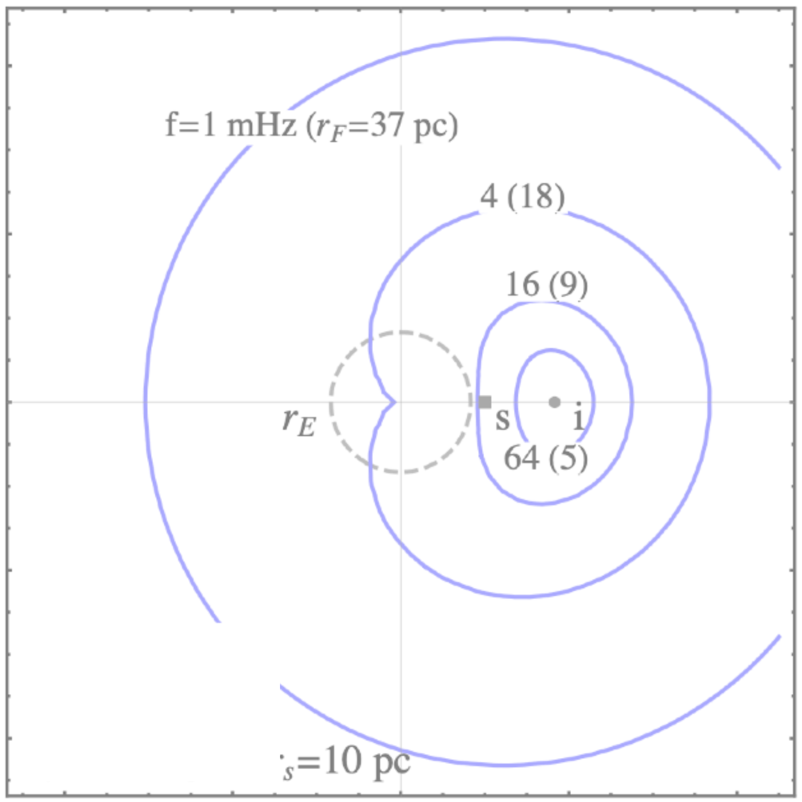
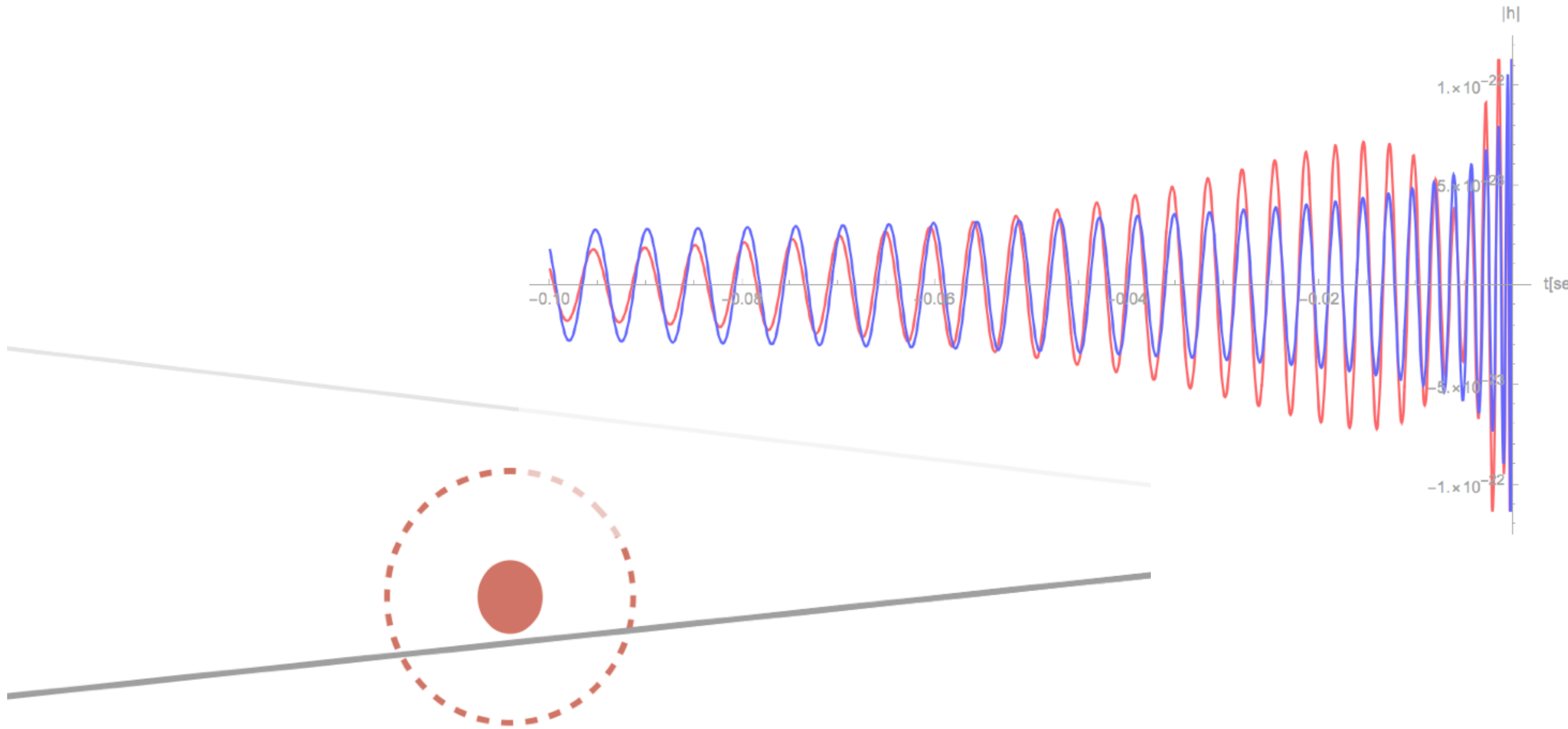
GW probes of dark matter





Sunghoon Jung

Seoul National University

Works with HanGil Choi, TaeHun Kim, Chanung Park, P.W.Graham, C.S.Shin, J.Soda, Y.Urakawa

Light Dark World 2021, Dec 15

Topics

1. **PBH DM**
   - Fringe: solar-mass PBH (& cosmic string)
   - Parallax: smallest PBH sDM

2. **NFW subhalo**
   - Small-scale shear

Gravitational lensing

3. Wave DM
   - Binary environmental effect

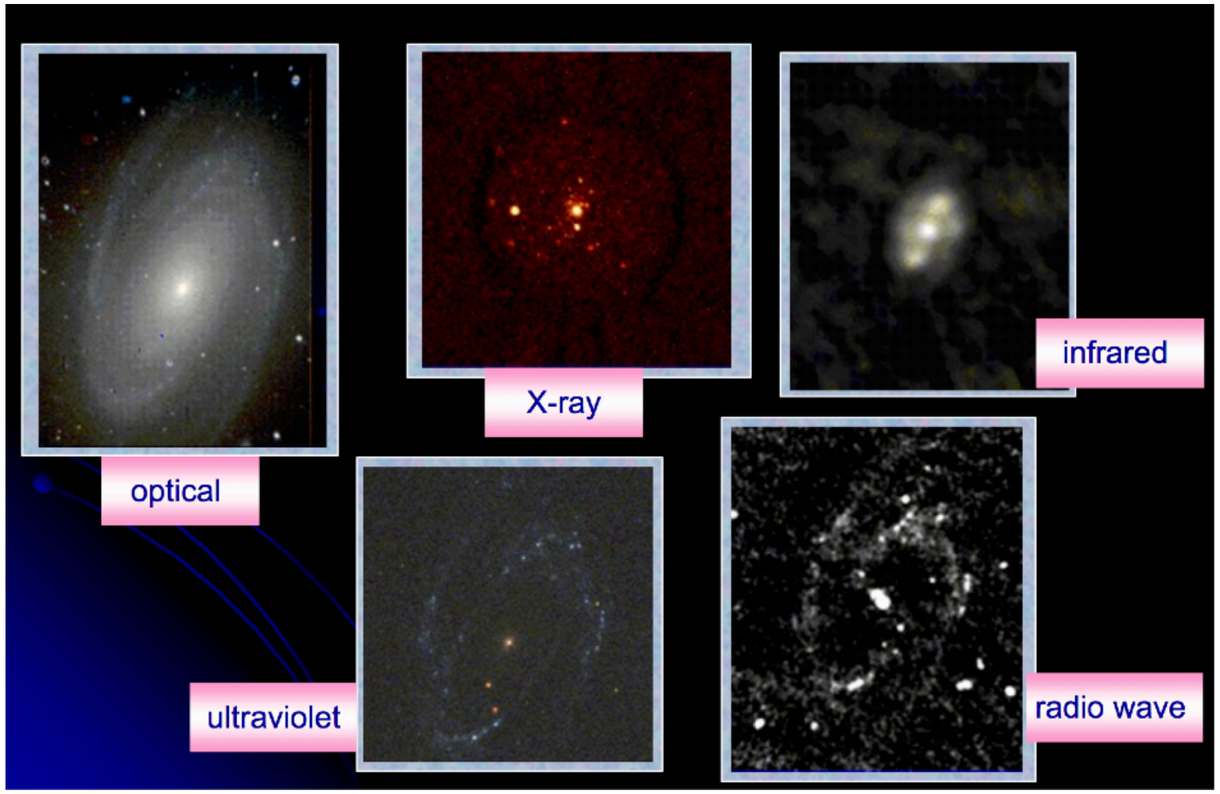
4. Axion DM with gravitational Chern-Simons
   - Parametric resonance

