Gravitational-wave astronomy in quantum gravity

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- QG is an umbrella name labeling theories attempting to quantize the gravitational force.
- Three main motivations: (1) unify the forces of Nature; (2) resolve the singularities of general relativity (big bang, black holes); (3) resolve the Λ problem.

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Perturbative QG

Effects important at high curvature, high energy, short distances, or early times. Example:

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Dimensional argument: in homogeneous cosmology, with only the Planck scale $\ell_{\rm Pl}$ and the Hubble scale H available, perturbative quantum corrections are of the form

$$(\ell_{\rm Pl} H)^n \overset{\rm today}{=} (\ell_{\rm Pl} H_0)^n \sim (10^{-60})^n, \qquad n = 1, 2, 3, \dots$$

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. . . Hold on . . .

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QG and GWs:

- Growing literature, but little or no knowledge about non-perturbative effects.
- Any imprint in GW production or propagation? Which theories?

Universal features in quantum gravity

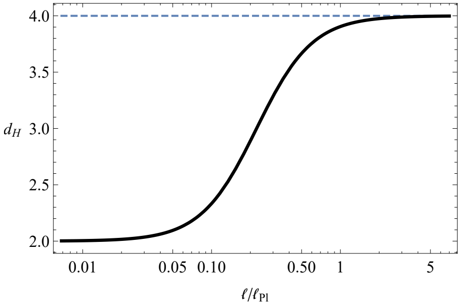
All theories of quantum gravity have something in common:

- Dimensional flow: Changing behaviour of correlation functions, spacetime with scale-dependent dimension d. $d < 4$ in the UV. Universal feature in QG ['t Hooft 1993; Carlip 2009; G.C. PRL 2010; Carlip 2017].
- Fuzziness: intrinsic uncertainty in measurements of times and distances.

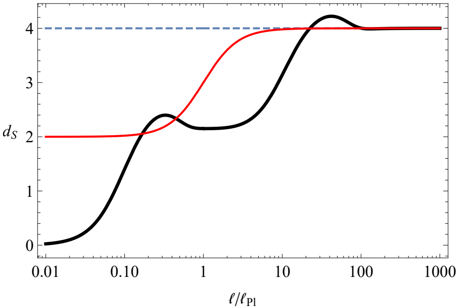
Dimensional flow

Universal non-perturbative effect (present at all scales): running Hausdorff and spectral dimensions.

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



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



Effective dynamics in QG

Assumptions: continuum limit, effective action

$$S = \frac{1}{2}\int \mathrm{d}\varrho(x)\, \varphi\mathcal{K}\varphi, \qquad [\varrho] = -d_\mathrm{H}, \qquad [\varphi] = \frac{d_\mathrm{H} - [\mathcal{K}]}{2}$$

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Return probability and spectral dimension

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

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Anomalous scaling

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

UV geometry in QG

	$d_{\rm H}^{\rm UV}$	$d_{\rm H}^{k,\rm UV}$	$d_{\rm S}^{\rm UV}$	$\Gamma_{\rm UV}$	$\Gamma_{\rm meso} \gtrsim 1$
GFT/spin foams/LQG	2	4	$1 \leq \cdot < 4$	$-3 \leq \cdot < 0$	✓
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 gravit	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	✓

Testing dimensional flow?

Strategy:

1. Concentrate on GW propagation (simpler than production).
2. Model-independent relation between luminosity distance d_L and GW amplitude h.
3. Use standard sirens to place model-independent constraints on this relation.
4. Apply them to specific QG theories.

Luminosity distance d_L^{EM}

Flux = power per unit area

$$\mathrm{F} =: \frac{\mathrm{L}}{4\pi (d_L^{\mathrm{EM}})^2}$$

Proper distance $r = \tau_0 - \tau(z)$, redshift $1 + z = a_0/a$.

$$d_L^{\mathrm{EM}} = \frac{a_0^2}{a} r = (1+z) \int_{t(z)}^{t_0} \frac{\mathrm{d}t}{a} = (1+z) \int_0^z \frac{\mathrm{d}z'}{H(z')}$$

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Possible modifications in QG: integration measure (distances) and/or Hubble parameter (dynamics).

GW amplitude h in QG (in $D = 4$)

Local wave zone $r \gg s \sim \lambda \sim \frac{1}{\omega}$: leading term of a $\omega r \gg 1$ expansion of $h(t, r)$.

