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

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IAP - 04/06/2024

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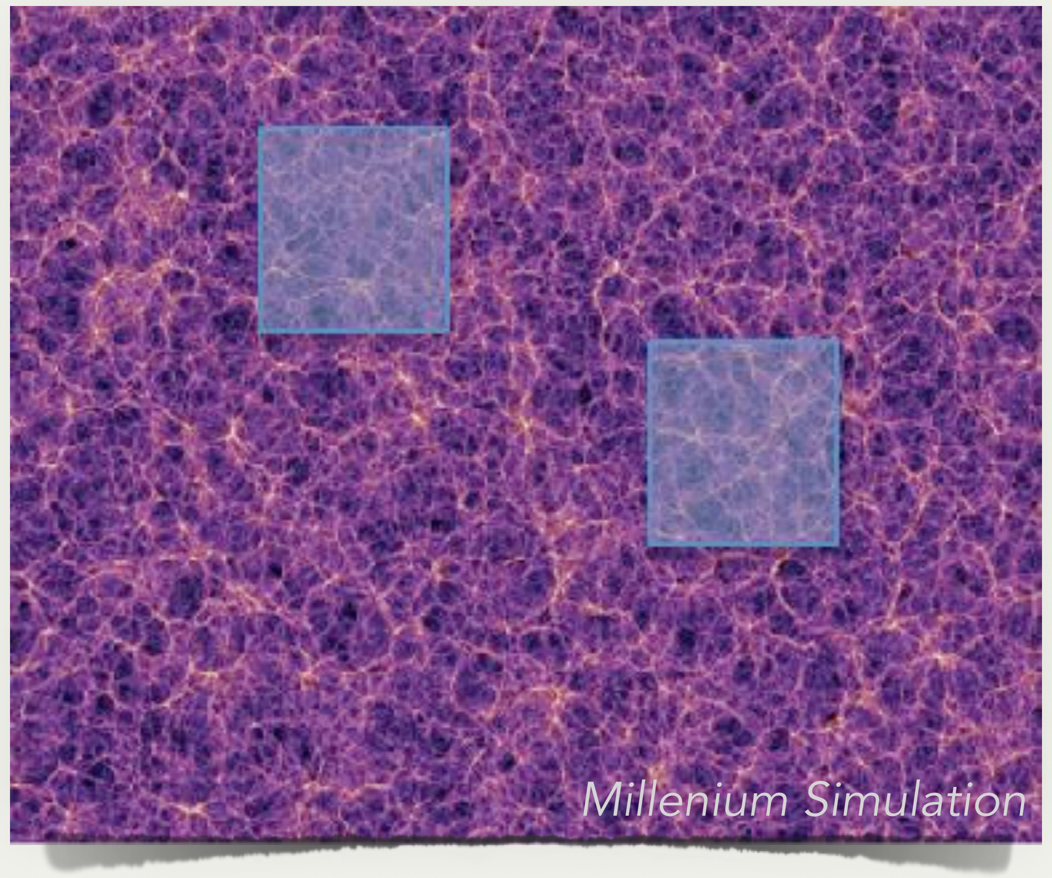
Introduction: the general paradigm

The standard model of Cosmology (ΛCDM)

Introduction: the general paradigm

One conjecture: cosmological principle



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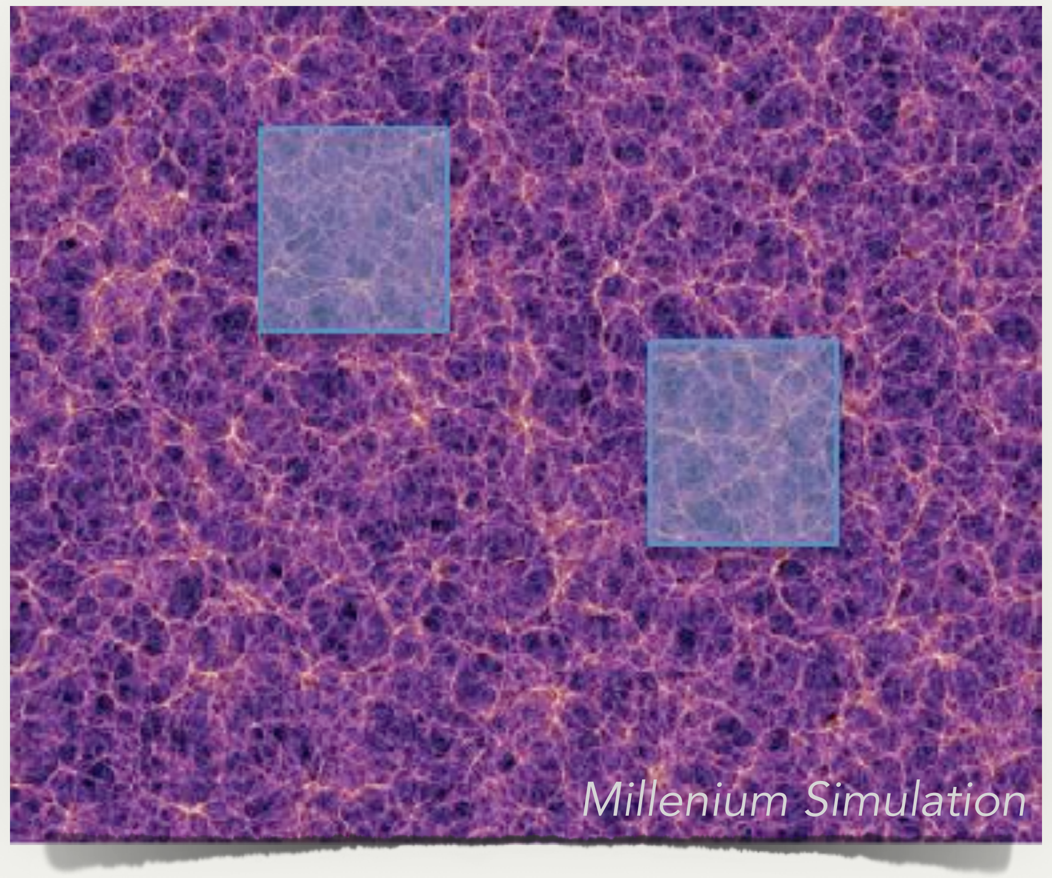

Two sets of fundamental equations:

Einstein's equations & Boltzmann's equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\frac{df}{dt} = C[f]$$

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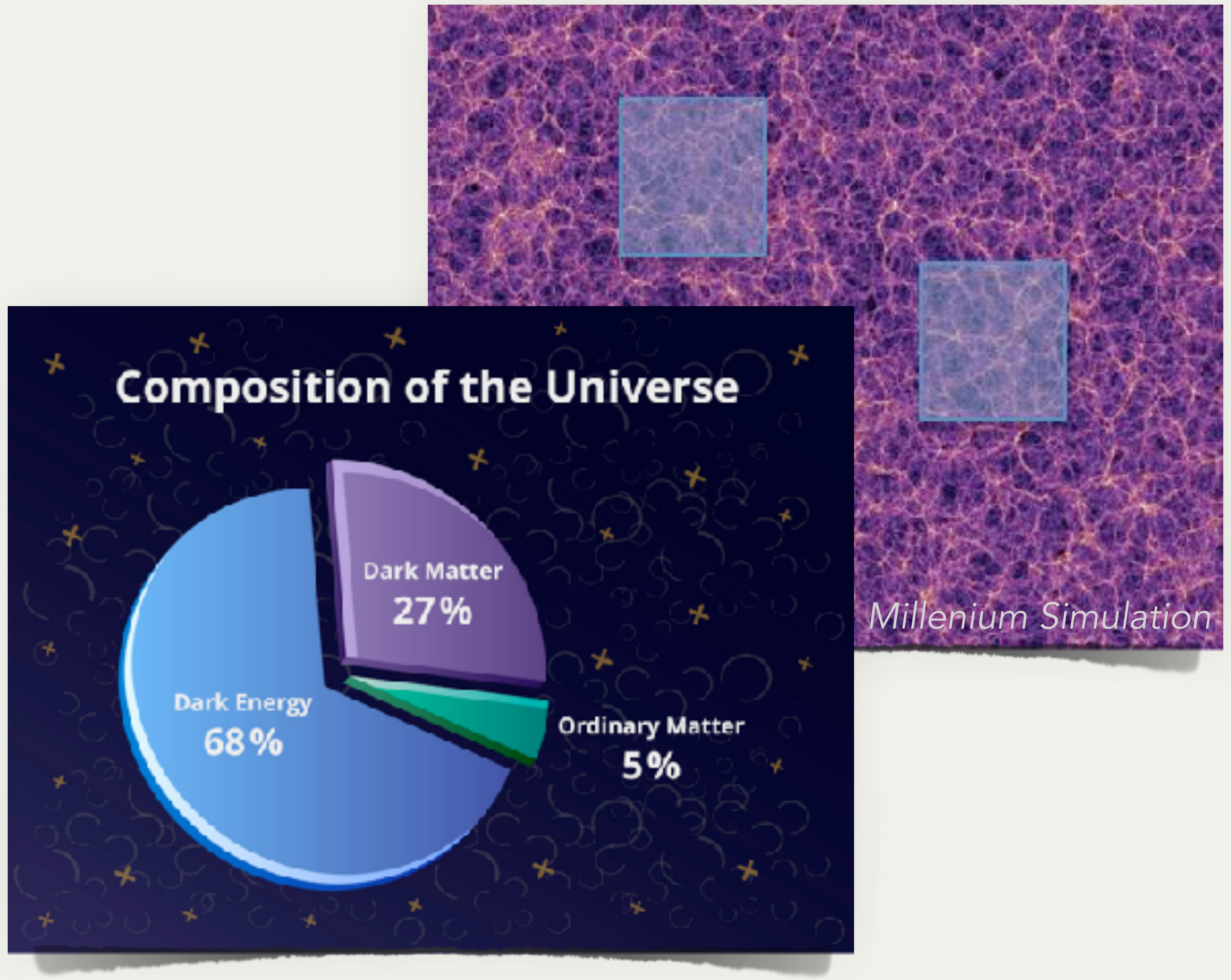

The standard model of Cosmology (ΛCDM)

Five main constituents: photons, baryons, neutrinos, dark matter and dark energy

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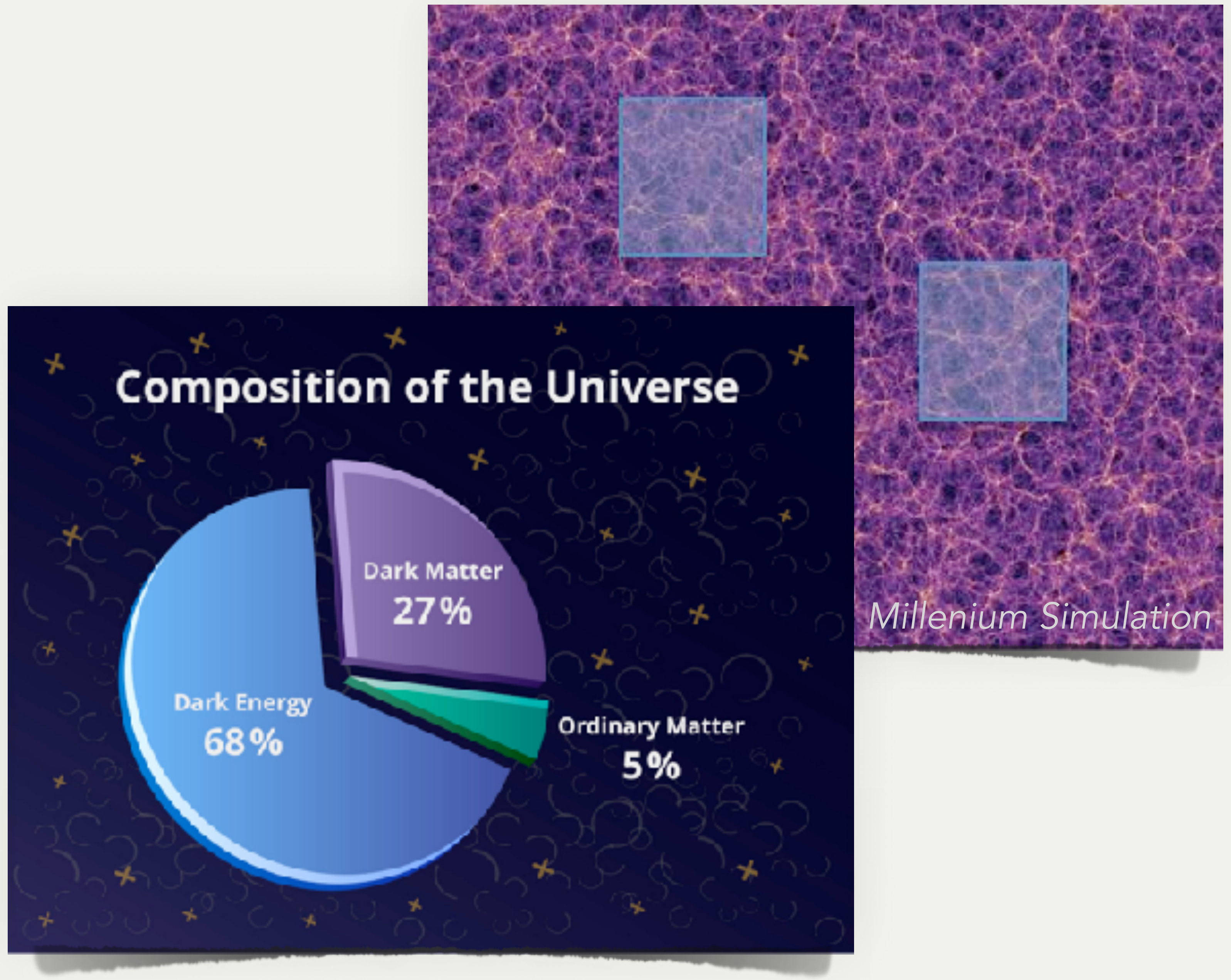

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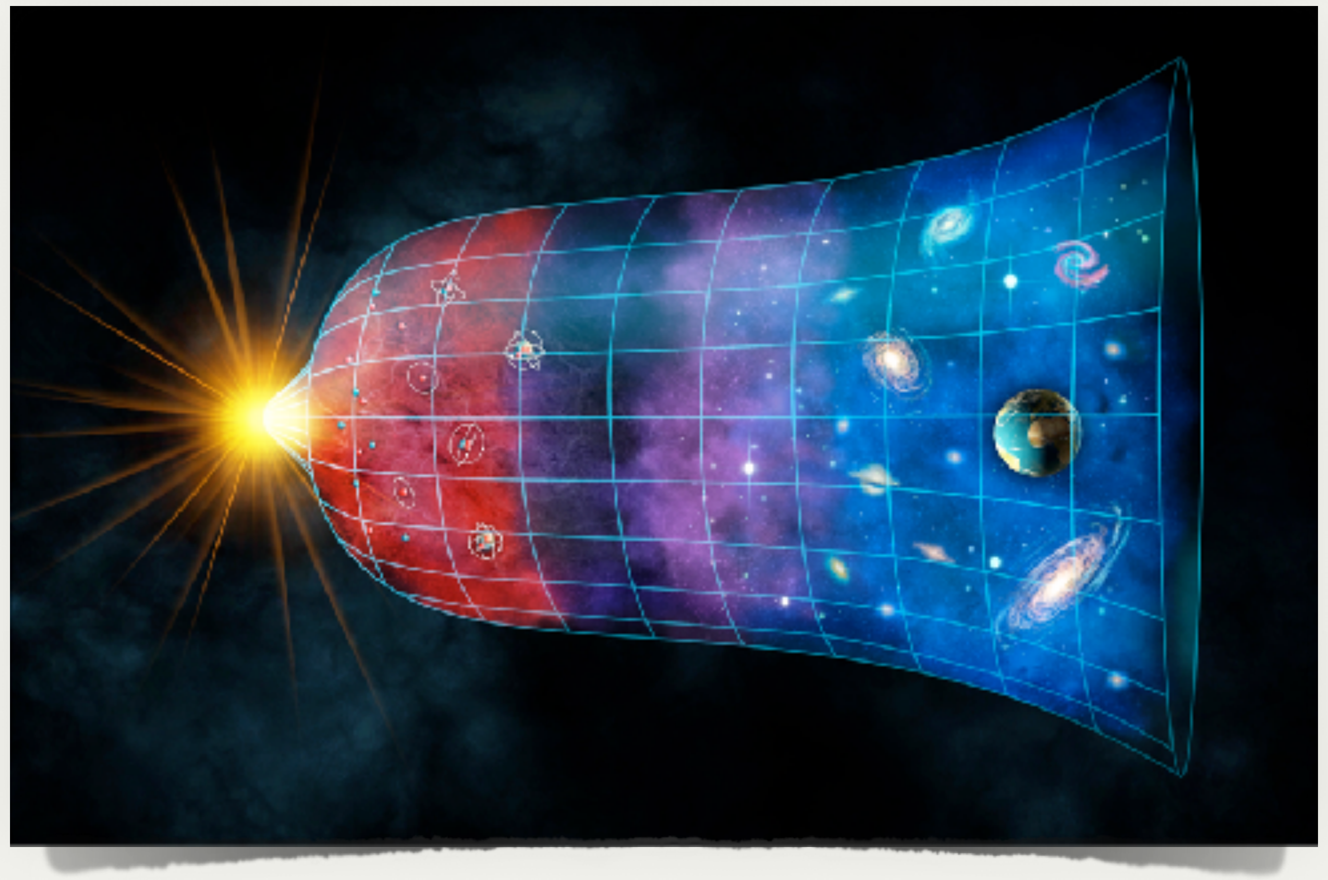
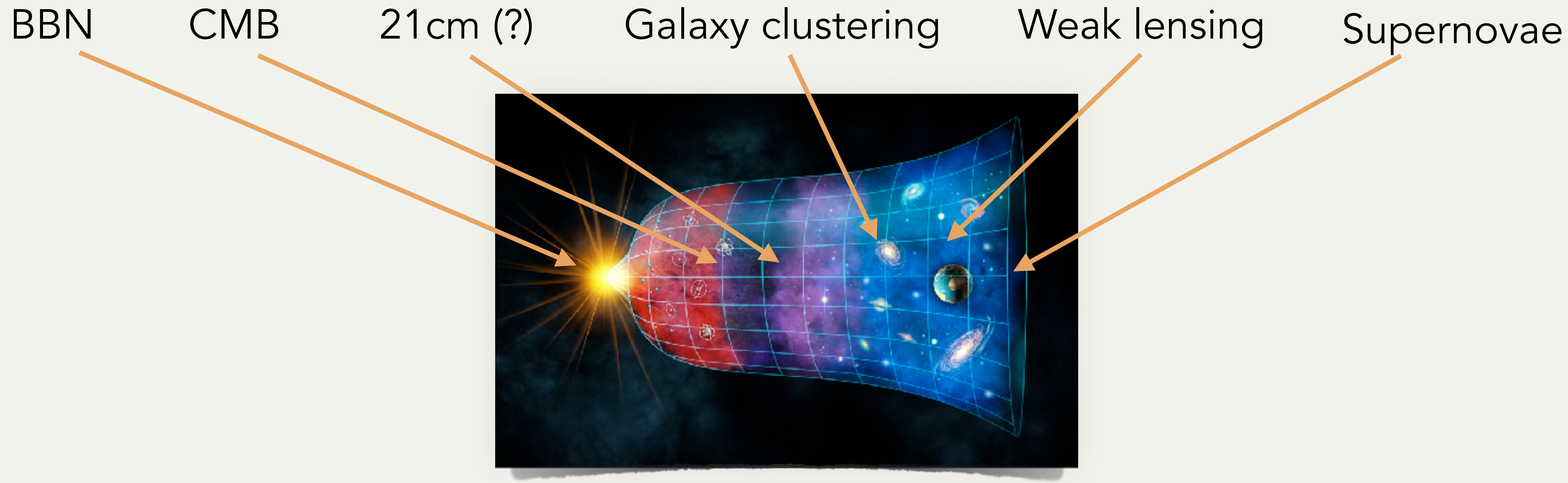


