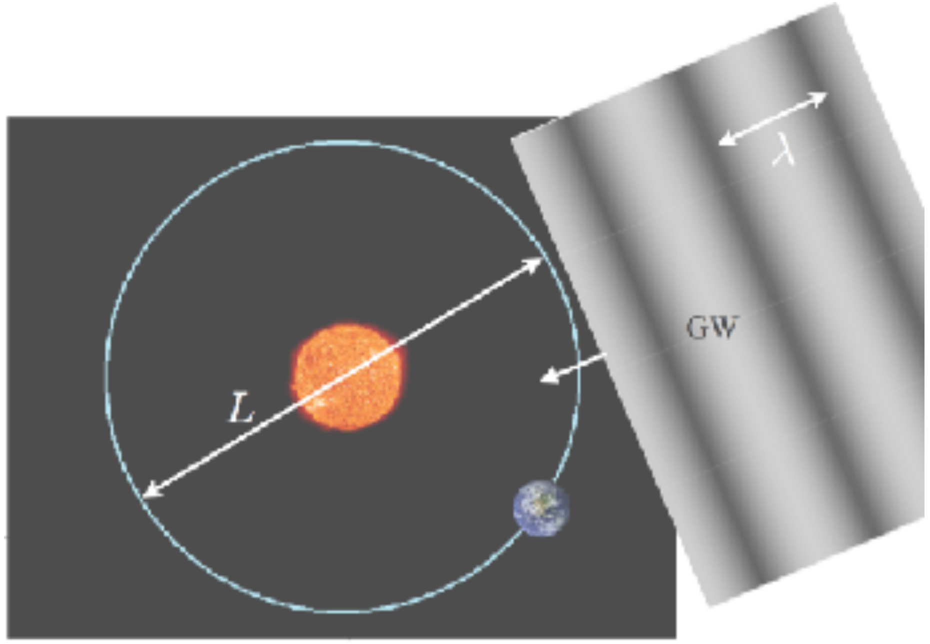
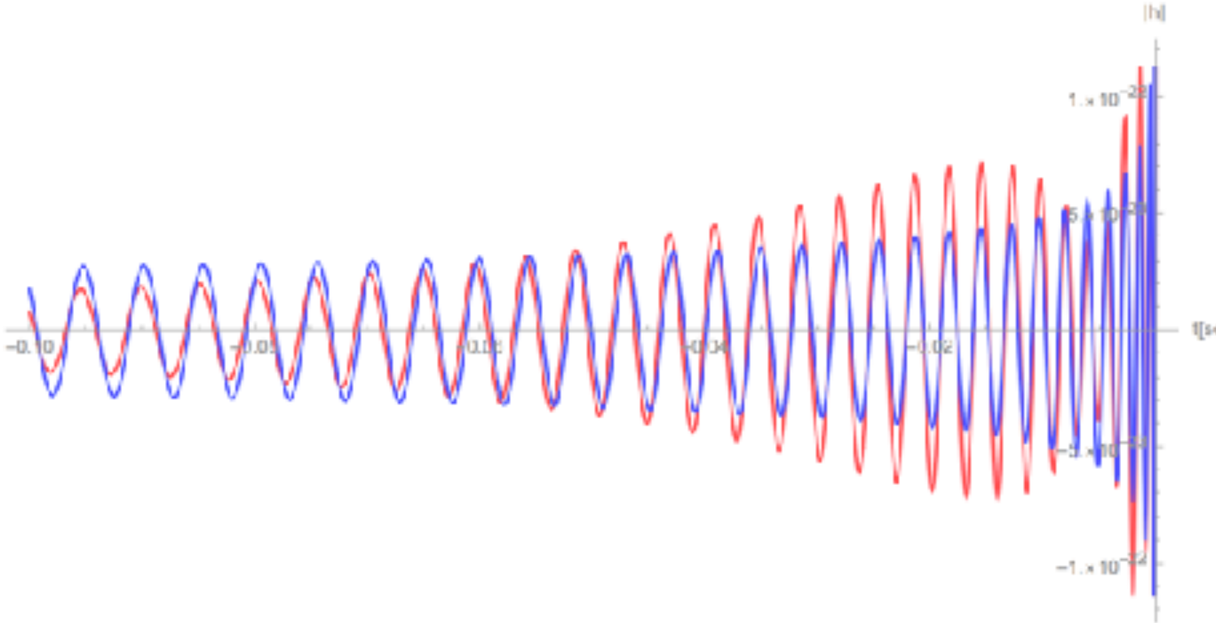
Dark Matter Probes with LIGO & Extended Freq Band

"LIGO and Beyond"





Sunghoon Jung

LIGO Meeting @ SNU, Sep 2018 (hosted by KASI, KISTI, KGWG)

1. Detecting Point-mass Lensing @ LIGO : "GW Fringe"

2. Overlooked Broadband : 0.1-1000 Hz = "highest-frequency" band where binaries can spend a "year"

   A. Natural localization — Doppler effect

   B. GW Fringe finer — Cosmic strings and early-Universe fossils

   C. Relaxion/Fuzzy/Axion-like scalar DM — astro-scale waves

3. Moving Farther Beyond : boosting high-f benefits

   A. Higher-frequency detectors?! - serious brainstorming

   B. Mapping & ringing with LIGO

To discuss

1. To improve/realize GW Fringe analysis at LIGO

    A. Spin precession

    B. Realistic lens and merger distributions

    C. Dedicated search analysis

    D. Understanding Fisher correlations better

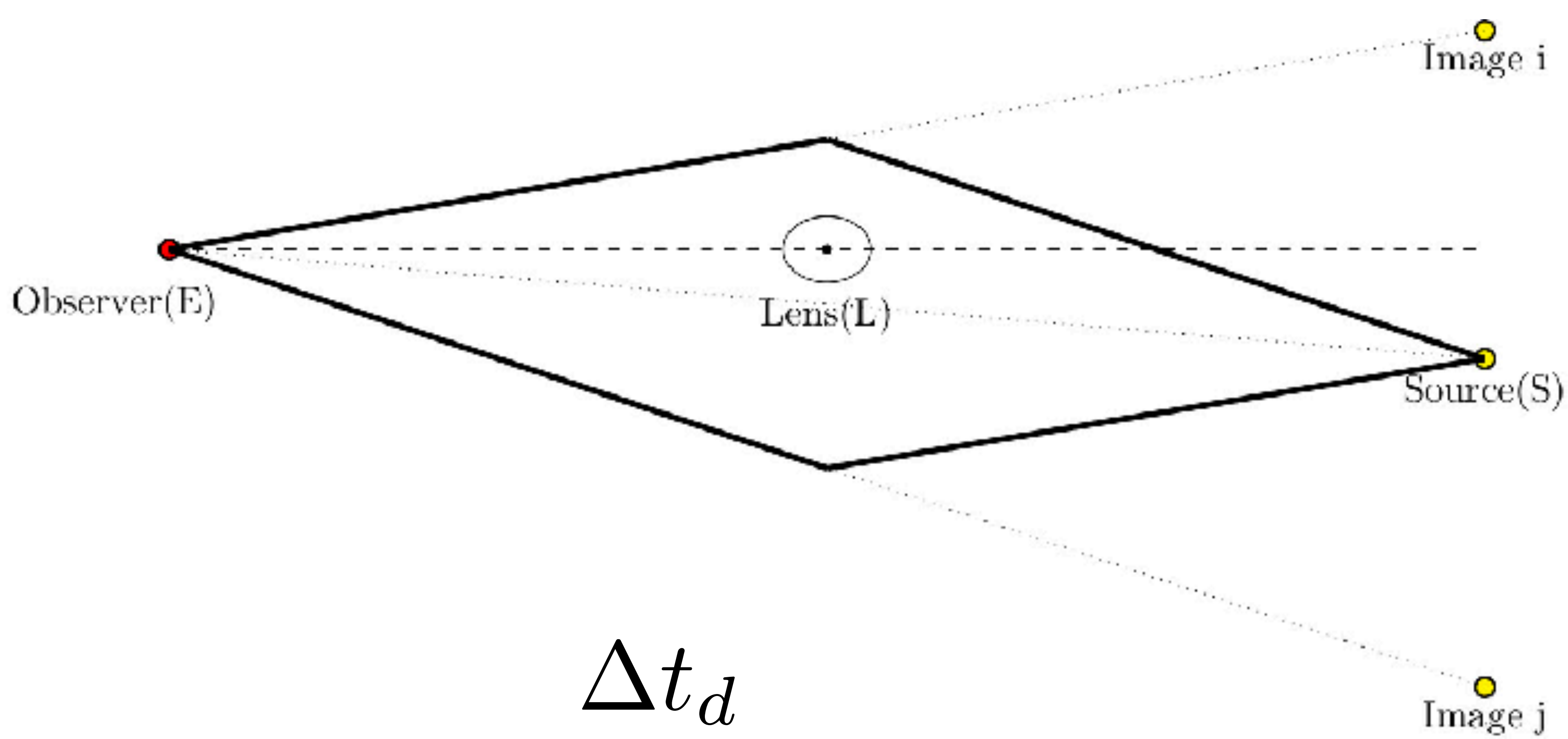
2. Which direction to go: Extended frequency bands?

