

Cosmic Acceleration from Abelian Symmetry Breaking

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Dark energy

- **Current acceleration** is compatible with **positive cosmological constant**
 - ▷ Impressive **fine-tuning** is required
- **Idea:** use **new fields** besides Einstein gravity to **drive acceleration**
 - ▷ Quintessence
Scalar field with appropriate interactions
 - ▷ Modified gravity
New gravitational d.o.f.'s control the cosmological dynamics at large scales

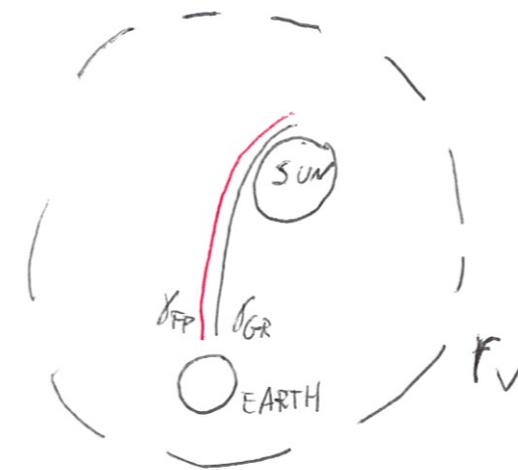
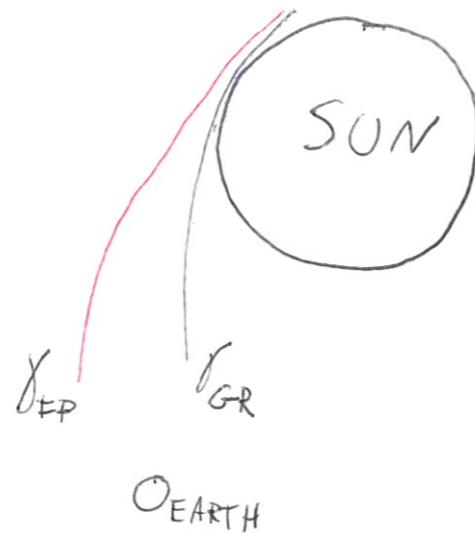
Problems:

- We need **very light fields** to drive dark energy ($m \simeq H$):
- Why don't we see them with observations at **solar system scales**?
- For scalars: What's keeping their mass **small**?
(scalar masses receive large corrections)

Dark energy

Screening mechanisms

- Chamaleon, Vainshtein mechanism



Non-linear dynamics at scales below a radius r_V :

Strong coupling effects suppress extra forces (\Rightarrow GR results)

Dark energy

Screening mechanisms

- Simplest realization of Vainshtein:

Scalars with appropriate derivative self-interactions

Galileons [Nicolis et al]

$$\mathcal{L}_2 = -\frac{1}{2} (\partial\pi)^2$$

$$\mathcal{L}_3 = (\partial\pi)^2 \square\pi$$

$$\mathcal{L}_4 = (\partial\pi)^2 \left[(\square\pi)^2 - (\partial_\mu\partial_\nu\pi)^2 \right]$$

$$\mathcal{L}_5 = (\partial\pi)^2 \left[(\square\pi)^3 + 2 (\partial_\mu\partial_\nu\pi)^3 - 3\square\pi (\partial_\mu\partial_\nu\pi)^2 \right]$$

Dark energy

Screening mechanisms

- Simplest realization of Vainshtein:

Scalars with appropriate derivative self-interactions

Galileons [Nicolis et al]

- ▷ Self-interactions **drive** cosmic acceleration: $\pi \propto t^2$
- ▷ At small scales (within r_V) non-linear self-interactions become dominant:
Scalar fifth force gets screened
- ▷ Scalar has zero mass because of a symmetry: $\pi \rightarrow \pi + c + b_\mu x^\mu$

Galileons

Some general considerations

- Screening mechanisms as Vainshtein are **very effective** \Rightarrow **hard to test**
 - Study systems without spherical symmetry:
then Galileons don't necessarily screen [Bloomfield et al]
 - Study BHs in centre of galaxies that are free-falling in an external gravitational field [Hui, Nicolis]
- Coupling to gravity one **breaks** galileon invariance:
can be extended to **more complex theories** with same theoretical dignity
 - Hordensky
 - Beyond Hordensky [Gleyzes et al; Gao]
 - Couple to vectors [Deffayet et al; GT et al]

Parameter space becomes very large \Rightarrow **hard to test**
- Connection Galileons \Leftrightarrow Vainshtein mechanism \Leftrightarrow **superluminality** [Adams et al]

