Dark Matter in the Time of Gravitational Waves

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work in preparation, with collaborators
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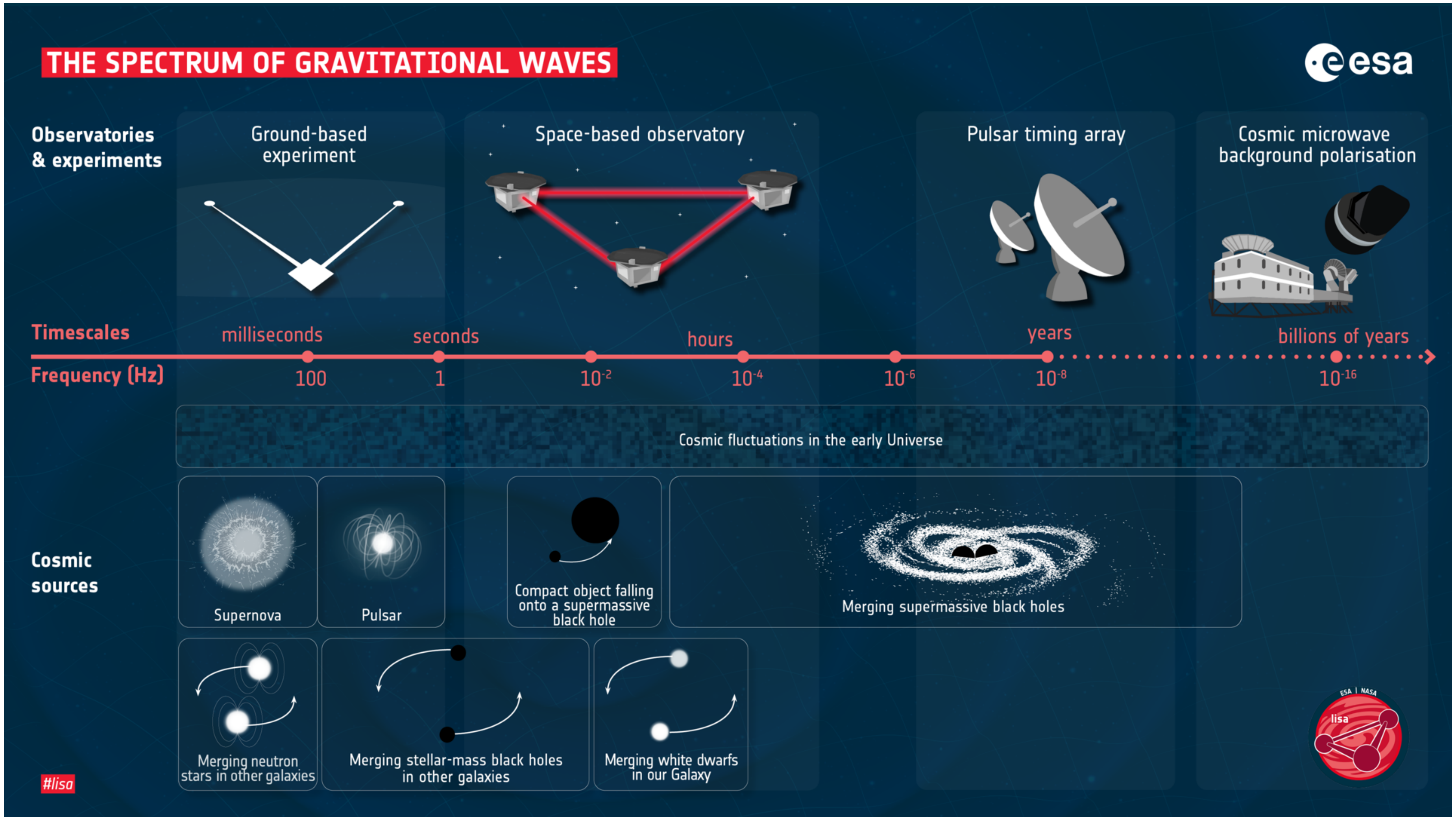
The Mitchell Conference 2024
College Station
May 24, 2024

Gravitational Wave Astronomy

The observation of Gravitational Waves provides a new method to explore the universe.



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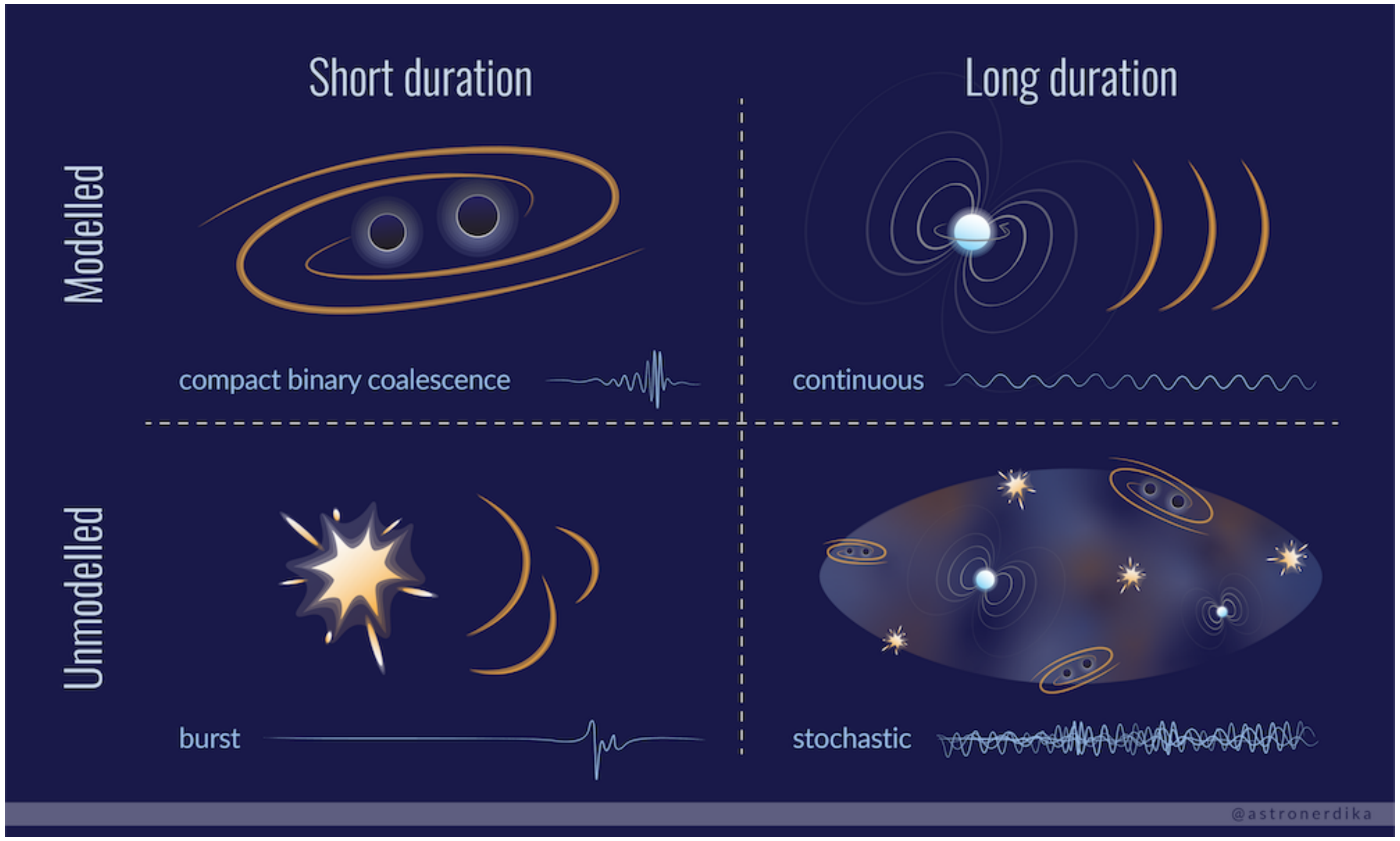
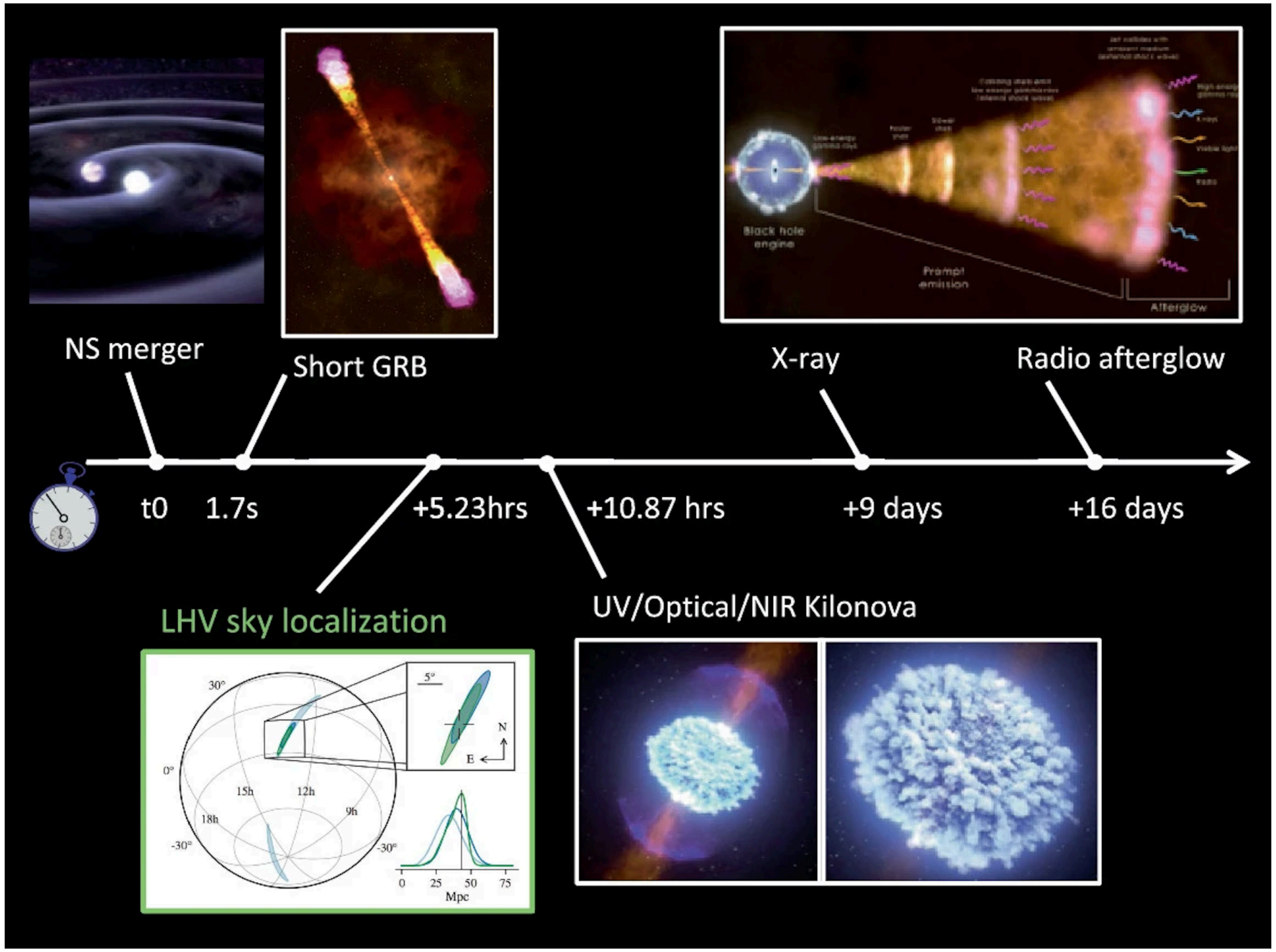


- GW messenger can pass regions that are opaque to electromagnetic waves, thus carry information from early universe and dense environments.
- GWs can be detected alongside multi-messenger counterparts
- GWs are measured with **time-domain** information.

Neutron star merger GW170817



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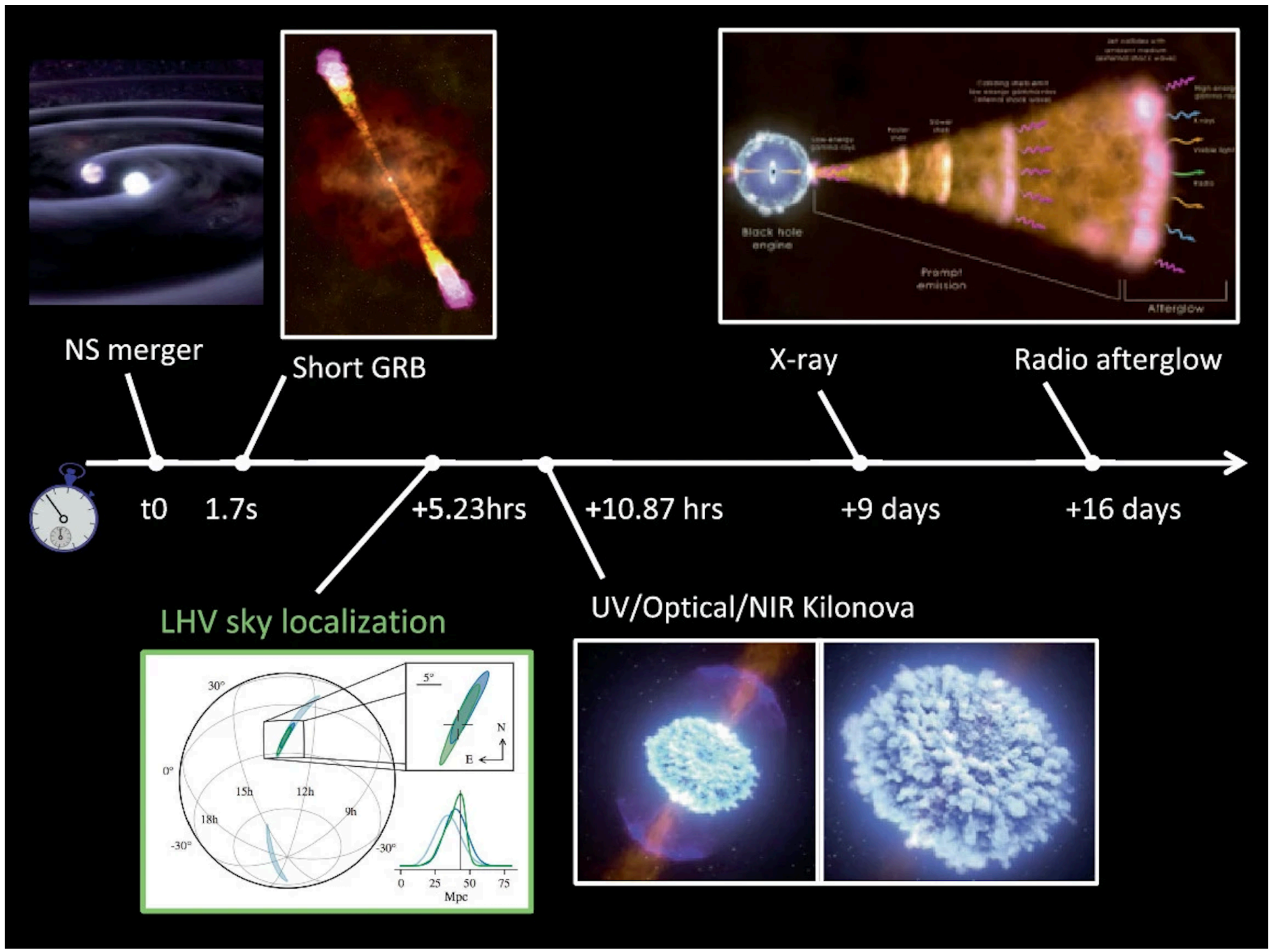

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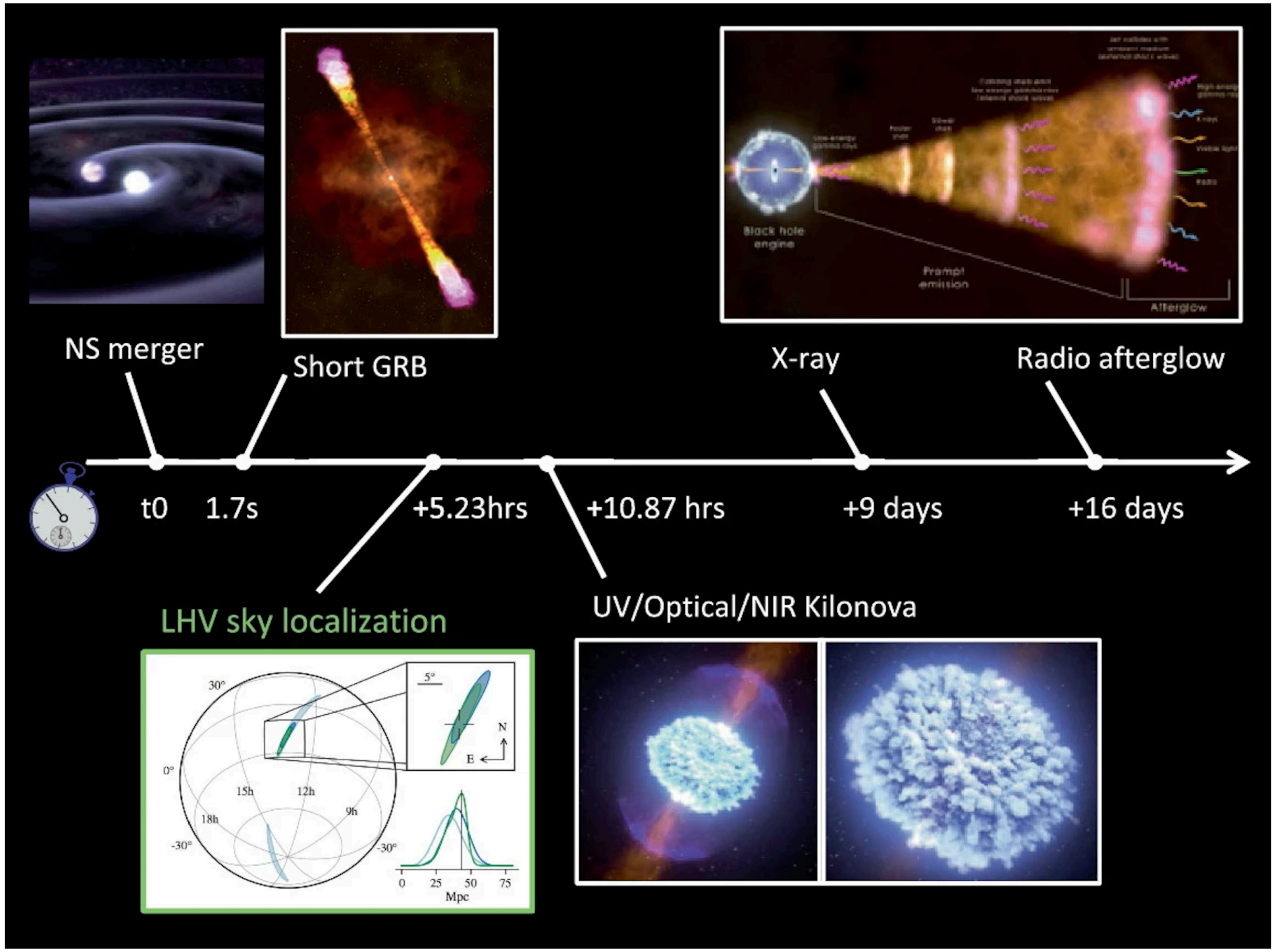

- Neutron star merger events include signals of GW and EM emissions at various frequencies.
- Multi-messenger measurements improve the sky localization of the merger event.
- The timing information can be used to understand the merger process. Deviation from the astrophysical model also probe new physics.

