Observable Gravitational Waves from Axion-Like Particles

Bhupal Dev

Washington University in St. Louis

BD, F. Ferrer, Y. Zhang and Y. C. Zhang, arXiv:1905.00891 [hep-ph].

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Outline

- Introduction to ALP
- Scalar Potential
- Gravitational Wave Spectrum
- Comparison with Other Constraints
- Conclusion

Axion-Like Particle (ALP)

- Light SM-singlet pseudoscalar.
- Pseudo-Nambu-Goldstone boson in theories with global $U(1)$ symmetry breaking.
- Originally introduced to solve the **strong CP problem**. [Peccei, Quinn (PRL '77)]
- Could also play important role in addressing other open issues of the SM, such as **hierarchy problem** [Graham, Kaplan, Rajendran (PRL '15)], **inflation** [Freese, Frieman, Olinto (PRL '90)], **dark matter** [Preskill, Wise, Wilczek (PLB '83); Abbott, Sikivie (PLB '83); Dine, Fischler (PLB '83)], **dark energy** [Kim, Nilles (JCAP '09)], **baryogenesis** [De Simone, Kobayashi, Liberati (PRL '17)].
- Could provide a common framework to simultaneously address many of these issues. [Ballesteros, Redondo, Ringwald, Tamarit (PRL '17); Ema, Hamaguchi, Moroi, Nakayama (JHEP '17); Gupta, Reiness, Spannowsky '19]

A Simple ALP Model

- ALP couplings to SM is suppressed by inverse powers of the $U(1)$-symmetry breaking scale f_a.
- Can be identified as the VEV of a SM-singlet complex scalar field Φ.
- The ALP field is the massless mode of the angular part of Φ:

$$\Phi(x) \;=\; \frac{1}{\sqrt{2}}\left[f_a + \phi(x)\right] e^{ia(x)/f_a} \,.$$

- Explicit low-energy $U(1)$-breaking effects can induce a small mass for $a(x)$.

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- **Key point:** The spontaneous $U(1)$-symmetry breaking at the f_a-scale could induce a strongly first-order phase transition, if Φ has a non-zero coupling to the SM Higgs doublet field.
- Gives rise to stochastic gravitational wave signals potentially observable in current and future GW detectors. [BD, Mazumdar (PRD '16)]

Scalar Potential

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- Tree-level: $\mathcal{V}_0 \;=\; -\mu^2|H|^2 + \lambda|H|^4 + \kappa|\Phi|^2|H|^2 + \lambda_a\left(|\Phi|^2 - \frac{1}{2}f_a^2\right)^2 .$

$$= \frac{\lambda_a}{4}\left(\phi^2 - f_a^2\right)^2 + \left[\frac{\kappa}{2}\phi^2 - \mu^2\right]\left(\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right)$$

$$+ \lambda\left[\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right]^2 .$$

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- One-loop: $\mathcal{V}_{\rm CW}\left(\phi\right) \;=\; \sum_i (-1)^F n_i \frac{m_i^4\left(\phi\right)}{64\pi^2}\left[\log\frac{m_i^2\left(\phi\right)}{\Lambda^2} - C_i\right] .$

- Finite-temperature: $\mathcal{V}_T\left(\phi, T\right) \;=\; \sum_i \left(-1\right)^F n_i \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m_i^2\left(\phi\right)}{T^2}\right) ,$

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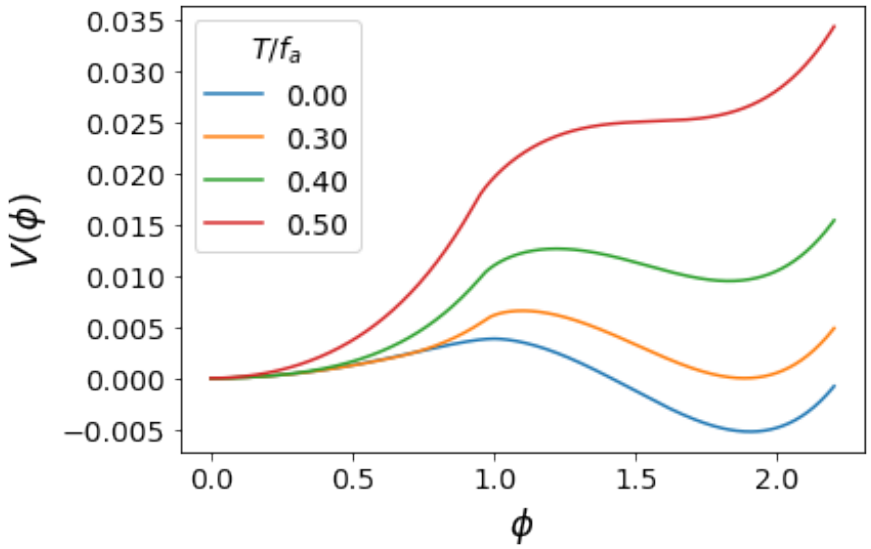
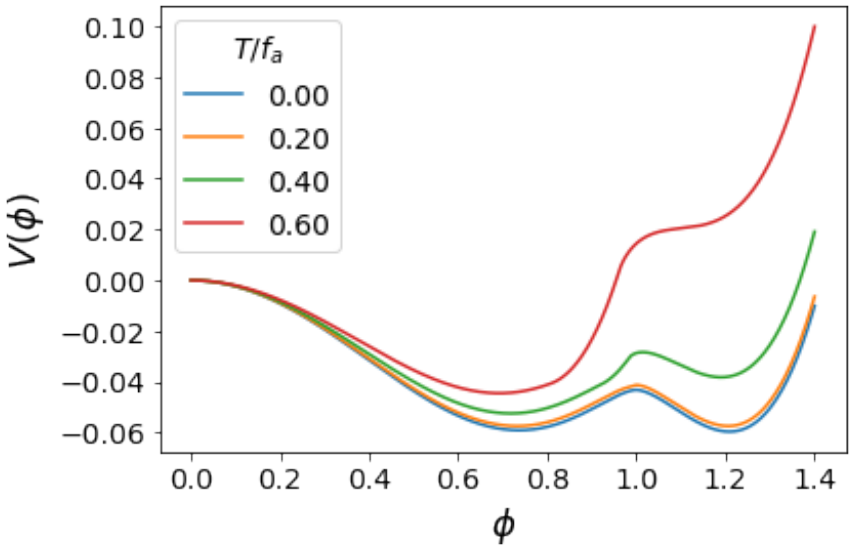
- Temperature-dependent mass terms:

$$\Pi_h\left(T\right) \;=\; \Pi_{G_{0,\pm}}\left(T\right) \quad = \quad \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda + 4\kappa\right)T^2 ,$$
$$\Pi_\phi\left(T\right) \quad = \quad \frac{1}{3}\left(\kappa + 2\lambda_a\right)T^2 .$$

