SEARCHING FOR MOTIVATION:

NEW PHYSICS AND THE HUBBLE TENSION

Fabrizio Rompineve, Tufts University

based on: **2006.13959**, with M. Gonzalez and M. Hertzberg

2004.05049, with G. Ballesteros and A. Notari

New England Theoretical Cosmology, Gravity and Fields Workshop,

July 21, 2020

OUTLINE

- The Hubble tension
- decaying Ultra-Light Scalars (dULS)
- Beyond GR
- Conclusions

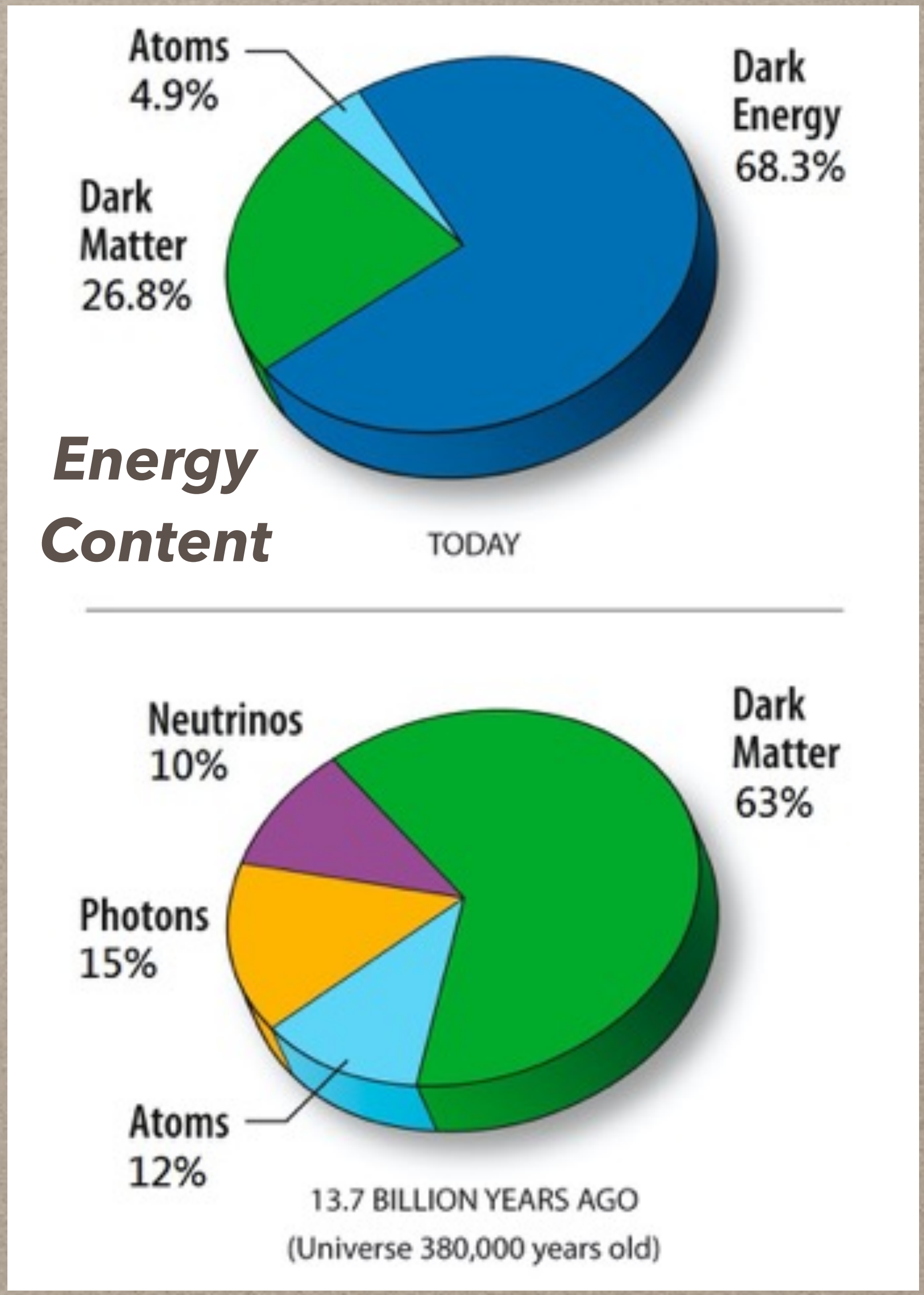
LAMBDA-CDM UNIVERSE

Flat and expanding

$$ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2$$

***Effective** picture*
is simple!

***Fundamentally**,*
we still don't understand
95% *of what is around us!*



nasa

THE HUBBLE PARAMETER

Expansion rate

$$H(t) \equiv \frac{\dot{a}}{a}$$

$$H_0 \equiv H(\text{today})$$

Measurement

Late Time

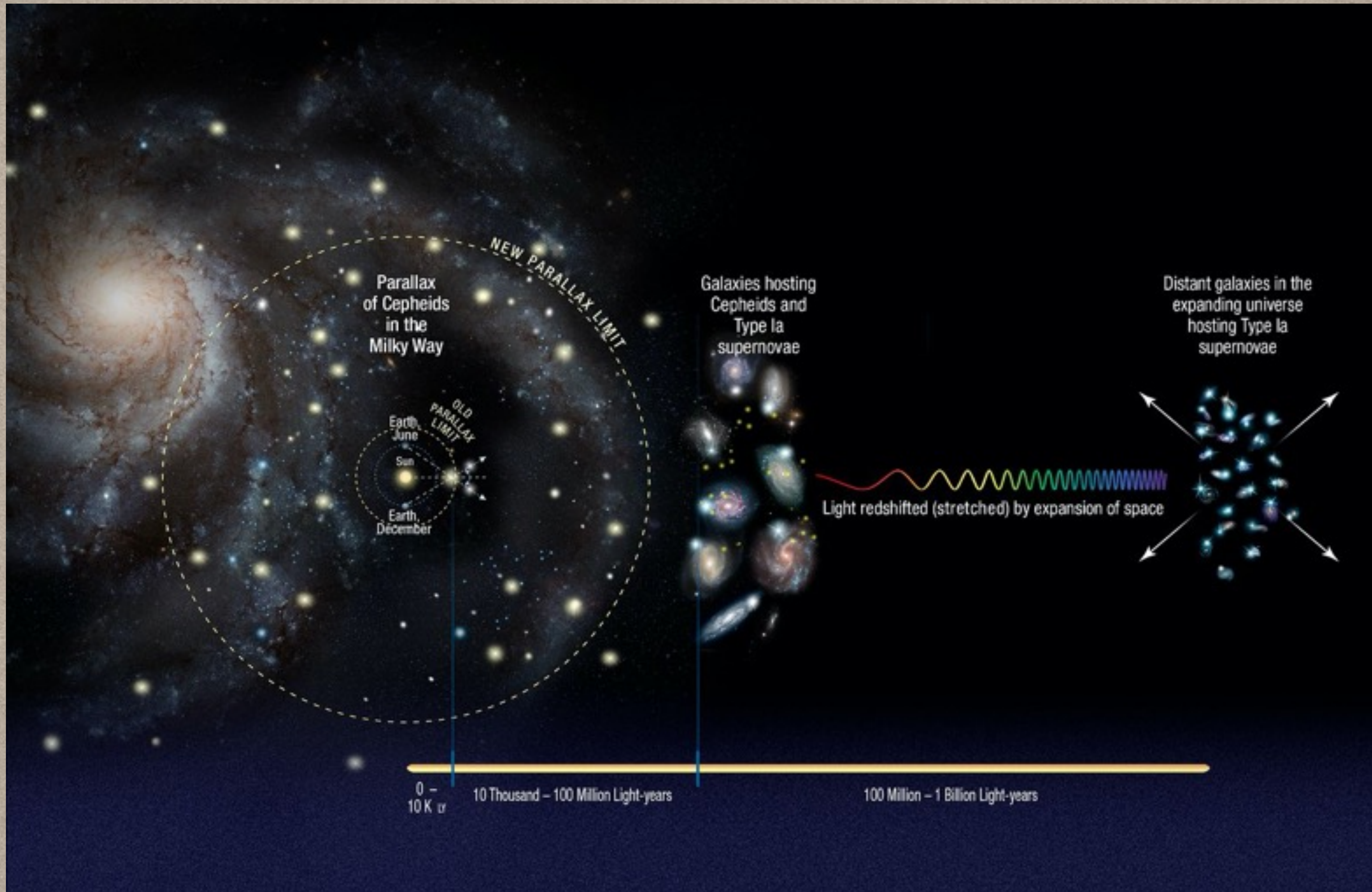
$$z \lesssim 1$$

model-independent

Early Time

$$z \sim 1000$$

model-dependent

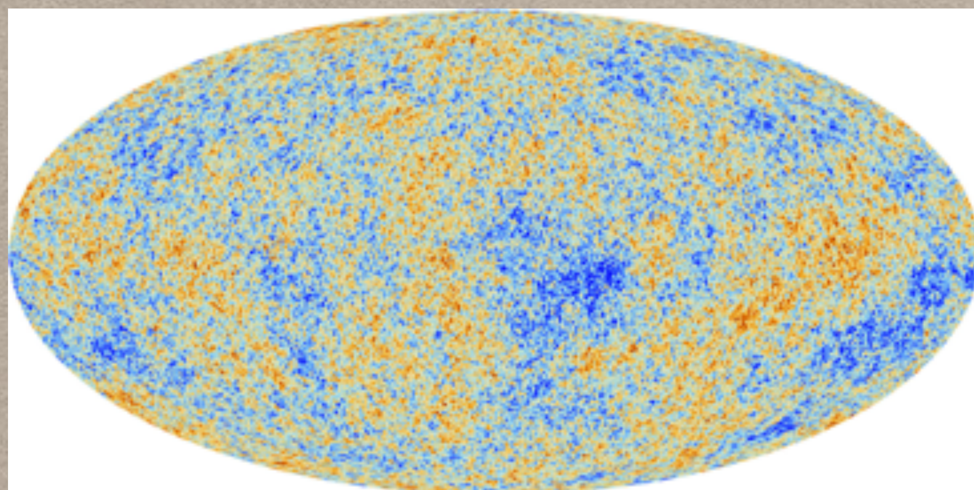


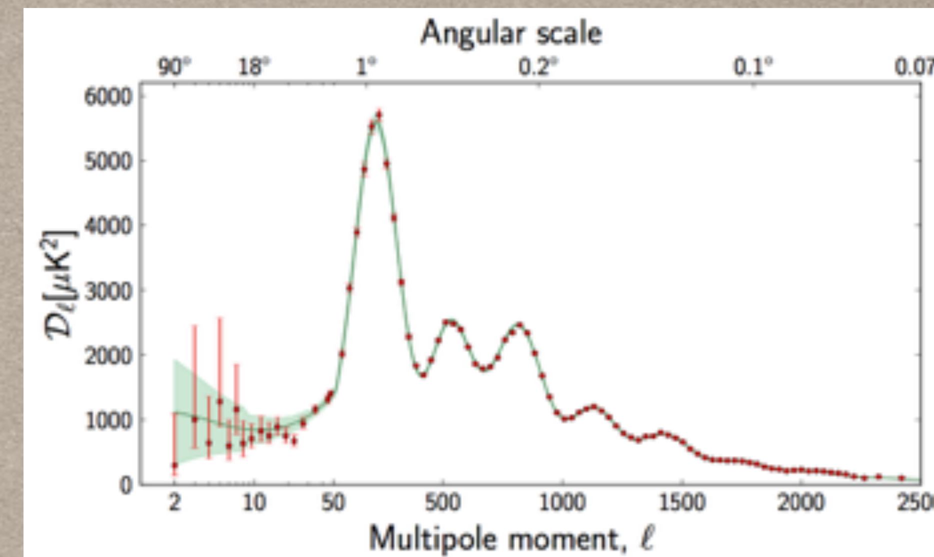
Credit:
NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

