# Viable interactions in the dark sector

Erik Jensko

**PASCOS 2026**

**31st International Symposium on Particles, Strings, and Cosmology**

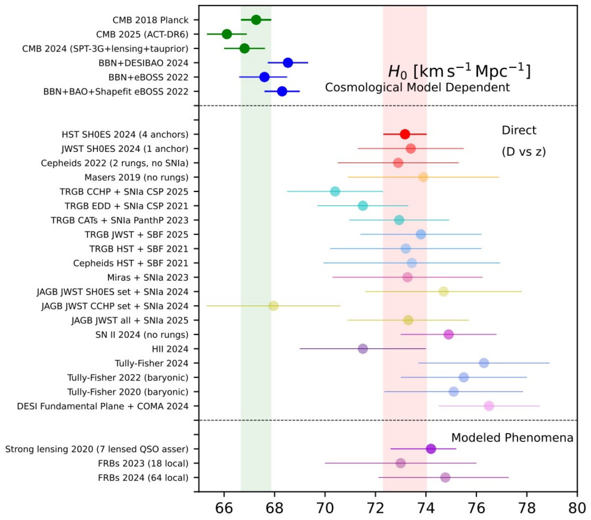
**June 26th 2026**

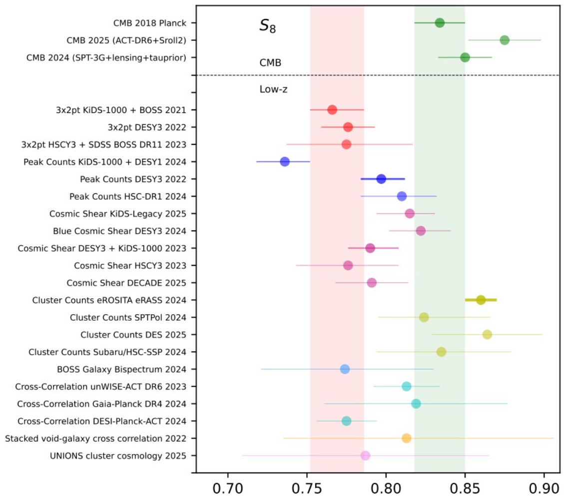
Image credit: ESA and the Planck Collaboration

# Introduction

## Challenges to $\Lambda$CDM

- Unknown nature of dark matter and dark energy
- Tensions & discrepancies in cosmology

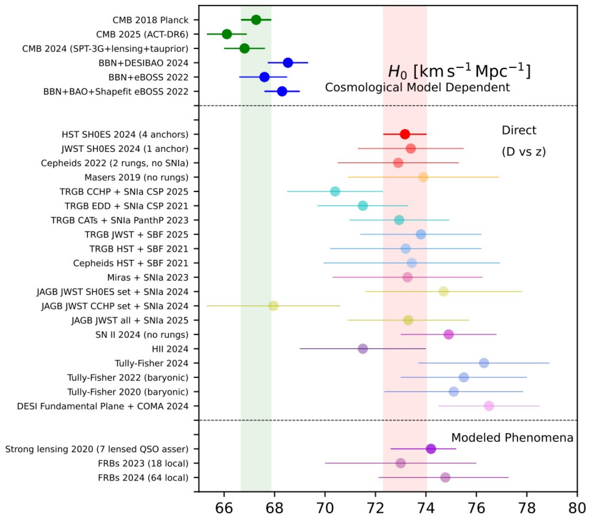


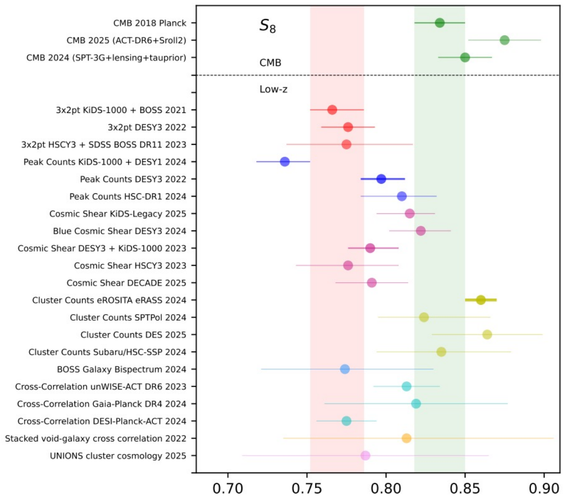




CosmoVerse White Paper [arXiv:2504.01669]

## Challenges to $\Lambda$CDM

- Unknown nature of dark matter and dark energy
- Tensions & discrepancies in cosmology




CosmoVerse White Paper [arXiv:2504.01669]

## Dark sector interactions

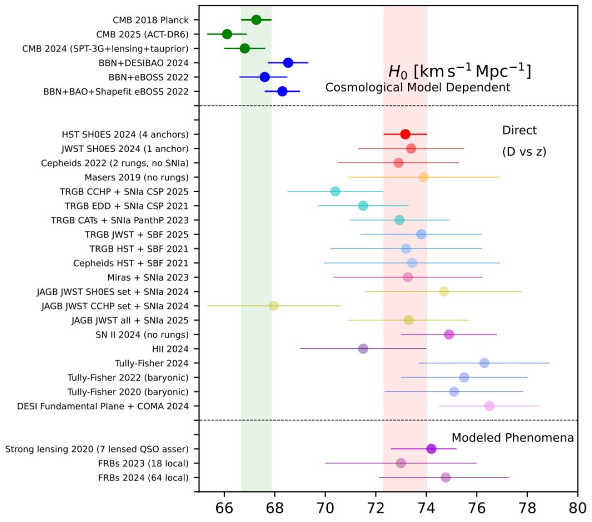
- **Interactions** in the dark sector explored as possible modifications to $\Lambda$CDM

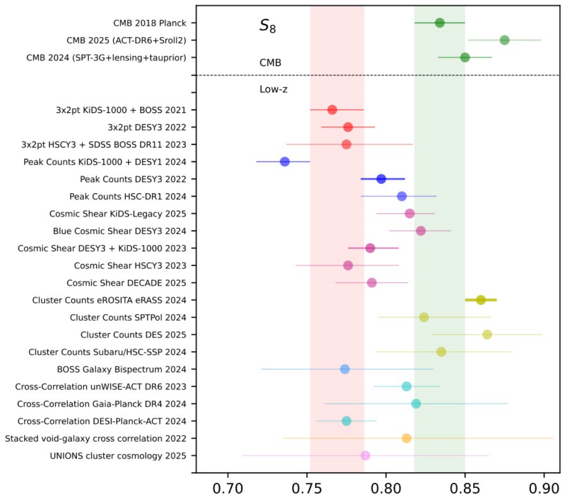
$$\dot{\rho}_c + 3H(\rho_c + p_c) = Q$$
$$\dot{\rho}_{DE} + 3H(\rho_{DE} + p_{DE}) = -Q$$

# Introduction

## Challenges to $\Lambda$CDM

- Unknown nature of dark matter and dark energy
- Tensions & discrepancies in cosmology




CosmoVerse White Paper [arXiv:2504.01669]

