Constraining the dark sector and the initial conditions of the Univers with the EFTofLSS

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ADE - 06/11/2025

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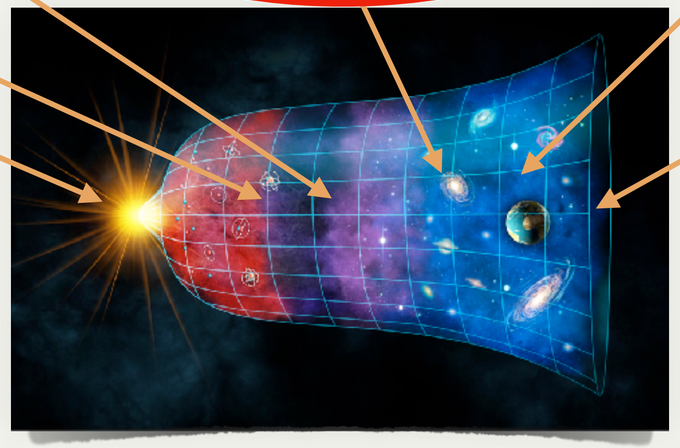
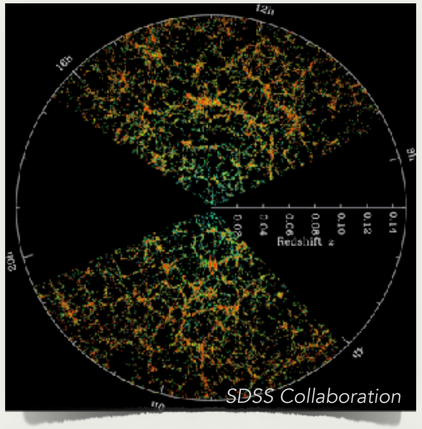
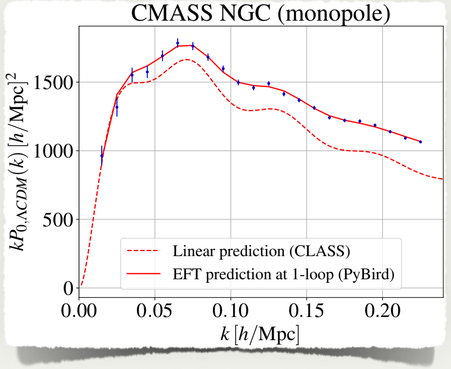
Introduction: the epistemic context

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



Galaxy clustering data



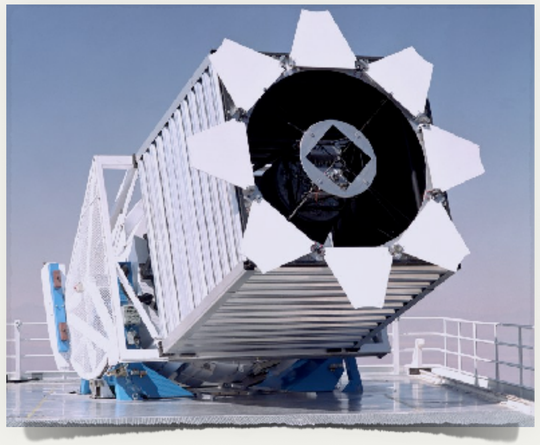


Part I: *How to obtain the most robust and optimised constraints on ΛCDM cosmological parameters from galaxy clustering data?*

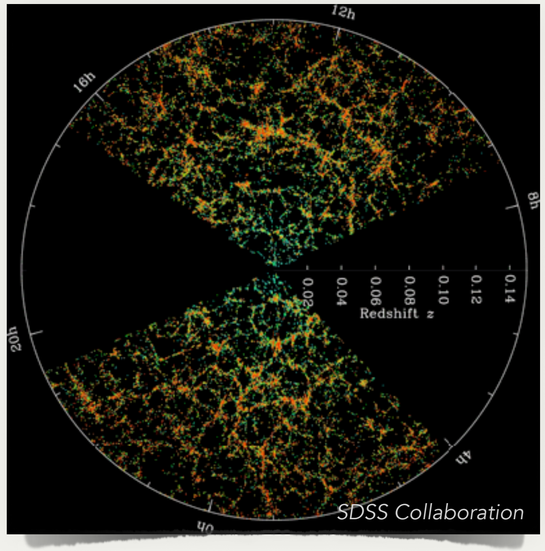
Part II: How can clustering data be used to constrain the nature of dark energy and the initial conditions?

Introduction: large-scale structure data

The Sloan Digital Sky Survey (SDSS)



www.sdss.org



SDSS

2000 - 2025

BOSS DR12 LRG (Luminous Red Galaxies)

Galaxies (~ 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 (~ 300 000) selected in one redshift range:

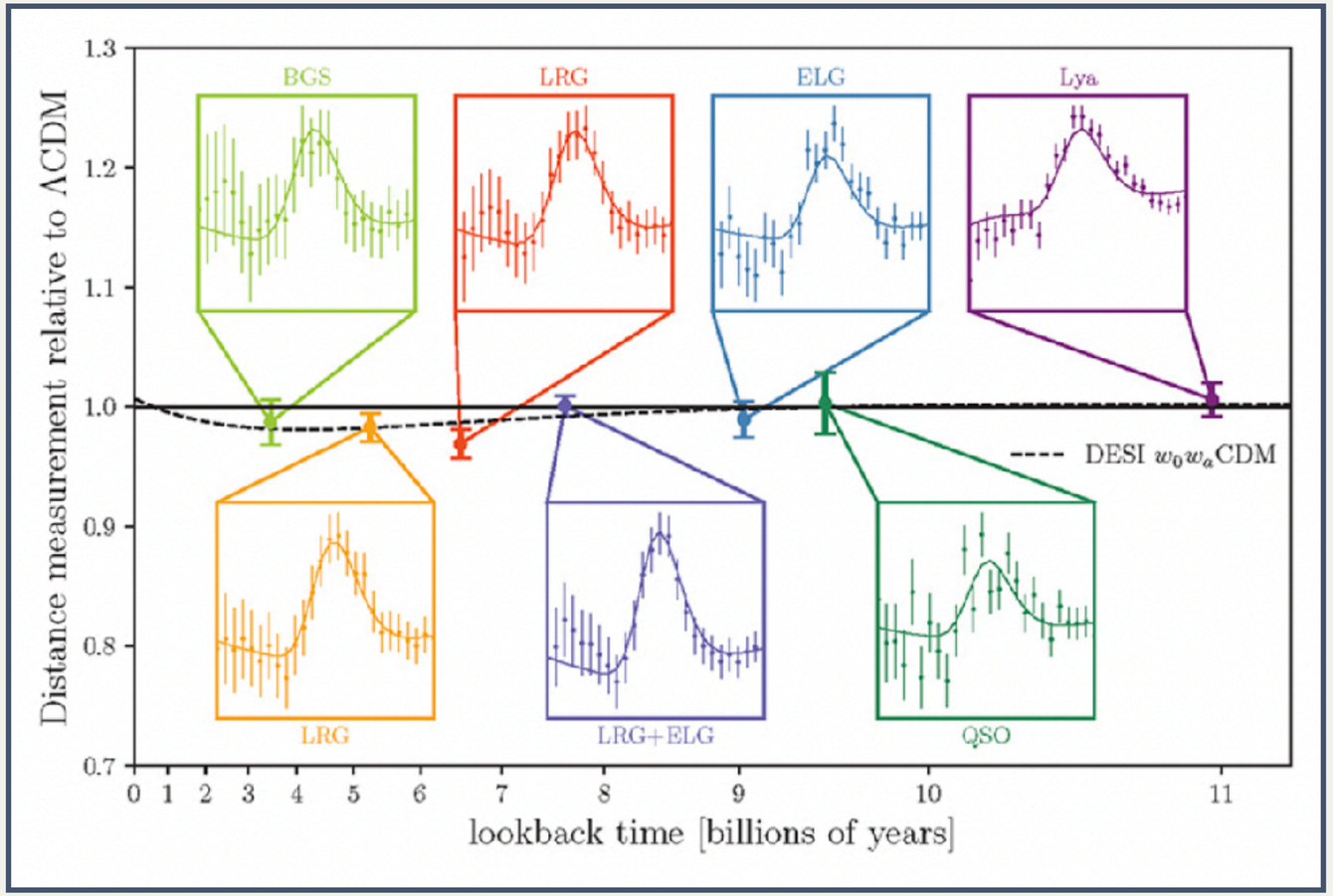
$0.8 < z < 2.2$ ($z_{\rm eff} = 1.5$)

eBOSS Collaboration [arXiv:2007.08991]

Introduction: large-scale structure data

DESI

Tracer	Redshift range	N_{tracer}	V_{eff} (Gpc^3)
BGS	0.1 – 0.4	1,188,526	3.8
LRG1	0.4 – 0.6	1,052,151	4.9
LRG2	0.6 – 0.8	1,613,562	7.6
LRG3+ELG1	0.8 – 1.1	4,540,343	14.8
ELG2	1.1 – 1.6	3,797,271	8.3
QSO	0.8 – 2.1	1,461,588	2.7
Lyα	1.8 – 4.2	1,289,874	—
LRG3	0.8 – 1.1	1,802,770	9.8
ELG1	0.8 – 1.1	2,737,573	5.8



DESI Collaboration [arxiv:2404.03002]
DESI Collaboration [arXiv:2503.14738]

I- Introduction to the Effective Field Theory of Large-Scale Structures (EFTofLSS)

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:

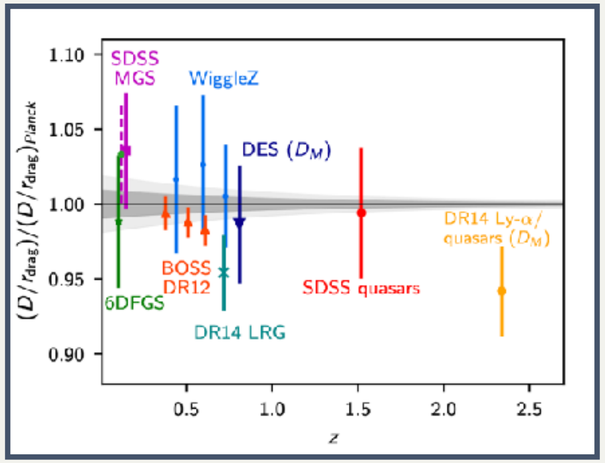
$$P_g(z,k,\mu) \simeq \left[b_1(z) + f\mu^2\right]^2 P_m(z,k)$$

Kaiser '87

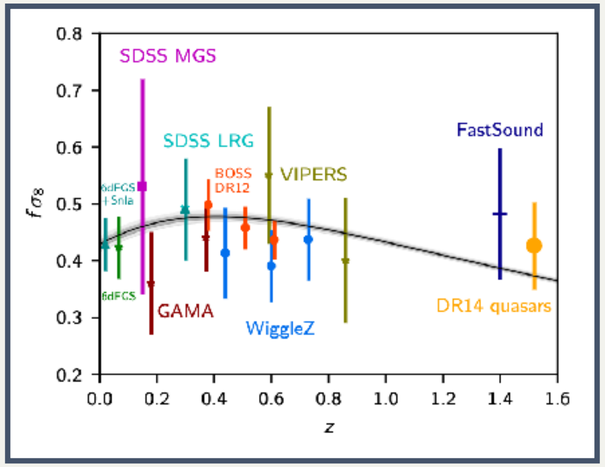
b_1: bias parameter, f: growth rate and $\mu = \hat{z} \cdot \hat{k}$

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

LSS collaborations conventionally used the second method



Planck Collaboration [arXiv:1807.06209]



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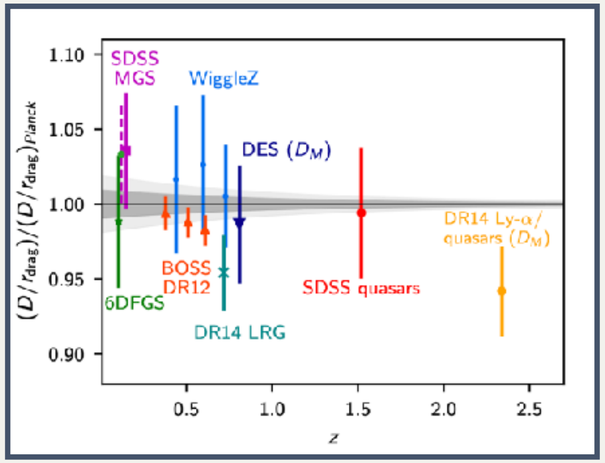

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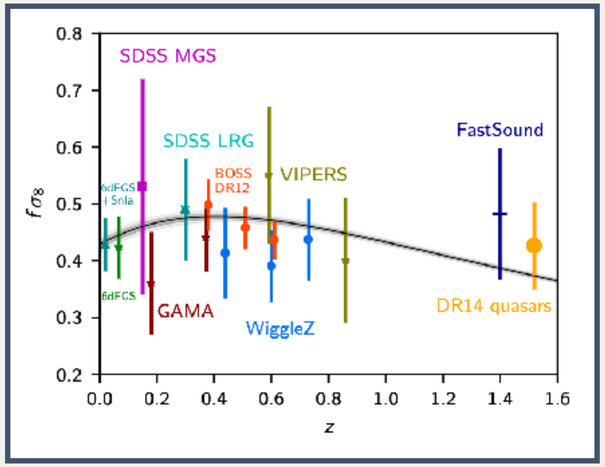

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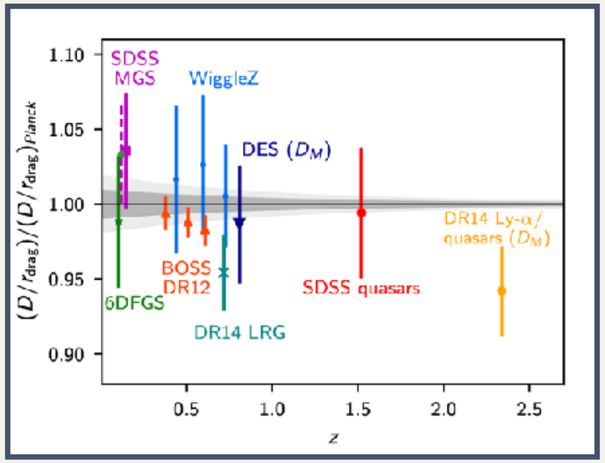

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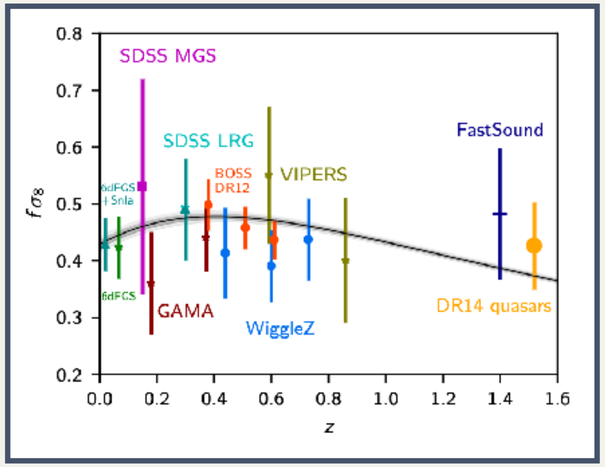

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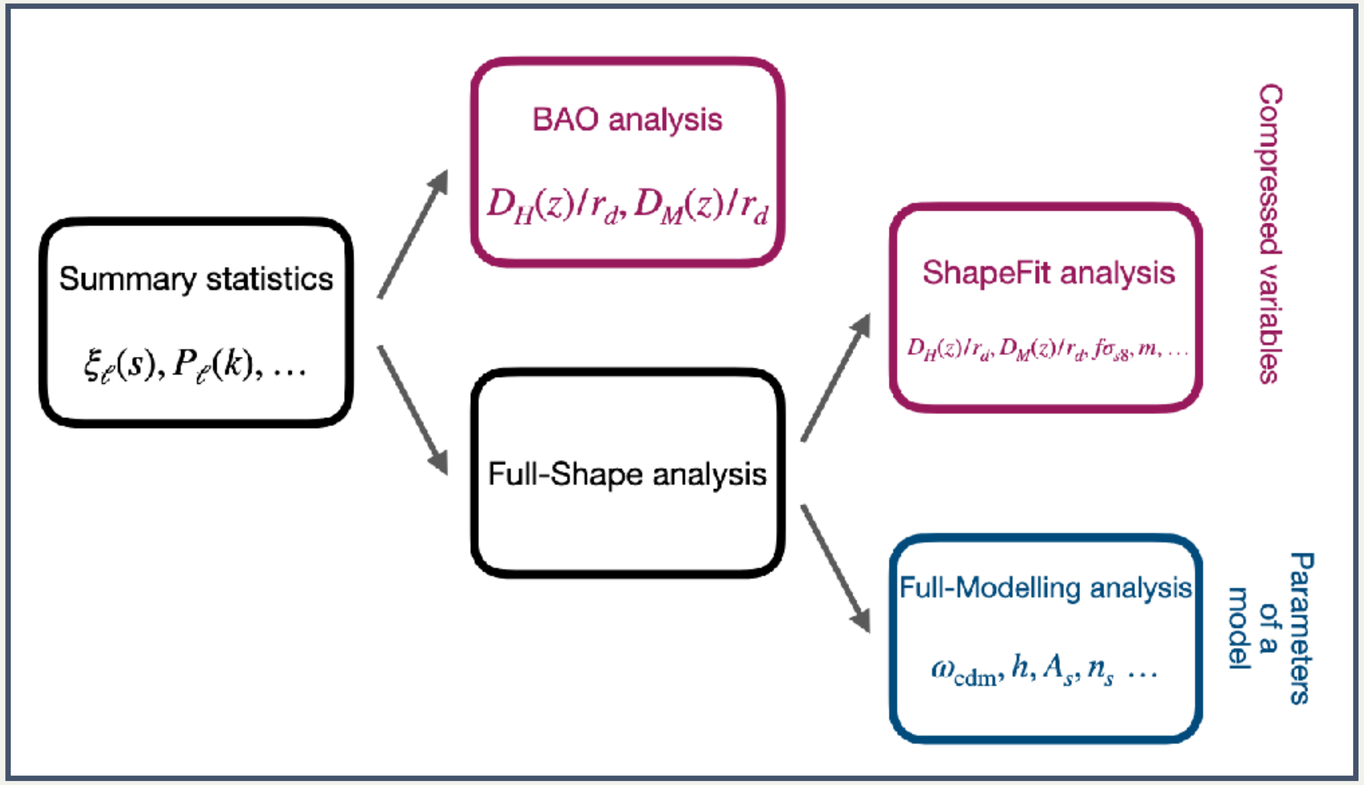
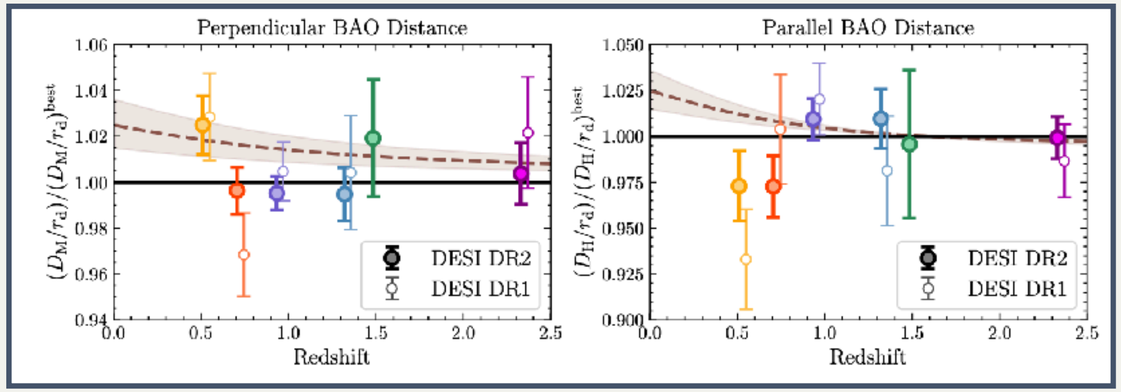


DESI Collaboration [arXiv:2411.12021]



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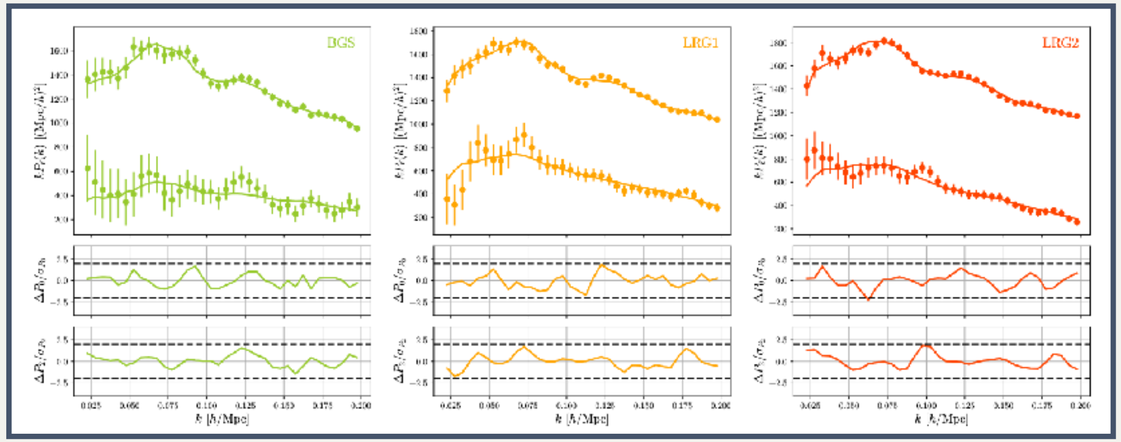

DESI Collaboration [arXiv:2411.12021]

