Snowmass2021 - Letter of Interest

Searching for Dynamical Dark Energy and Alternatives to Cold Dark Matter in Large Scale Structure and Galactic Rotation

Thematic Areas:

□ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF09) Astro-particle physics & Cosmology

Contact Information:
Emil Mottola (Los Alamos National Laboratory & Perimeter Institute)[emil@lanl.gov]

Author: Emil Mottola

Abstract: Any solution to the multiple fine tuning and hierarchy problems confronting the Standard Model of both High Energy physics and Cosmology should relate very disparate length scales. This is a natural feature of *conformal* theories, *i.e.* theories with no intrinsic length scale. The biggest hierarchy problem of all is that posed by the apparent value of the cosmological constant in ΛCDM. The natural setting for conformal invariance and its breaking is in curved spacetime, although without requiring a full UV complete quantum theory of gravity. Since conformal invariance is broken by the conformal anomaly, it plays a central role in any low energy theory based on these ideas. The effective action of the conformal anomaly implies the existence of a long range effective scalar field with several consequences for observational cosmology. These include:

(1) Space and/or Time-Dependent Dynamical Dark Energy, which can be tested by a number of cosmological probes in the coming decade and compared to standard ΛCDM; and
(2) Gravi-magnetic frame-dragging effects in rotating matter distributions, which would influence galactic rotation curves, and velocity dispersion on cluster and supercluster scales, now attributed to Cold Dark Matter.

The WMAP/Planck CMB data contain a number of 'anomalies' that suggest tensions with the simplest models of inflation, including a notable lack of power in the anisotropy at large scales, angular anisotropies and apparent statistical correlations in several dozen multipole moments, and an asymmetry between the northern and southern hemispheres of the sky.[8]. As the accuracy of cosmological data has improved, additional tensions with the ΛCDM model have appeared, most notably a $4.4\,\sigma$ discrepancy in the value of the Hubble parameter inferred from the Planck CMB data *vs.* that obtained by recalibration of the cosmic distance ladder from relatively nearby Cepheids.[9] These tensions have led to renewed interest in Dynamical Dark Energy (DDE),[10–13] and even some claimed evidence of DDE at the $3\,\sigma$ level.[14] DDE could relate the inflationary very large value of Λ with the present tiny value of Λ_{SNe} inferred from observations of type Ia Supernovae (SNe) at moderately large redshifts. DDE seems to be necessary both to relieve this enormous cosmological 'constant' hierarchy problem of why the value of Λ_{SNe} is so small in Planck units, as well as the cosmic *coincidence* problem of why it is of order $3H_0^2/c^2$ for the Hubble parameter H_0 *only just now*.

In addition ΛCDM requires about 25% of the energy density of the Universe to be in the form of non-relativistic Cold Dark Matter (CDM), but no DM particle has yet been detected, despite deployment of ever larger and more sensitive detectors in nearly four decades of searching.[15] The possibility that these various problems may be related is attracting more attention recently[16]. There is a growing recognition of the need for new ideas and new approaches to break the present logjam. A vigorous investigation of well-motivated alternatives to ΛCDM and particularly DDE is very timely now, in view of the trove of new data that will shortly be available, which can put new ideas and models to the test.

A first principles Effective Field Theory (EFT) approach to including quantum effects in gravity has been developed, based on the conformal or trace anomaly of the energy-momentum tensor of massless quantum fields,[1,2] the effective action corresponding to it, and the long range massless scalar degree of freedom this effective action implies.[3–7] This leads to a well-defined modification of classical GR, fully consistent with, and in fact *required* by quantum theory, the Standard Model (SM), and the Equivalence Principle, without any additional assumptions. This EFT has several consequences for Dark Energy and Dark Matter Cosmology that can be tested by forthcoming facilities, observations and data.

1. Dynamical Dark Energy

The conformal anomaly action[3,4,7] contains a new local massless scalar scalar of the EFT not present in classical GR, called a *conformalon* φ,

$$S_{\mathcal{A}}[\varphi] = \frac{b'}{2}\int d^4x\sqrt{-g}\left\{-(\Box\varphi)^2 + 2\left(R^{\alpha\beta}-\tfrac{1}{3}Rg^{\alpha\beta}\right)(\partial_\alpha\varphi)(\partial_\beta\varphi)\right\} + \frac{1}{2}\int d^4x\,\mathcal{A}\,\varphi \tag{1}$$

where

$$\frac{\mathcal{A}}{\sqrt{-g}} \;=\; b\,C^2 + b'\,\left(E - \tfrac{2}{3}\Box R\right) + \sum_i \beta_i\,\mathcal{L}_i \tag{2}$$

