Galileonic Higgs Cosmology

Including: JHEP **1503**, 154 (2015)
JCAP **1502** (2015) 02, 015
Phys.Rev. D93 (2016) no.6, 064012
& JCAP **1603** (2016) 03, 038

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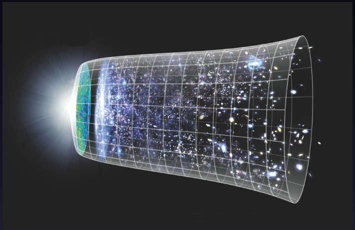
Introduction



?

Finding an *alternative* explanation for the accelerated expansion of the universe presents a challenge for model builders.

Self Acceleration

Can this phenomenon be understood via the existence of new degrees of freedom?

Want to:

- Reproduce the acceleration in the background.
- Satisfy Solar System constraints on gravitational interactions.

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$\Rightarrow$ Vector Galileons exhibit these properties!

Galileons: review

Galileons are scalar fields with an action that is invariant under a ‘Galileon’ transformation:

$$\phi \rightarrow \phi' = \phi + b_\mu x^\mu + c$$

and have an equation of motion that is formed of $\partial^2\phi$.

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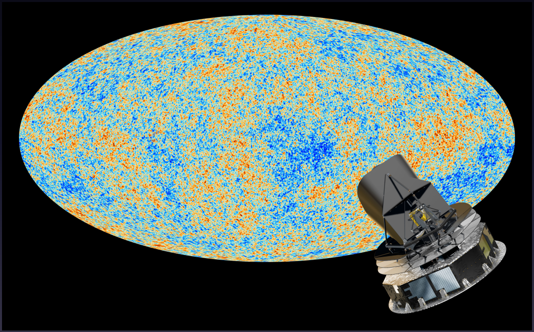
<u>and</u> have an equation of motion that is formed of $\partial^2\phi$.

- $\mathcal{L}_{Gal} \sim Z^{\mu\nu}[\partial^2\phi]\partial_\mu\phi\partial_\nu\phi + \frac{\alpha}{M_{Pl}}\phi T$
- $Z^{\mu\nu}[\partial^2\phi] \gg 1$ $\Rightarrow$ strongly self coupled $\Rightarrow$ screened from T.
- This is a realisation of the 'Vainshtein Mechanism'.

Vectors

Vectors are also useful for exchanging long range forces:



E.G. CMB Photons acting on Planck's sensor.

Vectors

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A mass term breaks the symmetry:

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Theorem

Weinberg: Leading order theory in IR for Spin 1 $\equiv$ Yang Mills.

$\Rightarrow$ actually just adding interactions with a scalar degree of freedom.

Vector Galileons

Tasinato 1402.6450 & Heisenberg 1402.7026:

Extension of Proca

Vector Galileons extend Proca with derivative self-interactions:

$$\mathcal{L}_v \sim -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - m^2 A_\mu A_\nu Z^{\mu\nu}(\partial A \partial A \dots)$$

They are constructed out of antisymmetric combinations of derivatives in exactly the same way as scalar Galileons.

- (Tasinato 1402.6450) $\Rightarrow$ Self acceleration ✓
- (De Felice et.al. 1602.00371) $\Rightarrow$ Vainshtein screening ✓ (See Ying Li's talk)

$\mathcal{E}$psilon tensor ubiquity

The totally antisymmetric ε-tensor can be found everywhere:

- Lovelock invariants $\Rightarrow$ Higher Dim. extension of GR with 2nd order EoM.
- Ghost free Massive Gravity.
- Bi-Gravity.
- Horndeski, Beyond Horndeski and Galileons.

$\mathcal{E}$psilon tensor construction I

We use the properties of the ε-tensor to construct the $Z^{\mu\nu}(\partial A \partial A)$ for the vector Galileons:

$$\mathcal{L} \sim \varepsilon^{\mu_1\mu_2\mu_3\cdots}\varepsilon^{\nu_1\nu_2\nu_3\cdots}A_{\mu_1}A_{\nu_1}(\partial_{\mu_2}A_{\nu_2}\,\partial_{\mu_3}A_{\nu_3}\ldots)$$

$\Rightarrow$ no time derivative acts on A_0 in its field equation.
$\Rightarrow \exists$ a constraint for A_0 $\Rightarrow$ 2 x spin 1 $+$ 1 x spin 0 $=$ 3 DOF.

