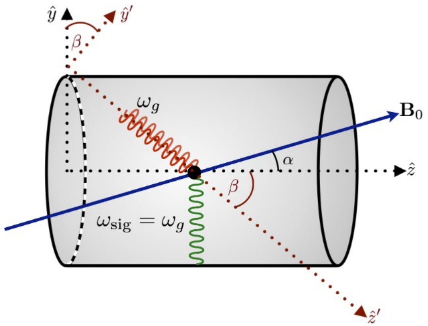
Gravitational Waves from the Thermal Plasma

Jan Schütte-Engel
September 17 2024

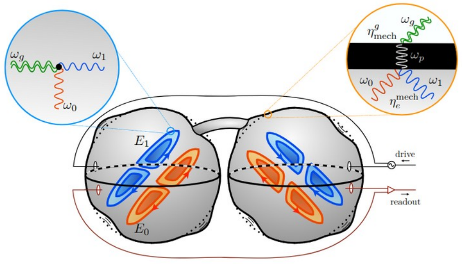
Fundamental physics and gravitational wave detectors, Pollica

Overview

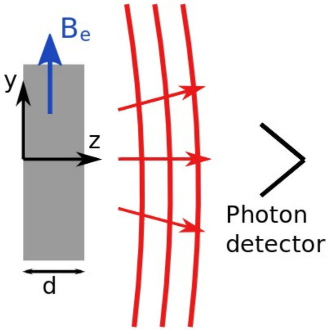
Novel proposals for GW and DM detection



[2112.11465]

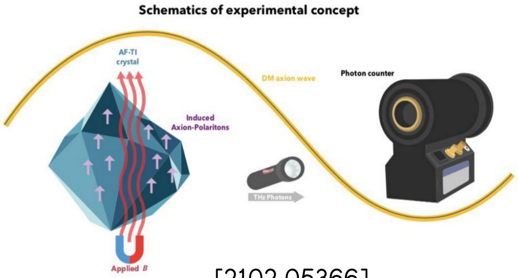


[2303.01518]



[2209.12909]

[2311.17147]



[2102.05366]

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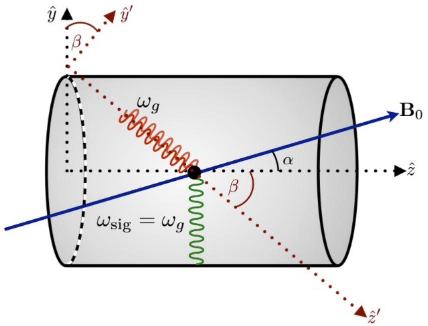

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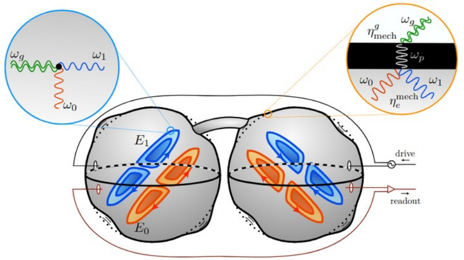

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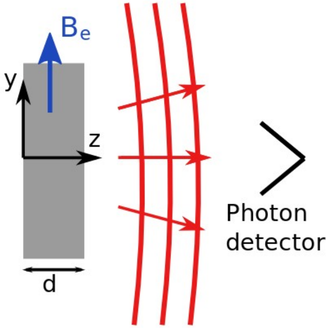

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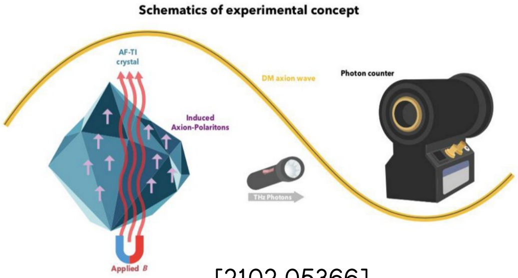

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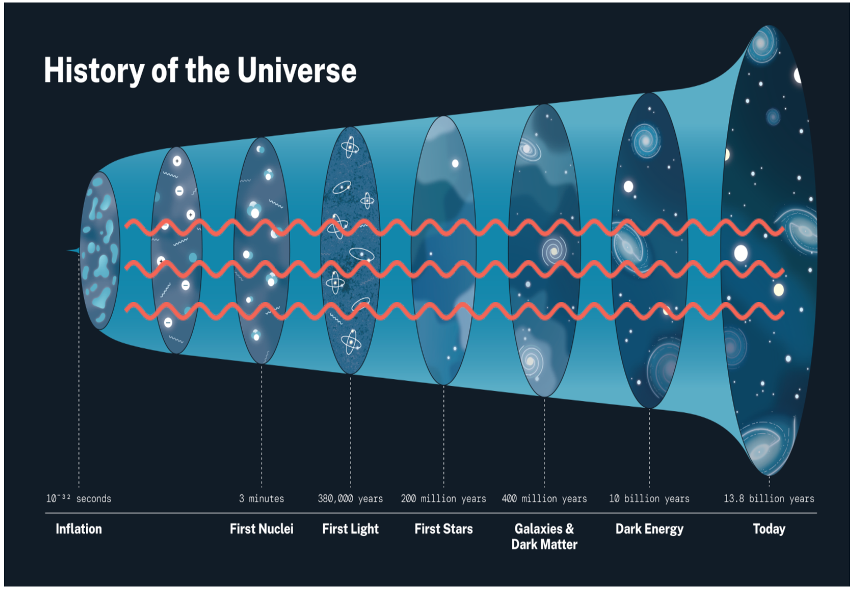
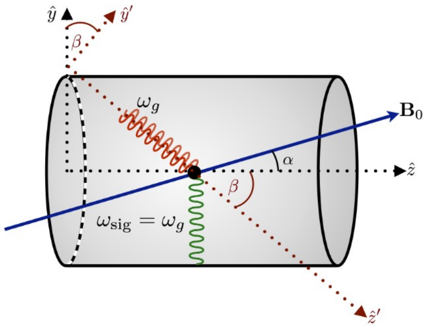
New Physics with Gravitational Waves



[nasa.gov]

Overview

Novel proposals for GW and DM detection



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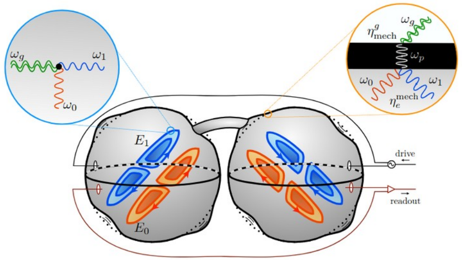

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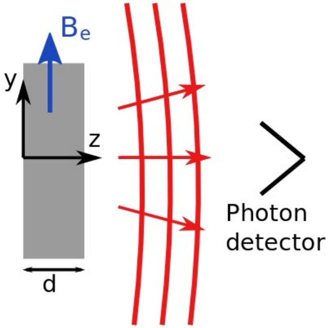

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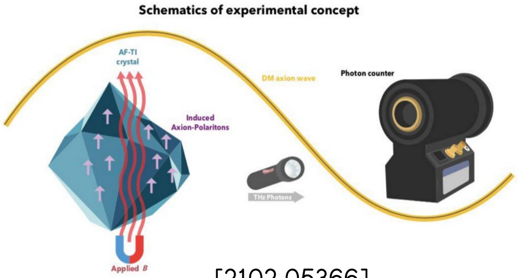