## Dark sector interactions

- **Interactions** in the dark sector explored as possible modifications to $\Lambda$CDM

$$\dot{\rho}_c + 3H(\rho_c + p_c) = Q$$
$$\dot{\rho}_{DE} + 3H(\rho_{DE} + p_{DE}) = -Q$$

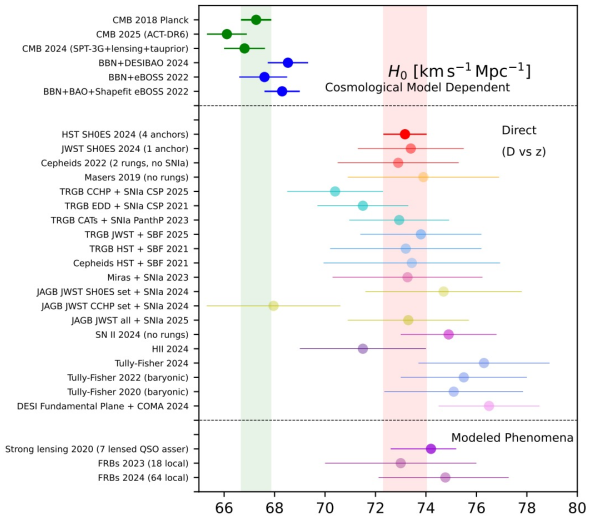
Problems:

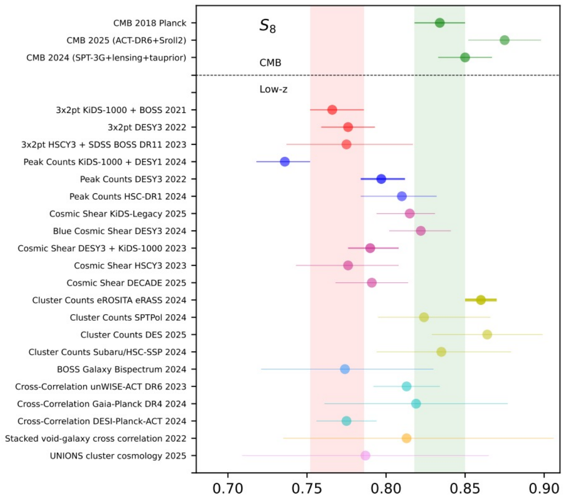
- Limited Lagrangian descriptions
- Phenomenological models prone to instabilities
- Interactions heavily constrained by background & CMB observations

# Introduction

## Challenges to $\Lambda$CDM

- Unknown nature of dark matter and dark energy
- Tensions & discrepancies in cosmology




`CosmoVerse White Paper [arXiv:2504.01669]`

## Dark sector interactions

- **Interactions** in the dark sector explored as possible modifications to $\Lambda$CDM

$$\dot{\rho}_c + 3H(\rho_c + p_c) = Q$$
$$\dot{\rho}_{DE} + 3H(\rho_{DE} + p_{DE}) = -Q$$

Problems:

- Limited Lagrangian descriptions
- Phenomenological models prone to instabilities
- Interactions heavily constrained by background & CMB observations

Construct **Lagrangian** models that modify **cosmological perturbations**

# Outline

## Part 1 – Theory

- Perfect fluid models & entropy
- Entropy coupled dark sector

## Part 2 – Cosmology

- Background & perturbations
- Observational signatures

# Perfect fluid action

Brown perfect fluid Lagrangian `Brown [arXiv:9304026]`

$$S_{\text{Brown}} = \int \sqrt{-g}\Big[-\rho(n,s) + \overbrace{n u^{\mu}(\partial_{\mu}\varphi + s\partial_{\mu}\Theta)}^{\text{constraints}}\Big] d^4x$$

Lagrange multipliers

### Dictionary

Fundamental d.o.f

- *number density* $n$
- *intrinsic entropy per particle* $s$

Thermodynamic variables

- *energy density* $\rho(n,s)$
- *pressure* $p(n,s) = n\frac{\partial\rho}{\partial n}\big|_s - \rho$

Perturbations

$$\delta p = c_a^2\delta\rho + \frac{\partial p}{\partial s}\bigg|_{\rho}\delta s$$

Brown perfect fluid Lagrangian `Brown [arXiv:9304026]`

$$S_{\text{Brown}} = \int \sqrt{-g}\Big[-\rho(n,s) + \overbrace{n u^{\mu}(\partial_{\mu}\varphi + s\partial_{\mu}\Theta)}^{\text{constraints}}\Big] d^4x$$

Lagrange multipliers

Variations produce perfect fluid $T_{\mu\nu}$ and fluid equation of motion

- Metric $g_{\mu\nu}$

$$\boxed{T_{\mu\nu} = (\rho + p)u_{\mu}u_{\nu} + p g_{\mu\nu}}$$

- Lagrange multipliers $\varphi$,$\Theta$

$$\boxed{\nabla_{\mu}(n u^{\mu}) = 0 \quad u^{\mu}\nabla_{\mu} s = 0}$$

- Fluid variables $n$, $s$

$$\boxed{\nabla_{\mu}T^{\mu\nu} = 0}$$

**Dictionary**

Fundamental d.o.f
- *number density* $n$
- *intrinsic entropy per particle* $s$

Thermodynamic variables
- *energy density* $\rho(n,s)$
- *pressure* $p(n,s) = n\frac{\partial\rho}{\partial n}|_s - \rho$

Perturbations

$$\delta p = c_a^2\delta\rho + \frac{\partial p}{\partial s}\bigg|_{\rho}\delta s$$

# Non-minimal couplings

Model interactions with non-minimal couplings to scalar field dark energy

$$\underbrace{}_{}S_{\mathrm{EH}} + \overbrace{S_{\mathrm{Brown}}}^{\textit{DM}} + \overbrace{S_{\phi}}^{\textit{DE}} + \overbrace{\int f(n, s, \phi, \ldots)\sqrt{-g}\,d^4x}^{\textit{Interactions}}$$

Modified EFE equations and matter energy-momentum conservation

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

$$\boxed{\nabla^{\mu}\left(T_{\mu\nu} + T_{\mu\nu}^{(\phi)} + T_{\mu\nu}^{\mathrm{int}}\right) = 0}$$

Number density & adiabatic constraints preserved

$$\boxed{\nabla_{\mu}(nu^{\mu}) = 0 \quad u^{\mu}\nabla_{\mu}s = 0} \Rightarrow \boxed{u^{\mu}\nabla^{\nu}T_{\mu\nu} = 0}$$

# Non-minimal couplings

Model interactions with non-minimal couplings to scalar field dark energy

$$S_{\rm EH} + \underbrace{S_{\rm Brown}}_{DM} + \underbrace{S_\phi}_{DE} + \underbrace{\int f(n, s, \phi, \dots)\sqrt{-g}\,d^4x}_{Interactions}$$

Modified EFE equations and matter energy-momentum conservation

$$\boxed{G_{\mu\nu} = \kappa\left(T_{\mu\nu} + T^{(\phi)}_{\mu\nu} + T^{\rm int}_{\mu\nu}\right)}$$

$$\boxed{\nabla^\mu\left(T_{\mu\nu} + T^{(\phi)}_{\mu\nu} + T^{\rm int}_{\mu\nu}\right) = 0}$$