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

Main ingredients

EFTofLSS

Carrasco++ [arXiv:1206.2926]

Baumann++ [arXiv:1004.2488]

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

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

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Dark matter: the Vlasov system

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

EFTofLSS

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EFTofLSS

$$\nabla^2\psi_l = \frac{3}{2}\Omega_m(a)(aH)^2\delta_l$$

Gravity: the Poisson equation

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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]

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

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

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

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$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2Z_1(\mu) P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm R}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm R}^2}\right)$$
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Carrasco++ [arXiv:1206.2926] ; Baumann++ [arXiv:1004.2488]
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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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P_{11}

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$$\begin{aligned}
P_g(k,\mu) &= \underbrace{Z_1(\mu)^2 P_{11}(k)}_{P_{11}} + \underbrace{2Z_1(\mu)P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm R}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm R}^2}\right)}_{P_{13}^{\rm ctr}} \\
&+ \underbrace{2\int\frac{d^3q}{(2\pi)^3}\, Z_2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q},\mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)P_{11}(q)}_{P_{22}} + \underbrace{6Z_1(\mu)P_{11}(k)\int\frac{d^3q}{(2\pi)^3}\, Z_3(\boldsymbol{q},-\boldsymbol{q},\boldsymbol{k},\mu)P_{11}(q)}_{P_{13}} \\
&+ \underbrace{\frac{1}{\bar{n}_g}\left(c_{\epsilon,0} + c_\epsilon^{\rm mono}\frac{k^2}{k_{\rm M}^2} + 3c_\epsilon^{\rm quad}\left(\mu^2 - \frac{1}{3}\right)\frac{k^2}{k_{\rm M}^2}\right)}_{P_{22}^{\rm ctr}}
\end{aligned}$$

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

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

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

$$\begin{aligned}
P_g(k,\mu) &= \underbrace{Z_1(\mu)^2 P_{11}(k)}_{P_{11}} + \underbrace{2Z_1(\mu)P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} - c_{r,1}\mu^2\frac{k^2}{k_{\rm R}^2} - c_{r,2}\mu^4\frac{k^2}{k_{\rm R}^2}\right)}_{P_{13}^{\rm ctr}} \\
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\end{aligned}$$

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

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

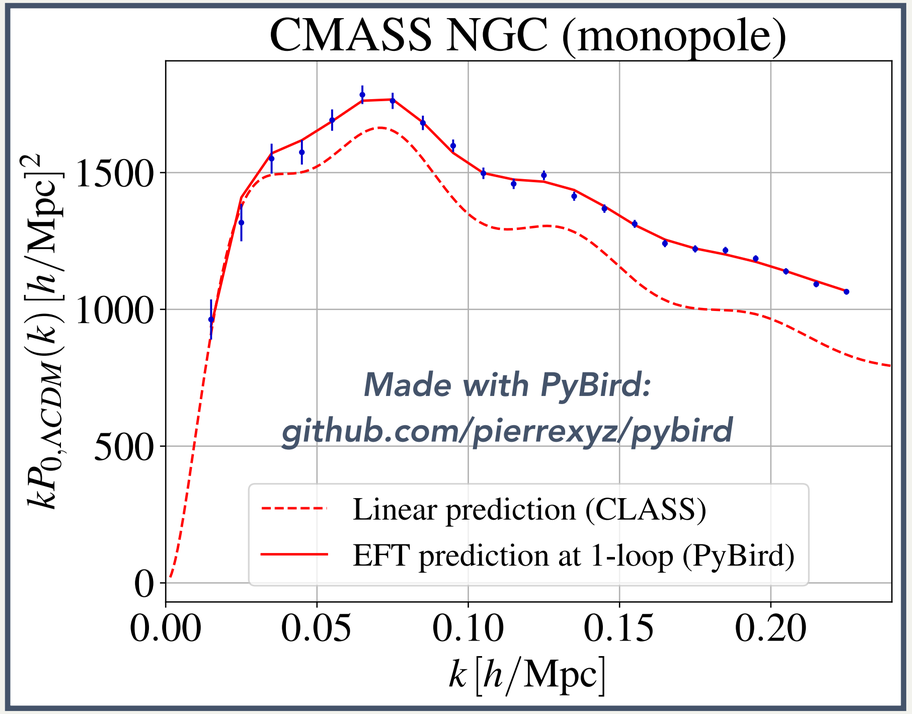
The Effective Field Theory of Large-Scale Structures (EFTofLSS)

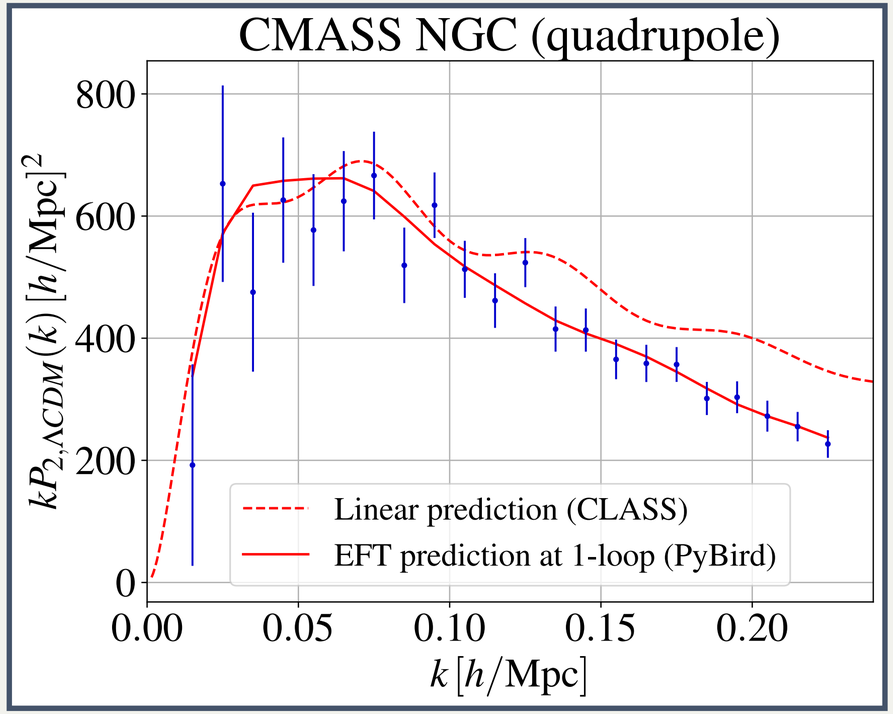
Application to BOSS data

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]
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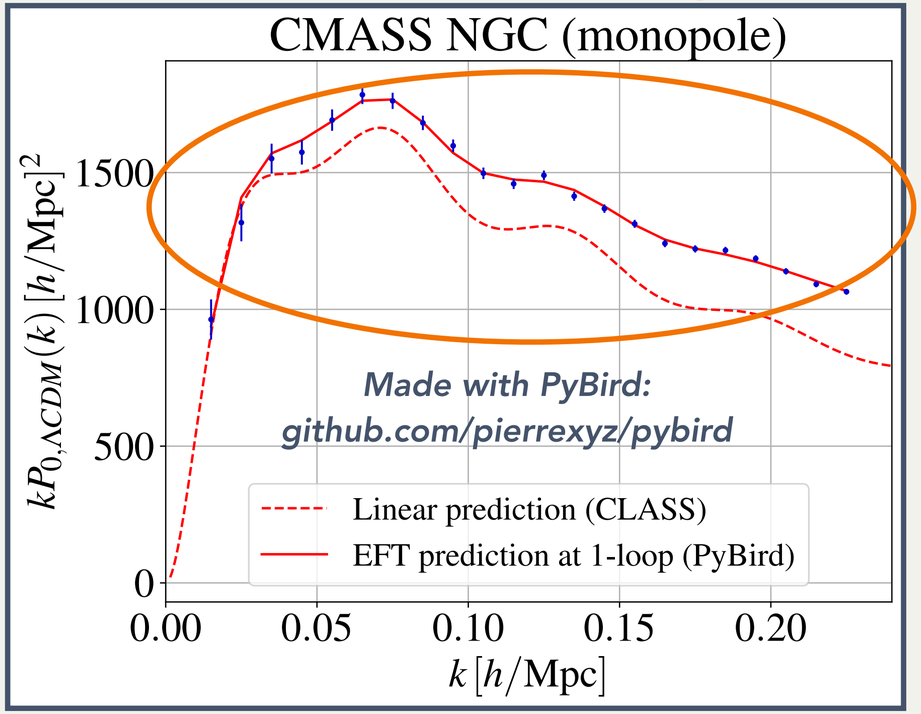
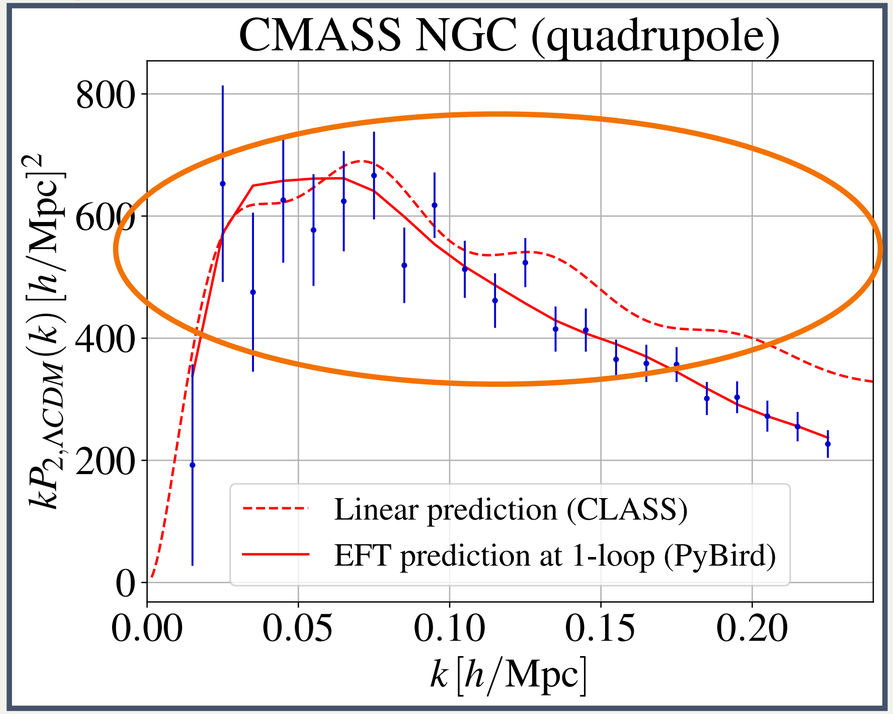
Improvement in precision!





D'Amico++ [arXiv:1909.05271] ; Colas++ [arXiv:1909.07951]
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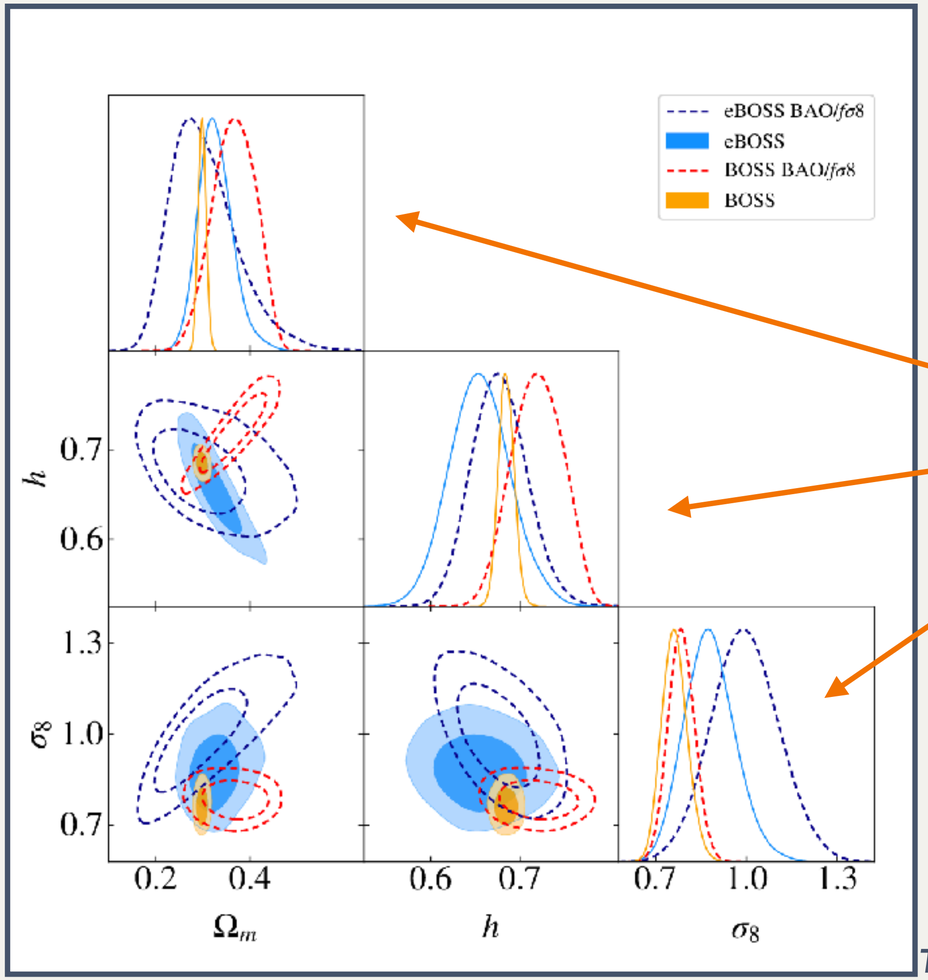
BAO/$f\sigma_8$ vs EFTofLSS

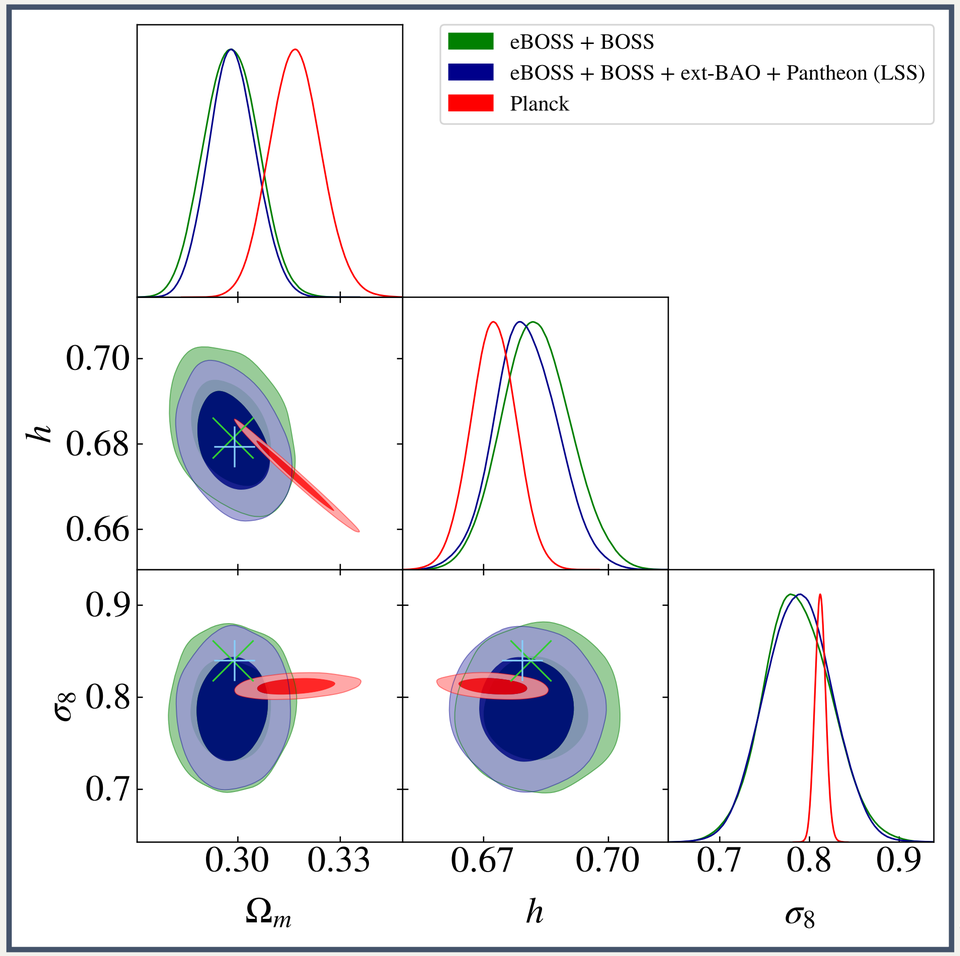


Additional information

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

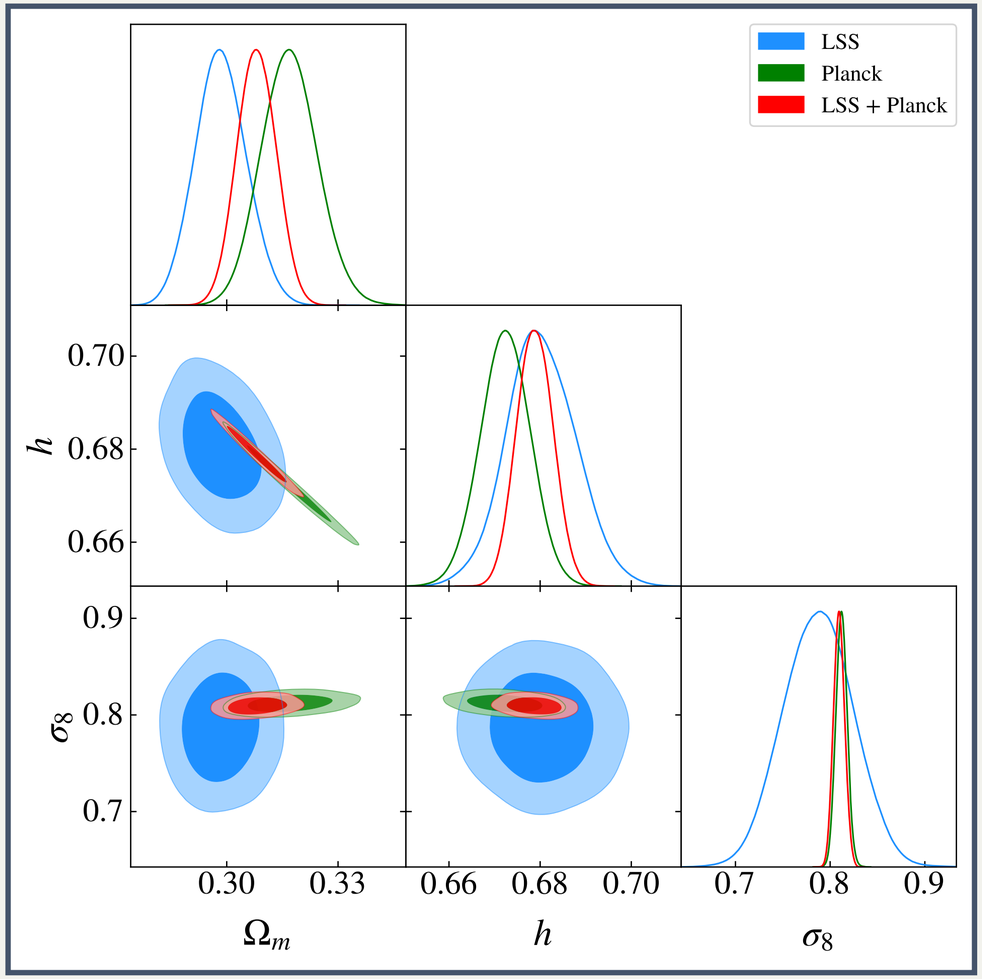


ext-BAO: 6dF & MGS (SDSS) data

- 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!**

TS++ [arXiv:2210.14931]

LSS data combined with Planck



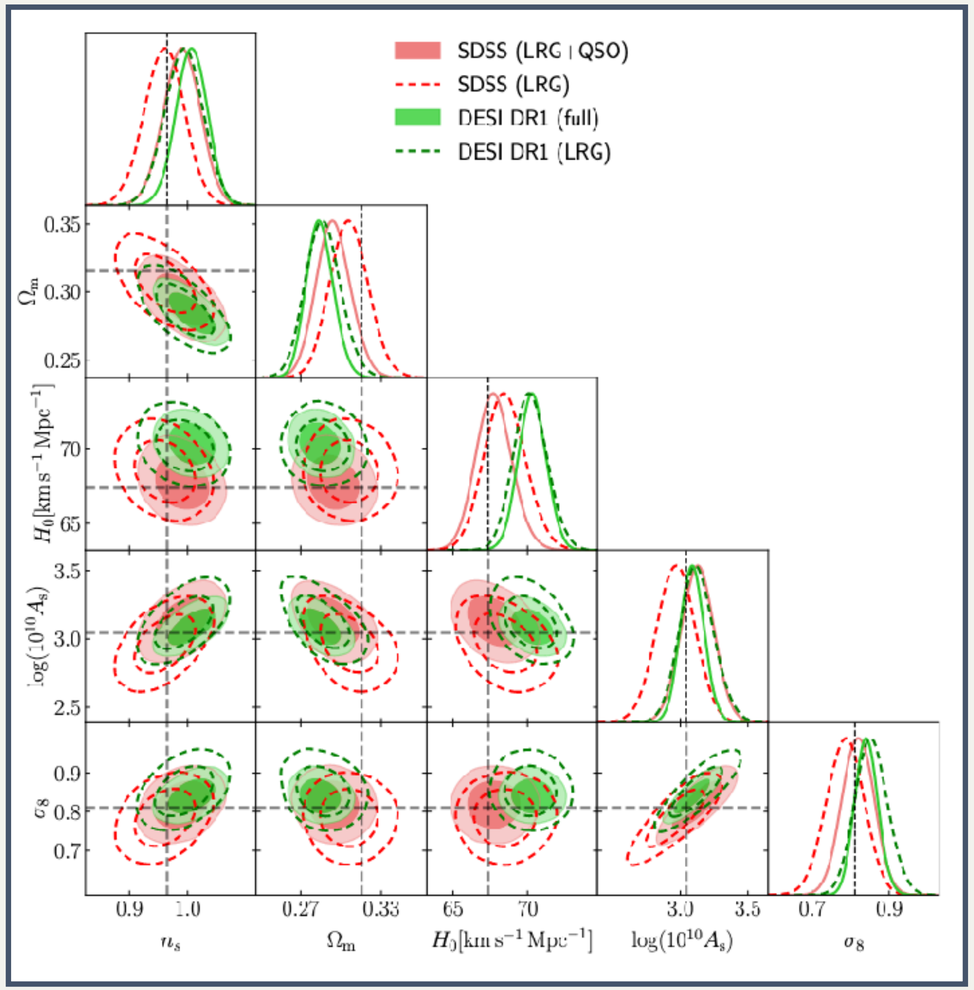
LSS: eBOSS + BOSS + ext-BAO + Pantheon

(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]

