Dark Matter in the Time of Gravitational Waves

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University of Oklahoma

work in preparation, with collaborators
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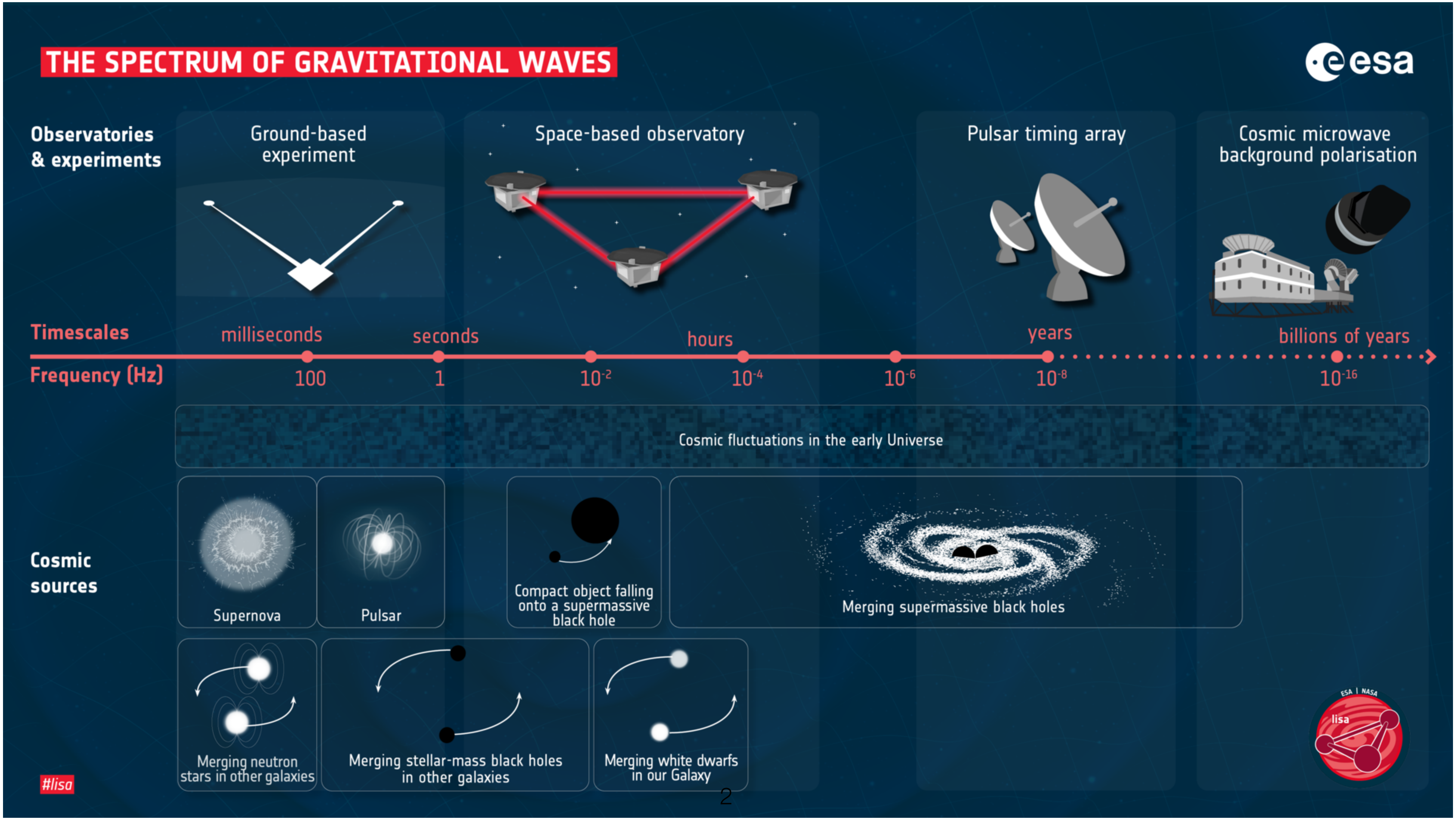
CETUP*
Lead, July 01, 2024

Gravitational Wave Astronomy

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



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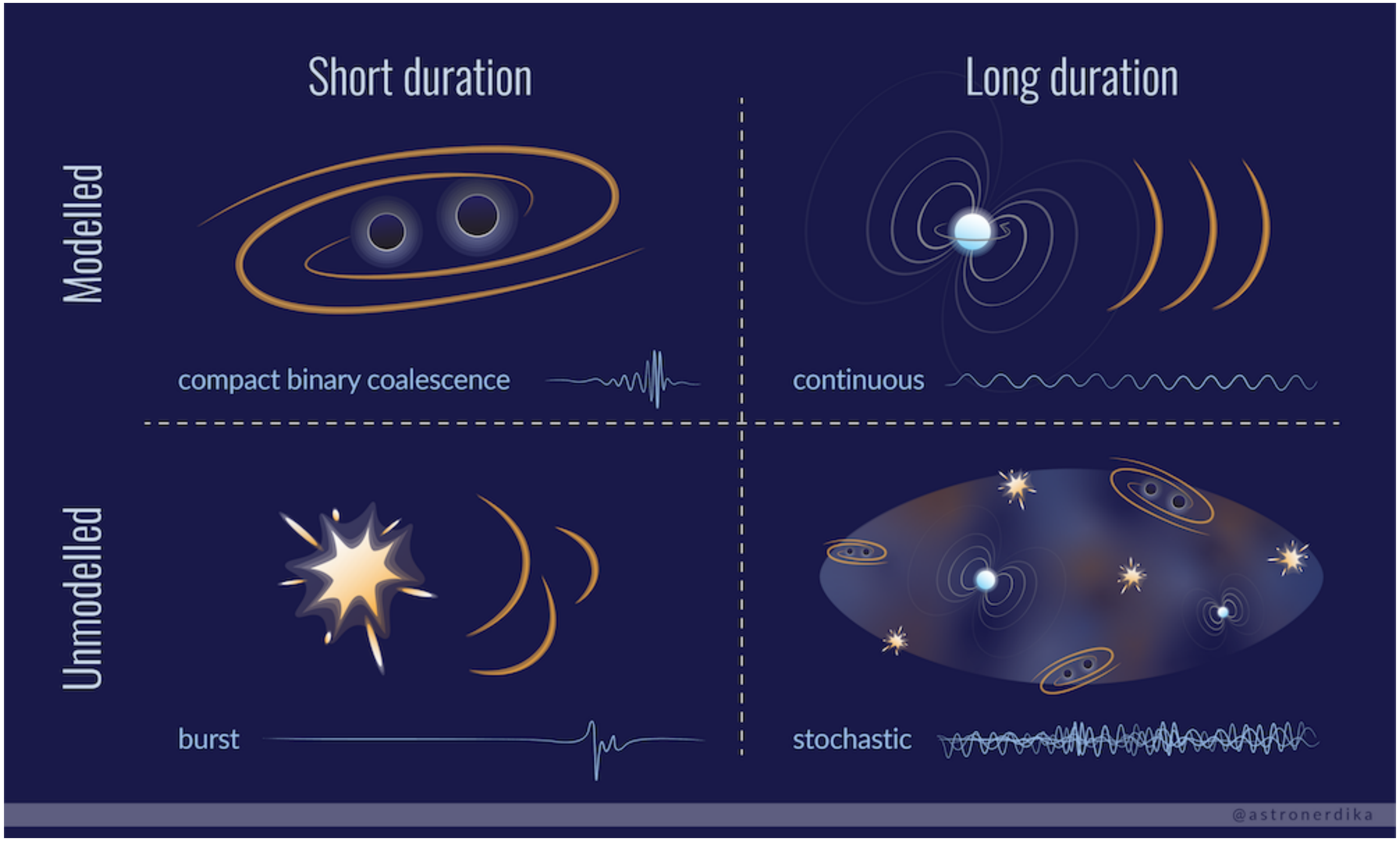
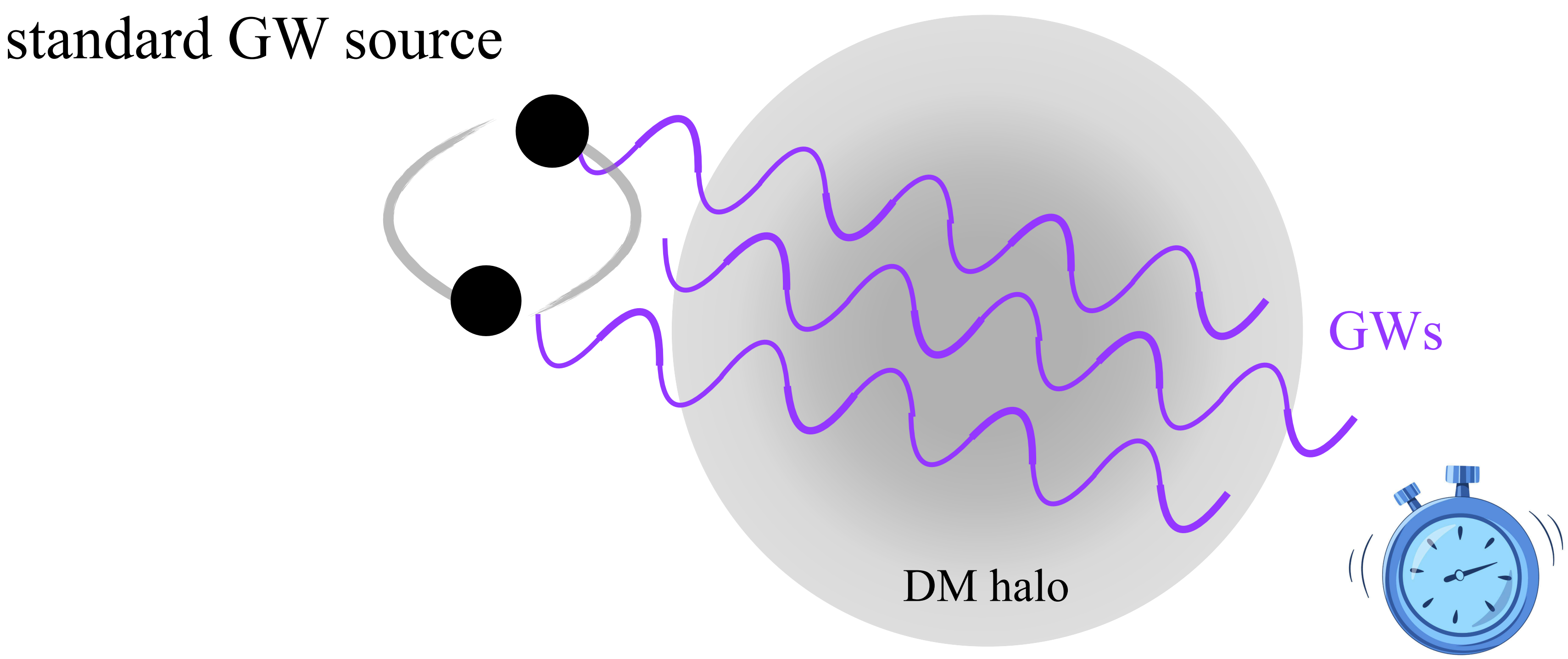


- GW messenger can pass regions that are opaque to electromagnetic waves, thus carry information from early universe and dense environments.
- GWs can be detected alongside multi-messenger counterparts
- GWs are measured with **time-domain** information.

Propagation Effect

We can use GW to probe new physics that modifies
the propagation of GWs — probing properties of the DM halo



this talk focus on
the arrival time of GWs

Propagation Effect

- The viscosity from DM halo is studied for the effect in reducing the intensity of GWs by modeling the DM as fluids.

G. Goswami. G.K. Chakravarty, S. Mohanty, A.R. Prasanna
PRD (2017)

- For DM mean free path smaller than the GW wavelength, the DM system is effectively described by collisionless matter.

R. Flauger, S. Weinberg, PRD (2018)

- The dominant effect on GW propagation is the change in GW velocity. The effect is proportional to the kinetic energy density of the local DM. Suppressed for non-relativistic CDM in the late universe.
  * Warm DM and primordial GWs leads to stronger effects, but still below the detection limit.

- The propagation effects can also be generated by massive graviton model, and wave DM model. ***This talk will focus on wave DM.***

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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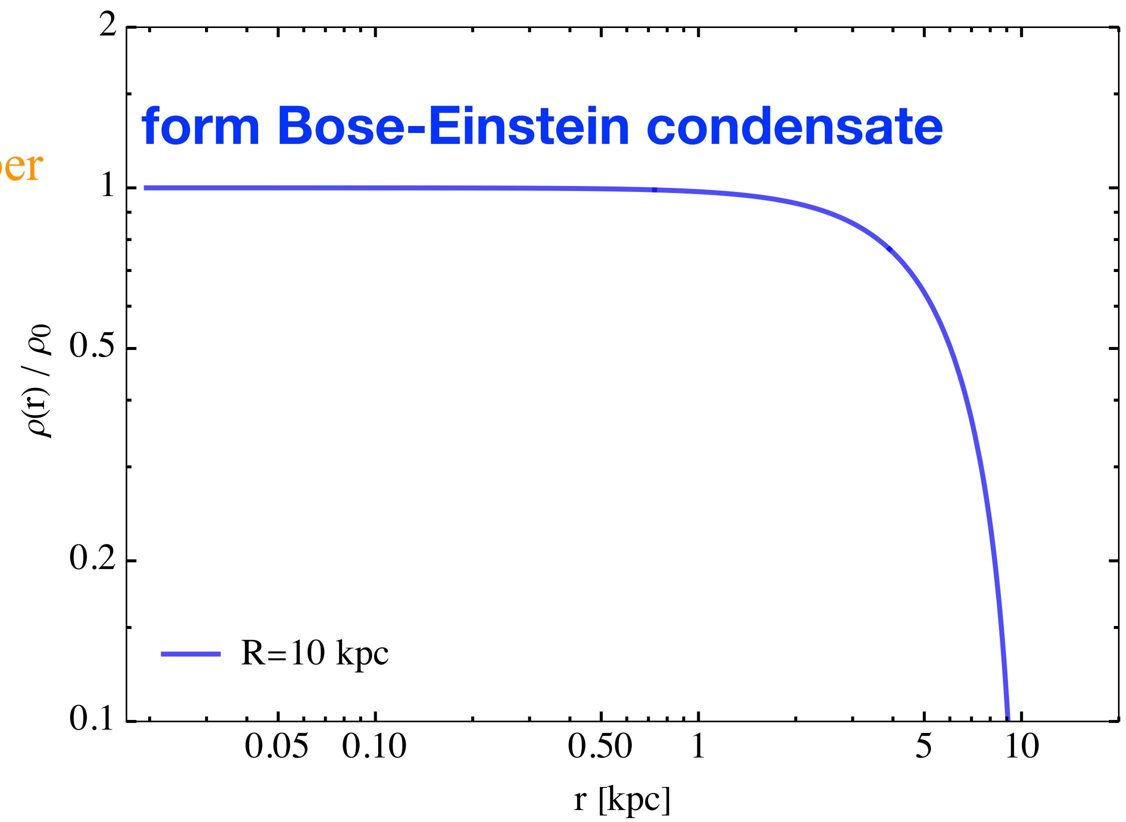
Density profile:

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

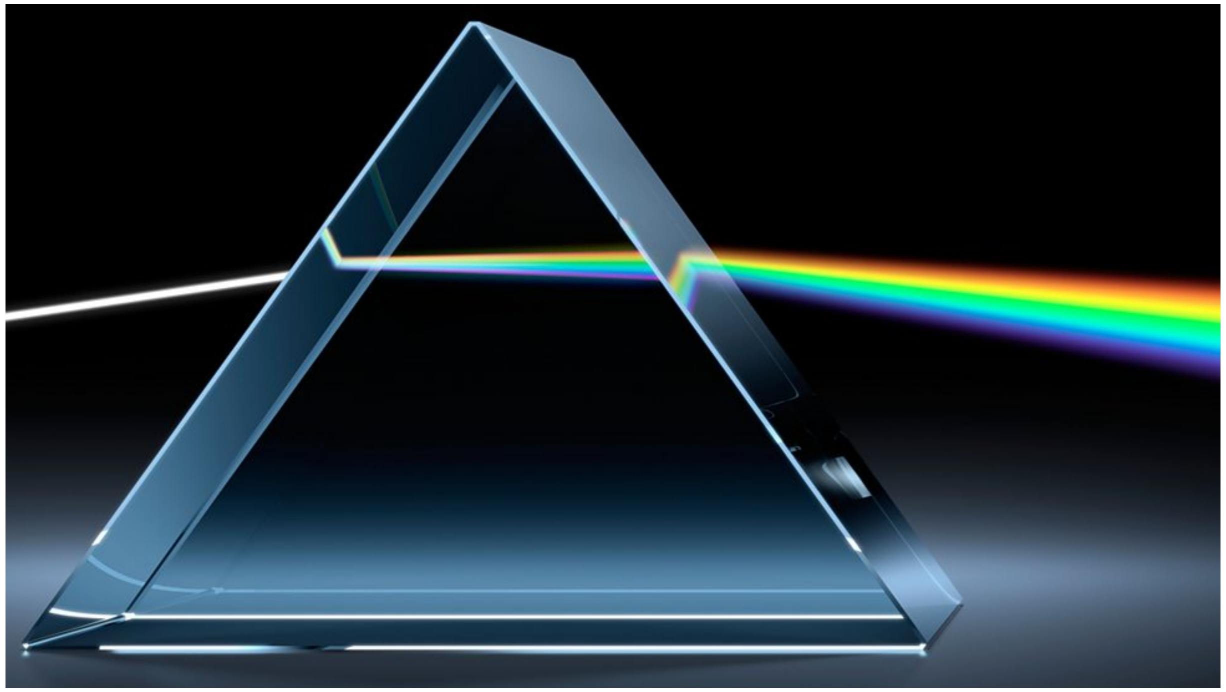
$$R = \frac{\pi M_{pl}\sqrt{\lambda}}{m^2}$$



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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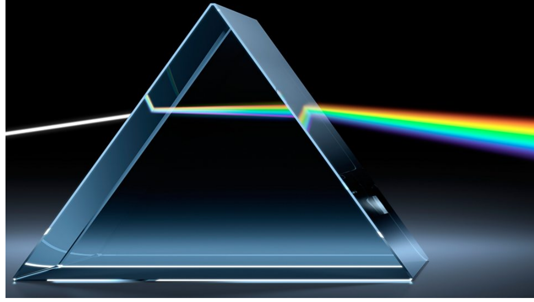

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Effectively, GWs get a modified refractive index $n_g > 1$ when in the BEC halo

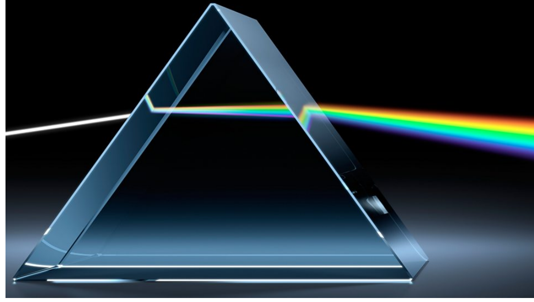
DM mass & density

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

coupling

GW strain and frequency

In-medium effect



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coupling   GW strain and frequency

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

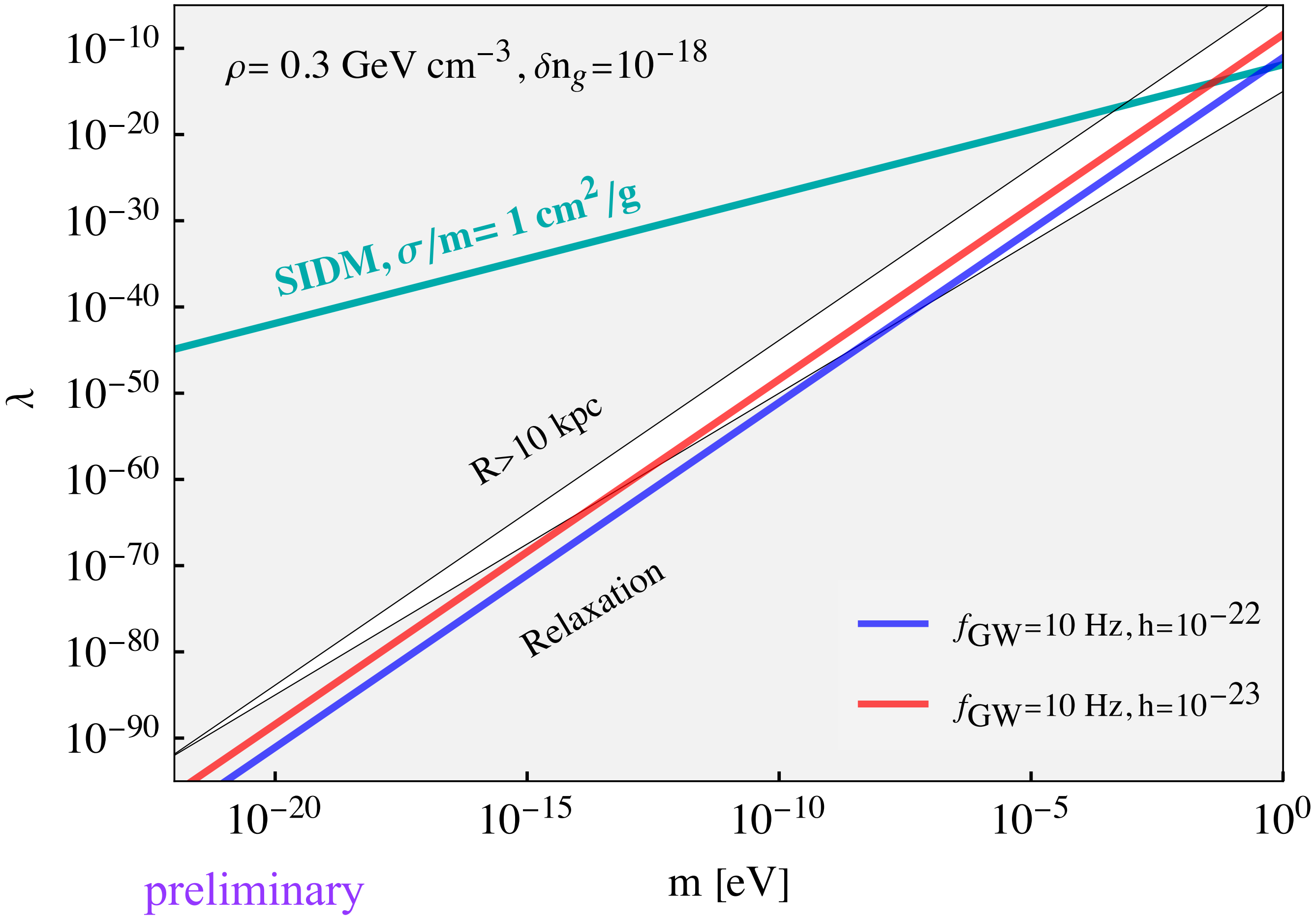
$$v_{\mathrm{GW}} = \frac{c}{1 + \delta n_g} < c$$

