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Cosmological Tensions in a Coupled Dark Sector

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Faculdade de Ciências da Universidade de Lisboa

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Based on arXiv:2007.15414 + soon to appear
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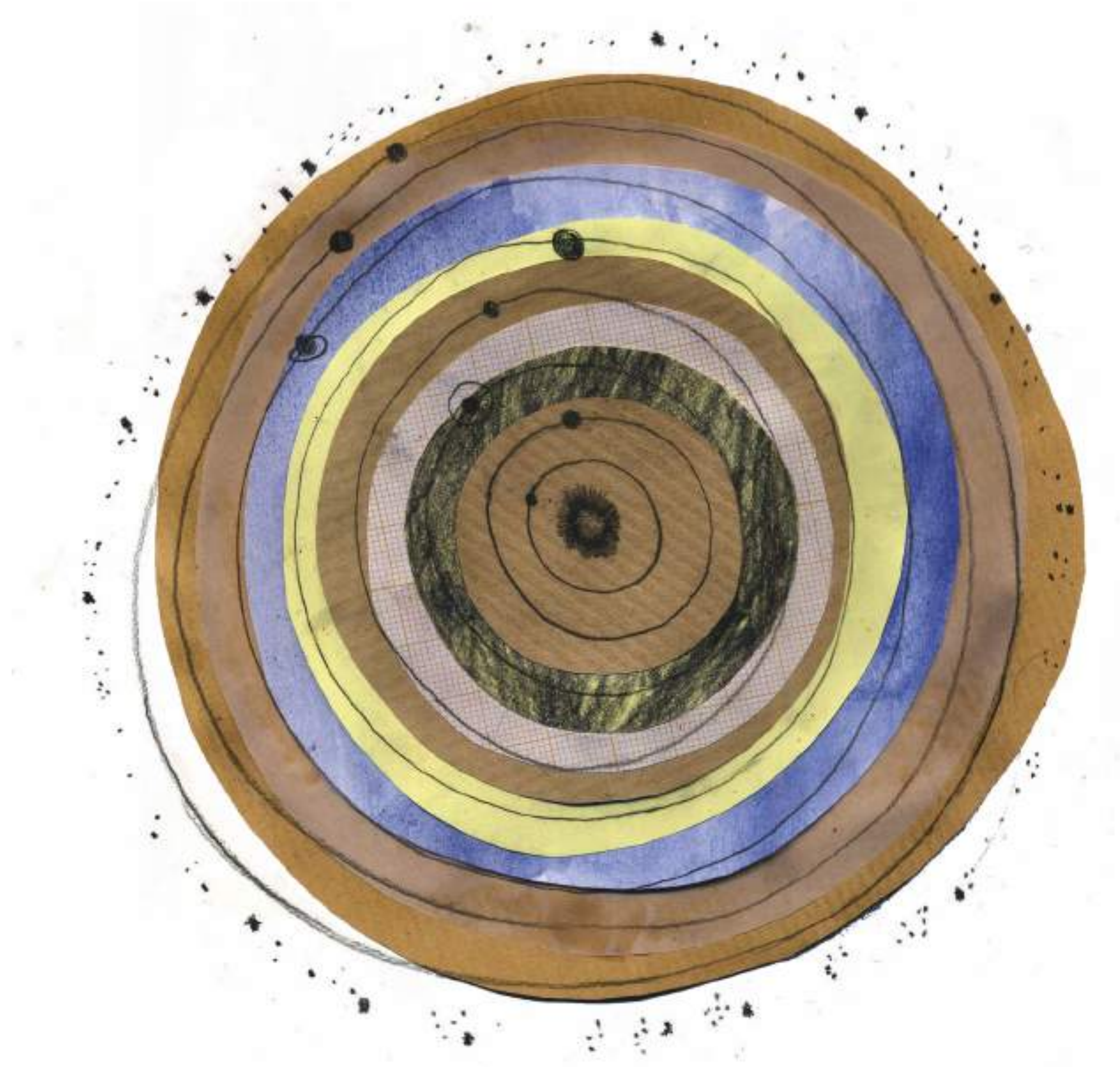
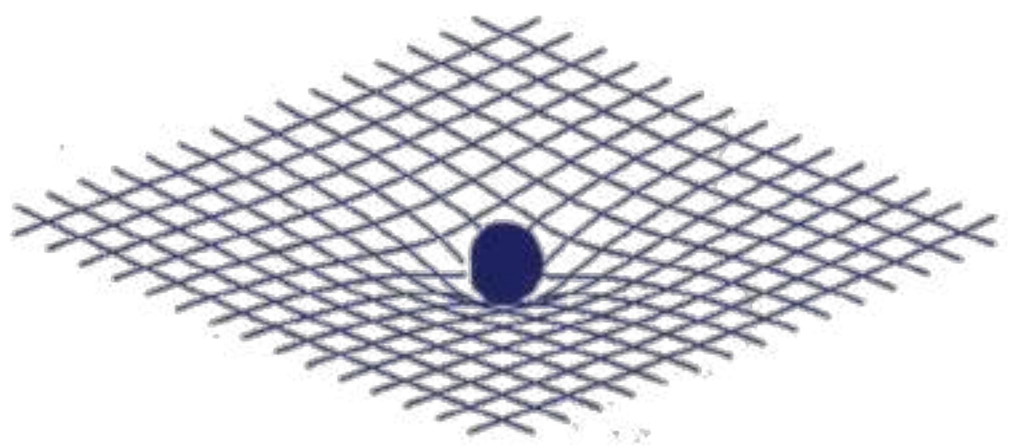


The Lambda Cold Dark Matter Model



THEORY OF GRAVITY

General Relativity:

$G_{\mu\nu} = 8\pi G T_{\mu\nu}$

METRIC ANSATZ

FLRW Metric:

