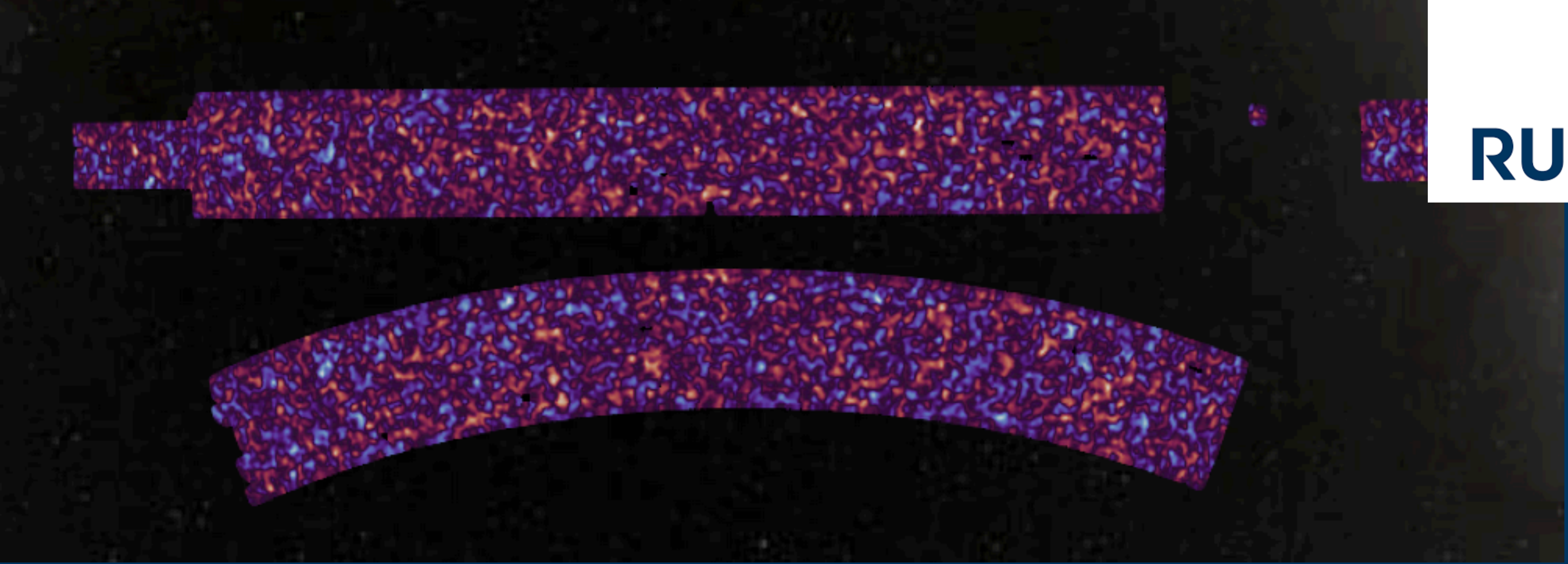


RUHR-UNIVERSITÄT BOCHUM

KiDS-Legacy

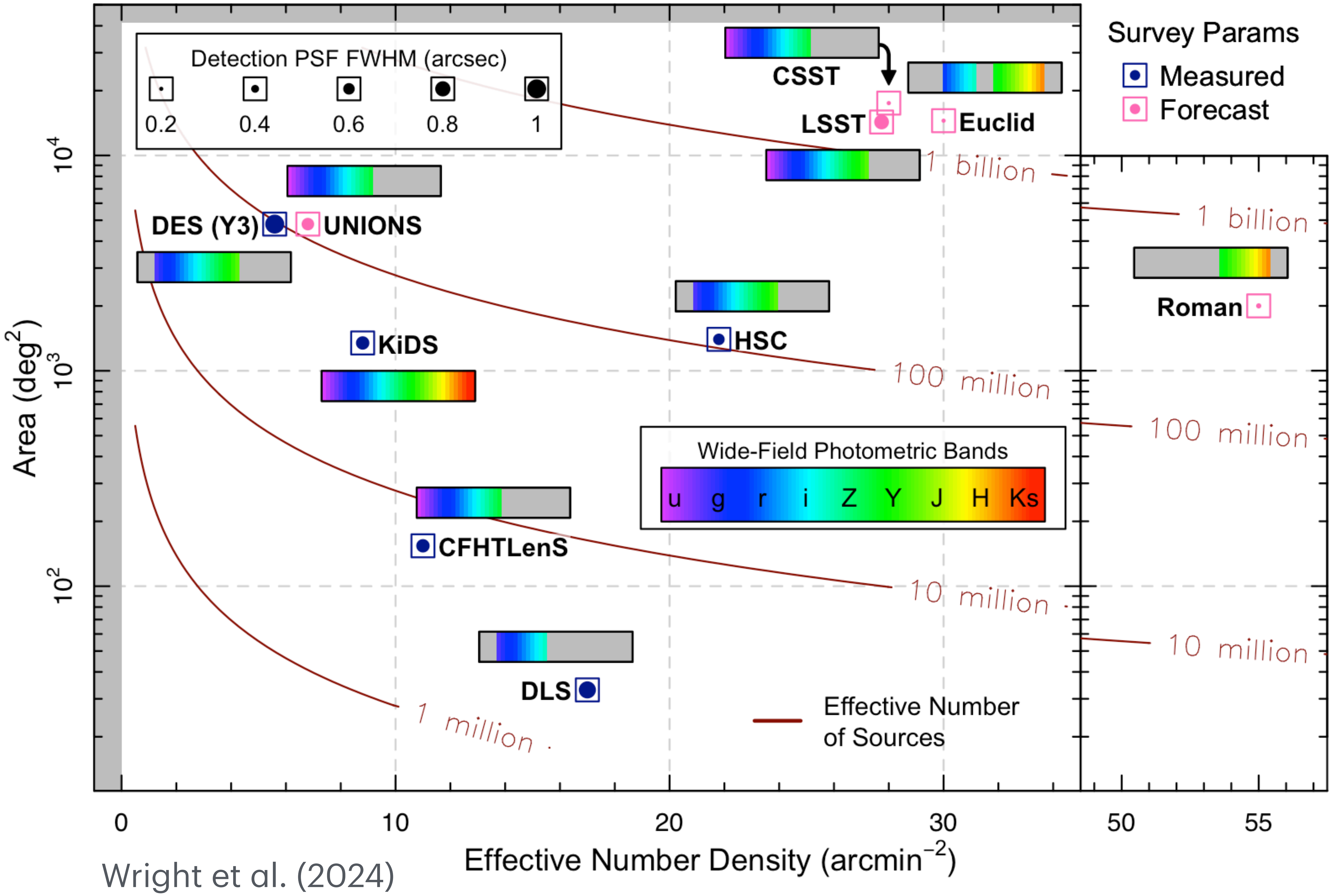
Constraints on Horndeski gravity

GGI conference: Exploring New Frontiers in Cosmology

Benjamin Stölzner

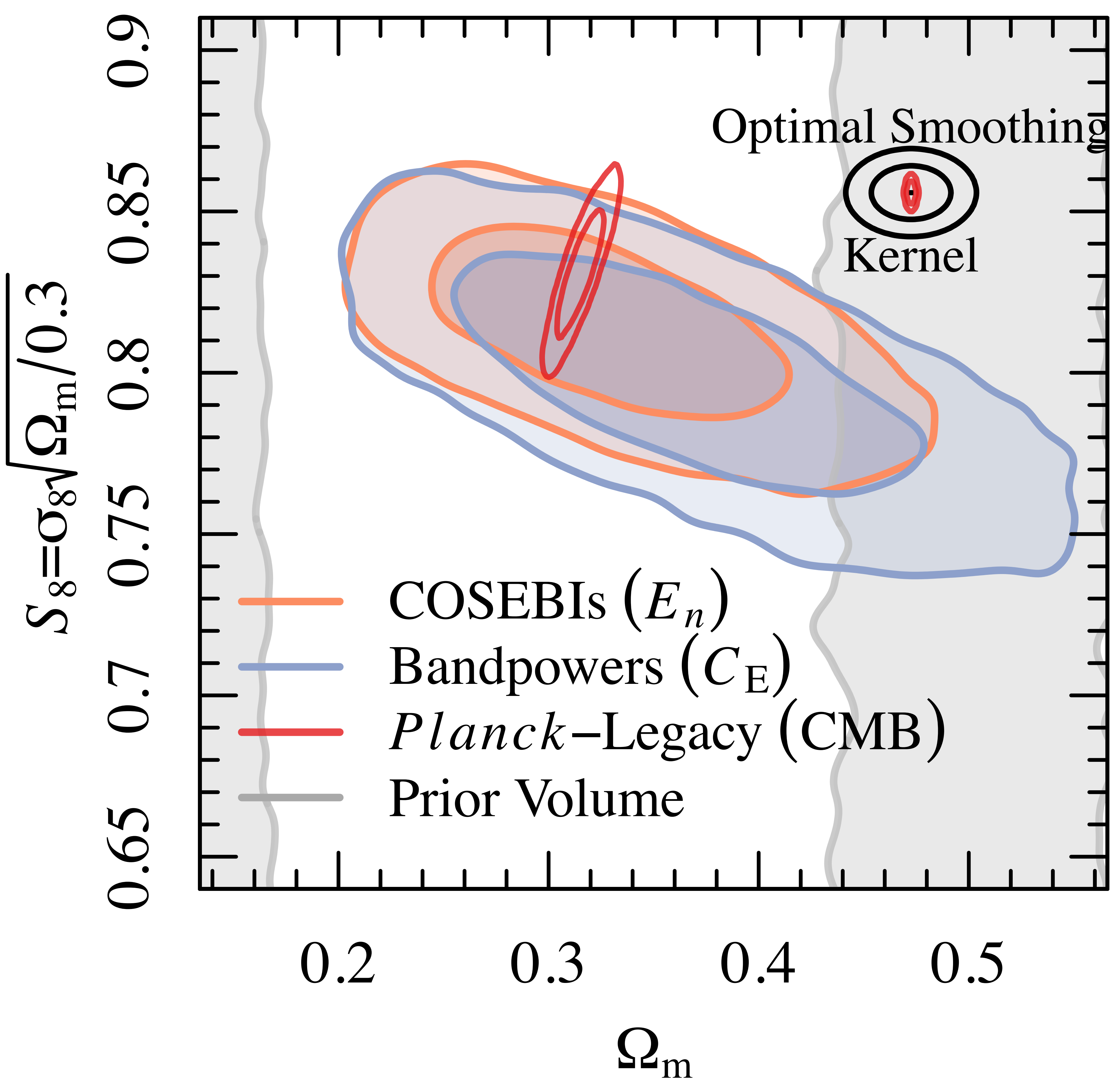
GERMAN CENTRE FOR COSMOLOGICAL LENSING

Imaging surveys for cosmology

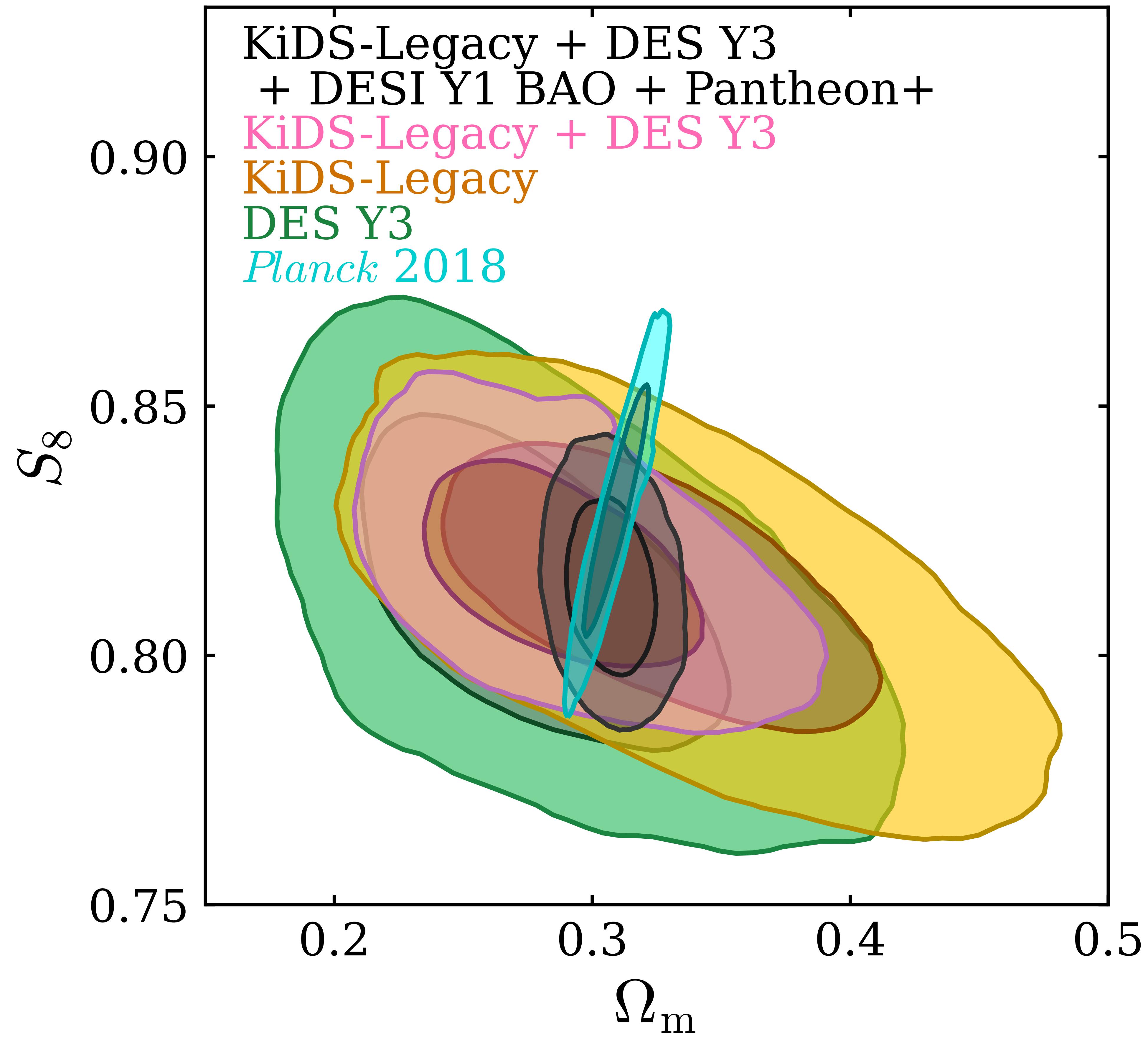


Wright et al. (2024)

KiDS-Legacy: Fiducial constraints



Wright et al. (2025)



Stölzner et al. (2025)

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arXiv: 2512.11039

KiDS-Legacy: Constraining dark energy, neutrino mass, and curvature

Robert Reischke[1,2,⋆], Benjamin Stölzner[2], Benjamin Joachimi[3], Angus H. Wright[2], Marika Asgari[4], Maciej Bilicki[5], Nora Elisa Chisari[6,7], Andrej Dvornik[2], Christos Georgiou[8], Benjamin Giblin[9], Joachim Harnois-Déraps[4], Catherine Heymans[2,9], Hendrik Hildebrandt[2], Henk Hoekstra[7], Shahab Joudaki[10], Konrad Kuijken[7], Shun-Sheng Li[11,12], Laila Linke[13], Arthur Loureiro[14,15], Constance Mahony[16,17,2], Lauro Moscardini[18,19,20], Nicola R. Napolitano[21], Lucas Porth[1], Mario Radovich[22], Tilman Tröster[23], Maximilian von Wietersheim-Kramsta[24,25], Ziang Yan[2,26], Mijin Yoon[7], and Yun-Hao Zhang[7,9]

arXiv: 2512.11041

KiDS-Legacy: Constraints on Horndeski gravity from weak lensing combined with galaxy clustering and cosmic microwave background anisotropies

Benjamin Stölzner[1,⋆], Robert Reischke[2,1], Matteo Grasso[3,4], Matteo Cataneo[2], Benjamin Joachimi[4], Arthur Loureiro[5,6], Alessio Spurio Mancini[7], Angus H. Wright[1], Marika Asgari[8], Maciej Bilicki[9], Andrej Dvornik[1], Christos Georgiou[10], Benjamin Giblin[11], Catherine Heymans[11,1], Hendrik Hildebrandt[1], Shahab Joudaki[12,13], Konrad Kuijken[14], Shun-Sheng Li[15,16], Laila Linke[17], Constance Mahony[18,19,1], Lauro Moscardini[20,21,22], Lucas Porth[2], Mario Radovich[23], Tilman Tröster[24], Maximilian von Wietersheim-Kramsta[25,26], Ziang Yan[27,1], Mijin Yoon[14], and Yun-Hao Zhang[11,14]