SDSS data vs DESI



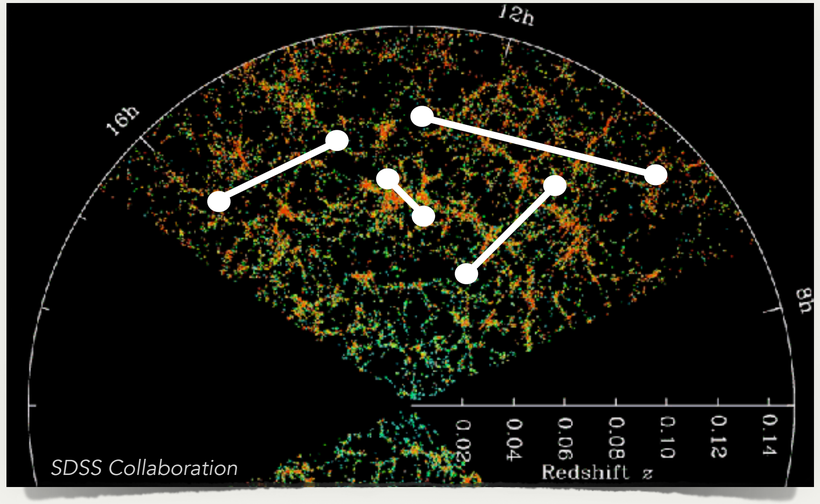
DESI Collaboration [arXiv:2411.12021]

- **Good agreement between DESI and SDSS**
- The current constraints of DESI are similar to those of SDSS
- **Slight discrepancy between DESI and Planck** for Ω_m and h

Beyond the two-point correlation function

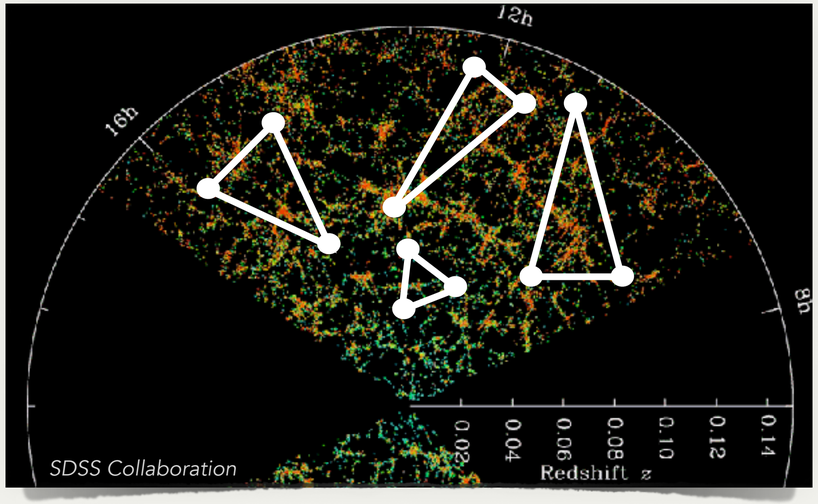
Power spectrum (2PCF)

$$< \delta_{g,r}(\vec{k})\delta_{g,r}(\vec{k}') > = (2\pi)^3\delta_D(\vec{k}+\vec{k}')P(k,\mu)$$



Bispectrum (3PCF)

$$< \delta_{g,r}(\overrightarrow{k_1})\delta_{g,r}(\overrightarrow{k_2})\delta_{g,r}(\overrightarrow{k_3}) > = (2\pi)^3\delta_D(\overrightarrow{k_1}+\overrightarrow{k_2}+\overrightarrow{k_3})B(k_1,k_2,k_3,\mu,\phi)$$



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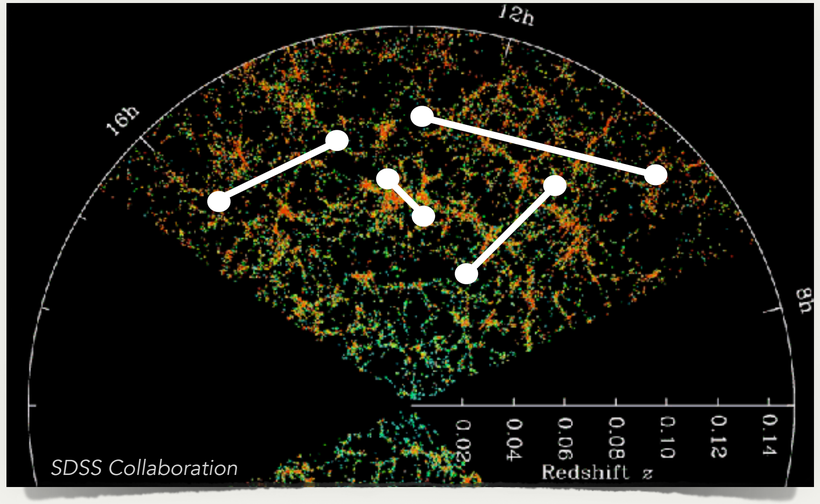
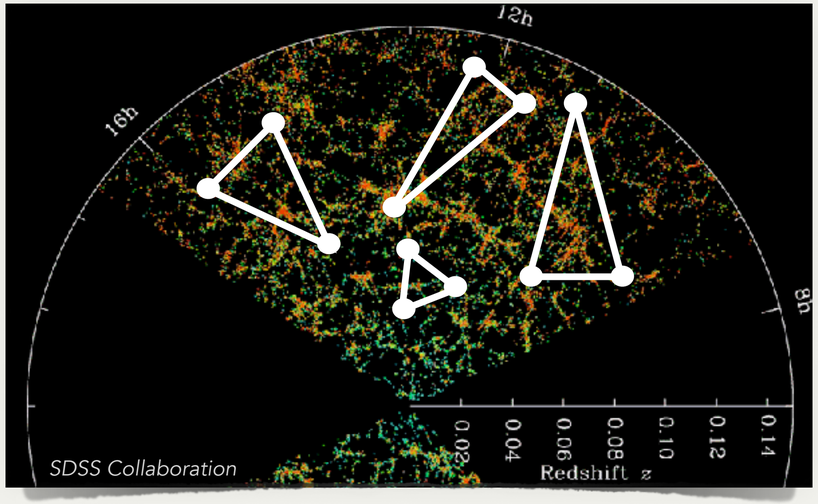


$$P = P_{11} + (P_{13} + P_{13}^{ct}) + (P_{22} + P_{22}^{\epsilon})$$

10 EFT parameters

Bispectrum (3PCF)

$$< \delta_{g,r}(\vec{k_1})\delta_{g,r}(\vec{k_2})\delta_{g,r}(\vec{k_3}) > = (2\pi)^3\delta_D(\vec{k_1}+\vec{k_2}+\vec{k_3})B(k_1,k_2,k_3,\mu,\phi)$$



$$B = B_{211} + (B_{321}^{(II)} + B_{321}^{(II),ct}) + (B_{411} + B_{411}^{ct}) + (B_{222} + B_{222}^{\epsilon}) + (B_{321}^{(I)} + B_{321}^{(I),\epsilon})$$

41 EFT parameters

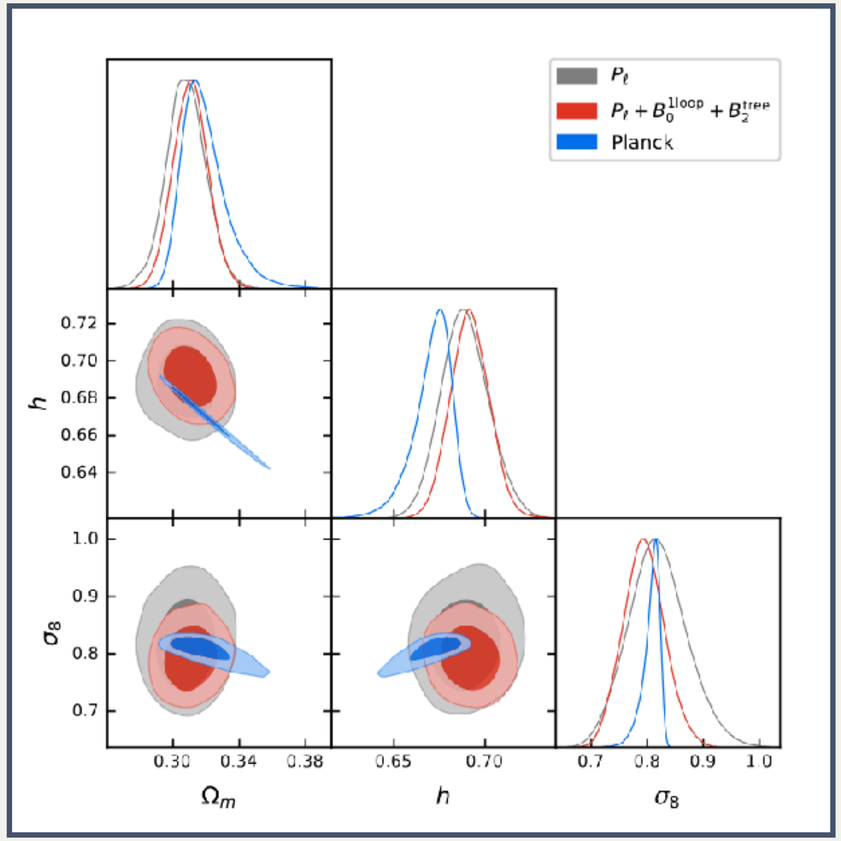
EFTofLSS computation

(Bias tracers, redshift space)

D'Amico++ [arXiv:2211.17130]
Philcox++ [arXiv:2206.02800]

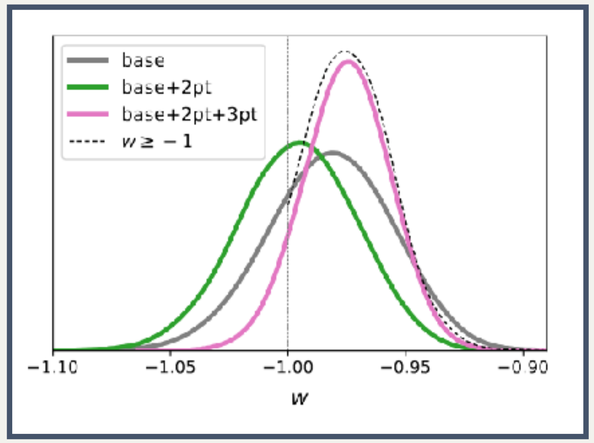
Beyond the two-point correlation function

Analysis of BOSS (LRG) with $P + B$, for $0.01 < k < 0.23$ $[h\mathrm{Mpc}^{-1}]$



D'Amico++ [arXiv:2206.08327]

- **Good agreement** between Planck and BOSS (again)
- $13\,\%$ improvement on Ω_m, $18\,\%$ on h and $30\,\%$ on σ_8 thanks to the bispectrum
- $30\,\%$ **of improvement on** w



(Base = Planck + PanPlus + ext-BAO)

Spaar++ [arXiv:2312.15164]

II- Constraining dark energy history with the EFTofLSS

Based on:

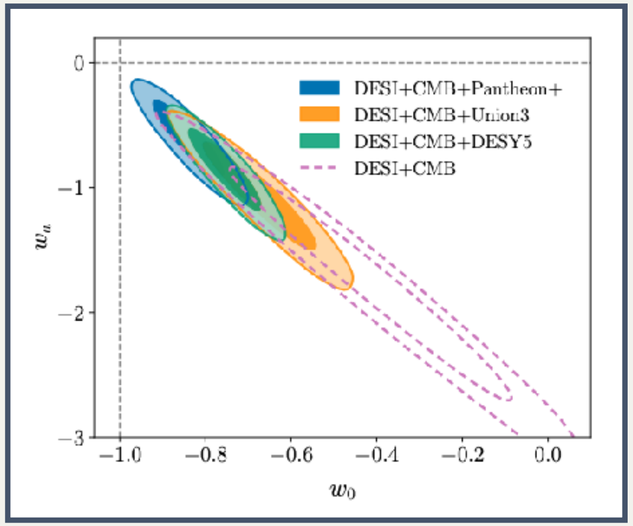
- Z. Lu, **TS** and P. Zhang **[arXiv:2503.04602]**
  Preference for evolving dark energy in light of the galaxy bispectrum

General context: preference for evolving dark energy

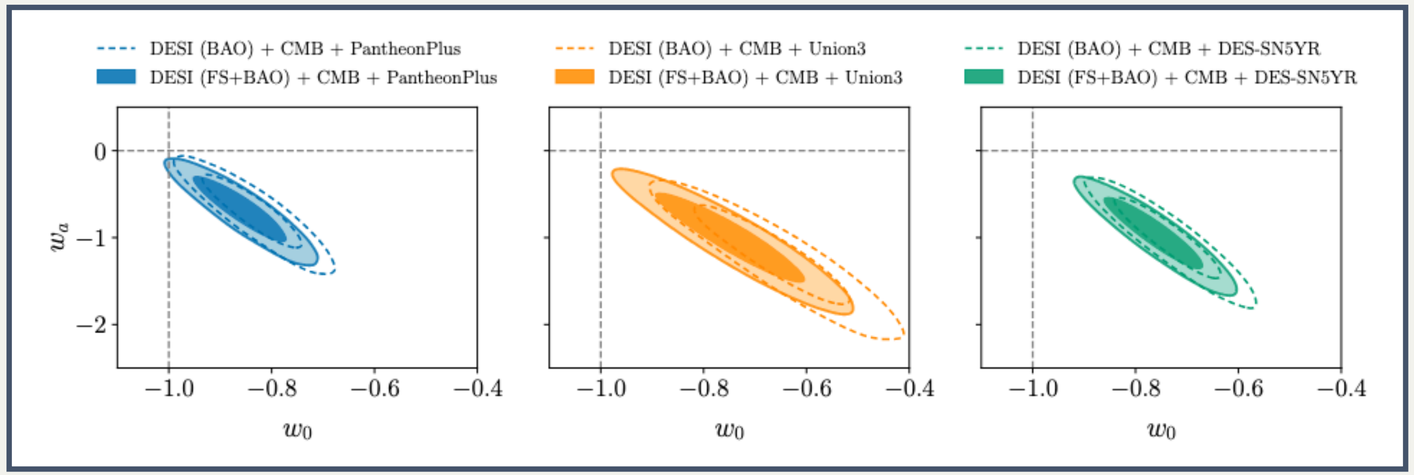
Extension of the ΛCDM model, where the dark energy equation-of-state is parametrized by

$$w_{\rm DE} = \frac{P(z)}{\rho(z)} = w_0 + w_a(1-a)$$

- **Preference for evolving dark energy over ΛCDM at 3.1σ for DESI BAO DR2 + CMB**
- 2.8σ, 3.8σ and 4.2σ when we add Pantheon+, Union3 or DES Y5
- Same level of preference for the DESI Y1 full-shape analysis (EFTofLSS)

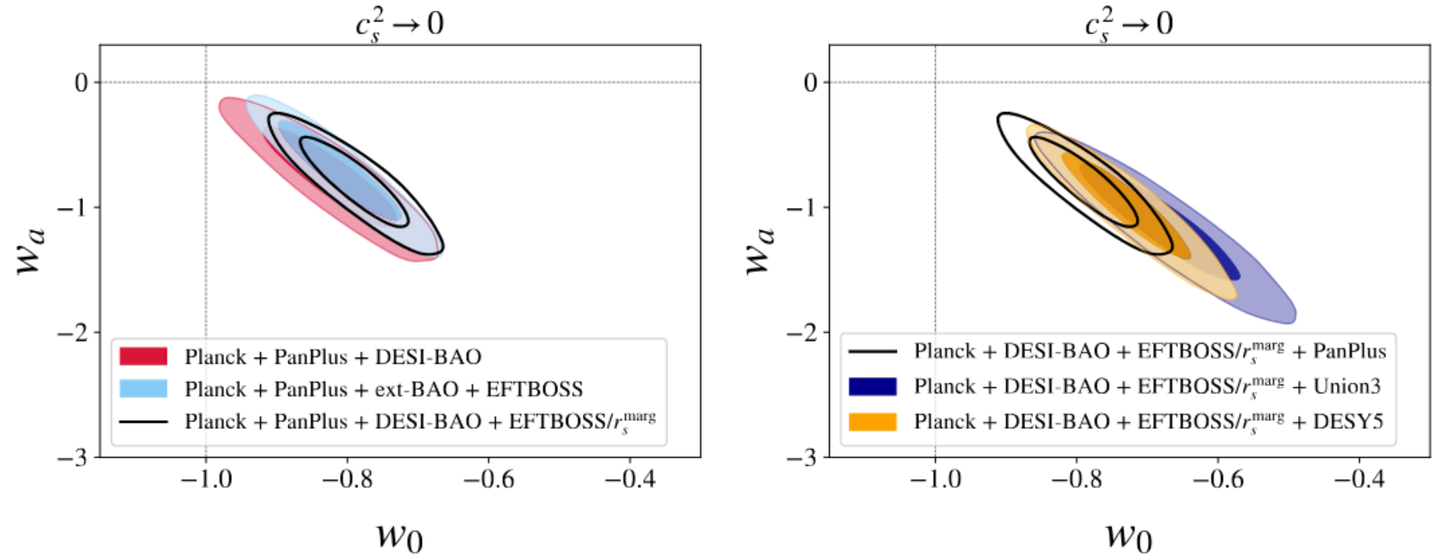


DESI Collaboration [arXiv:2503.14738]



DESI Collaboration [arXiv:2411.12021]

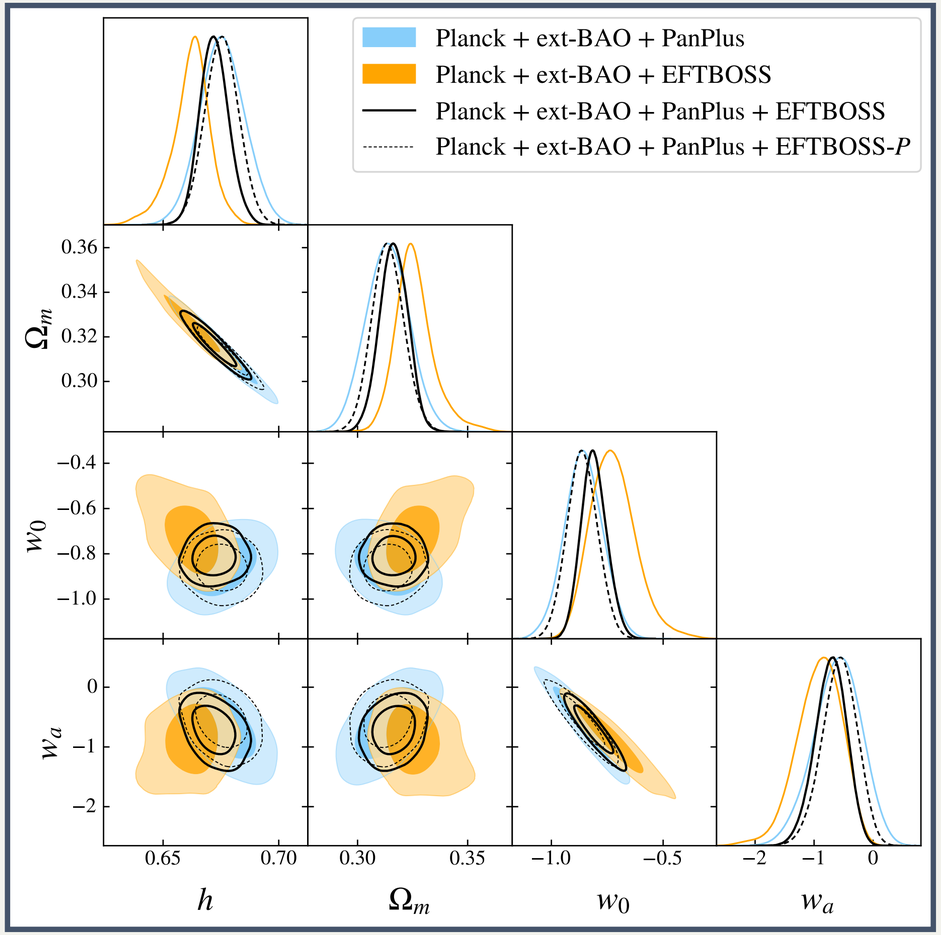
Main results



Dataset	w_0	w_a	$p > \Lambda$	$\Delta\chi^2$
Planck + PanPlus + DESI-BAO	-0.821 ± 0.063	-0.77 ± 0.27	2.5σ	-8.9
Planck + PanPlus + ext-BAO + EFTBOSS	$-0.809^{+0.053}_{-0.061}$	$-0.72^{+0.28}_{-0.25}$	2.8σ	-10.3
Planck + PanPlus + DESI-BAO + EFTBOSS/$r_s^{\rm marg}$	-0.789 ± 0.050	$-0.80^{+0.25}_{-0.22}$	3.7σ	-16.9
Planck + Union3 + DESI-BAO + EFTBOSS/$r_s^{\rm marg}$	-0.677 ± 0.075	$-1.14^{+0.33}_{-0.29}$	3.8σ	-17.7
Planck + DESY5 + DESI-BAO + EFTBOSS/$r_s^{\rm marg}$	-0.726 ± 0.060	$-1.00^{+0.30}_{-0.25}$	4.4σ	-22.9

