Unravelling Cosmic Acceleration with Gravitational Waves and Large-Scale Structure

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Cosmological constant

- Cosmic acceleration at late times

- Dark Energy: 69.2%
- Dark Matter: 25.9%
- Baryonic: 4.9%

Cosmological constant problem → old and new aspects

Λ = 0 & DE or MG?

No Problem with the Cosmological Constant
Cosmological constant

- Cosmic acceleration at late times
- Best candidate:

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = M_{\text{Pl}}^{-2} T_{\mu\nu} \]
Cosmological constant

- Cosmic acceleration at late times
- Best candidate:
  \[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = M_{\text{Pl}}^{-2} T_{\mu\nu} \]
- Cosmological constant problem
  \[ \rightarrow \text{old and new aspects} \]
Cosmological constant

- Cosmic acceleration at late times
- Best candidate:
  \[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = M_{\text{Pl}}^{-2} T_{\mu\nu} \]
- Cosmological constant problem
  → old and new aspects
- \( \Lambda = 0 \) & DE or MG?

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No Problem with the Cosmological Constant
Cosmological constant

- Observations in good agreement with \( \Lambda \) (Planck & DES: \( w = -1 \pm 0.05 \))
Cosmological constant

- Observations in good agreement with $\Lambda$ (Planck & DES: $w = -1 \pm 0.05$)
- Kinetic self-acceleration from DE always possible because of degeneracy (but engineered with $w = -1$?)

[Kennedy, L & Taylor (2019)]
Observations in good agreement with $\Lambda$ (Planck & DES: $w = -1 \pm 0.05$)

Kinetic self-acceleration from DE always possible because of degeneracy (but engineered with $w = -1$?)

[Kennedy, L & Taylor (2019)]

Genuine MG self-acceleration challenged by GW170817

[L & Taylor/Lima (2015/16)]
Horndeski scalar-tensor action: (simplest MG)

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

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

[Horndeski 1974; Deffayet, Gao, Steer, Zahariade 2011; Kobayashi, Yamaguchi, Yokoyama 2011]
Breaking the Dark Degeneracy with GWs

[Graph showing the relation between the change in gravitational coupling and the deviation in GW speed, with regions labeled: GR, Large-Scale Structure, Self-Accelerated Modified Gravity, GW Distances, Dark Degeneracy.]

[L & Taylor (2015)]
Breaking the Dark Degeneracy with GWs

![Graph showing deviation in GW speed and change in gravitational coupling.]

- **GW170817**: Deviation in GW Speed (in %)
- **GR**: Geometrically Regular
- **Large-Scale Structure**: Deviation in Deviation in GW Speed (in %)
- **GW Distances**: GW Speed
- **Self-Accelerated Modified Gravity**: Deviation in GW Speed (in %)
- **Dark Degeneracy**: Deviation in GW Speed (in %)
- **GW Speed**: Deviation in GW Speed (in %)

[L & Taylor (2015)]

No Problem with the Cosmological Constant
GW170817

[Abbott et al. 2017]

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No Problem with the Cosmological Constant
Breaking the Dark Degeneracy with GWs

![Diagram showing the relationship between GW speed deviation and cosmological constant](image)

- **GW170817**
- Deviation in GW Speed (in %)
- [L & Taylor (2015)]

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No Problem with the Cosmological Constant
Breaking the Dark Degeneracy with GWs

- Self-Accelerated Modified Gravity
- galaxy-ISW
- Large-Scale Structure
- GW Distances
- GR

GW170817

Deviation in GW Speed (in %)

[L & Lima (2016)]

[L & Taylor (2015)]

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No Problem with the Cosmological Constant
Breaking the Dark Degeneracy with GWs

- Self-Accelerated Modified Gravity
- Galaxy-ISW
- Large-Scale Structure
- GW Distances

GW170817

Deviation in GW Speed (in %)

[GR, GW, GW Speed]

[L & Lima (2016)]

[L & Taylor (2015)]

Standard Sirens
Outlook – *Standard Sirens*

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**Figure 1: GW170817 measurement of $H_0$.**

