SCUOLA NORMALE SUPERIORE

Gravitational Wave Oscillations in Bigravity

PLANCK 2017

Kevin Max – 24/05/2017

Based on 1703.07785 with Moritz Platscher & Juri Smirnov.

Proposal

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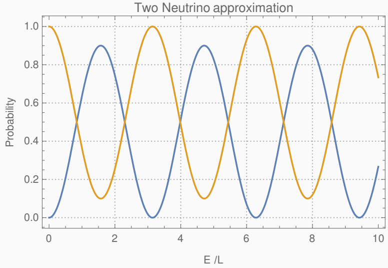

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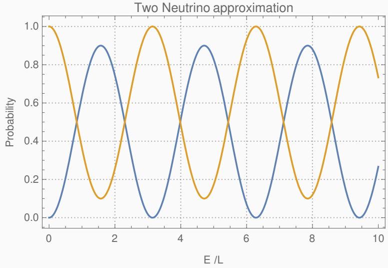

$\Rightarrow$ Expect to see Gravitational wave oscillations.

Making the graviton massive

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$$\mathcal{L} = \frac{1}{4} h_{\mu\nu} \Box h^{\mu\nu} - \frac{1}{2} h_{\mu\nu} \partial^\mu \partial_\alpha h^{\nu\alpha} + \frac{1}{2} h \, \partial_\mu \partial_\nu h^{\mu\nu} - \frac{1}{4} h \Box h$$

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$\rightarrow$ avoid ghosts by setting $a = -b$

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Giving a mass to $g_{\mu\nu} \Rightarrow$ 2nd 'metric' $\tilde{g}_{\mu\nu}$

3. **Massive Gravity:** (dRGT 2010)
   recover nonlinear coordinate invariance:

$$S = \frac{M_g^2}{2}\int d^4x\sqrt{-g}\,R(g) + m^2 M_g^2 \int d^4x\sqrt{-g}\sum_{n=0}^{4}\beta_n e_n(\sqrt{g^{-1}\tilde{g}})$$

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Coupling terms with $\sqrt{g^{-1}\tilde{g}} \equiv \mathbb{X}$:

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$\rightarrow$ GW150914 & GW151226!

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Reason: GWO will depend on 4 parameters $m_g, \sin^2(\theta), y_*, \tilde{c}$

Background cosmology

Ansatz: double-FRW with conformal time η

$$\mathrm{d}s^2 = a(\eta)^2(-\mathrm{d}\eta^2 + \mathrm{d}\vec{x}^2)$$
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$$\text{I.} \quad \frac{3}{a^2}\left(H^2 + k\right) = \Lambda(y) + \frac{\rho(\eta)}{M_g^2}$$

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dynamical CC: $\Lambda(y) \equiv m^2 \sin^2\theta\left[\beta_0 + 3\beta_1 y + 3\beta_2 y^2 + \beta_3 y^3\right]$

Take $y \xrightarrow{t\to\infty} y_* + \delta y$: $(y = b/a)$

$$\tilde{c}(\eta) \simeq 1 + \frac{\delta y'}{y_* H} = 1 - \underbrace{(1+\omega)\frac{\rho(\eta)}{m^2\Gamma_* M_{pl}^2}\frac{y_*^2}{\frac{2\tilde{\rho}_* y_*^4}{3m^2 M_{\tilde{g}}^2\Gamma_*} - \cos^2\theta}}_{\to 0}$$

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Results of background cosmology.

- Stable solution exists (von Strauss & co. 2012).
- Modes can be sub-/superluminous.
- For reasonable values, $\tilde{c} = 1$.

