

SOLUTIONS TO TENSIONS IN THE DARK SECTOR



Illustrations: Inês Viegas Oliveira (ivoliveira.com)

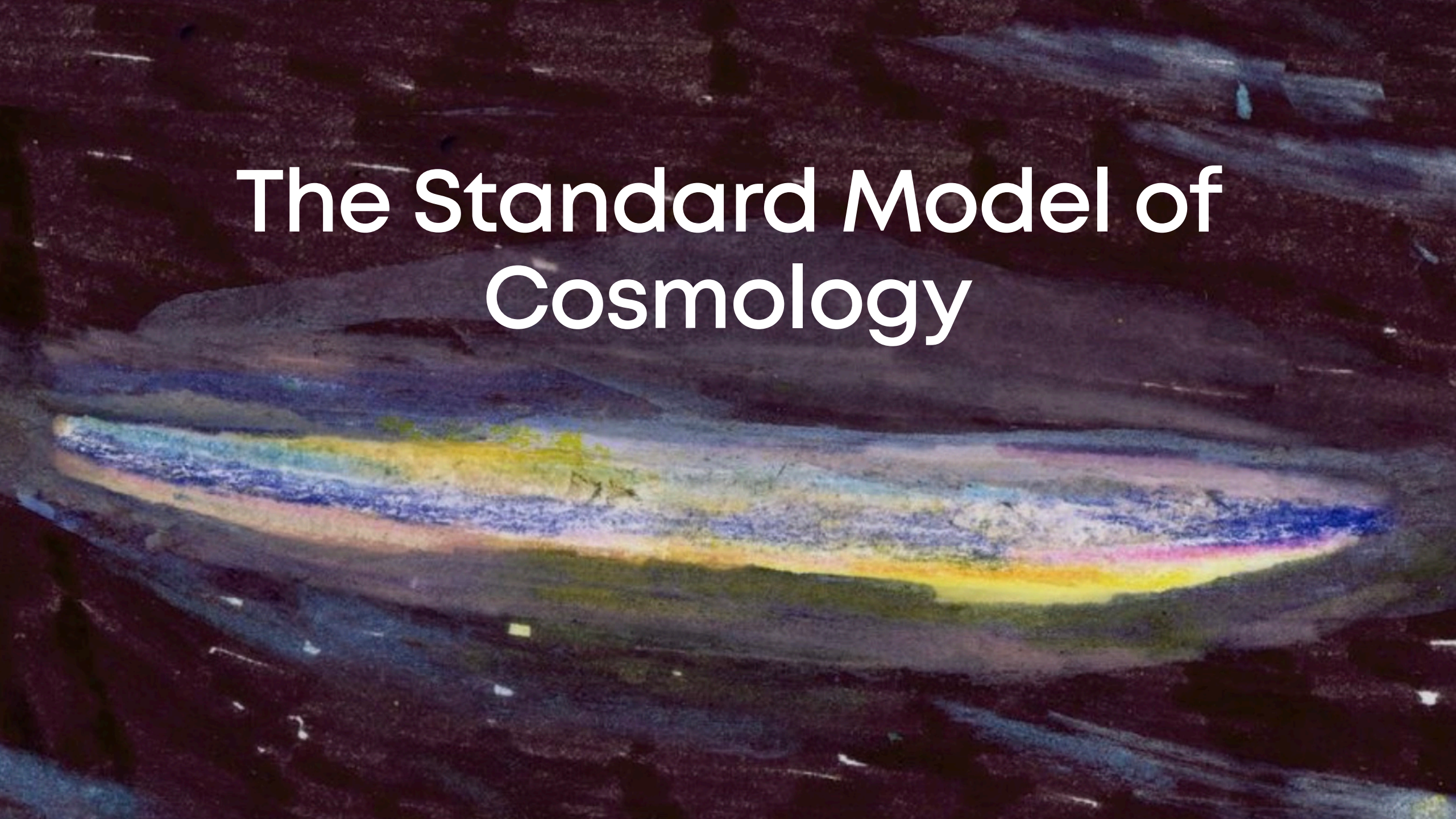
ELSA M. TEIXEIRA

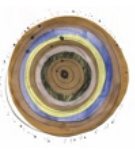
(elsa.teixeira@umontpellier.fr)

Based on:

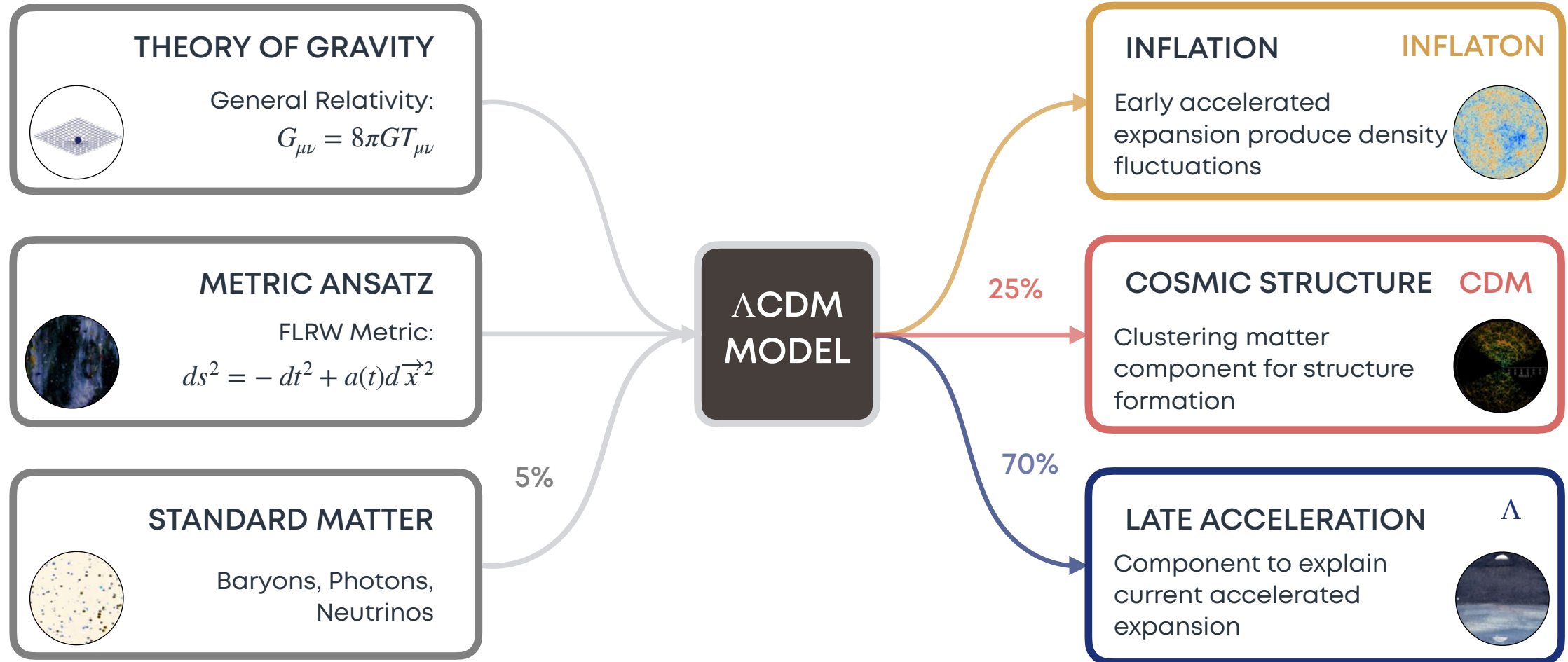
- [[arxiv:2503.01961](https://arxiv.org/abs/2503.01961)] with:
Saba Rahimy and Ivonne Zavala
- [[arxiv:2211.13653](https://arxiv.org/abs/2211.13653)] with:
Carsten van de Bruck and Gaspard Poulot
- [[arxiv:2412.14139](https://arxiv.org/abs/2412.14139)] with:
Carsten van de Bruck, Gaspard Poulot, Vivian Poulin and Eleonora Di Valentino
- [[arxiv:25xx.xxxxx](https://arxiv.org/abs/25xx.xxxxx)] with:
Erik Jensko, Vivian Poulin and Tristan L. Smith

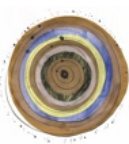
The Standard Model of Cosmology





The Lambda Cold Dark Matter Model





Challenges to the Λ CDM Model

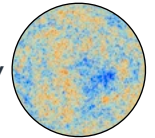
The Λ CDM model relies on:

- 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 (vacuum energy, properties of empty space, etc)

INFLATION

INFLATON

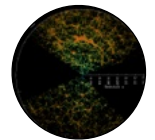
Early accelerated expansion produce density fluctuations



COSMIC STRUCTURE

CDM

Clustering matter component for structure formation

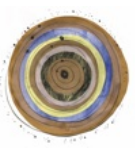


LATE ACCELERATION

Λ

Component to explain current accelerated expansion





Challenges to the Λ CDM Model

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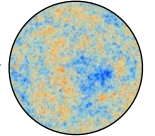
Cosmic tensions may signal that Λ CDM is incomplete:

- Anomalies in the CMB: lensing, curvature, etc
- The Hubble/ H_0 expansion rate tension
- Evidence for dynamical dark energy

INFLATION

INFLATON

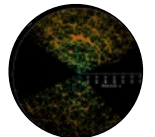
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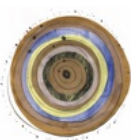


LATE ACCELERATION

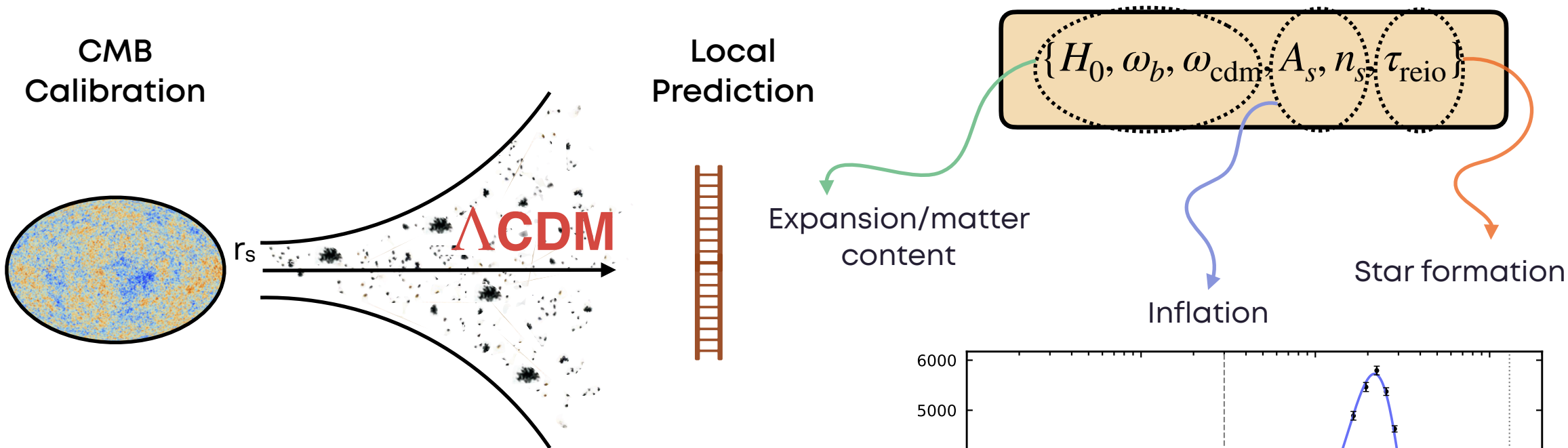
Λ

Component to explain current accelerated expansion

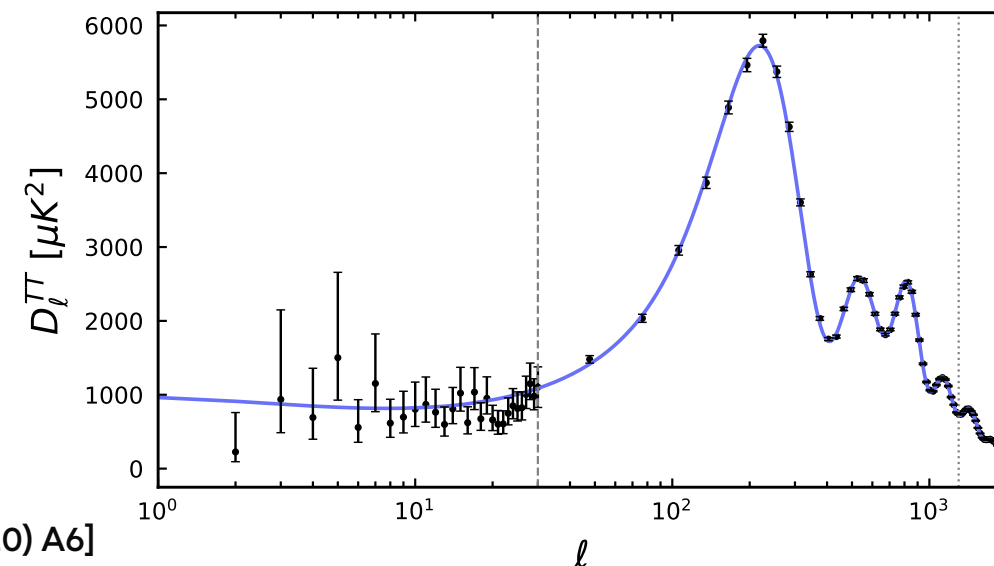


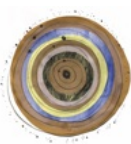


Successes of the Λ CDM Model

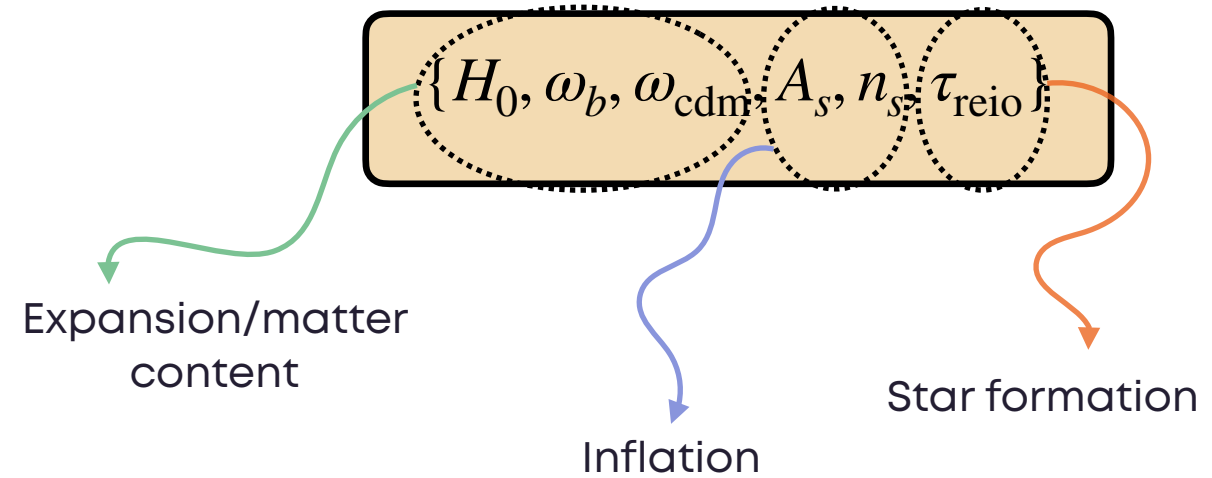
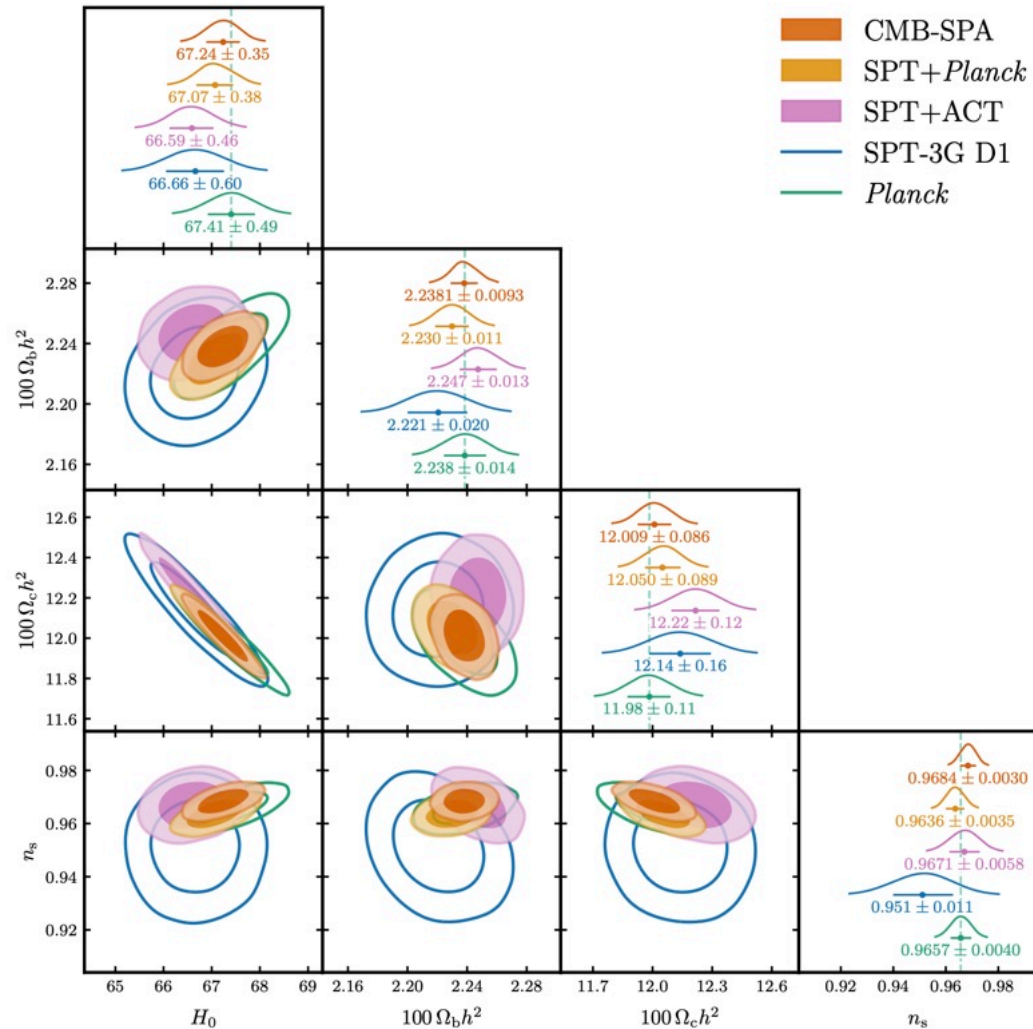


- Nature of the dark sector is unknown
- Mechanism for initial quantum fluctuations is unknown
- Star formation and reionisation process is unknown

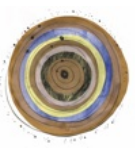




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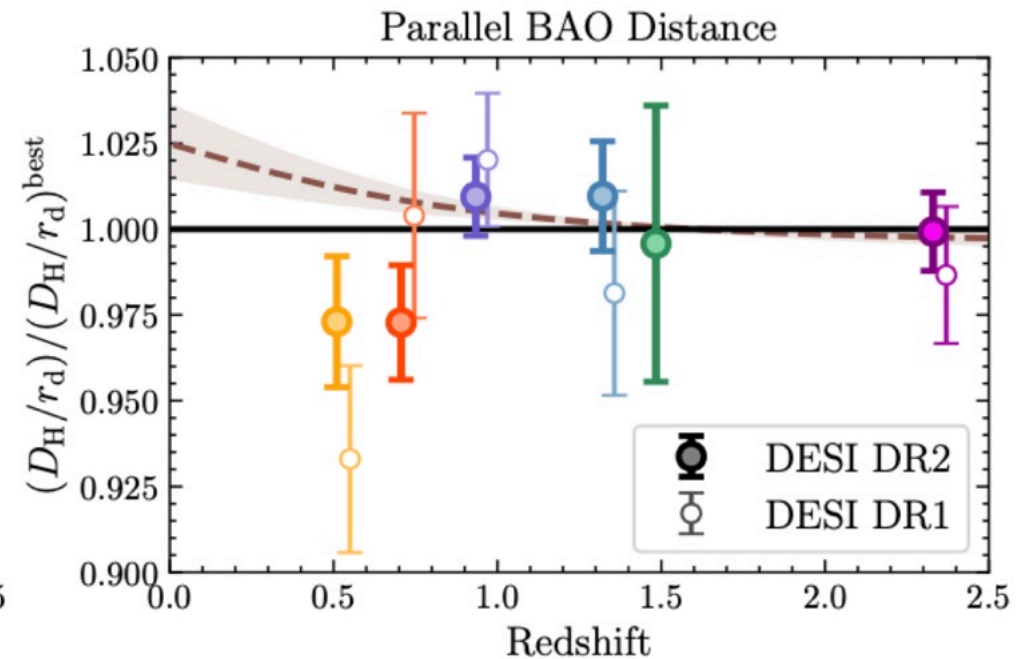
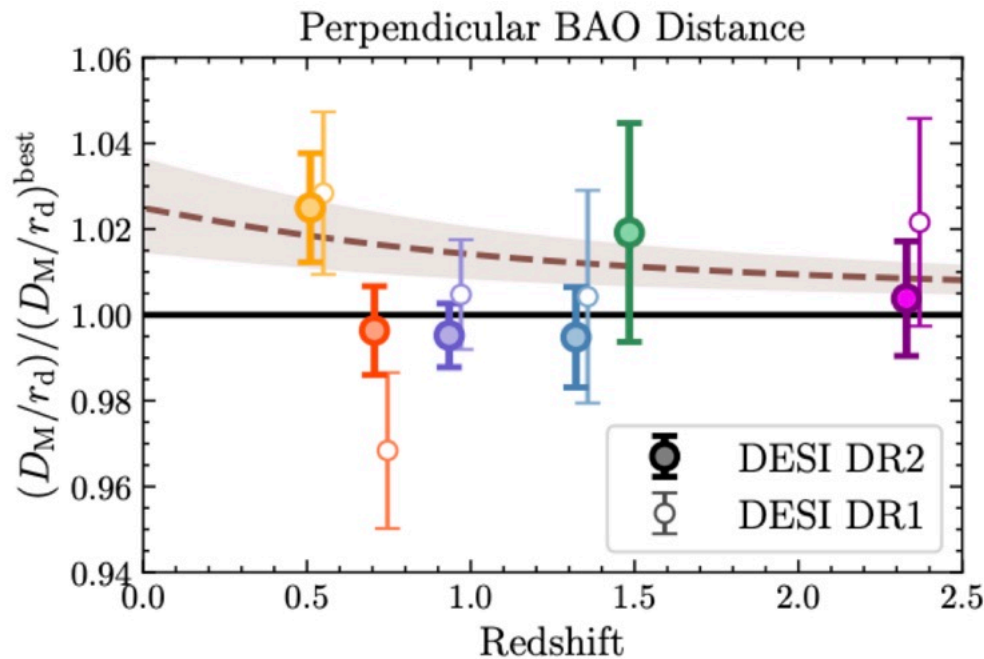


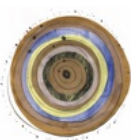
With just 6 parameters Λ CDM can fit a wide variety of CMB data within 2σ - Planck, ACT, SPT-3G



DESI BAO: Hints of new physics?

