DESIgning concordant cosmological distances in the age of precision cosmology

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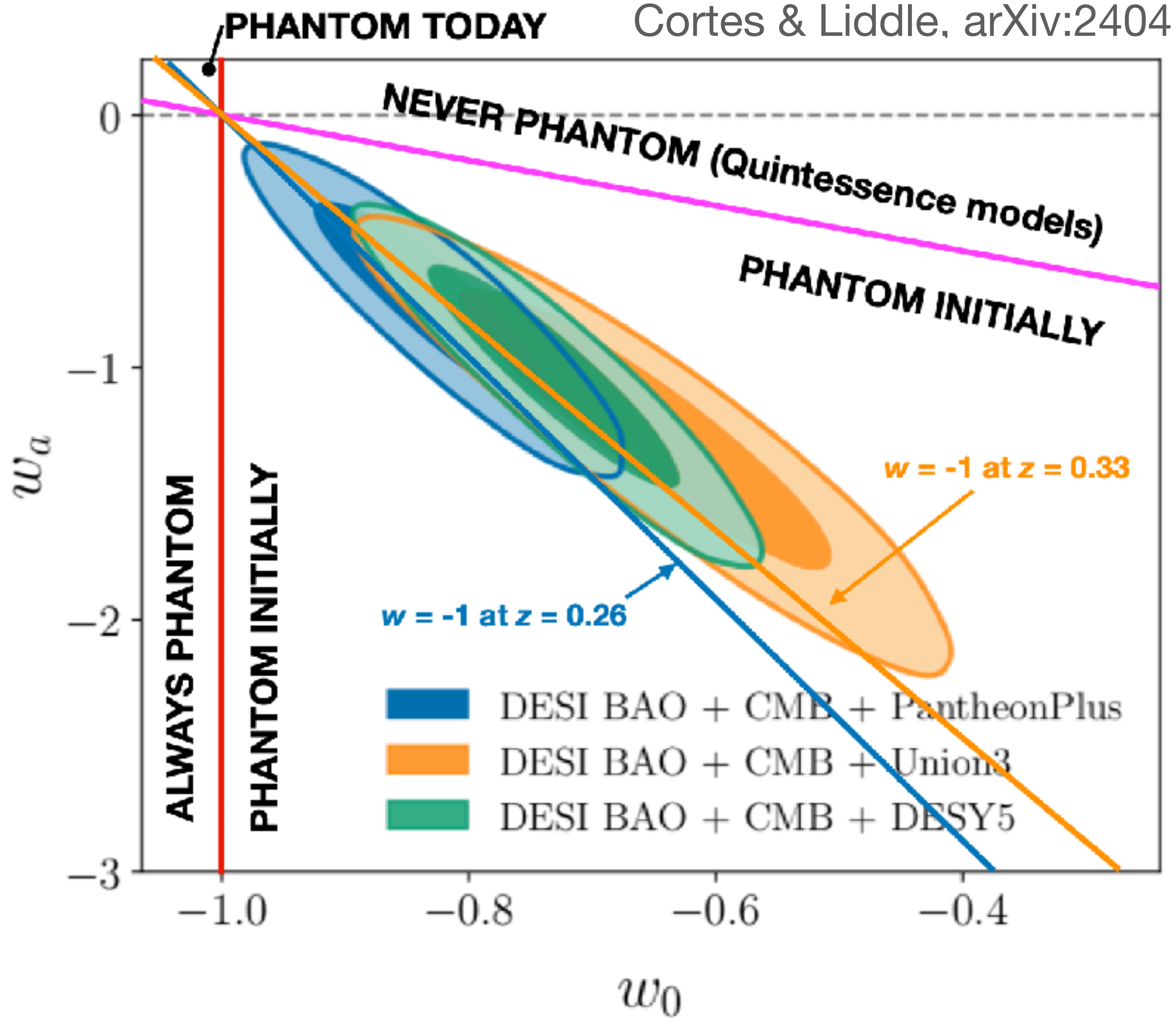
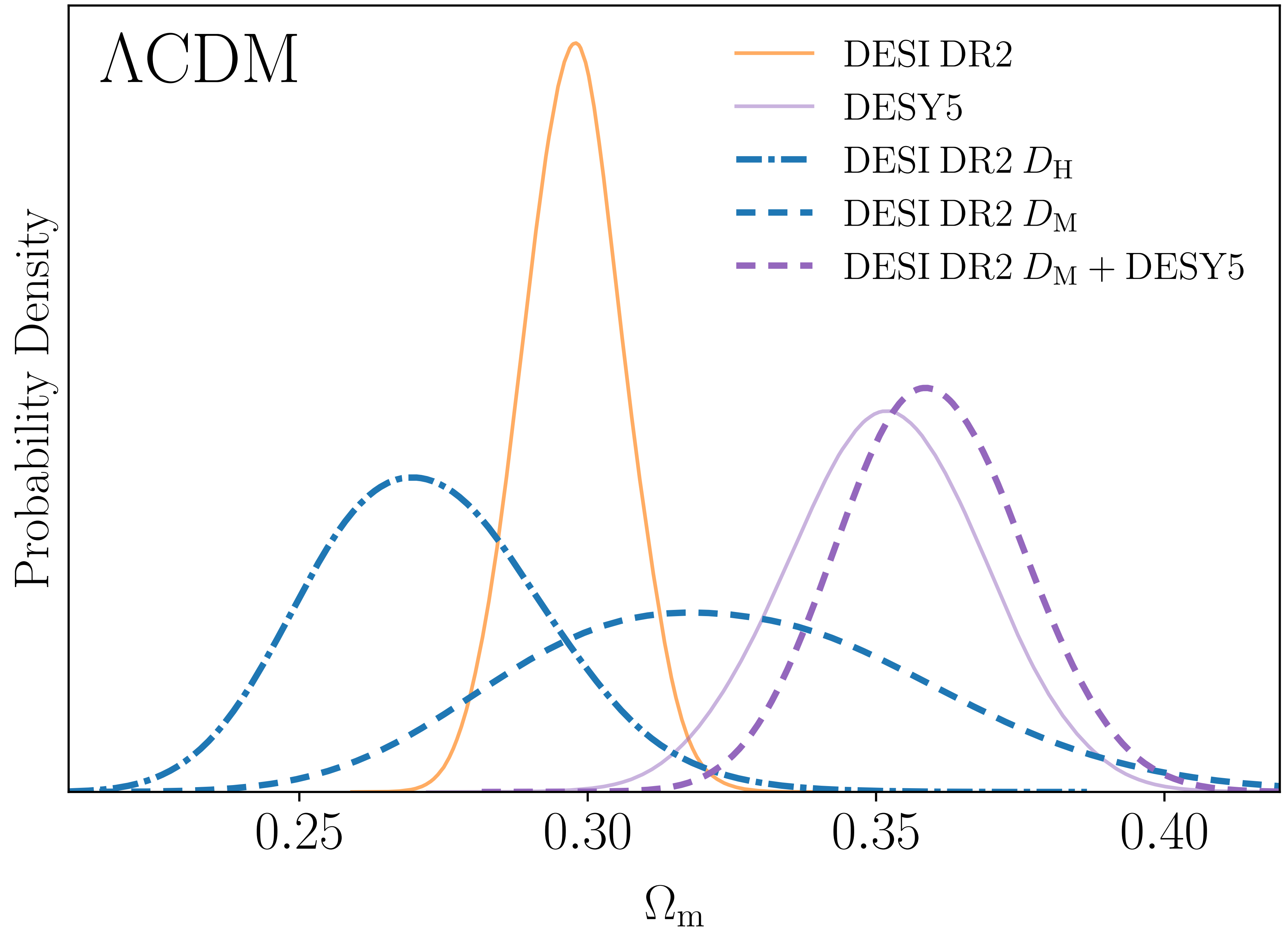
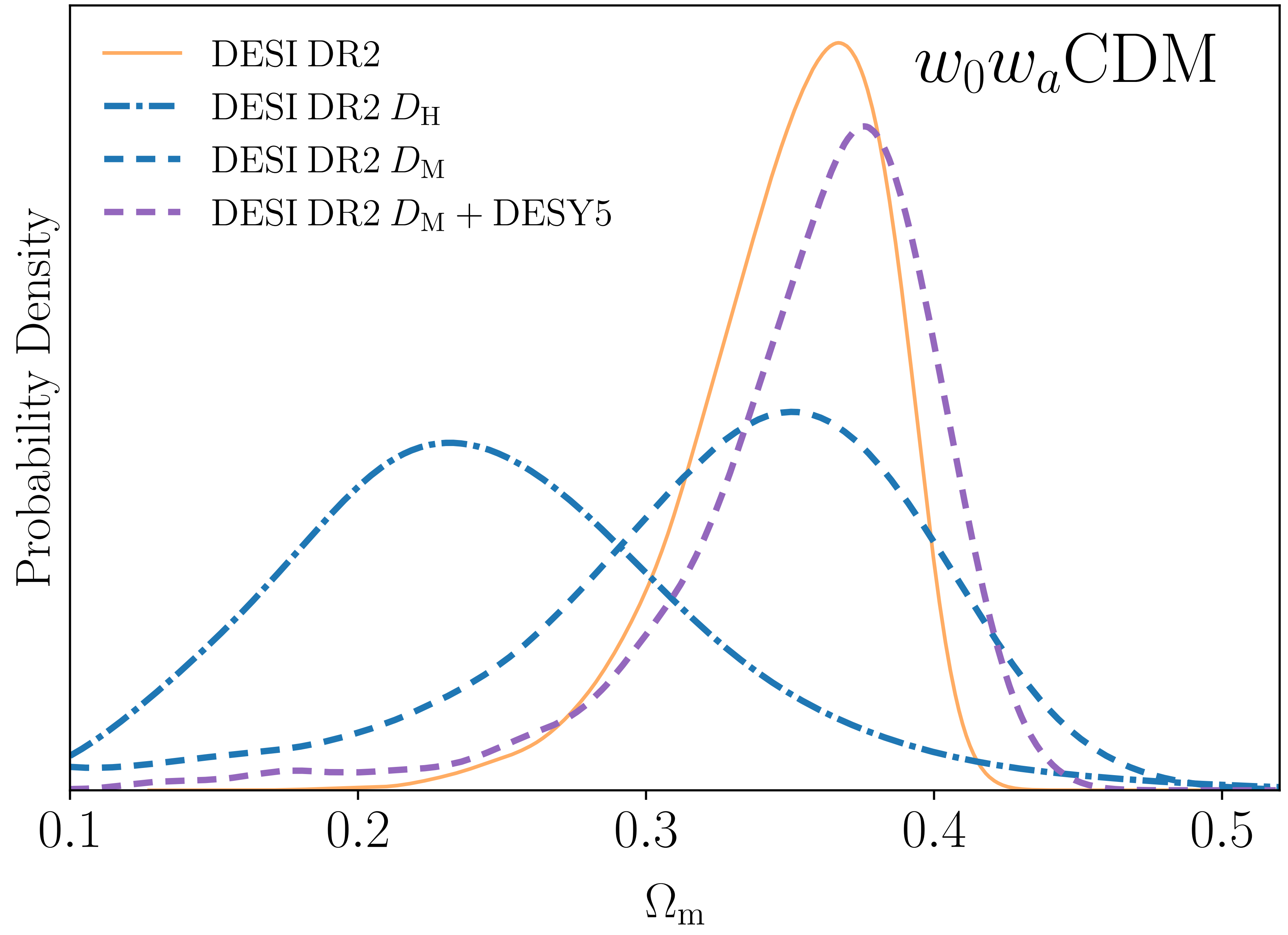
An early-hint for anisotropic expansion

Cortes & Liddle, arXiv:2404.08056







Summary

1. *Inhomogeneous cosmology: the ΛLTB model*
2. *Dynamic dark energy vs inhomogeneities*
3. *Profile likelihood analysis*
4. *Impact on the Hubble tension*
5. *Are inhomogeneous cosmologies a viable option?*
6. *Conclusions*

Inhomogeneous solutions: the LTB metric

We are merely typical observers:

FLRW metric:

$$ds^2 = -dt^2 + \frac{a^2(t)}{1-kr^2}dr^2 + a^2(t)r^2 d\Omega$$

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LTB metric:

$$ds^2 = -dt^2 + \frac{a_{||}^2(r,t)}{1-K(r)r^2}dr^2 + a_{\perp}^2(r,t)r^2 d\Omega$$

FLRW limit: $K(r) \rightarrow \mathrm{const.}$ and $R(r,t) \rightarrow a(t)r$

Three arbitrary functions: $m(r), t_{BB}(r)$, and $K(r)$

Inhomogeneous solutions: a tale about void models

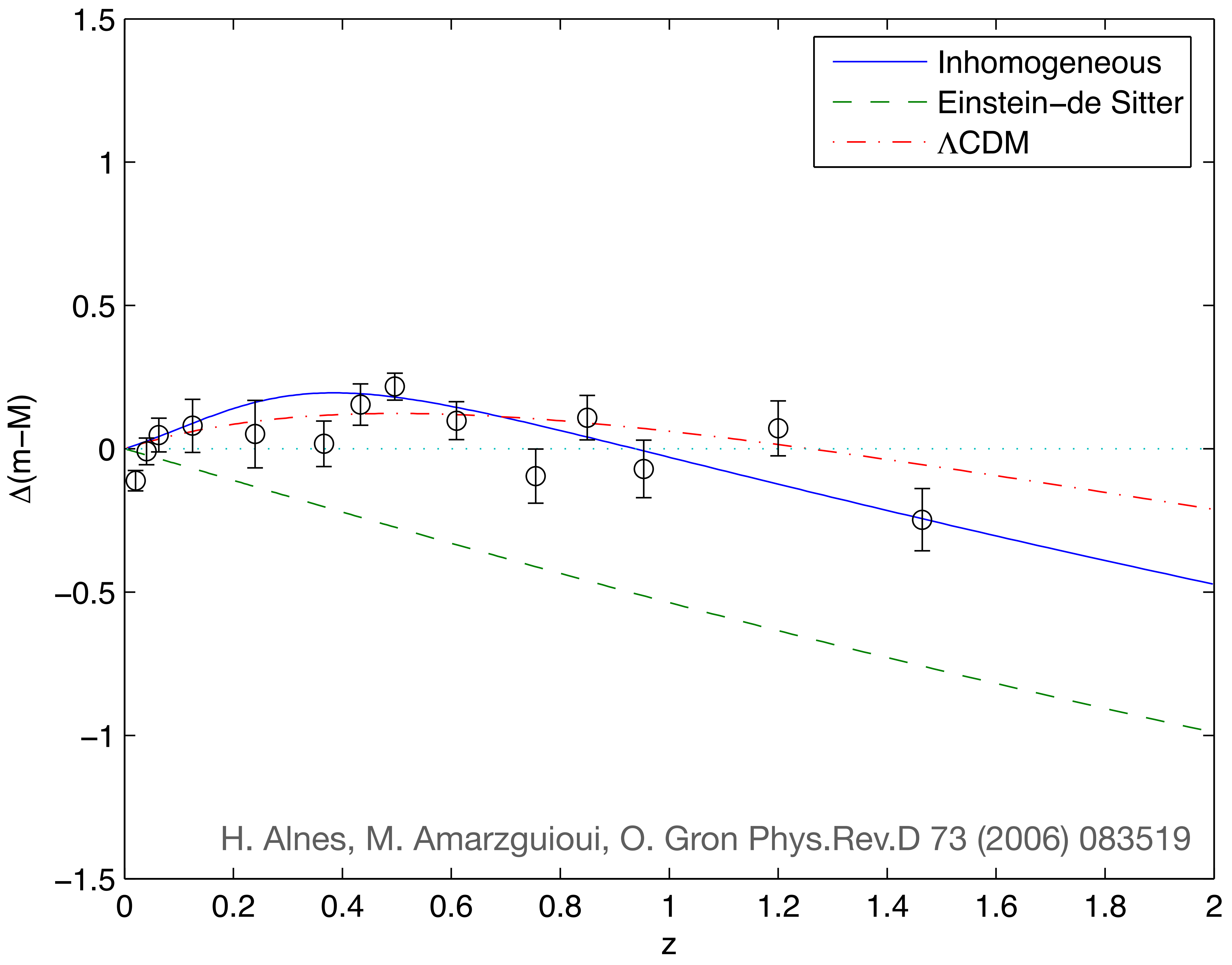
The directional derivative along the past lightcone:

$$\frac{d}{dt} \approx \frac{\partial}{\partial t} - \frac{\partial}{\partial r}$$

The acceleration of the Universe explained by:

$$\frac{\partial H}{\partial r} < 0$$

Apparent acceleration!



