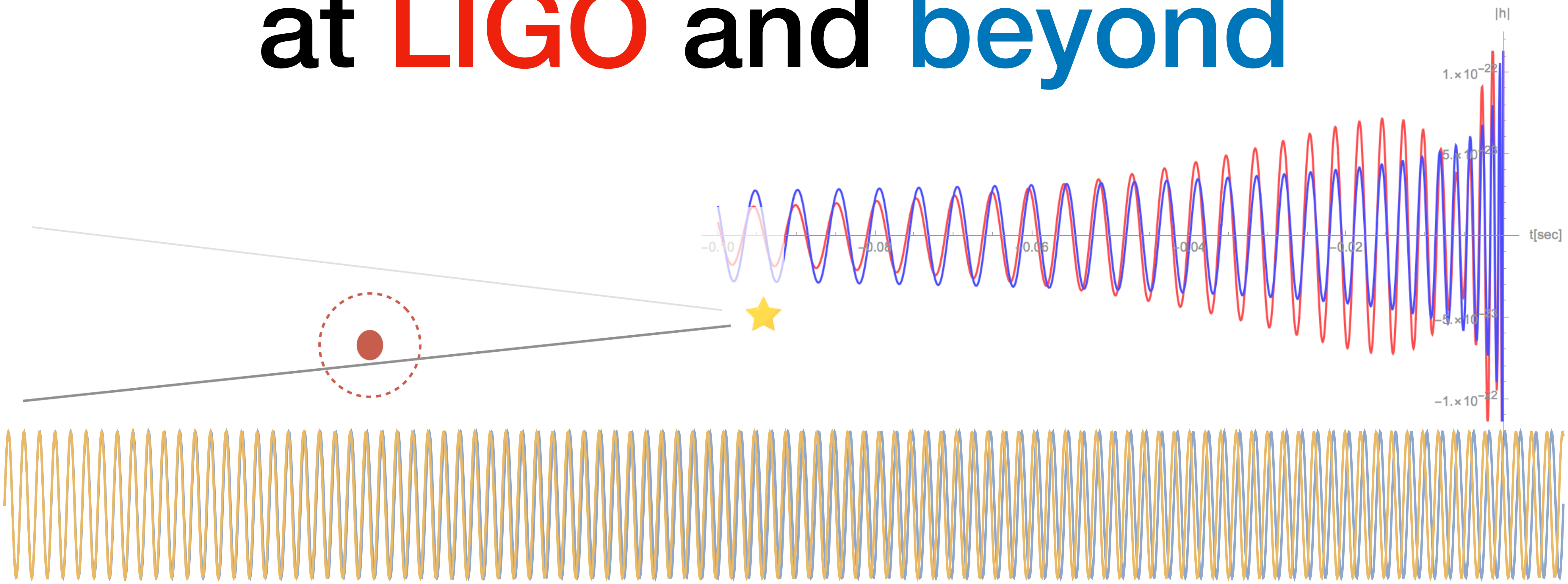
Probing Dark Matter at LIGO and beyond



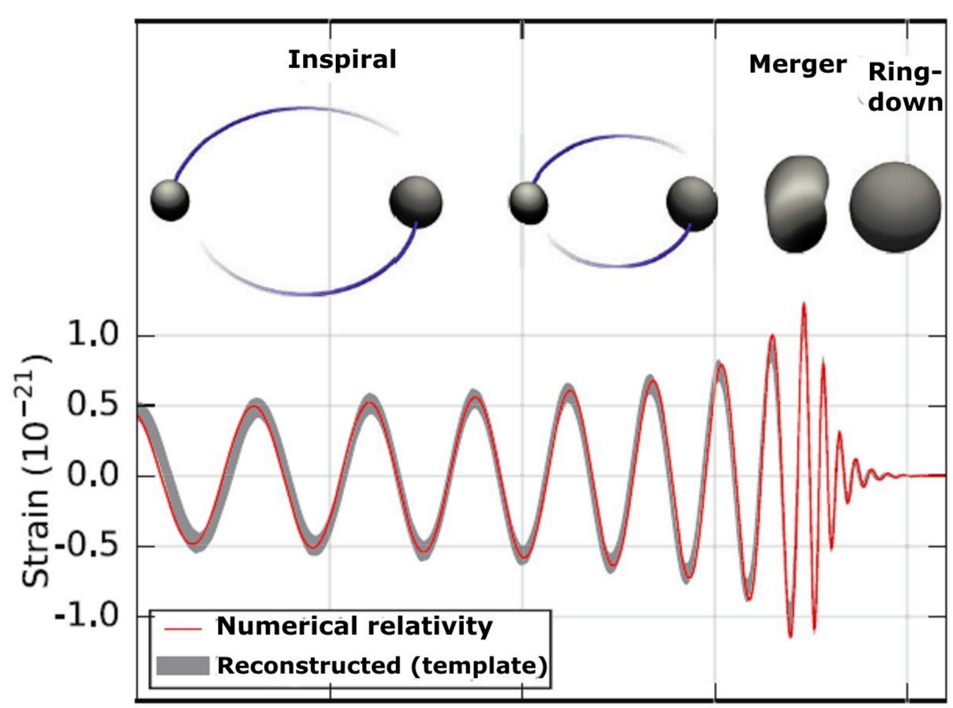
Sunghoon Jung
Seoul National University

Corfu Summer Institute 2019

- 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"

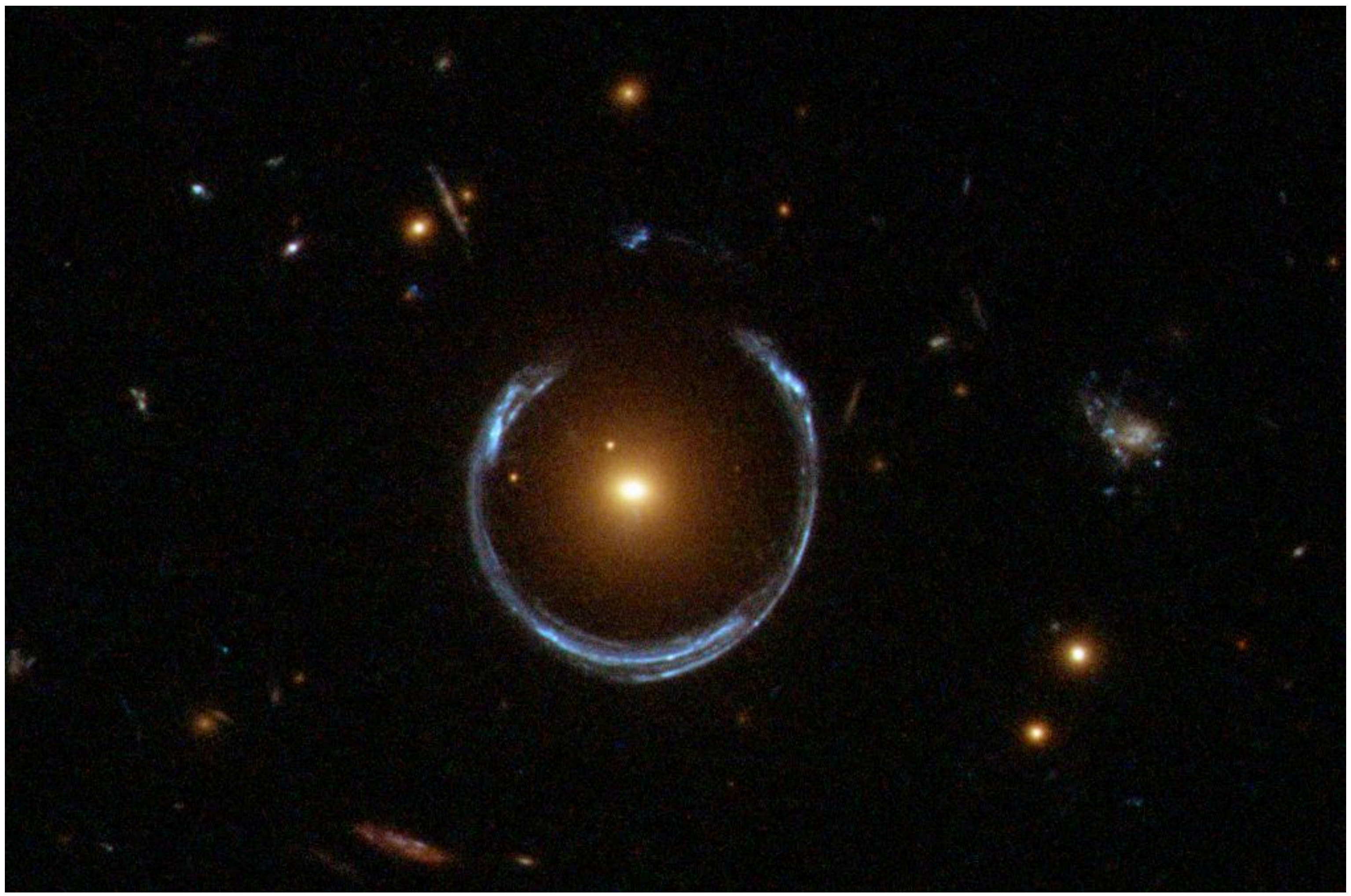
LIGO can see compact DM:

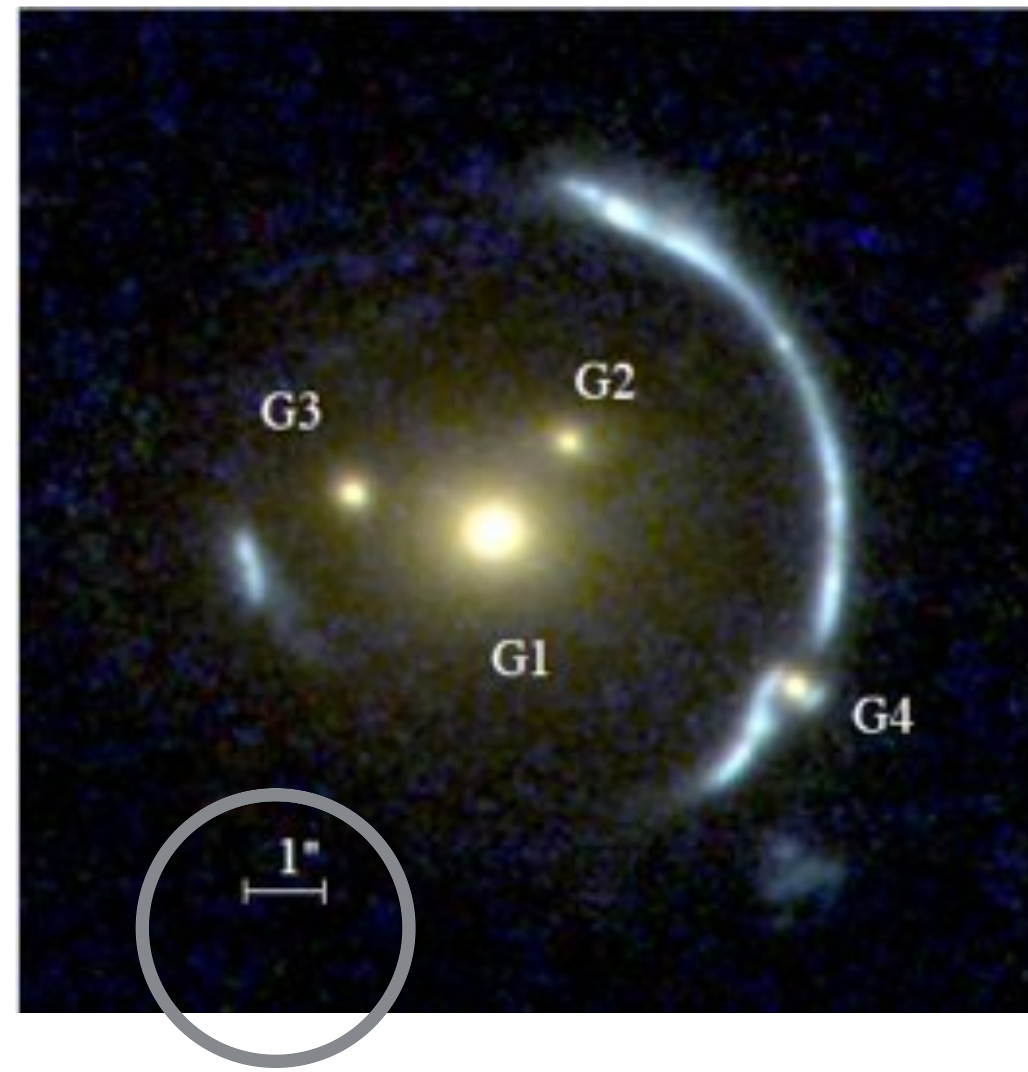
(Primordial BH, Dark stars/clusters/solitons)

"GW (lensing) Fringe"

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

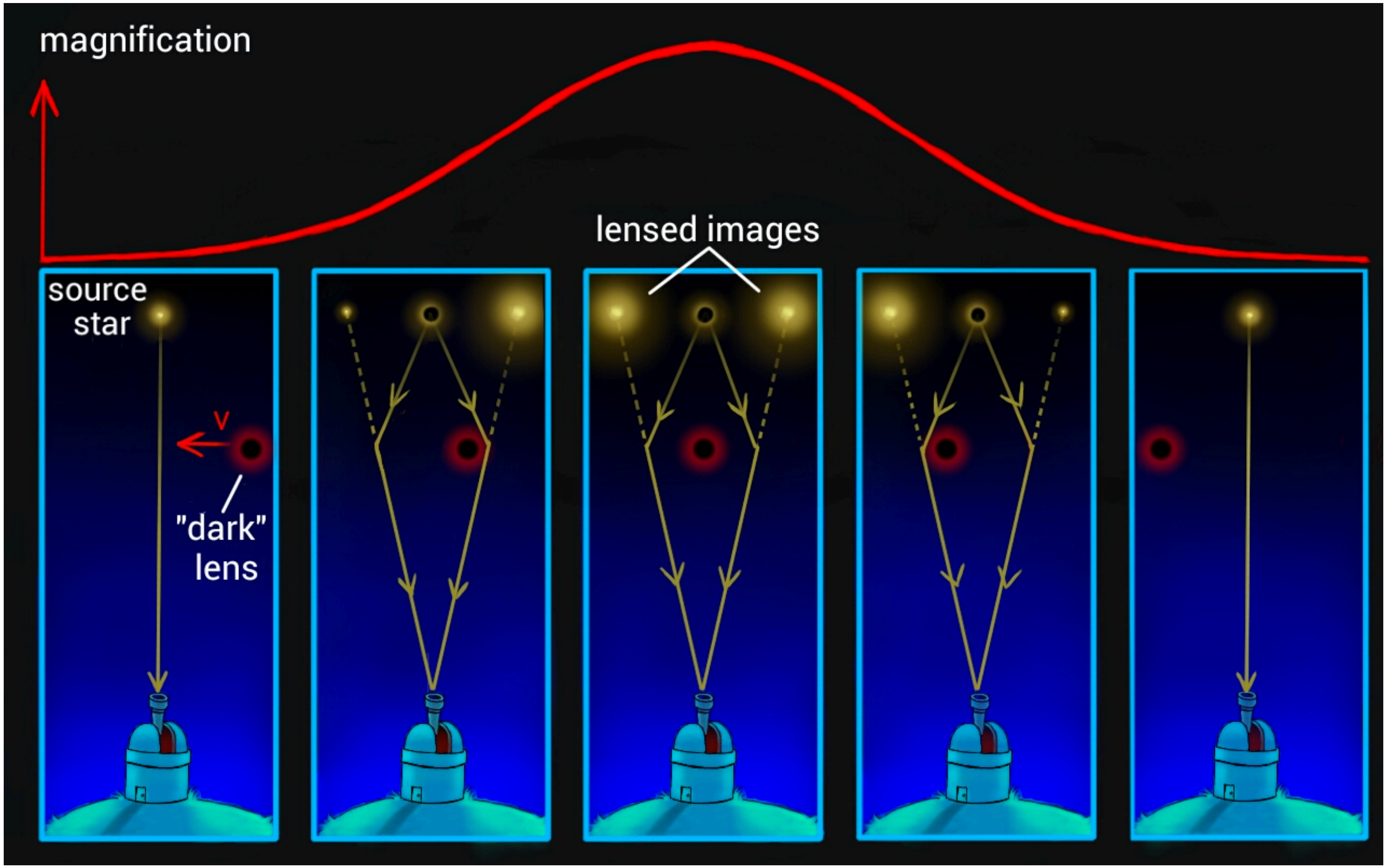
Strong lensing of light





- 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

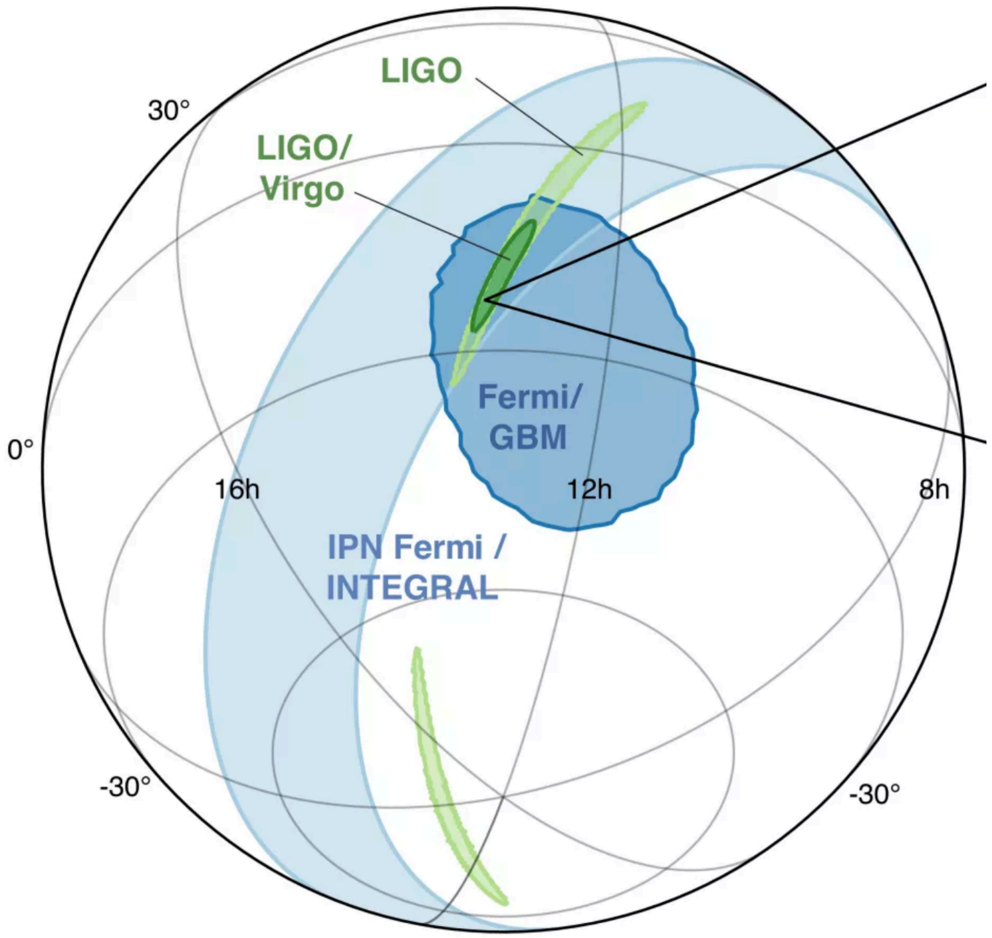
- Complicated statistical analysis of multiply and weakly lensed lights.

