Title: Axion-dilaton interactions in the dark sector

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Subject: Cosmology

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Abstract:

Axion-dilaton models provide a well-motivated, minimal class of models for which kinetic interactions between multiple scalar fields and their predictions can be explored, in particular in late time cosmology. I will review this class of models and present the formalism we developed for studying kinetic interactions between rapidly oscillating axion fields and their dilaton partners on cosmological scales.

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Axion-dilaton interactions in the dark sector

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Plan

- Why bother with multiple scalars & 2 derivative interactions?

- The case for axion-dilaton models

- The Madelung formalism (treatment of kinetically coupled axions)

- Applied to interesting phenomenological cases:
  - Minimal dark sector
  - Axion-like early dark energy

Beyond GR and LCDM

- Many signs of physics beyond GR and the standard model e.g. dark matter and dark energy
- Current experiments accommodate the possibility of these extensions being dynamical e.g. DESI
- Scalar fields provide a framework for studying how these extensions might interact and evolve

Scalar-tensor interactions

Scalar tensor theory in the low-energy semiclassical limit is at heart a derivative expansion

Typically well constrained locally

$$-\frac{\mathcal{L}_{\rm eff}}{\sqrt{-g}} = v^4 V(\theta) + \frac{M_p^2}{2}\, g^{\mu\nu}\Big[W(\theta)\, R_{\mu\nu} + G_{ij}(\theta)\, \partial_\mu\theta^i \partial_\nu\theta^j\Big]$$

$$+A(\theta)(\partial\theta)^4 + B(\theta)\, R^2 + C(\theta)\, R\, (\partial\theta)^2 + \frac{E(\theta)}{M^2}\, (\partial\theta)^6 + \frac{F(\theta)}{M^2}\, R^3 + \cdots$$

- Potential interactions have to be suppressed by symmetries

Multiple Scalar Reservations

More Scalars means more free parameters:

Want to consider scalars with simple couplings with few additional parameters

The form of multiple scalar interactions are very model dependent:

Want to consider scalars well motivated from generic extra-dimensional UV completions

Axion-dilaton Class

$$\mathcal{L}_{axio-dilaton} = -\frac{1}{2}M_p^2\sqrt{-g}\left[(\partial\chi)^2 + W^2(\chi)(\partial\mathfrak{a})^2\right]$$

Fundamental theory

- Combine into complex axion-dilaton fields in extra-dimensional UV completions

$$\Phi = \frac{1}{2}\left(e^{\zeta\chi} + i\mathfrak{a}\right)$$

Dilaton ≪=≫ Volume modulus

$$W = W_0 e^{-\zeta\chi}$$

Cosmology

- Dilaton is naturally light, DE scalar candidate

$$V = Ue^{-\lambda\chi}$$

- Axions have wide range of uses, e.g. CDM

$$V(\mathfrak{a}) = \frac{m_{\mathfrak{a}}^2}{2}\left(\mathfrak{a} - \mathfrak{a}_+\right)^2$$

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The Full Action

$$S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}M_p^2\left[R + \underbrace{\partial_\mu\chi\,\partial^\mu\chi}_{\text{Dilaton Kinetic Term}} + \underbrace{W^2(\chi)\,\partial_\mu\mathfrak{a}\,\partial^\mu\mathfrak{a}}_{\text{Axion Kinetic Term}}\right] + \underbrace{V(\chi,\mathfrak{a})}_{\text{Axio-dilaton Potential}}\right\} + \mathcal{L}_m(\Psi,\tilde{g})$$

The dilaton couples to matter as a pseudo-Brans-Dicke scalar:

$$\tilde{g}_{\mu\nu} := C^2(\chi)\,g_{\mu\nu} \qquad \frac{1}{\sqrt{-g}}\frac{\partial\mathcal{L}_m}{\partial\chi} = \mathbf{g}\rho_m$$

$$C(\chi) = e^{\mathbf{g}\chi} \qquad \boxed{m_B(\chi) = me^{\mathbf{g}\chi}}$$

The Full Action

$$S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}M_p^2\left[R + \underbrace{\partial_\mu\chi\,\partial^\mu\chi}_{\text{Dilaton Kinetic Term}} + \underbrace{W^2(\chi)\,\partial_\mu\mathfrak{a}\,\partial^\mu\mathfrak{a}}_{\text{Axion Kinetic Term}}\right] + \underbrace{V(\chi,\mathfrak{a})}_{\text{Axio-dilaton Potential}}\right\} + \mathcal{L}_m(\Psi,\tilde{g})$$

Everything dilaton related is a runaway exponential

$$m_B(\chi) = m e^{\mathbf{g}\chi}$$

+ How the axion couples to the SM!

