Title: Workshop

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Collection/Series: Emmy Noether Workshop: Quantum Space Time

Subject: Quantum Gravity

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Quantum Gravity in the era of Gravitational-Wave astronomy

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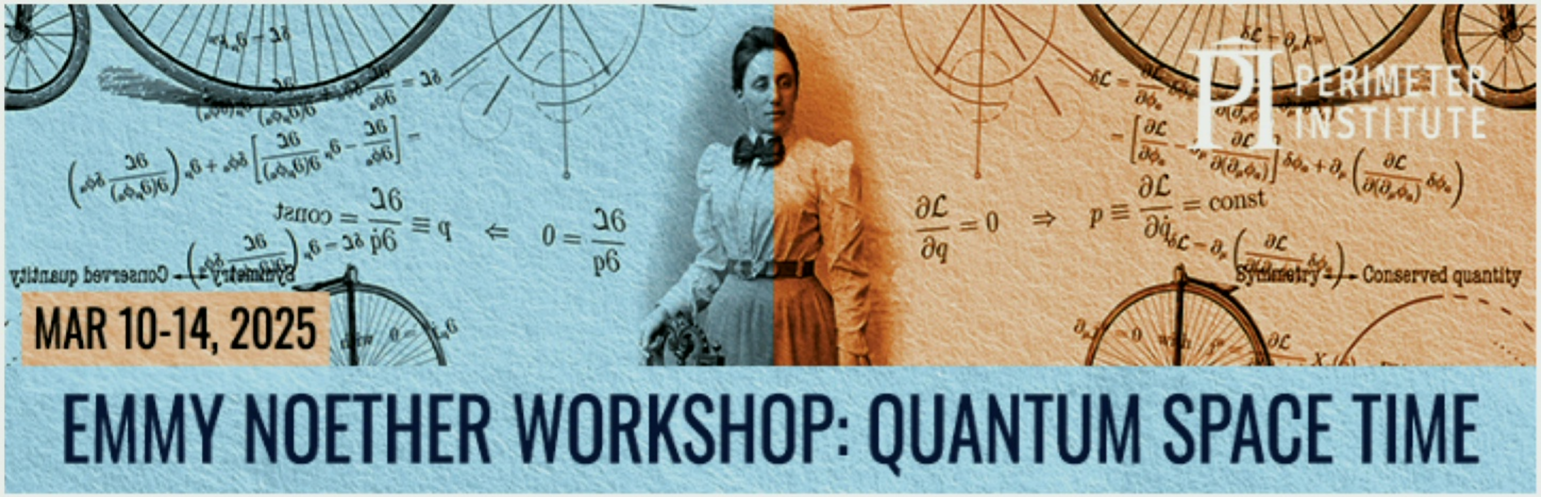

Question: **QG phenomenology in relation to GWs**

- model-dependent approach

- model-independent approach

Cosmological models motivated by QG proposals

Cosmological GW observables:

- amplitude of the GW background
- propagation speed of GWs
- luminosity distance of GW source

Question: **QG phenomenology in relation to GWs**

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Cosmological models motivated by QG proposals

Cosmological GW observables:
- amplitude of the GW background
- propagation speed of GWs
- luminosity distance of GW source

Many QG models : no observable signal
But some predict a **blue-tilted GWB** or a modified **luminosity distance** (detectable by future GW interferometers)

Difficult, but still possible, to test QG with GW observations

Observations of CBCs by LVK: confirmation of all GR predictions

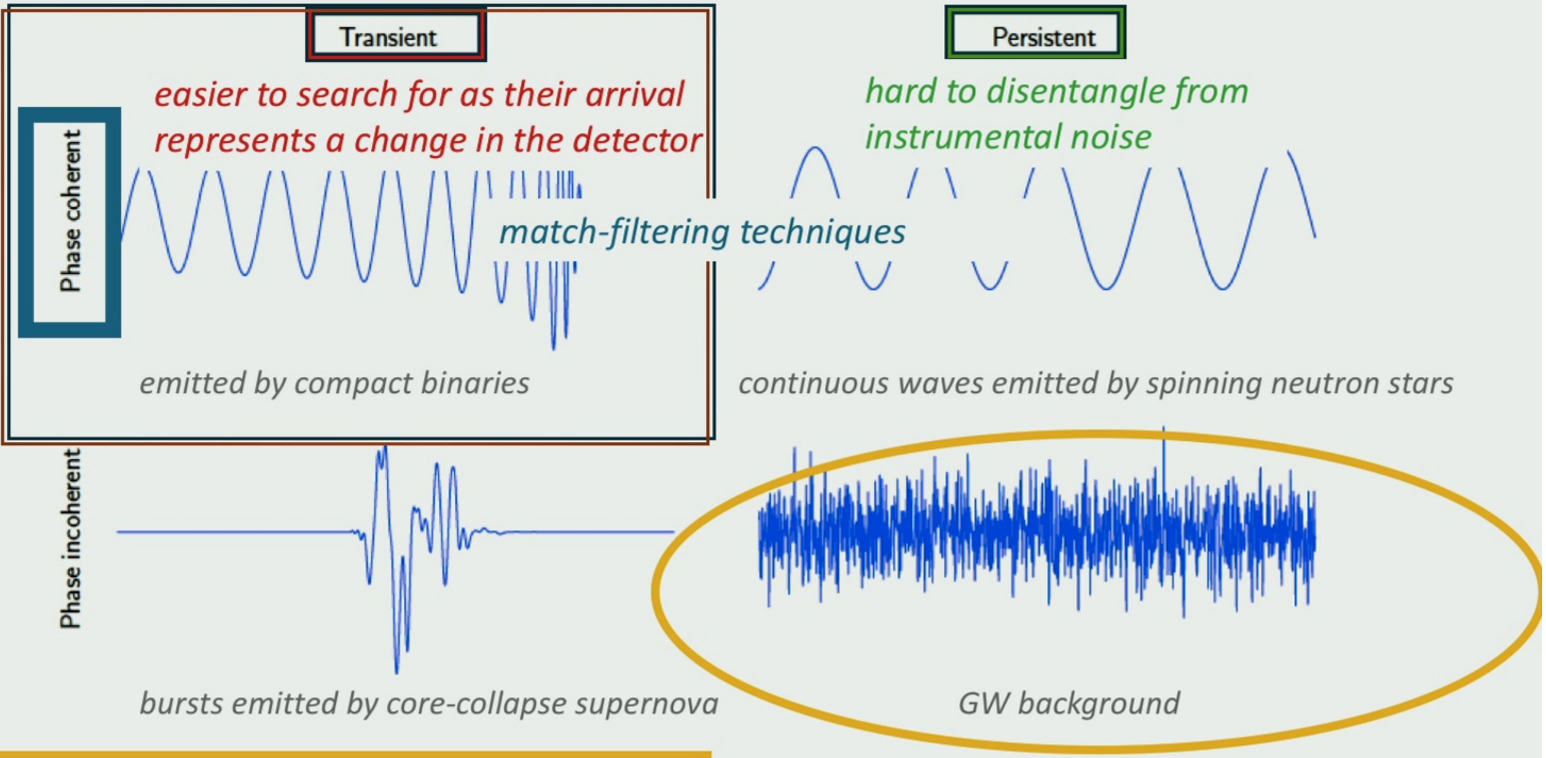
The low curvature, low energies and large distances characterising production and propagation of GWs
➡ difficult to probe Planck-size effects, unless cumulatively amplified by some cosmological mechanism

