COSMIC TENSIONS AND INTERACTIONS IN THE DARK SECTOR

Illustrations: Inês Viegas Oliveira (ivoliveira.com)

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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

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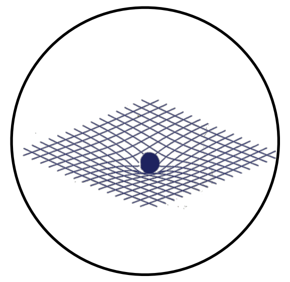
The Standard Model of Cosmology

The Lambda Cold Dark Matter Model

THEORY OF GRAVITY



General Relativity:

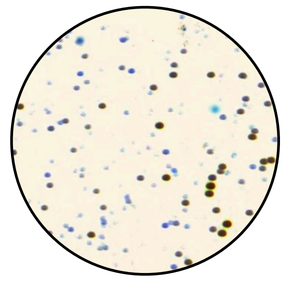
$G_{\mu\nu} = 8\pi G T_{\mu\nu}$

METRIC ANSATZ

FLRW Metric:

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

STANDARD MATTER



Baryons, Photons, Neutrinos

5%

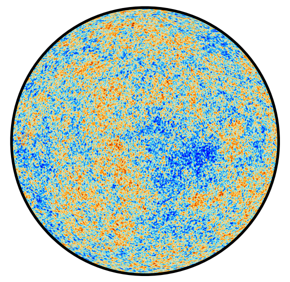
ΛCDM MODEL

25%

70%

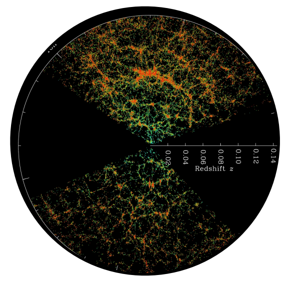
INFLATION — INFLATON

Early accelerated expansion produce density fluctuations



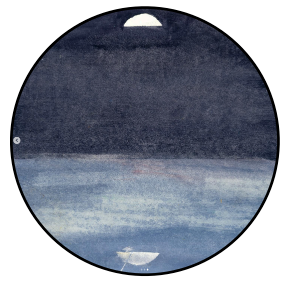
COSMIC STRUCTURE — CDM

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 Hubble/H_0 expansion rate tension
- Evidence for dynamical dark energy

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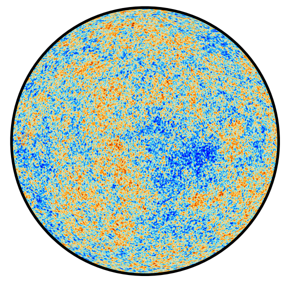

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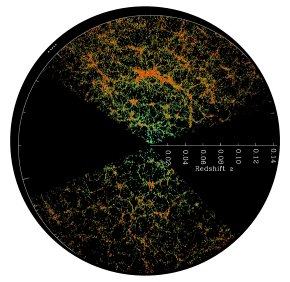

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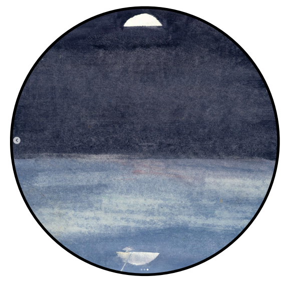
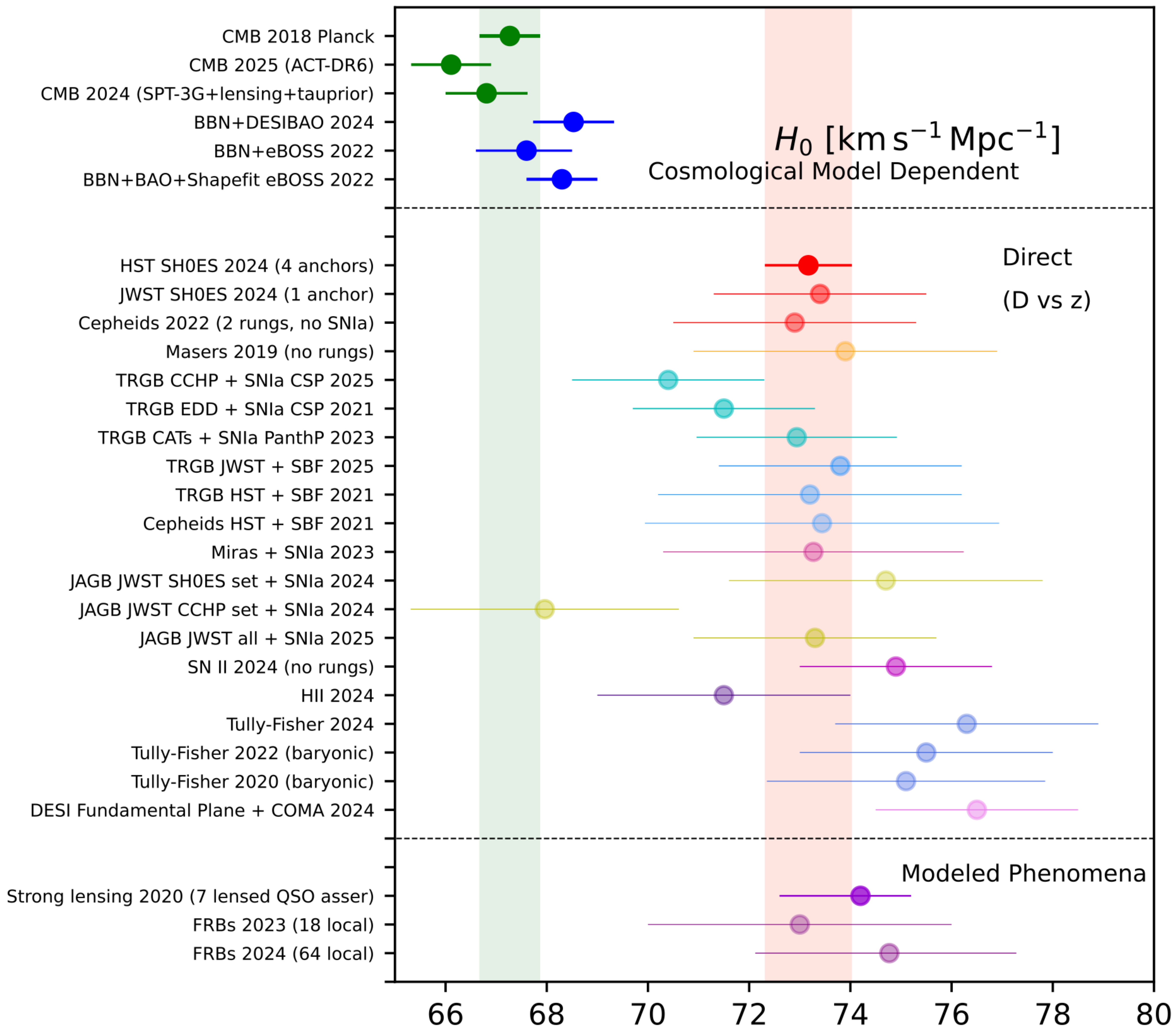


The Hubble Tension

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

- ~5σ tension between Planck 2018 and SH$_0$ES:
  - 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 model-dependent data vs direct measurements that disagree
- Could signal differences in the expansion history (nature of the dark sector)



[Cosmoverse white paper: arxiv:2504.01669]

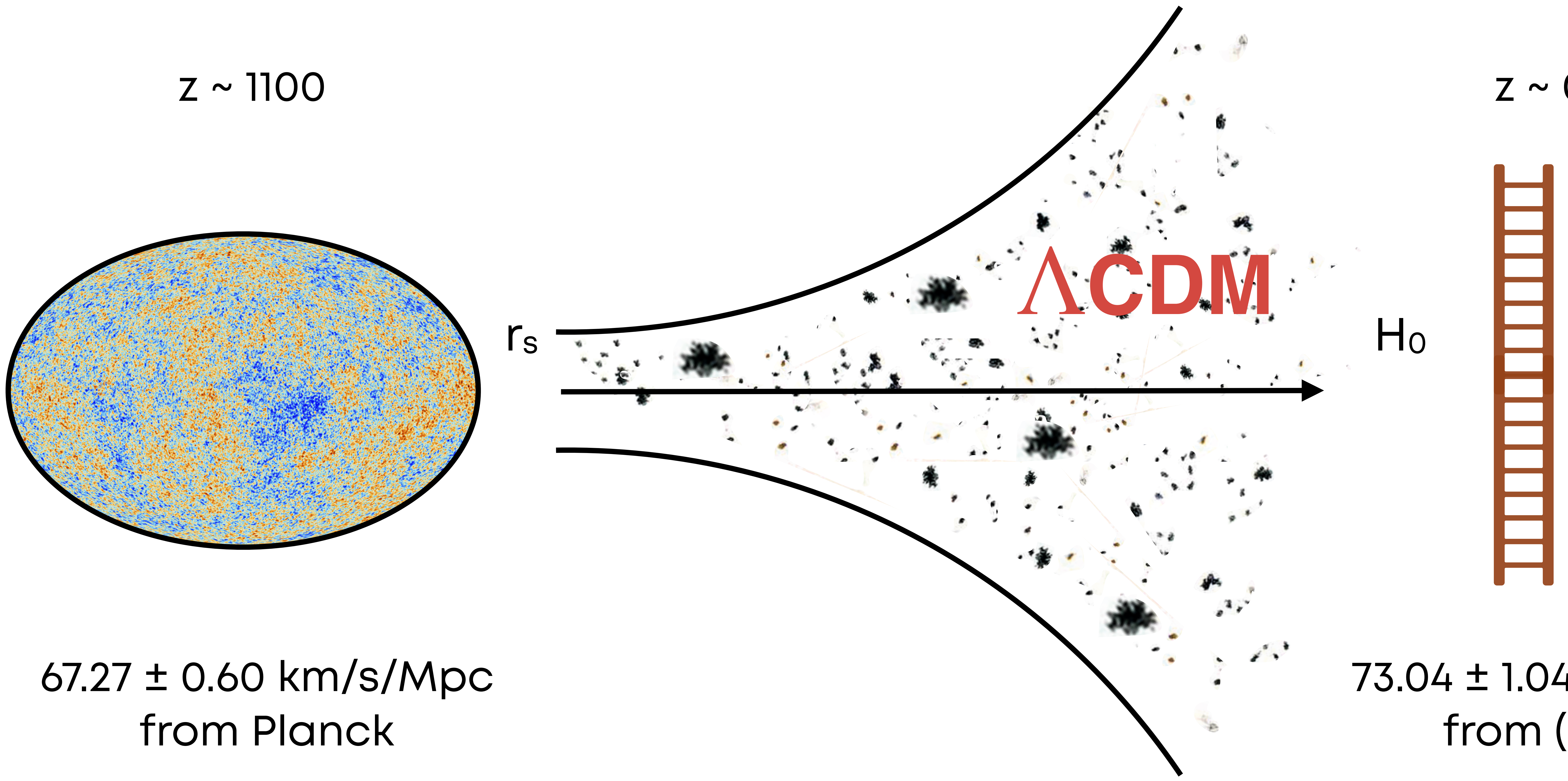
The Hubble Tension

CMB Calibration

$z \sim 1100$

Local Prediction

$z \sim 0 - 1$



67.27 ± 0.60 km/s/Mpc
from Planck

73.04 ± 1.04 km/s/Mpc
from (SH0ES)

Beyond the Standard Model: Interactions in the dark sector

Going Beyond the Standard Model

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General Relativity:
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$w_\Lambda = p_\Lambda / \rho_\Lambda = -1$

