Image: ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre, E. Bertin, G. Anselmi

Constraining Dark Energy with Complementary Probes of Large-Scale Structure

based on
arxiv: 260(6/7).XXXXX

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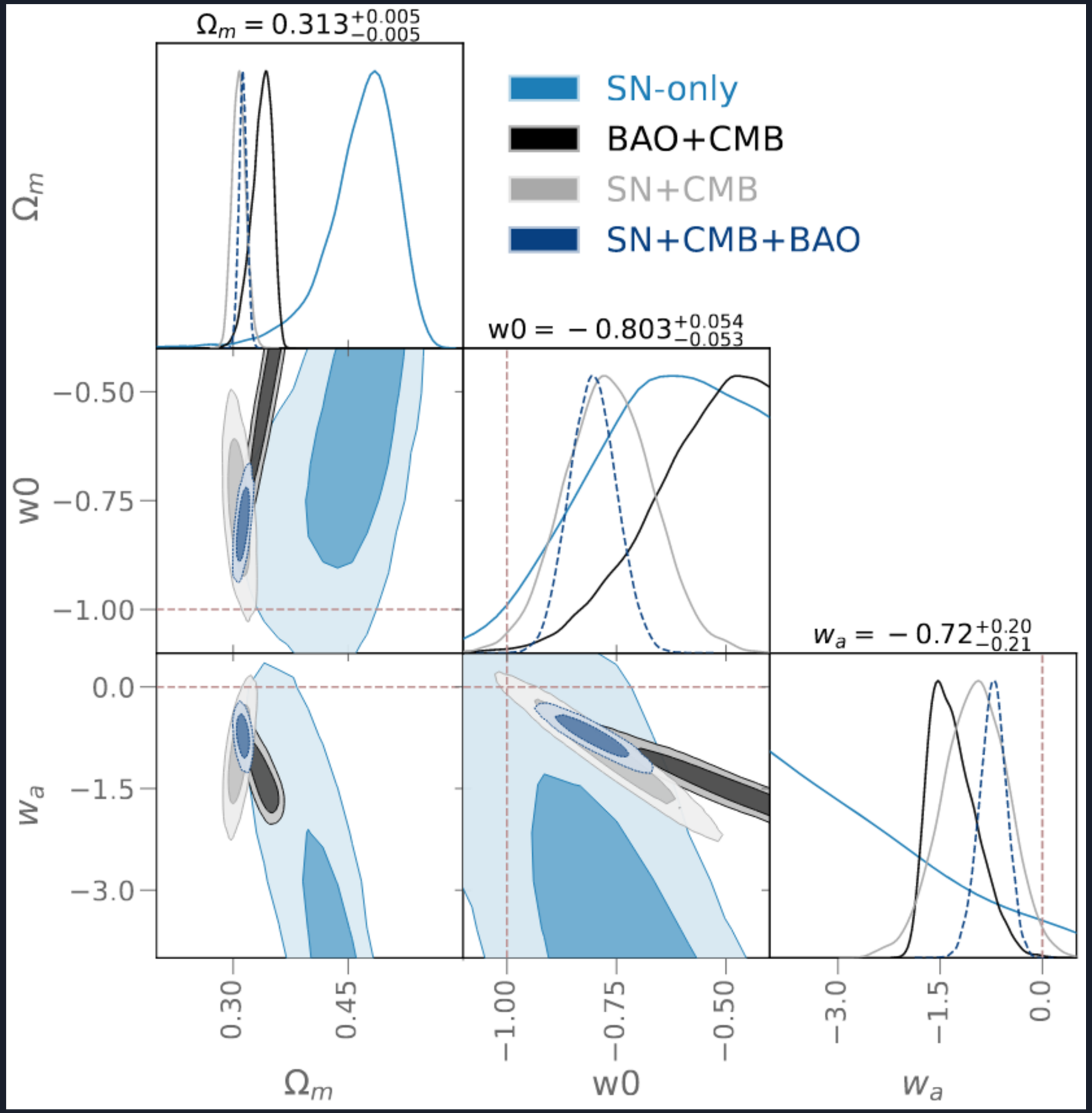
with Lanyang Yi, Kazuya Koyama, Johannes Noller

The power of complementary probes: an example



DES Collaboration, arXiv:2511.07517

Consistently modelling Dark Energy perturbations

- The Effective Field Theory of Dark Energy
  - Most general theory of a single scalar field and the metric with couplings consistent with the symmetries of the FLRW background
  - (same as Horndeski gravity on a cosmological background)

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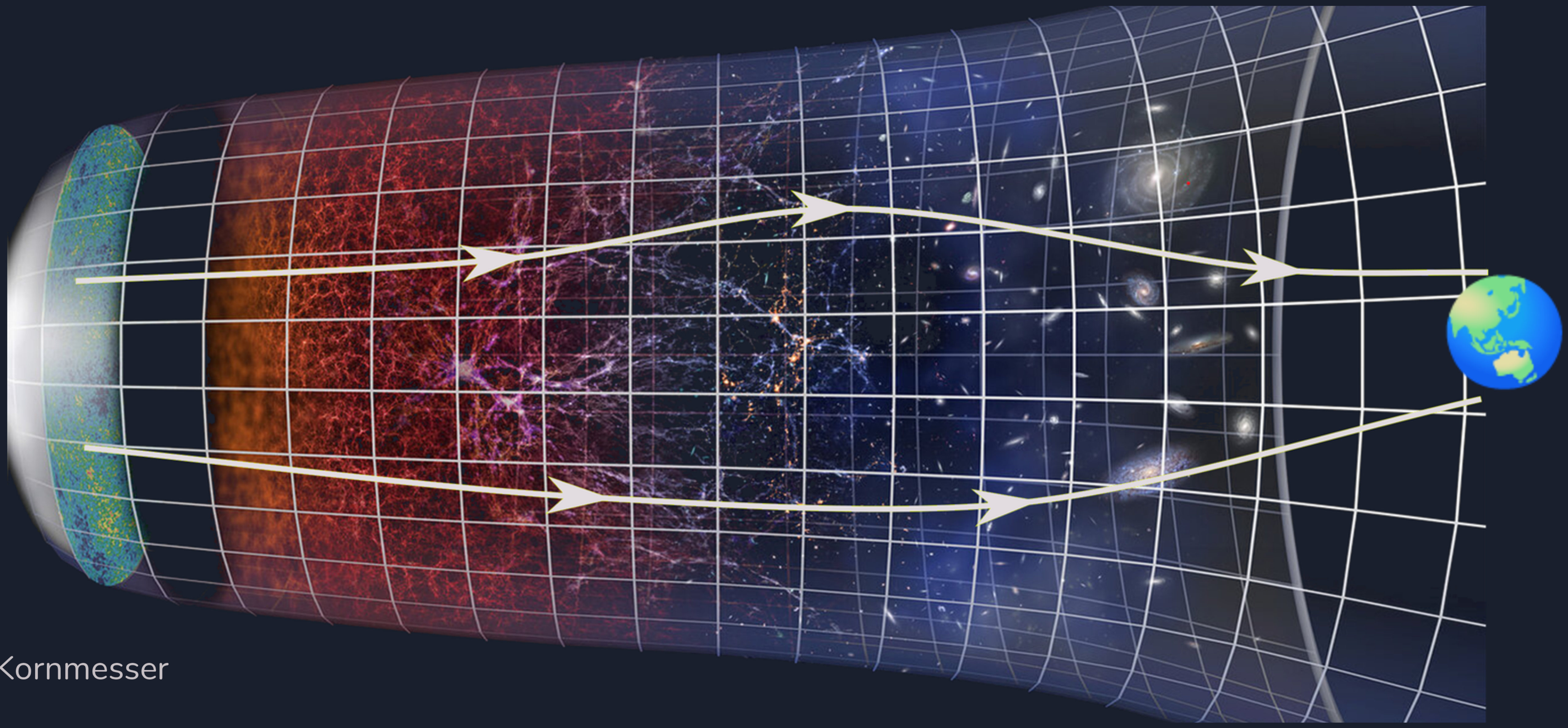
- The functional degrees of freedom we consider: (Convenient parametrisations)
  - Background expansion: $w(a) = w_0 + w_a(1-a)$
  - Perturbations: $\alpha_B(z) = c_B \Omega_{DE}(z), \ \alpha_M(z) = c_M \Omega_{DE}(z)$
- $\alpha_B(z)$ describes kinetic coupling between the metric and scalar field, $\alpha_M(z)$ describes the running of the effective Planck mass

Various probes of large-scale structure

CMB Lensing, Redshift Space Distortions, Weak Gravitational Lensing (3x2pt), Integrated Sachs-Wolfe Effect

