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`

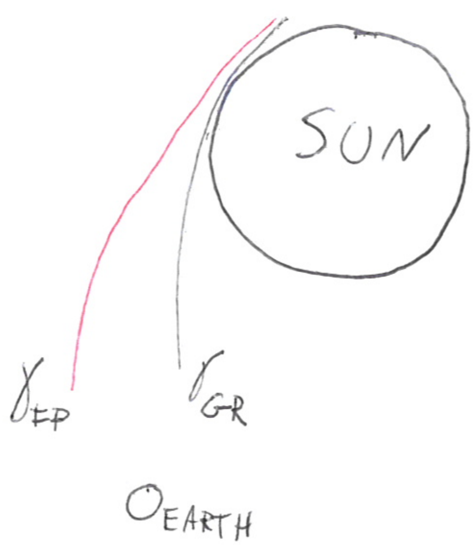
Problems:

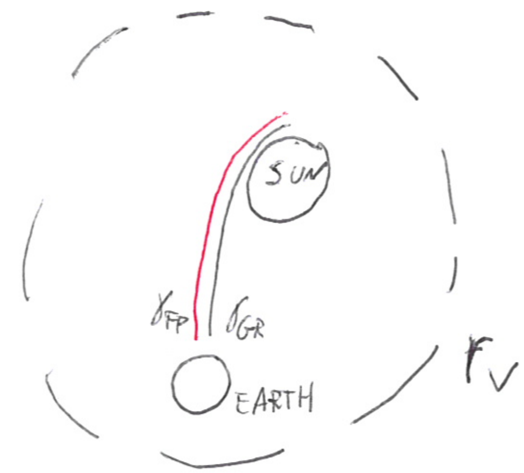
- We need **very light fields** to drive dark energy ($m \simeq H$):
- Why don't we see them with observations at **solar system scales**?
- For scalars: What's keeping their mass **small**?
  (scalar masses receive large corrections)

Dark energy

Screening mechanisms

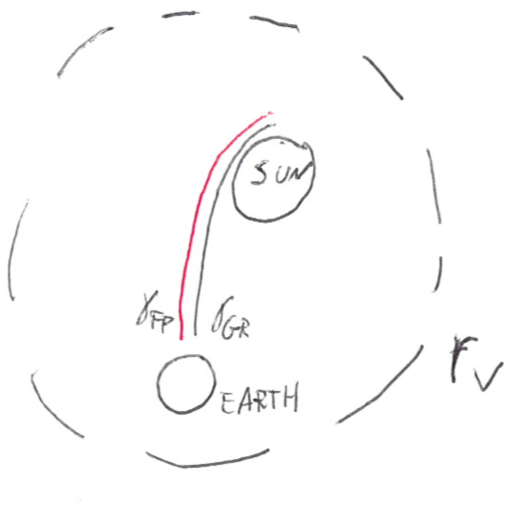
- Chamaleon, **Vainshtein mechanism**





Non-linear dynamics at scales below a **radius** r_V:
Strong coupling effects suppress extra forces ($\Rightarrow$ GR results)

Dark energy



Intuitive picture of how Vainshtein works

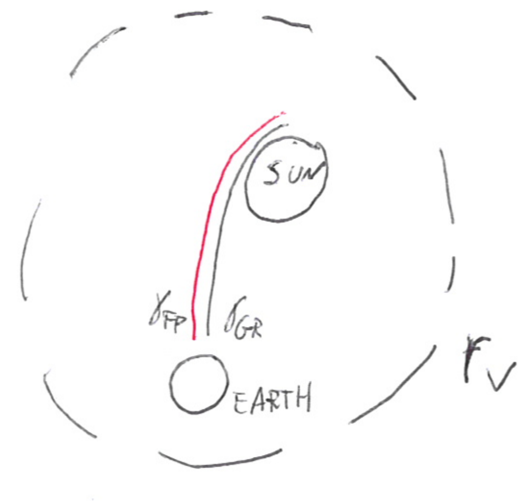
▷ Derivative Lagrangian coupled to `trace` of EMT

$$\mathcal{L} \simeq -\frac{1}{2} Z^{\mu\nu}(\phi)\, \partial_\mu \phi\, \partial_\nu \phi + \frac{\alpha}{M_{Pl}}\, \phi\, T$$

with $$Z_{\mu\nu} = g_{\mu\nu} + \frac{1}{\Lambda^3}\, \partial_\mu \partial_\nu\, \phi + \frac{1}{\Lambda^6}\, \partial_\mu \partial^\rho \phi\, \partial_\rho \partial_\nu\, \phi + \ldots$$