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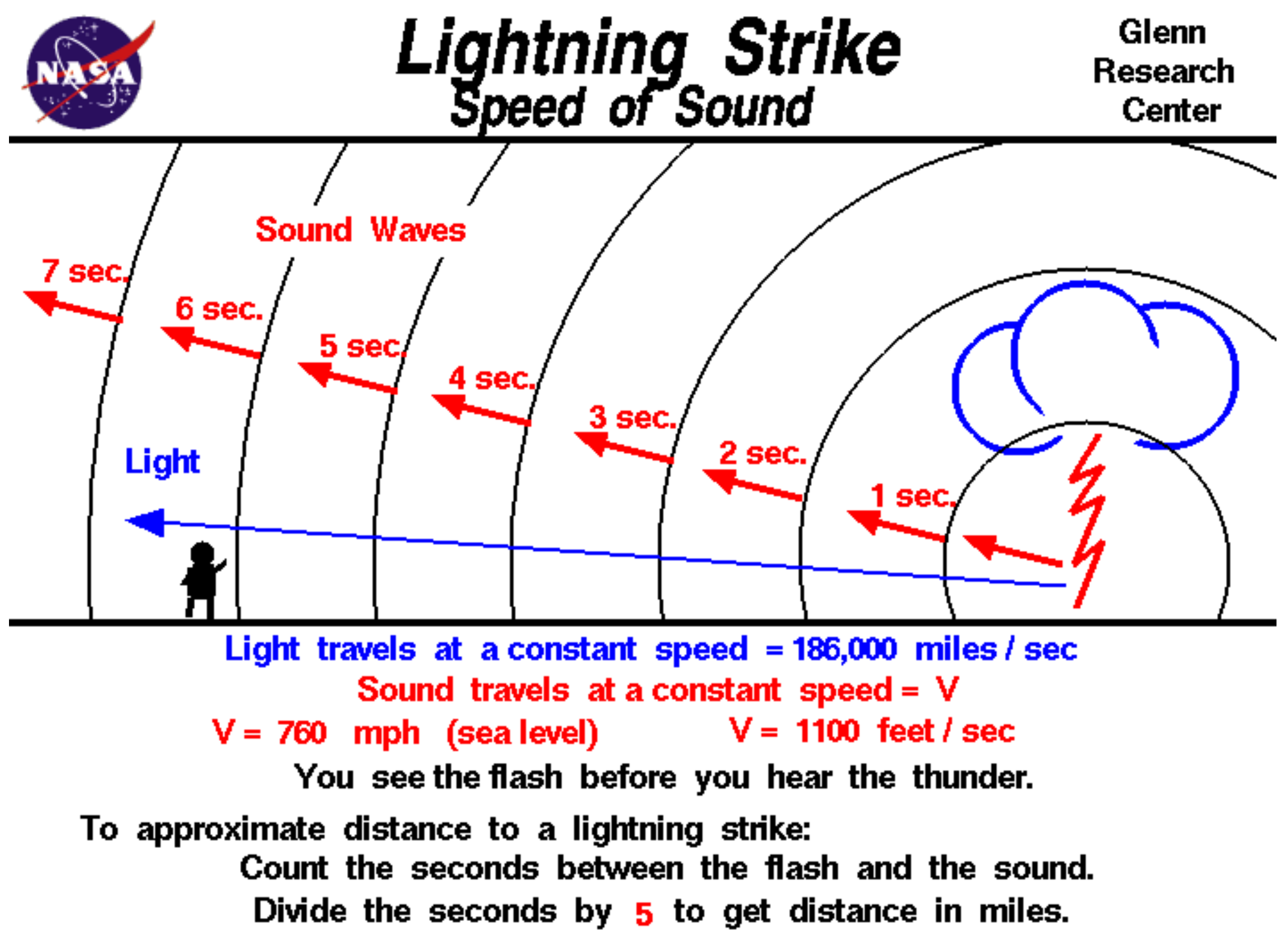
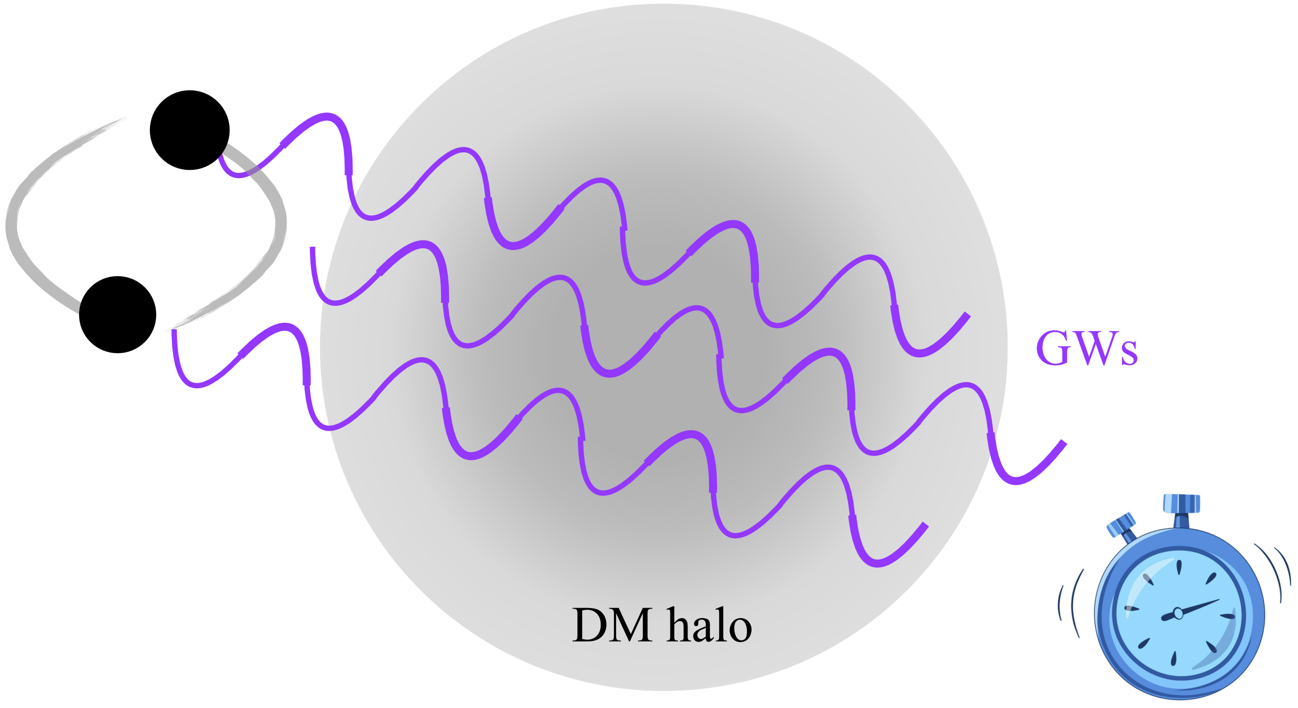
Propagation Time

- Lightning: light + sound signals
- Propagation time of light and sound tells us about properties of the medium



Propagation Time

We can use GW timing to probe new physics that modifies the propagation speed of GWs — property of DM halo



Wave Dark Matter

We study a wave DM model with self-interactions,

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

The DM self-interaction from $\lambda\phi^4$ is repulsive when $\lambda > 0$.

see JiJi Fan, 2016 *Phys. Dark Univ.*
for model building of repulsive force

→ in the BEC halo, repulsive self-interaction balances the gravitational attraction to keep the system stable.

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Mass range of wave DM: 10^{-22} eV $\lesssim m \lesssim$ 1eV

structures at small scales — occupation number

* *note this is still different from fuzzy DM*

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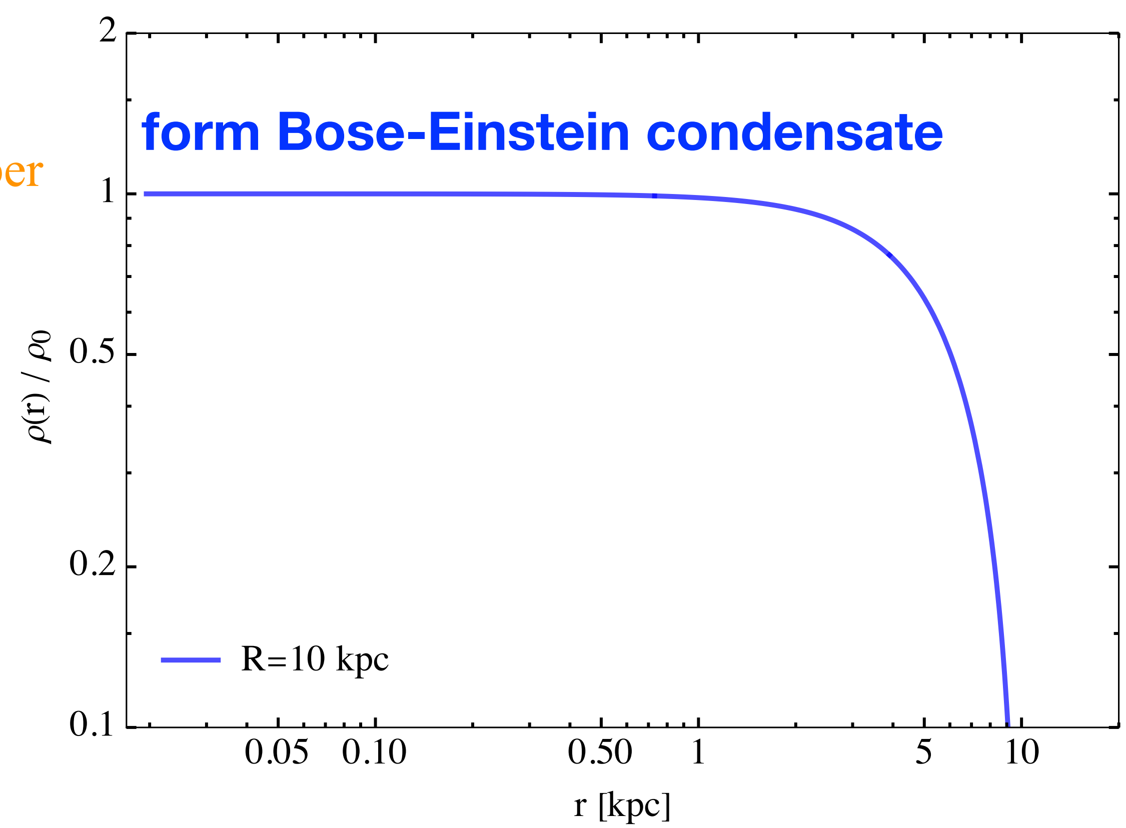
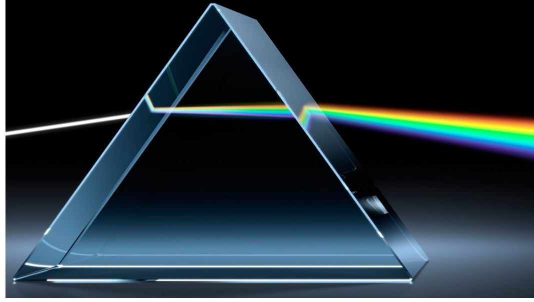
Density profile:

$$\rho(r) = \rho_0 \frac{\sin(\pi r/R)}{\pi r/R}$$

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



In-medium effect



Like photon propagation with a reduced phase velocity in medium, the scattering of GWs with long wavelength DM particles excite massless phonon modes in the BEC halo.

Bhupal Dev, Manfred Lindner, Sebastian Homer, 2017 *PLB*

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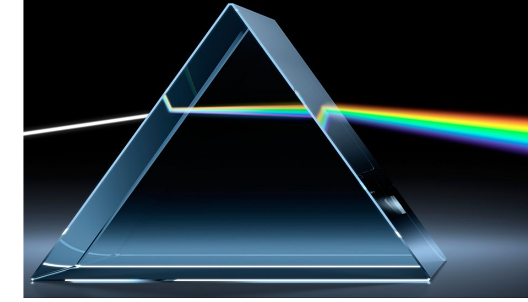

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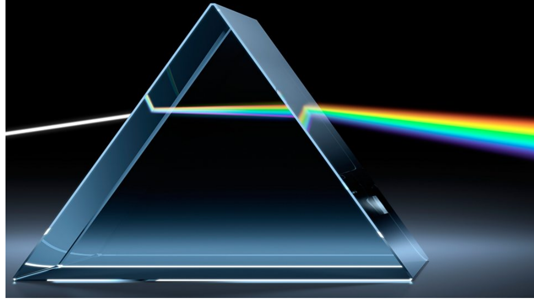
Effectively, GWs get a modified refractive index $n_g > 1$ when in the BEC halo

DM mass & density

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

coupling

GW strain and frequency



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coupling GW strain and frequency

The speed of GW is slower than the speed of light in BEC,

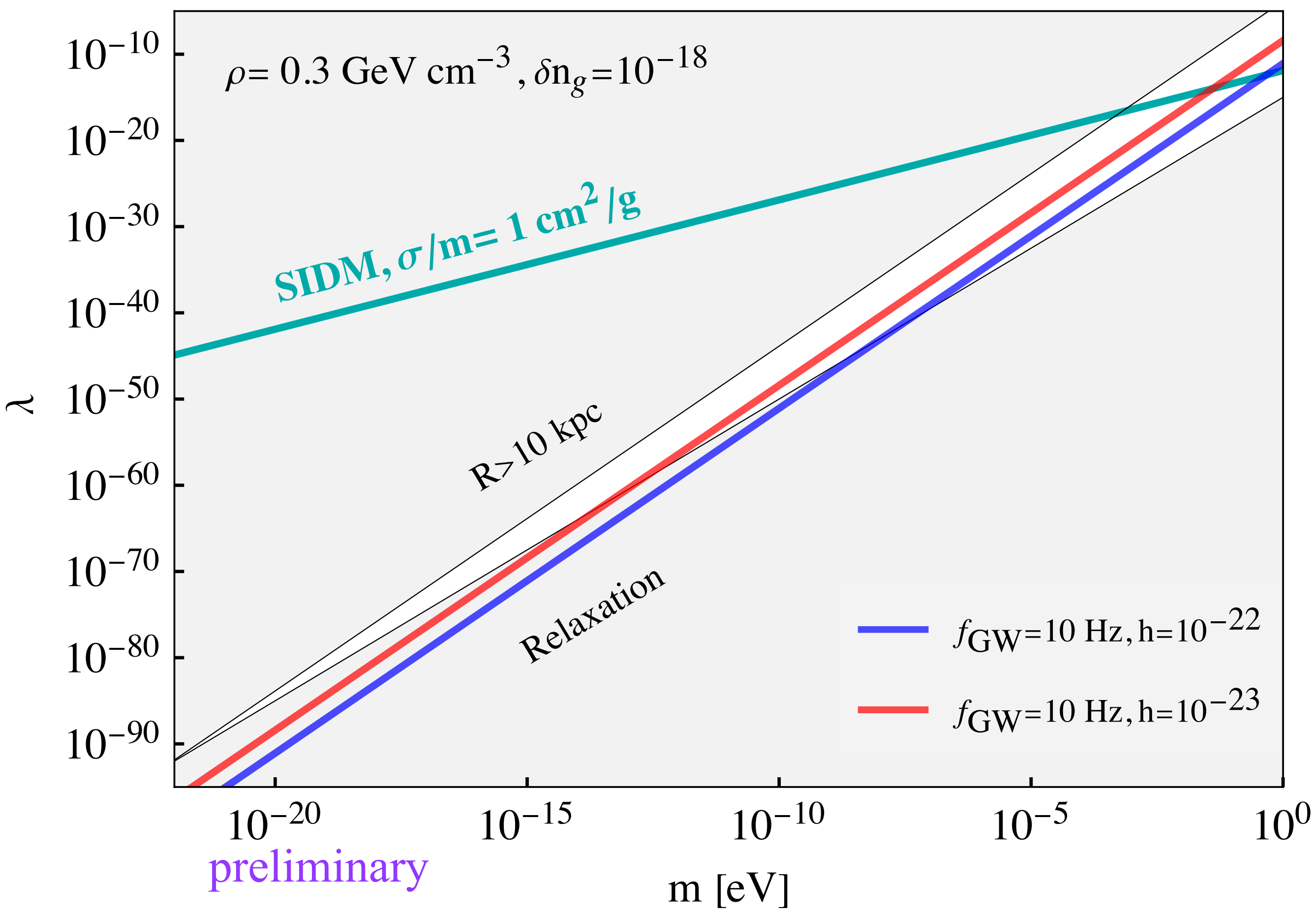
$$v_{\rm GW} = \frac{c}{1+\delta n_g} < c$$

