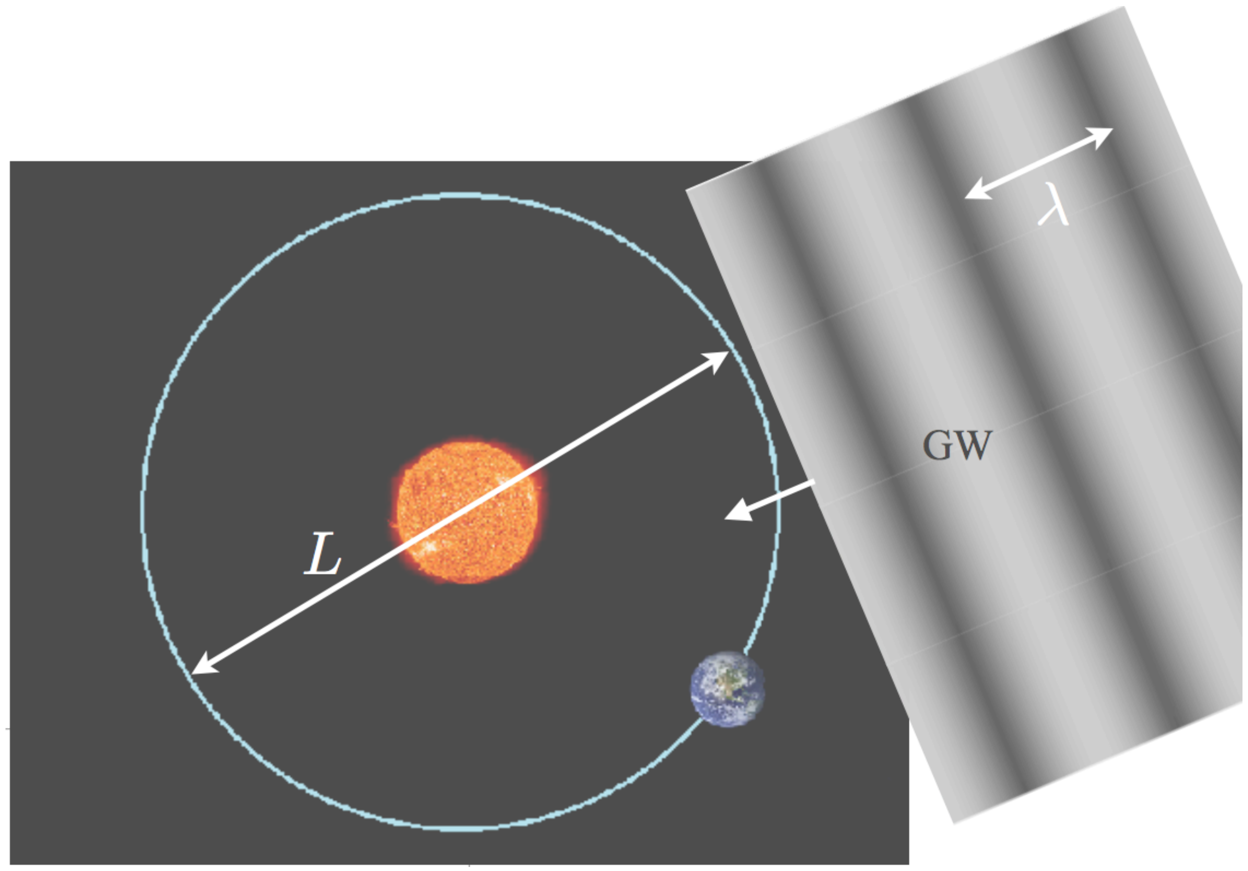
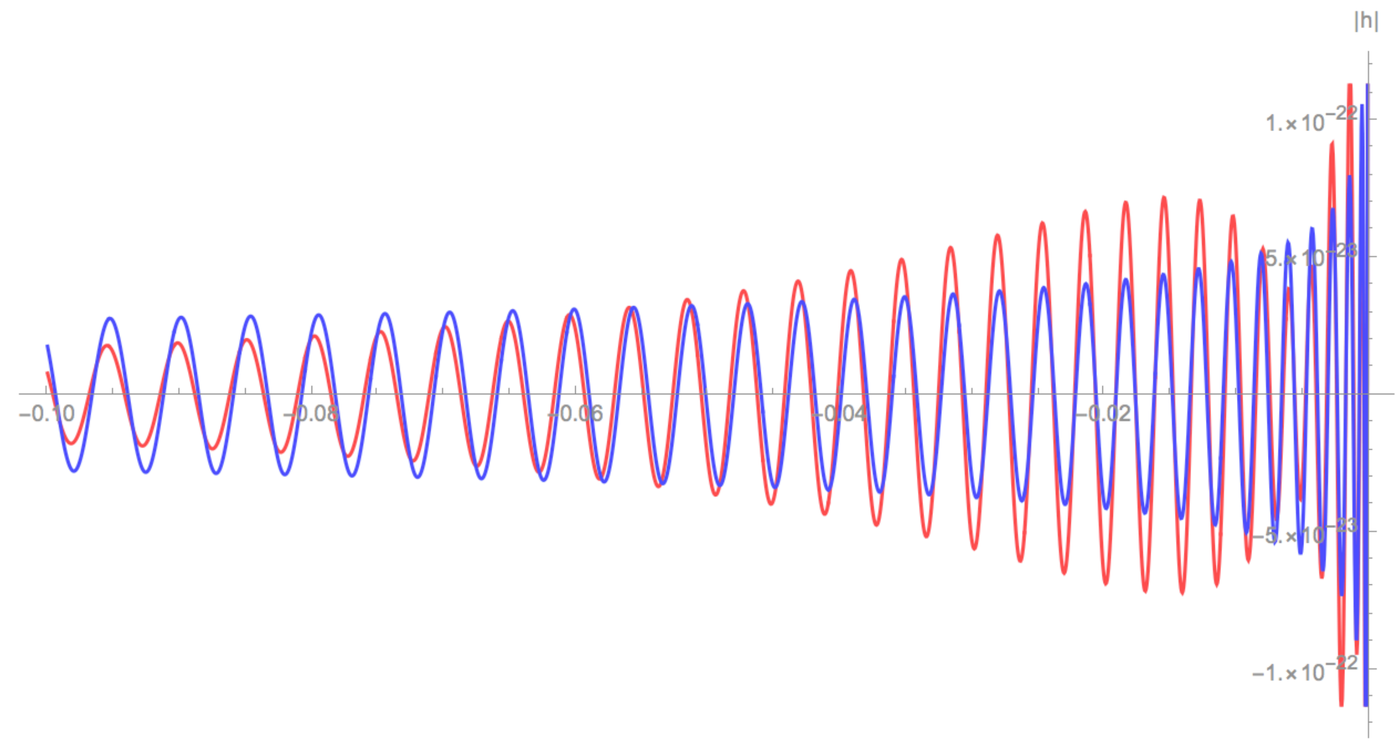
Utilities of GW for Probing Dark Matter





Sunghoon Jung
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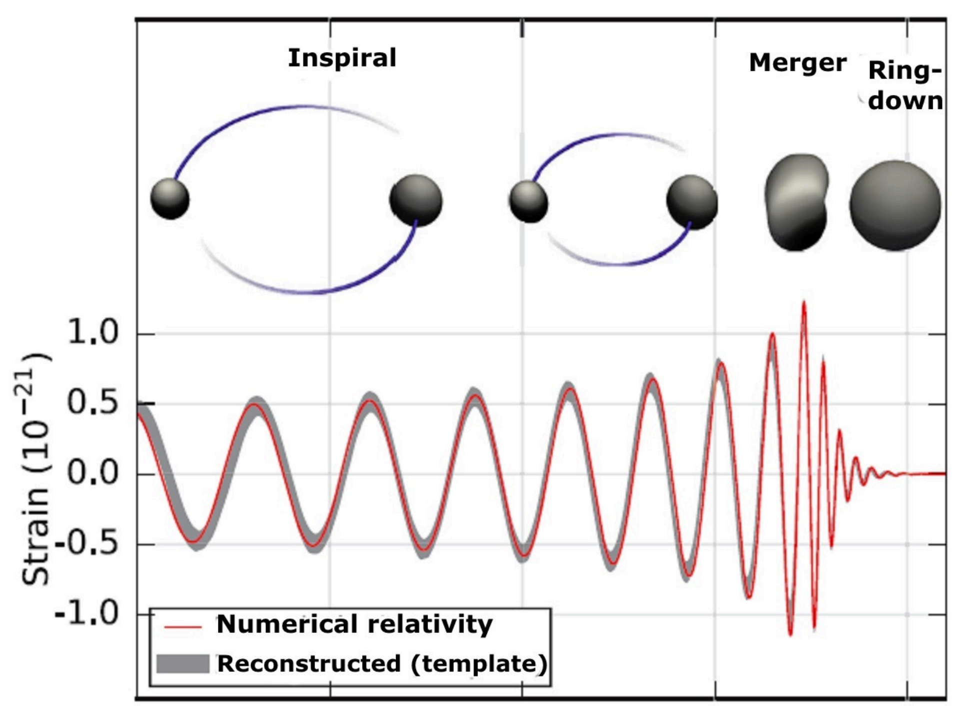
COSMO 2018 @ IBS

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

- It’s really the time to seriously put all the thoughts, because we do have a new eye — GW.

- GW waveform evolution is a key property.
  What particle physics info can be encoded/extracted?



Takehome messages

- We can do precision studies of DM/particle frontiers:
- *LIGO alone* can already see compact DM, even though short measurement and bad angular resolution: "GW Fringe"
- Combined with mid-frequency, GW network (0.01-1000Hz) becomes a unique and ideal test bed for DM & precision: "The *highest frequency*-band with *year-long* measurement".
- Examples: GW localization, cosmic strings, fuzzy/ALP/ vector DM coupled to neutrons.