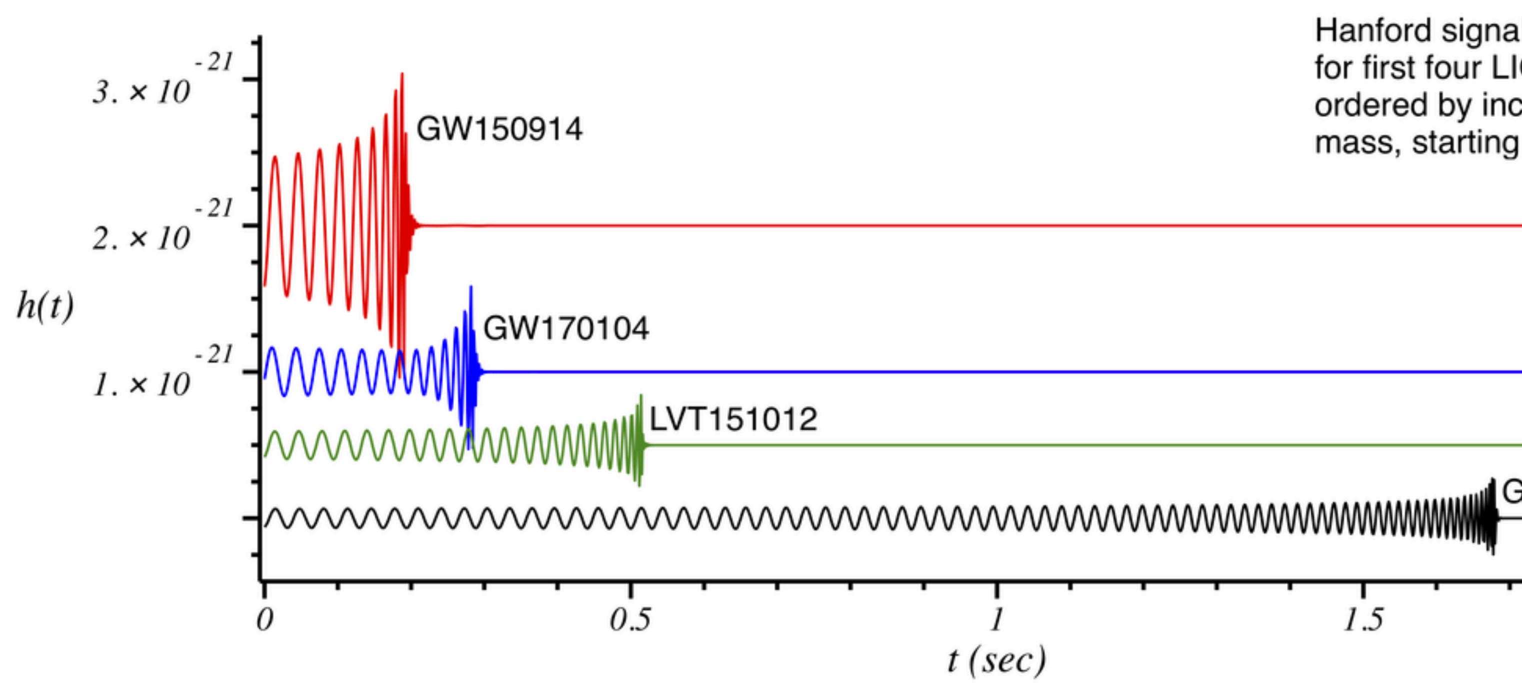
GW lensing observation seems very unlikely at LIGO!

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,,,

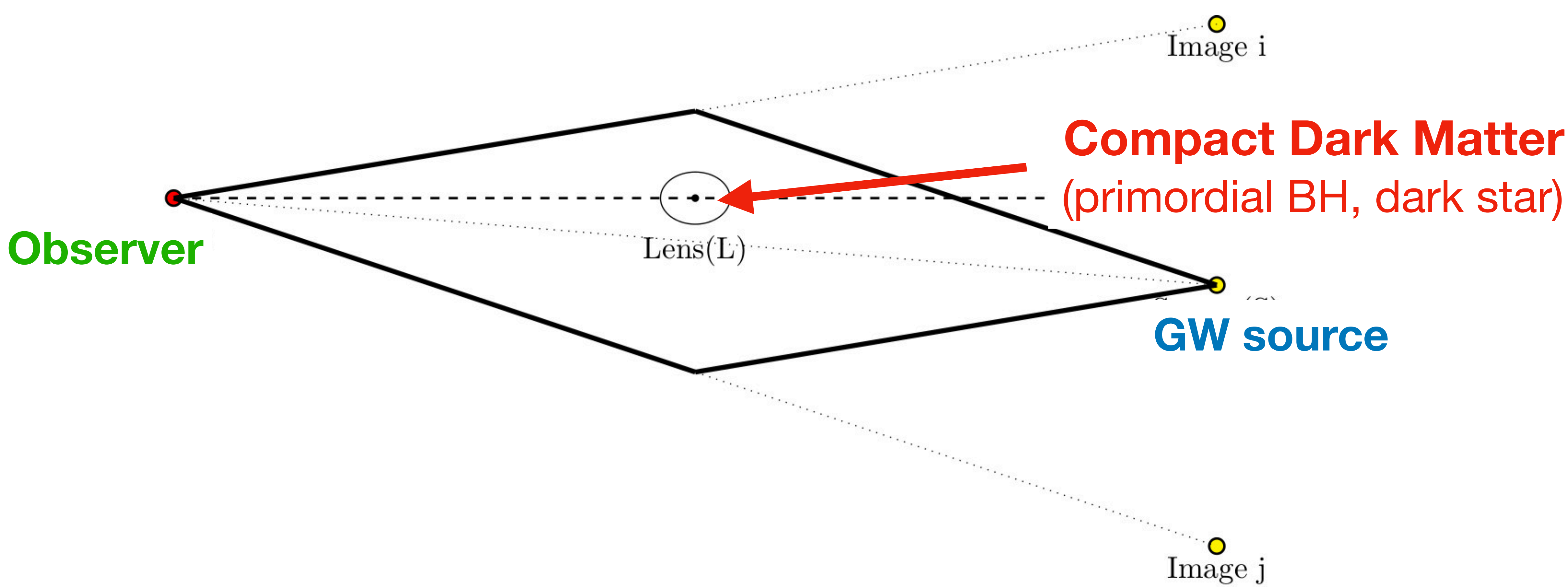
- GW chirps.
  - It provides non-trivial specific *change* of lensing pattern, which is extremely useful in lensing detection.

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

- (GW wavelength is typically much longer.)

Time-delayed images

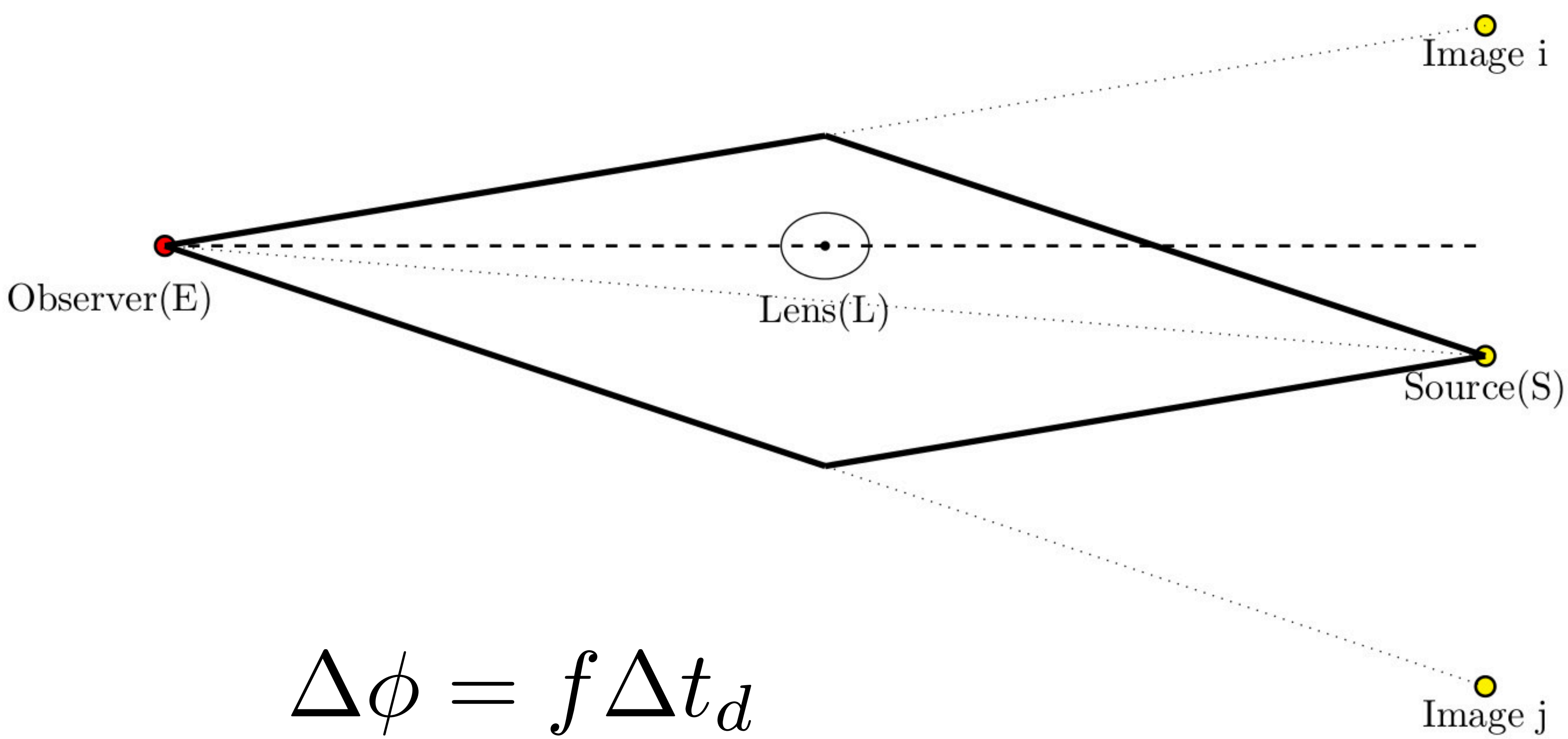
Consider time-delayed lensed images of GW.



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

Interfered images

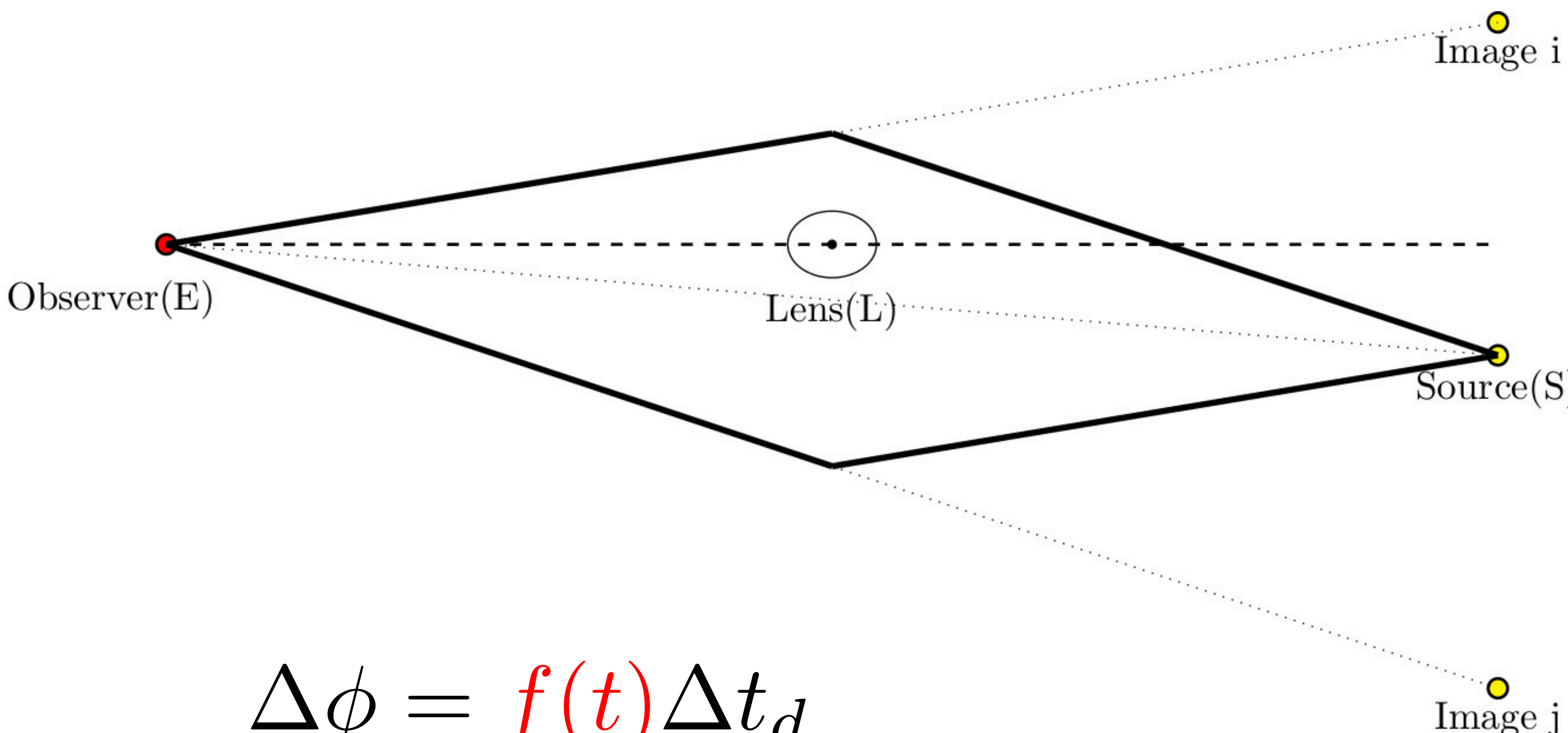
Unresolved GW images rather “interfere” in our observation.