[Dolan, Jackiw (PRD '74); Arnold, Espinosa (PRD '93); Curtin, Meade, Ramani (EPJC '18)]

First-order Phase Transition





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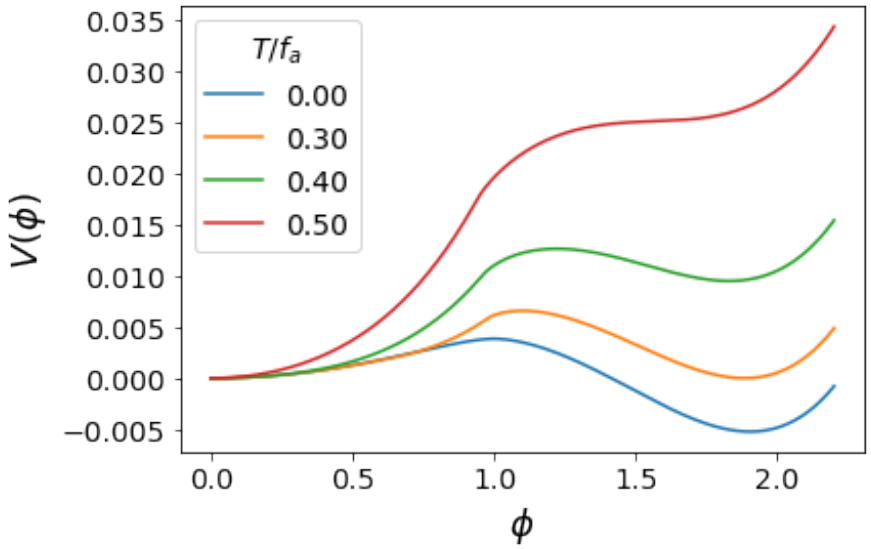

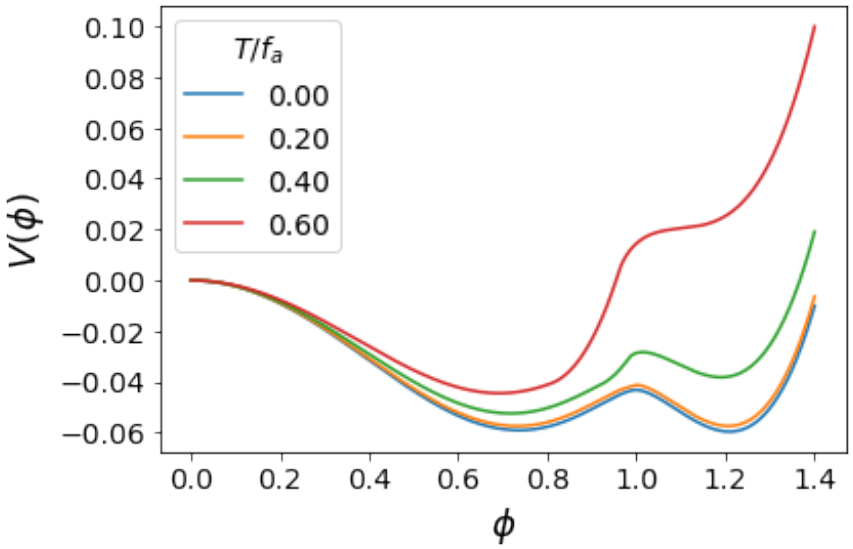

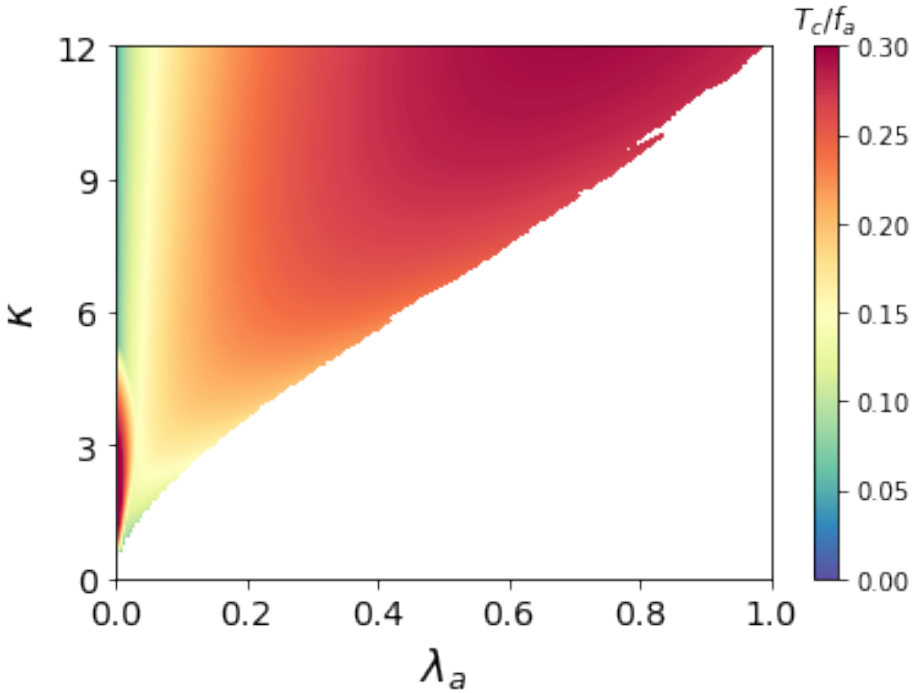

Gravitational Wave Production

$$h^2\Omega_{\text{GW}} \;=\; h^2\Omega_\phi + h^2\Omega_{\text{SW}} + h^2\Omega_{\text{MHD}}\,.$$

[Kosowsky, Turner, Watkins (PRL '92); Kamionkowski, Kosowsky, Turner (PRD '94); Caprini, Durrer, Servant (PRD '08); Huber, Konstandin (JCAP '08); Hindmarsh, Huber, Rummukainen, Weir (PRL '14); Ellis, Lewicki, No '18]