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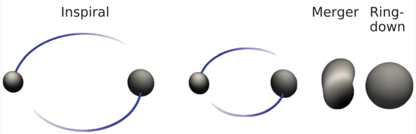

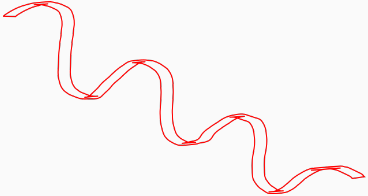

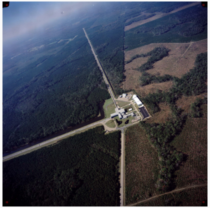

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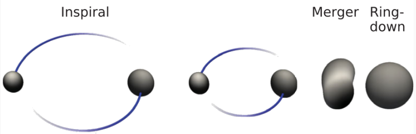

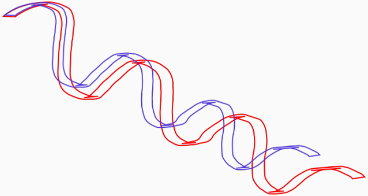

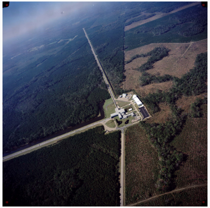

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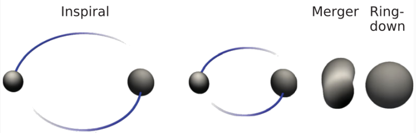
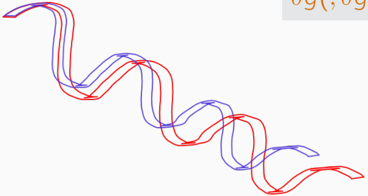
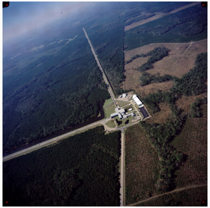




Production + detection

$\sqrt{-\det g}\;\mathcal{L}_{\text{matter}}$

$\delta g(, \delta\tilde{g})$ in ‘flavour’ basis



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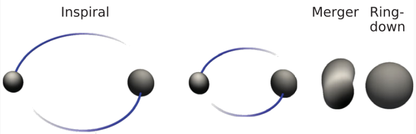

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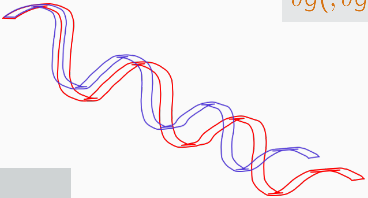
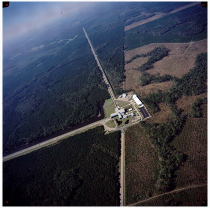


Propagation

h_1,h_2 in mass basis



Gravitational wave oscillations

Eom's of TT tensor perturbations: $\overset{(\sim)}{g}_{\mu\nu} = \eta_{\mu\nu} + \delta \overset{(\sim)}{g}_{\mu\nu}$

$$\delta g'' + k^2 \delta g + \sin^2\theta \, m^2 \, \Gamma_* a^2 (\delta g - \delta \tilde{g}) = 0$$

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GWO mixing angle: $\cos^2(\theta) \equiv \frac{M_{\text{eff}}^2}{M_g^2}, \ \sin^2(\theta) \equiv \frac{M_{\text{eff}}^2}{M_{\tilde{g}}^2}$

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Change of basis

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decouples one equation:

$$h_1'' + k^2 h_1 = 0$$

$$h_2'' + k^2 h_2 + a^2 m_g^2\, h_2 = a^2 m_g^2 \kappa(\theta, y_*) h_1$$

with $m_g^2 \equiv m^2 \Gamma_* (\sin^2\theta + \frac{\cos^2\theta}{y_*^2})$

Gravitational wave oscillations

Solution:

$$\delta g(t,k) = \frac{\cos^2\theta\cos(k\,t) + y_*^2\sin^2\theta\cos\left(\sqrt{k^2+m_g^2}\,t\right)}{\cos^2\theta + y_*^2\sin^2\theta}$$

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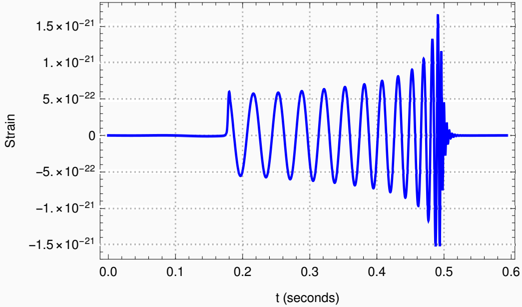
Note:

- frequency dependent modulation
- $m_g \to 0$ recovers linear. GR perturbations
- oscillation for $\tilde{c} = 1$!

