Viable, Physical & Descriptive Models of the Late Universe

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CosmoForward @IAC, Tenerife, Feb 2026

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Good Models for Dark Energy

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Adequate ~~Good~~ Models for Dark Energy

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Outline

1. Model requirements & linear constraints

2. Nonlinear tools for testing gravity

3. Hunting viable models

James Hallam

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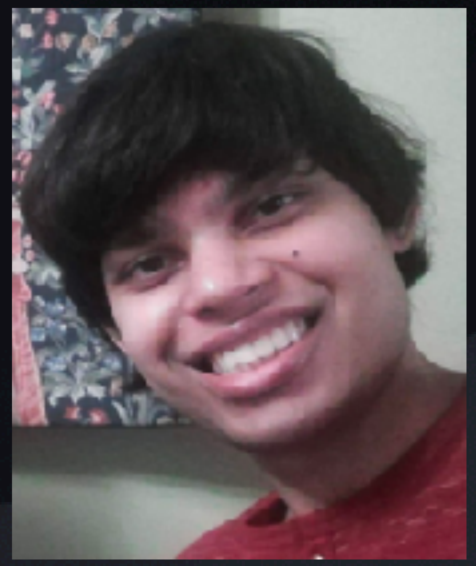
Ashim Sen Gupta
(now postdoc at Bielefeld)



Hert Niks via Unsplash.com

Requirements & linear constraints

Gravity theory wanted

🚙 Can drive late-time accelerated expansion

🌍 Has a screening mechanism → doesn't break local gravity constraints

😖 Not mess up structure formation at $z > 2$

💗 Consistent with GW propagation speed = c

😍 Stable growth of scalar & tensor perturbations (no gradient instabilities, no ghosts 👻)

Is that really *so* much to ask??

Theorists' preference: (luminal) Horndeski

The most general action with one new scalar field – a 'parent theory' to lots of offspring.

We'll deal with *luminal* Horndeski gravity, i.e. where $c_{GW} = 1$.

Motivated by GW170817 results. (There are loopholes here, but I don't recommend pursuing them right now)

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

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

where X = kinetic term of scalar field

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

E.g. cubic Galileon uses these two

G_3 is key in Vainshtein screening

where X = kinetic term of scalar field

The Bellini & Sawicki Alpha "Parameters"

These describe **linear** cosmological perturbations only.

$$\alpha_M(z) = \frac{d\,G_4(\phi)}{d\,\ln a}$$

$$\alpha_B(z) = \frac{X}{H^2 G_4}\left[K_X + 2XK_{XX} - 2G_{3\phi} - 2XG_{3\phi X}\right]$$

$$\alpha_K(z) = \frac{\dot{\phi}}{HG_4}\left[XG_{3X} - G_{4\phi}\right]$$

The Bellini & Sawicki Alpha "Parameters"

These describe **linear** cosmological perturbations only.

$\alpha_M(z) = \frac{d\,G_4(\phi)}{d\,\ln a}$ running of effective Planck mass.

$\alpha_B(z)$ = `braiding' — mixing of scalar + metric kinetic terms.

$\alpha_K(z)$ = kinetic term of scalar field.

The Bellini & Sawicki Alpha "Parameters"

These describe **linear** cosmological perturbations only.

$\alpha_M(z) = \frac{d\,G_4(\phi)}{d\,\ln a}$ running of effective Planck mass.

$\alpha_B(z)$ = `braiding' — mixing of scalar + metric kinetic terms.

$\alpha_K(z)$ = kinetic term of scalar field.

Must be accompanied by a free function fixing the background expansion, e.g. H(z) or w(z).

The alphas are linear combinations of K, G_3, G_4 and their derivatives, **evaluated on the background solution.**

[$\alpha_H(z)$ & $\alpha_T(z)$ — already ruled out by GW speed and GW decay (Baker+ 2017, Creminelli+ 2018)]

The Bellini & Sawicki Alpha "Parameters"

These describe **linear** cosmological perturbations only.

$$\alpha_M(z) = \frac{d\,G_4(\phi)}{d\,\ln a}$$ running of effective Planck mass.

$\alpha_B(z)$ = `braiding' — mixing of scalar + metric kinetic terms.

$\alpha_K(z)$ = kinetic term of scalar field.

Must be accompanied by a free function fixing the background expansion, e.g. H(z) or w(z).

Note the alphas are functions of *redshift*. Without specifying a model, we must choose an ansatz, e.g.

$$\alpha_i(z) = c_i \frac{\Omega_\Lambda(z)}{\Omega_{\Lambda 0}}$$ or $$\alpha_i(a) = c_i\, a^p$$

Debate over these choices:

E.g. Linder 201X - poor theory representation

Gleyzes 2017 - mild impact on observation

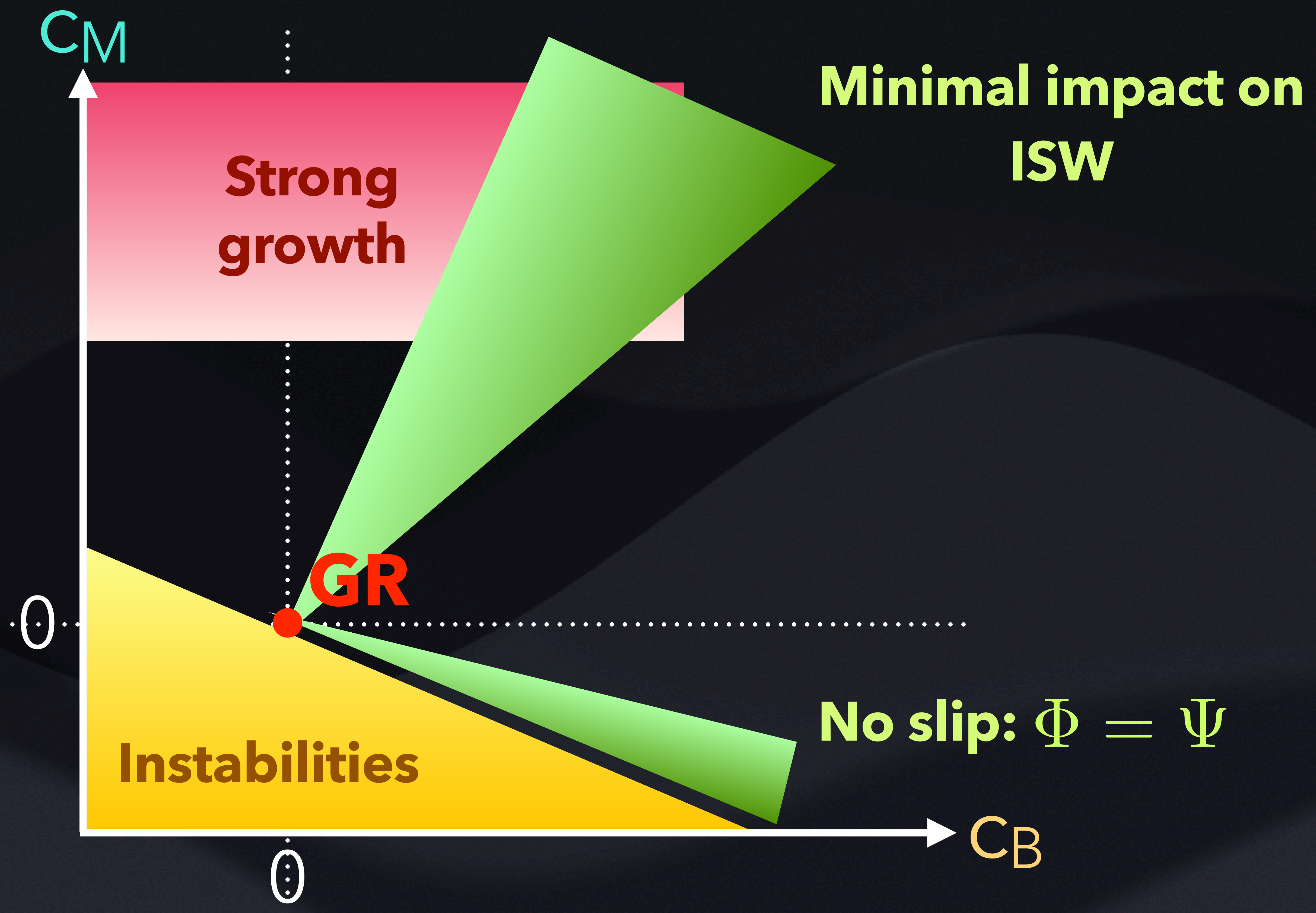
Linear phenomenology of the Alphas

$\alpha_K(z)$ drops out of the linearised field equations, so gets fixed – typically to a value ~0.1-1.

Stability conditions (absence of ghosts, gradient instabilities) place time-dependent bounds in the space of $\alpha_B(z)$ & $\alpha_M(z)$.

