Gravitational waves in self-accelerated scalar-tensor gravity

(*Or:* Linearly shielded modifications of gravity)

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EFT formalism

- EFT action:

$$
\begin{aligned}
S \;=\; \frac{1}{2\kappa^2}\int \mathrm{d}^4x\sqrt{-g}\,\Big[\, & \Omega(t)R - 2\Lambda(t) - \Gamma(t)\delta g^{00} \\
& + M_2^4(t)(\delta g^{00})^2 - \bar{M}_1^3(t)\delta g^{00}\delta K^{\mu}_{\ \mu} - \bar{M}_2^2(t)(\delta K^{\mu}_{\ \mu})^2 \\
& - \bar{M}_3^2(t)\delta K^{\mu}_{\ \nu}\delta K^{\nu}_{\ \mu} + \hat{M}^2(t)\delta g^{00}\delta R^{(3)} \\
& + m_2^2(t)(g^{\mu\nu} + n^{\mu}n^{\nu})\partial_{\mu}g^{00}\partial_{\nu}g^{00}\Big] + S_{\mathrm{m}}\left[\psi_{\mathrm{m}}; g_{\mu\nu}\right]
\end{aligned}
$$

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

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- FLRW metric: $a(t)$ or $H(t)$

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& - \bar{M}_3^2(t) \delta K^{\mu}_{\ \nu} \delta K^{\nu}_{\ \mu} + \hat{M}^2(t) \delta g^{00} \delta R^{(3)} \\
& + m_2^2(t) (g^{\mu\nu} + n^{\mu} n^{\nu}) \partial_{\mu} g^{00} \partial_{\nu} g^{00} \Big] + S_{\mathrm{m}} [\psi_{\mathrm{m}}; g_{\mu\nu}]
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- FLRW metric: $a(t)$ or $H(t)$
- Model space: $\dim(\mathcal{Q}) = 10$

$$
\mathcal{Q} \equiv \left\{ \Omega, \Lambda, \Gamma, M_2, \bar{M}_1, \bar{M}_2, \bar{M}_3, \hat{M}, m_2, H \right\}
$$

EFT formalism

- Background evolution:

$$
\begin{aligned}
H^2 + \frac{k_0}{a^2} + H\frac{\dot{\Omega}}{\Omega} &= \frac{\kappa^2\bar{\rho}_{\rm m} + \Lambda + \Gamma}{3\Omega} \\
3H^2 + 2\dot{H} + \frac{k_0}{a^2} + \frac{\ddot{\Omega}}{\Omega} + 2H\frac{\dot{\Omega}}{\Omega} &= \frac{\Lambda - \kappa^2\bar{P}_{\rm m}}{\Omega}
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- Effective modifications (quasistatic sub-Hubble limit):

$$\mu(a,k) \equiv -\frac{2k^2\Psi}{\kappa^2\bar{\rho}_\mathrm{m} a^2 \Delta} = \frac{g_1(a)\frac{k^2}{a^2} + g_2(a) + g_3(a)\frac{a^2}{k^2}}{g_4(a)\frac{k^2}{a^2} + g_5(a) + g_6(a)\frac{a^2}{k^2}}$$

$$\gamma(a,k) \equiv -\frac{\Phi}{\Psi} = \frac{g_7(a)\frac{k^2}{a^2} + g_8(a) + g_9(a)\frac{a^2}{k^2}}{g_1(a)\frac{k^2}{a^2} + g_2(a) + g_3(a)\frac{a^2}{k^2}}$$

GR: $\mu = \gamma = 1$

Example

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- Example: Brans-Dicke gravity

$$g_1 = g_4 = g_7 = 0$$

$$g_3 = g_6 = g_9 = 1$$

$$g_2 = \frac{2\omega + 4}{2\omega + 3} \frac{\bar{\varphi}}{M^2}$$

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Linear shielding

- Effective modifications (quasistatic sub-Hubble limit):

$$\mu(a,k) = \frac{g_1 \frac{k^2}{a^2} + g_2 + g_3 \frac{a^2}{k^2}}{g_4 \frac{k^2}{a^2} + g_5 + g_6 \frac{a^2}{k^2}} \qquad \gamma(a,k) = \frac{g_7 \frac{k^2}{a^2} + g_8 + g_9 \frac{a^2}{k^2}}{g_1 \frac{k^2}{a^2} + g_2 + g_3 \frac{a^2}{k^2}}$$

Classifying linearly shielded models in EFT

$\mathcal{M}_{\rm I}$: If g_1, g_4, and g_7 nonzero, $g_1/g_4 = g_7/g_1 = 1$.
EFT $\Rightarrow g_3/g_6 = g_9/g_3 = 1$.