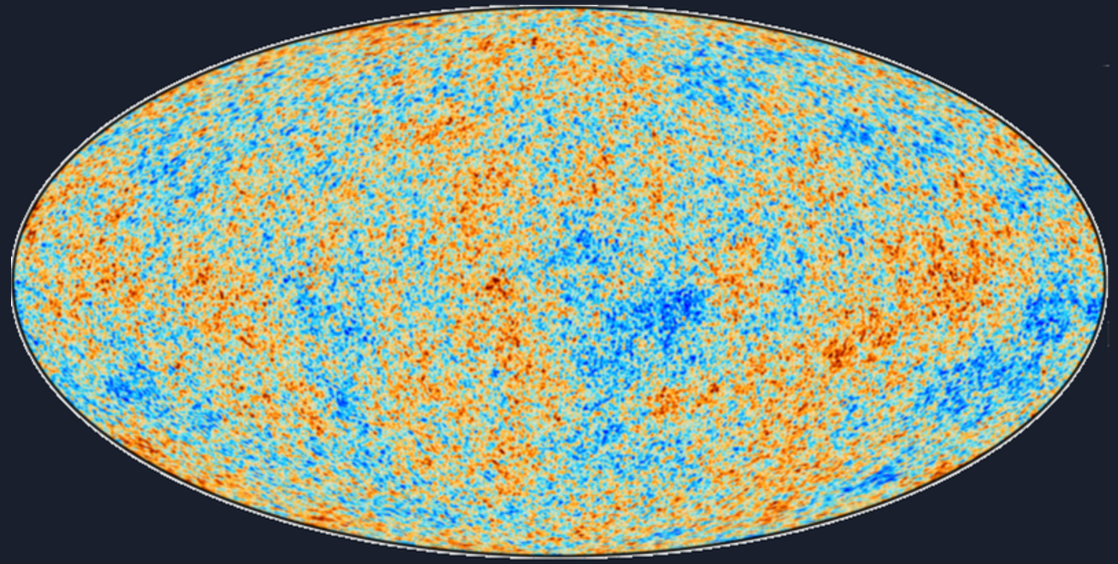


Original: ESO/M. Kornmesser

Various probes of background expansion

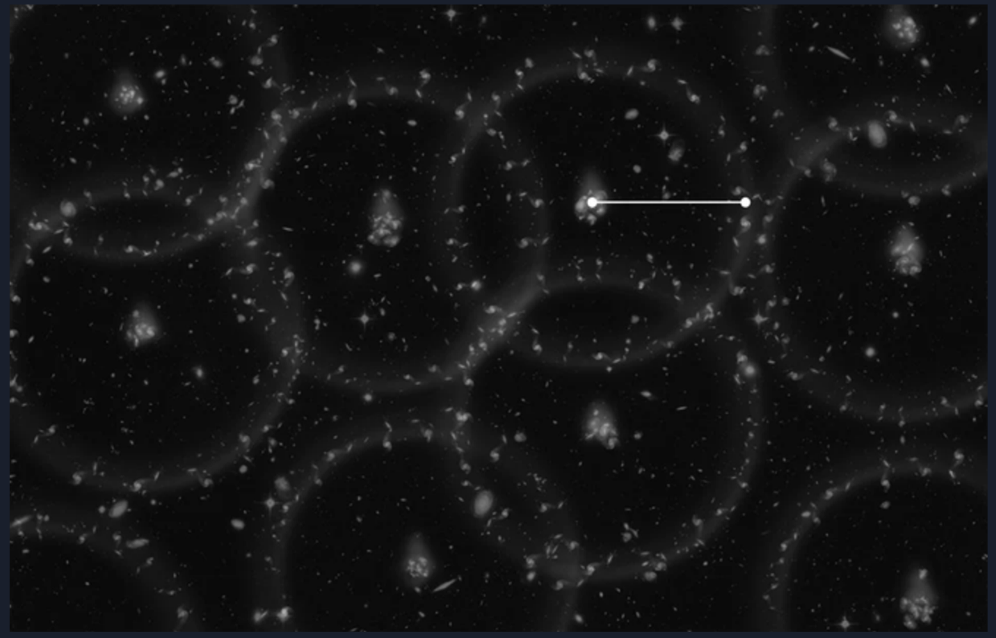
Cosmic Microwave Background, Baryon Acoustic Oscillations, Type IA Supernovae

Image: Planck Collaboration



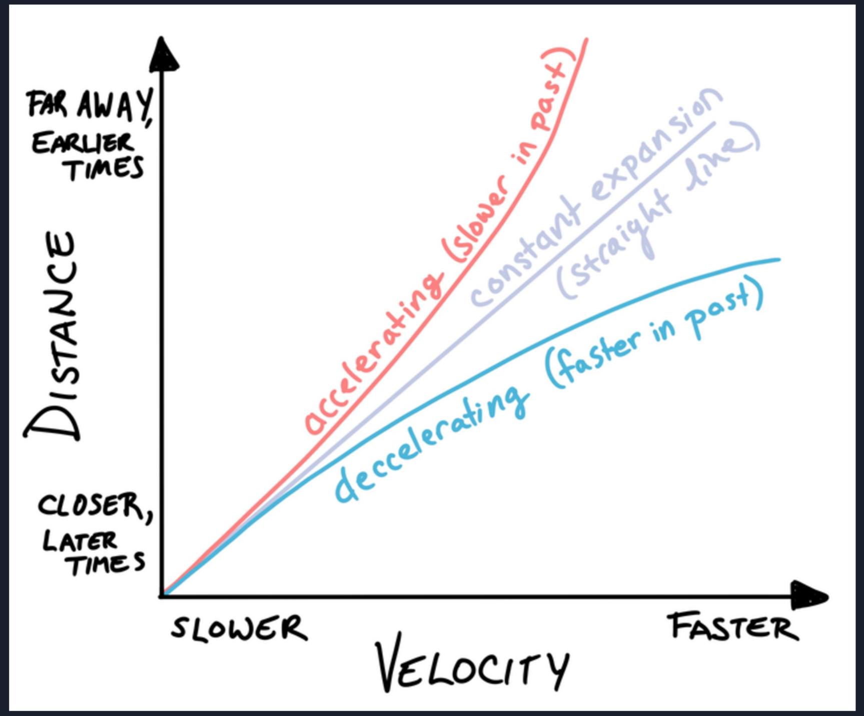
The size of the CMB sound horizon and distance to it