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Depends on two important parameters:

- Vacuum energy density: $\alpha \;=\; \dfrac{\rho_{\text{vac}}}{\rho^*_{\text{rad}}} \quad \text{with } \rho^*_{\text{rad}} \;=\; g_*\pi^2\dfrac{T_*^4}{30}\,.$

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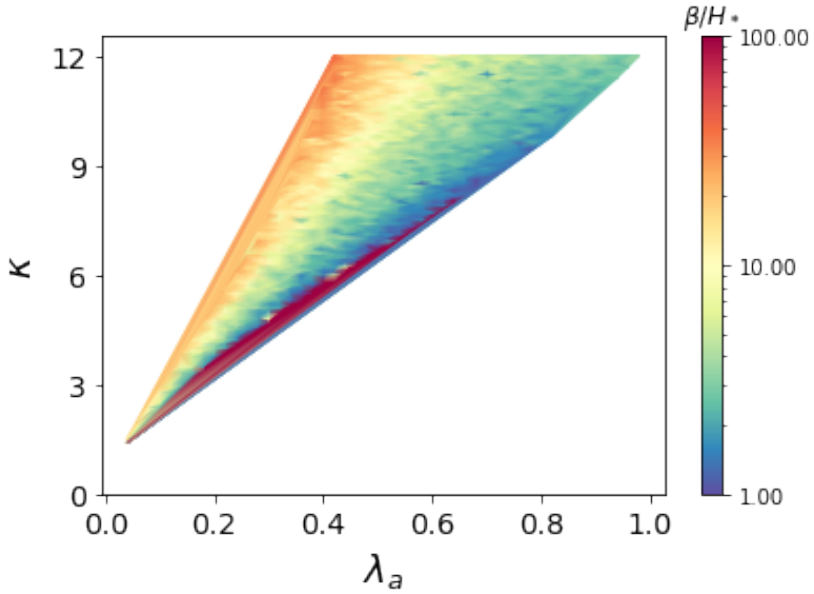

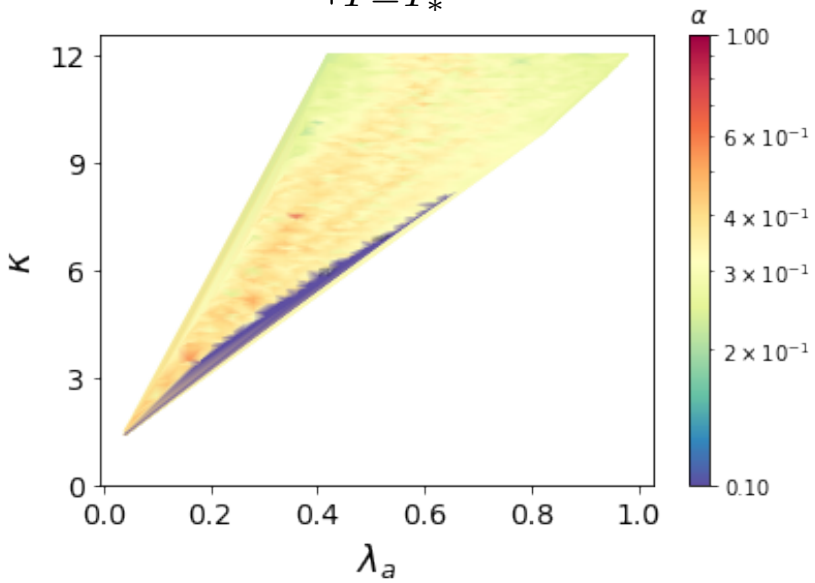

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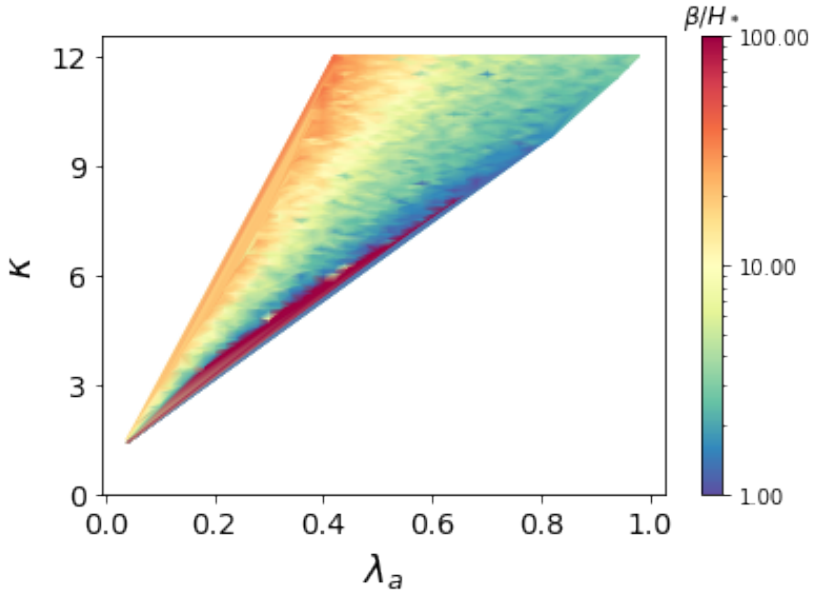
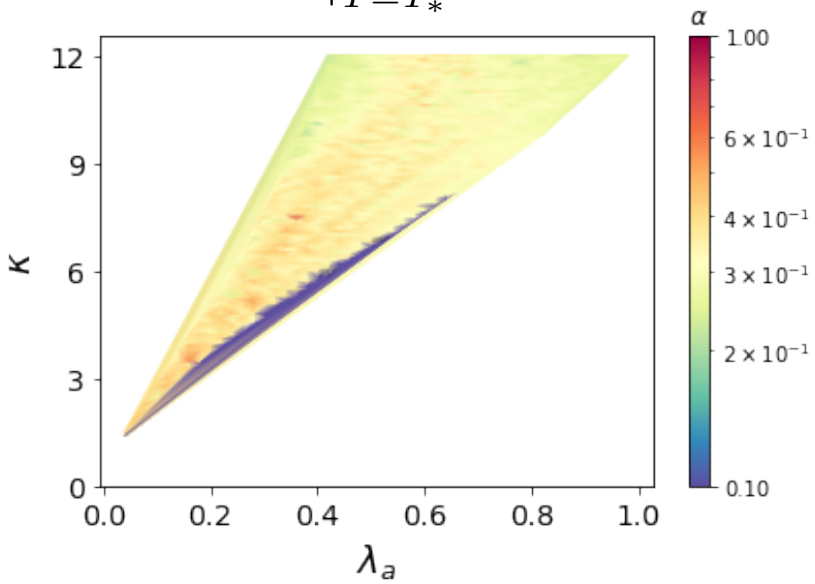
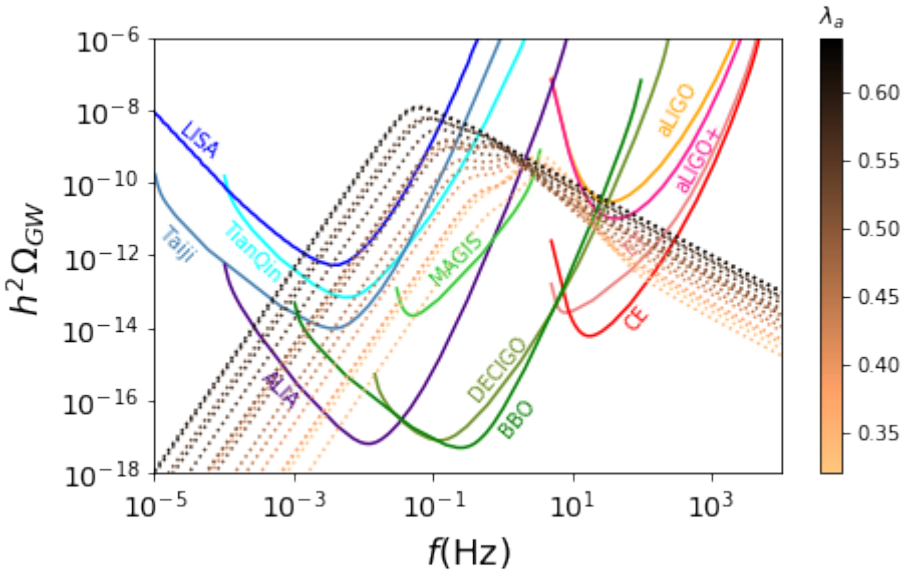




