Motivation
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Imminent test of quantum gravity with gravitational waves

arXiv:2206.06384, arXiv:2206.07066
with L. Modesto

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

IEM

May 5, 2024

01/21– Quantum gravity

- Many proposals: string theory, loop quantum gravity, asymptotic safety, nonlocal quantum gravity (**v1.0-1.3**), fractional gravity, . . .
- Some of them make contact with observations.
- Very few of them make falsifiable predictions.

01/21– Quantum gravity

- Many proposals: string theory, loop quantum gravity, asymptotic safety, nonlocal quantum gravity (**v1.0-1.3**), fractional gravity, . . .
- Some of them make contact with observations.
- Very few of them make falsifiable predictions.

Nonlocal quantum gravity generates falsifiable predictions (**v2.0**).

02/21– Stelle gravity

Stelle 1977, 1978:

$$\mathcal{L} = R + \gamma_0 R^2 + \gamma_2 R_{\mu\nu} R^{\mu\nu}, \qquad \gamma_{0,2} = \text{const}$$

Renormalizable but non-unitary (spin-2 ghost). (Can be made unitary introducing fakeons [Anselmi & Piva 2017ab,2018].)

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02/21– Stelle gravity

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Renormalizable but non-unitary (spin-2 ghost). (Can be made unitary introducing fakeons [Anselmi & Piva 2017ab,2018].)
Ostrogradski instability (ghost) from higher-order derivatives.
Example:

$$(\Box + \alpha\Box^2)\phi = 0 \qquad \Rightarrow \qquad \tilde{G}(k) = \frac{1}{k^2 - \alpha k^4} = -\frac{1}{k^2} + \frac{1}{k^2 - \alpha^{-1}}$$

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03/21– Nonlocal quantum gravity v1.0-1.3

Krasnikov 1987; Kuz'min 1989; Tomboulis 1997; Modesto 2011; Gerwick et al. 2011

$$
\begin{aligned}
\mathcal{L} &= R + R\gamma_0(\Box)R + R_{\mu\nu}\gamma_2(\Box)R^{\mu\nu} + R_{\mu\nu\sigma\tau}\gamma_4(\Box)R^{\mu\nu\sigma\tau} + \mathcal{V}(\mathcal{R}) + \mathcal{L}_{\mathrm{m}} \\
&= R + G_{\mu\nu}\gamma(\Box)R^{\mu\nu} + R_{\mu\nu\sigma\tau}\gamma_4(\Box)R^{\mu\nu\sigma\tau} + \mathcal{V}(\mathcal{R}) + \mathcal{L}_{\mathrm{m}}
\end{aligned}
$$

Minimal coupling to matter. Asymp. polynomial form factor:

$$
\gamma(\Box) = \frac{e^{\mathrm{H}(\Box)} - 1}{\Box}, \qquad e^{\mathrm{H}(\Box)} = e^{\gamma_{\mathrm{E}} + \Gamma[0,p(\Box)]}p(\Box) \overset{\mathrm{UV}}{\sim} e^{\gamma_{\mathrm{E}}}p(\Box)
$$

- **v1.0**: $\gamma_4 \neq 0$, $\mathcal{V}(\mathcal{R}) = 0$
- **v1.1**: $\gamma_4 = 0$
- **v1.2**: $\gamma_4 = 0$, $\mathcal{V}(\mathcal{R}) \neq 0$, conformal symmetry
- **v1.3**: add a mass scale in $\gamma_{0,2}(\Box)$ to get Starobinsky

04/21–   Properties of nonlocal quantum gravity v1.0-1.3

- Well-defined Cauchy problem [GC, Modesto & Nardelli 2019]
- Finite number of physical degrees of freedom* [GC et al. 2019]
- Super-renormalizable or finite [Modesto & Rachwał 2014,2015]
- Perturbatively unitary [Briscese & Modesto 2019]
- Big-bang singularity resolved classically [Biswas, Mazumdar & Siegel, 2005; GC, Modesto & Nicolini 2014]
- Black-hole singularities resolved classically by nonlocality (**v1.0**, $\gamma_4 \neq 0$) [Modesto et al. 2015; Frolov & Zelnikov 2016; Edholm et al. 2016; Buoninfante et al. 2018; Giacchini & de Paula Netto 2019; Boos 2020] or by conformal symmetry (**v1.2**, $\gamma_4 = 0$, finite) [Modesto & Rachwał 2016; Bambi et al. 2017ab; Zhou et al. 2019]
- Starobinsky inflation naturally embedded (**v1.3**) [Koshelev et al. 2016,2018,2020; Kumar & Modesto 2018; GC & Kuroyanagi 2021]
- **Forces not unified and no soon-falsifiable prediction**