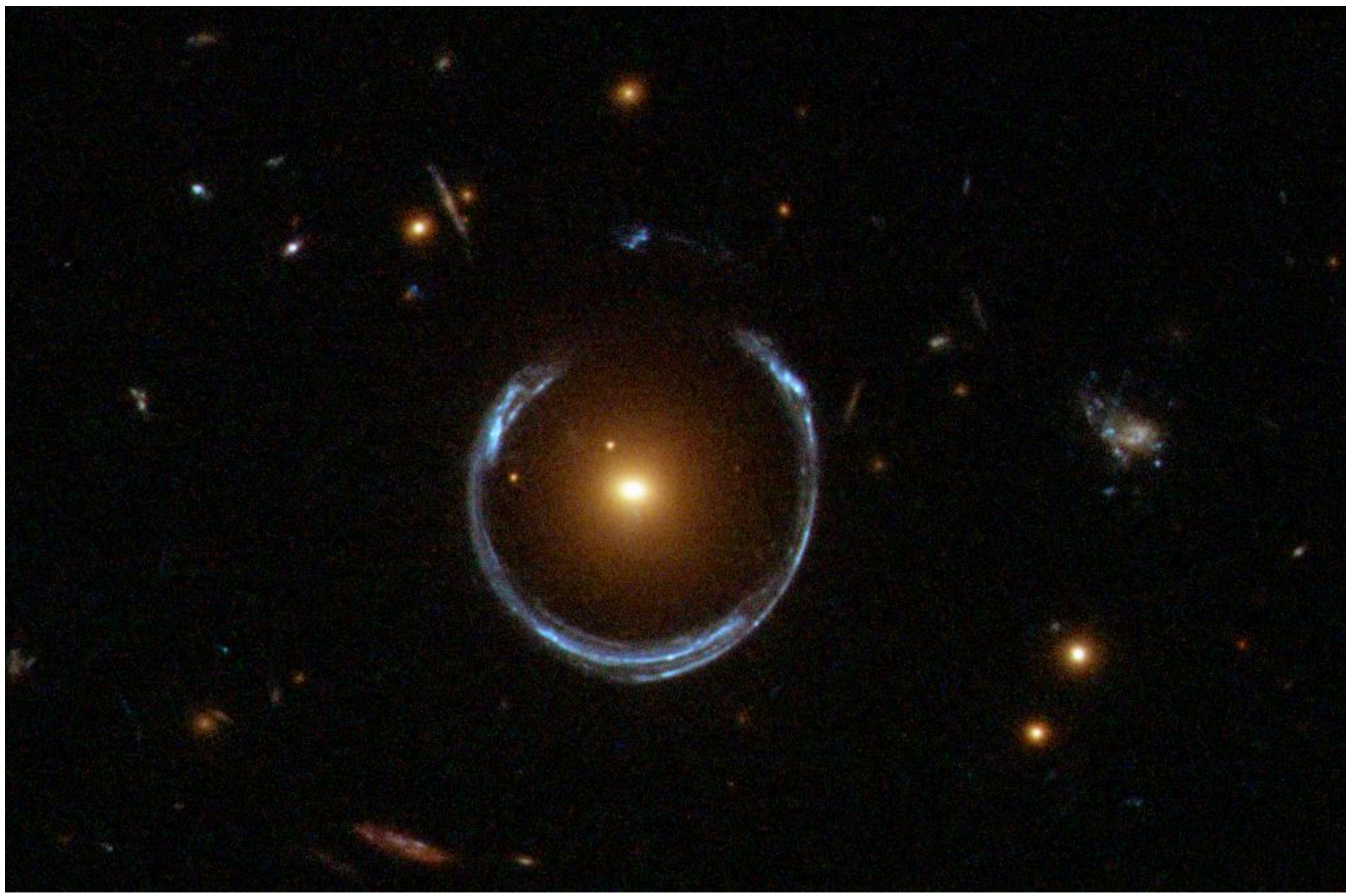
LIGO can see DM:

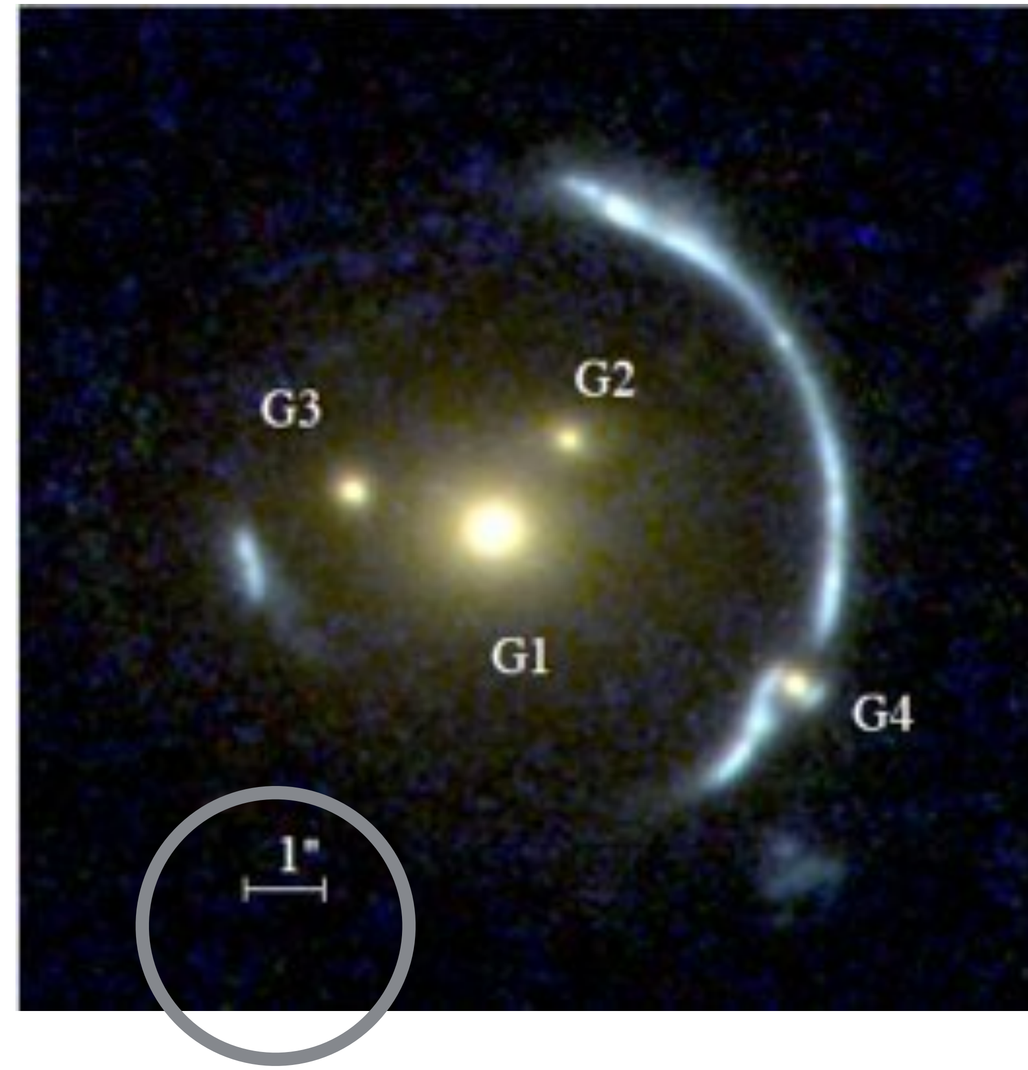
“GW Lensing Fringe”.

[1712.01396 with Chang Sub Shin]

At first sight, it sounds very unlikely!