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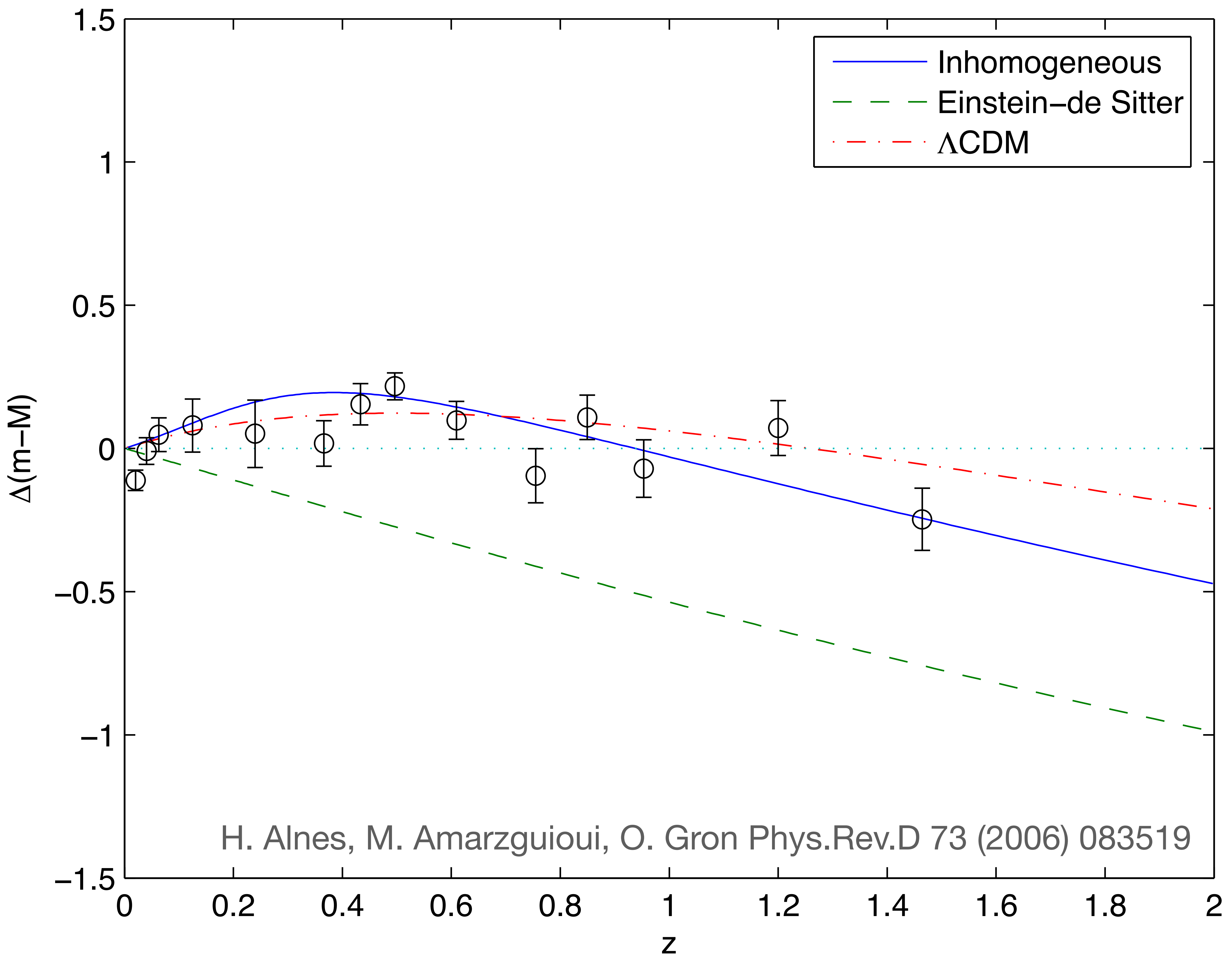

'Faster expansion now than before' → 'Faster expansion here than there'

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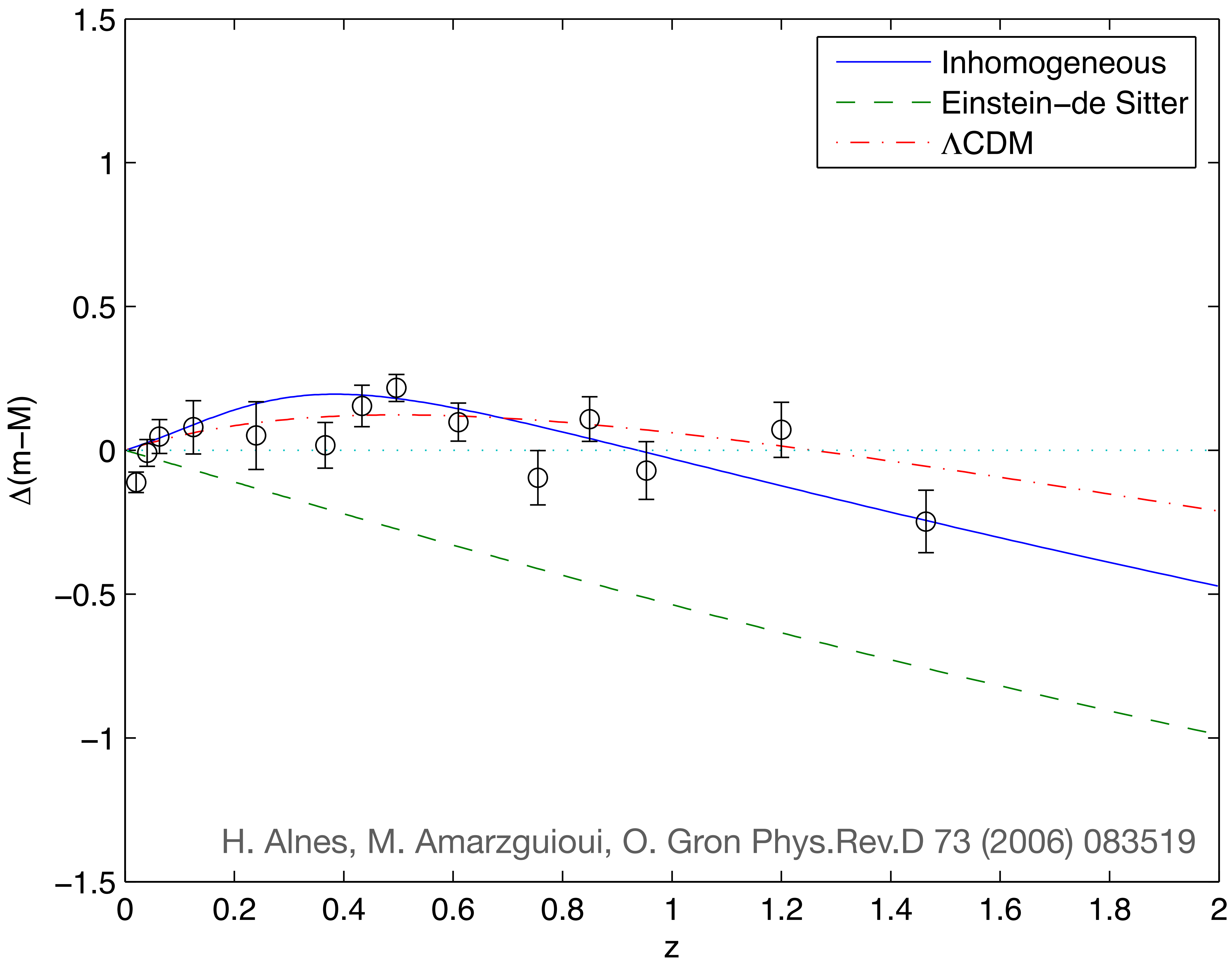

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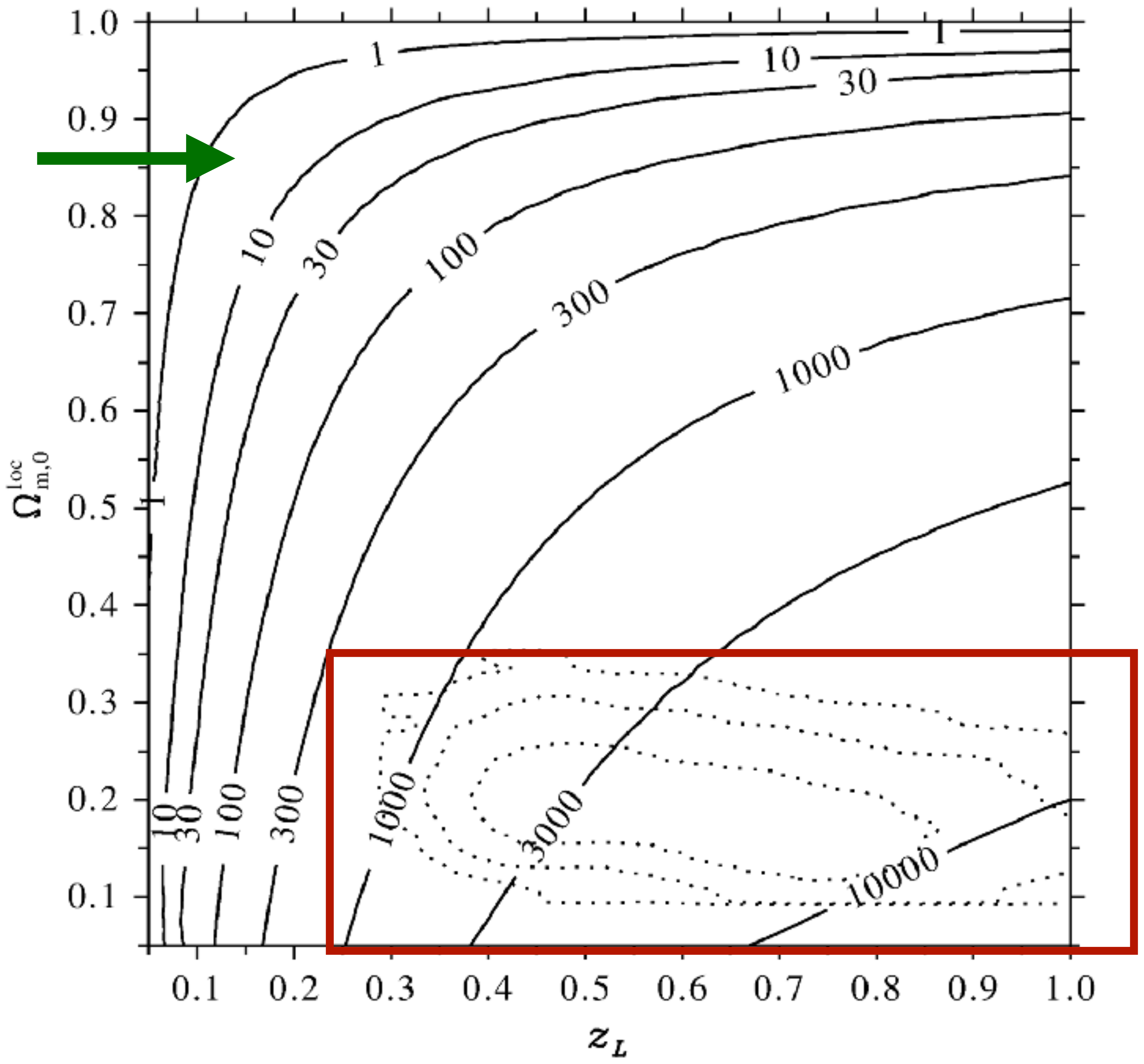
$$\Lambda \xrightarrow{\text{replace by}} \partial H/\partial r < 0$$

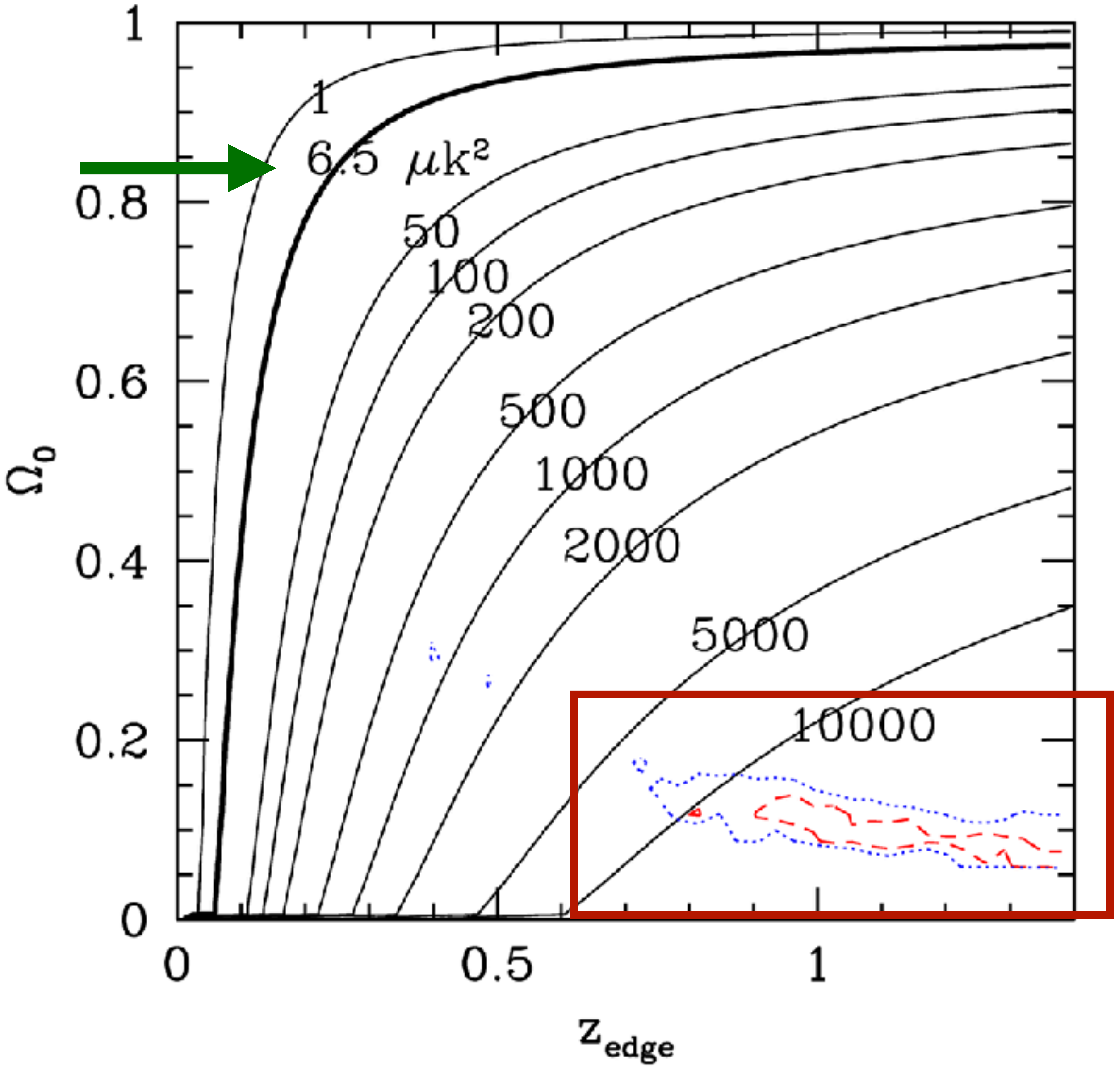
Inhomogeneous solutions: a tale about void models

