Signatures of quantum gravity in gravitational-wave observables

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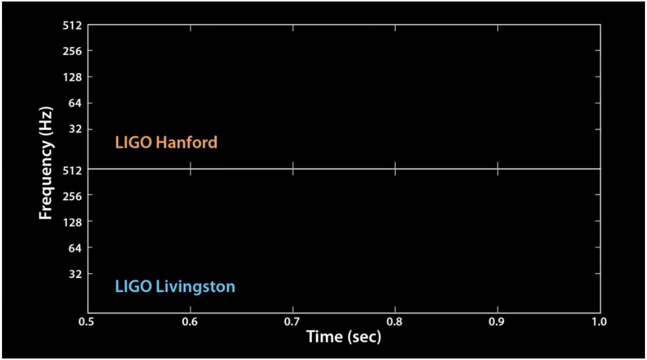
Gravitational waves (GWs)

Abbott et al. 2016



Theories beyond Einstein: any imprint in GW production or propagation?

QG modifications of propagation and generation

From modified dispersion relations:

- Propagation speed*.
- Waveform phase [Mirshekari et al. 2012].
- Luminosity distance*.
- EMRIs kludge waveform?

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From dimensional flow:

- All the above, with added ingredients*.

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From dimensional flow:

- All the above, with added ingredients*.

From primordial blue-tilted spectra:

- Stochastic GW background*.

Dispersion relation and propagation speed

Single GW events can place bounds on the propagation speed of gravitons [Ellis et al. 2016; Arzano & G.C. PRD 2016; Yunes et al. 2016], on violations of the equivalence principle and of Lorentz invariance in theories beyond Einstein [Yunes et al. 2016].

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Modified dispersion relation for the graviton ($\Delta v = |\mathrm{d}\omega/\mathrm{d}k - 1|$ group velocity) [Arzano & G.C. PRD 2016]

$$\omega^2 = k^2 \left(1 \pm \frac{k^n}{M^n}\right) + O\left(k^{n+3}\right) \qquad \Rightarrow \qquad M \simeq \frac{\omega}{\Delta v^{\frac{1}{n}}}$$

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$\rightarrow$ LISA: $\omega_{\text{LISA}}/\omega_{\text{LIGO}} \sim 10^{-5}$, about same constraint level on M if $|\Delta v| < 10^{-20-5n}$

Bounds

Ellis et al. MPLA 2016; Arzano & G.C. PRD 2016; G.C. EPJC 2017, JHEP 2017

Recovery of the entropy-area law [Padmanabhan 1997,1998]:

$$M > 6 \times 10^{-3}\,\mathrm{eV}\,, \qquad n = 2$$

Generic quantum-gravity/stringy arguments [Amelino-Camelia et al. 1997]:

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This range is typical of field theories on multifractal geometries [G.C. 2012-2017], where $n = 1 - d_{\mathrm{H}}/4$ is related to the UV Hausdorff dimension of spacetime. For the typical $d_{\mathrm{H}} = 2$,

$$M > 10^{17}\,\mathrm{GeV}\,, \qquad n = 0.5$$

Standard sirens: optical sources of GWs

EM luminosity distance: Flux = power per unit area

$$F =: \frac{L}{4\pi(d_L^{\rm EM})^2}\,, \qquad d_L^{\rm EM} = \frac{a_0^2}{a}\, r = (1+z)\int_0^z \frac{{\rm d}z'}{H(z')}$$

GW luminosity distance:

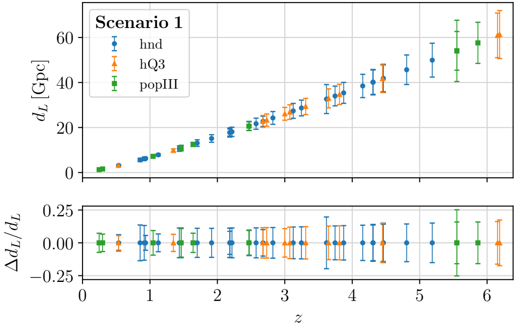
$$h \propto \frac{1}{d_L^{\rm GW}} \overset{\text{in GR}}{=} \frac{1}{d_L^{\rm EM}}$$

Known example (LIGO-Virgo/Fermi): BNS GW170817 / GRB170817A [Abbott et al. 2017]

