Searching for Viable Dark Energy with Phantom Crossing

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PASCOS @ U.Sheffield, June 22nd 2026

Outline

1. Desiderata for dark energy/modified gravity models.
2. Phantom crossing in Horndeski gravity.
3. Asymptotic Cubic Galileons — viable, testable dark energy models.

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2. Phantom crossing in Horndeski gravity.

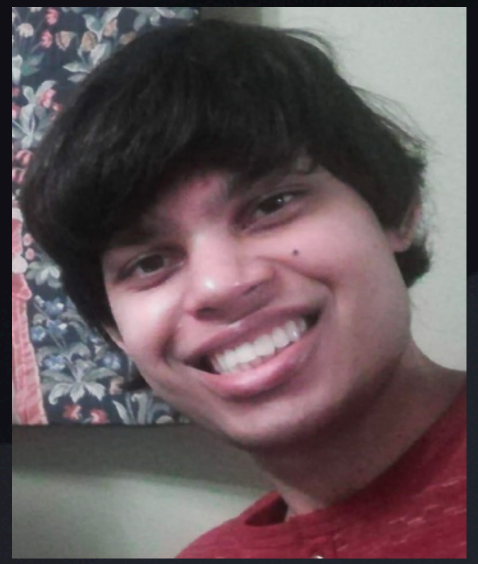
3. Asymptotic Cubic Galileons — viable, testable dark energy models.

James Hallam

Sergi Sierra

Krishna Naidoo

Ashim Sen Gupta (now at Bielefeld)



Team Hi-COLA

Desiderata for gravity models

‘Woods at Dusk’

G. Horndeski

Gravity theory wanted

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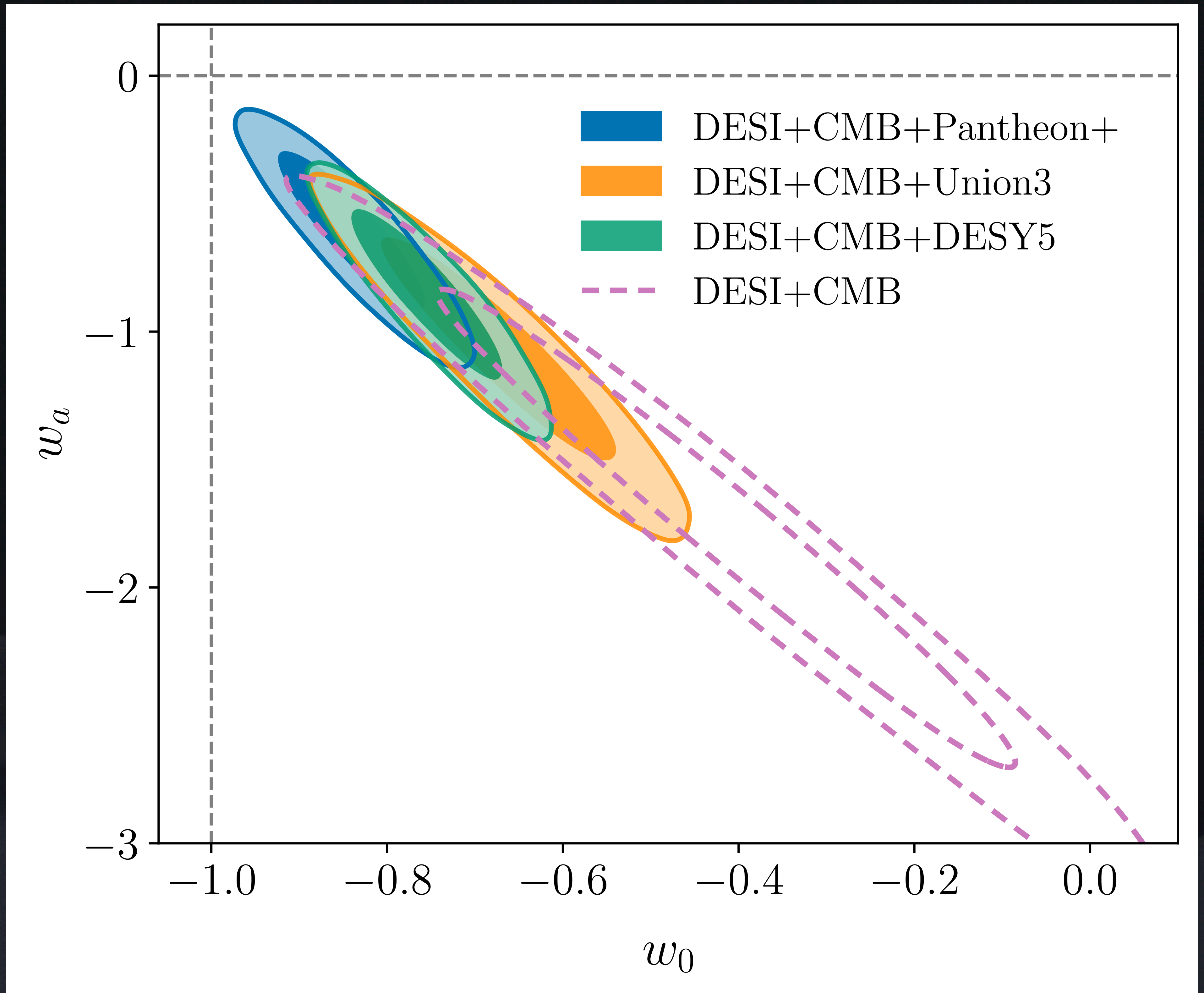
Is that really *so* much to ask??

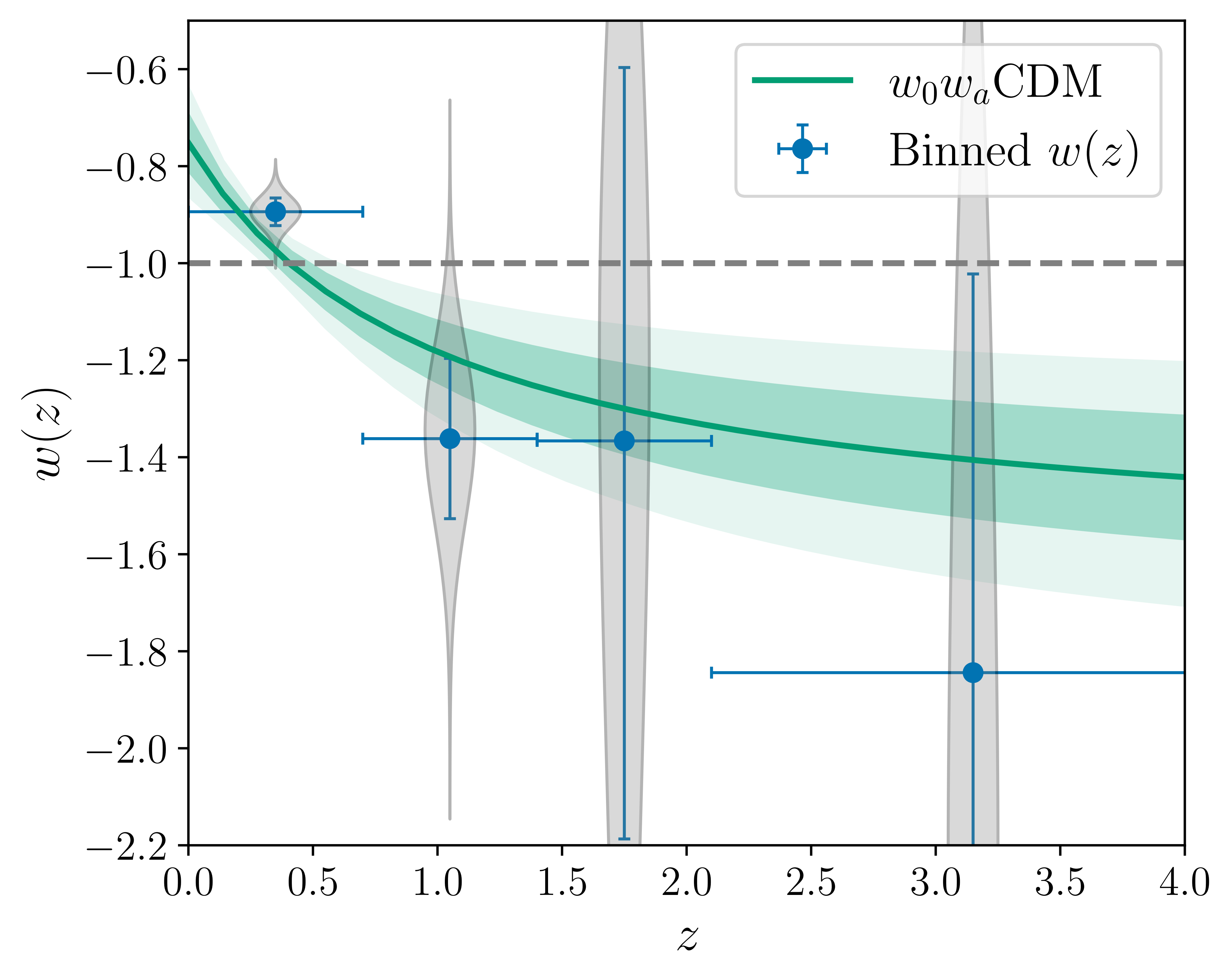
The Phantom Crossing 'Anomaly'

Fit from BAO+CMB+SN on the parameterised dark energy equation of state:

$$w(a) = w_0 + w_a\,(1 - a)$$



Abdul Karim+, DESI DRII results



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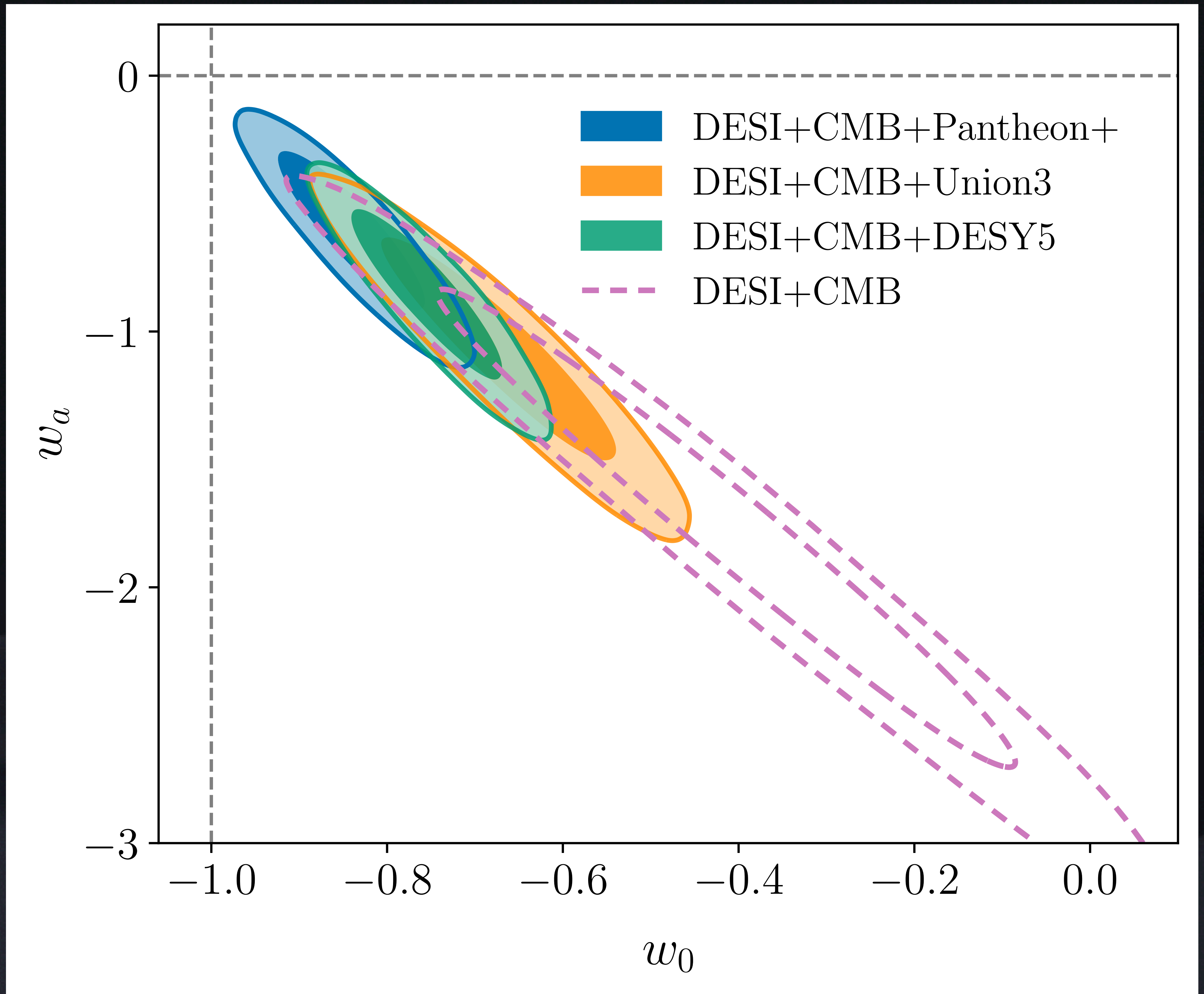

Abdul Karim+, DESI DRII results

See also talks by:

Patrick Adolf
Florian Beutler
Philippe Brax
Tamara Davis
James Hallam
Tanisha Jhaveri
Matteo Martinelli
Paul Shah
Suvedha Suresh Naik
+ probably others (sorry if I missed you)

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Either way, we take the exercise of reverse-engineering viable underlying cosmological gravity theories.