→ Delay of GW arrival time: $\Delta t \simeq t \times \delta n_g$

DM parameters

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

refractive index deviation: $\delta n_g = \sqrt{\frac{3}{2}}\,\frac{3\,m^6\,\rho_{\rm BEC}\,\zeta(\frac{3}{2})^2}{8\,\pi\,\lambda^{\frac{3}{2}}\,h^4\,\omega_{\rm GW}^4\,M_{\rm pl}^6}$



preliminary

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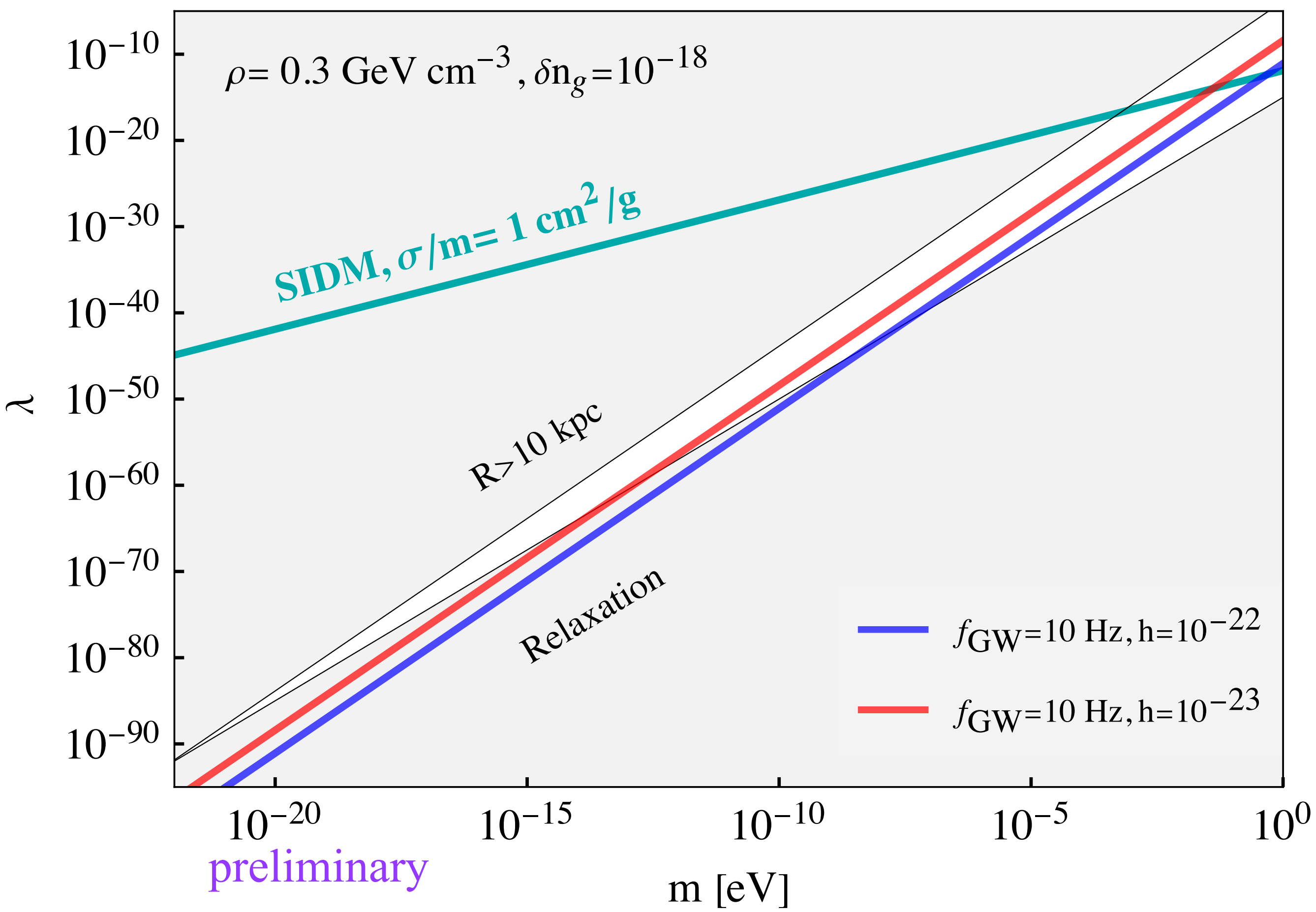

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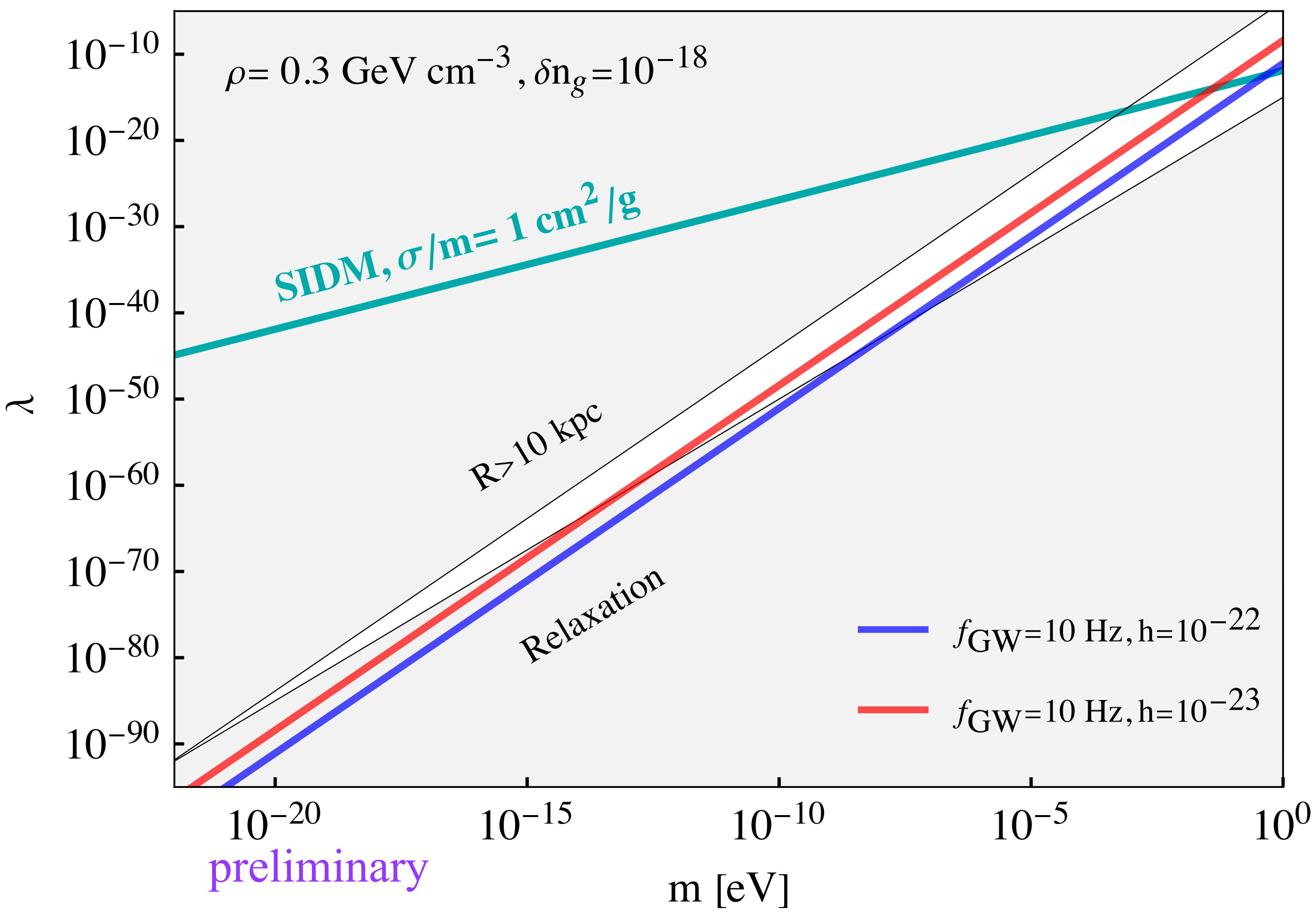
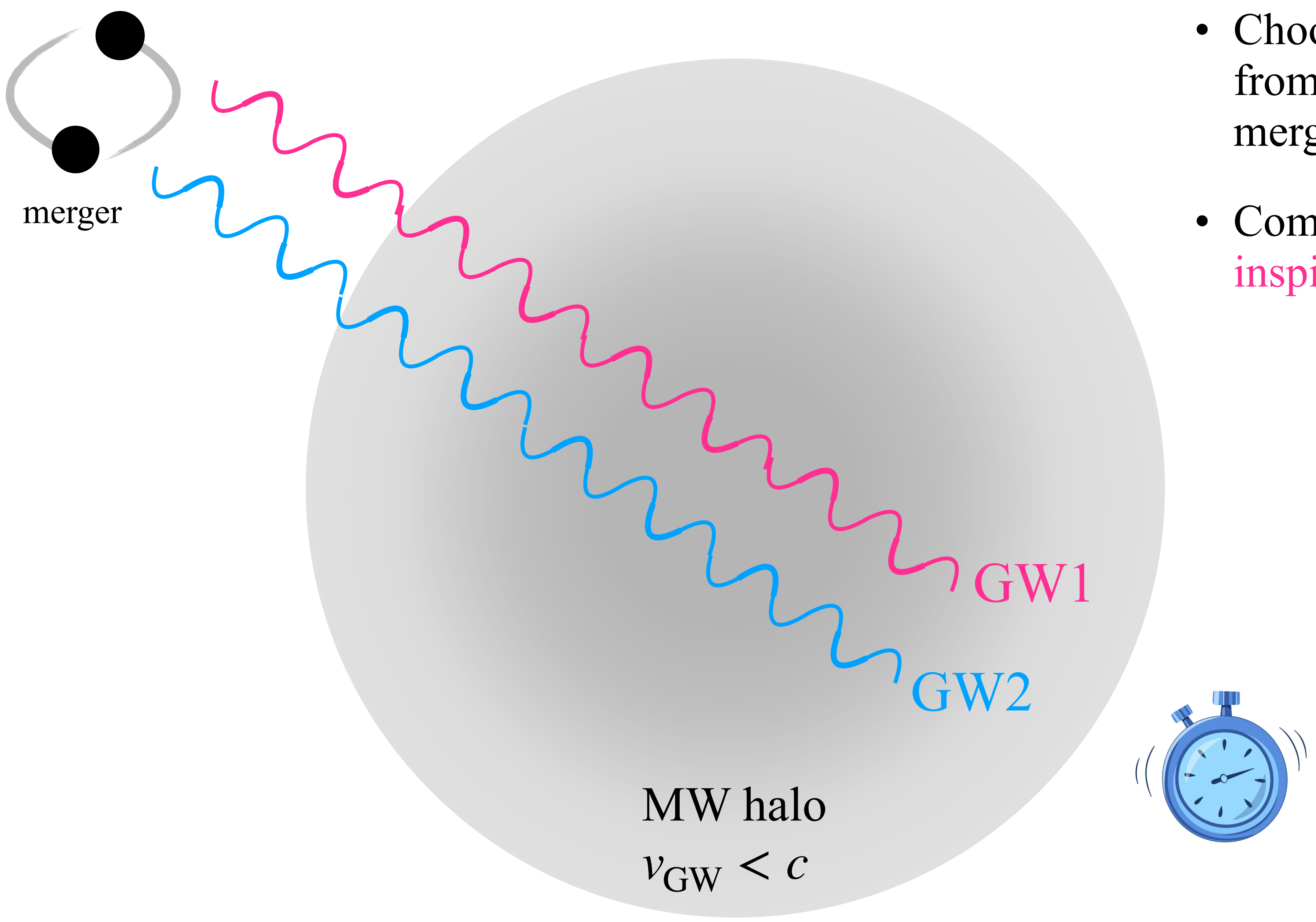


- $\lambda > 0$ is needed for repulsive interactions, but a large λ suppress the time delay effect.
- *top-left:* the core size can be too large to fit dwarf galaxy observations. *Might be alleviated for sub-fraction DM.*
- *lower-right:* the relaxation time scale is longer than the age of the Universe.

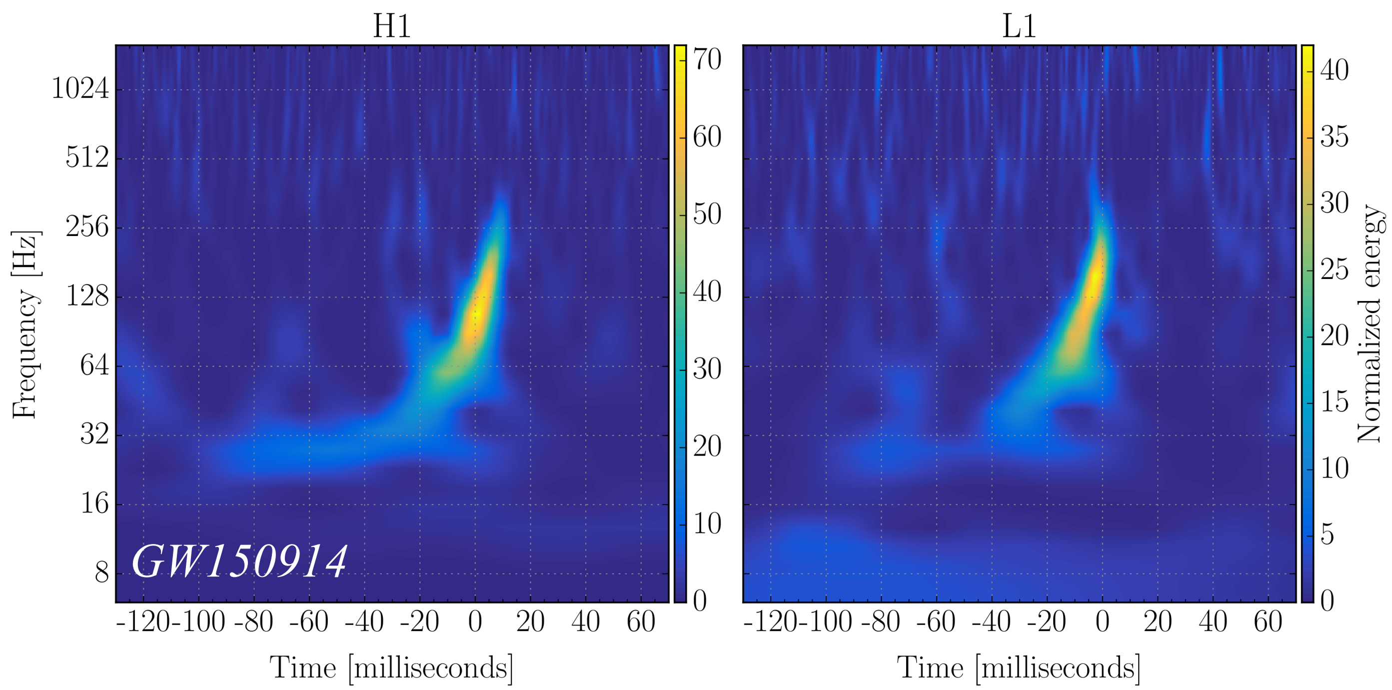
Signal: GW-GW Timing

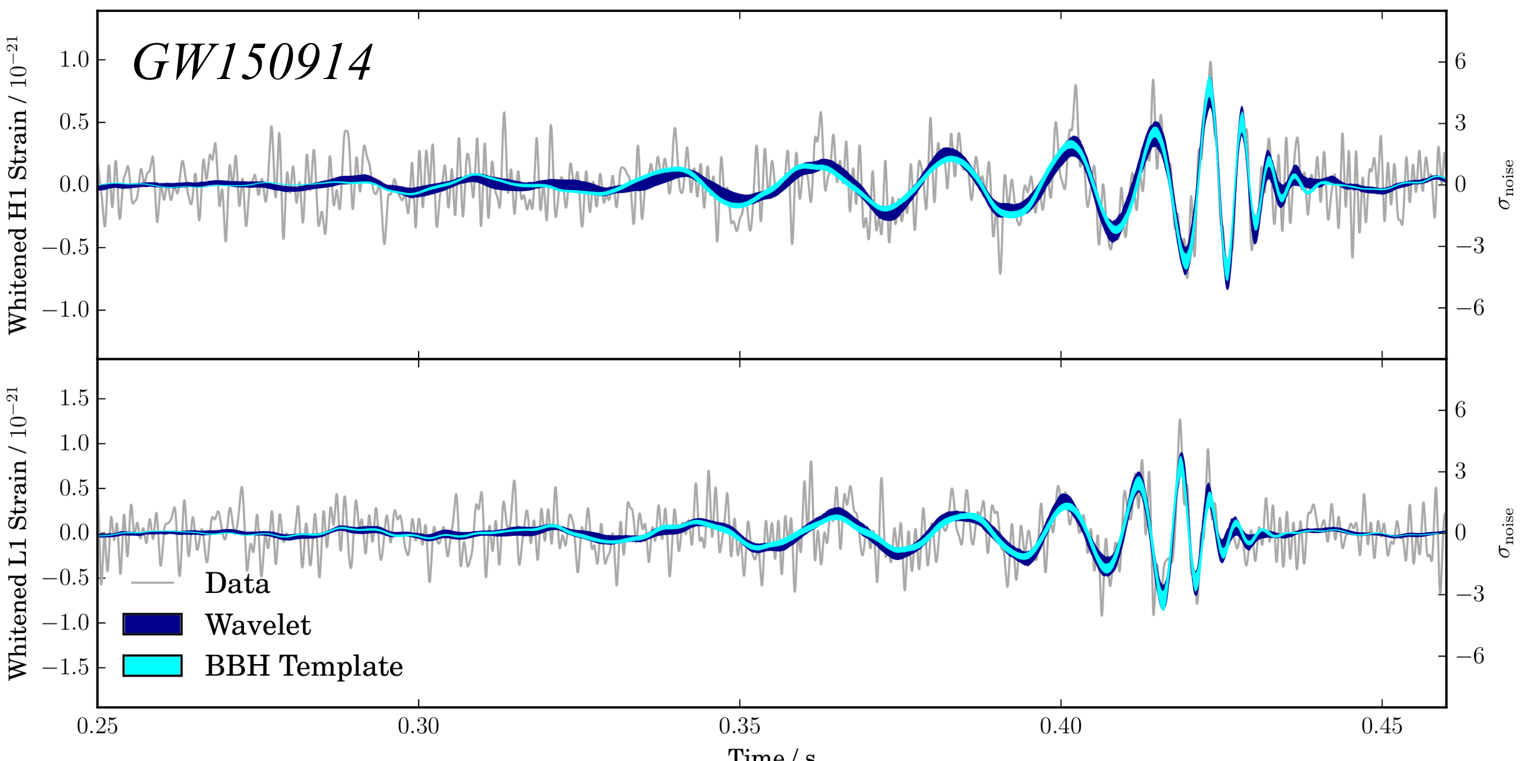


- Choose a binary event where GWs from the inspiral phase and the merger phase are observed.
- Compare time delay between the inspiral GWs and the merger GWs.

GW-GW timing

The frequency and strain of a GW event are evolving with time,





- Both the frequency and the strain increase with time from the inspiral phase to the merger phase.