Initial conditions: inflation

Introduction: the cosmological data



The 6 ΛCDM parameters

→ Initial conditions: A_s, n_s

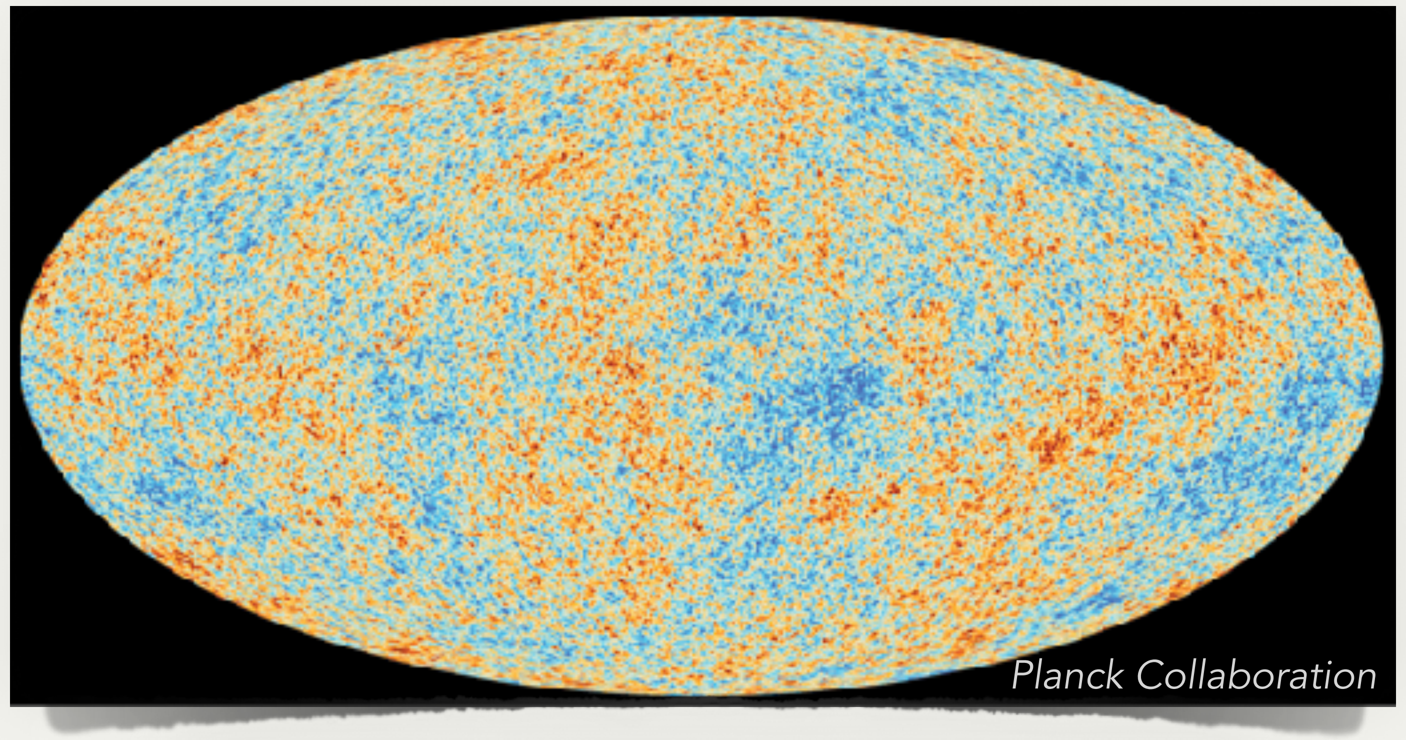
→ Expansion history: H_0, Ω_b and Ω_cdm

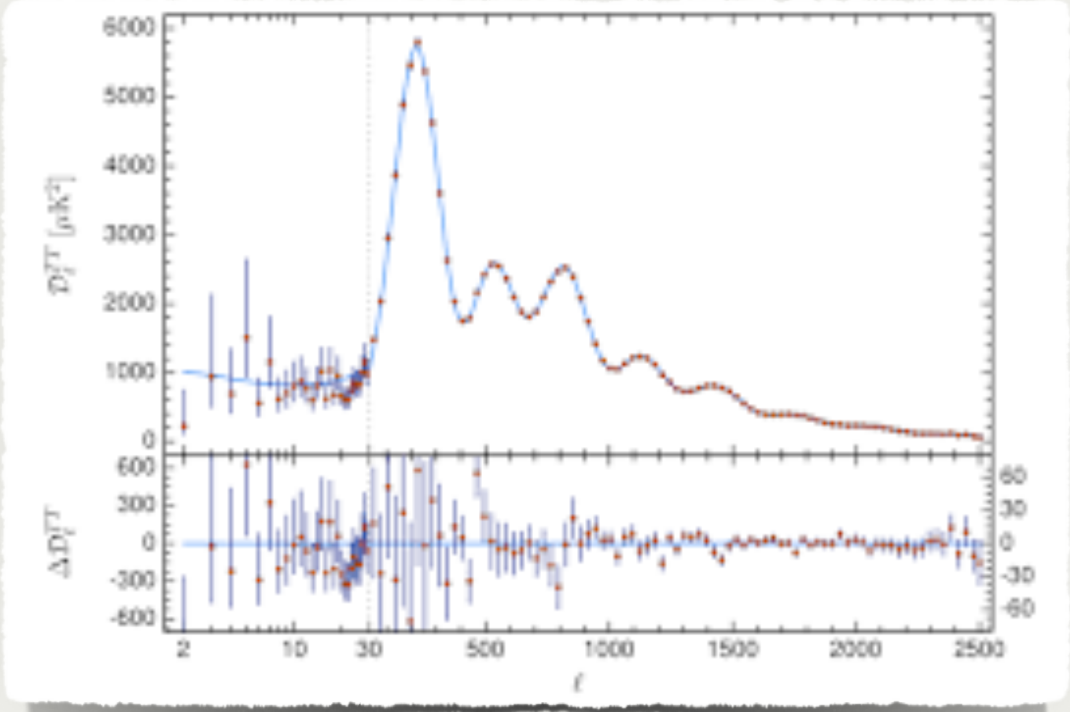
→ Reionization: τ_reio

Introduction: the cosmological data

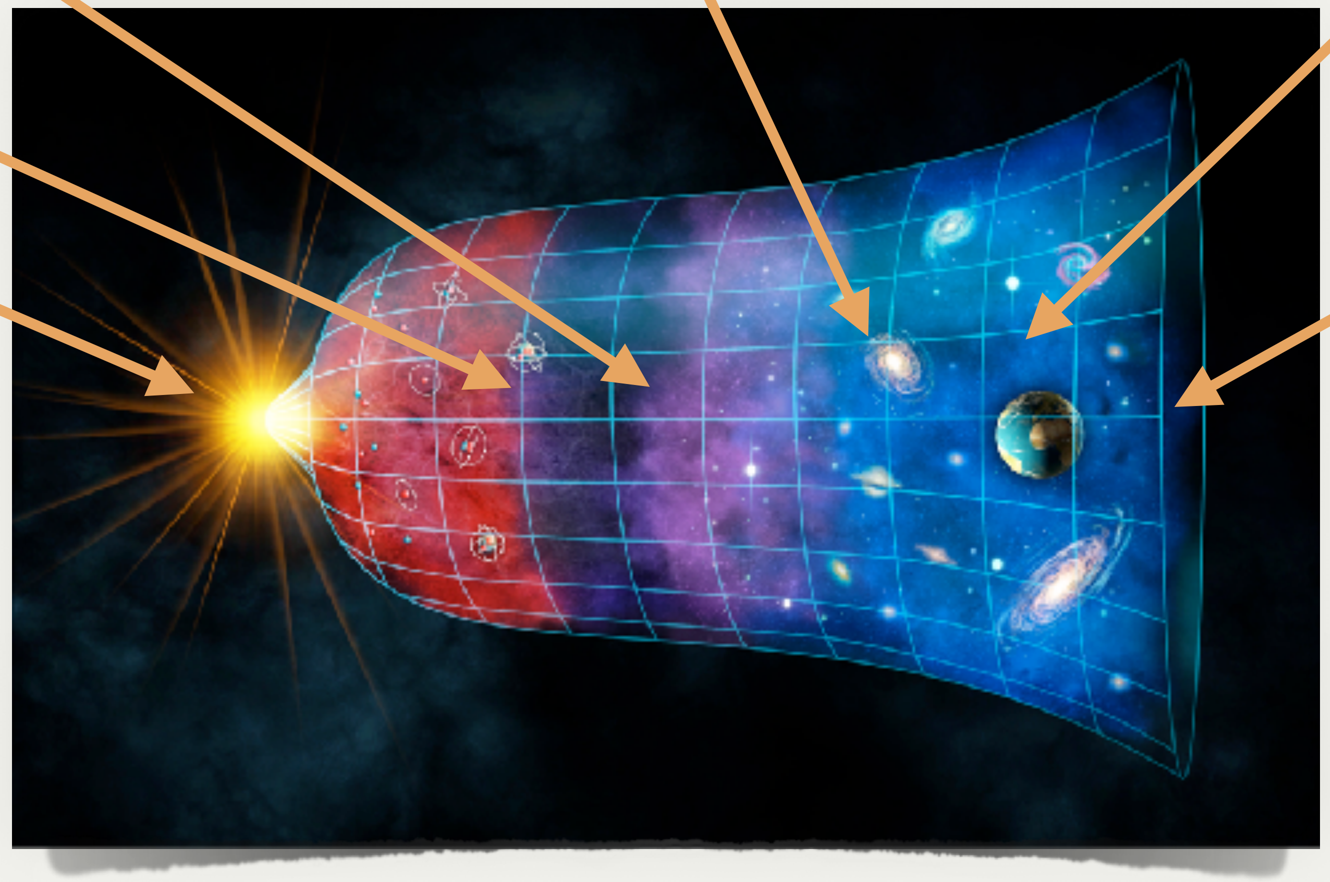
BBN CMB 21cm (?) Galaxy clustering Weak lensing Supernovae

CMB data $z \sim 1000$





Planck Collaboration [arXiv:1807.06209]



The 6 ΛCDM parameters

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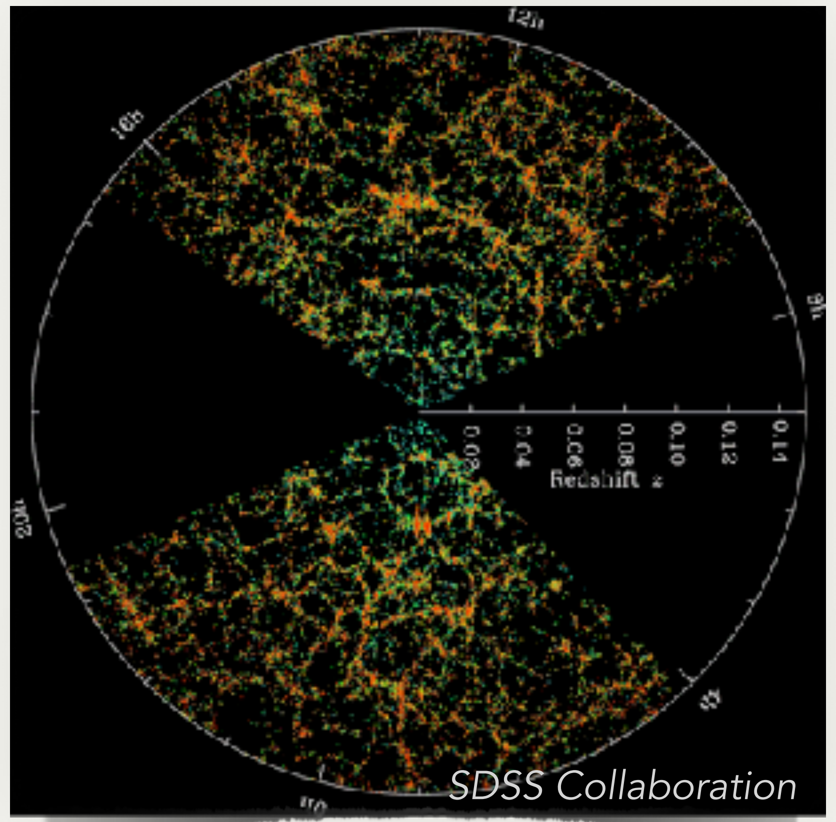
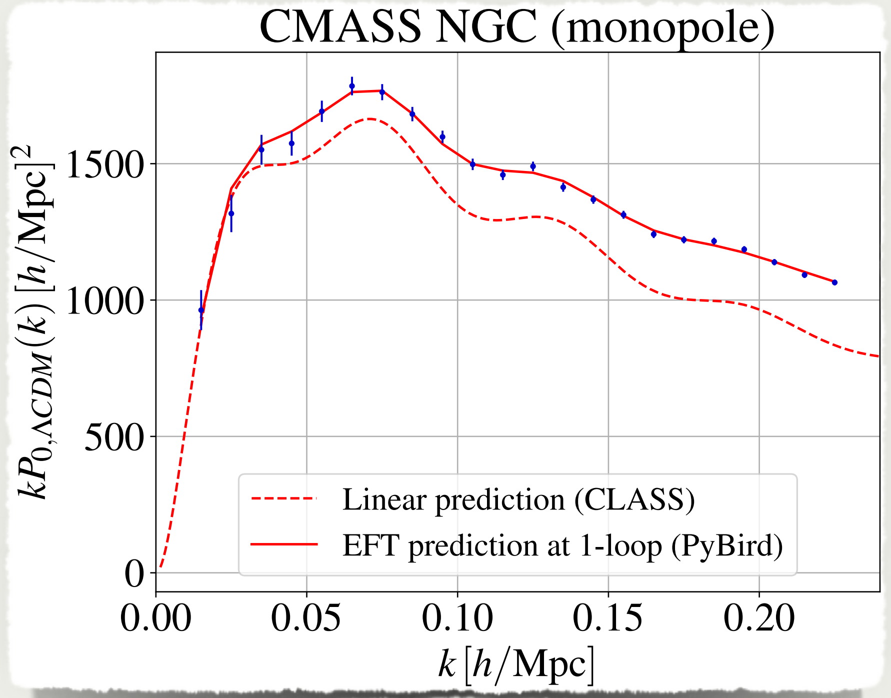
Galaxy clustering data $z \sim 1$





Introduction: the epistemic context

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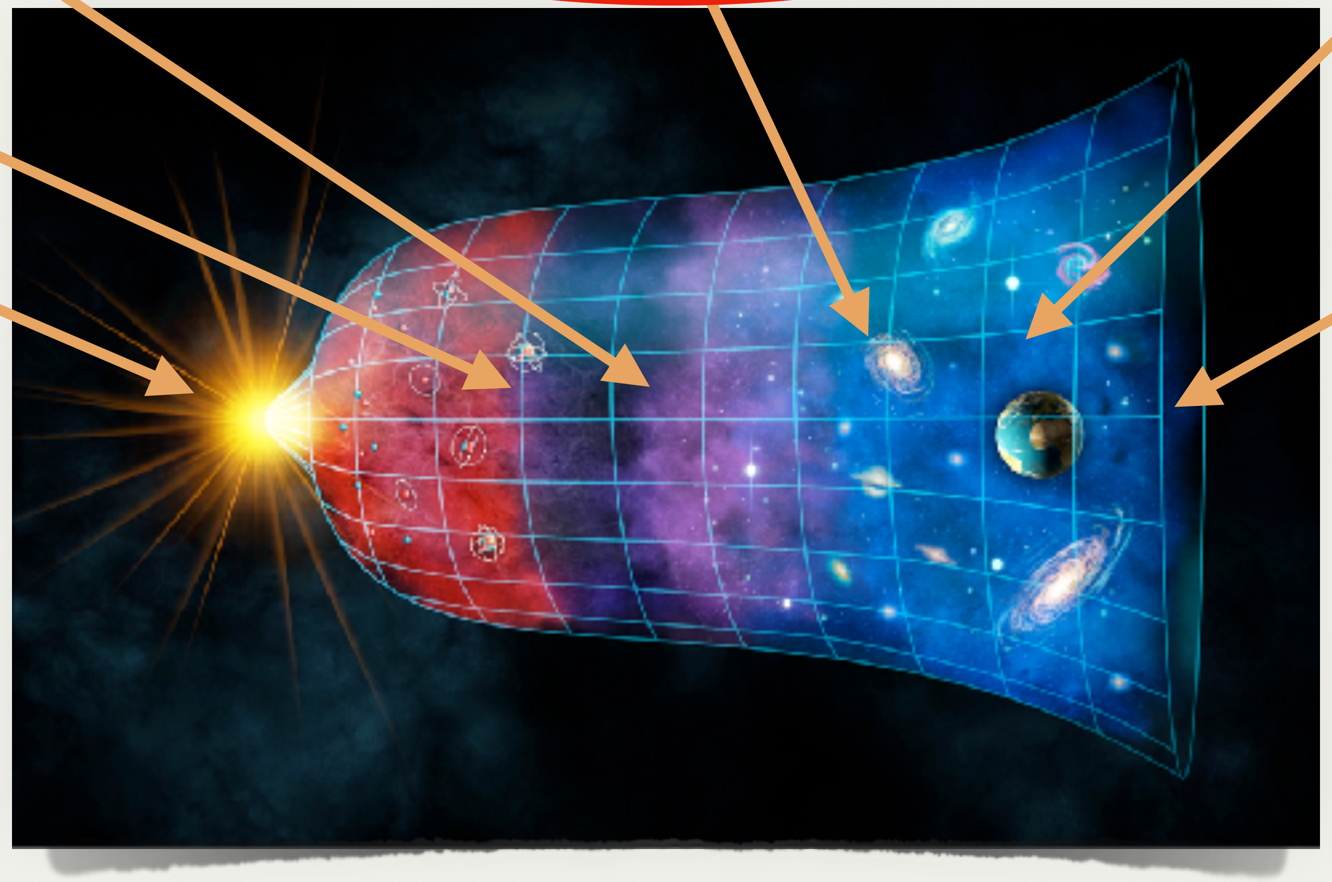

