Alternative theories of gravity, equivalence principles and neutron stars

Andrew Coates

Thursday 11th October, 2018

Eberhard Karls Univerity of Tübingen
Partly based on work carried out at the University of Nottingham

The takeaway

Three pieces:

The takeaway

Three pieces:

1. If we don't have exactly GR, shouldn't expect equivalence principles.

The takeaway

Three pieces:

1. If we don't have exactly GR, shouldn't expect equivalence principles.
2. That they work needs an explanation.

The takeaway

Three pieces:

1. If we don't have exactly GR, shouldn't expect equivalence principles.
2. That they work needs an explanation.
3. Equivalence in the solar system needn't mean everywhere.

Outline

- Why alternative theories?

Outline

- Why alternative theories?
- Equivalence Principles

Outline

- Why alternative theories?
- Equivalence Principles
- SEP Violations

Outline

- Why alternative theories?
- Equivalence Principles
- SEP Violations
- A toy model with WEP violation

Outline

- Why alternative theories?
- Equivalence Principles
- SEP Violations
- A toy model with WEP violation
- Future and ongoing work

Why alternative theories I: General motivation

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)
  - Techniques

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)
  - Techniques
  - Special properties

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)
  - Techniques
  - Special properties
- Theory independent tests

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)
  - Techniques
  - Special properties
- Theory independent tests
  - Understanding: meaning and strength

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)
  - Techniques
  - Special properties
- Theory independent tests
  - Understanding: meaning and strength
  - Inventing/reparametrizing

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)
  - Techniques
  - Special properties
- Theory independent tests
  - Understanding: meaning and strength
  - Inventing/reparametrizing
- Problems with the prevailing theory?

Why alternative theories I: General motivation

- Better understanding of prevailing theory (*c.f.* SUSY for QFT)
  - Techniques
  - Special properties
- Theory independent tests
  - Understanding: meaning and strength
  - Inventing/reparametrizing
- Problems with the prevailing theory?
- If something is fundamental, want to be sure as possible.

Why alternative theories II: Classical GR

- Dark whatever (*c.f.* Neptune Vs Vulcan)

Why alternative theories II: Classical GR

- Dark whatever (*c.f.* Neptune Vs Vulcan)
- Cosmology: coincidences and a plethora of "problems"

Why alternative theories II: Classical GR

- Dark whatever (*c.f.* Neptune Vs Vulcan)
- Cosmology: coincidences and a plethora of “problems”
- e.g. tensions in Hubble measurements

Why alternative theories II: Classical GR

- Dark whatever (*c.f.* Neptune Vs Vulcan)
- Cosmology: coincidences and a plethora of "problems"
- e.g. tensions in Hubble measurements
- Nasty things (often expect QM to fix these)

Why alternative theories II: Classical GR

- Dark whatever (*c.f.* Neptune Vs Vulcan)
- Cosmology: coincidences and a plethora of "problems"
- e.g. tensions in Hubble measurements
- Nasty things (often expect QM to fix these)
  - Singularities almost inevitable

Why alternative theories II: Classical GR

- Dark whatever (*c.f.* Neptune Vs Vulcan)
- Cosmology: coincidences and a plethora of "problems"
- e.g. tensions in Hubble measurements
- Nasty things (often expect QM to fix these)
  - Singularities almost inevitable
  - CTCs
  - Cauchy horizons *etc.*

Why alternative theories III: Quantum gravity

- GR is non-renormalizable (at least perturbatively)

[1] next slide

Why alternative theories III: Quantum gravity

- GR is non-renormalizable (at least perturbatively)
- GR is unique[1] classically

[1] next slide

Why alternative theories III: Quantum gravity

- GR is non-renormalizable (at least perturbatively)
- GR is unique[1] classically
- QG candidates

[1] next slide

Why alternative theories III: Quantum gravity

- GR is non-renormalizable (at least perturbatively)
- GR is unique[1] classically
- QG candidates

Once we go beyond GR quantum corrections threaten Equivalence Principles.

[1] next slide

Why alternative theories III: Quantum gravity

- GR is non-renormalizable (at least perturbatively)
- GR is unique[1] classically
- QG candidates

Once we go beyond GR quantum corrections threaten Equivalence Principles.

To see why, useful to know why GR is unique.

