Solidly unified dark sector

Based on arXiv:2606.27290

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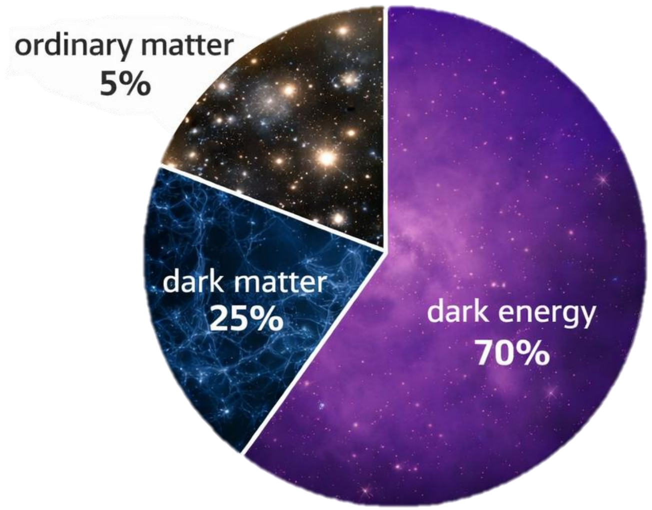
Motivation

ΛCDM building blocks:

$\sim$5% baryons

$\sim$25% cold dark matter (CDM) → Pressureless perfect fluid

$\sim$70% dark energy (DE) → Cosmological constant (Λ)



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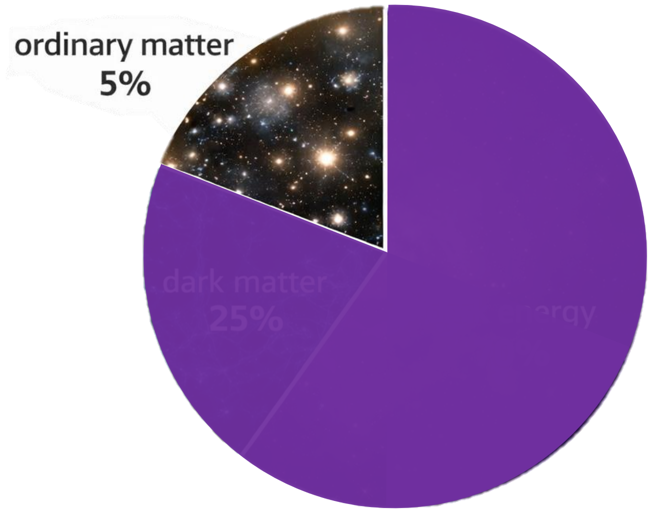
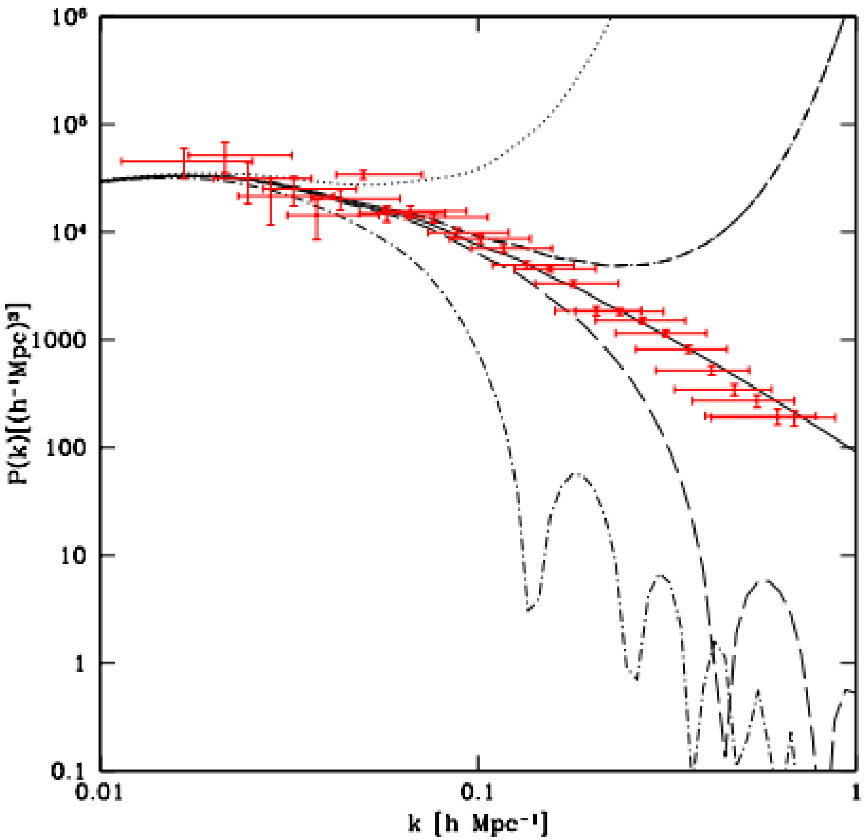


Unified dark sector

Motivation



H. Sandvik, M. Tegmark, M. Zaldarriaga and I. Waga, Phys. Rev. D 69, 123524 (2004).

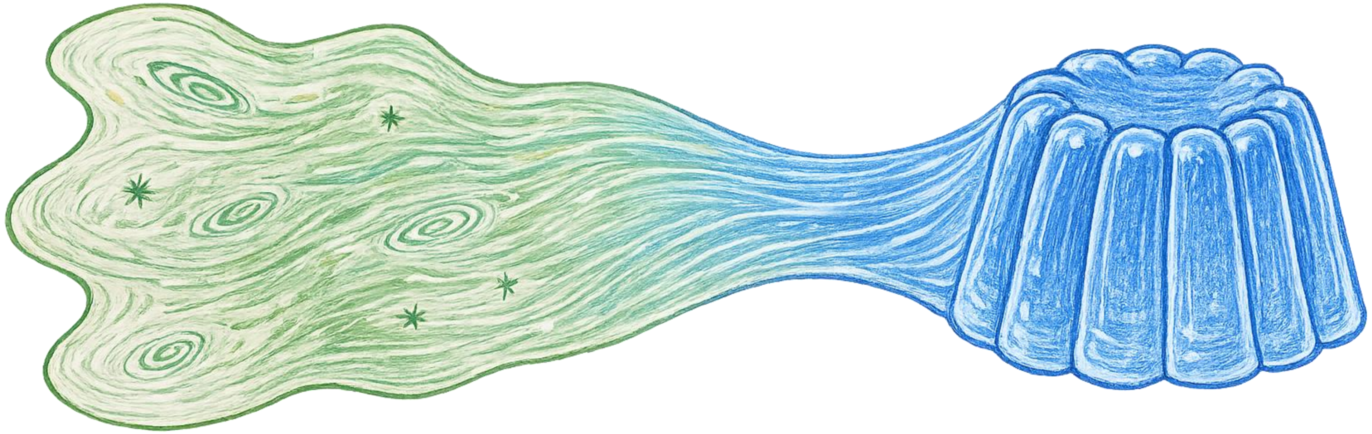
We would like to have a **unified description** of the dark sector.

However, some dark sector **fluids** have oscillations or exponential blowup of the matter power spectrum H. Sandvik, M. Tegmark, M. Zaldarriaga and I. Waga, Phys. Rev. D 69, 123524 (2004).