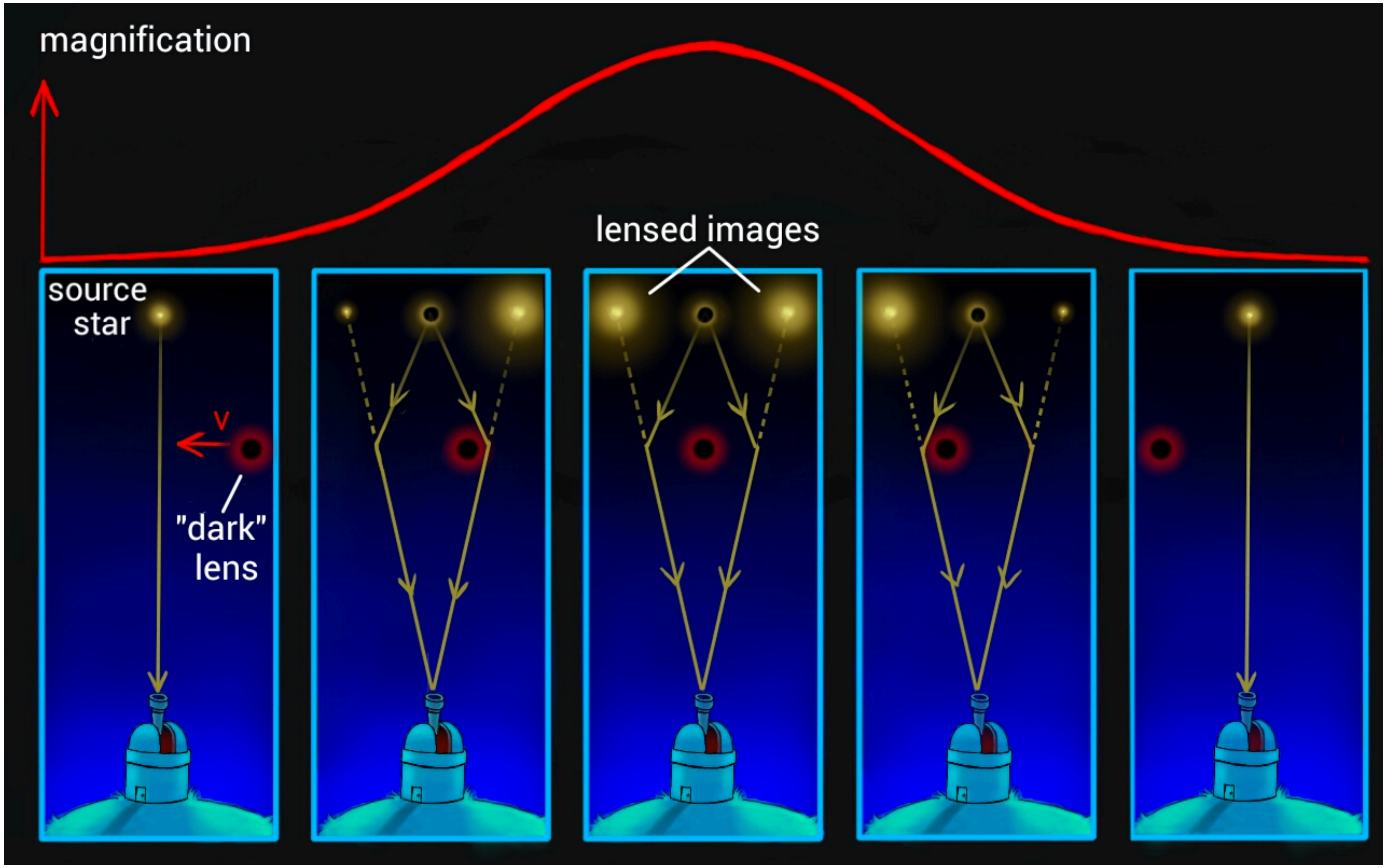
Strong lensing of light





- 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

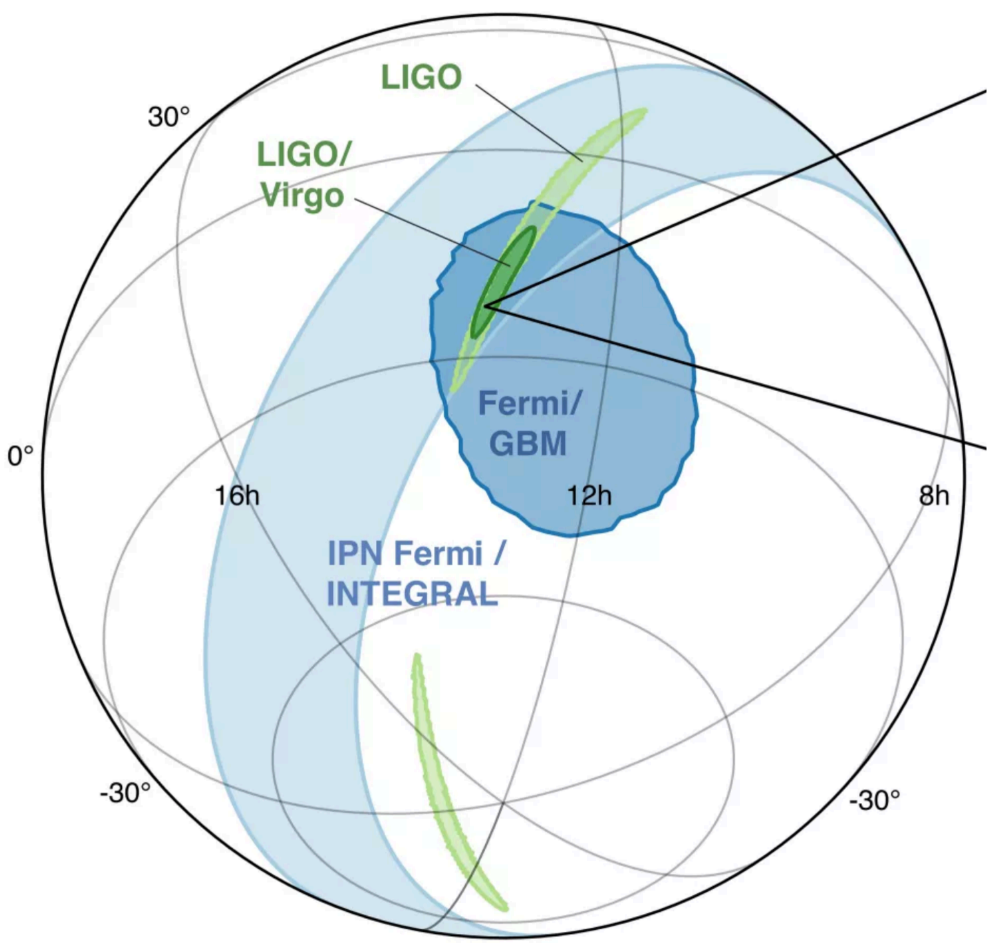
- Complicated statistical analysis of multiply and weakly lensed lights.

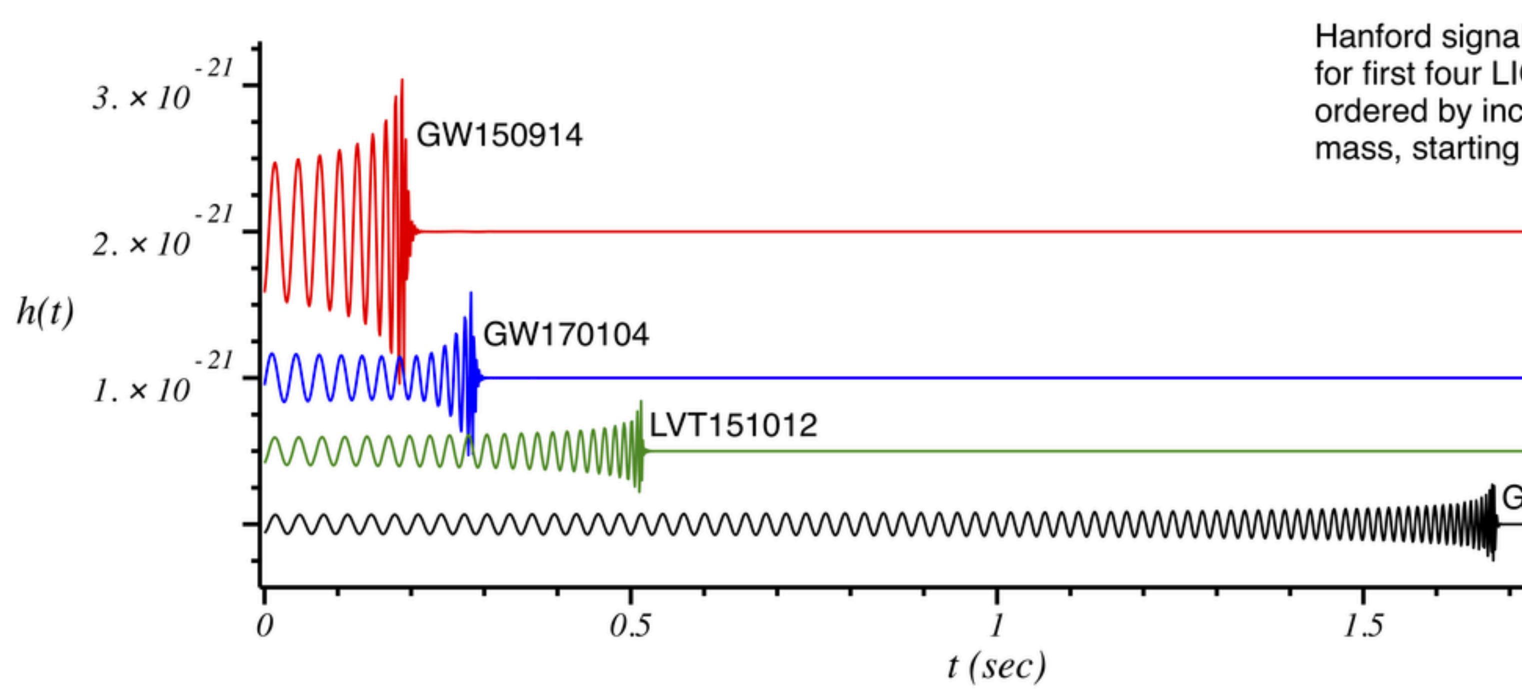
GW lensing observation is very unlikely at LIGO!

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,,,

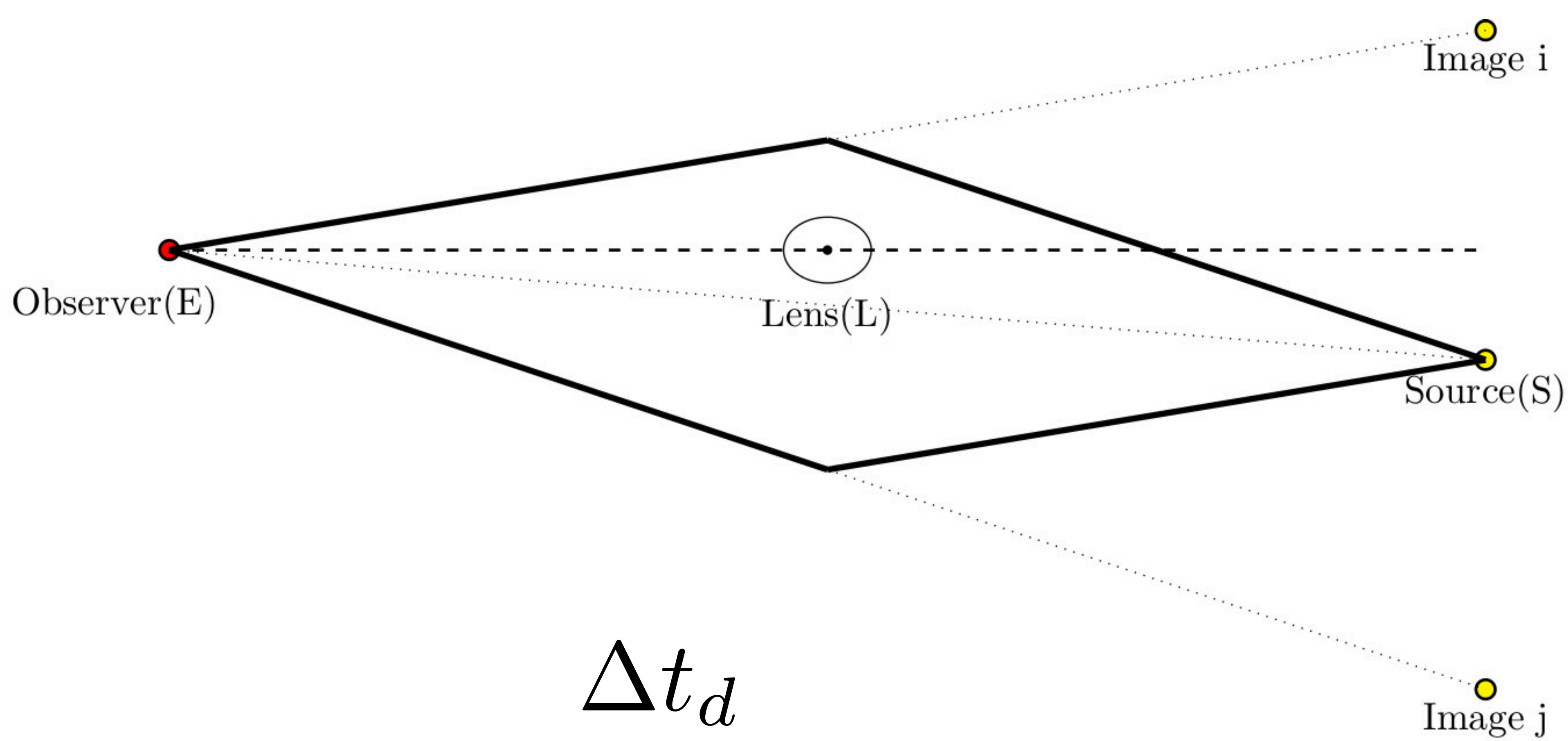
- GW chirps.
  - It provides the natural *change* of lensing pattern, which is extremely useful in lensing detection.