Despite its ability to explain the dimming of the luminosity of Supernovae
LTB **void** models were shown to be inconsistent with the several observations

J. P. Zibin and A. Moss, Class.Quant.Grav. 28 (2011) 164005



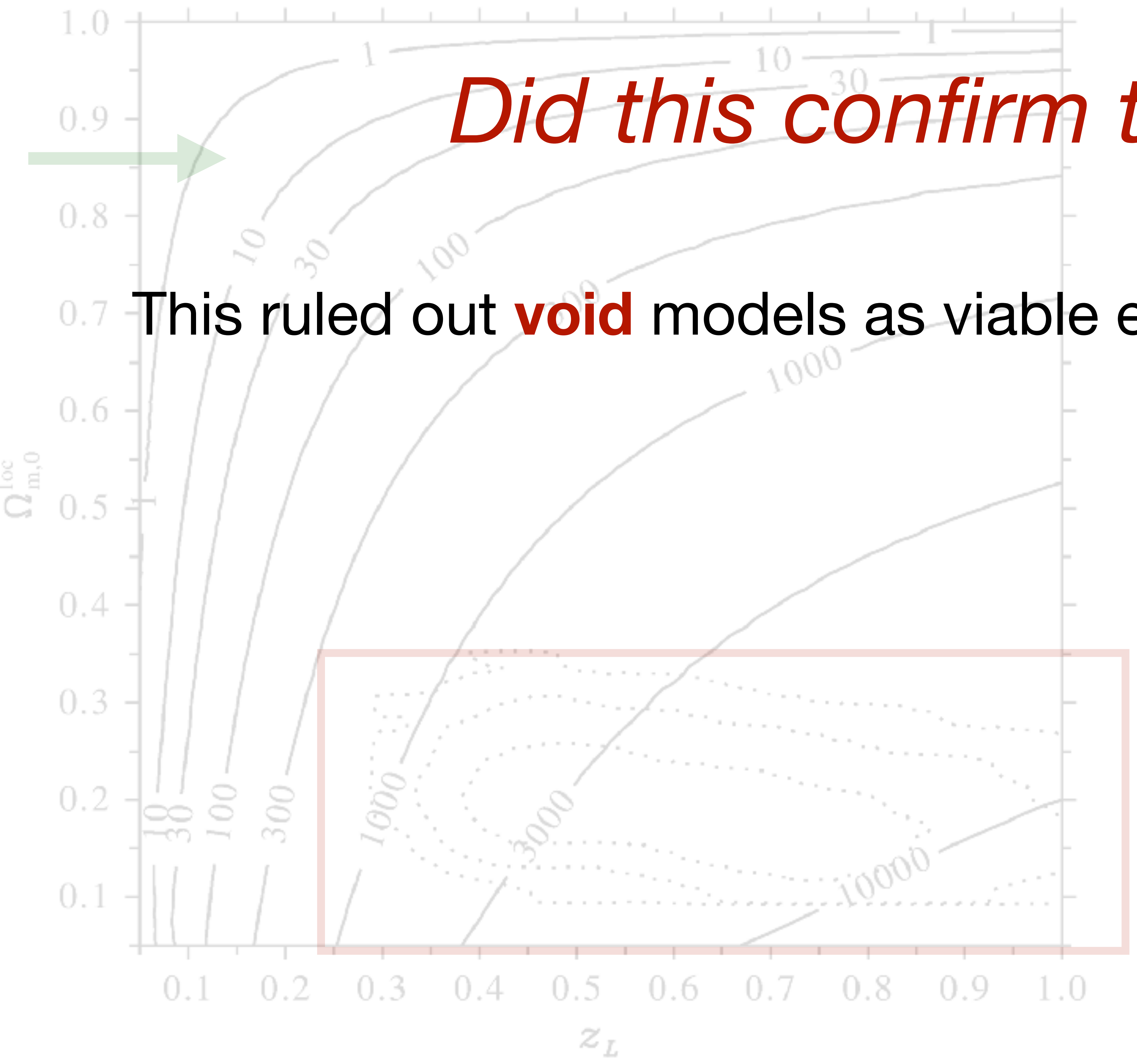
P. Zhang and A. Stebbins, Phys.Rev.Lett. 107 (2011) 041301

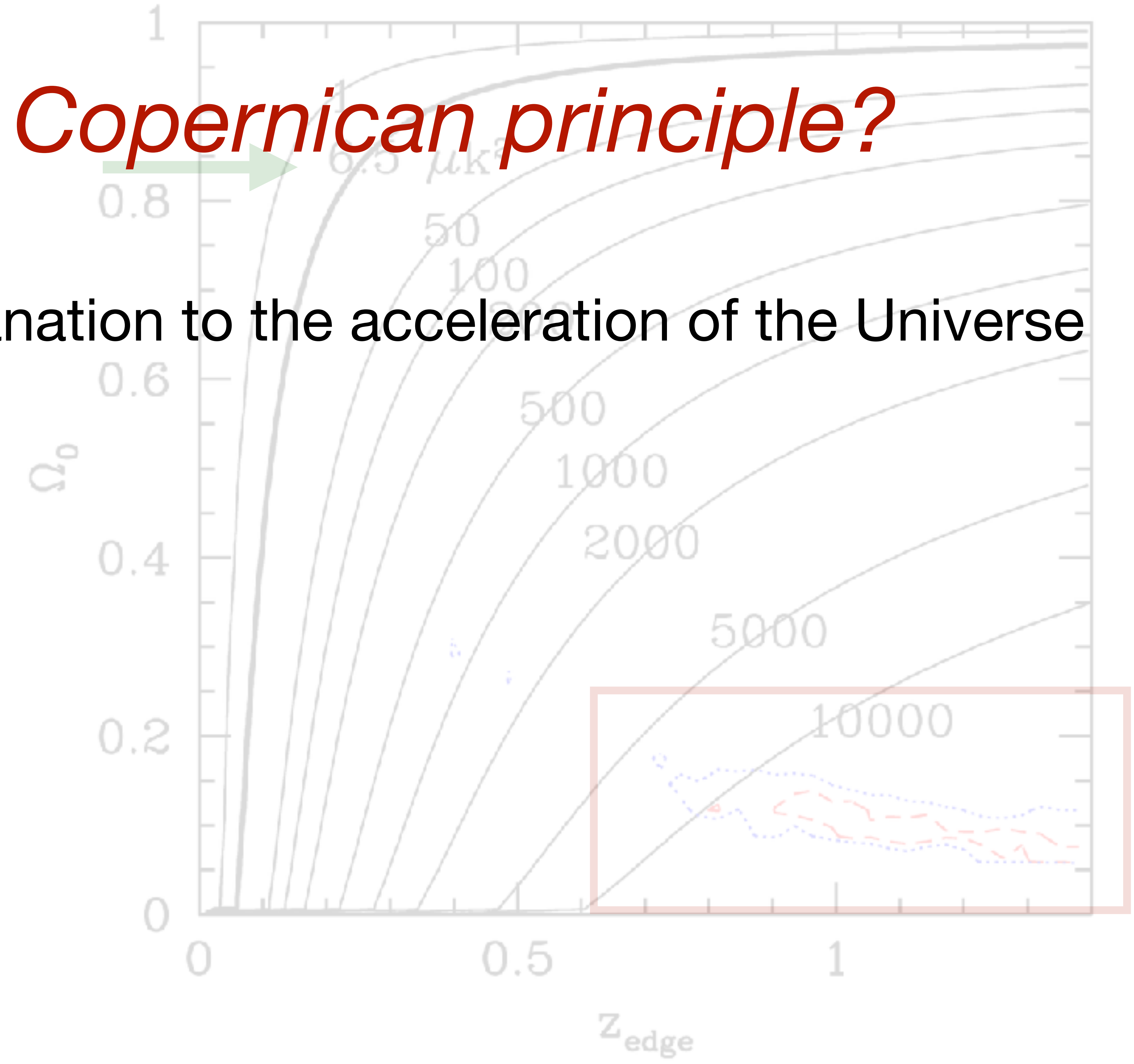


Inhomogeneous solutions: a tale about void models

Did this confirm the Copernican principle?

This ruled out **void** models as viable explanation to the acceleration of the Universe





The ΛLTB model

We model a violation to the Copernican principle by using the FLRW metric *+ radial inhomogeneities*

Three arbitrary functions: $m(r)$, $t_{BB}(r)$, and $K(r)$

$$\frac{\dot{R}^2}{R} = \frac{8\pi G}{3}\rho_\Lambda + \frac{2m(r)}{a_\perp^3 r^3} - \frac{K(r)}{a_\perp^2}$$

$$\rho_m(r,t) = \frac{m'(r)}{4\pi G a_{||}\, a_\perp^2}$$

$$t_0 - t_{BB}(r) = \frac{1}{H_\perp(r,t_0)} \int \frac{x}{\sqrt{\Omega_{m0}(r)x^{-1} + \Omega_{k0}(r) + \Omega_{\Lambda 0}(r)x^2}}$$

Cosmological distances in the ΛLTB model

$$ds^2 = -dt^2 + \frac{a_{||}^2(r,t)}{1-K(r)r^2}dr^2 + a_{\perp}^2(r,t)r^2 d\Omega$$

Inhomogeneity yields to anisotropic expansion rate!

$$D_H(z) = \frac{1}{H_{||}(r(z),t(z))}$$

$$D_M(z) = (1+z)r^2(z)a_{\perp}(r(z),t(z))$$

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$$D_M(z) = (1+z)r^2(z)a_{\perp}(r(z),t(z))$$

$$\frac{dt}{dz} = -\frac{1}{(1+z)H_{||}(r,t)}$$

$$\frac{dr}{dz} = \frac{1-K(r)r^2}{(1+z)\dot{a}_{||}(r,t)}$$

BAO distances in the ΛLTB model

BAO measurements are typically presented as ratios between coming distances:

$$\frac{D_H}{r_d} \to \frac{D_H}{(1+z)l_{||}(z)}$$

$$\frac{D_M}{r_d} \to \frac{D_M}{(1+z)l_{\perp}(z)}$$

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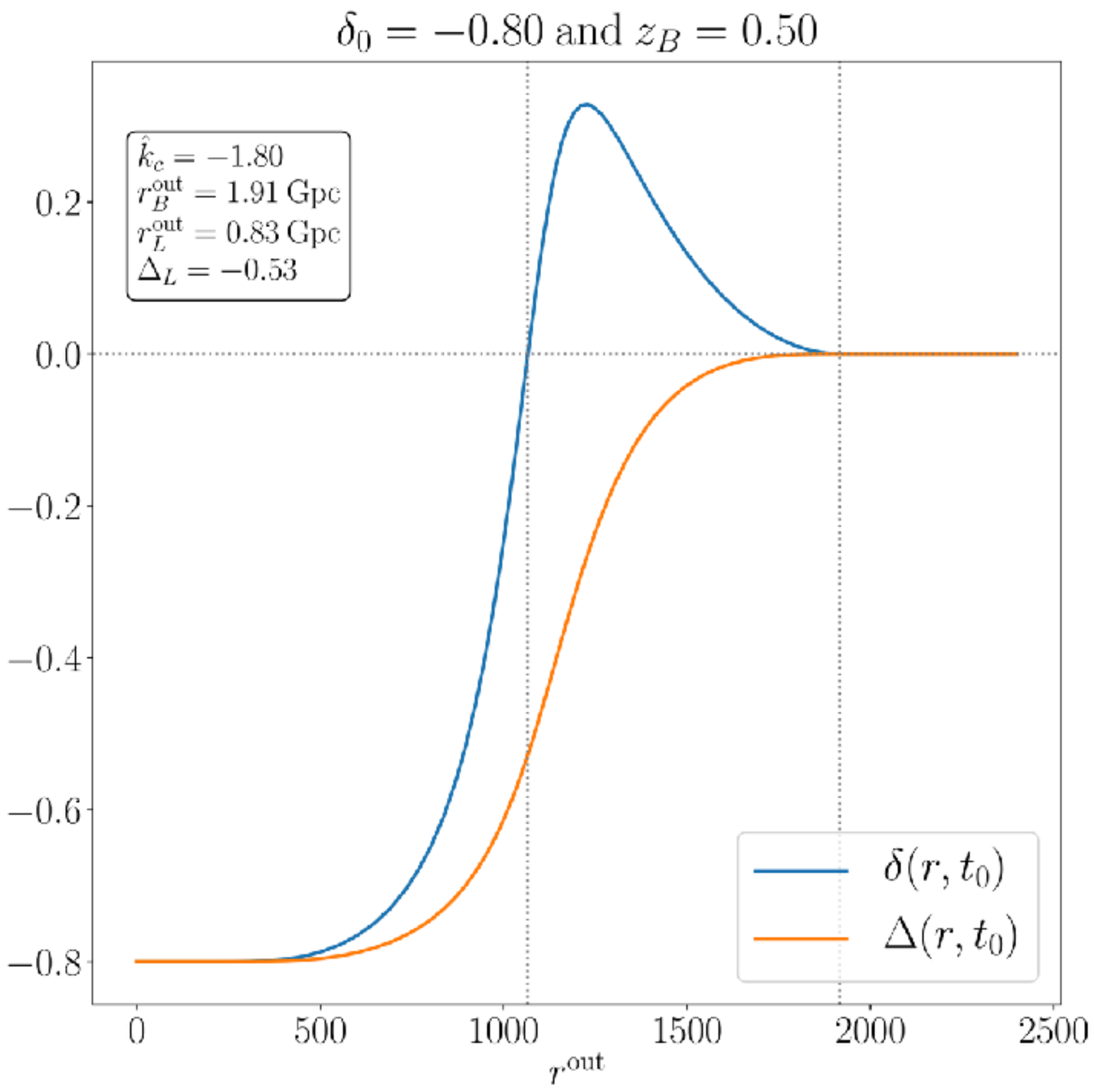
$$\frac{D_M}{r_d} \to \frac{D_M}{(1+z)l_{\perp}(z)}$$

The anisotropic expansion deform in a direction dependent way these ratios!

$$l_{\perp,\parallel}(z) = \frac{a_{\perp,\parallel}(r(z), t(z))}{a_{\perp,\parallel}(r(z), t_d)} \frac{r_d}{(1+z_d)}$$

The ΛLTB model

δ_0, r_B + 6 ΛCDM param .