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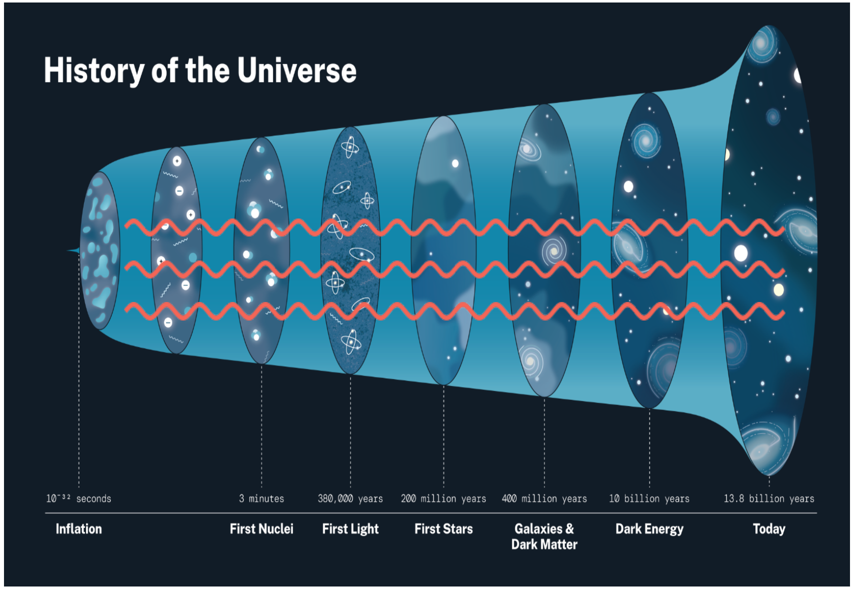
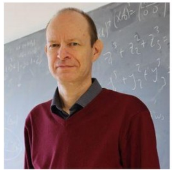


[nasa.gov]

This talk: 2401.08766, 2211.16513, 2011.04731

Jacopo Ghiglieri



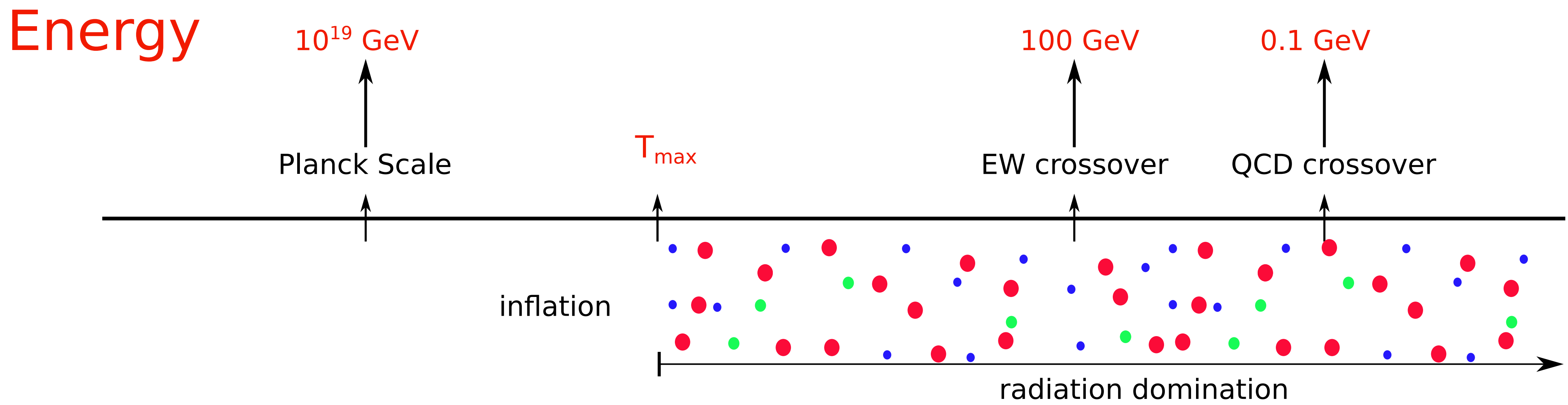
Mikko Laine

Andreas Ringwald

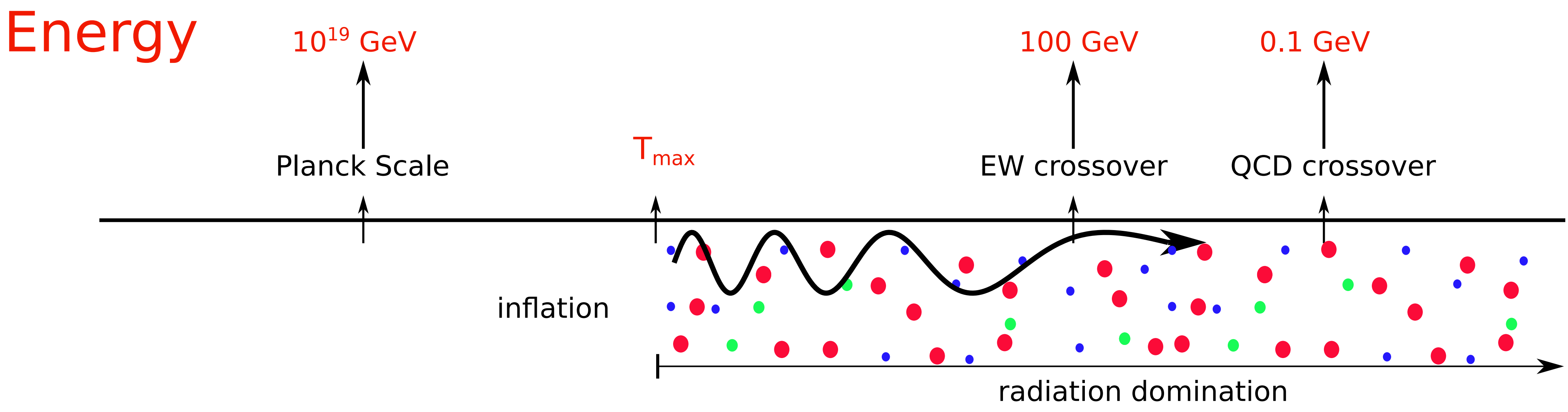
Carlos Tamarit

Enrico Speranza

GWs from the early universe



GWs from the thermal plasma



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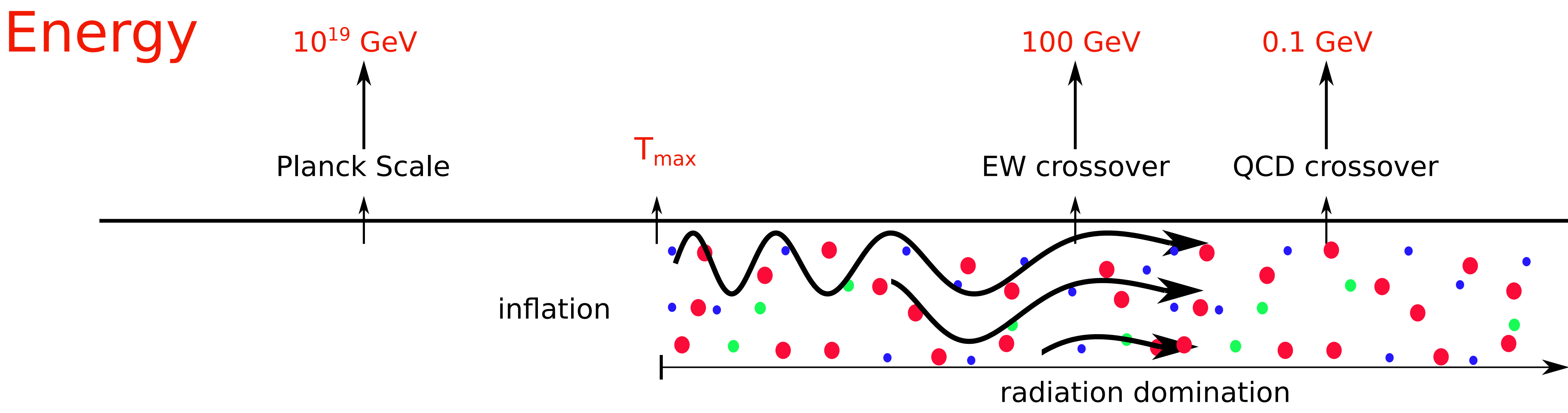