$$W = W_0 e^{-\zeta\chi}$$

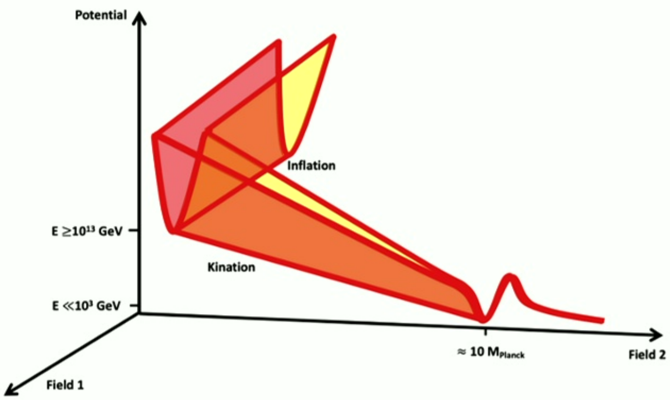
$$V = \mathcal{U}(\chi)e^{-\lambda\chi} + V(\mathfrak{a})$$

$$\mathcal{U}(\chi) = \mathcal{U}_0\left[1 - u_1\chi + \frac{u_2}{2}\chi^2\right]$$

Potential Motivations

$$V = \mathcal{U}(\chi)e^{-\lambda\chi} + V(\mathfrak{a}) \qquad \mathcal{U}(\chi) = \mathcal{U}_0\left[1 - u_1\chi + \frac{u_2}{2}\chi^2\right]$$

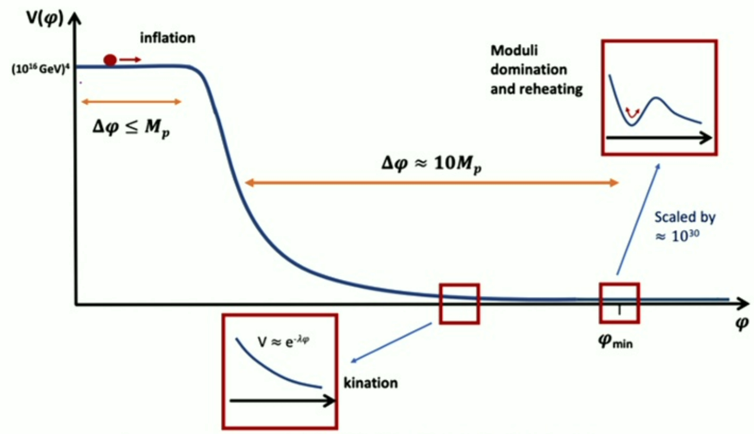
In the String phenomenology literature



Cicoli et al (2023) 2303.04819

String Cosmology: from the Early Universe to Today

Michele Cicoli, Joseph P. Conlon, Anshuman Maharana, Susha Parameswaran, Fernando Quevedo, Ivonne Zavala



Apers et al (2024) 2401.04064

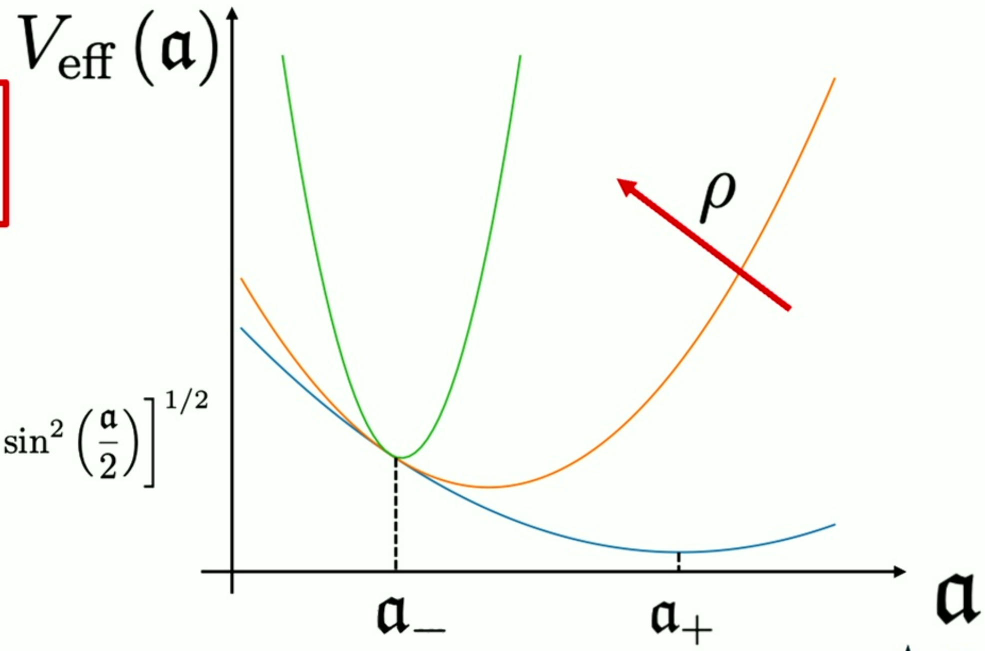
String Theory and the First Half of the Universe