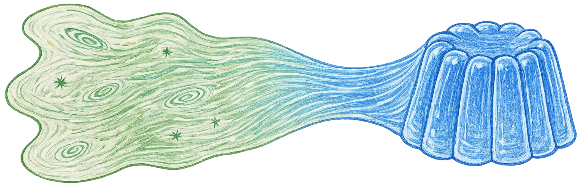
This problem can be fixed with a **solid component**

Solids in cosmology: EFT description

We are interested in a **unified DE and DM description** in which the medium behaves as fluid DM in the early Universe and as solid DE in the late Universe.



Solids in cosmology: EFT description



Solid:

Positions of the individual volume elements ϕ^a $(a = 1, 2, 3)$

$$\Downarrow$$

Internal homogeneity of the medium

$$\phi^a \to \phi^a + c^a$$

$$\Downarrow$$

Lorentz-invariant building block

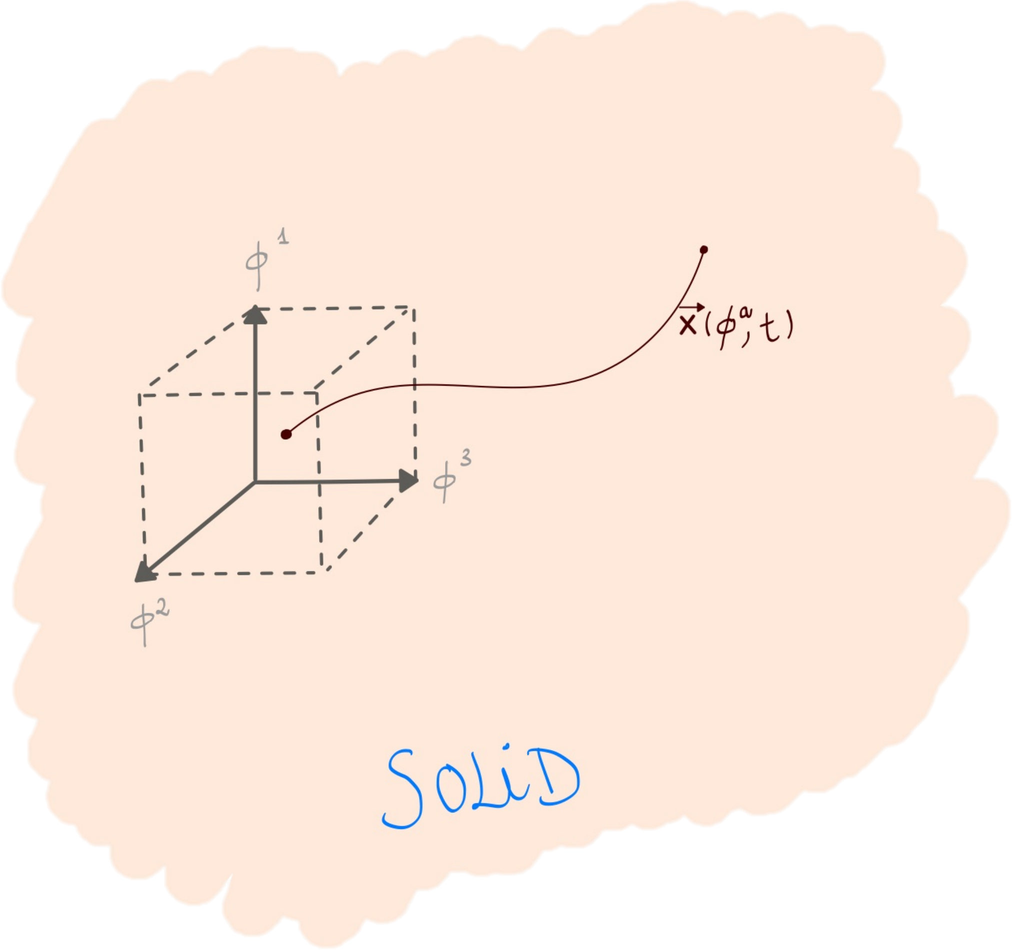
$$B^{ab} \equiv g^{\mu\nu}\partial_\mu\phi^a\partial_\nu\phi^b$$

$$\Downarrow$$

Three independent scalars under $SO(3)$ rotations

$$X \equiv [B] \qquad Y \equiv \frac{[B^2]}{[B]^2} \qquad Z \equiv \frac{[B^3]}{[B]^3}$$

$[B] = \delta_{ab}B^{ab}$



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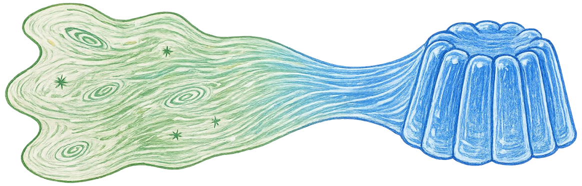
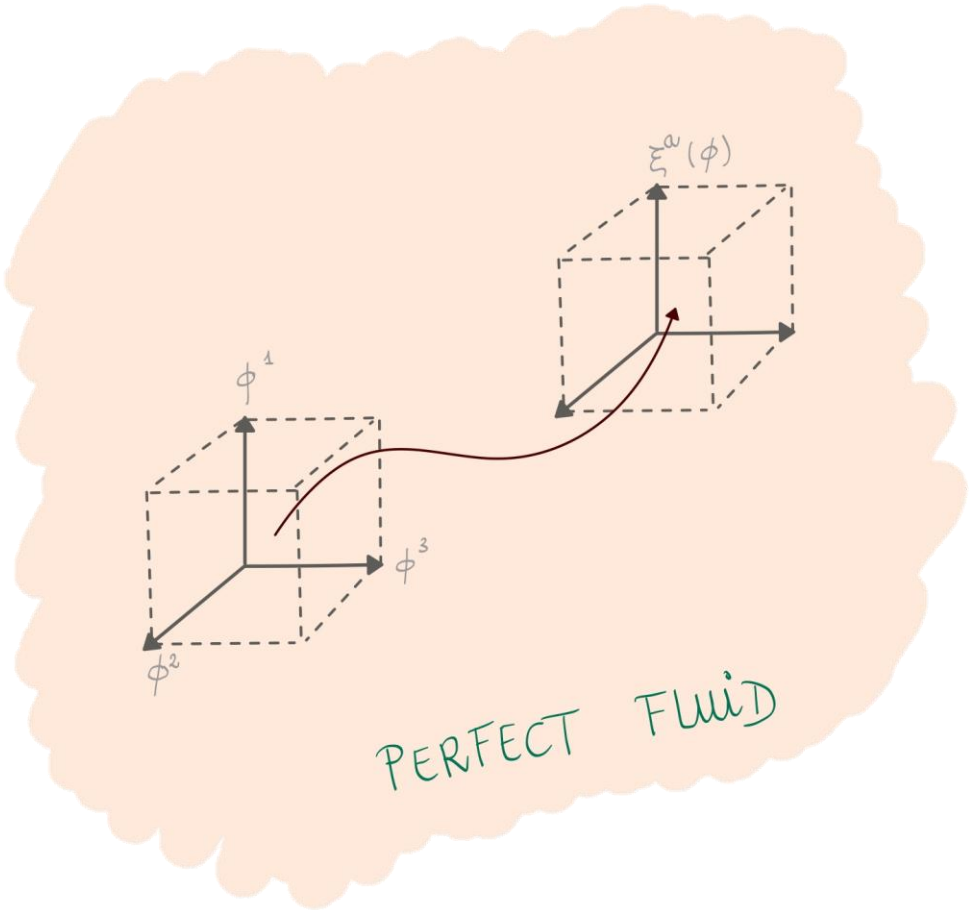