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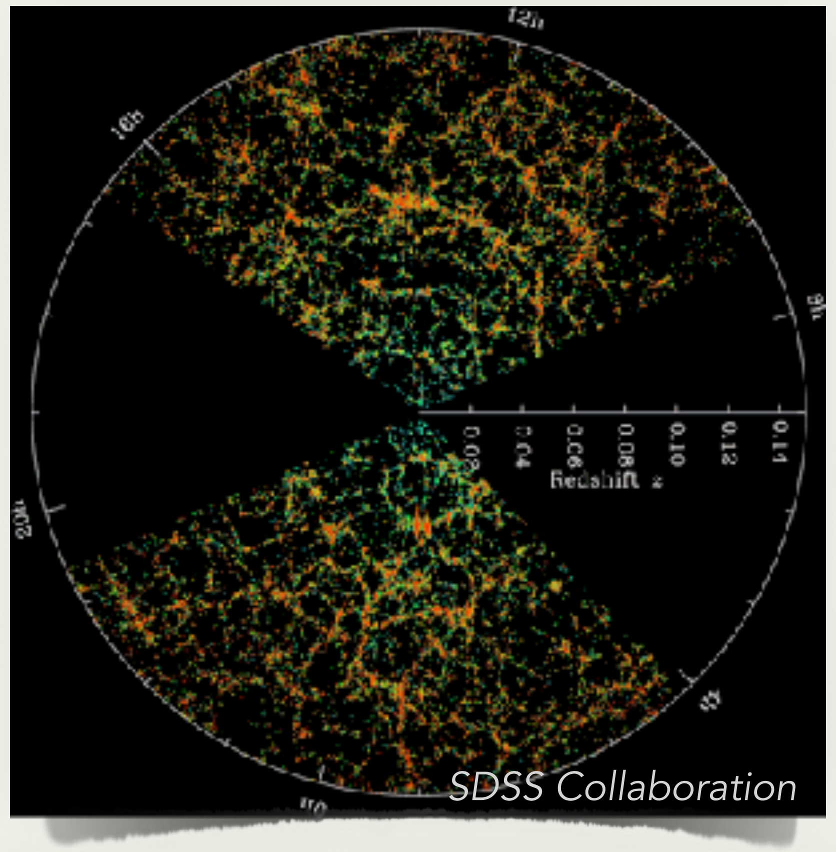
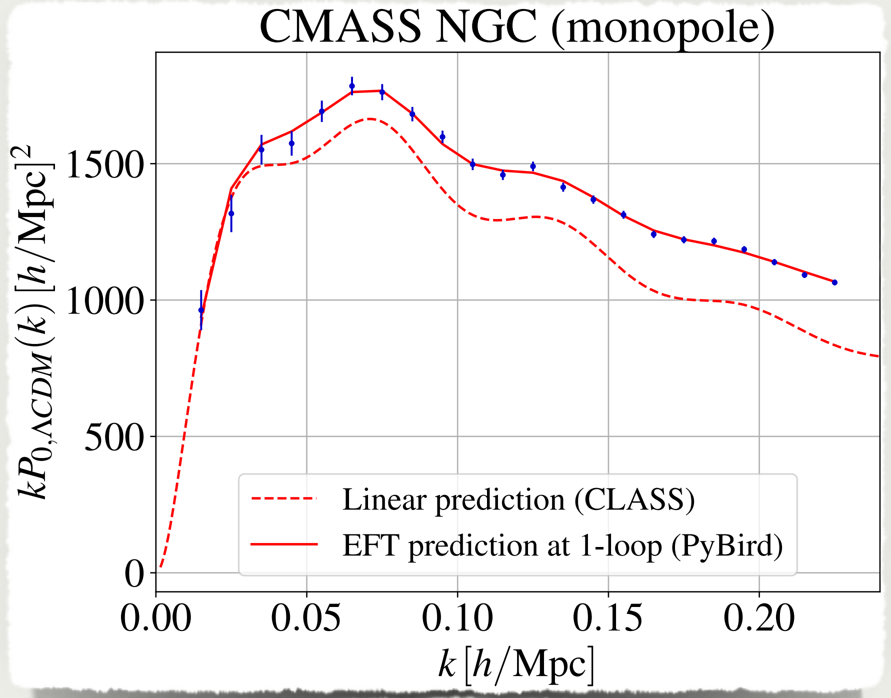


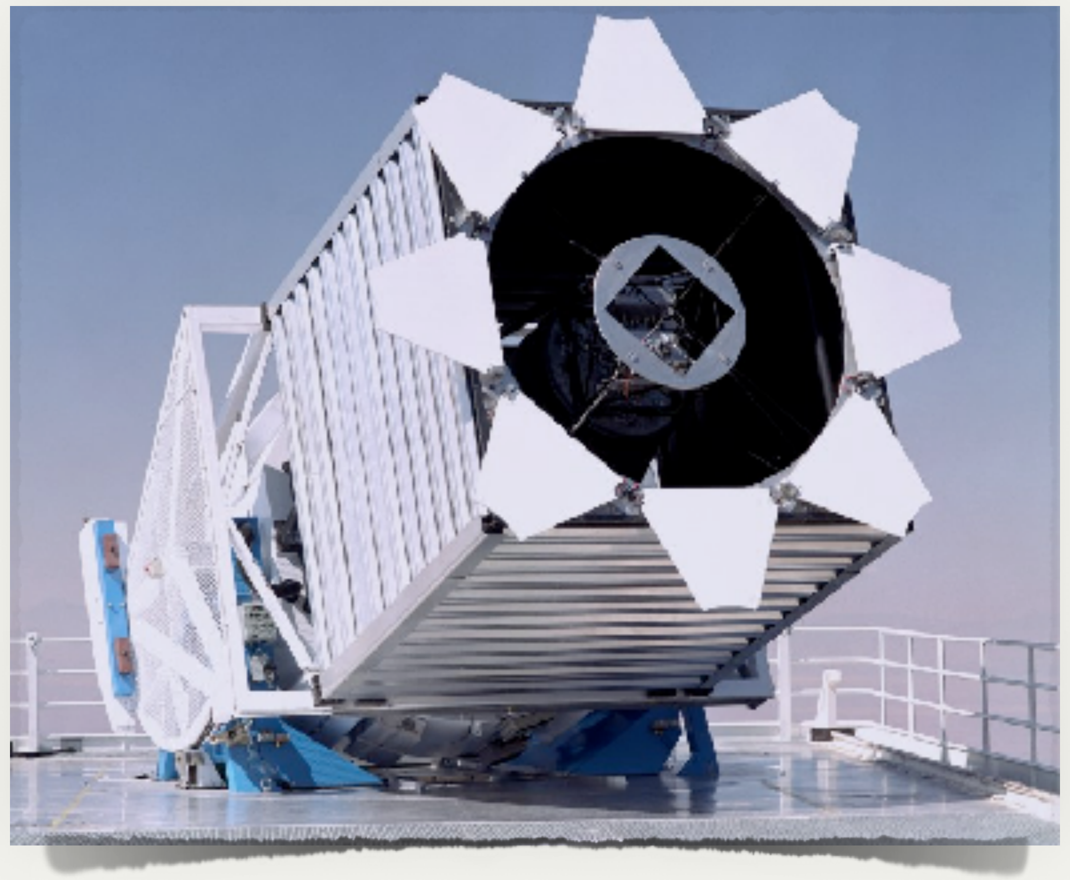


Part I: *How to obtain the most robust and optimised constraints on ΛCDM cosmological parameters from large-scale structure data?*

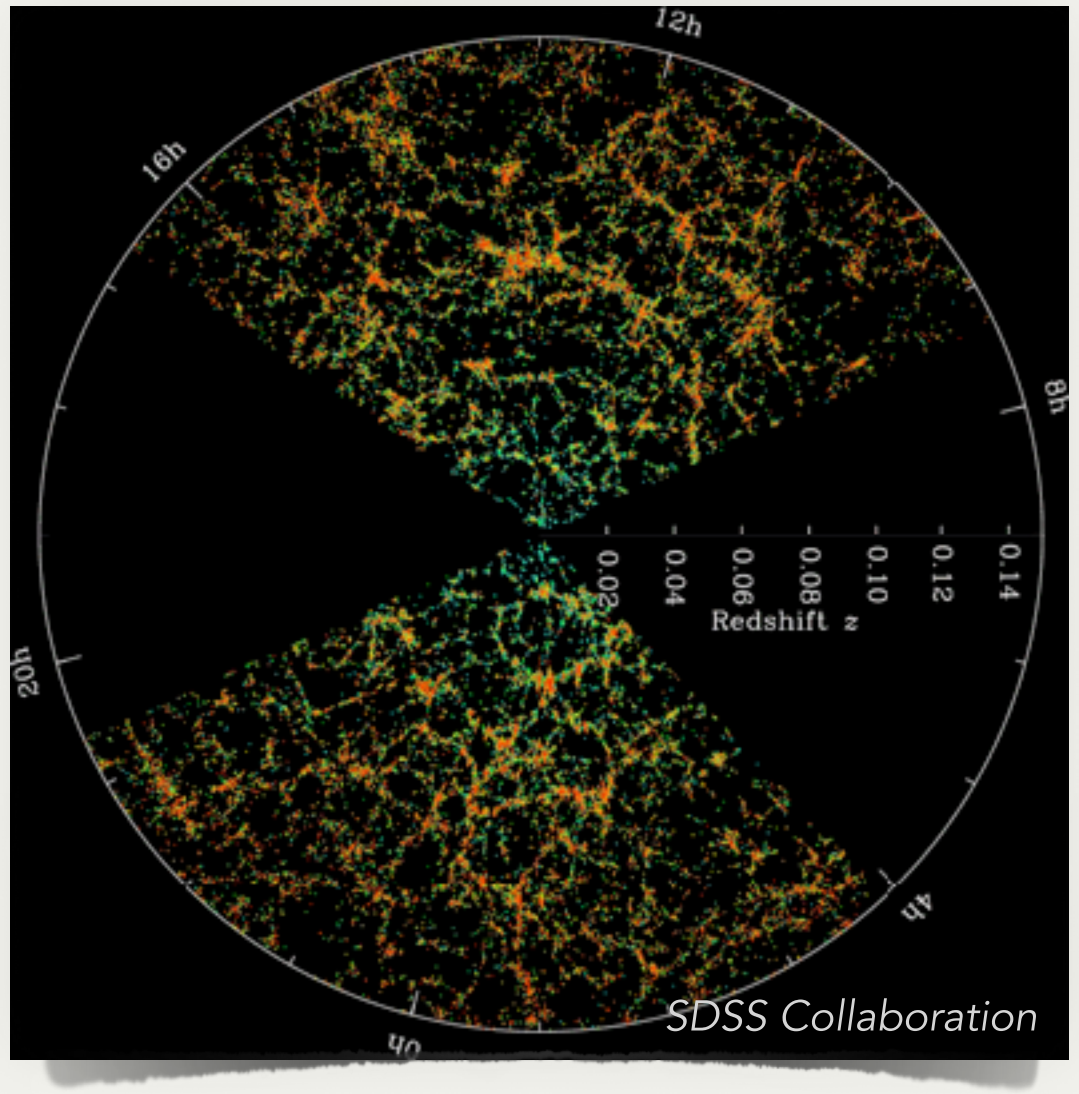
Part II: *What is the impact of large-scale structure data on the constraints on models beyond ΛCDM?*

Introduction: large-scale structure data

The Sloan Digital Sky Survey (SDSS)



www.sdss.org



SDSS

2000 - 2025

BOSS DR12 LRG (Luminous Red Galaxies)

Galaxies ($\sim$ 1.5 million) 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]

eBOSS DR16 QSO

Quasars ($\sim$ 300 000) selected in one redshift range:

$0.8 < z < 2.2$ ($z_{\rm eff} = 1.5$)

eBOSS Collaboration [arXiv:2007.08991]

I- EFTofLSS applied to (e)BOSS data and its consistency within the ΛCDM model

Based on:

- **TS** *et al.*, JCAP [arXiv:2210.14931]
  Cosmological inference from the EFTofLSS: the eBOSS QSO full-shape analysis

- **TS** *et al.*, Phys. Rev. D [arXiv:2208.05929]
  Consistency of effective field theory analyses of the BOSS power spectrum

- Emil B. Holm, Laura Herold, **TS**, *et al.*, Phys. Rev. D [arXiv:2208.05929]
  Bayesian and frequentist investigation of prior effects in EFTofLSS analyses of full-shape BOSS and eBOSS data

The Effective Field Theory of Large-Scale Structures (EFTofLSS)

Before EFTofLSS…

There are **two main** historical ways of using LSS data:

1. From the linear perturbation theory:

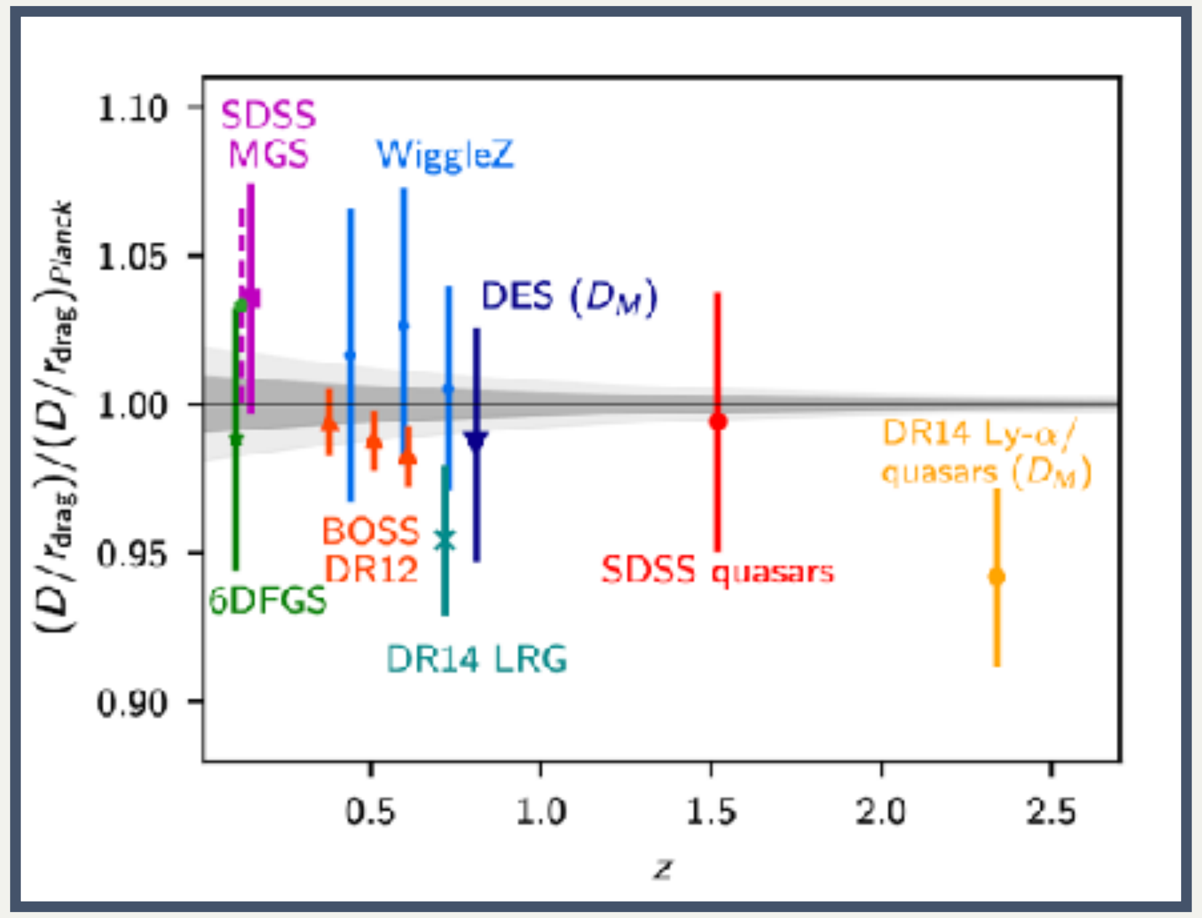
$$P_g(z,k,\mu) \simeq \left[b_1(z) + f\mu^2\right]^2 P_m(z,k)$$

Kaiser '87

b_1: bias parameter, f: growth factor and $\mu = \hat{z} \cdot \hat{k}$

2. BAO angles + Redshift Space Distortion (RSD) information: BAO/$f\sigma_8$

LSS collaborations conventionally use the second method



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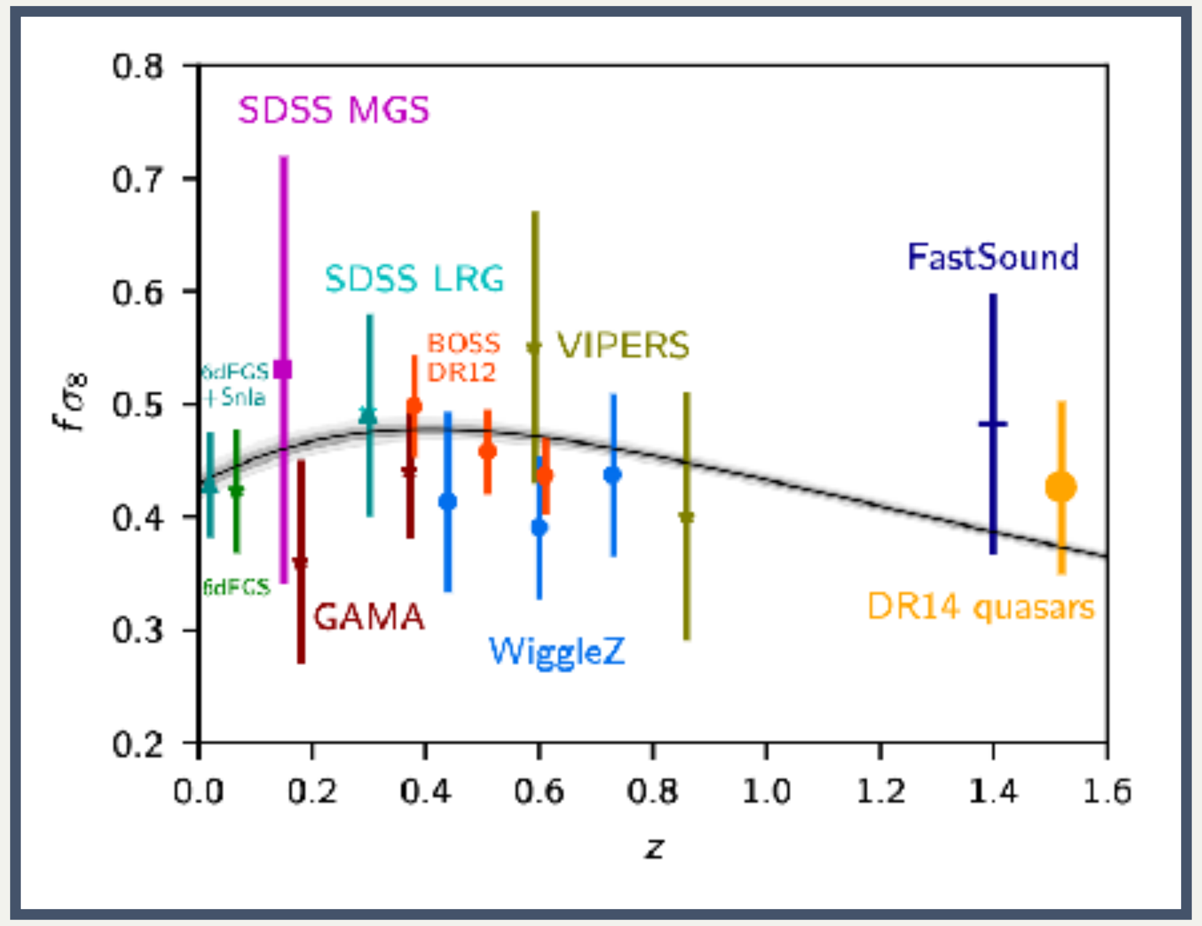