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

STANDARD MATTER

Baryons, Photons, Neutrinos

5%

ΛCDM MODEL

INFLATION — INFLATON

Early accelerated expansion produce density fluctuations

25%

COSMIC STRUCTURE — CDM

Clustering matter component for structure formation

70%

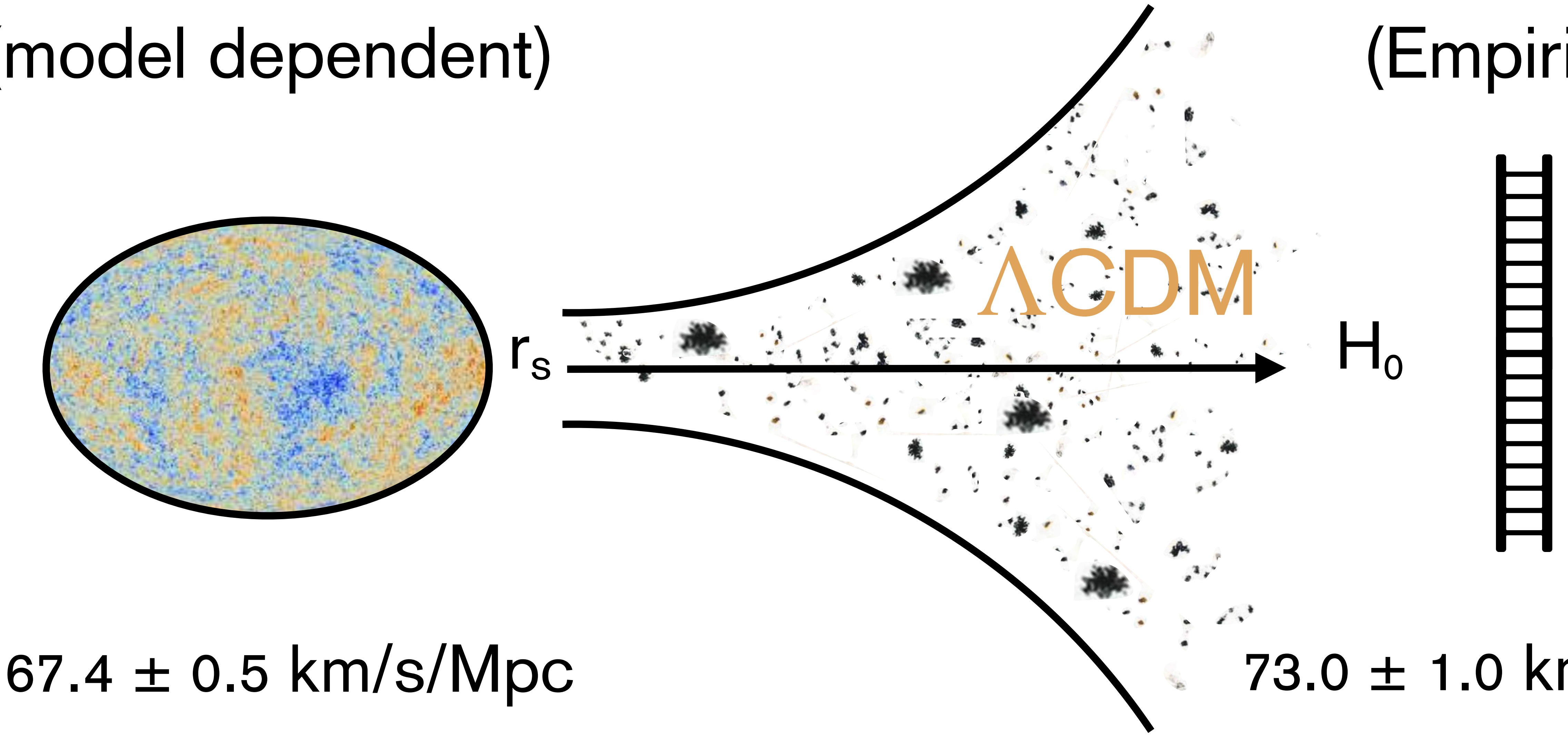
LATE ACCELERATION — Λ

Component to explain current accelerated expansion

Cosmological Tensions

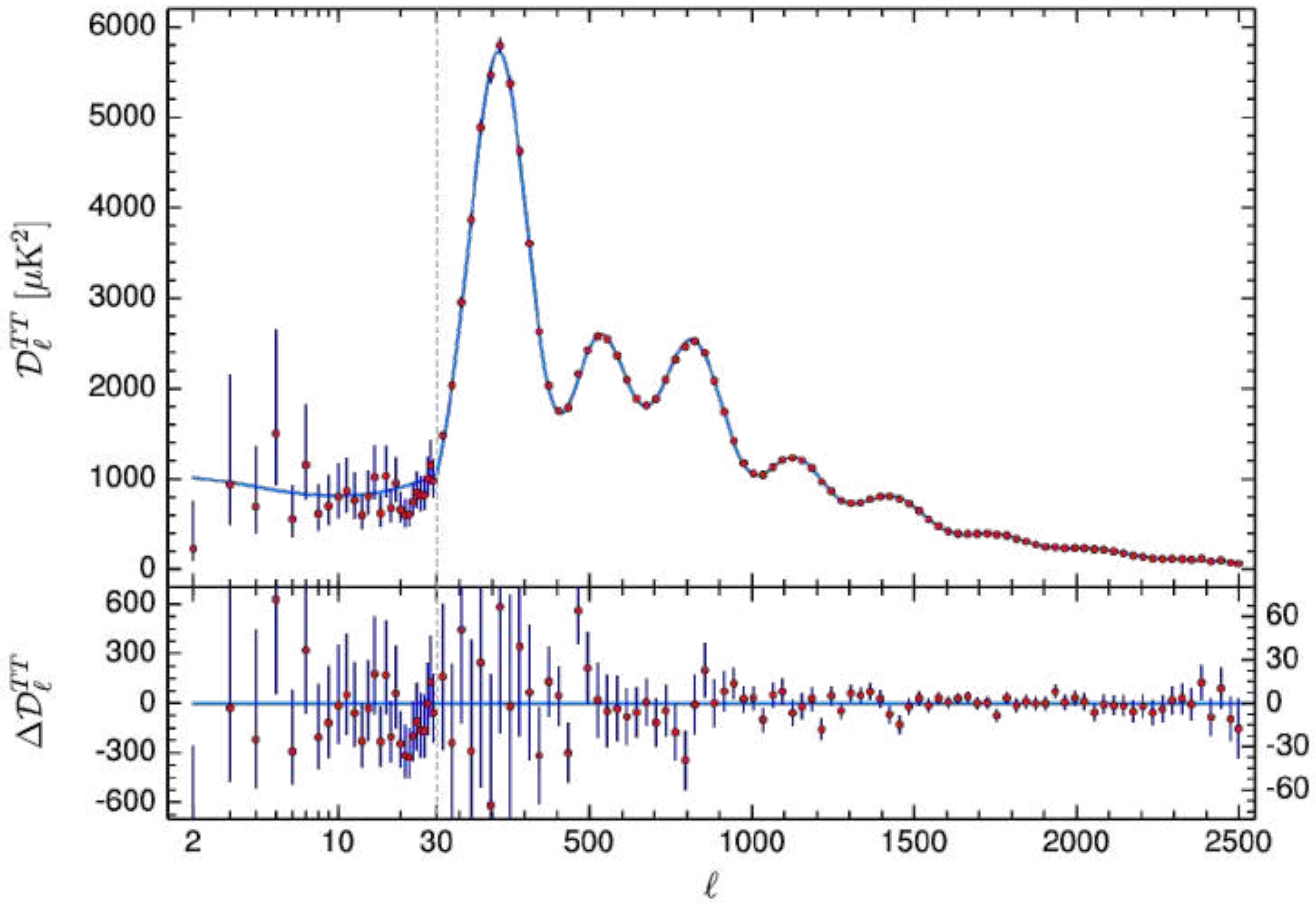
CMB
(model dependent)

Local
(Empirical)



67.4 ± 0.5 km/s/Mpc
from Planck

73.0 ± 1.0 km/s/Mpc
from (SH0ES)



[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

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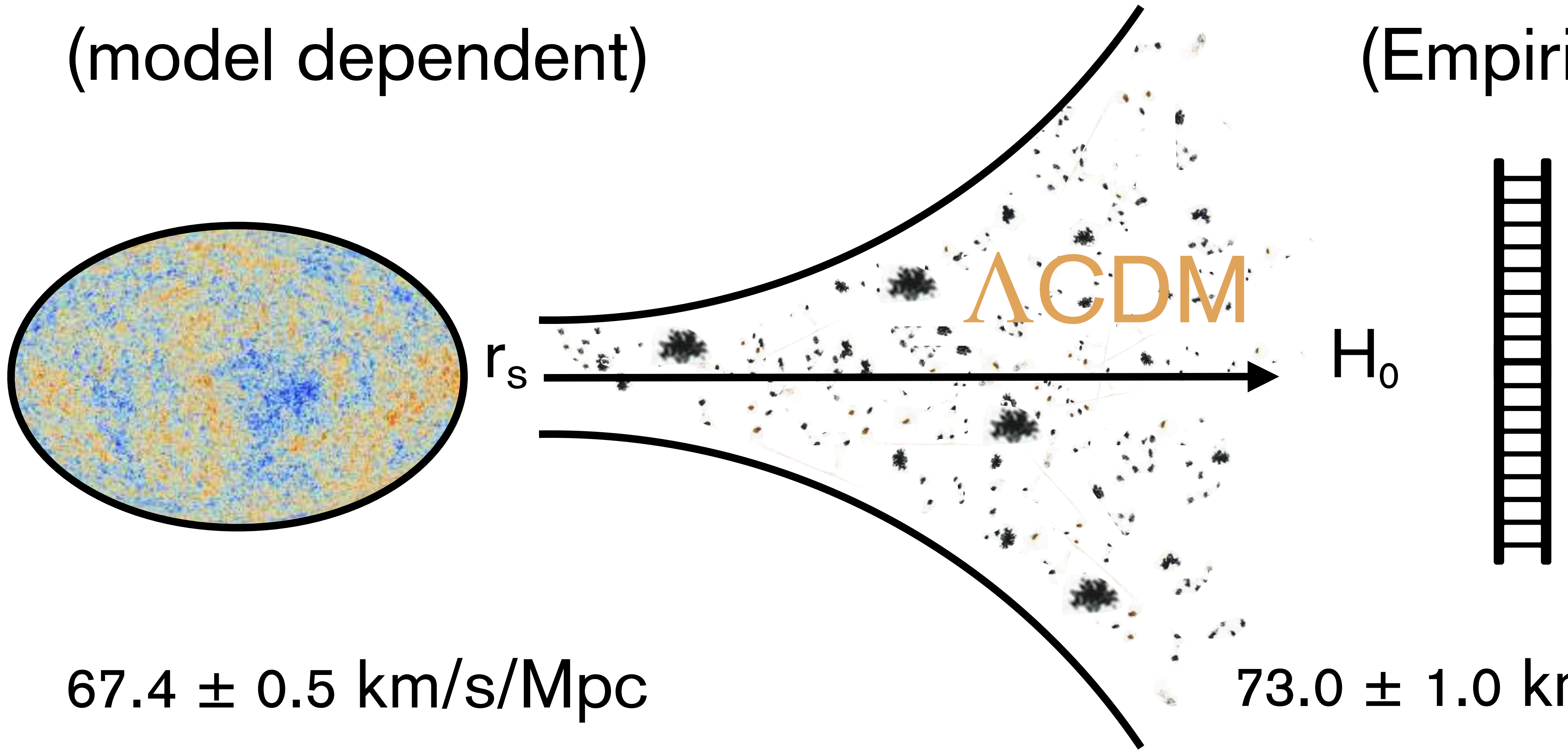