$\mathcal{M}_{\rm II}$: If $g_1 = g_4 = g_7 = 0$, $g_2/g_5 = g_8/g_2 = 1$.

$\mathcal{M}_{\rm III}$: $\mu(a,k) = \gamma(a,k) = 1$ on all quasistatic sub-Hubble scales.

L & Taylor (2014)

Linear shielding

Conditions on EFT functions

$$\alpha_1 \quad : \quad m_2^2 = \frac{1}{2}(\Omega - 1)$$

$$\alpha_2 \quad : \quad \hat{M}^2 = 0$$

$$\alpha_3 \quad : \quad \bar{M}_3^2 = -\bar{M}_2^2$$

$$\alpha_4 \quad : \quad \bar{M}_1^3 = \dot{\Omega} - H(\bar{M}_3^2 + 3\bar{M}_2^2)$$

$$\alpha_5 \quad : \quad \bar{M}_1^3 = -\dot{\Omega} + 2H\bar{M}_3^2$$

$$\alpha_6 \quad : \quad \partial_t \bar{M}_3^2 = \dots$$

$$\alpha_7 \quad : \quad \Gamma = \dots$$

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Classification of models: $\mathcal{A}_\mathrm{i} \equiv \{\, \mathcal{Q} |\, \alpha_\mathrm{i} \}$

$$\begin{aligned}
\mathcal{M}_\mathrm{I} &\equiv (\mathcal{A}_1 \cap \mathcal{A}_2) \backslash \mathcal{A}_3 \\
\mathcal{M}_\mathrm{II} &\equiv \mathcal{A}_3 \cap \mathcal{A}_6 \cap \mathcal{A}_7 \\
\mathcal{M}_\mathrm{III} &\equiv (\mathcal{A}_1 \cap \mathcal{A}_2 \cap \mathcal{A}_4) \cup (\mathcal{A}_1 \cap \mathcal{A}_2 \cap \mathcal{A}_5 \cap \mathcal{A}_6) \\
&\quad \cup (\mathcal{A}_3 \cap \mathcal{A}_6 \cap \mathcal{A}_7 \cap \mathcal{A}_8)
\end{aligned}$$

Linear shielding

Model space

- M_2^4 is always free
- $\dim(\mathcal{Q}) = 6$ in $\mathcal{M}_{\rm I}$
  $\dim(\mathcal{Q}) = 5$ in $\mathcal{M}_{\rm II}$
  $\dim(\mathcal{Q}) = 5$ in $(\mathcal{A}_1 \cap \mathcal{A}_2 \cap \mathcal{A}_4) \subset \mathcal{M}_{\rm III}$
  $\dim(\mathcal{Q}) = 4$ in other two $\mathcal{M}_{\rm III}$ models
- We can choose $H = H_{\Lambda{\rm CDM}}$: $\mathcal{M}_{\rm III}$ looks like ΛCDM !!!
- Application to Horndeski ($2\hat{M}^2 = -\bar{M}_3^2 = \bar{M}_2^2, m_2 = 0$):
  α_3 satisfied: $\nexists \mathcal{M}_{\rm I}$
  $\dim(\mathcal{Q}) = 3$ in $\mathcal{M}_{\rm II}$
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Self acceleration

- Re-parametrise (Horndeski) modifications: H

$$\alpha_{\rm K} \equiv \frac{\Gamma + 4M_2^4}{H^2(\Omega + \bar{M}_2^2)} \qquad \alpha_{\rm M} \equiv \frac{\Omega' + (\bar{M}_2^2)'}{\Omega + \bar{M}_2^2}$$

$$\alpha_{\rm B} \equiv \frac{H\Omega' + \bar{M}_1^3}{2H(\Omega + \bar{M}_2^2)} \qquad \alpha_{\rm T} \equiv \frac{-\bar{M}_2^2}{\Omega + \bar{M}_2^2}$$