Perfect fluid:

Invariance of the dynamics under internal volume-preserving diffeomorphisms

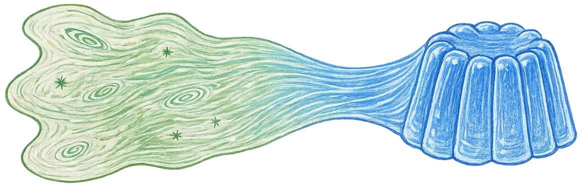
$$\phi^a \to \xi^a(\phi), \quad \text{with} \quad \det(\partial \xi^a / \partial \phi^b) = 1$$

$$\Downarrow$$

A particular combination consistent with the latter symmetry

$$b \equiv \det B^{ab} = \frac{X^3}{3}(1 - 3Y + 2Z)$$

Solids in cosmology: EFT description



Solid: $Y \equiv \frac{[B^2]}{[B]^2}$ $Z \equiv \frac{[B^3]}{[B]^3}$

Perfect fluid: $b \equiv \det B^{ab} = \frac{X^3}{3}(1 - 3Y + 2Z)$

The dark-sector Lagrangian

$$\mathcal{L}_D = -\mathcal{K}(b, Y, Z)$$

The total action is given by

$$\mathcal{S} = \int \mathrm{d}^4x \sqrt{-g}\left[\frac{R}{16\pi G} - \mathcal{K}(b, Y, Z) + \underbrace{\mathcal{L}_M}\right]$$

Other matter components (baryons and radiation)

Solids in cosmology: background

Spatially flat Friedmann-Lemaître-Robertson-Walker (FLRW) background

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\delta_{ij}\,\mathrm{d}x^i\mathrm{d}x^j.$$

Configuration compatible with the spatially flat FLRW background

$$\bar{\phi}^a = \lambda x^a \quad \Longrightarrow \quad \underbrace{b = \frac{\lambda}{a^6},}_{\text{Local volume change of the medium}} \qquad \underbrace{Y = \frac{1}{3}, \qquad Z = \frac{1}{9}.}_{\text{Volume-preserving deformations of the medium (shear distortions)}}$$

Solids in cosmology: perturbations

The perturbed FLRW background

$$\mathrm{d}s^2 = -(1+2\psi)\mathrm{d}t^2 + 2aS_i\mathrm{d}x^i\mathrm{d}t + a^2\left[(1-2\phi)\delta_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j \,.$$

We consider a perturbation ϕ^a on the background value, such that

$$\phi^a = \lambda(x^a + \pi^a), \quad \pi^a = \pi_T^a + \partial^a \pi_L \,,$$

where π_T^a satisfies $\partial_a \pi_T^a = 0$.

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Tensor perturbations

$$\mathcal{S}_t^{(2)} = \frac{1}{64\pi G}\int dt\ d^3x\, a^3\left[\dot{h}_{ij}^2 - \frac{\left(\partial h_{ij}\right)^2}{a^2} - \frac{64\pi G}{9}\left(\mathcal{K}_{,y} + \mathcal{K}_{,z}\right)h_{ij}^2\right].$$

S. Endlich, A. Nicolis, and J. Wang,
JCAP 10, 011 (2013).

A. Gruzinov, Phys. Rev. D. 70, 063
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Nonvanishing mass term!

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Vector perturbations

$$\mathcal{S}_v^{(2)} = \int \frac{dt d^3k}{(2\pi)^3} a^5 \frac{b\mathcal{K}_{,b}}{1+4\epsilon_b a^2H^2/k^2}\left(|\vec{\dot{\pi}}_T|^2 - c_T^2 \frac{k^2}{a^2}|\vec{\pi}_T|^2\right),$$

where

$$\epsilon_b = \frac{8\pi G b\mathcal{K}_{,b}}{H^2}, \qquad c_T^2 = \bar{c}_{\mathrm{T}}^2\left(1 + 4\epsilon_b \frac{a^2H^2}{k^2}\right),$$

with

$$\bar{c}_{\mathrm{T}}^2 = \frac{2}{9}\frac{\mathcal{K}_{,Y} + \mathcal{K}_{,Z}}{b\mathcal{K}_{,b}}\,.$$

Solids in cosmology: stability conditions

The perturbed FLRW background

$$\mathrm{d}s^2 = -(1+2\psi)\mathrm{d}t^2 + 2aS_i\mathrm{d}x^i\mathrm{d}t + a^2\left[(1-2\phi)\delta_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j\,.$$

We consider a perturbation ϕ^a on the background value, such that

$$\phi^a = \lambda(x^a + \pi^a),$$

where π_T^a satisfies $\partial_a \pi_T^a = 0$.

No Laplacian instabilities and tachyonic instabilities:

$$\mathcal{K}_{,Y} + \mathcal{K}_{,Z} > 0$$

No vector ghosts:

$$b\mathcal{K}_{,b} > 0$$

Tensor perturbations

$$\mathcal{S}_t^{(2)} = \frac{1}{64\pi G}\int dt\; d^3x\, a^3\left[\dot{h}_{ij}^2 - \frac{(\partial h_{ij})^2}{a^2} - \frac{64\pi G}{9}(\mathcal{K}_{,y} + \mathcal{K}_{,z})h_{ij}^2\right].$$

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Unified dark sector model

An explicit realisation of a unified dark sector model

$$\mathcal{K} = m\sqrt{b}\left[1 + \left(\frac{b^{\epsilon_0/3}}{m\sqrt{b}}\right)^{1+\alpha} f(Y,Z)\right]^{1/(1+\alpha)},$$

where m, $\alpha \geq 0$, and $0 < \epsilon_0 \ll 1$ are constants.

- Early universe $\Rightarrow \mathcal{K} \simeq m\sqrt{b} = m\lambda^3/a^3 \rightarrow$ **DM fluid**
- Late universe $\Rightarrow \mathcal{K} \simeq f^{1/(1+\alpha)} b^{\epsilon_0/3} \rightarrow$ **DE solid**

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- Late universe $\Rightarrow \mathcal{K} \simeq f^{1/(1+\alpha)} b^{\epsilon_0/3} \rightarrow$ **DE solid**
- In the limit $\epsilon_0 \rightarrow 0 \Rightarrow P_{\mathrm{D}} = -f\rho_{\mathrm{D}}^{-\alpha} \rightarrow$ Generalized Chaplygin gas model
- In the limit $\epsilon_0 \rightarrow 0$ with $\alpha = 0 \rightarrow \Lambda$CDM model

