Observational constraints on axion dark matter from GW propagation

Atsushi Nishizawa (Hiroshima U.)
with Lorenzo Valbusa Dall'Armi,
Takuya Tsutsui

Feb 23, 2024 @ YITP, Kyoto
YITP long-term workshop
Gravity and Cosmology 2024

Axions

- A CP symmetry is broken in the QCD Lagrangian.

- However, the electric dipole moment (EDM) measurement of neutrons gives $|\theta| \lesssim 10^{-10}$, Irastorza & Redondo, PPNP (2018)

  which requires the theory to be fine-tuned.

  strong CP problem

- The problem is solved by introducing axions, which are a pseudo-Nambu-Goldstone boson appearing from the spontaneous breaking of the chiral U(1) symmetry (PQ symmetry) and dynamically recover the CP symmetry.

  Peccei & Quinn, PRL (1977)

- Axion-like particles also appear in the string theory. We call them “axions” in this talk.

Axion gravitational coupling

A gravitational coupling of axions is obtained by replacing a gauge field in the QCD Lagrangian with Riemann curvatures:

$$\mathcal{L}_{\mathrm{axion}} = \frac{1}{2}\nabla_\mu a \nabla^\mu a + \frac{m_a^2}{2}a^2 + \underline{\frac{M_{\mathrm{Pl}}\ell^2}{4}aR\tilde{R}}$$

Jackiw & Pi, PRD (2003)

$$R\tilde{R} \equiv \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}R_{\rho\sigma\alpha\beta}R^{\alpha\beta}{}_{\mu\nu}$$

simplest form of the coupling

Such a coupling is hypothetical but possible in general.

The previous upper limit from Gravity Probe B: $\ell \lesssim 10^8\,\mathrm{km}$

Ali-Haimoud & Chen, PRD (2011); Nakamura+, CQG (2019)

We search for the gravitational coupling with GWs.

Axion DM

- axions oscillate uniformly below the coherent length

$$V(a) = \frac{m_a^2}{2} a^2 \quad \Longrightarrow \quad a(t) = a_0 \cos(m_a t)$$

- DM density determines the field amplitude

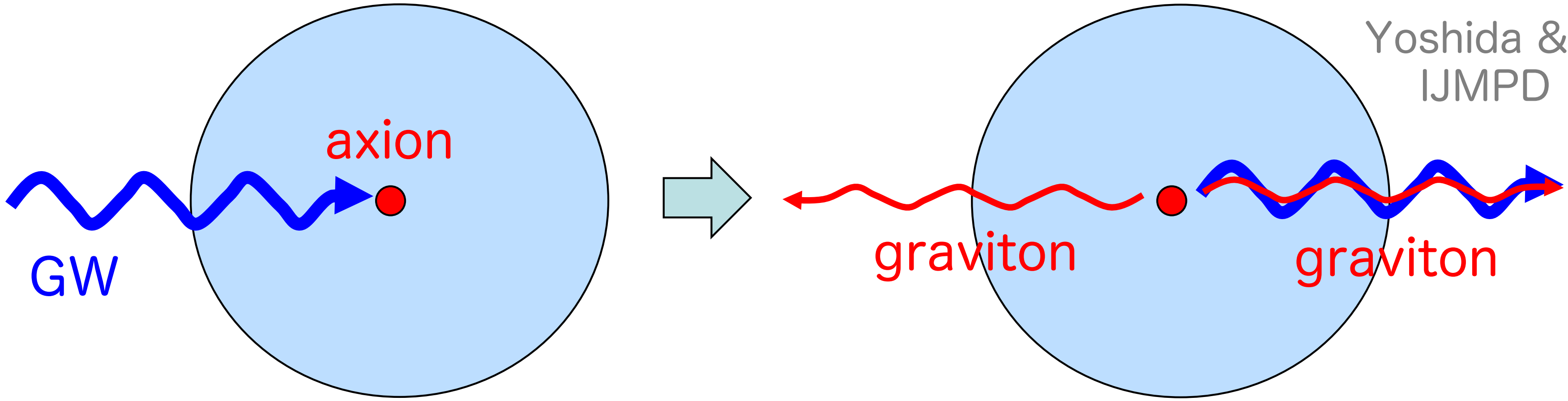
$$|a_0| = \frac{\sqrt{2\rho_a}}{m_a} \qquad \ell_{\text{eff}}^2 \equiv \ell^2 \sqrt{\frac{\rho_a}{\rho_{\text{DM}}}}$$

- characteristic size of axion clouds

  de Broglie wavelength ~ coherent length

$$L_c = \frac{2\pi}{m_a \Delta v} = 4.0 \times 10^{-8}\ \text{pc} \left(\frac{1 \times 10^{-12}\ \text{eV}}{m_a} \right) \left(\frac{\Delta v}{1 \times 10^{-3}} \right)$$

Stimulated emission of gravitons



Yoshida & Soda, IJMPD (2018)

resonant frequency

$$f_{\mathrm{res}} = \frac{1}{2\pi}\frac{m_a}{2} = 12\ \mathrm{Hz}\left(\frac{m_a}{10^{-13}\ \mathrm{eV}}\right)$$

amplification & time delay
(in a single axion cloud)

$$F_1 = (1 + \delta_{\mathrm{patch}})e^{i\psi_{\mathrm{patch}}}$$

Jung+, PRD (2020)

$$\Delta f_{\mathrm{res}} = 2 f_{\mathrm{res}} \Delta v$$

$$\Delta v \sim 10^{-3}$$

$$\zeta = 0.24$$

$$\delta_{\mathrm{patch}} := \frac{\pi^3 G \varsigma}{2} m_a^2 \ell_{\mathrm{eff}}^4 \frac{\rho_{\mathrm{DM}}}{\Delta v^2}$$

$$\psi_{\mathrm{patch}} := \frac{2\pi^4 G}{3} m_a^2 \ell_{\mathrm{eff}}^4 \frac{\rho_{\mathrm{DM}}}{\Delta v^2} \frac{f - f_{\mathrm{res}}}{\Delta f_{\mathrm{res}}}$$