The marginalized posterior density for $H_0$, $p(H_0 \mid GW170817)$, is shown by the blue curve. Constraints at 1σ (darker shading) and 2σ (lighter shading) from Planck⁰ and SHoES²¹ are shown in green and orange, respectively. The maximum posterior value and minimal 68.3% credible interval from this posterior density function is $H_0 = 70.0^{+12.0}_{-8.0}\, \text{km s}^{-1}\text{Mpc}^{-1}$. The 68.3% (1σ) and 95.4% (2σ) minimal credible intervals are indicated by dashed and dotted lines, respectively.

On 17 August 2017, the Advanced LIGO¹ and Virgo² detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system³.

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**No Problem with the Cosmological Constant**
Breaking the Dark Degeneracy with GWs

GW170817

Deviation in GW Speed (in %)

[GW Speed]

[Large-Scale Structure]

[Self-Accelerated Modified Gravity]

[Dark Degeneracy]

[GR]

[GW Distances]

[L & Taylor (2015)]

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No Problem with the Cosmological Constant
Remaining viable Horndeski (at low $z$)

- Horndeski action:

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

where $X \equiv -\frac{1}{2}(\partial_\mu \varphi)^2$
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[Kimura & Yamamoto (2011); McManus, L & Peñarrubia (2016)]
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+ L_m(g_{\mu\nu}, \psi_i) \right\}$$

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

[Kimura & Yamamoto (2011); McManus, L & Peñarrubia (2016)]

*also see:* [Ezquiaga & Zumalacárregui (2017); Creminelli & Vernizzi (2017); Sakstein & Jain (2017); Baker, Bellini, Ferreira, Lagos, Noller, Sawicki (2017); ...]
Remaining viable Horndeski (at low z)

Horndeski action:

\[
S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \left\{ G_2(\varphi, X) - G_3(\varphi, X) \square \varphi \\
+ G_4(\varphi, X) R + \frac{\partial G_4}{\partial X} \left[ (\square \varphi)^2 - (\nabla_\mu \nabla_\nu \varphi)^2 \right] \\
+ G_5(\varphi, X) G_{\mu\nu} \nabla^\mu \nabla^\nu \varphi \\
- \frac{1}{6} \frac{\partial G_5}{\partial X} \left[ (\square \varphi)^3 - 3 \square \varphi (\nabla_\mu \nabla_\nu \varphi)^2 + 2 (\nabla_\mu \nabla_\nu \varphi)^3 \right] \\
+ \mathcal{L}_m(g_{\mu\nu}, \psi_i) \right\} + \text{beyond?}
\]

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

[Kimura & Yamamoto (2011); McManus, L & Peñarrubia (2016)]

also see: [Ezquiaga & Zumalacárregui (2017); Creminelli & Vernizzi (2017); Sakstein & Jain (2017); Baker, Bellini, Ferreira, Lagos, Noller, Sawicki (2017); ...]
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+ \mathcal{L}_m(g_{\mu\nu}, \psi_i) \right\} + \text{beyond?} \rightarrow \text{GWs decay to } \delta \phi
\]

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

[Kimura & Yamamoto (2011); McManus, L & Peñarrubia (2016)]

also see: [Ezquiaga & Zumalacárregui (2017); Creminelli & Vernizzi (2017); Sakstein & Jain (2017); Baker, Bellini, Ferreira, Lagos, Noller, Sawicki (2017); ….]
**Cosmological constant**

**Large-Scale Structure & Gravitational Waves**

Planck mass variation and the $\Lambda$ problem

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**Linear shielding for GWs**

![Graph showing scale-dependent propagation of GWs](image)

