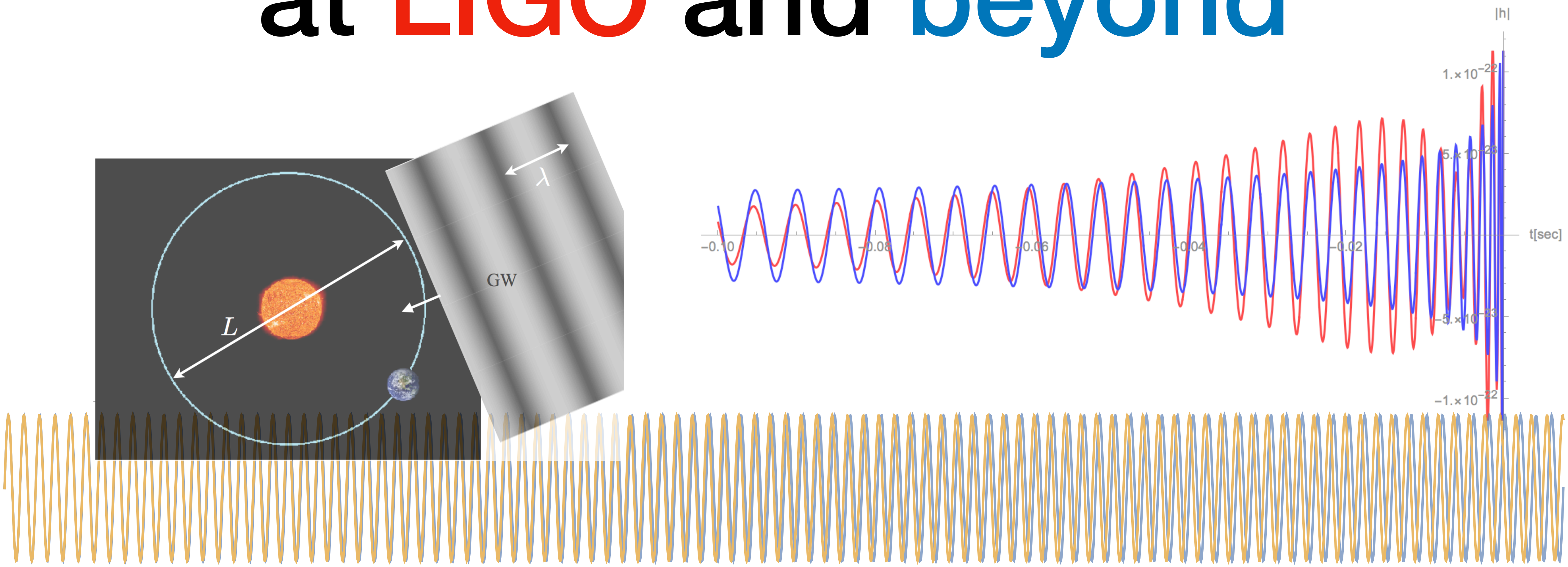
Probing Dark Matter at LIGO and beyond



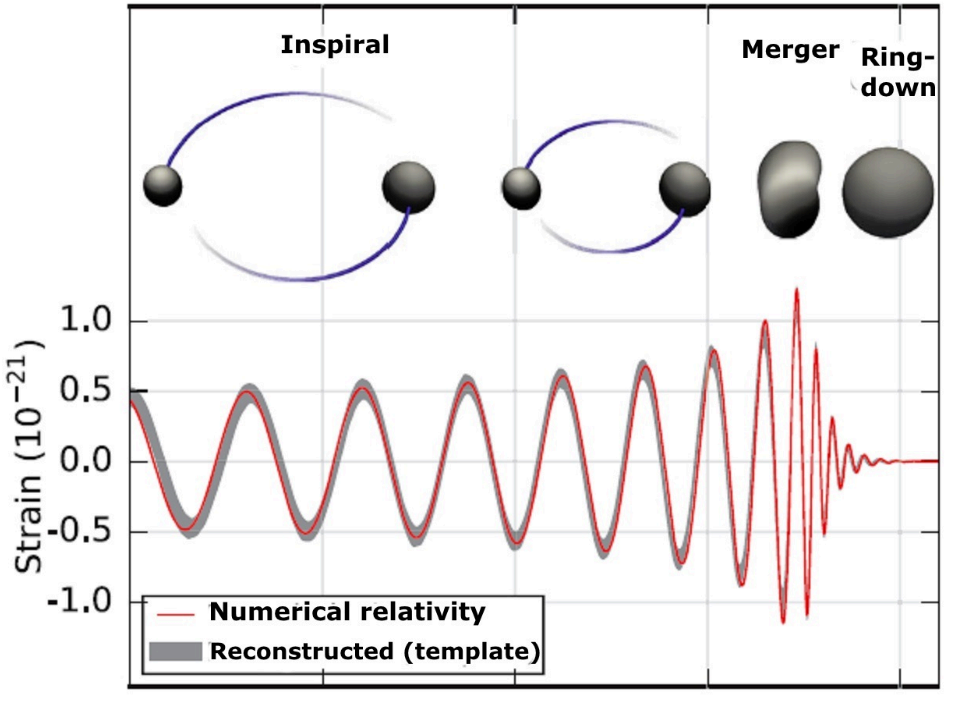
Sunghoon Jung
Seoul National University

Dark Odyssey 2020

- GW era!
  - What can we see?

- "seeing" = extracting encoded information.
  GW waveform evolution — *chirping* — is a key property.

- What "Dark Matter" info can be encoded & extracted?



Takehome messages

- LIGO (+ Mid-band) do provide precision capabilities for DM-frontier studies with chirping GW:

- 1. *LIGO alone* (10-1000Hz) : "GW Fringe"

- 2. *LIGO* + *mid-band* (0.01-1000Hz) synergies :
  "The *highest frequency*-band with *year-long* binary lifetime"

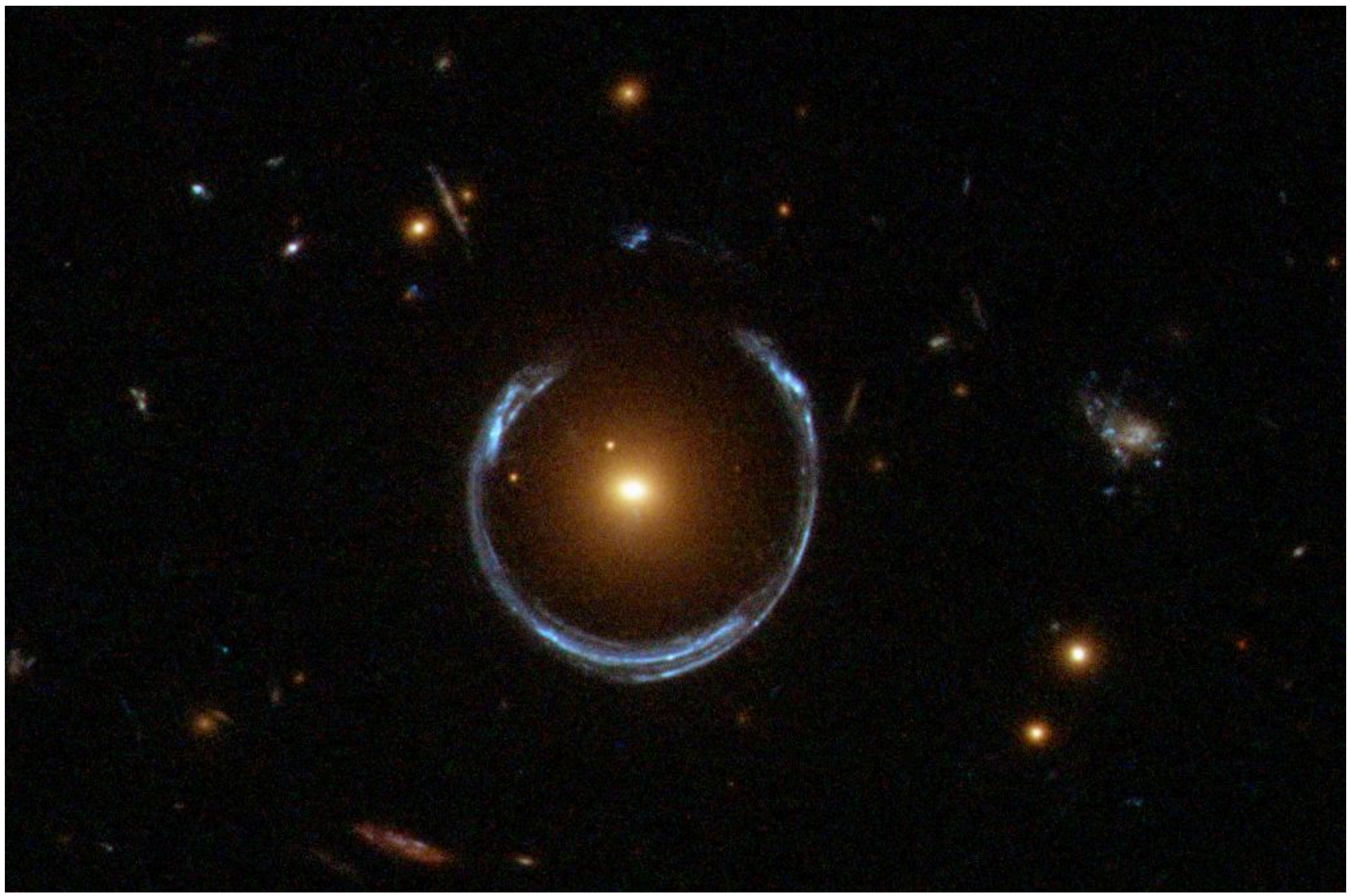
LIGO can see compact DM:

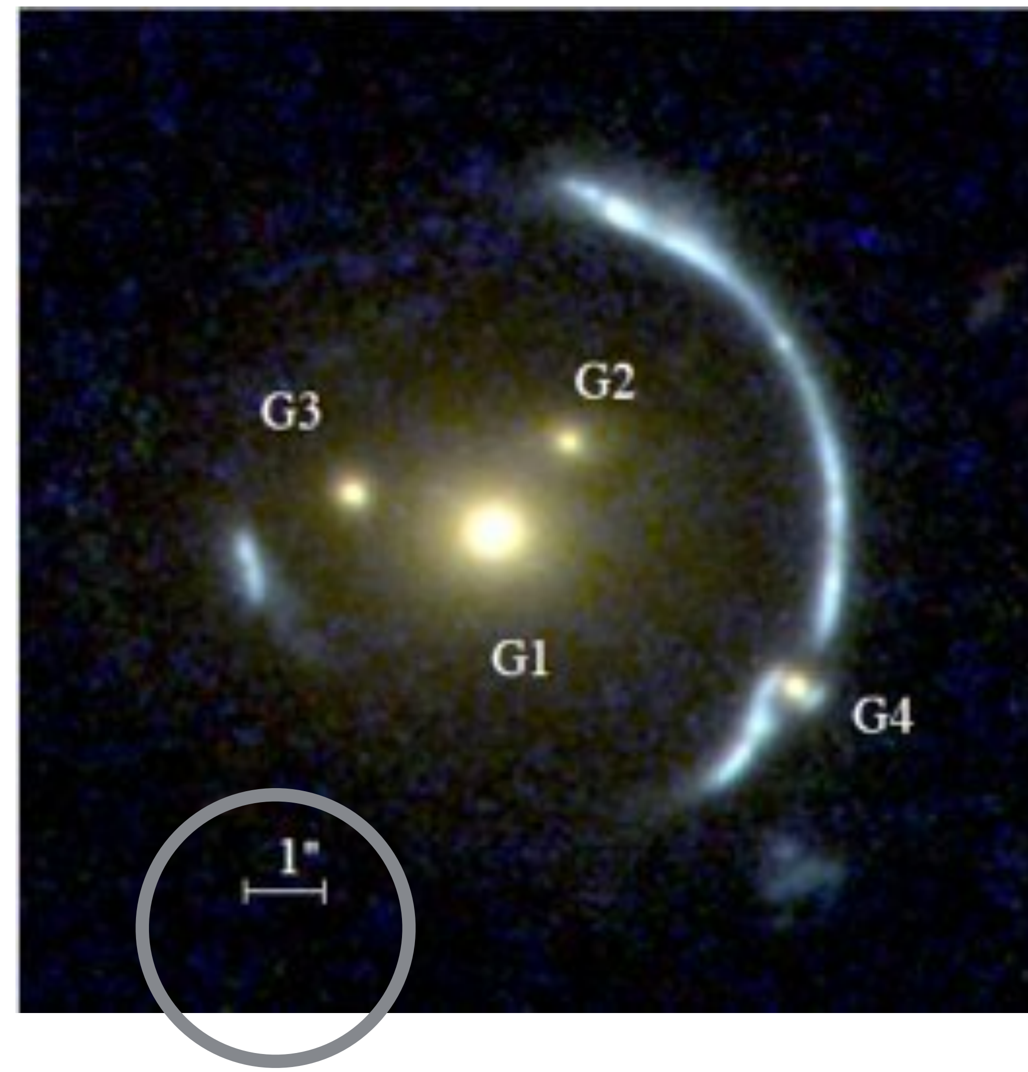
(Primordial BH, Dark stars/clusters/solitons)

"GW (lensing) Fringe"

1712.01396 PRL (2019), S.Jung et al.

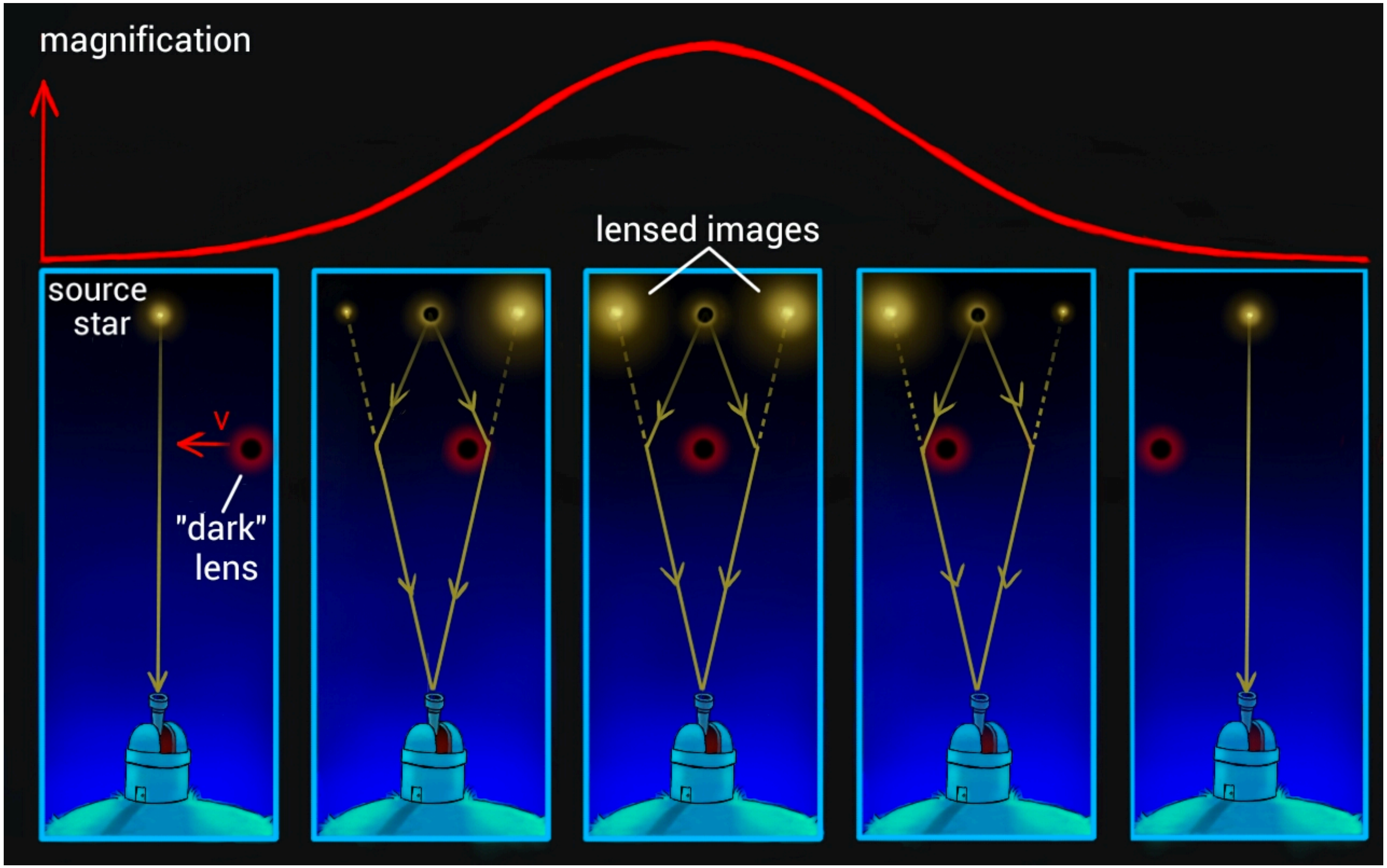
Strong lensing of light





- Multiple images (with <arcsec separation) or Einstein ring.