- We obtain **a** 2.8σ **preference** for the $w_0 w_a$CDM model with pre-DESI data, namely *Planck* + PanPlus + EFTBOSS
- **The preference increases to** 3.6σ / 3.9σ when considering Union3 / DES Y5
- When we add DESI BAO Y1 on top, we have a $3.7\sigma - 4.4\sigma$

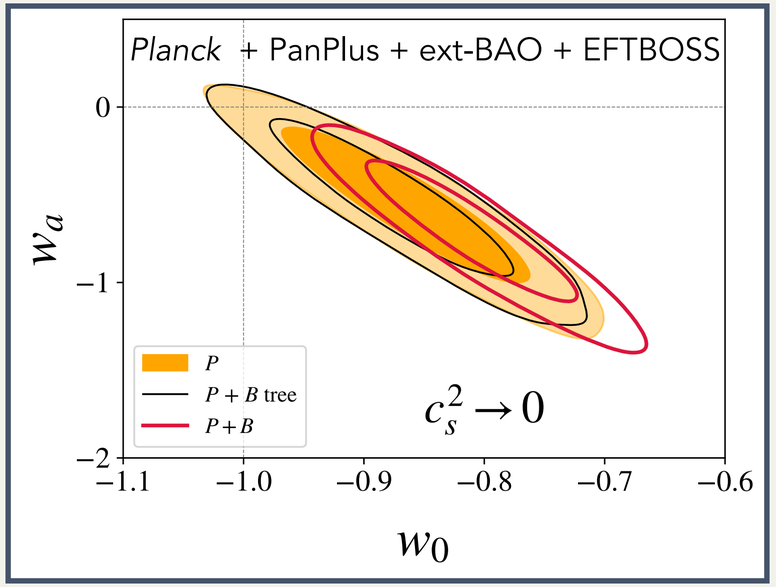
Breaking degeneracies between SN1a and galaxy clustering

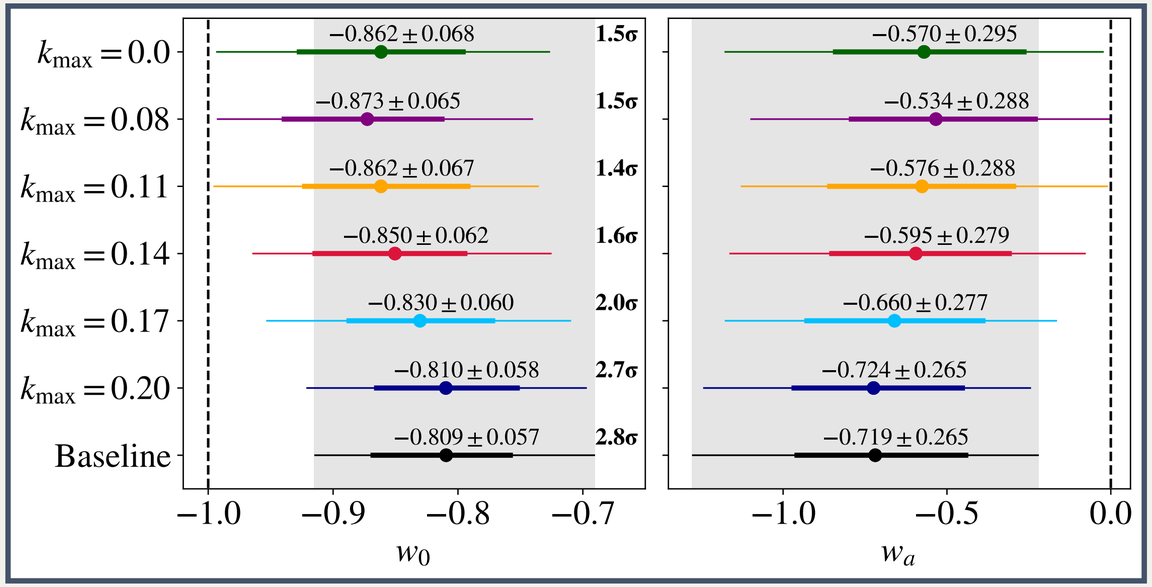


- The combinations of *Planck* with either PanPlus or EFTBOSS **do not show any preference** for evolving dark energy
- We we combine PanPlus with EFTBOSS we **break some degeneracies** between $h - w_0/w_a$ and $\Omega_m - w_0/w_a$
- **This is the first time that we have preference for evolving dark energy without data from DESI!!**

Impact of the bispectrum contribution

- Without the bispectrum, **we do not get a preference** over Λ (1.5σ)
- With the bispectrum, **we get a** $2.8 - 3.9\sigma$ **preference** over Λ (shift of $\sim 0.5\sigma$ + reduction of $30\,\%$ of $w_0 - w_a$)
- Deviations from Λ, together with improvement in the constraints, **start to be significant when** $k_{\rm max} = 0.14\,h{\rm Mpc}^{-1}$, where $k_{\rm max}$ is the highest Fourier mode included in the analysis of the bispectrum





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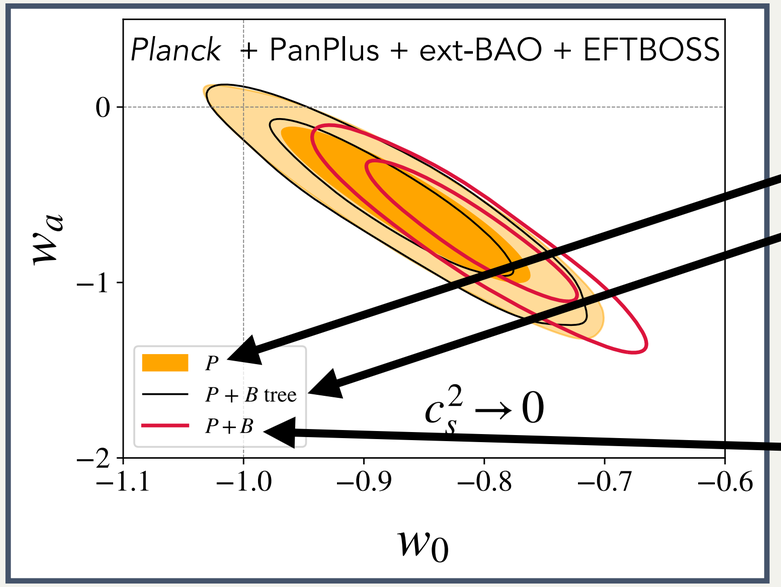

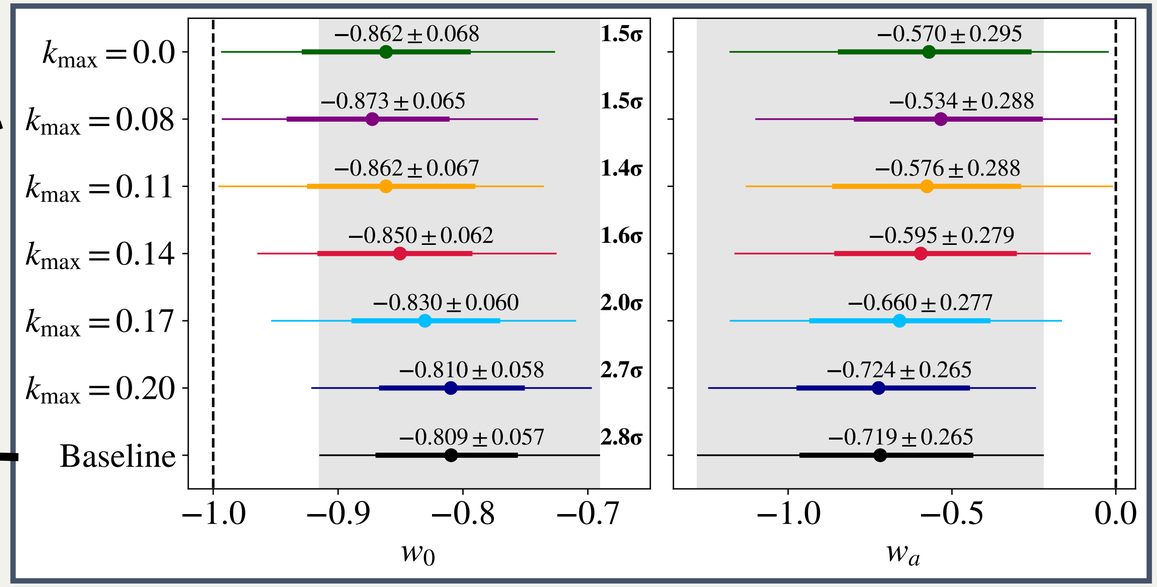

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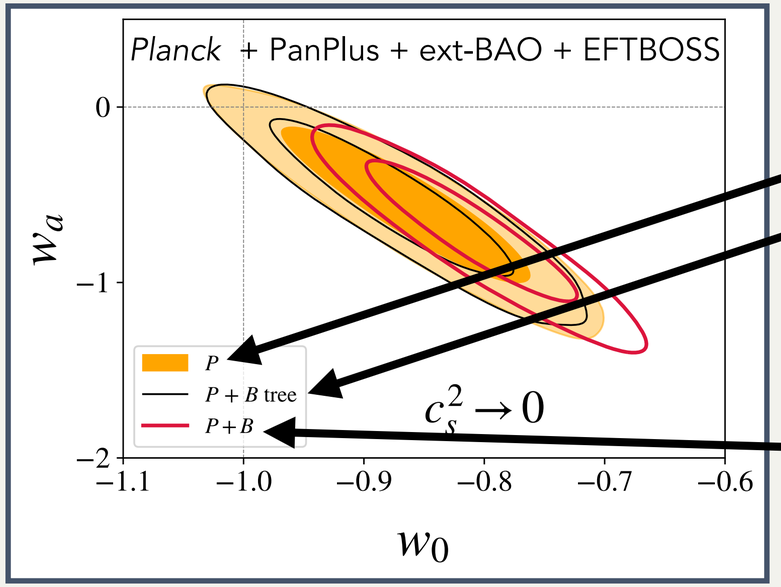
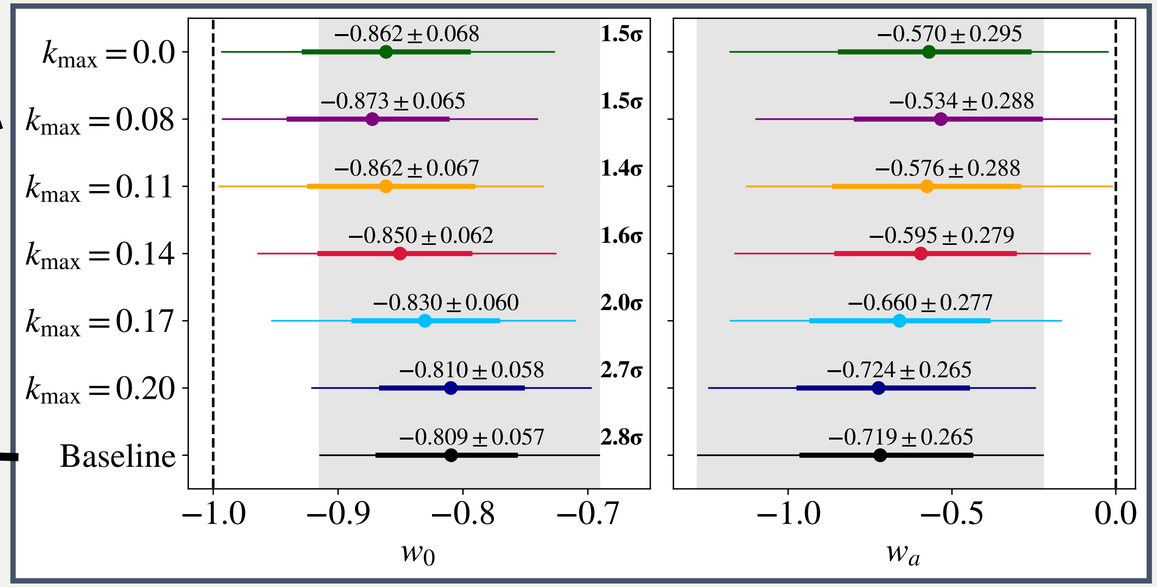




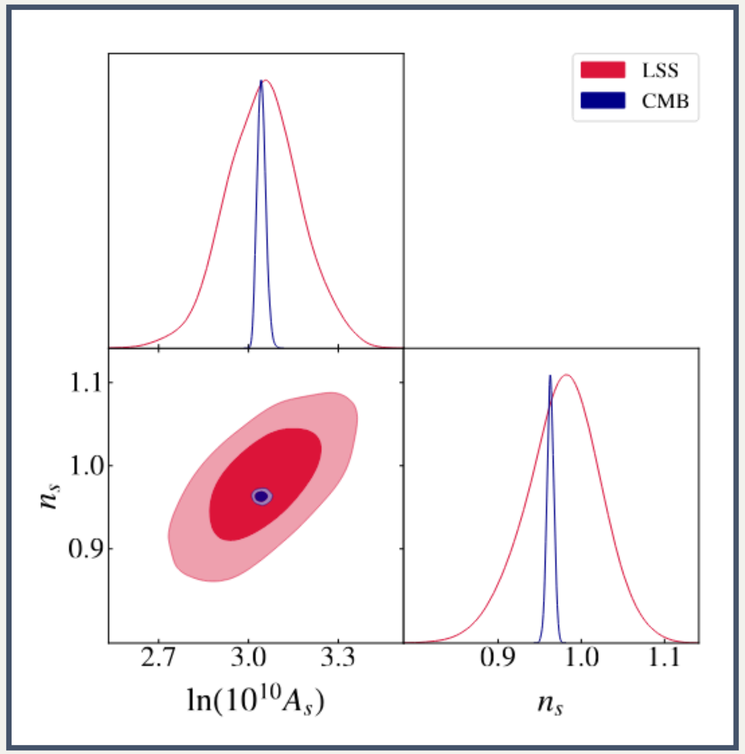
The preference for $w_0 w_a$ comes from the one-loop bispectrum contribution!

III- Constraining the initial conditions with the EFTofLSS

Based on:

- R. Calderon, **TS**, A. Shafieloo and D. K. Hazra **[arXiv:2504.06183]**
  Primordial Features in light of the Effective Field Theory of Large Scale Structure

EFTofLSS meets the standard initial conditions



$$P_{\phi,0} = \frac{2\pi^2 A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$$

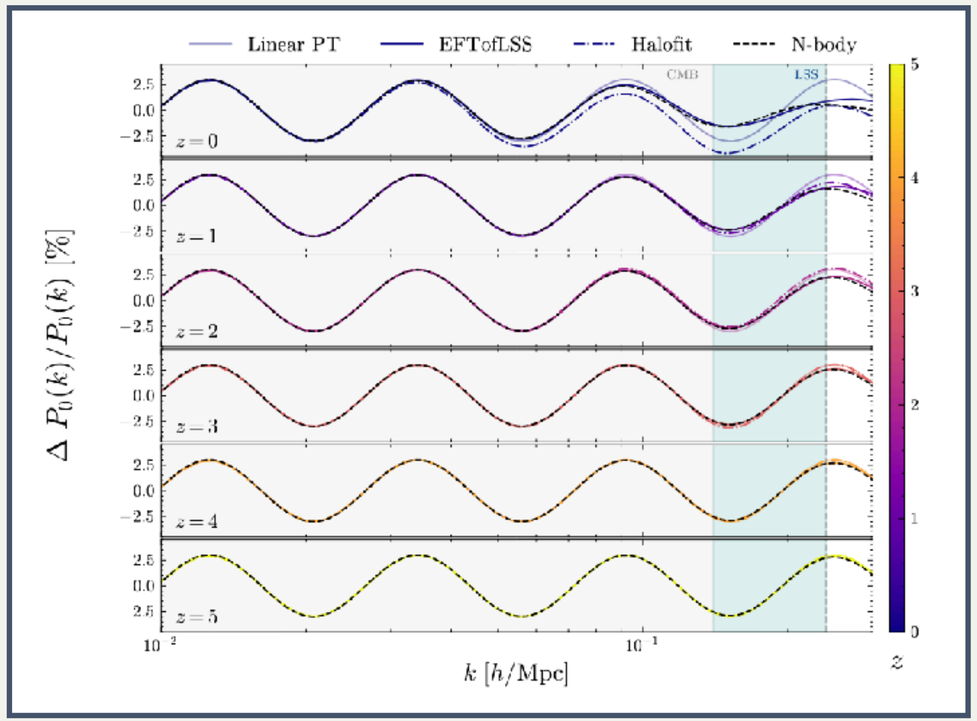
- The *Planck* constraints on $\ln(10^{10}A_s)$ and n_s are respectively **8 and 10 times better** than those of BOSS + eBOSS (LSS)

- **Question**: What is the sensitivity of the current large-scale structure data on inflationary dynamics beyond the standard "slow-roll" regime?

ETFofLSS meets primordial global oscillations

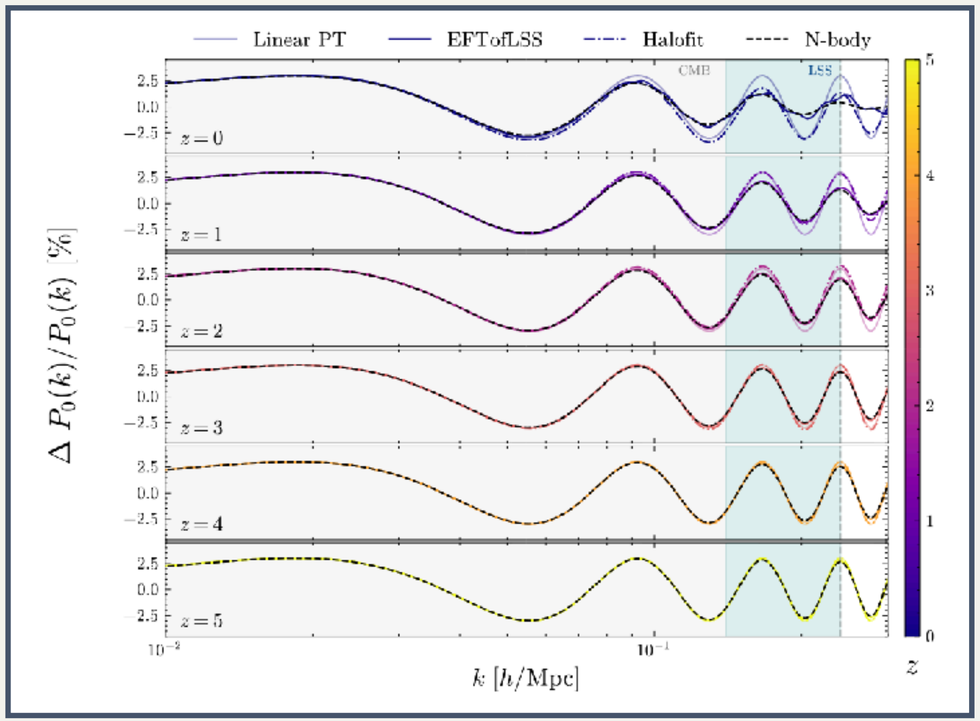
Linear oscillations

$$P_{\phi,0} \to P_{\phi,0}\left[1 + A_{\rm lin}\sin(\omega_{\rm lin}\frac{k}{k_*} + \phi_{\rm lin})\right]$$



Logarithmic oscillations

$$P_{\phi,0} \to P_{\phi,0}\left[1 + A_{\rm log}\sin(\omega_{\rm log}\ln\left(\frac{k}{k_*}\right) + \phi_{\rm log})\right]$$



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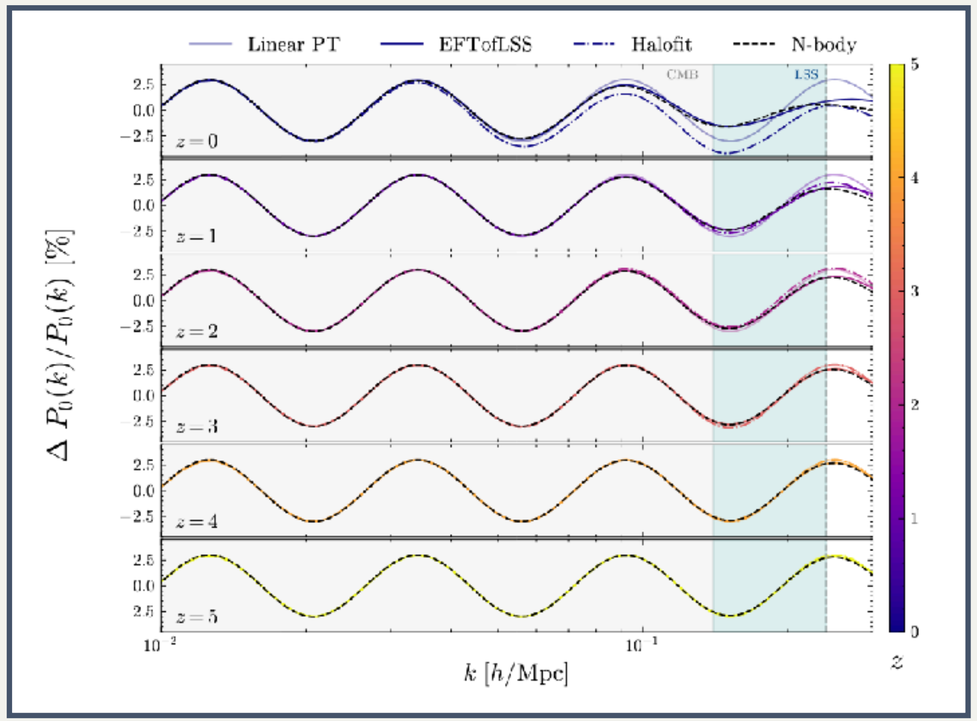