Fien Apers, Joseph P. Conlon, Edmund J. Copeland, Martin Mosny, Filippo Revello

Axion Phenomenology

$$V(\mathfrak{a}) = \frac{m_{\mathfrak{a}}^2}{2}(\mathfrak{a} - \mathfrak{a}_+)^2 \qquad U(\mathfrak{a}) = \frac{(\mathfrak{a} - \mathfrak{a}_-)^2}{2\Lambda_{\mathfrak{a}}^2}$$

$$V_{\text{eff}}(\mathfrak{a}) = V(\mathfrak{a}) + U(\mathfrak{a})\rho$$



e.g. The QCD Axion

$$V_{QCD}(\mathfrak{a}) = \Lambda^4 v(\mathfrak{a}) \quad \text{with} \quad v(\mathfrak{a}) \simeq -\left[1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{\mathfrak{a}}{2}\right)\right]^{1/2}$$

$$U_{\text{QCD}} = A\,|\cos(\mathfrak{a})|$$

The Madelung Formalism

Problem: Interested in cases where the axion oscillates around it's VEV much faster than the cosmological scale

Need to switch to a fluid description

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{x},t) = \left[\frac{-\hbar^2}{2m}\nabla^2 + V(\mathbf{x})\right]\psi(\mathbf{x},t)$$

$$\psi = \sqrt{\rho_m(\mathbf{x},t)}e^{iS(\mathbf{x},t)/\hbar}$$

$$\partial_t\rho_m + \nabla\cdot(\rho_m\mathbf{v}) = 0,$$

$$\frac{d\mathbf{v}}{dt} = \partial_t\mathbf{v} + \mathbf{v}\cdot\nabla\mathbf{v} = -\frac{1}{m}\nabla(Q+V)$$

$$\mathbf{v} = \frac{\nabla S}{m(t)}$$

The Madelung Formalism

$$V(\mathfrak{a}) = \frac{m_\mathfrak{a}^2}{2}(\mathfrak{a} - \mathfrak{a}_+)^2 \qquad U(\mathfrak{a}) = \frac{(\mathfrak{a} - \mathfrak{a}_-)^2}{2\Lambda_\mathfrak{a}^2}$$

$$\rho_{th} = m_\mathfrak{a}^2 \Lambda_\mathfrak{a}^2$$

$$\Box\mathfrak{a} + 2\frac{W_{,\chi}(\chi)}{W(\chi)}\partial_\mu \chi \partial^\mu \mathfrak{a} - \frac{1}{W^2 M_{PL}^2}(V_{,\mathfrak{a}} + U_{,\mathfrak{a}}\,\rho) = 0$$

$$\mathfrak{a} = \bar{\mathfrak{a}}(\bar{\rho}) + \frac{1}{\sqrt{2}}\left(e^{-i\int_0^t dt\,\mathfrak{m}(t)}\psi + e^{i\int_0^t dt\,\mathfrak{m}(t)}\psi^\star\right), \quad \text{where} \quad \mathfrak{m}^2(t) = \frac{m_\mathfrak{a}^2}{W^2(\bar{\chi})}\left(1 + \frac{\rho}{\rho_{th}}\right)$$

$$\psi = \frac{1}{\mathfrak{m}(t)}\sqrt{\rho_\mathfrak{a}}\, e^{iS}$$

- Substitute into action and average over oscillations

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Perturbation Theory

$$\partial_t\left([1-\Phi-3\Psi]\,W^2\rho_{\mathfrak{a}}\right)+\left(3H-\frac{\dot m}{m}\right)W^2\rho_{\mathfrak{a}}+\frac{1}{a}\vec{\nabla}.\left([1+\Phi-\Psi]\,W^2\rho_{\mathfrak{a}}\vec{v}_{\mathfrak{a}}\right)=0$$

Relativistic Euler and Continuity equations for an irrotational fluid!

$$\partial_t\mathbf{p}_{\mathfrak{a}}+H\,\mathbf{p}_{\mathfrak{a}}=-\frac{m}{a}\nabla\left[\Phi+\tfrac{1}{2}v_{\mathfrak{a}}^2+\Phi_\chi+\Phi_\rho+\Phi_Q\right]$$

