Cosmology and dark sector in TDiff models

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2 *Multi-field interacting models*

Multi-field interacting models / Phenomenology / Shift-symmetric model / Mixed-regime: Phantom model / Mixed-regime: Tracking model

3 *Conclusions*

References
[2507.16616]
[2409.11991]

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Introduction and theoretical framework

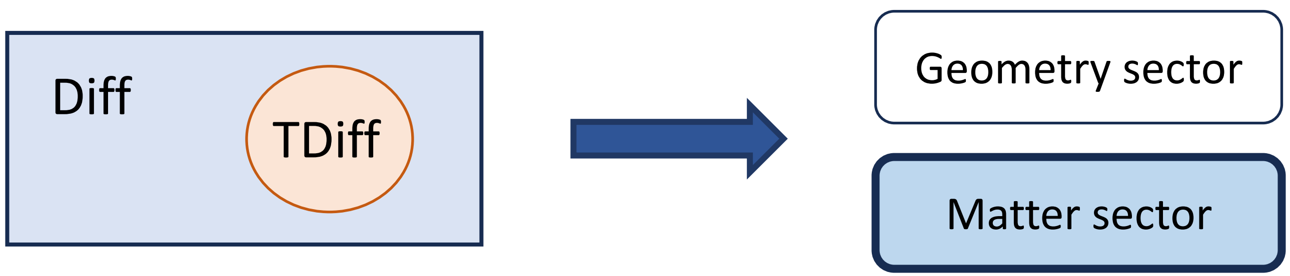
Motivation

- The Universe presents an accelerated expansion.
  - Standard model (ΛCDM): cosmological constant.
  - Vacuum-energy problem.
- Most of the matter contribution is dark matter.
  - Unknown nature.
- Observational tensions (H_0, σ_8).
  - Potentially alleviated by phantom / interacting models.
  - DESI (BAO) + CMB + SNe favors dynamical DE crossing the phantom divide in the past.

Modifications of gravity at cosmological scales → Break symmetries in the dark sector

TDiff formalism

- Diffeomorphism invariance is the main symmetry of GR.
  - Unimodular gravity: the metric determinant is taken to be a non dynamical field fixed to the value $g = 1$.
  - Diff invariance is broken down to TDiff + Weyl rescalings.
- We will break Diff invariance down to TDiff in the matter sector of the action.



TDiff formalism

- Variations of the action under coordinate transformations:

$$S_{\text{mat}} = \int \mathrm{d}^4x \, f(g)\mathcal{L}(g_{\mu\nu}, \phi_i, \partial_\rho \phi_i)$$

$$x^\mu \to x^\mu + \xi^\mu(x)$$

TDiff: $\partial_\mu \xi^\mu = 0$ → The coupling between gravity and the fields $f(g)$ is no longer fixed

- Matter field action (homogeneous scalar fields):

$$S_{\text{mat}} = \int \mathrm{d}^4x \left[\frac{1}{2} f_K(g) \partial_\mu \phi \partial^\mu \phi - f_V(g) V(\phi) \right]$$

- Flat Robertson-Walker background (Cosmology):

$$\mathrm{d}s^2 = b(\tau)^2 \mathrm{d}\tau^2 - a(\tau)^2 \mathbf{dx^2}$$

TDiff formalism

- Perfect fluid approach for the energy-momentum tensor:

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

- ρ is the energy density
- p is the pressure

Matter content

- Diff invariance $\Longrightarrow$ EMT conservation

Noether Theorem

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- TDiff invariance $\Longrightarrow$ less symmetry. However…
  - ➢ Geometry sector is left Diff invariant.

No longer trivial!

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \quad + \quad \nabla_\mu G^{\mu\nu} = 0 \quad \Longrightarrow \quad \nabla_\mu T^{\mu\nu} = 0$$

TDiff formalism

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

CONSTRAINT

- Introduces a new equation for g (New information).
- Allows to obtain the no longer gauge component $b(\tau)$.

Covariantized approach

- Equivalent approach: covariantized formalism.
  - Write the action in a covariantized way through the introduction of an extra field:

$$S_{\rm mat}^{\rm cov} = \int {\rm d}^4x\sqrt{g}[H_K(Y)X - H_V(Y)V(\phi)]$$

$$Y \equiv \bar{\mu}/\sqrt{g} \qquad \bar{\mu} = \partial_\mu(\sqrt{g}A^\mu)$$

$$X = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

$$H(Y) \equiv Y f(Y^{-2})$$

- Equivalent to the TDiff formalism when $\bar{\mu} = 1$ **(TDiff frame).**
- TDiff theory written in a Diff invariant way, more compact.