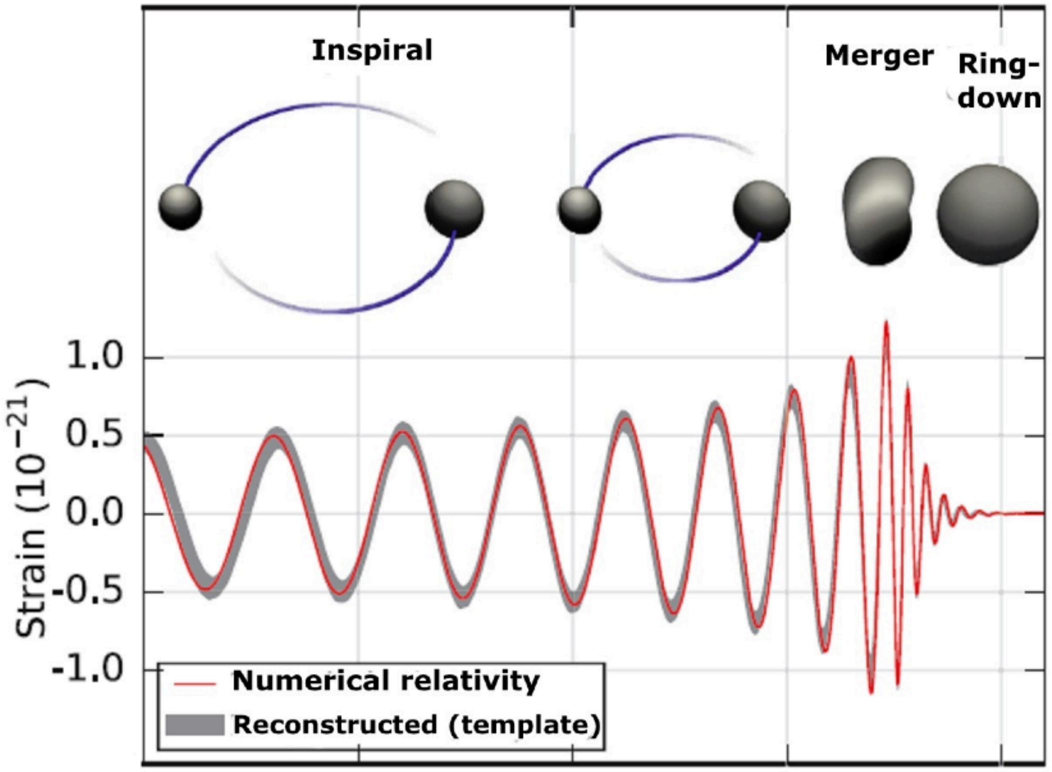
5. Fermi-ball DM
   - 1st-order phase transition

- GW era!
  - Let's explore, understand, and realize its physics potentials.

- What "Dark Matter" physics can we see and learn?

- In this talk, "GW chirping" is a key property.





1. Strong lensing : Fringe and Parallax

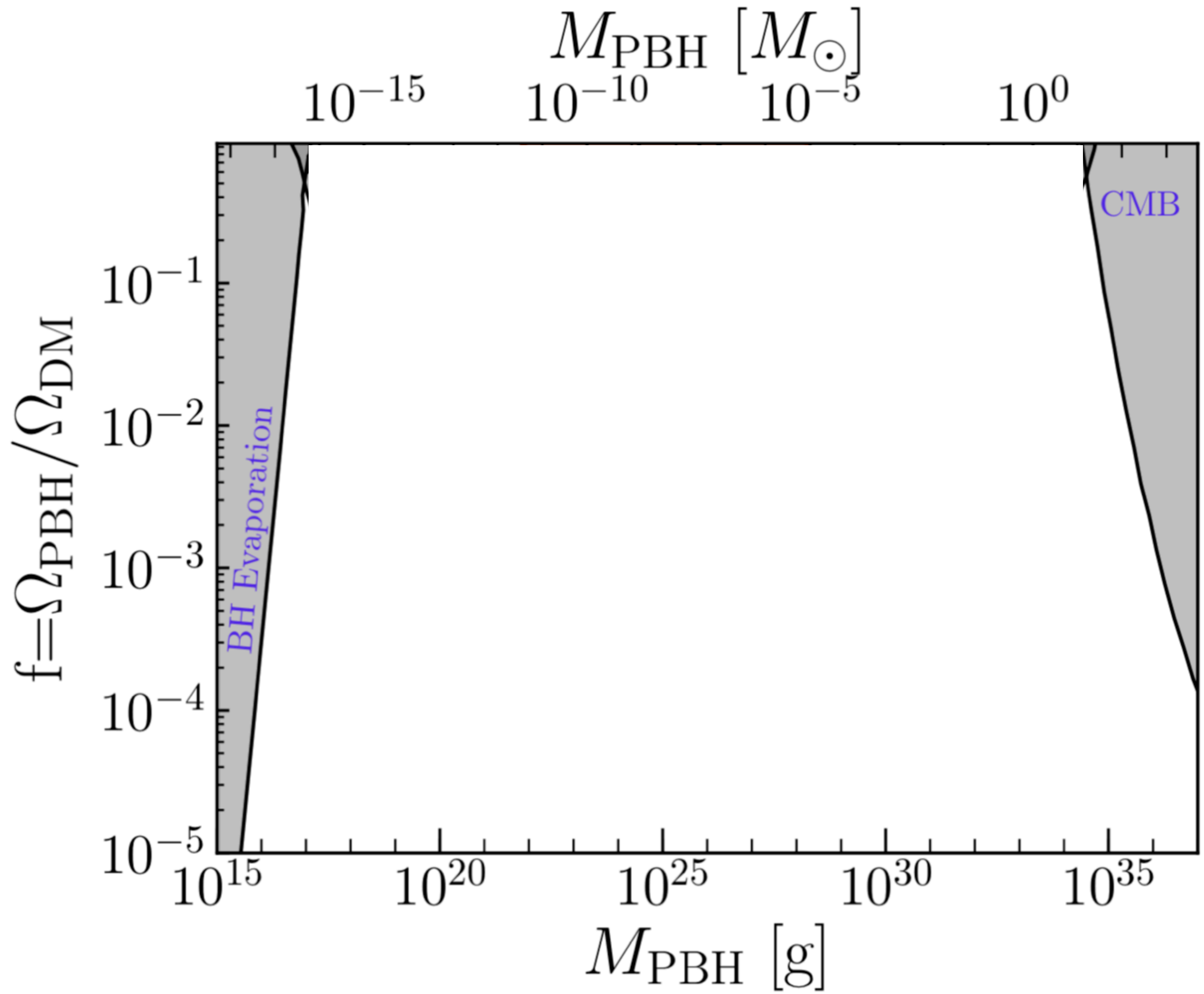
— Primordial Black Hole DM

SJ, C.S.Shin, 1712.01396 PRL(2019)