The distance ladder method

Measure redshift z and angular distance D → *Get* H_0

THE CMB





The shape of the CMB power spectrum is sensitive to variations of cosmological parameters

*By performing a **fit** of a **given model** prediction to CMB data, one infers the values of parameters, including* H_0

for details, see Knox, Millea 19

THE HUBBLE TENSION

Tension between
Planck '18 and SH0ES '19

4.4σ

Riess, Casertano, Yuan, Macri, Scolnic 19

Other late measurements tend to agree with SH0ES, but ***exceptions exist****!*

Until now, ***systematics*** *claimed to be under control.*

Motivates search for
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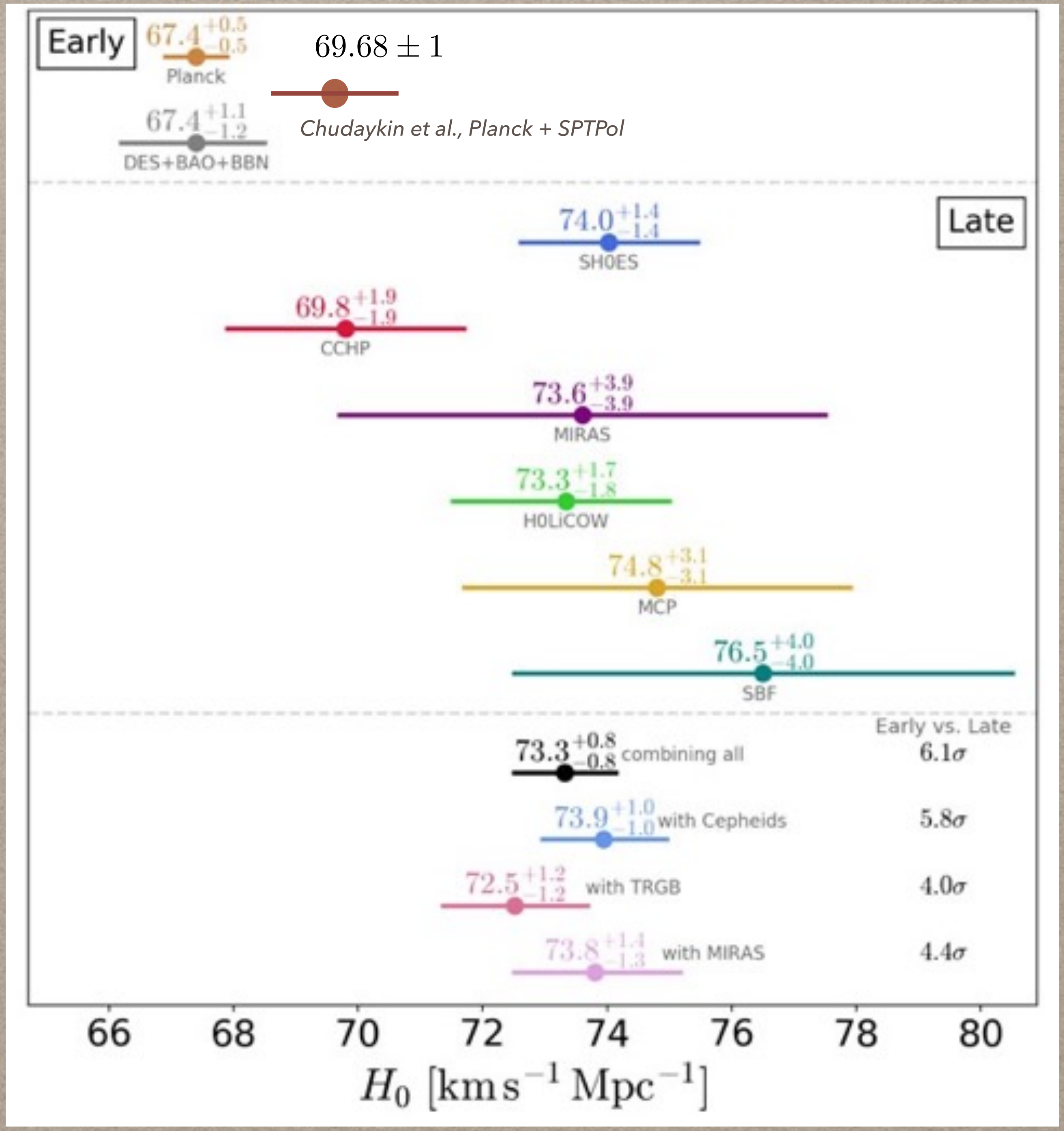
Assuming Lambda-CDM



adapted from Verde, Treu, Riess '19

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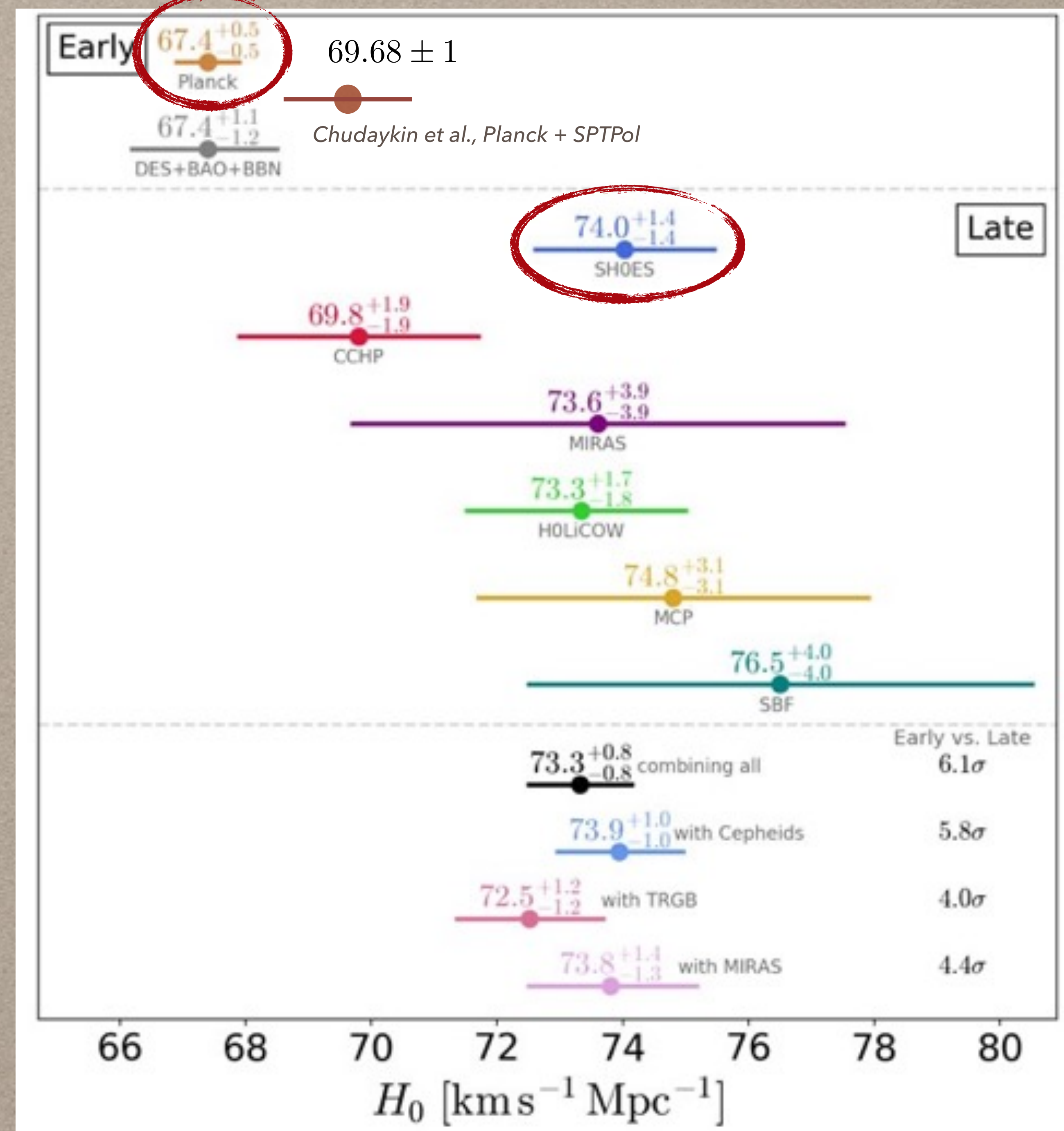

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BEYOND LAMBDA-CDM

***Early** time solutions mainly rely on **adding some extra energy before recombination** to **raise** the value of the Hubble parameter inferred from the CMB.*

Extra component should decay
*at least **as fast as radiation***
not to spoil fit to CMB

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Dark radiation

$$\Delta N_{\rm eff} = N_{\rm eff} - 3.046$$

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(Pseudo)scalar fields

with suitable potential which switches on around equality

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coincidence problem!

EARLY DARK ENERGY (EDE)

Poulin, Smith, Karwal, Kamionkowski 18

Consider axion-like field with

$$V = m^2 F^2 \left[1 - \cos\left(\frac{\phi}{F} \right) \right]^n$$

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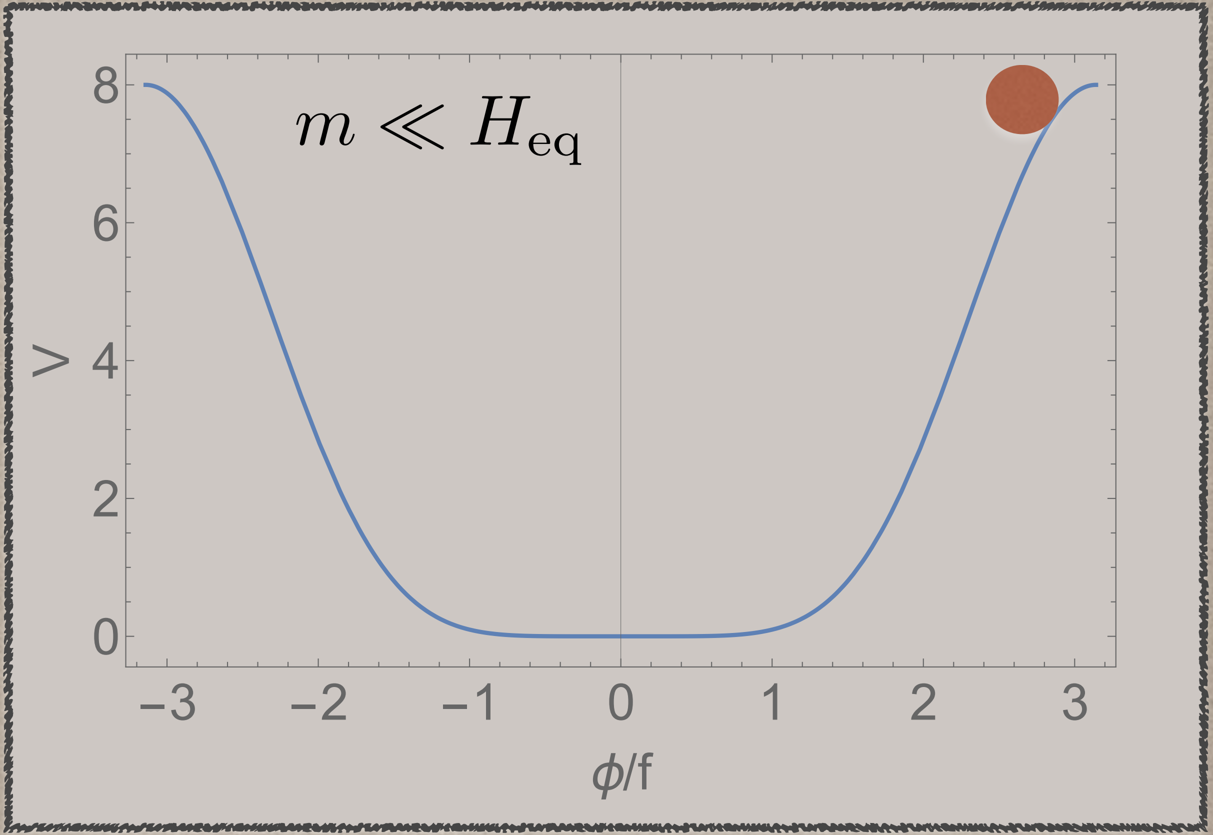