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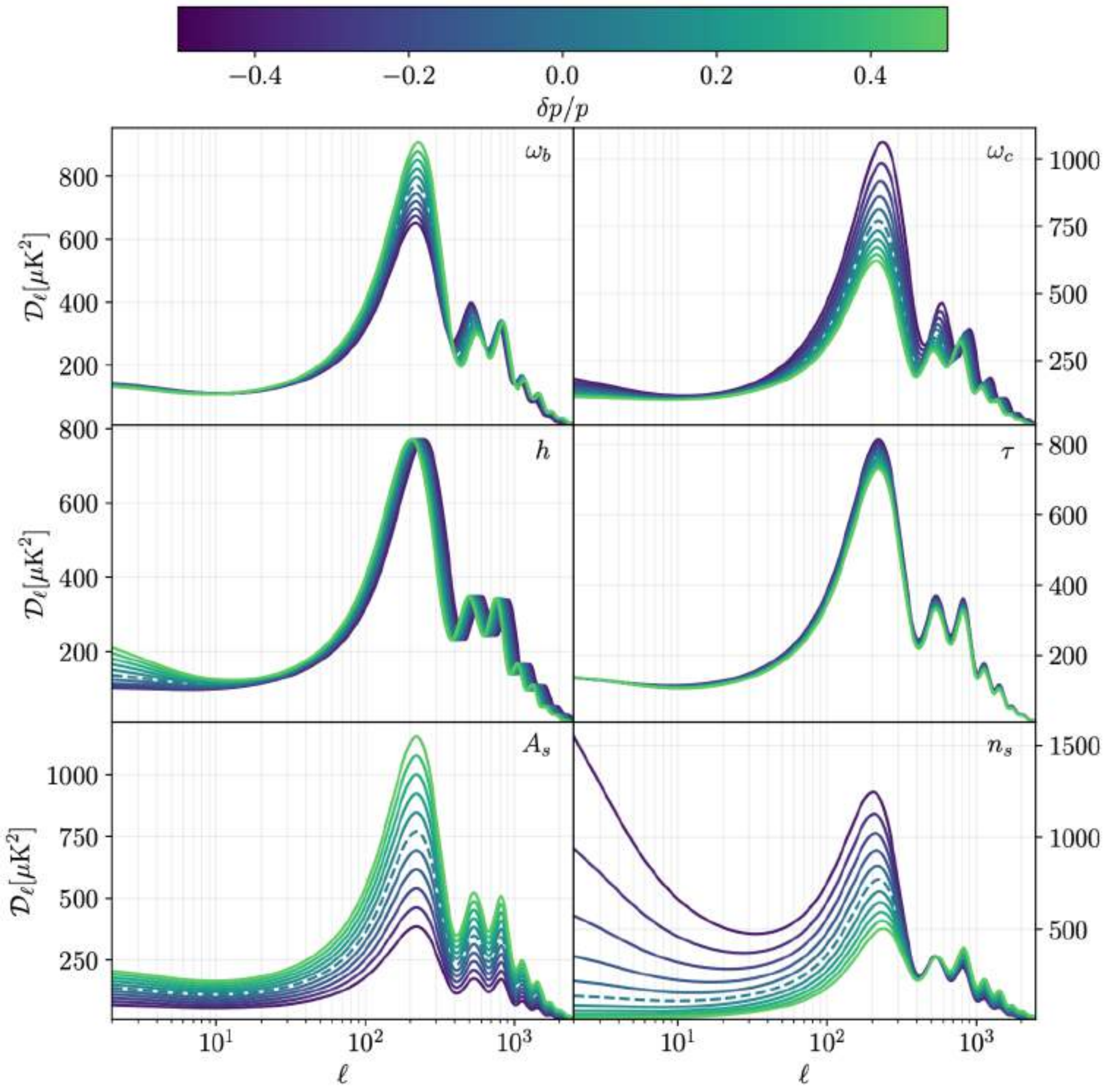


Missing Ingredients or New Physics?

[Luke Hart (2020)]

Extensions to ΛCDM

The observational tensions hint at missing ingredients or need for completely new physics

- "Quintessence" (ϕ) - dynamical scalar field that evolves in space and time, as opposed to Λ
- New forces between DE and "normal matter" are heavily constrained by observations No fundamental principle which forbids interactions between the dark species
- Modified predictions for the evolution could naturally address the cosmic tensions

Non-trivial Interaction between Dark Energy and Dark Matter

Introduce a non-minimal coupling between the scalar field and matter

$$S = \int d^4x\sqrt{-g}\left[\frac{R\left(g_{\mu\nu}\right)}{2\kappa^2} + \mathscr{L}_\phi\left(g_{\mu\nu},\phi\right)\right] + \sqrt{-\bar{g}}\,\bar{\mathscr{L}}_{\rm m}\left(\bar{g}_{\mu\nu}(g_{\mu\nu},\phi),\psi,\partial_\mu\psi\right)$$

$$\delta S = \delta S_\phi + \delta S_{\mathscr{C}} = \int d^4x\sqrt{-g}\frac{\delta\left(\mathscr{L}_\phi\right)}{\delta\phi}\delta\phi + \int d^4x\frac{\delta\left(\sqrt{-\bar{g}}\,\bar{\mathscr{L}}_{\rm m}\right)}{\delta\phi}\delta\phi = 0$$

Two related geometries: $g_{\mu\nu}$ is the gravitational metric and $\bar{g}_{\mu\nu}(g_{\mu\nu},\phi)$ defines the physical geometry according to which matter is propagating

Conformal Transformation

- Simplest way to relate two geometries
- Rescaling of the metric that preserves angles
- Functional dependence on scalar field already present in the theory
- Map non-standard theories of gravity into GR plus a scalar field ϕ minimally coupled to the geometry
- Preserve the structure of Scalar-Tensor theories of the Jordan-Brans-Dicke form, such as $f(R)$

$$\bar{g}_{\mu\nu} = C(\phi) g_{\mu\nu}$$

[Jordan: Z. Phys. 157 (1959), 112;
Brans and Dicke: Phys. Rev. 124 (1961), 925]