EMT conserved under solutions of EE

There is a new EoM for the extra field

TDiff frame →

CONSTRAINT

Covariantized approach

- Potential domination regime:

Y = constant
ϕ = constant

$$p = w\rho, \quad w = -1$$

Cosmological constant

Equation of state (EoS)

- Kinetic domination regime:

$$w = \frac{H_K(Y) - YH'_K(Y)}{H_K(Y) + YH'_K(Y)}$$

Power-law coupling

$$H_K(Y) \propto Y^{\hat{\alpha}}$$

$$w = \frac{1-\hat{\alpha}}{1+\hat{\alpha}}$$

Equation of state (EoS)

②

Multi-field Interacting models

Multi-field interacting models

- EMT conservation law:

$$T_{\mu\nu} = T^{(1)}_{\mu\nu} + T^{(2)}_{\mu\nu}$$

$$T^{(i)}_{\mu\nu} = (\rho_i + p_i)u_\mu u_\nu - p_i g_{\mu\nu}$$

$$\nabla_\mu T^{\mu\nu} = \nabla_\mu T^{(1)}_{\mu\nu} + \nabla_\mu T^{(2)}_{\mu\nu} = 0$$

No individual conservation imposed

$$\rho_1'(\tau) + 3\frac{a'(\tau)}{a(\tau)}[\rho_1(\tau) + p_1(\tau)] = Q(\tau),$$

$$\rho_2'(\tau) + 3\frac{a'(\tau)}{a(\tau)}[\rho_2(\tau) + p_2(\tau)] = -Q(\tau)$$

Energy exchange

- EMT conservation law ~ **CONSTRAINT:**

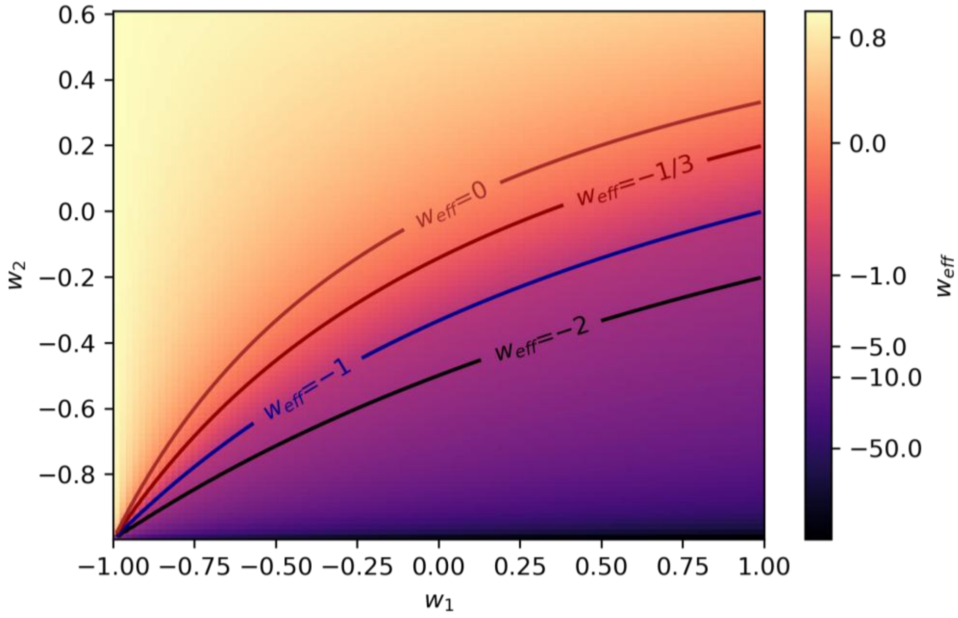
Contributions from both fields → $Y(a)$ → (TDiff frame) → $b(a)$

