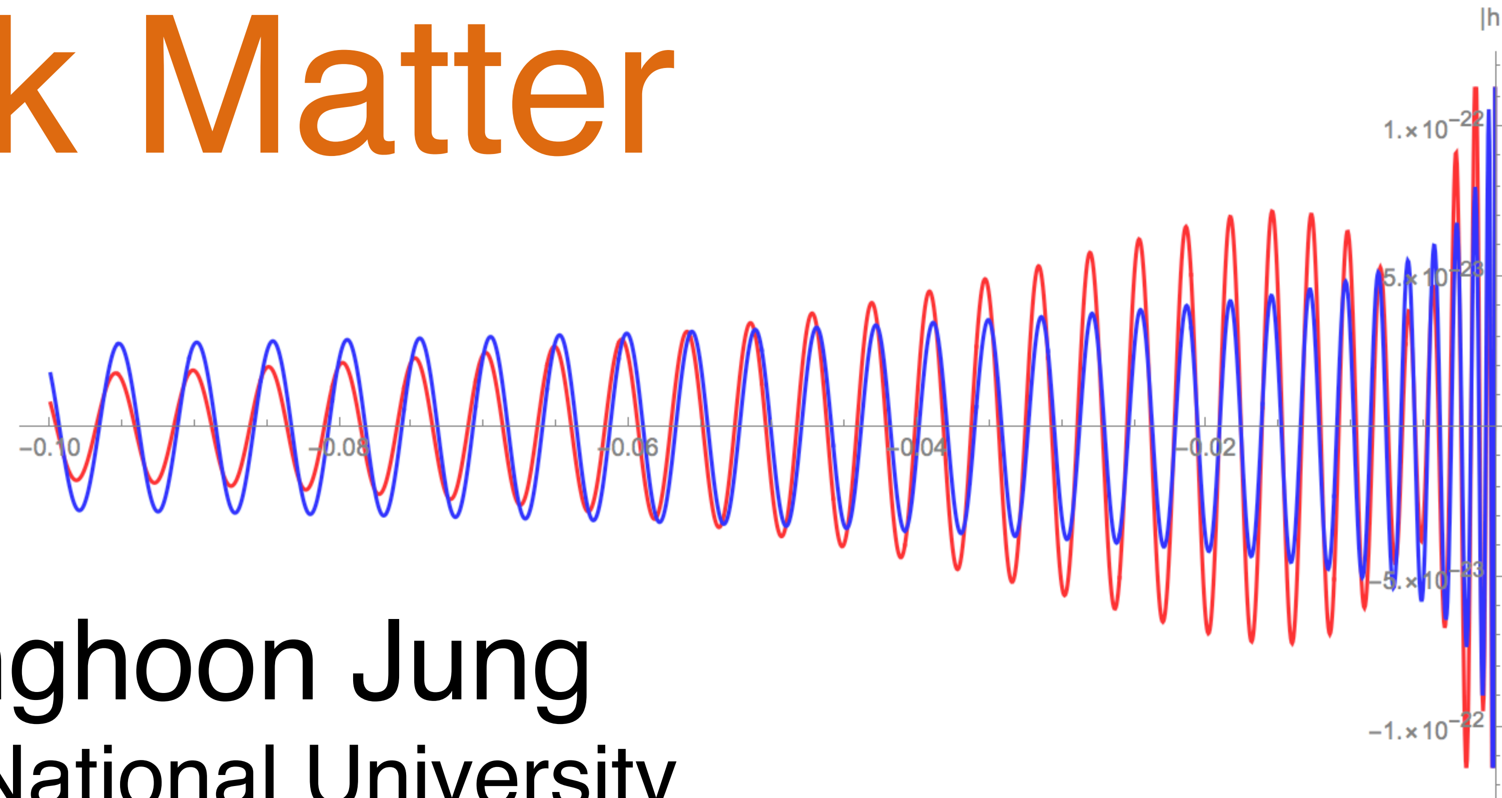
Gravitational Waves for Dark Matter

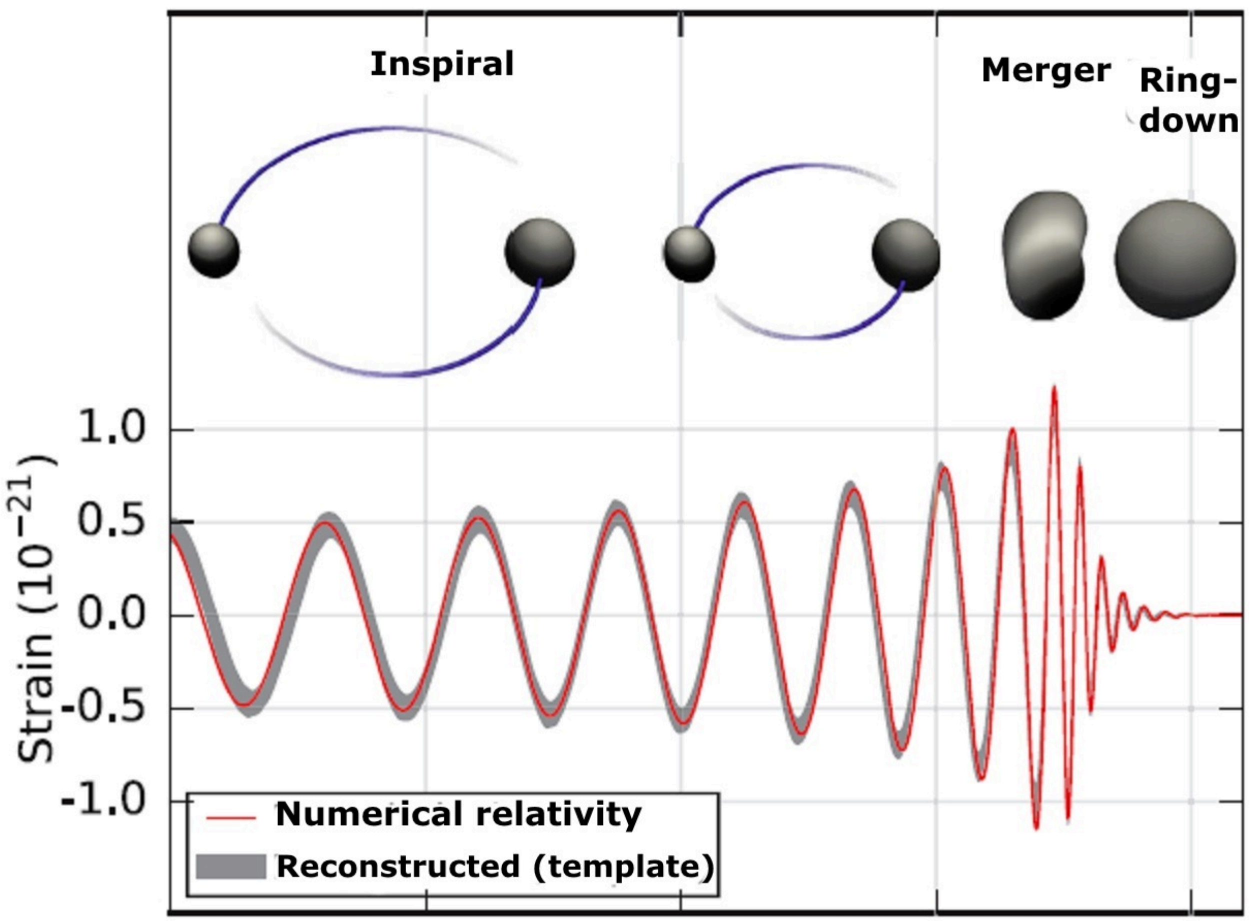


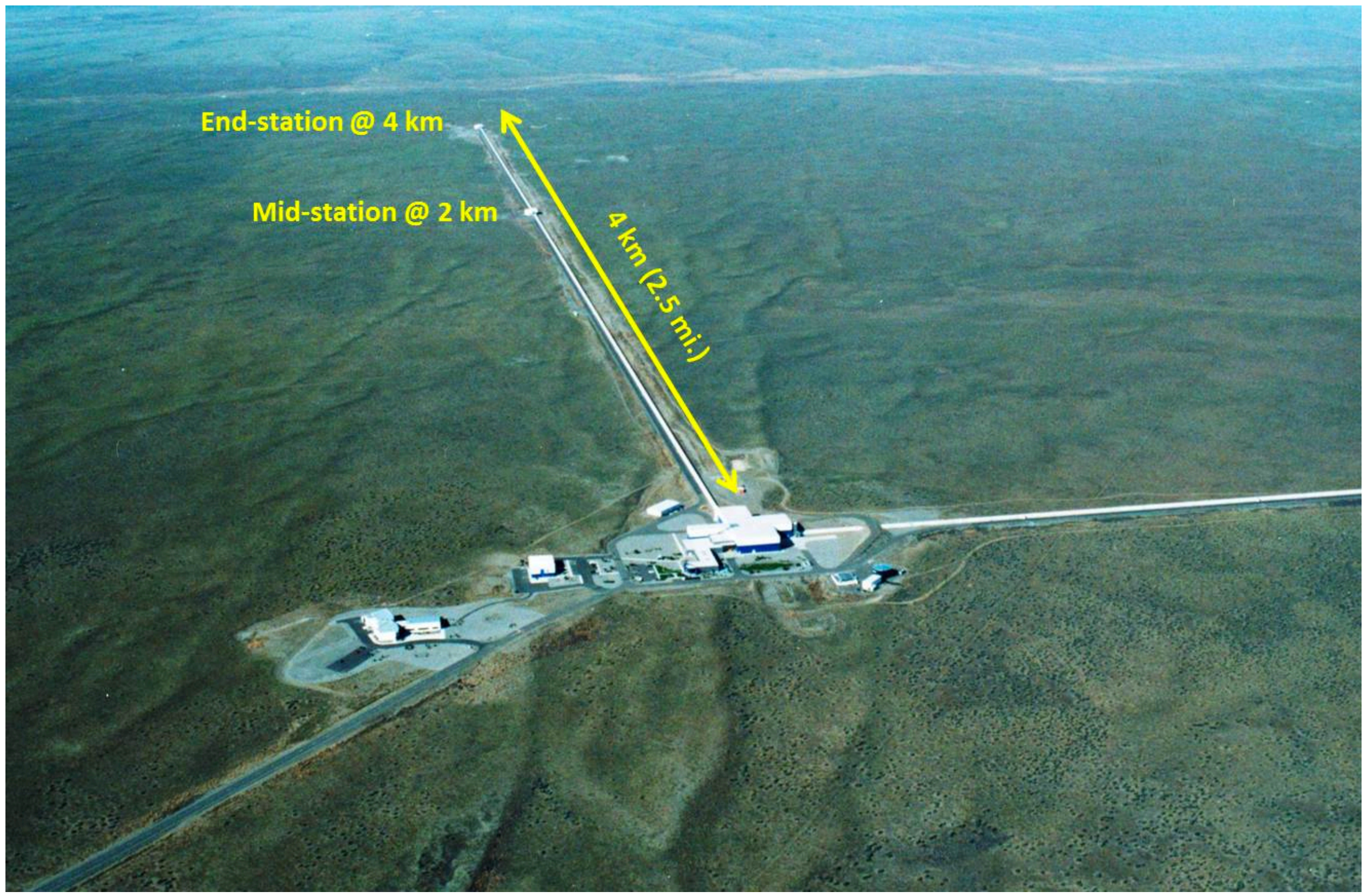
Sunghoon Jung
Seoul National University

2017. 12. 01 @ IBS Focus Meeting

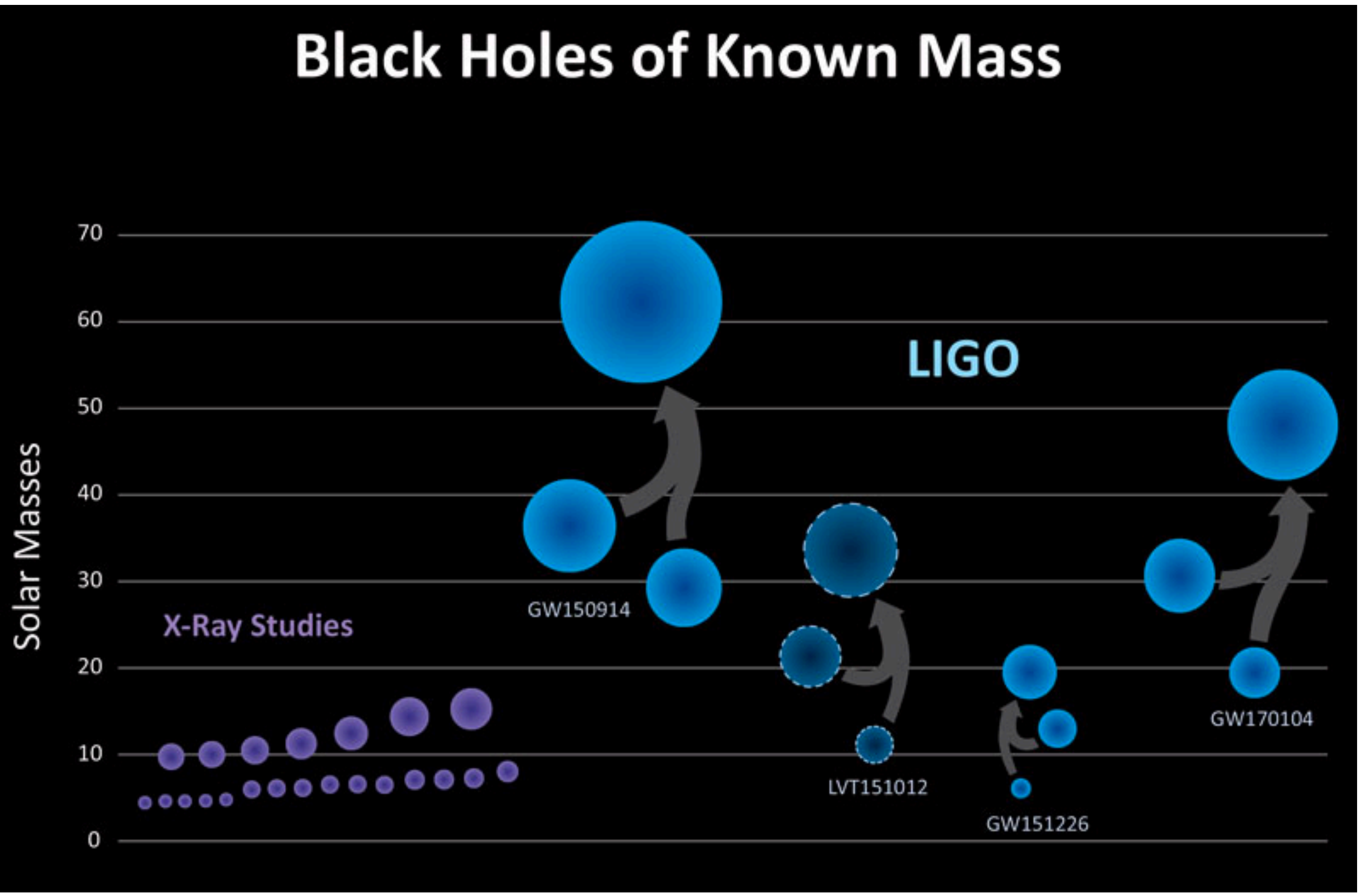
1710.03269 with Peter W. Graham
1712.xxxxx with Chang Sub Shin

