Challenges to Cosmic Self-Acceleration in Modified Gravity from Gravitational Waves & Large-Scale Structure

Lucas Lombriser

Institute for Astronomy
University of Edinburgh

TeV Particle Astrophysics 2016

CERN

15/9/2016

Horndeski scalar-tensor action

- Horndeski action:

$$
\begin{aligned}
S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,\Big\{ & G_2(\varphi,X) - G_3(\varphi,X)\Box\varphi \\
& + G_4(\varphi,X)R + \frac{\partial G_4}{\partial X}\left[(\Box\varphi)^2 - (\nabla_\mu\nabla_\nu\varphi)^2\right] \\
& + G_5(\varphi,X)G_{\mu\nu}\nabla^\mu\nabla^\nu\varphi \\
& - \frac{1}{6}\frac{\partial G_5}{\partial X}\left[(\Box\varphi)^3 - 3\Box\varphi(\nabla_\mu\nabla_\nu\varphi)^2 + 2(\nabla_\mu\nabla_\nu\varphi)^3\right] \\
& + \mathcal{L}_{\mathrm{m}}(g_{\mu\nu},\psi_i)\Big\},
\end{aligned}
$$

where $X \equiv -\frac{1}{2}(\partial_\mu\varphi)^2$

Self-acceleration

- Conformal transformation ($\tilde{g}_{\mu\nu} = \Omega\, g_{\mu\nu}$) from Jordan to *Einstein-Friedmann* frame

Self-acceleration

The breaking of the strong (or weak) equivalence principle in the cosmological background is responsible for cosmic acceleration.

Self-acceleration

- Conformal transformation ($\tilde{g}_{\mu\nu} = \Omega\, g_{\mu\nu}$) from Jordan to *Einstein-Friedmann* frame
- Self-acceleration ($a \gtrsim 0.6$) ($d^2a/dt^2 > 0$, $d^2\tilde{a}/d\tilde{t}^2 \leq 0$):

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1+\frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2 a}{dt^2} + \frac{a\,H^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0$$

Self-acceleration

The breaking of the strong (or weak) equivalence principle in the cosmological background is responsible for cosmic acceleration.

Self-acceleration

- Conformal transformation ($\tilde{g}_{\mu\nu} = \Omega\, g_{\mu\nu}$) from Jordan to *Einstein-Friedmann* frame
- Self-acceleration ($a \gtrsim 0.6$) ($d^2a/dt^2 > 0$, $d^2\tilde{a}/d\tilde{t}^2 \leq 0$):

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1 + \frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2a}{dt^2} + \frac{a\,H^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0 \Rightarrow \left|\frac{\Omega'}{\Omega}\right| \gtrsim \mathcal{O}(1)$$

Self-acceleration

The breaking of the strong (or weak) equivalence principle in the cosmological background is responsible for cosmic acceleration.

EFT of DE & MG

Cosmological background and linear perturbations

$H(t)$: Hubble parameter

Creminelli *et al.* (2008); Park *et al.* (2010); Gubitosi *et al.* (2012); Bloomfield *et al.* (2012); Bellini & Sawicki (2014); Gleyzes *et al.* (2014) ...

EFT of DE & MG

Cosmological background and linear perturbations

$H(t)$: Hubble parameter

$\alpha_{\rm K}(t)$: Kineticity

Creminelli *et al.* (2008); Park *et al.* (2010); Gubitosi *et al.* (2012); Bloomfield *et al.* (2012); Bellini & Sawicki (2014); Gleyzes *et al.* (2014) ...

EFT of DE & MG

Cosmological background and linear perturbations

$H(t)$: Hubble parameter

$\alpha_{\rm K}(t)$: Kineticity

$\alpha_{\rm M}(t)$: Planck mass evolution rate

Creminelli *et al.* (2008); Park *et al.* (2010); Gubitosi *et al.* (2012); Bloomfield *et al.* (2012); Bellini & Sawicki (2014); Gleyzes *et al.* (2014) ...

EFT of DE & MG

Cosmological background and linear perturbations

$H(t)$: Hubble parameter

$\alpha_{\rm K}(t)$: Kineticity

$\alpha_{\rm M}(t)$: Planck mass evolution rate

$\alpha_{\rm B}(t)$: Braiding

Creminelli *et al.* (2008); Park *et al.* (2010); Gubitosi *et al.* (2012); Bloomfield *et al.* (2012); Bellini & Sawicki (2014); Gleyzes *et al.* (2014) ...