Gravity model Olympics

HEATS

Background expansion

SEMIS

Linear perturbations

FINAL

Nonlinear scales

Gravity model Olympics

HEATS

Background expansion

CMB ang. diameter distance

SNIa luminosity distances

BAO distances $\alpha_{\parallel}$ and $\alpha_{\perp}$

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Gravity model Olympics

HEATS — **Background expansion**

- CMB ang. diameter distance
- SNIa luminosity distances
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- Linear growth, $f\sigma_8$
- Galaxy-ISW cross-correlation
- GW luminosity distance

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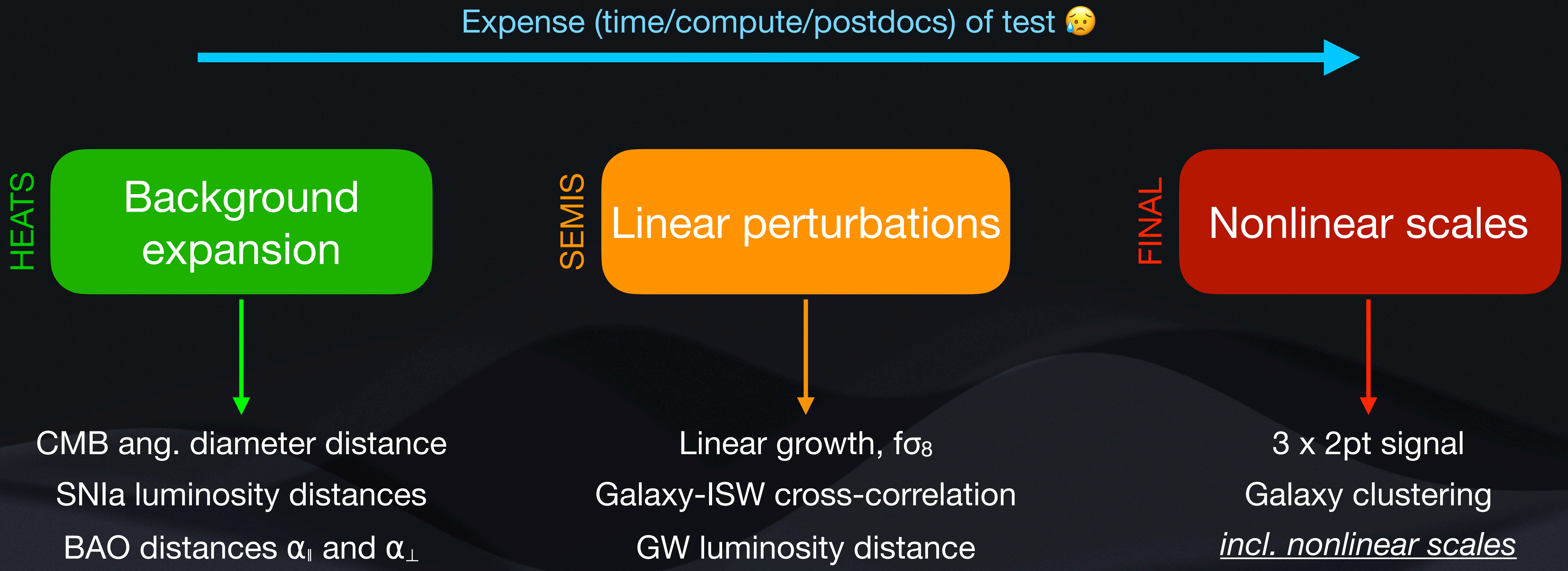
3 x 2pt signal

Galaxy clustering

incl. nonlinear scales

Gravity model Olympics



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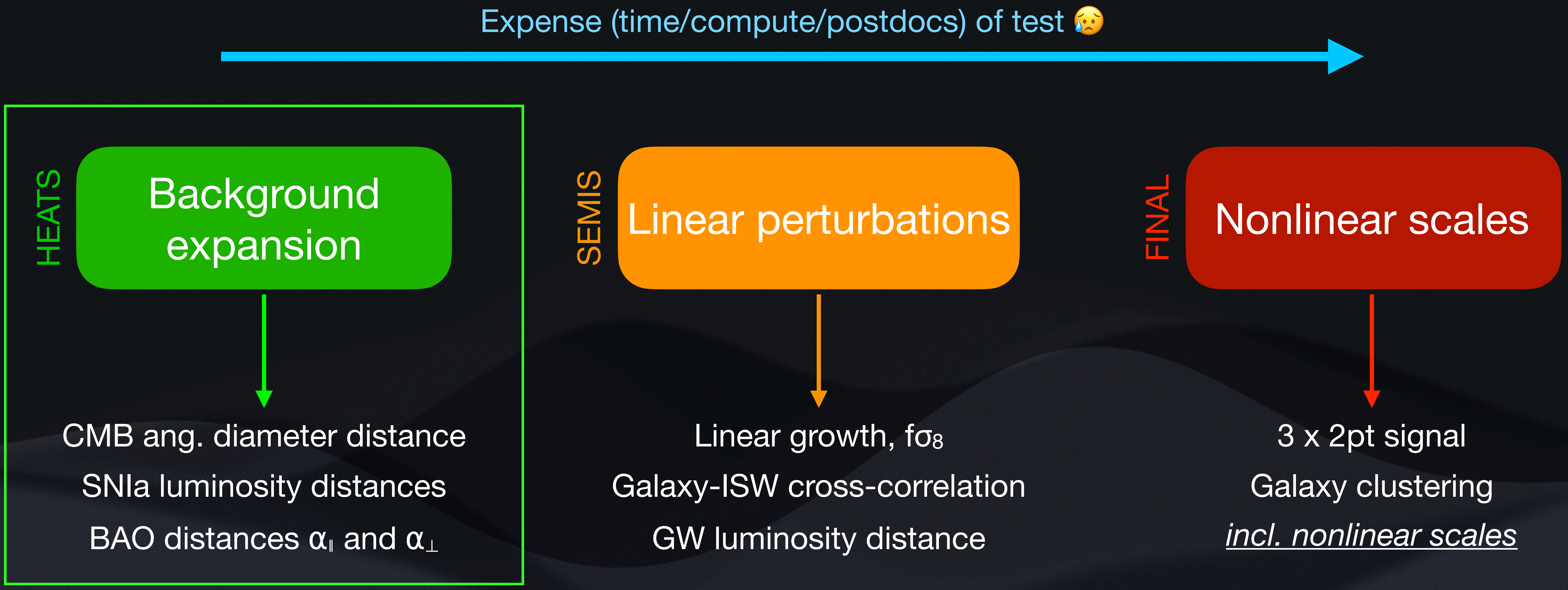

Gravity model Olympics

Expense (time/compute/postdocs) of test

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Phantom crossing in Horndeski gravity

‘Horndeski Scalar Theory
— Past, Present & Future’

G. Horndeski

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$$S = \int d^4x\sqrt{-g}\,[G_4(\phi)R + K(\phi, X) - G_3(\phi, X)\Box\phi - M_P^2\,\Lambda\,] + S_M$$

where X = kinetic term of scalar field = $-\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$

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E.g. f(R) gravity uses these two

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E.g. cubic Galileon uses these two

G_3 is key in Vainshtein screening

where X = kinetic term of scalar field = $-\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$

Routes to Phantom Crossing (non-exhaustive)

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1) **Non-minimal coupling:** non-trivial G_4 ⇒ see Philippe's talk.

Beware strong changes to $G_{\rm eff}$ (a.k.a. μ) in Poisson equation.

See: Yao+ 2025; Ye+ 2025, 2026; Wolf+ 2025a, 2025b.

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E.g. Dirac-Born-Infeld style kinetic term: $K(X) = \frac{-1}{\sqrt{1-X}}$

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3) G_3 **active + broken shift symmetry:** this talk. Keep minimal coupling, $G_4 = M_P^2/2$.

⇒ Kinetic Gravity Braiding (KGB) subspace of Horndeski.

See: Tsujikawa 2026; Calderon & Linder 2026; Wolf+ 2026.

G_3 required

Asymptotic Cubic Galileons

All figures & results from Naidoo et al. 2026.

(On arXiv on tomorrow).

‘The Fireball Approaches’

G. Horndeski

Crossing the phantom divide

where X = kinetic term of scalar field

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Important quantity for both models: $f_\phi = \dfrac{\Omega_\phi}{\Omega_\Lambda + \Omega_\phi}$

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Some degree of cosmo-constant-like behaviour is allowed.

LCDM recovered if $f_\phi \rightarrow 0$ at all z.

ISW-galaxy cross-correlation

The ISW* plateau in the CMB probes $\dot{\Phi} + \dot{\Psi}$. In ΛCDM this is negative at late times (potentials decay).

*ISW = Integrated Sachs Wolfe
→ effects large scales of CMB

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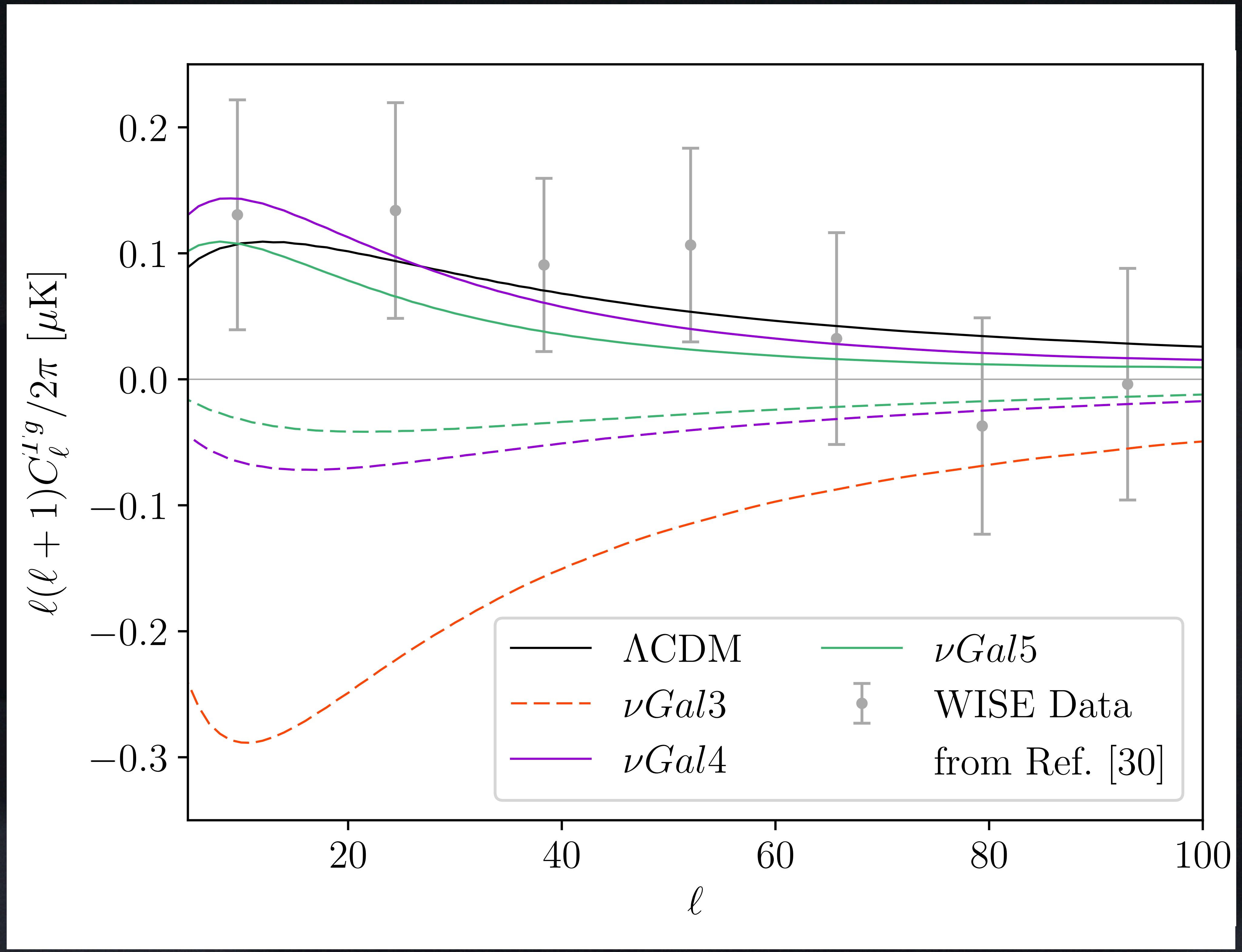
ISW-galaxy cross-spectrum

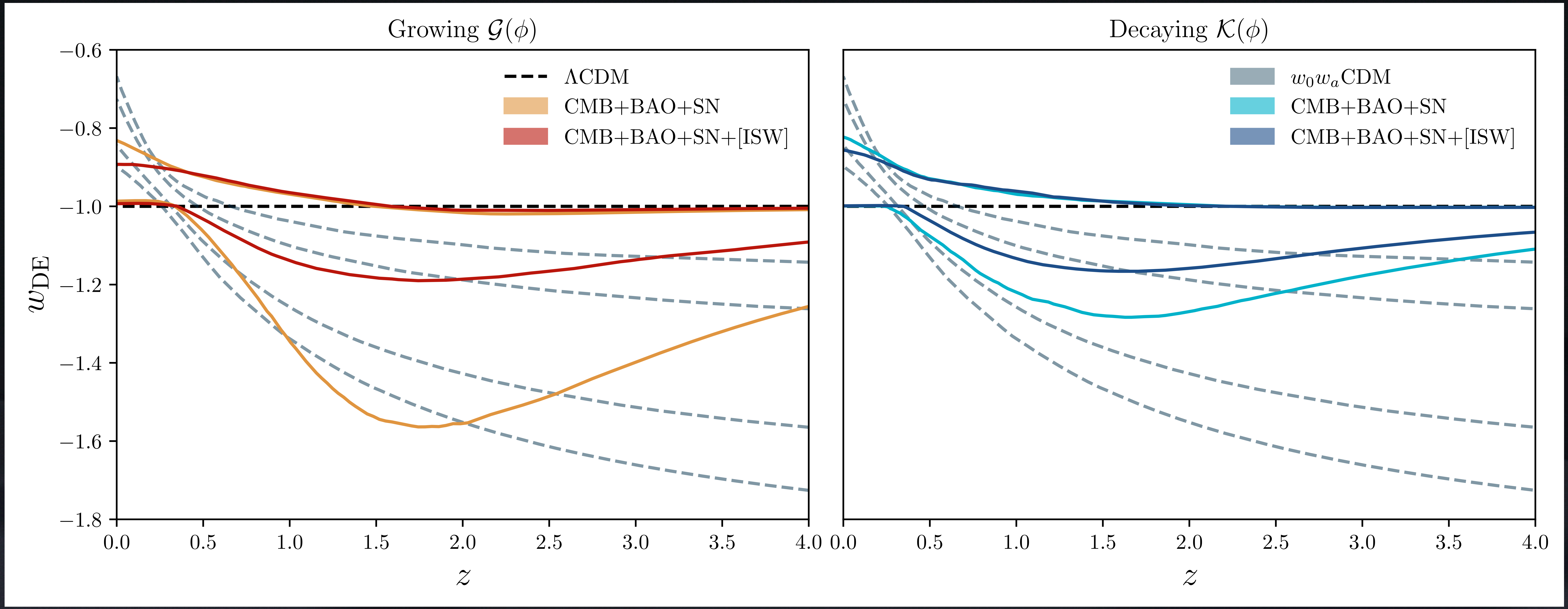


←Flipped sign!