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Horndeski theory

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\sum_{i=2}^{5} \frac{1}{8\pi G_N} \mathscr{L}_i \left[g_{\mu\nu}, \phi \right] + \mathscr{L}_\mathrm{m} \left[g_{\mu\nu}, \psi_\mathrm{m} \right] \right]$$

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$$\begin{aligned}
\mathscr{L}_2 &= \quad G_2(\phi, X) \\
\mathscr{L}_3 &= -G_3(\phi, X) \Box \phi \\
\mathscr{L}_4 &= \quad G_4(\phi, X) R + G_{4X}(\phi, X) \left[(\Box \phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu} \right] \\
\mathscr{L}_5 &= \quad G_5(\phi, X) G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6} G_{5X}(\phi, X) \\
&\quad \times \left[(\Box \phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi \right]
\end{aligned}$$

$G_i(\phi, X)$: arbitrary functions of the scalar field ϕ and its kinetic term X

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$G_i(\phi, X)$: arbitrary functions of the scalar field ϕ and its kinetic term X

In practice: Many well known MG models can be expressed via a specific choice of G_i (see Kobayashi et al. 2019)

Parameterisation

Parameterisation

1. **Background**
    - Constant dark energy equation of state
    - Varying equation of state (e.g. $w_0 w_a$)
2. **Perturbations**
    - Effective field theory of dark energy

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Bellini & Sawicki 2014: Describe the evolution of linear perturbations by four functions $\alpha_i(t)$

e.g. $\alpha_i(t) = \hat{\alpha}_i \Omega_{\mathrm{DE}}(t)$

α_{K}: kineticity
α_{B}: braiding
α_{M}: Planck-mass run rate
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Zumalacarregui et al. (2017), Bellini et al. (2020)

