The Weak Equivalence Principle in the strong gravity regime

Andrew Coates

March 25, 2018

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

Outline

Topics:

Outline

Topics:

- Equivalence Principles

Outline

Topics:

- Equivalence Principles
- Brans-Dicke and the solar system

Outline

Topics:

- Equivalence Principles
- Brans-Dicke and the solar system
- Spontaneous scalarization

Outline

Topics:

- Equivalence Principles
- Brans-Dicke and the solar system
- Spontaneous scalarization
- Solar system WEP tests

Outline

Topics:

- Equivalence Principles
- Brans-Dicke and the solar system
- Spontaneous scalarization
- Solar system WEP tests
- The gravitational Higgs mechanism: a toy model

Outline

Topics:

- Equivalence Principles
- Brans-Dicke and the solar system
- Spontaneous scalarization
- Solar system WEP tests
- The gravitational Higgs mechanism: a toy model
- Possible implications

Outline

Topics:

- Equivalence Principles
- Brans-Dicke and the solar system
- Spontaneous scalarization
- Solar system WEP tests
- The gravitational Higgs mechanism: a toy model
- Possible implications
- Future work

Equivalence Principles

Definitions based on[1]

[1] Will 2014.

Equivalence Principles

Definitions based on[1]

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

[1] Will 2014.

Equivalence Principles

Definitions based on[1]

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

[1] Will 2014.

Equivalence Principles

Definitions based on[1]

- 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*

[1] Will 2014.

Equivalence Principles

Definitions based on[1]

- 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"

[1] Will 2014.

Brans-Dicke theory [2]

Jordan frame:

$$S = \frac{1}{16\pi} \int \mathrm{d}^4 x \sqrt{-\tilde{g}} \left[\Phi \tilde{R} - \frac{\omega_0}{\Phi} \partial_\mu \Phi \partial^\mu \Phi \right] + S_m[\tilde{\mathbf{g}}, \psi_m].$$

[2]See Jordan 1959; Brans et al. 1961 and more generally *e.g.* Fujii et al. 2007; Faraoni 2004

Brans-Dicke theory [2]

Jordan frame:

$$S = \frac{1}{16\pi} \int \mathrm{d}^4 x \sqrt{-\tilde{g}} \left[\Phi \tilde{R} - \frac{\omega_0}{\Phi} \partial_\mu \Phi \partial^\mu \Phi \right] + S_m[\tilde{\mathbf{g}}, \psi_m].$$

Einstein frame:

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

[2]See Jordan 1959; Brans et al. 1961 and more generally *e.g.* Fujii et al. 2007; Faraoni 2004

Brans-Dicke theory [2]

Jordan frame:

$$S = \frac{1}{16\pi} \int \mathrm{d}^4 x \sqrt{-\tilde{g}} \left[\Phi \tilde{R} - \frac{\omega_0}{\Phi} \partial_\mu \Phi \partial^\mu \Phi \right] + S_m[\tilde{\mathbf{g}}, \psi_m].$$

Einstein frame:

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

Where:

$$\tilde{g} = A^2(\phi)\mathbf{g}, \quad A^2(\phi) = \frac{1}{G\Phi(\phi)}, \quad \mathrm{d}\phi = \frac{\sqrt{3 + 2\omega_0}}{\Phi} \mathrm{d}\Phi.$$

[2] See Jordan 1959; Brans et al. 1961 and more generally *e.g.* Fujii et al. 2007; Faraoni 2004

Brans-Dicke theory: Solar system tests

Two parameters at first PPN order:

- $\gamma = (1 + \omega_0) \,/\, (2 + \omega_0)$
- ϕ_∞ - *c.f.* isolated systems definition of SEP

Only γ from pure solar system. Current constraints effectively render BD uninteresting[3].

[3] Bertotti et al. 2003.

Scalar-tensor theories [4]

For our purposes need Einstein frame:

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

[4] Again see Fujii et al. 2007; Faraoni 2004

Scalar-tensor theories [4]

For our purposes need Einstein frame:

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

Addition of potential and $A^2(\phi)$ now much less restricted.

[4] Again see Fujii et al. 2007; Faraoni 2004

Scalar-tensor theories [4]

For our purposes need Einstein frame:

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

Addition of potential and $A^2(\phi)$ now much less restricted.