Coupling to Dilaton

Coupling to matter

Quantum Pressure

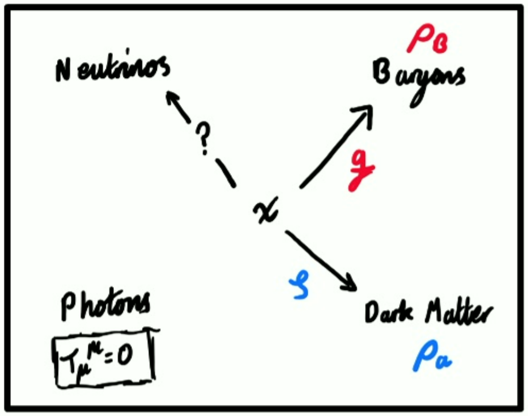
$$\partial_t\rho_m+\nabla\cdot(\rho_m\mathbf{v})=0,$$

$$\frac{d\mathbf{v}}{dt}=\partial_t\mathbf{v}+\mathbf{v}\cdot\nabla\mathbf{v}=-\frac{1}{m}\nabla(Q+V)$$

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{x},t)=\left[\frac{-\hbar^2}{2m}\nabla^2+V(\mathbf{x})\right]\psi(\mathbf{x},t)$$

Applying this stuff....

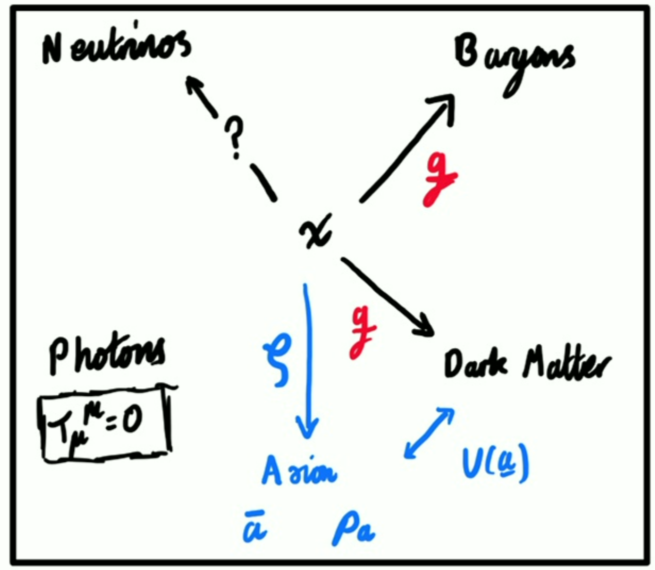
Uncoupled Axion plays the role of Dark Matter



$$\bar{\rho}_{\text{ax}} = \frac{C\mathfrak{m}(t)}{a^3}$$

$$\mathfrak{m}^2(t) = \frac{m_{\mathfrak{a}}^2}{W^2(\bar{\chi})}\left(1 + \frac{\rho}{\rho_{th}}\right)$$

Axion can couple to other species of matter



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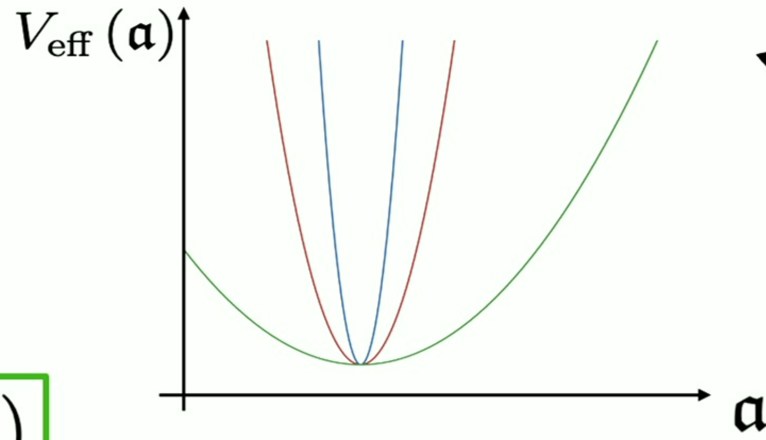
Dark Matter Axion

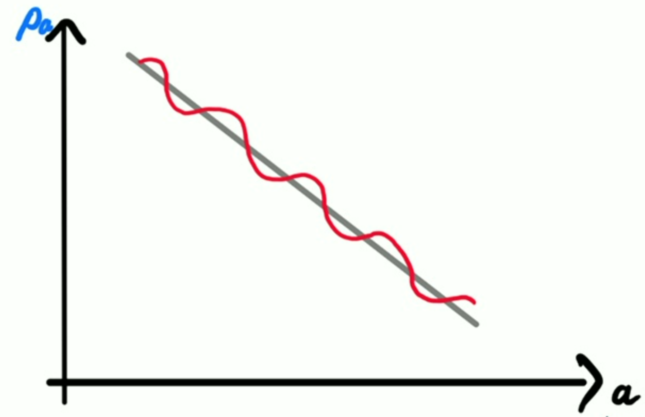
- Axion only couples to dilaton

$$\mathfrak{m}^2(t) = \frac{m_{\mathfrak{a}}^2}{W^2(\bar{\chi})}\left(1 + \cancel{\frac{\rho}{\rho_{th}}}\right)$$