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

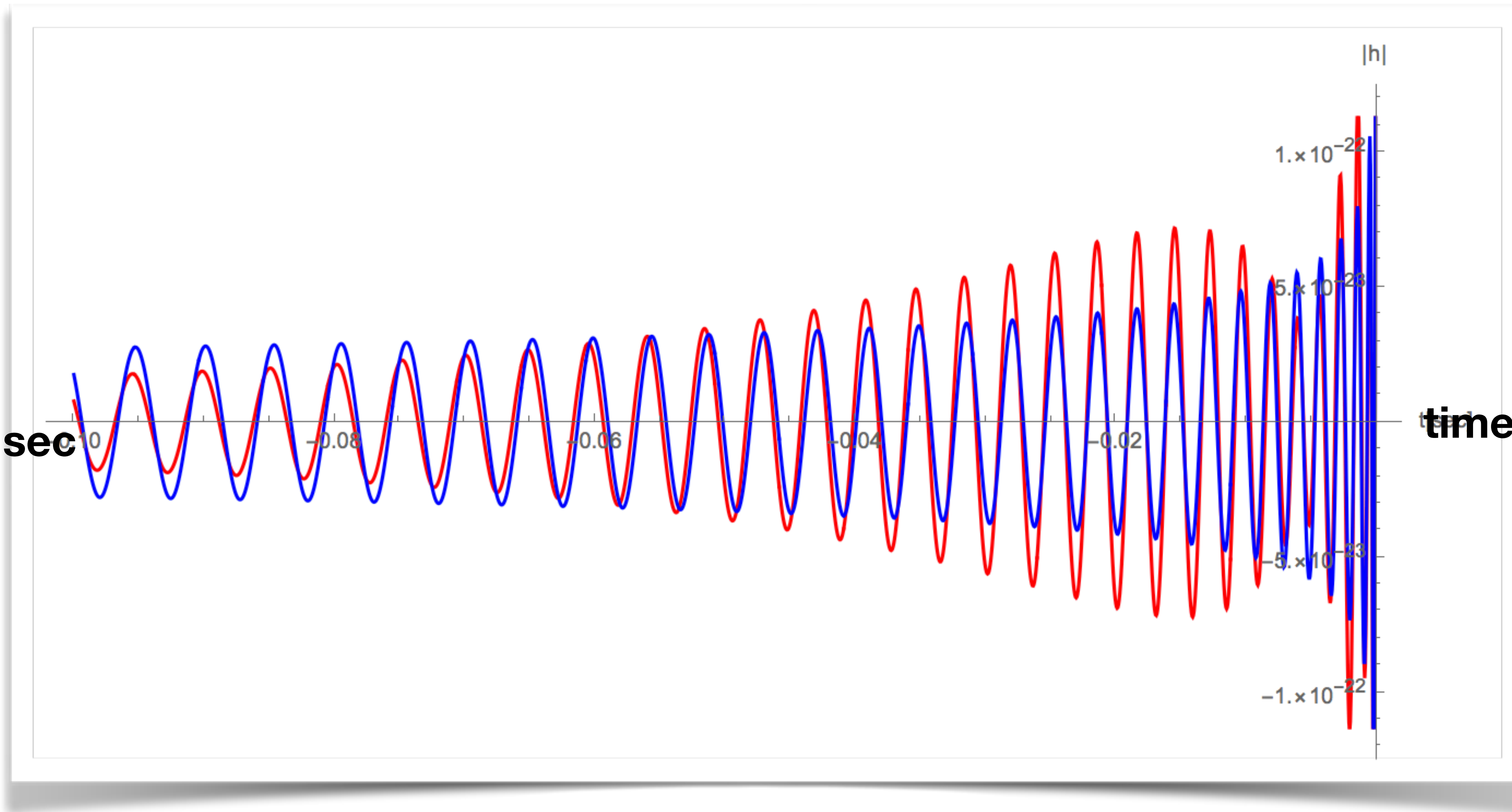
GW lensing Fringe

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”

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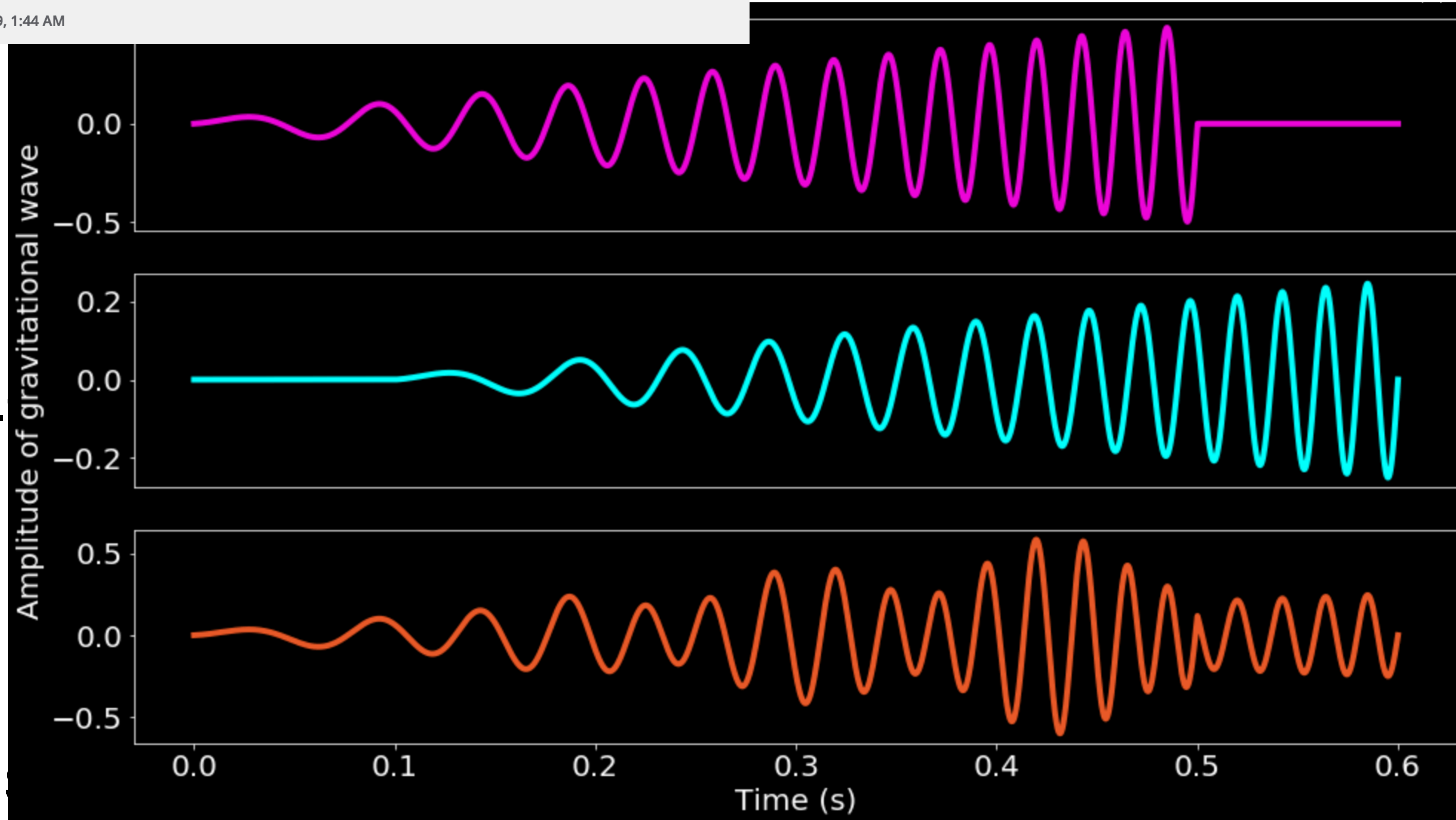
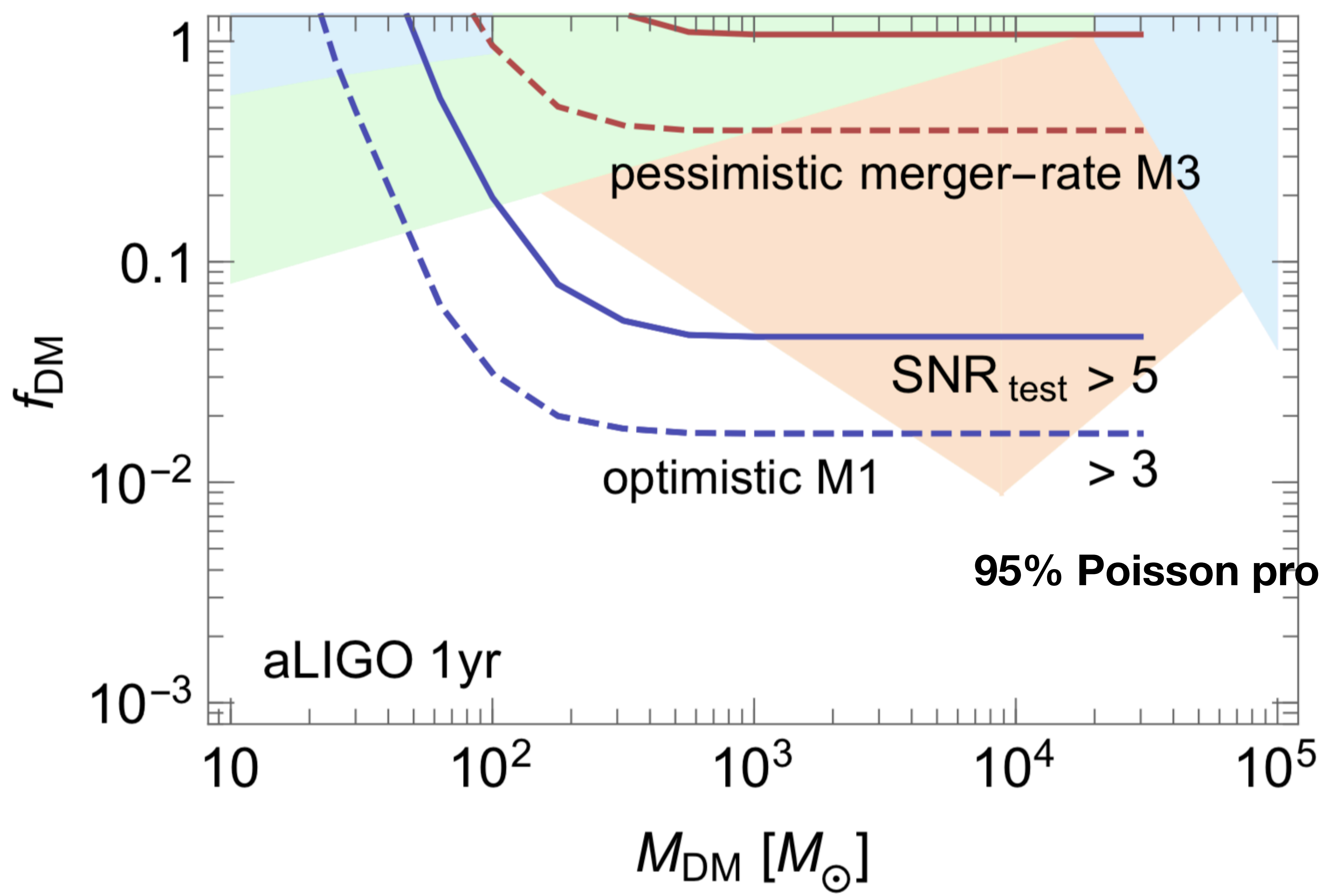
N



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

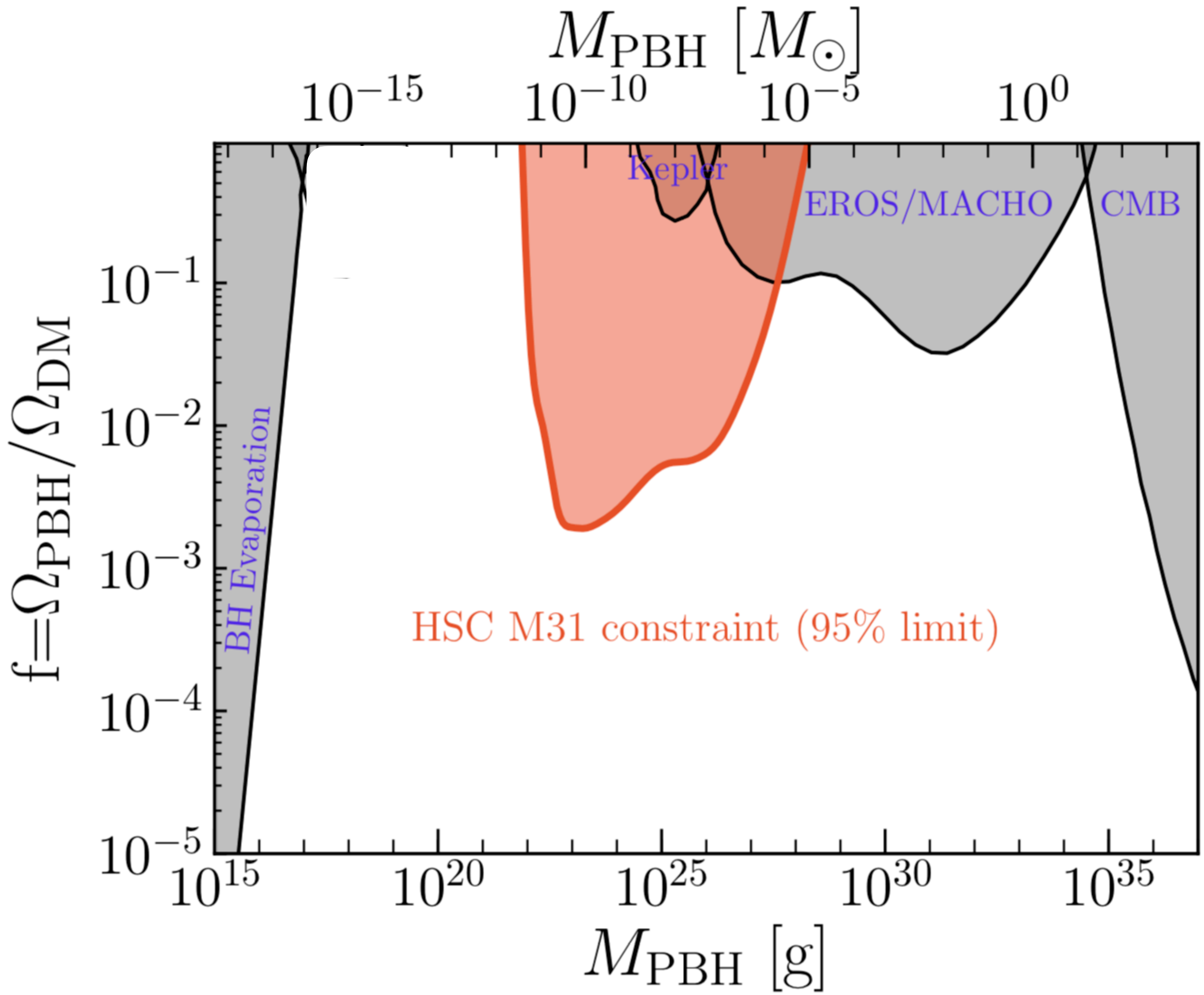
1712.01396 PRL (2019), S.Jung et al.

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)

Aside: New idea on PBH DM search gap



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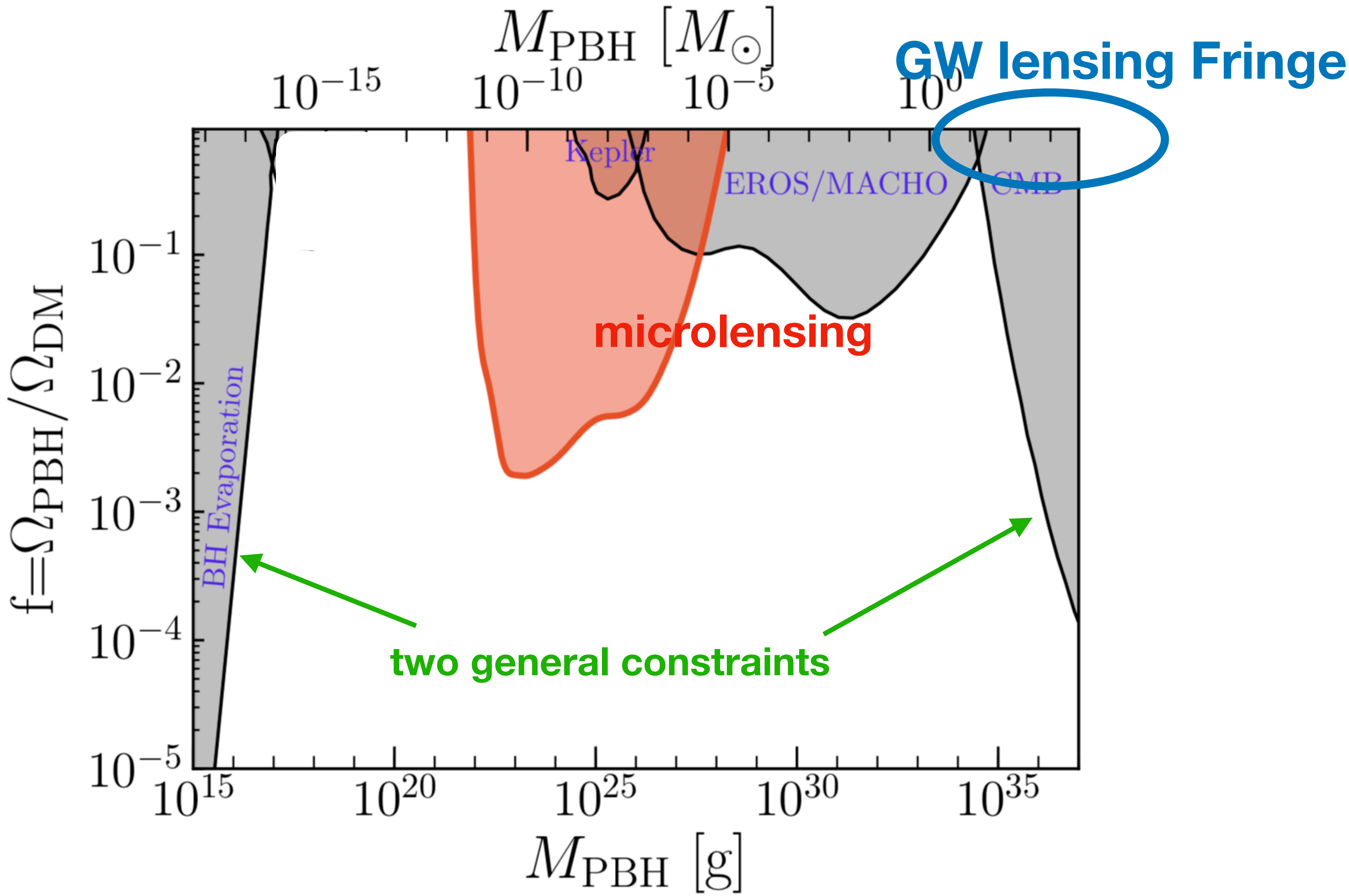

