Paolo Creminelli, ICTP (Trieste)

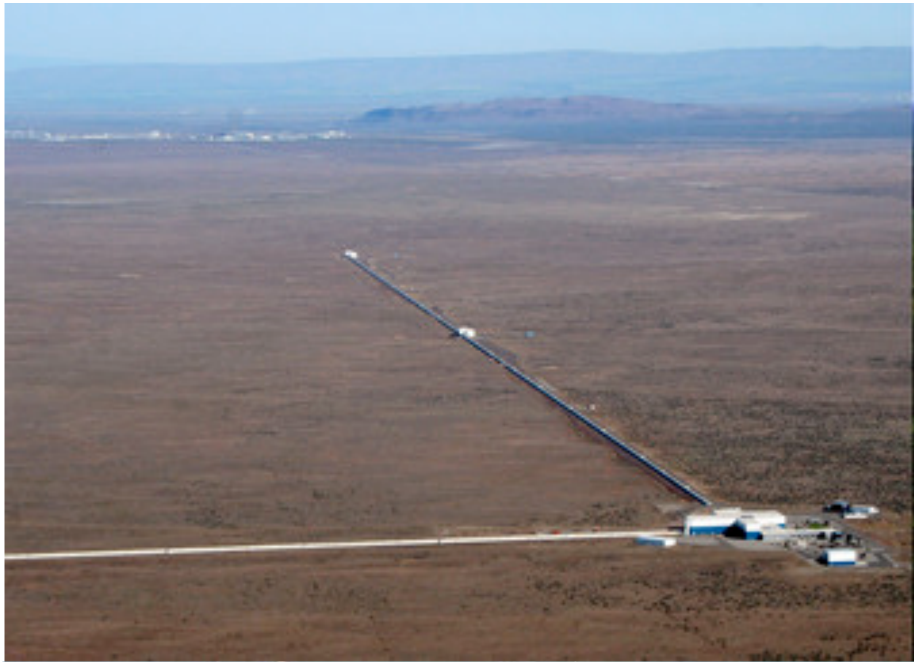
Dark Energy and GW Observations

with F. Vernizzi 1710.05877, with M. Lewandowski, G. Tambalo and F. Vernizzi 1809.03484

with G. Tambalo, F. Vernizzi and V. Yingcharoenrat 1906.07015 + 1910.14035 + ...