QG proposals where GW observables have been calculated:

- Stelle gravity (*issues about unitarity*)
- String theory
- Asymptotic safety
- Causal dynamical triangulations
- Non-local gravity
- Horava-Lifshitz gravity (*issues about violation of Lorentz invariance*)
- Canonical quantum cosmology
- Pre-big-gang cosmology
- String cosmology
- New ekpyrotic scenario
- Brandenberger–Ho non-commutative inflation
- Non-commutative κ-Minkowski
- Padmanabhan’s non-local field theory
- Multi-fractional spacetimes

Classification of GW signal morphologies

LVK Collaboration, O1, O2, O3



easier to search for as their arrival represents a change in the detector

hard to disentangle from instrumental noise

match-filtering techniques

emitted by compact binaries

continuous waves emitted by spinning neutron stars

bursts emitted by core-collapse supernova

GW background

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln f}\,. \qquad \rho_{\rm GW} \sim \dot{h}^2$$

$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{\alpha}$$

random nondeterministic phase evolution from a large number of distant sources

GWB of early universe origin

$\mathscr{P}_\mathrm{t}(f)$ primordial tensor spectrum of tensor perturbations of the metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j = a^2(\tau)\,(-\mathrm{d}\tau^2 + \delta_{ij}\mathrm{d}x^i\mathrm{d}x^j)$$

with proper wavelength λ : $f = k/(2\pi) = a/\lambda$

$\mathscr{P}_\mathrm{t}(f)$ small compared to $\mathscr{P}_\mathrm{s}(f)$

$$\boxed{r := \mathscr{P}_\mathrm{t}/\mathscr{P}_\mathrm{s} < 0.068 \text{ at 95\% CL}}$$

Planck Collaboration (2020)

$$\boxed{\mathscr{P}_\mathrm{t}(f) = \mathscr{P}_\mathrm{t}(f_0)\left(\frac{f}{f_0}\right)^{n_\mathrm{t}(f_0)+\frac{1}{2}\alpha_\mathrm{t}(f_0)\ln\frac{f}{f_0}}}$$

$n_\mathrm{t} := \mathrm{d}\ln\mathscr{P}_\mathrm{t}/\mathrm{d}\ln f$

$\alpha_\mathrm{t} := \mathrm{d}n_\mathrm{t}/\mathrm{d}\ln f$

$f_0 = 7.7\times10^{-17}\,\mathrm{Hz} \longrightarrow k_0 = 0.05\,\mathrm{Mpc}^{-1}$

GR + inflation: negative ⇨ red-tilted spectrum

GWB of early universe origin

$$\boxed{\Omega_{\rm GW}(f) := \frac{1}{\rho_{\rm crit}}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln f} = \frac{\pi^2 f^2}{3H_0^2}\,\mathscr{P}_{\rm t}(f)\,\mathscr{T}^2(f)}$$

$$\rho_{\rm GW} := [M_{\rm Pl}^2/(8a^2)]\langle(\partial_\tau h_{ij})^2 + (\nabla h_{ij})^2\rangle$$

transfer function (depends on expansion history of the universe)

GW amplitude of the mode which enters the horizon during RDE:

$$\boxed{\Omega_{\rm GW}(f) = \frac{\mathscr{A}}{h^2}\,r\left(\frac{f}{f_0}\right)^{n_{\rm t}+\frac{\alpha_{\rm t}}{2}\ln\frac{f}{f_0}}, \qquad \mathscr{A} \approx 1.4\times 10^{-15}}$$

A blue-tilted spectrum can produce a stochastic GWB with increasing amplitude that can reach the sensitivity thresholds of GW interferometers at high frequencies

