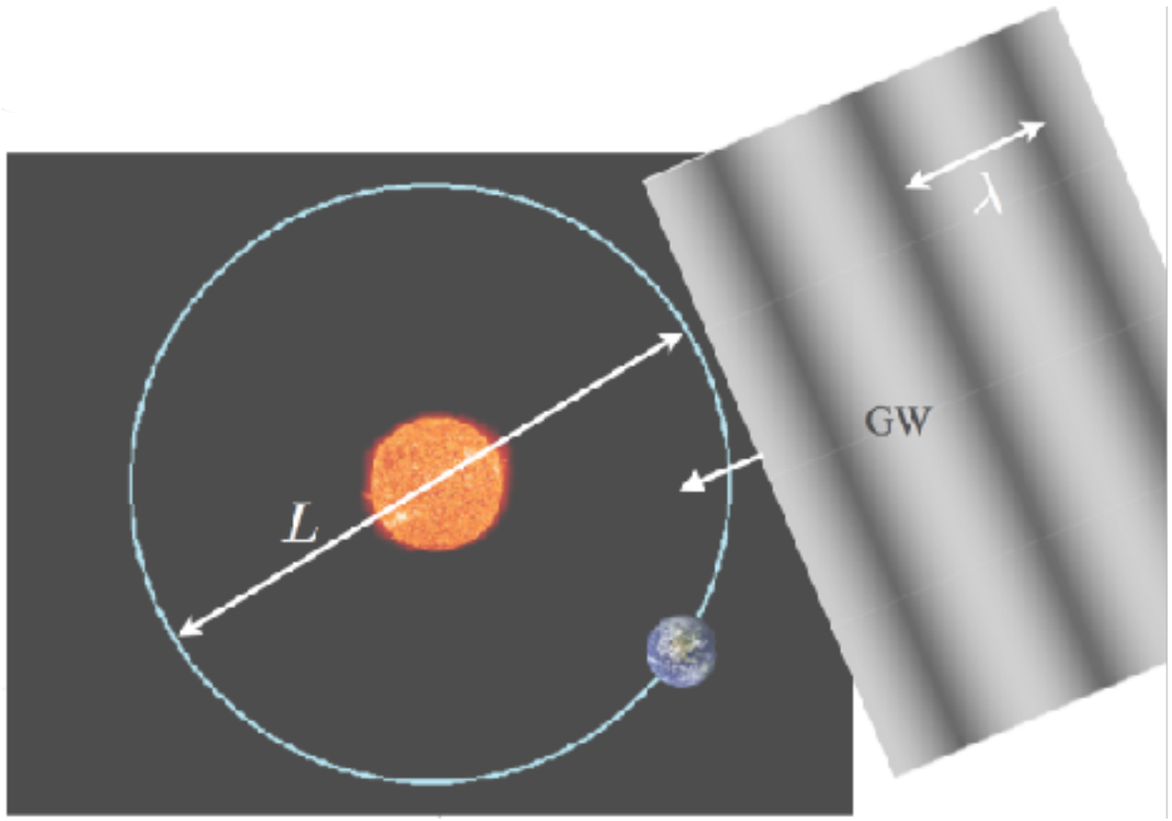
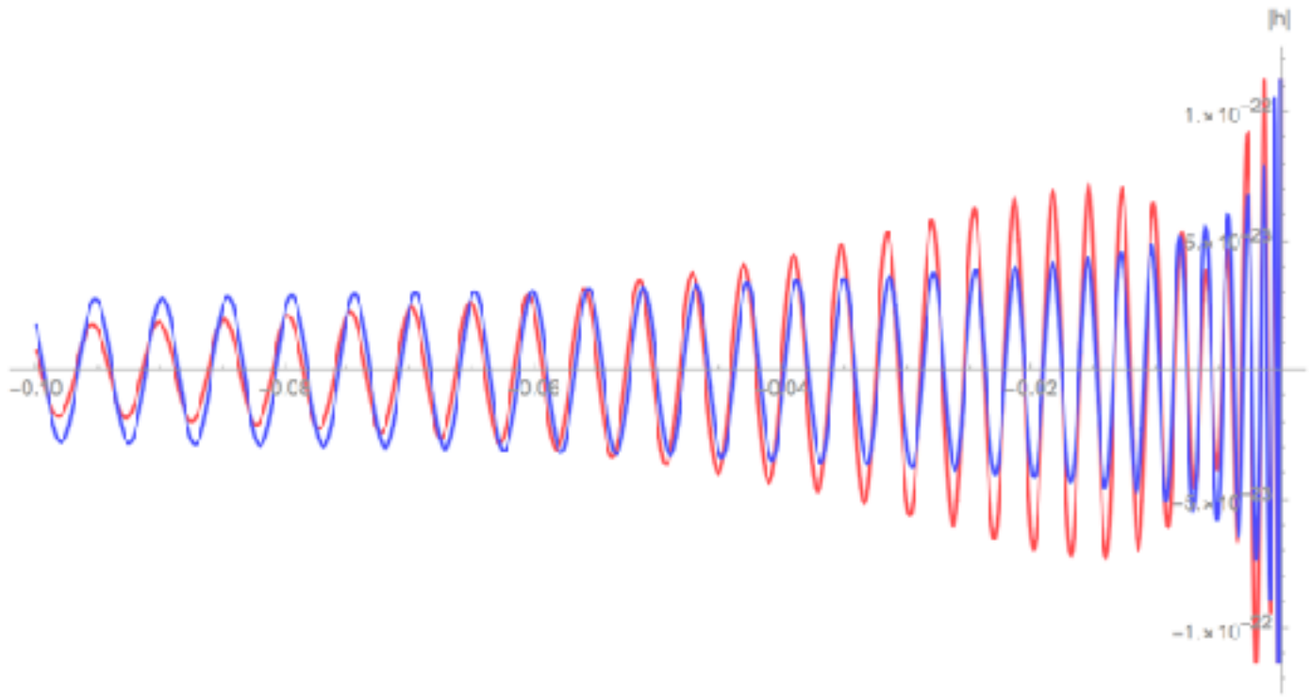
Probing Dark Matter at LIGO and beyond





Sunghoon Jung
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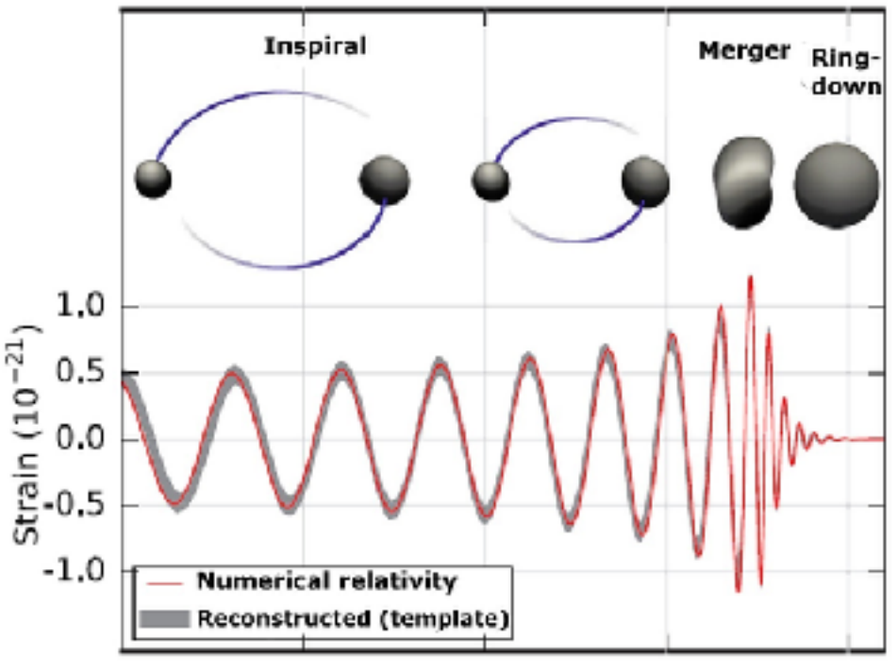
IBS Workshop on Prospects of Particle Physics and Cosmology

- GW era!
  - What can we see?
  - Can we learn anything about particle physics frontier too?

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

- What “Dark Matter” info can be encoded & extracted?



Takehome messages

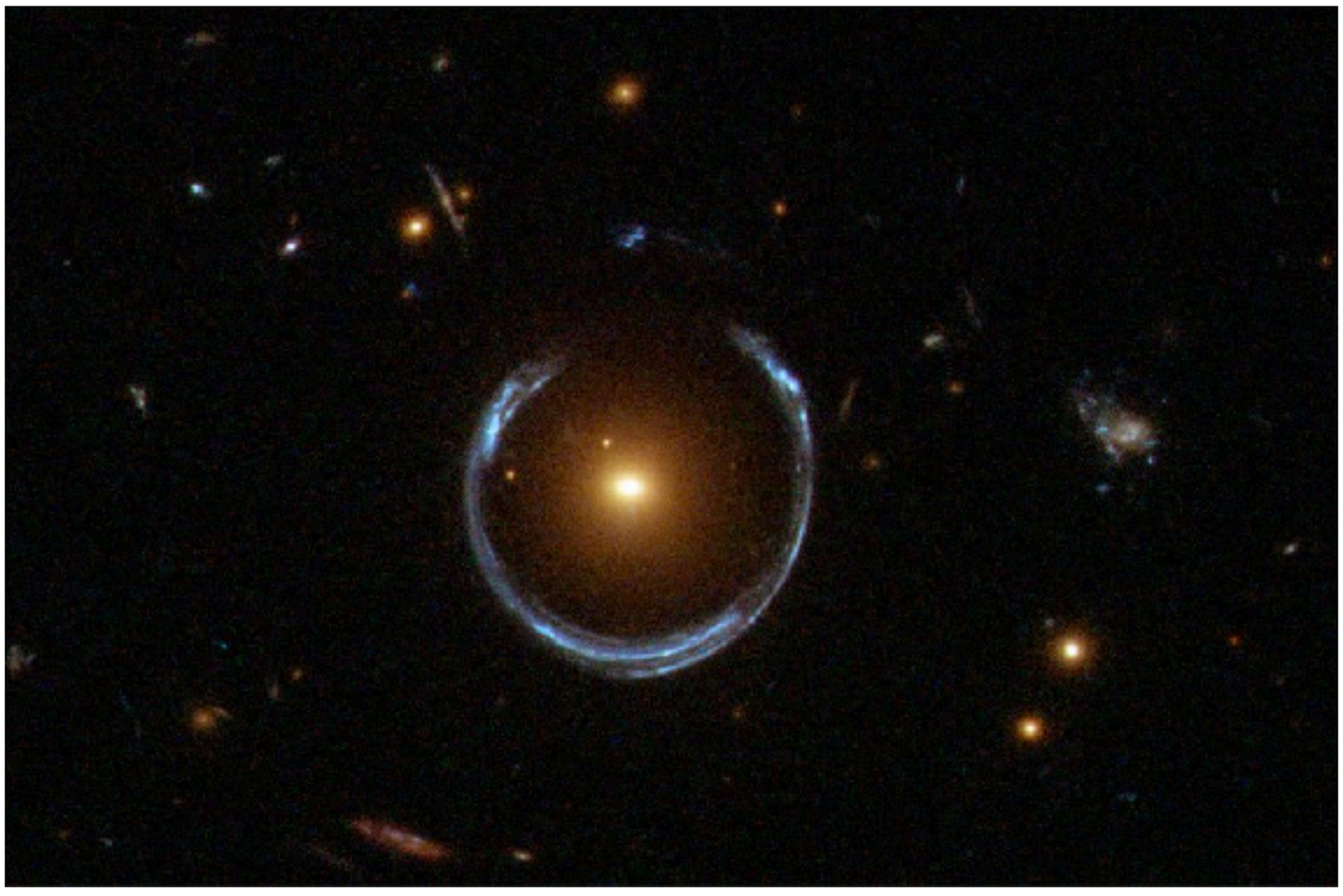
- LIGO and beyond do provide precision capabilities for DM frontier studies:

