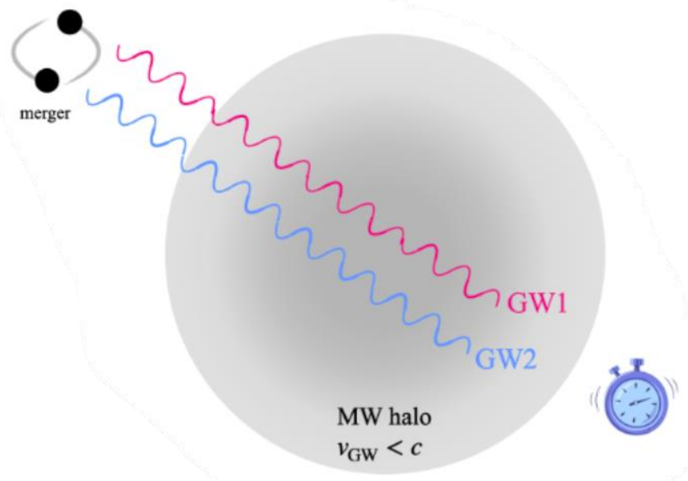
Gravitational Wave Distortion in Ultralight Dark Matter



Badal Bhalla

With Fazlollah Hajkarim, Mudit Rai, Kuver Sinha and Tao Xu

Numerous astrophysical studies suggest the existence of matter that interacts with normal matter predominantly via gravity.

Numerous astrophysical studies suggest the existence of matter that interacts with normal matter predominantly via gravity.

This so-called Dark Matter (DM) constitutes 27% of the mass-energy content of the universe.

Numerous astrophysical studies suggest the existence of matter that interacts with normal matter predominantly via gravity.

This so-called Dark Matter (DM) constitutes 27% of the mass-energy content of the universe.

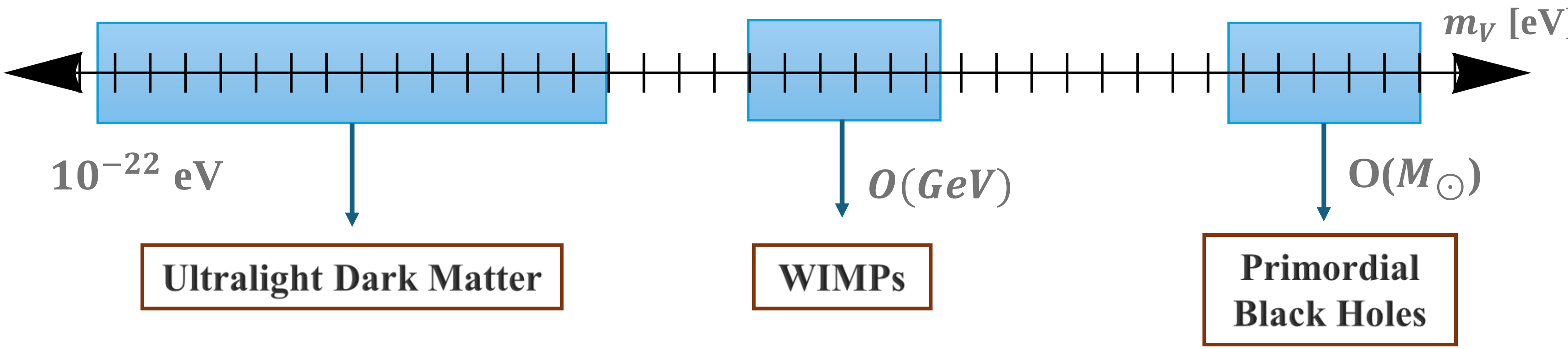
DARK MATTER (DM)