Covariant vector Galileons

- Tasinato 1402.6450 & Heisenberg 1402.7026: $\Rightarrow$ Use Horndeski!
- $\Rightarrow$ Alternative IR completion to the same degrees of freedom as Massive gravity.

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$$\mathcal{L}_{(4)} = -\frac{\beta_2}{m^2} A_\mu A^\mu \left[(\nabla_\nu A^\nu)^2 - (\nabla_\nu A_\lambda)^2 \underbrace{-\frac{1}{4} R A_\sigma A^\sigma}_{\text{NMC}} \right]$$

- Decoupling limit $\equiv$ quartic covariant Galileon.
- 1402.7026,1511.03101,1602.03410,1605.05565: Interactions with the transversal modes $\Rightarrow$ 4 Extra Functions!

Cosmological applications

Tasinato 1402.6450:

- Coupling to gravity $\Rightarrow$ deSitter & technically natural Hubble parameter.
- Including matter $\Rightarrow$ Renormalisation of G_N (From $\sqrt{-g}G_4(X)R$).

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Tasinato 1404.4883:

- Including Large $\Lambda_{\rm bare} \Rightarrow H^2 \propto \frac{1}{\Lambda_{\rm bare}}$
- Small value for the Hubble parameter protected by approximate abelian symmetry.

De Felice et.al. (See Shinji's talk)

- arXiv:1603.05806: $\exists$ stable solutions & deSitter attractor.
- arxiv:1605.05066: Higher order terms reduce $G_{\rm eff}$ & $f\sigma_8$.

Eg: Cubic vG with tachyonic mass

Cubic with tachyonic mass $\Rightarrow$ Self-acceleration.

$$\mathcal{L}_3 = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + m^2 A_\mu A^\mu - \beta A_\mu A^\mu (\partial \cdot A)$$

Work with isotropic (de Sitter) background so choose: $A_\mu = (A0(t), \vec{0})$. The background equations are:

$$-A0e^{3Ht}(m^2 + 6A0H\beta) = 0$$

$$\frac{1}{2}e^{3Ht}(A0^2m^2 + 6H^2M_{\rm Pl}^2 + 12A0^3H\beta) = 0$$

With the solutions:

$$\Rightarrow \; A0 = 0 \quad \text{or} \quad A0 = \frac{-m^2}{6H\beta}$$

$$\Rightarrow \; H = \frac{m^{3/2}}{6^{3/4}\sqrt{M_{\rm Pl}}\sqrt{\beta}}$$

Quadratic action for scalar perturbations

- At $O(\epsilon^2)$ have 3 constraints for 4 variables.
- $\Rightarrow$ non-canonical kinetic term for the ζ perturbations.

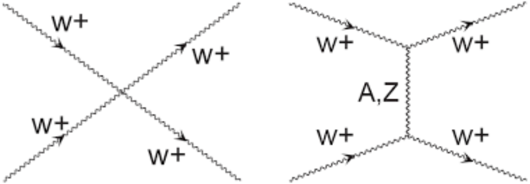
$$\mathcal{L}_{\epsilon^2} \sim \Big(\frac{3e^{Ht}M_{\rm Pl}^2}{m^2}\Big)k^2\Big\{\dot{\zeta}^2 - \Big(\frac{m^2}{18H^2e^{2Ht}}\Big)k^2\zeta^2\Big\}$$

- $\Rightarrow$ k-dependent kinetic term.
- No ghost or gradient instability.

G-Higgs: Motivation

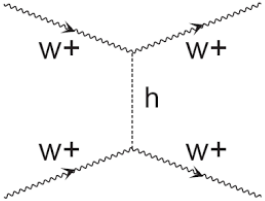
- Extend the Higgs mechanism to generate the extended Proca system (vG).
- Extra galileonic field can generate new dynamics.
- Can cure strong coupling issues related to mass terms for gauge fields.
- Found in condensed matter systems and the Standard Model.

Eg: Standard Model Renormalisation



Problem

Massive vectors ⇒ non-unitary S-matrix at tree level.



Restored by the Higgs.