- No evolution of VEV

$$\bar{\rho}_{\rm ax} = \frac{C\mathfrak{m}(t)}{a^3}$$



- Axion can behave as a component of dark matter

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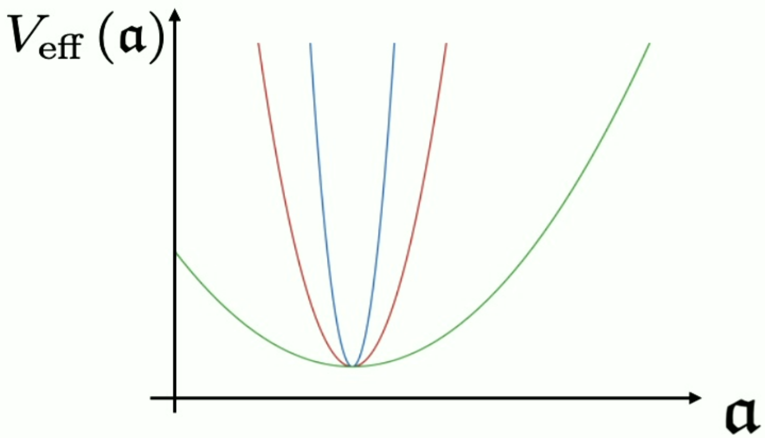
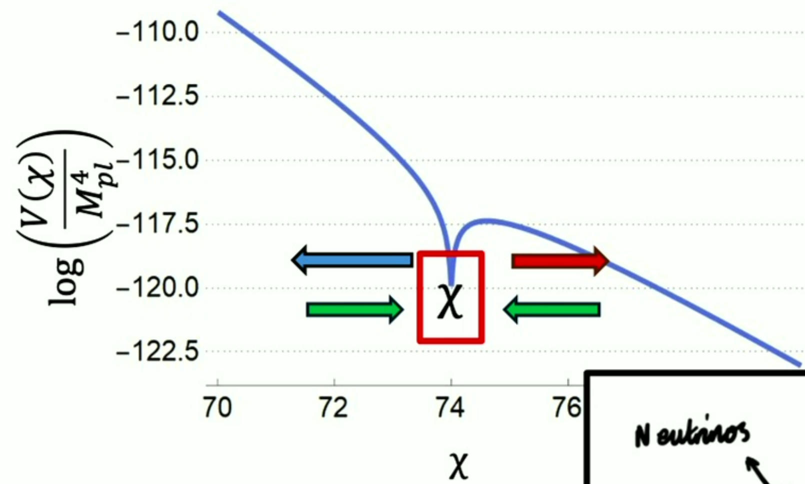
Axion

$$W = W_0 e^{-\zeta\chi}$$

Dilaton

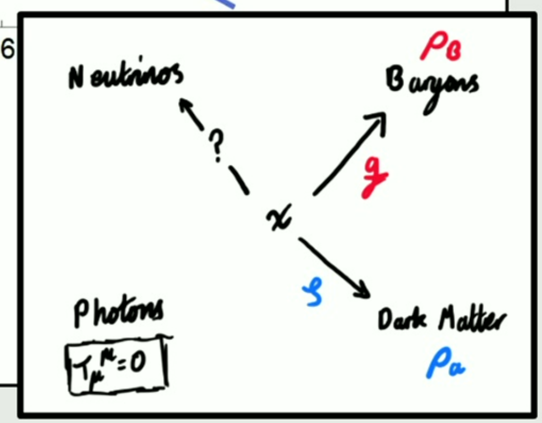
$$\bar{\chi}'' + 2\mathcal{H}\bar{\chi}' + \frac{a^2}{M_p^2} V_{,\chi} = \frac{a^2}{M_p^2}\left(-\mathbf{g}\bar{\rho}_B - \zeta\bar{\rho}_{\rm ax}\right)$$