**Scale-dependent propagation of GWs:**

$$h_{ij}^{''} + \left(3 + \frac{H'}{H} + \frac{(0)\alpha_M + (1)\alpha_M w(a)k_H^2}{1 + w(a)k_H^2}\right) h_{ij}'$$

$$+ \left(1 + \frac{(0)\alpha_T + (1)\alpha_T w(a)k_H^2}{1 + w(a)k_H^2}\right) k_H^2 h_{ij} = 0$$

with GW170817 $\Rightarrow (1)\alpha_T \simeq 0$ as $k_H \sim 10^{19}$

[Battye, Pace & Trinh (2018)]
Linear shielding for GWs

- Scale-dependent propagation of GWs:
  \[
  h'''_{ij} + \left(3 + \frac{H'}{H} + \frac{(0)\alpha_M + (1)\alpha_M w(a)k_H^2}{1 + w(a)k_H^2} \right) h'_{ij} \\
  + \left(1 + \frac{(0)\alpha_T + (1)\alpha_T w(a)k_H^2}{1 + w(a)k_H^2} \right) k_H^2 h_{ij} = 0
  \]

  with GW170817 \(\Rightarrow (1)\alpha_T \simeq 0\) as \(k_H \sim 10^{19}\)
  
  [Battye, Pace & Trinh (2018)]

- Self-acceleration driven by
  \[
  \left| \frac{\Omega'}{\Omega} \right| = \left| (0)\alpha_M + \frac{(0)\alpha_T}{1 + (0)\alpha_T} \right| \gtrsim \mathcal{O}(1)
  \]
  
  (cf. linear shielding for GWs) [L & Taylor (2014)]
- Observations in good agreement with $\Lambda$ (Planck & DES: $w = -1 \pm 0.05$)
- Kinetic self-acceleration from DE always possible because of degeneracy (but engineered with $w = -1$?)
  [Kennedy, L & Taylor (2019)]
- Genuine MG self-acceleration challenged by GW170817
  [L & Taylor/Lima (2015/16)]
Cosmological constant

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- DE & MG models typically do not address *old* $\Lambda$ problem
Cosmological constant

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- DE & MG models typically do not address *old* $\Lambda$ problem

- Back to $\Lambda$? Cosmological constant problem?

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No Problem with the Cosmological Constant
Planck mass variation

- Einstein-Hilbert action

\[ S = M_{P1}^2 \int d^4x \sqrt{-g} \left( \frac{R}{2} - \Lambda \right) + \int d^4x \sqrt{-g} \mathcal{L}_m(g_{\mu\nu}, \Phi_m) \]
Planck mass variation

- Einstein-Hilbert action

\[ S = \int d^4x \sqrt{-g} \mathcal{L}_m(g_{\mu\nu}, \Phi_m) + M_{Pl}^2 \int d^4x \sqrt{-g} \left( \frac{R}{2} - \Lambda \right) \]
Planck mass variation

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\[ S = \int d^4x \sqrt{-g} \mathcal{L}_m(g_{\mu\nu}, \Phi_m) + M_{Pl}^2 \int d^4x \sqrt{-g} \left( \frac{R}{2} - \Lambda \right) \]
Planck mass variation

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- Field and constraint equations

\[ G_{\mu \nu} + \Lambda g_{\mu \nu} = M_{Pl}^{-2} T_{\mu \nu}, \quad \int dV_4 \left( \frac{R}{2} - \Lambda \right) = 0 \]
Planck mass variation

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- Field and constraint equations

\[ G_{\mu\nu} + \Lambda g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu}, \quad \int dV_4 \left( \frac{R}{2} - \Lambda \right) = 0 \]

- Combined field equations

\[ G_{\mu\nu} + \frac{1}{2} M_{Pl}^{-2} \langle T \rangle g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu}, \quad M_{Pl}^2 \Lambda = \frac{1}{2} \int dV_4 \frac{T}{\langle T \rangle} \equiv \frac{1}{2} \langle T \rangle \]
Planck mass variation

- Einstein-Hilbert action

\[ S = \int d^4x \sqrt{-g} \mathcal{L}_m(g_{\mu\nu}, \Phi_m) + M_{Pl}^2 \int d^4x \sqrt{-g} \left( \frac{R}{2} - \Lambda \right) \]