- 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.

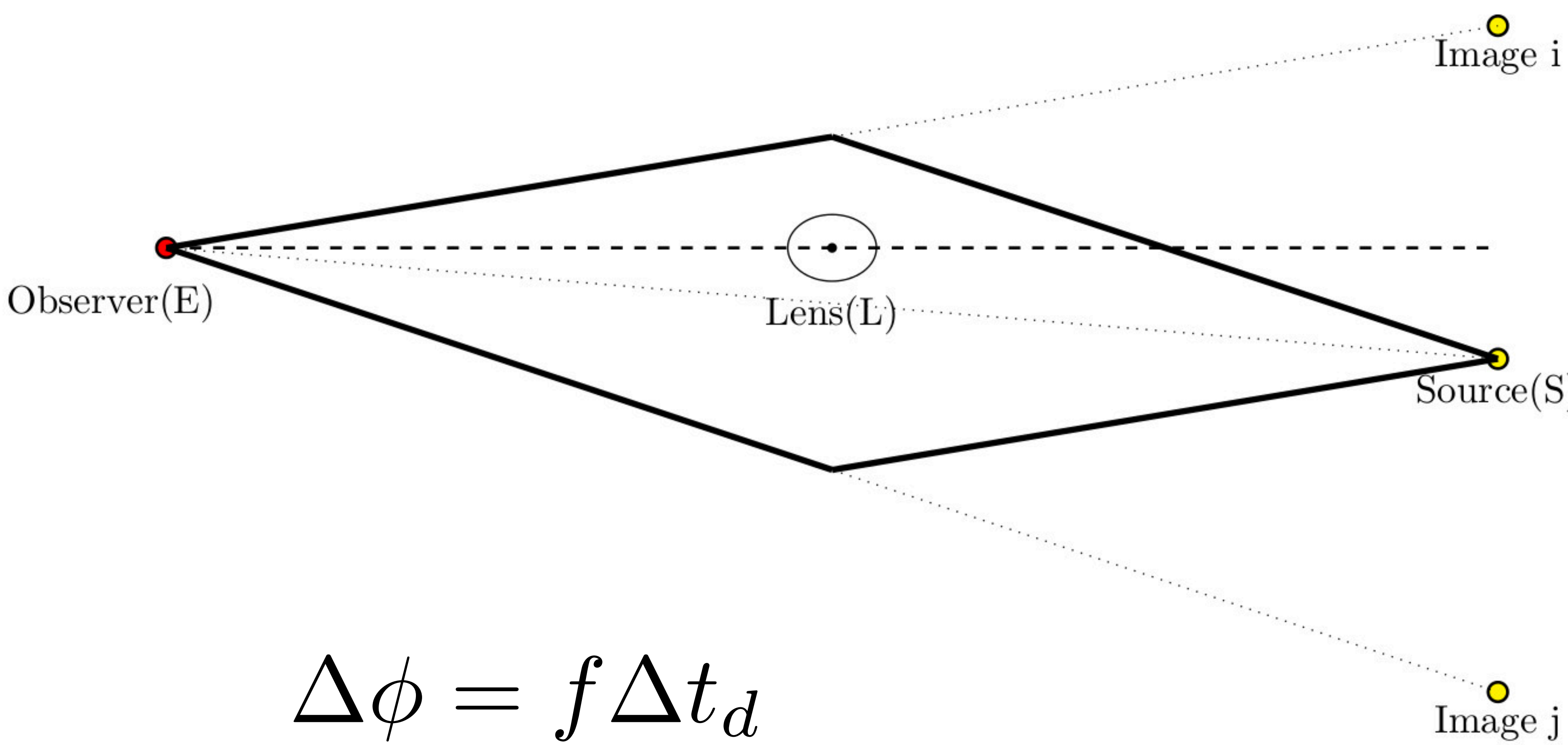


$$\Delta t_d$$

Two separate rays with different amplitude and time-delay

Interfered images

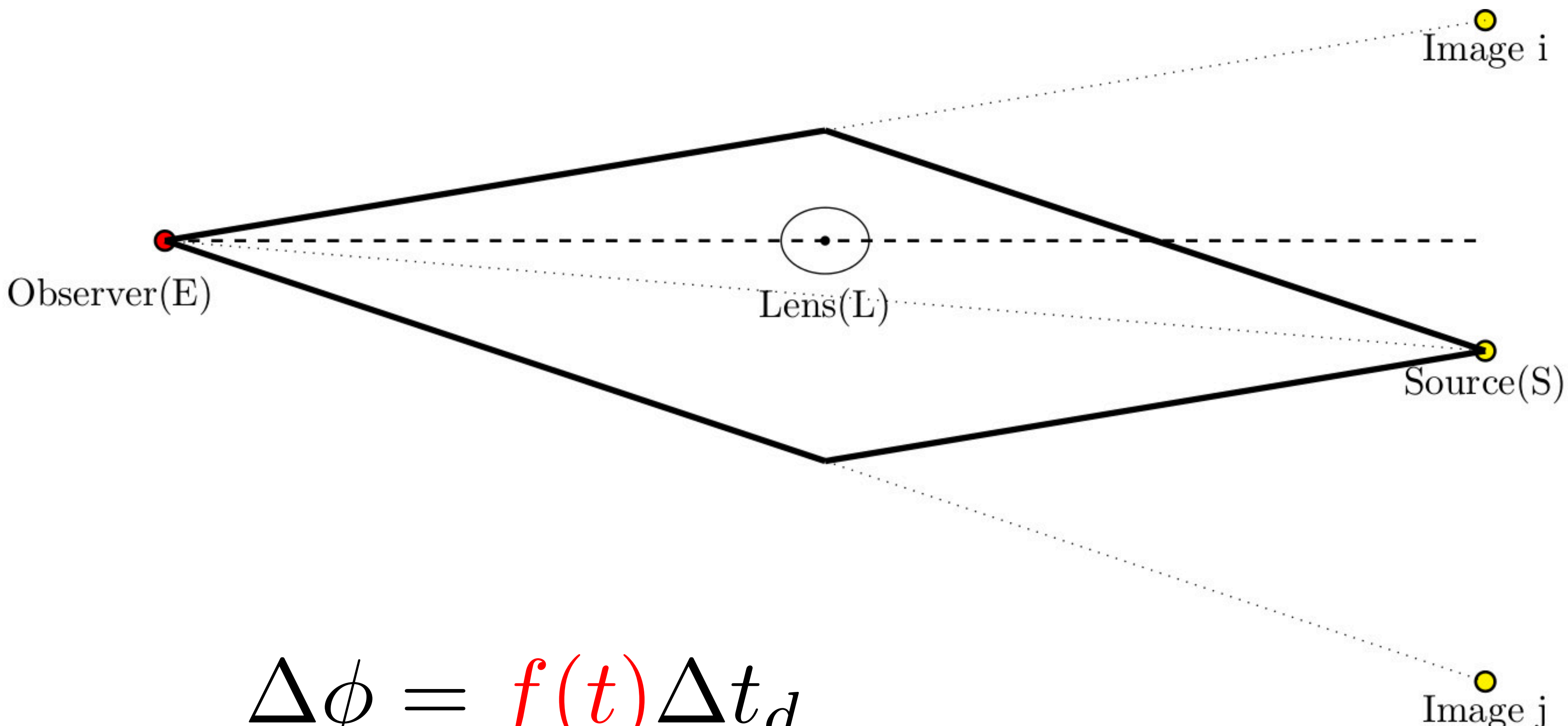
Unresolved GW images rather “interfere” in our observation.