Predictions of QG proposals: amplitude of GWB

Flux-compactification models in string cosmology

$\boxed{n_t < 0}$ red-tilted spectrum

Baumann, McAllister (2015)

Note:

- **old ekpyrotic** scenario: **strongly blue-tilted** tensor index $n_t = 2$
- recent single-field version: perturbations are generated before the ekpyrotic phase, and the scalar spectrum is red-tilted (previous versions are ruled out because of a blue-tilted scalar spectrum)
- in all the realisations of the ekpyrotic model: **tensor-to-scalar ratio is exceptionally small** and the resulting **stochastic GWB is well below the detection threshold of any present or future interferometer**

Predictions of QG proposals: amplitude of GWB

Flux-compactification models in string cosmology

$\boxed{n_t < 0}$ red-tilted spectrum

Baumann, McAllister (2015)

Wheeler-De Witt canonical quantum cosmology

pivot scale of the experiment

$$\mathscr{P}_{\rm t}(k) \simeq \underbrace{\mathscr{P}_{\rm t}^{(0)}(k)}_{\propto H^2} \left[1 \pm c(\ell_{\rm Pl}H)^2 \left(\frac{k_0}{k}\right)^3\right]$$

spectrum at HC: k=aH

- : blue tilt
+ : red tilt

known >0 numerical constant

<<1, strong suppression term; increased at late times by $(k_0/k)^3$

LISA or DECIGO: $k_0/k \sim 10^{-15} - 10^{-13}$

Kiefer, Krammer (2012)
Bini, et al (2013)
Brizuela, et al (106)
Kramenshchik, et al (2018), 2015)

Quantum correction is unobservable

Predictions of QG proposals: amplitude of GWB

Loop Quantum Cosmology

- Dressed-metric approach

quantum fluctuations are described as propagating on a quantum background spacetime which can be described by a dressed metric

Agullo, Morris (2015)
Li, Singh, Wang (2020)

$\boxed{n_t < 0}$ red-tilted spectrum

- Effective-constraints approach (quantum corrections from **inverse-volume operators**, from holonomies, or from both)

Inverse-volume corrections react to the discreteness scale of QG
- They depend only on triad variables and not also on connections
- They are not suppressed at the inflationary density scale

Red-tilted tensor spectrum

Bojowald, calcagni, Tsujikawa (2011)
Zhu, et al (2016)

Predictions of QG proposals: amplitude of GWB

Loop Quantum Cosmology

- Dressed-metric approach
- Effective-constraints approach (quantum corrections from inverse-volume operators, from holonomies, or from both)
- Hybrid-quantisation approach

combine different types of quantum representations for the different degrees of freedom

$n_t(k)$ depends on the vacuum on which to perturb the background solution

- for some choices of the vacuum: $n_t < 0$ red-tilted spectrum
- for others the spectrum oscillates rapidly and for some frequencies, there is a blue tilt

de Blas, Olmedo (2016)
Castello Gomar, et al (2017)

GWB decreases in *k* when *k* is sufficiently large

➡ spectrum is red-tilted at small scales; unlikely it could generate detectable GWB, for any vacuum choice

Predictions of QG proposals: amplitude of GWB

Non-local QG *(embedding of Starobinsky gravity into a fundamental theory)*

primordial tensor spectrum as a function of the comoving wave-number

$$\mathscr{P}_{\mathrm{t}}(k) \sim \left[1 - \frac{3}{2\ln(k_{\mathrm{e}}/k)}\right] \mathrm{e}^{-\tilde{\mathrm{H}}_2\left[\frac{2H^2(k)}{M_*^2}\right]}$$

at high frequencies (high k) the non-local term tends to unity

non-local Starobinsky gravity is out of reach of any present or future GW interferometer: at high frequencies it reduces to standard Starobinsky inflation (a red-tilted spectrum)

Predictions of QG proposals: amplitude of GWB

Pre-Big-Bang scenario

A dynamical dilaton field that satisfies the cosmological equations following from the string effective action

Gasperini, Veneziano (1993)

Isocurvature spectrum of scalar perturbations: inconsistency with CMB data for scalar perturbations

Durrer, Gasperini,Sakellariadou, Veneziano (1998)

Way out via the axion/curvaton mechanism: a viable spectrum of scalar perturbations

$r < 0.01$ at the pivot scale k0=0.05/Mpc

Blue-tilted GWB that can reach the sensitivity of present and future interferometers

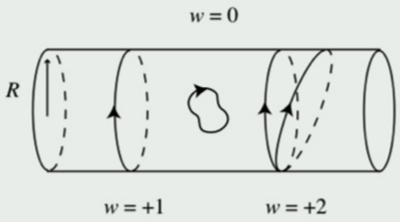
Gasperini (2016)

Predictions of QG proposals: amplitude of GWB

String gas cosmology

T-duality: $R \to \frac{\ell_s^2}{R}$

compact space



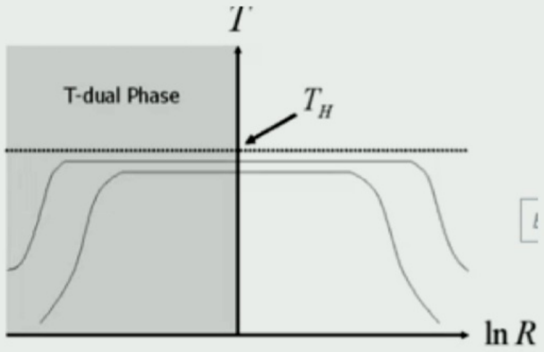
excitation modes of a thermal ensemble of strings

momentum modes $E_n = n\frac{1}{R}$

winding modes $E_m = mR$

Brandenberger, Vafa (1989)

temperature cannot rise indefinitely and reaches a maximal: Hagedorn temp.