Number density & adiabatic constraints preserved

$$\boxed{\nabla_\mu(nu^\mu) = 0 \quad u^\mu\nabla_\mu s = 0} \Rightarrow \boxed{u^\mu\nabla^\nu T_{\mu\nu} = 0}$$

Various models considered in the literature:

- *Algebraic* $f(n,\phi)$ and *derivative* $f(n)nu^\mu\nabla_\mu\phi$ Boehmer et al. [arXiv:1501.06540, arXiv:1502.04030]
- *Velocity-entrainment models* $f(\mathcal{Z})$ with $\mathcal{Z} = g_{\mu\nu}u^\mu_c u^\nu_{DE}$ Jiménez et al. [arXiv:2012.12204]
- *Type-1,2,3 models* $f(n,\phi,Z)$ with four-velocity coupling $Z = u^\mu\nabla_\mu\phi$ Pourtsidou et al. [arXiv:1307.0458]

Model interactions with non-minimal couplings to scalar field dark energy

$$\underbrace{S_{\mathrm{EH}} + S_{\mathrm{Brown}}}_{DM} + \underbrace{S_\phi}_{DE} + \underbrace{\int f(n, s, \phi, \ldots)\sqrt{-g}\, d^4x}_{Interactions}$$

Modified EFE equations and matter energy-momentum conservation

$$\boxed{G_{\mu\nu} = \kappa\left(T_{\mu\nu} + T^{(\phi)}_{\mu\nu} + T^{\mathrm{int}}_{\mu\nu}\right)}$$

$$\boxed{\nabla^\mu\left(T_{\mu\nu} + T^{(\phi)}_{\mu\nu} + T^{\mathrm{int}}_{\mu\nu}\right) = 0}$$

Number density & adiabatic constraints preserved

$$\boxed{\nabla_\mu(nu^\mu) = 0 \quad u^\mu\nabla_\mu s = 0} \Rightarrow \boxed{u^\mu\nabla^\nu T_{\mu\nu} = 0}$$

Various models considered in the literature:

- *Algebraic* $f(n, \phi)$ and *derivative* $f(n)nu^\mu\nabla_\mu\phi$ Boehmer et al. [arXiv:1501.06540, arXiv:1502.04030]
- *Velocity-entrainment models* $f(Z)$ with $Z = g_{\mu\nu}u^\mu_c u^\nu_{DE}$ Jiménez et al. [arXiv:2012.12204]
- *Type-1,2,3 models* $f(n, \phi, Z)$ with four-velocity coupling $Z = u^\mu\nabla_\mu\phi$ Pourtsidou et al. [arXiv:1307.0458]

No study of entropy couplings beyond background!

# Pure-entropy couplings

Consider **pure-entropy interactions** in the dark sector with *algebraic* and *derivative* couplings

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

# Pure-entropy couplings

Consider **pure-entropy interactions** in the dark sector with *algebraic* and *derivative* couplings

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

Interaction tensor

$$\boxed{T^{\text{int}}_{\mu\nu} = -g_{\mu\nu}f + 2f_{,\mathcal{S}}\nabla_{(\mu}\phi\nabla_{\nu)}s}$$

- Define total effective dark energy tensor $\tilde{T}^{\text{DE}}_{\mu\nu} \coloneqq T^{(\phi)}_{\mu\nu} + T^{\text{int}}_{\mu\nu}$

# Pure-entropy couplings

Consider **pure-entropy interactions** in the dark sector with *algebraic* and *derivative* couplings

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

Interaction tensor

$$\boxed{T^{\text{int}}_{\mu\nu} = -g_{\mu\nu} f + 2 f_{,\mathcal{S}} \nabla_{(\mu}\phi \nabla_{\nu)} s}$$

- Define total effective dark energy tensor $\tilde{T}^{\text{DE}}_{\mu\nu} := T^{(\phi)}_{\mu\nu} + T^{\text{int}}_{\mu\nu}$
- Perpendicular coupling current $\boxed{J_\nu := \nabla^\mu \tilde{T}^{\text{DE}}_{\mu\nu} = \nabla_\mu\left(f_{,\mathcal{S}} \nabla^\mu \phi\right)\nabla_\nu s - f_{,s} \nabla_\nu s}$
- Pure-momentum transfer $\boxed{u^\mu \nabla^\nu T_{\mu\nu} = 0 \quad , \quad h^\mu_\nu \nabla^\lambda T_{\mu\lambda} = -J_\nu \neq 0}$

No energy exchange in DM-rest frame

# Stability – algebraic couplings (ongoing work)

Quadratic action for the scalar cosmological perturbations for ***algebraic couplings*** $f(s, \phi)$

$$S_{\text{alg}} = \int dt\, d^3k \left( \dot{\vec{x}}^t \mathbf{K} \dot{\vec{x}} - \vec{x}^t \mathbf{V} \vec{x} - \overline{\vec{x}^t} \mathbf{B} \dot{\vec{x}}^t \right)$$

with $\vec{x} = (\delta\varphi_k, \delta\Theta_k, \delta\phi_k)$

# Stability – algebraic couplings (ongoing work)

Quadratic action for the scalar cosmological perturbations for ***algebraic couplings*** $f(s,\phi)$

$$S_{\rm alg} = \int dt\, d^3k \left( \dot{\vec{\chi}}^t \mathbf{K} \dot{\vec{\chi}} - \vec{\chi}^t \mathbf{V} \vec{\chi} - \overline{\vec{\chi}^t} \mathbf{B} \dot{\vec{\chi}}^t \right)$$

with $\vec{\chi} = (\delta\varphi_k, \delta\Theta_k, \delta\phi_k)$

In the large $k$-limit we recover standard sound speeds:

- Standard propagating fluid mode $\boxed{c_1^2 = \frac{n\rho_{,nn}}{\rho + p}}$
- Non-propagating entropy mode $\boxed{c_2^2 = 0}$
- Canonical scalar field propagating mode $\boxed{c_3^2 = 1}$

e.g., barotropic fluid $p = w\rho$ has $c_1^2 = w$

# Stability – algebraic couplings (ongoing work)

Quadratic action for the scalar cosmological perturbations for ***algebraic couplings*** $f(s,\phi)$

$$S_{\text{alg}} = \int dt\, d^3k \left( \dot{\vec{\chi}}^t \mathbf{K} \dot{\vec{\chi}} - \vec{\chi}^t \mathbf{V} \vec{\chi} - \overrightarrow{\chi}^t \mathbf{B} \dot{\vec{\chi}}^t \right)$$

with $\vec{\chi} = (\delta\varphi_k, \delta\Theta_k, \delta\phi_k)$

In the large $k$-limit we recover standard sound speeds:

- Standard propagating fluid mode $\boxed{c_1^2 = \dfrac{n\rho_{,nn}}{\rho + p}}$
- Non-propagating entropy mode $\boxed{c_2^2 = 0}$
- Canonical scalar field propagating mode $\boxed{c_3^2 = 1}$

e.g., barotropic fluid $p = w\rho$ has $c_1^2 = w$

Absence of ghost $\mathbf{K} > 0$ requires:

- Entropy condition $\rho_{,ss} + f_{,ss} > 0$
- Thermodynamic condition $\rho_{,nn} > \dfrac{(f_{,s} + n\rho_{,ns} + \rho_{,s})^2}{n^2(\rho_{,ss} + f_{,ss})}$

With absence of gradient instabilities $c_1^2 \geq 0$ gives

- Null energy condition $\rho + p > 0$

Generalises results in EFT approach for non-adiabatic perfect fluids `Ballesteros et al. [arXiv:1210.1561]`

Theoretically viable

# Outline

## Part 1 – Theory

- Perfect fluid models & entropy
- Entropy coupled dark sector

## Part 2 – Cosmology

- Background & perturbations
- Observational signatures

# Cosmology – background

Conformal time FLRW metric

$$ds^2 = -a(\tau)^2 d\tau^2 + a(\tau)^2(dx^2 + dy^2 + dz^2) \quad \text{with} \quad \mathcal{H} = a'/a$$

- Entropy conservation $u^\mu \nabla_\mu s = 0$ $\boxed{s = \text{const}}$
- Number conservation $\nabla_\mu (n u^\mu) = 0$ $\boxed{n \propto a^{-3}}$
- Standard continuity equation $\boxed{\rho_c' + 3\mathcal{H}(p_c + \rho_c) = 0}$

# Cosmology – background

Conformal time FLRW metric

$$ds^2 = -a(\tau)^2 d\tau^2 + a(\tau)^2(dx^2 + dy^2 + dz^2) \quad \text{with} \quad \mathcal{H} = a'/a$$

- Entropy conservation $u^\mu \nabla_\mu s = 0$ $\quad \boxed{s = \text{const}}$
- Number conservation $\nabla_\mu (n u^\mu) = 0$ $\quad \boxed{n \propto a^{-3}}$
- Standard continuity equation $\quad \boxed{\rho_c' + 3\mathcal{H}(p_c + \rho_c) = 0}$

Unchanged background dynamics from uncoupled quintessence

$$\boxed{\rho_{\mathrm{DE}} = \frac{1}{2a^2}\phi'^2 + \hat{V} \quad , \quad p_{\mathrm{DE}} = \frac{1}{2a^2}\phi'^2 - \hat{V}}$$

with effective potential $\hat{V}(\phi) \coloneqq V(\phi) + f$

Viable background evolution

# Cosmology – linear perturbations

Conformal Newtonian gauge

$$ds^2 = -a(\tau)^2(1+2\Phi)d\tau^2 + a(\tau)^2(1-2\Psi)(dx^2+dy^2+dz^2)$$

- Entropy conservation $u^\mu \nabla_\mu s = 0$

$$\boxed{(s' - s'\Phi + \delta s') = 0}$$

$$\boxed{s = \mathrm{const}} \qquad \boxed{\delta s' = 0}$$

*Frozen entropy perturbations*

# Cosmology – linear perturbations

Conformal Newtonian gauge

$$ds^2 = -a(\tau)^2(1+2\Phi)d\tau^2 + a(\tau)^2(1-2\Psi)(dx^2+dy^2+dz^2)$$

- Entropy conservation $u^\mu \nabla_\mu s = 0$ $\boxed{(s' - s'\Phi + \delta s') = 0}$

$\boxed{s = \text{const}}$ $\boxed{\delta s' = 0}$ *Frozen entropy perturbations*

Choose *entropic-CDM* fluid $\rho = n\gamma(s)$ (with $\delta p = p = 0$)

*Continuity Eq.*

$$\delta_c' + \theta_c - 3\Psi' = 0$$

*Euler Eq.*

$$\theta_c' + \theta_c\mathcal{H} - k^2\Phi = -k^2 Q_s(\tau)\delta s(k)$$

*Fifth-force term*

Modified Euler equation with **scale-dependent source term**

# CLASS implementation

- **Phenomenological parametrization** of intrinsic entropy perturbations with power-law spectrum & UV cutoff

$$\boxed{\langle \delta s_{\mathbf{k}}\, \delta s^*_{\mathbf{k}'} \rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k} - \mathbf{k}')\, P_s(k)}$$

$$\boxed{\mathcal{P}_s(k) = \mathcal{A}_{\mathrm{e}} \left(\frac{k}{k_p}\right)^n \exp\left[-\left(\frac{k}{k_c}\right)^{p_c}\right]}$$

- Inspired by isocurvature-like parameterisations
- Regularises $\mathcal{P}_s(k)$ on small scales

We then fix:

- Scale-invariant entropy perturbations $n = 0$ with $\mathcal{A}_e = 1$
- UV-suppression with cutoff $k_c = 1$ Mpc$^{-1}$ and $p_c = 2$

- **Phenomenological parametrization** of intrinsic entropy perturbations with power-law spectrum & UV cutoff

$$\langle \delta s_{\mathbf{k}}\, \delta s^*_{\mathbf{k}'} \rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k} - \mathbf{k}')\, P_s(k)$$

$$\mathcal{P}_s(k) = \mathcal{A}_\mathrm{e} \left(\frac{k}{k_p}\right)^n \exp\left[-\left(\frac{k}{k_c}\right)^{p_c}\right]$$

- Inspired by isocurvature-like parameterisations
- Regularises $\mathcal{P}_s(k)$ on small scales

We then fix:

- Scale-invariant entropy perturbations $n = 0$ with $\mathcal{A}_e = 1$
- UV-suppression with cutoff $k_c = 1$ Mpc$^{-1}$ and $p_c = 2$

