Effective Field Theory of Dark Energy: current constraints and forecasts

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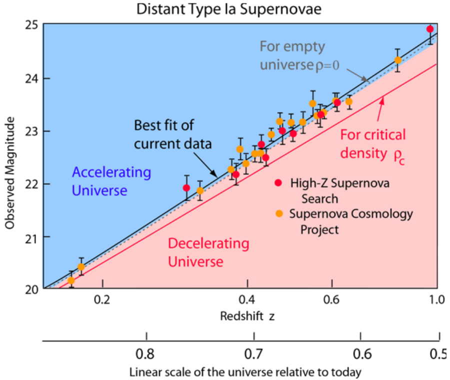
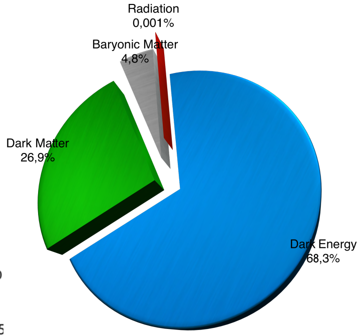
Beyond ΛCDM: why?





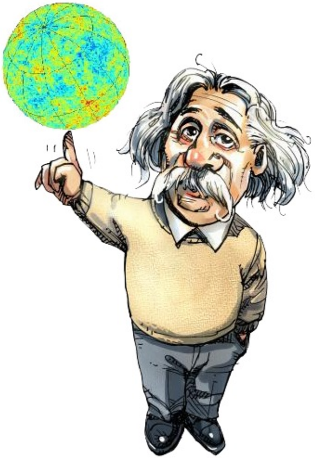
- CC problem
- others...

- H_0 tension ($\sim 4.4\sigma$)
- σ_8 tension ($\sim 3\sigma$)

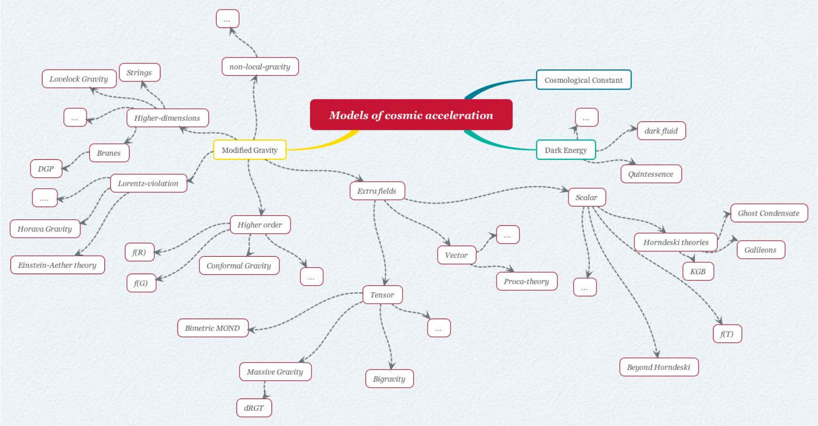
Beyond ΛCDM: how?

Breaking some of the Lovelock's theorem assumptions:

- extra DoF(s): scalar, vector, tensor field(s);
- going beyond the 2nd order differential equations;
- diffeomorphism invariance breaking;
- higher than 4 dimensions;
- non-locality;
- non-dynamical field(s).



Class of MG/DE



A General Approach

The effective field theory is used
to study generic theories of gravity
with a single additional scalar field

with application to:

- inflation
- LSS
- DE/MG

[S. Weinberg, Phys.Rev.D 77 (2008) 123541
P. Creminelli et al. , JCAP 02 (2009) 018
M. Park et al., Phys.Rev.D 81, 124008 (2010)
G. Gubitosi et al. JCAP 02 (2013) 032
J.K. Bloomfield et al. JCAP 08 (2013) 010]

EFT formulation

- *One extra scalar DoF*;
- *The background:* homogeneous and isotropic background (FLRW);
- *The unitary gauge:* basis in which the perturbation of the extra DoF, responsible for the spontaneous symmetry breaking, vanishes;
- *The operators:*
  - are constructed with all the invariants under the residual symmetries of unbroken spatial diffeomorphisms;
  - are accompanied by a time dependent function (EFT functions);
  - are expanded in perturbation;
- *Couplings with matter fields:*
  validity of the WEP assumed $\rightarrow$ Jordan Frame is the natural choice;
- Restoring full diffeomorphism invariance: *Stückelberg trick*,

$$t \rightarrow \tilde{t} = t + \pi(x^\mu)\,, \qquad x^i \rightarrow \tilde{x}^i = x^i$$