→ 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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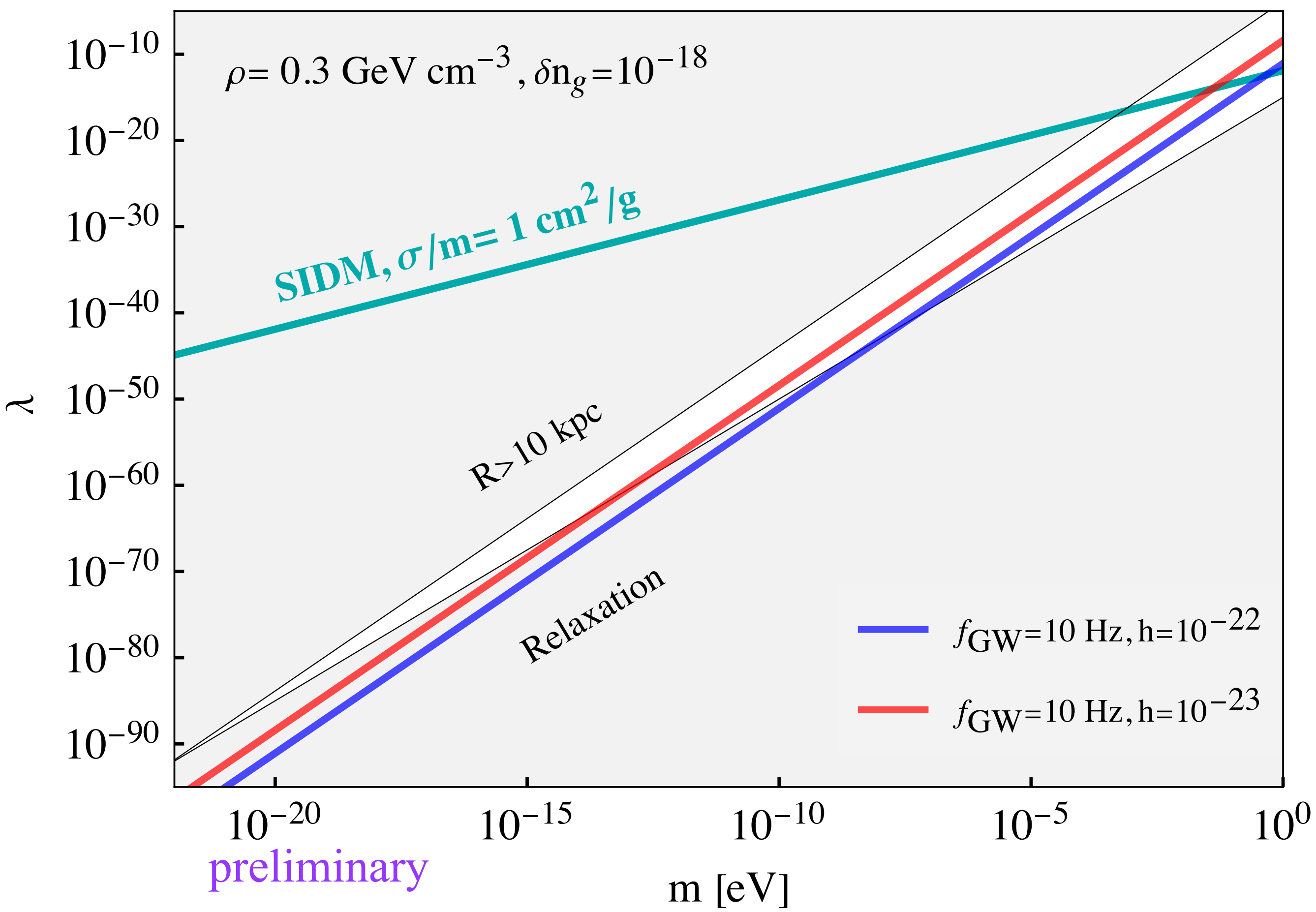

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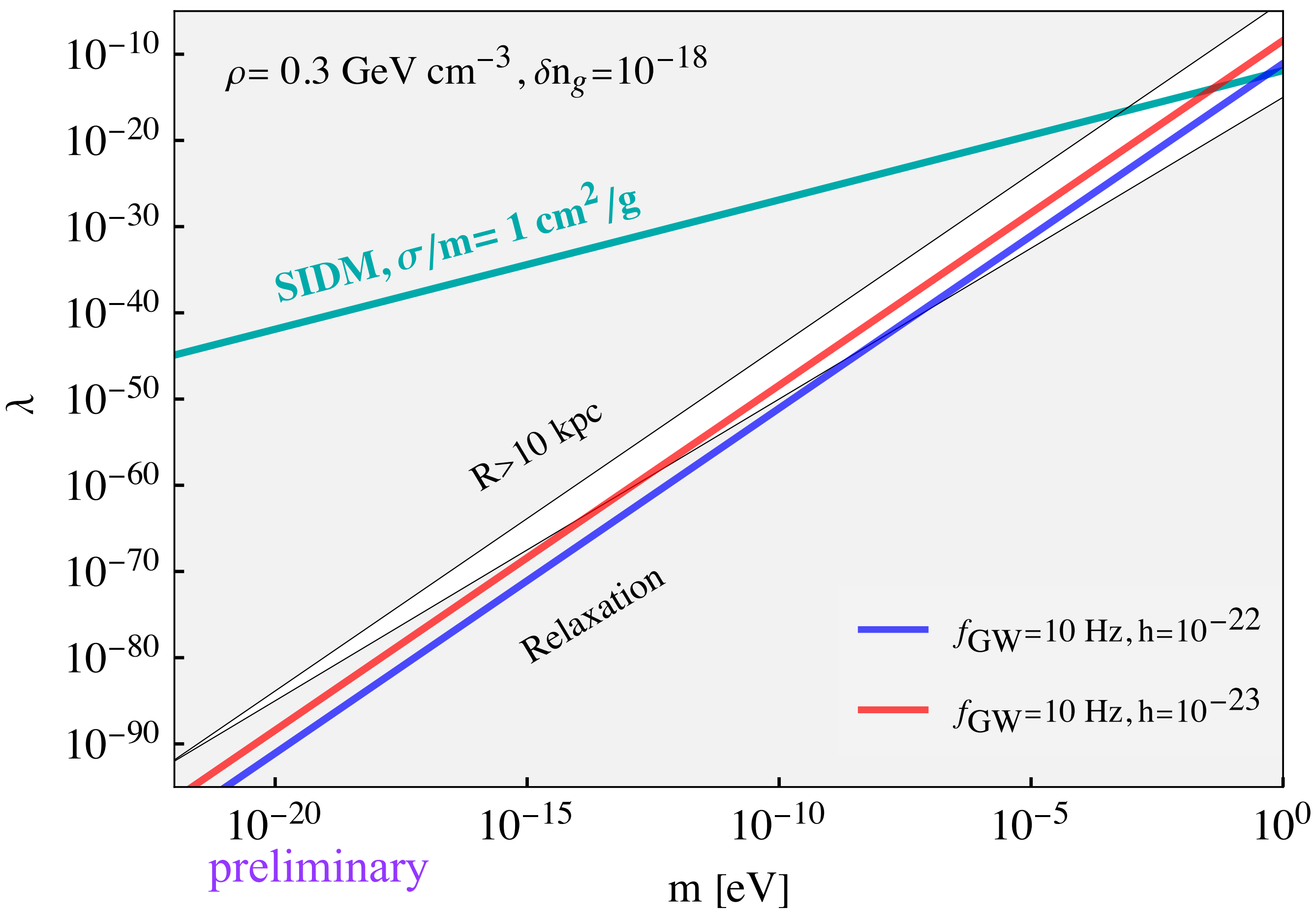
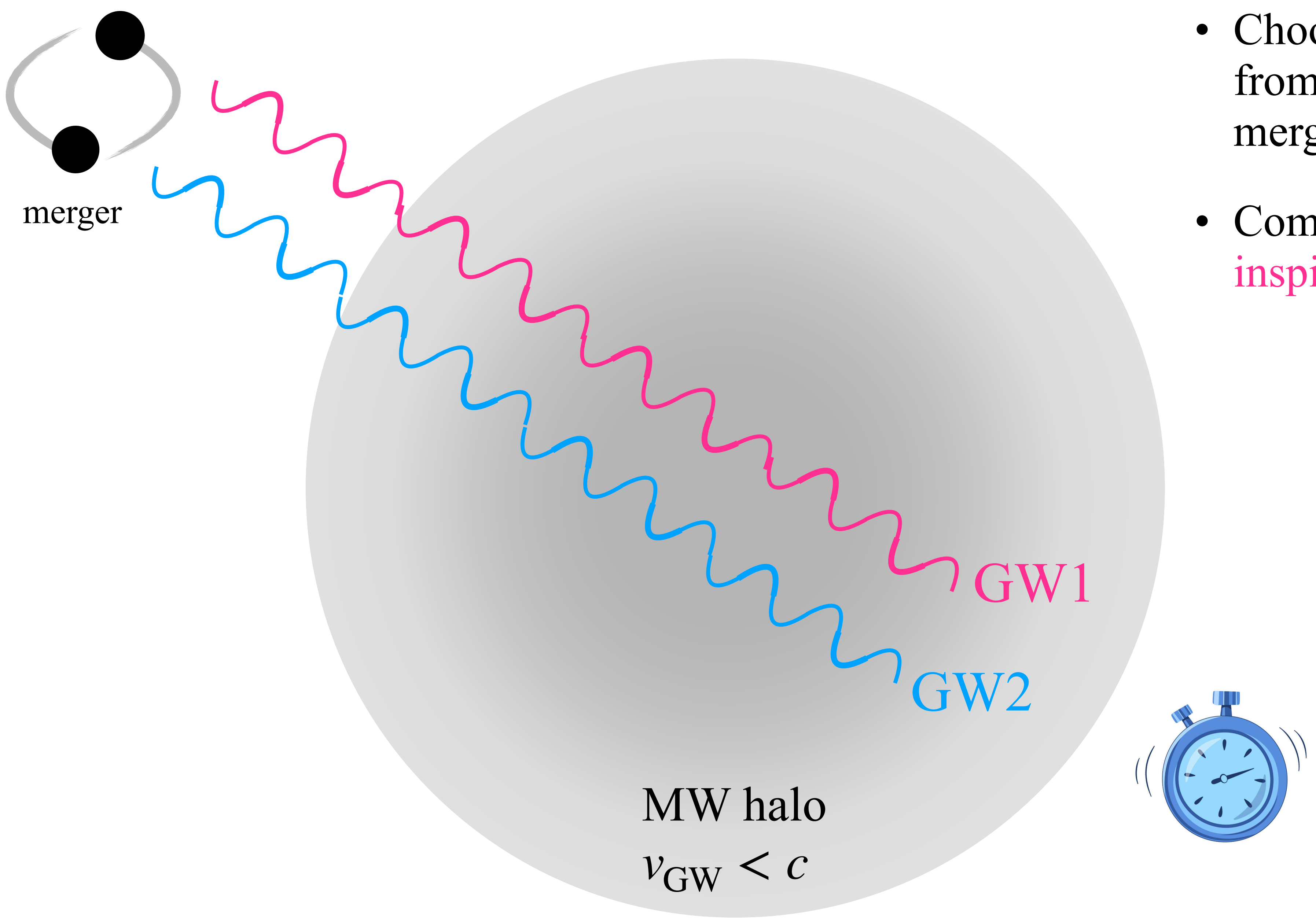


- $\lambda > 0$ is needed for repulsive interactions, but a large λ suppress the time delay effect.
- *top-left:* the core size can be too large to fit dwarf galaxy observations. *Might be alleviated for sub-fraction DM.*
- *lower-right:* the relaxation time scale is longer than the age of the Universe.

$$\lambda > 10^{-15}\left(\frac{m}{\rm eV}\right)^{7/2}$$

Viable parameter space for the modification of GW velocity.

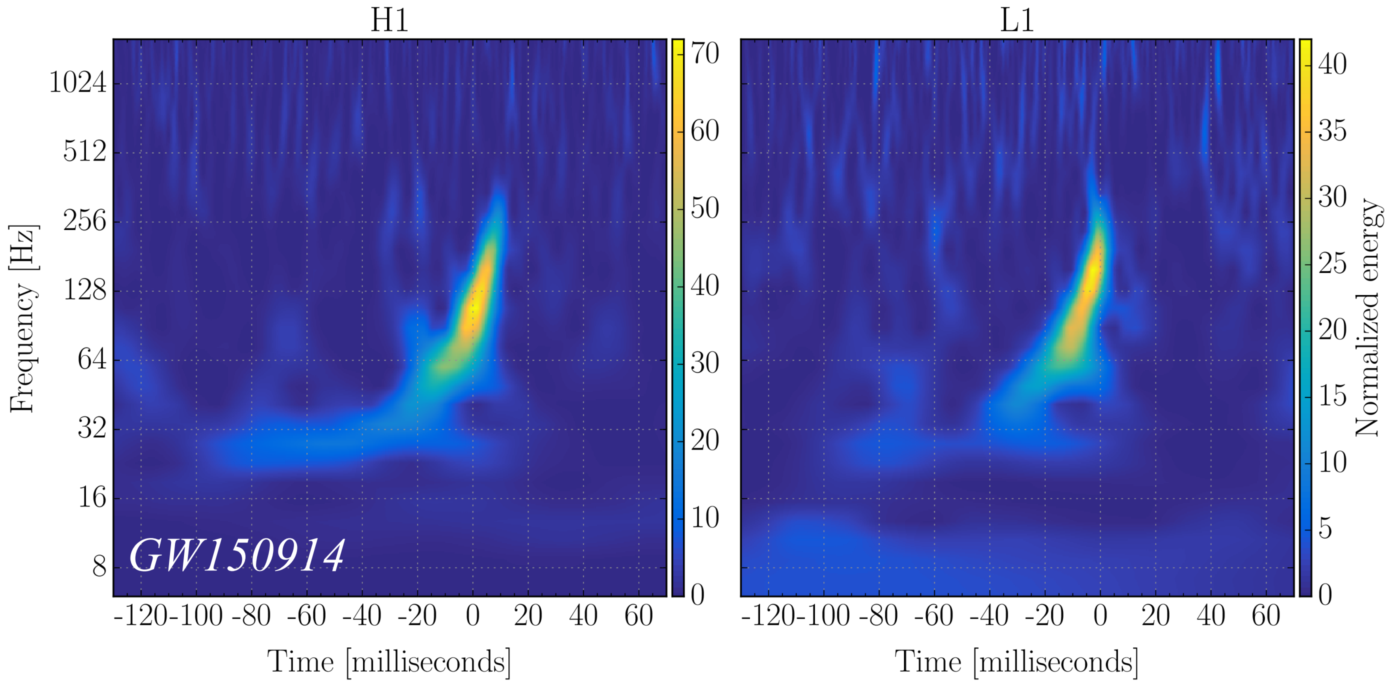
GW-GW Timing

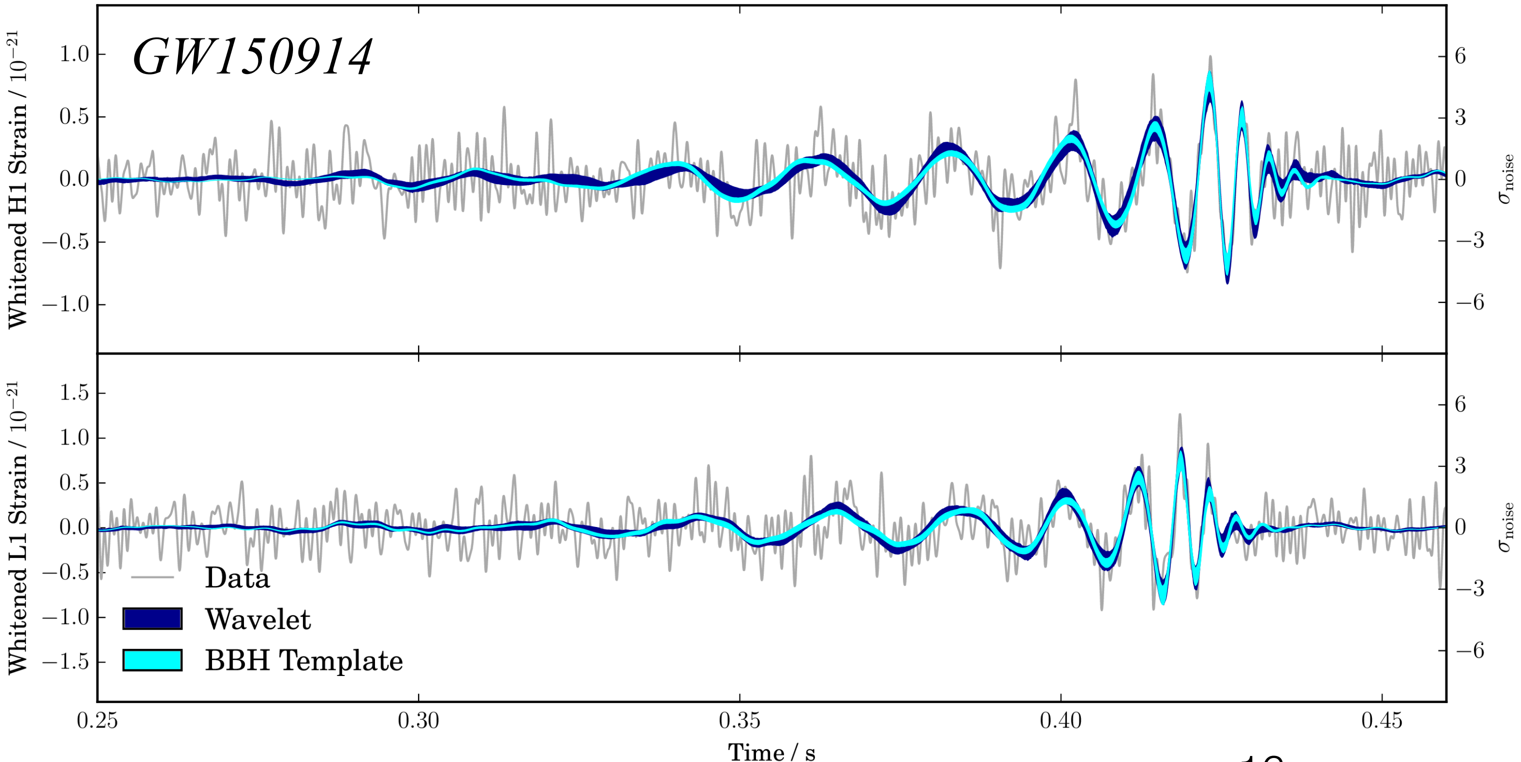


- Choose a binary event where GWs from the inspiral phase and the merger phase are observed.
- Compare time delay between the inspiral GWs and the merger GWs.