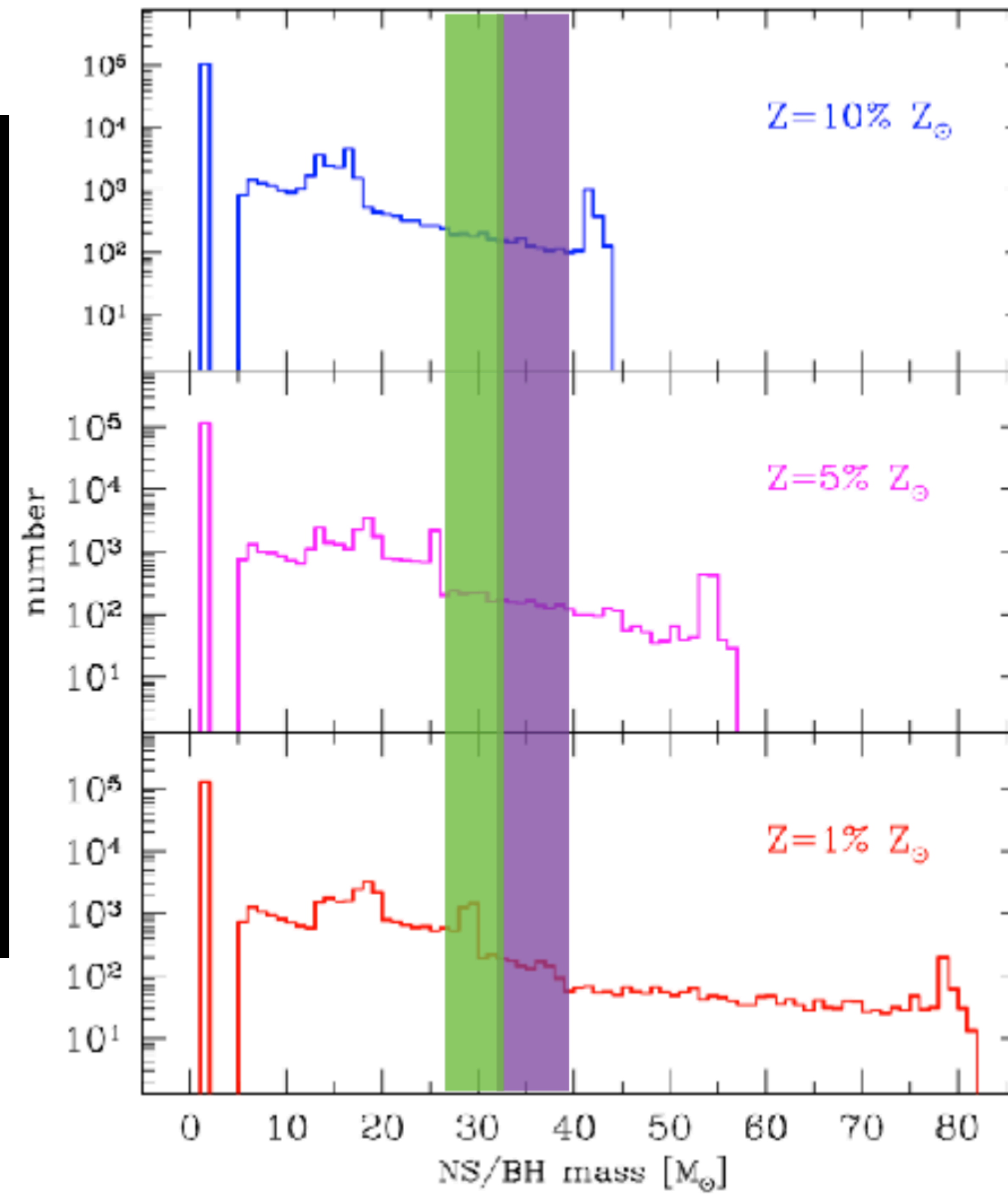
Gravitational Wave



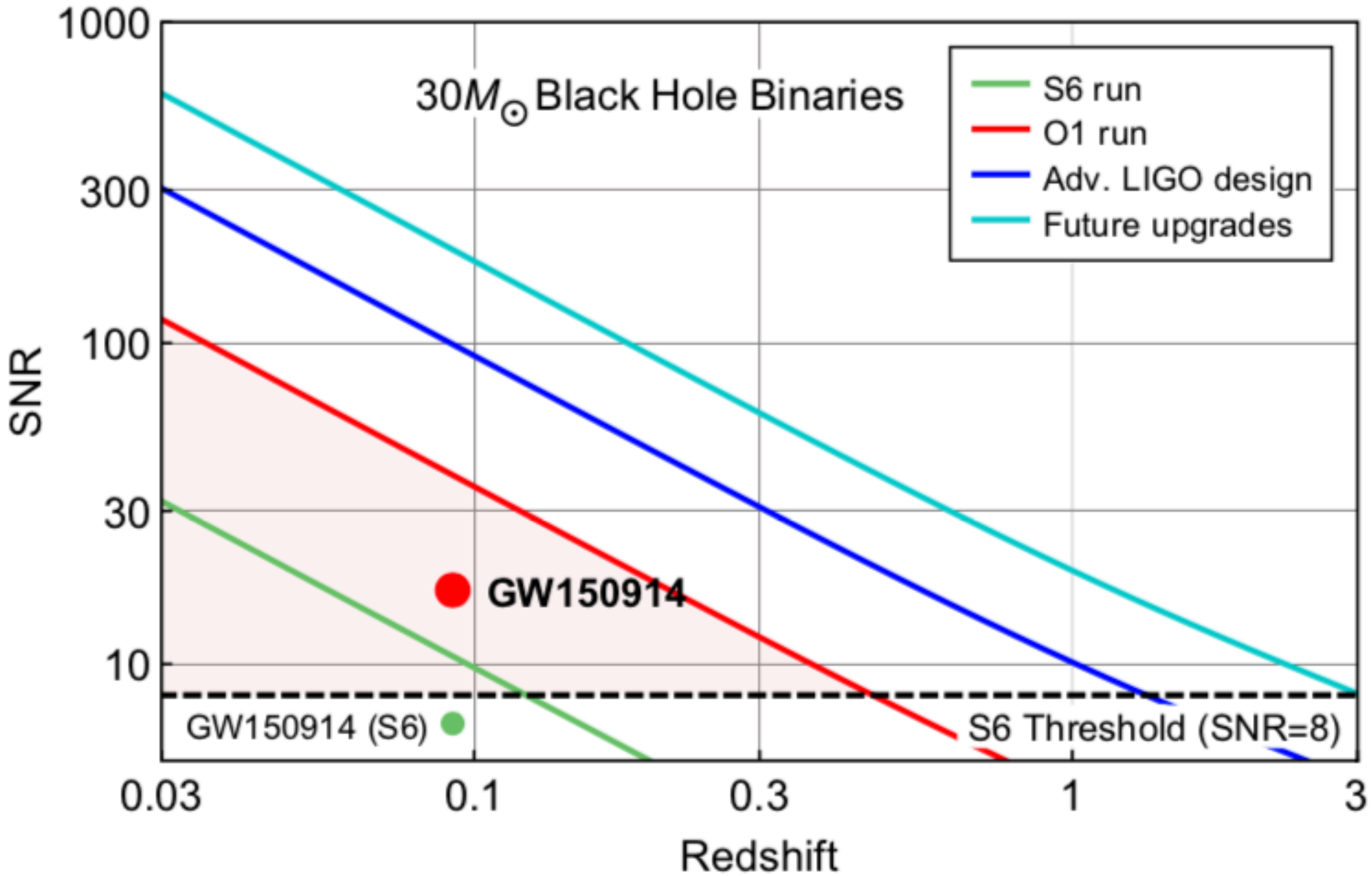


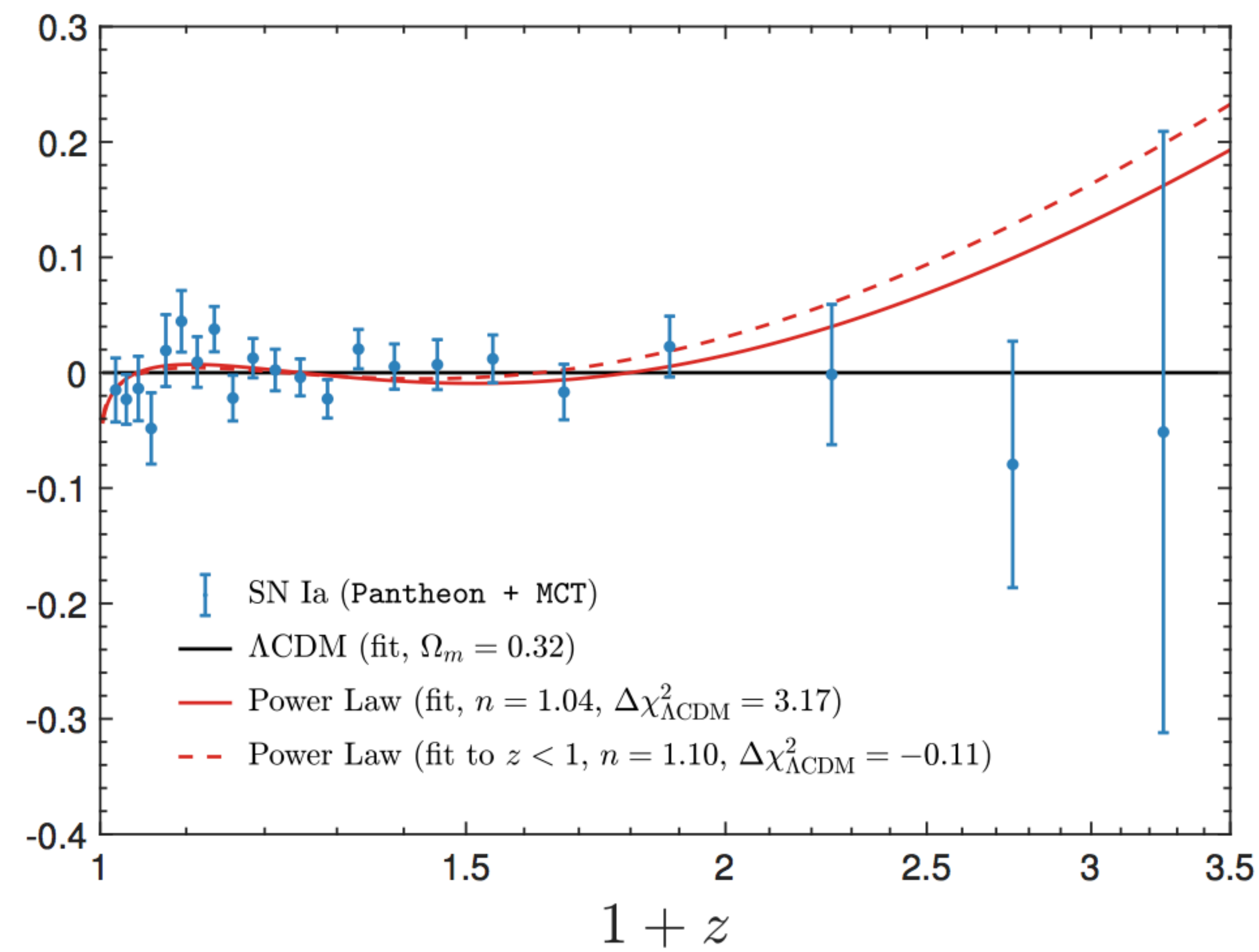
Seeing blacker and deeper





Seeing farther and more





- ~30 SNe Ia with z>1 total so far
- 500-10000 GW / year with z>1 from design sensitivity

What can we learn about particle physics in the Universe using GW?