Disformal Transformation

- Distortion of both angles and lengths related with the gradient of ϕ
- The most general covariant effective metric that can be constructed from the metric and a scalar field and leads to 2nd order equations
- The form of the Horndeski Lagrangian is preserved under disformal transformations
- Many cosmological applications

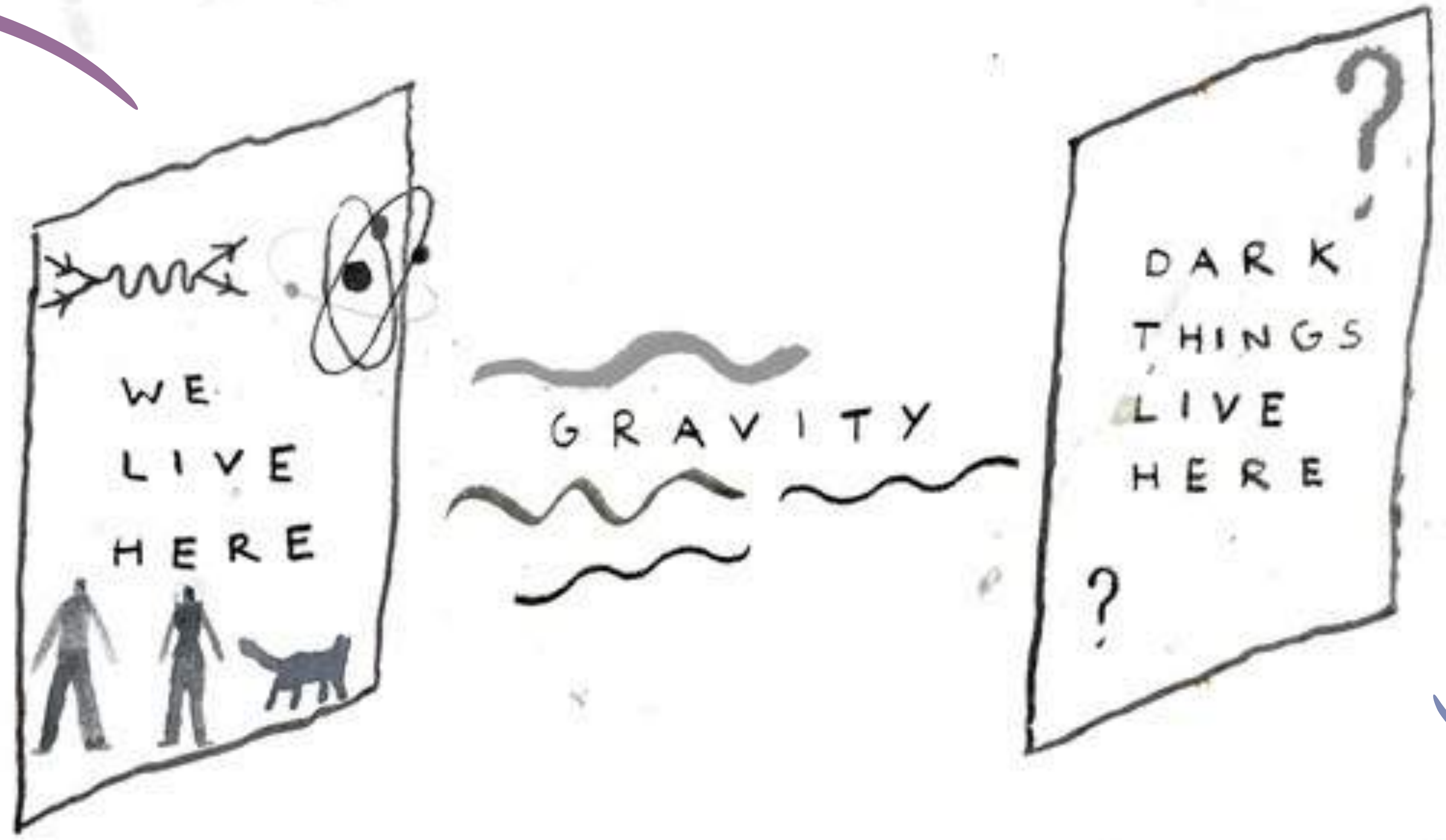
$$\bar{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi) \partial^\mu \phi \partial_\mu \phi$$

[Bettoni and Liberati: Phys. Rev. D88 (2013) 084020}]

The Dark D-Brane Model

The total Universe is a higher-dimensional spacetime composed of a bulk and stacked (mem)branes with gravity propagating in the bulk [Koivisto, Wills, and Zavala: JCAP 06 (2014) 036]

Visible Brane
where the SM particles and their interactions "live"



Dark D-brane
where the dark sector lives - no intersection with the visible sector

Dark sector: distinctive components with a joint higher-dimensional origin related to the geometry and dynamics of the Dark D-brane ($h(\phi)$) $\Longrightarrow$ inevitable non-universal coupling

The Dark D-Brane Model

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$$S = \int d^4x \sqrt{-g}\frac{R}{2\kappa^2} + \int d^4x\sqrt{-g}\left[h^{-1}(\phi)\left(1-\sqrt{1+h(\phi)\partial^\mu\phi\partial_\mu\phi}\right) - V(\phi)\right] + \sum_i \int d^4x\sqrt{-g}\mathscr{L}_S\left(g_{\mu\nu},\psi_i,\partial_\mu\psi_i\right) + \sum_j \int d^4x\sqrt{-\bar{g}}\bar{\mathscr{L}}_{DDM}\left(\bar{g}_{\mu\nu},\chi_j,\partial_\mu\chi_j\right)$$

- Dirac-Born-Infeld scalar field (ϕ) with non-trivial kinetic terms imposed by ST scenario and $h(\phi)$ is the warp factor of the brane
- Dark matter is coupled to ϕ through a disformal transformation

$$\bar{g}_{\mu\nu} = C(\phi)g_{\mu\nu} + D(\phi)\partial^\mu\phi\partial_\mu\phi$$

with $C(\phi)$ and $D(\phi)^{-1} \propto h(\phi)^{-1/2}$

Background Cosmology

In FLRW the modified Klein Gordon equation becomes

$$\phi'' - \mathcal{H}\left(1 - 3\gamma^{-2}\right)\phi' + \frac{h_{,\phi}}{2h^2}a^2\left(1 - 3\gamma^{-2} + 2\gamma^{-3}\right) + \gamma^{-3}a^2\left(V_{,\phi} - \kappa\rho_c\beta\right) = 0$$

