Paolo Creminelli, ICTP (Trieste)

Dark Energy after GW170817

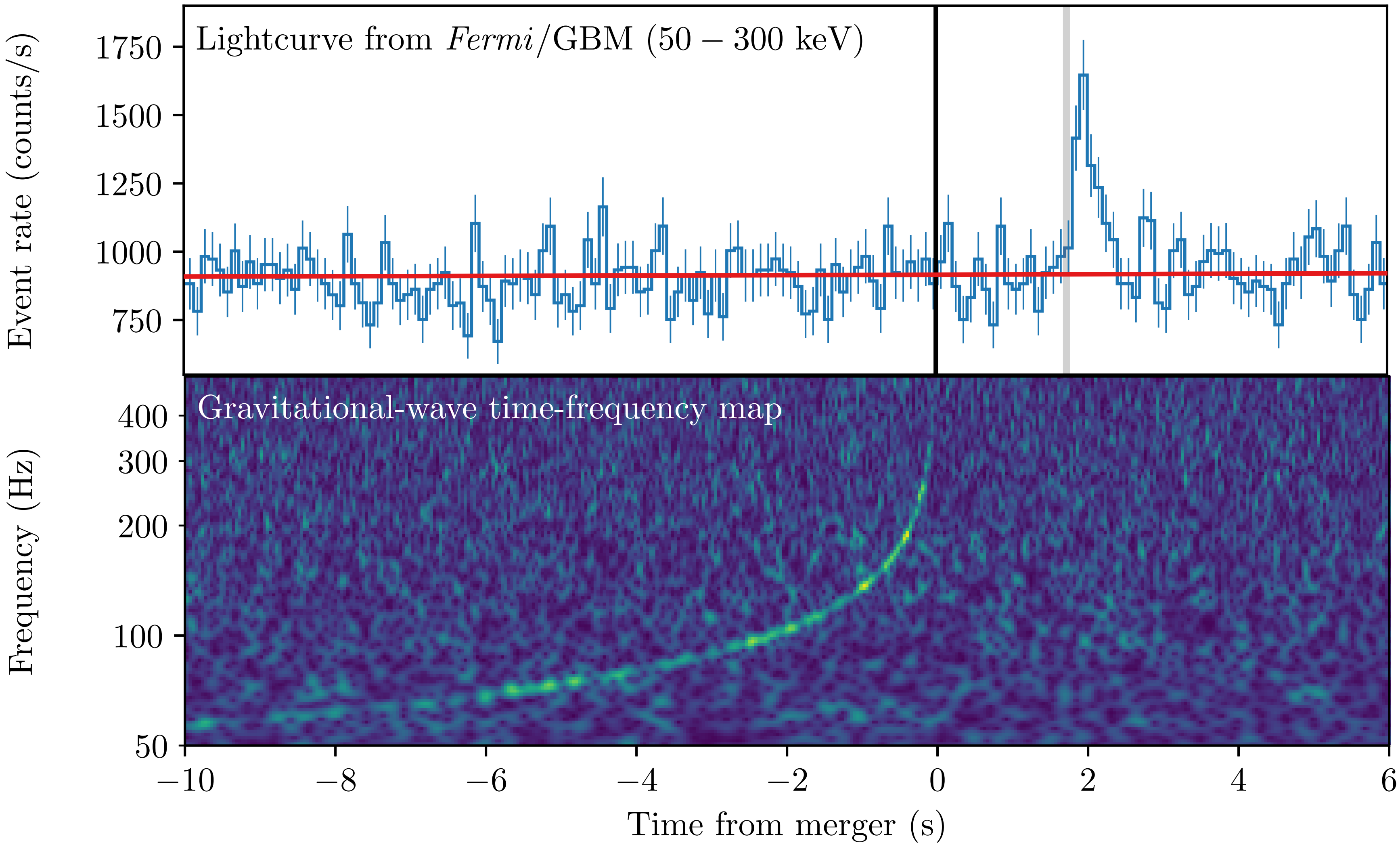
with Filippo Vernizzi, 1710.05877

+ work in progress with M. Lewandowski, G. Tambalo and F. Vernizzi

(see also Sakstein, Jain 1710.05893, Ezquiaga, Zumalacarregui 1710.05901, Baker etal 1710.06394)