    A. Motivations, physics cases, uniqueness

    B. Realization

Time-delayed images

Consider time-delayed lensed images of GW.

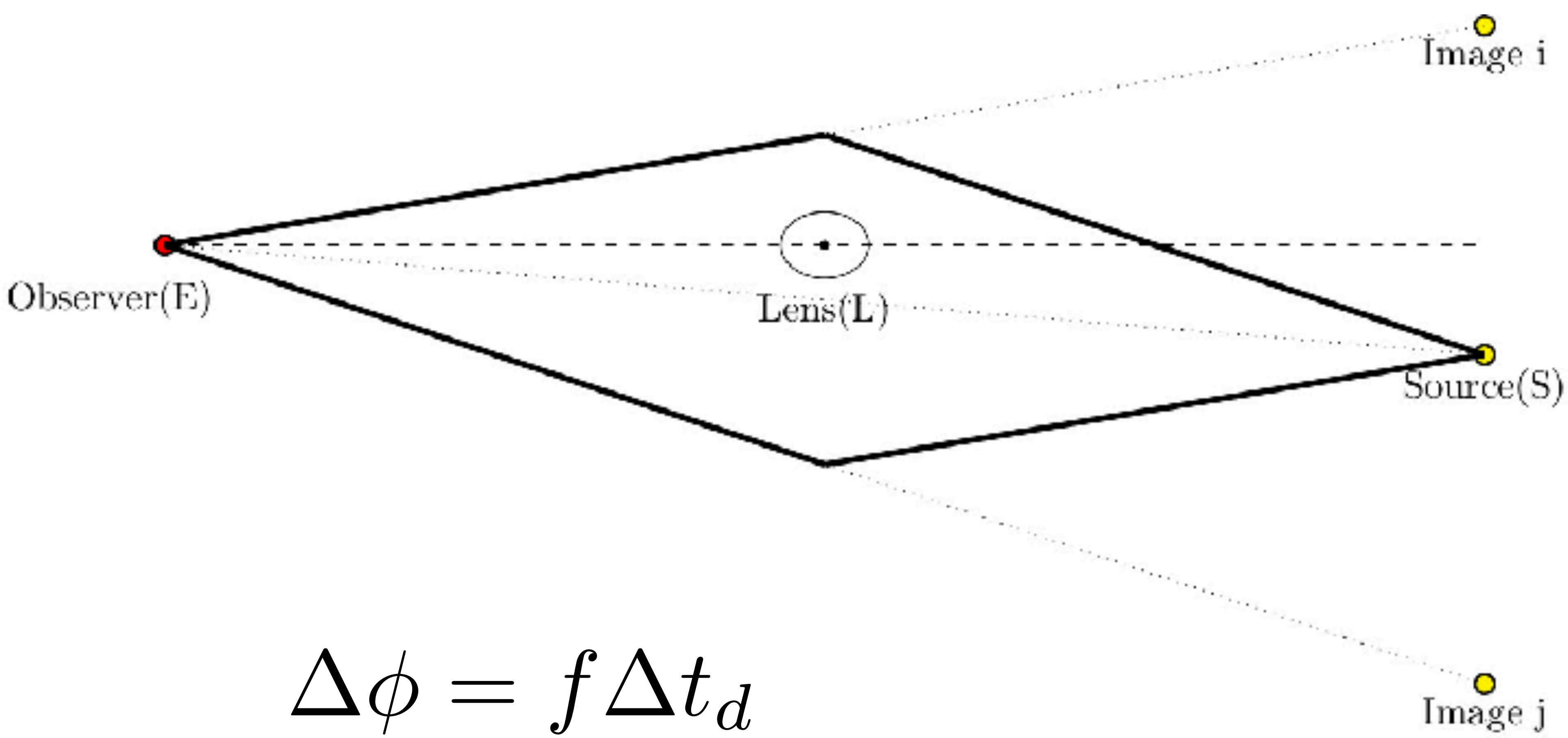


$$\Delta t_d$$

Two separate rays with different amplitude and time-delay

Interfered images

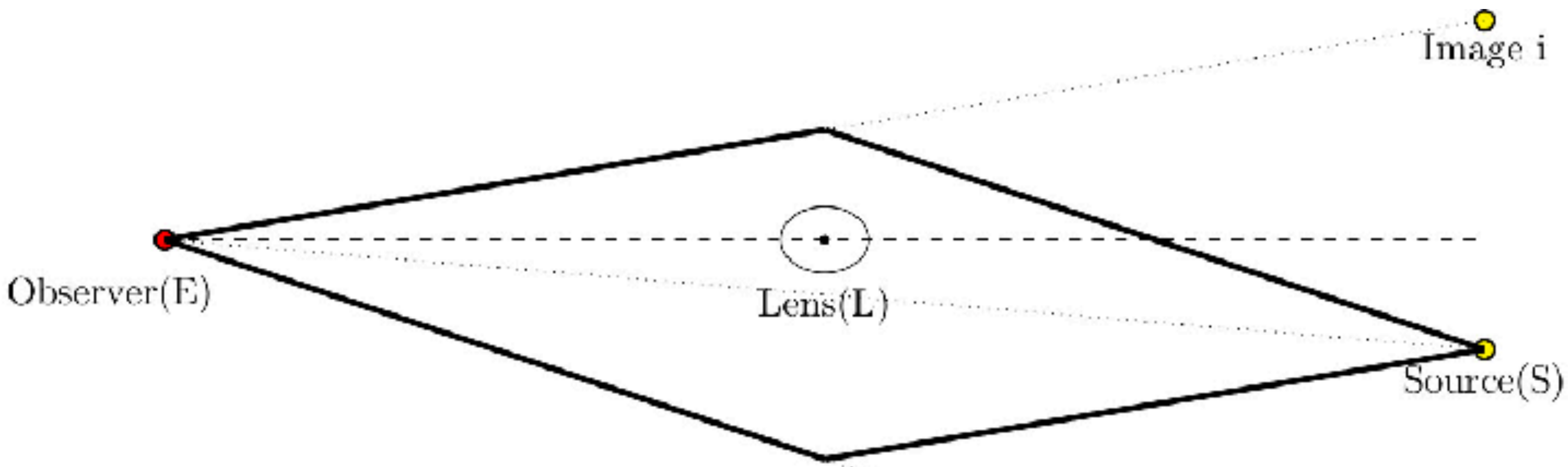
Unresolved GW images rather “interfere” in our observation.



