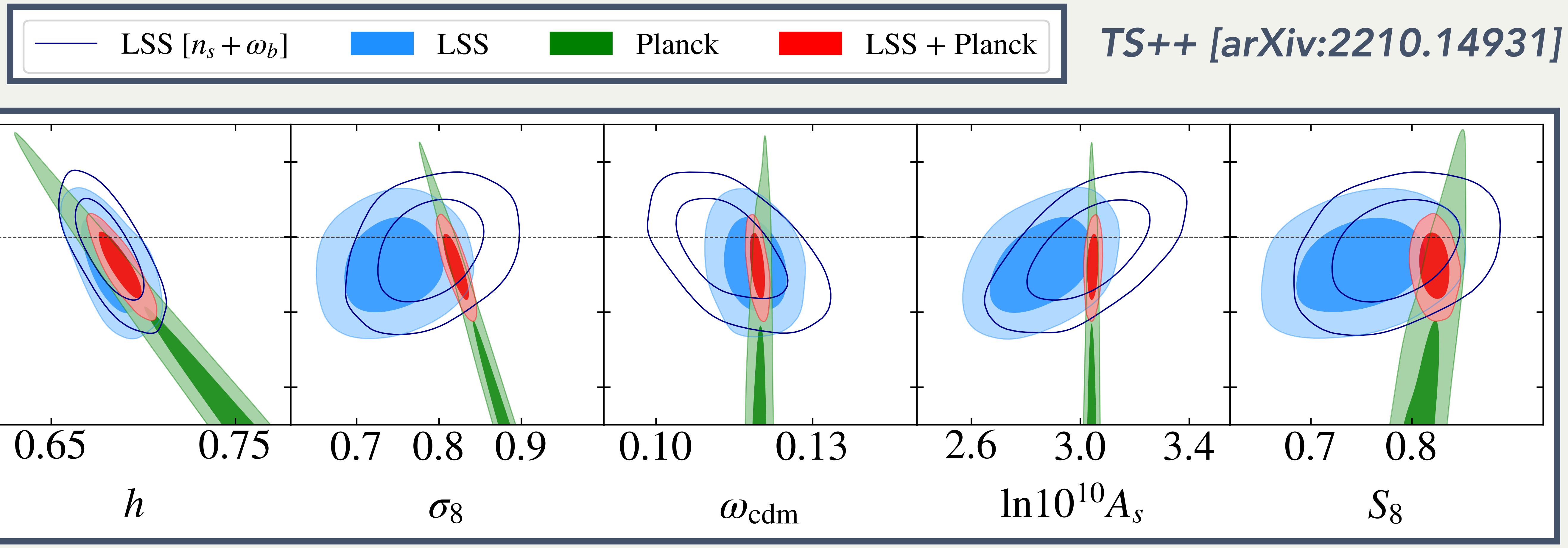
LSS:

$w_0 = -1.038 \pm 0.041$

LSS+Planck:

$w_0 = -1.039 \pm 0.029$

TS++ [arXiv:2210.14931]

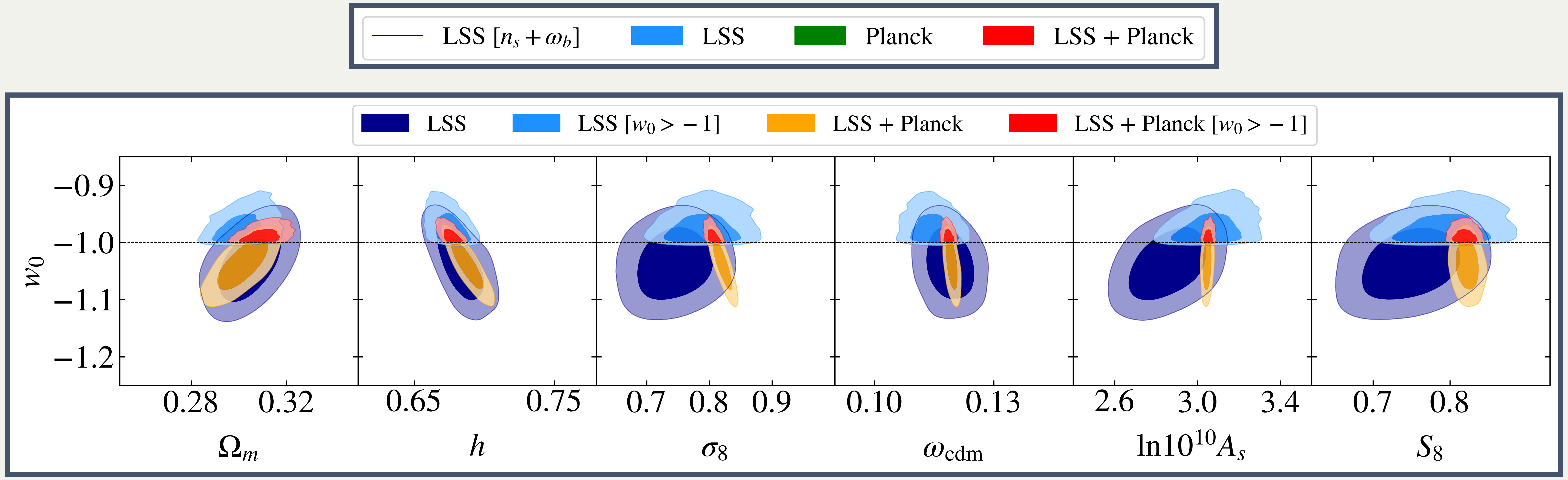


Dark energy equation of state $w_0 \geq -1$

- One can see that this new prior shifts the 2D posteriors inferred from the LSS data in a non-negligible way, while it remains globally stable for the LSS + Planck
- For these analyses, $\Delta\chi^2 = 0$ with respect to ΛCDM, since we obtain best-fit values of $w_0 = -1$

LSS:
$w_0 < -0.932$

LSS+Planck:
$w_0 < -0.965$



Extensions to ΛCDM: effective number of relativistic species N_{eff}

- The value of ΔN_{eff} is **compatible with the standard model**
- Unlike EFTofLSS, **the conventional BAO/$f\sigma_8$ analysis is unable to constrain this parameter**
- The addition of the LSS data **improves** the results of Planck alone by $\sim 20\,\%$

LSS:

$\Delta N_{\text{eff}} = 0.40^{+0.44}_{-0.91}$

LSS+Planck:

$\Delta N_{\text{eff}} = -0.07^{+0.15}_{-0.16}$

TS++ [arXiv:2210.14931]