Dynamics of Inspiraling Dark Energy

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arXiv:2111.12136 [hep-th], arXiv:2311.07839 [hep-th]
(with J. Dumancic, R. Gass, L.C.R. Wijewardhana)

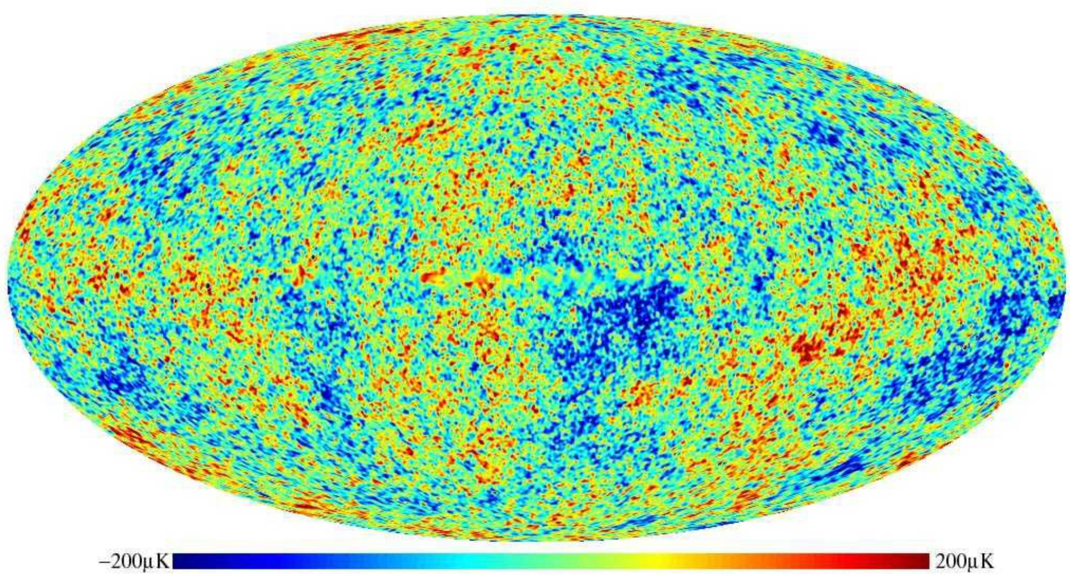
Motivation

At present: Plethora of accurate observational data

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

WMAP and Planck satellites:

Detailed map of CMB temperature fluctuations on the sky



$\overline{T} = 2.7\text{K}$

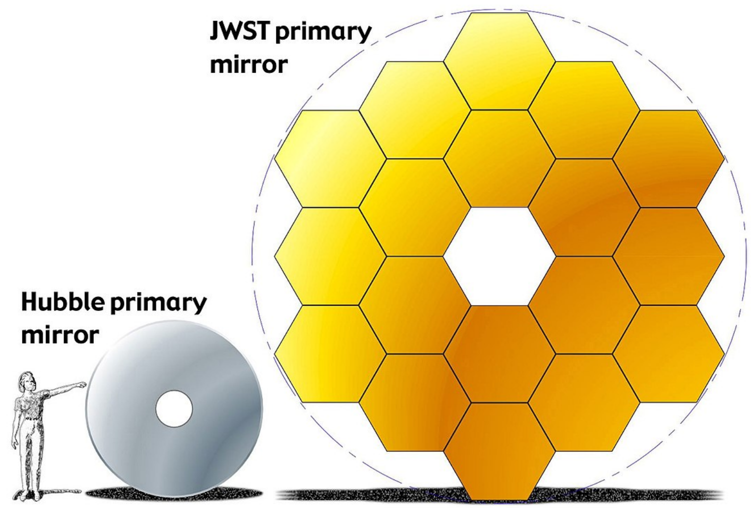
Many other independent observations:

Hubble Space Telescope

(1993 - present)

James Webb Space Telescope

(December 2021 - present)



James Webb ST: can see the first stars and galaxies !

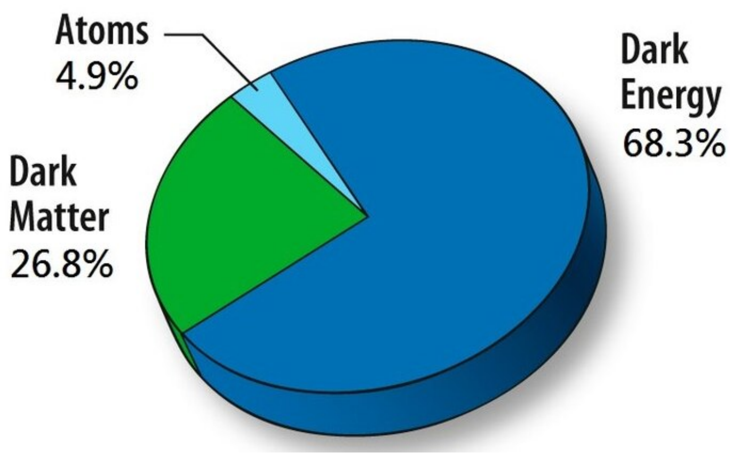
Many many other ground-based or space observatories...

$\rightarrow$ Overall: good pheno understanding (standard cosm. model: ΛCDM)

BUT: Observational data ⇒ fundamental puzzles

- Most of the content of the Universe is unknown !

Composition of the Universe today:



→ Nature of Dark Matter and Dark Energy ?

- Cosmological 'tensions': discrepancies between early and late Universe data → New cosm. model ?