for an adiabatic process, winding modes dominate the thermal bath in a small space

Explanation of ST dimensionality

Sakellariadou (1996)

Predictions of QG proposals: amplitude of GWB

String gas cosmology

inflation is replaced by a quasi-static era where thermal fluctuations generate an almost ***scale-invariant primordial scalar and tensor spectrum***

$$\boxed{\mathscr{P}_{\rm t}(k) \simeq \frac{1}{4(M_{\rm Pl} l_{\rm st})^4} \hat{T}(k) \left[1 - \hat{T}(k)\right] \ln^2 \left[\frac{1 - \hat{T}(k)}{l_{\rm st}^2 k^2}\right]}$$

$$\hat{T}(k) := T(k)/T_{\rm H}$$

during Hagedorn phase $T \approx \text{const} \lesssim T_{\rm H}$

during RDE $T \sim 1/a$

$$n_{\rm t} \simeq (1 - n_{\rm s}) - \frac{4}{\ln[(1 - \hat{T})(l_{\rm st} k)^{-2}]} > 0$$

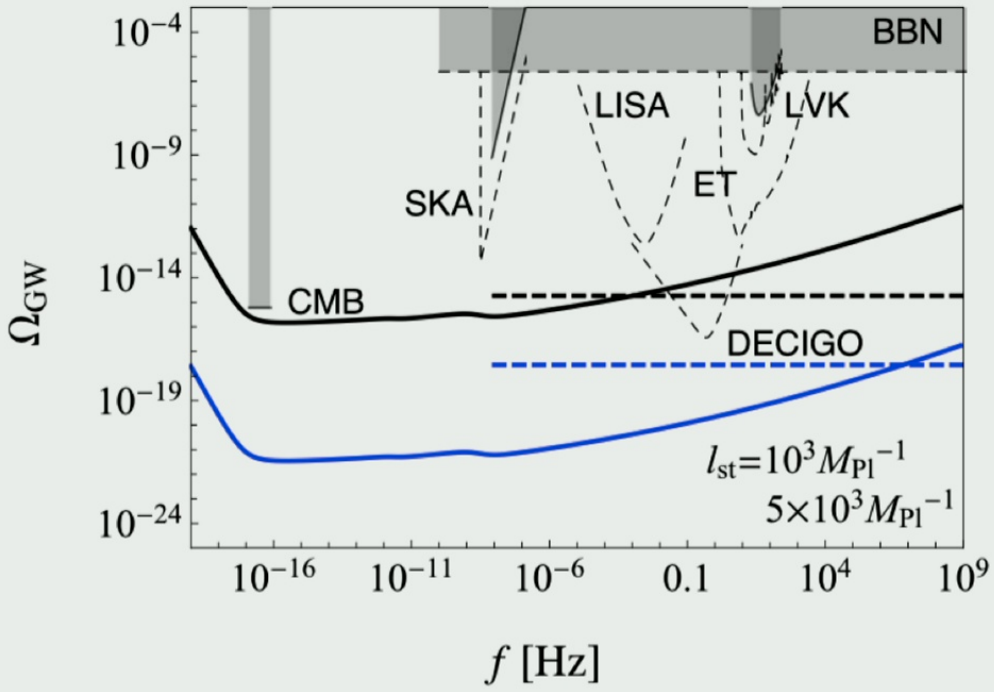
$$\alpha_{\rm t} \simeq -\alpha_{\rm s} \,.$$

Predictions of QG proposals: amplitude of GWB

String gas cosmology

In the most optimistic case of a tensor-to-scalar ratio saturating the CMB bound, the model reaches DECIGO sensitivity

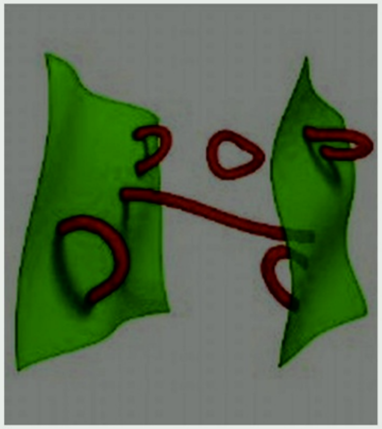
0.1Hz-10Hz (future Japanese GW space mission)



Calcagni, Kuroyanagi (2021)

Predictions of QG proposals: amplitude of GWB

New ekpyrotic scenario



2 flat 3dim branes (boundary of a 5dim ST)

They interact with attractive V(ϕ) along a compact 5th dim parametrised by the radion ϕ

The branes get closed

- ➡ gravitational energy in the bulk is converted to brane KE
- ➡ the branes collide
- ➡ part of the brane KE is converted into matter/radiation

An observer on one of the branes experiences the brane collision as a big bang after a period of contraction: **ekpyrosis**