Micro lensing of light



- Time-variation of brightness over a few days to weeks.

Weak lensing of light

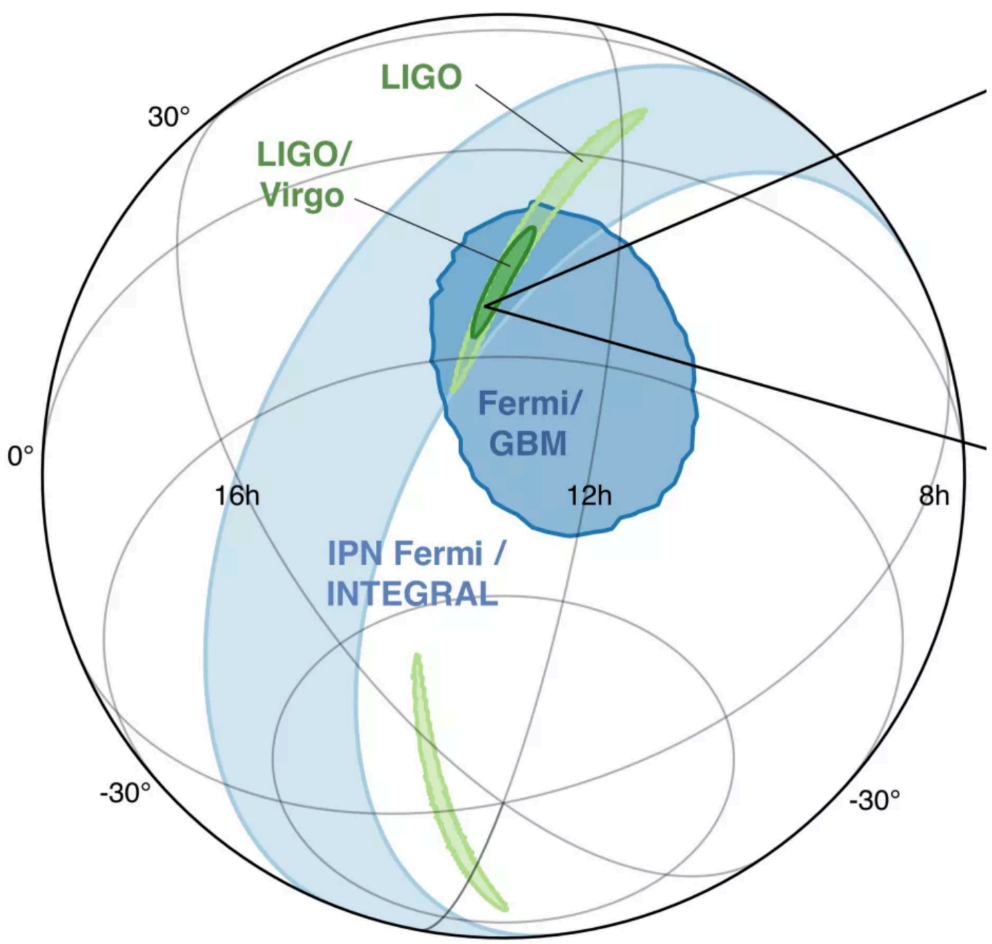
- Complicated statistical analysis of multiply and weakly lensed lights.

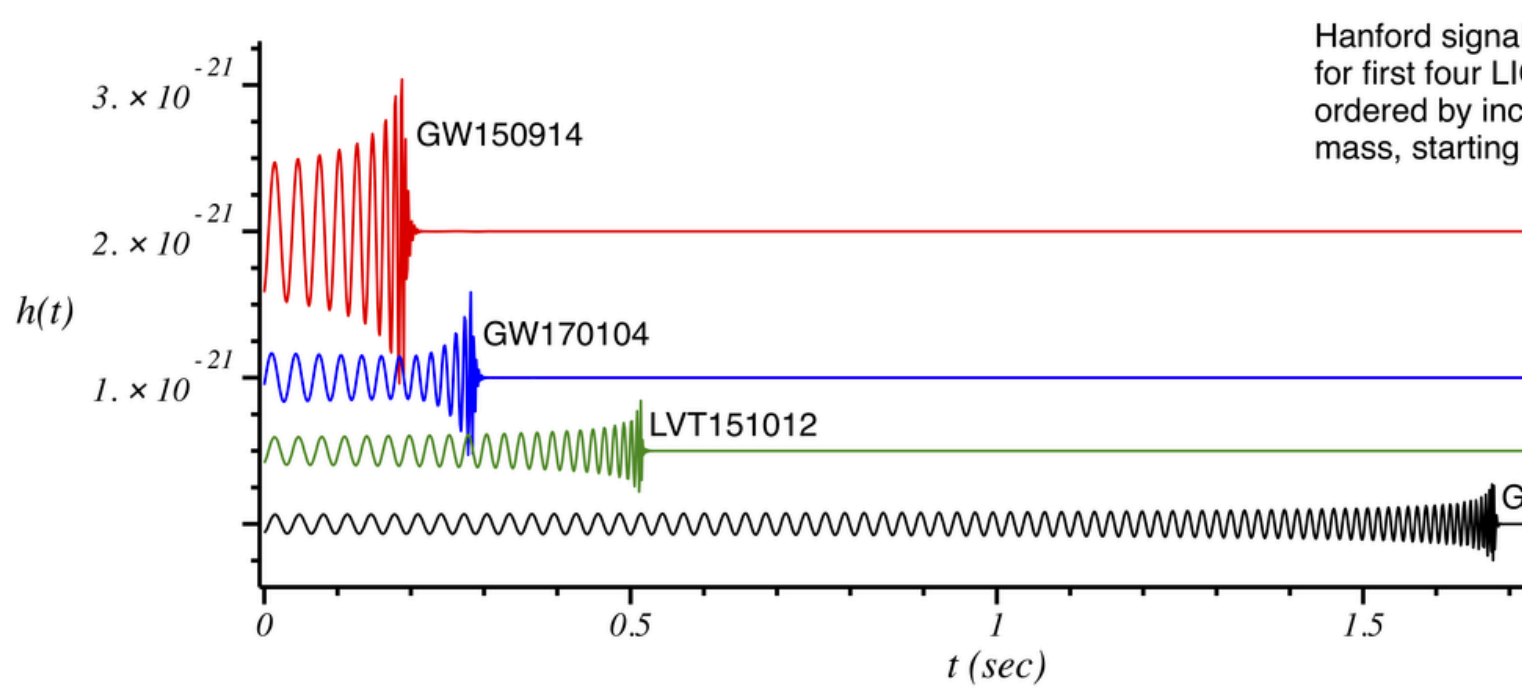
GW lensing observation seems very unlikely at LIGO!

LIGO can see only with

(1) angular resolution > 1 deg (let alone arcsec)

(2) measurement time < 1 sec ~ 1min (let alone days)





GW vs. light

Even though they follow the same null geodesics,,,

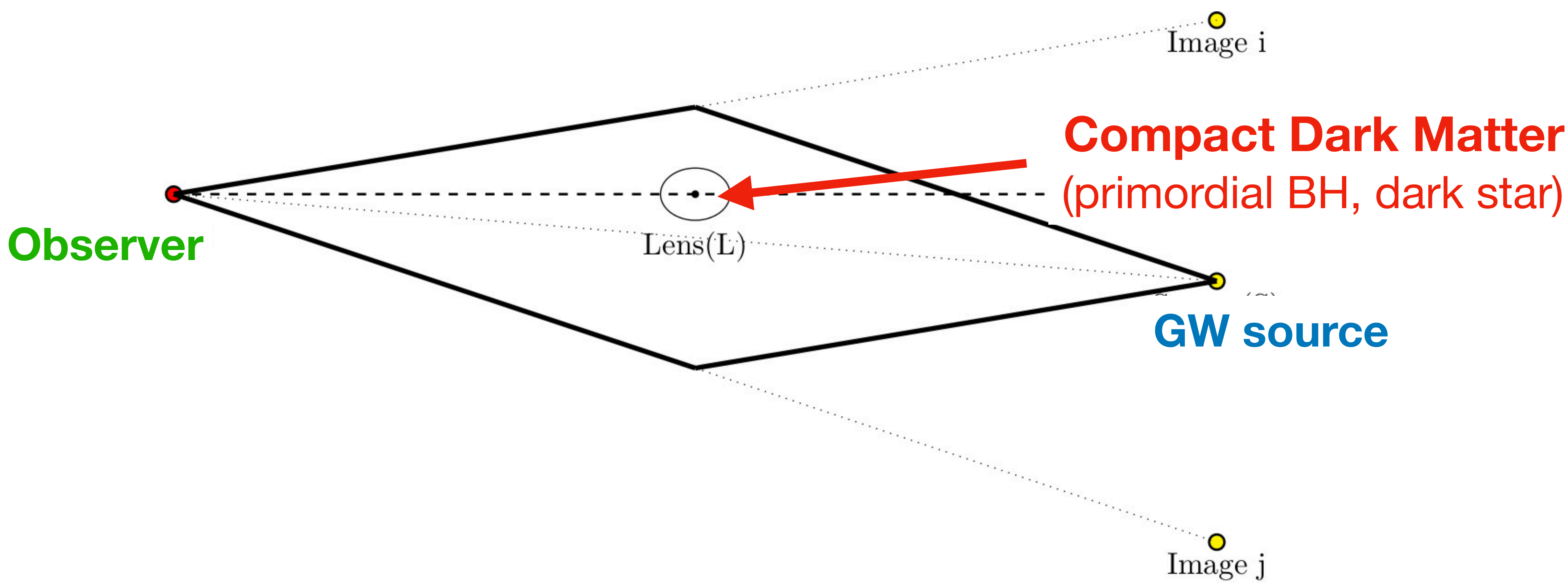
- GW chirps.
  - It provides non-trivial specific *change* of lensing pattern, which is extremely useful in lensing detection.

- GW angular resolution is much worse.
  - It actually turns out to provide a new observable!

- (GW wavelength is typically much longer.)

Time-delayed images

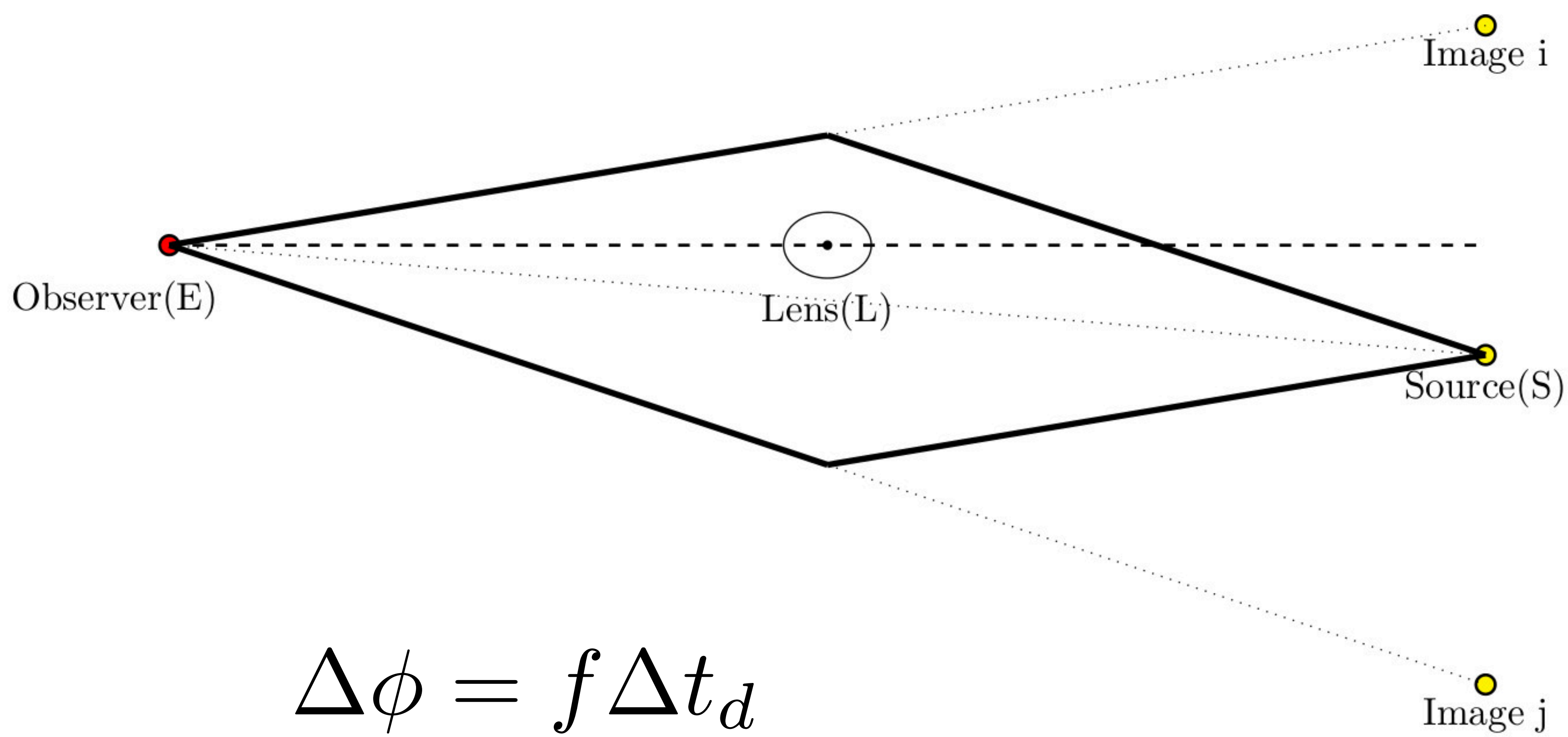
Consider time-delayed lensed images of GW.



$$\Delta t_d \sim 4GM_{\rm DM} = \ 2 \times 10^{-5} (M_{\rm DM}/M_\odot) \ \text{sec}$$