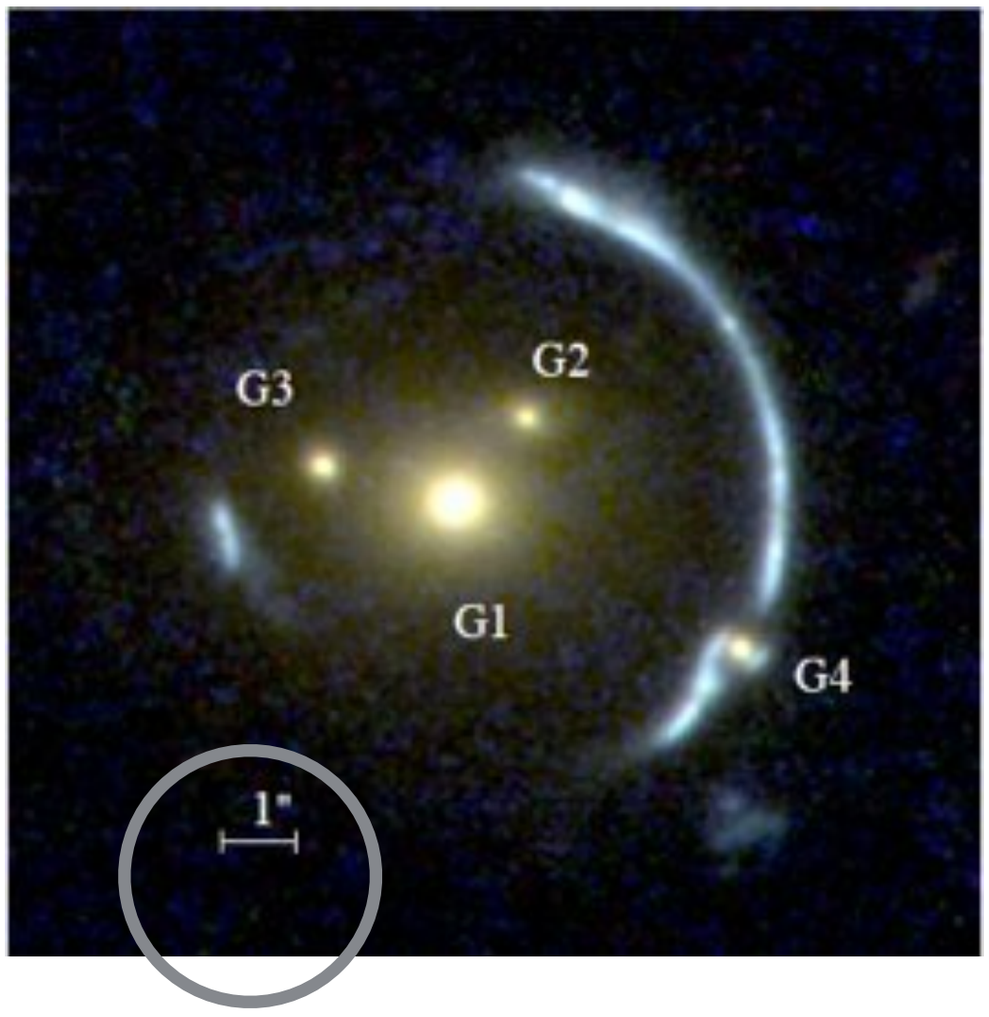
- LIGO plays primary roles. Mid-band provides synergies.

- 1. *LIGO alone* can see compact DM, even though short measurement and bad angular resolution:
  "GW Fringe"

- 2. *LIGO + mid-band* (0.01-1000Hz) form a unique test-bed for DM models:
  "The *highest frequency*-band with *year-long* binary lifetime"

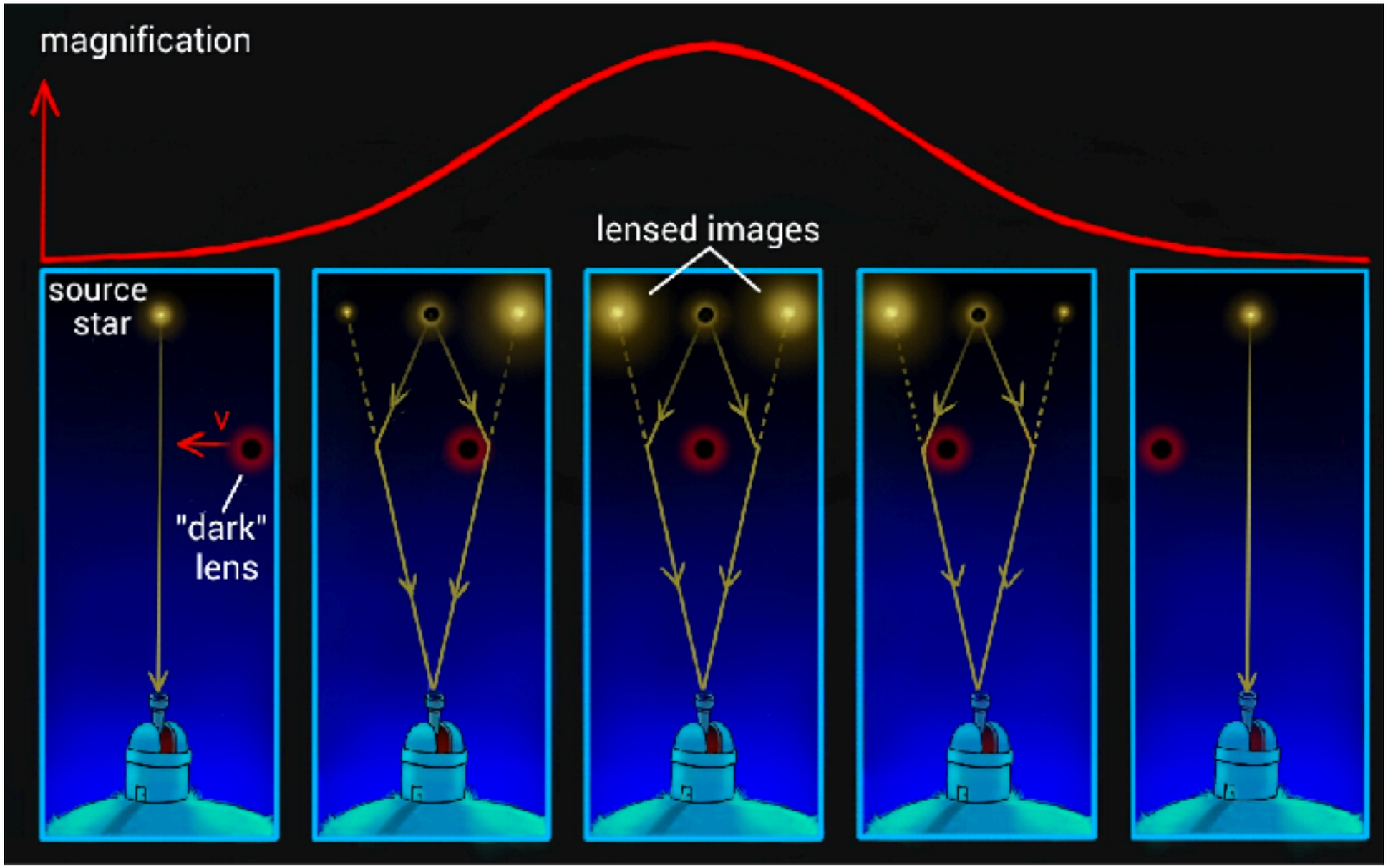
Strong lensing of light





- 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

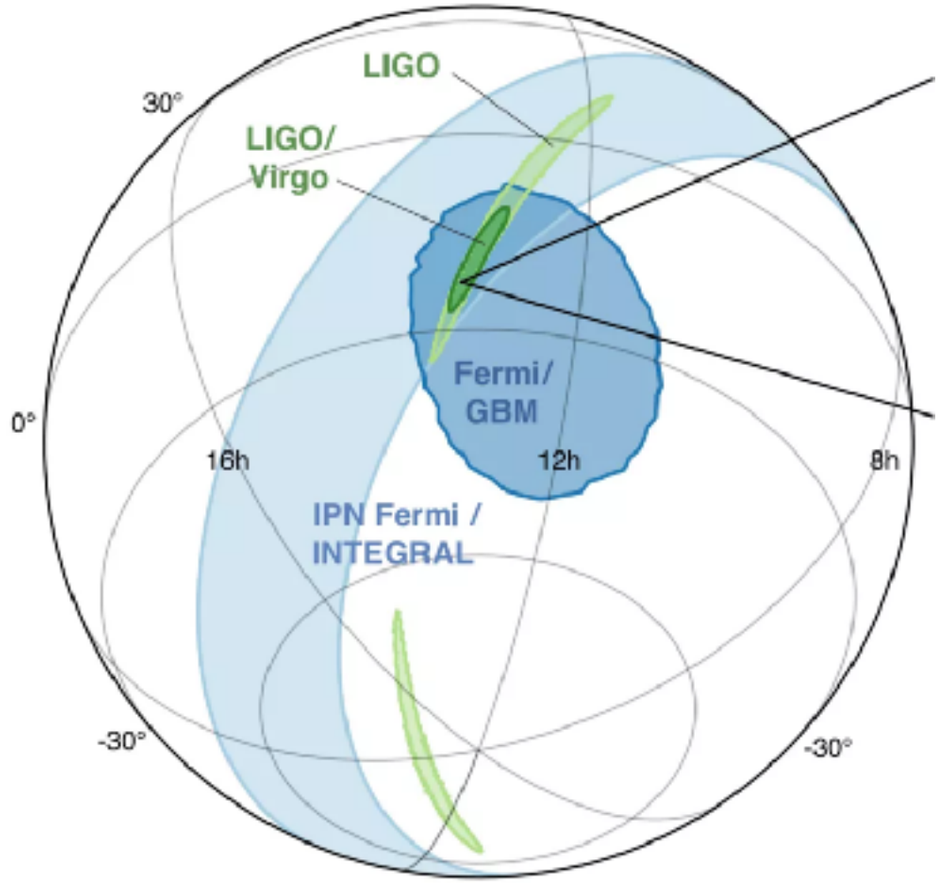
- Complicated statistical analysis of multiply and weakly lensed lights.