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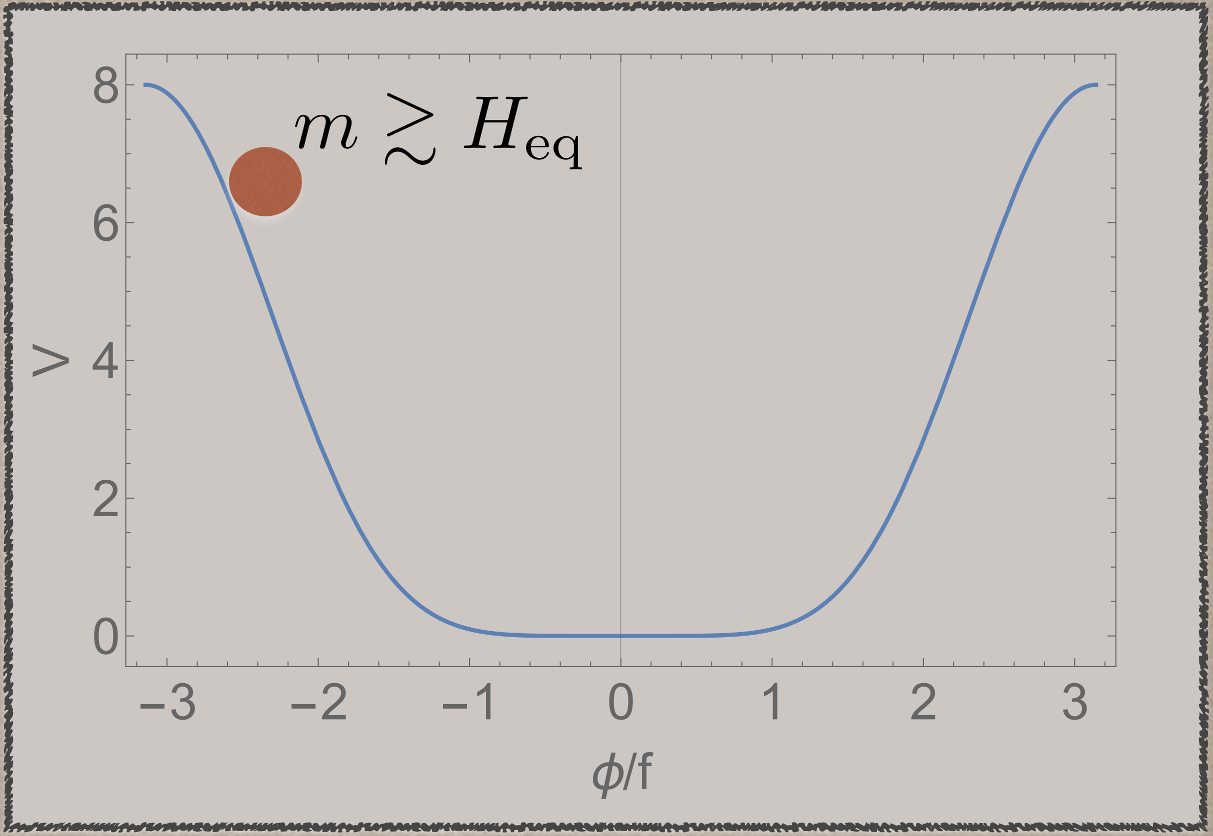

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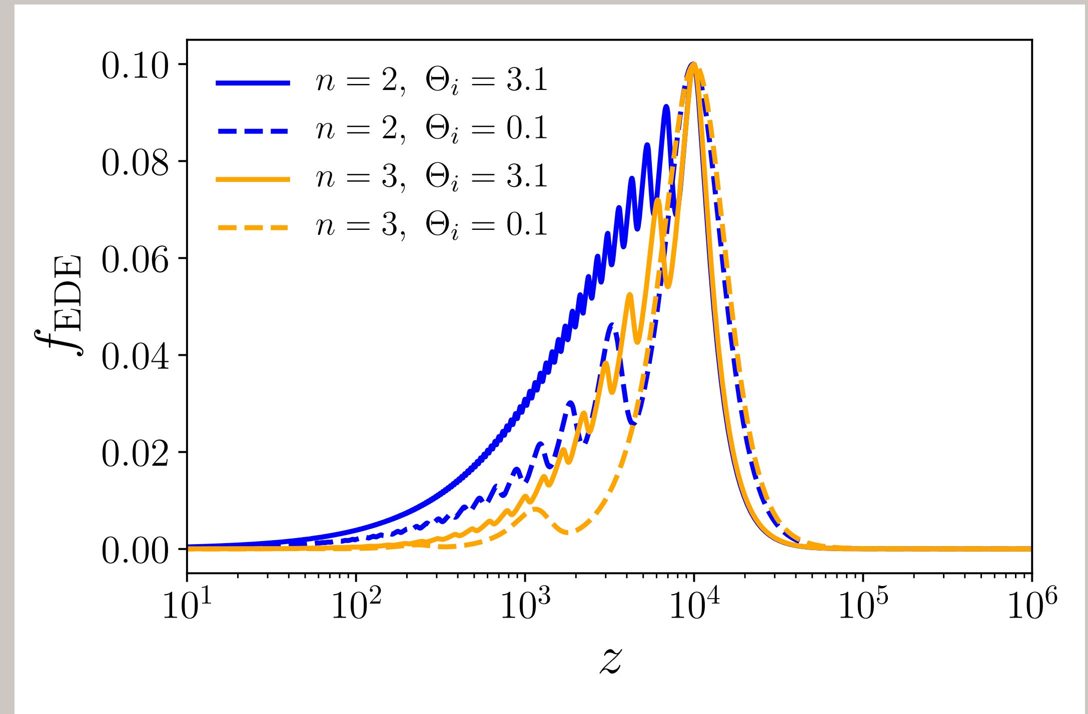
$$n = 3$$

$$m \sim H_{\rm eq}, F \sim 0.1\ M_p$$

provides best-fit to Planck+BAO+Pantheon+SH0ES



Smith, Poulin, Amin 19

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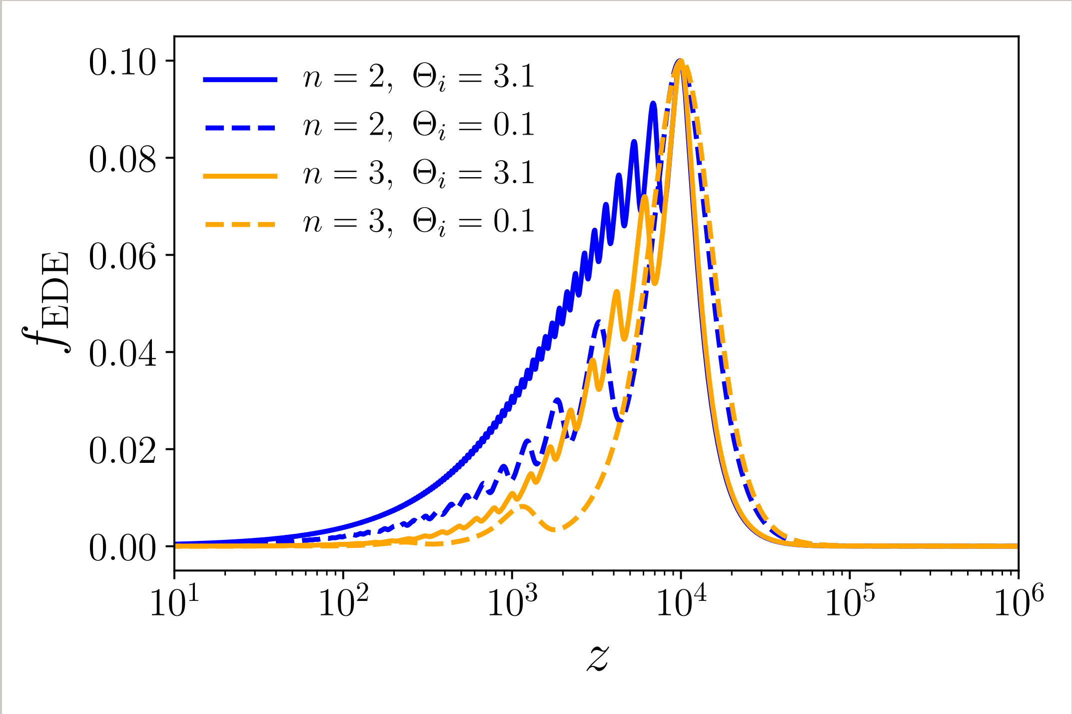

Smith, Poulin, Amin 19

Caveat: *Large Scale Structure (LSS) data constrains improvement over Lambda-CDM!*

see talk by Evan later today!

` S_8 tension'

Poulin, Smith, Karwal, Kamionkowski 18
Agrawal, Cyr-Racine, Pinner, Randall 19
Hill, McDonough, Toomey, Alexander 20

Recent addition of BOSS full-shape

Ivanov, McDonough, Hill, Simonovic, Toomey, Alexander, Zaldarriaga 20
D'Amico, Senatore, Zhang, Zheng 20

SEARCHING FOR MOTIVATION

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model-building perspective

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Can better-motivated models convincingly address the tension?

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EDE POTENTIAL

In general, for a field with a discrete shift-symmetry (axion)

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$$V(\phi) \sim [1 - \cos(\phi/f)]^3 \longrightarrow \begin{array}{c} c_2/c_1 = -2/5,\ c_3/c_1 = 1/15 \\ c_{i>3} = 0 \end{array}$$

Poulin, Smith, Karwal, Kamionkowski 18

conspiracy among harmonics hides severe tuning!

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CAN ONE USE A WELL-BEHAVED EFT?

Here instead we want to keep the standard axion potential

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to make the axion decay into (dark) gauge fields!

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RESONANT DECAY

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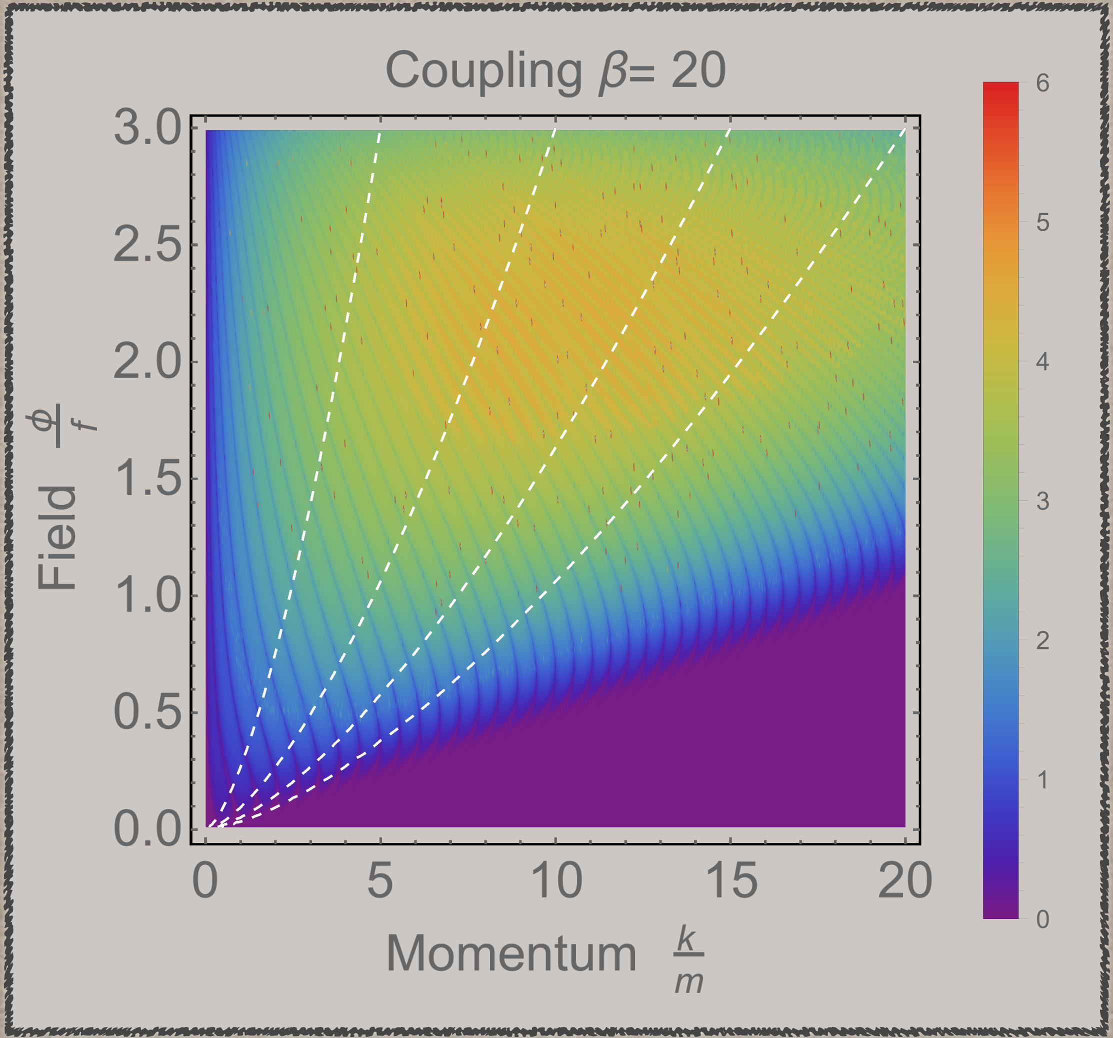