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05/21– A nonlocal theory of all fields

$$S[\Phi_i] = \int \mathsf{d}^D x \sqrt{|g|} \left[\mathcal{L}_{\mathrm{loc}} + E_i \, F^{ij}(\Delta) \, E_j + \mathcal{V}(E_i) \right]$$

$$S_{\mathrm{loc}} = \int \mathsf{d}^D x \sqrt{|g|} \, \mathcal{L}_{\mathrm{loc}}, \qquad \mathcal{L}_{\mathrm{loc}} = \frac{M_{\mathrm{Pl}}^2}{2} R + \mathcal{L}_{\mathrm{m}}(\Phi_i)$$

$$E_i := \frac{\delta S_{\mathrm{loc}}}{\delta \Phi_i(x)}, \qquad \Delta_{ki} := \frac{\delta E_i}{\delta \Phi_k} = \frac{\delta^2 S_{\mathrm{loc}}}{\delta \Phi_k \delta \Phi_i}$$

$$\Phi_i \in \{ g_{\mu\nu}, \Phi, \psi, A_\mu, \dots \}$$

$$F(\Delta) := \frac{\mathsf{e}^{\mathrm{H}(\Delta) - \mathrm{H}(0)} - 1}{2\Delta}, \qquad \mathrm{H}(z) = \int_0^{p(z)} \mathsf{d}w \, \frac{1 - \mathsf{e}^{-w}}{w}$$

$$p(z) = b_0 - b \, z + z^4$$

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06/21– Nonlocal quantum gravity v2.0: equations of motion

Extremals:

$$E_{\mu\nu} = \frac{1}{2} \left(M_{\mathrm{Pl}}^2 G_{\mu\nu} - T_{\mu\nu} \right)$$

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06/21– Nonlocal quantum gravity v2.0: equations of motion

Extremals:

$$E_{\mu\nu} = \frac{1}{2} \left(M_{\mathsf{Pl}}^2 G_{\mu\nu} - T_{\mu\nu} \right)$$

Nonlocal gravitational EOMs:

$$\left[e^{\bar{H}(\Delta)} \right]_{\mu\nu}^{\sigma\tau} E_{\sigma\tau} + O(E_{\mu\nu}^2) = 0$$

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07/21– Conformal invariance

Field redefinitions:

$$g_{\mu\nu} =: \phi^2 \, \hat{g}_{\mu\nu} \,, \quad \Phi = \frac{\hat{\Phi}}{\phi} \,, \quad \psi = \frac{\hat{\psi}}{\phi^{\frac{3}{2}}} \,, \quad A_\mu = \hat{A}_\mu$$

Action invariant under Weyl transformations

$$\hat{g}'_{\mu\nu} = \Omega^2(x) \, \hat{g}_{\mu\nu} \,, \qquad \phi' = \Omega^{-1}(x) \, \phi \,, \qquad \dots$$

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08/21– Properties of nonlocal quantum gravity v2.0

- Same basic characteristics as v1.0-1.2 [Modesto 2021].
- Super-renormalizable or finite [GC, Giacchini, Modesto, de Paula Netto & Rachwał 2023].
- Tree-level scattering amplitudes are the same as those of the underlying local theory [Modesto & GC 2021].
- Testable top-down cosmology [Modesto & GC 2022; GC & Modesto 2022] ⟵

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- Testable top-down cosmology [Modesto & GC 2022; GC & Modesto 2022] ⟸

Finiteness implies conformal invariance at the quantum level.

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09/21– Two phases

$$F(\Delta) := \frac{e^{H(\Delta)-H(0)} - 1}{2\Delta}, \qquad H(z) = \text{Ein}(z) = \int_0^{p(z)} dw \, \frac{1 - e^{-w}}{w}$$

$$p(z) = b_0 - b\,z + z^4$$

1. **Trans-Planckian conformal phase** $\Lambda_* \lesssim E \lesssim M_{\text{Pl}}$.
   Manifest Weyl invariance.

2. **Post-Planckian Higgs phase** $\Lambda_*/\sqrt{b} =: \Lambda_{\text{hd}} \lesssim E \lesssim \Lambda_*$.
   Intermediate UV regime $p(z) \simeq -bz$, broken Weyl symmetry.

