Probing Reheating with Primordial Gravitational Waves

Based on
NB, Quan-feng Wu, Xun-Jie Xu, Yong Xu 2503.10756
NB, Yong Xu 2410.21385

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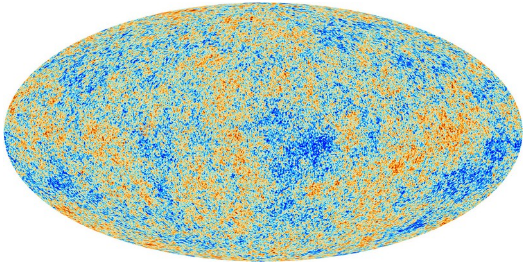
Scalars 2025: Higgs bosons and cosmology
September 22nd-25th, 2025

Cosmic backgrounds



* Photons → CMB

  $T_{CMB} \sim 2.73$ K

* Neutrinos → CνB

  $T_{c\nu B} = (4/11)^{1/3} \; * \; T_{CMB} \sim 1.95$ K

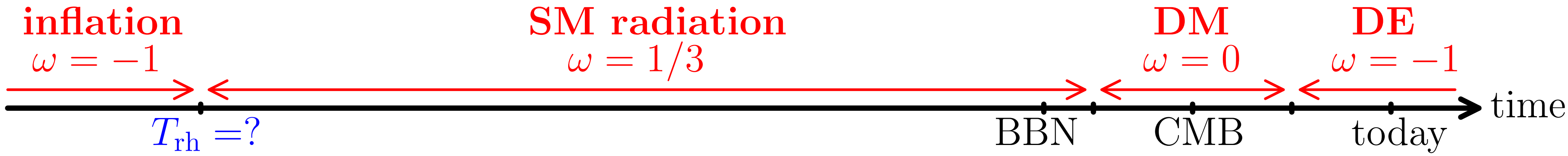
  Not yet measured, but particle physics and cosmo under control

* Gravitons → **Cosmic Gravitational Wave Background** (CGWB)

  Not yet measured → unique probe of the early Universe!

1. PGWs: Instantaneous Reheating

Instantaneous reheating



6×10^{15} GeV > $T_{\rm rh}$ > 4 MeV

Instantaneous reheating

Gravitons are unavoidably emitted from thermal fluctuations of the SM bath

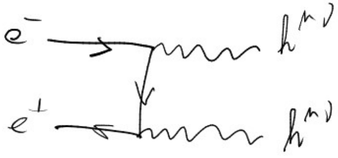
→ purely SM process!

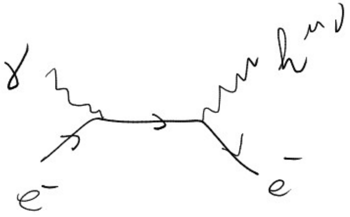
→ during the **SM radiation domination**

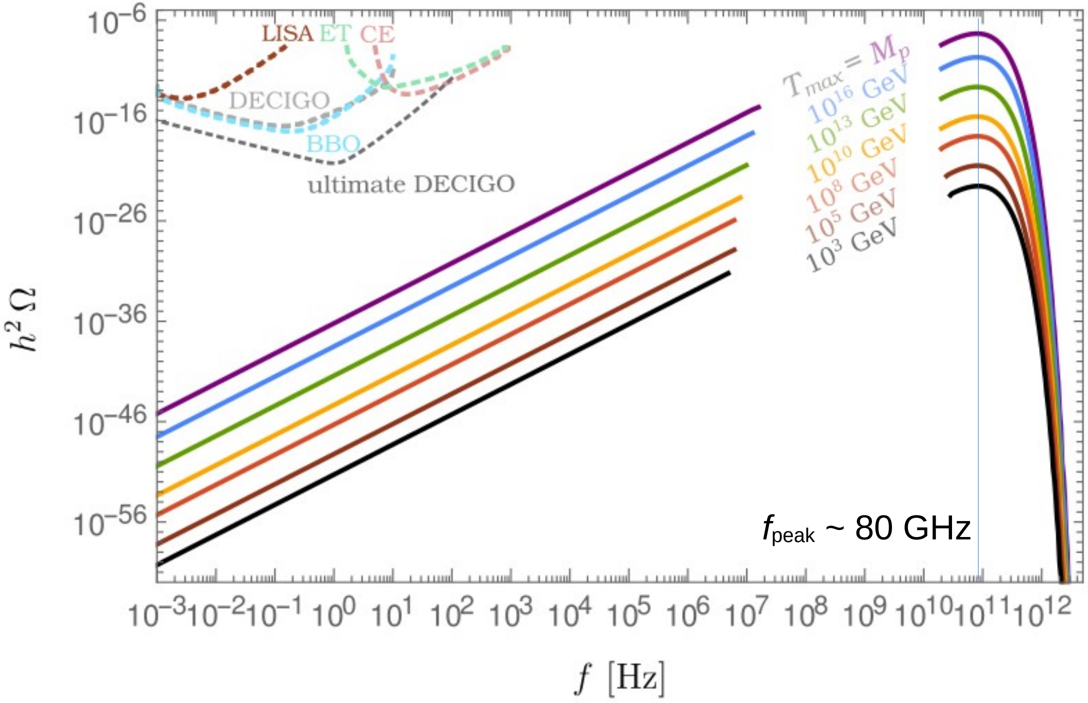
Ghiglieri, Laine ‘15
Ghiglieri, Jackson, Laine, Zhu ‘20
Ringwald, Schütte-Engel, Tamarit ‘20

$$\frac{d}{dt}\frac{d\rho_{\rm GW}}{d\ln f} + 4\,H\,\frac{d\rho_{\rm GW}}{d\ln f} = f\,\frac{d\gamma}{df}$$

$$\gamma \sim \frac{T^7}{M_P^2}$$

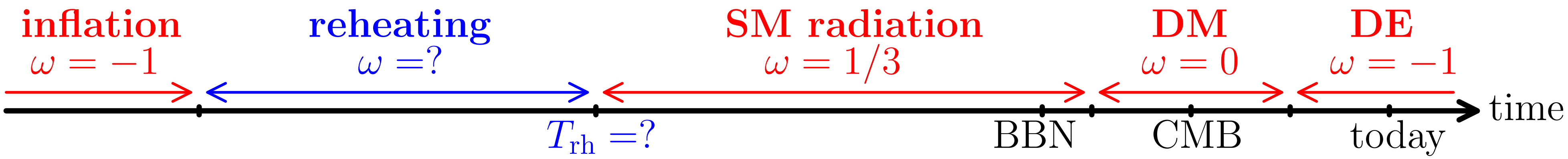






2. PGWs:
Non-instantaneous Reheating

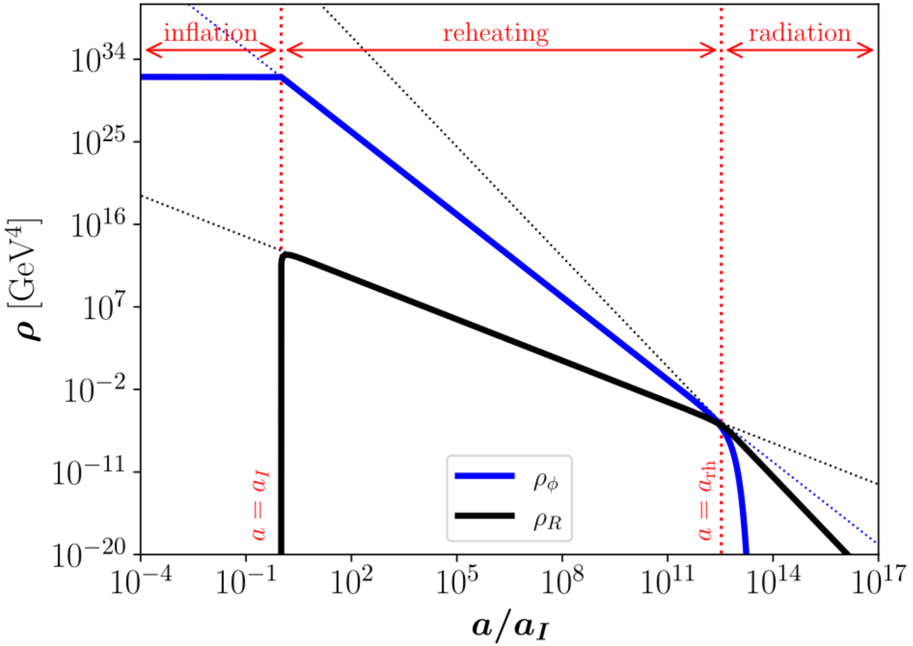
Non-instantaneous reheating



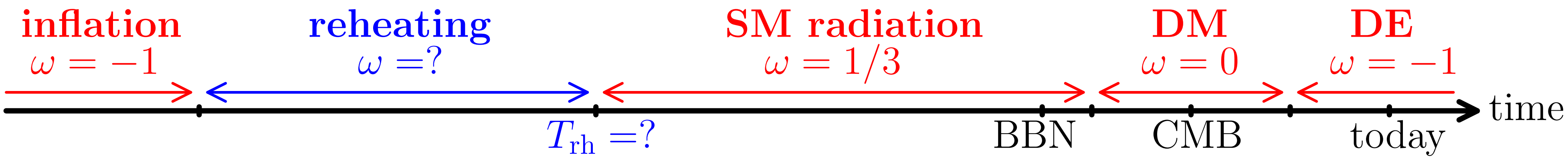
Decay or annihilation of inflatons into SM radiation is a *continuous process*