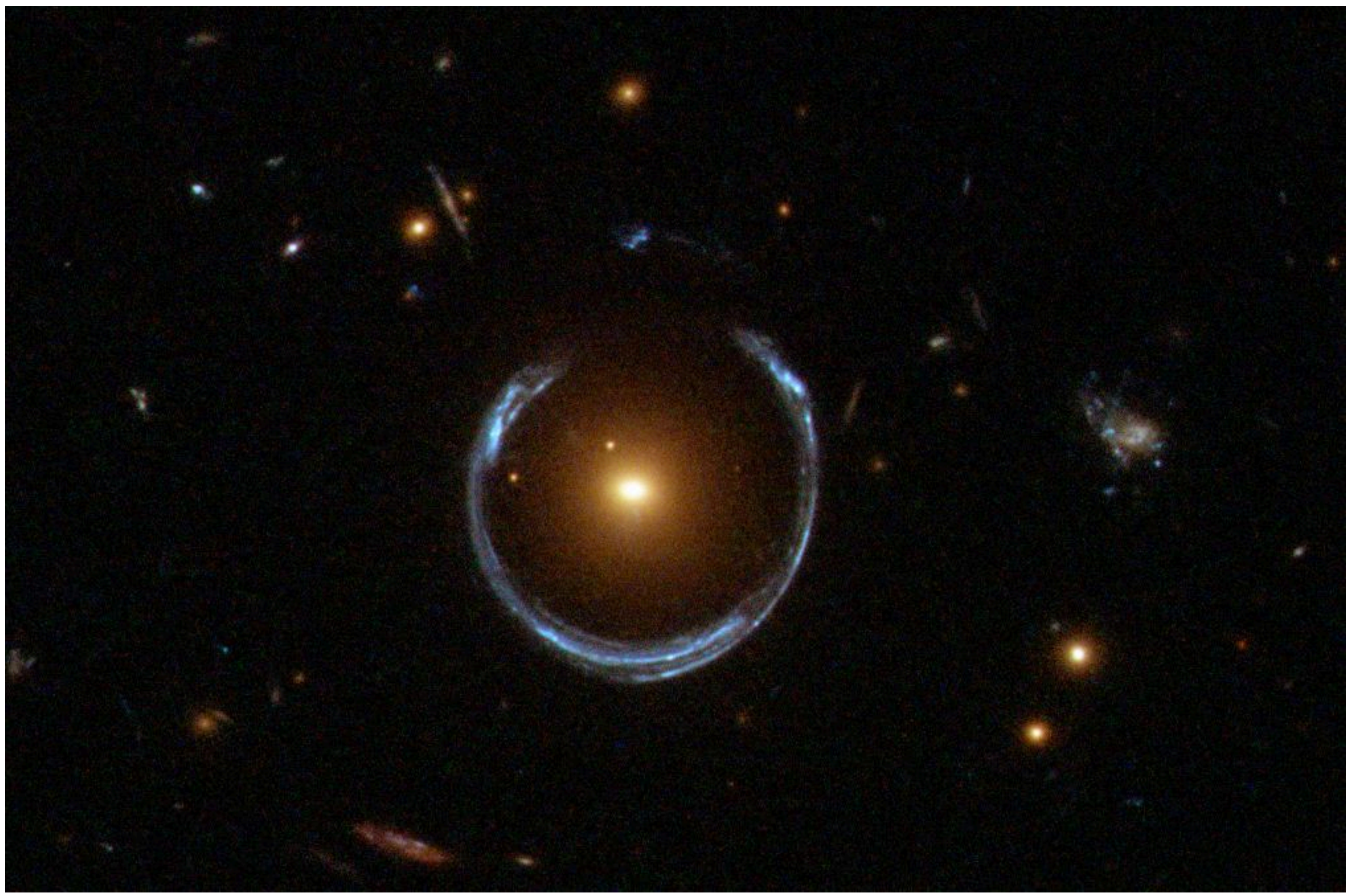
also several others…

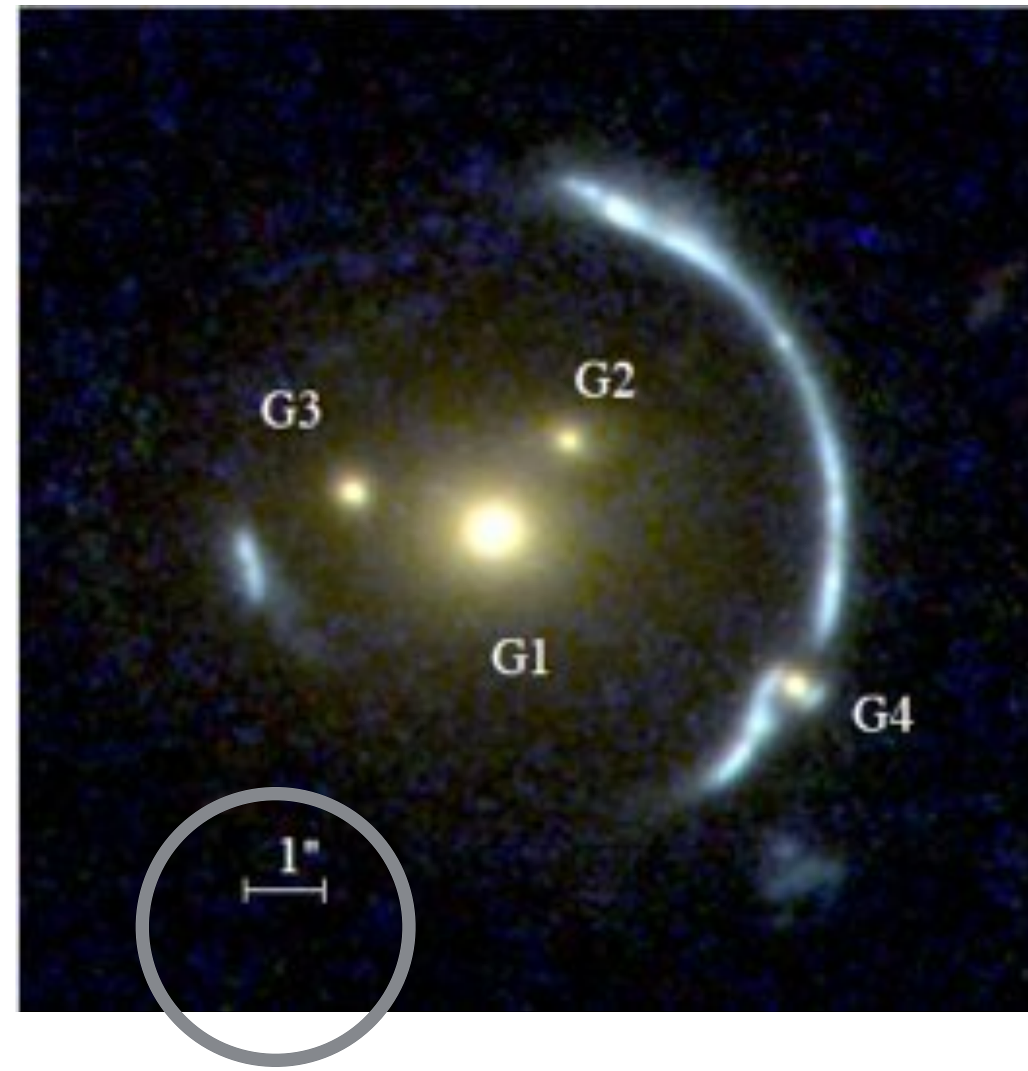
PBH DM

A wide mass range is possible btwn two general constraints.



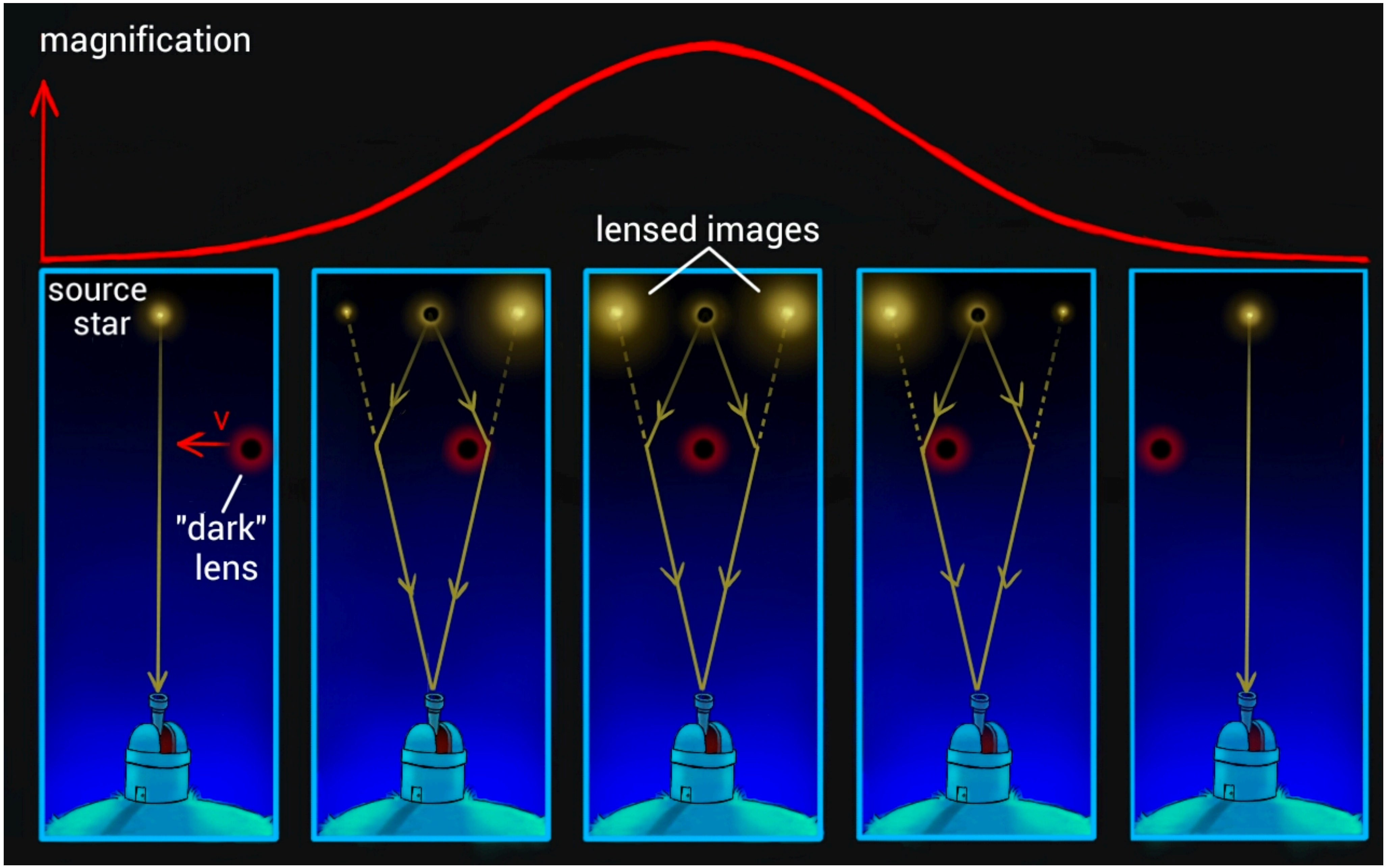
Strong lensing of light





- 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

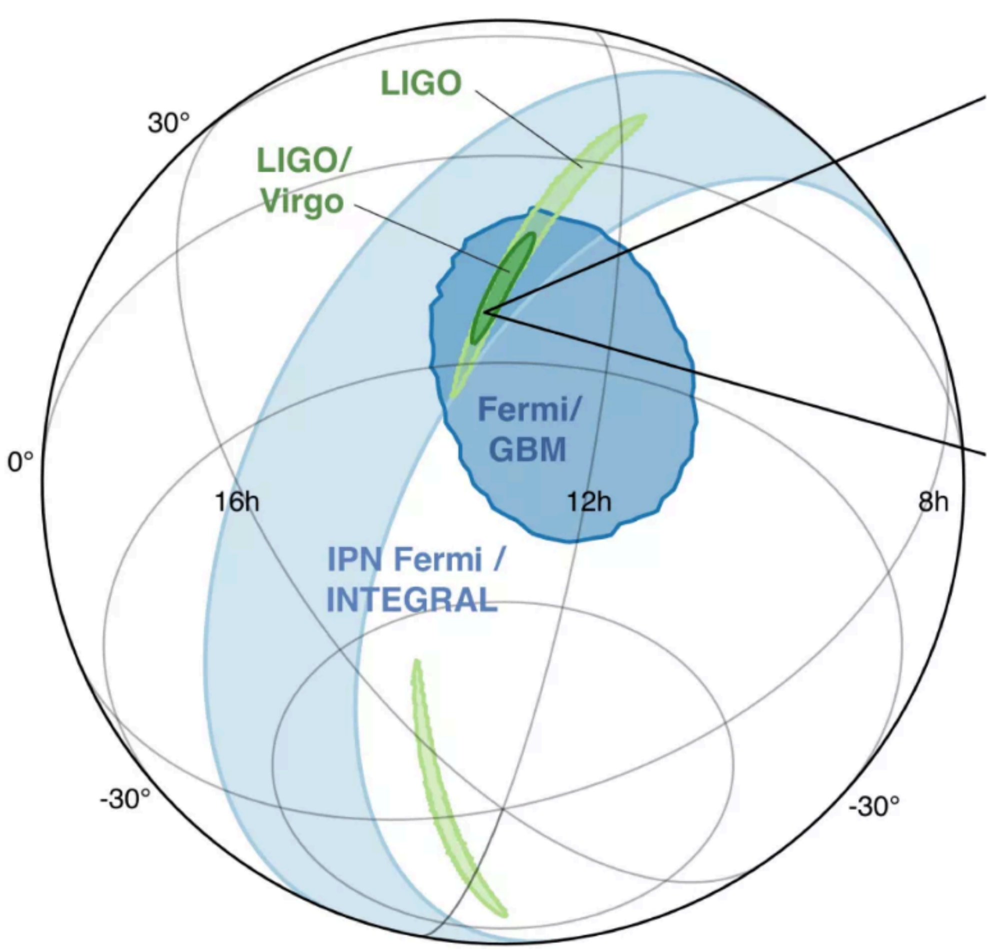
- Statistical analysis of multiply and weakly lensed lights.

