DARK ENERGY INTERACTING WITH DARK MATTER

Illustrations: Inês Viegas Oliveira (ivoliveira.com)

ELSA M. TEIXEIRA

(elsa.teixeira@umontpellier.fr)

Based on:

- [arxiv:2503.01961] with: Saba Rahimy and Ivonne Zavala
- [arxiv:2211.13653] with: Carsten van de Bruck and Gaspard Poulot
- [arxiv:2412.14139] with: Carsten van de Bruck, Gaspard Poulot, Vivian Poulin and Eleonora Di Valentino

[arxiv:2404.10524] with: Carsten van de Bruck, Gaspard Poulot and Nelson Nunes

SUPPORTED BY FUNDING FROM THE EUROPEAN RESEARCH COUNCIL (ERC) UNDER THE EUROPEAN UNION'S HORIZON-ERC-2022 (GRANT AGREEMENT NO. 101076865)

The Standard Model of Cosmology

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

5%

Baryons, Photons, Neutrinos

ΛCDM MODEL

INFLATION — INFLATON

Early accelerated expansion produce density fluctuations

COSMIC STRUCTURE — CDM

25%

Clustering matter component for structure formation

LATE ACCELERATION — Λ

70%

Component to explain current accelerated expansion

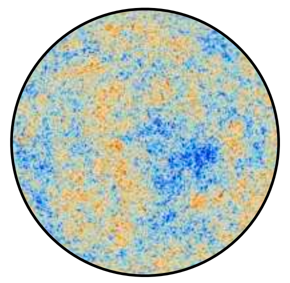
Challenges to the ΛCDM Model

The ΛCDM model relies on:

- Inflation but needs firm theoretical grounds: primordial power spectrum of quantum fluctuations (simplest parameterisation in terms of spectral index and amplitude)
- Dark matter being a pressureless fluid of unknown nature/origin and no detection success (new particle(s) in the SM)
- Dark energy being a cosmological constant (Λ) with unknown nature/origin (vaccuum energy, properties of empty space, etc)

INFLATION — **INFLATON**

Early accelerated expansion produce density fluctuations



COSMIC STRUCTURE — **CDM**

Clustering matter component for structure formation

LATE ACCELERATION — **Λ**

Component to explain current accelerated expansion

Challenges to the ΛCDM Model

The ΛCDM model relies on:

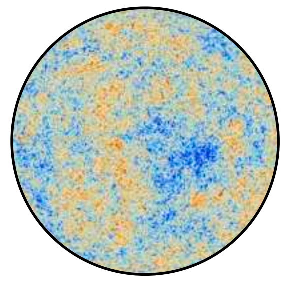
- Inflation but needs firm theoretical grounds: primordial power spectrum of quantum fluctuations (simplest parameterisation in terms of spectral index and amplitude)
- Dark matter being a pressureless fluid of unknown nature/origin and no detection success (new particle(s) in the SM)
- Dark energy being a cosmological constant (Λ) with unknown nature/origin (vaccuum energy, properties of empty space, etc)

Cosmic tensions may signal that ΛCDM is incomplete:

- Anomalies in the CMB: lensing, curvature, etc
- The matter clustering S_8 tension
- The Hubble/H_0 expansion rate tension

INFLATION — **INFLATON**

Early accelerated expansion produce density fluctuations



COSMIC STRUCTURE — **CDM**

Clustering matter component for structure formation

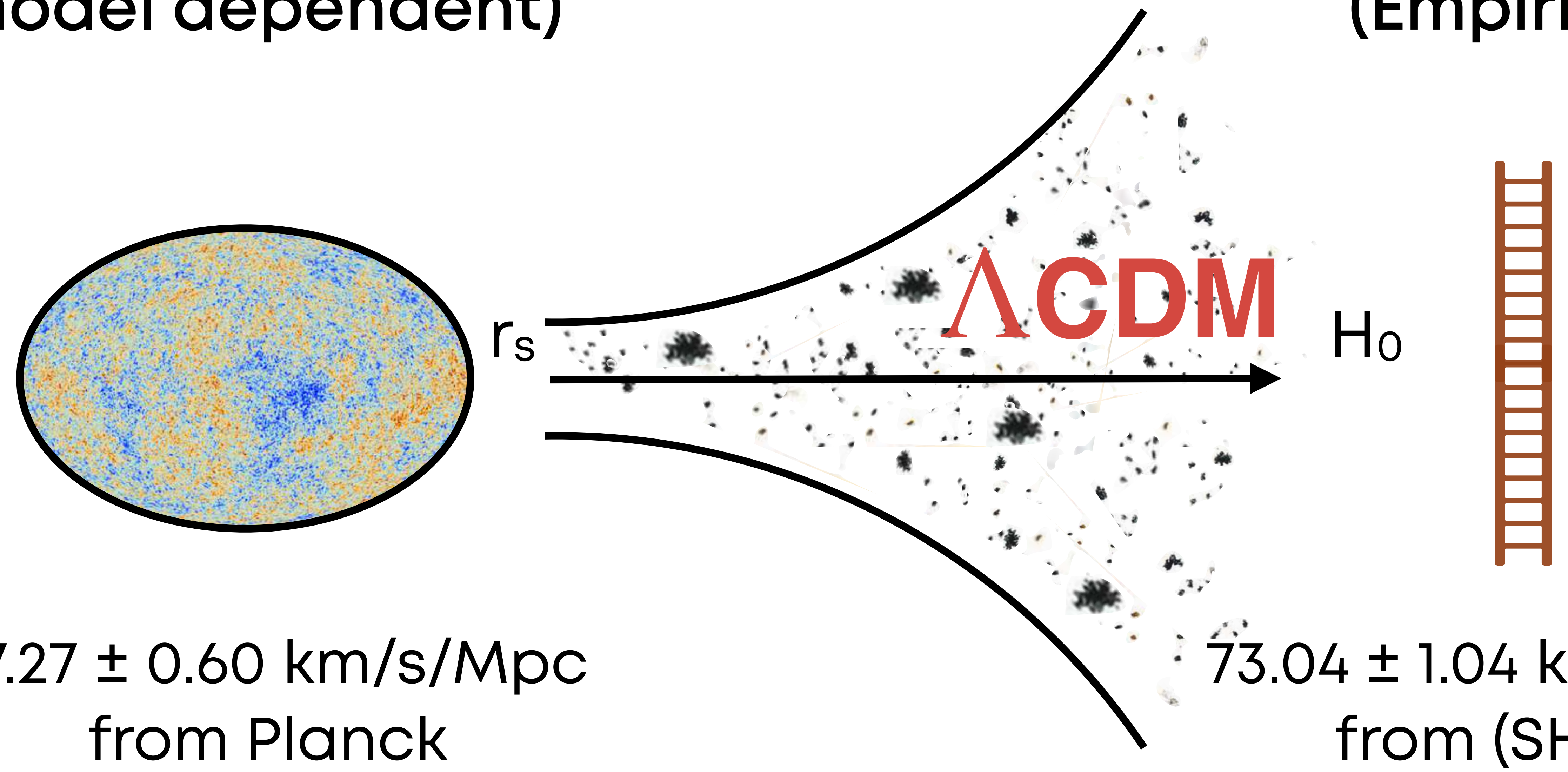
LATE ACCELERATION — **Λ**

Component to explain current accelerated expansion

Cosmological Tensions

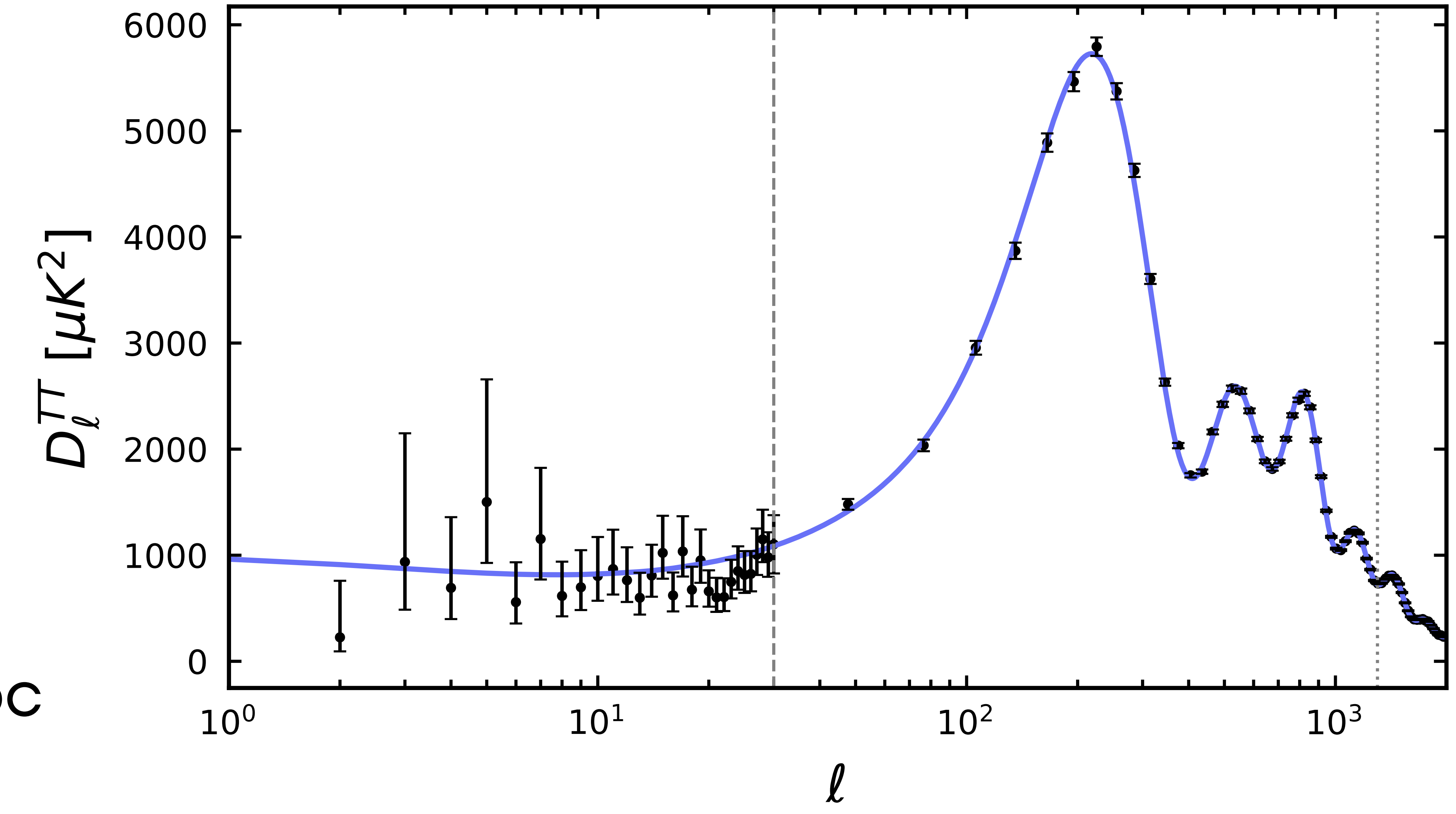
CMB
(model dependent)

Local
(Empirical)



67.27 ± 0.60 km/s/Mpc
from Planck

73.04 ± 1.04 km/s/Mpc
from (SH0ES)



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

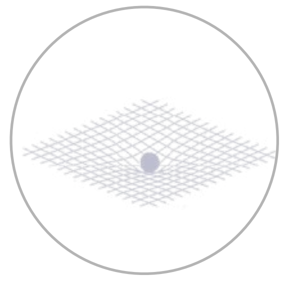
Missing Ingredients or New Physics?

Beyond the Standard Model: Coupled Scalar Dark Sectors

Based on: [S. Rahimy, E. M. Teixeira, I. Zavala: arxiv:2503.01961]

Going Beyond the Standard Model

THEORY OF GRAVITY

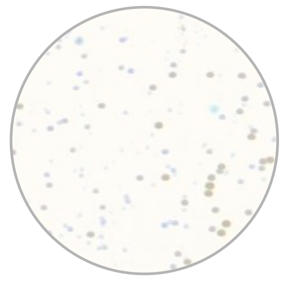


General Relativity:
$G_{\mu\nu} = 8\pi G T_{\mu\nu}$

METRIC ANSATZ

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

STANDARD MATTER



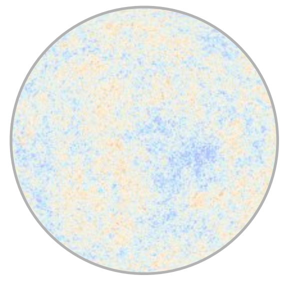
Baryons, Photons, Neutrinos

5%

ΛCDM MODEL

INFLATION — INFLATON

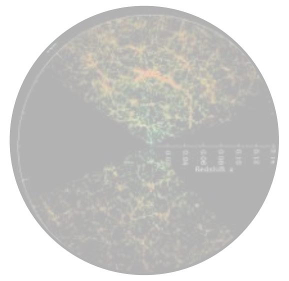
Early accelerated expansion produce density fluctuations



25%

COSMIC STRUCTURE — CDM

Clustering matter component for structure formation



70%

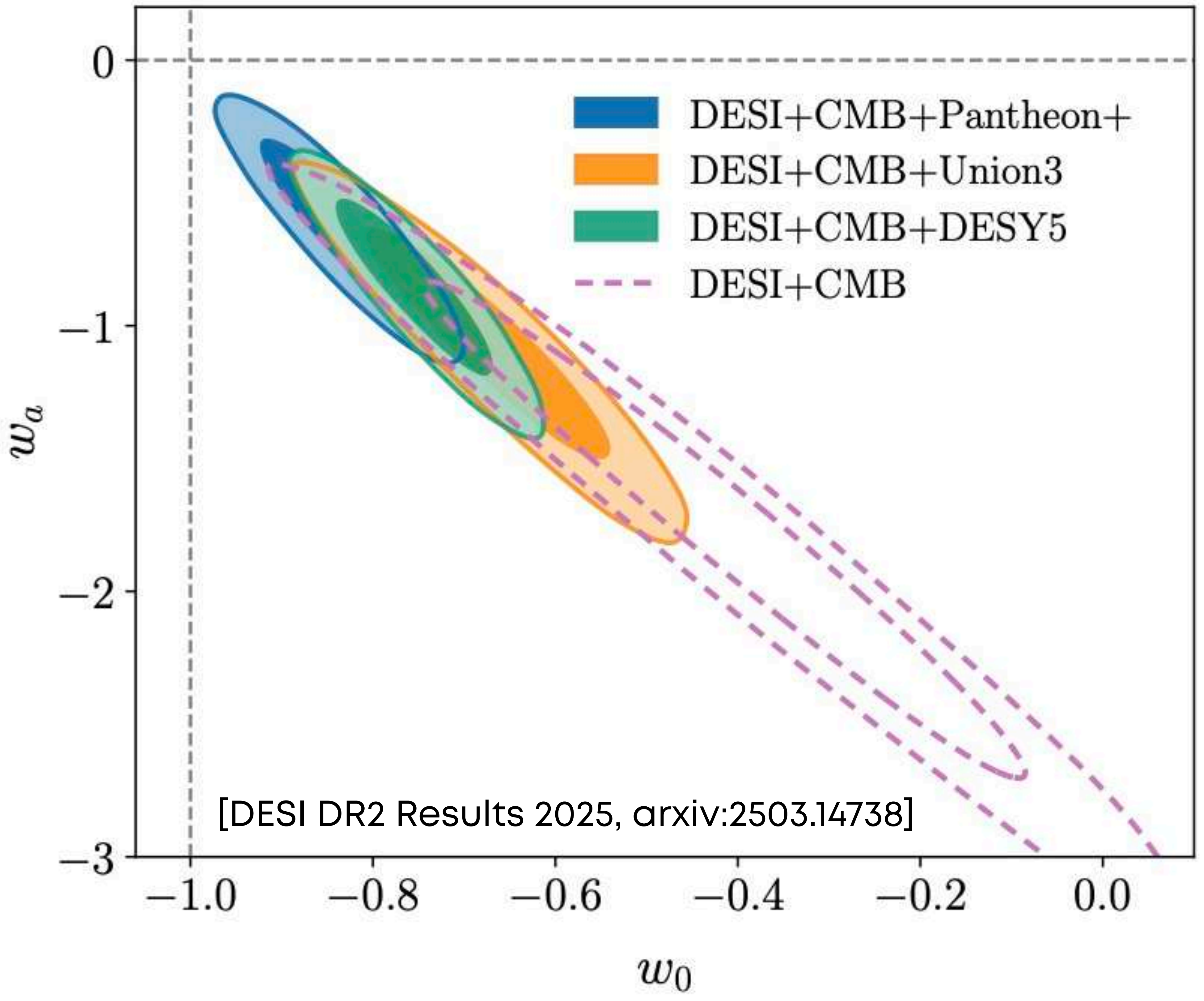
LATE ACCELERATION — Λ

Component to explain current accelerated expansion

Extensions to ΛCDM

Hints of dynamical DE in DESI BAO (baryonic accoustic oscillations) data when combined with CMB and SN data

$$\begin{cases} \dot{\rho}_{\rm DE} + 3H\rho_{\rm DE}(1 + w_{\rm DE}) = 0, \\ w_{\rm DE} = w_0 + w_a(1 - a) \end{cases}$$



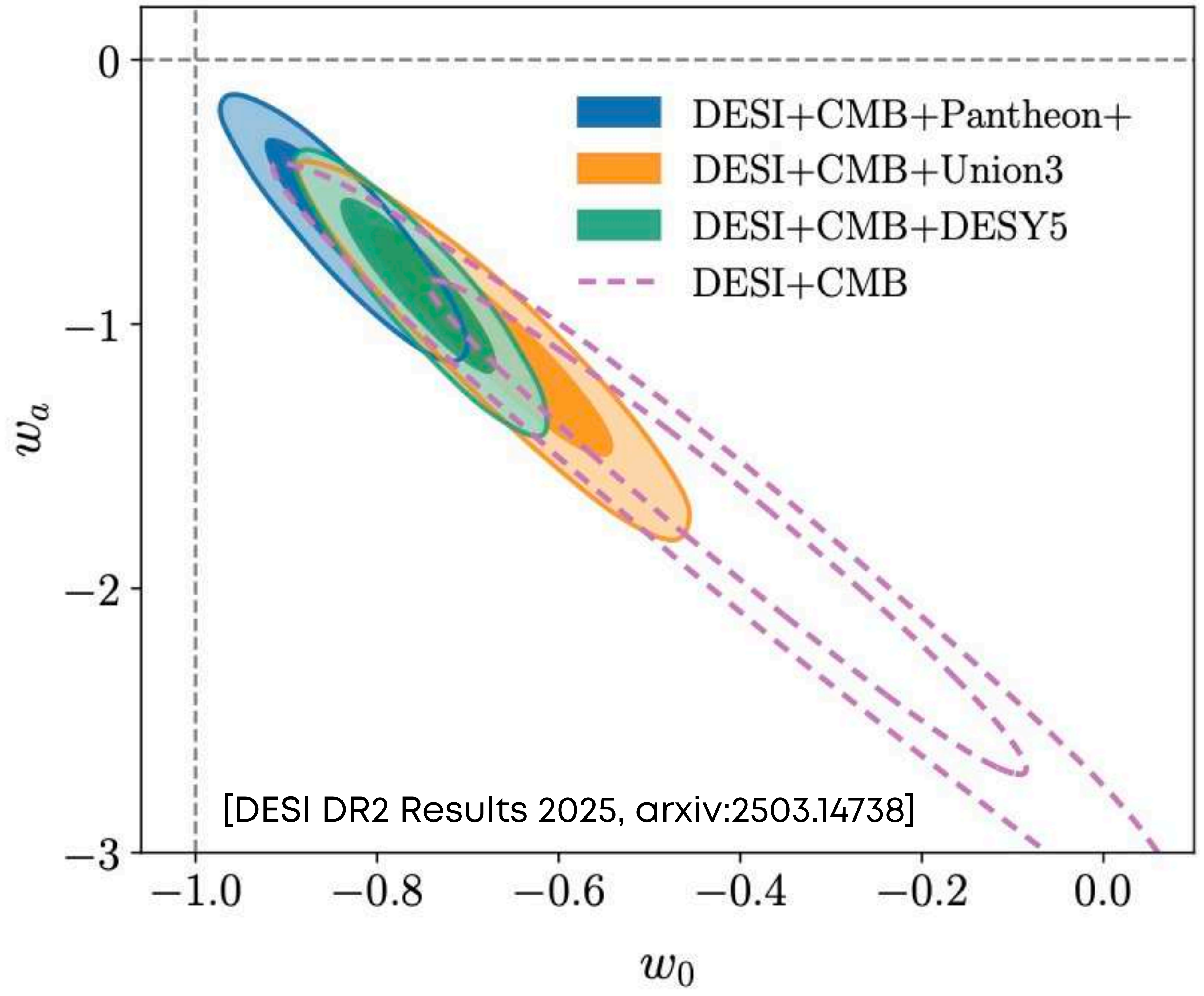
[DESI DR2 Results 2025, arxiv:2503.14738]

Extensions to ΛCDM

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

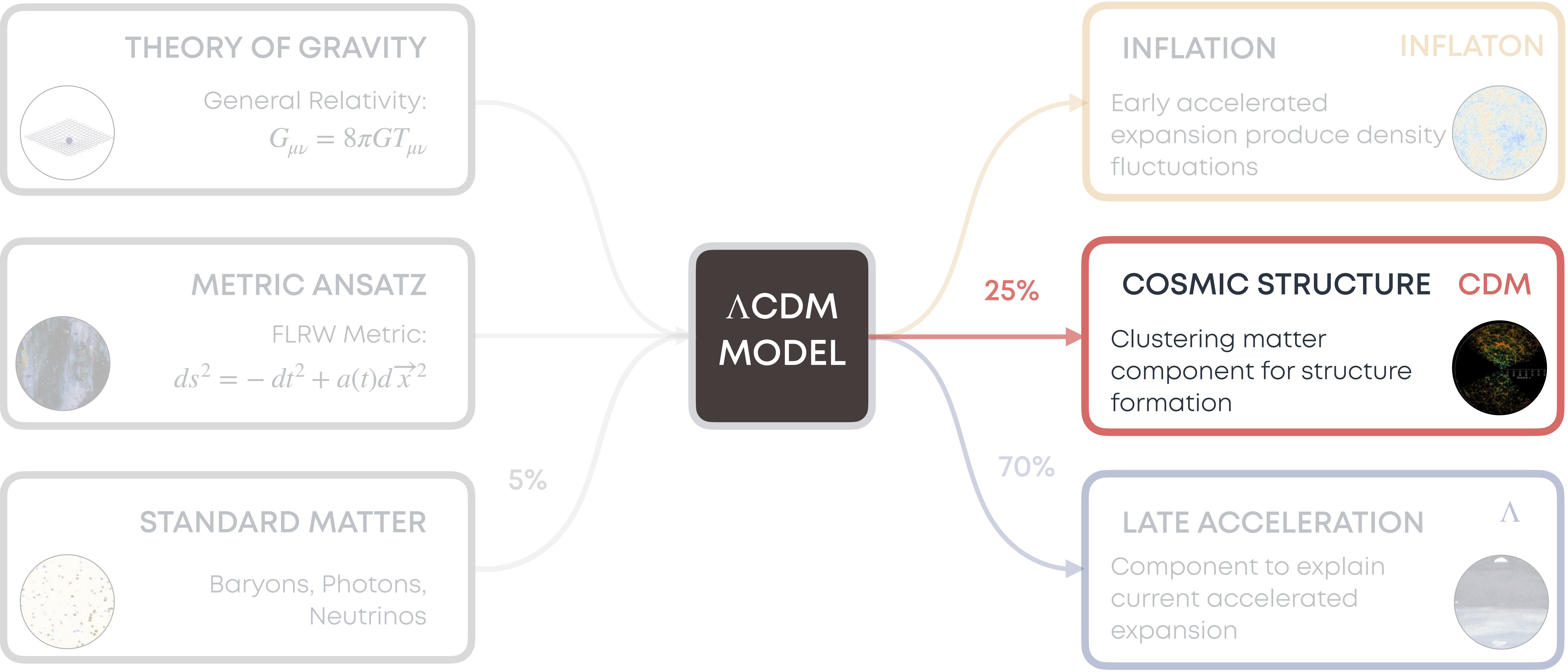
$$\begin{cases} \dot{\rho}_\phi + 3H\rho_\phi(1 + w_\phi) = 0, \\ \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \end{cases}$$

- "Quintessence" (ϕ) - dynamical scalar field that evolves in space and time, as opposed to Λ
- More physically motivated than a parametric fluid
- No fundamental principle/observational constraints which forbid interactions between the dark species
- Modified predictions for the evolution of the dark sector could naturally address the cosmic tensions



Non-trivial Dynamics in the Dark Sector

Going Beyond the Standard Model



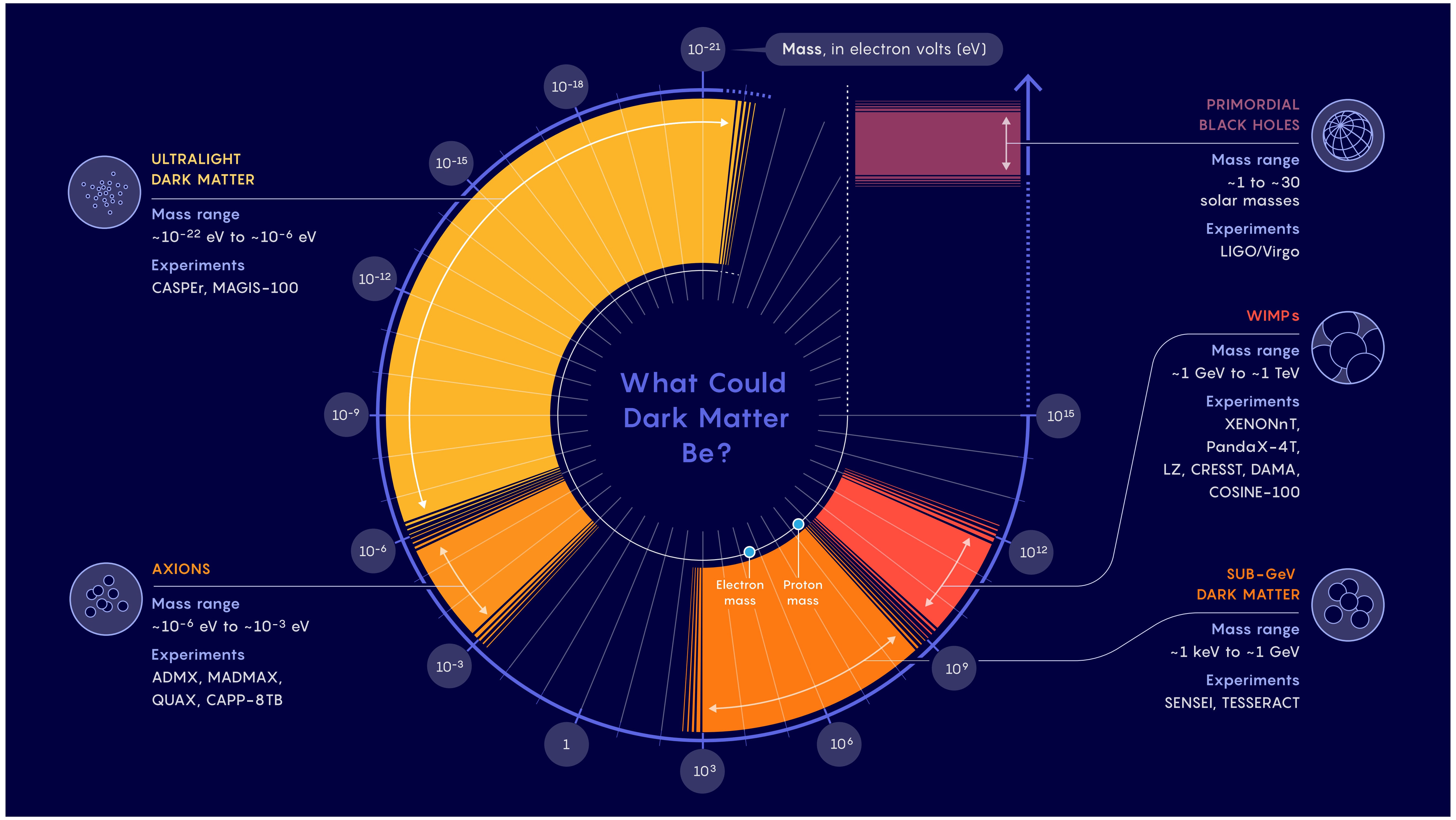
Elsa Teixeira • LUPM (CNRS / U. Montpellier)