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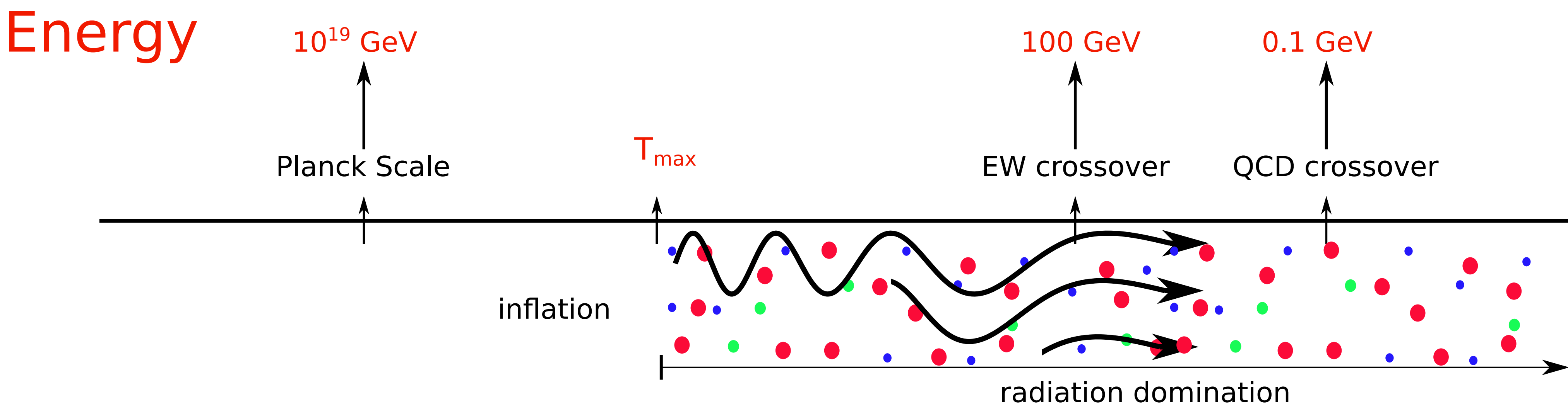
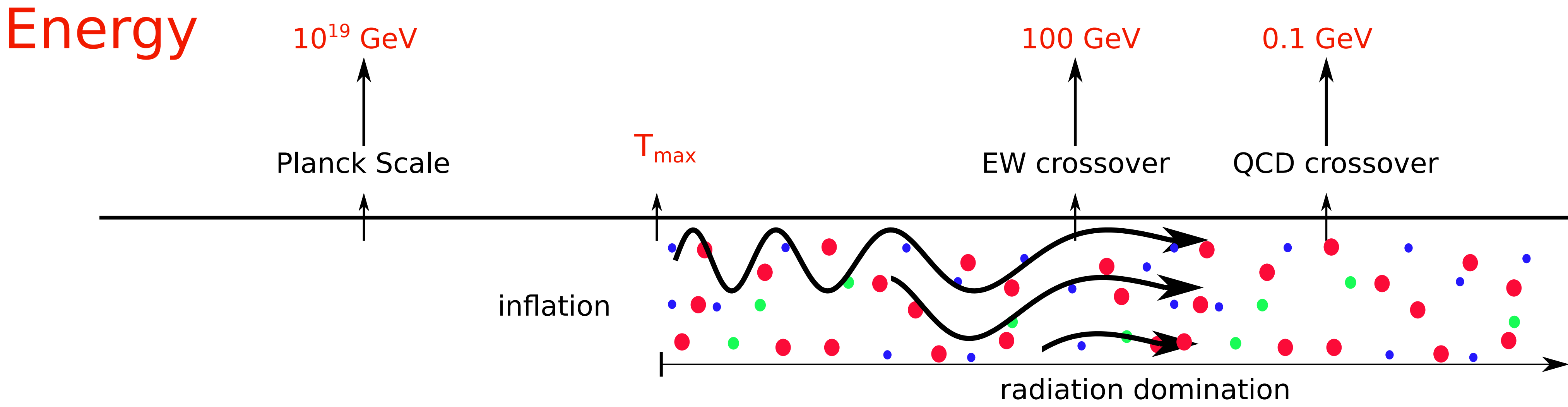


$$\omega_g^{\text{today}} = \left(\frac{g_{*s}(T_0)}{g_{*s}(T)}\right)^{\frac{1}{3}} \frac{k}{T} T_0$$

GWs from the thermal plasma



$$\omega_g^{\text{today}} = \left(\frac{g_{*s}(T_0)}{g_{*s}(T)}\right)^{\frac{1}{3}} \frac{k}{T} T_0$$

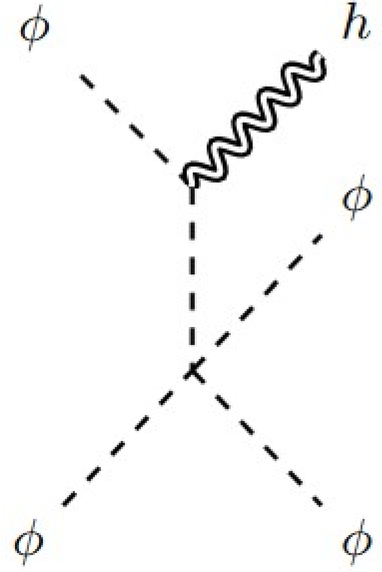
Cosmic Gravitational Microwave Background (CGMB)

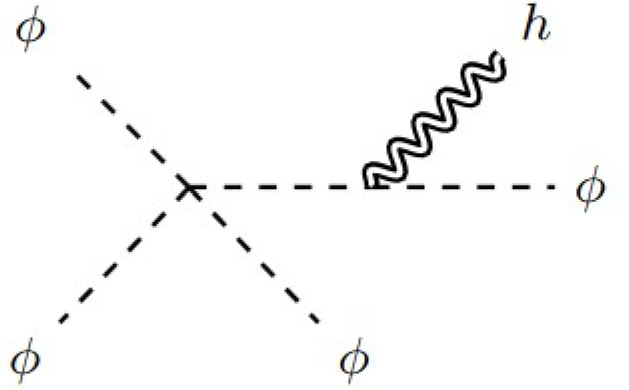
Outline

- Scalar model: $\mathcal{L} = -\partial_\mu \phi^\dagger \partial^\mu \phi + \frac{\lambda}{4}|\phi|^4$
- Standard Model (SM): $\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$
- Beyond the SM (BSM) theories: $\mathcal{L} = \mathcal{L}_{\mathrm{BSM}}$

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(\lambda^2 \psi^{(2,2)}\left(y_{\rm max}\right) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}\left(y_{\rm max}\right) + \frac{1}{3}\lambda^2 \left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(2,4)}\left(y_{\rm max}\right) + \cdots \right)$$

$$y_{\rm max} \equiv \frac{2\pi f_g}{T_0}\left(\frac{g_{*s}(T_{\rm max})}{g_{*s}(T_0)}\right)^{1/3} = 0.14\left(\frac{f_g}{10^{10}\,{\rm Hz}}\right)\left(\frac{g_{*s}(T_{\rm max})}{2}\right)^{1/3}$$