During the slow contraction phase: inhomogeneities

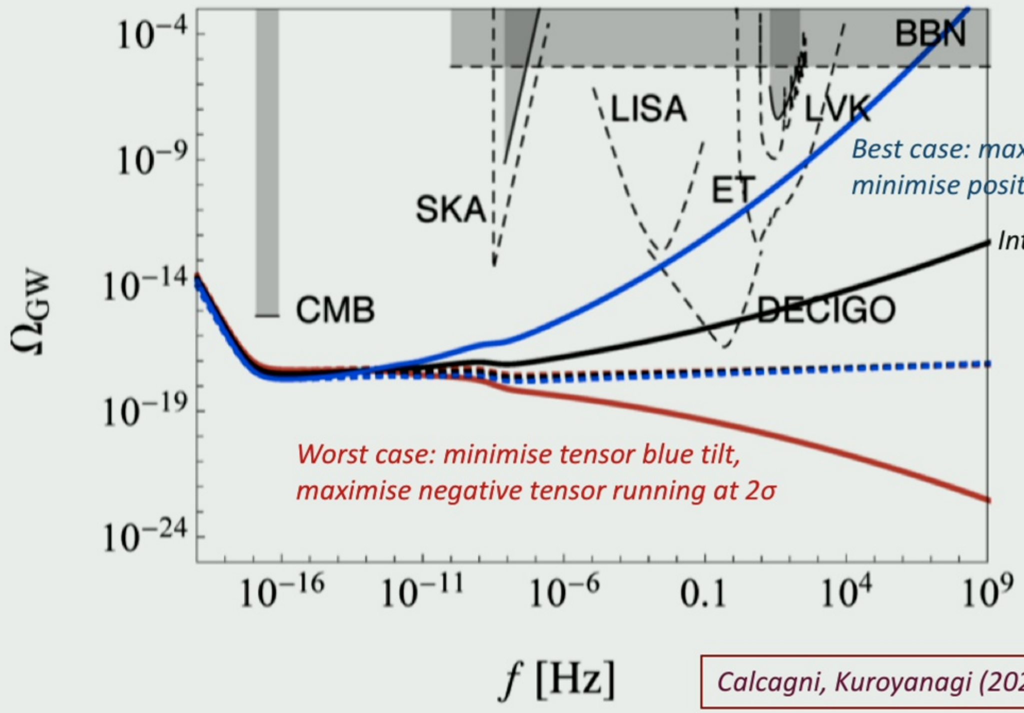
Predictions of QG proposals: amplitude of GWB

New ekpyrotic scenario

$$n_t = 1 - n_s > 0 \qquad \alpha_t = -\alpha_s$$

$$r(k_0) \simeq \frac{2^{n_s} 25}{\Gamma^2\left(1 - \frac{n_s}{2}\right)} (k_0 \tau_B)^{2(1-n_s)} (1 - n_s)^2$$

Brandenberger, Wang (2020)



Best case: maximise tensor blue tilt, minimise positive tensor running at 2σ

Intermediate case (central values of parameters)

Worst case: minimise tensor blue tilt, maximise negative tensor running at 2σ

Calcagni, Kuroyanagi (2021)

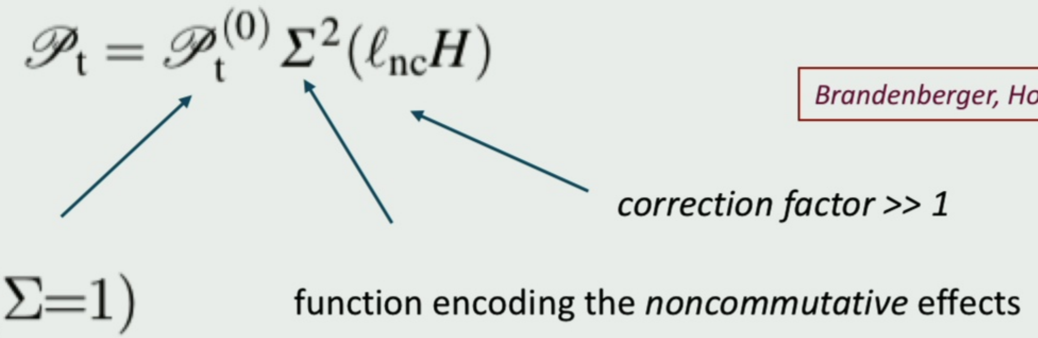
$$\tau_B = 5.8 \times 10^{-24}\,\mathrm{Mpc},$$

(conformal time at GUT)

Predictions of QG proposals: amplitude of GWB

Brandenberger-Ho noncommutative inflation

Time and space coordinates do not commute ➡ *inflaton obeys modified dynamics*



$$\mathscr{P}_{\rm t} = \mathscr{P}_{\rm t}^{(0)}\, \Sigma^2(\ell_{\rm nc} H)$$

Brandenberger, Ho (2002)

correction factor >> 1

amplitude in the commutative limit $\mathcal{P}_{\rm t}^{(0)} = \mathcal{P}_{\rm t}(\Sigma{=}1)$

function encoding the *noncommutative* effects

In natural inflation, one can achieve a blue-tilted tensor spectrum while the scalar spectrum can stay red-tilted

$$n_{\rm t} \simeq \frac{r}{4} \simeq 4\varepsilon, \qquad \alpha_{\rm t} \simeq 8\varepsilon(\varepsilon - \eta)$$

Predictions of QG proposals: amplitude of GWB

Multifractional spacetimes

Different scaling laws in copies of the same object with different sizes

Calcagni (2017)

Dimensional flow: typical for ST arising in QG

't Hoft (1993); carlip (2017)

$$\boxed{\mathscr{P}_{\mathrm{t}}(k) = r(k_0)\,\mathscr{P}_{\mathrm{s}}(k_0)\,\exp\left\{ n_{\mathrm{t}}(k_0)\ln\frac{p(k)}{p(k_0)} + \frac{\alpha_{\mathrm{t}}(k_0)}{2}\left[\ln\frac{p(k)}{p(k_0)}\right]^2 \right\}}$$

$$p(k) \simeq k\left[1 + \frac{1}{|\alpha|}\left(\frac{k}{k_*}\right)^{1-\alpha}\right]^{-1}$$

related to the Hausdorff dimension of space

fundamental comoving scale

Modified dispersion relation and propagation speed

$\underbrace{\text{Dimensional flow}}_{\text{change of ST dimension with probed scale}}$: feature common to all QG theories

change of ST dimension
with probed scale

Quantisation of ST geometry $\Rightarrow$

- Anomalous spacetime measure dρ(x) (*how volumes scale*)
- Kinetic operator $\mathcal{K}$ (*modified dispersion relations*)