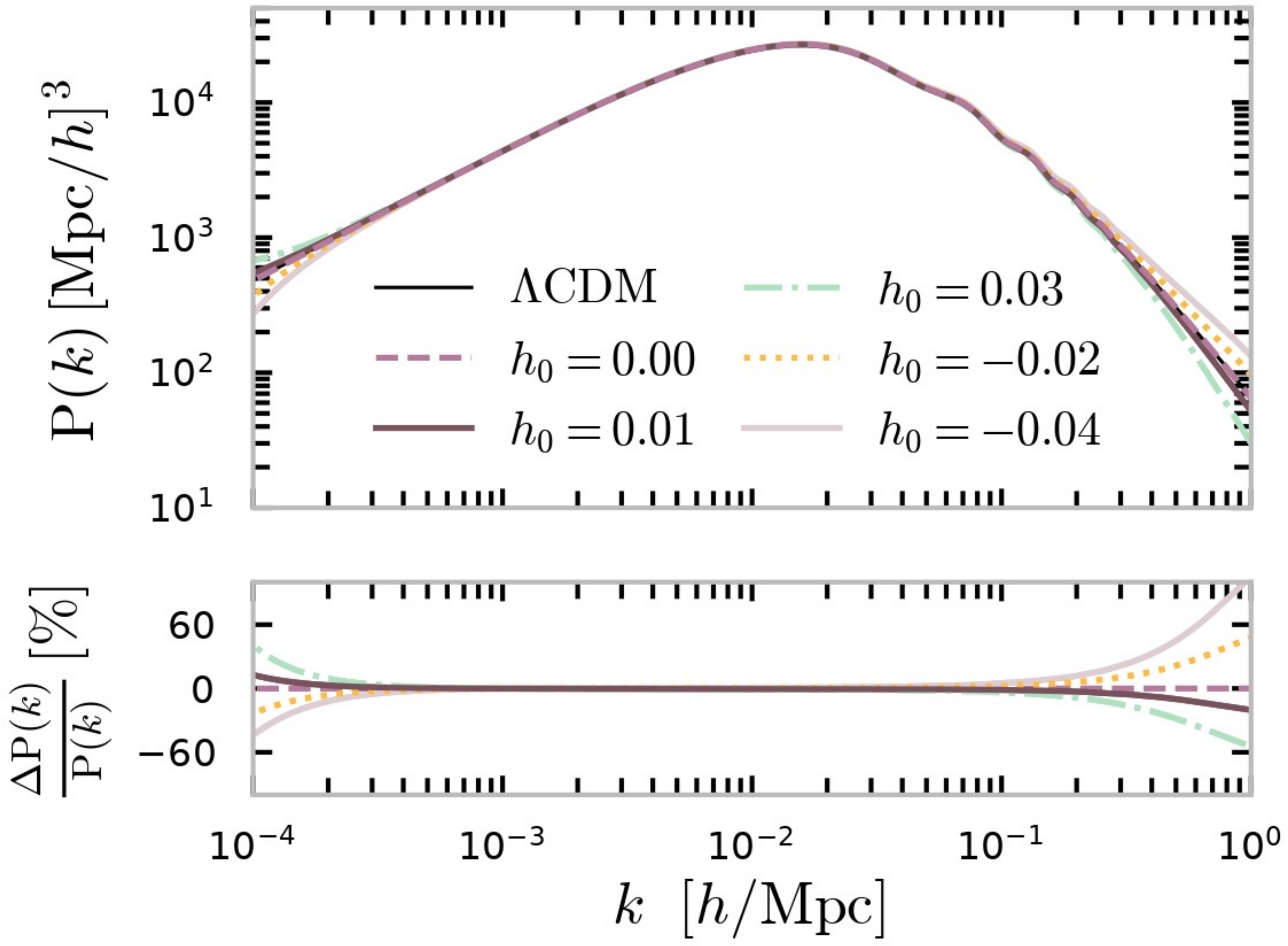
Consider linear couplings:

- Algebraic models $f = g_0 \phi s$
- Derivative models $f = h_0 \nabla^\mu \phi \nabla_\mu s$

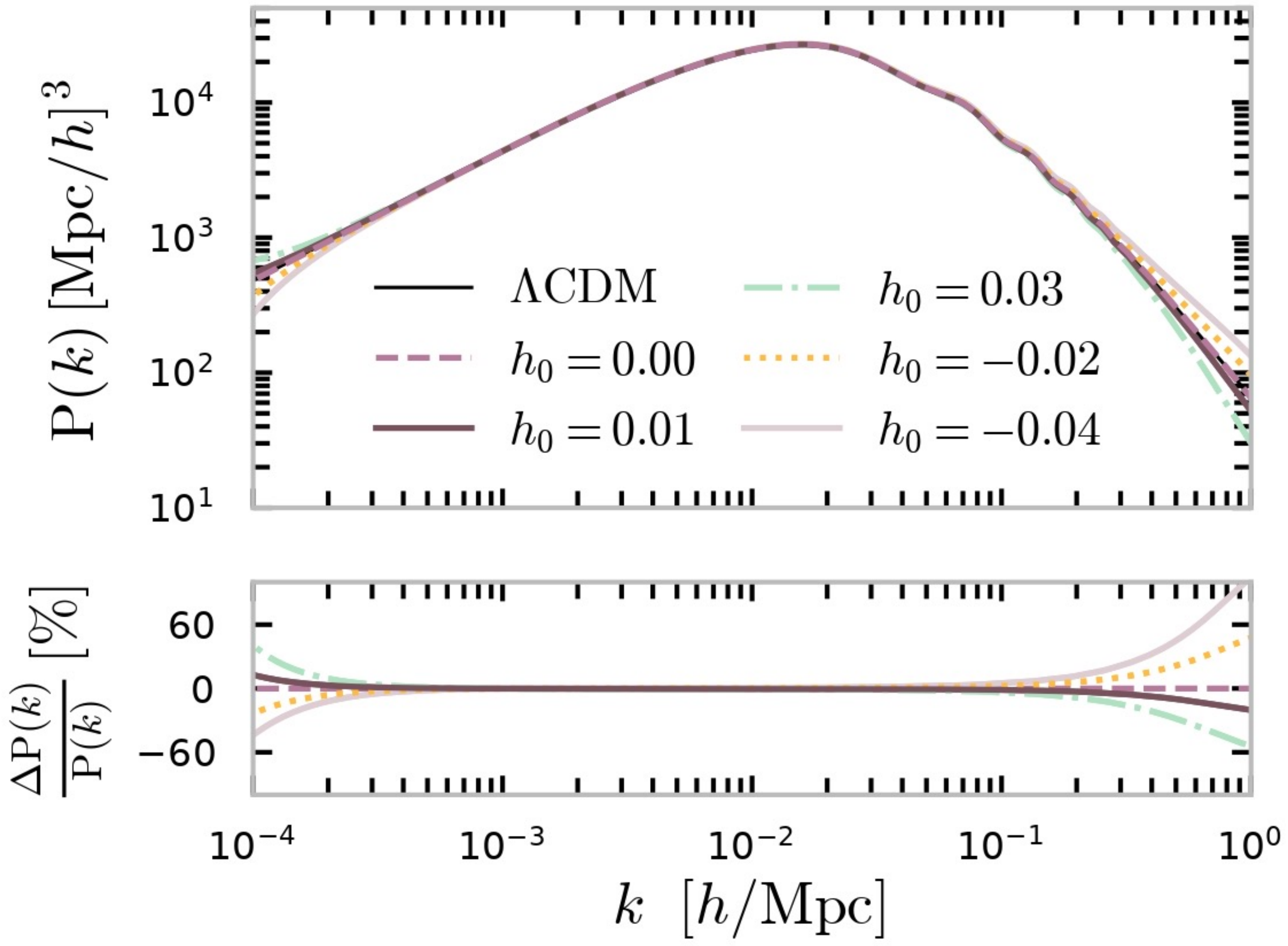
And exponential potential $\hat{V} \propto \exp(-\lambda\phi)$

# Observational signatures

Matter power spectrum $P(k)$



Matter power spectrum $P(k)$




Small scale suppression/enhancement

$$\boxed{\theta_c' + \theta_c \mathcal{H} - k^2 \Phi = -k^2 Q_s(\tau) \delta s}$$