Dark Matter Candidates

The dark matter paradigm is the only successful framework for understanding the entire range of observations from the time the Universe is 1 second old

- Dark matter is concrete clue of physics beyond the SM of PP
- The mass scale for DM spans many orders of magnitude
- Large range of parameter space requires particular search strategy
- For masses below eV, the DM has to be bosonic, non-thermal and can be described by a classical field
- Could explain cosmological observations such as PTA stochastic background of GW

[The NANOGrav 15 yr Data Set 2023, Astrophys.J.Lett. 951 (2023) 1, L8]



[Image credit: Quanta magazine]

Coupled Scalar Dark Sector

Two-scalar non-linear sigma model (NLSM) in a target manifold M

described by its metric $g_{ab}(\phi)$ and its curvature $R_{fs}(\phi)$ [SR, **EMT**, IZ: arxiv:2503.01961]

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R + P(X, \phi^a)\right], \quad X \equiv -\frac{1}{2}g_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b$$

Two scalars often originate in fundamental theories such as supergravity and string theory from a single complex scalar field

$$\Phi = \phi + i\chi$$

Coupled Scalar Dark Sector

Two-scalar non-linear sigma model (NLSM) in a target manifold M described by its metric $g_{ab}(\phi)$ and its curvature $R_{fs}(\phi)$ [SR, **EMT**, IZ: arxiv:2503.01961]

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R + P(X,\phi^a)\right], \quad X \equiv -\frac{1}{2}g_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b$$

Standard kinetic terms

$$S_{\rm dark} = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{f^2(\phi)}{2}\partial_\mu\chi\partial^\mu\chi - V(\phi,\chi)\right]$$

Two scalars often originate in fundamental theories such as supergravity and string theory from a single complex scalar field

$$\Phi = \phi + i\chi$$

$$R_{\rm fs} = -\frac{2f_{\phi\phi}}{f}$$

Coupled Scalar Dark Sector

Two-scalar non-linear sigma model (NLSM) in a target manifold M

described by its metric $g_{ab}(\phi)$ and its curvature $R_{fs}(\phi)$ [SR, **EMT**, IZ: arxiv:2503.01961]

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R + P(X,\phi^a)\right], \quad X \equiv -\frac{1}{2}g_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b$$

Standard kinetic terms

$$S_{\rm dark} = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{f^2(\phi)}{2}\partial_\mu\chi\partial^\mu\chi - V(\phi,\chi)\right]$$

Kinetic interaction via the metric through the function $f(\phi)$ just like in conformal transformations

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

Potential interaction between the fields in $g(\phi)$

Two scalars often originate in fundamental theories such as supergravity and string theory from a single complex scalar field

$$\Phi = \phi + i\chi$$

$$R_{\rm fs} = -\frac{2f_{\phi\phi}}{f}$$

Coupled Scalar Dark Sector

Two-scalar non-linear sigma model (NLSM) in a target manifold M described by its metric $g_{ab}(\phi)$ and its curvature $R_{fs}(\phi)$ [SR, **EMT**, IZ: arxiv:2503.01961]

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = ff_\phi\,\dot{\chi}^2,$$
$$\ddot{\chi} + 3H\dot{\chi} + \frac{V_\chi}{f^2} = -2\frac{f_\phi}{f}\,\dot{\phi}\dot{\chi}$$

FLRW background

$$\nabla_\mu T^{\mu\nu}_{(1)} = Q^\nu, \qquad \nabla_\mu T^{\mu\nu}_{(2)} = -\,Q^\nu$$

$$Q^\nu = \frac{f_\phi}{f}(\rho_\chi + p_\chi)\,\nabla^\nu\phi - \frac{g_\phi}{2g}(\rho_\chi - p_\chi)\,\nabla^\nu\phi$$

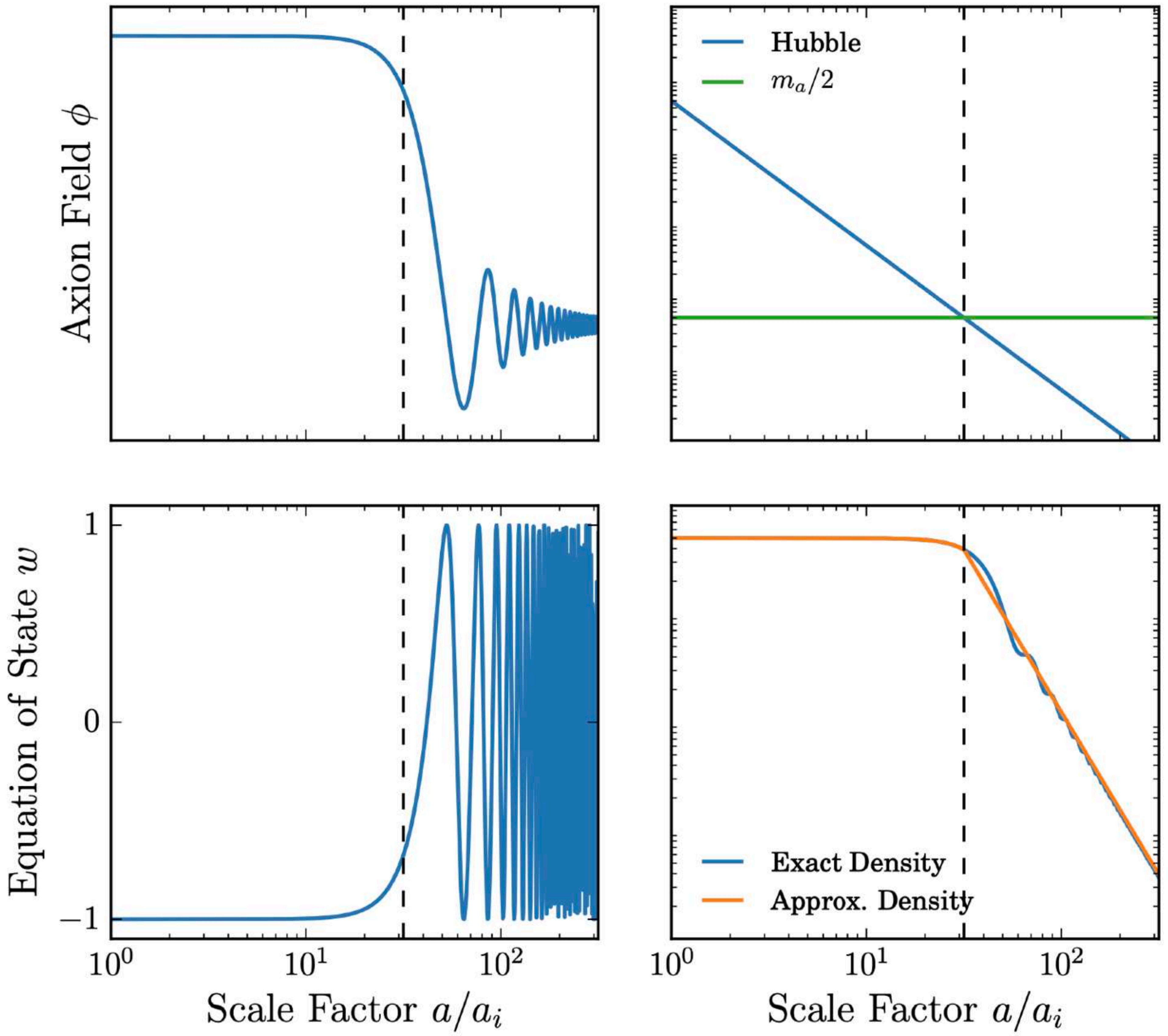
Interacting vector controlled independently by the field space metric $f(\phi)$ and the interaction potential $g(\phi)$

$$V(\phi,\chi) = W(\phi) + g(\phi)U(\chi)$$

Choice of role for the scalars driven by phenomenological considerations (e.g. target space metric independent of χ - continuous shift symmetry in the kinetic term which may be preserved, broken mildly or fully in the potential interaction)

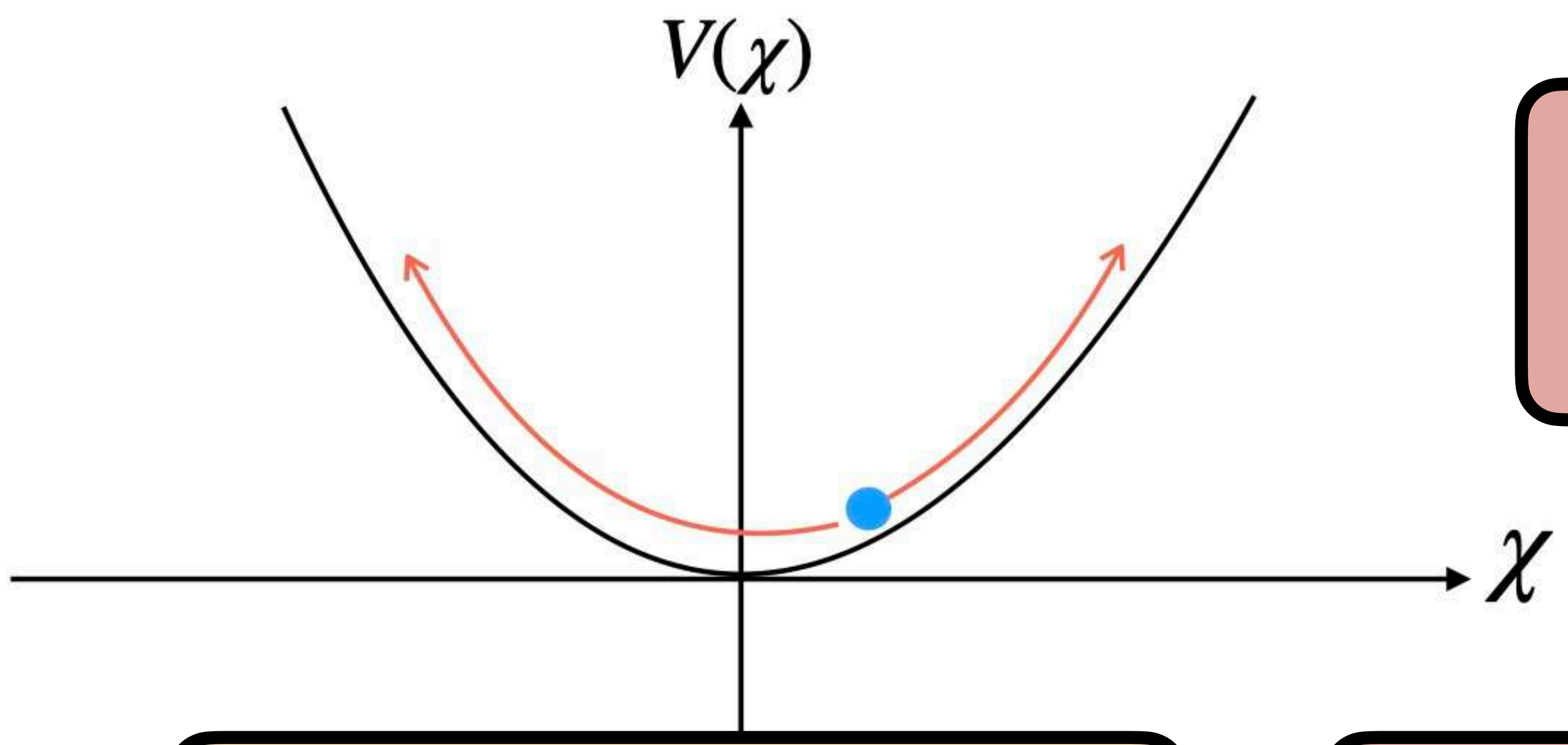
Scalar Field Dark Matter

$$\chi_{\rm osc}(t) = \left(a_0/a\right)^{3/2}\left[\chi_+ \sin(mt) + \chi_- \cos(mt)\right]$$



Energy density: $\rho = \frac{1}{2}\dot{\chi}^2 + \frac{m^2}{2}\chi^2$

Pressure: $p = \frac{1}{2}\dot{\chi}^2 - \frac{m^2}{2}\chi^2$



$$V(\chi) = \frac{1}{2}m^2\chi^2$$

$$\ddot{\chi} + 3H\dot{\chi} + m^2\chi = 0$$

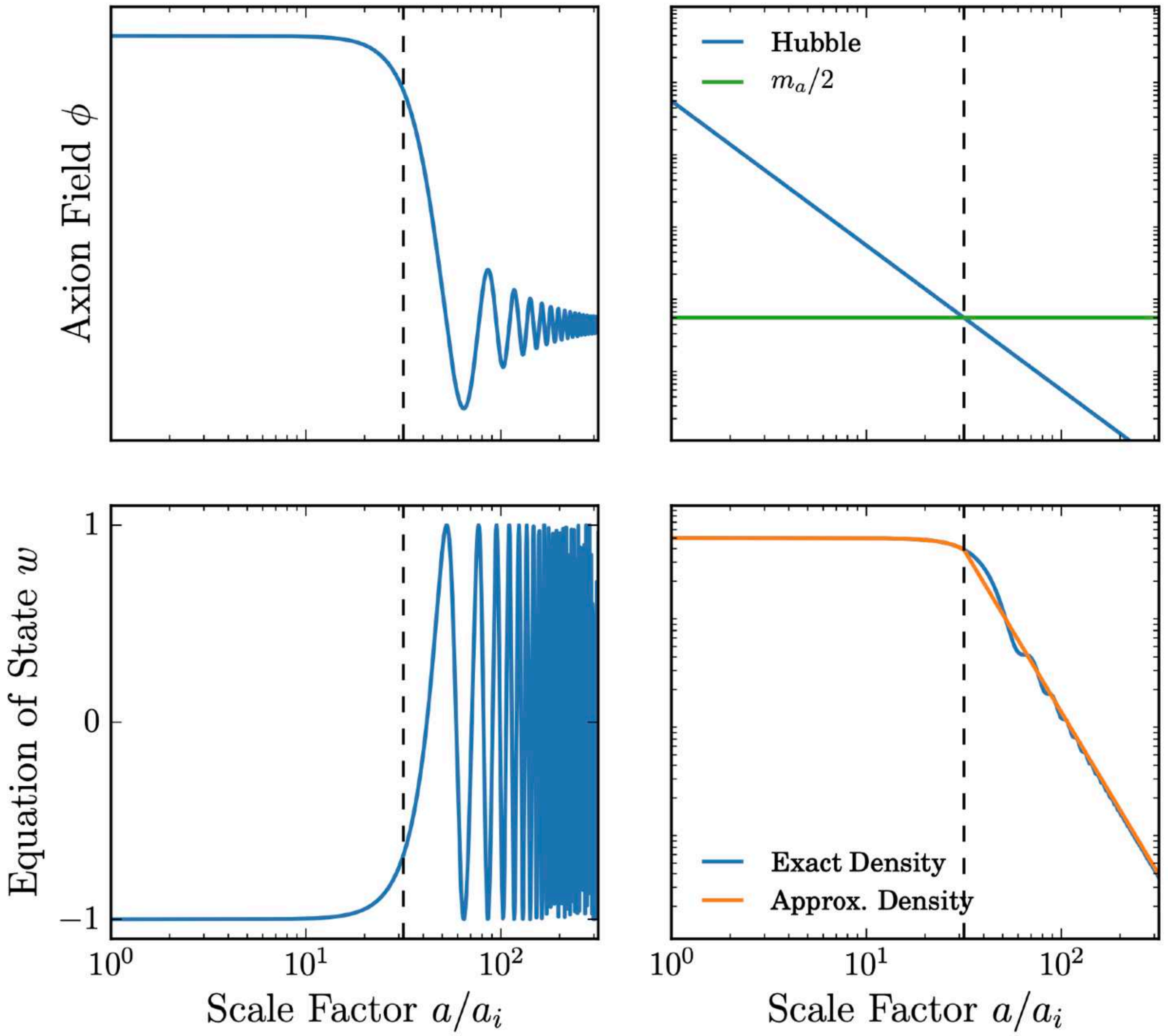
$$\dot{\rho} + 3H\rho(1+w) = 0$$

[R. Hlozek, D. Grin, D. Marsh, P. G. Ferreira, Phys. Rev. D, Phys.Rev.D 91 (2015) 10]

Scalar Field Dark Matter

$$V(\chi) = \frac{1}{2}m^2\chi^2$$

$$\chi_{osc}(t) = (a_0/a)^{3/2}\left[\chi_+ \sin(mt) + \chi_- \cos(mt)\right]$$



- Oscillating field for $m \gg H$ on time scales much faster than the expansion
- Rapid oscillations can be averaged
- Rewrite as a fluid approximation and recover CDM behaviour at the background level with additional scalar field properties

$$\ddot{\chi} + 3H\dot{\chi} + m^2\chi = 0$$

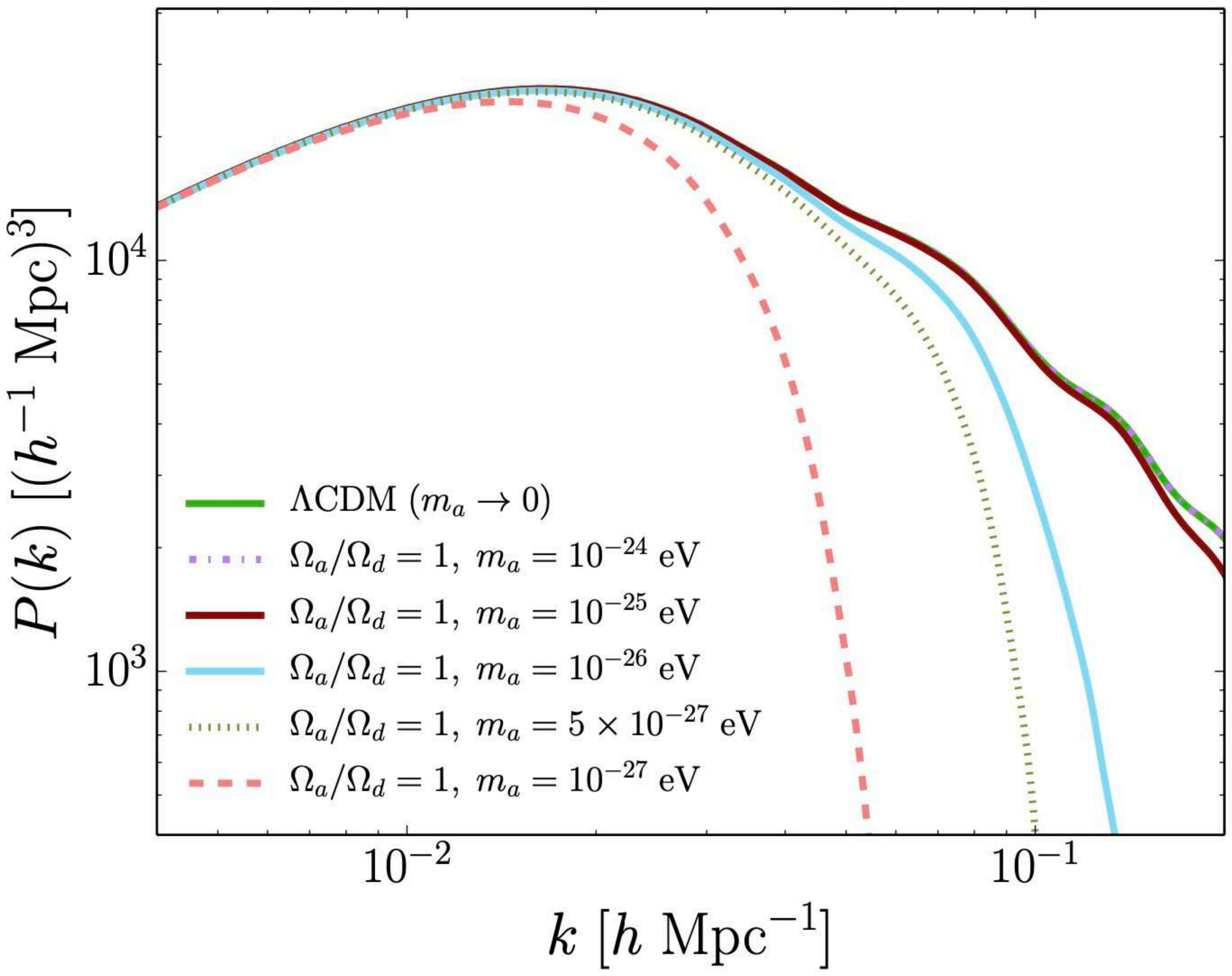
$$\dot{\rho} + 3H\rho(1+w) = 0$$

$$\begin{cases} \langle \rho_\chi \rangle \propto a^{-3} \\ \langle w_\chi \rangle = \left\langle \frac{p_\chi}{\rho_\chi} \right\rangle = 0 \end{cases}$$

[R. Hlozek, D. Grin, D. Marsh, P. G. Ferreira, Phys. Rev. D, Phys.Rev.D 91 (2015) 10]

Scalar Field Dark Matter

Cosmological axion model



- Same spirit of effective fluid formalism for the perturbations
- Dependent on the fraction of axions as DM Ω_a/Ω_d and their mass m_a
- On large scales ($k \ll m_a$), sound speed vanishes, but is non-zero at small scales ($k \gg m_a$)
- Results in a suppression of the matter power spectrum for small scales

$$c_a^2 \equiv \frac{\delta p}{\delta \rho} = \frac{k^2/(4m_a^2a^2)}{1 + k^2/(4m_a^2a^2)} = \begin{cases} k^2/(4m_a^2a^2),\ k \gg 2m_a \\ 1\ \ k \ll 2m_a \end{cases}$$

[R. Hlozek, D. Grin, D. Marsh, P. G. Ferreira, Phys. Rev. D, Phys.Rev.D 91 (2015) 10]

Testing interactions in the dark sector

- Work motivated by modelling the dark sector and understanding its impact for cosmic tensions
- Physical implications of different models and cosmological signatures
- In this talk: two models with couplings in the dark sector:

1. Interactions mediated by potential interaction in scalar field DE and DM (hybrid model)
2. Interactions mediated by kinetic interaction (conformal coupling) in scalar field DE and DM

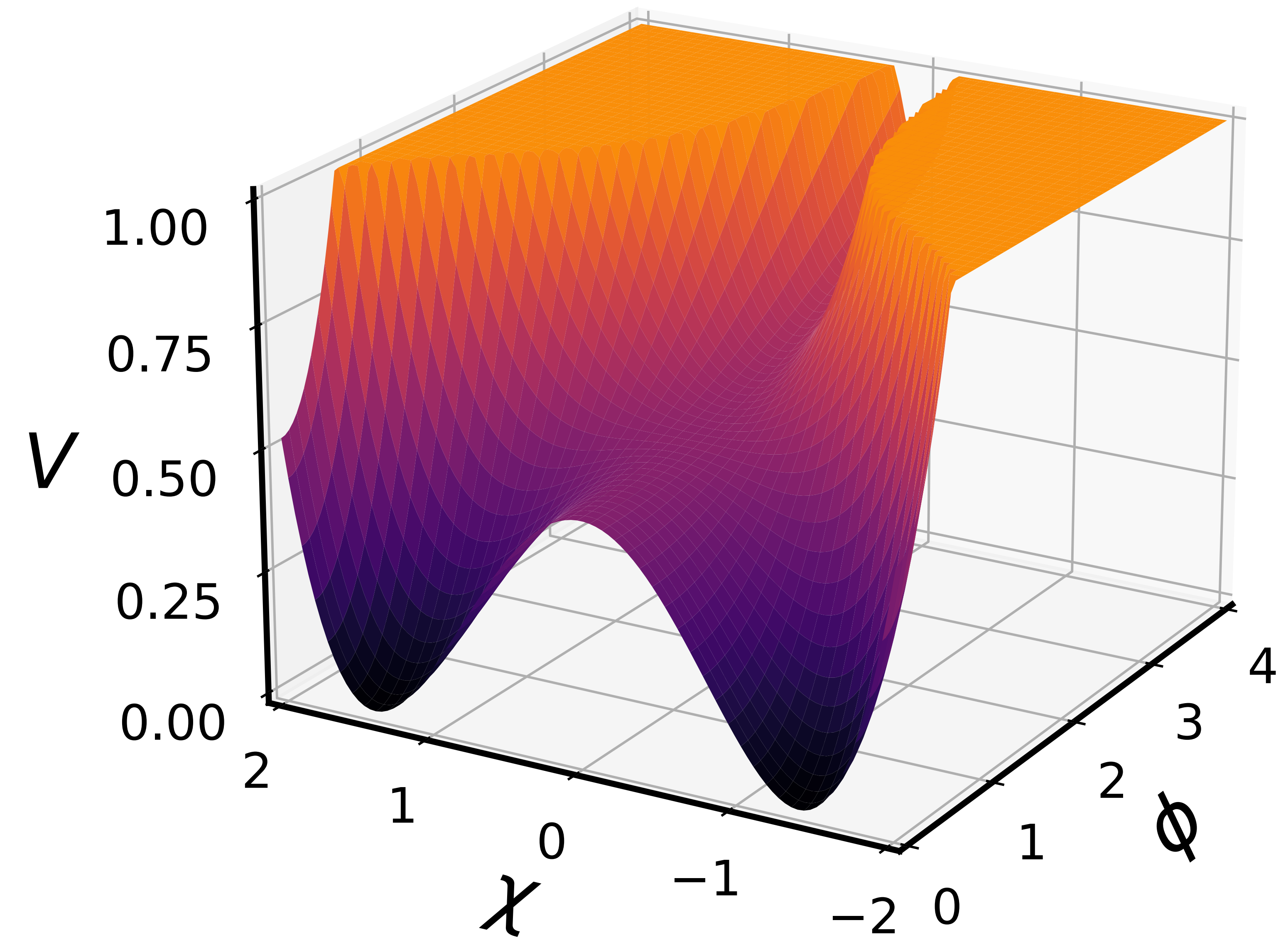
A Hybrid Model for the Dark Sector

Based on: [C. van de Bruck, G. Poulot, E. M. Teixeira: arxiv:2211.13653]