Perturbed action for a small perturbation $h_{\mu\nu}$ over the background $g^{(0)}_{\mu\nu}$ up to a source term

$$S = \frac{1}{2\ell_*^{2\Gamma}} \int \mathrm{d}\rho \sqrt{|g^{(0)}|}\,\left[h_{\mu\nu}\mathcal{K}\,h^{\mu\nu} + O(h_{\mu\nu}^2)\right]$$

constant

characteristic length scale around which QG effects become relevant
(if there is only one fundamental scale, then it is near to the Planch scale)

Modified dispersion relation and propagation speed

$\underbrace{\text{Dimensional flow}}_{\substack{\textit{change of ST dimension}\\ \textit{with probed scale}}}$: feature common to all QG theories

Geometric observable $d_{\mathrm{H}}(\ell) := \mathrm{d}\ln\rho(\ell)/\mathrm{d}\ln\ell$

Quantisation of ST geometry ⇒

- Anomalous spacetime measure dρ(x) (*how volumes scale*)
- Kinetic operator $\mathcal{K}$ (*modified dispersion relations*)

Related to Hausdorff dim in Fourier space
and the spectral dim (observable)

In any plateau of dimensional flow, where
all dim are approximately constant:

$$\boxed{\tilde{\mathcal{K}}(-k^2) = -\ell_*^{2-2\beta}k^2 + k^{2\beta}}$$

dispersion relation
of spin 2 graviton

The value of Hausdorff dimensions, spectral dimension
and of the parameter Γ for different QG theories is known

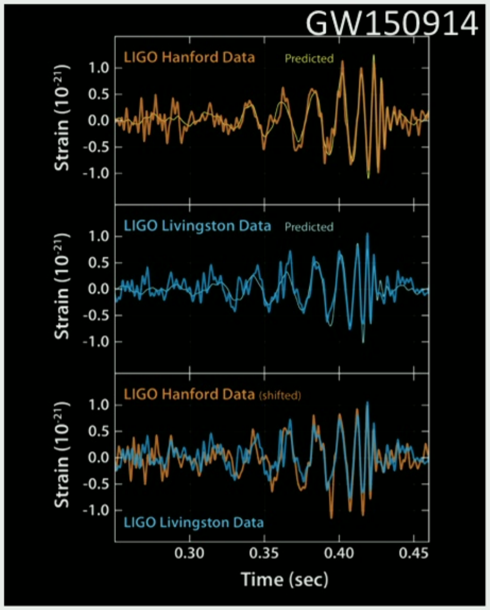
$$\beta = \frac{d_{\mathrm{H}}^k}{d_{\mathrm{S}}} \qquad \Gamma \simeq \frac{d_{\mathrm{H}}}{2} - \frac{d_{\mathrm{H}}^k}{d_{\mathrm{S}}}\,; \approx \mathrm{const}$$

Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato (2019)

Modified dispersion relation and propagation speed

GW propagation speed
(*group velocity*)

$$c_{\mathrm{GW}} := \frac{\mathrm{d}\omega}{\mathrm{d}|\mathbf{k}|}$$



Peaked at frequency: $f = \omega/(2\pi) = 100\,\mathrm{Hz}$

$$m < 1.2 \times 10^{-22}\,\mathrm{eV}.$$

$$\omega \approx 630\,\mathrm{Hz} \approx 4.1 \times 10^{-13}\,\mathrm{eV}$$

At that frequency: $\Delta c := c_{\mathrm{GW}} - 1$

$$\boxed{|\Delta c| < 4.2 \times 10^{-20}} \Rightarrow \boxed{m < 1.2 \times 10^{-22}\,\mathrm{eV}.}$$

LIGO/Virgo Collaboration (2016)

$$\omega^2 = |\mathbf{k}|^2 + m^2 \Rightarrow \Delta c \simeq -m^2/(2\omega^2)$$

if the mass is small

Modified dispersion relation and propagation speed

phenomenological parameters

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

massive gravity

$A_0 > 0$

$m_g = A_0^{1/2}/c^2$

doubly special relativity

$$\alpha = 0, 0.5, 1, 1.5, 2.5, 3, 3.5, 4$$

multi-fractal ST

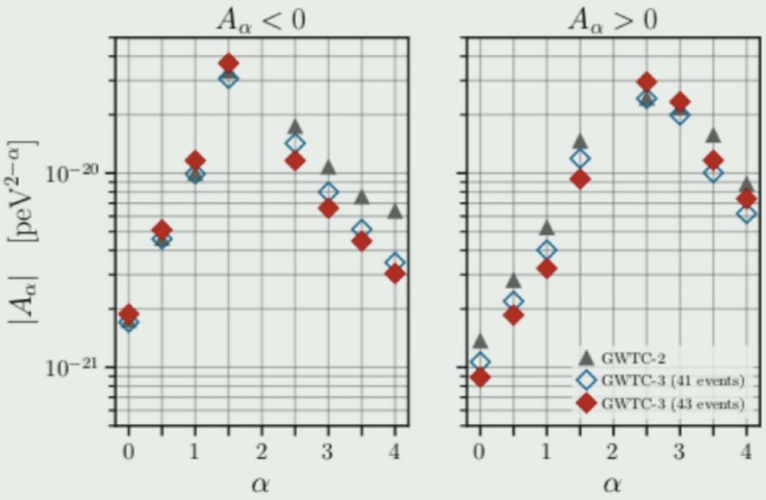
Horava-Lifshitz & extra dim

Frequency dependence of speed of GWs

$$\tilde{h}(\nu) = A(\nu)e^{i\Phi(\nu)}$$

$$\boxed{\tilde{h}(\nu) = A(\nu)e^{i(\Phi(\nu)+\delta\Phi_\alpha(\nu))}}$$

LIGO/Virgo/KAGRA Collaboration (2021)