Standard sirens @ LISA

Belgacem, G.C., et al. JCAP 2019

LISA
CosWG-19-01

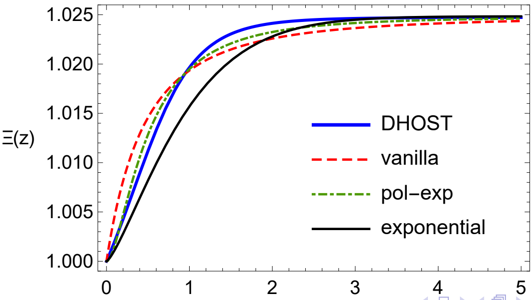


Parametrizing $d_L(z)$: model selection

Belgacem, G.C., et al. JCAP 2019

$$\frac{d_L^{\rm GW}}{d_L^{\rm EM}} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\,, \quad \Xi_0 + \frac{1-\Xi_0}{1+z^m}\,, \quad \Xi_0 + (1-\Xi_0)\,{\rm e}^{-z^n}$$

Checked with DHOST, bigravity, IR nonlocal gravity, QG, . . .



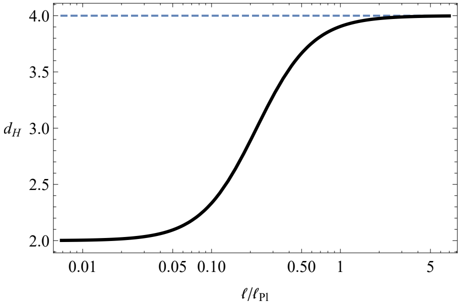
Quantum gravity (QG)

- Perturbative QG: effects important at high curvature/short distances. Homogeneous cosmology, only $\ell_{\rm Pl}$ and H available, corrections $(\ell_{\rm Pl}H)^n \overset{\rm today}{\sim} (10^{-60})^n$, $\qquad n = 1, 2, 3, \ldots$
- Non-perturbative QG effects, e.g., models with a third scale $L \gg \ell_{\rm Pl}$, quantum corrections $\sim \ell_{\rm Pl}^a H^b L^c$ with $a - b + c = 0$, not all of them small [Bojowald, G.C. & Tsujikawa, PRL 2011].

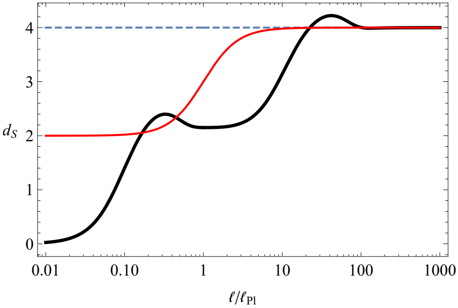
Dimensional flow

Universal non-perturbative effect in QG ['t Hooft 1993; Carlip 2009; G.C. PRL 2010; Carlip 2017]: running Hausdorff and spectral dimensions.

$d_{\rm H}$: scaling of volume



$d_{\rm S}$: scaling of dispersion rel.



Luminosity distance in QG: 1

G.C. et al. JCAP 2019; PLB 2019

$$S=\frac{1}{2}\int \mathrm{d}\varrho(x)\, h_{ij}\mathcal{K}(\Box)\, h^{ij}, \qquad [h_{ij}]=\frac{d_{\rm H}-[\mathcal{K}]}{2}$$

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Modified dispersion relation, e.g., $\mathcal{K}(-k^2)=-\ell_*^{2-2\beta}k^2+k^{2\beta}$.
Return probability and spectral dimension

$$\mathcal{P}(\sigma)\propto\int \mathrm{d}\tilde{\varrho}(k)\, \mathrm{e}^{-\sigma\ell_*^{[\mathcal{K}]}\mathcal{K}(-k^2)}, \quad d_{\rm S}:=-2\frac{\mathrm{d}\ln\mathcal{P}(\sigma)}{\mathrm{d}\ln\sigma}=2\frac{d_{\rm H}^k}{[\mathcal{K}]}$$

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$$\boxed{\Gamma=\frac{d_\mathrm{H}}{2}-\frac{d_\mathrm{H}^k}{d_\mathrm{S}}, \qquad d_\mathrm{S}\neq 0}$$

Luminosity distance in QG: 2

G.C. et al. JCAP 2019; PLB 2019

Local wave zone approximation $\omega r \gg 1$:

$$h_{ij}\frac{\kappa\mathcal{F}_{ij}(t-r)}{(r^2)^{\frac{\Gamma}{2}}} \sim \frac{1}{r^\Gamma} \to \frac{1}{(d_L^{\rm EM})^\Gamma}$$