[1] next slide

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action
- Only a metric ($\mathbf{g}$) and its derivatives

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action
- Only a metric ($\mathbf{g}$) and its derivatives
- Locality

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action
- Only a metric ($\mathbf{g}$) and its derivatives
- Locality
- Field equations second order

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action
- Only a metric ($\mathbf{g}$) and its derivatives
- Locality
- Field equations second order
- Diffeomorphisms

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action
- Only a metric ($\mathbf{g}$) and its derivatives
- Locality
- Field equations second order
- Diffeomorphisms

Note: most point to more DoFs.

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action
- Only a metric ($\mathbf{g}$) and its derivatives
- Locality
- Field equations second order
- Diffeomorphisms

Note: most point to more DoFs.

Action of GR:

$$S = \frac{1}{16\pi G} \int \mathrm{d}^4 x \sqrt{-g}\; R$$

Uniqueness of GR

Many theorems, most illustrative for us Lovelock:

- 4 Dimensions
- An action
- Only a metric ($\mathbf{g}$) and its derivatives
- Locality
- Field equations second order
- Diffeomorphisms

Note: most point to more DoFs.

Action of GR:

$$S = \frac{1}{16\pi G} \int \mathrm{d}^4 x \sqrt{-g}\ R$$

Include matter by using usual action but (plus some subtleties) with $\eta \to \mathbf{g}$.

Equivalence Principles

Definitions based on[2]

[2] Will 2014.

[3] isolated system when local flatness is not enough?

Equivalence Principles

Definitions based on[2]

- Weak Equivalence Principle
  - Test particles have universal free-fall

[2] Will 2014.

[3] isolated system when local flatness is not enough?

Equivalence Principles

Definitions based on[2]

- Weak Equivalence Principle
  - Test particles have universal free-fall
- Einstein Equivalence Principle
  - WEP + Local Lorentz Invariance

[2] Will 2014.

[3] isolated system when local flatness is not enough?

Equivalence Principles

Definitions based on[2]

- Weak Equivalence Principle
  - Test particles have universal free-fall
- Einstein Equivalence Principle
  - WEP + Local Lorentz Invariance
- Strong Equivalence Principle
  - EEP but test particles $\rightarrow$ self-gravitating systems*

[2] Will 2014.

[3] isolated system when local flatness is not enough?

Equivalence Principles

Definitions based on[2]

- Weak Equivalence Principle
  - Test particles have universal free-fall
- Einstein Equivalence Principle
  - WEP + Local Lorentz Invariance
- Strong Equivalence Principle
  - EEP but test particles $\rightarrow$ self-gravitating systems*
  - can also be formulated in terms of existence of "isolated systems"

[2] Will 2014.

[3] isolated system when local flatness is not enough?

Equivalence Principles

Definitions based on[2]

- Weak Equivalence Principle
  - Test particles have universal free-fall
- Einstein Equivalence Principle
  - WEP + Local Lorentz Invariance
- Strong Equivalence Principle
  - EEP but test particles $\rightarrow$ self-gravitating systems*
  - can also be formulated in terms of existence of "isolated systems"

Newtonian analogies...

[2] Will 2014.

[3] isolated system when local flatness is not enough?

Equivalence Principles

Definitions based on[2]

- Weak Equivalence Principle
  - Test particles have universal free-fall
- Einstein Equivalence Principle
  - WEP + Local Lorentz Invariance
- Strong Equivalence Principle
  - EEP but test particles $\to$ self-gravitating systems*
  - can also be formulated in terms of existence of "isolated systems"

Newtonian analogies...

GR only known viable theory with SEP[3] and WEP at risk outside of GR.

---

[2] Will 2014.

[3] isolated system when local flatness is not enough?

Scalar-tensor theories [4]

Easiest modification: add a scalar field

[4] See Fujii et al. 2007; Faraoni 2004

[5] for BD $V = 0, \alpha = \mathrm{const.}$ All deviations $\sim 10^{-5}$ Bertotti et al. 2003

Scalar-tensor theories [4]

Easiest modification: add a scalar field

For large class of scalar-tensor theories, action can be in the "Einstein frame":

$$S = \frac{1}{16\pi G} \int \mathrm{d}^4 x \sqrt{-g} \left[R - 2\partial_\mu \phi \partial^\mu \phi - V(\phi)\right] + S_m[A^2(\phi)\mathbf{g}, \psi_m].$$

[4]See Fujii et al. 2007; Faraoni 2004

[5]for BD $V = 0, \alpha = \mathrm{const.}$ All deviations $\sim 10^{-5}$ Bertotti et al. 2003

Scalar-tensor theories [4]