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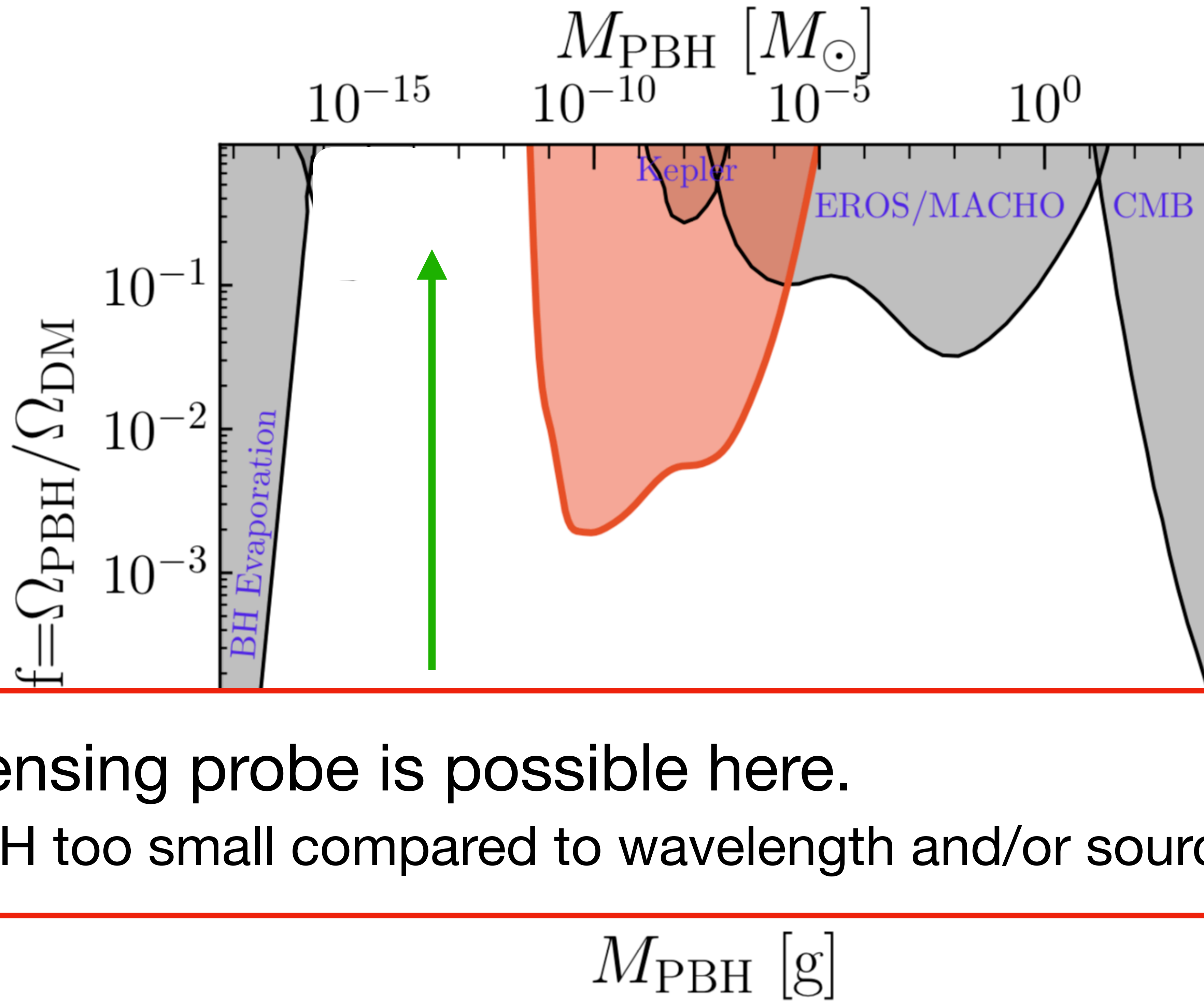
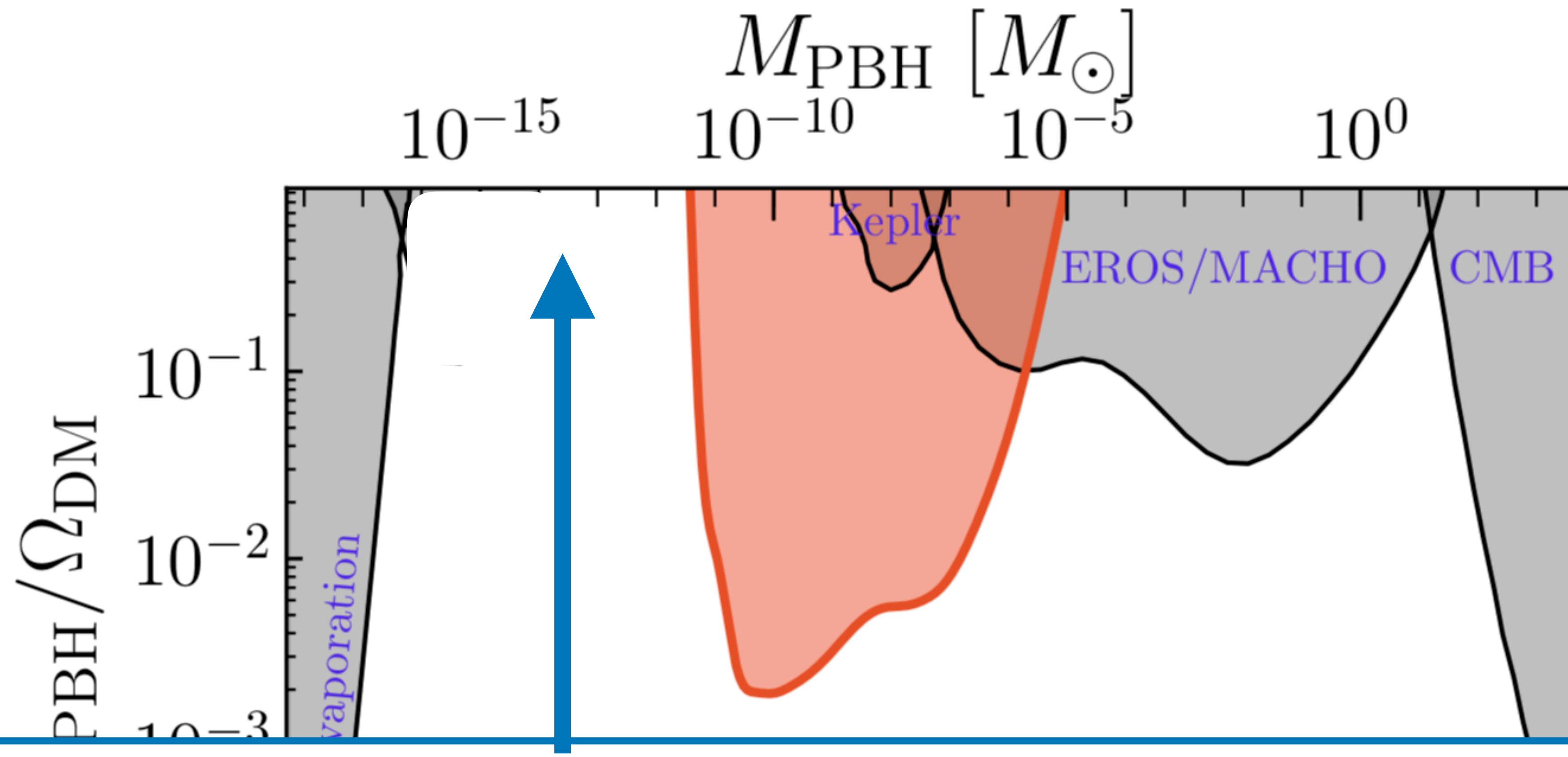


- No lensing probe is possible here.
  (PBH too small compared to wavelength and/or source.)

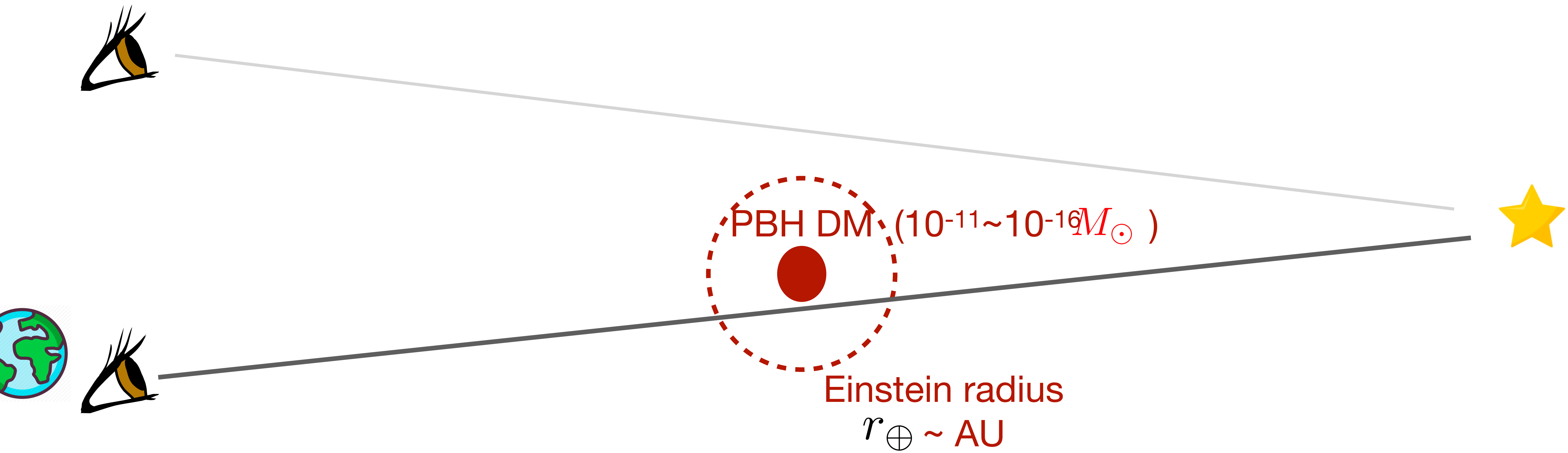
Aside: New idea on PBH DM search gap



- But! Fortunately, we have a natural access!
  The astrophysical scale accessible to us
  $r_\oplus$ ~ AU
  happens to be the Einstein radius of this mass range!

1908.00078, S.Jung, TaeHun Kim

GRB Lensing Parallax

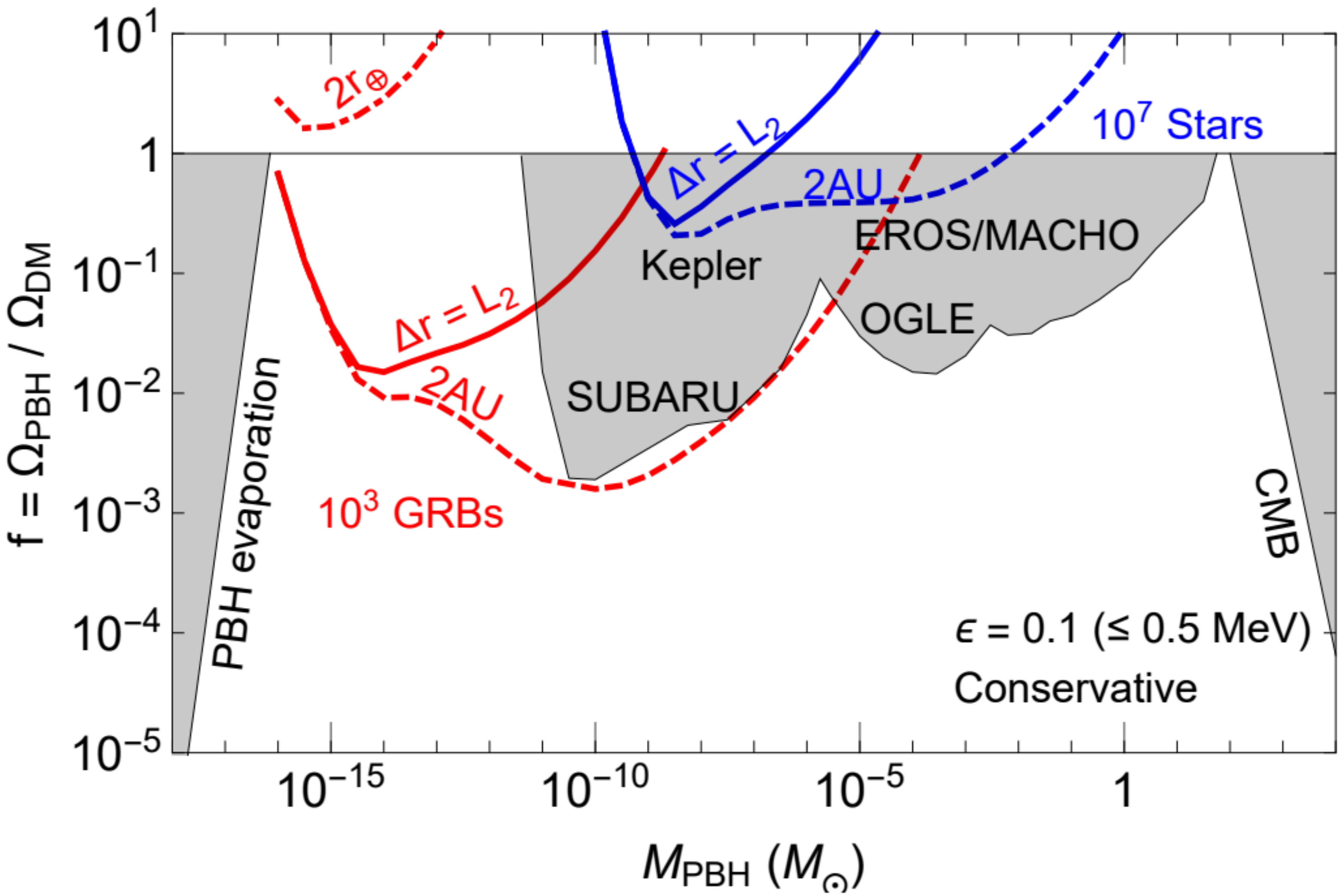


- If two detectors are spatially separated by those astro scales, they will observe different magnifications of GRB pulses.

1908.00078, S.Jung, TaeHun Kim

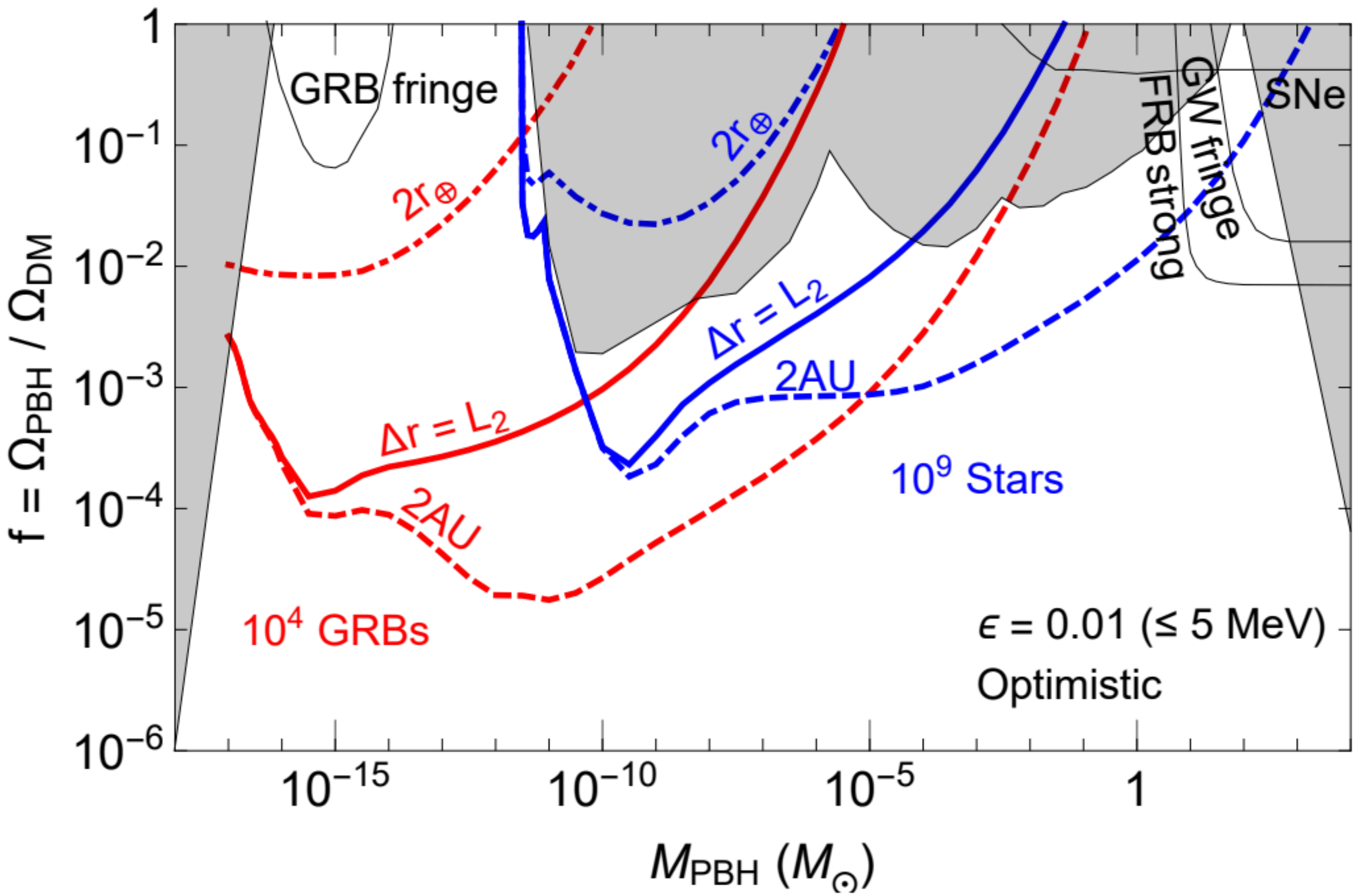
- Space gamma-ray technique is already available (e.g. Fermi). We just need one more!