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

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

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

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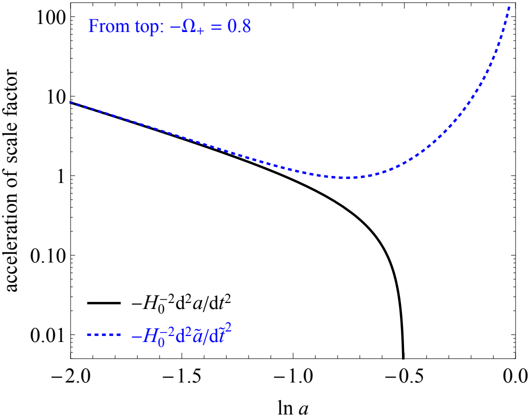
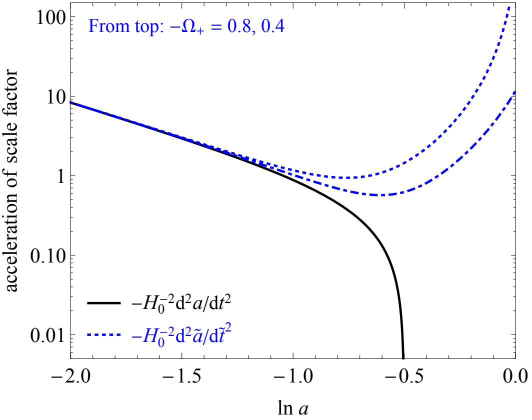


[L & Taylor 2015]

$$\Omega = 1 + \Omega_+ a^n, \quad n = 4$$

Self acceleration



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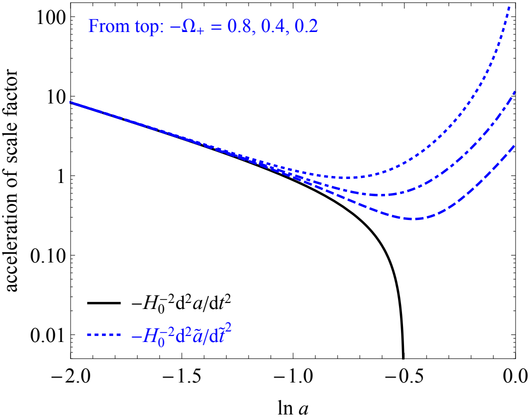

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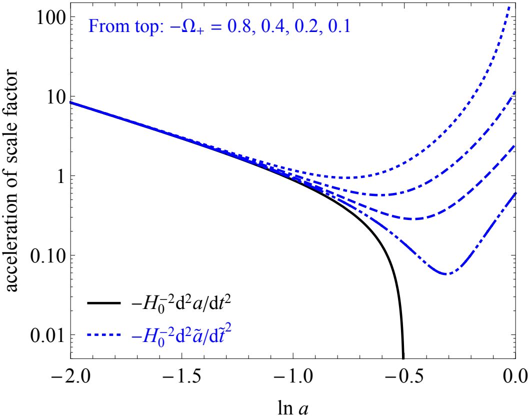

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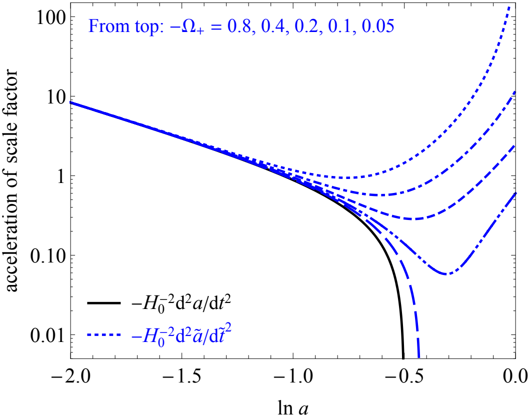

[L & Taylor 2015]

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A linearly shielded model

A self-accelerated, linearly shielded Horndeski scalar-tensor theory

- Choose ΛCDM $H(t)$ (in Jordan frame): fixes 1st EFT funct.
- $\Omega_+ \lesssim -0.1$: fixes 2nd EFT function
- Apply linear shielding conditions: fixes 3rd & 4th EFT function
- Set $c_s = c \equiv 1$: fixes 5th EFT function
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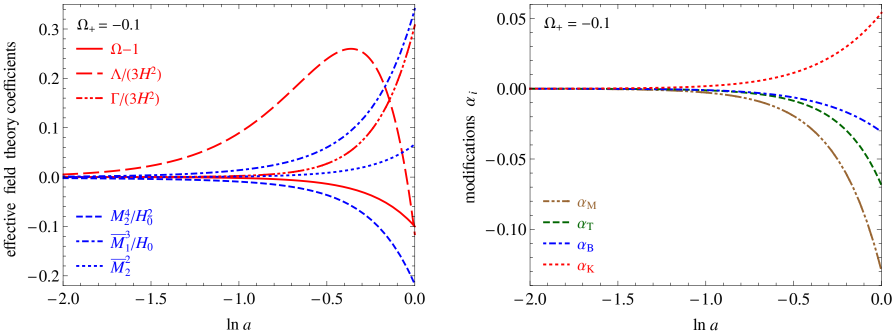