Easiest modification: add a scalar field

For large class of scalar-tensor theories, action can be in the "Einstein frame":

$$S = \frac{1}{16\pi G}\int \mathrm{d}^4 x\sqrt{-g}\,[R - 2\partial_\mu\phi\partial^\mu\phi - V(\phi)] + S_m[A^2(\phi)\mathbf{g}, \psi_m].$$

Scalar's equation of motion:

$$\Box\phi = -4\pi G T\alpha(\phi) + \frac{1}{4}V'(\phi), \quad \alpha(\phi) = \frac{\mathrm{d}\log A}{\mathrm{d}\phi}, \quad T = -\frac{2}{\sqrt{-g}}\frac{\delta S_m}{\delta g^{\mu\nu}}g^{\mu\nu}$$

[4] See Fujii et al. 2007; Faraoni 2004

[5] for BD $V = 0, \alpha = \mathrm{const.}$ All deviations $\sim 10^{-5}$ Bertotti et al. 2003

Scalar-tensor theories [4]

Easiest modification: add a scalar field

For large class of scalar-tensor theories, action can be in the "Einstein frame":

$$S = \frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\,[R - 2\partial_\mu\phi\partial^\mu\phi - V(\phi)] + S_m[A^2(\phi)\mathbf{g}, \psi_m].$$

Scalar's equation of motion:

$$\Box\phi = -4\pi G T\alpha(\phi) + \frac{1}{4}V'(\phi), \quad \alpha(\phi) = \frac{\mathrm{d}\log A}{\mathrm{d}\phi}, \quad T = -\frac{2}{\sqrt{-g}}\frac{\delta S_m}{\delta g^{\mu\nu}}g^{\mu\nu}$$

Solar system tests of SEP can be extremely powerful[5].

[4] See Fujii et al. 2007; Faraoni 2004

[5] for BD $V = 0, \alpha = \mathrm{const.}$ All deviations $\sim 10^{-5}$ Bertotti et al. 2003

Scalar-tensor theories [4]

Easiest modification: add a scalar field

For large class of scalar-tensor theories, action can be in the "Einstein frame":

$$S = \frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left[R - 2\partial_\mu\phi\partial^\mu\phi - V(\phi)\right] + S_m[A^2(\phi)\mathbf{g}, \psi_m].$$

Scalar's equation of motion:

$$\Box\phi = -4\pi G T\alpha(\phi) + \frac{1}{4}V'(\phi), \quad \alpha(\phi) = \frac{\mathrm{d}\log A}{\mathrm{d}\phi}, \quad T = -\frac{2}{\sqrt{-g}}\frac{\delta S_m}{\delta g^{\mu\nu}}g^{\mu\nu}$$

Solar system tests of SEP can be extremely powerful[5].

First: Why?

Second: Do we necessarily have suppressed deviations outside the solar system?

[4]See Fujii et al. 2007; Faraoni 2004

[5]for BD $V = 0, \alpha = \mathrm{const}$. All deviations $\sim 10^{-5}$ Bertotti et al. 2003

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

[6] Damour et al. 1993; Damour et al. 1996.
[7] requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

[6] Damour et al. 1993; Damour et al. 1996.

[7] requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

$$\Box\varphi = \left(m^2 - 4\pi G T \beta\right)\varphi$$

where

$$\phi = \phi_0 + \epsilon\varphi + \cdots\,, \quad m^2 = \frac{1}{4}V''(\phi_0), \quad \beta = \alpha'(\phi_0).$$

[6]Damour et al. 1993; Damour et al. 1996.
[7]requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

$$\Box\varphi = \left(m^2 - 4\pi GT\beta\right)\varphi$$

where

$$\phi = \phi_0 + \epsilon\varphi + \cdots, \quad m^2 = \frac{1}{4}V''(\phi_0), \quad \beta = \alpha'(\phi_0).$$

Heuristically (when $4\pi GT\beta > m^2$):

$$\omega^2 = \left(\frac{2\pi}{\lambda}\right)^2 - \mu^2$$

[6] Damour et al. 1993; Damour et al. 1996.

[7] requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

$$\Box\varphi = \left(m^2 - 4\pi GT\beta\right)\varphi$$

where

$$\phi = \phi_0 + \epsilon\varphi + \cdots, \quad m^2 = \frac{1}{4}V''(\phi_0), \quad \beta = \alpha'(\phi_0).$$

Heuristically (when $4\pi GT\beta > m^2$):

$$\omega^2 = \left(\frac{2\pi}{\lambda}\right)^2 - \mu^2$$

Need $\lambda_c \lesssim R_*$.