$$h^2\Omega_\phi \;\propto\; \left(\frac{\beta}{H_*}\right)^{-2}, \quad h^2\Omega_{\text{SW}} \;\propto\; \left(\frac{\beta}{H_*}\right)^{-1}, \quad h^2\Omega_{\text{MHD}} \;\propto\; \left(\frac{\beta}{H_*}\right)^{-1}.$$

Gravitational Wave Spectrum



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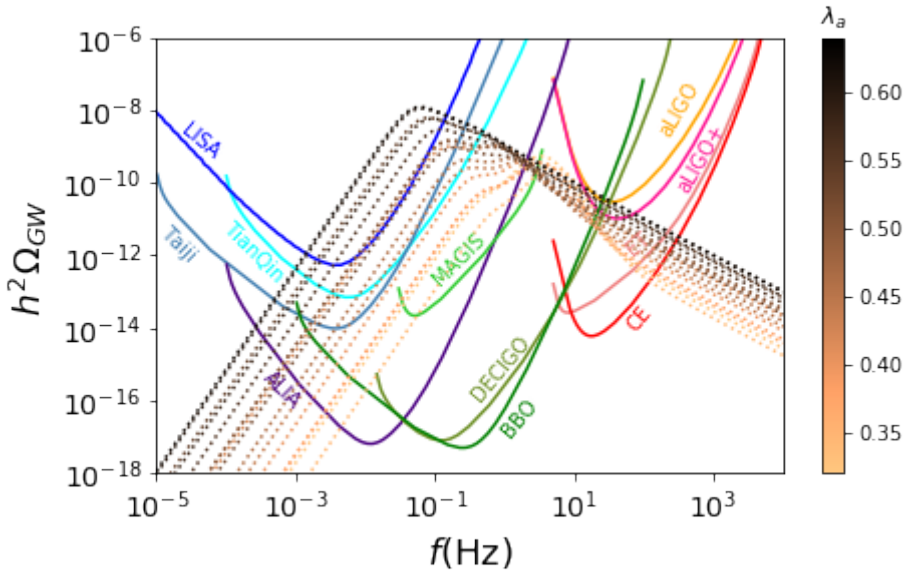