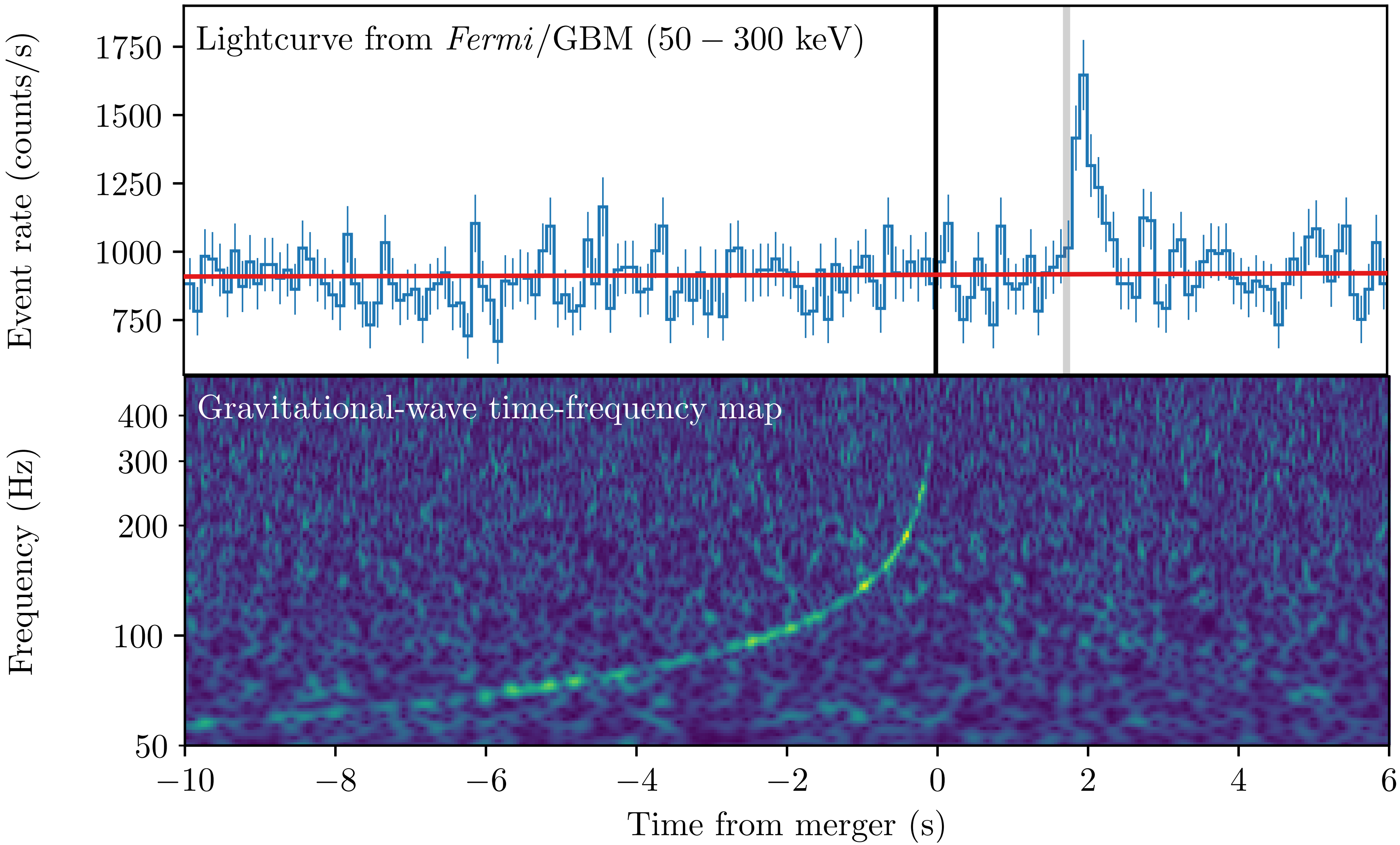
"La Thuile", 9 March 2021

First (direct) GW observation on 14.09.15



The two LIGO detectors (USA)
and VIRGO near Pisa, Italy

GW170817 = GRB170817A



Dark Energy = Lorentz-violating Medium

In general the speed of GWs is different from photons,
GWs can be absorbed, have dispersion...

Use GWs to probe Dark Energy as light probes a material

The (small) elephant in the room

$$\Lambda$$

GW170817 = GRB170817A

$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$$

- Low energy: $\lambda \sim$ 10 000 km

  Reasonable one can use the same EFT as for cosmo scales

- Over ~ cosmological distances: 40 Mpc

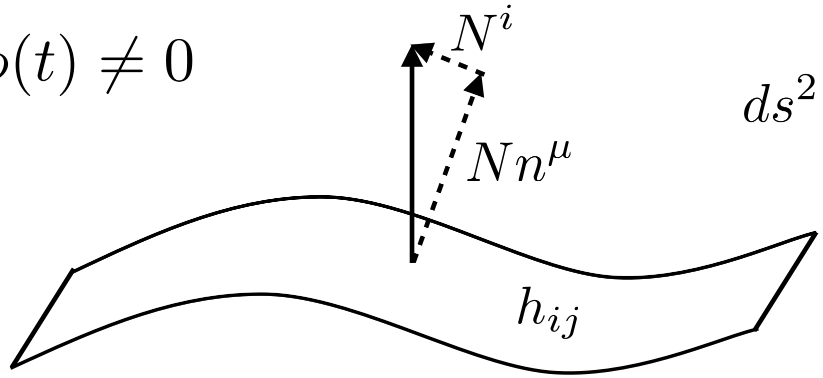
  Screening can (probably) be neglected

EFT of Dark Energy

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

Parametrization of possible deviations from CC

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



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

$$S = \int d^4x \sqrt{-g} L[t; N, K^i_j, {}^{(3)}R^i_j, \ldots] \qquad g^{00} = -N^{-2}$$

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

Assume universal metric coupled to SM and DM

EFT of Dark Energy

Focus on theories with second order EOM

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

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

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

EFT of 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 of Dark Energy

Galileon, Horndeski and Beyond Horndeski

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

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 $\tilde m_4^2 = m_4^2 \qquad \tilde m_6 = m_6$

Beyond Horndeski: more than 2 derivatives, but degenerate with no ghost

EFT of Dark Energy

This term changes the speed of GWs

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

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

Experiment also probes propagation in a perturbed universe

EFT of Dark Energy

see also Sakstein, Jain 17, Ezquiaga, Zumalacarregui 17, Baker etal 17, Copeland etal 18

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

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

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

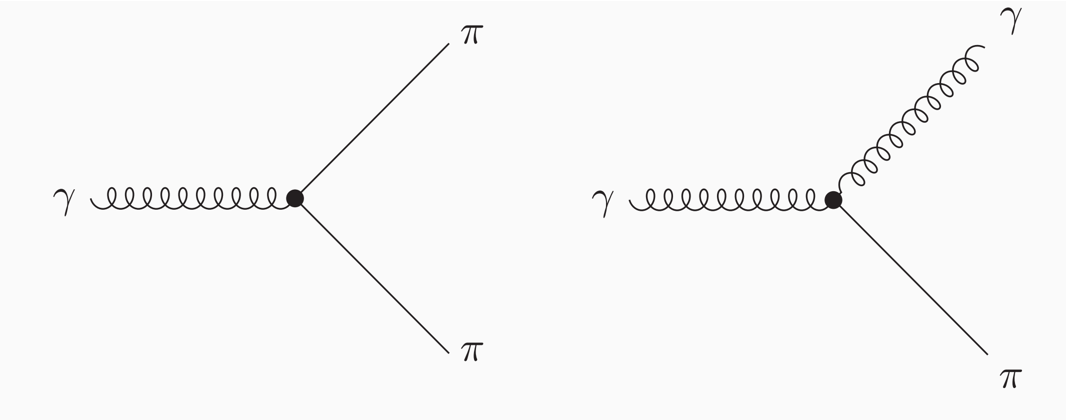
$$
\alpha_{\rm B} \equiv -\frac{m_3^3}{2M_{\rm Pl}^2 H} \qquad \alpha_{\rm H} \equiv \frac{2\tilde m_4^2}{M_{\rm Pl}^2}
$$