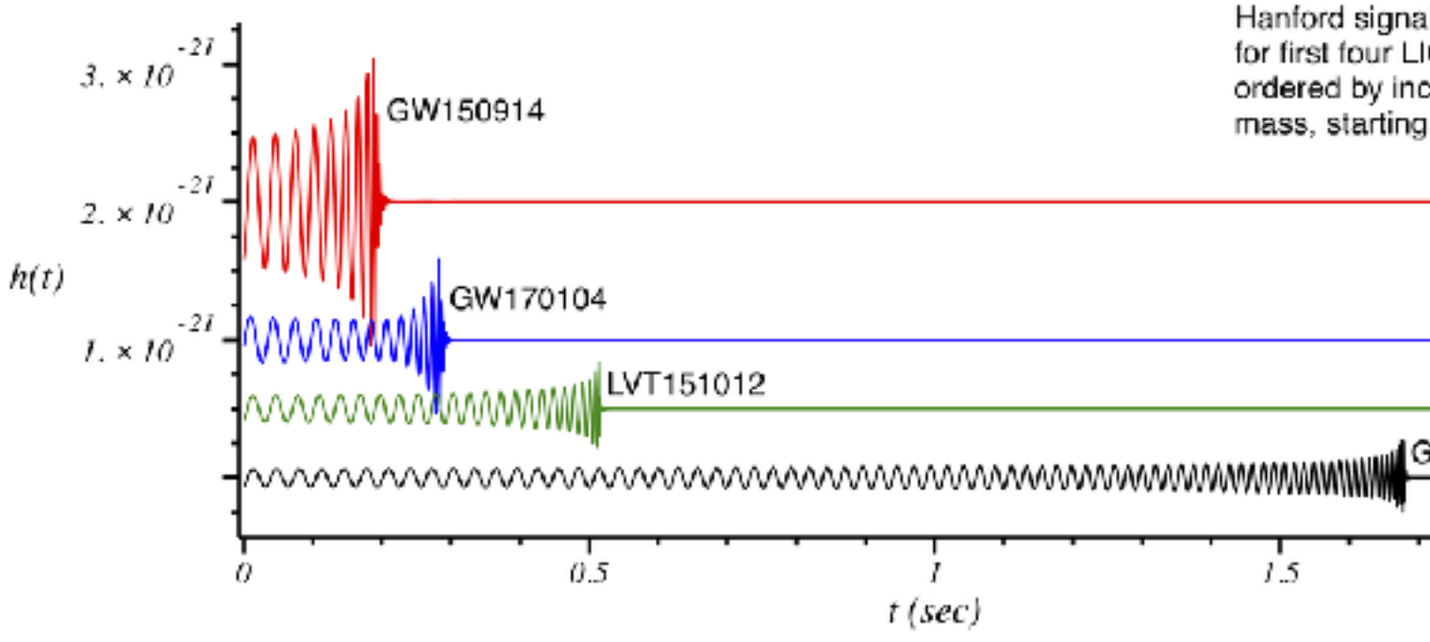
GW lensing observation seems very unlikely at LIGO!

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,,,

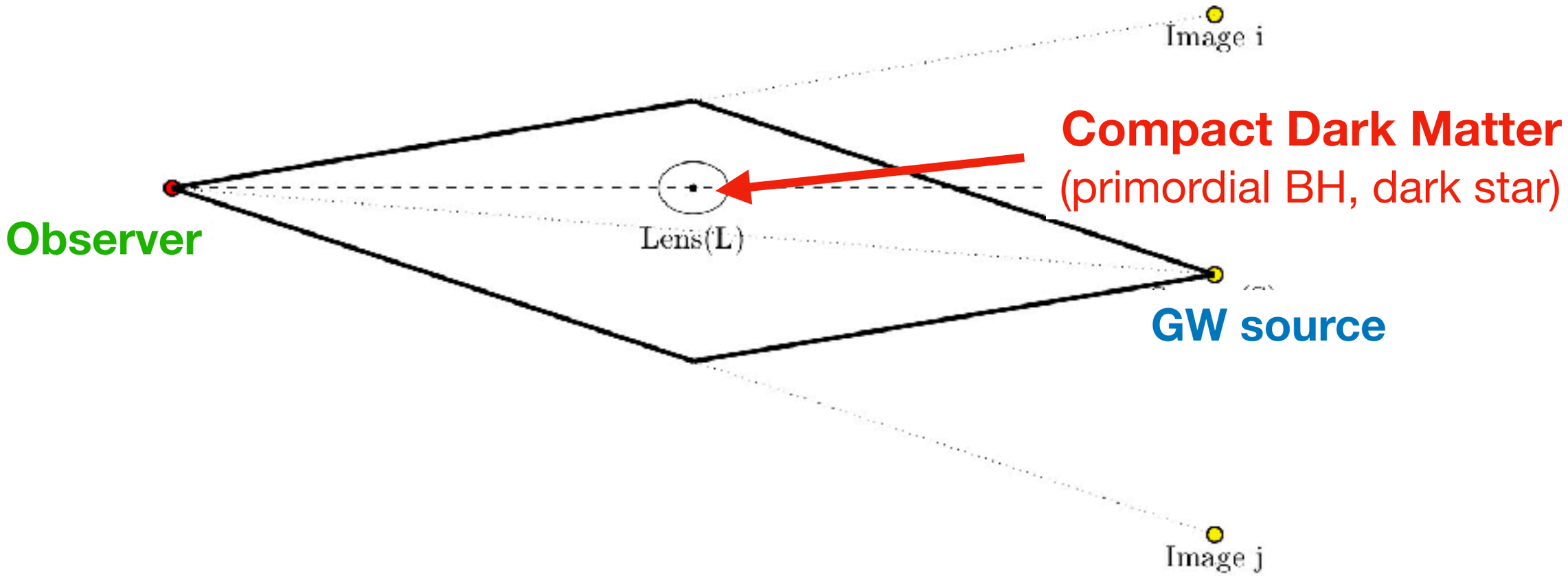
- GW chirps.
  - It provides non-trivial *change* of lensing pattern, which is extremely useful in lensing detection.

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

- (GW wavelength is typically much longer.)

Time-delayed images

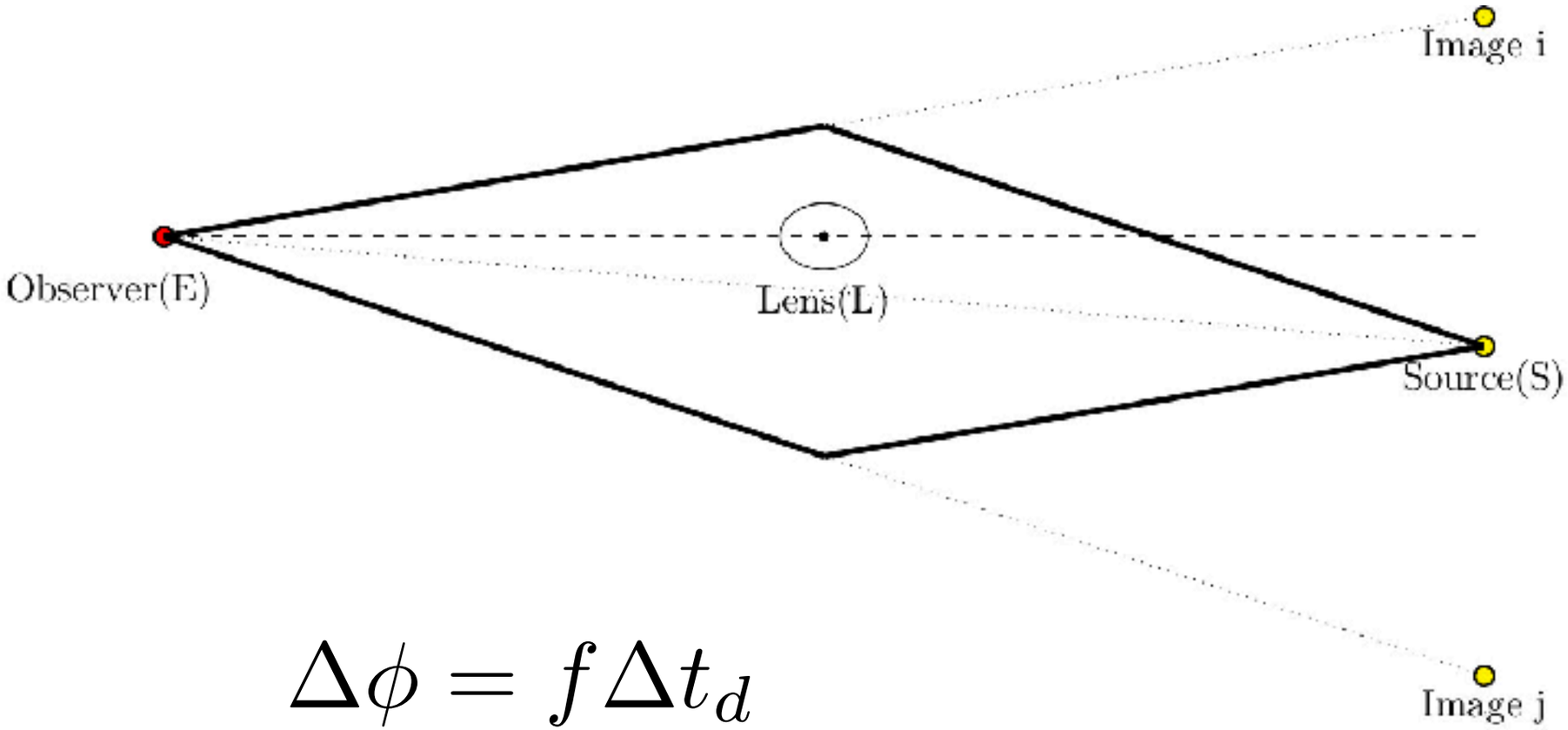
Consider time-delayed lensed images of GW.