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\, H\, \rho_\phi = -\Gamma_\phi\, \rho_\phi$$

$$\frac{d\rho_R}{dt} + 4\, H\, \rho_R = +\Gamma_\phi\, \rho_\phi$$

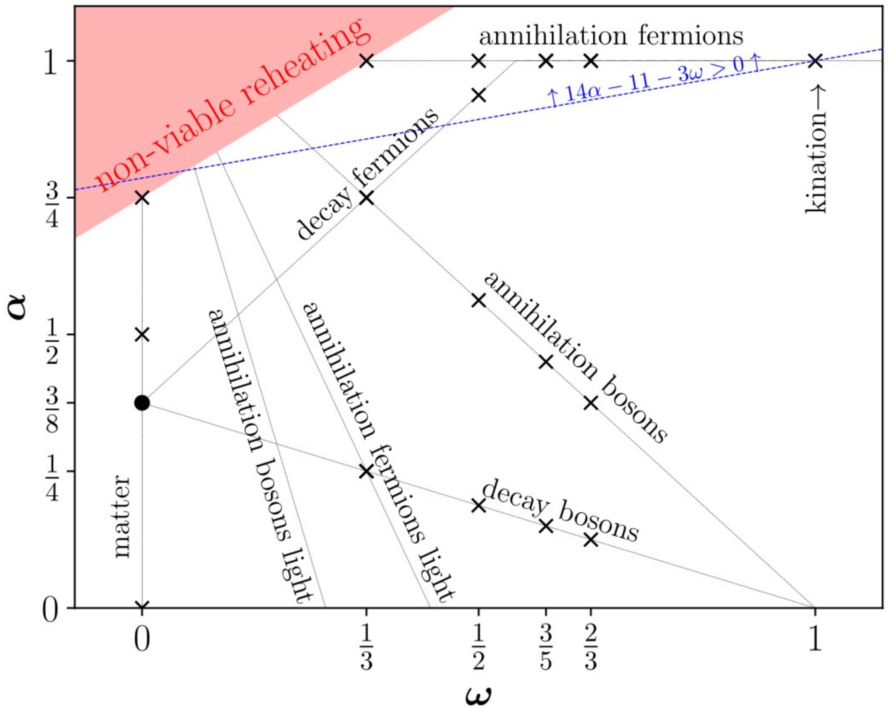


Non-instantaneous reheating



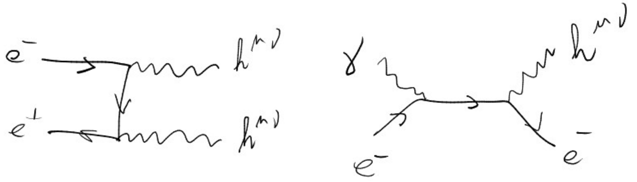
$$T(a) = T_{\rm rh} \left(\frac{a_{\rm rh}}{a}\right)^{\alpha}$$

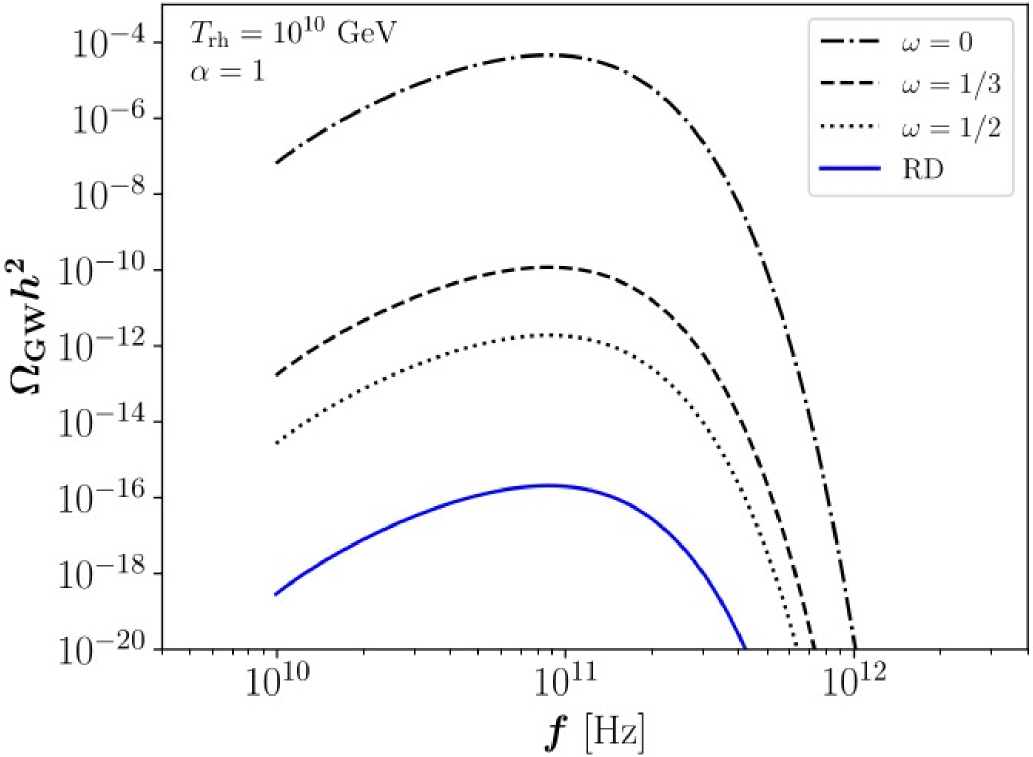
$$\rho_\phi(a) \propto a^{-3\,(1+\omega)}$$



Non-instantaneous reheating

Gravitons are unavoidably emitted from the SM bath
→ purely SM process!
→ during the **reheating** era





For $\alpha = 1$

$$\Omega_{\rm GW}^{\rm RH}(f) \simeq \Omega_{\rm GW}^{\rm RD}(f) \times \begin{cases} \dfrac{2}{3(1-\omega)}\left[\left(\dfrac{T_{\rm max}}{T_{\rm rh}}\right)^{\frac{3(1-\omega)}{2}} - 1\right] & \text{for } \omega < 1 \\ \log\left(\dfrac{T_{\rm max}}{T_{\rm rh}}\right) & \text{for } \omega = 1 \end{cases}$$

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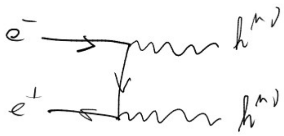

