Gravitational waves from preheating in the early Universe

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Based on:

- A. Tokareva, ‘Gravitational waves from inflaton decay and bremsstrahlung, arXiv:2312.16691 (PLB)
- … ongoing work

Stochastic GW from inflation and reheating - What can we learn about quantum gravity?

Realization of inflation and reheating

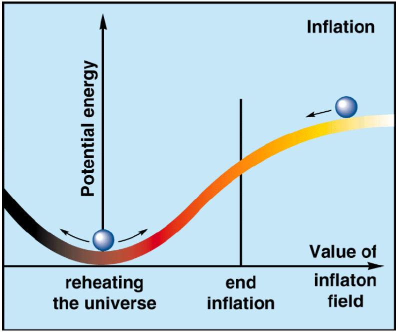
$$p = -\rho. \qquad a(t) = \text{const} \cdot e^{H_{vac}\, t}$$

$$S = \int d^4x \sqrt{-g} \left(\frac{M_P^2}{2} R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \right)$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi),$$
$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi).$$

Slowly rolling scalar field is a solution!

Oscillations after inflation decay to the SM particles → reheating of the Universe



Reheating temperature is unknown: from 1 GeV to 10^{16} GeV

EFT of inflaton and gravity

Expansion around the flat space:

$$S = \int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right)$$

$$S_{NR} = \int d^4x\sqrt{-g}\left(\frac{\phi}{\Lambda_1}R_{\mu\nu\lambda\rho}R^{\mu\nu\lambda\rho} + \frac{\phi}{\Lambda_2}R_{\mu\nu}R^{\mu\nu} + \frac{\phi}{\Lambda_3}R^2 + \frac{1}{\Lambda_4^2}G_{\mu\nu}\partial^\mu\phi\partial^\nu\phi\right)$$

$$S_{int}^{SM} = \int d^4x\sqrt{-g}\left(-|D_\mu H|^2 + \mu\phi H^\dagger H + \frac{1}{\Lambda_5^2}G_{\mu\nu}D^\mu H^\dagger D^\nu H\right)$$

Leading contribution to graviton production after inflation?

EFT of inflaton and gravity

$$S = \int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right)$$

$$S_{NR} = \int d^4x\sqrt{-g}\left(\boxed{\frac{\phi}{\Lambda_1}R_{\mu\nu\lambda\rho}R^{\mu\nu\lambda\rho}} + \frac{\phi}{\Lambda_2}R_{\mu\nu}R^{\mu\nu} + \frac{\phi}{\Lambda_3}R^2 + \frac{1}{\Lambda_4^2}G_{\mu\nu}\partial^\mu\phi\partial^\nu\phi\right)$$

$$S_{int}^{SM} = \int d^4x\sqrt{-g}\left(\boxed{-|D_\mu H|^2} + \boxed{\mu\phi H^\dagger H} + \boxed{\frac{1}{\Lambda_5^2}G_{\mu\nu}D^\mu H^\dagger D^\nu H}\right)$$

Decay to gravitons $\Gamma = \frac{m^7}{32\pi M_p^4\Lambda_1^2}$

reheating

bremsstrahlung

Other operators are suppressed by higher powers of Λs

Results are valid for ANY UV completion for quantum gravity

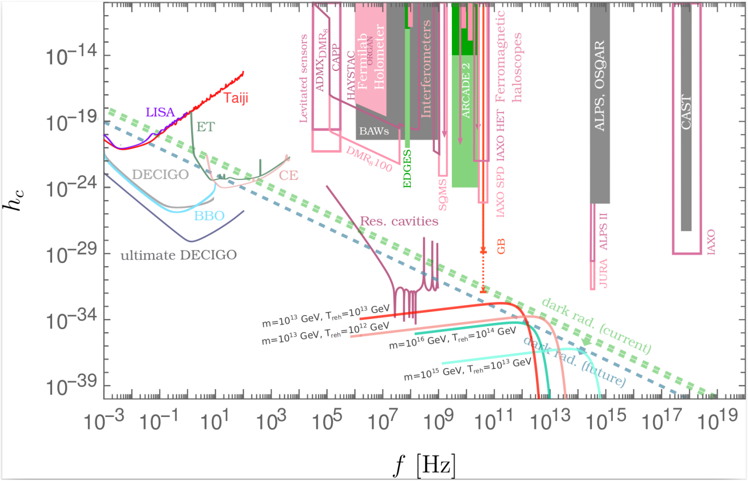
Gravitational waves from inflaton decay

$$\frac{d\Omega_{GW}}{d\log E} = \frac{16E^4}{M^4}\frac{\rho_{reh}}{\rho_0}\frac{\Gamma_{GW}}{H_{reh}}\frac{1}{\gamma(E)}e^{-\gamma(E)}$$

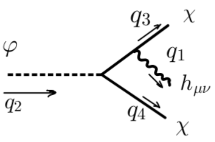
$$\gamma(E) = \left(\left(\frac{g_{reh}}{g_0}\right)^{1/3}\frac{T_{reh}}{T_0}\frac{2E}{M}\right)^{3/2}$$