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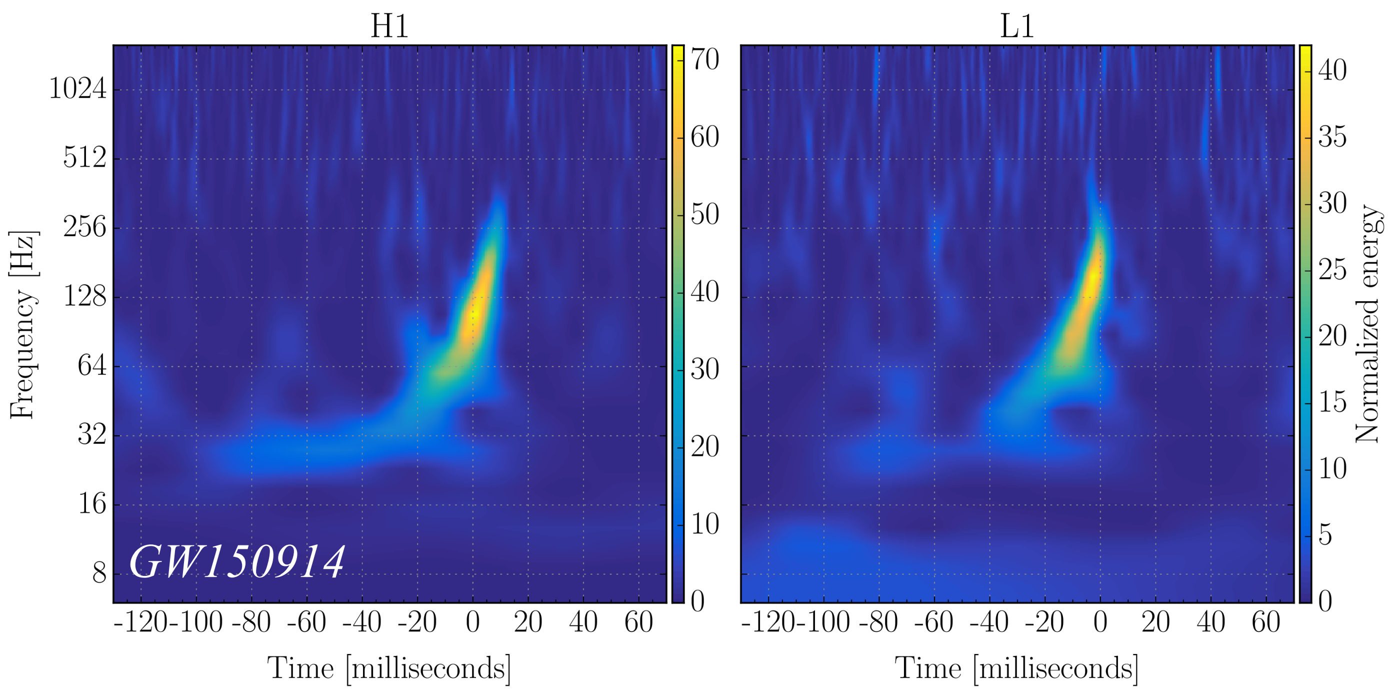

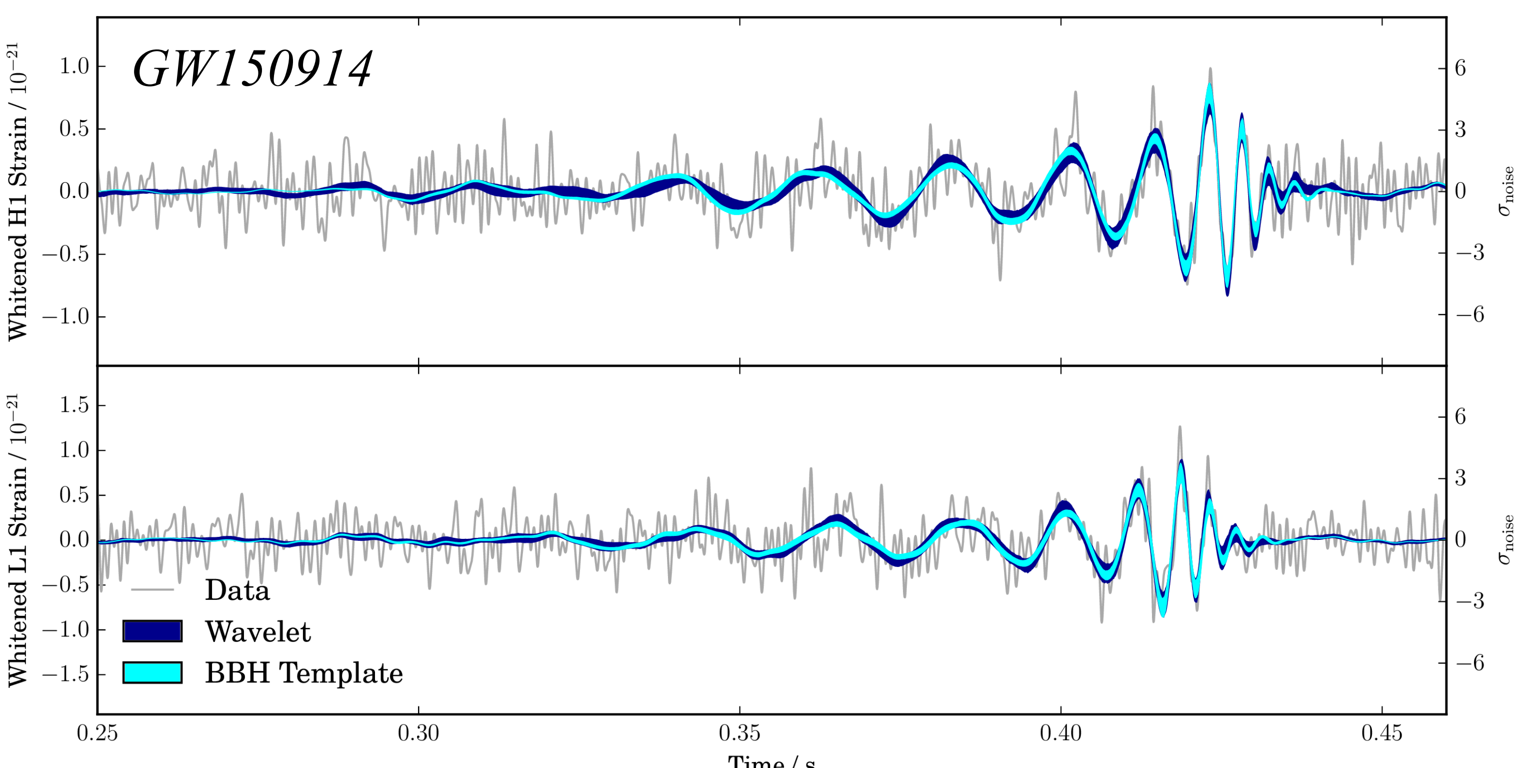

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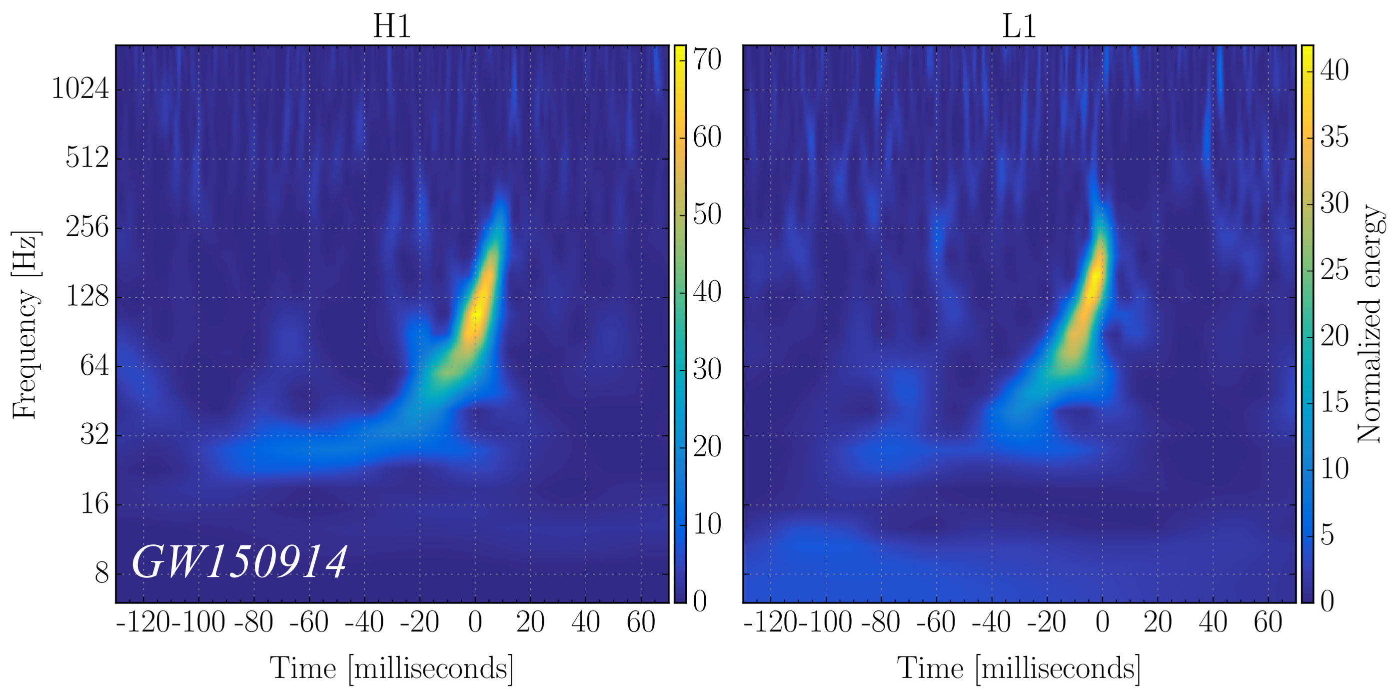
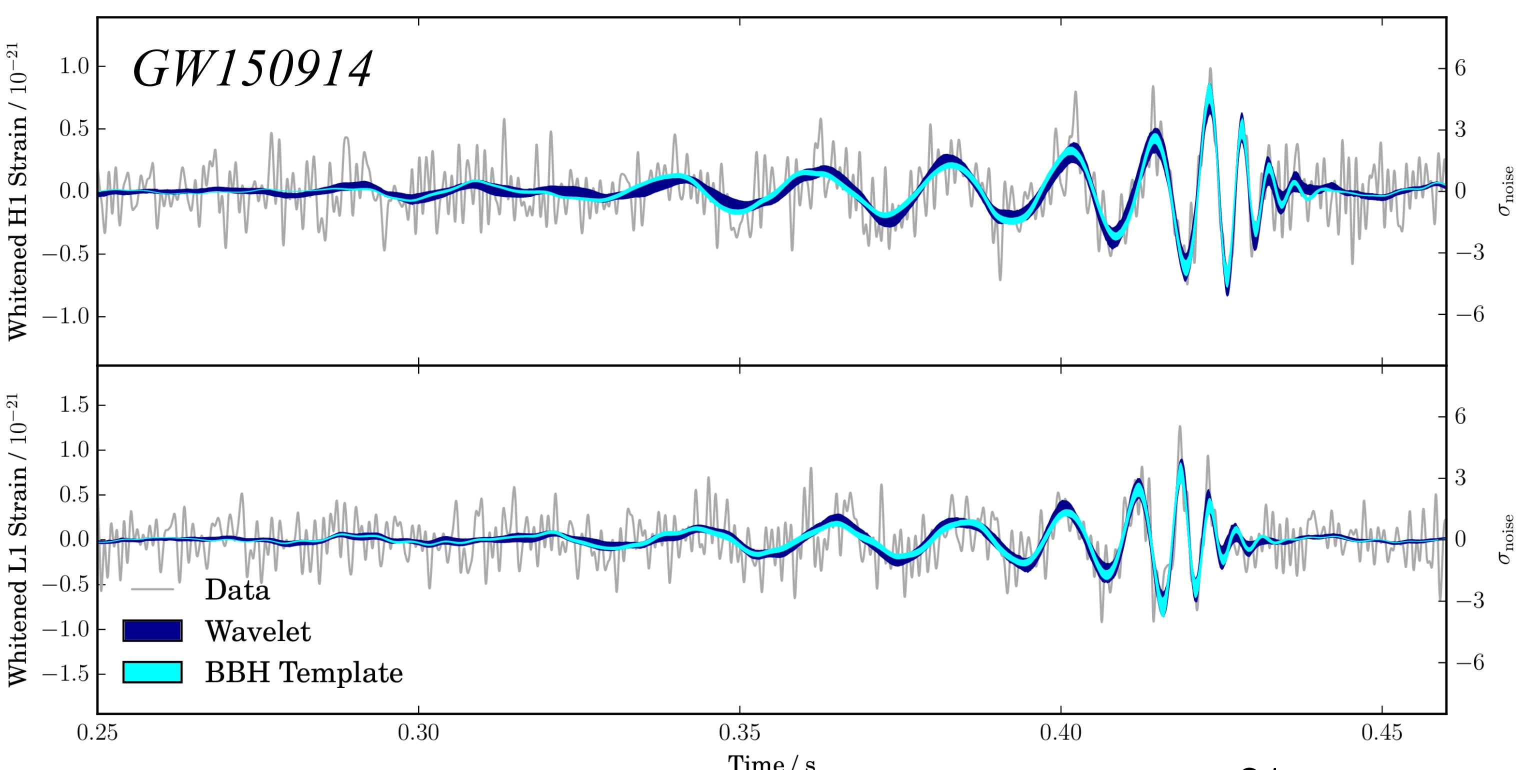


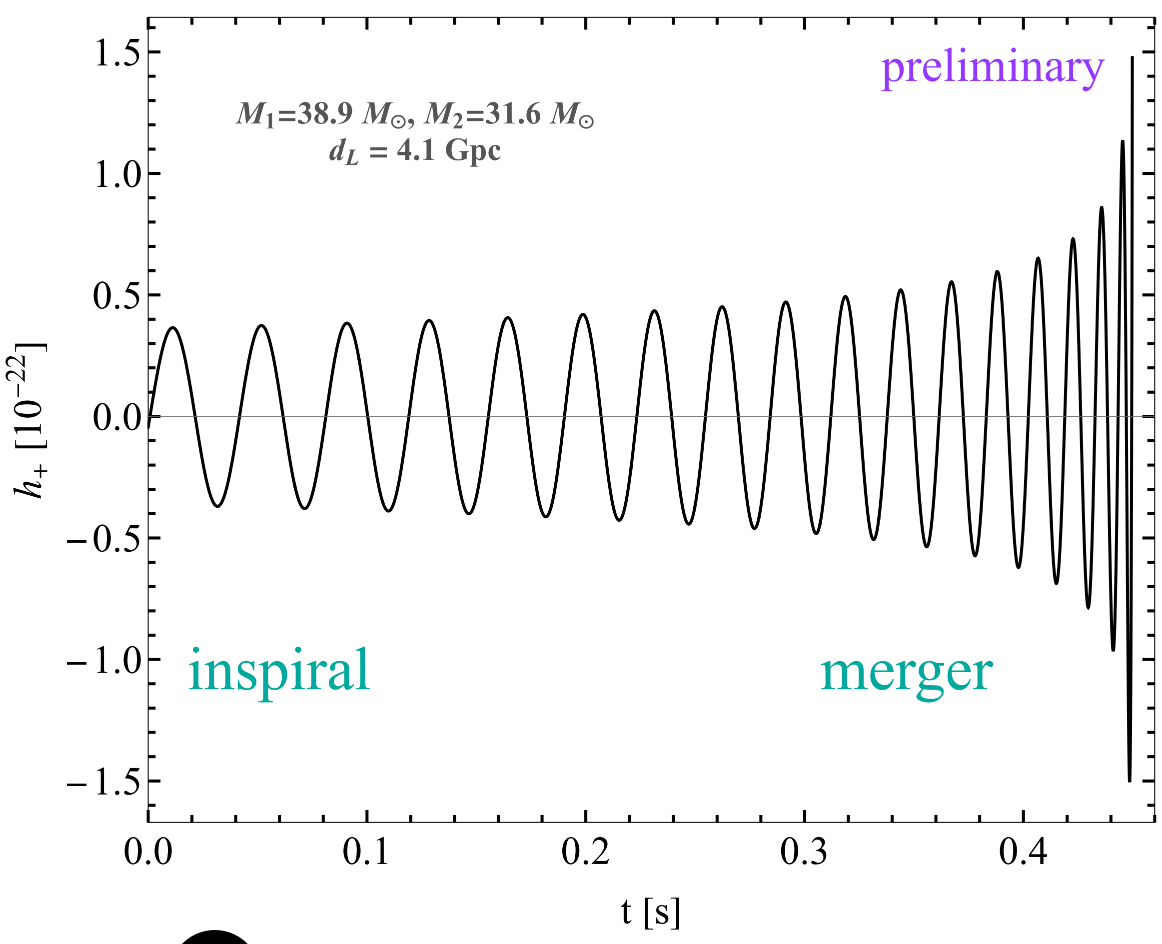


- Both the frequency and the strain increase with time from the inspiral phase to the merger phase.
- Since $\delta n_g \propto h^{-4} f^{-4}$, the wave DM effect is stronger (more time delay) in the inspiral phase, compared to the merger phase.
- We can compare GWs emitted during different time of a single event to test the effect.

