Final Scientific/Technical Report

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Abstract

The research funded by this award spanned a wide range of subjects in theoretical cosmology and in field theory. In the first part, the PI and his collaborators applied effective field theory techniques to the study of macroscopic media and of cosmological perturbations. Such an approach—now standard in particle physics—is quite unconventional for theoretical cosmology. They addressed several concrete questions where this formalism proved valuable, both within and outside the cosmological context, concerning for instance macroscopic physical phenomena for fluids, superfluids, and solids, and their relationship to the dynamics of cosmological perturbations. A particularly successful outcome of this line of research has been the development of "solid inflation": a cosmological model for primordial inflation where the expansion of the universe is driven by an exotic solid substance. In the second part, the PI and his collaborators investigated more fundamental questions and ideas, for the present universe as well as for the very early one, using quantum field theory as a guide. The questions addressed include: Is the present cosmic acceleration due to a new, 'dark' form of energy, or are we instead observing a breakdown of Einstein's general relativity at cosmological distances? Is the cosmic acceleration accelerating? Is the Big Bang unavoidable? Related to this, is early inflation the only sensible cure for the shortcomings of the standard Big Bang model, and the only possible source for the observed scale-invariant cosmological perturbations?

Report

The goal of the proposed research was to use quantum field theory (QFT)—more properly effective field theory (EFT)—to approach diverse questions in cosmology, gravitational physics, and condensed phases of matter in the most generic and model-independent way. The program has been extremely successful, and led to the publication of many papers:

1. *A. Esposito, S. Garcia-Saenz, A. Nicolis and R. Penco, "Conformal solids and holography," arXiv:1708.09391 [hep-th], JHEP* **1712**, *113 (2017).*
   In this paper we use the AdS/CFT correspondence to study solid states in a conformal field theory. In particular, we first derive from effective field theory the spectrum of excitations of conformal solid, and then we find its gravitational dual system. We also study finite temperature phenomena, including the melting phase transition.

2. *A. Nicolis and R. Penco, "Mutual Interactions of Phonons, Rotons, and Gravity," arXiv:1705.08914 [hep-th], submitted to Phys. Rev. B.*
   In this paper we apply an effective point-particle theory to characterize the interactions of a generic short-wavelength excitation or small object with long-wavelength superfluid modes and gravitational fields. We use this to compute scattering cross-sections between phonons and rotons in liquid He_4—thus correcting a classic result by Landau and Khalatnikov—and to compute the effect of gravity on phonons and rotons.

3. *A. Esposito, R. Krichevsky and A. Nicolis, "Vortex precession in trapped superfluids from effective field theory," arXiv:1704.08267 [hep-th], Phys. Rev. A* **96**, *no. 3, 033615 (2017).*
   In this paper we use effective field theory techniques to compute the precession of vortex lines in trapped superfluid clouds. In our formalism the leading effect comes from a single Feynman diagram, in which the vortex line exchanges a phonon with the trapping potential.

4. *J. Kang and A. Nicolis, "Platonic solids back in the sky: Icosahedral inflation," arXiv:1509.02942 [hep-th], JCAP* **1603**, *no. 03, 050 (2016).*
   In this paper we extend the model of solid inflation to anisotropic solids. In particular, for the theory to match the observed isotropy of the scalar perturbations' spectrum, we show that the underlying solid must have icosahedral symmetry. We compute the scalar three-point function, and show that it is not isotropic, but rather has features that are aligned with the underlying icosahedral geometry. This in principle allows for a large gaussian signal in the CMB data, which can only be unveiled by a dedicated analysis that takes into account the icosahedral symmetry.

5. *B. Horn, A. Nicolis and R. Penco, "Effective string theory for vortex lines in fluids and superfluids," arXiv:1507.05635 [hep-th], JHEP* **1510**, *153 (2015).*
   In this paper we develop an effective string theory to describe the dynamics of vortex lines in fluids and superfluids, including their interactions with long-wavelength hydrodynamical modes. We re-derive classic results in this language, and provide examples of new ones, both at the classical and at the quantum level.