Application to GW150914

NumGR by Einstein Toolkit et al. + SXS collab.



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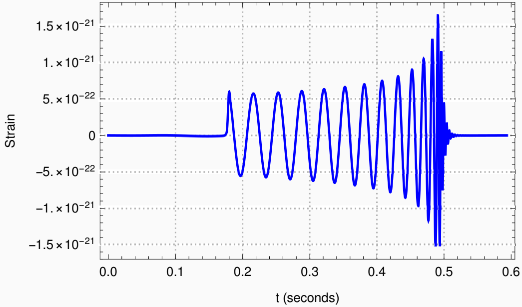

$$\left\langle (\delta g)^2(t,k) \right\rangle_{T_0 \ll t \ll T_*} = \frac{\cos^4\theta}{\left(\cos^2\theta + y_*^2 \sin^2\theta\right)^2} \left[1 + 2\,y_*^2\,\tan^2\theta\,\cos\left(\frac{m_g^2}{2k}t\right) + y_*^4\tan^4\theta\right]$$

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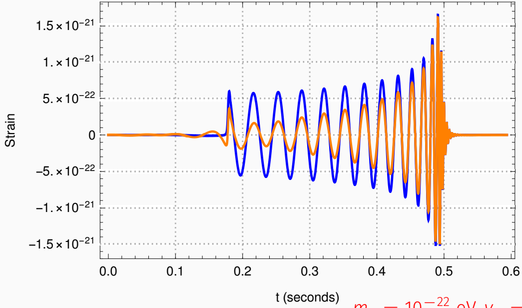
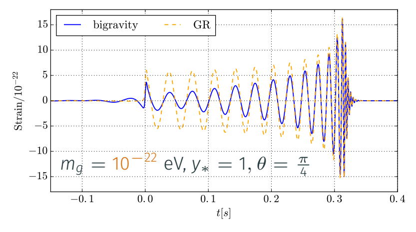
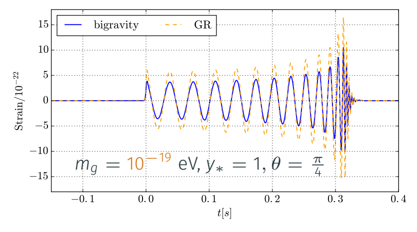


$m_g = 10^{-22}$ eV, $y_* = 1$, $\theta = \frac{\pi}{4}$

$$\left\langle (\delta g)^2(t,k) \right\rangle_{T_0 \ll t \ll T_*} = \frac{\cos^4\theta}{\left(\cos^2\theta + y_*^2 \sin^2\theta\right)^2} \left[1 + 2\,y_*^2\,\tan^2\theta\,\cos\left(\frac{m_g^2}{2k} t\right) + y_*^4 \tan^4\theta\right]$$

Graviton mass determines deviation of waveform profile:





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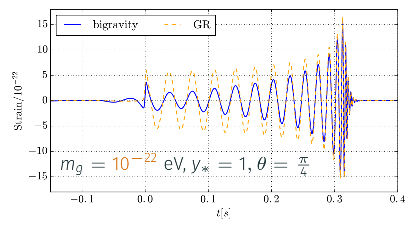
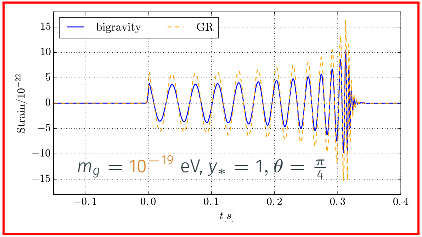
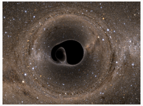
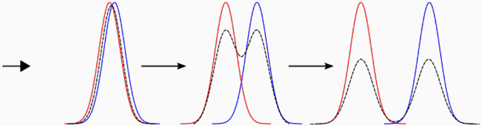




