Interacting dark sector: mapping fields and fluids, and observational signatures

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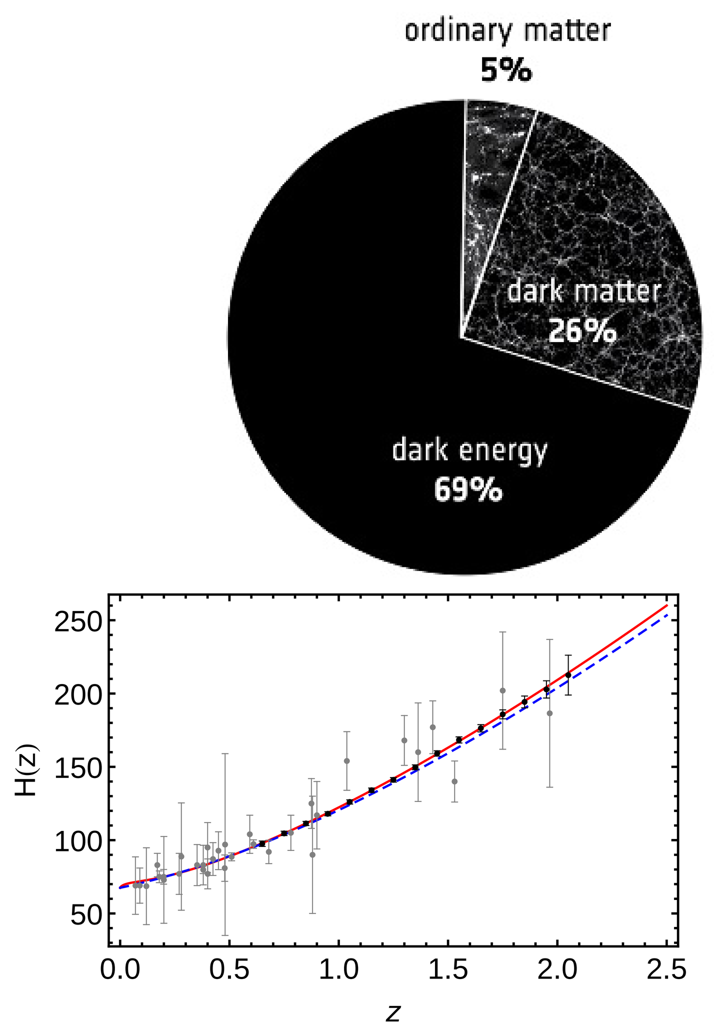
Joseph P Johnson[†], **Archana Sangwan and S. Shankaranarayanan**

[†]josephpj@iitb.ac.in

Department of Physics, IIT Bombay

Dark sector in the late universe



- Energy budget of the late universe is dominated by the dark energy and dark matter ($\sim 95\%$).
- Interaction between the dark sector and ordinary matter is purely gravitational.
- Current observations does not rule out the interaction between dark matter and dark energy.
- Can interacting dark sector alleviate H_0 tension ?
- Equivalent fluid and field theory descriptions of interacting dark sector.
- Potential observational signatures of interacting dark sector.

Fig.Source: ESA, arXiv:1712.07555

$$\nabla^\mu T^{(\mathrm{DE,DM})}_{\mu\nu} = Q^{(\mathrm{DE,DM})}_\nu, \nabla^\mu T^{(tot)}_{\mu\nu} = Q^{(\mathrm{DE})}_\nu + Q^{(\mathrm{DM})}_\nu = 0$$

DE-DM Interaction

Action formalism

Introduced by hand (Phenomenological)

Field theory description

Fluid description

Equivalent ?

Scalar field DE & scalar field DM

Background & Perturbation

Scalar field DE & fluid DM

$f(\tilde{R},\tilde{X})$ model $\rightarrow$ interacting scalar fields

[JPJ & SS-2020]

- We consider the following action

$$S_J = \int d^4x\sqrt{-\tilde{g}}\left[\frac{1}{2\kappa^2}f(\tilde{R},\tilde{X}) - \frac{1}{2}\tilde{g}^{\mu\nu}\tilde{\nabla}_\mu\tilde{X}\tilde{\nabla}_\nu\tilde{X} - V(\tilde{X})\right]$$

- Do a conformal transformation

$$g_{\mu\nu} = \Omega^2\tilde{g}_{\mu\nu}, \quad \text{where} \quad \Omega^2 = F(\tilde{R},\tilde{X}) \equiv \frac{\partial f(\tilde{R},\tilde{X})}{\partial\tilde{R}}$$