Niš, 11 June 2018

GW170817 = GRB170817A



GW170817 = GRB170817A

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

- Previous tight limit for GWs slower than light, Cherenkov radiation

  One-sided and only valid for high energy

- Low energy: $\omega^{-1} \sim$ 10 000 km

  Reasonable one can use the same EFT one has on cosmo scales

- Over ~ cosmological distances: 40 Mpc

  Screening can (probably) be neglected

The Universe accelerates

$$\Lambda$$

Dark Energy = Lorentz violating Medium

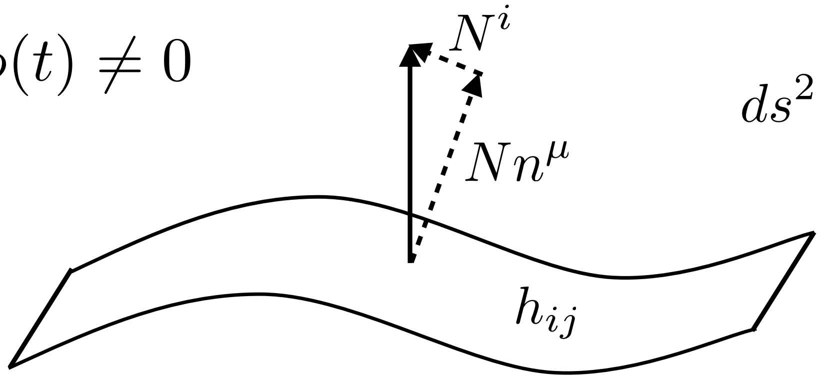
In general the speed of GWs is different from photons

EFT for Dark Energy

PC, Luty, Nicolis, Senatore 03
+ Vernizzi, Piazza + many others

Parametrization of possible deviation from CC

$$\dot{\phi}(t) \neq 0$$



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

$$S = \int d^4x \sqrt{-g} L[t; N, K^i_j, {}^{(3)}R^i_j, \ldots]$$

Action contains all possible scalars under spatial diffs, ordered by number of perturbations and derivatives

Assume universal metric coupled to SM and DM

EFT for Dark Energy

Focus on theories with second order EOM

$$S=\int d^4x\sqrt{-g}\Big[\frac{M_*^2}{2}f^{(4)}R-\Lambda-cg^{00}+\frac{m_2^4}{2}(\delta g^{00})^2$$
$$-\frac{m_3^3}{2}\,\delta K\delta g^{00}-m_4^2\delta\mathcal{K}_2+\frac{\tilde{m}_4^2}{2}\,\delta g^{00}R-\frac{m_5^2}{2}\delta g^{00}\delta\mathcal{K}_2$$
$$-\frac{m_6}{3}\delta\mathcal{K}_3-\tilde{m}_6\delta g^{00}\delta\mathcal{G}_2-\frac{m_7}{3}\delta g^{00}\delta\mathcal{K}_3\Big]\,.$$

$$\delta\mathcal{K}_2\equiv\delta K^2-\delta K_\mu^\nu\delta K_\nu^\mu\,,\qquad \delta\mathcal{G}_2\equiv\delta K_\mu^\nu R_\nu^\mu-\delta KR/2\,,$$
$$\delta\mathcal{K}_3\equiv\delta K^3-3\delta K\delta K_\mu^\nu\delta K_\nu^\mu+2\delta K_\mu^\nu\delta K_\rho^\mu\delta K_\nu^\rho\,.$$

$m_2^4=\alpha_K H^2 M_*^2$ For LSS we are interested in the regime α ~ 0.1

EFT for Dark Energy

Quintessence and Brans-Dicke

Speed of sound of DE

DGP and braiding

$$S = \int d^4x \sqrt{-g} \left[\frac{M_*^2}{2} f^{(4)} R - \Lambda - c g^{00} + \frac{m_2^4}{2} (\delta g^{00})^2 - \frac{m_3^3}{2} \delta K \delta g^{00} - m_4^2 \delta \mathcal{K}_2 + \frac{\tilde{m}_4^2}{2} \delta g^{00} R - \frac{m_5^2}{2} \delta g^{00} \delta \mathcal{K}_2 - \frac{m_6}{3} \delta \mathcal{K}_3 - \tilde{m}_6 \delta g^{00} \delta \mathcal{G}_2 - \frac{m_7}{3} \delta g^{00} \delta \mathcal{K}_3 \right] .$$

$$\delta \mathcal{K}_2 \equiv \delta K^2 - \delta K_\mu^\nu \delta K_\nu^\mu \,, \qquad \delta \mathcal{G}_2 \equiv \delta K_\mu^\nu R_\nu^\mu - \delta K R/2 \,,$$

$$\delta \mathcal{K}_3 \equiv \delta K^3 - 3 \delta K \delta K_\mu^\nu \delta K_\nu^\mu + 2 \delta K_\mu^\nu \delta K_\rho^\mu \delta K_\nu^\rho \,.$$

