Gravitational Wave Decay into Dark Energy

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Work in progress

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Introduction

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- Gravitational wave (GW) observations provide new tests of GR and of its modifications.

- Matter can affect GW propagation (GW damping by neutrinos after decoupling).
  Does DE provide similar effects (measurable by LIGO/Virgo)?

Introduction

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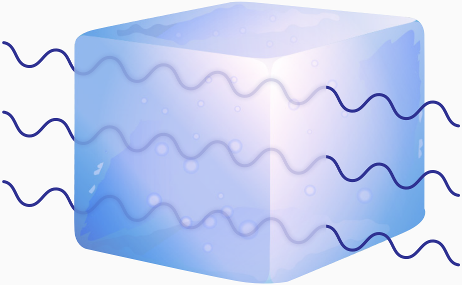
- Gravitational wave (GW) observations provide new tests of GR and of its modifications.
- Matter can affect GW propagation (GW damping by neutrinos after decoupling).
  Does DE provide similar effects (measurable by LIGO/Virgo)?
- *Can GW observations constrain DE models?* *Yes...*

Models of Dark Energy

Scalar-tensor theories

Additional scalar field: Lorentz violating fluid



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Scalar-tensor theories

- Simplest models of DE are given by scalar/tensor theories

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$$\mathscr{L} = R - \frac{1}{2}X - V(\phi)$$

Quintessence

$$\mathscr{L} = f(\phi)R - \frac{1}{2}X - V(\phi)$$

Brans-Dicke

$$\mathscr{L} = R - \mathcal{P}(\phi, X)$$

k-essence

$$X \equiv g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

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Scalar fluctuations $\phi = \phi_0(t) + \pi(t, x)$ in FRW can have a generic speed of sound c_s

$$X^2 \supset \dot{\phi}_0^2\,\dot{\pi}^2$$

$$\mathscr{L}_\pi \sim \dot{\pi}^2 - c_s^2(\partial_i\pi)^2$$

Scalar-tensor theories

- More general approach: consider also (stable) theories with higher-derivatives[1] $\mathscr{L}(\phi, \partial_\mu\phi, \nabla_\mu\nabla_\nu\phi)$

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[1] G. W. Horndeski *Int J Theor Phys* (1974)
C. Deffayet et al. *PRD* (2011)
J. Gleyzes et al. *PRL* (2014)

Scalar-tensor theories

- More general approach: consider also (stable) theories with higher-derivatives[1] $\mathscr{L}(\phi, \partial_\mu\phi, \nabla_\mu\nabla_\nu\phi)$

$$
\begin{aligned}
\mathscr{L}_2 &= G_2(\phi, X) \\
\mathscr{L}_3 &= G_3(\phi, X)\Box\phi \\
\mathscr{L}_4 &= G_4(\phi, X)R - 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - \phi_{\mu\nu}\phi^{\mu\nu}\right] \\
&\quad -F_4(\phi, X)\epsilon^{\mu\nu\rho}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'} \\
\mathscr{L}_5 &= G_5(\phi, X)G_{\mu\nu}\phi^{\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)[(\Box\phi)^3 - 3\Box\phi\phi_{\mu\nu}\phi^{\mu\nu} + 2\phi_{\mu\nu}\phi^{\sigma\mu}\phi^{\nu}_{\sigma}] \\
&\quad -F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}\,, \qquad \phi_\mu \equiv \nabla_\mu\phi
\end{aligned}
$$

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Scalar-tensor theories

- The cosmological background solution $\phi(t)$ spontaneously breaks time-translation invariance.
- Second derivatives give interesting phenomenology.