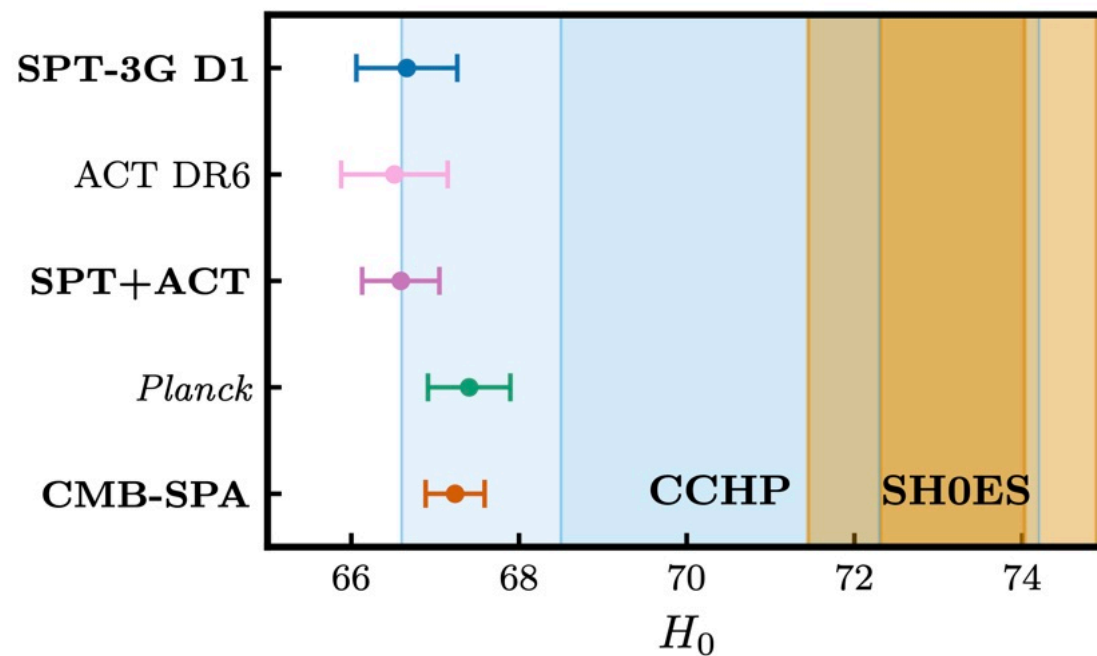
Under Λ CDM, 2.3σ tension between CMB and BAO data



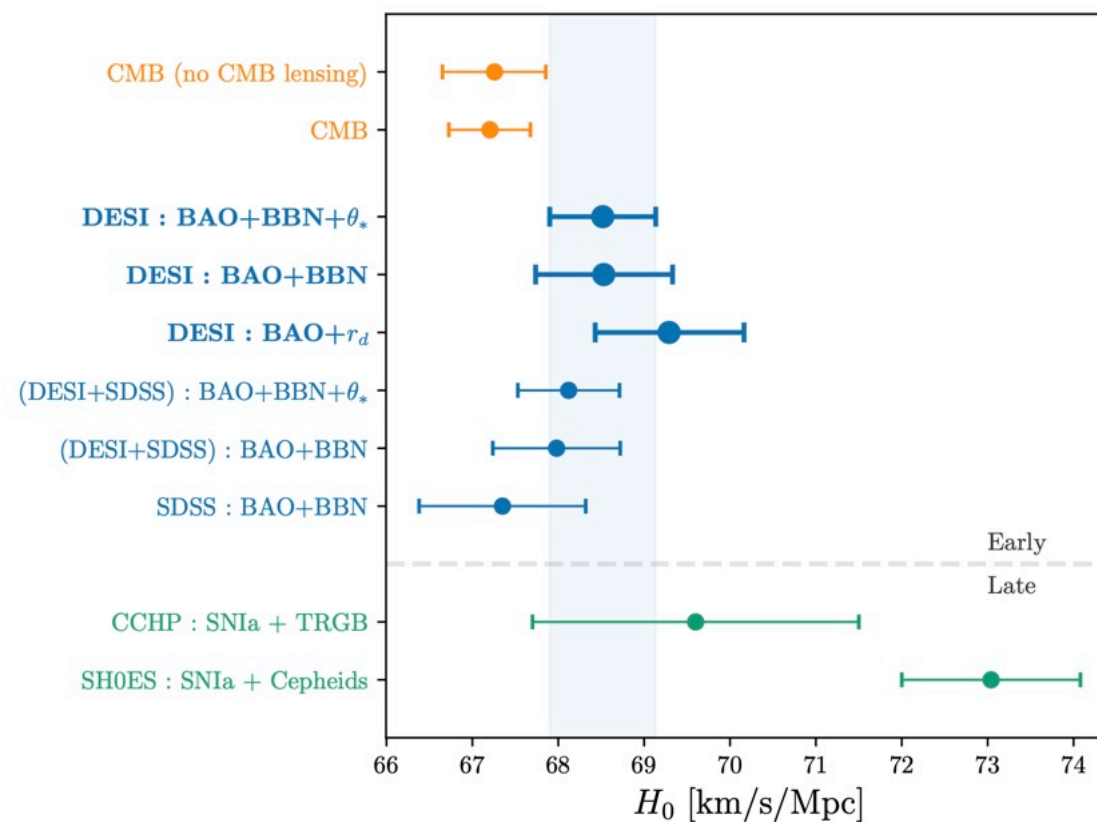


The Hubble Tension

Under Λ CDM, 2.3σ tension between CMB and BAO data



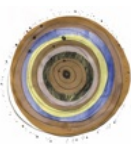
[SPT-3G D1 2025, arxiv:2506.20707]



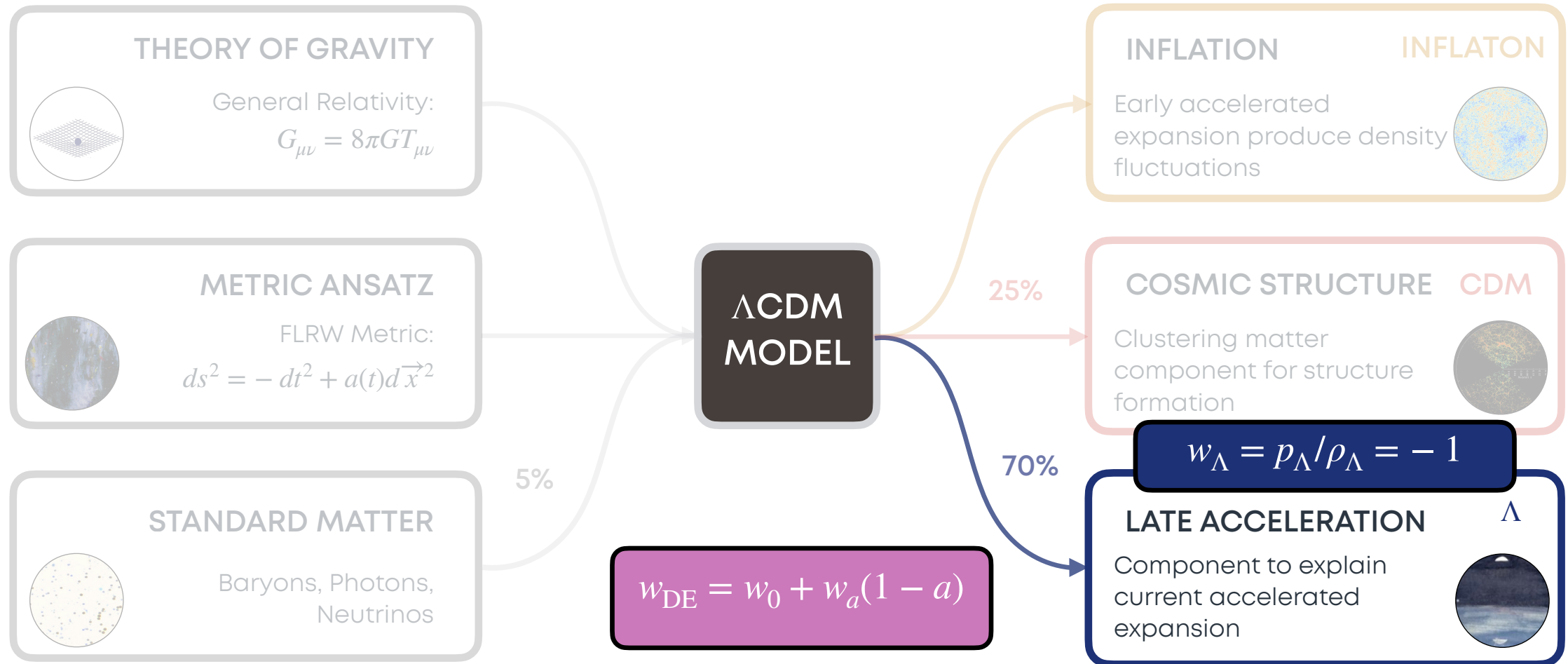
[DESI DR1 Results 2024, arxiv:2404.03002]

Beyond the Standard Model: Interactions in the dark sector

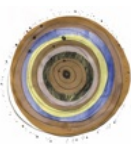




Going Beyond the Standard Model



Chevallier, Polarski 2001; Linder 2002

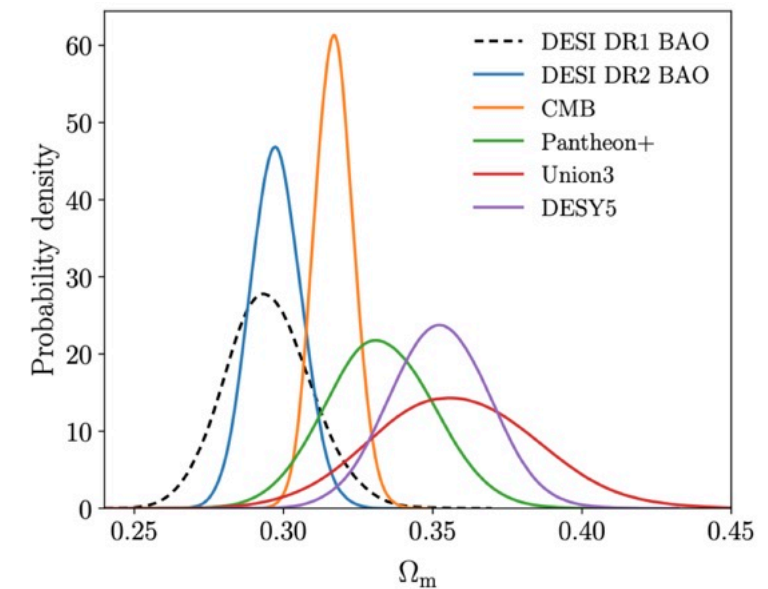
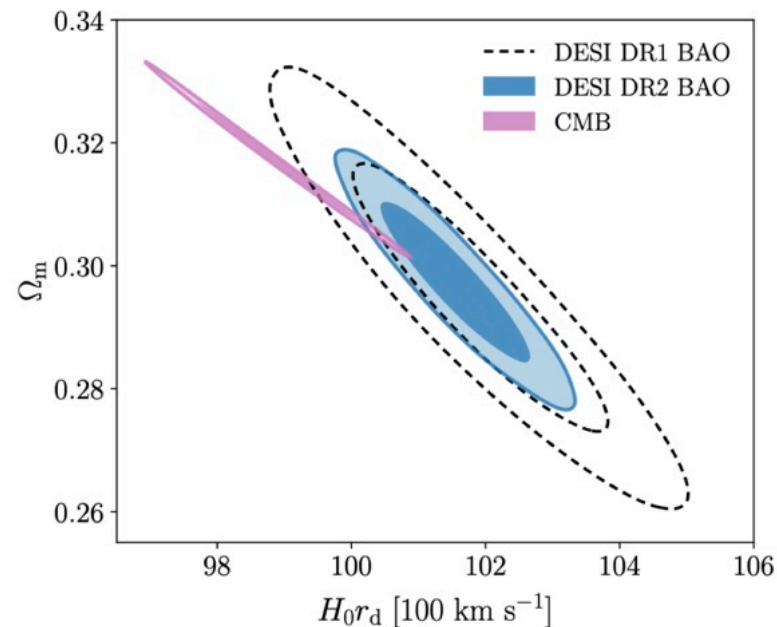


DESI BAO: Hints of new physics?

Under CDM, the BAO allows to measure $H_0 r_d$ and Ω_m

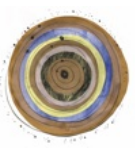
$$\frac{r_d}{D_M} \equiv \frac{H_0 r_s(z_d)}{\int_0^z dz (\Omega_m [(1+z)^3 - 1] + 1)^{-1/2}}$$

$$\frac{r_d}{D_H} \equiv H_0 r_s(z_d) \sqrt{\Omega_m [(1+z)^3 - 1] + 1}$$



DESI+CMB in tension at the $2\text{-}3\sigma$ level with SNIa in the determination of Ω_m

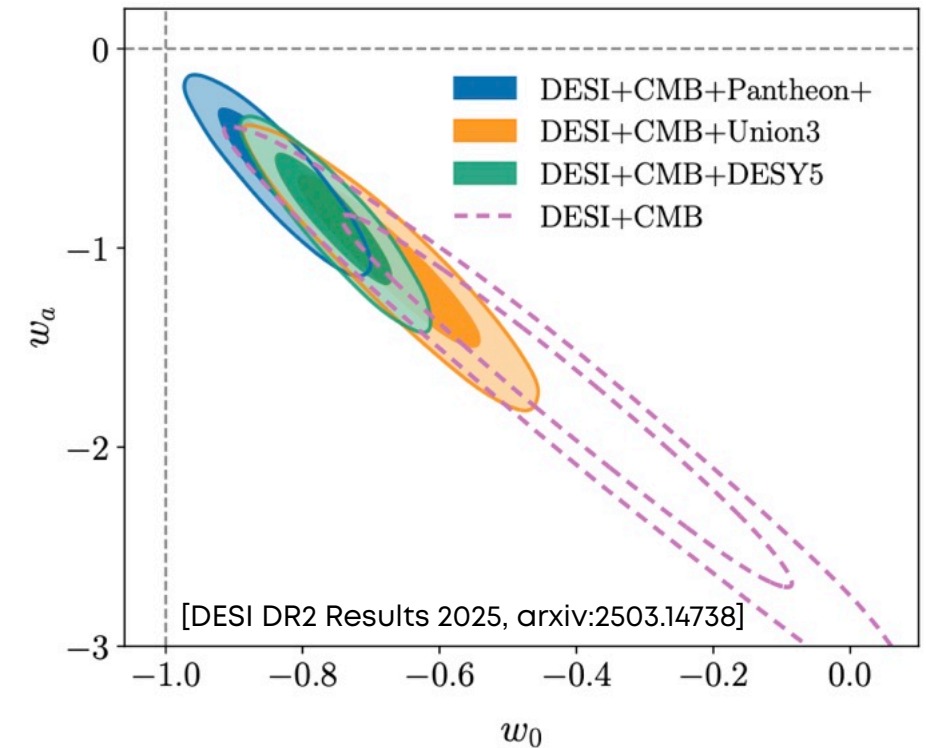
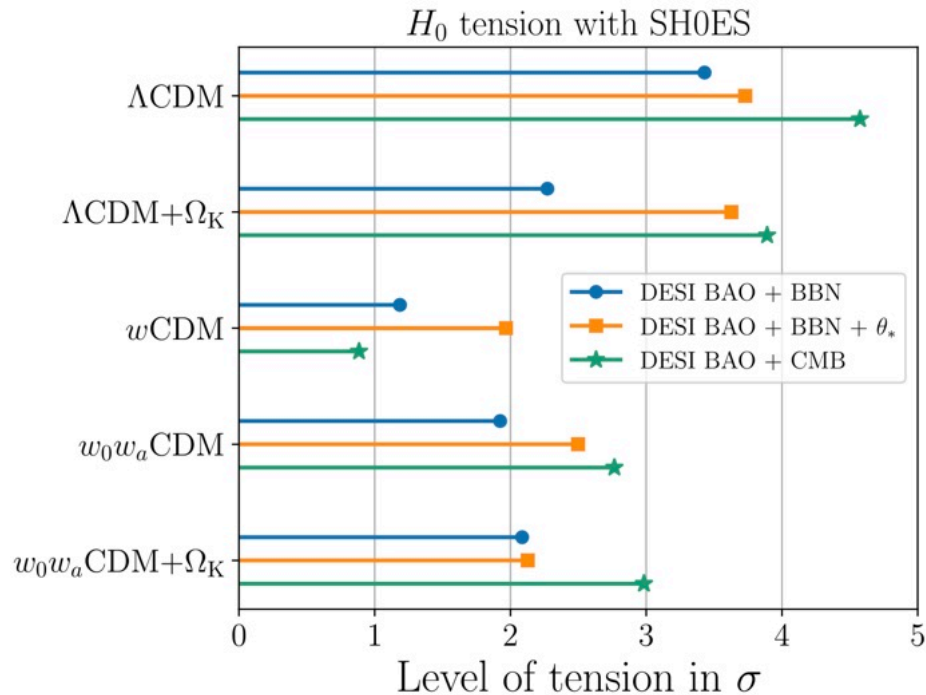
[DESI DR2 Results 2025, arxiv:2503.14738]



Evidence for dynamical DE

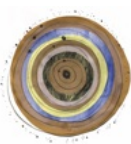
Hints of **phantom dynamical DE** in **DESI BAO data** when combined with CMB and SN data

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



2.5– 4 σ preference for $w_0 > -1$ and $w_a < 0$ (reduced to 2– 3.5 σ with SDSS)
Can this hint for **phantom dark energy** help resolve the Hubble tension?

[See Cortès&Liddle 2404.08056, Shlivko&Steinhardt 2405.03933, Berghaus++ 2404.14341, DESI 2405.04216, 2405.13588, Efsthathiou 2408.07175]



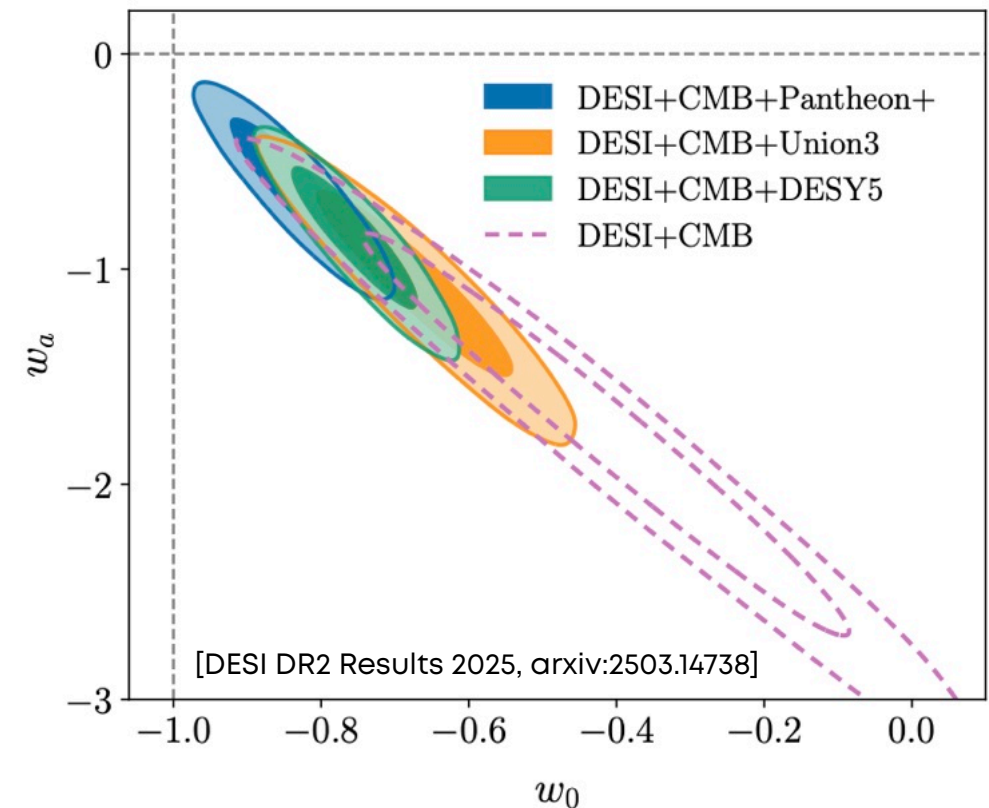
Extensions to Λ CDM

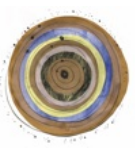
The observational tensions hint at **missing ingredients** or need for completely **new physics**

- “**Quintessence**” (ϕ) - dynamical scalar field that evolves in space and time, as opposed to Λ
- More physically motivated than a parametric fluid
- 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
- **Interaction and modified dark sector** could naturally **explain phantom dark energy evidence and address the cosmic tensions**

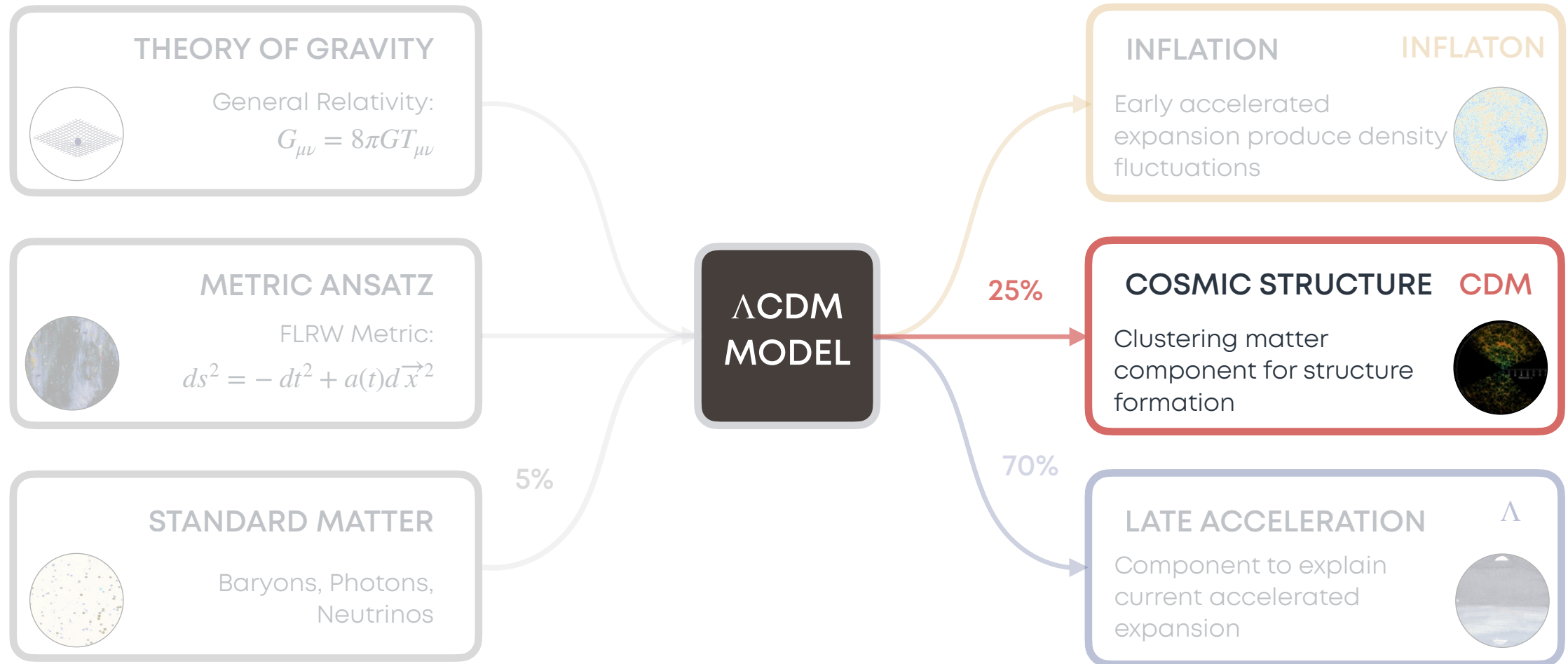
Non-trivial Dynamics in the Dark Sector

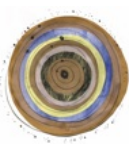
$$\begin{cases} \dot{\rho}_{\phi} + 3H\rho_{\phi}(1 + w_{\phi}) = 0, \\ \rho_{\phi} = \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad p_{\phi} = \frac{1}{2}\dot{\phi}^2 - V(\phi) \end{cases}$$





Going Beyond the Standard Model





Cosmological fluids

Perfect fluid energy-momentum tensor:

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + pg_{\mu\nu}, \quad \nabla^\mu T_{\mu\nu} = 0$$

Key thermodynamic quantities:

- ⊙ particle number density n
- ⊙ intrinsic entropy/particle s
- ⊙ energy density $\rho = \rho(n, s)$
- ⊙ pressure p
- ⊙ temperature T

⊙ chemical potential μ

+ four components of the 4-velocity u^μ with $u^\mu u_\mu = -1$

⊙ EoM (continuity & Euler equations) from projections along u_μ and $h_{\mu\nu}$

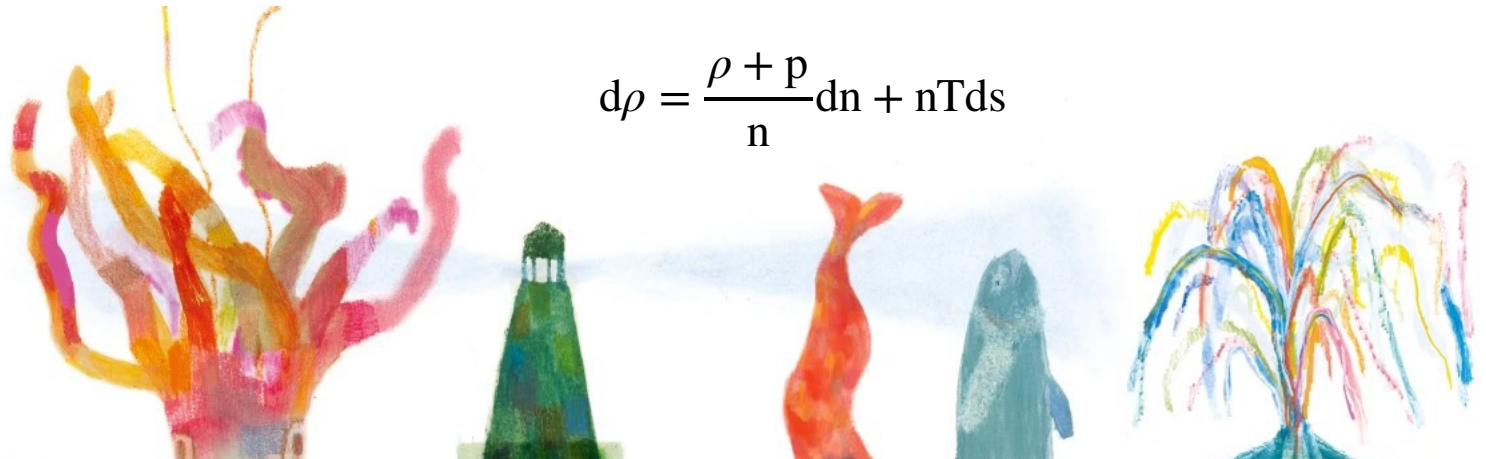
⊙ Thermodynamic identities

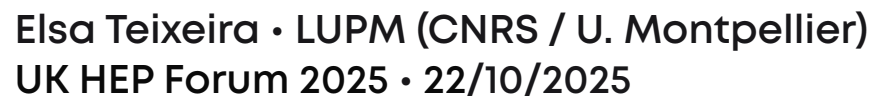
$$p(n, s) = n \left(\frac{\partial \rho}{\partial n} \right)_s - \rho$$

$$T(n, s) = \frac{1}{n} \left(\frac{\partial \rho}{\partial s} \right)_n$$

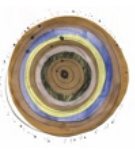
⊙ Satisfying 1st law of thermodynamics

$$d\rho = \frac{\rho + p}{n} dn + nTds$$





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



Perfect fluid action

- Model DM as a **perfect fluid** through action with variables $g_{\mu\nu}$, n^μ , s with Lagrange multipliers φ , θ - define the fluid's internal structure and conservation laws covariantly

$$S_{\text{Brown}} = \int \sqrt{-g} \left[-\rho(n, s) + n^\mu (\varphi_{,\mu} + s\theta_{,\mu}) \right] d^4x$$

[J. D. Brown, Class. Quant. Grav. 10, 1579 (1993), arXiv:gr-qc/9304026]

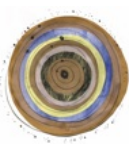
where we introduced the number flux $n^\mu := nu^\mu$ with $n = \sqrt{n^\mu n_\mu}$

constraints

- Variations give perfect fluid $T_{\mu\nu}$ with conservation equation $\nabla^\mu T_{\mu\nu} = 0$
- Additional constraints** preserving particle number and entropy fluxes

$$\nabla_\mu (nu^\mu) = 0, \quad \nabla_\mu (snu^\mu) = 0 \quad \implies \quad u^\mu \nabla_\mu s = 0$$