- Field and constraint equations

\[ G_{\mu\nu} + \Lambda g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu} , \quad \int dV_4 \left( \frac{R}{2} - \Lambda \right) = 0 \]

- Combined field equations

\[ G_{\mu\nu} + \frac{1}{2} M_{Pl}^{-2} \langle T \rangle g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu} , \quad M_{Pl}^2 \Lambda = \frac{1}{2} \frac{\int dV_4 T}{\int dV_4} \equiv \frac{1}{2} \langle T \rangle \]

[L (2019)] (also see, e.g., vacuum energy sequestering, unimodular gravity, Barrow & Shaw (2011), 4-form field strength of a 3-form gauge field, \( \delta \)-function from scalar-vector term, multiverse type II, higher-dimensional scalar-tensor theory, supergravity, string theory . . . )
**Old cosmological constant problem**

- Combined field equations: \( \int dV_4 (R - 2 \Lambda) = 0, \) \( M_{Pl}^2 \Lambda = \frac{1}{2} \frac{\int dV_4 T}{\int dV_4} \equiv \frac{1}{2} \langle T \rangle \)

\[
G_{\mu\nu} + \frac{1}{2} M_{Pl}^{-2} \langle T \rangle g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu}
\]
Old cosmological constant problem

- Combined field equations: \( \int dV_4 (R - 2\Lambda) = 0, \) \( M_{\text{Pl}}^2 \Lambda = \frac{1}{2} \frac{\int dV_4 T}{\int dV_4} \equiv \frac{1}{2} \langle T \rangle \)

\[
G_{\mu\nu} + \frac{1}{2} M_{\text{Pl}}^{-2} \langle T \rangle g_{\mu\nu} = M_{\text{Pl}}^{-2} T_{\mu\nu}
\]

- Non-gravitating vacuum energy (old \( \Lambda \) problem)
Old cosmological constant problem

- Combined field equations: $\int dV \, (R - 2\Lambda) = 0, \quad M_{\text{Pl}}^2 \Lambda = \frac{1}{2} \frac{\int dV T}{\int dV} \equiv \frac{1}{2} \langle T \rangle$

  \[ G_{\mu\nu} + \frac{1}{2} M_{\text{Pl}}^{-2} \langle T \rangle g_{\mu\nu} = M_{\text{Pl}}^{-2} T_{\mu\nu} \]

- Non-gravitating vacuum energy (old $\Lambda$ problem)
  - Example 1: $M_{\text{Pl}}^2 \Lambda_{\text{vac}} \propto M_{\text{Pl}}^2 M^2$
    
    (1-loop: $m_i \rightarrow \lambda_i M_{\text{Pl}}$; Wheeler space-time foam [Wang, Zhu & Unruh (2017)])
**Old cosmological constant problem**

- Combined field equations: \[ \int dV_4 (R - 2\Lambda) = 0, \quad M_{Pl}^2 \Lambda = \frac{1}{2} \frac{\int dV_4 T}{\int dV_4} \equiv \frac{1}{2} \langle T \rangle \]

\[ G_{\mu\nu} + \frac{1}{2} M_{Pl}^{-2} \langle T \rangle g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu} \]

- Non-gravitating vacuum energy (old \( \Lambda \) problem)
  - **Example 1:** \( M_{Pl}^2 \Lambda_{\text{vac}} \propto M_{Pl}^2 M^2 \)
    - (1-loop: \( m_i \to \lambda_i M_{Pl} \); Wheeler space-time foam [Wang, Zhu & Unruh (2017)])
  - **Example 2:** \( M_{Pl}^2 \Lambda_{\text{vac}} \propto M_{Pl}^2 \alpha M^{4-2\alpha} \) (\( \alpha = 1; \alpha = 0 \) local sequestering)

\[ G_{\mu\nu} + \frac{1}{2 - \alpha} \left[ (1 - \alpha)\Lambda + \frac{M_{Pl}^{-2} \langle T \rangle}{2} \right] g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu} \]
Cosmological constant