Image: BOSS Collaboration



The angular size of the sound horizon at low redshifts

Image: Jessie Muir

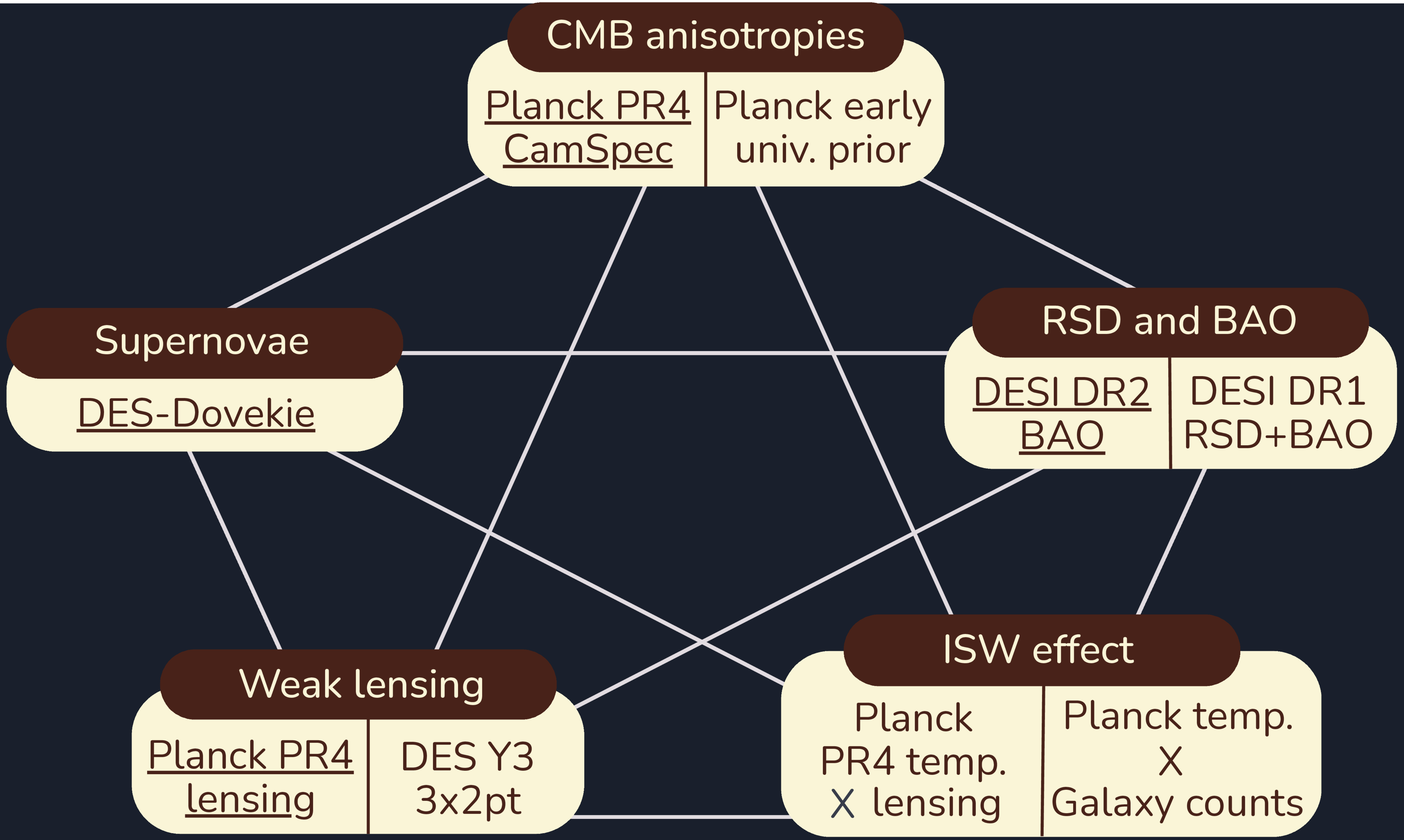


w(z) at very low redshifts

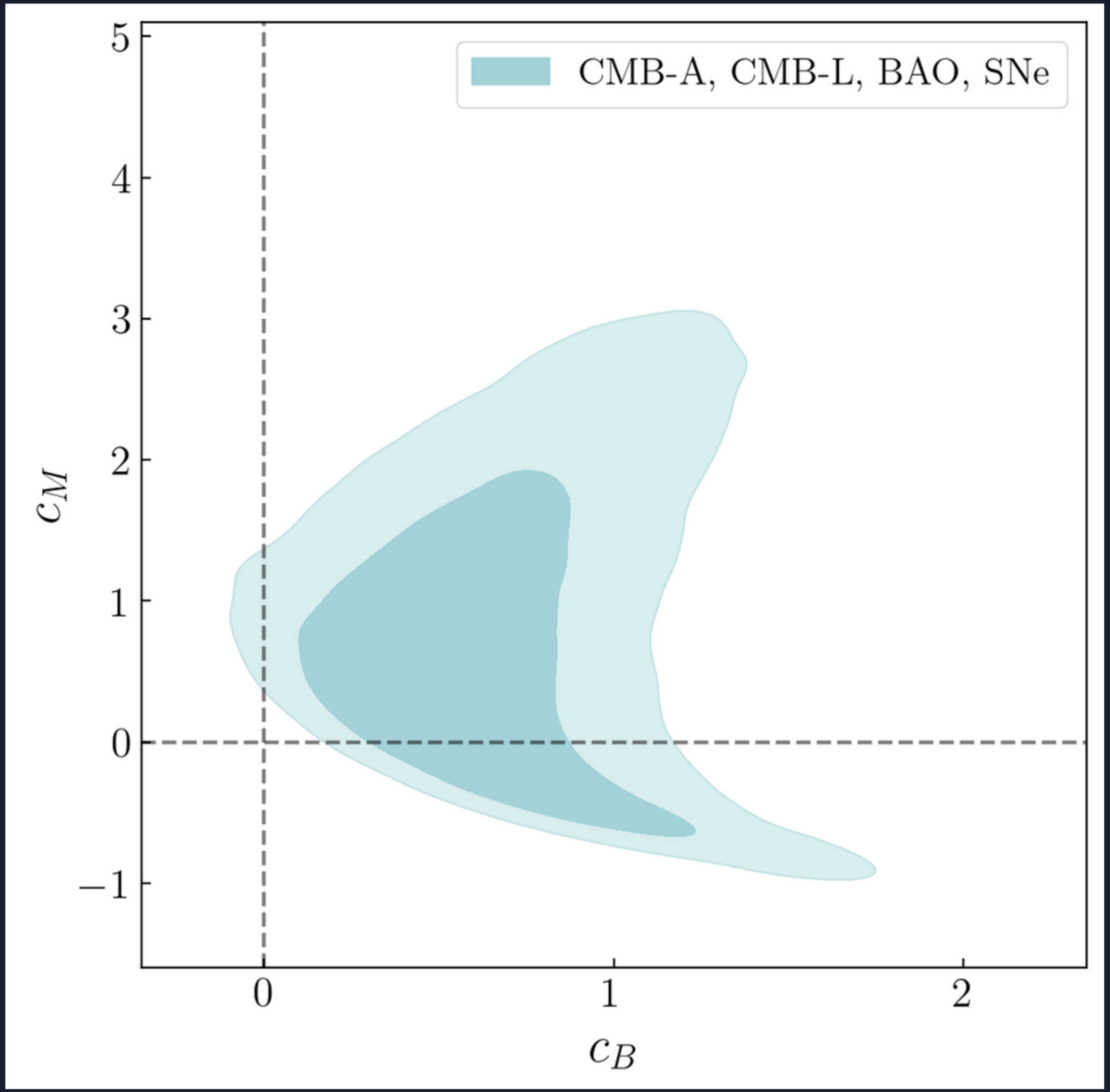
Our likelihoods

- CMB anisotropies and lensing: Planck PR4 CamSpec (Rosenberg et al. 2205.10869, Carron et al. 2206.07773) (or Planck early-universe prior when using as background-only probe) (Lemos et al. 2302.12911)
- RSD+BAO, including their cross-covariance: DESI DR1 (or DESI DR2 when using BAO alone) (DESI Collaboration 2411.12021, 2503.24738)
- 3x2pt: DES Y3 (DES Collaboration 2207.05766)
- ISW effect: Planck X galaxy counts (Stölzner et al. 1710.03238, Seraille et al. 2401.06221), Planck PR4 ISW-Lensing (Carron et al. 2209.07395)
- Supernovae: DES-Dovekie (DES Collaboration 2511.07517)

Respecting covariances: possible combinations



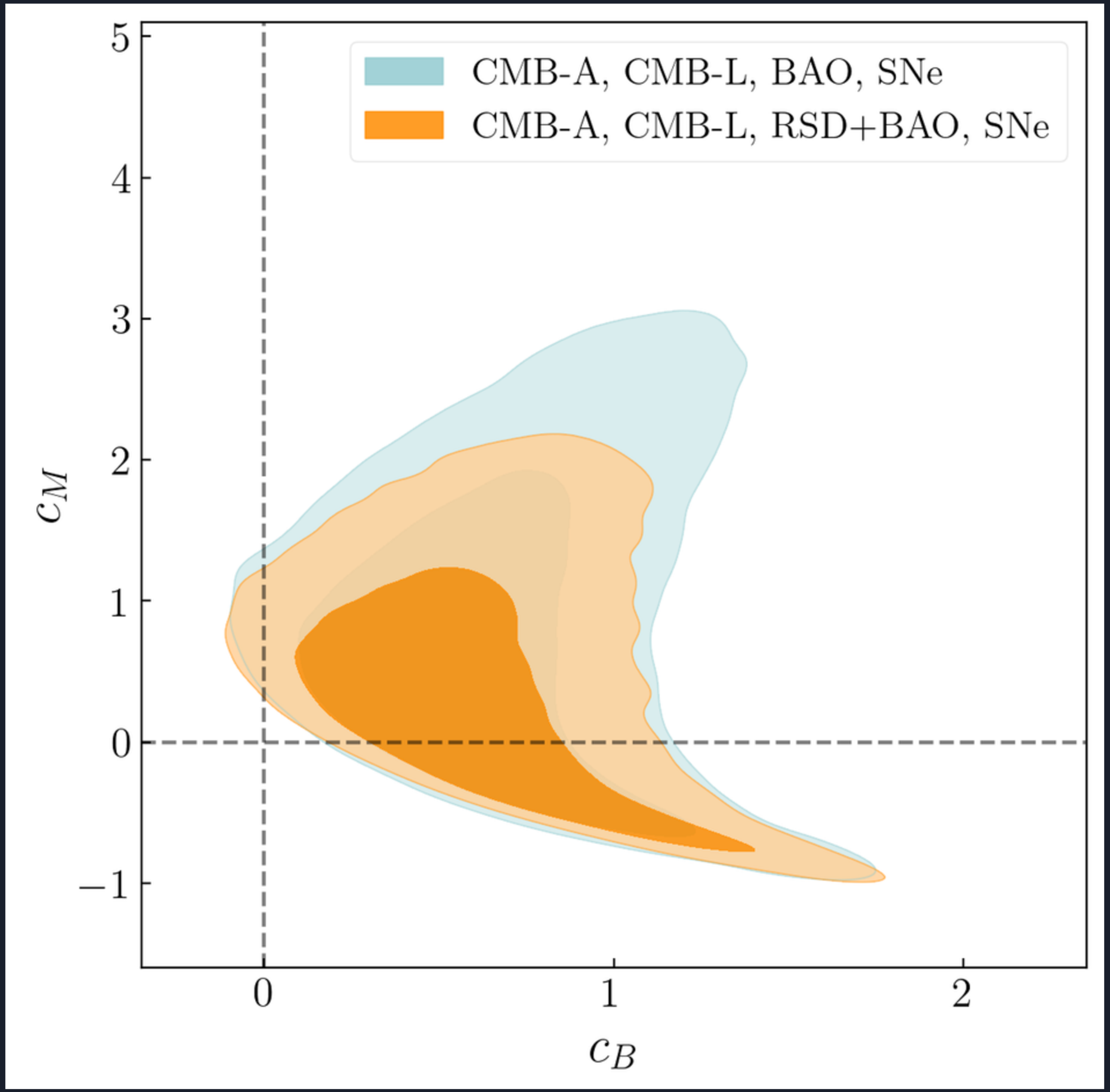
Complementary probes in action



Constraints from a minimal likelihood setup: CMB anisotropies, CMB lensing, BAO, supernovae