Dark sector interactions

- Interactions in the dark sector accomplished through non-minimally coupled scalar fields ϕ

$$S_{\text{tot}} = \int \sqrt{-g} f(n, s, \phi, \dots) d^4x + S_{\text{Brown}} + S_{\phi} + S_{\text{SM}}$$

Many different choices of interacting terms in the literature:

- Algebraic (“coupled quintessence”): $f(n, \phi)$
- Derivative (“momentum coupling”): $f(n) n^{\mu} \partial_{\mu} \phi$
- General with $Y = \partial_{\mu} \phi \partial^{\mu} \phi$ and $Z = u^{\mu} \partial_{\mu} \phi$: $f(n, \phi, Y, Z)$

[Boehmer et al., arxiv:1501.06540]

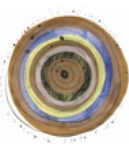
[Boehmer et al., arxiv:1502.04030]

[Pourtsidou et al., arxiv:1307.0458]

Type-1: $Y + V(\phi) + e^{\alpha(\phi)}$ Type-2: $Y + V(\phi) + nh(Z)$ Type-3: $Y + V(\phi) + \gamma(Z) + f(n)$

Interactions





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E.g. Type-1 are coupled quintessence: energy exchange in background and perturbations

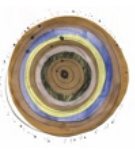
Interactions

[Boehmer et al., arxiv:1501.06540]

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[Poursidou et al., arxiv:1307.0458]





“Type-1” Models: Coupled quintessence

- Exponential-like exchange of energy from DM to DE that is $\propto \rho_c \phi'$ with exponential potential
- Smaller value of Ω_m and correlation of H_0 with α that helps alleviate the Hubble tension
- Disfavoured from Bayesian point of view wrt Λ CDM

$$L(n, Y, Z, \phi) = Y + V(\phi) + e^{\alpha\phi/M_{\text{Pl}}}, \quad Y = \partial_\mu \phi \partial^\mu \phi$$

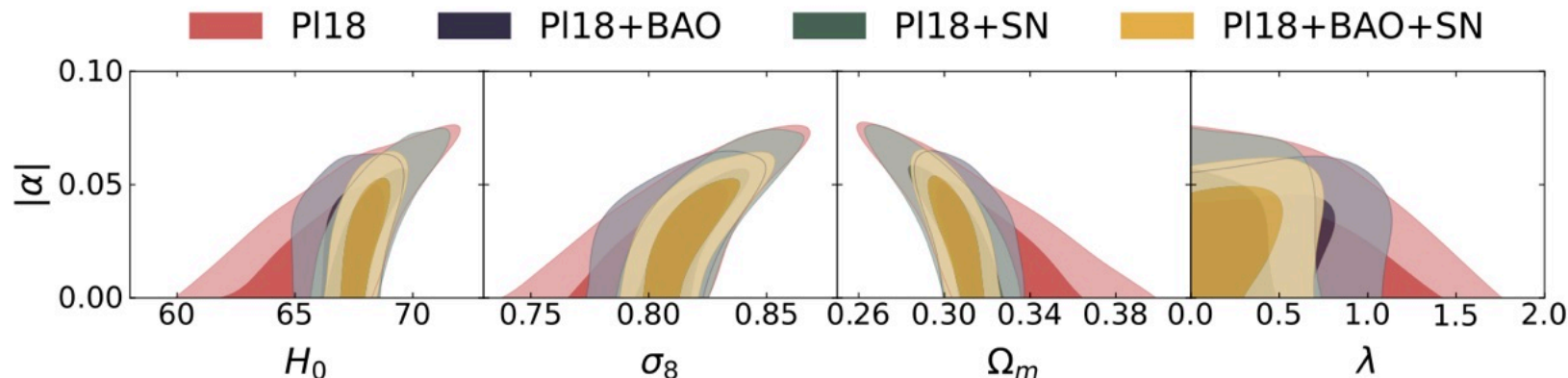
$$\phi'' + 2\mathcal{H}\phi' + a^2 V_{,\phi} = -a^2 \alpha \rho_c / M_{\text{Pl}}$$

$$V(\phi) = V_0 e^{-\lambda\phi/M_{\text{Pl}}}$$

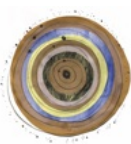
$$\rho'_c + 3\mathcal{H}\rho_c = \alpha \rho_c \phi' / M_{\text{Pl}}$$

$$\delta'_c = -\theta_c + 3\Phi' - \alpha\delta\phi'$$

$$\theta'_c + \mathcal{H}\theta_c = k^2\Psi + \alpha\phi'\theta_c - \alpha\delta\phi/M_{\text{Pl}}^2$$



$$G_{\text{eff}}/G = 1 + 2\alpha^2$$



“Type-1” Models: Coupled quintessence

- Exponential-like exchange of energy from DM to DE that is $\propto \rho_c \phi'$ with power-law potential
- Further smaller value of Ω_m that helps alleviate the Hubble tension
- Disfavoured from Bayesian point of view wrt Λ CDM

$$L(n, Y, Z, \phi) = Y + V(\phi) + e^{\alpha\phi/M_{\text{Pl}}}, \quad Y = \partial_\mu \phi \partial^\mu \phi$$

$$\phi'' + 2\mathcal{H}\phi' + a^2 V_{,\phi} = -a^2 \alpha \rho_c / M_{\text{Pl}}$$

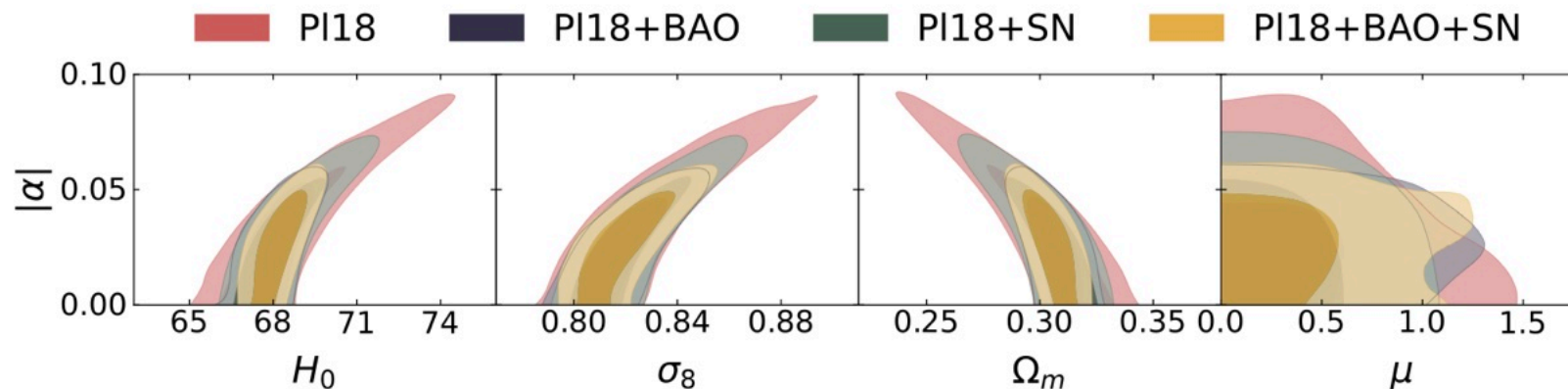
$$V(\phi) = V_0 (\phi / M_{\text{Pl}})^{-\mu}$$

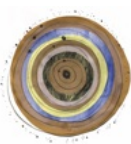
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“Type-1” Models: Swampland-like

- Power law—like exchange of energy from DM to DE that is $\propto \rho_c \phi \phi'$
- Smaller value of Ω_m that helps alleviate the Hubble tension
- Disfavoured from Bayesian point of view wrt Λ CDM

$$L(n, Y, Z, \phi) = Y + V(\phi) + e^{\gamma(\phi - \phi_*)^2/M_{\text{Pl}}^2}$$

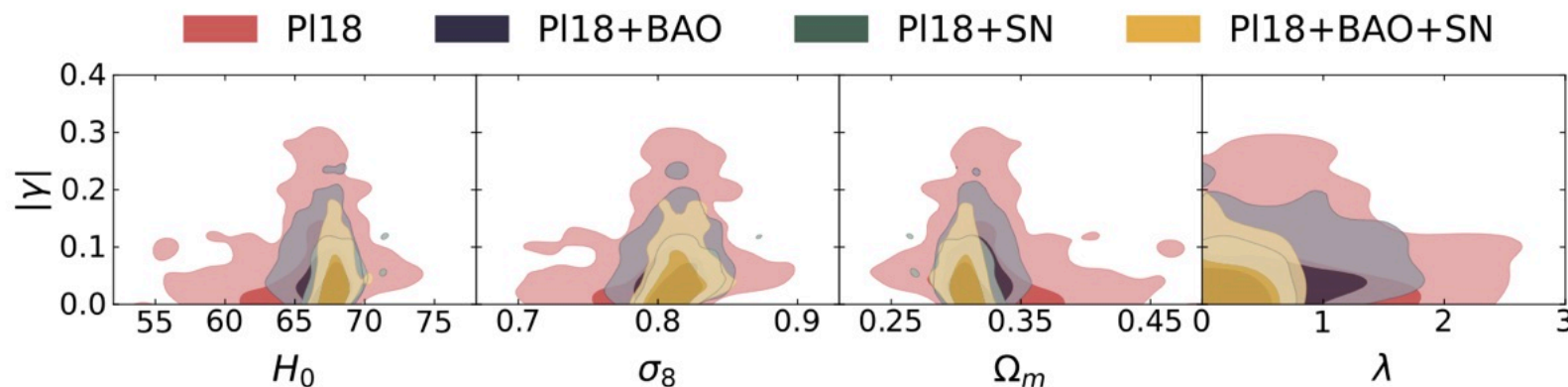
$$\phi'' + 2\mathcal{H}\phi' + a^2 V_{,\phi} = -a^2 \gamma(\phi - \phi_*) \rho_c / M_{\text{Pl}}$$

$$V(\phi) = V_0 e^{-\lambda \phi / M_{\text{Pl}}}$$

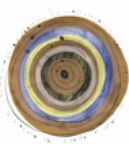
$$\rho'_c + 3\mathcal{H}\rho_c = \gamma(\phi - \phi_*) \rho_c \phi' / M_{\text{Pl}}$$

$$\delta'_c = -\theta_c + 3\Phi' - \gamma(\phi - \phi_*) \delta \phi'$$

$$\theta'_c + \mathcal{H}\theta_c = k^2 \Psi + \gamma(\phi - \phi_*) (\phi' \theta_c - \delta \phi / M_{\text{Pl}}^2)$$



$$G_{\text{eff}}/G = 1 + 2\gamma^2(\phi - \phi_*)^2$$



Dark sector interactions

- Interactions in the dark sector accomplished through non-minimally coupled scalar fields ϕ

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[Boehmer et al., arxiv:1501.06540]

[Boehmer et al., arxiv:1502.04030]

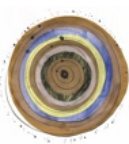
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Type-1: $Y + V(\phi) + e^{\alpha(\phi)}$ Type-2: $Y + V(\phi) + nh(Z)$ Type-3: $Y + V(\phi) + \gamma(Z) + f(n)$

E.g. Type-3 models is pure momentum-transfer up to linear order - background unchanged

Interactions





“Type-3” Models: Momentum exchange

- No changes in the background - interaction only affects the perturbations
- Interaction acts as additional friction, which translates into scale-independent growth

[Pourtsidou et al., arxiv:1307.0458]

[Pourtsidou, arxiv:2509.15091]

$$L(n, Y, Z, \phi) = Y + V(\phi) + \beta Z^2, \quad Z = u^\mu \nabla_\mu \phi$$

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

$$V(\phi) = V_0 e^{-\lambda\phi/M_{\text{Pl}}}$$

$$\rho'_c + 3\mathcal{H}\rho_c = 0$$

$$\delta'_c = -\theta_c + 3\Phi'$$

$$\theta'_c + \mathcal{H}\theta_c = k^2\Psi + \frac{(6\mathcal{H}\beta Z + 2\beta Z')\delta\phi + 2\beta Z\delta\phi'}{a(\rho_c - 2\beta Z^2)}$$

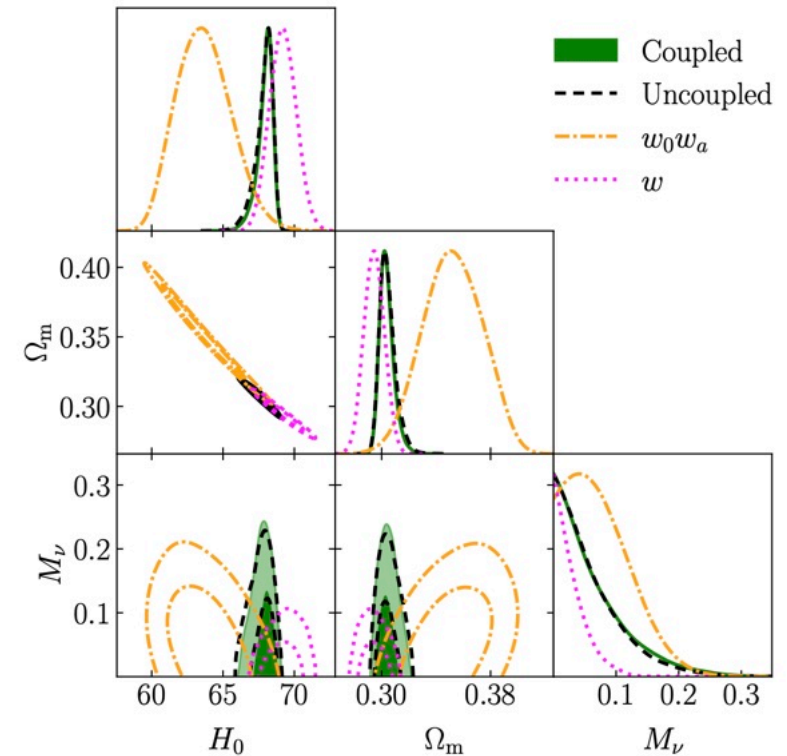
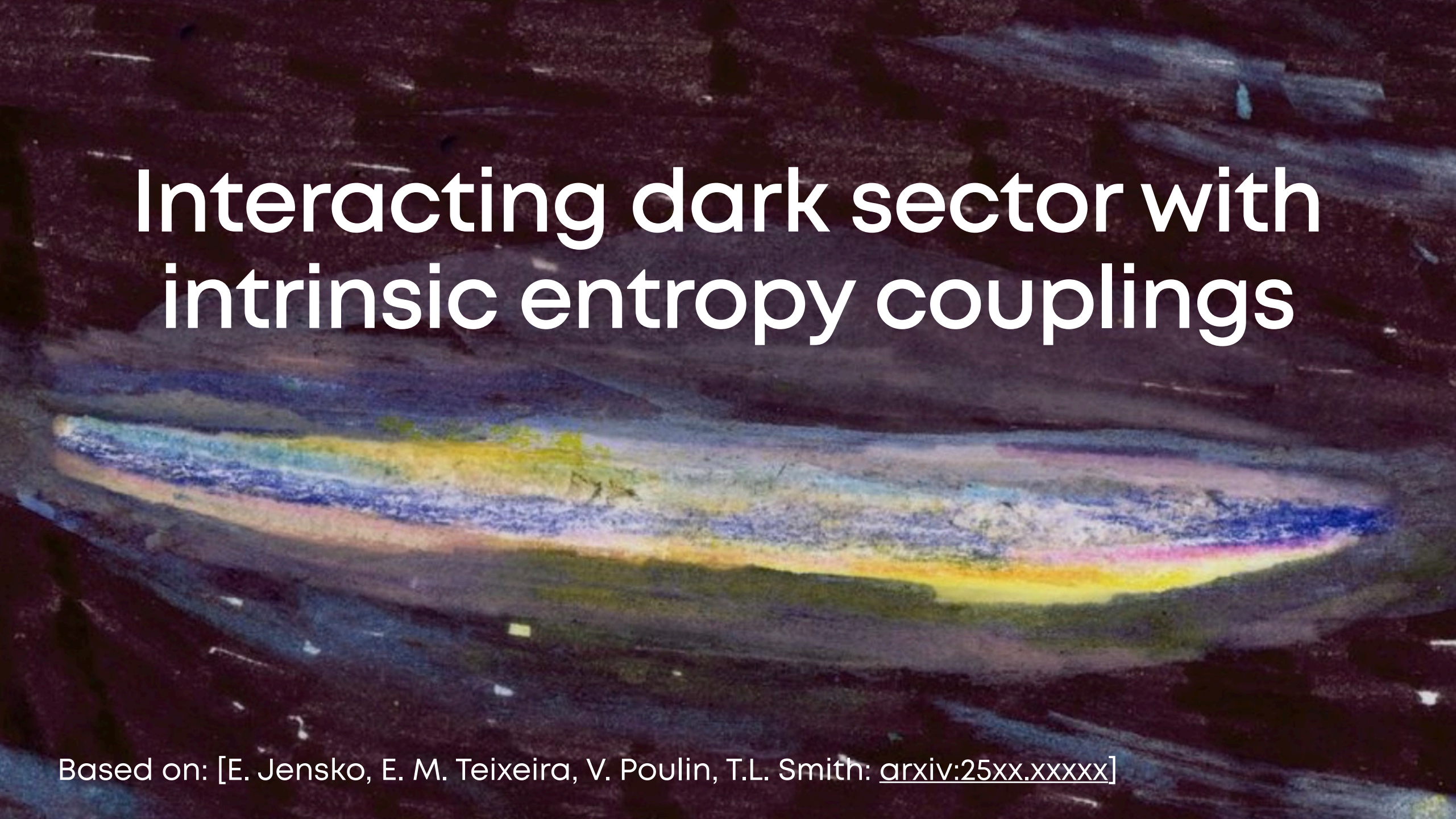
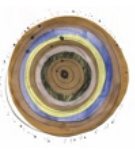


Figure 4. One dimensional posterior distributions of the parameters $\{H_0, \Omega_m, M_\nu\}$ together with the contours containing 68% and 95% of the posterior probability for the momentum coupling model (solid green lines) and uncoupled quintessence (dashed black lines), as well as the w_0w_a and constant w parametrisations (dotted dashed orange lines and dotted magenta lines, respectively). Neither quintessence models are able to reproduce the positive peak in the M_ν posterior of the w_0w_a parametrisation, but they allow for much more relaxed M_ν bounds than $w\Lambda$ CDM. Note that for the MCMC runs shown here we have used the CMB and BAO datasets only (without SN).



Interacting dark sector with intrinsic entropy couplings

Based on: [E. Jensko, E. M. Teixeira, V. Poulin, T.L. Smith: [arxiv:25xx.xxxxx](#)]



Cosmological fluids

$$\nabla_\mu(nu^\mu) = 0$$

$$\nabla_\mu(ns u^\mu) = 0$$

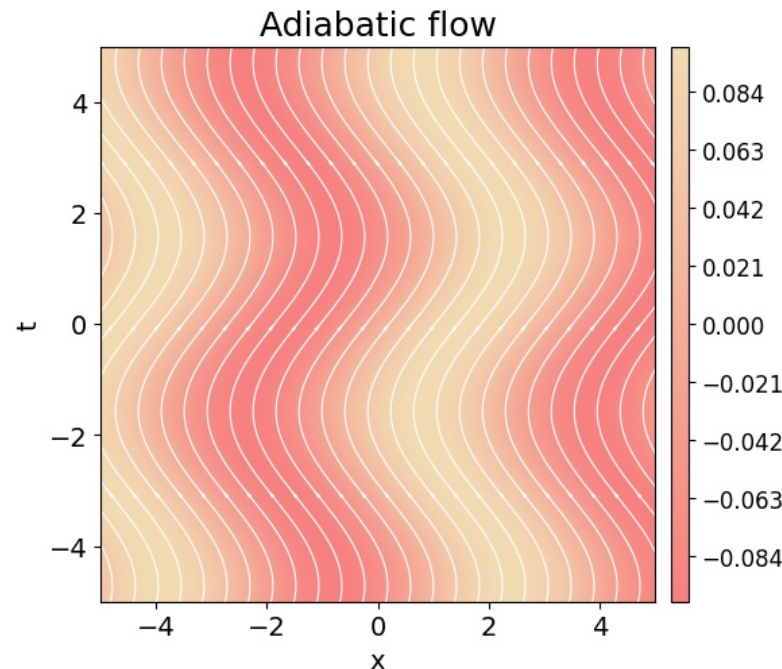
- Conservation of particle number and entropy along fluid flow lines
- Taken together these imply the entropy per particle is constant along fluid flow

adiabatic: $u^\mu \nabla_\mu s = 0 \not\Rightarrow$ isentropic: $\nabla_\mu s = 0$

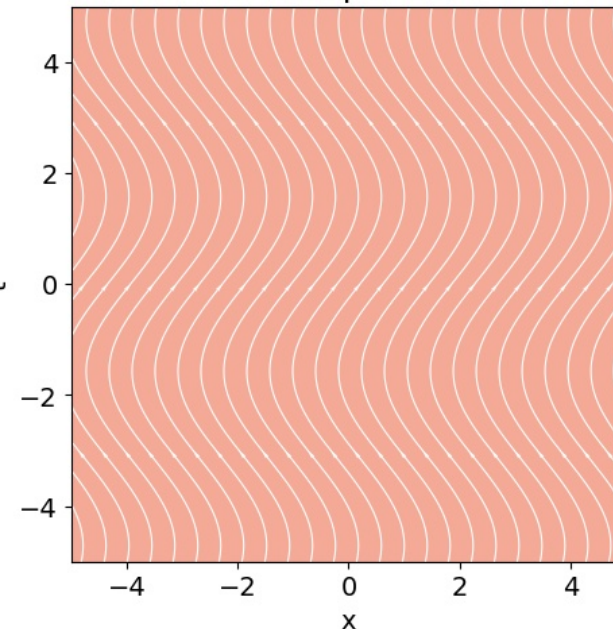
General fluid condition:

uniform entropy per particle s along the fluid flow (no shocks or heat conduction):

$$\rho = \rho(n, s)$$



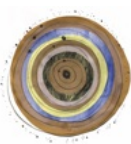
Isentropic flow



Usual assumption in cosmology:

the entropy per particle s is itself time and spatially uniform (irrotational flow):

$$\rho = \rho(n)$$



Perfect fluid dark matter in FLRW

Traditional CDM	General perfect fluid DM	“Entropic” CDM
Barotropic and isentropic ($\nabla_\mu s = 0$)	Non-barotropic and adiabatic ($u^\mu \nabla_\mu s = 0$)	Barotropic and adiabatic ($u^\mu \nabla_\mu s = 0$)
$\rho(n) = nm$	$\rho(n, s)$ arbitrary	$\rho(n, s) = nm\gamma(s)$
$p = 0$	$p \neq 0$	$p = 0$
$c_s^2 = 0$	$c_s^2 \neq 0$	$c_s^2 = 0$
$\Gamma = 0$	$\Gamma \neq 0$	$\Gamma = 0$
$\bar{s} = 0$	$\bar{s} = \text{constant}$	$\bar{s} = \text{constant}$
$\delta s = 0$	$\delta s = \delta s(x, y, z)$	$\delta s = \delta s(x, y, z)$
$T = 0$	$T \neq 0$	$T = m\gamma'(s)$

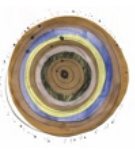
$$\delta p = c_a^2 \delta \rho + \Gamma$$

with non-adiabatic pressure perturbation

$$\Gamma = \left. \frac{\partial p}{\partial s} \right|_\rho \delta s$$

- intrinsic ~ fluctuations in fluid's internal entropy ($\Gamma = 0 \nRightarrow \delta s = 0$)

- relative ~ relative density isocurvature perturbations



Dark sector interactions

- Interactions in the dark sector accomplished through non-minimally coupled scalar fields ϕ

$$S_{\text{tot}} = \int \sqrt{-g} f(n, s, \phi, \dots) d^4x + S_{\text{Brown}} + S_{\phi} + S_{\text{SM}}$$

Many different choices of interacting terms in the literature:

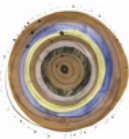
- Algebraic (“coupled quintessence”): $f(n, \phi)$
- Derivative (“momentum coupling”): $f(n) n^{\mu} \partial_{\mu} \phi$
- General with $Y = \partial_{\mu} \phi \partial^{\mu} \phi$ and $Z = u^{\mu} \partial_{\mu} \phi$: $f(n, \phi, Y, Z)$

All past studies neglect the role of entropy in couplings $f(n, s, \phi, \partial \phi)$ by assuming $\partial_{\mu} s = 0$

Type-1: $Y + V(\phi) + e^{\alpha(\phi)}$ Type-2: $Y + V(\phi) + nh(Z)$ Type-3: $Y + V(\phi) + \gamma(Z) + f(n)$

E.g. Type-3 models is pure momentum-transfer up to linear order - background unchanged





Entropy couplings in the dark sector

- Couple the intrinsic entropy of dark matter s in $\rho_c(n_c, s) = m_c n_c \gamma(s)$ to the dark energy scalar ϕ - excite the otherwise hidden degrees of freedom associated with the entropy perturbations in barotropic fluids

- For this we consider pure entropy-scalar interactions:

$$\mathcal{L}_{\text{int}}(\phi, s, \nabla_\mu \phi, \nabla_\mu s, \dots)$$

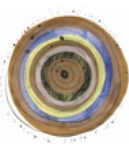
$$\mathcal{L}_{\text{alg}} = g(\phi, s)$$

$$\mathcal{L}_{\text{der}} = h(\nabla_\mu \phi, \nabla_\mu s)$$

- Later distinguish into algebraic and first-order derivative model
- Generally derived from an interaction action

$$S_{\text{int}} = - \int \sqrt{-g} f(s, \phi, \mathcal{S}) d^4x \quad \text{with} \quad \mathcal{S} := \nabla^\mu \phi \nabla_\mu s$$





Equations of motion

- Modified Einstein field equations

$$G_{\mu\nu} = \kappa \left(T_{\mu\nu} + T_{\mu\nu}^{\phi} + T_{\mu\nu}^{(\text{int})} \right)$$

with interaction EM tensor (with heat-fluxes $q_{\mu} = u^{\nu} h_{\mu}^{\lambda} T_{\nu\lambda}$):

$$T_{\mu\nu}^{(\text{int})} = -g_{\mu\nu} f + 2 \frac{\partial f}{\partial \mathcal{S}} \nabla_{(\mu} \phi \nabla_{\nu)} s$$

