Dark energy and the photon

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Cosmology

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  - ▷ Phenomenologically, it's hard to **avoid** fifth force constraints associated with light scalar fields

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Theoretical problem:

Find a technically natural theory for dark energy

Very similar situation with SM of particle physics

Why modifying gravity in the IR?

- Cosmic acceleration $\Leftrightarrow$ non-trivial dynamics of gravity
  Infrared modification of GR at large distances
  - ▷ Higher dimensional models as DGP:
    Brane with localized EH term embedded into infinite extra dimension.
    Gravity gets weaker at large distances: diluted into the extra dimension
    This induces **cosmological acceleration**
  - ▷ Massive gravity
    Gravity gets weaker because mass screens it at large distances.

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  Contributions to vacuum energy should curve the space: they **do not**.

  We don't understand why; GR has **nothing to say** on this respect.

  Hope

  ▷ Modifying the theory of gravity will shed light on this problem, enriching the dynamics of the theory (symmetries).
  Naturally small or vanishing cc.

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Symmetry arguments can explain the size of dark energy scale

- Issue: it's very hard to consistently modify GR.

  ▷ New degrees of freedom are unavoidable: we've to deal with them.

Massive gravity

- `Propagates 5 dofs`

From **Fierz-Pauli** theory (1939) (BD ghost appears beyond linear level)

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to **de Rham-Gabadadze-Tolley** theory (2010) (free of BD ghost)

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They are the additional graviton polarizations

Massive gravity

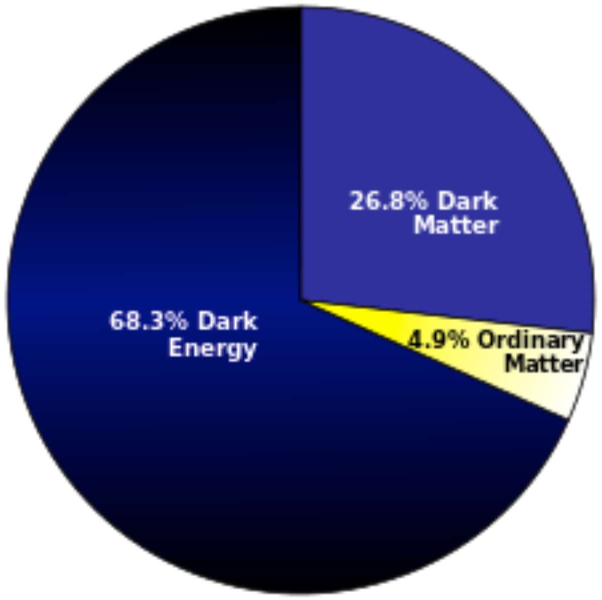
Cosmological acceleration and screening

- Interesting for **cosmology**: **self-acceleration**:

  De Sitter solutions in absence of cc [de Rham et al; Koyama, Niz, GT],

$$H^2 \simeq m^2$$

Small graviton mass $\Rightarrow$ small value for dark energy scale



`Technically natural choice` ['t Hooft]:

In the limit of $m \to 0$ one recovers diffeo invariance

Scale of dark energy is **protected** by symmetry arguments

`Great advantage with respect to the` **`scalar`** `case`

Massive gravity

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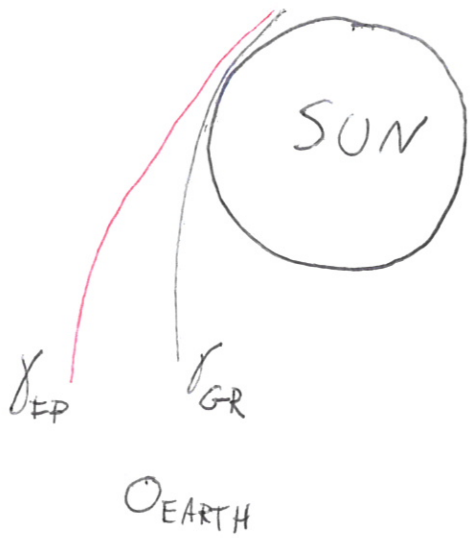
- What about **long range fifth forces** ?