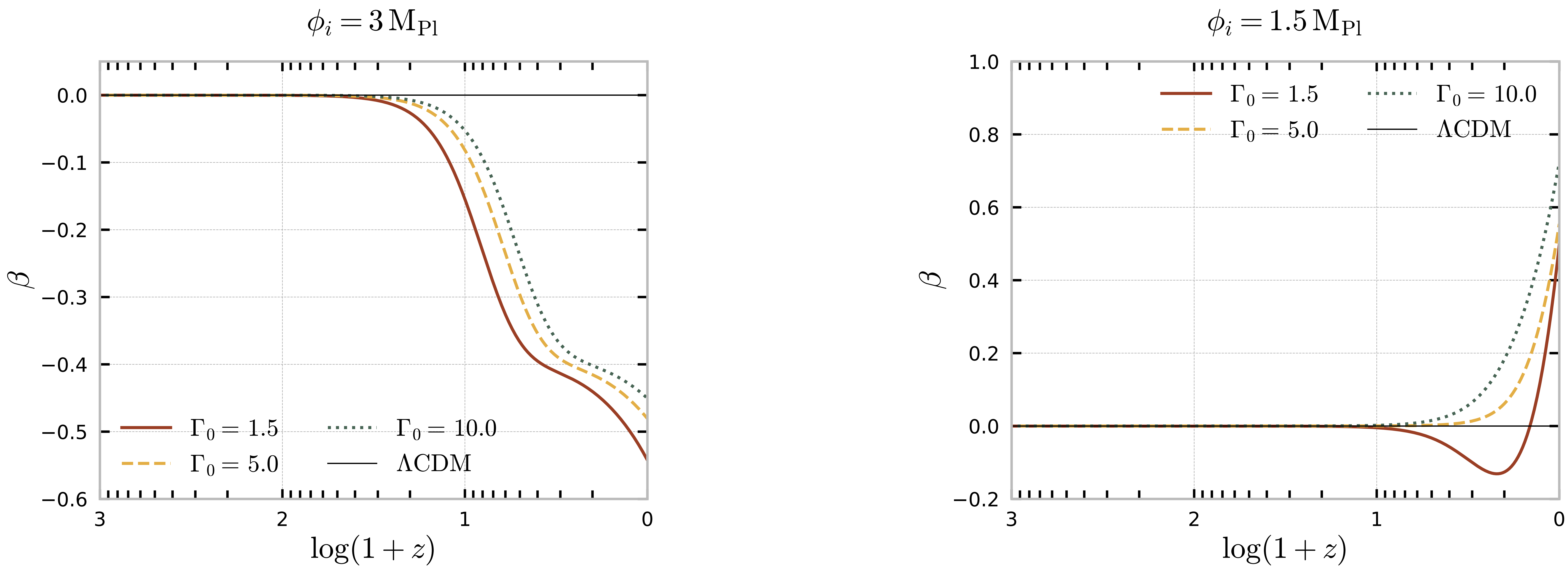
With the coupling function

$$\beta = \frac{1}{\kappa\rho_c}\left[\frac{h\left(V_{,\phi} + 3a^{-2}\mathcal{H}\gamma\phi'\right) + \frac{h_{,\phi}}{h}\left(1 - \frac{3}{4}\gamma\right)}{\gamma + h\rho_c}\right]\rho_c$$

- No well-defined ΛCDM or uncoupled limit
- AdS5 throat with a quadratic potential

$$h(\phi) = h_0\frac{1}{\phi^4}, \qquad V(\phi) = V_0\frac{\phi^2}{\kappa^2}$$

- Define a single key parameter $\Gamma_0 = h_0 V_0$



- Higher (lower) values ϕ_i lead to DM → DE (DE → DM) flux and both in intermediate cases $\Longrightarrow$ the coupling could be negligible at the present but significant in the past

- Coupling is only activated at later times for higher (lower) values of Γ_0

Linear Perturbations

Scalar perturbations in the conformal Newtonian gauge

$$\mathrm{d}s^2 = a^2(\tau)\left[-\left(1+2\Psi\right)d\tau^2 + (1-2\Phi)\,\delta_{ij}dx^i dx^j\right]$$

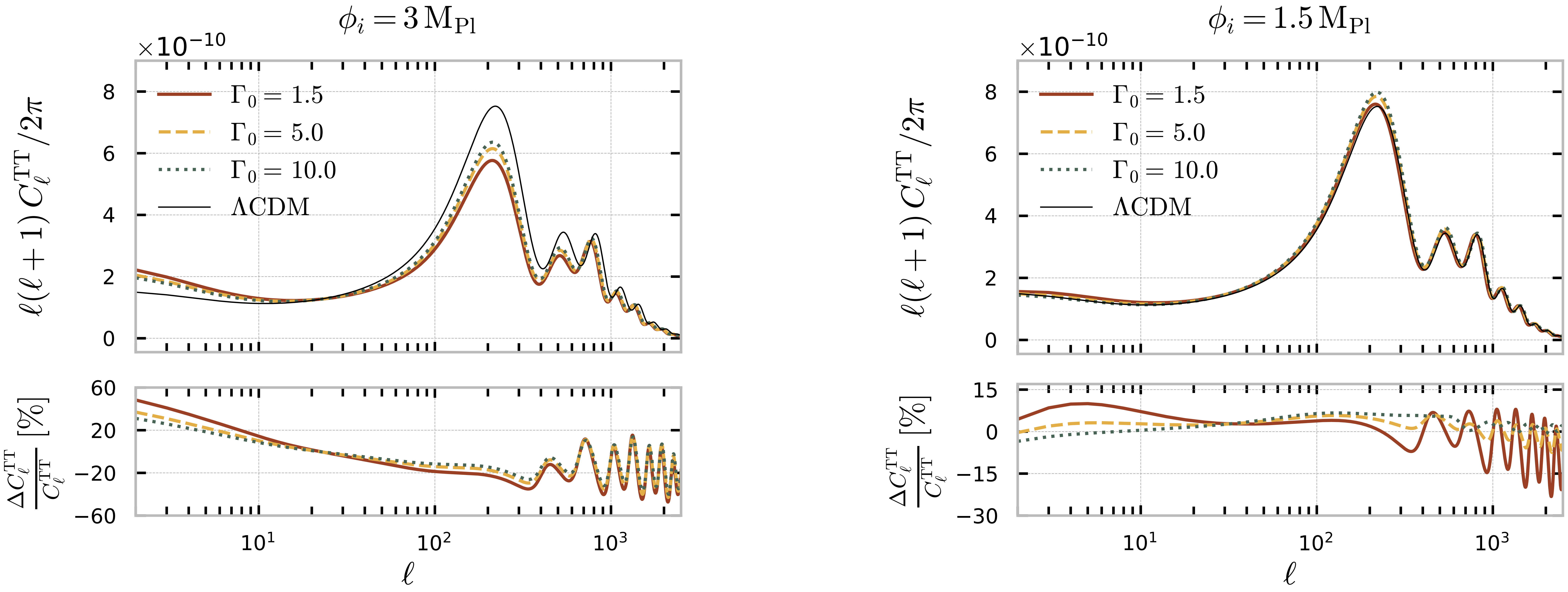
Perturbed continuity and Euler equations for DDM ($\delta_c = \delta\rho_c/\rho_c$ and $\theta_c = \partial_i\partial^i v_c$)

$$\begin{cases} \delta_c' = -\left(\theta_c - 3\Phi'\right) - \frac{Q}{\rho_c}\phi'\delta_c + \frac{Q}{\rho_c}\delta\phi' + \frac{\delta Q}{\rho_c}\phi' \\ \theta_c' + \mathcal{H}\theta_c = k^2\Psi - \frac{Q\phi'}{\rho_c}\theta_c + k^2\frac{Q}{\rho_c}\delta\phi \end{cases}$$

Where the perturbation of the coupling is given by

$$\delta Q = \frac{a^{-2}\rho_c}{\gamma^{-2} + h\rho_c\gamma^{-3}}\left(\mathcal{Q}_1\delta_c + \mathcal{Q}_2\Phi' + \mathcal{Q}_3\Psi + \mathcal{Q}_4\delta\phi' + \mathcal{Q}_5\delta\phi\right)$$

The coefficient $\mathcal{Q}_5$ is scale-dependent - well-known feature of disformal models!