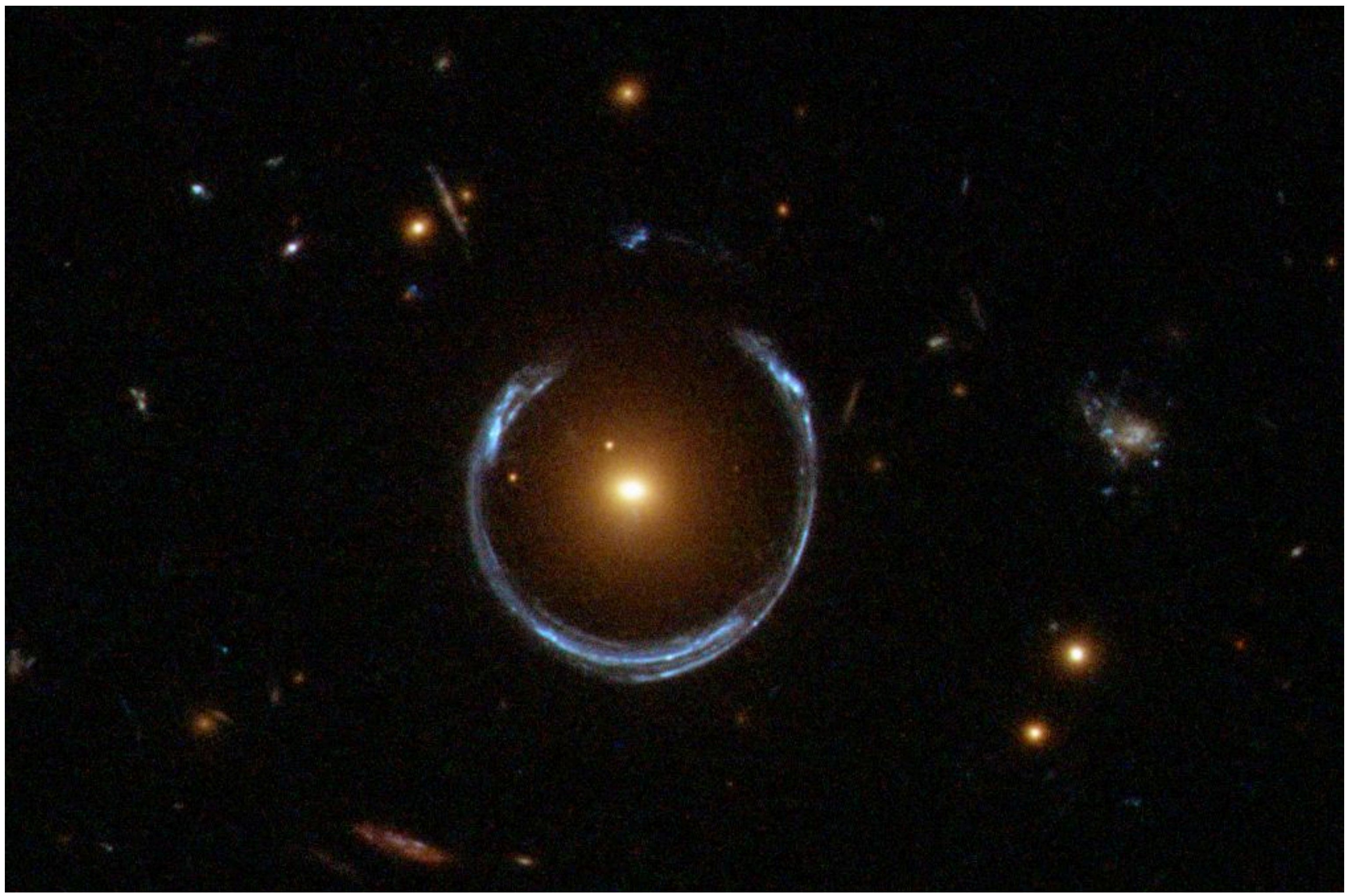
What do we need in order to fully realize the physics potential of GW?

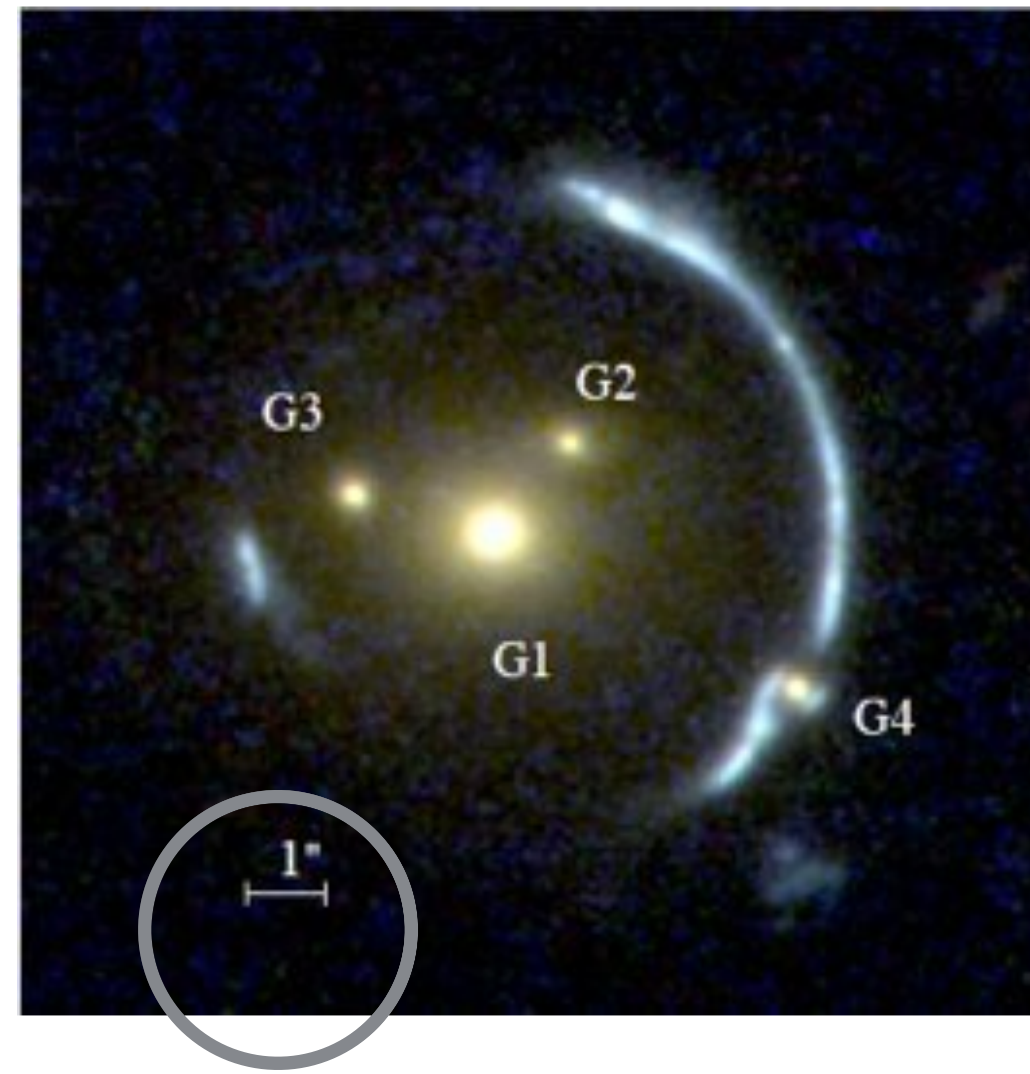
“(How) can GW see DM?”

Gravitational lensing of GW due to DM is an important observable.

(How) can the GW lensing due to DM be detected at LIGO?

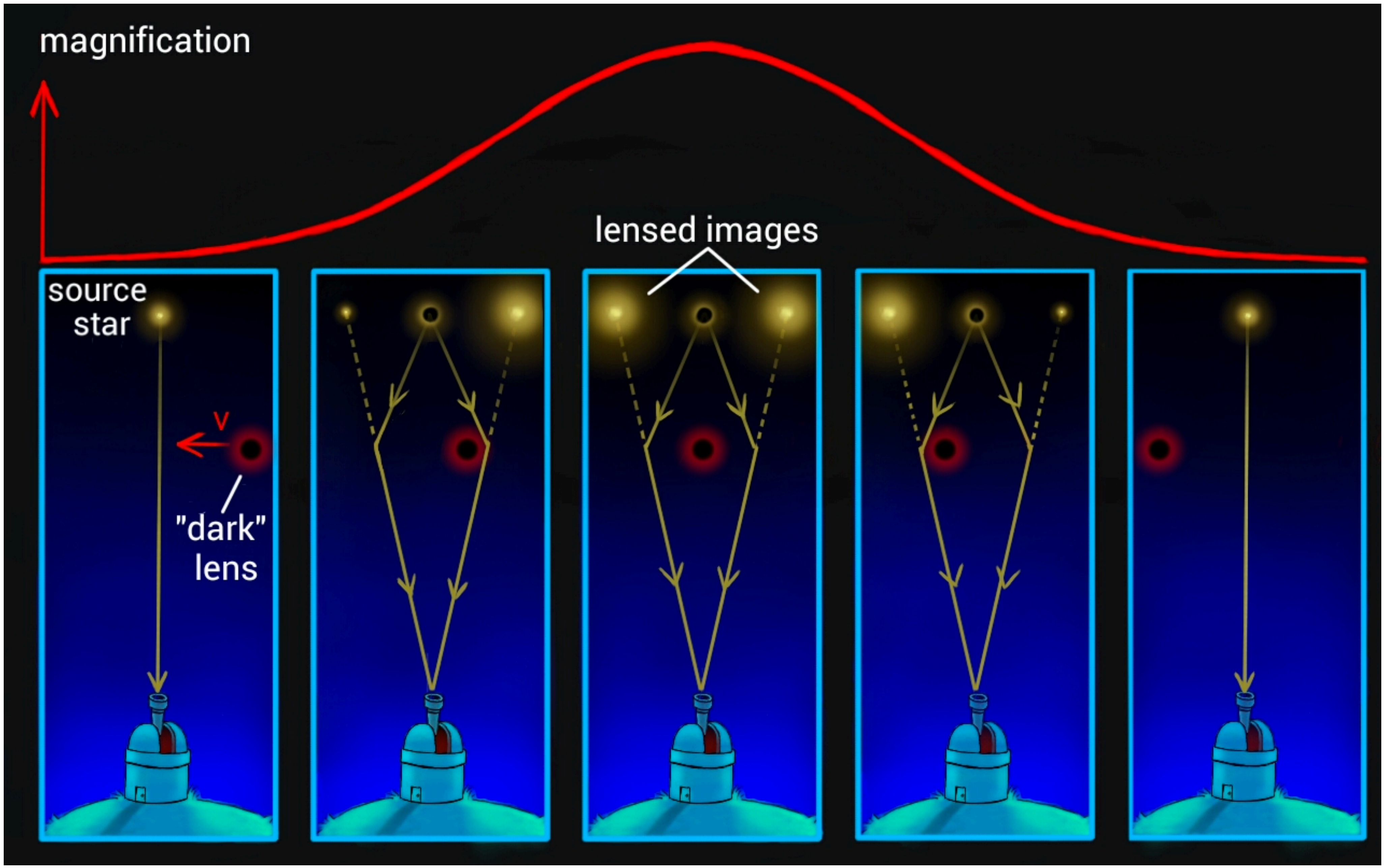
Strong lensing of light





- Multiple images (with time-delay) 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.