$\rightarrow$ large m_g or z: decoherence





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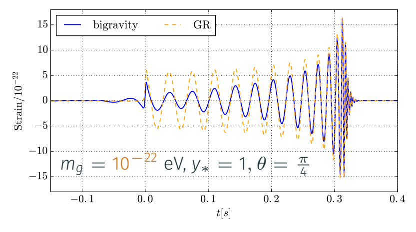

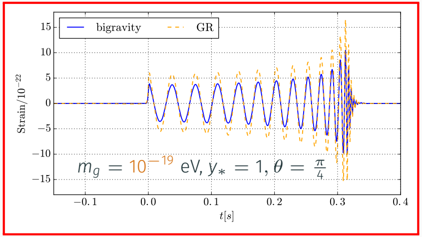

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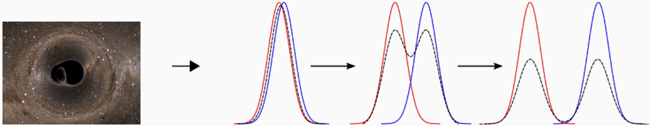
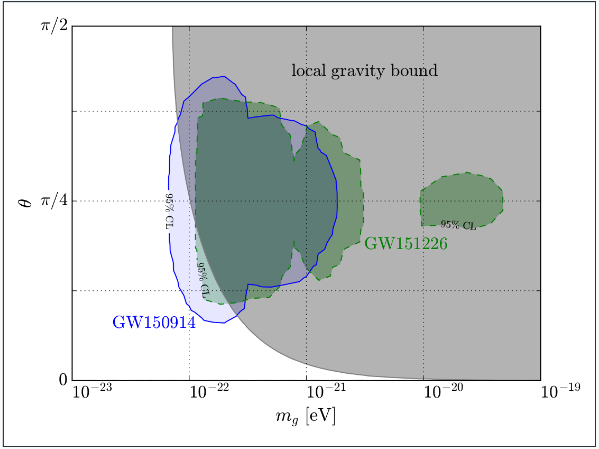


$\Rightarrow$ indistinguishable from GR at larger z

Bigravity mass bounds from LIGO



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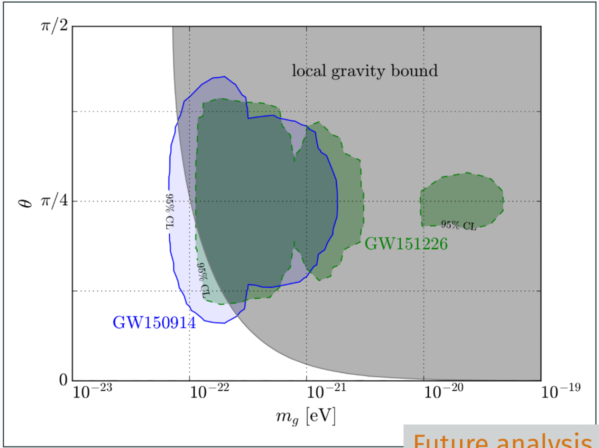
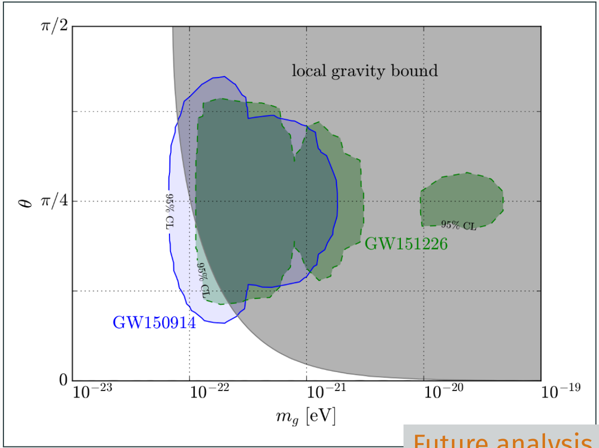
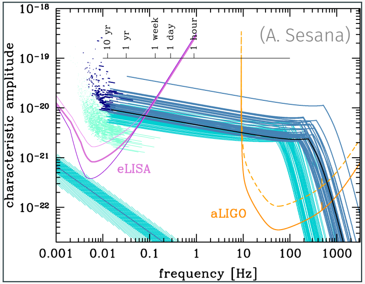