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10/21– Post-Planckian Higgs phase $\Lambda_{\mathrm{hd}} \lesssim E \lesssim \Lambda_*$

Intermediate UV regime $p(z) \simeq -bz$:

$$\sqrt{\frac{\max(1, b_0)}{b}} \, \Lambda_* =: \Lambda_{\mathrm{hd}} \lesssim E \lesssim \Lambda_*$$

Choice of vacuum: $\phi \to \langle\phi\rangle = \frac{M_{\mathrm{Pl}}}{\sqrt{2}} + \langle\varphi\rangle \simeq \frac{M_{\mathrm{Pl}}}{\sqrt{2}}$

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10/21– Post-Planckian Higgs phase $\Lambda_{\mathrm{hd}} \lesssim E \lesssim \Lambda_*$

Intermediate UV regime $p(z) \simeq -bz$:

$$\boxed{\sqrt{\frac{\max(1, b_0)}{b}}\, \Lambda_* =: \Lambda_{\mathrm{hd}} \lesssim E \lesssim \Lambda_*}$$

Choice of vacuum: $\phi \to \langle\phi\rangle = \frac{M_{\mathrm{Pl}}}{\sqrt{2}} + \langle\varphi\rangle \simeq \frac{M_{\mathrm{Pl}}}{\sqrt{2}}$ How to generate minima:

• Adding Λ_{cc} in $\mathcal{L}_{\mathrm{loc}} = \mathcal{L}_{\mathrm{loc}}[\phi^2 \hat{g}_{\mu\nu}, \phi^{-\Delta_i} \hat{\Phi}_i^{\mathrm{SM}}]$ generates a $\sqrt{|g|}\Lambda_{\mathrm{cc}} = \sqrt{|\hat{g}|}\Lambda_{\mathrm{cc}}\phi^4$ term.

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10/21– Post-Planckian Higgs phase $\Lambda_{\rm hd} \lesssim E \lesssim \Lambda_*$

Intermediate UV regime $p(z) \simeq -bz$:

$$\boxed{\sqrt{\frac{\max(1, b_0)}{b}} \Lambda_* =: \Lambda_{\rm hd} \lesssim E \lesssim \Lambda_*}$$

Choice of vacuum: $\phi \to \langle\phi\rangle = \frac{M_{\rm Pl}}{\sqrt{2}} + \langle\varphi\rangle \simeq \frac{M_{\rm Pl}}{\sqrt{2}}$ How to generate minima:

• Adding $\Lambda_{\rm cc}$ in $\mathcal{L}_{\rm loc} = \mathcal{L}_{\rm loc}[\phi^2 \hat{g}_{\mu\nu}, \phi^{-\Delta_i} \hat{\Phi}_i^{\rm SM}]$ generates a $\sqrt{|g|}\Lambda_{\rm cc} = \sqrt{|\hat{g}|}\Lambda_{\rm cc}\phi^4$ term.

• Modify $\mathcal{L}_{\rm loc} = \mathcal{L}_1^{\rm loc}[\phi^2 \hat{g}_{\mu\nu}, \phi^{-\Delta_i} \hat{\Phi}_i^{\rm SM}] + \mathcal{L}_2^{\rm loc}[\phi, \hat{g}_{\mu\nu}, \hat{\Phi}_i^{\rm SM}]$ and add Weyl-invariant dilaton-Higgs potential [Bars et al. 2006,2014]:

$$\mathcal{L}_2^{\rm loc}[\phi, \mathfrak{h}] = \lambda(\mathfrak{h}^\dagger\mathfrak{h} - \alpha\phi^2)^2 + \lambda'\phi^4$$

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11/21– Post-Planckian Higgs phase $\Lambda_{\mathrm{hd}} \lesssim E \lesssim \Lambda_*$

Local quadratic action + one-loop log quantum corrections:

$$
\begin{aligned}
\mathcal{L}_{\Lambda_{\mathrm{hd}}} &= \frac{M_{\mathrm{Pl}}^2}{2} R + \mathcal{L}_{\mathrm{m}} + E_{\mu\nu} E^{\mu\nu} + \mathcal{V}(E_{\mu\nu}) + \mathcal{L}_Q \\
\mathcal{L}_Q &= \beta_R R \ln\left(-\frac{\Box}{\Lambda_*^2 \delta_0^2}\right) R + \beta_{\mathrm{Ric}} R_{\mu\nu} \ln\left(-\frac{\Box}{\Lambda_*^2}\right) R^{\mu\nu}
\end{aligned}
$$