$E, C^2, \Box R$ in curved space, as well as matter invariants such as the gluonic contribution $\mathcal{L}_G = \mathrm{tr}\,\{G_{\alpha\beta}G^{\alpha\beta}\}$ of the strong nuclear interactions in the SM. The coefficients b, b', β_i are pure numbers multiplied by $\hbar$, depending upon the QFT[1,2], so the conformal anomaly is a quantum effect with *no intrinsic length scale*, and in particular does not involve the ultrashort Planck scale $L_{Pl} = \sqrt{\hbar G/c^3} \simeq 1.6\times 10^{-33}$ cm. Being massless, the Goldstone-like boson φ has an *a priori* infinite range and thus can affect even *macroscopic* phenomena in an otherwise classical Universe. Since the stress-energy tensor derived from (1) is the source of the gravitational metric field through Einstein's equations, the macroscopic effects of the conformal anomaly are transferred to the gravitational field. Qualitatively new phenomena are then predicted[3–6,17]. In particular, the cosmological vacuum energy is no longer constrained to be a constant, but can dynamically vary generically in both space and time,[11] depending upon the global geometry of the Universe on the cosmological Hubble scale H_0, and unrelated to the microscopic UV scale of L_{Pl}.

The linear coupling of φ to the topological Euler density E, which is a total derivative indicates that an integration by parts naturally defines a totally anti-symmetric 3-form Abelian gauge potential $A_{\beta\mu\nu}$ of mass dimension one. Then defining

$$F_{\alpha\beta\mu\nu} = \nabla_{[\alpha} A_{\beta\mu\nu]} \tag{3}$$

to be the $4-$form field strength tensor corresponding to the potential $A_{\beta\mu\nu}$, the linear $E\varphi$ coupling efines a $\int J \cdot A$ current source interaction for the 4-form field strength in close analogy to electrodynamics.[18] The 'Maxwell' eq. then becomes

$$\nabla_\alpha F^{\alpha\beta\mu\nu} = J^{\beta\mu\nu} = \kappa^2 \epsilon^{\alpha\beta\mu\nu} \nabla_\alpha \varphi \qquad \text{or} \qquad \partial_\alpha \tilde{F} = \kappa^2\, \partial_\alpha \varphi \qquad \text{so that} \qquad \tilde{F} = \kappa^2 \varphi + const. \tag{4}$$

with κ a coupling constant of mass dimension one that controls the fluctuations of $F^{\alpha\beta\mu\nu}$. It is the only free parameter if the coefficients b, b', β_i are fixed by the SM. For any $\kappa \neq 0$ the *effective* value of the cosmological vacuum energy $\frac{1}{2}\tilde{F}^2$ will be determined by the *dynamical conformalon field* $\varphi(x)$, and is no longer constrained to be a constant. This is a consistent EFT of gravitational vacuum energy that can vary in both space and time, depending upon the anomaly driven current source $J^{\beta\mu\nu}$ and φ, well-motivated from QFT first principles. It is quite different from previously proposed quintessence theories. The one integration constant in (4) is fixed by the requirement that the vacuum energy vanish in flat space with $\varphi = 0$. The difference from this zero value are then finite and calculable in the EFT, with no additional freedom or fine tuning possible. In particular Planck scale divergences do not enter.

We propose to investigate this theory of Dynamical Dark Energy (DDE) for several simple models, including an expanding Friedmann-Robertson-Walker Universe, in which case the solutions for $\tilde{F}$ and the cosmological DE will be time-dependent. The redshift z dependence of the effective EoS parameter, $w = -p/\rho$ and the growth rate of perturbations will be computed in the linear theory. By modifying existing LSS numerical codes and Monte Carlo methods for computing growth of structure developed for other scalar-tensor theories[19,20], one can solve the eqs. in the non-linear regime. Active input and collaborations with members of the DES, LSST, SPT, eBOSS and SKA surveys are needed, with the aim of rigorously testing the resulting theory of DDE and distinguishing it from the rigid ΛCDM models with all available LSS data, including gravitational weak lensing. GWs will also provide the possibility of 'standard sirens' and yet another source of information about DE, probing the geometry of the Universe to cosmological scales as more GW sources are observed.[21]