Logarithmic oscillations

- **Very good consistency** between Nbody simulations and EFTofLSS prediction
- Non-linearities introduce a **damping** of the oscillatory features
- The damping is **enhanced for small redshifts**
- (e)BOSS data allow to explore the regime $k \sim 0.1 - 0.2\,h/\mathrm{Mpc}$, **which is not accessible by *Planck***

ETFofLSS meets primordial global oscillations

Linear oscillations

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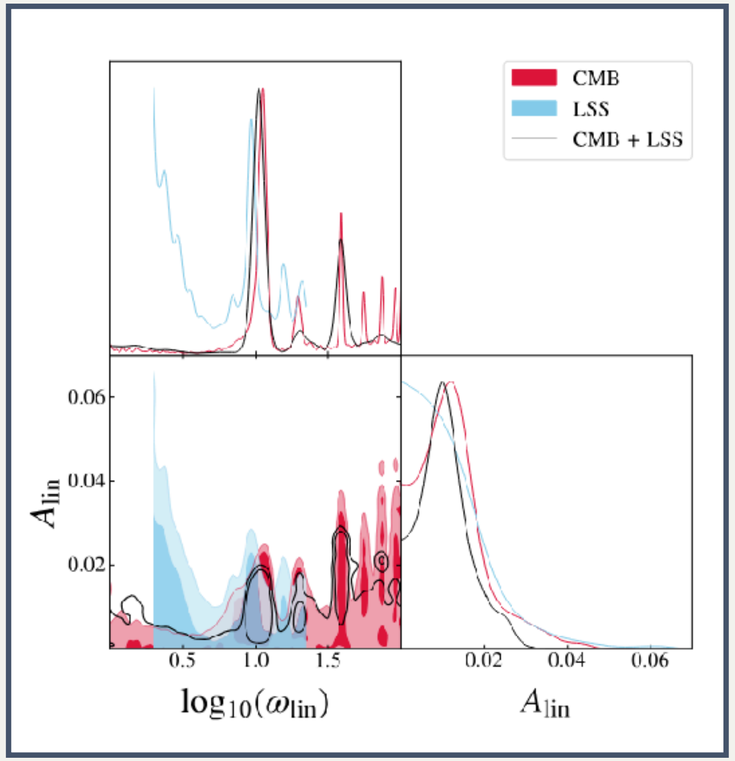


$A_{\rm lin}^{\rm LSS} < 0.031$

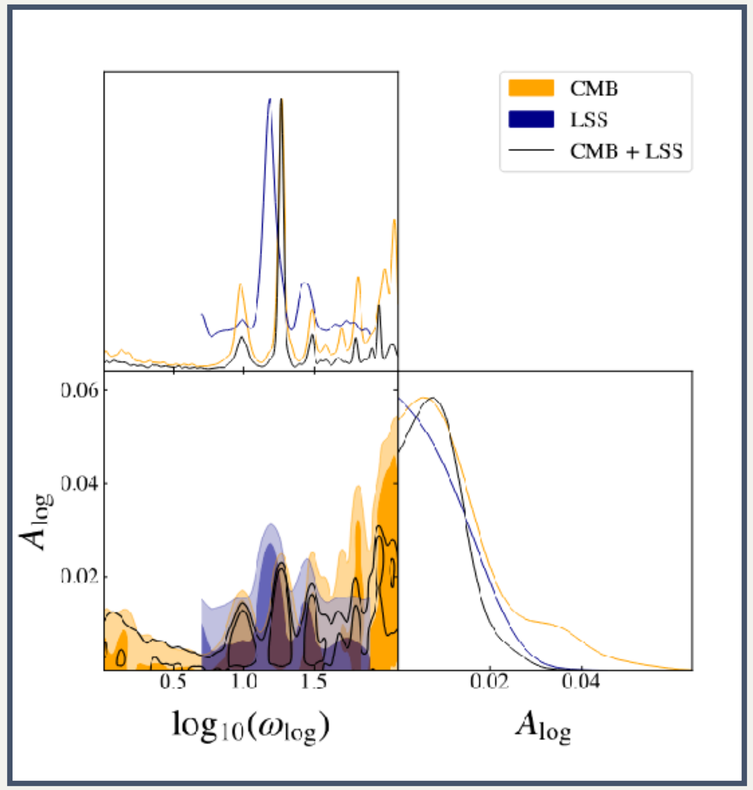
$A_{\rm lin}^{\rm CMB} < 0.019$

- The LSS constraint on $A_{\rm lin}$ is **only 1.6 times weaker** than that of the CMB
- When we combine LSS with CMB, **we improve the constraints by** $25\,\%$ compared to CMB
- $\phi_{\rm lin}$ and $\omega_{\rm lin}$ **are not (yet?) constrained** by CMB and LSS data

ETFofLSS meets primordial global oscillations

Logarithmic oscillations

$$P_{\phi,0} \to P_{\phi,0}\left[1 + A_{\log}\sin(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \phi_{\log})\right]$$

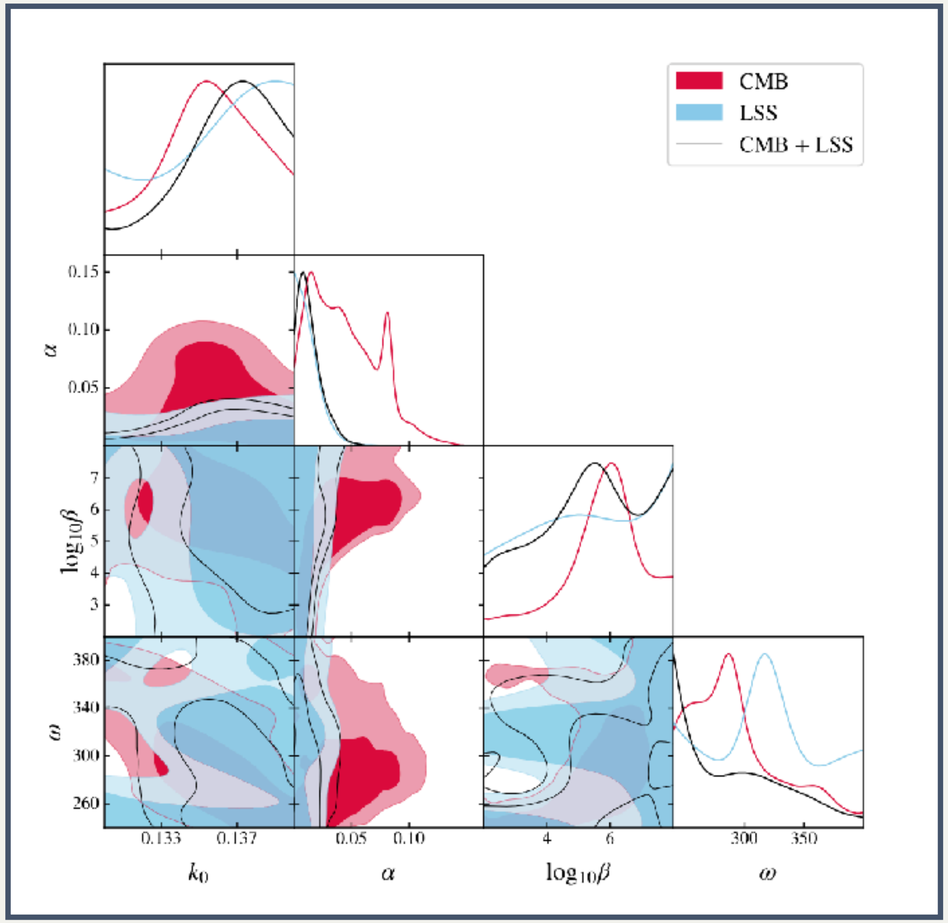


$A_{\log}^{\mathrm{LSS}} < 0.024$

$A_{\mathrm{lin}}^{\mathrm{CMB}} < 0.024$

- We obtain **the same constraint** on $A_{\log}$ between CMB and LSS!
- When we combine LSS with CMB, **we improve the constraints by** $50\,\%$ compared to CMB
- $\phi_{\log}$ and $\omega_{\log}$ **are not (yet?) constrained** by CMB and LSS data

ETFofLSS meets primordial local oscillations



One Spectrum

$$P_{\phi,0} \to P_{\phi,0}\left[1 + \alpha \frac{\sin(\omega(k-k_0))}{1+\beta(k-k_0)^4}\right]$$

Hazra++ [arXiv:2201.12000]

$\alpha^{\mathrm{CMB}} < 0.094$

$\alpha^{\mathrm{LSS}} < 0.034$

$\alpha^{\mathrm{CMB+LSS}} < 0.035$

- LSS data are **3 times more constraining** than CMB data!
- EFTofLSS analysis applied to (e)BOSS data is able to **disfavor localized primordial oscillations that are favored by *Planck***

General conclusion

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

→ EFTofLSS allows **much larger constraints** than the BAO/$f\sigma_8$ information on the ΛCDM model and its extensions

→ Constraints from LSS data are **competitive with CMB data**

→ One-loop bispectrum analysis (up to $k_{\rm max} = 0.23\,h{\rm Mpc}^{-1}$) **adds constraining power** (up to $30\,\%$)

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Part II: *How can clustering data be used to constrain the nature of dark energy and the initial conditions?*

→ For *Planck* + SN1a + EFTBOSS **we obtain a** $2.8 - 3.9\sigma$ **preference for** $w_0 w_a$ over Λ (good check of the DESI results)

→ This preference **disappears when we do not include the one-loop bispectrum** (it is important to consider it!)

→ EFTofLSS offers a **robust and fast way to put strong constraints on primordial features** with galaxy clustering

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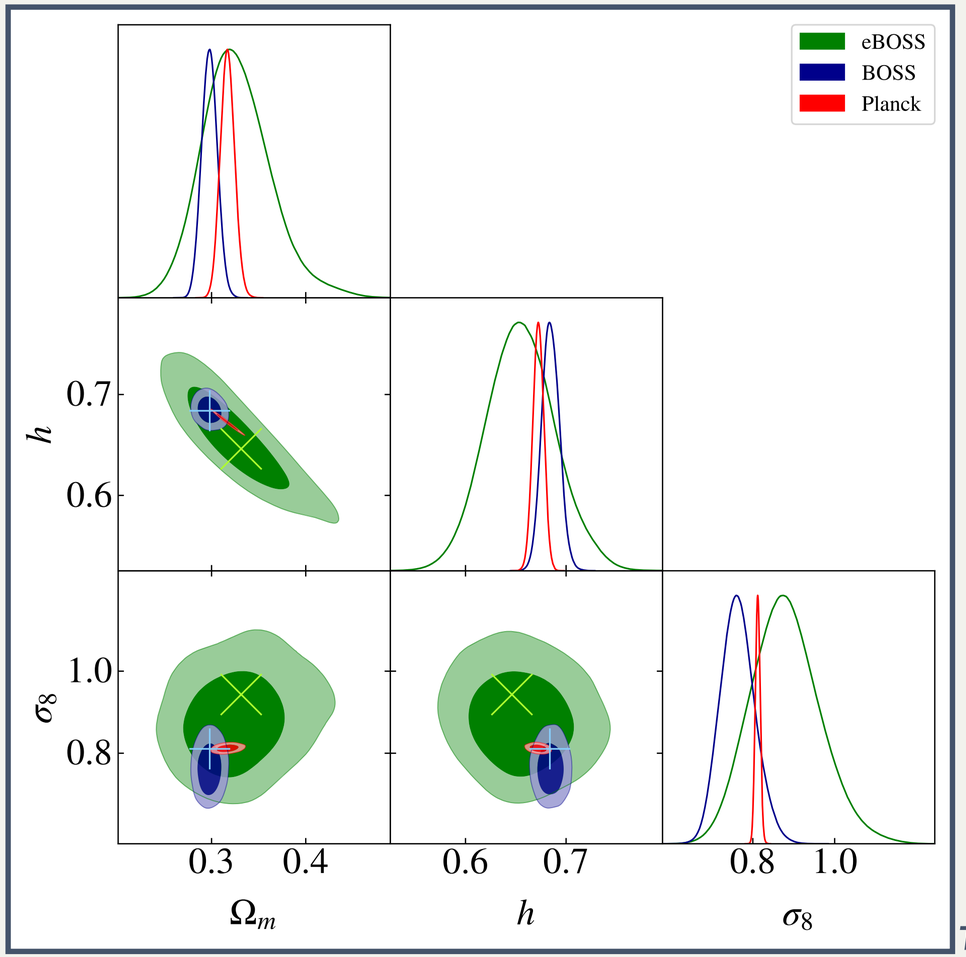
Thanks for your attention!

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**

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]*

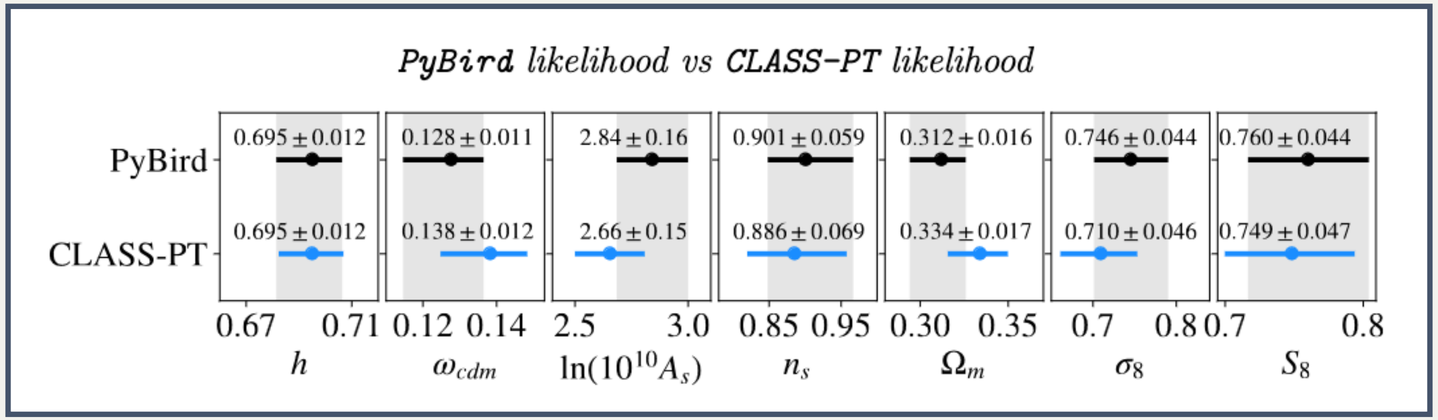
→ ***PyBird*** with the **WC** parametrization *D'Amico++ [arXiv:2003.07956]*

(+ **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]
Philcox++ [arXiv:2002.04035]



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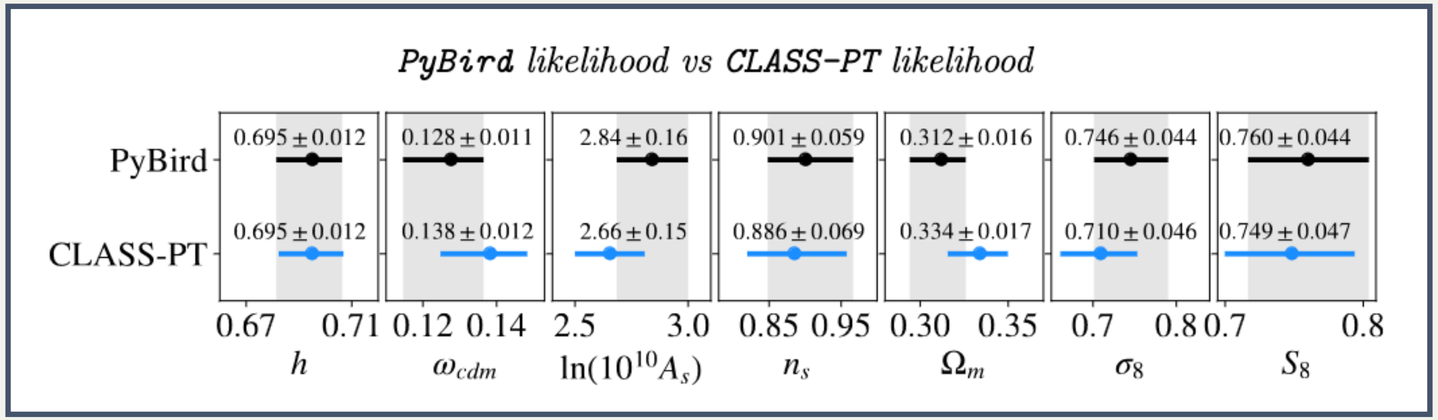
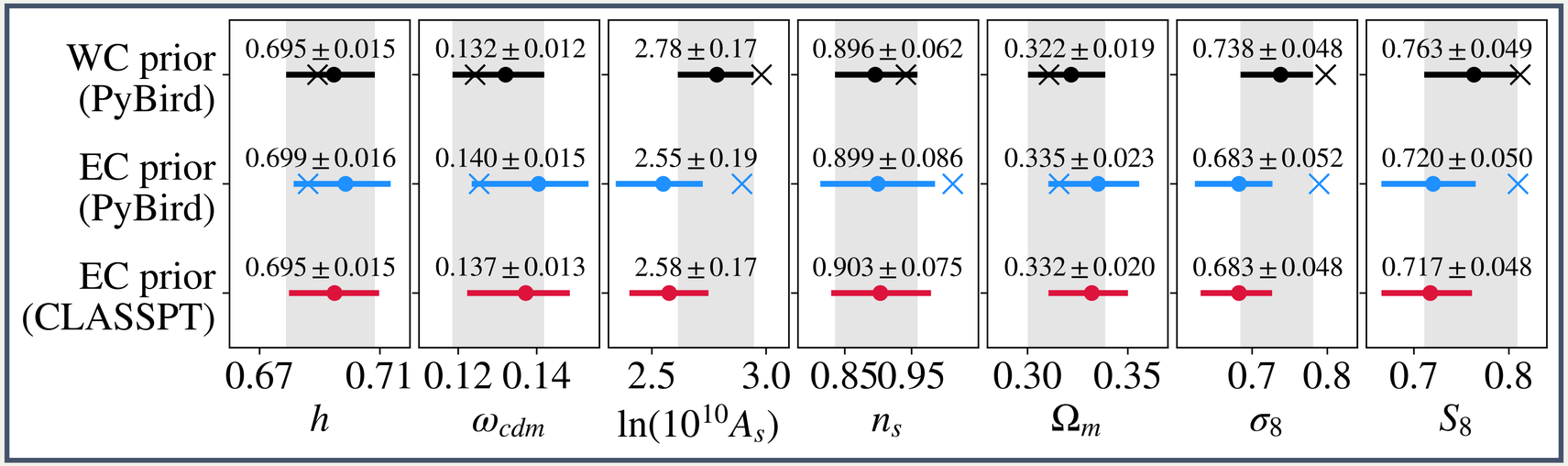


TS++ [arXiv:2208.05929]

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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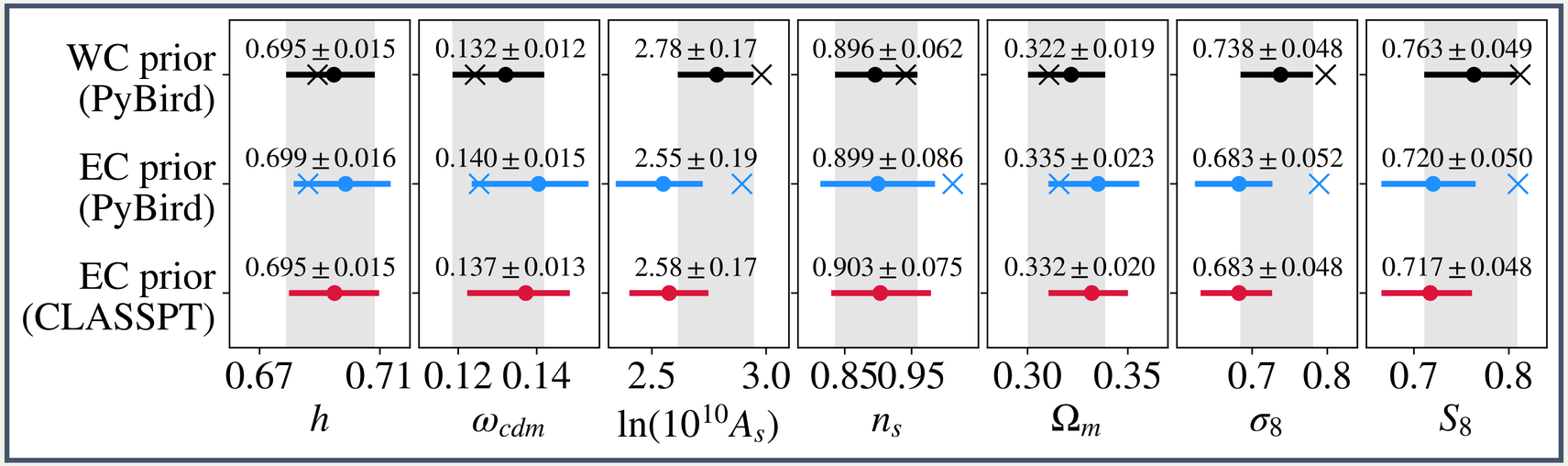


TS++ [arXiv:2208.05929]