EFT of DE action for linear perturbations

$$
\begin{aligned}
S_{EFT} = \frac{1}{2}\int d^4x\sqrt{-g}\,\Big[& M_{\rm pl}^2 \mathfrak{f}(t) R - 2\Lambda(t) - 2c(t) g^{00} \\
& + M_2^4(t)(\delta g^{00})^2 - \bar{m}_1^3(t)\,\delta g^{00}\delta K - \bar{M}_2^2(t)\,\delta K^2 \\
& - \bar{M}_3^2(t)\,\delta K_\mu{}^\nu \delta K^\mu_\nu + \mu_1^2(t)\delta g^{00}\delta R + m_2^2(t) h^{\mu\nu}\partial_\mu g^{00}\partial_\nu g^{00} \\
& + \ldots \Big] + S_m[g_{\mu\nu}, \chi_m]\,,
\end{aligned}
$$

1. Scalar-tensor theories *à la* Brans-Dicke (GBD): $\{\mathfrak{f}, \Lambda, c\}$;
2. Horndeski theories: $\bar{M}_2^2 = -\bar{M}_3^2 = 2\mu_1^2$ (and $m_2^2 = 0$) ;
3. GLPV theories: $\bar{M}_2^2 = -\bar{M}_3^2$ (and $m_2^2 = 0$);
4. Lorentz violating theories: $m_2^2 \neq 0$.

[G. Gubitosi et al. JCAP 02 (2013) 032, J.K. Bloomfield et al. JCAP 08 (2013) 010]

Extension

- *Extension to DHOST:* $\{\beta_1 \delta K \delta N, \beta_2 \dot{\delta N}, \beta_3 (\partial_i \delta N)^2\}$

  [Langlois et al., JCAP 1705 (05) (2017) 033]

- *Coupling with matter fields:* WEP assumption relaxed and it is considered a frame where the gravitational interaction between the additional scalar DoF and the matter fields is explicit

  [Gleyzes et al. JCAP 08 (2015) 054, Tsujikawa, PRD 92 (2015) 6, 064047, D'Amico et al. JCAP 02 (2017) 014]

- *Non-linear perturbations:* In principle the EFT scheme enables one to write down an action with operators expanded at any order;

  [NF et al., JCAP 1712 (12) (2017) 014, Yamauchi et al., PRD 96 (12) (2017) 123516, Cusin et al. JCAP 1804 (04) (2018) 061, Kennedy et al., PRD 100 (4) (2019) 044034]

- *Extension to vector-tensor and bimetric theories of gravity*

  [Baker et al. Phys. Rev. D 98, 023511 (2018)]

α-basis: physical interpretation

$$M^2 = M_{\rm pl}^2 \mathfrak{f} - \bar{M}_3^2 \qquad \alpha_M = \frac{1}{H}\frac{d\ln M^2}{d\ln t}\,,$$

$$\alpha_B = -\frac{M_{\rm pl}^2\dot{\mathfrak{f}} + \bar{m}_1^3}{HM^2}\,, \quad \alpha_T = \frac{\bar{M}_3^2}{M^2} \equiv c_T^2 - 1\,, \quad \alpha_K = \frac{2c + 4M_2^4}{H^2M^2}\,,$$

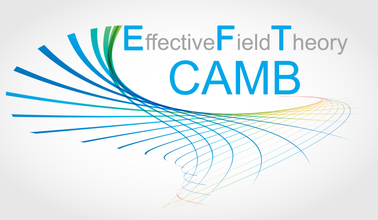
$$\alpha_{K_2} = \frac{8m_2^2}{M^2H^2}\,, \quad \alpha_H = \frac{2\mu_1^2 + \bar{M}_3^2}{M^2}\,, \quad \alpha_B^{GLPV} = \frac{\bar{M}_3^2 + \bar{M}_2^2}{M^2}\,,$$