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

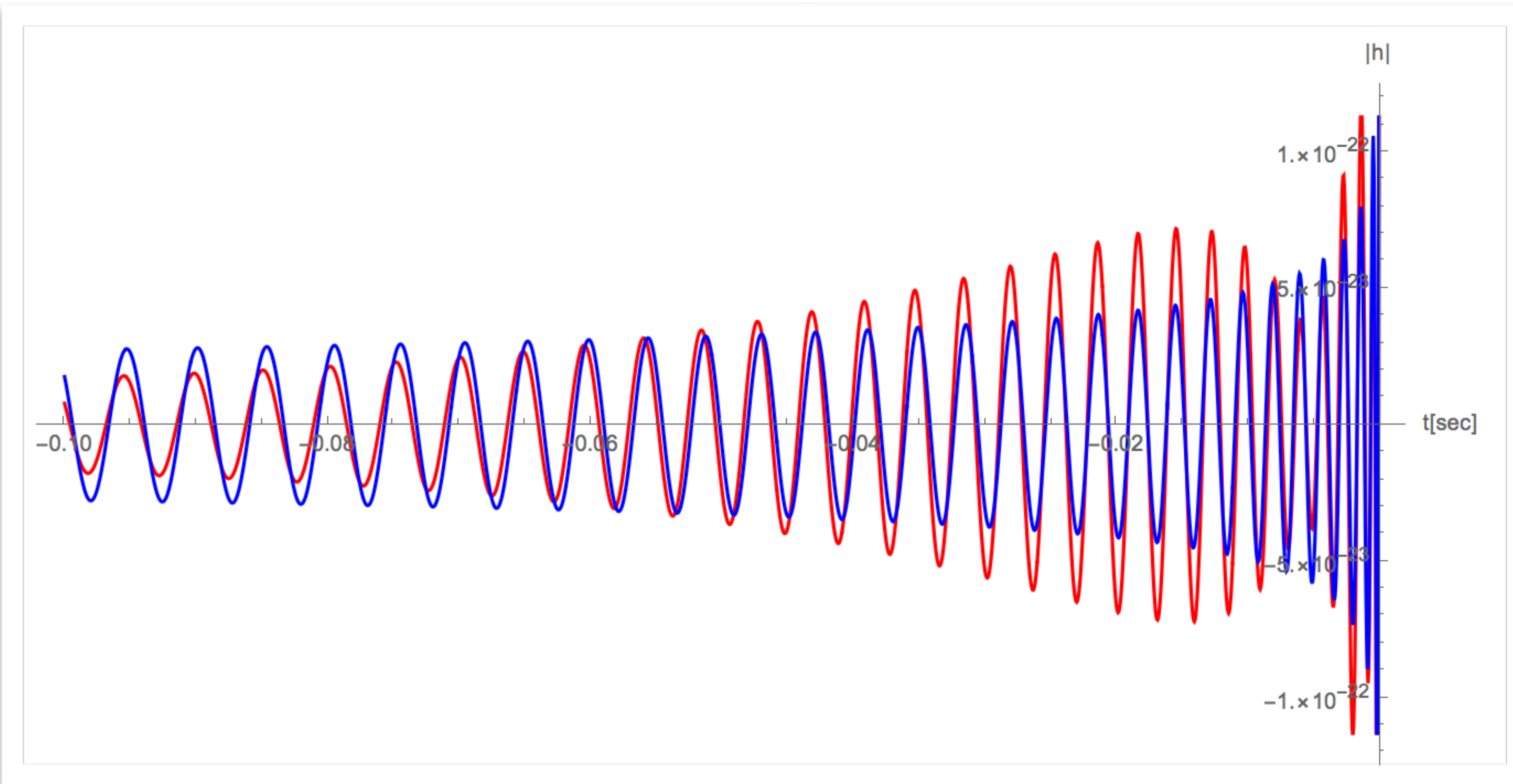
Fringe

It is the *GW chirping* that makes it observable — continuously changing the interference pattern: lensing "Fringe".



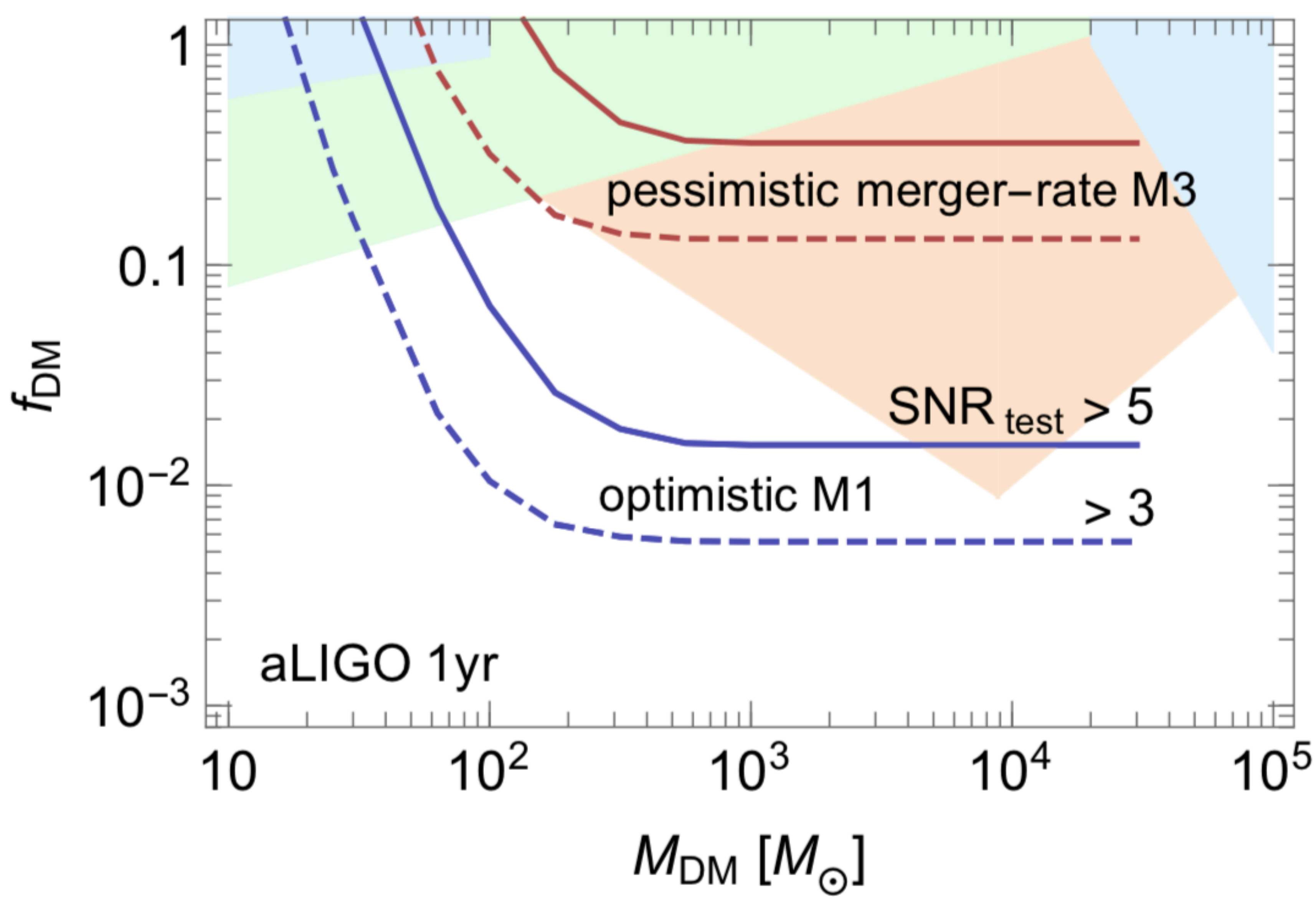
$$\Delta\phi = f(t)\Delta t_d$$

“GW Fringe”



NS-NS merger lensed by 100 Msun compact DM.

Compact DM fraction



LIGO is an ideal GW lensing detector

- GW Fringe is most pronounced at LIGO:
  - Highest frequency, changing a lot.
  - Chirping most quickly near merger.

- Highest-frequency GW can see the smallest compact DM.

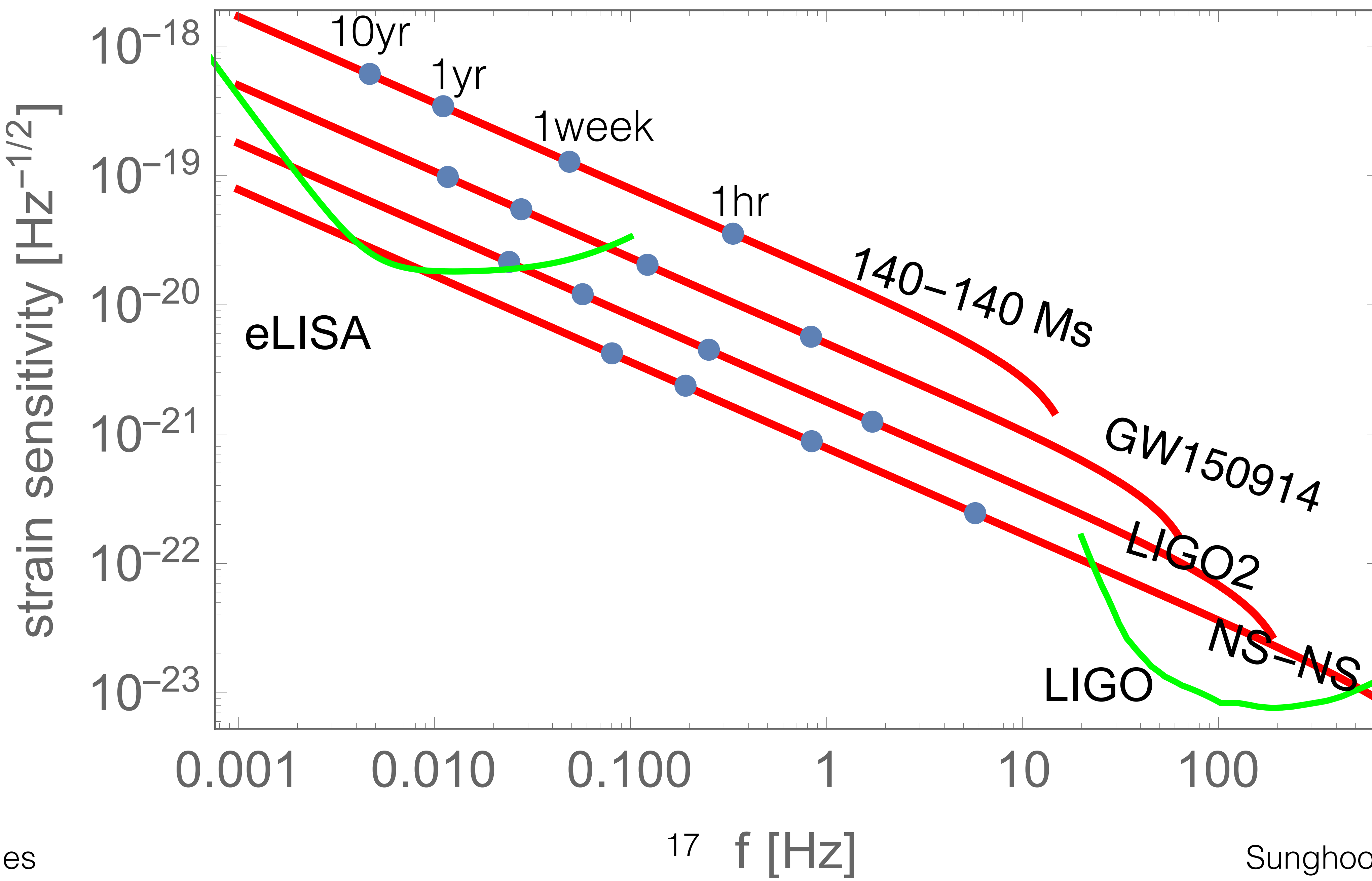
  10-1000 Hz = 10^2-10^4 Msun Schw radius

What can we see/do more?
What do we need to accomplish them?