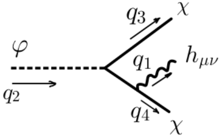
A. Koshelev, A. Starobinsky, AT, PLB, arXiv:2211.02070

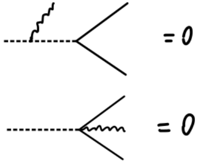
$$h_c(f) = \sqrt{\frac{3H_0^2}{\pi f^2}\frac{d\Omega_{GW}}{df}}$$



Graviton bremsstrahlung during reheating







$$G(k) = \frac{\partial \Gamma}{\partial k} = A \frac{(m-2k)^2}{m\,k}, \quad A = \frac{1}{64\pi^3}\frac{\mu^2}{3M_p^2}$$

Not sensitive to inflaton-graviton coupling

$$G(k) = \frac{\partial \Gamma}{\partial k} = A \frac{(m-2k)^2}{m\,k} + B_{UV}(k) \qquad A = \frac{1}{64\pi^3}\frac{\mu^2}{2M_p^2}\left(\frac{m^2}{\Lambda_5^2}+1\right)^2$$

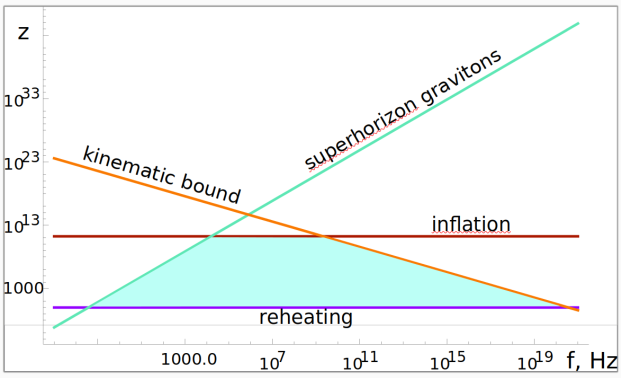
$$B_{UV}(k) = \frac{1}{64\pi^3}\frac{\mu^2}{2M_p^2}\frac{2(m-2k)^2}{15\Lambda_5^2}\left(\frac{m\,(7k-10m)}{\Lambda_5^2} - 10\right)$$

$$\frac{d\rho_{GW}}{dk} = \int \frac{kdN}{a_0^3} = \int dt \frac{k n_\phi(t) a(t)^3}{a_0^3} G(k\frac{a_0}{a(t)})$$

$$n_\phi = \frac{\rho_{reh}}{M}\left(\frac{a_{reh}}{a}\right)^3 e^{-\Gamma_{tot} t}$$

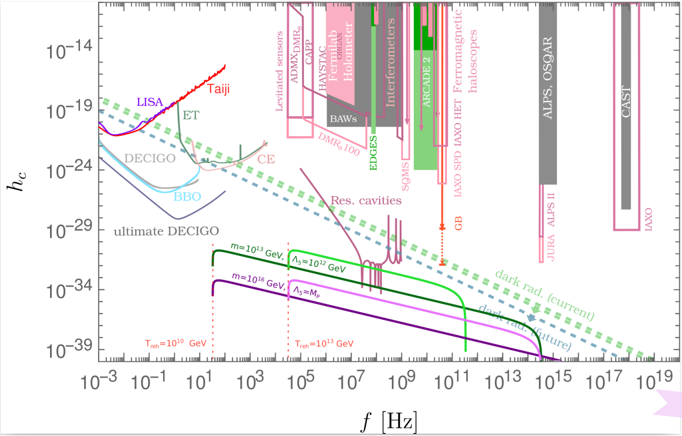
Limits on GW frequencies

$$\frac{d\Omega_{GW}}{d\log k} = \frac{k^2}{M\,H_{reh}}\frac{a_{reh}^2}{a_0^2}\frac{\rho_{reh}}{\rho_0}\int_{z_{min}}^{z_{max}} dz\, G(kz\frac{a_0}{a_{reh}})z^{-3/2}e^{-2z^{-3/2}/3}$$



- Kinematic bound – comoving momentum is less than m/2
- Causality requirement - no superhorizon gravitons!
- Gravitons were emitted between inflation and reheating

What if the quantum gravity scale is lower?



- GW signals for inflaton mass m=10^{13} GeV
- The shape does not change, the amplitude is becoming higher
- The unitarity breaking scale is $\Lambda_{UV}=(\Lambda_5 M_P)^{1/2} > m$
- From $\Lambda_{UV}=10^{15}$ GeV –

  tension with N_{eff} bound

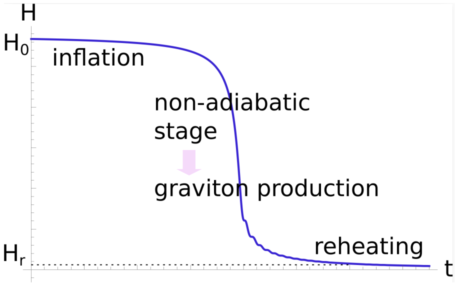
Reheating-dependend bounds on quantum gravity scale!