GW propagation in the Milky-Way halo (1)

- Number of axion clouds in the radial direction

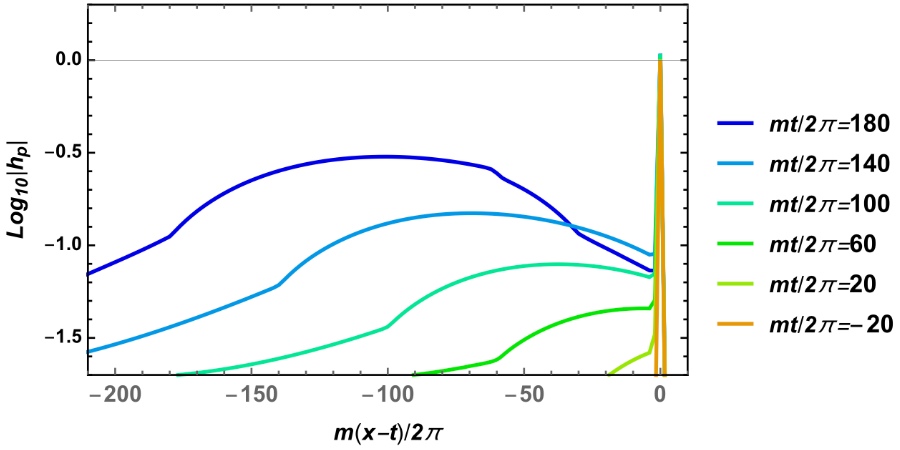
$$N = \frac{R}{L_c} = 2.5 \times 10^{11} \left(\frac{R}{100\ \mathrm{kpc}} \right) \left(\frac{\Delta v}{10^{-3}} \right) \left(\frac{m_a}{10^{-13}\ \mathrm{eV}} \right)$$

If the tiny phase shift is ignored, $\psi_{\mathrm{patch}} = 0$, Jung+, PRD (2020)

the amplification factor is

$$F_{\mathrm{total}} = \left(1 + \delta_{\mathrm{patch}}\right)^N = e^{N \delta_{\mathrm{patch}}}$$

In reality, the tiny phase shift accumulated cannot be neglected.



waveform in the time domain

Fujita+, CQG (2021)

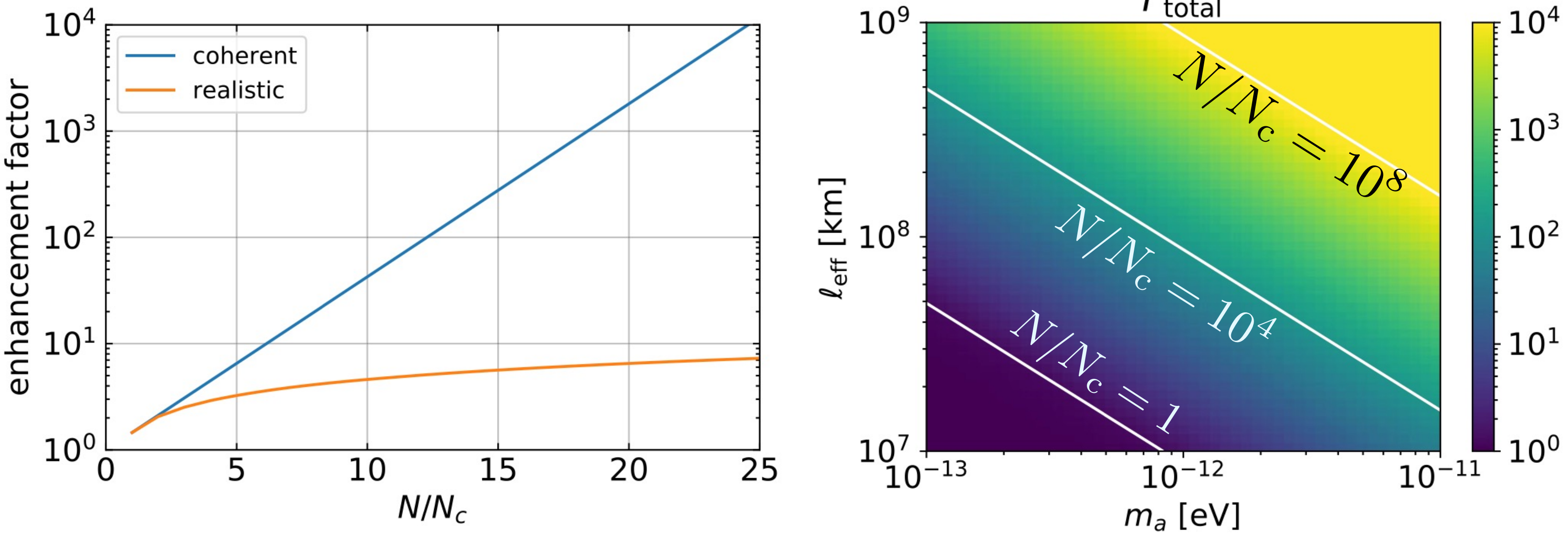
GW propagation in the Milky-Way halo (2)

If the accumulation of the tiny phase shift is considered, coherent amplification switches to incoherent one at N_c

⇨

$$F_\mathrm{total}^\mathrm{uni} \simeq \begin{cases} \mathrm{e}^{N\delta_\mathrm{patch}} & \text{for } N \leq N_\mathrm{c} \ (\text{or } \Delta\psi \leq \pi) \\ \mathrm{e}^{N_\mathrm{c}\delta_\mathrm{patch}} \sqrt{\dfrac{\Delta\psi}{\pi}} & \text{for } N > N_\mathrm{c} \ (\text{or } \Delta\psi > \pi) \end{cases}$$