[6]Damour et al. 1993; Damour et al. 1996.
[7]requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

$$\Box\varphi = \left(m^2 - 4\pi GT\beta\right)\varphi$$

where

$$\phi = \phi_0 + \epsilon\varphi + \cdots\,, \quad m^2 = \frac{1}{4}V''(\phi_0), \quad \beta = \alpha'(\phi_0).$$

Heuristically (when $4\pi GT\beta > m^2$):

$$\omega^2 = \left(\frac{2\pi}{\lambda}\right)^2 - \mu^2$$

Need $\lambda_c \lesssim R_*$. Also $T \propto \rho \sim M/R_*^3$.

[6] Damour et al. 1993; Damour et al. 1996.

[7] requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

$$\Box\varphi = \left(m^2 - 4\pi G T \beta\right)\varphi$$

where

$$\phi = \phi_0 + \epsilon\varphi + \cdots, \quad m^2 = \frac{1}{4}V''(\phi_0), \quad \beta = \alpha'(\phi_0).$$

Heuristically (when $4\pi G T\beta > m^2$):

$$\omega^2 = \left(\frac{2\pi}{\lambda}\right)^2 - \mu^2$$

Need $\lambda_c \lesssim R_*$. Also $T \propto \rho \sim M/R_*^3$. So "compactness".

[6] Damour et al. 1993; Damour et al. 1996.
[7] requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

$$\Box\varphi = \left(m^2 - 4\pi G T \beta\right)\varphi$$

where

$$\phi = \phi_0 + \epsilon\varphi + \cdots, \quad m^2 = \frac{1}{4}V''(\phi_0), \quad \beta = \alpha'(\phi_0).$$

Heuristically (when $4\pi G T\beta > m^2$):

$$\omega^2 = \left(\frac{2\pi}{\lambda}\right)^2 - \mu^2$$

Need $\lambda_c \lesssim R_*$. Also $T \propto \rho \sim M/R_*^3$. So "compactness".

Upshot: screening: exactly GR outside of strong gravity (just one example, future: how common is it?).

---

[6] Damour et al. 1993; Damour et al. 1996.

[7] requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[6]:

Linear scalar field equation around GR solution with constant scalar ϕ_0[7]:

$$\Box\varphi = \left(m^2 - 4\pi G T \beta\right)\varphi$$

where

$$\phi = \phi_0 + \epsilon\varphi + \cdots\,, \quad m^2 = \frac{1}{4}V''(\phi_0), \quad \beta = \alpha'(\phi_0).$$

Heuristically (when $4\pi G T\beta > m^2$):

$$\omega^2 = \left(\frac{2\pi}{\lambda}\right)^2 - \mu^2$$

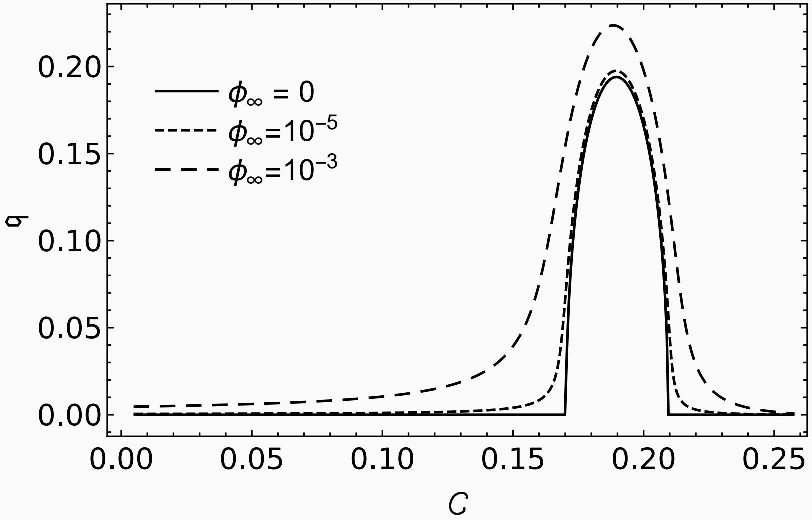
Need $\lambda_c \lesssim R_*$. Also $T \propto \rho \sim M/R_*^3$. So "compactness".

Upshot: screening: exactly GR outside of strong gravity (just one example, future: how common is it?).

[6] Damour et al. 1993; Damour et al. 1996.