Gravitational waves from preheating?
Quantum gravity effects?
Non-perturbative effects?

Graviton production from preheating

The leading EFT interaction: $$L_{int} = 4M_P^2\beta(R^2_{\mu\nu\lambda\rho} - 4R^2_{\mu\nu} + R^2)\phi$$

The dominant effect:
Hubble parameter can quickly drop down



The mode equation for graviton:

$$h(t)\left(-\frac{8\beta H k^2\sqrt{-H'}M_P}{a^2} + \frac{4\beta k^2\sqrt{-H'}H''M_P}{a^2H'} + \frac{k^2}{a^2} - \frac{9H^2}{2} - 24\beta H\sqrt{-H'}H'M_P - \frac{3H'}{2} - \frac{2\beta H^{(3)}H\sqrt{-H'}M_P}{H'} - \frac{12\beta H^2\sqrt{-H'}H''M_P}{H'} + \frac{\beta H\sqrt{-H'}\left(H''\right)^2 M_P}{\left(H'\right)^2} - 8\beta\sqrt{-H'}H''M_P\right) + h''(t) = 0$$

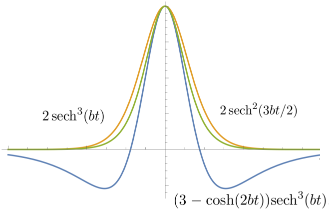
EFT rules: keep only first order terms in **β!**

Estimating the graviton production

Towards the analytically solvable model

$H(t) = H_0 - H_r \tanh(bt)$ $\quad b \gg H_0$ - inverse duration of the preheating stage

$$h''(t) + h(t)\left(\frac{k^2}{a^2} + 2b^2\beta H_0\sqrt{H_r b}M_P\,(3-\cosh(2bt))\mathrm{sech}^3(bt)\right) + O(b) = 0$$



The peak feature can be approximated as

$$h''(t) + h(t)\left(\frac{k^2}{a^2} + 4b^2\beta H_0\sqrt{H_r b}M_P\,\mathrm{sech}^2(3bt/2)\right) = 0$$

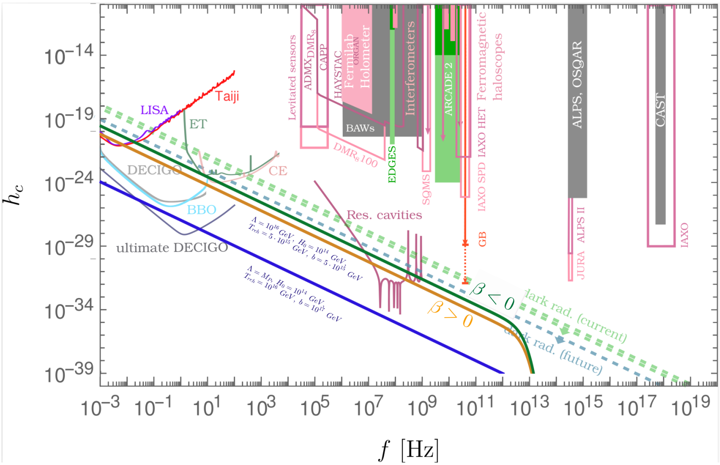
Analytically solvable! (Landau, Lifshitz, v.3)

The Bogolyubov coefficient:

$$|B|^2 = \cos^2\left(\frac{\pi}{2}\sqrt{1+\frac{64}{9}\beta H_0\sqrt{H_r\,b}\,M_P}\right)\frac{1}{\sinh^2\left(\frac{3\pi k b}{2a}\right)}$$

$$\frac{d\Omega_{GW}}{d(\log k)} = \frac{\Omega_{rad}}{6\pi^2 M_P^2}\left(\frac{g_0}{g_r}\right)^{1/3} q^2|B(q)|^2 \qquad q = k\frac{a_0}{a_r}$$

Gravitational wave spectrum



Main features:

- flat spectrum with the exponential UV cutoff
- significant effect for low cutoff scale ~ 10^{15} GeV
- no IR cutoff
- model independent inevitable contribution!

EFT cutoff

$$\Lambda = \beta^{-1/3}$$

Conclusions

- High frequency gravitational waves can be sensitive to the quantum gravity effects
- Perturbative decay of inflation to gravitons can be non-negligible for low reheating temperatures → high frequency GWs
- Graviton bremsstrahlung during reheating can provide a sizable HF GW signal → constraints on EFT
- Reheating-dependent constraints on quantum gravity scale from gravitational waves !
- The effect of non-adiabatic dropping down of Hubble scale can cause generation of stochastic graviational waves in a wide range of the spectrum from low to high frequences
- The effect can be significantly enhanced if the EFT cutoff is lower than Planck scale!
- Stochastic GWs can probe preheating stage and higher derivative EFT operators

Thank you for your attention!