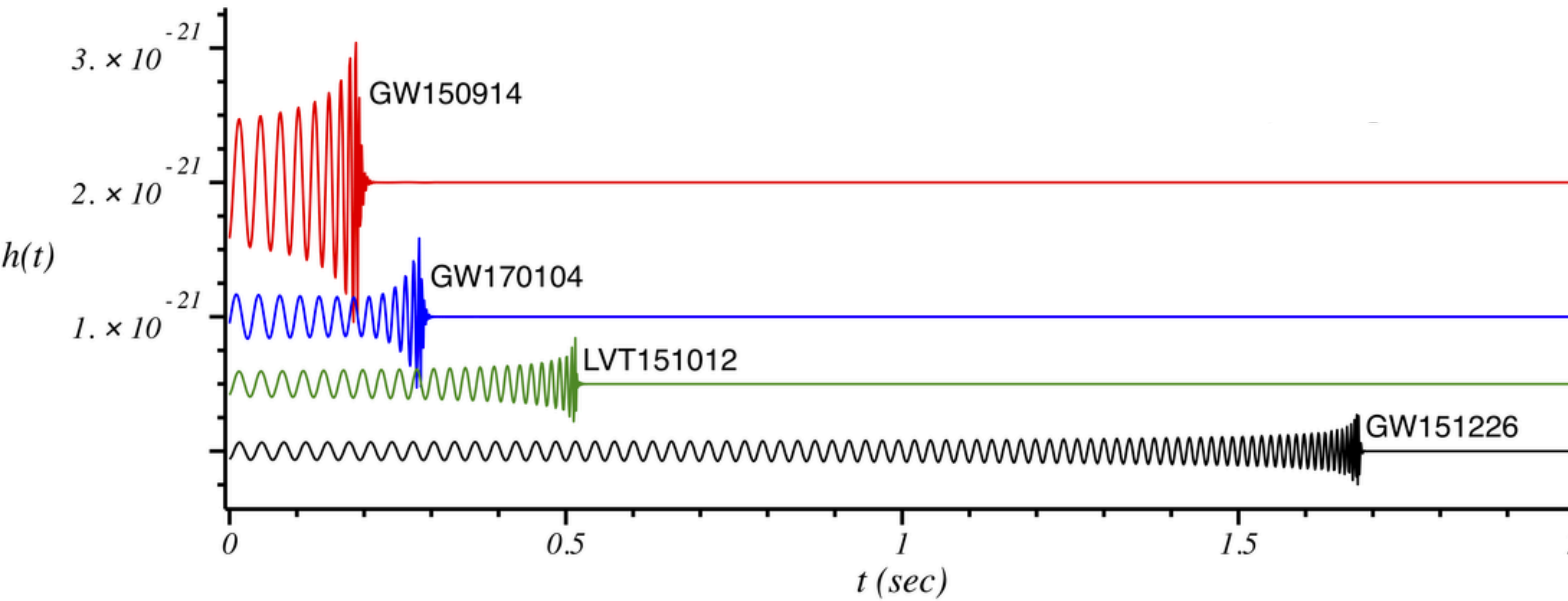
All these typical light lensing observables require

(1) very good angular resolution (arcsec or much better)

(2) long measurement time (few weeks or longer)

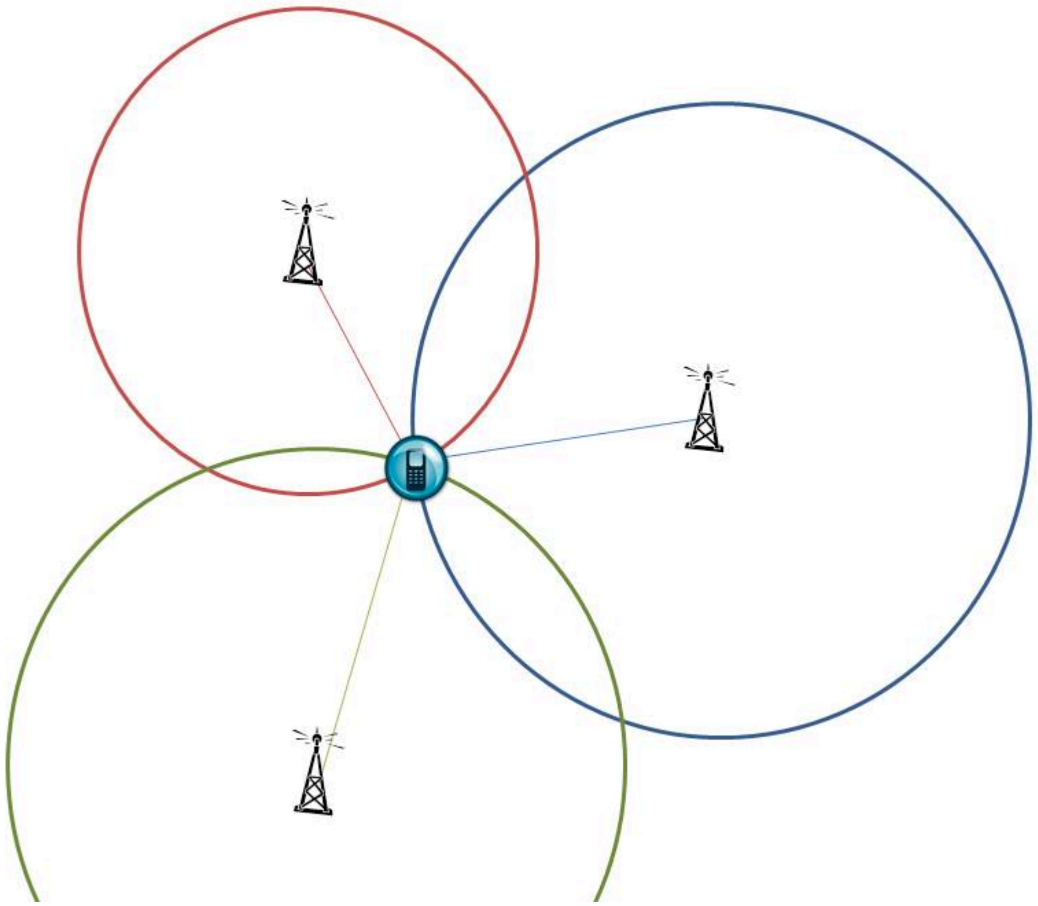
Does LIGO have any such utilities?

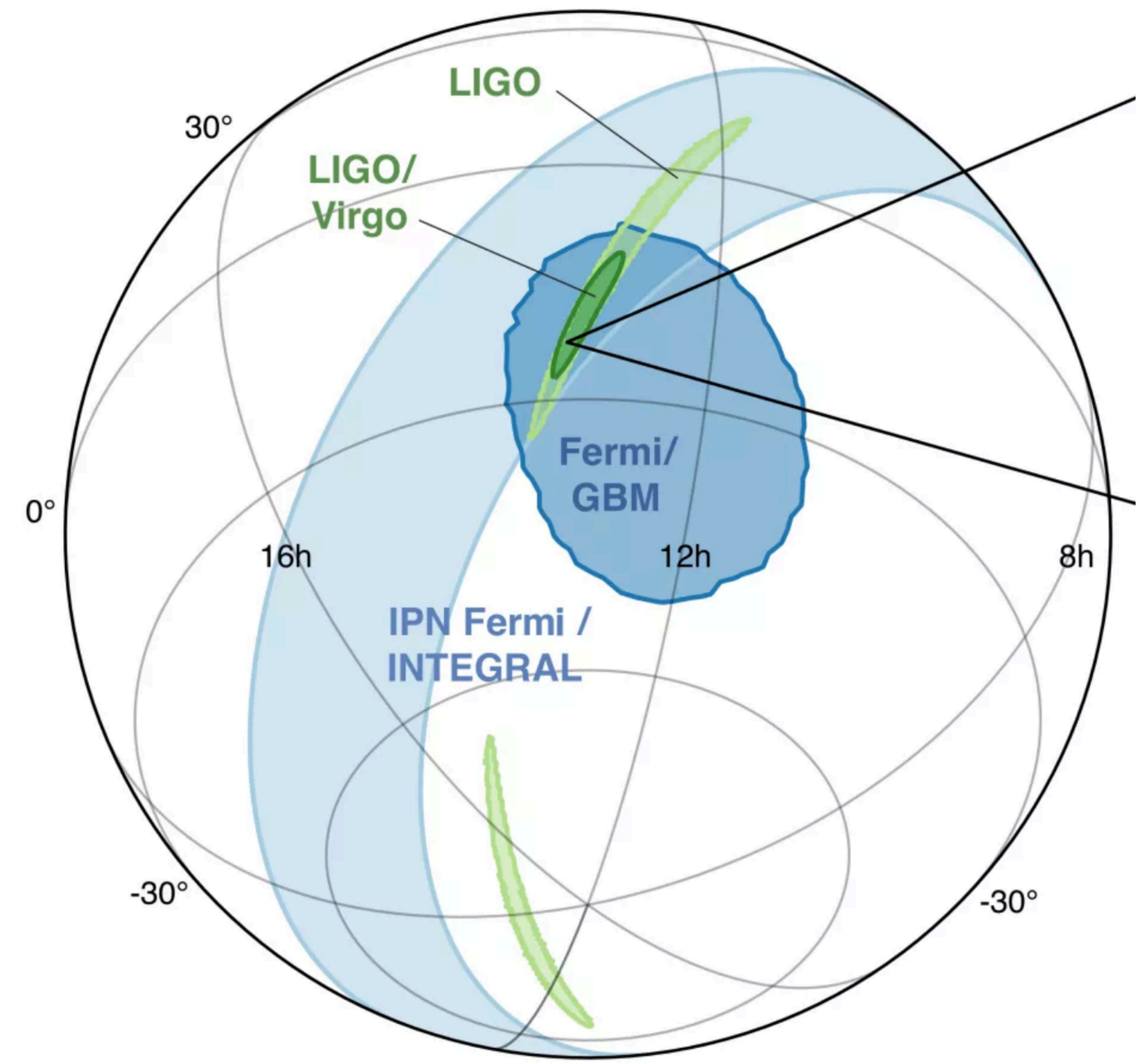
LIGO measuring final chirp/merger



- NS-NS persists longest, but still only for about a minute in the LIGO band, let alone days or weeks.

LIGO triangulation





- The best case of NS-NS with 3 detectors yielded ~5 deg resolution, let alone arcsec.

Q1. What is a best way for LIGO and future GW detectors to localize GW? And how well?

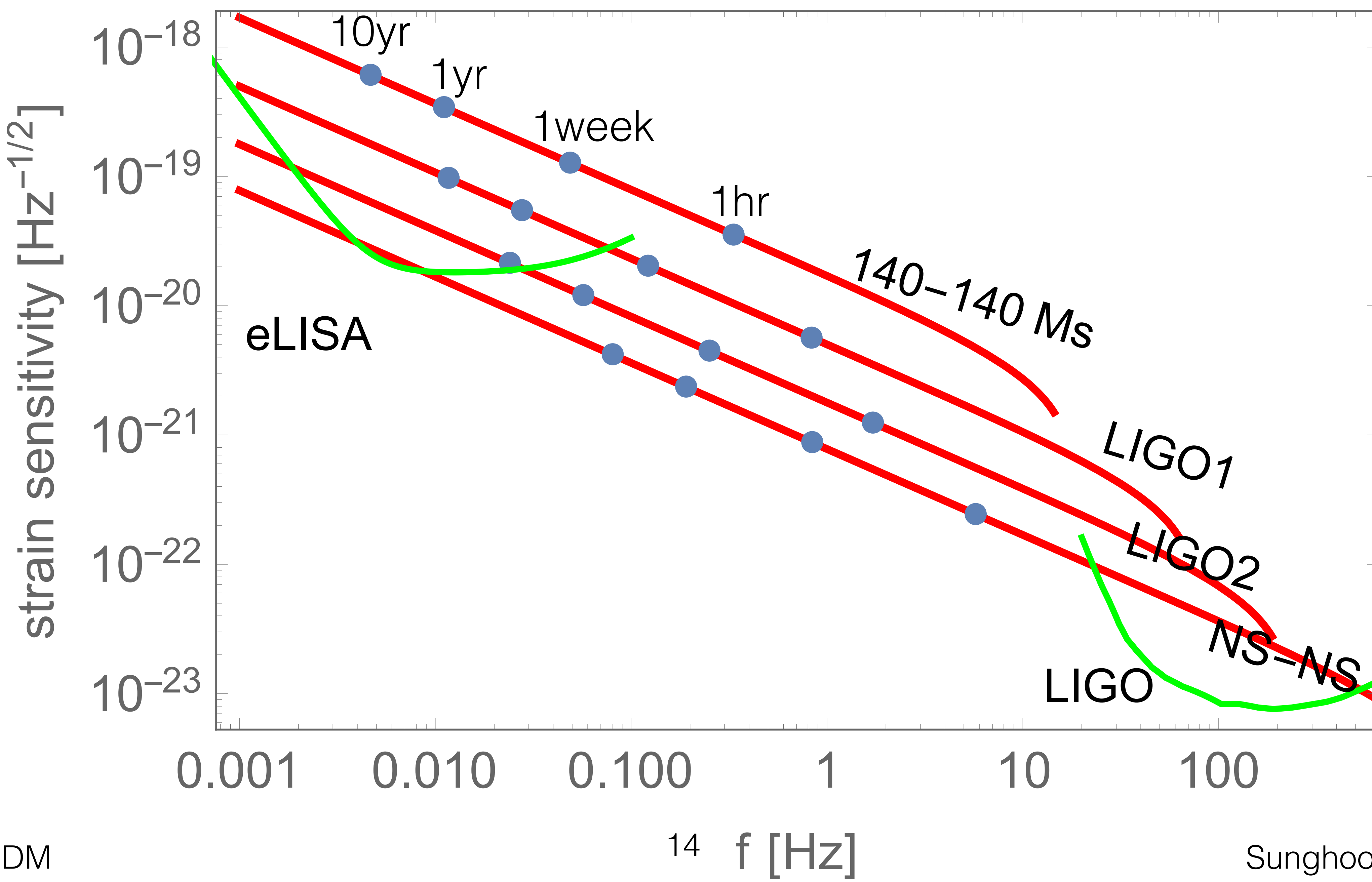
(1710.03269 with Peter W. Graham)

Q2. Given its coarse angular resolution and short measurement time, can LIGO detect any GW lensing?