Useful to define:

$$\alpha(\phi) = \frac{\mathrm{d}}{\mathrm{d}\phi} \log \phi$$

[4] Again see Fujii et al. 2007; Faraoni 2004

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[5]:

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

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[5]:

Linear scalar field equation around GR solution with constant scalar ϕ_0:

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

where

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

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

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[5]:

Linear scalar field equation around GR solution with constant scalar ϕ_0:

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

where

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

Heuristically:

$$\omega^2 = k^2 - \mu^2$$

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

Scalar-tensor theories: Spontaneous scalarization

Simple, and relevant, example of a "screening mechanism"[5]:

Linear scalar field equation around GR solution with constant scalar ϕ_0:

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

where

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

Heuristically:

$$\omega^2 = k^2 - \mu^2$$

Upshot: screened SEP violations which show up in strong gravity (just one example).

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

WEP violations: some motivation

Broad motivation:[6]

[6] This is based on Coates et al. 2017; Franchini et al. 2018 and my thesis (which is not yet available)

WEP violations: some motivation

Broad motivation:[6]

1. Overlooked possibilities (*c.f.* spontaneous scalarization)

[6]This is based on Coates et al. 2017; Franchini et al. 2018 and my thesis (which is not yet available)

WEP violations: some motivation

Broad motivation:[6]

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
2. Theoretical considerations

[6] This is based on Coates et al. 2017; Franchini et al. 2018 and my thesis (which is not yet available)

WEP violations: some motivation

Broad motivation:[6]

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
2. Theoretical considerations
3. Additional ways to search for extra degrees of freedom

[6] This is based on Coates et al. 2017; Franchini et al. 2018 and my thesis (which is not yet available)

Developing a toy model

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

Developing a toy model

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

Properties:

Developing a toy model

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

Properties:

- A screening mechanism

Developing a toy model

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

Properties:

- A screening mechanism
- Tractablilty

Developing a toy model

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

Properties:

- A screening mechanism
- Tractablilty
- Some WEP violation

The gravitational Higgs mechanism: the action

Einstein frame (because there is no true Jordan frame):

The gravitational Higgs mechanism: the action

Einstein frame (because there is no true Jordan frame):

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

$$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\left[F_{\mu\nu}F^{\mu\nu}\right] + S_m[A^2(|\phi|)\mathbf{g}, \psi_m],$$

where:

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

A_μ is a $U(1)$ gauge field and ϕ is $U(1)$ charged.

The gravitational Higgs mechanism: the action

Einstein frame (because there is no true Jordan frame):

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

$$-\frac{1}{4}\int \mathrm{d}^4 x\sqrt{-g}\left[F_{\mu\nu}F^{\mu\nu}\right] + S_m[A^2(|\phi|)\mathbf{g},\psi_m],$$

where:

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

A_μ is a $U(1)$ gauge field and ϕ is $U(1)$ charged.

In SI the $U(1)$ field has an effective mass:

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

The gravitational Higgs mechanism: the action

Einstein frame (because there is no true Jordan frame):

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

$$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\left[F_{\mu\nu}F^{\mu\nu}\right] + S_m[A^2(|\phi|)\mathbf{g}, \psi_m],$$

where:

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

A_μ is a $U(1)$ gauge field and ϕ is $U(1)$ charged.

In SI the $U(1)$ field has an effective mass:

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

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

The gravitational Higgs mechanism: spherical symmetry

By making a gauge choice we can write the gauge field's equation of motion in a Proca-like form:

$$\nabla^{\mu} F_{\mu\nu} = m_{\gamma}^{2}(|\phi|) A_{\nu}.$$

The gravitational Higgs mechanism: spherical symmetry

By making a gauge choice we can write the gauge field's equation of motion in a Proca-like form:

$$\nabla^\mu F_{\mu\nu} = m_\gamma^2(|\phi|)A_\nu.$$

This relies on that the 4-current contribution of the scalar field is

$$J_\mu \propto \overline{\phi}\partial_\mu\phi - \phi\partial_\mu\overline{\phi}.$$

The gravitational Higgs mechanism: spherical symmetry

By making a gauge choice we can write the gauge field's equation of motion in a Proca-like form:

$$\nabla^\mu F_{\mu\nu} = m_\gamma^2(|\phi|)A_\nu.$$

This relies on that the 4-current contribution of the scalar field is

$$J_\mu \propto \overline{\phi}\partial_\mu\phi - \phi\partial_\mu\overline{\phi}.$$

This can then be transformed away ($\phi = |\phi| \exp i\theta \to |\phi| \exp i(\theta + q\lambda)$ and so $\lambda = -\theta/q$ does this for us).