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

Interfered images

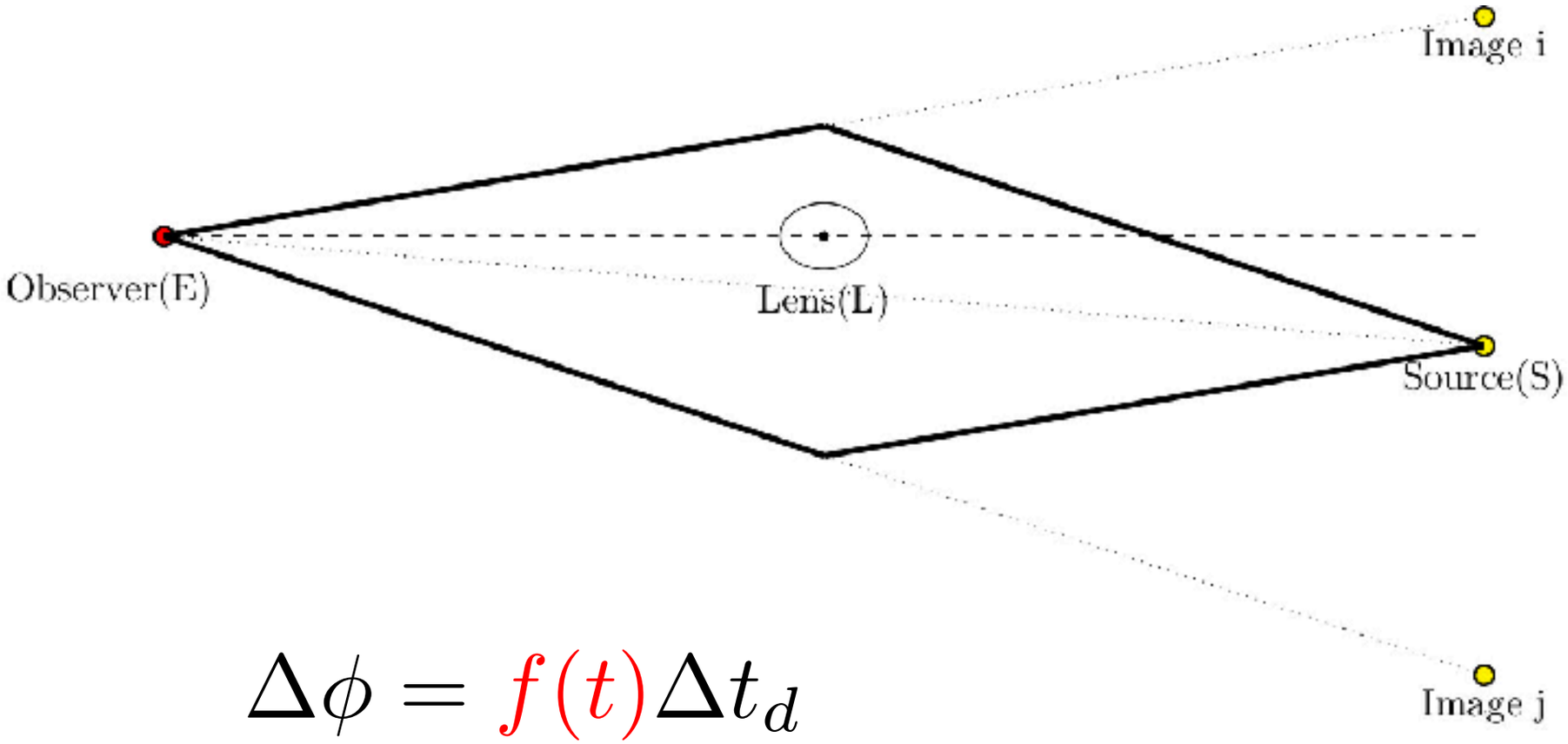
Unresolved GW images rather “interfere” in our observation.



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

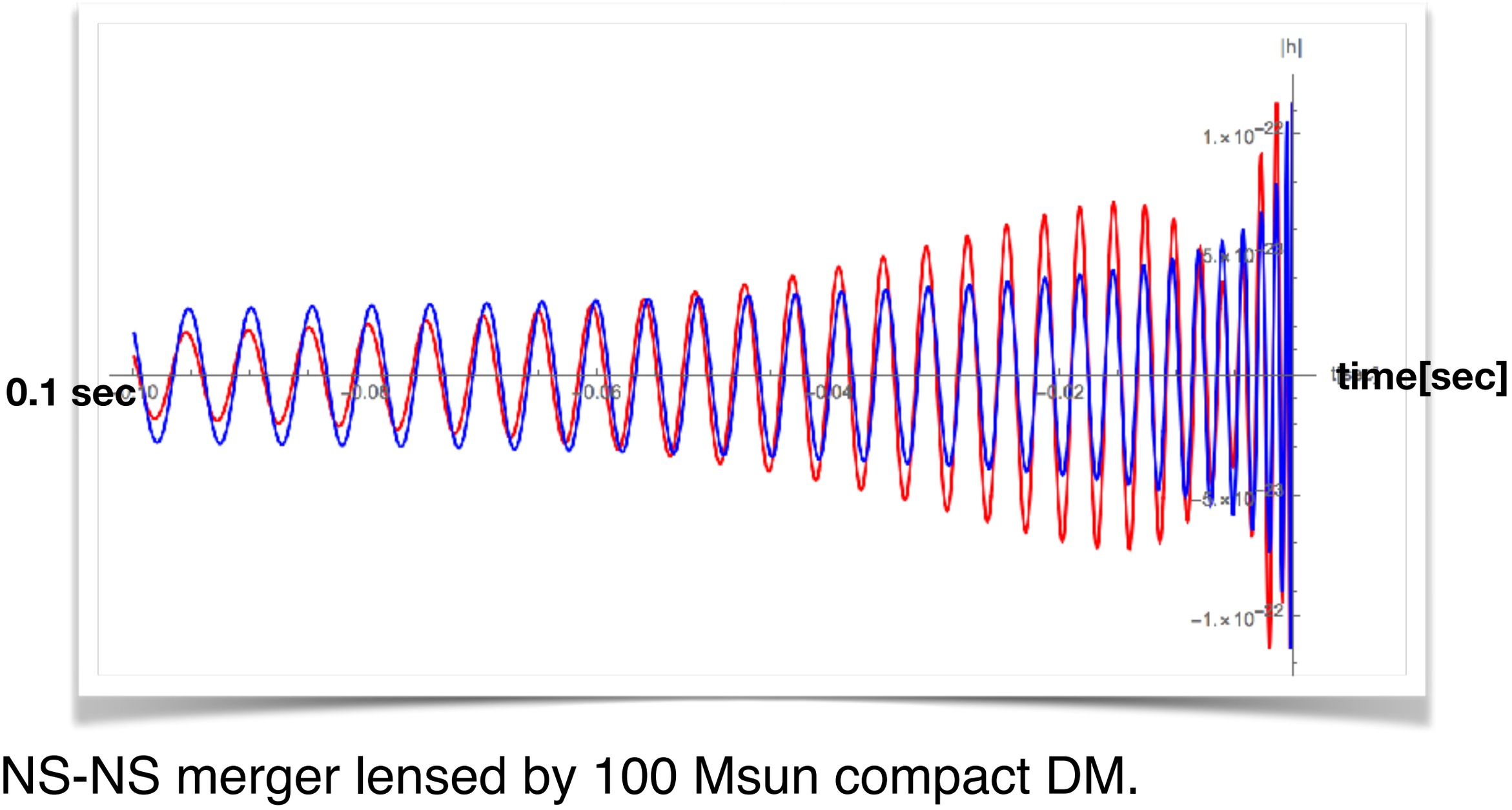
GW lensing Fringe

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



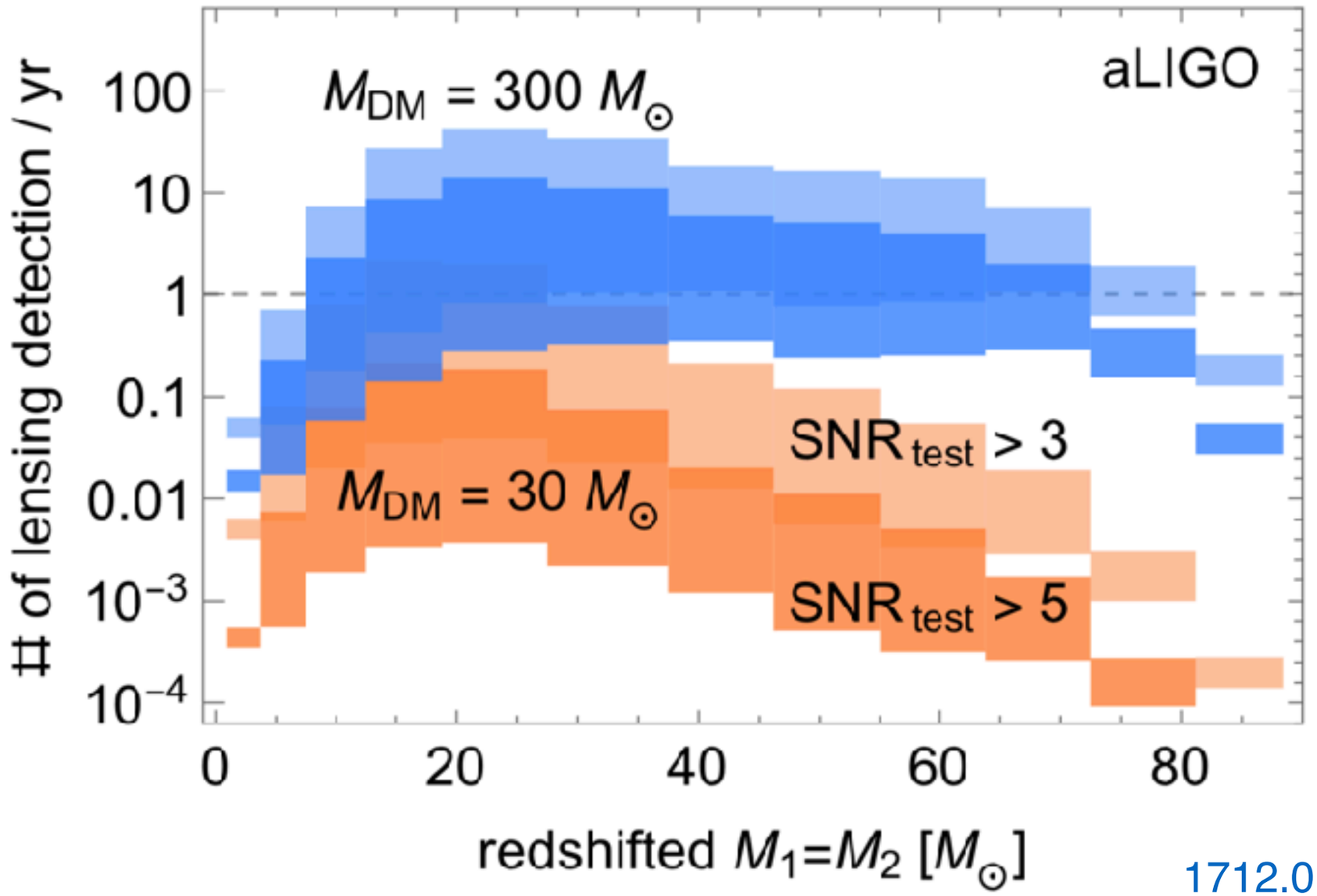
$$\Delta\phi = f(t)\Delta t_d$$

“GW Fringe”



NS-NS merger lensed by 100 Msun compact DM.