Interfered images

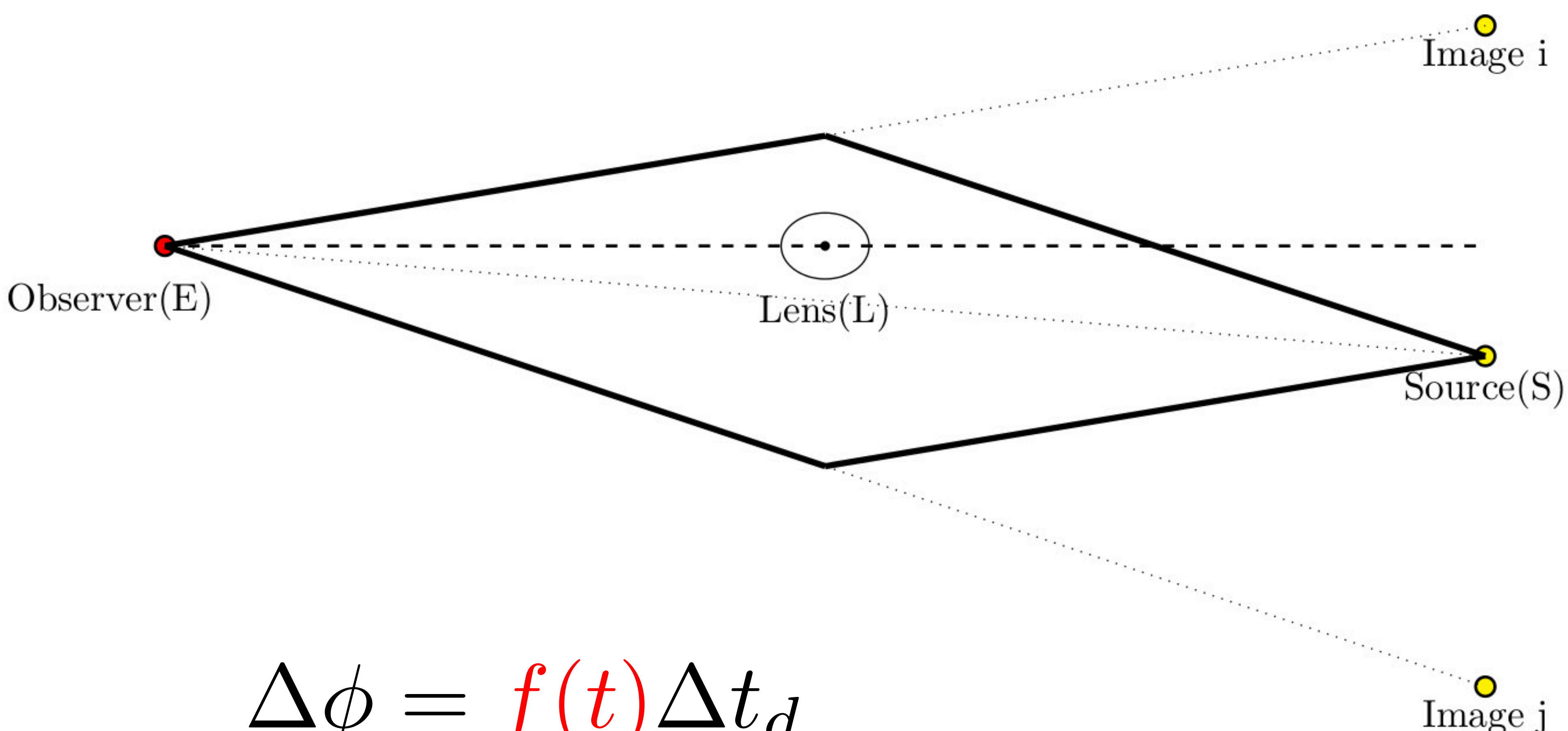
Unresolved GW images rather “interfere” in our observation.



$$\Delta\phi = f\Delta t_d$$

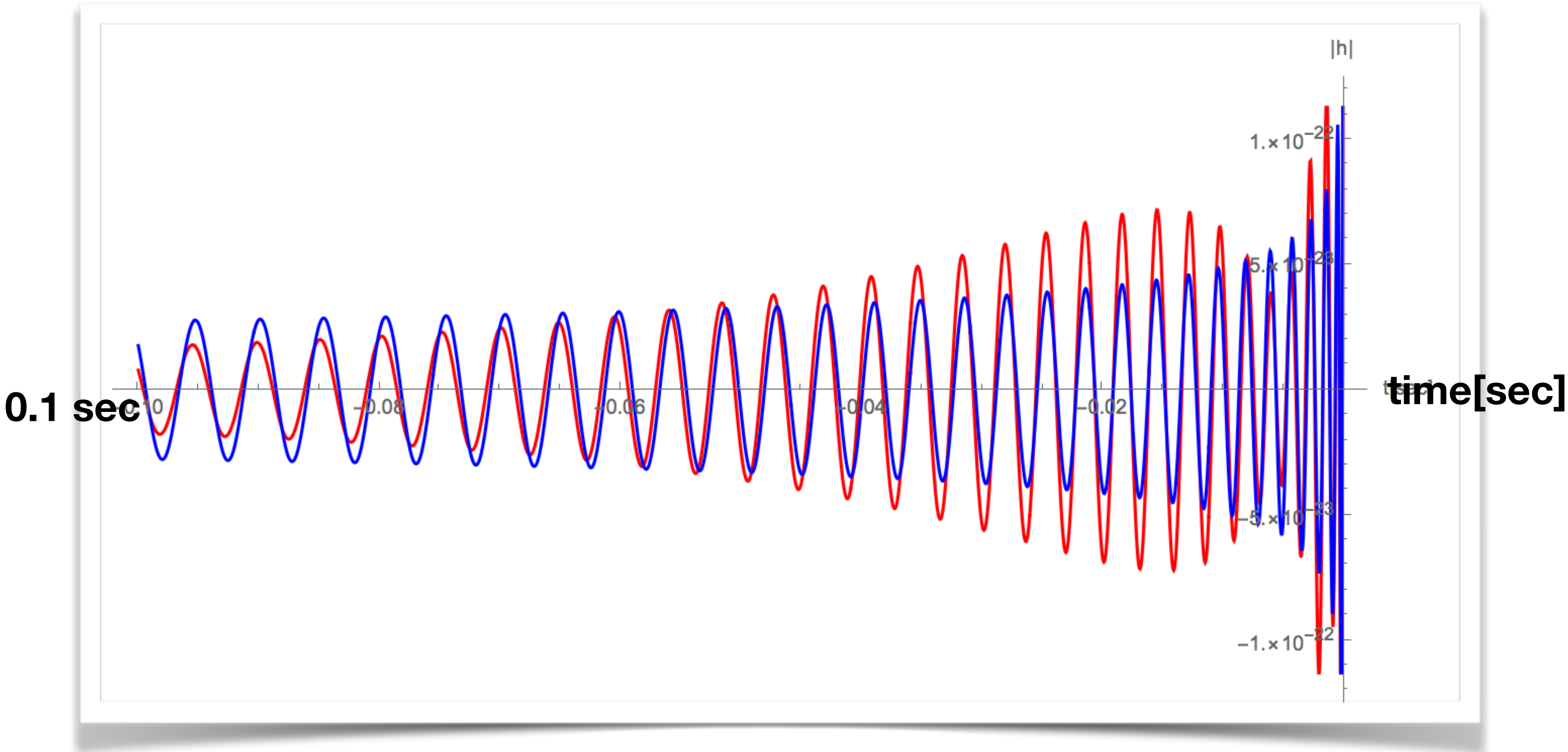
GW lensing Fringe

It is the *GW chirping* that makes the interference observable — sweeping the interference pattern over a range of freq.



$$\Delta\phi = f(t)\Delta t_d$$

“GW Fringe”



NS-NS merger lensed by 100 Msun compact DM.

ars TECHNICA — BIZ & IT | TECH | SCIENCE | POLICY | CARS | GAMING & CULTU

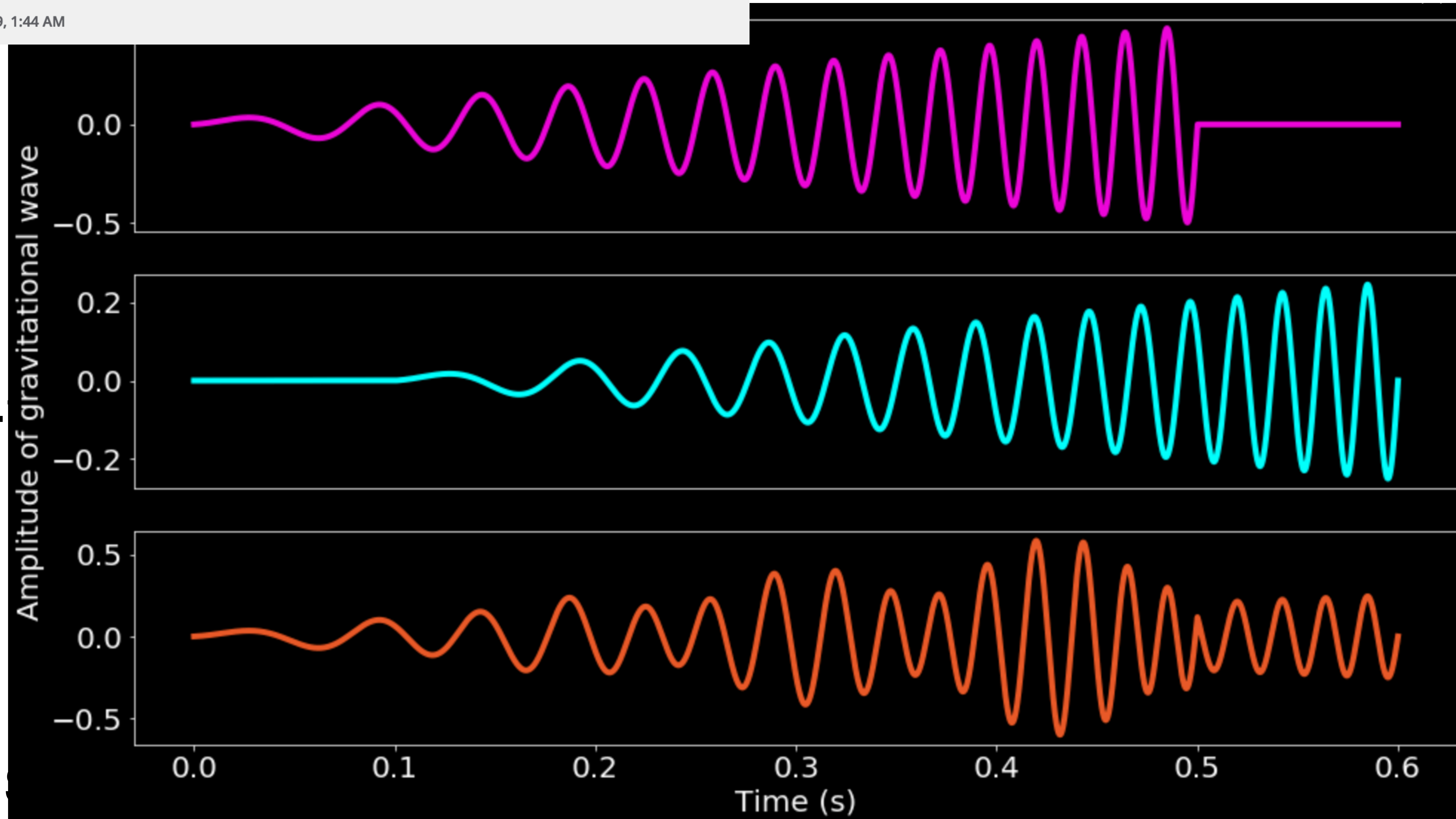
CHIRPING BLACK HOLES —

Lonely black holes revealed by passing gravitational waves

Black hole mergers may reveal large black holes in the foreground.

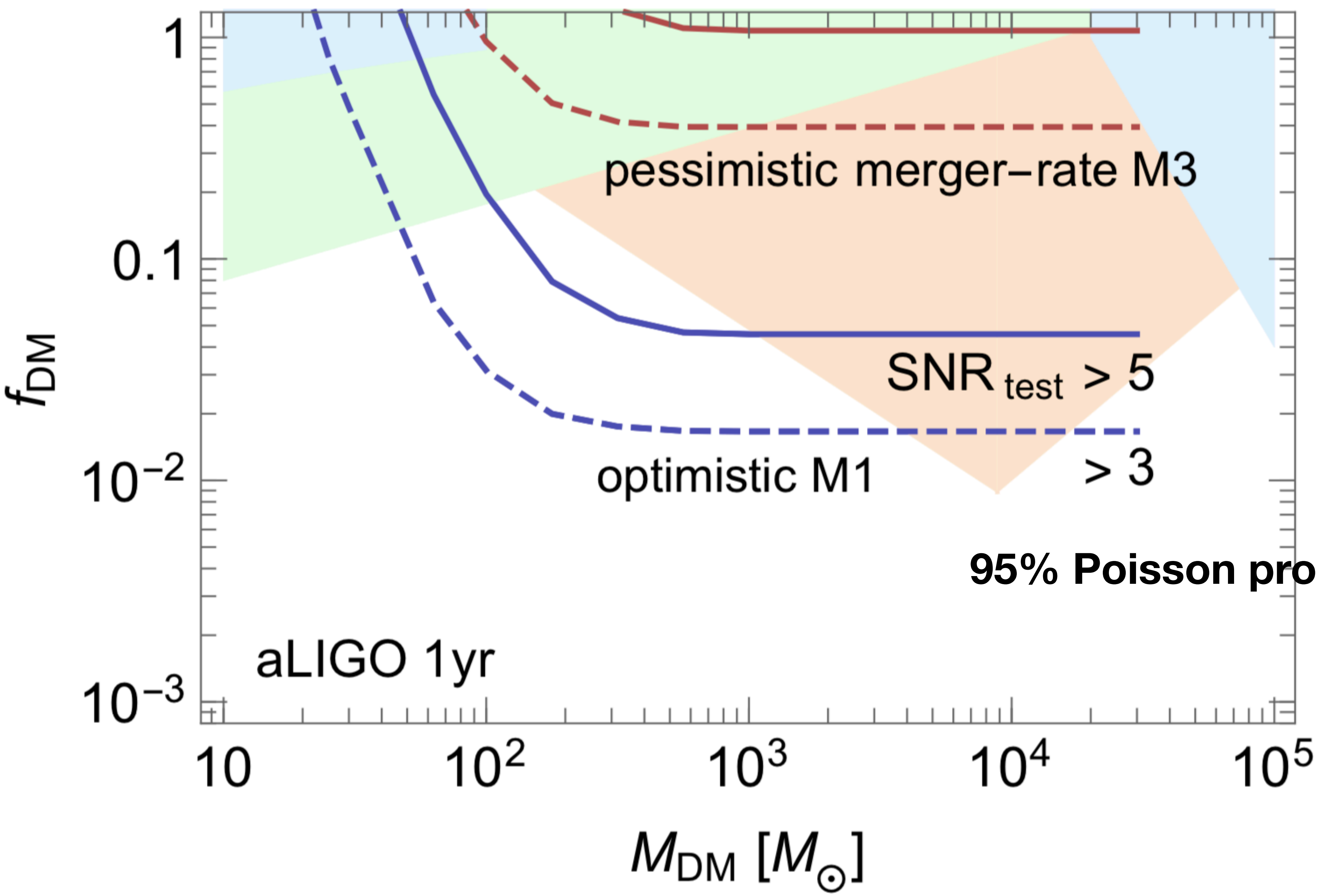
CHRIS LEE - 2/7/2019, 1:44 AM

"GW Fringe"



Top signal is the chirp that arrives directly from the merger. The middle signal has been delayed by a gravitational lens. The bottom signal is the signal we would measure. An analysis of the measured signal may reveal the gravitational lens.

Compact DM fraction



95% Poisson prob of >=1 detection

1712.01396 PRL (2019), S.Jung et al.

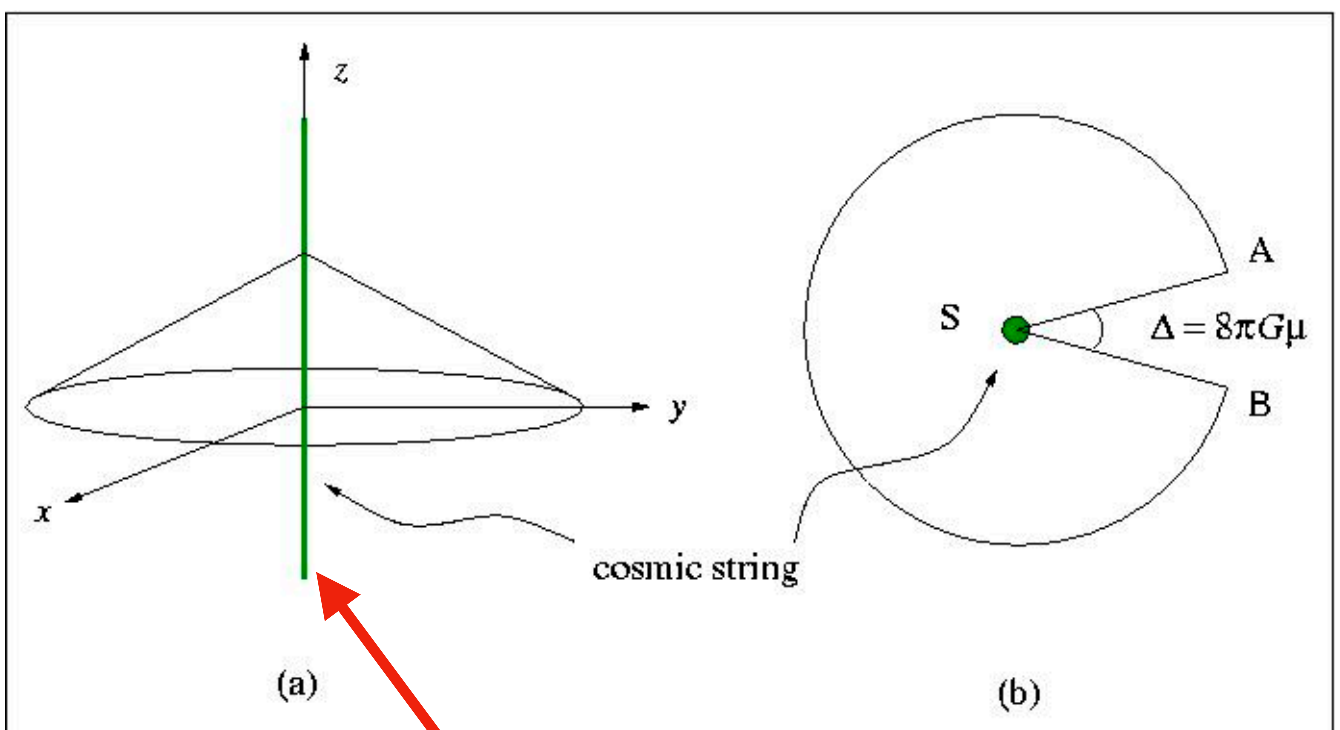
LIGO is an ideal DM Fringe detector

- GW Fringe is most pronounced at LIGO:
    - Highest frequency, producing most # of fringes.
    - Chirping most quickly near merger.