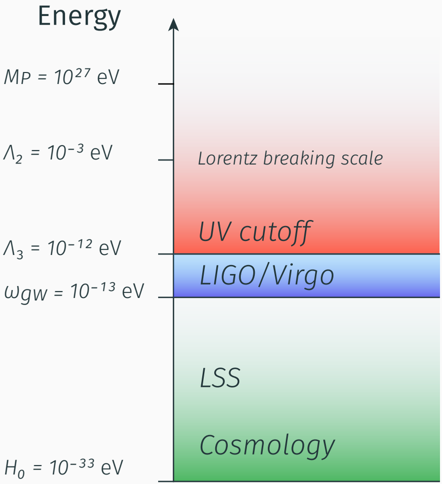
For example:

$$(\nabla_\mu \nabla_\nu \phi)^2 \supset \dot{\phi}_0 (\dot{\gamma}_{ij})^2$$

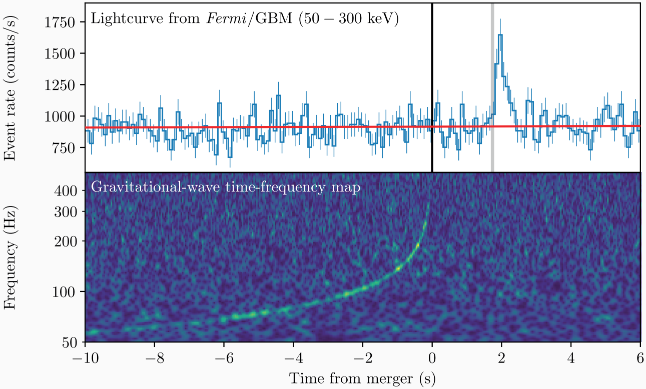
$$\mathscr{L}_\gamma \sim (\dot{\gamma}_{ij})^2 - c_T^2 (\partial_k \gamma_{ij})^2$$

Scalar-tensor theories

- The cosmological background solution $\phi(t)$ spontaneously breaks time-translation invariance, with $\dot{\phi} \sim \Lambda_2^2$.



Dark Energy after GW170817 and GRB170817A



$$\left|\frac{c_T - c}{c}\right| \lesssim 10^{-15}$$

LIGO Scientific and Virgo and Fermi-GBM and INTEGRAL Collaborations *Astrophys. J.* (2017)

Dark Energy after GW170817 and GRB170817A

- The condition $|\Delta c/c| \leq 10^{-15}$ sets constraints on DE models[2]

$$\mathscr{L}_2 = G_2(\phi, X)$$

$$\mathscr{L}_3 = G_3(\phi, X)\Box\phi$$

$$\mathscr{L}_4 = G_4(\phi, X)R - 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - \phi_{\mu\nu}\phi^{\mu\nu}\right]$$

$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{\mu}\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}$$

$$\mathscr{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)[(\Box\phi)^3 - 3\Box\phi\phi_{\mu\nu}\phi^{\mu\nu} + 2\phi_{\mu\nu}\phi^{\sigma\mu}\phi^{\nu}_{\sigma}]$$

$$-F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{\mu}\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}$$

$$XF_4 = 2G_{4,X} + G_{5,\phi}$$

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[2] P. Creminelli and F. Vernizzi, *PRL* (2017), J. M. Ezquiaga and M. Zumalacárregui, *PRL* (2017) T. Baker et al. *PRL* (2017), J. Sakstein and B. Jain *PRL* (2017)

Dark Energy after GW170817 and GRB170817A

- Overall the Lagrangian becomes[3]

$$\begin{aligned}\mathscr{L}_{c_T=1} &= G_2(\phi, X) + G_3(\phi, X)\Box\phi + B_4(\phi, X)R \\ &- \frac{4}{X}B_{4,X}(\phi, X)\left[\phi^{\mu}\phi^{\nu}\phi_{\mu\nu}\Box\phi - \phi^{\mu}\phi_{\mu\nu}\phi_{\lambda}\phi^{\lambda\nu}\right]\end{aligned}$$

- This might not be enough: interactions can modify the signal at LIGO/Virgo.