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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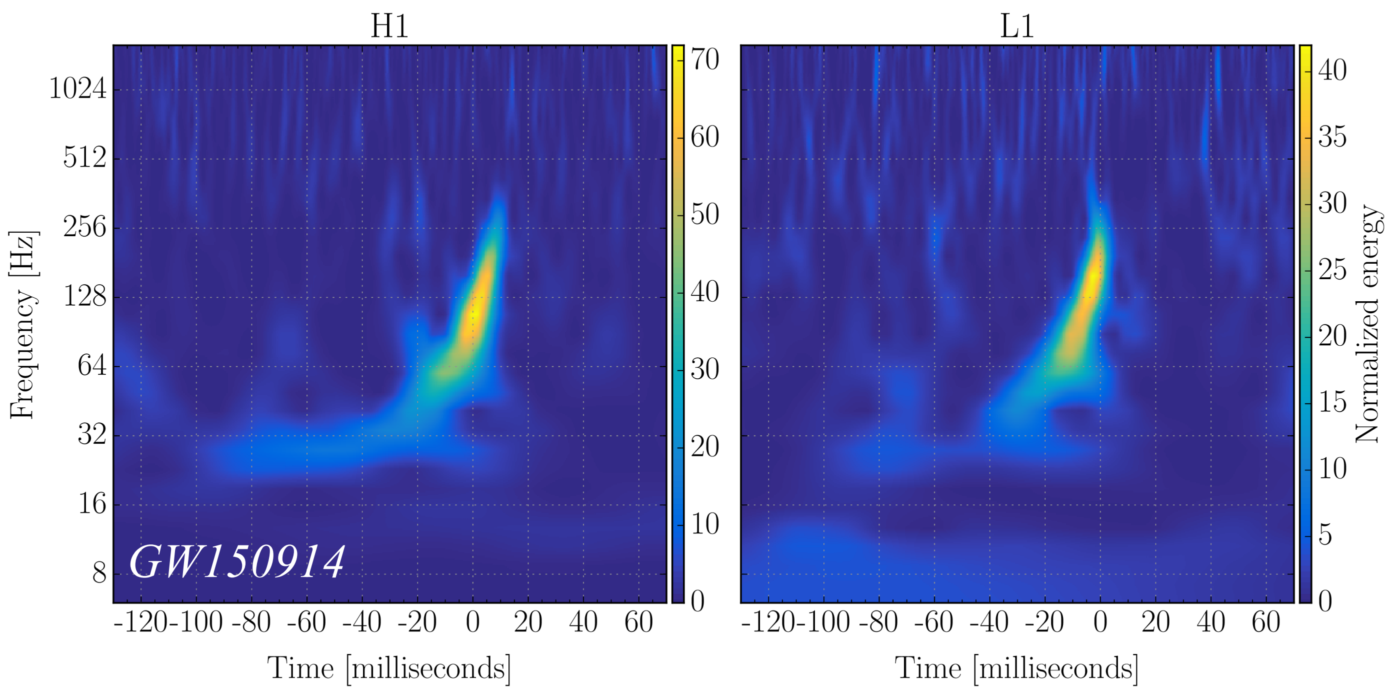

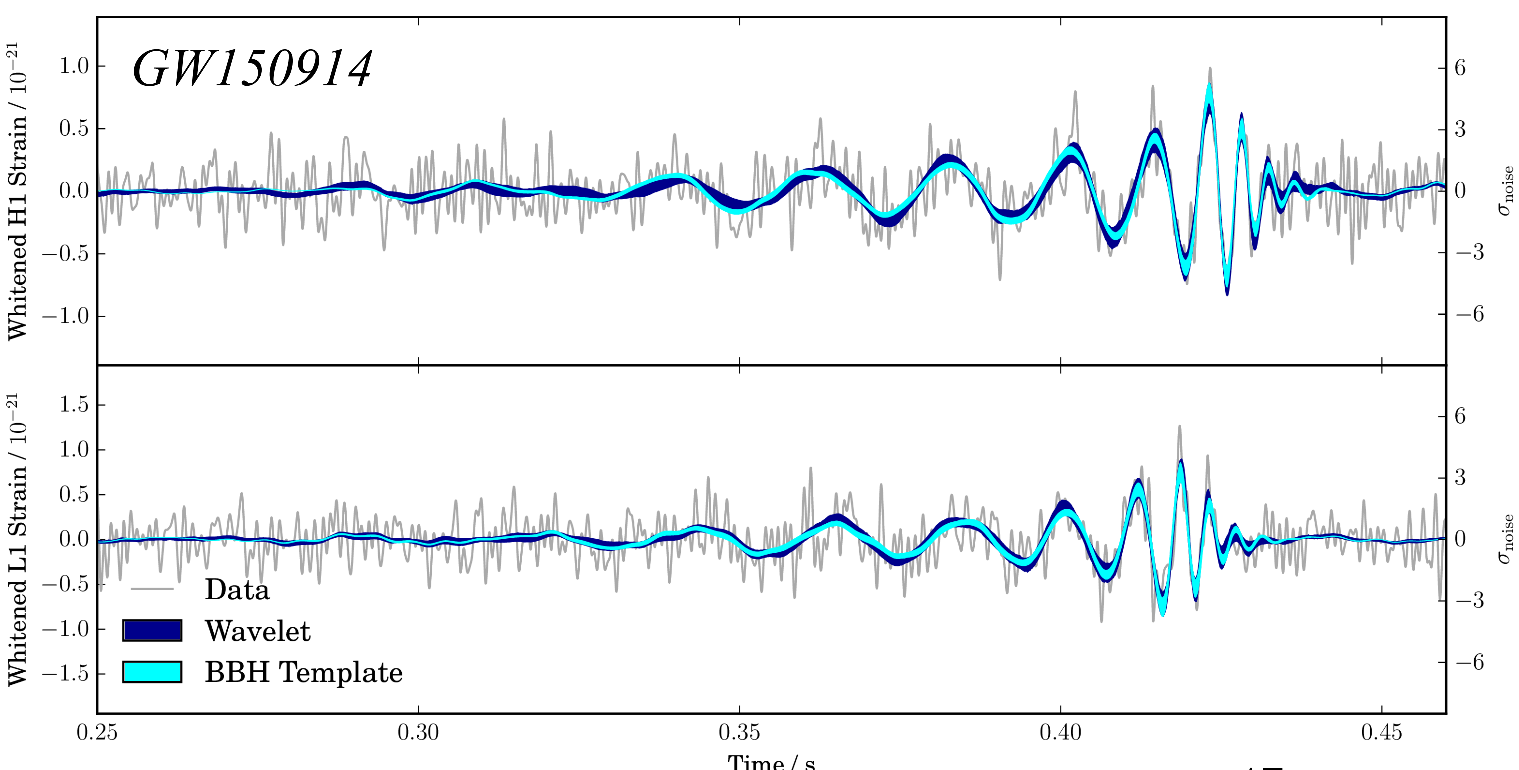

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- Since $\delta n_g \propto h^{-4} f^{-4}$, the wave DM effect is stronger (more time delay) in the inspiral phase, compared to the merger phase.

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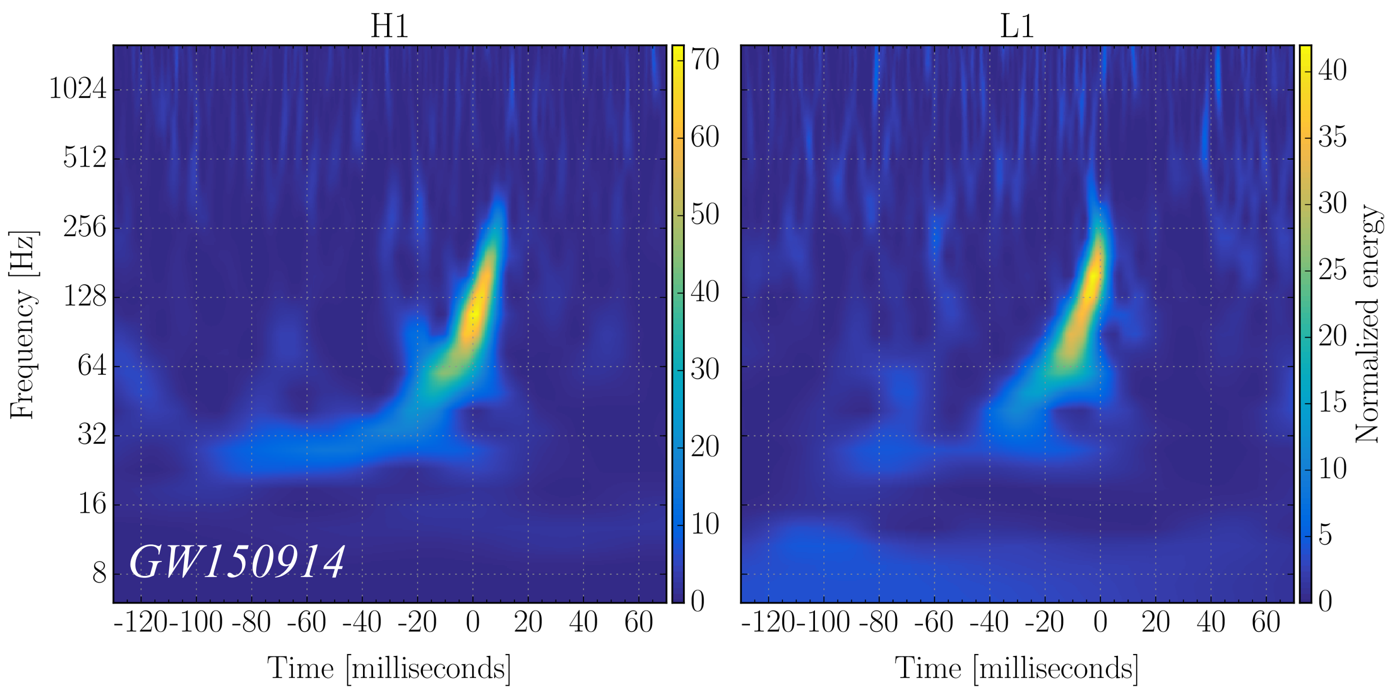
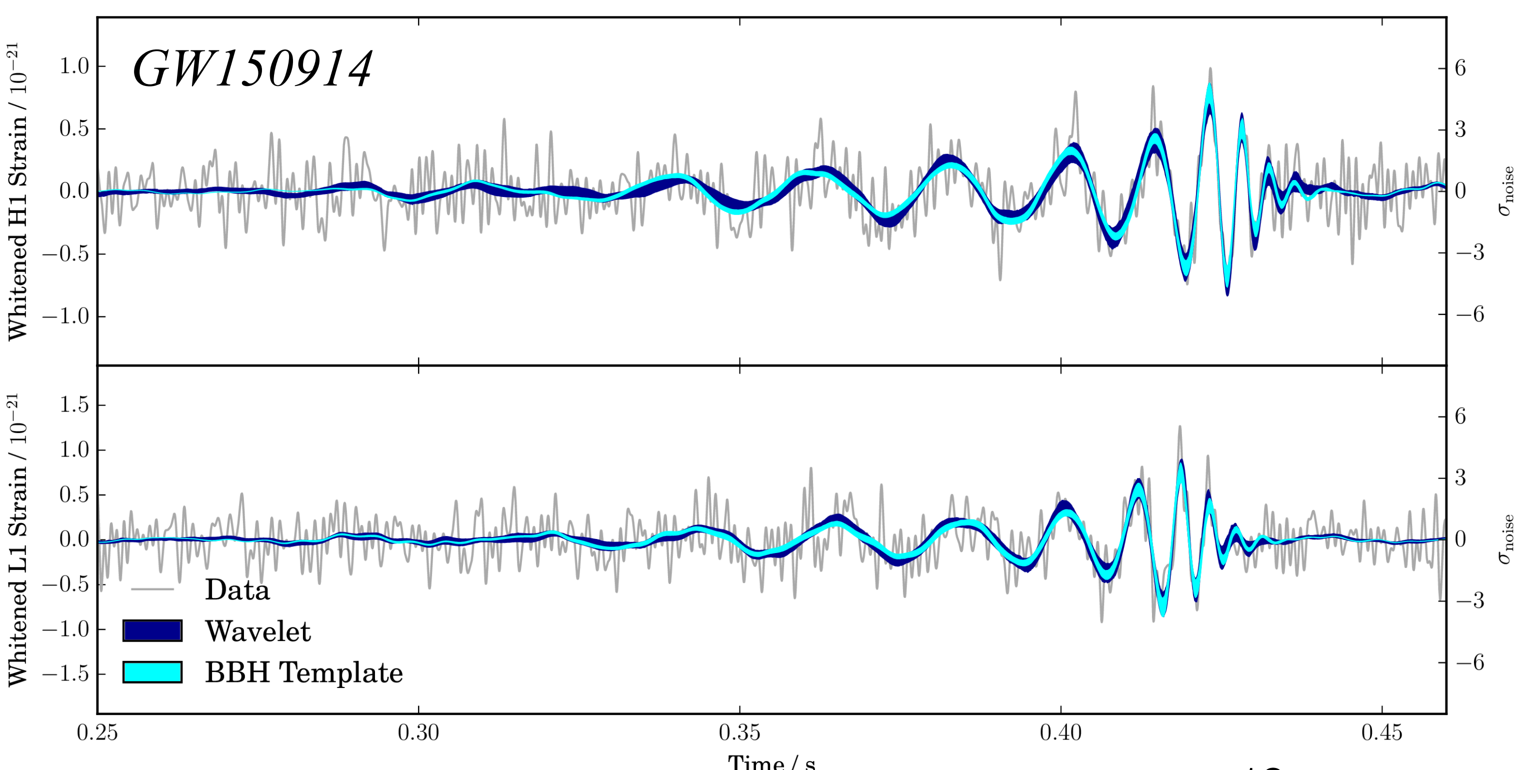


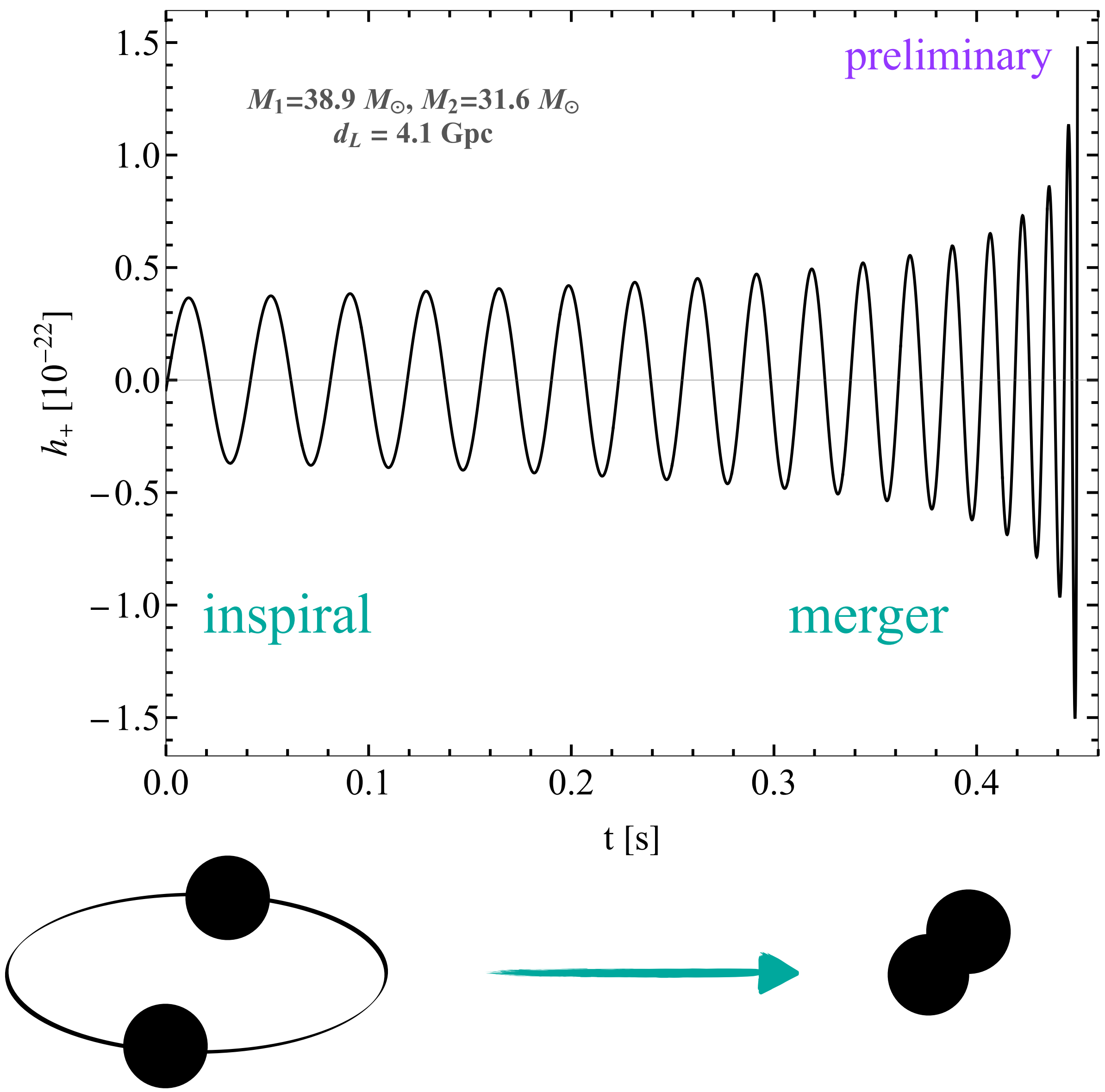


- Both the frequency and the strain increase with time from the inspiral phase to the merger phase.
- Since $\delta n_g \propto h^{-4} f^{-4}$, the wave DM effect is stronger (more time delay) in the inspiral phase, compared to the merger phase.
- We can compare GWs emitted during different time of a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