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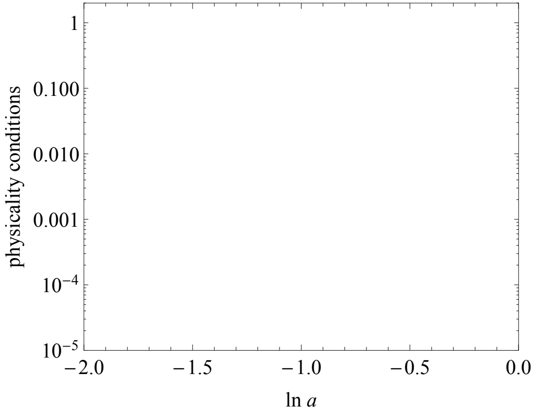
A linearly shielded model

A self-accelerated, linearly shielded Horndeski scalar-tensor theory

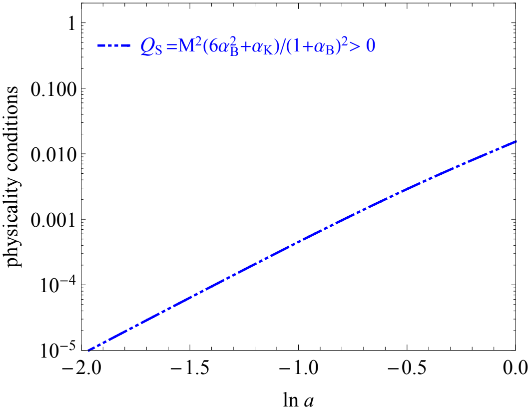
- Choose ΛCDM $H(t)$ (in Jordan frame): fixes 1st EFT funct.
- $\Omega_+ \lesssim -0.1$: fixes 2nd EFT function
- Apply linear shielding conditions: fixes 3rd & 4th EFT function
- Set $c_s = c \equiv 1$: fixes 5th EFT function
- Free of ghost and gradient instabilities

Stability & physicality



[L & Taylor 2015]

Stability & physicality



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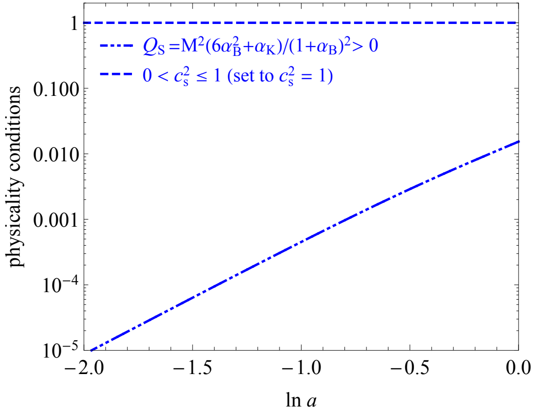

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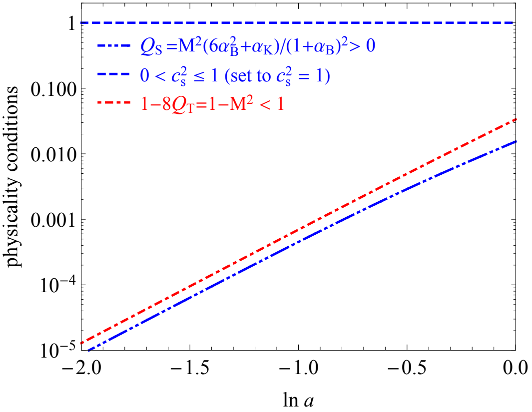