Using the ansatz:

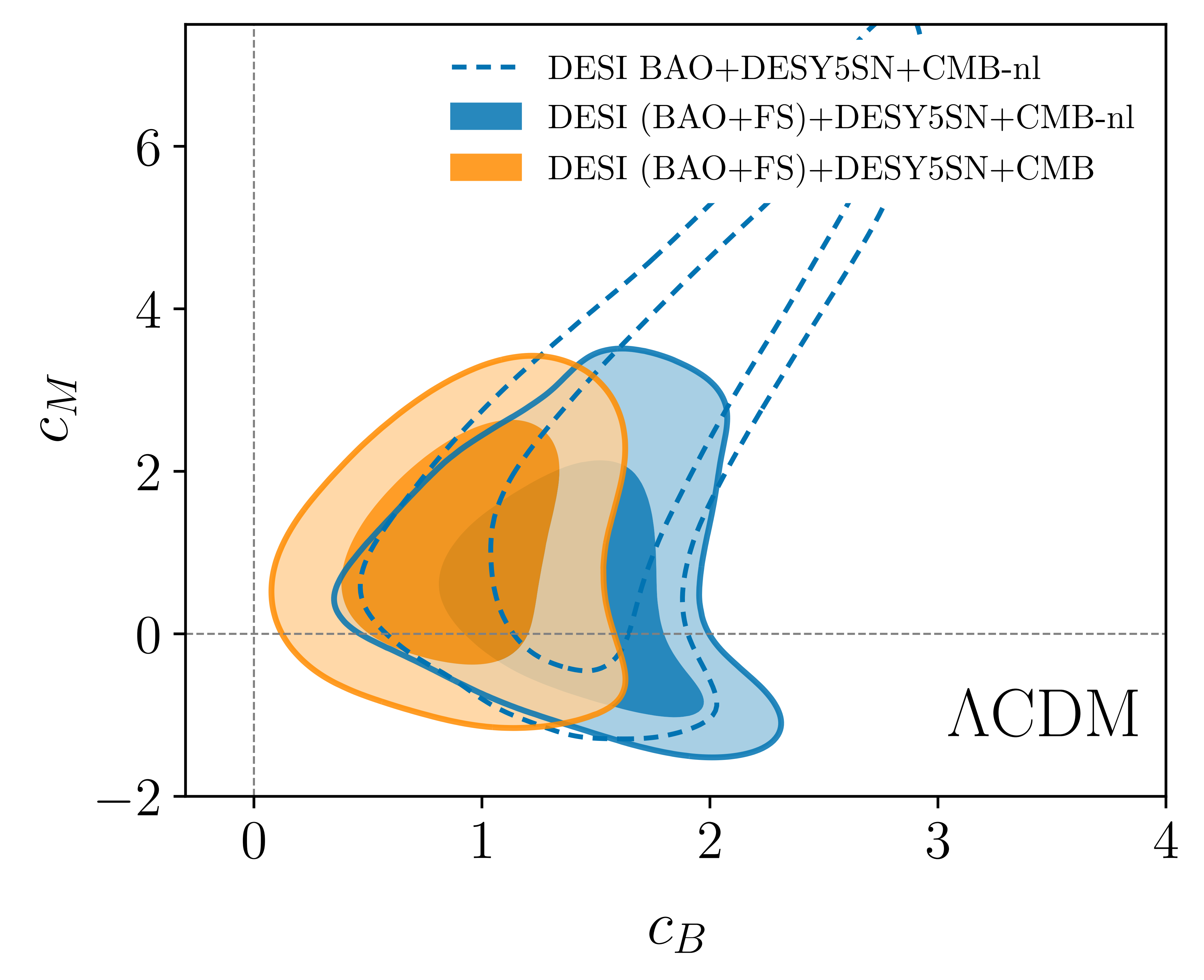
$$\alpha_i(z) = c_i \frac{\Omega_\Lambda(z)}{\Omega_{\Lambda 0}}$$



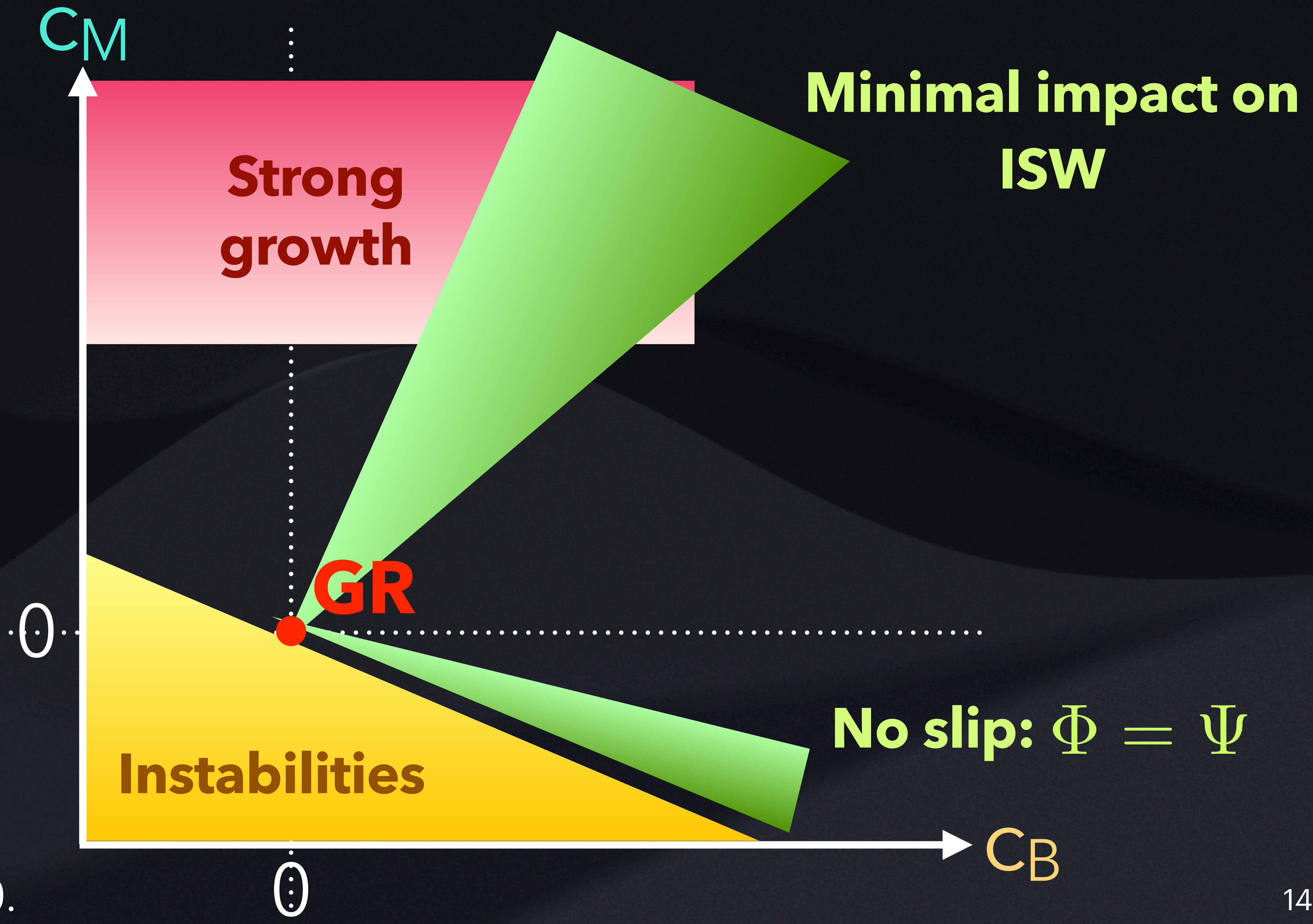
DESI constraints on the Alphas

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

BAO & SN probe the background expansion*, here fixed to ΛCDM.