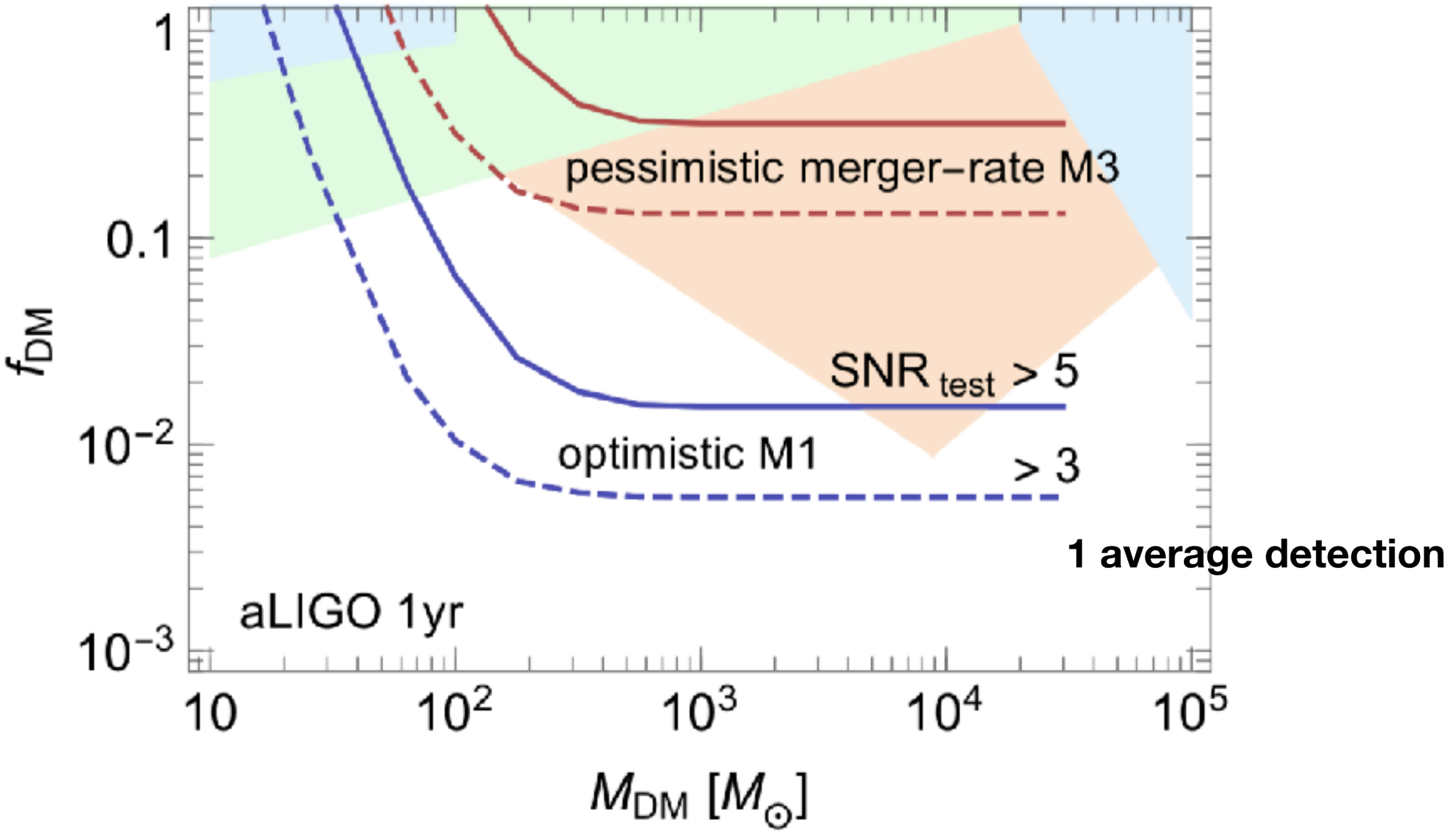
of GW fringe detections



1712.01396 SJ, C.S.Shin

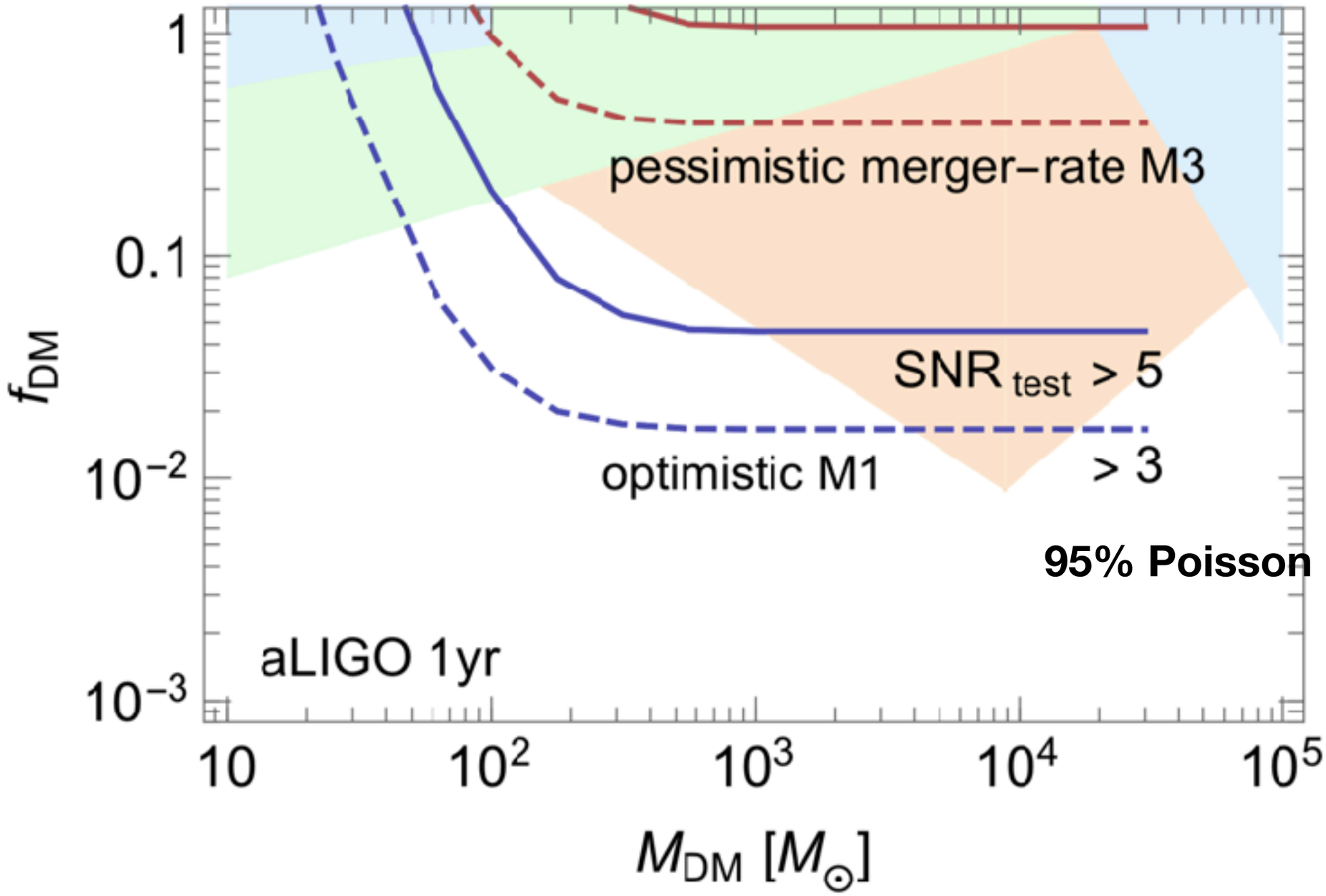
$$(\mathrm{SNR}_{\mathrm{test}})^2 \equiv 4\int_{f_0}^{f_1} \frac{\left|\widetilde{h}(f)^L - \widetilde{h}(f)_{\mathrm{best-fit}}\right|^2}{S_n(f)}\, df = \langle \tilde{h}^L | \tilde{h}^L \rangle - \langle \tilde{h}^L | \tilde{h}_{\mathrm{best-fit}} \rangle^2 / \langle \tilde{h}_{\mathrm{best-fit}} | \tilde{h}_{\mathrm{best-fit}} \rangle$$

Compact DM fraction



1 average detection

Compact DM fraction



95% Poisson prob of >=1 detection

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.

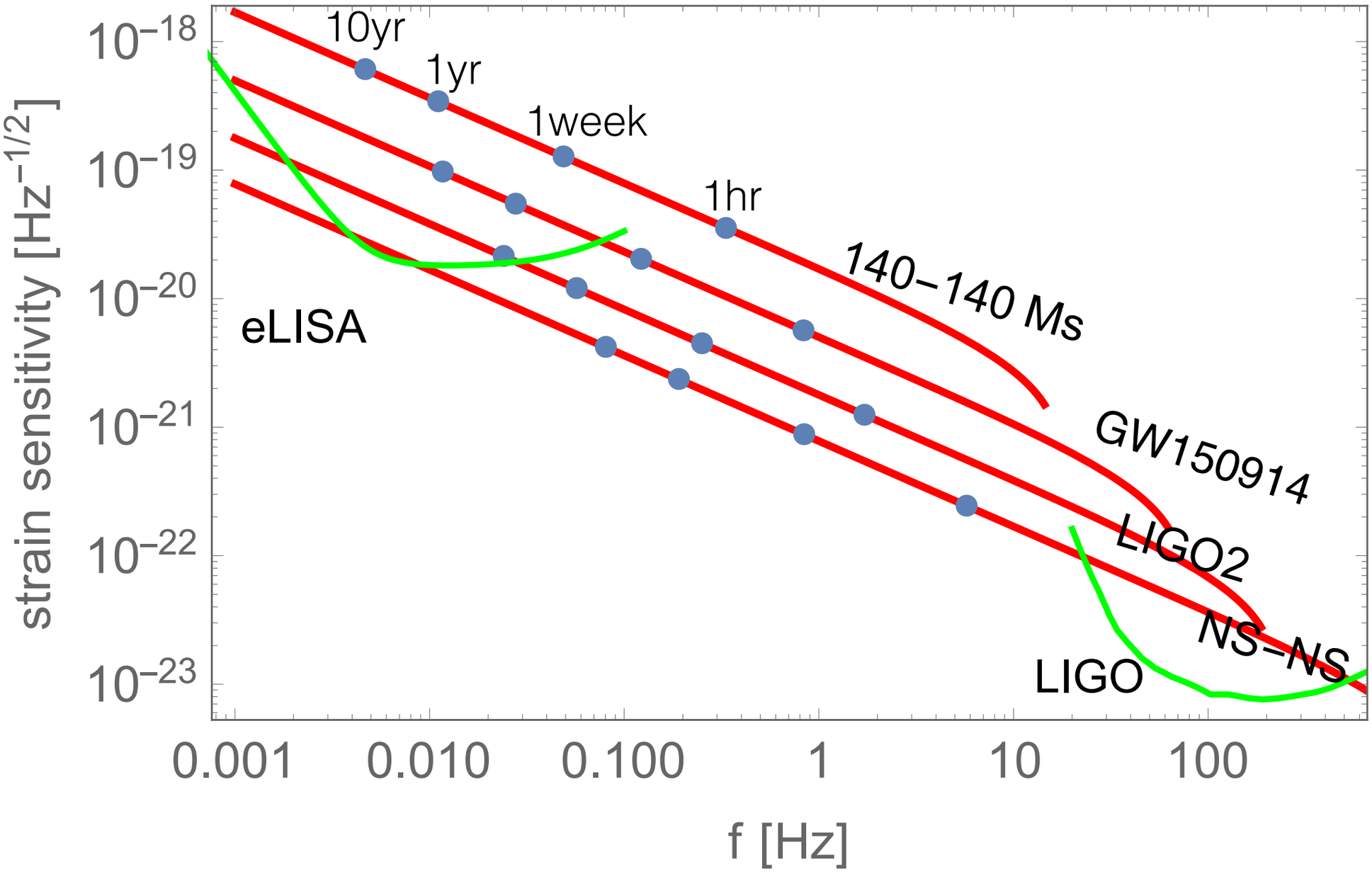
- Highest-frequency GW can see the smallest compact DM.
  (10-1000 Hz = 10^2-10^4 Msun Schw radius)

Let’s extend with the mid-band.

A lot more exciting physics can be done.