A Hybrid Model for the Dark Sector

Extension of the hybrid inflation model with two scalar fields and the conventional SM matter fields [A.D. Linde, Phys. Rev. D, 49:748–754, 1994]

Hybrid Inflation Potential



[CvB, GP, **EMT**: arxiv:2211.13653]

$$S_{\rm dark} = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}(\partial\chi)^2 - V(\phi,\chi)\right]$$

$$V(\phi,\chi) = V_0 - \frac{1}{2}\lambda M^2\chi^2 + \frac{1}{4}\lambda\chi^4 + \frac{1}{2}g^2\phi^2\chi^2 + \frac{1}{2}\mu^2\phi^2$$

second derivative

$$m_\chi^2 = g^2\phi^2 - \lambda M^2 + 3\lambda\chi^2$$
$$m_\phi^2 = g^2\chi^2 + \mu^2$$

Hybrid Potential interaction

ϕ is dark energy and χ is dark matter

Effective Fluid Description

- The mass of the DM field is effectively (small self-interactions):

$$m_\chi = g^2\phi^2 - \lambda M^2$$

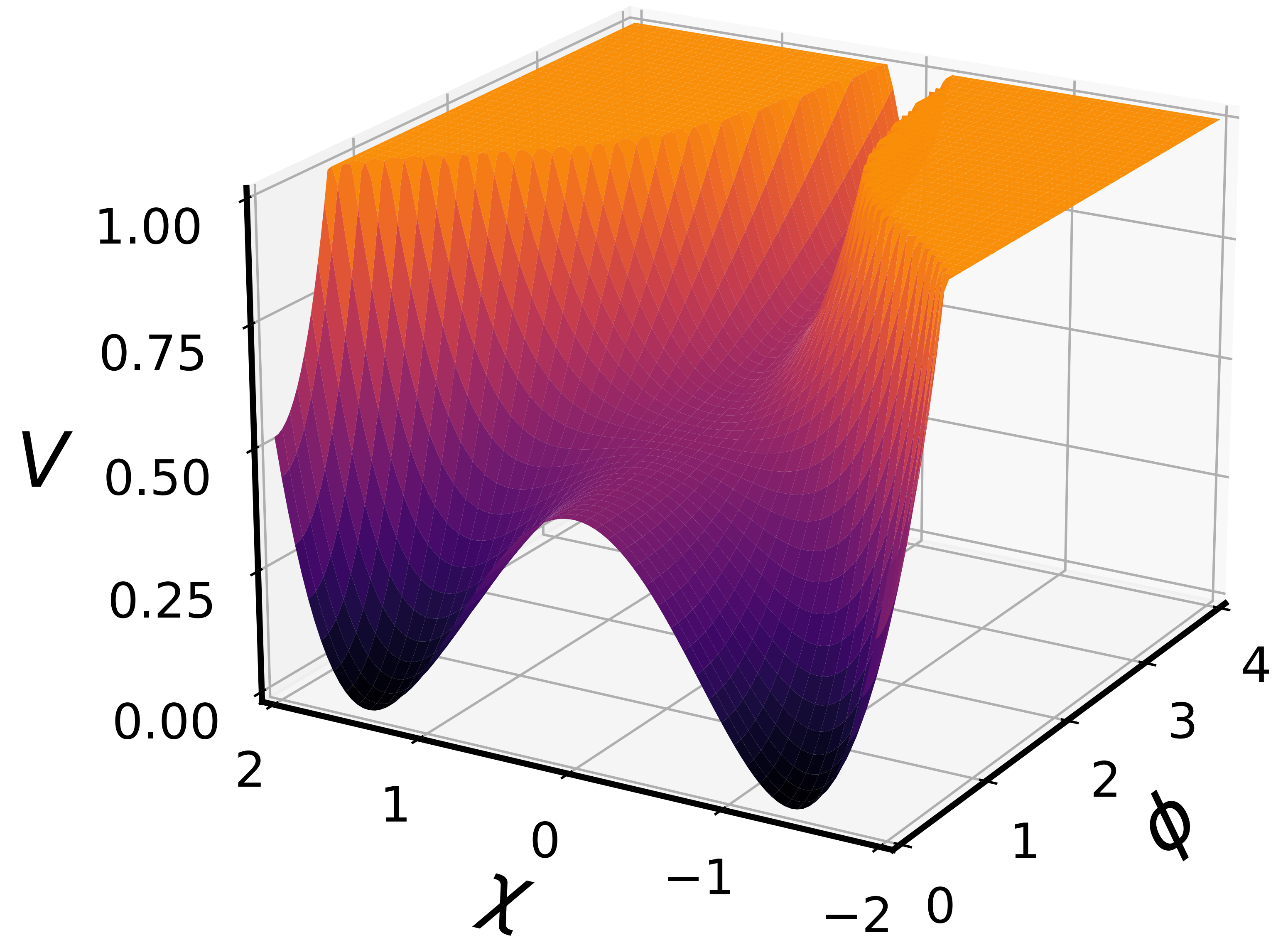
- Energy density of DM field:

$$\rho_\chi = \frac{1}{2}\dot{\chi} + \frac{1}{4}\lambda\chi^4 + \frac{1}{2}g^2\phi^2\chi^2 - \frac{1}{2}\lambda M^2\chi^2$$

- At the global minimum the potential vanishes and therefore period of DE is transient. Ends at (when $m_\chi \approx 0$ and $V \approx 0$):

$$\phi_c \approx \sqrt{\lambda}M/g$$

Hybrid Inflation Potential



For ϕ to act as DE we need

$$V_{\rm DE} = V_0 + \frac{1}{2}\mu^2\phi^2$$

This implies that $V_0 = \frac{1}{4}\lambda M^4$ is of order of DE scale and μ is sufficiently small (slow-roll)

Effective Fluid

Coupled quintessence model with a fluid description DM field χ

- For χ to act as DM, we need its mass to be suffciently large: $m_\chi \approx g\phi \gg H$
- χ is oscillating in a quadratic potential → WKB approximation ($g\phi \gg H$ and $\dot{\phi}/\phi \ll 1$)
- ϕ is slow rolling ($\phi/\phi_i \sim$ const.) and χ behaves like a pressureless fluid with $\rho_\chi \propto \chi^2 \propto a^{-3}$, $\rho_{\chi,i} = 1/2\, g^2\phi_i^2\chi_i^2$

$$\chi(t) = \chi_i \left(\phi_i/\phi\right)^{1/2} \left(a_i/a\right)^{3/2} \sin\left(g\phi\,(t - t_i)\right)$$

$$\langle\rho_\chi\rangle \approx \rho_{\chi,i}\left(\phi/\phi_i\right)\left(a_i/a\right)^3$$

Effective Fluid

Coupled quintessence model with a fluid description DM field χ

- For χ to act as DM, we need its mass to be suffciently large: $m_\chi \approx g\phi \gg H$
- χ is oscillating in a quadratic potential → WKB approximation ($g\phi \gg H$ and $\dot{\phi}/\phi \ll 1$)
- ϕ is slow rolling ($\phi/\phi_i \sim$ const.) and χ behaves like a pressureless fluid with $\rho_\chi \propto \chi^2 \propto a^{-3}$, $\rho_{\chi,i} = 1/2\, g^2\phi_i^2\chi_i^2$
- Continuity equation for interacting fluid
- Theory is equivalent to a model with conformal coupling $C(\phi) = \phi^2/M_{Pl}^2$

$$\chi(t) = \chi_i \left(\phi_i/\phi\right)^{1/2} \left(a_i/a\right)^{3/2} \sin\left(g\phi\,(t - t_i)\right)$$

$$\langle\rho_\chi\rangle \approx \rho_{\chi,i} \left(\phi/\phi_i\right) \left(a_i/a\right)^3$$

$$\dot{\rho}_c + 3H\rho_c = \frac{\dot{\phi}}{\phi}\rho_c, \quad \dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = -\frac{\dot{\phi}}{\phi}\rho_c$$

Effective Fluid

Coupled quintessence model with a fluid description DM field χ

- For χ to act as DM, we need its mass to be suffciently large: $m_\chi \approx g\phi \gg H$

- χ is oscillating in a quadratic potential → WKB approximation ($g\phi \gg H$ and $\dot{\phi}/\phi \ll 1$)

- ϕ is slow rolling ($\phi/\phi_i \sim$ const.) and χ behaves like a pressureless fluid with $\rho_\chi \propto \chi^2 \propto a^{-3}$, $\rho_{\chi,i} = 1/2\, g^2 \phi_i^2 \chi_i^2$

- Continuity equation for interacting fluid

- Theory is equivalent to a model with conformal coupling $C(\phi) = \phi^2/M_{Pl}^2$

- In the MDE ϕ scales with DM - only IDE theory with a constant potential with this feature

$$\chi(t) = \chi_i \left(\phi_i/\phi\right)^{1/2} \left(a_i/a\right)^{3/2} \sin\left(g\phi\,(t - t_i)\right)$$

$$\langle\rho_\chi\rangle \approx \rho_{\chi,i} \left(\phi/\phi_i\right) \left(a_i/a\right)^3$$

$$\dot{\rho}_c + 3H\rho_c = \frac{\dot{\phi}}{\phi}\rho_c, \quad \dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = -\frac{\dot{\phi}}{\phi}\rho_c$$

MDE

$$\frac{1}{a^3}\frac{\mathrm{d}}{\mathrm{d}t}\left(a^3\dot{\phi}\right) = -\frac{\rho_{\chi,i}}{\phi_i}\left(\frac{a_i}{a}\right)^3$$

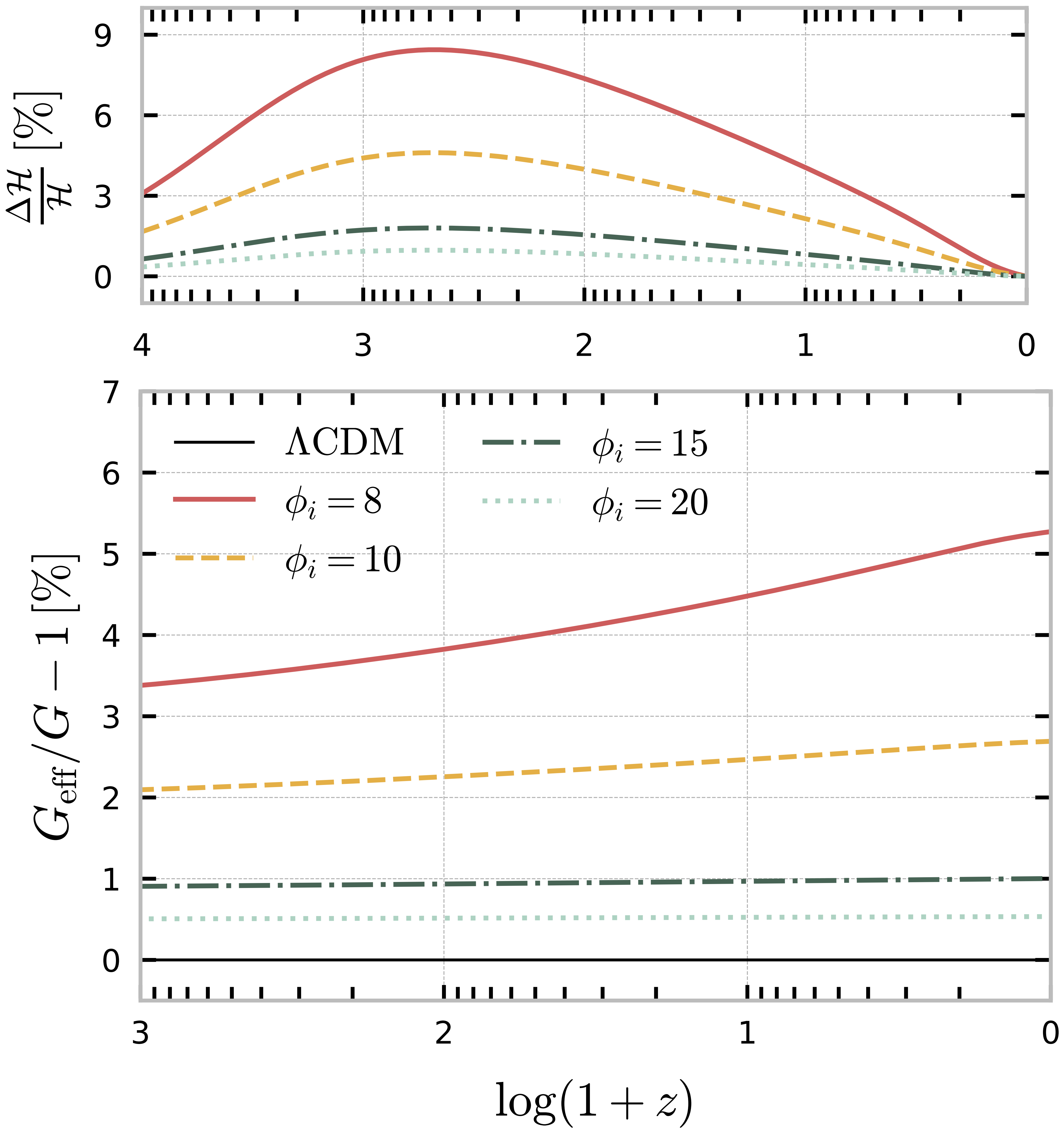
$$\rho_\phi \propto \dot{\phi}^2 \propto a^{-3}$$

Modified Dynamics

- Modified version of CLASS with different ϕ_i and $\dot{\phi}_i = 0$
  [Blas, Lesgourgues, Tram: JCAP 1107 (2011) 034]
- Effective Newton's constant between DM particles is modified with the coupling
- One result is that ϕ has to be trans-Planckian and hence the DM field is heavy in this theory (unless g is exceedingly small, direct contrast with models with ultralight and light scalar fields as DM candidates)
- More significant contribution from the coupling to the scalar field dynamics

$$G_{\text{eff}} \simeq G\left(1 + 2\mathbf{M}_{Pl}^2 \frac{Q^2}{\rho_\chi^2}\right)$$

$$Q = -\frac{\rho_\chi}{\phi}$$



Alleviating cosmological tensions with a hybrid dark sector

Based on: [E. M. Teixeira, G. Poulot, C. van de Bruck, E. Di Valentino, V. Poulin: arxiv:2412.14139]

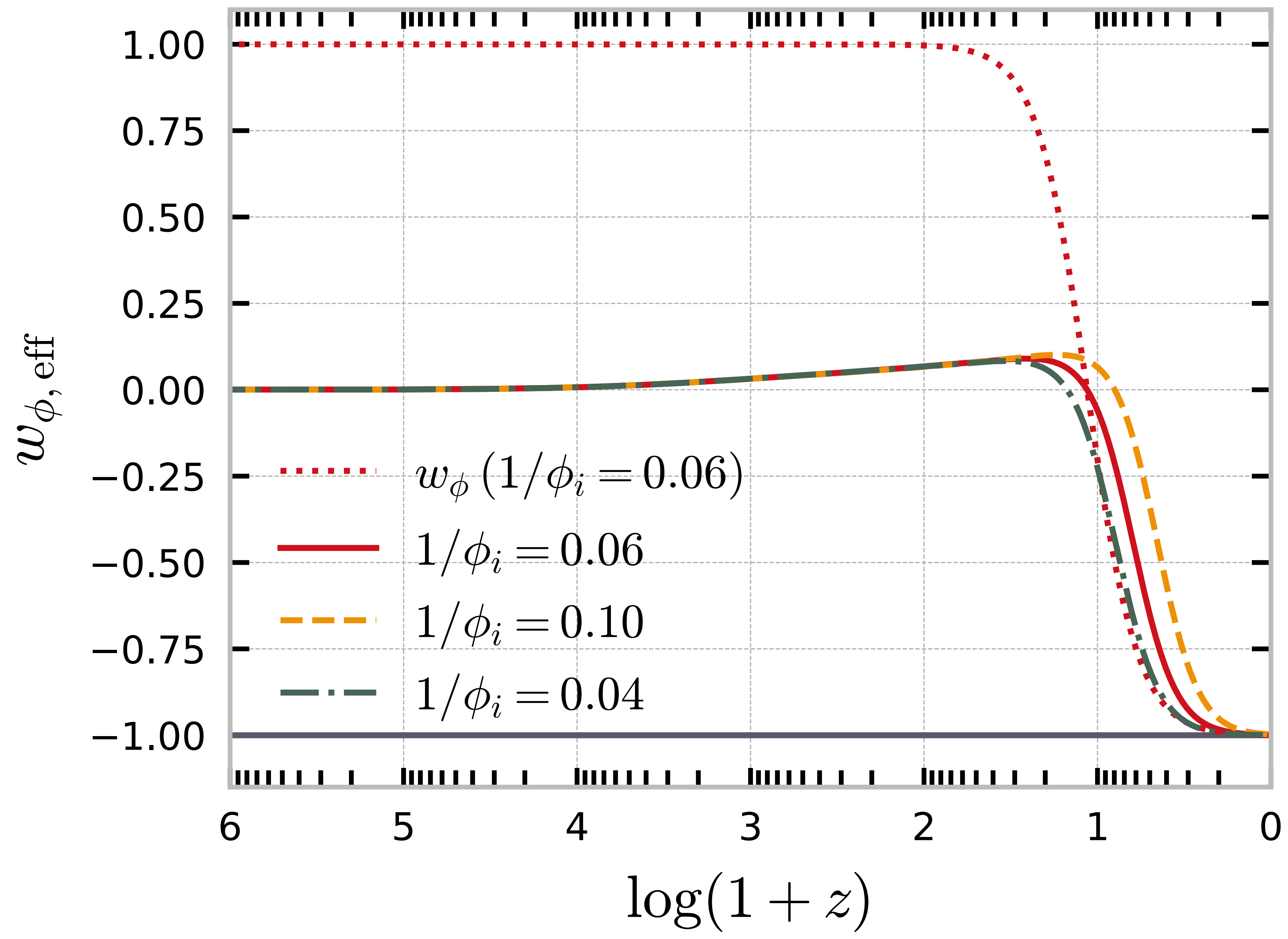
Effective Dynamics

$$\rho_{\phi,\text{eff}} = \rho_\phi + \rho_c - \rho_{c,0} a^{-3}, \; w_{\phi,\text{eff}} = \frac{p_\phi}{\rho_{\phi,\text{eff}}}$$

- In practice we have a coupled quintessence model
- The coupling is proportional to $1/\phi$
- Modified dynamics fully determined by the initial value of the DE field ϕ_i
- One parameter extension of ΛCDM $(1/\phi_i \to 0)$
- DM contribution from the coupling - a fraction of the DM energy density becomes DE at late times

$$\dot{\rho}_c + 3H\rho_c = \frac{\dot{\phi}}{\phi}\rho_c$$

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{1}{\phi}\rho_c$$

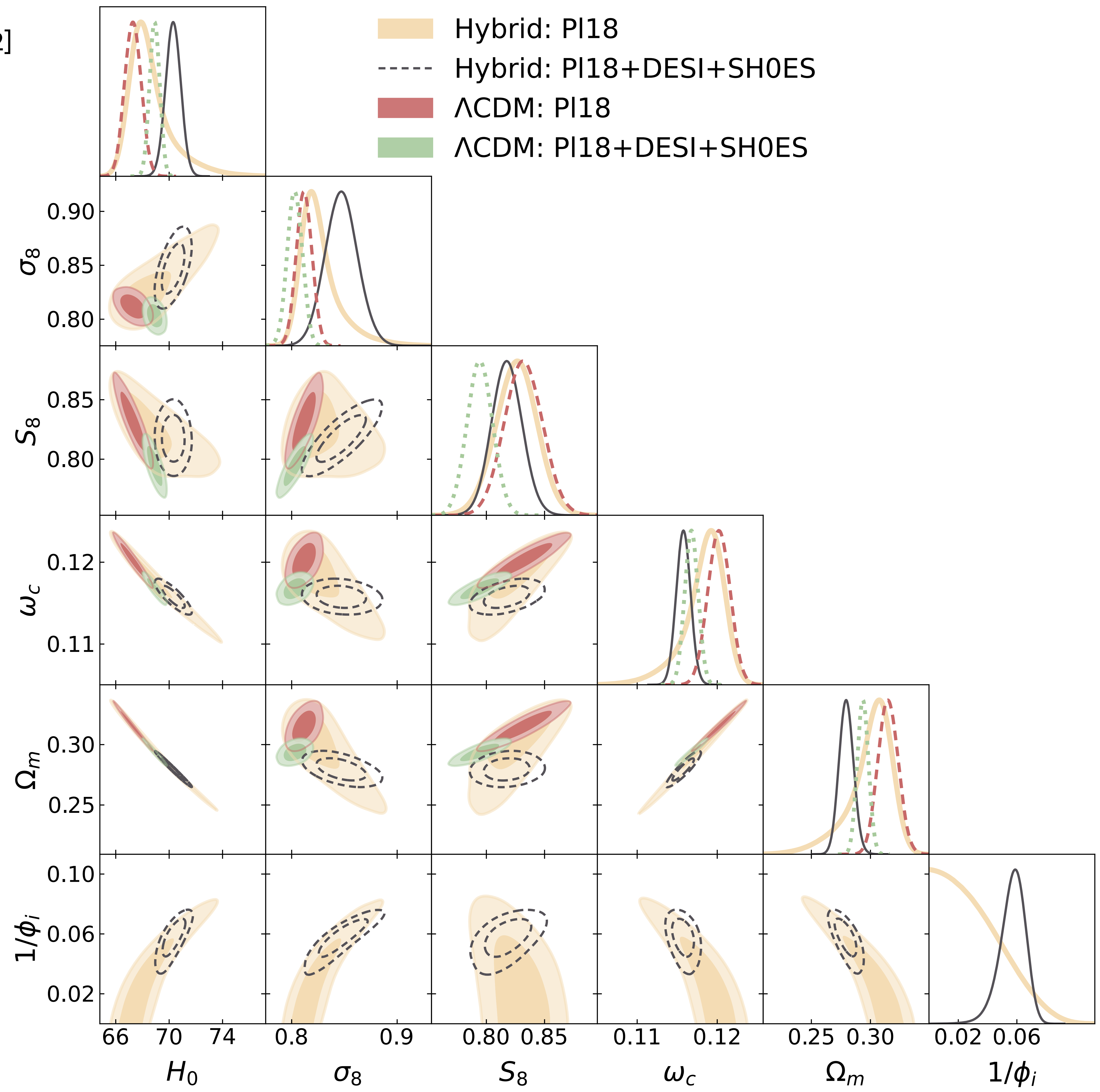


[**EMT**, GP, CvB, EDV, VP: arxiv:2412.14139]

Results

[Aghanim et al.: Astron.Astrophys. 641 (2020) A5]
[A. G. Adame et al. (DESI), (2024), arXiv:2404.03002]
[Brout et. al: Astrophys. J. 938 (2022) 110]
[Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]

- Constraints with Planck (Pl18) are very similar to the ΛCDM case but with enlarged errors
- Positive correlation between the coupling $(1/\phi_i)$ and H_0 and negative correlation with $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$ - alleviate cosmic tensions
- Detection of the coupling parameter with DESI data
- DESI breaks geometrical degeneracies in CMB - more sensitive to the dynamical behaviour of the dark sector at late times
- DESI data attempts to bring physical matter density down in ΛCDM (slight disagreement with Pl18) **[EMT, GP, CvB, EDV, VP: arxiv:2412.14139]**

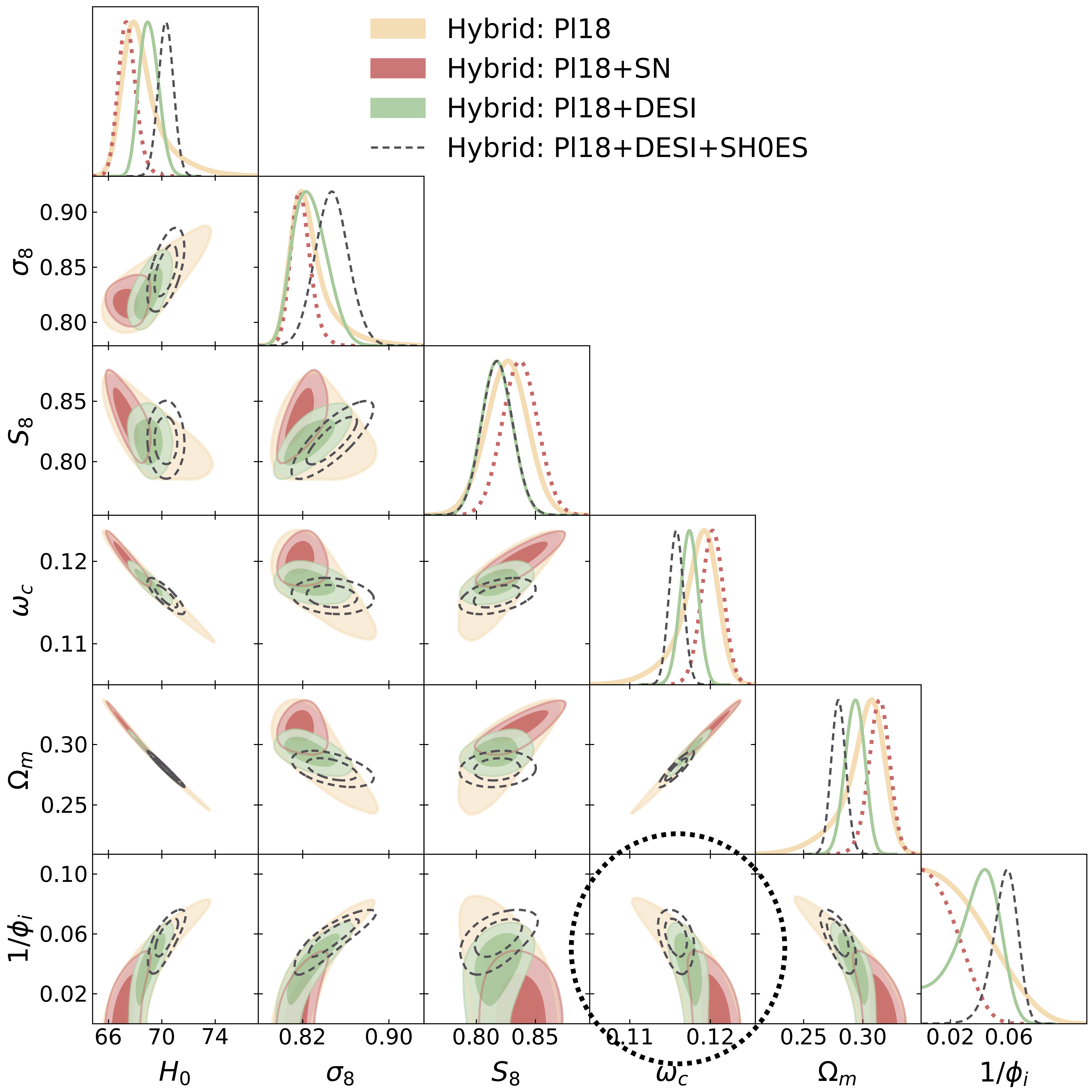


Results

- DM component decays faster than in ΛCDM due to scaling behaviour of DE and coupling