For LSS we are interested in the regime α ~ 0.1

Graviton decay into dark energy

Light is also absorbed as it travels in a material

The (spontaneous) breaking of Lorentz invariance allows graviton decay



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

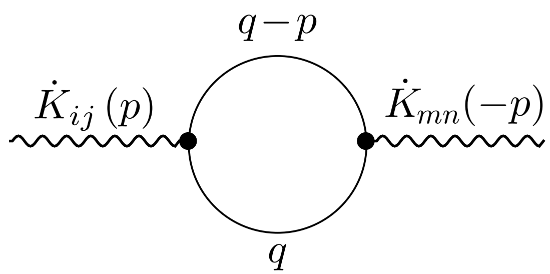
Solving constraints: $\dfrac{M_\star^2\tilde{m}_4^2}{M_\star^2+2\tilde{m}_4^2}\int \mathrm{d}^4x\, a\ddot{\gamma}_{ij}\partial_i\pi\partial_j\pi$

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

$\alpha_{\rm H} \equiv \dfrac{2\tilde{m}_4^2}{M_{\rm Pl}^2} \lesssim 10^{-10}$ irrelevant for LSS observations (unless c_s=1 with great precision)

Higher-derivative terms and dispersion

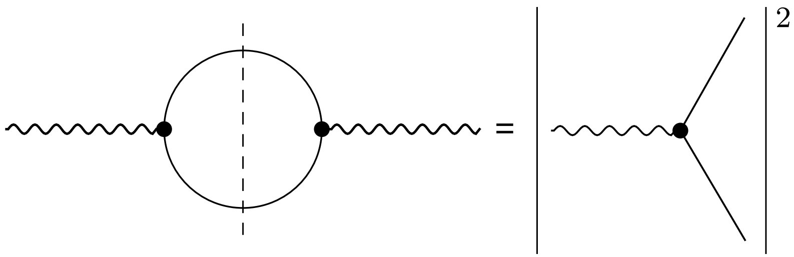
Loops generate higher-derivative corrections



$$S_{\rm eff} = \frac{M_{\rm Pl}^2}{480\pi^2\Lambda_*^6 c_s^7}\int \frac{{\rm d}^4 p}{(2\pi)^4}\bar{p}^4 \dot{K}_{ij}(p)\dot{K}_{ij}(-p)\left[\frac{1}{\varepsilon}+\frac{23}{15}-\frac{\gamma_{\rm E}}{2}-\frac{1}{2}\log\left(\frac{\bar{p}^2}{4\pi c_s^2\mu^2}-i\epsilon\right)\right]$$

$$\omega^2 = \boldsymbol{k}^2 - \frac{\boldsymbol{k}^8(1-c_s^2)^2}{480\pi^2\Lambda_*^6 c_s^7}\log\left(-(1-c_s^2)\frac{\boldsymbol{k}^2}{\mu_0^2}-i\epsilon\right)$$