- Redefine the scalar fields

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa^2}R - \frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi - U(\phi) - \frac{1}{2}e^{2\alpha(\phi)}g^{\mu\nu}\nabla_\mu X\nabla_\nu X - e^{4\alpha(\phi)}V(X)\right).$$

Fluid description of the interacting dark sector

- Define the energy density ρ_m, pressure p_m and four velocity u_μ of the dark matter fluid as

$$\rho_m = -\frac{1}{2}e^{2\alpha}\left[g^{\mu\nu}\nabla_\mu X\nabla_\nu X - e^{2\alpha}V(X)\right]$$

$$p_m = -\frac{1}{2}e^{2\alpha}\left[g^{\mu\nu}\nabla_\mu X\nabla_\nu X + e^{2\alpha}V(X)\right]$$

$$u_\mu = -\left[-g^{\alpha\beta}\nabla_\alpha X\nabla_\beta X\right]^{-\frac{1}{2}}\nabla_\mu X$$

- Energy momentus tensor $T^{(m)}_{\mu\nu} = p_m g_{\mu\nu} + (\rho_m + p_m)u_\mu u_\nu$
- Interaction term

$$Q^{(F)}_\nu = \nabla_\mu T^{(m)\mu}_\nu = -e^{2\alpha(\phi)}\alpha_{,\phi}(\phi)\nabla_\nu\phi\left[\nabla^\sigma X\nabla_\sigma X + 4e^{2\alpha(\phi)}V(X)\right]$$

$$= -\alpha_{,\phi}(\phi)\nabla_\nu\phi(\rho_m - 3p_m) = T^{(m)}\nabla_\nu\alpha(\phi)$$

Not all the models show this equivalence

[JPJ & SS-2020]

Interacting DE-DM model	**DE-DM Interaction** $\nabla^\mu T^{(\mathrm{DE,DM})}_{\mu\nu} = Q^{(\mathrm{DE,DM})}_\nu$	**Is $Q_\nu \propto Q^{(F)}_\nu$?**
Amendola - 1999 [32]	$\dot\rho_m + 3H\rho_m = -C\rho_m\dot\phi$	Yes
Amendola - 1999 [33]	$\dot\rho_m + 3H\rho_m = -C\rho_m\dot\phi$	Yes
Billyard & Coley -1999 [34]	$\dot\phi(\ddot\phi + 3H\dot\phi + kV) = \frac{(4-3\gamma)}{2\sqrt{\omega+\frac{3}{2}}}\dot\phi\mu$	Yes
Olivares.etal - 2005 [35]	$\frac{d\rho_c}{dt} + 3H\rho_c = 3Hc^2(\rho_c + \rho_x)$	No
Amendola.etal - 2006 [36]	$\dot\rho_{DM} + 3H\rho_{DM} - \delta(a)H\rho_{DM} = 0$	No
Olivares.etal - 2007 [37]	$\dot\rho_c + 3H\rho_c = 3Hc^2(\rho_x + \rho_c)$	No
Boehmer.etal - 2008 [38]	$\dot\rho_c + 3H\rho_c = -\sqrt{2/3}\kappa\beta\rho_c\dot\phi$ $\dot\rho_c + 3H\rho_c = -\alpha H\rho_c$	Yes No
Caldera-Cabral.etal - 2008 [39]	$\dot\rho_c = -3H\rho_c + 3H(\alpha_x\rho_x + \alpha_c\rho_c)$ $\dot\rho_c = -3H\rho_c + 3(\Gamma_x\rho_x + \Gamma_c\rho_c)$	No No

Background evolution and constraints

- Matter energy density $\overline{\rho}_m = \overline{\rho}_{m_0}a^{-3(1+\omega_m)}e^{[\alpha(\overline{\phi})-\alpha_0](1-3\omega_m)}$