$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(\lambda^2 \psi^{(2,2)}\left(y_{\rm max}\right) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}\left(y_{\rm max}\right) + \frac{1}{3}\lambda^2\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(2,4)}\left(y_{\rm max}\right) + \cdots \right)$$

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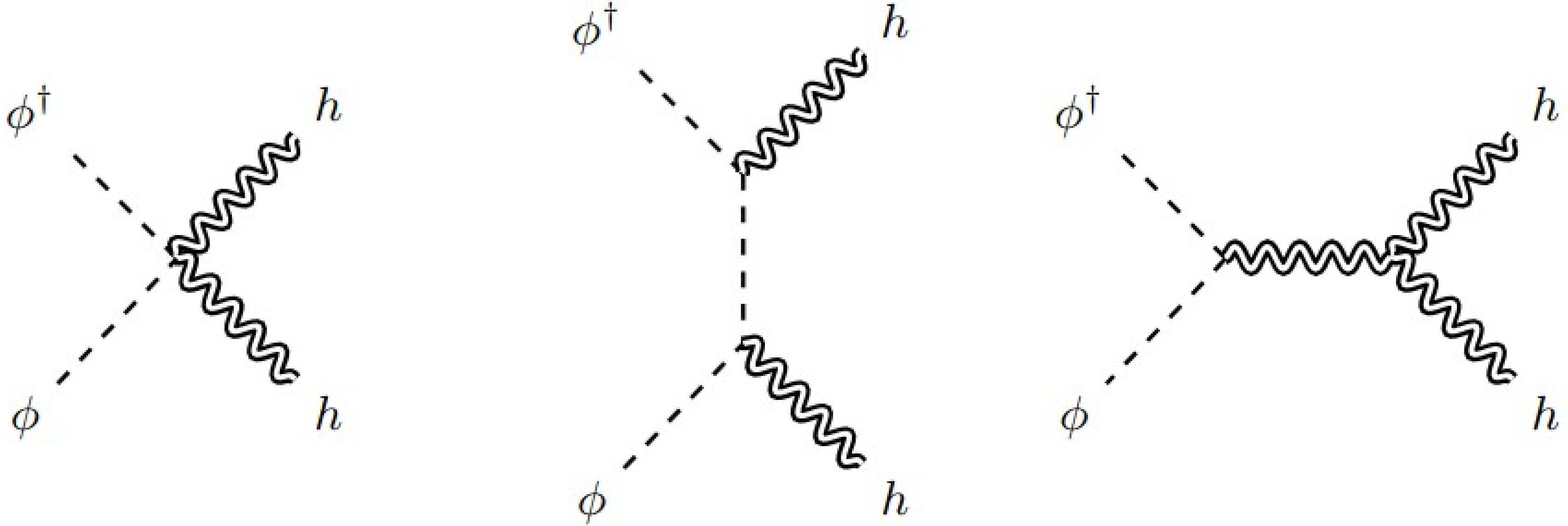

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(\lambda^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \frac{1}{3}\lambda^2 \left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(2,4)}(y_{\rm max}) + \cdots \right)$$

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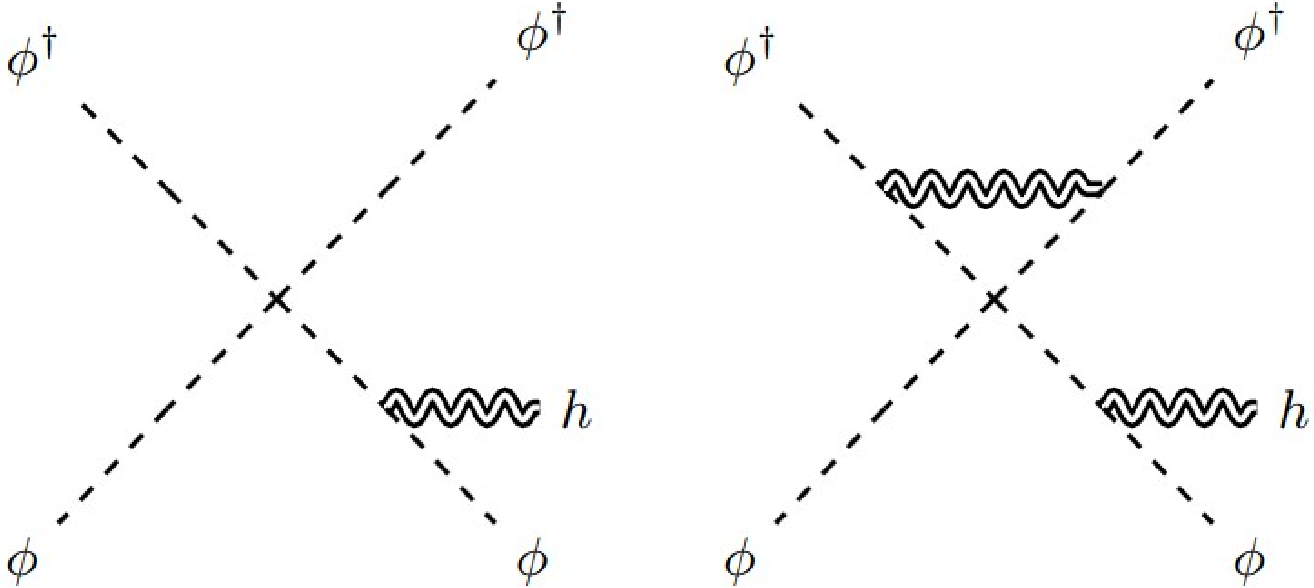

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Single graviton production dominates if

$$10\,\frac{T_{\max}}{m_p} < \lambda$$

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(\lambda^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \frac{1}{3}\lambda^2 \left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(2,4)}(y_{\rm max}) + \cdots \right)$$

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Quantum gravity effects are small corrections. They suppressed by a factor

$$\left(\frac{T_{\rm max}}{m_p}\right)^2$$

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(\lambda^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \frac{1}{3}\lambda^2 \left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(2,4)}(y_{\rm max}) + \cdots \right)$$

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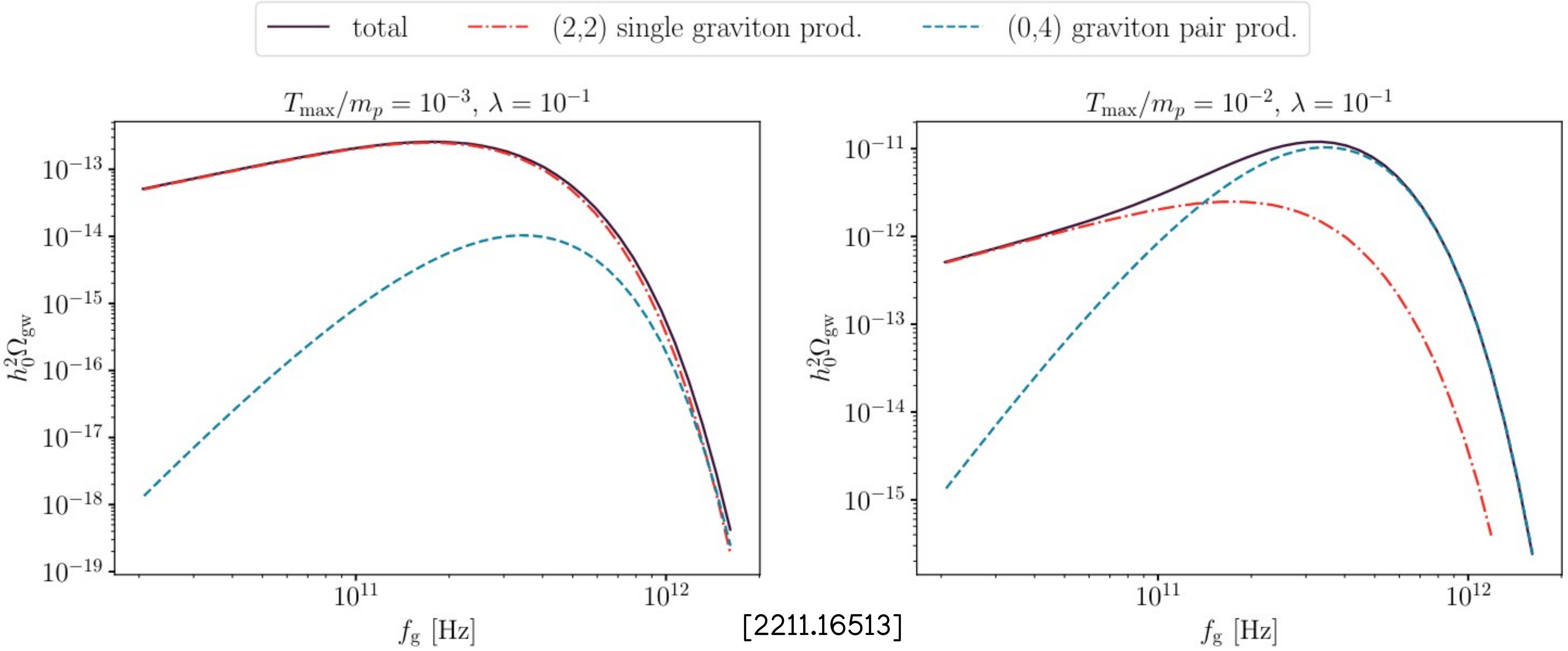