EFT for Dark Energy

Galileon, Horndeski and Beyond Horndeski

$$S = \int d^4x \sqrt{-g} \Big[\frac{M_*^2}{2} f^{(4)}R - \Lambda - c g^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2} \delta K \delta g^{00} - m_4^2 \delta \mathcal{K}_2 + \frac{\tilde{m}_4^2}{2} \delta g^{00} R - \frac{m_5^2}{2} \delta g^{00} \delta \mathcal{K}_2 - \frac{m_6}{3} \delta \mathcal{K}_3 - \tilde{m}_6 \delta g^{00} \delta \mathcal{G}_2 - \frac{m_7}{3} \delta g^{00} \delta \mathcal{K}_3 \Big] .$$

Non-linear terms, screening

$$\delta \mathcal{K}_2 \equiv \delta K^2 - \delta K_\mu^\nu \delta K_\nu^\mu , \qquad \delta \mathcal{G}_2 \equiv \delta K_\mu^\nu R_\nu^\mu - \delta K R/2 ,$$

$$\delta \mathcal{K}_3 \equiv \delta K^3 - 3 \delta K \delta K_\mu^\nu \delta K_\nu^\mu + 2 \delta K_\mu^\nu \delta K_\rho^\mu \delta K_\nu^\rho .$$

Horndeski: most generic theory with 2nd order EOM

Beyond Horndeski: terms with more than 2 derivatives, but they cancel

$$\tilde{m}_4^2 = m_4^2 \qquad \tilde{m}_6 = m_6$$

Some examples

$$-\frac{m_3^3}{2}\,\delta K \delta g^{00}$$

Braiding, the scalar mixes with gravity

Deffayet, Pujolas, Sawicki, Vikman 10

$$\delta g^{00} \to -2(\dot\pi - \Phi)\ , \qquad \delta K \to -(3\dot\Psi + a^{-2}\nabla^2\pi)$$

Different from usual Brans-Dicke, e.g. $\Phi = \Psi$

$$+\frac{\tilde m_4^2}{2}\,\delta g^{00} R$$

Kinetic matter mixing

Kobayashi, Watanabe, Yamauchi 14

$$\mathcal{L} = \frac{1}{2}\left\{\left(1+\frac{c_s^2}{c_{\rm m}^2}\lambda^2\right)\dot\pi_{\rm c}^2 - c_s^2(\nabla\pi_{\rm c})^2 + \dot v_{\rm c}^2 - c_{\rm m}^2(\nabla v_{\rm c})^2 + 2\frac{c_s}{c_{\rm m}}\lambda\,\dot v_{\rm c}\,\dot\pi_{\rm c}\right\}$$

Modifications inside matter:
violation of Vainshtein screening

$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = G_{\rm N}\left(\frac{\mathcal{M}}{r^2} - \epsilon\frac{\mathrm{d}^2\mathcal{M}}{\mathrm{d}r^2}\right)$$

EFT for Dark Energy

This term changes the speed of GWs

$$S = \int d^4x \sqrt{-g} \left[\frac{M_*^2}{2} f^{(4)} R - \Lambda - c g^{00} + \frac{m_2^4}{2} (\delta g^{00})^2 - \frac{m_3^3}{2} \delta K \delta g^{00} - m_4^2 \delta \mathcal{K}_2 + \frac{\tilde{m}_4^2}{2} \delta g^{00} R - \frac{m_5^2}{2} \delta g^{00} \delta \mathcal{K}_2 - \frac{m_6}{3} \delta \mathcal{K}_3 - \tilde{m}_6 \delta g^{00} \delta \mathcal{G}_2 - \frac{m_7}{3} \delta g^{00} \delta \mathcal{K}_3 \right] .$$