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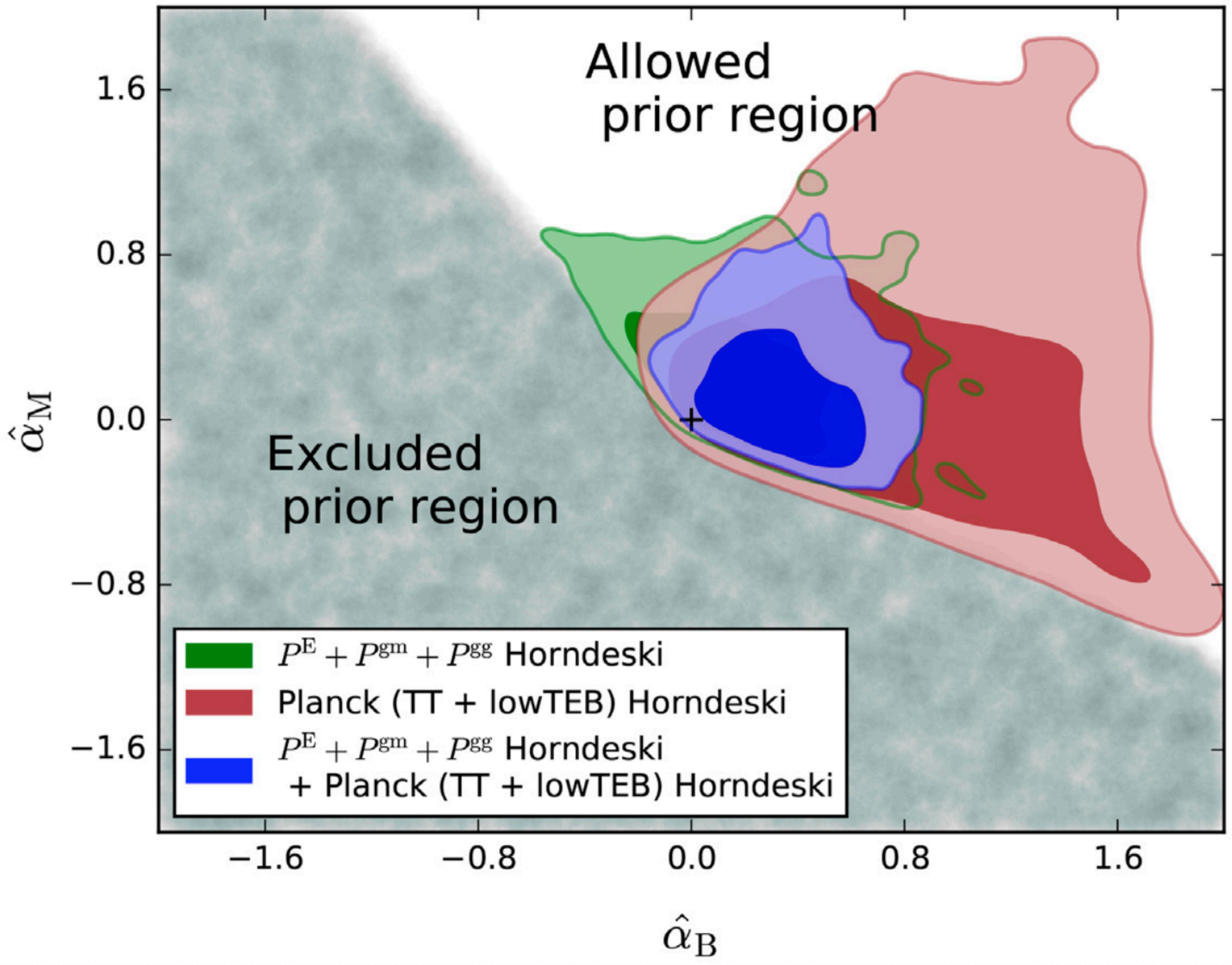
KV450



Spurio Mancini et al. (2019)

Stable parameterisation

$$\alpha_i(t) \longrightarrow D_{\mathrm{kin}} > 0, M_*^2 > 0, c_{\mathrm{s}}^2 > 0, \alpha_{\mathrm{B},0}$$

(Kennedy at al. 2018, Lombriser et al. 2019)

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(Kennedy at al. 2018, Lombriser et al. 2019)

- **Gradient instabilities** (negative square of sound speed)
- **Ghost instabilities** (wrong sign of kinetic term of background perturbations)
- **Tachyonic instabilities** (negative effective mass squared of scalar field perturbation)
- **Mathematical (or classical) instabilities** (can cause exponentially growing perturbations)

Stable parameterisation

$$\alpha_i(t) \longrightarrow D_{\rm kin} > 0, M_*^2 > 0, c_{\rm s}^2 > 0, \alpha_{\rm B,0}$$

(Kennedy at al. 2018, Lombriser et al. 2019)

$$D_{\rm kin} = \alpha_{\rm K} + \frac{3}{2}\alpha_{\rm B}^2$$

$$\alpha_{\rm M} = \frac{{\rm d}\ln M_*^2}{{\rm d}\ln a}$$

$$c_{\rm s}^2 = \frac{1}{D_{\rm kin}}\left[\left(2-\alpha_{\rm B}\right)\left(-\frac{H'}{aH^2} + \frac{1}{2}\alpha_{\rm B} + \alpha_{\rm M}\right) - \frac{3\left(\rho_{\rm M} + p_{\rm M}\right)}{H^2 M_*^2} + \frac{\alpha_{\rm B}'}{aH}\right]$$

$\alpha_{\rm B,0}$: initial condition for the braiding term

Stable parameterisation

mochi_class: Modelling Optimisation to Compute Horndeski in CLASS

Authors: Matteo Cataneo, Emilio Bellini

This code is an extension of the hi_class code (http://miguelzuma.github.io/hi_class_public/), itself a patch to the Einstein-Boltzmann solver CLASS (http://class-code.net). The new features include:

- α-functions replaced by stable basis $\{ M_*^2, D_{\rm kin}, c_s^2 \}$ to ensure stability from the start.
- No need for hard-coding of basis function parametrisations. The code can take general functions of time as input, including the dark energy equation of state (w_ϕ) or its normalised background energy-density ($\tilde{\rho}_\phi$).
- Accurate quasi-static approximation connecting (μ, γ)-parametrisation to the Horndeski α's.
- Additional stability test checking for mathematical (classical) instabilities in the scalar field fluctuations.
- GR approximation scheme. Modified gravity/dark energy activated at late times, deep in the matter dominated era.

- Free from gradient and ghost instabilities by design
- Implemented in mochi_class (Cataneo & Bellini 2024)

Cosmic shear in modified gravity

Weyl potential: $\Phi_{\mathrm{W}} = (\Phi + \Psi)/2$

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$$\boxed{C_\mathrm{GG}^{ij}(\ell) = \int_0^{\chi_\mathrm{H}} \mathrm{d}\chi \, \frac{W_\mathrm{G}^i(\chi) W_\mathrm{G}^j(\chi)}{f_\mathrm{K}^2(\chi)} \Sigma^2\left(k(\chi), z(\chi)\right) P_\mathrm{m,NL}^\mathrm{MG}\left(k(\chi), z(\chi)\right)}$$

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Additionally:
- Phenomenological Vainshtein screening in the non-linear regime (recovering GR at high k)
- Non-linear matter power spectrum from HMcode2020 within an approach inspired by the reaction framework of Cataneo et al. (2019)

Sampling parameters

Horndeski parameters

Stable 1	$\hat{D}_{\mathrm{kin}}$	$\mathcal{U}(0.0, 10.0)$	De-mixed kinetic term of the scalar field perturbation
	$\hat{c}_{\mathrm{s}}^2$	1.0	Effective sound speed of the scalar field perturbation
	$\Delta\hat{M}_*^2$	$\mathcal{U}(-1.0, 10.0)$	Deviation of the effective Planck mass from its fiducial value

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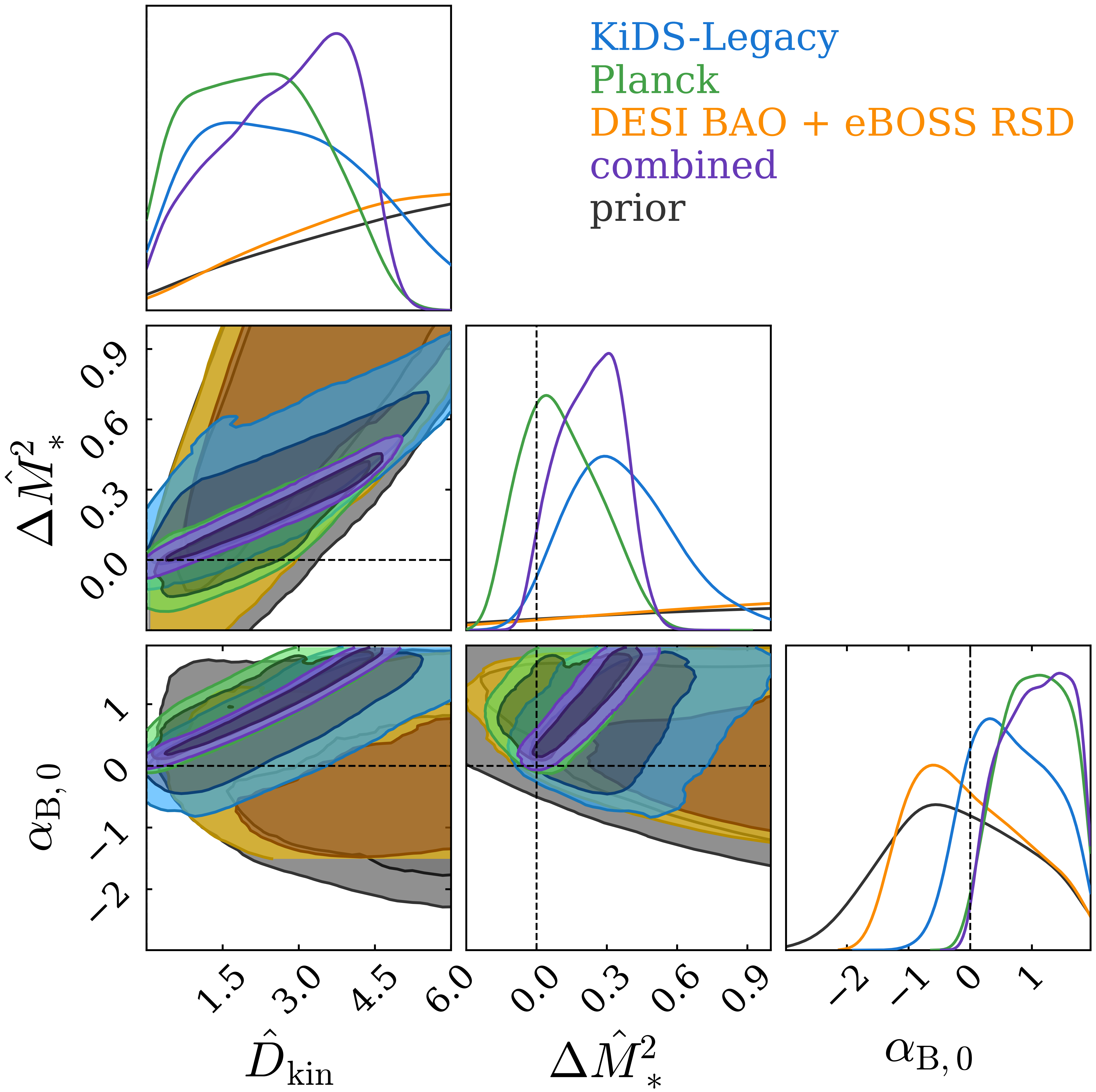
+ cosmological & nuisance parameters