Renk et al. 2017.

Expansion History Constraints

- We solve background & linear growth in our Asymptotically Cubic Galileon models.
- Constrain using compressed Planck likelihood, DESI DR2 BAO & DES Dovekie SN sample.



Naidoo+ 2026 .

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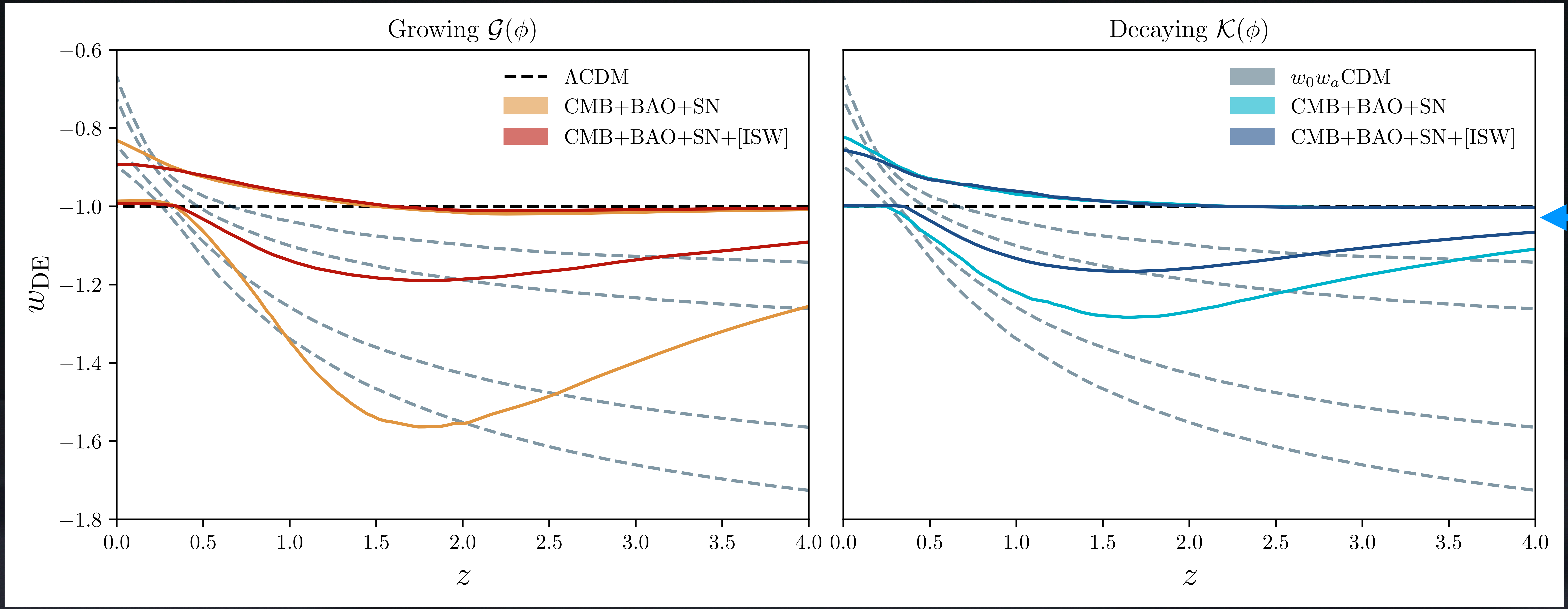


Naidoo+ 2026.

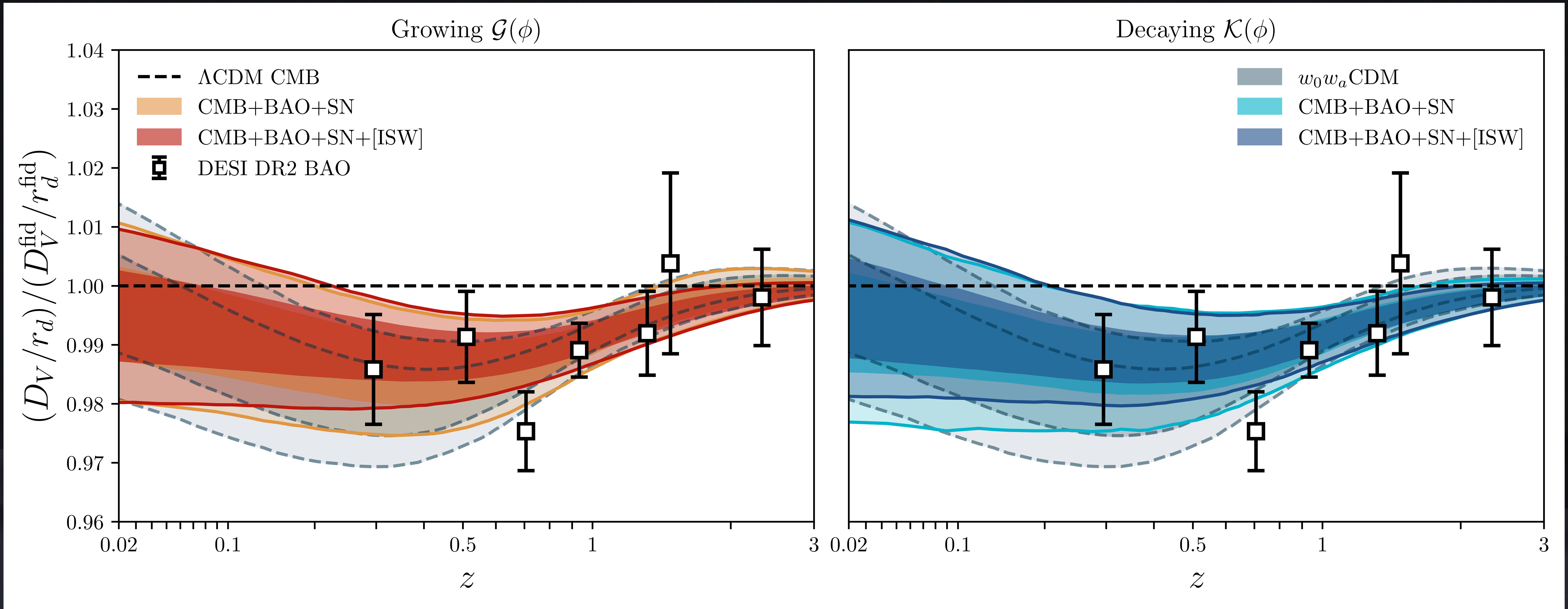
Dark bands = reject models where integrated galaxy-ISW signal is negative (NB: not a full data analysis at present.)

BAO fits

$K = -\mathcal{K}(\phi)\, X \qquad G_3 = g_3\, \mathcal{G}_3(\phi)\, X$

Volume-average BAO measurements from DESI DR2.

BAO scale normalised to LCDM (volume averaged)



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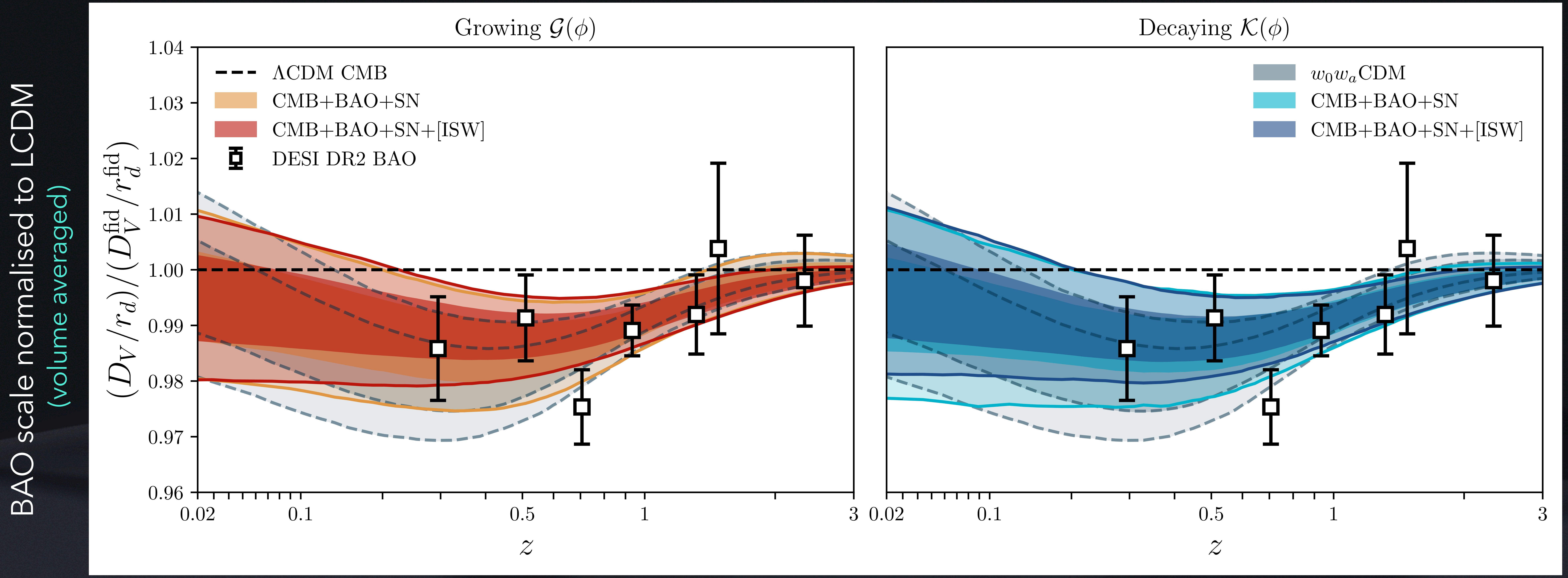

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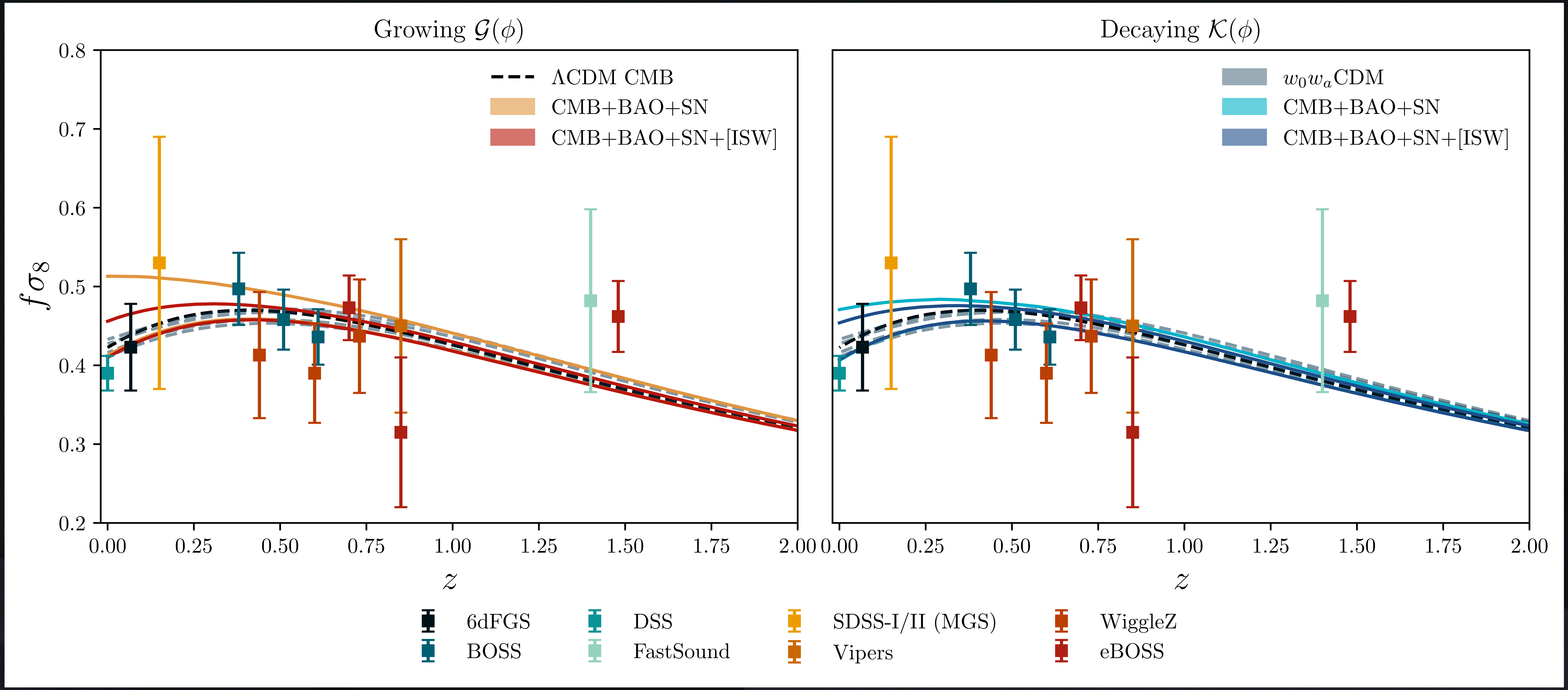
Linear scales

- Linear growth rates – no unpleasant surprises here.