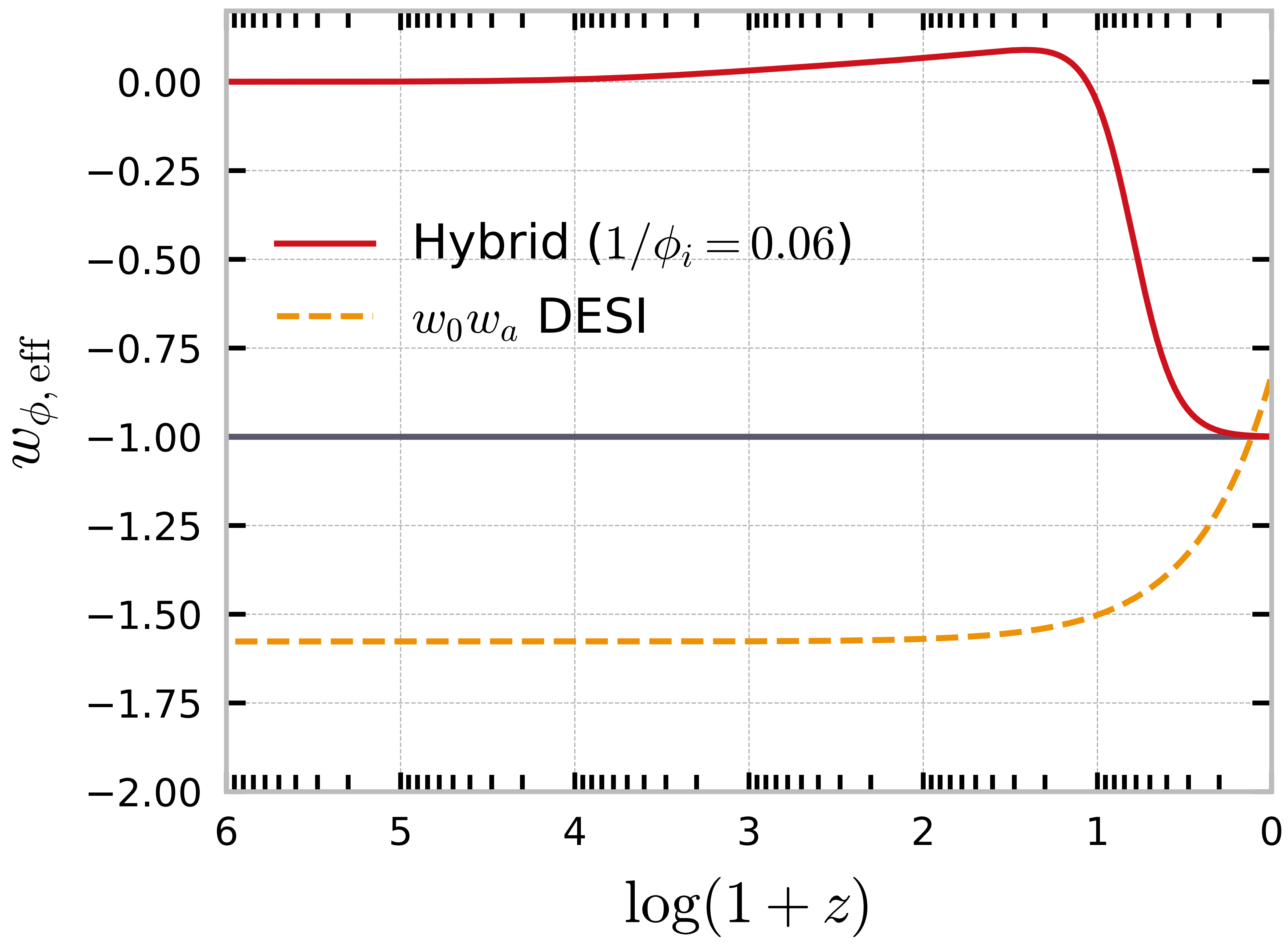
- Initially the matter density is slightly larger than in ΛCDM and smaller at present, decreasing ω_c

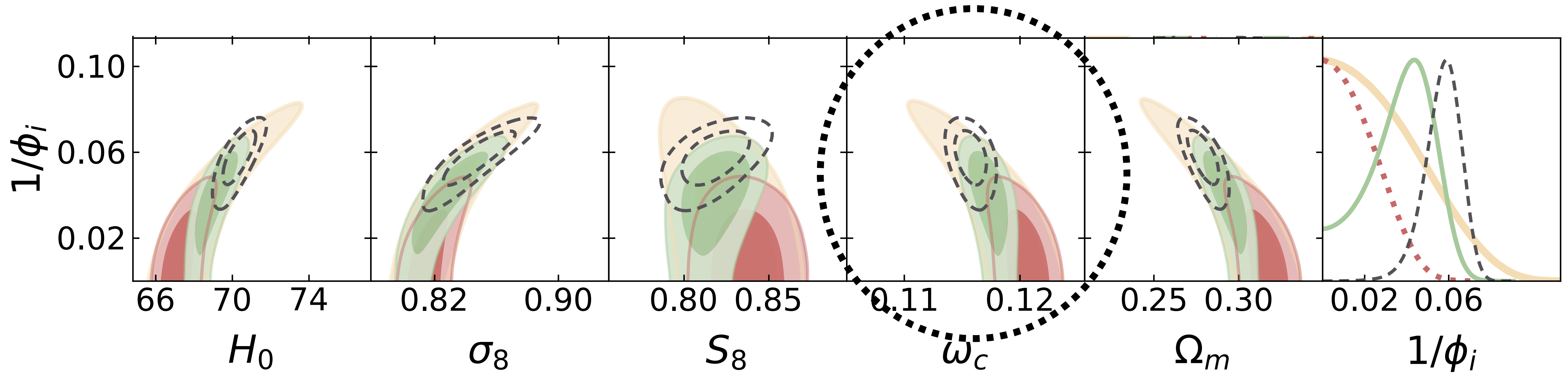
- The additional contribution to ρ_c coming from coupling/effective fluid is favoured with DESI ($\Delta\chi^2_{\rm min} = 0.14 \rightarrow -2.8$)



Results

- DM component decays faster than in ΛCDM due to scaling behaviour of DE and coupling
- Initially the matter density is slightly larger than in ΛCDM and smaller at present, decreasing ω_c
- The additional contribution to ρ_c coming from coupling/effective fluid is favoured with DESI ($\Delta\chi^2_{\rm min} = 0.14 \to -2.8$)
- DESI found preference for phantom DE over ΛCDM
- Instead we have a coupled dark sector with a non-vanishing detection of $1/\phi_i > 0$ and $w_{\phi,\rm eff}$ never becomes phantom

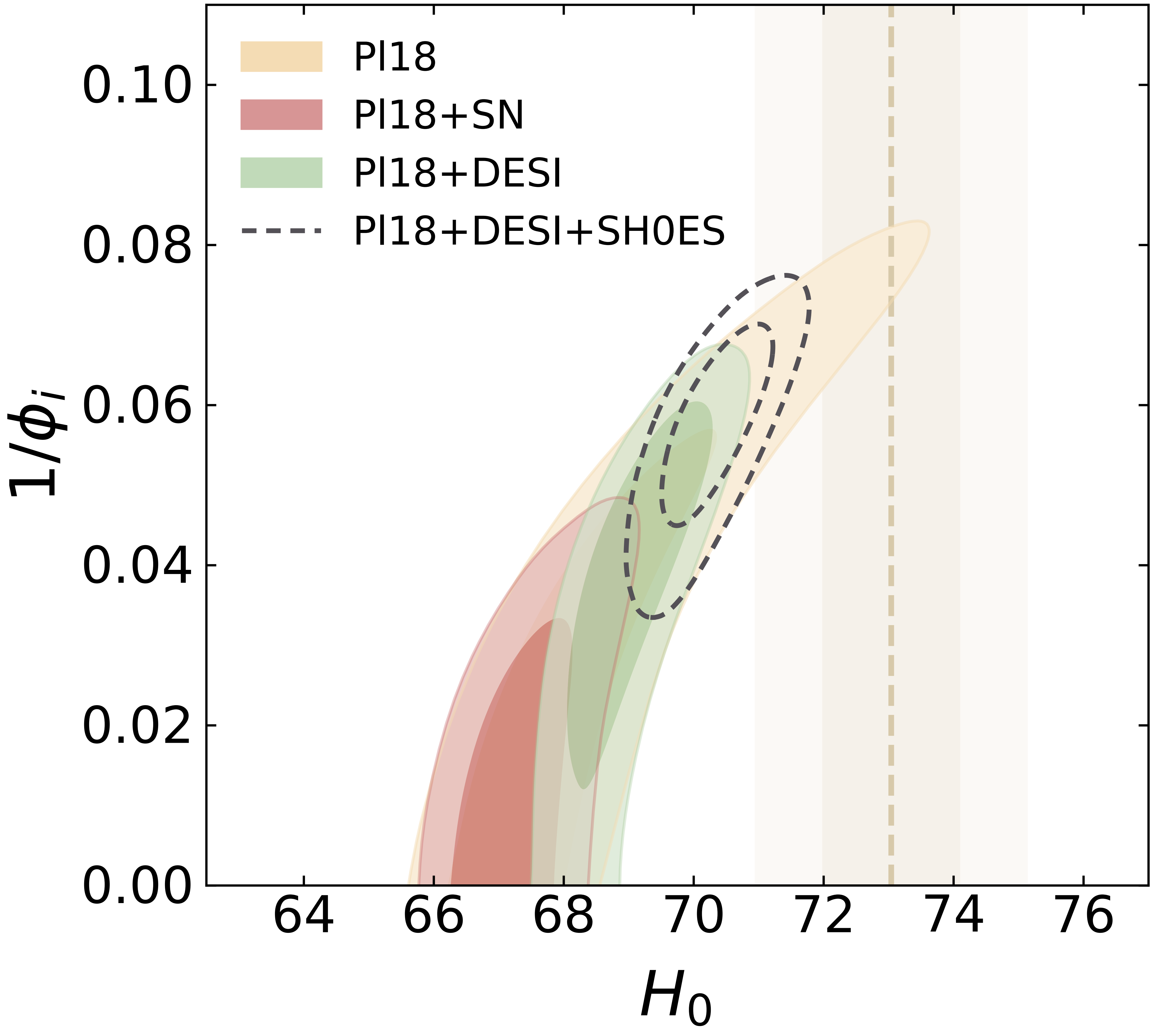




Results

- Alleviate the H_0 tension by increasing the coupling
- More significance when imposing SH0ES calibration
- SH0ES calibration: increase in $\Delta\chi^2_{\rm min} = 0.08 \to -16.32$, for Pl18+SH0ES, $\Delta\chi^2_{\rm min} = -1.06 \to -12.76$ for Pl18+DESI+SH0ES
- Bayesian evidence indicates support for hybrid model with SH0ES but is inconclusive otherwise
- The QDMAP tension metric shows that there is still a residual tension hidden in worsened fit to Pl18 and DESI (~4 in Hybrid vs ~6 in ΛCDM)

$$Q^{\rm SH0ES}_{\rm DMAP,\,D} = \sqrt{\chi^2_{\rm min}({\rm D}+M_B) - \chi^2_{\rm min}({\rm D})}$$



Scalar field dark matter with time-varying equation of state

Based on: [G. Poulot, E. M. Teixeira, C. van de Bruck, N. Nunes: arxiv:2404.10524]

Coupled SF Dark Matter

Extension of the cosmological axion model coupled to quintessence dark energy

Interacting dark energy

$f^2(\phi) = C(\phi)$

$g(\phi) = C^2(\phi)$

$$S_{\text{dark}} = \int d^4x \left[\sqrt{-g}\mathscr{L}_\phi\left(g_{\mu\nu}, \phi\right) + \sqrt{-\bar{g}}\bar{\mathscr{L}}_{\text{m}}\left(\bar{g}_{\mu\nu}(g_{\mu\nu}, \phi), \chi\right)\right]$$

IDE's that seem to address the Hubble tension:
[E. Di Valentino, A. Melchiorri and O. Mena: Phys. Rev. D 96 (2017) 043503]

Conformal Transformation: Kinetic+Potential Coupling

- Simplest way to relate two geometries
- Functional dependence on scalar field already present in the theory
- Map non-standard theories of gravity into GR plus ϕ minimally coupled to the geometry [Jordan: Z. Phys. 157 (1959), 112; Brans and Dicke: Phys. Rev. 124 (1961), 925]

$$\bar{g}_{\mu\nu} = C(\phi) g_{\mu\nu}, \quad \nabla T_{\text{dark}} \propto \pm Q, \quad Q \propto \frac{C_{,\phi}}{C}\rho_\chi$$

$Q \propto H\xi\rho_\phi$ → **Two scalar fields - Exchange role of DM and DE in R_{fs}/Q!**

Coupled SF Dark Matter

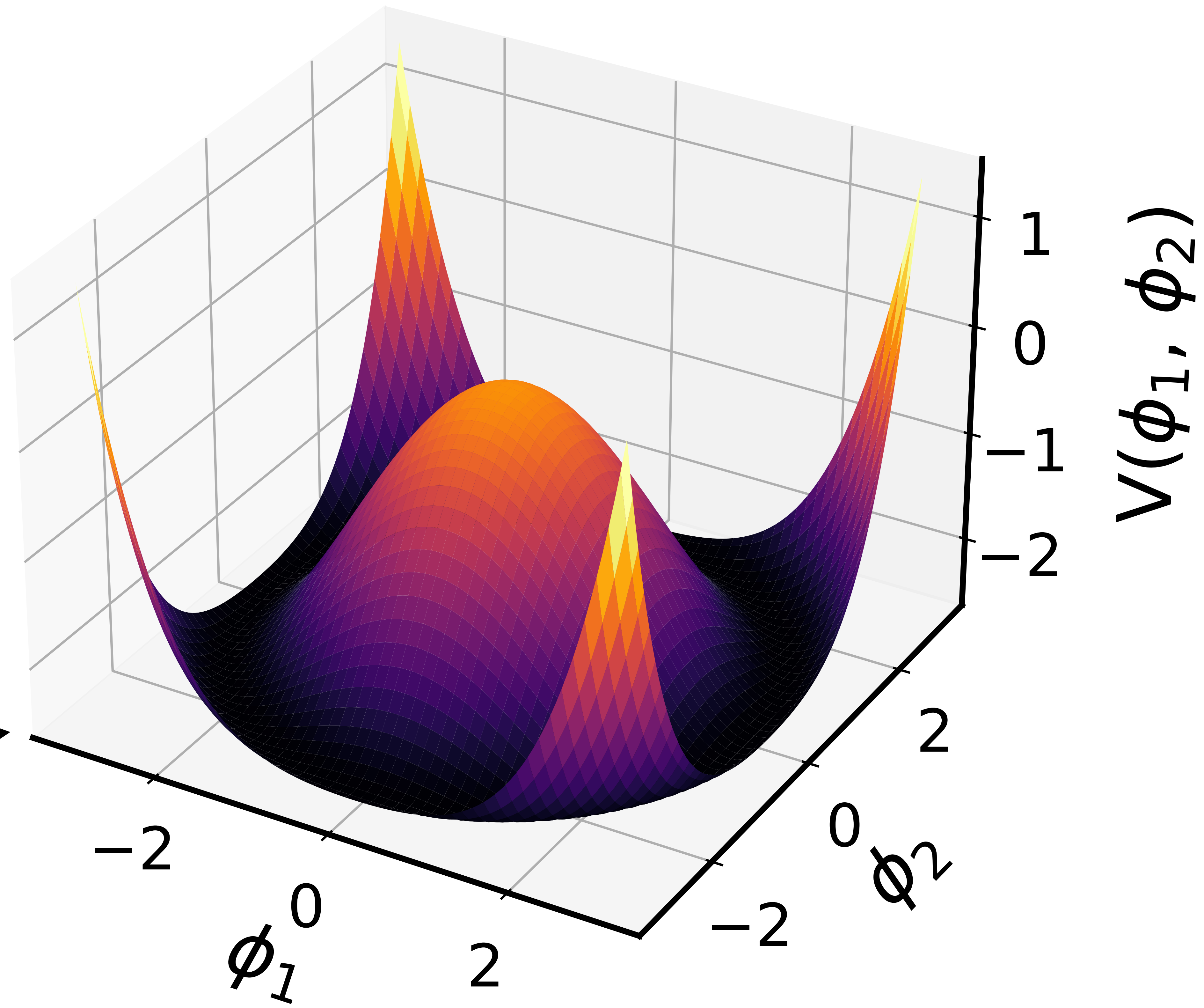
Extension of the cosmological axion model coupled to quintessence dark energy [GP, **EMT**, CvB, NN: arxiv:2404.10524]

$$S_{DM} = \int d^4x\sqrt{-g}\left(-\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi)\right)$$

$$V(\chi) = \frac{1}{2}m^2\chi^2 \quad \text{and} \quad \bar{g}_{\mu\nu} = C(\chi)g_{\mu\nu}$$

$$S_{DE} = \int d^4x\sqrt{-g}\left(-\frac{C(\chi)}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - C^2(\chi)U(\phi)\right)$$

Axion-like Potential



The conformal factor C depends on DM (χ)

DE (ϕ) which is coupled conformally to DM

Coupled SF Dark Matter

Extension of the cosmological axion model coupled to quintessence dark energy [GP, **EMT**, CvB, NN: arxiv:2404.10524]

- Interaction between DM and DE
- Q_0 and Q_1 are coupling terms
- Rapid oscillations ($m \gg H$) that can be averaged over one cycle
- Find solution for χ and apply effective fluid

$$\ddot{\chi} + 3H\dot{\chi} + m^2\chi = -Q(t)$$

$$Q(t) = Q_0(t) + Q_1(t)\chi$$

$$\ddot{\chi} + 3H\dot{\chi} + m_{\text{eff}}^2\chi = -Q_0, \quad \text{with} \quad m_{\text{eff}}^2 = m^2 + Q_1$$

Coupled SF Dark Matter

Extension of the cosmological axion model coupled to quintessence dark energy [GP, **EMT**, CvB, NN: arxiv:2404.10524]

- Interaction between DM and DE
- Q_0 and Q_1 are coupling terms
- Rapid oscillations ($m \gg H$) that can be averaged over one cycle
- Find solution for χ and apply effective fluid

$$\ddot{\chi} + 3H\dot{\chi} + m^2\chi = -Q(t)$$

$$Q(t) = Q_0(t) + Q_1(t)\chi$$

$$\ddot{\chi} + 3H\dot{\chi} + m_{\text{eff}}^2\chi = -Q_0, \quad \text{with} \quad m_{\text{eff}}^2 = m^2 + Q_1$$

Effective Fluid

$$\chi_{\text{osc}}(t) = \left(\frac{a_0}{a}\right)^{3/2}\left(\frac{m_0}{m_{\text{eff}}}\right)^{1/2}\left[\chi_+ \sin(m_{\text{eff}}t) + \chi_- \cos(m_{\text{eff}}t)\right]$$

- Field no longer oscillates around zero

$$\chi(t) = \chi_{\text{osc}}(t) + A(t)$$

$$A(t) \approx -\frac{Q_0}{m_{\text{eff}}^2}$$

- Average <.> of the oscillating field $\langle\chi\rangle$ and its derivatives and powers
- Derive fluid approximated quantities $\langle\rho\rangle$, $\langle p\rangle$, $\langle w\rangle$

Effective Fluid Background

- The averaged behavior no longer leads to CDM, the pressure no longer vanishes:

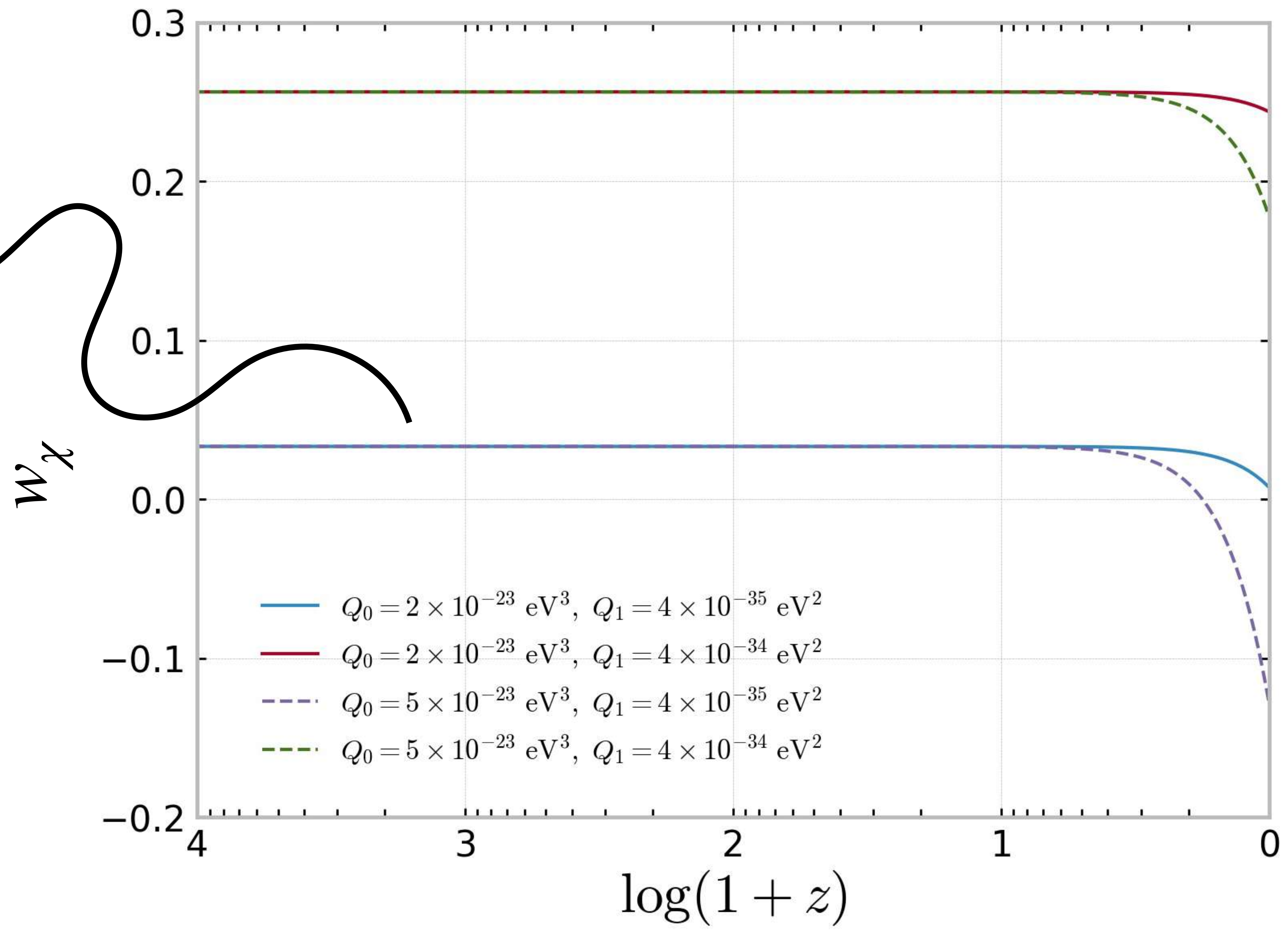
$$\langle w \rangle \equiv \langle p \rangle / \langle \rho \rangle \neq 0!$$

- The EoS of DM remains slightly positive for most of the cosmic history

- But it becomes negative at late times - Hubble tension?

$$\langle w_\chi \rangle = \left(1 - \frac{m^2 A^2}{2\langle \rho_\chi \rangle}\right) \frac{m_{\rm eff}^2 - m^2}{m_{\rm eff}^2 + m^2} - \frac{m^2 A^2}{2\langle \rho_\chi \rangle}$$

Change the physical properties of DM!