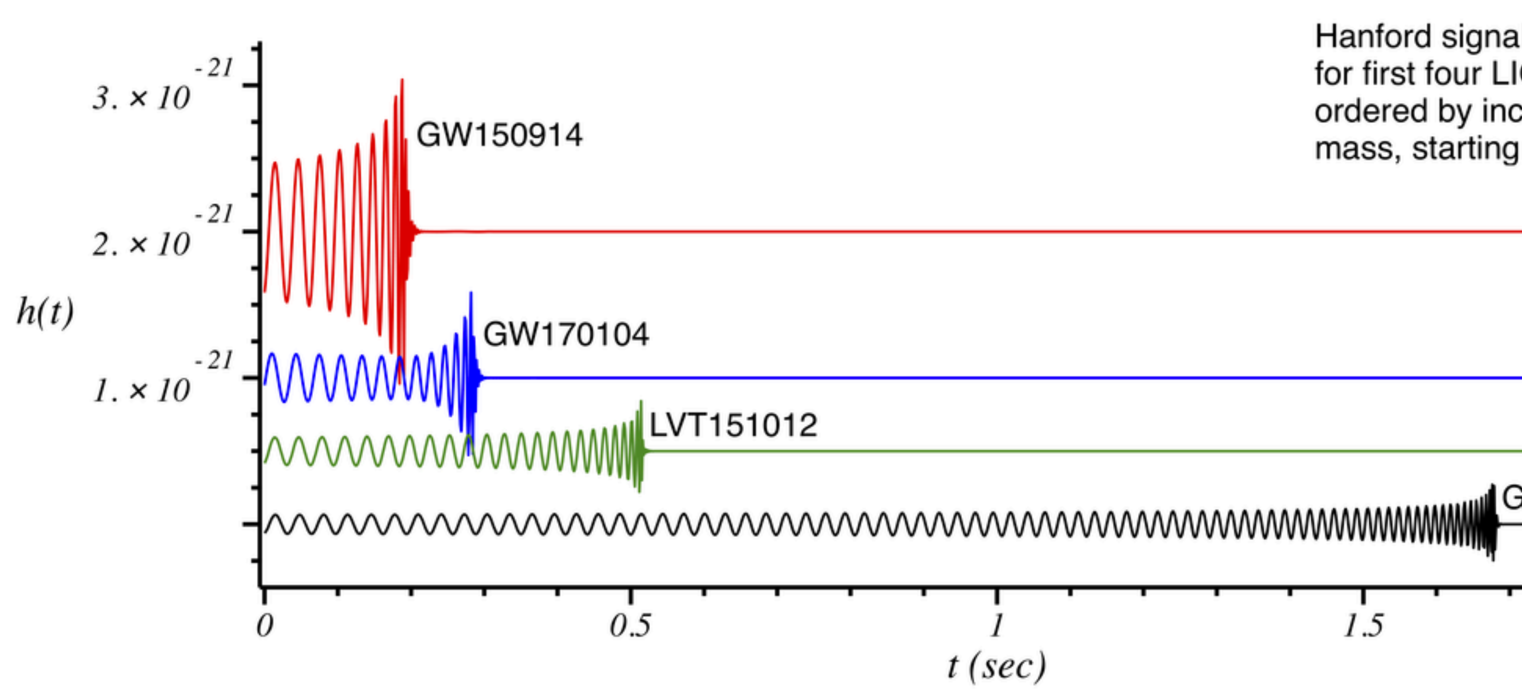
‘GW lensing’ observation seems very unlikely at LIGO!

LIGO can see only with

(1) angular resolution > 1 deg (let alone arcsec)

(2) measurement time < 1 sec ~ 1 min (let alone days)





GW vs. light

Even though they follow the same null geodesics,,,

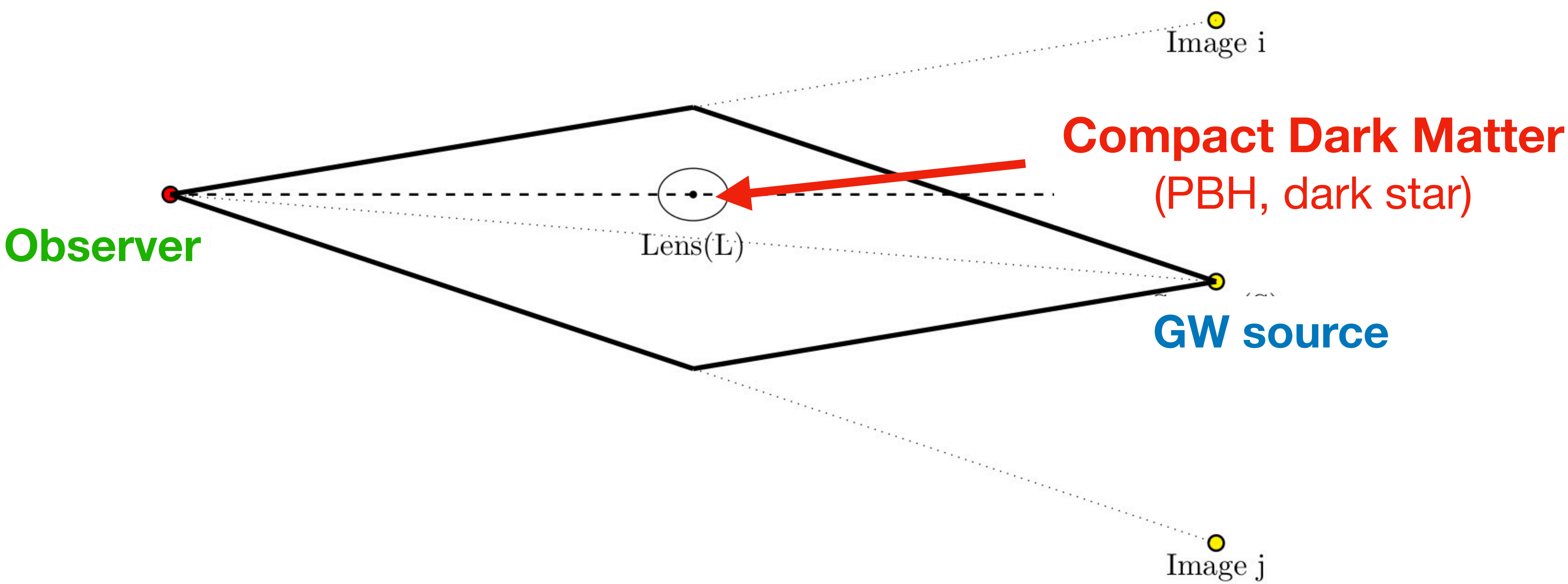
- GW chirps.
  - It provides characteristic lensing pattern, which is extremely useful in lensing detection.

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

- (GW wavelength is typically much longer.)

Time-delayed images

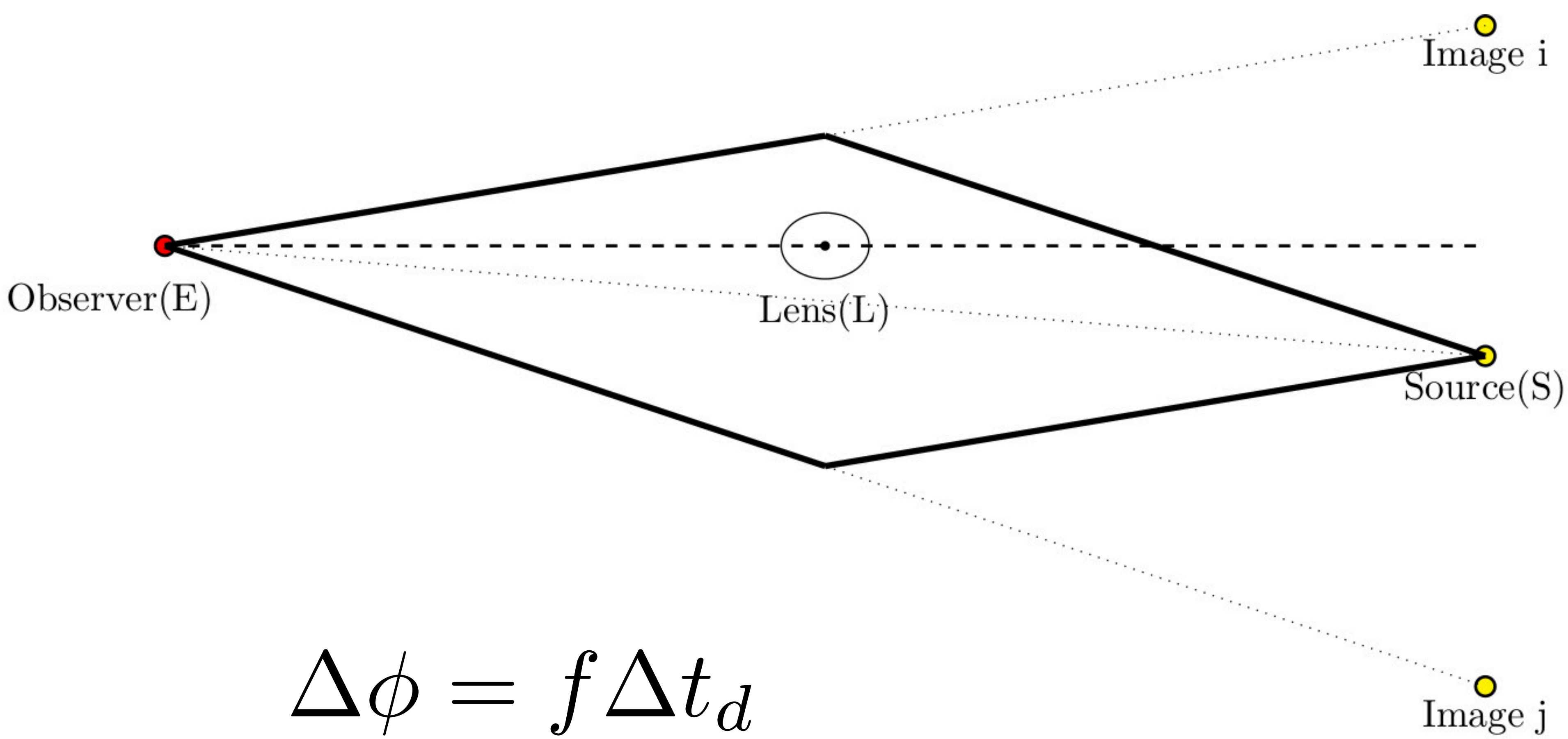
Consider time-delayed lensed images of GW.