The Higgs Mechanism I

Locally $U(1)$-invariant Lagrangian for a complex scalar field, (where $\mathcal{D}_\mu \equiv \partial_\mu - igA_\mu$):

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - (\mathcal{D}_\mu\phi)(\mathcal{D}^\mu\phi)^* - V(\phi\phi^*)$$

with the usual 'Mexican Hat' potential:

$$V(\phi\phi^*) = -\mu^2\phi\phi^* + \frac{\lambda}{2}(\phi\phi^*)^2$$

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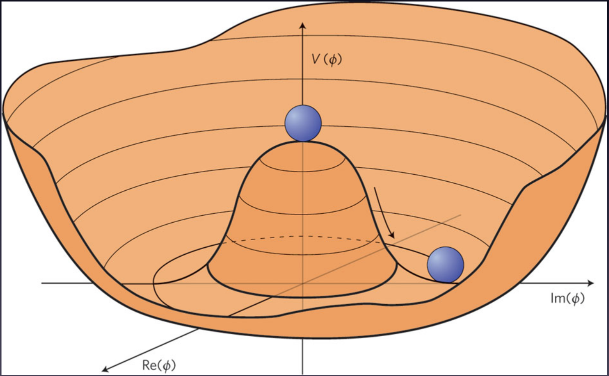
The minimum of $V(\phi)$ gives us the background vacuum expectation value (vev): $\langle\phi\rangle \equiv v = \left(\frac{\mu^2}{\lambda}\right)^{1/2}$.

The Higgs Mechanism II

Decompose ϕ into a norm, φ and phase, π: $\phi = \varphi e^{ig\pi}$.
φ doesn't transform whereas π parametrises the coset $U(1)/Z_2$ and transforms nonlinearly: $\pi \to \frac{\pi}{\xi g}$.



The Higgs Mechanism III

Expanding about the background vev $\langle\phi\rangle \equiv v$ with a small perturbation, $\varphi = \left(v + \frac{h}{\sqrt{2}}\right)$ where $h << v, \partial h$ gives us the Proca equation:

$$\mathcal{L}_h = -\frac{1}{2}\left(\partial h\right)^2 - \mu^2 h^2 + \dots$$
$$\mathcal{L}_A = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - g^2\, v^2\, \hat{A}^2$$

where $\hat{A}_\mu \equiv A_\mu - \partial_\mu \pi$.

Higgsing Vector Galileons: 1408.6871

Usual complex scalar Higgs Lagrangian with additional higher order terms:

$$\begin{aligned} \mathcal{L}_{tot} &= -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - (\mathcal{D}_\mu\phi)(\mathcal{D}^\mu\phi)^* - V(\phi\phi^*) \\ &+ \mathcal{L}_{(8)} + \mathcal{L}_{(12)} + \mathcal{L}_{(16)} \,. \end{aligned}$$

Construct $\mathcal{L}_{(8)}, \mathcal{L}_{(12)}, \mathcal{L}_{(16)}$ out of abelian invariants:

$$L_{\mu\nu} \equiv \Re[\mathcal{D}_\mu\phi\mathcal{D}_\nu\phi^*] \quad \text{and} \quad P_{\mu\nu} \equiv \Re[\phi^*\mathcal{D}_\mu\mathcal{D}_\nu\phi]$$

$$Q_{\mu\nu} \equiv \Im[\phi^*\mathcal{D}_\mu\mathcal{D}_\nu\phi]$$

Operator Decomposition

Setting $\phi = \varphi e^{ig\pi}$ and $\hat{A}_\mu = A_\mu - \partial_\mu \pi$ gives:

$$L_{\mu\nu} = \partial_\mu \varphi \partial_\nu \varphi + g^2 \varphi^2 \hat{A}_\mu \hat{A}_\nu,$$
$$P_{\mu\nu} = \varphi \partial_\mu \partial_\nu \varphi - g^2 \varphi^2 \hat{A}_\mu \hat{A}_\nu,$$
$$Q_{\mu\nu} = \frac{g}{2}\left[\partial_\mu(\varphi^2 \hat{A}_\nu) + \partial_\nu(\varphi^2 \hat{A}_\mu)\right].$$

We contract with the Levi-Civita epsilon tensor to construct antisymmetric combinations.