[7] requires $V'(\phi_0) = \alpha(\phi_0) = 0$

Scalar-tensor theories: Spontaneous scalarization



Developing a toy model

Can the same be done for the WEP?

[8] This is not so bad when the screening mechanism is inverted, *c.f.* some inflation scenarios involving the Higgs *etc.* The why...

Developing a toy model

Can the same be done for the WEP?

WEP violations very broad, should first study a toy model[8].

[8] This is not so bad when the screening mechanism is inverted, *c.f.* some inflation scenarios involving the Higgs *etc.* The why...

Developing a toy model

Can the same be done for the WEP?

WEP violations very broad, should first study a toy model[8].

Properties:

[8] This is not so bad when the screening mechanism is inverted, *c.f.* some inflation scenarios involving the Higgs *etc.* The why...

Developing a toy model

Can the same be done for the WEP?

WEP violations very broad, should first study a toy model[8].

Properties:

- A screening mechanism

[8]This is not so bad when the screening mechanism is inverted, *c.f.* some inflation scenarios involving the Higgs *etc.* The why...

Developing a toy model

Can the same be done for the WEP?

WEP violations very broad, should first study a toy model[8].

Properties:

- A screening mechanism
- Tractablilty

[8] This is not so bad when the screening mechanism is inverted, *c.f.* some inflation scenarios involving the Higgs *etc.* The why...

Developing a toy model

Can the same be done for the WEP?

WEP violations very broad, should first study a toy model[8].

Properties:

- A screening mechanism
- Tractablilty
- Some WEP violation

[8] This is not so bad when the screening mechanism is inverted, *c.f.* some inflation scenarios involving the Higgs *etc.* The why...

The gravitational Higgs mechanism: the action[9]

[9]This is based on Coates et al. 2017; Franchini et al. 2018 and part of my thesis. Available at arXiv 1606.03981, arXiv 1708.02113 and Nottingham's Ethesis page
[10]*c.f.* charged boson stars Jetzer et al. 1989

The gravitational Higgs mechanism: the action[9]

$$\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left[R-2g^{\mu\nu}\overline{\mathcal{D}_\mu\phi}\mathcal{D}_\nu\phi-V(|\phi|)\right]$$
$$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\,[F_{\mu\nu}F^{\mu\nu}]+S_m[A^2(|\phi|)\mathbf{g},\psi_m],$$

where:

$$\mathcal{D}_\mu\phi=\partial_\mu\phi-iqA_\mu\phi,$$

A_μ is a $U(1)$ gauge field.[10]

[9] This is based on Coates et al. 2017; Franchini et al. 2018 and part of my thesis. Available at arXiv 1606.03981, arXiv 1708.02113 and Nottingham's Ethesis page

[10] *c.f.* charged boson stars Jetzer et al. 1989

The gravitational Higgs mechanism: the action[9]

$$\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left[R-2g^{\mu\nu}\overline{\mathcal{D}_\mu\phi}\mathcal{D}_\nu\phi-V(|\phi|)\right]$$
$$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\left[F_{\mu\nu}F^{\mu\nu}\right]+S_m[A^2(|\phi|)\mathbf{g},\psi_m],$$

where:

$$\mathcal{D}_\mu\phi=\partial_\mu\phi-iqA_\mu\phi,$$

A_μ is a $U(1)$ gauge field.[10]

Restoring constants the $U(1)$ field has an effective mass:

$$m_\gamma^2(|\phi|)=\frac{\mu_0 q^2c^2}{4\pi G}\bar{\phi}\phi.$$

[9] This is based on Coates et al. 2017; Franchini et al. 2018 and part of my thesis. Available at arXiv 1606.03981, arXiv 1708.02113 and Nottingham's Ethesis page

[10] *c.f.* charged boson stars Jetzer et al. 1989

The gravitational Higgs mechanism: the action[9]

$$\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left[R - 2g^{\mu\nu}\overline{\mathcal{D}_\mu\phi}\mathcal{D}_\nu\phi - V(|\phi|)\right]$$
$$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\left[F_{\mu\nu}F^{\mu\nu}\right] + S_m[A^2(|\phi|)\mathbf{g},\psi_m],$$

where:

$$\mathcal{D}_\mu\phi = \partial_\mu\phi - iqA_\mu\phi,$$

A_μ is a $U(1)$ gauge field.[10]

Restoring constants the $U(1)$ field has an effective mass:

$$m_\gamma^2(|\phi|) = \frac{\mu_0 q^2 c^2}{4\pi G}\bar{\phi}\phi.$$

If the spontaneous scalarization mechanism is undamaged, this is the $U(1)$ Higgs mechanism*.