Tsutsui & Nishizawa, PRD (2022)



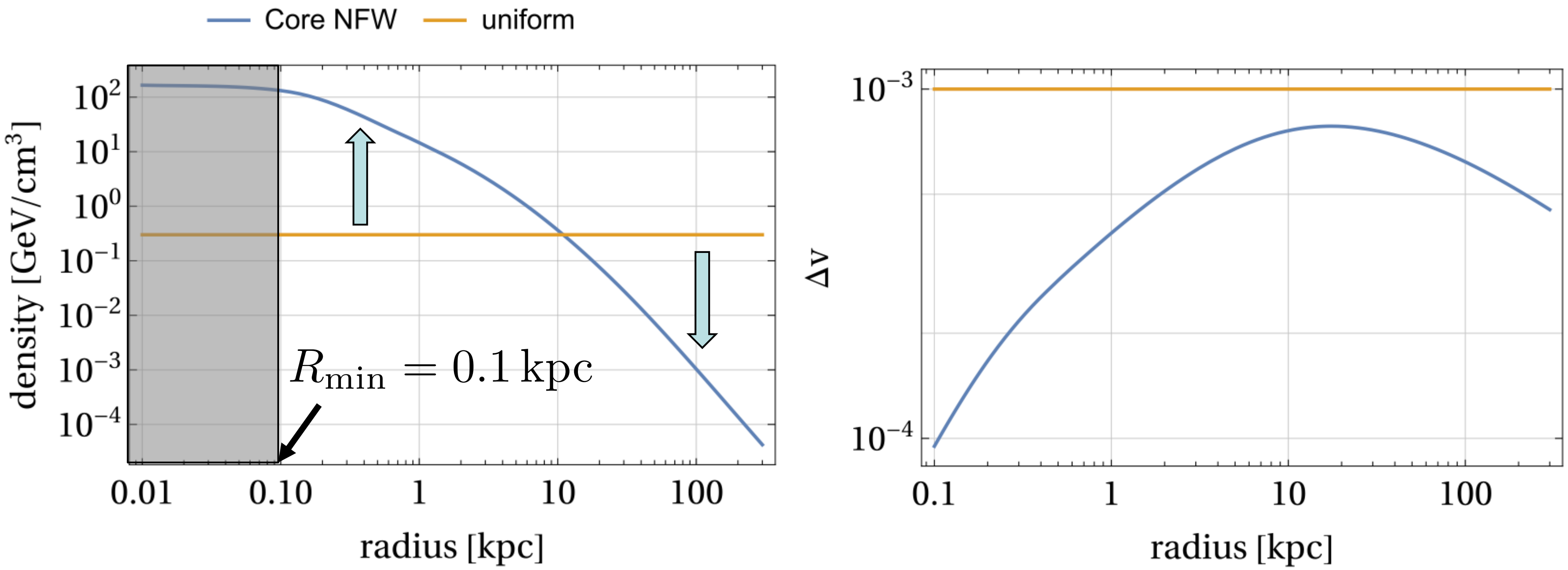
In a realistic DM halo profile

Axions are massive and clustered in a DM halo.

Core NFW profile (almost same as the NFW file outside)

Read+, MNRAS (2016a, 2016b); Khelashvili+, arXiv:2207.14165

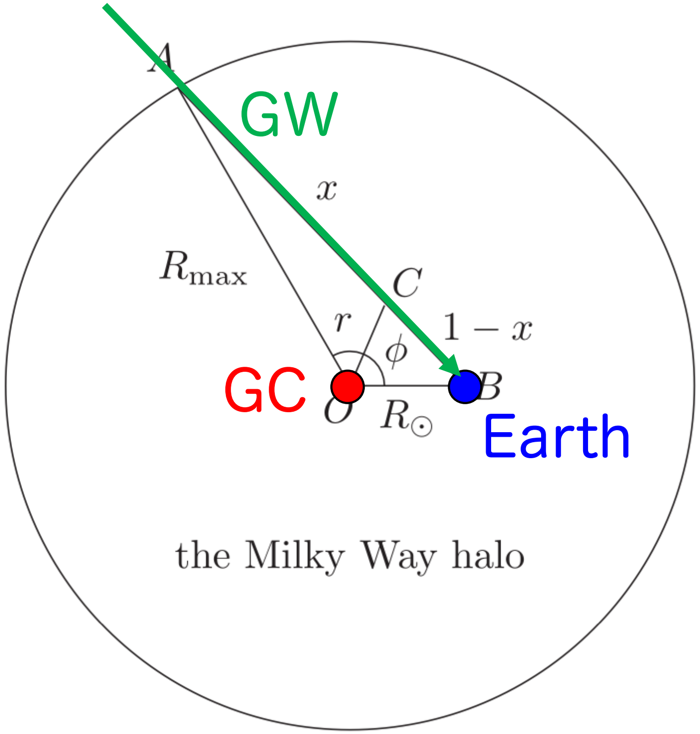
$$\rho_{\mathrm{cNFW}}(r) := \frac{1}{4\pi r^2}\frac{\mathrm{d}M_{\mathrm{cNFW}}(r)}{\mathrm{d}r} \qquad \Delta v^{\mathrm{cNFW}}(r) = \sqrt{\frac{6}{5}\frac{GM_{\mathrm{cNFW}}(r)}{r}}$$



