Cosmological gravity after GW170817 & GRB 170817A

Based on arXiv:1710.06394 (with T. Baker, E. Bellini, P. Ferreira, M. Lagos, I. Sawicki)

Johannes Noller, ETH Zurich

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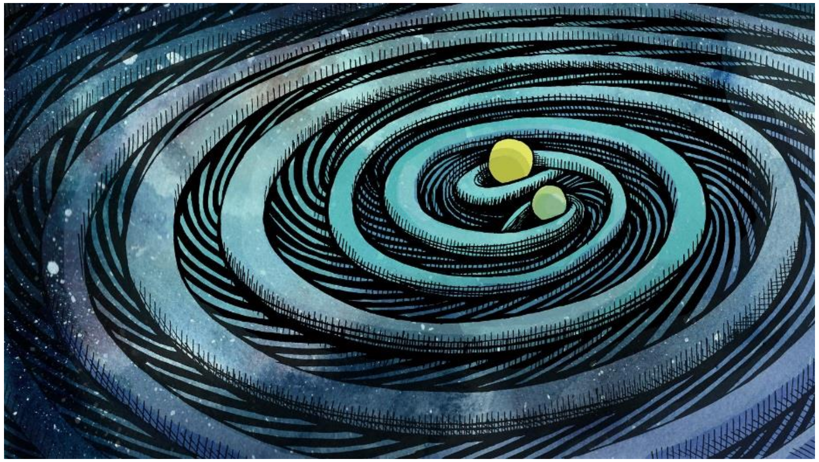
Gravitational waves

$$S_h = \frac{1}{2}\int d^3x dt\, M_*^2 \left[\dot{h}_A^2 - c_T^2 (\nabla h_A)^2\right]$$



- Previous constraints: $-10^{-15} > c_T^2 - 1 > 0.42$.
- New constraints: $|c_T^2 - 1| \lesssim 10^{-15}$.
- c_T^2 depends on structure of full theory.
- New gravitational degrees of freedom can easily lead to $\alpha_T \equiv c_T^2 - 1 \neq 0$.

Moore, Nelson '01
Blas, Ivanov, Sawicki, Sibiryakov '16
Cornish, Blas, Nardini '17

LIGO & Virgo Collaborations '17, Fermi, IGAL '17

Gravitational waves

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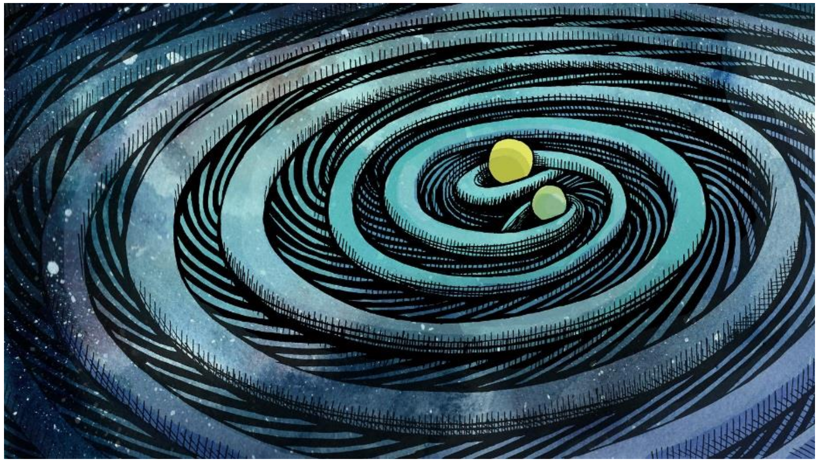

- New gravitational degrees of freedom can easily lead to $\alpha_T \equiv c_T^2 - 1 \neq 0$.
- General Relativity (GR) = massless spin-2.
- Promising alternatives/precision tests of GR.