Cosmological propagation (flat FLRW): $r \to ar$ rule from covariance:

$$h \propto \frac{1}{(d_L^{\rm EM})^\Gamma} \qquad \Rightarrow \qquad h \overset{\rm UV}{\sim} \frac{1}{(d_L^{\rm EM})^{\Gamma_{\rm UV}}}\,, \qquad h \overset{\rm IR}{\sim} \frac{1}{d_L^{\rm EM}}$$

Master formula

G.C. et al. JCAP 2019; PLB 2019

$$\frac{d_L^{\mathrm{GW}}}{d_L^{\mathrm{EM}}} = 1 \pm |\gamma - 1| \left(\frac{d_L^{\mathrm{EM}}}{\ell_*}\right)^{\gamma-1}$$

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$$\frac{d_L^{\rm GW}}{d_L^{\rm EM}} = 1 \pm |\gamma - 1| \left(\frac{d_L^{\rm EM}}{\ell_*}\right)^{\gamma-1}$$

Very similar to models with extra dimensions [Deffayet & Menou 2007; Pardo et al. 2018; Abbott et al. 2018]

$$\frac{d_L^{\rm GW}}{d_L^{\rm EM}} = \left[1 + \left(\frac{d_L^{\rm EM}}{R_{\rm c}}\right)^{n_{\rm c}}\right]^{\frac{D-4}{2n_{\rm c}}}$$

UV geometry in QG (unobservable)

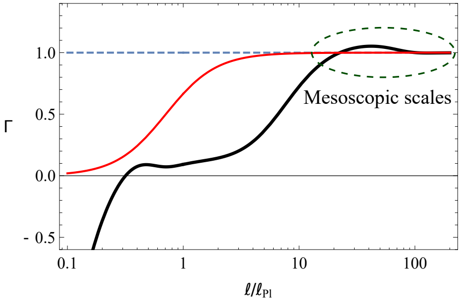
G.C. et al. JCAP 2019

	$d_{\rm H}^{\rm UV}$	$d_{\rm H}^{k,\rm UV}$	$d_{\rm S}^{\rm UV}$	$\Gamma_{\rm UV}$	$\Gamma_{\rm meso} \gtrsim 1$
GFT/spin foams/LQG	2	4	$[1,4)$	$[-3,0)$	✓
Causal dynamical triangulations (phase C)	4	4	$3/2$	$-2/3$	
κ-Minkowski bicovariant ∇^2 (c.i.m.)	1	3	3	$-1/2$	
κ-Minkowski bicross-product ∇^2 (c.i.m.)	1	3	6	0	
Stelle gravity	4	4	2	0	
String theory (low-energy limit)	D	D	2	0	
Asymptotic safety	4	4	2	0	
Hořava–Lifshitz gravity	4	4	2	0	
κ-Minkowski relative-locality ∇^2 (c.i.m.)	1	3	$+\infty$	$1/2$	
κ-Minkowski bicovariant ∇^2 (o.m.)	4	3	3	1	
κ-Minkowski bicross-product ∇^2 (o.m.)	4	3	6	$3/2$	✓
κ-Minkowski relative-locality ∇^2 (o.m.)	4	3	$+\infty$	2	✓
Padmanabhan's non-local model	4	4	$+\infty$	2	✓

QG and standard sirens. 1

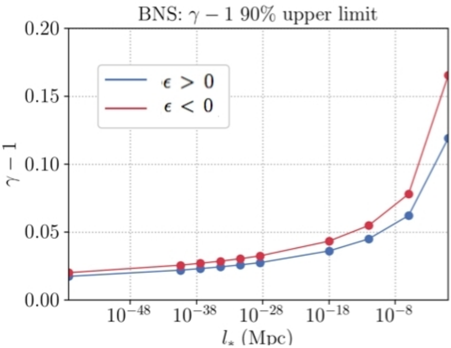
G.C. et al. JCAP 2019

Standard sirens: BNS GW170817/GRB 170817A (LIGO-Virgo public data) and simulated SMBH, $d_L^{\rm EM} = 15.96$ Gpc, $z = 2$ (LISA catalogs). Detectable QG effect if $\gamma \gtrsim 1$, even when $\ell_* = O(\ell_{\rm Pl})$:



QG and standard sirens. 2

G.C. et al. JCAP 2019; Belgacem, G.C., et al. JCAP 2019



$$\Gamma_{\rm meso} - 1 < 0.02$$

QG and standard sirens. 3

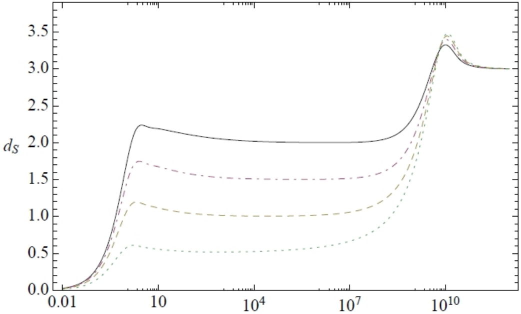
G.C. et al. JCAP 2019

Theories where $\gamma = \Gamma_{\rm meso} \gtrsim 1$:

- Non-commutative κ-Minkowski spacetime
  $\Gamma_{\rm meso} \simeq 1 + \frac{5}{96\pi}\frac{\ell_{\rm Pl}^2}{\ell^2} \sim 1 + 10^{-120}$.
- Padmanabhan's model near BH horizon
  $\Gamma_{\rm meso} \simeq 1 + \frac{5\pi}{2}\frac{\ell_{\rm Pl}^2}{\ell^2} \sim 1 + 10^{-120}$.
- QGs with discrete pre-geometries: GFT, spin foams, LQG.
  $\Gamma_{\rm meso}$ strongly state dependent.

Future work: testing GFT/spin foams/LQG

Numerical analysis of dimensional flow [G.C., Oriti & Thürigen 2013,2014,2015]



$\Gamma_{\rm meso}$ can be calculated from realistic quantum states of geometry.

Nonlocal quantum gravity

Briscese, G.C. & Modesto PRD 2019

Linearized perturbation equation:

$$\Box\tilde{h} = 0\,, \qquad \tilde{h} = \mathrm{e}^{\mathrm{H}(\Box)}h\,, \qquad \mathrm{H}(\Box) = -\ell_*^2\Box$$

Luminosity distance:

$$\tilde{h} \propto \frac{1}{d_L^{\rm GW}} \qquad \Rightarrow \qquad h \propto \mathrm{e}^{-\mathrm{H}}\frac{1}{d_L^{\rm GW}}\,.$$

$$\frac{d_L^{\rm GW}}{d_L^{\rm EM}} \simeq 1 + c(\ell_* H_0)^2 \sim 1 + 10^{-120}\,, \qquad c = O(1)–O(10)$$

Unobservable, sorry!

Strain noise and QG

Amelino-Camelia 1998, 2013; Amelino-Camelia et al. PLB 2017, G.C. et al. JCAP 2019

What if QG spacetime uncertainty (fuzziness) $\sim$ strain noise?

$$\left(\frac{\ell_*}{L}\right)^{2(1-\alpha)} = \frac{\sigma_{\rm QG}^2}{L^2} \sim \sigma_{\rm exp}^2 \simeq f\,\mathcal{S}^2(f)\Big|_{f=\frac{c}{L}}\,.$$

Uncertainty/fuzziness at Planck scales $\ell_* = \ell_{\rm Pl}$ (intrinsic QG noise) no greater than the strain noise:

	$\mathcal{S}$ (Hz$^{-1/2}$)	f (Hz)	α
LIGO/Virgo/KAGRA	10^{-23}	10^{2}	< 0.47
LISA	10^{-20}	10^{-2}	< 0.54
DECIGO	10^{-23}	10^{-1}	< 0.47

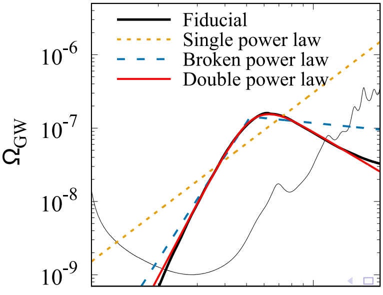
Model-independent bound in the UV:

$$d_{\rm H}^{\rm UV} = 4\alpha < 1.9\,.$$

Stochastic GB background

Kuroyanagi & G.C., in progress

Origin: • Overlapped astrophysical GWs (compact binaries).
• Cosmological GWs (blue-tilted spectra, preheating, . . .).
Theoretical approach + template analysis. Example: superradiant instabilities generated by ultralight scalars around spinning black holes [Yoshino & Kodama 2014; Brito et al. 2017].



What to bring home

- We can and should ask more from our theories and push them to get phenomenology in GW astronomy (even negative one).
- Better to make this effort in fundamental theories (strings, quantum gravities, etc.) rather than in ad-hoc models.

ご清聴ありがとうございました

Thank you

Muchas gracias

Grazie

Muito obrigado

Kiitos paljon

Danke schön

Merçi beaucoup

Спасибо