It applies to $c_s > 1$ as well. For $c_s = 1$ one still has power divergences

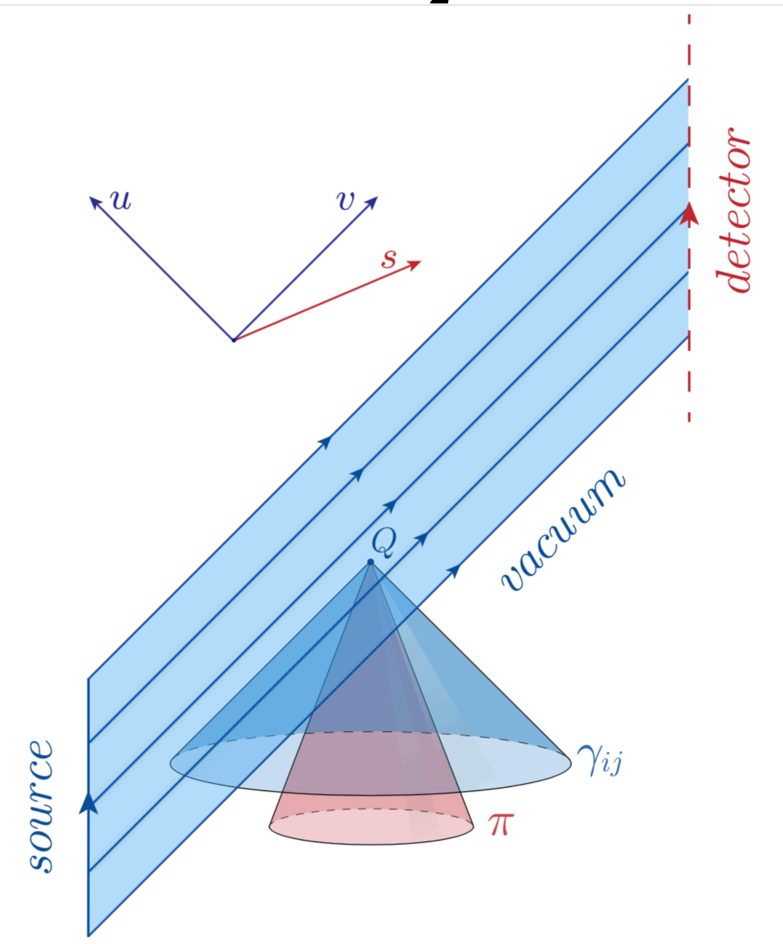


It is inconsistent to look at Horndeski only

Coherent decay

The decay of γ enhanced by the large occupation number of GW
~ preheating

$$\mathcal{L}_{m_3} = -\frac{1}{2}\sqrt{-g}\; m_3^3 \delta K \delta g^{00}$$



$$\ddot{\pi} - c_s^2 \nabla^2 \pi + \frac{2}{\Lambda^2} \dot{\gamma}^{ij} \partial_i \partial_j \pi = 0$$

$$\ddot{\pi} - c_s^2 \nabla^2 \pi + c_s^2 \beta \cos[\omega(t-z)](\partial_x^2 - \partial_y^2)\pi = 0$$

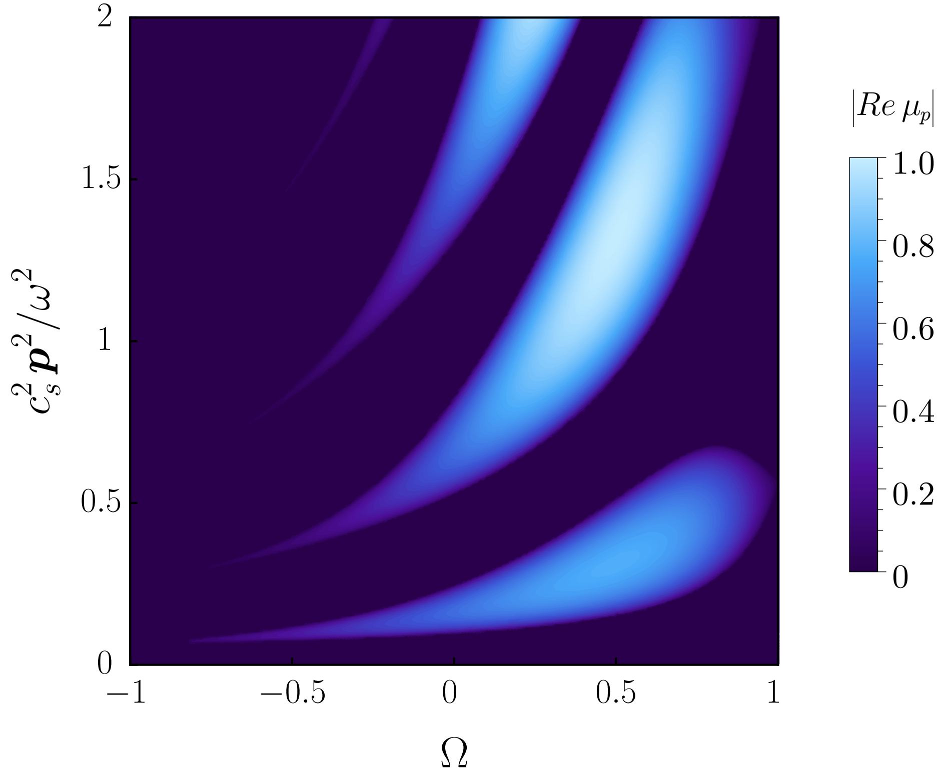
$$\beta \equiv \frac{2\omega M_{\rm Pl} h_0^+}{c_s^2 |\Lambda^2|}$$

$$u = t - z\,, \qquad s = -t + c_s^{-2} z\,, \qquad v = t + z$$

Similar to a Mathieu equation:
parametric resonance

Narrow resonance (β << 1)

$$\frac{\mathrm{d}^2}{\mathrm{d}\tau^2}\varphi + [A - 2q\cos(2\tau)]\varphi = 0 \qquad \tau \equiv \frac{\omega u}{2}$$



$$A = 4\frac{c_s^2\,\boldsymbol{p}^2}{\omega^2}\frac{(1-c_s\Omega)^2}{(1-c_s^2)^2} = \frac{4p_u^2}{\omega^2}\,,$$

$$q = 2\beta\frac{c_s^2\,\boldsymbol{p}^2}{\omega^2}\frac{(1-\Omega^2)\cos(2\phi)}{1-c_s^2}\,.$$