LATE ACCELERATION — Λ
Component to explain current accelerated expansion

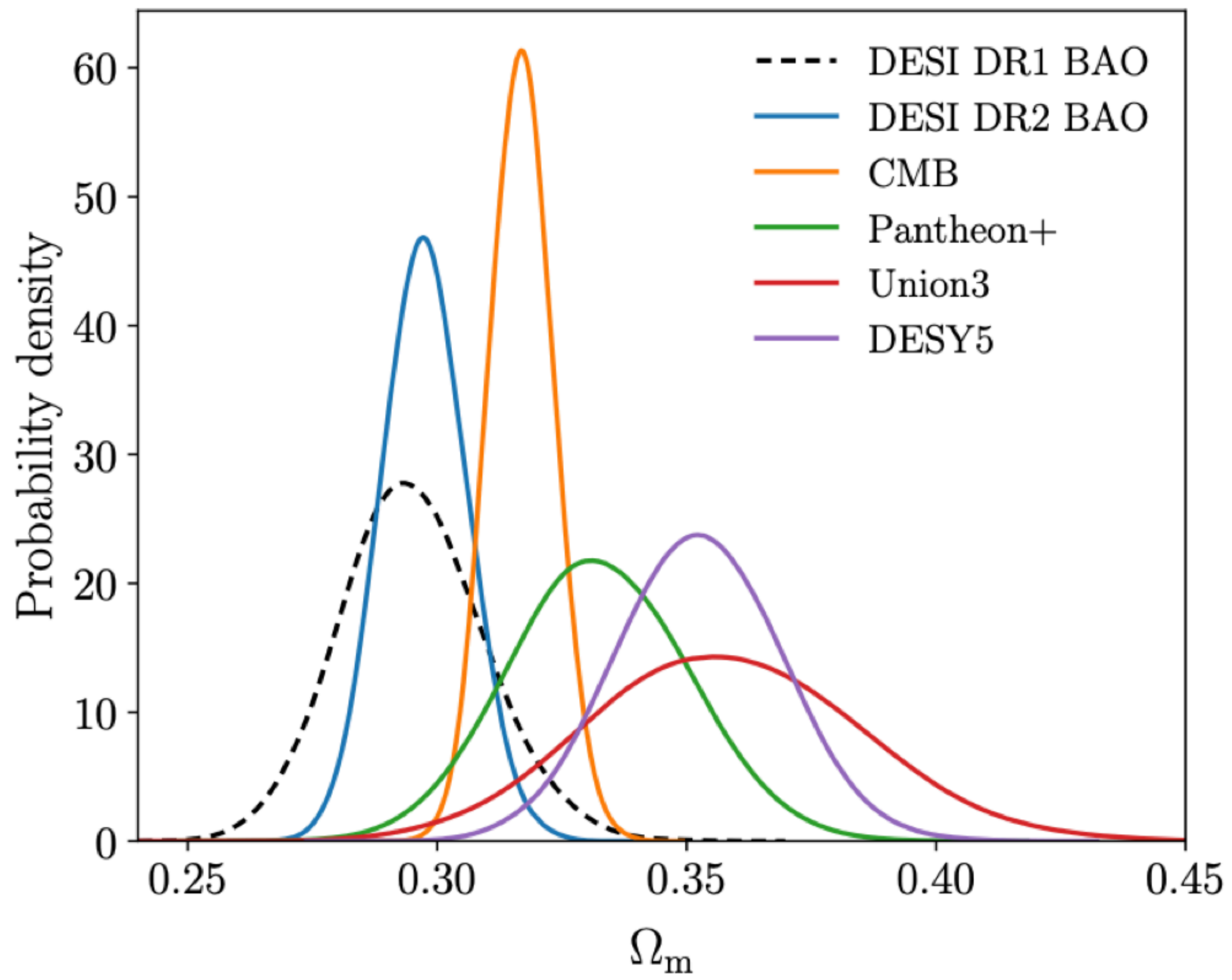
$$w_{\rm DE} = w_0 + w_a(1-a)$$

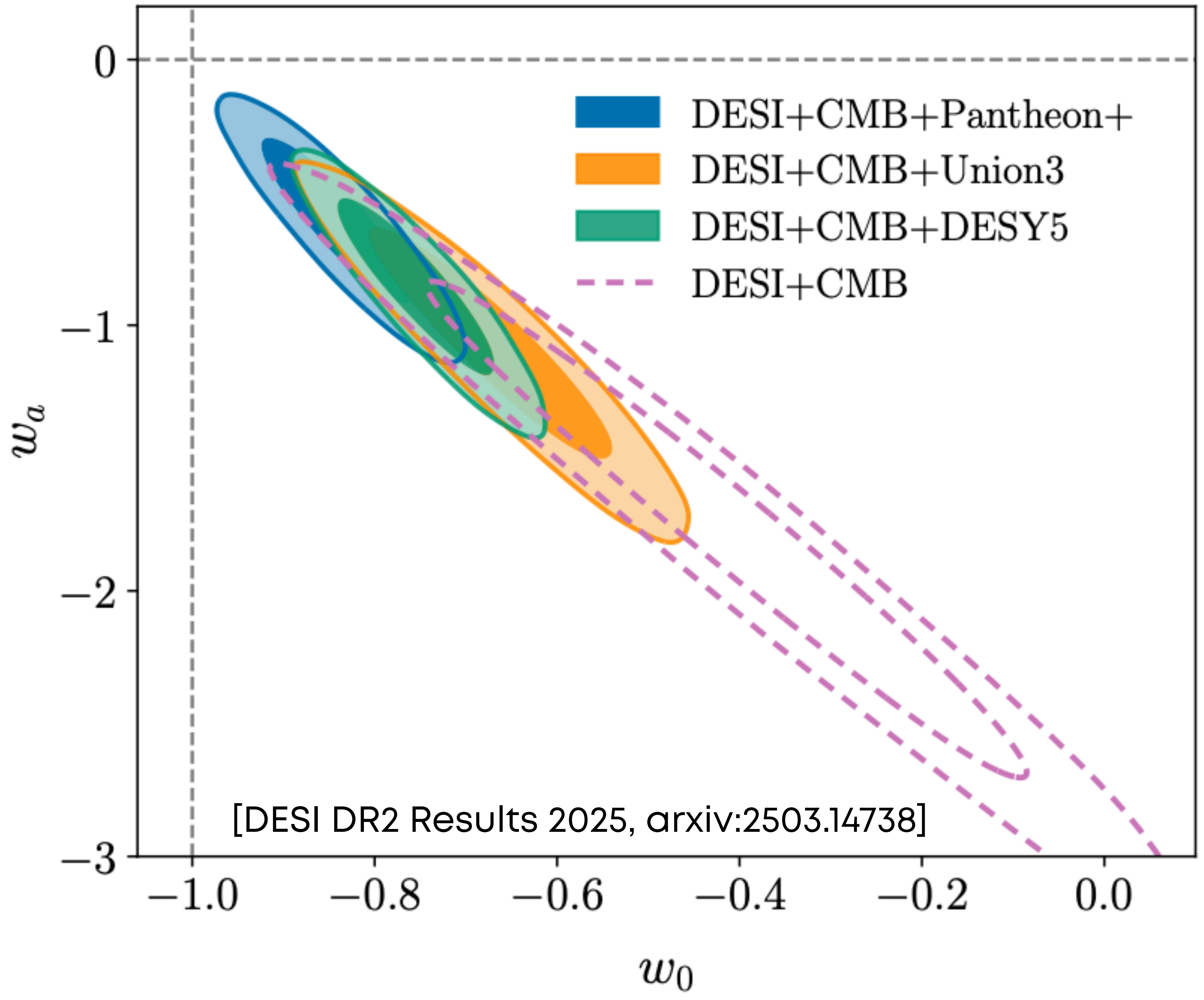
Chevallier, Polarski 2001; Linder 2002

Hints of new physics

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

DESI predicts lower value of Ω_m - 2-3σ tension with SNIa when combined with CMB





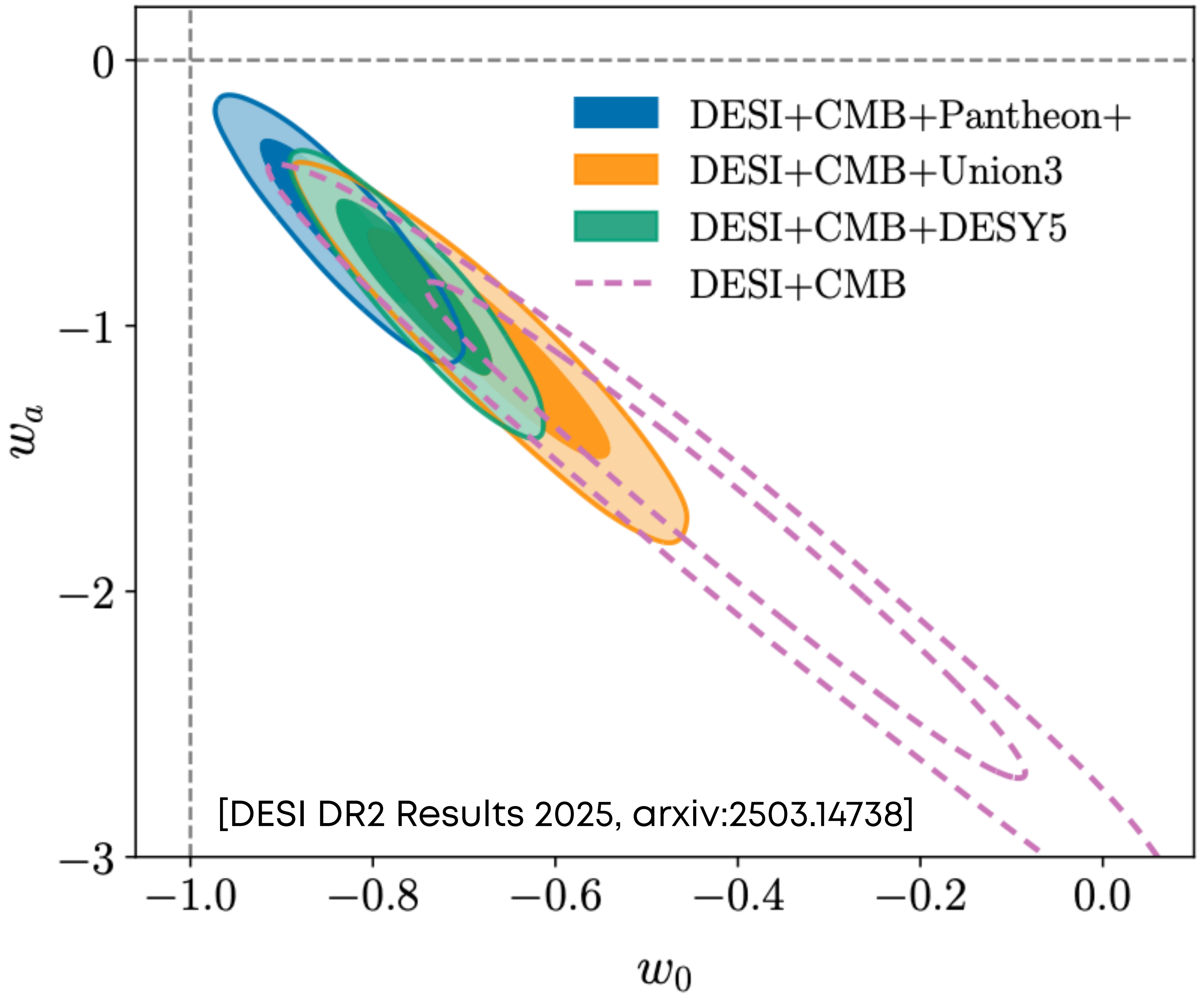
DESI+SNIa find 2.5– 4σ preference for phantom dark energy - unphysical and prone to instabilities

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
- No fundamental principle/observational constraints which forbid interactions between the dark species
- The enigmatic nature of DM lies in its poorly understood interactions with other particles
- Modified dark sector could naturally explain phantom dark energy evidence and address cosmic tensions



[DESI DR2 Results 2025, arxiv:2503.14738]

Non-trivial Dynamics in the Dark Sector

Going Beyond the Standard Model

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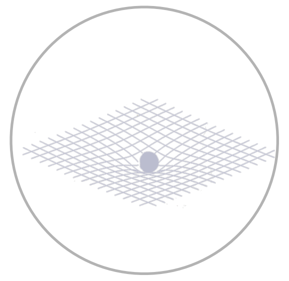

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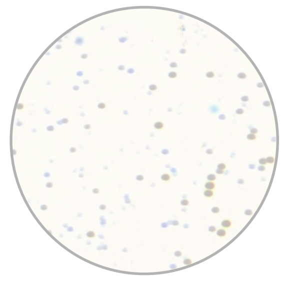

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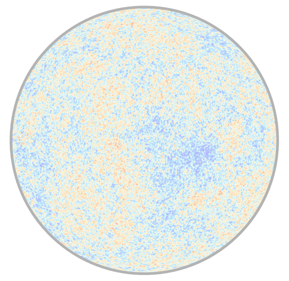