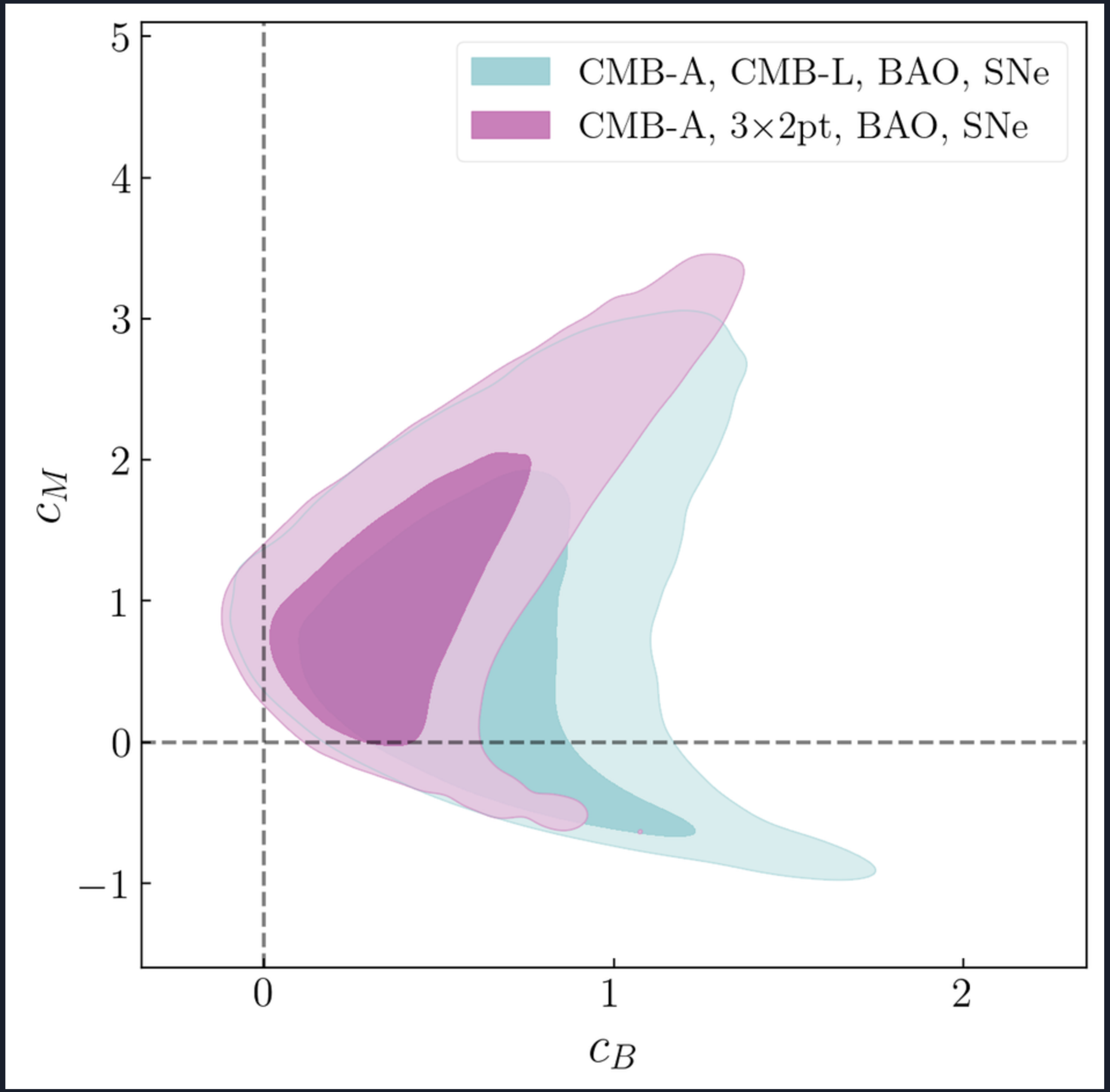
Complementary probes in action

RSD is a probe of structure growth which is affected more by c_M in this model



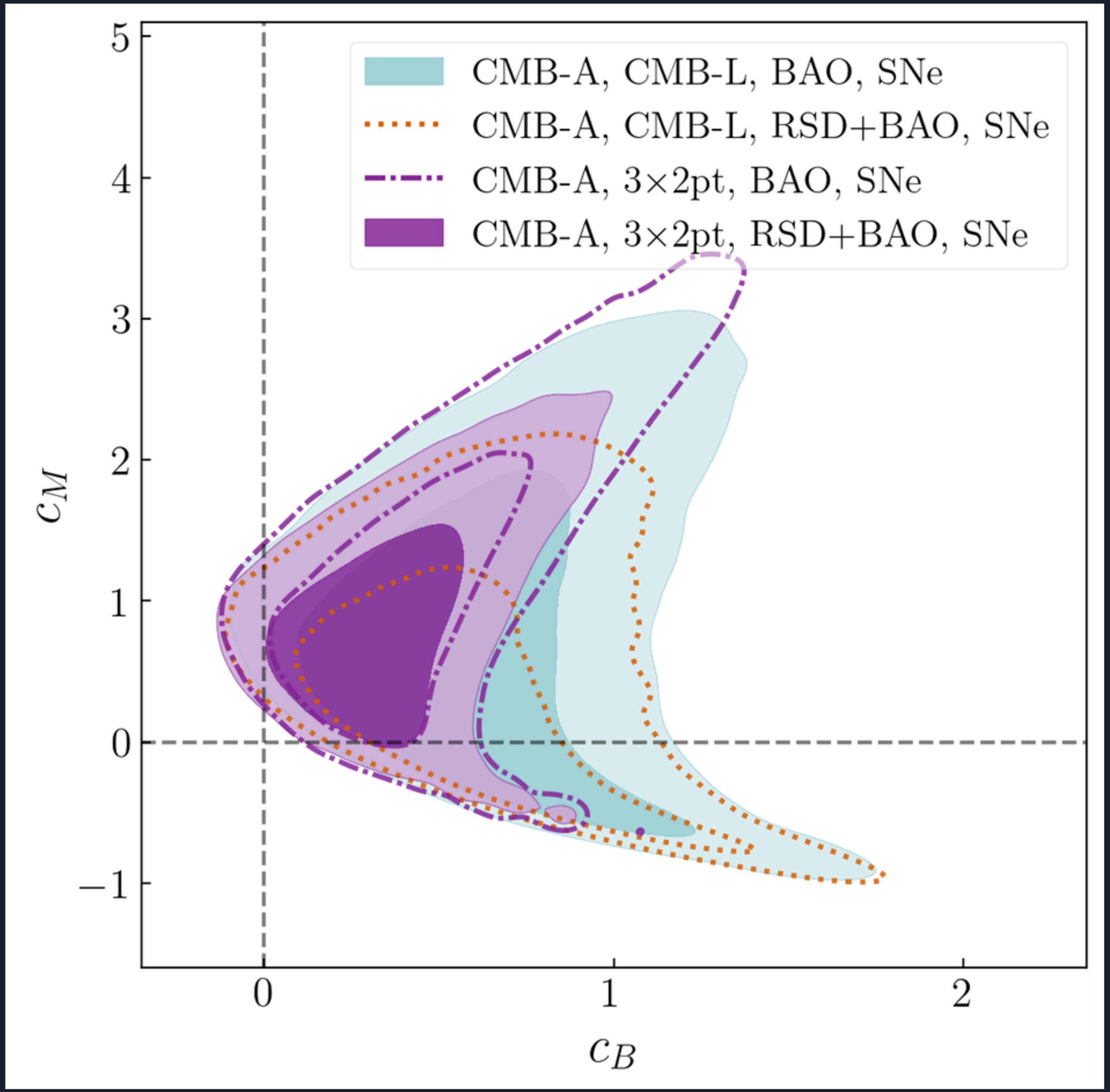
Complementary probes in action

The 3x2pt likelihood is a strong probe of weak gravitational lensing at low redshifts



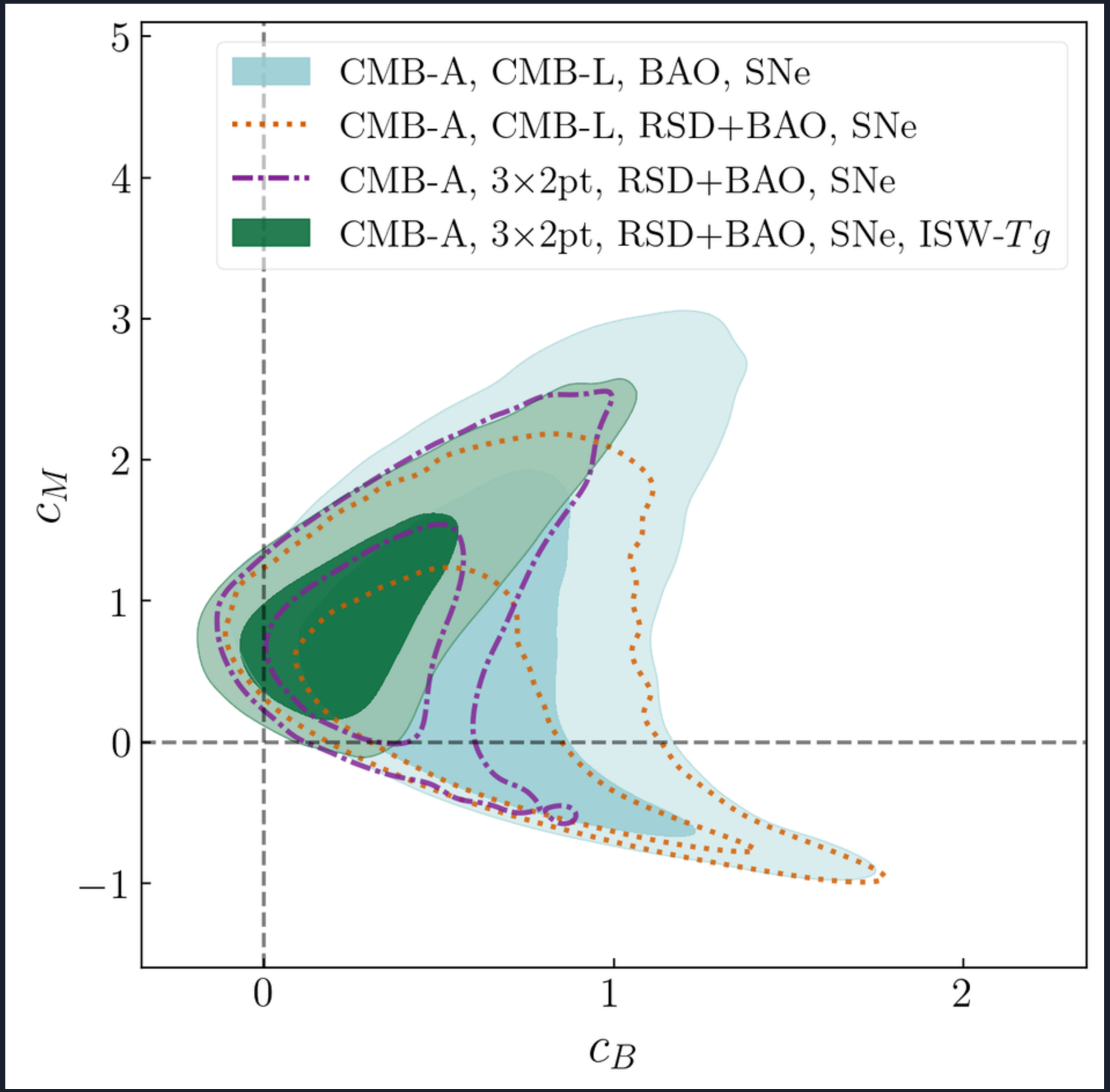
Complementary probes in action

The combination gives a factor of 2.4 improvement in the 68% area over the minimal dataset combination