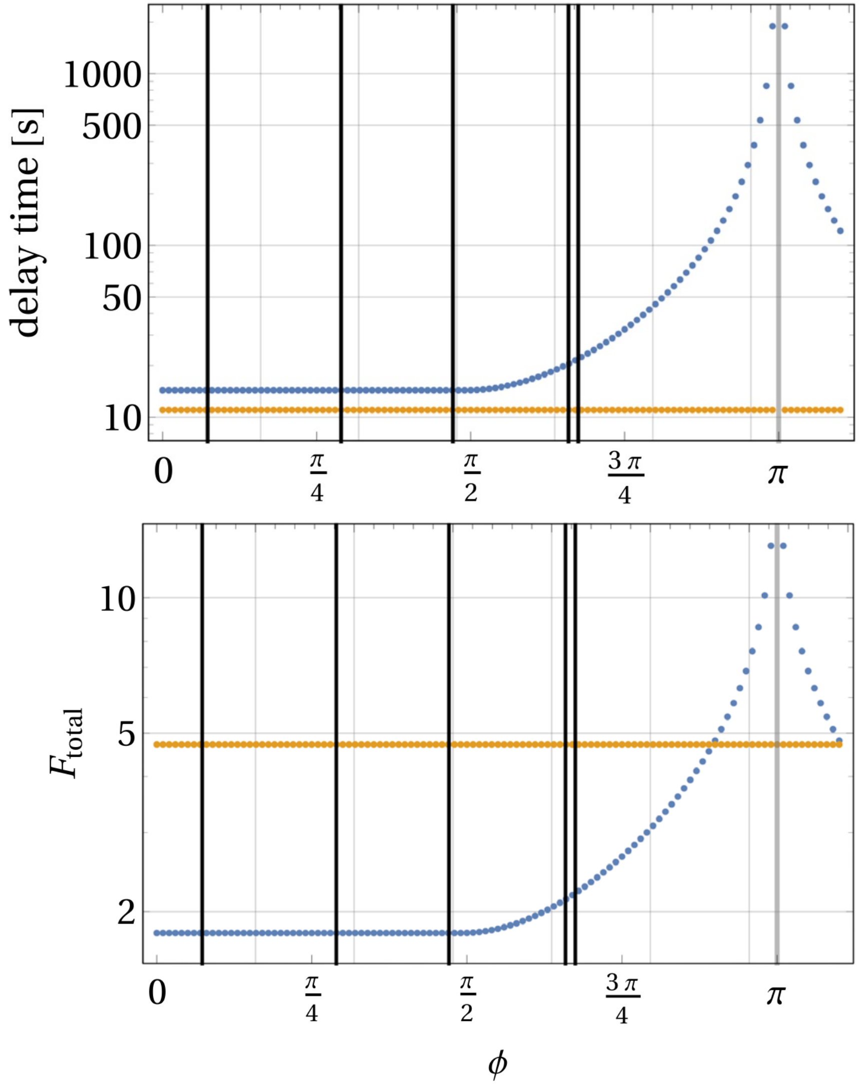
Amplification and time delay of secondary GWs

Tsutsui & Nishizawa, PRD (2023)

Coherent length, resonant width, signal duration, time delay are modified.

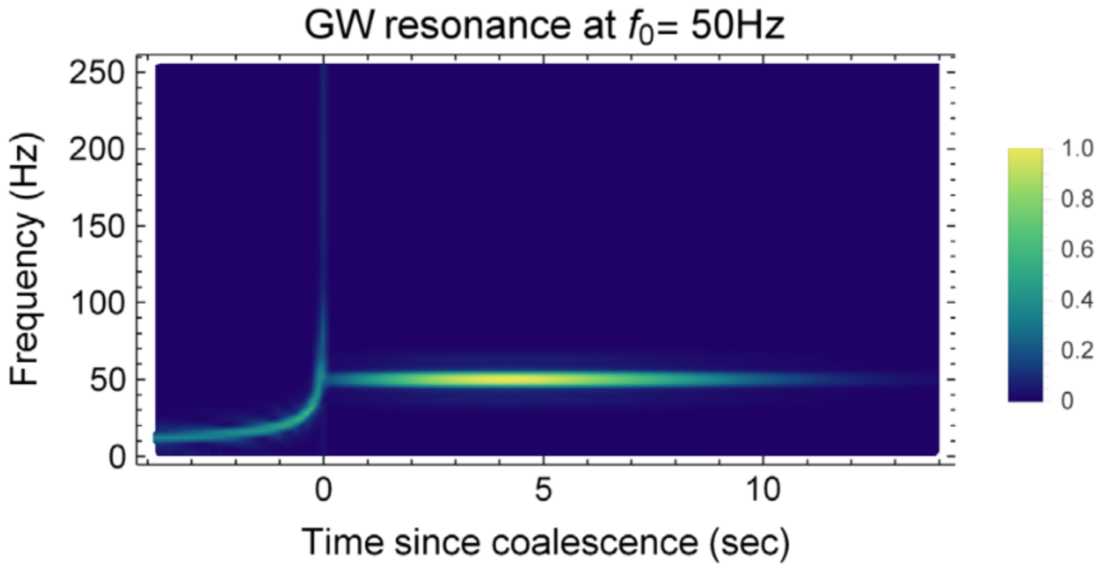


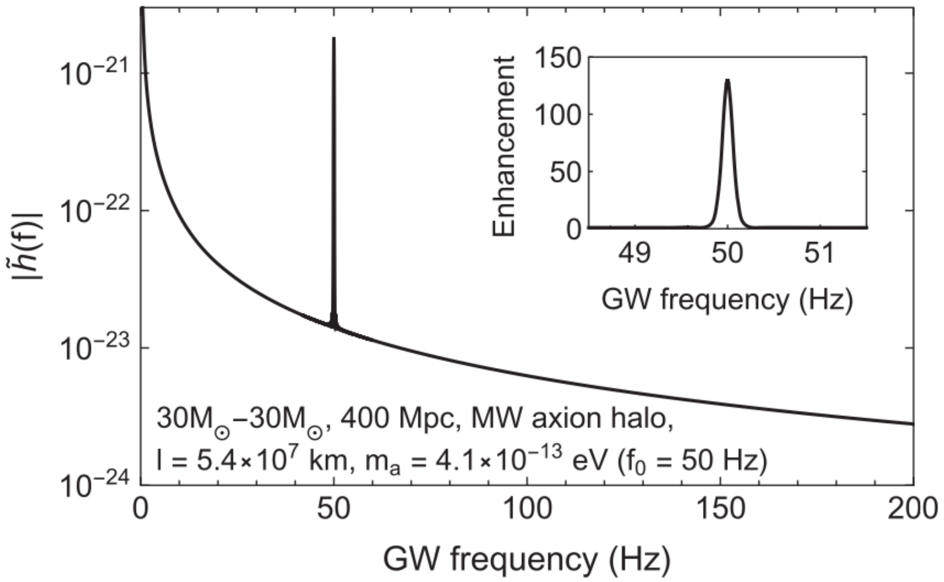
$m_a = 1 \times 10^{-12}\,\mathrm{eV} \quad \ell_{\rm eff} = 1 \times 10^{7}\,\mathrm{km}$