EFT of DE & MG

Cosmological background and linear perturbations

- $H(t)$: Hubble parameter
- $\alpha_{\rm K}(t)$: Kineticity
- $\alpha_{\rm M}(t)$: Planck mass evolution rate
- $\alpha_{\rm B}(t)$: Braiding
- $\alpha_{\rm T}(t)$: Tensor speed alteration ($c_{\rm T}^2 = 1 + \alpha_{\rm T}$)

Creminelli *et al.* (2008); Park *et al.* (2010); Gubitosi *et al.* (2012); Bloomfield *et al.* (2012); Bellini & Sawicki (2014); Gleyzes *et al.* (2014) ...

Self-acceleration

- Self-acceleration ($a \gtrsim 0.6$) ($d^2a/dt^2 > 0$, $d^2\tilde{a}/d\tilde{t}^2 \leq 0$):

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1 + \frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2a}{dt^2} + \frac{a\,H^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0$$

$$\left|\frac{\Omega'}{\Omega}\right| \qquad \gtrsim \mathcal{O}(1)$$

[L & Taylor (2015)]

Self-acceleration

- Self-acceleration ($a \gtrsim 0.6$) ($d^2a/dt^2 > 0$, $d^2\tilde{a}/d\tilde{t}^2 \leq 0$):

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1 + \frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2a}{dt^2} + \frac{a\,H^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0$$

$$\left|\frac{\Omega'}{\Omega}\right| = \left|\alpha_{\rm M} + \frac{\alpha'_{\rm T}}{1+\alpha_{\rm T}}\right| \gtrsim \mathcal{O}(1)$$

[L & Taylor (2015)]

Self-acceleration

- Self-acceleration ($a \gtrsim 0.6$) ($d^2a/dt^2 > 0$, $d^2\tilde{a}/d\tilde{t}^2 \leq 0$):

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1 + \frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2a}{dt^2} + \frac{a\,H^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0$$

$$\left|\frac{\Omega'}{\Omega}\right| = \left|\alpha_{\rm M} + \frac{\alpha_{\rm T}'}{1+\alpha_{\rm T}}\right| \gtrsim \mathcal{O}(1)$$

- Consistency relation: $\Omega = M^2\,c_{\rm T}^2$, where $\alpha_{\rm M} = (M^2)'/M^2$

[L & Taylor (2015)]

Linear LSS

$$ds^2 = -(1+\Psi)dt^2 + a(t)^2(1+2\Phi)dx^2$$

Conservation equations unchanged; modified Einstein equations:

$$\begin{aligned} k^2\Psi &= -\frac{\kappa^2}{2}\mu(a,k)\bar{\rho}_{\rm m}a^2\Delta_{\rm m} \\ \Phi &= -\gamma(a,k)\Psi \end{aligned}$$

Closure relations:

Linear LSS

$$ds^2 = -(1+\Psi)dt^2 + a(t)^2(1+2\Phi)dx^2$$

Conservation equations unchanged; modified Einstein equations:

$$\begin{aligned} k^2\Psi &= -\frac{\kappa^2}{2}\mu(a,k)\bar{\rho}_{\rm m} a^2 \Delta_{\rm m} \\ \Phi &= -\gamma(a,k)\Psi \end{aligned}$$

Closure relations:

- ΛCDM: $\mu = 1$; $\gamma = 1$

Linear LSS

$$ds^2 = -(1+\Psi)dt^2 + a(t)^2(1+2\Phi)dx^2$$

Conservation equations unchanged; modified Einstein equations:

$$\begin{aligned} k^2\Psi &= -\frac{\kappa^2}{2}\mu(a,k)\bar{\rho}_{\rm m}a^2\Delta_{\rm m} \\ \Phi &= -\gamma(a,k)\Psi \end{aligned}$$

Closure relations:

- ΛCDM: $\mu = 1$; $\gamma = 1$
- Horndeski (quasistatic): $\mu = h_1\left(\frac{1+h_4k^2}{1+h_5k^2}\right)$; $\gamma = h_2\left(\frac{1+h_3k^2}{1+h_4k^2}\right)$

Linear Shielding

Linearly shielded Horndeski scalar-tensor theory

- $\lim_{k\to\infty} \mu(a,k) = \gamma(a,k) = 1$
  with 3 free functions of time (1 acting only beyond QS limit)
- $\mu(a,k) = \gamma(a,k) = 1$
  with 2 free functions of time
- Can set $H = H_{\Lambda\mathrm{CDM}}$ on top of that