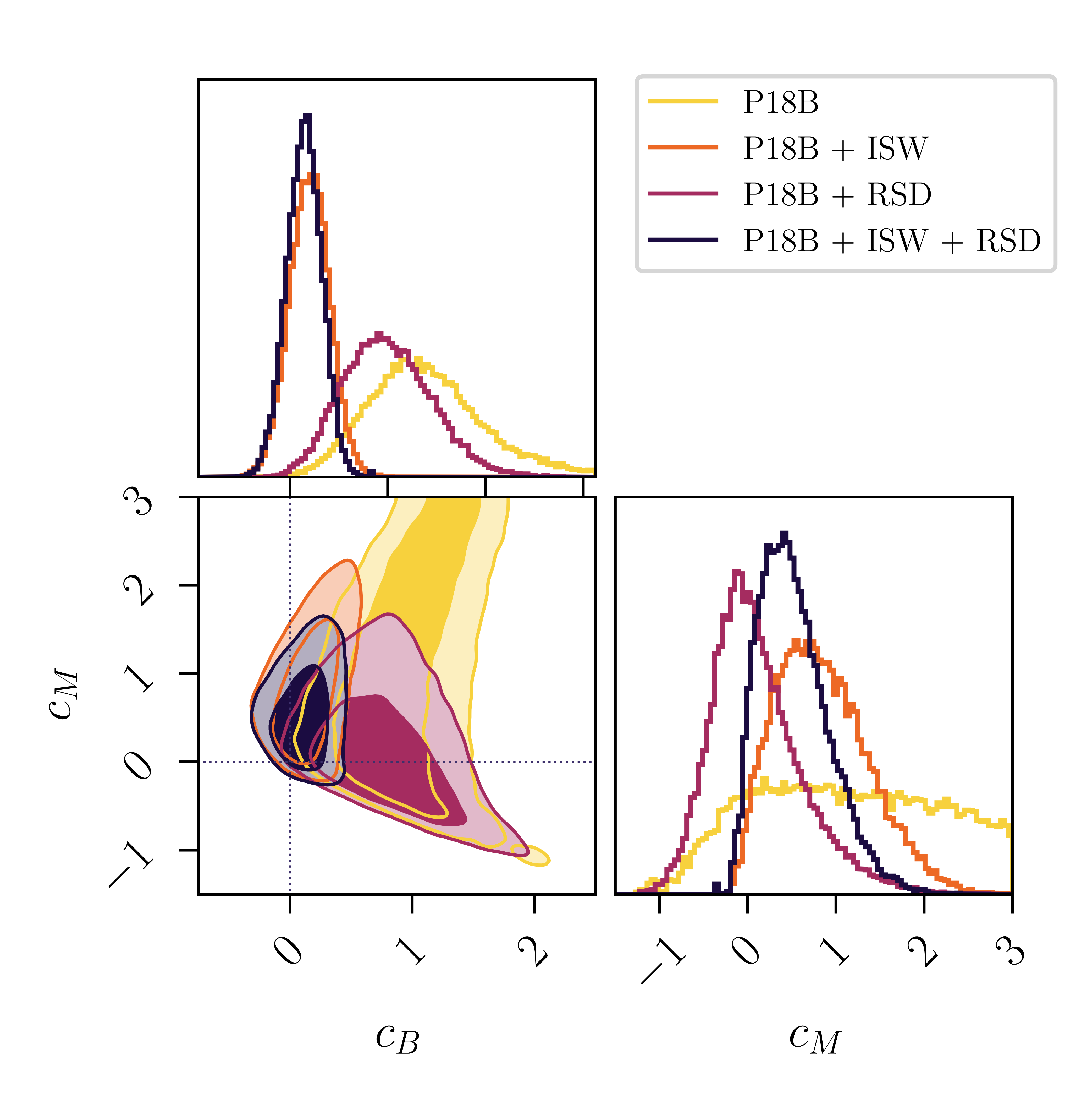
Ishak et al. 2024



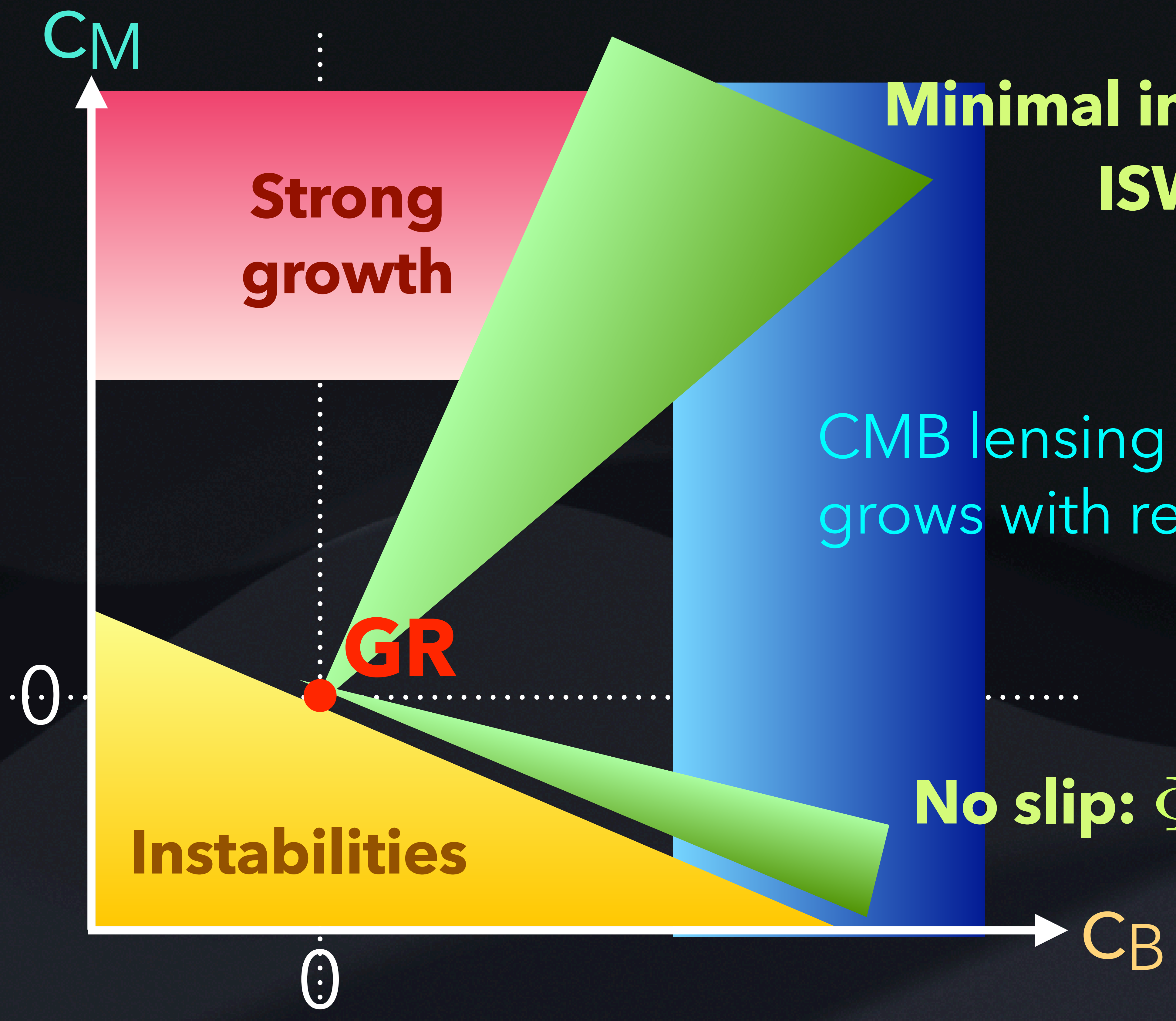
*Subtlety here about what it means to have ΛCDM background when $\alpha_M \neq 0$.

Bringing in ISW-galaxy cross-correlation

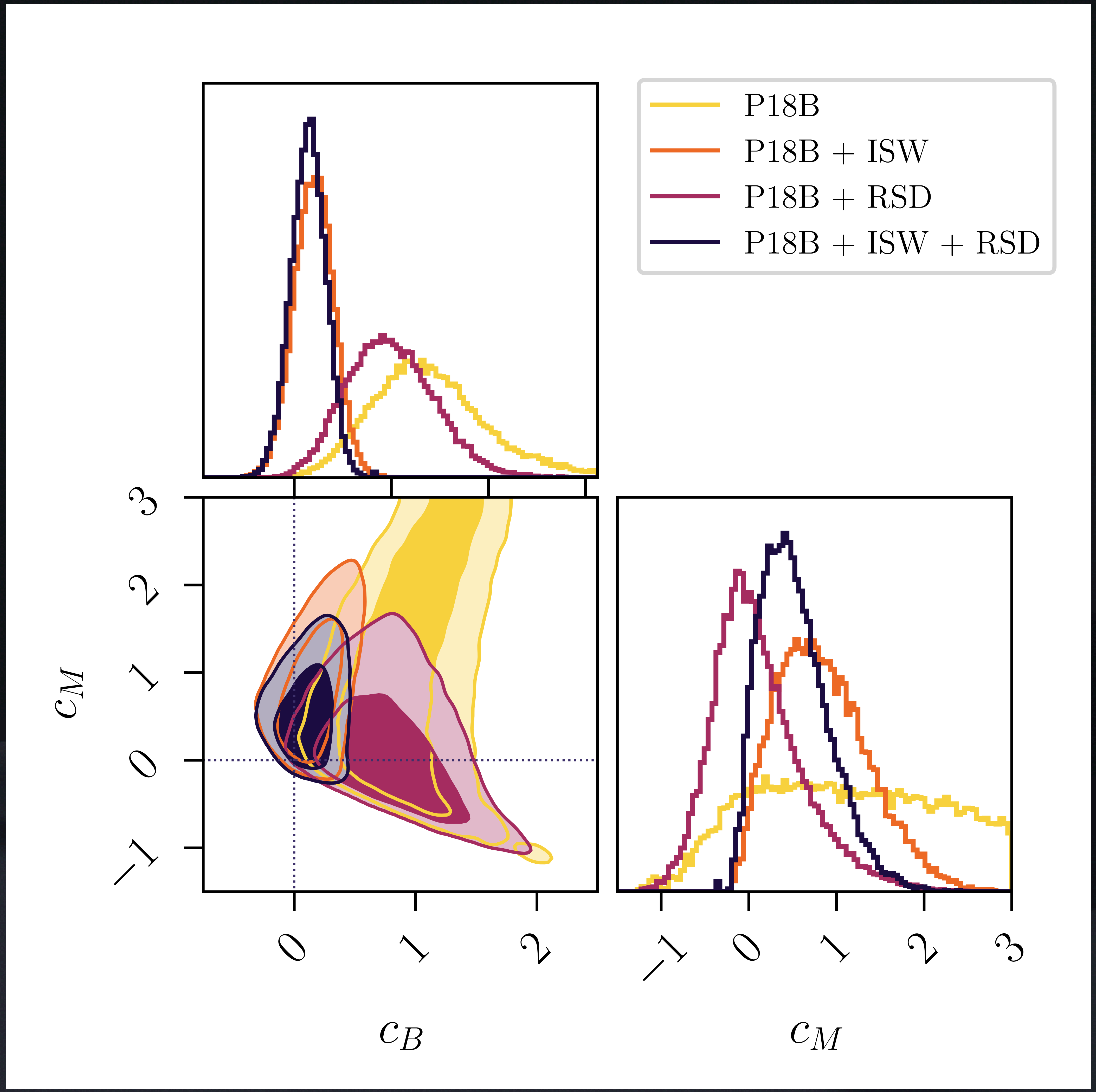
Seraille, Noller & Sherwin (2024)



← Using Planck CMB + BOSS, SDSS, 6dF & 2MPZ.



Linear constraints on the Horndeski Alphas



Seraille, Noller & Sherwin (2024)

From the DESI MG paper:

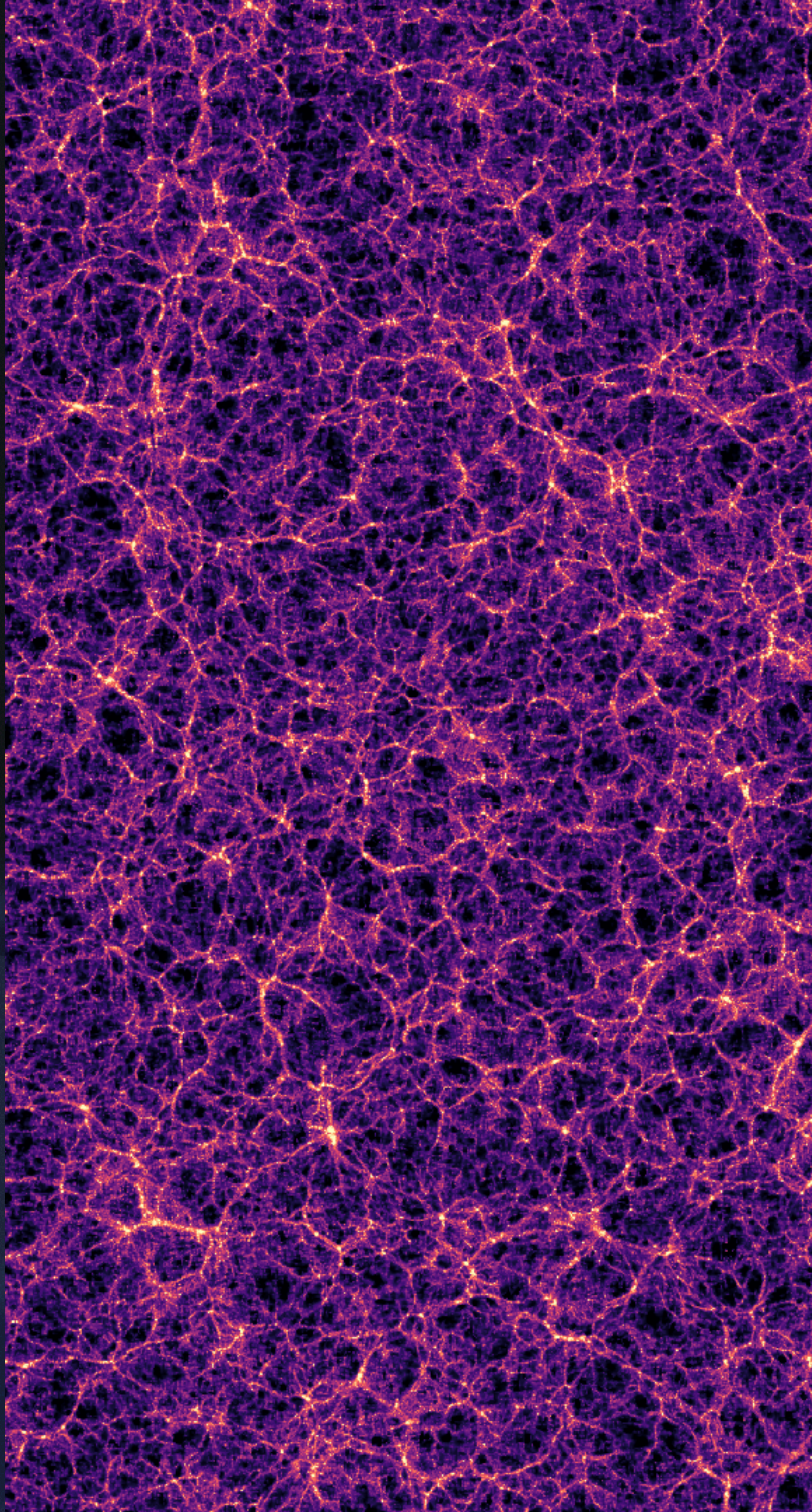
$$\left.\begin{aligned} c_M &= 1.05 \pm 0.96, \\ c_B &= 0.92 \pm 0.33, \end{aligned}\right\} \quad \text{DESI (FS+BAO) + DESY5SN + CMB}\ .$$

From Seraille et al. (left):

	c_B	c_M
P18B + ISW + RSD	$0.12^{+0.28}_{-0.29}$	$0.54^{+0.90}_{-0.60}$

Slight preferences for $c_B>0$ allowed by CMB & clustering can probably be removed with ISW-gal.

Simulating nonlinear scales in Horndeski gravity



Back to the Horndeski Lagrangian

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

where X = kinetic term of scalar field

18

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

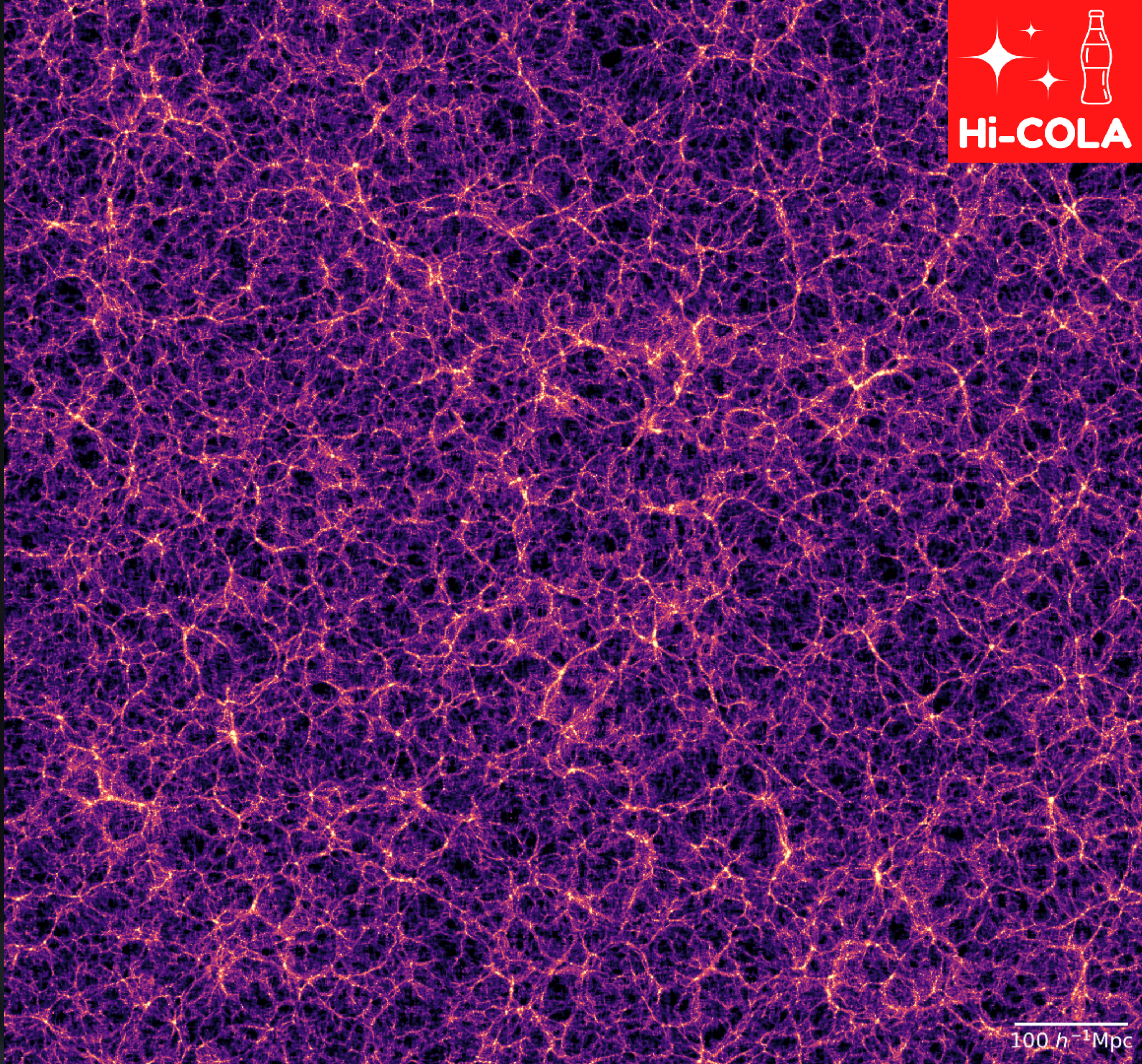
Currently Hi-COLA can do:

- Vainshtein screening
- K-mouflage screening

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

*but, Garbage In ⇒ Garbage Out™

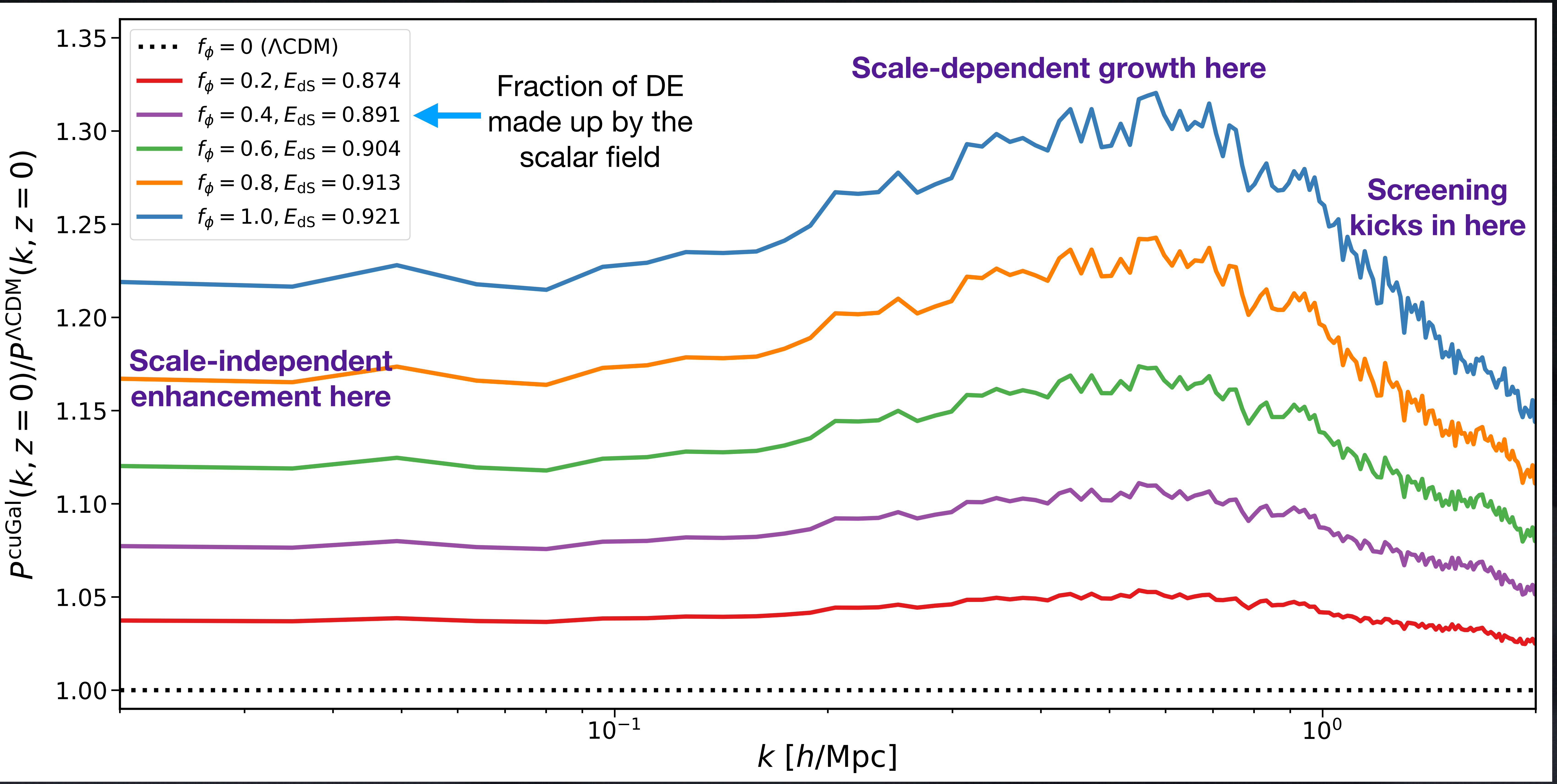
Density field snapshot



Results — Cubic Galileon

- $K \propto X$, $G_3 \propto X$, $G_4 = M_P^2/2$ (⇒ 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.