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

Interfered images

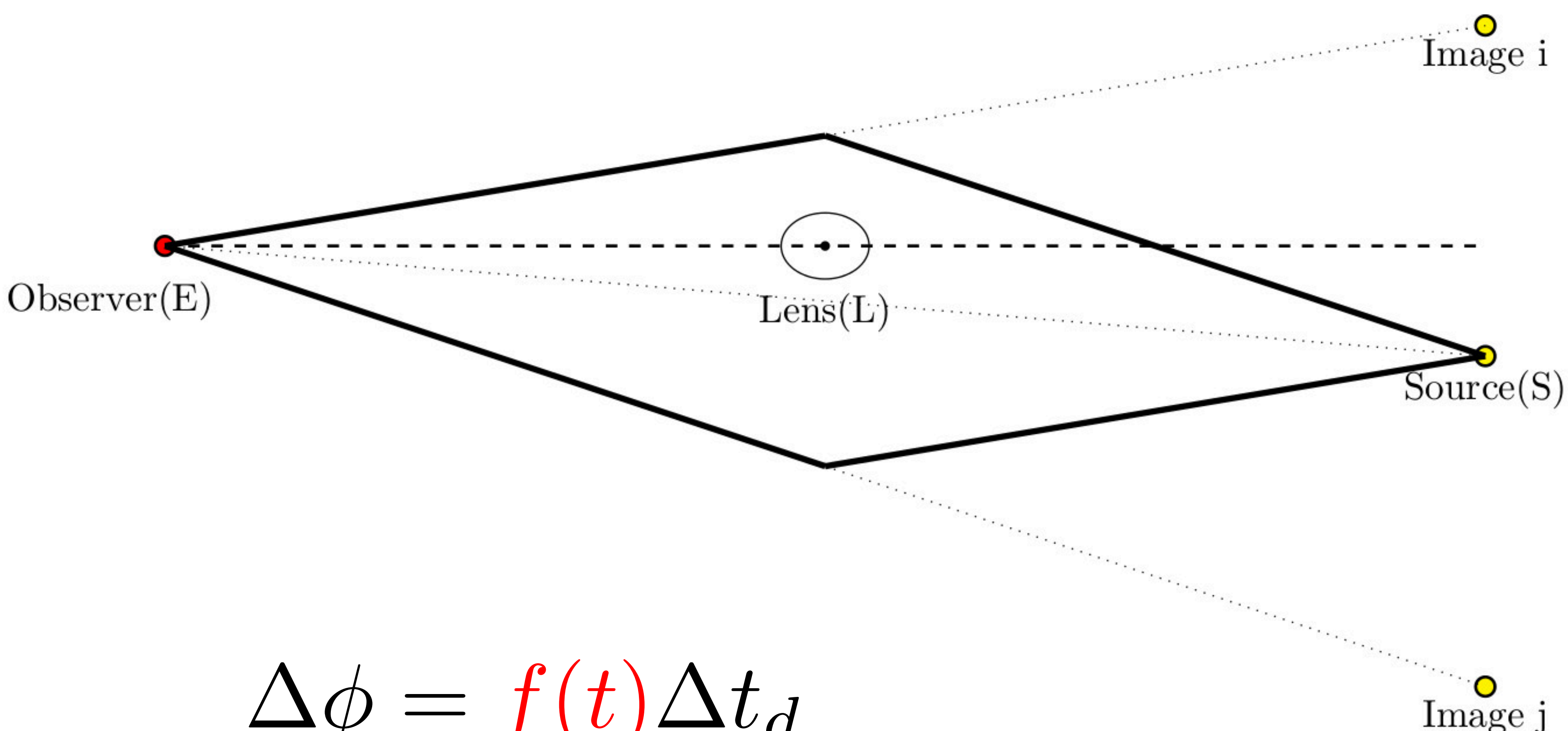
Unresolved GW images rather “interfere” in our observation.



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

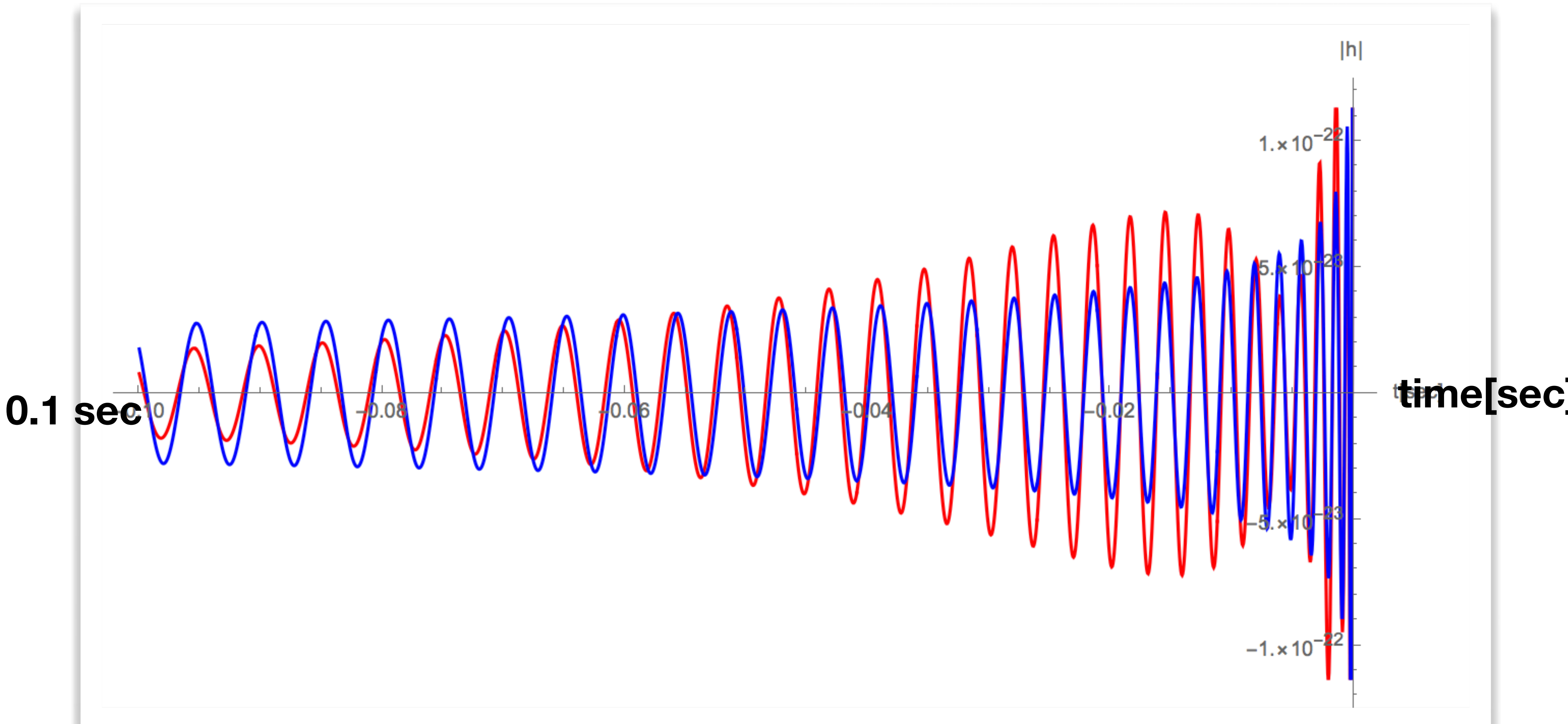
GW lensing Fringe

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 PBH.