GW-GW timing

Let's first look at the strain evolution without the time delay, shape is similar to production

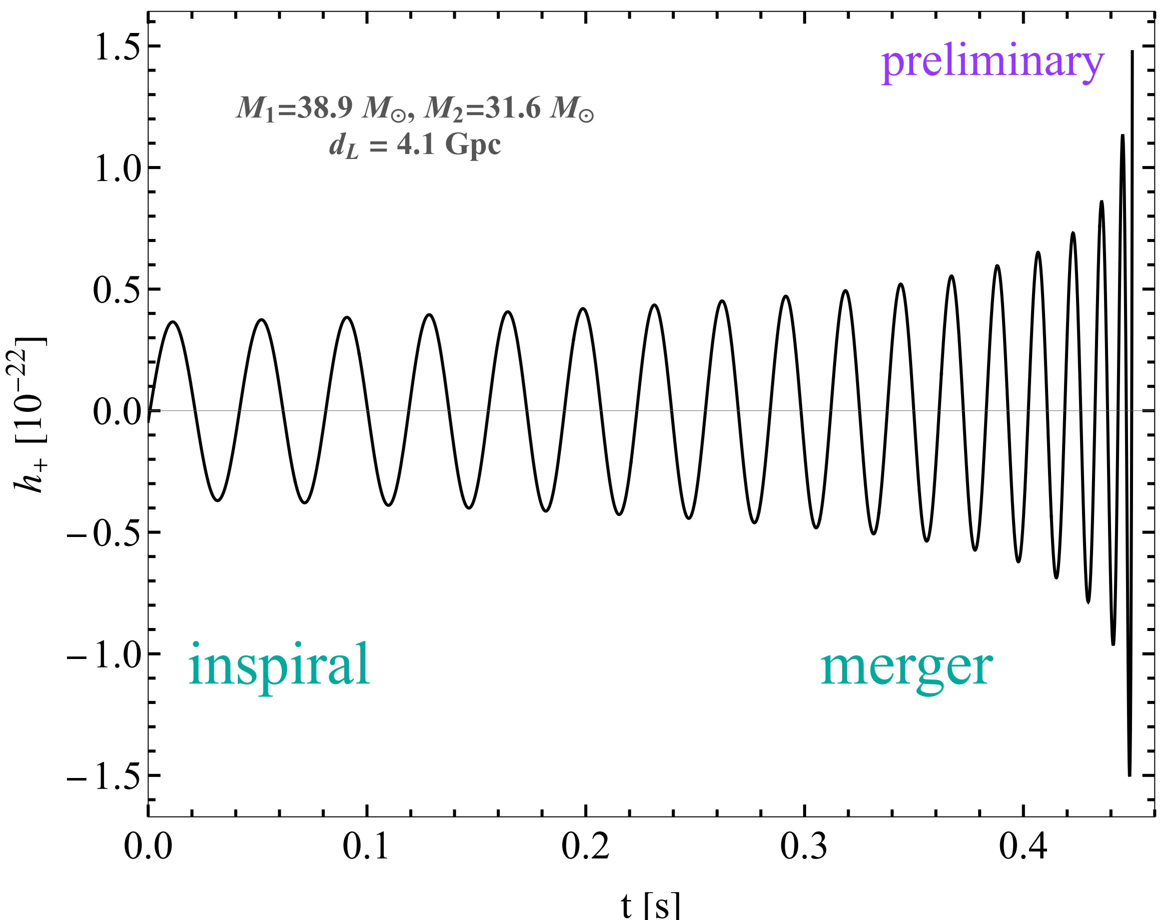
without BEC halo



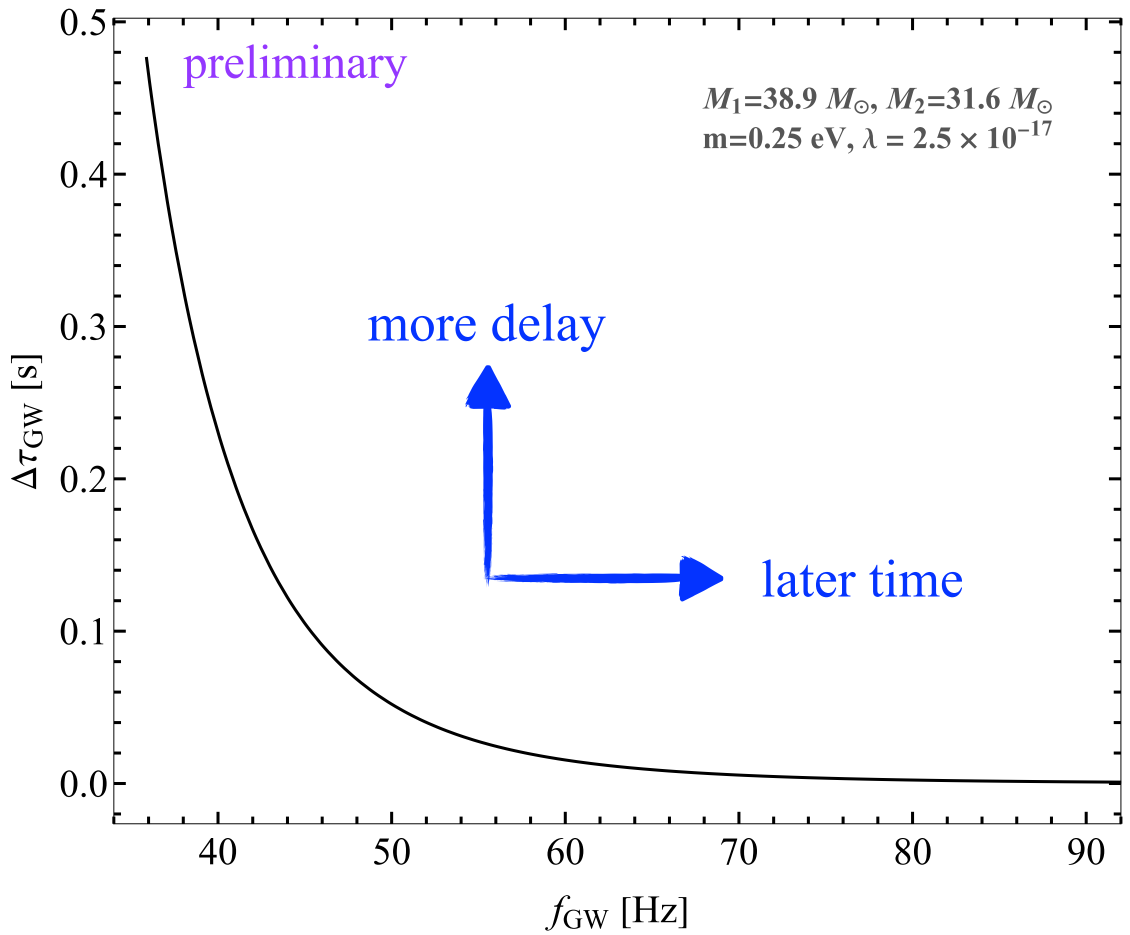
GW-GW timing

The BEC will induce refractive indices depending on the strain and frequency

without BEC halo



frequency dependence



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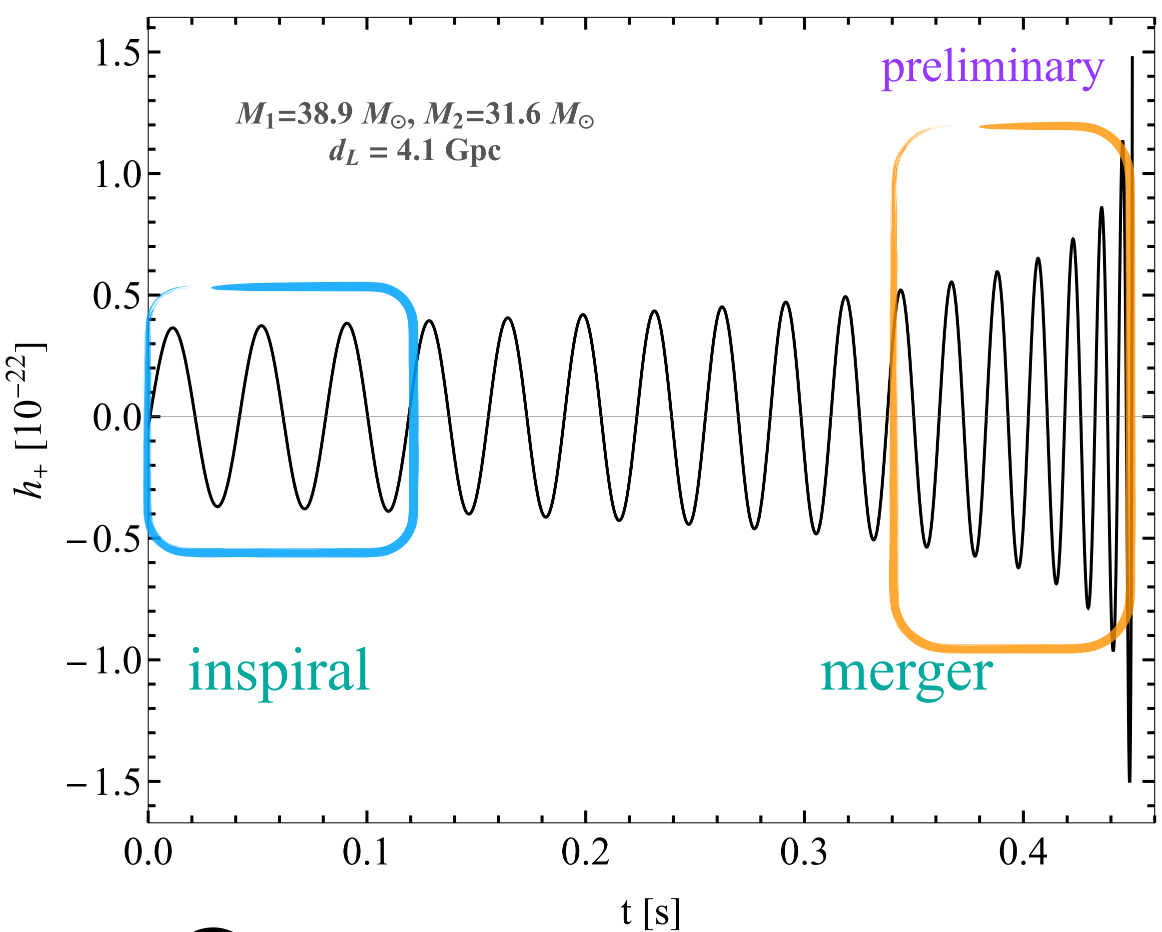

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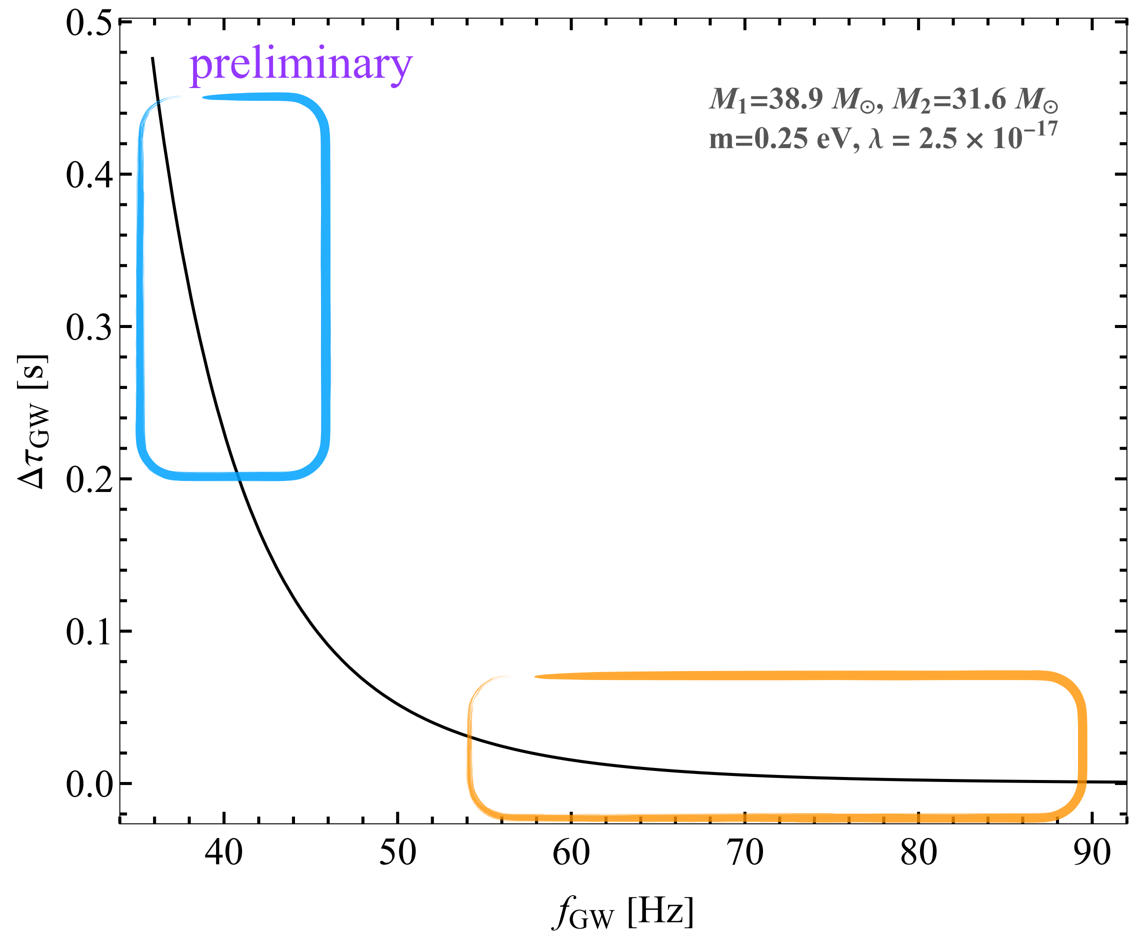
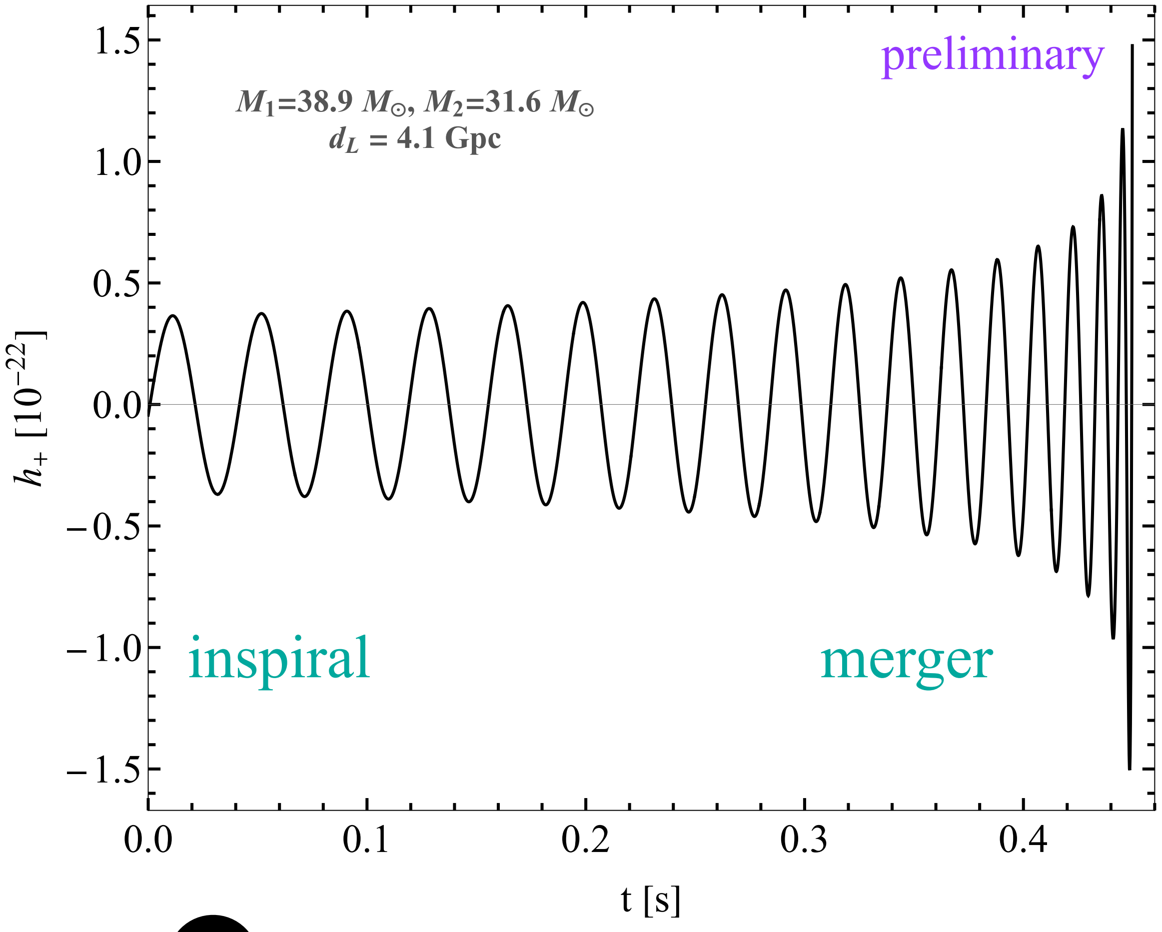


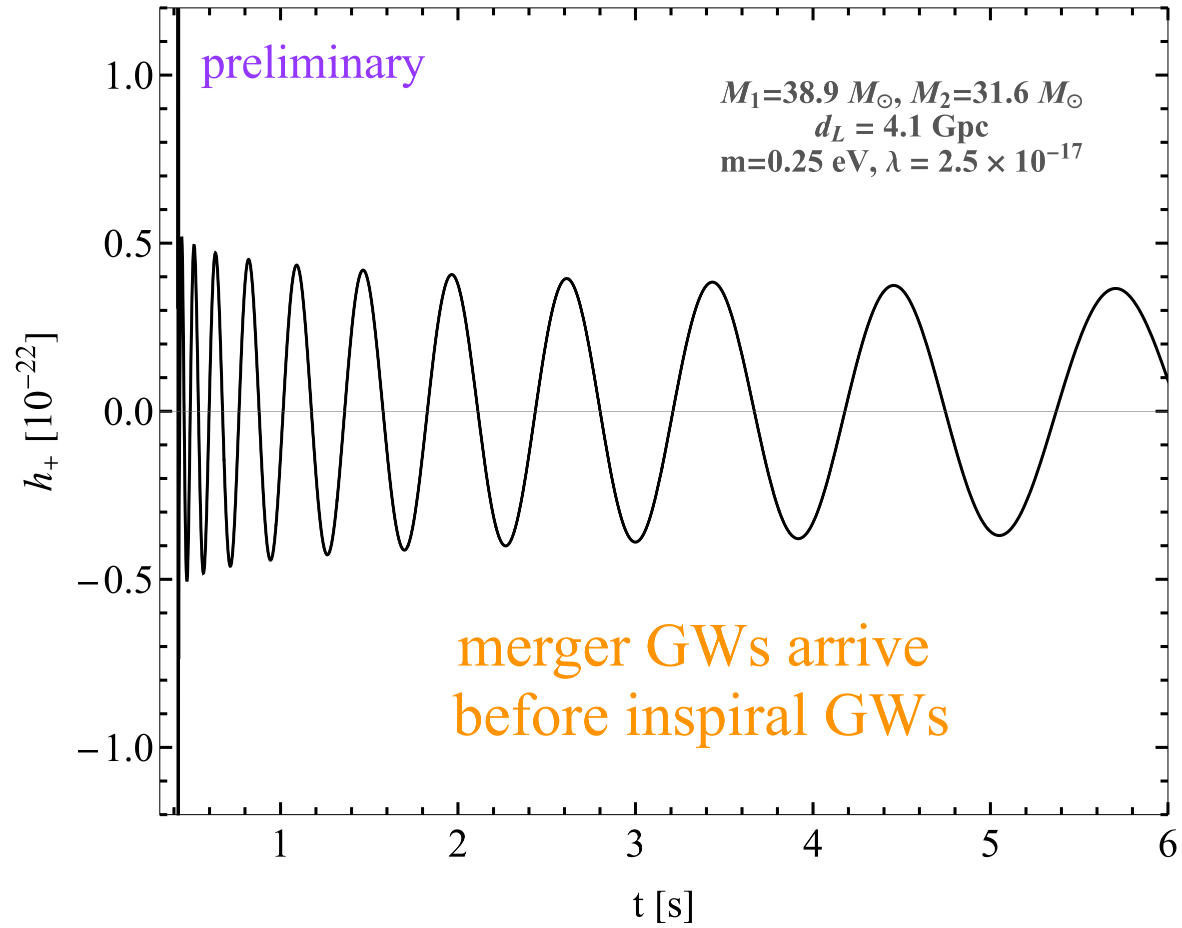
GW-GW timing

Strong BEC effect may completely change the temporal relation of a GW event when it is observed. Interesting feature for the matched filtering of LIGO data.

