Multifield Cosmology and the Dark Universe

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JCAP 03 (2022) 018 , Eur. Phys. J. C 84 (2024) 365

(with J. Dumancic, R. Gass, L.C.R. Wijewardhana)

Basic idea:

At present: Plethora of accurate observational data

($\Rightarrow$ very precise determination of cosmological parameters)

$\rightarrow$ Overall: good phenomenological understanding

(standard cosmological model: ΛCDM)

BUT: Observational data $\Rightarrow$ fundamental puzzles

(Nature of dark matter and dark energy? Cosmological tensions?...)

$\rightarrow$ Motivation for non-standard cosmological models

- Multifield cosmology: a very promising possibility!

  (multifield cosmological models: multiple scalars coupled to gravity)

Why multifield, and not single-field, models:

- Theoretical motivations:
  - Various criteria (‘swampland’ conjectures) for compatibility of effective field theories with quantum gravity (constraints on potential: very restrictive for single-scalar models)
  - String compactifications: many scalars in 4d effective action (even number)
- Richer phenomenology:
  - non-Gaussianity of primordial perturbations
  - generation of primordial black holes
  - novel models of cosmic acceleration (on steep potentials !)

Plan

- Multifield cosmological models

  [main characteristics of the case with two scalar fields]

- Rapid-turn regime

  [solutions with strongly non-geodesic field-space trajectories: new effects relevant for inflation, dark matter or dark energy]

- Multifield model of late dark energy

  [reduced sound speed of dark energy perturbations; potential to alleviate simult. the σ_8 and Hubble tensions]

Multifield Cosmological Models

(broadly motivated by quantum gravity)

Action:

$$S = \int d^4x \sqrt{-\det g} \left[\frac{R}{2} - \frac{1}{2} G_{IJ}(\phi)\, g^{\mu\nu}\, \partial_\mu \phi^I\, \partial_\nu \phi^J - V(\phi) \right] ,$$

$g_{\mu\nu}(x)$ - spacetime metric , $\mu, \nu = 0, ..., 3$

$G_{IJ}(\phi)$ - field space metric , $I, J = 1, 2, ..., n$

Standard background Ansatze:

$$ds_g^2 = -dt^2 + a(t)^2 d\vec{x}^2 \quad , \quad \phi^I = \phi_0^I(t) \quad ,$$

$$H(t) \equiv \frac{\dot{a}(t)}{a(t)} \quad - \quad \text{Hubble parameter}$$

Conceptual note:

In single-field models potential $V(\phi)$ plays key role:

Always: field redefinition $\rightarrow$ canonical kinetic term

(Can transfer complexity to the potential)

In multi-field models:

Cannot redefine away the curvature of G_{IJ} !

(I.e., kinetic term becomes important !)

$\Rightarrow$ Can have: - Genuine multi-field trajectories in field space even when $\partial_{\phi^I} V = 0$ for some I

- New phenomena due to non-geodesic background trajectories in field space

Characteristics of a background trajectory:

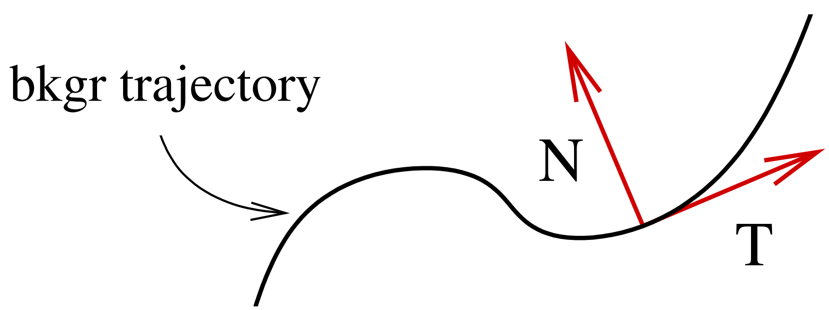
From now on consider 2 scalars, i.e. $I, J = 1, 2$

Background trajectory $(\phi_0^1(t), \phi_0^2(t))$ in field space:

– Tangent and normal vectors:

$$T^I = \frac{\dot{\phi}_0^I}{\dot{\sigma}} \quad , \quad N_I = (\det G)^{1/2} \epsilon_{IJ} T^J \quad , \quad \dot{\sigma}^2 = G_{IJ} \dot{\phi}_0^I \dot{\phi}_0^J$$

(Note: $N_I T^I = 0 \;\; , \;\; T_I T^I = 1 \;\; , \;\; N_I N^I = 1$)



Characteristics of a background trajectory:

– Turning rate of the trajectory:

$$\Omega = -N_I D_t T^I \quad , \quad D_t T^I \equiv \dot{\phi}_0^J \, \nabla_J T^I$$

(measure for deviation from geodesic)

– Slow-roll parameters: [Cespedes, Atal, Palma 2012]

$$\varepsilon = -\frac{\dot{H}}{H^2} \quad , \quad \eta^I = -\frac{1}{H\dot{\phi}_0} D_t \dot{\phi}_0^I$$

Expand: $\eta^I = \eta_{||} T^I + \eta_\perp N^I \quad \rightarrow \quad \eta_{||} = -\frac{\ddot{H}}{2H\dot{H}} \;\; , \;\; \eta_\perp = \frac{\Omega}{H}$

Note: $\varepsilon \, , \eta_{||}$ - same as Hubble slow-roll parameters in single-field case

Rapid Turn Regime

(strongly non-geodesic field-space trajectories)

Pheno viability and perturbative stability:

In the past:

Slow roll & slow turn: $\varepsilon\,, |\eta_{||}| \ll 1 \quad \& \quad |\eta_{\perp}| \ll 1$

[Sasaki, Stewart 1996; Gordon, Wands, Bassett, Maartens 2001; Groot Nibbelink, van Tent 2002; D. Langlois and S. Renaux-Petel 2008; Peterson, Tegmark 2011;...]

Recently also:

Slow roll & rapid turn: $\varepsilon\,, |\eta_{||}| \ll 1 \quad \& \quad \eta_{\perp}^2 \gg 1$

[Cespedes, Atal, Palma 2012; Achucarro, Atal, Germani, Palma 2017; Garcia-Saenz, Renaux-Petel, Ronayne 2018; Bjorkmo, Ferreira, Marsh 2019;...]

Slow roll on steep potentials:

Slow roll $\&$ rapid turn: [Achucarro, Palma 2019]

$$\varepsilon \;=\; \varepsilon_V \left(1 + \frac{\eta_\perp^2}{9}\right)^{-1} \quad ,$$

$$\varepsilon_V = \tfrac{1}{2}\frac{G^{IJ}V_I V_J}{V^2} \quad , \quad V_I = \partial_{\phi_0^I} V$$

$\Rightarrow$ For large $\eta_\perp^2$ can have simult.: small ε and large ε_V

$\rightarrow$ Spacetime expansion in slow-roll regime: decoupled from flatness of scalar potential

- easy to evade swampland constraints
- useful for realizing inflation in fundam. set-ups

Primordial black holes (PBHs): natural candidate for DM

A generation mechanism:

Large enough fluctuations during inflation can seed PBHs

- Single-field models: PBH-formation is a challenge...

- Two-field models: (recall: $\eta_\perp = \Omega/H$)

Power spectrum of curvature perturbation ζ:

$$\mathcal{P}_\zeta \sim \mathcal{P}_0 \, e^{c\,|\eta_\perp|} \quad , \qquad c = const > 0$$

For PBH generation, need δt with: $\mathcal{P}_\zeta / \mathcal{P}_0 \sim 10^7$

$\rightarrow$ easy to achieve with a brief rapid turn

[Palma, Sypsas, Zenteno 2020; Anguelova 2021;
Fumagalli, Renaux-Petel, Ronayne, Witkowski 2023]

Multifield dark energy:

Key characteristics of dynamical dark energy:

- equation-of-state parameter w_{DE}
- dark energy perturbations' speed of sound c_s^{DE}

