Ultra-high frequency gravitational waves from inflaton decay

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Based on PLB 2211.02070 (A. Koshelev, A. Starobinsky, AT) and ongoing work

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Realization of inflation and reheating

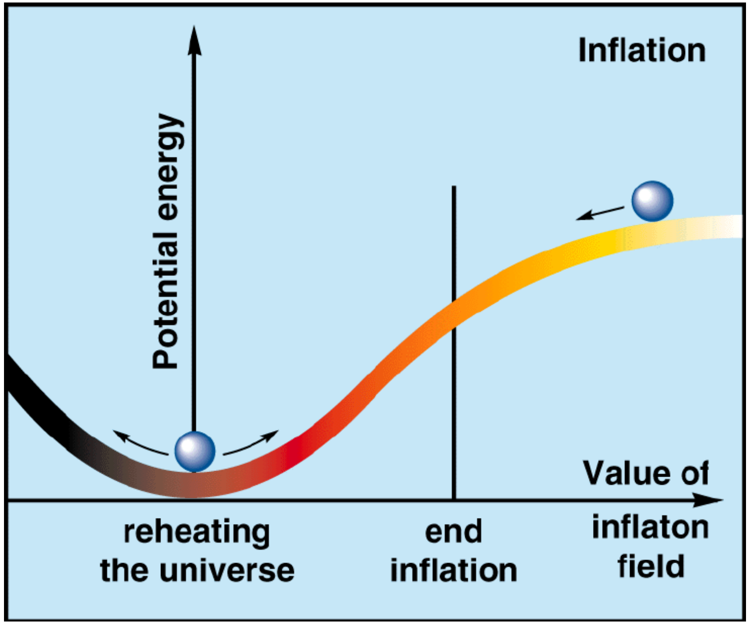
$$p = -\rho. \qquad a(t) = \text{const} \cdot e^{H_{vac}\, t}$$

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

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

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

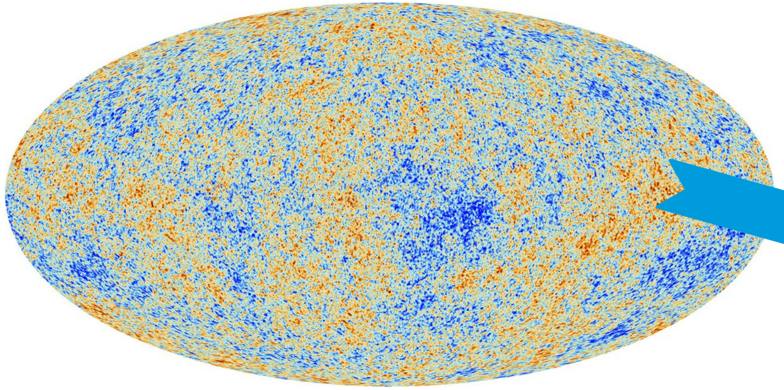
Slowly rolling scalar field is a solution!