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

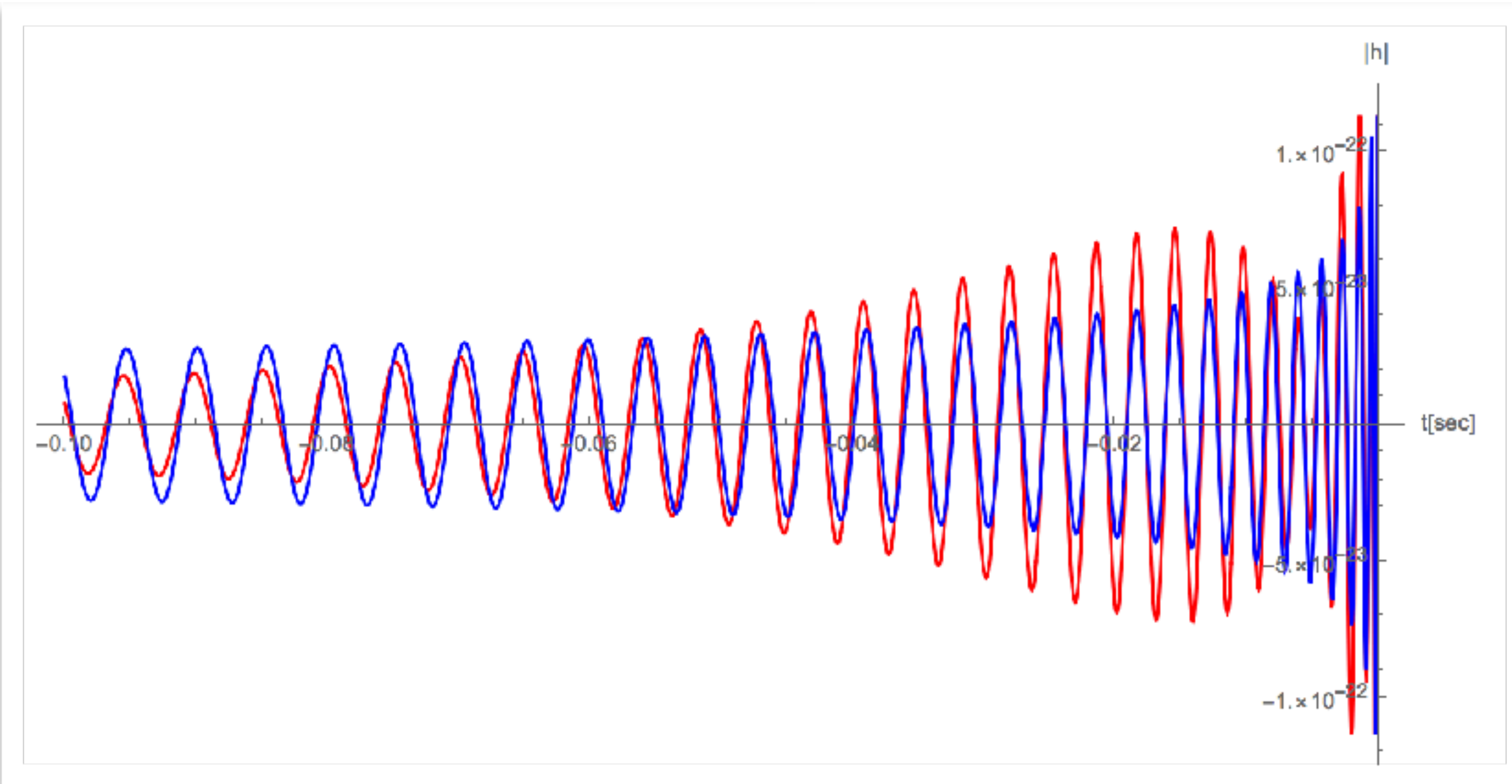
Fringe

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



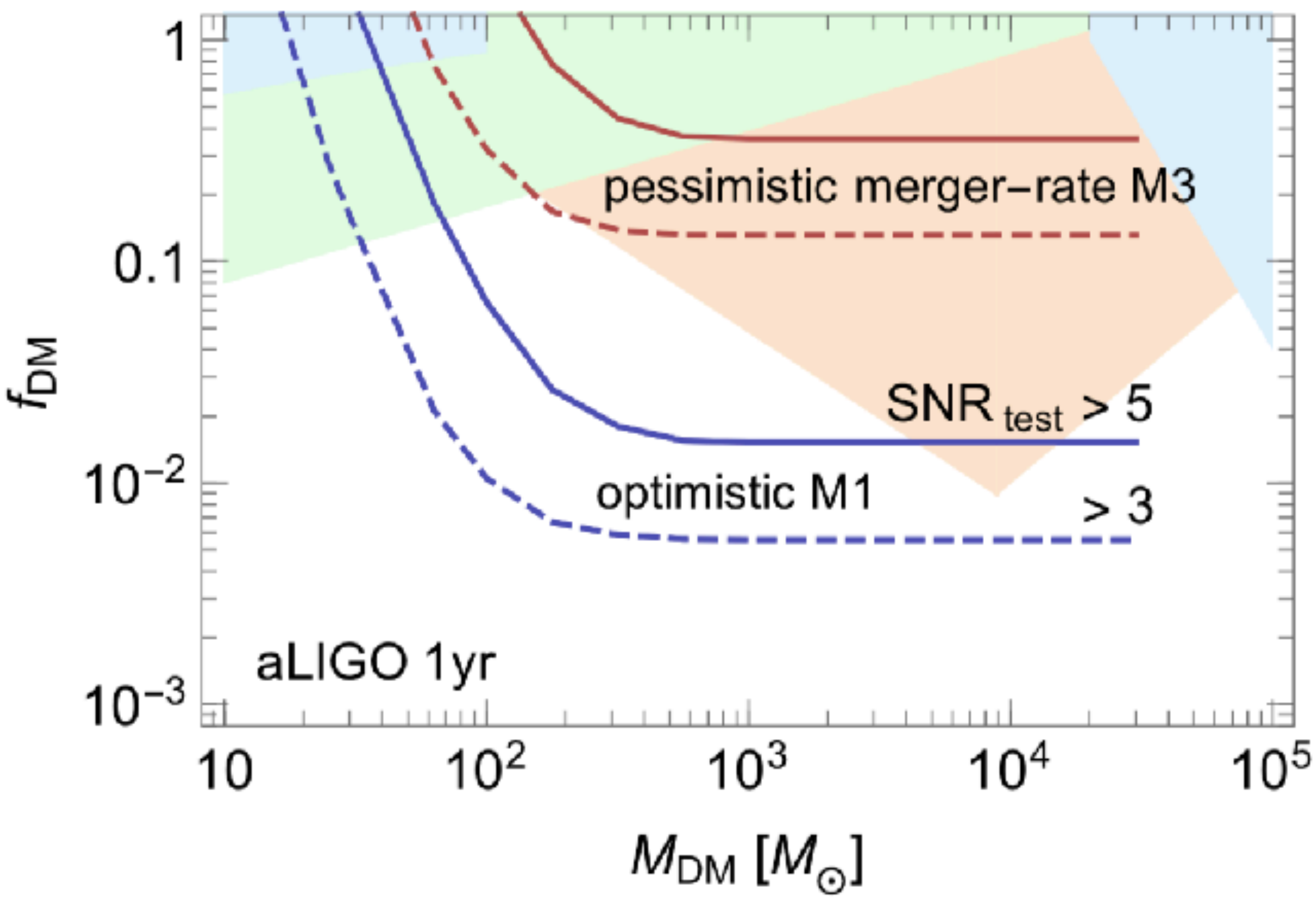
$$\Delta\phi = f(t)\Delta t_d$$

“GW Fringe”



NS-NS merger lensed by 100 Msun compact DM.