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Scaling argument from the retarded Green function:

$$[h/\kappa] = \Gamma \qquad \Rightarrow \qquad h \simeq \frac{\kappa \mathcal{F}(t,r)}{(r^2)^{\Gamma/2}} \overset{\Gamma=1}{\propto} \frac{1}{r}.$$

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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

$$h \propto \frac{1}{d_L^{\rm GW}}\,, \qquad d_L^{\rm GW} = d_L^{\rm EM}\left[1 \pm |\gamma - 1|\left(\frac{d_L^{\rm EM}}{\ell_*}\right)^{\gamma-1}\right]$$

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

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

QG and standard sirens. 1

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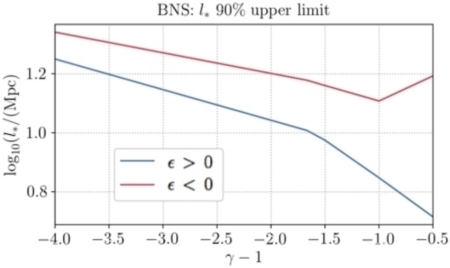

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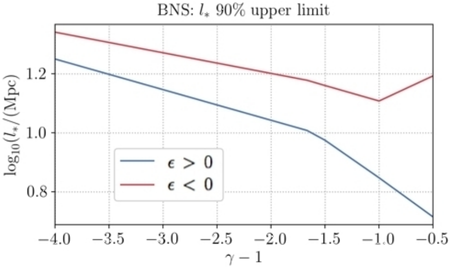

$\gamma = \Gamma_{\rm UV} < 1$: UV regime of QG unobservable.

QG and standard sirens. 2

GW interferometers: $\Delta d_L/d_L \sim 0.01 - 0.2$. Detectable QG effect if $\gamma \gtrsim 1$, even when $\ell_* = O(\ell_{\rm Pl})$:

$$\left(\frac{d_L^{\rm EM}}{\ell_*}\right)^{\gamma-1} \gtrsim 10^{-3} - 10^{-1}$$

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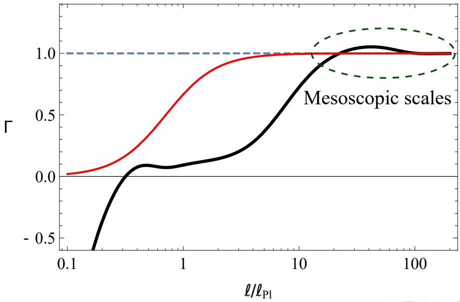
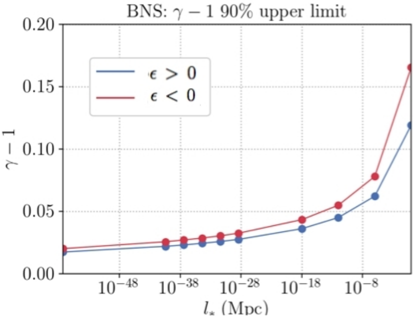


QG and standard sirens. 3

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.

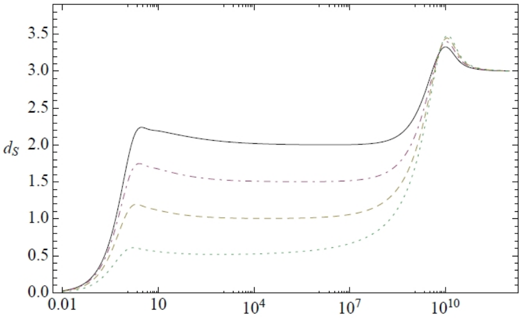
Fixed ℓ_*, infer γ



$$\Gamma_{\rm meso} - 1 < 0.02, \qquad d_{\rm S}^{\rm meso} - 4 < 8\%$$

Future work: testing GFT/spin foams/LQG

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



Γ_{meso} can be calculated from realistic quantum states of geometry.

Excluding some LQC semi-classical states

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Mukhanov equation ($w_k := a_{\rm LQC} h_k$):

$$w_k'' + \left[(1+2\alpha_0\delta_{\rm Pl})k^2 - \frac{a_{\rm LQC}''}{a_{\rm LQC}}\right] w_k = 0\,, \qquad a_{\rm LQC} := a\left(1-\frac{\alpha_0}{2}\delta_{\rm Pl}\right)$$

$$\frac{d_L^{\rm GW}(z)}{d_L^{\rm EM}(z)} = \frac{a}{a_{\rm LQC}} \simeq 1 + \frac{1}{2}\alpha_0\delta_{\rm Pl}$$

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But the correction is constrained to be too small from the GW170817 $+$ GRB170817A bound on propagation speed: $\alpha_0\delta_{\rm Pl} < 10^{-15}$.

Strain noise and QG

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 on the small-scale Hausdorff dimension of spacetime:

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

Perspective

- Different QGs have common non-perturbative effects present at all scales (dimensional flow).
- In most theories, dimensional flow is not observable in standard-sirens observations. Possible exception: GFT/spin foams/LQG.
- Model-independent bounds are possible and go beyond back-of-the-envelope arguments about quantum corrections.
- Future work?
    - LQC in hybrid quantization (avoids speed bound);
    - full GFT/spin foams/LQG states of quantum geometry;
    - production of GWs in QG.

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