Let's extend our scope. A lot more exciting is just beyond…

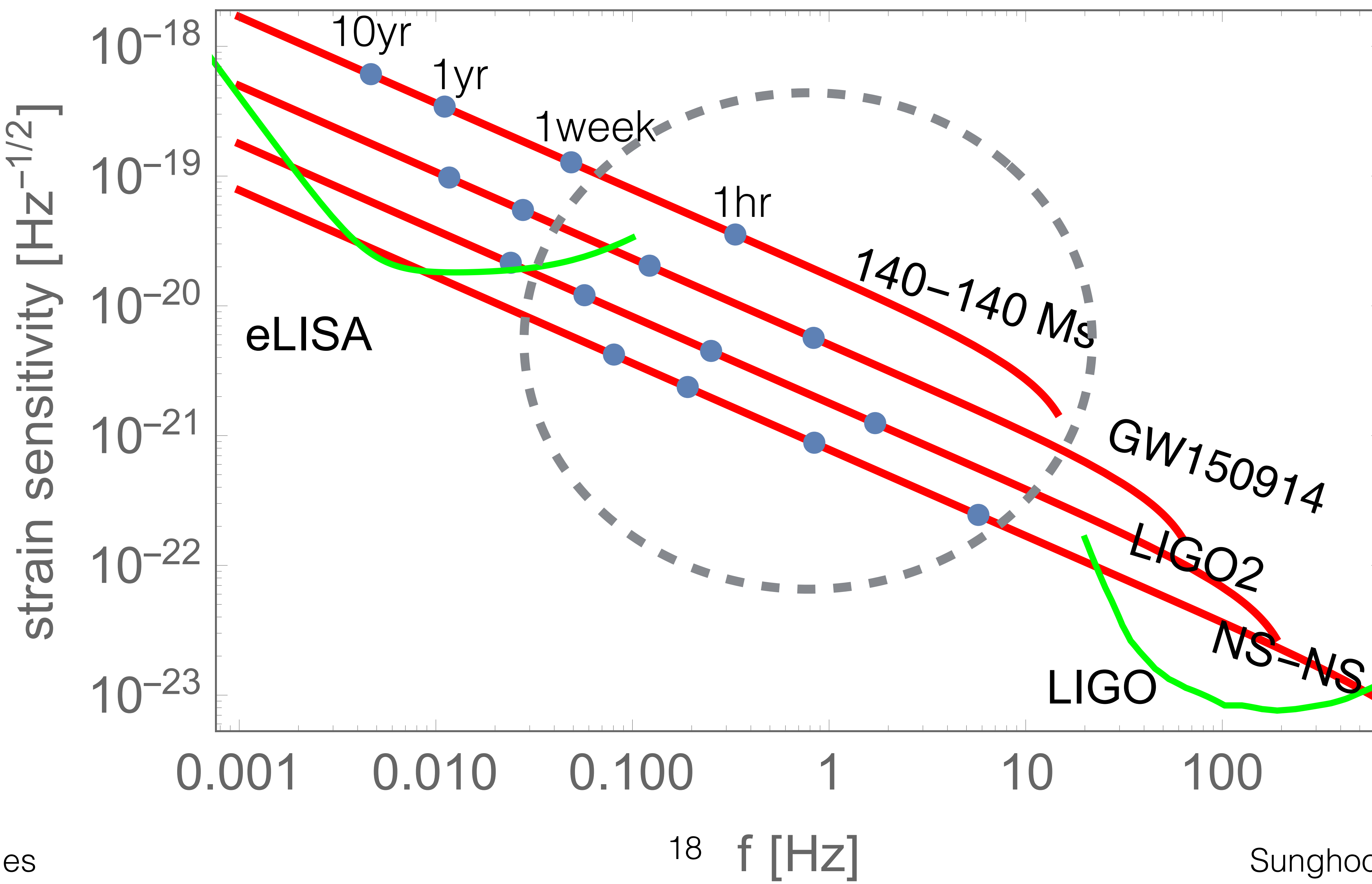
GW lifetime curve

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



GW lifetime curve

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



Mid + LIGO

- Unique & ideal test bed for dark matter and precision GW:

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

[1710.03269 with Peter W. Graham]

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

[works to appear with Hangil Choi, Taehun Kim and related previous works]

Why Localization?

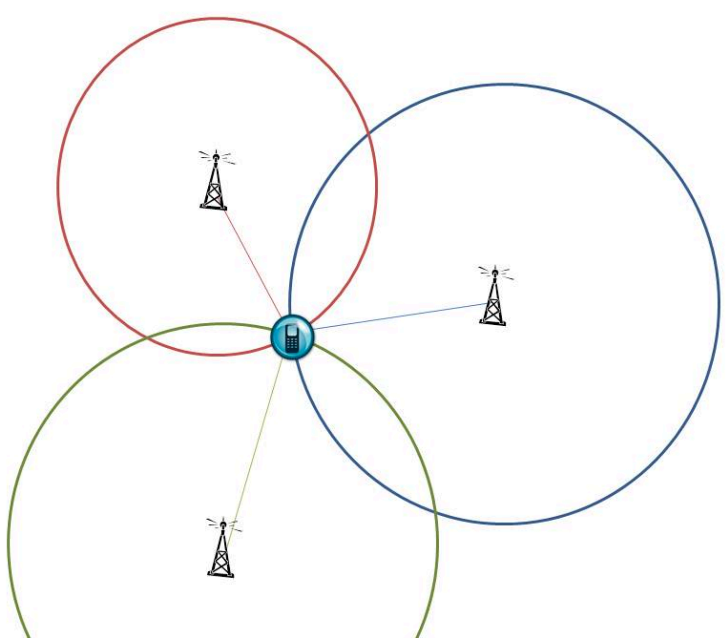
- Location on the sky is the most primitive but crucial information.

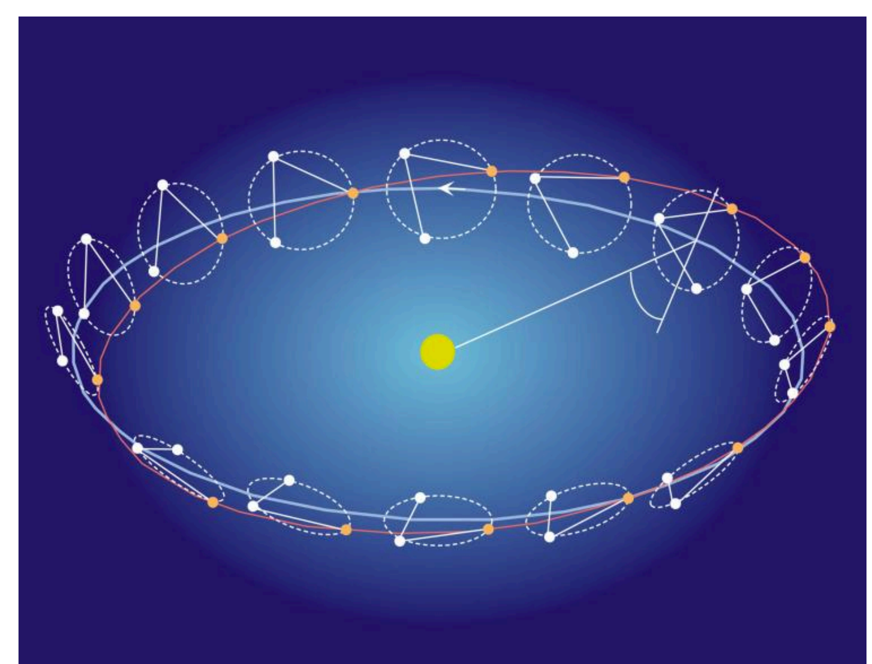
- *Multi-Messenger* truly begins :   Knowing where & when merges at LIGO well before the actual merger.

- *Precision GW* aided : removing degeneracies, lensing detection improved

How to localize at LIGO/LISA

- Triangulation — time difference (LIGO, LISA)
- Reorientation — directional difference   (LISA)





But let's consider a much simpler situation:

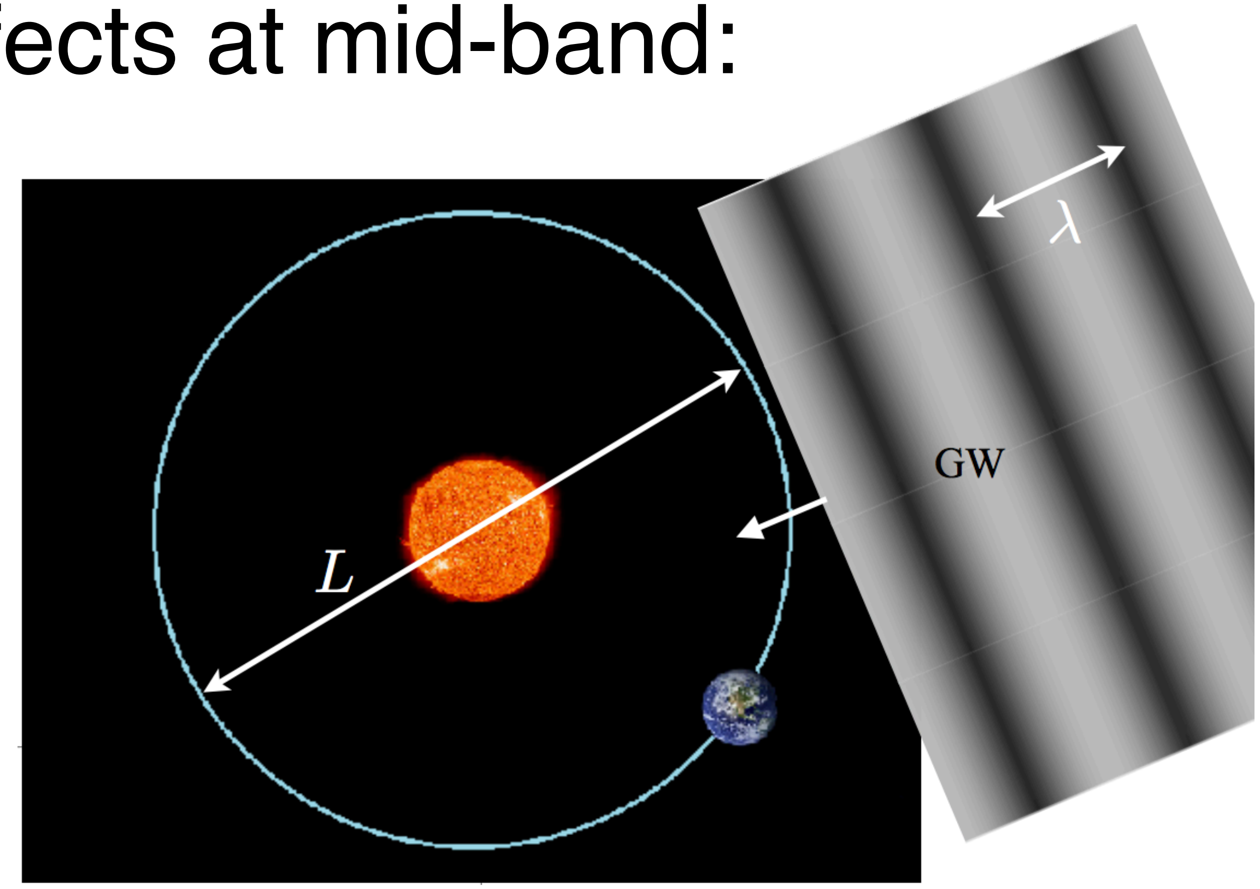
One single-baseline detector measuring mid-band (0.03 Hz-) on the Earth orbit.