ΛCDM background endowed with a spherical over/underdensity

Early-FLRW cosmologies:

- *Mass function:* $m(r) = m_0 r^3$
- *Homogeneous Big Bang time:* $t_{\rm BB}(r) = 0$
- *Compensated curvature profile:*

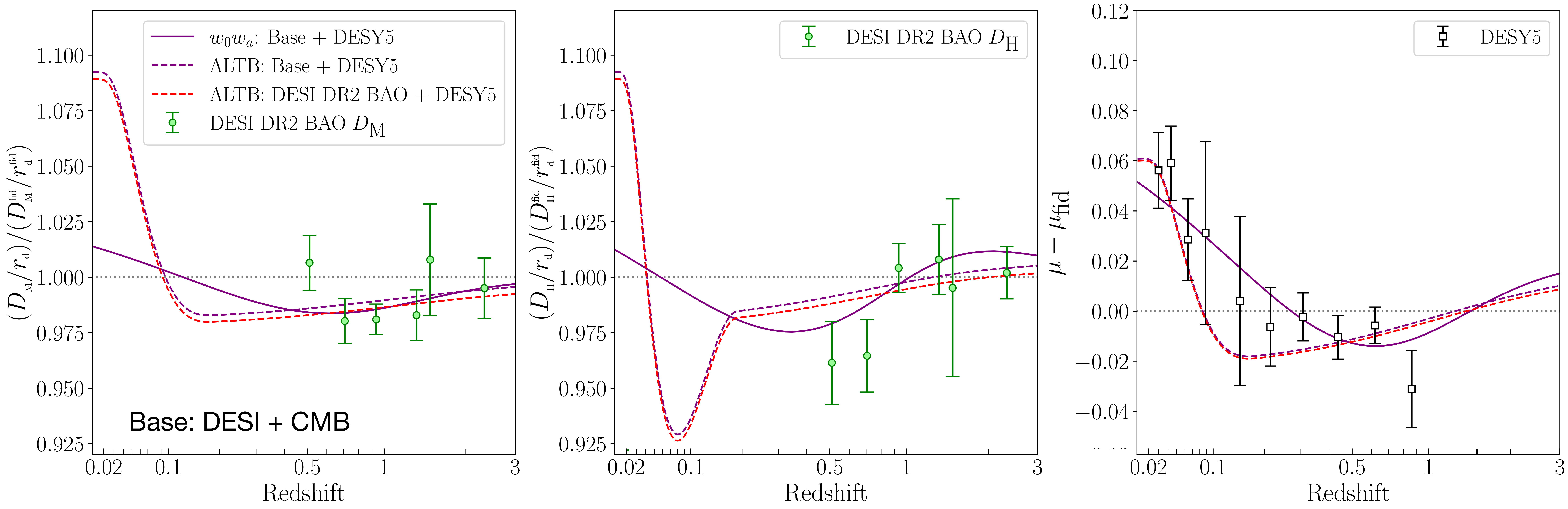
$$k(r) = k_B + (k_C - k_B) P_3(r/r_B)$$

$$P_3(x) = \begin{cases} 1 - \exp\left[-(1-x)^3/x\right] & \text{if } 0 \geq x < 1 \\ 0 & \text{if } 1 \geq x \end{cases}$$

$$\delta(r,t) \equiv \frac{\rho_m(r,t)}{\rho_m(r_B,t)} - 1 \quad \Delta(r,t) \propto \int_0^r d\bar{r}\delta(\bar{r},t) a_\perp^2 a_\parallel r^2$$

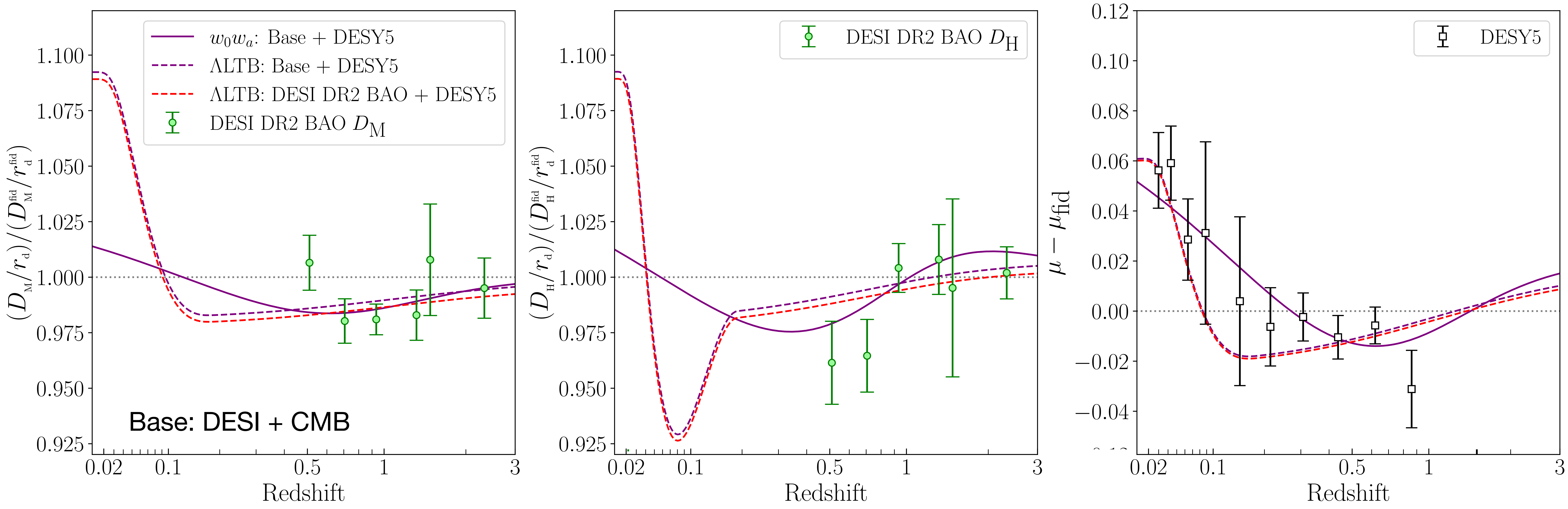
Matter and mass dens. Contrast

Dynamic dark energy vs inhomogeneities



Dynamic dark energy vs inhomogeneities

Local inhomogeneities bring back the agreement between different probes!



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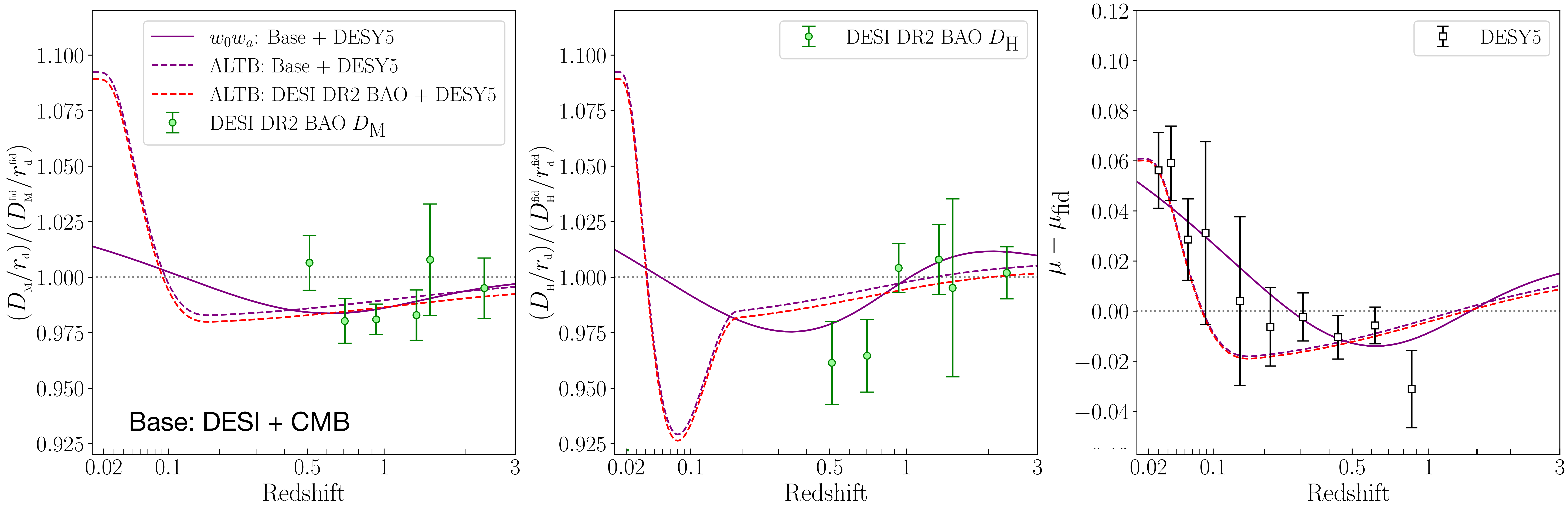

BF parameters: $\delta_0 \approx 0.2$ & $r_B \approx 800$ Mpc ($z_B \approx 0.19$)

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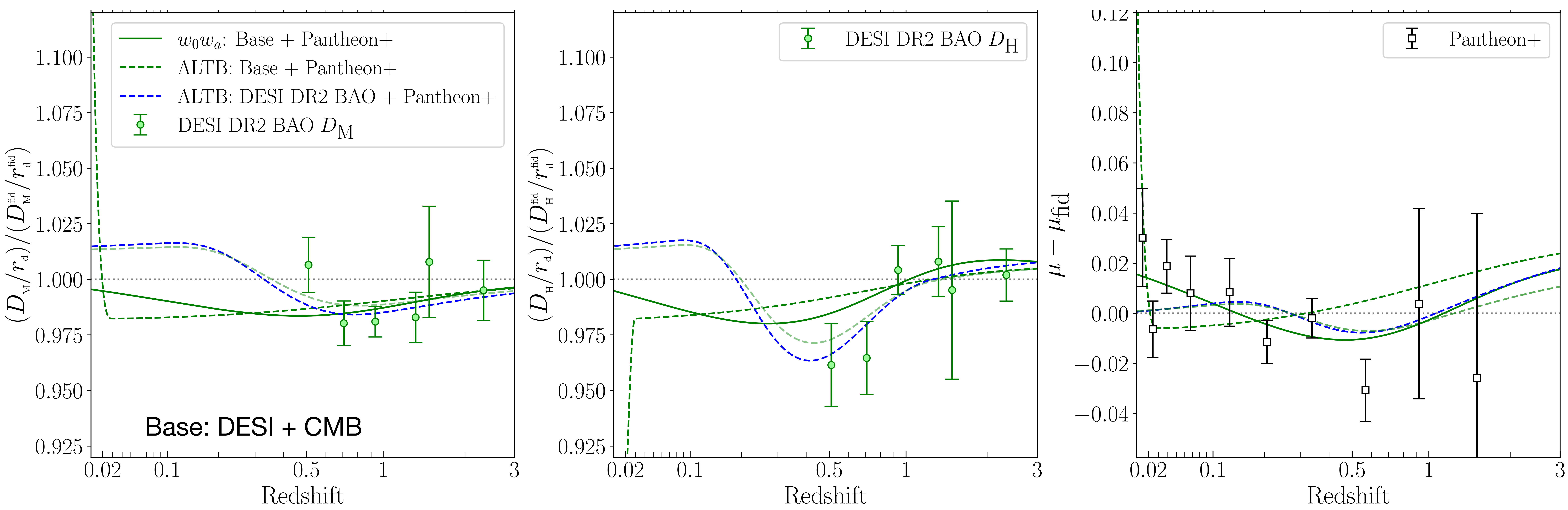

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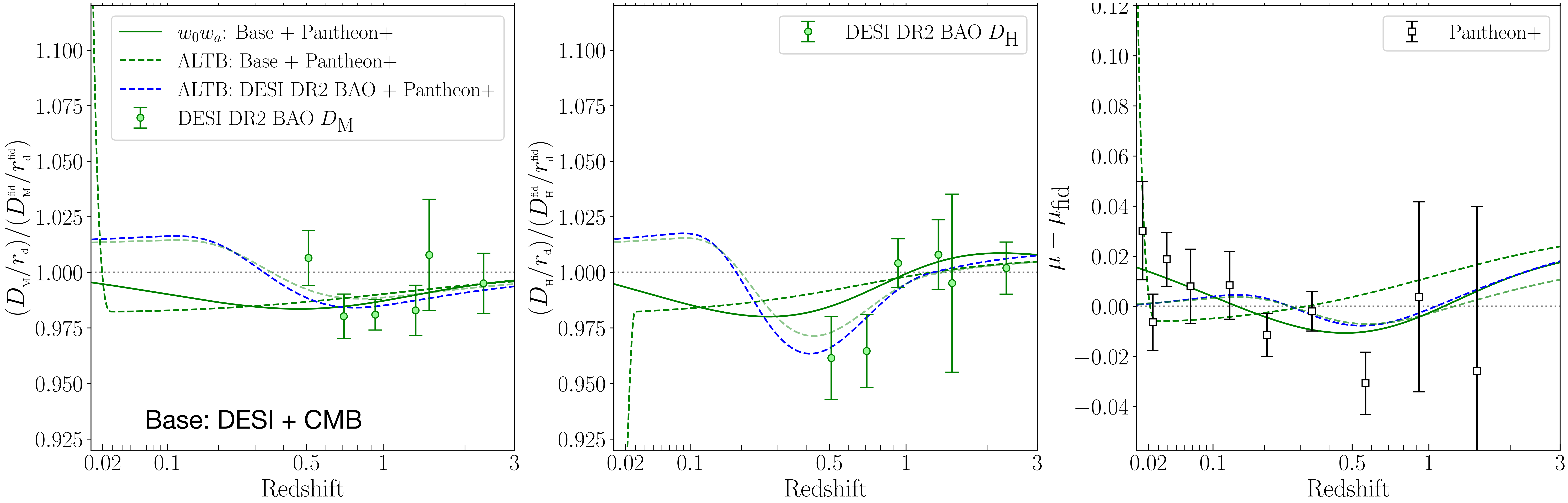

