Snowmass2021 - Letter of Interest

Searching for Evidence of a Conformal Scalar and Conformal Invariance in the Universe

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

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Abstract: Any solution to the multiple fine tuning and hierarchy problems confronting the Standard Model of both High Energy physics and Cosmology must relate very disparate length scales. This is a natural feature of *conformal* theories, *i.e.* theories with no intrinsic length scale. The nearly scale invariant power spectrum of the CMB also suggests that scale invariance, if not full conformal invariance, plays an important role in Cosmology. 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 φ with several consequences that can be tested in the coming decade. These include:

(1) a $\varphi F_{\mu\nu}F^{\mu\nu}$ coupling to electromagnetism, so that the scalar φ behaves as a 'Axion-Like Particle' (ALP), mixing with HE γ-rays propagating through magnetic fields, interaction with the Extragalactic Background Light, and the CMB; and

(2) a specific non-Gaussian CMB bi-spectrum that can be searched for in existing Planck data, and the next generation of high precision CMB experiments CMB-S4.

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. The existence of the massless scalar gravitational scattering processes due to the anomaly was established in several papers.[4,8,9]This massless scalar of the EFT of low energy gravity (called a *conformalon*) has several consequences for Cosmology and Physics of the Universe that can be tested by forthcoming facilities, observations and data. In this LOI we focus on two of them.

(1) A Scalar Axion-Like Particle from the Conformal Anomaly

At energies much larger than the two-electron threshhold $2m_ec^2 \simeq 1$ MeV, the electron mass can be neglected and the QED fine structure 'constant' runs. This implies that there is a $F_{\mu\nu}F^{\mu\nu}$ term in the conformal anomaly of the SM, and consequently a $\varphi F_{\mu\nu}F^{\mu\nu}$ in its one-loop effective action, expressed in local form in terms of the effective conformalon scalar φ.[4,7] This interaction is analogous to the two-photon coupling of the pseudoscalar axion, so that at these energies, the conformalon scalar φ behaves in many respects as an 'Axion-Like Particle' (ALP), with consequences for both High Energy (HE) astrophysics and terrestrial experiments. In particular, propagation of HE ($\gg 1$ MeV) γ-rays through magnetic fields, the Extragalactic Background Light (EBL), and the Cosmic Microwave background (CMB) will be affected by γ/φ mixing due to this interaction. Over Mpc scales, a fraction of φ would reconvert back to γ-rays before reaching earth, leading to an increase in the observed γ-ray flux than that expected if there were no mixing and the γ-rays were attenuated by the usual SM interactions: *cf.* Fig. 1

There is already a tension between the lower bounds on the EBL obtained by adding the light of all known sources and the fact that very HE γ-rays are being observed by the VERITAS, HESS and MAGIC experiments[10]. Measurements of the spectrum of several AGNs at TeV energies suggest a $4\,\sigma$ suppression of EBL absorption, consistent with γ-ALP mixing.

The next generation of HE γ-ray imaging Cerenkov telescopes and the all-sky coverage of the proposed Southern Wide-Field of View Gamma-Ray Observatory (SWGO)[11] have the potential to either resolve this tension or provide the first unambiguous evidence of light pseudoscalar or scalar ALPs, such as that predicted by the conformal anomaly. This LOI expresses interest in adapting well-developed methods for calculating the mixing of axions with photons,[12] to compute the production of the scalar conformalon φ in strong magnetic fields, the strong gravitational fields of NSs and BHs, and the γ/φ mixing from interaction with the EBL and the CMB. These calculations will then be compared to observations of distant sources of 100 GeV to 1 TeV γ-rays, such as blazars, to search for evidence of the conformalon scalar φ, or other light scalar ALPs as the new data on HE γ-rays becomes available.