6. *A. Nicolis, R. Penco, F. Piazza and R. Rattazzi, "Zoology of condensed matter: Framids, ordinary stuff, extra-ordinary stuff," arXiv:1501.03845 [hep-th], JHEP* **1506** *(2015) 155.*
   In this paper we classify all ways in which the Poincaré group can be broken down to the Euclidean one (translations and rotations), possibly while mixing certain spacetime symmetries with internal ones. The question is relevant because it corresponds to understanding

condensed phases of matter in terms of the spacetime symmetries they break, with crucial implications for the dynamics of the corresponding Goldstone bosons. We unveil a novel condensed matter system—the *framid*—which corresponds to the simplest symmetry breaking pattern, but which is, to the best of our knowledge, not realized in nature.

7. *L. V. Delacrétaz, A. Nicolis, R. Penco and R. A. Rosen, "Wess-Zumino Terms for Relativistic Fluids, Superfluids, Solids, and Supersolids," arXiv:1403.6509 [hep-th], Phys. Rev. Lett.* **114**, *no. 9, 091601 (2015).*
   In this paper we employ the celebrated coset construction for Goldstone boson effective Lagrangians, to derive systematically possible Wess-Zumino terms for condensed matter systems. We find novel Wess-Zumino terms, whose physical consequences and relation to anomalies are still being worked out.

8. *L. Hui and A. Nicolis, "Two-dimensional Lorentz invariance of spherically symmetric black holes," arXiv:1402.6707 [hep-th], Phys. Rev. D* **89**, *no. 6, 064009 (2014).*
   In this paper we prove that all static, spherically symmetric black holes in *any* metric theory of gravity, with arbitrary matter fields, enjoy a two-dimensional Lorentz symmetry acting in the radius-time plane. This can be thought of as a rewriting of the time-translational invariance of the solution, which, close to the horizon, loses its original meaning and behaves as *boost* invariance.

9. *S. Endlich, A. Nicolis and R. Penco, "UV completion without symmetry restoration," arXiv:1311.6491 [hep-th], Phys. Rev. D* **89**, *no. 6, 065006 (2014).*
   In this paper we prove that for Goldstone boson systems with spontaneously broken *spacetime* symmetries, one can have unconventional UV completions where the non-linear sigma model gets enlarged by the addition of *gapped* Goldstones, and the strong coupling scale gets moved to parameterically higher energies. This is to be contrasted with the usual phenomenon whereby any Poincaré-invariant non-linear sigma model admits a weakly coupled UV completion into a linear sigma model via the addition of massive "radial" modes. In this sense, in our unconventional systems the broken symmetries are not restored by the UV completion.

10. *S. Endlich, A. Nicolis and R. Penco, "Spontaneously broken mass," arXiv:1310.2272 [hep-th], JHEP* **1501**, *146 (2015).*
    In this paper we prove that superselection rules associated either with central charges—like the mass in the Galilei algebra—or with the non-trivial topology of certain symmetry groups—like the Poincaré group, or the group of rotations—are directly testable experimentally via systems that exhibit spontaneous breaking of the corresponding symmetry.

11. *S. Endlich, B. Horn, A. Nicolis and J. Wang, "The squeezed limit of the solid inflation three-point function," arXiv:1307.8114 [hep-th], Phys. Rev. D* **90**, *no. 6, 063506 (2014).*
    In this paper we prove that one can consistently compute certain "soft" limits of correlation functions in solid inflation—which violate the celebrated consistency relations of inflationary perturbations—by treating the soft mode as an homogeneous classical background, thus relating $(n+1)$-point functions to the background dependence of n-point functions.

12. *A. Nicolis, R. Penco and R. A. Rosen, "Relativistic Fluids, Superfluids, Solids and Supersolids from a Coset Construction," arXiv:1307.0517 [hep-th], Phys. Rev. D* **89**, *no. 4, 045002 (2014).*
    In this paper we systematically derive from the coset construction of Goldstone boson effective actions the low-energy effective field theories for fluid and solid systems. We prove that the

effective actions that had been written down by us and others for these systems are indeed the most general ones consistent with the symmetries.