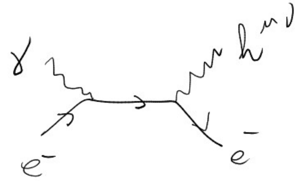

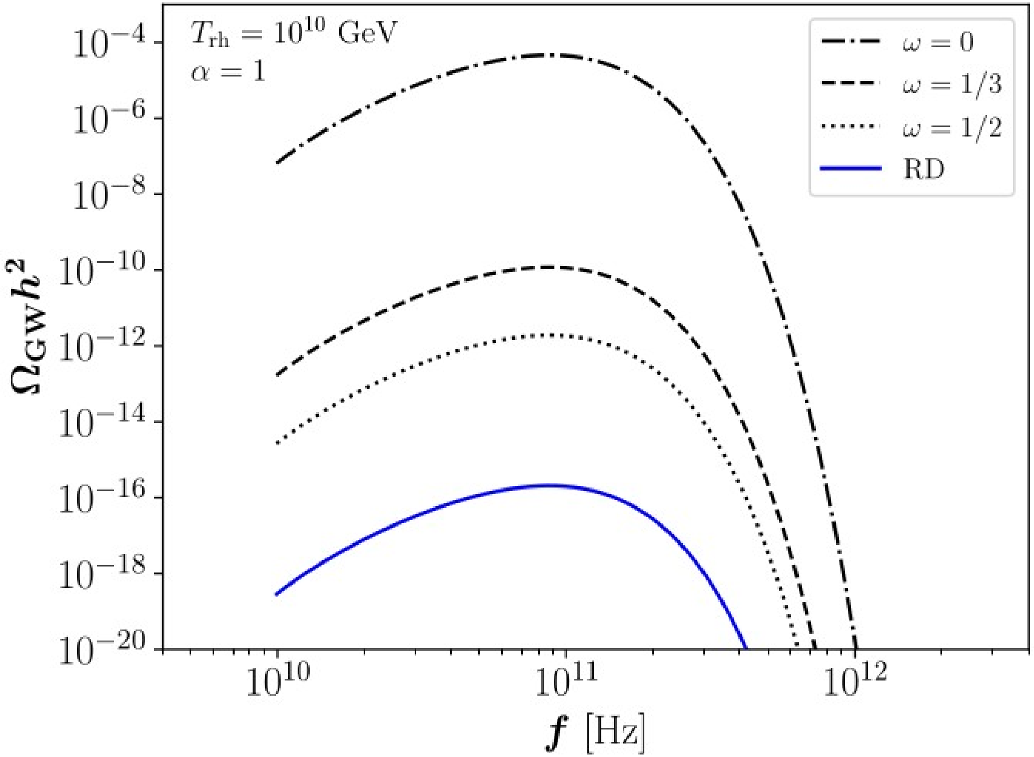

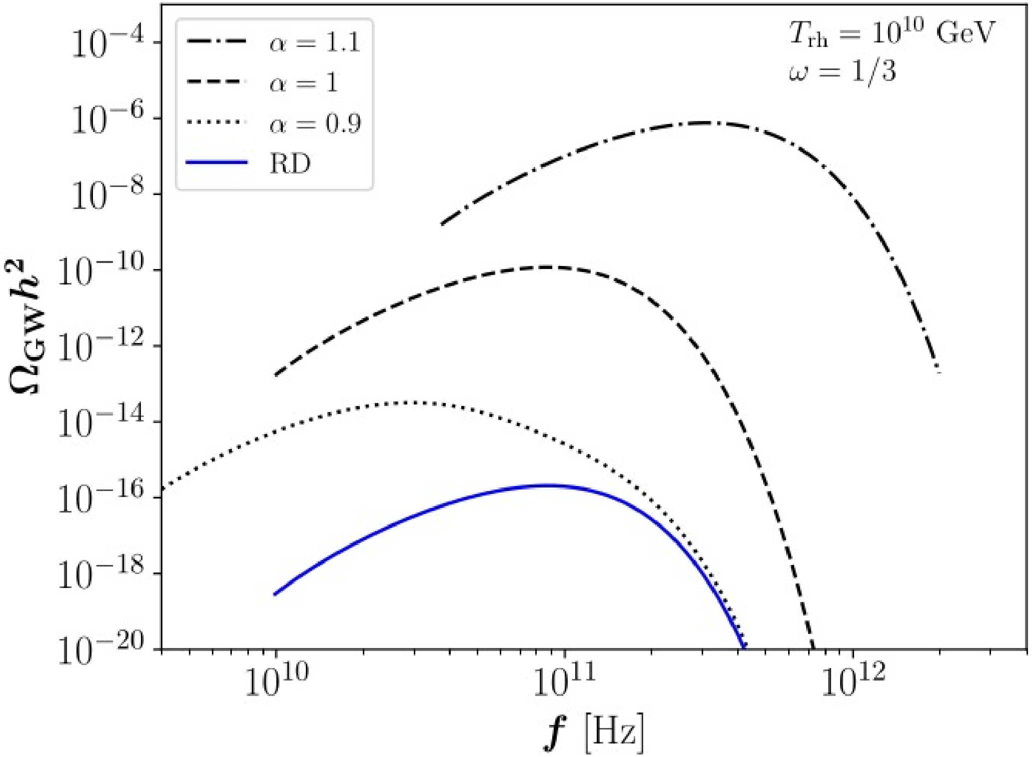

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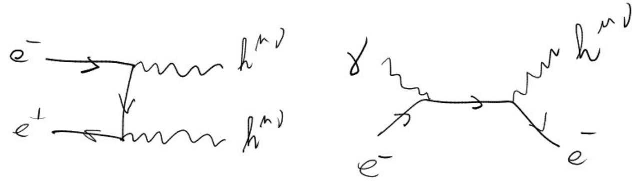

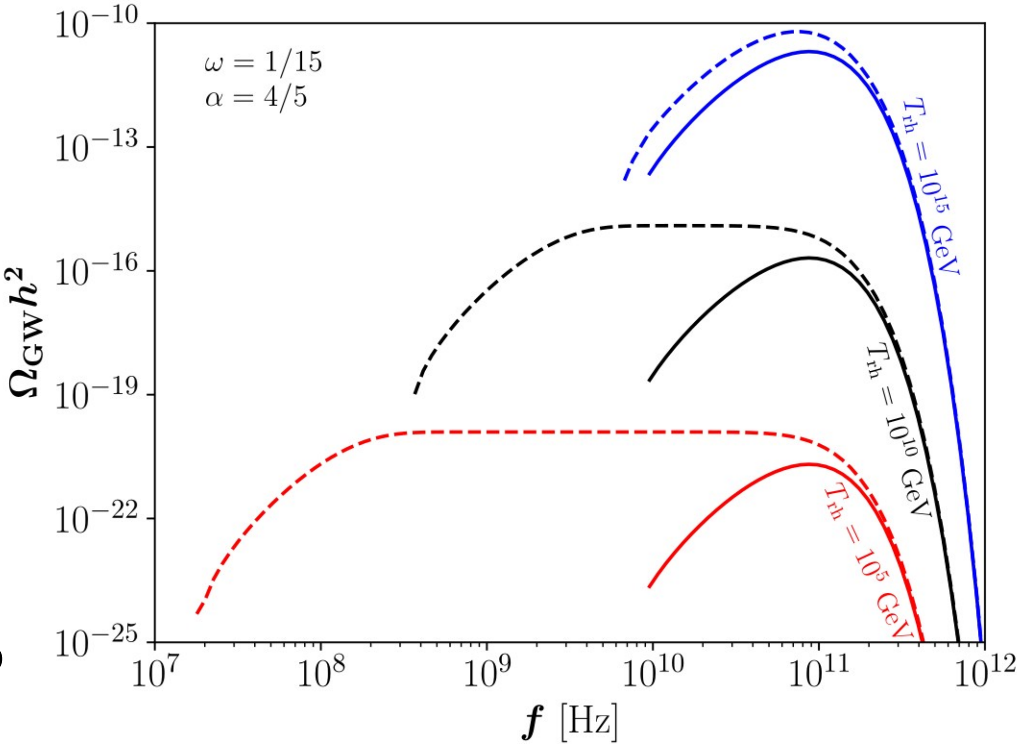

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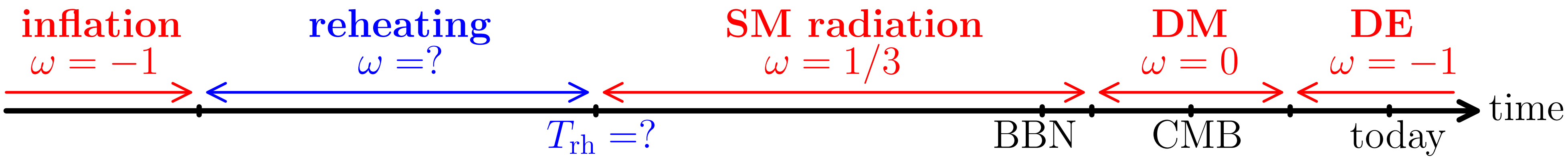