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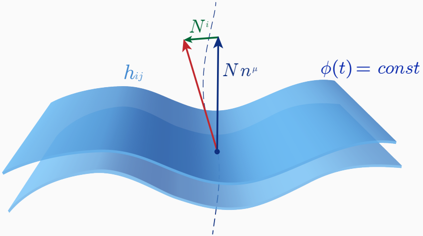
[3] For caveats see C. de Rham and S. Melville 1806.09417, E. Copeland et al. 1810.08239.

Effective Field Theory Of Dark Energy

- Efficient way to study perturbations.
- Clear connection with cosmological observables.
- In a FRW and in unitary gauge $\delta\phi(t,x)=0$ the action is geometrical.



$$ds^2 = -N^2 dt^2 + h_{ij}(N^i dt + dx^i)(N^j dt + dx^j)$$

$$S_{\text{EFT}} = \int d^4x\, N\sqrt{h}\left[\frac{M^2}{2}R - \Lambda(t) - c(t)N + \frac{m_2(t)^4}{2}\delta N^2 + \sum_i \alpha_i(t)\mathcal{O}_i(\delta N, {}^{(3)}R, \delta K_{ij}, \ldots)\right]$$

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[3] G. Gubitosi, F. Piazza and F. Vernizzi *JCAP* (2013)
C. Cheung et al. *JHEP* (2008)

Gravitational Wave Decay

Gravitational Wave Decay

- Lets move to Newtonian gauge

$$\mathrm{d}s^2 = -(1+2\Phi)\mathrm{d}t^2 + a(t)^2(\delta_{ij}(1-2\Psi)+\gamma_{ij})\mathrm{d}x^i\mathrm{d}x^j\,, \qquad \phi = \phi_0(t) + \pi(t,x)$$

- After imposing $c_T = 1$ we still have $c_s \neq 1$.
- Also, the action contains

$$\begin{aligned} S_4 &= \alpha_{\mathrm{H}} M_p^2 \int \mathrm{d}^4x\, N\sqrt{h}\,\delta N \left[{}^{(3)}R + \delta K_{ij}\delta K^{ij} - \delta K^2\right] \\ &\supset \frac{\alpha_{\mathrm{H}}}{\Lambda_3^3}\int \mathrm{d}^4x\, a(t)\,\ddot{\gamma}_{ij}\partial_i\pi\partial_j\pi \end{aligned}$$

- In covariant language $\alpha_{\mathrm{H}} = -2XB_{4,X}/B_4$

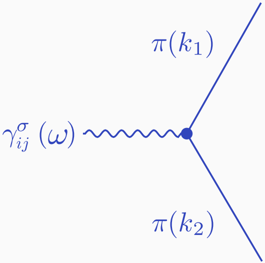
Gravitational Wave Decay

- For $c_s < 1$ GW can decay into Dark Energy fluctuations $\pi(t,x)$ via $\gamma \to \pi\pi$.
- Similar to photon absorption in a material (e.g. photon-phonon interaction).
- Rate of the process:

$$\Gamma_{\gamma\to\pi\pi} \simeq \left(\frac{\alpha_{\rm H}}{\Lambda_3^3}\right)^2 \frac{\omega^7(1-c_s^2)^2}{480\pi\, c_s^7}$$

$$\omega = 2\pi f_{gw}$$

$$\Lambda_3 \simeq (1000\,{\rm Km})^{-1}$$



Gravitational Wave Decay

- LIGO/Virgo events are at a distance $d_s \sim 40\,\mathrm{Mpc}$ with $f_{gw} \sim 100\,\mathrm{Hz}$.

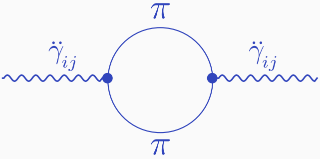
- The coupling α_{H} is compatible with observations if

$$d_s\,\Gamma_{\gamma\to\pi\pi} \lesssim 1 \implies \alpha_{\mathrm{H}} < 10^{-8}$$

- Appreciable modifications of GR on large-scales require $\alpha_{\mathrm{H}} \sim 0.1$. Hence for all practical purposes we can rule out α_{H}.