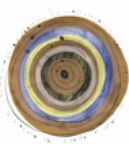
- Total effective dark energy tensor $\tilde{T}_{\mu\nu}^{(\phi)} := T_{\mu\nu}^{(\phi)} + T_{\mu\nu}^{(\text{int})}$ with coupling current

$$J_{\nu} := \nabla^{\mu} \tilde{T}_{\mu\nu}^{(\phi)} = \nabla_{\mu} (f_{,\mathcal{S}} \nabla^{\mu} \phi) \nabla_{\nu} s - f_{,s} \nabla_{\nu} s$$

which acts only in the perpendicular direction $u^{\nu} J_{\nu} = 0$ (from $u^{\nu} \nabla_{\nu} s = 0$)

Pure “momentum” transfer (up to linear order) - preserve background dynamics

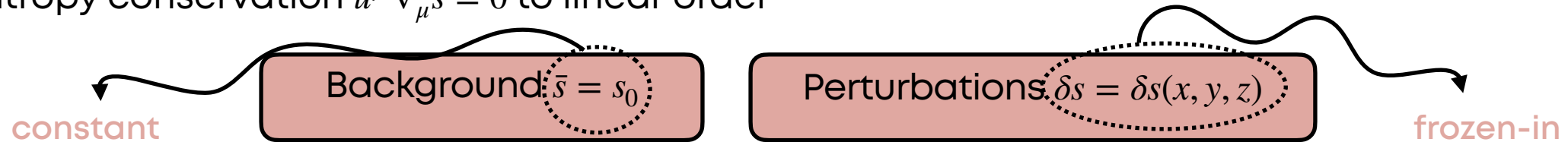




Cosmology

● Conformal Newtonian gauge at linear order: $ds^2 = -a(\tau)^2(1 + 2\Phi)d\tau^2 + a^2(1 - 2\Psi)(dx^2 + dy^2 + dz^2)$

● Entropy conservation $u^\mu \nabla_\mu s = 0$ to linear order

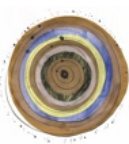


● Trivial background modification with effective potential $\hat{V}(\bar{\phi}) = V(\bar{\phi}) + f(\bar{\phi}, s_0, 0)$

$$\bar{\rho}_{\text{DE}} = \frac{1}{2a^2} \bar{\phi}'^2 + \hat{V}(\bar{\phi}), \quad \bar{p}_{\text{DE}} = \frac{1}{2a^2} \bar{\phi}'^2 - \hat{V}(\bar{\phi})$$

● Uncoupled dark sector in the background - perturbative effects only

$$\bar{\rho}'_I + 3\mathcal{H}(\bar{p}_I + \bar{\rho}_I) = 0 \quad \Rightarrow \quad \text{indistinguishable from uncoupled quintessence or } \Lambda\text{CDM}$$



Cosmological perturbations

- Split interaction term and take $p_c = \delta p_c = 0$ for simplicity

$$f(\phi, s, \nabla_\mu \phi \nabla^\mu s) = \underbrace{g(\phi, s)}_{\text{Algebraic}} + \underbrace{h(\nabla_\mu \phi \nabla^\mu s)}_{\text{Derivative}}$$

- Unchanged continuity equation but modified Euler equation with **scale-dependent** source

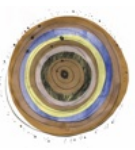
$$\delta'_c + \theta_c - 3\Psi' = 0$$

$$\theta'_c + \theta_c \mathcal{H} - k^2 \Psi = -k^2 Q_s \delta s(k), \quad \text{with} \quad Q_s := \frac{\bar{g}_{,s} - h_0 \hat{V}_{,\bar{\phi}}}{\bar{\rho}_c}$$

- In the quasi-static limit ($k \gg \mathcal{H}$) this becomes:

$$\delta''_c + \mathcal{H} \delta'_c - 4\pi G a^2 [\bar{\rho}_c \delta_c + \Delta \rho_s(k, a) \delta s] \simeq k^2 Q_s(a) \delta s$$

- The coupling appears as “fifth-force” $Q_s(a)$ and “effective density source” contribution $\Delta \rho_s(k, a)$



Observational signatures

Pure derivative interaction with scale invariant entropy perturbations with standard DE exponential potential

$$f(\phi, s, \mathcal{S}) = h_0 \mathcal{S} = h_0 \nabla_\mu \phi \nabla^\mu s$$

$$\delta s(k) = \mathcal{A} (k/k_s)^n$$

- In the QS limit algebraic and derivative couplings reduce to similar effective source

$$k^2 \Psi \propto -a^2 (\delta \rho_m + \delta \rho_{\text{DE}})$$

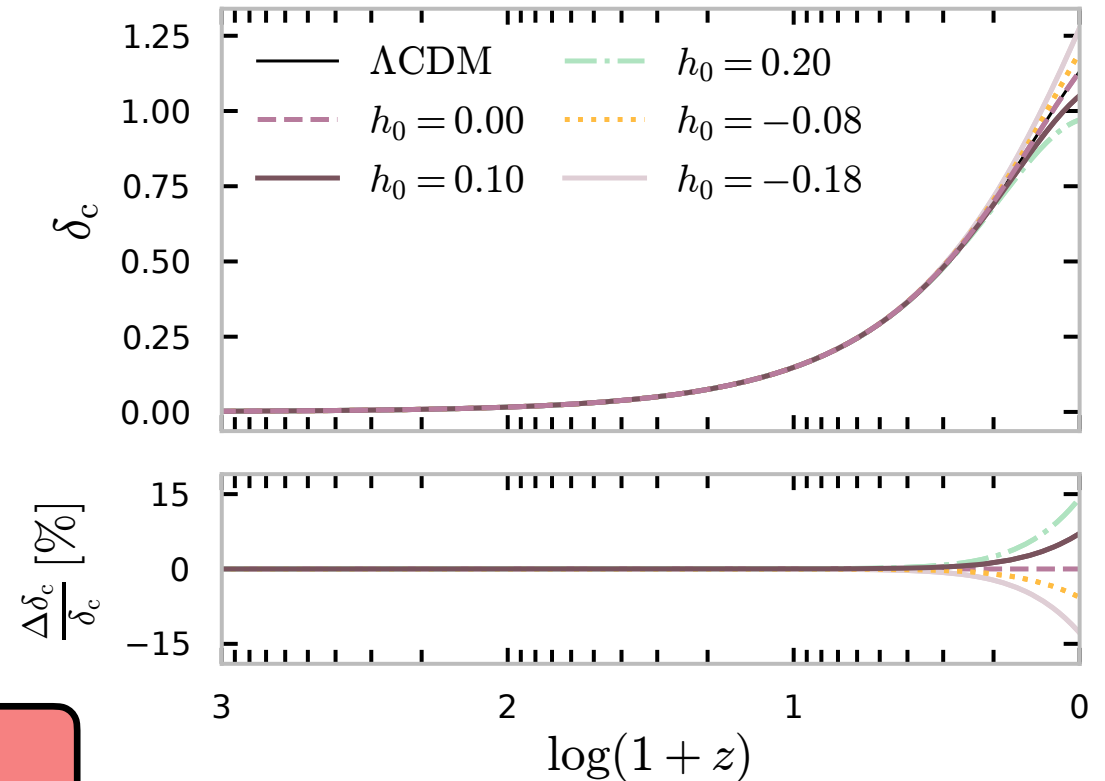
$$k^2 (\Psi' + \mathcal{H} \Psi) \propto a^2 (\theta_m + \theta_{\text{DE}})$$

- Modification in $\theta_{\text{DE}} = -k^2 (h_0 \delta s + \delta \phi) / \phi'$

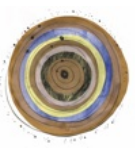
- If $n \neq 0$ need to tame large effects of the coupling at small scales

$$Q_s^{\text{der}}(a) = -\frac{h_0}{\bar{\rho}_c} \hat{V}_{,\bar{\phi}}$$

$$\Delta \rho_s^{\text{der}}(k, a) = -\frac{k^2 h_0}{k^2 + a^2 m_{\text{eff}}^2} \hat{V}_{,\bar{\phi}}$$



$$[k = 0.1h, \mathcal{A} = 1, k_s = 1 \text{ Mpc}^{-1}, n = 0]$$



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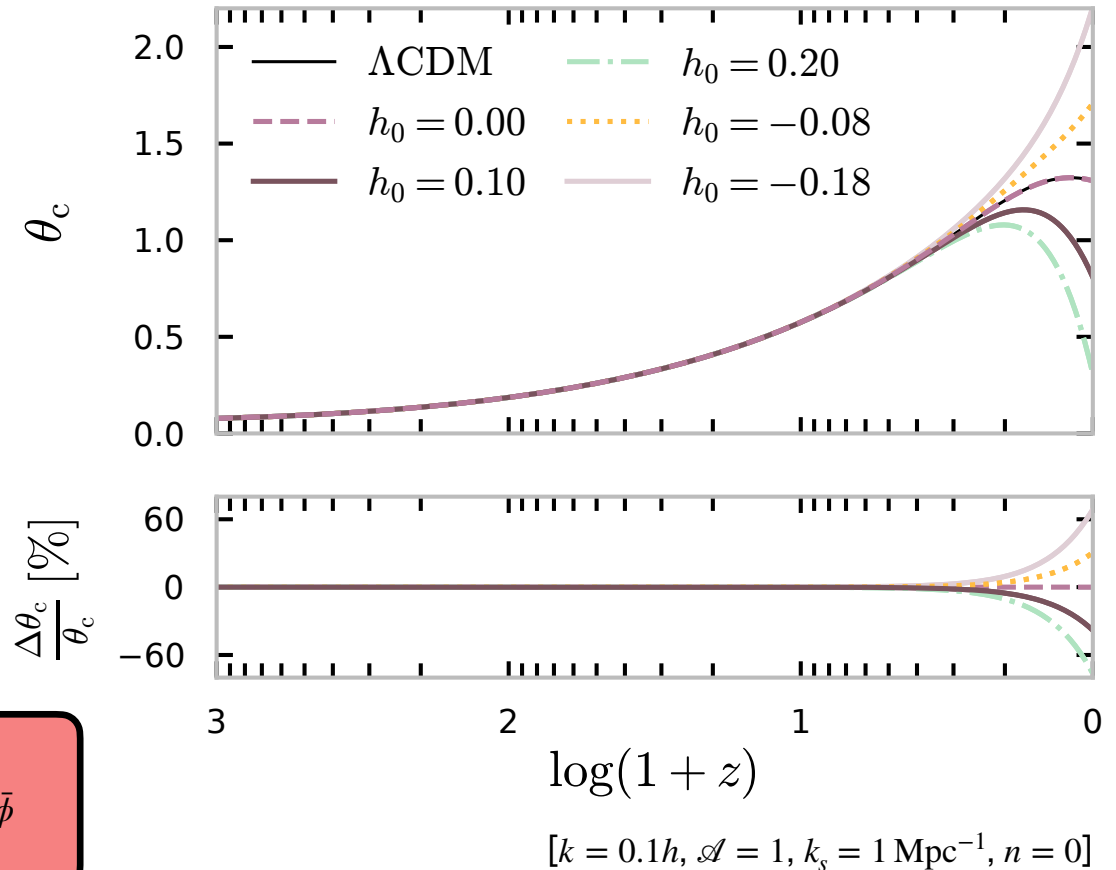
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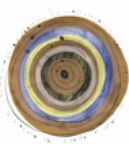
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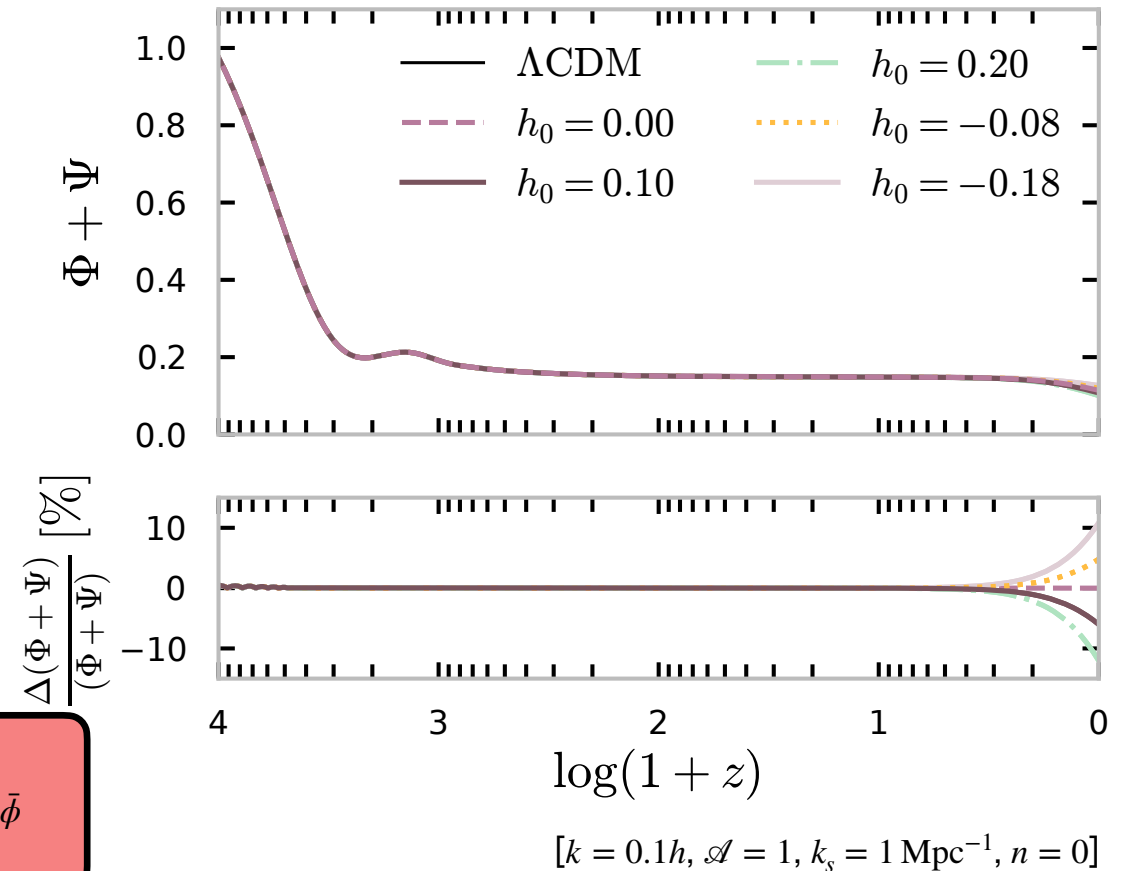
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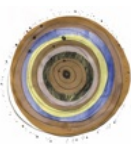
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Observational signatures

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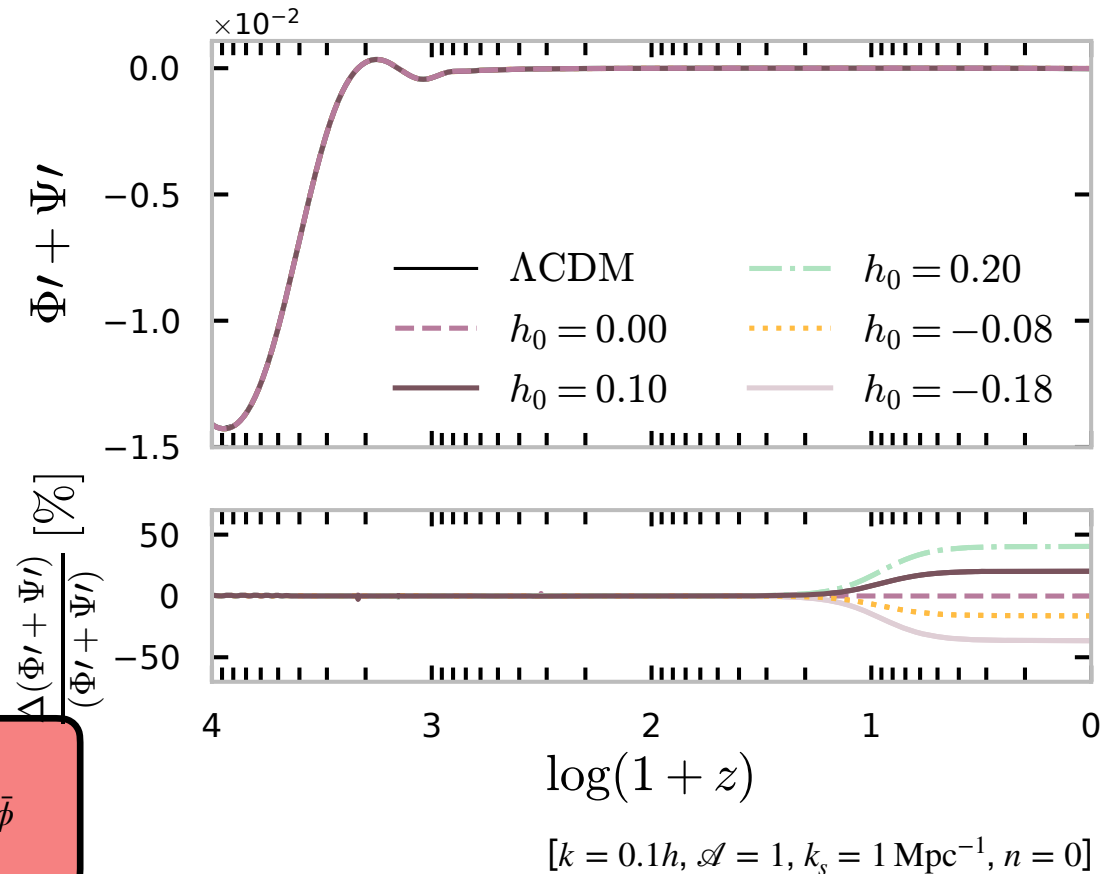
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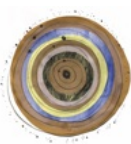
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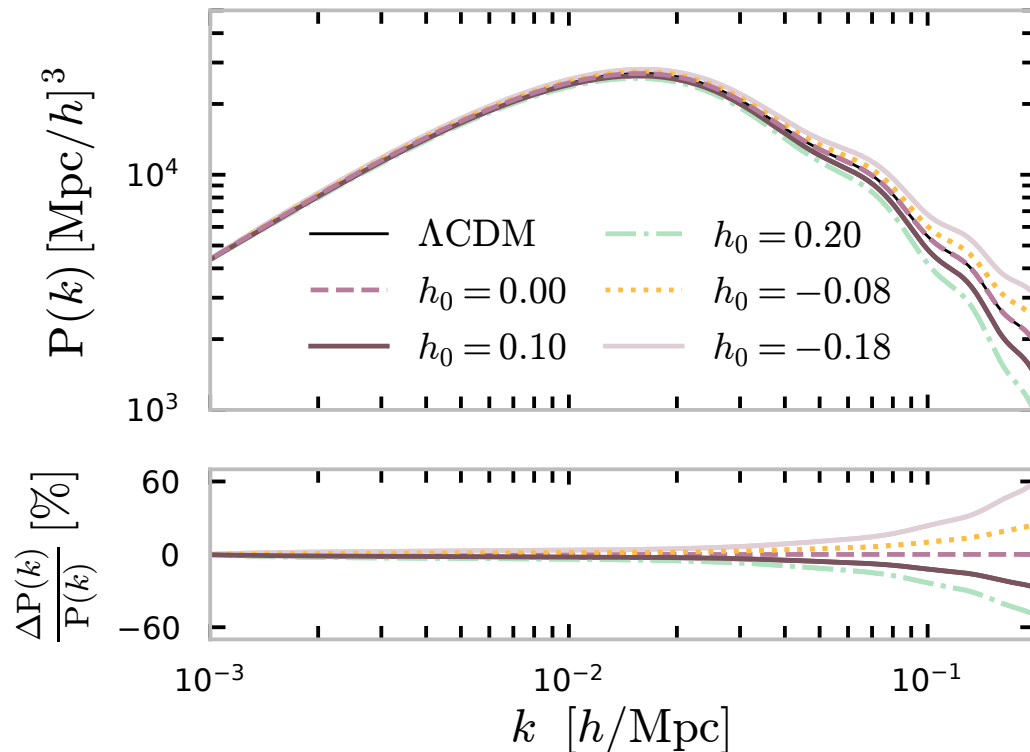


Observational signatures

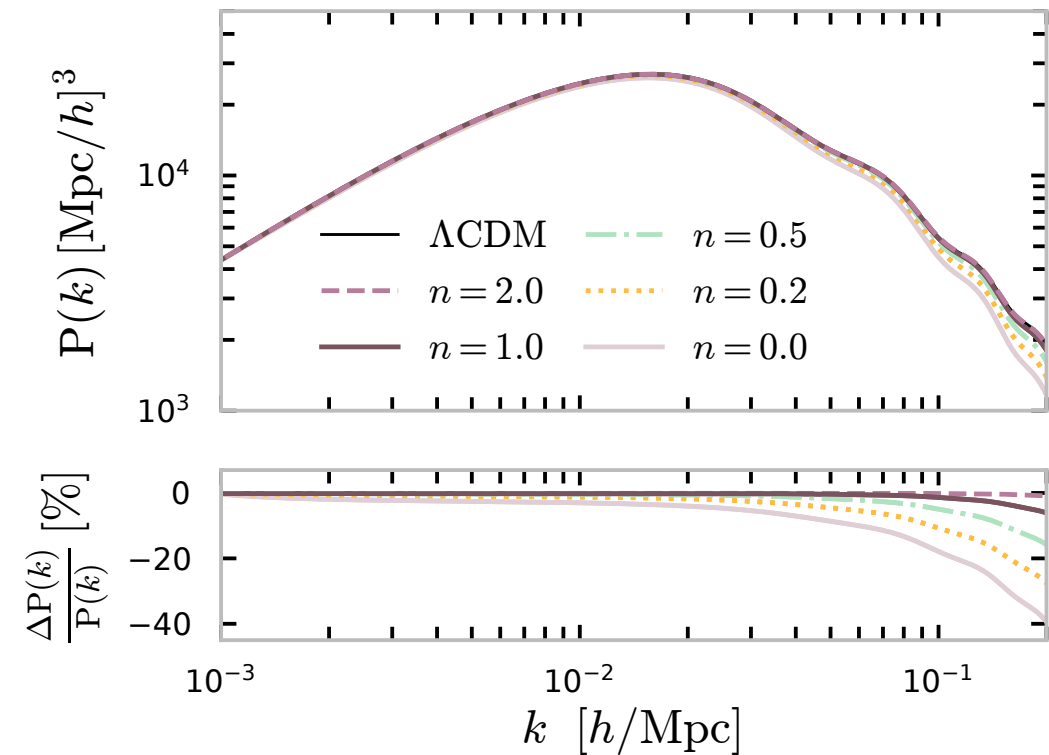
Suppression/enhancement of matter power spectrum on small scales

$$f(\phi, s, \mathcal{S}) = h_0 \mathcal{S} = h_0 \nabla_\mu \phi \nabla^\mu s$$

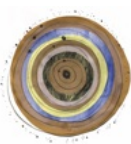
$$\delta s(k) = \mathcal{A} (k/k_s)^n$$



$[\mathcal{A} = 1, k_s = 1 \text{ Mpc}^{-1}, n = 0]$



$[\mathcal{A} = 1, k_s = 1 \text{ Mpc}^{-1}, h_0 = 0.15]$

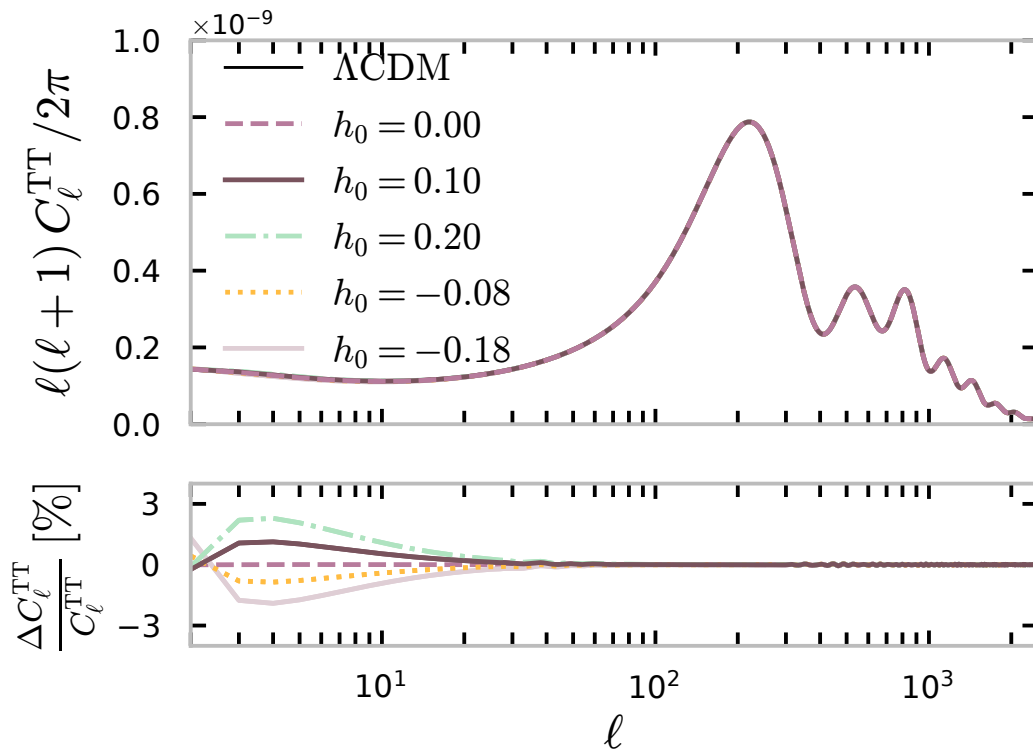


Observational signatures

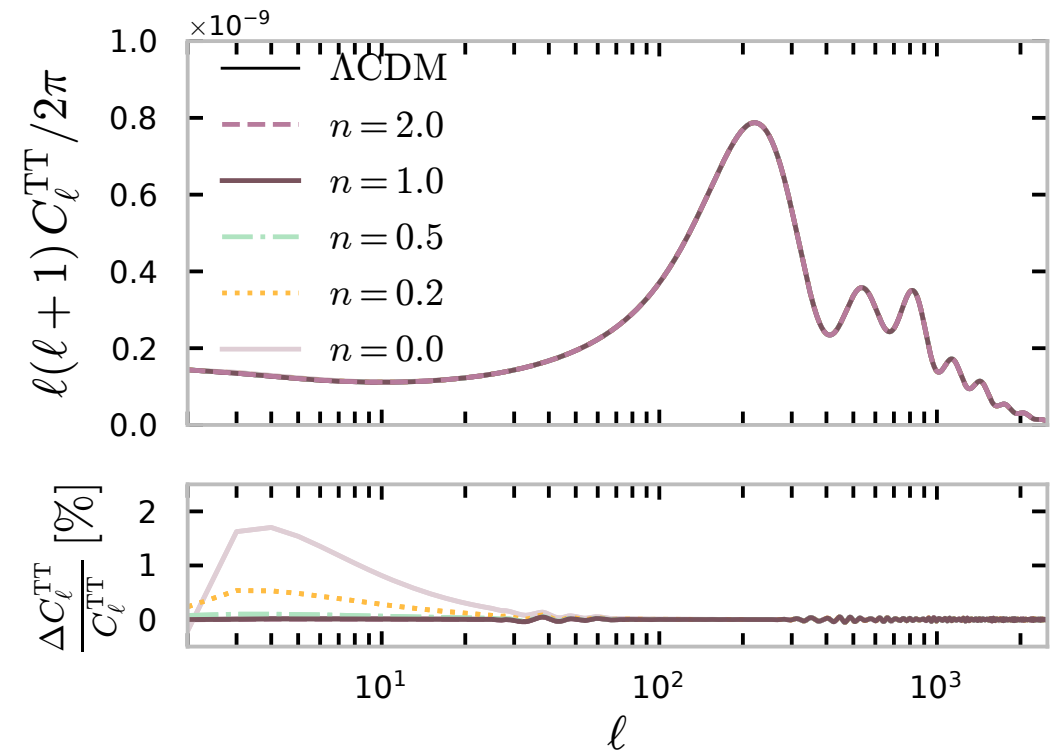
Tiny ISW changes to CMB temperature spectrum $\mathcal{C}_\ell^{TT}$ at low- ℓ

$$f(\phi, s, \mathcal{S}) = h_0 \mathcal{S} = h_0 \nabla_\mu \phi \nabla^\mu s$$

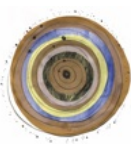
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$[\mathcal{A} = 1, k_s = 1 \text{ Mpc}^{-1}, h_0 = 0.15]$