Backreaction on γ

$$\ddot{\gamma}_{ij} - \nabla^2\gamma_{ij} + \frac{2}{\Lambda^2}\Lambda_{ij,kl}\partial_t\left(\partial_k\pi\partial_l\pi\right) = 0$$

Saddle point

$$J(\tau) = \int g(X) e^{\tau f(X)} \mathrm{d}^3 X \qquad\qquad J(\tau) \approx \frac{1}{\sqrt{\det(-\partial_i \partial_j f(X_0))}} \left(\frac{2\pi}{\tau}\right)^{3/2} g(X_0) e^{\tau f(X_0)}$$

$$\Delta\gamma_{ij}(u,v) \simeq -\frac{v}{4\Lambda^2} \frac{(1-c_s^2)^2}{c_s^5 \sqrt{\beta}} \frac{\omega^{5/2}}{(8u\pi)^{3/2}} \sin\left(\omega u + \frac{\beta}{2}\right) \exp\left(\frac{\beta}{4}\omega u\right) \epsilon_{ij}^{+}$$

- Generalize the perturbative formula
- At higher order in β one gets harmonics.
  They enter in the obs window before: precursors

π interactions

BUT one expects the exp growth is quenched when π self-interactions are relevant

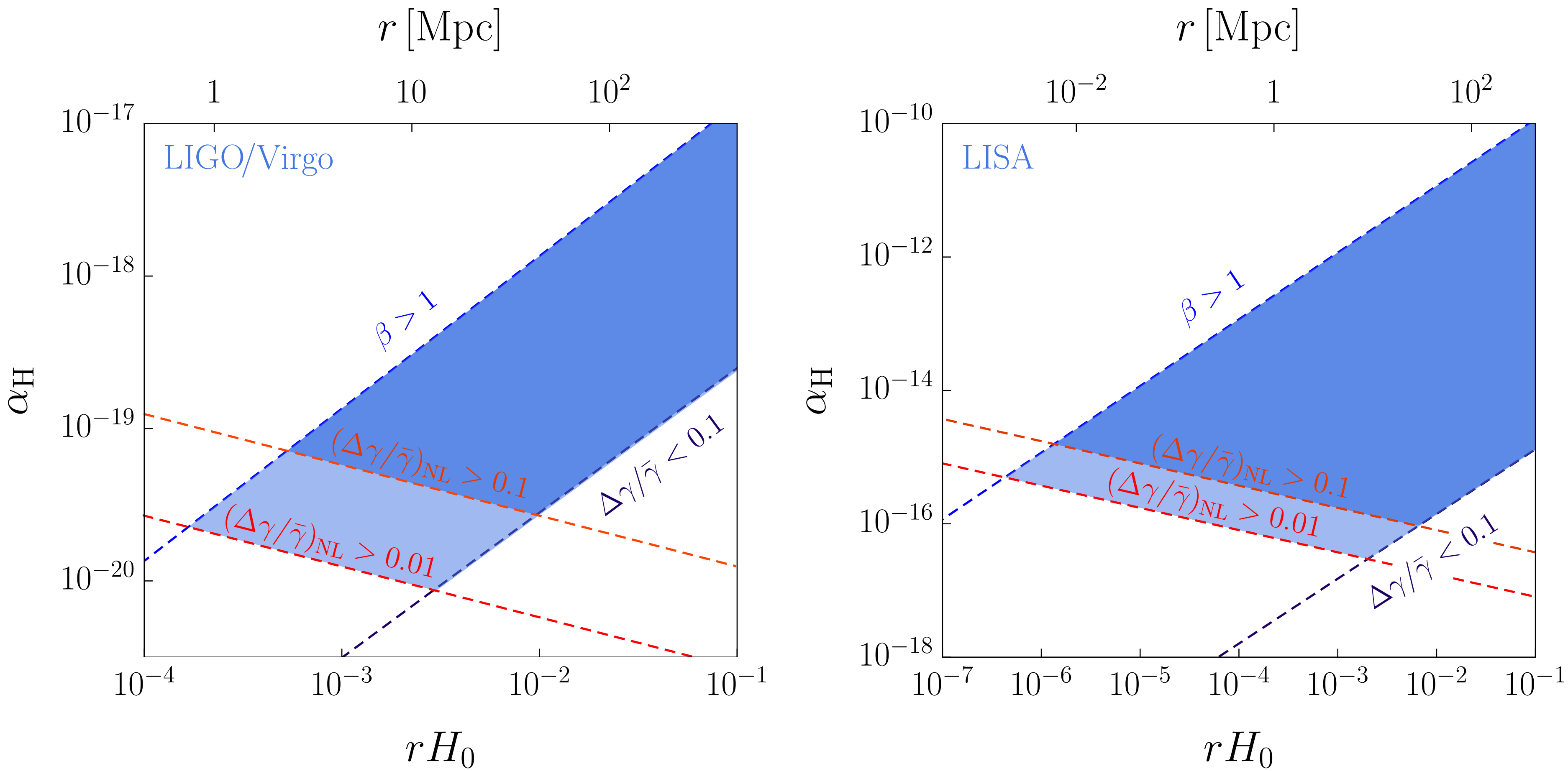
$$\frac{1}{\Lambda_3^3}\nabla^2\pi(\partial\pi)^2 \qquad \text{VS} \qquad \frac{1}{\Lambda_2^2}\dot{\gamma}_{ij}\partial_i\pi\partial_j\pi$$