GRB Lensing Parallax



1908.00078, S.Jung, TaeHun Kim

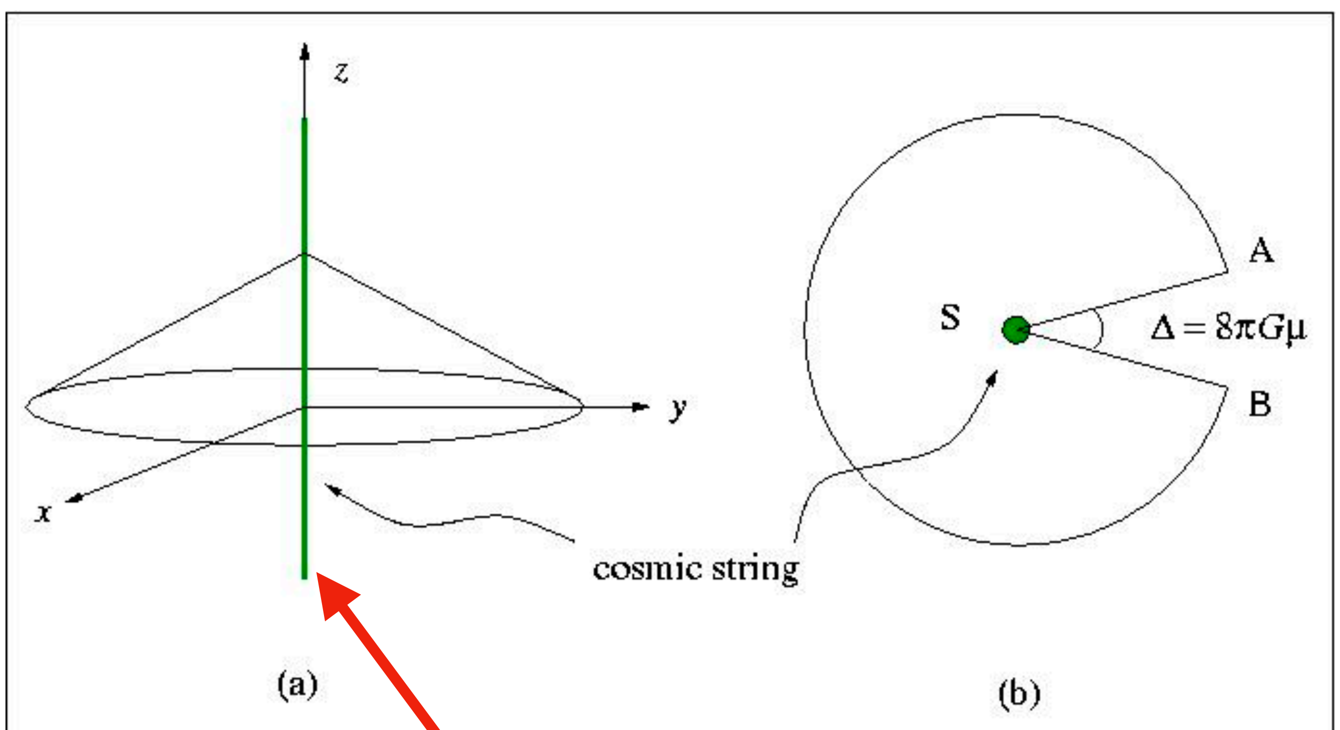
GRB Lensing Parallax



1908.00078, S.Jung, TaeHun Kim

GW Fringe from Cosmic string

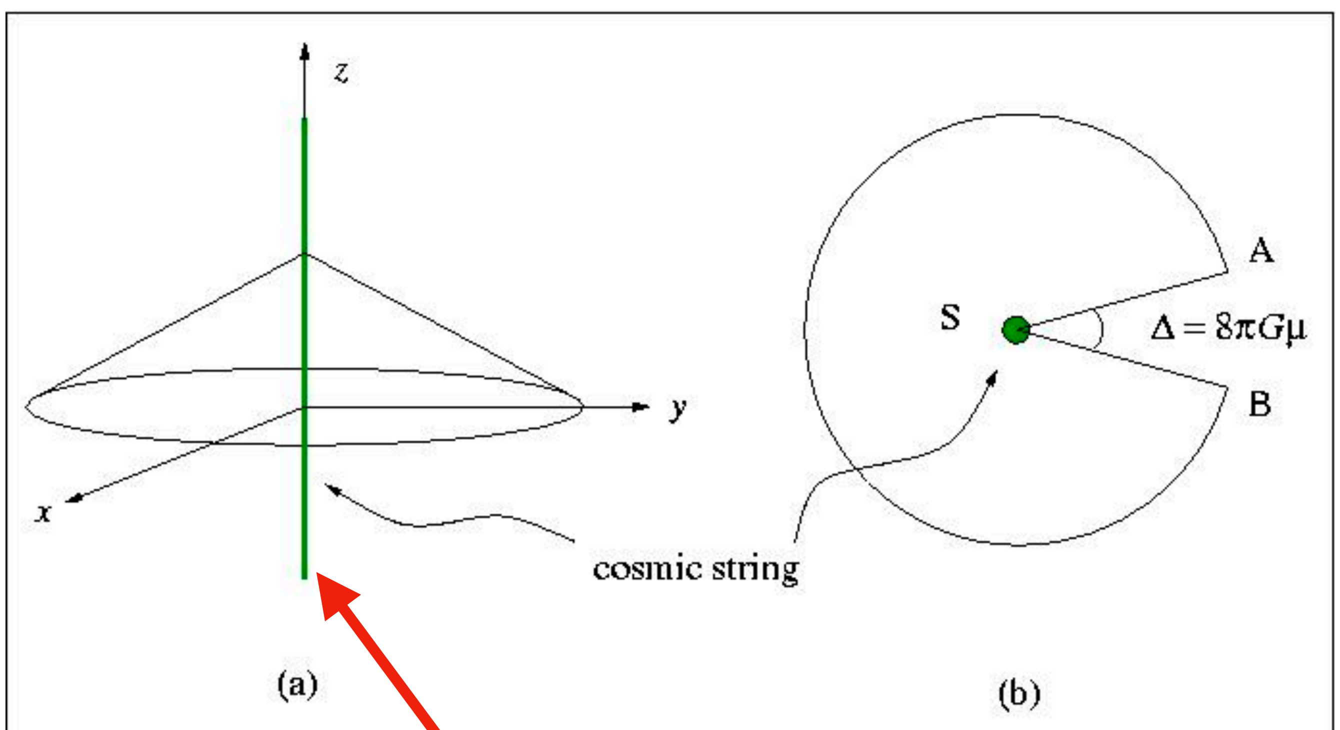
- A new way to see “cosmic strings”