Results

Stable 1	$\hat{D}_{\rm kin}$	$\mathcal{U}(0.0, 10.0)$
	$\hat{c}_{\rm s}^2$	1.0
	$\Delta\hat{M}_*^2$	$\mathcal{U}(-1.0, 10.0)$



Stölzner et al. (2026)

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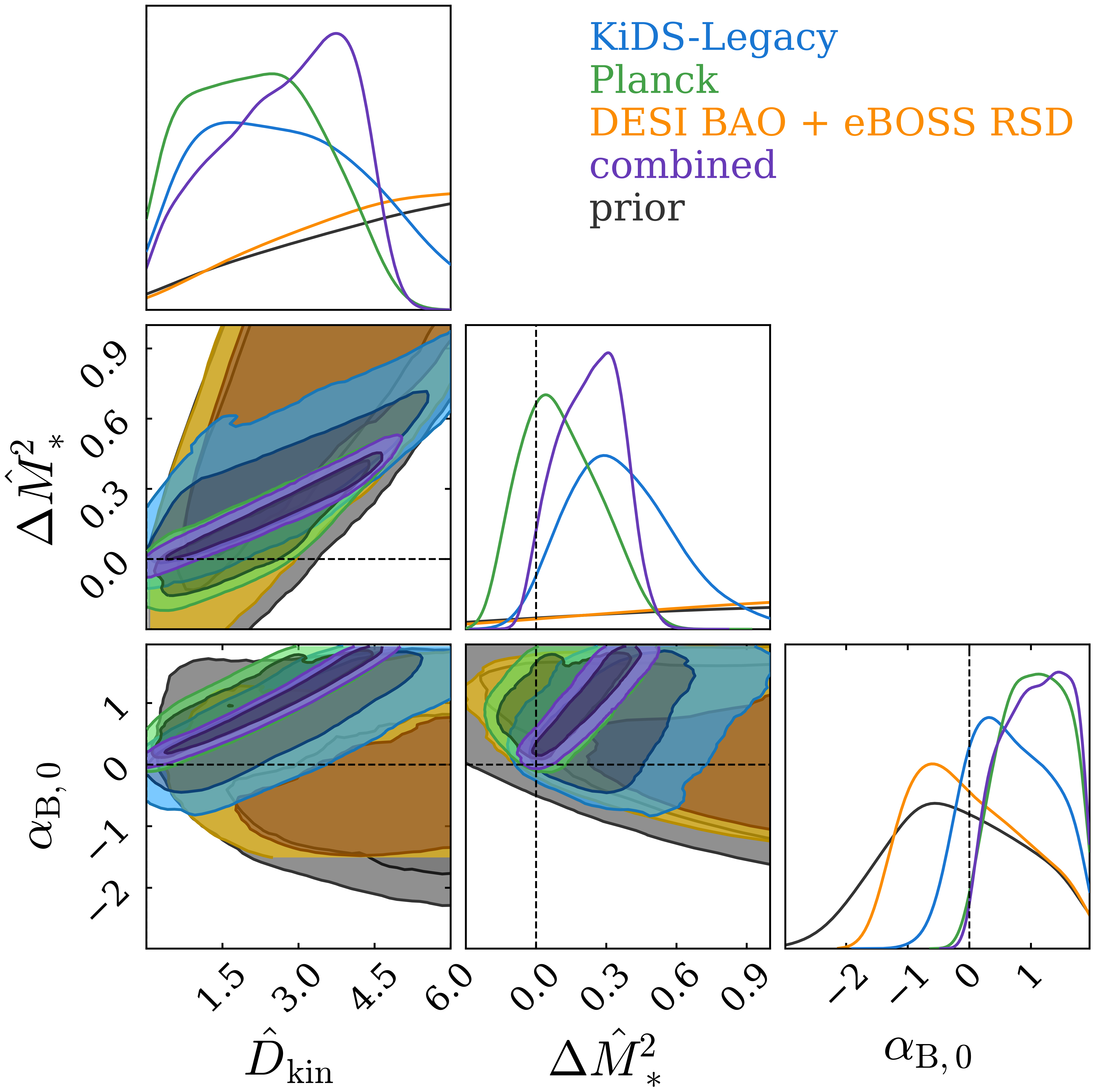
Results

Stable 1	$\hat{D}_{\rm kin}$	$\mathcal{U}(0.0, 10.0)$
	$\hat{c}_{\rm s}^2$	1.0
	$\Delta\hat{M}_*^2$	$\mathcal{U}(-1.0, 10.0)$

Best-fit $\Delta\chi^2 = -3.12$

Bayesian suspiciousness: $N_\sigma = 1.40$



Stölzner et al. (2026)

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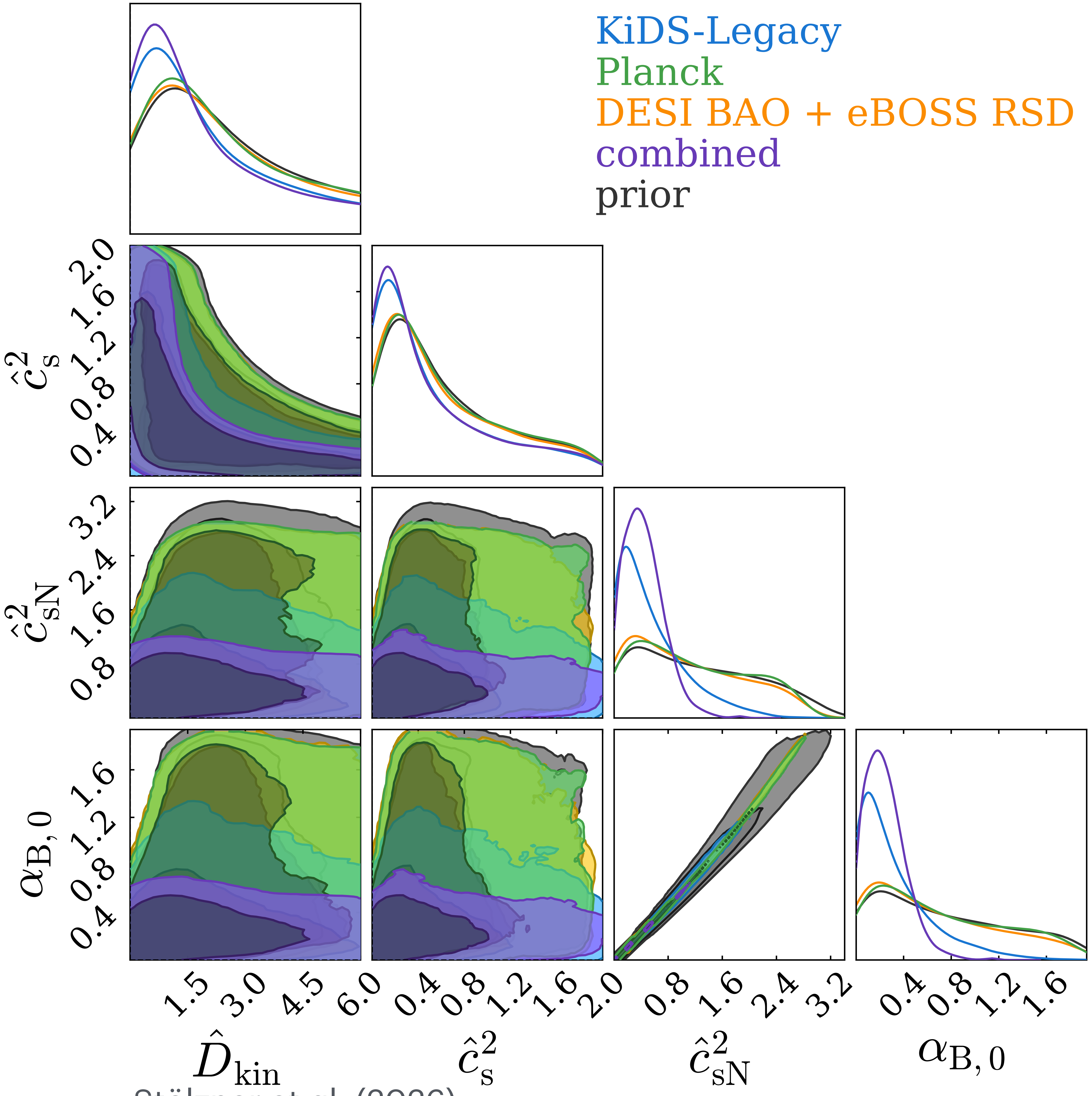
Results

Stable 2	$\hat{D}_{\rm kin}$	$\mathcal{U}(0.0, 10.0)$
	$\hat{c}_{\rm s}^2$	$\mathcal{U}(0.0, 2.0)$
	$\Delta\hat{M}_*^2$	0.0



Stölzner et al. (2026)