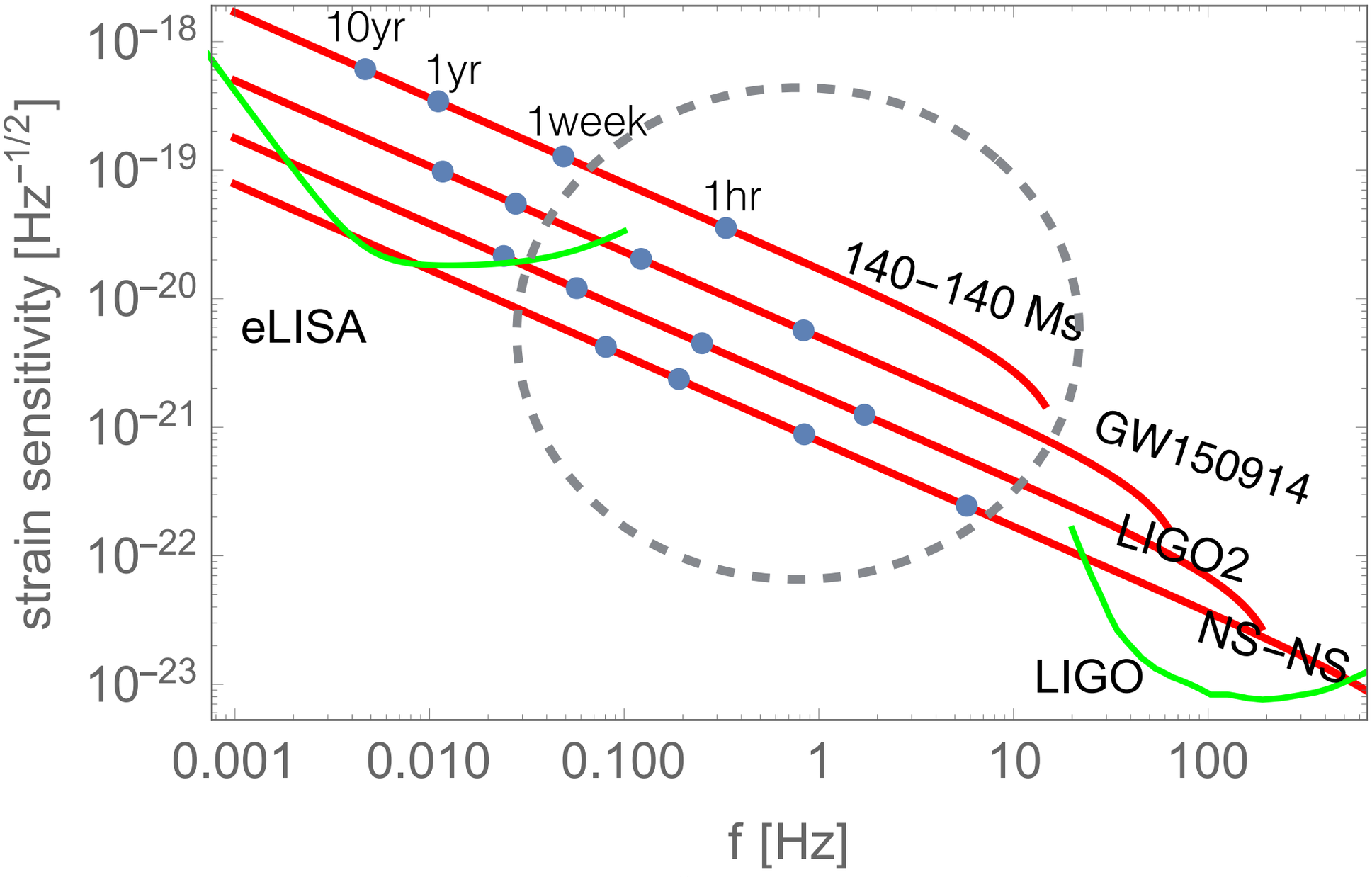
GW lifetime curve

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



GW lifetime curve

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



Power of LIGO + Mid-band

- Unique & precision test-bed for dark matter:

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

[1810.01421 with Han Gil Choi,
1810.04172 with TaeHun Kim]

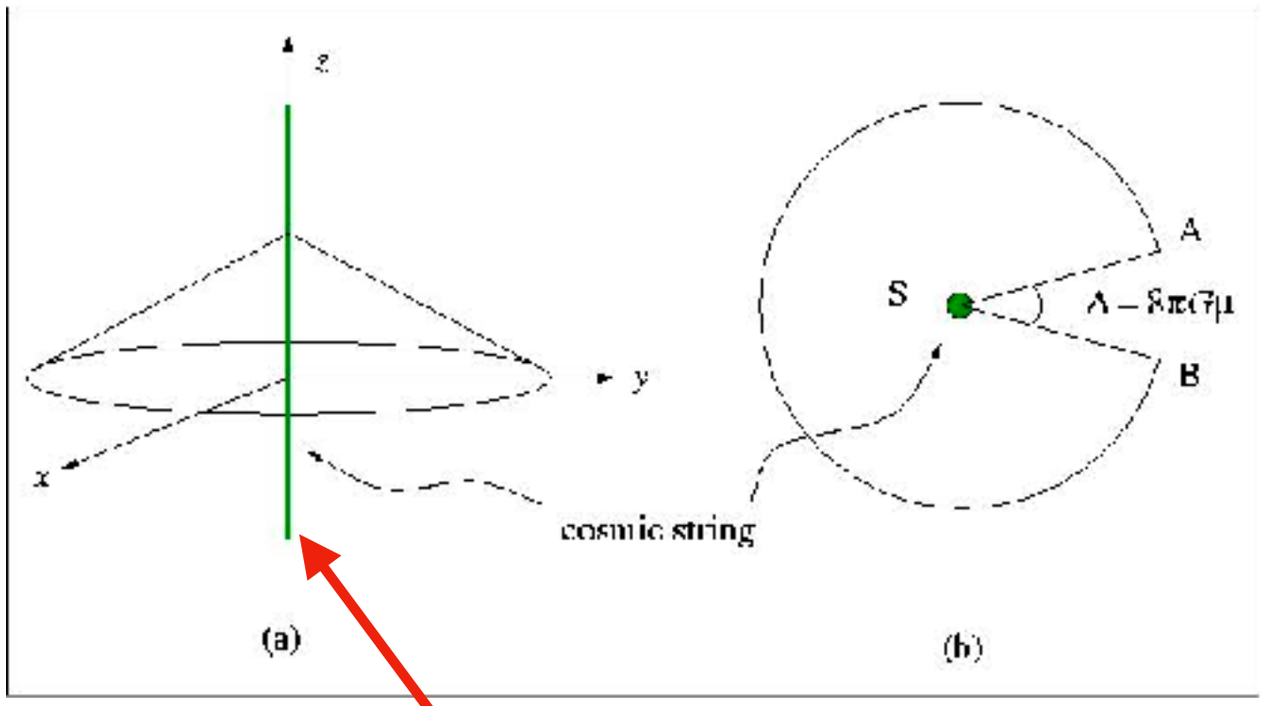
- 2. **GW Localization** on the sky is most naturally well done here!

[1710.03269 with Peter W. Graham]

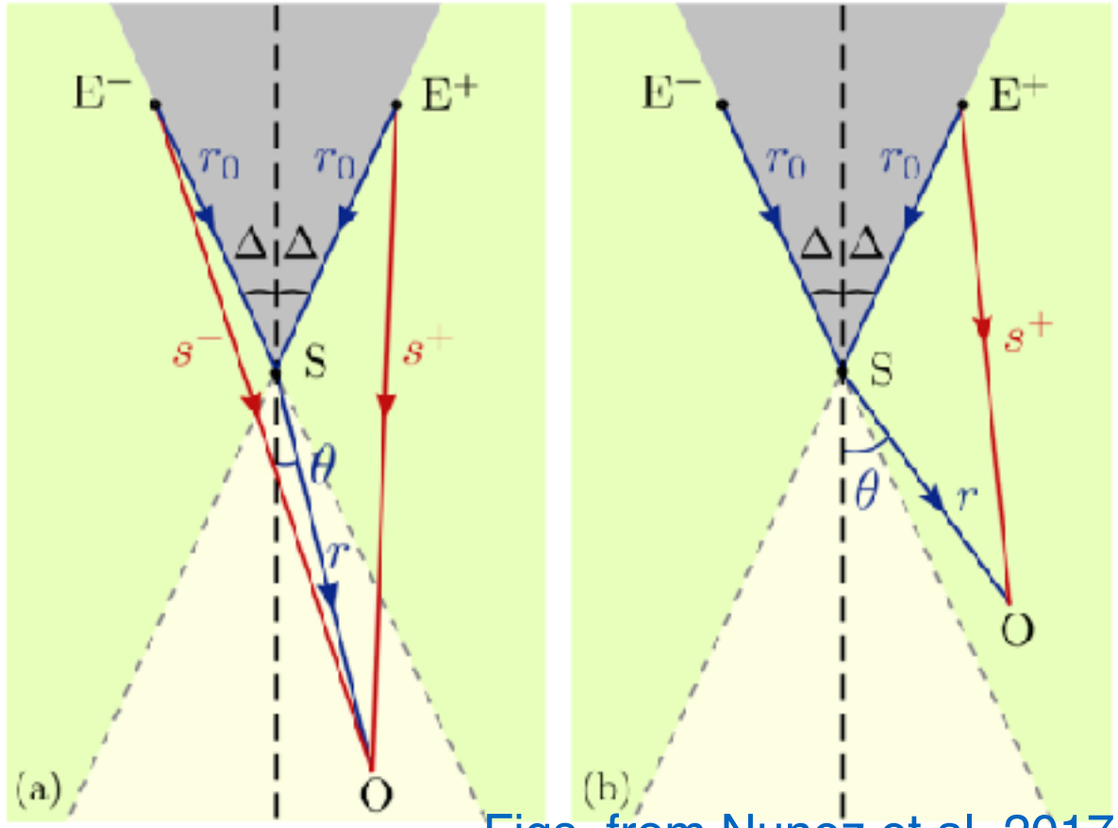
GW Fringe from Cosmic string

- Early-Universe remnants of U(1) phase transitions.