δ_0, β_R, β_{Ric} numerical constants (not beta functions!).
Overconstrained Stelle limit:

$$
E_{\mu\nu} E^{\mu\nu} = -\frac{M_{\mathrm{Pl}}^4}{4}\left(R_{\mu\nu} R^{\mu\nu} + \frac{D-4}{4} R^2\right)
$$

$$
\mathcal{L}_{\Lambda_{\mathrm{hd}}}^{D=4} = -\frac{\mathrm{e}^{\tilde{\gamma}_{\mathrm{E}}} M_{\mathrm{Pl}}^2 b}{2\Lambda_*^2} R_{\mu\nu} R^{\mu\nu} + \mathcal{L}_{\mathrm{m}} + \mathcal{L}_Q
$$

12/21– Early universe

I. Solutions of hot-big-bang problems

All problems of the hot big-bang model are solved **without inflation** in the conformal phase

II. Primordial perturbations

Quasi-scale-invariant primordial spectra generated by **quantum and thermal fluctuations** in the Higgs phase

III. Testable prediction

Large tensor-to-scalar ratio, **observable by BICEP Array** and **LiteBIRD**

13/21–   Conformal invariance

- Conformal invariance as an alternative to inflation is not new [Antoniadis et al. 1997,2012; Amelino-Camelia et al. 2013,2015; Agrawal et al. 2020] . . .

- . . . but until now it was not known how to make it work in a fundamental theory.

- We provide a concrete setting thanks to UV finiteness. . .

- . . . and extract rigid, falsifiable predictions on the tensor sector.

- Such rigidity comes from the fact that our cosmological model is derived *directly* from the full theory.

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14/21–   Flat spacetime approximation

Two assumptions

1. Quadratic-gravity limit, $\Lambda_{\mathrm{hd}} \lesssim E \lesssim \Lambda_*$.
2. One-loop quantum corrections in the propagator subdominant with respect to classical part, $E \gtrsim \Lambda_*/10$.

$$\Longrightarrow \qquad E \simeq \frac{\Lambda_*}{10}$$

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15/21–   Tensor spectrum

From sub-horizon quantum fluctuations. Graviton two-point correlation function:

$$\langle h_{ij}(x) h_{kl}(x') \rangle = -C \Lambda_*^{2\epsilon_2} P_{ijkl}^{(2)}(\partial_x) \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \frac{\mathrm{e}^{\mathrm{i}k \cdot (x-x')}}{k^{4+2\epsilon_2}} = -P_{ijkl}^{(2)}(\partial_x) \int_0^{+\infty} \frac{\mathrm{d}k}{k} \Delta_h^2(k) \frac{\sin(kr)}{kr}$$

$$C := \frac{4\Lambda_*^2}{b \, \mathrm{e}^{\tilde{\gamma}_{\mathrm{E}}} M_{\mathrm{Pl}}^2} \,, \qquad \epsilon_2 = -\frac{2\beta_{\mathrm{Ric}} \Lambda_*^2}{b \, \mathrm{e}^{\tilde{\gamma}_{\mathrm{E}}} M_{\mathrm{Pl}}^2}$$

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15/21–   Tensor spectrum

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$$\langle h_{ij}(x)h_{kl}(x')\rangle = -\mathrm{C}\Lambda_*^{2\epsilon_2}\,P_{ijkl}^{(2)}(\partial_x)\int\frac{\mathrm{d}^4k}{(2\pi)^4}\,\frac{\mathrm{e}^{\mathrm{i}k\cdot(x-x')}}{k^{4+2\epsilon_2}} = -P_{ijkl}^{(2)}(\partial_x)\int_0^{+\infty}\frac{\mathrm{d}k}{k}\,\Delta_h^2(k)\,\frac{\sin(kr)}{kr}$$

$$\mathrm{C} := \frac{4\Lambda_*^2}{b\,\mathrm{e}^{\tilde{\gamma}_{\mathrm{E}}}M_{\mathrm{Pl}}^2}\,, \qquad \epsilon_2 = -\frac{2\beta_{\mathrm{Ric}}\Lambda_*^2}{b\,\mathrm{e}^{\tilde{\gamma}_{\mathrm{E}}}M_{\mathrm{Pl}}^2}$$