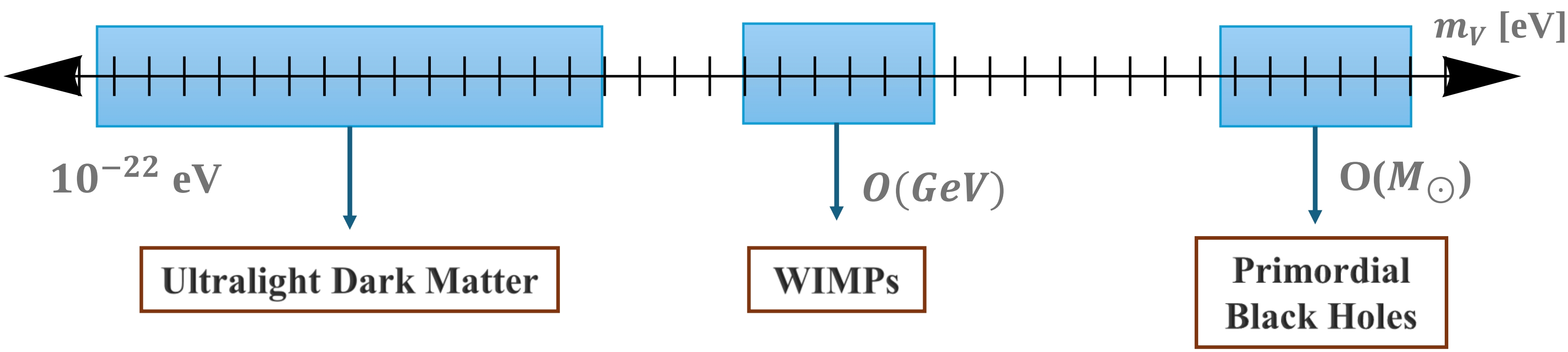
What we know?

1. Invisible Nature.
2. Gravitational Influence.
3. Cosmic Abundance.
4. Stability.

What do we not know?

1. Precise Composition.
2. Formation and Evolution.
3. Interaction via other forces.


m_V [eV]
10^{-22} eV
$O(GeV)$
$O(M_\odot)$
Ultralight Dark Matter
WIMPs
Primordial Black Holes



In this study, we aim to investigate the changes in gravitational waves caused by ultralight DM that form a Bose-Einstein Condensate (BEC)

We introduce a scalar DM field φ that can be described with the following Lagrangian

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m}{2}\phi^2 - \lambda\phi^4.$$

m denotes the scalar mass
λ is the strength of repulsive self-interaction

We introduce a scalar DM field φ that can be described with the following Lagrangian

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m}{2}\phi^2 - \lambda\phi^4.$$

m denotes the scalar mass
λ is the strength of repulsive self-interaction

In the presence of a repulsive self-interaction, the DM mass can extend up to m≲1 eV and form a Bose-Einstein condensate (BEC) on a galactic scale. The repulsive self-interaction counteracts gravitational attraction, stabilizing the BEC core

The GWs can excite the massless phonon modes in the ground state of the BEC wave function. This effect is analogous to light traveling through an optically transparent medium with a non-zero refractive index

The GWs can excite the massless phonon modes in the ground state of the BEC wave function. This effect is analogous to light traveling through an optically transparent medium with a non-zero refractive index

The change in refractive index experienced by the GWs inside the BEC medium is given by

$$\delta n_{\mathrm{g}} \equiv n_{\mathrm{g}} - 1 = \sqrt{\frac{3}{2}}\,\frac{3\,m^6\,\rho_{\mathrm{BEC}}\,\zeta(\frac{3}{2})^2}{8\,\pi\,\lambda^{\frac{3}{2}}\,h^4\,\omega_{\mathrm{GW}}^4\,M_{\mathrm{pl}}^6}$$

The speed of GWs in a BEC DM halo is modified to

$$v_{\mathrm{GW}} = \frac{c}{n_g}$$

The GWs can excite the massless phonon modes in the ground state of the BEC wave function. This effect is analogous to light traveling through an optically transparent medium with a non-zero refractive index

The change in refractive index experienced by the GWs inside the BEC medium is given by

$$\delta n_{\rm g} \equiv n_{\rm g} - 1 = \sqrt{\frac{3}{2}}\, \frac{3\, m^6\, \rho_{\rm BEC}\, \zeta(\frac{3}{2})^2}{8\, \pi\, \lambda^{\frac{3}{2}}\, h^4\, \omega_{\rm GW}^4\, M_{\rm pl}^6}$$

arXiv:1609.03939

The speed of GWs in a BEC DM halo is modified to

$$v_{\rm GW} = \frac{c}{n_g}$$

For a graviton, the time of flight is given by

$$t_{\rm GW} = \frac{D - \langle D_{\rm BEC}\rangle}{c} + \frac{\langle D_{\rm BEC}\rangle}{v_{\rm GW}}$$