The gravitational Higgs mechanism: spherical symmetry

By making a gauge choice we can write the gauge field's equation of motion in a Proca-like form:

$$\nabla^\mu F_{\mu\nu} = m_\gamma^2(|\phi|)A_\nu.$$

This relies on that the 4-current contribution of the scalar field is

$$J_\mu \propto \overline{\phi}\partial_\mu \phi - \phi \partial_\mu \overline{\phi}.$$

This can then be transformed away ($\phi = |\phi| \exp i\theta \to |\phi| \exp i(\theta + q\lambda)$ and so $\lambda = -\theta/q$ does this for us).

In spherical symmetry and staticity the r (areal radius) component of the gauge fields equation reads:

$$m_\gamma^2 A_r = 0,$$

(in the above guage) and so $A_\mu = (A_t, 0, 0, 0)$.

The gravitational Higgs mechanism: spherical symmetry

Following the Bekenstein proof[7] of the no-hair theorem for the Einstein-Proca system we can also prove that in this situation the $U(1)$ field must be trivial.

[7] Bekenstein 1972.

The gravitational Higgs mechanism: spherical symmetry

Following the Bekenstein proof[7] of the no-hair theorem for the Einstein-Proca system we can also prove that in this situation the $U(1)$ field must be trivial.

Sketch: Contract the Proca-like equation with A^ν and integrate over some spacetime volume, $\mathcal{V}$,

$$\int_{\mathcal{V}} \mathrm{d}^4 x \sqrt{-g}\,[A^\nu \nabla^\mu F_{\mu\nu} - m_\gamma A^\nu A_\nu] = 0.$$

[7] Bekenstein 1972.

The gravitational Higgs mechanism: spherical symmetry

Following the Bekenstein proof[7] of the no-hair theorem for the Einstein-Proca system we can also prove that in this situation the $U(1)$ field must be trivial.

Sketch: Contract the Proca-like equation with A^ν and integrate over some spacetime volume, $\mathcal{V}$,

$$\int_{\mathcal{V}} \mathrm{d}^4 x \sqrt{-g}\, [A^\nu \nabla^\mu F_{\mu\nu} - m_\gamma A^\nu A_\nu] = 0.$$

Integrate the first term by parts:

$$\int_{\mathcal{V}} \mathrm{d}^4 x \sqrt{-g} \left[\frac{1}{2} F^{\mu\nu} F_{\mu\nu} + m_\gamma A^\nu A_\nu\right] = \int_{\partial\mathcal{V}} \mathrm{d}^3 \sigma\, n^\nu A^\nu \nabla^\mu F_{\mu\nu}.$$

[7] Bekenstein 1972.

The gravitational Higgs mechanism: spherical symmetry

Following the Bekenstein proof[7] of the no-hair theorem for the Einstein-Proca system we can also prove that in this situation the $U(1)$ field must be trivial.

Sketch: Contract the Proca-like equation with A^ν and integrate over some spacetime volume, $\mathcal{V}$,

$$\int_{\mathcal{V}} \mathrm{d}^4 x \sqrt{-g}\, [A^\nu \nabla^\mu F_{\mu\nu} - m_\gamma A^\nu A_\nu] = 0.$$

Integrate the first term by parts:

$$\int_{\mathcal{V}} \mathrm{d}^4 x \sqrt{-g} \left[\frac{1}{2} F^{\mu\nu} F_{\mu\nu} + m_\gamma A^\nu A_\nu\right] = \int_{\partial\mathcal{V}} \mathrm{d}^3\sigma\, n^\nu A^\nu \nabla^\mu F_{\mu\nu}.$$

We're interested in stars so we can take a single boundary, a constant r surface, and take $r \to \infty$. Asymptotic flatness then kills the boundary integral.

[7] Bekenstein 1972.

The gravitational Higgs mechanism: spherical symmetry

Following the Bekenstein proof[7] of the no-hair theorem for the Einstein-Proca system we can also prove that in this situation the $U(1)$ field must be trivial.

Sketch: Contract the Proca-like equation with A^ν and integrate over some spacetime volume, $\mathcal{V}$,

$$\int_{\mathcal{V}} \mathrm{d}^4 x \sqrt{-g}\left[A^\nu \nabla^\mu F_{\mu\nu} - m_\gamma A^\nu A_\nu\right] = 0.$$

Integrate the first term by parts:

$$\int_{\mathcal{V}} \mathrm{d}^4 x \sqrt{-g}\left[\frac{1}{2} F^{\mu\nu} F_{\mu\nu} + m_\gamma A^\nu A_\nu\right] = \int_{\partial\mathcal{V}} \mathrm{d}^3\sigma\, n^\nu A^\nu \nabla^\mu F_{\mu\nu}.$$

We're interested in stars so we can take a single boundary, a constant r surface, and take $r \to \infty$. Asymptotic flatness then kills the boundary integral.