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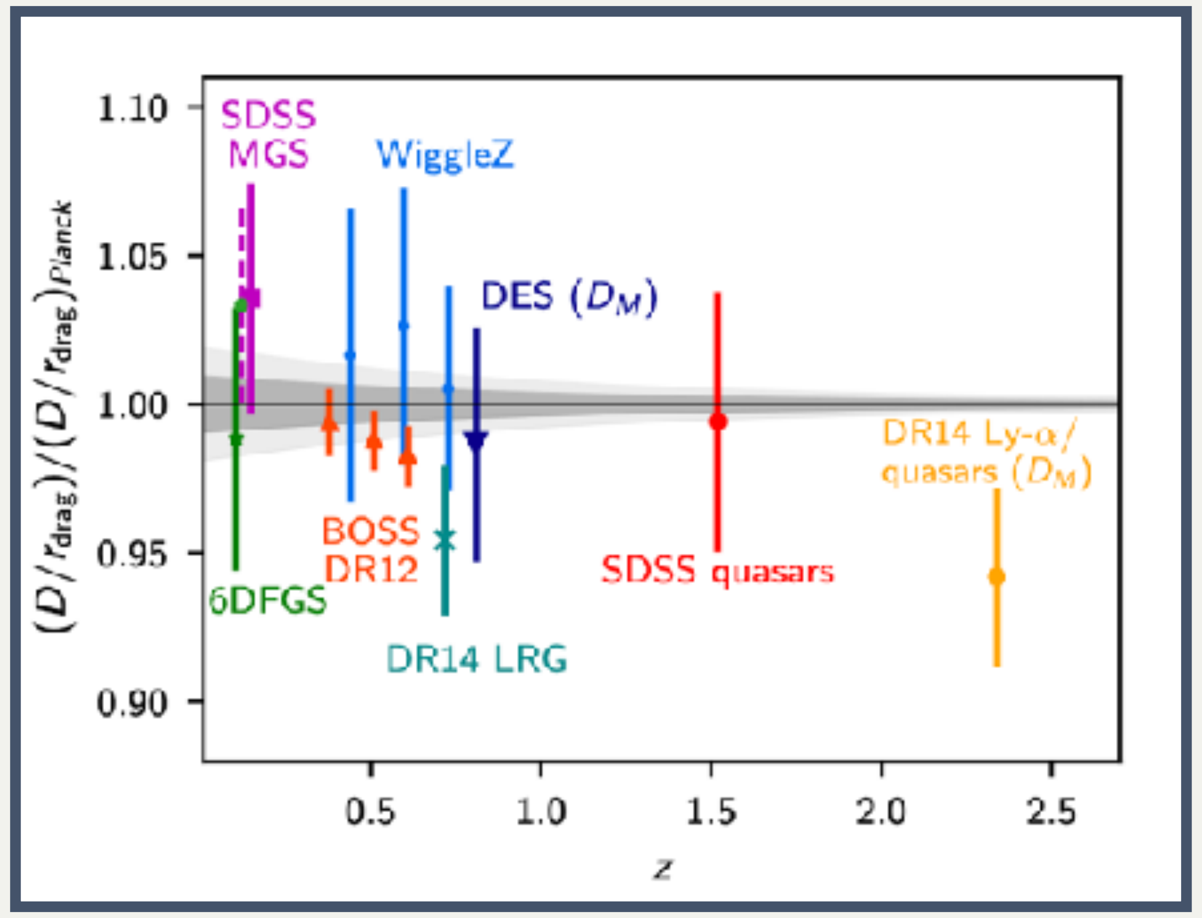

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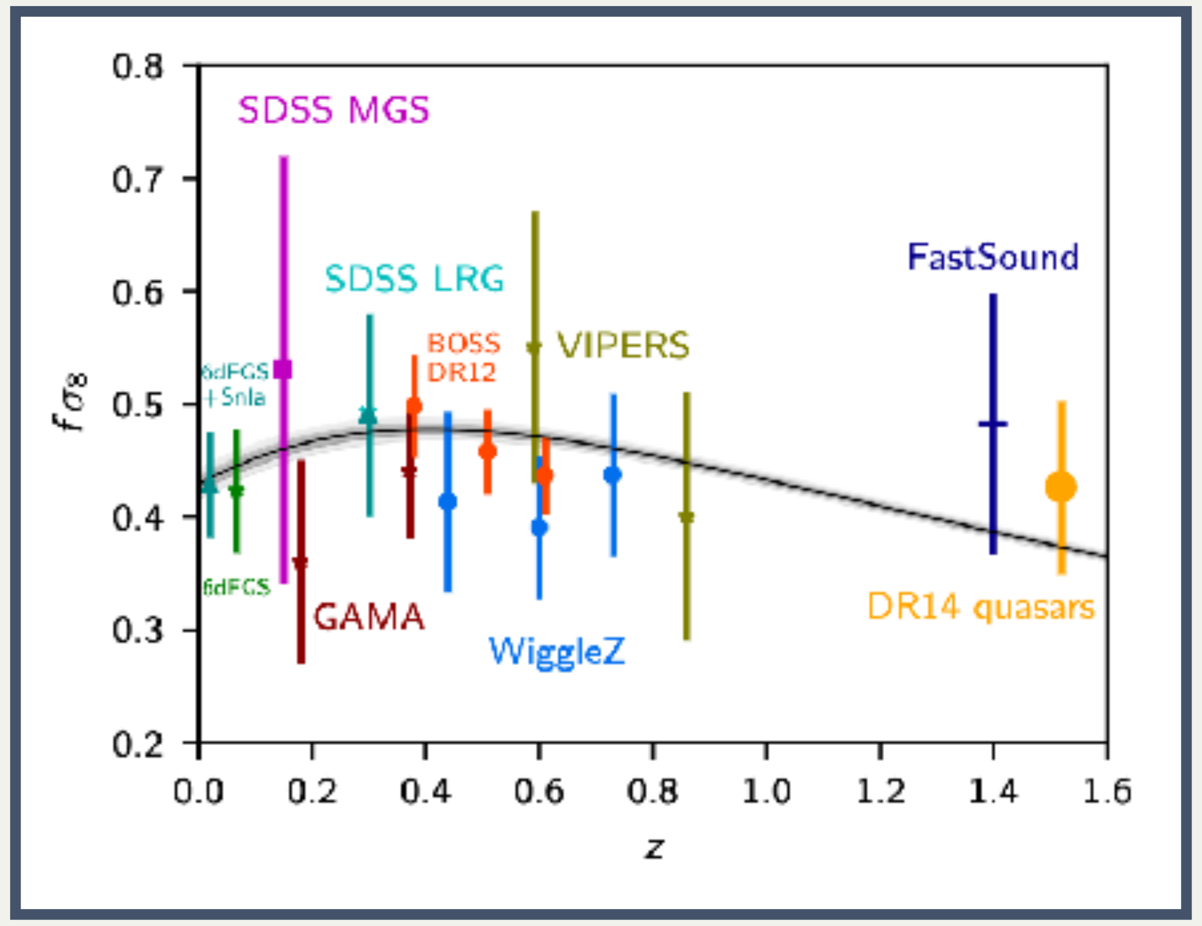

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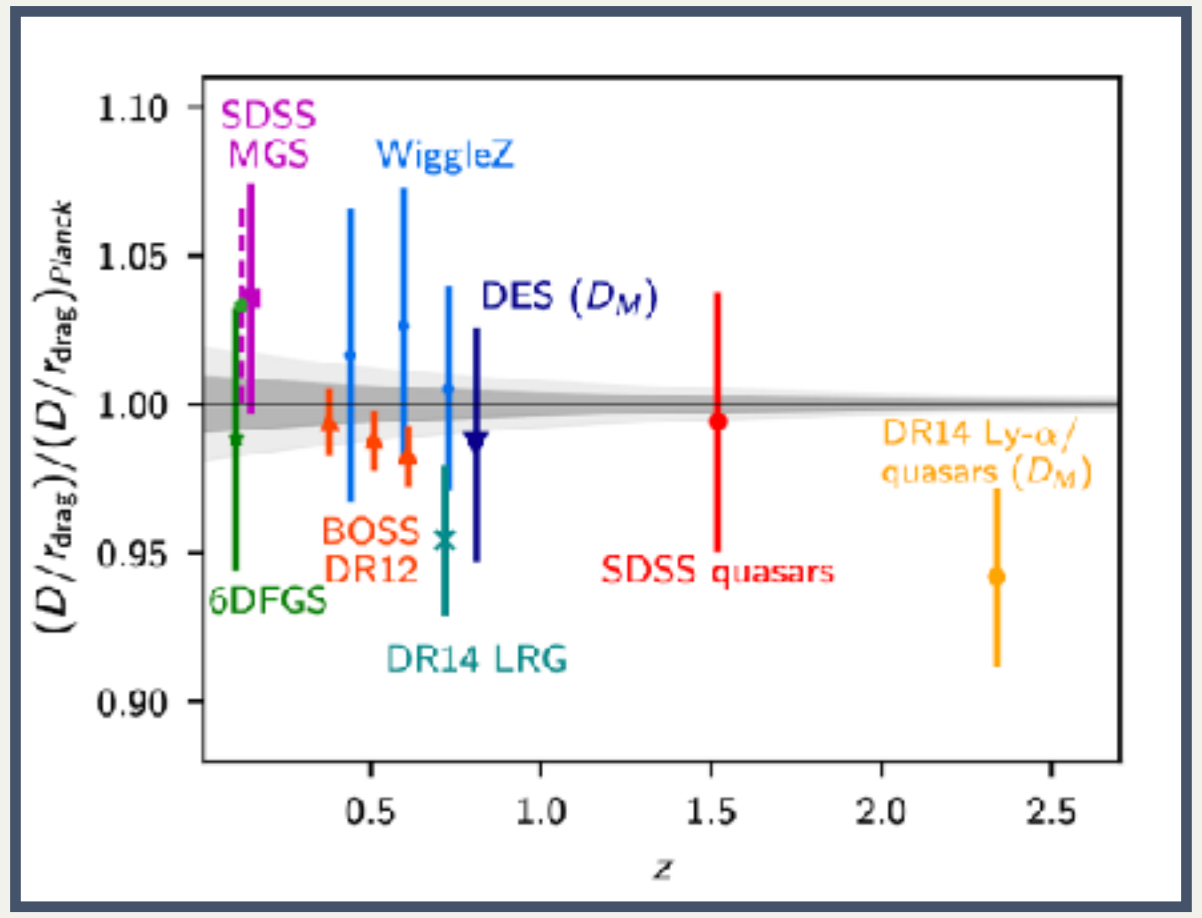

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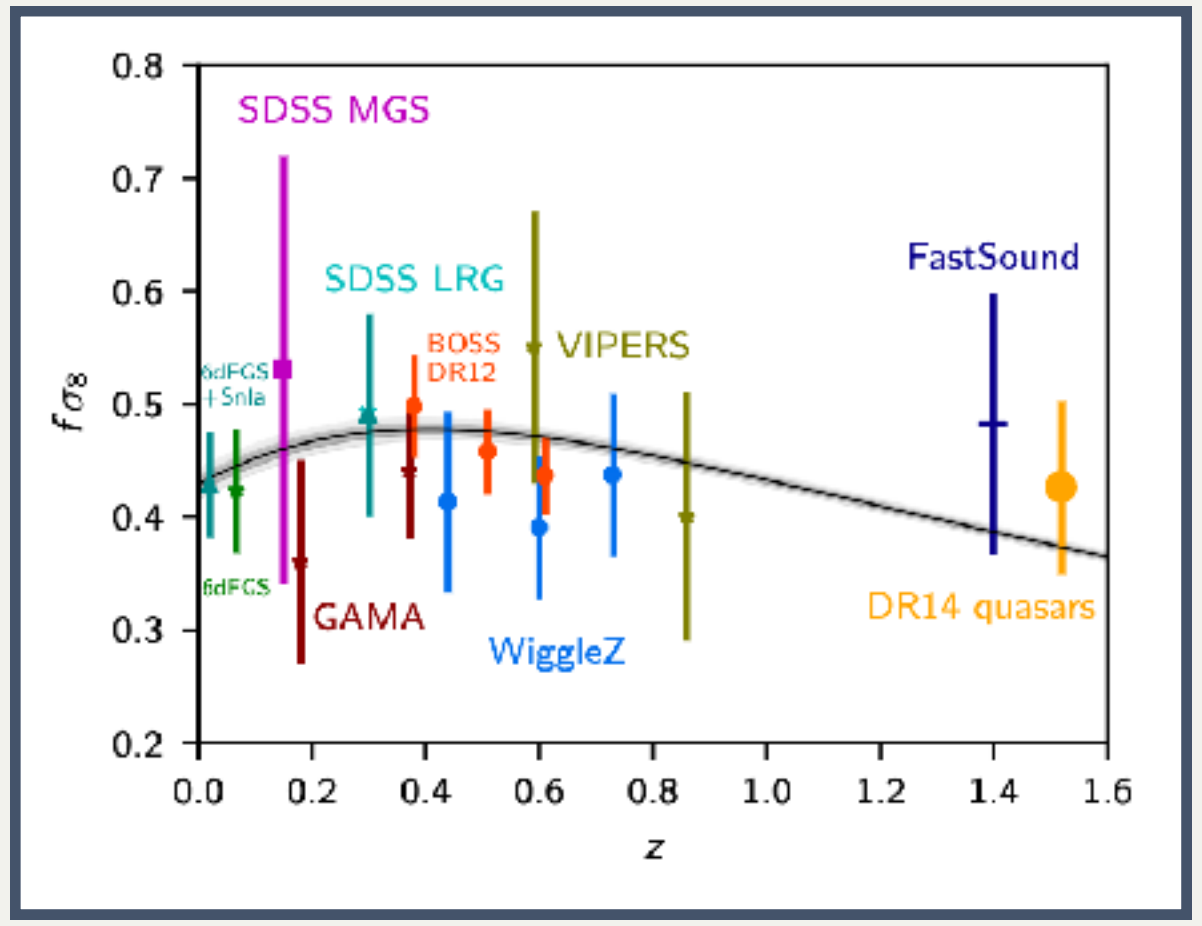

The effective field theory of large-scale structures (EFTofLSS)

Main ingredients

Carrasco++ [arXiv:1206.2926]

Baumann++ [arXiv:1004.2488]

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Solve cosmological equations only for **large-scale physics**

$$\delta(\boldsymbol{k}) = \delta_l(\boldsymbol{k}) + \delta_s(\boldsymbol{k}) \,,$$
$$\delta_l(\boldsymbol{k}) = \delta(\|\boldsymbol{k}\| < \Lambda^{-1})$$

EFTofLSS

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Dark matter: the Vlasov system

$$\dot{\delta}_l + \theta_l = -\delta\theta_l - v^j \partial_j \delta_l\,,$$
$$\dot{\theta}_l + aH\theta_l + \nabla^2\psi_l = -v^j\partial_j\theta_l - \partial_i v_l^j \cdot \partial_j v_l^i - \boldsymbol{\partial}_j\left(\frac{1}{\boldsymbol{\rho}_l}\boldsymbol{\partial}_i\left[\boldsymbol{\tau}^{ij}\right]_{\boldsymbol{\Lambda}}\right)$$

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EFTofLSS

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EFTofLSS

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$$\vec{x} \to \vec{x} + \vec{a}$$
$$\vec{v} \to \vec{v} + \partial_t \vec{a}$$

Symmetries: Galilean invariance

Carrasco++ [arXiv:1206.2926]

Baumann++ [arXiv:1004.2488]

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

Main steps

Step by Step…

1- **Solve** dark matter equations **perturbatively**: $\delta_l(\vec{x},t) = \delta_l^{(1)}(\vec{x},t) + \delta_l^{(2)}(\vec{x},t) + \ldots + \delta_l^{(n)}(\vec{x},t)$ *Bernardeau++ '01*

2- Obtain the **mildly non-linear matter power spectrum**:

Carrasco++ [arXiv:1206.2926]

$$P_m(k,\tau) = P_{11}(k,\tau) + P_{22}^{\Lambda}(k,\tau) + 2P_{13}^{\Lambda}(k,\tau) + 2P_{c^2_{\text{comb}}}^{\Lambda}(k,\tau)$$

Senatore [arXiv:1406.7843]

Mirbabayi++ [arXiv:1412.5169]

3- Write down **all possible operators in the galaxy bias expansion**: $\delta_g = b_1\,\delta_l^{(1)} + b_2\,\delta_l^{(2)} + R_*^2\,\partial^2\delta_l^{(1)} + \ldots$

4- Take into account the **redshift-space distortion** (RSD) effect (to subtract the contribution of the peculiar velocity of the galaxies to the cosmological redshift) *Senatore++ [arXiv:1409.1225]*

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Tree-level — One-loop level — Counterterm

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Galaxy power spectrum

The **galaxy power spectrum** in the EFTofLSS framework:

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

We go from 1 to 10 free parameters

$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2Z_1(\mu)P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm R}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm R}^2}\right)$$
$$+ 2\int \frac{d^3q}{(2\pi)^3}\, Z_2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}, \mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)P_{11}(q) + 6Z_1(\mu)P_{11}(k)\int \frac{d^3q}{(2\pi)^3}\, Z_3(\boldsymbol{q}, -\boldsymbol{q}, \boldsymbol{k}, \mu)P_{11}(q)$$
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Carrasco++ [arXiv:1206.2926] ; Baumann++ [arXiv:1004.2488]
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2 renormalization scales

(green circle) Renormalization scale controlling the **spatial derivative expansion**, given by the typical size of a **virialized halo**

(red circle) Renormalization scale of the **velocity products** appearing in the redshift-space expansion

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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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Carrasco++ [arXiv:1206.2926] ; Baumann++ [arXiv:1004.2488]
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10 EFT 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