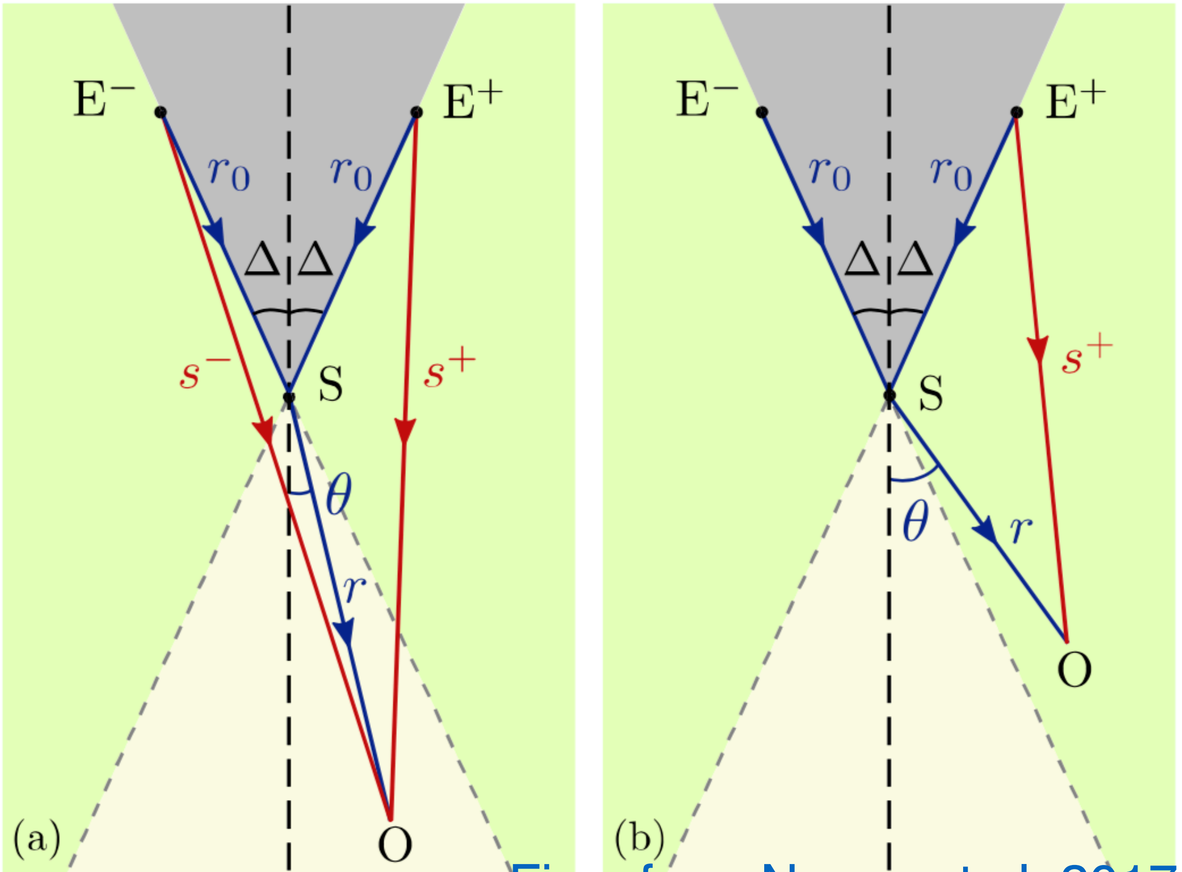
Cosmic String = 1-dim energy locus

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

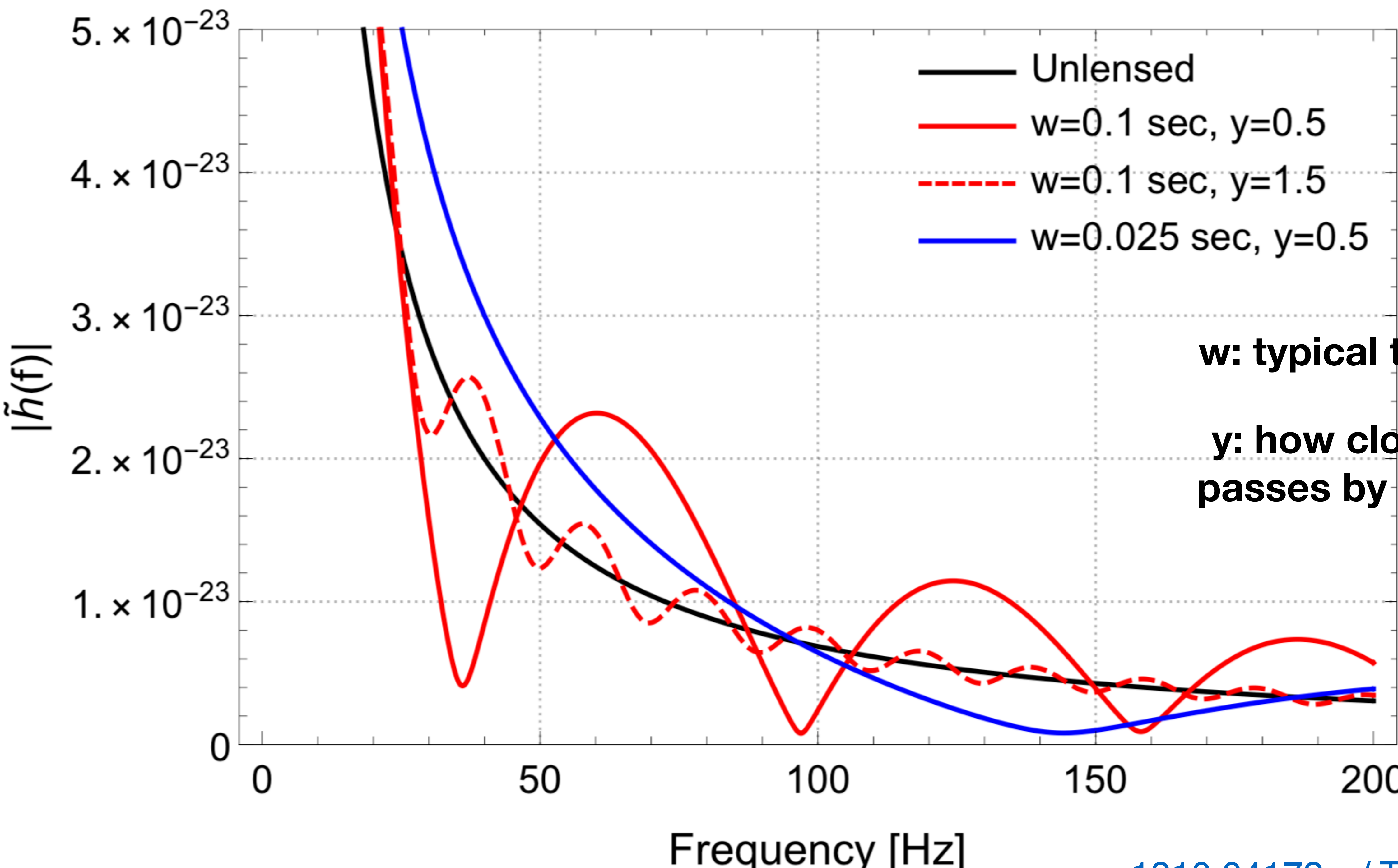


Cosmic String = 1-dim energy locus



Figs. from Nunez et al. 2017

GW Fringe from Cosmic string

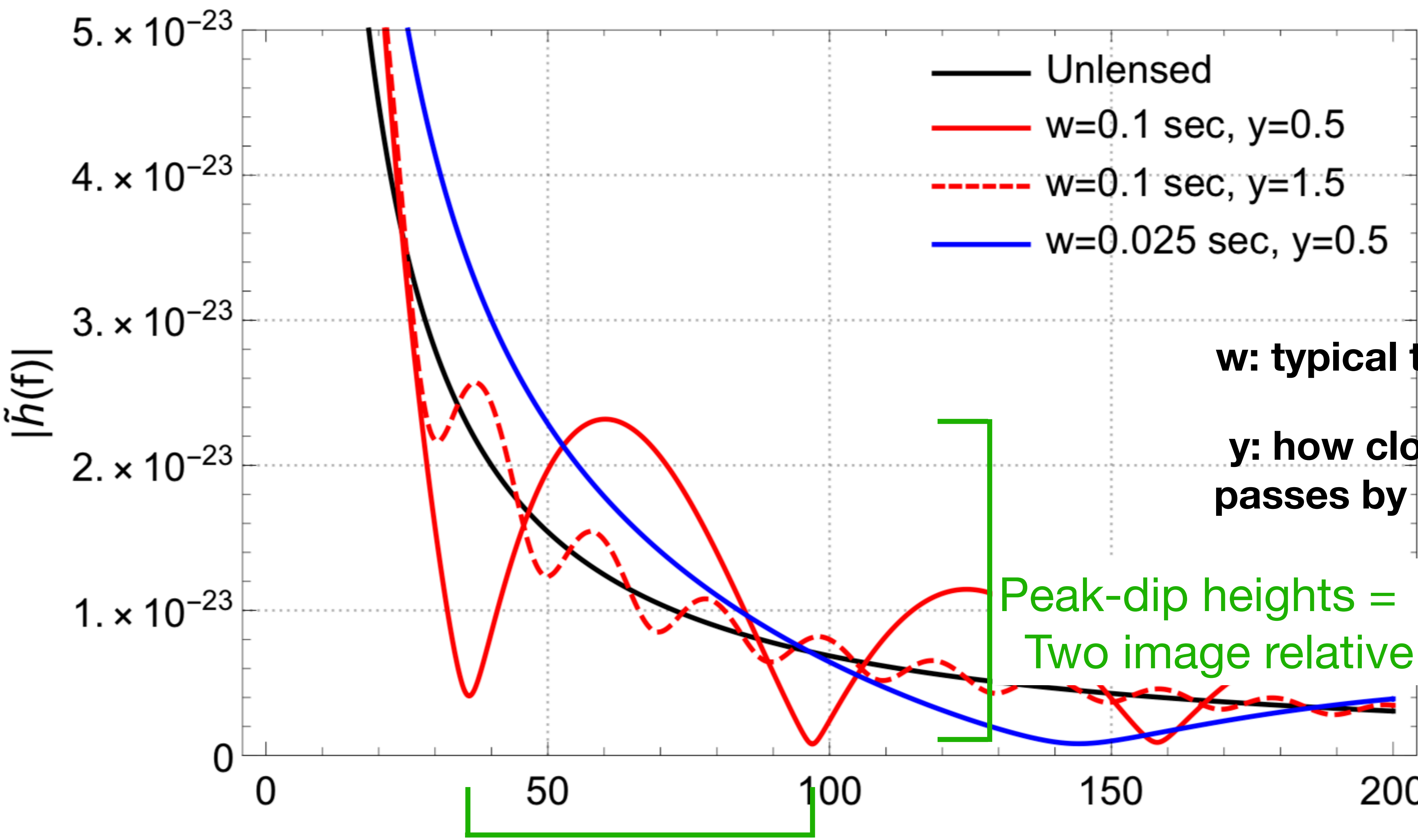


w: typical time-delay

y: how close GW passes by a string

1810.04172 w/ TaeHun Kim

GW Fringe from Cosmic string



w: typical time-delay

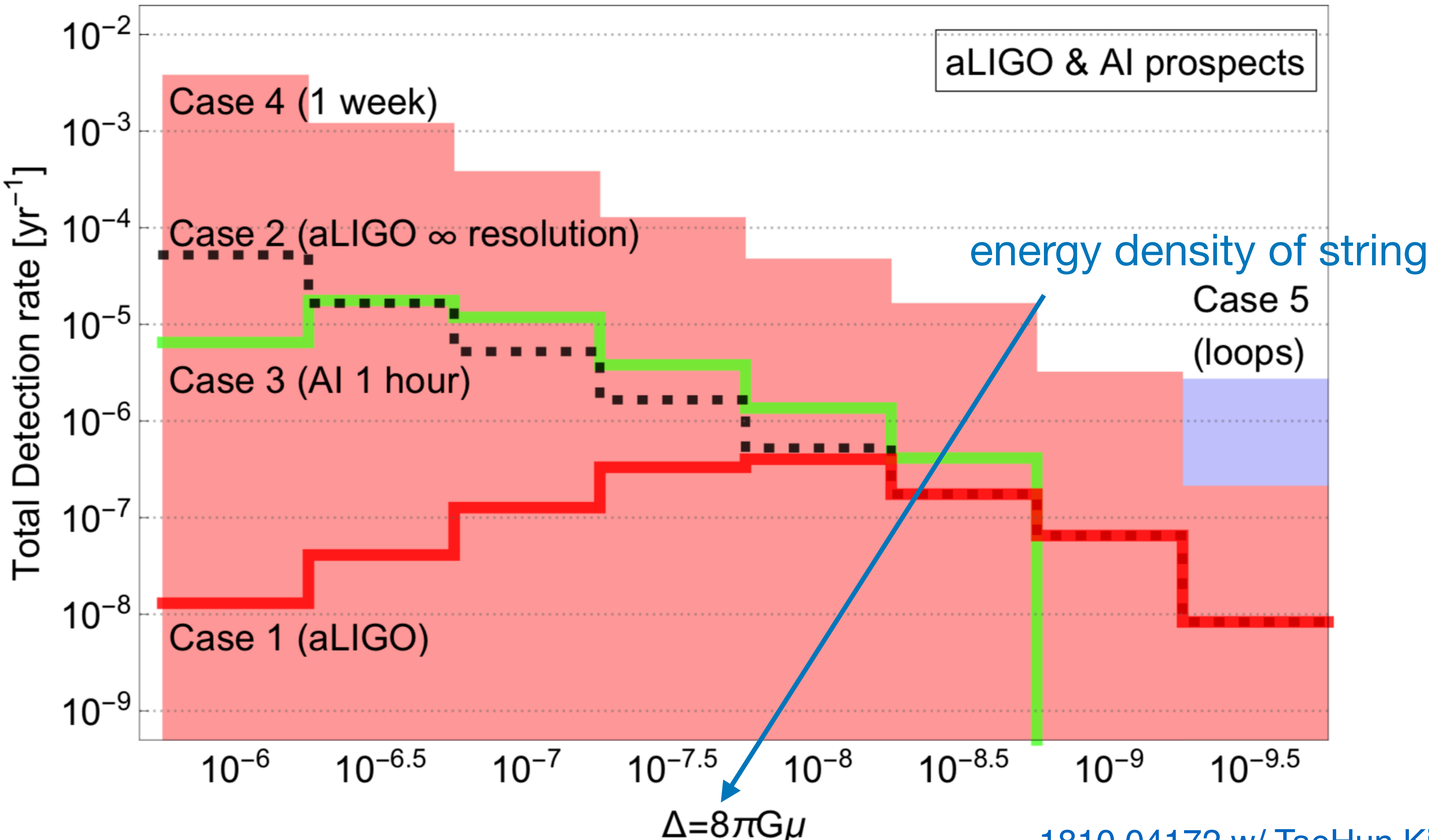
y: how close GW passes by a string

Peak-dip heights = Two image relative mag

Fringe width = time-delay = DM mass

1810.04172 w/ TaeHun Kim

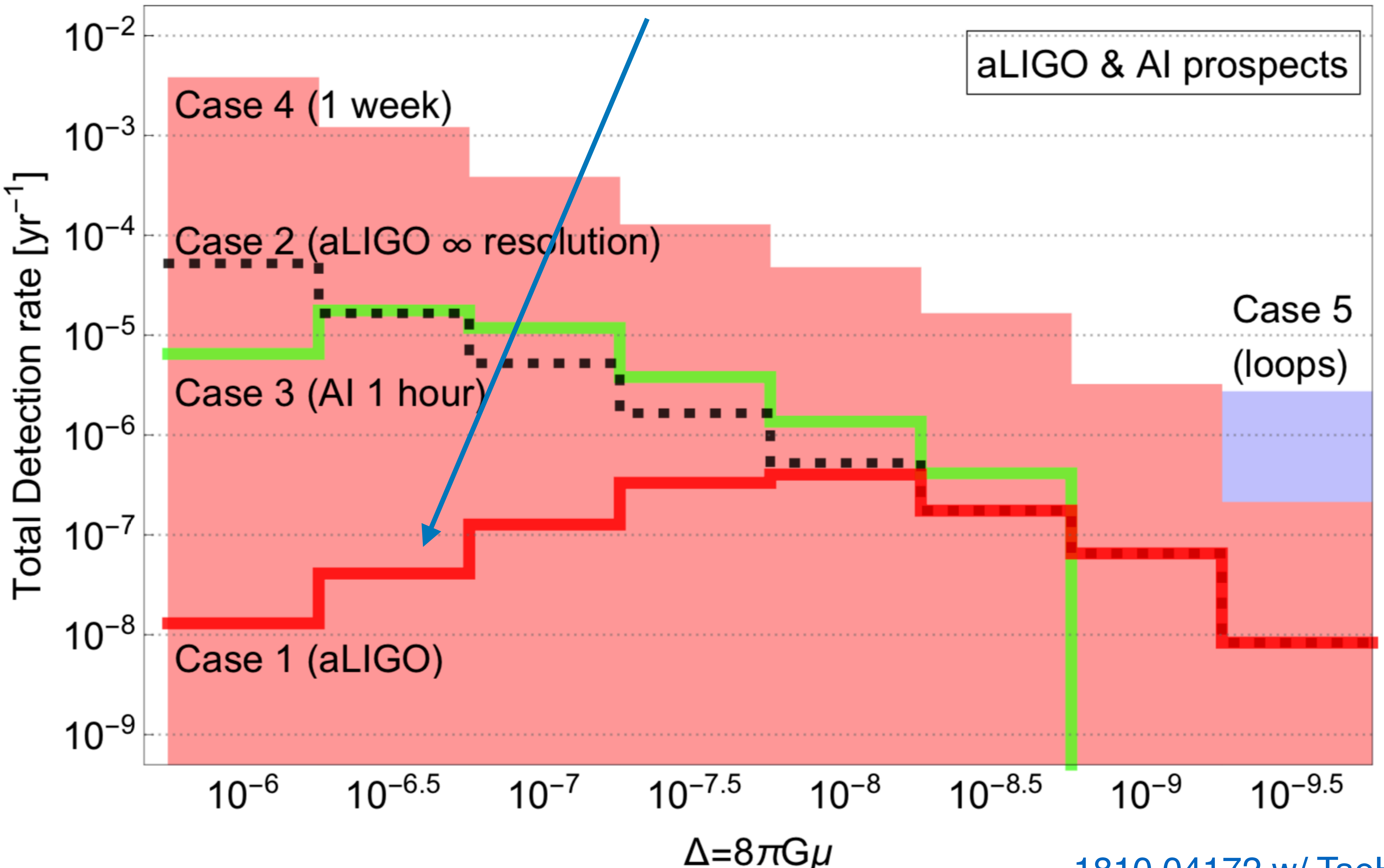
Detection prospects



1810.04172 w/ TaeHun Kim

Detection prospects

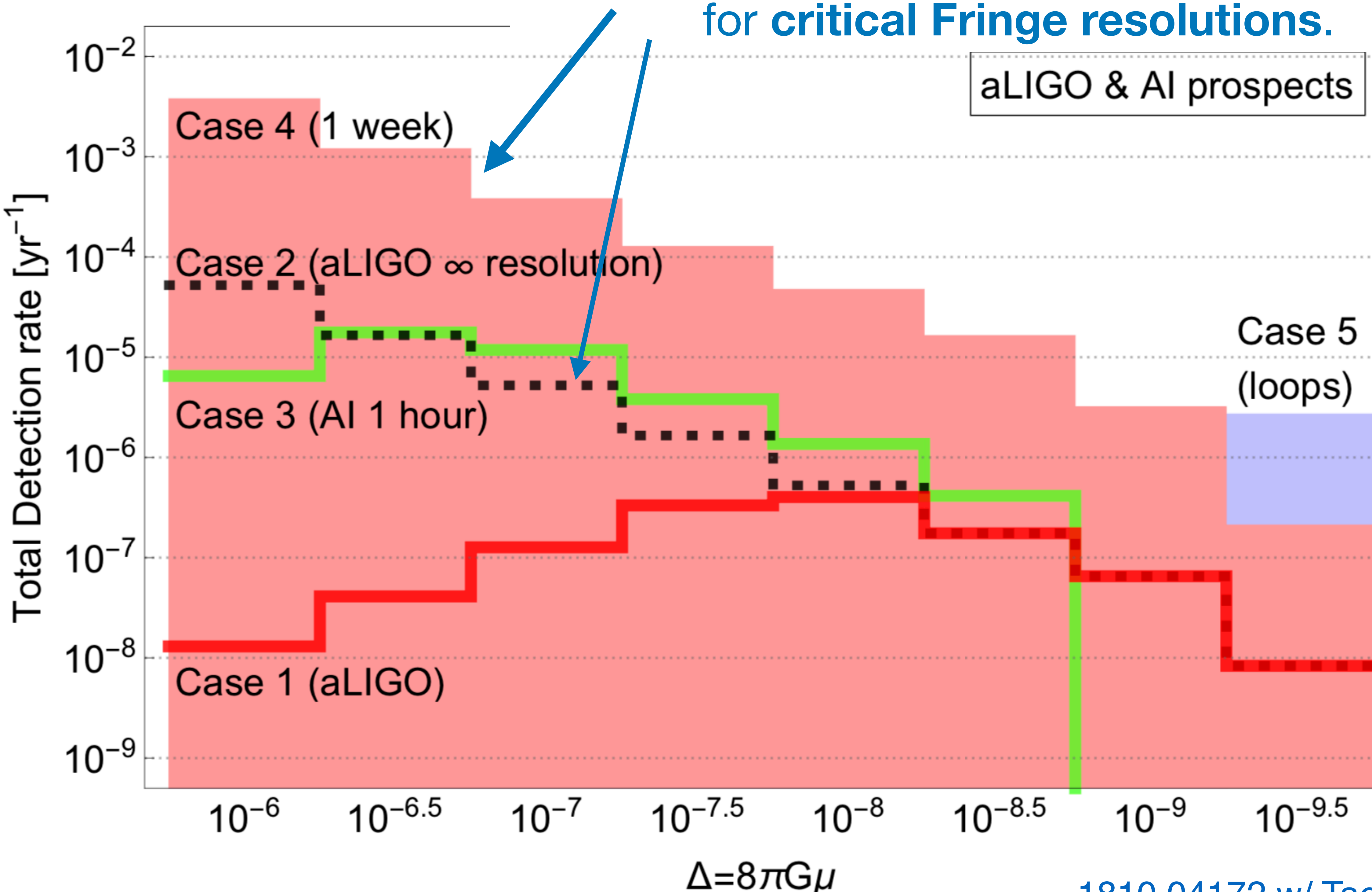
Why is heavier string harder to probe at LIGO?