[2211.16513]

GWs from the thermal plasma in SM

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(g^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \cdots \right)$$

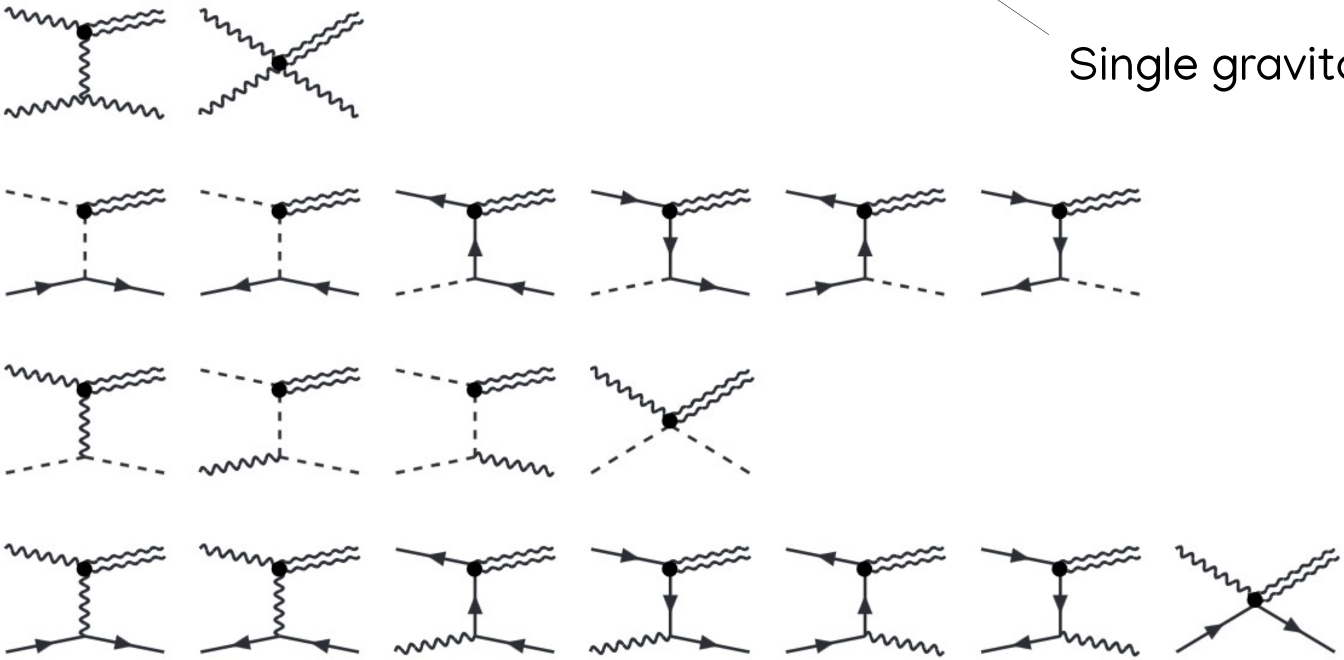
SM gauge couplings

GWs from the thermal plasma in SM

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\rm max}}{m_p} n_{\rm B}(y_{\rm max}) \left(g^2 \psi^{(2,2)}(y_{\rm max}) + \frac{1}{3}\left(\frac{T_{\rm max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\rm max}) + \cdots \right)$$