- Kills the effect!? Simulations ~ preheating
- For $\tilde{m}_4^2$ self-interactions are small: same scale $\Lambda_\star \gg \Lambda_3$

On saddle point, accidental cancellation due to Galileon structure

$$\frac{\Delta\gamma}{\bar{\gamma}} \sim \frac{v\,\omega(\partial_i\pi)^2}{\Lambda_*^3 M_{\rm Pl} h_0^+} \lesssim \beta c_s^3\alpha(vH_0)\frac{H_0}{\omega h_0^+}\sqrt{\beta\tau}$$

GW modification



f = 30 Hz, M_c = 1.2 M_{sun}

f = 10^{-2} Hz, M_c = 30 M_{sun}

Perturbative bound: $\alpha_H < 10^{-10}$

β>1: π instability

$$\ddot{\pi} - c_s^2\nabla^2\pi + c_s^2\beta\cos[\omega(t-z)](\partial_x^2 - \partial_y^2)\pi = 0$$ Gradient instability

- Generically present for m_3 (but π non-linearities must be considered)

- To be constrasted with non-linear stability of cubic Galileon

Nicolis Rattazzi 04

$$\mathscr{L}_{(2)} = Z^{\mu\nu}\partial_\mu\pi\partial_\nu\pi$$

Eom imply eigenvalues of the matrix $Z^{\mu\nu}$ do not flip sign

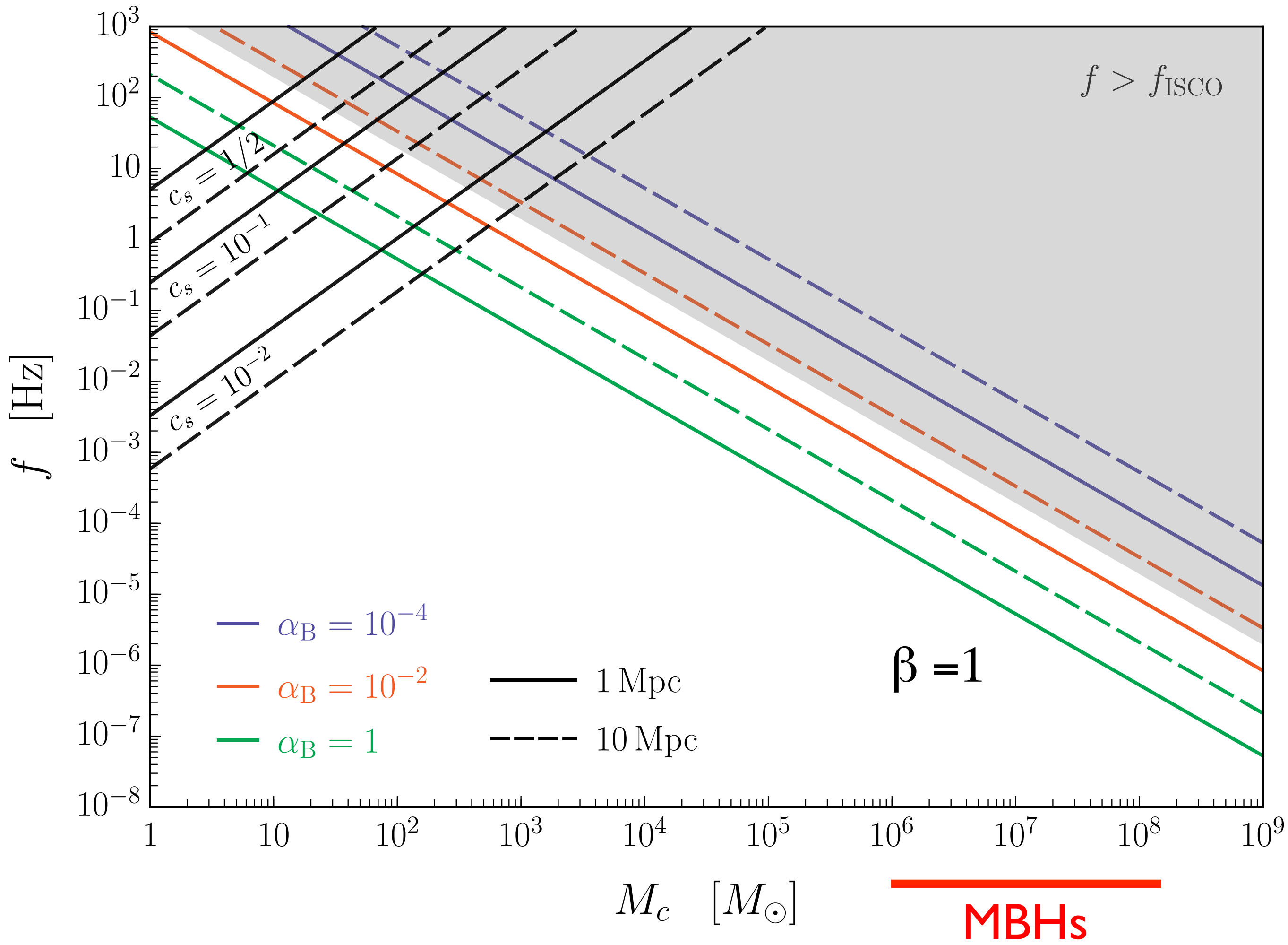
- Fate of instability is UV sensitive. Does it affect GWs?