(1712.xxxxx with Chang Sub Shin)

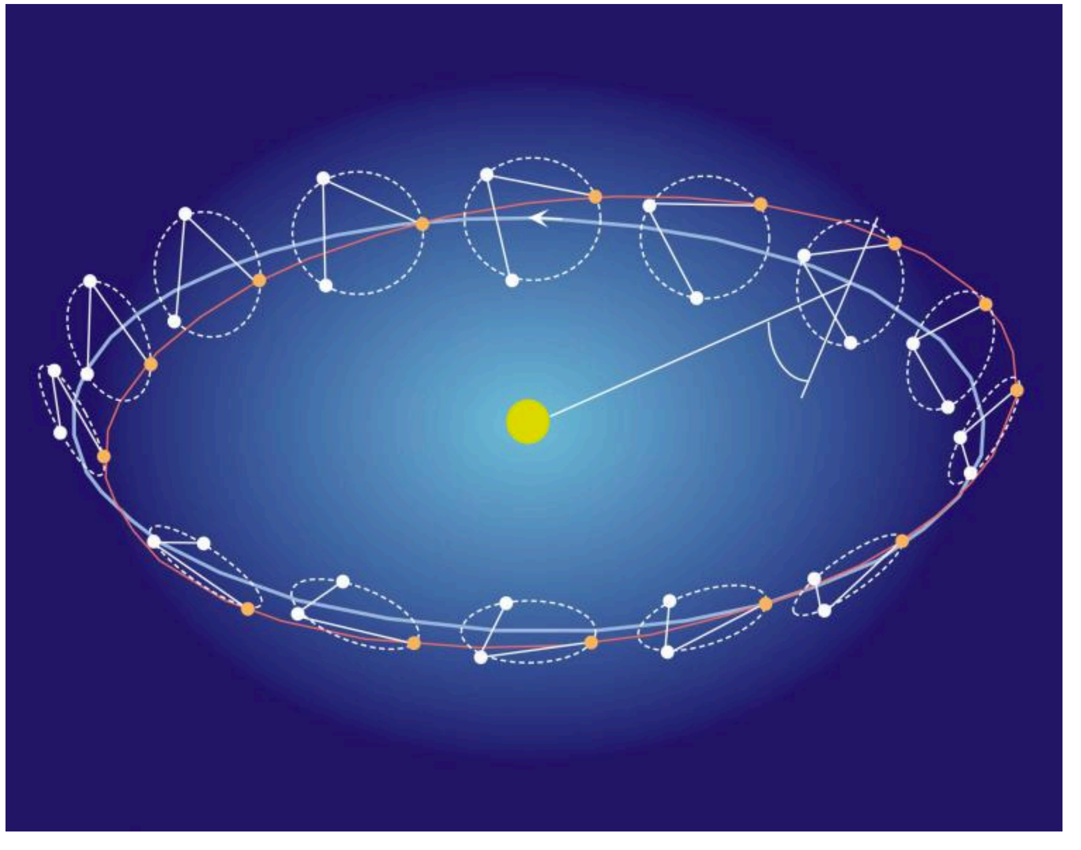
How do LISA localize btw?

- One main difference of LIGO vs LISA is GW lifetimes (and frequencies): several years in the LISA band.



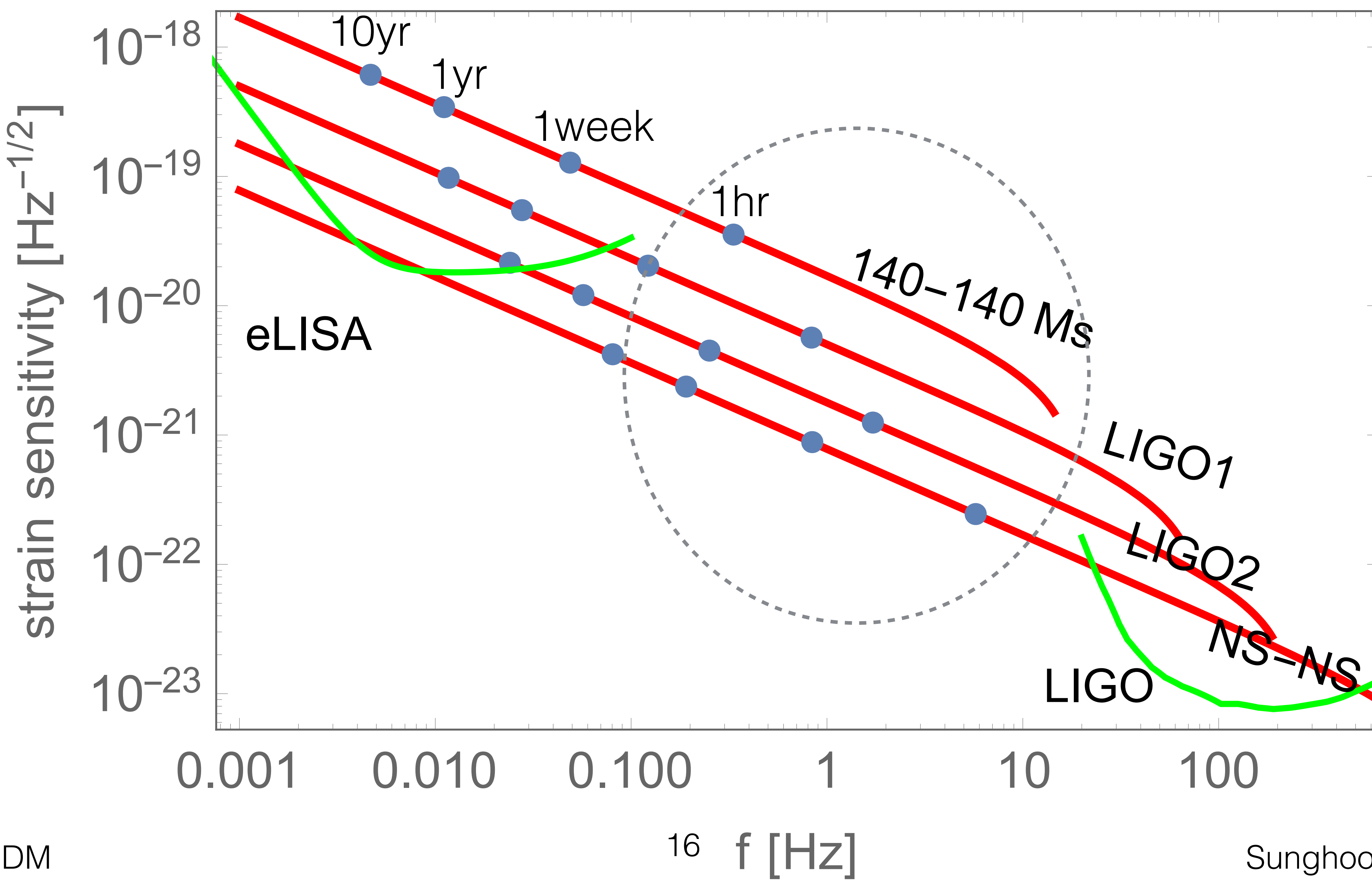
How do LISA localize btw?

- Many satellites and high SNR.
- Signal modulation over annual orbit around the Sun.



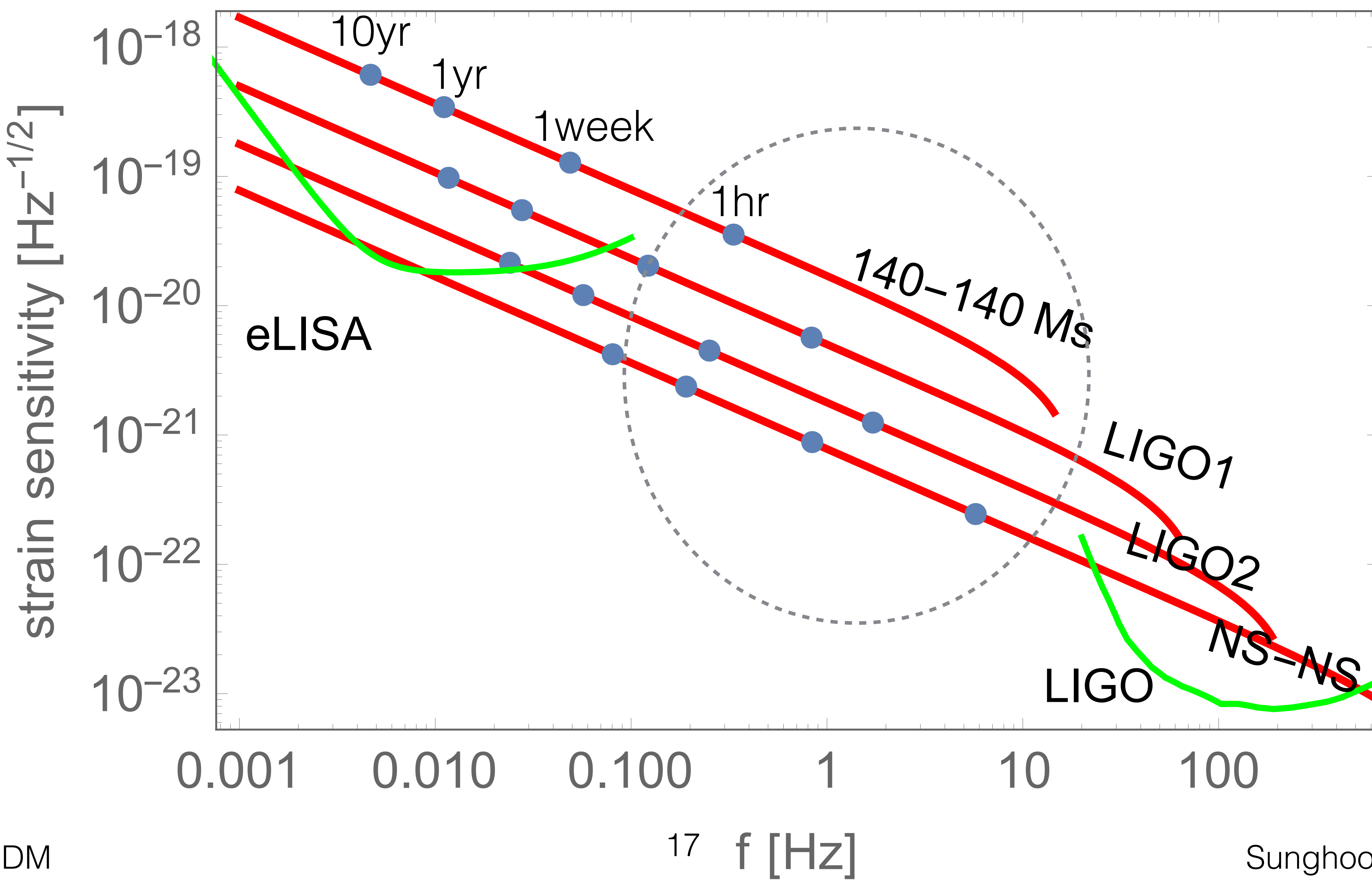
Mid-frequency band

- Is it just an interpolation btwn LIGO and LISA?



We claim that mid-band is best

- It has an ideal balance of frequency and lifetime.



