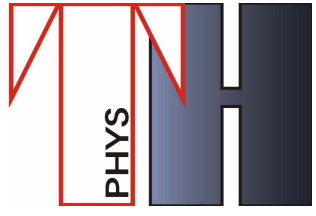
Dark matter-dark energy interactions and their cosmological implications

Matteo Lucca
Université Libre de Bruxelles (ULB)

Based on
Lucca & Hooper 2020 [2002.06127]
and Lucca 2021a [2105.09249]

Presentation for the
16th Marcel Grossmann Meeting



The model

Dark matter-dark energy interactions:

- **Main difference** with respect to ΛCDM: DM and DE **energy densities not conserved singularly** but coupled via an energy transfer function Q

$$\dot{\rho}_c + 3H\rho_c = Q \quad \text{and} \quad \dot{\rho}_x + 3H\rho_x(1+w_x) = -Q$$

- **Many possible choices for coupling function** due to large freedom in the phenomenology of the interaction

$$\mathcal{L} = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - V(\varphi) + i\bar{\psi}\partial\!\!\!/\psi + M(\varphi)\bar{\psi}\psi\,,$$

where $V(\varphi)$ is the scalar field potential and $M(\varphi)$ is a time-varying mass term describing the interaction between the fields.
$\rightarrow$ Q can be shown to be a function of $V(\varphi)$ and $M(\varphi)$, and inherits therefore the same freedom

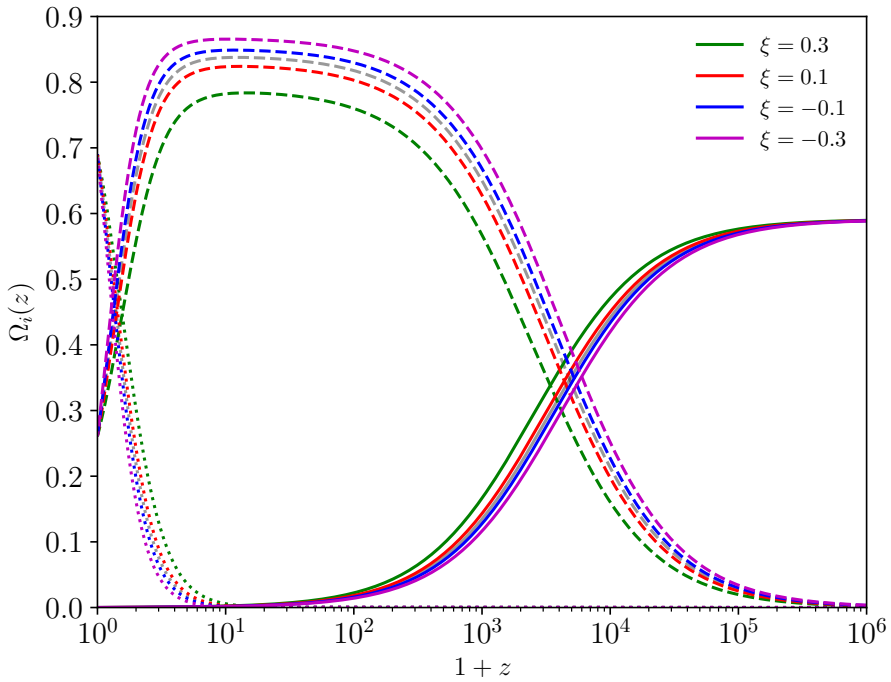
- Intuitive approach: dependence on the fluids' energy densities and H
- One of the most **stable and successful options** is $Q = \xi H \rho_x$ (Gavela et al. '09, '10 [0901.1611, 1005.0295], Di Valentino et al. '17, '19 [1704.08342, 1908.04281], see also David Wands' talk for alternatives), with clear cosmological meaning: from $\dot{\rho}_x = -Q$ (with $w_x \simeq -1$) and $\rho_x = \Lambda/(8\pi G)$ one has that

$$Q = -\dot{\Lambda}/(8\pi G) = \xi H \rho_x$$

  if $\Lambda = \Lambda_0 (1+z)^\xi$ and not constant as in ΛCDM.
- As a consequence of this choice:
  1. If ξ is zero: one recovers ΛCDM
  2. If ξ is negative: the energy flows from the DM to the DE (iDMDE model)
  3. If ξ is positive: the energy flows from the DE to the DM (iDEDM model)

Key consequences:

- If ξ is negative (positive) Ω_c increases (decreases) in the past with respect to ΛCDM, while Ω_x decreases (increases)



- The Hubble parameter increases (decreases) during the MD epoch
- The redshift of matter-radiation equality z_{eq} increases (decreases)