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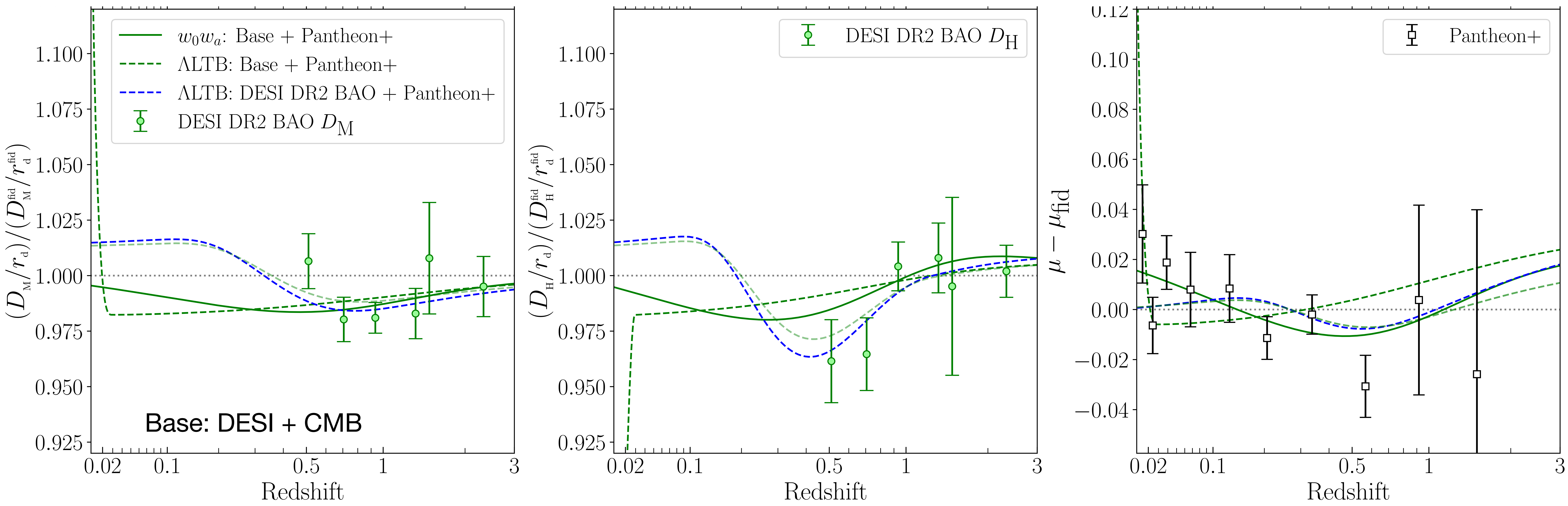

BF parameters: $\delta_0 \approx 0.6$ & $r_B \approx 130$ Mpc ($z_B \approx 0.03$)

Dynamic dark energy vs inhomogeneities

Dynamic dark energy vs inhomogeneities

$$\Delta\chi^2 \equiv \chi^2_{\rm model} - \chi^2_{\Lambda\rm CDM}$$

	Base	Base + DESY5	Base + Pantheon+
		$w_0 w_a$CDM	
$\Delta\chi^2_{\rm BAO}$	-4.18	-5.57	-2.72
$\Delta\chi^2_{\rm CMB}$	-3.36	-1.66	-1.96
$\Delta\chi^2_{\rm SNe}$	-	-21.73	-3.47
$\Delta\chi^2_{\rm min}$	-7.54	-28.96	-8.15
		ΛLTB	
$\Delta\chi^2_{\rm BAO}$	-3.50	-2.18	-0.04 (-4.07)
$\Delta\chi^2_{\rm CMB}$	0.41	1.45	0.25 (0.94)
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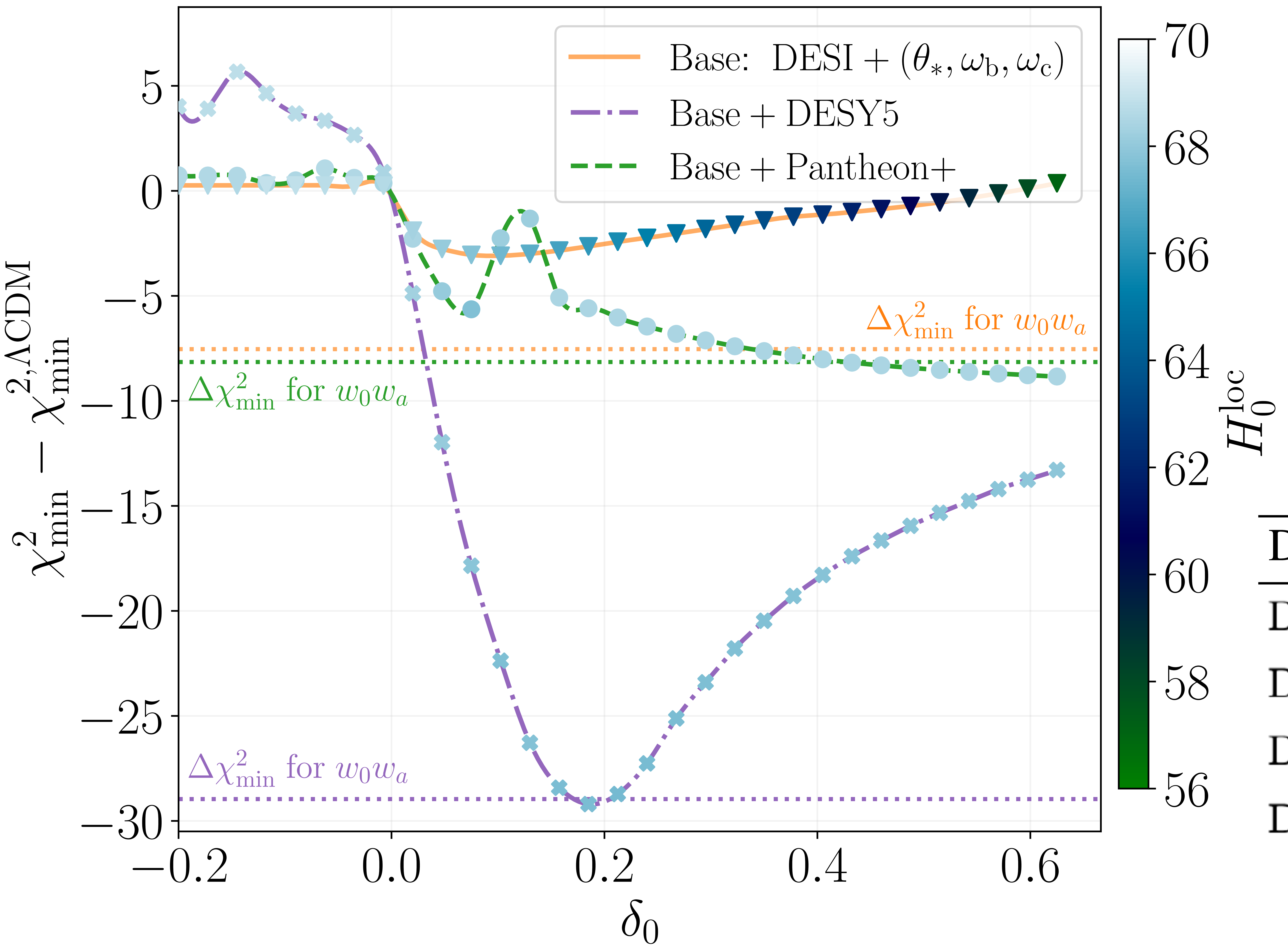
When considering SNe, fits obtained with inhomogeneous models are statistically indistinguishable from the dynamical dark energy scenario!

Profile likelihood analysis and impact on H_0



$w_0 w_a$CDM

Data	H_0
DESI+CMB	$63.6^{+1.6}_{-2.1}$
DESI+CMB+Pantheon+	67.51 ± 0.59
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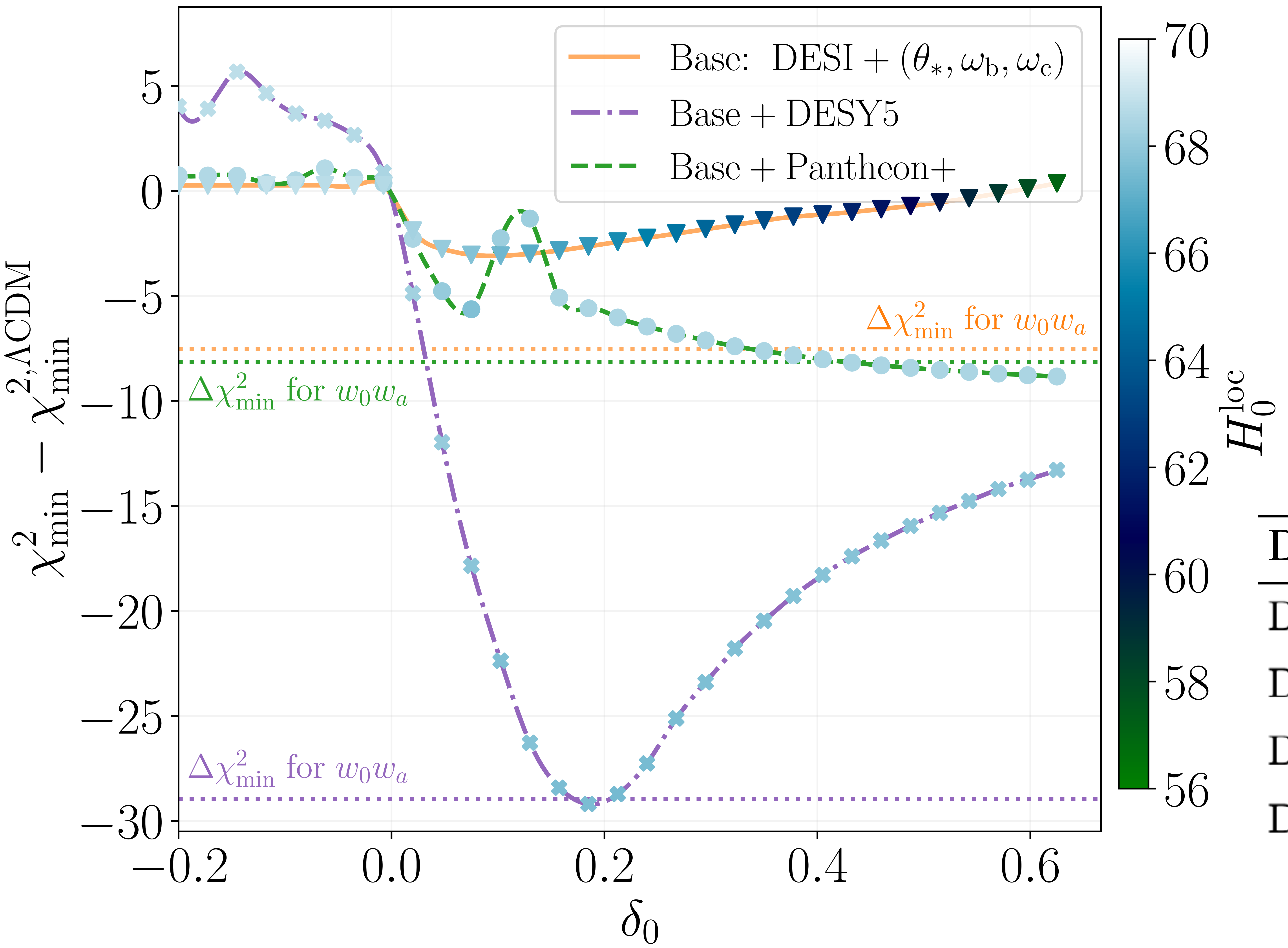

Without SNe: $H_0^{loc} \in [57, 68.9]$

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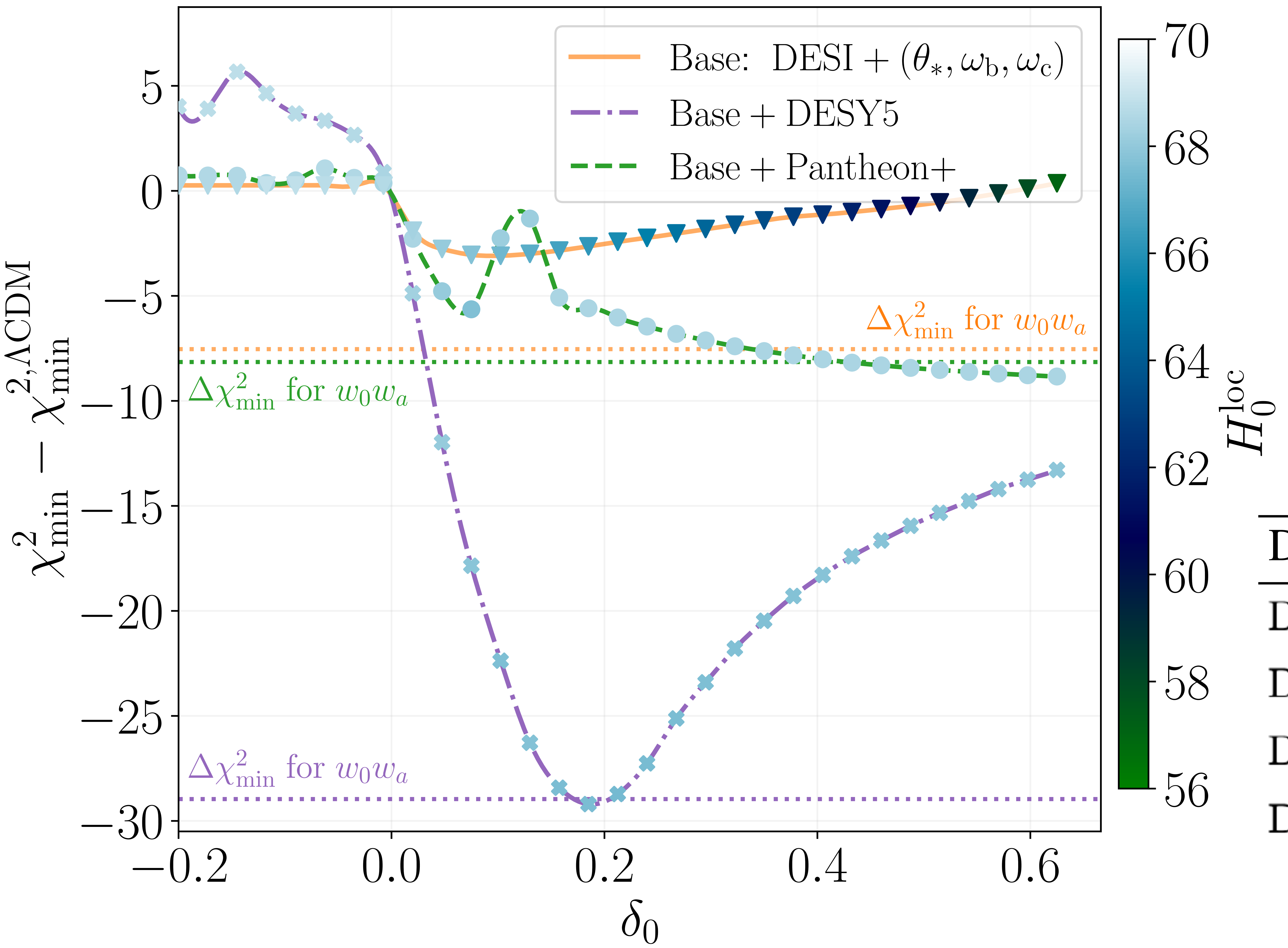