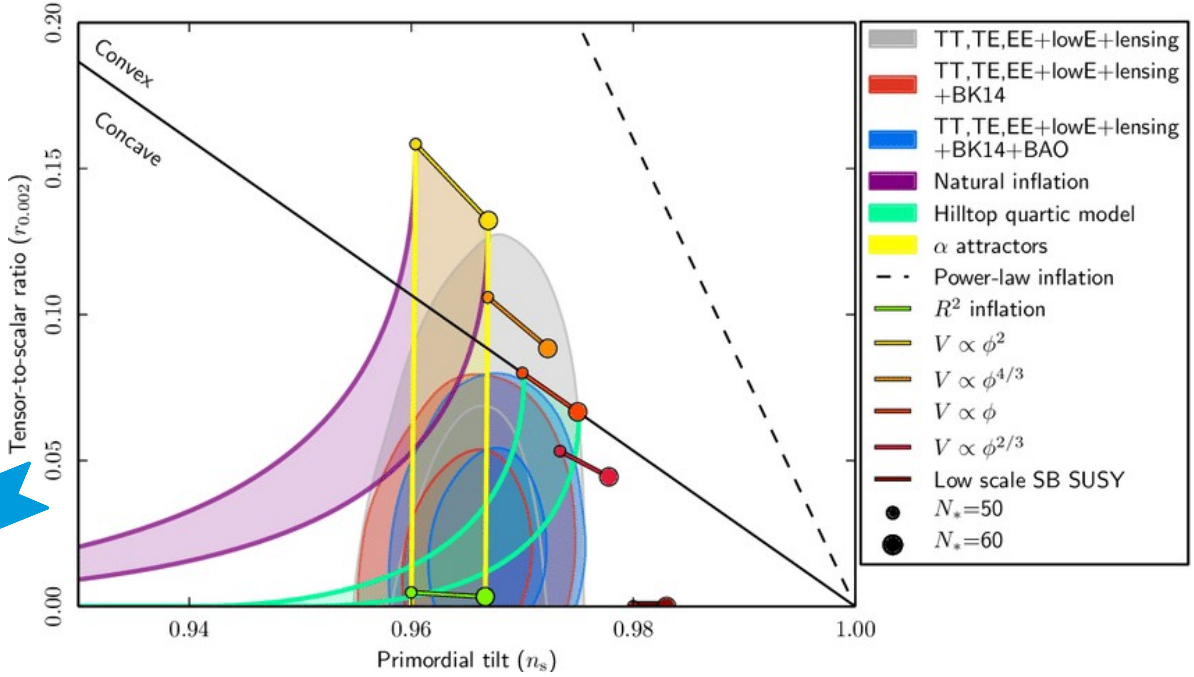


Oscillations after inflation decay to the SM particles $\Longrightarrow$ reheating of the Universe

Reheating temperature is unknown: from 1 GeV to 10^{15} GeV

Planck Constraints on the Potential





Serious QFT challenge – there is no renormalizable model left!

Inflation can be described by Effective Field Theory valid until the scale $\Lambda < M_P$ and $\Lambda > H_{inf}$

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

Expansion around the flat space:

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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

Inflaton decay to gravitons: selected results

- Planck-suppressed operators **do matter** for low T_{reh} !

$$T_{reh} \lesssim \frac{m^{7/2}}{M_P^{3/2}\Lambda_1}$$

Overproduction of dark radiation

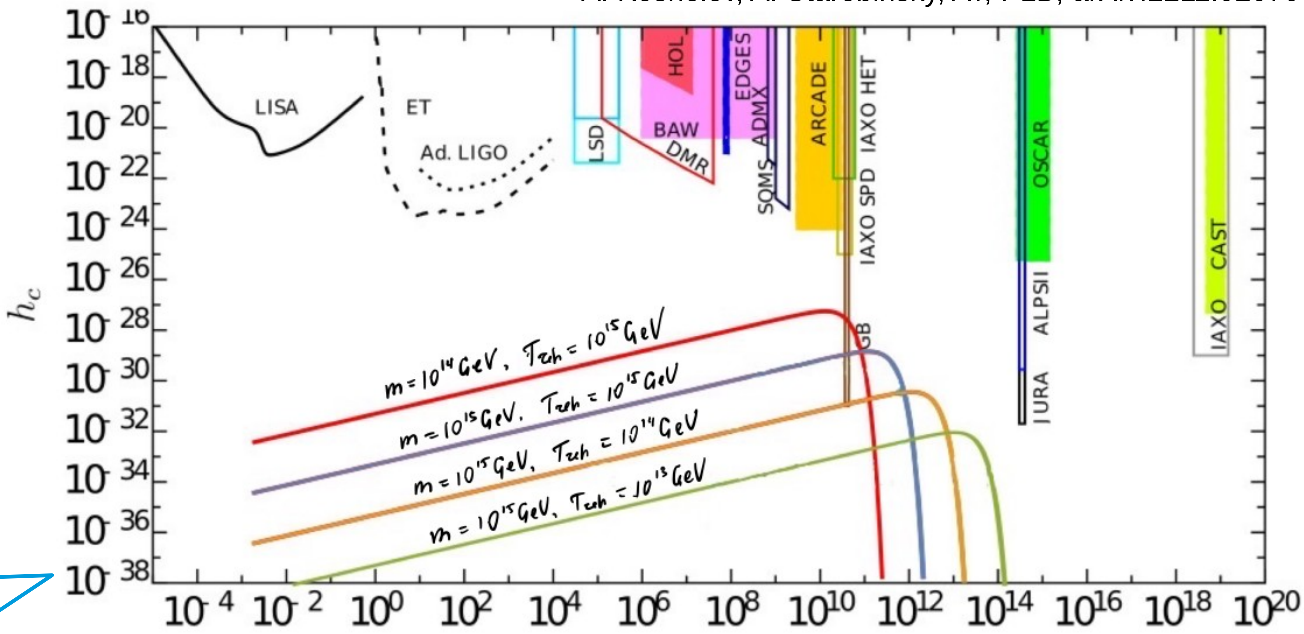
$$m = 10^{13}\ \text{GeV} \quad T_{reh}^{min} = 1\ \text{GeV}$$

