Nonlocal quantum gravity and the early Universe: imminent test with gravitational waves

arXiv:2206.06384, arXiv:2206.07066

with L. Modesto

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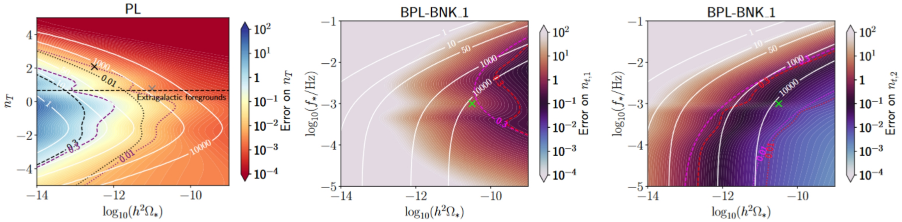
IEM

01/29– Single- and double-power-law GWB

Braglia, GC et al. [LISA Cosmology Working Group] to appear (2024)

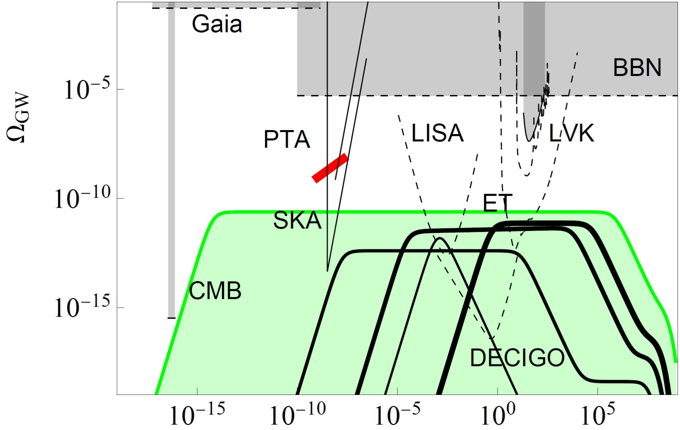
LISA
CosWG-24-03



02/29– Quantum gravity and GWs I

Ben-Dayan, GC et al. arXiv:2406.13521

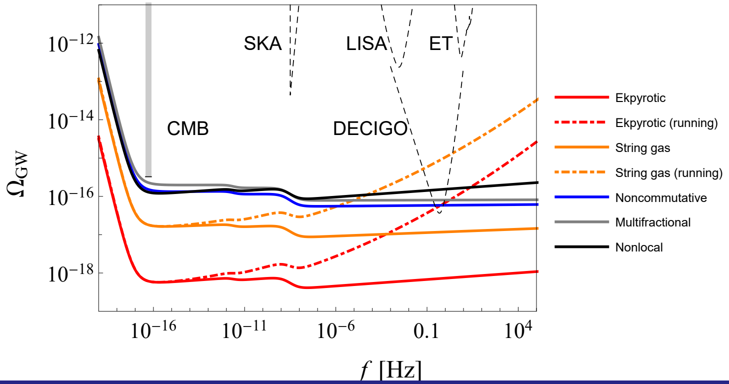
Pre-big-bang cosmology can reach LISA and ET windows.



03/29– Quantum gravity and GWs II

GC & Kuroyanagi, JCAP 2021; in progress (2024)

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



04/29– 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.

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

05/29– 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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Ostrogradski instability (ghost) from higher-order derivatives.
Example:

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

06/29– Nonlocal quantum gravity v1.0-1.3

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

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

Minimal coupling to matter. Asymp. polynomial form factor:

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

- **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

07/29– Properties of nonlocal quantum gravity v1.0-1.3

- Lorentzian and Euclidean path integrals [GC & Modesto 2024]
- 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 et al. 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**

08/29– A nonlocal theory of all fields

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

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

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

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

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

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

09/29– Nonlocal quantum gravity v2.0: equations of motion

Extremals:

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

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Nonlocal gravitational EOMs:

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

10/29– 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

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

11/29– 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] $\Longleftarrow$

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Finiteness implies conformal invariance at the quantum level.