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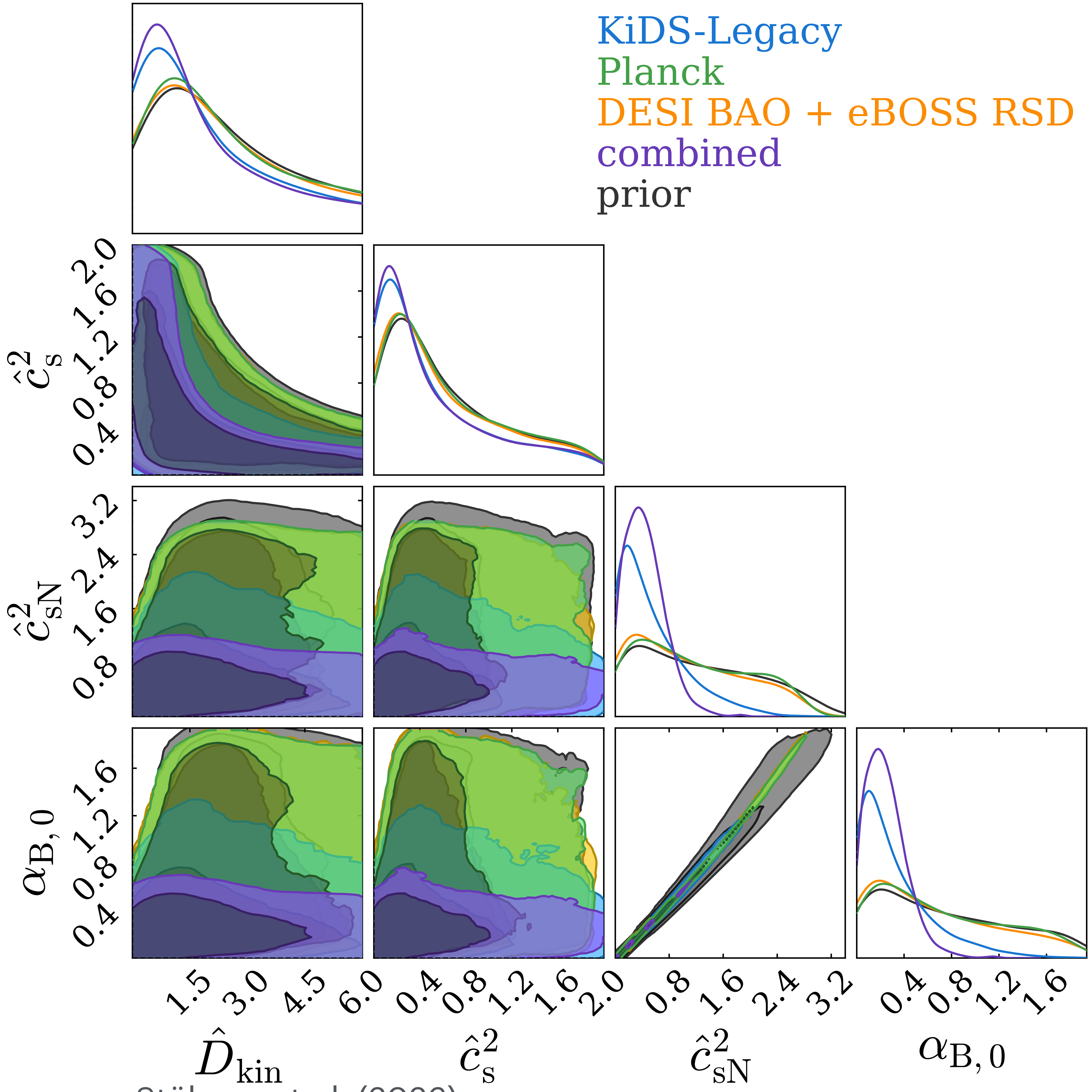
	$\hat{c}_{\text{s}}^2$	$\mathcal{U}(0.0, 2.0)$
	$\Delta\hat{M}_*^2$	0.0

Best-fit $\Delta\chi^2 = -1.33$

Bayesian suspiciousness: $N_\sigma = 1.09$



Stölzner et al. (2026)

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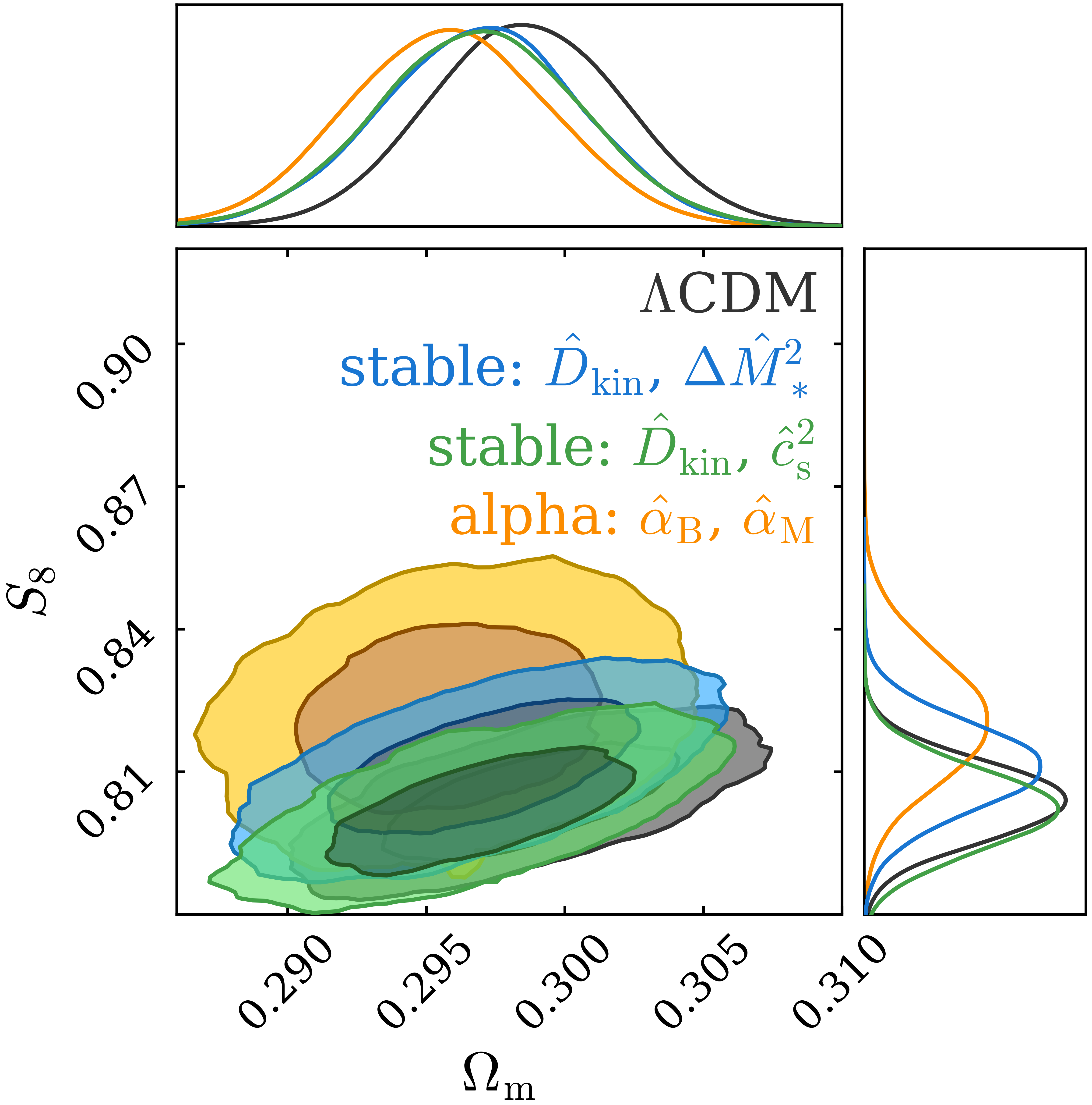
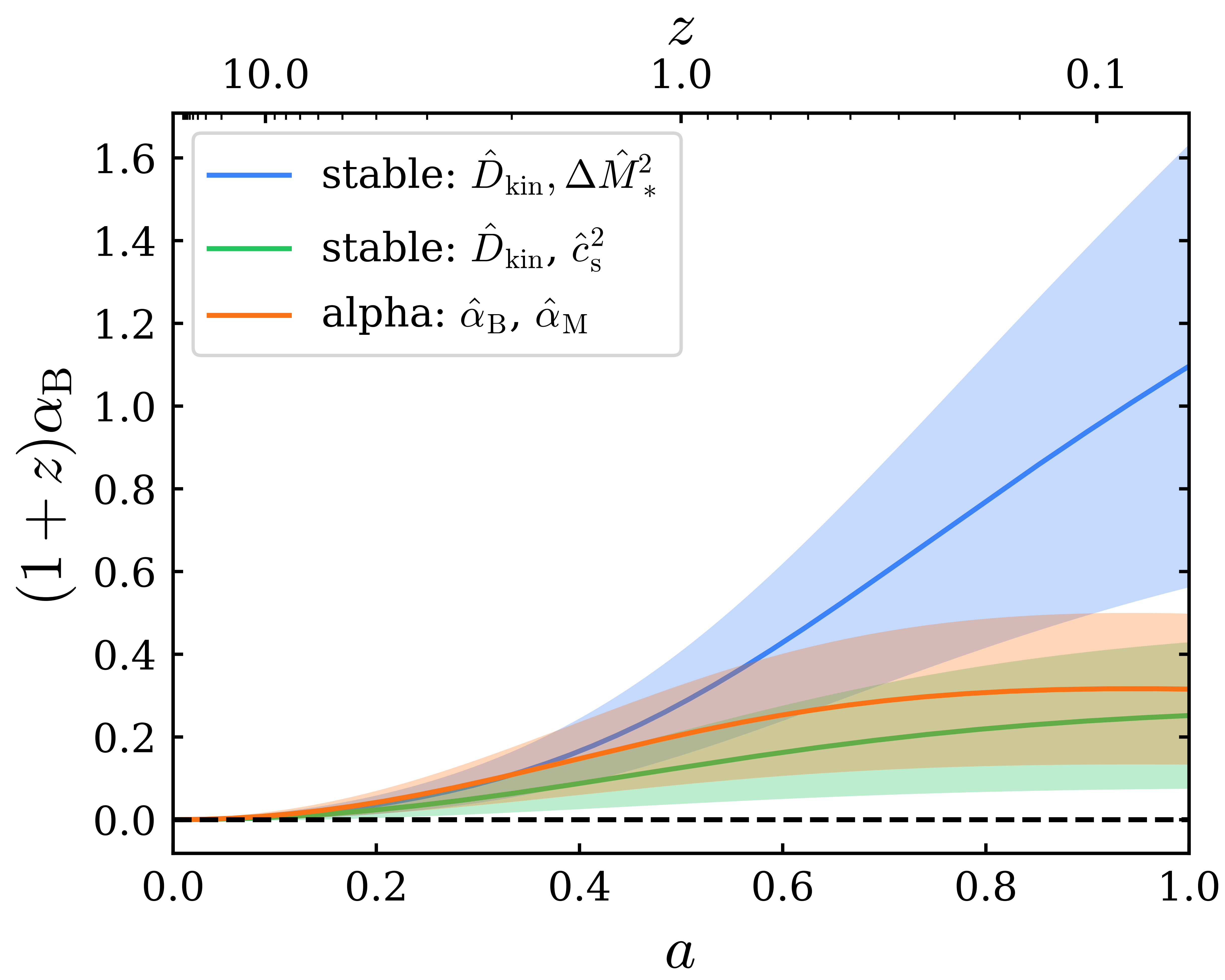
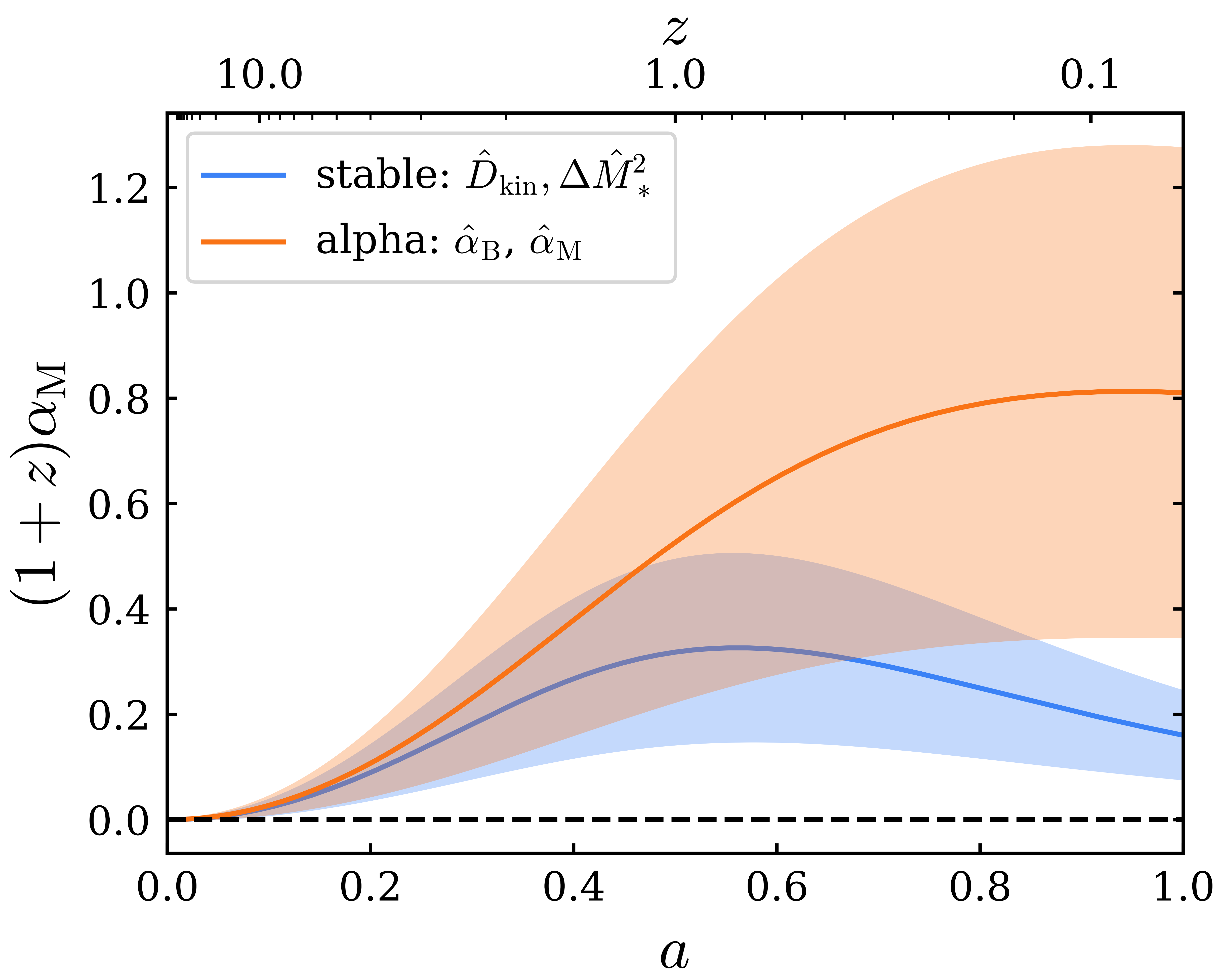