Large-Scale Structure & Gravitational Waves

Planck mass variation and the $\Lambda$ problem

Additional variation wrt Planck mass

Old cosmological constant problem

New cosmological constant problem

Old cosmological constant problem

Combined field equations: \[ \int dV_4 (R - 2\Lambda) = 0, \quad M_{Pl}^2 \Lambda = \frac{1}{2} \int \frac{dV_4 T}{dV_4} \equiv \frac{1}{2} \langle T \rangle \]

\[ G_{\mu\nu} + \frac{1}{2} M_{Pl}^{-2} \langle T \rangle g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu} \]

Non-gravitating vacuum energy (*old* $\Lambda$ problem)

- **Example 1:** \[ M_{Pl}^2 \Lambda_{vac} \propto M_{Pl}^2 M^2 \]
  (1-loop: $m_i \rightarrow \lambda_i M_{Pl}$; Wheeler space-time foam [Wang, Zhu & Unruh (2017)])

- **Example 2:** \[ M_{Pl}^2 \Lambda_{vac} \propto M_{Pl}^{2\alpha} M^{4-2\alpha} \quad (\alpha = 1; \quad \alpha = 0 \quad \text{local sequestering}) \]

  \[ G_{\mu\nu} + \frac{1}{2-\alpha} \left[ (1-\alpha)\Lambda + \frac{M_{Pl}^{-2} \langle T \rangle}{2} \right] g_{\mu\nu} = M_{Pl}^{-2} T_{\mu\nu} \]

- **Example 3:** expansion of $\Lambda_{vac}$ in $M_{Pl}^2$ cancelled by expansion of classical $\Lambda$
Value of the cosmological constant, \( M_P^2 \Lambda = \frac{1}{2} \frac{\int dV_4 T}{\int dV_4} \equiv \frac{1}{2} \langle T \rangle \)

assume spatially perfectly homogeneous matter-only universe with instantaneous collapse at \( t_{end} \)
New cosmological constant problem

- Value of the cosmological constant, \( M_{\text{Pl}}^2 \Lambda = \frac{1}{2} \left( \frac{1}{T} \int \frac{dV_4 T}{dV_4} \right) \equiv \frac{1}{2} \langle T \rangle \)

  Assume spatially perfectly homogeneous matter-only universe with instantaneous collapse at \( t_{\text{end}} \)

  
  - Collapse at \( a = 0.926 \) at age of \( 0.88 H_0^{-1} \) (1 Gyr in the past)
New cosmological constant problem

- Value of the cosmological constant, \( M_{P1}^2 \Lambda = \frac{1}{2} \int \frac{dV_T}{dV_4} \equiv \frac{1}{2} \langle T \rangle \)

  assume spatially perfectly homogeneous matter-only universe with instantaneous collapse at \( t_{end} \)
  - collapse at \( a = 0.926 \) at age of \( 0.88H_0^{-1} \) (1 Gyr in the past)
  - collapse today instead accounts for 81% of observed value
New cosmological constant problem

- Value of the cosmological constant, $M_P^2 \Lambda = \frac{1}{2} \frac{\int dV_4 T}{\int dV_4} \equiv \frac{1}{2} \langle T \rangle$
  - Assume spatially perfectly homogeneous matter-only universe with instantaneous collapse at $t_{\text{end}}$
    - Collapse at $a = 0.926$ at age of $0.88 H_0^{-1}$ (1 Gyr in the past)
    - Collapse today instead accounts for 81% of observed value
    - Interesting proximity (but not exact and no imminent collapse predicted)
New cosmological constant problem

- Value of the cosmological constant, \( M_{P1}^2 \Lambda = \frac{1}{2} \langle T \rangle \)

  Assume spatially perfectly homogeneous matter-only universe with instantaneous collapse at \( t_{\text{end}} \)
  - Collapse at \( a = 0.926 \) at age of 0.88\( H_0^{-1} \) (1 Gyr in the past)
  - Collapse today instead accounts for 81% of observed value
  - Interesting proximity (but not exact and no imminent collapse predicted)

- Universe is inhomogeneous on small scales (backreaction)