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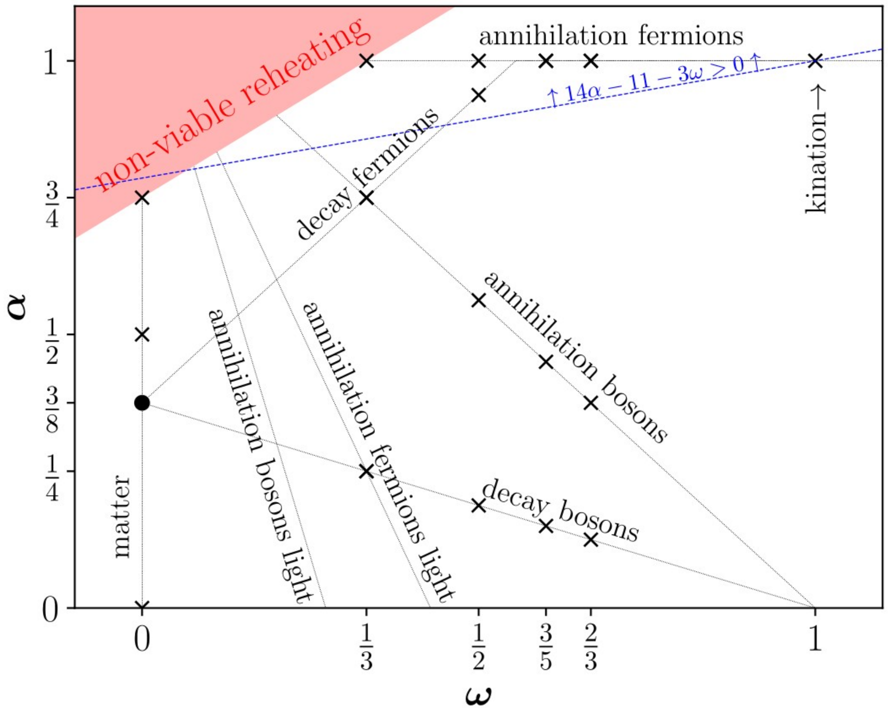
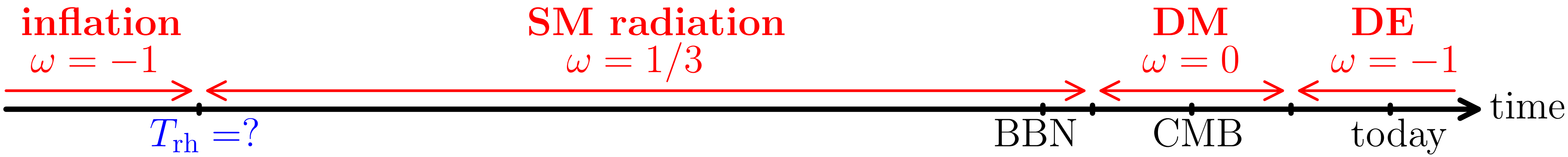


2. PGWs:
Non-instantaneous Reheating
Non-instantaneous Thermalization

Non-instantaneous thermalization



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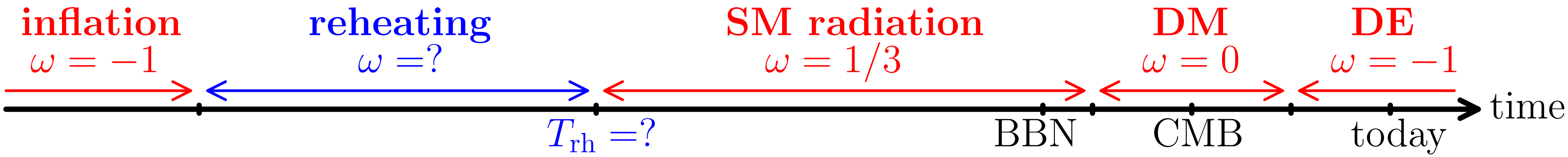

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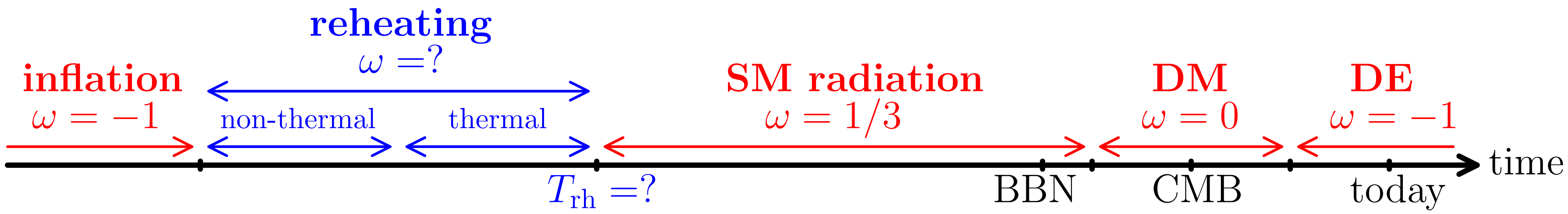
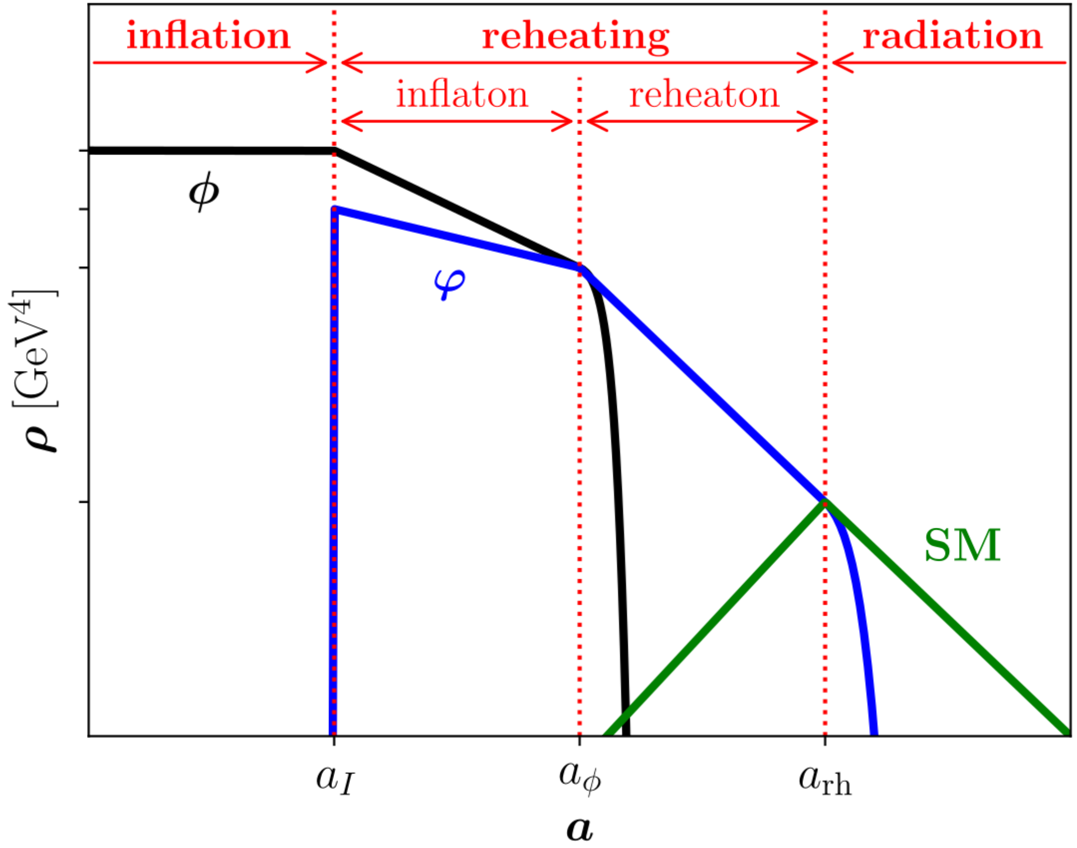


Non-instantaneous thermalization

m_ϕ: inflaton mass
μ: coupling $\phi \to \varphi\varphi$

$m_\varphi << m_\phi$: reheaton mass
μ': coupling $\varphi \to$ SM SM

* Reheaton φ assumed to be **non-thermal**
* Phase-space distribution solved analytically



Phase-space distributions

inflaton → $$f_\phi(t, p_\phi) = 2\pi^2 \, \frac{n_\phi(t)}{p_\phi^2} \, \delta(p_\phi)$$

reheaton → $$f_\varphi(t, p_\varphi) = 32\pi^2 \, \frac{\Gamma_\phi}{H(a')} \, \frac{n_\phi(a')}{m_\phi^3} \, \tilde{\Theta} \left[\frac{m_\phi}{2} \, \frac{a_I}{a(t)} \leq p_\varphi \leq \frac{m_\phi}{2} \right]$$

The GW spectrum is proportional to the graviton phase-space

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c} \, \frac{d\rho_{\rm GW}(a_0)}{d\ln p_h} = 16\pi^2 \, \frac{f^4}{\rho_c} \, f_h(a_0, 2\pi \, f)$$

Possible to solve *analytically* the full graviton phase-space distribution

$$\frac{\partial f_h}{\partial t} - H \, p_h \, \frac{\partial f_h}{\partial p_h} = \Gamma_h$$