- Highest-frequency GW can see the smallest compact DM.
  (10-1000 Hz = 10^2-10^4 Msun Schw radius)

GW Fringe from Cosmic string

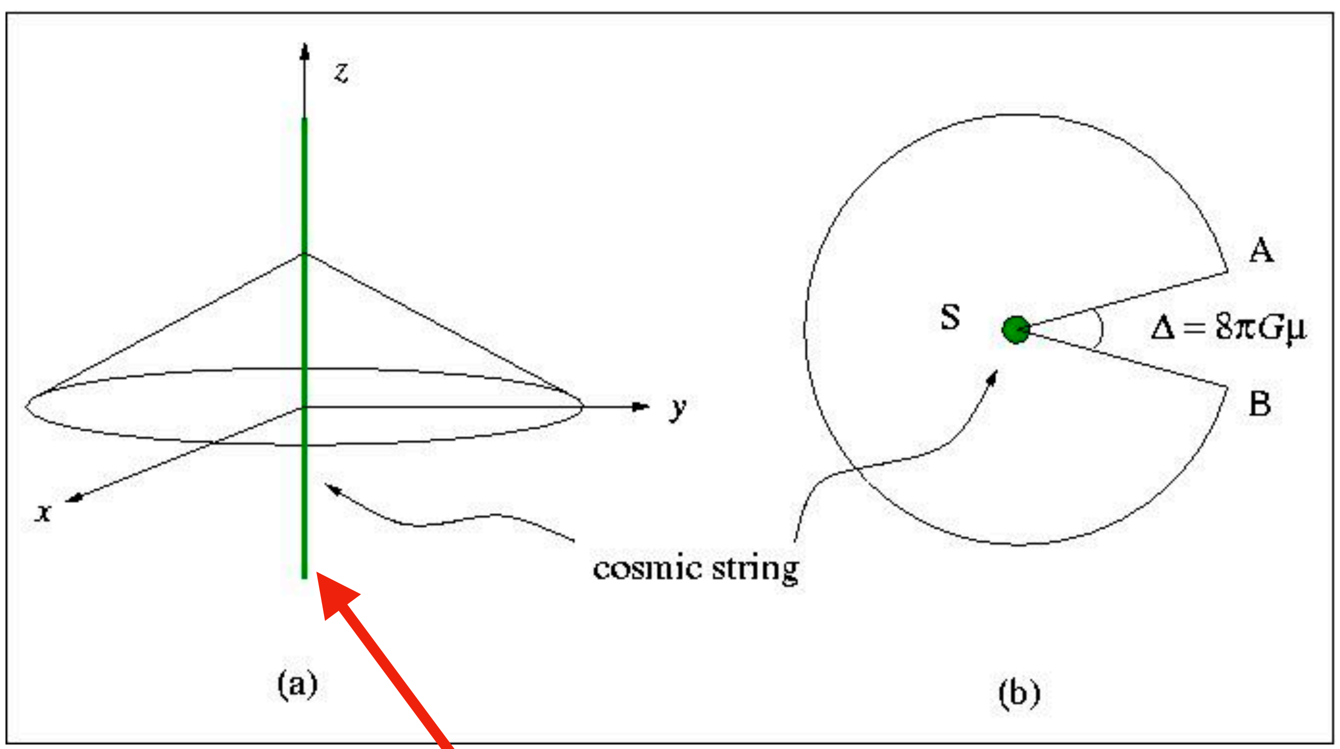
- A new way to see “cosmic strings”



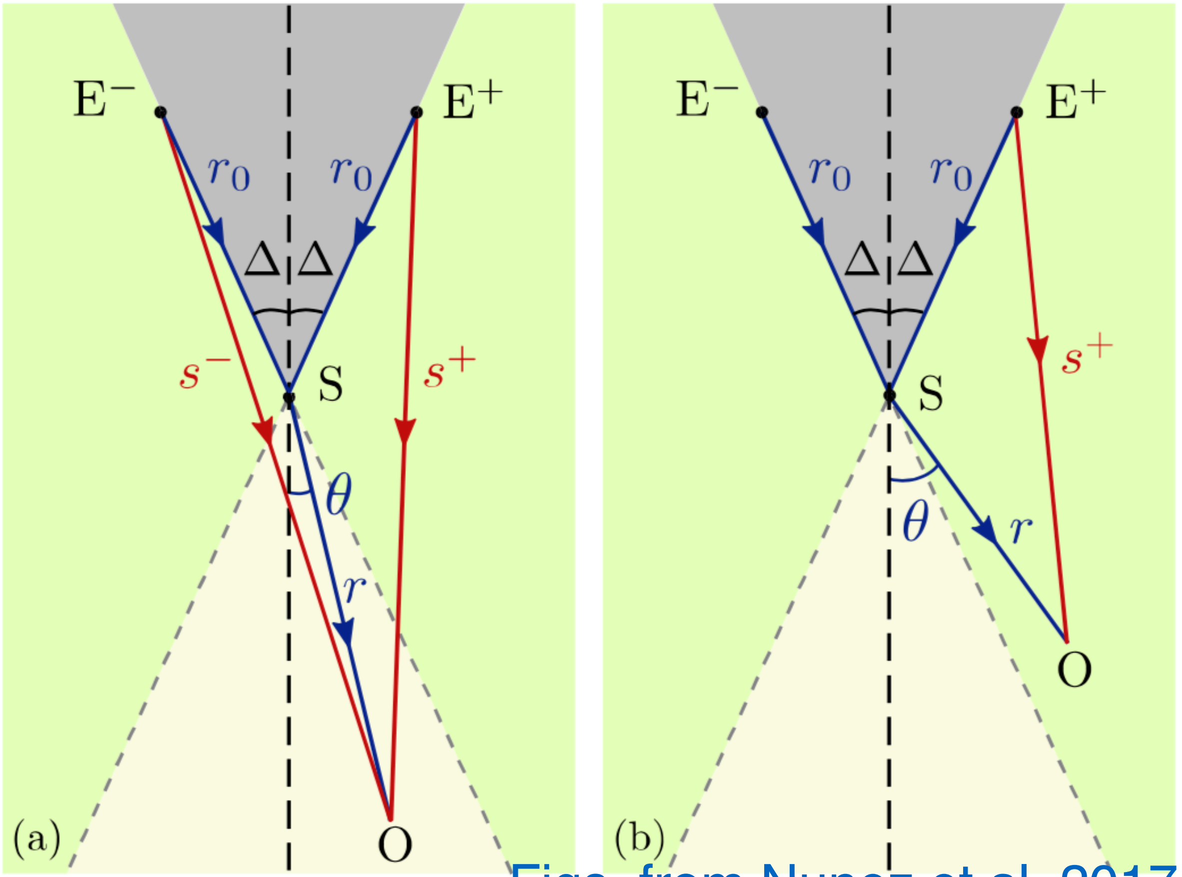
Cosmic String = 1-dim energy locus

GW Fringe from Cosmic string

- A new way to see "cosmic strings"
- GW Fringe from the interference btwn *three* rays:
  2 geometric rays + 1 diffracted ray