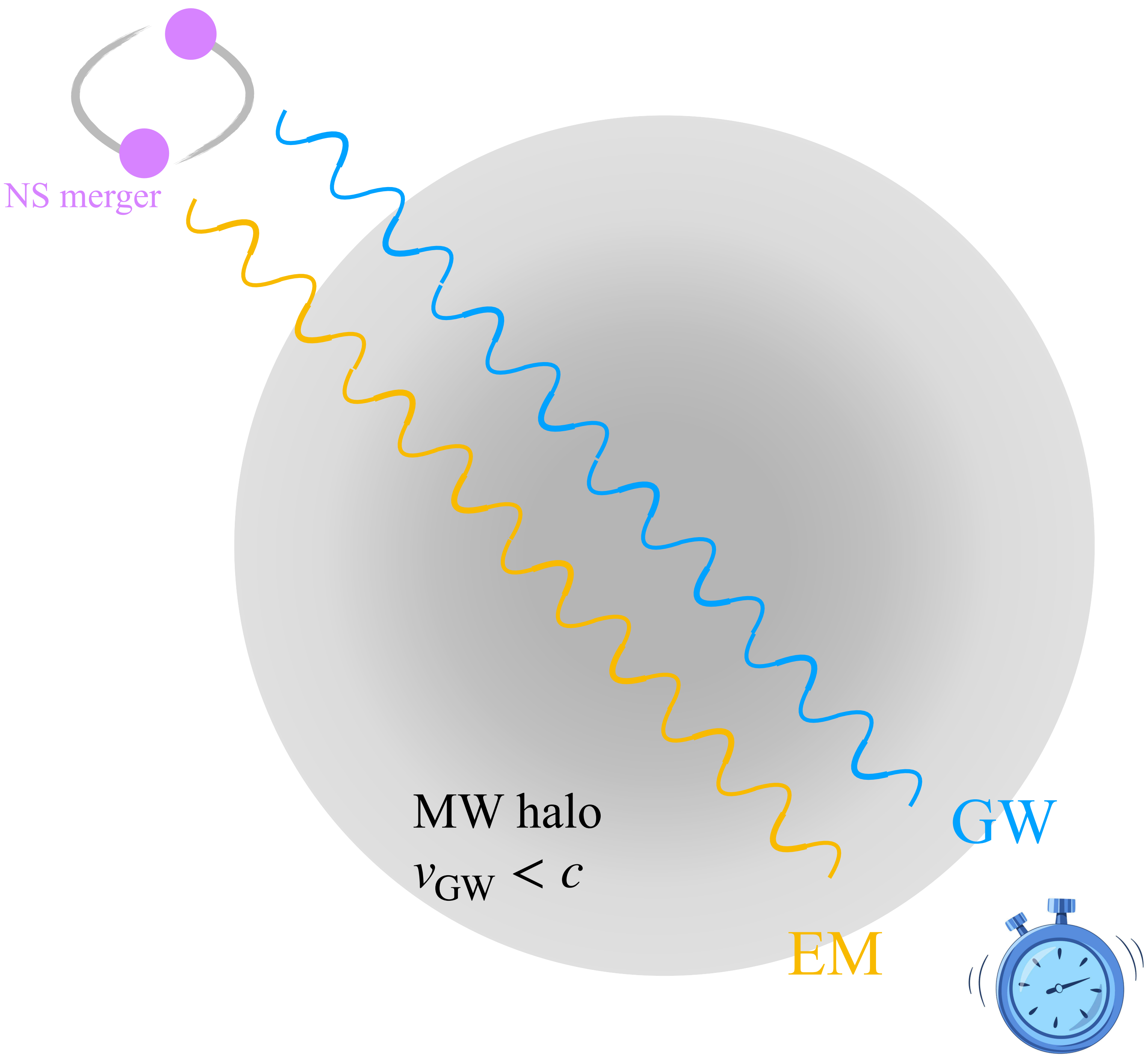
without BEC halo



with BEC halo



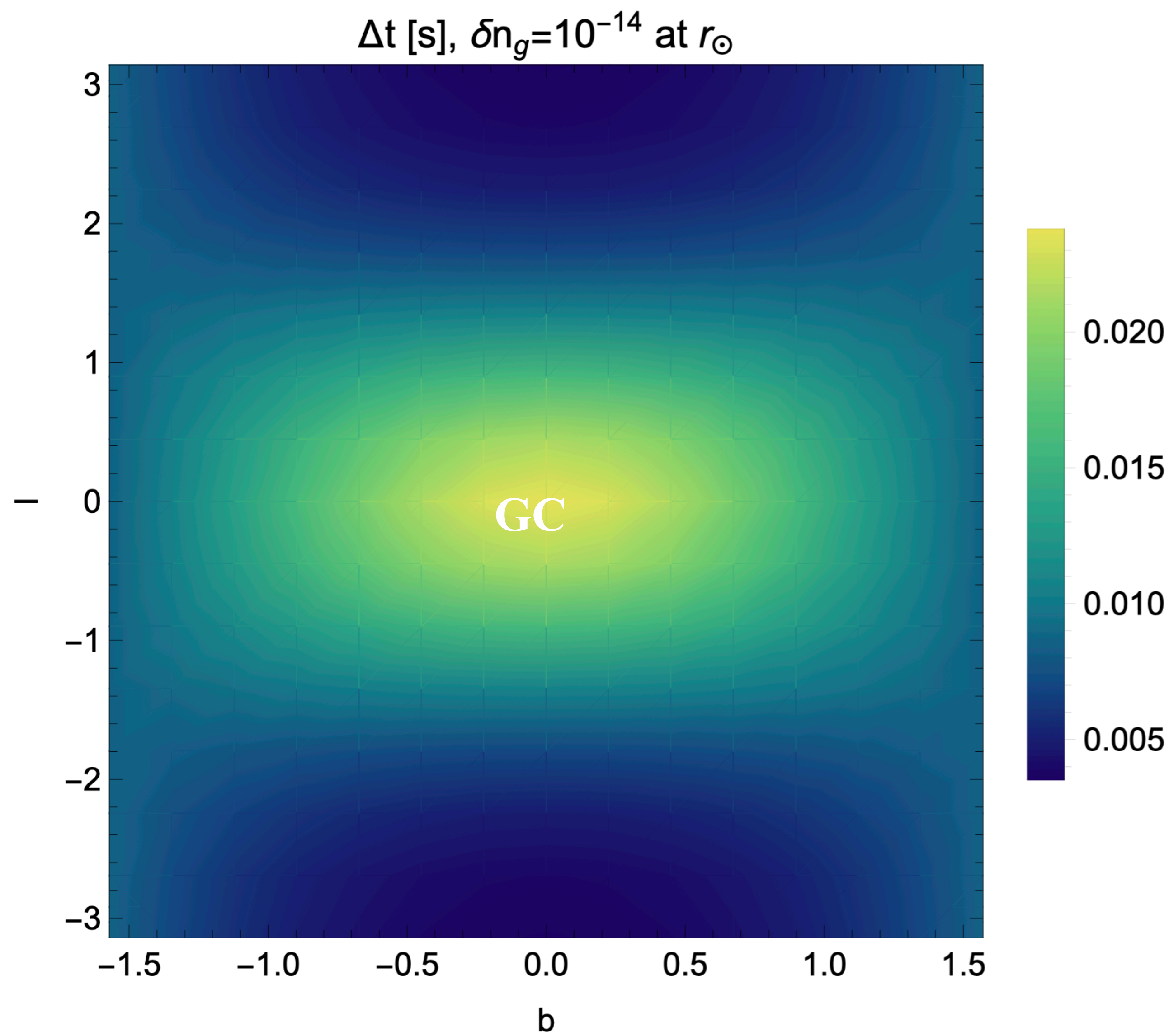
Signal: GW-photon timing



- Choose a neutron star merger event where both EM and GW emissions are observed.
- Compare time delay of the GWs compared with the speed of light (timestamp from photons)

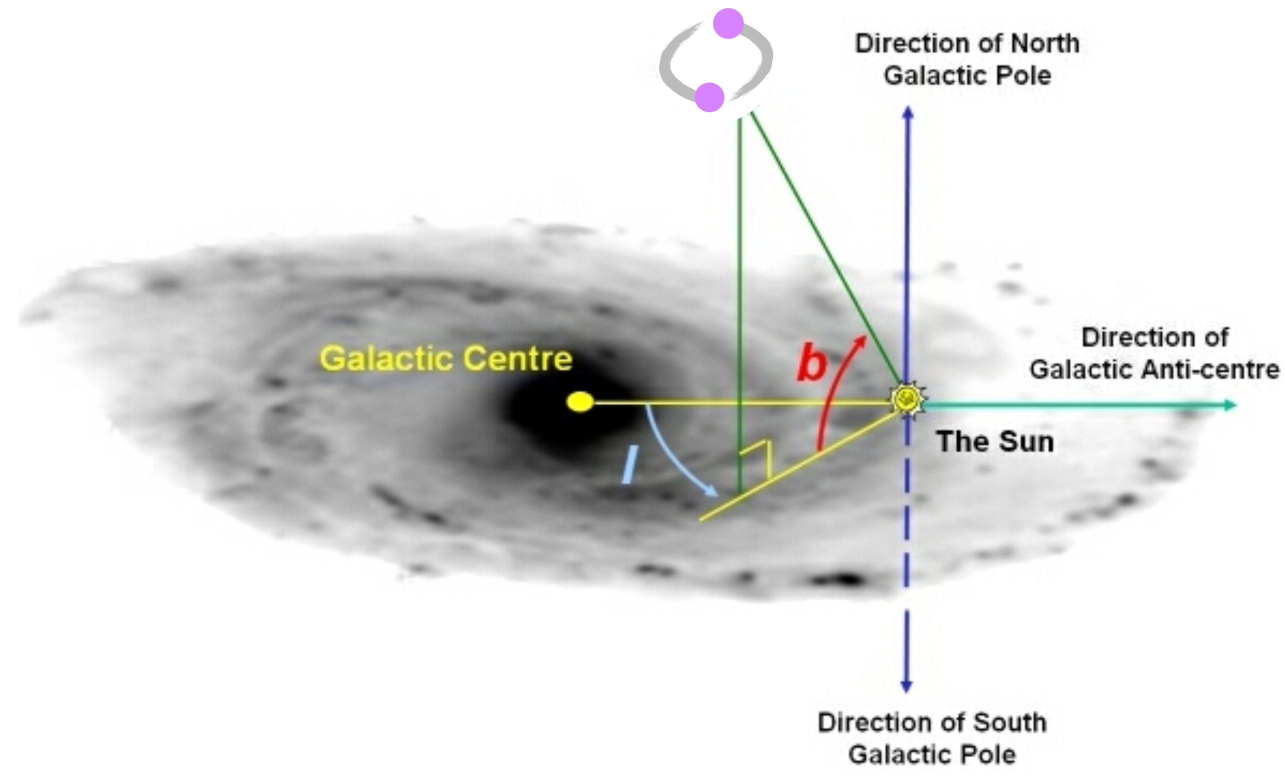
GW-photon timing

Timing delay between GW and photon from binary neutron star events at different directions



preliminary

galactic coordinarte



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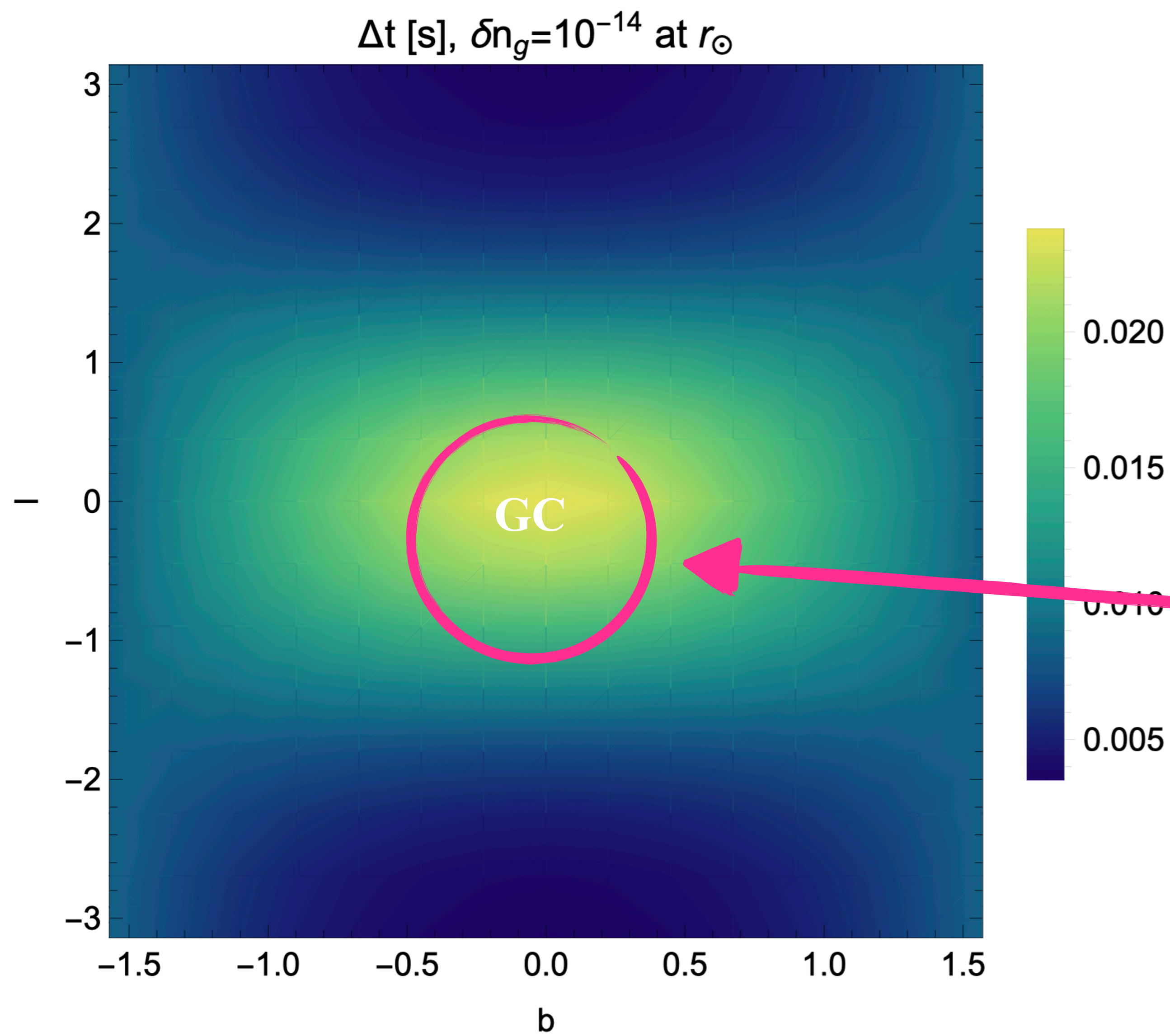

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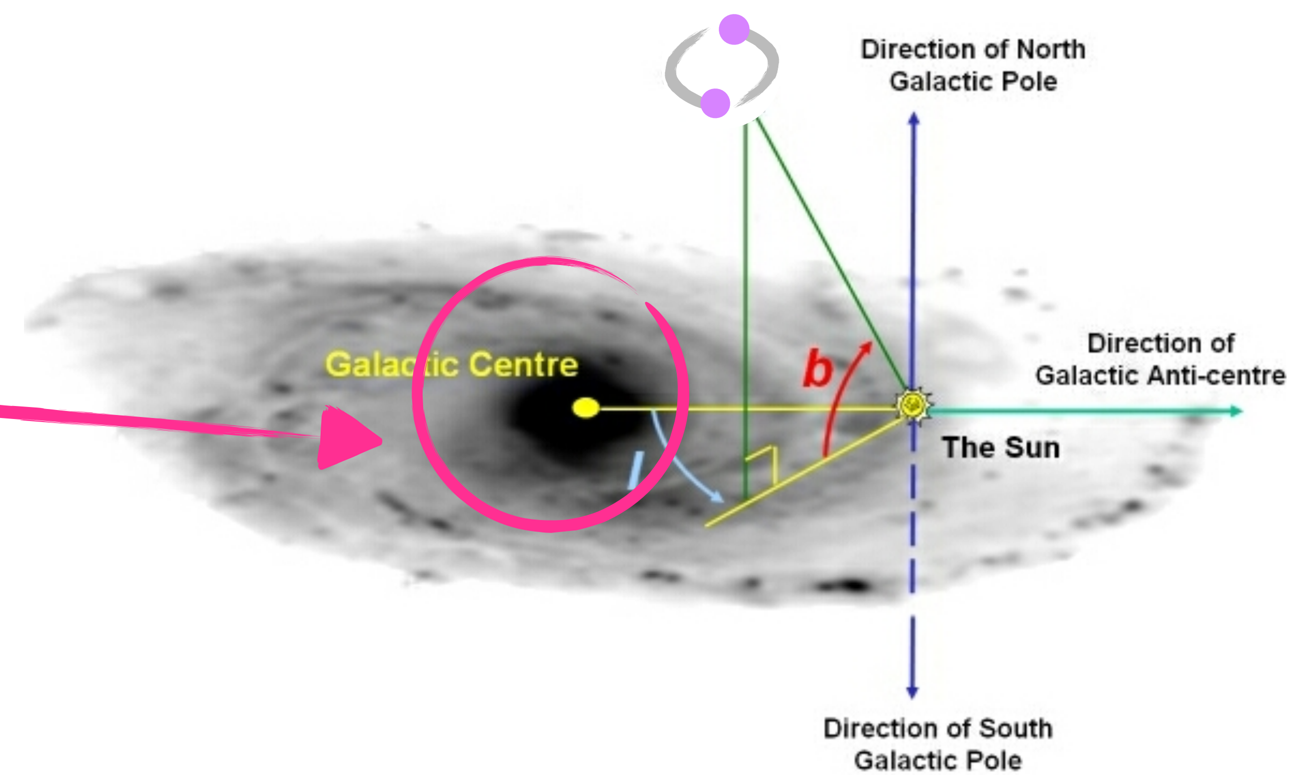