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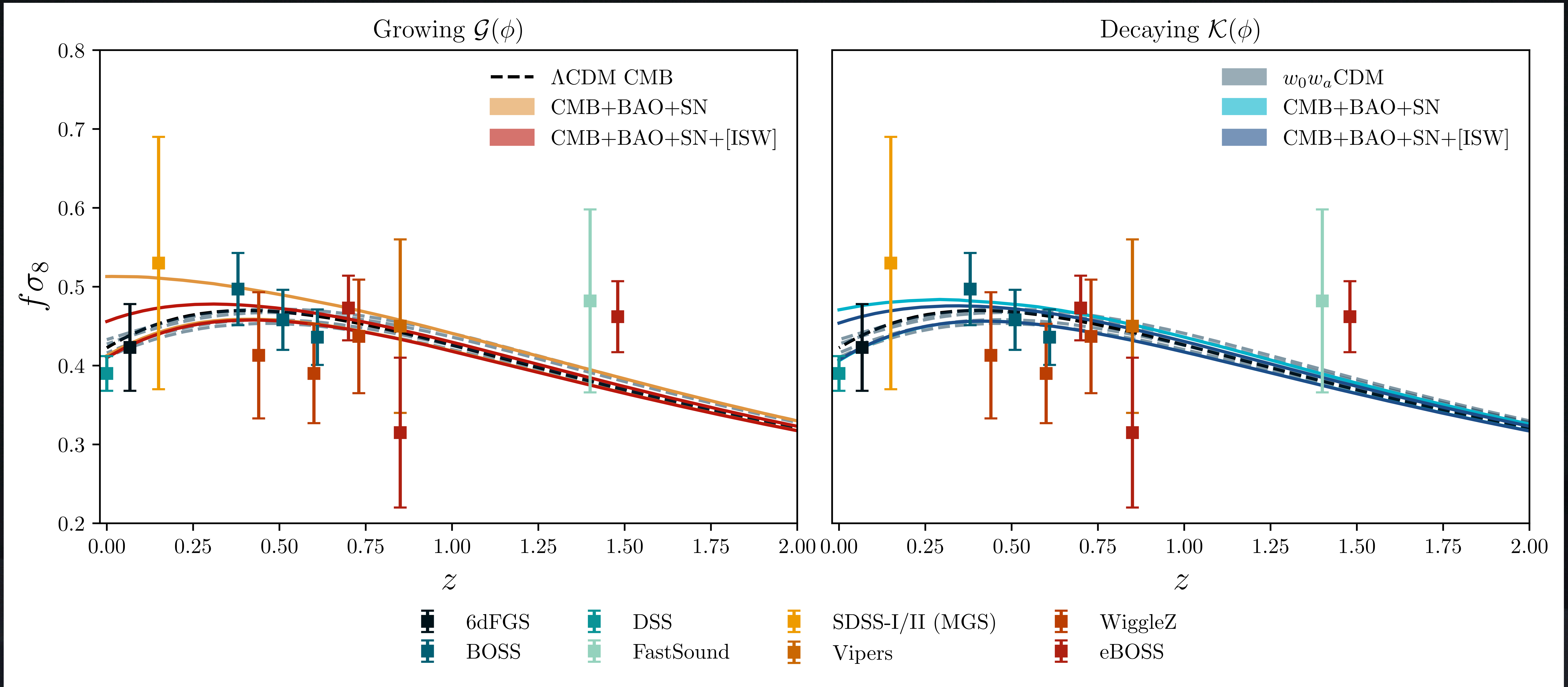

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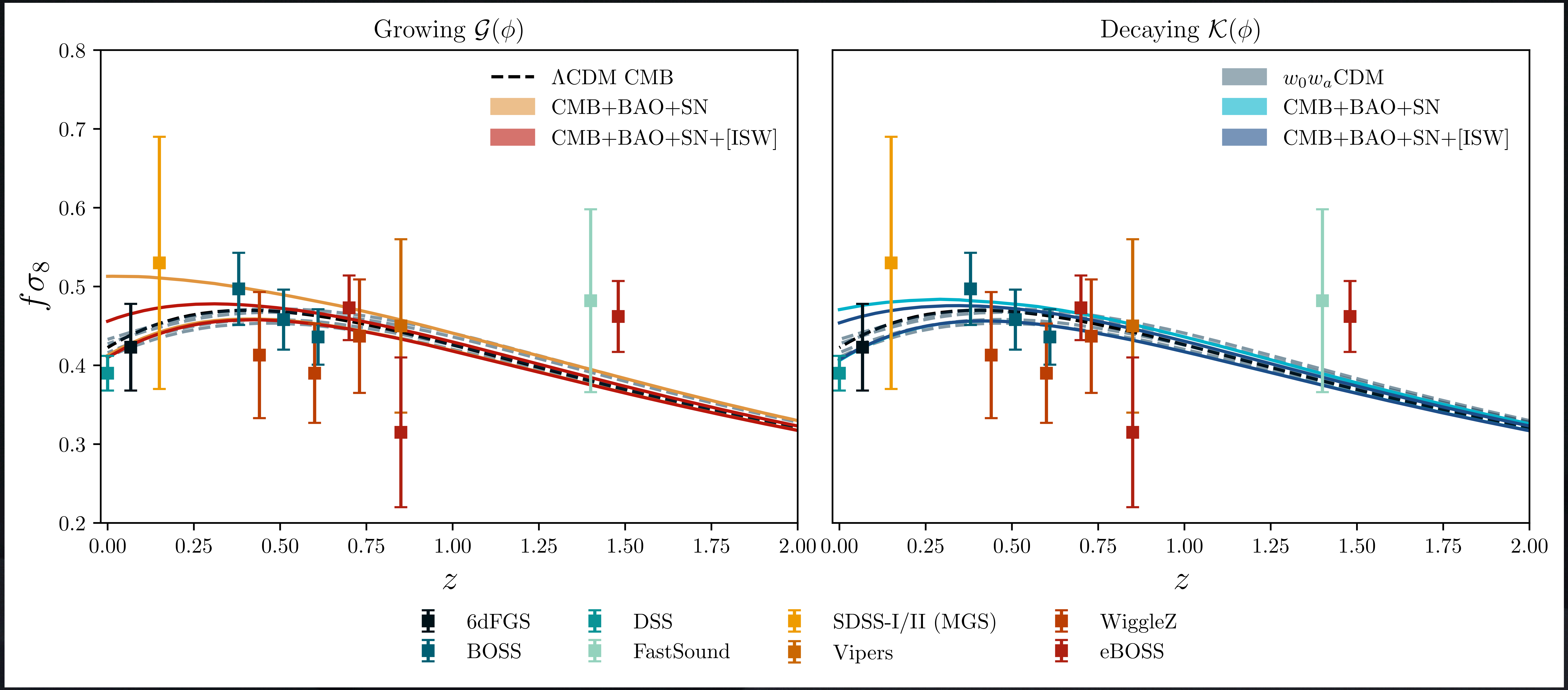

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- Because G_4 is standard (minimal coupling), these ACG models have no gravitational slip: "$\mu = \Sigma$" .
- Automatically consistent with GW propagation bounds.

How significant is the fit?

	ΛCDM	$w_0 w_a$CDM	Growing $\mathcal{G}(\phi)$	... + [ISW]	Decaying $\mathcal{K}(\phi)$	... + [ISW]
$\Delta\chi^2_{\rm MAP}$	0	−13.3	−11.4	−10.5	−11.2	−10.6
Significance	0	3.01σ	2.71σ	2.57σ	2.68σ	2.58σ
$\Delta \ln Z$	0	1.72	2.95	2.09	1.52	2.27
Betting Odds	1	5.67	19.1	8.09	4.59	9.68

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These 2-parameter MG models perform about the same as w_0-w_a.

How significant is the fit?

		ΛCDM	$w_0 w_a$CDM	Growing $\mathcal{G}(\phi)$	... + [ISW]	Decaying $\mathcal{K}(\phi)$	... + [ISW]
Frequentist	$\Delta\chi^2_{\rm MAP}$	0	−13.3	−11.4	−10.5	−11.2	−10.6
	Significance	0	3.01σ	2.71σ	2.57σ	2.68σ	2.58σ
Bayesian	$\Delta \ln Z$	0	1.72	2.95	2.09	1.52	2.27
	Betting Odds	1	5.67	19.1	8.09	4.59	9.68

These 2-parameter MG models perform about the same as w_0-w_a.

But, our models are predictive → we can evaluate their consequences on linear & nonlinear scales.

Nonlinear scales

- **Horndeski models can suffer pathologies in voids.**

See: Barreira+2013; Winther & Ferreira 2015; Baker+ 2017; Moretti+ 2026.

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  Today's ACG models are have Vainshtein screening, which likely dominates.

  BUT what happens for general choice K, G_3, G_4 ?

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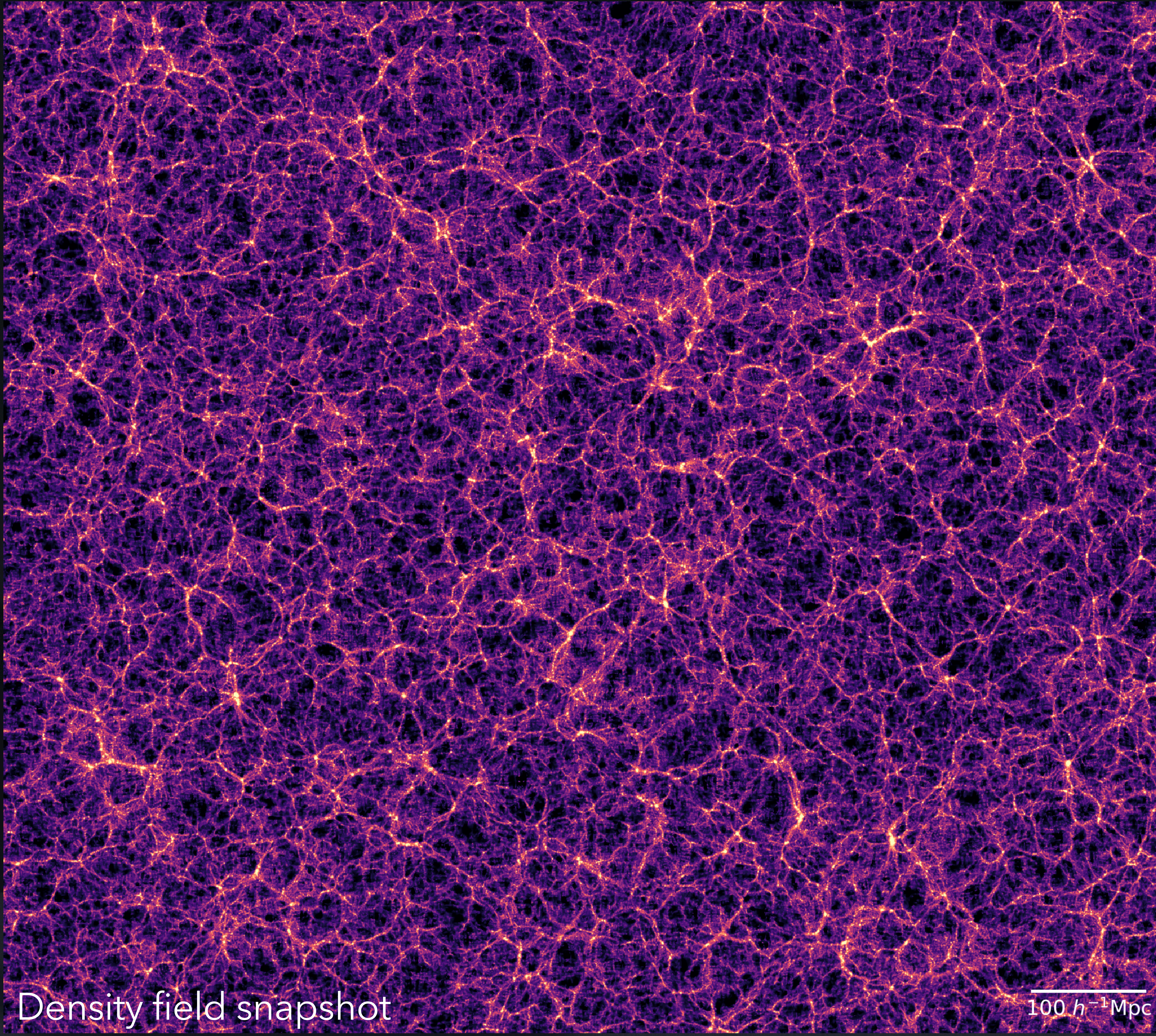
- Predictions for nonlinear scales – **requires a simulation which can run Horndeski models**….

Hi-COLA

A COLA solver for rapid simulations of Horndeski cosmologies.

