Observational constraint on axion dark matter with propagating gravitational waves

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based on arXiv:2207.00667

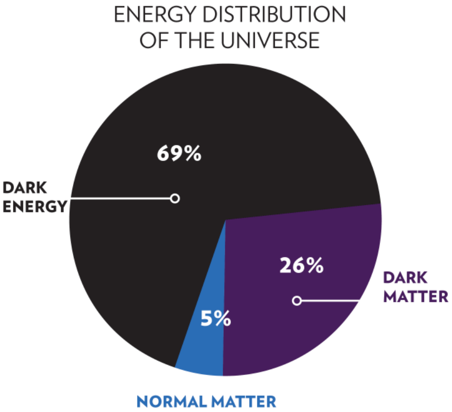
Contents

Who is dark matter?

Candidates

- WIMPs
- axion
- (sub)solar mass BBHs
- neutralino

⋮



(https://chandra.harvard.edu)

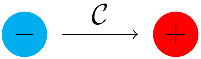
Which candidate is good?

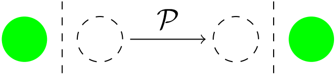
↓

If a candidate solves other problems, the candidate is better.

strong CP problem

$$\mathcal{L}_{\mathrm{QCD}} = \bar{Q}_i(\mathrm{i}\gamma^\mu D_\mu - m_{ij})Q_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a + \overbrace{\frac{g^2\theta}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a}^{CP\ \ violation}$$





$$\mathcal{CP}\mathcal{L}_{\mathrm{QCD}} = \bar{Q}_i(\mathrm{i}\gamma^\mu D_\mu - m_{ij})Q_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a - \frac{g^2\theta}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

However, from many experiments, CP is conserved in our nature...

$$\downarrow$$

$$|\theta| < 10^{-10}$$

$$\downarrow$$

fine tuning

(e.g. T. Mannel (2007))

Axion (QCD)

By considering chiral symmetry $U(1)_{\mathrm{PQ}}$ (f_a: breaking scale of $U(1)_{\mathrm{PQ}}$)

$$\mathcal{L}_{\mathrm{QCD}} = \bar{Q}_i(\mathrm{i}\gamma^\mu D_\mu - m_{ij})Q_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a + \frac{g^2\theta}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

$$\mathcal{L}_{\mathrm{axion}} = \frac{1}{2}\partial_\mu a \partial^\mu a + V(a) - \frac{g^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

SSB of $U(1)_{\mathrm{PQ}}$

→ axion as NG boson

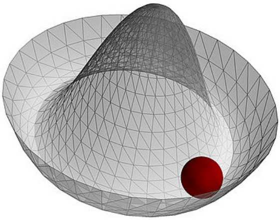
→ $\theta = a/f_a$

→ CP violation terms are canceled

→ strong CP problem is solved

→ let's consider axion as the DM candidate

(R. Peccei and H. Quinn (1977))



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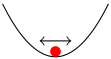
Axion (gravity)

From QCD axion's Lagrangian & gauge theory (gravitational field strength is $R_{\mu\nu}$):

$$\mathcal{L}_{\text{axion}} = \frac{1}{2}\partial_\mu a \partial^\mu a + V(a) - \underbrace{\frac{M_{\text{pl}}\ell^2}{4} a R\tilde{R}}_{\substack{CS\ \ term \\ (easiest\ \ higher\ \ term)}} \qquad \left(\tilde{R}^{\alpha\ \gamma\delta}_{\ \beta} = \frac{1}{2}\epsilon^{\gamma\delta\rho\sigma} R^{\alpha}_{\ \beta\rho\sigma}\right)$$

$\downarrow$

Assume: $V(a) =$ 

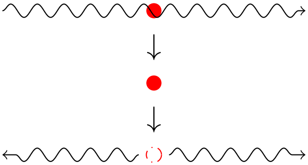
$\downarrow$

$a(t) = a_0 \cos(m_a t)$

$\downarrow$

$\downarrow$

Induced by GW, axion decays into GWs



Let's discuss 2ndary GWs later $\rightarrow$

Axion oscillates uniformly over a sufficiently wide area

(coherent clouds, size $\sim \frac{2\pi}{m_a v_a}$)

(D. Yoshida and J. Soda (2018))

Milky Way halo with many axion patches

axion cloud size

$$\sim \frac{2\pi}{m_a v_a}$$

$$\sim 4.0 \times 10^{-7}\,\mathrm{pc}\left(\frac{10^{-13}\,\mathrm{eV}}{m_a}\right)\left(\frac{10^{-3}}{v_a}\right)$$