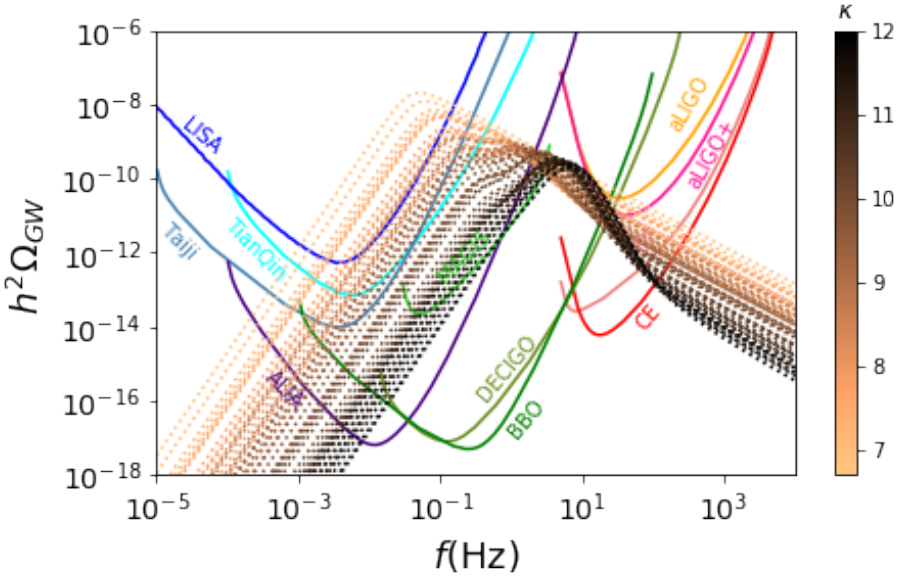

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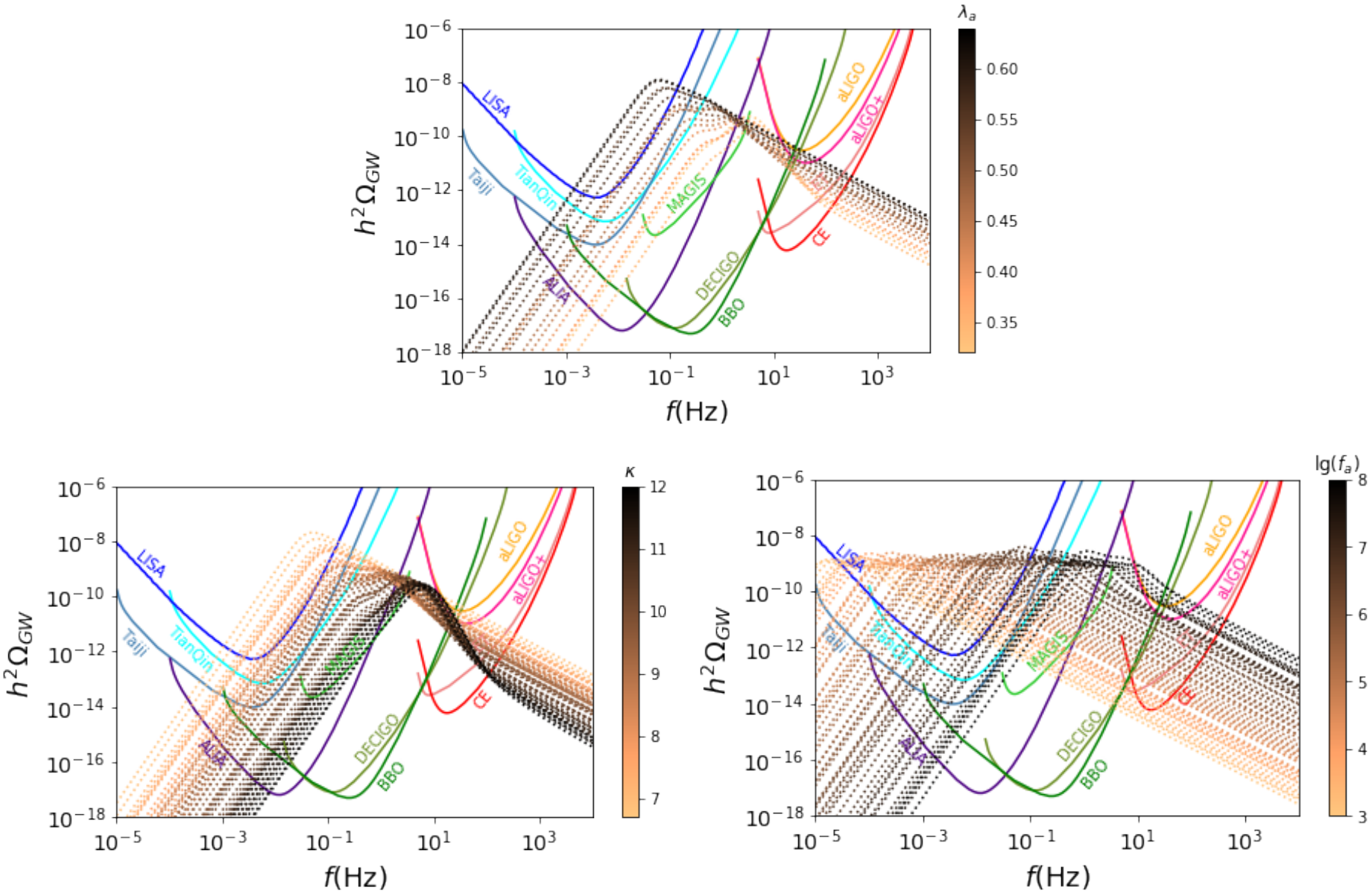
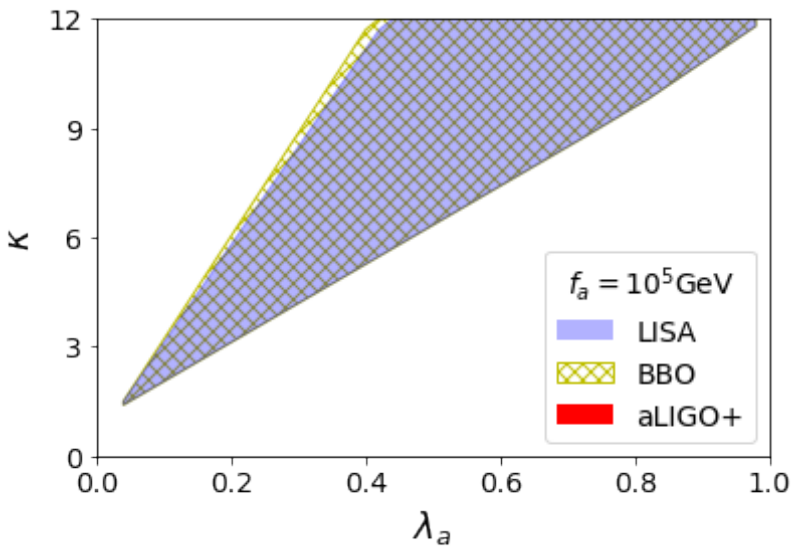