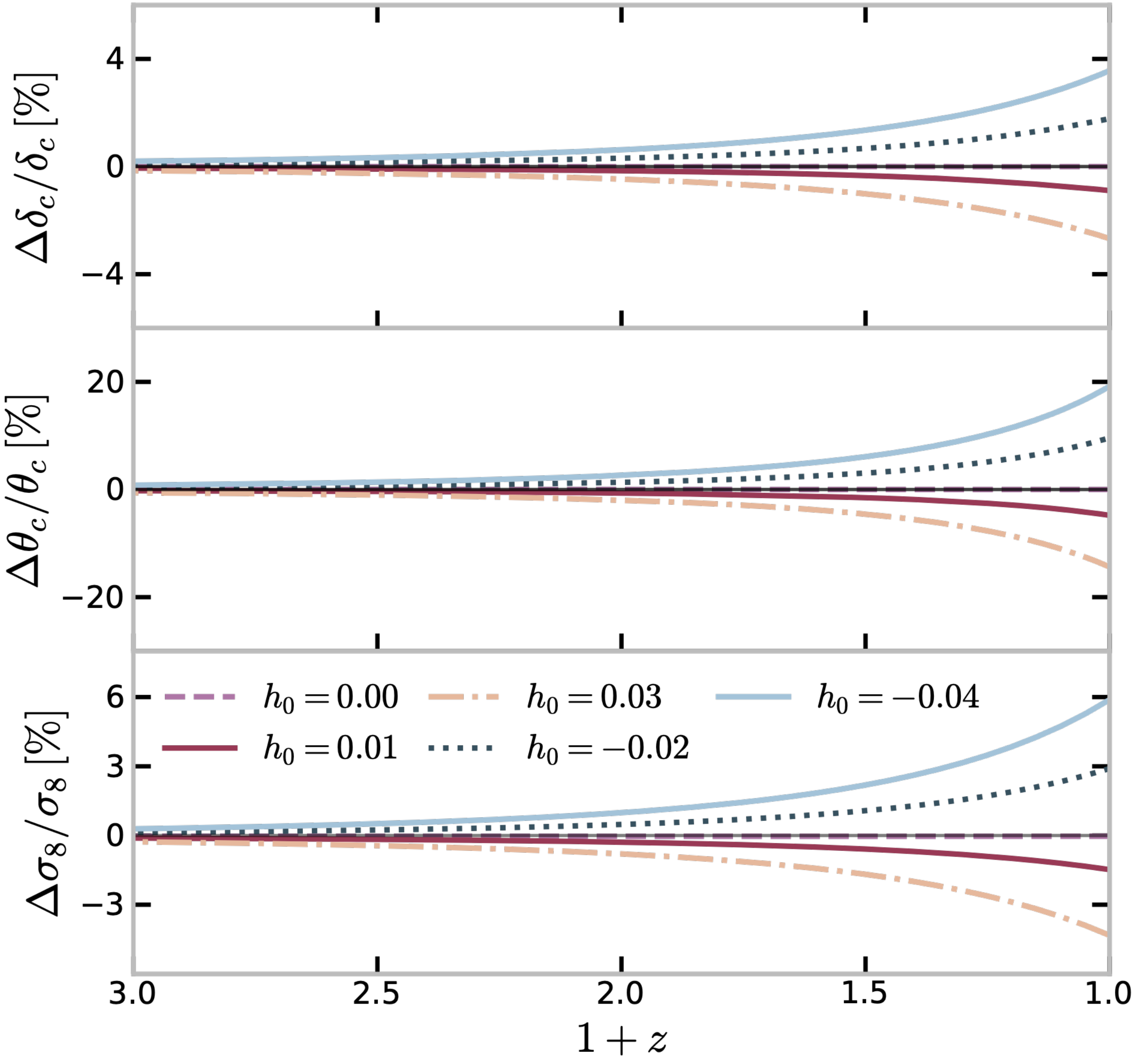
$$\boxed{Q_s = -\frac{h_0}{\rho_c} \hat{V}_{,\phi}}$$

Modified time-evolution of metric potentials → large-scale features

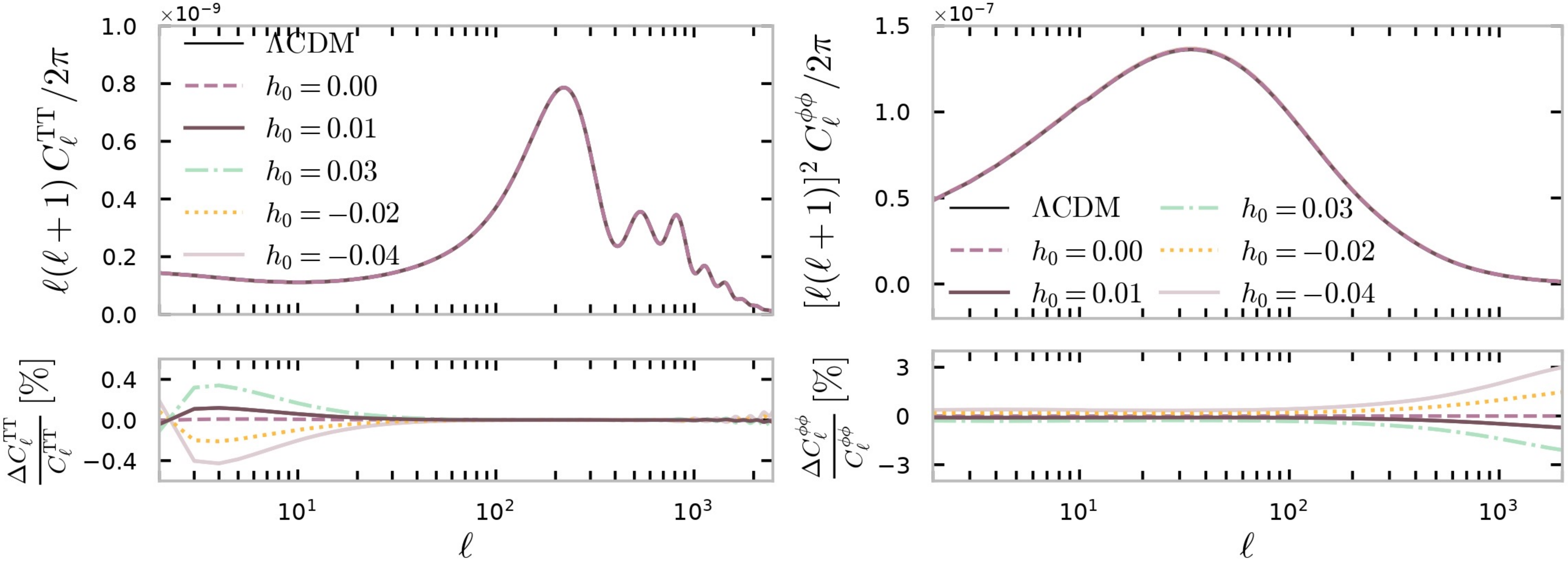
$$\boxed{\Psi' + \mathcal{H}\Phi \approx \frac{4\pi G a^2}{k^2} \theta_c \rho_c}$$