`New light dof appear`



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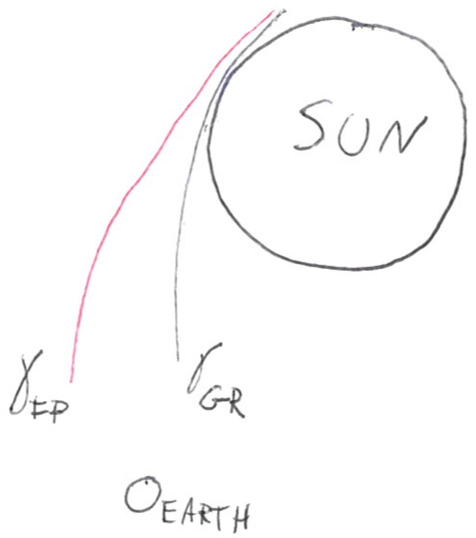

Non-linearities **screen** fifth forces nearby sources: **Vainshtein mechanism**

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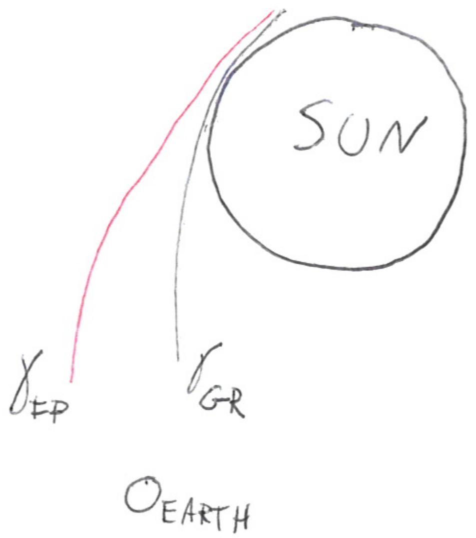

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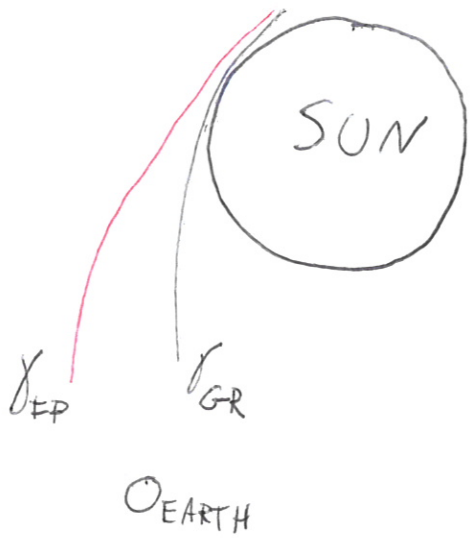

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Strong coupling effects
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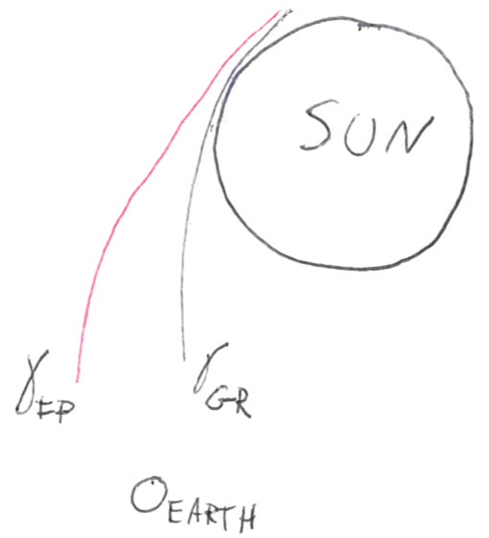