GW Sensitivity



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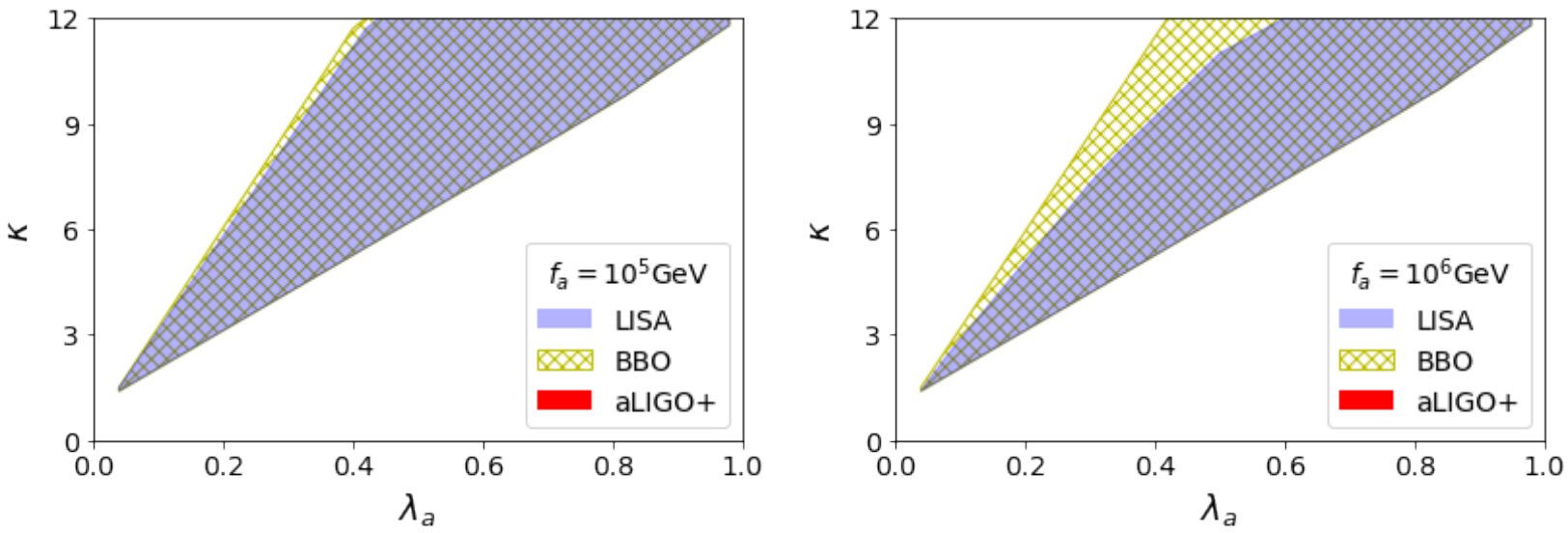

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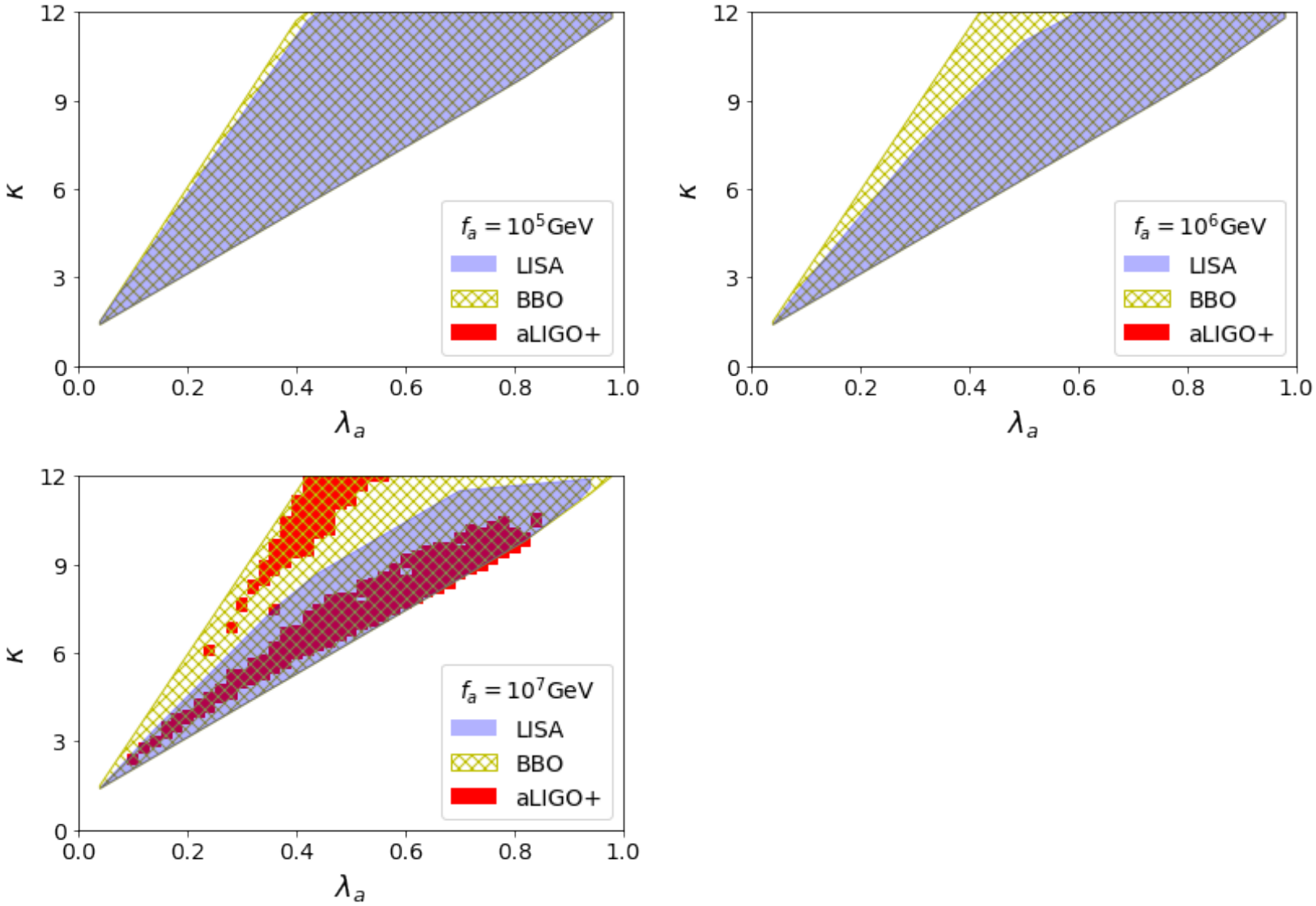