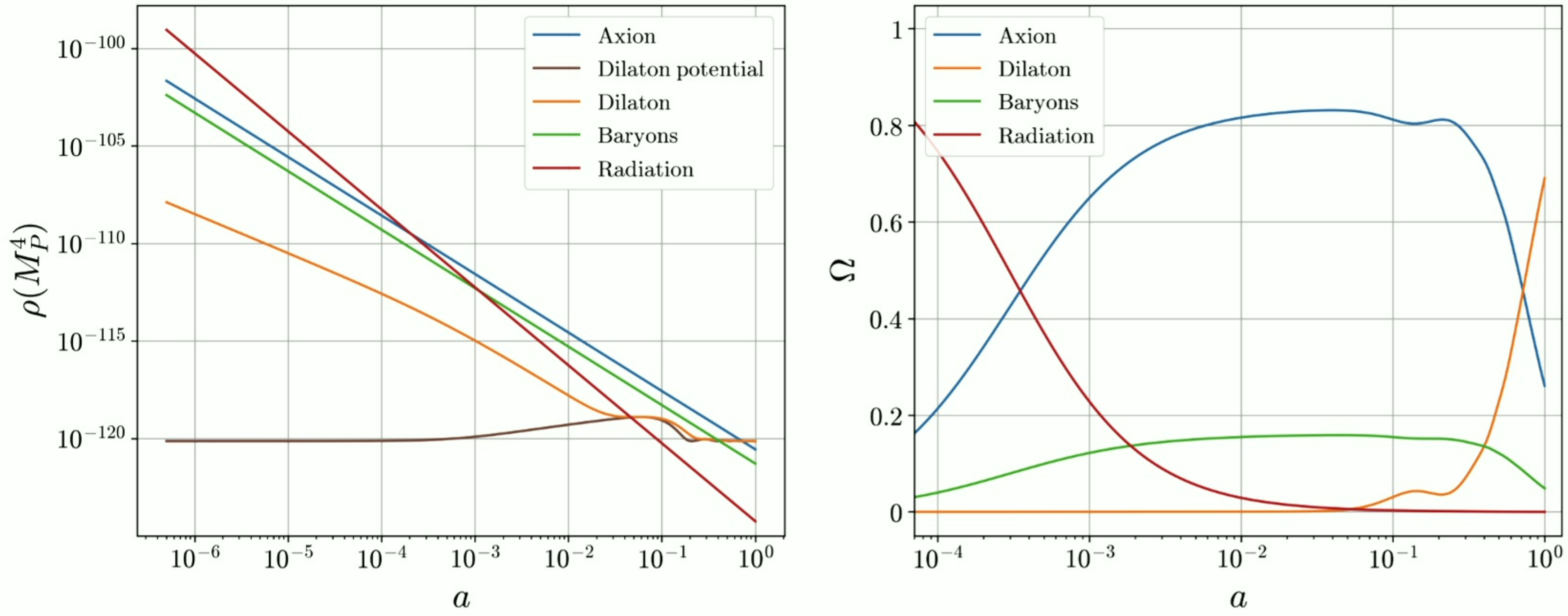


$$\bar{\rho}_{\rm ax} = \frac{C\mathfrak{m}(t)}{a^3}$$

$$\mathfrak{m}^2(t) = \frac{m_{\mathfrak{a}}^2}{W^2(\bar{\chi})}$$



Minimal Dark Sector



$$\zeta = 0.1 \quad \text{and} \quad \mathbf{g} = -10^{-3}$$

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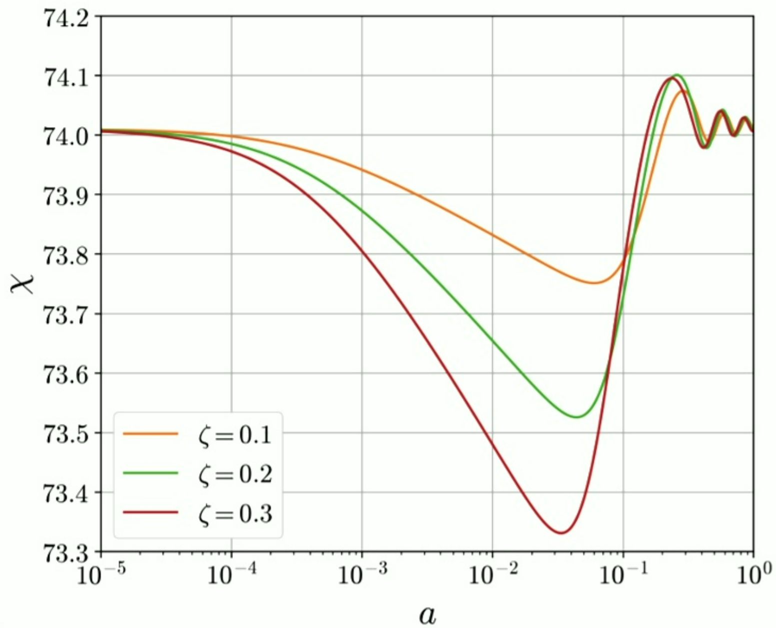
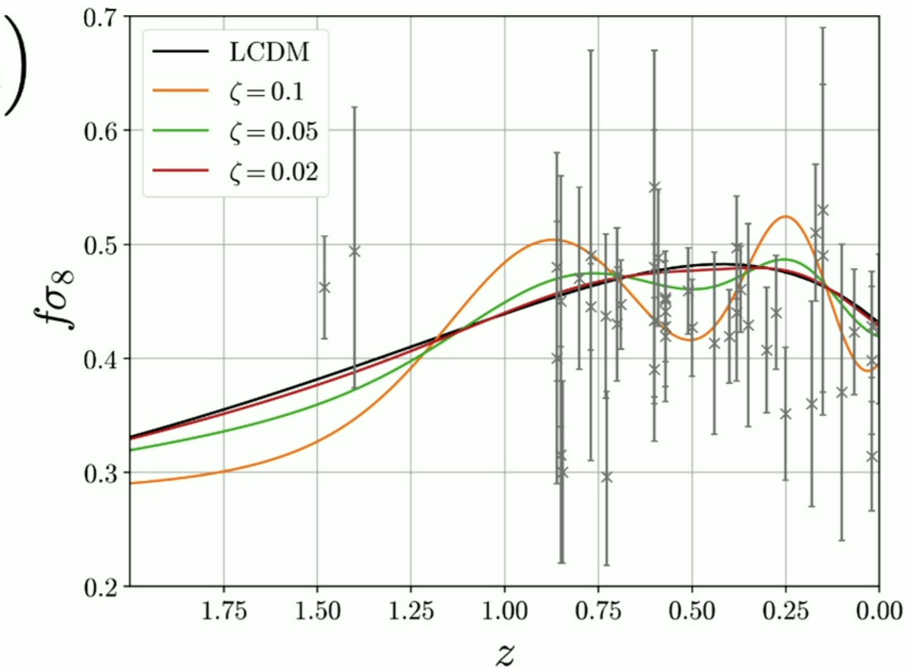
1. Structure Growth