PRL (2019), SJ, CSShin

ars TECHNICA   BIZ & IT   TECH   SCIENCE   POLICY   CARS   GAMING & CULTU

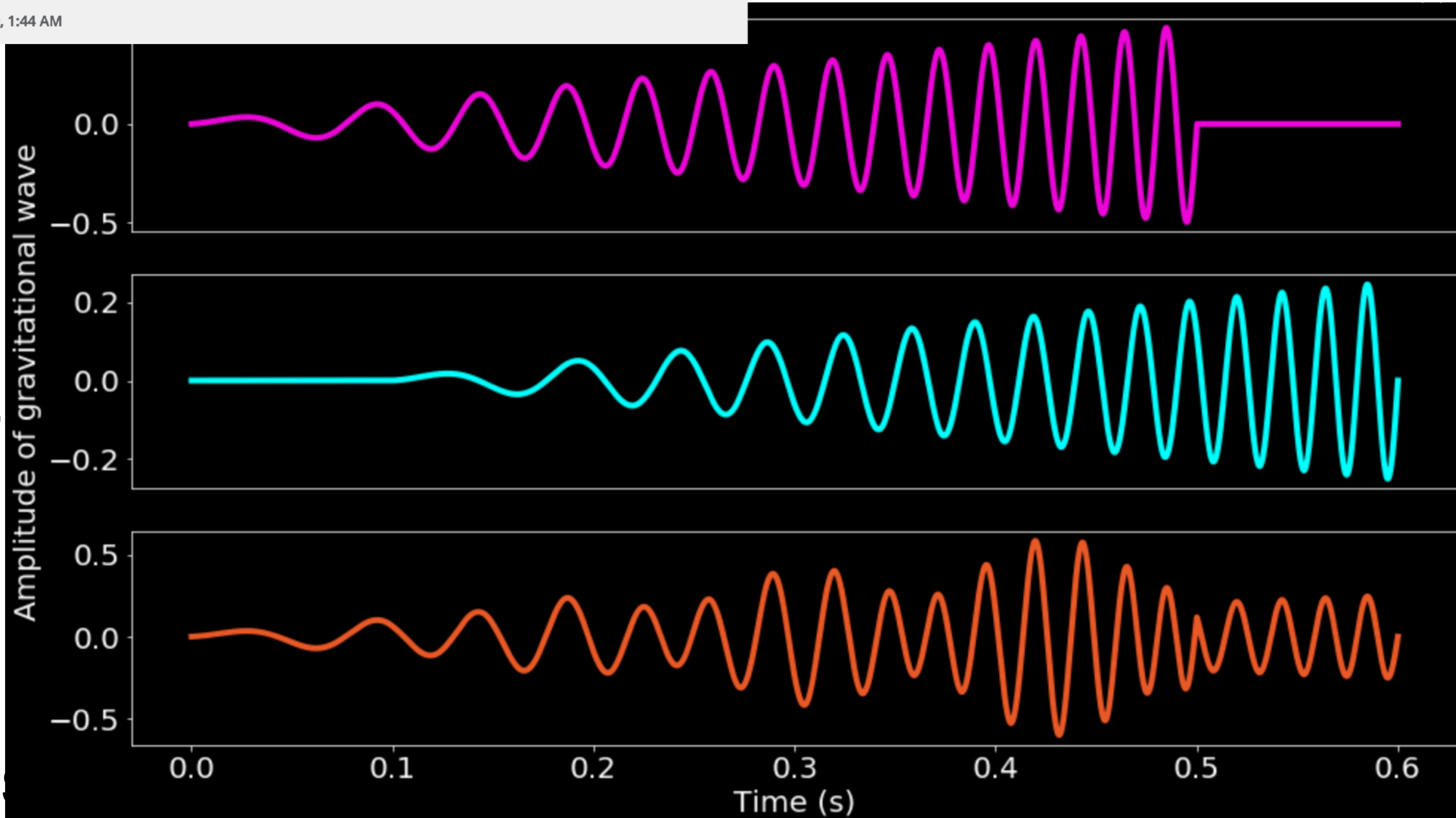
CHIRPING BLACK HOLES —

Lonely black holes revealed by passing gravitational waves

Black hole mergers may reveal large black holes in the foreground.

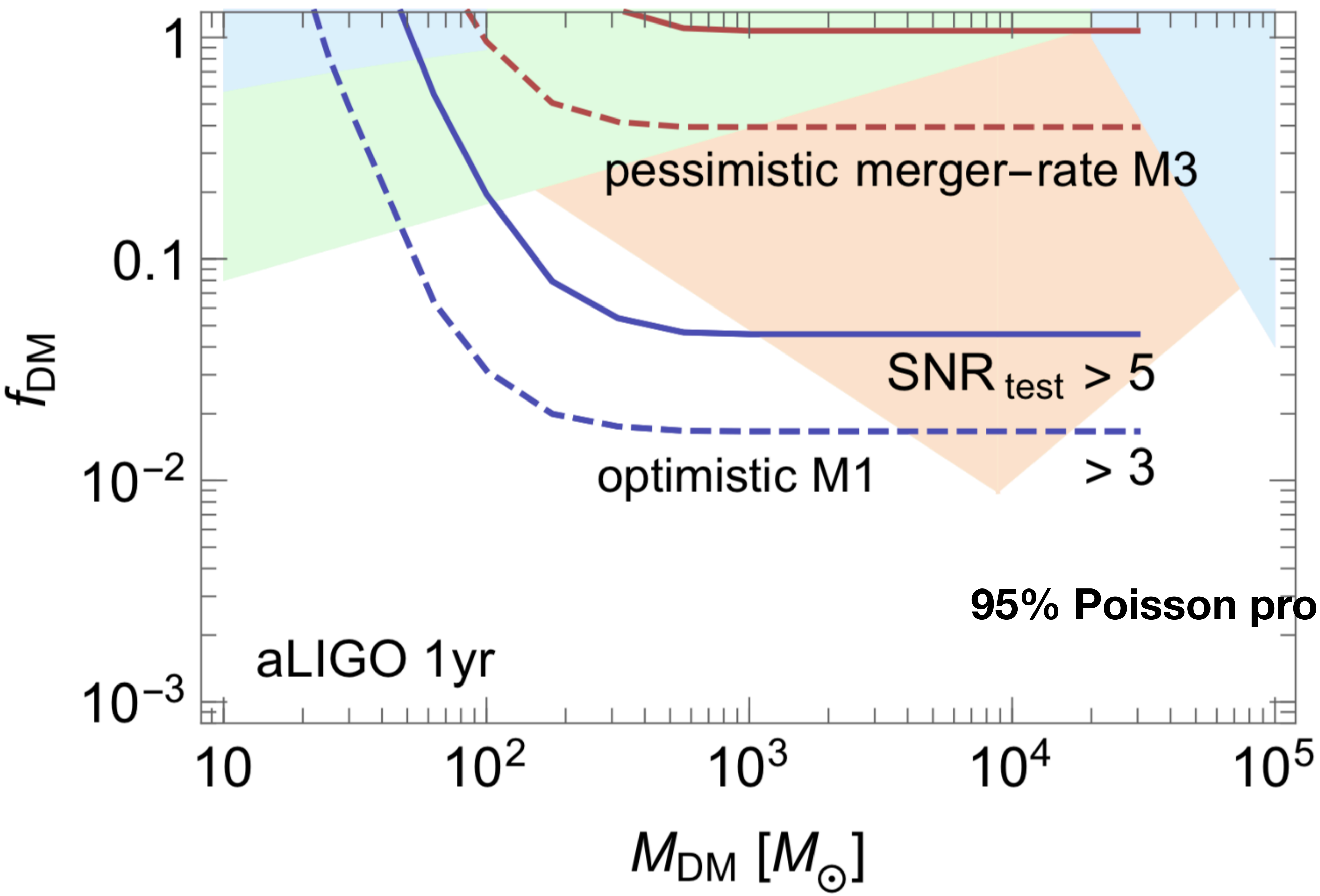
CHRIS LEE - 2/7/2019, 1:44 AM

"GW Fringe"



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.