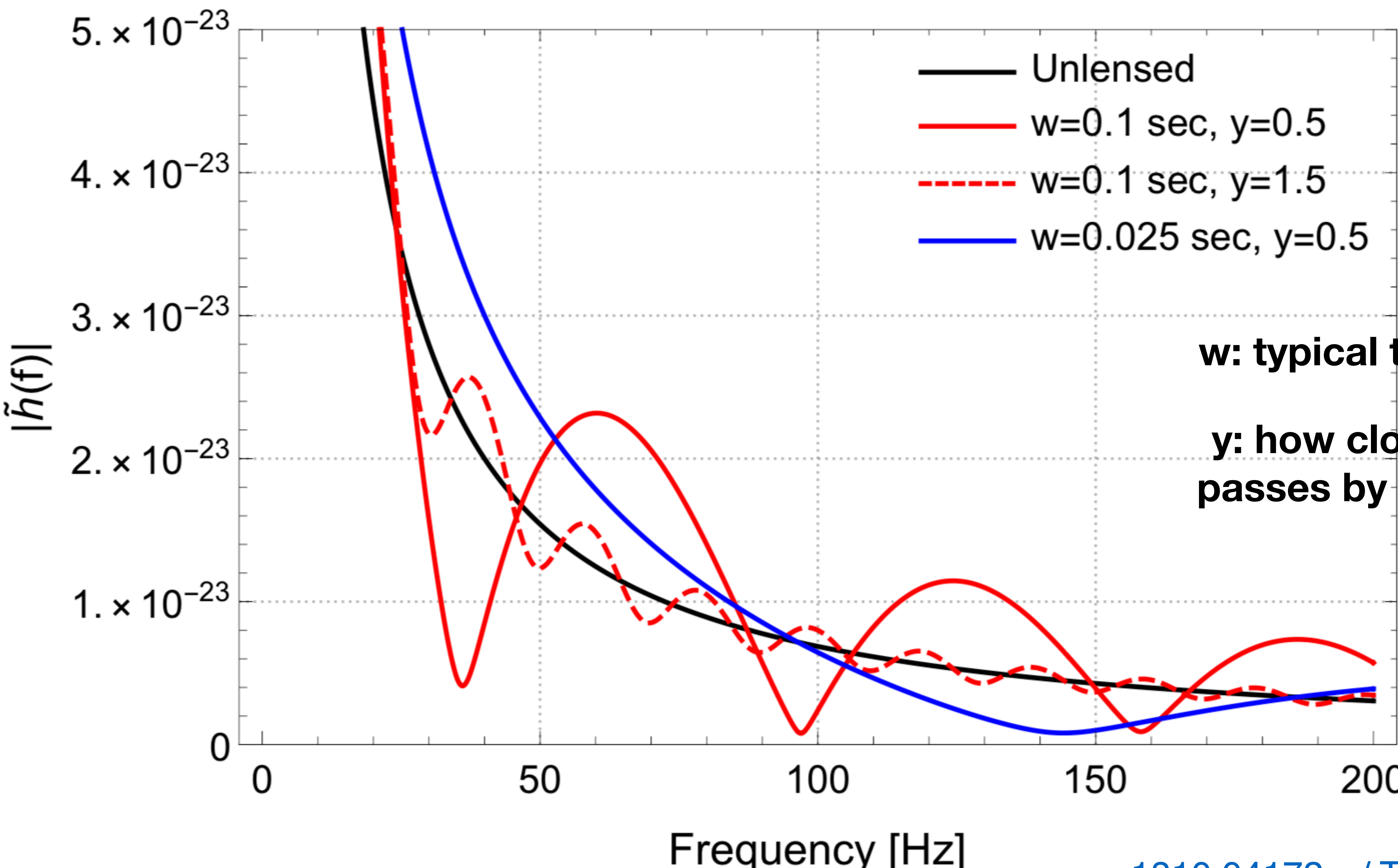


Cosmic String = 1-dim energy locus



Figs. from Nunez et al. 2017

GW Fringe from Cosmic string

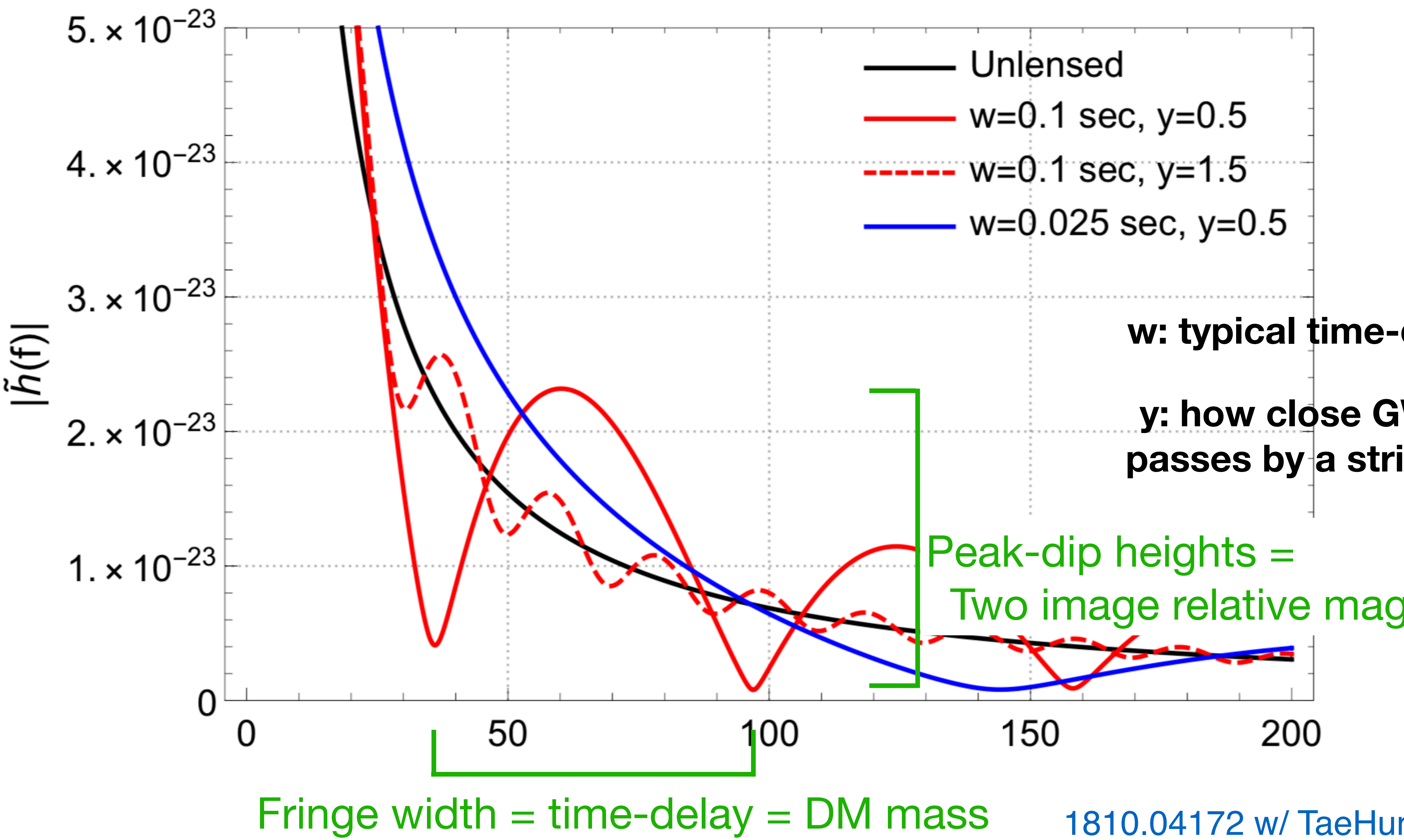


w: typical time-delay

y: how close GW passes by a string

1810.04172 w/ TaeHun Kim

GW Fringe from Cosmic string



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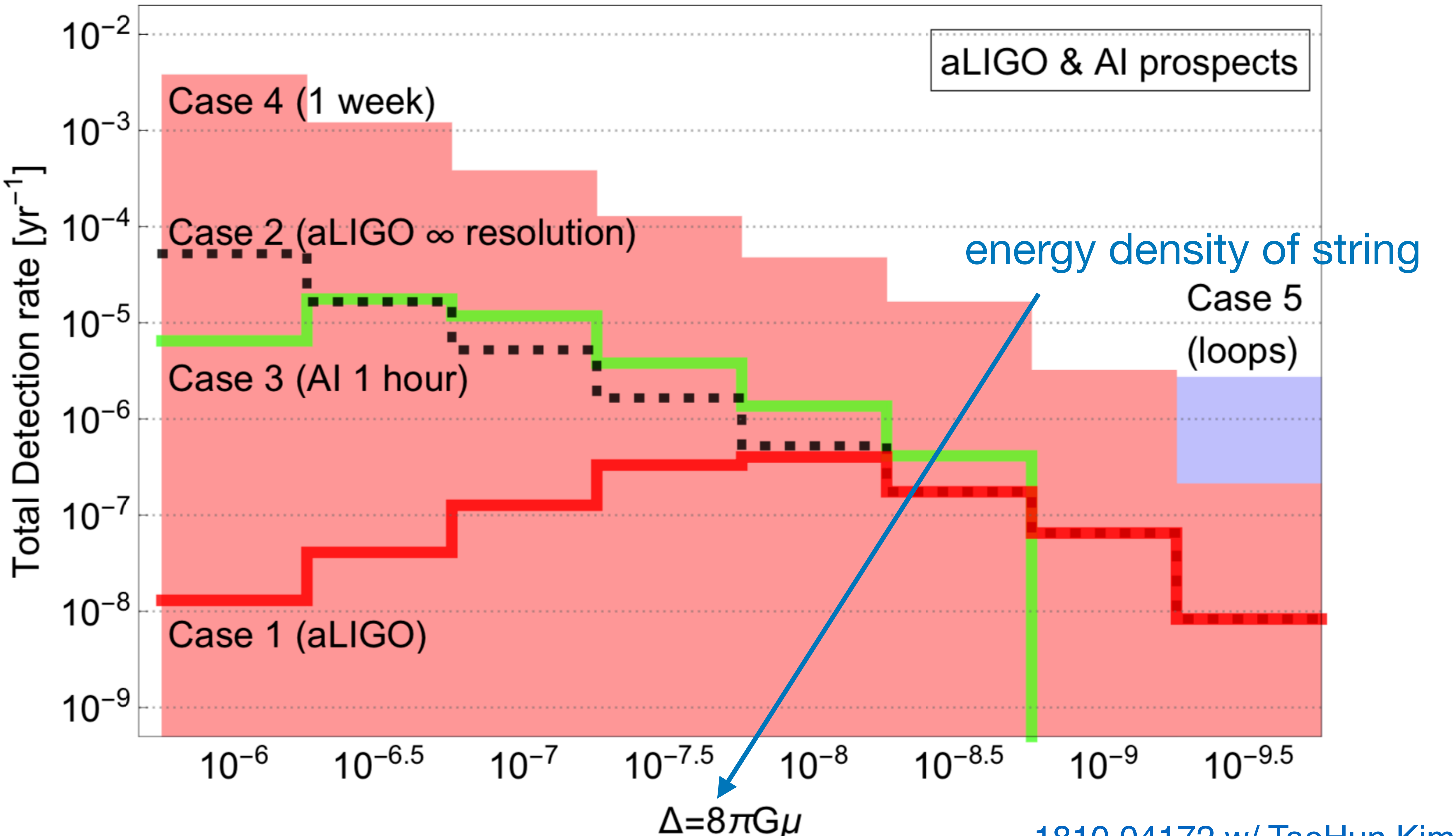
1810.04172 w/ TaeHun Kim

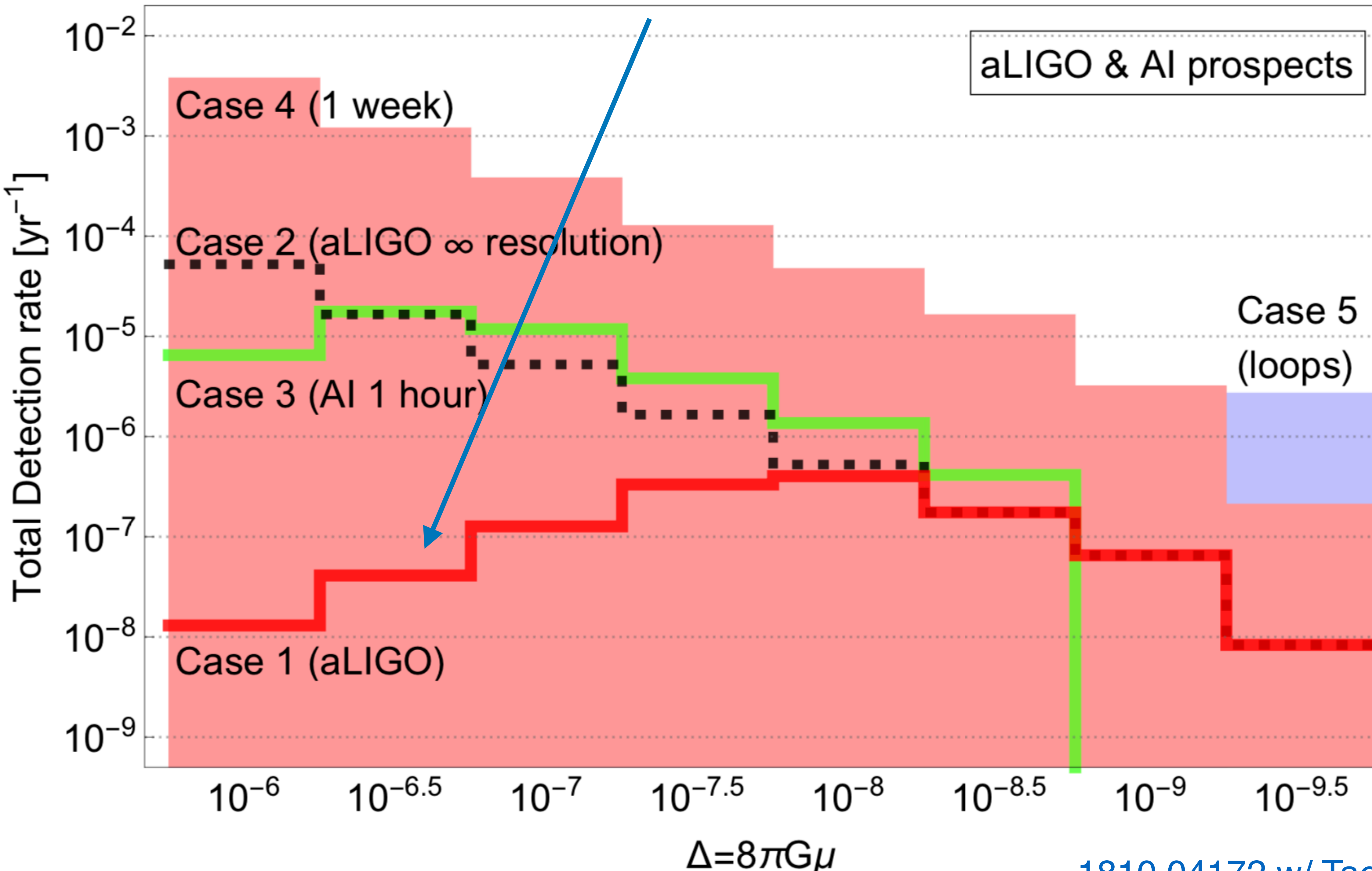
Detection prospects



1810.04172 w/ TaeHun Kim

Detection prospects

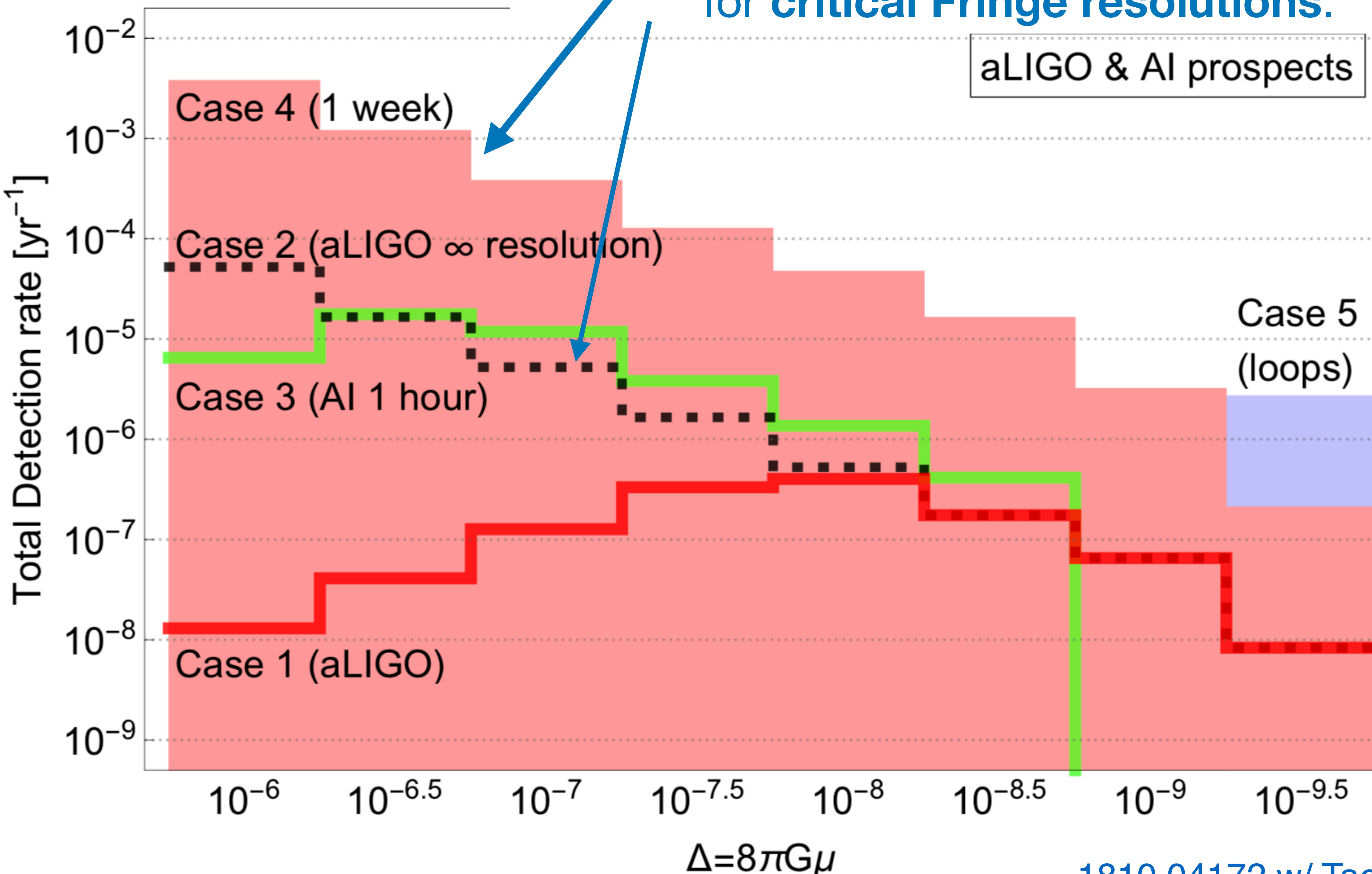
Why is heavier string harder to probe at LIGO?



1810.04172 w/ TaeHun Kim

Detection prospects

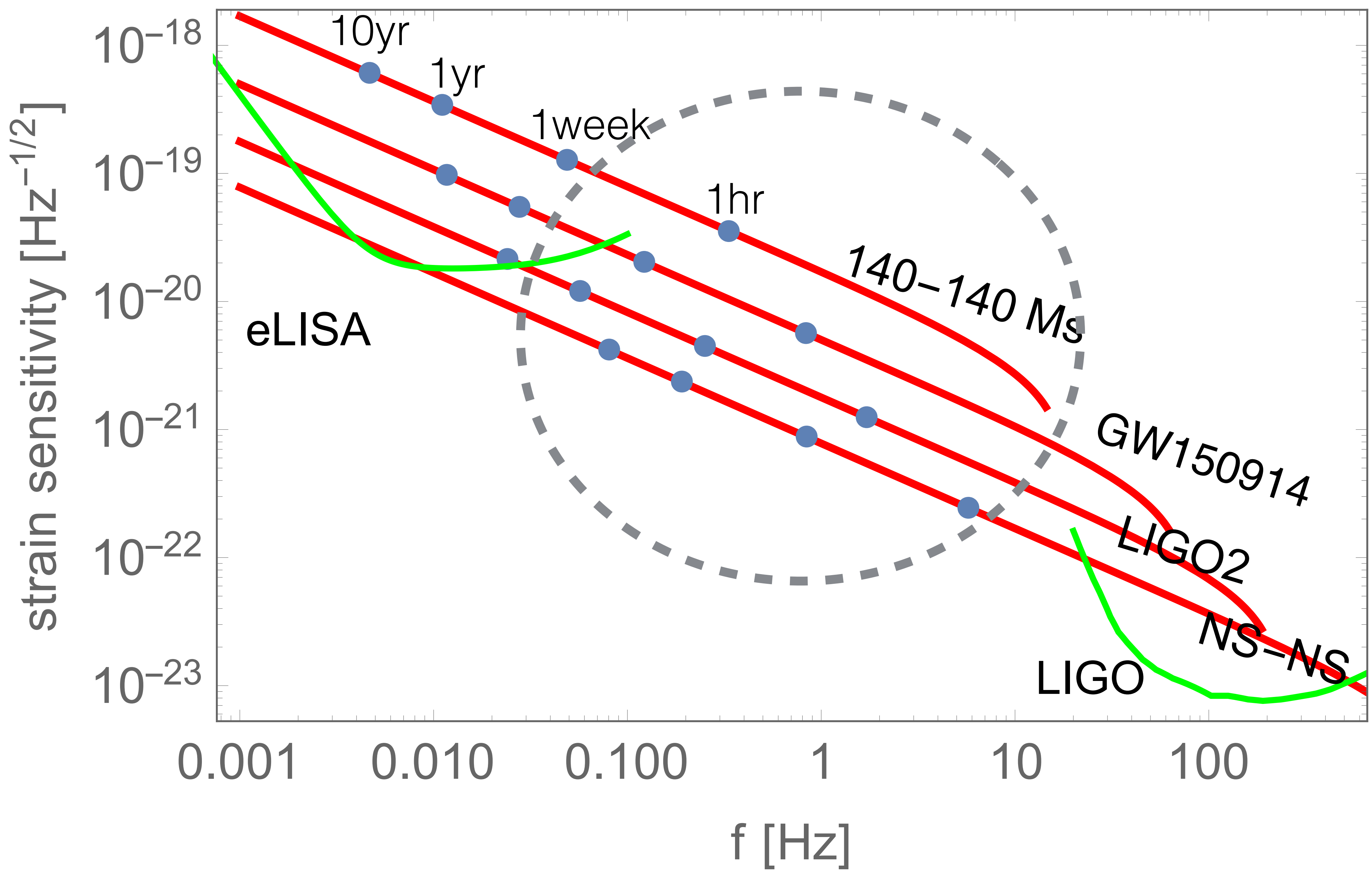
“LIGO + mid-band” allows longer measurements for **critical Fringe resolutions**.