Data set	**1σ Confidence**	**2σ confidence**	**3σ confidence**	Best-fit values
Hz	$64.19\leq H_0 \leq 72.11$ $0.24\leq \Omega_m \leq 0.34$ $-1\leq w_0 \leq -0.67$ $-1\leq C \leq 1$	$61.19\leq H_0 \leq 74.12$ $0.21\leq \Omega_m \leq 0.39$ $-1\leq w_0 \leq -0.24$ $-1\leq C \leq 1$	$59.76\leq H_0 \leq 75.91$ $0.19\leq \Omega_m \leq 0.43$ $-1\leq w_0 \leq 0.04$ $-1\leq C \leq 1$	$H_0=69.34$ $\Omega_m=0.29$ $w_0=-0.989$ $C=0.98$
BAO+Hz	$69.31\leq H_0 \leq 71.61$ $0.269\leq \Omega_m \leq 0.309$ $-1\leq w_0 \leq -0.989$ $-1\leq C \leq -0.261$	$68.95\leq H_0 \leq 71.98$ $0.264\leq \Omega_m \leq 0.316$ $-1\leq w_0 \leq -0.987$ $-1\leq C \leq -0.132$	$68.42\leq H_0 \leq 72.57$ $0.254\leq \Omega_m \leq 0.32$ $-1\leq w_0 \leq -0.985$ $-1\leq C \leq 0.067$	$H_0=70.4$ $\Omega_m=0.29$ $w_0=-0.997$ $C=-0.63$
HIIG	$67.78\leq H_0 \leq 77.2$ $0.091\leq \Omega_m \leq 0.447$ $-1\leq w_0 \leq -0.87$ $-1\leq C \leq 1$	$66.29\leq H_0 \leq 78.9$ $0.041 \leq \Omega_m \leq 0.53$ $-1\leq w_0 \leq -0.84$ $-1\leq C \leq 1$	$64.07\leq H_0 \leq 80$ $0.01\leq \Omega_m \leq 0.6$ $-1\leq w_0 \leq -0.81$ $-1\leq C \leq 1$	$H_0=72.49$ $\Omega_m=0.25$ $w_0=-0.92$ $C=-0.94$
SN+Hz	$69.18\leq H_0 \leq 70.02$ $0.25\leq \Omega_m \leq 0.33$ $-1\leq w_0 \leq -0.97$ $-1\leq C \leq -0.51$	$69.06\leq H_0 \leq 70.19$ $0.24\leq \Omega_m \leq 0.34$ $-1\leq w_0 \leq -0.93$ $-1\leq C \leq 1$	$68.87\leq H_0 \leq 70.36$ $0.22\leq \Omega_m \leq 0.35$ $-1\leq w_0 \leq -0.9$ $-1\leq C \leq 1$	$H_0=69.51$ $\Omega_m=0.31$ $w_0=-1$ $C=-0.69$

- Need to look at perturbed evolution to detect the signatures of interacting dark sector

Evolution of first order perturbations : Fluid description

- Evolution of dark energy scalar field and dark matter fluid

$$\delta\dot{\rho}_m + 3H(\delta p_m + \delta\rho_m) + (\bar{p}_m + \bar{\rho}_m)\left[\frac{\nabla^2 \delta u^s}{a^2} - 3\dot{\Psi}\right] = -\delta Q$$

$$\dot{\bar{\phi}}\left(\delta\ddot{\phi} - \frac{\nabla^2\delta\phi}{a^2} - 2\Phi\ddot{\bar{\phi}} + U_{,\phi\phi}(\bar{\phi})\delta\phi\right) + \delta\dot{\phi}\left(\ddot{\bar{\phi}} + 6H\dot{\bar{\phi}} + U_{,\phi}(\bar{\phi})\right) - \frac{\dot{\bar{\phi}}^2}{2}\left(3\dot{\Psi} + \dot{\Phi} + 6H\Phi\right) = \delta Q,$$