The time delay between a graviton and a photon is

$$\Delta t_{{\rm GW},\gamma} = \delta n_g \frac{x\, D}{c}\ .$$

The time delay between a graviton and a graviton is

$$\Delta t_{\rm GW1,GW2} = (\delta n_{g1} - \delta n_{g2}) \frac{x\, D}{c}$$

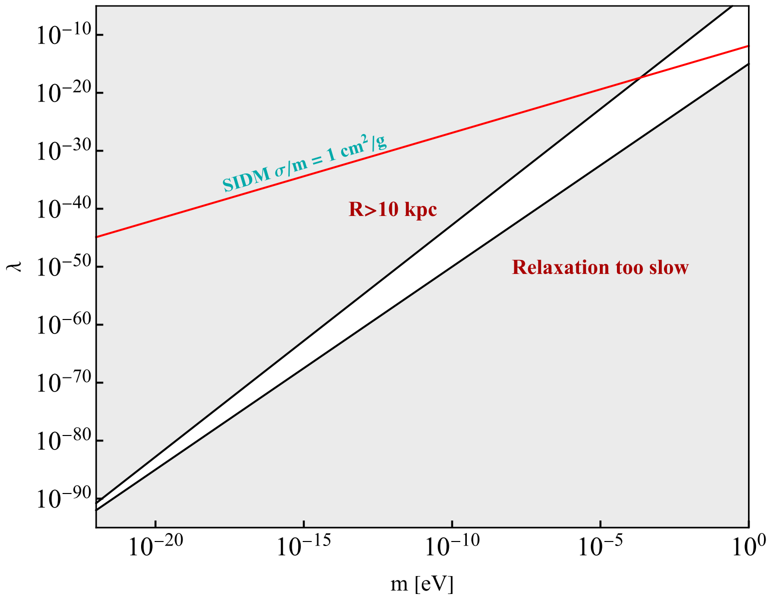
In general, the BEC consists of a solitonic core and a halo surrounding it

Radius of the core: $R = \frac{\pi\, M_{pl} \sqrt{\lambda}}{m^2}$

$$\sqrt{\lambda} = \frac{m^2\, R}{\pi\, M_{\rm pl}}$$

it convenient to trade the self-coupling λ with the core radius R

$$\delta n_g = \sqrt{\frac{3}{2}\,\frac{3\,\pi^2\,\rho_{\rm BEC}\,\zeta(\frac{3}{2})^2}{8\,R^3 M_{\rm pl}^3\, h^4\,\omega_{\rm GW}^4}}$$



The BEC induces a frequency-dependent time delay $\Delta t_{GW_1 GW_2}$ that modifies the waveform

$$h_+(t_{GW,\oplus}) = h_+(t_{\rm GW} + \Delta t_{\rm GW_{IN}, GW_{MG}})$$

$$\Delta t_{\rm GW1,GW2} = (\delta n_{g1} - \delta n_{g2}) \frac{x\, D}{c}$$

Observer time on Earth	Travel Time	BEC induced time-delay

The BEC induces a frequency-dependent time delay $\Delta t_{GW_1 GW_2}$ that modifies the waveform