Search for secondary GWs

Jung+, PRD (2020)





The characteristic secondary GWs follow the primary CBC GW.

- almost monochromatic
- delayed and enhanced at $f_{\rm res}$,

$$\Delta t_{\rm delay} \propto \ell_{\rm eff}^4 m_a^2$$

$$\Delta t_{\rm duration} \propto m_a^{-1}$$

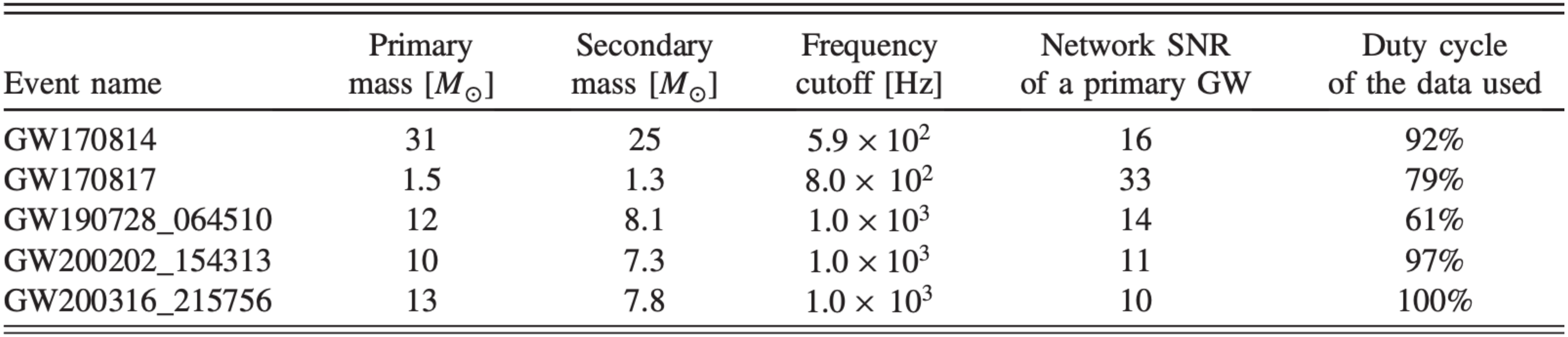
$$F_{\rm total} \propto \ell_{\rm eff}^2 m_a$$

(for $N > N_{\rm c}$)

The data analyzed

Tsutsui & Nishizawa, PRD (2023)

GW events chosen are observed by HLV, high SNR, long data available.



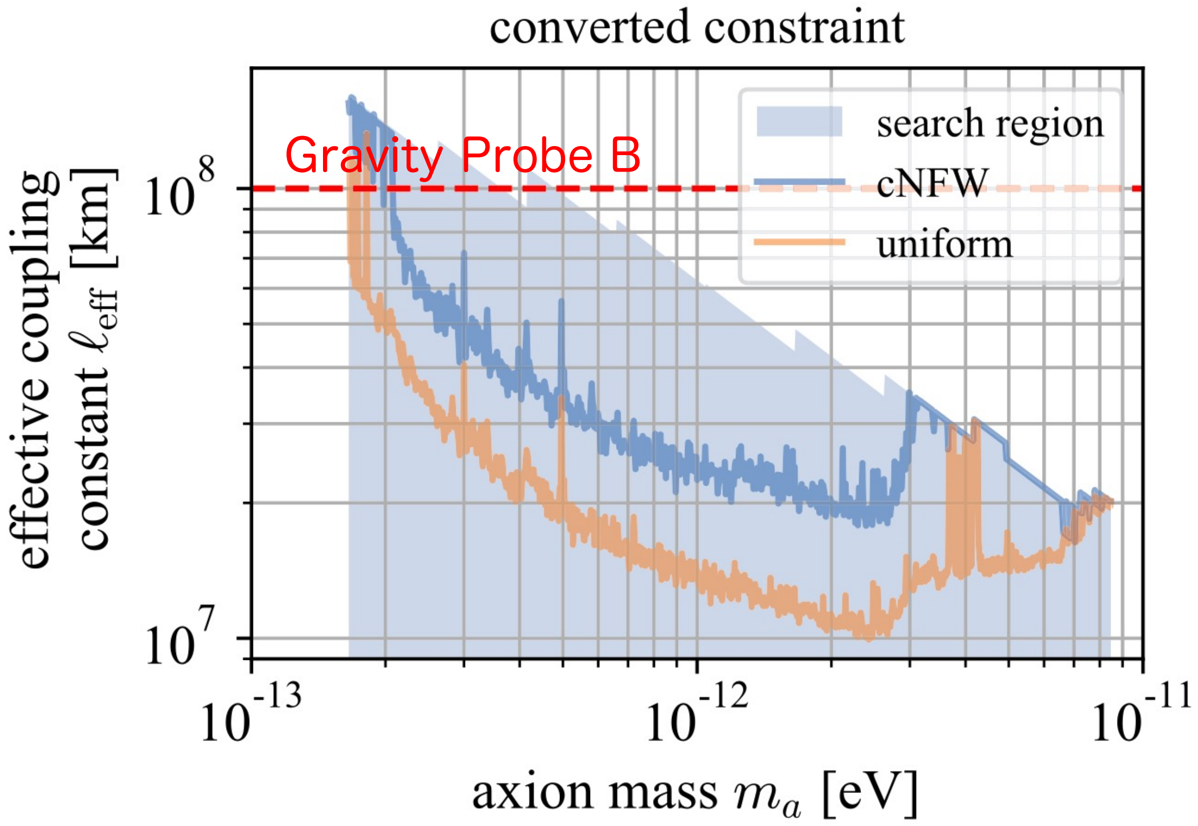
Event name	Primary mass $[M_\odot]$	Secondary mass $[M_\odot]$	Frequency cutoff [Hz]	Network SNR of a primary GW	Duty cycle of the data used
GW170814	31	25	5.9×10^2	16	92%
GW170817	1.5	1.3	8.0×10^2	33	79%
GW190728_064510	12	8.1	1.0×10^3	14	61%
GW200202_154313	10	7.3	1.0×10^3	11	97%
GW200316_215756	13	7.8	1.0×10^3	10	100%