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

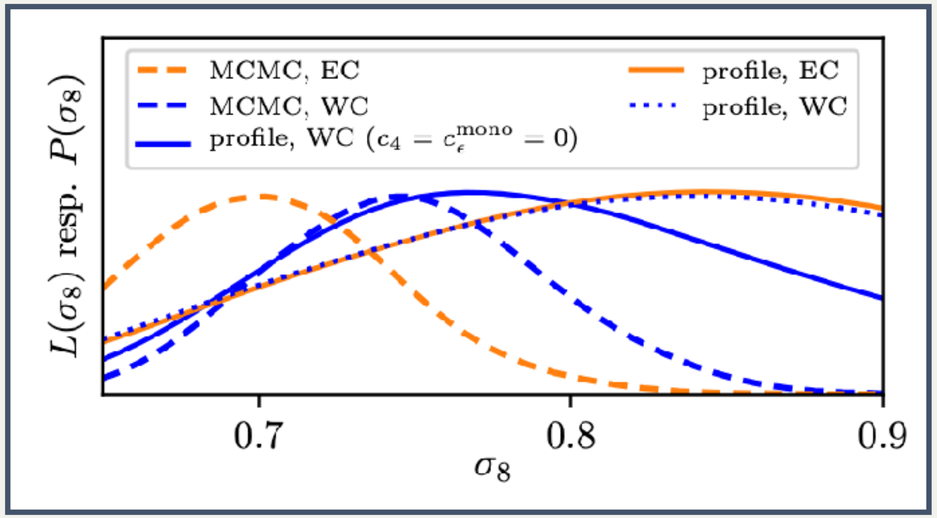
Bayes' theorem:
$P \propto \mathscr{L} \times p$

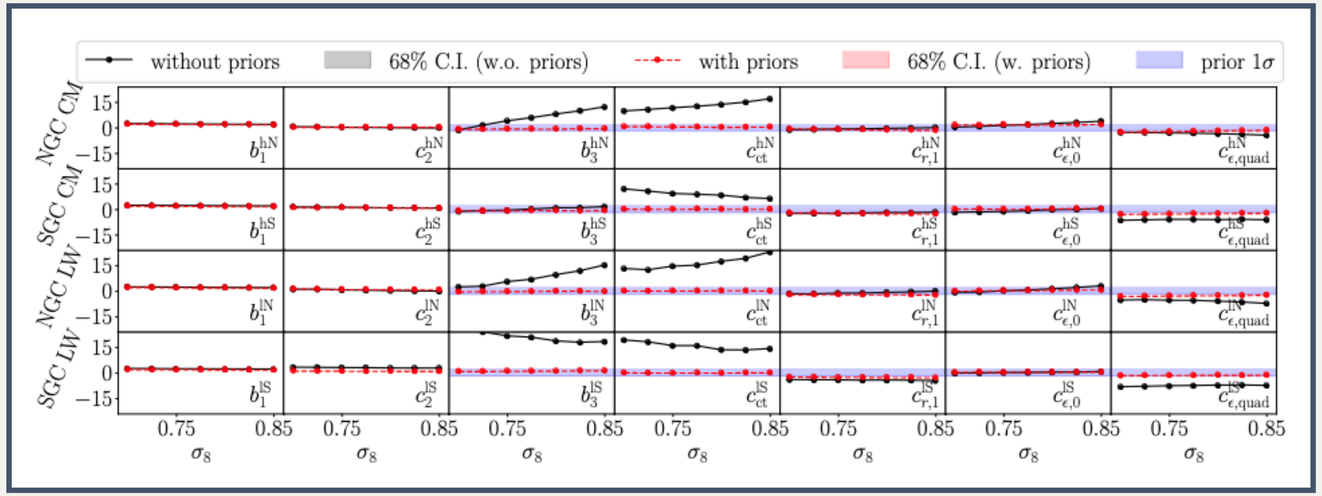
On the consistency of EFTofLSS

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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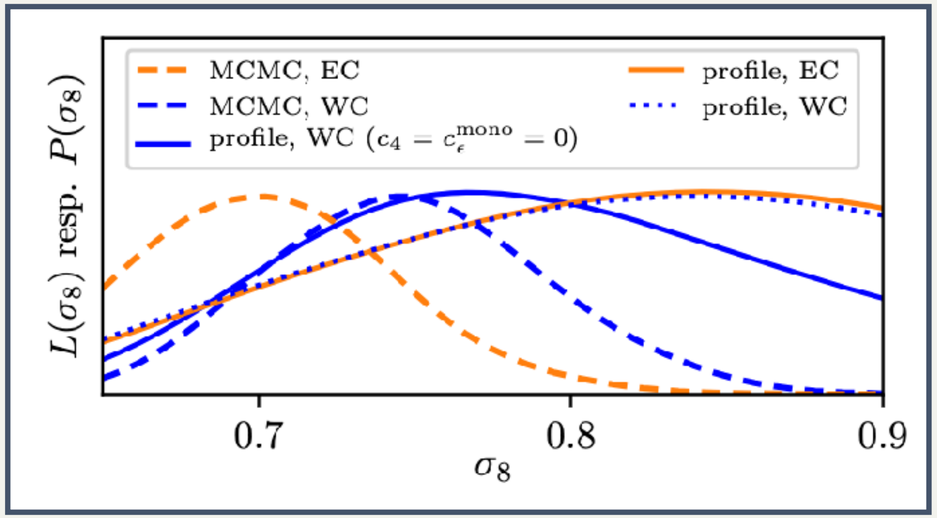
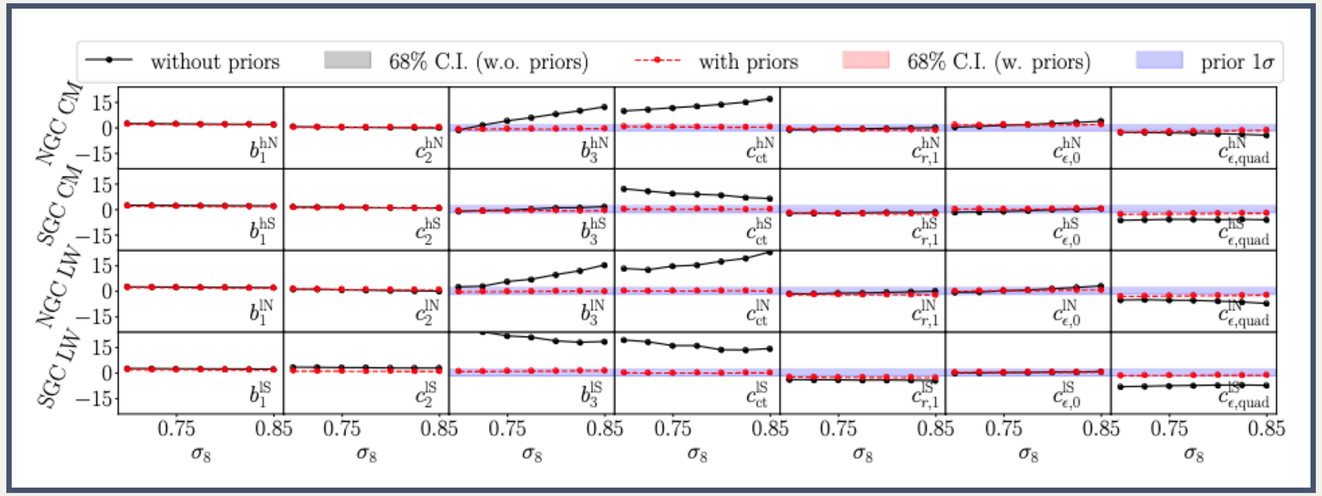


The low value of σ_8 is due to prior effects!



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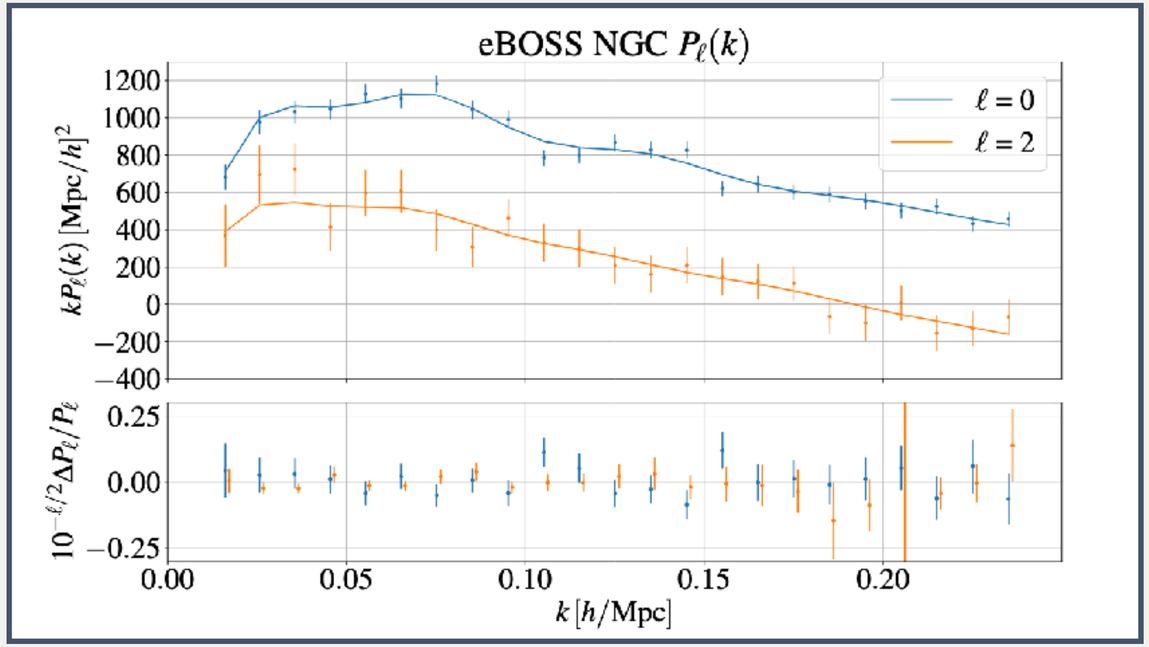
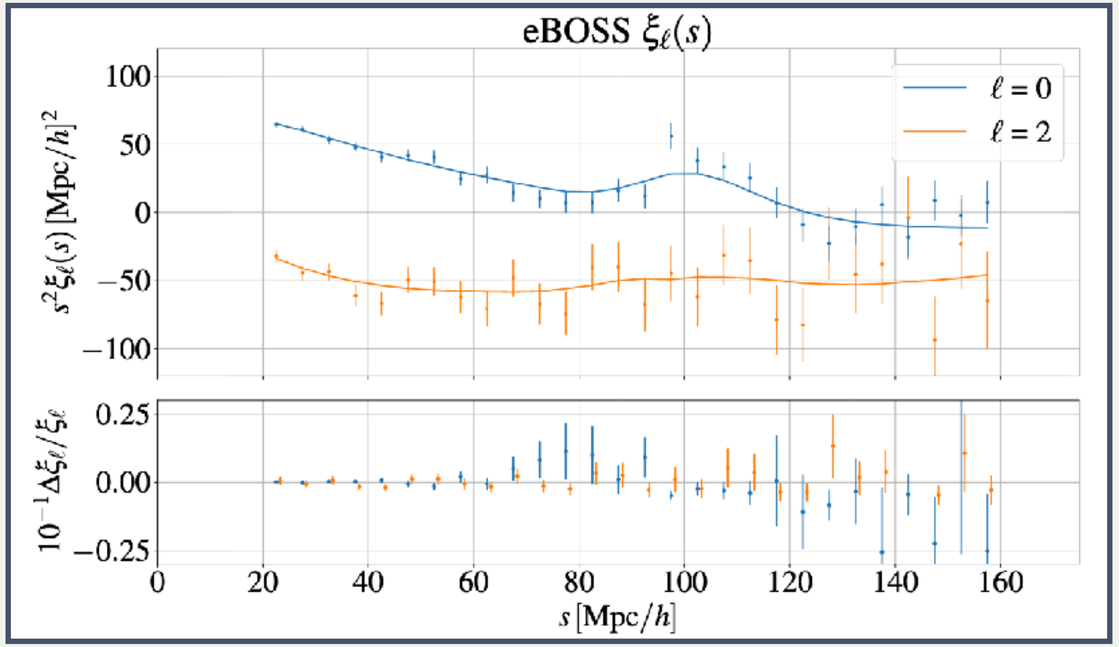
EFTofLSS applied to eBOSS QSO data

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

eBOSS Collaboration [arXiv:2007.08991]





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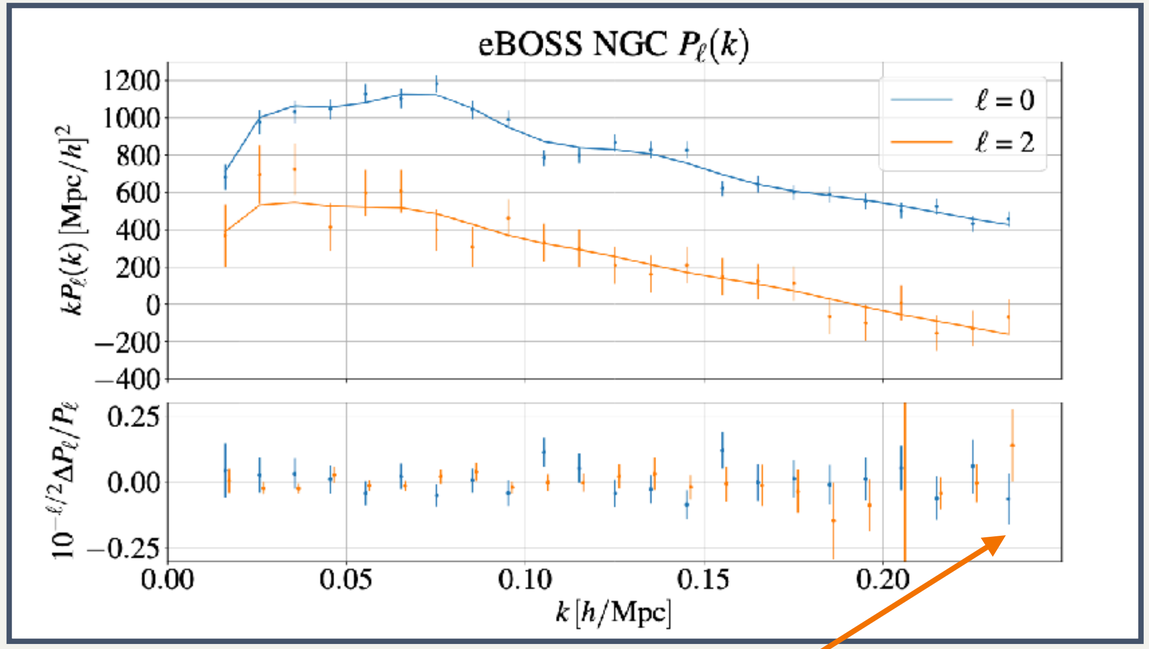

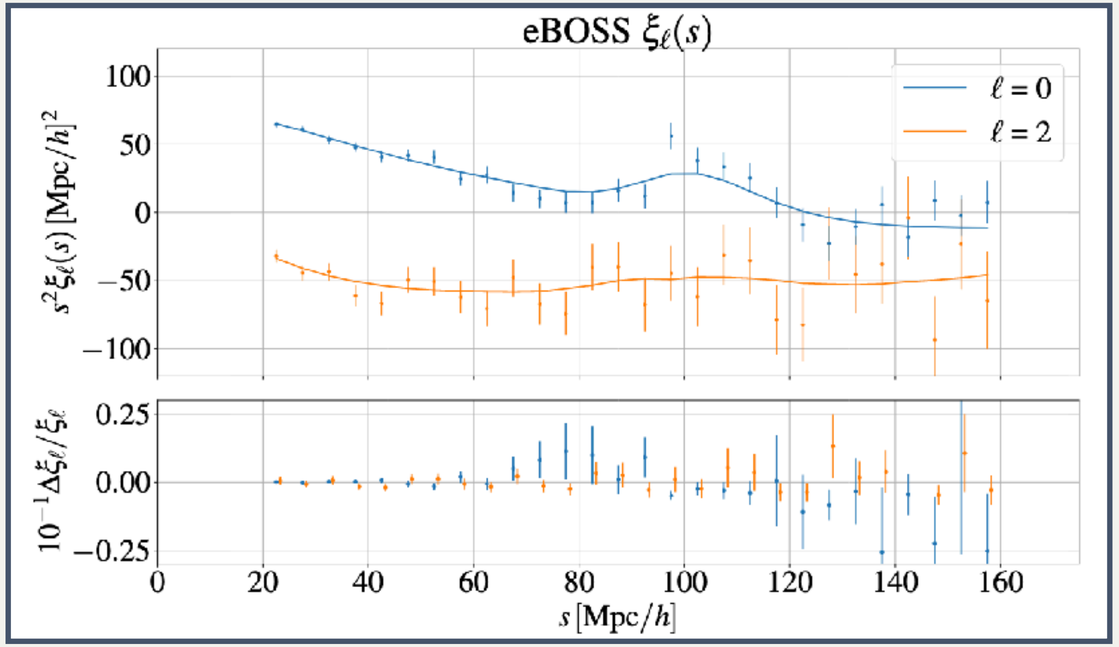

cut-off scale $k_{\rm max} = 0.24\,h\,.\,{\rm Mpc}^{-1}$

TS++ [arXiv:2210.14931]

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

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2 new EFT parameters

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$$P_g(k,\mu) = Z$$
$$+ 2\int \frac{d^3q}{(2\pi)^3}$$
$$+ \frac{1}{\bar{n}_g}\left(c_{\epsilon,0} +\right.$$

$k, \mu)P_{11}(q)$

One can add the **NI**

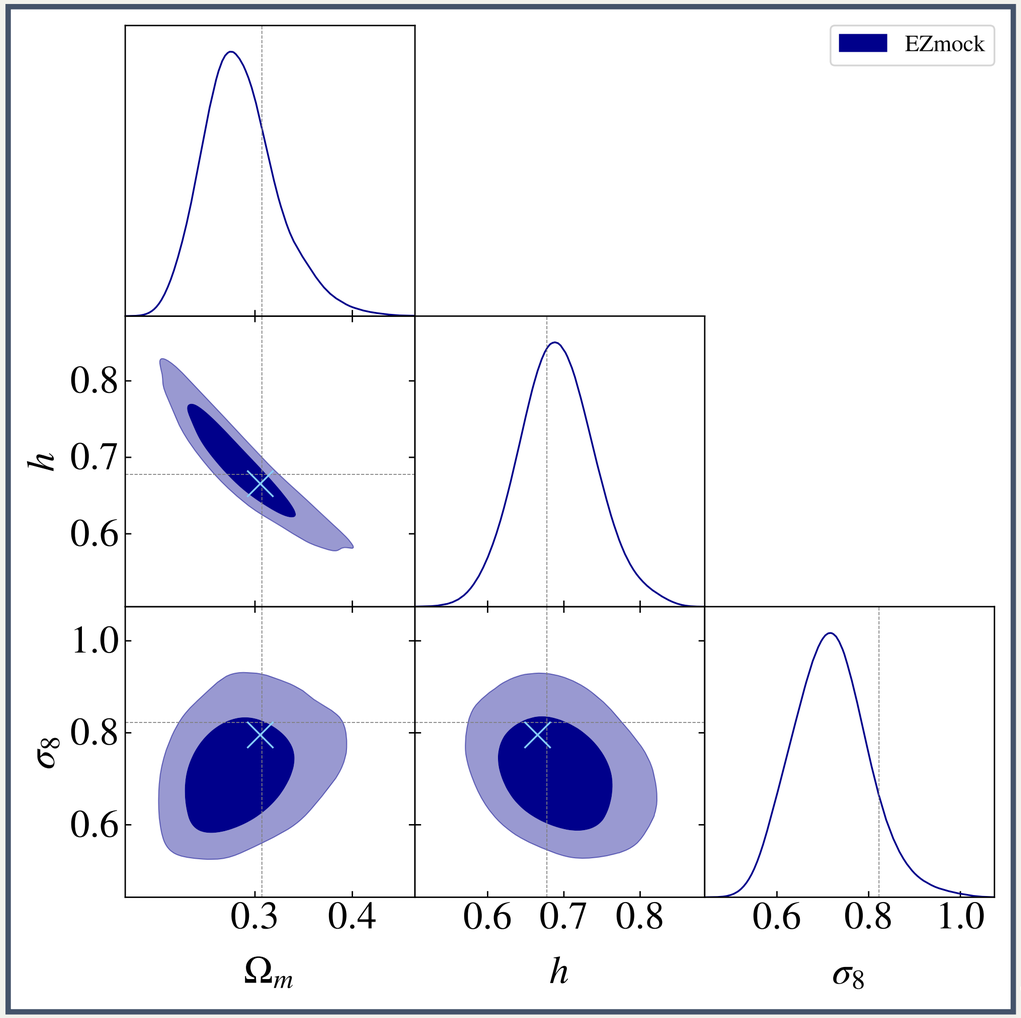
$\Delta^{\text{shift}}_{\text{NNLO}}/\sigma^{\text{eBOSS}}_{\text{stat}}$				
$k_{\max}$ $[h\,\text{Mpc}^{-1}]$	0.21	0.24	0.27	0.30
Ω_{m}	0.09	-0.01	0.09	-0.49
h	-0.09	-0.05	0.09	0.21
σ_8	-0.01	-0.02	0.22	-0.02
b_1^{N}	0.02	-0.01	0.01	-0.10
c_2^{N}	0.07	0.07	0.62	0.38
b_1^{S}	0.05	-0.01	0.05	-0.01
c_2^{S}	0.06	-0.07	0.49	0.35

[arXiv:2110.07539]

If the contribution o ction is **not**
accurate enough → on

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

The EZmock



- **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 $\lesssim 1/3 \cdot \sigma$