&

MW halo size

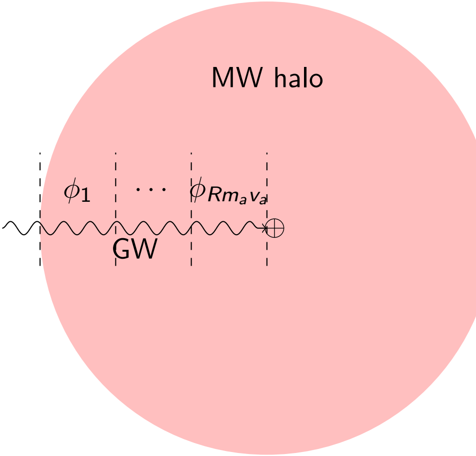
$R \sim 100\,\mathrm{kpc}$

↓

Axion clouds are clustered in MW halo

↓

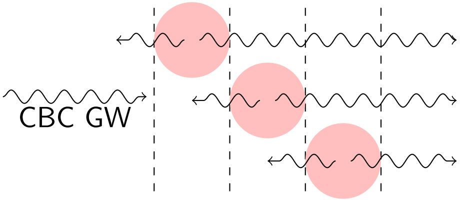
MW halo contains $R \Big/ \left(\frac{1}{m_a v_a}\right)$ ($\gg 1$) patches on a line of sight



→ All observed GWs must induce axion decay

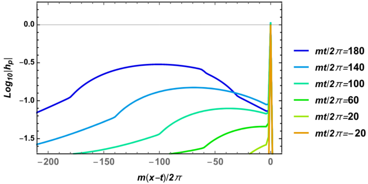
(S. Jung et al (2020))

Milky Way halo with many axion patches (Time delay)



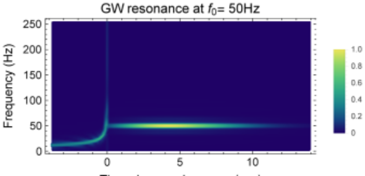
superposition →

(Fujita et al (2021))



$$\langle v_g \rangle|_{f=m_a/2} = \left\langle \frac{\mathrm{d}\omega}{\mathrm{d}k} \right\rangle = \overbrace{1}^{\text{prop.}} - \overbrace{\frac{1}{3}\left(\frac{\sqrt{\pi^3 G \rho_a}\ell^2 m_a}{v_a}\right)^2}^{\text{correction from axion}}$$

(S. Jung et al (2020))



↓

The group velocity becomes slower than the light speed

Milky Way halo with many axion patches (Amplification)

axion cloud size: $\sim \frac{2\pi}{m_a v_a} \sim 4.0 \times 10^{-7}\,\mathrm{pc}\left(\frac{10^{-13}\,\mathrm{eV}}{m_a}\right)\left(\frac{10^{-3}}{v_a}\right)$

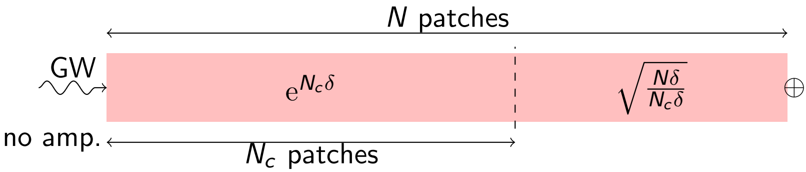
MW halo size: $R \sim 10\,\mathrm{kpc}$

- MW halo contains $N = R \Big/ \left(\frac{2\pi}{m_a v_a}\right)$ ($\gg 1$) patches on a line of sight
- All observed GWs are amplified by each axion patch ($\times(1+\delta \mathrm{e}^{\mathrm{i}\theta})$, $\theta \ll 1$)

$$F_{\mathrm{total}} = (1+\delta \mathrm{e}^{\mathrm{i}\theta})^N \quad : \text{Total amp. factor}$$

coherent: $F_{\mathrm{total}} \to \mathrm{e}^{N\delta}$ if θ can be neglected.

incoherent: $F_{\mathrm{total}} \to \sqrt{\frac{N\delta}{N_c\delta}}$ if θ is accumulated (brownian motion).