[L & Taylor (2014)]

Linear Shielding

Linearly shielded Horndeski scalar-tensor theory

- $\lim_{k\to\infty} \mu(a,k) = \gamma(a,k) = 1$
  with 3 free functions of time (1 acting only beyond QS limit)
- $\mu(a,k) = \gamma(a,k) = 1$
  with 2 free functions of time
- Can set $H = H_{\Lambda\text{CDM}}$ on top of that

[L & Taylor (2014)]

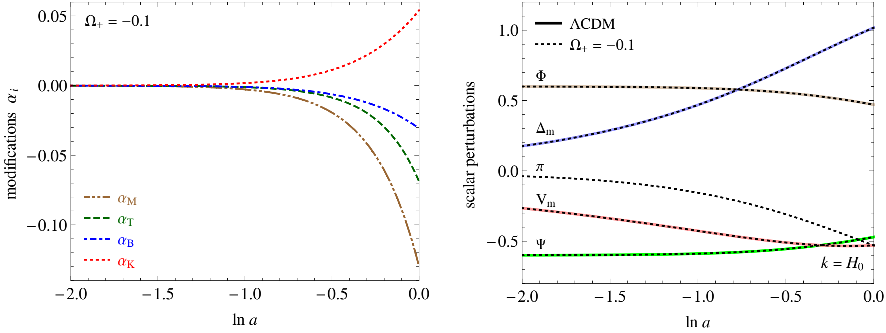
Linear Shielding

Linearly shielded Horndeski scalar-tensor theory

- $\lim_{k\to\infty} \mu(a,k) = \gamma(a,k) = 1$
  with 3 free functions of time (1 acting only beyond QS limit)
- $\mu(a,k) = \gamma(a,k) = 1$
  with 2 free functions of time
- Can set $H = H_{\Lambda\mathrm{CDM}}$ on top of that

[L & Taylor (2014)]

A Dark Degeneracy



[L & Taylor (2015)]

Breaking the Dark Degeneracy with GW

- Propagation of gravitational waves:

$$h''_{ij} + \left(\alpha_{\mathrm{M}} + 3 + \frac{H'}{H}\right) h'_{ij} + (1 + \alpha_{\mathrm{T}}) k_H^2 h_{ij} = 0$$

- Different propagation speed: can be tested by comparing arrival time of signals
- Different damping of GW amplitude: can be tested with standard sirens

Breaking the Dark Degeneracy with GW

- Propagation of gravitational waves:

$$h_{ij}'' + \left(\alpha_{\mathrm{M}} + 3 + \frac{H'}{H}\right) h_{ij}' + (1 + \alpha_{\mathrm{T}}) k_H^2 h_{ij} = 0$$

- Different propagation speed: can be tested by comparing arrival time of signals
- Different damping of GW amplitude: can be tested with standard sirens

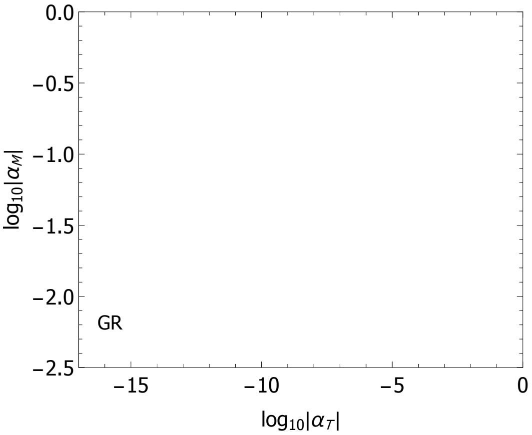
Breaking the Dark Degeneracy with GW

- Propagation of gravitational waves:

$$h''_{ij} + \left(\alpha_{\mathrm{M}} + 3 + \frac{H'}{H}\right) h'_{ij} + (1 + \alpha_{\mathrm{T}}) k_H^2 h_{ij} = 0$$

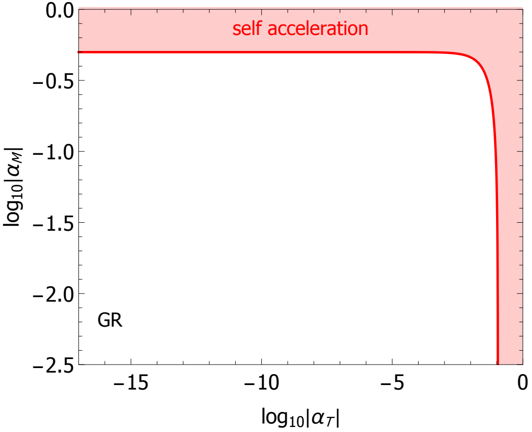
- Different propagation speed: can be tested by comparing arrival time of signals
- Different damping of GW amplitude: can be tested with standard sirens