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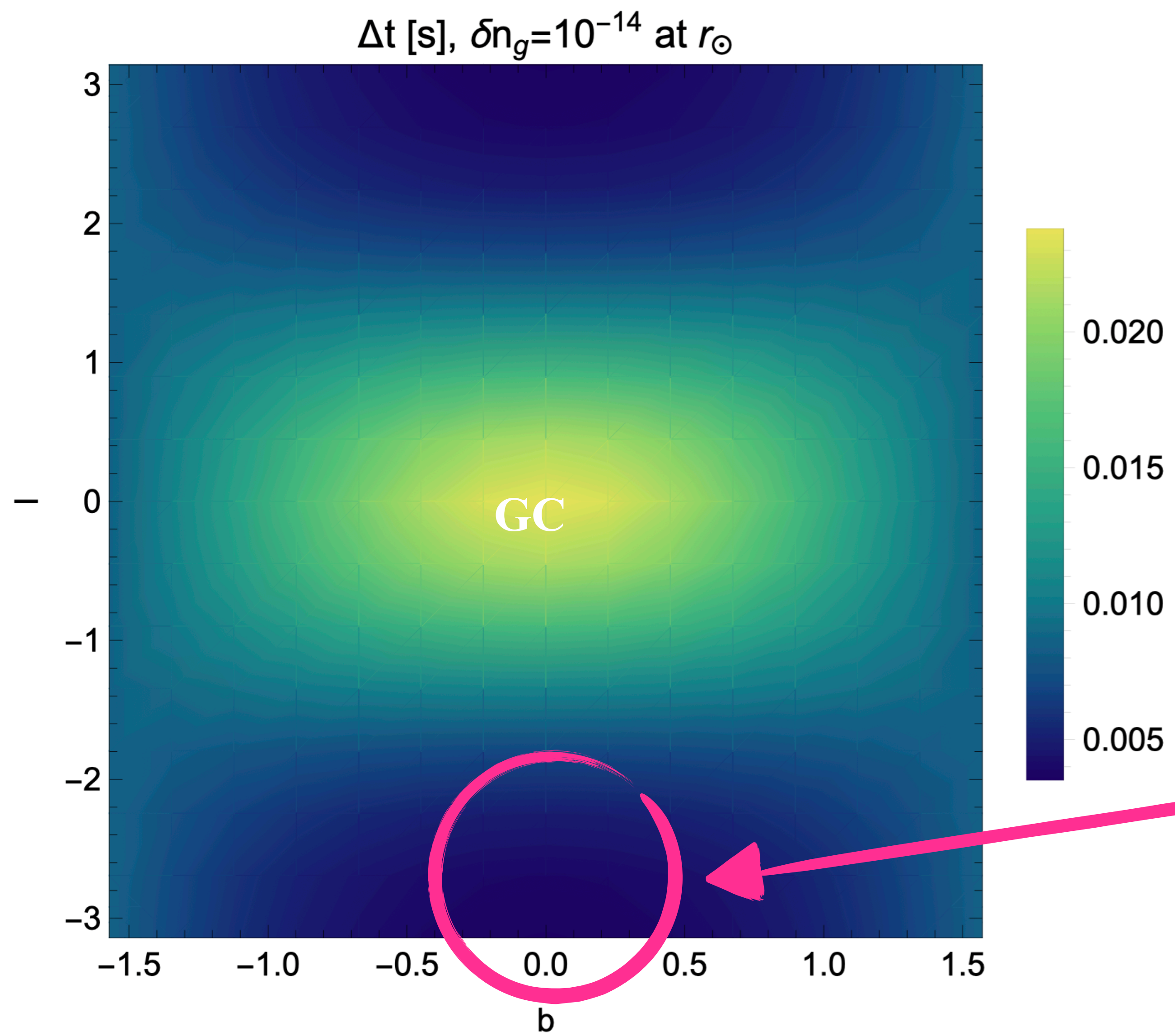

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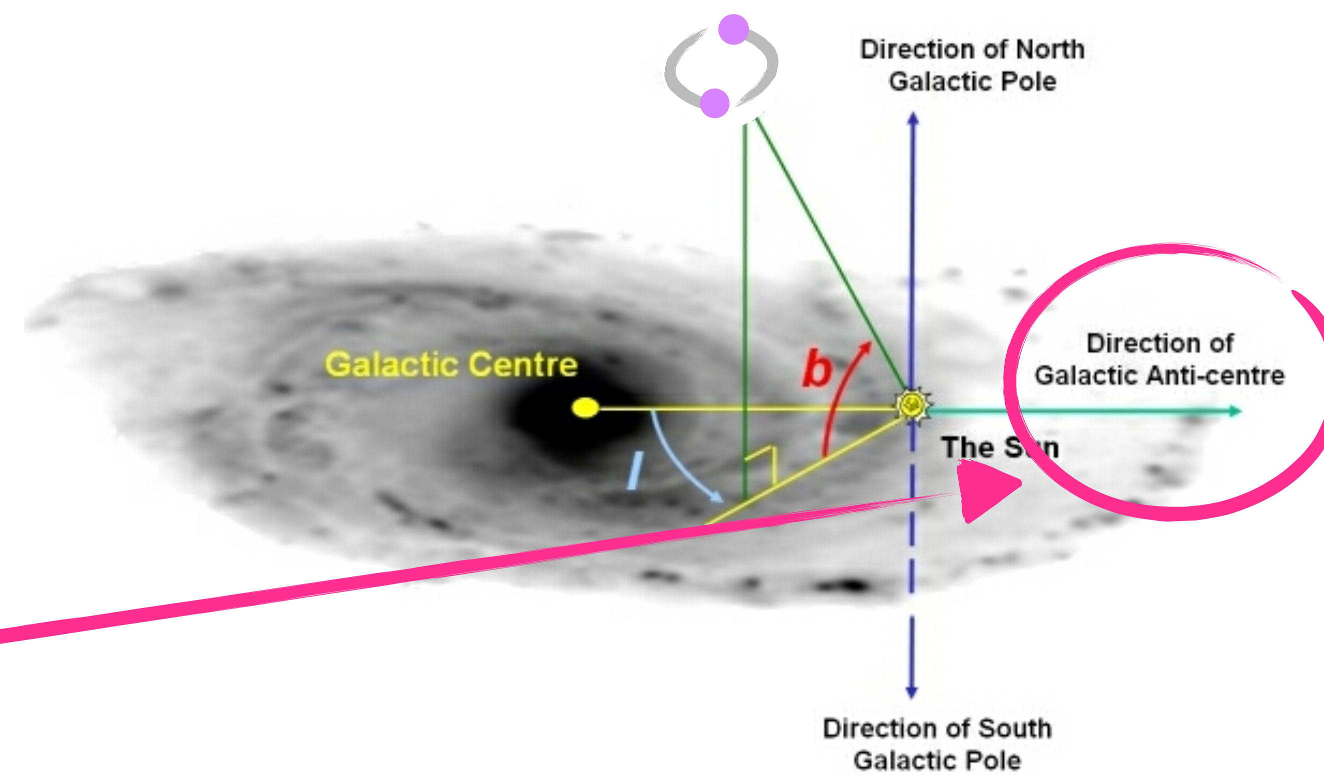

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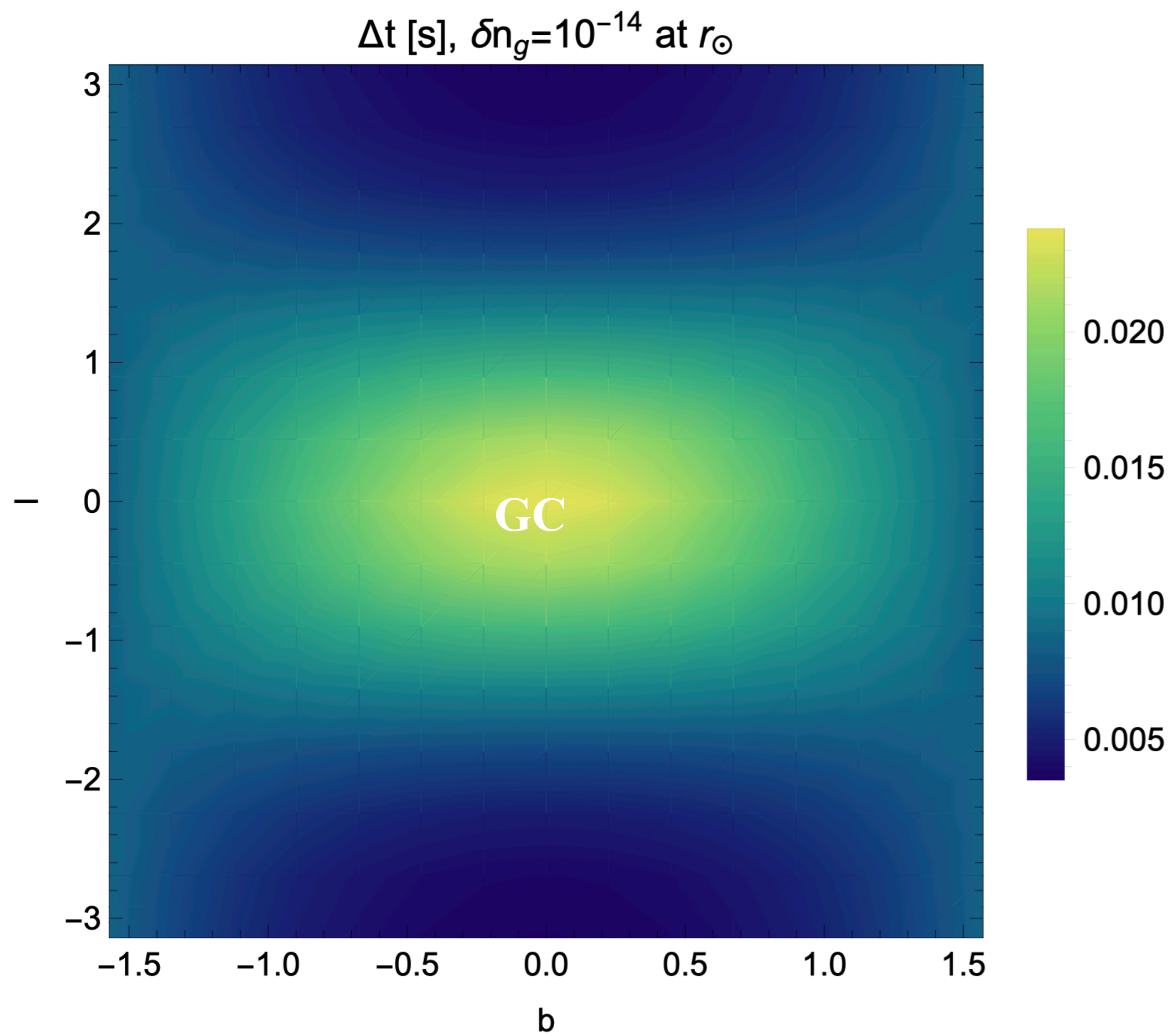
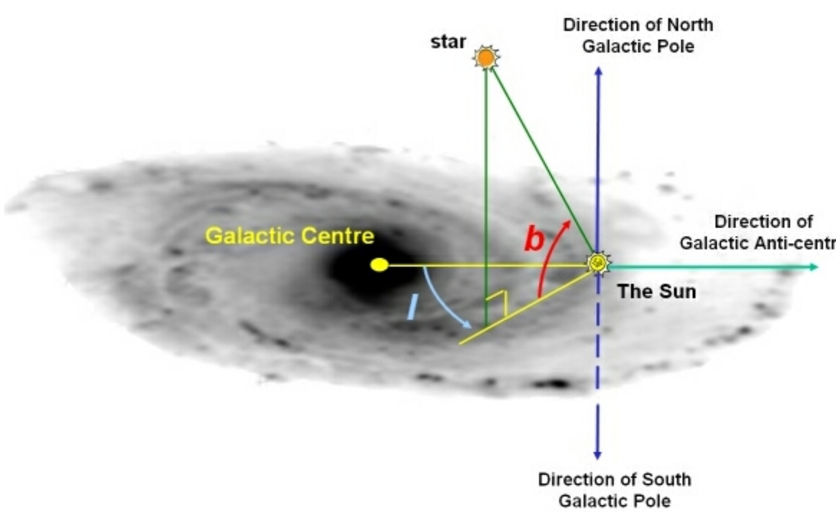


preliminary

For a BNS event from the direction (b,l), time delay is proportional to the integral of the DM density along the line-of-sight

$$\Delta t(b,l)\, h^4\, \omega_{\rm GW}^4 = \frac{x_\phi}{c} \int_0^{s_{\rm max}} ds\, \rho_{\rm BEC}(b,l,s)$$

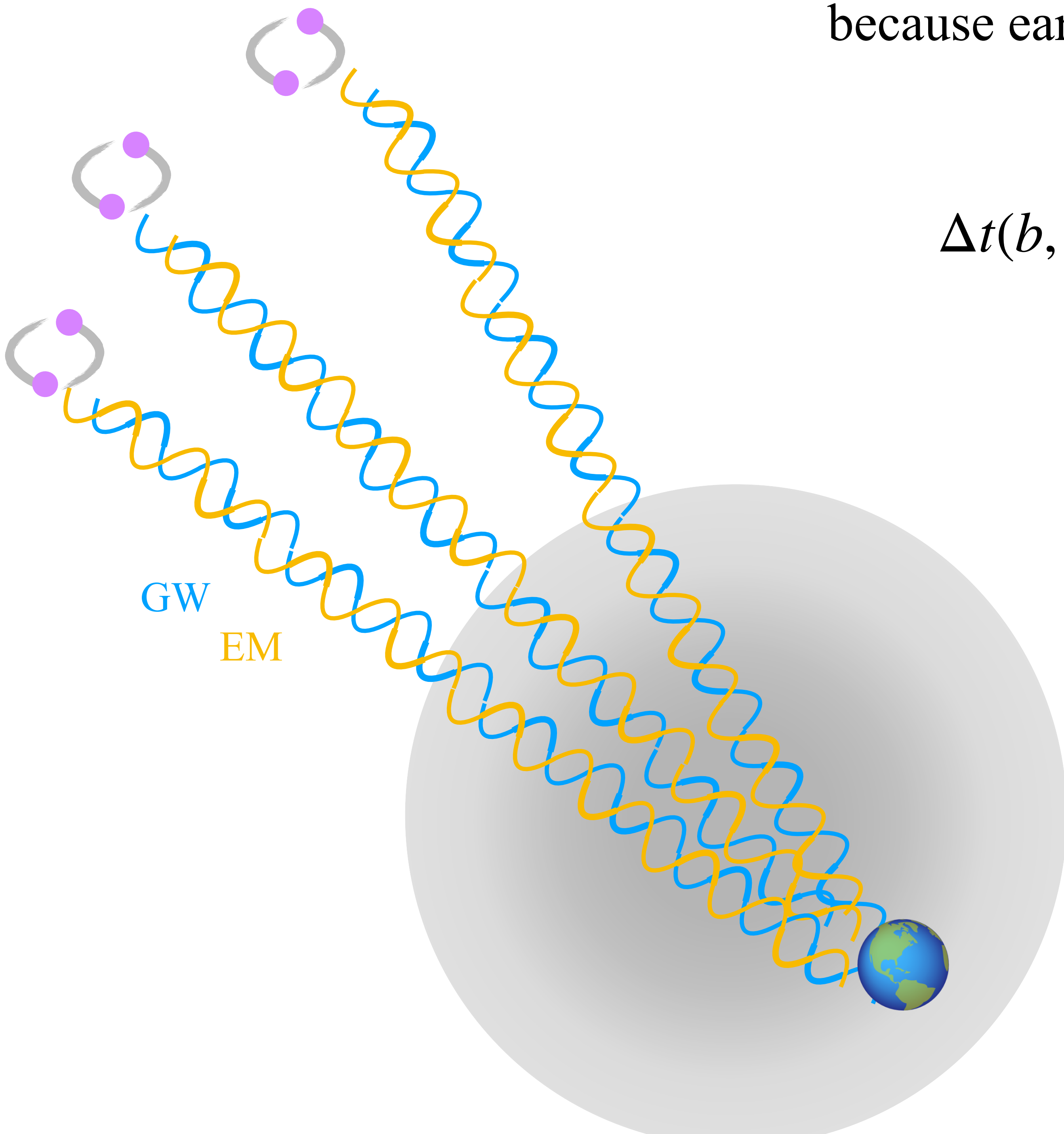


$$x_\phi \equiv \sqrt{\frac{3}{2}}\, \frac{3\, m^6\, \zeta(\frac{3}{2})^2}{8\, \pi\, \lambda^{\frac{3}{2}}\, M_{\rm pl}^6}$$

independent of DM density

Halo Tomography

Time delay of events from different directions are anisotropic because earth is not located at the center of the galaxy.