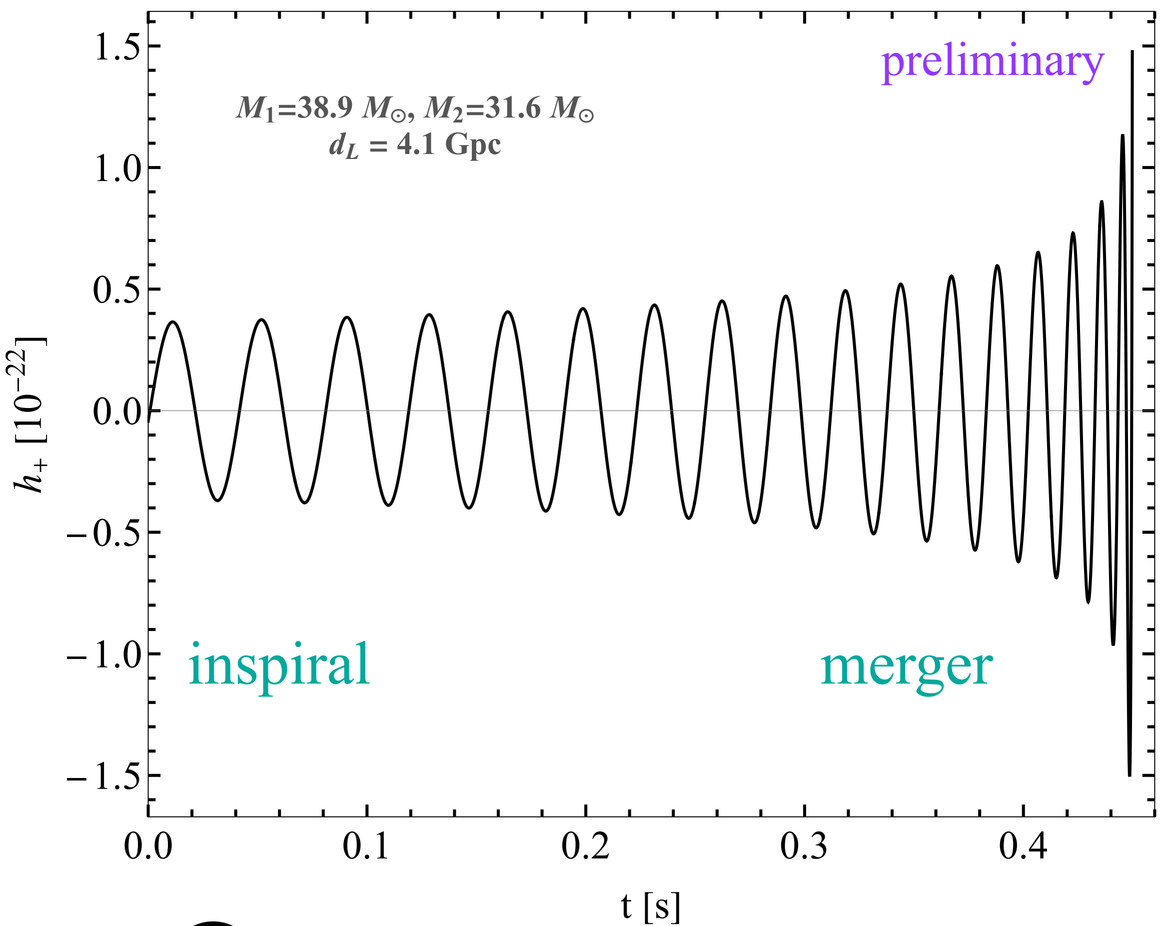
without BEC halo



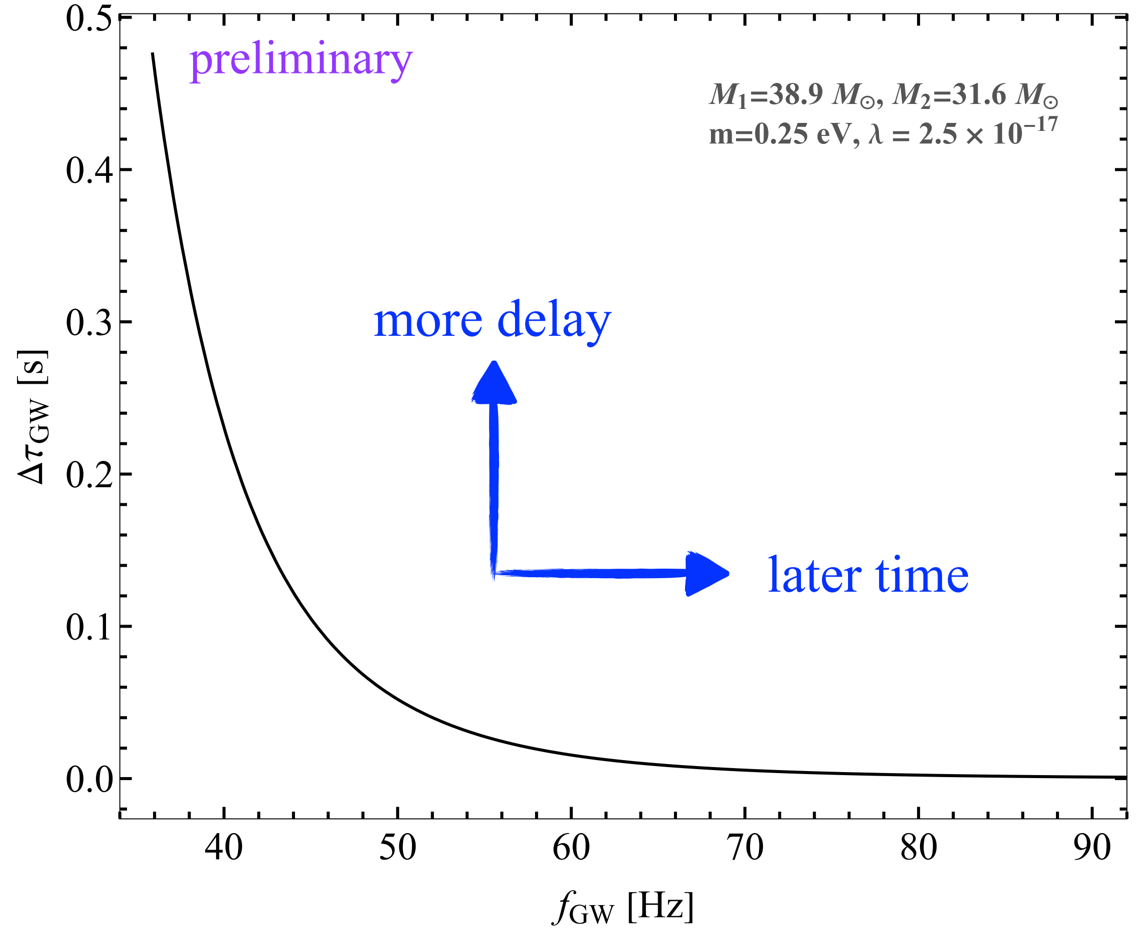
GW-GW Timing

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

without BEC halo



frequency dependence



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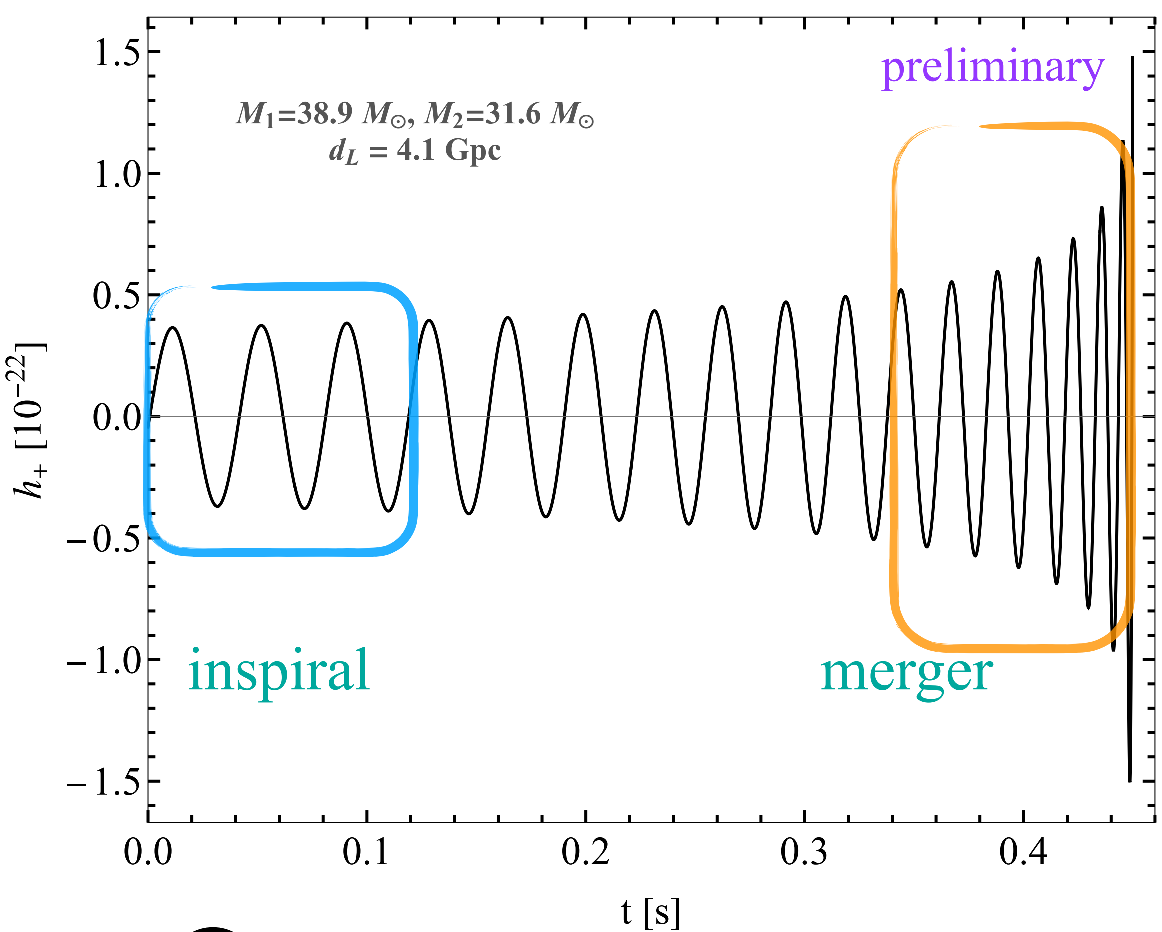

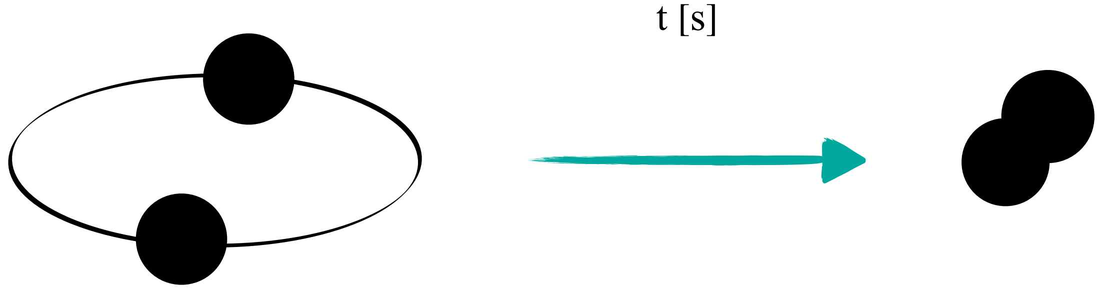

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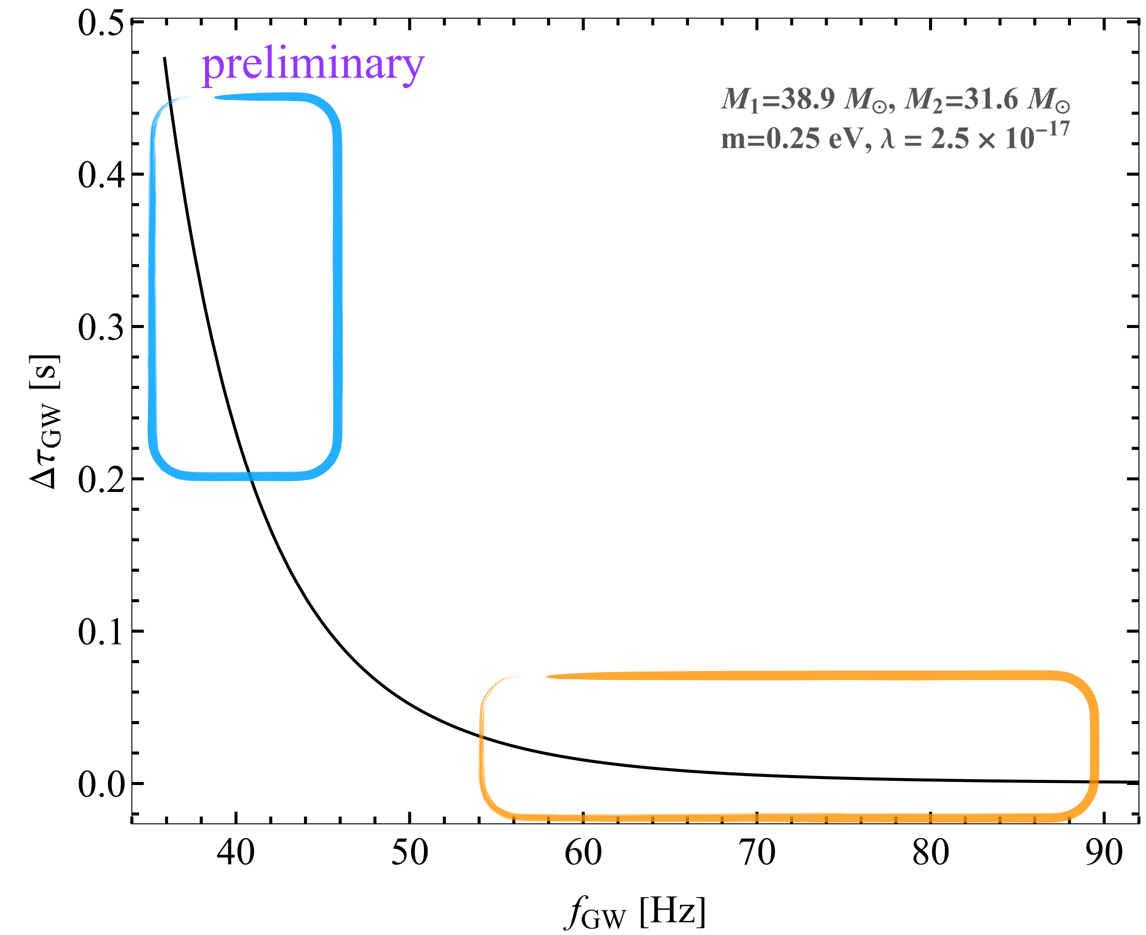
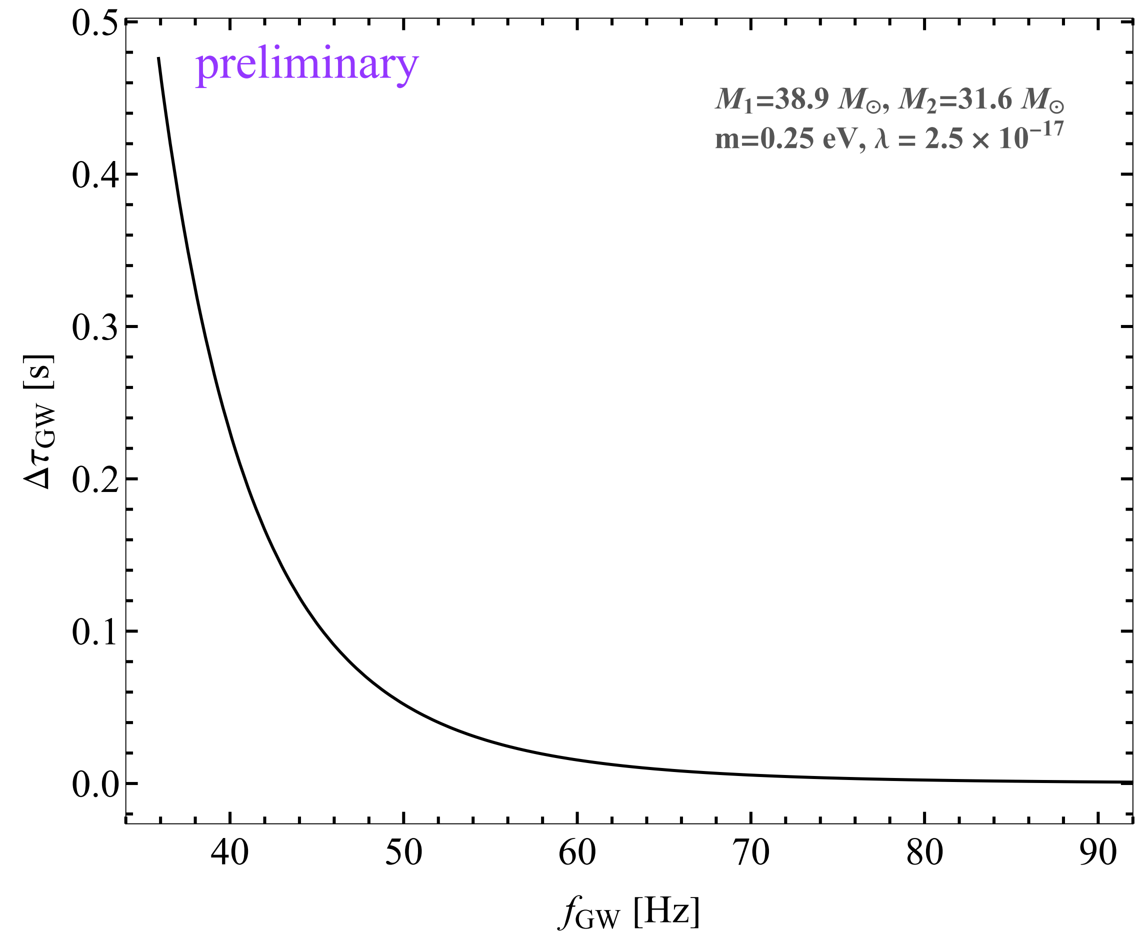