Breaking the Dark Degeneracy with GW



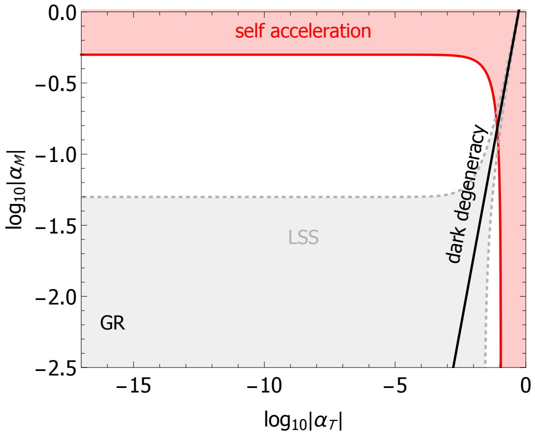
[L & Taylor 2015]

Breaking the Dark Degeneracy with GW



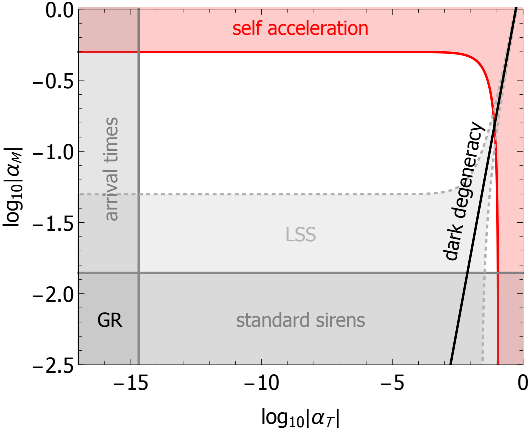
[L & Taylor 2015]

Breaking the Dark Degeneracy with GW



[L & Taylor 2015]

Breaking the Dark Degeneracy with GW



[L & Taylor 2015]

Minimal self-acceleration

- Assume $\alpha_{\mathrm{T}} \simeq 0$ ($c_{\mathrm{T}} = 1$) and $H = H_{\Lambda\mathrm{CDM}}$
  cosmic rays, binary pulsars, aLIGO GW + GRB (2017?)
- Cosmic self-acceleration must be due to α_{M}:

$$\left|\frac{\Omega'}{\Omega}\right| = \left|\alpha_{\mathrm{M}} + \frac{\alpha_{\mathrm{T}}'}{1+\alpha_{\mathrm{T}}}\right| \gtrsim \mathcal{O}(1)$$

- Minimal acceleration:

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1+\frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2 a}{dt^2} + \frac{a H^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0$$

$$\Rightarrow \quad \left(1+\frac{H'}{H}\right)\left(1+\frac{1}{2}\alpha_{\mathrm{M}}\right) + \frac{1}{2}\alpha_{\mathrm{M}}' \leq 0$$

$$\Rightarrow \quad \kappa^2 M^2 \leq \left(\frac{a_{\mathrm{acc}}}{a}\right)^2 e^{C(\chi_{\mathrm{acc}}-\chi)}, \quad C = 2H_0 a_{\mathrm{acc}}\sqrt{3(1-\Omega_{\mathrm{m}})}$$

Minimal self-acceleration

- Assume $\alpha_{\rm T} \simeq 0$ ($c_{\rm T} = 1$) and $H = H_{\Lambda\rm CDM}$
  cosmic rays, binary pulsars, aLIGO GW + GRB (2017?)
- Cosmic self-acceleration must be due to $\alpha_{\rm M}$:

$$\left|\frac{\Omega'}{\Omega}\right| = \left|\alpha_{\rm M} + \frac{\alpha_{\rm T}'}{1+\alpha_{\rm T}}\right| \gtrsim \mathcal{O}(1)$$

- Minimal acceleration:

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1+\frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2a}{dt^2} + \frac{aH^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0$$

$$\Rightarrow \quad \left(1+\frac{H'}{H}\right)\left(1+\frac{1}{2}\alpha_{\rm M}\right) + \frac{1}{2}\alpha_{\rm M}{}' \leq 0$$

$$\Rightarrow \quad \kappa^2 M^2 \leq \left(\frac{a_{\rm acc}}{a}\right)^2 e^{C(\chi_{\rm acc}-\chi)}, \quad C = 2H_0 a_{\rm acc}\sqrt{3(1-\Omega_{\rm m})}$$

Minimal self-acceleration

- Assume $\alpha_{\rm T} \simeq 0$ ($c_{\rm T} = 1$) and $H = H_{\Lambda{\rm CDM}}$
  cosmic rays, binary pulsars, aLIGO GW + GRB (2017?)
- Cosmic self-acceleration must be due to $\alpha_{\rm M}$:

$$\left|\frac{\Omega'}{\Omega}\right| = \left|\alpha_{\rm M} + \frac{\alpha_{\rm T}'}{1+\alpha_{\rm T}}\right| \gtrsim \mathcal{O}(1)$$

- Minimal acceleration:

$$\frac{d^2\tilde{a}}{d\tilde{t}^2} = \frac{1}{\sqrt{\Omega}}\left[\left(1+\frac{1}{2}\frac{\Omega'}{\Omega}\right)\frac{d^2a}{dt^2} + \frac{aH^2}{2}\left(\frac{\Omega'}{\Omega}\right)'\right] \leq 0$$

$$\Rightarrow \quad \left(1+\frac{H'}{H}\right)\left(1+\frac{1}{2}\alpha_{\rm M}\right) + \frac{1}{2}\alpha_{\rm M}' \leq 0$$

$$\Rightarrow \quad \kappa^2 M^2 \leq \left(\frac{a_{\rm acc}}{a}\right)^2 e^{C(\chi_{\rm acc}-\chi)}, \quad C = 2H_0 a_{\rm acc}\sqrt{3(1-\Omega_{\rm m})}$$

Minimal self-acceleration

- Minimise modification in growth of structure: $\alpha_{\mathrm{B}} = \alpha_{\mathrm{M}}$ follows from

$$\mu_\infty = \frac{2(\alpha_{\mathrm{B}} - \alpha_{\mathrm{M}})^2 + \alpha\, c_{\mathrm{s}}^2}{\alpha\, c_{\mathrm{s}}^2 \kappa^2 M^2}$$

  and $M^2,\ \alpha,\ c_{\mathrm{s}}^2 > 0$ for stability

- Minimal self-acceleration: $\mu = (\kappa^2 M^2)^{-1} \geq 1$ and $\gamma = 1$ with $\mu(a \leq a_{\mathrm{acc}} \simeq 0.6) = 1$ increasing to $\mu(a = 1) \simeq 1.04$

Minimal self-acceleration

- Minimise modification in growth of structure: $\alpha_{\rm B} = \alpha_{\rm M}$ follows from

$$\mu_\infty = \frac{2(\alpha_{\rm B} - \alpha_{\rm M})^2 + \alpha\, c_{\rm s}^2}{\alpha\, c_{\rm s}^2 \kappa^2 M^2}$$

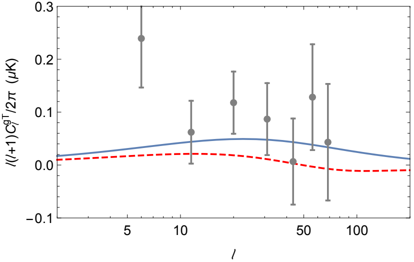
  and $M^2, \ \alpha, \ c_{\rm s}^2 > 0$ for stability
- Minimal self-acceleration: $\mu = (\kappa^2 M^2)^{-1} \geq 1$ and $\gamma = 1$ with $\mu(a \leq a_{\rm acc} \simeq 0.6) = 1$ increasing to $\mu(a = 1) \simeq 1.04$

Incompatibility with observations

- Background:
  SN Ia, BAO, H_0, CMB
- Perturbations:
  CMB (Planck 2015), E_G,
  galaxy-ISW
- ISW sensitive to $\Sigma' = -\alpha_{\rm M}\Sigma$
  where $\Sigma = (1+\gamma)\mu/2$
- Overall:
  3σ worse fit than ΛCDM
  strong evidence for Λ ($B \simeq 39$)

[L & Lima (2016)]