  (Final conditions clearer than initial conditions: ultimate critical matter cells)

\[
S_m = \sum_i \int_{U_i} dV_4 \mathcal{L}_{m,i} + \int_{\mathcal{M} \setminus \bigcup_i U_i} dV_4 \mathcal{L}_\emptyset
\]

Matching \( \Lambda \) between \( U_i \) and \( \mathcal{M} \setminus \bigcup_i U_i \): \( \mathcal{L}_\emptyset = M_{P1}^2 (\Lambda/n + M_{P1}^2 \bar{\Lambda}_\emptyset) \)
New cosmological constant problem

- Spherical collapse equation from energy-momentum conservation in matter cell

\[ y'' + \left(2 + \frac{H'}{H}\right)y' + \frac{1}{2} \Omega_m(a)(y^{-3} - 1)y = 0 \]

where \( y \equiv (\rho_m/\bar{\rho}_m)^{-1/3} \) and primes denote derivatives wrt \( \ln a \)
New cosmological constant problem

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- Self-consistent production of cosmological constant

\[ \frac{1}{2} M_{Pl}^{-2} \langle T \rangle \Lambda_{obs} = \frac{\Omega_m}{4(1 - \Omega_m)} \int_{t_0}^{t_{\text{turn}}} dt \ a^3 \frac{t_{\text{max}}}{a^3 y^3} > \frac{t_{\text{max}}}{2t_{\text{turn}}} = 1 \]
New cosmological constant problem

- Spherical collapse equation from energy-momentum conservation in matter cell

\[ y'' + \left(2 + \frac{H'}{H}\right) y' + \frac{1}{2} \Omega_m(a)(y^{-3} - 1)y = 0 \]

where \( y \equiv (\rho_m / \bar{\rho}_m)^{-1/3} \) and primes denote derivatives wrt \( \ln a \)

- Self-consistent production of cosmological constant

\[ \frac{1}{2} M_{Pl}^{-2} \langle T \rangle \Lambda_{obs} = \frac{\Omega_m}{4(1 - \Omega_m)} \int_{t_0}^{t_{turn}} dt \frac{t_{max}}{a^3 y^3} > \frac{t_{max}}{2t_{turn}} = 1 \]

- Standard field equations (w/ non-gravitating vacuum)

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda_{obs} = M_{Pl}^{-2} T_{\mu\nu} \]
New cosmological constant problem

- Measure for likelihood for our location in process: \( y \in [0, 1) \).
**New cosmological constant problem**

- Measure for likelihood for our location in process: $y \in [0, 1)$.
- Uniform prior: $\langle y \rangle = 1/2$
New cosmological constant problem

- Measure for likelihood for our location in process: $y \in [0, 1)$.
- Uniform prior: $\langle y \rangle = \frac{1}{2}$
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$\Rightarrow \Omega_\Lambda = 0.704$
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- $1\sigma$ & $3\sigma$ agreement w/ DES & Planck
Conclusions

- Challenges to cosmic acceleration from DE or MG.
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- Variation of Einstein-Hilbert action \textit{wrt} Planck mass yields a topological constraint equation that prevents vacuum energy from gravitating \textit{(old \(\Lambda\) problem)}.

\[ \Omega_{\Lambda} = 0 \]

No problem with the cosmological constant.
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Conclusions

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Hubble tension?

But what about the $4.4\sigma$ $H_0$ tension?

Image of a graph showing the comparison between Planck and Local measurements of the Hubble constant ($H_0$), with a peak at $70$.
Hubble tension?

[Riess et al. (2016)]

Lucas Lombriser: No Problem with the Cosmological Constant
Hubble tension?

[Image of a graph showing Type Ia Supernovae vs. redshift (z) with a scatter plot and a linear fit.]

\[ \mu(z) = H_0(z) \Delta M \]

40 Mpc

[Riess et al. (2016)]

No Problem with the Cosmological Constant

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Hubble tension?

\[ \hat{B}_{eq} = 4 \]
Thank you!