- GW Fringe from the Interference btwn *three* rays
  = 2 geometric ray + 1 diffracted ray

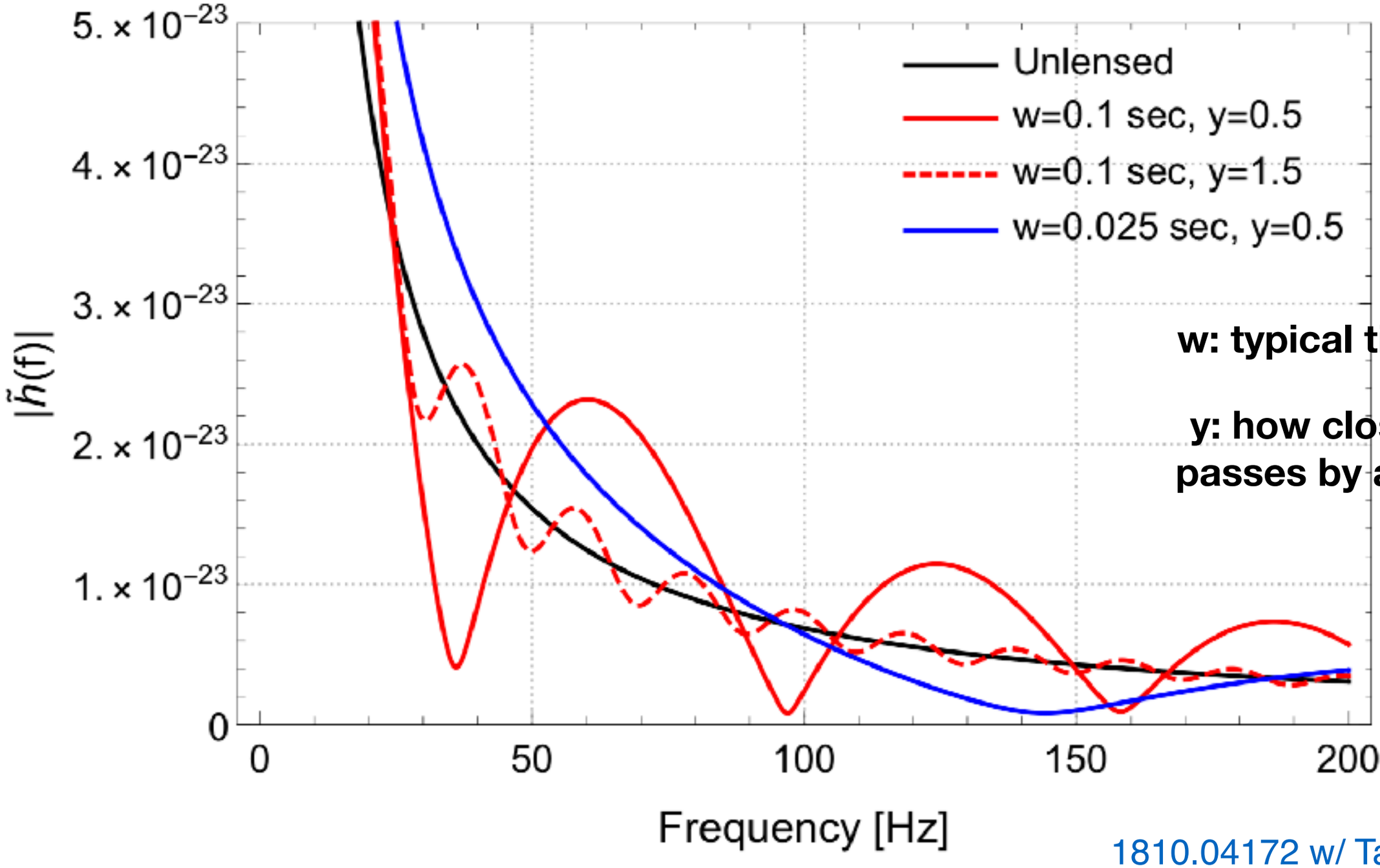


Cosmic String = 1-dim energy locus



Figs. from Nunez et al. 2017

GW Fringe from Cosmic String



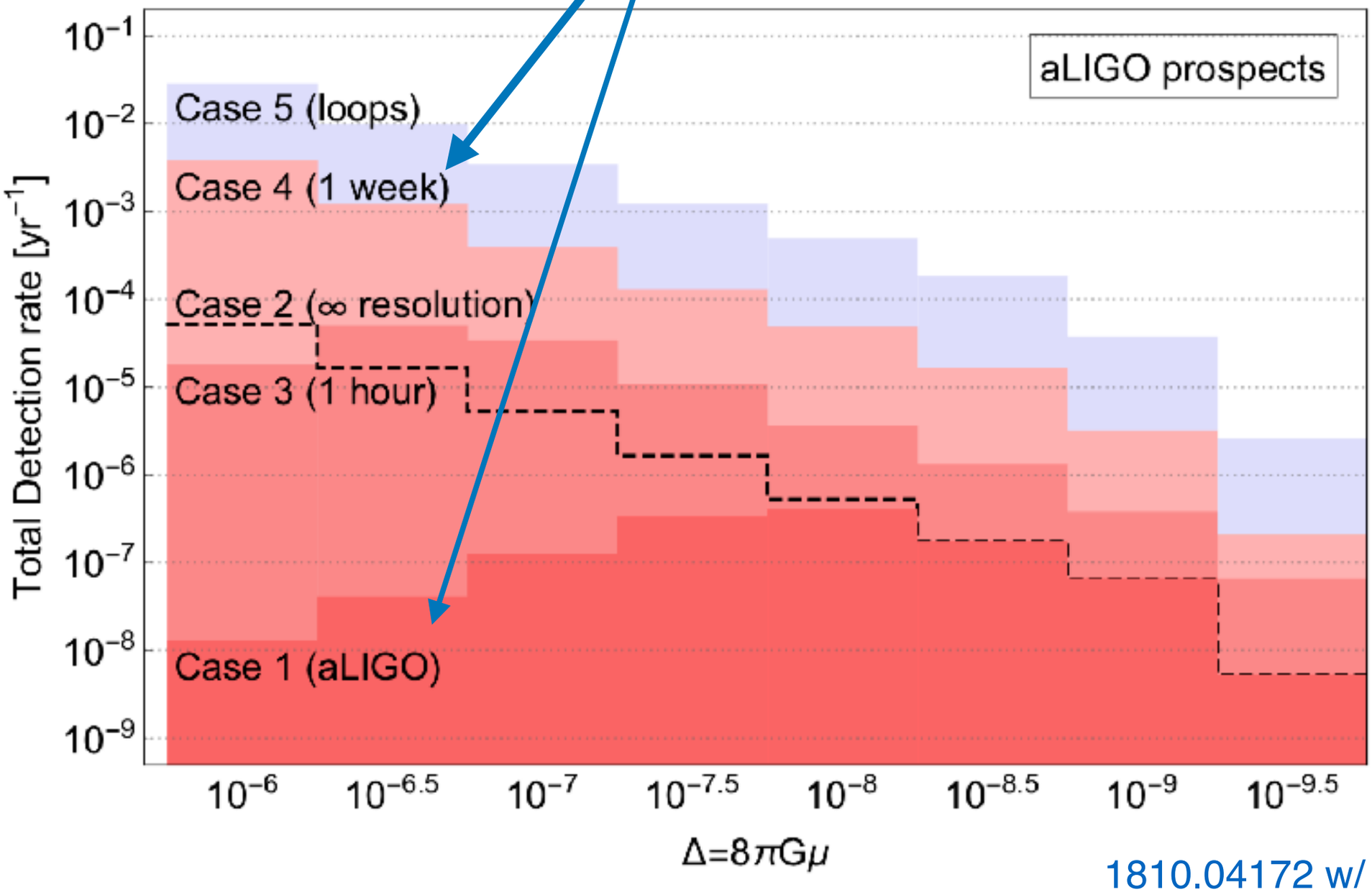
w: typical time-delay

y: how close GW passes by a string

1810.04172 w/ TaeHun Kim

Detection prospects

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



1810.04172 w/ TaeHun Kim

Dark matter detection

- Scalar DM of fuzzy/axion-like as light as 10^-23 eV.

- It is a classical wave, almost coherently oscillating at its Compton frequency, in the background.

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

$$\frac{1}{m_{\rm DM}}$$ ~ 1 yr for 10^-22 eV, 1 month for 10^-20 eV

Exquisite chirp-mass accuracy

- Again aided by highest-frequency year-long measurement,

- GW phase evolution is governed by the chirp mass.
  → A tiny phase-shift due to the mass-shift accumulates over millions of GW cycles!

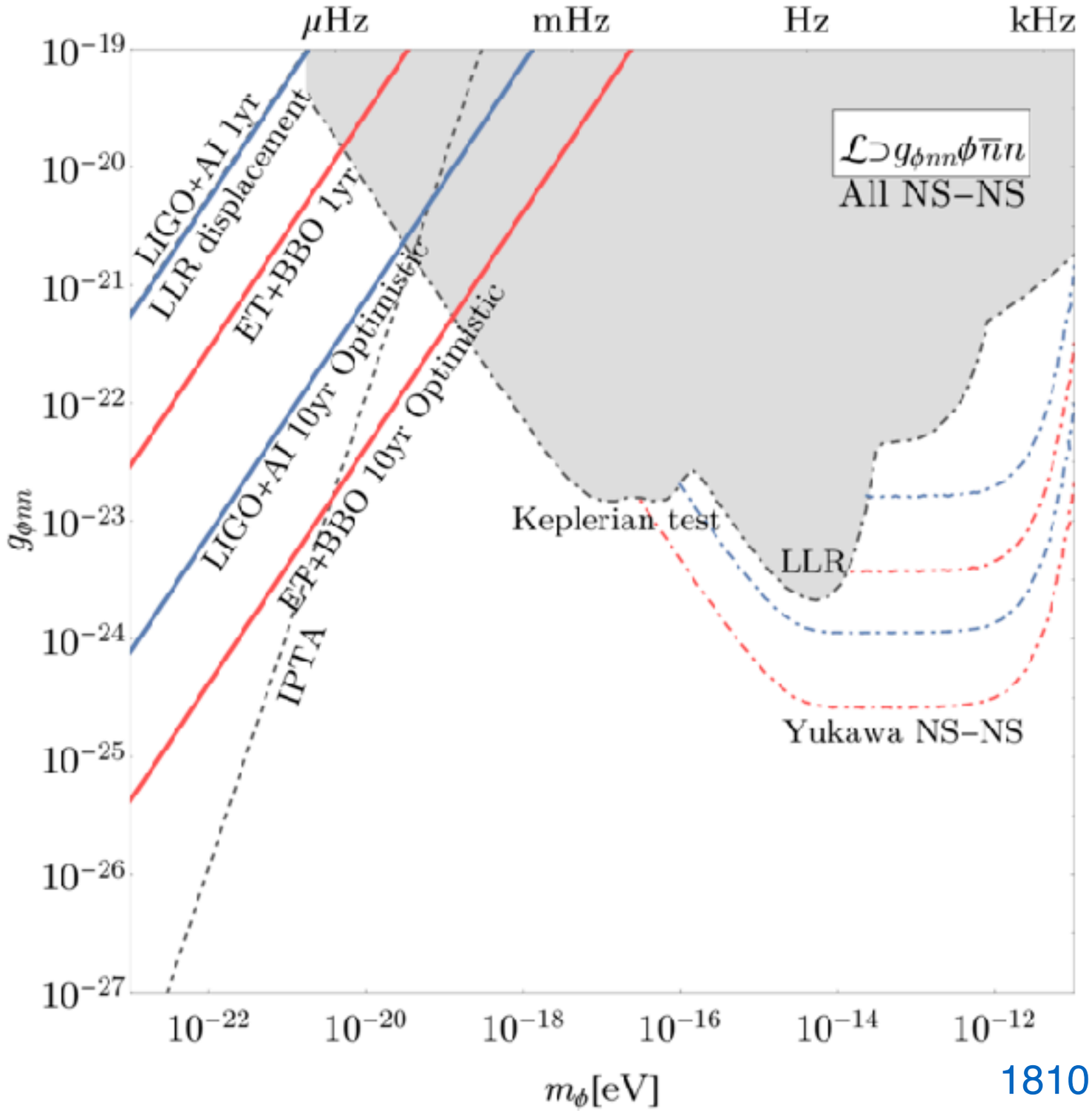
$$\frac{\Delta\mathcal{M}}{\mathcal{M}} \sim (\mathrm{SNR})(N_{\mathrm{cyc}}) \sim 10^{-8}$$