M. C. Bento, O. Bertolami, and A. A. Sen, Phys. Rev. D 66, 043507 (2002)

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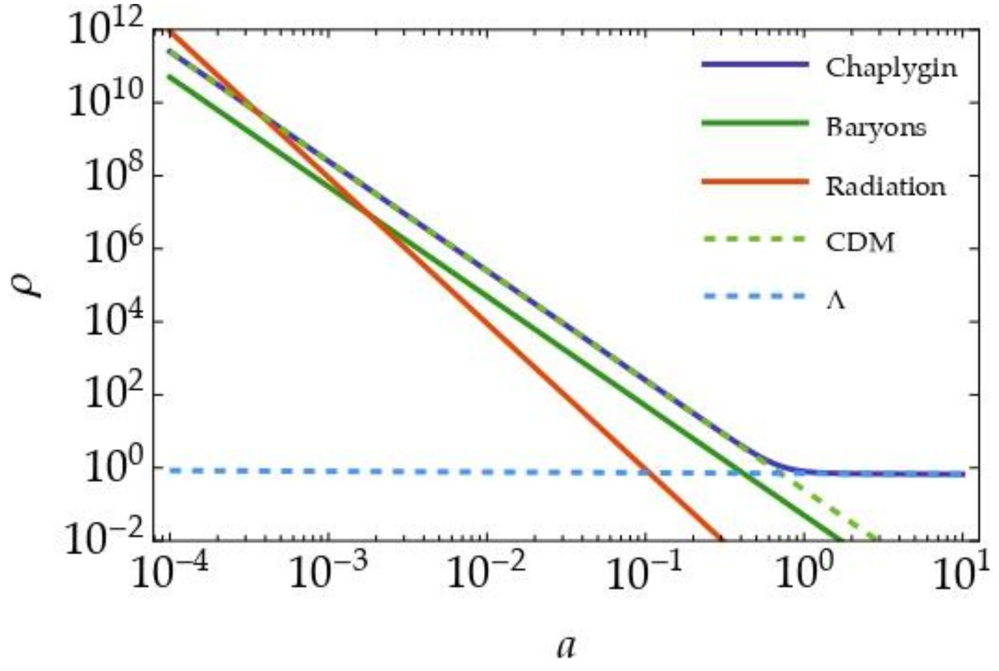
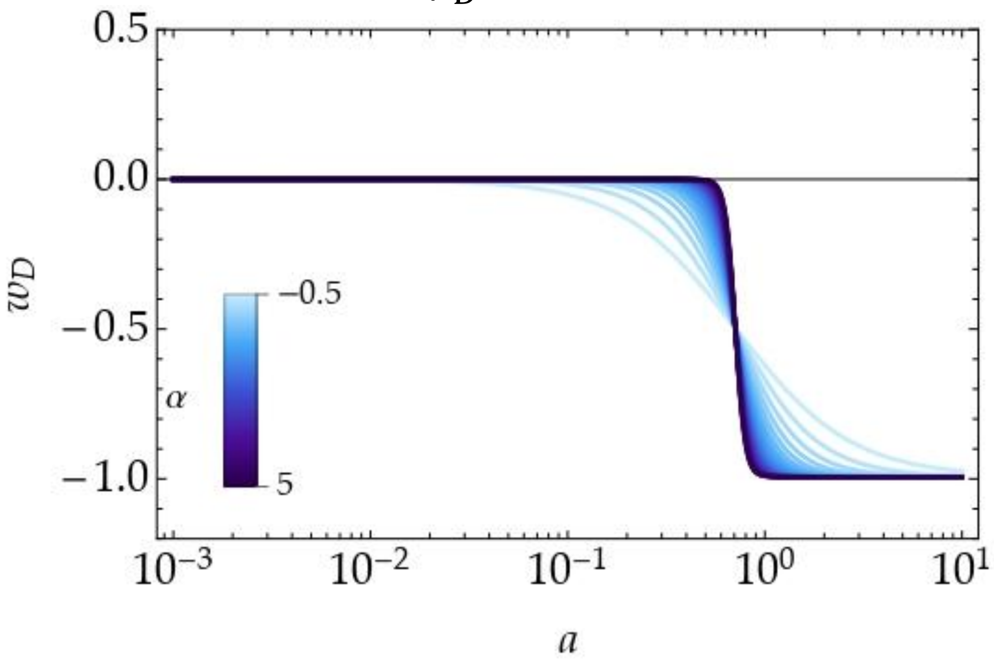
where m, $\alpha \geq 0$, and $0 < \epsilon_0 \ll 1$ are constants.