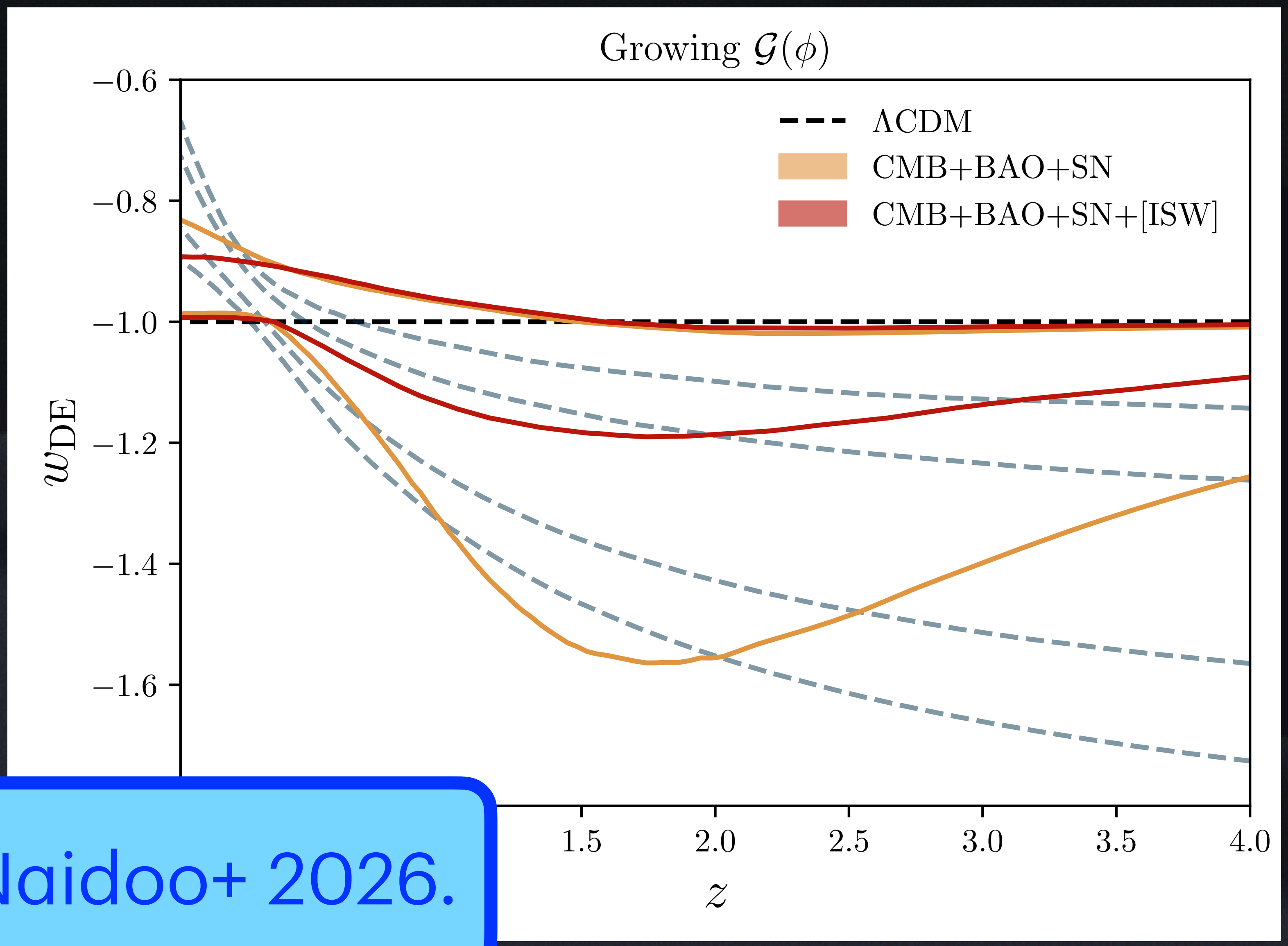


Conclusions

$$S = \int d^4x\sqrt{-g}\,[G_4(\phi)R + K(\phi,X) - G_3(\phi,X)\Box\phi - M_P^2\Lambda] + S_M$$

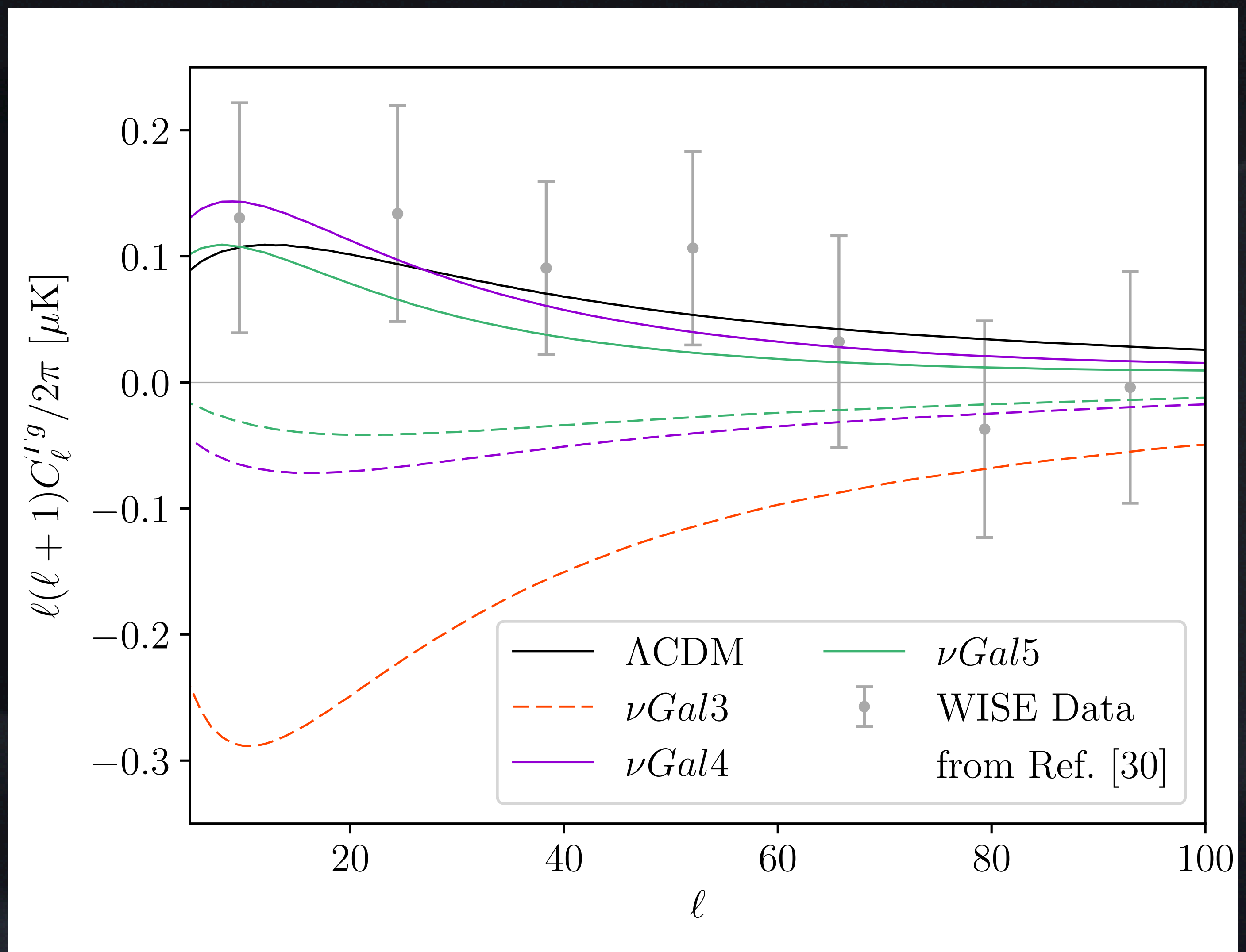
Background expansion → Linear perturbations → Nonlinear scales

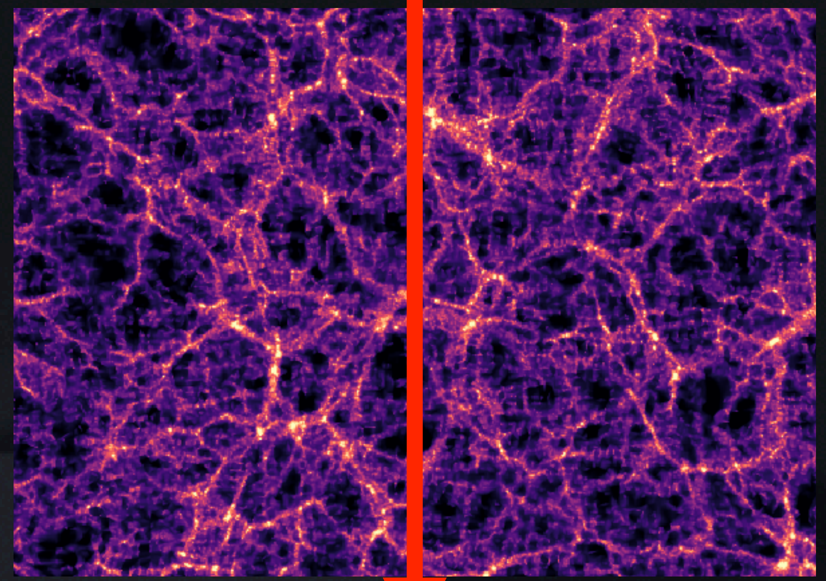
w(z)



Naidoo+ 2026.

ISW-galaxy cross-corr.





https://github.com/Hi-COLACode/Hi-COLA

Main publications: 2209.01666, 2407.00855

Validation exercise: 2406.13667
Unified screening: 2605.04154

Back-up Slides

Hi-COLA Components

The code takes any *user-specified* form of K, G_3 and G_4* and computes:

Background

$$H, \dot{H}, \dot{\phi}, \Omega_M, \Omega_\phi$$

2LPT growth

Linear growth factor, D_1

2nd-order growth, D_2

Screening factor

Inter-particle forces

$$F_{\rm tot} = F_{\rm N} + F_\phi$$

+ Initial conditions

Back-scaled from z=0 with appropriate growth factors

Currently Hi-COLA can do:

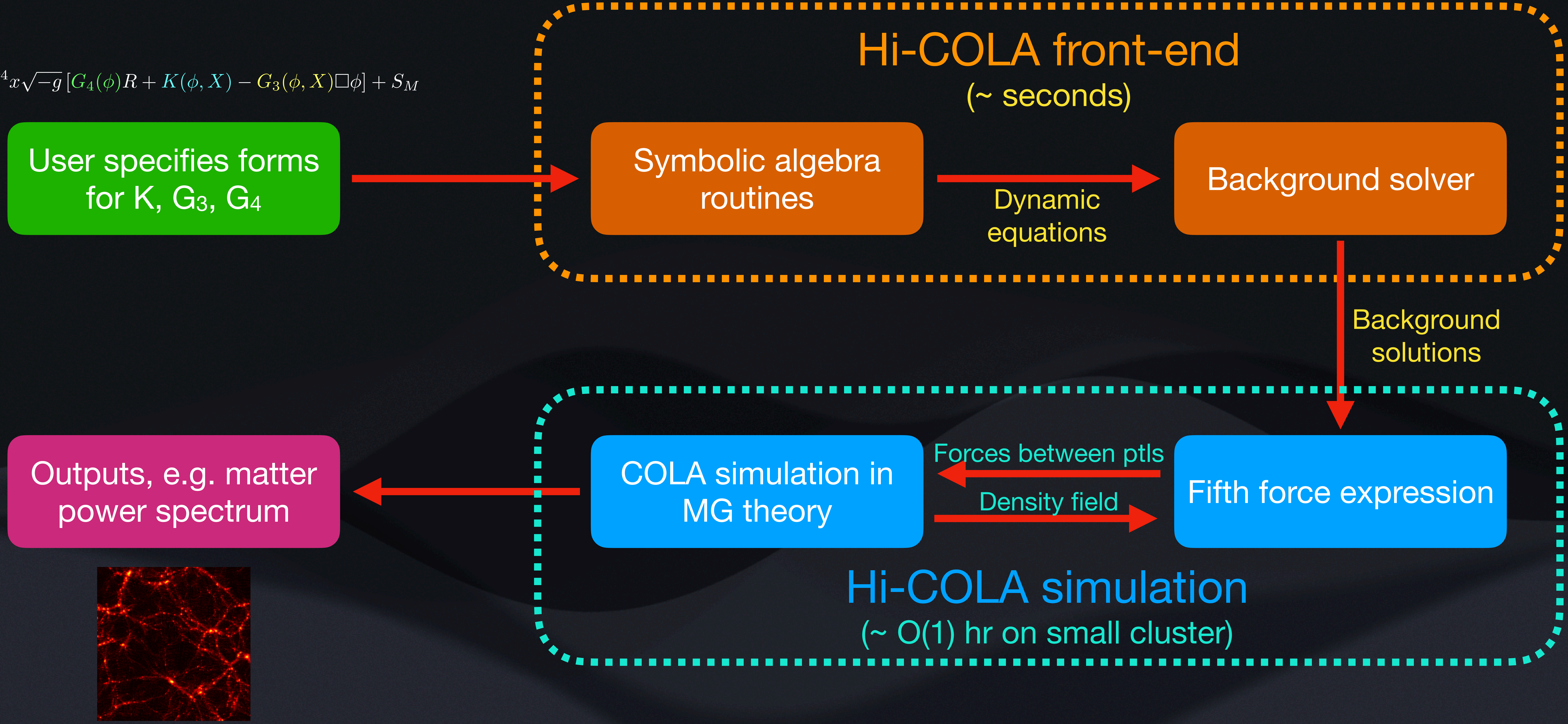
- Vainshtein screening
- K-mouflage screening

No Chameleon yet, but we're working on it…

*but, Garbage In ⇒ Garbage Out™

Code Diagram

$$S = \int d^4x \sqrt{-g} \left[G_4(\phi) R + K(\phi, X) - G_3(\phi, X) \Box\phi \right] + S_M$$



Force Expression in Hi-COLA

- Start with: i) spherically symmetric mass distribution

  ii) Quasi-static approximation (drop time derivatives of metric potentials and ϕ)

- The force experienced outside the mass is of the form: (derivation in arXiv 2209.01666)

Effective G — NB: unscreened, modifies Newtonian force

$$F_{\text{tot}} = F_{\text{N}} \frac{G_{G_4}}{G_{\text{N}}} \left[1 + \beta(z)\, S(z, \delta_m)\right]$$

Coupling
Gives overall strength of fifth force (function of time)