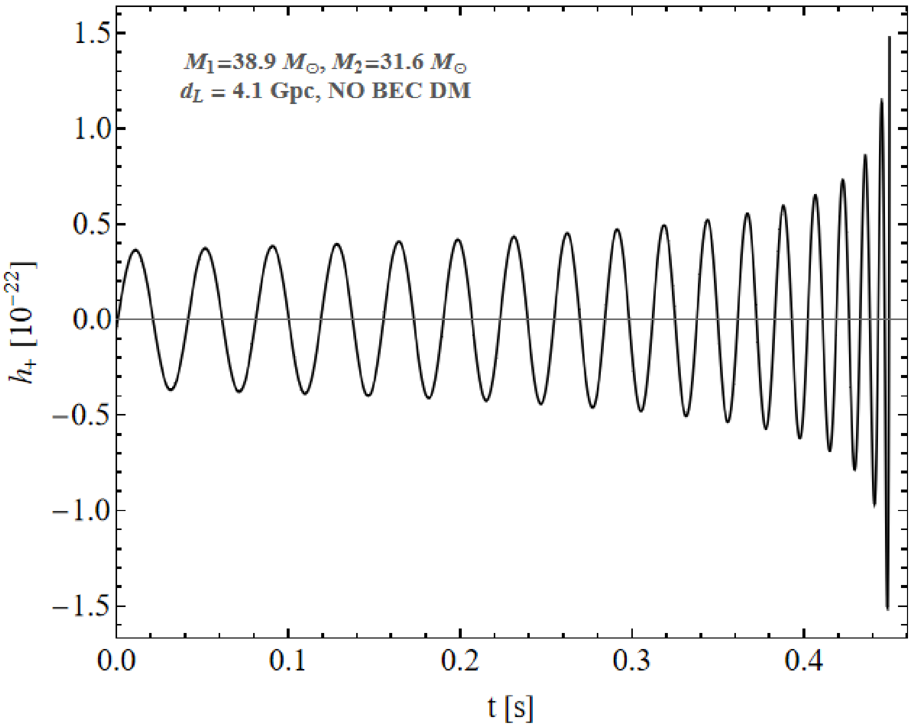
$$h_+(t_{GW,\oplus}) = h_+(t_{\mathrm{GW}} + \Delta t_{\mathrm{GW_{IN},GW_{MG}}})$$

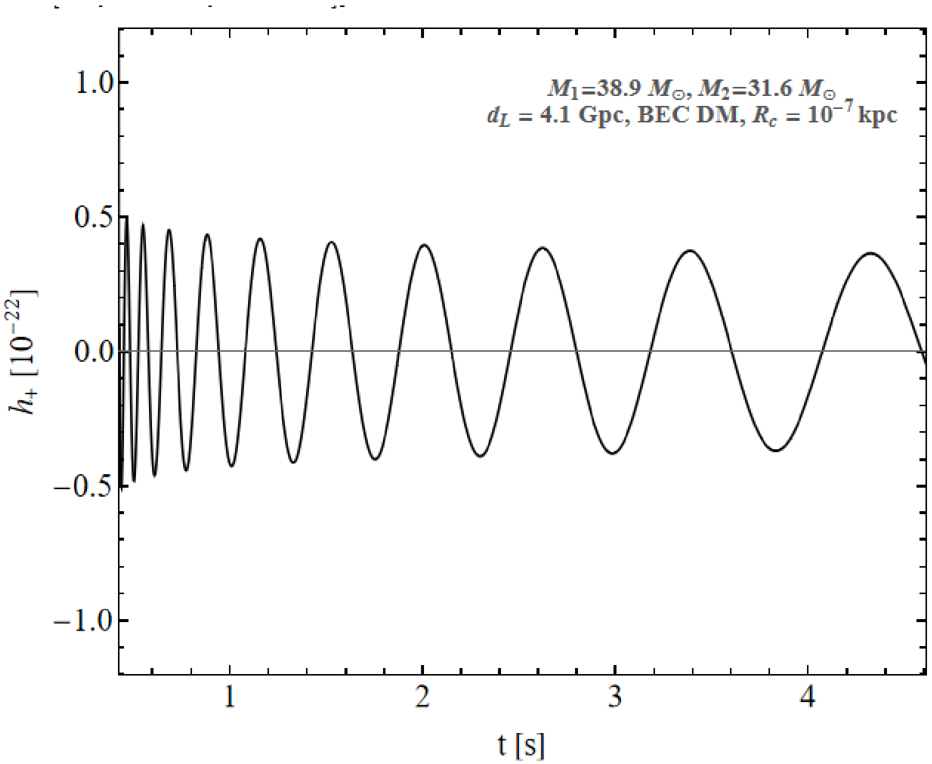
$$\Delta t_{\mathrm{GW1,GW2}} = (\delta n_{g1} - \delta n_{g2})\frac{x\,D}{c}$$

Observer time on Earth | **Travel Time** | **BEC induced time-delay**

$$h_+(t) = \frac{1}{d_L}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{5/4}\left(\frac{5}{c\,\tau}\right)^{1/4}\left(\frac{1+cos^2\theta}{2}\right) cos\left[\Phi_0 - 2\left(\frac{5\,G\,\mathcal{M}_c}{c^3}\right)^{-5/8}\tau^{5/8}\right]$$

$$h_\times(t) = \frac{1}{d_L}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{5/4}\left(\frac{5}{c\,\tau}\right)^{1/4} cos\,\theta\, sin\left[\Phi_0 - 2\left(\frac{5\,G\,\mathcal{M}_c}{c^3}\right)^{-5/8}\tau^{5/8}\right]$$





