Generalized Galileons
for
Particle Physics & Cosmology

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Motivations
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- Used to break the electroweak symmetry, solve the strong CP problem, inflate the universe, accelerate it at late times, ...
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• We’ll see - too early to know if these will be useful or not - but it is turning out to be great fun trying.
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\[ \pi(x) \to \pi(x) + c + b_\mu x^\mu \]

The Galilean symmetry!
Galileons

Can consider this symmetry as interesting in its own right
• Yields a novel and fascinating 4d effective field theory
• Relevant field referred to as the Galileon

(Nicolis, Rattazzi, & Trincherini 2009)
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\[ \mathcal{L}_{n+1} = n \eta_{\mu_1 \nu_1} \mu_2 \nu_2 \cdots \mu_n \nu_n \left( \partial_{\mu_1} \pi \partial_{\nu_1} \pi \partial_{\mu_2} \partial_{\nu_2} \pi \cdots \partial_{\mu_n} \partial_{\nu_n} \pi \right) \]
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Luty, Porrati, Rattazzi (2003); Nicolis, Rattazzi (2004)
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\sim \Lambda^3 R_V^{3/2} \sqrt{r} + \text{const.} & r \ll R_V \\
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\[ \frac{F_\pi}{F_{\text{Newton}}} = \frac{\pi'(r) / M_{Pl}}{M / (M_{Pl}^2 r^2)} = \begin{cases} \sim \left( \frac{r}{R_V} \right)^{3/2} & R \ll R_V \\ \sim 1 & R \gg R_V \end{cases} \]
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So forces much smaller than gravitational strength within the Vainshtein radius - hence safe from 5th force tests.
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Thus, if we canonically normalize the kinetic term of the perturbations, we raise the effective strong coupling scale, and, more importantly, heavily suppress the coupling to matter!
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\[ r \approx \frac{1}{\Lambda} \quad \text{and} \quad r \approx R_V \]
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A new classical regime, with order one nonlinearities

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Multi-field Galileons and Higher co-Dimension Branes
Higher co-Dimension Probe Branes

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Covariant Derivative \quad Intrinsic Curvature

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\text{Covariant Derivative} \\
\text{Intrinsic Curvature} \\
\text{Normal Bundle Curvature} \\
\text{Extrinsic curvature}
\end{array}
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\[ g_{\mu\nu} = \eta_{\mu\nu} + \partial_\mu \pi^I \partial_\nu \pi_I \]
Higher co-Dimension Probe Branes

With some work, can extend probe brane construction to multiple co-dimensions

$$X^\mu(x) = x^\mu, \quad X^I(x) \equiv \pi^I(x)$$

Induced Metric on Brane

$$g_{\mu\nu} = \eta_{\mu\nu} + \partial_\mu \pi^I \partial_\nu \pi_I$$

More general version of action de Rham & Tolley wrote

$$S = \int d^4x \sqrt{-g} F \left( g_{\mu\nu}, \nabla_\mu, R^i_{j\mu\nu}, R^\rho_\sigma{}^{\mu\nu}, K^i_\mu \nu \right)$$

In co-dimension 1, for 2nd order equations, use Lovelock terms and associated boundary terms. Here, for 4d brane, prescription depends on co-dimension

If N = 2, boundary terms include only brane cosmological constant, and

$$\mathcal{L}_{N=2} = \sqrt{-g} \left( R[g] - (K^i)^2 + K^i_{\mu\nu} K_i^{\mu\nu} \right)$$
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Can even add a mass term and remains technically natural
Generalized Galileons on Curved Geometries
Galileons on General Backgrounds

Goon, Hinterbichler, M. T., JCAP 1107, 017 (2011).]
Main point:

- Have emphasized probe brane construction because it can be extended to more general geometries. e.g. other maximally-symmetric examples
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Galileons with symmetry

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\begin{align*}
(\delta_K + \delta_{g,\text{comp}}) \pi &= -a^i k^\mu_i(x) \partial_\mu \pi + a^I K^5_I(x, \pi) - a^I K^{\mu}_I(x, \pi) \partial_\mu \pi
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The Maximally-Symmetric Taxonomy
Potentially different Galileons corresponding to different ways to foliate a maximally symmetric 5-space by a maximally symmetric 4-d hypersurface.
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<table>
<thead>
<tr>
<th>Ambient metric</th>
<th>Brane metric</th>
<th>AdS$_4$</th>
<th>$M_4$</th>
<th>dS$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AdS_5$</td>
<td>AdS DBI galileons</td>
<td>so(4, 2) $\rightarrow$ so(3, 2)</td>
<td>Conformal DBI galileons</td>
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</tr>
<tr>
<td></td>
<td>$f(\pi) = R \cosh^2 (\rho/R)$</td>
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<tr>
<td>$M_5$</td>
<td>DBI galileons</td>
<td>$p(4, 1) \rightarrow p(3, 1)$</td>
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<td>$dS_5$</td>
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Small field limit

- AdS galileons
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  - An appearance in the decoupling limit of some massive gravity theories (I’ll mention a little more in my plenary)
Summary

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• Couplings to matter and stability still need investigating in generality - some simple couplings display instabilities.
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Thank You!
Acknowledgements & References