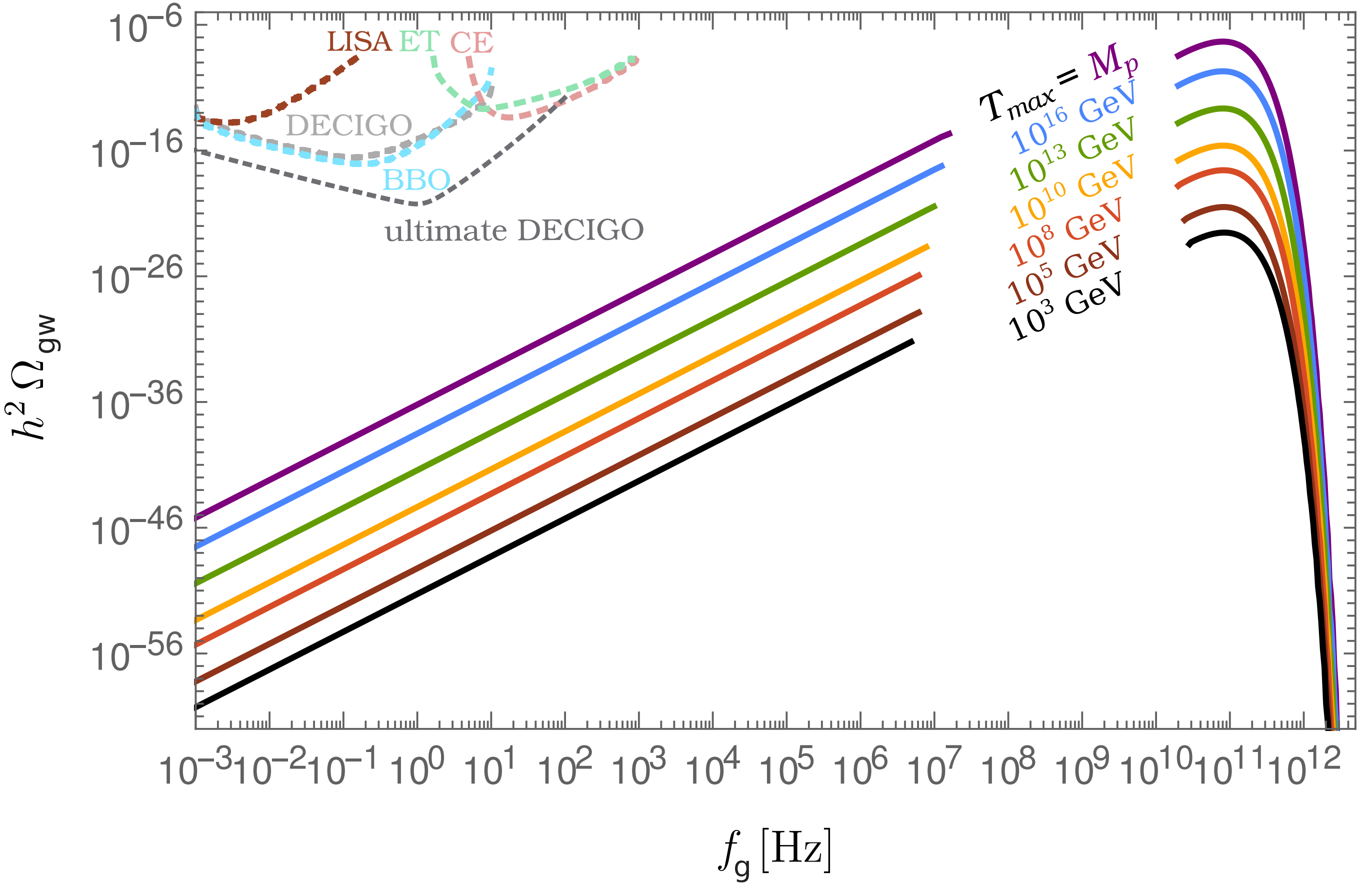
Single graviton production processes

$$|\mathcal{M}|^2 \sim g^2 \frac{1}{m_p^2}$$



[2004.11392]

GWs from the thermal plasma



[2011.04731]

$$f_{\rm peak} \sim \left(\frac{1}{g_{*s}(T_{\rm max})}\right)^{\frac{1}{3}}$$

	SM	MSSM
$g_{*s}(T_{\rm max})$	106.75	228

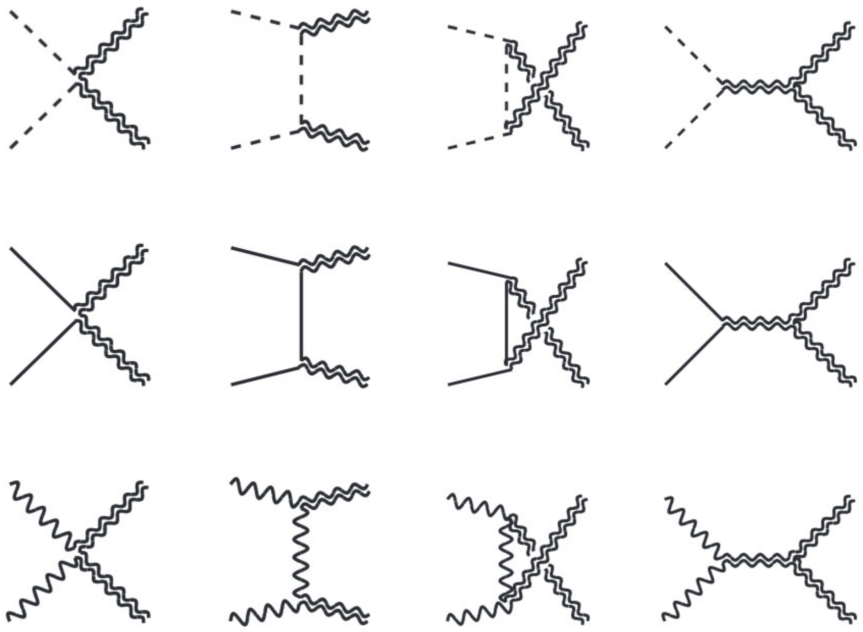
$$\Omega_{\rm gw} \sim \frac{T_{\rm max}}{m_p}$$

From BBN and CMB:

$$h^2\Omega_{\rm gw} < 10^{-6}$$

GWs from the thermal plasma in SM

$$h_0^2\Omega_{\rm gw}(f_g) \sim \frac{T_{\max}}{m_p} n_{\rm B}(y_{\max}) \left(g^2\psi^{(2,2)}(y_{\max}) + \frac{1}{3}\left(\frac{T_{\max}}{m_p}\right)^2 \psi^{(0,4)}(y_{\max}) + \cdots \right)$$



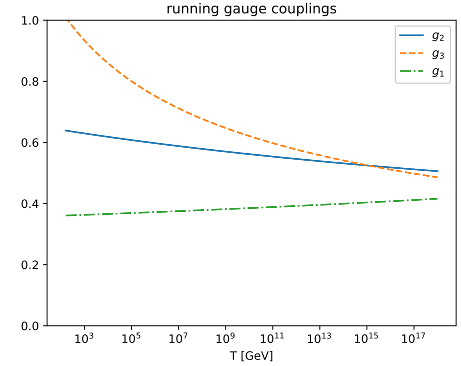
[2401.08766]

Graviton pair production processes

$$|\mathcal{M}|^2 \sim \frac{1}{m_p^4}$$

In SM double graviton production dominates if

$$\frac{T_{\max}}{m_p} > 0.4$$



Conclusions

- CGMB is guaranteed stochastic GW background which peaks in GHz regime
- Powerful probe of particle physics models
- Peak amplitude determines maximum temperature
- Quantum gravity effects are encoded as density perturbations in GW spectrum

Backup

Distribution functions

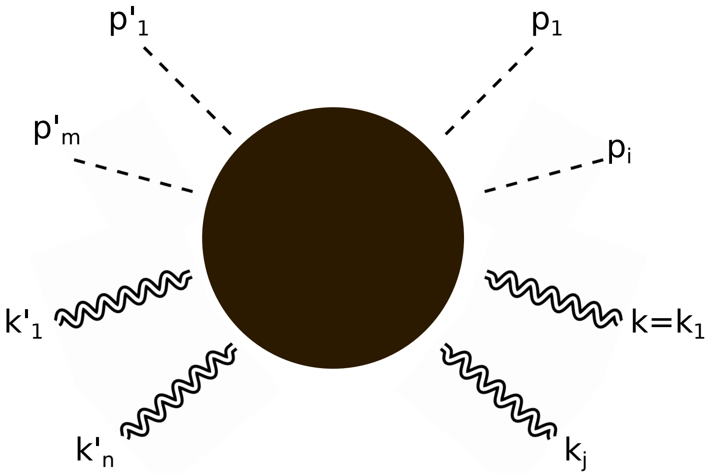
$$f_\phi(t,k) \equiv \frac{\text{Number of } \phi\text{-states with momentum } k \text{ in } d^3k \text{ interval}}{V\, d^3k/(2\pi)^3}$$

$$f_h(t,k) \equiv \frac{\text{Number of gravitons with momentum } k \text{ in } d^3k \text{ interval}}{V\, d^3k/(2\pi)^3}$$