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**

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

LSS+Planck:
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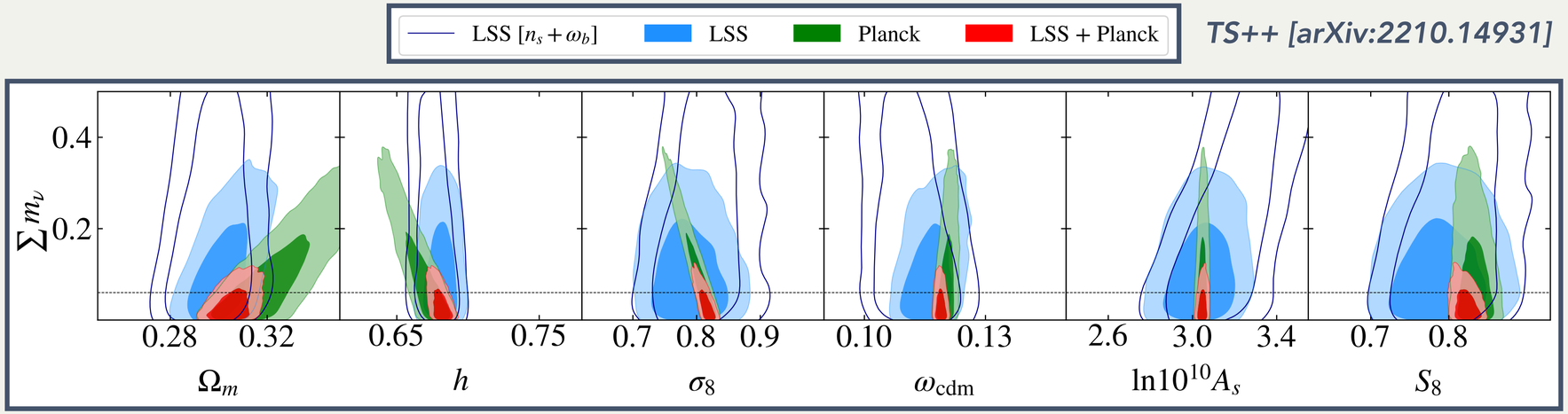

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DESI++ [arXiv:2411.12022]

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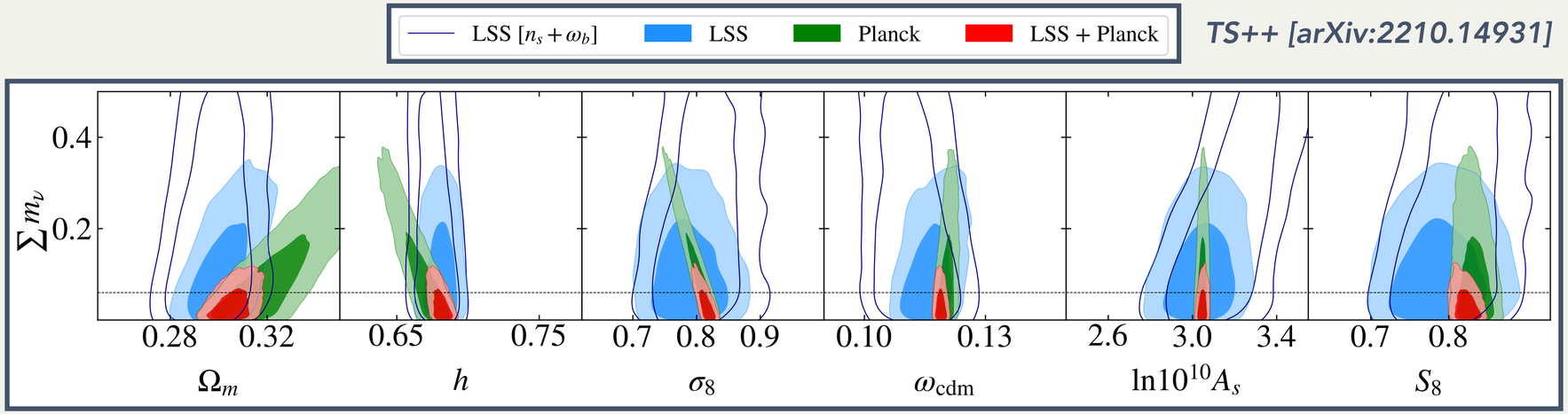


TS++ [arXiv:2210.14931]

Extensions to ΛCDM: curvature density fraction Ω_k

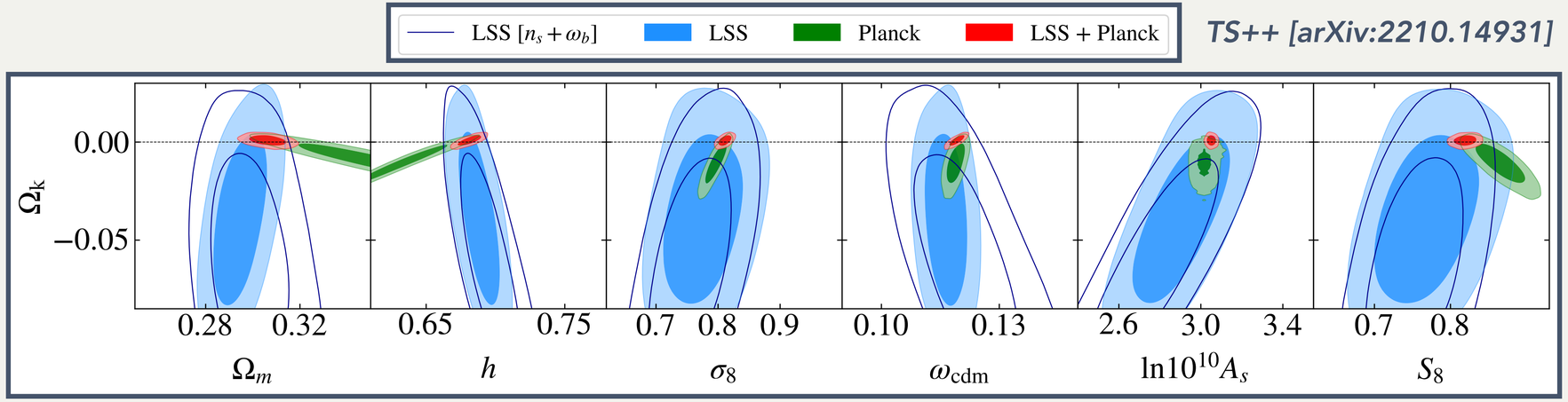
- With LSS data only, we find Ω_k **compatible with zero curvature at** 1.3σ
- The EFT analysis **significantly improves the constraints** on Ω_k by $\sim 50\,\%$ compared to the conventional BAO/$f\sigma_8$ analysis
- The combination of LSS and Planck leads to a **strong constraint** and excludes the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

LSS:

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

LSS+Planck:

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



TS++ [arXiv:2210.14931]

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

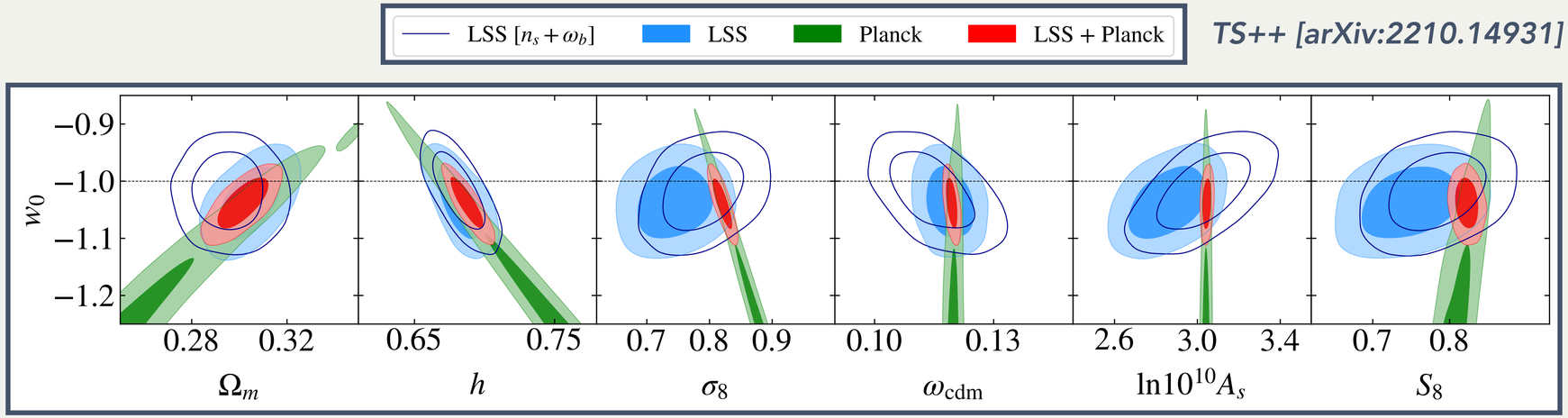
TS++ [arXiv:2210.14931]

LSS:

$w_0 = -1.038 \pm 0.041$

LSS+Planck:

$w_0 = -1.039 \pm 0.029$



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

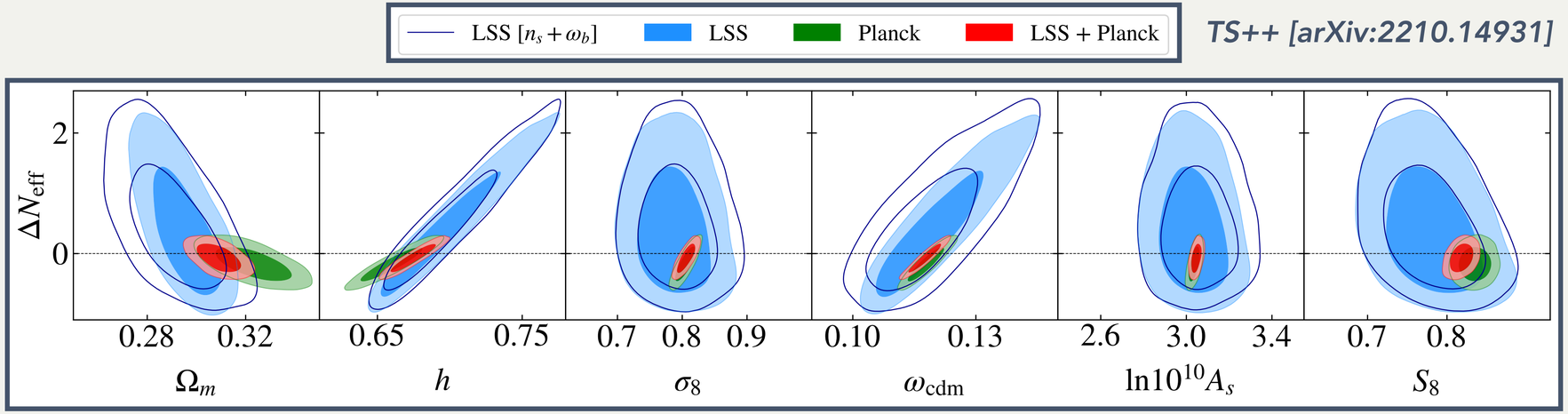
- The value of $\Delta N_{\rm eff}$ is **compatible with the standard model**
- Unlike EFTofLSS, **the conventional BAO/$f\sigma_8$ analysis is unable to constrain this parameter**
- The addition of the LSS data **improves** the results of Planck alone by $\sim 25\,\%$

LSS:

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

LSS+Planck:

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



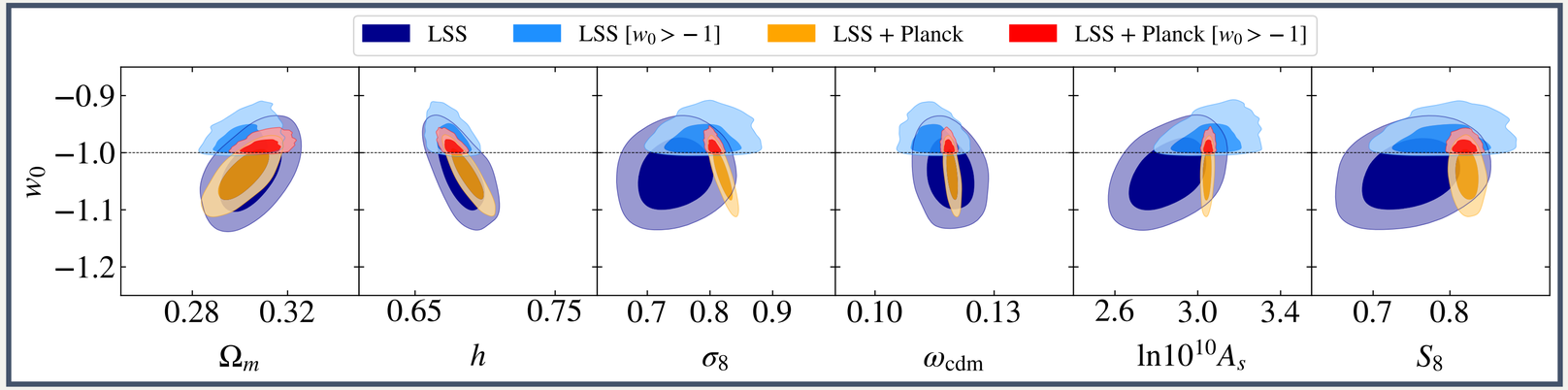
TS++ [arXiv:2210.14931]

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 $w_0 = -1$

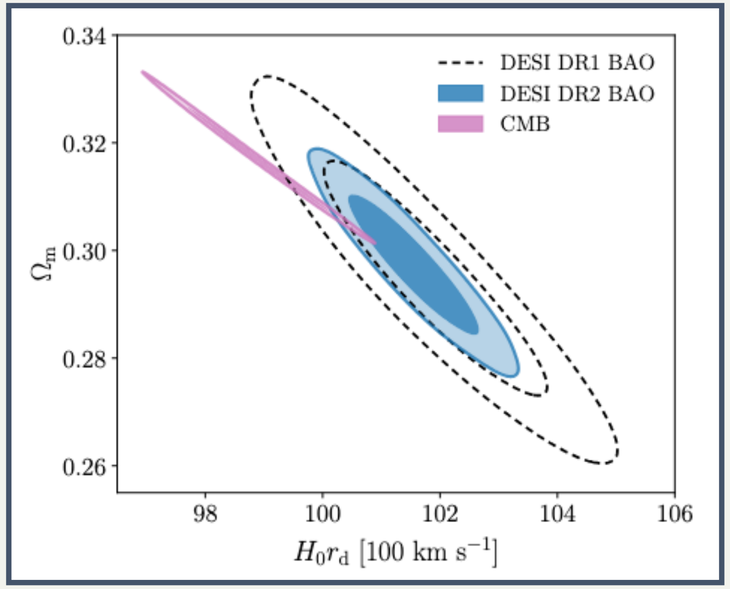
LSS:
$w_0 < -0.932$

LSS+Planck:
$w_0 < -0.965$

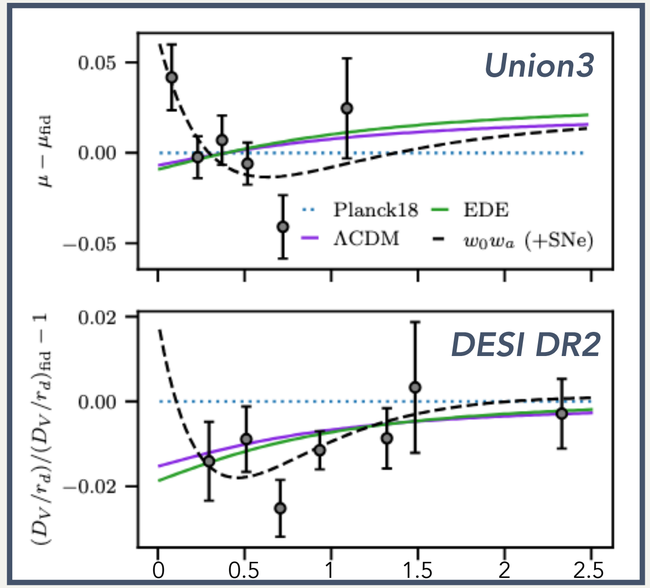


General context: preference for evolving dark energy

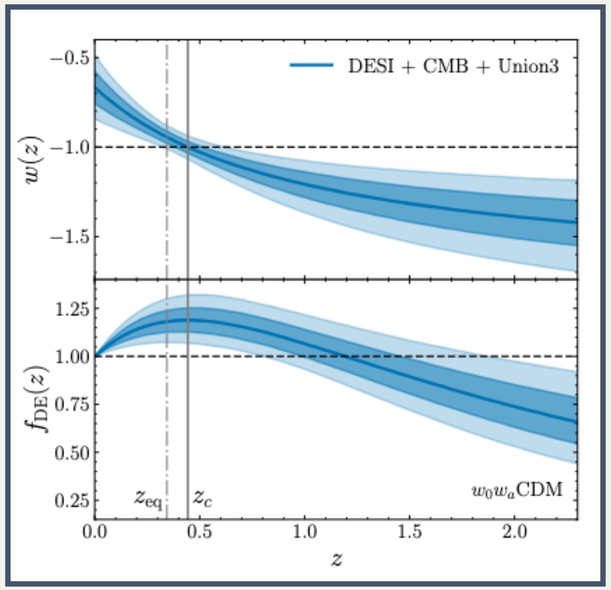
The $w_0 w_a$CDM model allows
- to reduce the **tension between Planck and DESI BAO** in the $H_0 r_d - \Omega_m$ plane
- to provide a **better fit of the low-z distance modulus** data from supernovae
- to provide of **the bump at $z \sim 0.7$ in the DESI DR2** (isotropic) BAO



DESI Collaboration [arXiv:2503.14738]



DESI Collaboration [arXiv:2503.24343]



DESI Collaboration [arXiv:2503.14743

Dark energy perturbations

In this work, we consider two parametrizations of the dark energy perturbations

Smooth quintessence ($c_s^2 \to 1$)

No perturbation (like DESI results)

Clustering quintessence ($c_s^2 \to 0$)

Dark energy clusters exactly like dark matter

Creminelli++ [arXiv:0811.0827]

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$$\delta_A = \delta_m + \delta_d$$

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Euler

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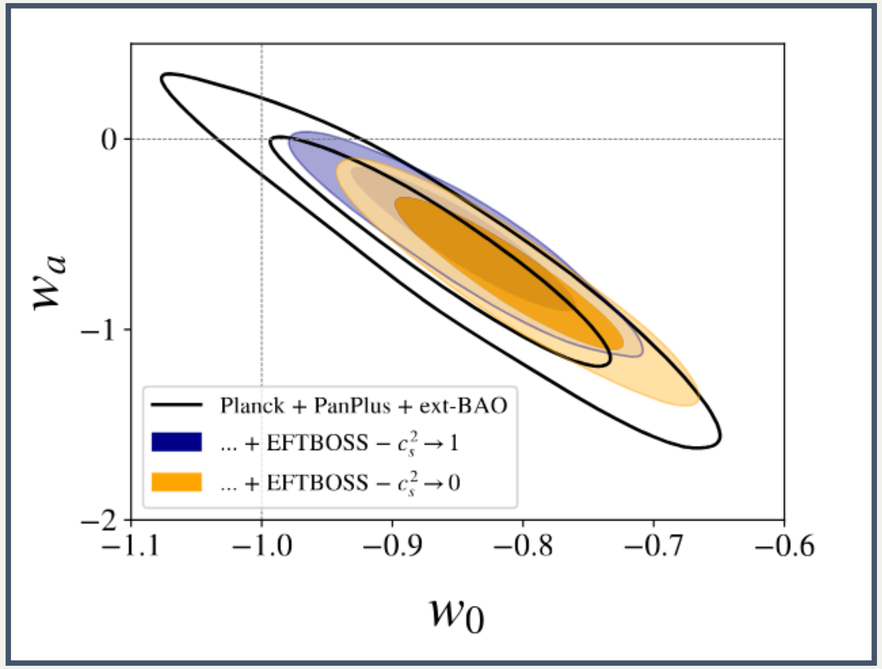
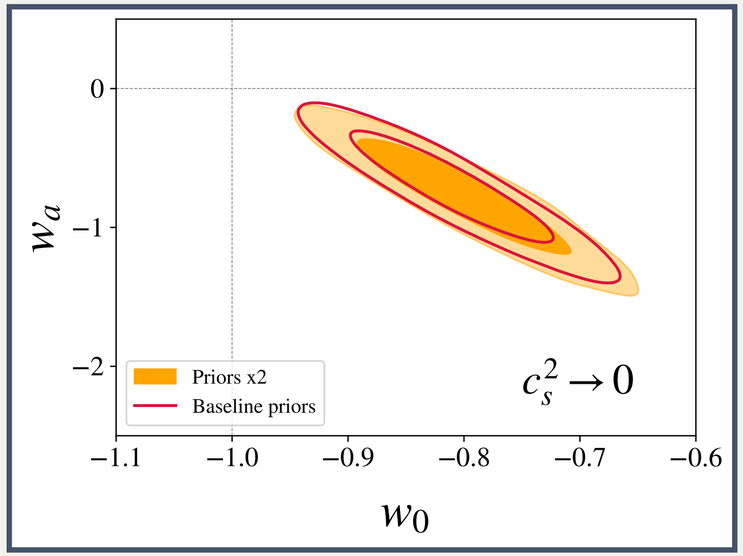
Dark energy perturbation



- The evidence for $w_0 w_a$ is 2.6σ for **smooth quintessence** and 2.8σ for **clustering quintessence**

- Constraints on (w_0, w_a) depend not only on the background but also **on the propagation of dark energy perturbations**, affecting clustering differently

EFT prior effects



Our analysis is not affected by EFT prior effects:

→ the constraints in the $w_0 - w_a$ plane are unchanged the EFT priors are multiplied by 2

→ the relative shifts between the maximum a posteriori and the posterior means are $\lesssim 0.2\sigma$

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:
$P \propto \mathscr{L} \times p$

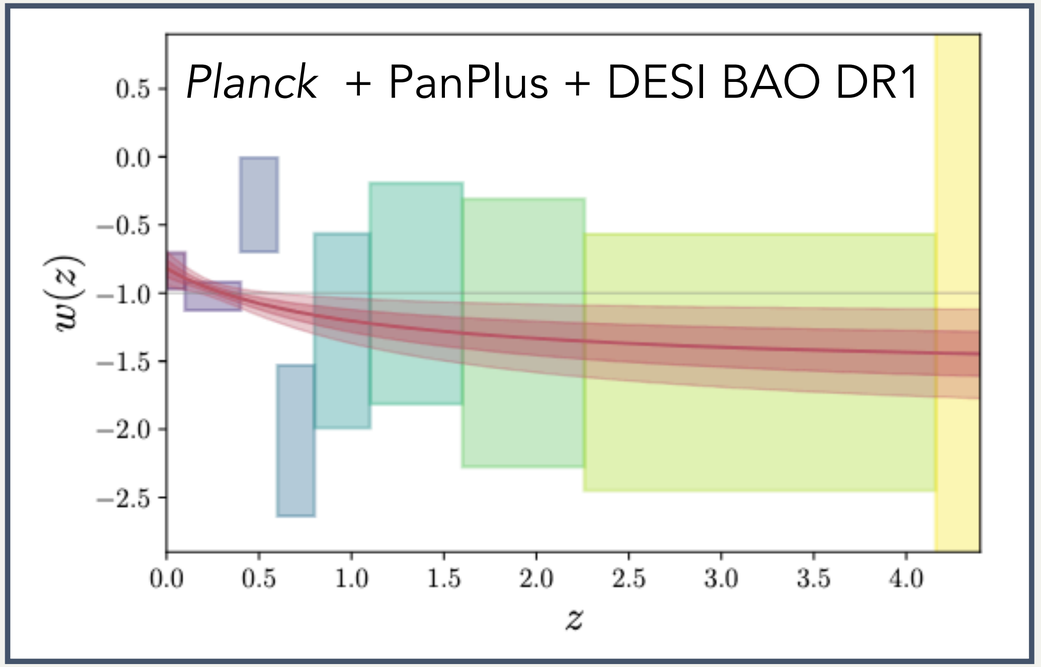
TS++ [arXiv:2208.05929]

Dark energy history

Where does the information to constrain $w(z)$ come from?