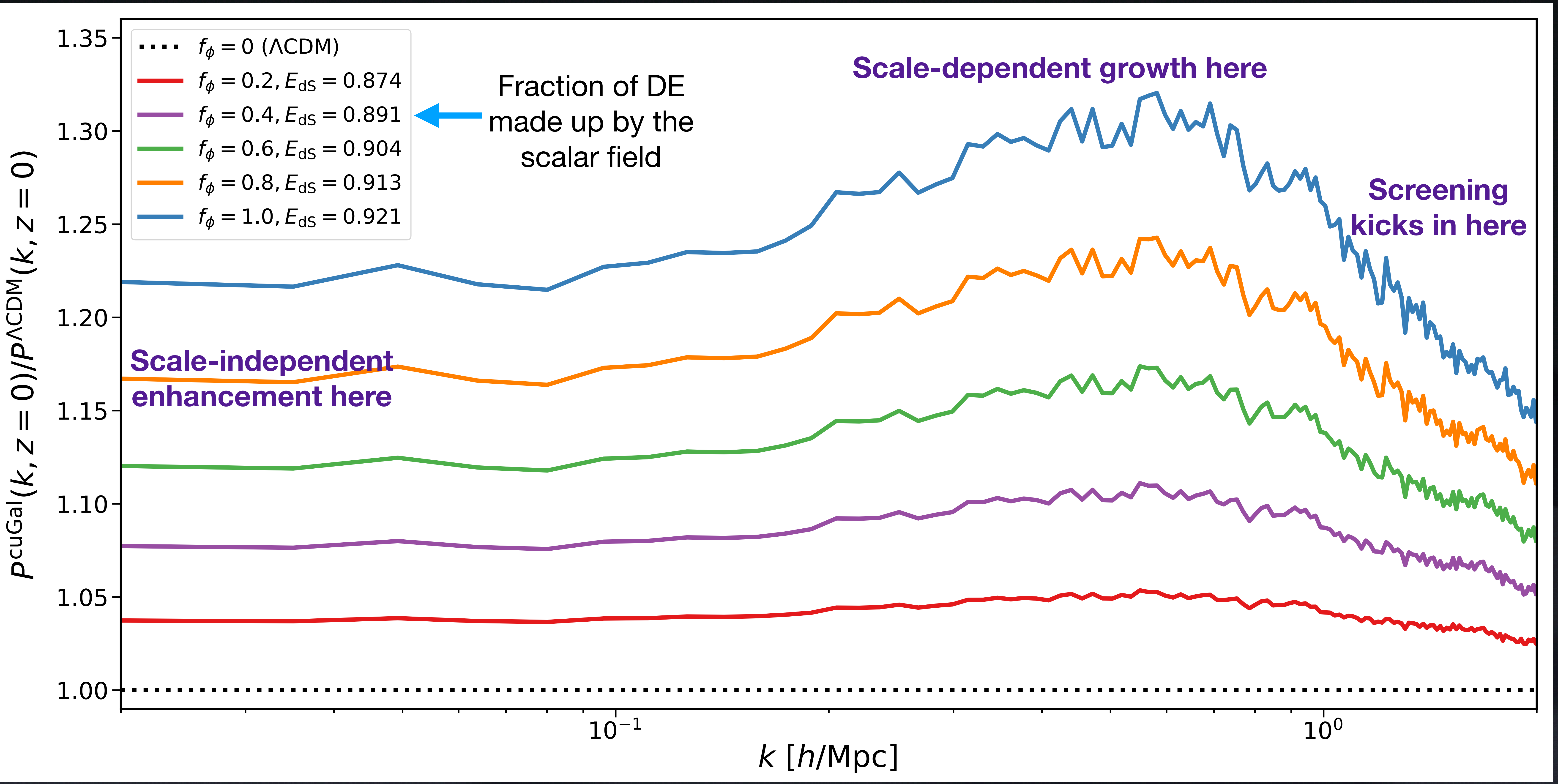
Screening factor
Modulates fifth force between 0 and 1 depending on environment

- Removes need to solve e.o.m. for ϕ everywhere → major speed-up (~same speed as LCDM). Introduces a well-characterised error on small scales (k ≳ 1 h/Mpc)

Results — Cubic Galileon

- K ∝ X, G_3 ∝ X, $G_4 = M_P^2/2$ (⇒ no change to Newtonian forces).
- Validated against the N-body simulations of Barreira et al. (2014).

NB: as a ratio to LCDM predictions, i.e. the BOOST (B)



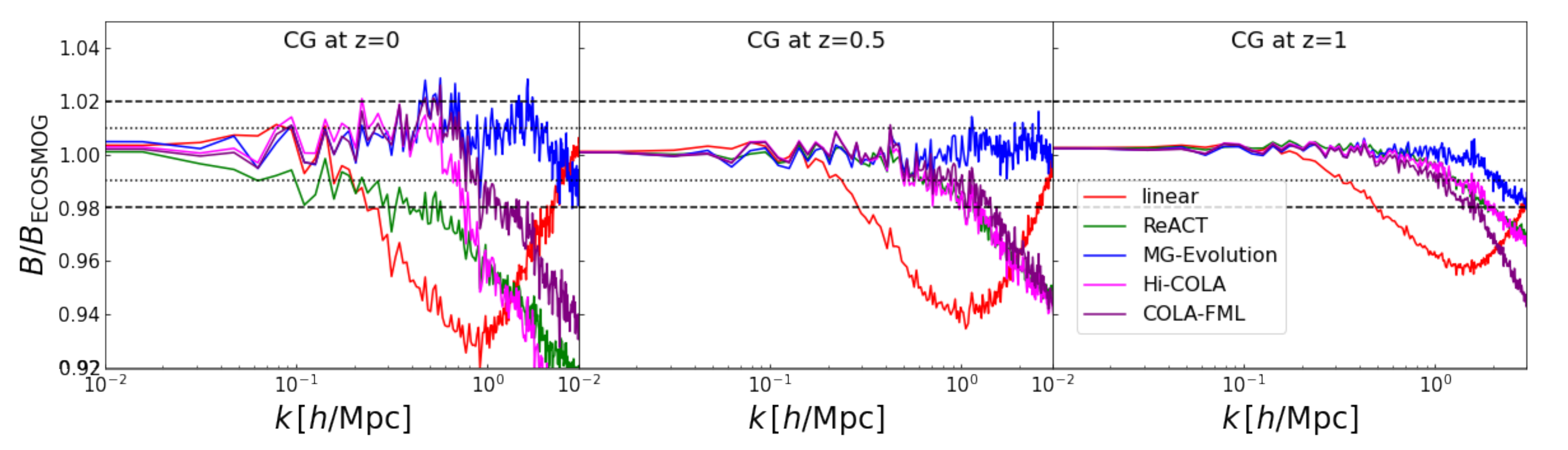
This plateau + bump shape is classic Vainshtein behaviour.

Validation

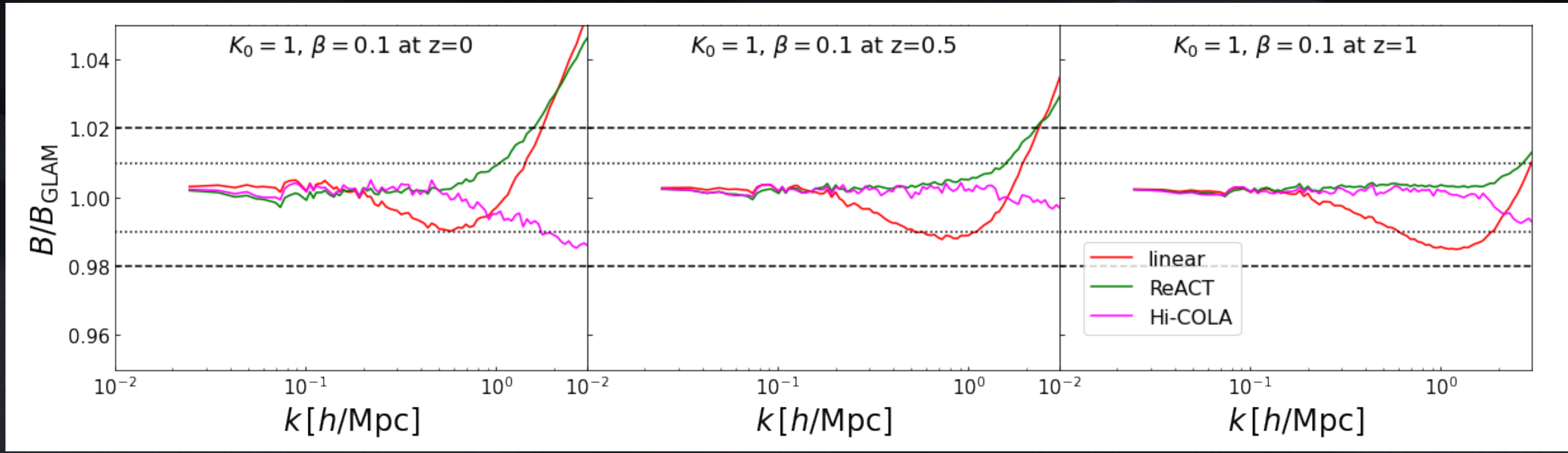
Comparison of approximate simulation methods with N-body results:

Cubic Galileon

(Vainshtein screening)

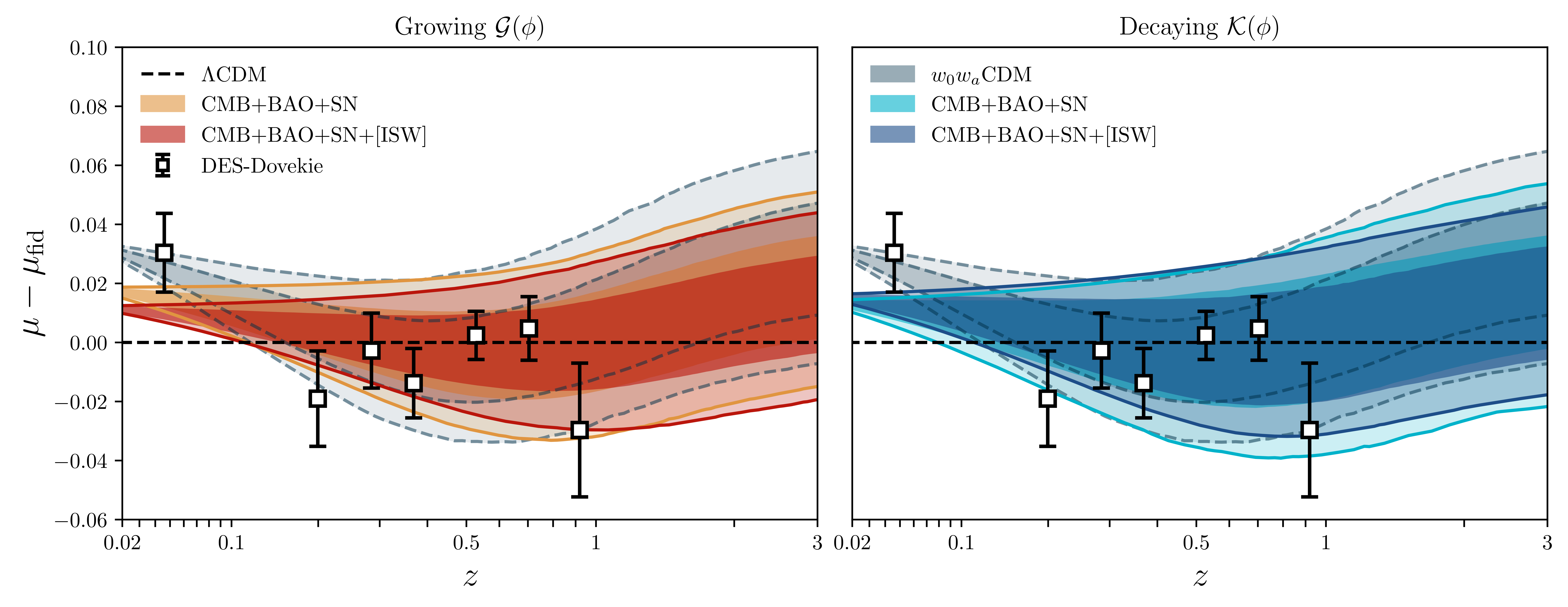


K-mouflage



Bose+, arXiv 2406.13667

SN fits



Growing $\mathcal{G}(\phi)$
Decaying $\mathcal{K}(\phi)$
ΛCDM
CMB+BAO+SN
CMB+BAO+SN+[ISW]
DES-Dovekie
w_0w_aCDM
CMB+BAO+SN
CMB+BAO+SN+[ISW]
$\mu - \mu_{\rm fid}$
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
0.02
0.1
0.5
1
3
z