- Scale dependence: general enhancement (suppression) for low multipoles and suppression (enhancement) for medium multipoles when DM → DE (DE → DM) ⟹ ISW effect (degeneracy between H_0 and Γ_0)
- Also observe narrowing (broadening) and shift of the accoustic peaks to the left (right)
- Consistent evidence that larger values of Γ_0 also lead to a sort of ΛCDM limit in the perturbations

Bayesian Parameter Inference

Given a data set d, we want to sample posteriors on the model parameters θ that maximise the likelihood

$$p\left(\theta \mid d\right) = \frac{p\left(d \mid \theta\right) \, p\left(\theta\right)}{p\left(d\right)} \Leftrightarrow \text{Posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

Modified version of Einstein-Boltzmann code CLASS interfaced with the MontePython sampler
[Blas, Lesgourgues, Tram: JCAP 1107 (2011) 034; Audren et al.: JCAP 1302 (2013) 001; Brinckmann, Lesgourgues: Phys. Dark Univ. 24 (2019) 100260]

Employ an MCMC sampling method and analyse results in GetDist
[Lewis: arXiv:2008.11284]

Sampled Cosmological Parameters

The ΛCDM model is based on 6 free parameters:

- the baryon and dark matter densities $\Omega_b h^2$ and $\Omega_c h^2$
- the angular size of the sound horizon at decoupling θ_s
- the reionisation redshift $z_{\rm reio}$
- the spectral index n_s and the amplitude A_s of inflationary scalar perturbations

Parameter	Prior
$\Omega_b h^2$	[0.005, 0.1]
$\Omega_c h^2$	[0.001, 0.99]
$100^*\theta_s$	[0.5, 10]
z_{reio}	[0., 20.]
n_s	[0.7, 1.3]
$\log(10^{10}A_s)$	[1.7, 5.0]

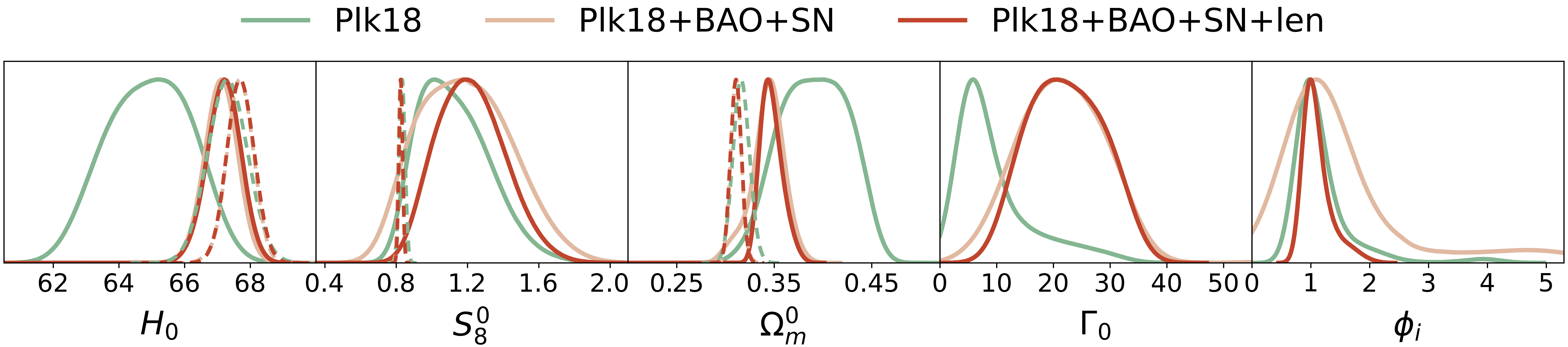
In the Dark D-Brane Model scenario we also allow sampling of:

- the effective coupling parameter through $1/h_0$ (compactness) and the initial condition $\phi_i \implies$ 2 additional parameters

Parameter	Prior
$1/h_0$	[0.005, 0.1]
ϕ_i	[0.001, 0.99]

The remaining cosmological parameters are either fixed to standard Planck 2018 values or derived from the main ones

Cosmological Bounds



- Lower mean value of H_0 and larger Ω_m and S_8 for all data sets $\Longrightarrow$ does not address S_8 and H_0 tensions
- The parameters Γ_0 and ϕ_i are consistently constrained even with no ΛCDM limit
- Inclusion of BAO and SN data - narrower constraints on Ω_m

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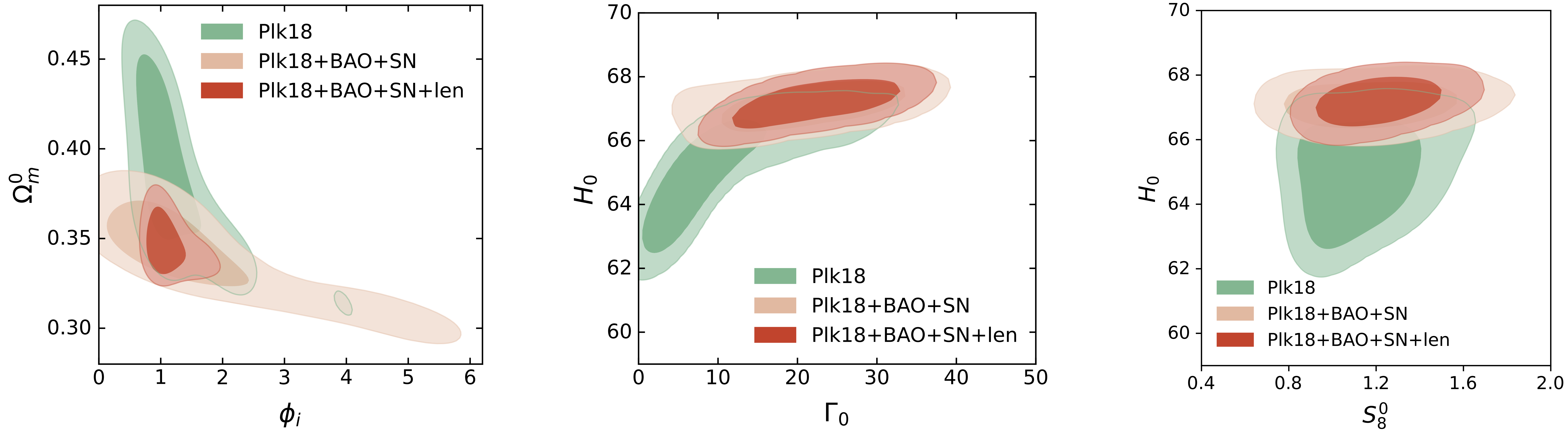

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- The parameters Γ_0 and ϕ_i are consistently constrained even with no ΛCDM limit
- Inclusion of BAO and SN data - narrower constraints on Ω_m
- Clear saturation point between H_0 and Γ_0 when cosmologies stop differing from each other for different Γ_0

Model Selection Analysis

	Plk18	Plk18 + BAO + SN	Plk18 + BAO + SN + len
$\Delta\chi^2$	−5.04	−2.70	−1.86
B	-5.7	-8.0	-7.4

- $\Delta\chi^2_{\rm eff}$ to assess the goodness of fit and $B_{\text{DBI}\,\Lambda}$ to quantify the preference
- Considerable evidence for the Dark D-Brane model for the Planck data
- Slight preference remains for the other data combinations
- BAO and SN data change the fit to the TT likelihood and the CMB lensing data shows an excess of power - enhancement for large multipoles for lower values of Γ_0 (as preferred by Planck)
- However, the Bayesian evidence shows a clear preference for ΛCDM for all the data sets

Conclusions

- The ΛCDM makes impressive predictions but the cosmological tensions hint at the need for new physics
- Framework with joint geometrical origin for the dark sector from string theory compactifications
- Cosmological constraints on the parameters of the theory using CMB, CMB lensing, BAO and SN data
- The parameters Γ_0 and ϕ_i are consistently constrained
- Apparent ΛCDM limit for high Γ_0 leads to saturation point in correlations
- The S_8 tension is exacerbated, while the H_0 tension is still present - consider different geometries or scalar field potentials?

Thank you! Do you have any questions?