Tensor spectrum:

$$\boxed{\mathcal{P}_{\mathrm{t}}(k) := 2\Delta_h^2(k) = \frac{n_{\mathrm{t}}}{(2\pi)^2\,\beta_{\mathrm{Ric}}}\,(\ell_* k)^{n_{\mathrm{t}}}}$$

Tensor spectral index:

$$\boxed{n_{\mathrm{t}} := \frac{\mathrm{d}\ln\mathcal{P}_{\mathrm{t}}}{\mathrm{d}\ln k} = -2\epsilon_2 = \frac{4\beta_{\mathrm{Ric}}}{b\,\mathrm{e}^{\tilde{\gamma}_{\mathrm{E}}}}\,\frac{\Lambda_*^2}{M_{\mathrm{Pl}}^2} > 0}$$

16/21– Scalar spectrum

From thermal fluctuations. Radiation-dominated universe.

$$\delta h \quad \overset{\delta\text{EOM}}{\longrightarrow} \quad \delta T_{00} = \delta\rho\Big|_{E\simeq\frac{\Lambda_*}{10}} \quad \overset{\text{Poisson eq.}}{\longrightarrow} \quad \delta\Phi\Big|_{\text{lss}} \quad \longrightarrow \quad \frac{\delta T_{\text{CMB}}}{T_{\text{CMB}}}\Big|_{\text{lss}}$$

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16/21– Scalar spectrum

From thermal fluctuations. Radiation-dominated universe.

$$\delta h \quad \xrightarrow{\delta \text{EOM}} \quad \delta T_{00} = \delta \rho \Big|_{E \simeq \frac{\Lambda_*}{10}} \quad \xrightarrow{\text{Poisson eq.}} \quad \delta \Phi \Big|_{\text{lss}} \quad \longrightarrow \quad \frac{\delta T_{\text{CMB}}}{T_{\text{CMB}}} \Big|_{\text{lss}}$$

Scalar spectrum:

$$\mathcal{P}_{\text{s}}(k) = \frac{9}{4} \Delta_{\Phi}^2(k) = \frac{15}{64} \frac{(n_{\text{s}} - 1)^2}{(2\pi)^2 \beta_{\text{Ric}}} (\ell_* k)^{n_{\text{s}} - 1}$$

Scalar spectral index:

$$n_{\text{s}} - 1 := \frac{\mathsf{d} \ln \mathcal{P}_{\text{s}}}{\mathsf{d} \ln k} = 2\epsilon_2 = -\frac{4\beta_{\text{Ric}}\Lambda_*^2}{b \, \mathsf{e}^{\tilde{\gamma}_{\text{E}}} M_{\text{Pl}}^2} < 0$$

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17/21–

Tensor-to-scalar ratio and consistency relation

Tensor-to-scalar ratio:

$$r := \frac{\mathcal{P}_{\text{t}}(k_0)}{\mathcal{P}_{\text{s}}(k_0)} = \frac{64}{15(1 - n_{\text{s}})} \, (\ell_* k_0)^{2(1 - n_{\text{s}})}$$

17/21–   Tensor-to-scalar ratio and consistency relation

Tensor-to-scalar ratio:

$$r := \frac{\mathcal{P}_{\text{t}}(k_0)}{\mathcal{P}_{\text{s}}(k_0)} = \frac{64}{15(1 - n_{\text{s}})} \, (\ell_* k_0)^{2(1 - n_{\text{s}})}$$

Consistency relation:

$$n_{\text{t}} = 1 - n_{\text{s}} > 0$$

Typical of non-inflationary scenarios such as string-gas cosmology [Brandenberger 2015; Bernardo et al. 2020] and new ekpyrotic model [Brandenberger & Wang 2020ab].

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18/21– Primordial GWs

PLANCK Legacy with $dn_s/d\ln k = 0$ [Aghanim et al. 2020],
$k_0 = 0.05\,\mathrm{Mpc}^{-1}$, n_t and r uniquely specified:

$$n_t \approx 0.0351 , \qquad r_{0.05} = 0.009 - 0.011$$

For $\ell_* = \ell_{\mathrm{Pl}}$:

$$\boxed{r_{0.05} = 0.011}$$

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- Three times larger than $r_{\mathrm{Starobinsky}} = 0.0037$.