$$w_D = \frac{P_D}{\rho_D} = -1 + \frac{2b\mathcal{K}_{,b}}{\mathcal{K}}$$

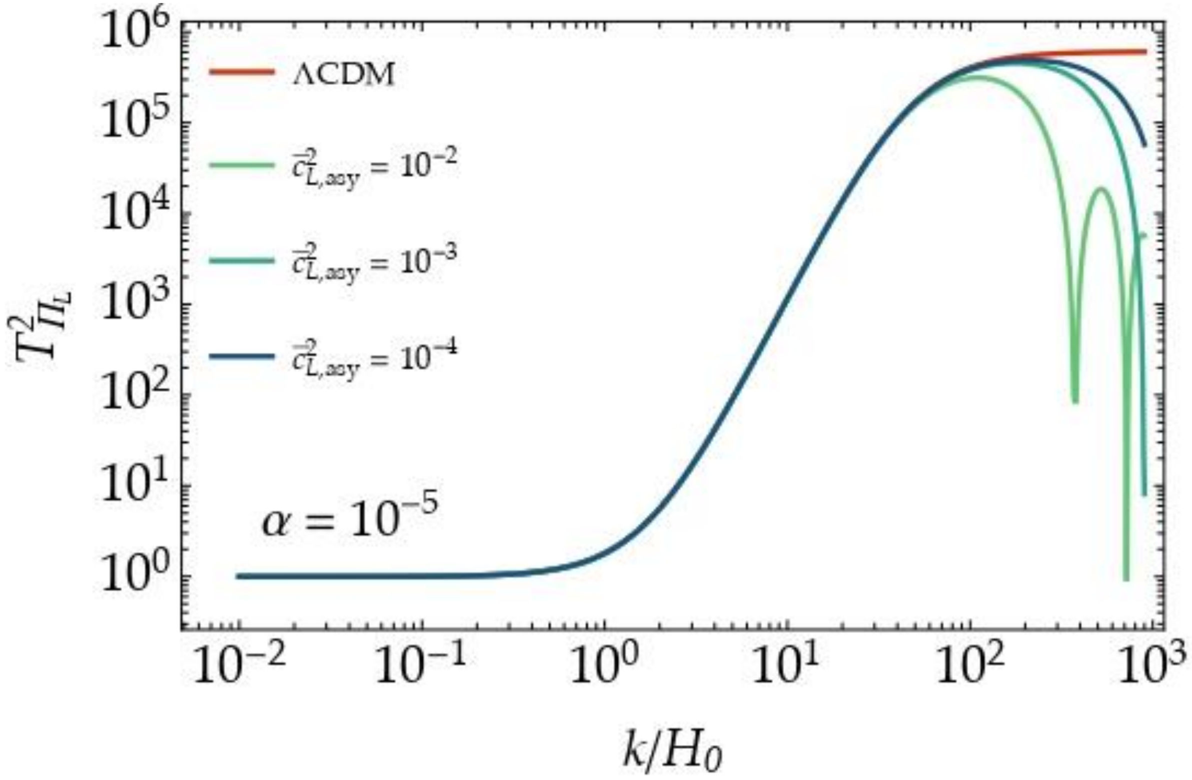


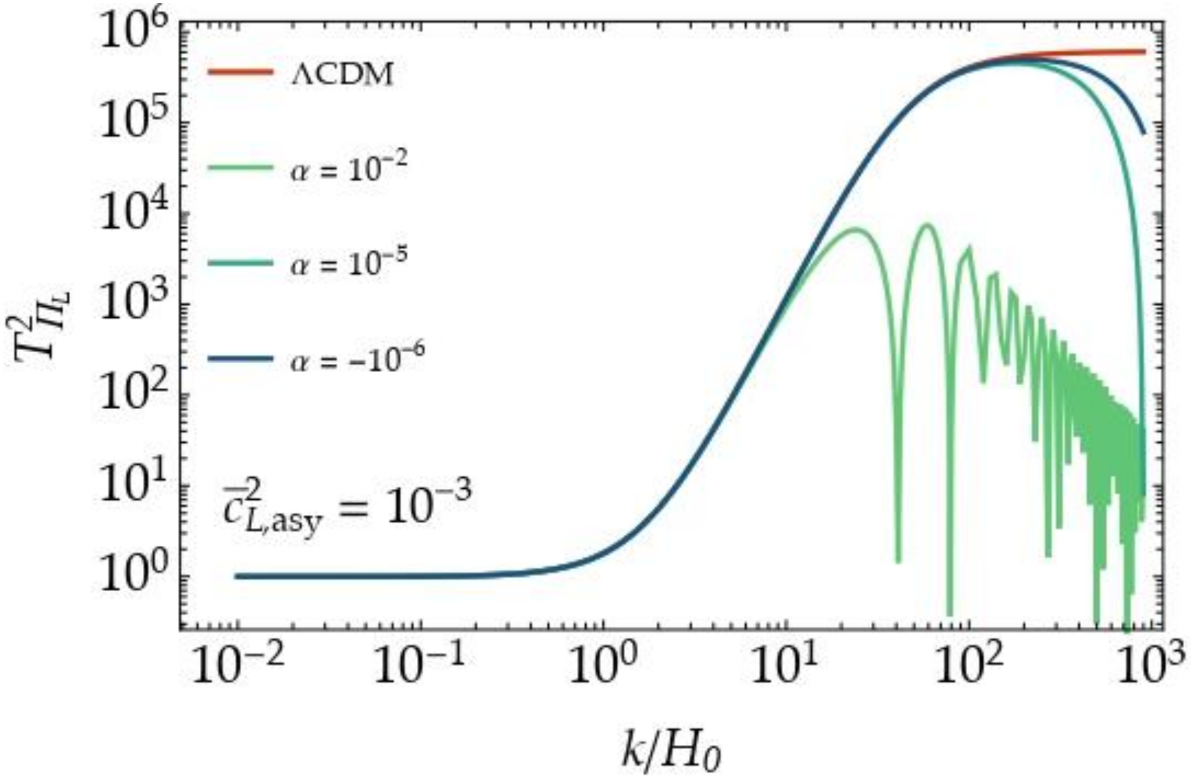


Unified dark sector model: observational signatures

Suppresion of the transfer function of the dark sector

$$T^2_{\pi_L} \equiv \frac{|\pi_L(z=0)|^2}{\left|\pi_L(z=z_{\text{ini}})\right|^2}$$





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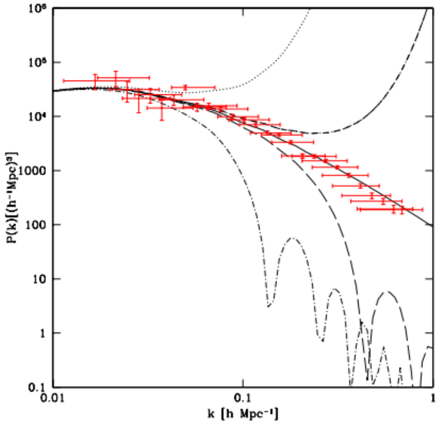
$$\bar{c}_L{}^2 \simeq -1 + \frac{4}{3}\bar{c}_T{}^2$$



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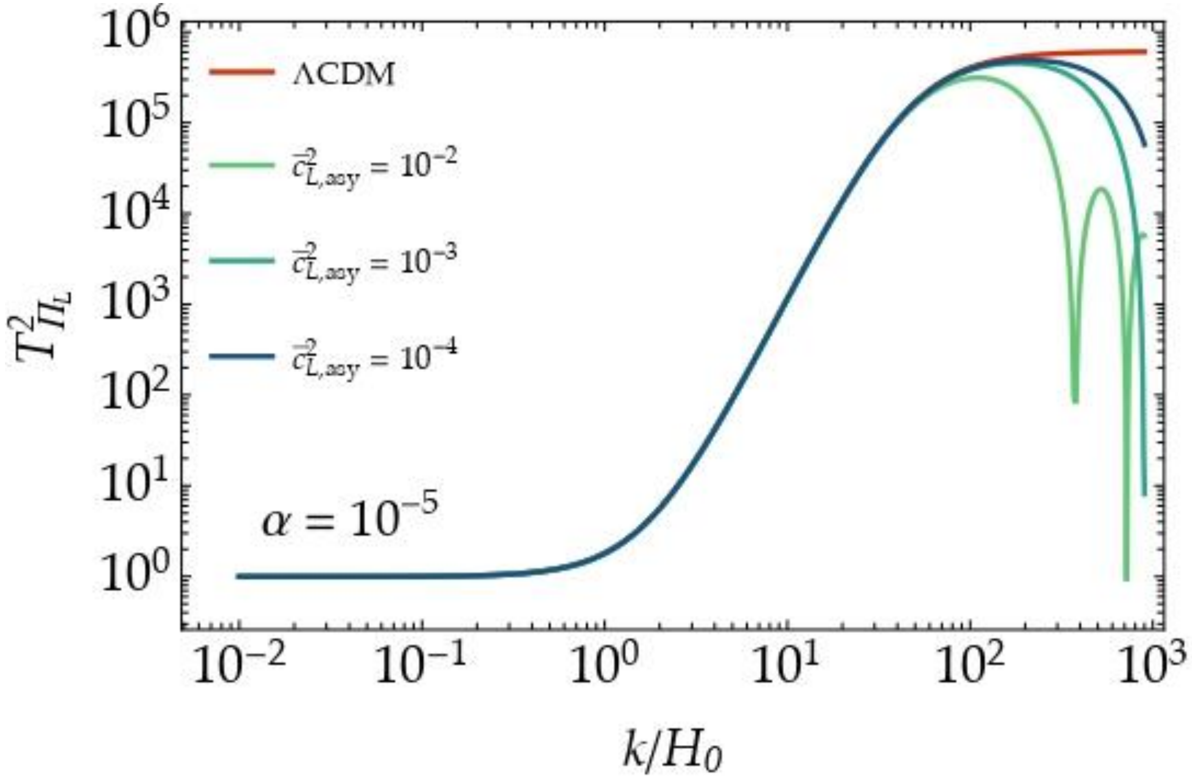
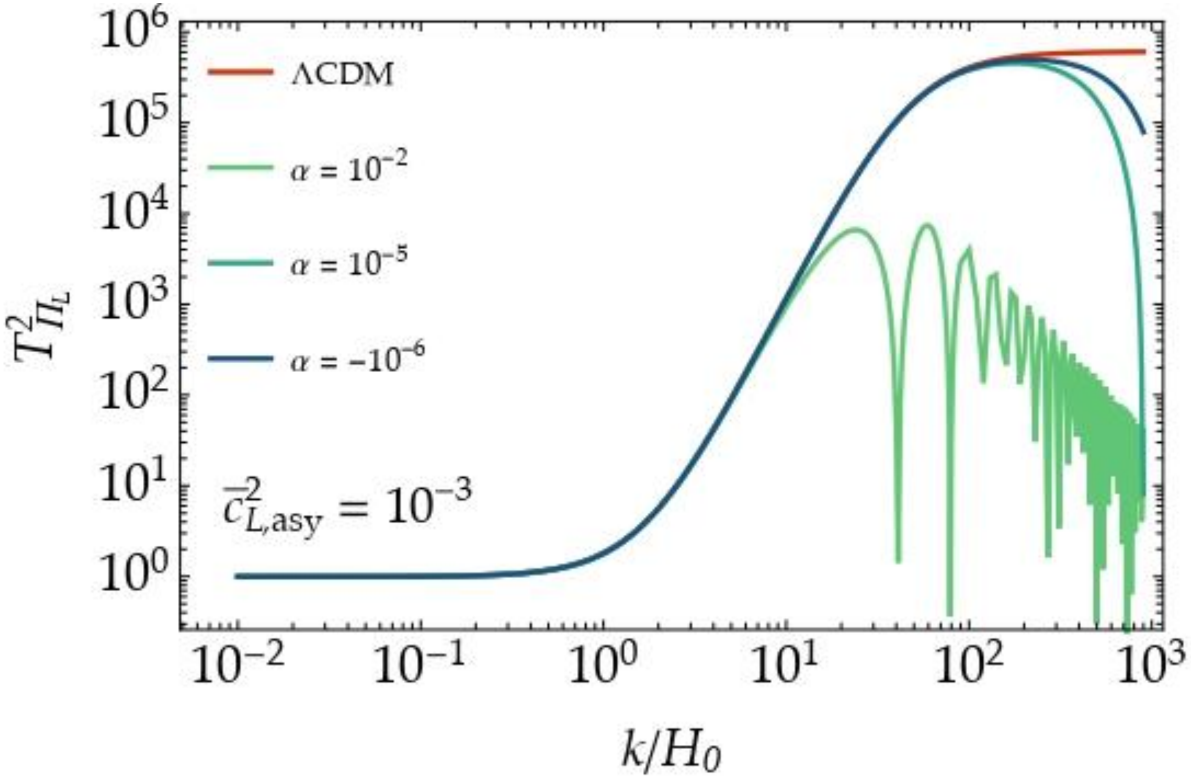