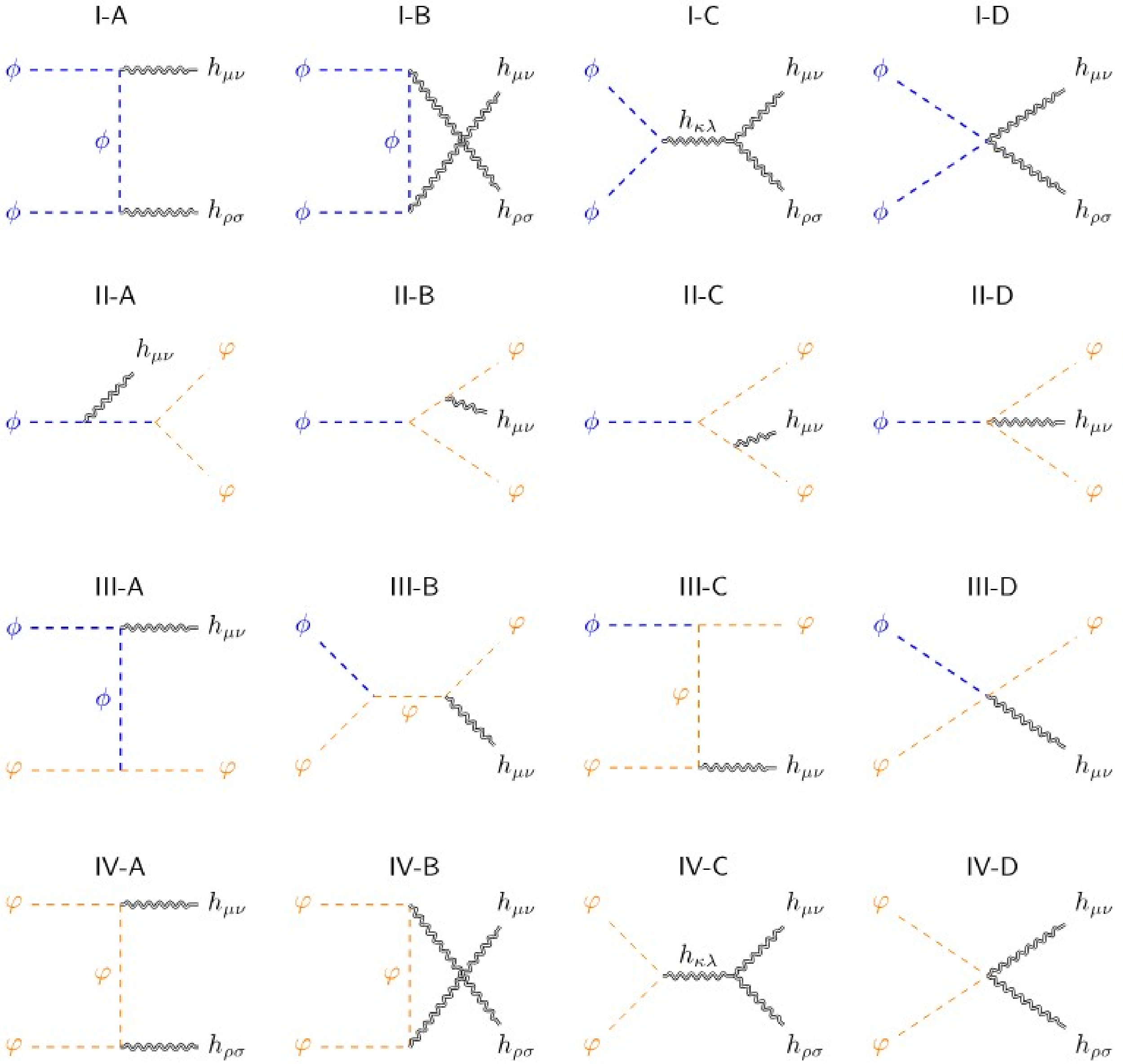
Processes with
* an external graviton
* at most 4 external legs

$$\phi\phi \to hh$$

$$\phi \to \varphi\varphi h$$

$$\phi\varphi \to h\varphi$$

$$\varphi\varphi \to hh$$



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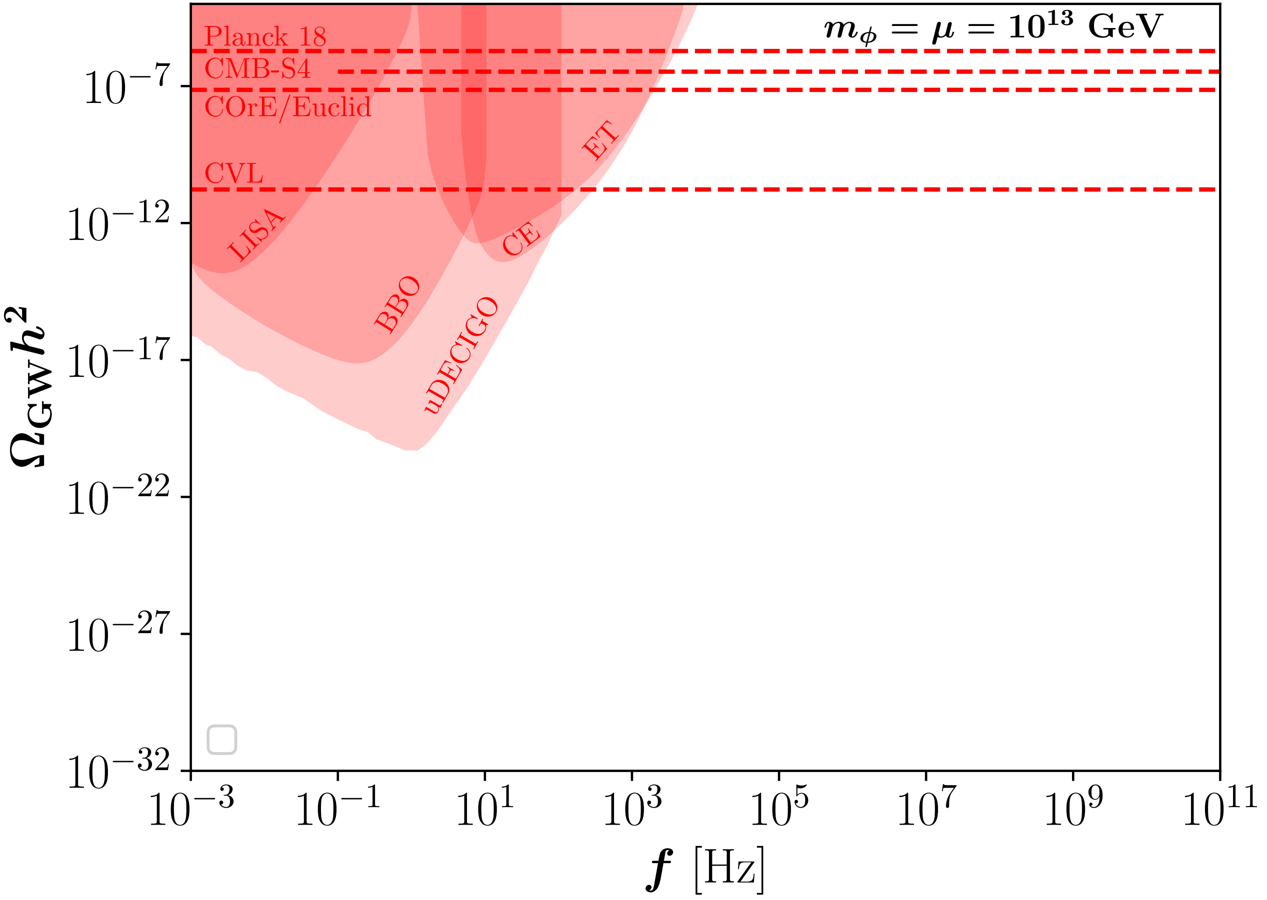