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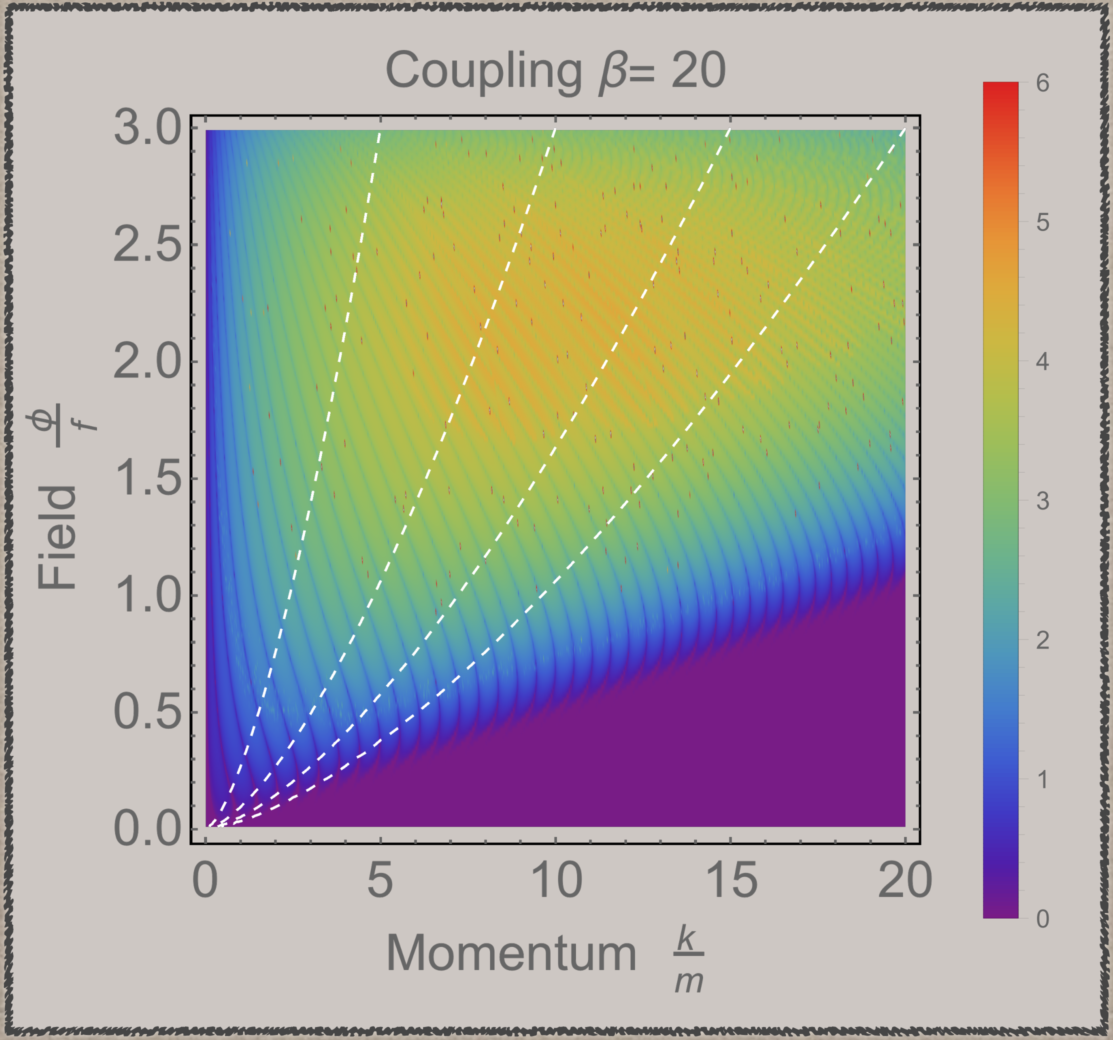
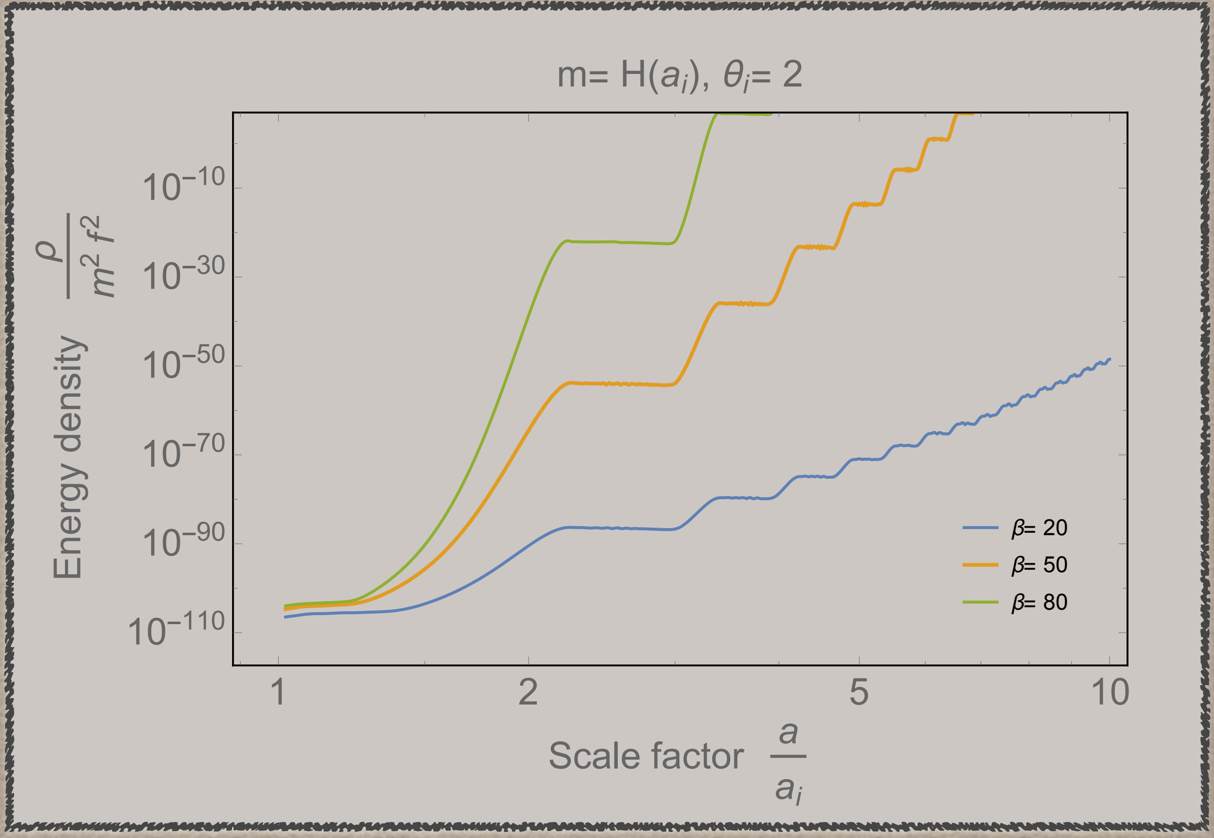


Energy density in gauge fields



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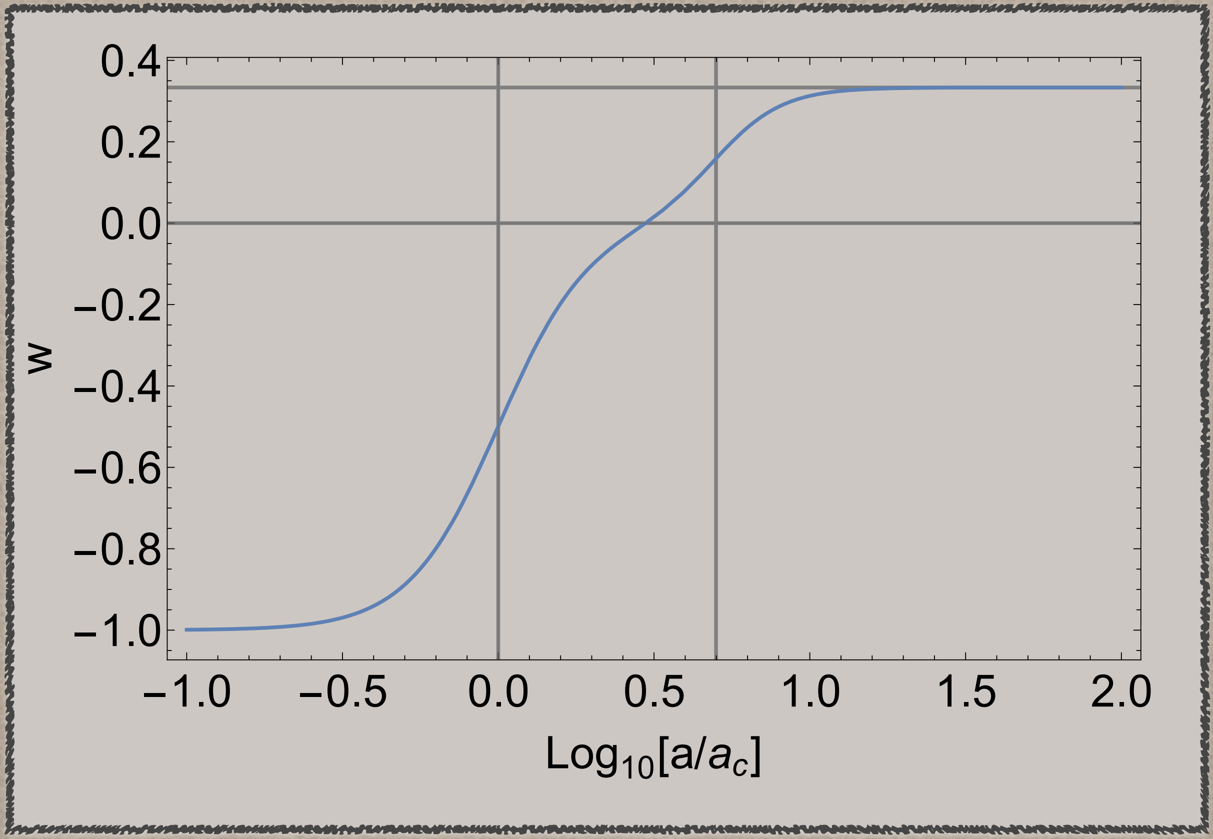