Evolution equations

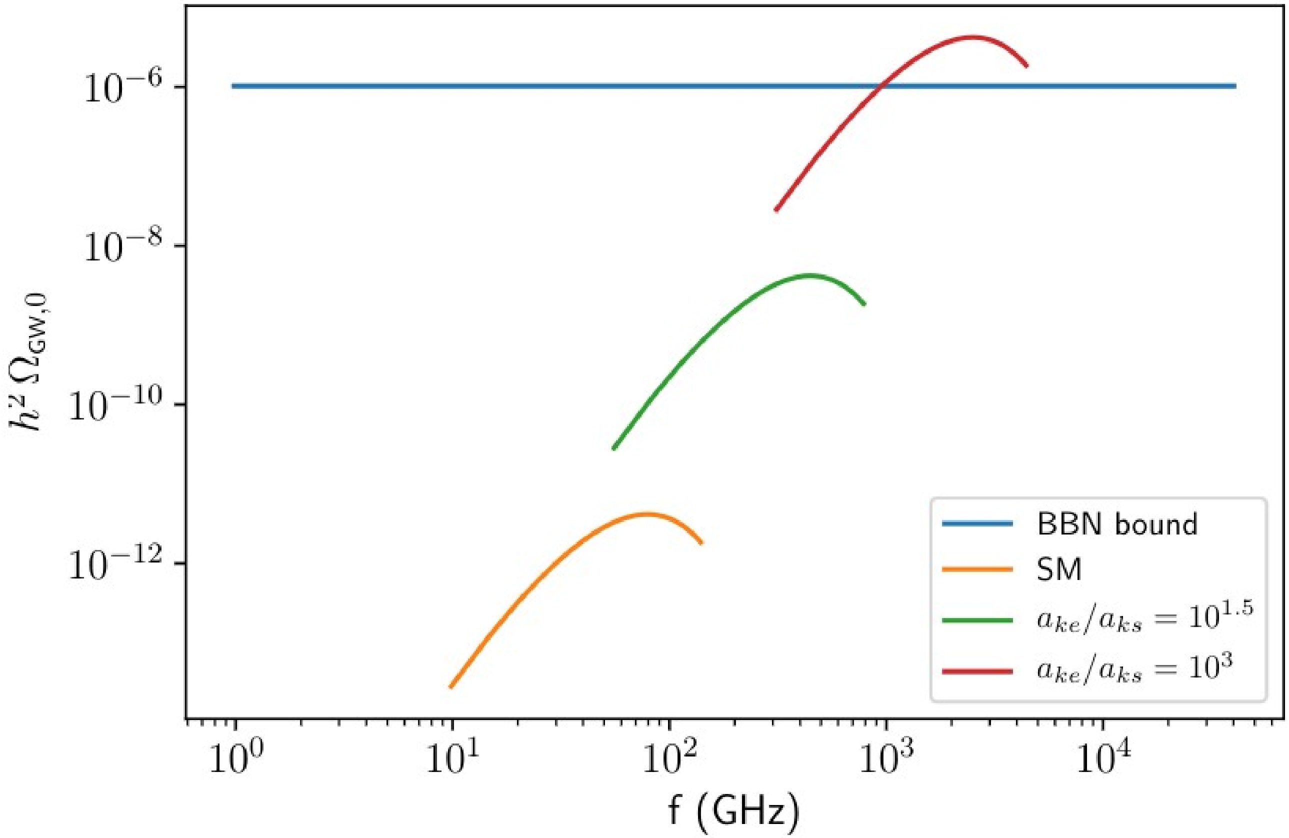
$$\dot{f}_\phi(t,k) = G_\phi(t,k) - L_\phi(t,k)$$

$$\dot{f}_h(t,k) = G_h(t,k) - L_h(t,k)$$



$$G_h(t,k) = \frac{1}{4k} \sum_{\substack{\text{all processes } r \\ \text{with at least one} \\ \text{final state graviton}}} S_r \int d\Omega_r\, |\mathcal{M}_r|^2 \times f_\phi(p_1') \cdots f_\phi(p_m')\, f_h(k_1') \cdots f_h(k_n') \times$$
$$\times (1+f_\phi(p_1)) \cdots (1+f_\phi(p_i))\, (1+f_h(k)) \cdots (1+f_h(k_j))$$

CGMB in modifierd cosmology



[Muia, Quevedo, Schachner, Villa 23]

Sensitivity to stochastic GWs

$$\mathrm{SNR} = \frac{S_{\mathrm{sig}}}{S_{\mathrm{noise}}} = \frac{\omega_n Q}{4\pi T} \left|\eta\right|^2 B_0^2 V_{\mathrm{cav}} S_h(\omega)$$

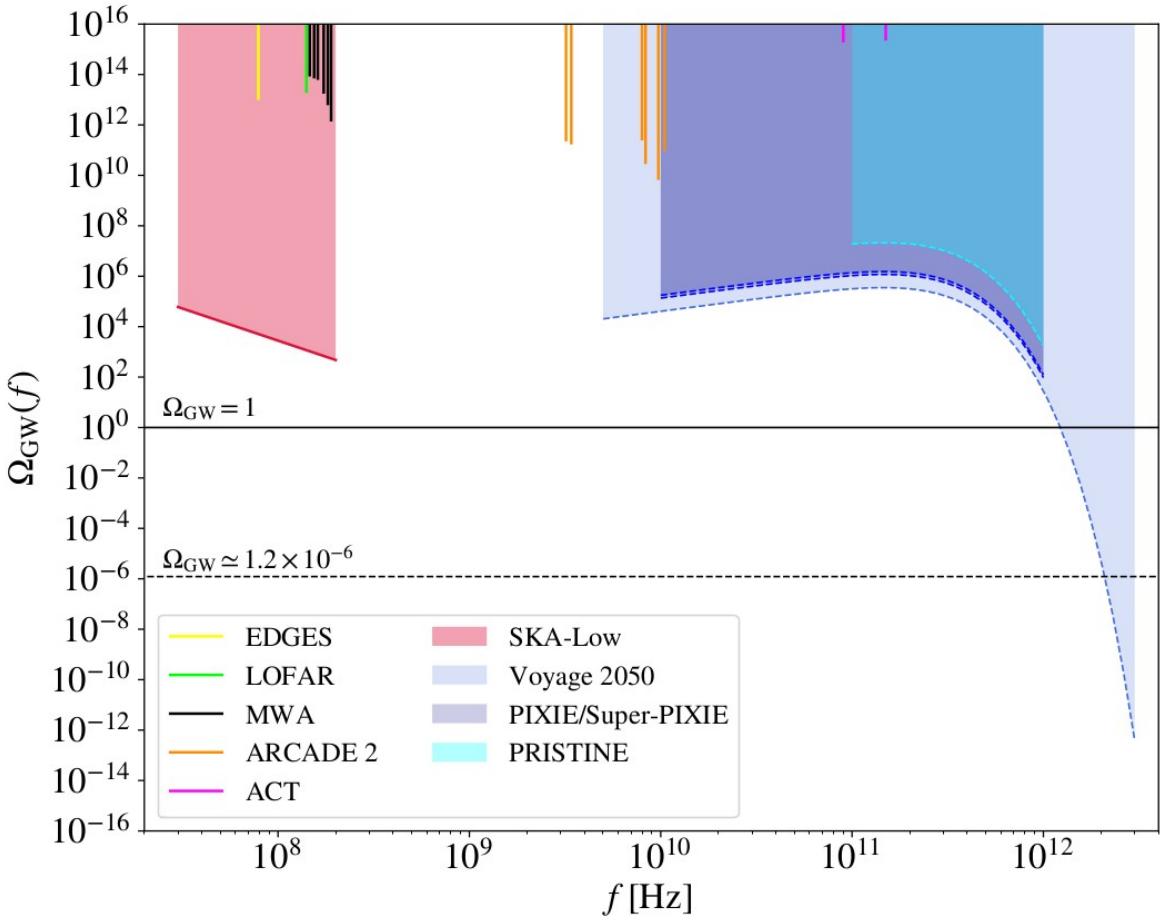
We can only constrain: $\Omega_{\mathrm{GW}} > 1$

BUT

From BBN and CMB: $\Omega_{\mathrm{GW}} < 10^{-6}$

Graviton photon conversion in galactic or earth magnetic field seems more promising...