$m = 10^{-17}$ eV, [GP, **EMT**, CvB, NN: arxiv:2404.10524]

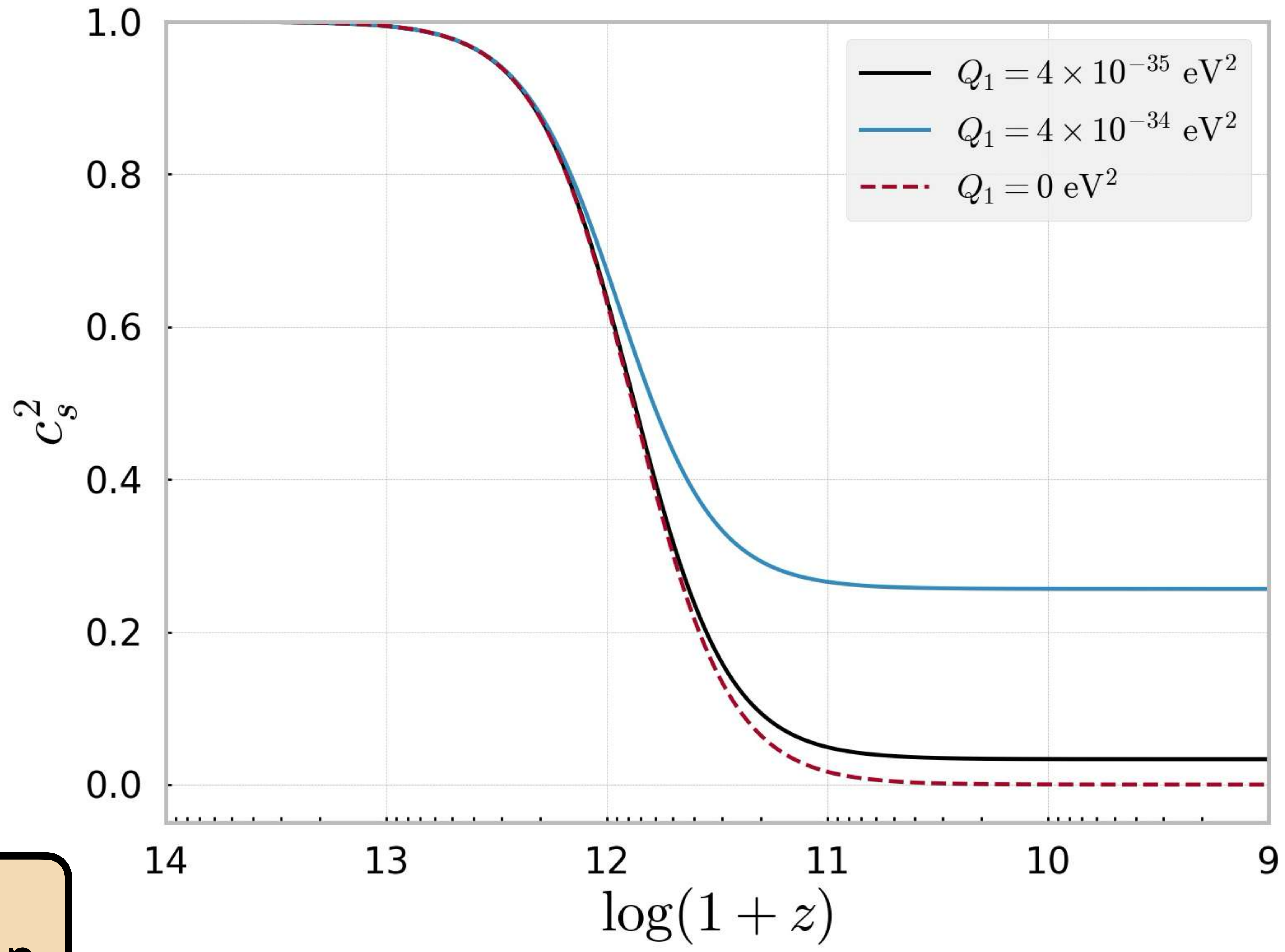
Effective Fluid Perturbations

- At linear level in approximation compute $c_a^2 \approx \langle \delta p \rangle / \langle \delta \rho \rangle$ using similar approach and calculations (independent of Q_0)

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2 m^2} + \frac{Q_1}{m^2}}{\frac{1}{2}\frac{k^2}{a^2 m^2} + 2 + \frac{Q_1}{m^2}}$$

- Changes mostly at late times when coupling becomes important

$\delta p = c_a^2 \delta \rho +$ terms$(Q, \delta Q)$ $\rightarrow$ non-adiabatic contribution



$m = 10^{-17}$ eV, $k = 10$ Mpc^{-1}, [GP, **EMT**, CvB, NN: arxiv:2404.10524]

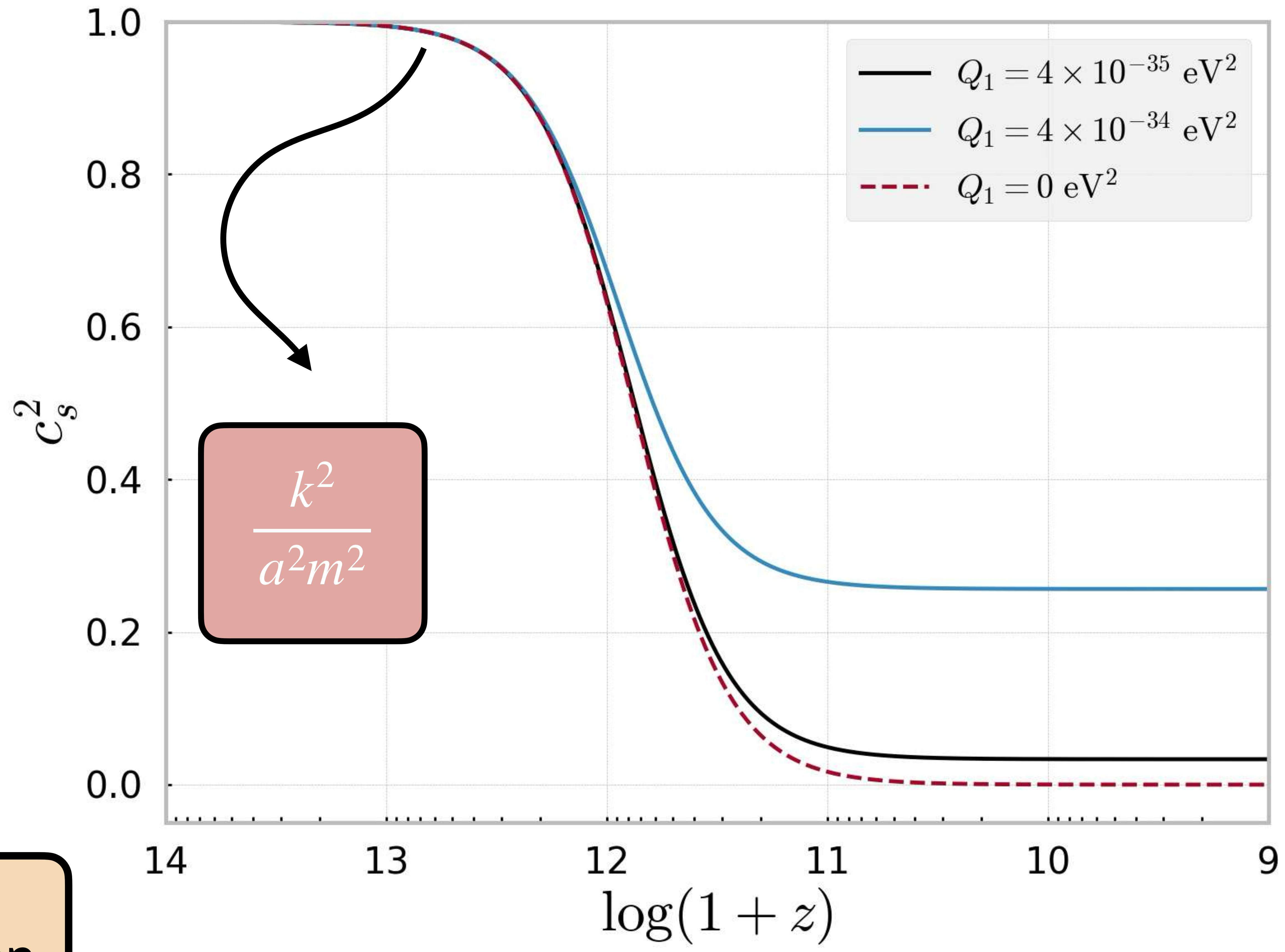
Effective Fluid Perturbations

- At linear level in approximation compute $c_a^2 \approx \langle \delta p \rangle / \langle \delta \rho \rangle$ using similar approach and calculations (independent of Q_0)

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2 m^2} - \frac{Q_1}{m^2}}{\frac{1}{2}\frac{k^2}{a^2 m^2} + 2 + \frac{Q_1}{m^2}}$$

- Changes mostly at late times when coupling becomes important

$\delta p = c_a^2 \delta \rho + \text{terms}(Q, \delta Q)$ → non-adiabatic contribution



$m = 10^{-17}$ eV, $k = 10$ Mpc^{-1}, [GP, **EMT**, CvB, NN: arxiv:2404.10524]

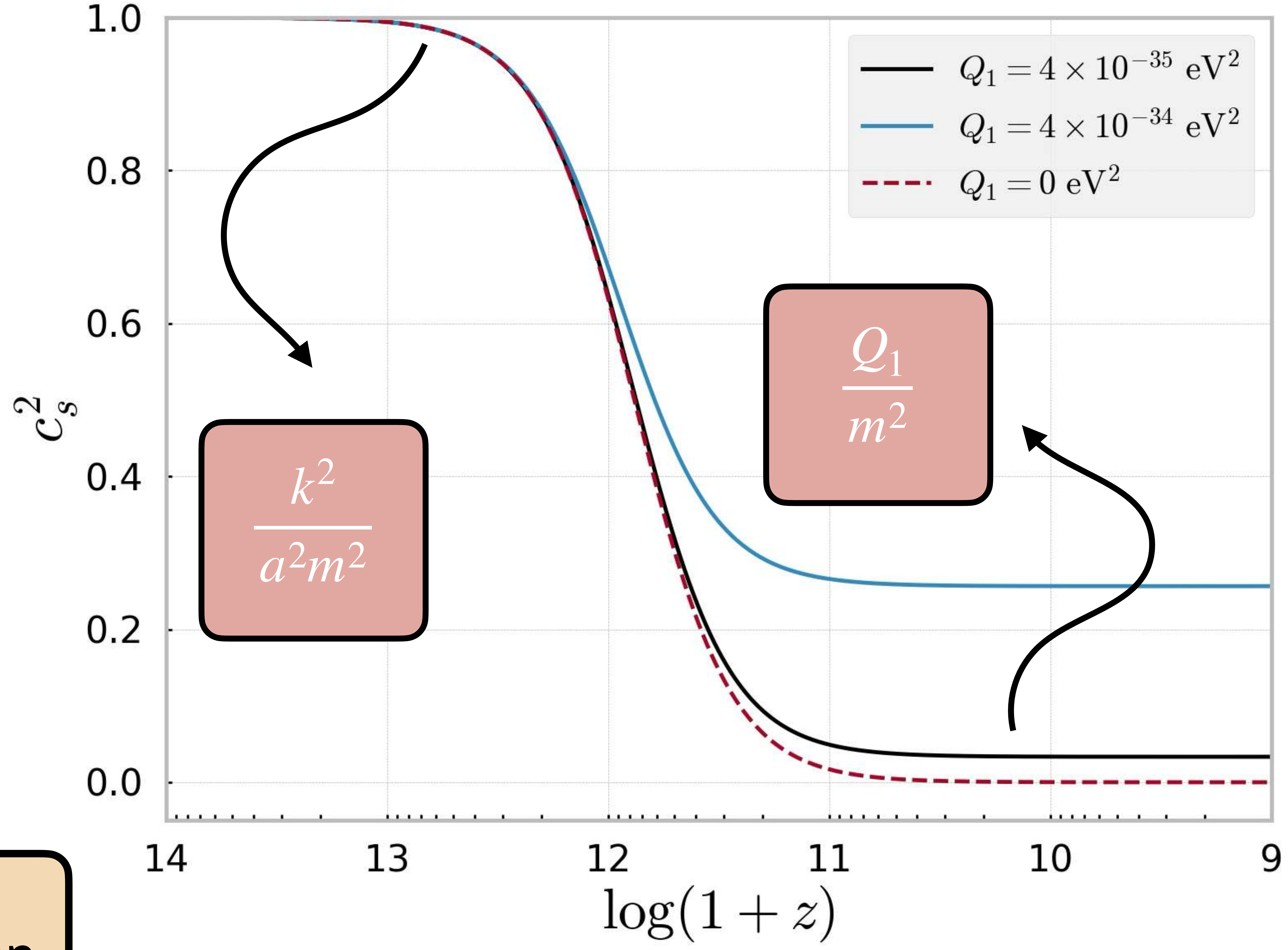
Effective Fluid Perturbations

- At linear level in approximation compute $c_a^2 \approx \langle \delta p \rangle / \langle \delta \rho \rangle$ using similar approach and calculations (independent of Q_0)

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2 m^2} + \frac{Q_1}{m^2}}{\frac{1}{2}\frac{k^2}{a^2 m^2} + 2 + \frac{Q_1}{m^2}}$$

- Changes mostly at late times when coupling becomes important

$\delta p = c_a^2 \delta \rho + \text{terms}(Q, \delta Q) \;\rightarrow\;$ non-adiabatic contribution



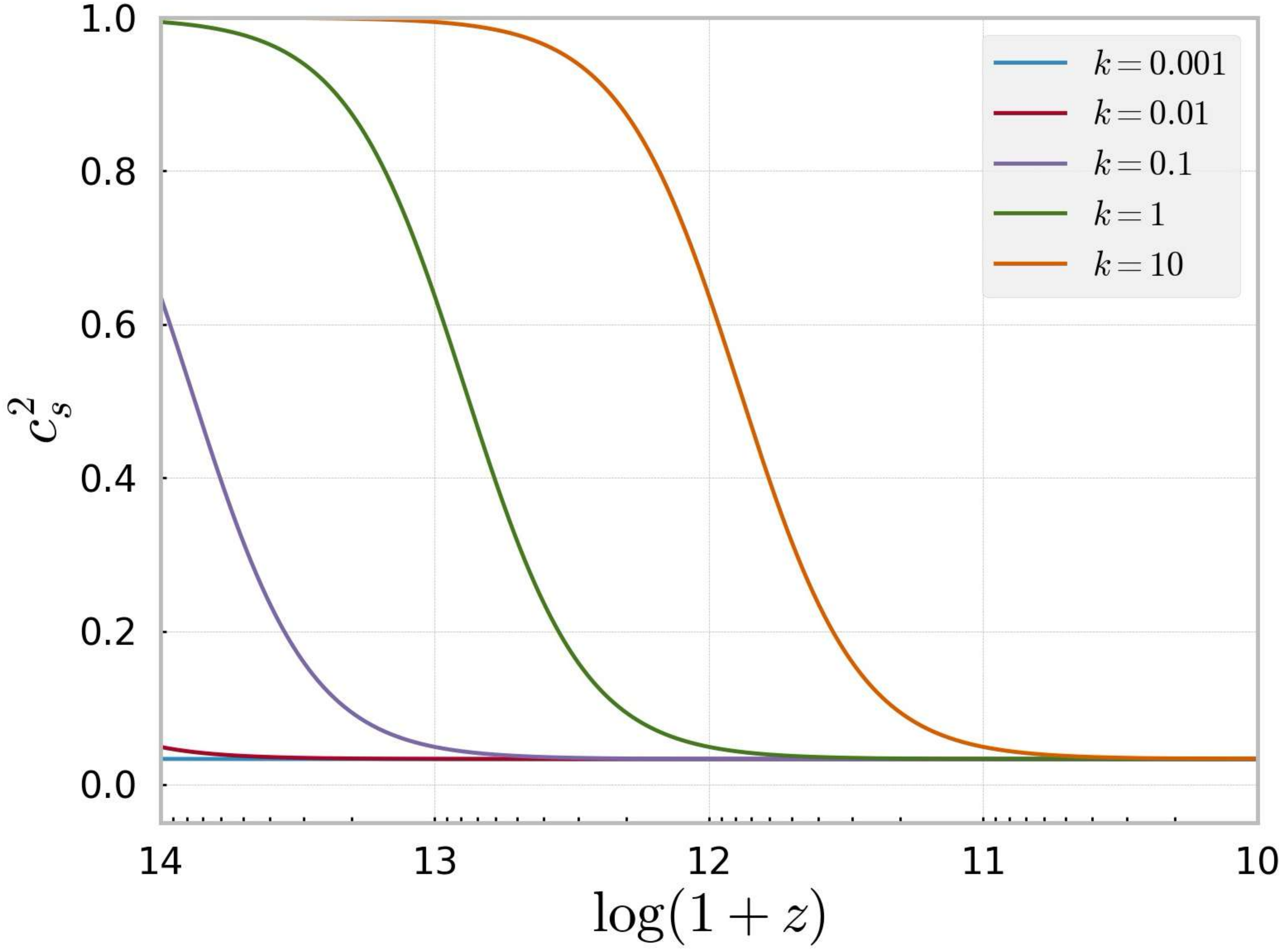
$m = 10^{-17}$ eV, $k = 10\,$Mpc^{-1}, [GP, **EMT**, CvB, NN: arxiv:2404.10524]

Effective Fluid Perturbations

- At linear level in approximation compute $c_a^2 \approx \langle \delta p \rangle / \langle \delta \rho \rangle$ using similar approach and calculations (independent of Q_0)

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2 m^2} + \frac{Q_1}{m^2}}{\frac{1}{2}\frac{k^2}{a^2 m^2} + 2 + \frac{Q_1}{m^2}}$$

- Changes mostly at late times when coupling becomes important
- Due to the coupling the sound speed is enhanced on all scales
- Suppresion on small scales - S_8 tension



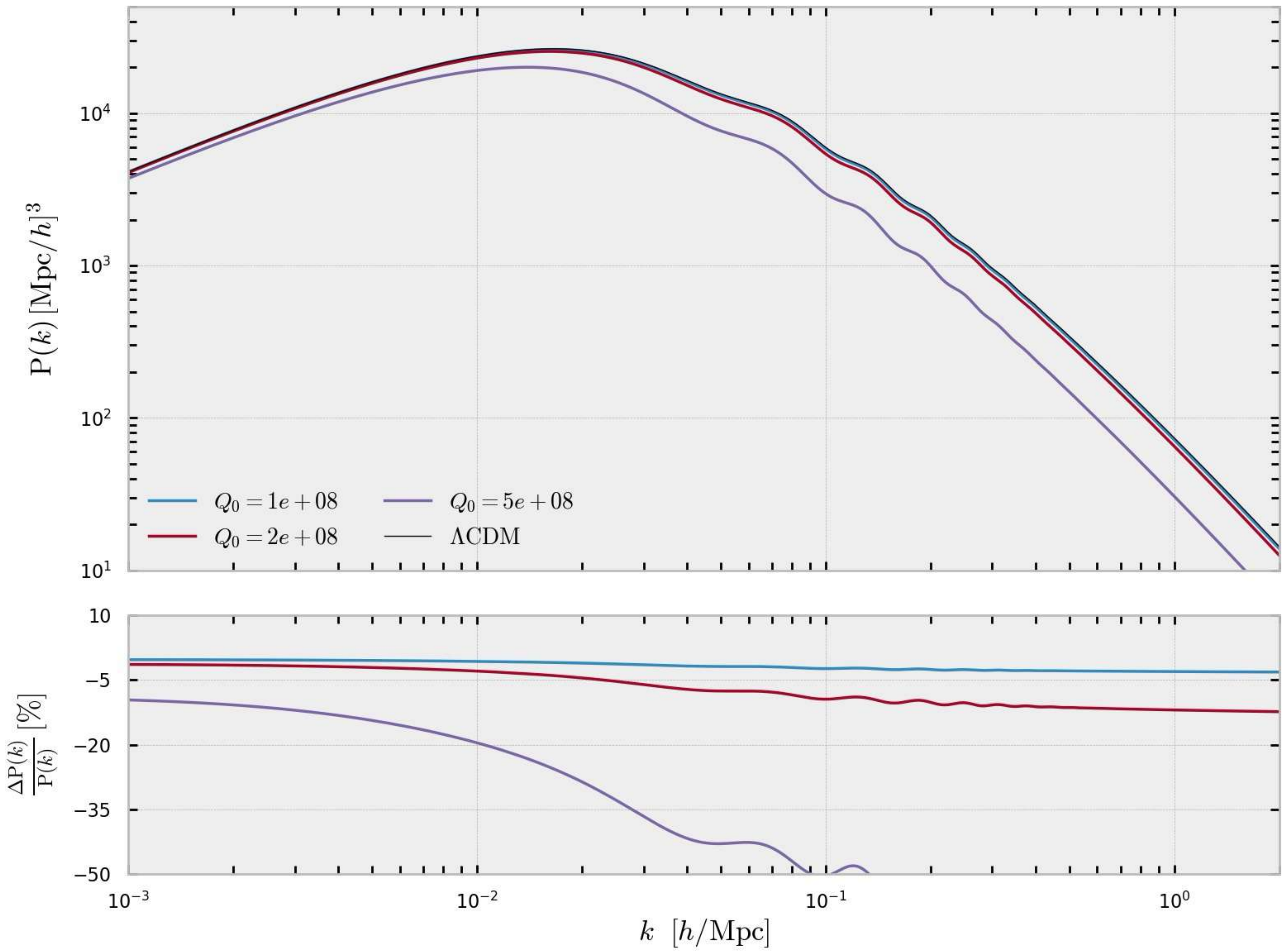
$m = 10^{-17}$ eV, $Q_1 = 10^{-35}$ eV^2, [GP, **EMT**, CvB, NN: arxiv:2404.10524]

Effective Fluid Perturbations

- First approximation: ϕ is constant, Q_0 is constant and $Q_1 = 0$

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2m^2}}{\frac{1}{2}\frac{k^2}{a^2m^2} + 2}$$

- Same as uncoupled axion but with coupling in the background
- Due to the coupling the sound speed is enhanced mostly on small scales



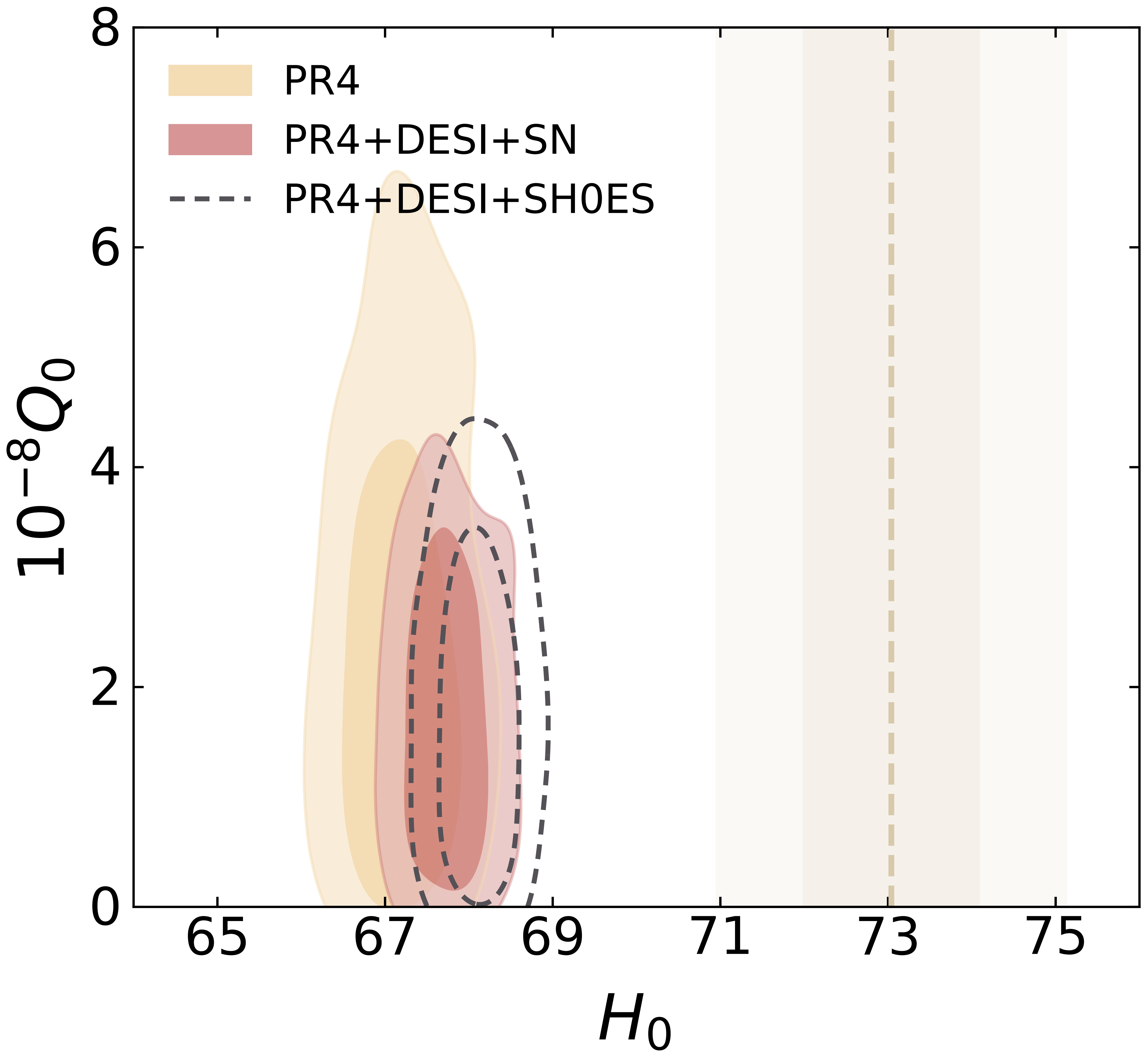
$m = 10^{-17}$ eV, $Q_1 = 0$, [GP, **EMT**, CvB, NN: arxiv:2404.10524]

Observational Imprints (preliminary results)

- First approximation: ϕ is constant, Q_0 is constant and $Q_1 = 0$

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2m^2}}{\frac{1}{2}\frac{k^2}{a^2m^2} + 2}$$

- Same as uncoupled axion but with coupling in the background
- Due to the coupling the sound speed is enhanced mostly on small scales
- Background coupled dynamics - H0 tension



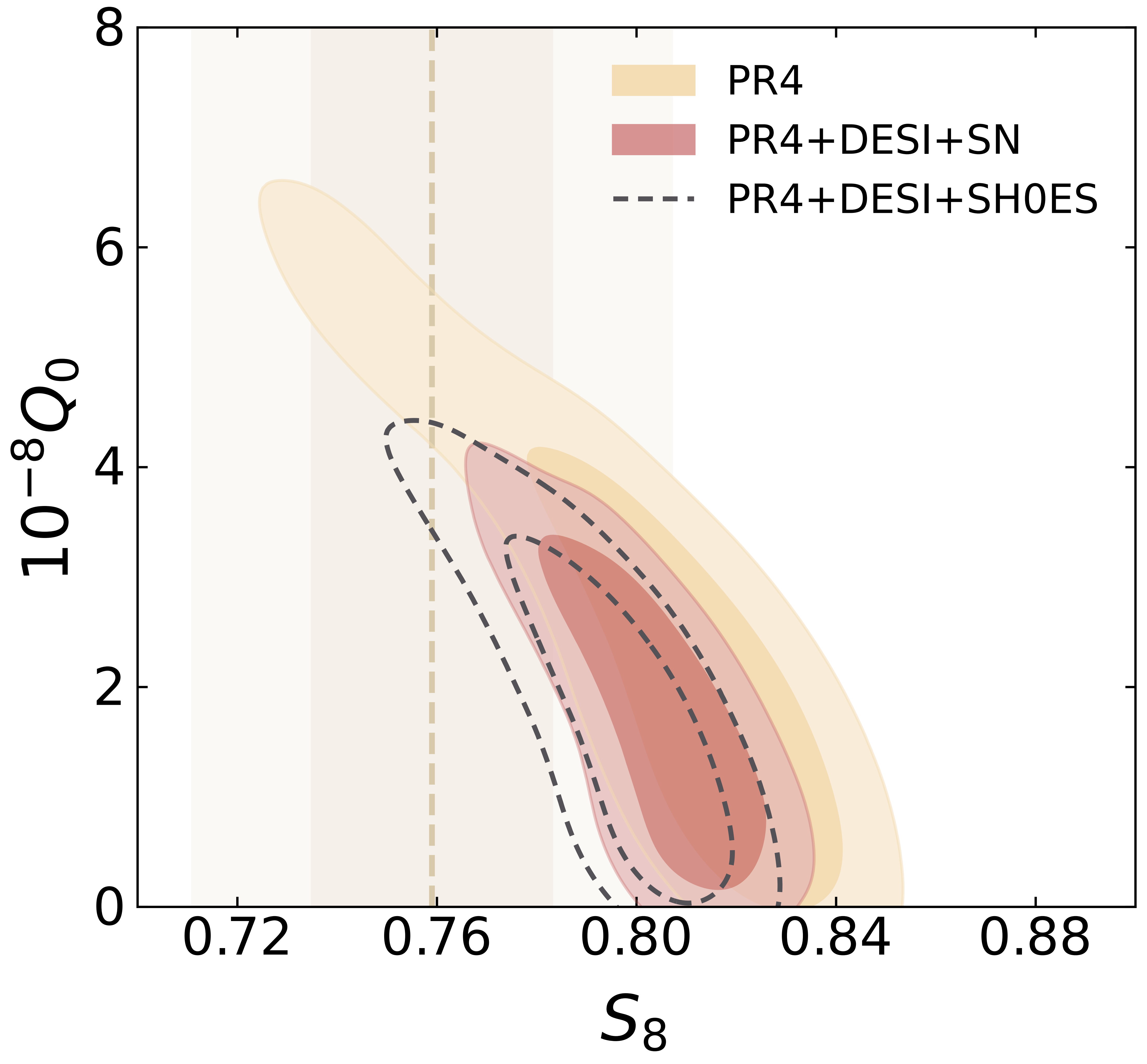
Planck PR4: [Tristam et al.: A&A, Volume 682 (2024), A37]
DESI: [A. G. Adame et al. (DESI), (2024), arXiv:2404.03002]
PantheonPlus: [Brout et. al: Astrophys. J. 938 (2022) 110]
SH0ES: [Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]