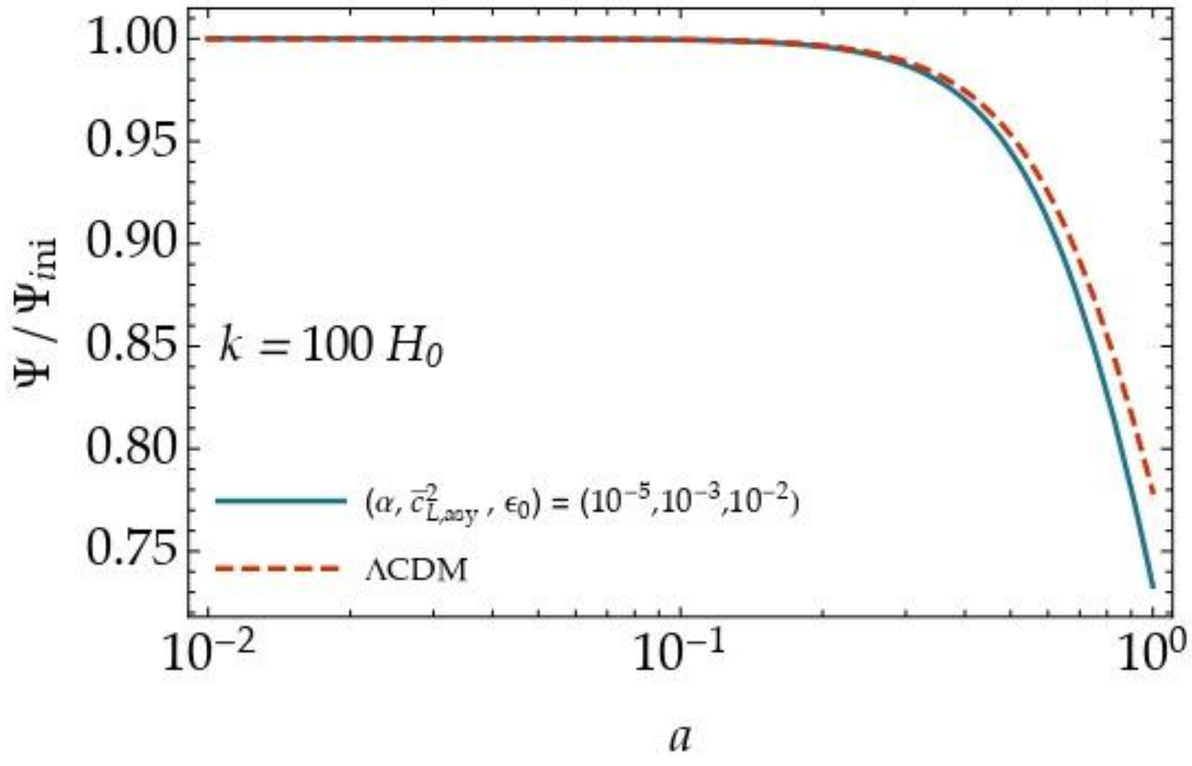


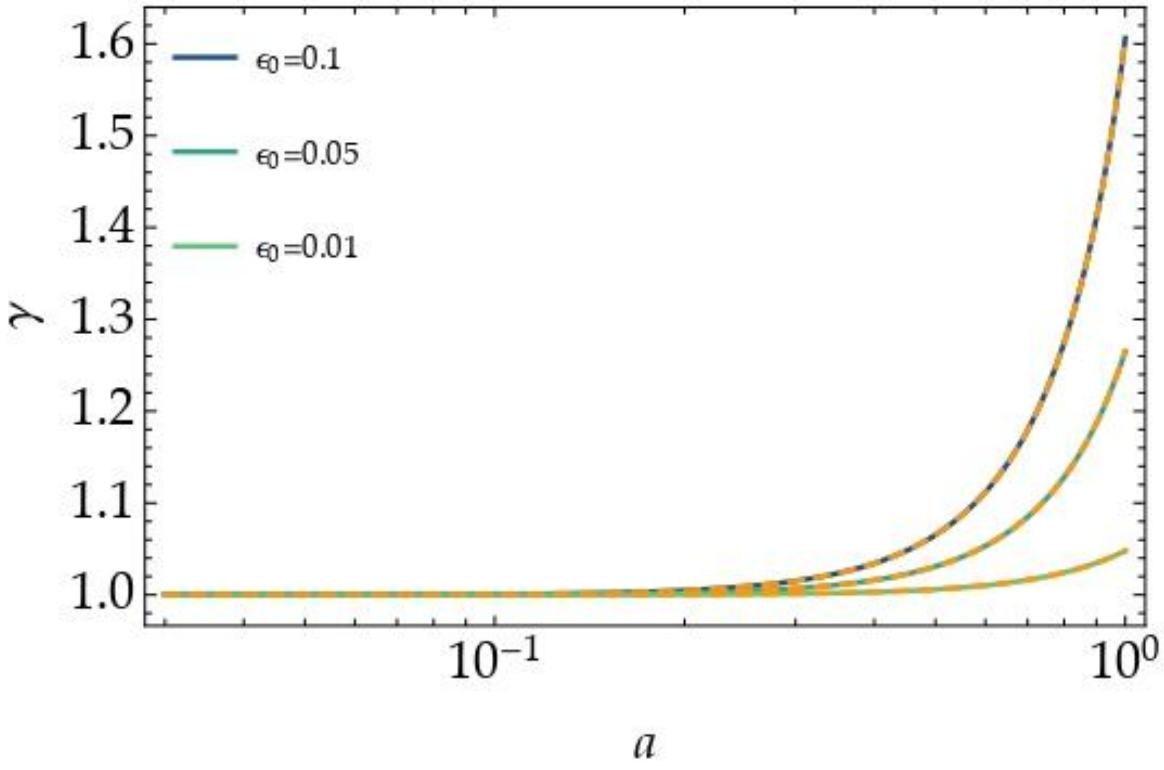
Unified dark sector model: observational signatures