Two physics underlying GW localization

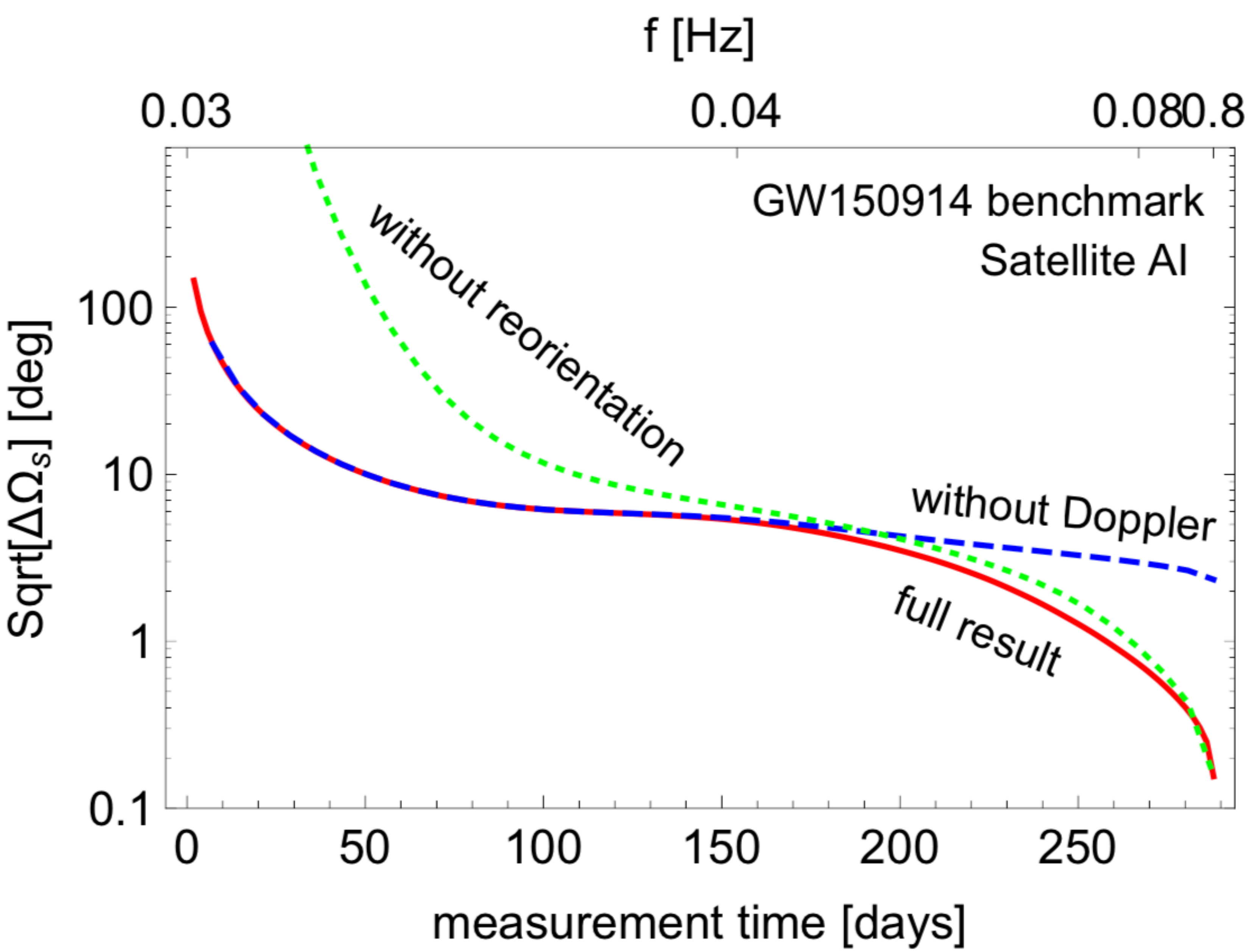
- "Reorientation" of baselines —
  modulation of signal strength and phase (rapid, O(1)-size)

- periodic change of "Doppler" shift —
  around the Sun. Modulation of phase (slow, but can be large in proportion to the frequency)

GW150914 in the mid-band

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

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

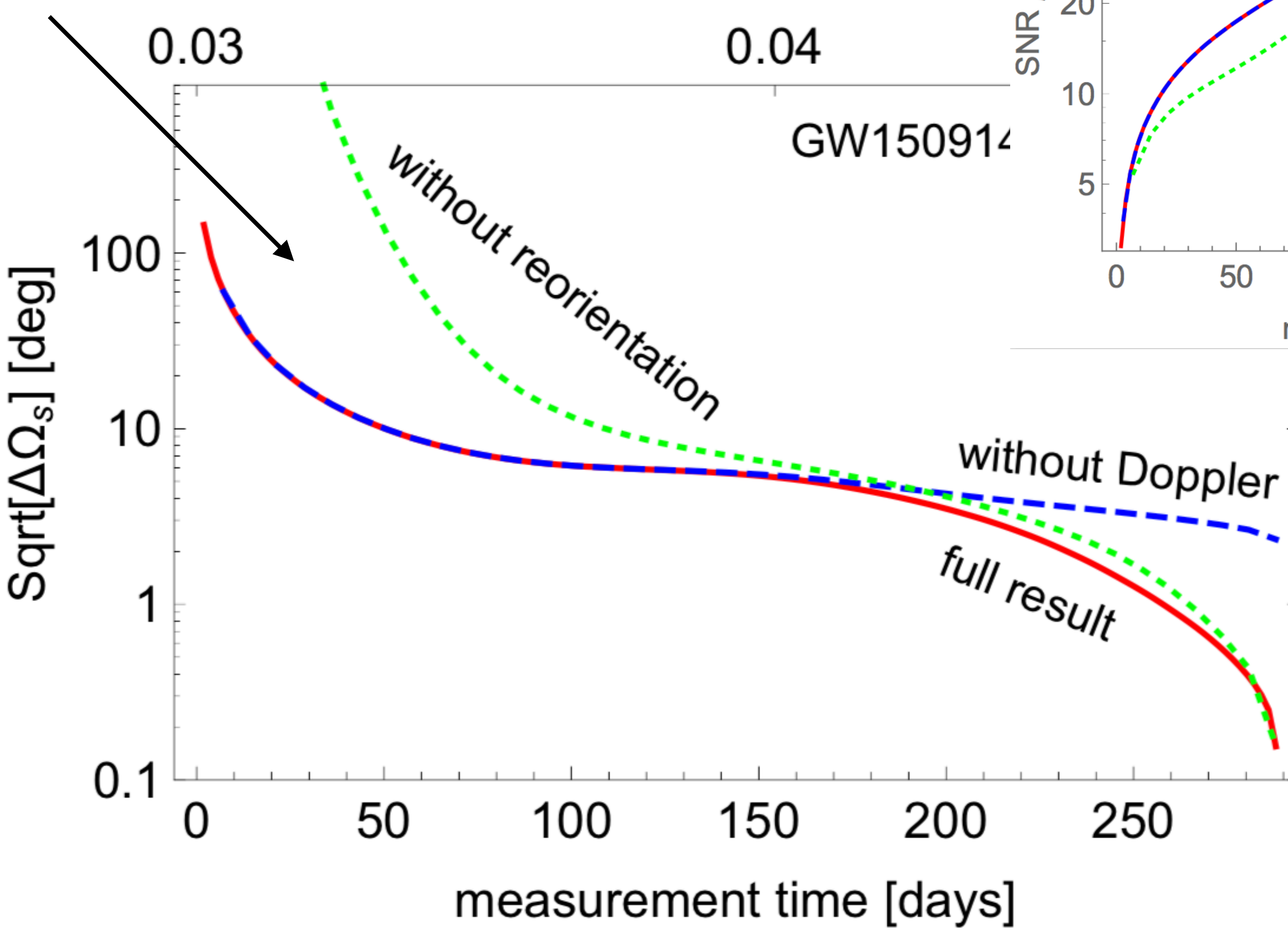


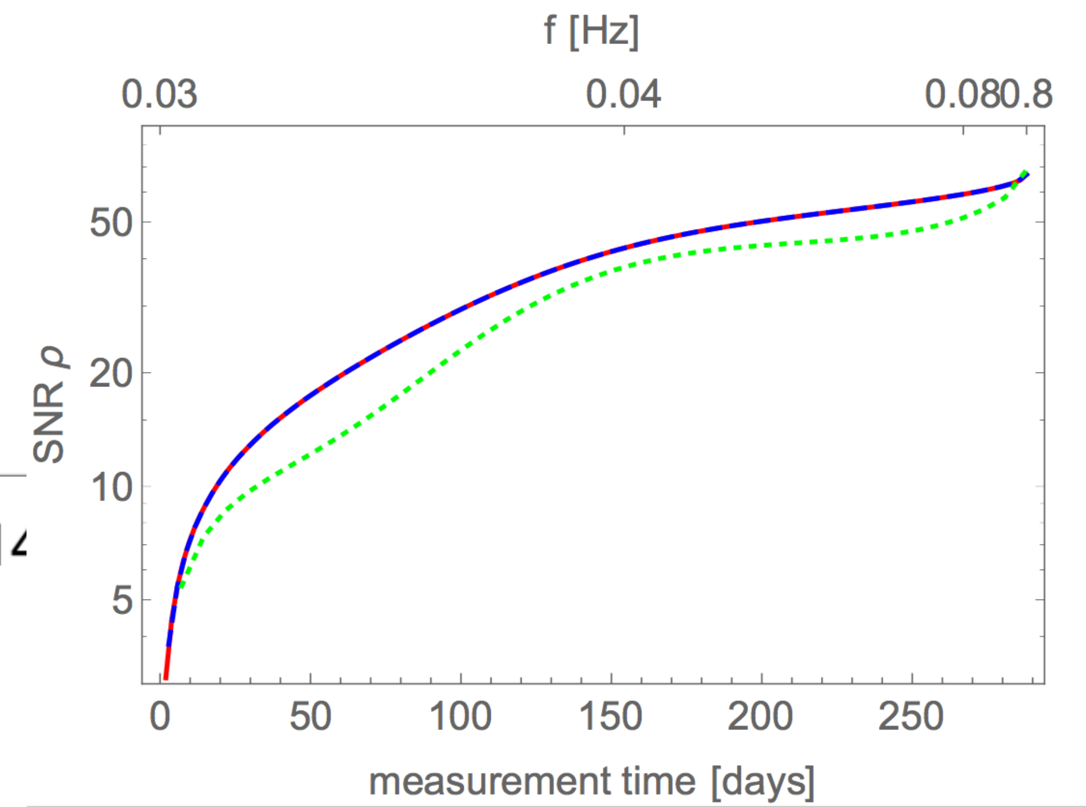
space AI resonant-mode

Fisher matrix method (10 parameters)

Reorientation

Quick reorientation from
dominates early,
growing as $\sim 1/\rho$



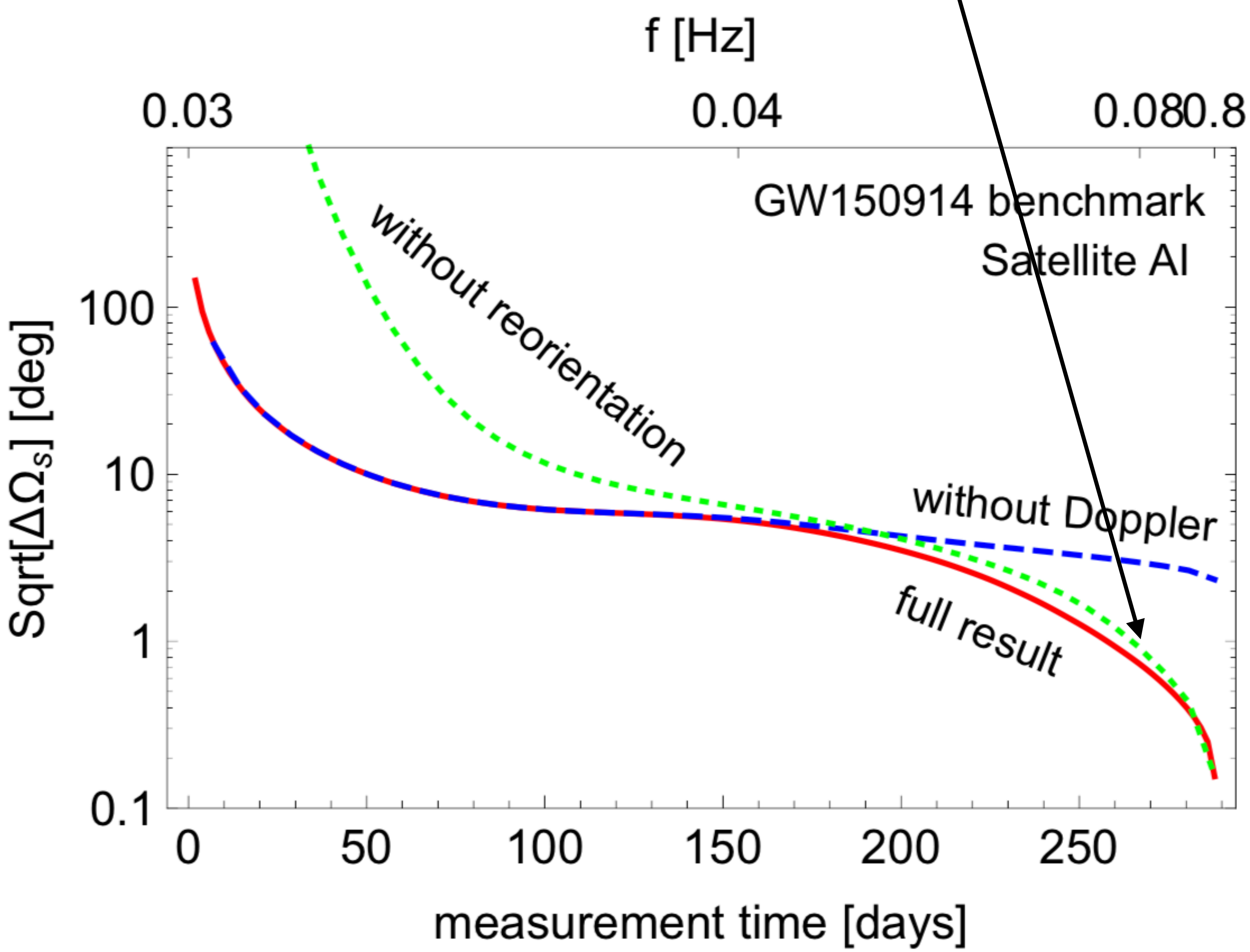


Doppler

Earth-Sun Doppler improves much further (only) after a few months.