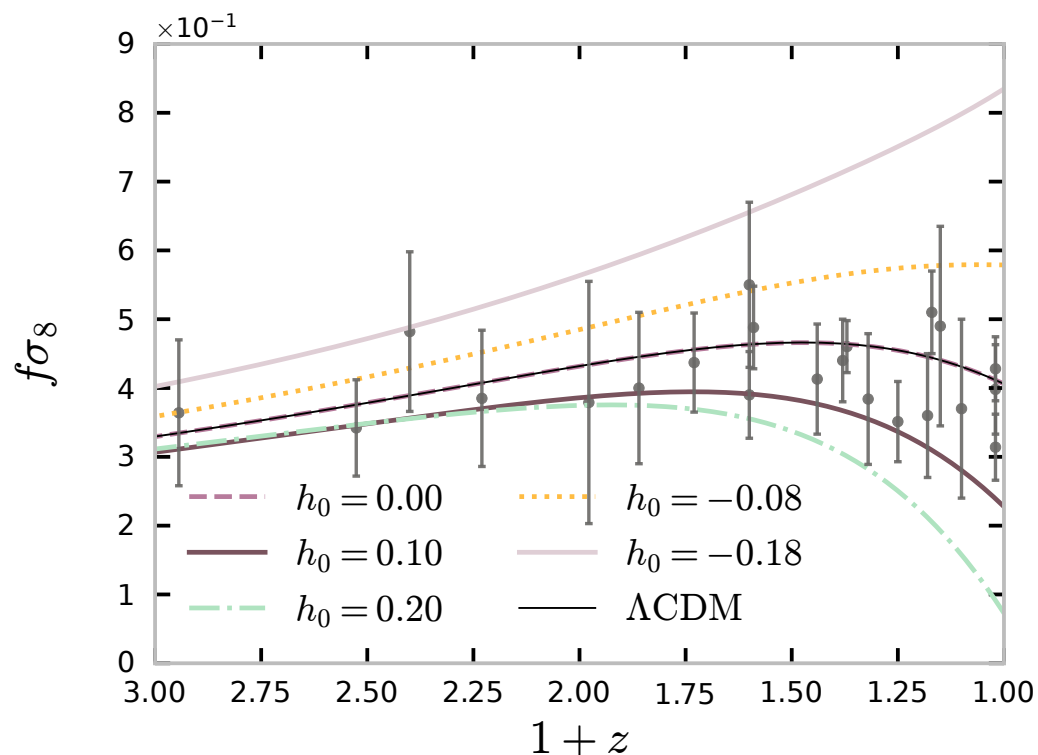


Observational signatures

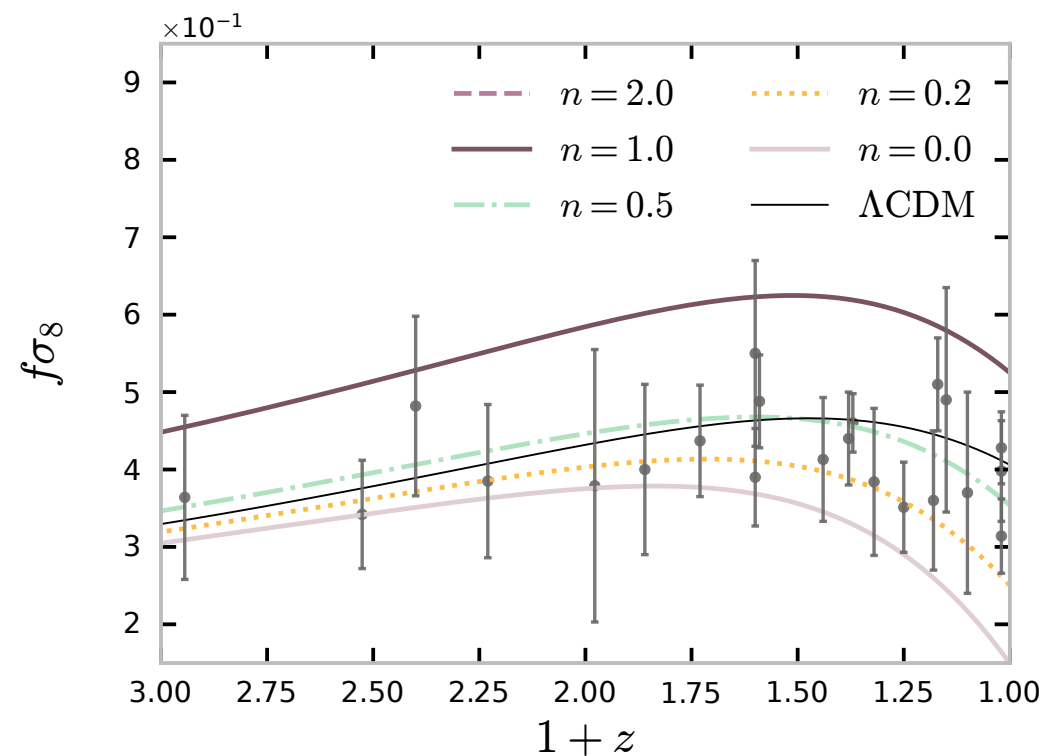
Significant changes to the growth - observational constraints

$$f(\phi, s, \mathcal{S}) = h_0 \mathcal{S} = h_0 \nabla_\mu \phi \nabla^\mu s$$

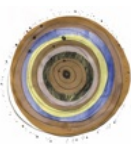
$$\delta s(k) = \mathcal{A} \left(k/k_s \right)^n$$



$[\mathcal{A} = 1, k_s = 1 \text{ Mpc}^{-1}, n = 0]$



$[\mathcal{A} = 1, k_s = 1 \text{ Mpc}^{-1}, h_0 = 0.15]$



Observational signatures

Similar behaviour for algebraic models except for scale-dependent effects

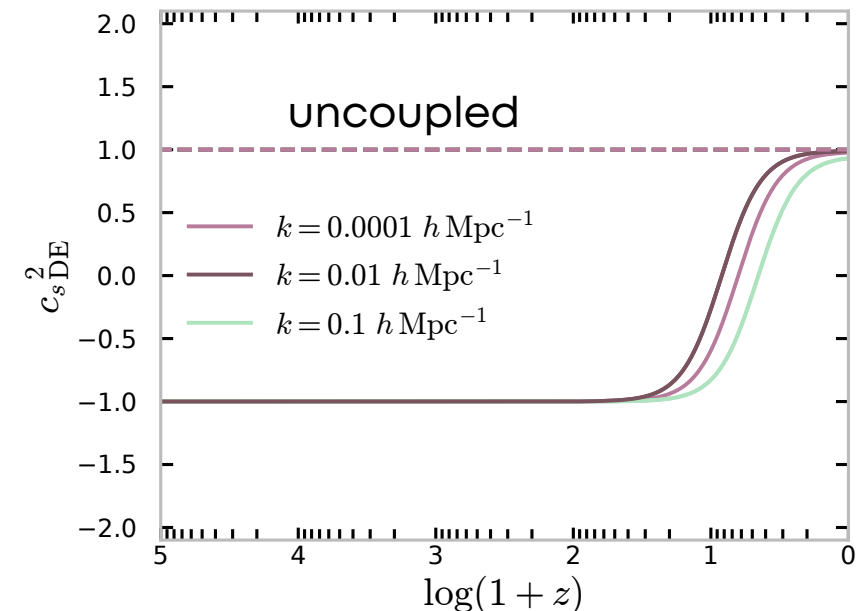
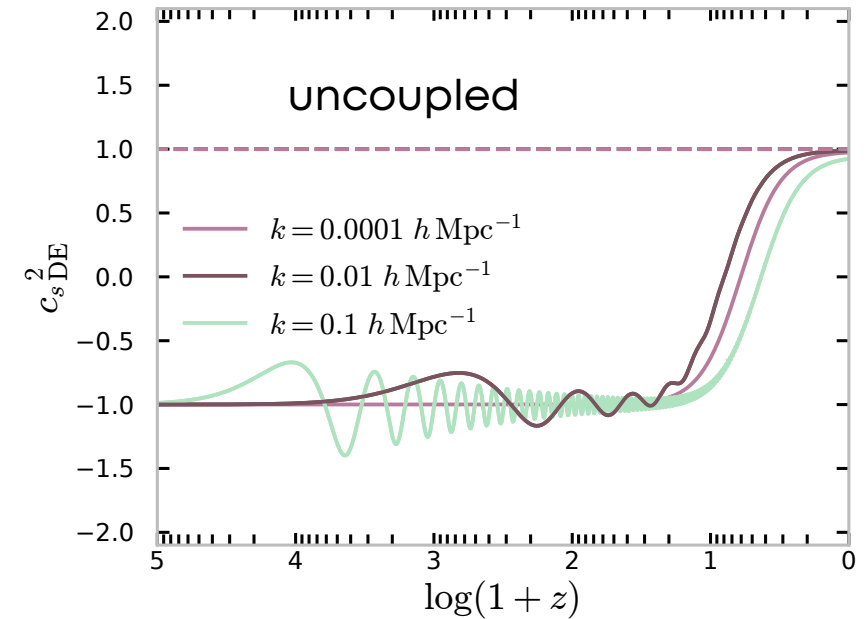
- © Different scale-dependence of source term

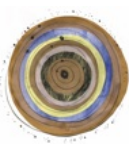
$$\Delta\rho_s^{\text{der}}(k, a) = -\frac{k^2 h_0}{k^2 + a^2 m_{\text{eff}}^2} \hat{V}_{,\bar{\phi}}$$

$$\Delta\rho_s^{\text{alg}}(k, a) = \bar{g}_{,s} - \frac{a^2 \bar{g}_{,s\phi}}{k^2 + a^2 m_{\text{eff}}^2} \hat{V}_{,\bar{\phi}}$$

- © Different sound speed in the fluid rest frame ($c_s^2 \neq 1$):

$$c_s^2 := \left. \frac{\delta p}{\delta \rho} \right|_{\text{restframe}} = 1 - \frac{2a^2 \delta s (h_0 \hat{V}_{,\bar{\phi}} - \bar{g}_{,s})}{a^2 \delta s (h_0 \hat{V}_{,\bar{\phi}} - \bar{g}_{,s}) + \phi'(\delta\phi' - \bar{\phi}'\Psi)}$$





Observational signatures

$$\delta\phi'' + 2\mathcal{H}\delta\phi' + (k^2 + a^2\hat{V}_{,\bar{\phi}\bar{\phi}})\delta\phi = -2a^2\Psi\hat{V}_{,\bar{\phi}} + 4\Psi'\bar{\phi}' - \left(a^2\bar{g}_{,s\phi} + \textcircled{k^2 h_0}\right)\delta s$$

- © Different scale-dependance of source term

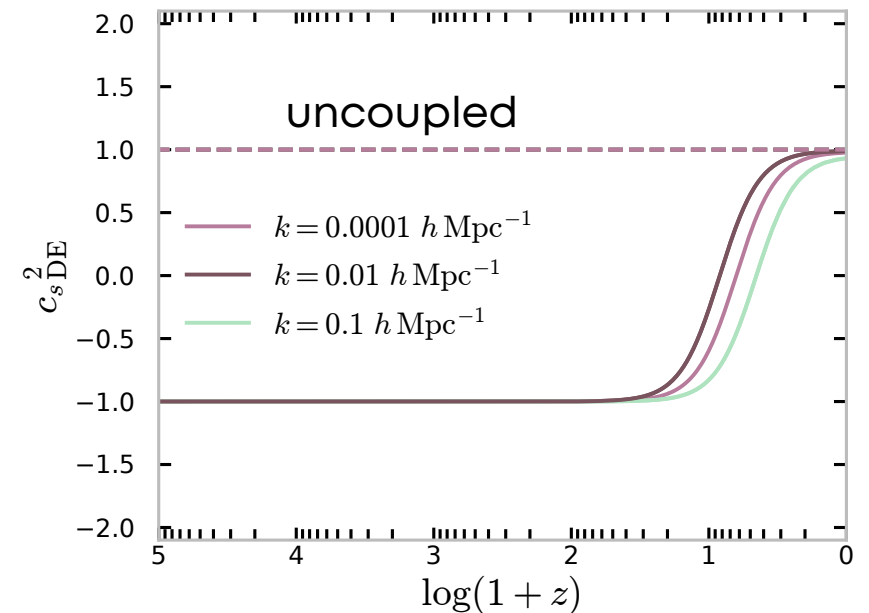
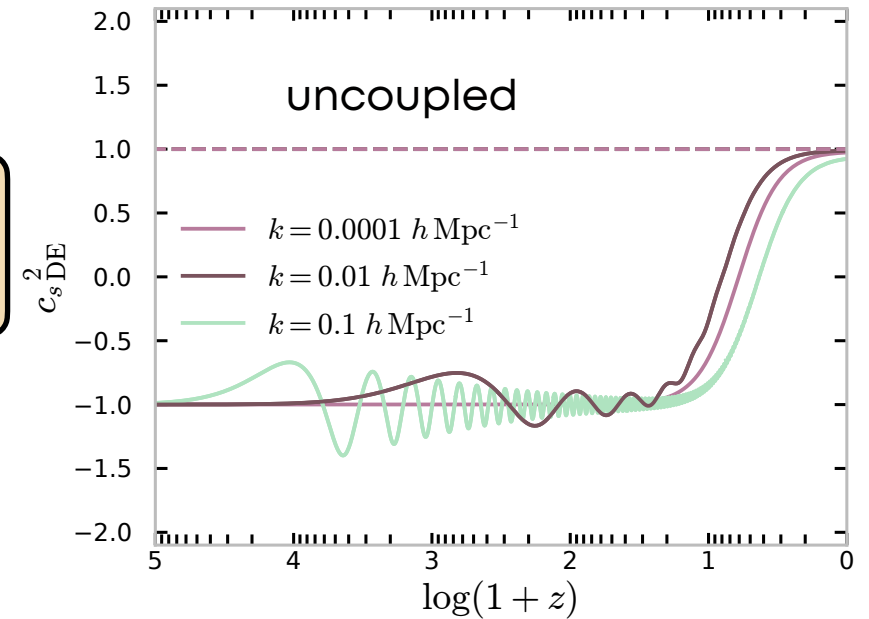
$$\Delta\rho_s^{\text{der}}(k, a) = -\frac{k^2 h_0}{k^2 + \textcircled{a^2 m_{\text{eff}}^2}} \hat{V}_{,\bar{\phi}}$$

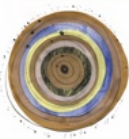
$$\Delta\rho_s^{\text{alg}}(k, a) = \textcircled{\bar{g}_{,s}} - \frac{a^2 \bar{g}_{,s\phi}}{k^2 + a^2 m_{\text{eff}}^2} \hat{V}_{,\bar{\phi}}$$

Oscillations in $\delta\phi$ in
the derivative
coupling for small
scales

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Conclusions

- New interacting scenarios from coupling DM intrinsic entropy to DE
 - Unchanged background expansion
 - No energy transfer (pure-momentum only)
 - Scale-dependent suppression/enhancement of matter clustering at late-times
-
- Observational constraints on allowed couplings - cosmic tensions
 - Explore different primordial power spectrum for $\delta s(k)$ and initial conditions
 - Early dark energy/neutrino scenarios
 - Key observational signatures: scale-dependent clustering



Thank you for your attention!

ELSA M. TEIXEIRA

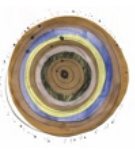
Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier
elsa.teixeira@umontpellier.fr

Illustrations: Inês Viegas Oliveira
(ivoliveira.com)



Beyond the Standard Model: Coupled Scalar Dark Sectors

Based on: [S. Rahimy, E. M. Teixeira, I. Zavala: [arxiv:2503.01961](https://arxiv.org/abs/2503.01961)]



Dark sector interactions

- Interactions in the dark sector accomplished through non-minimally coupled scalar fields ϕ

$$S_{\text{tot}} = \int \sqrt{-g} f(n, s, \phi, \dots) d^4x + S_{\text{Brown}} + S_{\phi} + S_{\text{SM}}$$

Many different choices of interacting terms in the literature:

- Algebraic (“coupled quintessence”): $f(n, \phi)$
- Derivative (“momentum coupling”): $f(n)n^{\mu}\partial_{\mu}\phi$
- General with $Y = \partial_{\mu}\phi\partial^{\mu}\phi$ and $Z = u^{\mu}\partial_{\mu}\phi$: $f(n, \phi, Y, Z)$

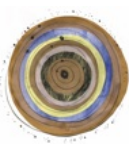
Type-1: $Y + V(\phi) + e^{\alpha(\phi)}$ Type-2: $Y + V(\phi) + nh(Z)$ Type-3: $Y + V(\phi) + \gamma(Z) + f(n)$

E.g. Type-3 models is pure momentum-transfer up to linear order - background unchanged

Interactions

What if dark matter is described by a scalar field χ ?
Can we find a fluid description?





Coupled Scalar Dark Sector

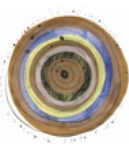
Two-scalar non-linear sigma model (NLSM) in a target manifold M

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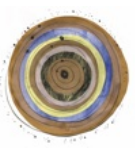
$$S_{\text{dark}} = \int d^4x \sqrt{-g} \left[-\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{f^2(\phi)}{2} \partial_\mu \chi \partial^\mu \chi - V(\phi, \chi) \right]$$

Standard
kinetic
terms

Two scalars often
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$$\Phi = \phi + i\chi$$

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



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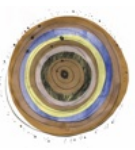
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$$S_{\text{dark}} = \int d^4x \sqrt{-g} \left[-\frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{f^2(\phi)}{2} \partial_\mu \chi \partial^\mu \chi + V(\phi, \chi) \right]$$

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 $g(\phi)$

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



Coupled Scalar Dark Sector

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

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

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

FLRW
background

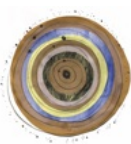
$$\nabla_{\mu} T^{\mu\nu}_{(1)} = Q^{\nu}, \quad \nabla_{\mu} T^{\mu\nu}_{(2)} = -Q^{\nu}$$

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

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)

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

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

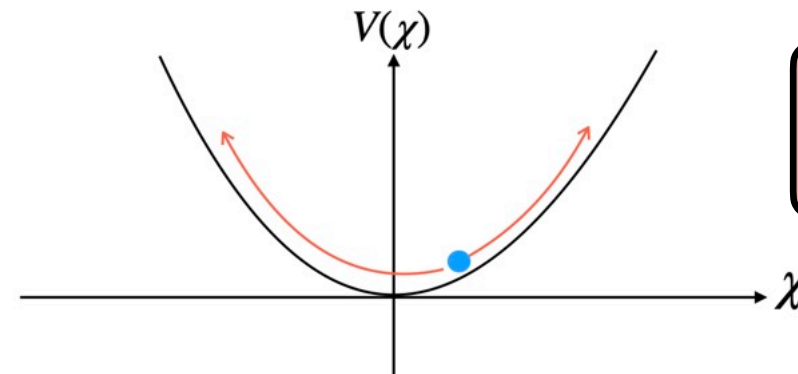
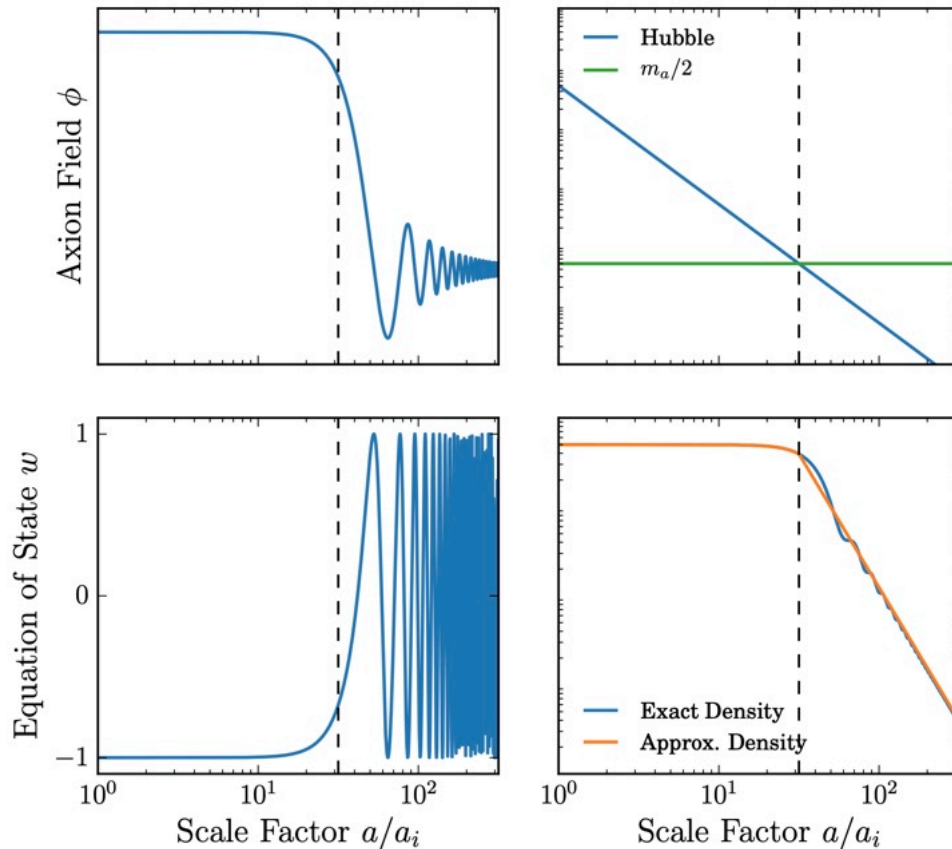


Scalar Field Dark Matter

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

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

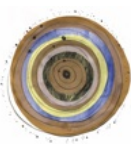
$$\text{Pressure: } p = \frac{1}{2} \dot{\chi}^2 - \frac{m^2}{2} \chi^2$$



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

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

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



Scalar Field Dark Matter

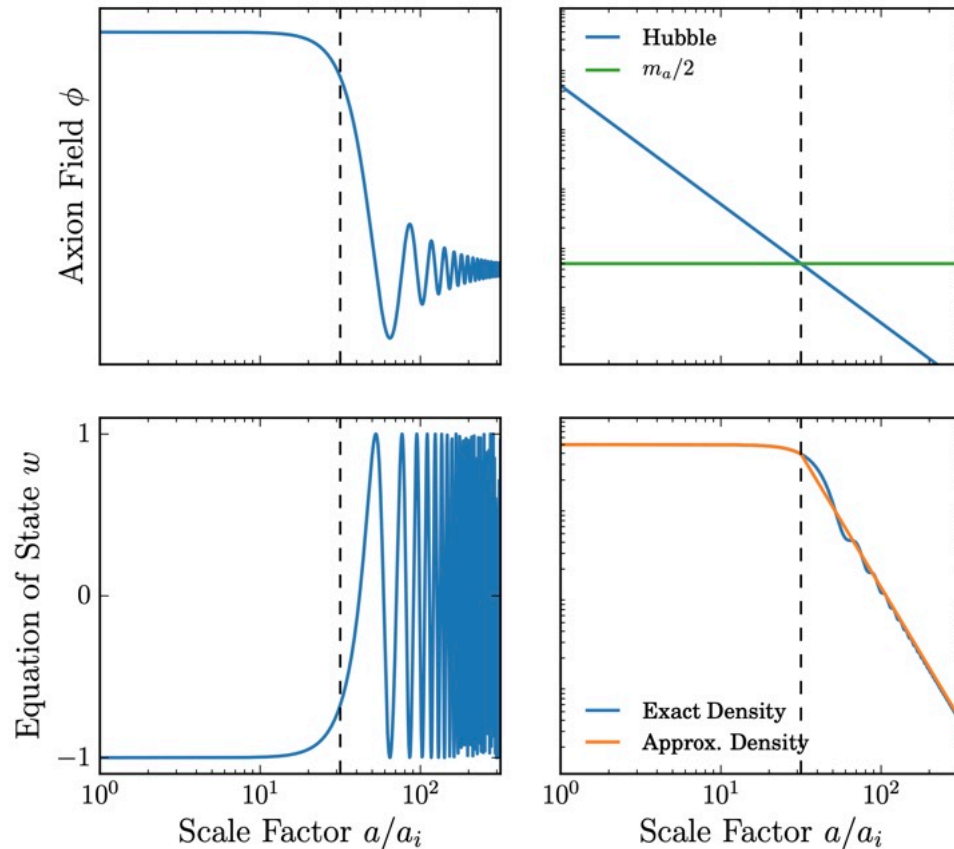
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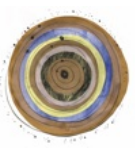
- **Oscillating** field for $m \gg H$ on time scales much faster than the expansion
- Rapid oscillations can be **averaged**
- Rewrite as a **fluid approximation** and recover CDM behaviour at the background level with additional scalar field properties

