GWs from Bremsstrahlung, Scattering and Decay

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First One Hour...

...was on the blackboard

Bremsstrahlung GWs

$$\Omega_{GW}h^2 \simeq 10^{-19} \left(\frac{m}{10^{13}\ \text{GeV}}\right) \left(\frac{T_{rh}}{10^{13}\ \text{GeV}}\right) \left(\frac{f}{10^{9}\ \text{Hz}}\right)$$

Peak frequency: $f_{peak} \simeq \frac{m}{2}\,\frac{1}{2}\,\frac{a_{rh}}{a_0} \simeq 10^{10} \left(\frac{m}{10^{13}\ \text{GeV}}\right) \left(\frac{10^{13}\ \text{GeV}}{T_{rh}}\right)\ \text{Hz}$

At the peak: $\Omega_{GW} \propto \left(\frac{m}{10^{13}\ \text{GeV}}\right)^{2}$

[YX, 2407.03256]

Probing Reheating with Bremsstrahlung GWs

If null signal at a frequencyÔ m à 10^{13} GeV with a speci cT_{rh} less likely

In aton scattering with decay product

$$ {}^{2}_{g}\ {}^{2}\ \begin{cases} \frac{3}{4\ ^{3}} \frac{^{2}T^{4}}{M_P^2 m^3} & F\ ' \\ \frac{y^2}{48\ ^{3}} \frac{m\ \ T^{2}}{M_P^2} & F \end{cases} \quad \hat{O} \quad {}^{2}_{g}\ {}^{2}\ \ {}^{1}_{g}\ {}^{3} \begin{cases} \check{S}\frac{T}{m}\bullet^{4} & F\ ' \\ \check{S}\frac{T}{m}\bullet^{2} & F \end{cases} $$

In aton decays

$$ {}^{1}_{g}\ {}^{2}\ \frac{3\,m^3\ \ ^{2}}{2048\ \ ^{5}M_P^4} $$

[YX, 2407.03256]

Pure In aton Scattering

In aton In aton

$$\overset{2}{g}\quad{}^{2}\qquad\frac{}{m}\,\frac{m^{2}}{32\quad M_P^{4}}\qquad\frac{m}{32\quad M_P^{4}}$$

[Choi, Ke, Olive, 2402.04310]

[See talk by Wenqi Ke on July 18]

A Systematic Comparison among Four Sources

Left m A T_{rh}: 1 3 Bremsstrahlung typically dominates before the peak

Right m ß T_{rh}: 2 2 in aton scattering with the decay product can dominate

[YX, 2407.03256]

Summary and Outlook

Summary

- Bremsstrahlung typically dominates the spectrum (unless m @T_{rh})

$$_{GW}h^2 \quad 10^{19} \left(\frac{m}{10^{13}\ \mathrm{GeV}} \right) \left(\frac{T_{rh}}{10^{13}\ \mathrm{GeV}} \right) \left(\frac{f}{10^{9}\ \mathrm{Hz}} \right)$$

$$f_{peak} \quad 10^{10} \left(\frac{m}{10^{13}\ \mathrm{GeV}} \right) \left(\frac{10^{13}\ \mathrm{GeV}}{T_{rh}} \right) \ \mathrm{Hz}$$

- Probing reheating via Bremsstrahlung

Outlook

- Beyond Einstein-Hilbert, e.g. including ^2R

$$\frac{1}{M_P} T \quad h \qquad \frac{}{M_P} T \quad h \qquad \hat{O} \qquad \text{enhancement??}$$

Question:

- How to detect high frequency GWs?

Thanks for your attention!

Spectrum

Inflaton scattering with decay product

$$\Omega_{\rm GW}^{2\to 2} h^2(f) \simeq \begin{cases} 2 \times 10^{-18} \left(\frac{}{10^{11}~\text{GeV}}\right)^2 \left(\frac{T_{\rm rh}}{10^{13}~\text{GeV}}\right)^3 \left(\frac{10^{13}~\text{GeV}}{m}\right)^4 \left(\frac{f}{10^9~\text{Hz}}\right) \\ 5 \times 10^{-21} \left(\frac{y}{10^{-2}}\right)^2 \left(\frac{T_{\rm rh}}{10^{13}~\text{GeV}}\right)^{\frac{7}{4}} \left(\frac{10^{13}~\text{GeV}}{m}\right)^{\frac{3}{4}} \left(\frac{f}{10^9~\text{Hz}}\right)^{\frac{7}{4}} \end{cases}$$

Inflaton Decay

$$\Omega_{\rm GW}^{1\to 2} h^2(f) \simeq 4 \times 10^{-34} \left(\frac{}{10^{11}~\text{GeV}}\right)^2 \left(\frac{T_{\rm rh}}{10^{13}~\text{GeV}}\right)^{1/2} \left(\frac{m}{10^{13}~\text{GeV}}\right)^{1/2} \left(\frac{f}{10^9~\text{Hz}}\right)^{5/2}$$

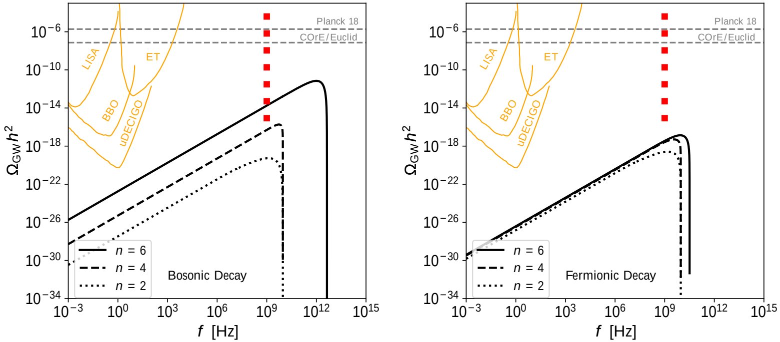
Inflaton Inflaton Scattering

$$\Omega_{\rm GW}^{2\to 2} h^2(f) \simeq 3 \times 10^{-22} \left(\frac{T_{\rm rh}}{10^{13}~\text{GeV}}\right)^{3/2} \left(\frac{m}{10^{13}~\text{GeV}}\right)^{3/2} \left(\frac{10^9~\text{Hz}}{f}\right)^{1/2}$$

[**YX**, 2407.03256]

What if ^{n} with $n > 2$?

Bosonic: $\Gamma \;\square\; \frac{2}{8\;\; m}$ with $m \;\square\; V'' \;\square\; ^{n-2}$ Fermionic: $\Gamma \;\square\; \frac{y^2 m}{8}$



GW amplitude **larger in bosonic decay** for $n > 2$ with $V(\;\;) \;\square\; ^n$

$$\Omega_{\rm GW}(f) \;\square\; \frac{d(\;_{\rm GW}/\;_R)}{d \ln f}$$

[Barman, Bernal, **YX**, Zapata 2305.16388]