[9] This is based on Coates et al. 2017; Franchini et al. 2018 and part of my thesis. Available at arXiv 1606.03981, arXiv 1708.02113 and Nottingham's Ethesis page
[10] *c.f.* charged boson stars Jetzer et al. 1989

The gravitational Higgs mechanism: the action[9]

$$\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left[R - 2g^{\mu\nu}\overline{\mathcal{D}_\mu\phi}\mathcal{D}_\nu\phi - V(|\phi|)\right]$$
$$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\left[F_{\mu\nu}F^{\mu\nu}\right] + S_m[A^2(|\phi|)\mathbf{g}, \psi_m],$$

where:

$$\mathcal{D}_\mu\phi = \partial_\mu\phi - iqA_\mu\phi,$$

A_μ is a $U(1)$ gauge field.[10]

Restoring constants the $U(1)$ field has an effective mass:

$$m_\gamma^2(|\phi|) = \frac{\mu_0 q^2 c^2}{4\pi G}\bar{\phi}\phi.$$

If the spontaneous scalarization mechanism is undamaged, this is the $U(1)$ Higgs mechanism*. For simplicity we take $V = 0$ (this alone makes it a toy).

[9] This is based on Coates et al. 2017; Franchini et al. 2018 and part of my thesis. Available at arXiv 1606.03981, arXiv 1708.02113 and Nottingham's Ethesis page

[10] *c.f.* charged boson stars Jetzer et al. 1989

The gravitational Higgs mechanism: mass generation

For spherically symmetric stars, can show we have only standard scalar-tensor theory solutions[11].

[11] Note that, if we interpret the $U(1)$ field as the photon, we would have to use different equations of state

[12] 10^{17} observable universes

The gravitational Higgs mechanism: mass generation

For spherically symmetric stars, can show we have only standard scalar-tensor theory solutions[11].

It turns out that this mechanism is extremely effective. Using the expression for the effective mass from earlier:

$$m_\gamma \approx \left(\frac{|q|}{e}\right)\left(\frac{|\phi|}{0.01}\right)\left(10^{-3} M_{\mathrm{Pl}}\right).$$

[11] Note that, if we interpret the $U(1)$ field as the photon, we would have to use different equations of state

[12] 10^{17} observable universes

The gravitational Higgs mechanism: mass generation

For spherically symmetric stars, can show we have only standard scalar-tensor theory solutions[11].

It turns out that this mechanism is extremely effective. Using the expression for the effective mass from earlier:

$$m_\gamma \approx \left(\frac{|q|}{e}\right)\left(\frac{|\phi|}{0.01}\right)\left(10^{-3}M_{\rm Pl}\right). \qquad (M_{\rm Pl} \approx 20\mu g)$$

[11] Note that, if we interpret the $U(1)$ field as the photon, we would have to use different equations of state

[12] 10^{17} observable universes

The gravitational Higgs mechanism: mass generation

For spherically symmetric stars, can show we have only standard scalar-tensor theory solutions[11].

It turns out that this mechanism is extremely effective. Using the expression for the effective mass from earlier:

$$m_\gamma \approx \left(\frac{|q|}{e}\right)\left(\frac{|\phi|}{0.01}\right)\left(10^{-3} M_{\rm Pl}\right). \qquad (M_{\rm Pl} \approx 20\mu g)$$

For comparison, weak field tests of the photon mass give an upper bound $\sim 10^{-42} M_{\rm Pl}$

[11] Note that, if we interpret the $U(1)$ field as the photon, we would have to use different equations of state

[12] 10^{17} observable universes

The gravitational Higgs mechanism: mass generation

For spherically symmetric stars, can show we have only standard scalar-tensor theory solutions[11].

It turns out that this mechanism is extremely effective. Using the expression for the effective mass from earlier:

$$m_\gamma \approx \left(\frac{|q|}{e}\right)\left(\frac{|\phi|}{0.01}\right)\left(10^{-3}M_{\rm Pl}\right). \qquad (M_{\rm Pl} \approx 20\mu g)$$

For comparison, weak field tests of the photon mass give an upper bound $\sim 10^{-42}M_{\rm Pl}$, *i.e.* even for small amounts of scalarization there can be large changes in the matter sector.

[11] Note that, if we interpret the $U(1)$ field as the photon, we would have to use different equations of state

[12] 10^{17} observable universes

The gravitational Higgs mechanism: mass generation

For spherically symmetric stars, can show we have only standard scalar-tensor theory solutions[11].