1810.04172 w/ TaeHun Kim

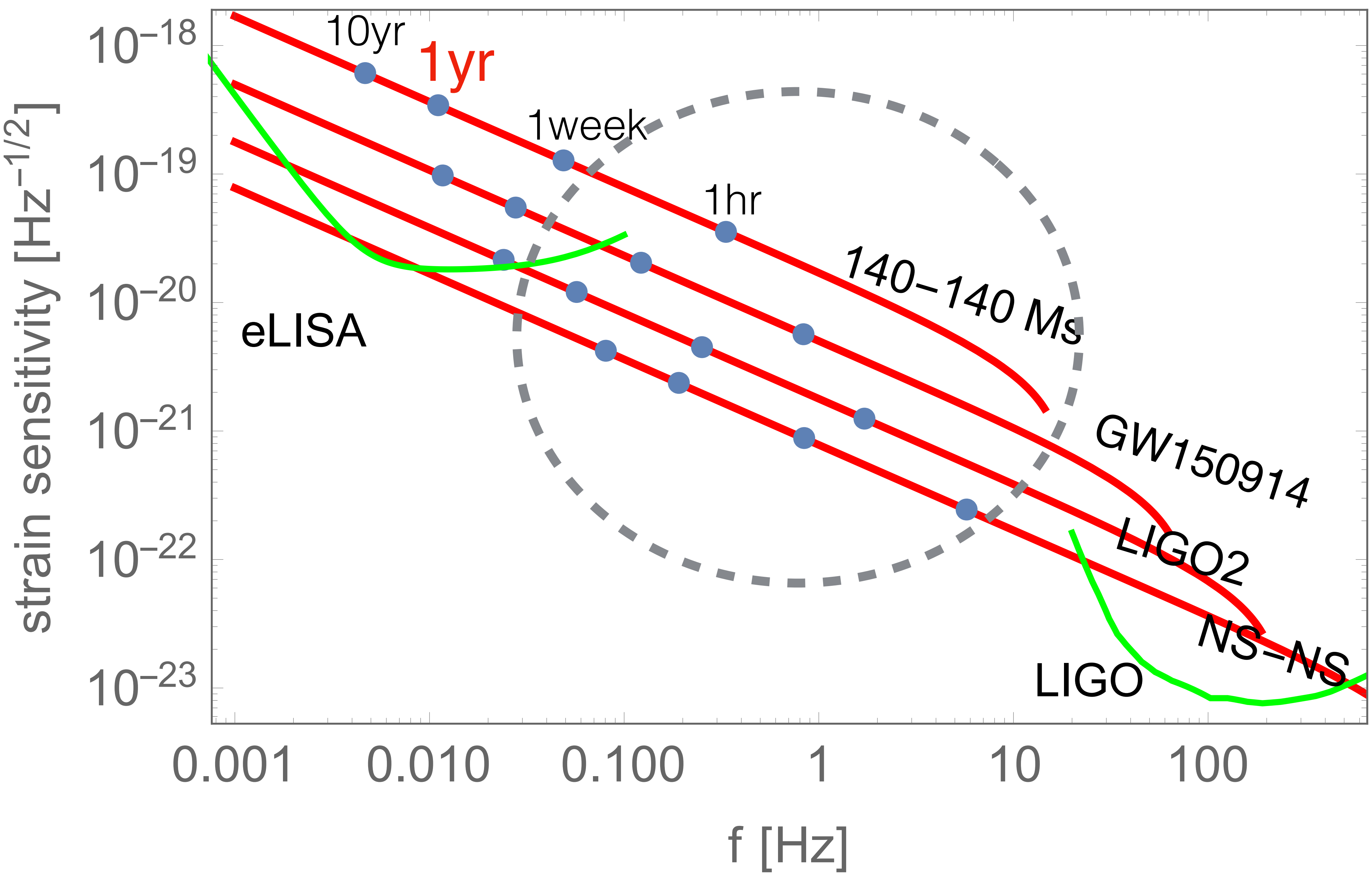
Mid-frequency band

Is mid-frequency just an interpolation btwn LIGO and LISA?



Mid-frequency band

No! Forming a highest-frequency band with year-long measurement,,,



Synergy of LIGO + Mid-band

- Unique & precision test-bed for dark matter:

- 1. Various **Dark matter effects** are most pronounced here!

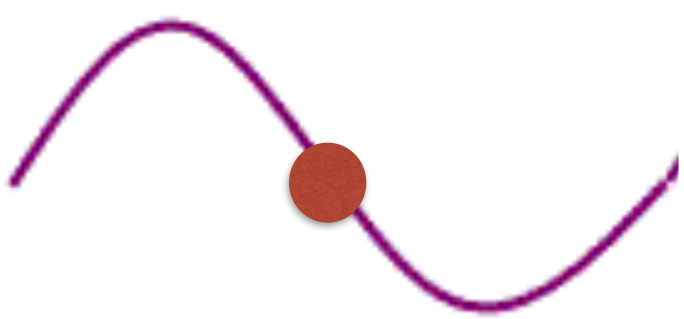
[PRD (2019) with Han Gil Choi, 1810.04172 with TaeHun Kim]

- 2. **GW Localization** on the sky is most naturally well done here too!

[PRD (2018) with Peter W. Graham]

DM wave

- Lightest possible spin-0 DM 10^-22 eV. (cf. m(electron)=0.5 MeV)



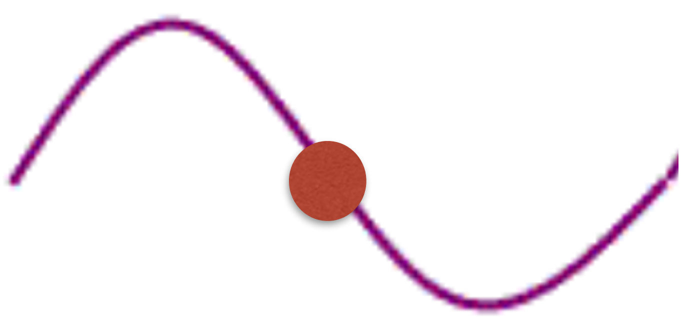
$$\phi(t) \propto \cos m_\phi t$$

Compton frequency $\frac{1}{m_\phi} = \frac{\hbar}{m_\phi c}$ ~ **1 yr** for 10^-22 eV, **1 min** for 10^-16 eV

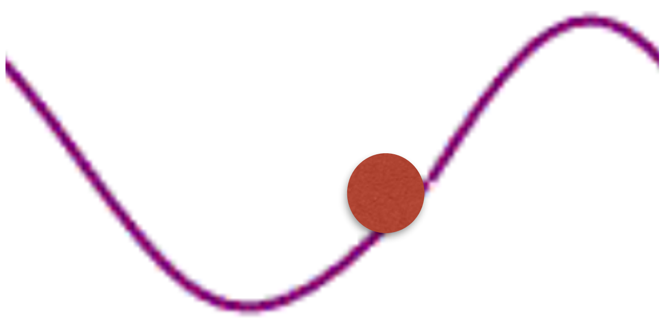
DM wave

- Lightest possible spin-0 DM 10^-22 eV. (cf. m(electron)=0.5 MeV)

$$\phi(t) \propto \cos m_\phi t \qquad \phi(t) \propto \cos(m_\phi t + \alpha)$$



+

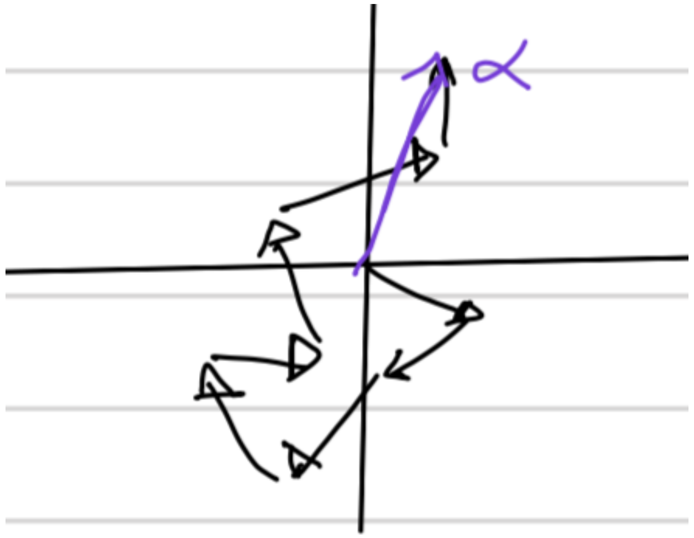


Second DM quanta with "same Compton frequency" but with "different phase" is added.

DM wave

- Lightest possible spin-0 DM 10^-22 eV. (cf. m(electron)=0.5 MeV)

$$\phi(t) \propto \sqrt{N_{\rm DM}} \cos m_\phi t$$

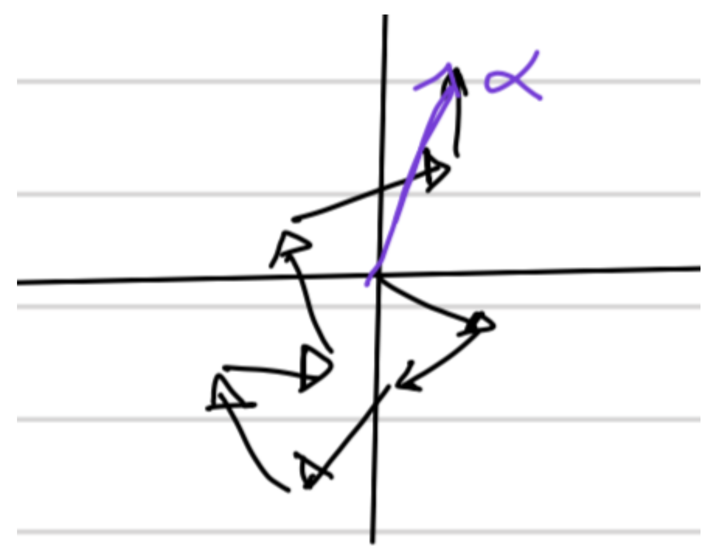


Adding N DM quanta is a “N-random walk”.

DM wave

- Lightest possible spin-0 DM 10^-22 eV. (cf. m(electron)=0.5 MeV)
- Although light, their effects are astronomically enhanced and time-oscillating.
- GW is again an exciting lab to probe them.

$$\phi(t) \propto \sqrt{N_{\rm DM}} \cos m_\phi t$$



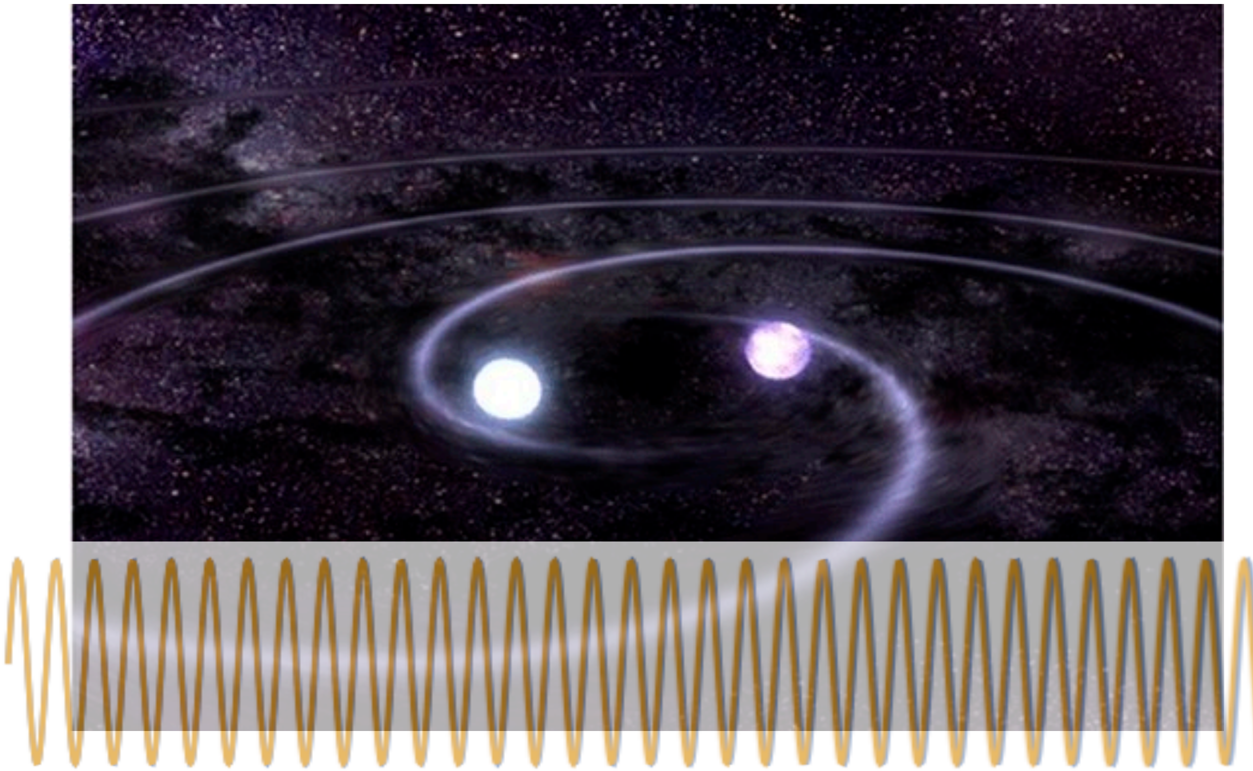
Neutron mass-shift

- If such scalar DM interacts with the neutron,
  the neutron-star mass shifts and oscillates in time.

$$\frac{\delta \mathcal{M}}{\mathcal{M}}(t) \propto \phi(t) \propto \sqrt{\rho_{\rm DM}}\cos m_\phi t$$

$$\frac{1}{m_\phi} = \frac{\hbar}{m_\phi c}$$

~ 1 yr for 10^-22 eV,   1 min for 10^-16 eV



Gravity inherently sensitive to mass-shift

GW exquisite sensitivity to mass-shift

- GW evolution is governed by the binary masses.

  → A tiny phase-shift due to mass-shift in each GW cycle accumulates over millions of GW cycles!

PRD(2019) H.G.Choi and S.Jung

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$$\frac{\Delta \mathcal{M}}{\mathcal{M}} \sim (\mathrm{SNR})(N_{\rm cyc}) \sim 10^{-8}$$

c.f.) $\Delta D_L / D_L \sim \mathrm{SNR} \sim 10^{-2}$

Ncyc ~ 10^7 huge enhancement

(for last 1-year measurement of NS-NS merger)

PRD(2019) H.G.Choi and S.Jung

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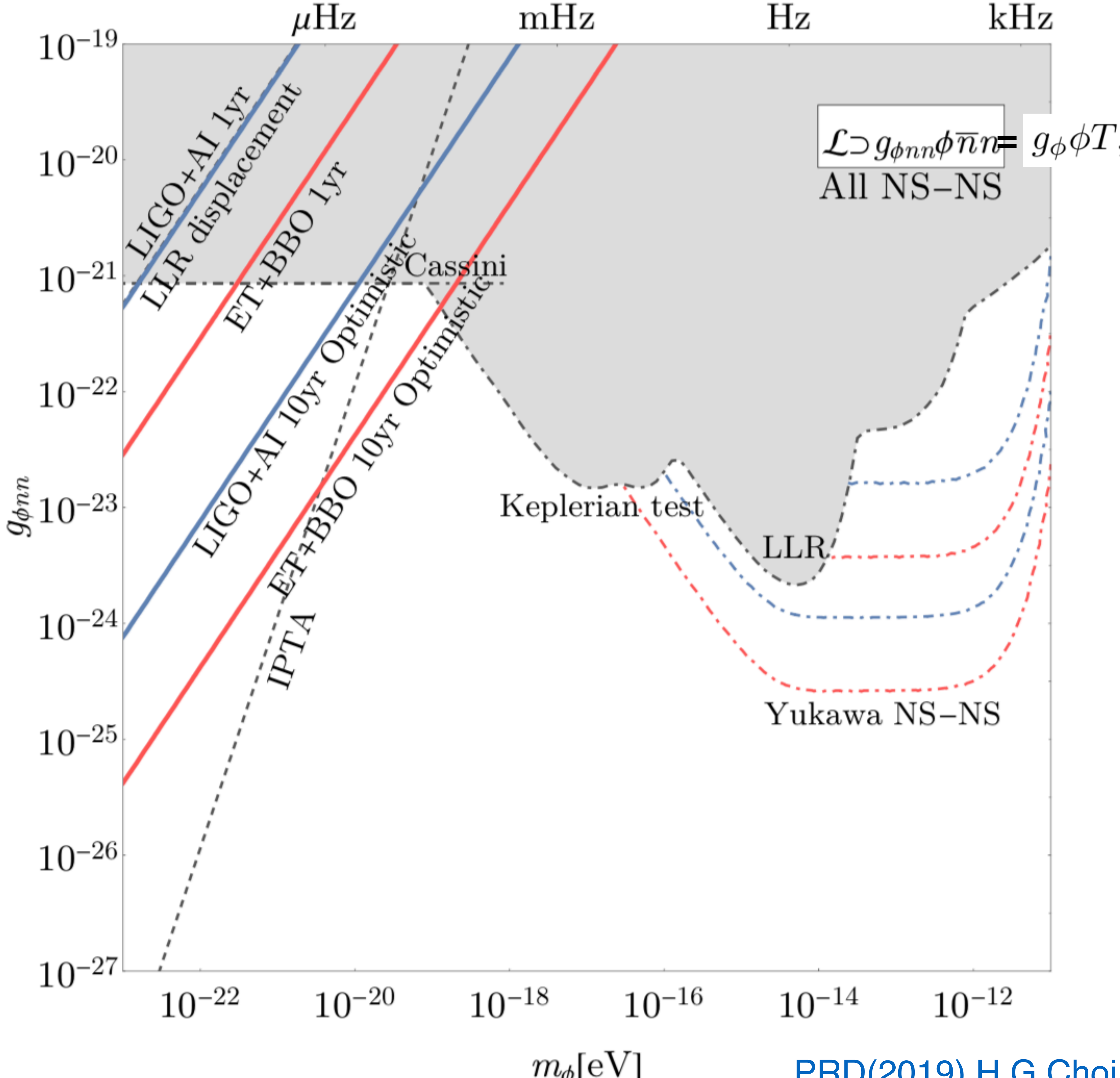
c.f.) $\Delta D_L / D_L \sim \mathrm{SNR} \sim 10^{-2}$

Ncyc ~ 10^7 huge enhancement

- Ncyc is max for highest-freq long-time measurement.