Modified dispersion relation and propagation speed

In several QG proposals. the propagation speed of GWs may vary as a function of the energy scale

LVC: BNS GW170817 ⇨ $-3\times10^{-15} \leq c_T - 1 \leq 7\times10^{-16}$ (in $c = 1$ units)

Construct a function for $c_T(f)$ which satisfies the LIGO-Virgo bounds whilst modifying the millihertz regime significantly

⇨ sharp transitions for. $c_T(f)$ in the frequency band between LISA and LIGO frequencies

A general theoretical and numerical toolkit for quantifying the perspective of LISA to measure a frequency-dependent propagation speed of GWs only through its effects on GW waveforms from merging massive BH binaries

Baker, Sakellariadou, et al (2022)

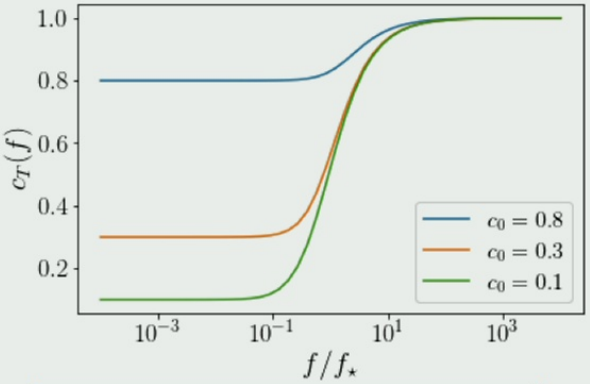
Modified dispersion relation and propagation speed

Quadratic action for the linearised transverse-traceless GW modes

$$S_T = \frac{M_{\rm Pl}^2}{8} \int dt\, d^3x\, a^3(t)\, \bar{\alpha} \left[\dot{h}_{ij}^2 - \frac{c_T^2(f)}{a^2(t)} (\vec{\nabla} h_{ij})^2 \right]$$

Sharp transitions for c_T in the frequency band between LISA and LIGO frequencies, to ensure consistency with results from GW170817

- Polynomial ansatz $c_T(f) = 1 + \sum_n \beta_n \left(\frac{f}{f_*}\right)^n$ LIGO bound implies: $|\beta_n| \lesssim 10^{-15-n} (f_*/\mathrm{Hz})^n$
- EFT-inspired ansatz $c_T(f) = \left[1 + \frac{f_\star^2}{f^2} - \frac{f_\star^2}{f^2} \sqrt{1 + 2\left(1 - c_0^2\right) \frac{f^2}{f_\star^2}} \right]^{1/2}$



Baker, Sakellariadou, et al (2022)

Luminosity distance

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

power per unit area emitted by the source

flux of light reaching an observer

luminosity distance

GR: $$d_L^{\mathrm{EM}}(z) = (1+z)\int_{t(z)}^{t_0} \frac{\mathrm{d}t}{a} = (1+z)\int_0^z \frac{\mathrm{d}z}{H_{\mathrm{GR}}} \overset{\text{at small } z}{\simeq} z/H_0,$$

$$a(z) = (1+z)^{-1}$$

$$H_{\mathrm{GR}}^2 = (\kappa^2/3)\rho$$

Amplitude of GWs in the local wave zone of the source

$$\boxed{h \simeq \frac{\kappa \mathscr{F}_h(t-r)}{r^{\frac{D-2}{2}}} \overset{D=4}{\propto} \frac{1}{r}}$$

function in retarded time

topological dimensions

comoving distance from source

rescaling with scale factor

$$\boxed{h \sim \frac{1}{(d_L^{\mathrm{EM}})^{\frac{D-2}{2}}} \overset{D=4}{=} \frac{1}{d_L^{\mathrm{EM}}}}$$

Cardoso, Dias, Lemos (2003)
Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato (2019)

Luminosity distance

Standard sirens

GR: $$\boxed{h \sim \frac{1}{(d_L^{\mathrm{EM}})^{\frac{D-2}{2}}} \overset{D=4}{=} \frac{1}{d_L^{\mathrm{EM}}}}$$

In theories beyond GR, this relation can be different

Standard sirens: *strain measured in an interferometer* observations in the optical spectrum

GW luminosity distance

(up to a retarded time-dependent function)

$$\boxed{h \simeq \frac{\kappa \mathscr{F}_h(t-r)}{r^{\frac{D-2}{2}}} \overset{D=4}{\propto} \frac{1}{r}}$$

$$\boxed{d_L^{\mathrm{GW}}(z)/d_L^{\mathrm{EM}}(z)}$$ deviates from 1

cosmological observable that can be determined from standard sirens

Predictions of QG proposals: luminosity distance

Luminosity distance in QG in a model-independent way: dimensional flow

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

$d_L^{\rm GW}(z)/d_L^{\rm EM}(z)$

Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato (2019)