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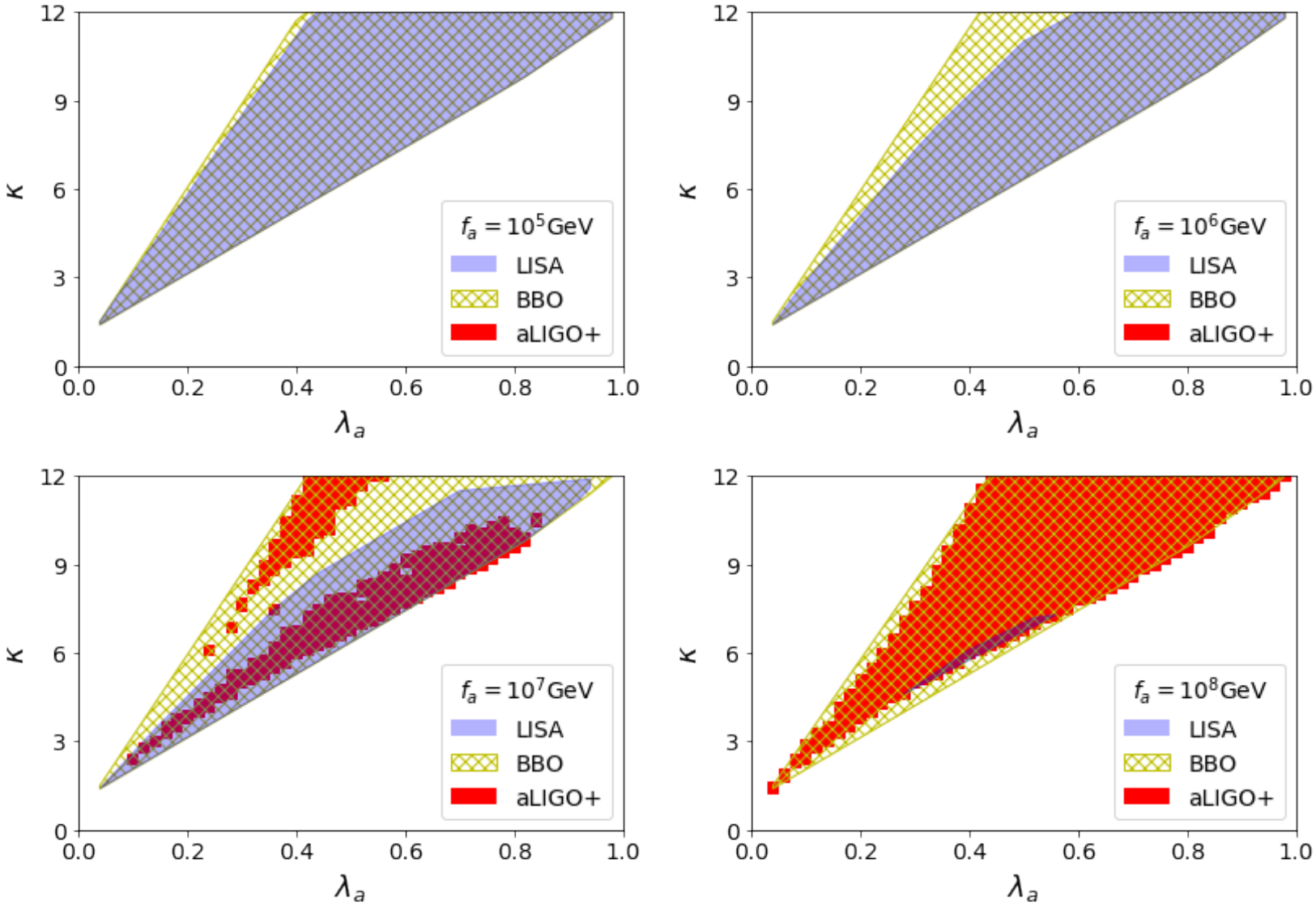