Distinctive scale dependence of the dark solid reflected in the gravitational potentials

$$\Psi - \Phi = -\frac{64\pi G a^2}{9}\left(\mathcal{K}_{,Y} + \mathcal{K}_{,Z}\right)\pi_L$$

$$\gamma \equiv \frac{\Phi}{\Psi} = 1 + \frac{64\pi G a^2}{9}\left(\mathcal{K}_{,Y} + \mathcal{K}_{,Z}\right)\frac{\pi_L}{\Psi} \simeq \frac{1}{1 - 4\overline{c_T^2}}$$



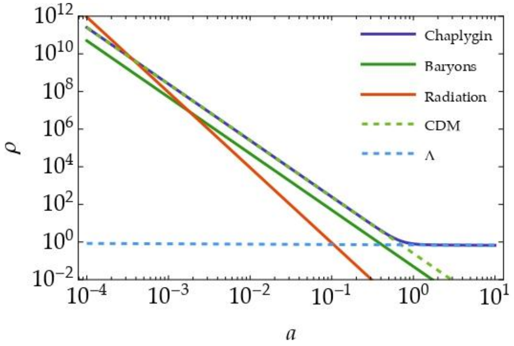


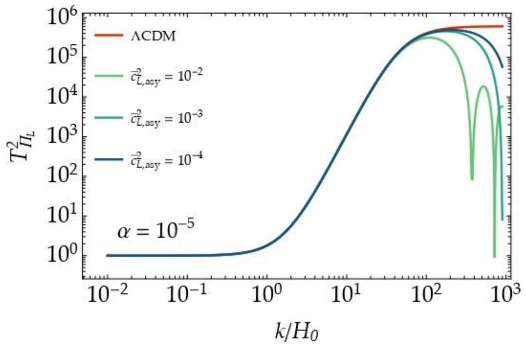
Summary

- We provide a **unified description of DE and DM** in which the medium behaves as **fluid** in the early Universe and as **solid** in the late Universe.
- The **solid** nature of the dark medium **prevents the instabilities** and strong acoustic oscillations.
- **Distinctive signatures** in cosmological perturbations at low redshift:
  - Suppression of structure growth
  - Nontrivial gravitational slip
  - Effective mass for gravitational waves

A solid unification of the dark sector, arXiv: 2606.27290

Future work ⟹ Confront this framework with cosmological data





Solids in cosmology: stability conditions

The perturbed FLRW background

$$\mathrm{d}s^2 = -(1+2\psi)\mathrm{d}t^2 + 2aS_i\mathrm{d}x^i\mathrm{d}t + a^2\left[(1-2\phi)\delta_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j\,.$$

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where π_T^a satisfies $\partial_a\pi_T^a = 0$.

Scalar perturbations

$$\mathcal{S}_\mathrm{L} = \frac{1}{2}\int\frac{\mathrm{d}t\mathrm{d}^3k}{(2\pi)^3}a^5\frac{k^2 b\mathcal{K}_{,b}}{1+3\epsilon_b a^2H^2/k^2}\left[|\dot{\pi}_L|^2 - \left(\frac{c_L^2k^2}{a^2} + m_L^2\right)|\pi_L|^2\right]$$

with

$$c_L^2 = \frac{\bar{c}_L^2}{1+3\epsilon_b a^2H^2/k^2}, \qquad \bar{c}_L{}^2 = 1 + 2\frac{b\mathcal{K}_{,bb}}{\mathcal{K}_{,b}} + \frac{4}{3}\bar{c}_T{}^2$$

No scalar ghosts:

$$b\mathcal{K}_{,b} > 0$$

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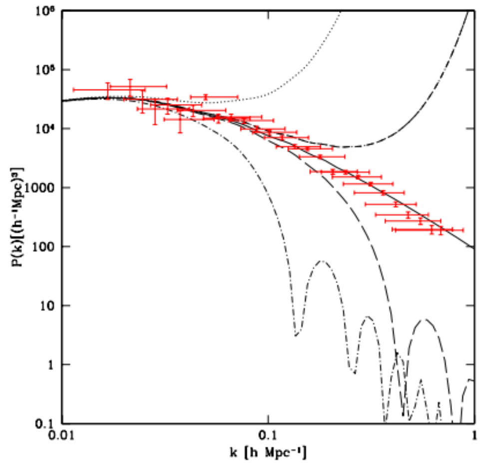

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Low-redshift

Solids in cosmology: Growth of large-scale structure

Equation for the phonon field:

$$\ddot{\pi}_L - H\left(1 + \frac{6b\mathcal{K}_{,bb}}{\mathcal{K}_{,b}}\right)\dot{\pi}_L + \left(c_L^2\frac{k^2}{a^2} + m_L^2\right)\pi_L = \frac{1}{a^2}\left[\Psi + 3\left(1 + \frac{2b\mathcal{K}_{,bb}}{\mathcal{K}_{,b}}\right)\Phi\right].$$

The density contrast of the solid dark sector can be related to the phonon field and the gravitational potential

$$\delta_{\mathrm{D}} = \frac{\delta\rho_{\mathrm{D}}}{\rho_{\mathrm{D}}} = -\frac{2b\mathcal{K}_{,b}}{\mathcal{K}}(k^2\pi_L - 3\Phi), \qquad v_{\mathrm{D}} = a^2\dot{\pi}_L\,.$$

Solids in cosmology: Growth of large-scale structure

Einstein equations read (Newtonian gauge):

$$3H\left(\dot{\Phi} + H\Psi\right) + \frac{k^2}{a^2}\Phi = -4\pi G\left(\delta\rho_{\mathrm{D}} + \delta\rho_{\mathrm{N}}\right)$$

$$\dot{\Phi} + H\Psi = 4\pi G\left[\left(\rho_{\mathrm{D}} + P_{\mathrm{D}}\right)v_{\mathrm{D}} + \left(\rho_{\mathrm{M}} + P_{\mathrm{M}}\right)v_{\mathrm{N}}\right],$$

$$\ddot{\Phi} + H\left(3\dot{\Phi} + \dot{\Psi}\right) + \left(3H^2 + 2\dot{H}\right)\Psi + \frac{k^2}{3a^2}(\Phi - \Psi) = 4\pi G\left(\delta P_{\mathrm{D}} + \delta P_{\mathrm{N}}\right),$$

$$\boxed{\Psi - \Phi = -\frac{64\pi G a^2}{9}\left(\mathcal{K}_{,Y} + \mathcal{K}_{,Z}\right)\pi_L,}$$