Dark energy

Intuitive picture of how Vainshtein works



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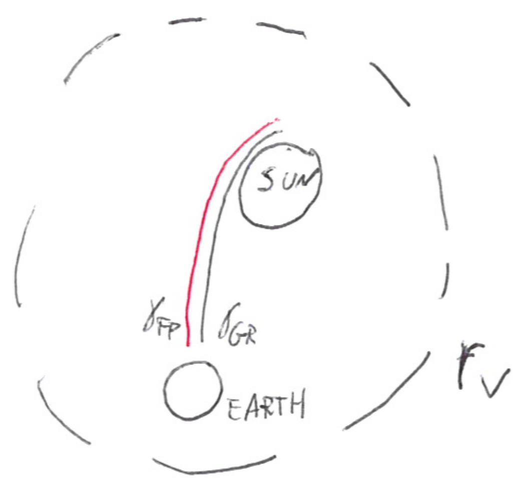
▷ Consider strong-coupling regime $$\frac{\partial^2\phi_0}{\Lambda^3} \equiv \Sigma \gg 1$$

Decompose ϕ in background plus fluctuation, $\phi = \phi_0 + \varphi$

Dark energy

Intuitive picture of how Vainshtein works



- Derivative Lagrangian coupled to `trace` of EMT

$$\mathcal{L} \simeq -\frac{1}{2} Z^{\mu\nu}(\phi)\, \partial_\mu \phi\, \partial_\nu \phi + \frac{\alpha}{M_{Pl}}\, \phi\, T$$

with $\quad Z_{\mu\nu} = g_{\mu\nu} + \frac{1}{\Lambda^3}\, \partial_\mu \partial_\nu\, \phi + \frac{1}{\Lambda^6}\, \partial_\mu \partial^\rho \phi\, \partial_\rho \partial_\nu\, \phi + \ldots$

- Consider strong-coupling regime $\quad \frac{\partial^2 \phi_0}{\Lambda^3} \equiv \Sigma \gg 1$

  Decompose ϕ in background plus fluctuation, $\phi = \phi_0 + \varphi$

- Hence $\quad Z^{\mu\nu}(\phi_0)\, \partial_\mu \varphi\, \partial_\nu \varphi \simeq \left(\frac{\partial^2 \phi_0}{\Lambda^3} \right)^n (\partial \varphi)^2 \overset{\texttt{canonically normalize}}{\Rightarrow} \hat{\varphi} = \sqrt{Z}\, \varphi$

  so that $$\mathcal{L} \simeq -\frac{1}{2}\, \partial_\mu \hat{\varphi}\, \partial_\nu \hat{\varphi} + \frac{\alpha}{\sqrt{Z}\, M_{Pl}}\, \hat{\varphi}\, T$$

Dark energy

Screening mechanisms

- Simplest realization of Vainshtein:

  Scalars with appropriate derivative self-interactions

Galileons [Nicolis et al]

$$
\begin{aligned}
\mathcal{L}_2 &= -\frac{1}{2}(\partial\pi)^2 \\
\mathcal{L}_3 &= (\partial\pi)^2\,\Box\pi \\
\mathcal{L}_4 &= (\partial\pi)^2\left[(\Box\pi)^2 - (\partial_\mu\partial_\nu\pi)^2\right] \\
\mathcal{L}_5 &= (\partial\pi)^2\left[(\Box\pi)^3 + 2\,(\partial_\mu\partial_\nu\pi)^3 - 3\Box\pi\,(\partial_\mu\partial_\nu\pi)^2\right]
\end{aligned}
$$

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: $\pi \to \pi + c + b_\mu x^\mu$

`Galileon symmetry + Vainsthein mechanism`

$\Downarrow$

`Powerful non-renormalization theorems!`

Galileon Lagrangians are stable under quantum corrections

Galileons

Some general considerations

- Screening mechanisms as Vainsthein are **very effective** ⇒ **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 fiel [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` ⇒ **hard to test**