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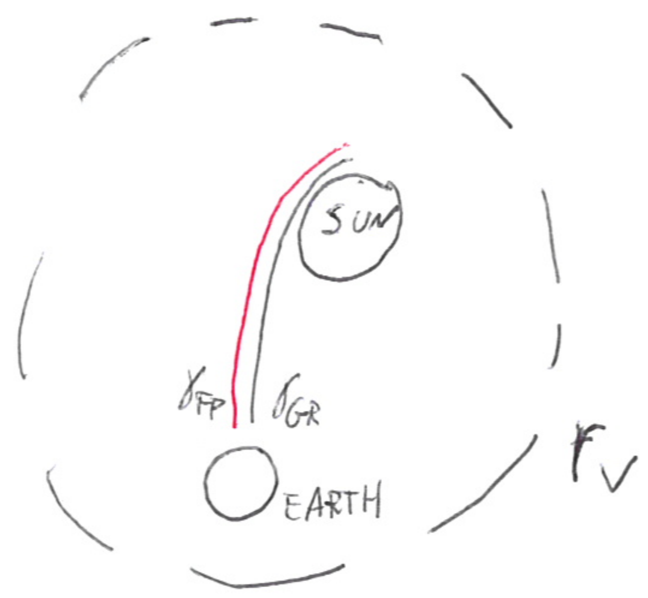

...but...

de Rham-Gabadadze-Tolley theory (2010)

- It is a **complex theory**
  (this's maybe why it took 80 years to be discovered)
  - ▷ Difficult to handle, delicate to study dynamics of perturbations

- It has **instabilities** around self-accelerating configurations
  - ▷ The **vector component** of the 5 dof is a ghost [GT et al; Gumrukcuoglu et al]

- Subtle environmental effects:
  - ▷ It enters in an **untrustable** strong coupling regime when Vainshtein mechanism takes place [Burrage, Kaloper, Padilla]

- **Superluminal propagation** [Deser, Waldron]

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Ways out?

To **save self-acceleration**, one can **enrich the theory**:

- ▷ Quasi-dilaton: add a scalar field coupled to massive gravity [D'Amico et al, Gabadadze et al]
- ▷ Bigravity: consider couple dynamics of two physical metrics with mass term [Hassan-Rosen, Fasiello-Tolley]. But see also [Crisostomi et al]

Result: ghost **eliminated** from cosmological configurations

Another approach:
try something simpler, saving the best features

Massive gravity $\Leftrightarrow$ **Galileons**

[Nicolis, Rattazzi, Trincherini]

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$\Rightarrow$ Corresponding EOMs contain at most two time derivatives!!

$\Rightarrow$ Invariant under **Galileon symmetry** $\pi \to \pi + c + b_\mu x^\mu$

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Massive gravity reduces to a **combination** of Galileons in decoupling limit

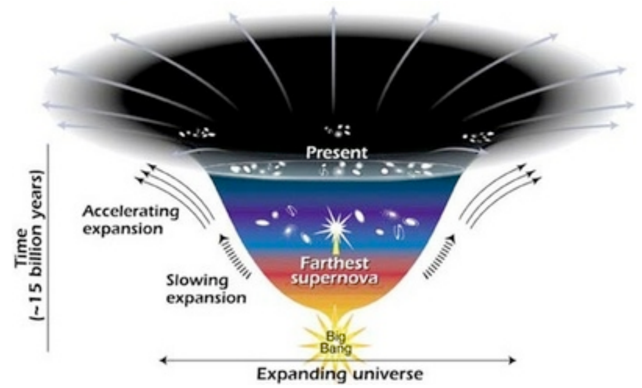
π `scalar graviton polarization`

$$
m \to 0 \quad , \quad M_{Pl} \to \infty \quad , \quad \Lambda_3 \equiv m^2 M_{Pl} = \text{fixed.}
$$