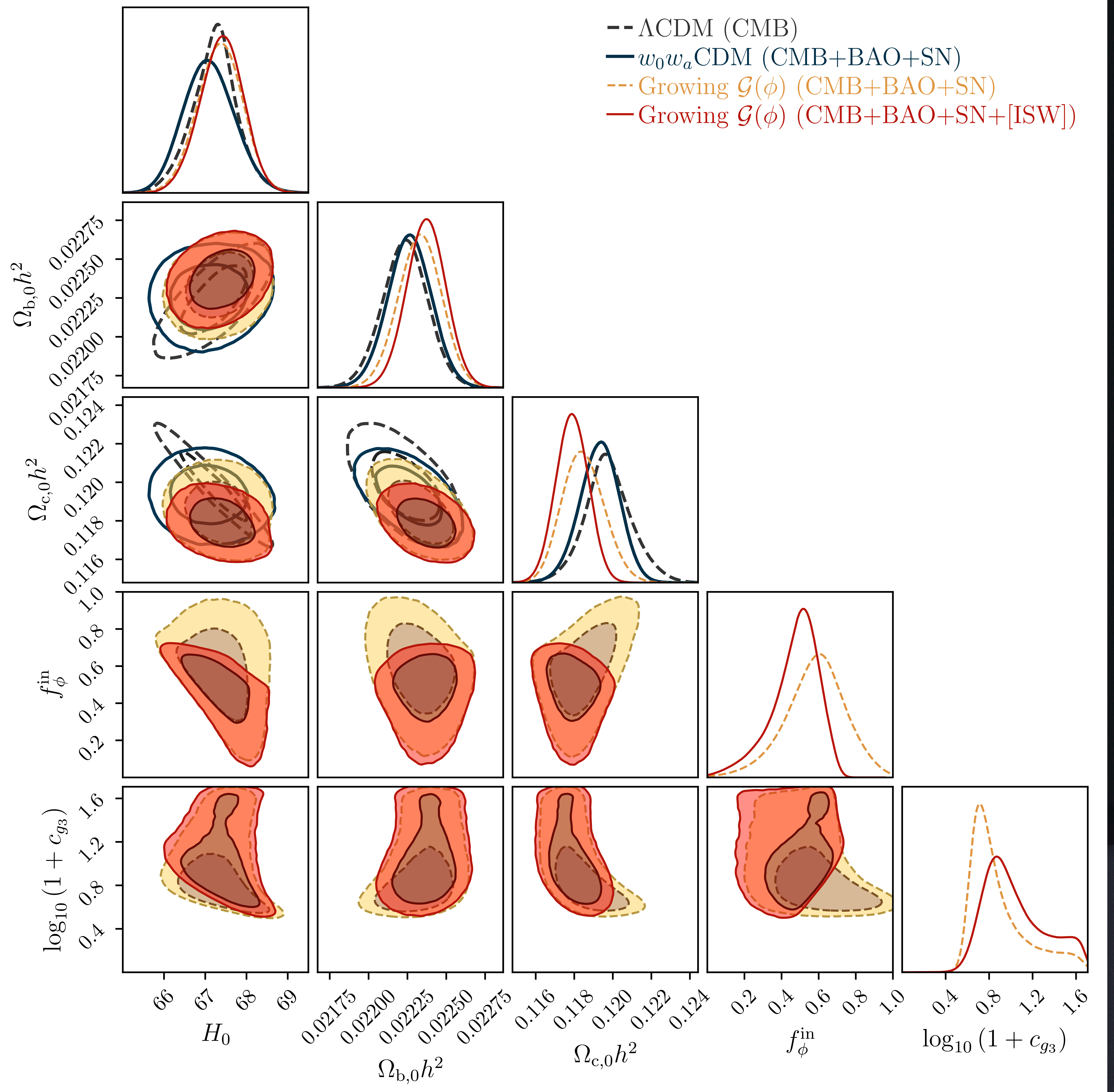
Posteriors

(For the Growing G model)

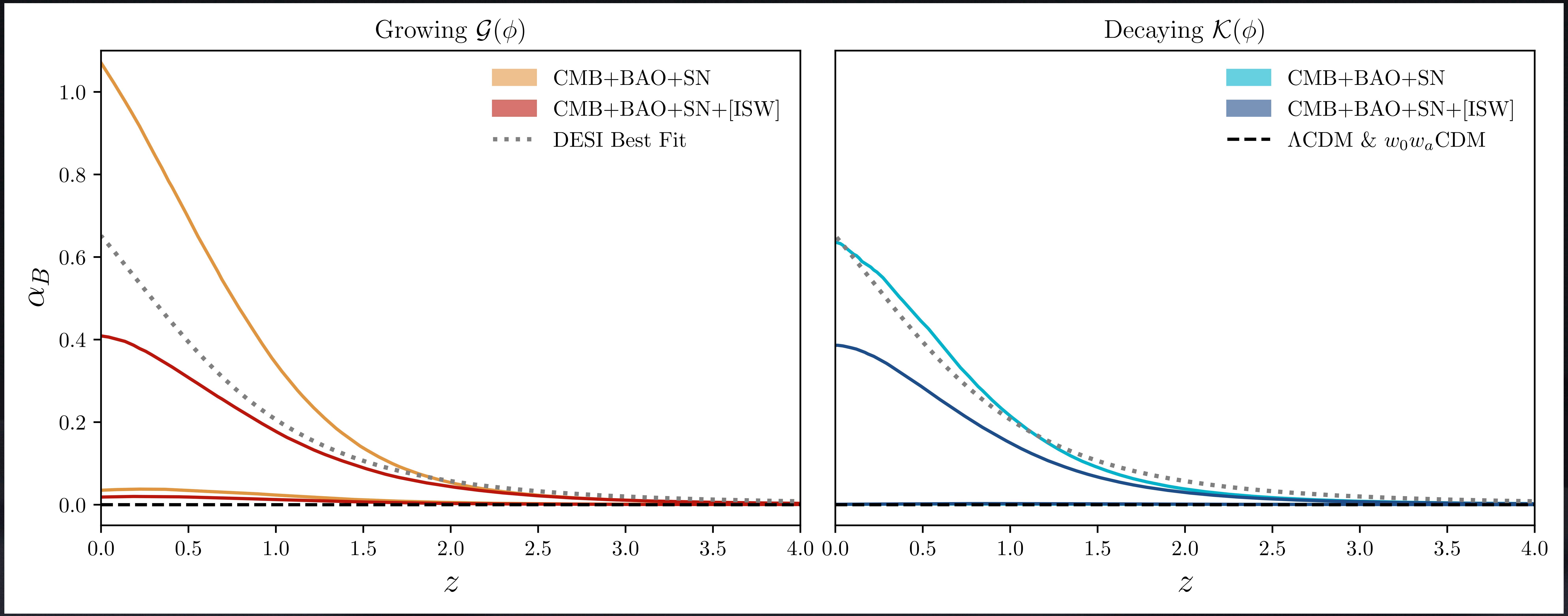
Recall:

$$f_\phi = \frac{\Omega_\phi}{\Omega_\Lambda + \Omega_\phi}$$

→ ISW constraint disfavours models with high f_ϕ.

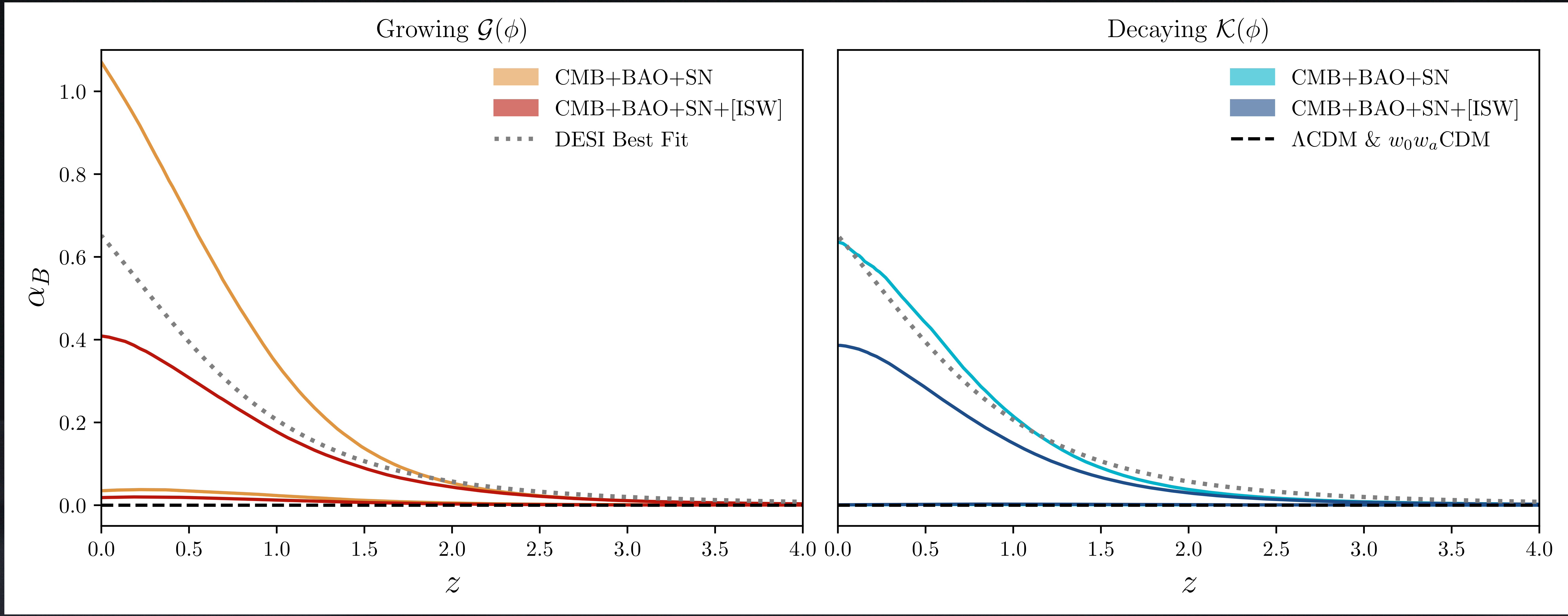


DESI constraints on the Alphas



DESI constraints on the Alphas

The best-fit DESI model probably breaks the ISW-galaxy cross-correlation sign.



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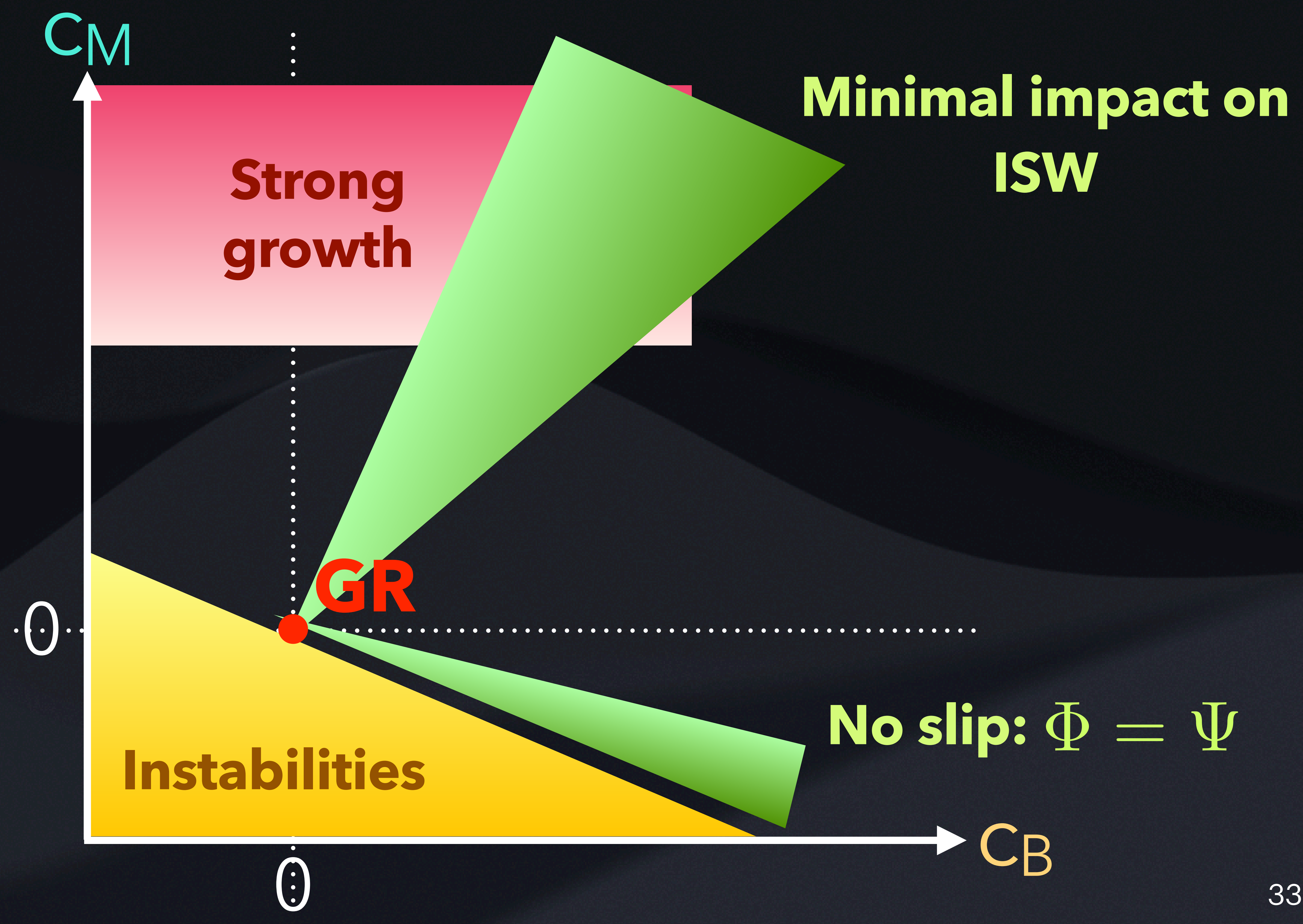
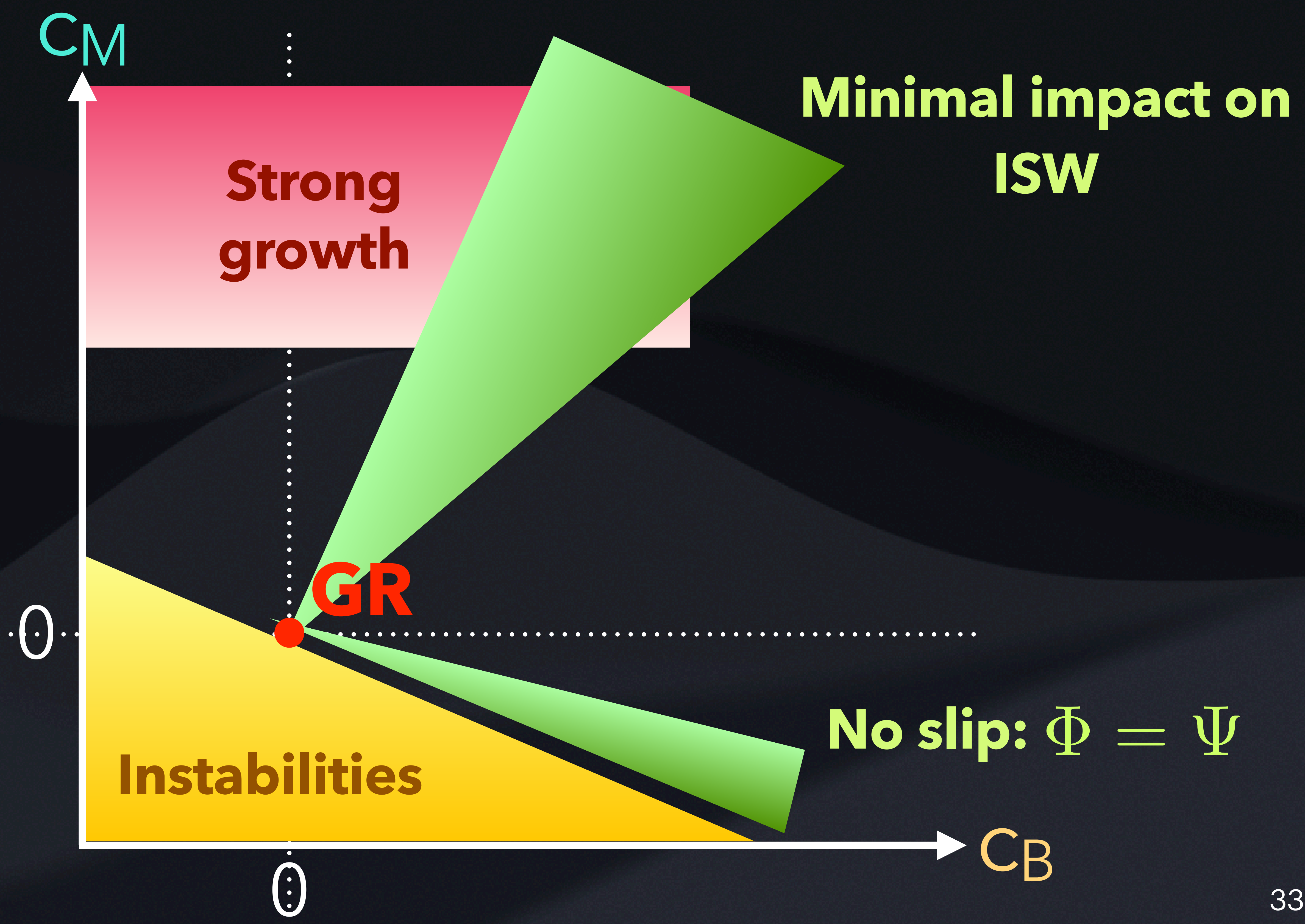