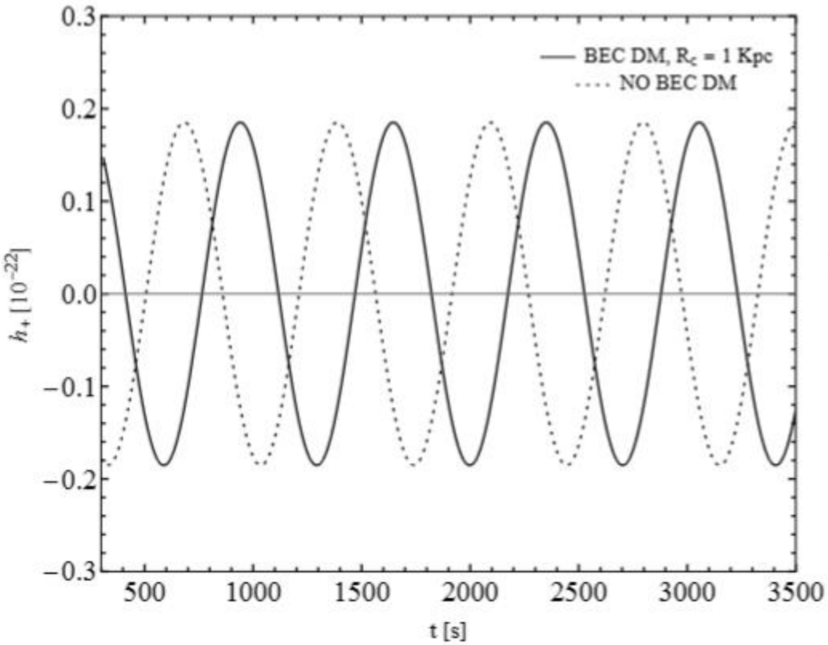
In the absence of BEC DM

In the presence of BEC DM

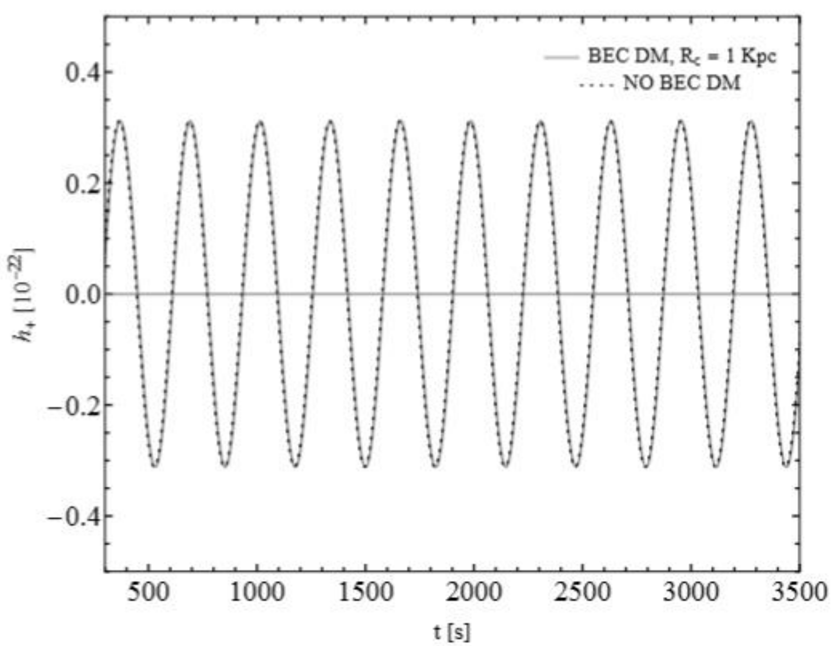
The benchmark BEC parameters are chosen such that the solitonic core size is $R_c = 10^{-7}\ kpc$

The low-frequency GWs detected by LISA offer a way to probe larger solitonic cores.

The low-frequency GWs detected by LISA offer a way to probe larger solitonic cores.