Nice features of Galileons

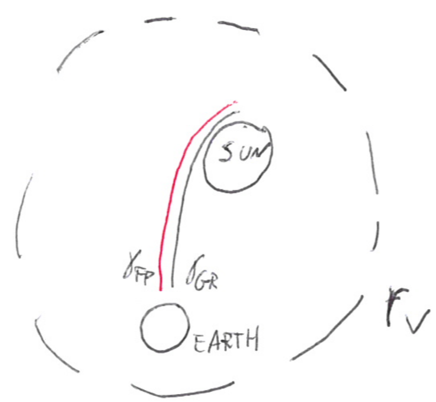
▷ **Derivative self-interactions** lead to **cosmological acceleration** with technically natural value of H

— `Large scale effect`



▷ **Screening of fifth forces**
Vainshtein mechanism recovers GR

— `Small scale effect`



▷ **Non-renormalization** theorems
Structure of these operators stable under corrections

Our universe is currently accelerating

¿ Due to a dynamical long range force ?

- **Extra spin 0 scalar degree of freedom**

  Curves the space-time at large scales, but gets screened at short scales

  `Galileon!`

- **Self-interaction of spin 2 graviton degree of freedom**

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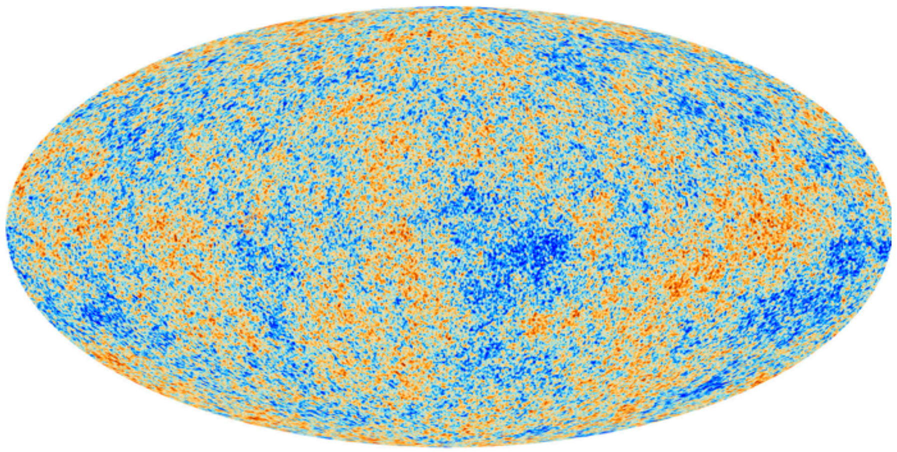
Can we find other systems with such a useful link to Galileons?

Modified electromagnetism

- Gravity is **not** the only observed long range force.

Electromagnetic force is also long range!



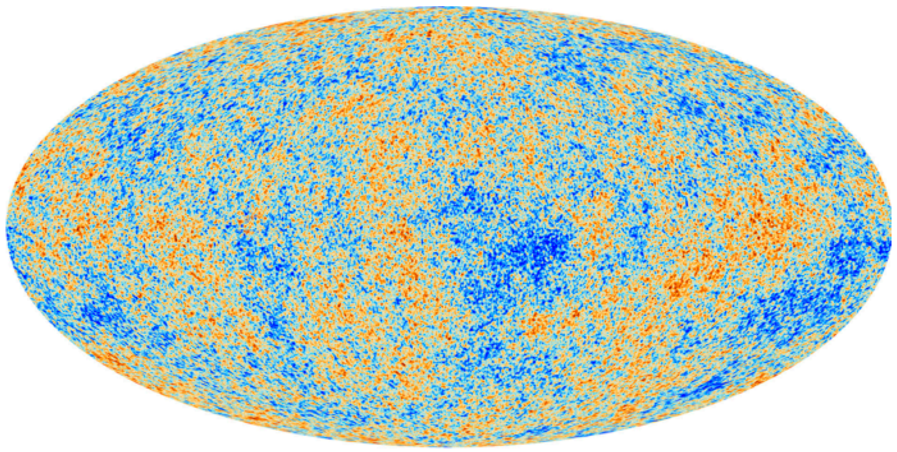
Electromagnetic force mediated by spin 1 vector $A_\mu = (A_0, A_1, A_2, A_3)$

- Photon has **two** degrees of freedom: $A_\mu = \left(A_0,\, A_i^T + \partial_i\,\chi\right)$ with $\partial_i\, A_i^T = 0$
  - ▷ The longitudinal component χ can be gauged away
  - ▷ The EOM for A_0 is a constraint: this component does not propagate
  - ▷ One ends with two transverse components A_i^T

Modified electromagnetism

- Gravity is **not** the only observed long range force.