- where

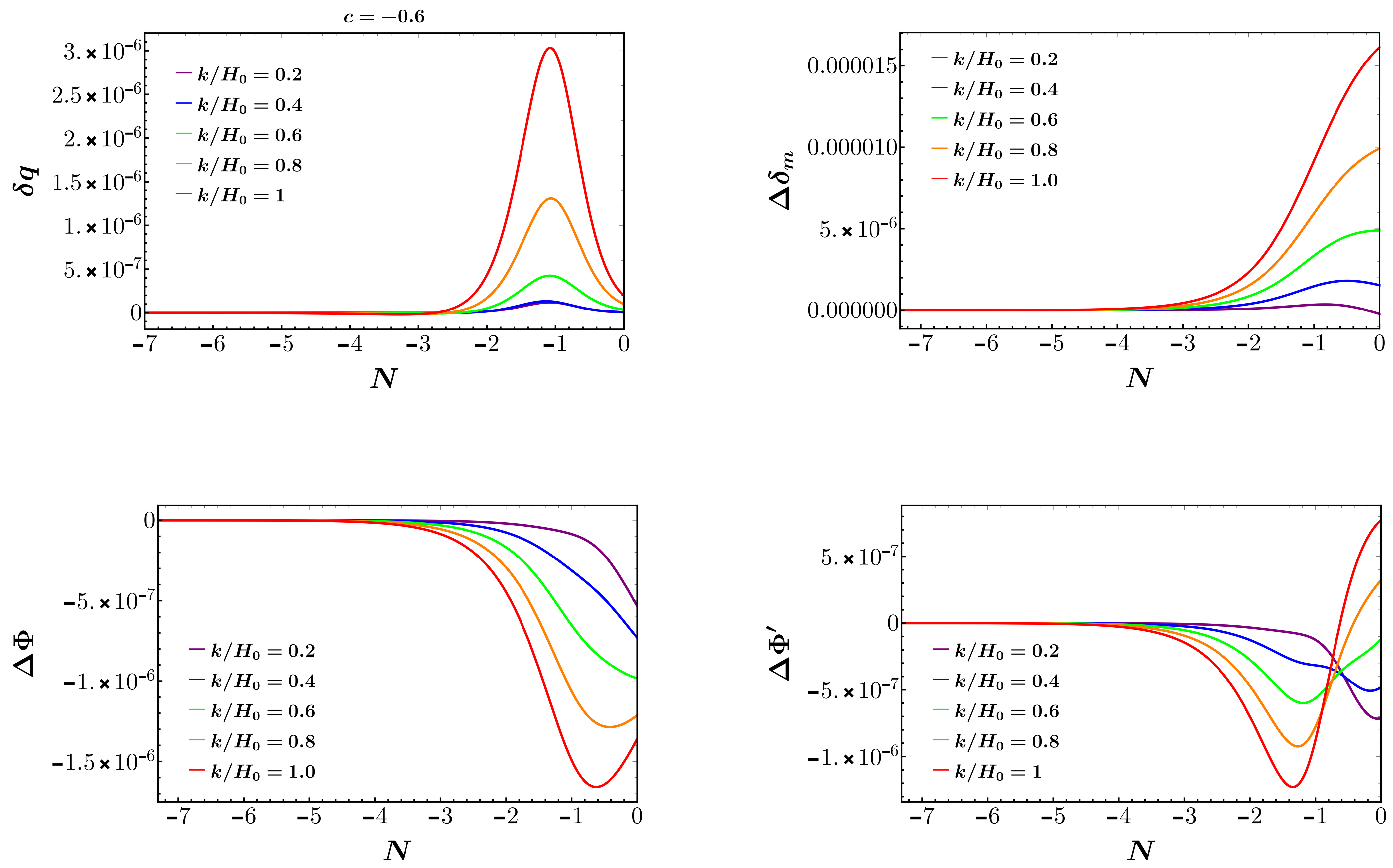
$$\delta Q^{(\mathrm{F})} = -(\delta\rho_m - 3\delta p_m)\alpha_{,\phi}(\bar{\phi})\dot{\bar{\phi}} - (\bar{\rho}_m - 3\bar{p}_m)\left[\alpha_{,\phi\phi}(\bar{\phi})\dot{\bar{\phi}}\delta\phi + \alpha_{,\phi}(\bar{\phi})\delta\dot{\phi}\right]$$

Evolution of observables

[JPJ.etal-2021]

- Three perturbed quantities related to:
  1. Structure formation: δ_m
  2. Weak gravitational lensing: $\Phi + \Psi$
  3. Integrated Sachs Wolfe effect: $\Phi' + \Psi'$
- Evolve the first order perturbations in the range $0 < z < 1500$
- Study the effect of DE-DM interaction on the evolution of perturbed quantities at different length scales

$$\Delta\delta_m = \delta_{m_i} - \delta_{m_{ni}}, \quad \Delta\Phi = \Phi_i - \Phi_{ni}, \quad \Delta\Phi' = \Phi'_i - \Phi'_{ni}$$



Key points

- Interacting dark sector can be obtained from a classical field theory action.
- Field theory action can be obtained from $f(\tilde{R}, \tilde{\chi})$ via conformal transformation.
- Energy-momentum of individual components of dark sector is not conserved.
- There is a one to one mapping between field theory description and fluid description of interacting dark sector for a unique interaction term $Q^{(F)}$.
- Analysis of background evolution alone is not sufficient to constrain the interaction.
- Cosmological observations related to the LSS, Lensing and ISW effect can potentially detect the signatures of dark matter - dark energy interaction.