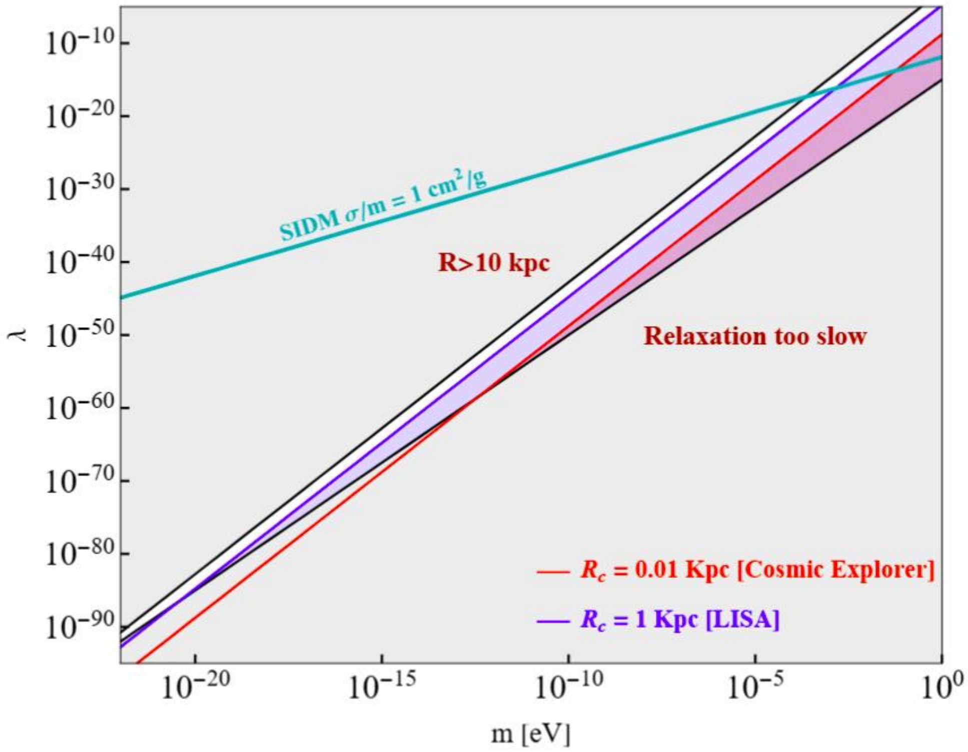
8 years before ISCO



1 year before ISCO

Gravitational wave from an Extreme Mass Ratio Inspiral (EMRI). The benchmark BEC parameters are chosen such that the solitonic core size is $R_c = 1\ kpc$

Discernible deformations to the waveforms are obtained for BEC radius of $R_c = 1\ kpc$ (LISA), $R_c = 10^{-2}\ kpc$ (Cosmic Explorer), and $R_c = 10^{-7}\ kpc$ (LIGO)



Precision Waveform Studies with Fisher Matrix Analysis

$$\Gamma_{\mathrm{ij}} = \left(\frac{\partial h}{\partial \theta_i} \middle| \frac{\partial h}{\partial \theta_j} \right)$$

The inner product is defined as

$$(h_1|h_2) = 4\,\mathrm{Re} \int_{f_{\min}}^{f_{\max}} df \, \frac{\tilde{h_1}(f)\,\tilde{h_2}(f)}{S_n(f)}$$

The Fourier transform of the distorted waveform is

$$\tilde{h}(f_{\mathrm{GW},\oplus}) = \tilde{h}(f_{\mathrm{GW}})\, e^{i\, f_{\mathrm{Gw}}\, \Delta t_{\mathrm{GW_{IN}},\mathrm{GW_{MG}}}}$$

The variance of Θ_i is given by

$$\sigma^2(\theta_i) = (\Gamma^{-1})\mathrm{ii}$$

Gravitational waves can serve as a probe of ultra-light DM that can form a Bose-Einstein condensate (BEC) on a galactic scale.

BEC acts as an optically transparent medium to gravitational waves, causing a reduction in speed and resulting in a time delay.

The amount of time delay depends on the frequency of the GWs, leading to a distorted gravitational waveform.

With future GW detectors, a lot of parameter space for BEC DM can be explored through precise gravitational waveform studies.

THANK YOU