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:

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

$$H(t) \equiv \frac{\dot{a}(t)}{a(t)}$$ - 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 even when $\partial_{\phi^I} V = 0$ for some I

- New phenomena due to non-geodesic motion in field space

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:

[L.A., E. M. Babalic, C. Lazaroiu, JHEP 04 (2019) 148 ; JHEP 09 (2019) 007]

Imposing hidden symmetry: powerful technical tool for obtaining exact solutions

- 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}:

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

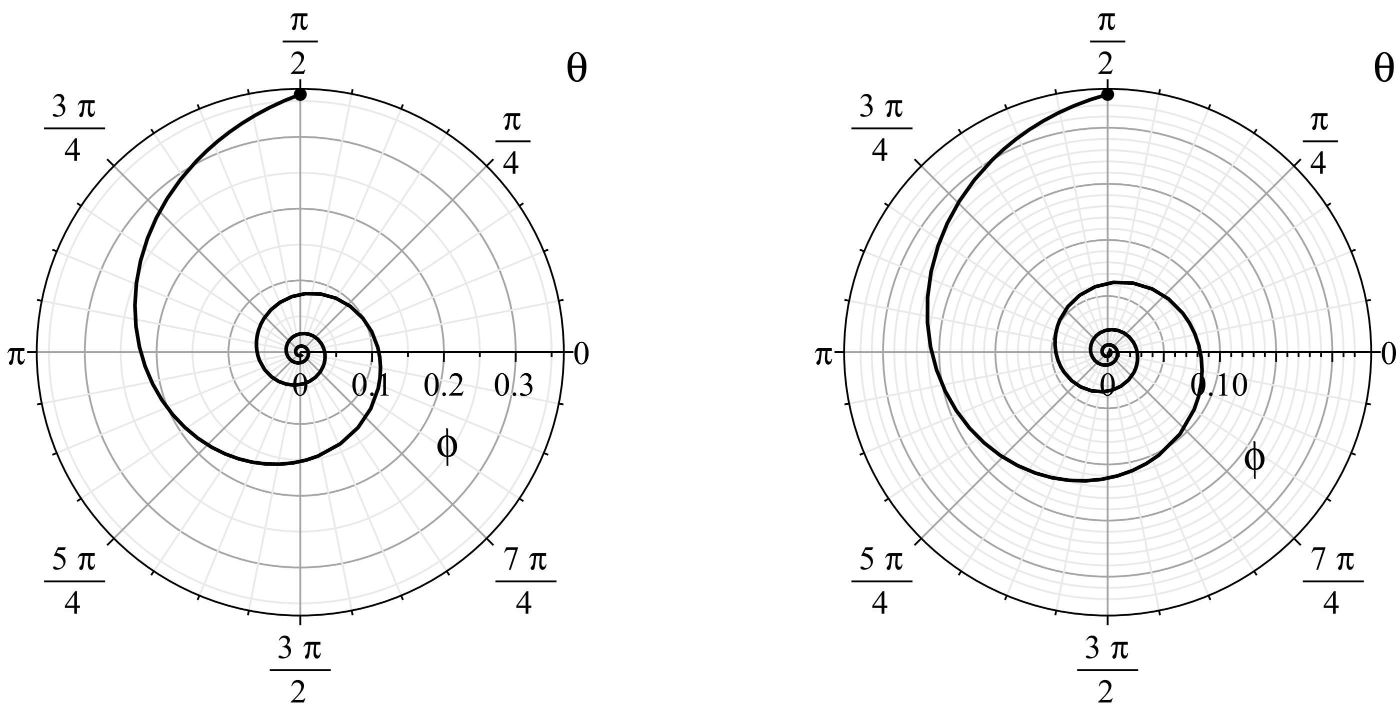
(Also showed: Hidden symmetry $\Rightarrow$ this ds_G^2: hyperbolic surface)

Dark energy

Exact solutions: [L.A., J.Dumancic, R.Gass, L.C.R.Wijewardhana, JCAP 03 (2022) 018]

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

[L.A., J.Dumancic, R.Gass, L.C.R.Wijewardhana, JCAP 03 (2022) 018]

Field-space trajectories: always (rapid-)turning

Spacetime of solutions:

Monotonically tending 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

[L.A., J.Dumancic, R.Gass, L.C.R.Wijewardhana, Eur. Phys. J. C 84 (2024) 365]

Dark energy scalars can fluctuate around background:

$$\phi^I(t,\vec{x}) = \phi_0^I(t) + \delta\phi^I(t,\vec{x})$$

[recall: $(\phi_0^1, \phi_0^2) \equiv (\varphi, \theta)$]

Found these perturbations' sound speed:

$$c_s^{-2} \approx 1 + \frac{4\Omega^2}{M_T^2 + M_N^2} \quad ,$$

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

Dark energy: perturbations

[L.A., J.Dumancic, R.Gass, L.C.R.Wijewardhana, Eur. Phys. J. C 84 (2024) 365]

Included matter in the exact solution, describing DE

$\rightarrow$ enables study of transition from matter domination to dark energy epoch

- σ_8 tension: generically alleviated

  [σ_8 tension: discrepancy between magnitudes of linear matter perturbations' amplitude, obtained from early and from late Universe data]

- Hubble tension: constraints on parameter space

  [Hubble tension: discrepancy between values of Hubble constant, obtained from early and from late Universe data]

$\Rightarrow$ Earlier (than in ΛCDM) transition to dark energy epoch

In conclusion

Inspiraling Dark Energy:

- Class of exact solutions to background EoMs, tending fast to de Sitter space
  - Solutions' trajectories in field-space: always rapid-turning [ex. of 'rapid-turn' cosmic acceleration]
- Dark energy perturbations around the exact solutions: $c_s < 1 \;\rightarrow\;$ observ. distinct physics
  - Many open questions for the future...

Thank you!