Gravitational Wave Dispersion

- For generic c_s, the coupling affects the dispersion of GW's.

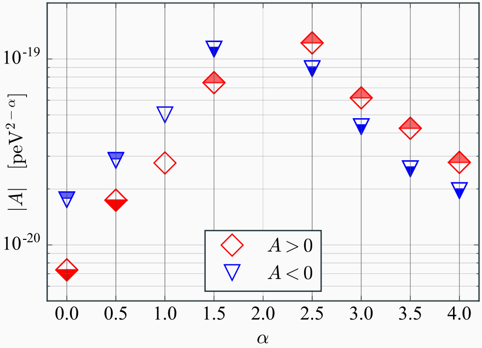


- Similar to a (frequency-dependent) refractive index in a material.
  - The modified dispersion relation for GW's is

$$\omega^2 = \boldsymbol{k}^2 - \left(\frac{\alpha_{\mathrm{H}}}{\Lambda_3^3}\right)^2 \frac{\boldsymbol{k}^8(1-c_s^2)^2}{480\pi^2 c_s^7} \log\left(-(1-c_s^2)\frac{\boldsymbol{k}^2}{\mu_0^2} - i\epsilon\right)$$

Gravitational Wave Dispersion

- Bounds from LIGO constrain α_{H} as strongly as the decay.
- They also constrain the case $c_s > 1$.



Bounds on the dispersion relation $\omega^2 = \boldsymbol{k}^2 + A\boldsymbol{k}^\alpha$ from GW170104. LIGO Scientific Collaboration *PRL* (2017).

Surviving models

- The landscape of viable DE models is reduced to[4] (modulo DHOST)

$$\mathscr{L}_{c_T=1}^{\text{no decay}} = G_2(\phi, X) + G_3(\phi, X)\Box\phi + f(\phi)R$$

- Also $G_3(\phi, X)$ gives a GW decay but suppressed by $(\Lambda_3/\Lambda_2)^4 \sim 10^{-40}$

$$X\,\Box\phi \supset \dot{\phi}_0\dot{\pi}\gamma_{ij}\partial_i\partial_j\pi$$

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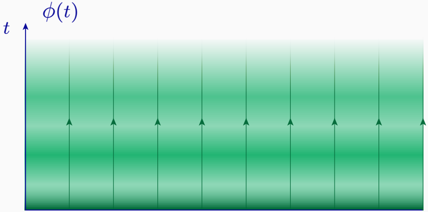
[4] P. Creminelli, M. Lewandowski, GT, F. Vernizzi, 1809.03484

Future constraints

- Realistic GW's have large occupation numbers $\gamma_{ij} \sim \epsilon^{\sigma}_{ij} |h^{\sigma}| \cos(\omega(t - z))$
- The π's produced by the small decay fill the phase-space quickly $\Longrightarrow$ Bose enhancement

- Analogous to inflaton decay during *preheating*: parametric resonance.
- Oscillations are along a null direction $t - z$.



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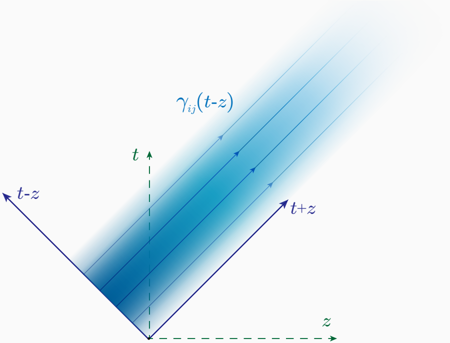

Conclusions

Conclusions and open questions

- After GW170817, *five* coefficients of the EFT are removed.
- Spontaneous breaking of Lorentz invariance allows for GW decay.
- Bounds on GW decay and dispersion set to zero additional terms.
- Can $G_3(\phi, X)$ be ruled out as well?

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Thank you for listening