It turns out that this mechanism is extremely effective. Using the expression for the effective mass from earlier:

$$m_\gamma \approx \left(\frac{|q|}{e}\right)\left(\frac{|\phi|}{0.01}\right)\left(10^{-3}M_{\rm Pl}\right). \qquad (M_{\rm Pl} \approx 20\mu g)$$

For comparison, weak field tests of the photon mass give an upper bound $\sim 10^{-42}M_{\rm Pl}$, *i.e.* even for small amounts of scalarization there can be large changes in the matter sector.

Note: $1/r$ falloff means need $\sim 10^{39}$ NS radii $\sim 10^{40}\mathrm{km}$ to satisfy that bound[12]...

---

[11] Note that, if we interpret the $U(1)$ field as the photon, we would have to use different equations of state

[12] 10^{17} observable universes

The gravitational Higgs mechanism: takeaway

Simple arguments: WEP violations should exist, where are they?

The gravitational Higgs mechanism: takeaway

Simple arguments: WEP violations should exist, where are they?

- WEP violations can be screened in principle. Solar system tests not enough

The gravitational Higgs mechanism: takeaway

Simple arguments: WEP violations should exist, where are they?

- WEP violations can be screened in principle. Solar system tests not enough
- Strong signature

The gravitational Higgs mechanism: takeaway

Simple arguments: WEP violations should exist, where are they?

- WEP violations can be screened in principle. Solar system tests not enough
- Strong signature
- NS EoS even less certain?

Future work

- Smoking guns:

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology
  - Strong influence on electromagnetic phenomena

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology
  - Strong influence on electromagnetic phenomena
    - Magnet field configurations

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology
  - Strong influence on electromagnetic phenomena
    - Magnet field configurations
    - Blackbody spectra

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology
  - Strong influence on electromagnetic phenomena
    - Magnet field configurations
    - Blackbody spectra
- Beyond the $U(1)$ (toy) model

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology
  - Strong influence on electromagnetic phenomena
    - Magnet field configurations
    - Blackbody spectra
- Beyond the $U(1)$ (toy) model
  - Example that better fits the motivation

Future work

- Smoking guns:
  - Those based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology
  - Strong influence on electromagnetic phenomena
    - Magnet field configurations
    - Blackbody spectra
- Beyond the $U(1)$ (toy) model
  - Example that better fits the motivation
  - ϕ dependent equations of state, likely strongest signal for NSs

Parametric oscillator analogy

Compare the flatspace Klein-Gordon equation with a field dependent mass[13]:

$$-\partial_t^2 \psi = \left(k^2 + m^2(|\phi|) \right) \psi,$$

[13]Note: our equation for the $U(1)$ field is not exactly this but is still a wave equation. So similar, if not identical, behaviour can be expected.

Parametric oscillator analogy

Compare the flatspace Klein-Gordon equation with a field dependent mass[13]:

$$-\partial_t^2 \psi = \left(k^2 + m^2(|\phi|)\right)\psi,$$

to the parametric oscillator:

$$-\frac{\mathrm{d}^2}{\mathrm{d}t^2} x = \omega^2(t) x.$$

[13] Note: our equation for the $U(1)$ field is not exactly this but is still a wave equation. So similar, if not identical, behaviour can be expected.

Parametric oscillator analogy

Compare the flatspace Klein-Gordon equation with a field dependent mass[13]:

$$-\partial_t^2 \psi = \left(k^2 + m^2(|\phi|) \right) \psi,$$

to the parametric oscillator:

$$-\frac{\mathrm{d}^2}{\mathrm{d}t^2} x = \omega^2(t) x.$$

So in dynamical situations can expect some excitation of ψ (*c.f.* reheating).

[13]Note: our equation for the $U(1)$ field is not exactly this but is still a wave equation. So similar, if not identical, behaviour can be expected.

Beyond the $U(1)$ model

We plan to consider an effective model with a ϕ dependent equation of state for neutron stars.

Beyond the $U(1)$ model

We plan to consider an effective model with a ϕ dependent equation of state for neutron stars.

For:

- Testing robustness of screening mechanisms to WEP violations

Beyond the $U(1)$ model

We plan to consider an effective model with a ϕ dependent equation of state for neutron stars.

For:

- Testing robustness of screening mechanisms to WEP violations
- Making astrophysically relevant predictions

Beyond the $U(1)$ model

We plan to consider an effective model with a ϕ dependent equation of state for neutron stars.