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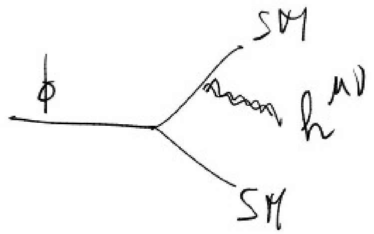
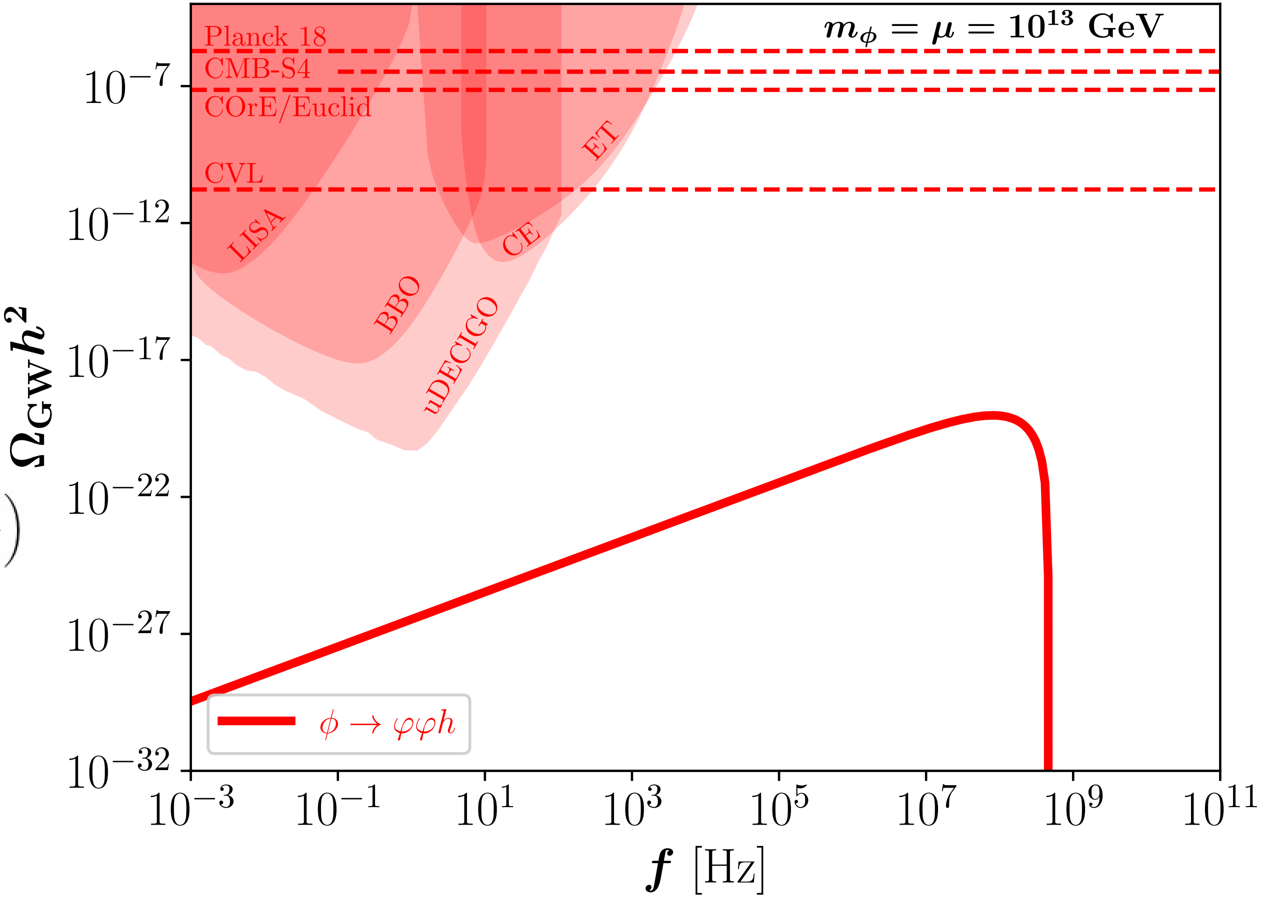


$$\Omega_{\rm GW}h^2(f) \simeq 9.77\times 10^{-21}\left(\frac{\mu}{10^{12}\ {\rm GeV}}\right)\left(\frac{m_\phi}{10^{13}\ {\rm GeV}}\right)^{\frac{1}{2}}\left(\frac{f}{10^7\ {\rm Hz}}\right)$$

$$f \lesssim f_{\rm peak} \simeq f_{\rm max}/2$$



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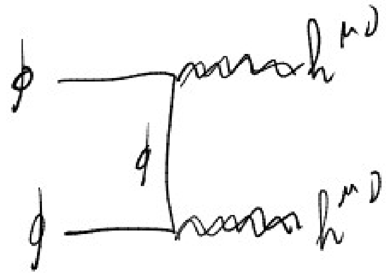
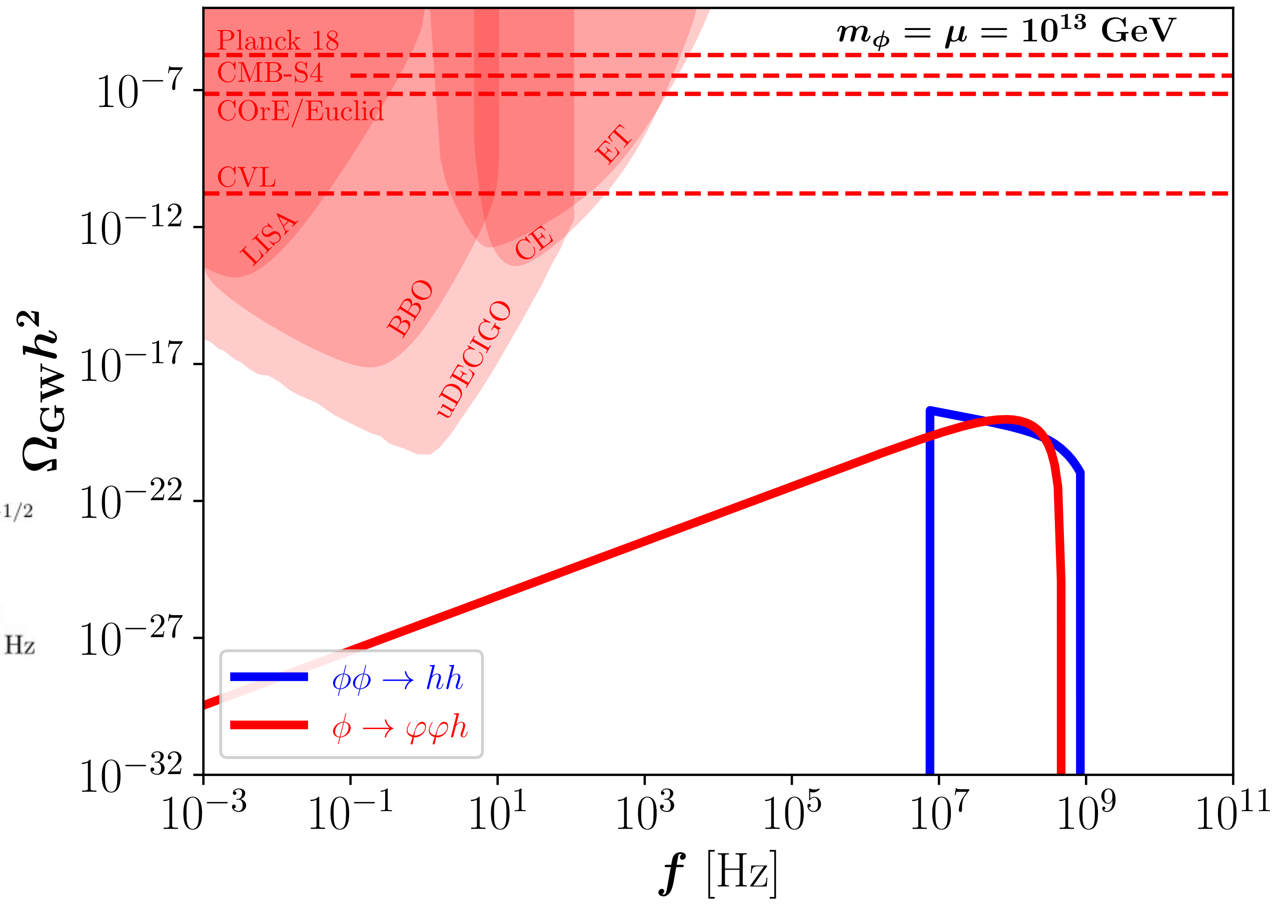


$$\Omega_{\rm GW}h^2(f) \simeq 5.66\times 10^{-20}\left(\frac{\mu}{10^{12}\ \rm GeV}\right)^{3/2}\left(\frac{m_\phi}{10^{13}\ \rm GeV}\right)^{3/4}\left(\frac{f}{10^{7}\ \rm Hz}\right)^{-1/2}$$

$$f_{\rm min} \simeq 6.4\times 10^{6}\left(\frac{m_\phi}{10^{13}\ \rm GeV}\right)^{5/6}\left(\frac{\mu}{10^{12}\ \rm GeV}\right)^{1/3}\left(\frac{2.0\times 10^{-5}\,M_P}{H_I}\right)^{2/3}\ \rm Hz$$

$$f_{\rm max} \simeq 1.1\times 10^{10}\left(\frac{m_\phi}{10^{13}\ \rm GeV}\right)^{3/2}\left(\frac{10^{12}\ \rm GeV}{\mu}\right)\ \rm Hz.$$