- α_M: *running* of the effective Planck mass
- α_B: *braiding* function
- α_K: *kineticity* function
- α_T: modification in c_T^2
- α_H, α_B^{GLPV} and α_{K_2} : beyond Horndeski functions

[E. Bellini and I. Sawicki, JCAP 07 (2014) 050
J. Gleyzes et al., JCAP 02 (2015) 018
NF et al., JCAP 07 (2016) 018]

Advantages of a general approach

- Model independent exploration (pure EFT): Fix the forms of the EFT functions + $w_{DE}(a)$;
- Link with theory: full mapping;
- Stability requirements: General expressions to avoid ghost, gradient and tachyon instabilities;
- General purpose EB codes:



[B.Hu, M. Raveri, NF, A. Silvestri, PRD89 (2014) 103530]

EFTCAMB (http://eftcamb.org),
hi_class (www.hiclass-code.net),
COOP(www.cita.utoronto.ca/zqhuang),
EoS_class(https://github.com/fpace)

[see Bellini et al (NF), Phys. Rev. D 97, 023520 (2018) for their comparison]

- Novel predictions: powerful theoretical tool to systematically identify clear patterns and predictions of MG and DE proposals.

Connection with theory

Example: Quintessence

$$\mathcal{S}_\phi = \int d^4x\sqrt{-g}\left[\frac{m_0^2}{2}R - \frac{1}{2}\partial^\nu\phi\partial_\nu\phi - V(\phi)\right],$$

in the ADM formalism, the following action:

$$\mathcal{S}_\phi = \int d^4x\sqrt{-g}\left\{\frac{m_0^2}{2}\mathcal{R} + \frac{\dot{\phi}^2}{2} - V(\phi_0) - \frac{\dot{\phi}_0^2}{2}\delta g^{00}\right\},$$

the EFT functions:

$$\mathfrak{f}(t) = 1, \qquad c(t) = \frac{\dot{\phi}_0^2}{2}, \qquad \Lambda(t) = \frac{\dot{\phi}_0^2}{2} - V(\phi_0).$$

GWs constraints

LIGO/Fermi: $-3 \times 10^{-15} \leq c_T - c \leq 7 \times 10^{-16}$

[Abbott, B.P. et al. Phys.Rev.Lett. 119 (2017) no.16, 161101
Goldstein, A. et al. Astrophys.J. 848 (2017) no.2, L14]

$$c_T^2(t) = 1 + \alpha_T(t) \quad \rightarrow \quad \alpha_T(t) \sim \mathcal{O}(10^{-15}) \qquad (c = 1)$$

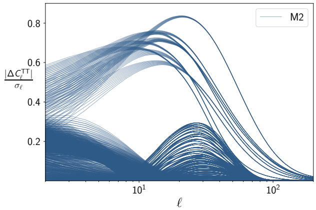
- e.g. Horndeski class: $\bar{M}_2^2 = -\bar{M}_3^2 = 2\mu_1^2 = 0$

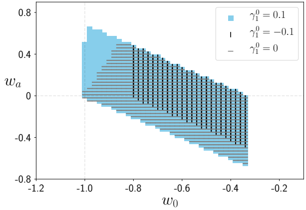
  [Baker, T. et al. PRL 119 (2017) no.25, 251301, Creminelli, P. et al. PRL 119 (2017) no.25, 251302, Sakstein, J. PRL 119 (2017) no.25, 251303, Ezquiaga, J. et al. PRL 119 (2017) no.25, 251304, Amendola, L. et al. PRL 120 (2018) no.13, 131101, others]

- Decay of GWs into DE/instability of GWs: $\alpha_H \lesssim O(10^{-20})$ and $\alpha_B \sim O(10^{-2})$

  [Creminelli et al. JCAP 12 (2018) 025, JCAP 10 (2019) 072, JCAP 05 (2020) 002]

α_K and M_2^4





- no impact on the observables
- no direct impact on the constraints
- impact on the stability space

[Figs. from NF et al. PRD 99, 063538 (2019)
see also Bellini et al. JCAP 1602, 053 (2016),
Piazza et al. JCAP 05 (2014) 043,
Kreisch et al. JCAP 12 (2018) 030]

$$\gamma_1(a) = \frac{M_2^4}{M_{\rm pl}^2 H_0^2}$$

$$\text{CPL: } w_{DE}(a) = w_0 + w_a(1-a)$$

Novel predictions

Two phenomenological functions prove useful to interpret theoretical predictions in light of observations:

- $\mu(t,k)$: the *effective gravitational coupling*
- $\Sigma(t,k)$: the *light deflection parameter*

They are defined in Fourier space as

$$-\frac{k^2}{a^2}\Psi = 4\pi G_{\rm N}\,\mu(t,k)\rho_{\rm m}\Delta_{\rm m}\,, \qquad -\frac{k^2}{a^2}(\Psi+\Phi) = 8\pi G_N\Sigma(t,k)\rho_{\rm m}\Delta_{\rm m}\,,$$

A third quantity called the *gravitational slip parameter*, is

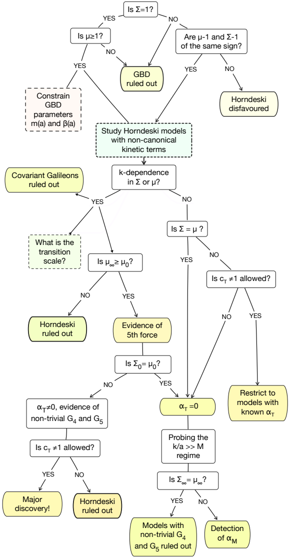
$$\eta(t,k) = \frac{\Phi}{\Psi}\,.$$

The three phenomenological functions are thus linked by the relation

$$\Sigma(t,k) = \frac{\mu(t,k)}{2}\left(1+\eta(t,k)\right)\,.$$

EFT approach $\Rightarrow$ algebraic expressions in the QSA limit
observables $\Leftrightarrow$ EFT functions

Phenomenology from μ, Σ



On super-Compton scales:

$$\mu_0 = \frac{M_{\rm pl}^2}{M^2}\frac{1}{\eta_0}\,, \quad \eta_0 = \frac{1}{1+\alpha_T}\,, \quad \Sigma_0 = \frac{M_{\rm pl}^2}{M^2}\left(1+\frac{\alpha_T}{2}\right)$$

In the sub-Compton regime:

$$\mu_\infty = \frac{M_{\rm pl}^2}{M^2}\left(1+\alpha_T+\beta_\xi^2\right)\,, \quad \eta_\infty = \frac{1+\beta_B\beta_\xi/2}{1+\alpha_T+\beta_\xi^2}\,,$$

$$\Sigma_\infty = \frac{M_{\rm pl}^2}{M^2}\left(1+\frac{\alpha_T}{2}+\frac{\beta_\xi^2}{2}+\frac{\beta_B\beta_\xi}{4}\right)\,,$$

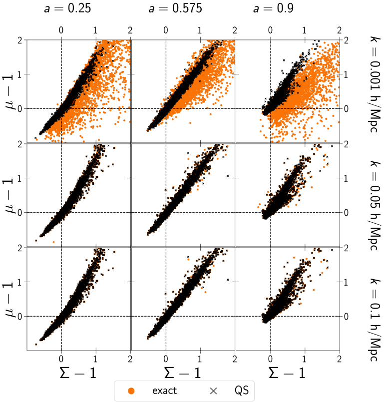
where

$$\beta_B^2 = \frac{2}{c_s^2\alpha}\alpha_B^2\,, \quad \alpha = \alpha_K + \frac{3}{2}\alpha_B^2$$

$$\beta_\xi^2 = \frac{2}{c_s^2\alpha}\left(\frac{\alpha_B}{2}(1+\alpha_T)+\alpha_M-\alpha_T\right)^2$$

[Pogosian & Silvestri PRD 94 (2016) 10, 104014]

μ-Σ conjecture & QSA validity



$$(\mu - 1)(\Sigma - 1) \geqslant 0$$

BUT

$k \lesssim 0.001$ h/Mpc

breaking of conjecture & QSA

QSA to hold: $\frac{k}{aH} > c_s$

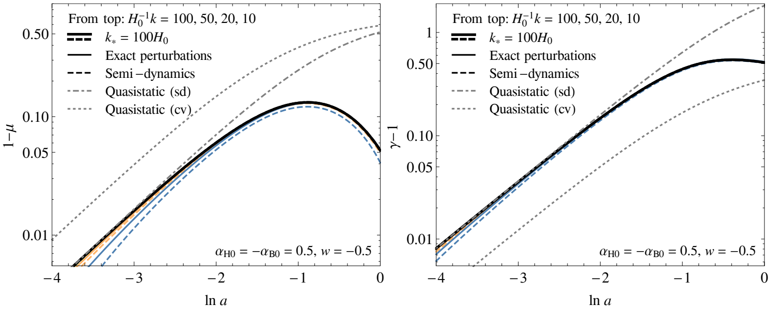
necessary condition but not sufficient !