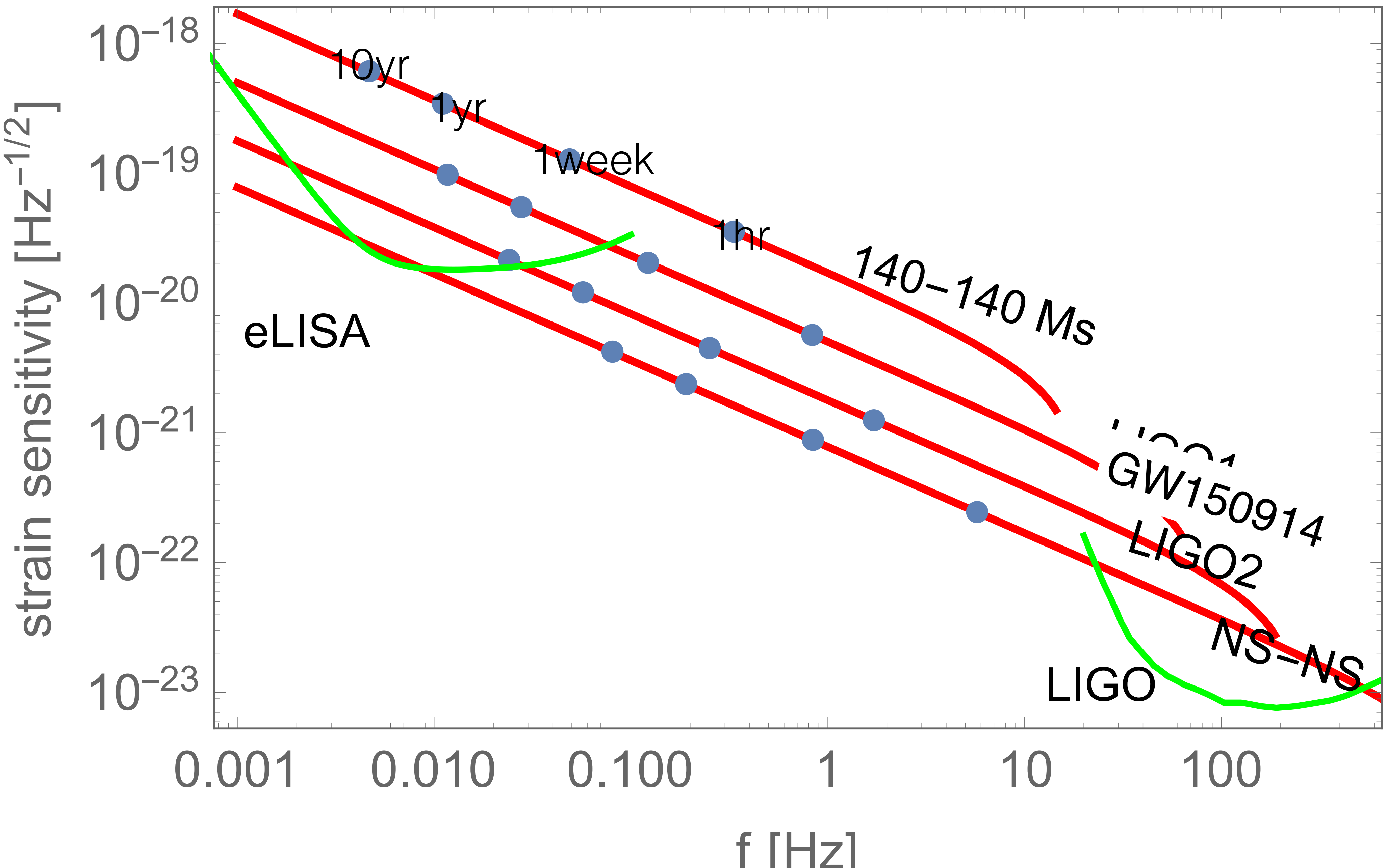
Compact DM fraction



Blackboard discussion of lensing calculation

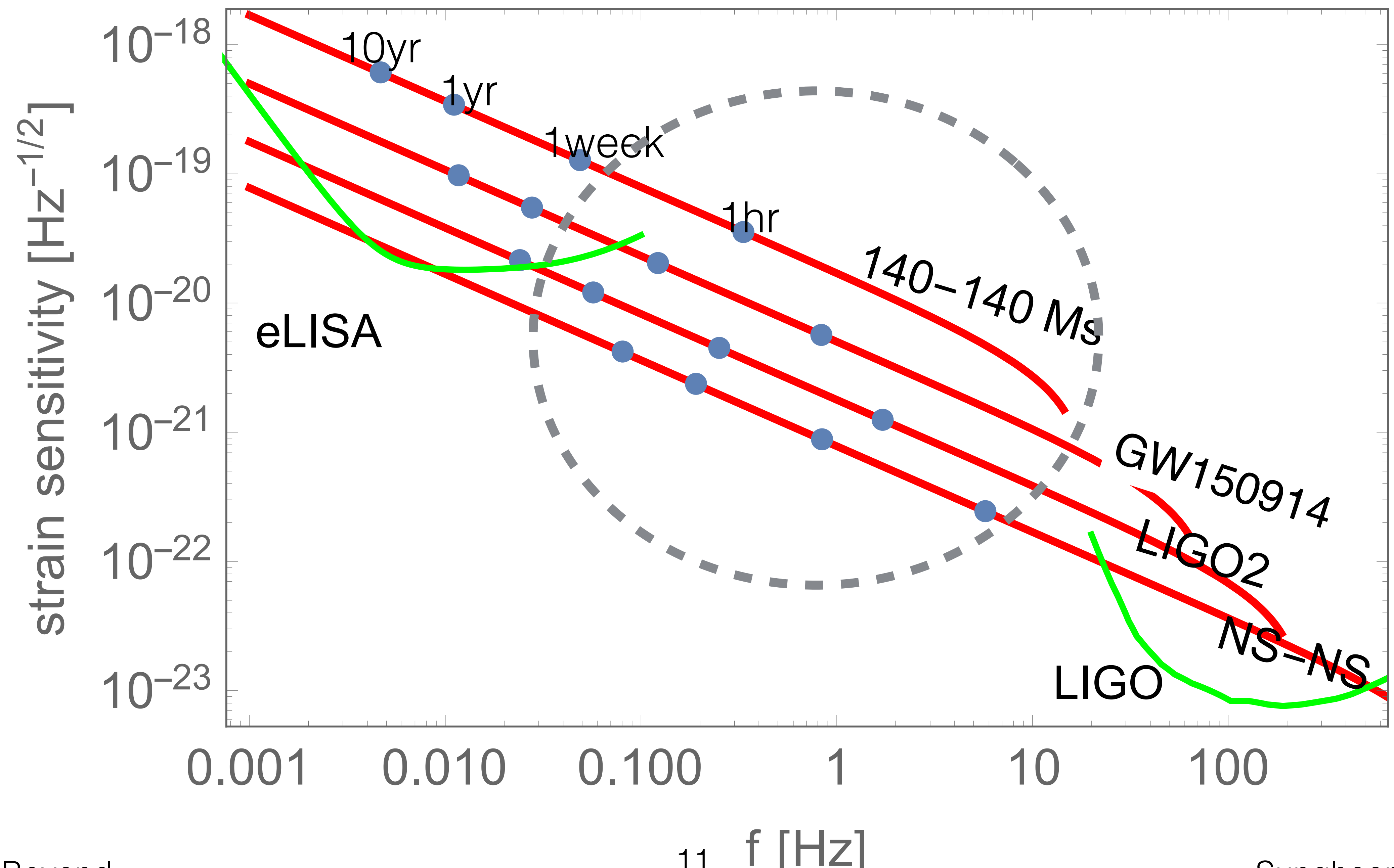
GW lifetime curve

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 soon:
Cosmic String : GW Fringe — w/ TaeHun Kim
Scalar DM : NS Mass Shift — w/ HanGil Choe]

Let's consider a simple detector:

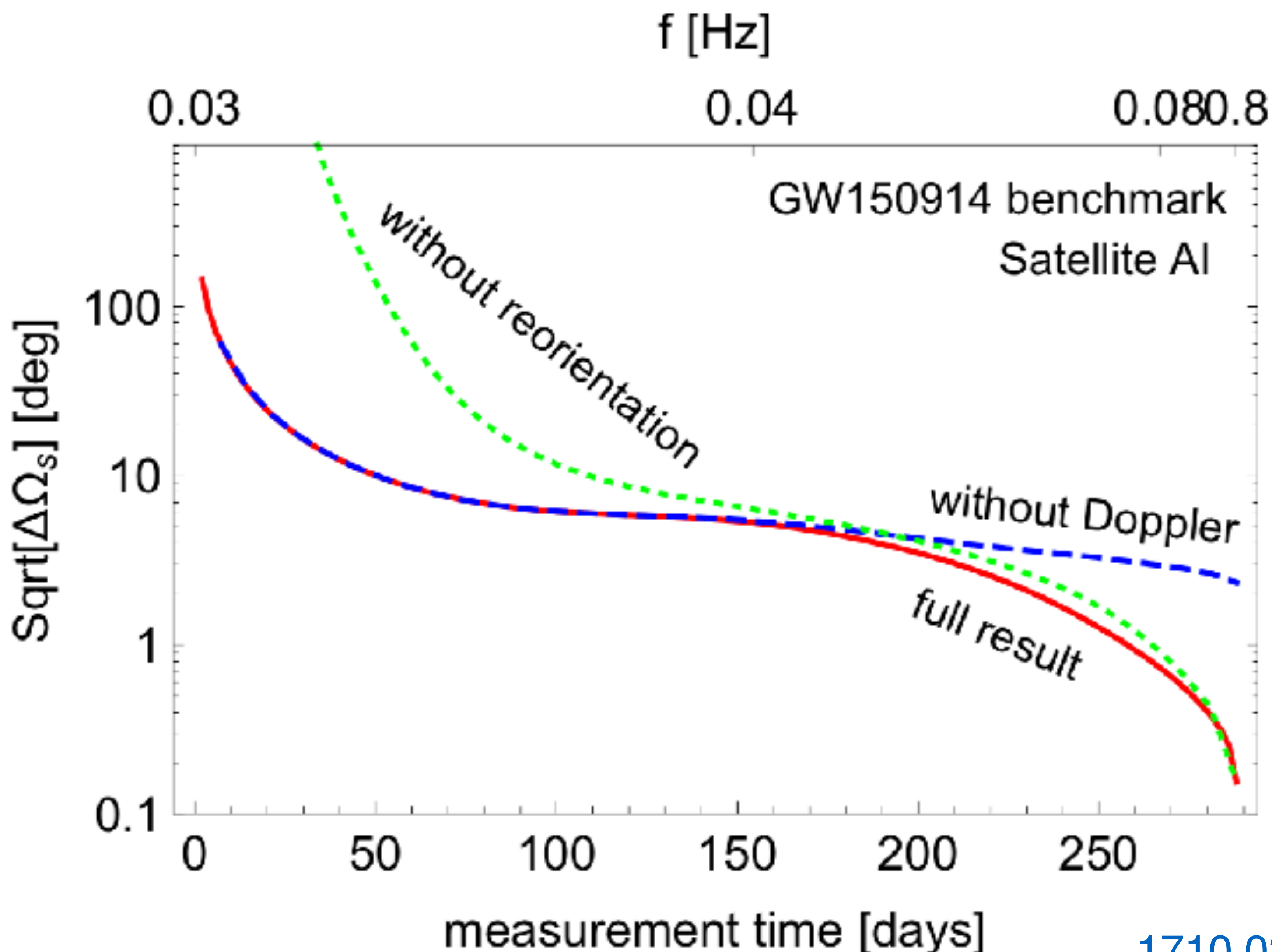
One single-baseline detector
measuring mid-band (0.03 Hz-)
on the Earth orbit.