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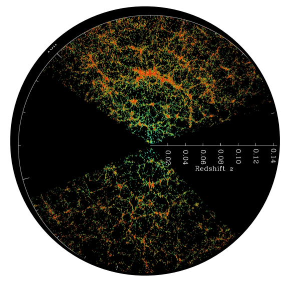

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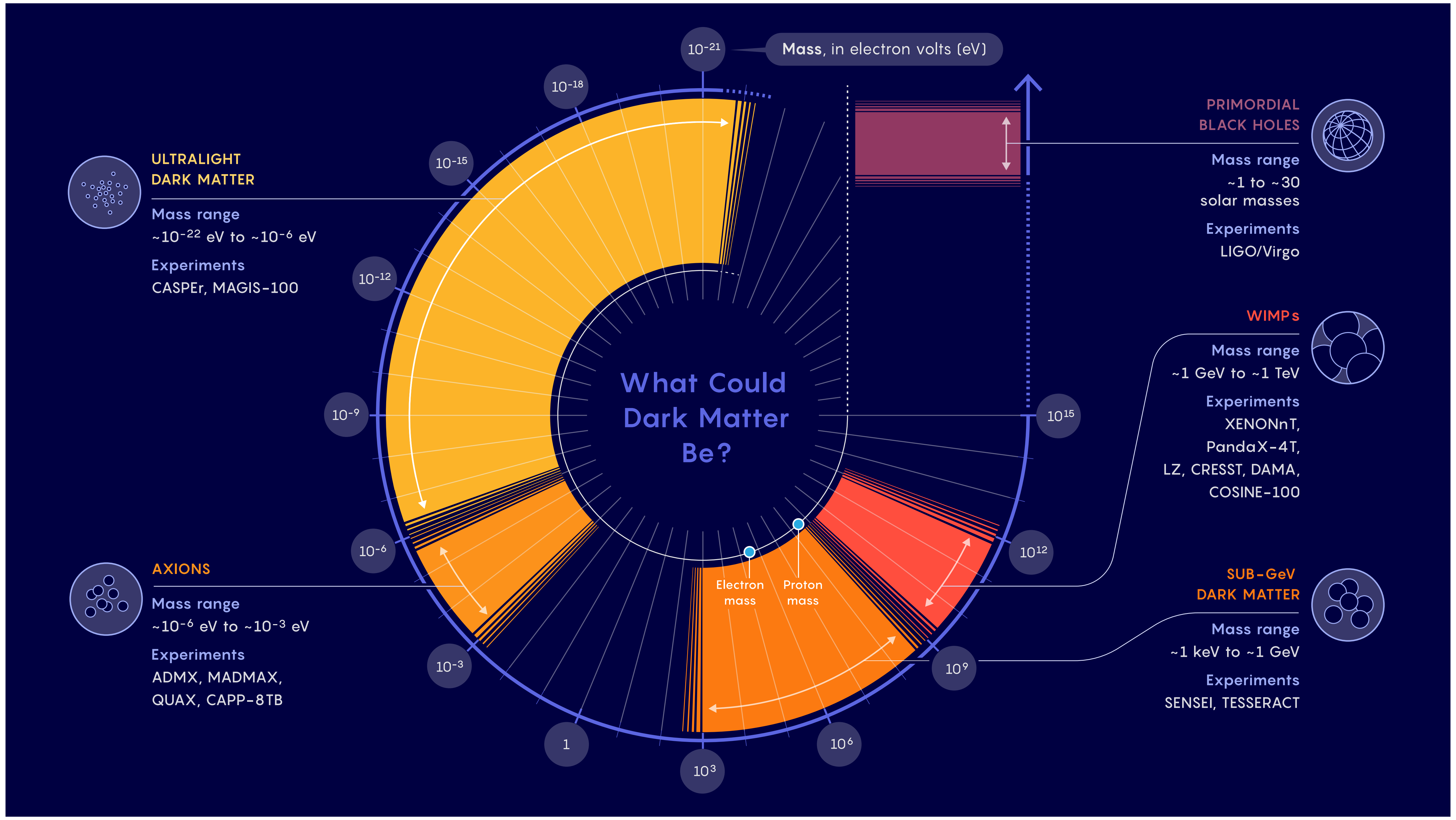
LATE ACCELERATION — Λ

Component to explain current accelerated expansion

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



[Image credit: Quanta magazine]

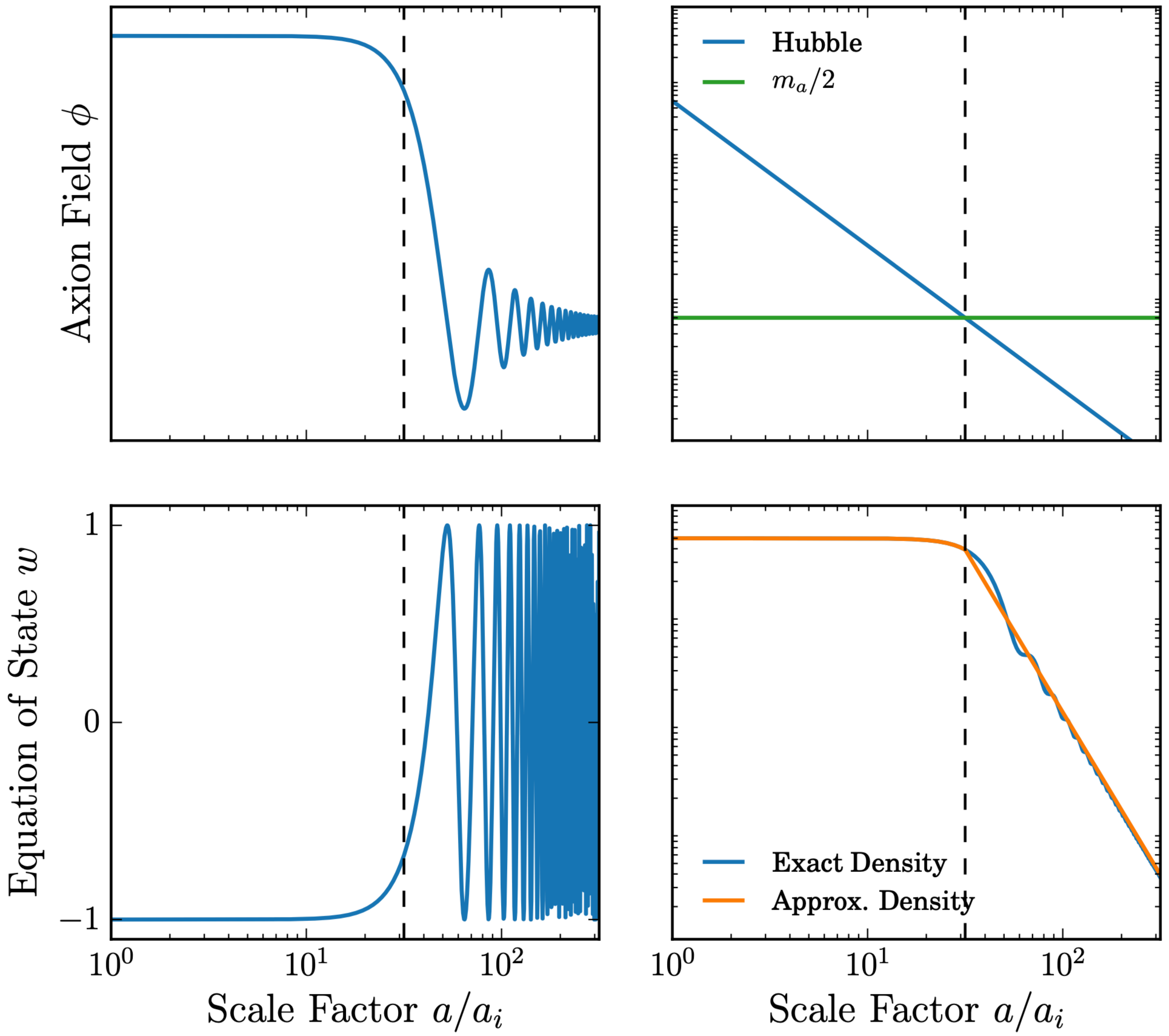
[The NANOGrav 15 yr Data Set 2023, Astrophys.J.Lett. 951 (2023) 1, L8]