2. Implications for Dark Matter, Galactic Rotation Curves and Tully-Fisher Relation

A long range scalar such as the conformalon φ also produces enhanced gravi-magnetic frame-dragging effects in rotating matter distributions, and hence also influences galactic rotation curves, similar to Chern-Simons theories or MOND.[22,23] If most or all galaxies contain a central BH-like object, and if this collapsed object is a rapidly rotating gravitational condensate star,[24,25] its surface acts as a source for φ and for frame-dragging effects extending over galactic distances due to φ being long range. This raises the intriguing possibility that the *same* mechanism for producing DDE could also be responsible for the flat galactic rotation curves, now ascribed to CDM. The effect of the long range scalar in the EFT on galactic rotation curves will be determined, and the velocity dispersion of galaxies and the Tully-Fisher relation at cluster and supercluster scales investigated. If DE and at least some DM effects have the same fundamental source, or they can mutually interact in this way, the cosmic coincidence problem would be alleviated or solved. The stress-energy of the EFT[3,7] will also be found under the assumption of axial symmetry and can therefore provide the dark component to rotating matter distributions with arbitrary angular momentum that can mimic the gravitational effects of CDM without requiring a DM particle that has so far failed to show up.

The promise of discovery of the first deviations from Einstein's classical GR due to quantum physics could *revolutionize* our understanding of both the Dark Universe, and point a new pathway to a synthesis of gravitation and quantum theory.

References

[1] M. Duff, Nucl. Phys. B **125**, 334 (1977).

[2] N. D. Birrell, N. D. Birrell, and P. Davies, *Quantum fields in curved space* (Cambridge Univ. Press, 1984).

[3] E. Mottola and R. Vaulin, Phys. Rev. D **74**, 064004 (2006).

[4] M. Giannotti and E. Mottola, Phys. Rev. D **79**, 045014 (2009).

[5] E. Mottola, Acta Phys. Pol. B **41**, 2031 (2010), https://www.actaphys.uj.edu.pl/R/41/9/2031/pdf.

[6] E. Mottola, arXiv:1103.1613 (2011), published in *Proc. XLV Rencontres de Moriond, 2010 Cosmology*, E. Auge, J. Dumarchez, J. Tran Tranh Van, eds. (Vietnam, Gioi).

[7] E. Mottola, Jour. High Ener. Phys. **2017**, 43 (2017).

[8] D. J. Schwarz, C. J. Copi, D. Huterer, and G. D. Starkman, Class. Quan. Grav. **33**, 184001 (2016).

[9] A. G. Riess, S. Casertano, W. Yuan, L. M. Macri, and D. Scolnic, Astrophys. Jour. **876**, 85 (2019).

[10] K. Freese, F. C. Adams, J. A. Frieman, and E. Mottola, Nucl. Phys. B **287**, 797 (1987).

[11] I. Antoniadis, P. O. Mazur, and E. Mottola, New Jour. Phys. **9**, 11 (2007).

[12] G.-B. Zhao and *al.*, Nature Astron. **1**, 627 (2017).

[13] E. Di Valentino, Nature Astron. **1**, 569 (2017).

[14] J. Solà Peracaula, A. Gómez-Valent, and J. de Cruz Pérez, Phys. Dark Universe **25**, 100311 (2019).

[15] G. Bertone and T. M. P. Tait, Nature **562**, 51 (2018).

[16] E. Di Valentino, A. Melchiorri, O. Mena, and S. Vagnozzi, Phys. Dark Universe **30**, 100666 (2020).

[17] E. Mottola, Jour. Phys. Conf. Ser. **314**, 012010 (2011).

[18] M. Henneaux and C. Teitelboim, Found. Phys. **16**, 593 (1986), https://link.springer.com/content/pdf/10.1007/BF01889624.pdf.

[19] M. Raveri, P. Bull, A. Silvestri, and L. Pogosian, Phys. Rev. D **96**, 083509 (2017).

[20] J. Espejo, S. Peirone, M. Raveri, K. Koyama, L. Pogosian, and A. Silvestri, Phys. Rev. D **99**, 023512 (2019).

[21] E. Di Valentino, D. E. Holz, A. Melchiorri, and F. Renzi, Phys. Rev. D **98**, 083523 (2018).

[22] K. Konno, T. Matsuyama, Y. Asano, and S. Tanda, Phys. Rev. D **78**, 024037 (2008).

[23] M. Milgrom, Astrophys. Jour. **698**, 1630 (2009).

[24] P. O. Mazur and E. Mottola, Proc. Nat. Acad. Sci. (U.S.) **101**, 9545 (2004).

[25] P. O. Mazur and E. Mottola, Class. Quant. Grav. **32**, 215024 (2015).