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For $\ell_* = \ell_\mathrm{Pl}$:

$$\boxed{r_{0.05} = 0.011}$$

• Three times larger than $r_\mathrm{Starobinsky} = 0.0037$.
• Within reach of **BICEP Array** (uncertainty $\sigma(r) \sim 0.003$)
within 4 years [Ade et al. 2021]. Detection if $r > 0.009$, implication
if $r \sim 0.006 - 0.009$, exclusion if $r < 0.006$.

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18/21– Primordial GWs

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• Within reach of **BICEP Array** (uncertainty $\sigma(r) \sim 0.003$)
within 4 years [Ade et al. 2021]. Detection if $r > 0.009$, implication
if $r \sim 0.006 - 0.009$, exclusion if $r < 0.006$.
• LiteBIRD: $\sigma(r) \sim 0.001$ (exclusion if $r < 0.002$) [Allys et al. 2022].

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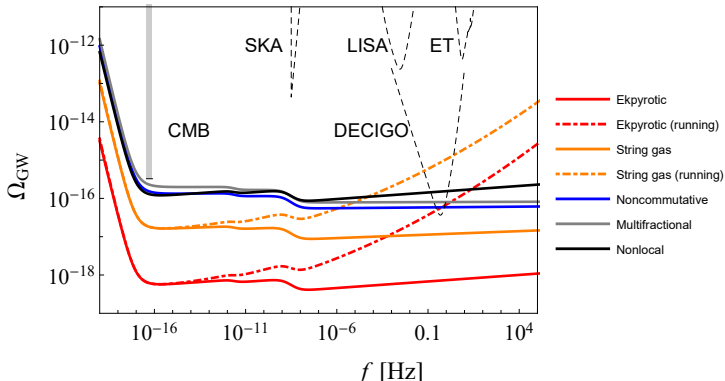Cosmology
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19/21– Stochastic GW background

Blue-tilted tensor spectrum at CMB scales, stochastic GW background observable by DECIGO. Can serve as discriminator against other high-r models.

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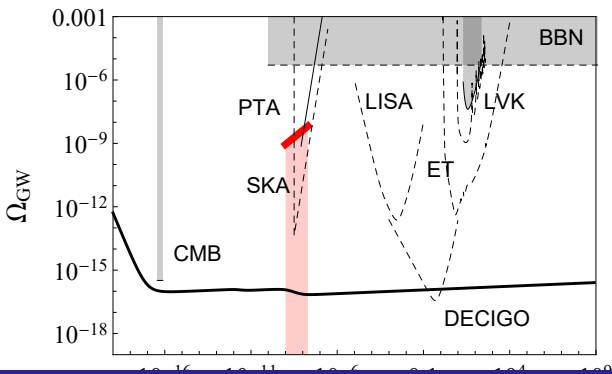
20/21– Quantum gravity and GWs

GC & Kuroyanagi, to appear (2024)

Only DECIGO will be able to see a stochastic background from
blue-tilted quantum-gravity-motivated primordial spectra.

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21/21– Discussion

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21/21– Discussion

- Unique predictions for $n_{\rm t}$ and r, only one free parameter b.
  Genuine evidence of perturbative quantum gravity.

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21/21– Discussion

- Unique predictions for n_t and r, only one free parameter b. Genuine evidence of perturbative quantum gravity.
- The test of the theory is imminent. If it fails, the theory will need an inflaton and be much less appealing.

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- Unique predictions for n_t and r, only one free parameter b. Genuine evidence of perturbative quantum gravity.

- The test of the theory is imminent. If it fails, the theory will need an inflaton and be much less appealing.

- Primordial non-Gaussianity expected larger than inflationary one but still within observational bounds
  [Antoniadis et al. 1997,2012; Agrawal et al. 2020].

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21/21– Discussion

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- Primordial non-Gaussianity expected larger than inflationary one but still within observational bounds [Antoniadis et al. 1997,2012; Agrawal et al. 2020].

- Investigate value of β_{Ric}.

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21/21–   Discussion

- Unique predictions for n_t and r, only one free parameter b. Genuine evidence of perturbative quantum gravity.

- The test of the theory is imminent. If it fails, the theory will need an inflaton and be much less appealing.

- Primordial non-Gaussianity expected larger than inflationary one but still within observational bounds [Antoniadis et al. 1997,2012; Agrawal et al. 2020].

- Investigate value of β_{Ric}.

- Dark energy? H_0 and σ_8?

TO BE CONTINUED . . .