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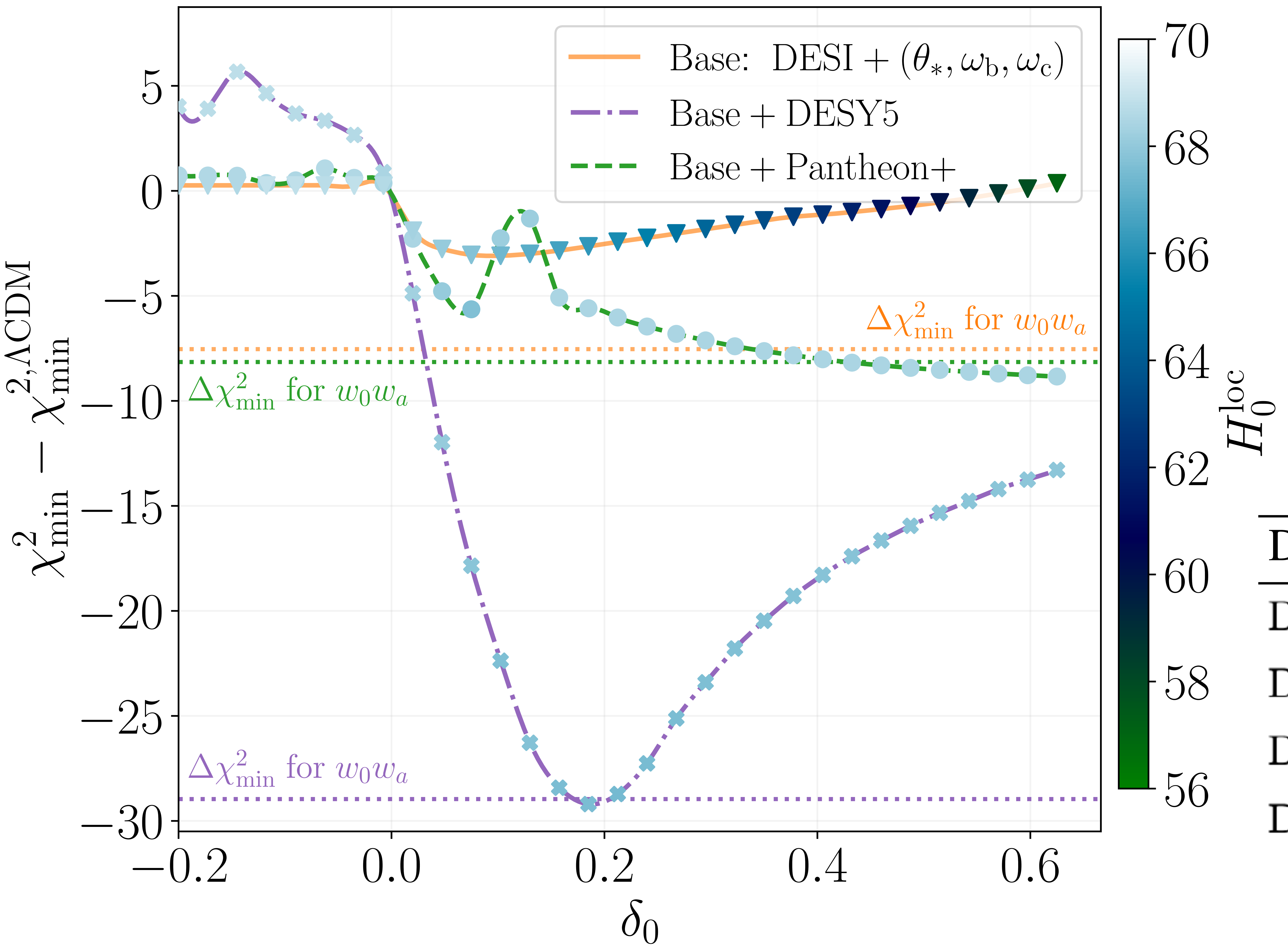

(Weak to strong) preference for an overdense region.

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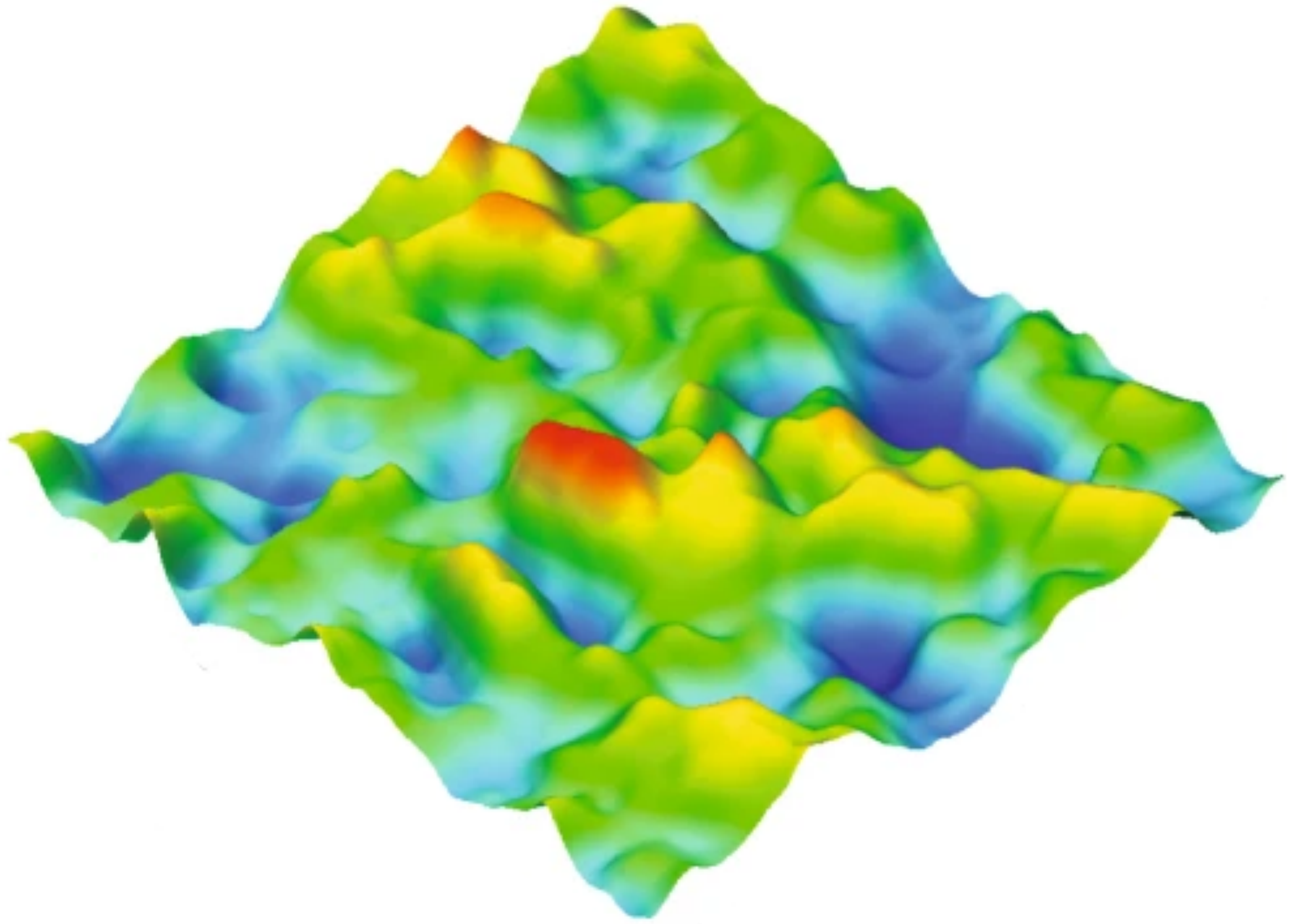

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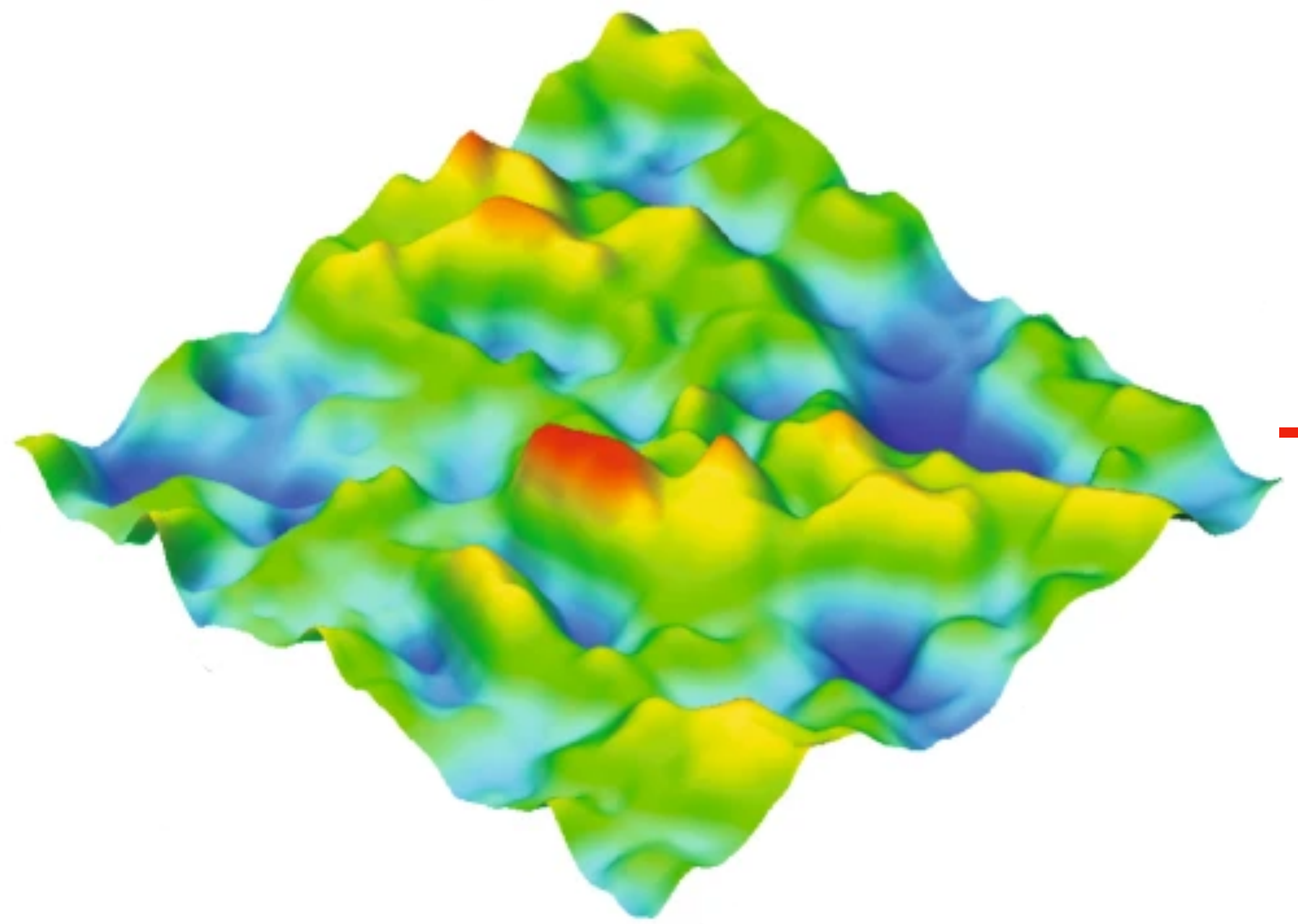

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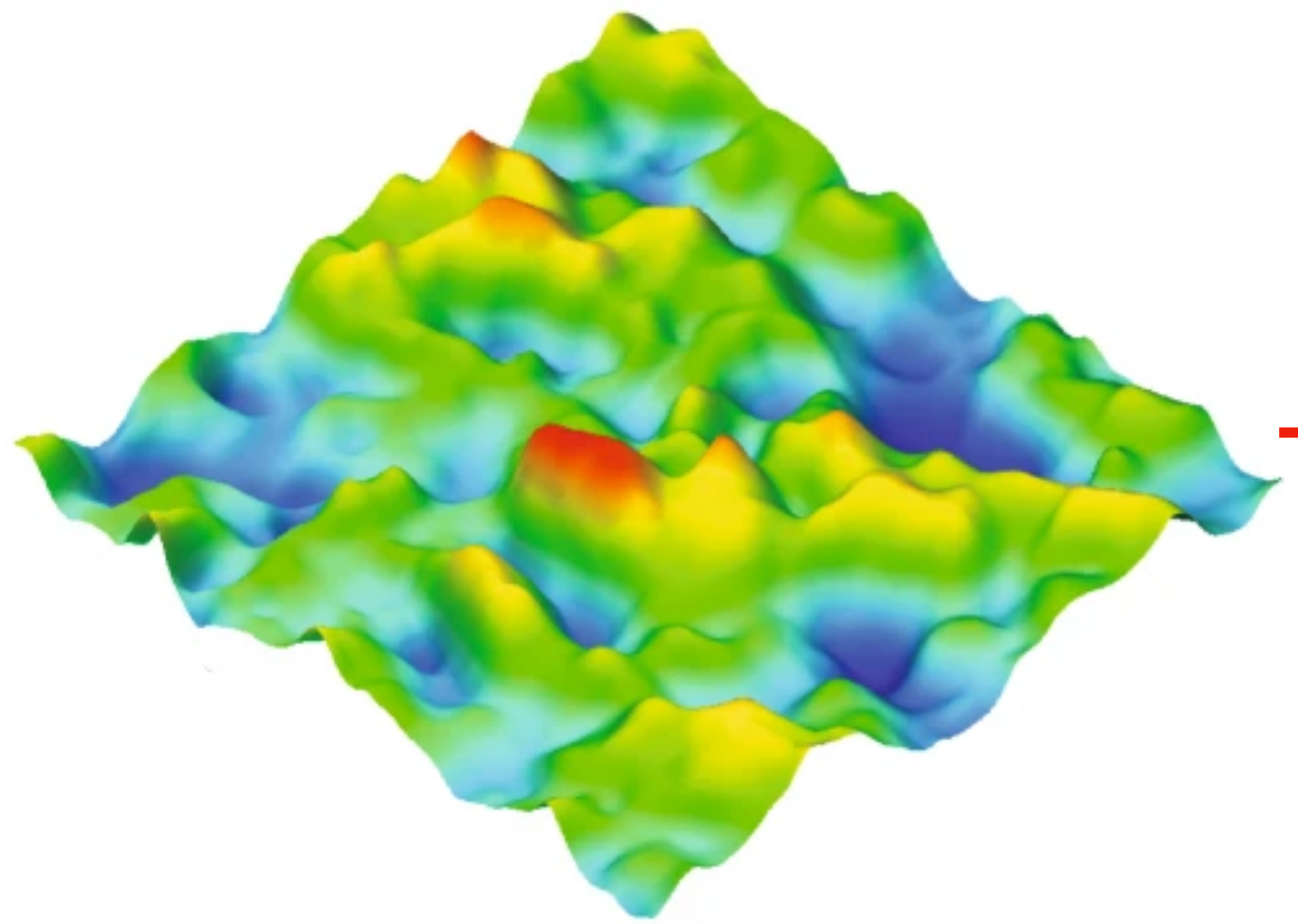