PRD(2019) H.G.Choi and S.Jung

Detection prospects



PRD(2019) H.G.Choi and S.Jung

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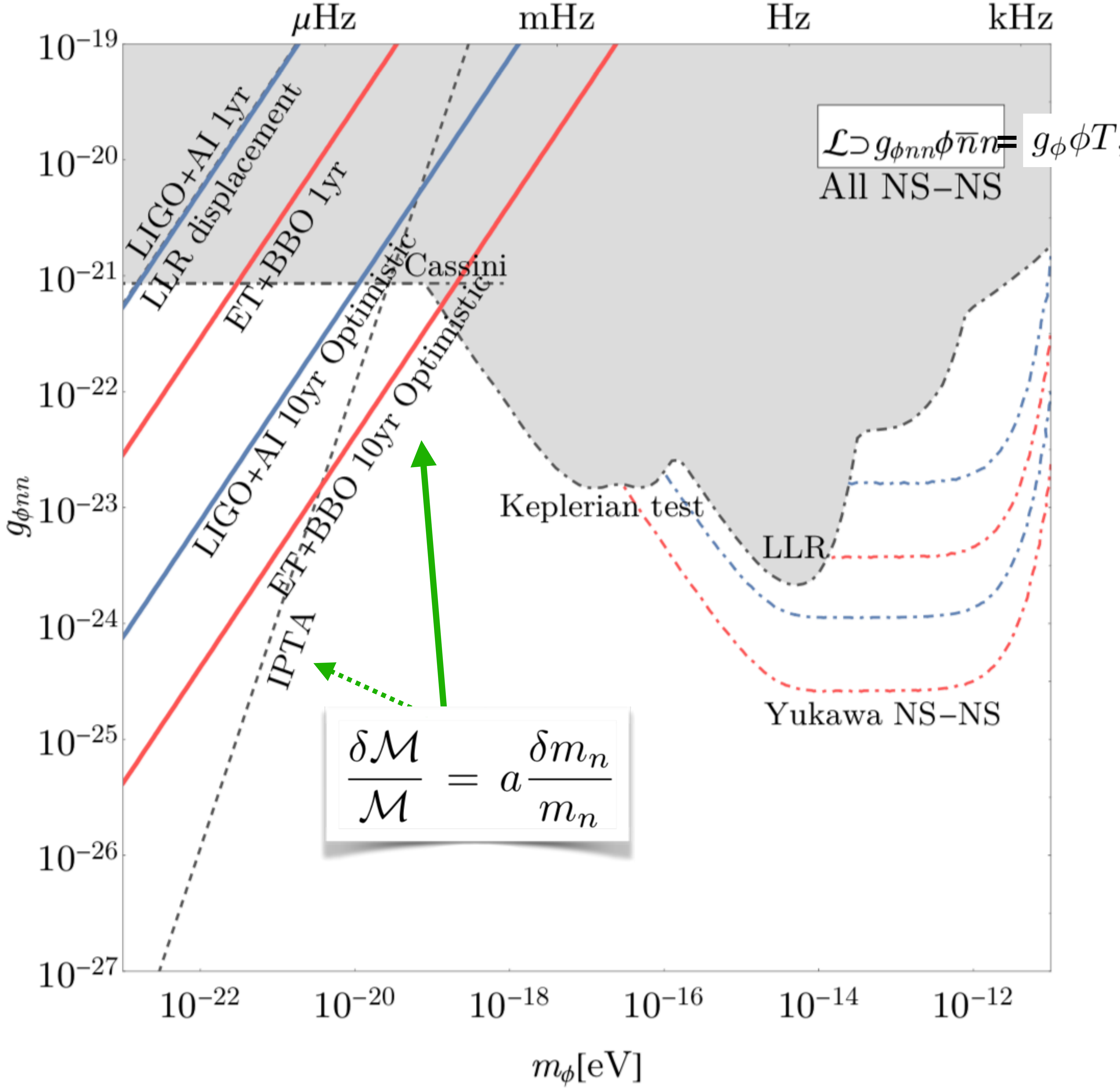

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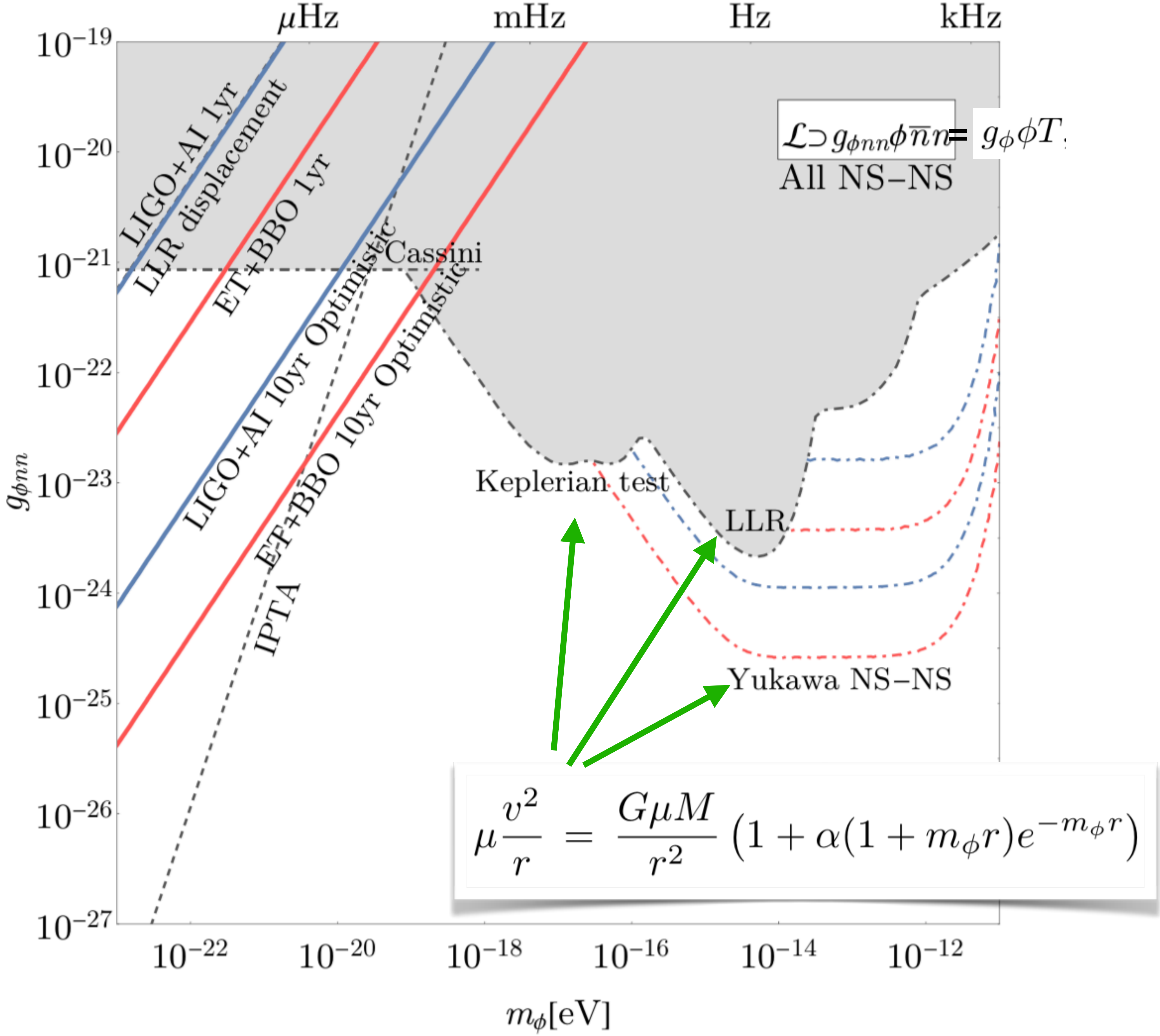
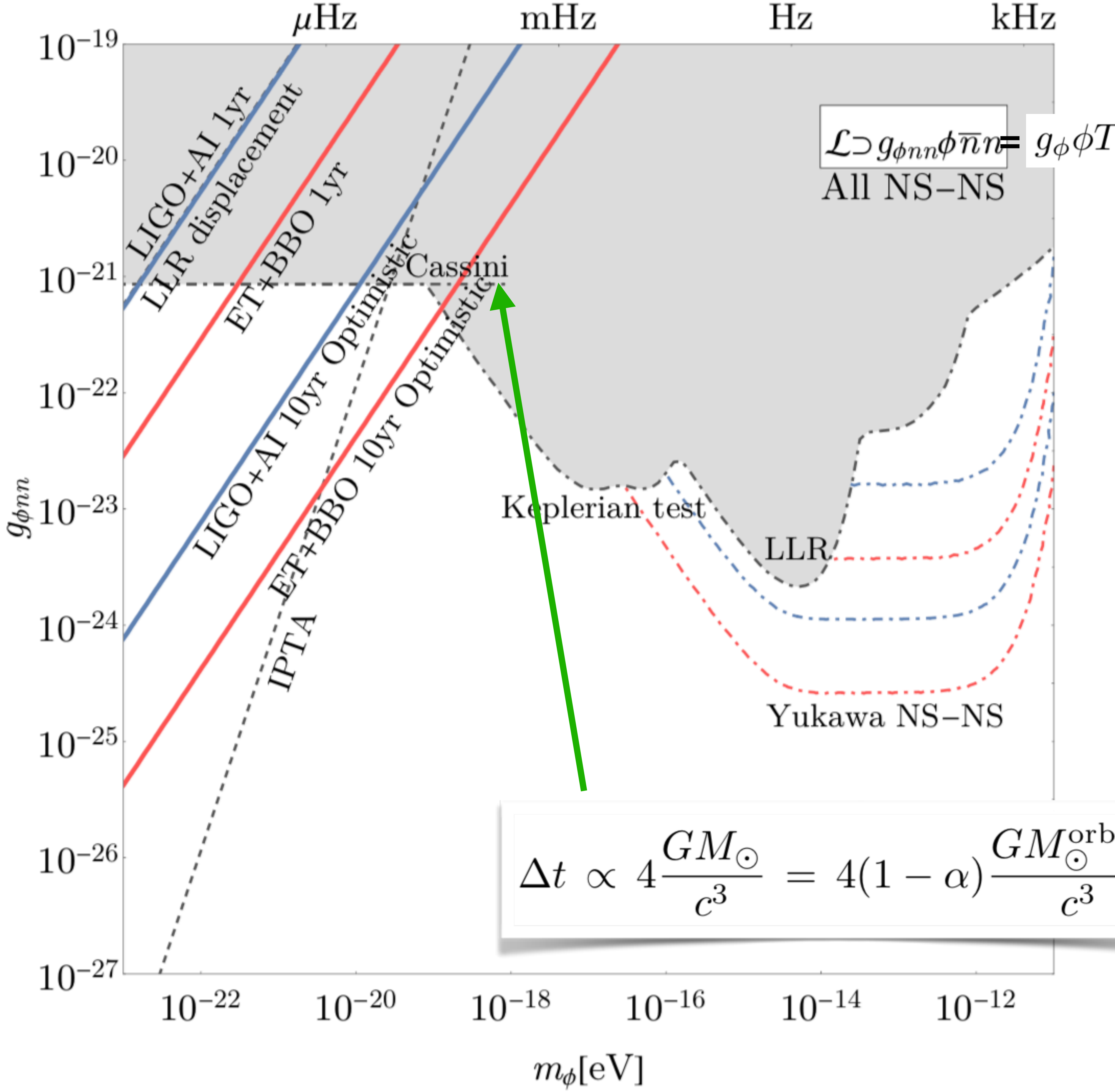


$$\mu\frac{v^2}{r} = \frac{G\mu M}{r^2}\left(1+\alpha(1+m_\phi r)e^{-m_\phi r}\right)$$

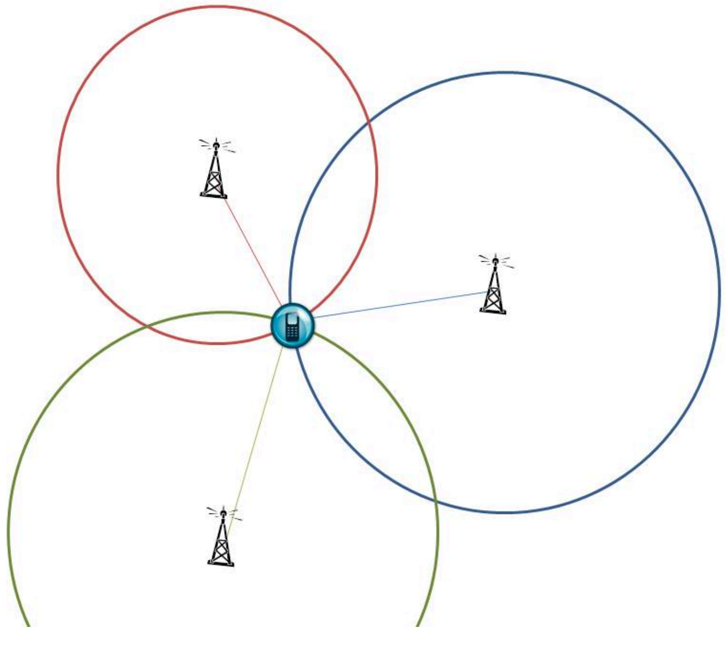
Detection prospects

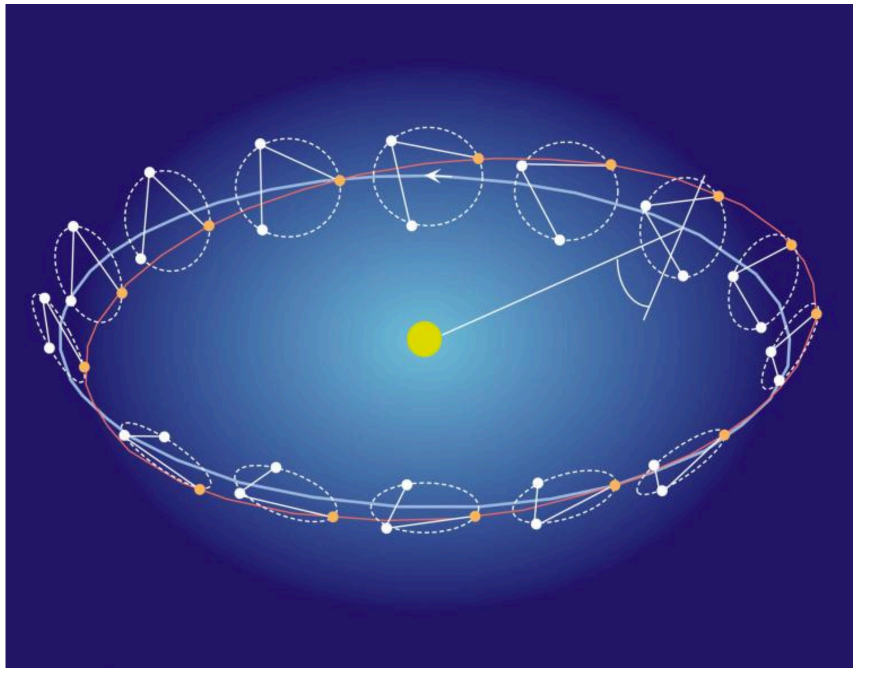


$$\Delta t \propto 4\frac{GM_\odot}{c^3} = 4(1-\alpha)\frac{GM_\odot^{\text{orbital}}}{c^3}$$