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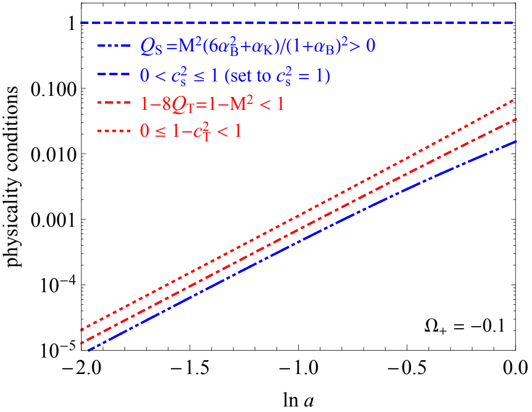
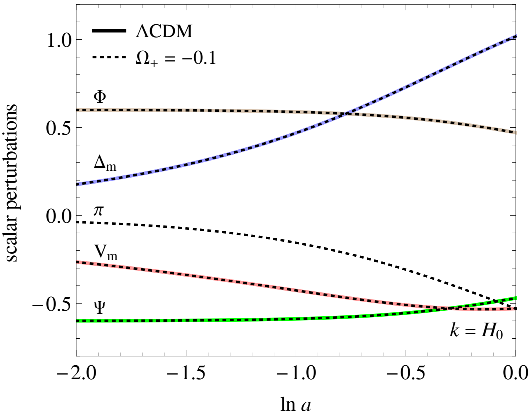


[L & Taylor 2015]

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
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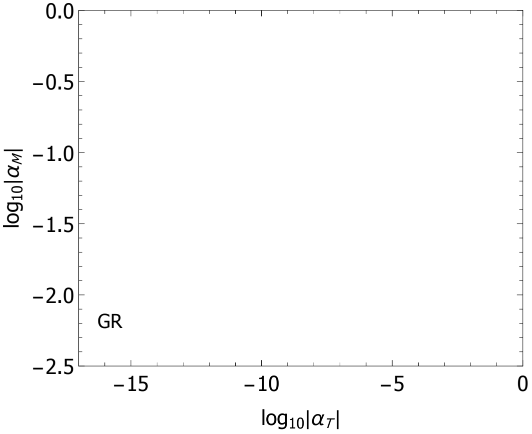

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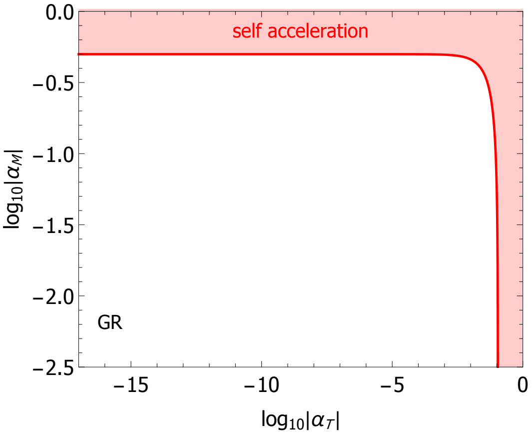

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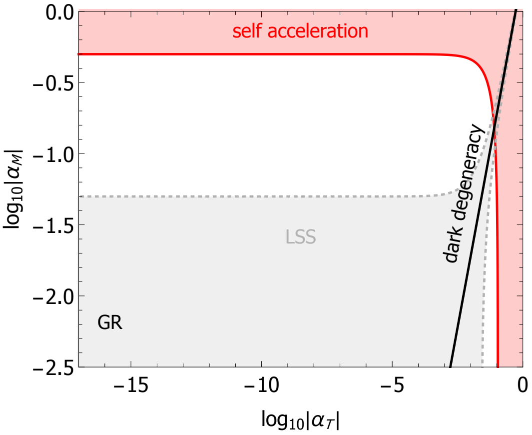

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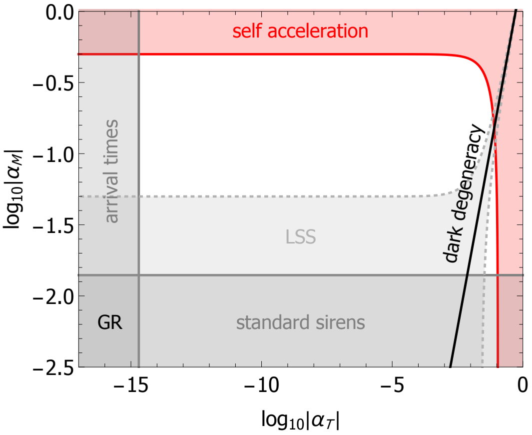

[L & Taylor 2015]

Conclusions & Outlook

- Modifications of gravity can cancel on linear small scales.
- Linearly shielded, self-accelerated, self-consistent Horndeski scalar-tensor theories can be degenerate with ΛCDM in the cosmological background and the LSS.
- GW cosmology will break this degeneracy and discriminate between a cosmological constant (or dark energy) and a scalar-tensor modification of gravity.

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Thank you!