sensitive frequency band: 20 Hz – 1024 Hz

mass range searched: $1.7 \times 10^{-13}\,\mathrm{eV} < m_a < 8.5 \times 10^{-13}\,\mathrm{eV}$

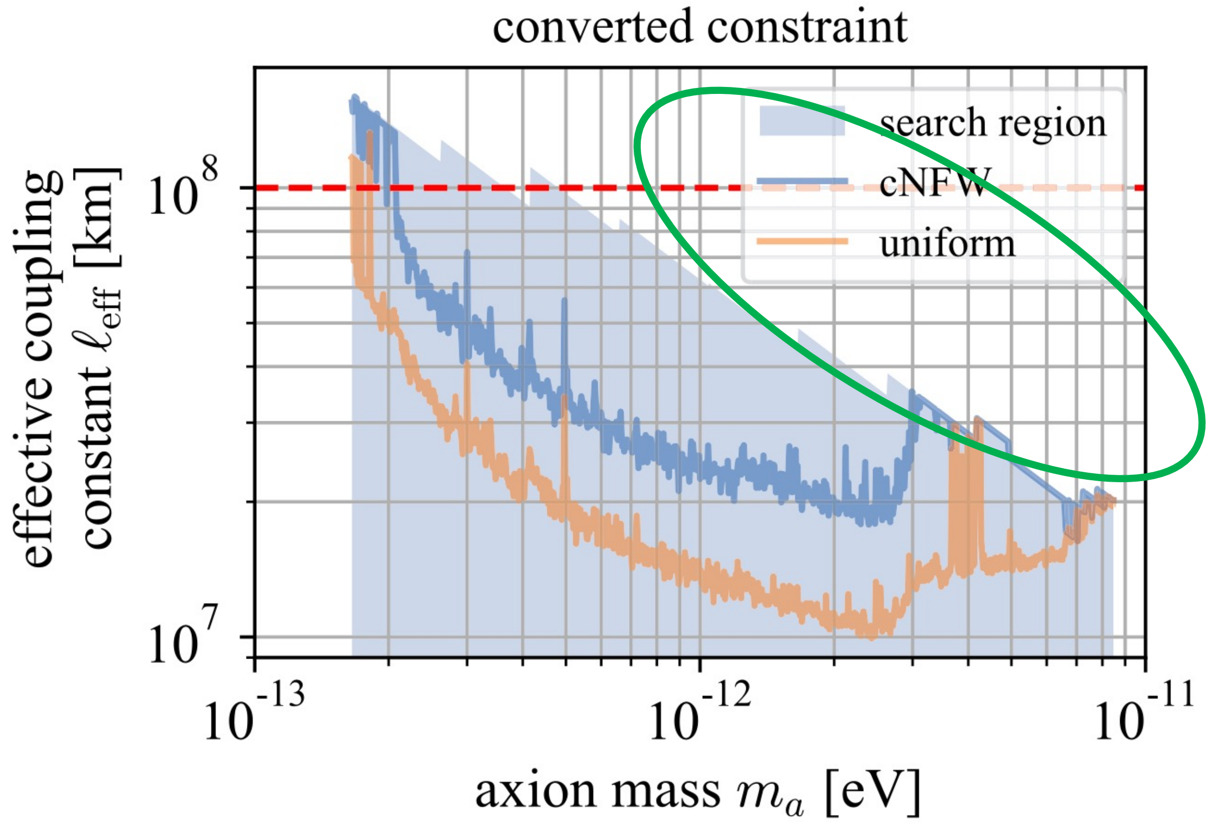
Observational constraint on the coupling

In the data after GW170814, GW170817, GW190728, GW200202, and GW200316, no power excess was found.



The constraint is robust to the differences of the DM profiles.