[L. Pogosian and A. Silvestri, Phys. Rev. D94, 104014 (2016)
Peirone et al. Phys.Rev.D 97 (2018) 4, 043519]

Beyond QSA: a semi-dynamical treatment

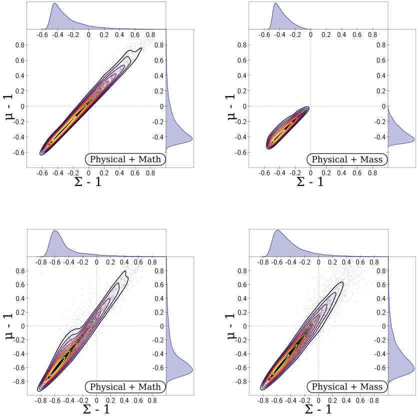
Time derivatives of the metric potentials and velocity fields on large scales are considered: perturbations are evolved at a given pivot scale and the relations between the perturbations to other scale are extrapolated

μ, Σ, η differ from the QS ones by factors proportional to α_H.



[L. Lombriser et. al JCAP 11 (2015) 040]

Impact of stability conditions in the $\mu - \Sigma$ plane



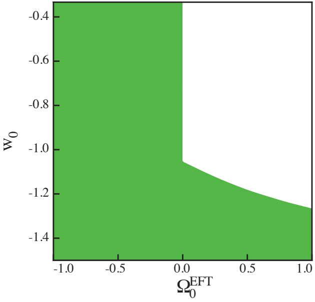
Marginalized 2D/1D distributions of μ and Σ at $z = 0.1$ GBD (*top doublet*) and Horndeski models (*bottom doublet*)

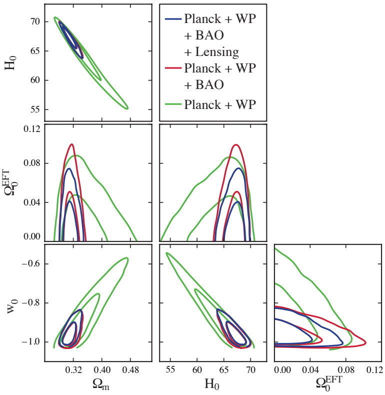
- physical: no-ghost, positive speed
- mass: no-tachyon
- math: stability of the dynamical equation for the perturbations of the scalar field

[NF et al. JCAP 02 (2019) 029]

Running of the effective Planck mass

$$\mathfrak{f}(t) = \frac{1}{2}\left(1 + \Omega_0^{\rm EFT}\, a(t)\right)$$





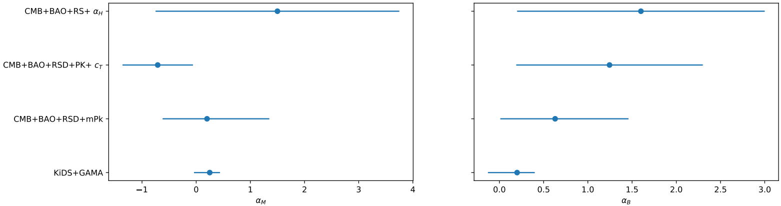
[M. Raveri, B. Hu, NF, A. Silvestri, Phys.Rev.D 90 (2014) 4, 043513]

Cosmological constraints on Horndeski and GLPV

- depend on the chosen parametrization

For

$$\alpha_i(a) = \alpha_i \Omega_{DE}(a) \quad \text{on a } \Lambda\text{CDM background}$$