Benchmark for single-baseline detector: atom interferometer

Angular localization

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

- "Doppler" shift — Unique effects at mid-band:
  huge phase-lag across the Sun.



Angular localization

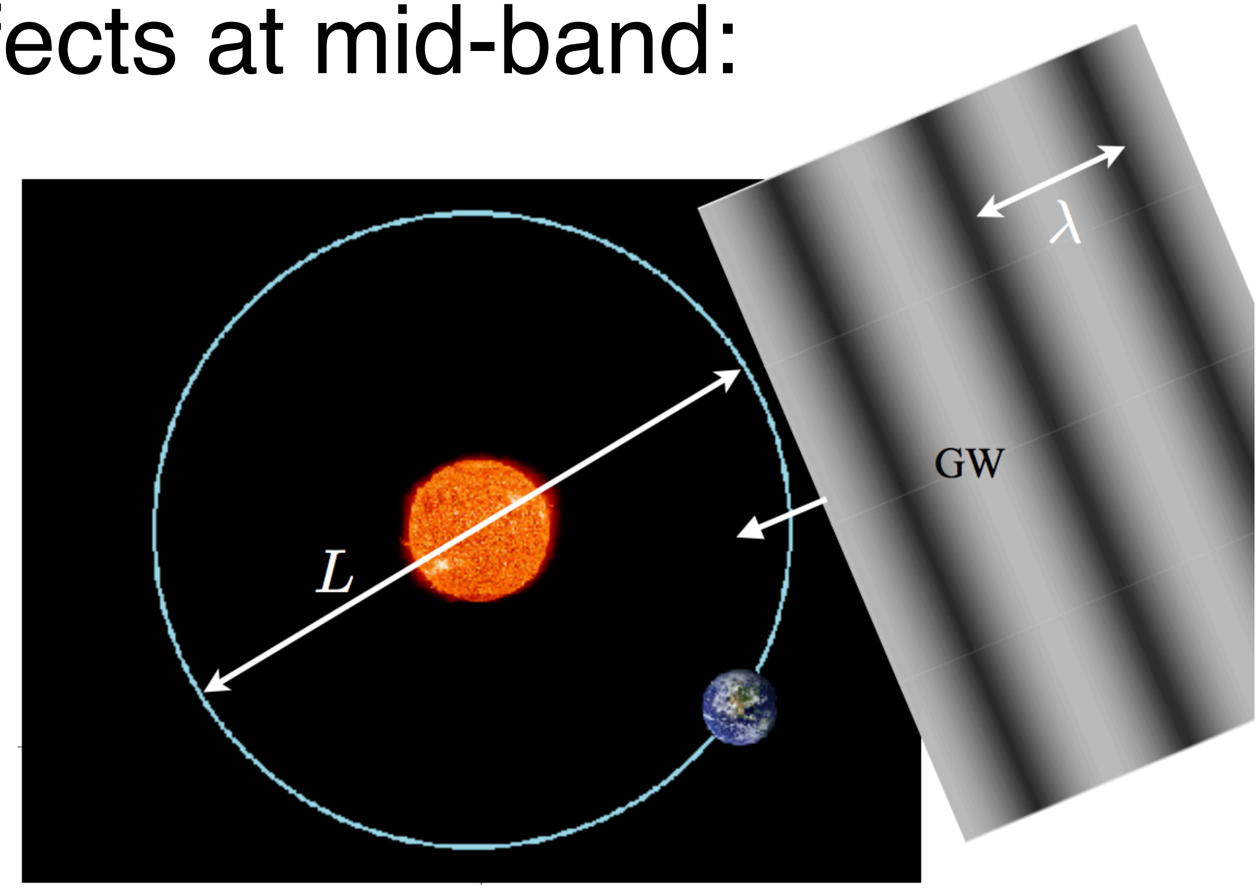
- "Reorients" hourly and monthly.
  This already makes it able to localize w/ one detector.

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

- "Doppler" shift — Unique effects at mid-band: huge phase-lag across the Sun.

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

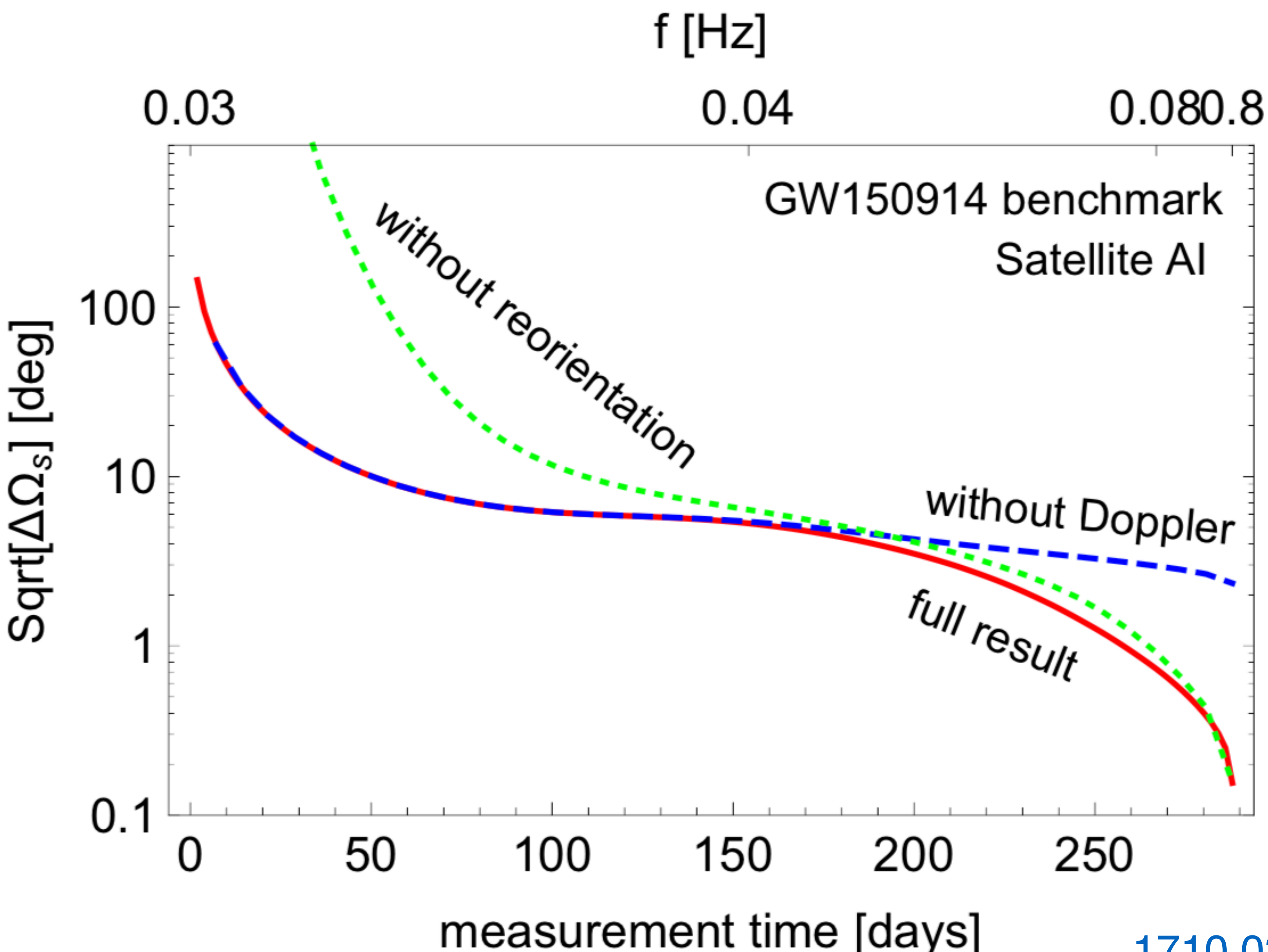
is largest for highest frequency that lasts for 0.5~1 year