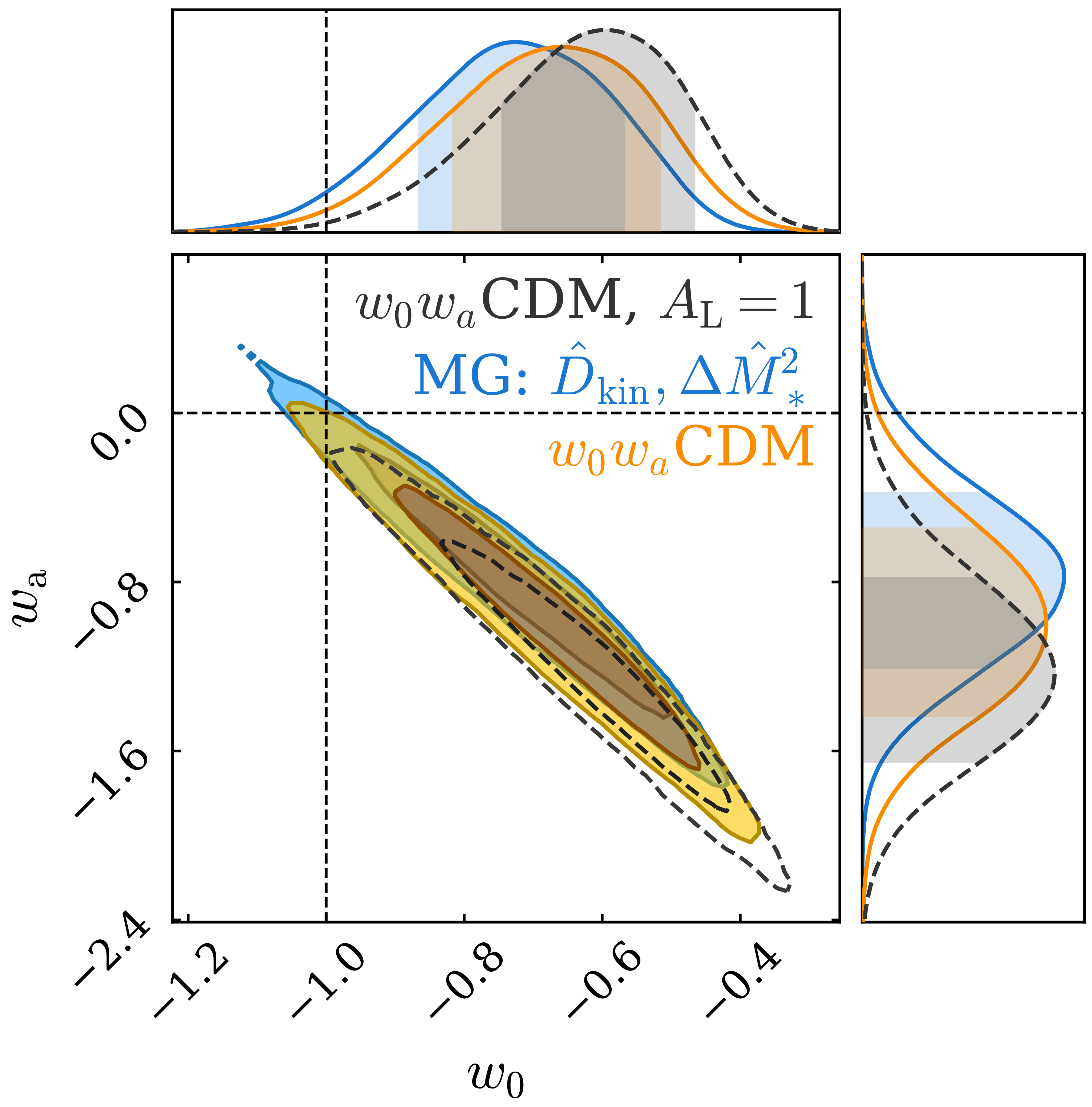
Stölzner et al. (2026)