- When ξ is negative:
  1. Ω_c needs to be lowered to preserve a good fit to the data
  2. The last-scattering distance $r_a(z_d) = \int_0^{z_d} \mathrm{d}z/H(z)$ with $H(z) \simeq H_0 \left(\Omega_c(z) + \Omega_x(z)\right)^{1/2}$ needs to stay constant because the sound horizon $r_s(z_d)$ is (almost) unmodified and the angular scale of the sound horizon $\theta_s = r_s(z_d)/r_a(z_d)$ is fixed
  3. Since $\Omega_x(z)$ can decrease very rapidly H_0 can be increased

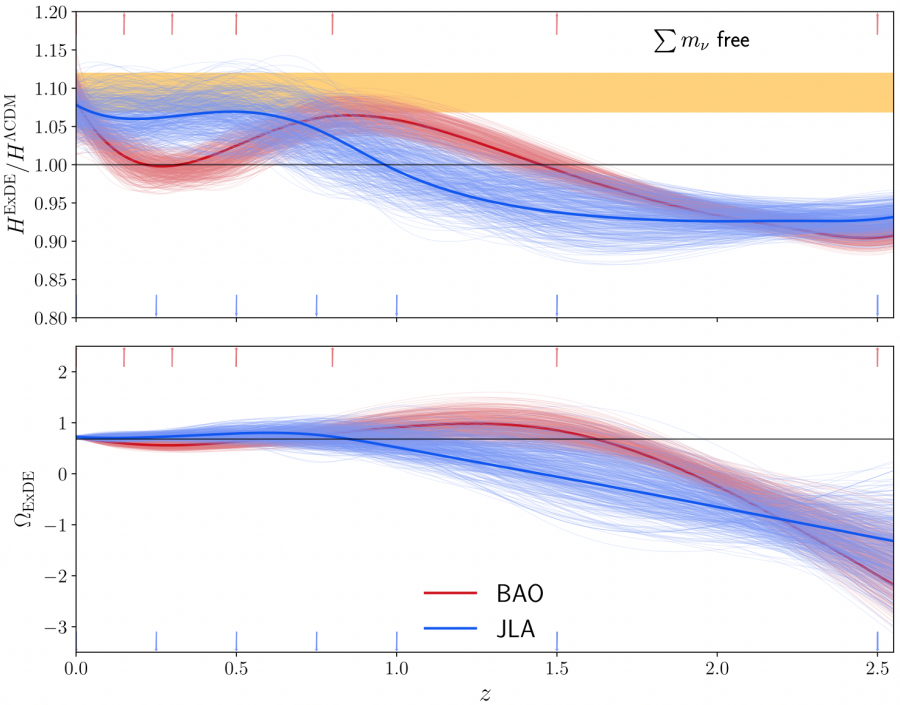
  $\rightarrow$ **iDMDE** model potentially good candidate to solve H_0 **tension**
- When ξ is positive:
  1. Ω_c needs to be increased but only to a point where z_{eq} can still decrease
  2. In this way the scale of matter-radiation equality $k_{eq} \propto \sqrt{\omega_m(1+z_{\rm eq})}$ and therefore the amplitude of the matter power spectrum can do so too
  3. S_8 can be lowered

  $\rightarrow$ **iDEDM** model potentially good candidate to solve S_8 **tension**

DM-DE interactions as a solution to the H_0 tension (the iDMDE model)

Generalities of late-time "solutions":