- Connection Galileons ⇔ Vainsthein mechanism ⇔ **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?`

  Advantage: Goldstones have only derivative interactions

  (see e.g. [Goon et al])

First example: dRGT massive gravity

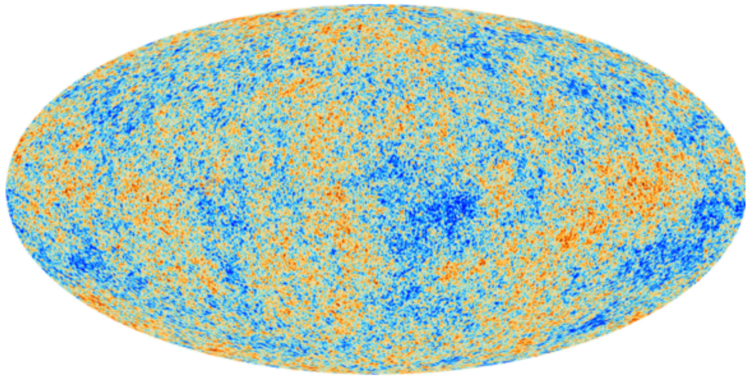
- GR propagates 2 d.o.f.s. Massive gravity propagates 5 (2+2+1).
- In a suitable decoupling limit, the **scalar graviton polarization** acquires (restricted) Galileon self-interactions
- **Challenging** to investigate cosmological dynamics

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`

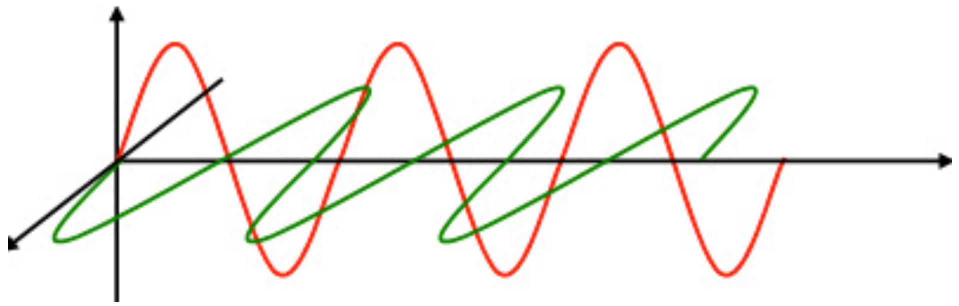
Second (simpler) example:

Vectors breaking abelian symmetry

`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`

$$
\begin{aligned}
\mathcal{L}_{(0)} &= -m^2 \, A_\mu A^\mu \, , \\
\mathcal{L}_{(1)} &= -\beta_2 \, A_\mu A^\mu \, \left(\partial_\rho A^\rho\right) \, , \\
\mathcal{L}_{(2)} &= -\frac{\beta_3}{m^2} \, A_\mu A^\mu \, \left[\left(\partial_\rho A^\rho\right)\left(\partial_\nu A^\nu\right) - \left(\partial_\rho A^\nu\right)\left(\partial^\rho A_\nu\right)\right] \, , \\
\mathcal{L}_{(3)} &= -\frac{\beta_4}{m^4} \, A_\mu A^\mu \Big[-2 \left(\partial_\mu \, A^\mu\right)^3 + 3 \, \left(\partial_\mu \, A^\mu\right) \, \left(\partial_\rho \, A^\sigma \partial^\rho A_\sigma\right) + 3 \, \left(\partial_\mu \, A^\mu\right) \, \left(\partial_\rho \, A^\sigma \partial_\sigma A^\rho\right) \\
&\quad - \partial_\mu \, A^\nu \, \partial_\nu \, A^\rho \, \partial_\rho \, A^\mu - 3 \, \partial_\mu \, A^\nu \, \partial_\nu \, A^\rho \, \partial^\mu \, A_\rho \Big] \, ,
\end{aligned}
$$

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

Second (simpler) example:

Vectors breaking abelian symmetry

Decoupling limit

- Take first symmetry breaking operators $\mathcal{L} = -m^2 A_\mu A^\mu - \beta A_\mu A^\mu \partial_\nu A^\nu$
- Use Stückelberg trick, adding a scalar π to make it gauge invariant

$$\begin{aligned}\mathcal{L} &= -m^2 \left(A_\mu - \partial_\mu \pi\right)\left(A^\mu - \partial^\mu \pi\right) \\ &\quad -\beta \left(A_\mu - \partial_\mu \pi\right)\left(A^\mu - \partial^\mu \pi\right)\left(\partial_\nu A^\nu - \Box \pi\right)\end{aligned}$$

Gauge transformation: $A_\mu \to A_\mu + \partial_\mu \xi \quad ; \quad \pi \to \pi + \xi$

3 d.o.f. in total: π plays the role of vector longitudinal polarization

Second (simpler) example:

Vectors breaking abelian symmetry

`Decoupling limit`

- Take first symmetry breaking operators $\mathcal{L} \;=\; -m^2\, A_\mu A^\mu - \beta\, A_\mu A^\mu\, \partial_\nu A^\nu$

- Canonically normalize, $\hat{\pi} \equiv \sqrt{2}\, m\, \pi$,

$$\mathcal{L} \;=\; -\frac{1}{2}\left(\sqrt{2}\, m\, A_\mu - \partial_\mu \hat{\pi}\right)\left(\sqrt{2}\, m\, A^\mu - \partial^\mu \hat{\pi}\right)$$
$$-\frac{\beta}{2\sqrt{2}\, m^3}\left(\sqrt{2}\, m\, A_\mu - \partial_\mu \hat{\pi}\right)\left(\sqrt{2}\, m\, A^\mu - \partial^\mu \hat{\pi}\right)\left(\sqrt{2}\, m\, \partial_\nu A^\nu - \Box \hat{\pi}\right)$$

- Take limit $m \to 0$; $\beta \to 0$; $\frac{\beta}{m^3} \;=\; \text{fixed} \;=\; \frac{1}{\Lambda^3}$

$$\mathcal{L} \;=\; -\frac{1}{2}\, \partial_\mu \hat{\pi} \partial^\mu \hat{\pi} + \frac{1}{2\sqrt{2}\, \Lambda^3}\, \partial_\mu \hat{\pi} \partial^\mu \hat{\pi}\, \Box \hat{\pi}$$

$\Downarrow$

`Cubic Galileon`

Second (simpler) example:

Vectors breaking abelian symmetry

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

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

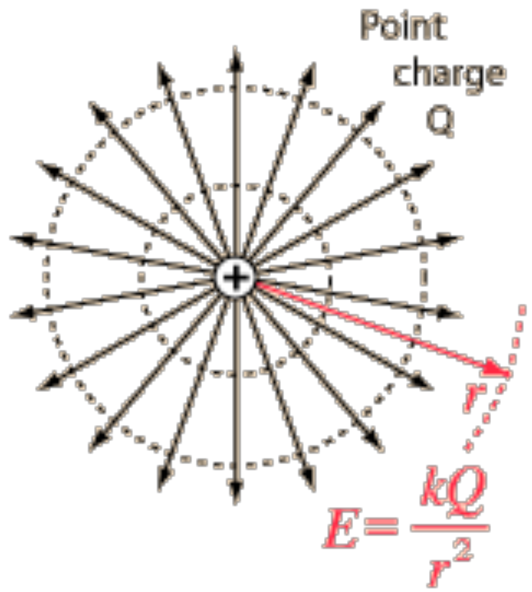
- **Break gauge symmetry**: the longitudinal vector polarization gets dynamical and acquires Galileon interactions in a decoupling limit.

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

Screening with vectors

Example: Electric field produced by point charge

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



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

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

$$A_0 \;\simeq\; -\frac{Q}{r}$$
$$\chi \;\simeq\; -\frac{\beta\,Q}{m^2\,r^2}$$

Coupling to gravity

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

`Must ensure that EOMs remain second order`

- The result is

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

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

- The total action is

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

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

`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:

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

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

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

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

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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- Vector Fluctuations

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

- 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 $\Rightarrow$ Is it possible to do it in a natural way ?

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

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

Higgs mechanism

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

The resulting Lagrangian is

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

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

$\Rightarrow$ New couplings with possibly interesting cosmological consequences (to avoid instabilities?)

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?