Hunting viable models in Horndeski space

'The Fireball Approaches'

G. Horndeski

Gravity model Olympics

Expense (time/compute/postdocs) of test 😥

HEATS

Background expansion

- CMB ang. diameter distance
- SNIa luminosity distances
- BAO distances $\alpha_\parallel$ and $\alpha_\perp$

SEMIS

Linear perturbations

- Linear growth, $f\sigma_8$
- Galaxy-ISW cross-correlation
- GW luminosity distance

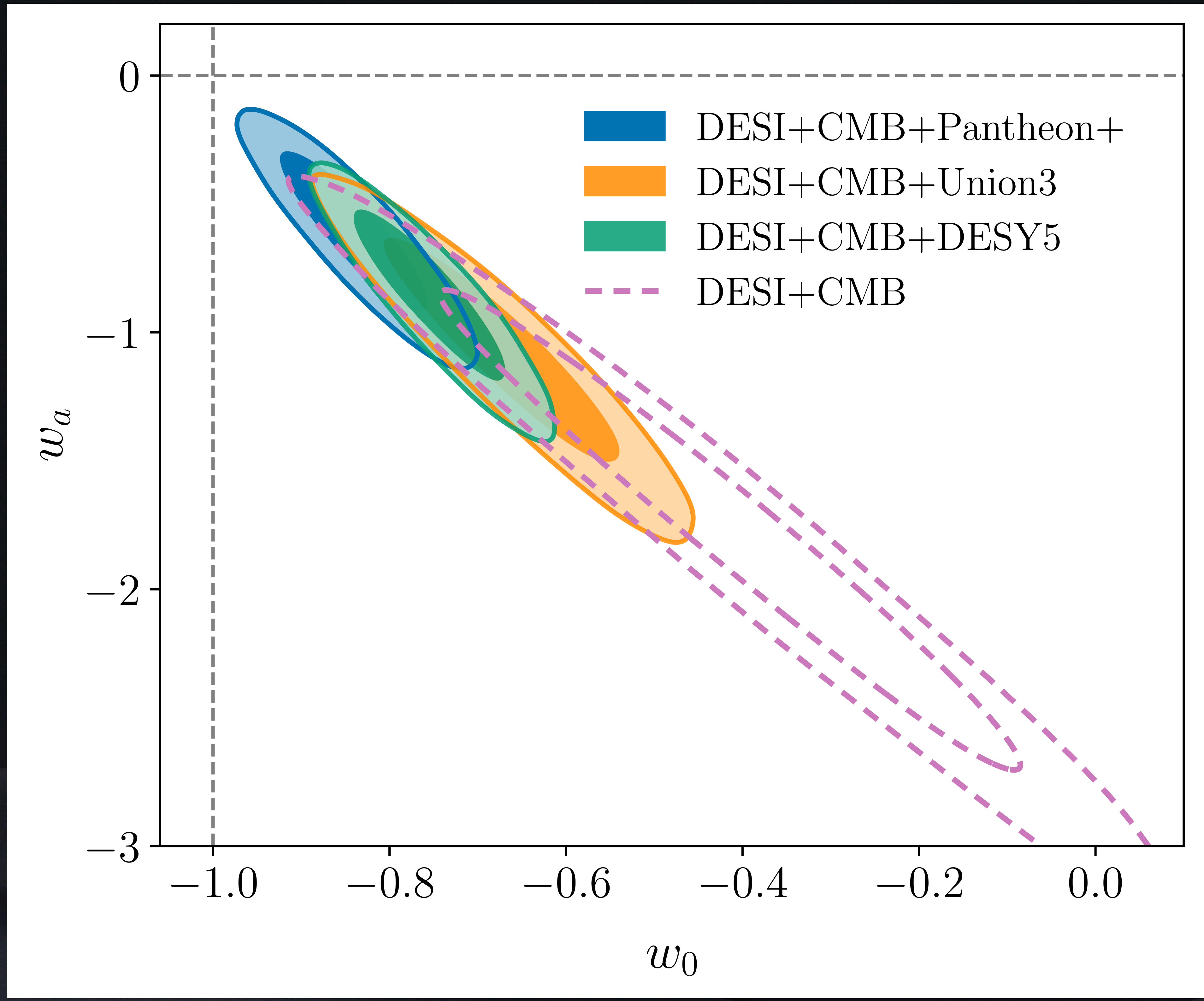
FINAL

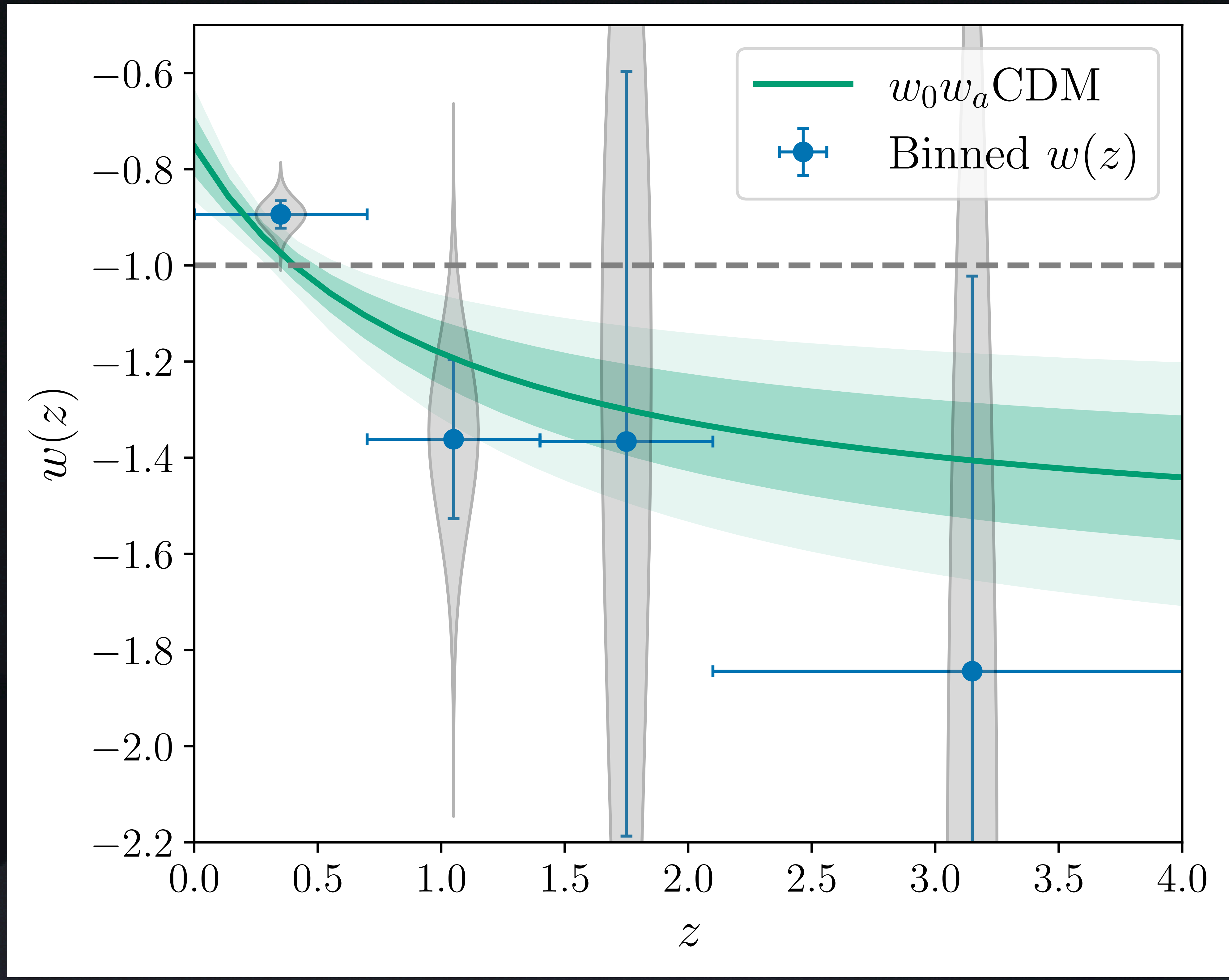
Nonlinear scales

- 3 x 2pt signal
- Galaxy clustering
- *incl. nonlinear scales*

Some contenders for 'good' models

What does the fit from BAO+CMB+SN imply?





Abdul Karim+, DESI DRII results

→ Prefers models which cross w=-1 (from below to above) at late redshift.

Crossing the phantom divide

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

where X = kinetic term of scalar field

Simplest choice: $G_4 = M_P^2/2$ (standard value)

Start from Cubic Galileon: $K = -X$ $G_3 = g_3\,X$ Cannot cross w=-1

To cross w=-1, G_3 must 'overtake' K at late times ⇒ either G_3 grows or K weakens.