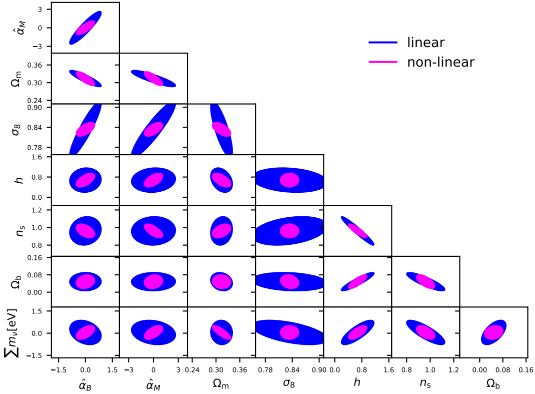


$$-0.90 < \alpha_T < -0.41 \quad , \quad 0.382 < \alpha_H < 2.457 \quad \text{at 95\% C.L.}$$

[for review see NF and L. Perenon, Phys.Rept. 857 (2020) 1-63
data are from: Mancini et al. MNRAS 490 (2) (2019) 2155-2177
Bellini et al. JCAP 1602 (02) (2016) 053, Traykova et al. JCAP 08 (2019) 035,
Noller et al. PRD 99 (10) (2019) 103502]

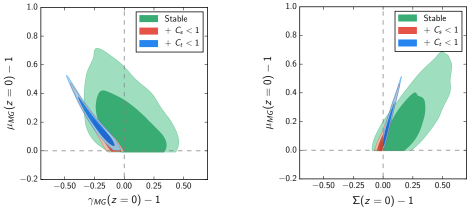
Forecasts for Euclid-like survey: linear vs non linear P(k)

$$\alpha_i(t,k) = \alpha_i^0 \, \frac{\Omega_{\rm DE}(t)}{\Omega_{\rm DE,0}} \, e^{-\frac{1}{2}\left(\frac{k}{k_V}\right)^2} \,, \quad \text{on a } \Lambda\text{CDM background}$$

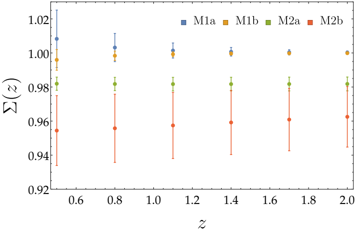


[A. S. Mancini et al. MNRAS 480 (2018) 3, 3725-3738]

Constraints and Forecasts on μ & Σ



[Salvatelli et al. JCAP 09 (2016) 027]

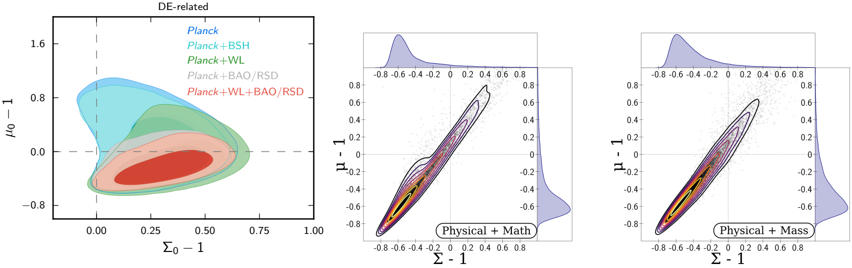


[NF et al. Phys.Rev.D 99 (2019) 6, 063538]

- top: 68% and 95% C.L CMB constraints for a *linear-de* form
- left: Forecasts 2σ errors from DESI and SKA2 like-surveys (scaling-a and DE density forms)

μ, Σ: EFT vs direct parametrization

Direct par.	Features	EFT
✓	null test of ΛCDM	✗
✓	identify tendencies of data with few free parameters	(✗)
✗	based on gravity theory	✓
✗	stability/normalization/additional priors	✓
✗	allow to retain the link μ, Σ share	✓



[Planck 2015 Results XIV, A&A 594, A14 (2016)]

Take home messages

- Unifying framework for gauging general classes of DE/MG theories;
- Predictions and interpretations of observations are made directly in the space of class of theories and not within a single paradigm;
- Specific trends can be translated into specific models;
- Numerical tools based on EFT made the explorations of DE/MG effects on observables straightforward;
- Started a systematic analysis of alternative models against cosmological data;
- General and theoretically rigorous conditions were derived which are systematically enforced in EB codes;
- It comes at a price: challenges of general parameterizations against oversimplifications. The risk would be to miss significant DE/MG signatures or eventually to give a false alert.