But in general the system finds a new vacuum with a different EFT

Instability triggered by binaries

$$\beta \equiv \frac{2\omega M_{\rm Pl} h_0^+}{c_s^2|\Lambda^2|} = \frac{2\sqrt{2}|\alpha_{\rm B}|}{\alpha c_s^2}\frac{\omega}{H}h_0^+ \sim 1$$

For typical LIGO-Virgo event



Population of MBHs is enough to globally trigger the instability

Down to 10^{10} km

Conclusions

GWs probe Dark Energy as light probes a material

In many cases better than what LSS can do

- Speed of GWs
- Perturbative graviton decay and dispersion
- Resonant graviton decay
- Instability due to GW

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

$$\Lambda$$

Backup slides

Covariant theory

Horndeski 74
Gleyzes, Langlois, Piazza, Vernizzi 14

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

Horndeski
Beyond Horndeski

$$L_2 \equiv G_2(\phi,X)\,, \qquad L_3 \equiv G_3(\phi,X)\Box\phi\,,$$
$$L_4 \equiv G_4(\phi,X)\,{}^{(4)}R - 2G_{4,X}(\phi,X)(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu})$$
$$+ \underline{F_4(\phi,X)}\varepsilon^{\mu\nu\rho}{}_{\sigma}\,\varepsilon^{\mu'\nu'\rho'\sigma}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\,,$$
$$L_5 \equiv G_5(\phi,X)\,{}^{(4)}G_{\mu\nu}\phi^{\mu\nu}$$
$$+\frac{1}{3}G_{5,X}(\phi,X)(\Box\phi^3 - 3\Box\phi\,\phi_{\mu\nu}\phi^{\mu\nu} + 2\,\phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}{}_{\sigma})$$
$$+ \underline{F_5(\phi,X)}\varepsilon^{\mu\nu\rho\sigma}\varepsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}\,,$$

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

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

$$\Longrightarrow \quad G_{5,X} = 0\,, \qquad F_5 = 0\,, \qquad 2G_{4,X} - XF_4 + G_{5,\phi} = 0$$

$$L_{c_T=1} = G_2(\phi,X) + G_3(\phi,X)\Box\phi + B_4(\phi,X)\,{}^{(4)}R$$
$$-\frac{4}{X}B_{4,X}(\phi,X)(\phi^\mu\phi^\nu\phi_{\mu\nu}\Box\phi - \phi^\mu\phi_{\mu\nu}\phi_\lambda\phi^{\lambda\nu})\,,$$

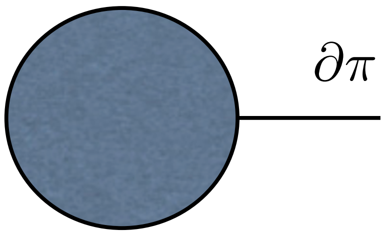
Radiative stability

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

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

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

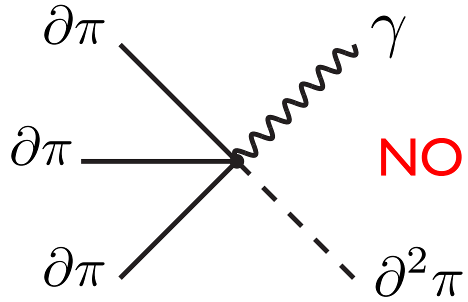
- Non renormalization of Galileons — Luty, Porrati, Rattazzi 03



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

- Broken by gravity — Pirstkhalava, Santoni, Trincherini, Vernizzi 15

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



Radiative stability

$$\Lambda_3 \sim (M_P H_0^2)^{1/3}$$ ~ 1000 km

$$\Lambda_2 \sim (M_P H_0)^{1/2}$$ ~ 0.1 mm

$$\mathcal{L}_2^{\rm WBG} = \Lambda_2^4 \, G_2(X) \; ,$$

$$\mathcal{L}_3^{\rm WBG} = \frac{\Lambda_2^4}{\Lambda_3^3} \, G_3(X)[\Phi] \; ,$$

$$\mathcal{L}_4^{\rm WBG} = \frac{\Lambda_2^8}{\Lambda_3^6} \, G_4(X) R + 2\frac{\Lambda_2^4}{\Lambda_3^6} \, G_{4X}(X) \left([\Phi]^2 - [\Phi^2] \right) \; ,$$

$$\mathcal{L}_5^{\rm WBG} = \frac{\Lambda_2^8}{\Lambda_3^9} \, G_5(X) G_{\mu\nu} \Phi^{\mu\nu} - \frac{\Lambda_2^4}{3\Lambda_3^9} \, G_{5X}(X) \left([\Phi]^3 - 3[\Phi][\Phi^2] + 2[\Phi^3] \right)$$