E.g.1 Linear (G_3 grows): $K = -X$ $G_3 = g_3\,X\left[1 + \frac{\phi}{\phi_0}\right]$

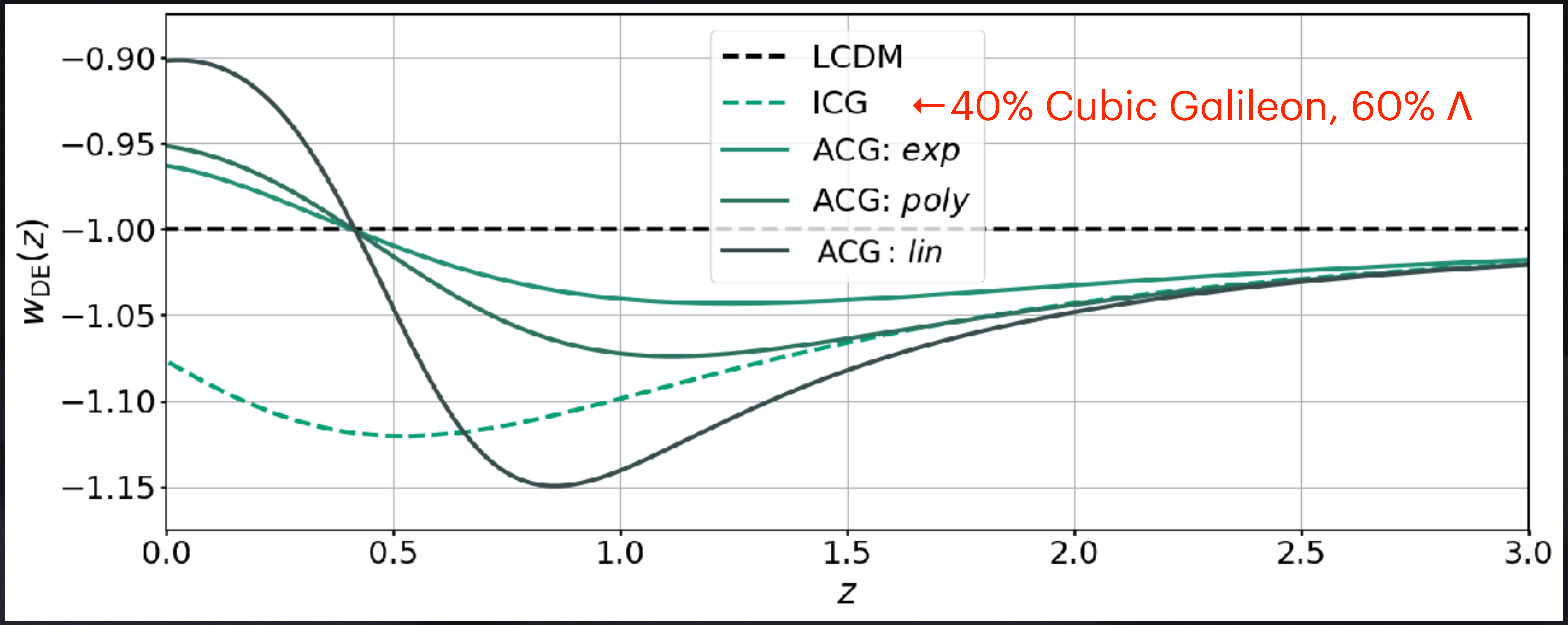
E.g.2 Exponential (K weakens): $K = -X\exp\left(-\frac{\phi}{\phi_0}\right)$ $G_3 = g_3\,X$

Crossing the phantom divide

Fig. by James Hallam

E.g.1 Linear (G_3 grows): $K = -X$ $\quad G_3 = g_3\, X \left[1 + \frac{\phi}{\phi_0}\right]$

E.g.2 Exponential (K weakens): $K = -X \exp\left(-\frac{\phi}{\phi_0}\right)$ $\quad G_3 = g_3\, X$



*ACG = Asymptotic Cubic Galileon

Figs. by Krishna Naidoo

BAO & SN data

E.g.1 Linear (G_3 grows):

$$K = -X$$

$$G_3 = g_3\, X \left[1 + \frac{\phi}{\phi_0}\right]$$

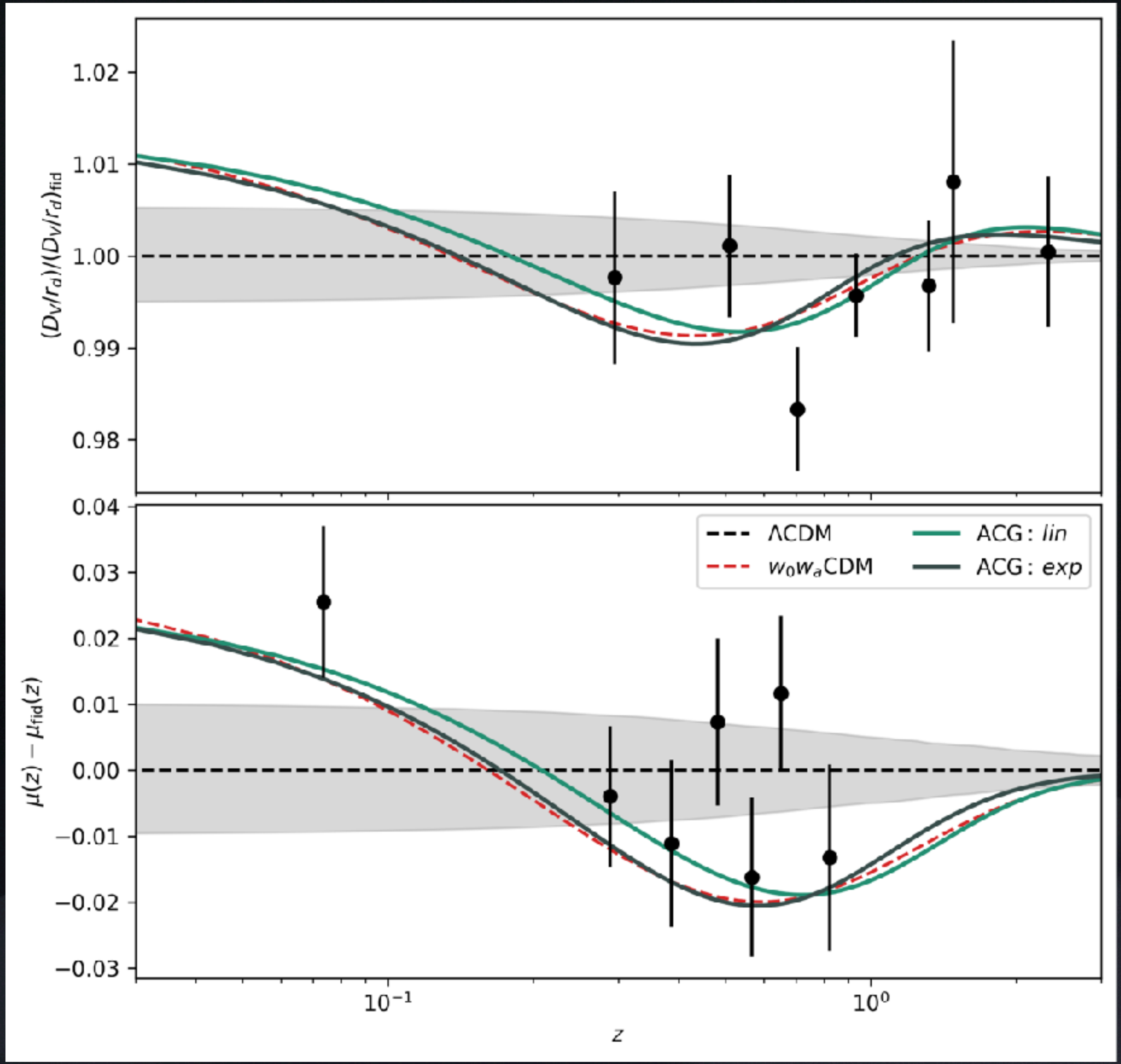
E.g. 2 Exponential (K weakens):

$$K = -X \exp\left(-\frac{\phi}{\phi_0}\right)$$

$$G_3 = g_3\, X$$

BAO (DESI)

SN (DES)



Linear model vs. Background data

- For the linear model: $K = -X$

$$G_3 = g_3\, X \left[1 + \frac{\phi}{\phi_0}\right]$$

- g_3 set to 'tracker' value

(even though model is not perfectly shift symmetric)

- Model has some degree of cosmological const.:

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

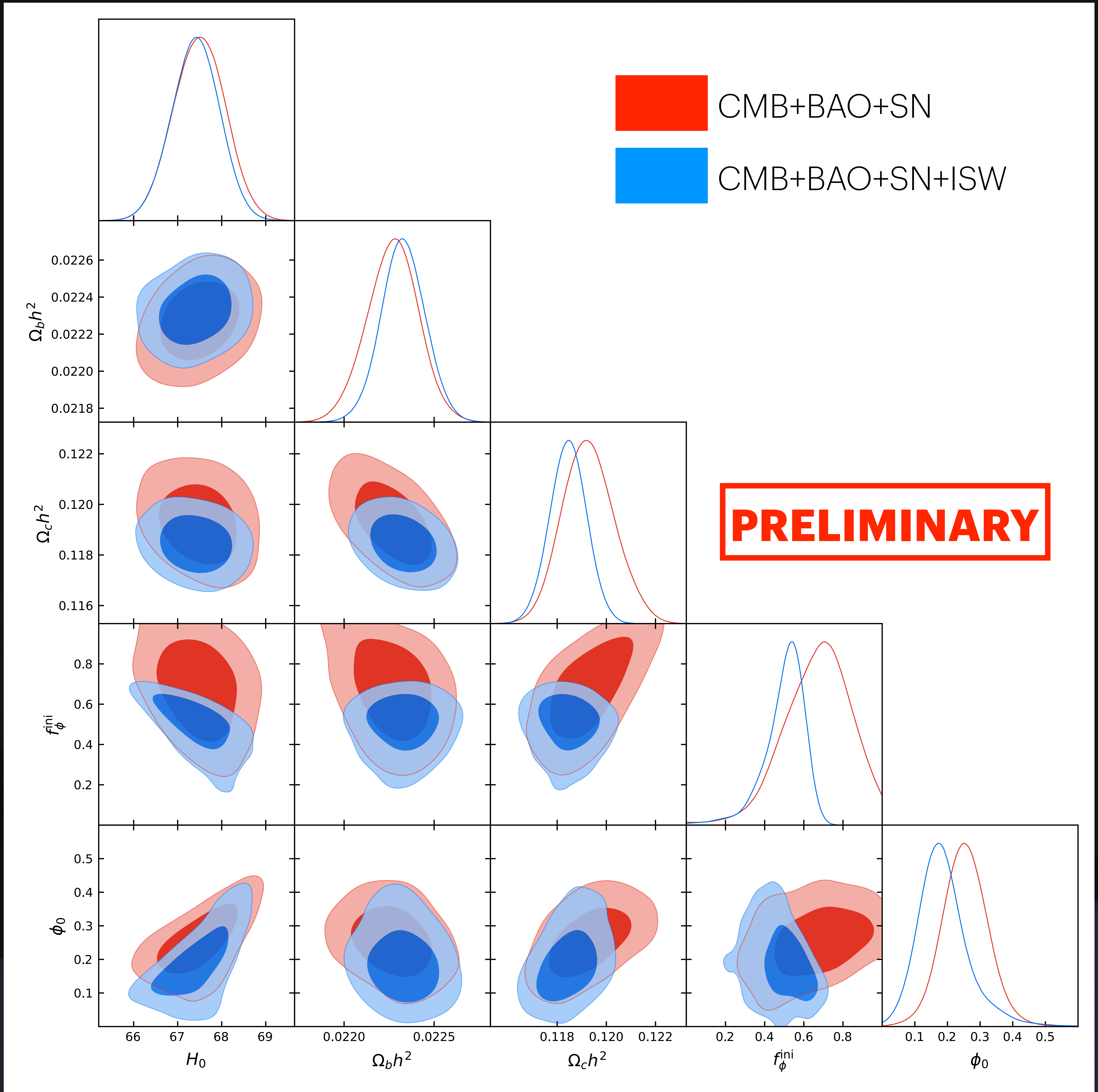


Fig. by Krishna Naidoo

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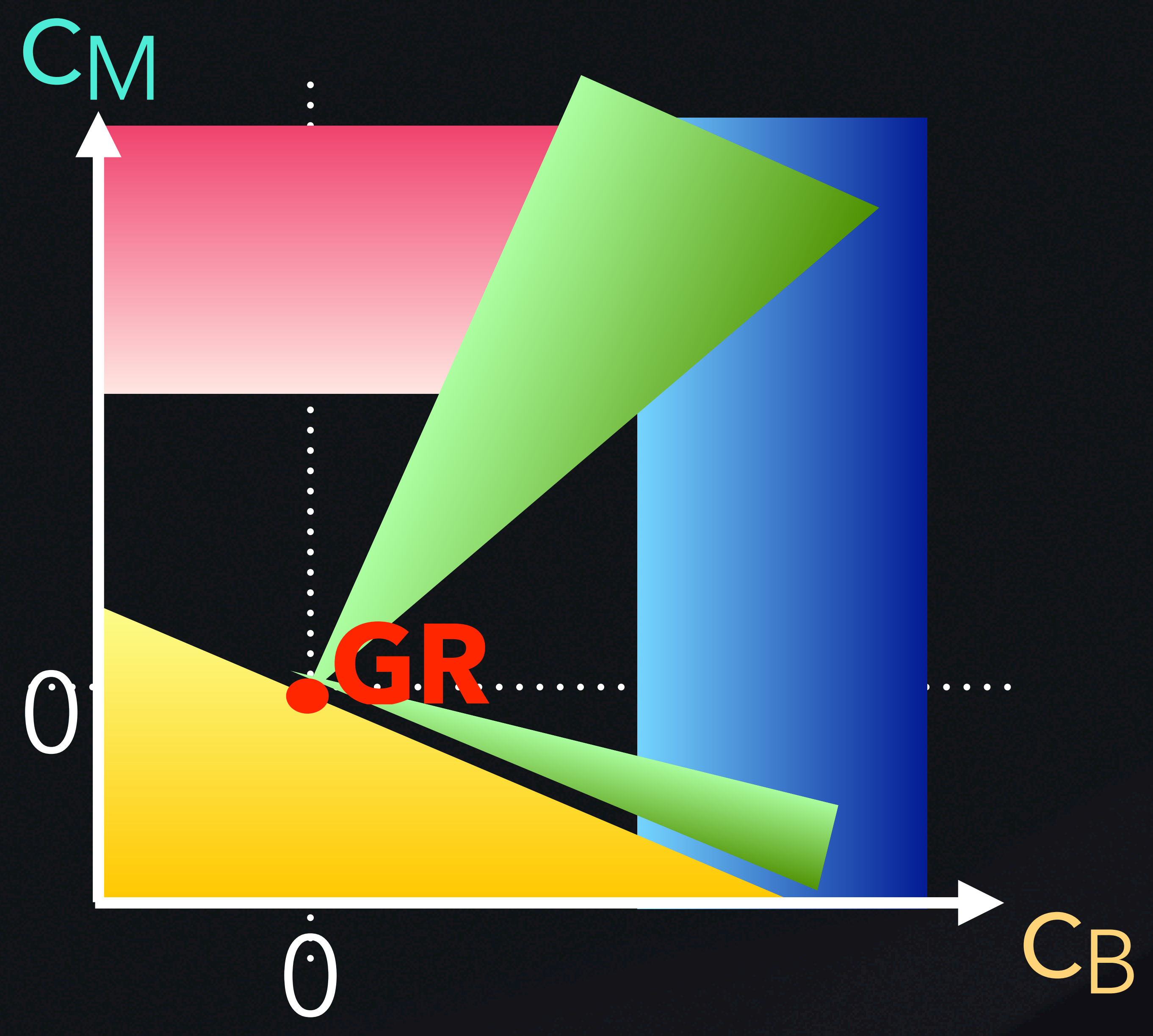
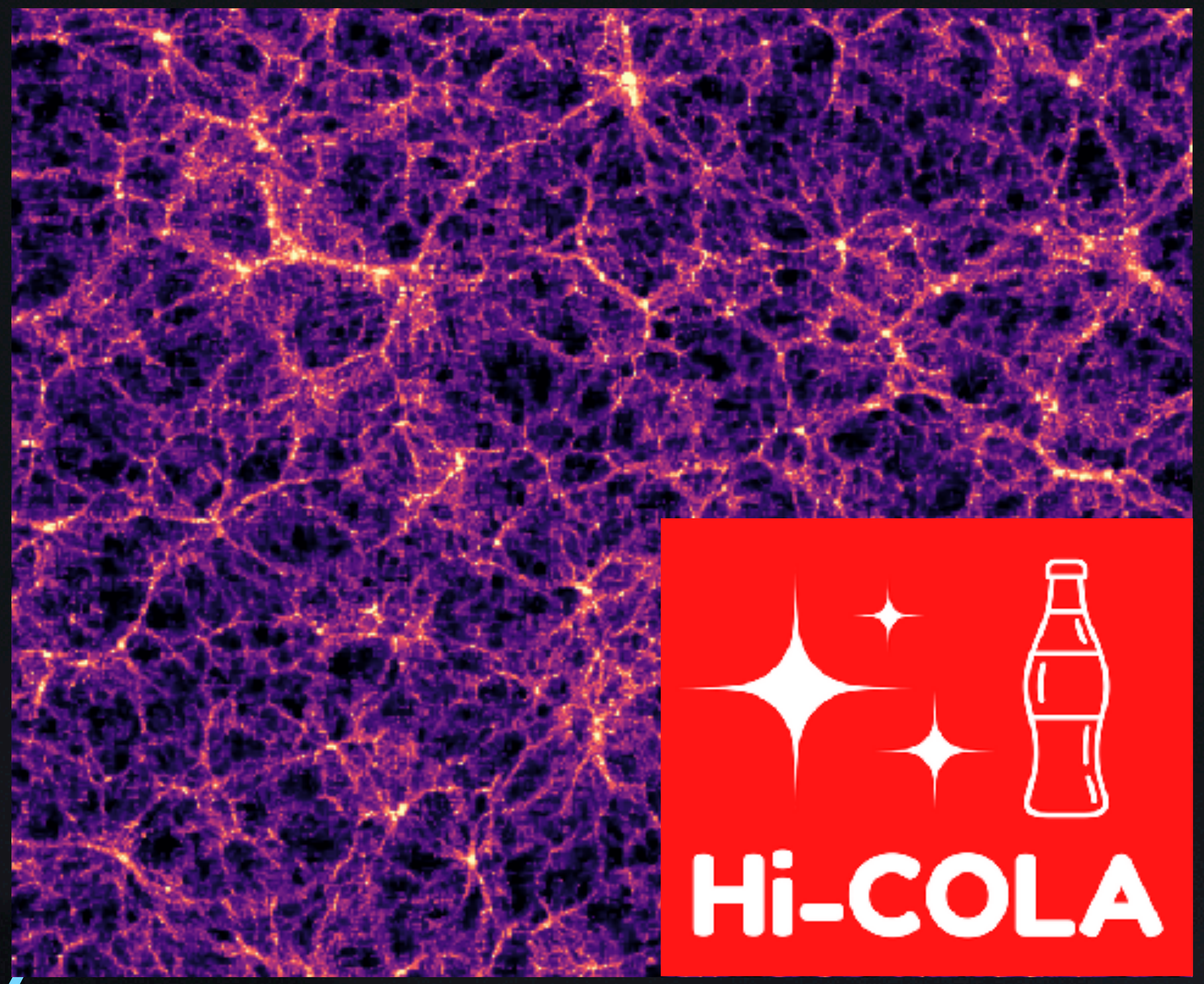
Conclusions