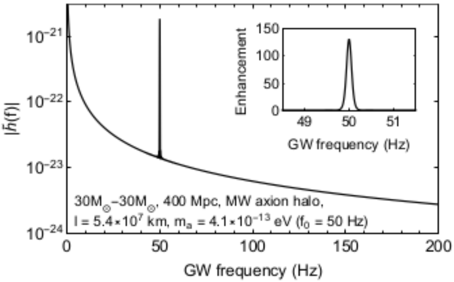


(At the N_c patch, the amp. factor is changed)

Short summary of properties of GWs through axion clouds

GWs in axion clouds are, at f_{peak},

- amplified
- delayed

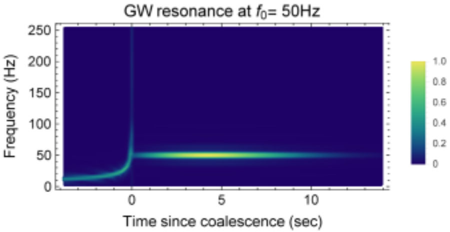


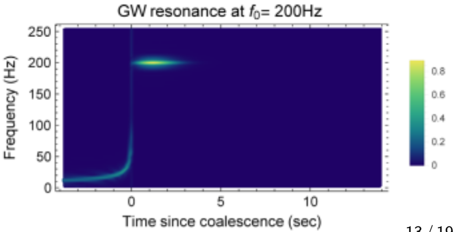
(S. Jung et al (2020))

↙

The corrections are in narrow frequency range

→ ∼ monochromatic wave





What signal do we observe?

purpose

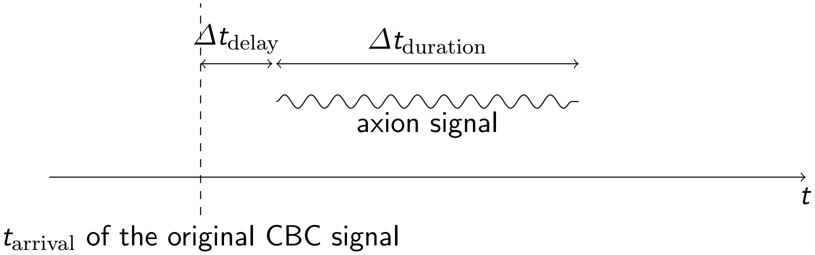
exploring GW from axion-halo

property of axion signal:

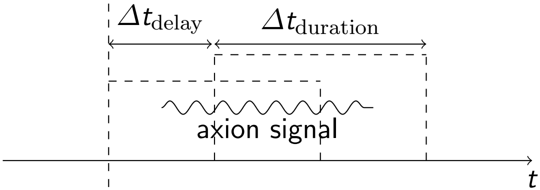
- almost monochromatic waves
- delay determined from m_a & ℓ
- signal duration determined from m_a

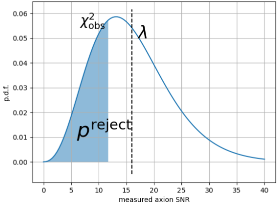
↓

characteristic monochromatic-wave search



How do we search the axion signal?





$t_{\rm arrival}$ of the original CBC signal

1. get a chunk corresponding to m_a & ℓ ($\Delta t_{\rm duration}$ & $\Delta t_{\rm delay}$)
2. get $\chi^2_{\rm obs}$-value of $f_{\rm peak}$ from the chunk
3. repeat for other m_a & ℓ

$\rightarrow$ We get axion-SNR-map on m_a-ℓ plane

$\rightarrow$ We get p-values to reject the existence of axion

$$p^{\rm reject}(m_a, \ell) = \int_0^{\chi^2_{\rm obs}} p_\chi \left(x; \lambda = \langle \chi^2 \rangle\right) \, {\rm d}x$$

where p_χ is χ^2-distribution, λ is non-central parameter and $S_n(f)$ is PSD.

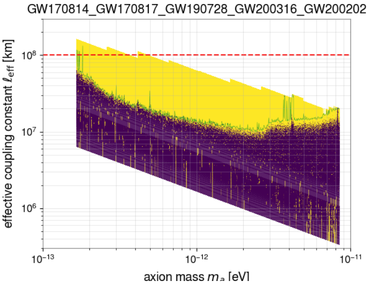
e.g. If $p^{\rm reject} = 0.5\%$, the observed $\chi^2_{\rm obs}$ is much smaller than the expected $\langle \chi^2 \rangle$

Result: 99.5% rejection

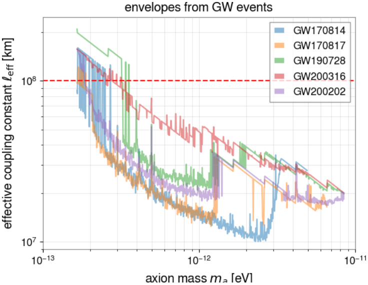
From data after GW170814, GW170817, GW190728, GW200202, and GW200316 (long available):

COMBINE: Unless axion signals are seen ($p^{\rm reject}_{\rm event}(m_a, \ell) > 0.5\%$) for all the events, we reject the coupling ℓ for m_a.