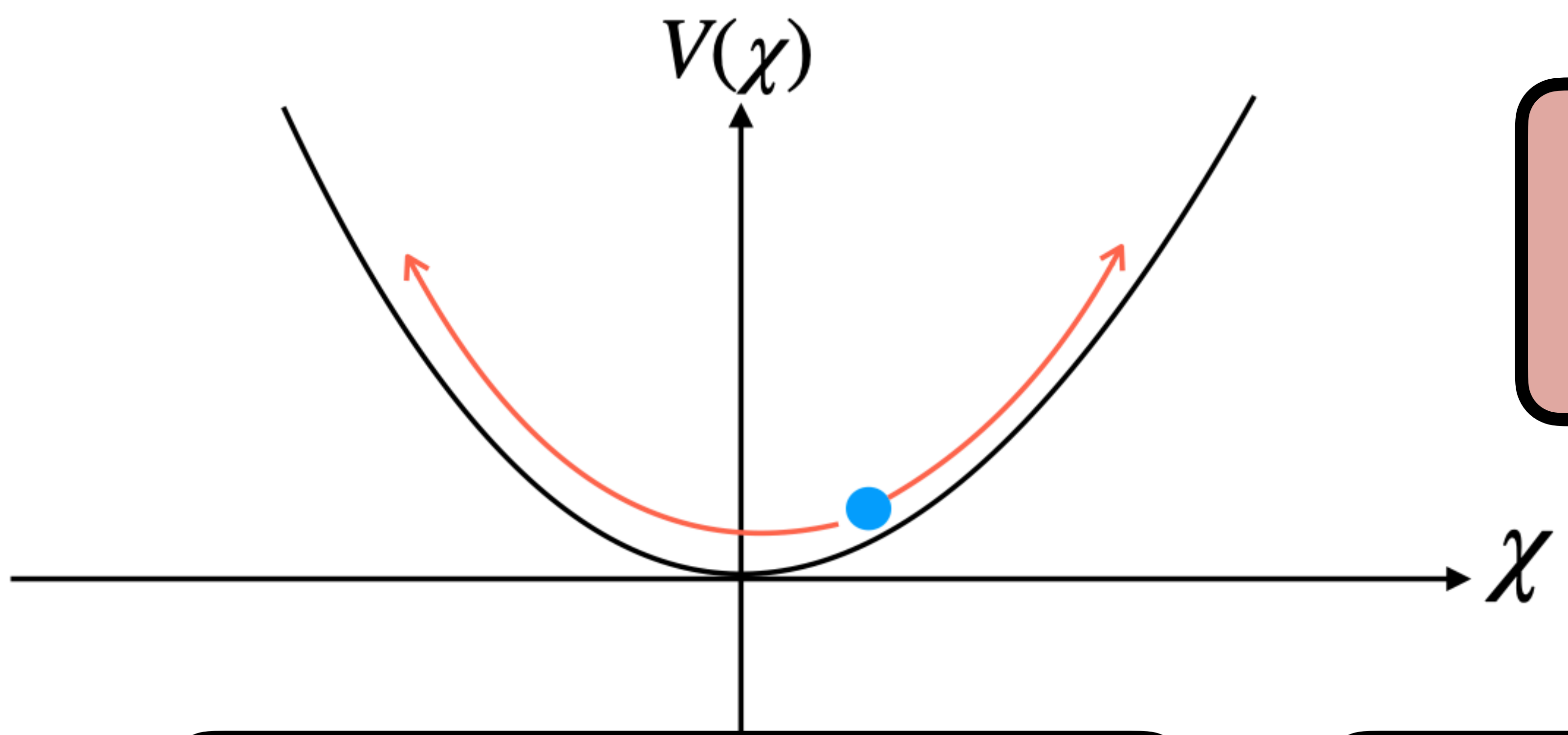
Scalar Field Dark Matter

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

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

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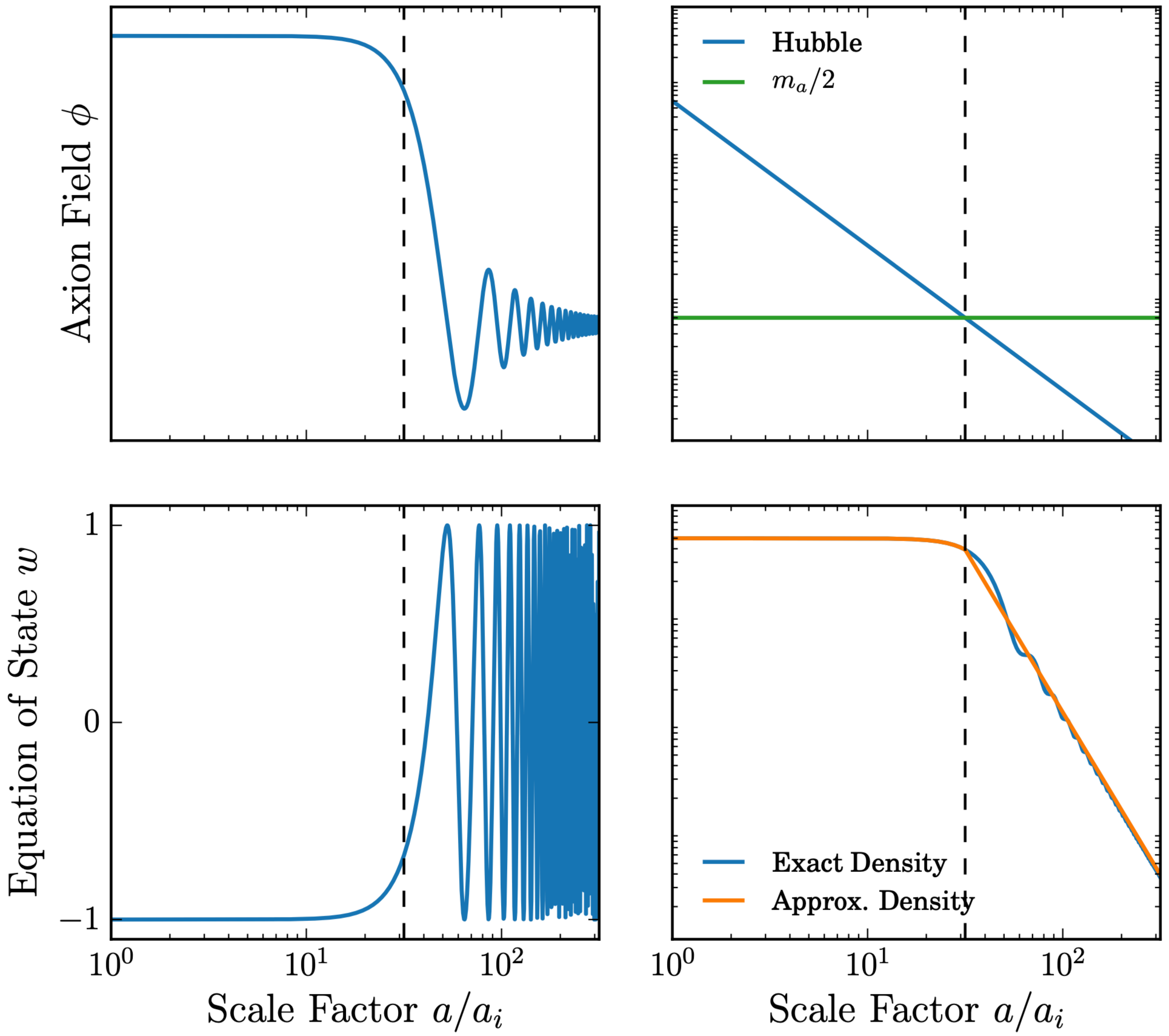

- **Oscillating** field for $m \gg H$ on time scales much faster than the expansion
- Rapid oscillations can be **averaged**
- Rewrite as a **fluid approximation** and recover CDM behaviour at the background level with additional scalar field properties

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

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

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

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

Beyond the Standard Model: Coupled Scalar Dark Sectors

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

Interacting dark sector

- Background cosmological couplings between dark matter (DM) and dark energy (DE) can be imposed at the level of the field equations:
- However, these are just phenomenological modifications
- Prone to instabilities [Valiviita et. al. arxiv:0804.0232]
- Ambiguous definition of cosmological perturbations (e.g., added by hand)
- Couplings often heavily constrained by background observations
- Focus on Lagrangian formulations

$$\dot{\rho}_{\rm DM} + 3H\left(\rho_{\rm DM} + p_{\rm DM}\right) = Q$$
$$\dot{\rho}_{\rm DE} + 3H\left(\rho_{\rm DE} + p_{\rm DE}\right) = -Q$$

$$\delta'_{\rm DM} + 3\mathscr{H}\left(\frac{\delta p_{\rm DM}}{\delta \rho_{\rm DM}} + w_{\rm DM}\right)\delta_{\rm DM} = -\left(1 + w_{\rm DM}\right)\left(\theta_{\rm DM} - 3\Phi'\right) + F(Q, \delta Q)$$
$$\theta'_{\rm DM} + \left[\mathscr{H}(1 - 3w_{\rm DM}) + \frac{w'_{\rm DM}}{1+_{\rm DM}}\right]\theta_{\rm DM} = k^2\left[\Psi + \frac{\delta p_{\rm DM}}{\delta \rho_{\rm DM}}\frac{\delta_{\rm DM}}{1 + w_{\rm DM}} + G(Q, \delta Q)\right]$$

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

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

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Standard kinetic terms

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

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

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

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

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 $g(\phi)$

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]

The result is a "conformal"-like coupled DM-DE model

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

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

FLRW background

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

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

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

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)

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

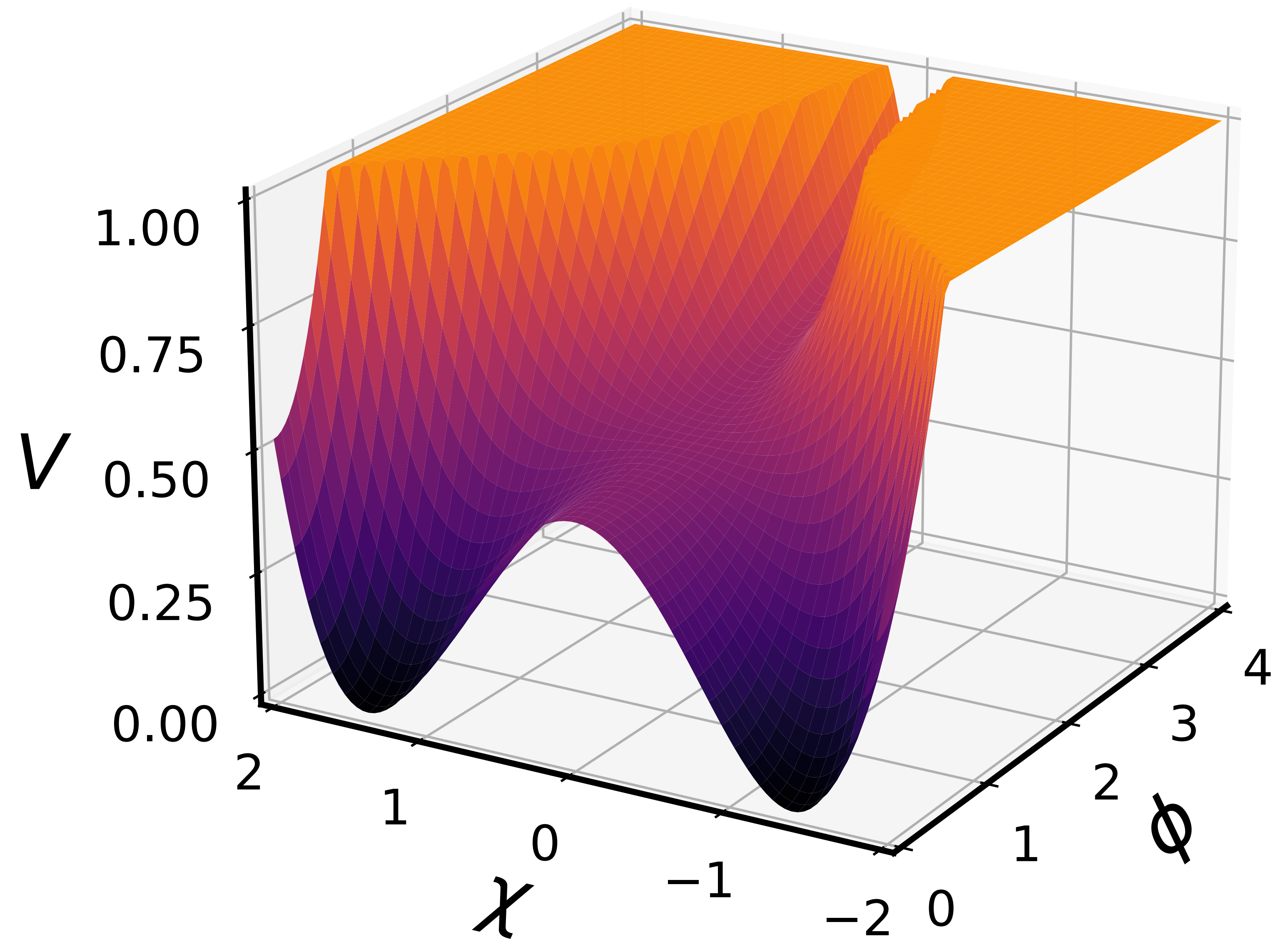
A Hybrid Model for the Dark Sector

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]

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



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

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

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

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

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

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

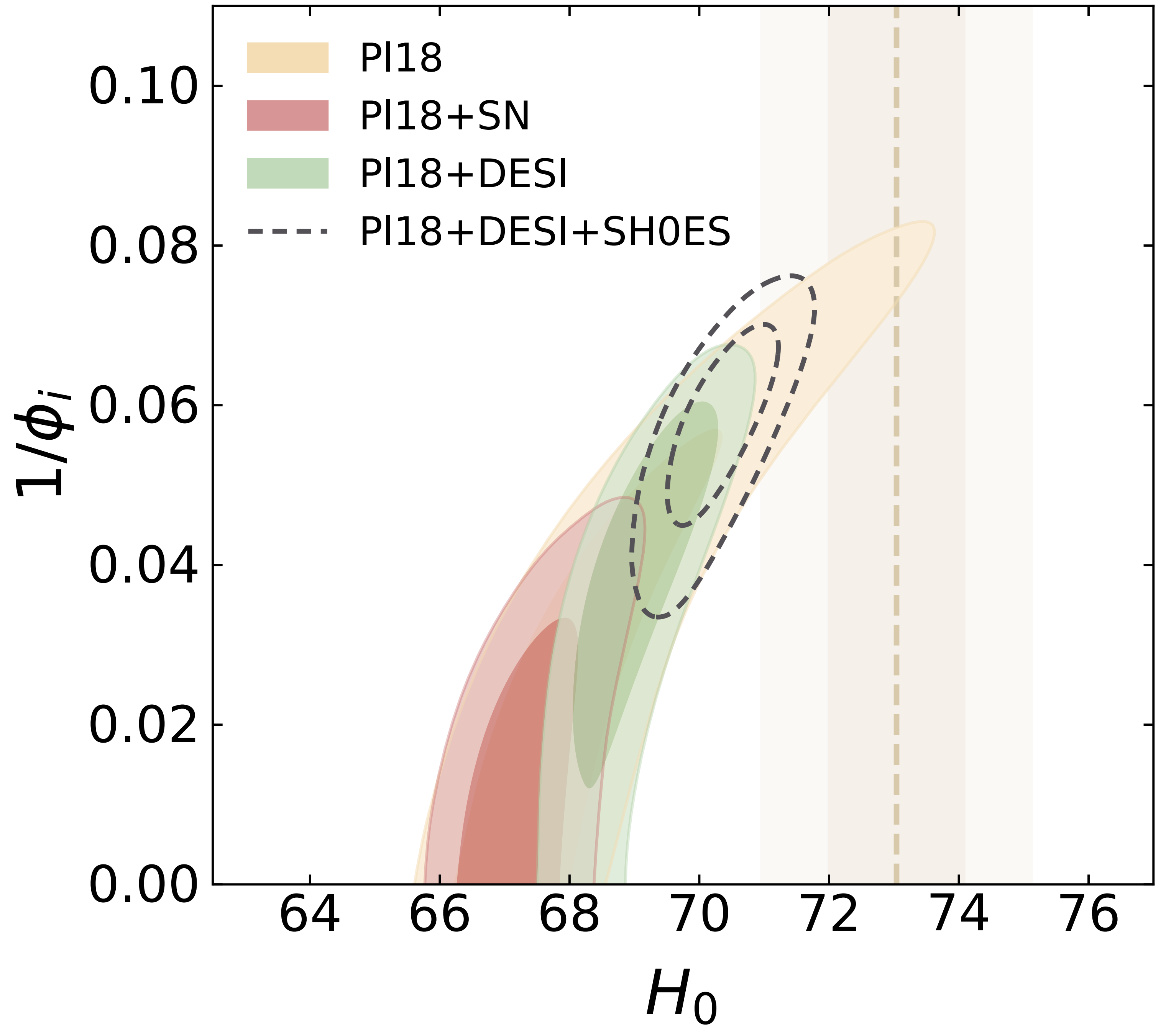
Alleviating cosmological tensions with a hybrid dark sector