Embedding Galileons in a more fundamental set-up

- ▷ **Consistency conditions** (absence of ghosts, new symmetries) impose constraints on the structure of the theory: This **reduces parameter space**
- ▷ **Prescription** for coupling with matter or extra fields
- ▷ Suggest **new ways** to test the theory, or cure theoretical issues

What one can look for:

- ▷ Galileons are not put by hand, but arise in well motivated particle physics set-ups.
- ▷ Goldstone bosons of broken symmetries?
(see e.g. [\[Goon et al\]](#))

First example: dRGT massive gravity

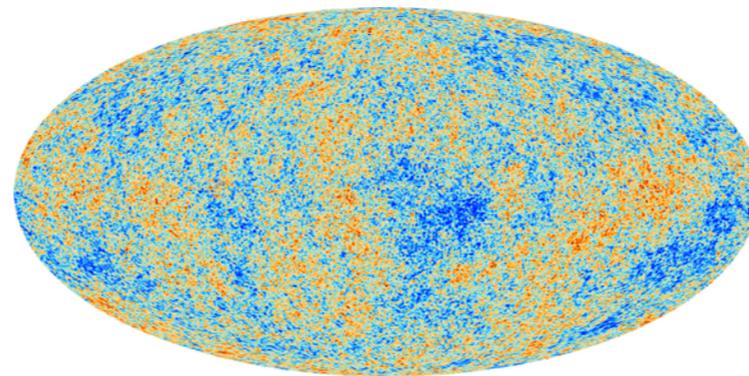
- GR propagates 2 d.o.f.s. Massive gravity propagates 5 (2+2+1).
- In a suitable decoupling limit, the **scalar graviton polarization** acquires (restricted) Galileon self-interactions
- **Challenging** to investigate cosmological dynamics

Second (simpler) example:

Vectors breaking abelian symmetry

Longitudinal polarization of vector mediates dark energy

- Vectors have been important in the history of modifications of GR, since the early days (**Kaluza-Klein**, Einstein-Aether, TeVeS)
- Vectors are able to **mediate long range forces**: think to electromagnetism!



- A small mass m_A or small vector couplings can be **technically natural**.

Task: build vector theory that is ghost-free and interesting

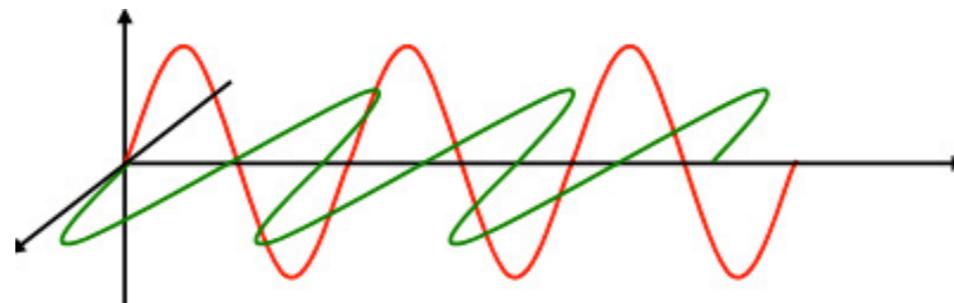
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Task: build vector theory that is ghost-free and interesting

[GT, Heisenberg]

- **Break gauge symmetry:** the longitudinal vector polarization gets dynamical and acquires Galileon interactions in a decoupling limit.



- **Don't introduce ghosts:** the time-component A_0 remains non-dynamical

Second (simpler) example:

Vectors breaking abelian symmetry

Task: build vector theory that is ghost-free and interesting

$$\mathcal{L}_{(0)} = -m^2 A_\mu A^\mu ,$$

$$\mathcal{L}_{(1)} = -\beta_2 A_\mu A^\mu (\partial_\rho A^\rho) ,$$

$$\mathcal{L}_{(2)} = -\frac{\beta_3}{m^2} A_\mu A^\mu [(\partial_\rho A^\rho)(\partial_\nu A^\nu) - (\partial_\rho A^\nu)(\partial^\rho A_\nu)] ,$$

$$\mathcal{L}_{(3)} = -\frac{\beta_4}{m^4} A_\mu A^\mu \left[-2(\partial_\mu A^\mu)^3 + 3(\partial_\mu A^\mu)(\partial_\rho A^\sigma \partial^\rho A_\sigma) + 3(\partial_\mu A^\mu)(\partial_\rho A^\sigma \partial_\sigma A^\rho) \right. \\ \left. - \partial_\mu A^\nu \partial_\nu A^\rho \partial_\rho A^\mu - 3\partial_\mu A^\nu \partial_\nu A^\rho \partial^\mu A_\rho \right] ,$$

- **Break gauge symmetry:** the longitudinal vector polarization gets dynamical and acquires Galileon interactions in a decoupling limit.