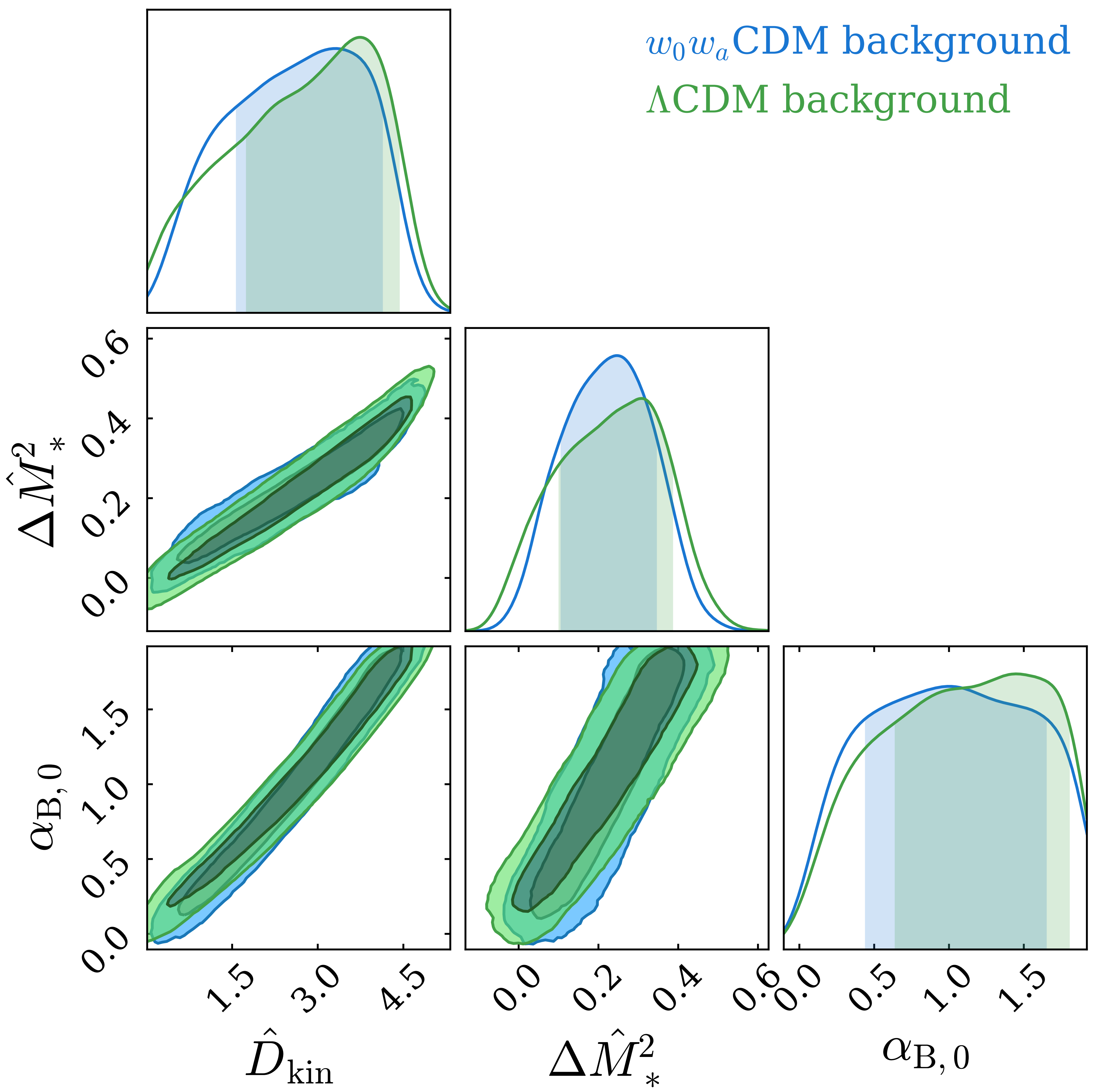
Constraints on derived parameters





Background cosmology: w_0wa





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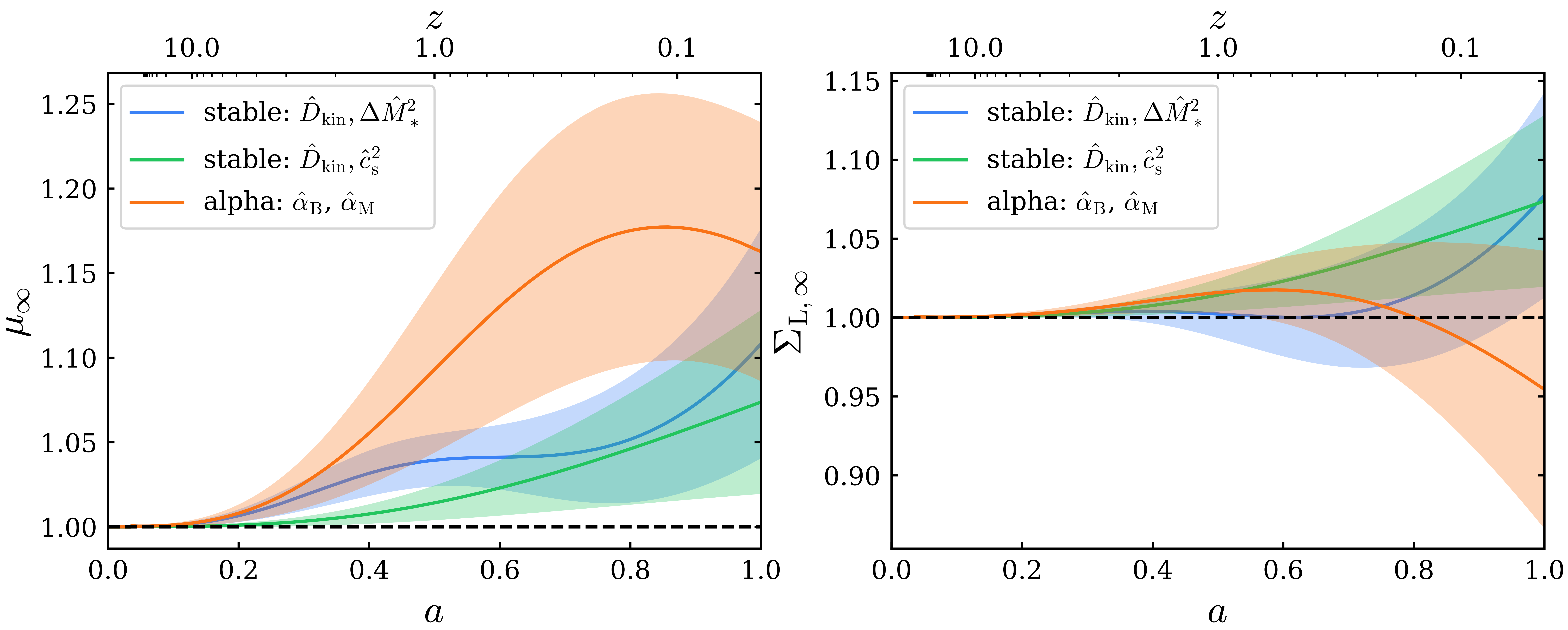
Conclusions

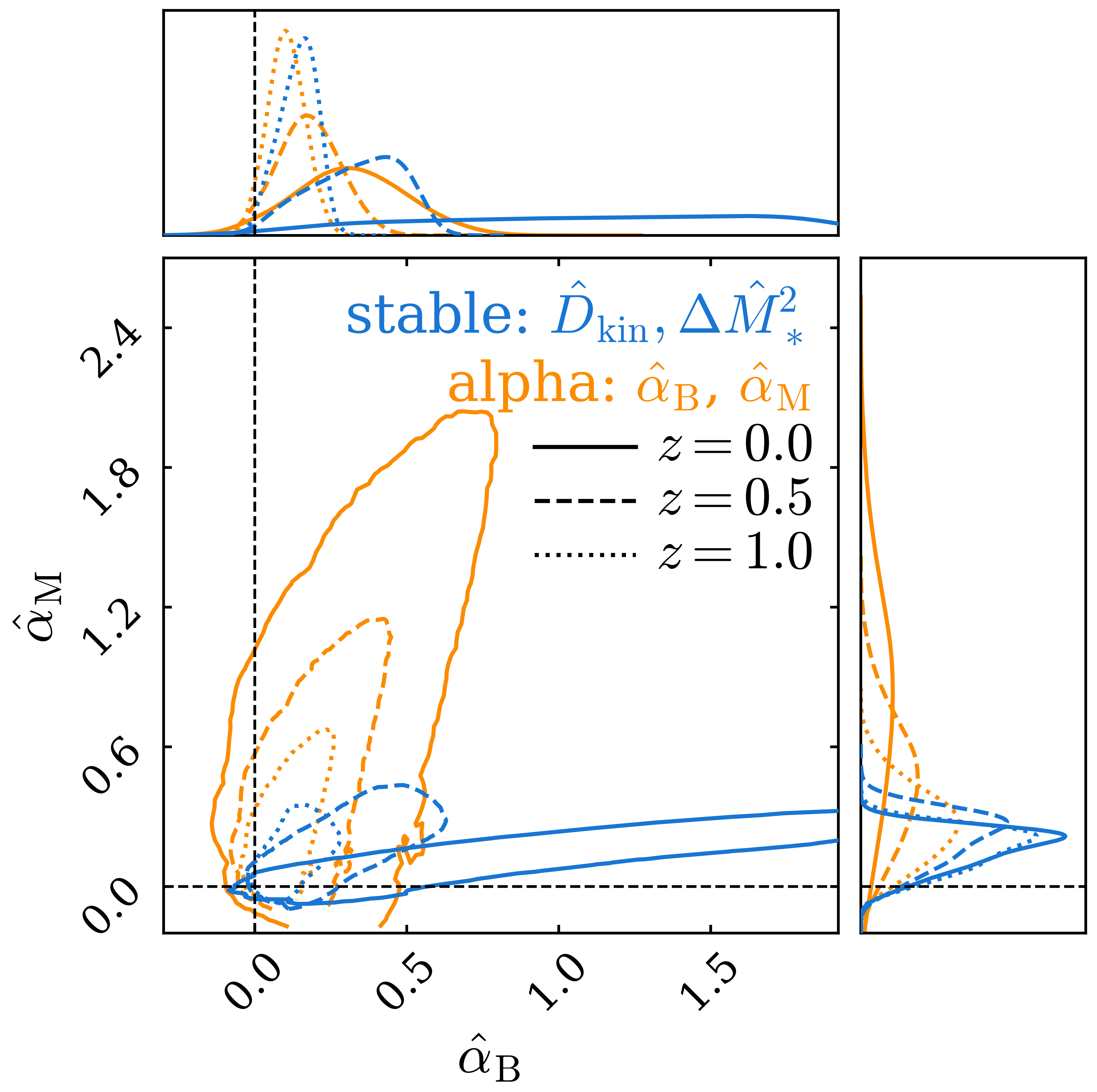
- Cosmic shear can place significant constraints on the Horndeski parameter space
- KiDS-Legacy constraints are competitive with those from the CMB
- Current data show no significant preference for modified gravity over GR
- S_8 constraints are robust with respect to changes in the cosmological model