Benchmark for single-baseline detector: atom interferometer

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

Angular localization

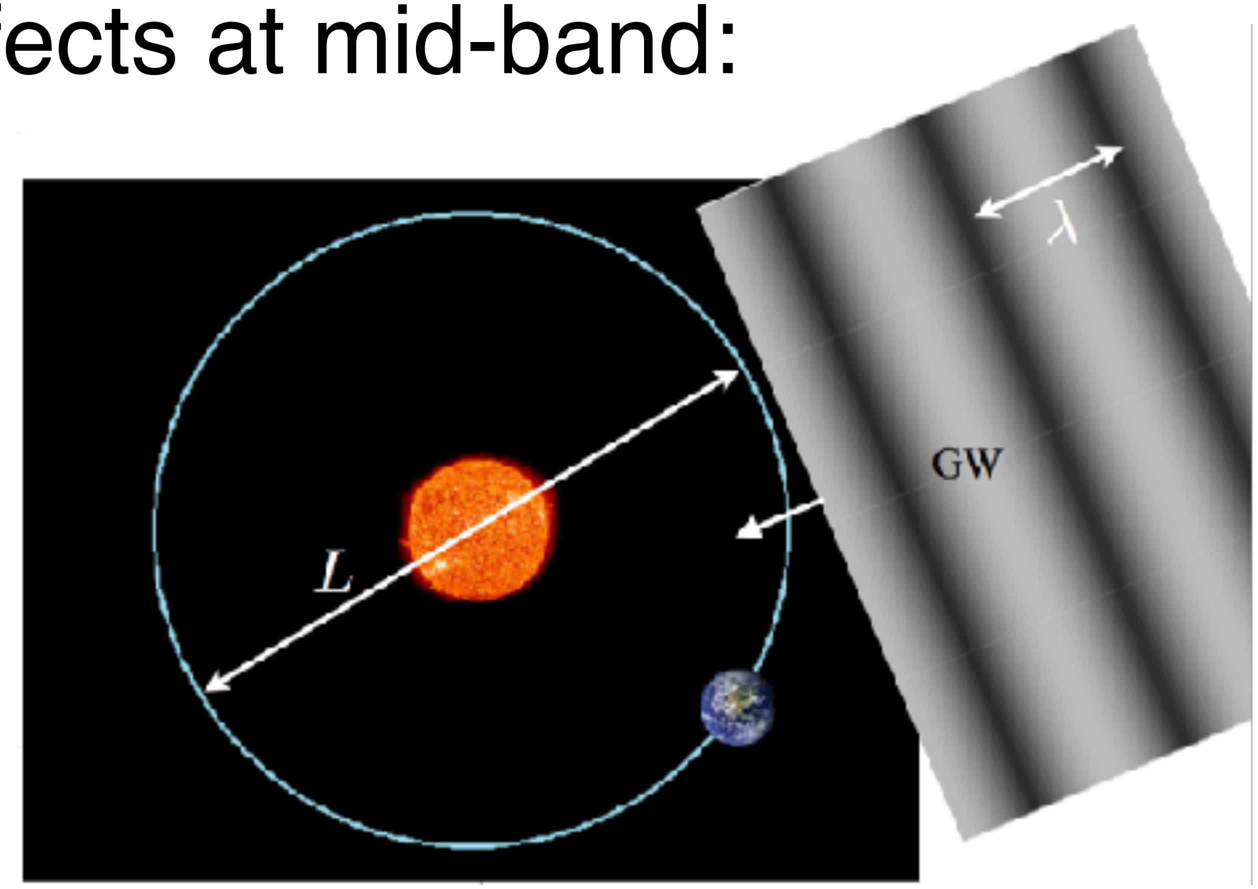
- “Reorients” hourly and monthly.
  This already makes it able to localize w/ one detector.

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

- “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



Fisher matrix element

$$\Gamma_{ij} = 4\,\mathrm{Re}\int \frac{(\partial_i \tilde{h}^*)\partial_j \tilde{h}}{S_n(f)} df$$

$$\Psi(f) \;=\; 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128}(\pi \mathcal{M}_z f)^{-5/3} - \phi_P(t) - \phi_D(t) \;+\; \cdots$$

$$\phi_D \;=\; 2\pi f \left(R_{AI} \mathbf{r}_{AI} \cdot \mathbf{n}/c + R_{AU} \mathbf{r}_{Ea} \cdot \mathbf{n}/c \right)$$

Sky-location n=n(theta, phi) components grow with (f R)^2!

(N.B. Note that tc component also grow with f^2)

What info in the Fisher?

Appendix C: Optimal separation of measurements

Given that the *change* of Doppler shift contains measurable angular information, which two angles from a circular orbit can yield maximum angular information? By solving the 2×2 Fisher matrix $\Gamma_{2\times2}$ composed of θ and ϕ (thus, ignoring any uncertainties correlated with other parameters), we obtain

$$\Delta\Omega_s \approx 2\pi \sin\theta \, (\det \Gamma_{2\times2})^{-1/2}. \tag{C1}$$

From the two measurements of δ-duration($\delta \ll 1$ rad) separated by an orbit angle α, the above 2×2 Fisher with Doppler effects only gives

$$\begin{aligned} \Delta\Omega_s^{-1} &\propto (fR)^2 \sin 2\theta \sqrt{4\delta^2 + \cos 2\delta - 1 - 2\sin^2\delta \cos 2\alpha} \\ &\approx (fR)^2 \sin 2\theta \sqrt{2\delta^2 \, (1 - \cos 2\alpha)}. \end{aligned} \tag{C2}$$

Thus, Doppler effects are maximized for $\alpha \simeq \pi/2$. Locating two detectors separated by $\pi/2$ along the orbit, or measuring a GW at two different times separated by $\pi/2$ can thus maximize the Doppler effect. The former result is

Only accumulation of info over 6 months (alpha>0)
can tell sky-localization.