13. *A. Nicolis, R. Penco, F. Piazza and R. A. Rosen, "More on gapped Goldstones at finite density: More gapped Goldstones," arXiv:1306.1240 [hep-th], JHEP* **1311***, 055 (2013).*
In this paper we extend previous work by Piazza and the PI about the gap of certain Goldstone excitations of condensed matter systems. We re-derive our previous results from effective field theory, and we unveil new gapped excitations.

14. *S. Endlich and A. Nicolis, "The incompressible fluid revisited: vortex-sound interactions," arXiv:1303.3289 [hep-th].*
In this paper we use EFT techniques to describe fluids in the nearly incompressible regime, which physically corresponds to slow fluid flows compared to the speed of sound. In such a regime, compressional modes (sound waves) are difficult to excite, and can be "integrated out". We re-derive via EFT and Feynman diagrams a number of known results, and, more interestingly we pose and answer new questions including what is the long-range potential between two vortices mediated by the exchange of (virtual) sound waves. We find an explicit expression for it at lowest order in perturbation theory, which scales roughly as

$$V \sim E_{\rm kin}(v/c_s)^2(\ell/r)^3 \,, \tag{1}$$

where $E_{\rm kin}$ is the vortices' kinetic energy, ℓ their typical size, r their distance, v their typical circulation velocity, and c_s the speed of sound. With Slava Rychkov (ENS, Paris) we plan to specialize the formalism to vortex rings, which present a number of surprising features that are being extensively investigated experimentally, for example by our collaborator William Irvine (U. of Chicago).

15. *W. D. Goldberger, L. Hui and A. Nicolis, "One-particle-irreducible consistency relations for cosmological perturbations," arXiv:1303.1193 [hep-th], Phys. Rev. D* **87** *(2013) no.10, 103520.*
In this paper we study the systematics of the inflationary consistency relations from a quantum field theory standpoint. We capitalize on certain zero-momentum residual gauge invariances that one is left with in the so-called ζ-gauge, to derive a number of soft pion-type relations between inflationary correlation functions with different number of fields. This approach has—among other properties—the advantage of elucidating the regime of validity of the consistency relations, beyond the semi-classical approximation.

16. *C. de Rham, K. Hinterbichler, R. A. Rosen and A. J. Tolley, "Evidence for and Obstructions to Non-Linear Partially Massless Gravity," arXiv:1302.0025 [hep-th], Phys. Rev. D* **88***, no. 2, 024003 (2013).*
In this paper we look for a theory of non-linear partially massless gravity among the known ghost-free massive gravity models with a de Sitter reference metric. We find that despite the existence of strong supporting evidence for the existence of a such a theory, technical obstructions arise which preclude its formulation using the standard massive gravity framework.

17. *S. Endlich, A. Nicolis, R. A. Porto and J. Wang, "Dissipation in the effective field theory for hydrodynamics: First order effects," arXiv:1211.6461 [hep-th], Phys.Rev.* **D88** *(2013) 105001.*
In this paper we extend the effective field theory of hydrodynamics to include dissipative effects. We do this by coupling the EFT low-energy, long distance degrees of freedom to a

generic sector that "lives in the fluid"—modeling the fluid's microscopic constituents, which are physically responsible for dissipative effects. The assumption that such a sector is thermalized is enough to restrict the form of the leading dissipative effects at low frequencies and long distances so much so that these can be parameterized via three coefficients only, corresponding to shear viscosity, bulk viscosity, and heat conduction. We recover via our methods the celebrated Kubo relations for these coefficients.

18. *I-S. Yang, "The Negative Mode for small CDL instantons," arXiv:1210.4740 [hep-th], Phys. Rev. D* **87**, *no. 8, 084026 (2013)*
In this paper we clarify a technical subtlety in determining the negative modes of the so-called type-B Coleman-de Luccia instantons: the previously claimed absence of negative modes stem from an over-restriction on the Euclidean path integral. We explain in geometric terms why such a restriction could be removed, and then explicitly construct this negative mode. We also show that type B and type A instantons have the same thermal interpretation for mediating tunnelings.