GW-GW Timing

GW rainbow in time domain

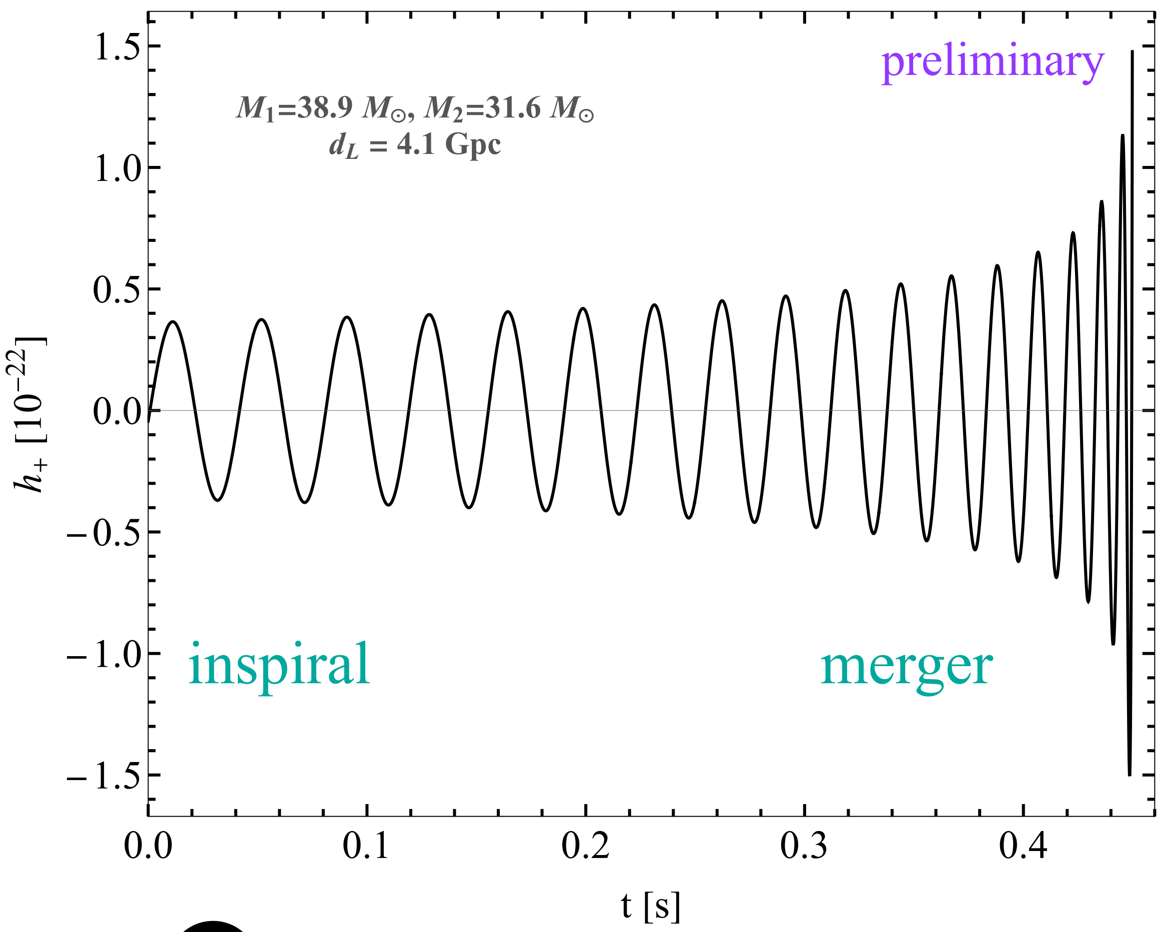
frequency dependence



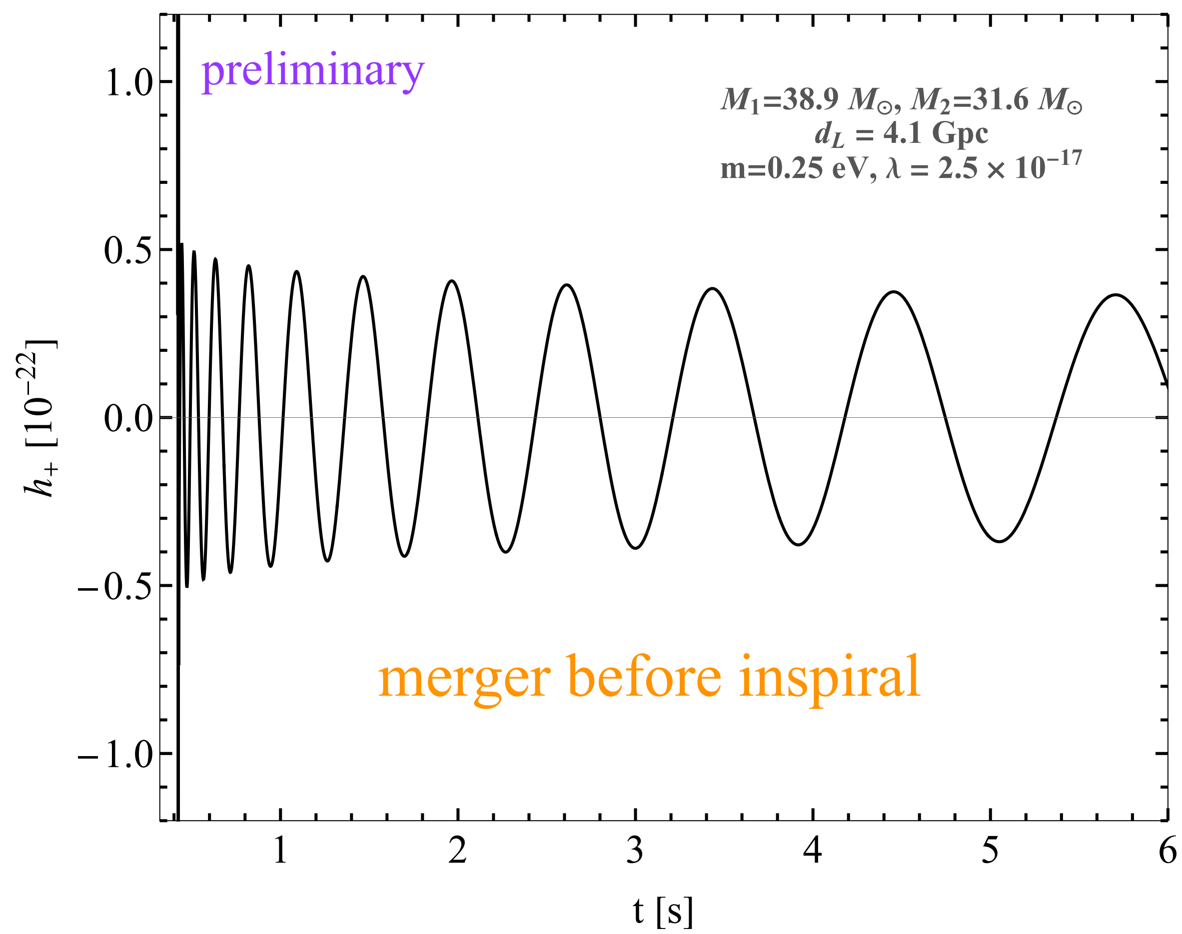
GW-GW Timing

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



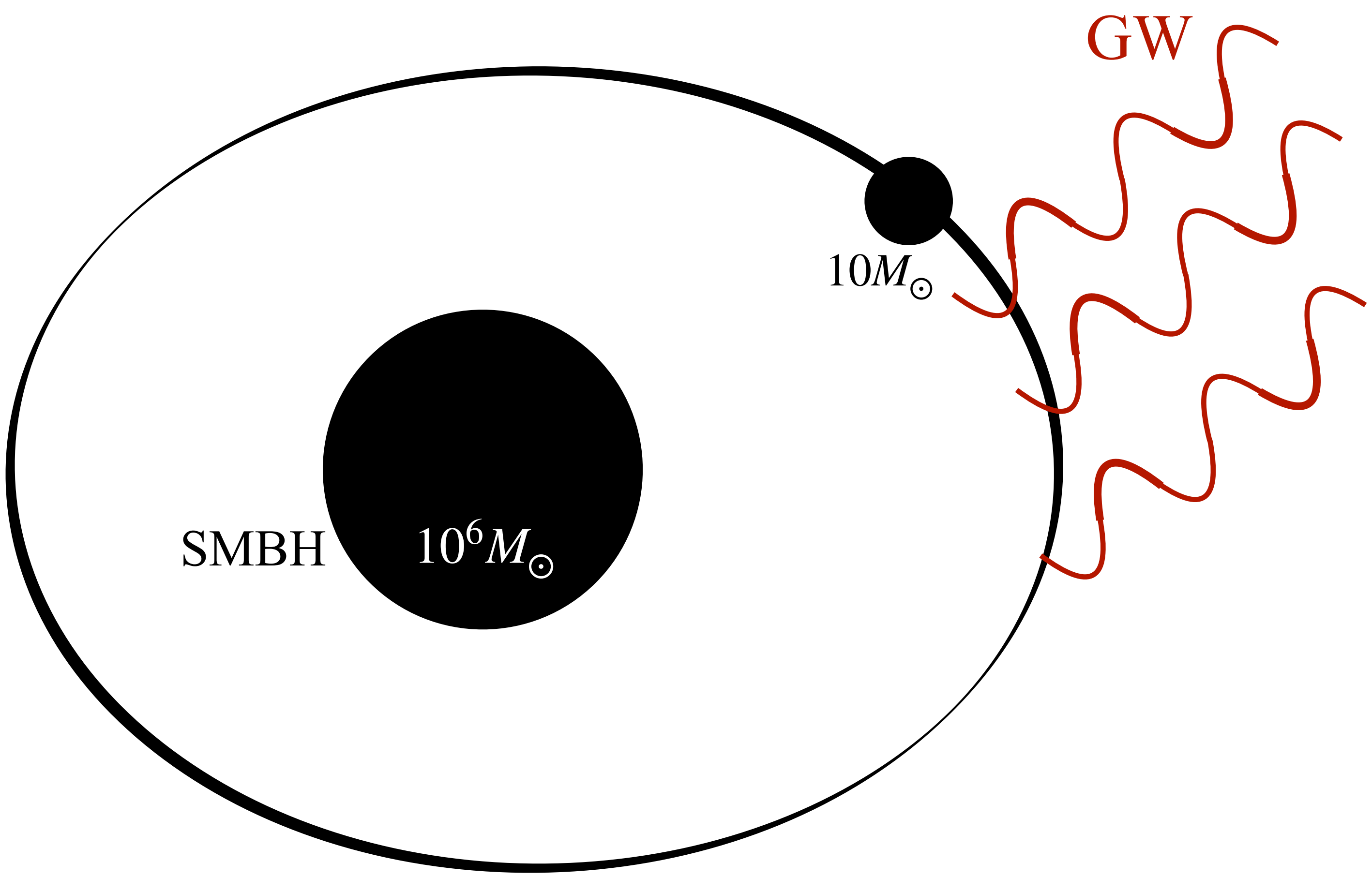
with BEC halo



GW-GW Timing at LISA

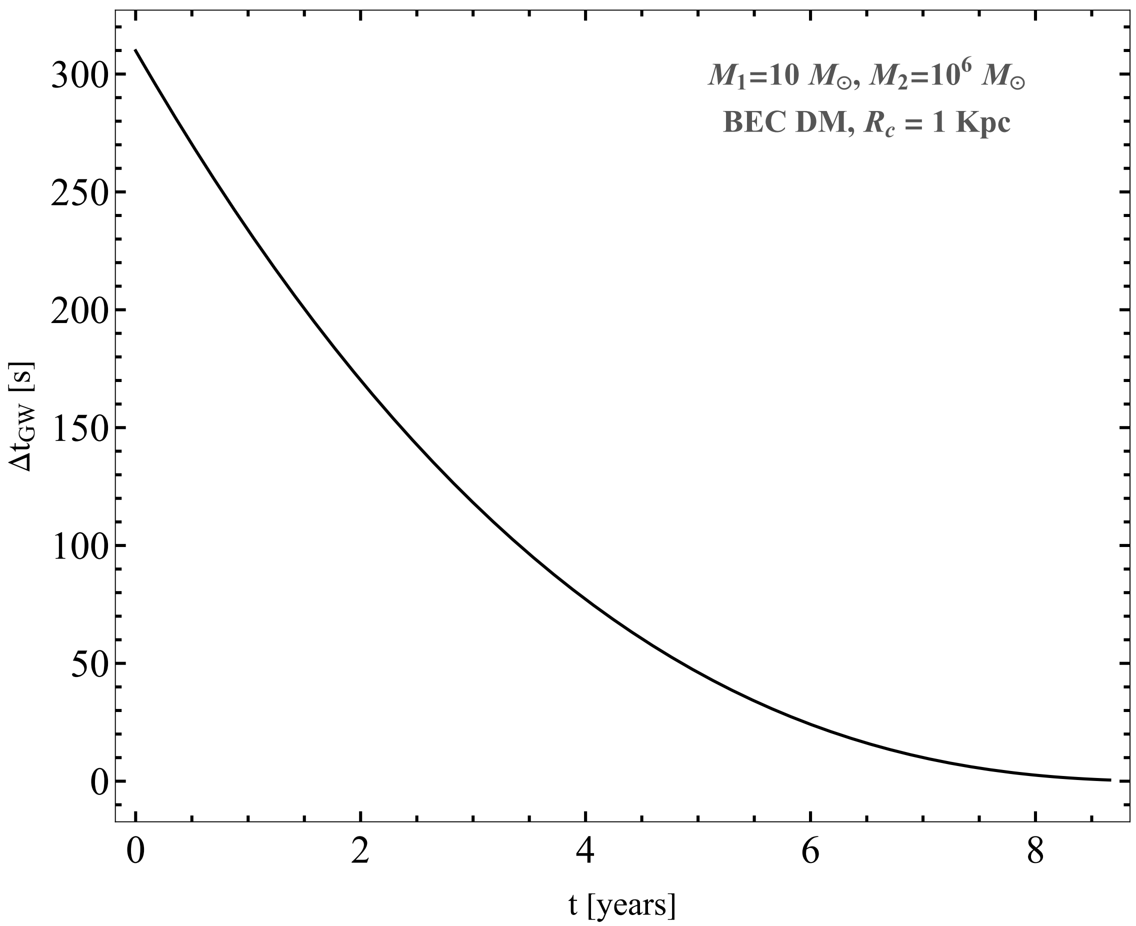
refractive index deviation: $\delta n_g = \sqrt{\frac{3}{2}} \frac{3\, m^6\, \rho_{\rm BEC}\, \zeta(\frac{3}{2})^2}{8\,\pi\,\lambda^{\frac{3}{2}}\, h^4\, \omega_{\rm GW}^4\, M_{\rm pl}^6}$

a stronger effect is expected for GW events in the LISA frequency band, *e.g.* EMRIs



Extreme Mass Ratio Inspiral

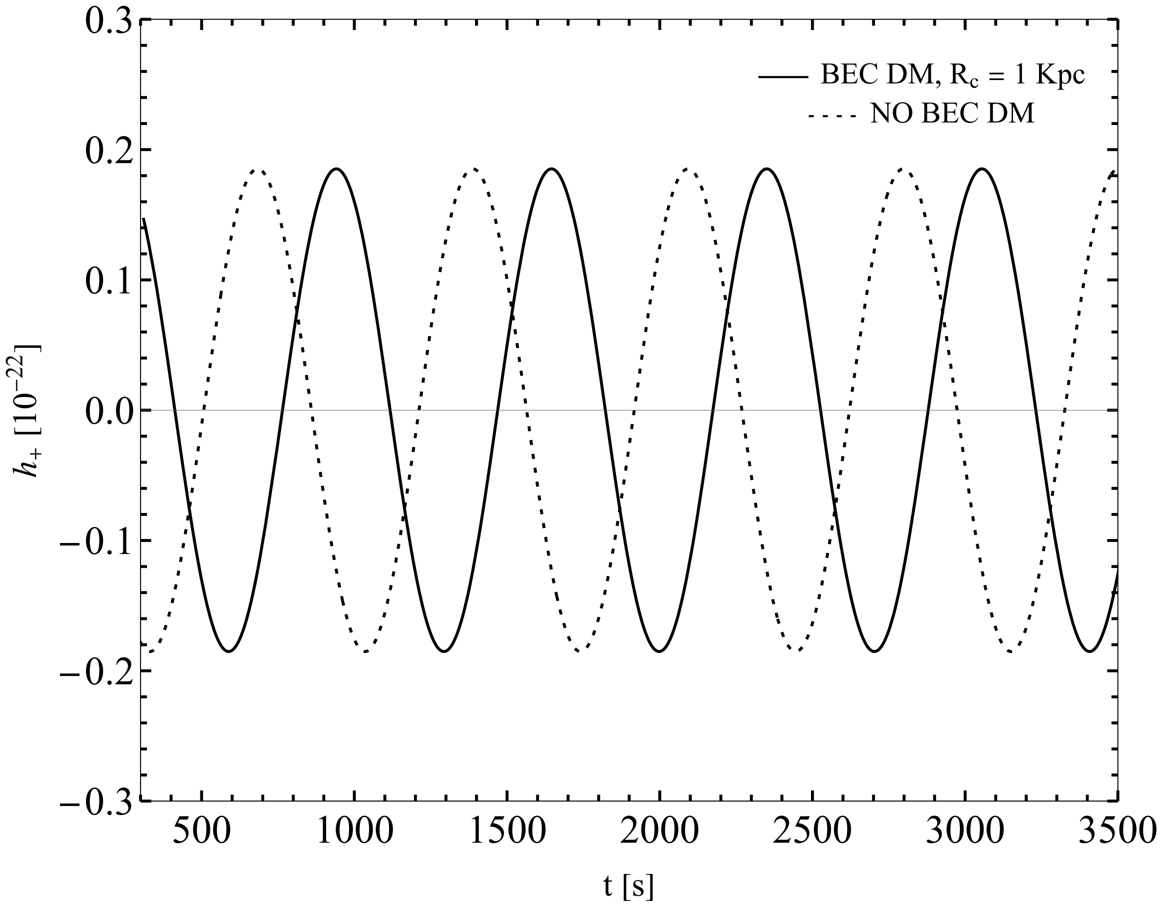
larger time delay



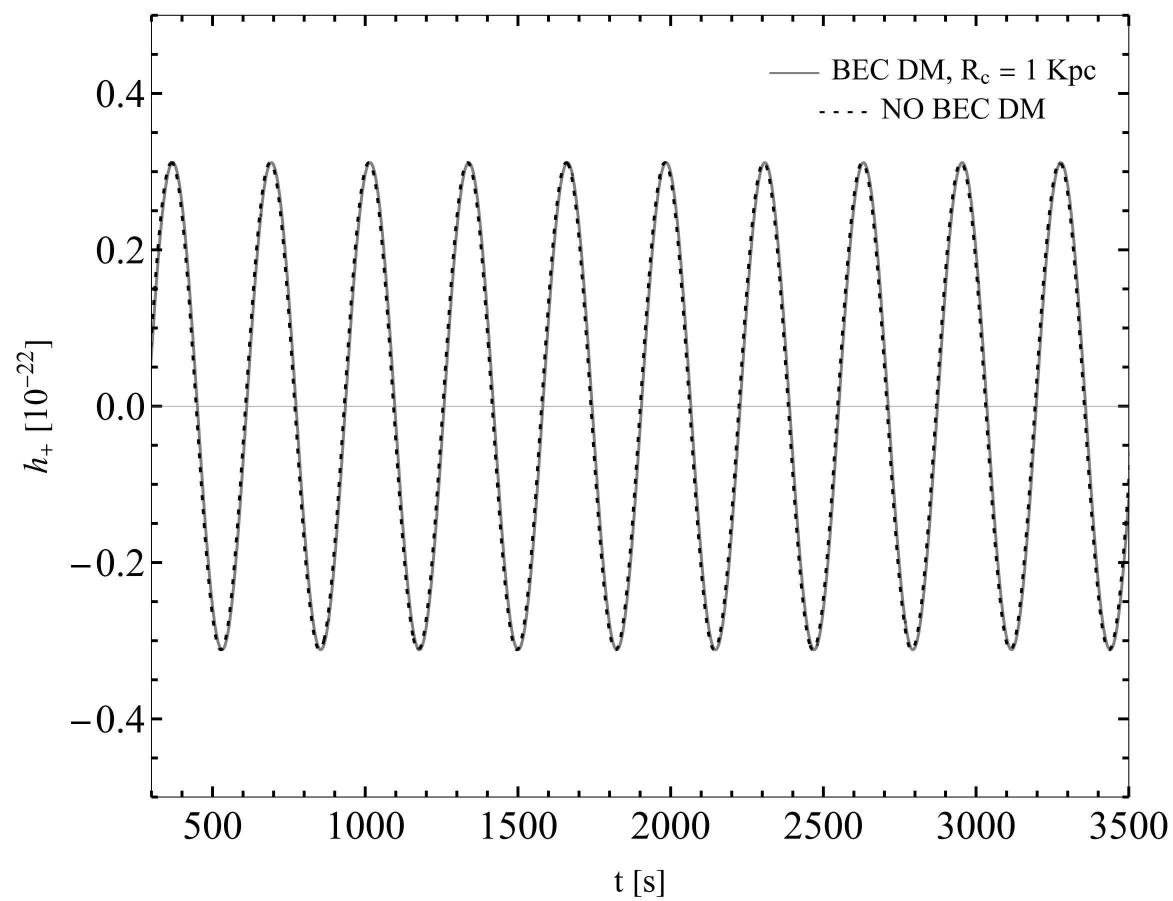
longer observation time ~ yrs

GW-GW Timing at LISA

8 yrs before ISCO

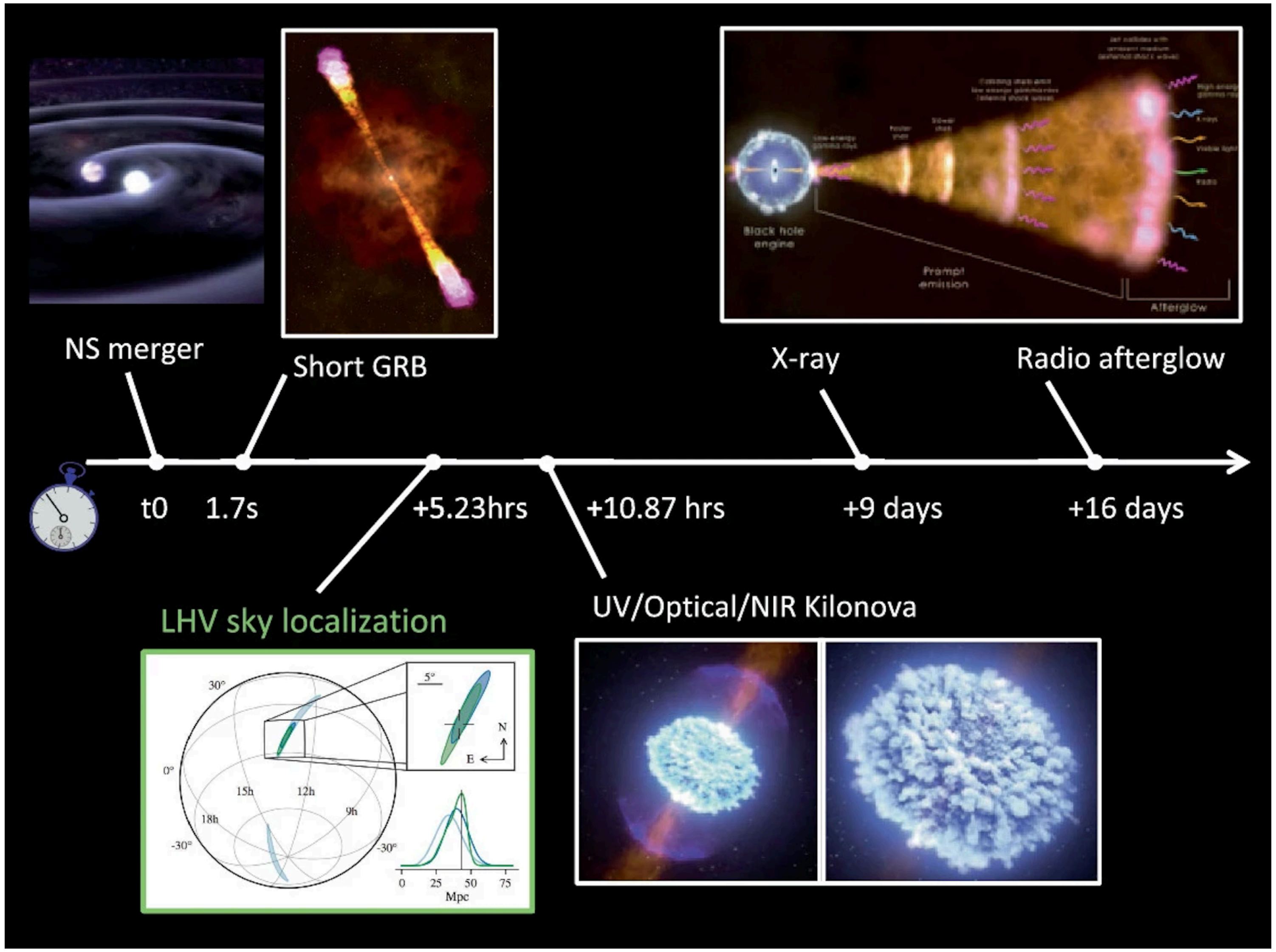


1 yr before ISCO



constant time shifts fail to fit the EMRI waveform

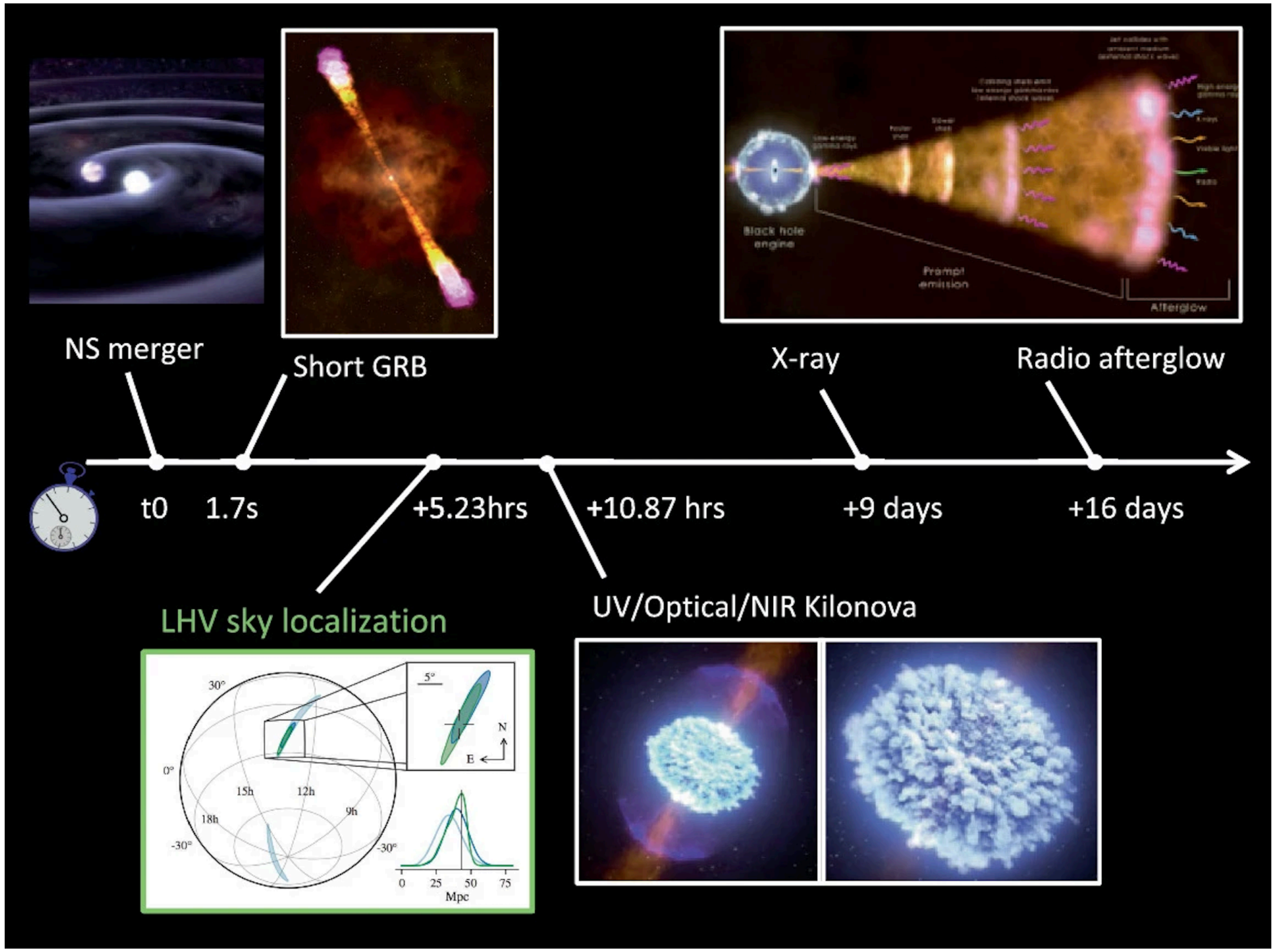
Timing with NS merger GW170817



- Neutron star merger events include signals of GW and EM emissions at various frequencies.