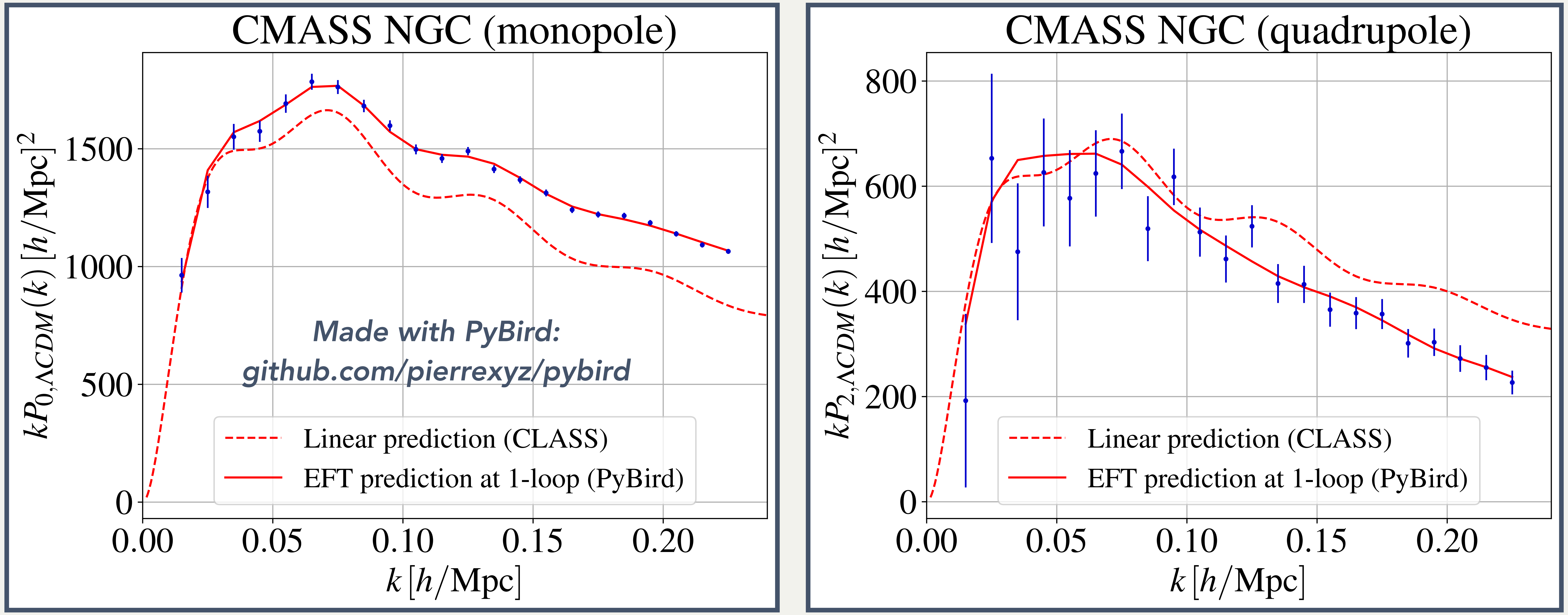
The effective field theory of large-scale structures (EFTofLSS)

Application to BOSS data

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** ($\ell = 2$)



D'Amico++ [arXiv:1909.05271] ; Colas++ [arXiv:1909.07951]
Philcox++ [arXiv:2002.04035] ; Ivanov++ [arXiv:1909.05277]

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

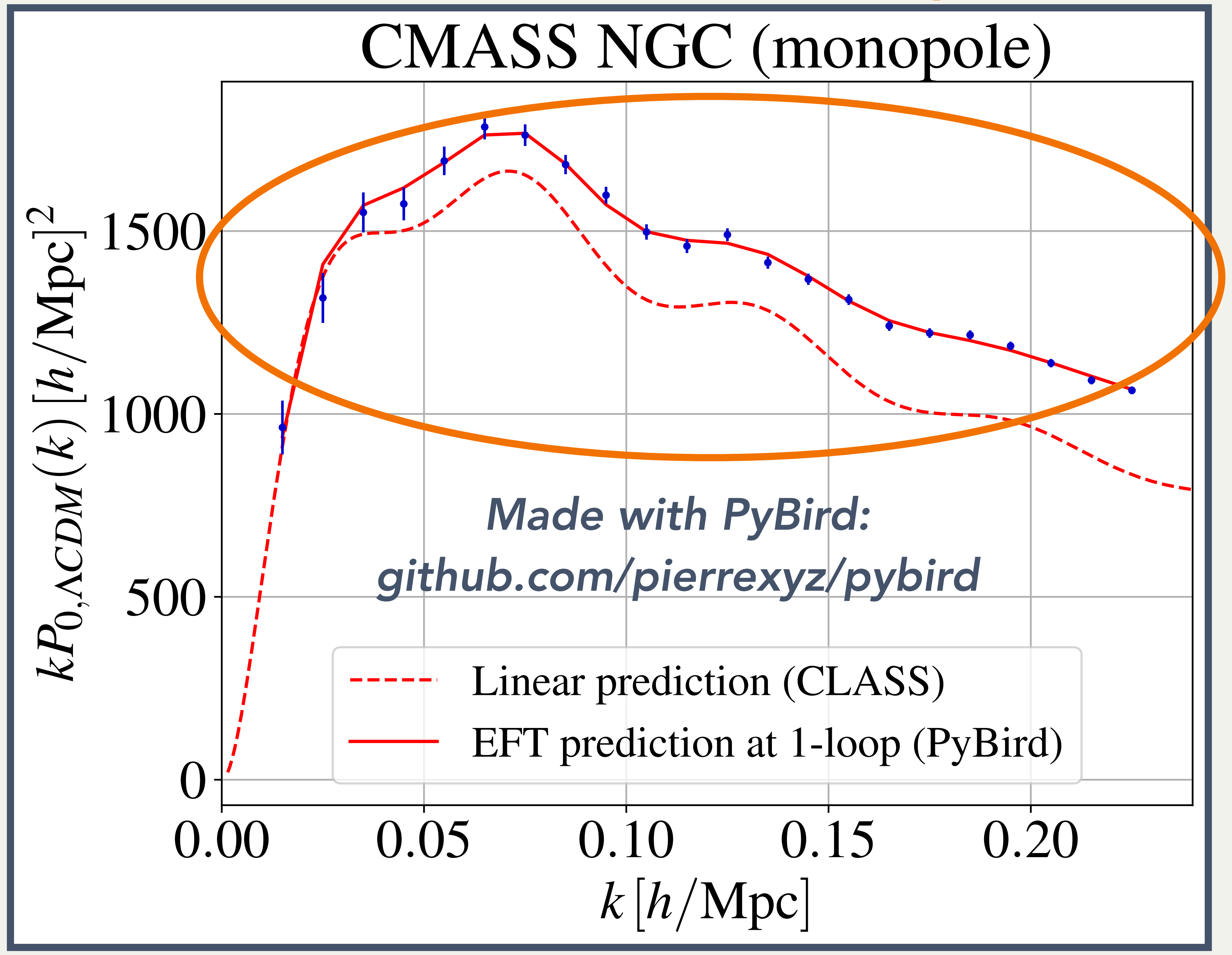
Application to BOSS data

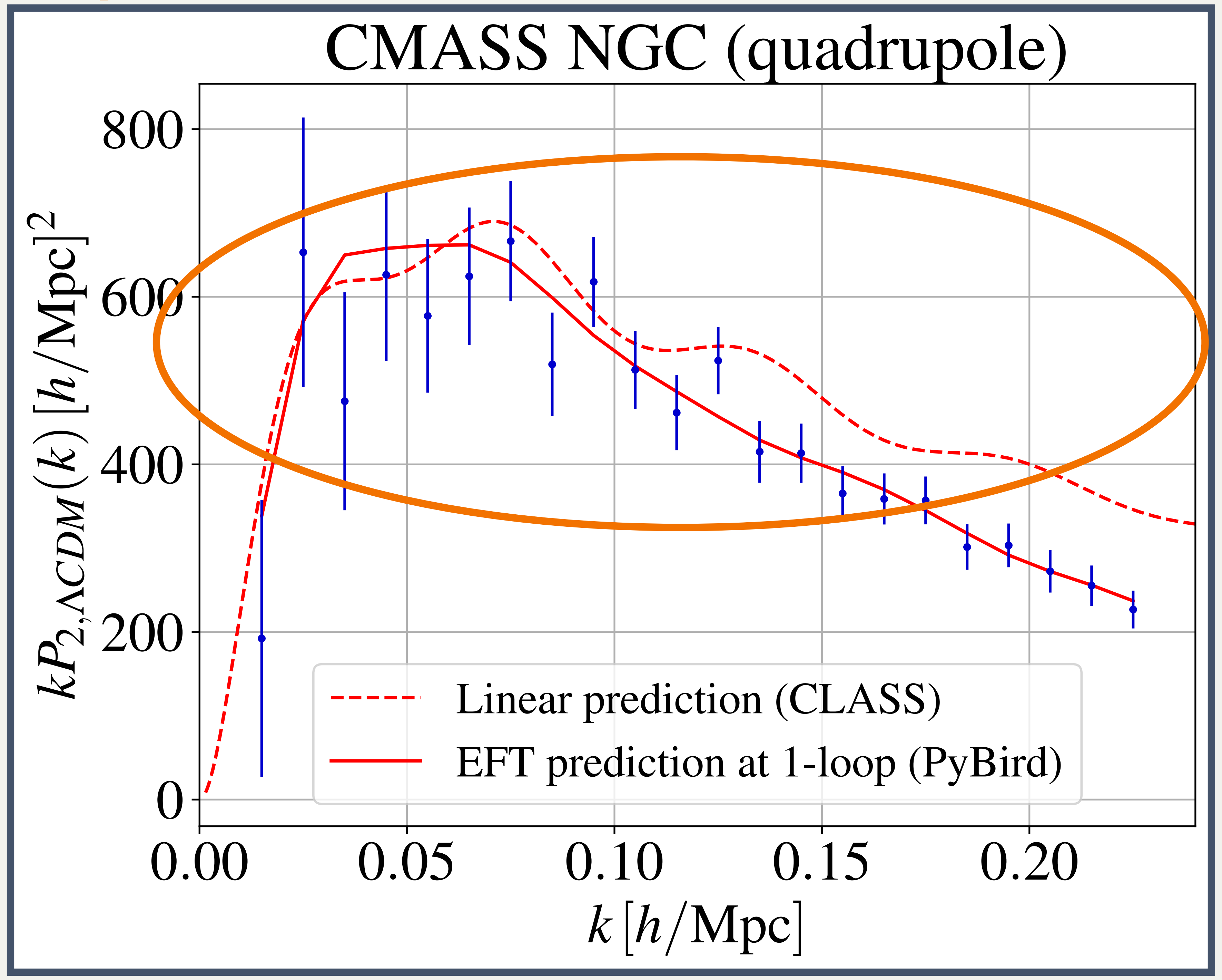
Multipoles of the galaxy power spectrum, obtained through a **Legendre** polynomials ($\mathscr{L}_\ell$) decomposition:

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

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

Improvement in precision!





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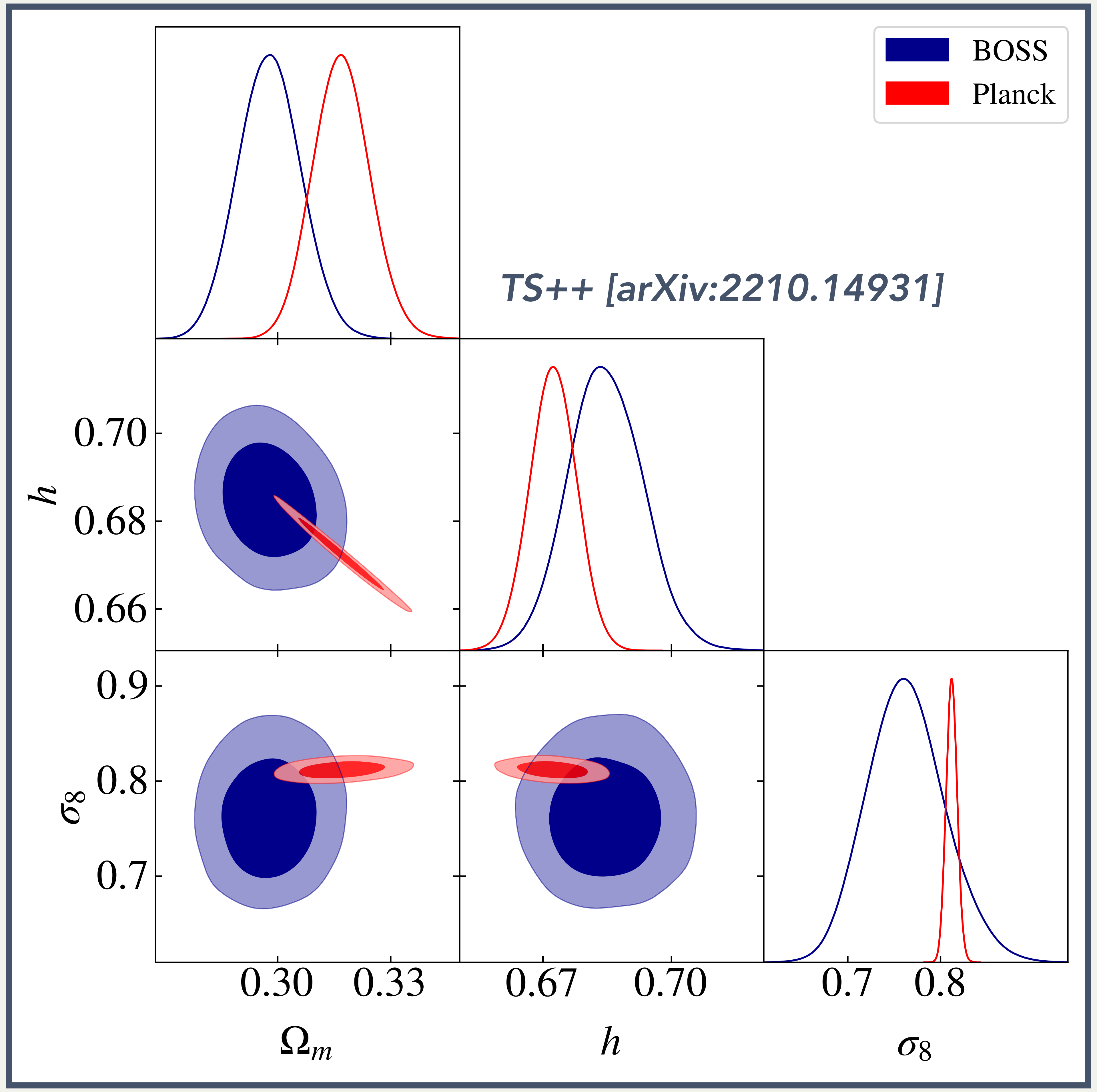

The EFTofLSS analysis of BOSS data allows to determine Ω_m and h at a **precision only** $10\,\%$ **and** $60\,\%$ worse than Planck

This is ~ 5.4 (for Ω_m) and ~ 3.2 (for h) times better than the BAO/$f\sigma_8$ analysis

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

On the consistency of EFTofLSS

Presentation of the problem

There are **several codes** in the literature with **different parametrizations**:

→ ***CLASS PT*** with the **EC** parametrization *Chudaykin++ [arXiv:2004.10607]*

→ ***PyBird*** with the **WC** parametrization *D'Amico++ [arXiv:2003.07956]*

(+ **Velocileptors** + **CLASS-OneLoop**)

Chen++ [arXiv:2005.00523] ; Linde++ [arXiv:2402.09778]

→ these codes use **different sets of priors** on EFT parameters

D'Amico++ [arXiv:1909.05271]
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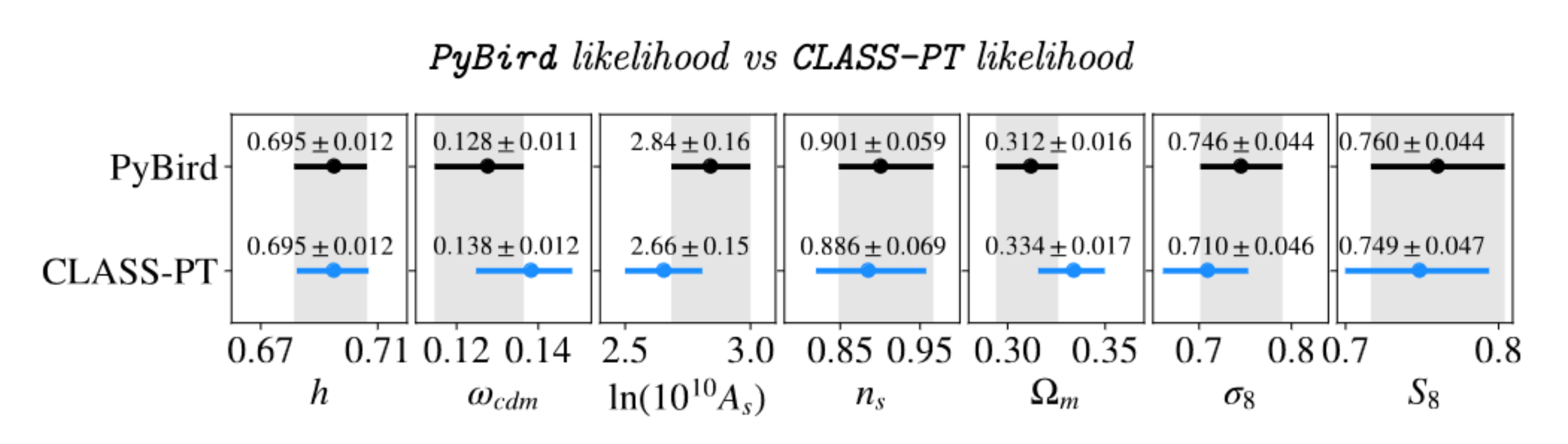

TS++ [arXiv:2208.05929]