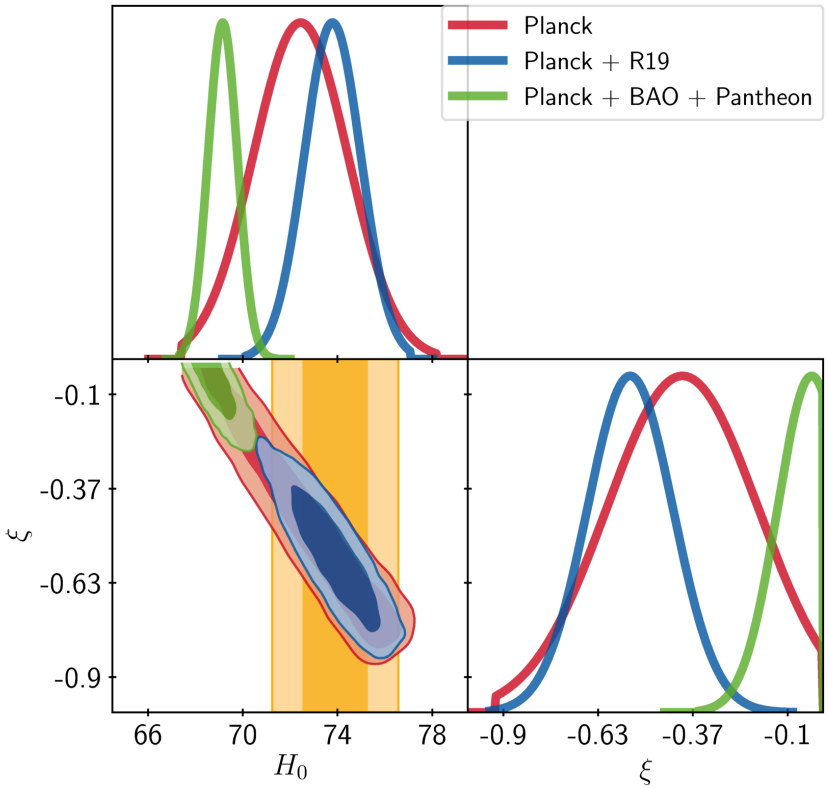
- **CMB anisotropy data alone unsuitable** to constrain late-time modifications of ΛCDM (only effect is to enlarge error bars)
- Fundamental to consider at least **BAO and SNIa data**, which have however been shown to **strongly prefer ΛCDM** over late-time variations of the expansion history (Poulin et al. '18 [1803.02474], see also Eleonora Di Valentino's talk)
- Additional intrinsic inability to lower sound horizon (Bernal et al. '16 [1607.05617], Millea & Knox '19 [1908.03663])



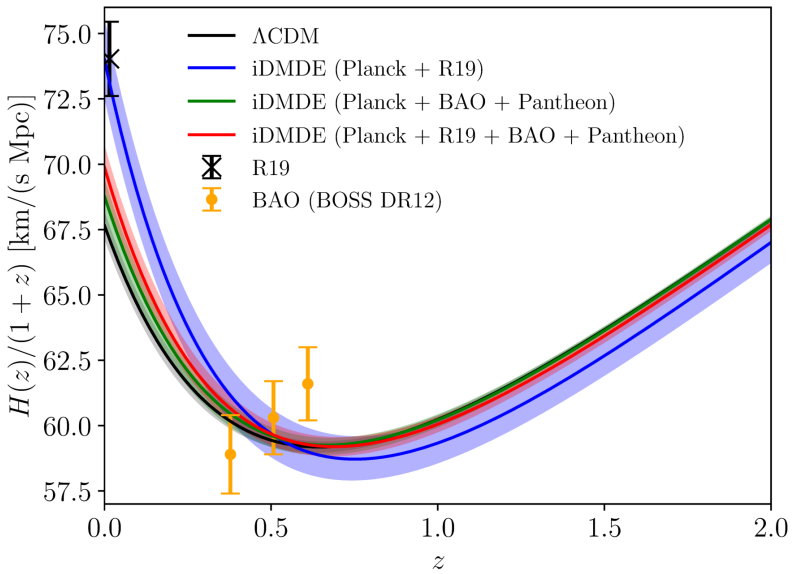
Adapted from Poulin et al. '18 [1803.02474]

- Emergence of general **no-go theorem** for late-time solutions (see David Wands' talk)

For the specific case of DM-DE interactions:



Adapted from Lucca & Hooper '20
(see e.g., also Di Valentino et al. '19a,b [1908.04281,1910.09853])