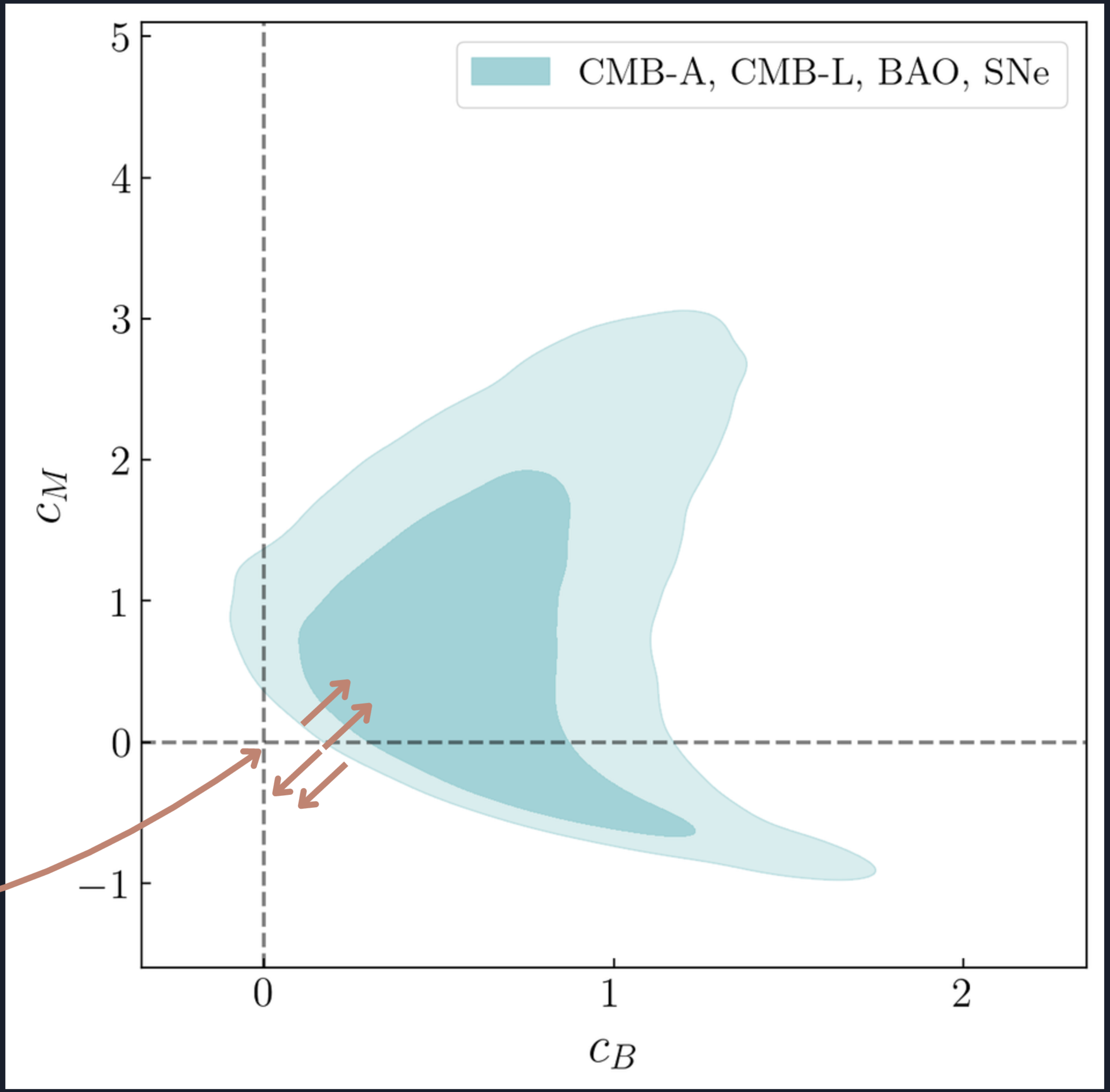


Complementary probes in action

Adding the ISW effect measured from CMB temperatire X galaxy counts into the mix:
now the factor of improvement is 2.7

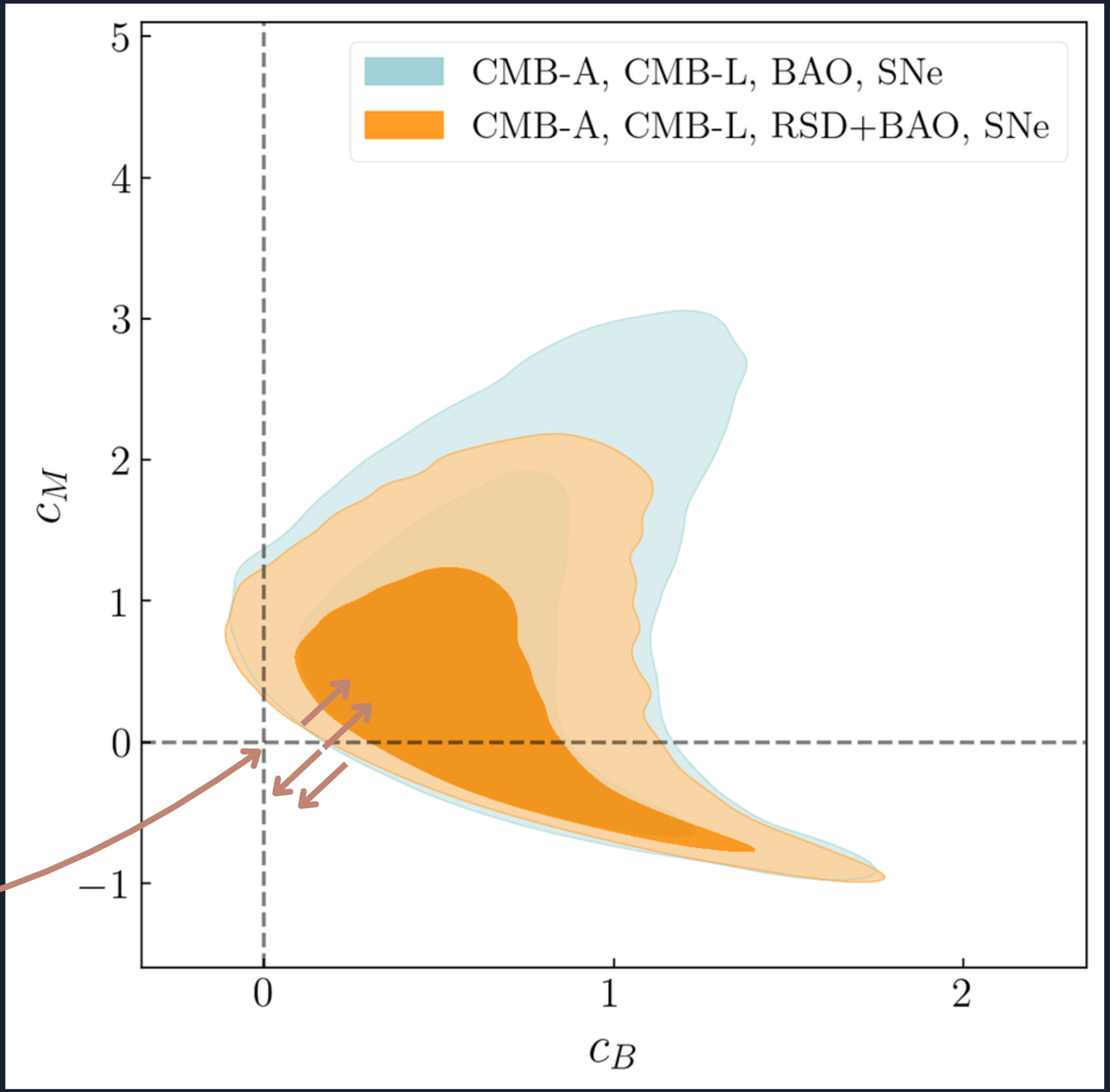


Observation 1: A stubborn boundary



Why does the data have very little effect on this direction?

Observation 1: A stubborn boundary



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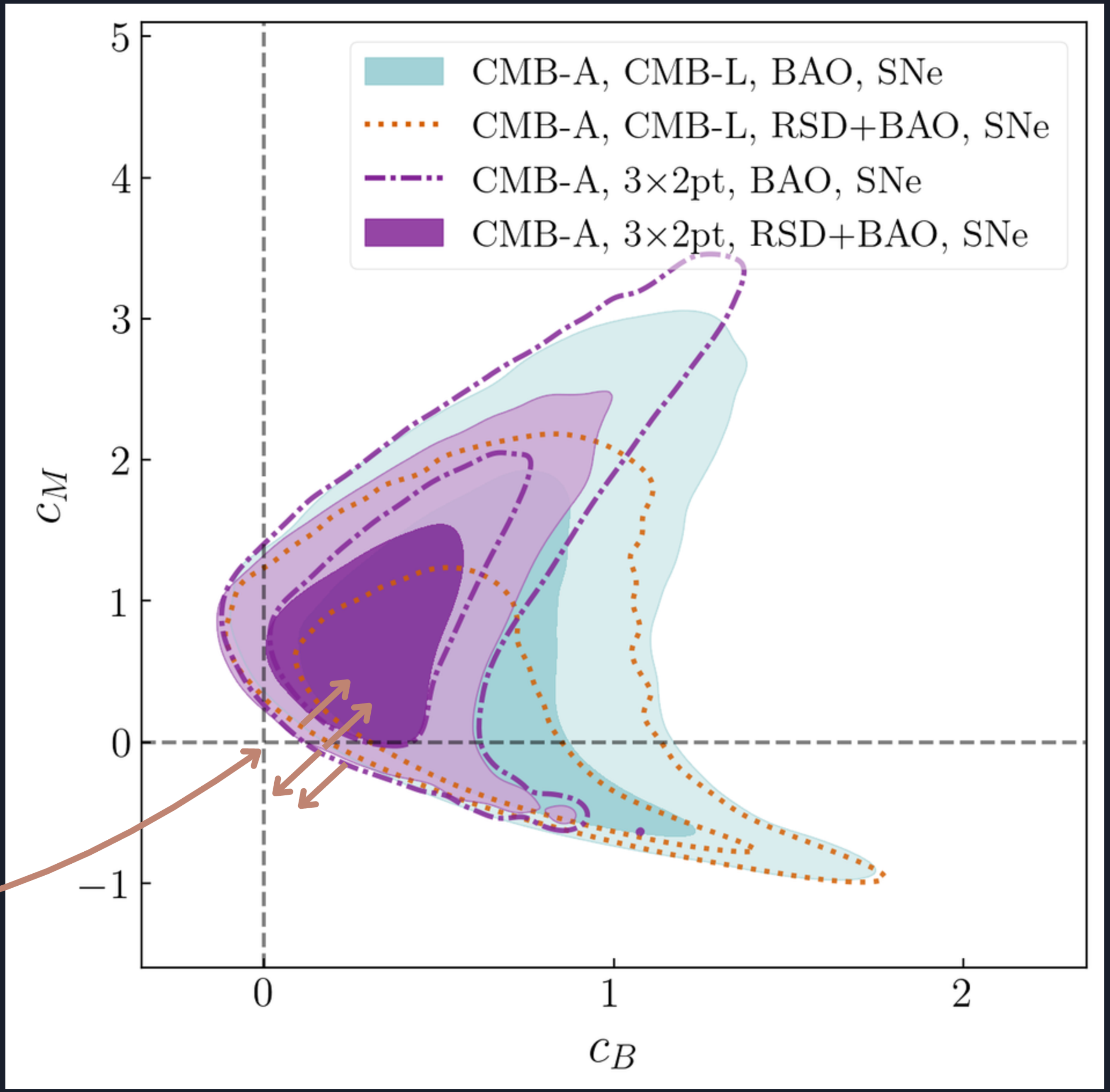