19. *S. Endlich, A. Nicolis and J. Wang, "Solid Inflation," arXiv:1210.0569 [hep-th], JCAP* **1310** *(2013) 011.*
In this paper we construct an alternative to ordinary inflation in which an accelerated cosmic expansion phase is driven by a *solid*. According to our EFT description of fluids and solids, such systems can be described by a set of scalar fields that break spacial translations and rotations. Since the so-called effective field theory of inflation assumes that the matter fields spontaneously break *time*-translations, our system does not conform to that analysis. The symmetry breaking pattern is totally different, and so are the dynamics of the Goldstone bosons. We show that density perturbations have a nearly scale invariant two-point function, with a distinctive non-Gaussian signal at the level of the three-point function.

20. *P. Creminelli, K. Hinterbichler, J. Khoury, A. Nicolis and E. Trincherini, "Subluminal Galilean Genesis," arXiv:1209.3768 [hep-th], JHEP* **1302**, *006 (2013).*
In this paper we generalize the "Galilean Genesis" scenario of Creminelli, Trincherini, and the PI to include terms that are invariant under scale transformations but that break the special conformal ones. By restricting to a subset of such couplings, we are able to construct an effective field theory that *(a)* can drive a super-accelerated (null energy condition violating) early cosmology; *(b)* has no negative energy excitations ("ghosts"); *(c)* has no superluminal excitations; *(d)* is stable under radiative corrections; and *(e)* yields a nearly scale-invariant spectrum of density perturbations. This is, to our knowledge, the only cosmological scenario that replaces primordial inflation with a null-energy-condition violating phase and agrees with observations while obeying all the above consistency properties.

21. *I-S. Yang, "Probability of Slowroll Inflation in the Multiverse," arXiv:1208.3821 [hep-th], Phys. Rev. D* **86**, *103537 (2012).*
In this paper we provide a heuristic estimation for the probability of false vacuum eternal inflation in a landscape with a large number of fields. We find that the chance to slow-roll is exponentially suppressed, where the exponent comes from the number of fields. However, the relative probability to have more e-foldings is only mildly suppressed as $N^{-\alpha}$ with $\alpha \sim 3$.

22. *J. T. Deskins, J. T. Giblin, Jr. and I-S. Yang, "Classical Transitions for Flux Vacua," arXiv:1207.6636 [hep-th], JHEP* **1210**, *035 (2012).*
In this paper we present the simplest model for classical transitions in flux vacua. A complex field with a spontaneously broken $U(1)$ symmetry is embedded in $M_2 \times S_1$. We numerically

construct different winding number vacua, the vortices interpolating between them, and simulate the collisions of these vortices. We show that classical transitions are generic at large boosts, independent of whether or not vortices miss each other in the compact S_1.

23. *A. Nicolis and F. Piazza, "Implications of Relativity on Nonrelativistic Goldstone Theorems: Gapped Excitations at Finite Charge Density," arXiv:1204.1570 [hep-th], Phys. Rev. Lett.* **110***, no. 1, 011602 (2013) Addendum: [Phys. Rev. Lett.* **110***, 039901 (2013)].*
In this paper we look at the 'Spontaneous Symmetry Probing' phenomenon of paper 26 below, from a different but equivalent perspective—that of relativistic field theories at finite charge density. It is customary to treat systems at finite density via non-relativistic Hamiltonians. We stress the importance of the underlying relativistic dynamics for certain phenomena in these systems. In particular, we prove that in the presence of spontaneous symmetry breaking at finite charge density, certain excitations that are usually assumed to be gapless Goldstone bosons are, in fact, gapped, with a gap proportional to the chemical potential.