Unsearched parameter region



$$\Delta t_{\rm delay} \propto \ell_{\rm eff}^4 m_a^2$$

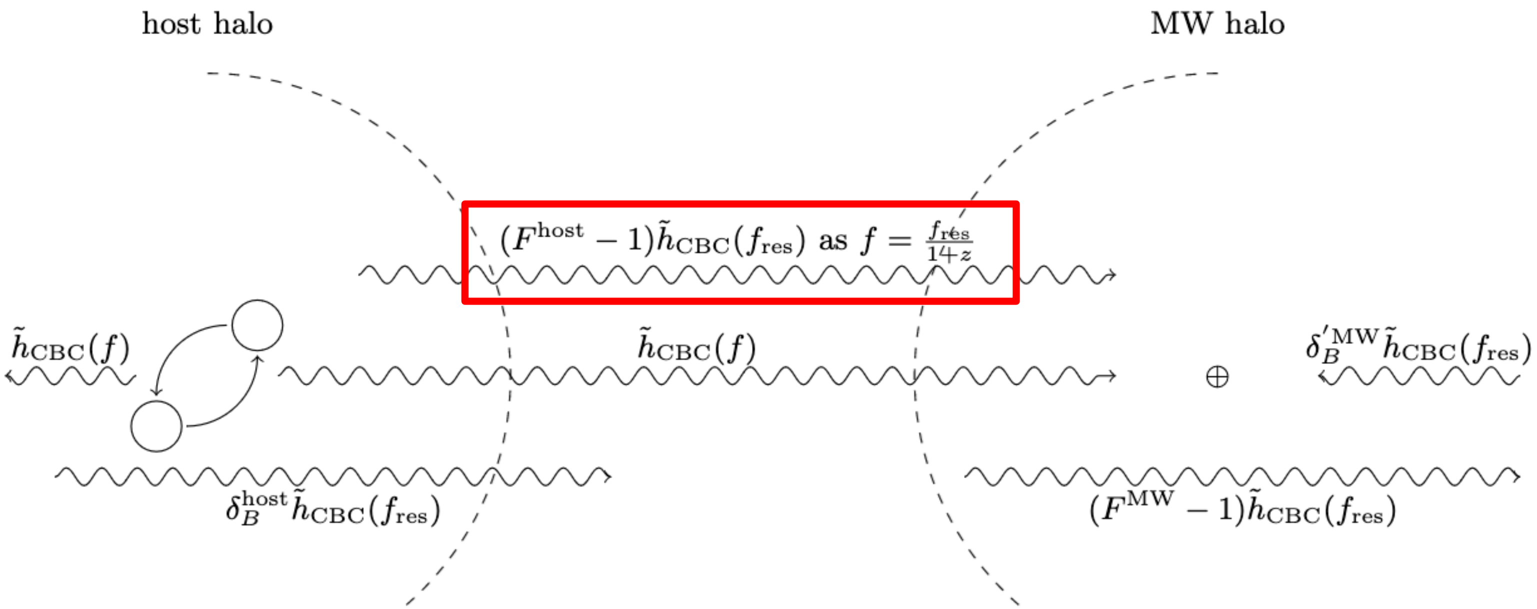
$$\Delta t_{\rm duration} \propto m_a^{-1}$$

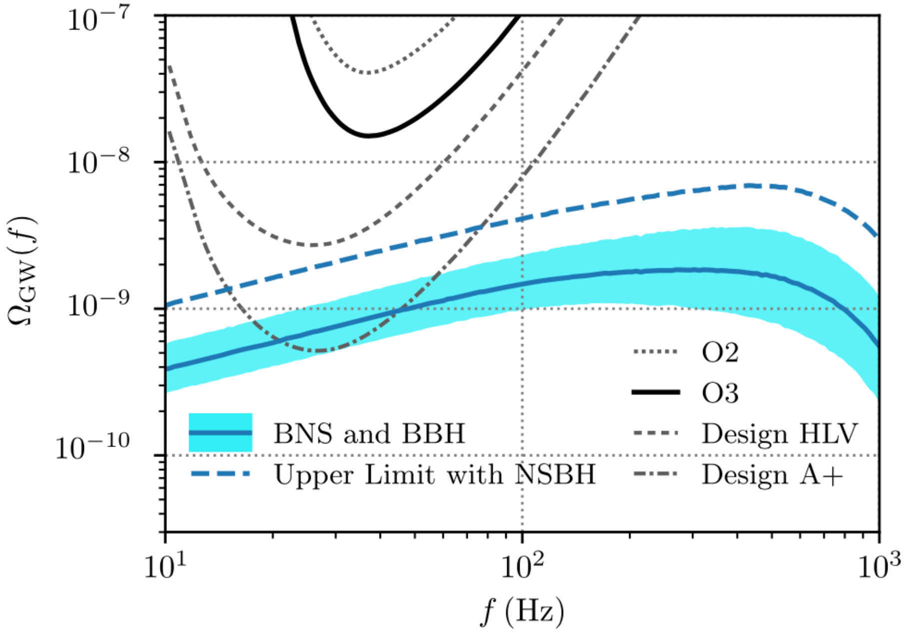
$$F_{\rm total}^{\rm uni} \propto \ell_{\rm eff}^2 m_a$$

(for $N > N_{\rm c}$)

Larger amplification,
but too long time delay.