Combined result



Each results



- $\ell_{\rm eff} = \ell(\Omega_{\rm axion}/\Omega_{\rm Dark\ Matter})^{1/4}$ where Ω_X is the density parameter for X
- Yellow regions are rejected by 99.5%
- Purple regions can't be rejected by 99.5%
- Green line is the upper limit

c.f. Gravity Probe B: $\ell_{\rm eff} \lesssim 10^8\,{\rm km}$

$\rightarrow$ $\sim$ 10 times improved!

Summary

- Axion is a candidate of dark matter
- Axion forms clouds which amplify and delay GW
- We can search characteristic 2ndary GWs and constrain $(m_a, \ell_{\rm eff})$
- We analyzed data after GW170814, GW170817, GW190728, GW200202, and GW200316
- The constraint is at most $\sim$ 10 times improved

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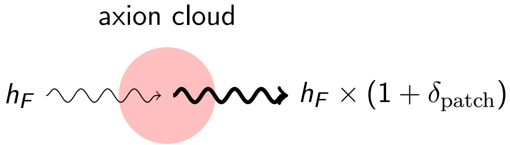
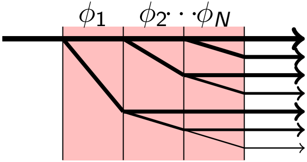
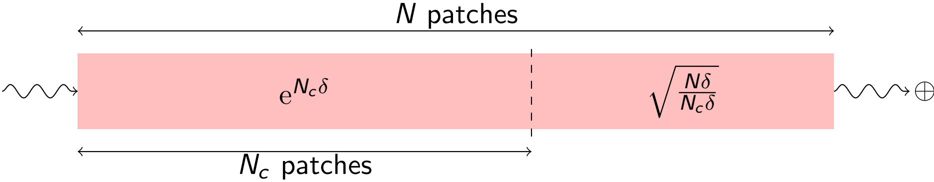
multiple coherent patches (S. Jung et al (2020))



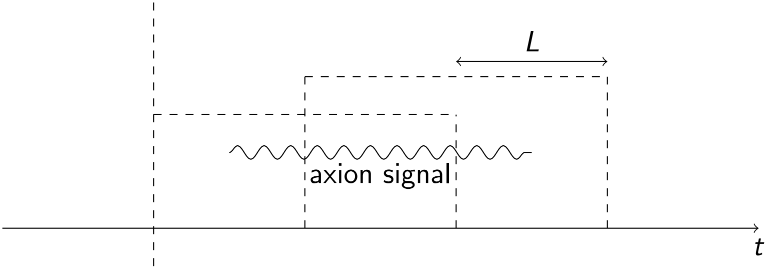


amplifying factor:
$(1 + \delta_{\rm patch})^N \sim {\rm e}^{N\delta_{\rm patch}}$

$$N\delta_{\rm patch} = 9.3 \left(\frac{R}{100\,{\rm kpc}}\right)\left(\frac{10^{-3}}{v_a}\right)\left(\frac{m_a}{10^{-13}\ {\rm eV}}\right)^3\left(\frac{\ell_{\rm eff}}{10^8\ {\rm km}}\right)^4\left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV/cm^3}}\right)$$



Optimal binning



t_{arrival} of the original CBC signal

mass bin

From $\Delta f_{\mathrm{peak}} \sim f_{\mathrm{peak}} v_a$
and $f_{\mathrm{peak}} = m_a/2$,

$$\Delta f_{\mathrm{sample}} \sim f_{\mathrm{sample}} v_a$$
$$\Delta \log m_a = v_a$$

chunk shift

By shifting the chunk by L,

$$\text{max SNR loss} \propto L/2$$

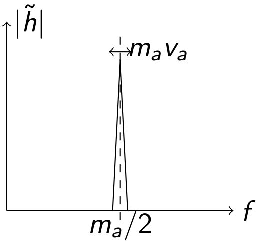
Thus, accepting 10% SNR loss,

$$L = 20\% \times \Delta t_{\mathrm{duration}}$$

NOTE: dispersion relation

$$\omega(k) = \overbrace{k}^{\text{prop.}} - \overbrace{\left(k - \frac{m_a}{2}\right)\left(\frac{m_a}{2}\gamma t\right)}^{\text{correction from axion}}$$