1810.04172 w/ TaeHun Kim

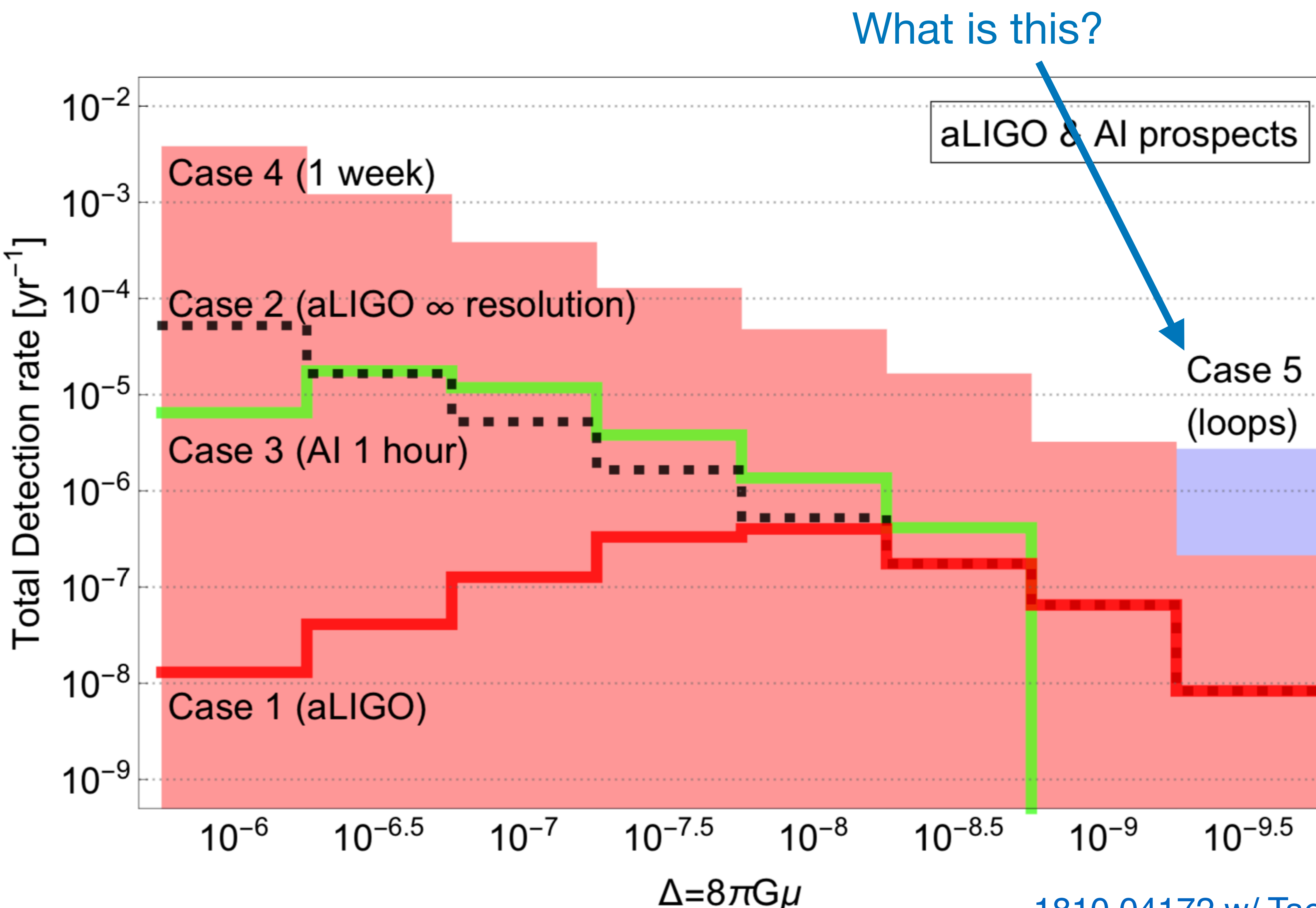
Detection prospects

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



1810.04172 w/ TaeHun Kim

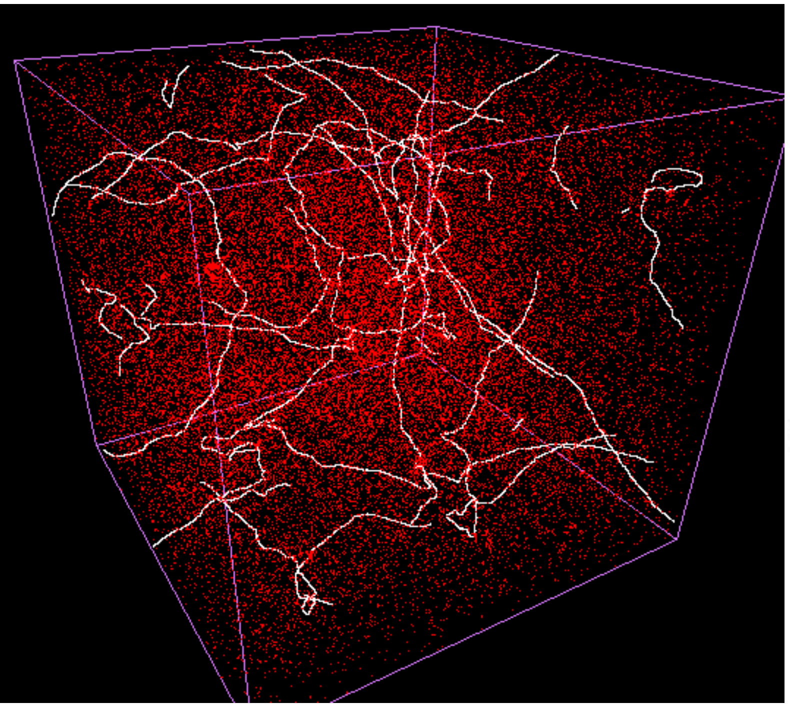
Detection prospects

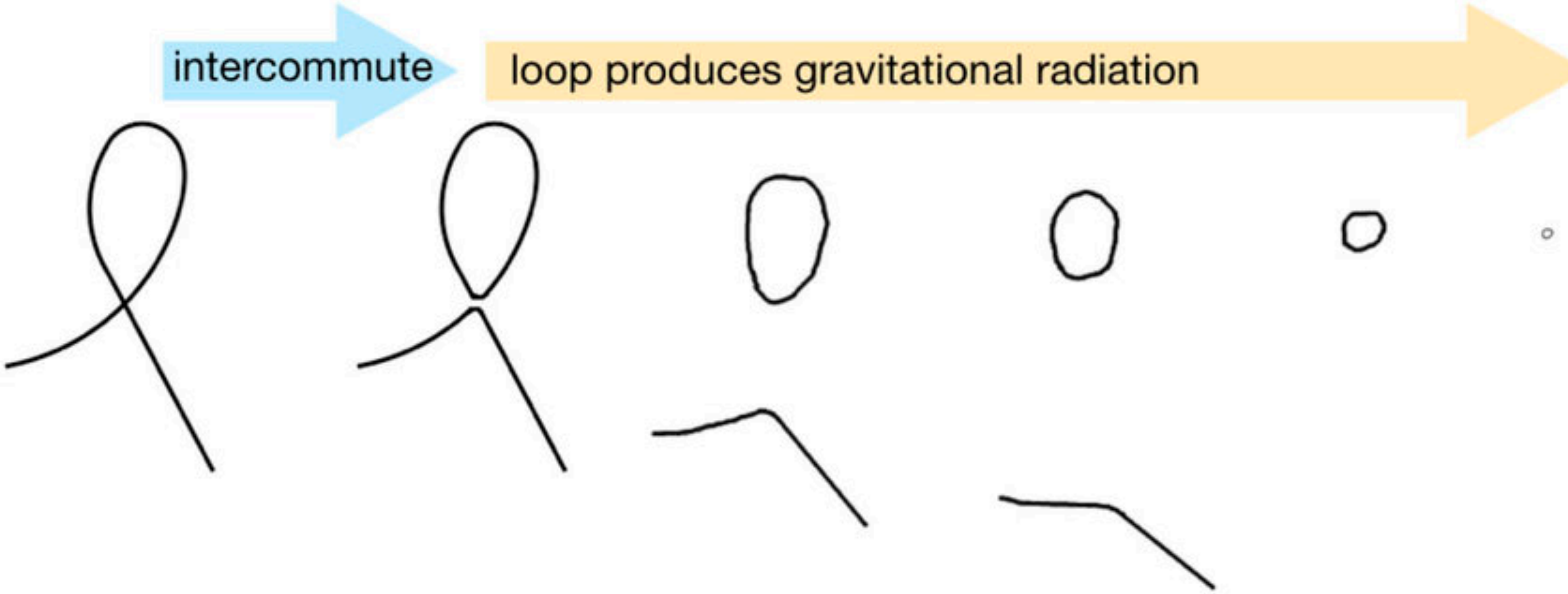


1810.04172 w/ TaeHun Kim

Model-independent searches

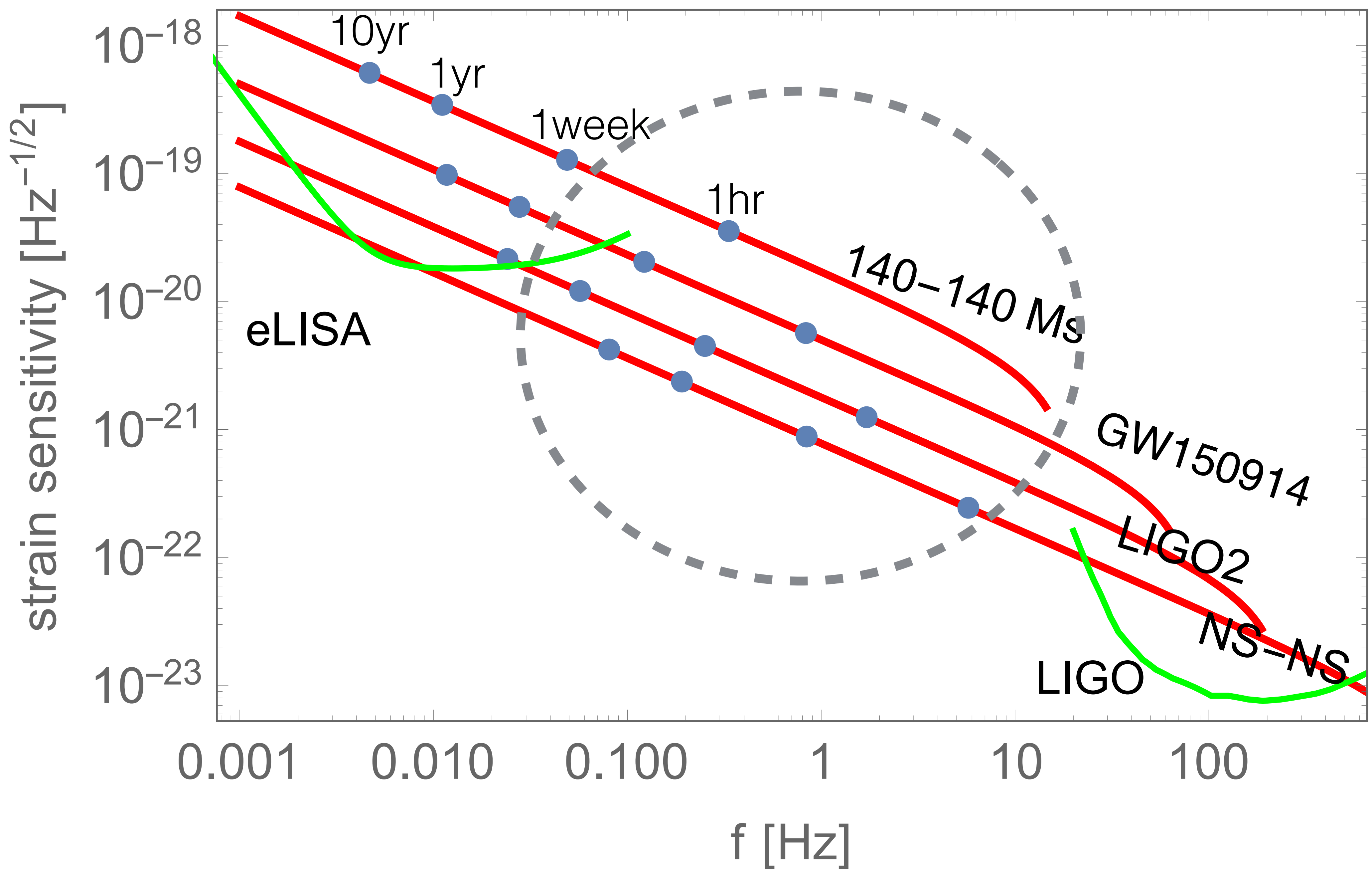
- Typical searches of “Stochastic GW” is from loop decays.
- This exists only in gauged U(1) model, not in local U(1).
- GW fringe probes “straight” strings, *model independently*.





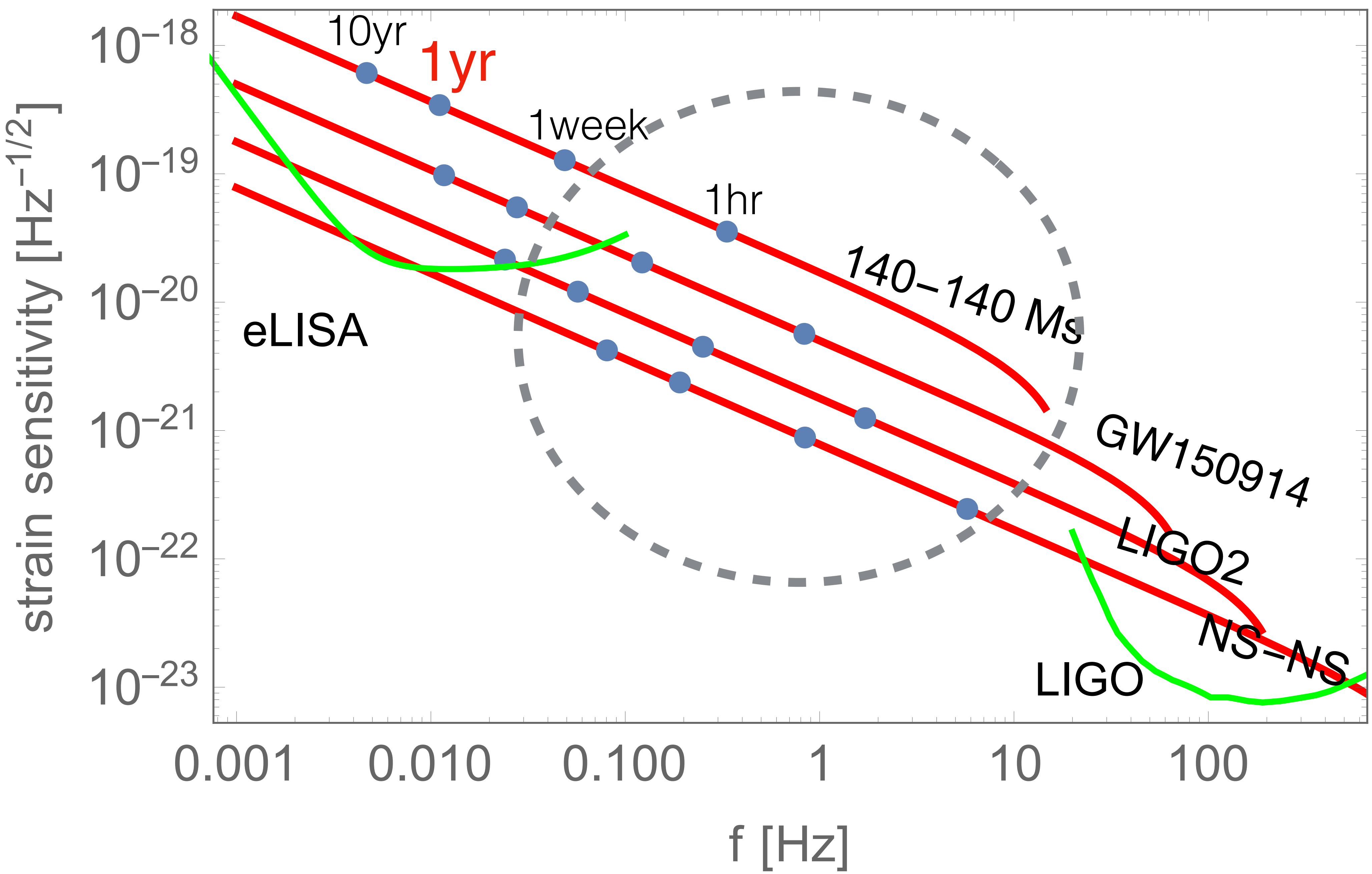
Mid-frequency band

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:

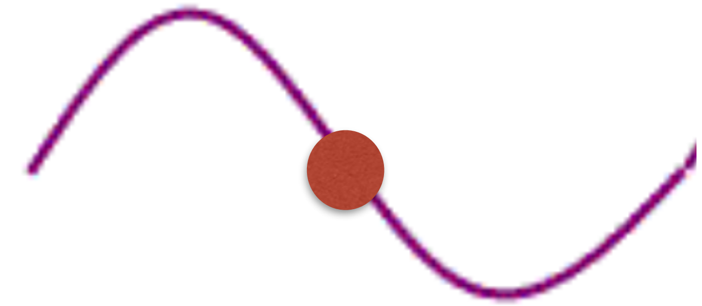
- 1. Various **Dark matter effects** are most pronounced here!

[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^-23 eV. (cf. m(electron)=0.5 MeV)
- Although light, their effects can be astronomically enhanced and time-oscillating.
- GW is again an exciting lab to probe them.

DM wave

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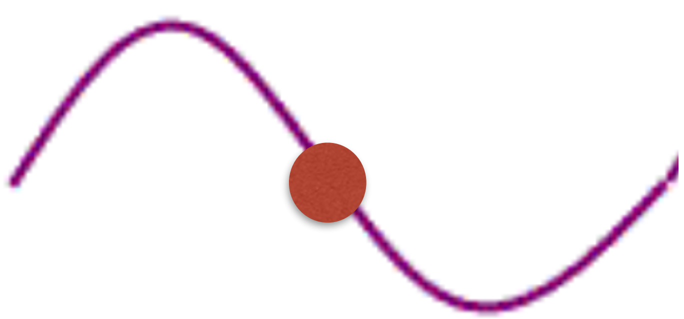

$$\phi(t) \propto \cos m_\phi t$$

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

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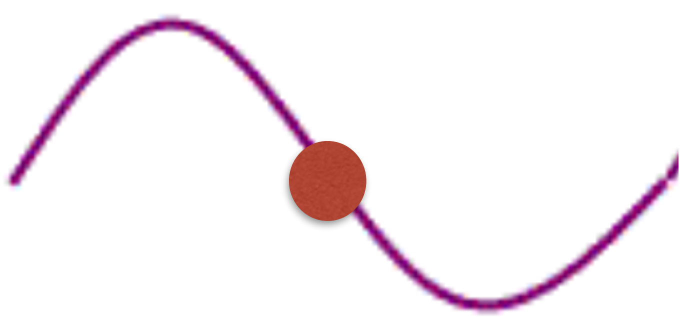
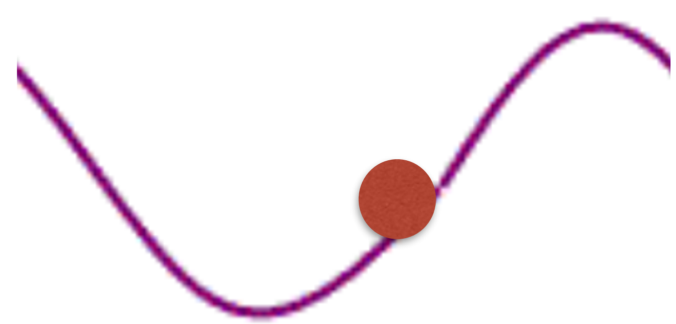


+

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



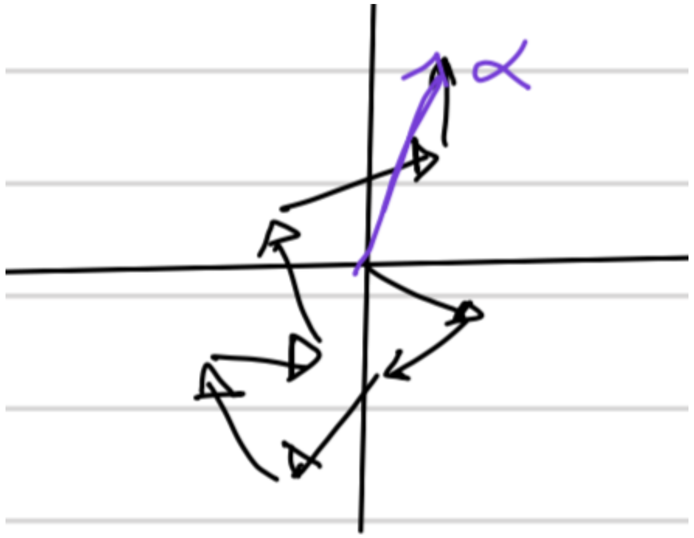
Second DM quanta with “same Compton frequency” but with “different phase” is added.

DM wave

- Lightest possible spin-0 DM 10^-23 eV. (cf. m(electron)=0.5 MeV)
- Although light, their effects are astronomically enhanced and time-oscillating.

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

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



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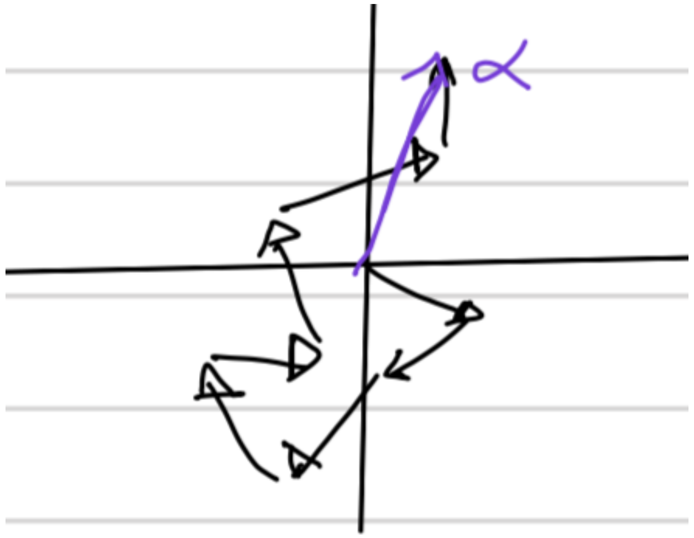
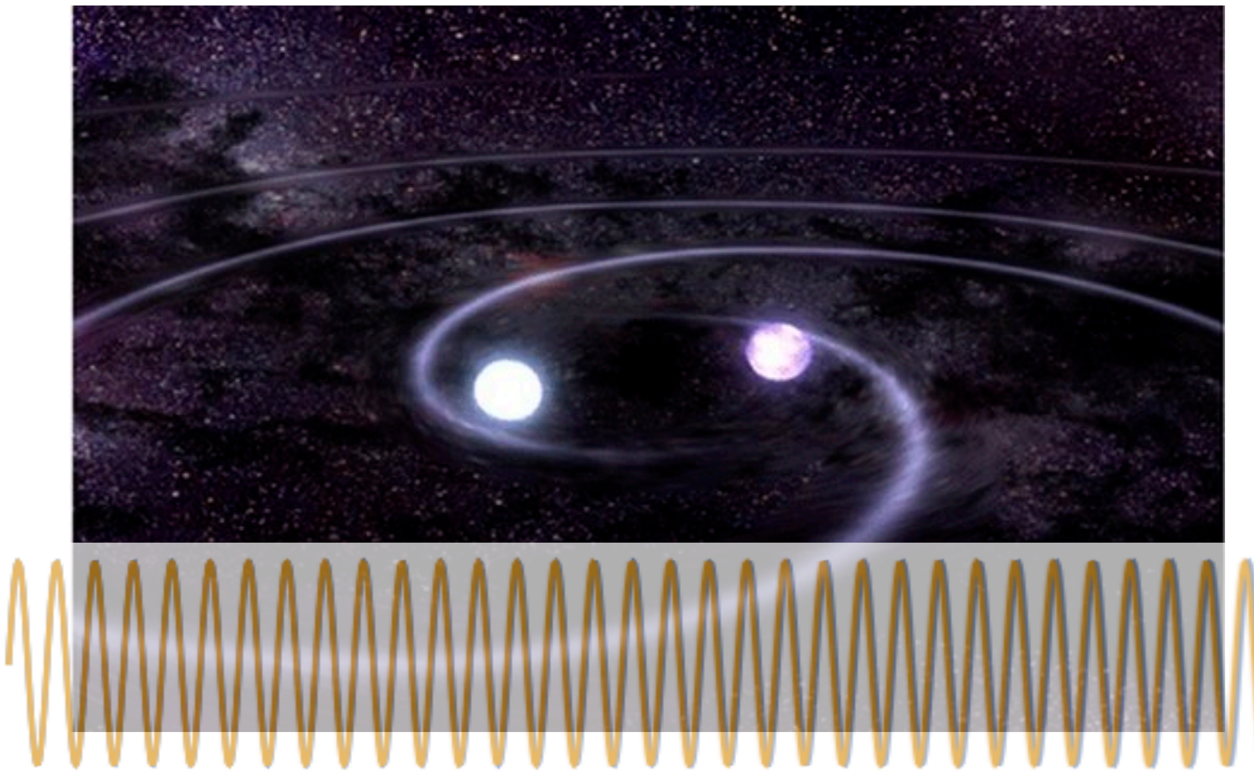


DM wave (density) is **collectively enhanced** to astronomical size and **oscillating in time**!