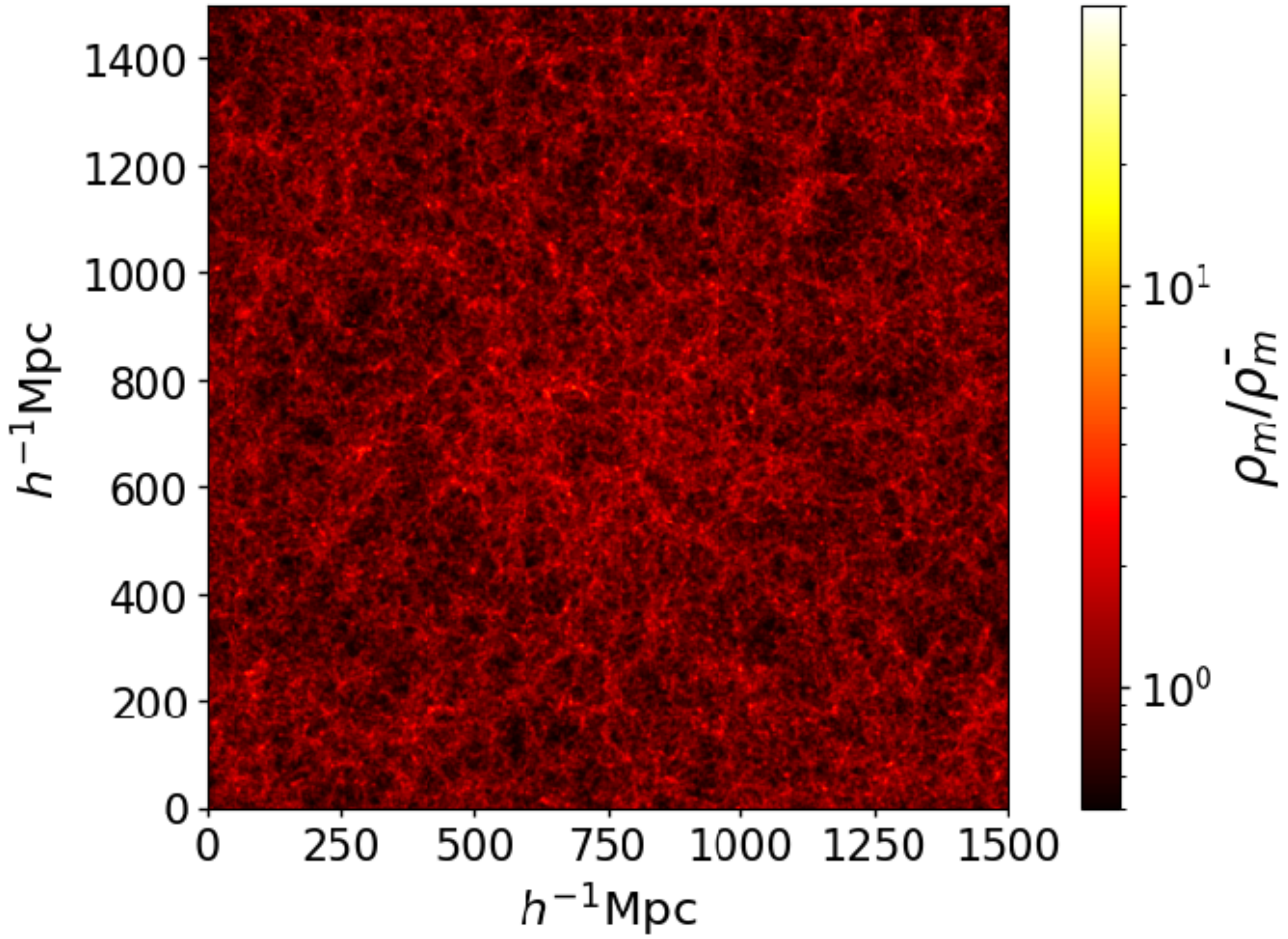

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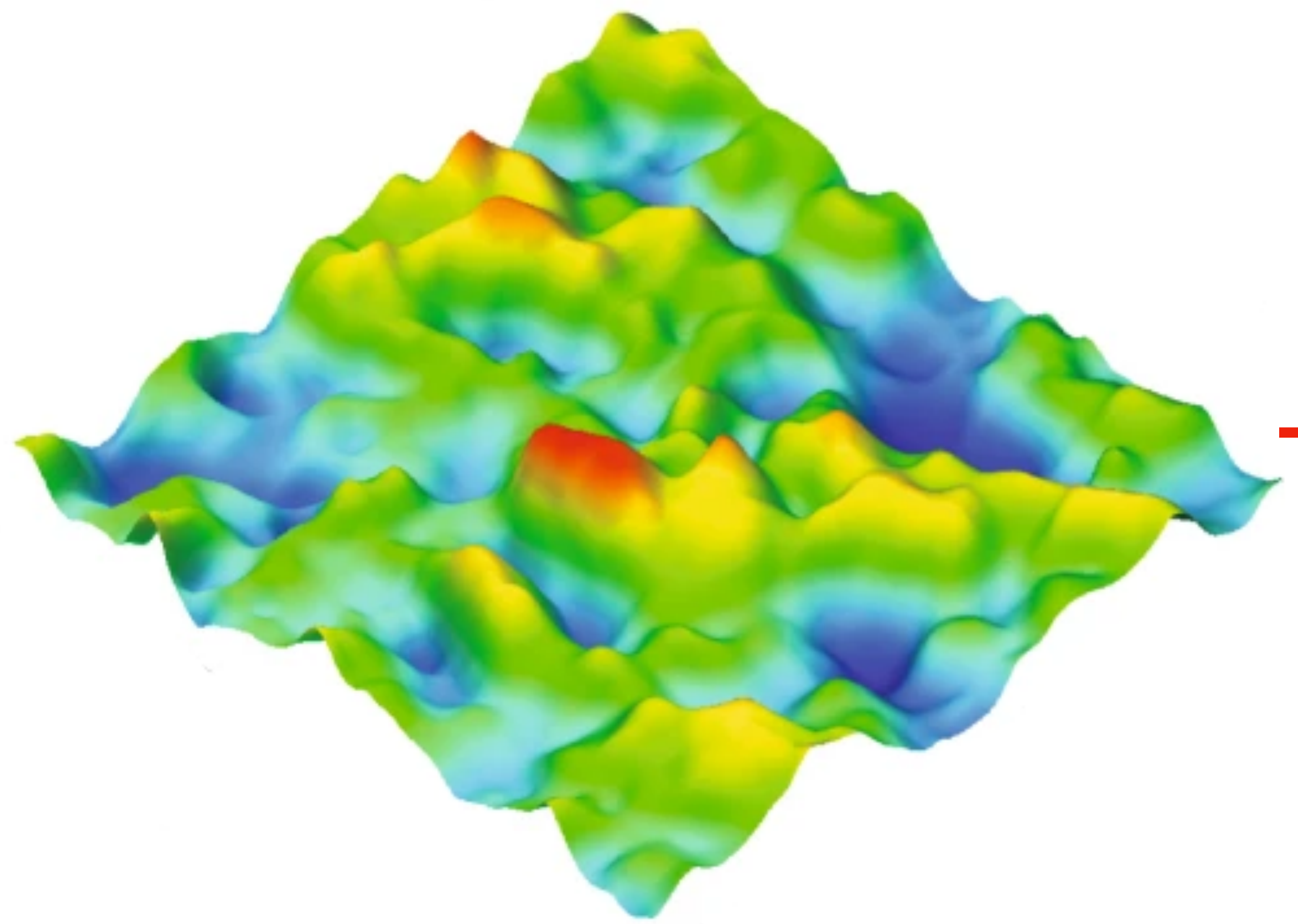

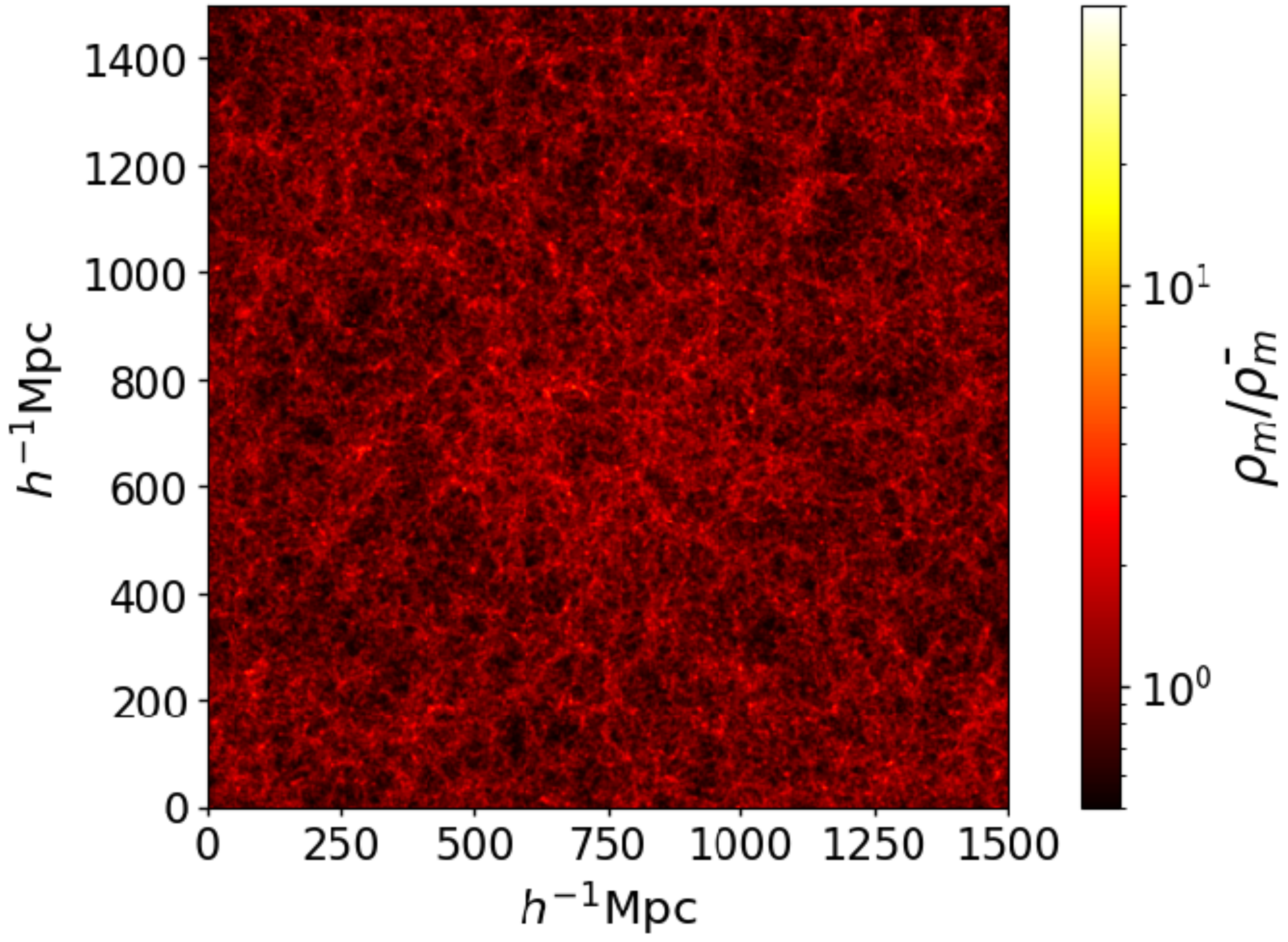

$$\sigma^2(r) = \int_0^\infty \frac{dk}{k} \Delta^2_{m0}(k) \left[\frac{3j_1(rk)}{rk}\right]^2$$

$$\mathscr{P}(\Delta, r) \propto \exp\left[-\frac{1}{2}\frac{\Delta^2(r)}{\sigma^2(r)}\right]$$

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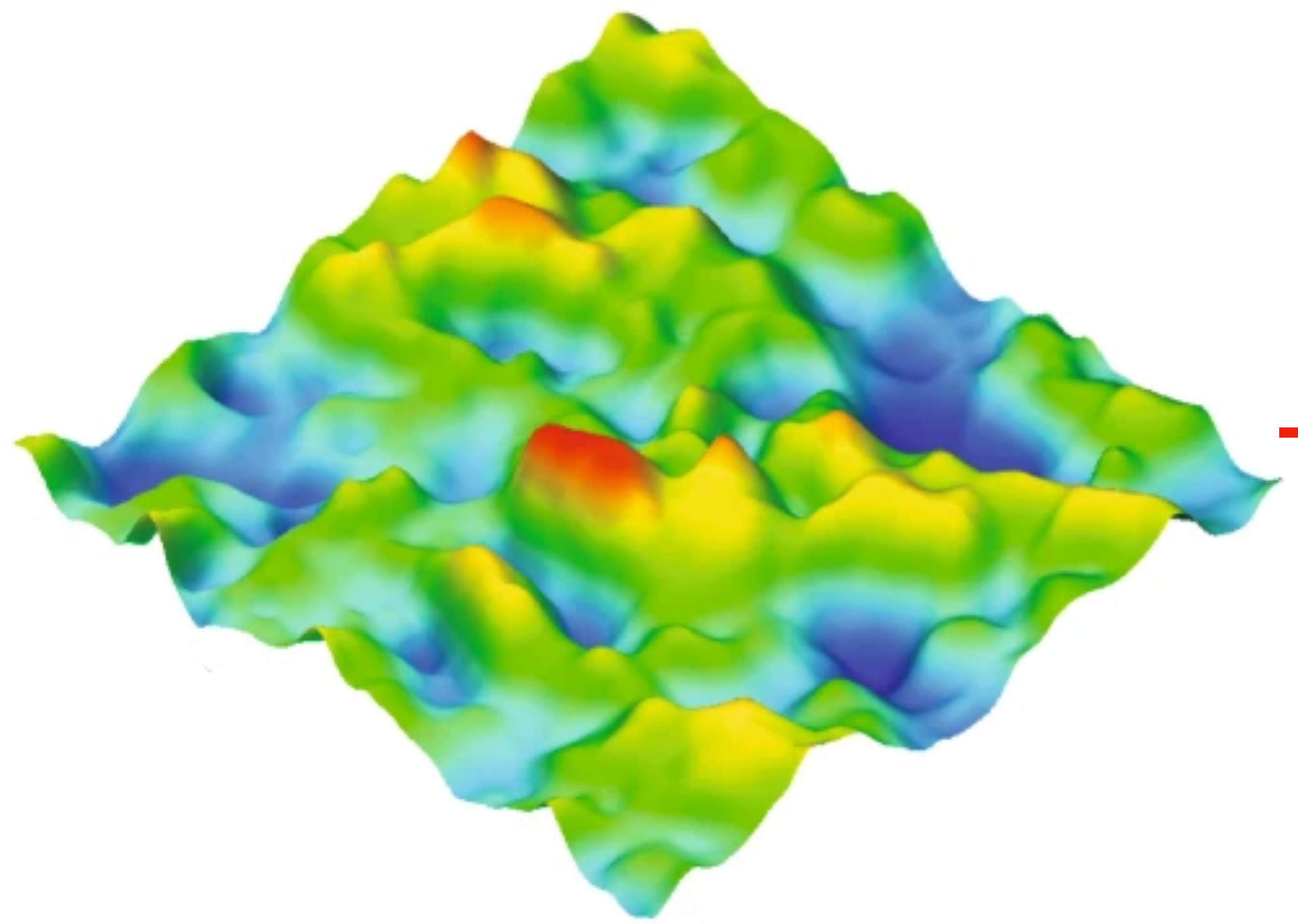