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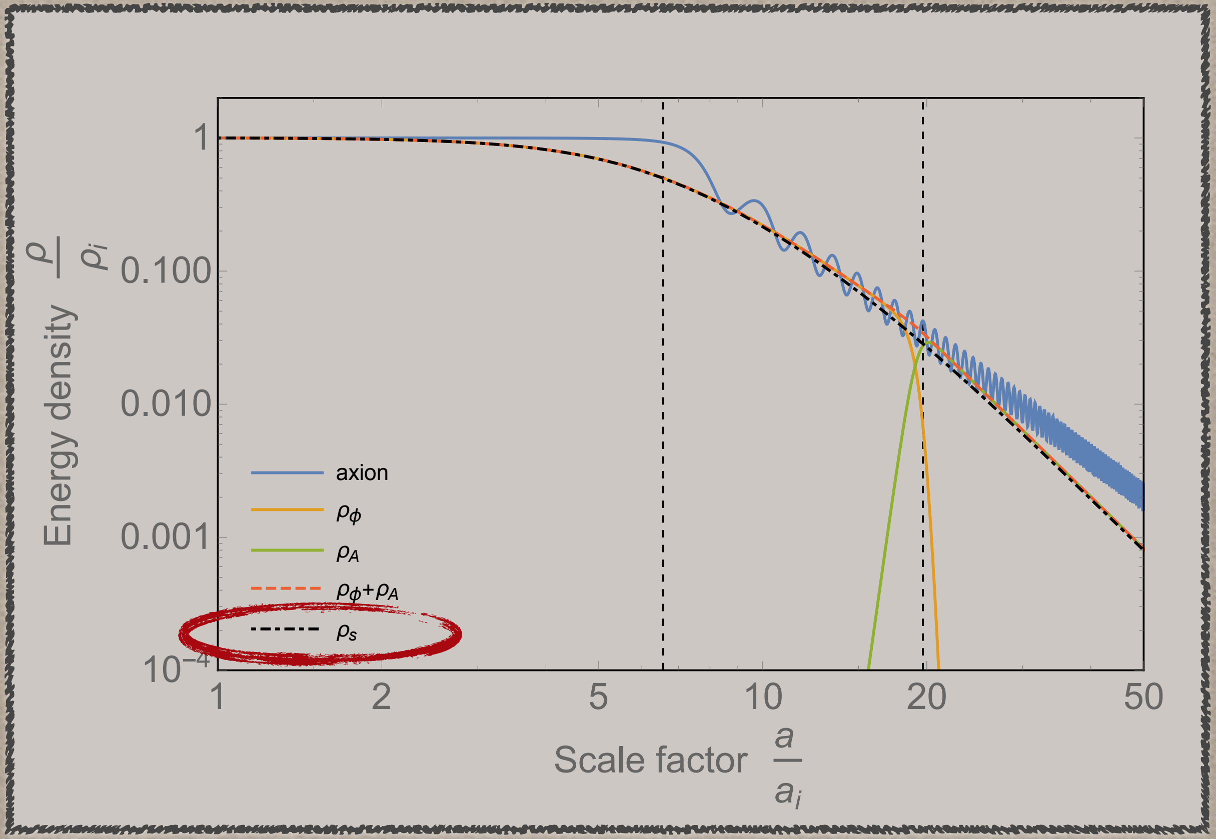

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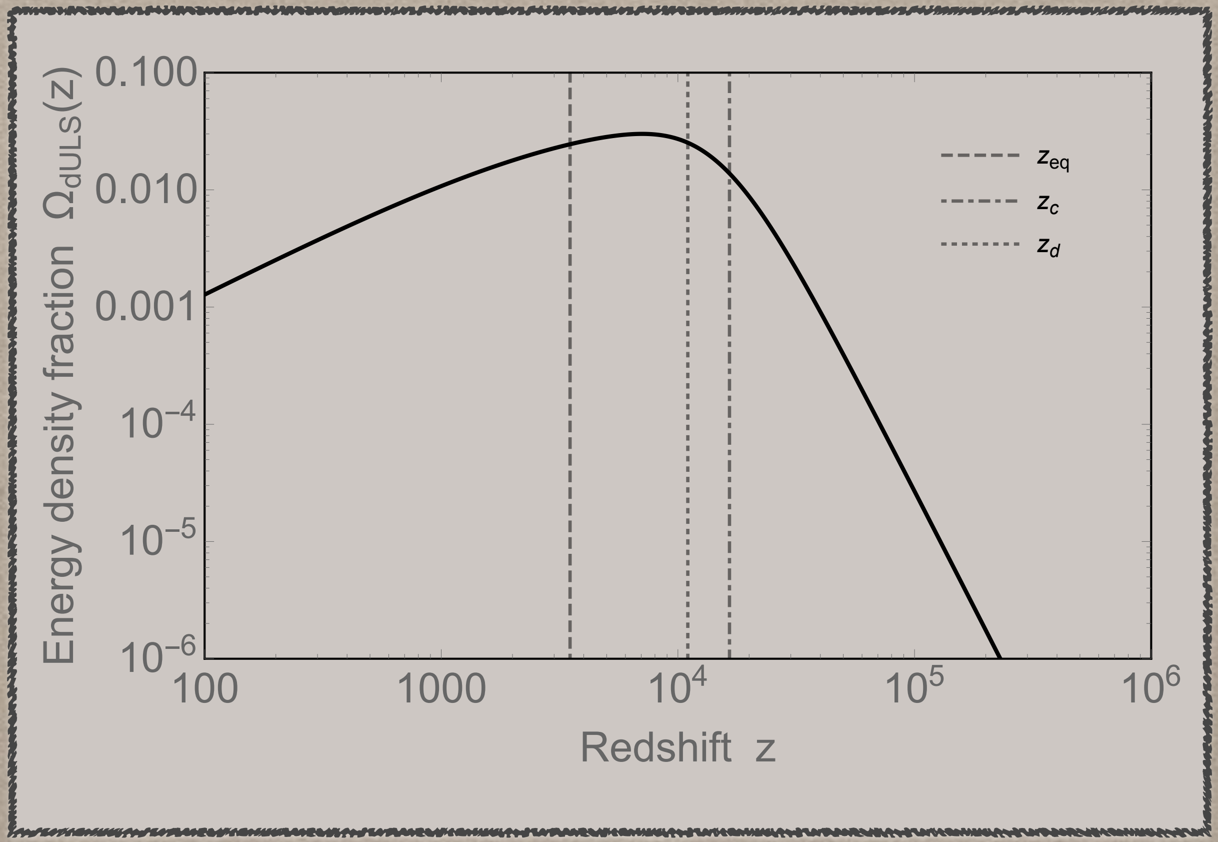

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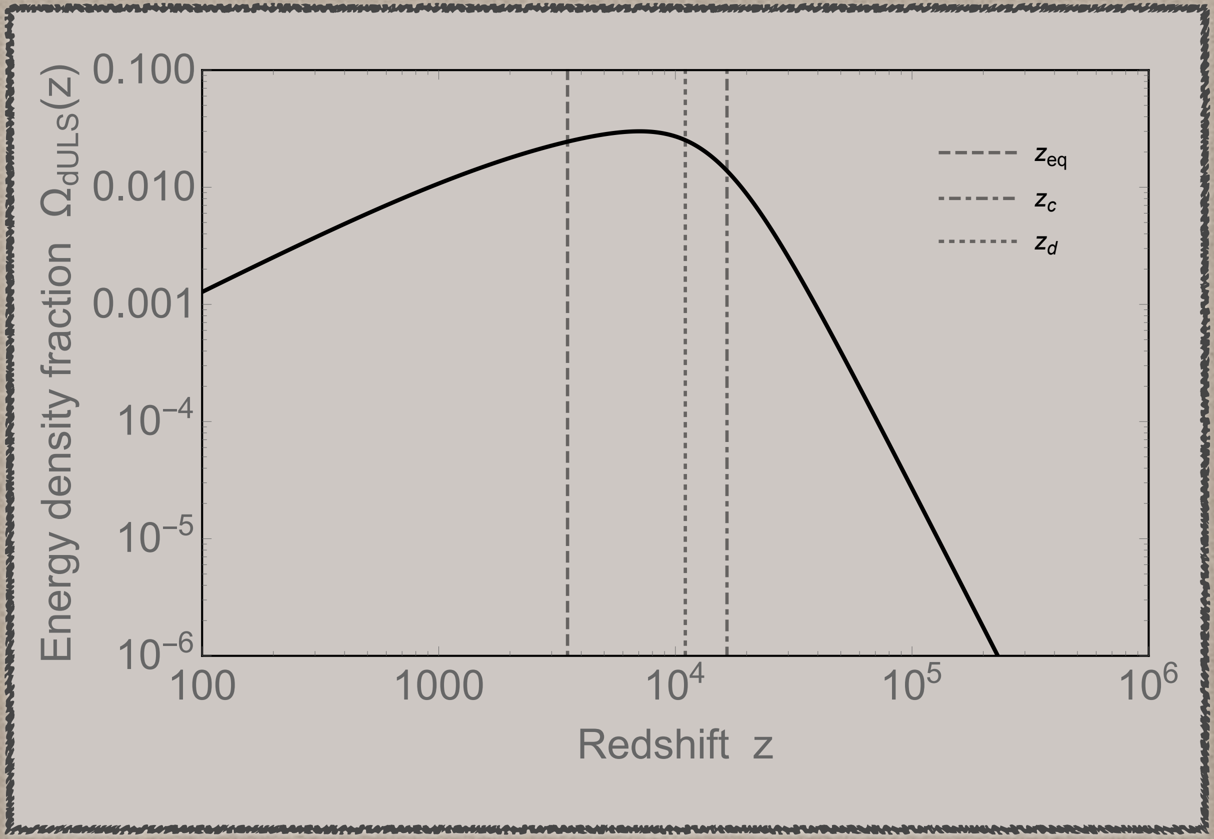

Treatment of perturbations is more subtle.
We used a simplified picture with sound speed tracking the equation of state parameter

RESULTS

Dataset: Planck 18 + BAO + Pantheon + SH0ES 19

Parameter	ΛCDM	dULS	$\Delta N_{\rm eff}$
$100\ \omega_b$	$2.254\ (2.26)^{+0.013}_{-0.014}$	$2.261\ (2.249)^{+0.019}_{-0.019}$	$2.272\ (2.268) \pm 0.017$
$\omega_{\rm cdm}$	$0.1183\ (0.1189)^{+0.00087}_{-0.00092}$	$0.1232\ (0.124)^{+0.0023}_{-0.0024}$	$0.1235\ (0.123)_{\pm}0.0029$
$10^9 A_s$	$2.122\ (2.123)^{+0.03}_{-0.035}$	$2.138\ (2.143)^{+0.035}_{-0.04}$	$2.147\ (2.135)^{+0.033}_{-0.036}$
n_s	$0.97\ (0.9699)^{+0.0038}_{-0.0036}$	$0.9812\ (0.9822)^{+0.0079}_{-0.0085}$	$0.9793\ (0.98) \pm 0.0062$
$\tau_{\rm reio}$	$0.06053\ (0.06027)^{+0.007}_{-0.0084}$	$0.06042\ (0.05883)^{+0.0079}_{-0.0086}$	$0.0604\ (0.05753)^{+0.0072}_{-0.0081}$
H_0	$68.24\ (68.06) \pm 0.41$	$69.69\ (69.67)^{+0.81}_{-0.83}$	$69.96\ (69.82)^{+0.98}_{-1}$
$10^6 \Omega_{\rm dULS}/\Delta N_{\rm eff}$	–	$7.387\ (9.021)^{+2.9}_{-3}$	$0.3107\ (0.2865)^{+0.16}_{-0.17}$
$10^5 a_c$	–	$4.526\ (6.053)^{+2.4}_{-2.5}$	–
g_d	–	fixed to 1.5	–
σ_8	$0.8097\ (0.8119)^{+0.0061}_{-0.0067}$	$0.8231\ (0.8251)^{+0.0094}_{-0.01}$	$0.8245\ (0.8215) \pm 0.01$
$\Delta\chi^2$	0	-7.92	-2.78

Table I. The mean (best-fit in parenthesis) $\pm 1\sigma$ error of the cosmological parameters obtained by fitting ΛCDM, the dULS and the $\Delta N_{\rm eff}$ models to our combined cosmological dataset.