EFFECTIVE INTERACTION BETWEEN THE FIELDS

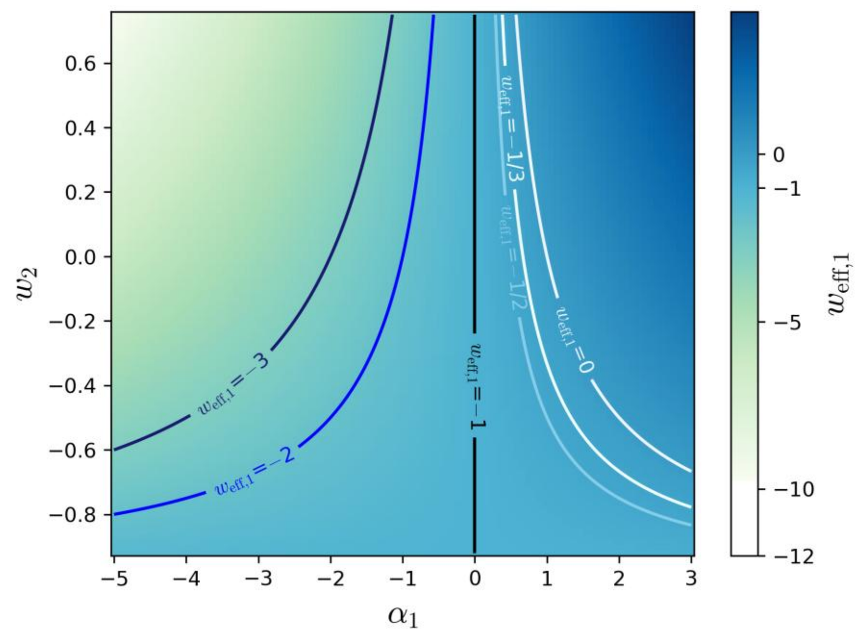
Phenomenology

Effective behavior in the asymptotic single/field dominationregimes

A) Shift-symmetric

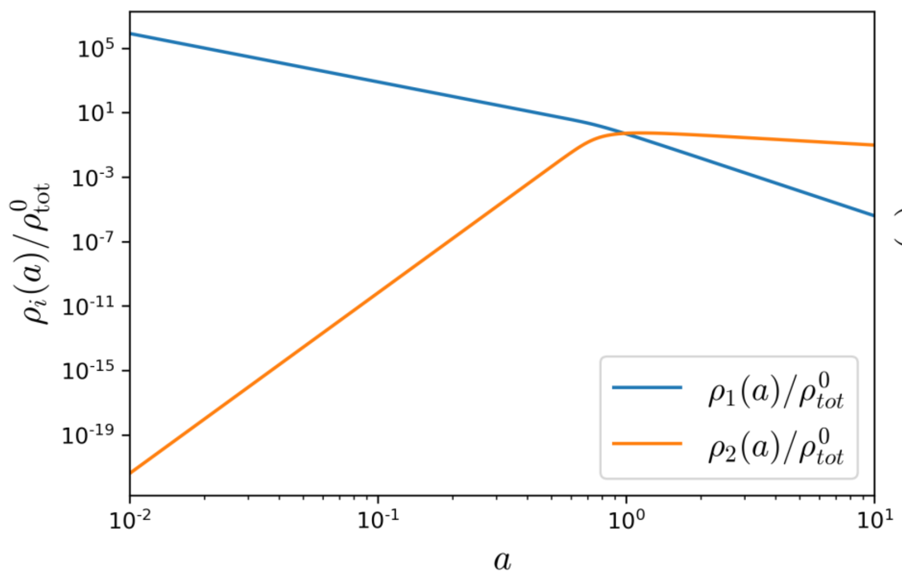