Future analysis

- More LIGO events $\Rightarrow$ better exclusion?

Bigravity mass bounds from LIGO



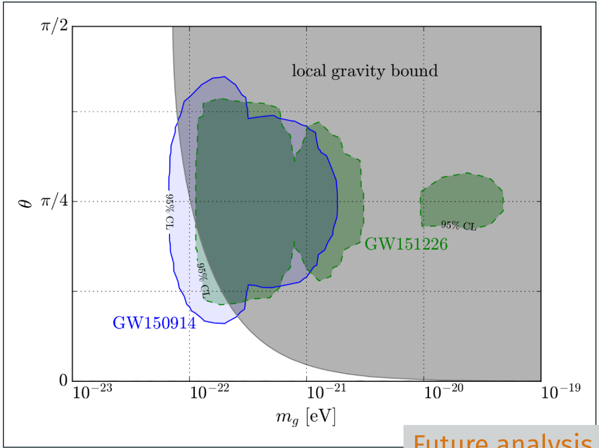


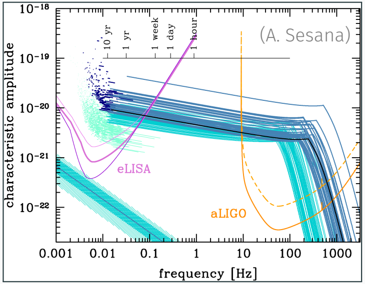
$$L_{\text{coh}} \approx \frac{2k}{m_g^2}$$

Future analysis

- More LIGO events $\Rightarrow$ better exclusion? Probably not.

Bigravity mass bounds from LIGO





$$L_{\text{coh}} \approx \frac{2k}{m_g^2}$$

Future analysis

- More LIGO events $\Rightarrow$ better exclusion? Probably not.
- But: compare expected distribution of BBH systems with observed event rates at large z.

Summary

Bimetric gravity:

- natural extension of (massive) GR
- many phenomenological implications
- double-FRW cosmology ✓
- nonlinearities not yet fully understood

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- double-FRW cosmology ✓
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Extensions to GR testable today!

Questions?

Effects on observations

Bounds on m_g – and do they apply?

- GW150914: $m_g < 1.2 \cdot 10^{-22}$ eV ✓
- weak lensing: $m_g < 6 \cdot 10^{-32}$ eV X
  ΛCDM without Bigravity effects
- precession of mercury: $m_g < 7.2 \cdot 10^{-23}$ eV ?
  $R_{\text{Vainshtein}} > R_{\text{solar system}}$

Nonlinearities

Helicity-0 mode π – why don't we see it locally?

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \pi)^2 - \frac{1}{\Lambda^3}(\partial_\mu \pi)^2 \Box \pi + \frac{1}{M_{pl}} \pi\, T$$

$$\text{Renormalised} \rightarrow \frac{1}{M_{pl}\sqrt{Z}} \ll \frac{1}{M_{pl}}$$

π is screened – **'Vainshtein effect'**