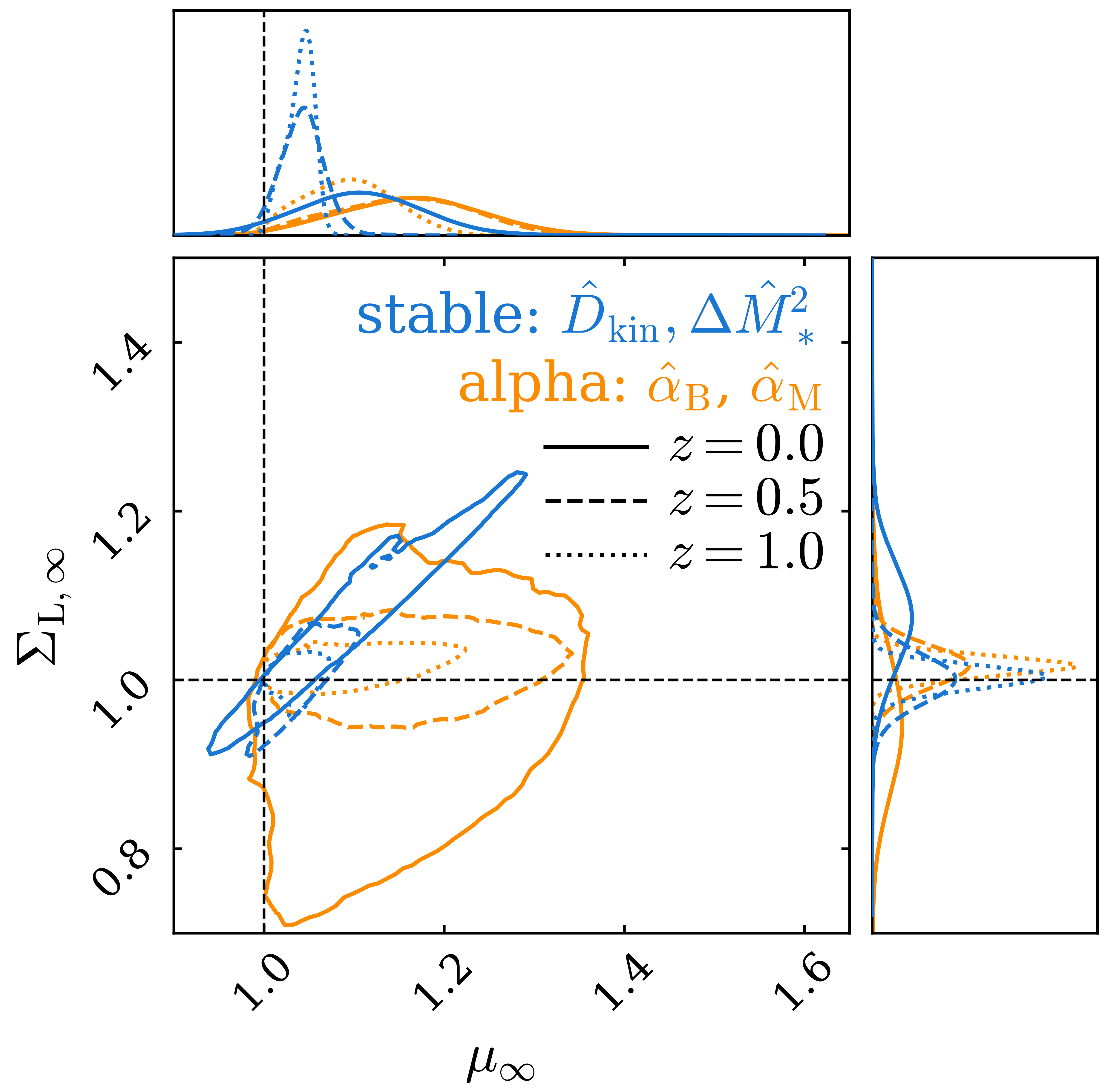
Backup slides

Constraints on derived parameters



Constraints on derived parameters





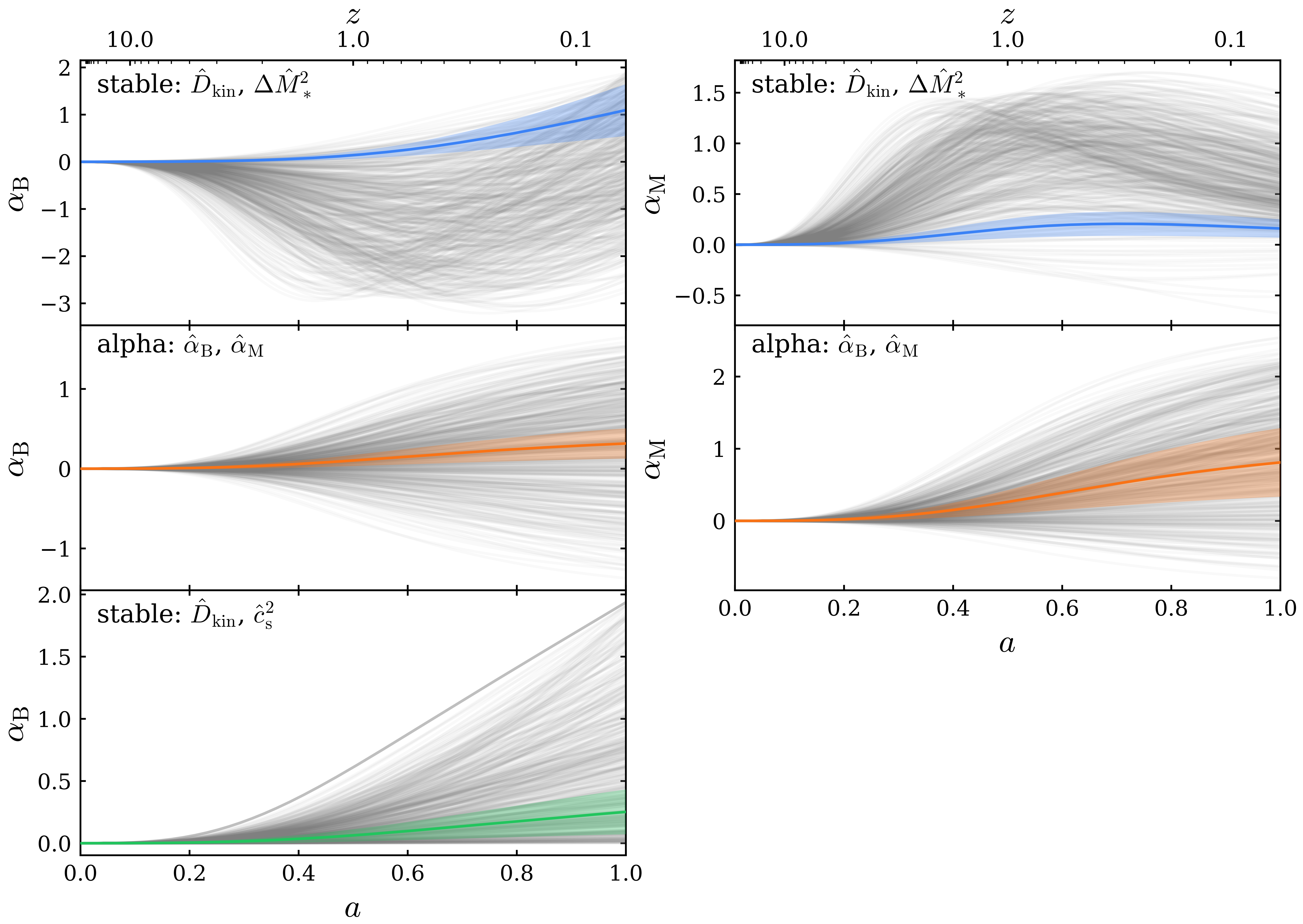
Non-linear power spectrum and screening

- Non-linear matter power spectrum: $P^{\mathrm{MG}}_{\mathrm{m,NL}}(k,a) = \mathscr{R}(k,a) P^{\mathrm{pseudo}}_{\mathrm{m,NL}}(k,a)$
- $P^{\mathrm{pseudo}}_{\mathrm{m,NL}}(k,a)$: non-linear power spectrum in a reference (pseudo) cosmology
- Reaction: $\mathscr{R}(k,a) = \left[\left(1 - \mathscr{S}\left(k,a\right)\right)\sqrt{P^{w_0 w_a}_{\mathrm{m,NL}} / P^{\mathrm{pseudo}}_{\mathrm{m,NL}}} + \mathscr{S}(k,a)\right]^2$
- Screening factor: $\mathscr{S}(k,a) = \exp\left[-\left(k/k_{\mathrm{V}}\right)^{n(a)}\right]$
- $P^{\mathrm{MG}}_{\mathrm{m,NL}} \approx P^{w_0 w_a}_{\mathrm{m,NL}}$ for $k \gg k_{\mathrm{V}}$ (recover GR on small scales)
- $P^{\mathrm{MG}}_{\mathrm{m,NL}} \approx P^{\mathrm{pseudo}}_{\mathrm{m,NL}}$ for $k \ll k_{\mathrm{V}}$ (modified gravity on large scales)
- $\Sigma_{\mathrm{NL}}(k,a) = 1 + \mathscr{S}(k,a)\left[\Sigma_{\mathrm{L}}(k,a) - 1\right]$

Best fit (KiDS + Planck + DESI + eBOSS)

Model	S_8	Ω_m	$\chi^2_{\rm bestfit}$	PTE	$\Delta\chi^2_{\rm bestfit}$	N_σ
ΛCDM	$0.804^{+0.008}_{-0.008}$	$0.299^{+0.003}_{-0.003}$	1147.63	0.73	—	—
MG: $\hat{D}_{\rm kin}$, $\Delta\hat{M}^2_*$	$0.813^{+0.008}_{-0.011}$	$0.298^{+0.003}_{-0.004}$	1144.51	0.78	−3.12	1.40
MG: $\hat{D}_{\rm kin}$, $\hat{c}^2_{\rm s}$	$0.803^{+0.008}_{-0.009}$	$0.297^{+0.003}_{-0.004}$	1146.30	0.76	−1.33	1.09
MG: $\hat{\alpha}_{\rm B}$, $\hat{\alpha}_{\rm M}$	$0.822^{+0.011}_{-0.015}$	$0.296^{+0.004}_{-0.004}$	1142.69	0.78	−4.93	1.43

Priors



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