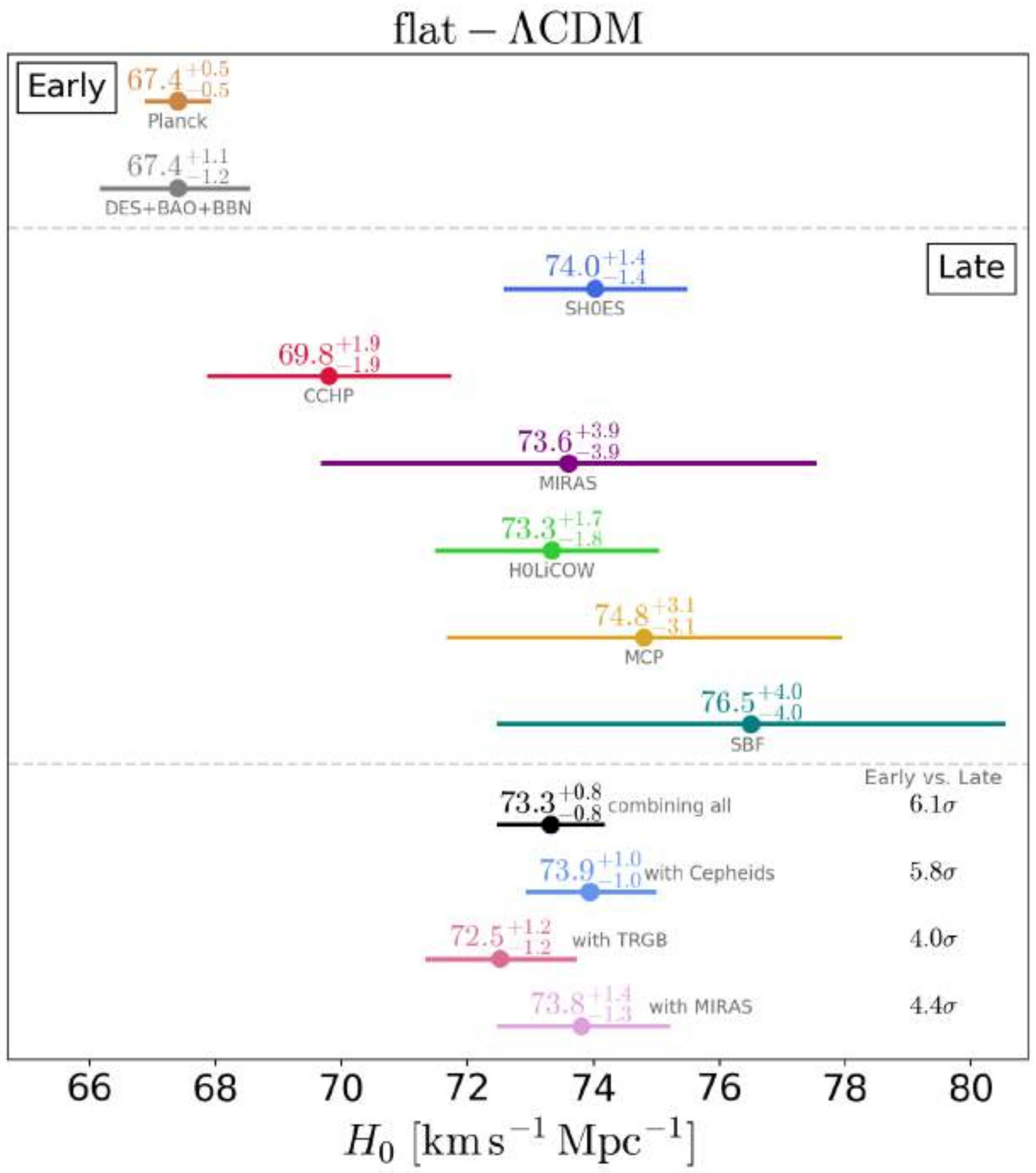
Illustration Credits: Inês Viegas Oliveira (ivoliveira.com)

The Hubble Tension

Unreconcilable values for H_0 from the CMB and from direct local distance ladder measurements

- 4.4σ tension between Planck 2018 and SH0ES:
  - CMB (Planck): H0 = 67.4 ± 0.5 km/s/Mpc
  - SNe (SH0ES): H0 = 74.0 ± 1.4 km/s/Mpc
- The Planck 2018 results are a grand confirmation of the ΛCDM model but they are model dependent
- Unlikely that the discrepancies could be explained by a single systematic error
- The magnitude and persistence hints at standard model flaws

[Di Valentino et al.: arXiv:2008.11284]

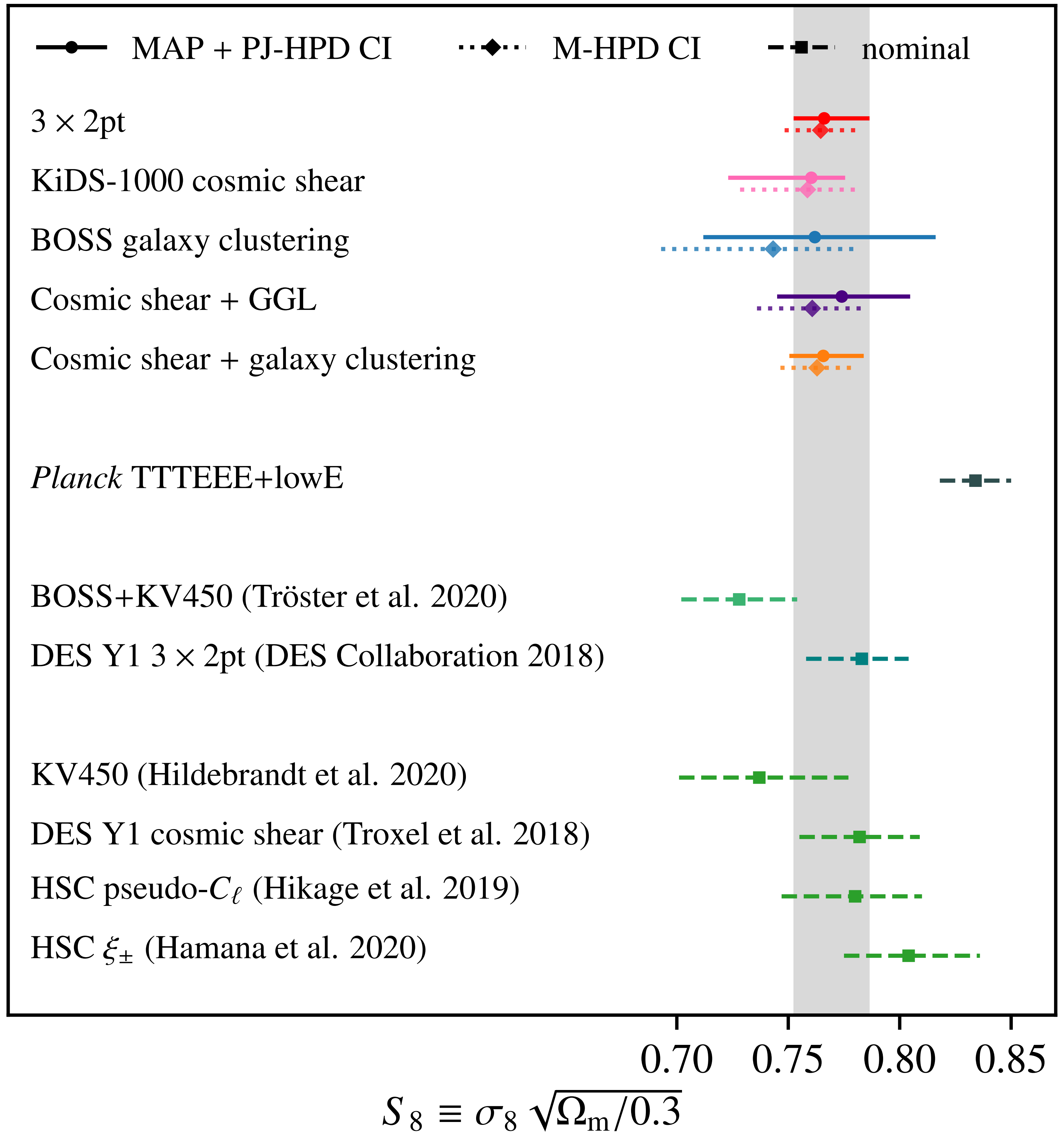


[Verde, Treu, Riess: Nature Astron. 3 891 (2019)]