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

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

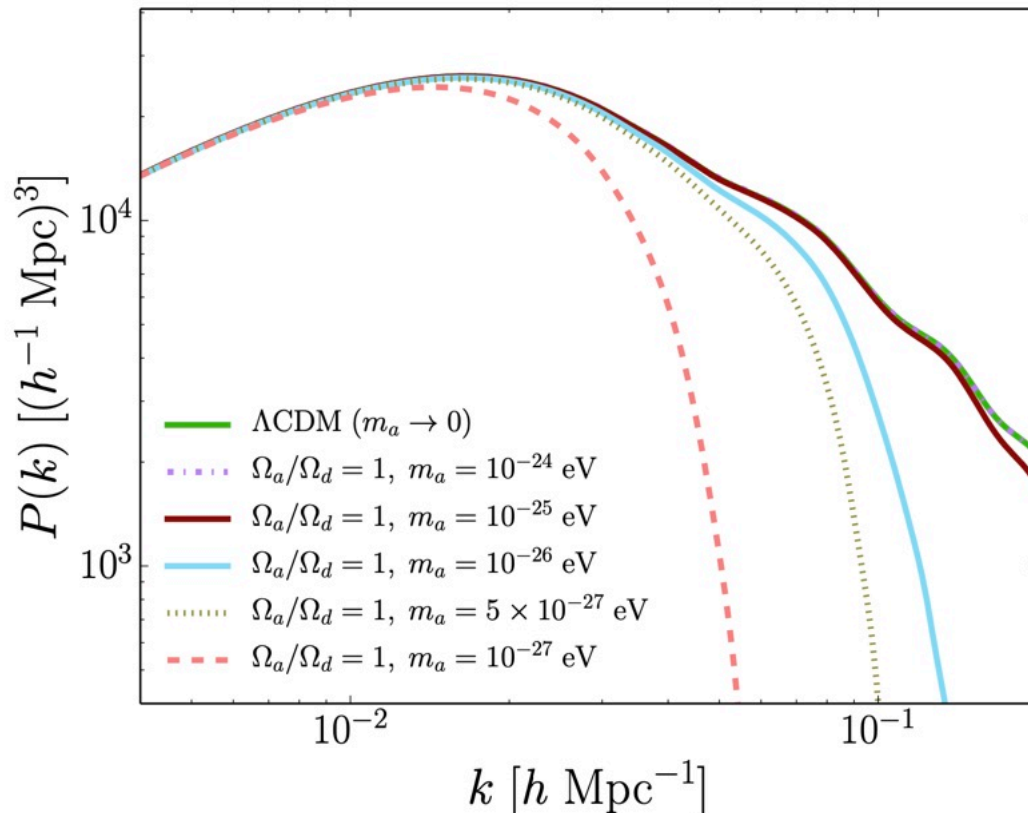


$$\begin{cases} \langle \rho_\chi \rangle \propto a^{-3} \\ \langle w_\chi \rangle = \left\langle \frac{p_\chi}{\rho_\chi} \right\rangle = 0 \end{cases}$$



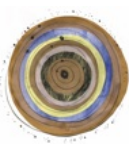
Scalar Field Dark Matter

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

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

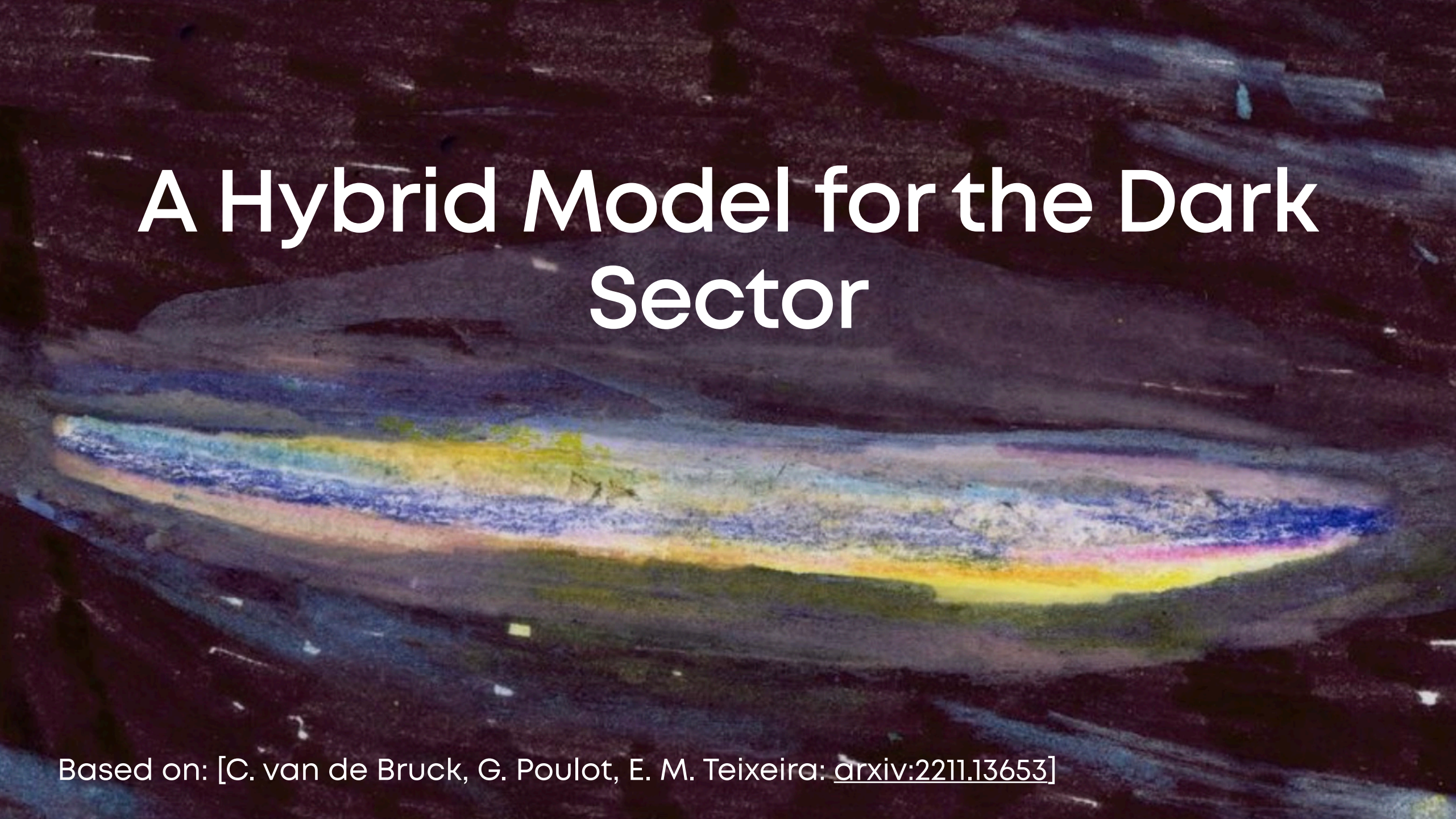


Testing interactions in the dark sector

- Work motivated by modelling the dark sector and understanding its impact for cosmic tensions
- Physical implications of different models and cosmological signatures
- Interaction in the dark sector could explain evidence for phantom dynamical dark energy
- In this talk:

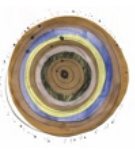
Hybrid model with interactions mediated by potential interaction in scalar field DE and DM





A Hybrid Model for the Dark Sector

Based on: [C. van de Bruck, G. Poulot, E. M. Teixeira: [arxiv:2211.13653](https://arxiv.org/abs/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]

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

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

Hybrid Potential interaction

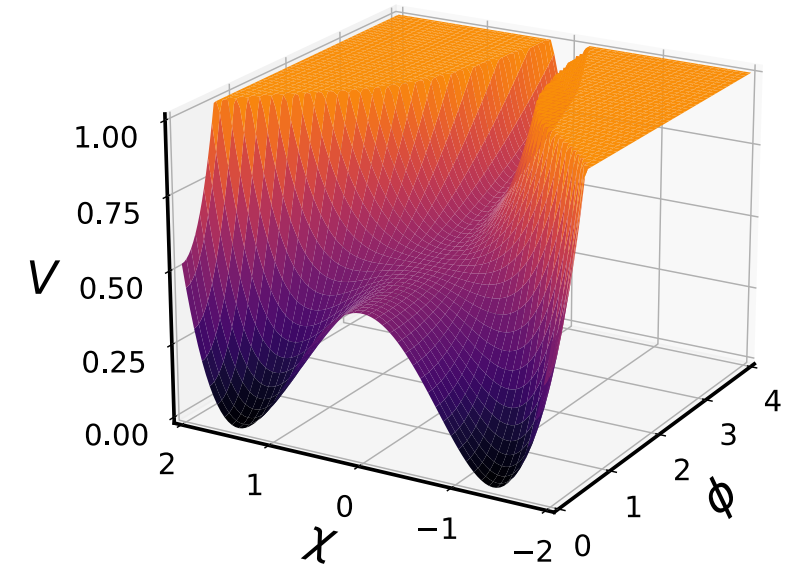
ϕ is dark energy and χ is dark matter

second
derivative

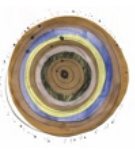
$$m_\chi^2 = g^2 \phi^2 - \lambda M^2 + 3\lambda \chi^2$$

$$m_\phi^2 = g^2 \chi^2 + \mu^2$$

Hybrid Inflation Potential



[CvB, GP, EMT: arxiv:2211.13653]



Effective Fluid Description

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

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

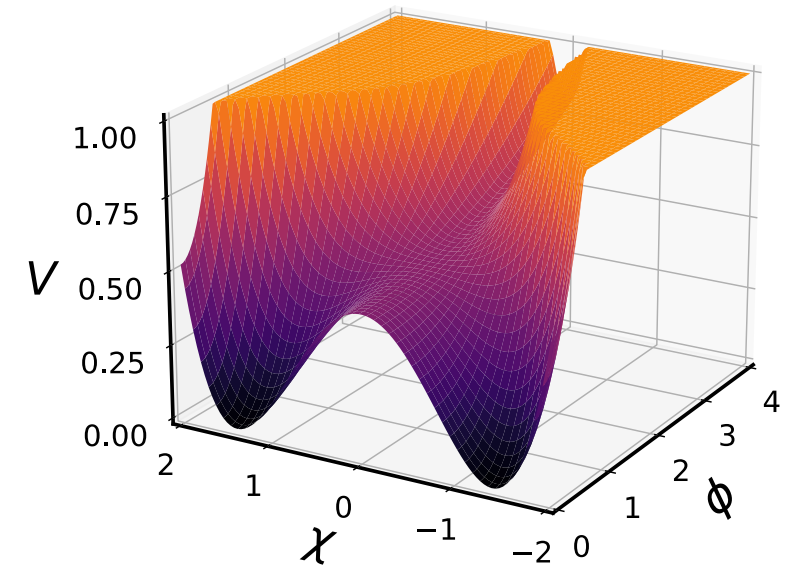
- Energy density of DM field:

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

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

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

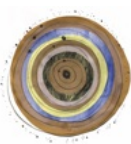
Hybrid Inflation Potential



For ϕ to act as DE we need

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

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



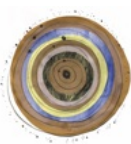
Effective Fluid

Coupled quintessence model with a fluid description DM field χ

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

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

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



Effective Fluid

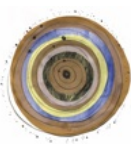
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- Continuity equation for **interacting fluid**
- Theory is equivalent to a model with conformal coupling $C(\phi) = \phi^2/M_{\text{Pl}}^2$

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



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- Continuity equation for **interacting fluid**
- Theory is equivalent to a model with conformal coupling $C(\phi) = \phi^2/M_{\text{Pl}}^2$
- In the **MDE** ϕ scales with DM - only IDE theory with a constant potential with this feature

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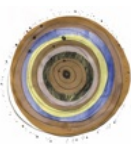
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MDE

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

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

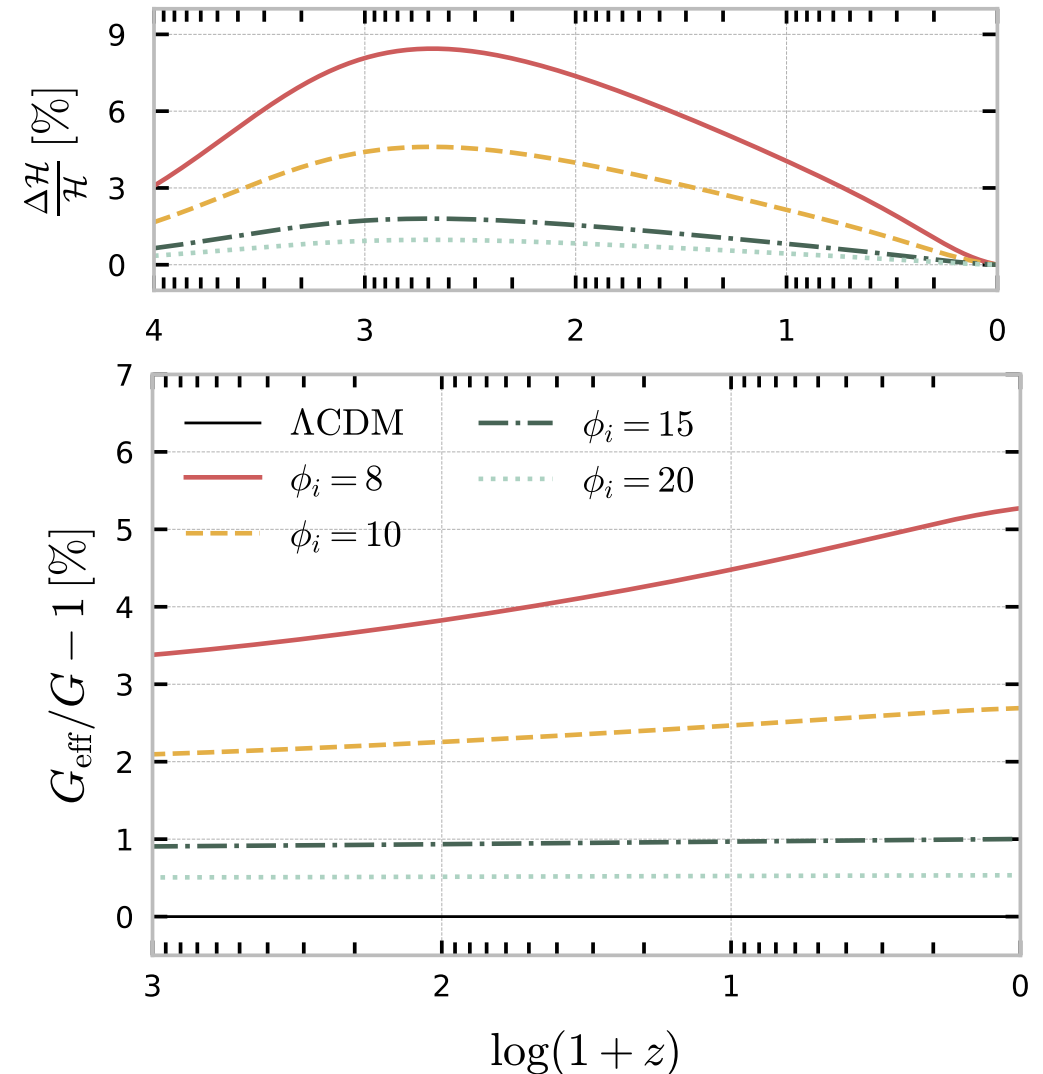


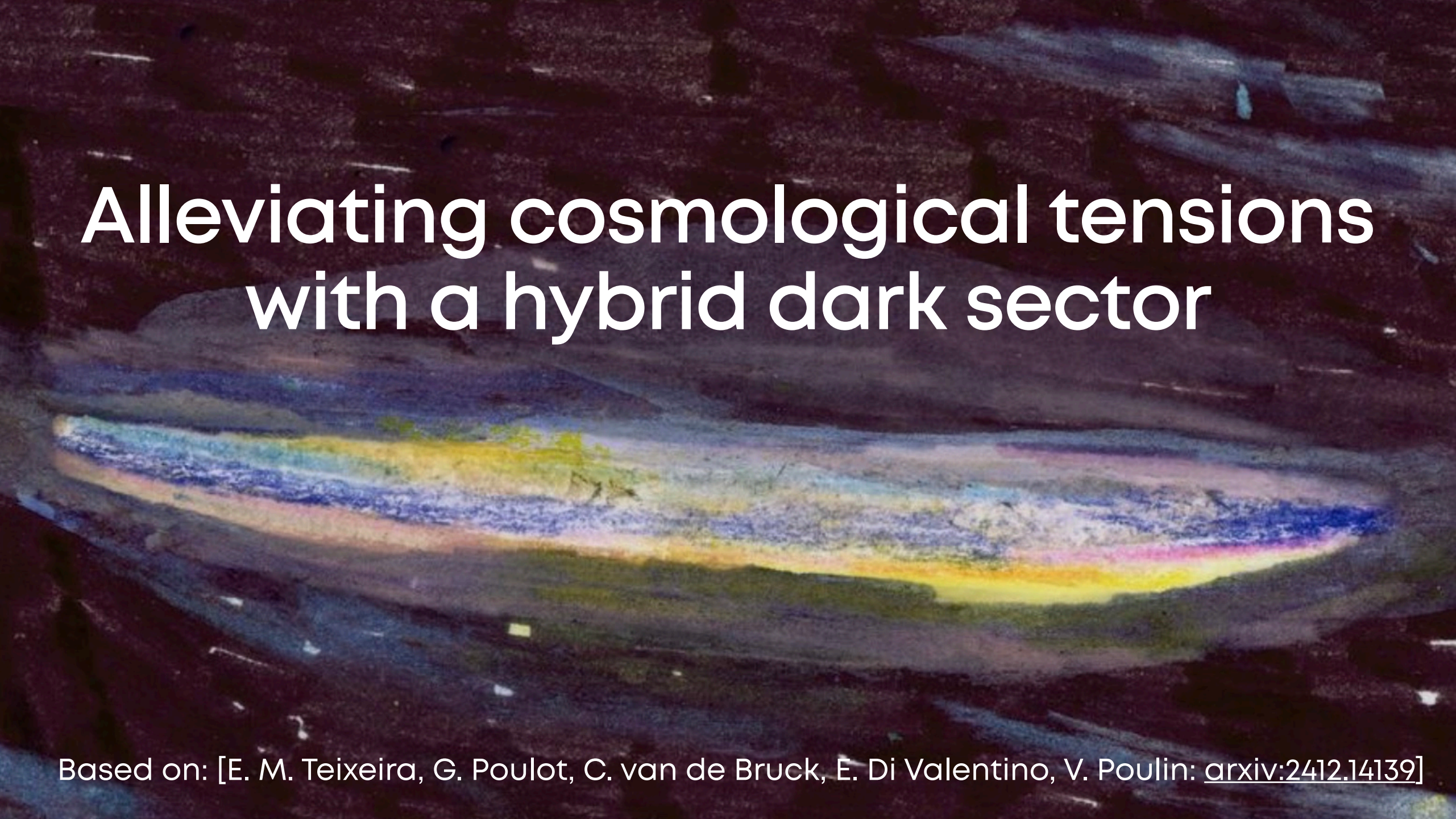
Modified Dynamics

- 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

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

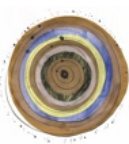
$$Q = -\frac{\rho_\chi}{\phi}$$





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](https://arxiv.org/abs/2412.14139)]



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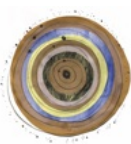
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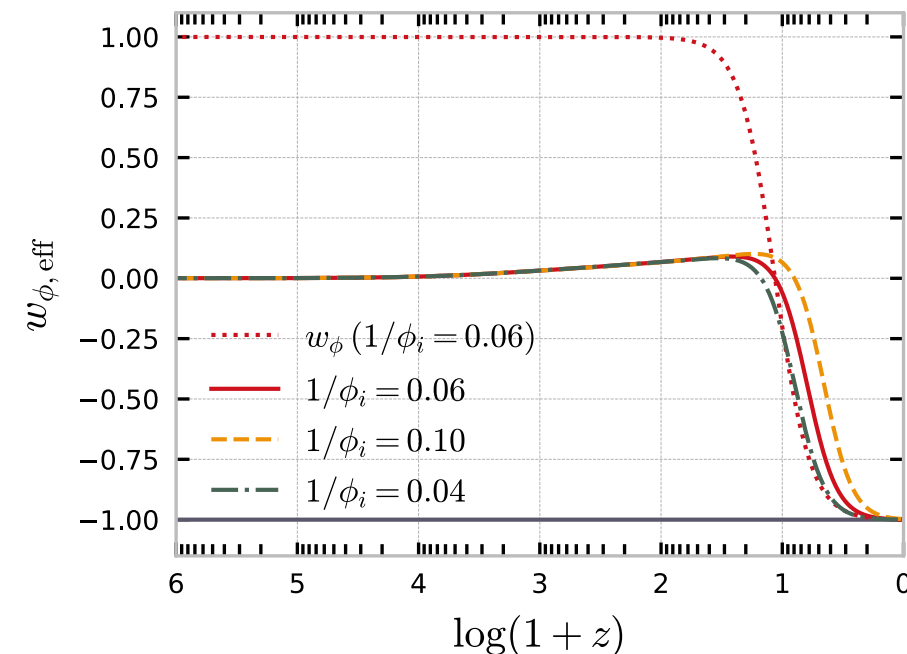
Effective Dynamics

- In practice we have a “Type-1” **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 Λ CDM ($1/\phi_i \rightarrow 0$)
- DM contribution from the coupling - a fraction of the DM energy density becomes DE at late times

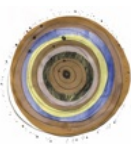
$$\dot{\rho}_c + 3H\rho_c = \frac{\dot{\phi}}{\phi}\rho_c$$

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



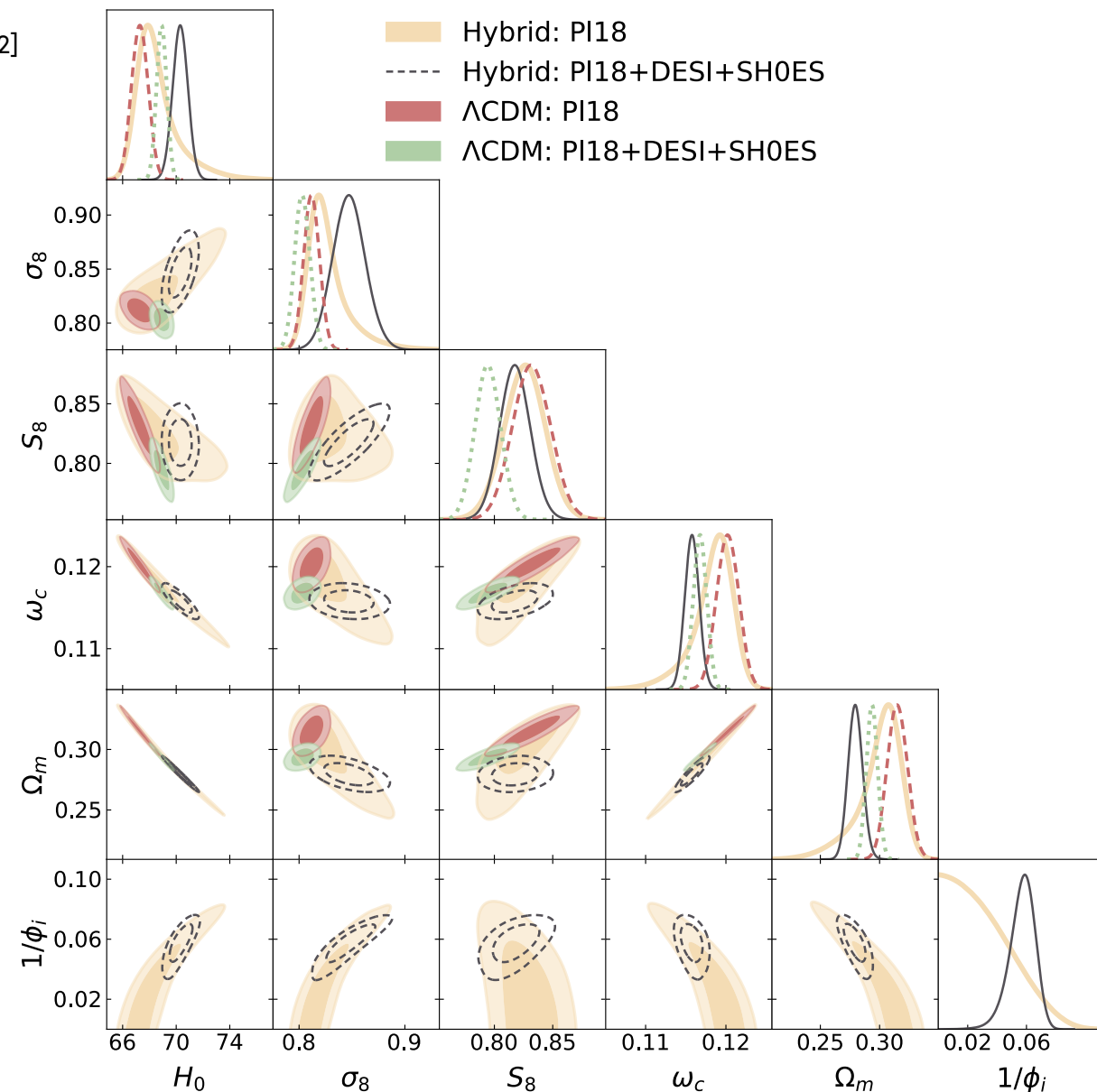
[EMT, GP, CvB, EDV, VP: arxiv:2412.14139]