Example: Cubic Vector Galileon

The cubic vector Galileon is generated from:

$$\mathcal{L}^{\beta}_{(8)} = -\frac{\beta_{(8)}}{\Lambda^4} \left(L_{\rho}^{\ \rho} Q_{\sigma}^{\ \sigma} - L_{\mu}^{\ \nu} Q_{\nu}^{\ \mu} \right)$$

Expanding about the background:

$$\mathcal{L}_h = -\frac{1}{2} (\partial h)^2 - \mu^2 h^2 + \dots$$

$$\mathcal{L}_A = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - g^2 v^2 \hat{A}^2 + \frac{2\, \beta\, g^3\, v^4}{\Lambda^4} \, (\hat{A}^2 \, \partial_\nu \hat{A}^\nu)$$

$$\mathcal{L}_{Ah} = \frac{\beta\, g\, v^2}{\Lambda^4} \left[(\partial h)^2 \, \partial_\rho \hat{A}^\rho - \partial_\rho h \partial^\rho \hat{A}^\sigma \partial_\sigma h) + \dots \right]$$

Covariantisation

- Use non-minimal coupling but must be U(1) invariant.
- Quartic parameters constrained to be equal $\alpha_{(12)} = \beta_{(12)} \equiv \gamma_{(12)}$.
- Non-minimal coupling: $\mathcal{L}^{NMC}_{(12)} = -\gamma\sqrt{-g}\frac{1}{2\Lambda^8}\phi^*\phi L L_{\mu\nu} G^{\mu\nu}$.
- This contains both conformal and disformal couplings that are $U(1)$ invariant.
- There seems to be an obstruction for the quintic theory.

Ghost Galileonic Higgs

- Aim: to generate the Tachyonic Cubic vG cosmology.
- Use wrong sign U(1) gauged kinetic term:
- $\mathcal{L}_{\mathcal{GGH}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + (\mathcal{D}_\mu\phi)(\mathcal{D}^\mu\phi)^* - V(\phi\phi^*) + \mathcal{L}_{(8)}$
- Isotropic background (de Sitter): have $A0$ and $\rho0$.
- Expand around the $\rho0 =$ vev of the Higgs: Include compensating Λ_0

Background Solutions

Sub. in background solutions $A0 = 2/9Hq\beta\rho0^2$ and $\rho0 = \mu/\sqrt{\lambda}$:

$$\frac{4e^{3Ht}\sqrt{\lambda}(2\lambda - 27H^2\alpha\mu^2)}{243H^2\beta^2\mu^3} = 0$$

$$\frac{e^{3Ht}}{81H^2}\left(243H^4M_{\rm Pl}^2 - \frac{4\lambda}{\beta^2\mu^2}\right) = 0$$

Which have solutions:

$$H = \frac{\sqrt{\frac{2}{3}\lambda}}{3\sqrt{\alpha}\mu}$$

$$\beta = \frac{\sqrt{3}\alpha\mu}{M_{\rm Pl}\sqrt{\lambda}}$$

$\Rightarrow$ Self-accelerating system.

Perturbations

At $O(\epsilon^2)$ we find that the kinetic matrix has eigenvalues:

$$\lambda_1 = \frac{3e^{Ht}k^2 M_{\rm Pl}^2 \lambda}{2q^2\mu^2},$$
$$\lambda_2 = \frac{e^{Ht}(k^2 M_{\rm Pl}^2 q^2 \lambda \mu^2 - 7e^{2Ht} M_{\rm Pl}^2 q^2 \lambda \mu^2 - 18 e^{2Ht} q^2 \mu^4)}{54 q^2 \mu^2}$$

- Recover dynamics for the vector longitudinal mode.
- Low energy *tachyonic* ghost?:

$$k^2 << \frac{e^{2Ht} q^2 \mu^2 (7 M_{\rm Pl}^2 \lambda + 18 e^{2Ht} \mu^2)}{M_{\rm Pl}^2 \lambda^2} \sim e^{2Ht} vev^2$$

- No gradient instability.

Summary

- Vector Galileons have interesting cosmological applications.
- The Higgs mechanism can be extended to create ghost free combinations of scalar-vector galileons.
- Recover bi-Galileons in the decoupling limit.
- U(1) invariance reduces the parametric freedom.
- Higgs Inflation $\Rightarrow$ Higher derivatives soften the effective potential.
- Wrong sign Higgs + Cubic $\Rightarrow$ self acceleration.
- Physics of the low energy (tachyonic) ghost? (currently under investigation).

Thanks!

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