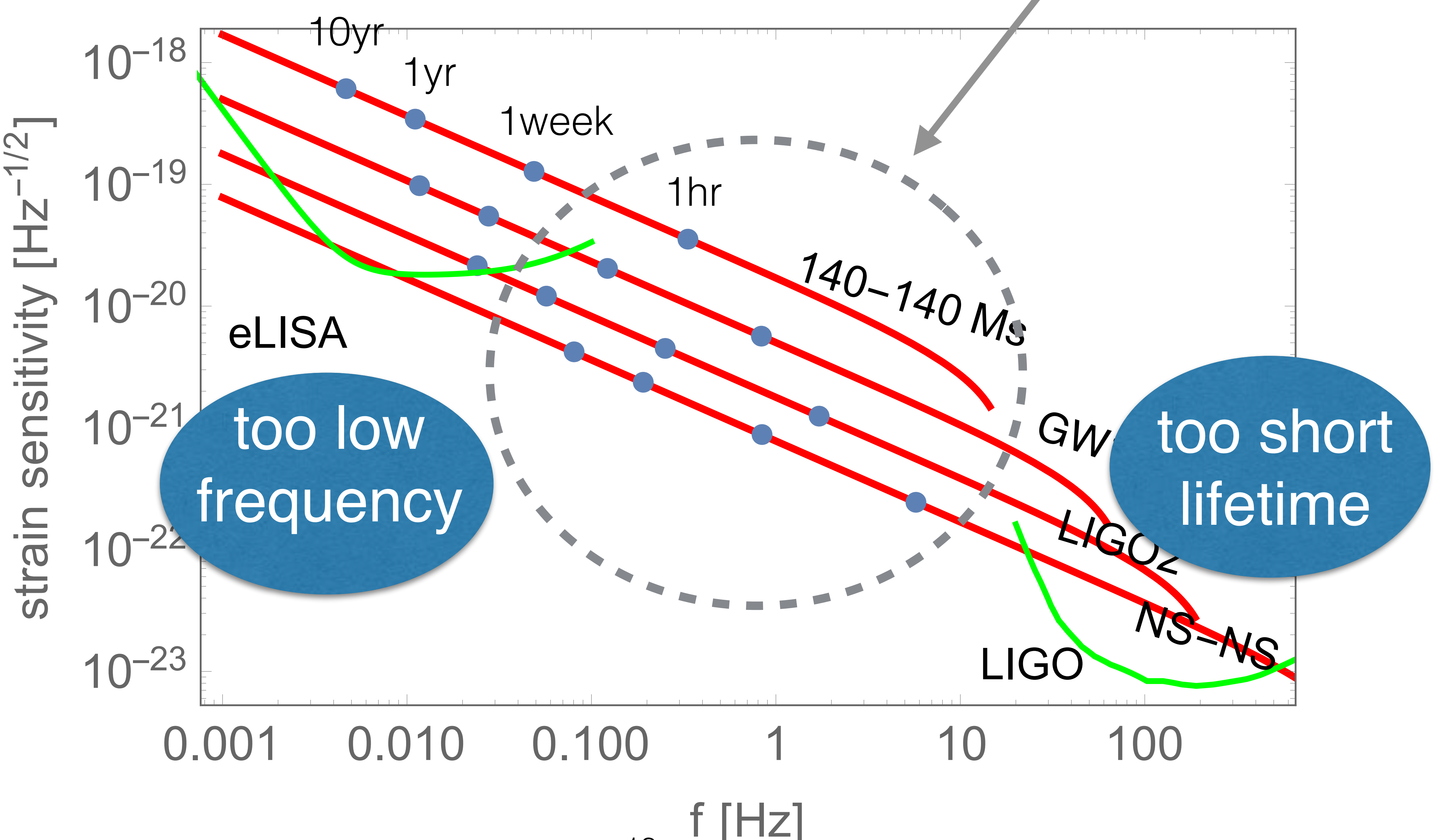
=

Only non-linear motion (alpha>0) can tell.

Doppler can dominate

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

is largest for highest frequency that lasts for 6 months



DM effect most pronounced

- Scalar DM as light as 10^-23 eV.
  (ex: relaxion/fuzzy/axion-like. all very important today.)

- 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.

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

$\frac{1}{m_{\rm DM}}$ ~ 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!

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

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)

Fisher matrix element

$$\Gamma_{ij} = 4\,\mathrm{Re}\int \frac{(\partial_i \tilde{h}^*)\partial_j \tilde{h}}{S_n(f)} df$$

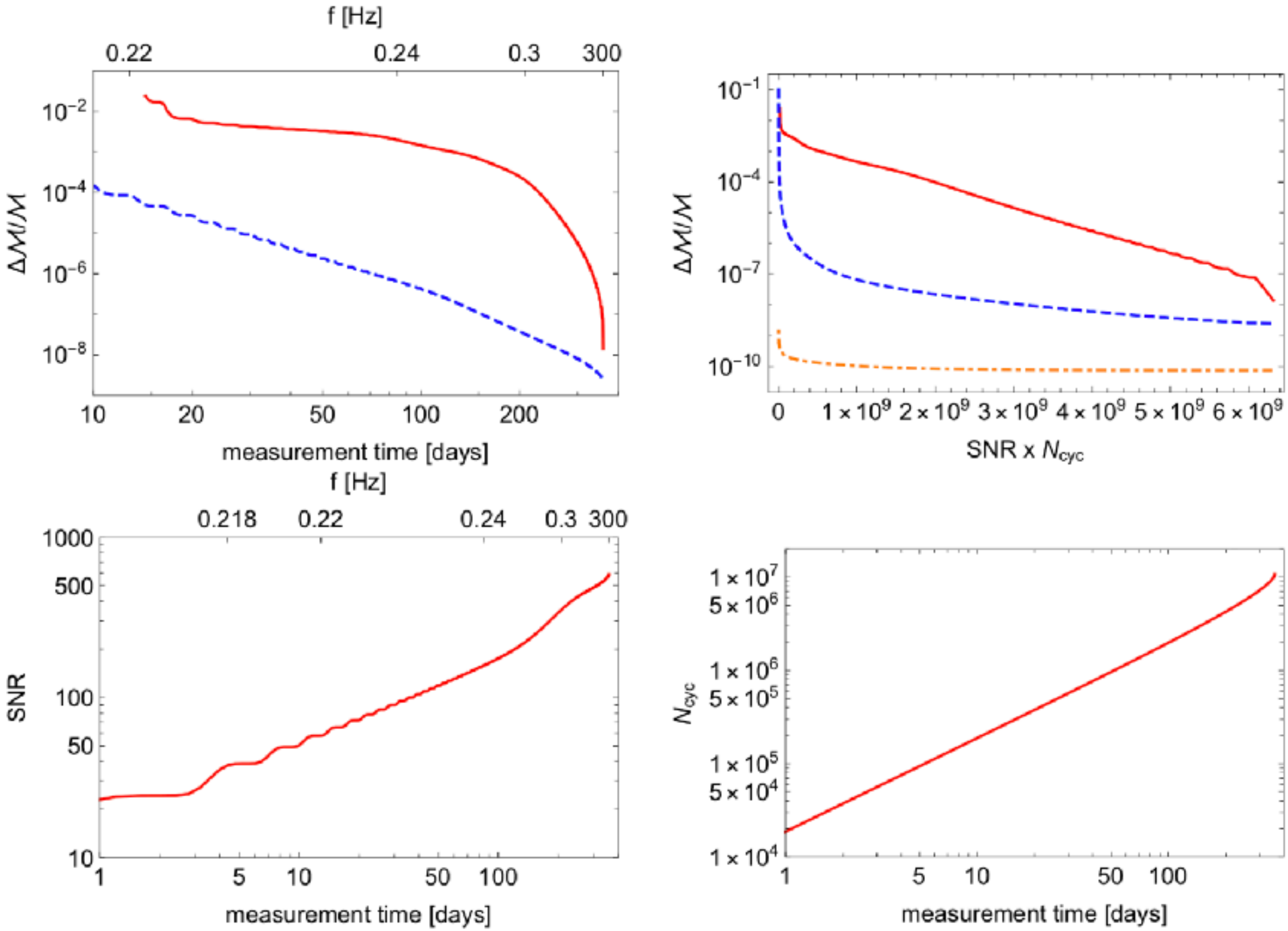
$$\frac{\partial \tilde{h}(f)}{\partial \ln \mathcal{M}} = -\frac{5i}{4}(8\pi\mathcal{M}f)^{-5/3}\tilde{h}(f)\left[\ 1 + \frac{55\mu}{6M}x\ + (8\pi - 2\beta)\,x^{3/2}\right]$$

$$\sim\ N_{\rm cyc}\cdot(\mathrm{SNR})\ (1+\cdots)$$

$$N_{\rm cyc}\ \approx\ 2.44\times 10^7\left(\frac{\mathcal{M}_z}{1.5M_\odot}\right)^{-5/3}\left(\frac{f_i}{10^{-1}\mathrm{Hz}}\right)^{-5/3}$$