Observational Imprints (preliminary results)

- First approximation: ϕ is constant, Q_0 is constant and $Q_1 = 0$

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2m^2}}{\frac{1}{2}\frac{k^2}{a^2m^2} + 2}$$

- Same as uncoupled axion but with coupling in the background
- Due to the coupling the sound speed is enhanced mostly on small scales
- Background coupled dynamics - H0 tension
- Matter power spectrum suppresion on small scales - S_8 tension

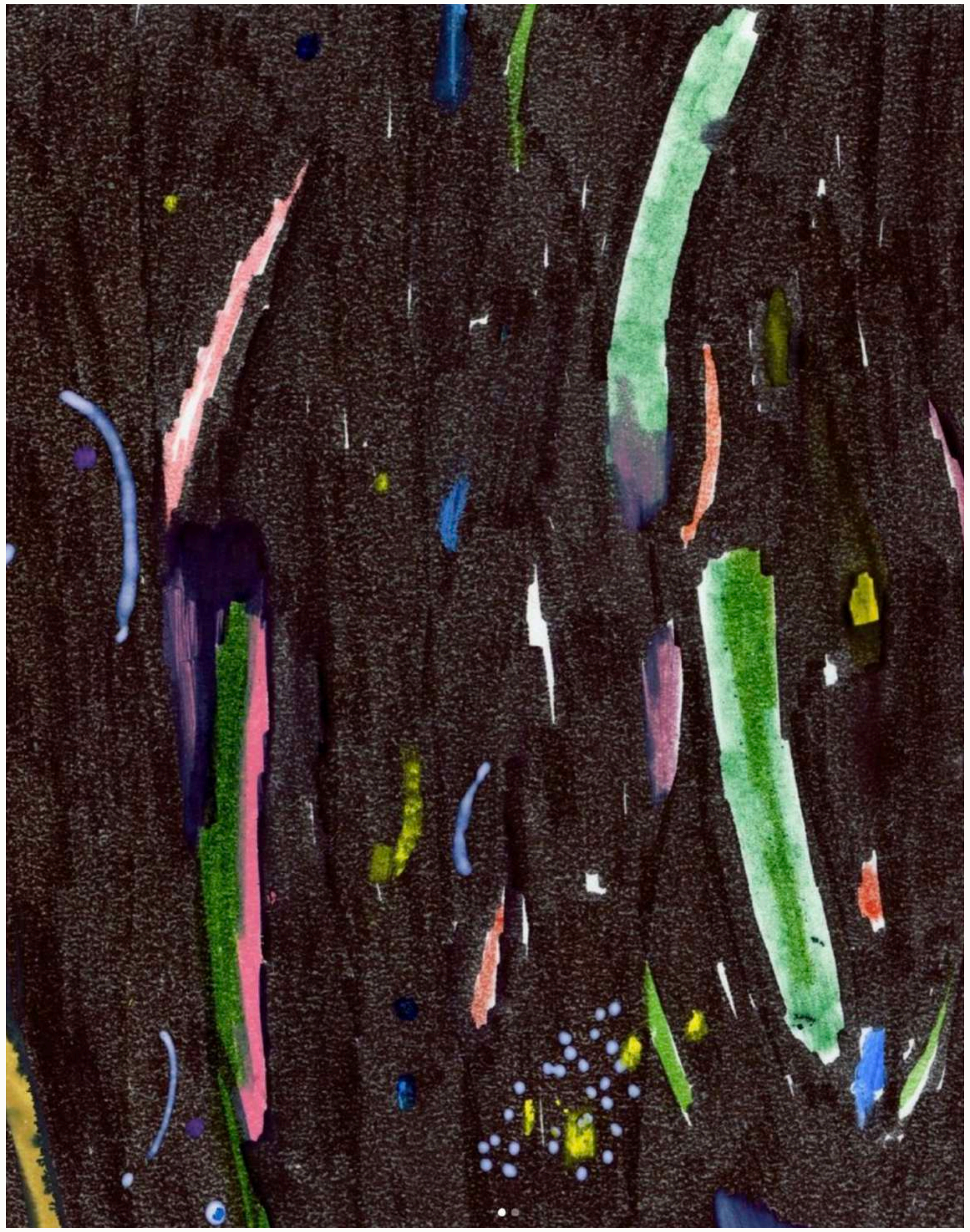


Summary and Conclusions

Conclusions

- ΛCDM model facing challenges with increasing precision
- Incompatibility of early- and late-Universe measurements
- Address the H0 tension for expansion history - dark energy
- The S8 tension could be related to a suppression of the matter power spectrum on small smales - dark matter
- Coupled dark sector models are natural extension of ΛCDM

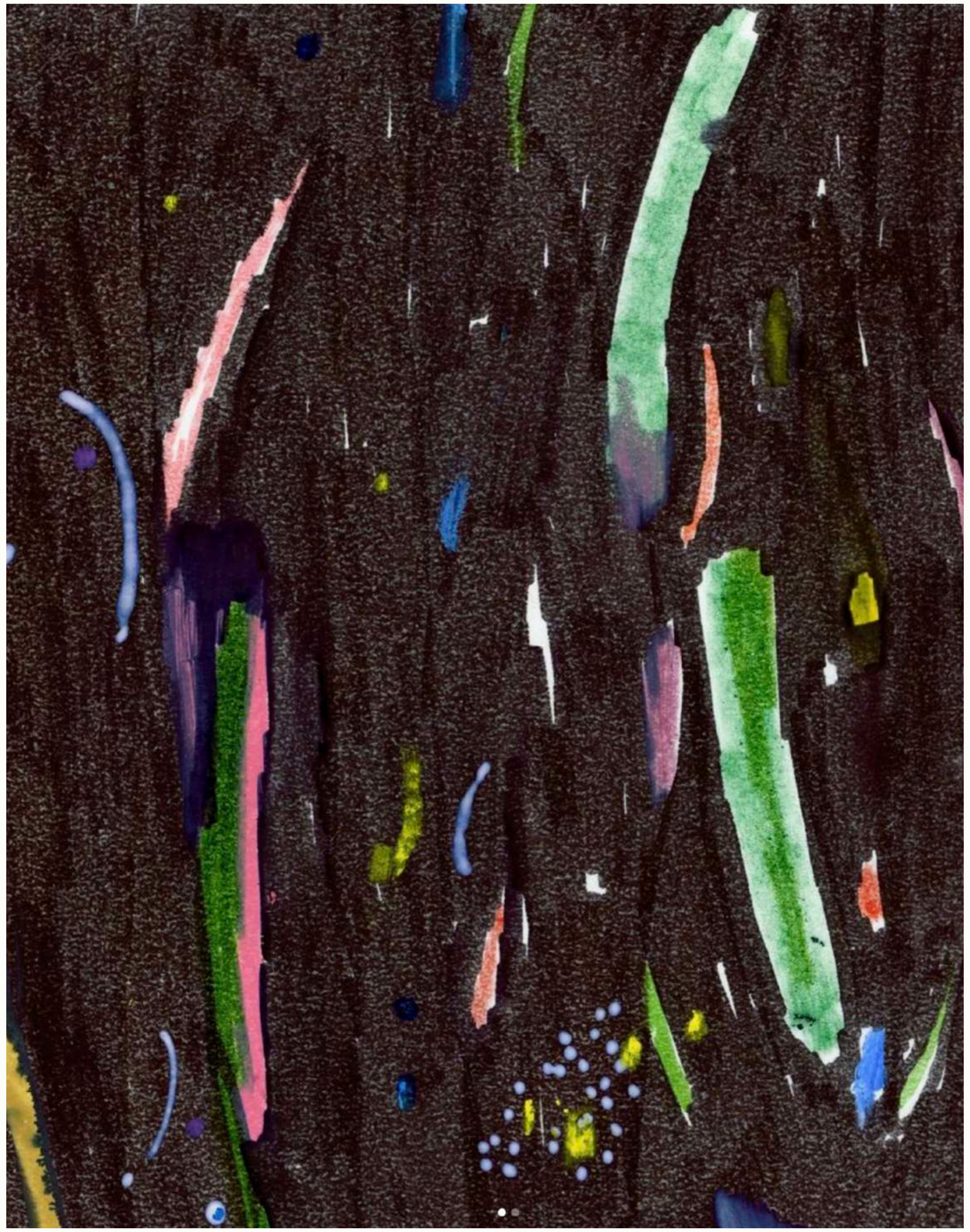
- Late-time scenario based on hybrid inflation for DM and DE
- DE scales with DM during MDE and characteristic effective fluid behaviour lead to suppressed matter density today
- Characteristic correlations between coupling and H_0, S_8, ω_c that alleviate cosmic tensions but cannot solve them



Conclusions

- ΛCDM model facing challenges with increasing precision
- Incompatibility of early- and late-Universe measurements
- Address the H0 tension for expansion history - dark energy
- The S8 tension could be related to a suppression of the matter power spectrum on small smales - dark matter
- Coupled dark sector models are natural extension of ΛCDM

- Coupled scalar model in which the DM axion has a a non-zero equation of state/pressure at all times
- The sound speed of DM perturbations is enhanced at all scales - suppression of matter P(k) at all scales
- Cosmological constraints and impact on cosmic tensions



Thank you for your attention!

ELSA M. TEIXEIRA

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier
elsa.teixeira@umontpellier.fr

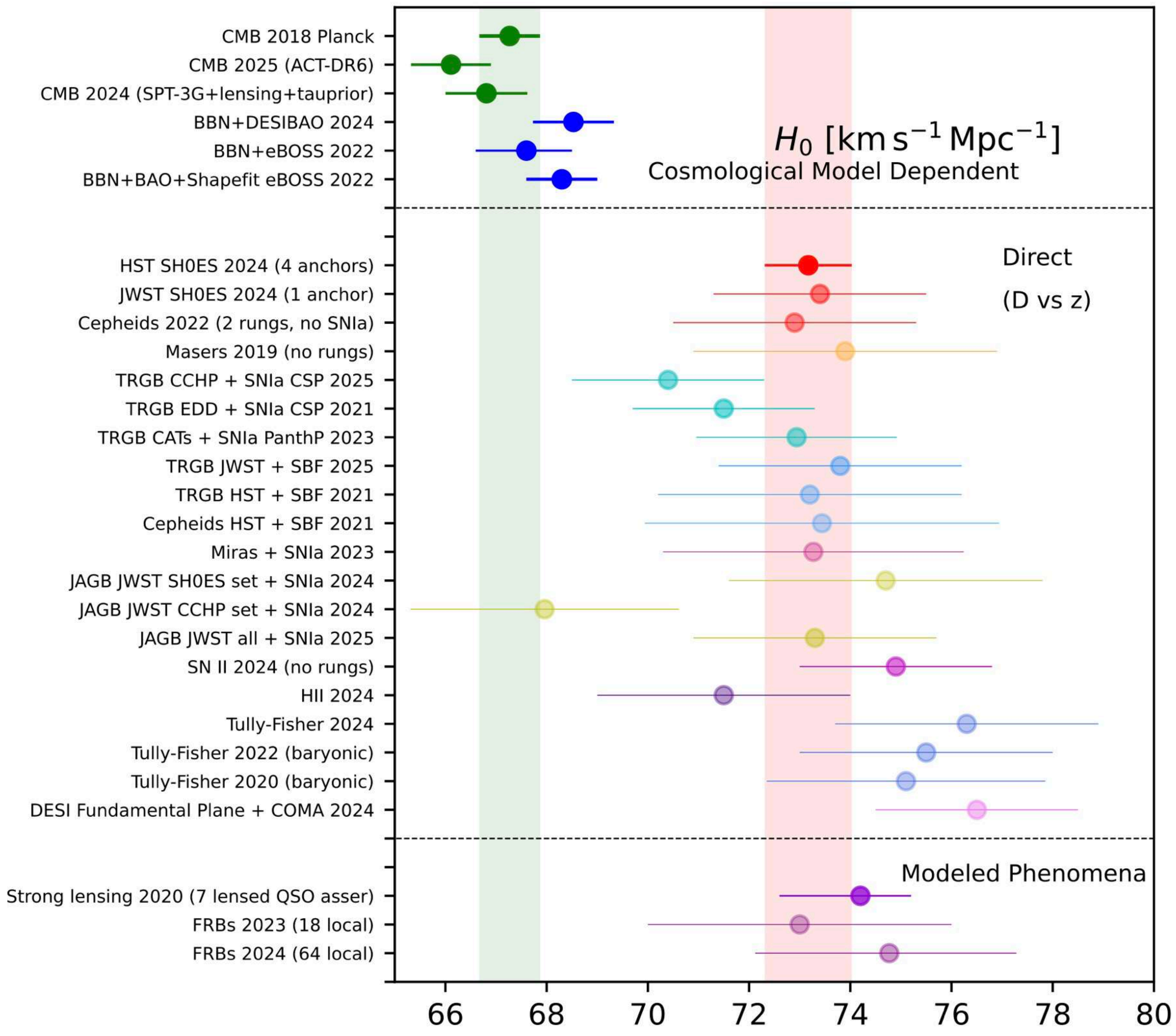
Illustrations: Inês Viegas Oliveira
(ivoliveira.com)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or ERCEA. Neither the European Union nor the ERCEA can be held responsible for them.

The Hubble Tension

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

- ~5σ tension between Planck 2018 and SH_0ES:
  - CMB (Planck): $H_0 = 67.27 \pm 0.60$ km/s/Mpc
  - SNe (R22): $H_0 = 73.04 \pm 1.04$ km/s/Mpc
- The CMB data assumes the ΛCDM model
- DESI BAO (+BBN+CMB): $H_0 = 68.45 \pm 0.47$ km/s/Mpc [DESI Collaboration DR2 2025: arXiv:2503.14738]
- Compilation of early vs late time data that disagree
- Could signal differences in the expansion history (nature of the dark sector)

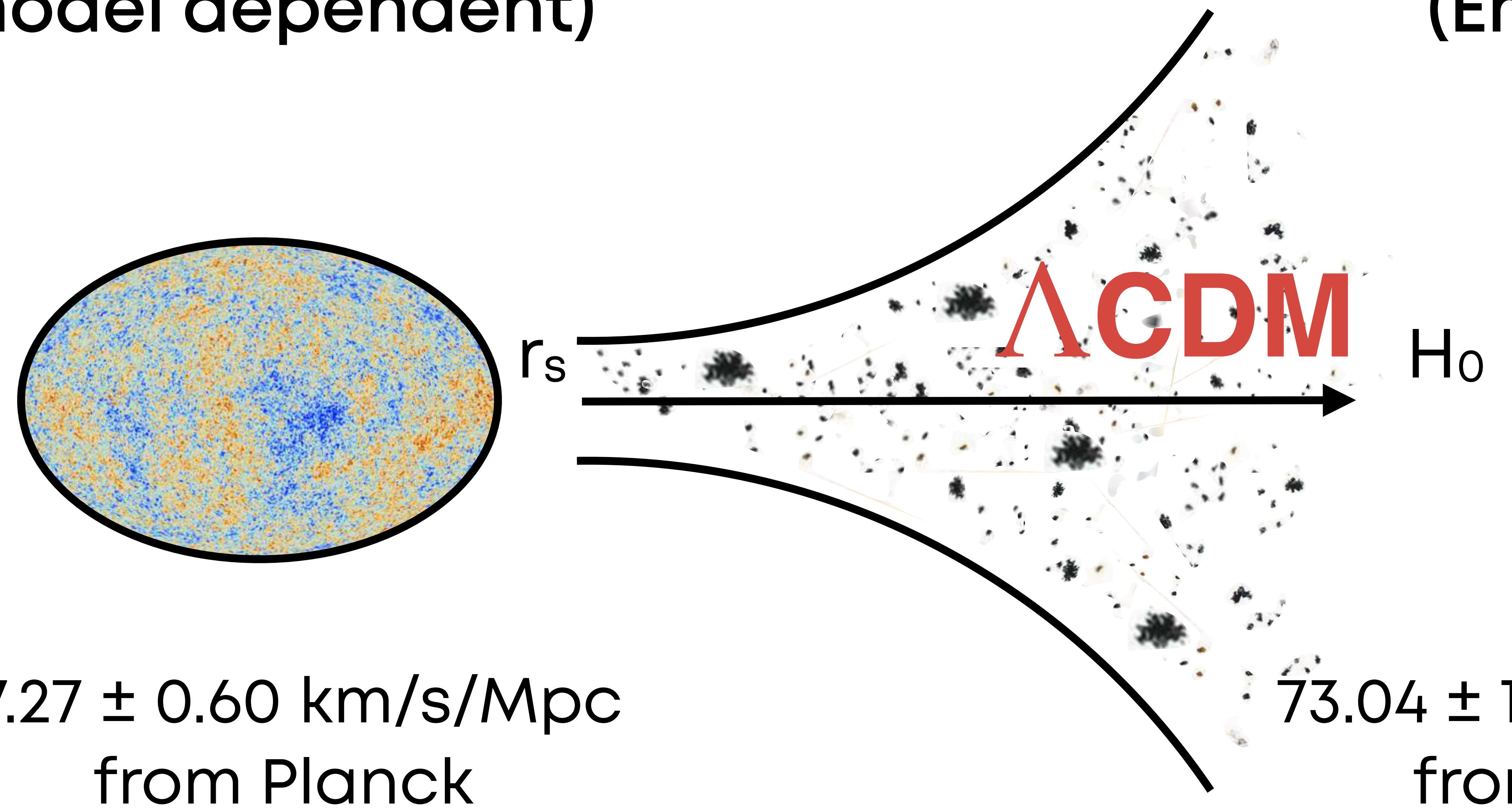


[Cosmoverse white paper arxiv:2504.01669]

Cosmological Tensions

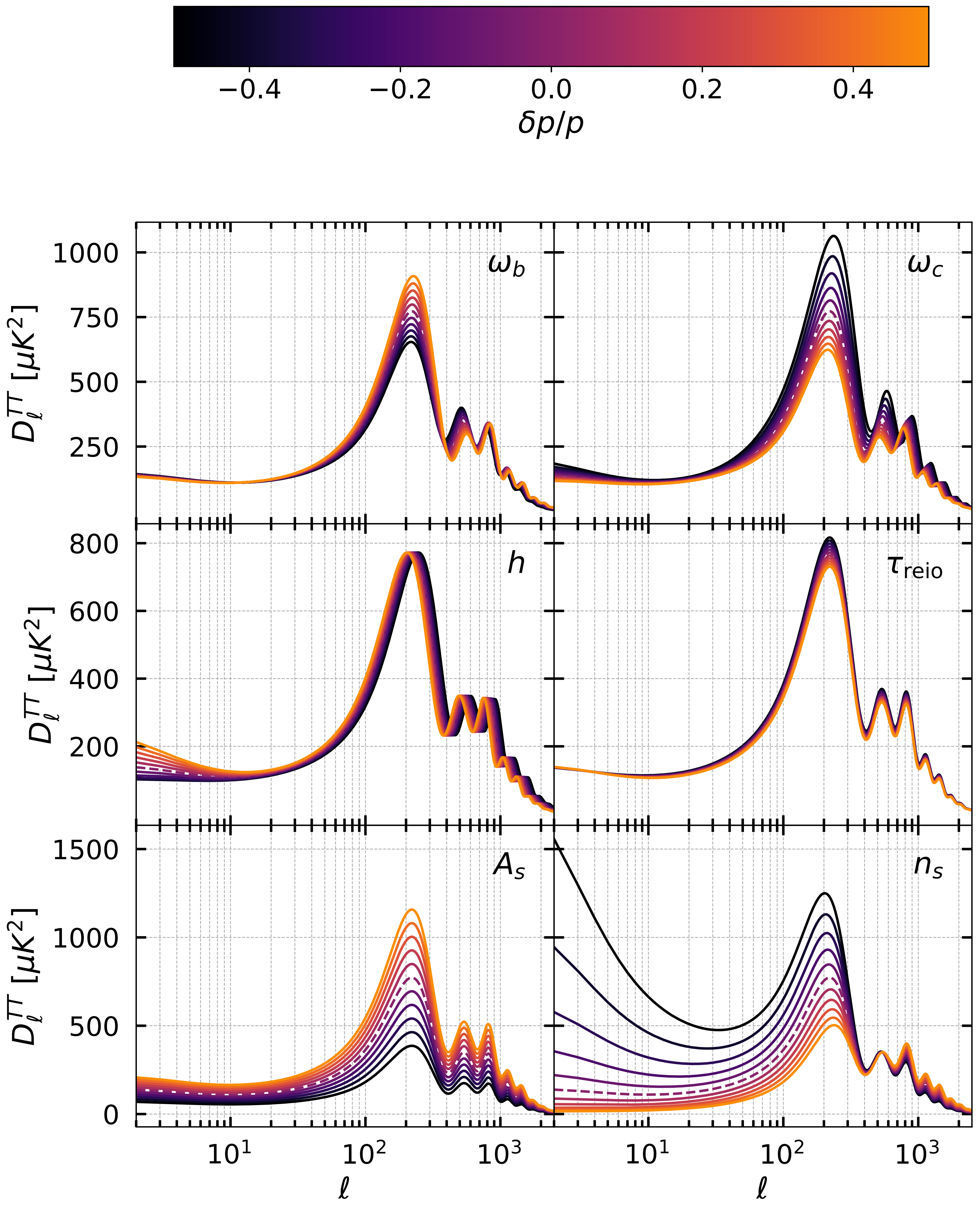
CMB
(model dependent)

Local
(Empirical)



67.27 ± 0.60 km/s/Mpc
from Planck

73.04 ± 1.04 km/s/Mpc
from (SH0ES)

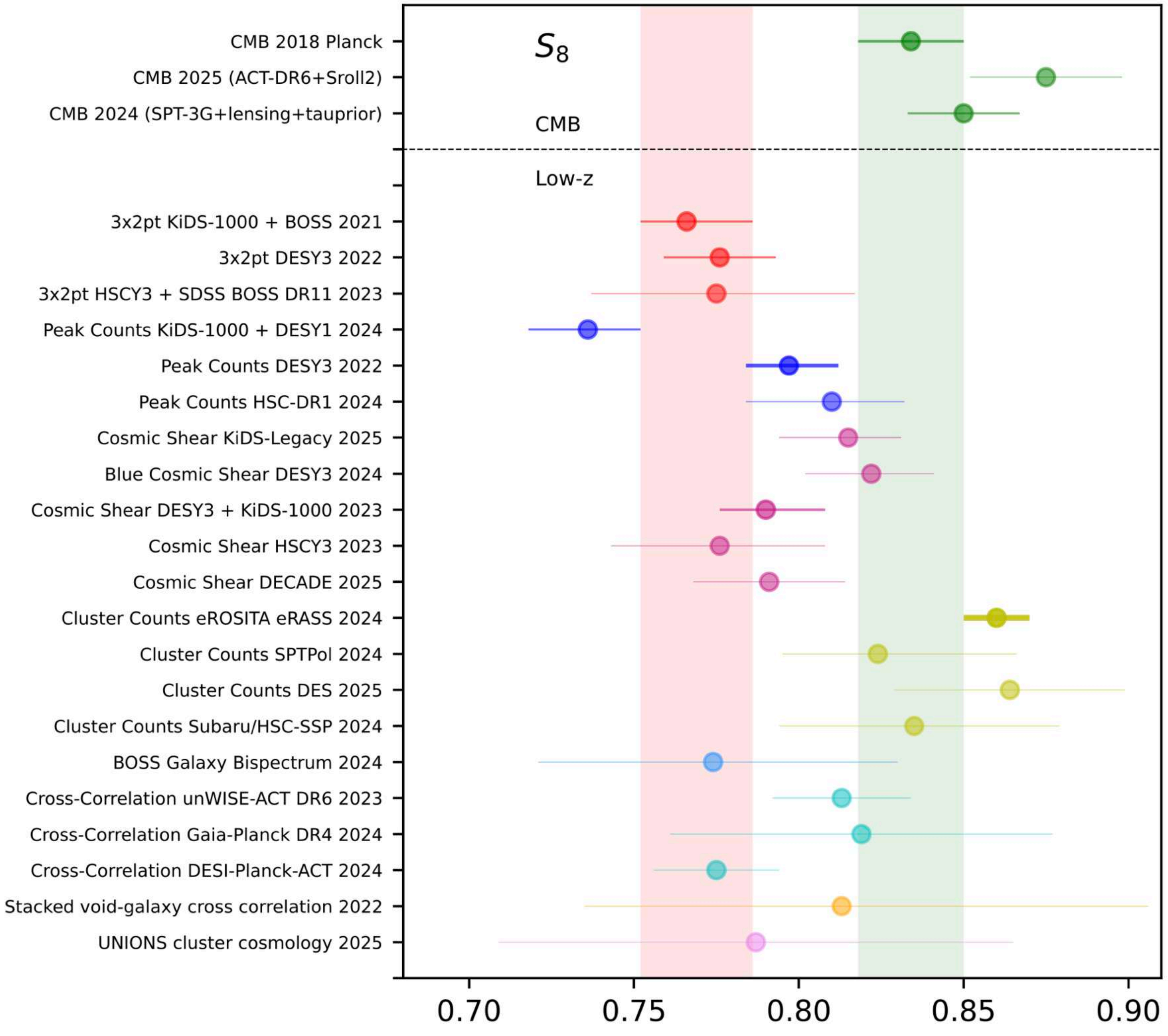


Missing Ingredients or New Physics?