$\sim 1/\rho/(2\pi f R/c) \ll 1/\rho$

Doppler phase-shift grows with f and R.



Change of Doppler is appreciable only after months.

Improving quickly as frequency chirps.

Final Angular Resolution

- Typically sub-degree resolution (with single detector).
- Good enough for most ground-based telescopes; but not for the HST, not for identifying host galaxies.

Benchmark	Satellite $\sqrt{\Omega_s}$ [deg]	Satellite SNR	lifetime
GW150914	0.16	67	9.6 months
GW151226	0.20	16	5.5 years
NS-NS	0.19	5.2	140 years
140-140	0.75	190	25 days

Last 1 yr
or
full lifetime

Aside: Angular Resolution vs SNR

In this band:
SNR 10-100 for O(0.1)deg

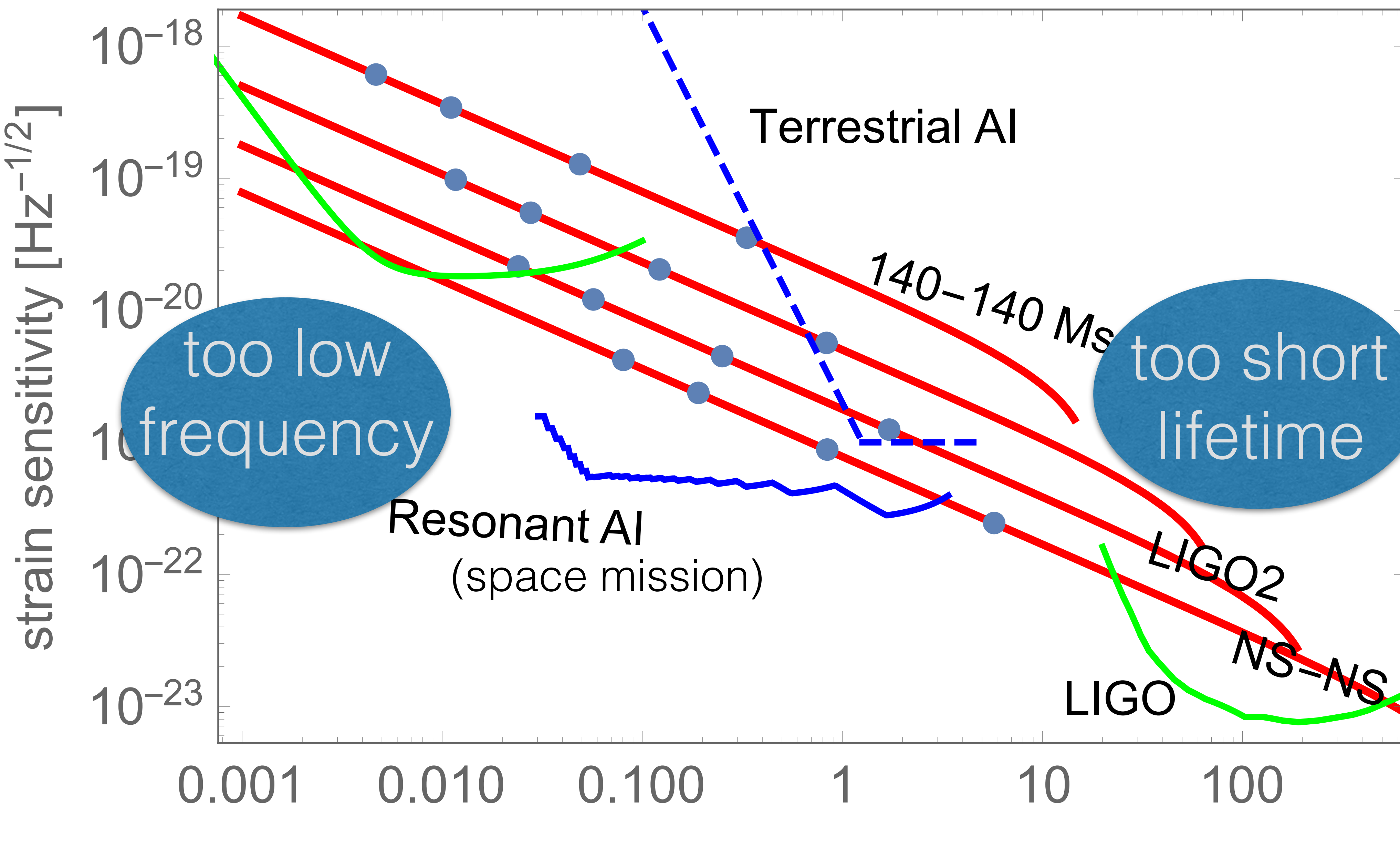
Benchmark	Satellite $\sqrt{\Omega_s}$ [deg]	Satellite SNR
GW150914	0.16	67
GW151226	0.20	16
NS-NS	0.19	5.2
140-140	0.75	190

S_I/N	S/N	$\Delta\Omega_{S,I}$ (10^{-5} str)	$\Delta\Omega_S$ (10^{-5} str)
975	1336	153	1.52
1435	2085	256	15.5
3150	4907	148	29.1
2505	3361	234	24.5
4610	6715	53.8	13.0
2386	3940	164	38.8
3411	3984	457	78.7
469	641	125	1.53
687	1001	188	12.4
1483	2310	104	20.9
1182	1589	154	18.1
2193	3188	42.3	9.61
1125	1853	[illegible]	[illegible]
1612	1884	[illegible]	[illegible]
2774	3806	[illegible]	[illegible]
4091	5935	[illegible]	[illegible]
9016	14041	[illegible]	[illegible]
7165	9607	104	13.8
13152	19172	27.5	6.93
6826	11280	76.8	20.8
9749	11385	220	39.8
1318	1809	152	1.67
1943	2820	164	16.6
4280	6666	99.5	25.3
3402	4561	135	23.8
6246	9104	43.0	10.5
3241	5355	109	34.5
4628	5405	289	60.0
667	913	294	4.54
982	1425	331	42.4
2157	3359	238	62.4
1715	2301	312	61.5

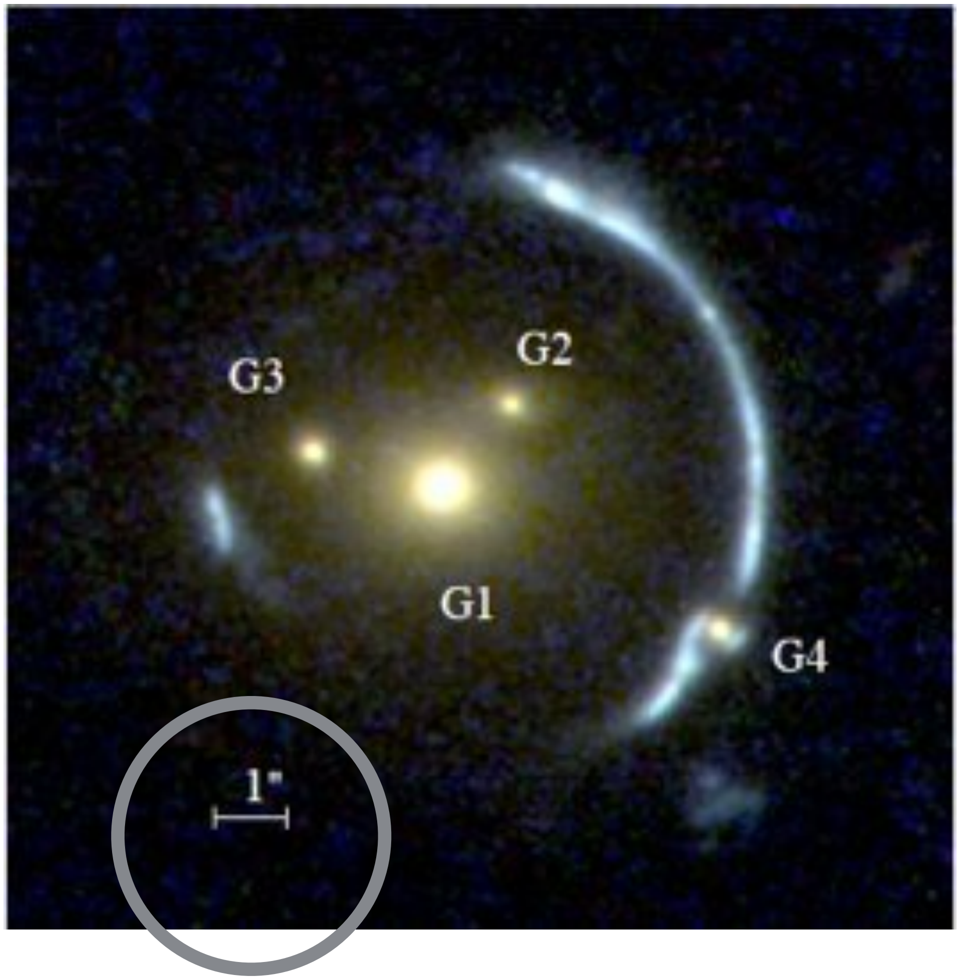
LISA: SNR 10^3-4
for O(0.1)deg

Ref: C.Cutler, 9703068

Thus, this mid frequency band 0.01~5 Hz
is ideal and economical for
(1) sub-degree angular resolution,
(2) to warn merger follow-ups.



Good. But, sub-degree is not good enough to identify strongly lensed GW images.



We still claim that LIGO is an ideal lab to detect the GW lensing by DM.

GW vs. light

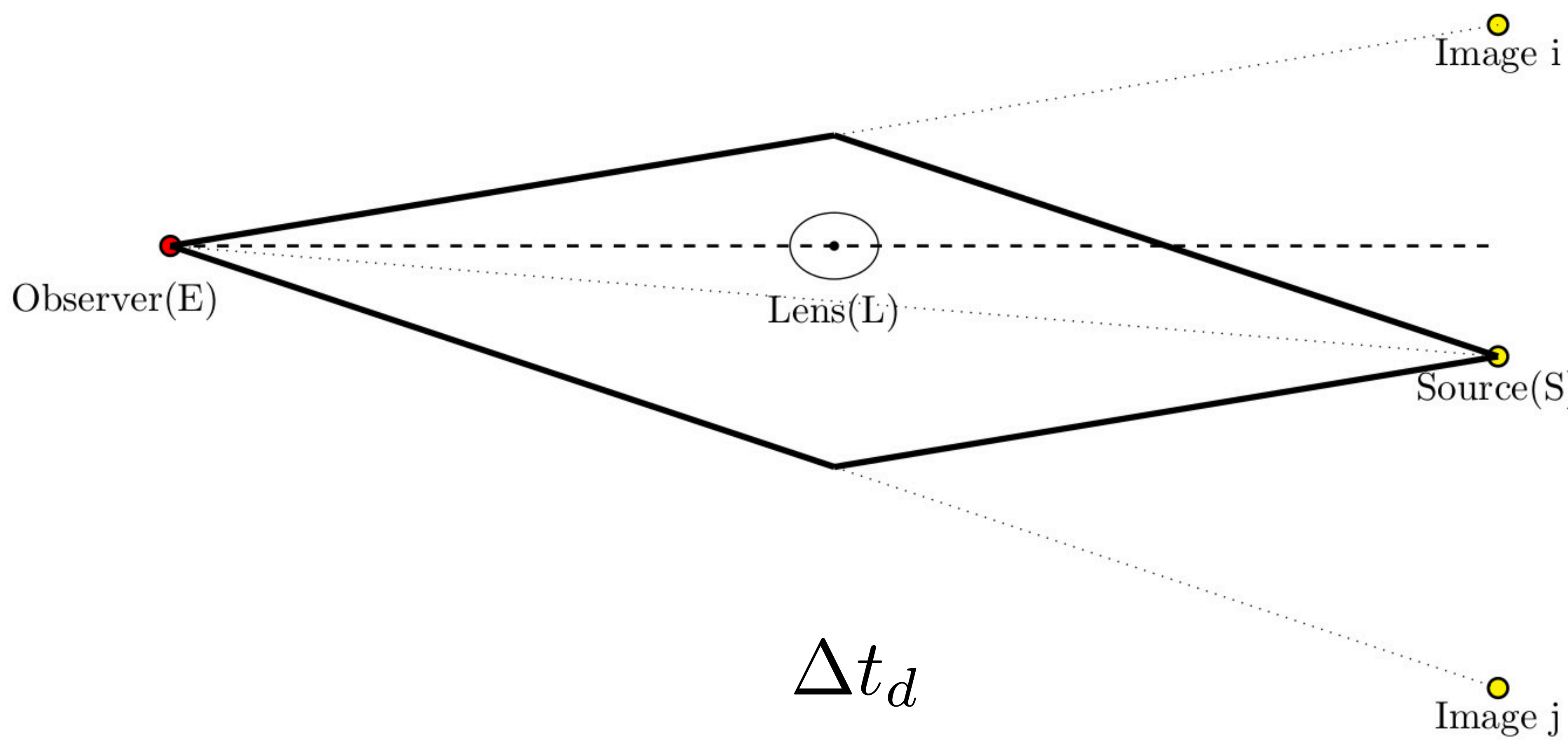
- GW chirps.
  - It provides a natural change of lensing pattern, which is extremely useful in lensing detection.