12/29– Two phases

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

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

1. **Trans-Planckian conformal phase** $\Lambda_* \lesssim E \lesssim M_{\mathrm{Pl}}$. Manifest Weyl invariance.
2. **Post-Planckian Higgs phase** $\Lambda_*/\sqrt{b} =: \Lambda_{\mathrm{hd}} \lesssim E \lesssim \Lambda_*$. Intermediate UV regime $p(z) \simeq -bz$, broken Weyl symmetry.

13/29– Trans-Planckian conformal phase $\Lambda_* \lesssim E \lesssim M_{\rm Pl}$

Manifest Weyl invariance, correlation functions of nonconformal fields ($\Delta_i \neq 0$) identically zero [Di Francesco 1997]:

$$\begin{aligned}\langle O_1(x_1)\dots O_n(x_n)\rangle &:= \frac{1}{Z_0}\int[\mathcal{D}O]\, O_1(x_1)\dots O_n(x_n)\mathrm{e}^{\mathrm{i}S[O]}\\ &= \Omega^{\Delta_1}(x_1)\dots\Omega^{\Delta_n}(x_n)\langle O_1(x_1)\dots O_n(x_n)\rangle = 0\end{aligned}$$

Gravity disappears!

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Gravity disappears!
Quantum corrections are $O(h^3)$, $O(h^2\phi)$ and do not affect propagators in this phase.

14/29– 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: $\phi \to \langle\phi\rangle = \frac{M_{\rm Pl}}{\sqrt{2}} + \langle\varphi\rangle \simeq \frac{M_{\rm Pl}}{\sqrt{2}}$.

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• 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.

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- 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]:

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

15/29– Post-Planckian Higgs phase $\Lambda_{\rm hd} \lesssim E \lesssim \Lambda_*$

Local quadratic action + one-loop log quantum corrections:

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

δ_0, β_R, $\beta_{\rm Ric}$ numerical constants (not beta functions!).
Overconstrained Stelle limit:

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

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

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**

17/29– 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.

18/29– Initial conditions in the Higgs phase

The metric at the onset of the Higgs phase is either Minkowski or flat FLRW:

Conformal invariance $\Longrightarrow$ (A) homogeneity $\longrightarrow$ Bianchi I,V,IX; (B) isotropy; (C) $\mathrm{FLRW}_{\kappa=\pm1}\equiv\mathrm{FLRW}_{\kappa=0}$ $\longrightarrow$ Minkowski, $\mathrm{FLRW}_{\kappa=0,\pm1}$ $\longrightarrow$ Minkowski, $\mathrm{FLRW}_{\kappa=0}$

19/29– Big-bang problem

Singularity issue not solved: it simply becomes meaningless.

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Singularity issue not solved: it simply becomes meaningless.

- Conformal gravity evades BGV theorem because it is impossible to talk about expanding backgrounds. Average expansion condition not a conformally invariant statement.
- Independent of the underlying theory but requires finiteness.
- Example:

1. Solutions of the EOMs grouped into equivalence classes:

$$\hat{g}^*_{\mu\nu} := S(x)\,\hat{g}_{\mu\nu}\,, \qquad \phi^* := S^{-\frac{1}{2}}(x)\,\phi$$

2. Flat FLRW is a solution, conformally equivalent to Minkowski (plus dilaton).
3. Dilaton decouples from the geodesic equation of massless particles. Minkowski spacetime is geodesically complete.

20/29– Horizon problem

• In the conformal phase, spacetime distances do not have any physical meaning: large and small distances are actually the same.

• After breaking conformal symmetry, distance between particles always smaller than Hubble radius.

• Independent of the underlying theory but requires finiteness.