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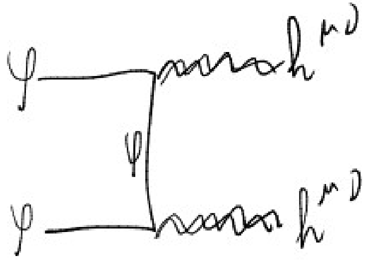
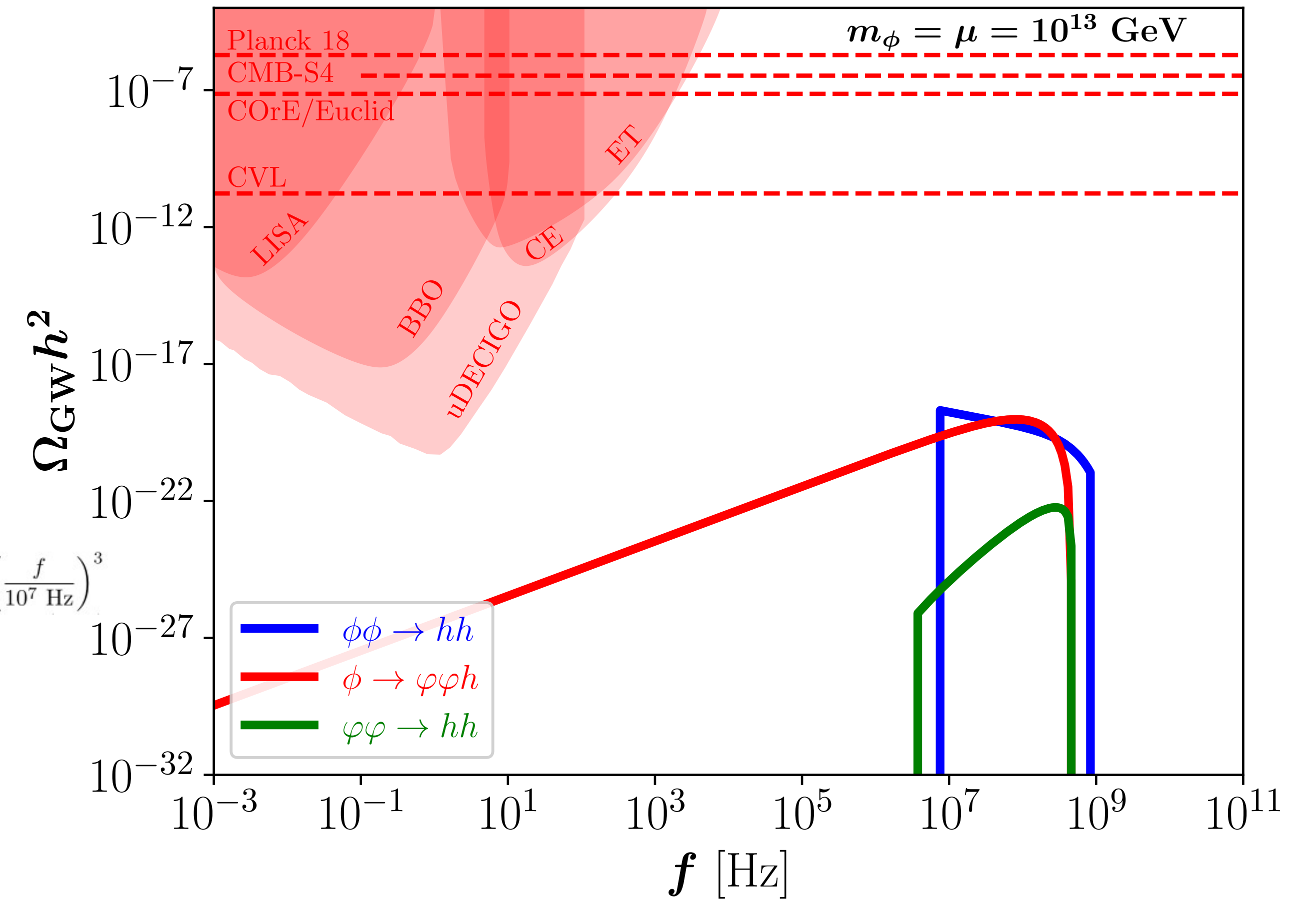


$$\Omega_{\rm GW}h^2(f) \simeq 1.32\times10^{-29}\left(\frac{H_I}{2.0\times10^{-5}\ M_P}\right)^{\frac{1}{3}}\left(\frac{\mu}{10^{12}\ \text{GeV}}\right)^{\frac{13}{3}}\left(\frac{10^{13}\ \text{GeV}}{m_\phi}\right)^{\frac{25}{6}}\left(\frac{f}{10^7\ \text{Hz}}\right)^3$$

$$f_{\rm min}/2 \lesssim f < f_{\rm max}/2.$$



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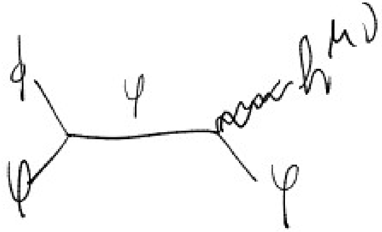
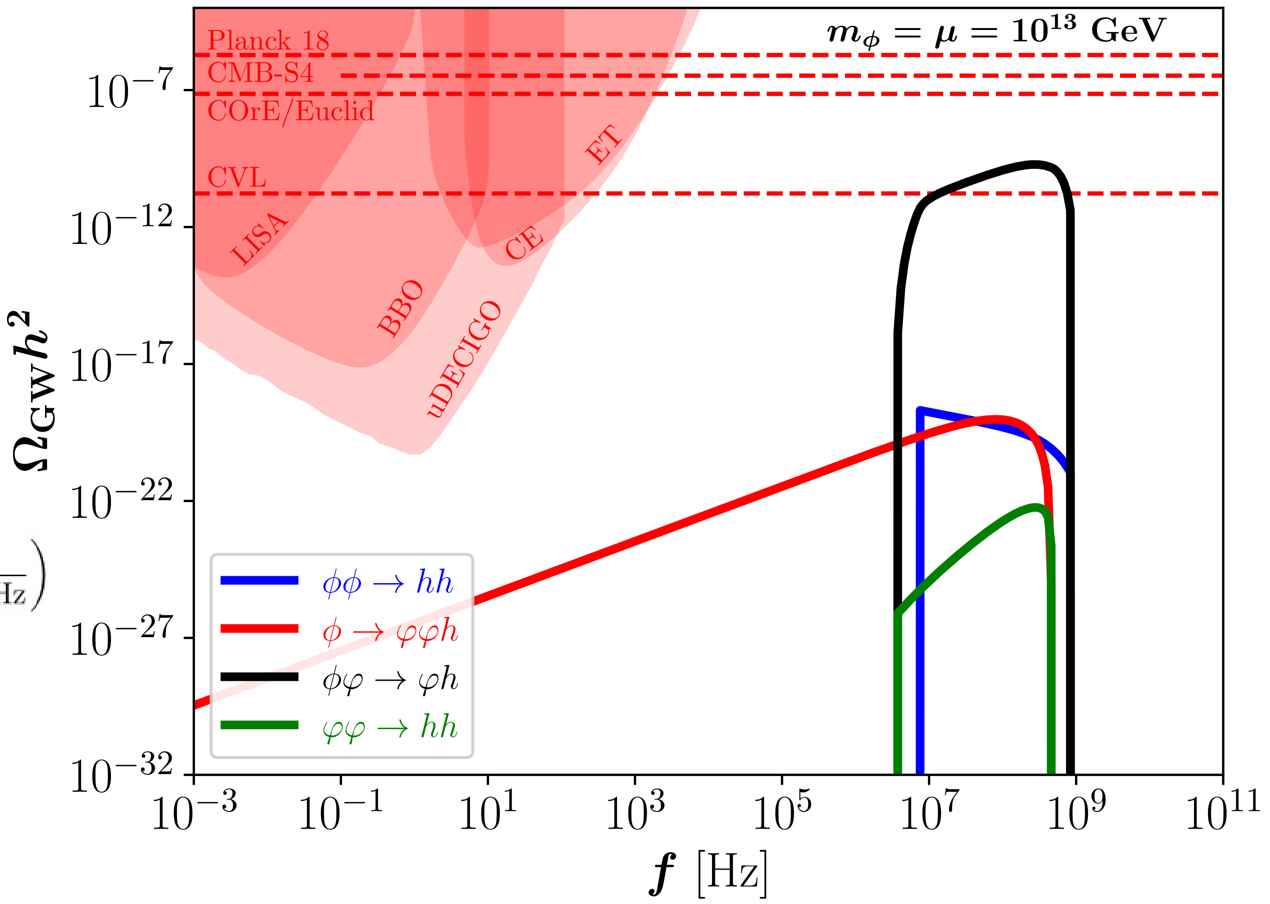


$$\Omega_{\rm GW} h^2(f) \simeq 5.86 \times 10^{-16} \left(\frac{\mu}{10^{12}\ \text{GeV}}\right)^5 \left(\frac{10^{13}\ \text{GeV}}{m_\phi}\right)^{\frac{11}{2}} \left(\frac{f}{10^7\ \text{Hz}}\right)$$