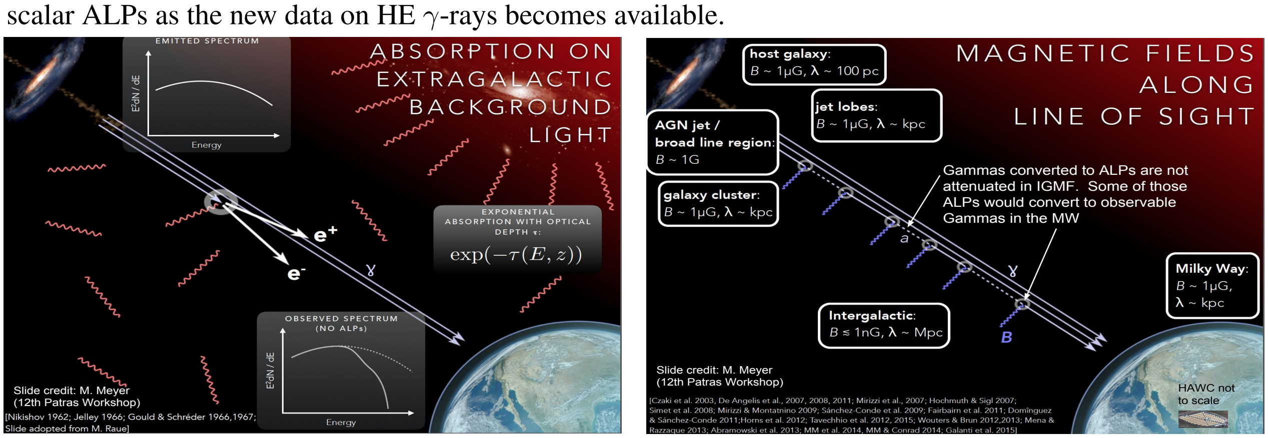

Figure 1: LeftPanel: Effect of γ-ray/ALP mixing on Absorption by the EBL (or CMB photons), and the spectrum of HE γ-rays observed on earth; Right Panel: Effect of γ-ray/ALP mixing on HE γ-ray Interaction with magnetic fields. Slide Credit: M. Meyer (12^{th} Patras Workshop).

(2) Non-Gaussian CMB Bi-spectrum from Conformal Invariance

The approximate scale invariance of the primordial CMB may be due to a deeper conformal invariance. The EFT based on conformal invariance and its breaking by the anomaly makes this the most natural expectation and motivates a systematic search for signals of conformal invariance in the Universe. One of the striking predictions of conformal invariance is non-Gaussianity in the CMB and a definite shape prediction for the angular correlations of CMB bi-spectrum, given by[13,14]

$$G_3(\vec{k}_1, \vec{k}_2, \vec{k}_3; w) \propto \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\,(k_1)^{3w-6}\, S\,(X, Y; w) \tag{1}$$

where in (1) and the accompanying Fig. 2 the triangle of the non-Gaussian bi-spectrum has edges $\vec{k}_1, \vec{k}_2, \vec{k}_3$ in Fourier space, $X \equiv k_2^2/k_1^2, Y \equiv k_3^2/k_1^2$ and w is the conformal weight of the fluctuations responsible for the CMB, related to the scalar spectral index $n_S = 2w - 3$ of the power spectrum. The analytic form for the shape function $S(X, Y; w)$ is determined by solution of the conformal Ward Identities for the three-point function, and is known in terms of special (Appell) functions[14]. It is quite different than that predicted by slow roll inflationary models, and neither its magnitude nor weight w is fixed by small slow roll parameters. As a result, the bounds on non-Gaussianity quoted in terms of the f_{NL} parameter for typical shapes arising from inflationary models do not apply to the conformal shape function (1) and should be searched for independently.

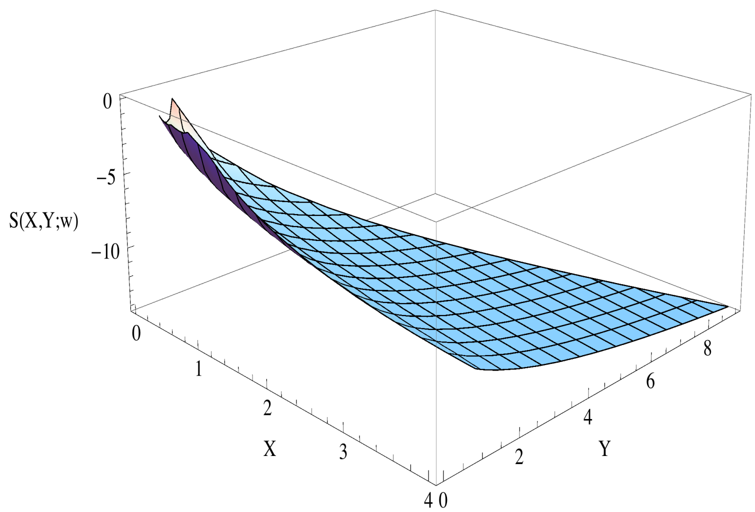

Figure 2: The non-Gaussian bispectral shape function (1) for conformal weight $w = 1.98$, corresponding to a CMB scalar spectral index $n_S = 0.96$, as a function of the ratios $X = k_2^2/k_1^2$ and $Y = k_3^2/k_1^2$.[14]

A closer collaboration between theorists and members of the Planck team is necessary to make use of the Planck CMB data, templates, and data analysis expertise in order to search for evidence of the non-Gaussian bi-spectral shape predicted by conformal invariance (1) in the data–or at worst derive a more stringent bound than that provided by presently quoted f_{NL} values. This bound is relevant for testing the standard ŁCDM model and comparing predictions of new cosmological models to the forthcoming data on Large Scale Structure (LSS) and Baryon Acoustic Oscillations (eBOSS) at larger redshifts. Indirect observation of the conformalon scalar φ by its effects on forthcoming CMB polarization measurements for the next generation of high precision CMB experiments, CMB-S4 is likewise of high interest.[15,16] Any positive detection of non-Gaussianity would require revision of our understanding of early Universe Cosmology, and in particular, the origins and history of the fluctuations that give rise to the CMB temperature anisotropies.

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