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

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

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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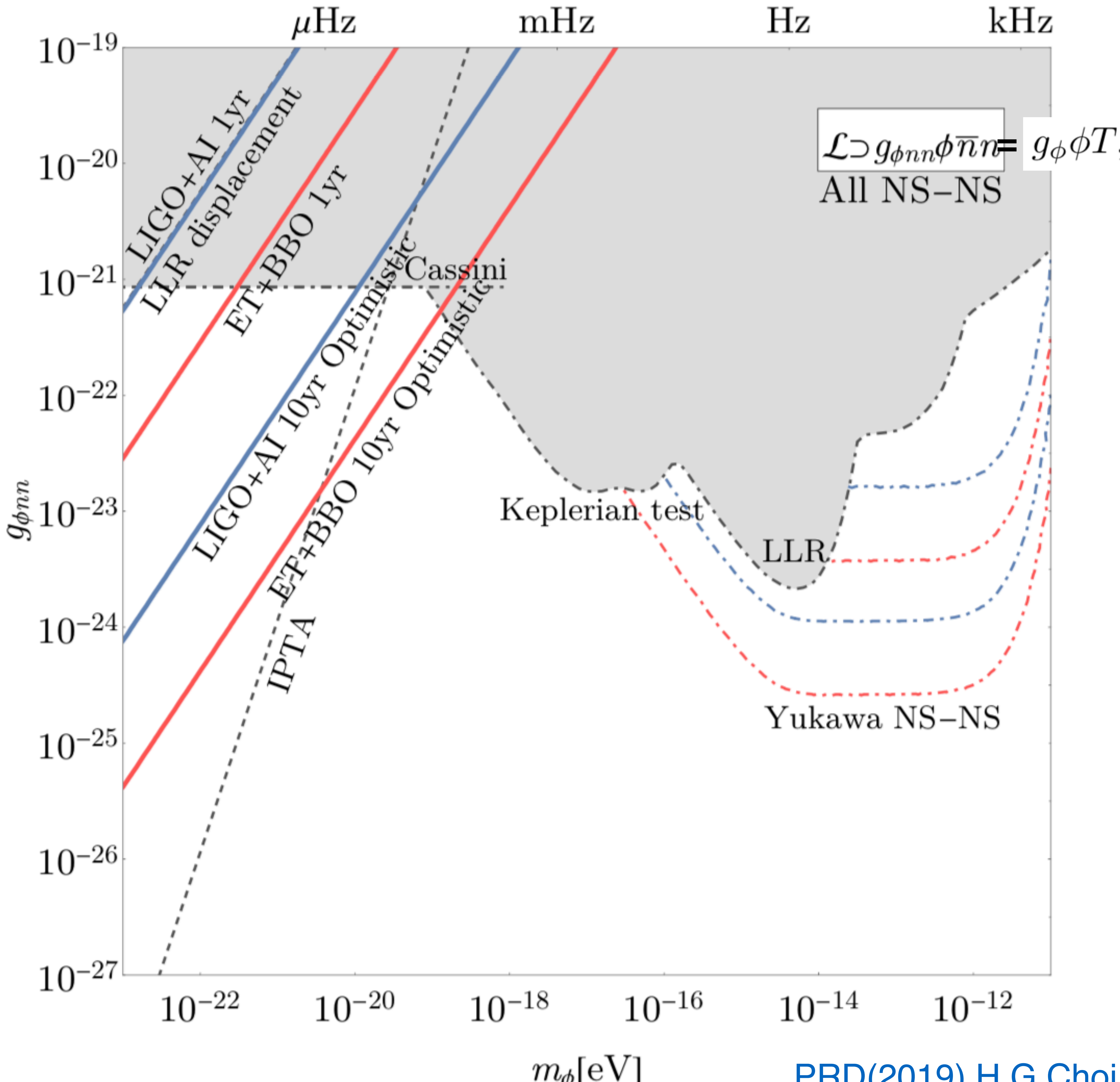
Ncyc ~ 10^7 huge enhancement

- 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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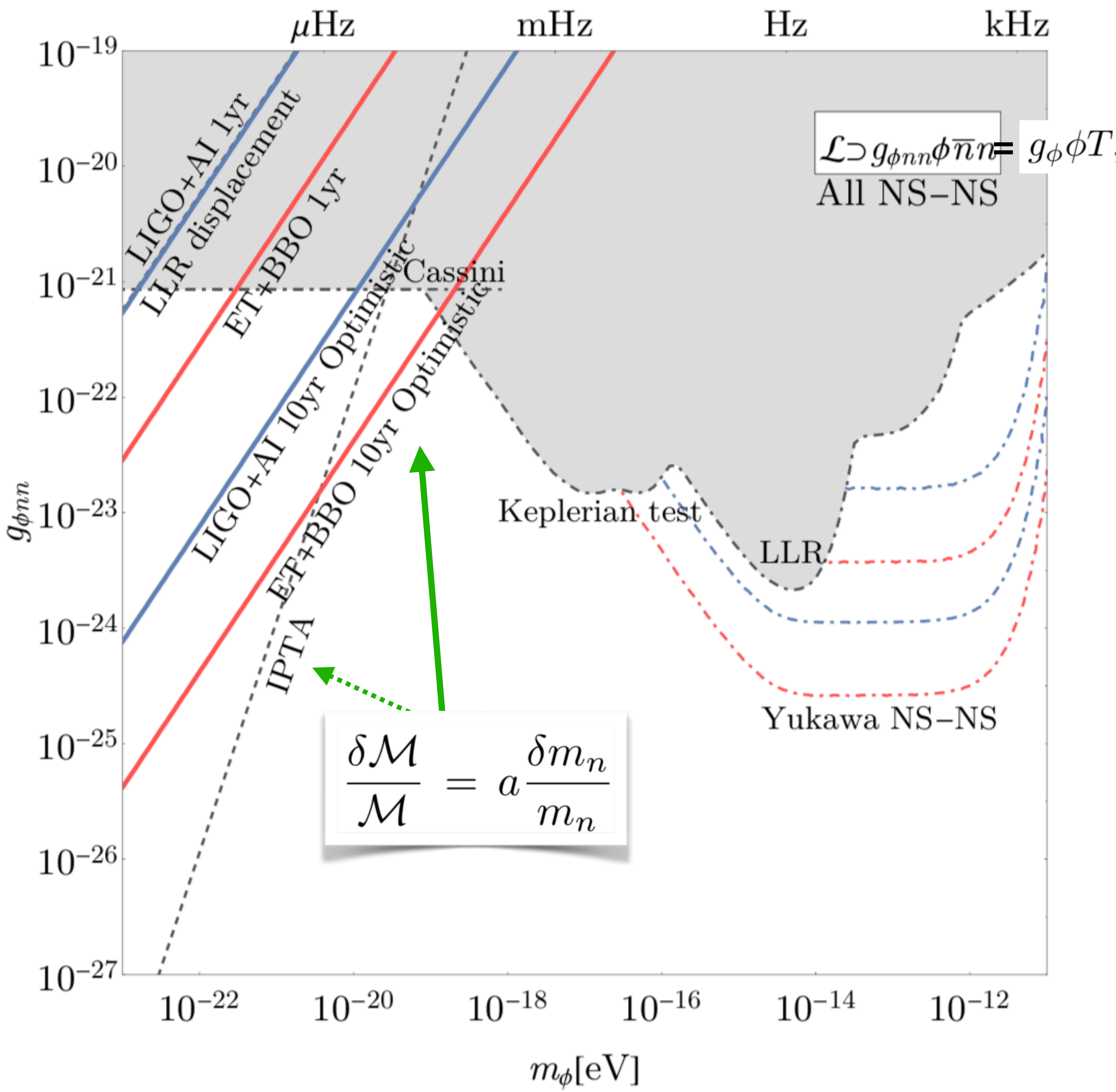
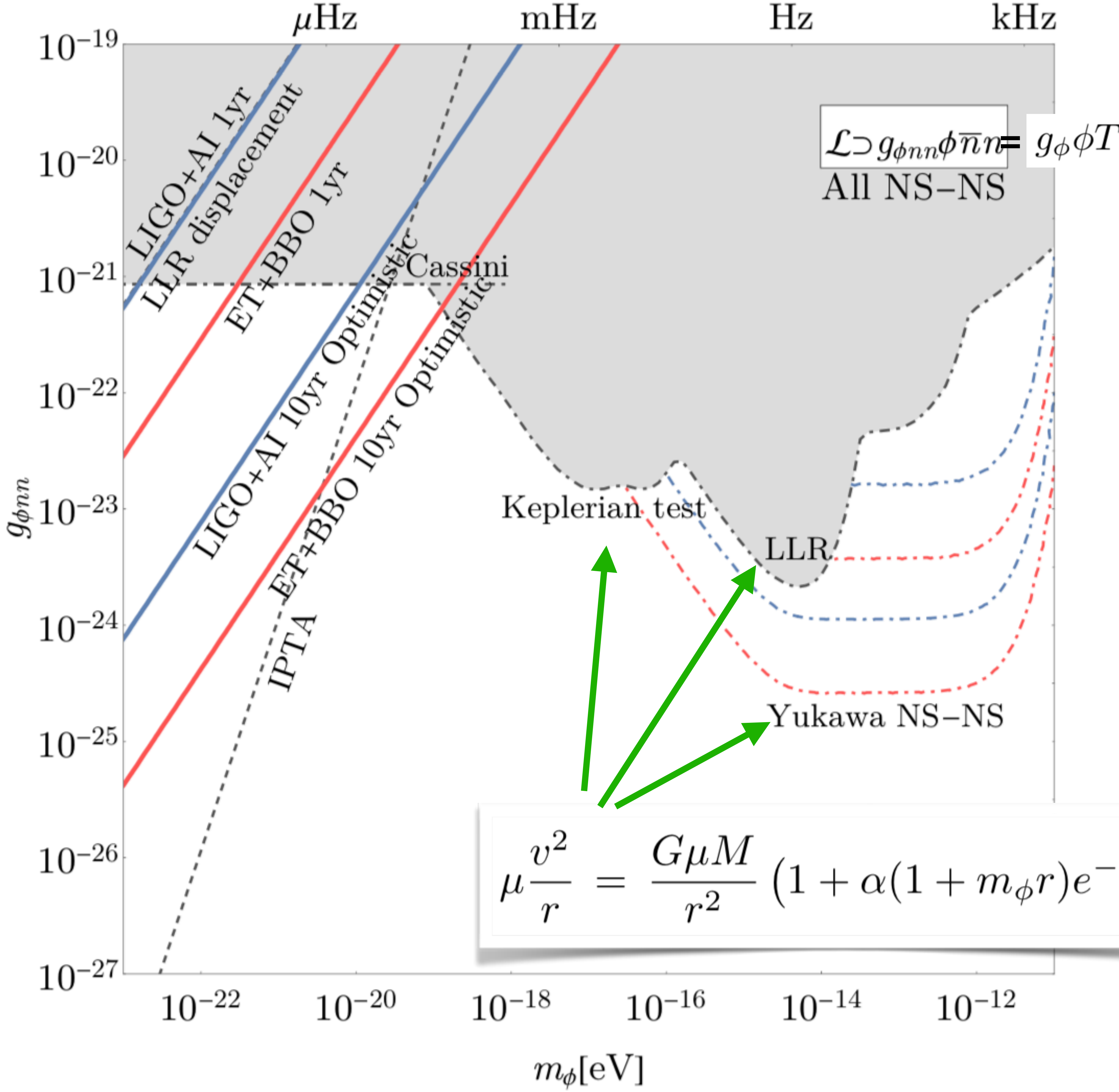
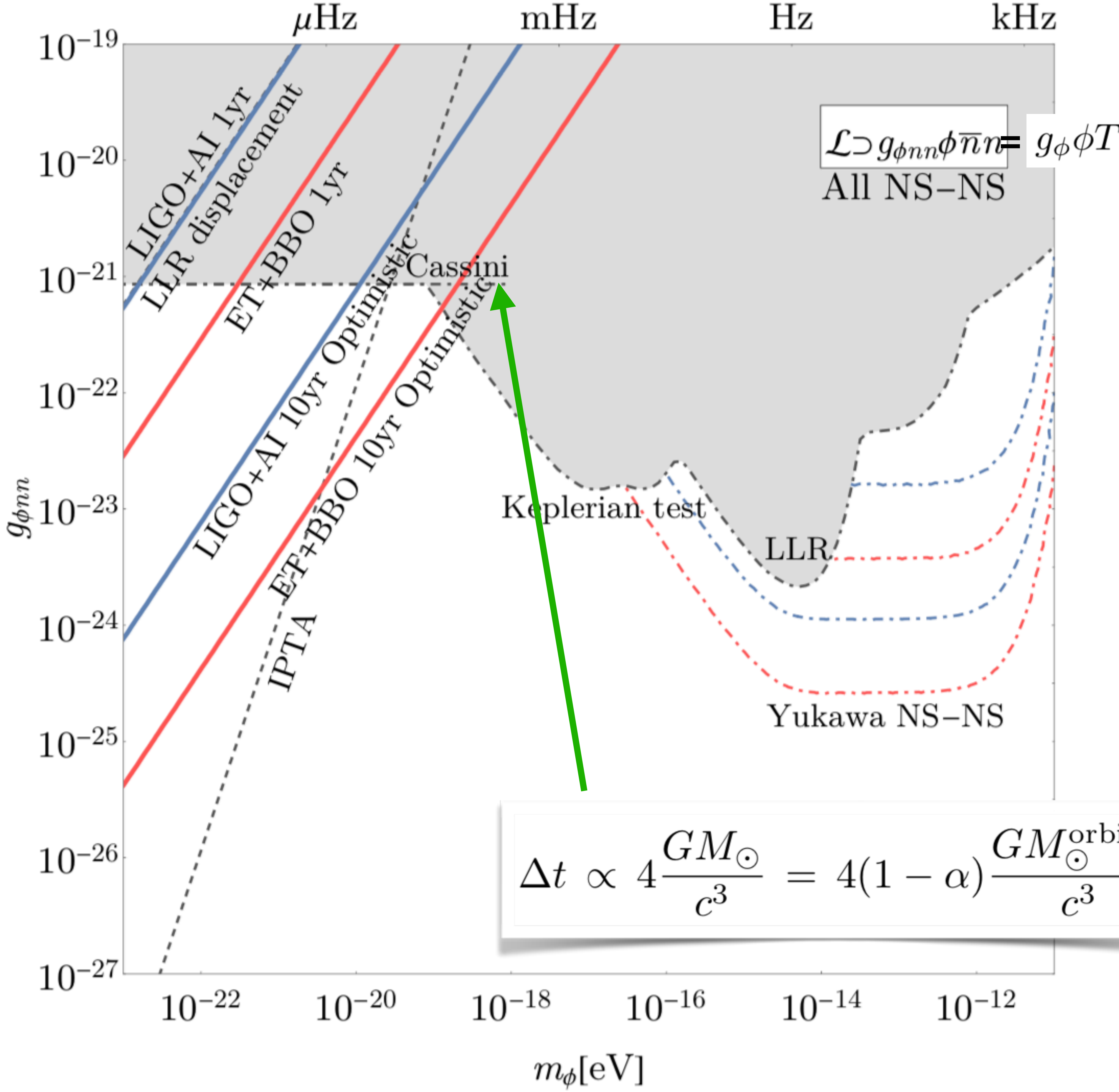


Detection prospects



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

Detection prospects



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

Summary

- GW is a powerful new eye to DM and early Universe.

- New ways to see PBH DM:
  "GW Fringe" (and "GRB Lensing Parallax")

- "LIGO + mid-band" provides synergies
  for probing cosmic strings and axion-like DM waves.

Dark Odyssey 2020

GW Probes of Dark Universe

- Interdisciplinary workshop on GW, DM, particle, astro, cosmology.

- January 4-6 (Sat-Mon), 2020 @ Seoul National University
  (1st Bosan Workshop at Center for Theoretical Physics)

  Registration and homepage will open soon.

- Organizers: Sunghoon Jung, Seung J. Lee, Yue Zhao, Chunglee Kim, Chan Park