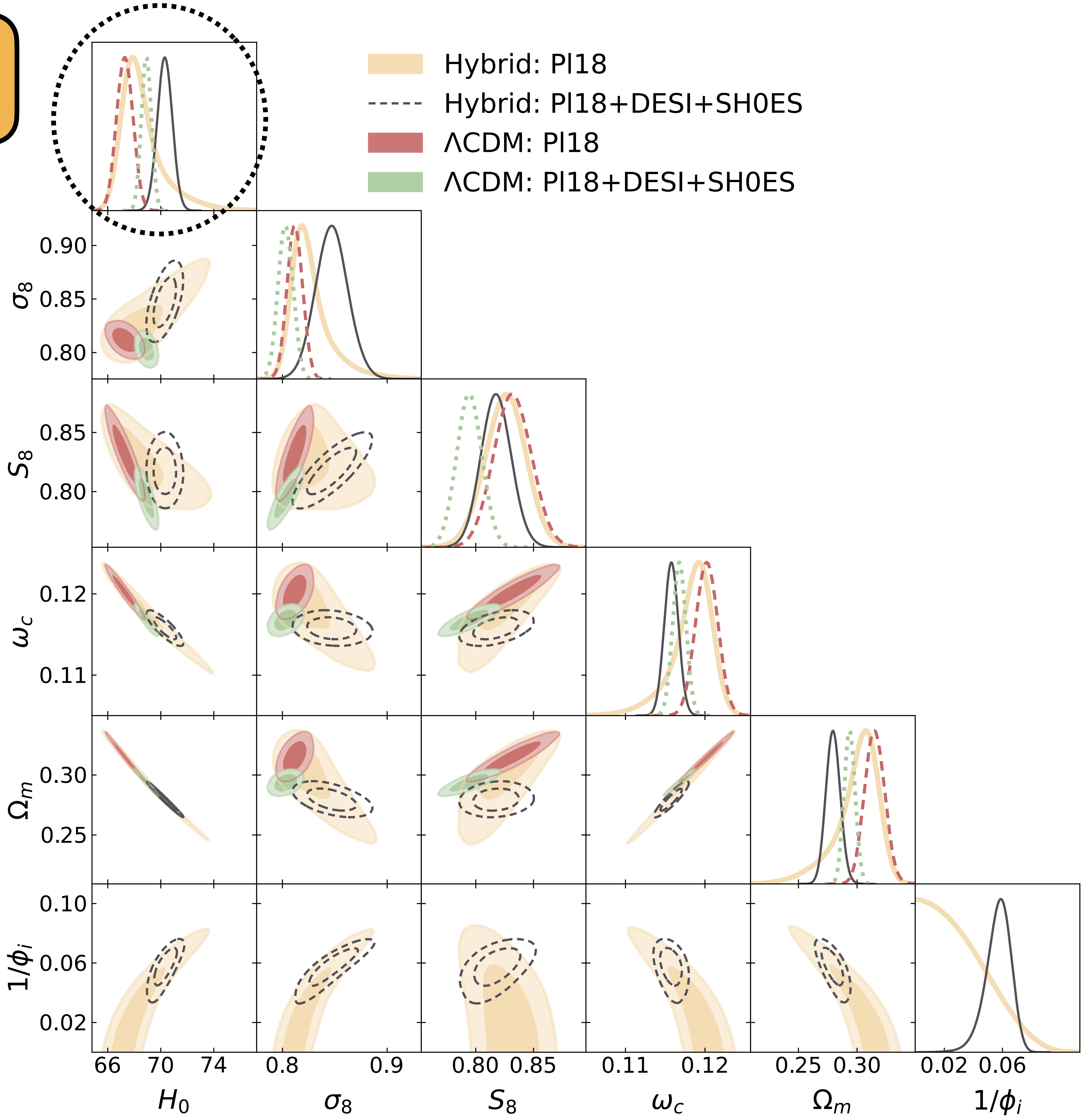
Based on: [E. M. Teixeira, G. Poulot, C. van de Bruck, E. Di Valentino, V. Poulin: arxiv:2412.14139]

Results

The energy exchange between the components allows to lower ω_c/Ω_m

- DM component decays faster than in ΛCDM due to scaling behaviour of DE and coupling
- Positive correlation between the coupling $(1/\phi_i)$ and H_0 and negative correlation with Ω_m - alleviate cosmic tensions





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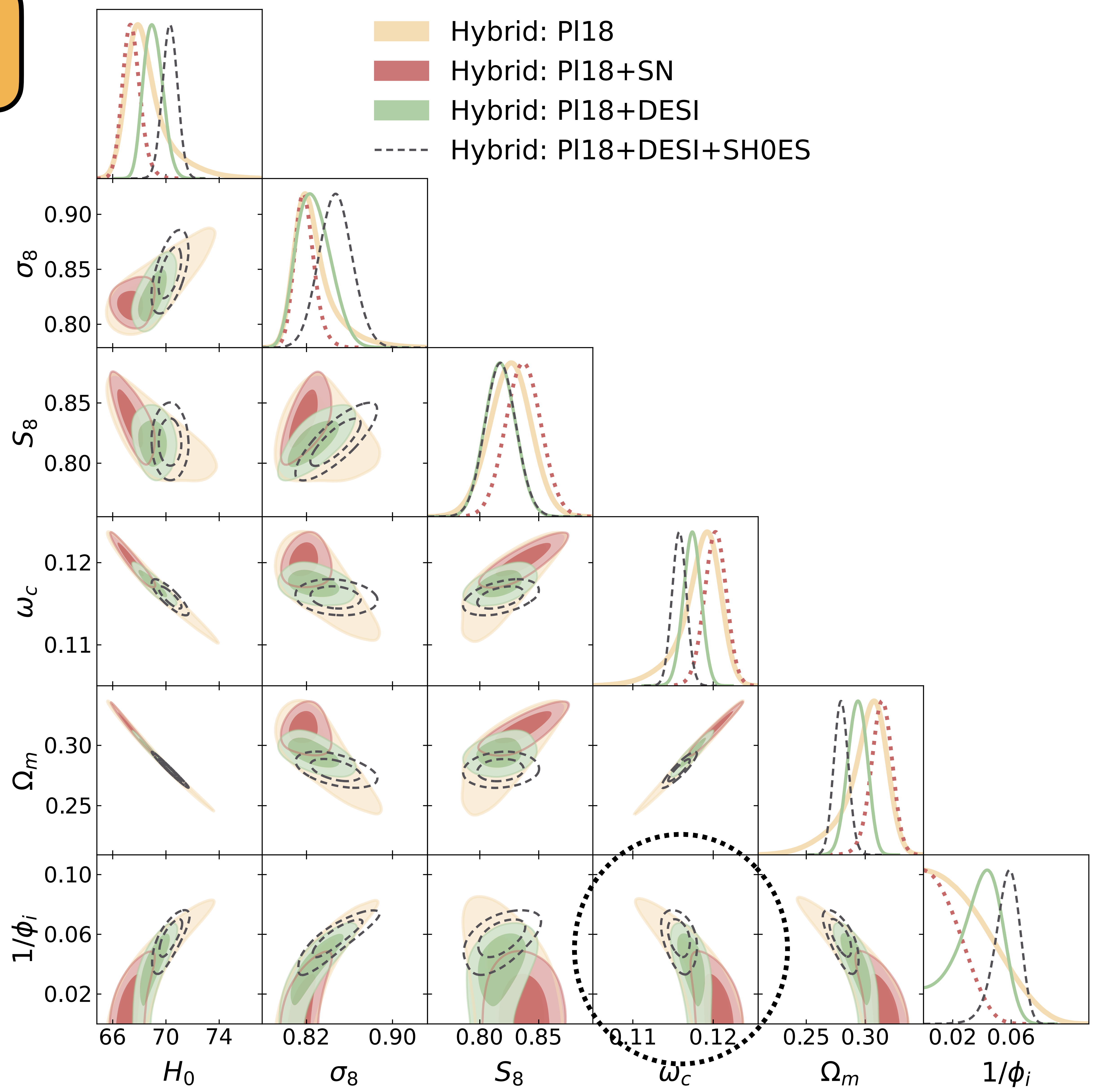

Results

No phantom behaviour - "mirage" from assuming vanishing interactions

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

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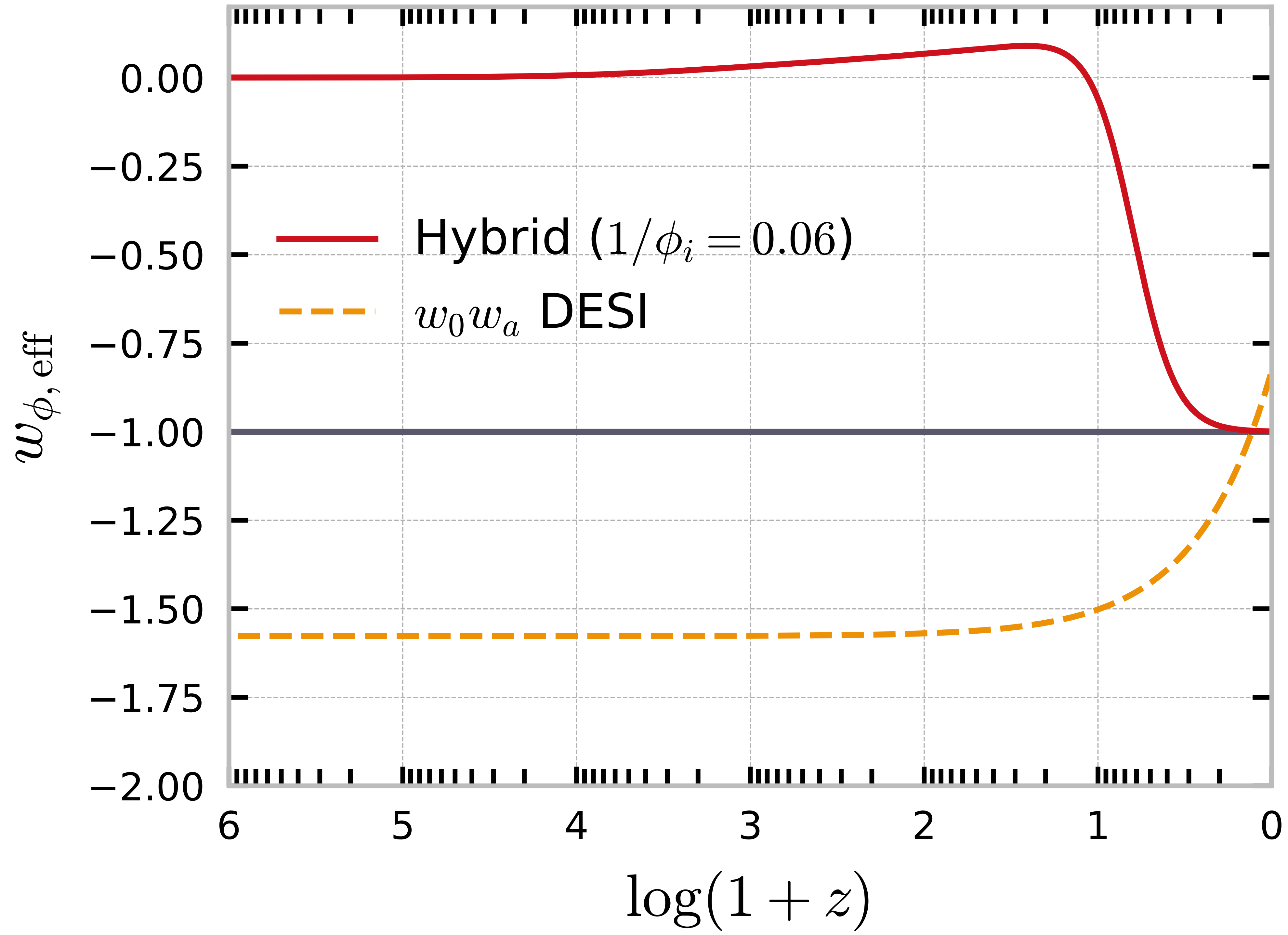
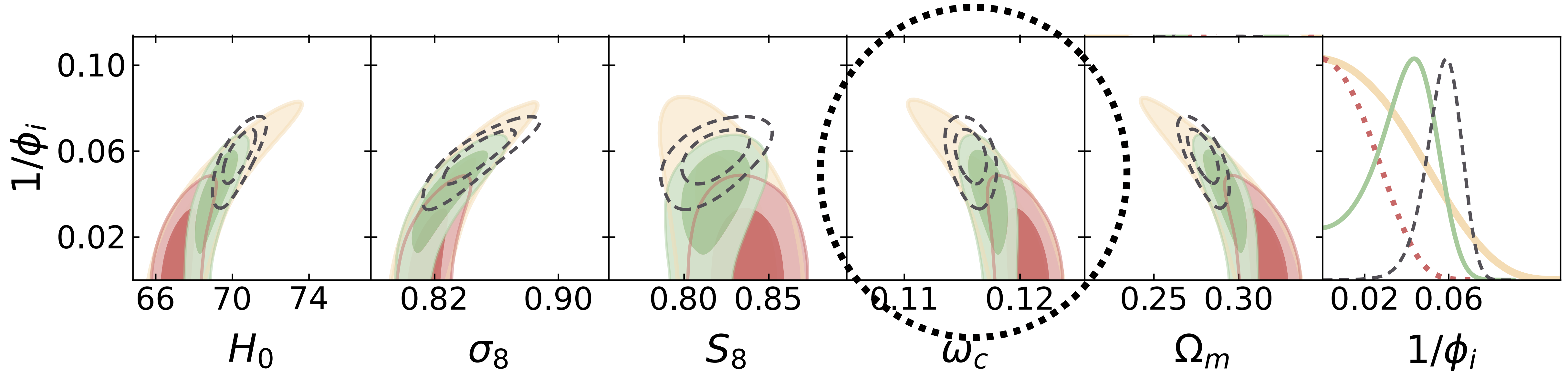
- Positive correlation between the coupling ($1/\phi_i$) and H_0 and negative correlation with Ω_m - alleviate cosmic tensions
- Detection of the coupling parameter with DESI data
- DESI found preference for phantom DE over ΛCDM
- Instead we have a coupled dark sector with a non-vanishing detection of $1/\phi_i > 0$ and $w_{\phi,\mathrm{eff}}$ never becomes phantom