$$m = 10^{16}\ \text{GeV} \quad T_{reh}^{min} = 10^{10}\ \text{GeV}$$

- Larger inflaton mass - more HF GWs

$\Lambda_1 = 10^8$ GeV

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



Detection proposals: G. Franciolini, A. Maharana, F. Muia, arxiv:2205.02153

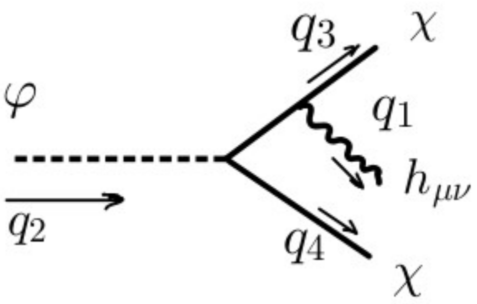
$$\Delta N_{eff} \lesssim 0.2$$

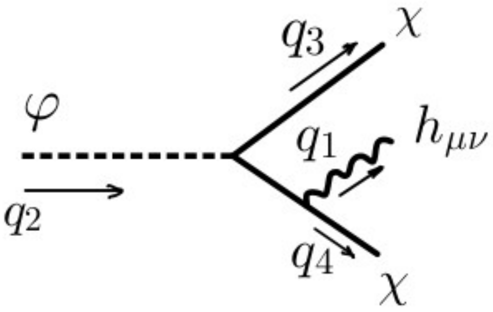
$$\Delta N_{eff} = 2.85\frac{\rho_{GW}}{\rho_{SM}} = 2.85\frac{\Gamma_{GW}}{\Gamma_H}$$

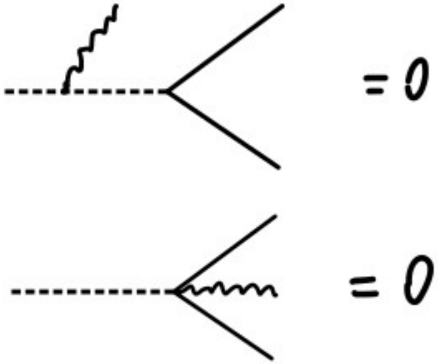
$$\frac{d\Omega_{GW}}{d\log E} = \frac{16E^4}{M^4}\frac{\rho_{reh}}{\rho_0}\frac{\Gamma_{GW}}{H_{reh}}\frac{1}{\gamma(E)}e^{-\gamma(E)}$$

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

Graviton bremsstrahlung during reheating







$$G(k) = \frac{\partial \Gamma}{\partial k} = A\frac{(m-2k)^2}{m\,k}, \quad A = \frac{1}{64\pi^3}\frac{\mu^2}{3M_p^2}\left(1+\frac{m^4}{\Lambda_5^4}\right)$$

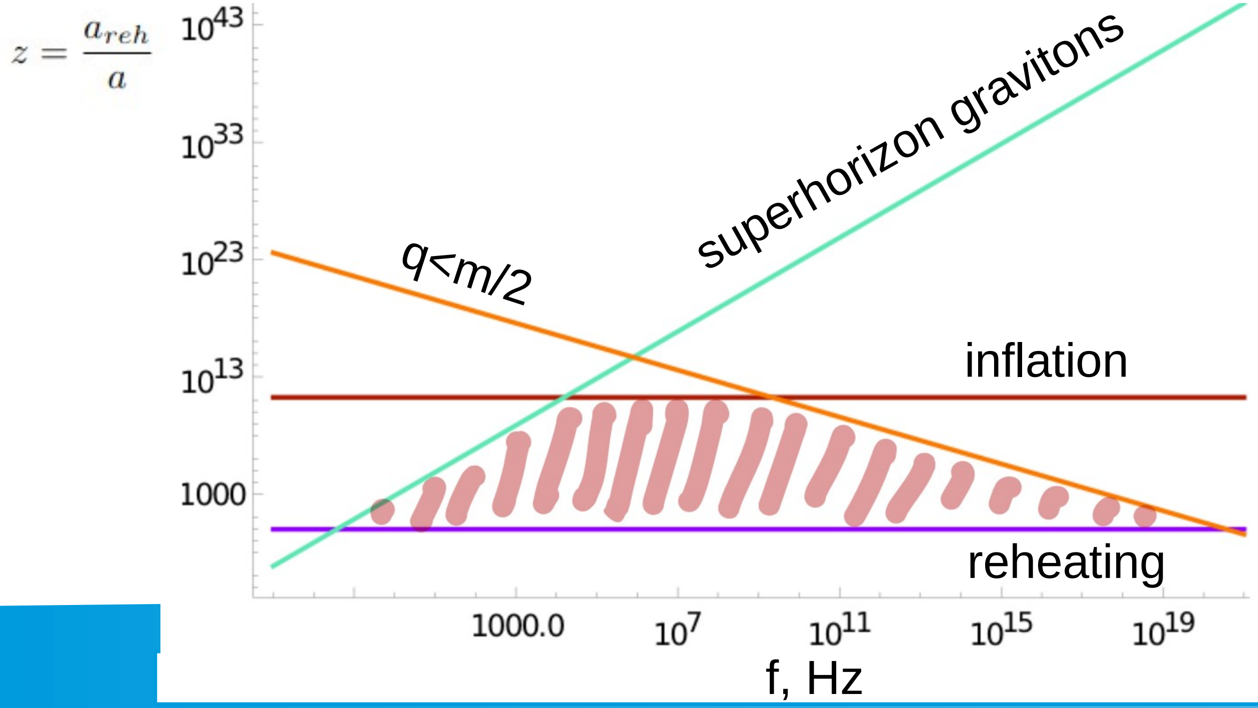
Not sensitive to inflaton-graviton coupling