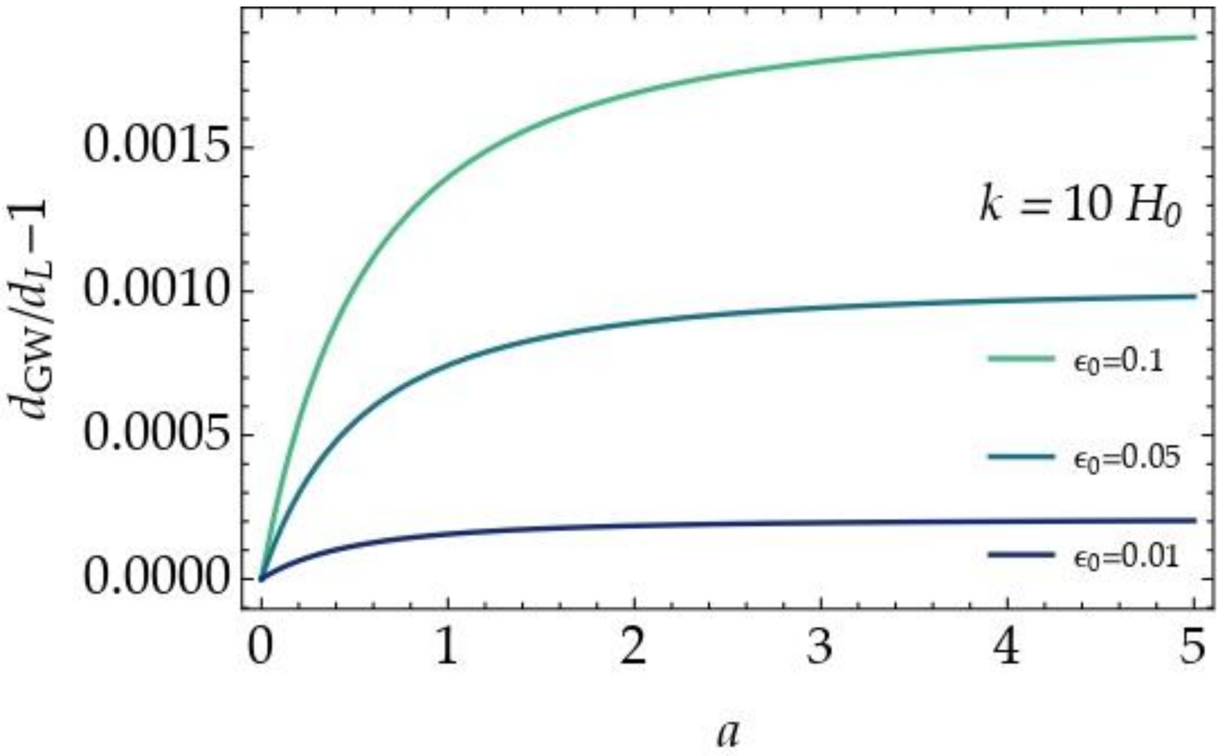
where

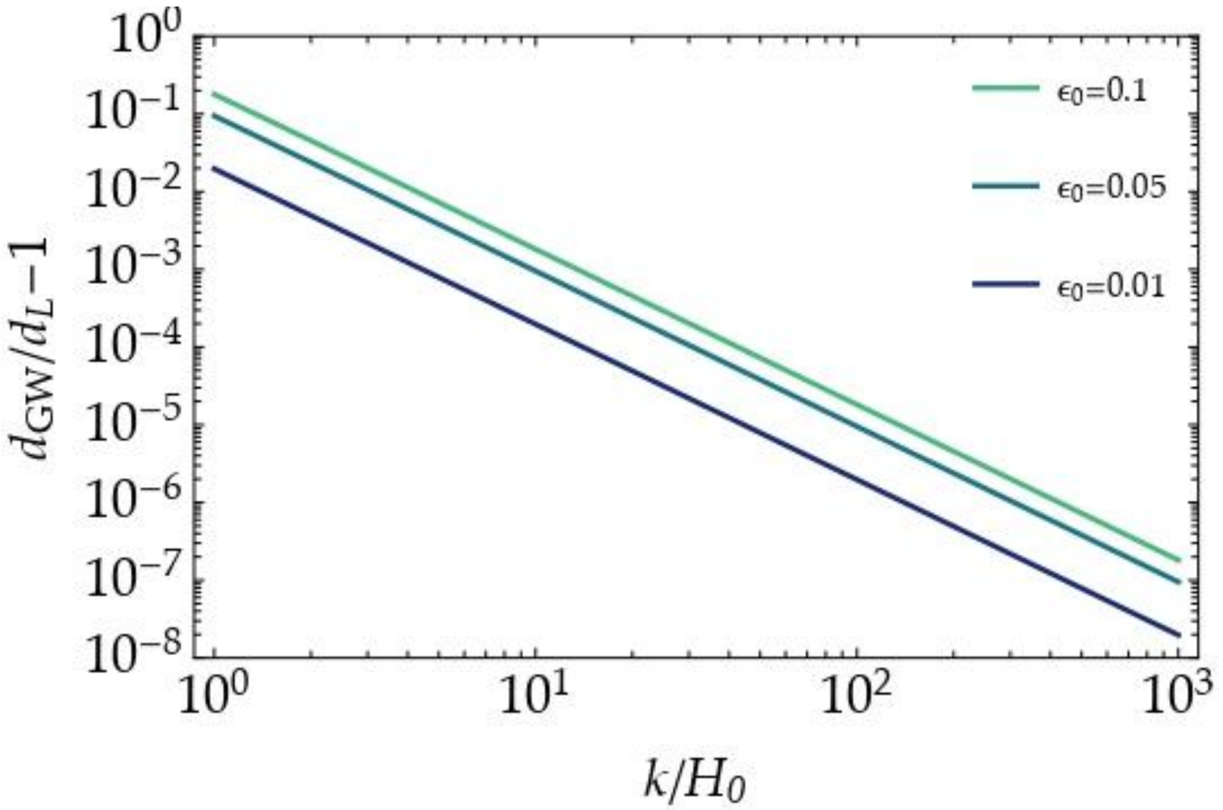
$$\delta\rho_{\mathrm{D}} = -2b\mathcal{K}_{,b}(k^2\Pi_L - 3\Phi), \qquad \left(\rho_{\mathrm{D}} + P_{\mathrm{D}}\right)v_{\mathrm{D}} = 2a^2 b\mathcal{K}_{,b}\dot{\Pi}_L\,, \qquad \delta P_{\mathrm{D}} = 2b\mathcal{K}_{,b}\left(1 + \frac{2b\mathcal{K}_{,bb}}{\mathcal{K}_{,b}}\right)(3\Phi - k^2\Pi_L)\,.$$

Unified dark sector model: observational signatures

Time-dependent mass term for GW

$$\ddot{h}_i + 3H\dot{h}_i + \left(\frac{k^2}{a^2} + M_{\rm GW}^2\right) h_i = 0\,, \qquad M_{\rm GW}^2 \equiv \frac{64\pi G}{9}\left(\mathcal{K}_{,Y} + \mathcal{K}_{,Z}\right)$$





Unified dark sector model: observational signatures

Evolution of propagations speeds:

$$\bar{c}_{\mathrm{T}}^2 = \frac{4\left(f_{,Y} + f_{,Z}\right)}{3(1+\alpha)\left(2\epsilon_0 r_f + 3\right) f} r_f, \qquad \bar{c}_{\mathrm{L}}^2 = \frac{3(1+\alpha)(2\epsilon_0 - 3)\left[\alpha(2\epsilon_0 - 3) + 2\epsilon_0\left(r_f + 1\right)\right] f + 16\left(r_f + 1\right)\left(f_{,Y} + f_{,Z}\right)}{9(1+\alpha)\left(r_f + 1\right)\left(2 r_f \epsilon_0 + 3\right) f} r_f, \qquad r_f = \left(\frac{\Omega_\Lambda}{\Omega_{\mathrm{DM}}} a^{(3-2\epsilon_0)}\right)^{1+\alpha}$$