PBH DM fraction

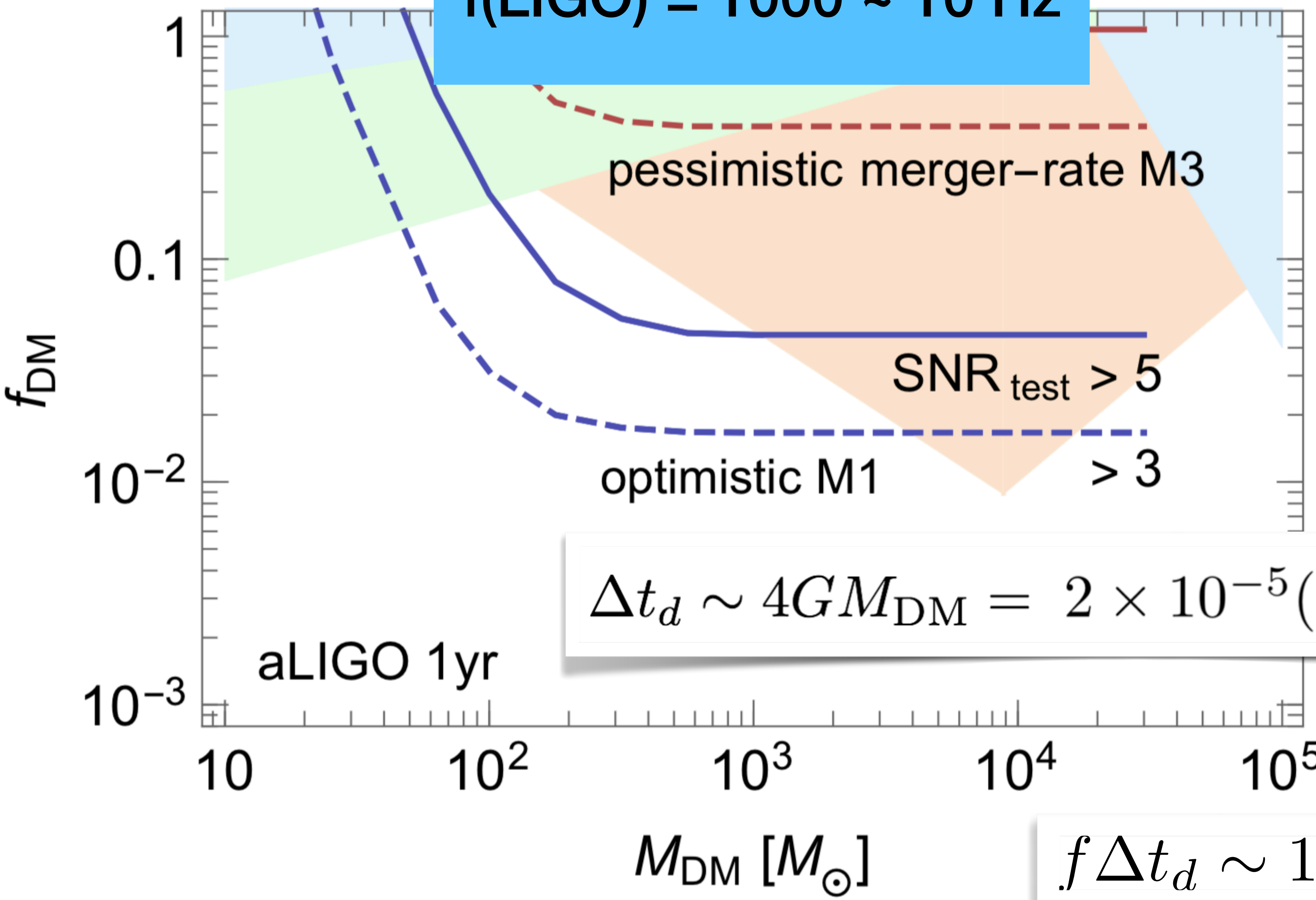


95% Poisson prob of >=1 detection

SJ, CSShin, 1712.01396 PRL

PBH DM fraction

f(LIGO) = 1000 ~ 10 Hz

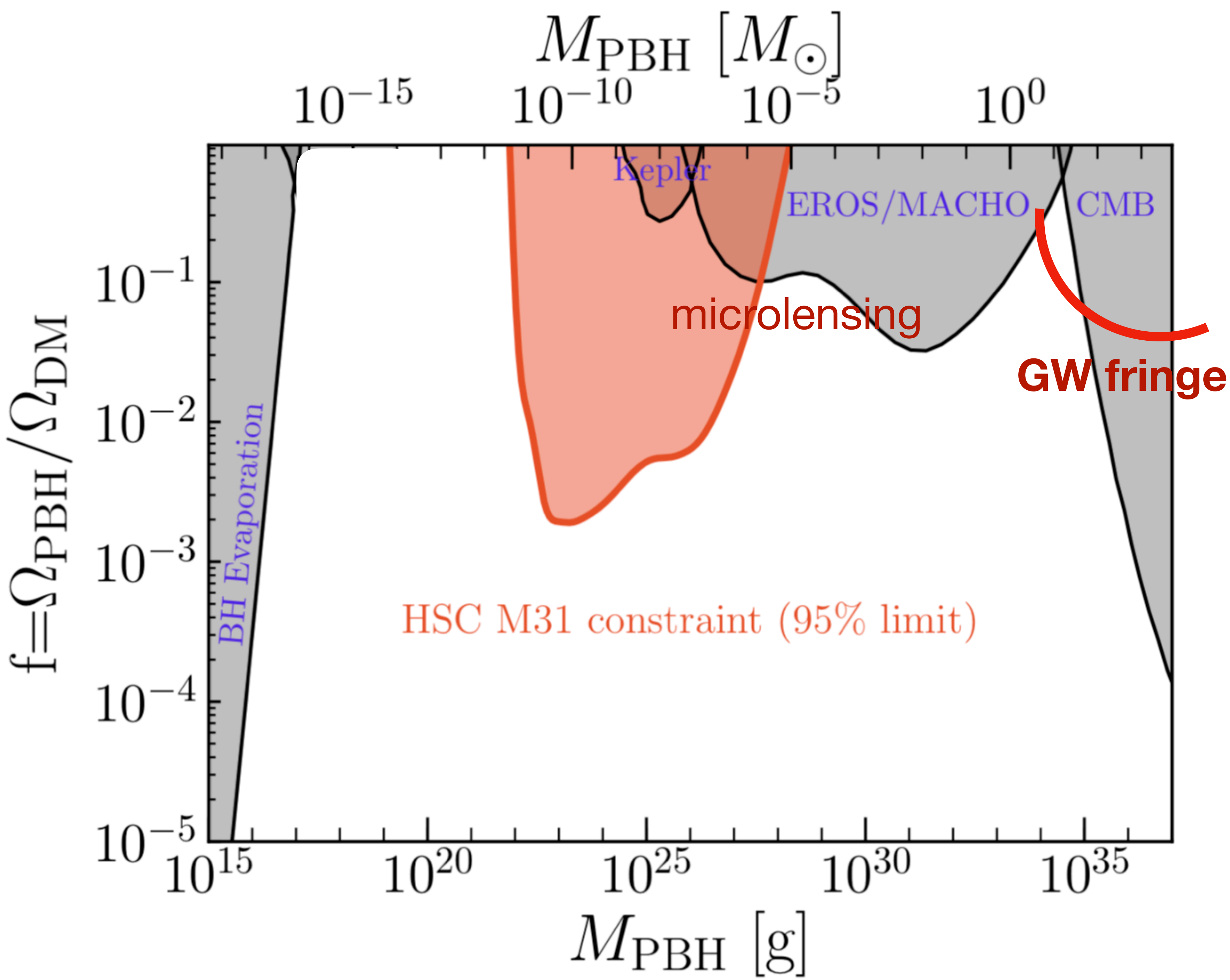


$$\Delta t_d \sim 4GM_{\rm DM} = \ 2\times 10^{-5}(M_{\rm DM}/M_\odot)\ {\rm sec}$$

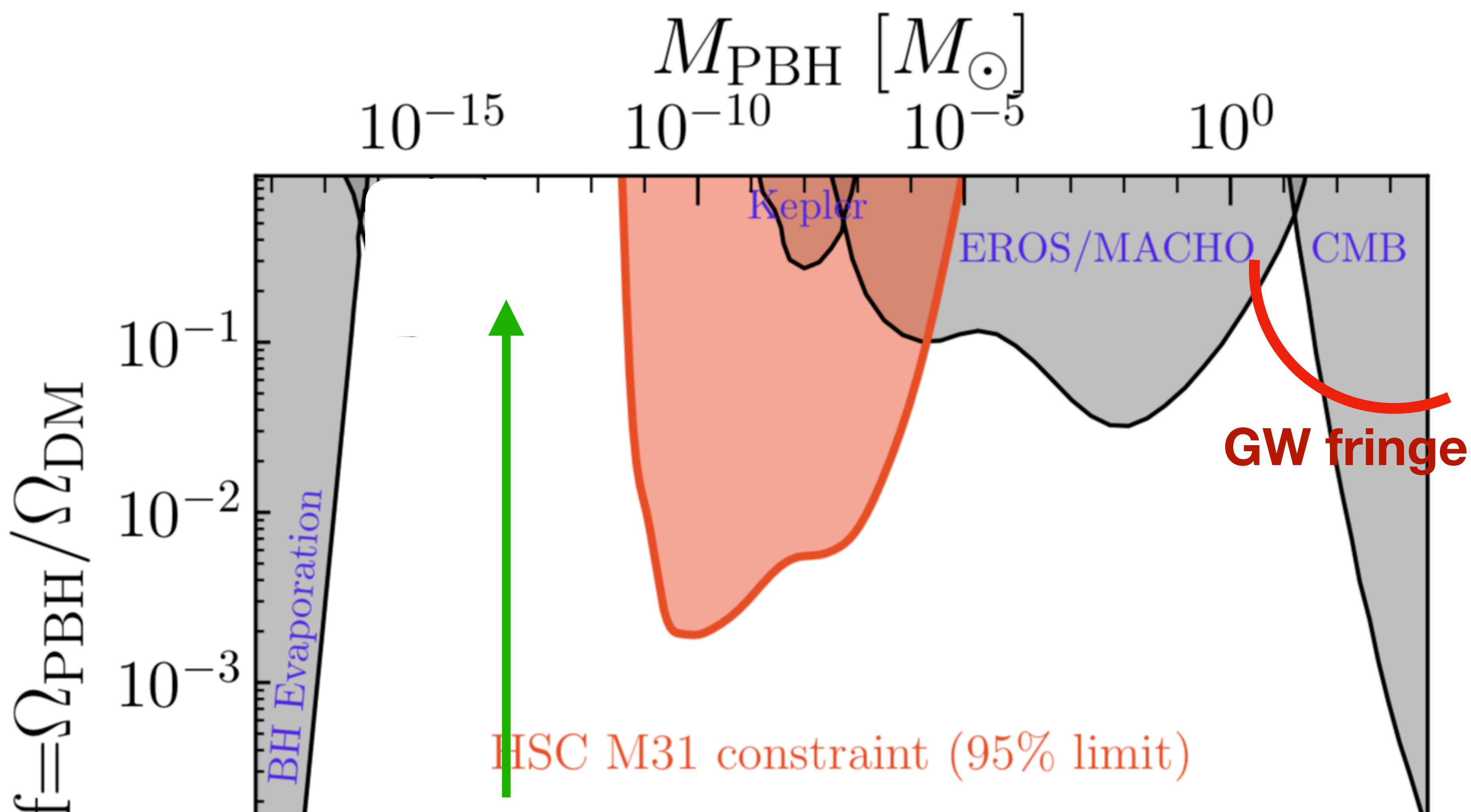
$$f\Delta t_d \sim 1+$$

$$\lambda \sim R_{\rm Sch}$$

PBH DM window



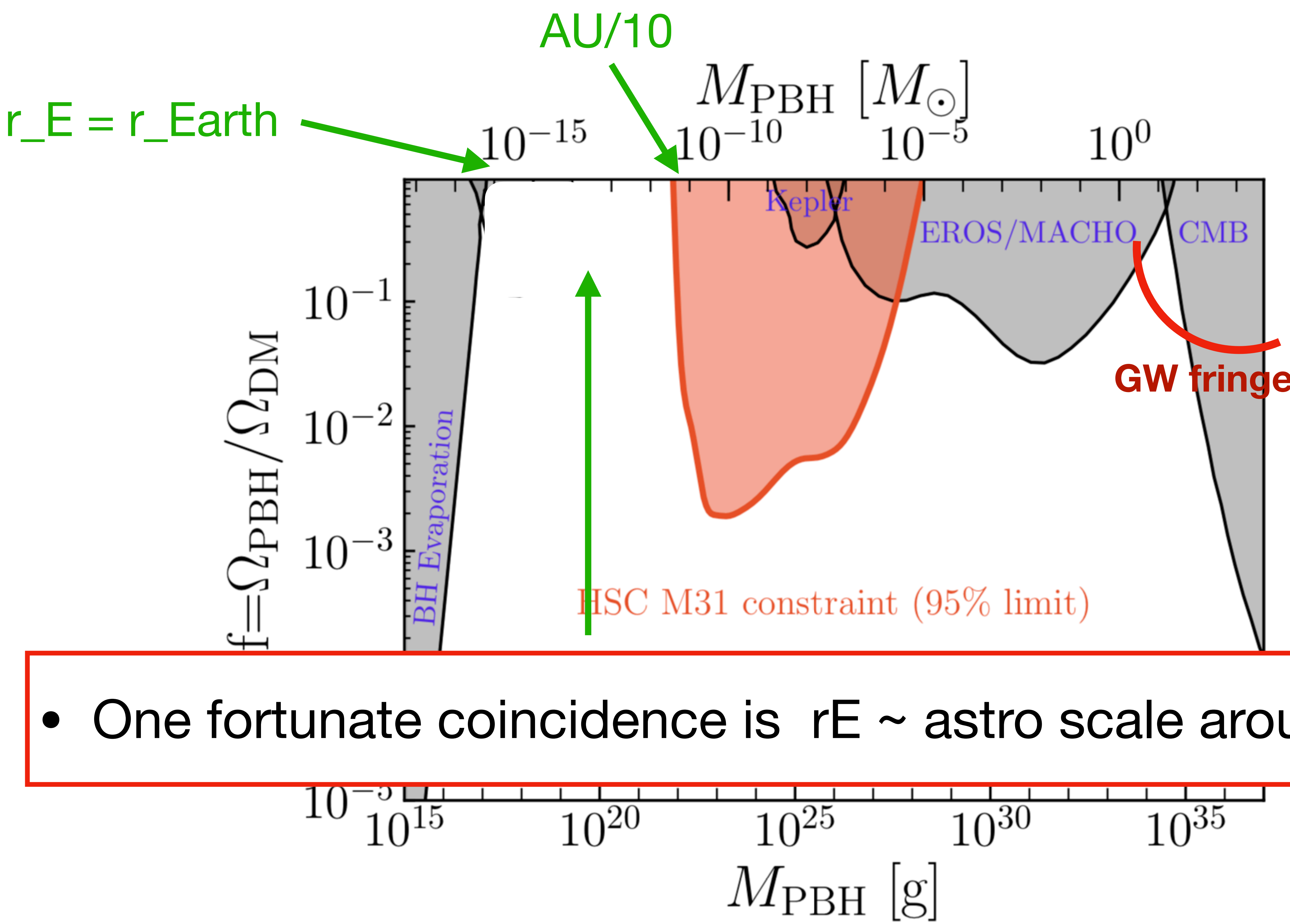
Aside 1: A notable loophole



- No lensing can completely probe these lightest PBH DM.