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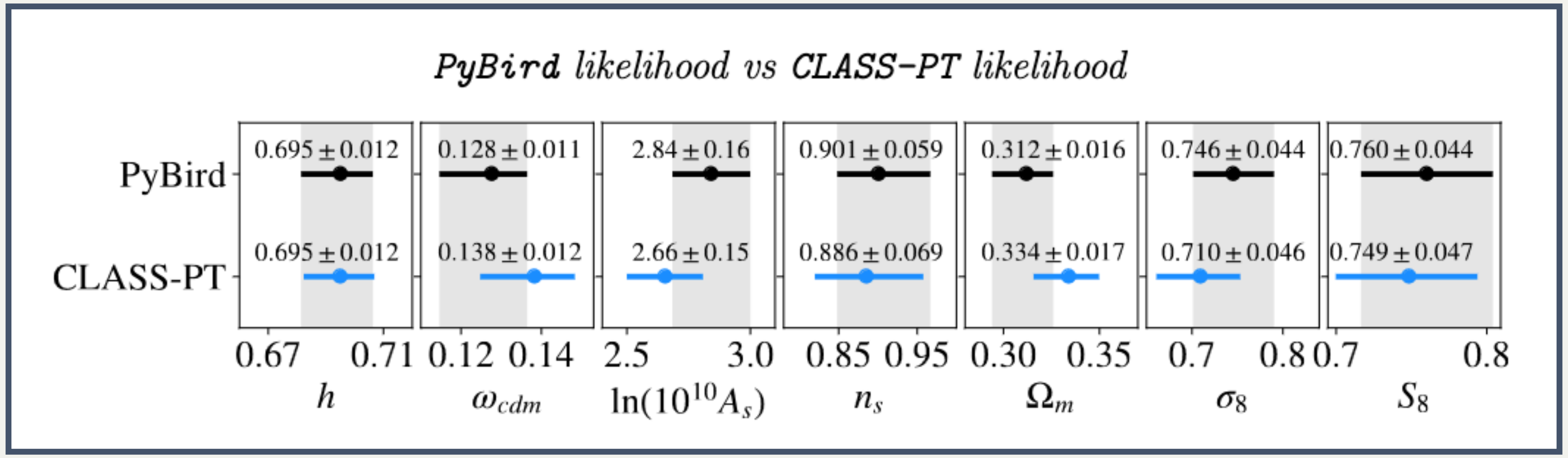
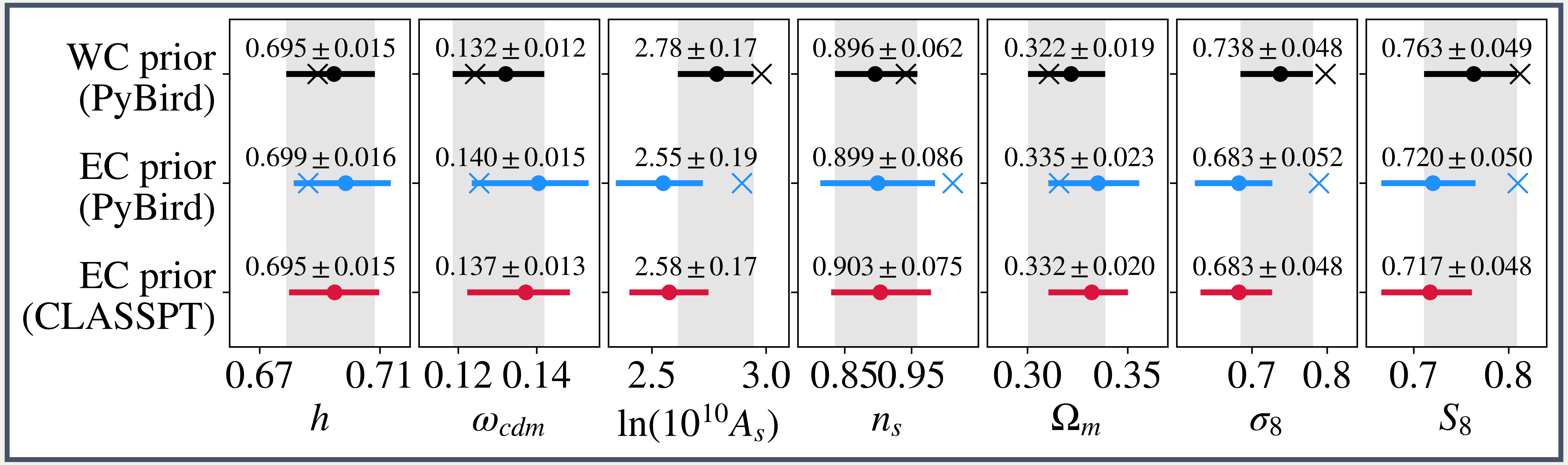


TS++ [arXiv:2208.05929]

Data, theoretical **parametrizations** and **codes** are supposed to be **equivalent**: **what is going on?**

On the consistency of EFTofLSS

The EFT prior issue



TS++ [arXiv:2208.05929]

On the consistency of EFTofLSS

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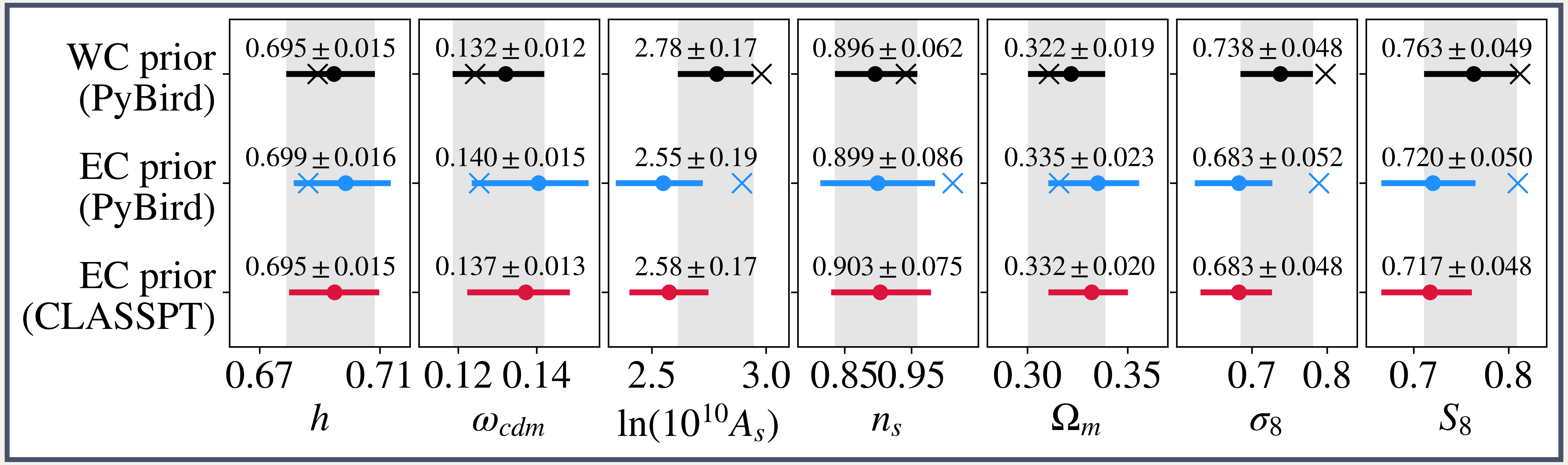


TS++ [arXiv:2208.05929]

Prior effects

→ ***The prior weight effect***: if the region allowed by the prior is far from the true value of a parameter, then the posterior and bestfit will be shifted from the true value

→ ***The prior volume effect***: a posterior depends on the volume enclosed by the priors $\Longrightarrow$ large parameter regions are emphasized compared to smaller regions

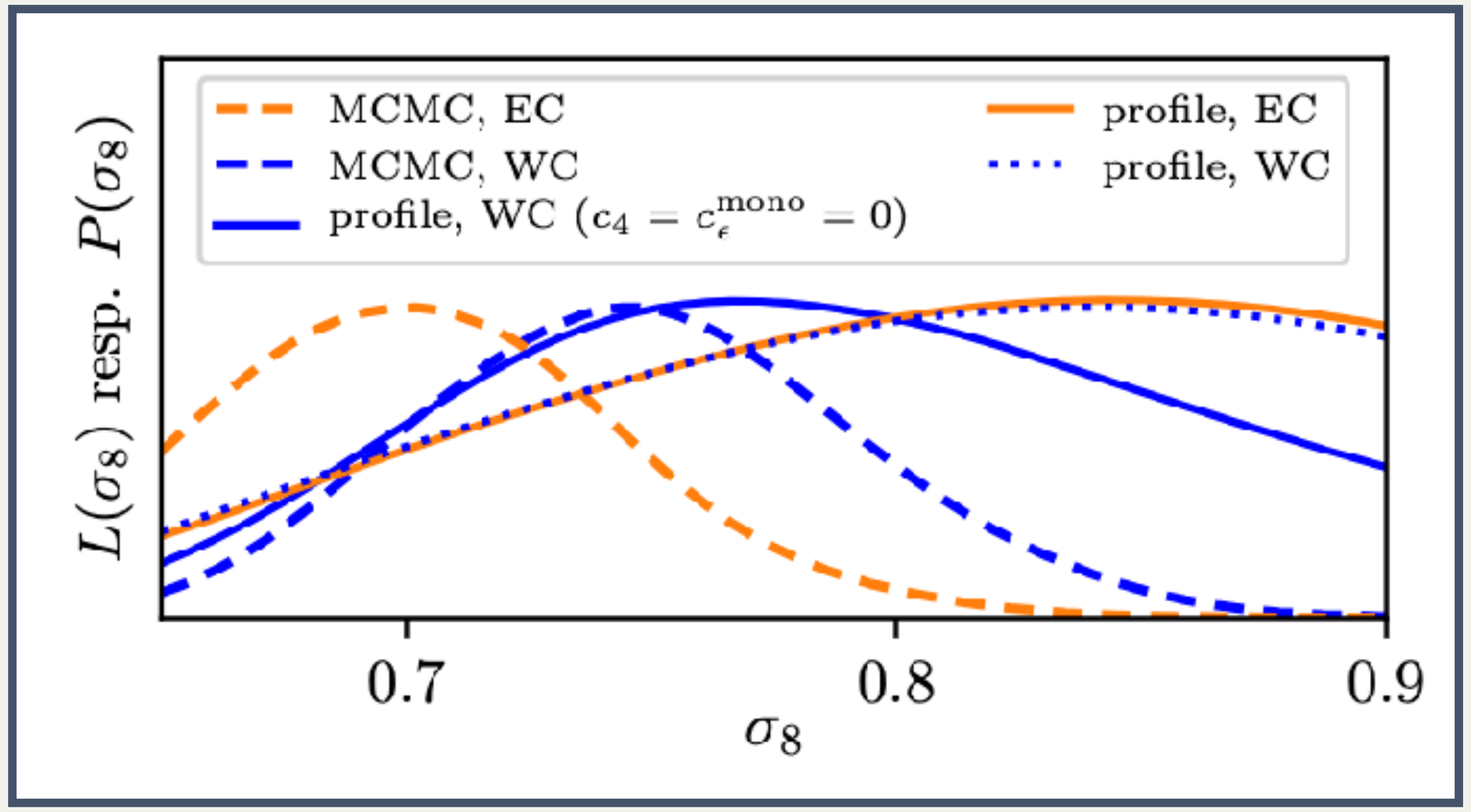
Bayes' theorem:
$P \propto \mathcal{L} \times p$

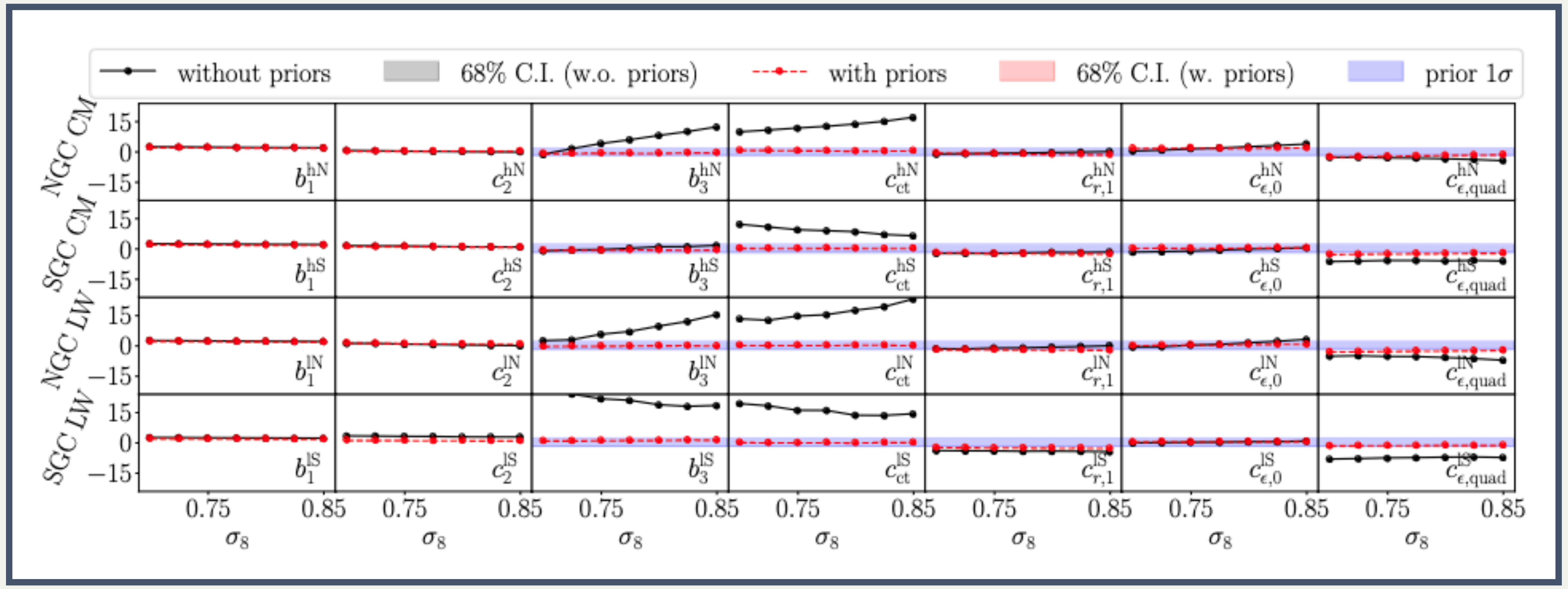
On the consistency of EFTofLSS

Profile likelihood

Advantage: frequentist analysis is **independent of priors** and therefore of projection effects

Disadvantage: the data prefers several EFT parameters to take on **extreme values**, possibly breaking the perturbative nature of the theory





Brinch, Herold, TS++ [arXiv:2309.04468]

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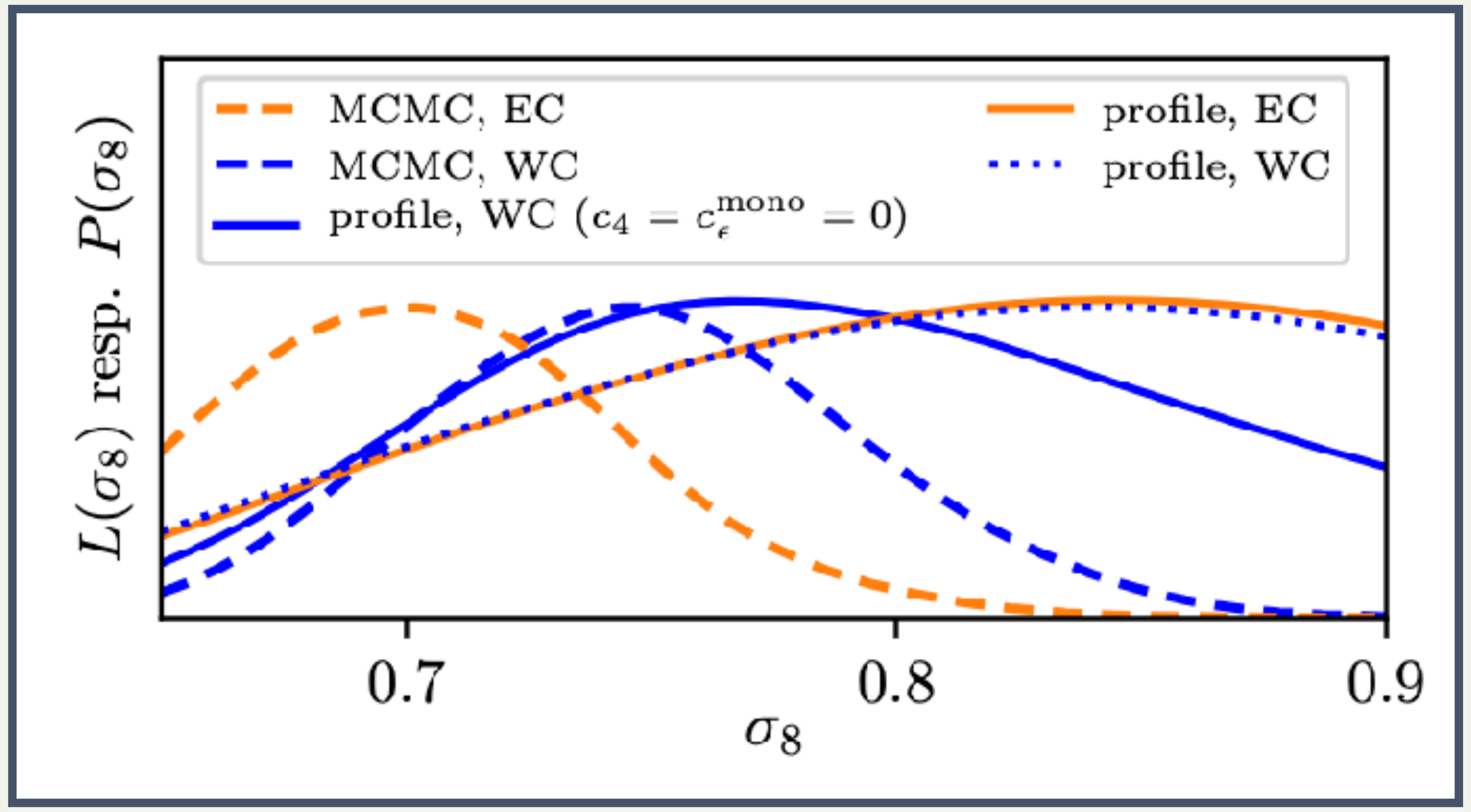
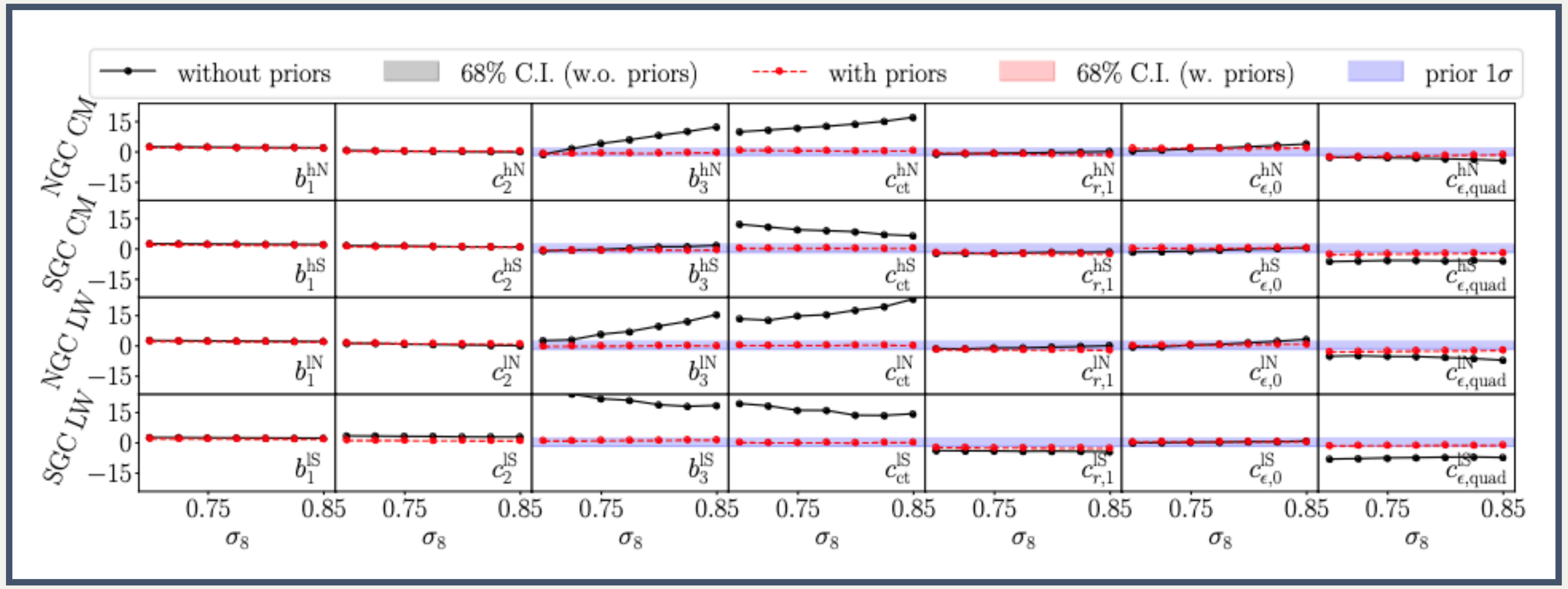


The low value of σ_8 is due to prior effects!