$$\dot{\gamma}_{ij}^2 \subset \quad \delta \mathcal{K}_2 \equiv \delta K^2 - \delta K_\mu^\nu \delta K_\nu^\mu , \qquad \delta \mathcal{G}_2 \equiv \delta K_\mu^\nu R_\nu^\mu - \delta K R/2 ,$$

$$\delta \mathcal{K}_3 \equiv \delta K^3 - 3 \delta K \delta K_\mu^\nu \delta K_\nu^\mu + 2 \delta K_\mu^\nu \delta K_\rho^\mu \delta K_\nu^\rho .$$

One can modify a bit the solution, say
changing DM abundance. Background for: $\delta g^{00}_{\rm bkgd} \qquad \delta K_{\rm bkgd} \sim \delta H$

EFT for Dark Energy

$$S = \int d^4x\sqrt{-g}\left[\frac{M_*^2}{2}f^{(4)}R - \Lambda - cg^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 - \frac{m_3^3}{2}\,\delta K\delta g^{00} - m_4^2\delta\mathcal{K}_2 + \frac{\tilde{m}_4^2}{2}\,\delta g^{00}R - \frac{m_5^2}{2}\delta g^{00}\delta\mathcal{K}_2 - \frac{m_6}{3}\delta\mathcal{K}_3 - \tilde{m}_6\delta g^{00}\delta\mathcal{G}_2 - \frac{m_7}{3}\delta g^{00}\delta\mathcal{K}_3\right].$$

= 0 Horndeski

=

$$\dot{\gamma}_{ij}^2 \subset \quad \delta\mathcal{K}_2 \equiv \delta K^2 - \delta K_\mu^\nu \delta K_\nu^\mu\,, \qquad \delta\mathcal{G}_2 \equiv \delta K_\mu^\nu R_\nu^\mu - \delta K R/2\,,$$

$$\delta\mathcal{K}_3 \equiv \delta K^3 - 3\delta K\delta K_\mu^\nu \delta K_\nu^\mu + 2\delta K_\mu^\nu \delta K_\rho^\mu \delta K_\nu^\rho\,.$$

Covariant theory

Horndeski 74
Gleyzes, Langlois, Piazza, Vernizzi 14

$$S = \int d^4x \sqrt{-g} \sum_I L_I$$

$$L_2 \equiv G_2(\phi, X) , \qquad L_3 \equiv G_3(\phi, X) \Box\phi ,$$

$$L_4 \equiv G_4(\phi, X)\, {}^{(4)}\!R - 2G_{4,X}(\phi, X)(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu})$$

$$+ \underline{F_4(\phi, X)} \varepsilon^{\mu\nu\rho}{}_{\sigma} \varepsilon^{\mu'\nu'\rho'\sigma} \phi_\mu \phi_{\mu'} \phi_{\nu\nu'} \phi_{\rho\rho'} ,$$

Horndeski

Beyond Horndeski

$$L_5 \equiv G_5(\phi, X)\, {}^{(4)}G_{\mu\nu}\phi^{\mu\nu}$$

$$+ \frac{1}{3} G_{5,X}(\phi, X)(\Box\phi^3 - 3\Box\phi\, \phi_{\mu\nu}\phi^{\mu\nu} + 2\, \phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}{}_{\sigma})$$

$$+ \underline{F_5(\phi, X)} \varepsilon^{\mu\nu\rho\sigma} \varepsilon^{\mu'\nu'\rho'\sigma'} \phi_\mu \phi_{\mu'} \phi_{\nu\nu'} \phi_{\rho\rho'} \phi_{\sigma\sigma'} ,$$

Constraint: $X G_{5,X} F_4 = 3F_5 \left[G_4 - 2X G_{4,X} - (X/2) G_{5,\phi} \right]$

$c_T = 1$ $\quad m_4^2 = X^2 F_4 - 3H\dot{\phi} X^2 F_5 - \left[2X G_{4,X} + X G_{5,\phi} + \left(H\dot{\phi} - \ddot{\phi} \right) X G_{5,X} \right] = 0$