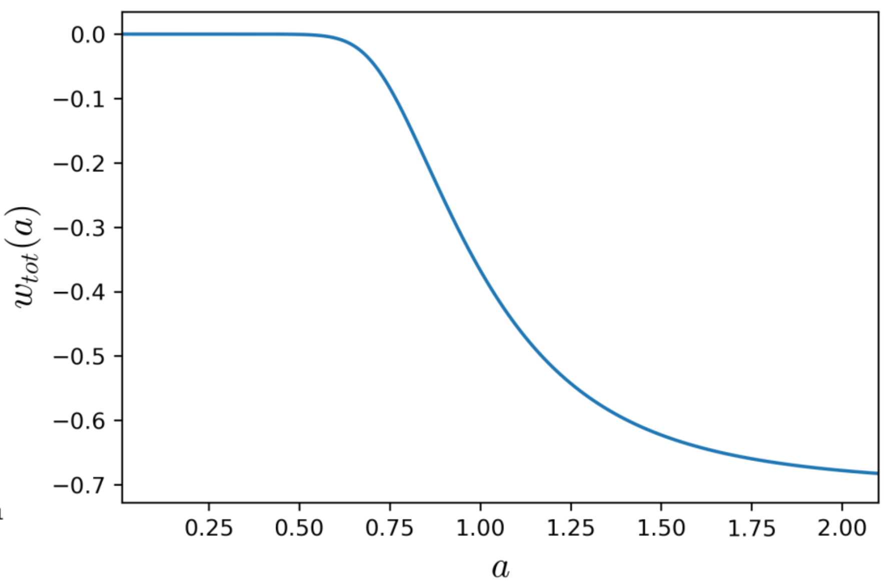
B) Mixed-regime



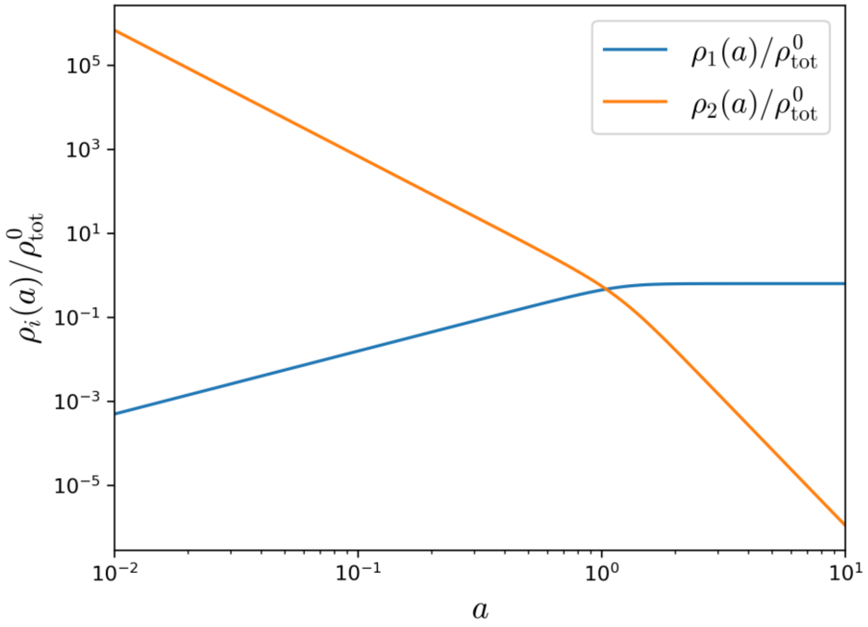
If one (the) kinetic field ϕ_2 has $\alpha_2 = 1$ ($w_2 = 0$):
Asymptotic Dark Matter behavior in the past