$$\bar{\chi}'' + 2\mathcal{H}\bar{\chi}' + \frac{a^2}{M_p^2}V_{,\chi} = \frac{a^2}{M_p^2}\left(-\mathbf{g}\bar{\rho}_B - \zeta\bar{\rho}_{\mathrm{ax}}\right)$$





$$f\sigma_8 = \frac{\sigma_8(z, k_{\sigma 8})}{\mathcal{H}}\frac{\delta_m'(z, k_{\sigma 8})}{\delta_m(z, k_{\sigma 8})}$$

$$\mathbf{g} = -10^{-3}$$

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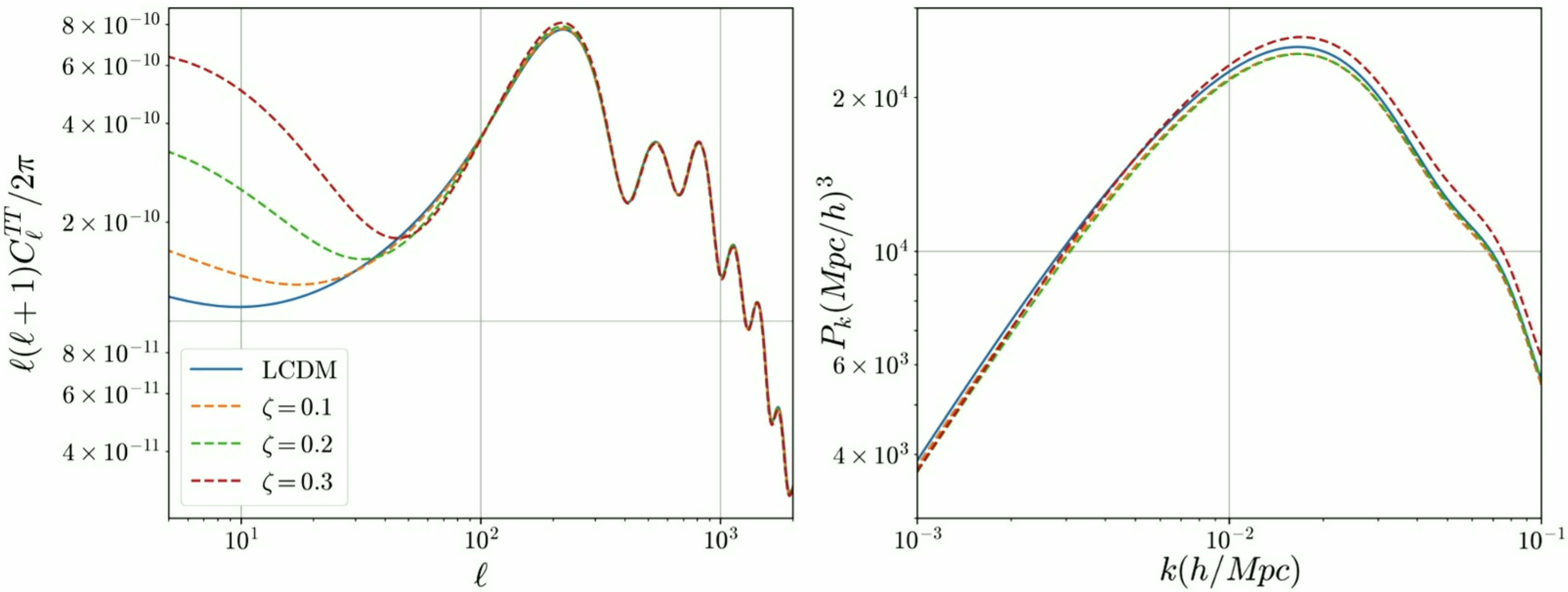
Data points catalogued from SDSS redshift space distortions