Finally look at the integrand of the left-hand-side, it is sign definite and one gets $A_t = 0$.

[7] Bekenstein 1972.

The gravitational Higgs mechanism: mass generation

All that we saw previously means that, for spherically symmetric stars, we have standard scalar-tensor theory solutions[8].

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

The gravitational Higgs mechanism: mass generation

All that we saw previously means that, for spherically symmetric stars, we have standard scalar-tensor theory solutions[8].

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

$$m_\gamma \approx \left(\frac{|q|}{e}\right)|\phi|\left(0.1 M_{\mathrm{Pl}}\right).$$

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

The gravitational Higgs mechanism: mass generation

All that we saw previously means that, for spherically symmetric stars, we have standard scalar-tensor theory solutions[8].

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

$$m_\gamma \approx \left(\frac{|q|}{e}\right) |\phi| \left(0.1 M_{\rm Pl}\right) . \qquad (M_{\rm Pl} \approx 20\mu g)$$

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

The gravitational Higgs mechanism: mass generation

All that we saw previously means that, for spherically symmetric stars, we have standard scalar-tensor theory solutions[8].

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

$$m_\gamma \approx \left(\frac{|q|}{e}\right) |\phi| \left(0.1 M_{\mathrm{Pl}}\right). \qquad (M_{\mathrm{Pl}} \approx 20 \mu g)$$

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

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

The gravitational Higgs mechanism: mass generation

All that we saw previously means that, for spherically symmetric stars, we have standard scalar-tensor theory solutions[8].

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

$$m_\gamma \approx \left(\frac{|q|}{e}\right)|\phi|\,(0.1 M_{\rm Pl})\,. \qquad\qquad (M_{\rm Pl} \approx 20\mu g)$$

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.

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

Future work

Two main directions:

Future work

Two main directions:

- Smoking guns.

Future work

Two main directions:

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

Future work

Two main directions:

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

Future work

Two main directions:

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

Future work

Two main directions:

- Smoking guns. Based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
  - Collapse
  - Cosmology
- Beyond the $U(1)$ (toy) model

Future work

Two main directions:

- Smoking guns. Based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
  - Collapse
  - Cosmology
- Beyond the $U(1)$ (toy) model
  - More directly relevant examples

Future work

Two main directions:

- Smoking guns. Based on nathematical analogy between field dependent mass and parametric oscillators ($\omega^2(t)$).
    - Collapse
    - Cosmology
- Beyond the $U(1)$ (toy) model
    - More directly relevant examples
    - ϕ dependent equations of state

Future: smoking guns

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

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

Future: smoking guns

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

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

to the parametric oscillator:

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

Future: smoking guns

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

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

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).

Future: beyond the $U(1)$ model

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

Future: 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

Future: 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

Future: 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

Future: what we stand to learn

Examining the motivations:

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
   - Demonstrated the possibility of large WEP violations in strong gravity

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
   - Demonstrated the possibility of large WEP violations in strong gravity
   - Future work on ϕ dependent equations of state

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
    - Demonstrated the possibility of large WEP violations in strong gravity
    - Future work on ϕ dependent equations of state
2. Theoretical considerations

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
    - Demonstrated the possibility of large WEP violations in strong gravity
    - Future work on ϕ dependent equations of state
2. Theoretical considerations
    - Given the strength of the mechanism: possible strong requirements for QG

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
    - Demonstrated the possibility of large WEP violations in strong gravity
    - Future work on ϕ dependent equations of state
2. Theoretical considerations
    - Given the strength of the mechanism: possible strong requirements for QG
3. Additional ways to search for extra degrees of freedom

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
   - Demonstrated the possibility of large WEP violations in strong gravity
   - Future work on ϕ dependent equations of state
2. Theoretical considerations
   - Given the strength of the mechanism: possible strong requirements for QG
3. Additional ways to search for extra degrees of freedom
   - Even very mild scalarization can lead to large effects

Future: what we stand to learn

Examining the motivations:

1. Overlooked possibilities (*c.f.* spontaneous scalarization)
    - Demonstrated the possibility of large WEP violations in strong gravity
    - Future work on ϕ dependent equations of state
2. Theoretical considerations
    - Given the strength of the mechanism: possible strong requirements for QG
3. Additional ways to search for extra degrees of freedom
    - Even very mild scalarization can lead to large effects
    - Possible smoking gun phenomena

Thank you!

Questions?