Electromagnetic force is also long range!



Electromagnetic force mediated by spin 1 vector $A_\mu = (A_0, A_1, A_2, A_3)$

Question: How to modify EM so to find connection with Galileons?

Modified electromagnetism

- Gravity is **not** the only observed long range force.

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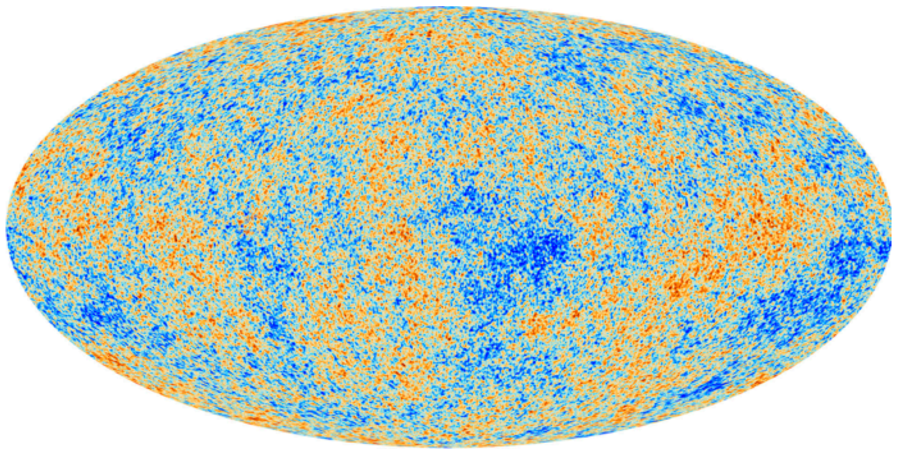
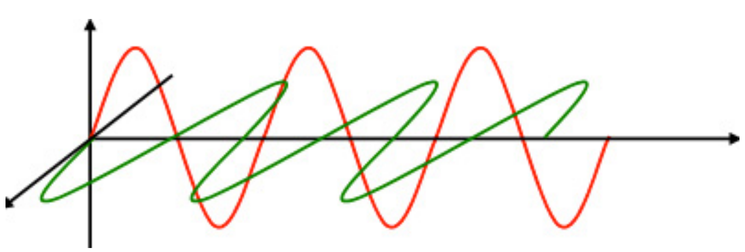


Electromagnetic force mediated by spin 1 vector $A_\mu = (A_0, A_1, A_2, A_3)$

Question: How to modify EM so to find connection with Galileons?

Idea: Renounce to Abelian gauge invariance:



– Gauge symmetry: 2 transverse polarizations (2 dof)

– No gauge symmetry: 2 transverse + 1 longitudinal (3 dof)

Modified electromagnetism

Let's give interesting dynamics to vector longitudinal degree of freedom

- The **minimal** interesting Lagrangians with derivative self-couplings are (`gravity added later`)

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

`Proca mass term`

`New interactions`

`I spare to you the details: the aim is to get an interesting consistent set-up`

Modified electromagnetism

Let's give interesting dynamics to vector longitudinal degree of freedom

- The **minimal** interesting Lagrangians with derivative self-couplings are (`gravity added later`)

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

- **Nice theoretical features**
  - ▷ EOM for time-component A_0 is constraint: no ghost!
  - ▷ In decoupling limit the longitudinal polarization is controlled by Galileons. Galileon and Abelian symmetries are recovered!