⟹ $\quad G_{5,X} = 0 , \qquad F_5 = 0 , \qquad 2G_{4,X} - X F_4 + G_{5,\phi} = 0$

$$L_{c_T=1} = G_2(\phi, X) + G_3(\phi, X)\Box\phi + B_4(\phi, X)\, {}^{(4)}\!R$$

$$- \frac{4}{X} B_{4,X}(\phi, X)(\phi^\mu \phi^\nu \phi_{\mu\nu} \Box\phi - \phi^\mu \phi_{\mu\nu} \phi_\lambda \phi^{\lambda\nu}) ,$$

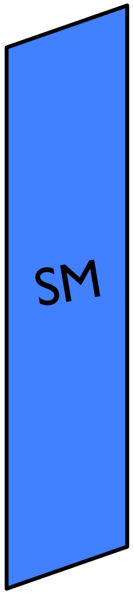
Why consider so complicated theories??

To modify gravity one has to introduce extra dof

Scalars will play with the graviton through $\partial_\mu \partial_\nu \pi$

- Massive gravity. Longitudinal mode $g_{\mu\nu} \supset \partial_\mu \partial_\nu \pi$ — E.g. De Rham, Gabadadze, Tolley 10

- DGP model



5D Minkowski bulk

Dvali, Gabadadze, Porrati 00

Brane bending mode

$$g_{5\mu} \sim \partial_\mu \pi$$

Actions for scalars with many derivatives
(but 2^{nd} order equations)

Radiative stability

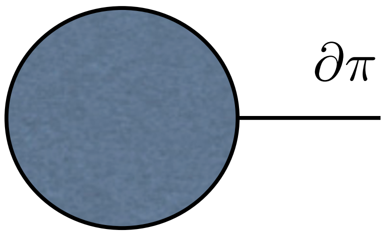
Some operators must be set to zero: is this choice stable?

- Approximate Galilean invariance $\phi \to \phi + b_\mu x^\mu$

$$
\begin{aligned}
\mathcal{L}_3 &= (\partial\phi)^2\ [\Phi]\ , \\
\mathcal{L}_4 &= (\partial\phi)^2\ \left([\Phi]^2 - [\Phi^2]\right)\ , \\
\mathcal{L}_5 &= (\partial\phi)^2\ \left([\Phi]^3 - 3[\Phi][\Phi^2] + 2[\Phi^3]\right)
\end{aligned}
$$

- Non renormalization of Galileons

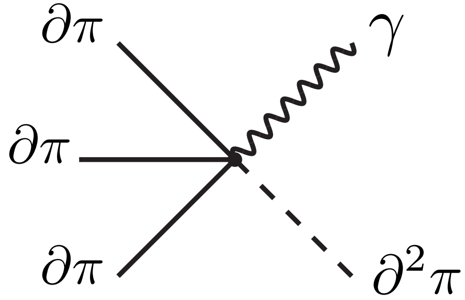
Luty, Porrati, Rattazzi 03



$$\partial^\mu \pi_{\rm ext} \partial_\mu \pi_{\rm int} \Box_4 \pi_{\rm int} = \partial^\mu \pi_{\rm ext} \partial_\nu \left[\partial_\mu \pi_{\rm int} \partial_\nu \pi_{\rm int} - \tfrac{1}{2}\eta_{\mu\nu}\partial^\rho \pi_{\rm int} \partial_\rho \pi_{\rm int}\right]$$

- Broken by gravity

Pirstkhalava, Santoni, Trincherini, Vernizzi 15



The particular coupling giving 2nd order EOM keeps approximate Galilean invariance

Radiative stability

$$\Lambda_3 \sim (M_P H_0^2)^{1/3}$$

$$\Lambda_2 \sim (M_P H_0)^{1/2}$$

$$\mathcal{L}_2^{\rm WBG} = \Lambda_2^4 \; G_2(X) \; ,$$
$$\mathcal{L}_3^{\rm WBG} = \frac{\Lambda_2^4}{\Lambda_3^3} \; G_3(X)[\Phi] \; ,$$
$$\mathcal{L}_4^{\rm WBG} = \frac{\Lambda_2^8}{\Lambda_3^6} \; G_4(X) R + 2 \frac{\Lambda_2^4}{\Lambda_3^6} \; G_{4X}(X) \left([\Phi]^2 - [\Phi^2] \right) \; ,$$
$$\mathcal{L}_5^{\rm WBG} = \frac{\Lambda_2^8}{\Lambda_3^9} \; G_5(X) G_{\mu\nu} \Phi^{\mu\nu} - \frac{\Lambda_2^4}{3\Lambda_3^9} \; G_{5X}(X) \left([\Phi]^3 - 3[\Phi][\Phi^2] + 2[\Phi^3] \right)$$