Summary and Conclusions

Conclusions

- ΛCDM model facing challenges with increasing precision
- Address the H0 tension for expansion history
- Extended models make predictions that can be tested
- Coupled dark sector models are natural extension of ΛCDM

- Explain the signal of phantom dark energy in DESI with couplings in the dark sector
- 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 expansion history that alleviate cosmic tensions but cannot solve them

Thank you for your attention!

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Cosmological Tensions

Extensions to ΛCDM

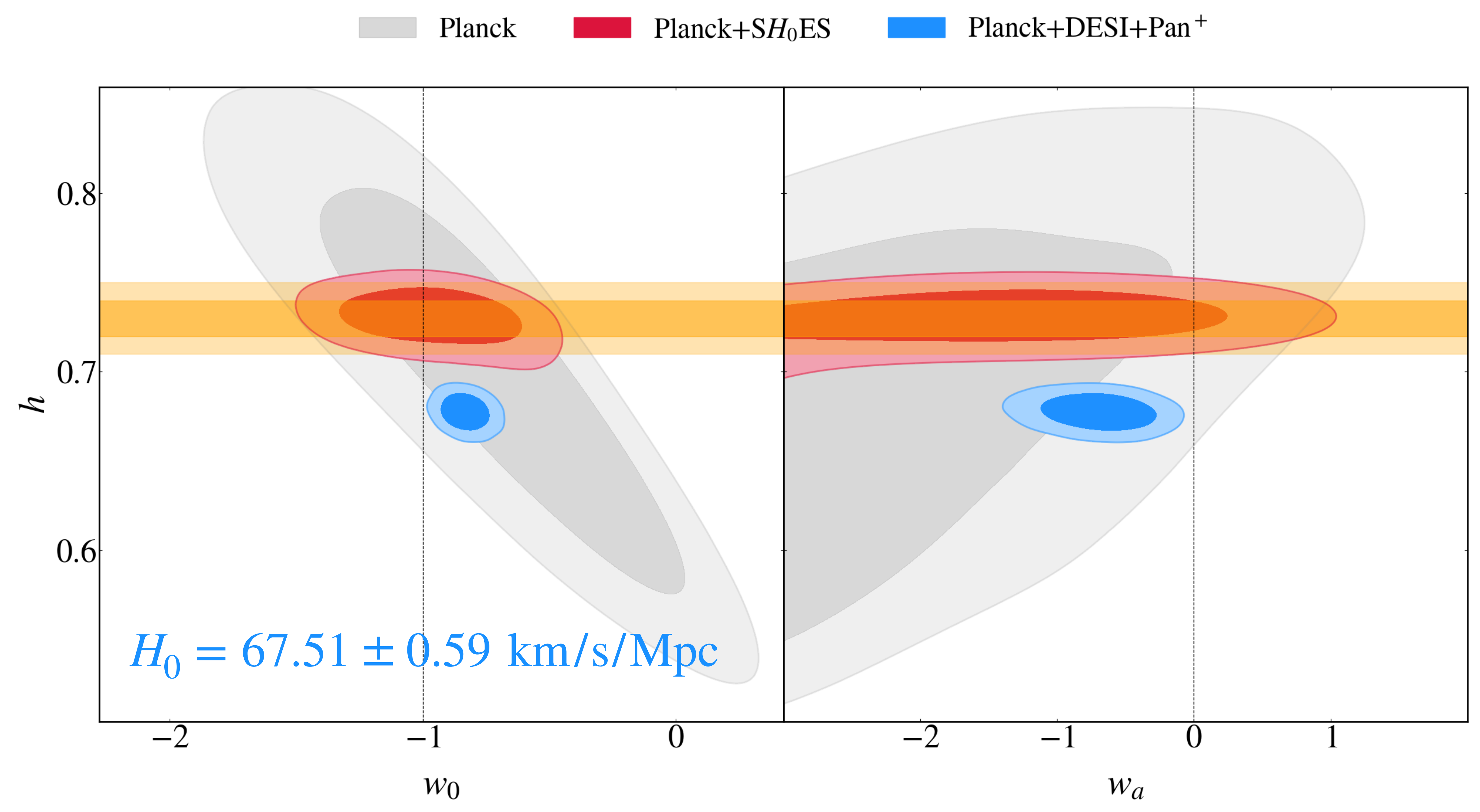
"Late-time" solutions to the Hubble tension from extensions in the dark sector

- 'Phantom dark energy' ($w < -1$), DE-DM interactions, decaying DM, and many more…
- Planck data can easily accommodate a higher H_0 , but **BAO and SN1a** exclude this resolution
- Models affecting expansion history can reduce tension to 2-3σ level

[Poulin et al, arxiv:2407.18292]

CMB: $\theta_s \equiv \frac{r_s(z_*)}{D_A(z_*)}$

$$D_A(z) \equiv \int_0^z \frac{dz'}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{\rm DE}(1+z)^{3(1+w)} + \cdots}}$$



Conformal Transformation

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

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
- 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}]

Effective Fluid Description

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

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

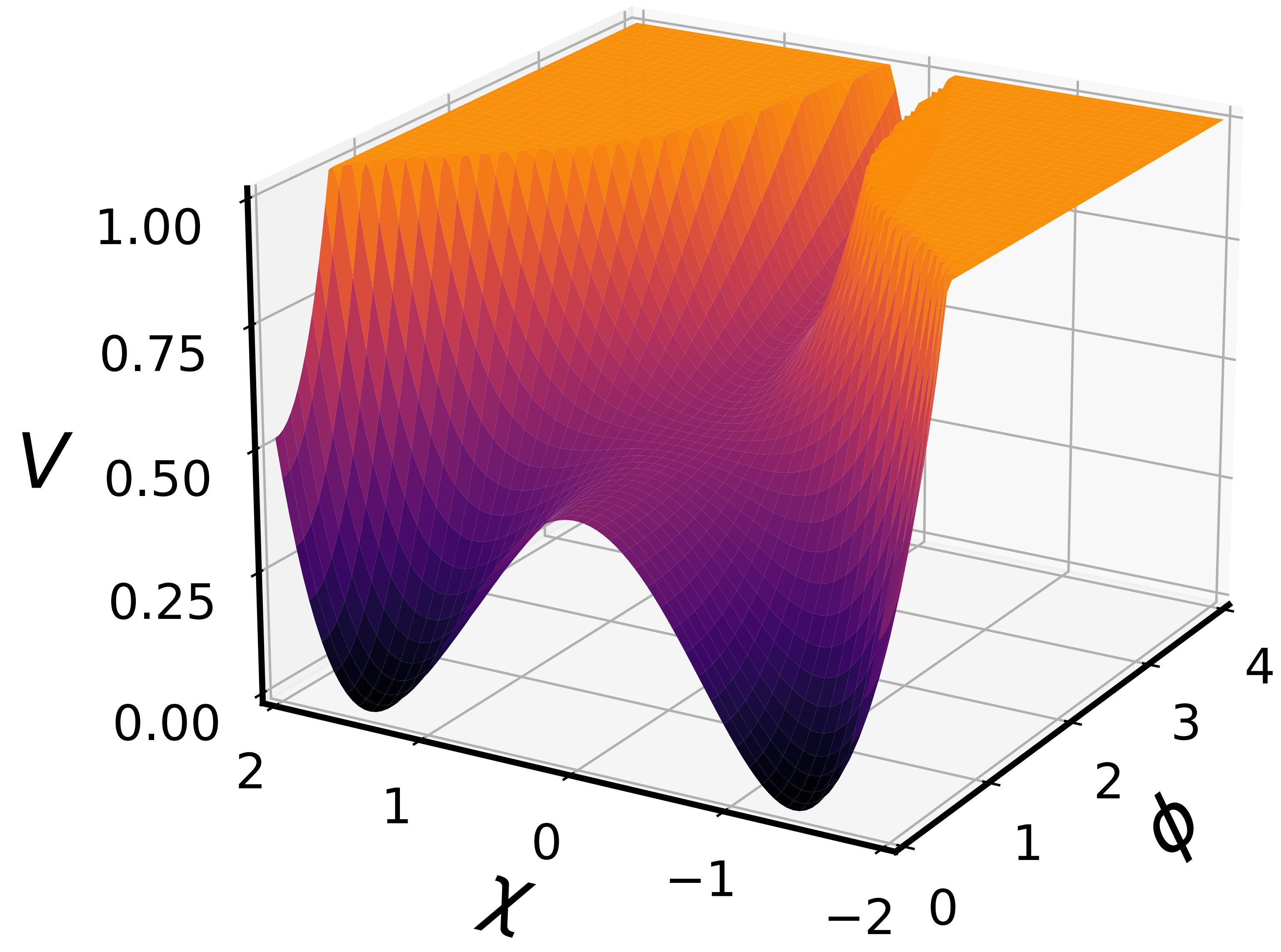
- Energy density of DM field:

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

- 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 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 $\dot{\phi}/\phi \ll 1$):

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

- 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

$$\boxed{m_\chi \approx g\phi \gg H}$$

$$\boxed{g^2\chi^2 \ll H^2}$$

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 ($\phi \gg$ M$_{\mathrm{Pl}}$)

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

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

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

Hybrid Model

In FLRW the equations of motion for each field are:

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

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

χ oscillates around 0 and m_χ changes sign at critical ϕ

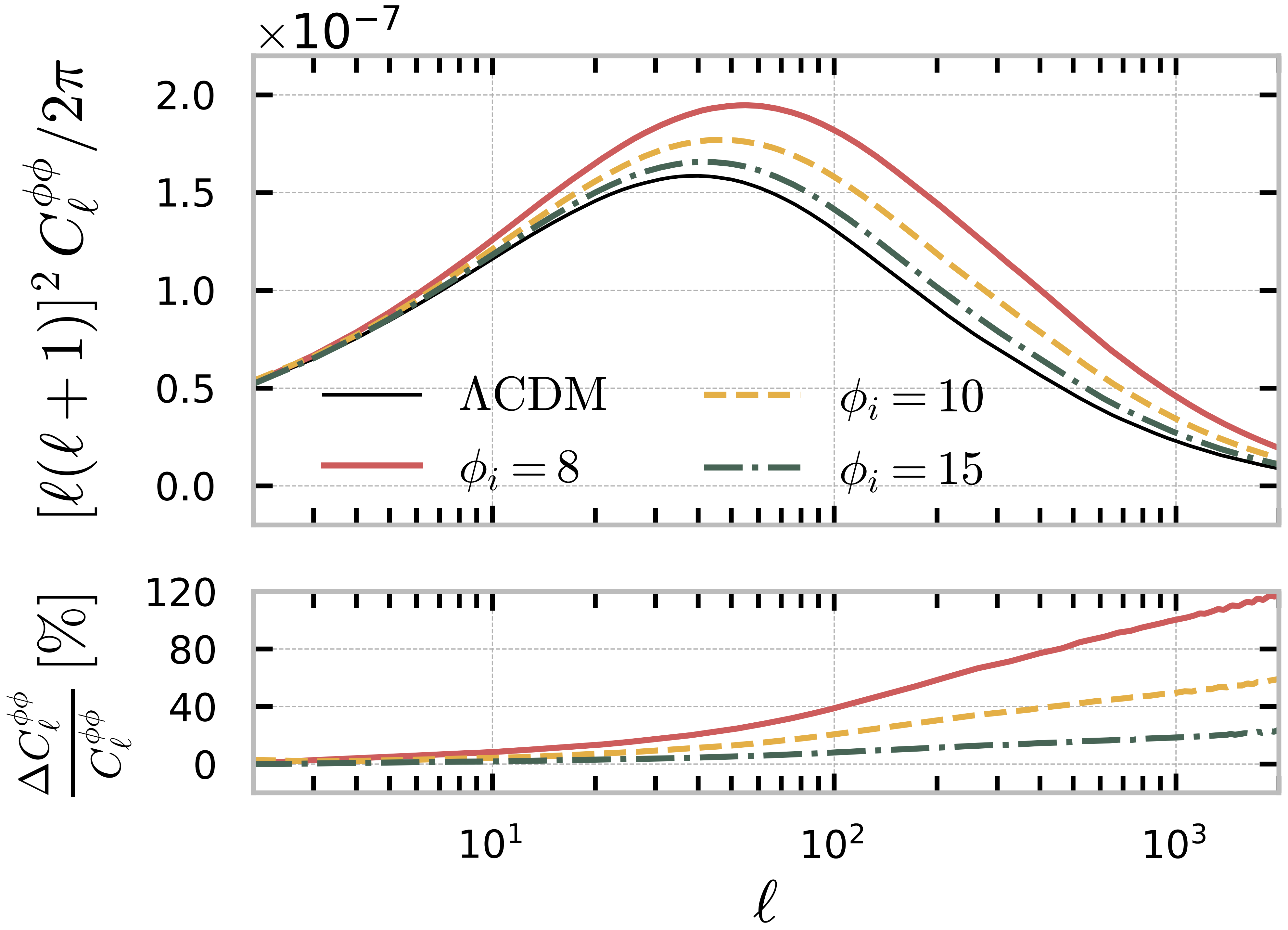
$$\rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{\lambda M^2\chi^2}{2} + \frac{\lambda\chi^4}{4} + \frac{g^2\phi^2\chi^2}{2}$$
$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_0 + \frac{\mu^2\phi^2}{2}$$

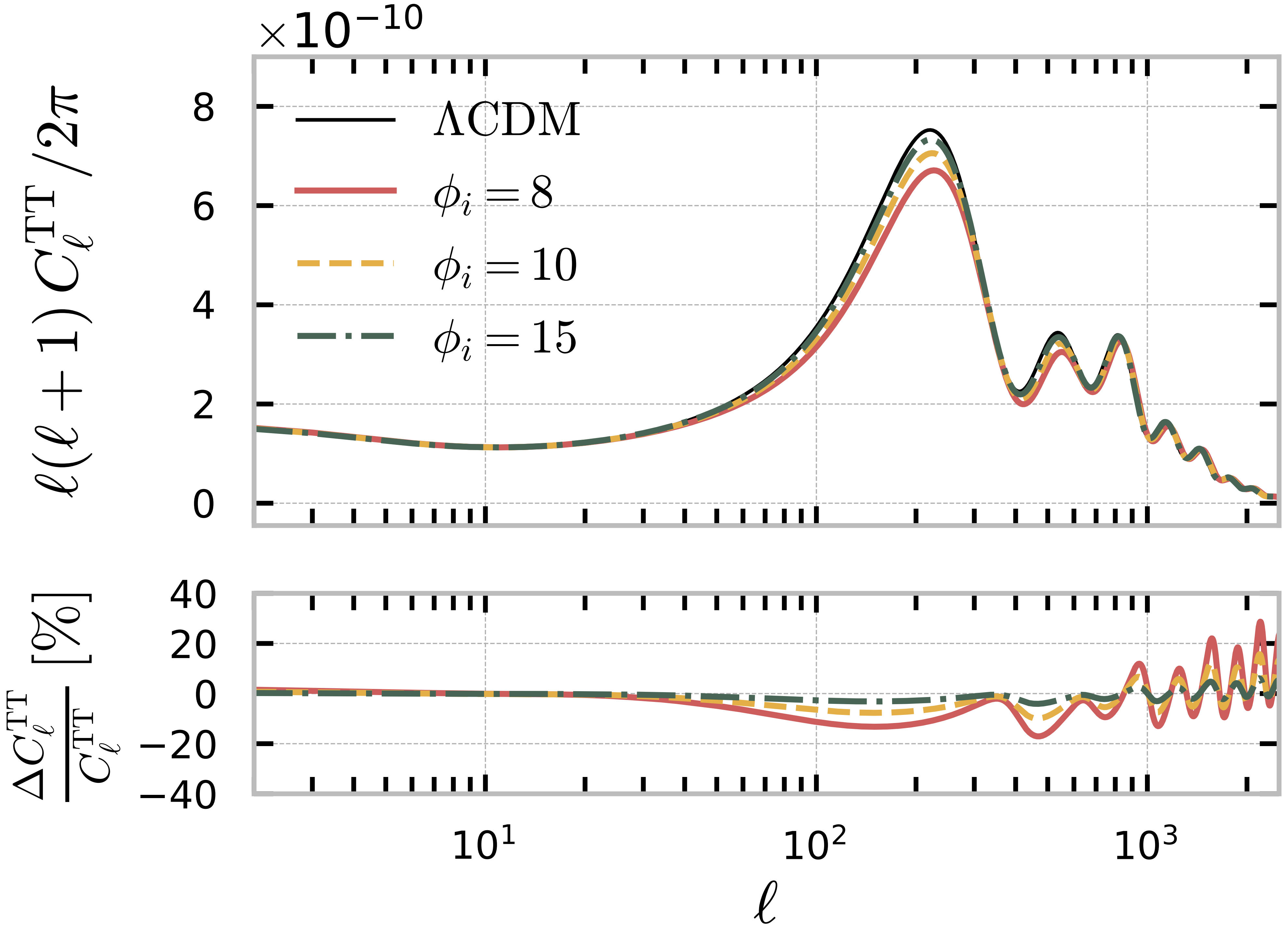
Potential acts as an effective interaction between the fields

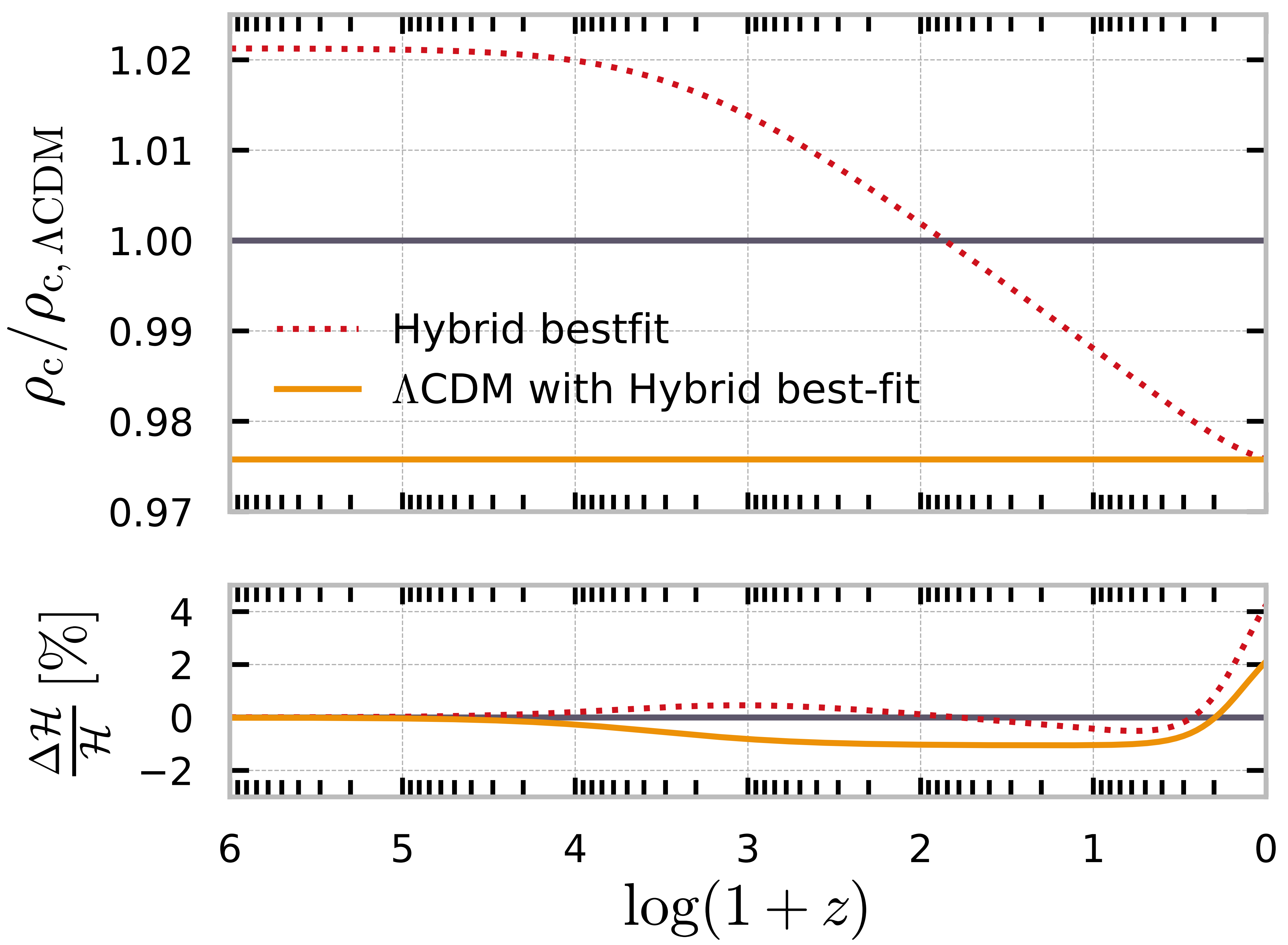
- When $\phi > \phi_c$, χ acts as dark matter
- ϕ slowly rolls down the potential, primarily due to V_0 and the interaction with χ
- As $\phi \to \phi_c$, χ drops abruptly and starts oscillating around $\chi = \pm M$
- $V(\phi, \chi) \to 0$ signalling a rapid decay of dark energy → DE domination is a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