`Chosen such that only 3 dof propagate`

Modified electromagnetism

Focus on the first two interactions

▷ In decoupling limit the longitudinal polarization is controlled by Galileons. Galileon and Abelian symmetries are recovered!

`Stückelberg trick: an alternative way to write the Lagrangian`

$$\begin{aligned}\mathcal{L}_T \;=\; & -\frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\left(\sqrt{2}\,m\,A_\mu + \partial_\mu\phi\right)\left(\sqrt{2}\,m\,A^\mu + \partial^\mu\phi\right)\\ & -\;\frac{\beta}{\sqrt{8}\,m^3}\left(\sqrt{2}\,m\,A_\mu + \partial_\mu\phi\right)\left(\sqrt{2}\,m\,A^\mu + \partial^\mu\phi\right)\left(\sqrt{2}\,m\,\partial_\nu A^\nu + \partial_\nu\partial^\nu\phi\right)\end{aligned}$$

`Choose` $\phi = 0$: `you get the same as before`

- Included Stückelberg scalar to make the Lagrangian gauge invariant: $A_\mu \to A_\mu + \partial_\mu\xi$, $\phi \to \phi - \sqrt{2}m\xi$
  - ϕ plays the same physical role of longitudinal photon polarization

Modified electromagnetism

Focus on the first two interactions

- In decoupling limit the longitudinal polarization is controlled by Galileons. Galileon and Abelian symmetries are recovered!

$$\begin{aligned}\mathcal{L}_T \;=\; & -\frac{1}{4}\,F_{\mu\nu}F^{\mu\nu}-\frac{1}{2}\left(\sqrt{2}\,m\,A_\mu+\partial_\mu\phi\right)\left(\sqrt{2}\,m\,A^\mu+\partial^\mu\phi\right)\\ & -\;\frac{\beta}{\sqrt{8}\,m^3}\left(\sqrt{2}\,m\,A_\mu+\partial_\mu\phi\right)\left(\sqrt{2}\,m\,A^\mu+\,\partial^\mu\phi\right)\left(\sqrt{2}\,m\,\partial_\nu A^\nu+\,\partial_\nu\partial^\nu\phi\right)\end{aligned}$$

Modified electromagnetism

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$$
\begin{aligned}
\mathcal{L}_T \;=\; & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2}\left(\sqrt{2}\, m\, A_\mu + \partial_\mu \phi\right)\left(\sqrt{2}\, m\, A^\mu + \partial^\mu \phi\right) \\
& - \frac{\beta}{\sqrt{8}\, m^3}\left(\sqrt{2}\, m\, A_\mu + \partial_\mu \phi\right)\left(\sqrt{2}\, m\, A^\mu + \partial^\mu \phi\right)\left(\sqrt{2}\, m\, \partial_\nu A^\nu + \partial_\nu \partial^\nu \phi\right)
\end{aligned}
$$

`Decoupling limit (different from massive gravity)`

Modified electromagnetism

Focus on the first two interactions

- In decoupling limit the longitudinal polarization is controlled by Galileons. Galileon and Abelian symmetries are recovered!

$$\mathcal{L}_T = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\left(\sqrt{2}\,m\,A_\mu + \partial_\mu\phi\right)\left(\sqrt{2}\,m\,A^\mu + \partial^\mu\phi\right)$$
$$- \frac{\beta}{\sqrt{8}\,m^3}\left(\sqrt{2}\,m\,A_\mu + \partial_\mu\phi\right)\left(\sqrt{2}\,m\,A^\mu + \partial^\mu\phi\right)\left(\sqrt{2}\,m\,\partial_\nu A^\nu + \partial_\nu\partial^\nu\phi\right)$$

`Decoupling limit (different from massive gravity)`

$$m \to 0,\ \beta \to 0, \qquad \frac{\beta}{m^3} = \text{fixed} = \frac{\sqrt{2}}{\Lambda_G^3}$$

Modified electromagnetism

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$$\mathcal{L}_{dec} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2\,\Lambda_G^3}\left(\partial_\mu \phi\, \partial^\mu \phi\right) \partial_\nu \partial^\nu \phi$$