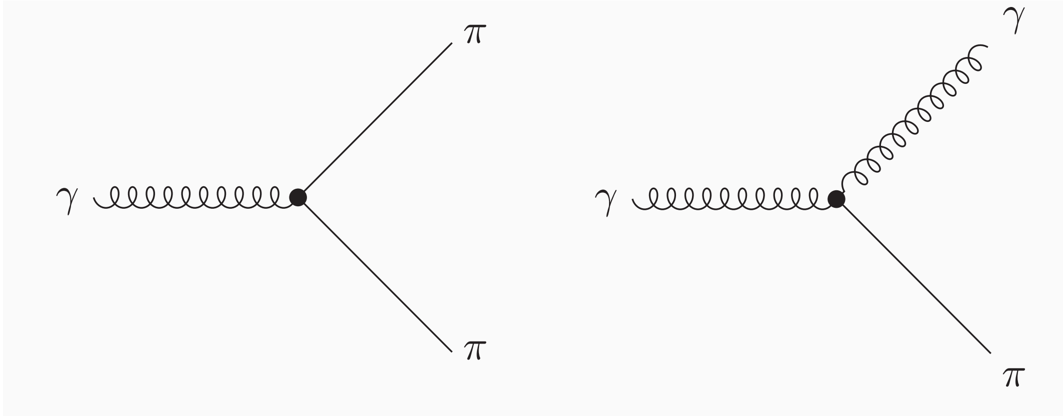
$$\delta c_n \sim (\Lambda_3/\Lambda_2)^4 \sim 10^{-40} \qquad \ll 10^{-15}$$

The tuning is stable

Same holds for Beyond Horndeski theories

Graviton decay into dark energy

The (spontaneous) breaking of Lorentz invariance allows graviton decay



$$\frac{\tilde{m}_4^2}{2}\delta g^{00}\left({}^{(3)}R - \delta\mathcal{K}_2\right)$$

Solving constraints: $$\frac{M_\star^2 \tilde{m}_4^2}{M_\star^2 + 2\tilde{m}_4^2}\int \mathrm{d}^4x\, a\ddot{\gamma}_{ij}\partial_i\pi\partial_j\pi$$

Non-relativistic kinematic: $$\Gamma_\gamma = \frac{p^7(1-c_s^2)^2}{480\pi c_s^7\Lambda^6}$$ $$\Lambda \sim (H_0^2 M_P)^{1/3}$$

$\tilde{m}_4^2$ very constrained: irrelevant for LSS observations
(unless c_s=1 with great precision)

Effect of large γ occupation number in progress (c_s >1?)

Conclusions

- Measurement speed of GWs: dramatic cut in the available DE models
- Future: even more cosmological distances and lower energy
- Further constraints from graviton decay
- Compare with what future LSS mission will do...

$$\Lambda$$

Backup slides

Beyond Beyond Horndeski: DHOST

Even more general theories propagating a single dof

A combination of: $$\int d^4x\sqrt{-g}\frac{M^2}{2}\left(-\frac{2}{3}\alpha_L\delta K^2+4\beta_1\delta KV+\beta_2V^2+\beta_3a_ia^i\right)$$

These do not affect GWs on any background

Can be obtained by: $g_{\mu\nu}\to C(\phi,X)g_{\mu\nu}$

$$\begin{aligned}L_{c_T=1} &= \tilde{B}_2+\tilde{B}_3\Box\phi+CB_4\,{}^{(4)}R-\frac{4CB_{4,X}}{X}\phi^\mu\phi^\nu\phi_{\mu\nu}\Box\phi \\ &+\left(\frac{4CB_{4,X}}{X}+\frac{6B_4C_{,X}{}^2}{C}+8C_{,X}B_{4,X}\right)\phi^\mu\phi_{\mu\nu}\phi_\lambda\phi^{\lambda\nu} \\ &-\frac{8C_{,X}B_{4,X}}{X}(\phi_\mu\phi^{\mu\nu}\phi_\nu)^2\,.\end{aligned}$$