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line-of sight integral similar to the J-factor in indirect detection observation

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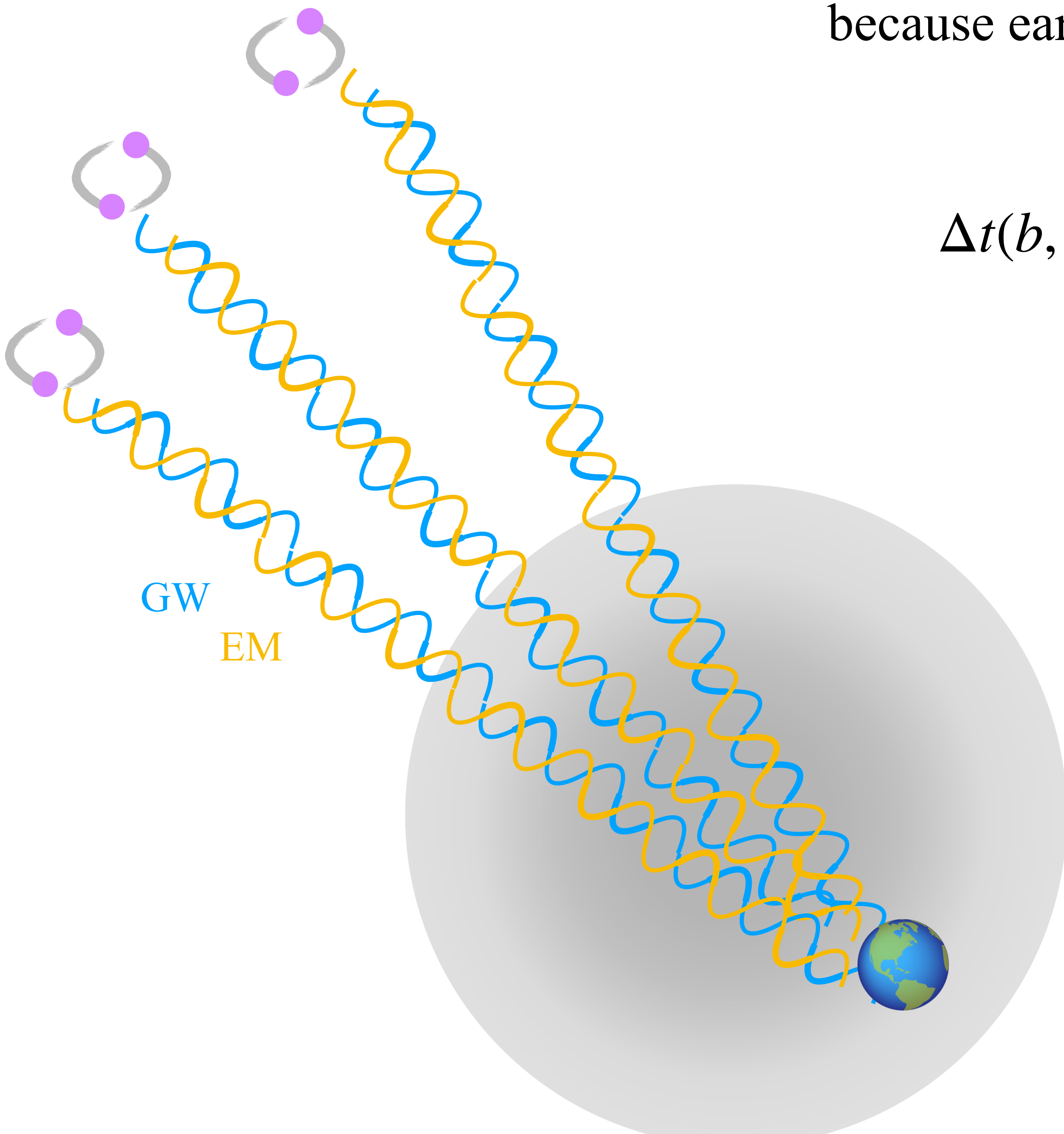

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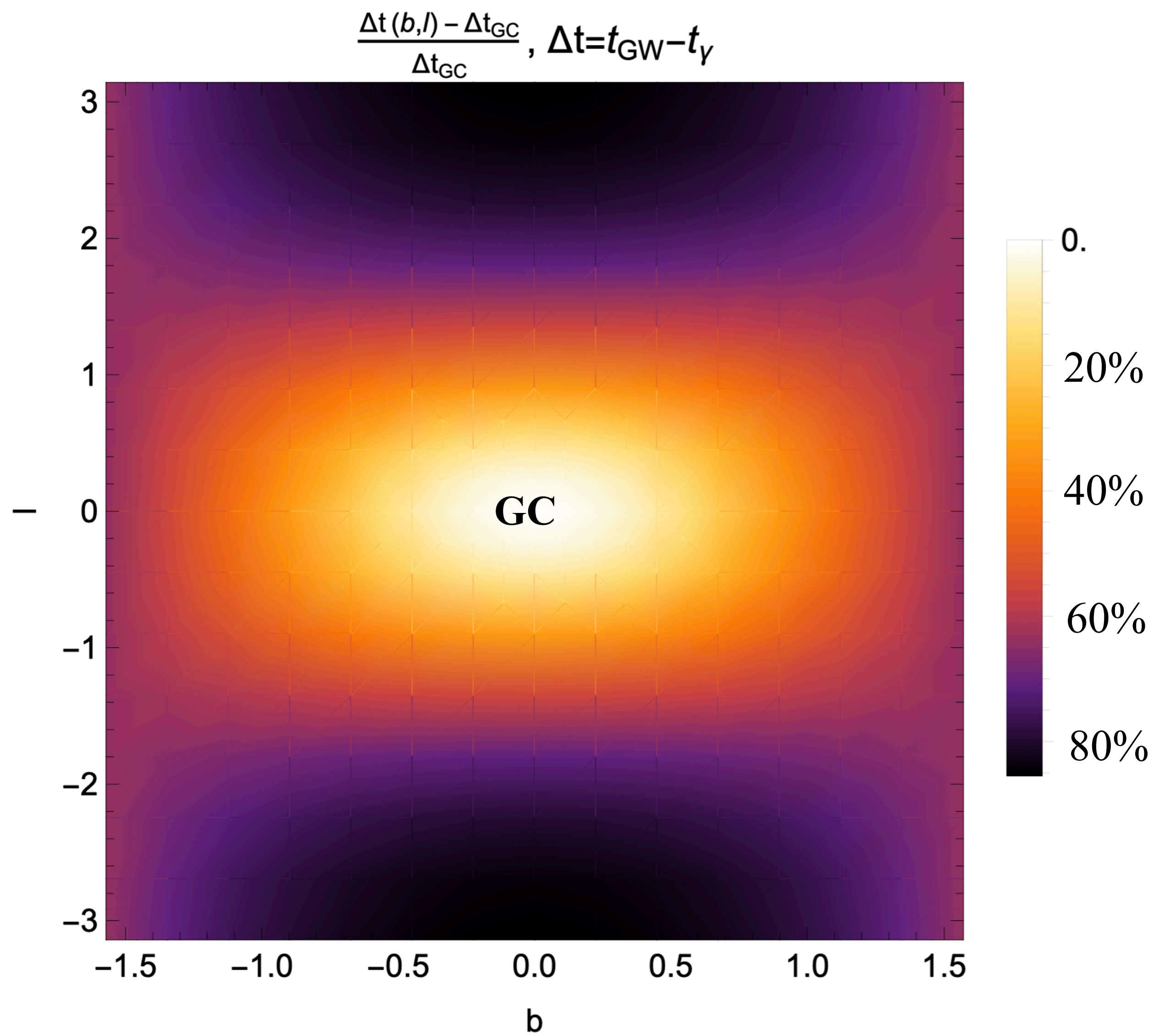
a new method to probe halo profile through comparing time delay of BNS events from different directions

Halo Tomography

Anisotropy of time delay
(percentage compared to the GC direction)



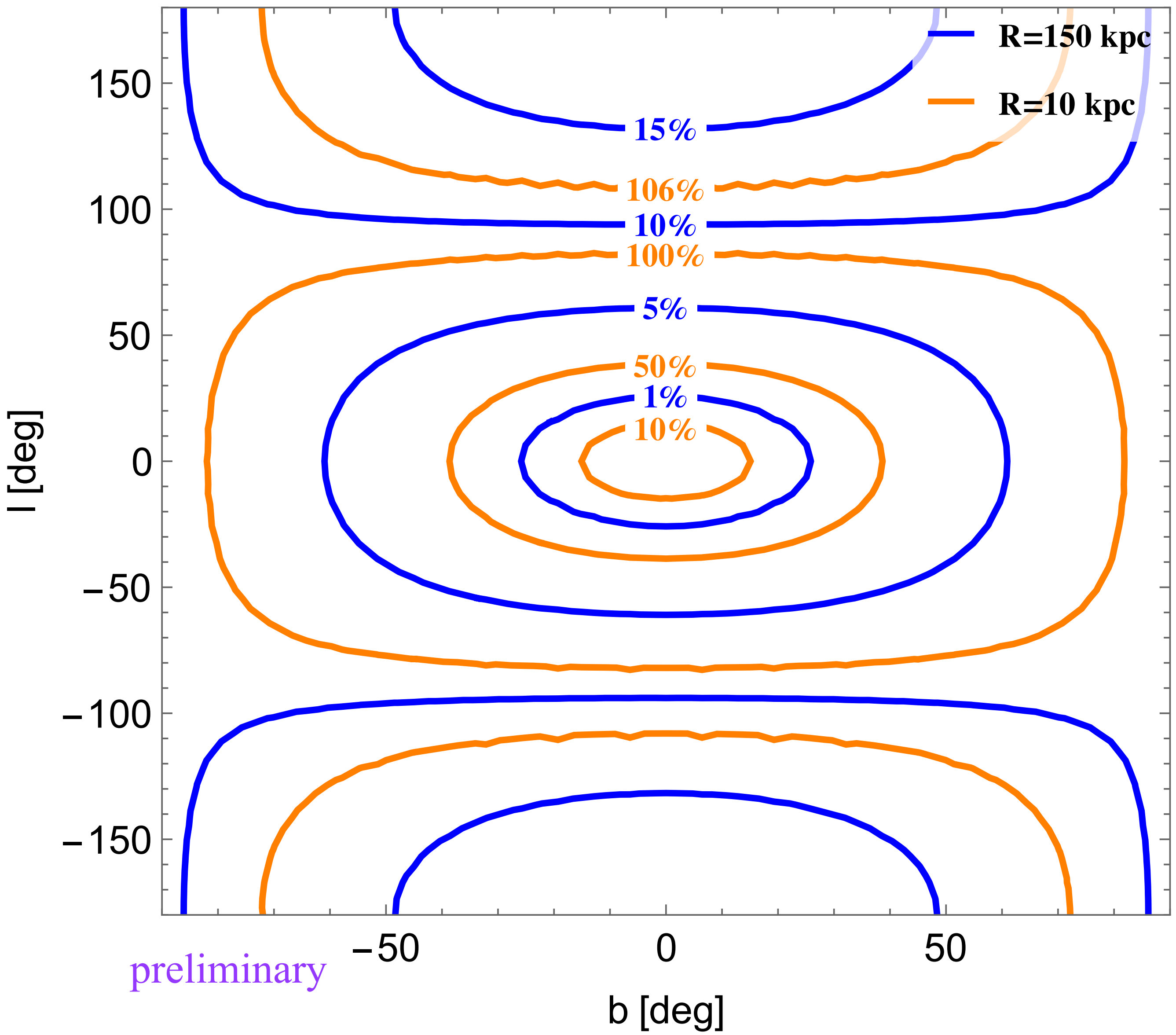
preliminary

$R = 20$ kpc

- Largest time delay coming from GC direction—higher DM density
$$\Delta t \propto \rho_{\rm BEC}$$
- $\mathcal{O}(10\%)$ deviation from the GC direction can be seen within a set of binary NS events.
- Feature of DM-induced effects from the correlation to the MW halo.

Halo Tomography

Choose different halo profile



- The anisotropy also depends on the halo density profile, especially the characteristic radius scale R.
- Larger anisotropy is observed for a smaller $R = 10$ kpc value; but $\mathcal{O}(10\%)$ effect still available with $R \simeq 150$ kpc.

Halo Tomography

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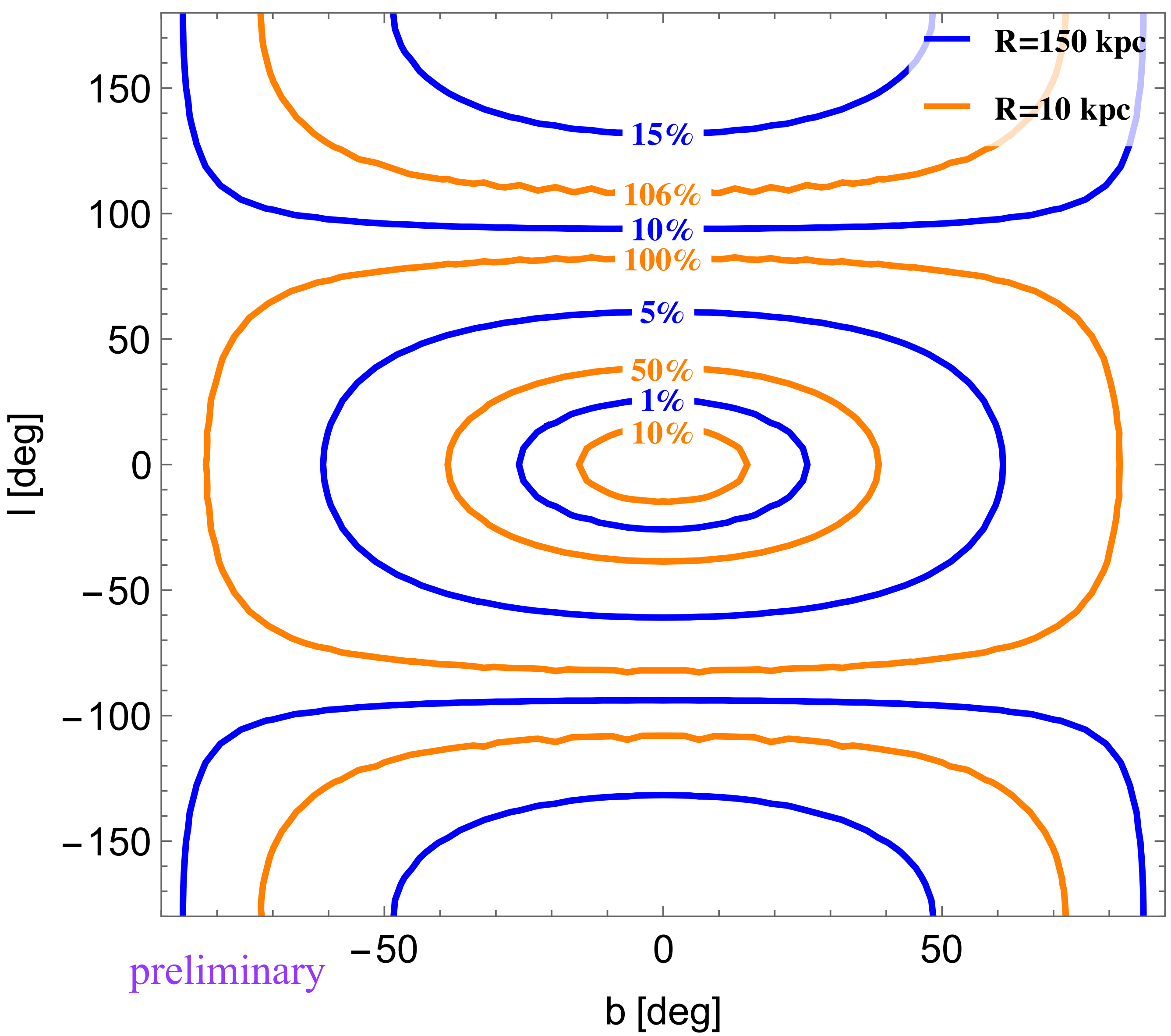

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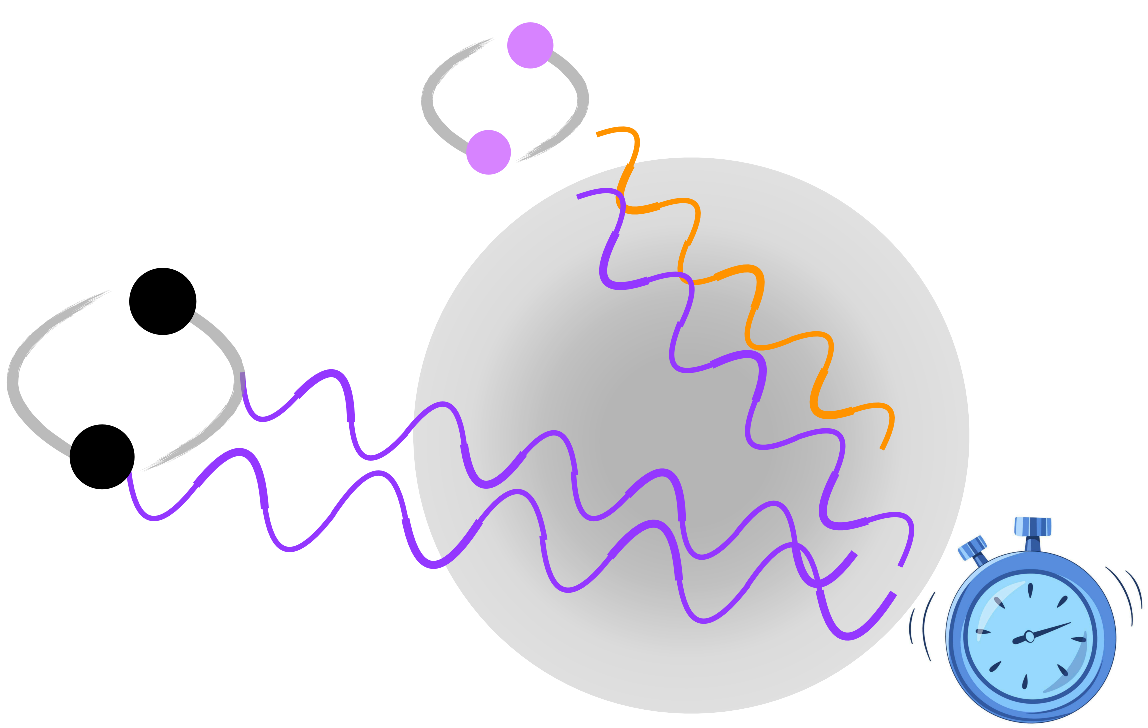
- Larger anisotropy is observed for a smaller $R = 10$ kpc value; but $\mathcal{O}(10\%)$ effect still available with $R \simeq 150$ kpc.
- Time delay effect can still be induced when the wave DM relic abundance is a sub-fraction of total DM. New method to probe the wave DM component.
- Precise timing and localization of future GW observation and GRB observation are needed.

Summary

- Gravitational Wave astronomy opens new opportunities to probe new physics with precise measurements of the GW timing and localization.
- Propagation of GWs in the DM halo can probe the nature of DM. Wave DM can induce an effective refractive index for GWs, which causes a delay in the arrival time of GWs.
- We study time-delay between GWs of different frequencies and strain strengths, and time-delay between GW and EM waves. If positive signals are detected, the directional distribution measures the DM halo density profile.



Thank you!