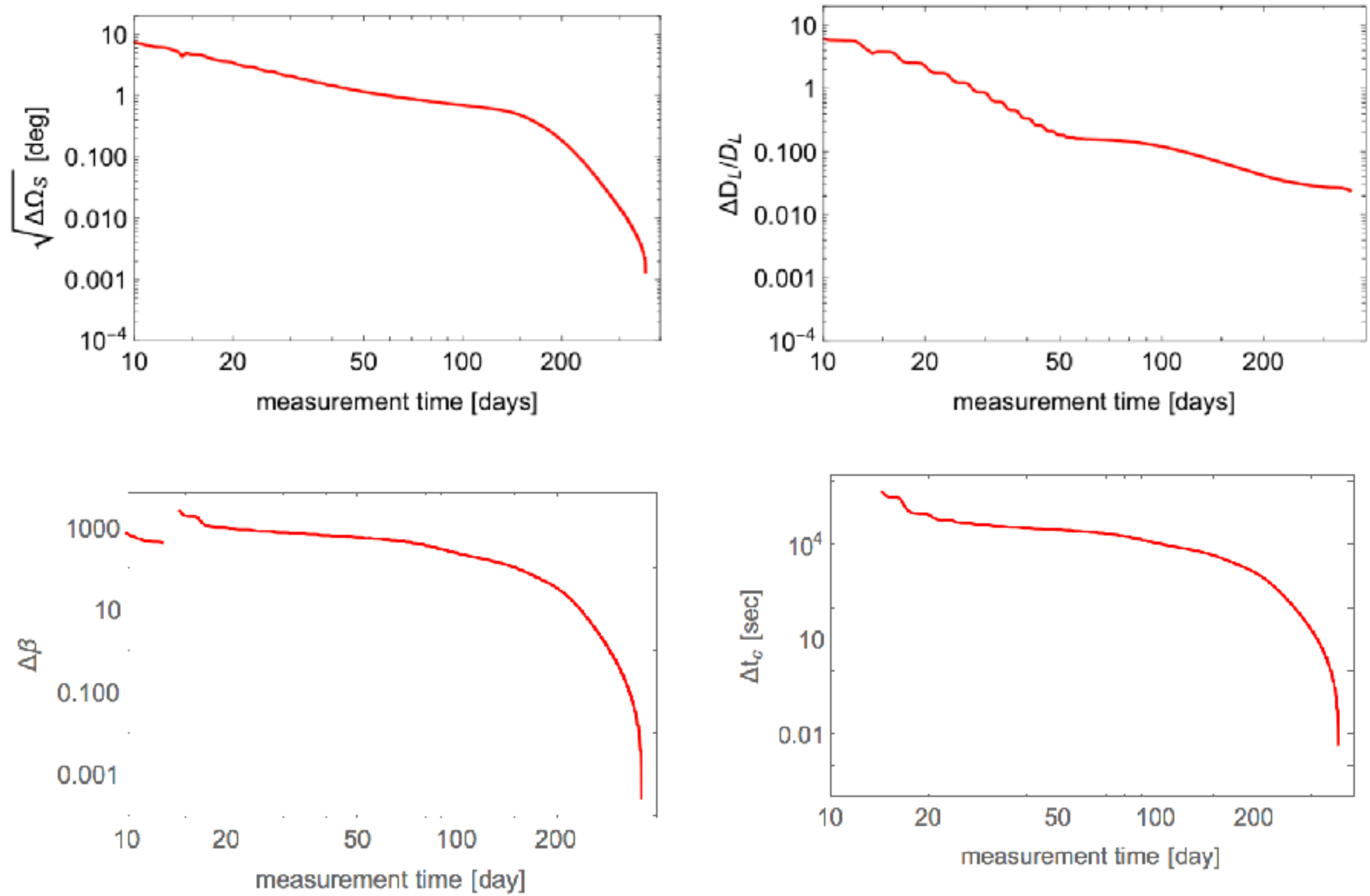
Long-time spent at low frequency accumulates
a lot of cycles and SNR!

Long measurement at low-frequency accumulates Ncyc (and SNR)



1809.xxxxx HanGil Choe, SJ

But that's not all. Highest-frequency resolves important correlations.



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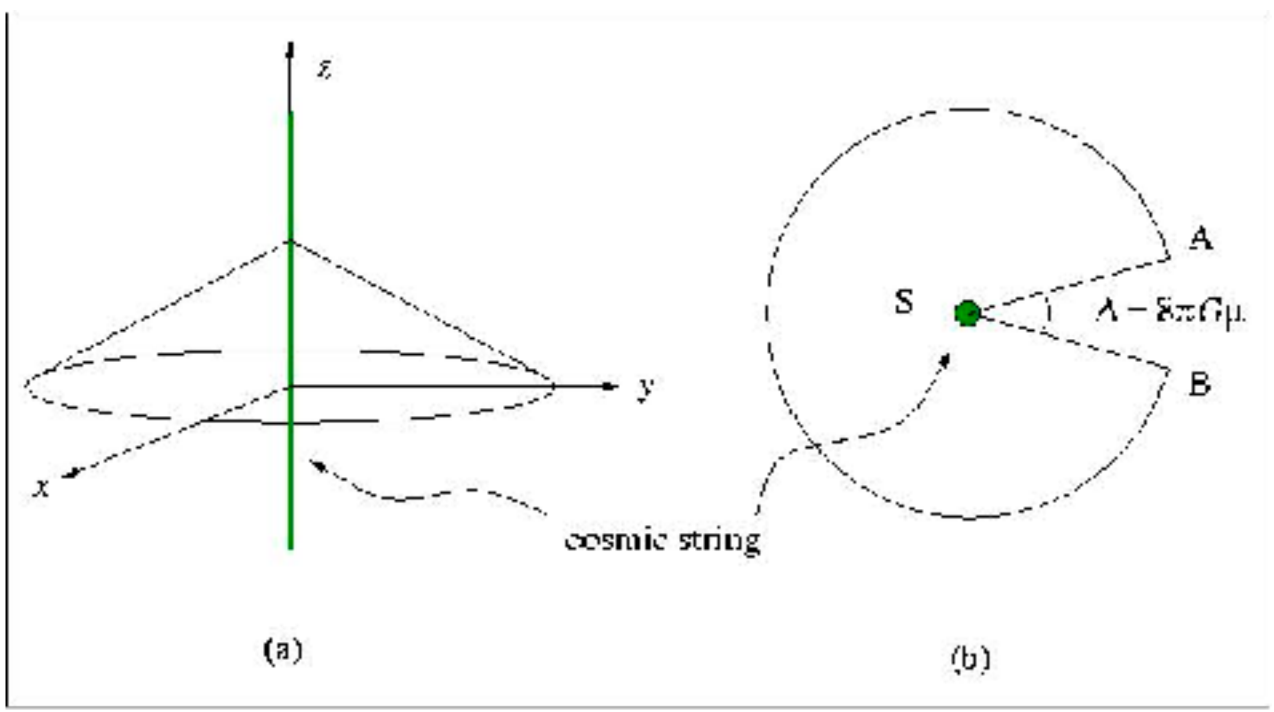
Can we better understand correlated part of Fisher?

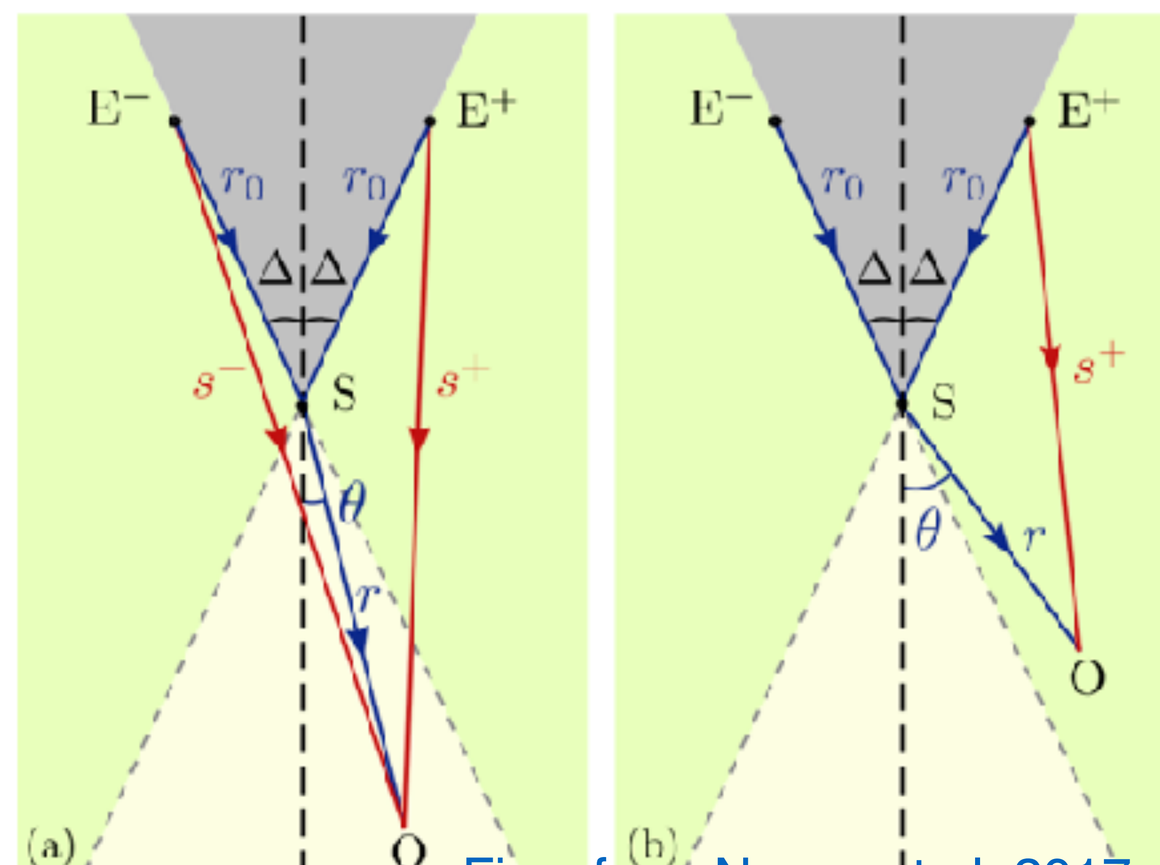
???
Which parameter improves by itself?
Which improves by resolving correlations?
How much?