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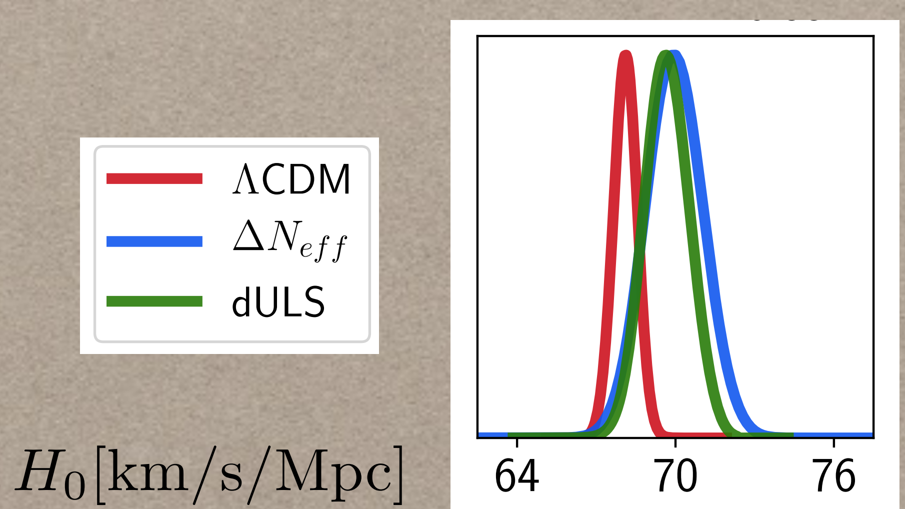

Very similar to dark radiation, but significantly improved χ^2

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Concrete UV setups to generate such a large coupling require
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see e.g. Kim, Nilles, Peloso 04/…/
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↓

Take home:
*Scenarios of **EDE/dULS***
*do not **convincingly** address*
the Hubble tension.

A DIFFERENT ATTEMPT: BEYOND GR 2004.05049

*EDE/dULS models feature a **coincidence problem**:*
*why should a dynamical transition occur **at equality**?*

A simple theory where such a transition occurs
naturally around equality is that of a
non-minimally coupled scalar

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left[M^2 f(\phi)R + \partial_\mu\phi\partial^\mu\phi + L_{\rm tot}\right]$$

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non-minimally coupled scalar

Matter, radiation, cosmological constant

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left[M^2 f(\phi)R + \partial_\mu\phi\partial^\mu\phi + L_{\rm tot}\right]$$

$$f(\phi) = 1 + \beta\left(\frac{\phi}{M}\right)^2$$

with $\beta < 0$

A DIFFERENT ATTEMPT: BEYOND GR 2004.05049

EDE/dULS models feature a ***coincidence problem****:*
why should a dynamical transition occur ***at equality****?*

A simple theory where such a transition occurs naturally around equality is that of a ***non-minimally coupled scalar***

Matter, radiation, cosmological constant

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left[M^2 f(\phi)R + \partial_\mu\phi\partial^\mu\phi + L_{\rm tot}\right]$$

e.g.

$$f(\phi) = 1 + \beta\left(\frac{\phi}{M}\right)^2$$

with $\beta < 0$

Variation of Newton constant from early time to today

$$\Delta G_{\rm N} \approx \beta\phi^2$$

see also Lin et al. 18/Rossi et al/Solá et al/ Sakstein et al. 19/Zumalacarregui 20/… for related ideas

DYNAMICAL TRANSITION AROUND EQUALITY

$$\ddot{\phi} + 3H\dot{\phi} - \beta R\phi = 0 \quad \text{with} \quad R = 6\dot{H} + 12H^2$$

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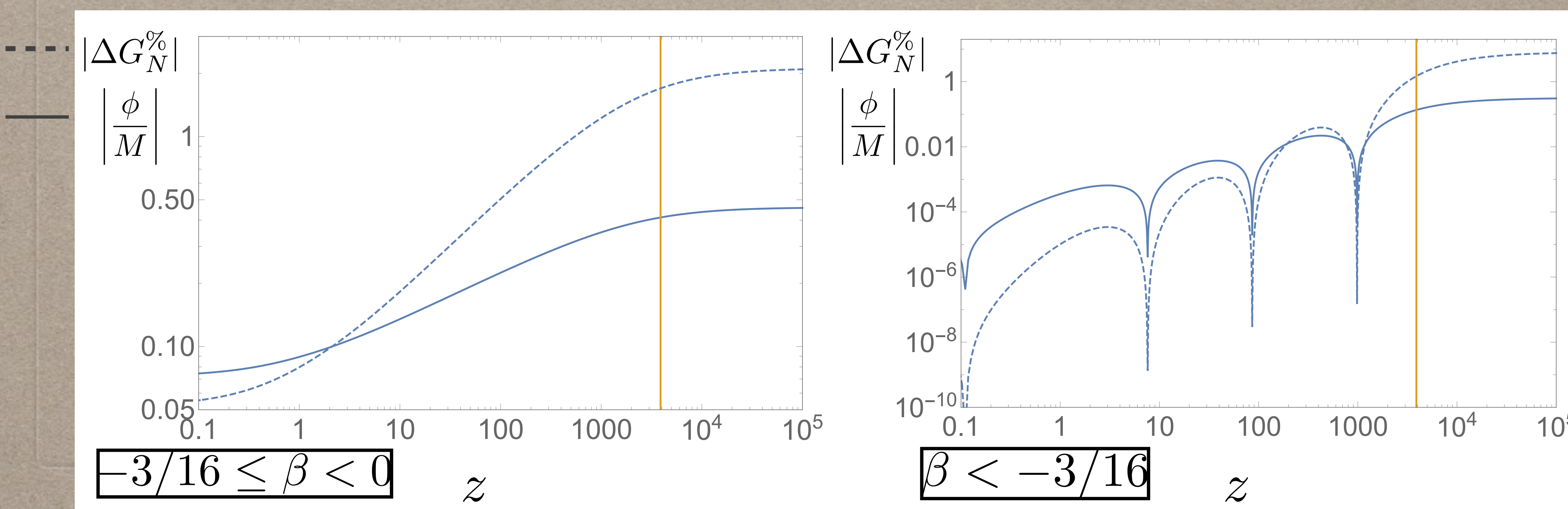

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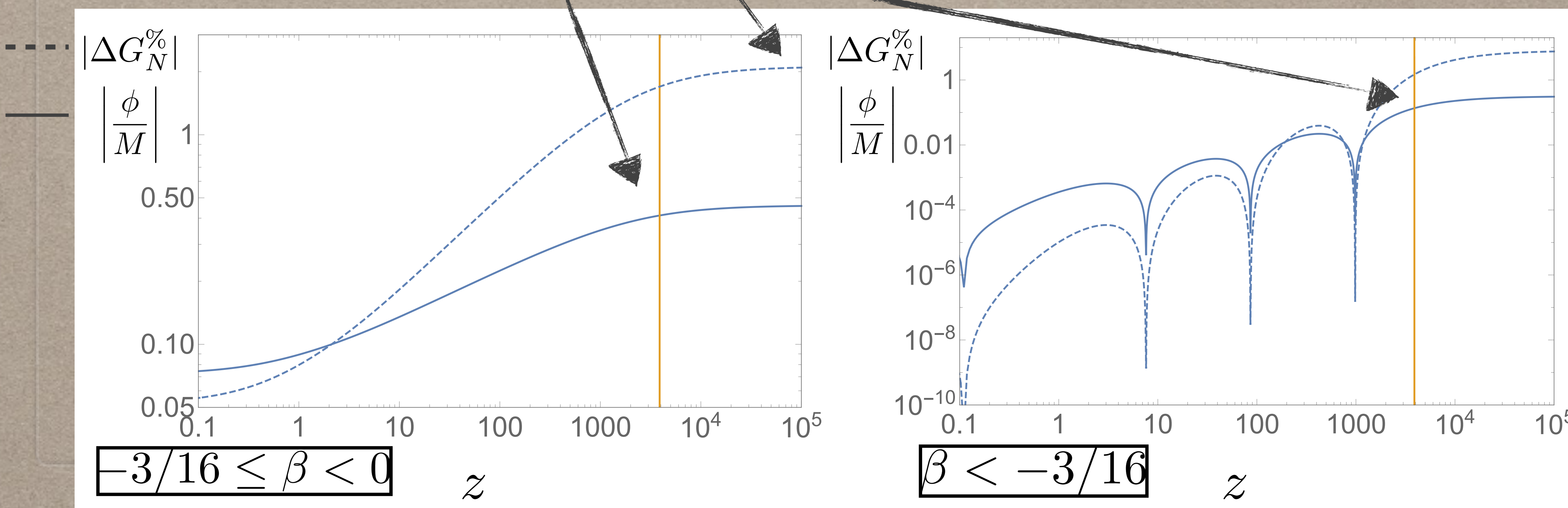

DISCUSSION

Fit to CMB gives results similar to
dark radiation when neglecting post-newtonian constraints
(screening mechanisms? late time dynamics of the field?)

see **2004.05049** for details

Constraints from LSS?

CONCLUSIONS

- Hubble tension may hint at additional **complexity** beyond Lambda-CDM.
- **Early Dark Energy (EDE)** models require **tuned UV setups**.
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Evidence that EDE/dULS models not convincingly address Hubble tension!

(complementary to LSS-driven constraints)

- **Non-minimally coupled scalars** explain why dynamical transition occurs around equality!
- **However**, tension is only alleviated in simple models.

THE SEARCH CONTINUES

Thank you for the attention!

BACKUP

RESONANT DECAY

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

caveat: neglect back reaction!

see Kitajima, Sekiguchi, Takahashi 17

$$\ddot{\mathbf{A}} + H\dot{\mathbf{A}} - \frac{\nabla^2}{a^2}\mathbf{A} + \frac{\beta}{f}\ \dot{\phi}\frac{\nabla}{a} \times \mathbf{A} = 0$$

in Fourier space

$$\ddot{s}_{\mathbf{k},\pm} + H\dot{s}_{\mathbf{k},\pm} + \left[\left(\frac{k}{a}\right)^2 \mp \frac{k}{a}\frac{\beta}{f}\dot{\phi}\right] s_{\mathbf{k},\pm} = 0$$

Tachyonic resonance

Effective frequency

$$\omega_k^2 \equiv k(k \mp \beta/f\dot{\phi})$$

can go negative

Parametric resonance

see Floquet bands where

$$s_{\mathbf{k},\pm} \sim e^{\mu_k t} P(t)$$

$$\mu_k > 0$$

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RESONANT DECAY

Energy in the gauge fields

$$\rho_A = \frac{1}{2a^4} \int \frac{d^3k}{(2\pi)^3} \sum_{\pm} \left(a^2 |\dot{s}_{\pm}|^2 + k^2 |s_{\pm}|^2 - 2k \right)$$

SCALAR RESONANT DECAY

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{2}\epsilon\phi\chi^2$$

Efficient resonant decay for $\epsilon \gg \frac{m^2}{\phi_i}$ *fine, since* $m \ll f$

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However, *how to justify lightness of* χ *?*

$$\mathcal{L}_{\rm UV} = |\partial\Phi|^2 - \lambda(|\Phi|^2 - v^2)^2$$

with $\Phi = v + (\phi + i\chi)/\sqrt{2}$

then $m = \sqrt{2\lambda}v, \quad \epsilon = 2\lambda v$

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then $m = \sqrt{2\lambda}v, \quad \epsilon = 2\lambda v$

and condition above requires $|\phi_i| \gg v$ ***standard resonance analysis does not apply!***