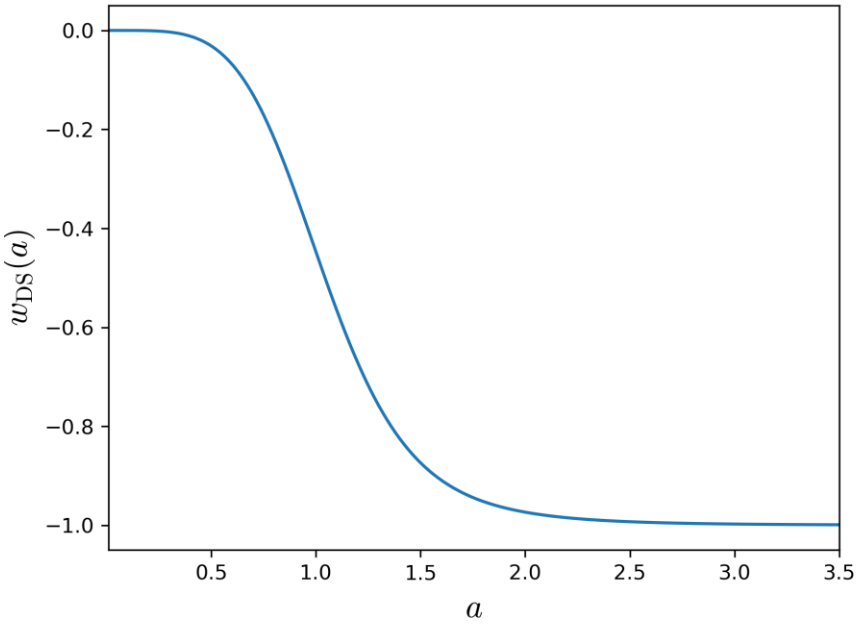
Shift-symmetric model



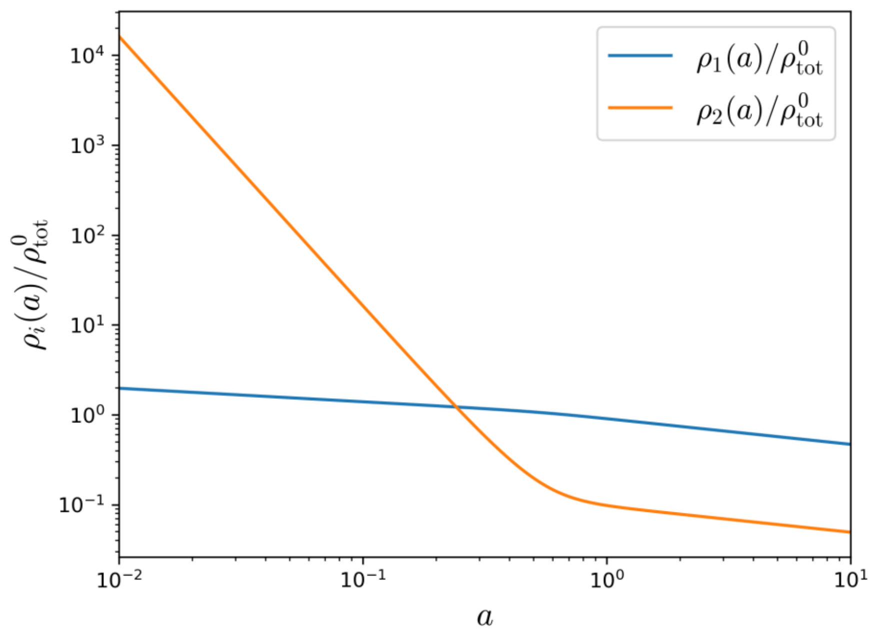


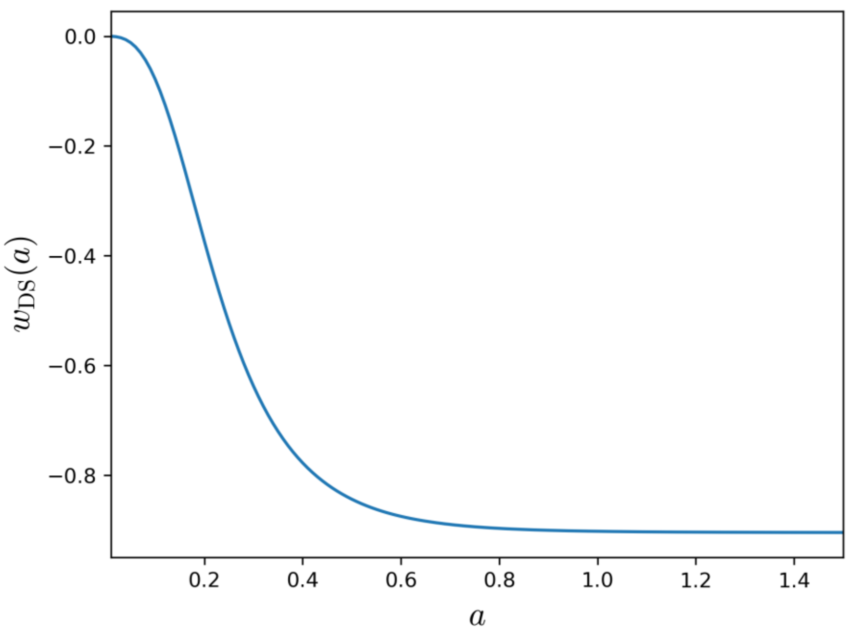
Mixed-regime: Phantom model





Mixed-regime: Tracking model





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Conclusions

Conclusions

- Diff symmetry breaking in the matter sector:
  - ➢ Non-trivial conservation of the EMT.
  - ➢ Physical constraint → energy exchange (**effective interaction**).
- Model: shift-symmetric and mixed-regime:
  - ➢ The **interaction** affects the behavior of each component.
  - ➢ The potential field presents a **dynamical evolution** that can be in the range of **dark energy**.
  - ➢ Compatible with **late-time accelerated expansion**.