In single-scalar (quintessence) models: [speed of light: $c = 1$]

$c_s^{DE} \equiv 1 \quad \rightarrow \quad$ observ. distinctions from Cosm. Const. Λ only for w_{DE} significantly $\neq -1$

In multifield (rapid-turn) case: [Akrami, Sasaki, Solomon, Vardanyan 2021]

Can have $c_s^{DE} < 1$ even for $w_{DE} \approx -1$

$\rightarrow$ dynamical DE: observ. distinguishable from Λ

Background Solutions

Background equations of motion:

Equations for the scalar fields:

$$D_t\dot{\phi}_0^I + 3H\dot{\phi}_0^I + G^{IJ}V_J = 0 \quad , \quad V_J \equiv \partial_{\phi_0^J} V \quad ,$$

$$D_t\dot{\phi}_0^I \equiv \dot{\phi}_0^J \nabla_J \dot{\phi}_0^I = \ddot{\phi}_0^I + \Gamma^I_{JK}\dot{\phi}_0^J\dot{\phi}_0^K$$

Einstein equations:

$$G_{IJ}\dot{\phi}_0^I\dot{\phi}_0^J = -2\dot{H} \quad , \quad 3H^2 + \dot{H} = V$$

In general: EoMs are a rather complicated coupled system

$\rightarrow$ Many numerical studies in the literature for specific choices of G_{IJ} and V...

Finding solutions analytically:

[Anguelova, Babalic, Lazaroiu 2019]

Imposing hidden symmetry: powerful technical tool for obtaining exact solutions

[Method familiar from extended theories of gravity: Capozziello, de Ritis 1993; Capozziello, Marmo, Rubano, Scudellaro 1997; Capozziello, Nesseris, Perivolaropoulos 2007; Capozziello, De Felice 2008...]

– restricts the form of the scalar potential

– facilitates finding exact solutions of the background EoMs by transforming to generalized coords adapted to the symmetry

Found: Most general hidden symmetries (and compatible potentials) for rot.-invariant metric G_{IJ}:

$$ds_G^2 = d\varphi^2 + f(\varphi)d\theta^2$$

(Also showed: Hidden symmetry $\Rightarrow$ this ds_G^2: hyperbolic surface)