$2\, f_{\min} \lesssim f \lesssim f_{\max}$



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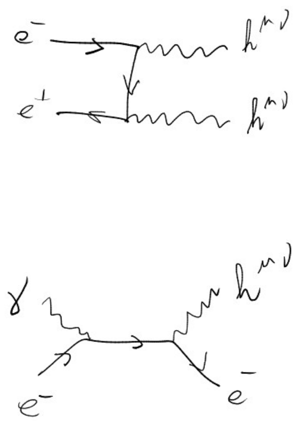

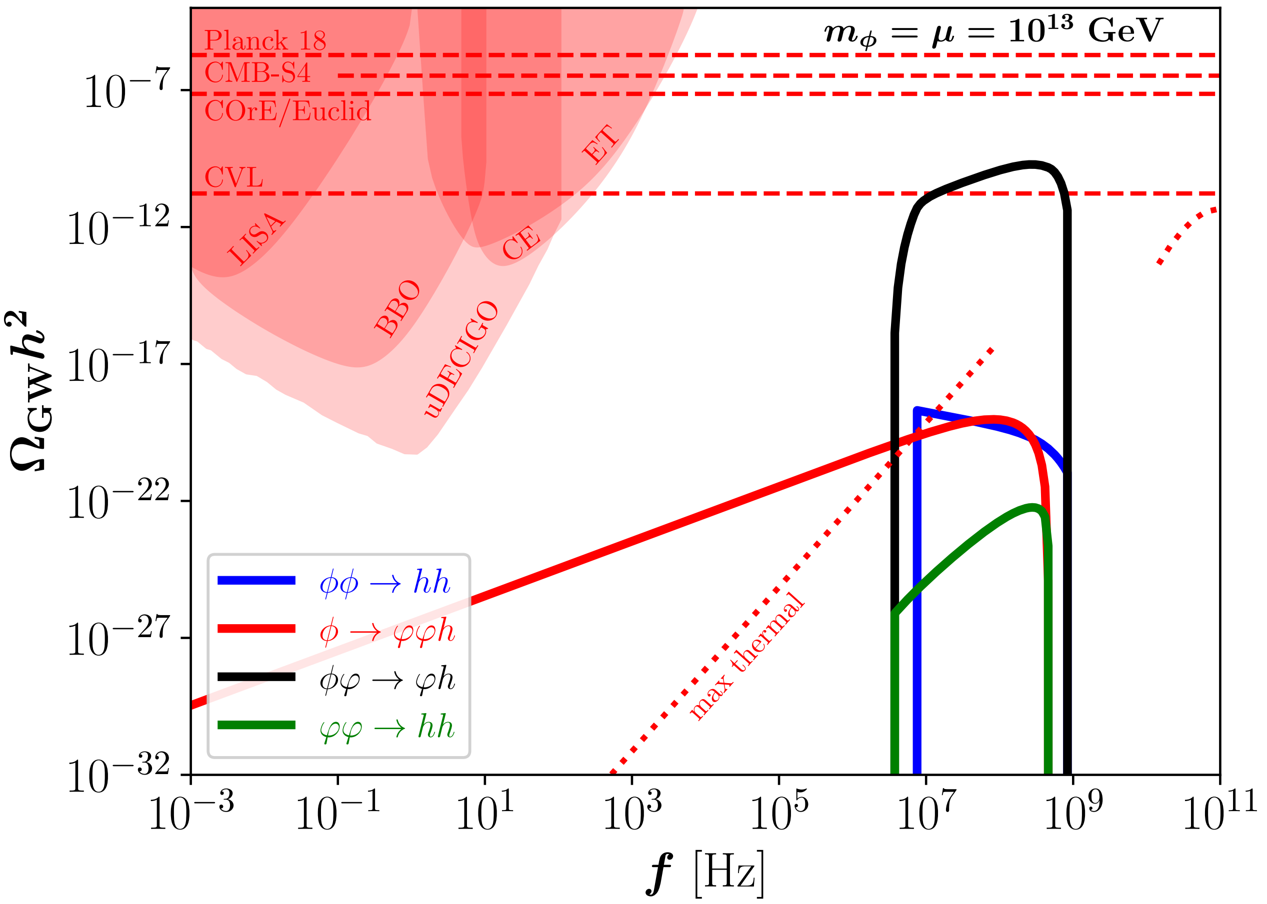

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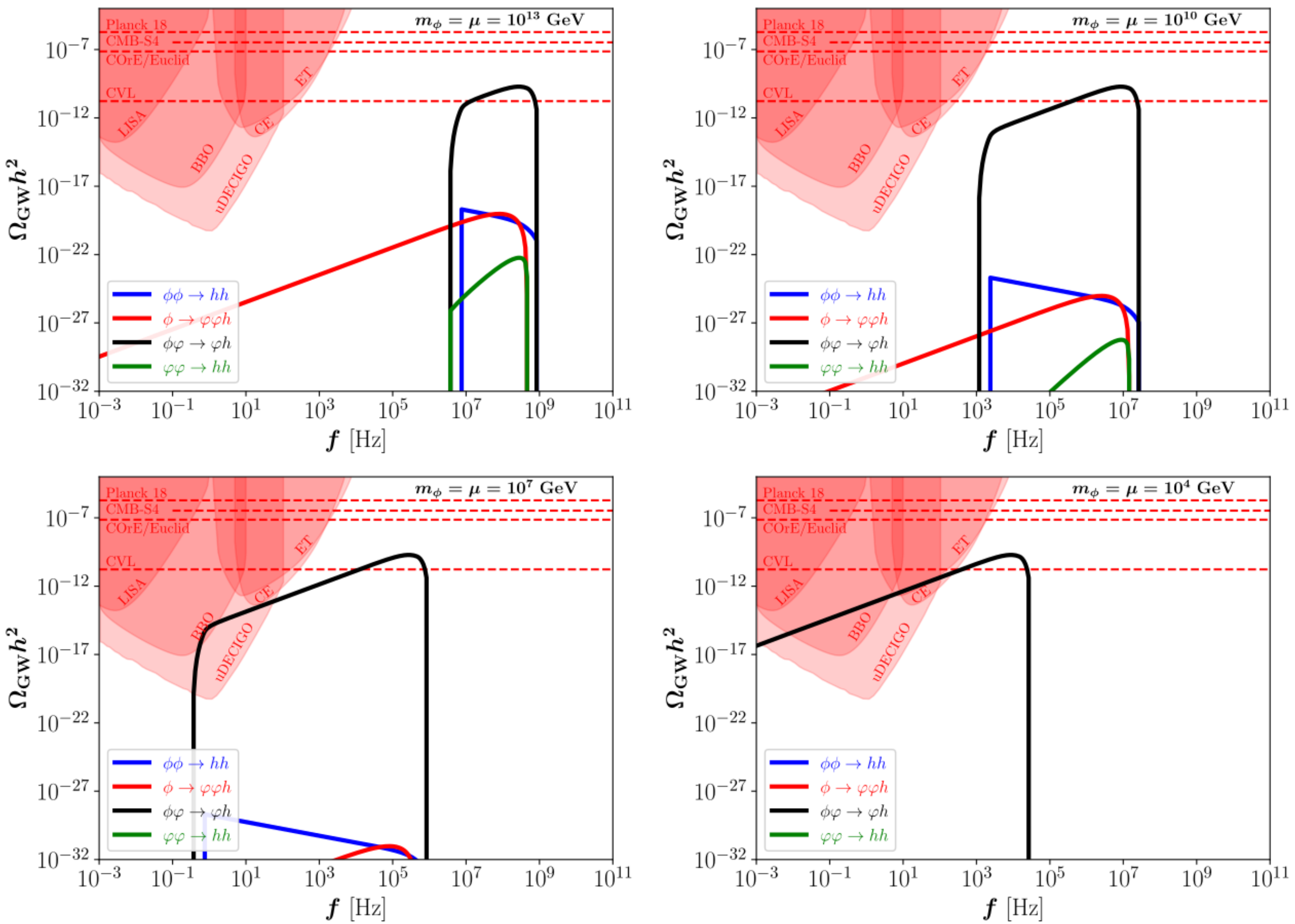

Conclusions

* Cosmic GW background: guaranteed background

* PGWs as a Big Bang thermometer...
 → much more than a Big Bang thermometer!

* Novel PGWs from the pre-thermal phase
 → within the reach of future GW observatories

* Scenarios with low inflaton mass $m_\phi < 10^7$ GeV could be probed

* PGWs as a unique tool to probe cosmic reheating

Dziękuję!