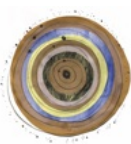


Results

[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]

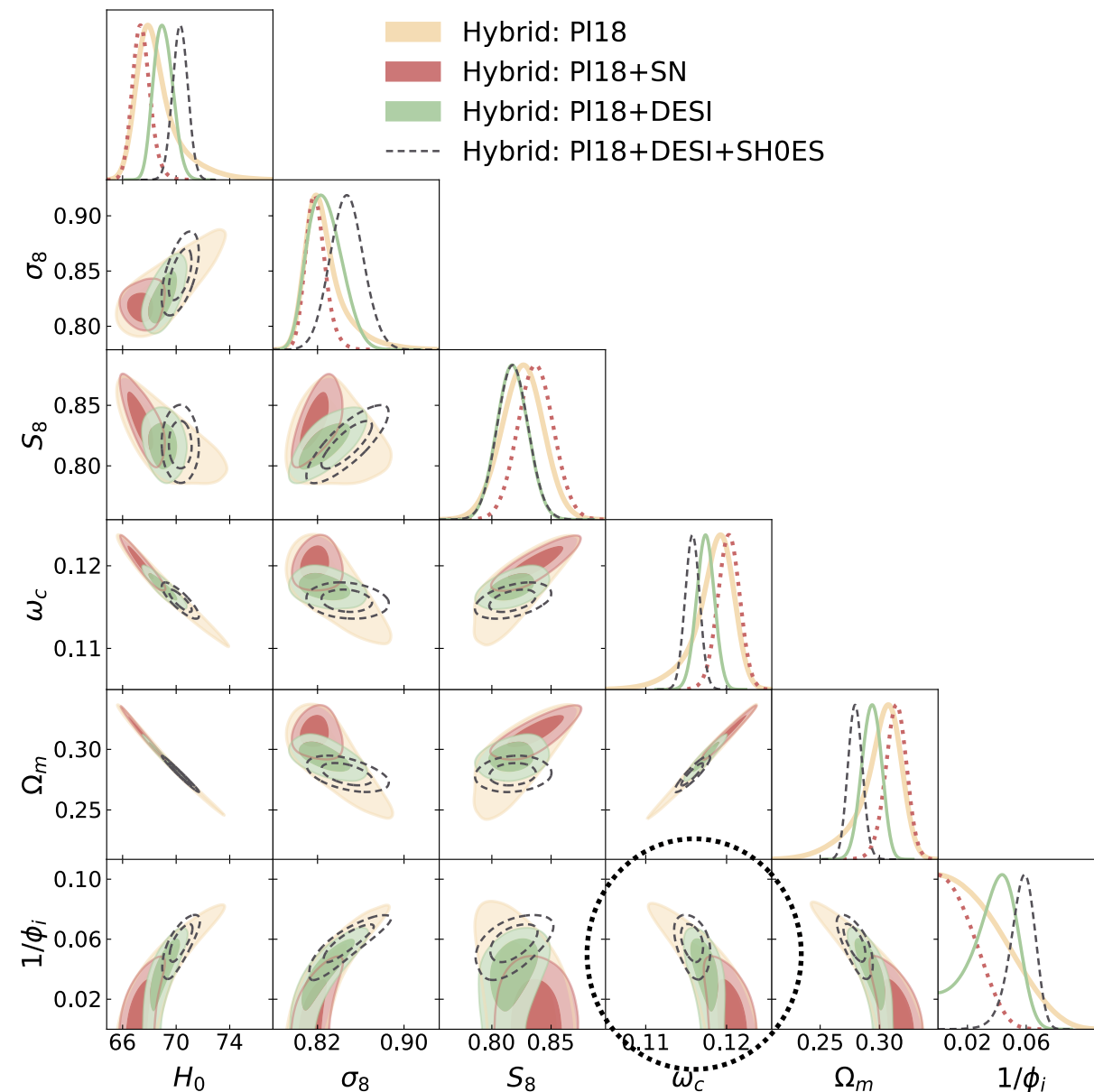
- Constraints with Planck (Pl18) are very similar to the Λ CDM case but with enlarged errors
- Positive correlation between the coupling ($1/\phi_i$) and H_0 and negative correlation with $S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$ - **alleviate cosmic tensions**
- Detection of the coupling parameter** with 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 Λ CDM (slight disagreement with Pl18) [EMT, GP, CvB, EDV, VP: arxiv:2412.14139]

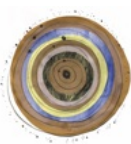




Results

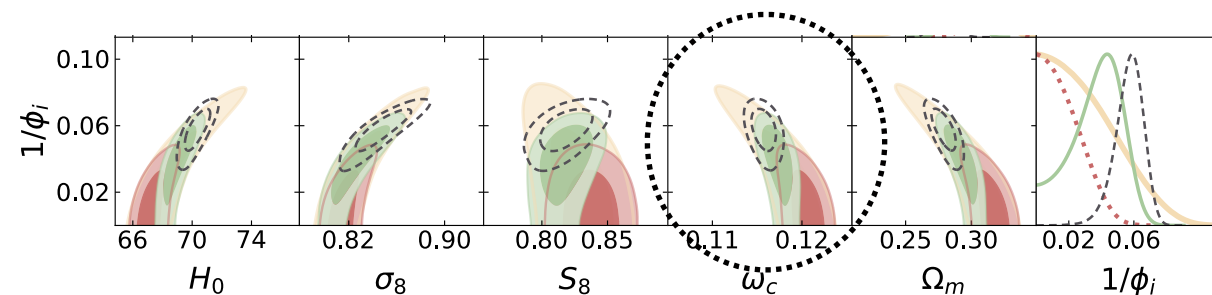
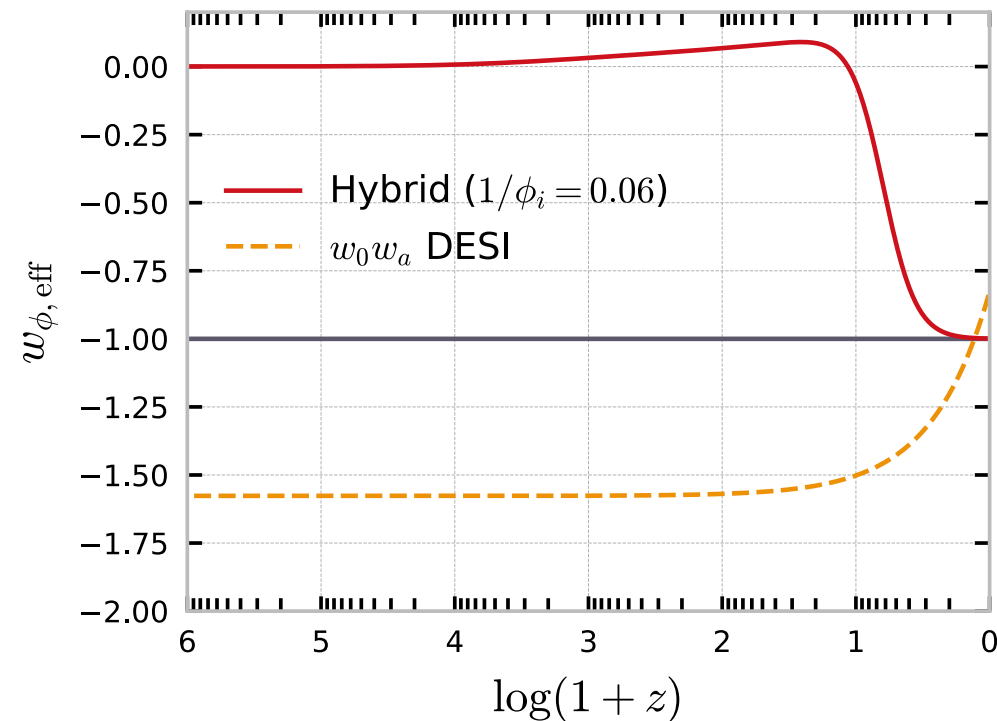
- DM component decays faster than in Λ CDM due to scaling behaviour of DE and coupling
- Initially the matter density is slightly larger than in Λ CDM and smaller at present, decreasing ω_c
- The additional contribution to ρ_c coming from coupling/effective fluid is favoured with DESI ($\Delta\chi^2_{\min} = 0.14 \rightarrow -2.8$)

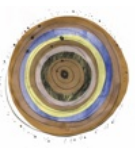




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- The additional contribution to ρ_c coming from coupling/effective fluid is favoured with DESI ($\Delta\chi^2_{\min} = 0.14 \rightarrow -2.8$)
- DESI found preference for phantom DE over Λ CDM
- Instead we have a coupled dark sector with a non-vanishing detection of $1/\phi_i > 0$ and $w_{\phi,\text{eff}}$ never becomes phantom

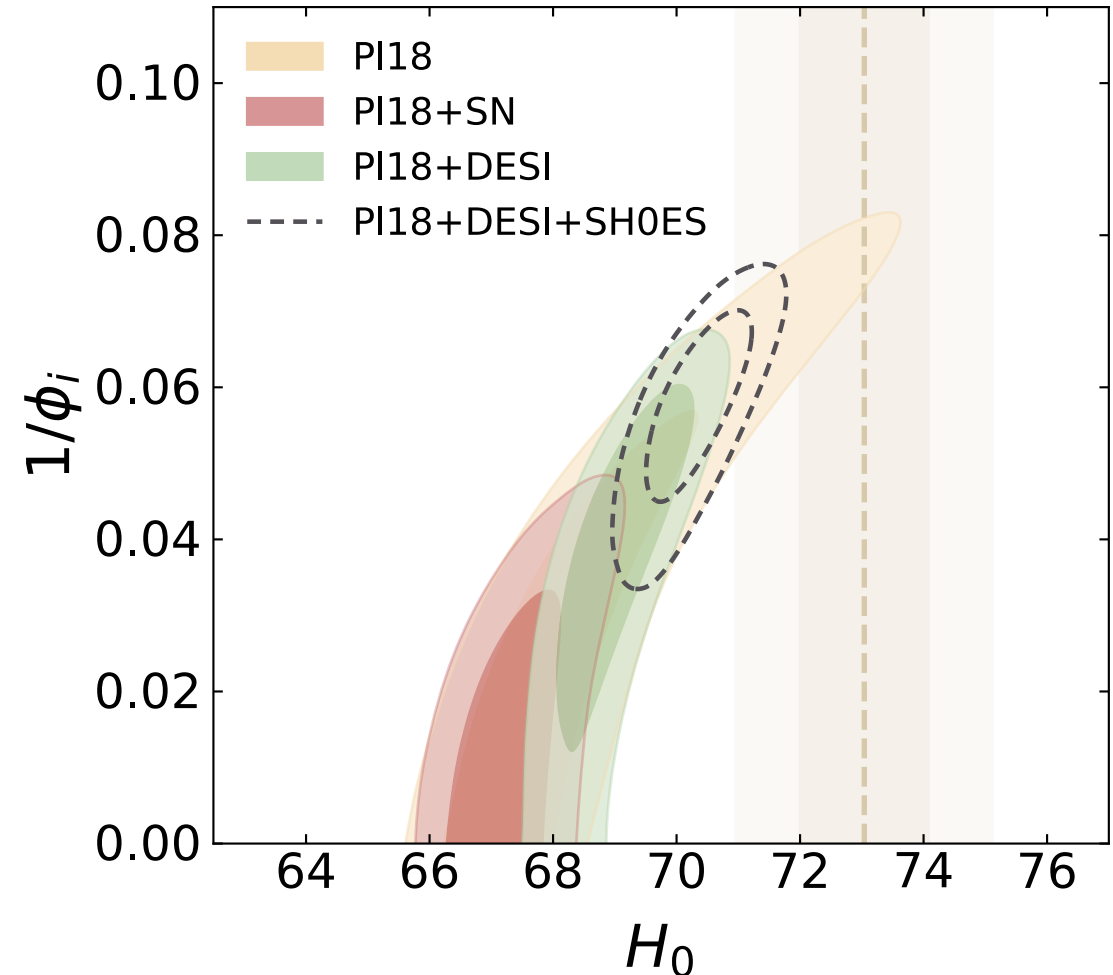




Results

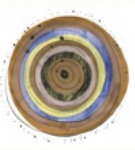
- Alleviate the H_0 tension by increasing the coupling
- More significance when imposing SH0ES calibration
- SH0ES calibration: increase in $\Delta\chi^2_{\min} = 0.08 \rightarrow -16.32$, for PI18+SH0ES, $\Delta\chi^2_{\min} = -1.06 \rightarrow -12.76$ for PI18+DESI+SH0ES
- Bayesian evidence indicates 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 PI18 and DESI (~4 in Hybrid vs ~6 in Λ CDM)

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



Summary and Conclusions





Conclusions

- Λ CDM model facing **challenges** with increasing precision
 - Incompatibility of **early- and late-Universe measurements**
 - Address the **H_0 tension** for expansion history
 - **Extended models** make predictions that can be tested
 - **Coupled dark sector** models are natural extension of Λ CDM
-
- 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, ω_c that **alleviate cosmic tensions** but cannot solve them



Thank you for your attention!

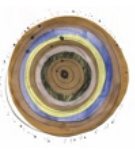
ELSA M. TEIXEIRA

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Illustrations: Inês Viegas Oliveira
(ivoliveira.com)

Cosmological Tensions

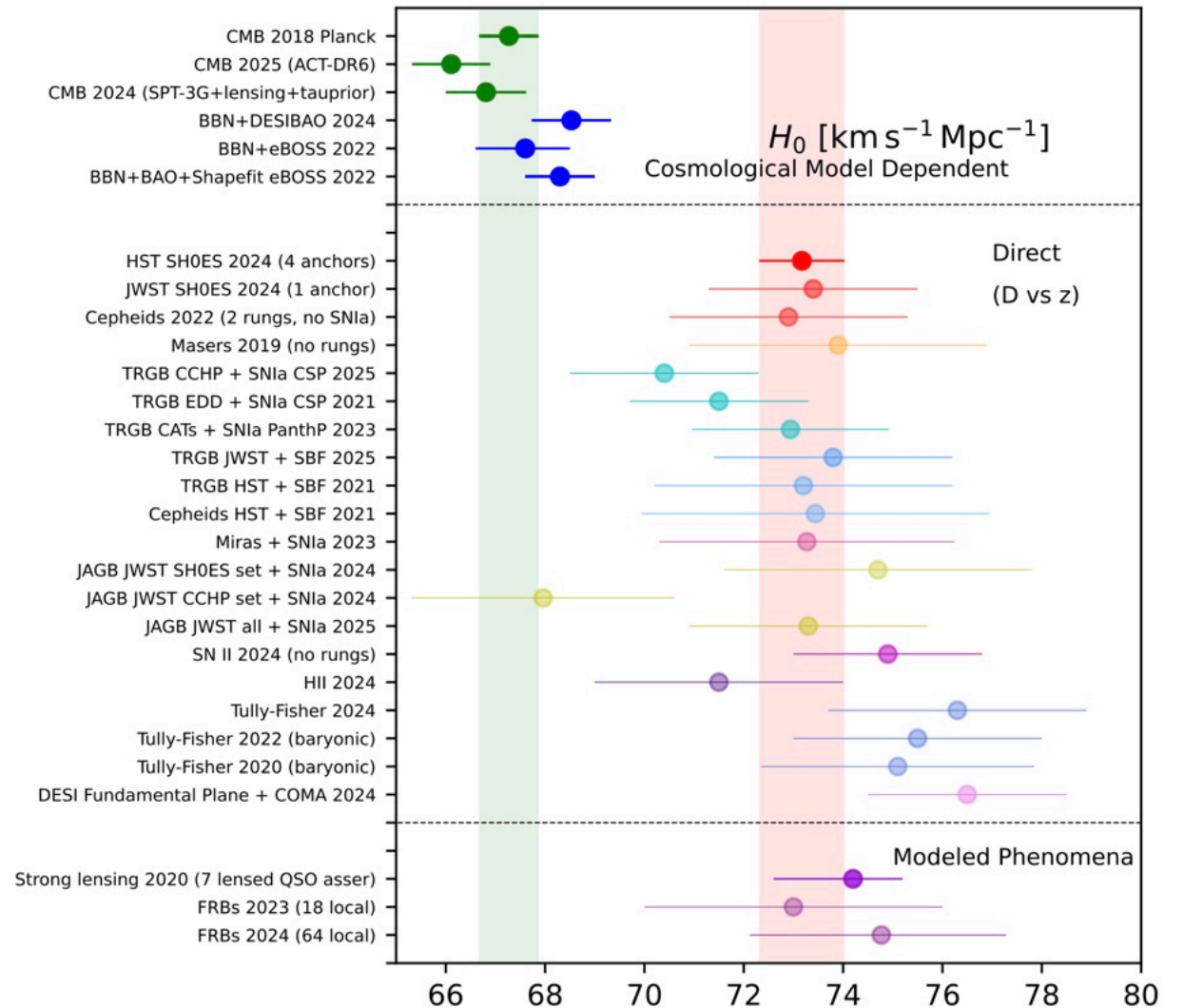
The background of the slide is a dark, textured surface, possibly a rock face or a cosmic scene. A prominent, horizontal band of light and color stretches across the middle. This band is composed of various shades of blue, green, yellow, and pink, creating a vibrant, multi-colored effect. The overall composition suggests a deep, mysterious, and perhaps geological or cosmic theme, which aligns with the title 'Cosmological Tensions'.

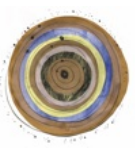


The Hubble Tension

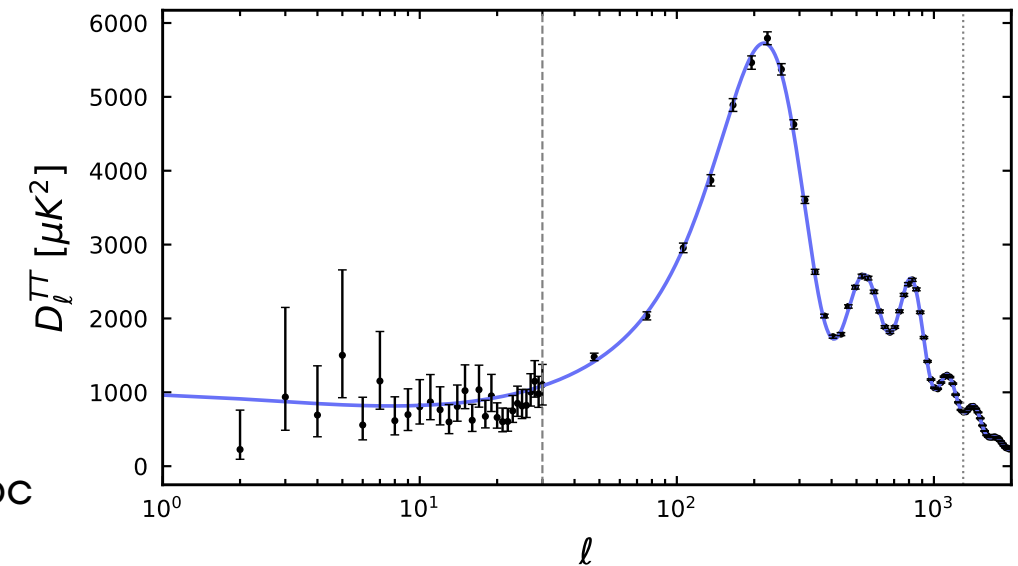
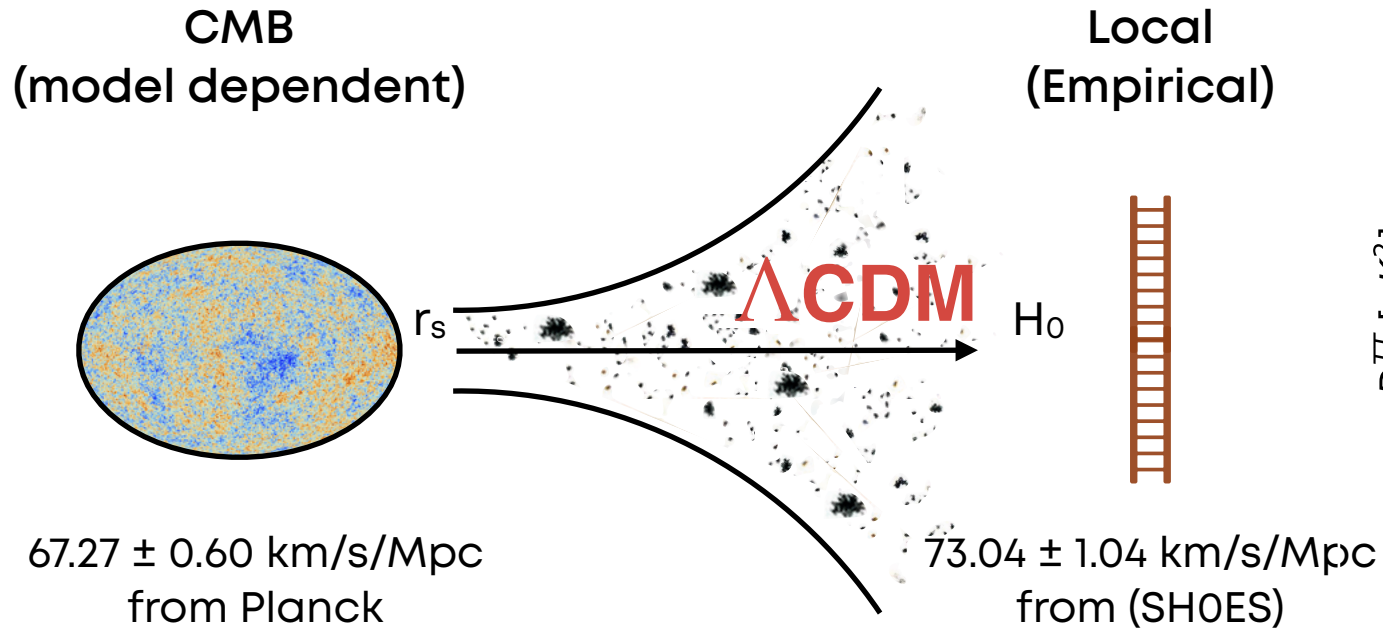
Unreconcilable values for H_0 from the CMB and from direct local distance ladder measurements

- $\sim 5\sigma$ tension between Planck 2018 and SH₀ES:
 - ▶ **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 Λ CDM model



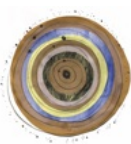


The Hubble tension



But how do we measure H_0 ?