24. *L. Hui and A. Nicolis, "A no-hair theorem for the galileon," arXiv:1202.1296 [hep-th], Phys. Rev. Lett.* **110** *(2013) 241104.*
In this paper we prove a no-hair theorem for the galileon field coupled to gravity, for spherically symmetric static black holes. Our proof holds both for the minimally coupled case and for the non-minimal couplings of the covariant galileon type.

25. *L. Hui and A. Nicolis, "An observational test of the Vainshtein mechanism," arXiv:1201.1508 [astro-ph.CO], Phys. Rev. Lett.* **109** *(2012) 051304.*
In this paper we propose looking for an offset in the central massive black hole, correlated with the bulk motion of the host galaxy, as a signature of the Vainshtein mechanism in galileon scalar-tensor theories.

26. *A. Nicolis and F. Piazza, "Spontaneous Symmetry Probing," arXiv:1112.5174 [hep-th], JHEP* **1206** *(2012) 025 .*
In this paper we consider relativistic field theories with internal symmetries, in a state that spontaneously breaks time-translations and one of the internal symmetries in such a way as to leave a particular linear combination thereof unbroken. Our main motivation comes from inflationary cosmology: the inflaton time-dependent background solution breaks time translations and an approximate internal shift symmetry, while preserving a combination of the two. We show at the non-perturbative level a number of properties that follow purely from the symmetry breaking pattern, including the existence of a gapless excitation (Goldstone boson.) Remarkably, in such a state the would-be Goldstones associated with other spontaneously broken internal symmetry generators can be gapped.

27. *A. Nicolis, "Low-energy effective field theory for finite-temperature relativistic superfluids," arXiv:1108.2513 [hep-th].*
Here we combine the ingredients used by Son for zero-temperature superfluids, and by the PI and his collaborators for ordinary hydrodynamics, to develop an effective field theory for finite temperature relativistic superfluids. In EFT terms, such systems are described by four scalar fields, acted upon by a number symmetries, which at lowest order in the derivative expansion force the action to take a simple universal form. This formalism reproduces straightforwardly the known properties of relativistic superfluids, and allows to compute quite easily new observables, e.g. the scattering matrix for sound waves and superfluid vortices.

28. *S. Dubovsky, L. Hui, A. Nicolis and D. T. Son, "Effective field theory for hydrodynamics: thermodynamics, and the derivative expansion," arXiv:1107.0731 [hep-th], Phys. Rev. D* **85** *(2012) 085029.*
In this paper we extend the EFT for hydrodynamics that the PI and his collaborators have developed in previous publications, to accommodate conserved charges carried by the fluid. Moreover, we clarify the matching between hydrodynamical/thermodynamical variables and field theoretical ones, and the systematics of the derivative expansion.

29. *S. Dubovsky, L. Hui and A. Nicolis, "Effective field theory for hydrodynamics: Wess-Zumino term and anomalies in two spacetime dimensions," arXiv:1107.0732 [hep-th], Phys. Rev. D* **89** *(2014) no.4, 045016.*
In this paper we approach the problem of describing hydrodynamics anomalous charges—a problem that has recently received a lot of attention—in EFT terms. This should be possible via Wess-Zumino-like terms in the low-energy EFT Lagrangian. We managed to construct such a term for 1+1-dimensional hydrodynamics, thus giving an EFT description of the 1+1-dimensional analog of the so-called chiral vortical effect. We are working on extending the same ideas to more relevant 3+1-dimensional case, which however presents a number of technical subtleties over its lower-dimensional analog.

30. *I. S. Yang, "The Strong Multifield Slowroll Condition and Spiral Inflation," arXiv:1202.3388 [hep-th], Phys. Rev. D* **85***, 123532 (2012).*
In this paper we point out some existing confusions in the literature about the slow-roll conditions for multifield inflation. In particular, we argue that it is possible to have a multi-field slow-roll model that does not follow the gradient flow, thus bypassing some no-go theorems from string theory. We provide "spiral inflation" as a generic blueprint for such inflationary models, and show that it relies on a monodromy locus—a common structure in string theory effective potentials.

All the research results are publicly available at `https://arxiv.org`, with the relevant arXiv ID numbers quoted above.

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