# Observational signatures

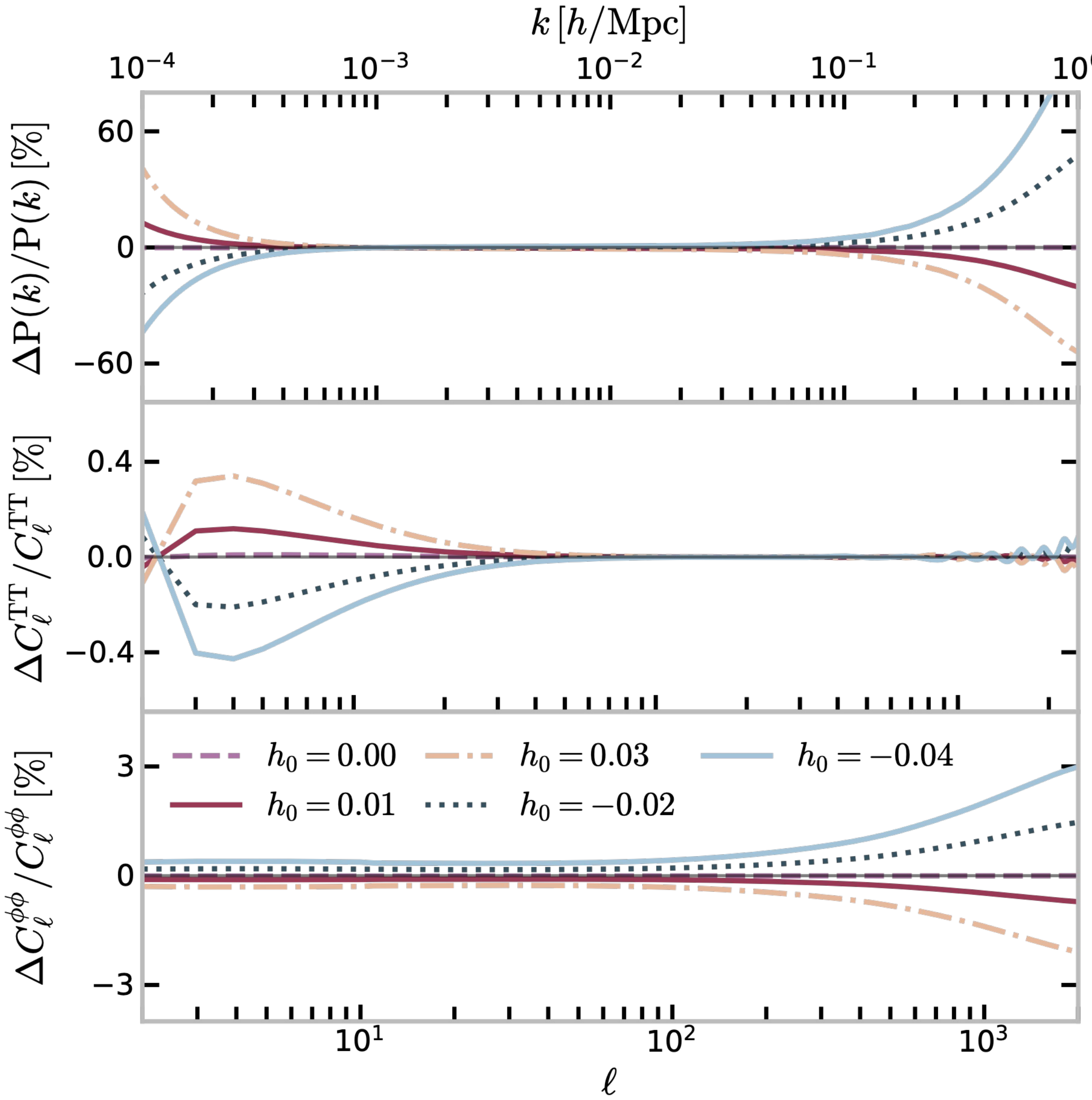
CDM density and velocity perturbations, and amplitude of matter fluctuations $\sigma_8$ at $k = 0.125h\ \mathrm{Mpc}^{-1}$



CMB lensing spectrum $C_\ell^{\phi\phi}$ and temperature spectrum $C_\ell^{TT}$



# Observational signatures




- Suppression/enhancement of matter power spectrum on very small/large scales (at late times)
- Minimal changes to TT spectrum
- Potential observable signatures in lensing potentials

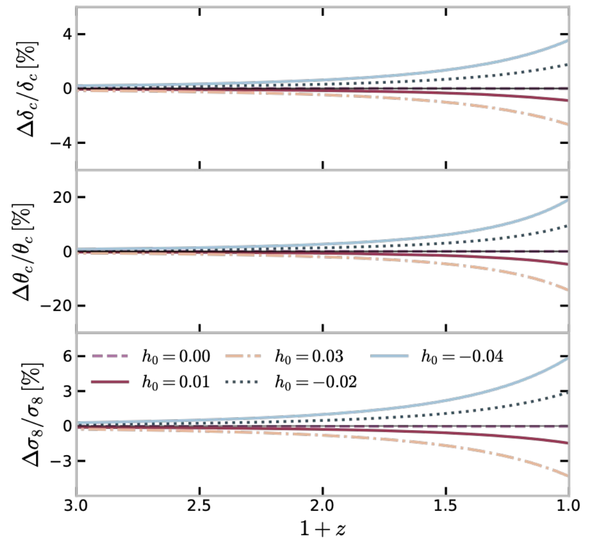
Viable phenomenology with late-time suppression of matter clustering

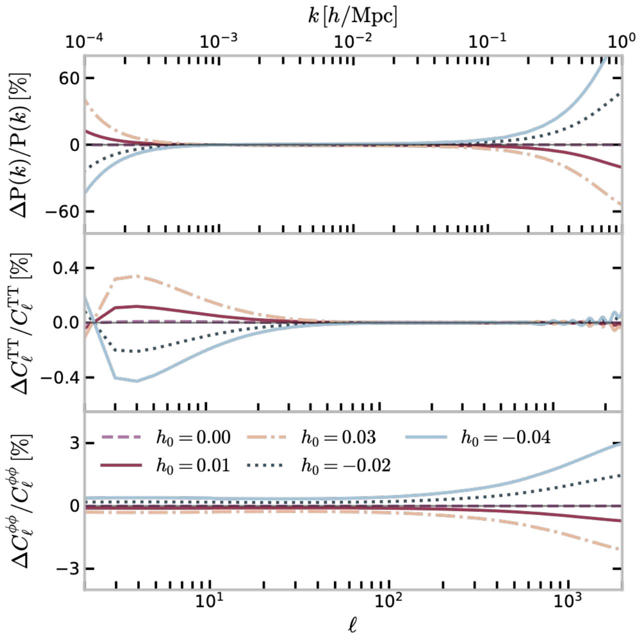
# Summary

UCL

Results:

- New interacting scenarios from **coupling DM intrinsic entropy** $s$ to DE $\phi$
- Unchanged background expansion & modified cosmological perturbations
- Unique Lagrangian realisation of **pure-momentum transfer**
- Viable new models with late-time suppression of structure growth