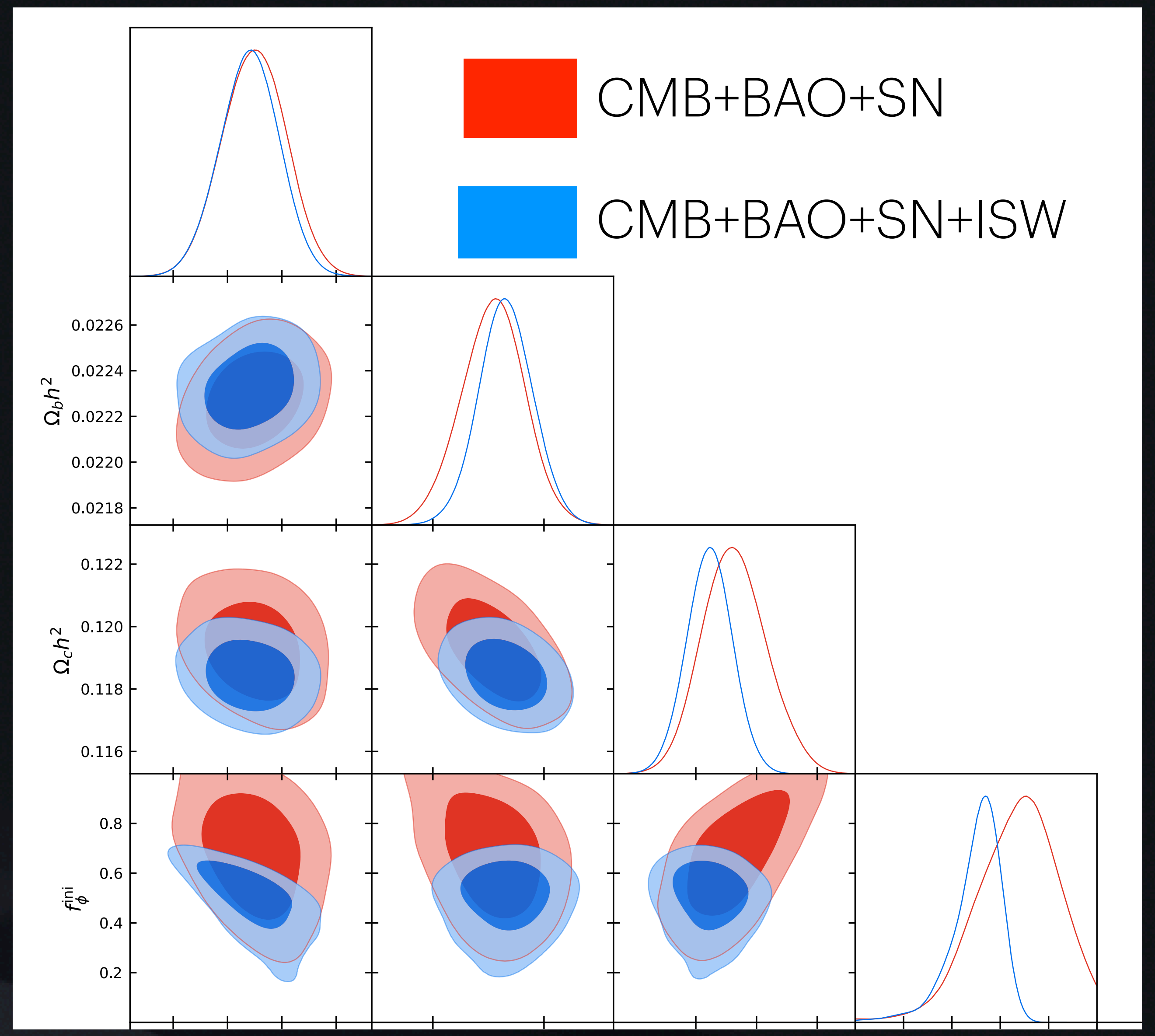
Horndeski parameter space



Hi-COLA simulations



Models crossing w=-1



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

Main publications:
2209.01666, 2407.00855

Comparison/validation exercise:
2406.13667

Send like to modified gravity?

Back-up Slides

Code Diagram

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

User specifies forms for K, G_3, G_4

Hi-COLA front-end
(~ seconds)

Symbolic algebra routines

Dynamic equations

Background solver

Background solutions

Hi-COLA simulation
(~ O(1) hr on small cluster)

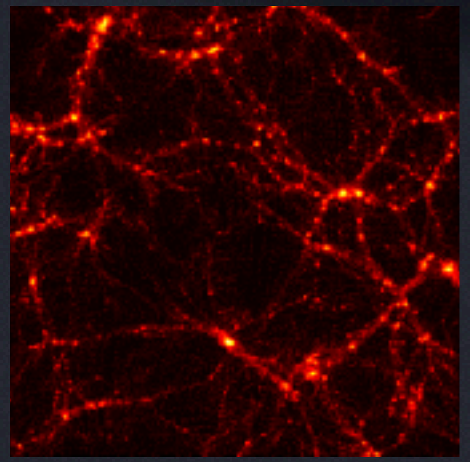
Fifth force expression

Forces between ptls

Density field

COLA simulation in MG theory

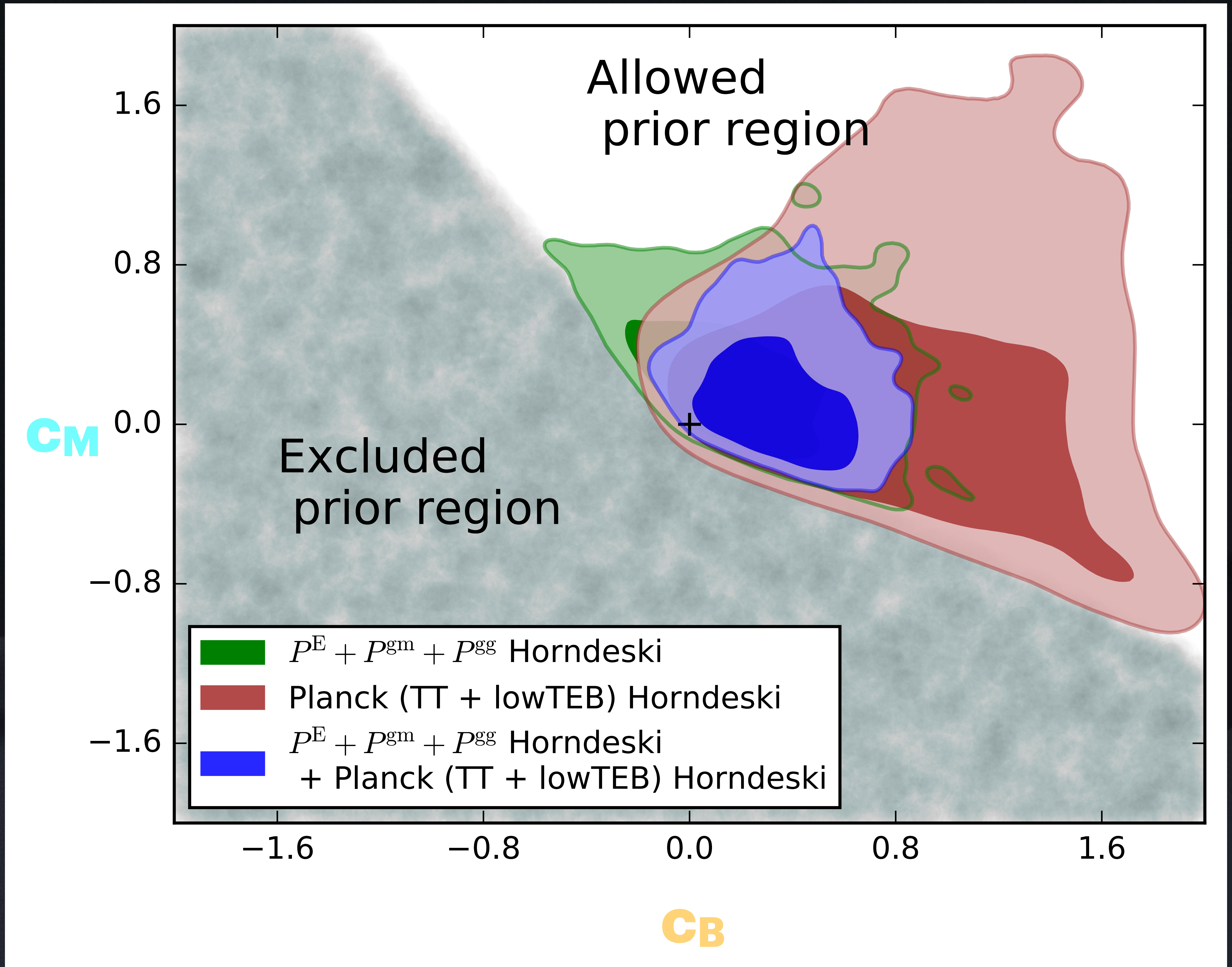
Outputs, e.g. matter power spectrum



3 x 2 pt from KiDS+GAMA

They map {μ,Σ} into Horndeski alphas. Also some treatment of nonlinear scales with HMCode (bit dodgy).

(+ treatment of intrinsic alignments)



Including Planck they find:

$$c_B = 0.36^{+0.18}_{-0.22}$$

$$c_M = 0.15^{+0.13}_{-0.31}$$

32

3 x 2 pt forecast for Rubin

KiDS+GAMA +Planck : $c_B = 0.36^{+0.18}_{-0.22}$ $c_M = 0.15^{+0.13}_{-0.31}$

Now *binning* μ into four redshift bins:

Bin 1	$0 \leq z \leq 0.43$
Bin 2	$0.43 \leq z \leq 0.91$
Bin 3	$0.91 \leq z \leq 1.47$
Bin 4	$1.47 \leq z \leq 2.15$
Bin 5	$2.15 \leq z \leq 3.0$

← unconstrained

Model	$k_{\rm cut}\,[h\,{\rm Mpc}^{-1}]$	μ_1	μ_2	μ_3	μ_4
LSST Y10	0.1 (Linear)	18.1%	42.6%	10.3%	7.8%
	0.5	7.0%	5.0%	3.1%	4.2%
	1.0	2.2%	1.7%	1.3%	1.7%
LSST Y10 + BNT	0.1 (Linear)	18.1%	31.1%	7.6%	6.5%
	0.5	5.2%	3.3%	2.5%	2.3%
	1.0	1.5%	1.4%	1.0%	1.4%
LSST Y10 + BNT + conc	0.1 (Linear)	17.5%	30.6%	7.1%	6.5%
	0.5	1.4%	1.2%	2.1%	1.9%
	1.0	0.4%	0.4%	0.6%	1.3%

BNT transform makes lensing kernels compact in redshift →

Including concentration-mass fit into ReACT →

33

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: <u>unscreened</u>, modifies Newtonian force

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

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)