NON-MINIMALLY COUPLED SCALAR

Scalings

When writing Friedmann equation as

$$3H^2 M^2 = \rho_\phi + \rho_{\rm tot}$$

one finds

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 - 6\beta H \dot{\phi}\phi - 3\beta H^2 \phi^2$$

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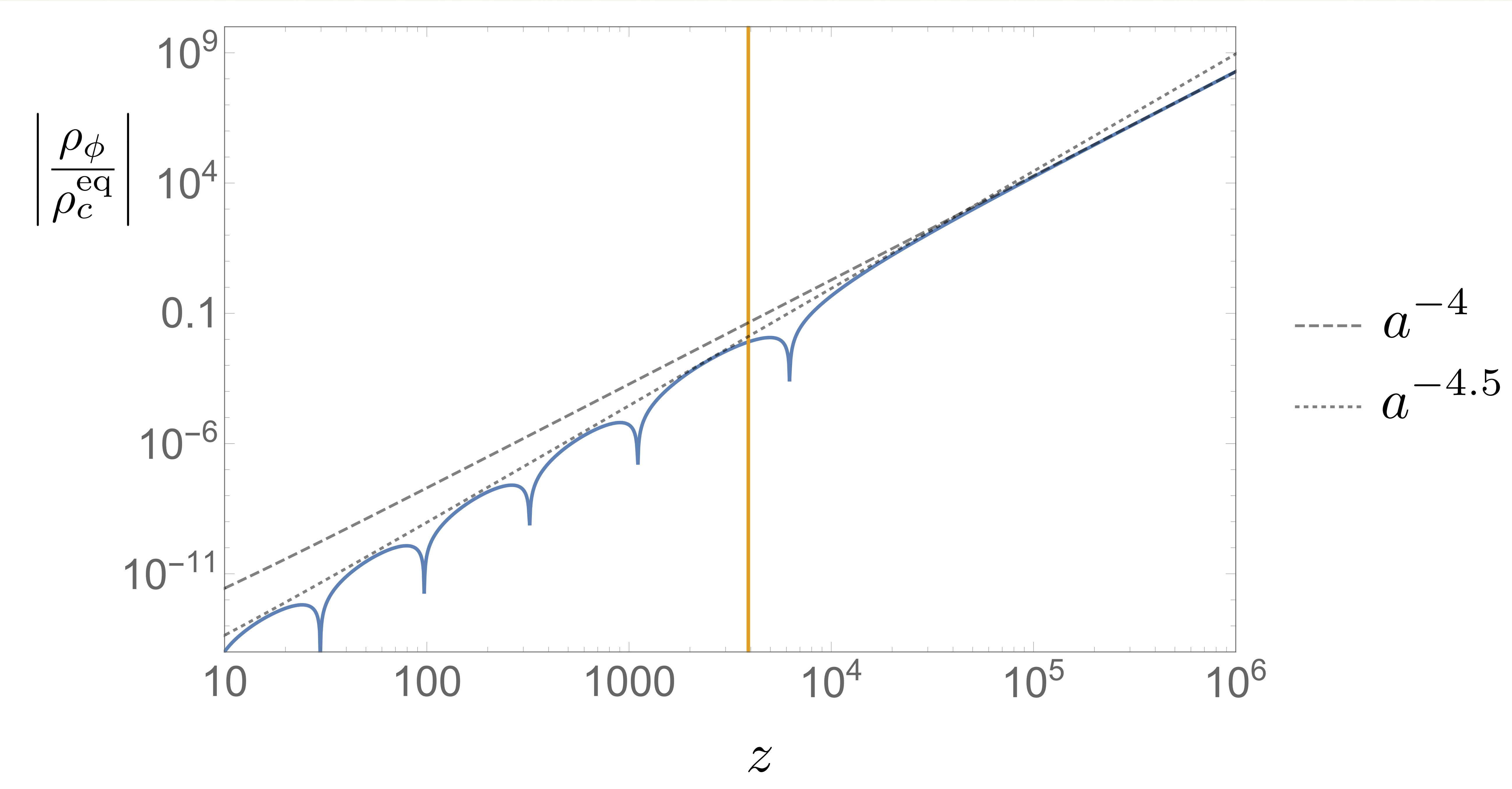
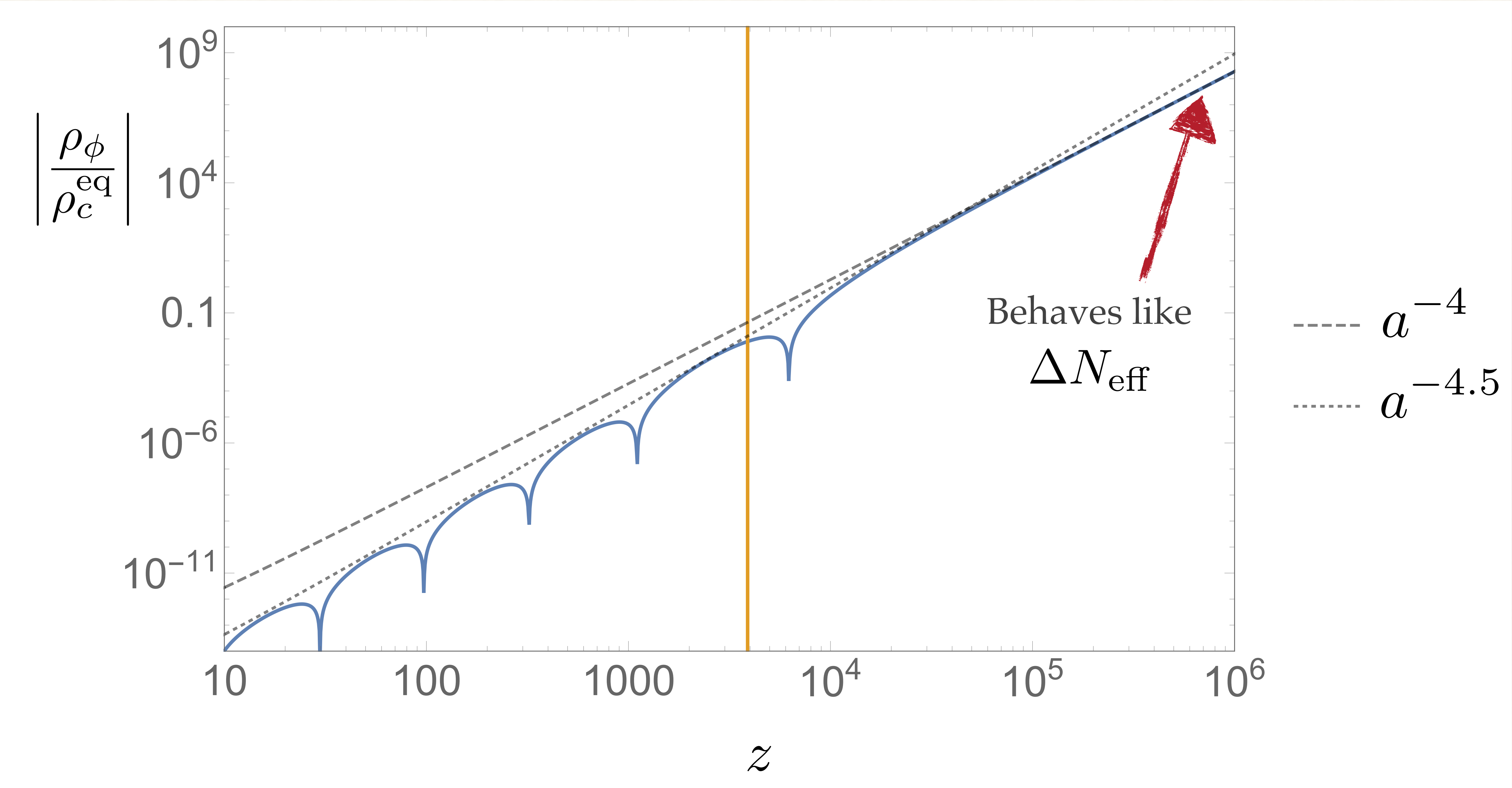
After equality

$$\rho_\phi \sim a^{-9/2}$$

Scalings


$\left|\frac{\rho_\phi}{\rho_c^{\rm eq}}\right|$
10^9
10^4
0.1
10^{-6}
10^{-11}
10
100
1000
10^4
10^5
10^6
z
a^{-4}
$a^{-4.5}$

Scalings



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100
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10^4
10^5
10^6
z
Behaves like
$\Delta N_{\rm eff}$
a^{-4}
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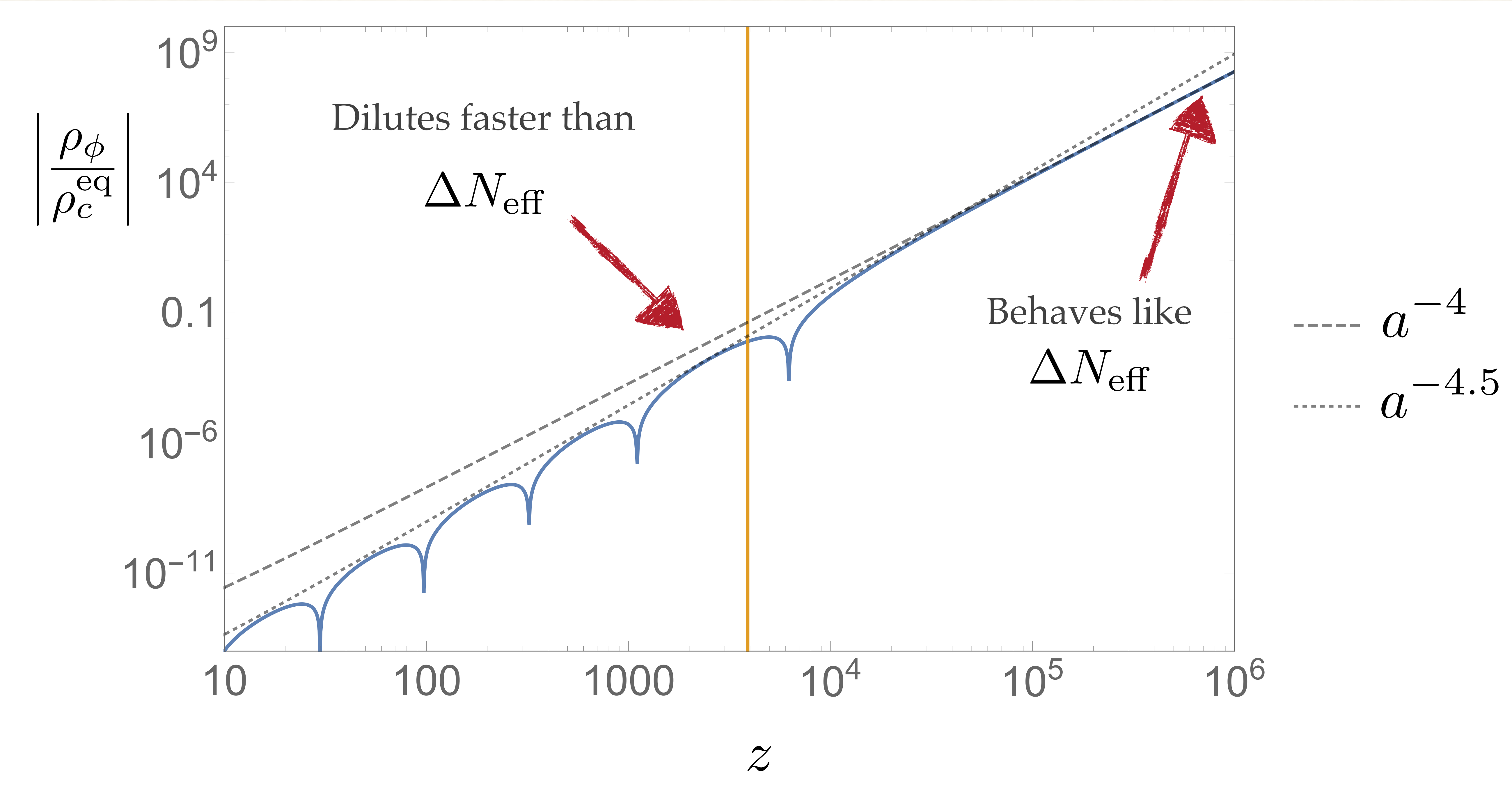