General observations

- $w(z)$ is **most constrained** at $z \sim 0.25$
- The **preference for** $w_0 > -1$ is driven by w_1^z, while **the preference for** $w_a < 0$ is driven by the bins spanning from $z \sim 0.6$ to $z \sim 2.3$
- **Beyond** $z \sim 2.3$**, the data has no constraining power on** w_0 **and** w_a (since $\Omega_{\rm DE}(z)/\Omega_{\rm m}(z) \to 0$)



Model independent reconstruction of $w(z)$ based on a general piecewise parametrization $w_i^z, i \in [1,9]$

Dark energy history

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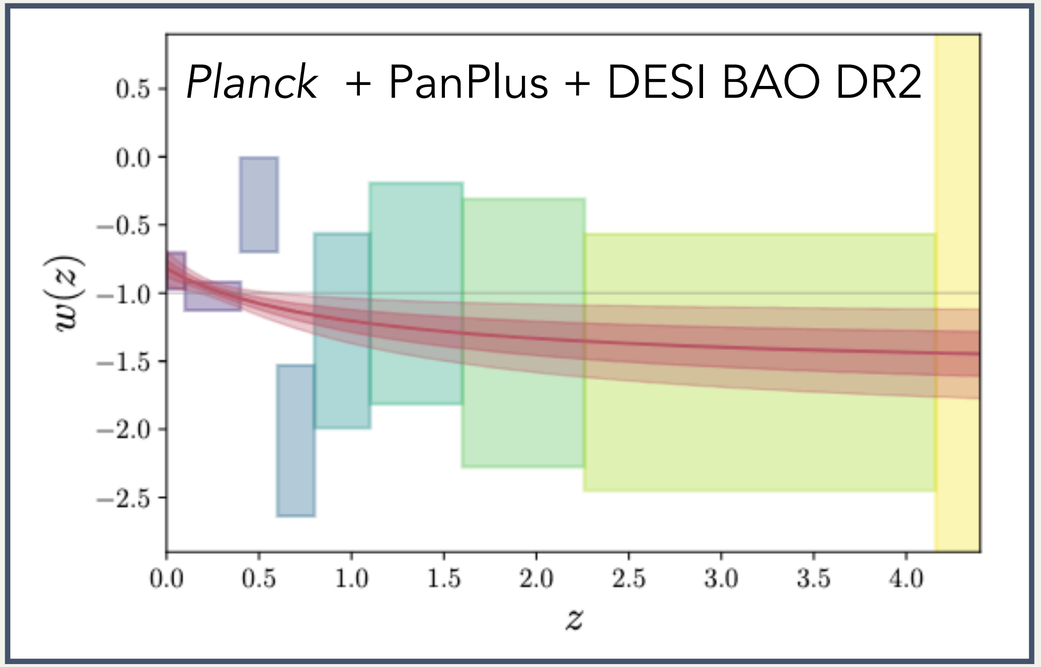
Conclusions

- So **we should not consider** the (w_0, w_a) parameterization after $z \sim 2.3$
- From the model-independent reconstruction, we find a 1.7σ **deviation from** Λ
- **The phantom crossing occurs at** $z \sim 0.4$ (which is bellow $z \sim 2.3$!), and we find a 2.3σ **preference** for a phantom phase within the $w_0 w_a$



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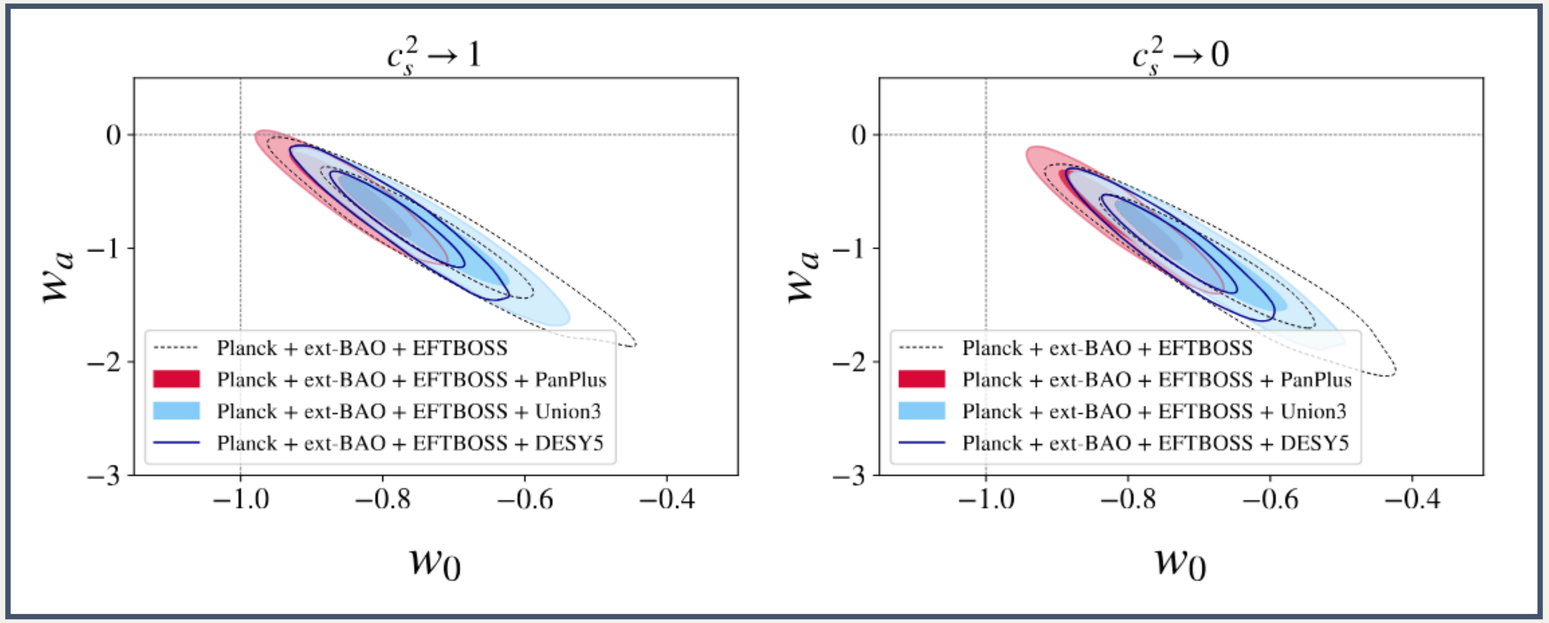
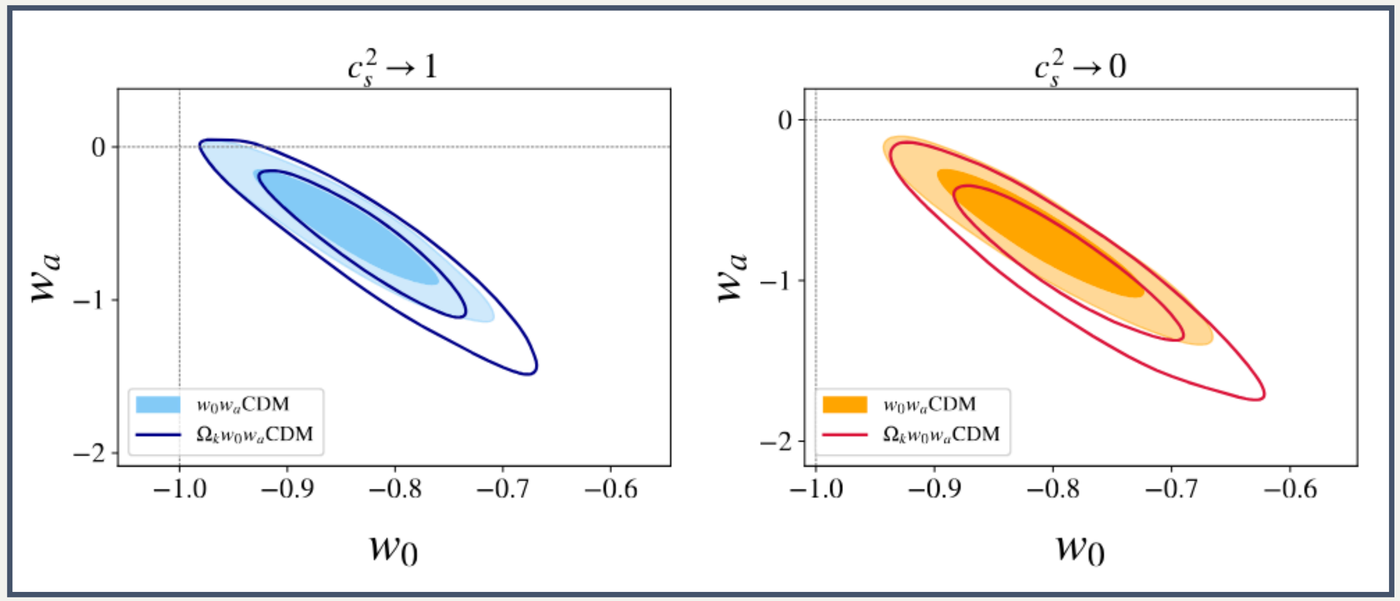
Variation of the supernovae data



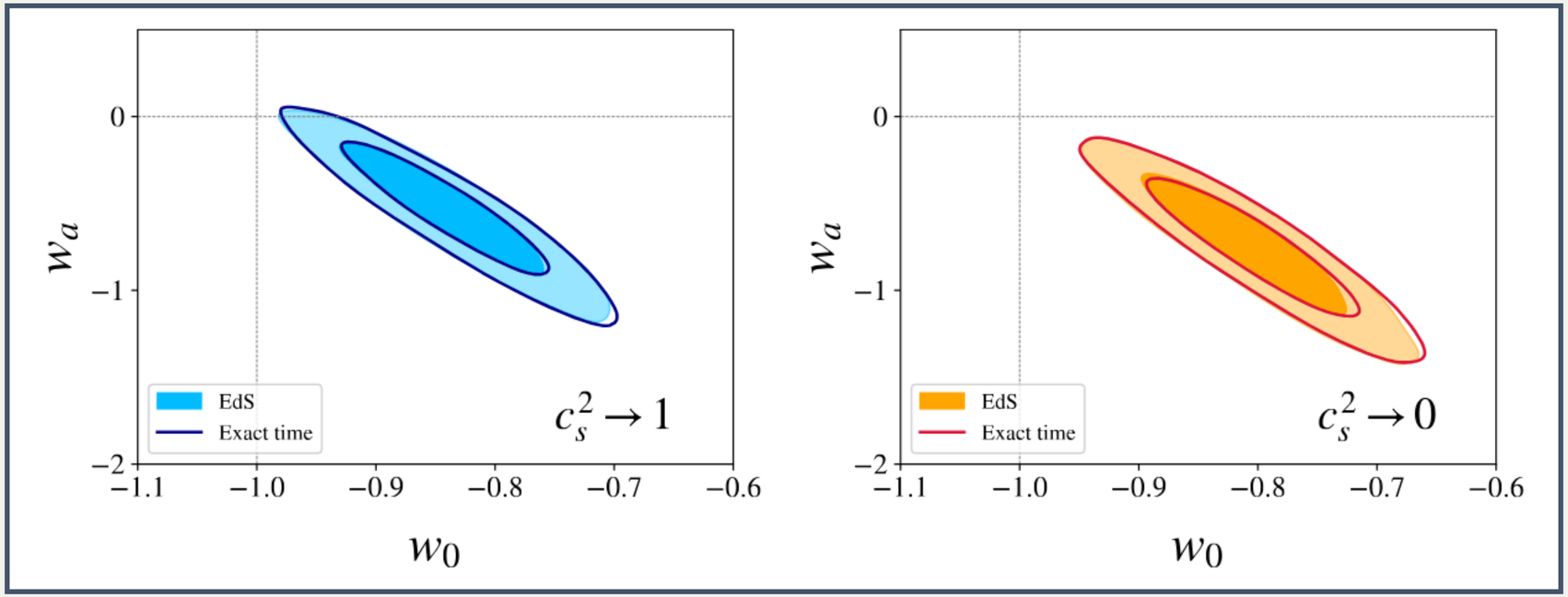
Evolving dark energy and curvature

$\Omega_k = -0.0014 \pm 0.0027$ $\Omega_k = -0.0027 \pm 0.0025$

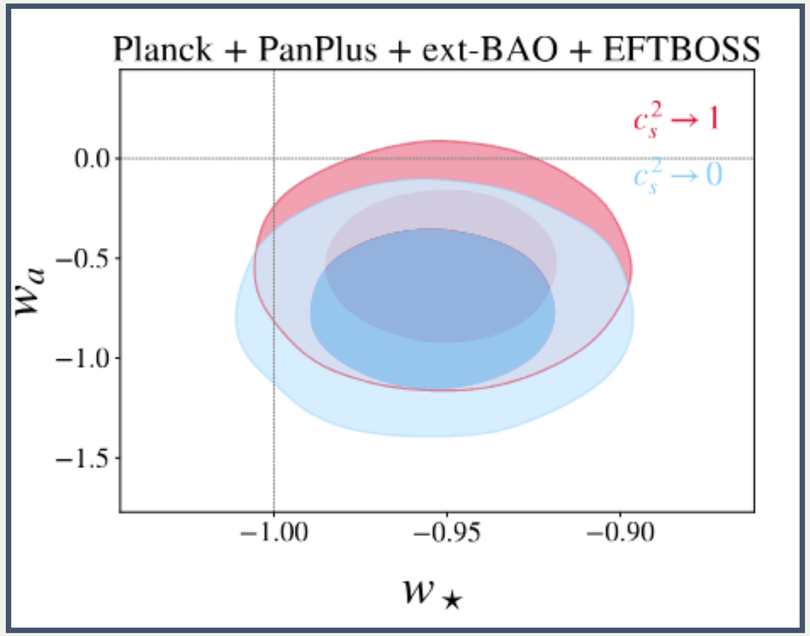


- The constraints on $w_0 - w_a$ are weakened because of the degeneracy with Ω_k
- Yet, the preference over Λ remains similar as in the flat case

Exact-time dependance

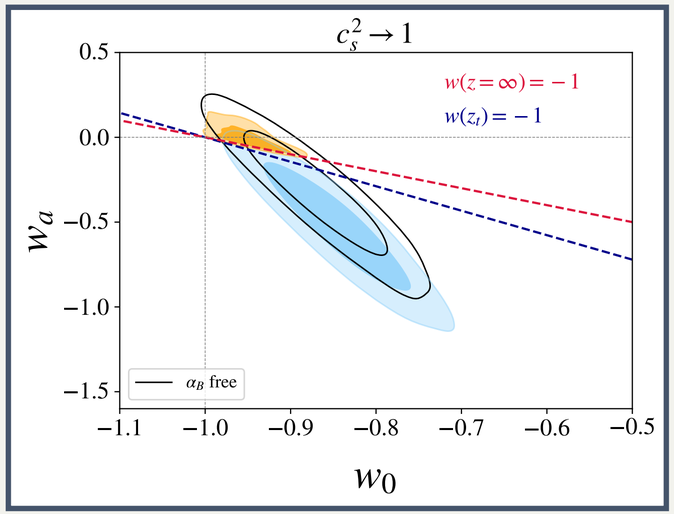


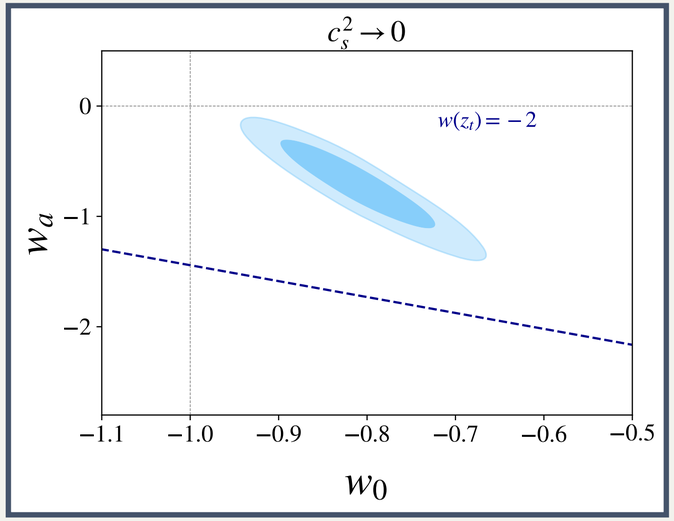
Dark energy pivot scale



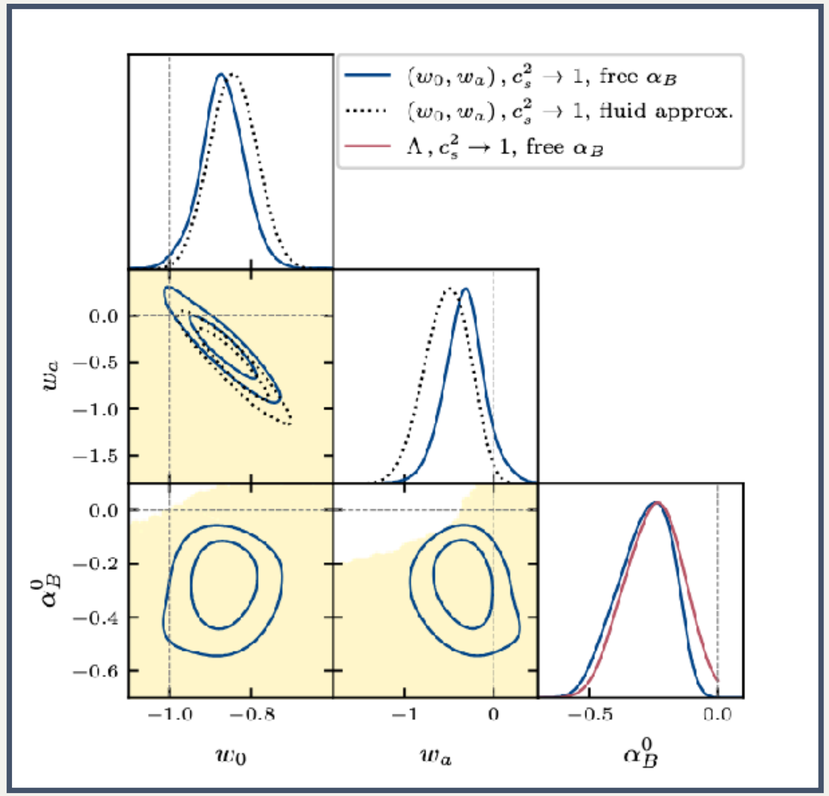
- We define $w_* = w_0 + (1 - a_*)w_a$, such that $w(a) = w_* + (a_* - a)w_a$
- The pivot epoch a_* is chosen such that w_* has minimal variance (w_* is the principal component of $w_0 - w_a$)
- We obtain $z_* = 0.25$

Stability condition





- *K-essence model* (in orange): $w < -1$ is prohibited. It remains consistent with Λ
- $c_s^2 \to 1$ *limit*: stable for $w < -1$ when additional EFTofDE parameters stabilizing the gradient are present. This is the case with α_B, the braiding parameter, for which we find a 2.9σ preference over Λ (α_B is detected at 2σ)
- $c_s^2 \to 0$ *limit*: stable if $w > -1$ when stabilized using higher-order operators



D'Amico++ [arXiv:2012.07554]