Nice feature: The full theory is relatively easy to study – also **beyond decoupling limit!**

Screening with vectors

Example: Electric field produced by point charge

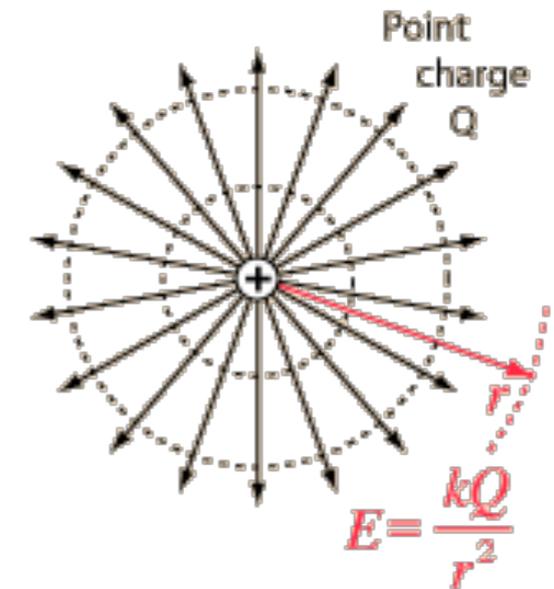
$$A_\mu = (A_0, A_1, A_2, A_3)$$

$$-\vec{\nabla}^2 A_0 = \rho - 2m^2 A_0 - 2\beta A_0 \partial_i A_i,$$

$$2m^2 A_i = \vec{\nabla}^2 A_i - \partial_i \partial_j A^j + \beta \partial_i (-A_0^2 + A_j^2) - 2\beta A_i \partial_j A_j,$$

With $A_i = A_i^T + \partial_i \chi$ and $\partial_i A_i^T = 0$

Sufficiently far from the source, electric potential and longitudinal polarization scale with different powers of r



Safe regime

$$\frac{\sqrt{\beta}}{m} \ll r \ll 1/(\sqrt{2}m)$$

$$A_0 \simeq -\frac{Q}{r}$$

$$\chi \simeq -\frac{\beta Q}{m^2 r^2}$$

Coupling to gravity

- Same **technical issues** one meets coupling to gravity scalar Galileons

Must ensure that EOMs remain second order

- The result is

$$\mathcal{L}_{(1)}^{cov} = -\beta_1 A_\mu A^\mu (\nabla_\rho A^\rho) ,$$

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

- The total action is

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{M_*^2}{2} R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \mathcal{L}_{(0)}^{cov} - \mathcal{L}_{(1)}^{cov} - \mathcal{L}_{(2)}^{cov} - \Lambda_{cc} \right]$$

Vector dark energy

- Look for homogeneous cosmological expansion driven by vectors

▷ Metric Ansatz $ds^2 = -dt^2 + a^2(t) \delta^{ij} dx_i dx_j$

▷ Matter content: Λ_{cc} and vector $A_\mu = (A_0(t), 0, 0, 0)$

Vector equation is algebraic $A_0 \left(m^2 - 3 \beta_1 A_0 H + 9 \frac{\beta_2}{m^2} A_0^2 H^2 \right) = 0$

Vector solution:

$$A_0^\pm(t) = \frac{\beta_1 \pm \sqrt{\beta_1^2 - 4\beta_2}}{6\beta_2} \frac{m^2}{H(t)},$$
$$= \frac{c_\pm m^2}{H(t)}.$$

Although A_0 does not propagate, it acquires a non-trivial profile

The Friedmann equation

- It is convenient to re-express $\beta_2 = \frac{(1 - \gamma^2) \beta_1^2}{4}$, $\Lambda_{cc} = \frac{m^3 M_*}{3 \beta_1} \lambda$

Hence

$$H_{\mp}^2 = \frac{m^3}{18 \beta_1 M_*} \left[\lambda \mp \sqrt{\lambda^2 - \frac{24(1 + 3\gamma)}{(1 + \gamma)^3}} \right]$$

- ▷ The **negative branch** allows to compensate large cc:

$$H_-^2 = \frac{m^3}{3 \beta_1 \lambda M_*} = \left(\frac{m^3}{3 \beta_1} \right)^2 \frac{1}{\Lambda_{cc}}$$