Modified electromagnetism

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- In decoupling limit the longitudinal polarization is controlled by Galileons. Galileon and Abelian symmetries are recovered!

$$\mathcal{L}_T = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \left(\sqrt{2}\, m\, A_\mu + \partial_\mu \phi\right) \left(\sqrt{2}\, m\, A^\mu + \partial^\mu \phi\right)$$
$$- \frac{\beta}{\sqrt{8}\, m^3} \left(\sqrt{2}\, m\, A_\mu + \partial_\mu \phi\right) \left(\sqrt{2}\, m\, A^\mu + \partial^\mu \phi\right) \left(\sqrt{2}\, m\, \partial_\nu A^\nu + \partial_\nu \partial^\nu \phi\right)$$

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You get plenty of symmetries that protect the theory!

Modified electromagnetism

Focus on the first two interactions

- ▷ In decoupling limit the longitudinal polarization is controlled by Galileons. Galileon and Abelian symmetries are recovered!

$$\mathcal{L}_T = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \left(\sqrt{2}\, m\, A_\mu + \partial_\mu \phi\right) \left(\sqrt{2}\, m\, A^\mu + \partial^\mu \phi\right) - \frac{\beta}{\sqrt{8}\, m^3} \left(\sqrt{2}\, m\, A_\mu + \partial_\mu \phi\right) \left(\sqrt{2}\, m\, A^\mu + \partial^\mu \phi\right) \left(\sqrt{2}\, m\, \partial_\nu A^\nu + \partial_\nu \partial^\nu \phi\right)$$

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You get plenty of symmetries that protect the theory!

`Concrete IR completion of Galileons`

Modified electromagnetism

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

Idea: Longitudinal polarization acquires Galileon dynamics

In certain limits, the theory has both Galileon and gauge symmetries

Modified electromagnetism

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

Question: Before starting to talk about cosmology, isn't all this ruled out by precision measurements?

Modified electromagnetism

$$
\begin{aligned}
\mathcal{L}_{(0)} &= -m^2\, A_\mu A^\mu \,, \\
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&\qquad - \partial_\mu\, A^\nu\, \partial_\nu\, A^\rho\, \partial_\rho\, A^\mu - 3\,\partial_\mu\, A^\nu\, \partial_\nu\, A^\rho\, \partial^\mu\, A_\rho \Big]\,,
\end{aligned}
$$

Question: Before starting to talk about cosmology, isn't all this ruled out by precision measurements?

`Not in an obvious way`

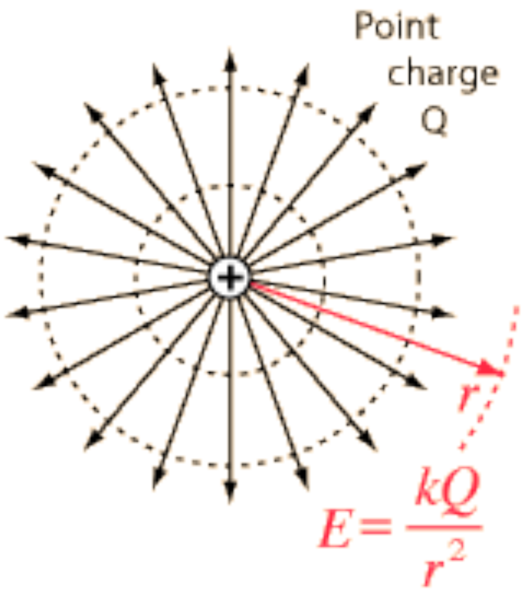
- Current constraints on photon mass: $m_\gamma \leq 10^{-19} eV$.
  Tiny, but technically natural: **protected** by gauge symmetry.
- Non-linear self interactions might lead to strong coupling effects **screening** the longitudinal polarization

  (Analogue of Vainshtein mechanism)