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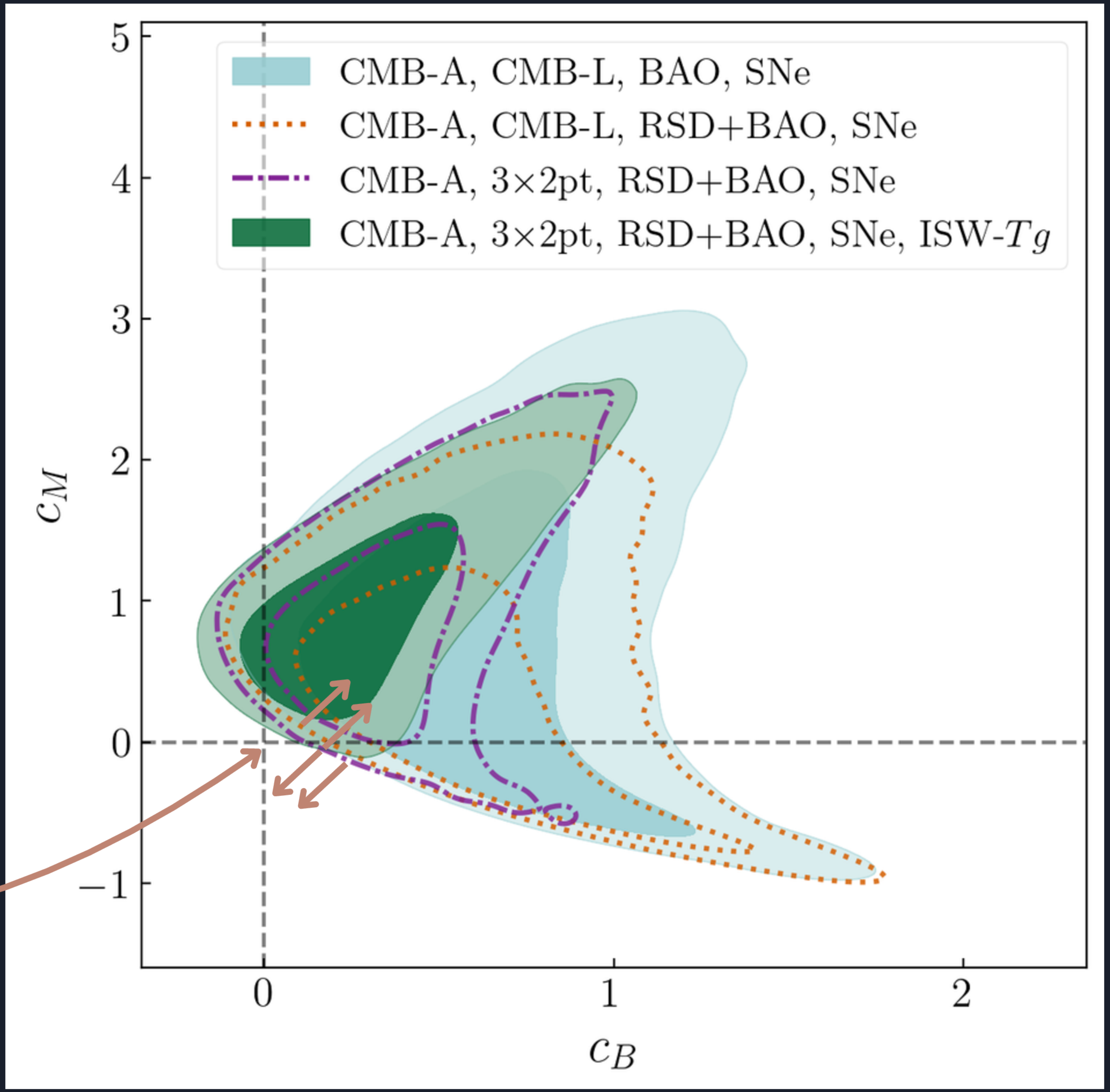
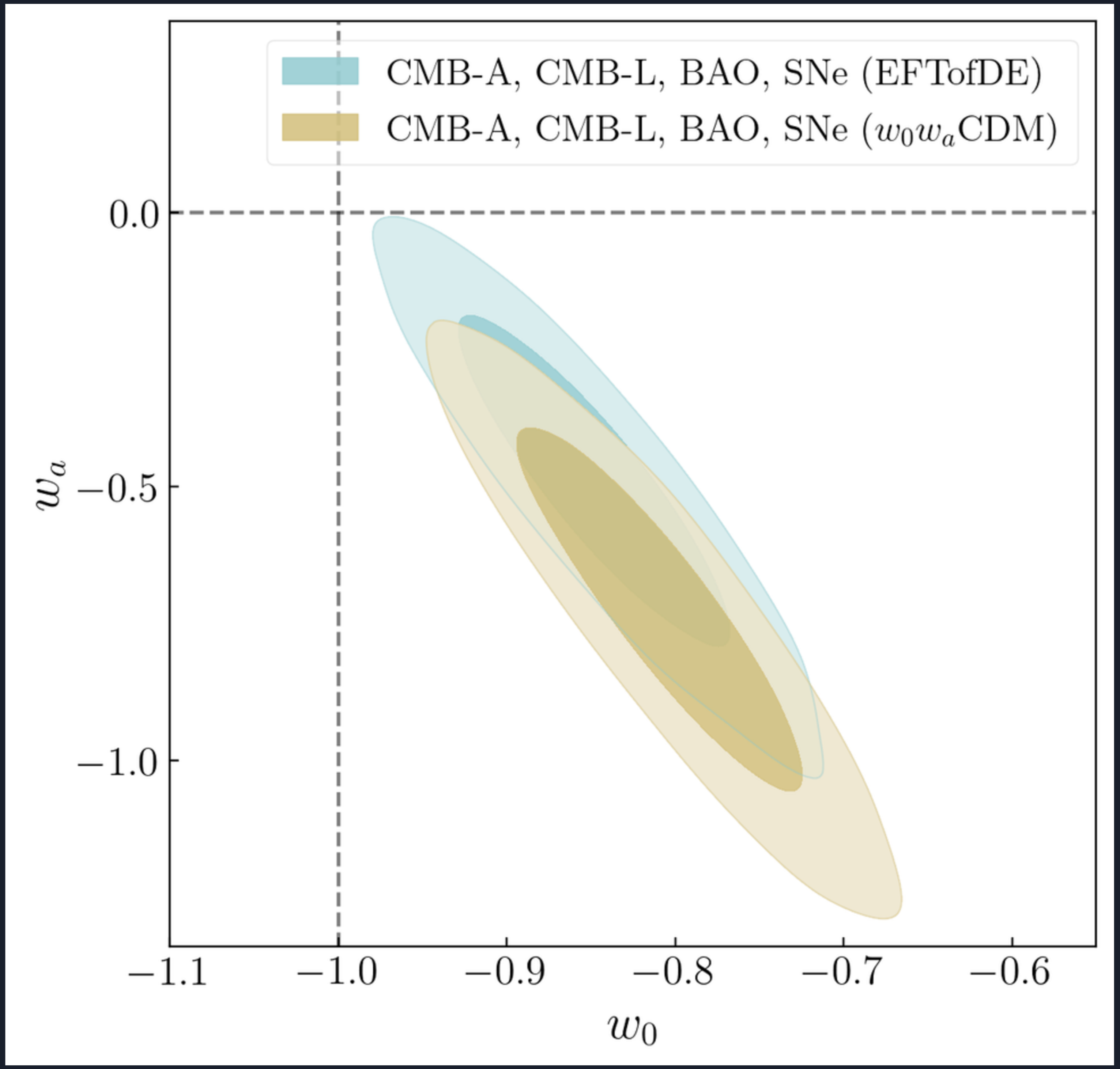


Why does the data have very little effect on this direction?