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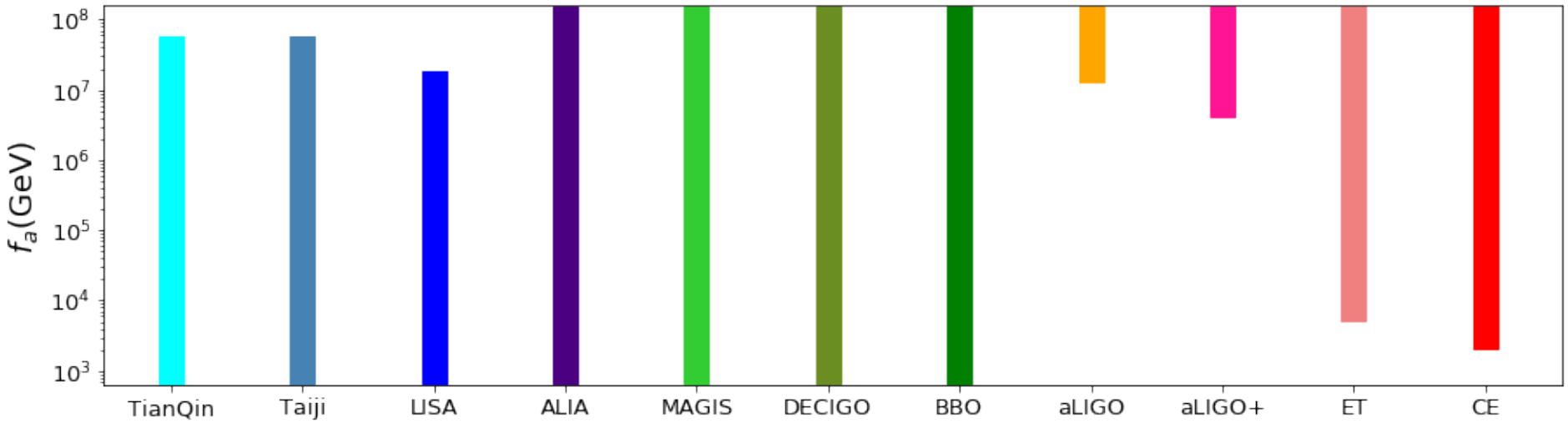
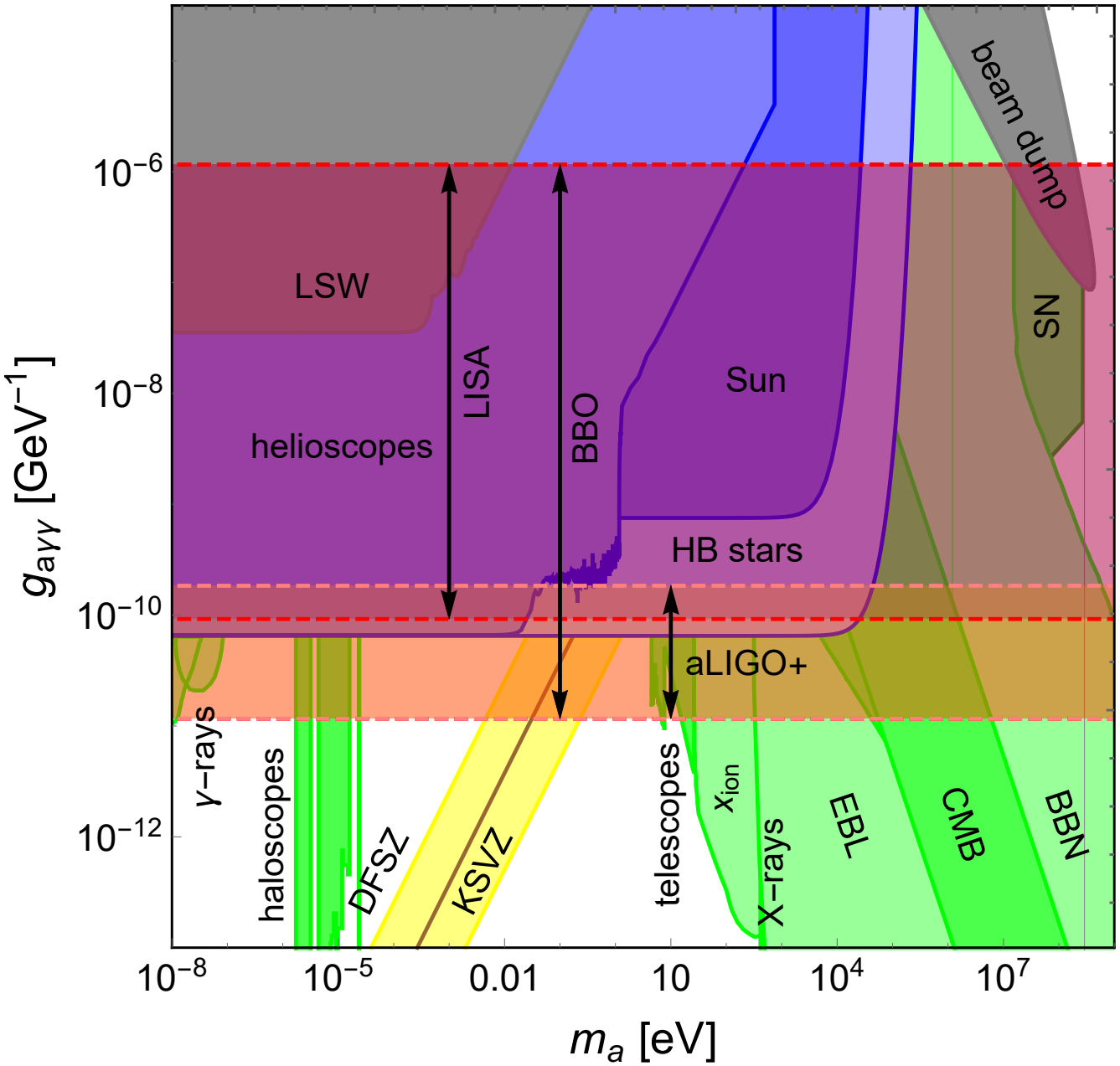
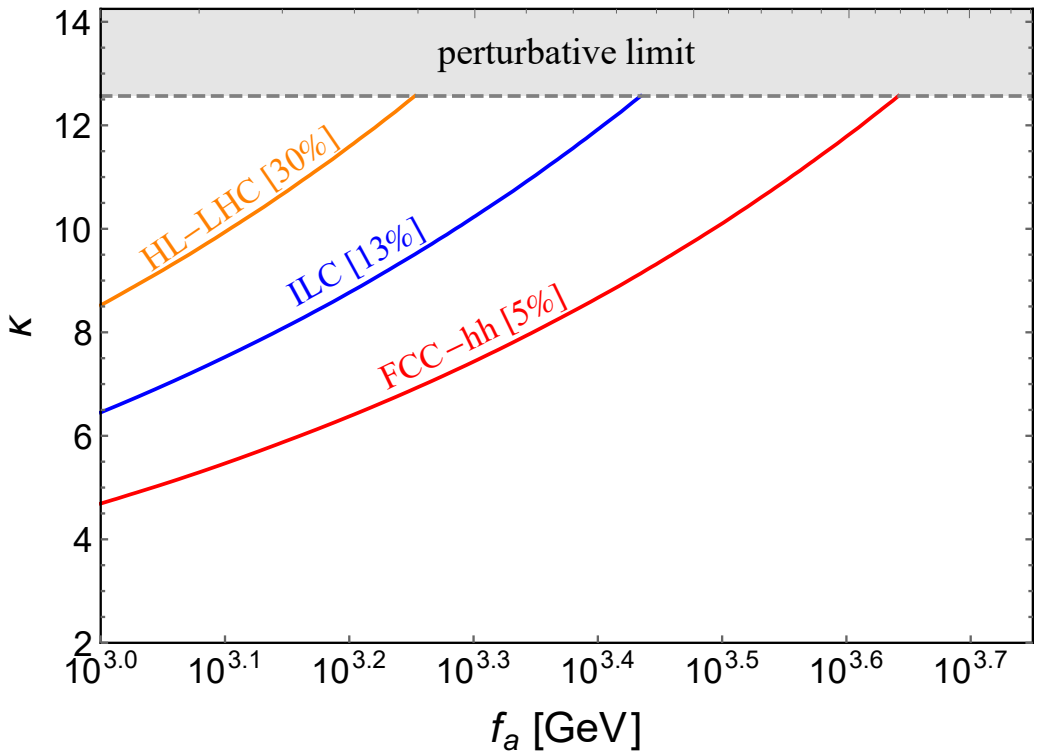


- **Independent of the ALP mass.**
- Provides a new probe of f_a, complementary to other laboratory, cosmological and astrophysical probes, which depend on *both* f_a and m_a.

GW Complementarity



Higgs Trilinear Coupling



$$\lambda_3 \simeq \lambda_3^{\rm SM} + \frac{\kappa^3 v_{\rm EW}^3}{24\pi^2 m_\phi^2}\,, \qquad \text{with } \lambda_3^{\rm SM} = \frac{m_h^2}{2v_{\rm EW}}\,.$$

Current LHC limit: $-9 \lesssim \lambda_3/\lambda_3^{\rm SM} \lesssim 15.$

Conclusion

- Considered generic ALP scenarios with the VEV of a complex scalar field Φ breaking the global $U(1)$ symmetry.
- Gives rise to strong first-order phase transition and stochastic gravitational waves for a sizable coupling to the SM Higgs.
- Current and future GW experiments can probe a broad range of ALP parameter space with $10^3\ \mathrm{GeV} \lesssim f_a \lesssim 10^8\ \mathrm{GeV}$.
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