Scalar-tensor theories

$$\mathcal{L}_2 = G_2, \quad \mathcal{L}_3 = G_3\Box\phi, \quad \mathcal{L}_4 = G_4 R + G_{4,X}\left\{(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right\},$$

$$\mathcal{L}_5 = G_5 G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,X}\left\{(\nabla\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi + 2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\right\}.$$

where $G_i \equiv G_i(\phi, X)$ and $X \equiv -\frac{1}{2}\nabla^\mu\phi\nabla_\mu\phi$

Horndeski theory as the most general ST theory with second order *eoms*

Horndeski '74, Deffayet, Gao, Steer, Zahariade '11

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$$\alpha_T = \frac{2X}{M_*^2}\left[2G_{4,X} - 2G_{5,\phi} - \left(\ddot{\phi} - \dot{\phi}H\right)G_{5,X}\right] = 0$$

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integration-by-parts

no fine-tuning

Scalar-tensor theories

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$$\Downarrow$$

$$\boxed{\mathcal{L} = G_4(\phi)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi}$$

cf. Creminelli, Vernizzi '17, Ezquiaga, Zumalacarregui '17, Sakstein, Jain '17

Scalar-tensor theories

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where $G_i \equiv G_i(\phi, X)$ and $X \equiv -\frac{1}{2}\nabla^\mu\phi\nabla_\mu\phi$

Generalisation to **Beyond Horndeski theories**

Gleyzes, Langlois, Piazza, Vernizzi '14

$$\alpha_T = \frac{2X}{M_*^2}\left[2G_{4,X} - 2G_{5,\phi} - \left(\ddot{\phi} - \dot{\phi}H\right)G_{5,X} - 2\tilde{G}_{4,X} - \dot{\phi}H\tilde{G}_{5,X}\right] = 0$$

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$$\Downarrow$$

$$\boxed{\mathcal{L} = G_4(\phi, X) R + G_2(\phi, X) + G_3(\phi, X) \Box\phi + G_{4,X} \left\{ (\Box\phi)^2 - \nabla_\mu \nabla_\nu \phi \nabla^\mu \nabla^\nu \phi - \tilde{\mathcal{L}}_4 \right\}}$$

Vector-tensor theories

$$\mathcal{L}_2 = G_2(X,F,Y), \qquad \mathcal{L}_3 = G_3(X)\nabla_\mu A^\mu,$$

$$\mathcal{L}_4 = G_4(X)R + G_{4,X}(X)\left[(\nabla_\mu A^\mu)^2 + c_2\nabla_\rho A_\sigma\nabla^\rho A^\sigma - (1+c_2)\nabla_\rho A_\sigma\nabla^\sigma A^\rho\right] ,$$

$$\mathcal{L}_5 = G_5(X)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,X}(X)[(\nabla_\mu A^\mu)^3 - 3d_2\nabla_\mu A^\mu\nabla_\rho A_\sigma\nabla^\rho A^\sigma - 3(1-d_2)\nabla_\mu A^\mu\nabla_\rho A_\sigma\nabla^\sigma A^\rho$$
$$+ (2-3d_2)\nabla_\rho A_\sigma\nabla^\gamma A^\rho\nabla^\sigma A_\gamma + 3d_2\nabla_\rho A_\sigma\nabla^\gamma A^\rho\nabla_\gamma A^\sigma] .$$

where $F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$, $X = -\frac{1}{2}A_\mu A^\mu$, $F = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$, $Y = A^\mu A^\nu F_\mu^\alpha F_{\nu\alpha}$.

Generalised Proca theory as the most general VT theory with second order *eoms*

Tasinato '14, Heisenberg '14, Allys, Peter, Rodriguez '15, Beltran Jimenez, Heisenberg '16

Vector-tensor theories

$$\mathcal{L}_2 = G_2(X, F, Y), \qquad \mathcal{L}_3 = G_3(X)\nabla_\mu A^\mu,$$

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$$\alpha_T = \frac{A^2}{q_T}\left[2G_{4,X} - (HA - \dot{A})G_{5,X}\right] = 0.$$

$$\Downarrow$$

$$\boxed{\mathcal{L} = G_2(X, F, Y) + G_3(X)\nabla_\mu A^\mu + G_4 R + G_5 G_{\mu\nu}\nabla^\mu A^\nu}$$