Observation 2: Shift in Background Constraints



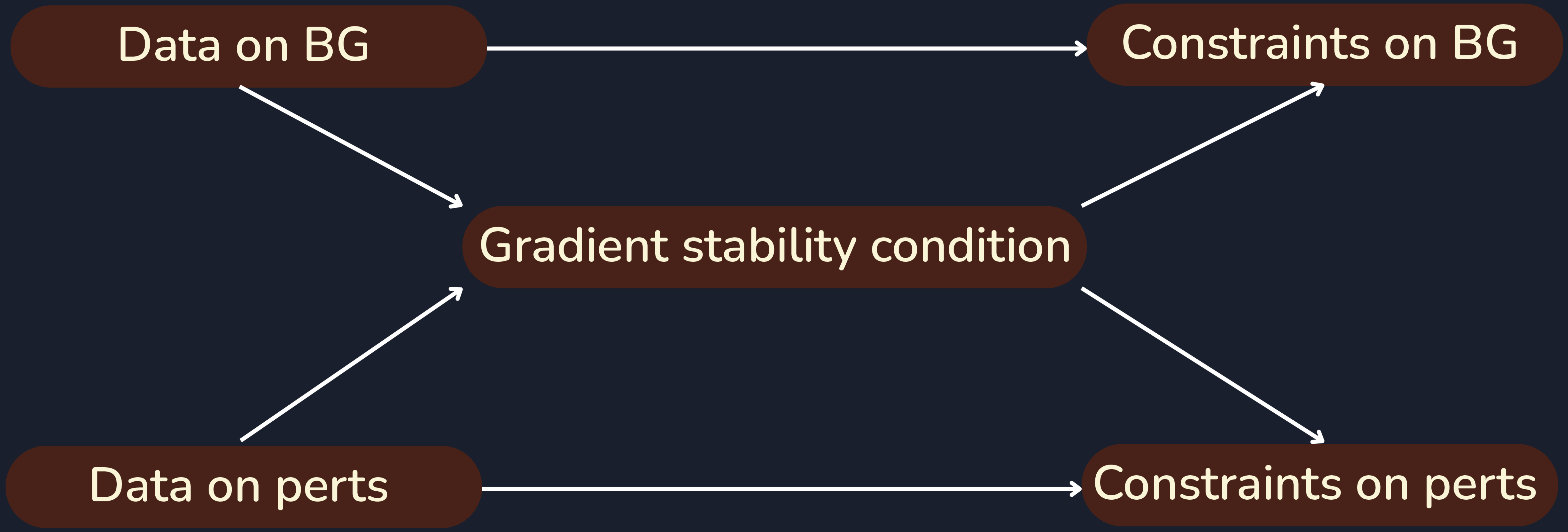
Phantom crossing is still possible, but why the shift?

A theoretical prior connecting BG and perturbations

In phenomenological DE/MG,

A theoretical prior connecting BG and perturbations

In EFTofDE,



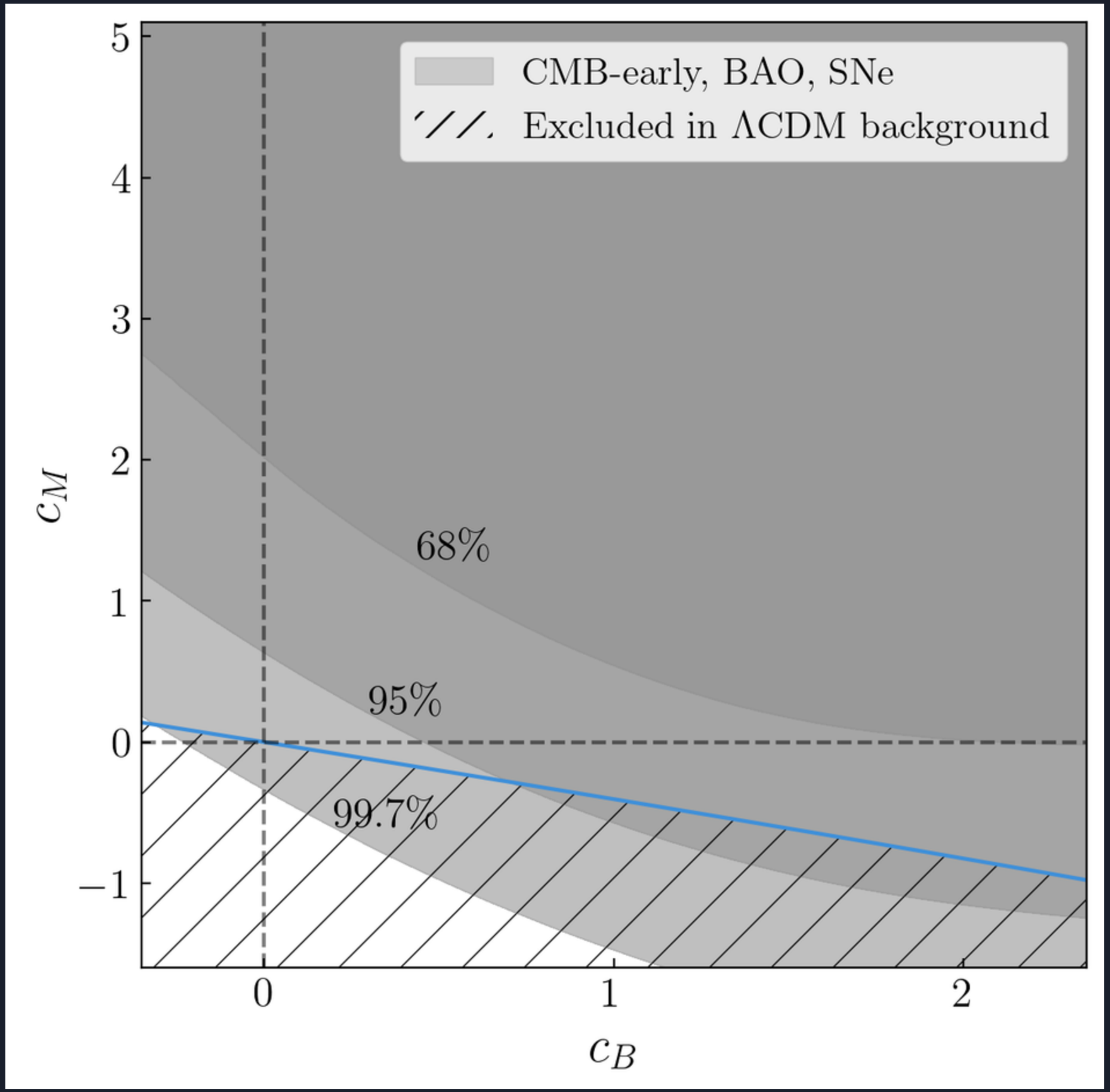
The gradient stability boundary

- The sound speed squared of the scalar field's perturbations is given by

$$c_s^2 = \frac{1}{\alpha_K + \frac{3}{2}\alpha_B^2}\left((2-\alpha_B)\left(\frac{1}{2}\alpha_B + \alpha_M - \frac{\dot{H}}{H^2}\right) - 3\frac{\rho_m + p_m}{H^2 M^2} + \frac{\dot{\alpha}_B}{H}\right)$$

- This has to remain positive to avoid exponentially growing perturbations.
- Gives a constraint on c_B, c_M, w_0, w_a

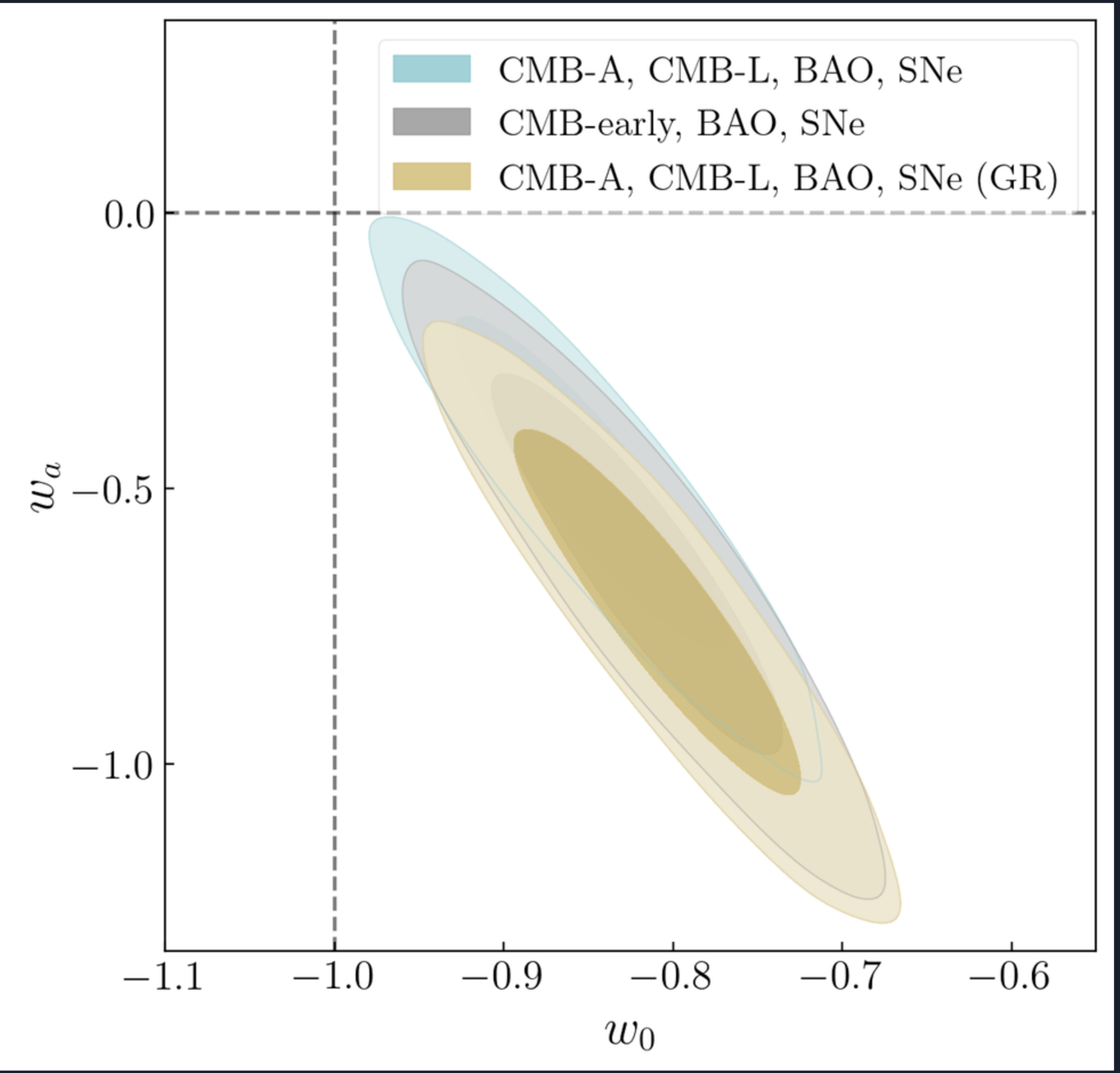
Explaining the perturbations disfavouring GR



The CMB early-universe prior is completely insensitive to late-time perturbations.