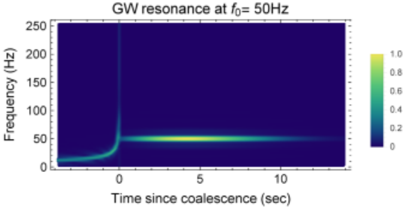
$$\langle v_g \rangle = \left\langle \frac{d\omega}{dk} \right\rangle = 1 - \left\langle \left(\frac{m_a}{2}\gamma t\right)^2 \right\rangle = 1 - \frac{1}{3}\left(\frac{\pi\gamma}{v_a}\right)^2$$

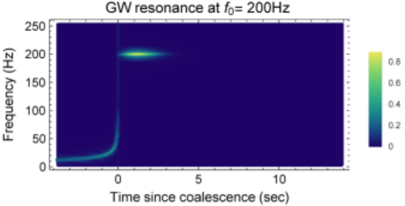


The correction term appears ONLY near the peak frequency

↓

GW with ONLY $f \sim \frac{m_a}{2}$ is slower





(S. Jung et al (2020))

List of the formulae

$$
\begin{aligned}
f_{\rm peak} &= \frac{1}{2\pi}\frac{m_a}{2} = 12\,{\rm Hz}\left(\frac{m_a}{10^{-13}\,{\rm eV}}\right) \\
\Delta t_{\rm duration} &= \frac{2\pi}{m_a v_a} = 41.4\,{\rm s}\left(\frac{10^{-13}\,{\rm eV}}{m_a}\right)\left(\frac{10^{-3}\,{\rm eV}}{v_a}\right) \\
\Delta t_{\rm delay} &= \frac{\pi^3 R}{3}\frac{G\ell^4 m_a^2 \rho_a}{v_a^2} \\
&= 1.1\times 10^3\,{\rm s}\left(\frac{R}{100\,{\rm kpc}}\right)\left(\frac{10^{-3}}{v_a}\right)^2\left(\frac{\ell_{\rm eff}}{10^8\,{\rm km}}\right)^4\left(\frac{m_a}{10^{-13}\,{\rm eV}}\right)^2\left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV/cm^3}}\right) \\
\langle N\delta_{\rm patch}\rangle &= 9.3\left(\frac{R}{100\,{\rm kpc}}\right)\left(\frac{10^{-3}}{v_a}\right)\left(\frac{m_a}{10^{-13}\,{\rm eV}}\right)^3\left(\frac{\ell_{\rm eff}}{10^8\,{\rm km}}\right)^4\left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV/cm^3}}\right) \\
|\tilde{h}^{\rm axion}(f_{\rm peak})| &= \left[{\rm e}^{\langle N\delta_{\rm patch}\rangle}\ {\rm or}\ {\rm e}^{3/8}\sqrt{N\delta_{\rm patch}/(3/8)}\right]|\tilde{h}^{\rm CBC}(f_{\rm peak})|
\end{aligned}
$$

- almost monochromatic waves
- delay determined from m_a & ℓ
- signal duration determined from m_a

where ℓ is coupling constant (S. Jung et al (2020))

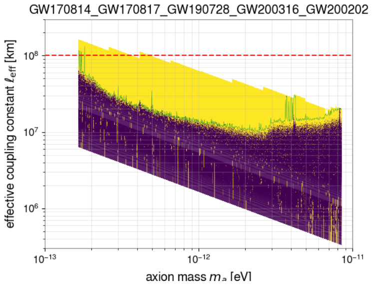
Result: 99.5% rejection

If there is axion with m_a & ℓ, the parameter set can NOT be rejected for all events:

$$p^{\rm reject}_{\rm combined}(m_a,\ell) = \left(p^{\rm reject}_{\rm GW170814}(m_a,\ell) < 0.5\%\right) \text{ OR } \left(p^{\rm reject}_{\rm GW170817}(m_a,\ell) < 0.5\%\right) \text{ OR } \cdots$$

From data after GW170814, GW170817, GW190728, GW200202, and GW200316 (long available):

Combined result



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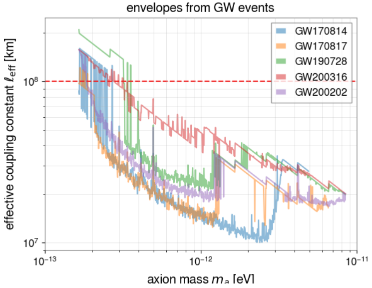

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