21/29– Flatness problem

- In any theory, any FLRW line element is conformally ($\neq$ physically) equivalent to Minkowski (inhomogeneous if $\kappa = \pm 1$).
- In any Weyl$\times$Diff invariant theory, any FLRW solution with $\kappa = 0, \pm 1$ is physically equivalent to FLRW with $\kappa = 0$.
- A Diff$\times$Weyl transformation changes $\kappa = 0, \pm 1$, so during the conformal phase $\kappa = 0$ FLRW is selected by symmetry (analogy with longitudinal polarization of photon) and holds through symmetry breaking by analytic continuation of $g_{\mu\nu}$.
- Independent of the underlying theory but requires finiteness.

22/29– Flat spacetime approximation

Two assumptions

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

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

23/29– Tensor spectrum

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

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

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

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Tensor spectrum:

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

Tensor spectral index:

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

24/29– Scalar spectrum

From thermal fluctuations. Radiation-dominated universe.

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

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Scalar spectrum:

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

Scalar spectral index:

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

25/29– Tensor-to-scalar ratio and consistency relation

Tensor-to-scalar ratio:

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

25/29– Tensor-to-scalar ratio and consistency relation

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Consistency relation:

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

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

26/29– Parameter space

$$\mathcal{P}_{\rm s}(k_0) \simeq \frac{7.9\times 10^{-4}}{\beta_{\rm Ric}} \approx 2.2\times 10^{-9}$$

How to explain the observed small value of $\mathcal{P}_{\rm s}$?

I. Large $\beta_{\rm Ric} \propto N_{\rm fields} \approx 3.6\times 10^{5}$ [Buchbinder et al. 1992; Avramidi 2000]. Assumption compatible with a many-particle GUT scenario: $\Lambda_{\rm hd} = M_{\rm Pl}/\sqrt{b} = 5\times 10^{14}\,{\rm GeV}$.

II. Conformal rescaling of the metric from Minkowski to

$$ds^{*2} = -\left(A + B\tanh\frac{\tau}{\tau_{\rm Pl}}\right)\left(-d\tau^2 + d\boldsymbol{x}^2\right), \qquad \lim_{\tau\to\pm\infty} a^2 = A \pm B > 0$$

$$\mathcal{P}'_{\rm s,t} = \Omega^4 \mathcal{P}_{\rm s,t}\,, \qquad r' = r.$$

$\mathcal{P}'_{\rm s}$ consistent with observations if, e.g., $\beta_{\rm Ric} = 1$ and $A + B = 1.7\times 10^{-3}$ or $\beta_{\rm Ric} = 40$ and $A + B = 10^{-2}$

27/29– Primordial GWs

GC & Modesto arXiv:2206.07066

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

$$n_\mathrm{t} \approx 0.0351\,, \qquad r_{0.05} = 0.009 - 0.011$$

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

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

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- Three times larger than $r_\mathrm{Starobinsky} = 0.0037$.
- Within reach of **BICEP Array** (uncertainty $\sigma(r) \lesssim 0.003$) **within 3 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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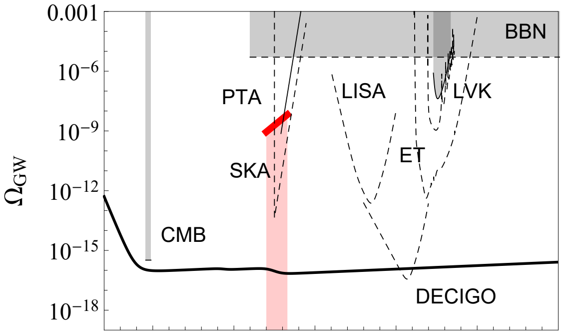
- LiteBIRD: $\sigma(r) \sim 0.001$ (exclusion if $r < 0.002$) [Allys et al. 2022].

28/29– GW background

GC & Modesto arXiv:2206.07066

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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- 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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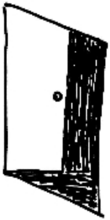

TO BE CONTINUED . . .