GW150914 in the mid-band

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

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

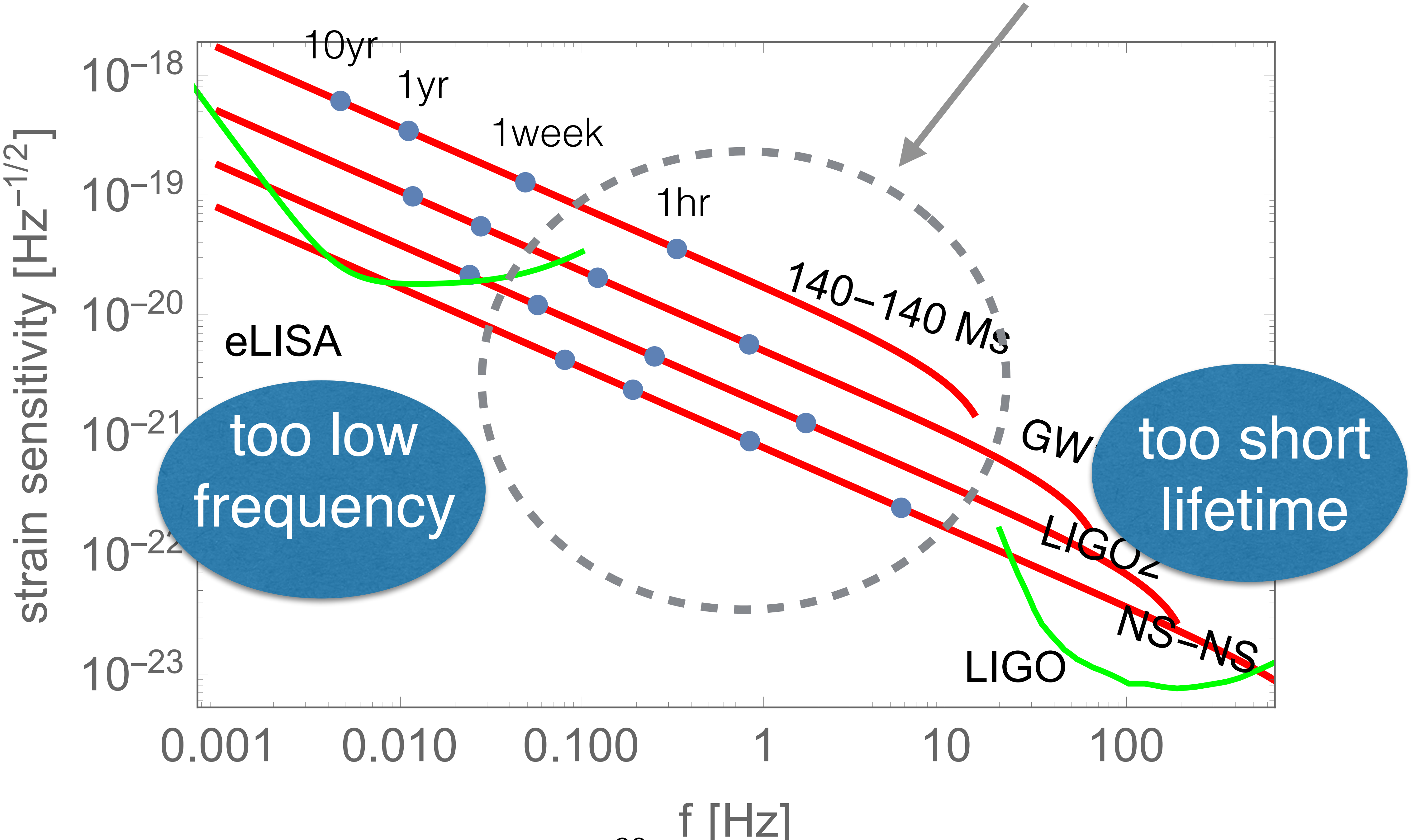


1710.03269 SJ, P.W.Graham

Doppler can dominate

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

is largest for highest frequency that lasts for 6 months



Dark matter detection

- Scalar DM of fuzzy/axion-like as light as 10^-23 eV.
- As a light DM, 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 will shift and oscillate 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 measure!
- 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

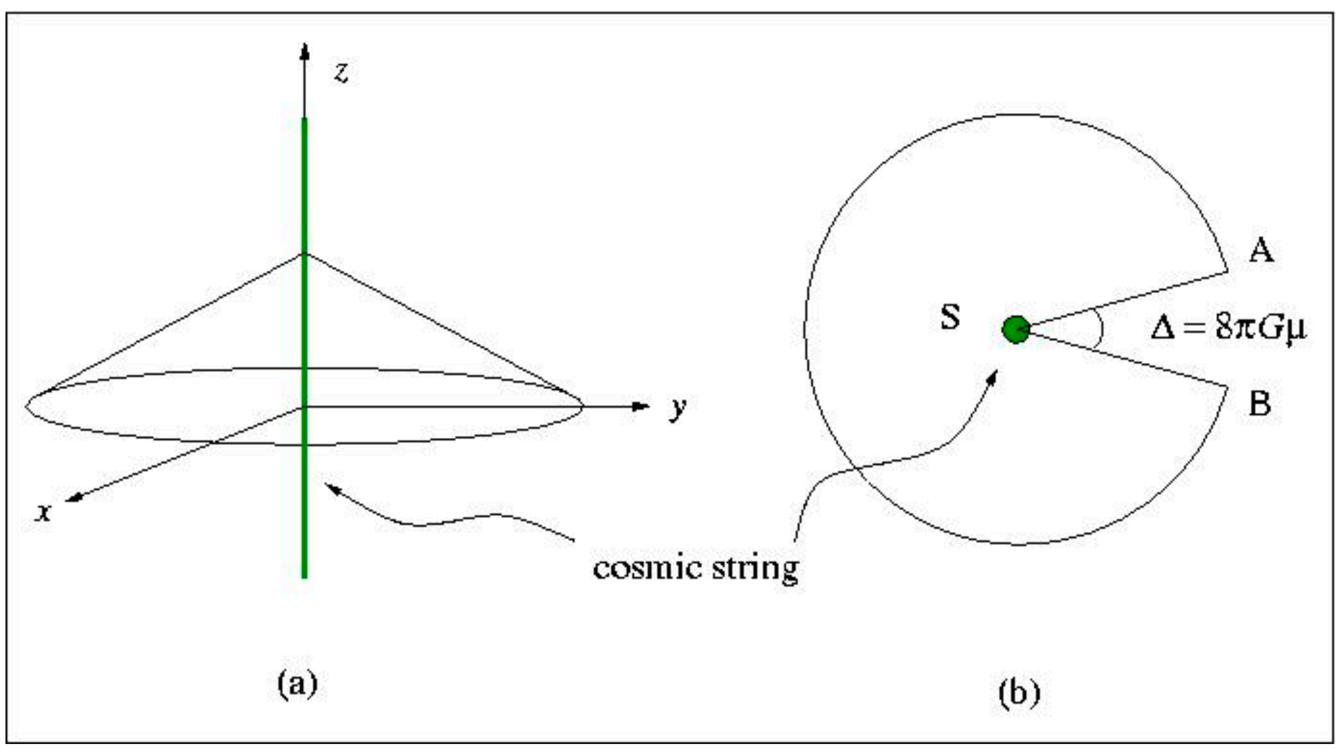
(NS-NS @ 10Mpc, last 1year)

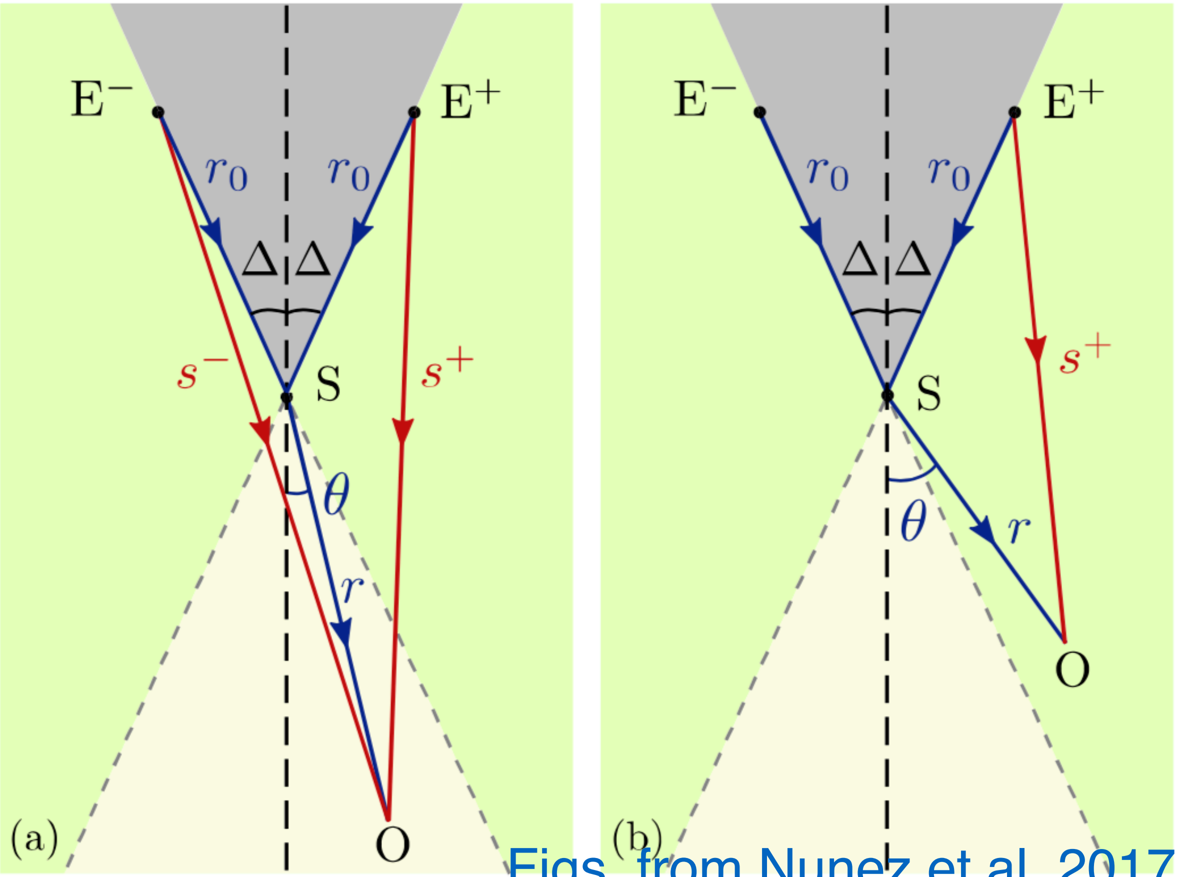
1809.xxxxx HanGil Choi, SJ

Cosmic string detection

- Likely fossils of early Universe w/ U(1) phase transitions.
- Again with GW Fringe aided by highest-frequency year-long measure, providing quickest and longest change!

1809.xxxxx SJ, TaeHun Kim





Figs. from Nunez et al. 2017

Summary

- GW is a new eye to dark matter and early Universe:
- *LIGO alone* can see compact DM via "GW Fringe".
- Combined with mid-frequency, forms "the *highest frequency*-band (0.01-1000Hz) with *year-long* lifetime".
- GW localization (with sub-degree resolution), Cosmic strings and fuzzy/ALP/vector DM are example applications.
- Extreme cases so far, but a lot more might be inside!