- Only one fundamental scale: $\gamma \neq 0$

  Equation for the ratio is exact and $\ell_* = O(\ell_{\rm Pl})$ with $\gamma = \Gamma_{\rm UV}$

- If $-3 \leq \Gamma_{\rm UV} \leq 2$ is a mesoscopic scale much larger than the Planck scale, the equation for the ratio is valid only near the IR: ℓ_*

Observations can place bounds on the two parameters γ and $\gamma = \Gamma_{\rm UV} \leq 1$ in a model-independent way, by constraining the ratio as a function of the redshift of the source

Predictions of QG proposals: luminosity distance

Luminosity distance in QG in a model-independent way: dimensional flow

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

$d_L^{\mathrm{GW}}(z)/d_L^{\mathrm{EM}}(z)$

Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato (2019)

BNS merger GW170817 and a simulated *z* = 2 SMBH merging event that could be observed by LISA:

the only theories that can be tested are those for which $\Gamma_{\mathrm{meso}} > 1 > \Gamma_{\mathrm{UV}}$

LQC / SF / GFT

Observations can place bounds on the two parameters γ and [illegible] in a model-independent way, by constraining the ratio as a function of the redshift of the source

Brane/String theory: Extra dimensions

Constraints on the number of spacetime dimensions from GWs

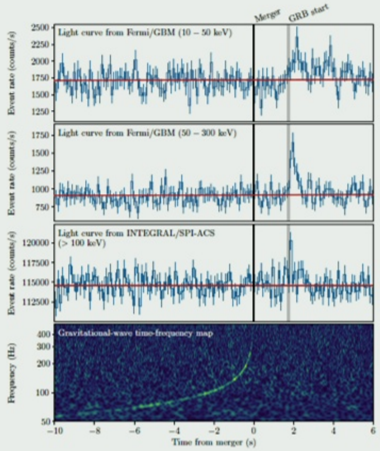
$$\frac{d_L^{GW}}{d_L^{EM}} = 1 \pm |\gamma - 1| \left(\frac{d_L^{EM}}{l_*} \right)^{\gamma - 1}$$

Damping of the waveform due to gravitational leakage (beyond R_c) into extra dim

Deviation depends on the number of dimensions D and would result to a systematic **overestimation of the source** d_L^{EM} **inferred from GW data**

$$\boxed{h \propto \frac{1}{d_L^{\mathrm{GW}}} = \frac{1}{d_L^{\mathrm{EM}}} \left[1 + \left(\frac{d_L^{\mathrm{EM}}}{R_c} \right)^n \right]^{-(D-4)/(2n)}}$$

$$h \propto \frac{1}{d_L^{\mathrm{GW}}} = \frac{1}{d_L^{\mathrm{EM}}} \left[1 + \left(\frac{d_L^{\mathrm{EM}}}{R_c} \right)^n \right]^{-(D-4)/(2n)}$$



Strain *measured in a GW interferometer* ⟷ ***Luminosity distance*** *measured for the optical counterpart of the standard siren*

- Consistency with GR in D=4 dim
- Some models based on extra dimensions are ruled out

LIGO/Virgo/KAGRA Collaboration(2019)

GRB 170817A and GW170817

GW event 1.7 s before γ-ray observation

BNS merger at 40 Mpc

What I have not discussed

Predictions of beyond GR theories:

- generation : relates the outgoing radiation to the properties of the source, a hard problem even in GR
- propagation : birefringence (I've discussed only dispersion relation and amplitude damping)

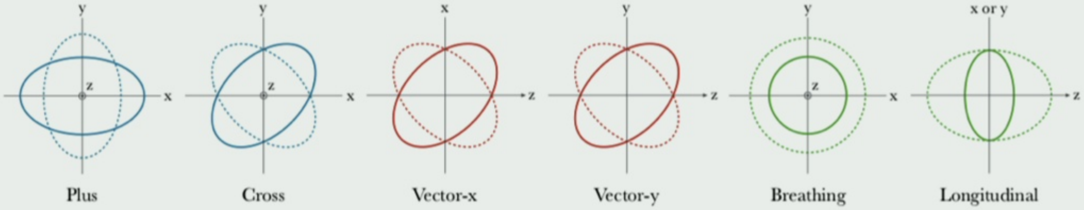
GWs propagate from the source to the detector, the amplitudes of left versus right polarised modes are exponentially enhanced or suppressed, a **parity-violating effect**

Martinovic, Badger, Sakellariadou, Mandic, PRD 104 (2021) 8, L081101

What I have not discussed

Predictions of beyond GR theories:

- generation : relates the outgoing radiation to the properties of the source, a hard problem even in GR
- propagation : birefringence (I've discussed only dispersion relation and amplitude damping)
- polarisation : a metric theory of gravity can allow up to six modes of polarisation: two tensor (helicity ± 2), two vector (helicity ± 1), and two scalar (helicity 0) modes



Callister, Sakellariadou et al, PRX 7 (2017) 041058

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- remnant properties (exotic ultracompact objects without horizon, gravastars, fuzballs, etc)

compact object with an interior de Sitter condensate phase and an exterior Schwarzschild geometry

a ball-shaped mess of interacting fundamental strings

Conclusions

Quite unlikely to have, in the near future, laboratory experiments that test quantum gravity:

$$d_L^{\mathrm{EM}} \simeq \frac{z(1+z)}{H_0} \overset{z \ll 1}{\simeq} \frac{z}{H_0}$$

Cosmology provides a test of quantum theory of gravity (a quantum theory of spacetime geometry

Difficult, but still possible, to test QG with GW observations