2. Power Spectra of the CMB



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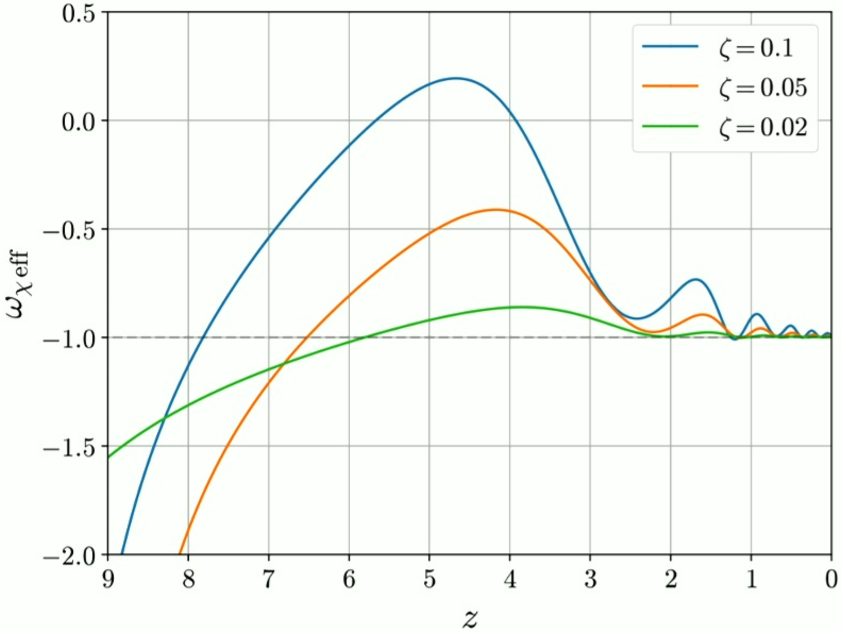
The effective equation of state



- The preference for a phantom equation of state from DESI results assumes matter species evolve $\propto 1/a^3$
- To compare we extract the matter-coupling energy density and give it to the dilaton

$$\rho_\chi^{\mathrm{eff}} = \rho_\chi + \left[\frac{W(\chi_0)}{W(\chi)} - 1\right]\frac{\rho_{\mathrm{ax}0}}{a^3}$$

$$\omega_{\chi\,\mathrm{eff}} = \frac{\omega_\chi(\chi)}{1 + \left[e^{\zeta(\chi-\chi_0)} - 1\right]\frac{\rho_{\mathrm{ax}0}}{a^3\rho_\chi}}$$

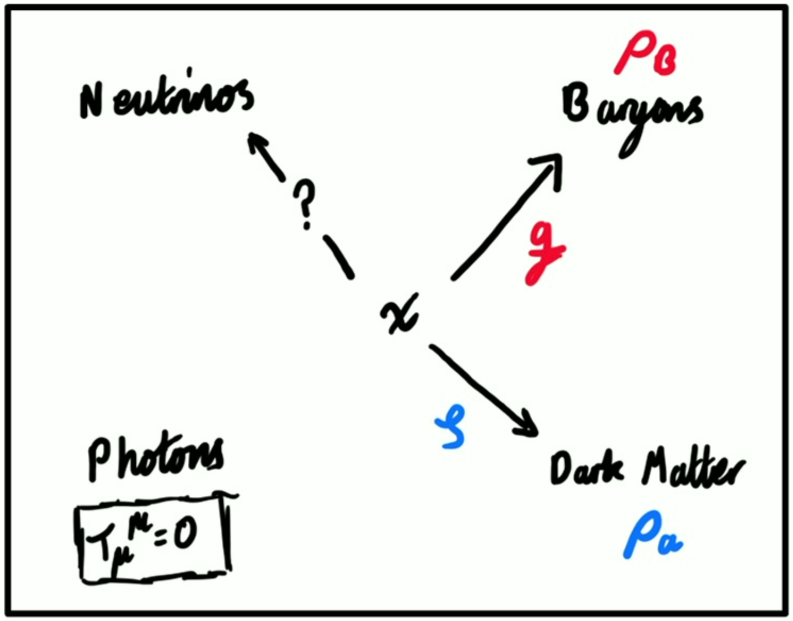
Quick Recap

- Axion can play the role of dark matter
- Dilaton can play the role of dark energy

- Interactions between them can give:

i. Oscillations in structure growth
ii. Oscillations in particle masses
iii. Deviations in the CMB

- What happens when the axion plays the role of another dark sector component?



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