The Hubble scale is **inversely proportional** to Λ_{cc}

- ▷ The **positive branch** allows to drive acceleration with vector only when $\lambda = 0$:

$$H_+^2 = \frac{m^3}{18 \beta_1 M_*} \sqrt{-\frac{24(1 + 3\gamma)}{(1 + \gamma)^3}}$$

The size of dark energy is **technically natural** thanks to approximate symmetries

Linearized fluctuations around de Sitter

- Tensor Fluctuations

The non-minimal coupling of the vector to gravity induces a renormalization of the Planck mass

$$M_{\pm}^2 = \left(1 + \frac{24(1+\gamma)}{(\gamma-1)^3 \left(\lambda \pm \sqrt{\lambda^2 - \frac{24(3\gamma-1)}{(\gamma-1)^3}} \right)^2} \right) M_*^2$$

This imposes a *lower bound* on Λ_{cc}

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Good news: The photon mass vanishes around de Sitter solutions!!

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- Scalar Fluctuations

No dynamics: longitudinal photon dof is non-dynamical around de Sitter

Is it a problem?

Possibly, due to strong coupling

To do: Check what happens coupling to other fields

Higgs mechanism

Vector naturally couple to scalar when implementing a Higgs mechanism.

Spontaneous breaking of gauge symmetry

Good news: A Higgs mechanism can be found in this scenario

Typically theories with hard symmetry breaking encounter issues:

- ▷ Lack of unitarity
- ▷ Difficult to quantize

Spontaneous symmetry breaking leads to better behaved set-ups

Higgs mechanism

A Higgs mechanism for derivative vector self-interactions

[Hull, Koyama, GT]

$$\mathcal{L}_{tot} = -(\mathcal{D}_\mu\phi)(\mathcal{D}^\mu\phi)^* - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - V(\phi) + \mathcal{L}_{(8)}$$

Derivative self-interactions for the Higgs boson

Expanding covariant derivatives we get couplings with vectors

$$\mathcal{L}_{(8)} = \frac{i\beta}{\Lambda^4} [(\mathcal{D}_\mu\phi)^*(\mathcal{D}_\nu\phi) + (\mathcal{D}_\nu\phi)^*(\mathcal{D}_\mu\phi)] \cdot [\phi^*(\mathcal{D}_\rho\mathcal{D}_\sigma\phi)^* - \phi^*(\mathcal{D}_\sigma\mathcal{D}_\rho\phi)] \cdot (\eta^{\mu\nu}\eta^{\rho\sigma} - \eta^{\mu\rho}\eta^{\nu\sigma})$$

Higgs mechanism

Decompose Higgs in vev plus fluctuation $\varphi = \left(v + \frac{h}{\sqrt{2}} \right)$

The resulting Lagrangian is

$$\begin{aligned} \mathcal{L}_{tot} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - m_A^2 \hat{A}^2 - \tilde{\beta} \hat{A}_\mu \hat{A}^\mu \partial_\rho \hat{A}^\rho \\ & -\frac{1}{2} (\partial h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{\sqrt{\lambda} m_h}{2} h^3 - \frac{\lambda}{8} h^4 - \sqrt{2} g m_A h A_\mu A^\mu - \frac{g^2}{2} h^2 A_\mu A^\mu \\ & + \frac{4g\tilde{\beta}}{3m_A} \left(\sqrt{2} h + \frac{3g}{2m_A} h^2 + \frac{g^2}{\sqrt{2}m_A^2} h^3 + \frac{g^3}{8m_A^3} h^4 \right) \left(\hat{A}_\mu \hat{A}^\nu \partial_\nu \hat{A}^\mu - \hat{A}_\mu \hat{A}^\mu \partial_\rho \hat{A}^\rho \right) \\ & + \frac{\tilde{\beta}}{3m_A^2} \left(1 + \frac{\sqrt{2}g}{m_A} h + \frac{g^2}{2m_A^2} h^2 \right) \left(\partial_\mu h \partial^\nu h \partial_\nu \hat{A}^\mu - \partial_\mu h \partial^\mu h \partial_\rho \hat{A}^\rho \right), \end{aligned}$$

Decoupling limit: Bi-galileon coupling **Higgs + Goldstone boson**

Summary

- **Consistent set-up** breaking gauge symmetry with derivative vector interactions
 - ▷ In appropriate decoupling limit, Goldstone boson has Galileon self-interactions
 - ▷ The symmetry can be spontaneously broken by Higgs mechanism

Simple embedding of Galileons in particle physics motivated scenario

- Interesting phenomenology
 - ▷ Screening mechanism
 - ▷ Consistent vector model for dark energy?