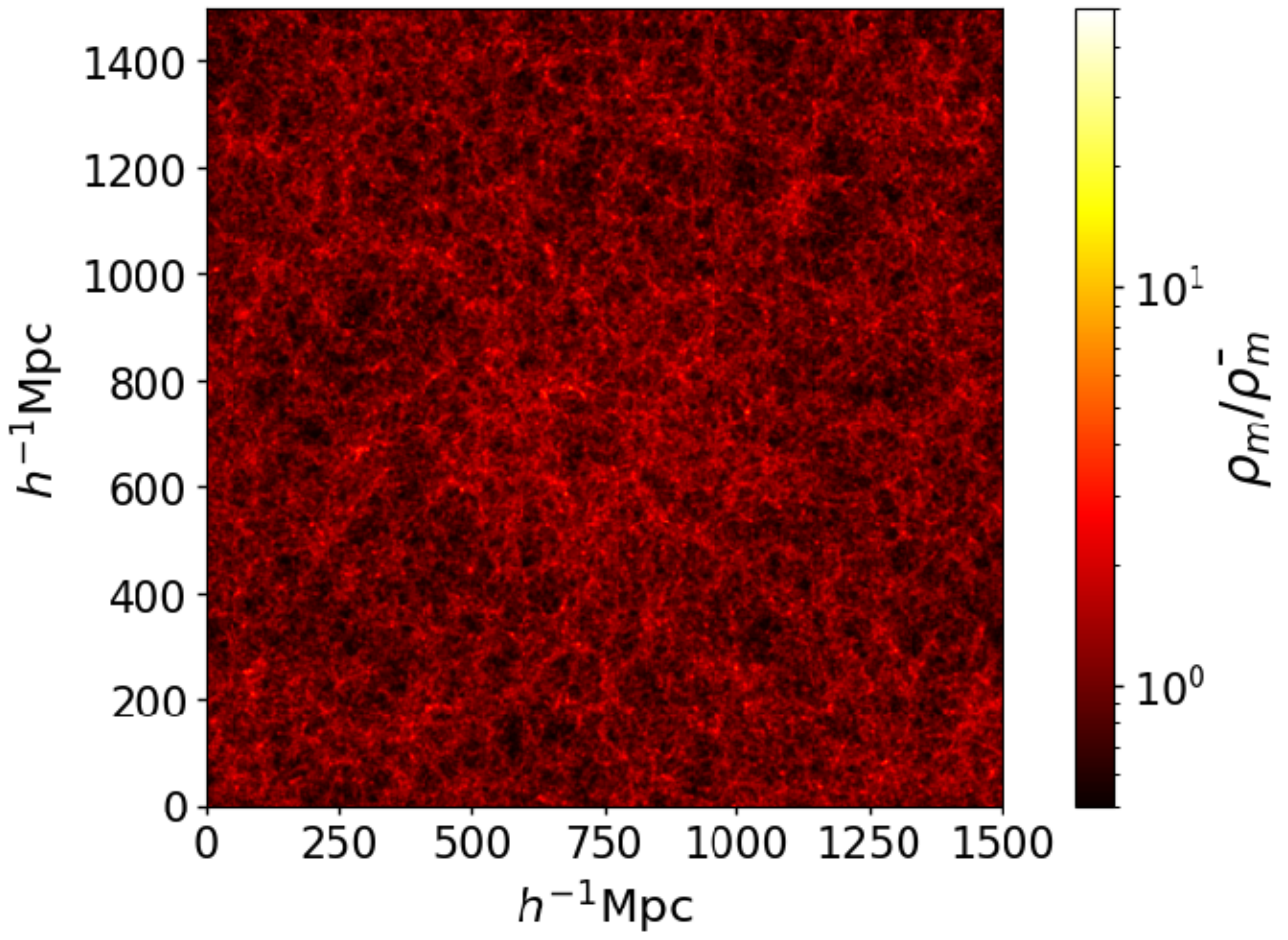

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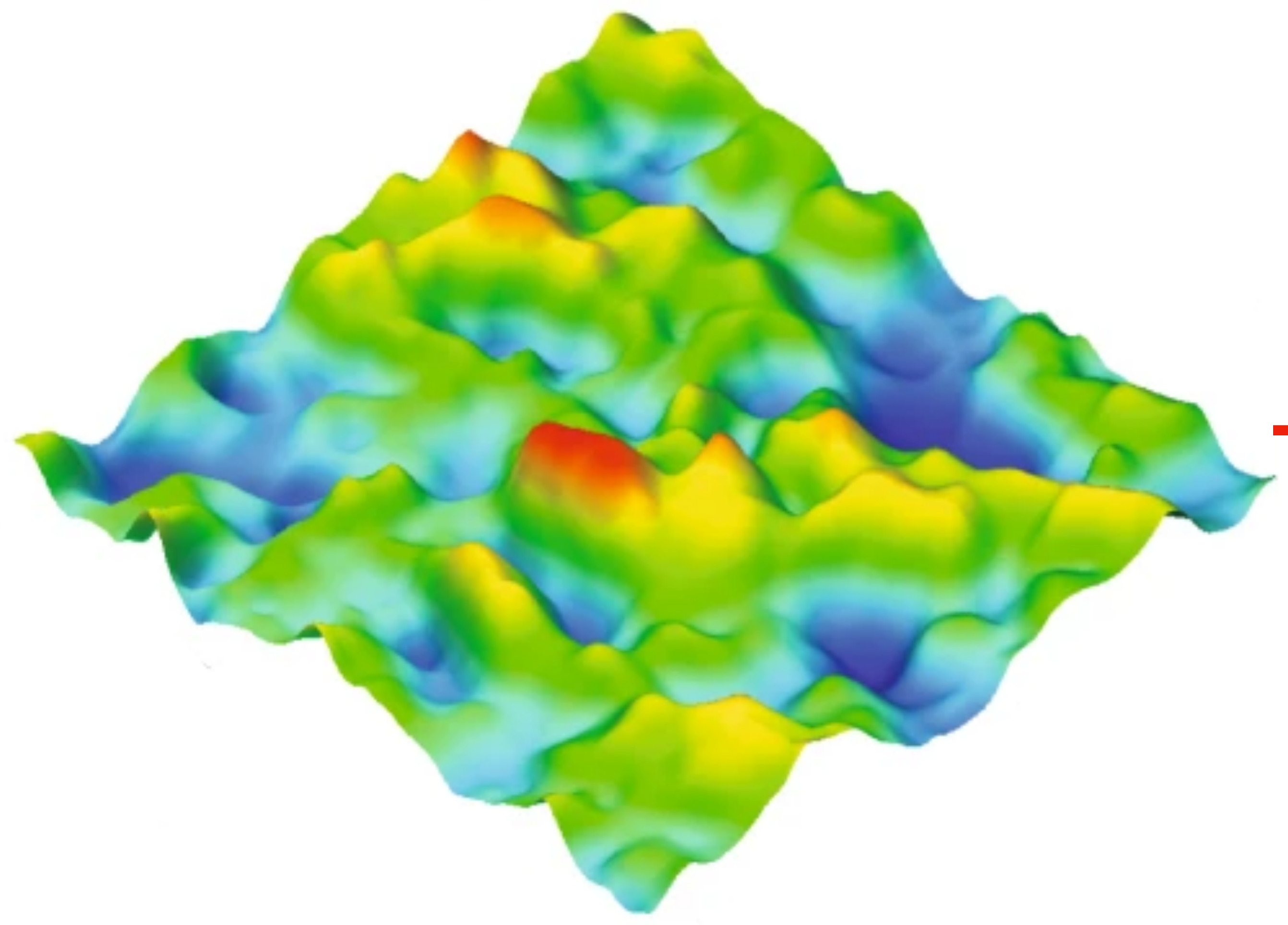
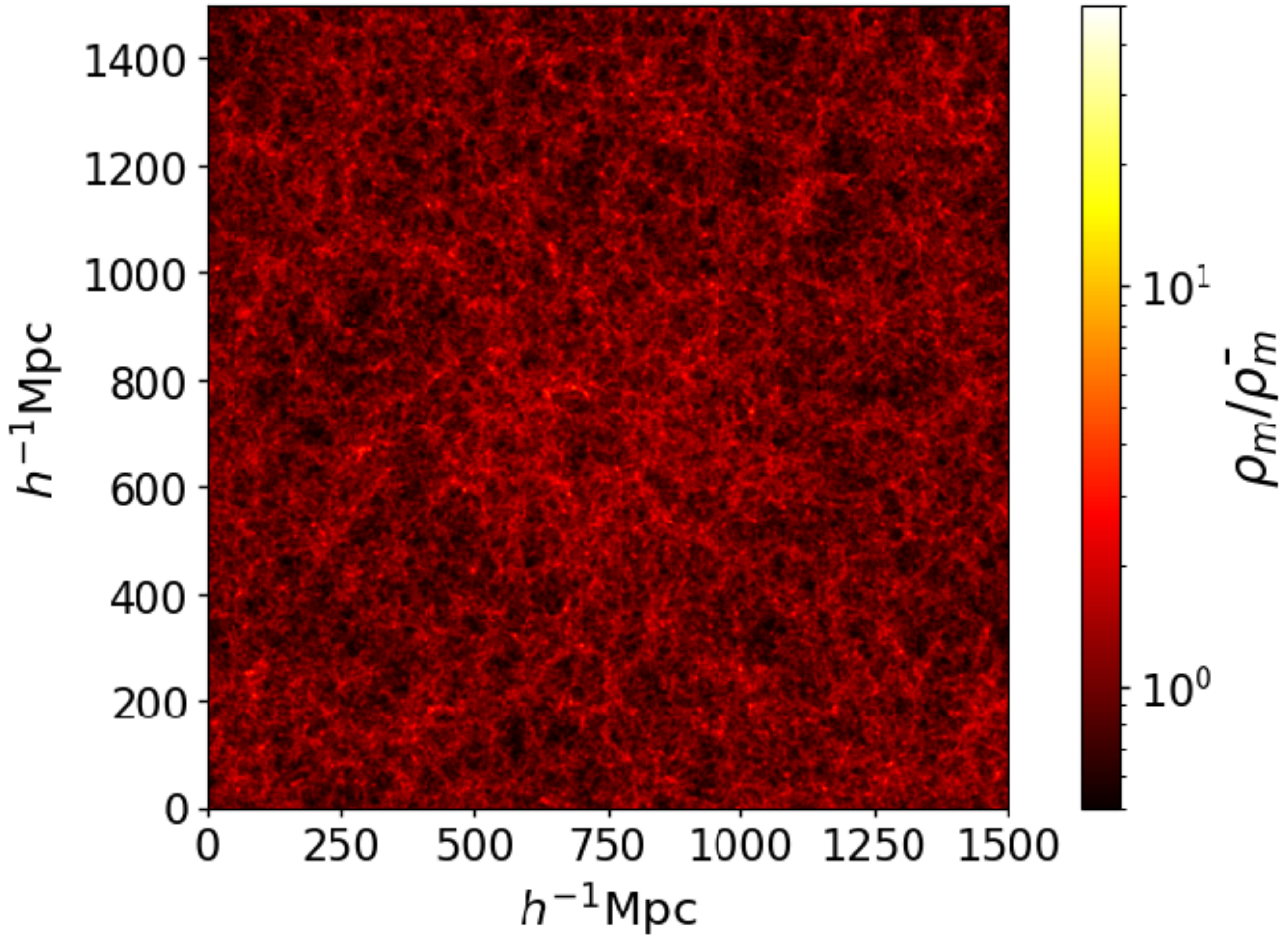
Given a nearly-invariant adiabatic power spectrum, how likely is to find these ΛLTB structure?



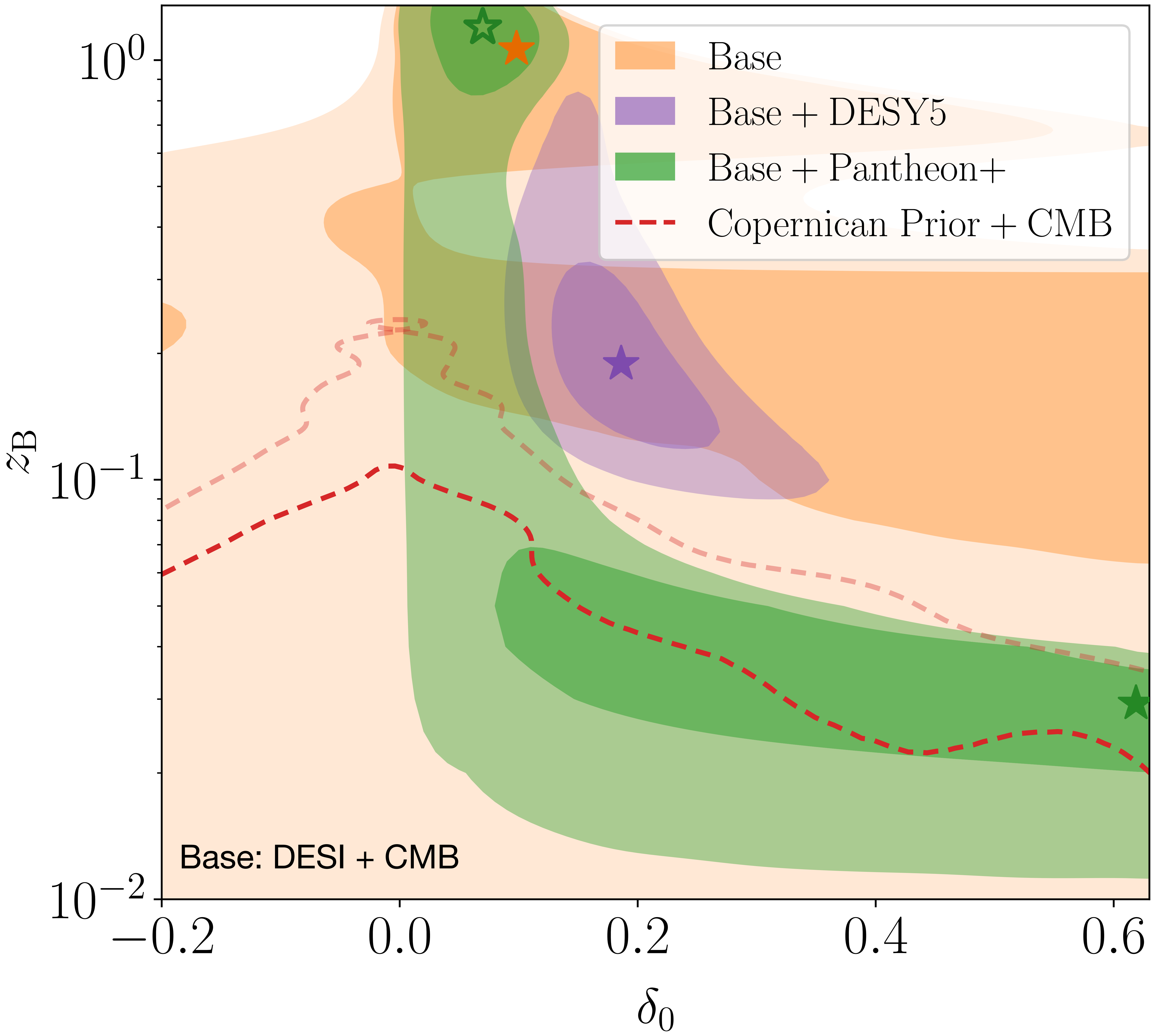


$$\sigma^2(r) = \int_0^\infty \frac{dk}{k} \Delta^2_{m0}(k) \left[\frac{3j_1(rk)}{rk}\right]^2$$

$$\mathscr{P}(\Delta, r) \propto \exp\left[-\frac{1}{2}\frac{\Delta^2(r)}{\sigma^2(r)}\right]$$

Constraints on the ΛLTB parameter space (Copernican prior)

How viable are these structures?



Conclusions

- *Non-standard features can be explained by deviation of the FLRW paradigm:* *density fluctuations impact the way we measure distances.*

- *Data allows a wide range of scenarios:* *both Copernican and non-Copernican fluctuations are allowed.*

- *Current cosmological distances favor overdense regions:* *with a significance of* 2.8σ *when considering Pantheon+ and at more than 5.2*σ *when using DESY5.*

- *Draws the attention to whether the perfectly homogeneous and isotropic FLRW paradigm can still be assumed to accurately predict cosmological distances in the era of precision cosmology.*