- GW wavelength is typically much longer than that of light.
  - Wave optics/diffraction becomes relevant.
  - GW cannot see too small lenses.

- GW angular resolution is much worse.
  - It actually turns out to help.

Time-delayed images

Consider time-delayed images of light and GW.



$$\Delta t_d$$

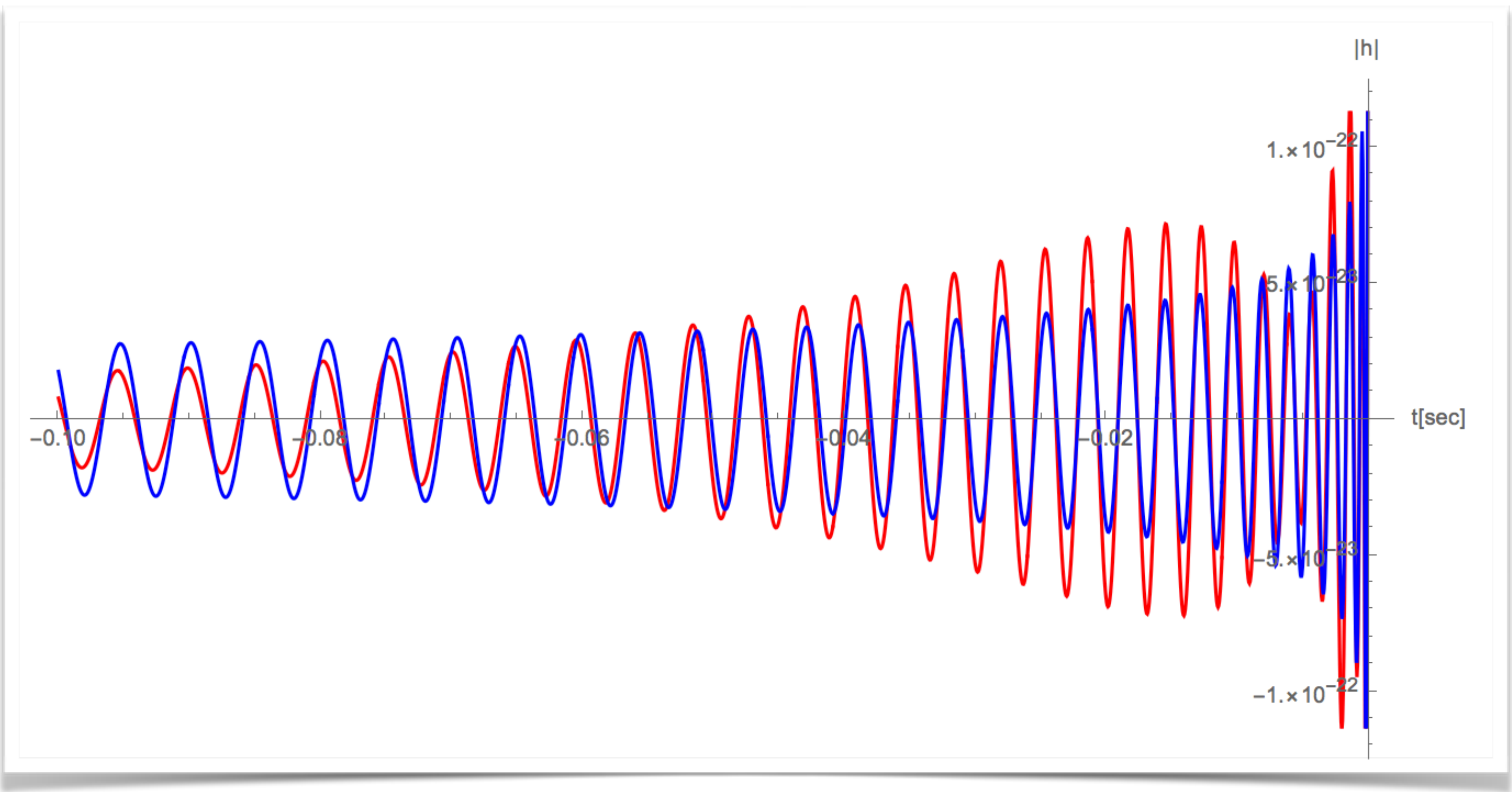
Time-delayed images

- As the two GW images cannot be resolved, they interfere in final observation.
- Their phase-shift grows with frequency chirping.

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

- Interference pattern changes with chirping/time!

GW lensing "fringe"



NS-NS merger lensed by 100 Msun compact DM.

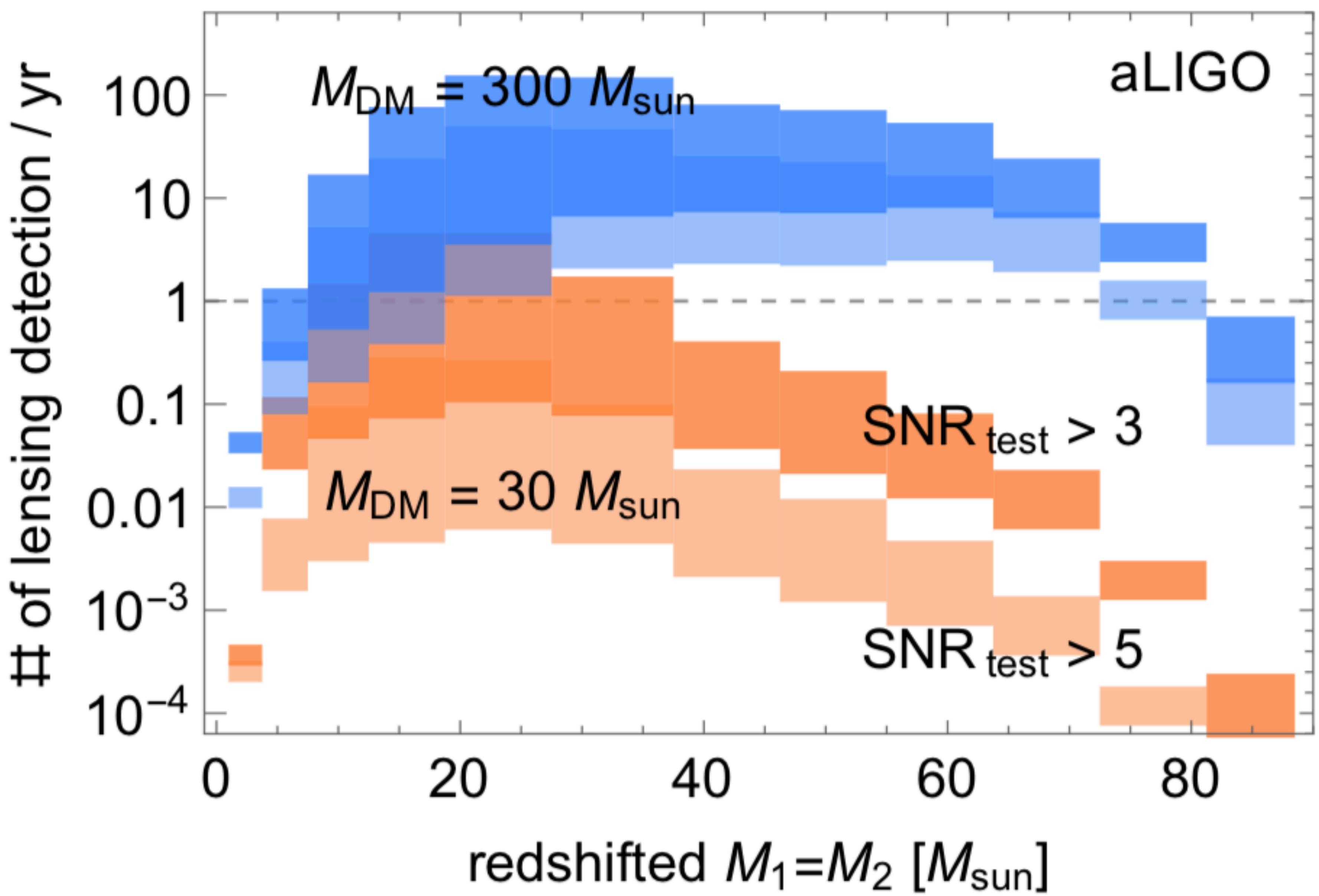
LIGO is an ideal GW lensing detector

- GW lensing fringe is most pronounced at LIGO:
  - Highest frequency.
  - Chirping most quickly near merger.

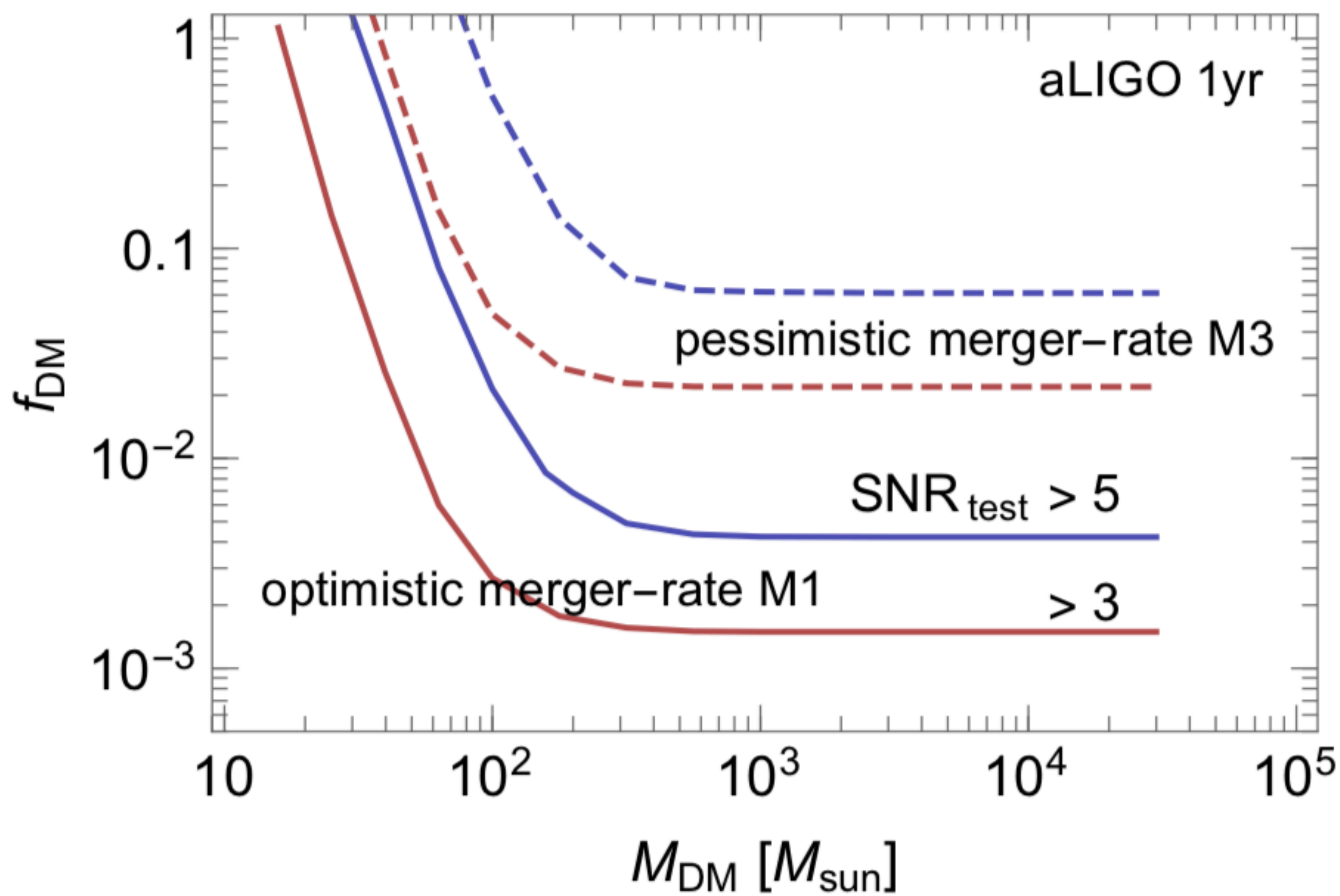
LIGO can see the smallest compact DM

- Highest-frequency detector means that LIGO can detect the lensing by smallest compact DM.
- 10-1000 Hz correspond to the Schwarzschild radius of 10^4-10^2 Msun compact DM.
- Any heavier DM can produce lensing fringe observable at LIGO, in principle.

Many detectable lensings



Compact DM fraction



Thank you