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

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

Limits on GW frequencies

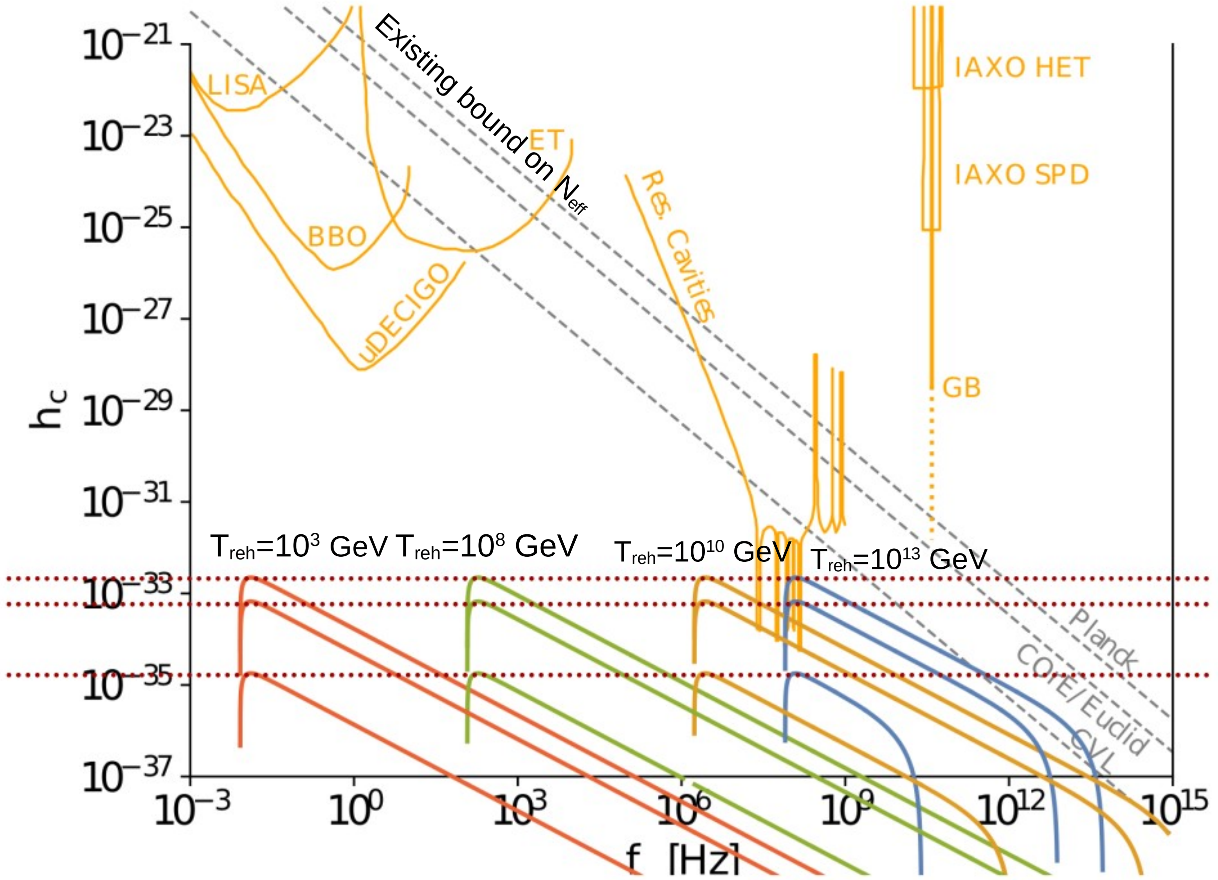
$$\frac{d\Omega_{GW}}{d\log k} = \frac{k^2}{M\, H_{reh}} \frac{a_{reh}^2}{a_0^2} \frac{\rho_{reh}}{\rho_0} \int_{z_{min}}^{z_{max}} dz\, G(kz\frac{a_0}{a_{reh}}) z^{-3/2} e^{-2z^{-3/2}/3}$$