Modified electromagnetism

Example: Electric field produced by point charge

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



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

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

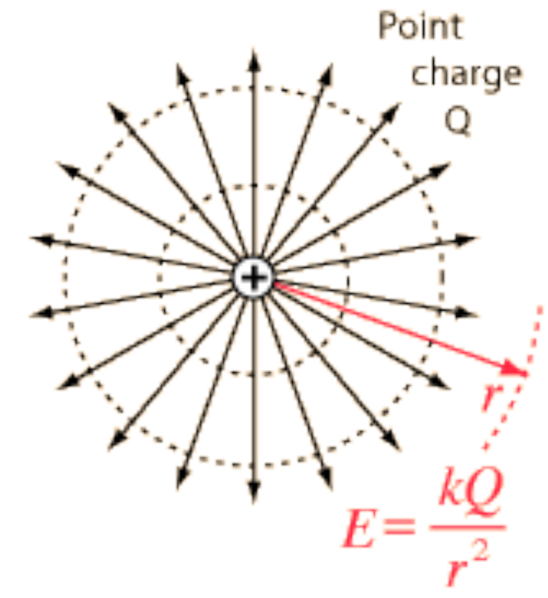
`Safe regime` $$\frac{\sqrt{\beta}}{m} \;\ll\; r \;\ll\; 1/\left(\sqrt{2}\, m\right)$$

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

Modified electromagnetism

Example: Electric field produced by point charge

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



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

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

`Opportunity to explore screening mechanism in ‘realistic’ settings`

- Go beyond spherically symmetric configurations
- Include quantum effects (QED)

Coupling to gravity

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

`Must ensure that EOMs remain second order`

- The result is

$$
\begin{aligned}
\mathcal{L}^{cov}_{(1)} &= -\beta_1\, A_\mu A^\mu\, (\nabla_\rho A^\rho)\ ,\\
\mathcal{L}^{cov}_{(2)} &= -\frac{\beta_2}{m^2}\, A_\mu A^\mu \left[(\nabla_\rho A^\rho)\,(\nabla_\nu A^\nu) - (\nabla_\rho A^\nu)\,(\nabla^\rho A_\nu) - \frac{1}{4}\, R\, A_\sigma A^\sigma\right]
\end{aligned}
$$

- The total action is

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

Cosmology

- **Vector-tensor** theories have long history in cosmology
  - ▷ Will, Nordvedt, Hellings theories of early '70.
  - ▷ Einstein-Aether [Jacobson, Mattingly]
  - ▷ TeVeS covariantization of MOND [Bekenstein]

The approach here emphasizes **symmetry principles** to build the set-up: in particular the connection with Galileons.

Symmetry arguments can explain the size of dark energy scale

This vector theory has **all nice features** of dRGT massive gravity, but in a much simpler setting

Cosmology

- 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 $$A_\mu \;=\; \left(A_0(t)\,,0\,,0\,,0\right)$$

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

`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}

`For example, requiring` $H \simeq 10^{-33}\,eV$, $\Lambda_{cc}^{\frac{1}{4}} = 10^{19}\,GeV$, `one gets`

$$m \simeq (3\,\beta_1)^{\frac{1}{3}}\;10^7\,eV$$

The Friedmann equation

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

  Hence

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  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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- Vector Fluctuations

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

Linearized fluctuations around de Sitter

- `Tensor Fluctuations`

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

- `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. To check what happens coupling vector to standard matter

Summary

- I presented consistent a theory of **vector-tensor interactions** with approximate **Abelian** and **Galileon symmetries**
  - ▷ Enjoys features of Galileon interactions – non-renormalization theorems
  - ▷ Cosmological accel solutions with technically natural dark energy scale
  - ▷ The vector mass is zero around accelerating configurations
- Possibly the **photon** can play the role of the vector, realizing an example of **modified electromagnetism**
  - ▷ Still to carefully test constraints on photon-matter interactions taking into account non-linearities (Vainsthein effect in a simpler set-up)
  - ▷ Study in detail cosmological fluctuations when vector couples to matter