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

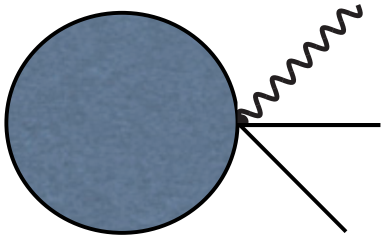
The tuning is stable

Same holds for Beyond Horndeski theories

Santoni, Trincherini, Trombetta

Generic loops

External graviton lines



$$\Lambda_3^4 F\left(\frac{(\partial\phi)^2}{\Lambda_2^4}, \frac{\partial^2\phi}{\Lambda_3^3}, \frac{\gamma^{(c)}}{\Lambda_3}, \frac{\partial}{\Lambda_3}\right)$$

Quartic/quintic Horndeski give large higher derivative terms: not exp viable

Cubic case scales in a different way

$$H M_{\rm Pl}^2 \delta g^{00} \delta K \sim H M_{\rm Pl}^2 \dot{\pi} \partial_i \partial_j \pi \gamma_{ij} \qquad \Lambda_2 \equiv (H_0 M_{\rm Pl})^{1/2}$$

A leg with one derivative must go inside

Caveat

De Rham, Melville 18

We do not really know whether the EFT of cosmological scales applies to LIGO/Virgo

The theory may break down (new states appear) at energy scales parametrically lower than the cut-off (~ 1000 km)

The speed of GWs may go back to 1 at "short" scale

Analogous to : $n(\omega) \simeq 1 + \frac{2\pi N e^2}{m} \frac{f}{\bar{\omega}^2 - \omega^2 - i\bar{\nu}\omega}$

- Naively requires new physics at scales of order 10^8 x 1000 km to satisfy constraints
- How to reconcile with local tests of gravity?
- Can we say something general about the UV completion? ~ Kramers-Kronig?

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. $\Phi = \Psi$

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

Modifications inside matter:
violation of Vainshtein screening

Kobayashi, Watanabe, Yamauchi 14

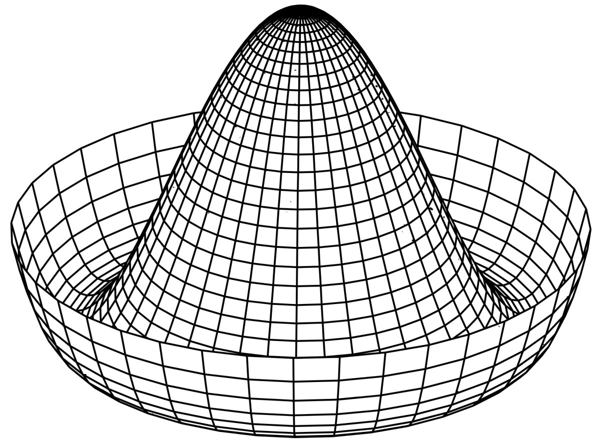
$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = G_{\rm N}\left(\frac{\mathcal{M}}{r^2} - \epsilon \frac{\mathrm{d}^2\mathcal{M}}{\mathrm{d}r^2}\right)$$

D'amico, Huang, Mancarella, Vernizzi 14

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

Kinetic matter mixing

Instabilities in a UV complete model



Spontaneously broken global U(1)

$$\mathscr{L}_{\rm UV} = -|\partial h|^2 - V(|h|)\,, \qquad V(|h|) = \lambda\big(|h|^2 - v^2\big)^2$$

Integrate out radial direction $P(X) \simeq -\frac{1}{4\lambda}\,X\big(\mu^2 - X\big)$

Gradient instabilities for $\frac{1}{6}\mu^2 < \hat{X} < \frac{1}{2}\mu^2$

In UV theory, instability is saturated at μ: stable for k >> μ

Ghost instabilities for $\hat{X} > \frac{1}{2}\mu^2$

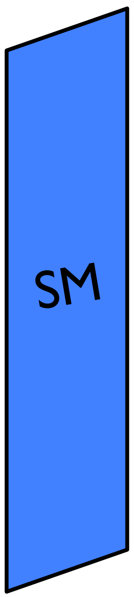
EFT has no applicability: radial mode becomes massless

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 2nd order equations)

Another caveat

Copeland, Kopp, Padilla, Saffin, Skordis 18

We imposed that c_T=1 is robust to changes of H(t) and ϕ(t), but there are possible cancellations that we missed

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

=

The cancellation does not work in the presence of curvature and thus in the perturbed universe

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: $g_{\mu\nu}\to C(\phi,X)g_{\mu\nu}$

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