The S_8 Tension

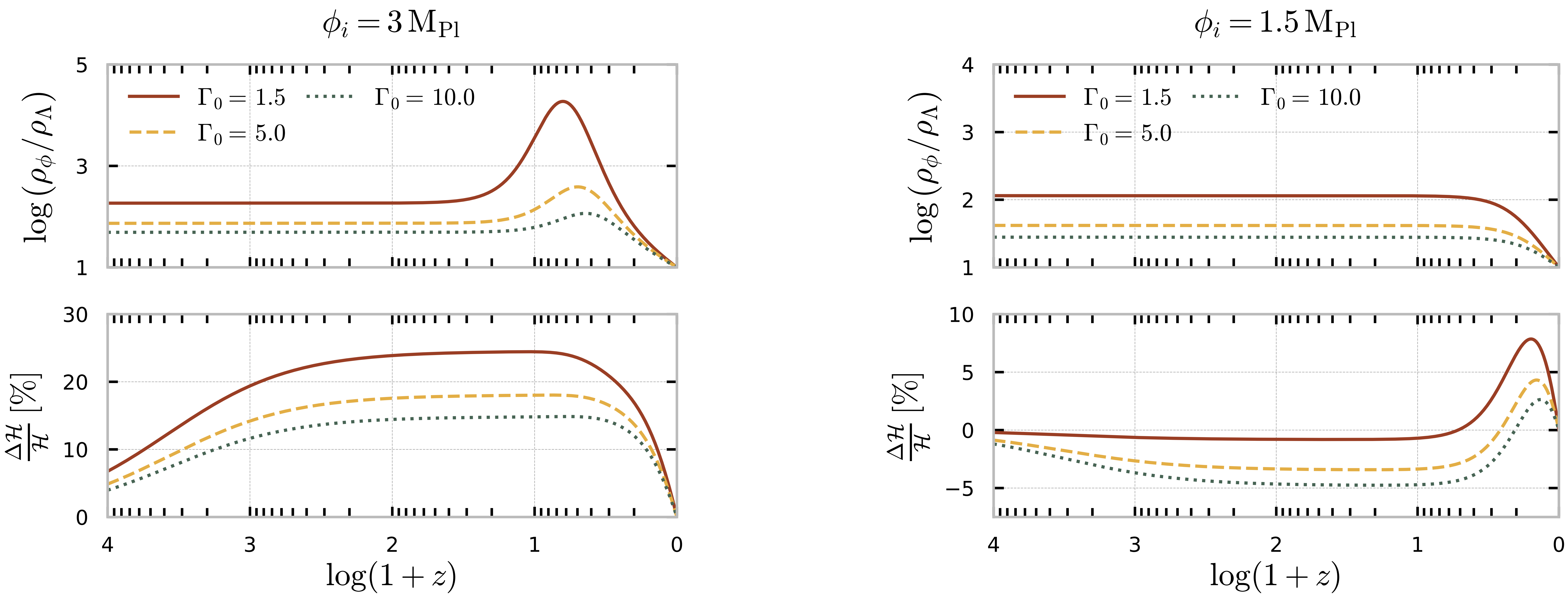
Discrepancy between CMB data and weak lensing and redshift surveys on the combined value of Ω_m and σ_8 expressed as $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$

- ~ 3σ tension between Planck 2018 CMB data and KiDS-1000 combination of Cosmic Shear and Galaxy Clustering:
  - CMB (Planck): $S_8 = 0.834 \pm 0.016$
  - CS+GC (KiDS-1000): $S_8 = 0.766^{+0.020}_{-0.014}$
- Could be related to the excess of lensing measured by Planck, mimicking a larger S_8
- Correlation between the H_0 and S_8 tensions - conjoined analysis
- Formulate extensions to the standard cosmological framework and test against the relevant constraints

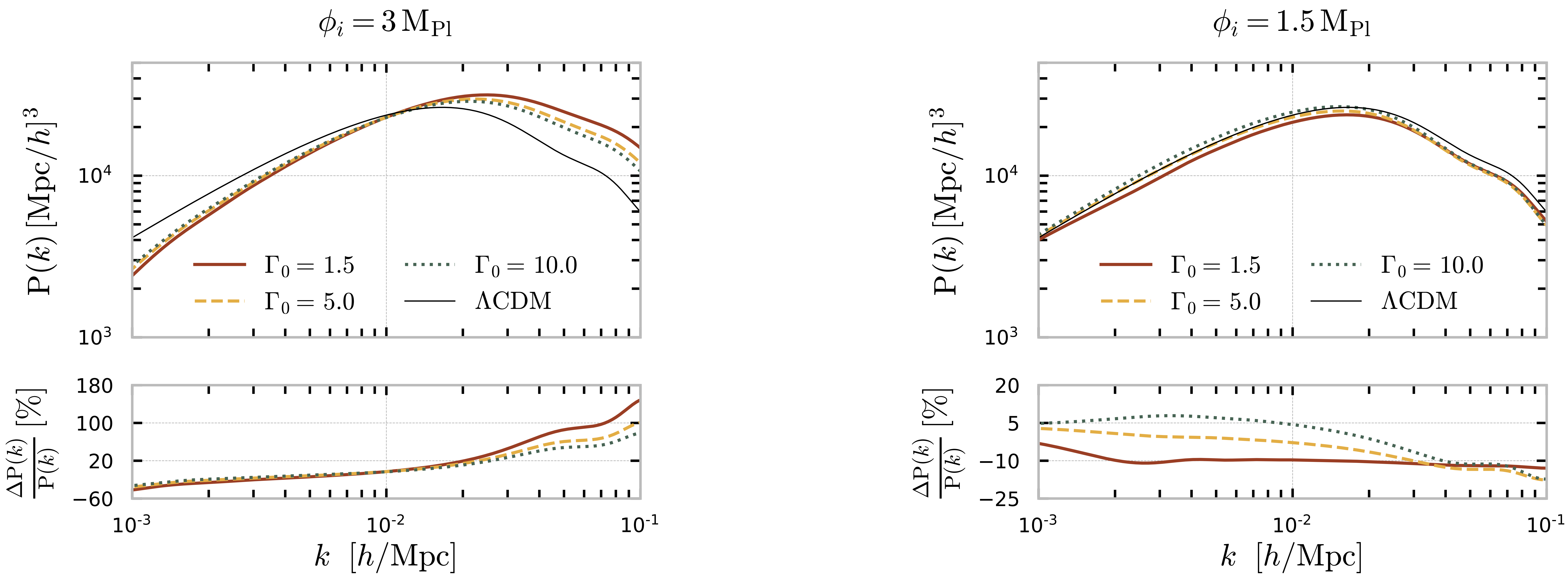


[Di Valentino et al.: arXiv:2008.11285]

[C. Heymans et al.: \textbf{Astron.Astrophys. 646 (2021)]



- Emergence of a late-time scaling regime and a future attractor solution with an “excess of DE"
- Enhanced (suppressed) values of $\mathscr{H}$ connected to amplification (repression) of ρ_c



- Clear scale dependence from the addition of Q and δQ + shift of the peak
- Suppression/enhancement of the growth of structures $\Longrightarrow$ change in the background affected by sign of β
- In general deviations more pronounced for lower (higher) Γ_0 but not trivial for sign change

Data Sets

- Baseline data set is "Plk18": CMB Planck 2018 data for large angular scales $\ell = [2, 29]$ and a joint of TT, TE and EE likelihoods for the small angular scales [Aghanim et al.: Astron.Astrophys. 641 (2020) A5]

- "Plk18+BAO+SN": "Plk18" plus compilation of baryon acoustic oscillations (BAO) distance and expansion rate measurements and distance moduli measurements of type Ia Supernova (SN) data from Pantheon. [Ross et. al: Mon. Not. Roy. Astron. Soc. 449 (2015) 835; Beutler et al.: Mon. Not. Roy. Astron. Soc. 464 (2017) 3409; Beutler et al.: Mon. Not. Roy. Astron. Soc. 416 (2011) 3017; Scolnic et. al: Astrophys. J. 859 (2018) 101]

- "Plk18+BAO+SN+len": "Plk18+BAO+SN" plus CMB lensing potential data from Planck 2018 [Aghanim et al.: Astron.Astrophys. 641 (2020) A8]