10^9
10^4
0.1
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Dilutes faster than
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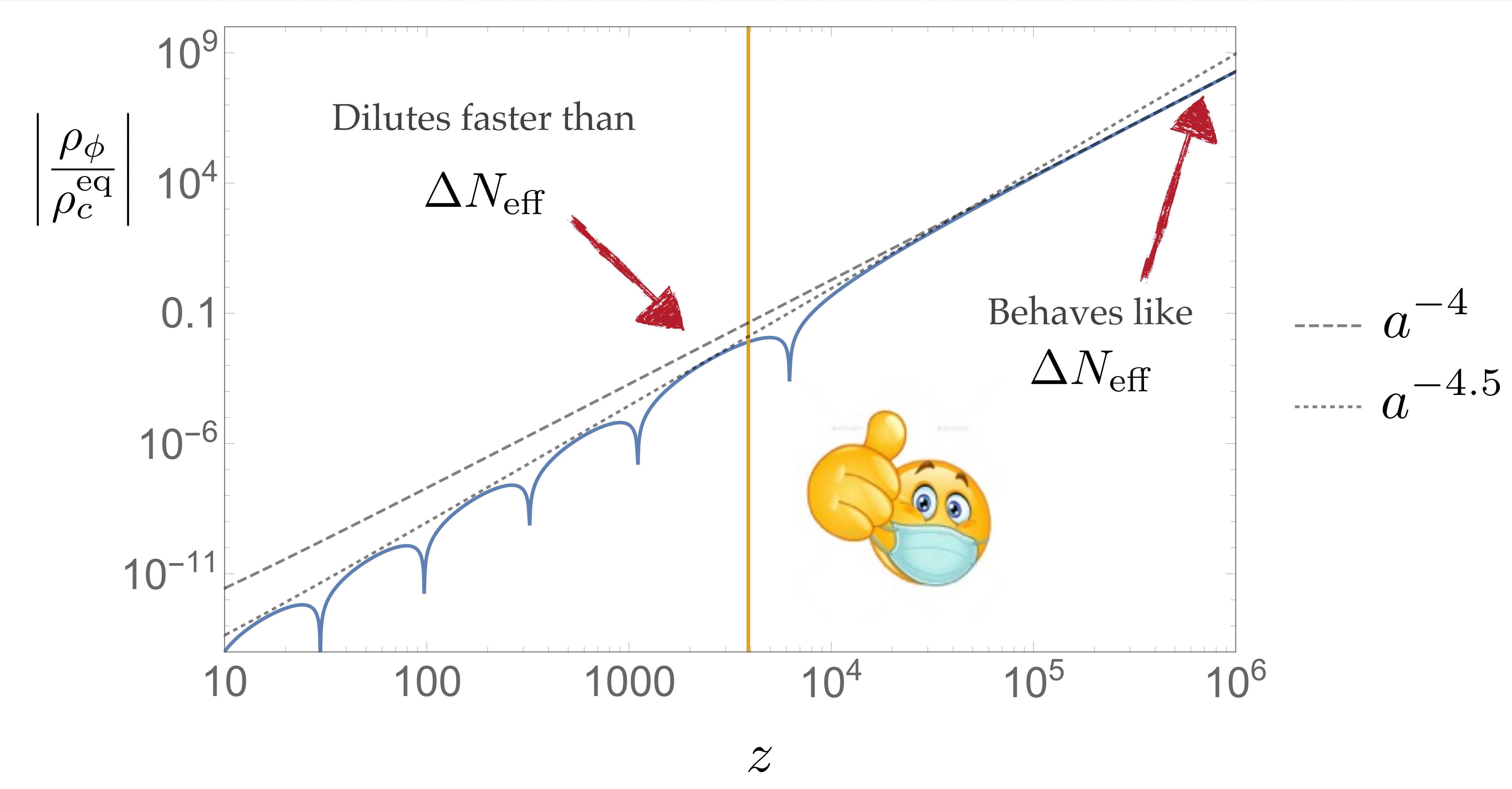
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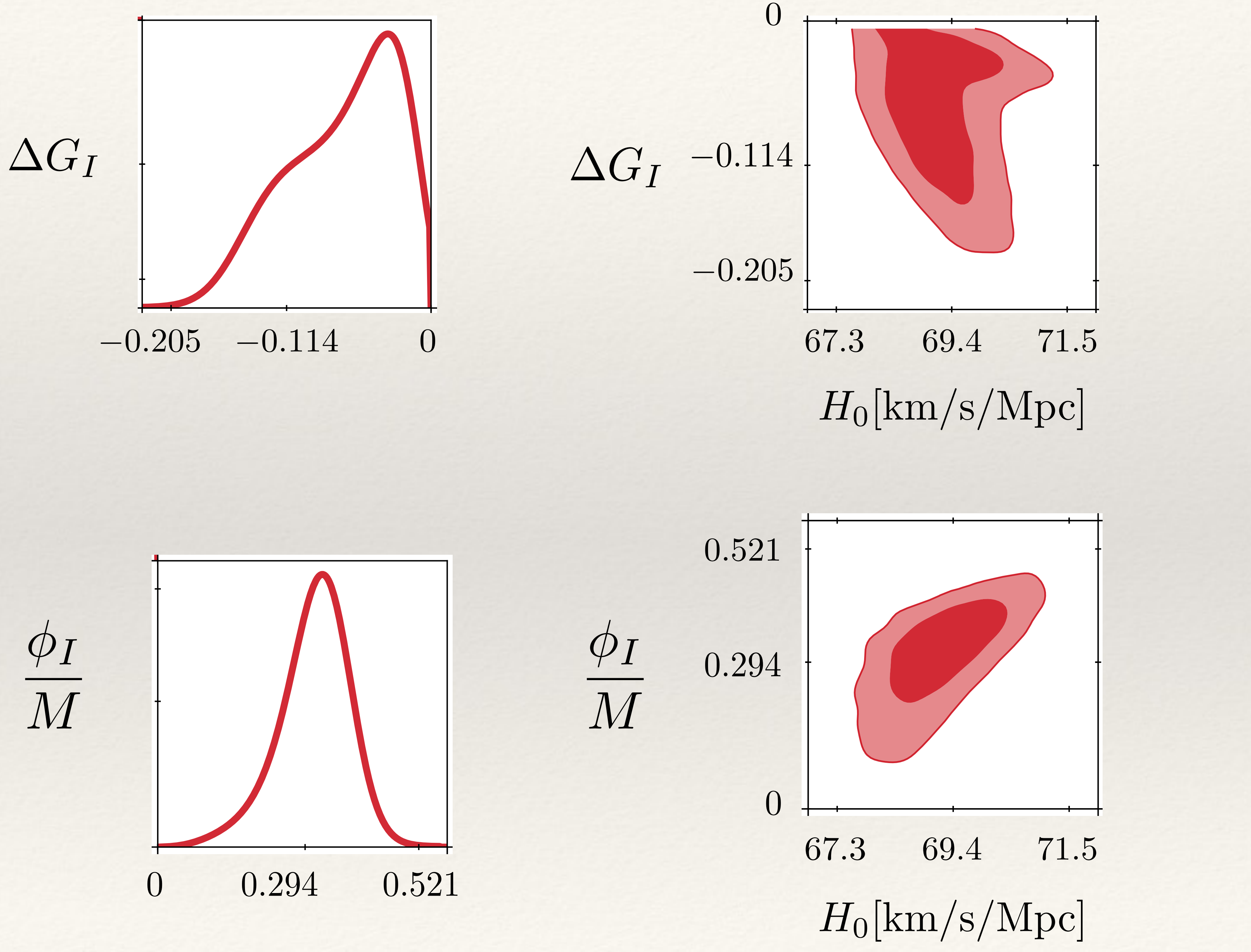
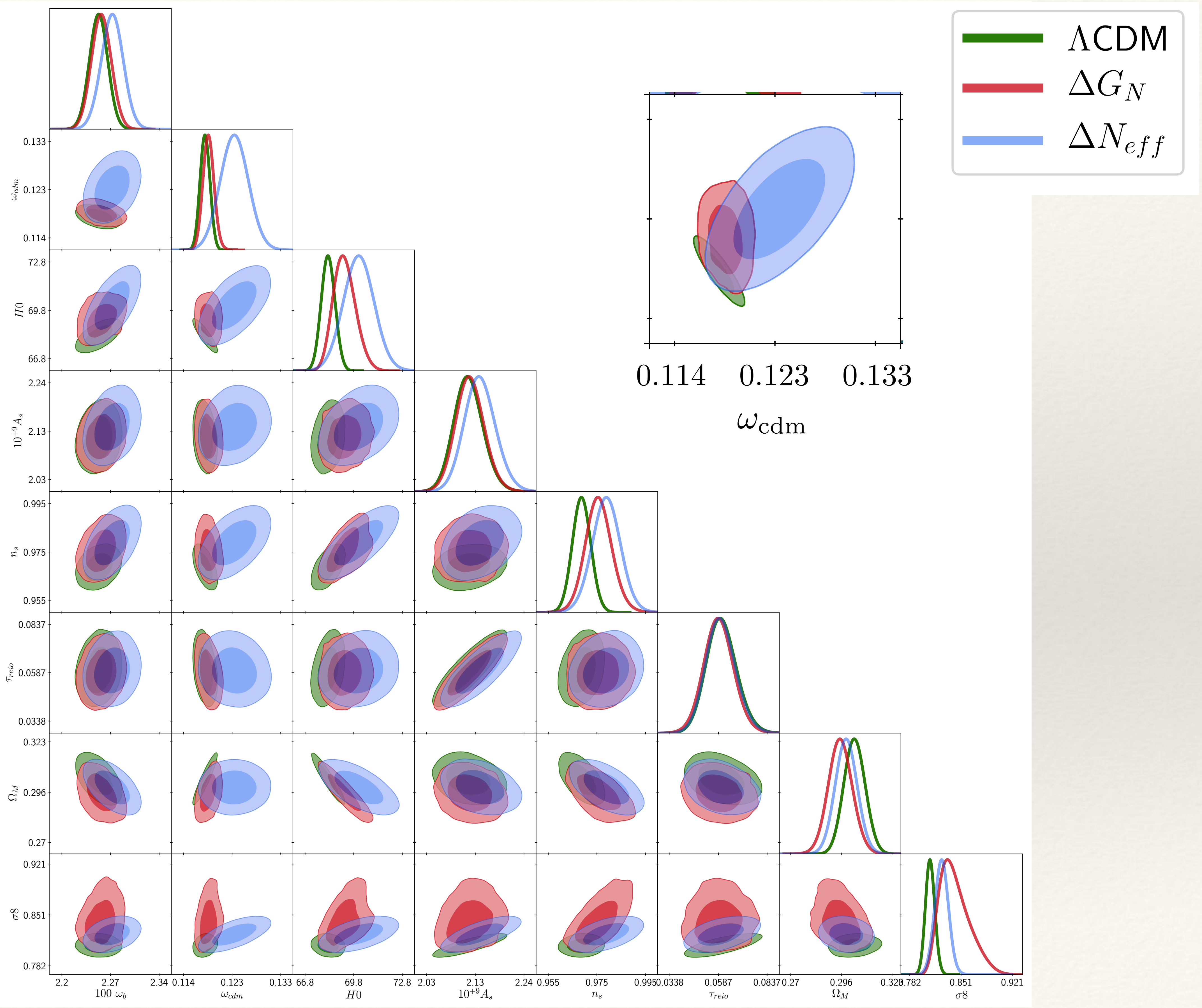
Results



ΔG_I
−0.205
−0.114
0
H_0[km/s/Mpc]
67.3
69.4
71.5
$\frac{\phi_I}{M}$
0.294
0.521

Comparison with Dark Radiation



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