Thus, the constraints on perturbations here only come from the observations of the background.

Explaining the background shifting towards LCDM



The CMB early-universe prior is completely insensitive to late-time perturbations.

Once we significantly relax perturbations constraints, the background is allowed to have large deviations from LCDM.

The significance of deviation from LCDM

- Which model do we expect to be further from LCDM in terms of N-sigma significance*: EFTofDE or w_0w_aCDM?

  *(for the minimal CMB+BAO+SNe datasets)

Two extra parameters in EFTofDE w.r.t. w_0w_aCDM

Background posterior closer to LCDM in EFTofDE

Stronger significance in w_0w_aCDM

The significance of deviation from LCDM

- Which model do we expect to be further from LCDM in terms of N-sigma significance*: EFTofDE or w_0w_aCDM?

  *(for the minimal CMB+BAO+SNe datasets)

EFTofDE is a better fit to data (lower chi-squared)

Perturbations posterior in EFTofDE away from GR

Stronger significance in EFTofDE

The significance of deviation from LCDM

- Which model do we expect to be further from LCDM in terms of N-sigma significance*: EFTofDE or $w_0 w_a$CDM?

*(for the minimal CMB+BAO+SNe datasets)

2.9σ

Two extra parameters in EFTofDE w.r.t. $w_0 w_a$CDM

Background posterior closer to LCDM in EFTofDE

≈

3.1σ

EFTofDE is a better fit to data (lower chi-squared)

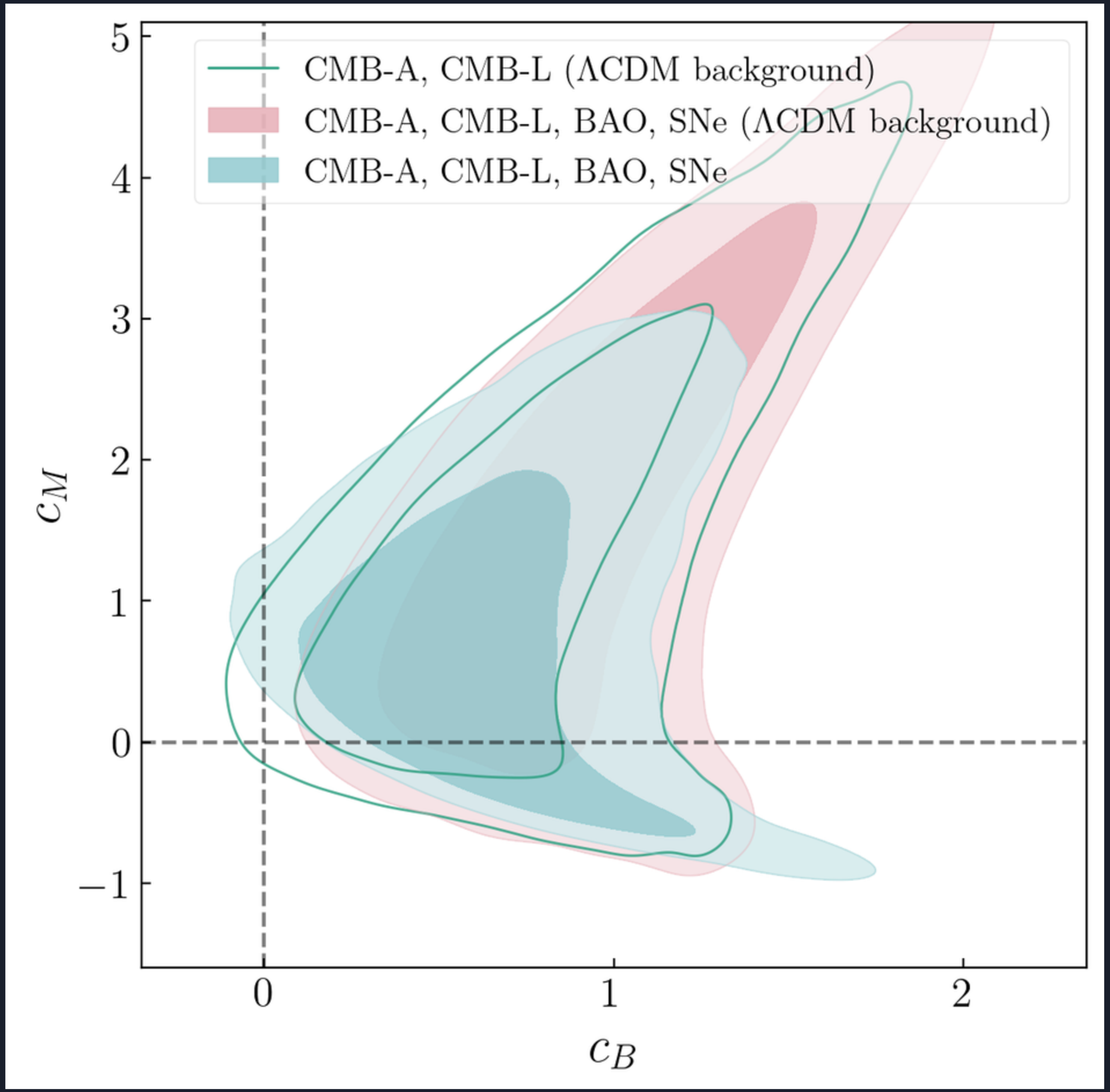
Perturbations posterior in EFTofDE away from GR

Summary

- Various complementary probes of DE perturbations: CMB lensing, RSD, 3x2pt, ISW effect.
- The gradient stability condition in the EFTofDE is a theoretical prior causing the posteriors of the DE background and perturbations to affect each other.
- The significance of deviation from LCDM is similar for both EFTofDE and $w_0 w_a$CDM.

Backup slides

Perturbations constraints in LCDM vs $w_0 w_a$



Modified gravity phenomenology

- We capture this by modified Poisson-like equations for the Newtonian potential which affects clustering and Weyl potential which affects lensing:

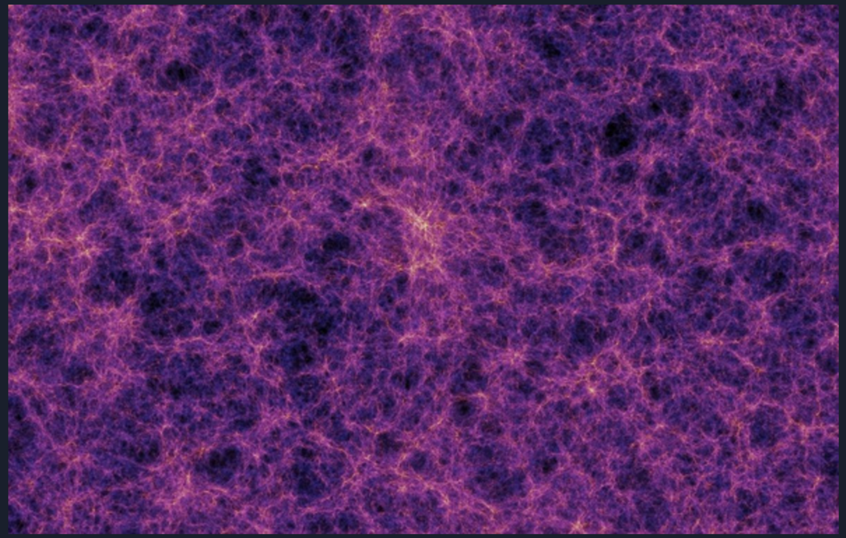


Image: Volker Springel

$$\frac{k^2}{a^2}\Phi = -4\pi G \mu(z) \rho\delta$$

$$\frac{k^2}{a^2}(\Phi + \Psi) = -8\pi G \Sigma(z) \rho\delta$$

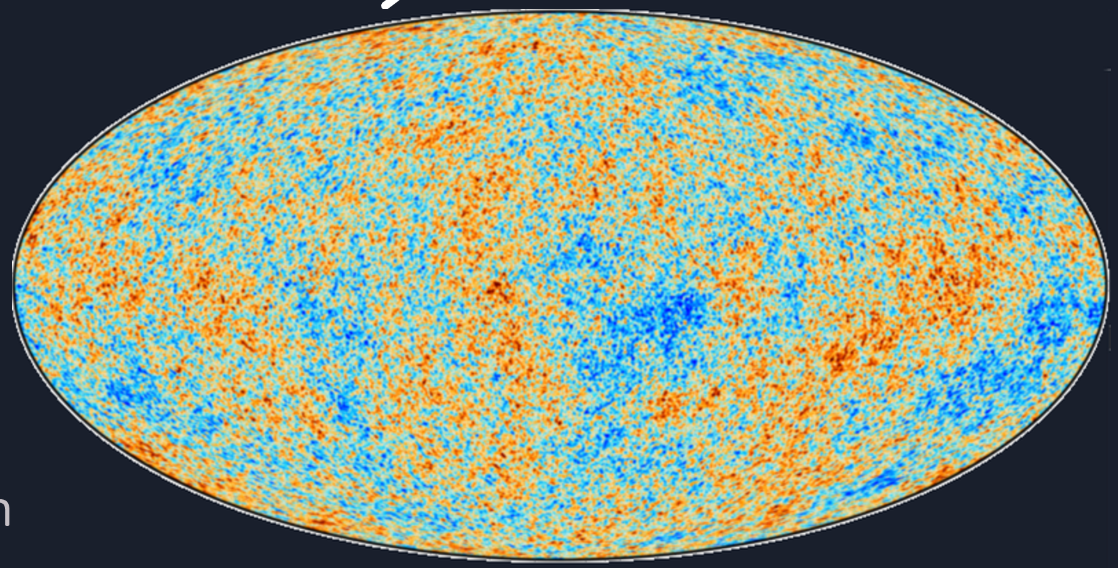


Image: Planck Collaboration

Modified gravity phenomenology