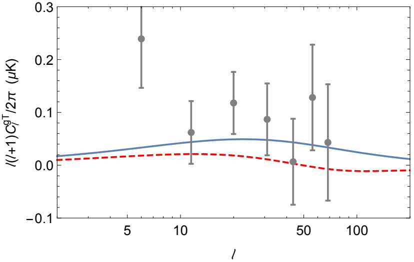
Incompatibility with observations



- Background:
  SN Ia, BAO, H_0, CMB
- Perturbations:
  CMB (Planck 2015), E_G,
  galaxy-ISW
- ISW sensitive to $\Sigma' = -\alpha_M \Sigma$
  where $\Sigma = (1+\gamma)\mu/2$
- Overall:
  3σ worse fit than ΛCDM
  strong evidence for Λ ($B \simeq 39$)

[L & Lima (2016)]

Incompatibility with observations

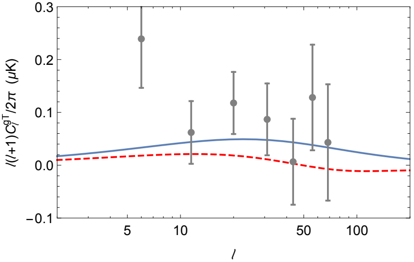


- Background:
  SN Ia, BAO, H_0, CMB
- Perturbations:
  CMB (Planck 2015), E_G,
  galaxy-ISW
- ISW sensitive to $\Sigma' = -\alpha_M \Sigma$

  where $\Sigma = (1+\gamma)\mu/2$
- Overall:
  3σ worse fit than ΛCDM
  strong evidence for Λ ($B \simeq 39$)

[L & Lima (2016)]

Incompatibility with observations



- Background:
  SN Ia, BAO, H_0, CMB
- Perturbations:
  CMB (Planck 2015), E_G,
  galaxy-ISW
- ISW sensitive to $\Sigma' = -\alpha_{\mathrm{M}}\Sigma$
  where $\Sigma = (1+\gamma)\mu/2$
- Overall:
  3σ worse fit than $\Lambda\mathrm{CDM}$
  strong evidence for Λ ($B \simeq 39$)

[L & Lima (2016)]

Conclusions & Outlook

- Horndeski (self-accelerated) MG can be degenerate in background and (linear) LSS (parametrised tests?)
- GW cosmology will break this degeneracy and discriminate between a cosmological constant (or dark energy) and a scalar-tensor modification of gravity
- Minimal self-acceleration with standard GW speed performs 3σ worse than ΛCDM
- Weak lensing or galaxy CMB lensing cross correlations may increase significance
- More complicated theories introduce more freedom (are there sufficient observations to break degeneracies?)

Conclusions & Outlook

- Horndeski (self-accelerated) MG can be degenerate in background and (linear) LSS (parametrised tests?)
- GW cosmology will break this degeneracy and discriminate between a cosmological constant (or dark energy) and a scalar-tensor modification of gravity
- Minimal self-acceleration with standard GW speed performs 3σ worse than ΛCDM
- Weak lensing or galaxy CMB lensing cross correlations may increase significance
- More complicated theories introduce more freedom (are there sufficient observations to break degeneracies?)

Conclusions & Outlook

- Horndeski (self-accelerated) MG can be degenerate in background and (linear) LSS (parametrised tests?)
- GW cosmology will break this degeneracy and discriminate between a cosmological constant (or dark energy) and a scalar-tensor modification of gravity
- Minimal self-acceleration with standard GW speed performs 3σ worse than ΛCDM
- Weak lensing or galaxy CMB lensing cross correlations may increase significance
- More complicated theories introduce more freedom (are there sufficient observations to break degeneracies?)

Conclusions & Outlook

- Horndeski (self-accelerated) MG can be degenerate in background and (linear) LSS (parametrised tests?)
- GW cosmology will break this degeneracy and discriminate between a cosmological constant (or dark energy) and a scalar-tensor modification of gravity
- Minimal self-acceleration with standard GW speed performs 3σ worse than ΛCDM
- Weak lensing or galaxy CMB lensing cross correlations may increase significance
- More complicated theories introduce more freedom (are there sufficient observations to break degeneracies?)

Conclusions & Outlook

- Horndeski (self-accelerated) MG can be degenerate in background and (linear) LSS (parametrised tests?)
- GW cosmology will break this degeneracy and discriminate between a cosmological constant (or dark energy) and a scalar-tensor modification of gravity
- Minimal self-acceleration with standard GW speed performs 3σ worse than ΛCDM
- Weak lensing or galaxy CMB lensing cross correlations may increase significance
- More complicated theories introduce more freedom (are there sufficient observations to break degeneracies?)

Thank you!