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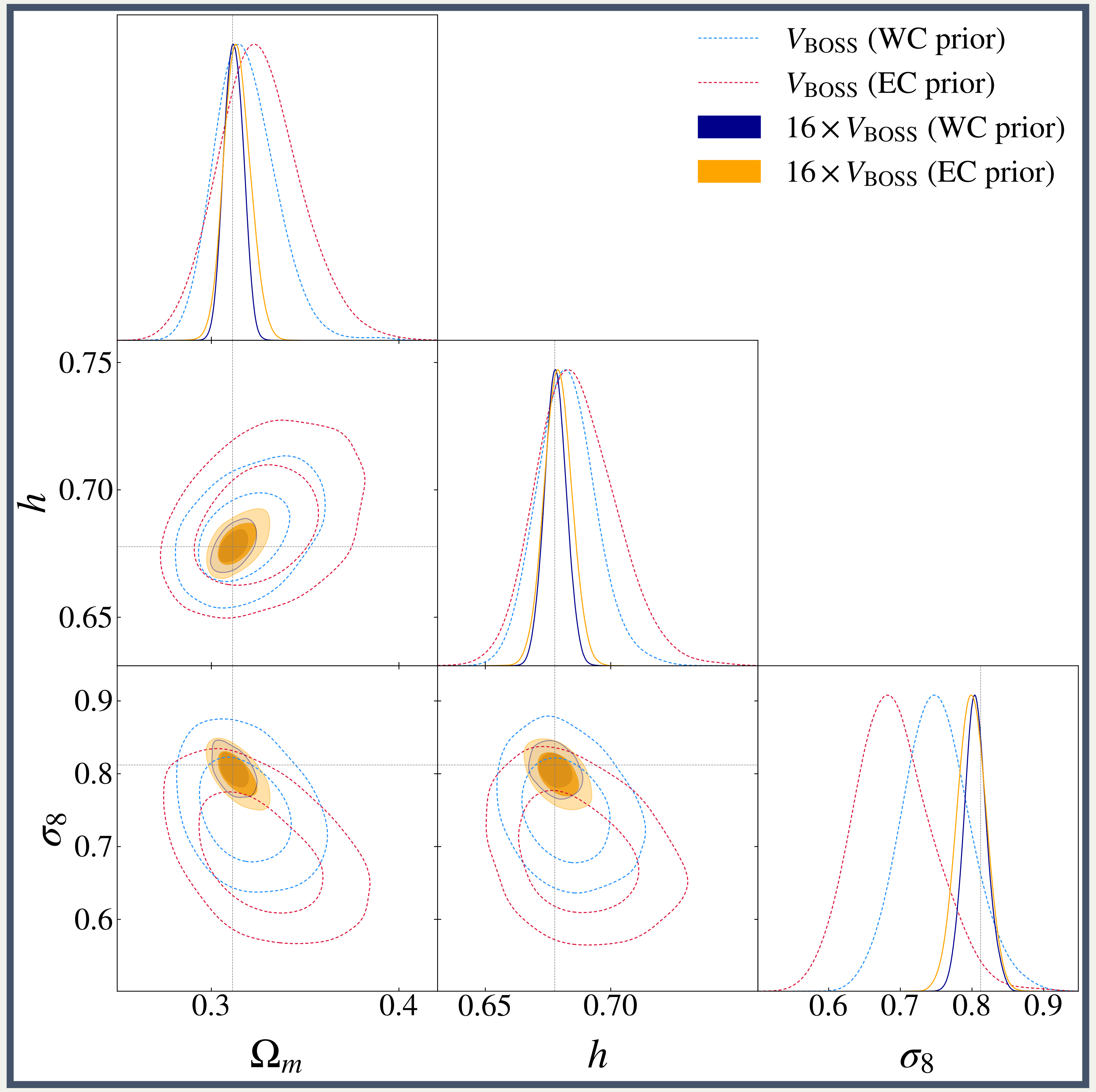
On the consistency of EFTofLSS

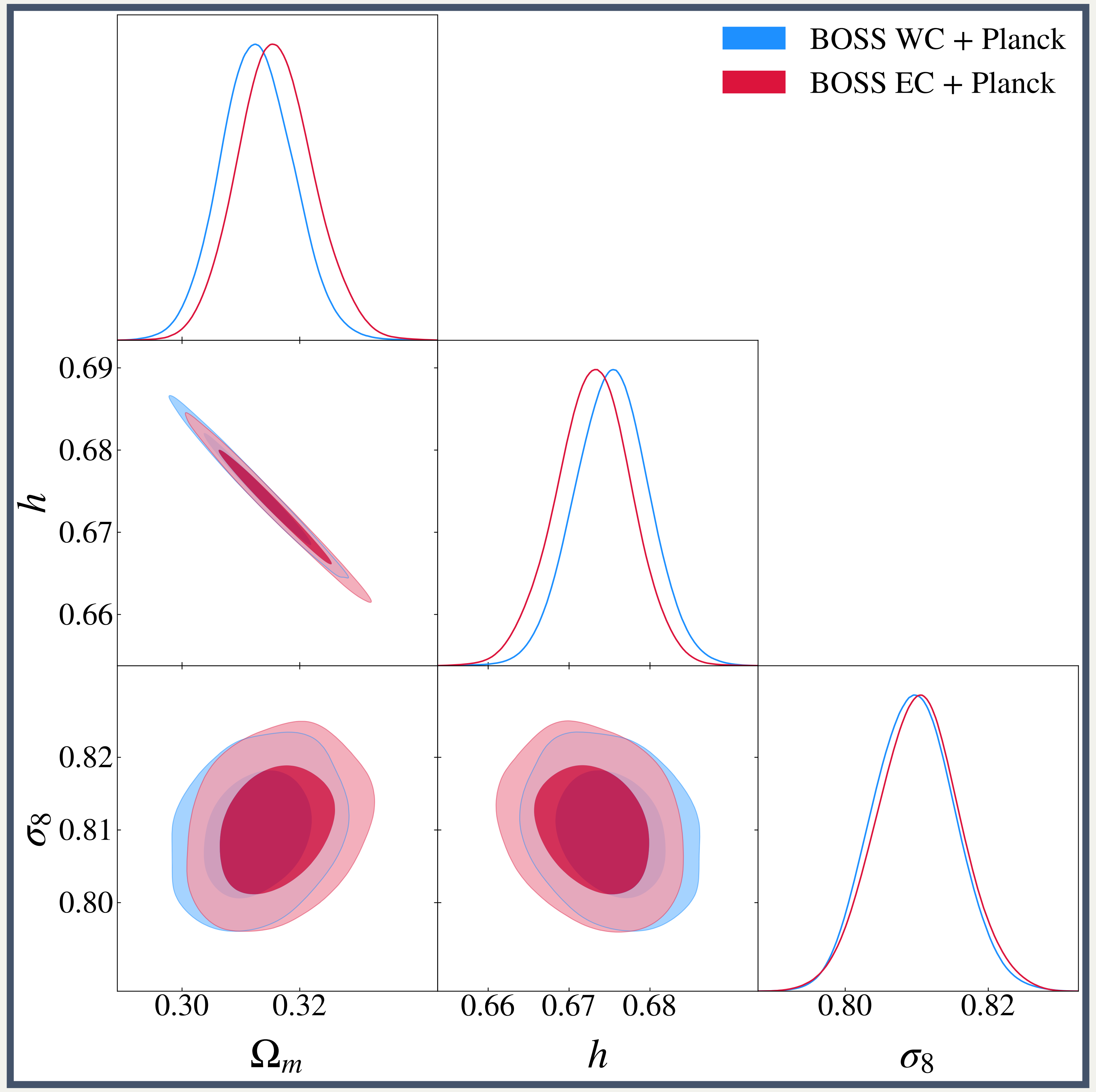
How to overcome this problem?



We find good consistency for:

- a larger volume of data (future experiments like DESI or EUCLID)
- a combination with Planck data

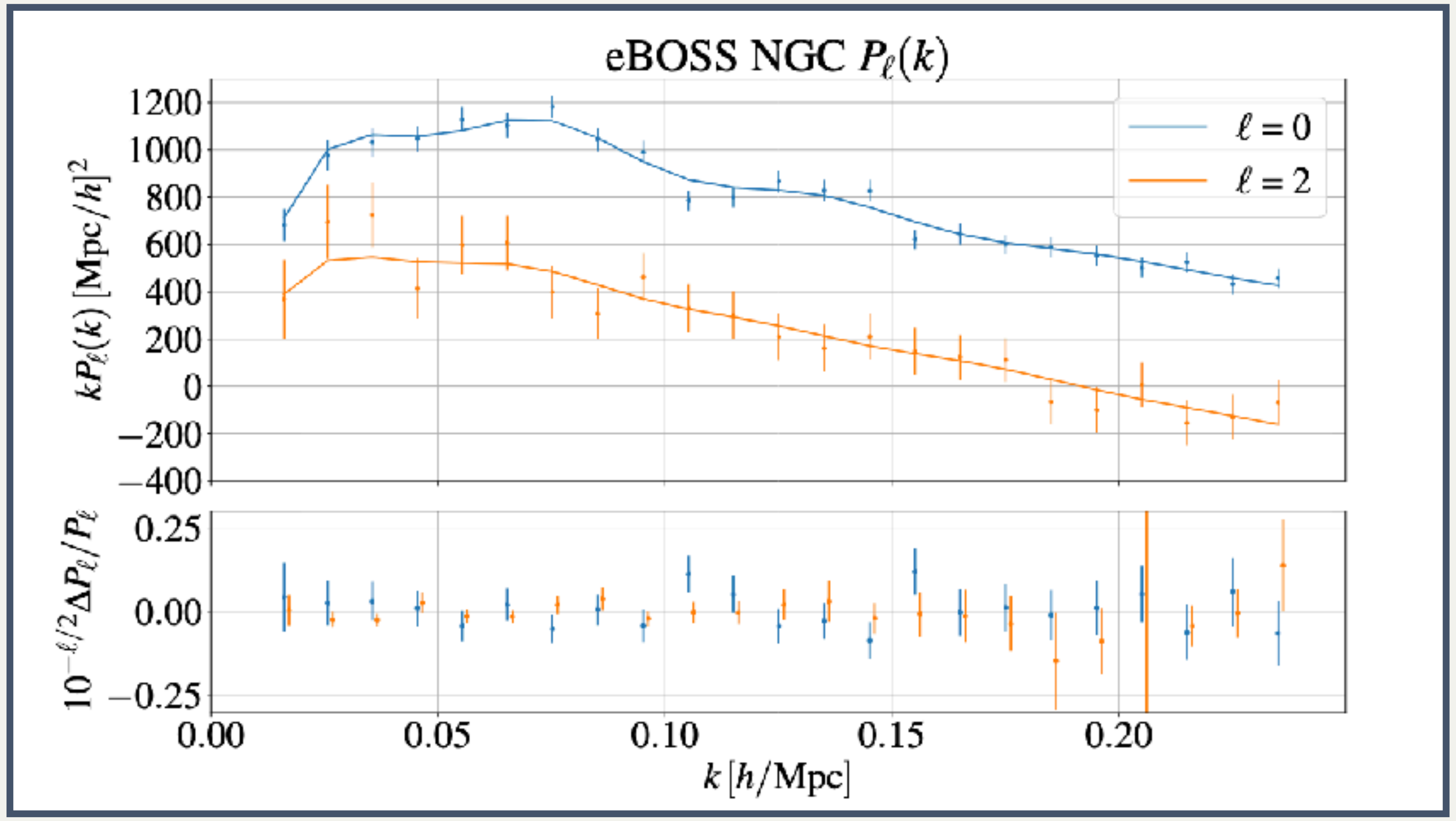
TS++ [arXiv:2208.05929]

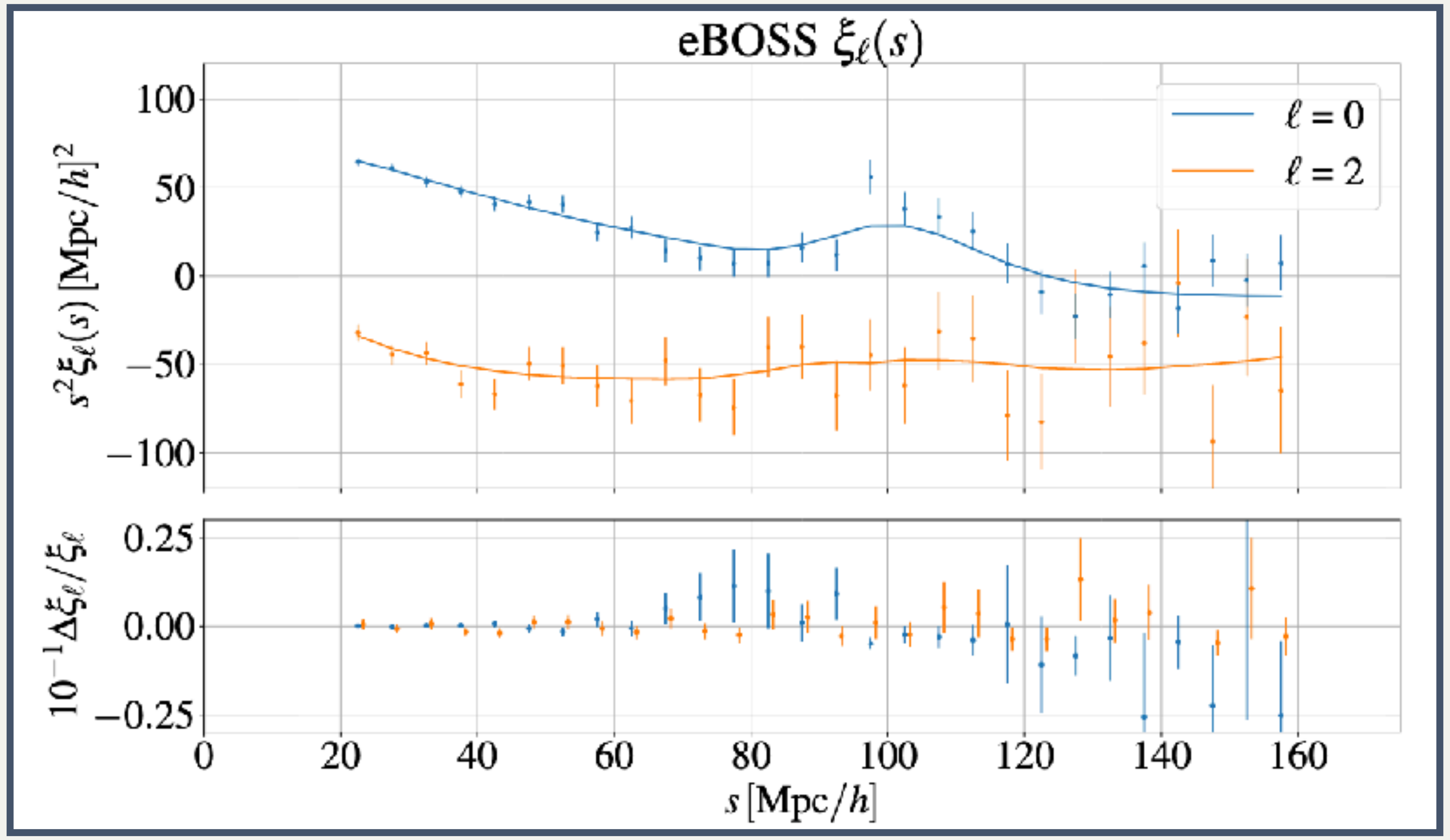


EFTofLSS applied to eBOSS QSO data

- **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]

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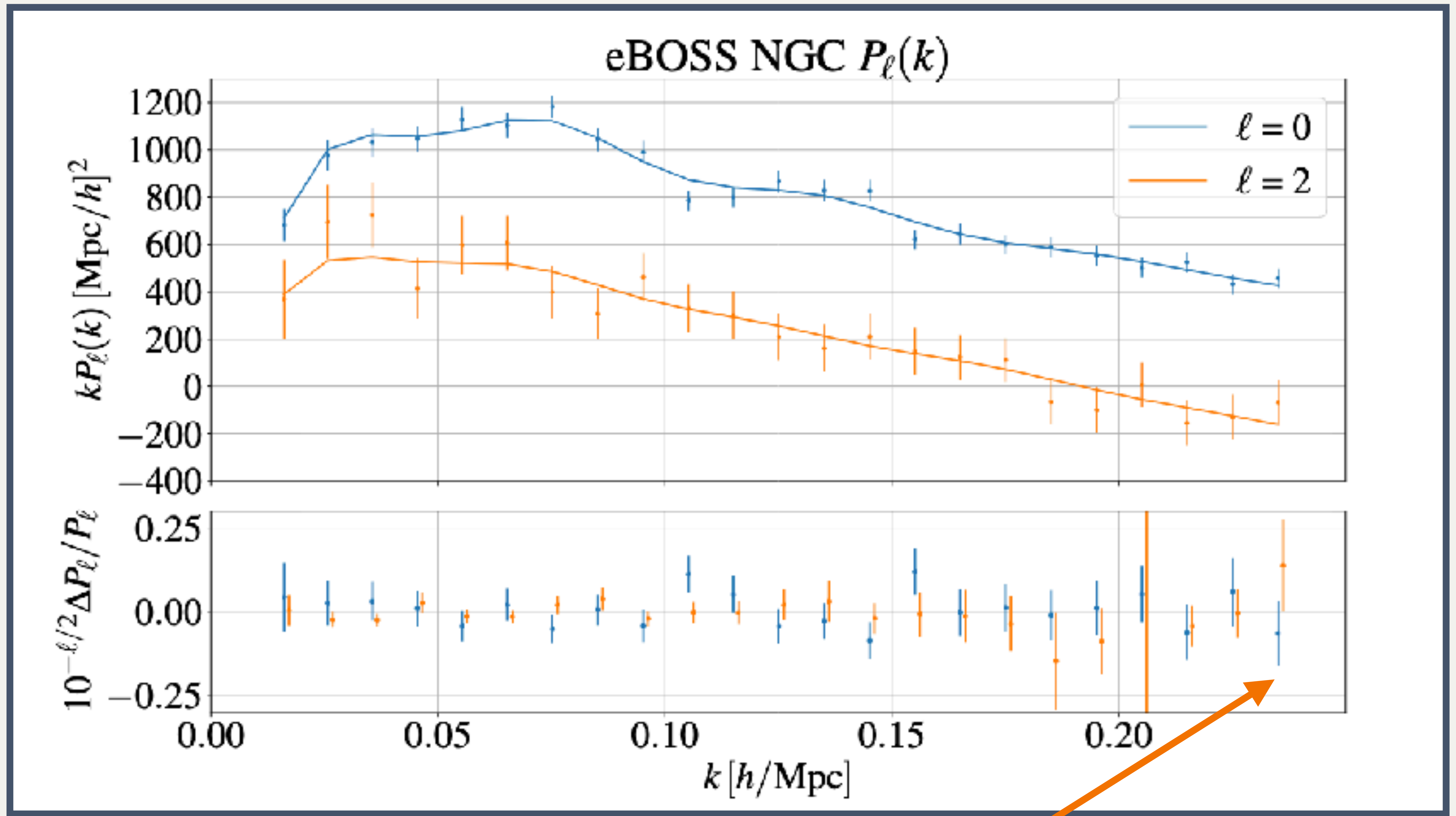