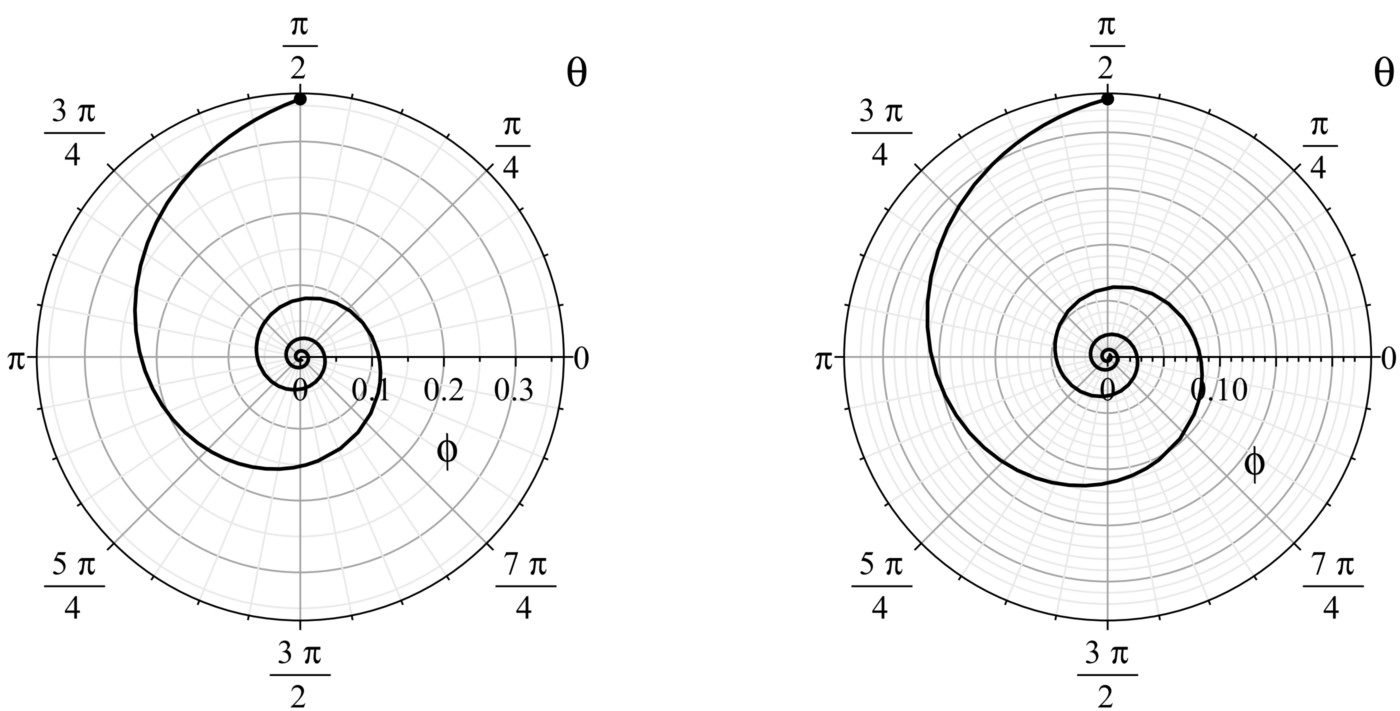
Multifield Model of Late Dark Energy

Exact solutions:

[Anguelova, Dumancic, Gass, Wijewardhana 2022]

Four-param. family of exact solutions obtained by taking:

ds^2_G : Poincaré disk and $V = V_{hid.sym.} + const$



Two examples of field-space trajectories $(\varphi(t), \theta(t))$ of the exact solutions

Dark energy: exact solutions

[Anguelova, Dumancic, Gass, Wijewardhana 2022]

Field-space trajectories: always (rapid-)turning

Spacetime of solutions:

Monotonically tending (fast) to de Sitter space with time

[de Sitter space: const. positive scalar curvature]

$\rightarrow$ As background solutions: not very different from cosmological constant

BUT: Perturbations around them can lead to distinguishing features (different large-scale clustering of structure)...

Dark energy: perturbations

[Anguelova, Dumancic, Gass, Wijewardhana 2024]

Dark energy scalars can fluctuate around background:

$$\phi^I(t,\vec{x}) = \phi_0^I(t) + \delta\phi^I(t,\vec{x}) \qquad [\text{ recall: } (\phi_0^1, \phi_0^2) \equiv (\varphi, \theta)]$$

Found these perturbations' sound speed:

$$c_s^{-2} \approx 1 + \frac{4\Omega^2}{M_T^2 + M_N^2} \quad , \qquad [\text{ speed of light: } c = 1]$$

T^I and N^I : vectors tangent and normal to field-space trajectory $(\phi_0^1(t), \phi_0^2(t))$,
$\Omega = -N_I D_t T^I$: turning rate of field-space trajectory ,
M_T and M_N : masses of projections $\delta\phi_T = T_I \delta\phi^I$ and $\delta\phi_N = N_I \delta\phi^I$

Rapid turning $\Rightarrow$ $c_s < 1$ $\Rightarrow$ enhanced clustering on scales
(large Ω)
$\sim r_s = c_s \tau_*$, τ_* - age of Universe

Dark energy: perturbations

Our model: $r_s^{DE} \approx 6.5\,\text{Gpc}$

Detecting effects of DE clustering on such large scales?:

May be possible from cross-correlations between galaxy surveys and ISW effect in CMB... [Hu, Scranton 2004]

Included matter in the exact solution, describing DE:

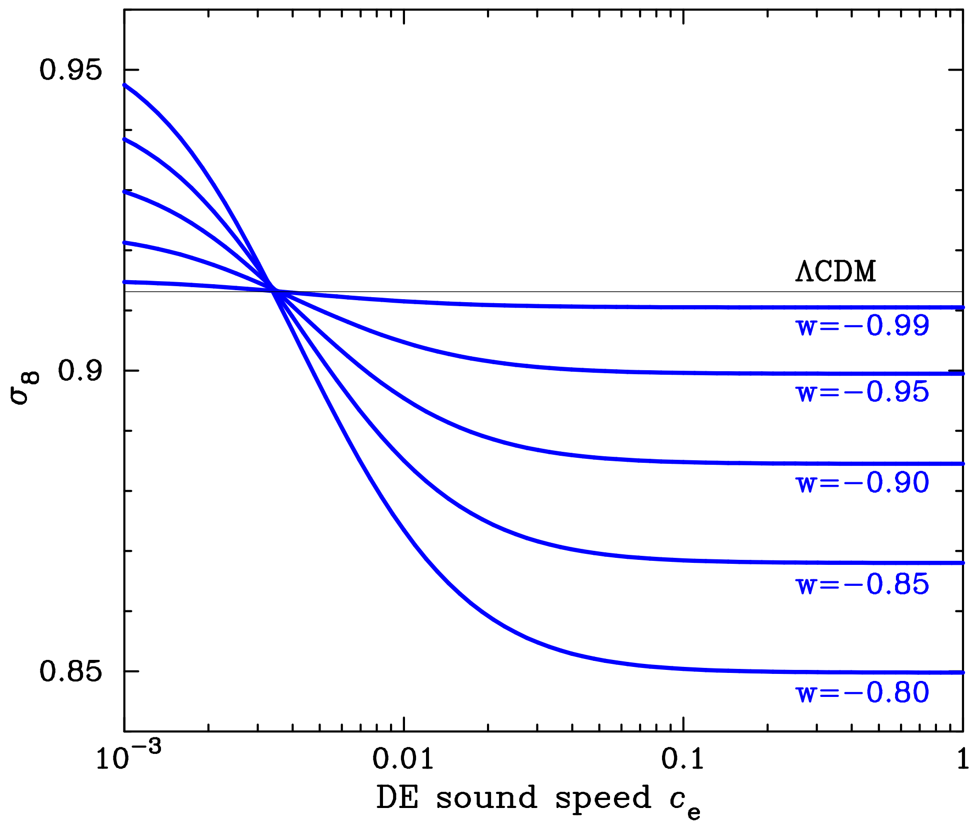
[Anguelova, Dumancic, Gass, Wijewardhana 2024]

– enables study of transition from matter domination to dark energy epoch...

– allows us to address cosmological tensions...

σ_8 tension:

Dependence of σ_8 on w_{DE} and c_s^{DE} : [Takada 2006]



Our model: $w_{DE} \approx -1$ and $c_s^{DE} \approx 0.447$ [although: $w_{DE}(t)$, $c_s^{DE}(t)$]

$\Rightarrow$ $\sigma_8^{\rm DE} < \sigma_8^{\Lambda\rm CDM}$ (tension alleviated; need detailed comparison with data…)

Hubble tension:

(H_0 - Hubble constant)

Our model:

Modification of late Universe

[at earlier times: matter domination (MD), before that RD etc.]

Starting, during MD, with same value of Hubble par. $H(t)$, one finds different (compared to ΛCDM) value today:

- in some part of param. space: $H_0^{DE} < H_0^{\Lambda CDM}$

  (tension exacerbated)

- in other part of param. space: $H_0^{DE} > H_0^{\Lambda CDM}$ $(*)$

  (tension alleviated)

$(*)$ $\Rightarrow$ earlier (than in ΛCDM) transition to DE epoch

In conclusion

Multifield cosmology:

– Promising theoretical framework for understanding the Dark Universe

  · Novel features: due to solutions with (strongly) non-geodesic field-space trajectories ['rapid-turn' regime]

– Multifield model(s) of late Dark Energy: promising for simult. alleviation of σ_8 and Hubble tensions

  · For future work: detailed comparison with observ. data...

Thank you!