Cosmic string detection

- Likely fossils of early Universe w/ U(1) phase transitions.
- Flat spacetime with azimuthal angle deficit $\Delta = 8\pi G\mu$
- Fringe pattern more varieties (btwn 3 rays & phase flip)

1809.xxxxx SJ, TaeHun Kim





Figs. from Nunez et al. 2017

Cosmic string detection

- Again detectable at LIGO(+mid band) with GW Fringe.
- An example that highest-frequency broadband can see smaller objects with precision.

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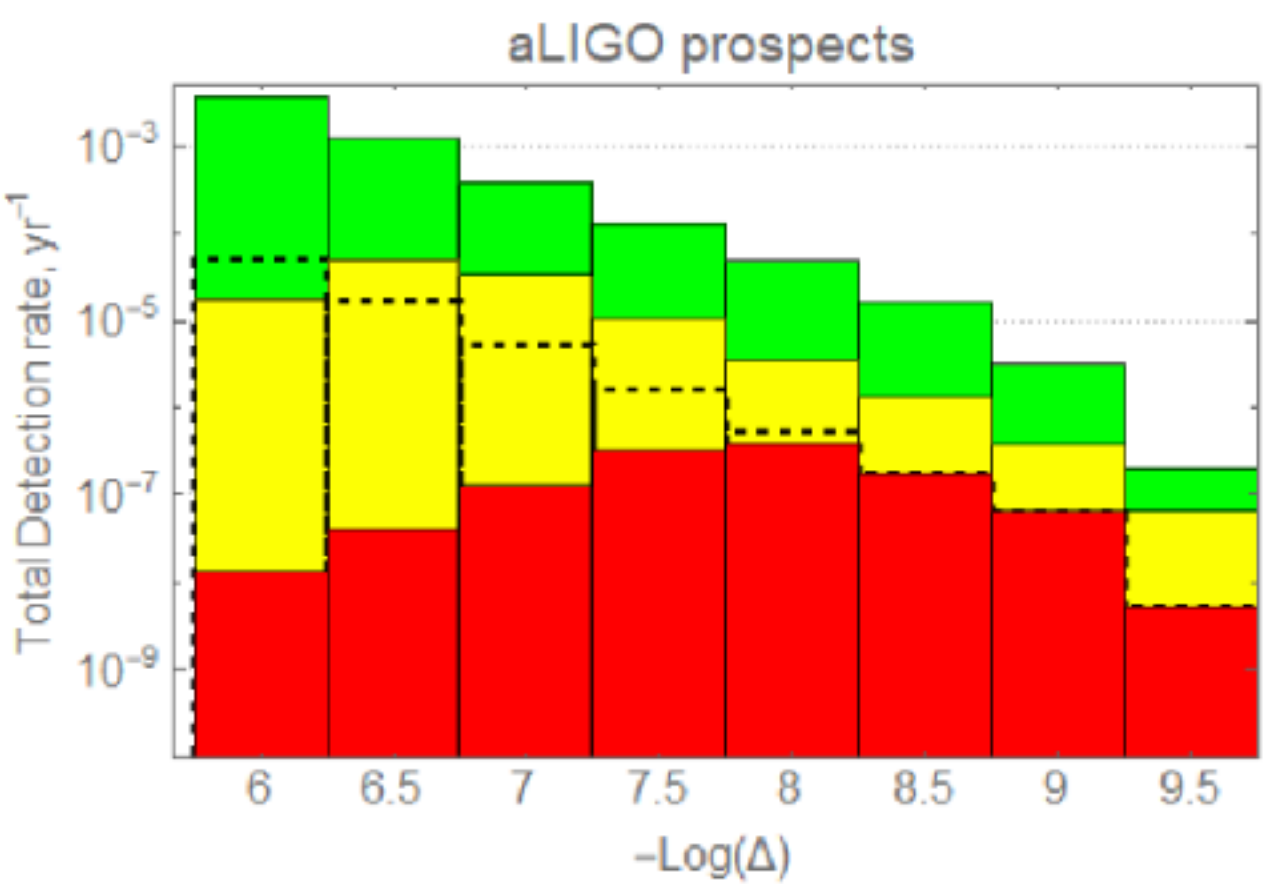

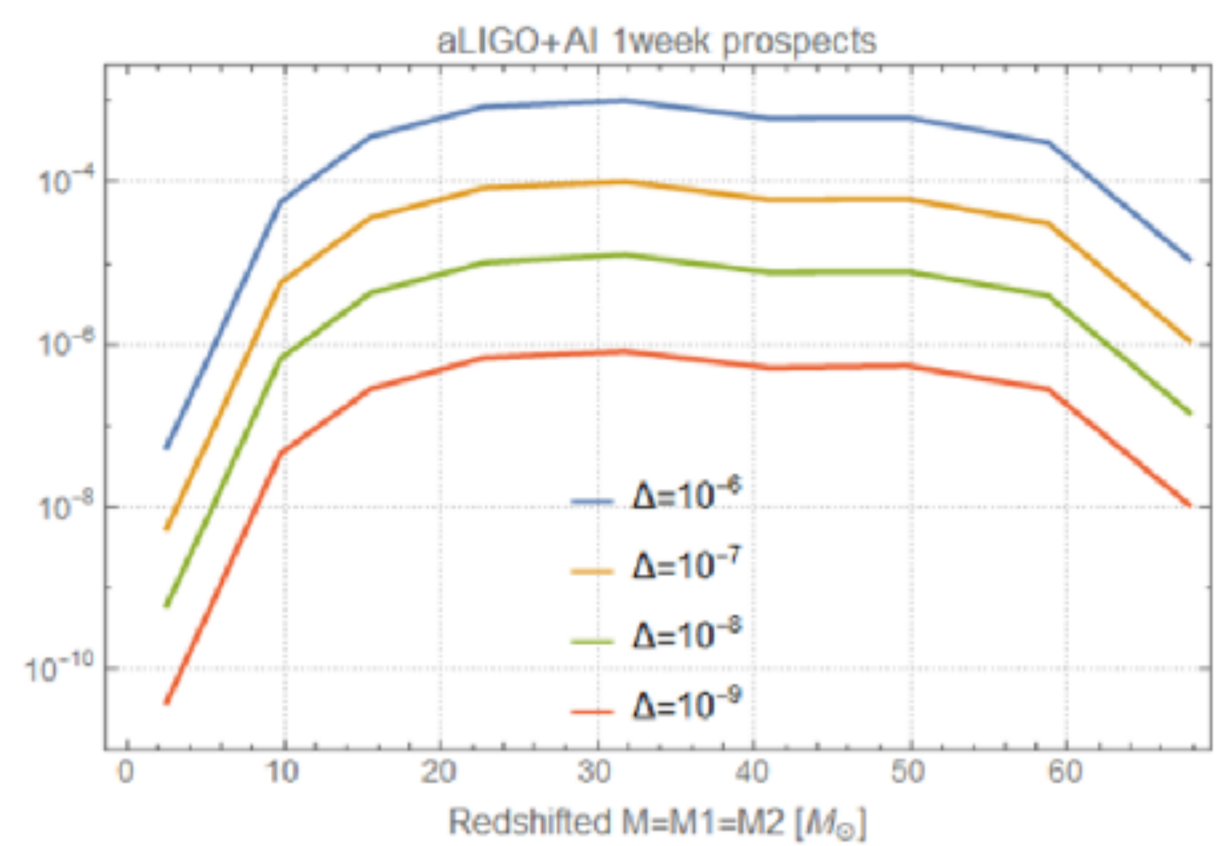

Moving Farther Beyond

Boosting high-frequency benefits:

1. Higher-frequency detectors?!
   A. Sub-solar mass PBH, compact DM, Inflation
   B. Technology?

2. Mapping & ringing with LIGO (with HanGil Choe)
   A. Arc-sec precision of LIGO for sub-solar mass DM (Doppler)
   B. Any comments, suggestions, ideas?