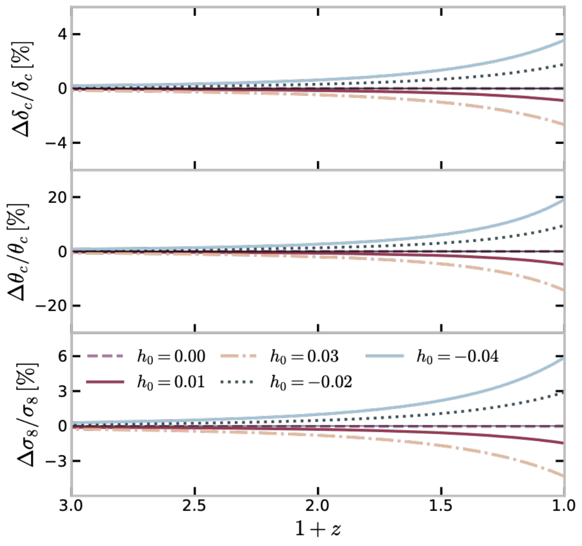



E. Jensko, E. M. Teixeira, V. Poulin, *Interacting dark sector from intrinsic entropy couplings* [arXiv:2603.10622]

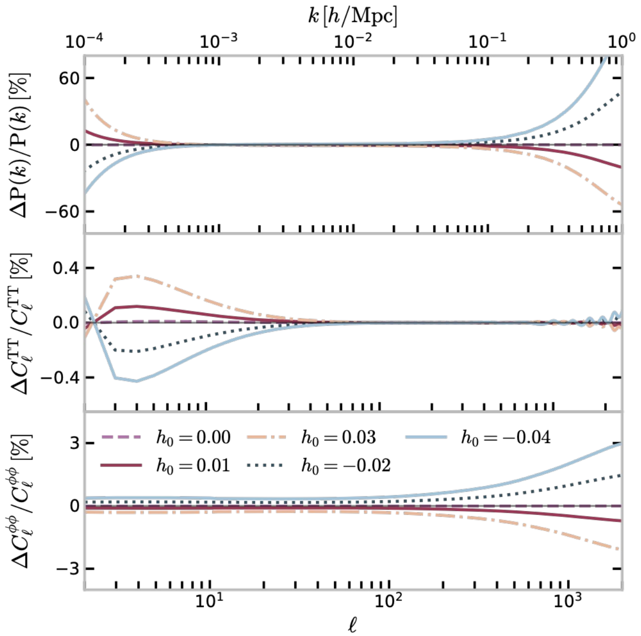
Results:

- New interacting scenarios from **coupling DM intrinsic entropy** $s$ to DE $\phi$
- Unchanged background expansion & modified cosmological perturbations
- Unique Lagrangian realisation of **pure-momentum transfer**
- Viable new models with late-time suppression of structure growth




*Ongoing work:*

- Detailed study of stability & ghosts
- Observational constraints on allowed interactions (with E. M. Teixeira, V. Poulin, T. Smith & Anna Chiara Ferri)
- Connections with EFT approach (with J. Beltrán Jiménez, L. J. Garay & M. Pérez Garrote)




Thanks for listening

E. Jensko, E. M. Teixeira, V. Poulin, *Interacting dark sector from intrinsic entropy couplings* [arXiv:2603.10622]

# Backup slides – quasi-static limit

Quasi-static limit

*Effective density source* *Fifth-force term*

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

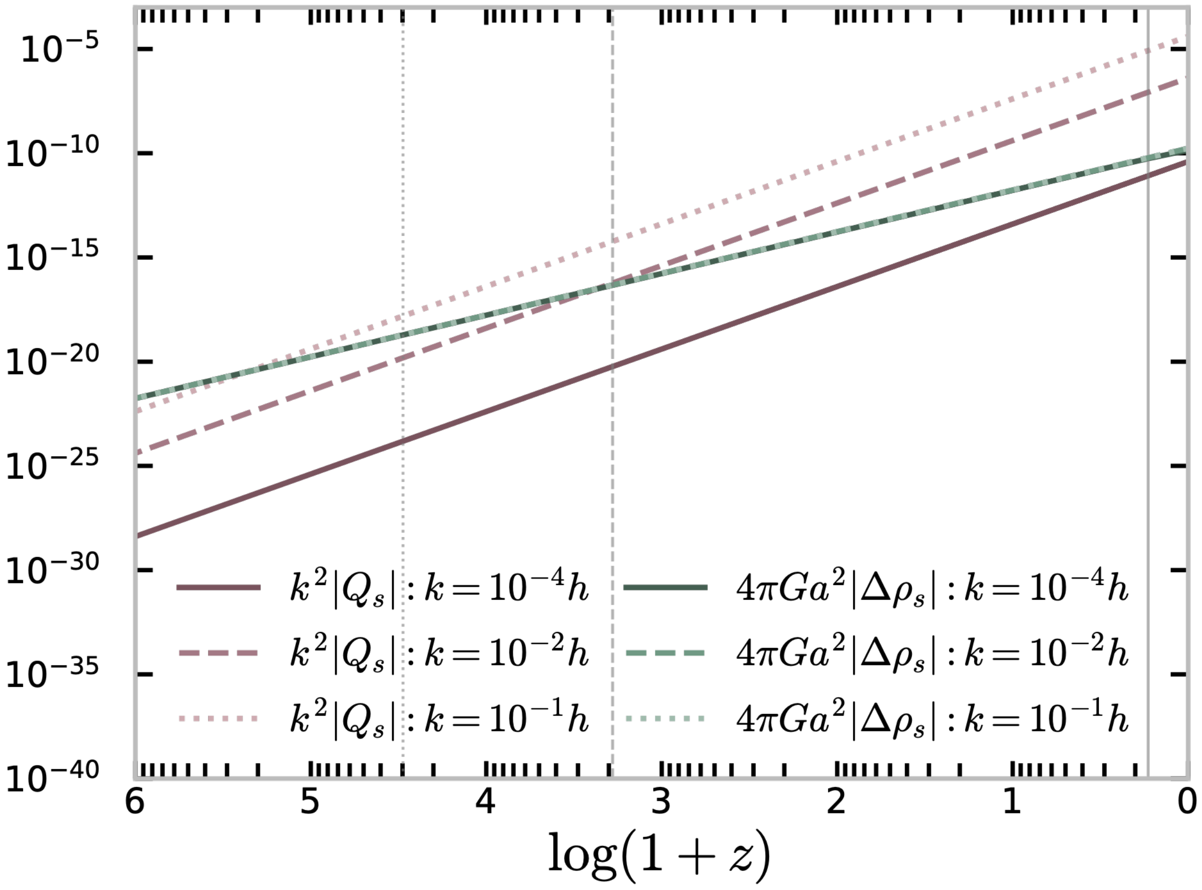
with effective density source $\Delta\rho_s(k,\tau)$ and fifth-force $Q_s(\tau)$

Choose algebraic models $f = g_0\phi s$

$$\boxed{Q_s^{\mathrm{alg}} = \frac{g_0\phi}{\rho_c}} \quad \boxed{\Delta\rho_s^{\mathrm{alg}} = g_0\phi - \frac{a^2 g_0}{k^2 + a^2\widehat{V_{,\phi\phi}}}\widehat{V_{,\phi}}}$$

$$\boxed{\hat{V} \propto \exp(-\lambda\phi)}$$

- Fifth-force term dominates on sub-Hubble scales
- Changes to $P(k)$ on small scales



# Backup slides – large-scale limit

- Momentum constraint modified by $\theta_c$ −coupling via Euler equation

- Time-evolution of metric potentials modified at small-$k$

$$\Psi' + \mathcal{H}\Phi = \frac{4\pi G a^2}{k^2} \sum_{c,b,r,\mathrm{DE}} \theta_I(\rho_I + p_I)$$

- Coupling un-suppressed on large scales

$$\theta_c' + \theta_c\mathcal{H} - k^2\Phi = -k^2 Q_s(\tau)\delta s(k)$$

- Leads to changes in $P(k)$ on large scales