The S_8 Tension

Discrepancy between CMB data and lensing surveys on combined quantity $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$

- $\sim 3\sigma$ tension between Planck 2018 CMB data and KiDS-1000 combination of Cosmic Shear and Galaxy Clustering:
  - CMB (Planck 2018): $S_8 = 0.832 \pm 0.013$
  - Cosmic Shear (DES-Y3): $S_8 = 0.759^{+0.025}_{-0.023}$
- eRosita (eRASS1): $S_8 = 0.86 \pm 0.01$ [Ghirardini et al. 2024]
- Kids-Legacy ($S_8 = 0.815^{+0.016}_{-0.021}$) find possible resolution with Planck but not for the other measurements (improved redshift distribution estimation and calibration, as well as new survey area and improved image reduction)
- Could signal changes in clustering of matter (nature of CDM)

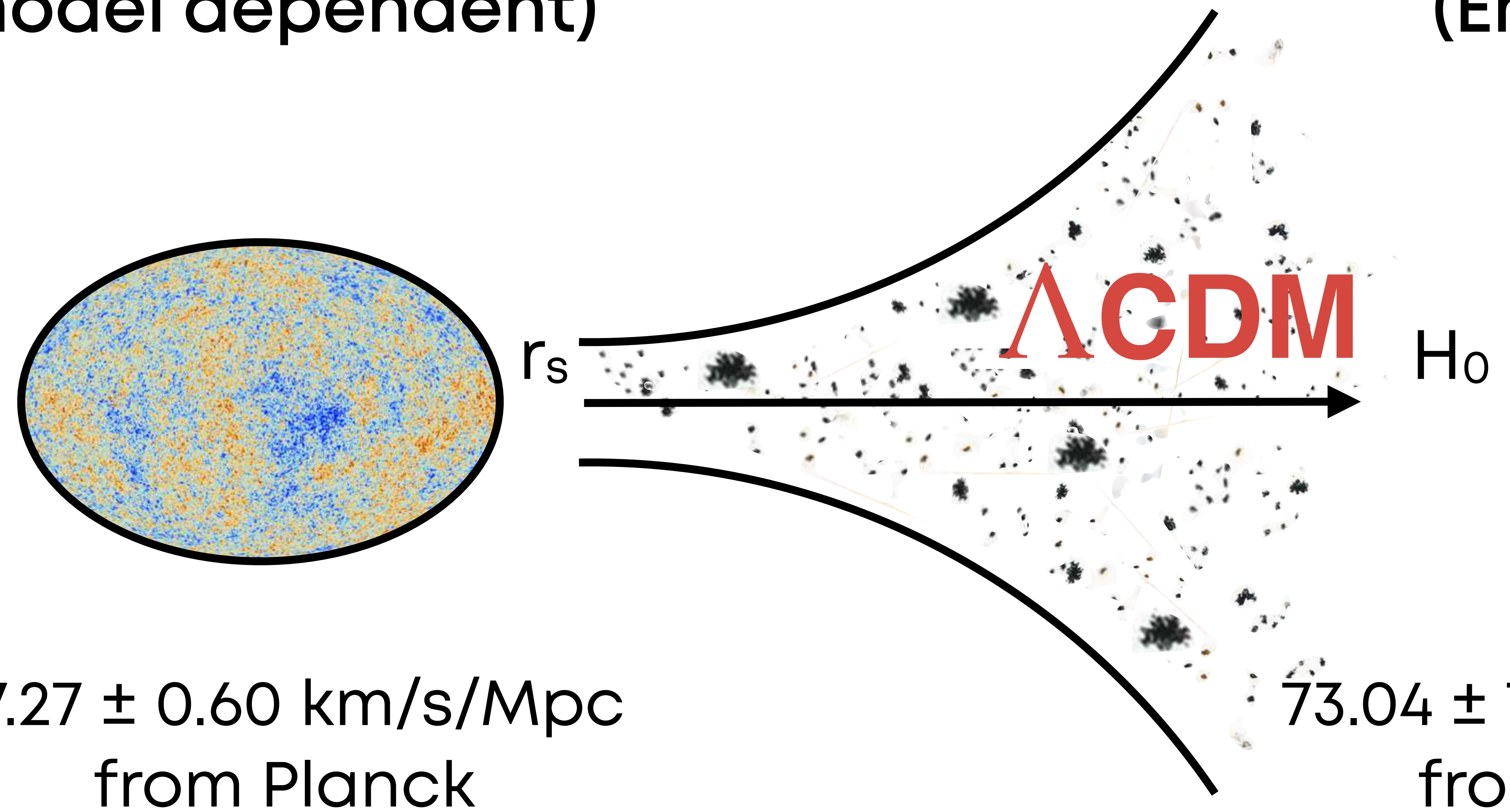


[Cosmoverse white paper arxiv:2504.01669]

Cosmological Tensions

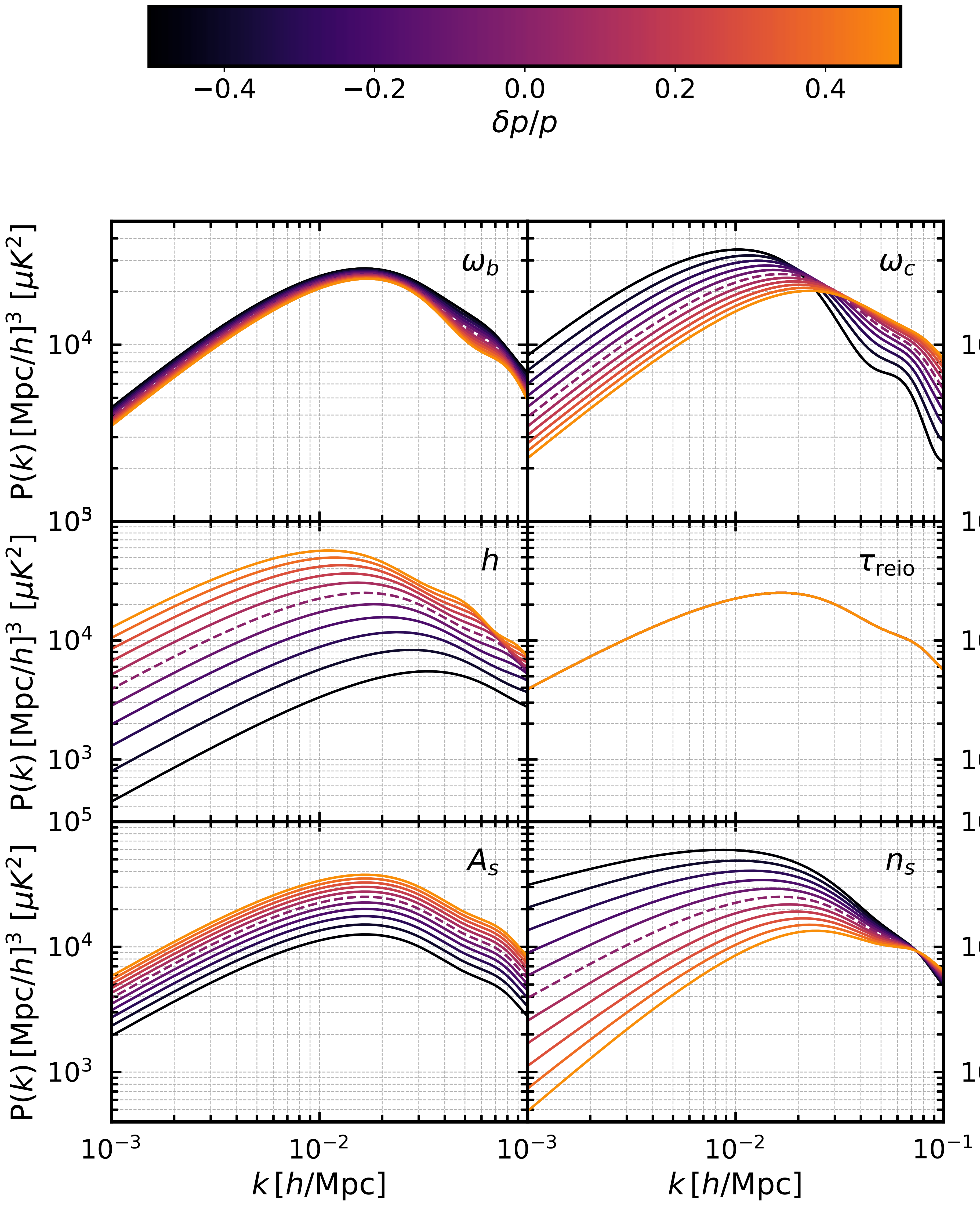
CMB
(model dependent)

Local
(Empirical)



67.27 ± 0.60 km/s/Mpc
from Planck

73.04 ± 1.04 km/s/Mpc
from (SH0ES)



Missing Ingredients or New Physics?

Conformal Transformation

- Simplest way to relate two geometries
- Rescaling of the metric that preserves angles
- Functiona
  present in
- Map non-
  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]

Non-Universal Coupling in the Dark Sector

Disformal Transformation

- Distortion of both angles and lengths related with the gradient of ϕ
- The most general covariant effective metric
  etric and a
  equations
- an 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}]

Effective Fluid Description

- For χ to act as DM, we need its mass to be suffciently large (prevent damping of oscillations, quadratic term in potential)

- χ is oscillating in a quadratic potential → WKB approximation ($g\phi \gg H$ and $\dot{\phi}/\phi \ll 1$):

$$\chi(t) = \chi_i \left(\frac{\phi_i}{\phi}\right)^{1/2} \left(\frac{a_i}{a}\right)^{3/2} \sin\left(g\phi(t - t_i)\right)$$

- ϕ is slow rolling ($\phi/\phi_i \sim$ const.) and χ behaves like a pressureless fluid with $\rho_\chi \propto \chi^2 \propto a^{-3}$, $\rho_{\chi,i} = 1/2\, g^2 \phi_i^2 \chi_i^2$

Oscillating DM field and slow-rolling DE field

$$m_\chi \approx g\phi \gg H$$

$$g^2\chi^2 \ll H^2$$

Field oscilates if m<H

[CvB, GP, **EMT**: arxiv:2211.13653]

Model Parameters

1. ϕ is dark energy (negligible $\mu^2\phi^2$ contribution)
2. χ field oscillates in a quadratic potential - quadratic term in V must dominate over quartic
3. $\phi_i \gg \phi_c \rightarrow g\phi_i \gg \sqrt{\lambda}M$ and $g\phi_i \gg H$. But ϕ must also evolve slowly, requiring $m^2\phi \ll H^2$ (with $\mu \ll g\chi$)
4. Ensuring $\rho_\phi \ll \rho_\chi$ for matter dominated epoch
5. χ-field oscillates rapidly and is pressureless when averaged over multiple oscillation periods
6. Compare with χ dominant contribution
7. ϕ must be trans-Planckian ($\phi \gg$ MPl)

$$V_0 = \frac{1}{4}\lambda M^4 \approx 10^{-47}\text{GeV}^4$$ 1.

$$m\chi \approx g\varphi \gg H, \quad g^2\phi^2 - \lambda M^2 \gg \lambda\chi^2/2$$ 2.

$$g^2\chi^2 \ll H^2$$ 3.

$$\mu^2\phi^2 + 2V_0 \ll g^2\phi^2\chi^2$$ 4.

$$\rho_\chi = \dot{\chi}^2/2 + m_\chi^2\chi^2/2 \simeq m_\chi^2\chi^2$$ 5.

$$g^2\frac{\rho_\chi}{m_\chi^2} \ll H^2, \quad H^2 \simeq \frac{\rho_\chi}{3M_{\rm Pl}^2}$$ 6.

$$1 \ll \frac{1}{3}\left(\frac{\phi}{M_{\rm Pl}}\right)^2, \quad m_\chi \simeq g\phi$$ 7.

Hybrid Model

In FLRW the equations of motion for each field are:

$$\ddot{\phi} + 3H\dot{\phi} = -(g^2\chi^2 + \mu^2)\phi$$
$$\ddot{\chi} + 3H\dot{\chi} = -\lambda\chi^3 + (\lambda M^2 - g^2\phi^2)\chi$$

$$|\phi_c| \approx \frac{\sqrt{\lambda}M}{g}$$

χ oscillates around 0 and m_χ changes sign at critical ϕ

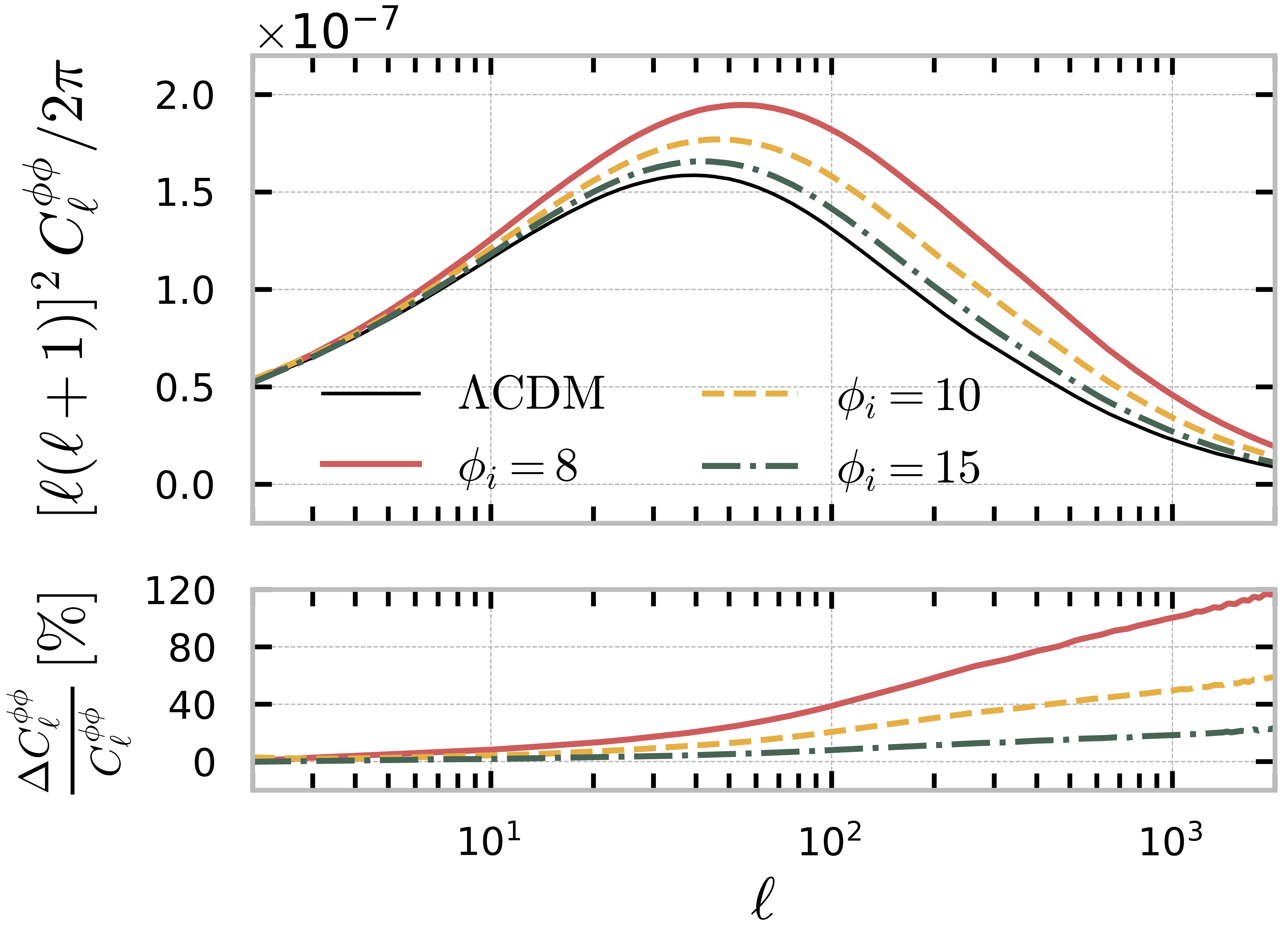
$$\rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{\lambda M^2\chi^2}{2} + \frac{\lambda\chi^4}{4} + \frac{g^2\phi^2\chi^2}{2}$$
$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_0 + \frac{\mu^2\phi^2}{2}$$

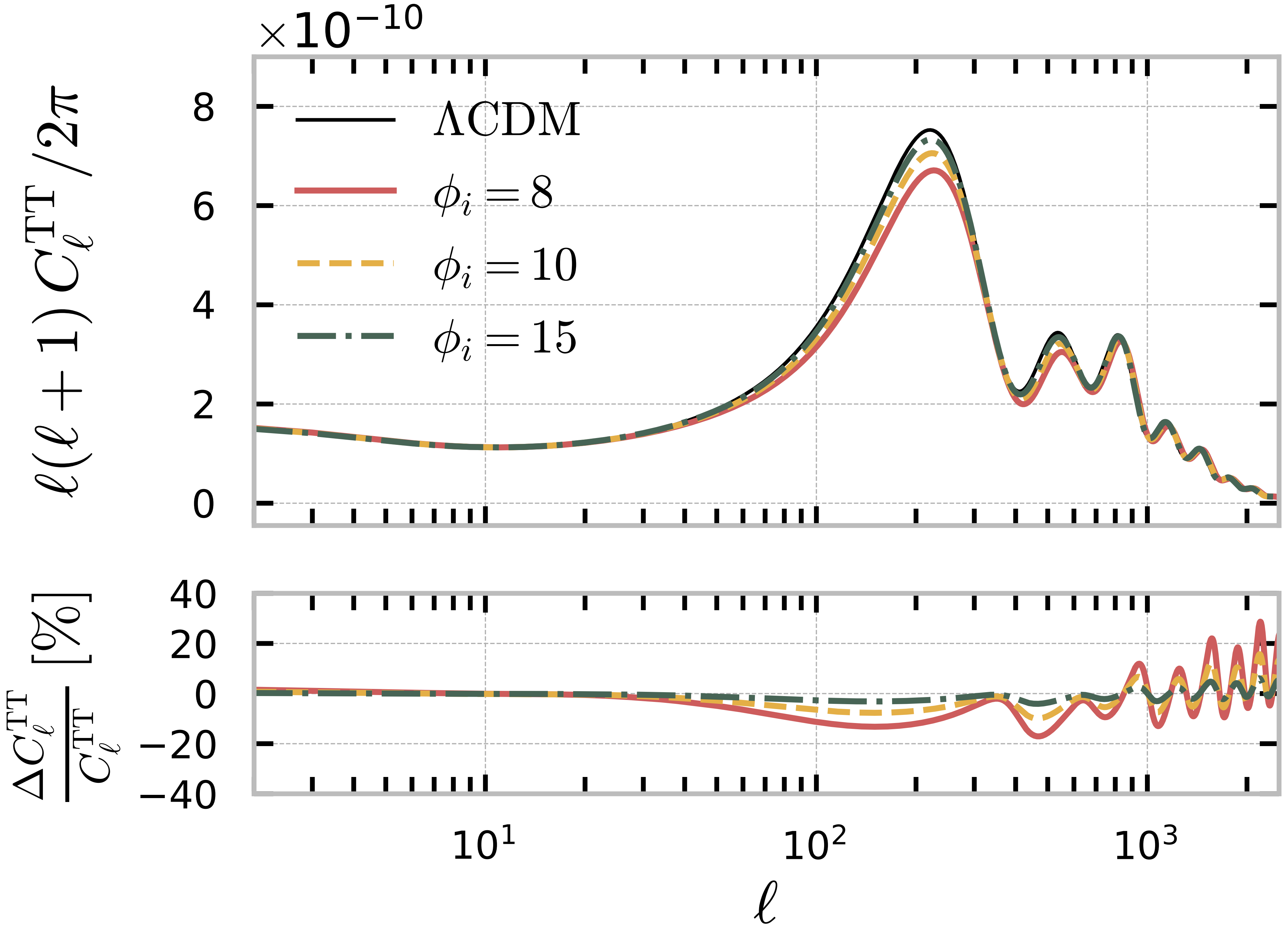
Potential acts as an effective interaction between the fields

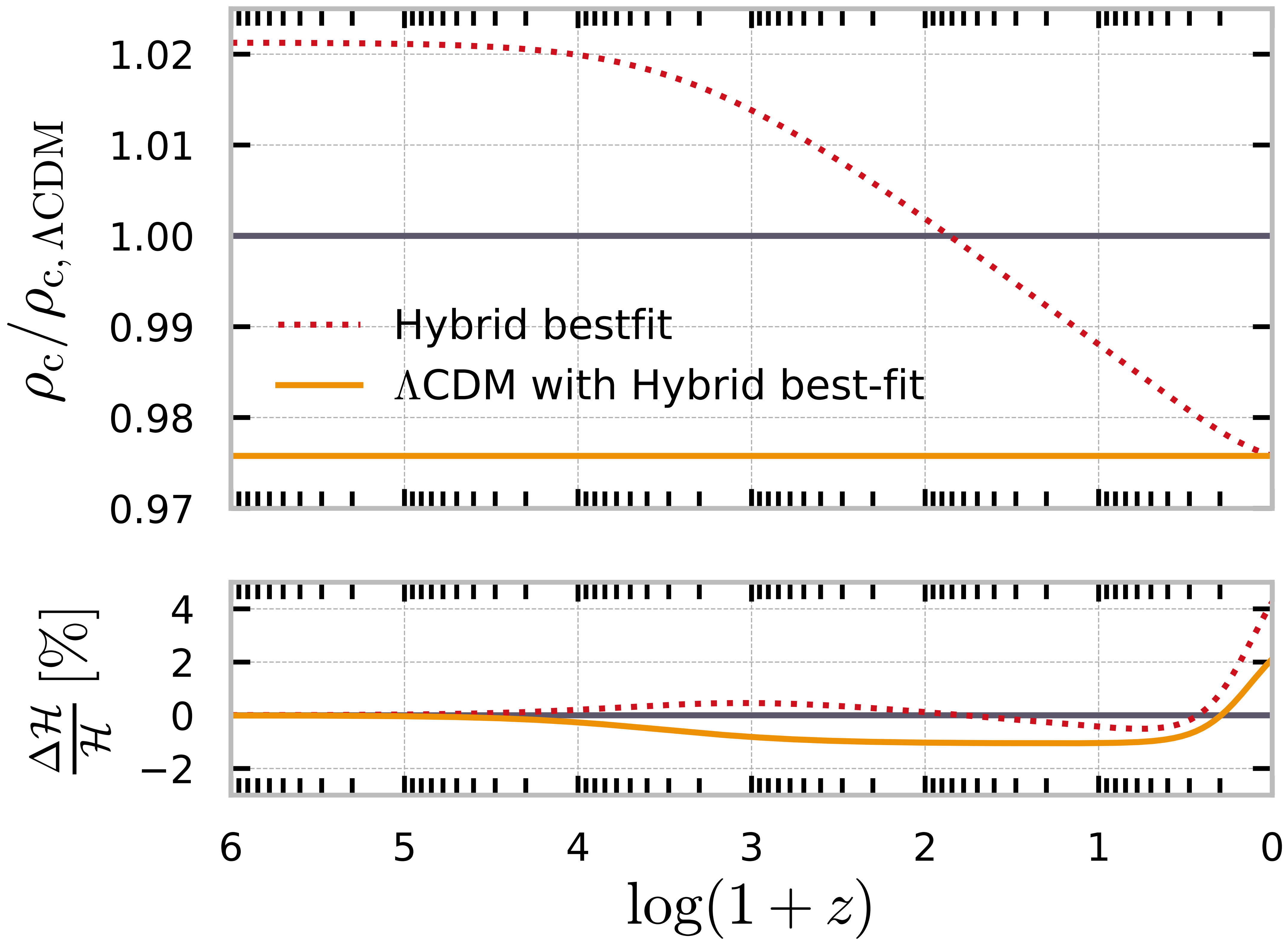
- When $\phi > \phi_c$, χ acts as dark matter
- ϕ slowly rolls down the potential, primarily due to V_0 and the interaction with χ
- As $\phi \to \phi_c$, χ drops abruptly and starts oscillating around $\chi = \pm M$
- $V(\phi, \chi) \to 0$ signalling a rapid decay of dark energy → DE domination is a transient phenomenon

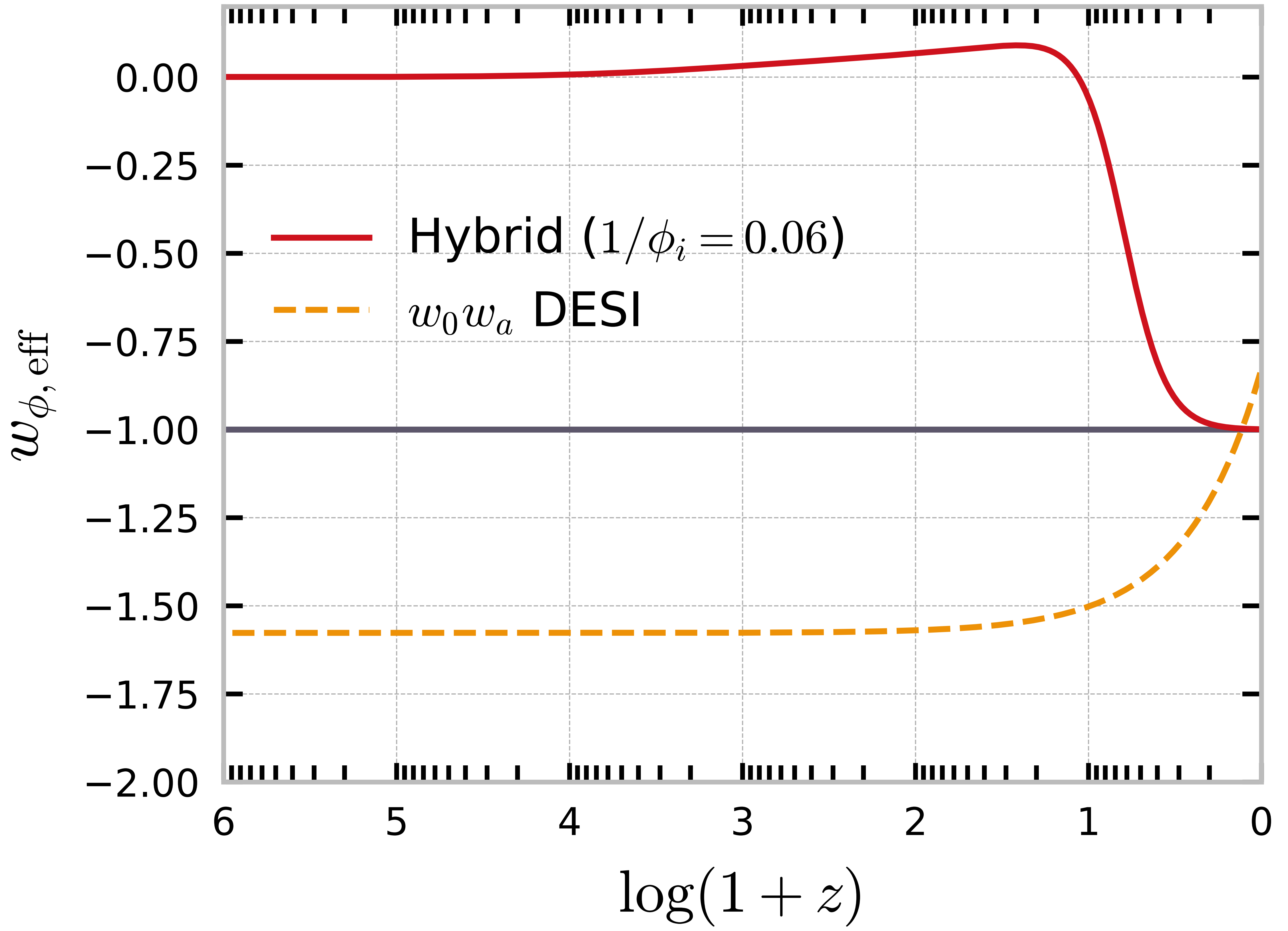
Angular Spectra

- Enhancement of $C_{\phi\phi}$ - amplified gravitational interaction for DM particles
- Suppression of TT spectrum and narrowing of the peaks - reduction in ρ_b/ρ_{DM} at recombination
- Degeneracy between the coupling and the Hubble rate drives the spectra towards higher ℓ