How to localize at LIGO/LISA

- “Triangulation” : time difference (LIGO, LISA)
- “Reorientation” : directional dependence (LISA)





But let's consider a much simpler possibility:

One single-baseline detector

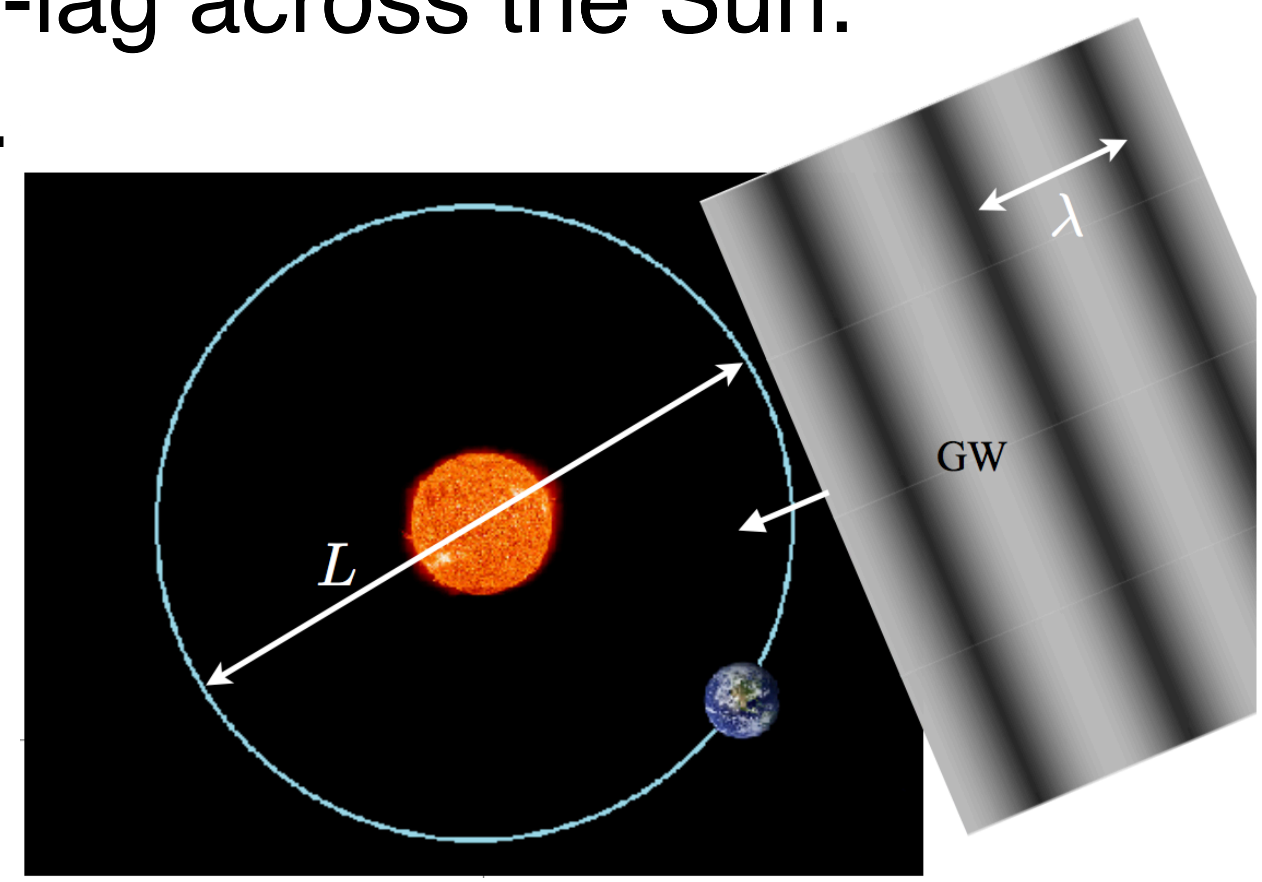
on the Earth orbit (T=7.8hrs)
measuring from the mid- to LIGO-band.

Benchmark for single-baseline detector: atom interferometer

Angular localization

- The single-baseline “Reorients” hourly and monthly.

- “Doppler” shift : huge phase-lag across the Sun. Most significant at mid-band.



Angular localization

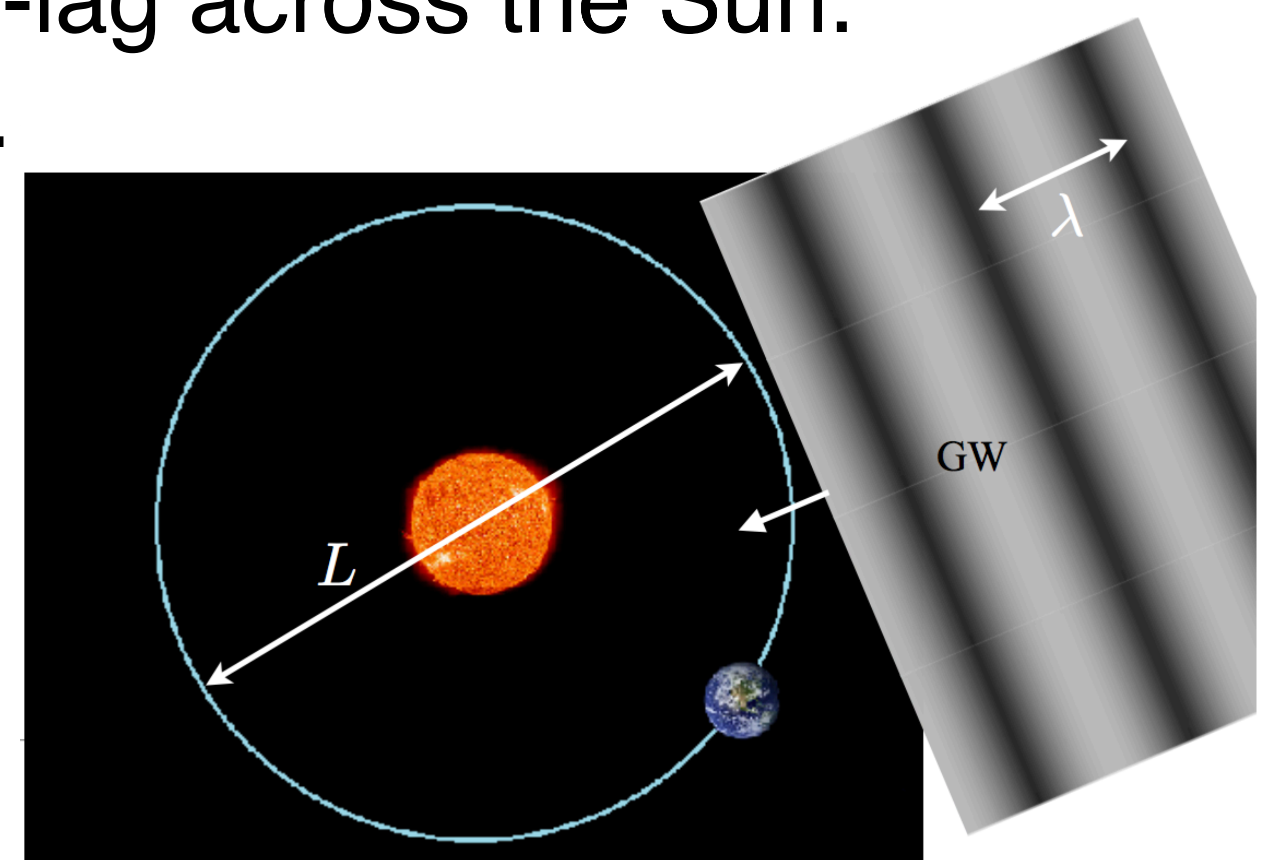
- The single-baseline "Reorients" hourly and monthly.

$$\Delta\theta \sim \mathrm{SNR}$$

- "Doppler" shift : huge phase-lag across the Sun. Most significant at mid-band.

$$\Delta\theta \sim \mathrm{SNR} \cdot \frac{L}{\lambda}$$

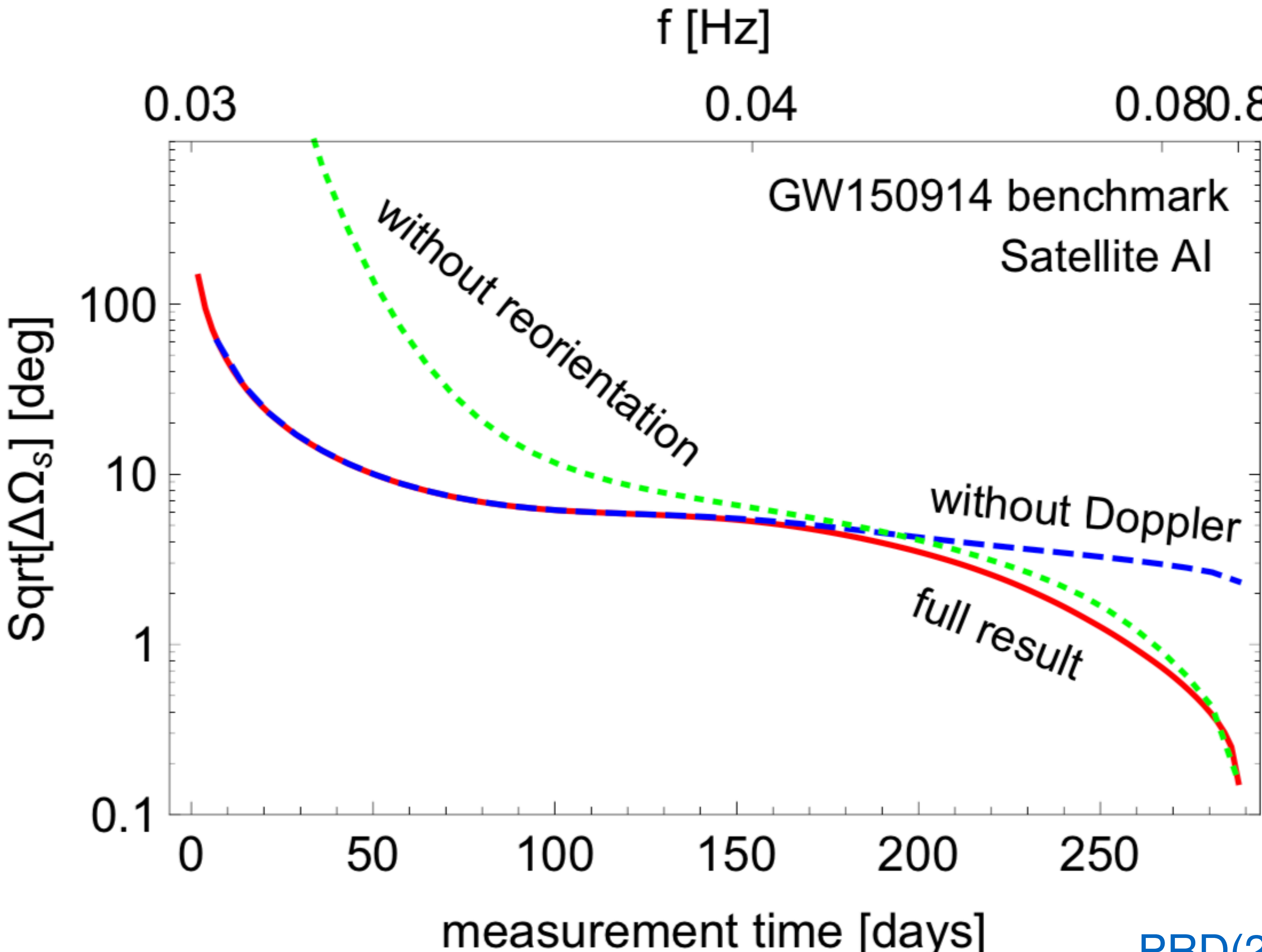
is largest for highest frequency
that lasts for 0.5~1 year



GW150914 in the mid-band

GW150914 (36-29 Ms) spends 9.6 months in the mid-band.

$$\Delta\Omega_s \equiv 2\pi \sin\theta \sqrt{\Gamma^{-1}_{\theta\theta}\Gamma^{-1}_{\phi\phi} - (\Gamma^{-1}_{\theta\phi})^2}.$$

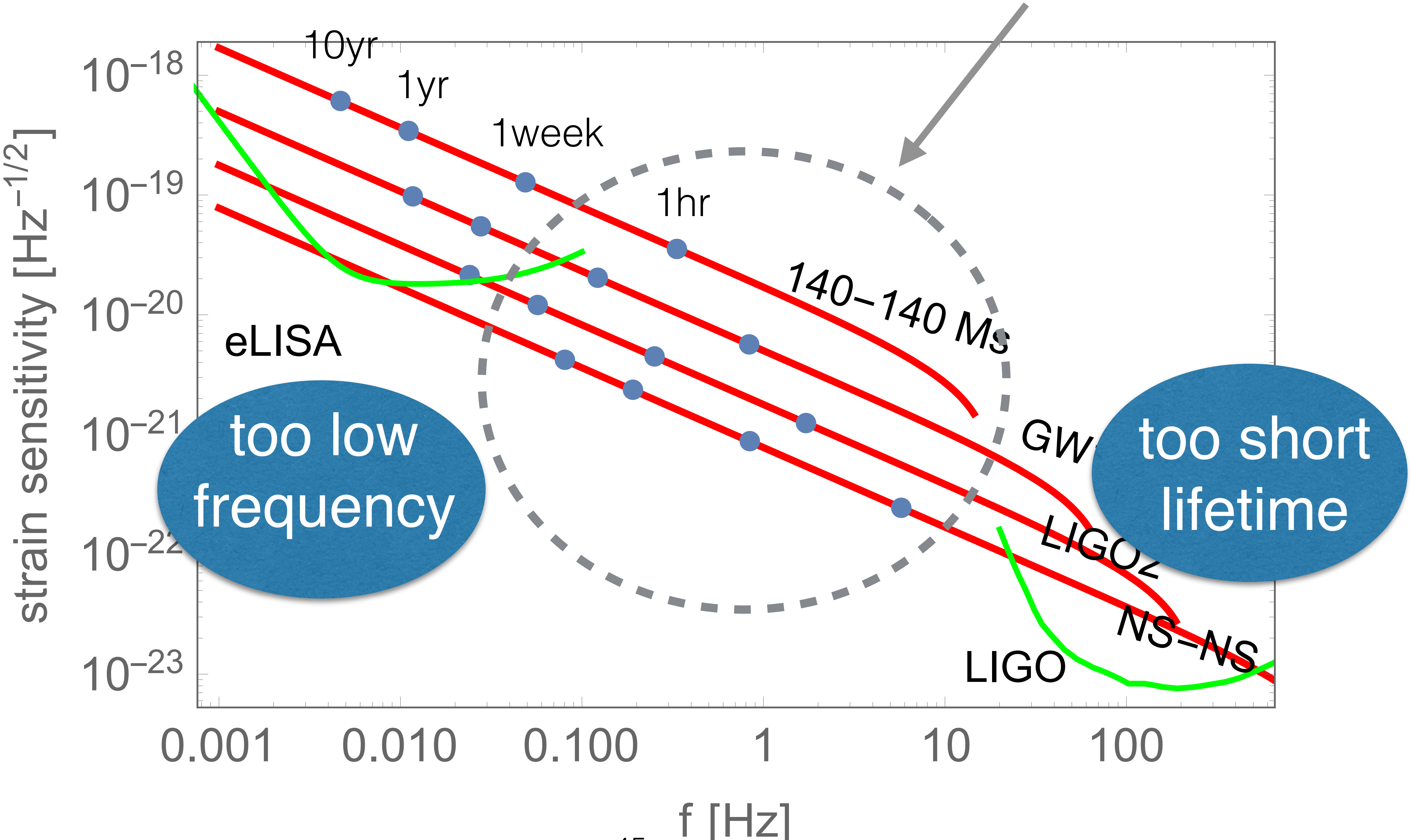


PRD(2018) SJ, P.W.Graham

Doppler is naturally largest

$$\Delta\theta \sim \mathrm{SNR} \cdot \frac{L}{\lambda}$$

is largest for highest frequency that lasts for 6 months



Summary

- GW is a powerful probe of Dark Universe.
- "GW Fringe"
- "LIGO + mid-band" synergies:
  for probing cosmic strings and axion-like DM waves,
  as well as localization.