Marica Branchesi, "multi-messenger astronomy" (2023)

Timing with NS merger GW170817



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- Multi-messenger measurements improve the sky localization of the merger event.

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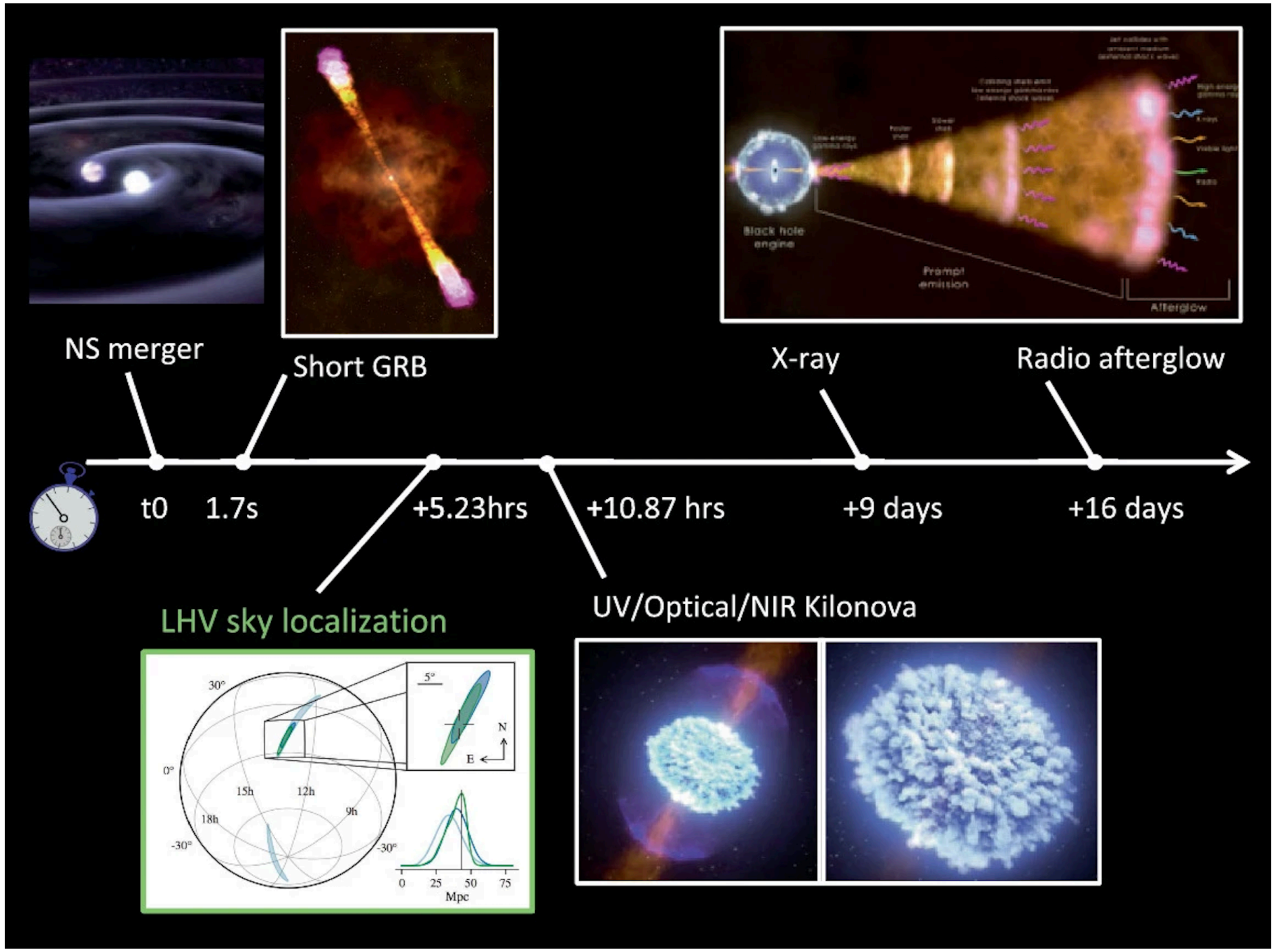
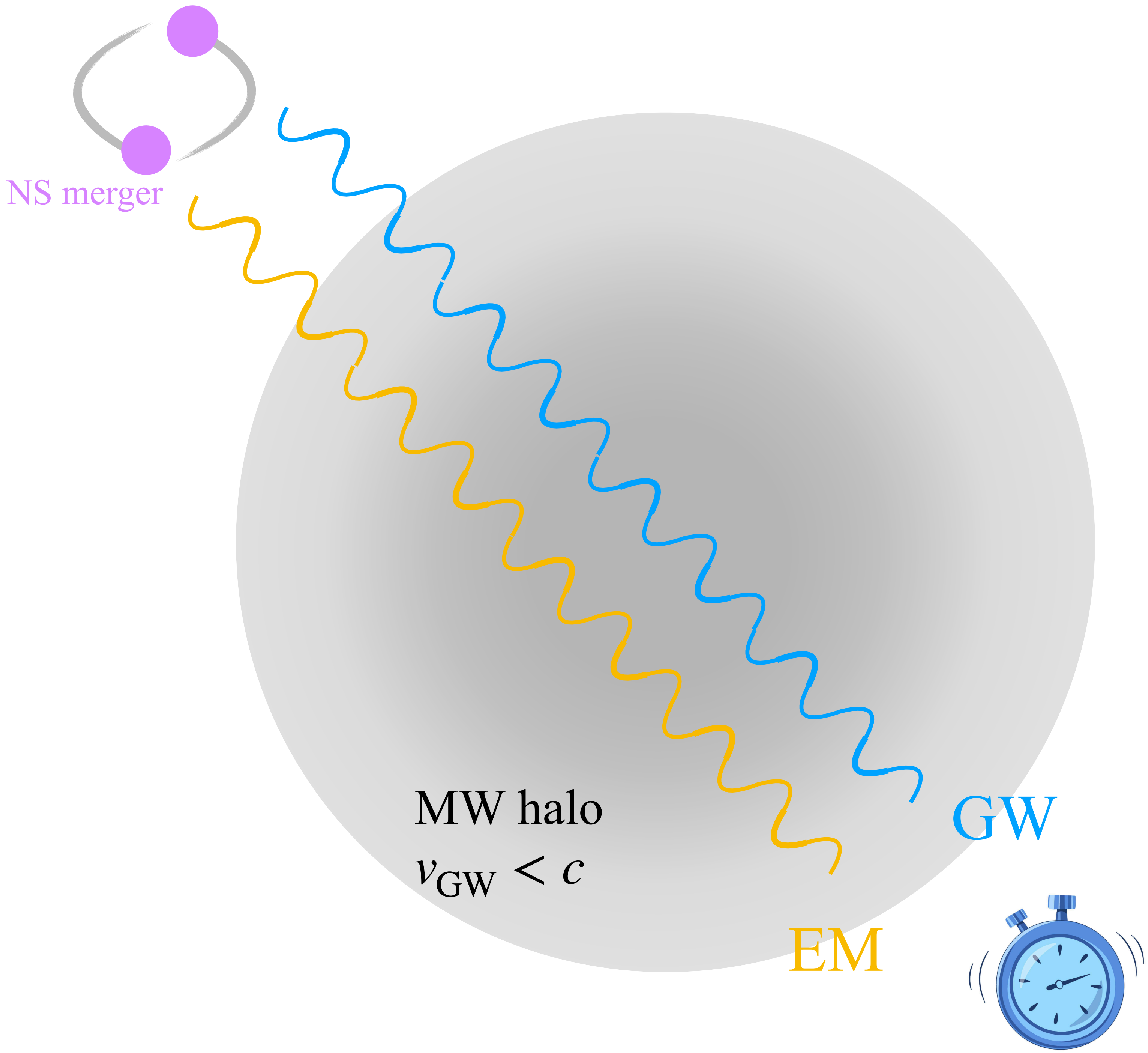


- Neutron star merger events include signals of GW and EM emissions at various frequencies.
- Multi-messenger measurements improve the sky localization of the merger event.
- The timing information can be used to understand the merger process. Deviation from the astrophysical model also probe new physics.

Marica Branchesi, "multi-messenger astronomy" (2023)

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)
- We try to map the DM halo with timing measurements.

Table 1: Expected detections per year (N), number detected with a resolution of < 1, < 10 and < 100 sq. deg. (N_1, N_{10} and N_{100}, respectively) and median localization error (M in sq. deg.), in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV plus KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).

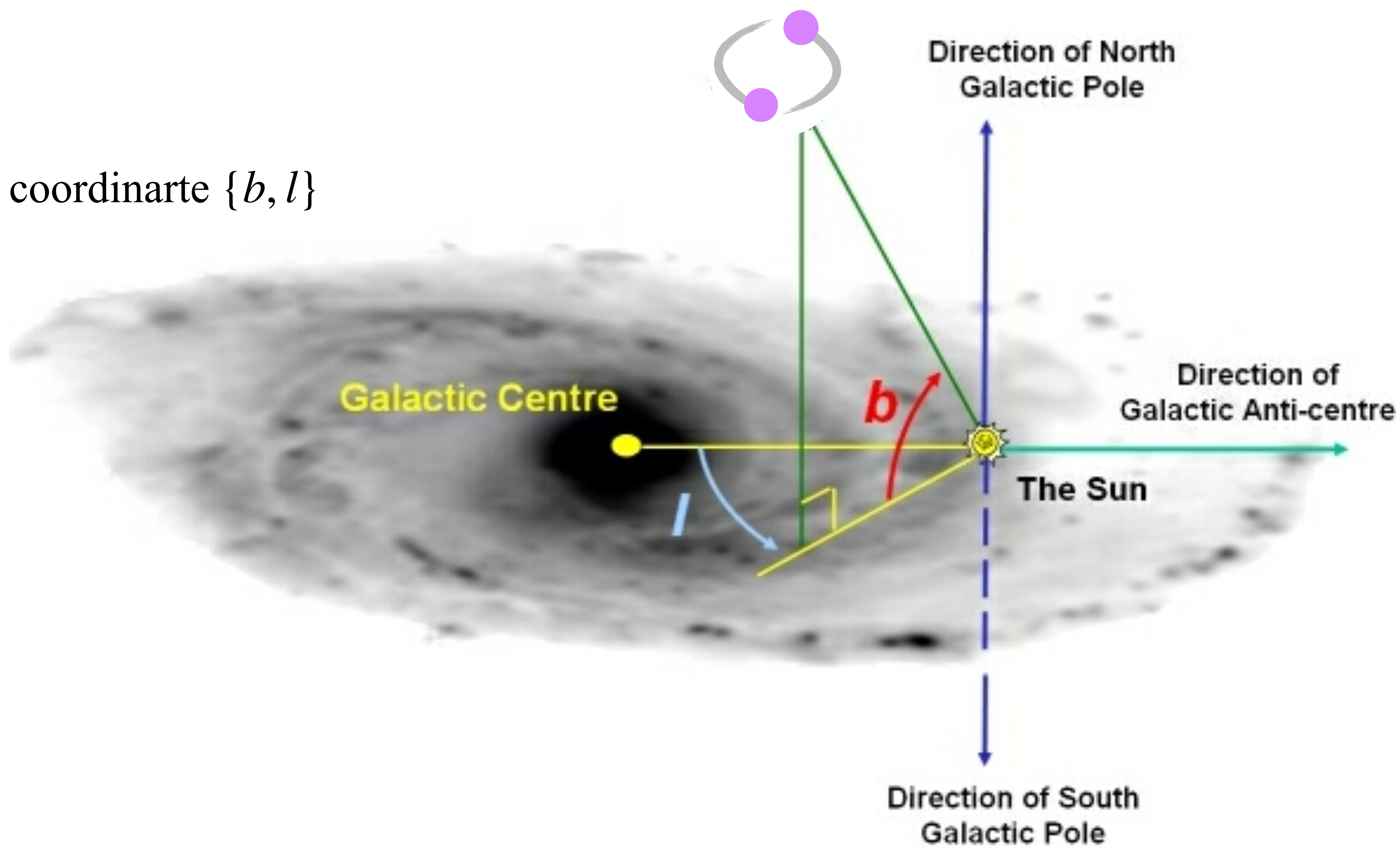
Network	N	N_1	N_{10}	N_{100}	M
HLV	48	0	16	48	19
HLVKI	48	0	48	48	7
1ET+2CE	990k	14k	410k	970k	12

NS+CO binary, 1903.09277

GW-photon timing

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

galactic coordinarte $\{b, l\}$



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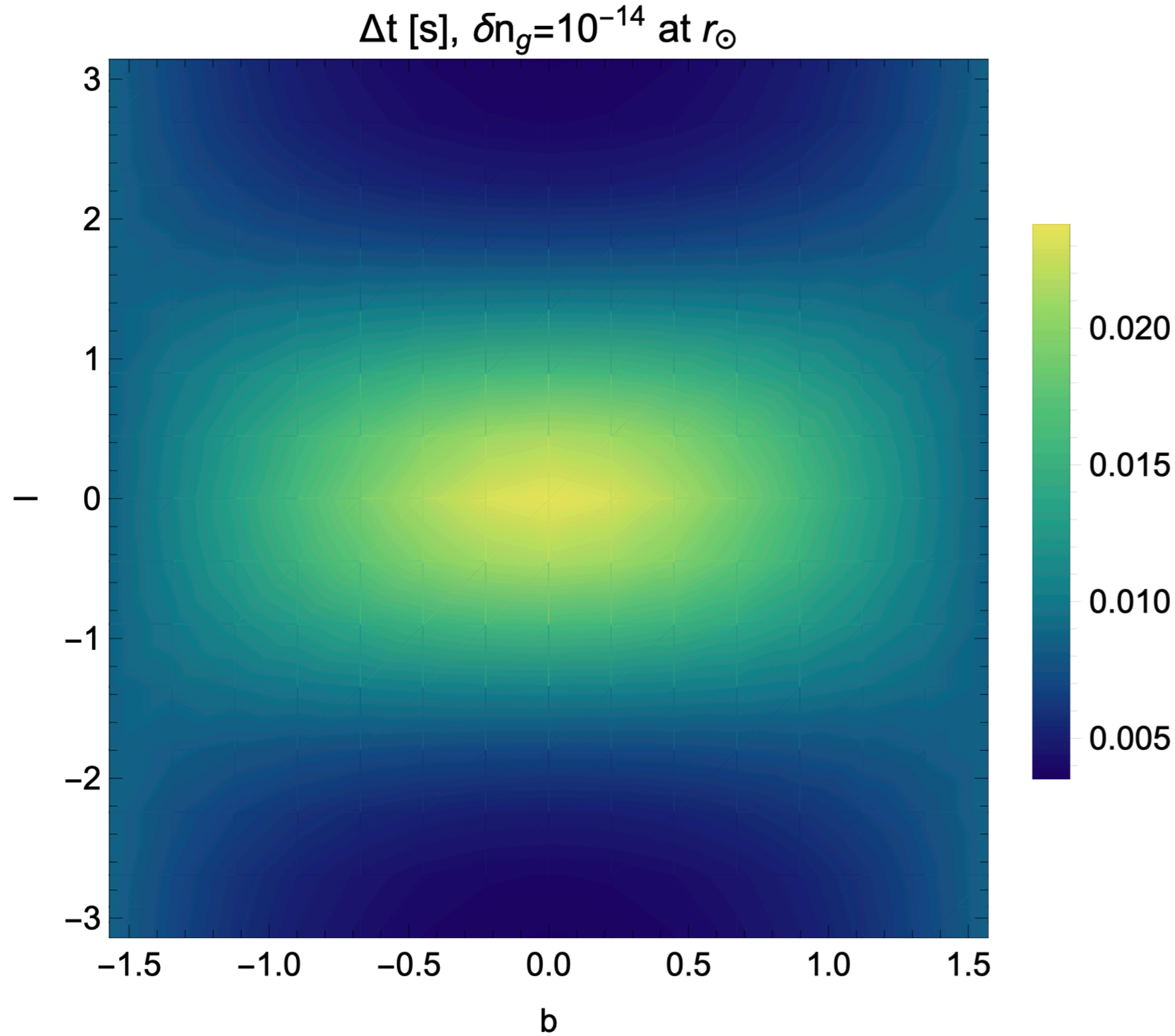

preliminary

GW-photon timing

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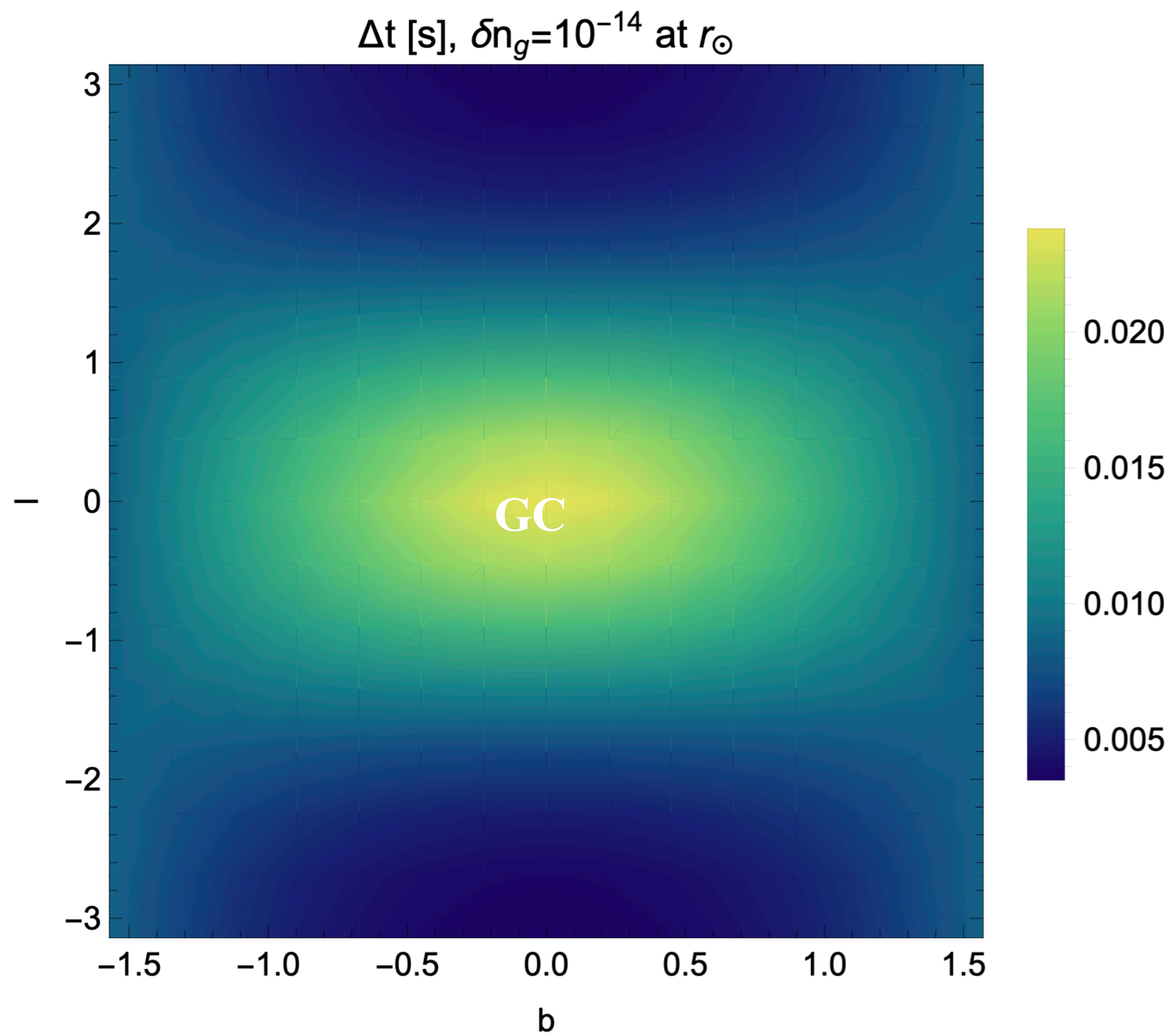
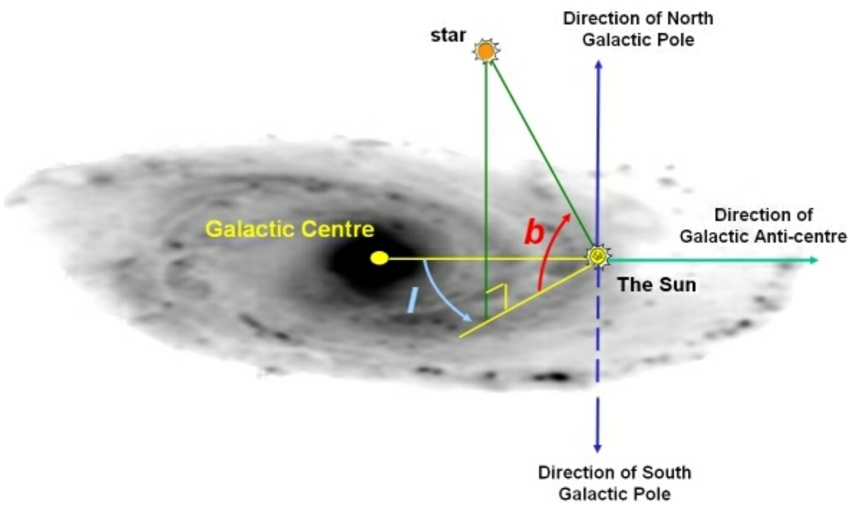