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

SNR ~ 500, Ncyc ~ 10^7 huge enhancement
(NS-NS @ 10Mpc, last 1year)

1810.01421 w/ HanGil Choi

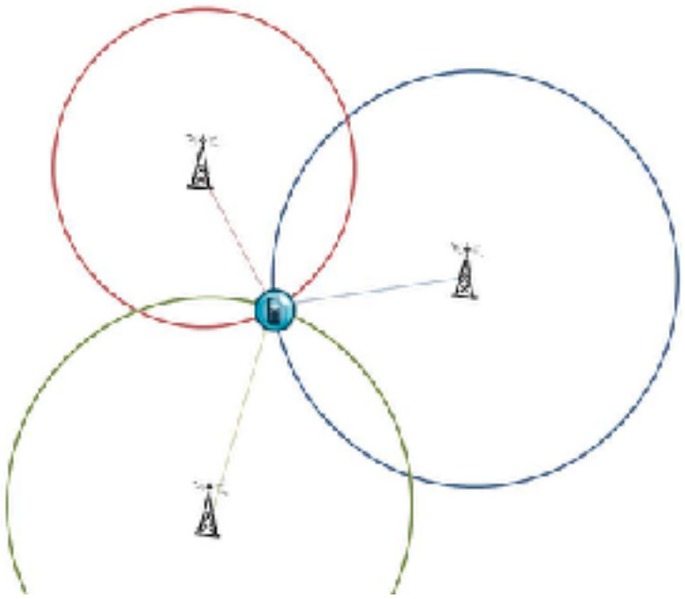
Detection prospects

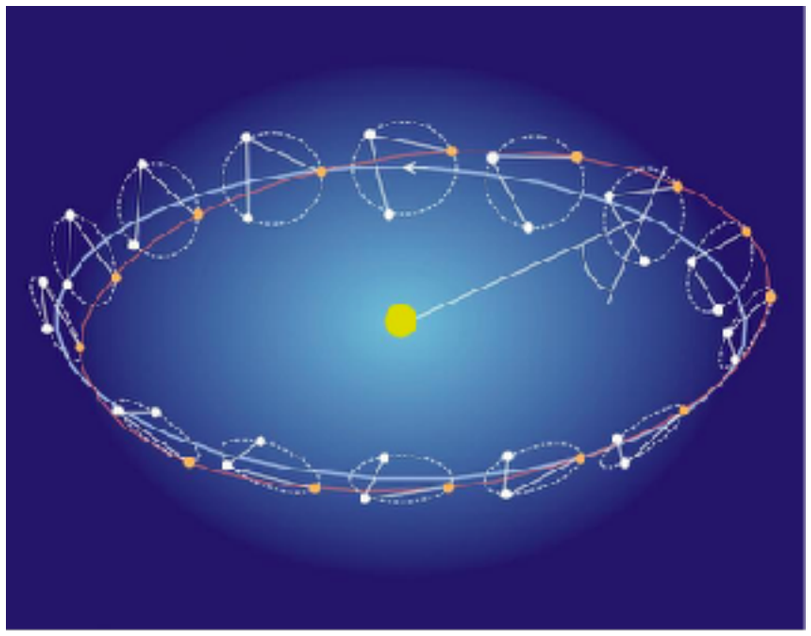


1810.01421 w/ HanGil Choi

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 measuring from mid-band (0.03 Hz-) on the Earth orbit (T=7.8hrs).

Benchmark for single-baseline detector: atom interferometer

Angular localization

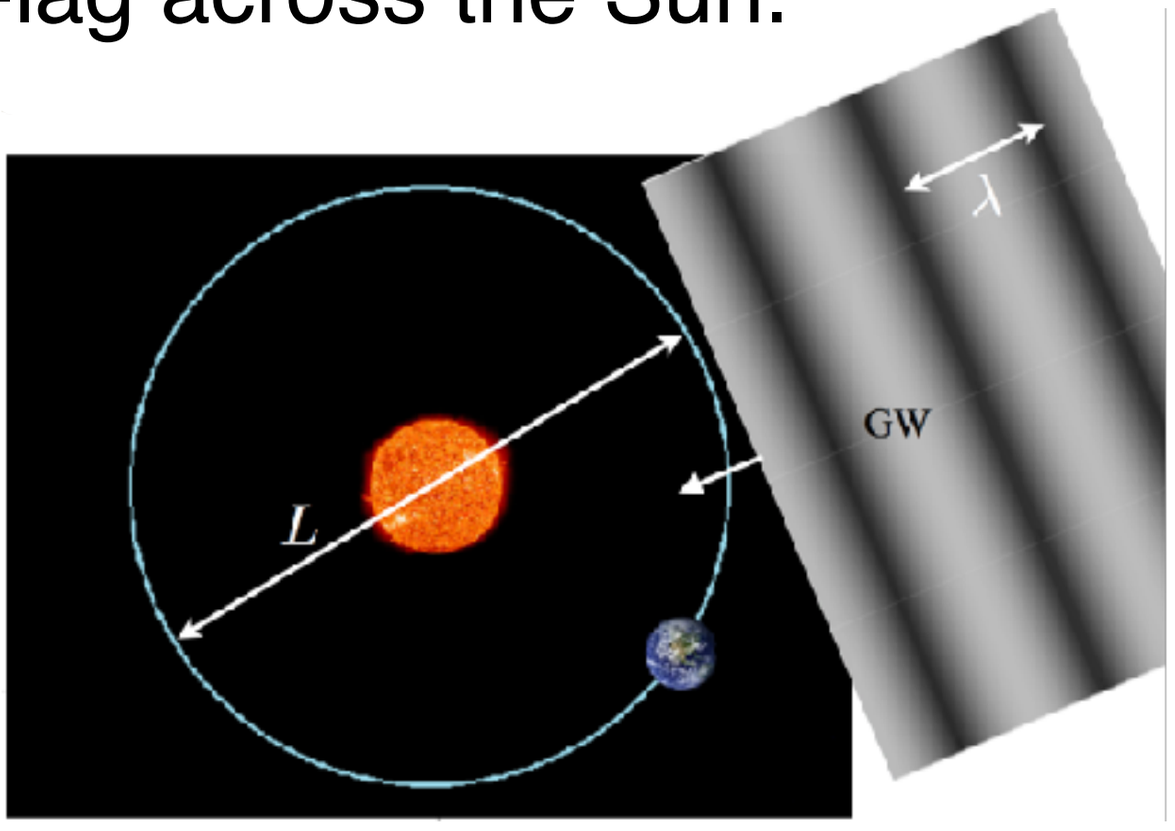
- The single-baseline "Reorients" hourly and monthly.
  This already makes it able to localize w/ one detector.

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

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

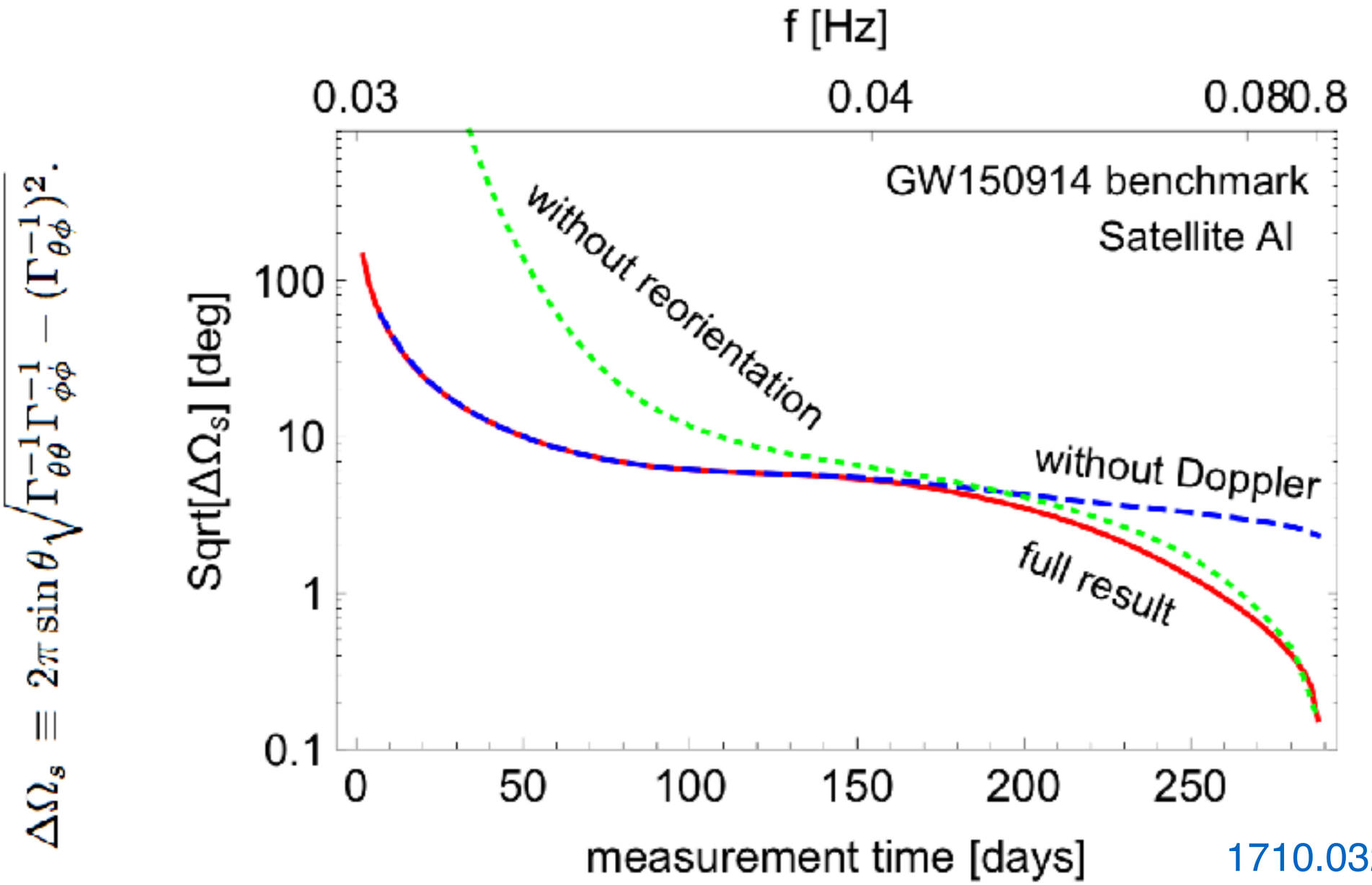
$$\Delta\theta \sim \mathrm{SNR} \cdot \frac{L}{\lambda}$$

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.



1710.03269 SJ, P.W.Graham

Summary

- GW is a powerful new eye to DM and early Universe.
- *LIGO alone* can see compact DM via “GW Fringe”.
- LIGO + mid-band:
  “*highest frequency* (0.01-1000Hz) with *year-long* lifetime”, is unique and much more powerful than LIGO alone:
- GW localization, Cosmic strings, Light scalar DM
- It just started. A lot more will be ahead!