Tensor-tensor theories

$$\mathcal{S} = \frac{1}{2}M_g^2 \int d^4x\sqrt{-g}R_g + \frac{1}{2}M_f^2 \int d^4x\sqrt{-f}R_f + m^2M^2 \int d^4x\sqrt{-g}V(\sqrt{g^{-1}f})$$

de Rham, Gabadadze '10, de Rham, Gabadadze, Tolley '10, Hassan, Rosen '11

- Direct GW measurements give $m \lesssim 10^{-22}$ eV.

  c.f. LIGO & Virgo Collaborations '16

- (Model-dependent) solar system bounds: $m \lesssim 10^{-33}$ eV.

  de Rham, Deskins, Tolley, Zhou '16

- Different Planck masses can relax bound.

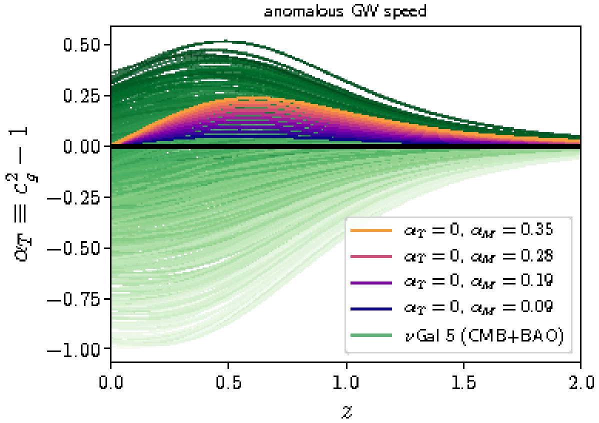
  Max, Platscher, Smirnov '17

- Frequency dependence can produce further signals.

  De Felice, Nakamura, Tanaka '14, Narikawa, Ueno, Tagoshi, Tanaka, Kanda, Nakamura '14, Brax, Davis, JN '17, Max, Platscher, Smirnov '17

Caveats/Outlook

- Only one event so far.
- GW170817 is a low redshift source ($z \sim 0.01$) $\Rightarrow$ constraint on α_T today.
- Dependence on particular ‘path’ of GW170817?

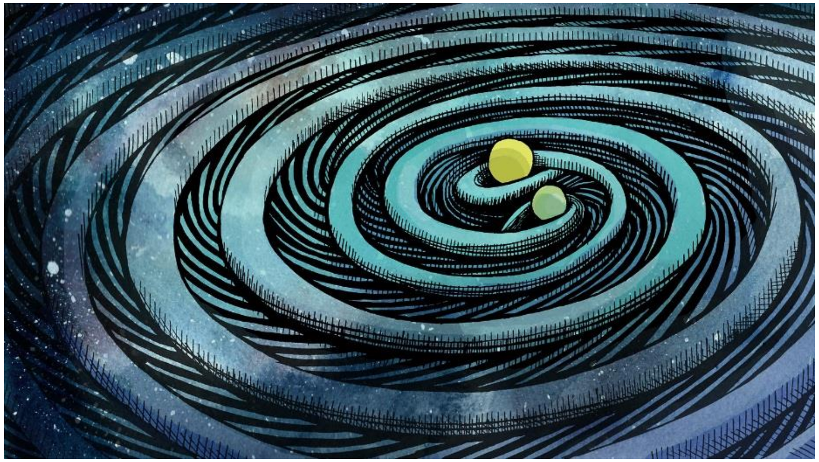


Ezquiaga, Zumalacarregui ’17

- Do ‘surviving’ theories have smoking gun signatures?
- Physics in “1.7 seconds”?

Conclusions

- GW170817 & GRB170817A enormously improve constraints on c_T.
- ST & VT theories significantly constrained, TT theories not.
- Analogous future observations will eliminate degeneracies.



Thank you!