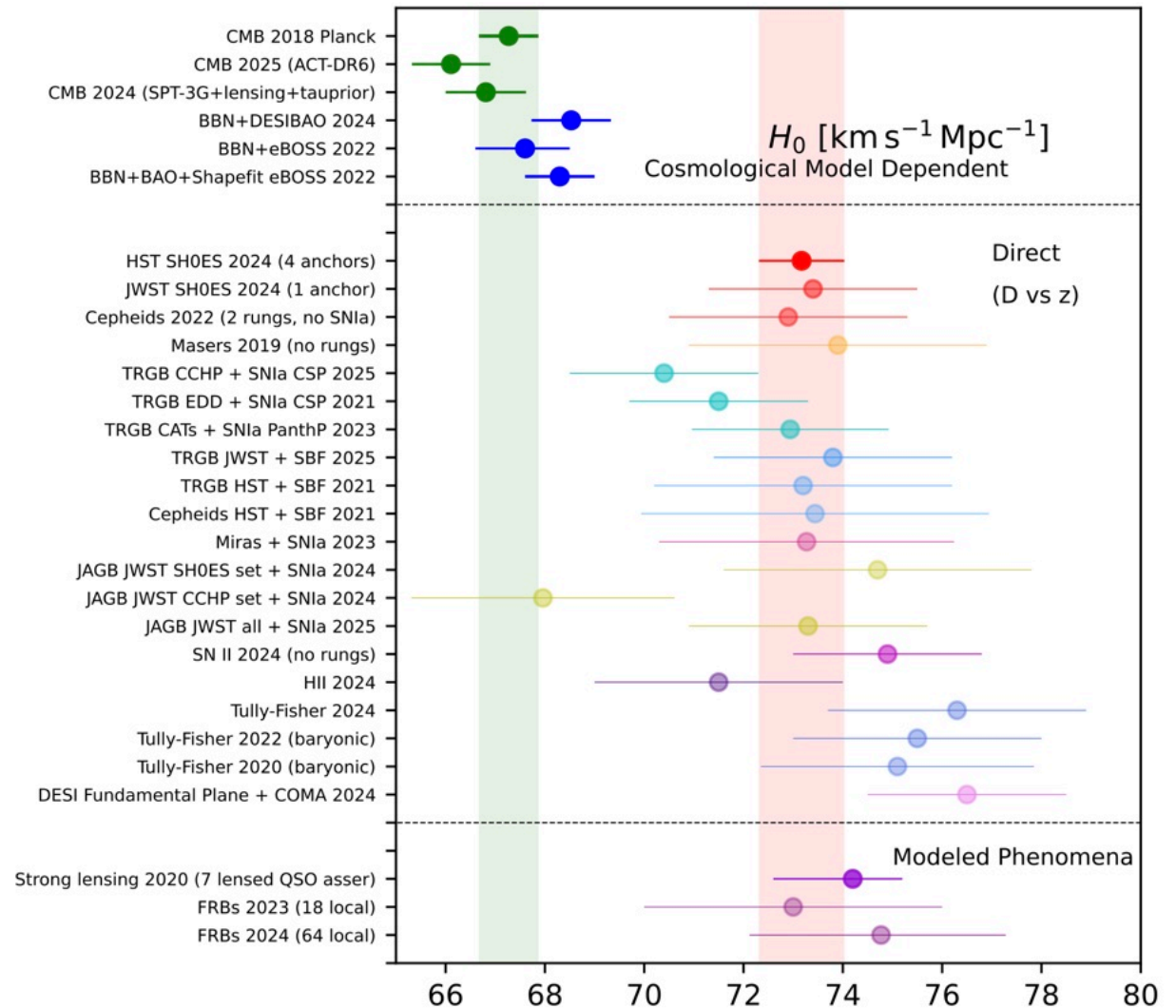
[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

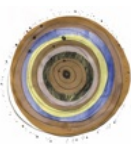


The Hubble Tension

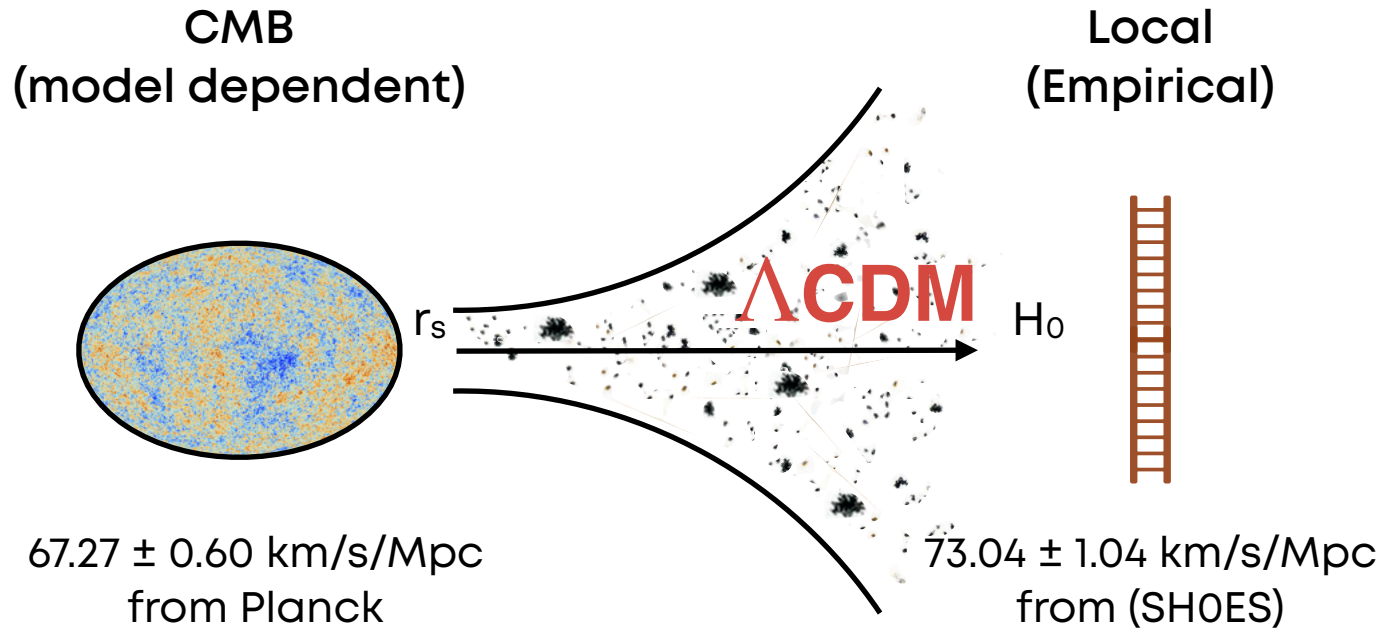
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- **DESI BAO (+BBN+CMB):** $H_0 = 68.45 \pm 0.47$ km/s/Mpc [DESI Collaboration DR2 2025: arXiv:2503.14738]
- Compilation of model-dependent data vs direct measurements that disagree
- Could signal differences in the expansion history (nature of the dark sector)



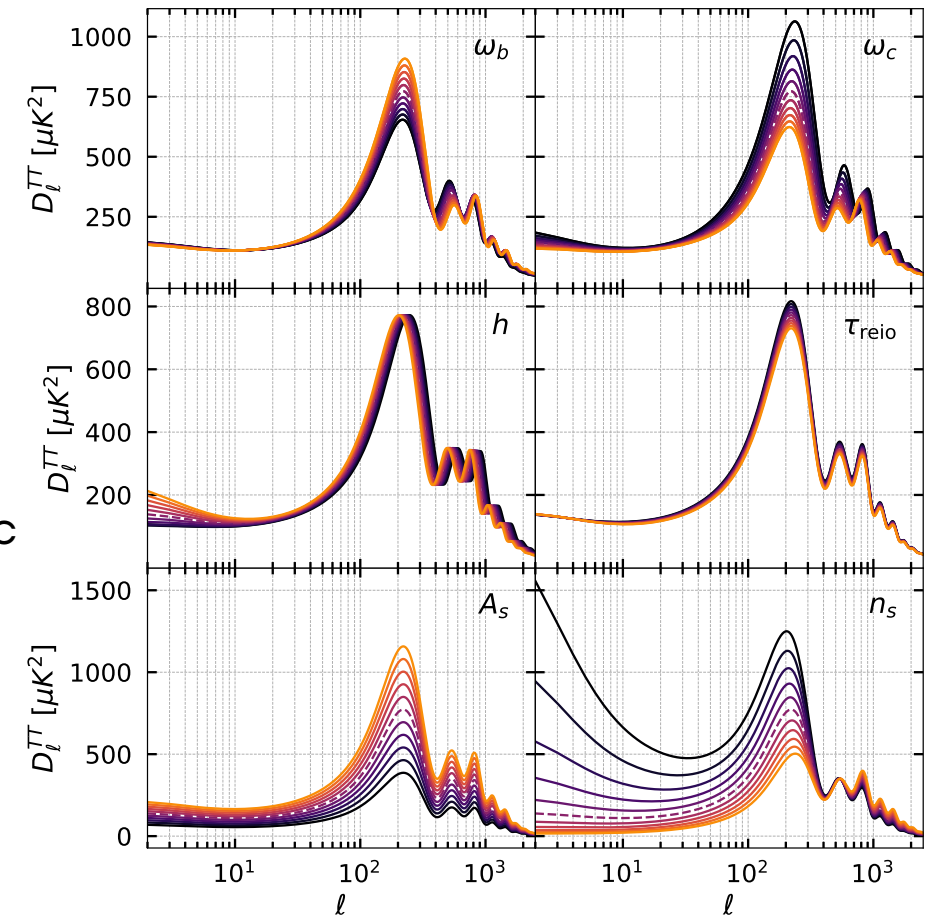


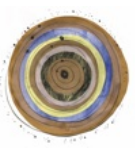
The Hubble Tension



$$H^2(z) = H_0^2 [\Omega_m(1+z)^3 + \Omega_\Lambda]$$

Missing Ingredients or New Physics?





Cosmic Discordances

Precision cosmology has revealed incompatibilities in Λ CDM:

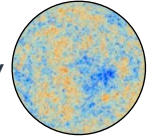
- Cosmic dipole anomaly? The universe is not isotropic? [Colin++ 1703.09376, 1808.04597, Secrest++ 2009.14826, Alari++ 2207.05765, Guandalin++ 2212.04925]
- Cosmic void? The universe is not locally homogeneous? [Wu&Huterer 1706.09723, Kenworthy++ 1901.08681, Cai++ 2012.08292, Camarena++ 2205.05422]
- Tensions in cosmological parameters like H_0 ? [Abdalla++ 2203.06142]
- Anomalies in Planck and ACT? Evidence for a curved universe? [Di Valentino++ 1911.02087, Calderón++ 2302.14300]
- Hints of phantom dynamical dark energy? [Union3 2311.12098, DES 2401.02929, DESI 2404.03002]
- (Too) High redshift galaxies with JWST? [Labbé++ 2207.12446, Boylan-Kolchin 2208.01611]

Are these the first signs of the nature of the break down of Λ CDM's simplified assumptions?

INFLATION

INFLATON

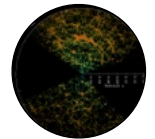
Early accelerated expansion produce density fluctuations



COSMIC STRUCTURE

CDM

Clustering matter component for structure formation

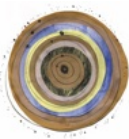


LATE ACCELERATION

Λ

Component to explain current accelerated expansion





Conformal Transformation

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

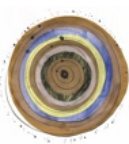
Disformal Transformation

- Distortion of both angles and lengths related with the gradient of ϕ
- The most general covariant effective metric tensor and a set of equations
- The form of the Einstein-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]

Non-Universal Coupling in the Dark Sector



Bayesian Parameter Inference

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

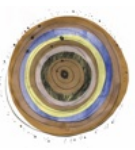
$$p(\theta | d) = \frac{p(d | \theta) p(\theta)}{p(d)} \Leftrightarrow \text{Posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

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]





Effective Fluid Description

- For χ to act as DM, we need its mass to be sufficiently large (prevent damping of oscillations, quadratic term in potential)
- χ is oscillating in a quadratic potential $\rightarrow$ WKB approximation ($g\phi \gg H$ and $\dot{\phi}/\phi \ll 1$):

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

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

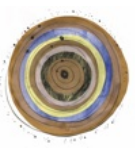
Oscillating DM field and slow-rolling DE field

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

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

Field oscillates 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 ($\phi \gg M_{\text{Pl}}$)

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

1.

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

2.

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

3.

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

4.

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

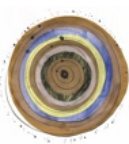
5.

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

6.

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

7.



Hybrid Model

In FLRW the equations of motion for each field are:

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

χ oscillates around 0 and m_χ
changes sign at critical ϕ

Potential acts as an effective interaction between the fields

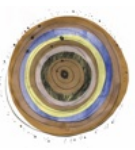
$$\ddot{\phi} + 3H\dot{\phi} = -(g^2\chi^2 + \mu^2)\phi$$

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

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

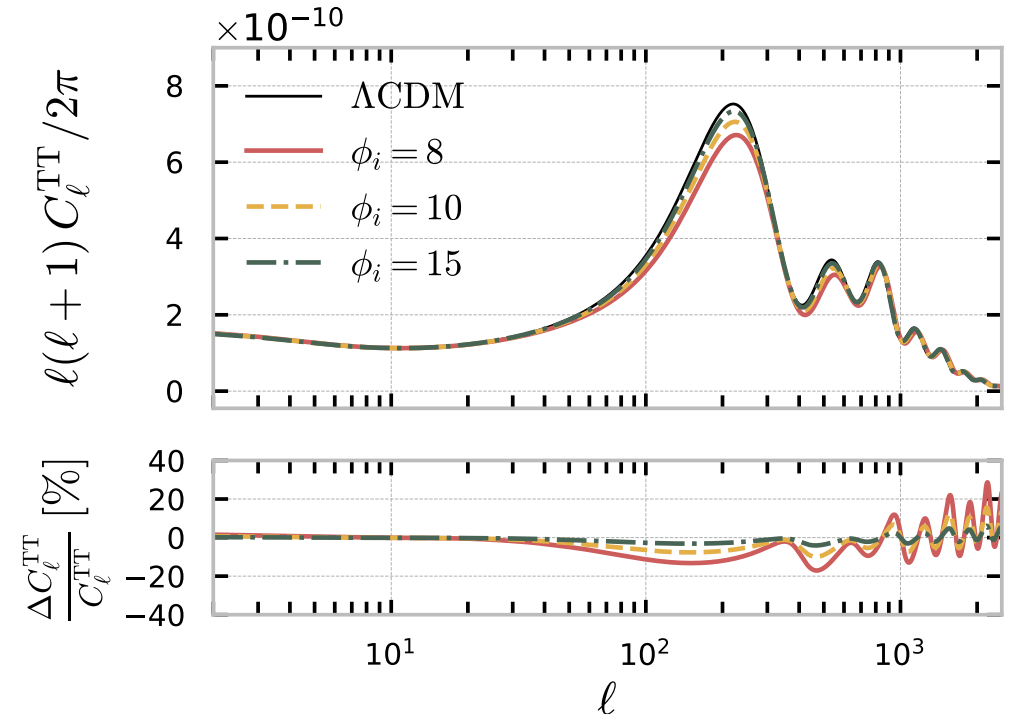
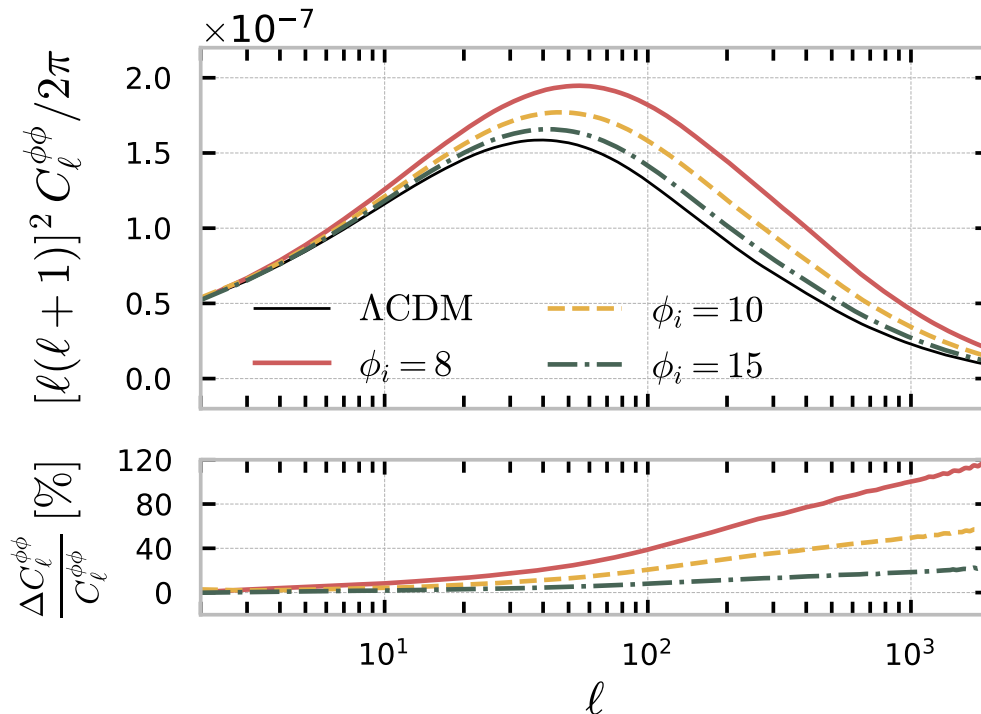
$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_0 + \frac{\mu^2\phi^2}{2}$$

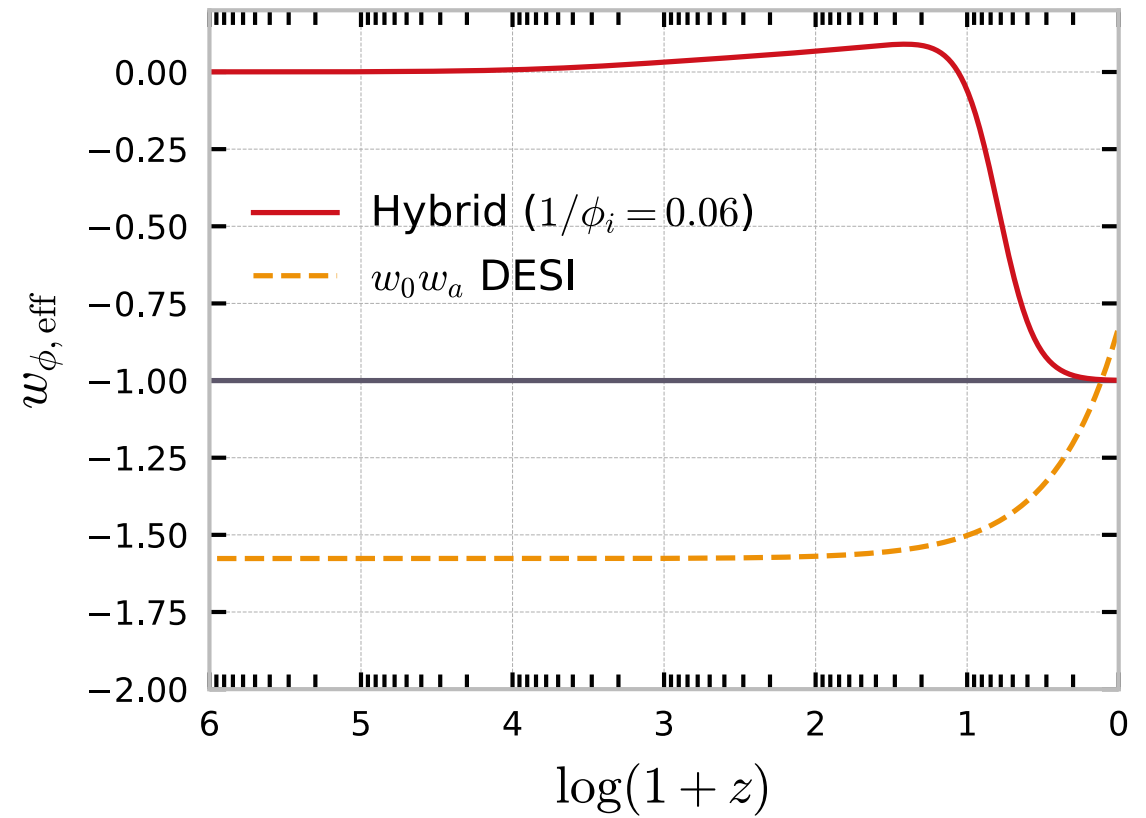
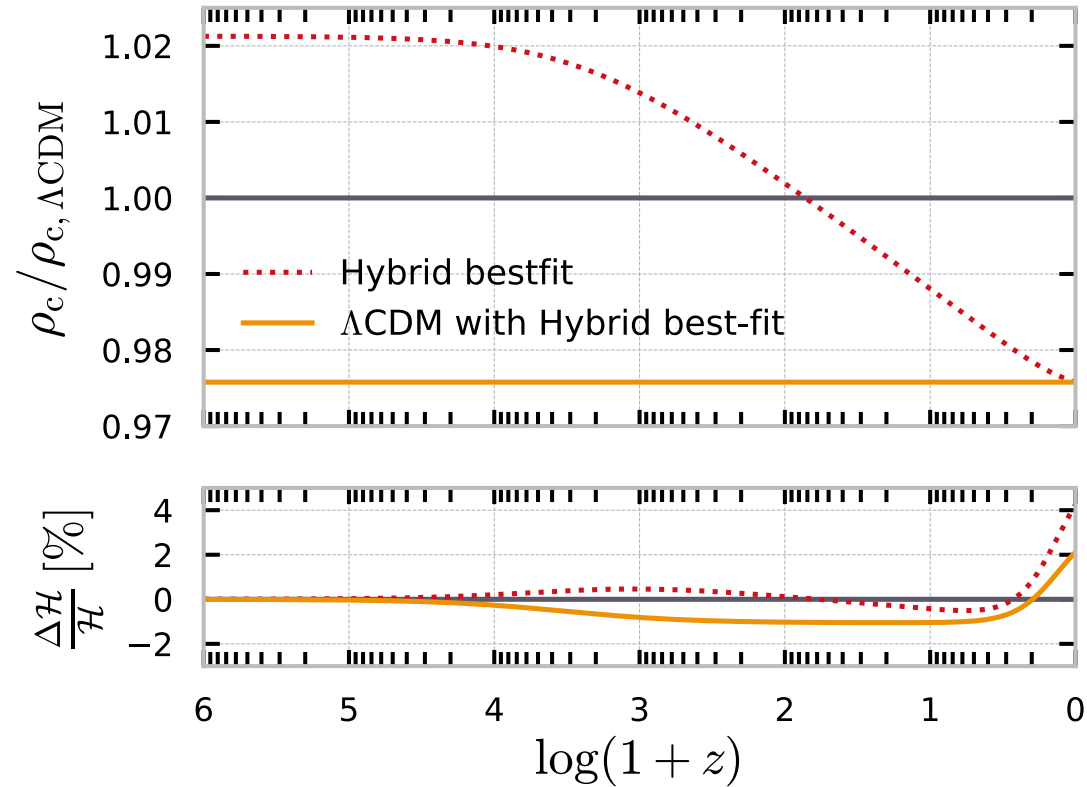
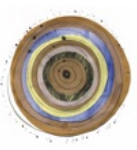
- When $\phi > \phi_c$, χ acts as dark matter
- ϕ slowly rolls down the potential, primarily due to V_0 and the interaction with χ
- As $\phi \rightarrow \phi_c$, χ drops abruptly and starts oscillating around $\chi = \pm M$
- $V(\phi, \chi) \rightarrow 0$ signalling a rapid decay of dark energy $\rightarrow$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

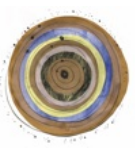


Angular Spectra

- 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



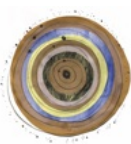




Data Sets

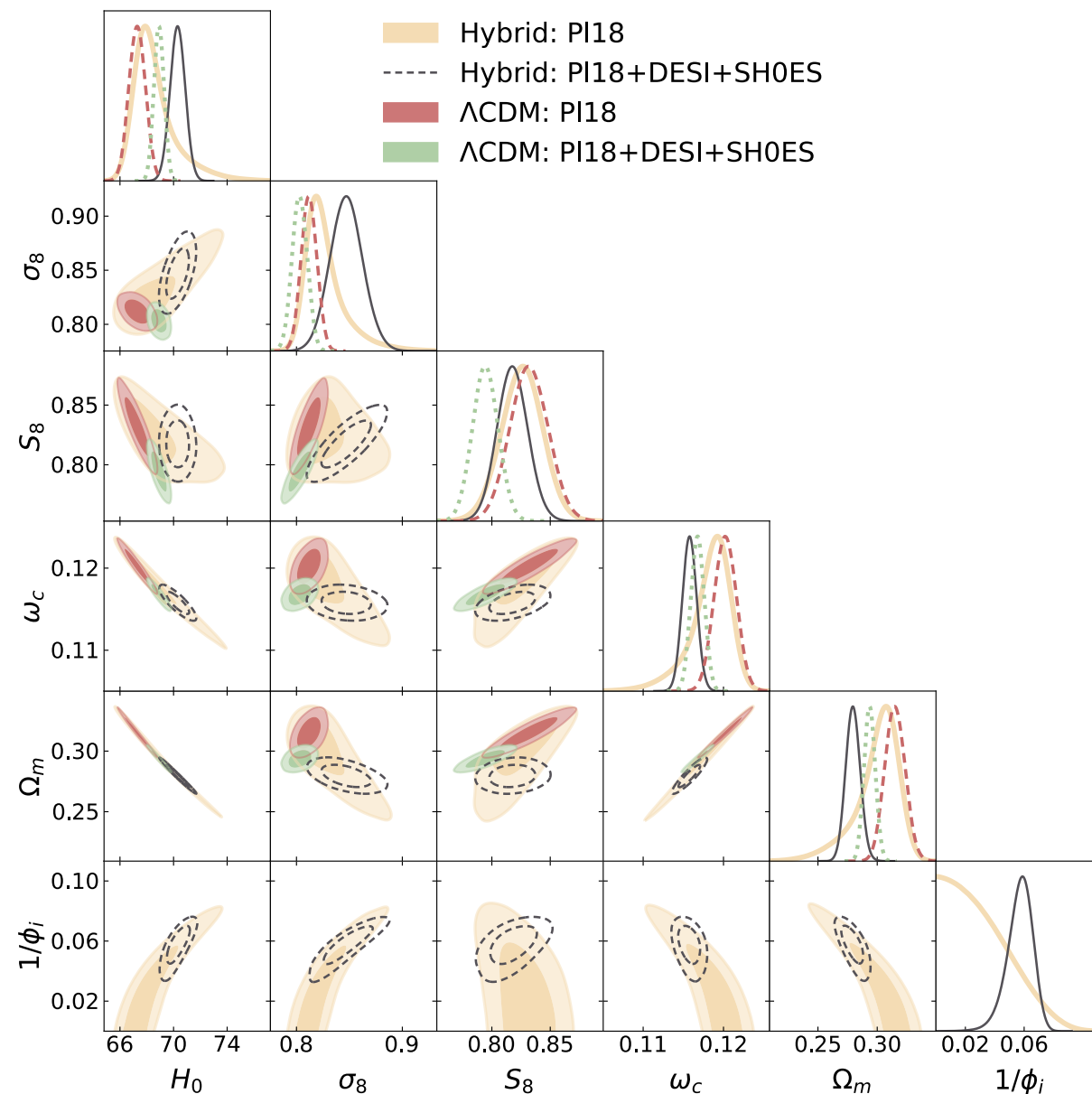
- Baseline data set is “**PI18**”: CMB Planck 2018 data for large angular scales $\ell = [2, 29]$ and a joint of TT, TE and EE likelihoods for the small angular scales [Aghanim et al.: Astron.Astrophys. 641 (2020) A5]
- “**PI18+DESI+SN**”: “PI18” plus compilation of baryon acoustic oscillations (BAO) 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]
- “**PI18+DESI+SN+H0**”: “PI18+DESI+SN” plus prior on magnitude M_b from SH0ES [Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]





Cosmological Constraints

- Constraints with Planck (Pl18) are very similar to the Λ CDM 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 Λ CDM (slight disagreement with Pl18)



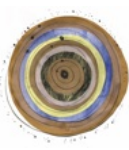


Table of constraints at a 68% confidence level

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
$\Delta\chi^2_{\text{min}}$	0.14	0.08	-16.32	-2.8	-1.06	-12.76
$\log B_{\text{M},\Lambda\text{CDM}}$	-3.3	-3.6	4.5	-2.0	-2.8	2.5
$Q_{\text{DMAP}}^{\text{SH0ES}}$	--	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. $\Delta\chi^2_{\text{min}}$ represents the difference in the best-fit χ^2 of the profile likelihood global minimisation, and $\log B_{\text{M},\Lambda\text{CDM}}$ indicates the ratio of the Bayesian evidence, both computed with respect to ΛCDM . The value of $Q_{\text{DMAP}}^{\text{SH0ES}}$ is calculated according to Eq. (14). For reference, the same results for ΛCDM are given in Table III of Appendix A.

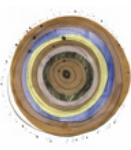


Table of constraints at a 68% confidence level

Parameter	P118	P118+SN	P118+SH0ES	P118+DESI	P118+DESI+SN	P118+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
$Q_{\text{DMAP}}^{\text{SH0ES}}$	--	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 Λ CDM model, as detailed in Section III A. The value of $Q_{\text{DMAP}}^{\text{SH0ES}}$ is calculated according to Eq. (14).