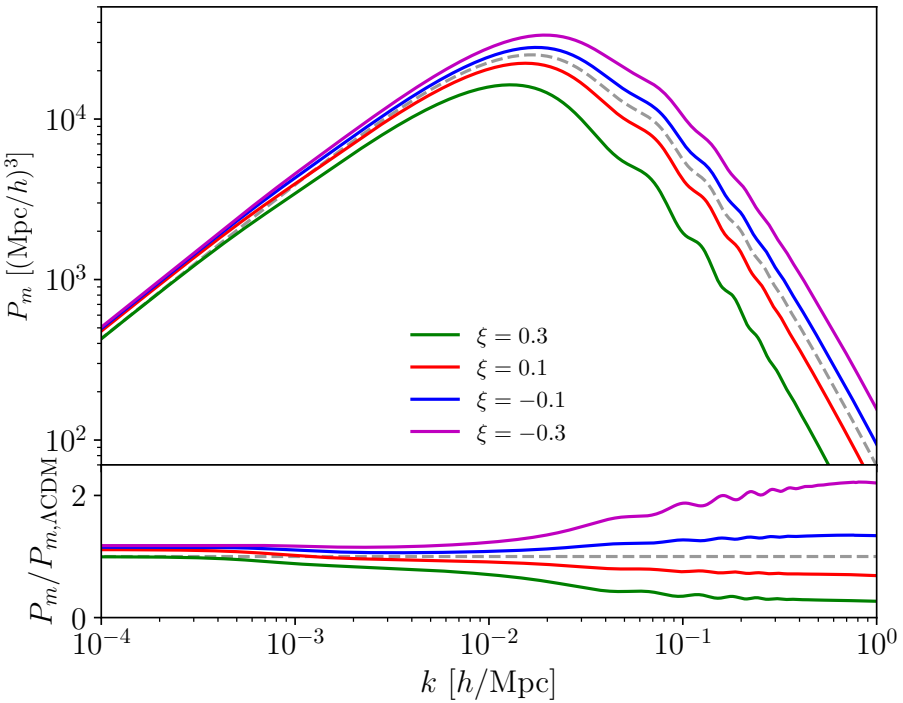


- *No-go theorem* still applies
- DM-DE interactions are therefore **not a successful solution**

DE-DM interactions as a solution to the S_8 tension (the iDEDM model)

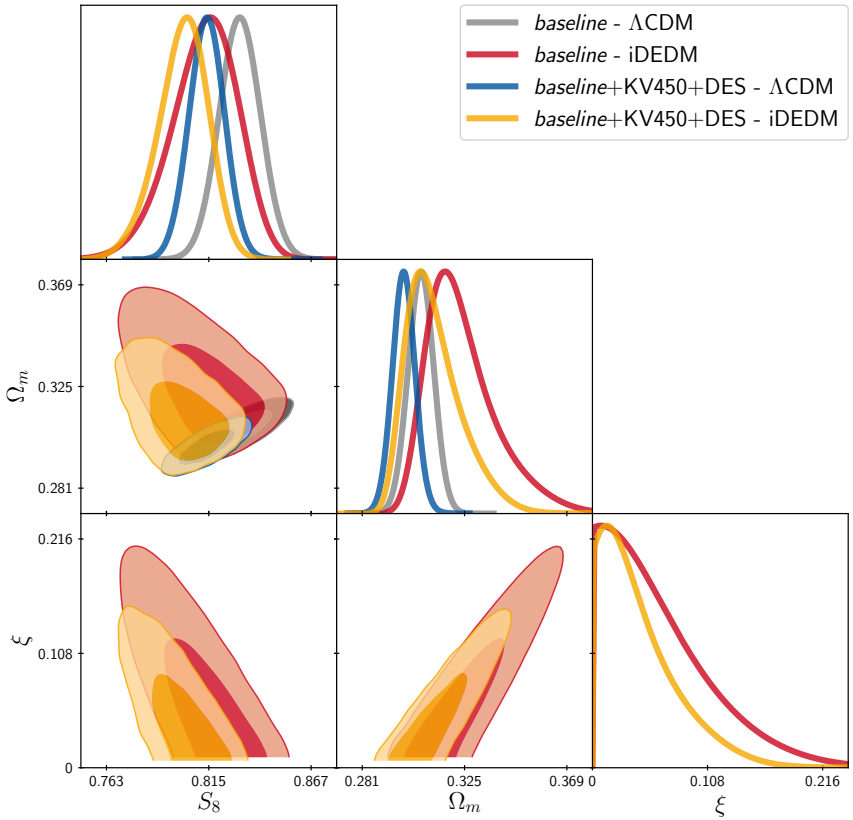
Recap:

- When ξ is positive $\Omega_c(z)$ is lower in the past compared to ΛCDM
- The redshift of matter-radiation equality decreases
- Shift of the peak of the matter power spectrum to lower values and overall suppression of the amplitude (in particular for $k > k_{eq}$)



Adapted from Lucca '21a

Considering data from Planck+BAO+Pantheon and from KV450+DES:



Adapted from Lucca '21a

- Successful solution (tension below 1.5σ once all data is included)
- Without worsening nor introducing any other tension and without worsening fit to data

Summary

Summary:

- DM-DE interactions can be motivated at a very fundamental level and present large phenomenological freedom
- A very appealing choice assumes a coupling of the form $Q = \xi H \rho_x$
- This interacting model could in principle solve both the H_0 and the S_8 tensions depending on the sign of the coupling parameter ξ
- The model fails to successfully solve the H_0 tension when ξ is negative because of a broad *no-go theorem* against late-time models
- It can however significantly reduce the S_8 tension when ξ is positive without worsening other tensions nor the fit to the data
- Possible seed for more inclusive interacting models (see e.g., Lucca '21b [2106.15196])