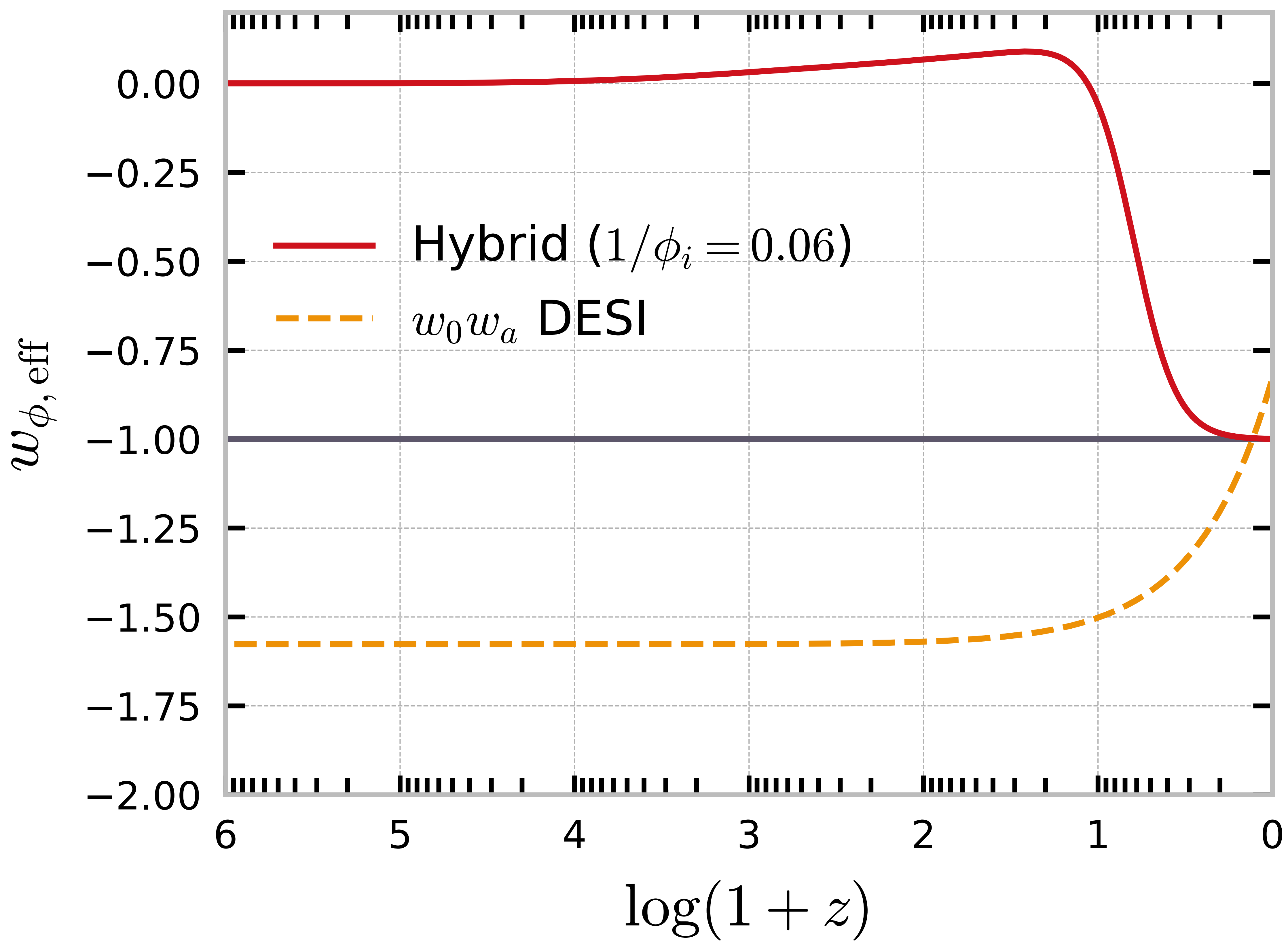
Angular Spectra

- 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



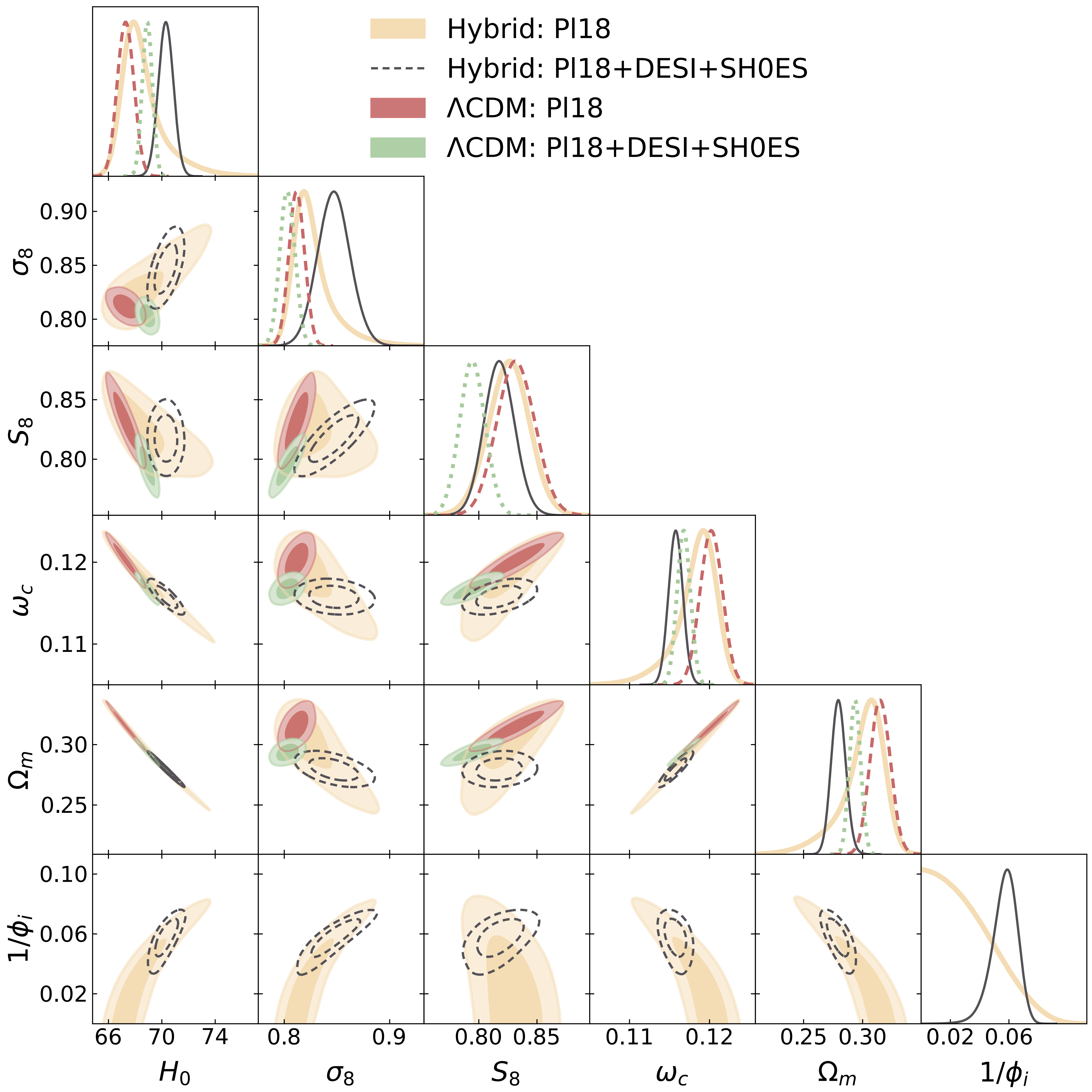



1.02
1.01
1.00
0.99
0.98
0.97
$\rho_c/\rho_{c,\Lambda\mathrm{CDM}}$
Hybrid bestfit
ΛCDM with Hybrid best-fit
4
2
0
−2
$\frac{\Delta\mathcal{H}}{\mathcal{H}}$ [%]
6
5
4
3
2
1
0
$\log(1+z)$


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
$\log(1+z)$

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)



Results

- Alleviate the H_0 tension by increasing the coupling
- More significance when imposing SH0ES calibration
- SH0ES calibration: increase in $\Delta\chi^2_{\rm min} = 0.08 \rightarrow -16.32$, for Pl18+SH0ES, $\Delta\chi^2_{\rm min} = -1.06 \rightarrow -12.76$ 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)

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

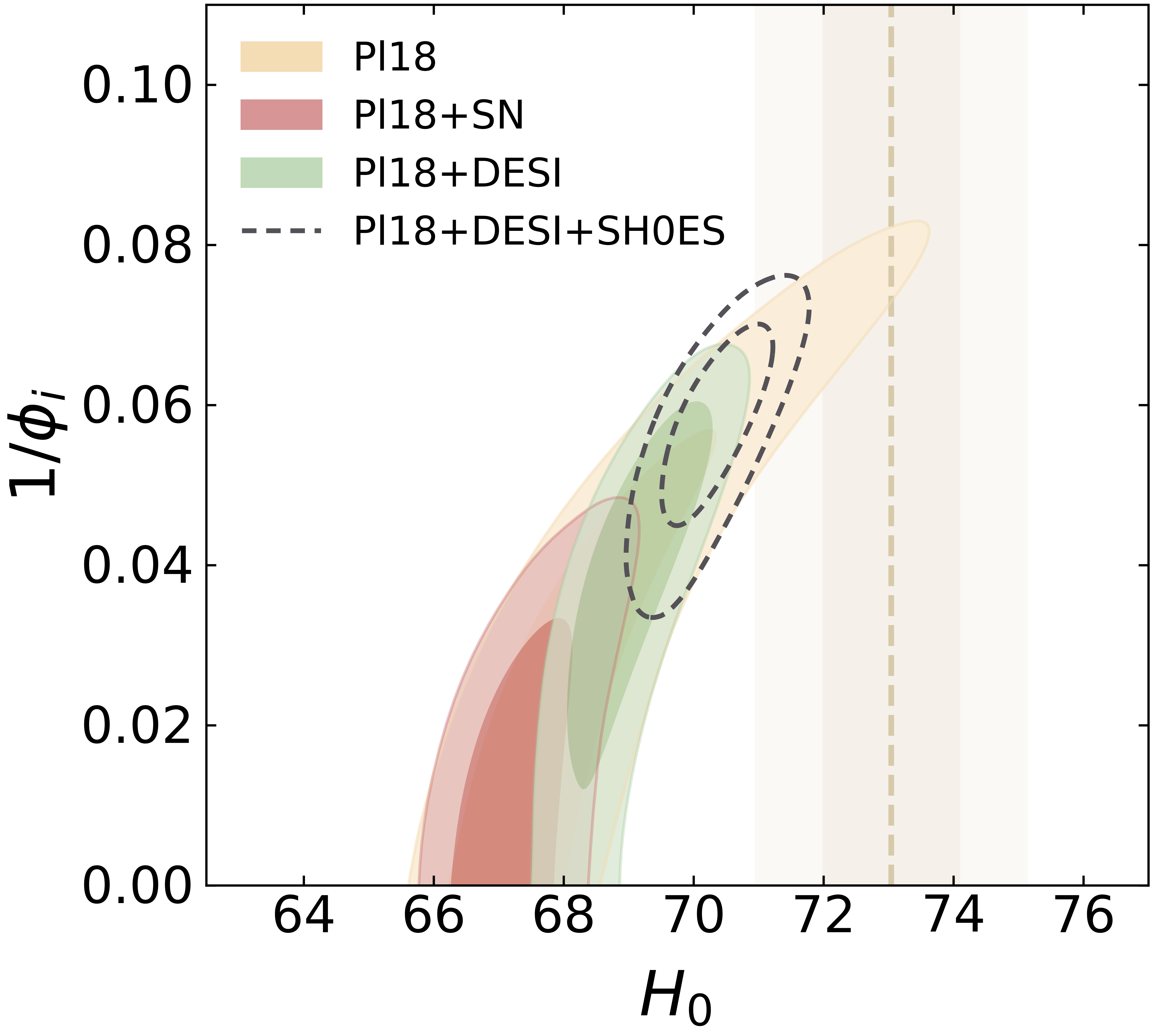


Table of constraints at a 68% confidence level

Parameter	Pl18	Pl18+SN	Pl18+SH0ES	Pl18+DESI	Pl18+DESI+SN	Pl18+DESI+SH0ES
$\omega_{\rm b}$	0.02236 ± 0.00015	0.02231 ± 0.00014	0.02237 ± 0.00015	0.02240 ± 0.00015	0.02239 ± 0.00015	0.02237 ± 0.00015
$\omega_{\rm c}$	$0.1184^{+0.0029}_{-0.0016}$	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
$\tau_{\rm reio}$	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
ω_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
ω_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
τ_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
$Q_\mathrm{DMAP}^\mathrm{SH0ES}$	$--$	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 $Q_\mathrm{DMAP}^\mathrm{SH0ES}$ is calculated according to Eq. (14).