Kinematic bound – comoving momentum is less than m/2

- Causality requirement - no superhorizon gravitons!
- Gravitons were emitted between inflation and reheating

Gravitational waves from bremsstrahlung: $\Lambda_5 = M_P$



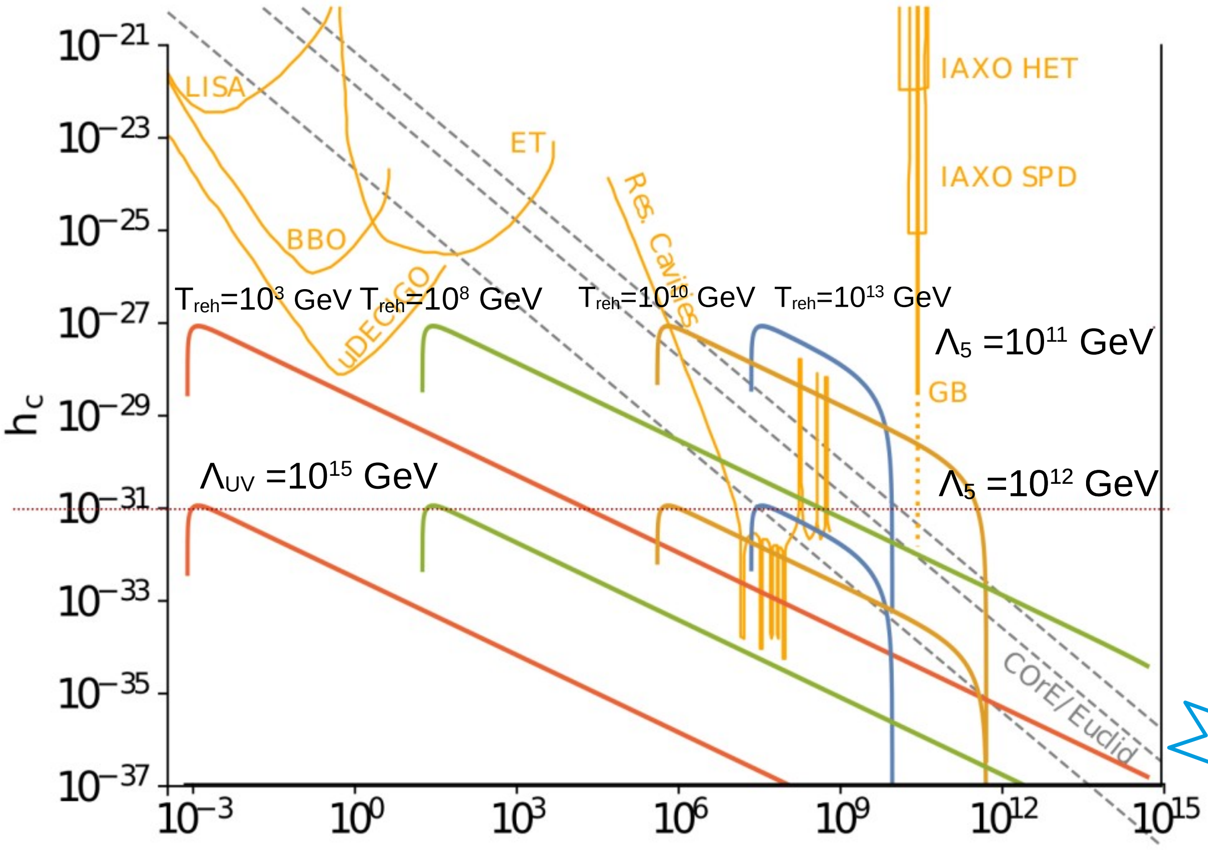
Detection prospects from Barman, Bernal, Xu, Zapata, 2301.11325

- Signals for different inflaton masses and reheating temperatures
- HF GW domain
- Can be also probed as contribution to the dark radiation

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

Results coincide with 2301.11325, except the IR cutoff

What if the quantum gravity scale is lower?



Detection prospects from Barman, Bernal, Xu, Zapata, 2301.11325

- 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!

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 !

Thank you!