For:

- Testing robustness of screening mechanisms to WEP violations
- Making astrophysically relevant predictions
- Maintaining some tractability

Thank you!

Questions?

References

Bertotti, B., L. Iess, and P. Tortora (2003). "A test of general relativity using radio links with the Cassini spacecraft". In: *Nature* 425, pp. 374–376. DOI: 10.1038/nature01997.

Coates, A., M. W. Horbartsch, and T. P. Sotiriou (2017). "Gravitational Higgs Mechanism in Neutron Star Interiors". In: *Phys. Rev.* D95.8, p. 084003. DOI: 10.1103/PhysRevD.95.084003. arXiv: 1606.03981 [gr-qc].

Damour, Thibault and Gilles Esposito-Farese (1993). "Nonperturbative strong field effects in tensor - scalar theories of gravitation". In: *Phys. Rev. Lett.* 70, pp. 2220–2223. DOI: 10.1103/PhysRevLett.70.2220.

– (1996). "Tensor - scalar gravity and binary pulsar experiments". In: *Phys. Rev.* D54, pp. 1474–1491. DOI: 10.1103/PhysRevD.54.1474. arXiv: gr-qc/9602056 [gr-qc].

Faraoni, Valerio (2004). *Cosmology in scalar tensor gravity*. Springer.

Franchini, Nicola, Andrew Coates, and Thomas P. Sotiriou (2018). "Constructing Neutron Stars with a Gravitational Higgs Mechanism". In: *Phys. Rev.* D97.6, p. 064013. DOI: 10.1103/PhysRevD.97.064013. arXiv: 1708.02113 [gr-qc].

Fujii, Y. and K. Maeda (2007). *The scalar-tensor theory of gravitation*. Cambridge University Press. ISBN: 9780521037525, 9780521811590, 9780511029882. URL: http://www.cambridge.org/uk/catalogue/catalogue.asp?isbn=0521811597.

Jetzer, P. and J. J. van der Bij (1989). "CHARGED BOSON STARS". In: *Phys. Lett.* B227, pp. 341–346. DOI: 10.1016/0370-2693(89)90941-6.

Will, Clifford M. (2014). "The Confrontation between General Relativity and Experiment". In: *Living Rev. Rel.* 17, p. 4. DOI: 10.12942/lrr-2014-4. arXiv: 1403.7377 [gr-qc].

Backup 1: WEP violations in GHiggs

For those curious about whether this “really” violates the weak equivalence principle

Backup 1: WEP violations in GHiggs

For those curious about whether this “really” violates the weak equivalence principle

- Take the field equation for the $U(1)$ field and take standard geometric optics limit

Backup 1: WEP violations in GHiggs

For those curious about whether this "really" violates the weak equivalence principle

- Take the field equation for the $U(1)$ field and take standard geometric optics limit
- You will find a proper acceleration $a_\mu \propto -\partial_\mu \log \phi$
- This is a different proper acceleration than is felt by the matter in this frame.

Backup 1: WEP violations in GHiggs

For those curious about whether this “really” violates the weak equivalence principle

- Take the field equation for the $U(1)$ field and take standard geometric optics limit
- You will find a proper acceleration $a_\mu \propto -\partial_\mu \log \phi$
- This is a different proper acceleration than is felt by the matter in this frame.
- This is of the form that can be removed by conformal transformation

Backup 1: WEP violations in GHiggs

For those curious about whether this "really" violates the weak equivalence principle

- Take the field equation for the $U(1)$ field and take standard geometric optics limit
- You will find a proper acceleration $a_\mu \propto -\partial_\mu \log \phi$
- This is a different proper acceleration than is felt by the matter in this frame.
- This is of the form that can be removed by conformal transformation
- But it is a different conformal transformation than needed for matter (Unless $A^2 = b\phi^2$, for some specific b, related to q).

Backup 1: WEP violations in GHiggs

For those curious about whether this “really” violates the weak equivalence principle

- Take the field equation for the $U(1)$ field and take standard geometric optics limit
- You will find a proper acceleration $a_\mu \propto -\partial_\mu \log \phi$
- This is a different proper acceleration than is felt by the matter in this frame.
- This is of the form that can be removed by conformal transformation
- But it is a different conformal transformation than needed for matter (Unless $A^2 = b\phi^2$, for some specific b, related to q).
- Of course, there is always the ambiguity of what you consider to be a gravitational field.