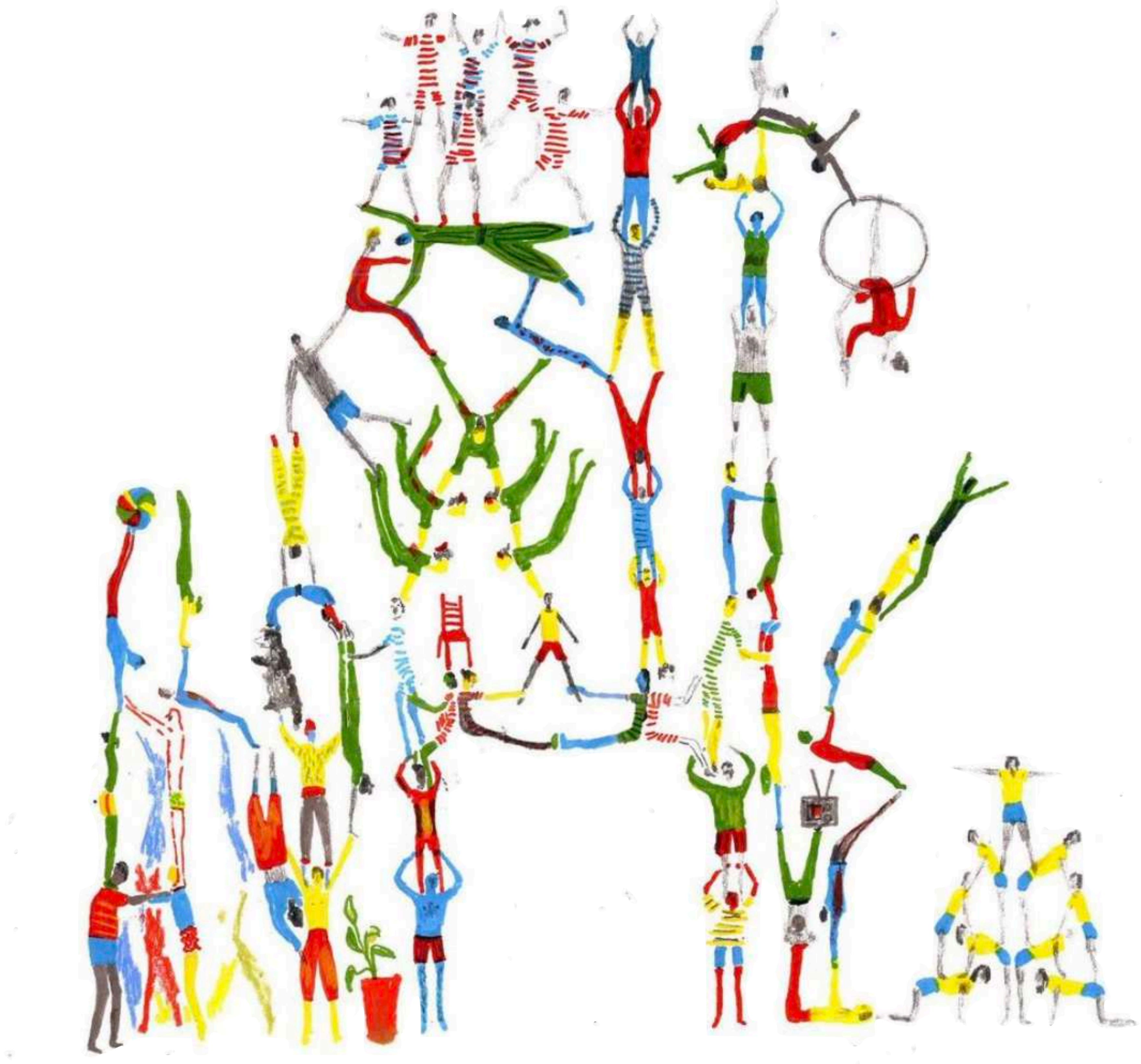

1.02
1.01
1.00
0.99
0.98
0.97
$\rho_c/\rho_{c,\Lambda CDM}$
Hybrid bestfit
ΛCDM with Hybrid best-fit
4
2
0
−2
$\frac{\Delta\mathcal{H}}{\mathcal{H}}$ [%]
6
5
4
3
2
1
0
$\log(1+z)$


0.00
−0.25
−0.50
−0.75
−1.00
−1.25
−1.50
−1.75
−2.00
$w_{\phi,\mathrm{eff}}$
Hybrid ($1/\phi_i = 0.06$)
$w_0 w_a$ DESI
6
5
4
3
2
1
0
$\log(1+z)$

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]

Data Sets

- Baseline data set is “Pl18”: CMB Planck 2018 data for large angular scales ℓ = [2, 29] and a joint of TT, TE and EE likelihoods for the small angular scales [Aghanim et al.: Astron.Astrophys. 641 (2020) A5]

- “Pl18+DESI+SN”: “Pl18" plus compilation of baryon acoustic oscillations (BAO) distance and expansion rate measurements from DESI, and distance moduli measurements of type Ia Supernova (SN) data from Pantheon+ [A. G. Adame et al. (DESI), (2024), arXiv:2404.03002; Brout et. al: Astrophys. J. 938 (2022) 110]

- “Pl18+DESI+SN+H0”: “Pl18+DESI+SN" plus prior on magnitude Mb from SH0ES [Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]

Cosmological Constraints

- Constraints with Planck (Pl18) are very similar to the ΛCDM case but with enlarged errors
- Positive correlation between the coupling $(1/\phi_i)$ and H_0 and negative correlation with $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$ - alleviate cosmic tensions
- Detection of the coupling parameter with DESI data
- DESI breaks geometrical degeneracies in CMB - more sensitive to the dynamical behaviour of the dark sector at late times
- DESI data attempts to bring physical matter density down in ΛCDM (slight disagreement with Pl18)

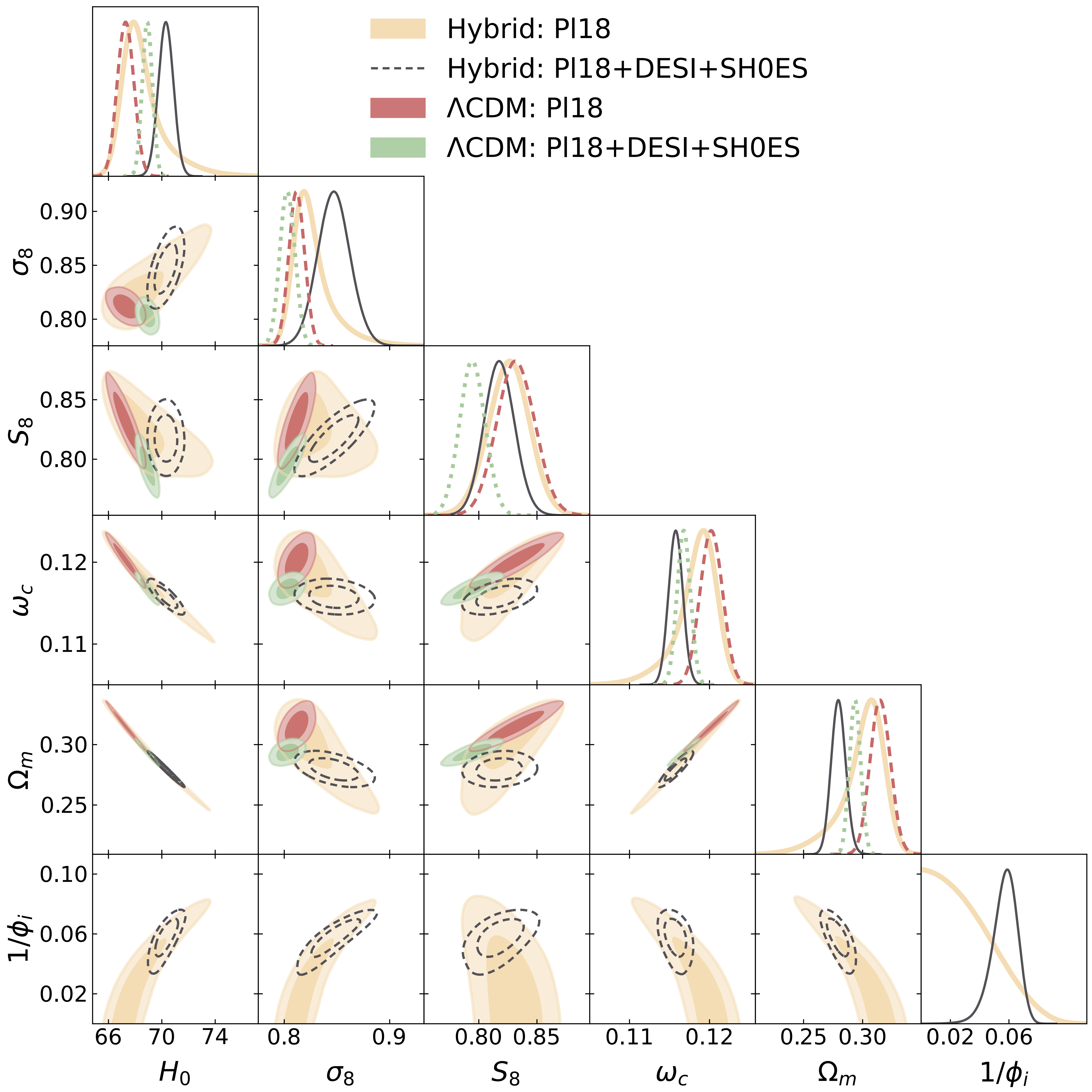


Table of constraints at a 68% confidence level

Parameter	Pl18	Pl18+SN	Pl18+SH0ES	Pl18+DESI	Pl18+DESI+SN	Pl18+DESI+SH0ES
ω_b	0.02236 ± 0.00015	0.02231 ± 0.00014	0.02237 ± 0.00015	0.02240 ± 0.00015	0.02239 ± 0.00015	0.02237 ± 0.00015
ω_c	$0.1184^{+0.0029}_{-0.0016}$	0.1202 ± 0.0014	0.1139 ± 0.0014	0.1174 ± 0.0011	0.11820 ± 0.00099	0.11577 ± 0.00089
$100\theta_s$	1.04187 ± 0.00030	1.04182 ± 0.00029	1.04190 ± 0.00030	1.04193 ± 0.00030	1.04194 ± 0.00029	1.04188 ± 0.00029
τ_{reio}	0.0548 ± 0.0077	0.0539 ± 0.0077	0.0558 ± 0.0079	0.0557 ± 0.0079	0.0557 ± 0.0077	0.0554 ± 0.0078
n_s	0.9660 ± 0.0045	0.9640 ± 0.0041	0.9683 ± 0.0041	0.9677 ± 0.0040	0.9673 ± 0.0039	0.9670 ± 0.0041
$\log 10^{10} A_s$	3.047 ± 0.016	3.046 ± 0.016	3.049 ± 0.016	3.047 ± 0.016	3.047 ± 0.016	3.048 ± 0.016
$1/\phi_i$	< 0.0390	< 0.0220	$0.0661^{+0.0095}_{-0.0073}$	$0.037^{+0.019}_{-0.012}$	$0.029^{+0.017}_{-0.015}$	$0.0570^{+0.0096}_{-0.0070}$
Best-fit:	[0.0054]	[0.0019]	[0.0676]	[0.0455]	[0.0341]	[0.0591]
σ_8	$0.8263^{+0.0095}_{-0.021}$	$0.8185^{+0.0079}_{-0.010}$	0.858 ± 0.017	$0.827^{+0.013}_{-0.018}$	$0.821^{+0.010}_{-0.015}$	0.847 ± 0.015
H_0	$68.55^{+0.80}_{-1.8}$	$67.42^{+0.59}_{-0.72}$	71.49 ± 0.87	$69.04^{+0.65}_{-0.76}$	$68.51^{+0.51}_{-0.63}$	70.30 ± 0.56
Ω_m	$0.300^{+0.021}_{-0.011}$	$0.3138^{+0.0093}_{-0.0084}$	0.2669 ± 0.0091	0.2934 ± 0.0080	$0.2997^{+0.0073}_{-0.0065}$	0.2796 ± 0.0061
S_8	0.826 ± 0.018	0.837 ± 0.015	0.809 ± 0.014	0.817 ± 0.013	0.821 ± 0.013	0.818 ± 0.013
$\Delta\chi^2_{\rm min}$	0.14	0.08	−16.32	−2.8	−1.06	−12.76
$\log B_{\rm M,\Lambda CDM}$	−3.3	−3.6	4.5	−2.0	−2.8	2.5
$Q^{\rm SH0ES}_{\rm DMAP}$	−−	4.78	−−	−−	4.65	−−

TABLE II: Observational constraints at a 68% confidence level on the independent and derived cosmological parameters using different dataset combinations for the hybrid model, as detailed in Section III A. $\Delta\chi^2_{\rm min}$ represents the difference in the best-fit χ^2 of the profile likelihood global minimisation, and $\log B_{\rm M,\Lambda CDM}$ indicates the ratio of the Bayesian evidence, both computed with respect to ΛCDM. The value of $Q^{\rm SH0ES}_{\rm DMAP}$ is calculated according to Eq. (14). For reference, the same results for ΛCDM are given in Table III of Appendix A.

Table of constraints at a 68% confidence level

Parameter	Pl18	Pl18+SN	Pl18+SH0ES	Pl18+DESI	Pl18+DESI+SN	Pl18+DESI+SH0ES
$\omega_{\rm b}$	0.02235 ± 0.00015	0.02231 ± 0.00015	0.02264 ± 0.00014	0.02249 ± 0.00013	0.02246 ± 0.00013	0.02265 ± 0.00013
$\omega_{\rm c}$	0.1202 ± 0.0014	0.1207 ± 0.0013	0.1169 ± 0.0011	0.11817 ± 0.00094	0.11862 ± 0.00091	0.11678 ± 0.00083
$100\theta_s$	1.04187 ± 0.00030	1.04182 ± 0.00029	1.04221 ± 0.00028	1.04206 ± 0.00028	1.04203 ± 0.00028	1.04223 ± 0.00028
$\tau_{\rm reio}$	0.0543 ± 0.0078	0.0536 ± 0.0077	0.0591 ± 0.0079	0.0572 ± 0.0078	0.0565 ± 0.0077	0.0595 ± 0.0078
n_s	0.9647 ± 0.0045	0.9635 ± 0.0042	0.9729 ± 0.0039	0.9697 ± 0.0038	0.9686 ± 0.0036	0.9733 ± 0.0035
$\log 10^{10} A_s$	3.045 ± 0.016	3.045 ± 0.016	3.048 ± 0.016	3.046 ± 0.016	3.046 ± 0.016	3.048 ± 0.016
σ_8	0.8118 ± 0.0074	0.8125 ± 0.0074	0.8026 ± 0.0074	0.8066 ± 0.0071	0.8078 ± 0.0071	0.8030 ± 0.0071
H_0	67.29 ± 0.61	67.08 ± 0.56	68.86 ± 0.49	68.21 ± 0.42	68.01 ± 0.40	68.91 ± 0.38
Ω_m	0.3150 ± 0.0085	0.3179 ± 0.0078	0.2944 ± 0.0062	0.3024 ± 0.0055	0.3050 ± 0.0053	0.2936 ± 0.0047
S_8	0.832 ± 0.016	0.836 ± 0.015	0.795 ± 0.013	0.810 ± 0.012	0.815 ± 0.012	0.794 ± 0.011
$Q_{\rm DMAP}^{\rm SH0ES}$	−−	6.25	−−	−−	5.76	−−

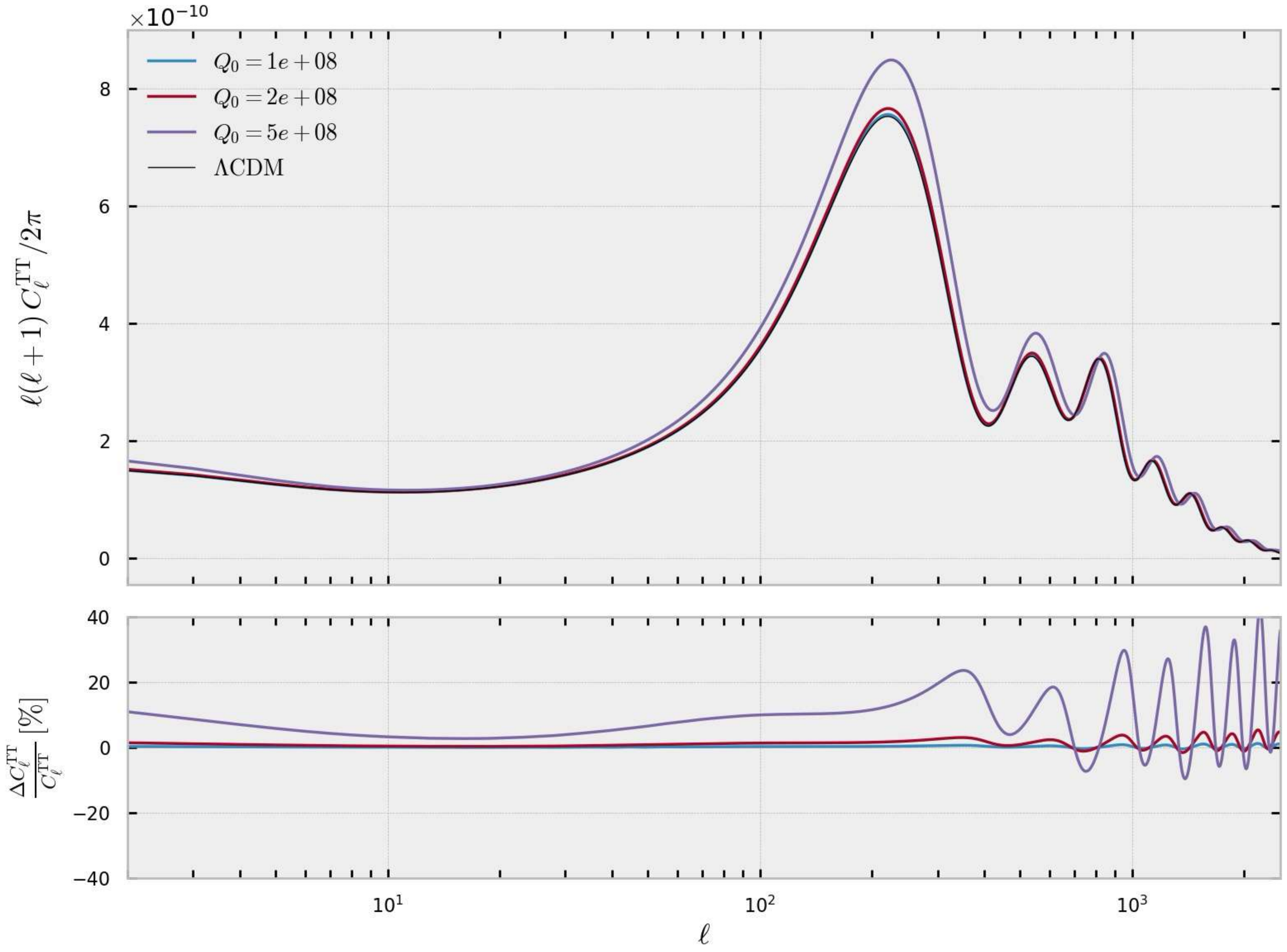
TABLE III: Observational constraints at a 68% confidence level on the independent and derived cosmological parameters using different dataset combinations for the ΛCDM model, as detailed in Section III A. The value of $Q_{\rm DMAP}^{\rm SH0ES}$ is calculated according to Eq. (14).

Observational Imprints (preliminary results)

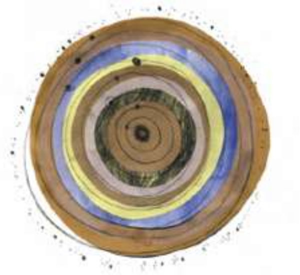
- First approximation: ϕ is constant, Q_0 is constant and $Q_1 = 0$

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2m^2}}{\frac{1}{2}\frac{k^2}{a^2m^2} + 2}$$

- Same as uncoupled axion but with coupling in the background
- Due to the coupling the sound speed is enhanced mostly on small scales
- Background coupled dynamics - H0 tension
- Matter power spectrum suppresion on small scales - S_8 tension



$m = 10^{-17}$ eV, $Q_1 = 0$, [GP, **EMT**, CvB, NN: arxiv:2404.10524]

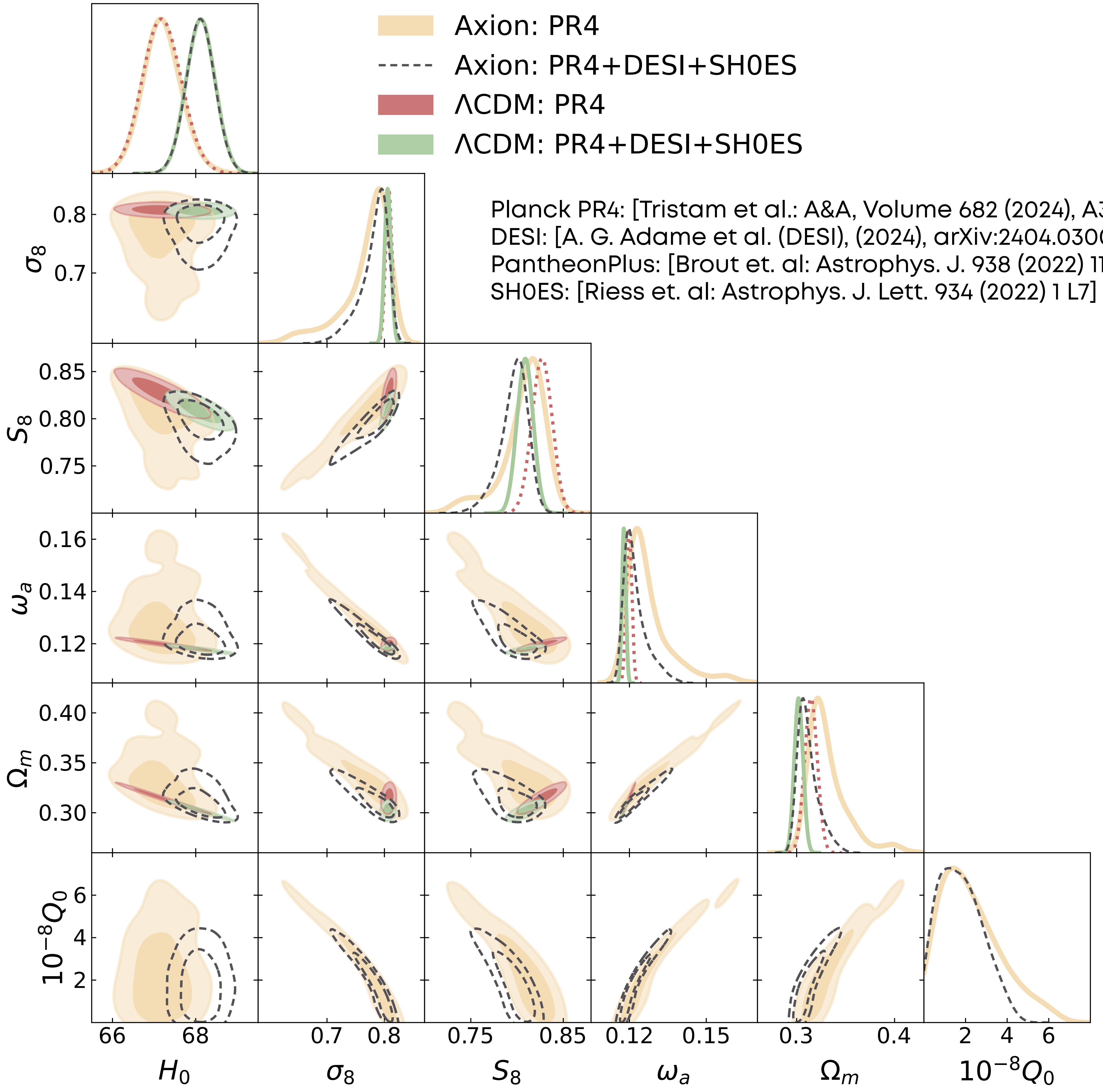


Observational Imprints (preliminary results)

- First approximation: ϕ is constant, Q_0 is constant and $Q_1 = 0$

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2m^2}}{\frac{1}{2}\frac{k^2}{a^2m^2} + 2}$$

- Same as uncoupled axion but with coupling in the background
- Due to the coupling the sound speed is enhanced mostly on small scales
- Background coupled dynamics - H0 tension
- Matter power spectrum suppresion on small scales - S_8 tension



Planck PR4: [Tristam et al.: A&A, Volume 682 (2024), A37]
DESI: [A. G. Adame et al. (DESI), (2024), arXiv:2404.03002]
PantheonPlus: [Brout et. al: Astrophys. J. 938 (2022) 110]
SH0ES: [Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]

Observational Imprints (preliminary results)

- First approximation: ϕ is constant, Q_0 is constant and $Q_1 = 0$

$$c_a^2 = \frac{\frac{1}{2}\frac{k^2}{a^2m^2}}{\frac{1}{2}\frac{k^2}{a^2m^2} + 2}$$

- Same as uncoupled axion but with coupling in the background
- Due to the coupling the sound speed is enhanced mostly on small scales
- Background coupled dynamics - H0 tension
- Matter power spectrum suppresion on small scales - S_8 tension