Secondary GWs from other galaxies





redshifted resonant frequency

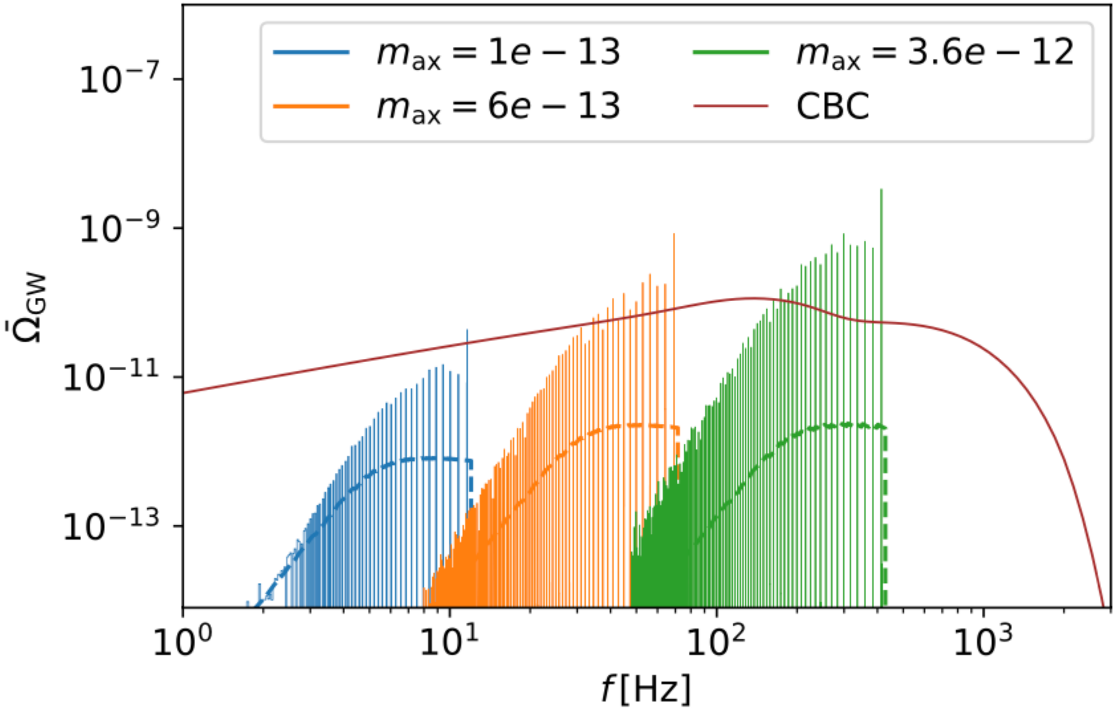
$$f=\frac{f_0}{1+z}$$

LVK, PRD (2021)
[stochastic, O3]

Secondary GWB spectrum

amplification factor $\mathcal{F}_{\rm total} = 15.4 \times \left(\frac{m_a}{10^{-12}\,{\rm eV}}\right)^{3/2} \left(\frac{\ell_{\rm eff}}{10^7\,{\rm km}}\right)^2$

secondary GWB spectrum $\Omega^{\rm ax}_{\rm GWB}(f) \propto \mathcal{F}^2_{\rm total}\Omega_{\rm AGWB}[f_0/(1+z)]$

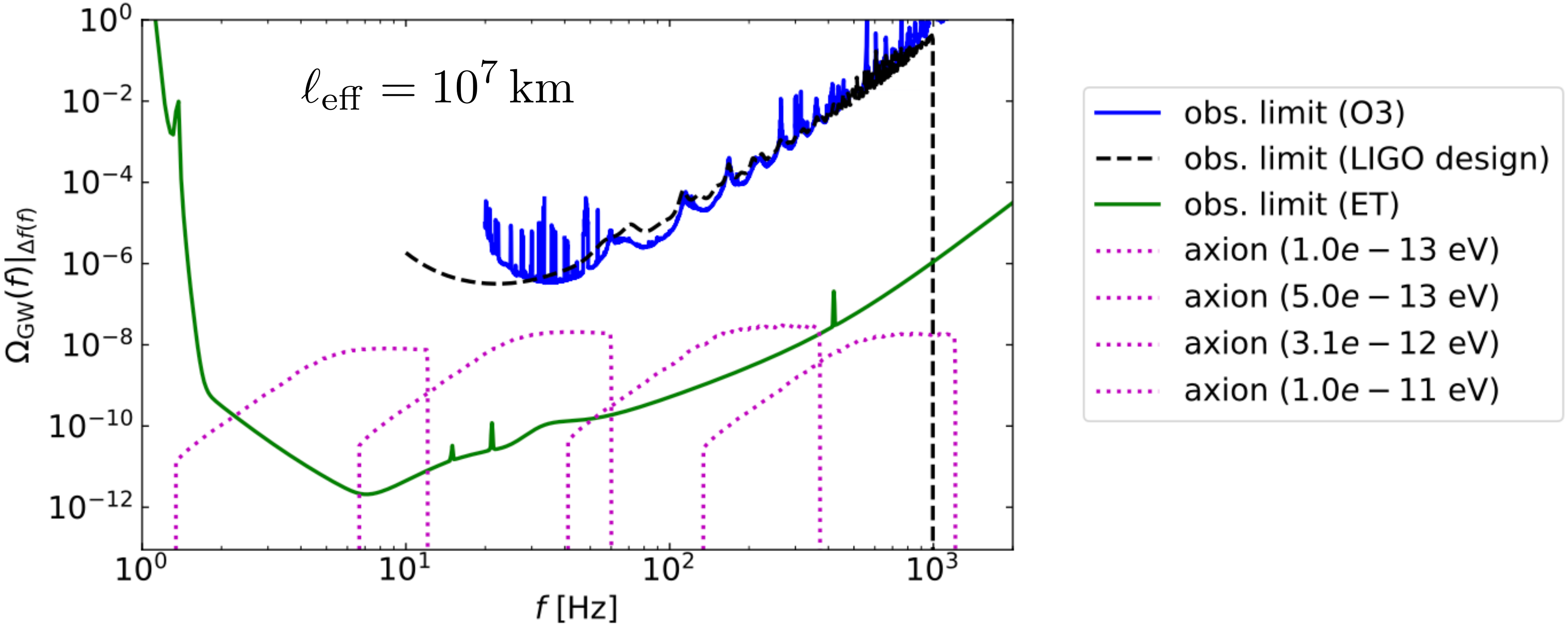


$\ell_{\rm eff} = 10^7\,{\rm km}$

Detector sensitivity to a GWB

frequency binning 1/32 Hz

Axion signals are scaled with $\Omega^{\mathrm{ax}}_{\mathrm{GWB}}(f) \propto \mathcal{F}^2 \propto m_{\mathrm{a}}^3 \ell_{\mathrm{eff}}^4$



Summary

- Axions are a candidate of DM motivated by a solution for the strong CP problem.

- Axions can have the parity-violating coupling to gravity.

- We analyzed 5 GW event data and obtained the constraint on the axion gravitational coupling:

  At most 5 times tighter than that of Gravity Probe B
  for the mass range $2 \times 10^{-13}\,\mathrm{eV} < m_a < 8 \times 10^{-12}\,\mathrm{eV}$

  Tsutsui & Nishizawa, PRD Lett. (2022); PRD (2023).

- The upper limit on a GWB gives a similar constraint but a previously unsearched region has been excluded.

  paper in preparation.