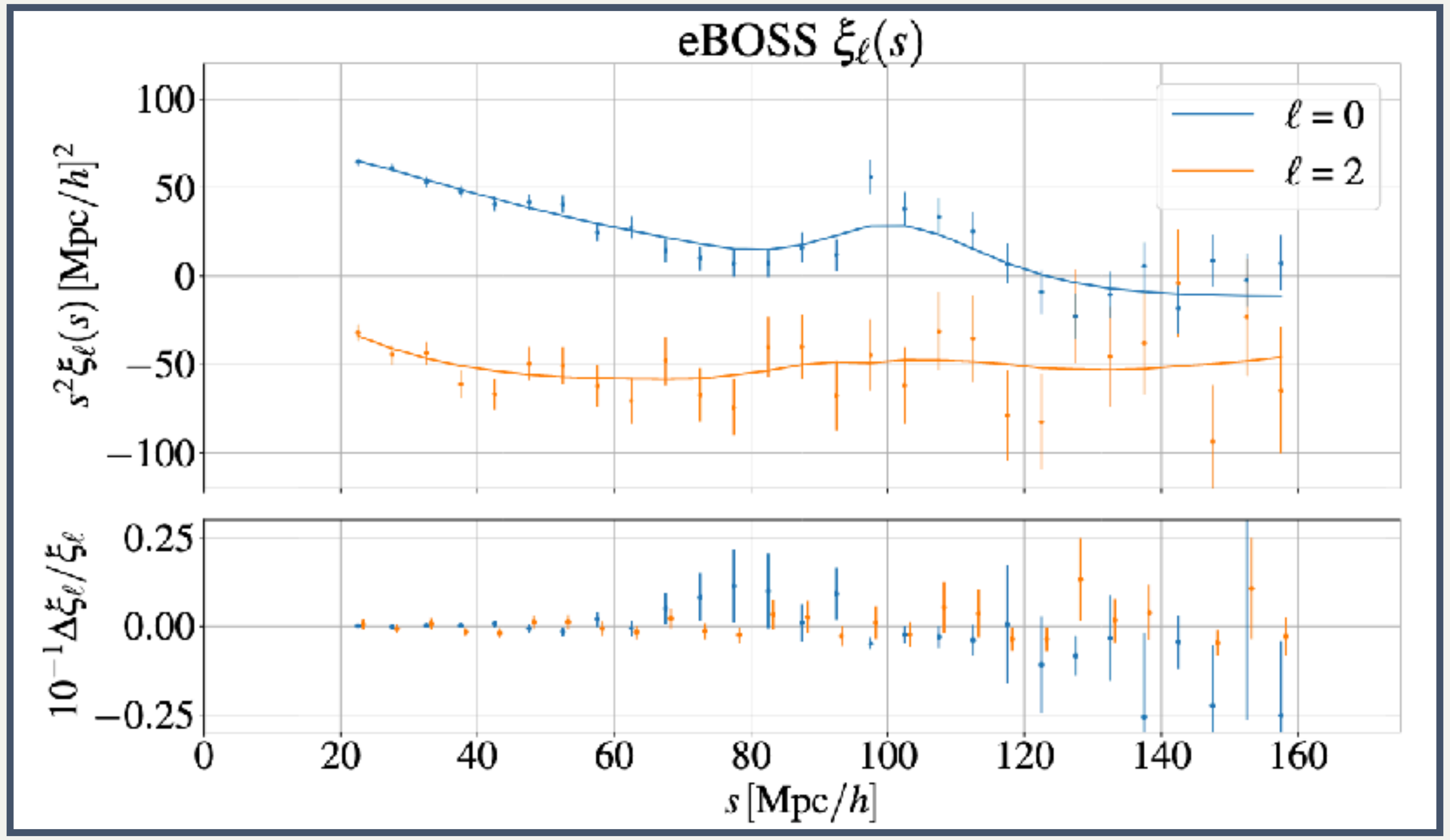

cut-off scale $k_{\rm max} = 0.24\, h\,.\,{\rm Mpc}^{-1}$

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:

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

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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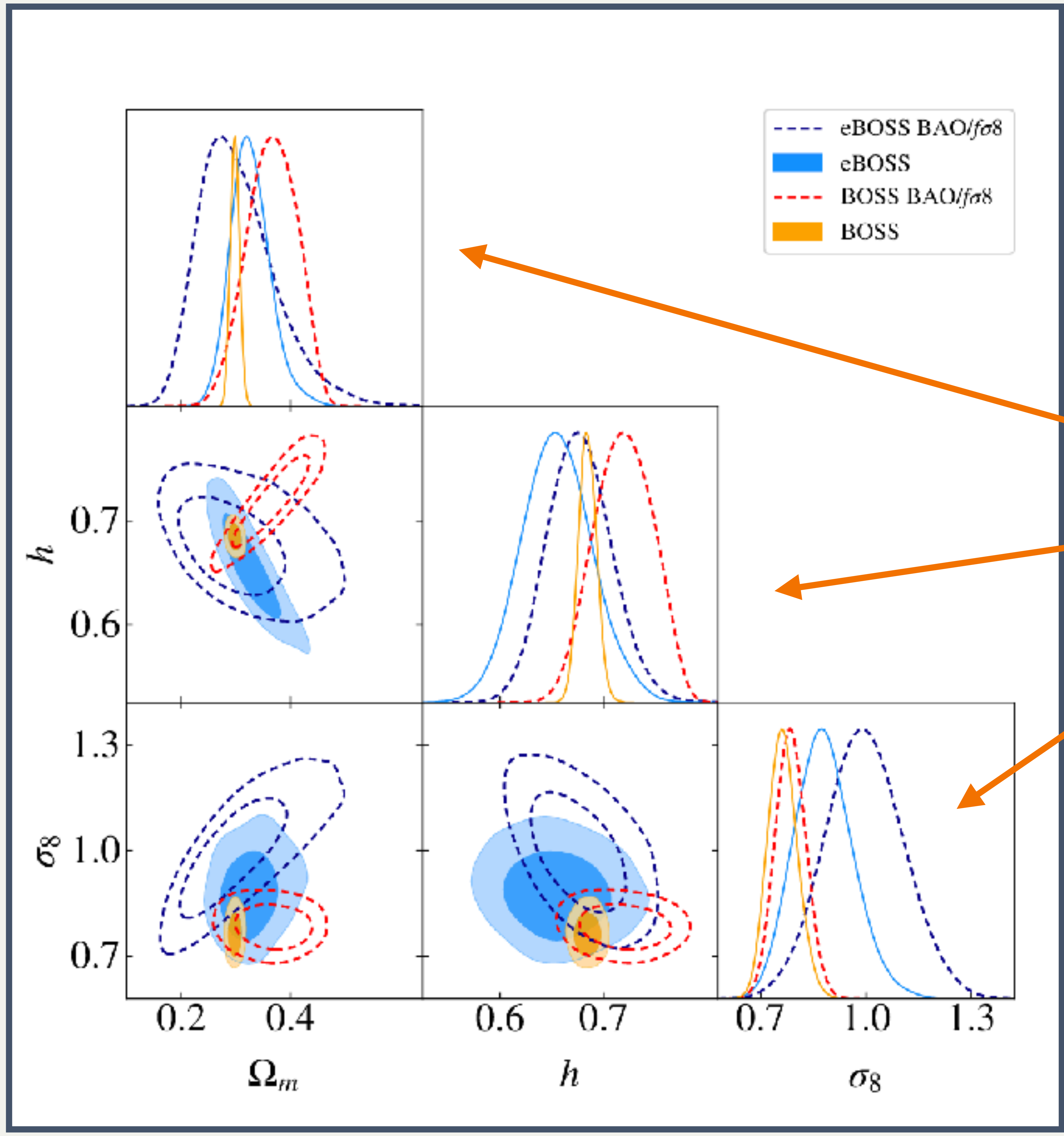
2 new EFT parameters

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

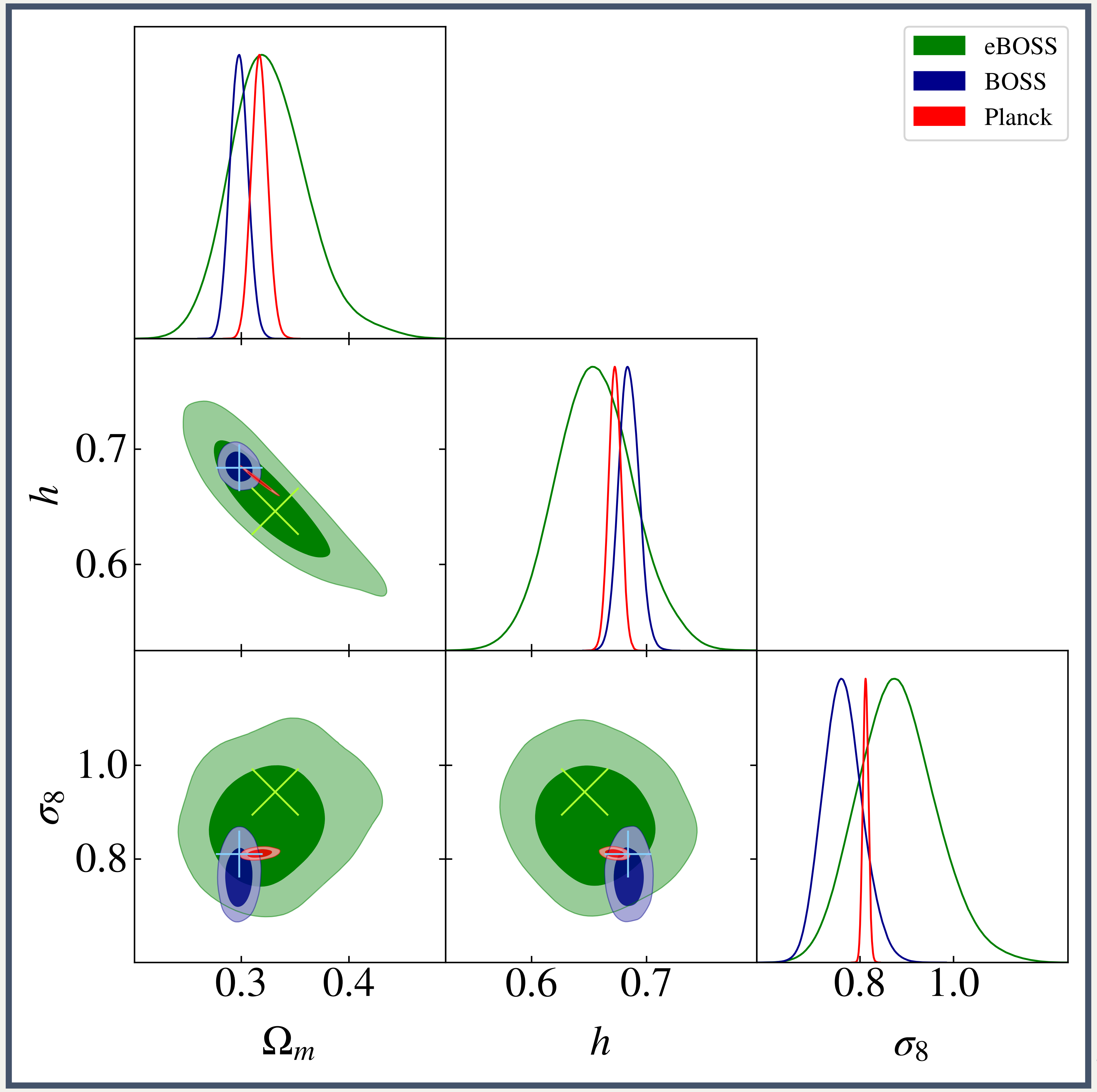


Additional information

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

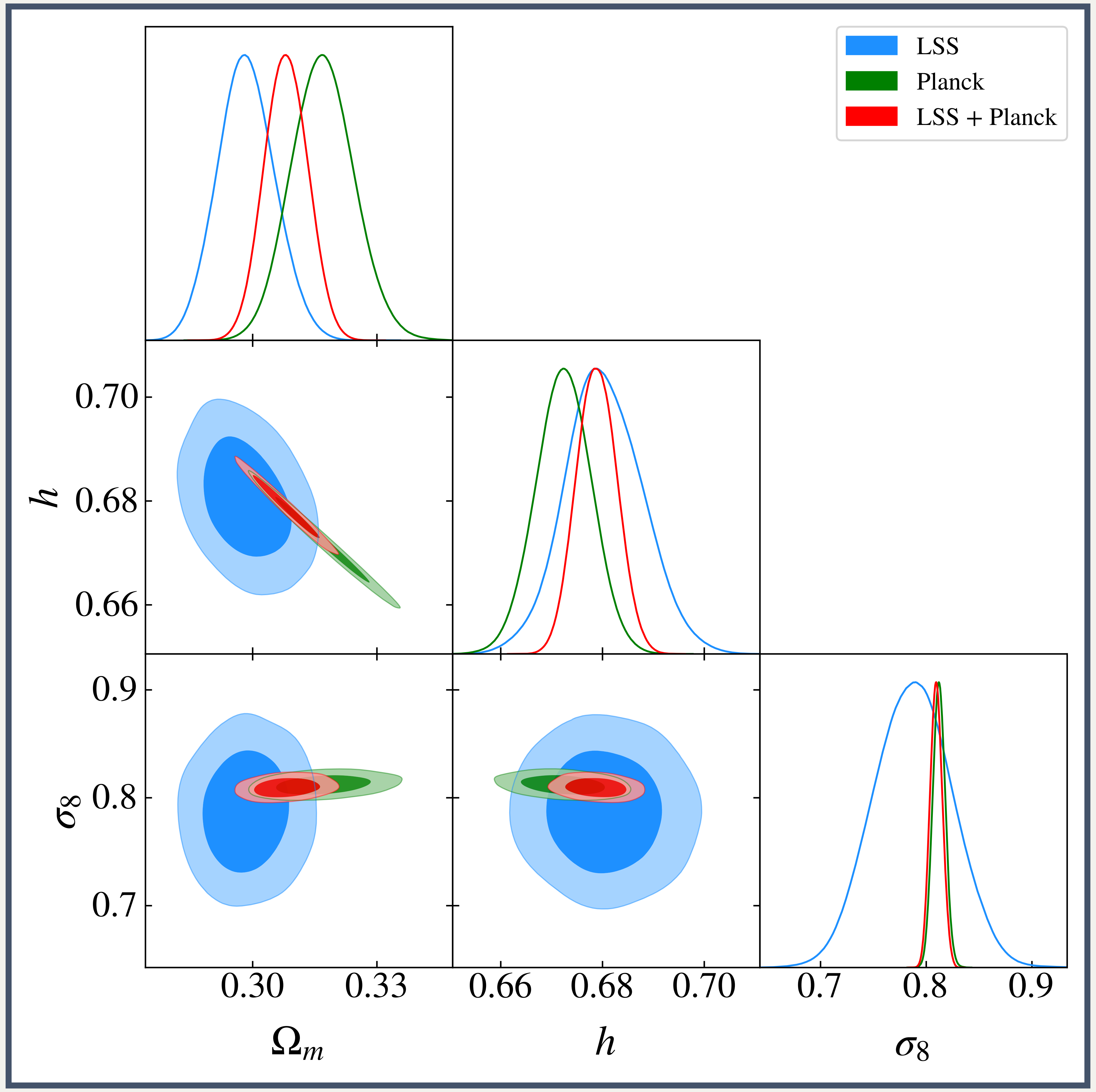


TS++ [arXiv:2210.14931]

- **eBOSS, BOSS and Planck are consistent** at $\lesssim 1.8\sigma$ on all cosmological parameters
- 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 (Uncalibrated Supernovae)

- **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 $\sum m_\nu$

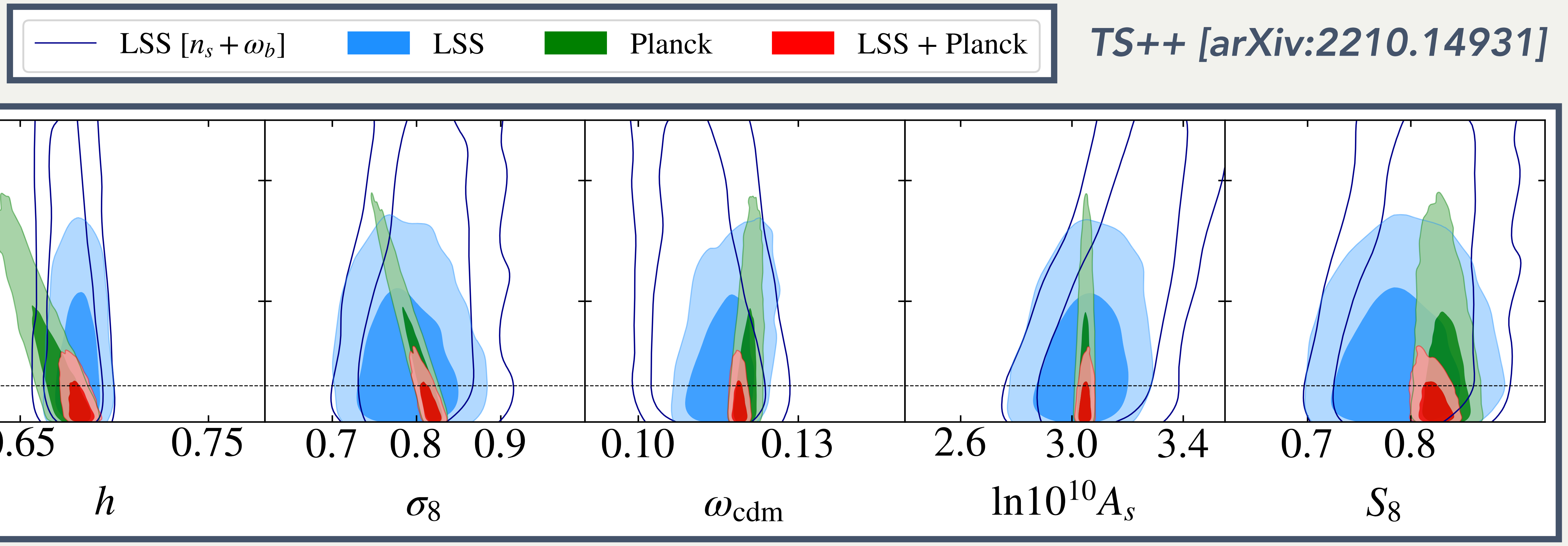
- The LSS constraint derived in this work is **only** $\sim 10\,\%$ **weaker than the Planck constraint** ($\sum m_\nu < 0.241 eV$)
- The EFT analysis **significantly improves the constraints** on $\sum m_\nu$ (by a factor of ~ 18) over the conventional BAO/$f\sigma_8$ analysis ($\sum m_\nu < 4.84 eV$)

  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]



Conclusion

- The EFTofLSS is a novel method that provides an **accurate description of LSS data (up to mildly non linear scales) at a controlled precision**

- Constraints from LSS data are **competitive with CMB data** and their combination **improves over Planck alone**

- 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: $\sum m_\nu < 0.093e$V

- Does EFTofLSS provide **interesting constraints on non-canonical extensions** to the ΛCDM model ?