DESI constraints on the Alphas

Large scales of the CMB, CMB lensing and galaxy clustering probe $\alpha_B(z)$ & $\alpha_M(z)$.



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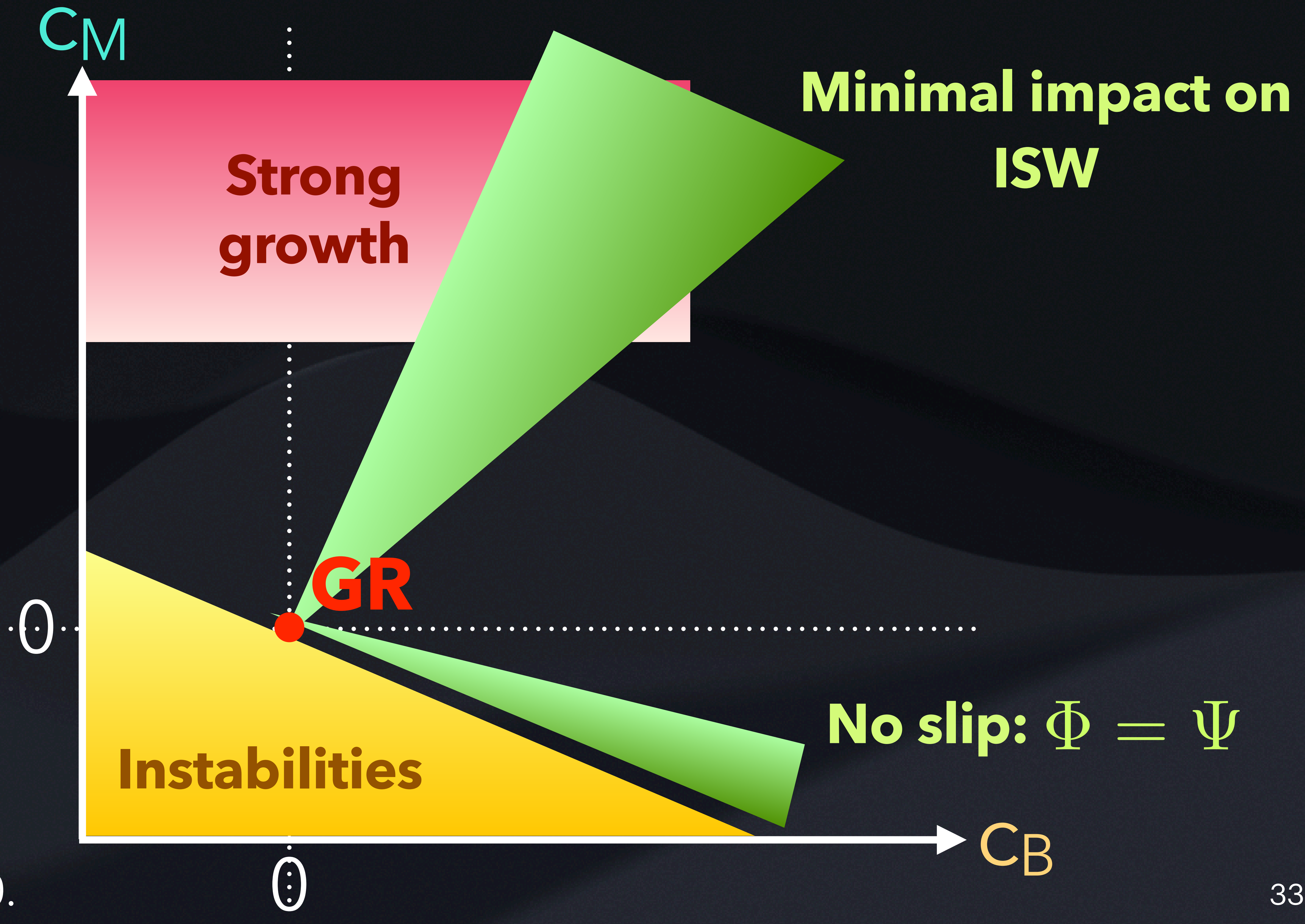

*Subtlety here about what it means to have ΛCDM background when $\alpha_M \neq 0$.

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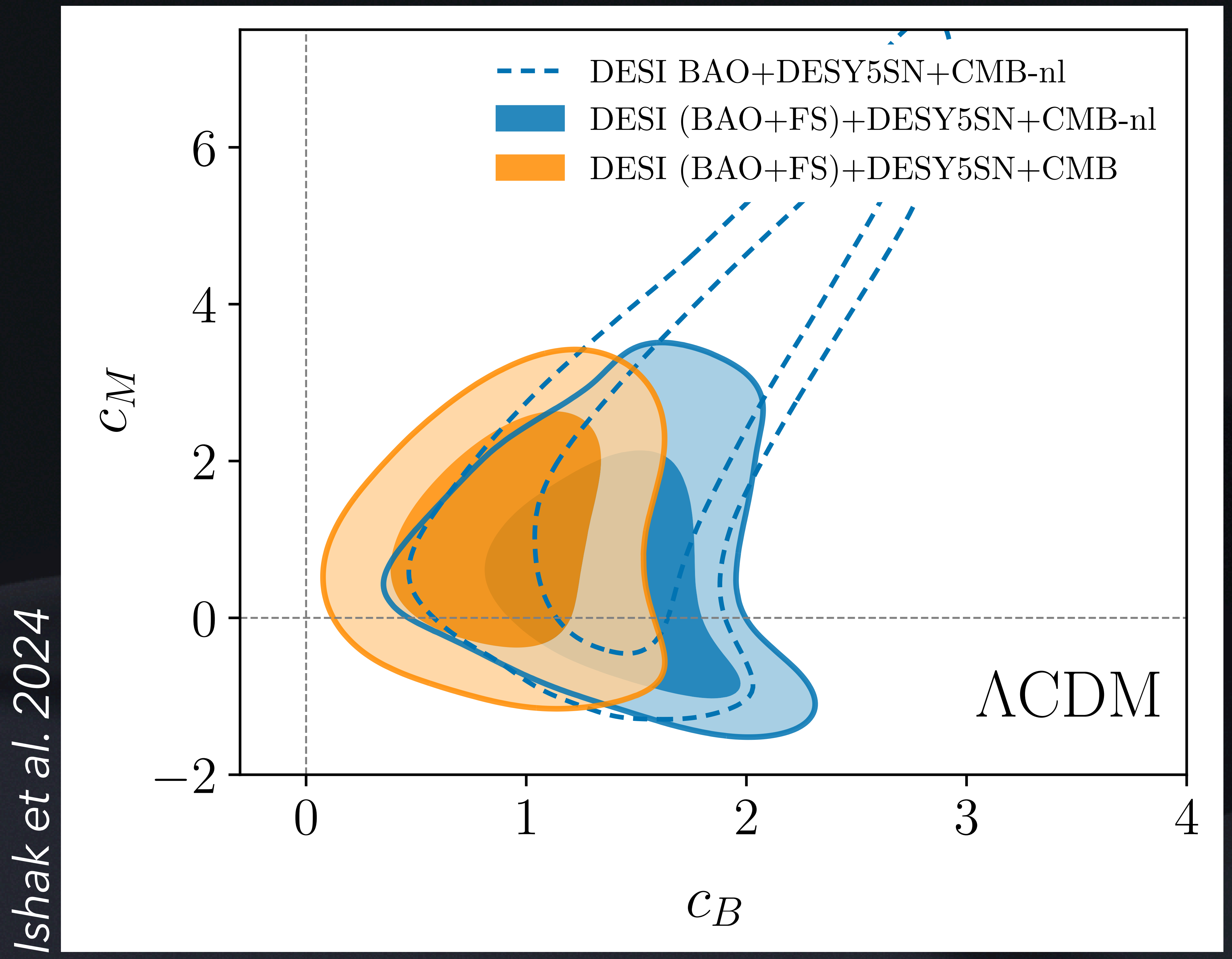

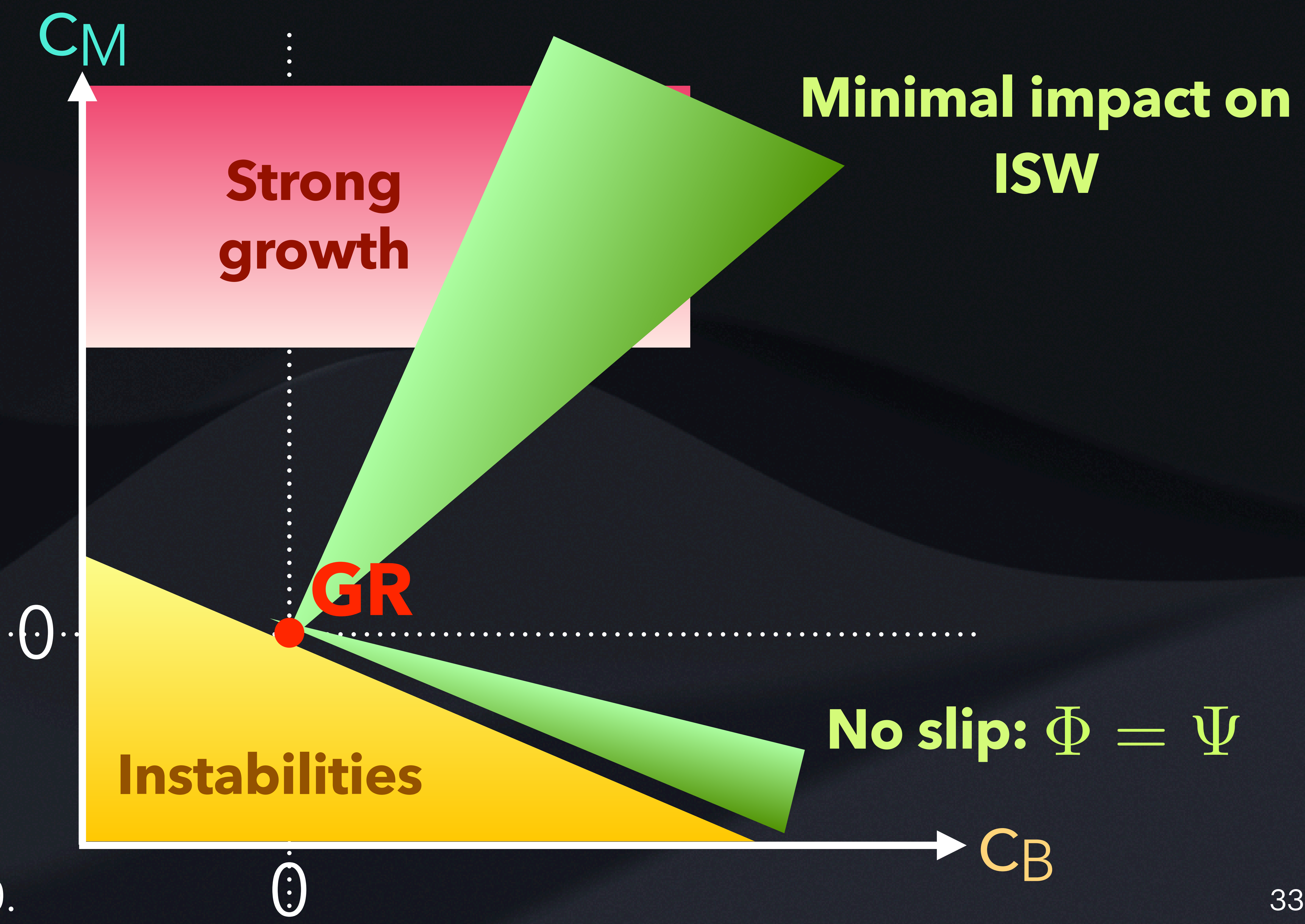

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