preliminary

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

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

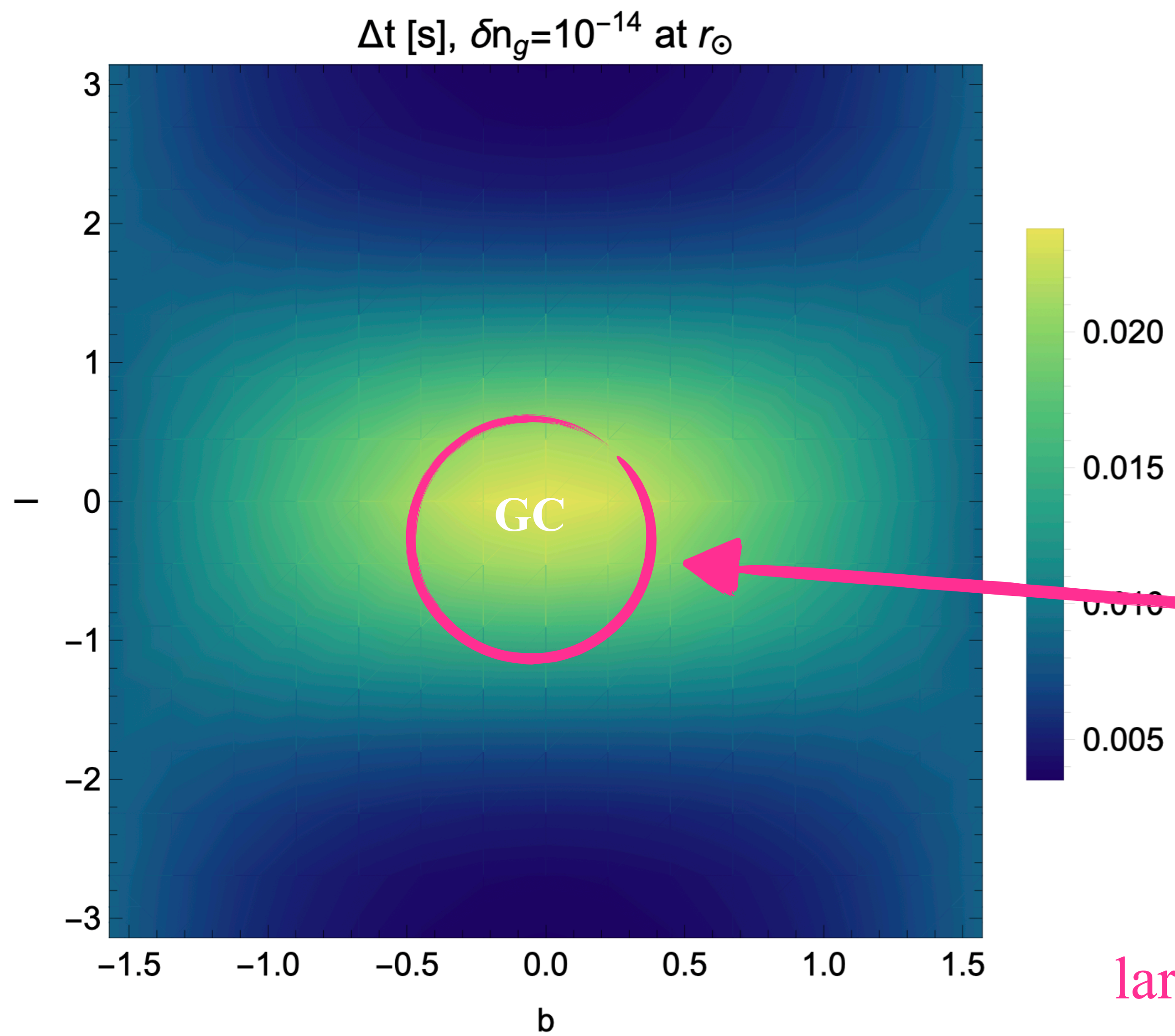


$$x_\phi \equiv \sqrt{\frac{3}{2}}\, \frac{3\, m^6\, \zeta(\frac{3}{2})^2}{8\,\pi\,\lambda^{\frac{3}{2}}\, M_{\rm pl}^6}$$

independent of DM density

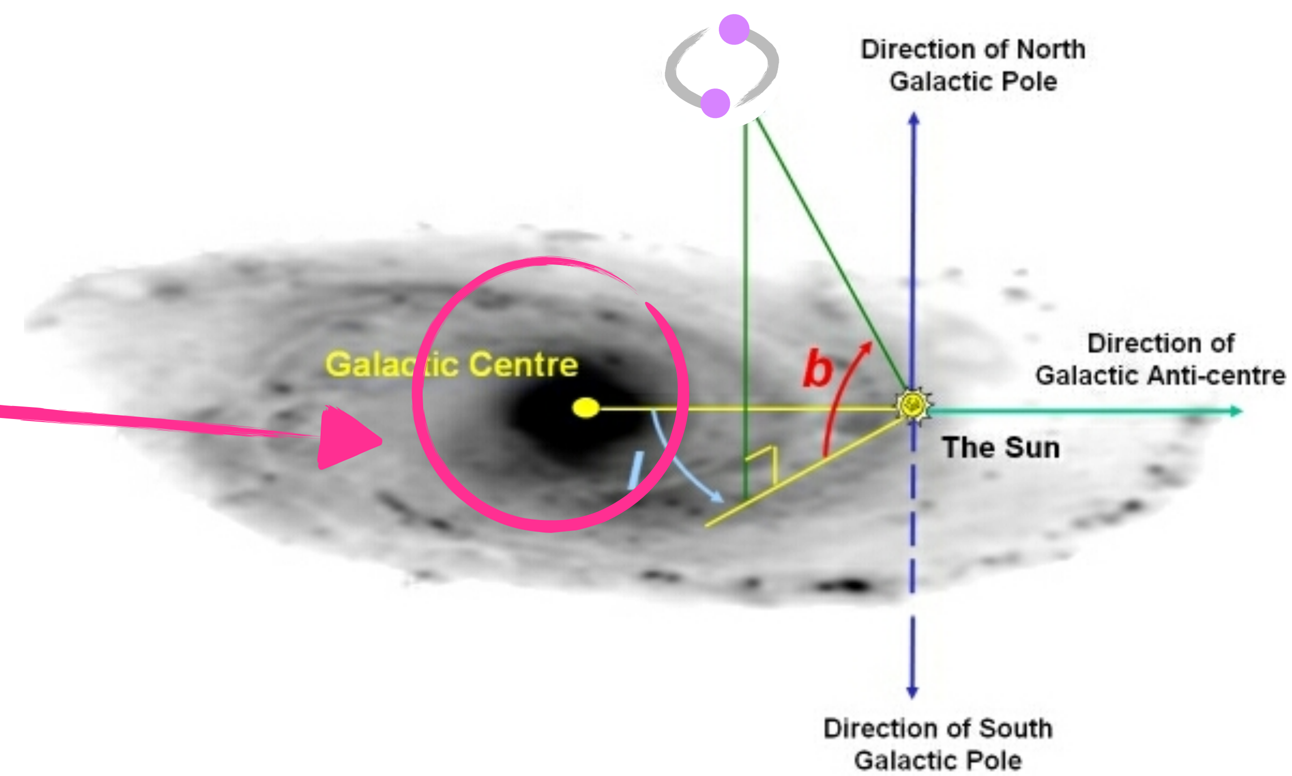
GW-photon timing

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



preliminary

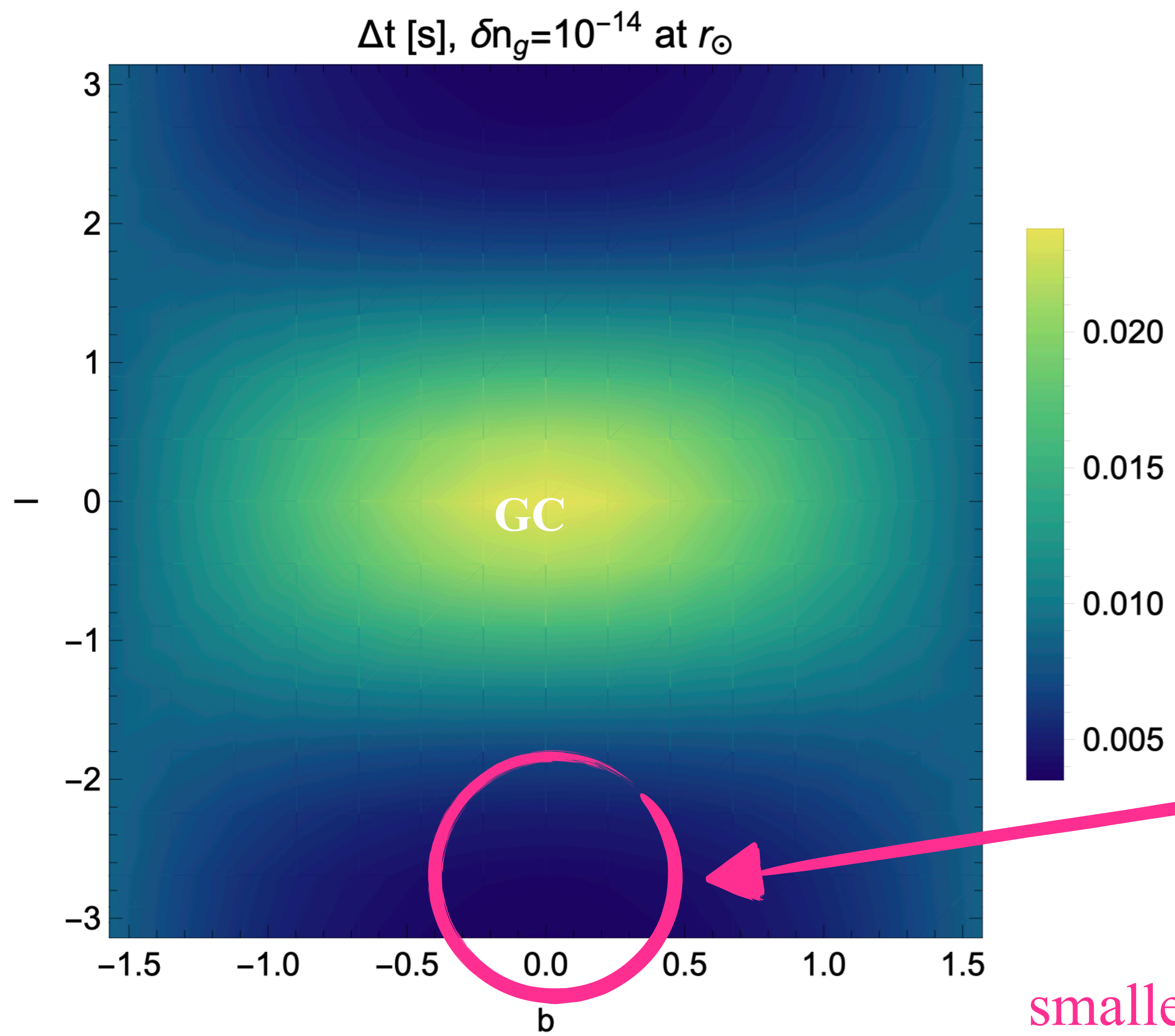
galactic coordinarte



largest delay from GC direction

GW-photon timing

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



preliminary

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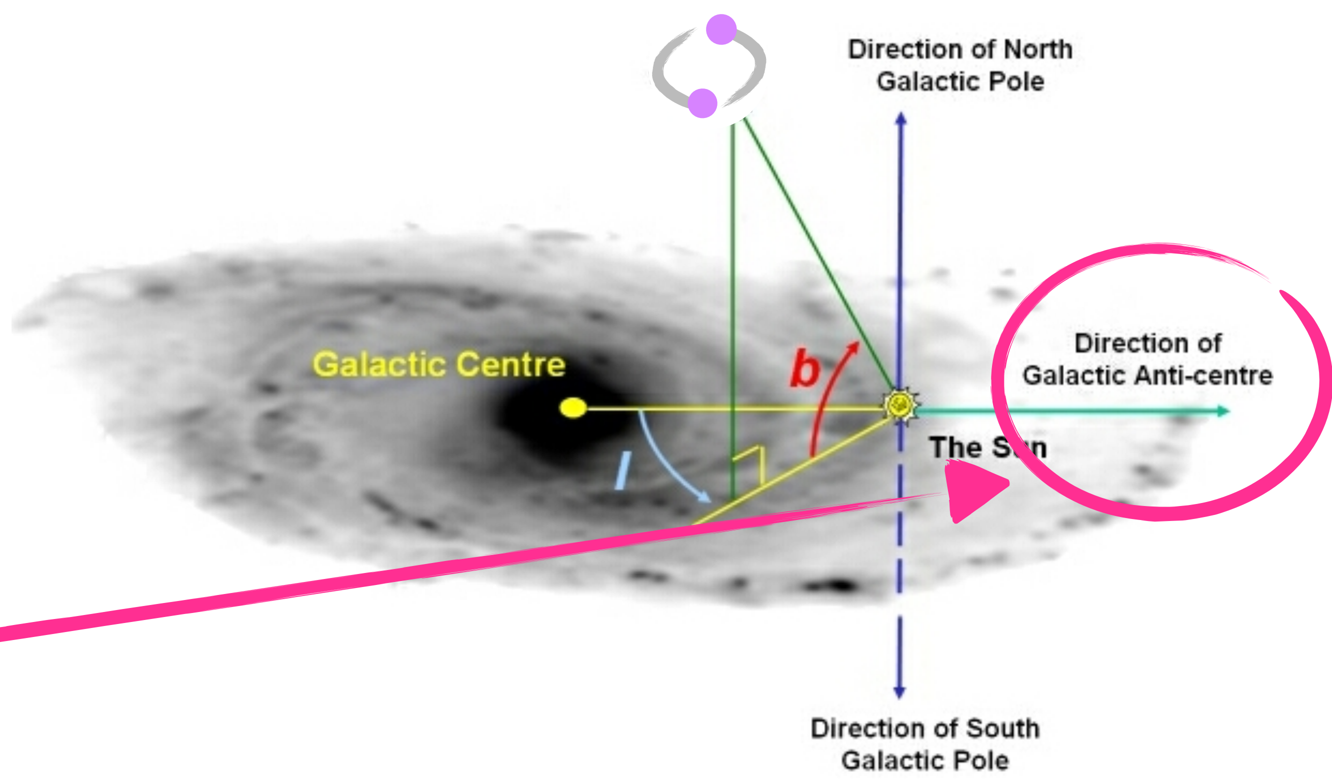
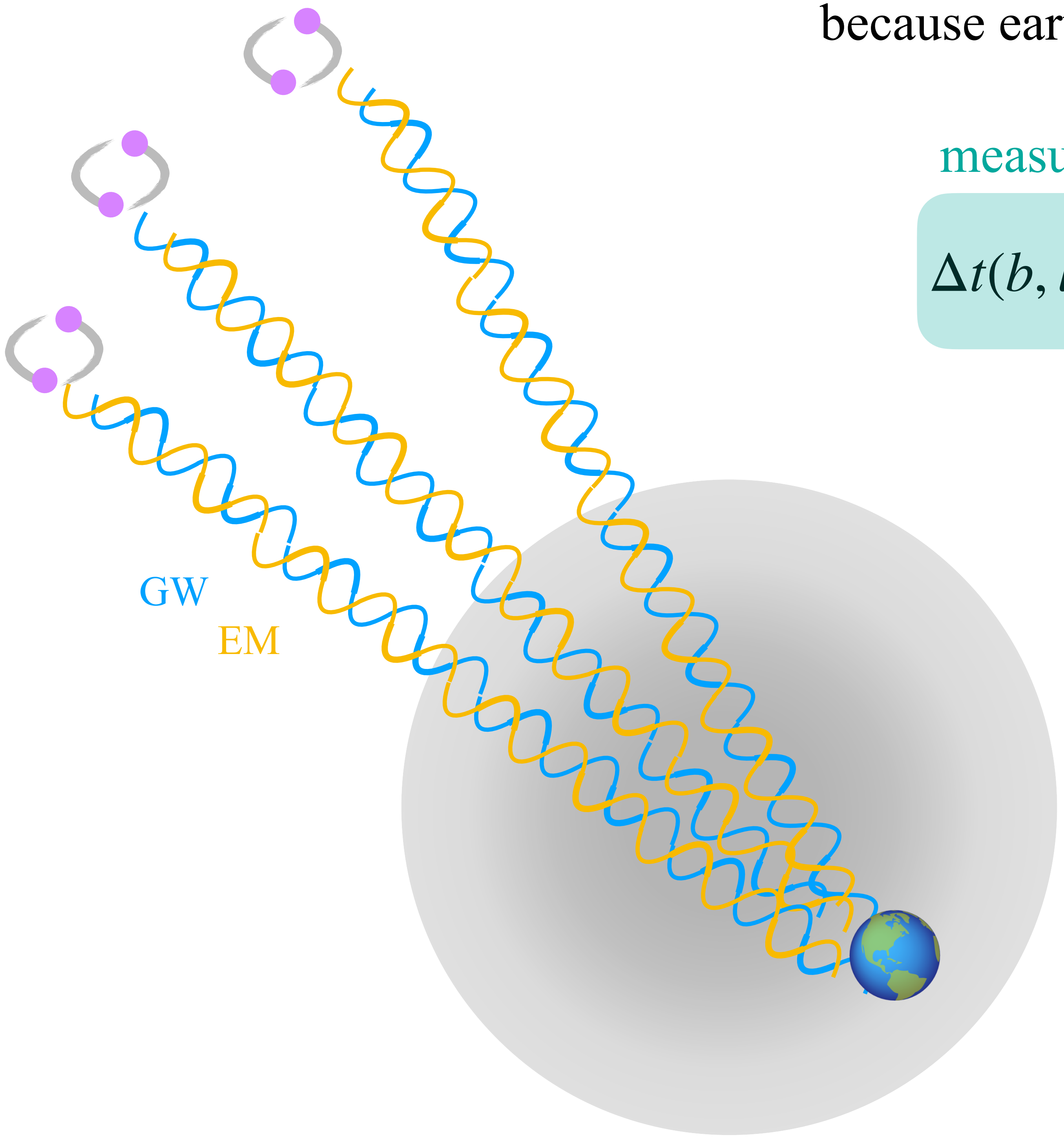