Astrophysical detection of Stochastic GWs



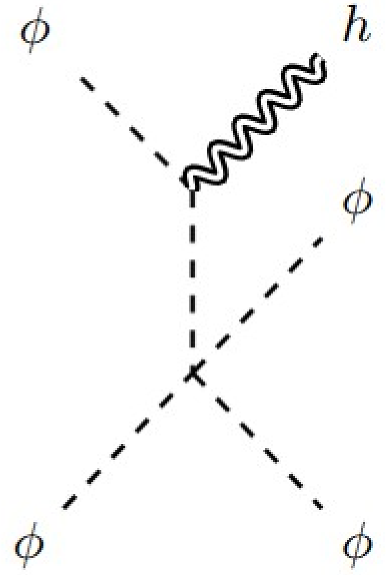
[He, Giri, Sharma, Mtchedlidze, Georgiev, 23]

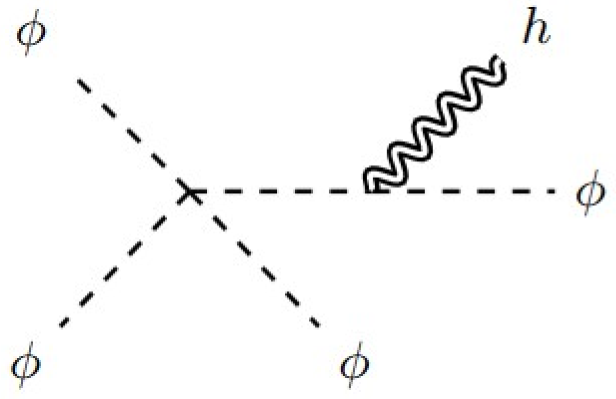
$$f_\phi(k) = n_\mathrm{B}(k) + \cdots \,, \quad n_B = \frac{1}{e^{k/T} - 1}$$

$$f_h(k) = 0 \cdots$$

$$f_\phi(k) = n_{\mathrm{B}}(k) + \cdots$$

$$f_h(k) = 0 + f_h^{(2,2)}(k) + \cdots$$

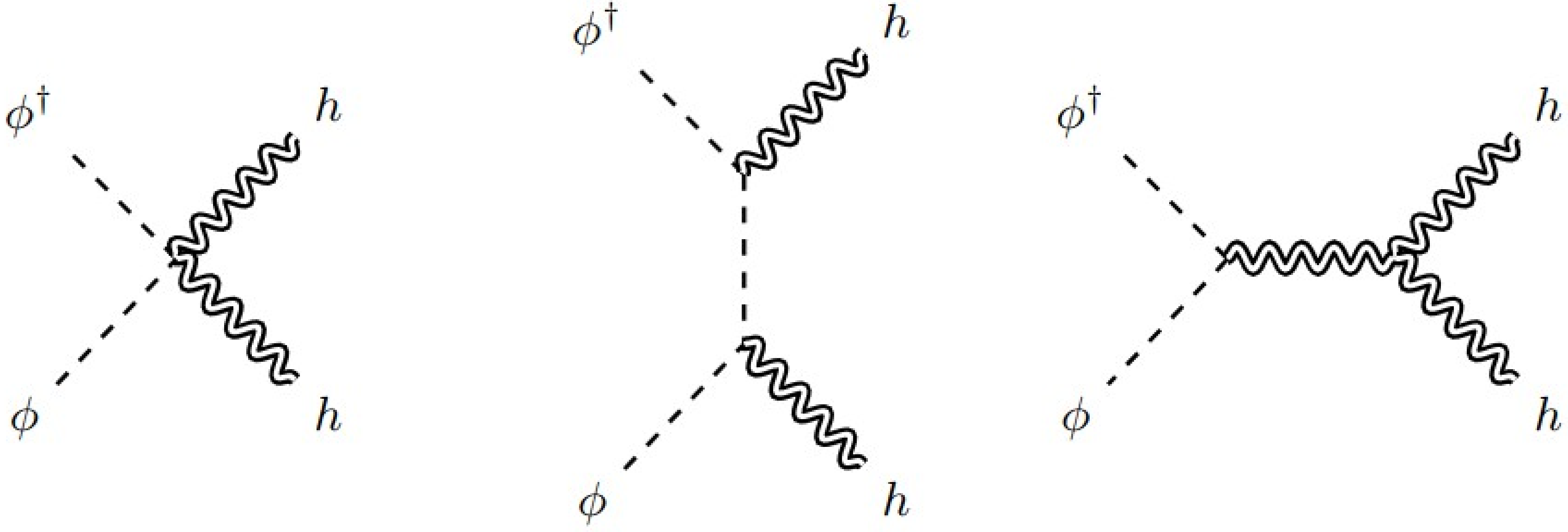




$$|\mathcal{M}|^2 \sim \lambda^2 \left(\frac{1}{m_p}\right)^2$$

$$f_\phi(k) = n_{\mathrm{B}}(k) + \cdots$$

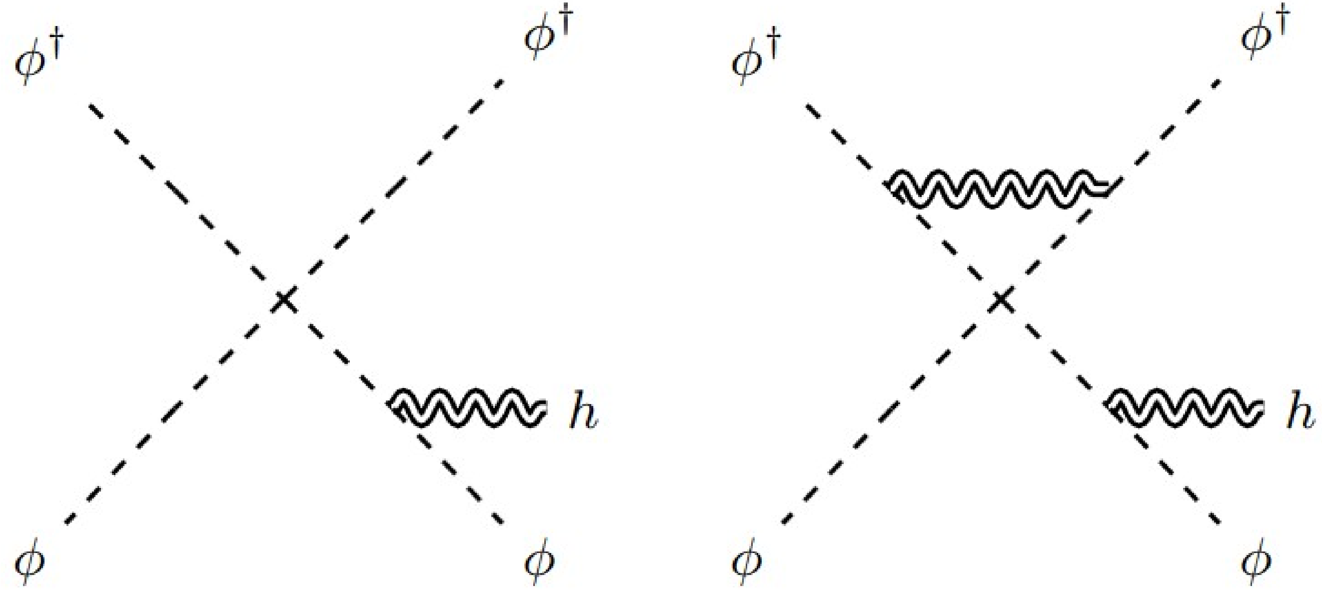
$$f_h(k) = 0 + f_h^{(2,2)}(k) + f_h^{(0,4)}(k) + \cdots$$



$$|\mathcal{M}|^2 \sim \left(\frac{1}{m_p}\right)^4$$

$$f_\phi(k) = n_{\rm B}(k) + \cdots$$

$$f_h(k) = 0 + f_h^{(2,2)}(k) + f_h^{(0,4)}(k) + f_h^{(2,4)}(k) + \cdots$$



$$|\mathcal{M}|^2 \sim \lambda^2 \left(\frac{1}{m_p}\right)^4$$