smallest delay from outer halo direction

Halo Tomography

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

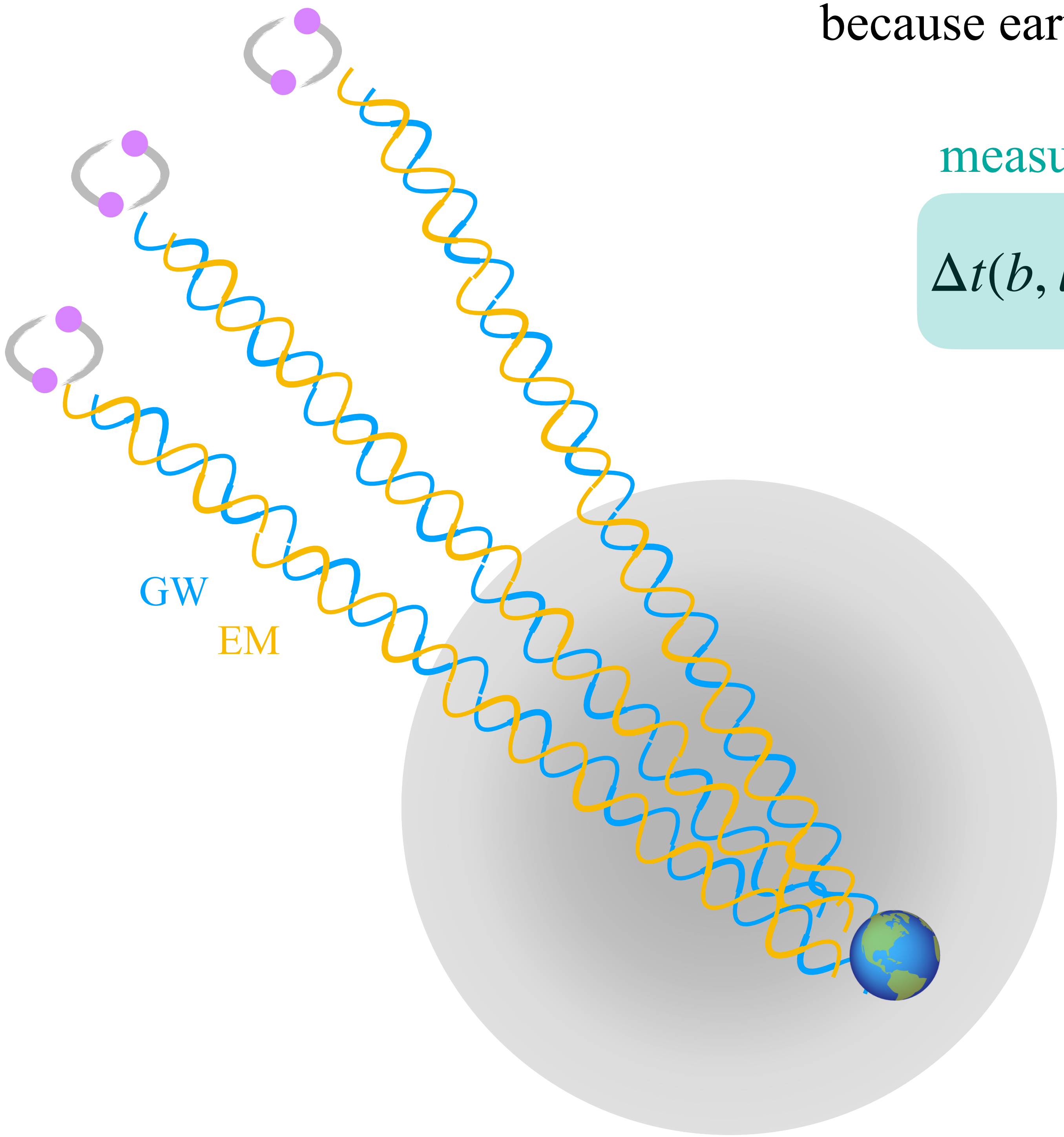


measurements

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

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

Halo Tomography



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

measurements

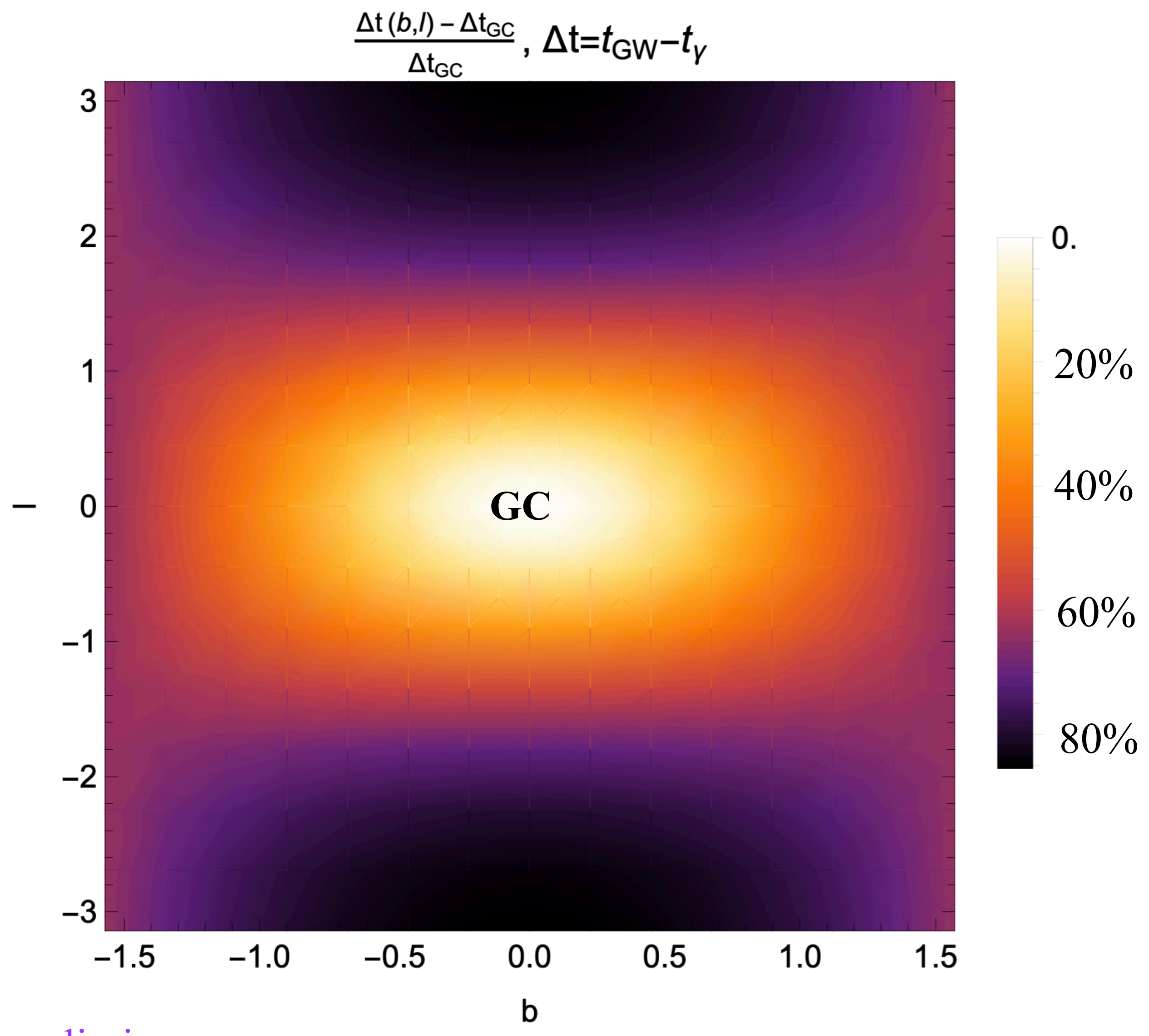
$$\Delta t(b,l)\, h^4\, \omega_{\rm GW}^4 = \frac{x_\phi}{c} \int_0^{s_{\max}} ds\, \rho_{\rm BEC}(b,l,s)$$

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

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)



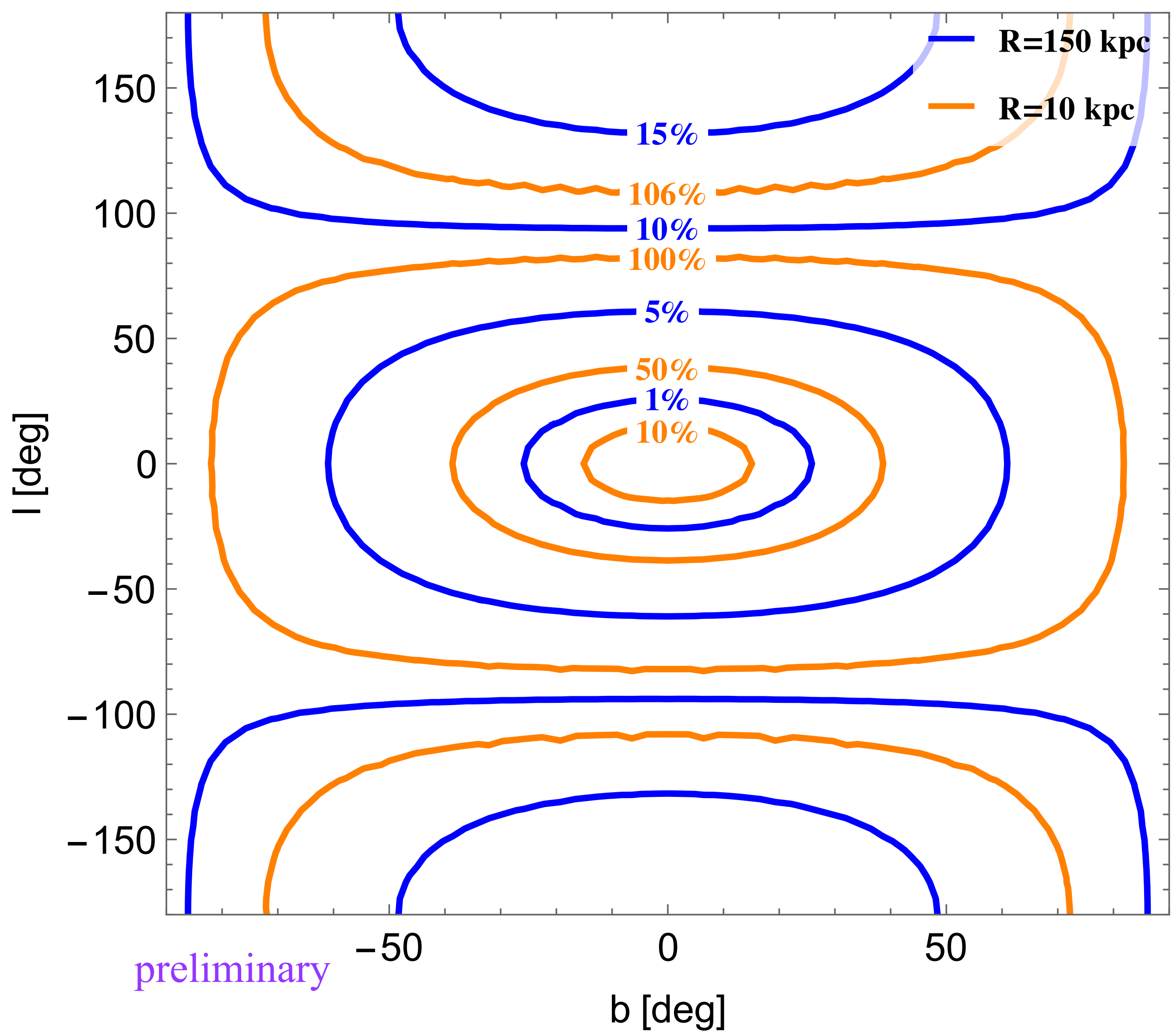
preliminary

$R = 20$ kpc

- Largest time delay coming from the GC direction—higher DM density
  $$\Delta t \propto \rho_{\text{BEC}}$$
- $\mathcal{O}(10\%)$ 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

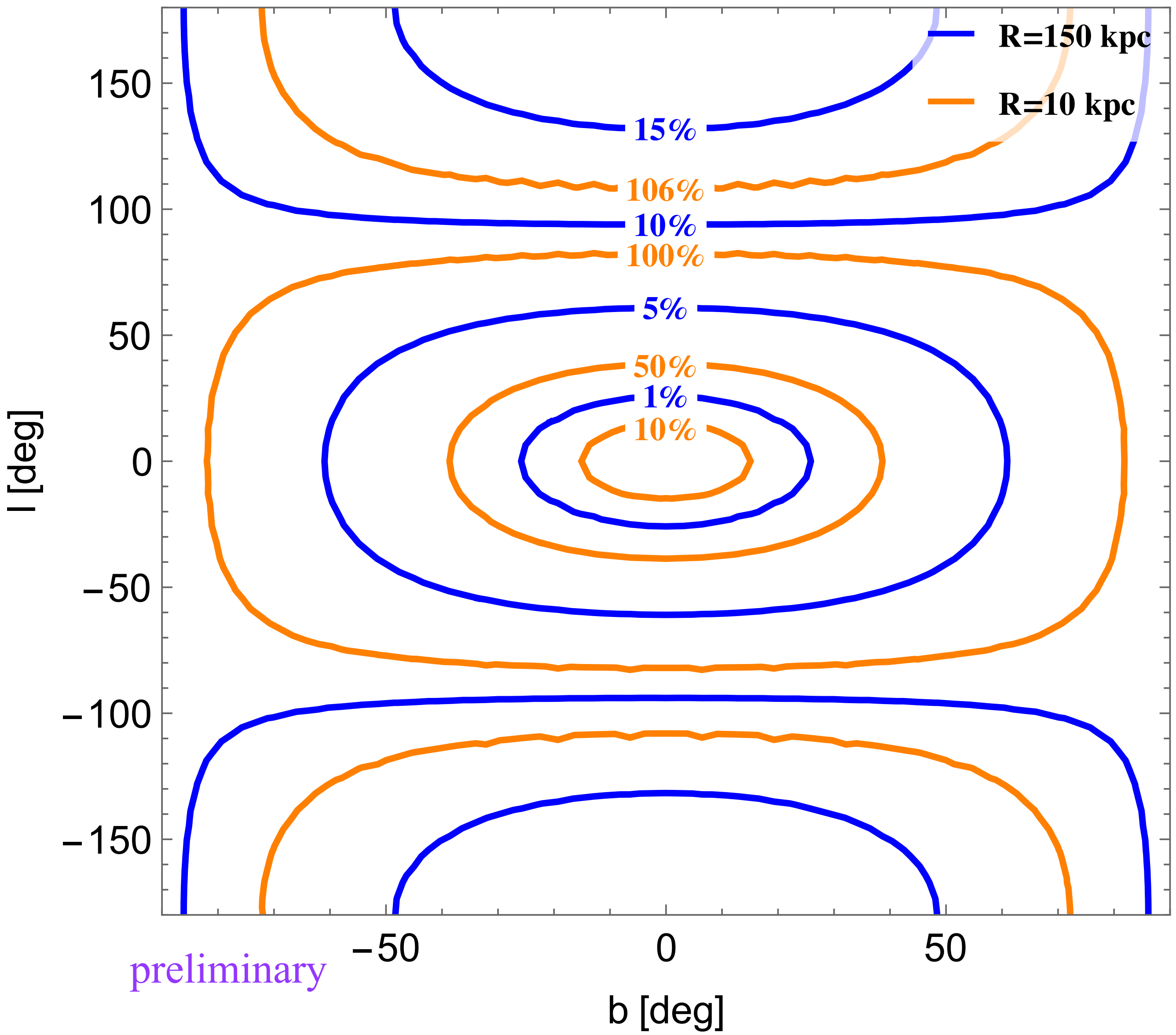
Choose different halo profile



- 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

Choose different halo profile



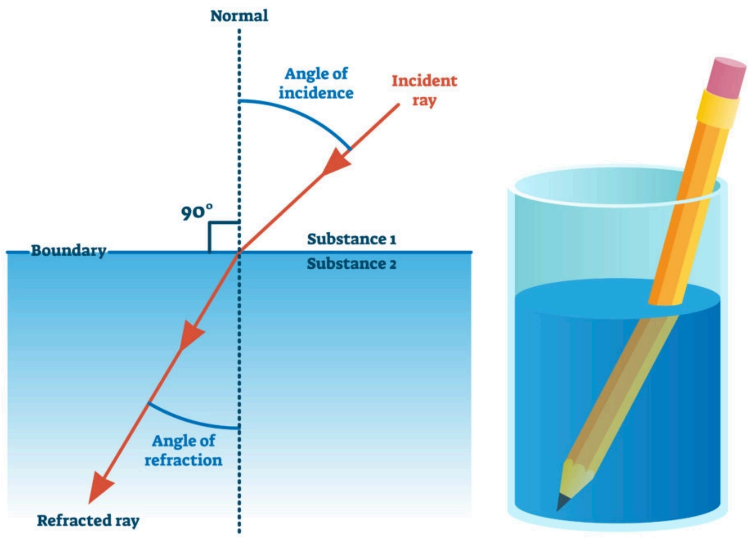
preliminary

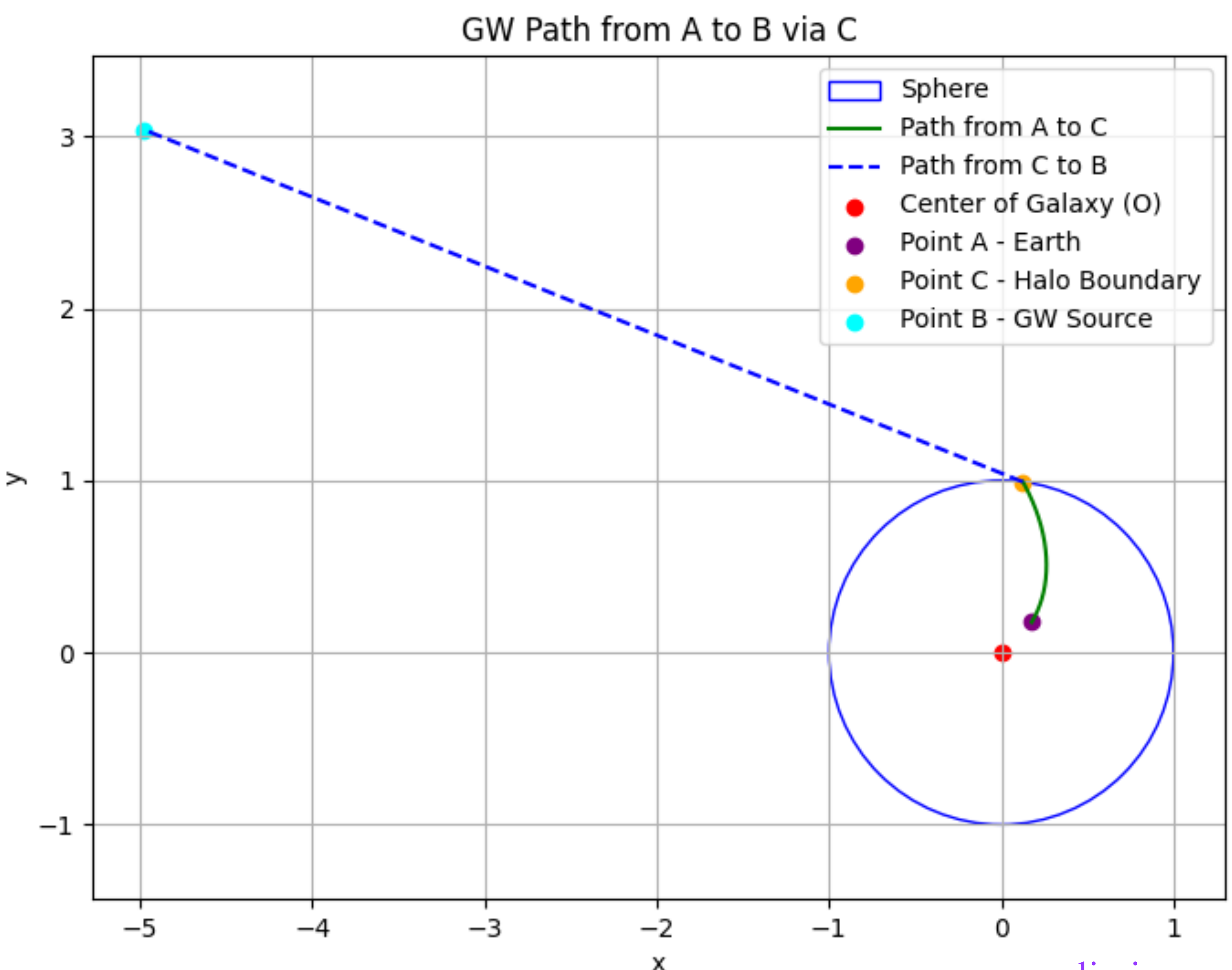
- The anisotropy also depends on the halo density profile, especially the characteristic radius scale R.
- Larger anisotropy is observed for a smaller $R = 10$ kpc value; but $\mathcal{O}(10\%)$ effect still available with $R \simeq 150$ kpc.
- Time delay effect can still be induced when the wave DM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

Next step: localization

In the geometrical optics limit, we can use Snell's law to model the propagation of GWs.

The propagation direction of GWs is modified compared to photons,
especially for future EMRIs and binary white dwarf events.





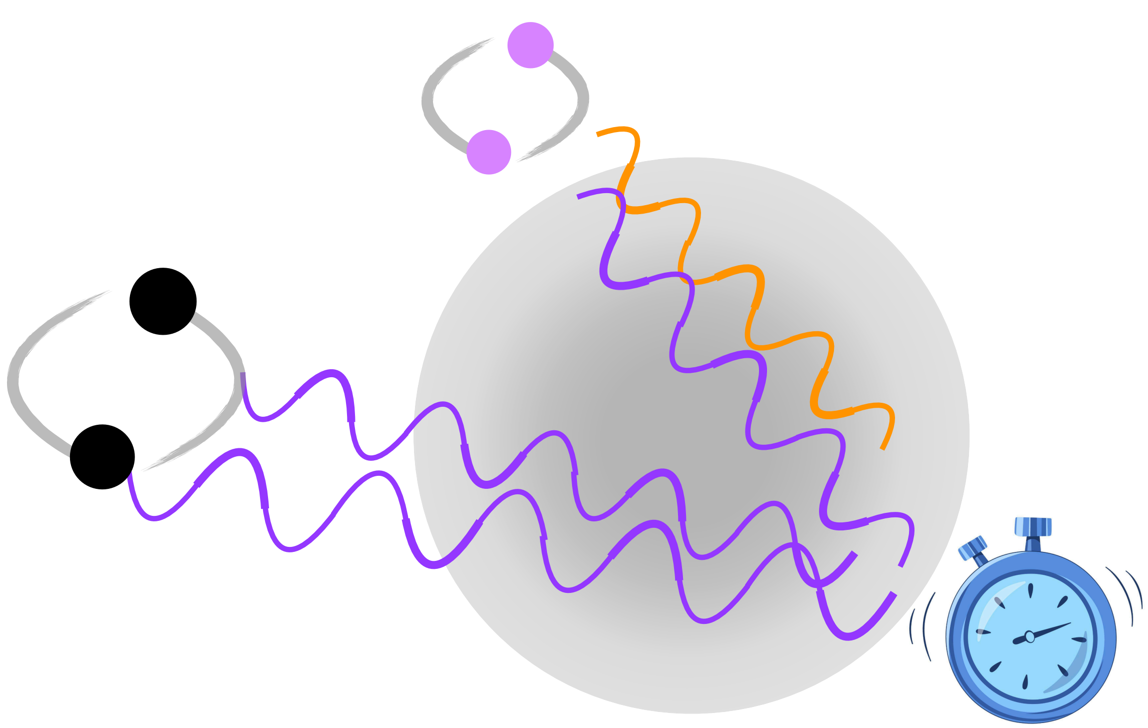
preliminary

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!