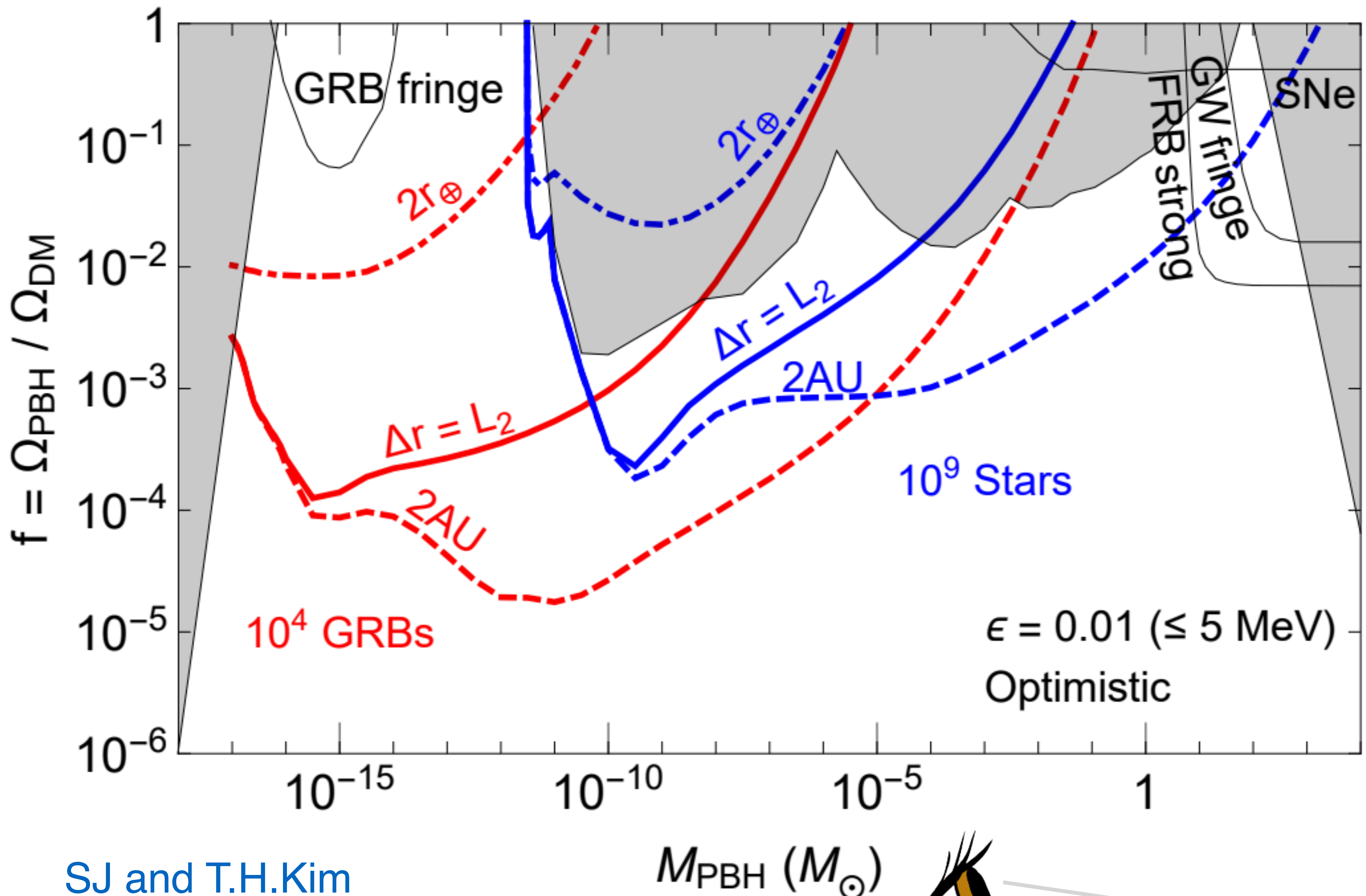
(limited by large source size, probe wavelength)

Aside 1: A notable loophole

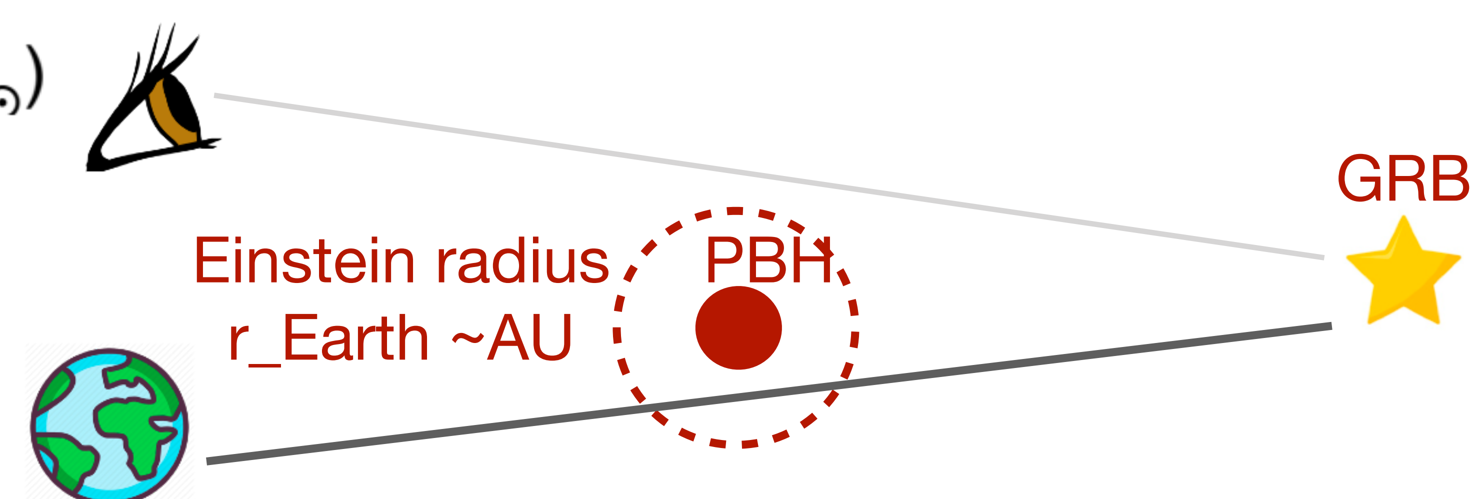


- One fortunate coincidence is rE ~ astro scale around us!

Aside 1: GRB Lensing Parallax

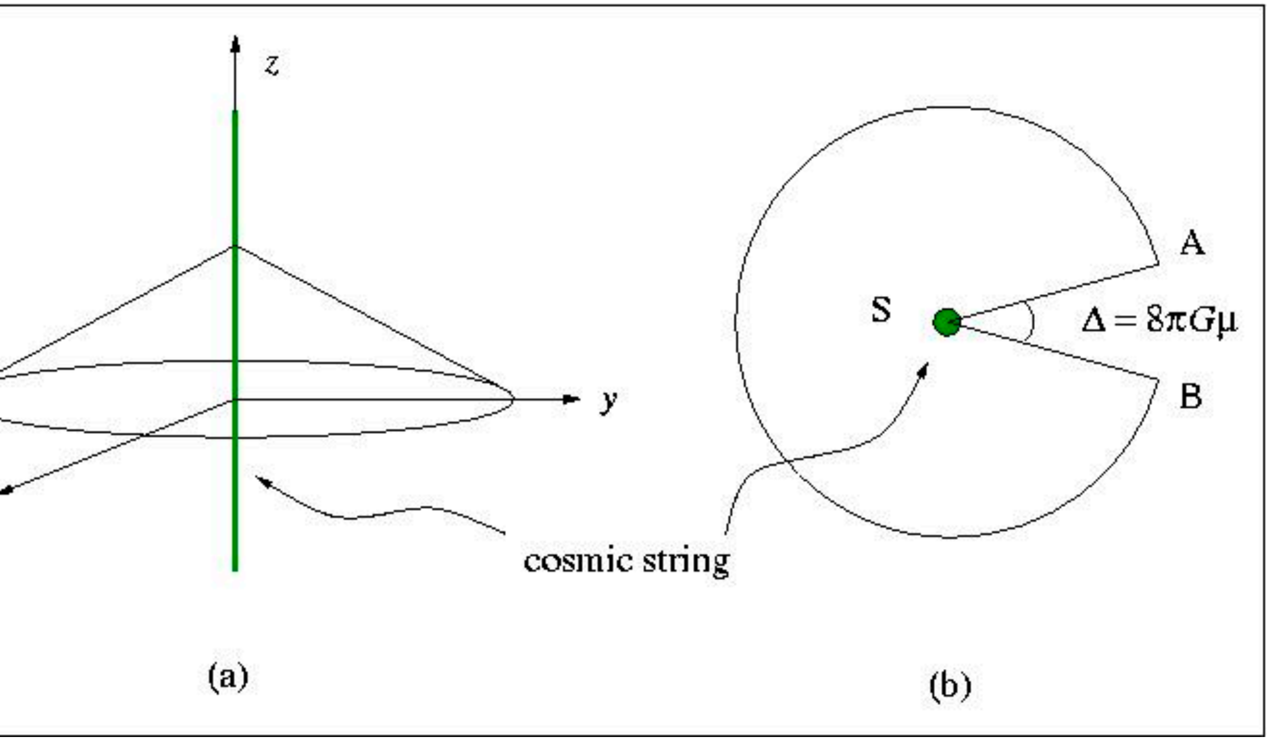


SJ and T.H.Kim
1908.00078 PRR



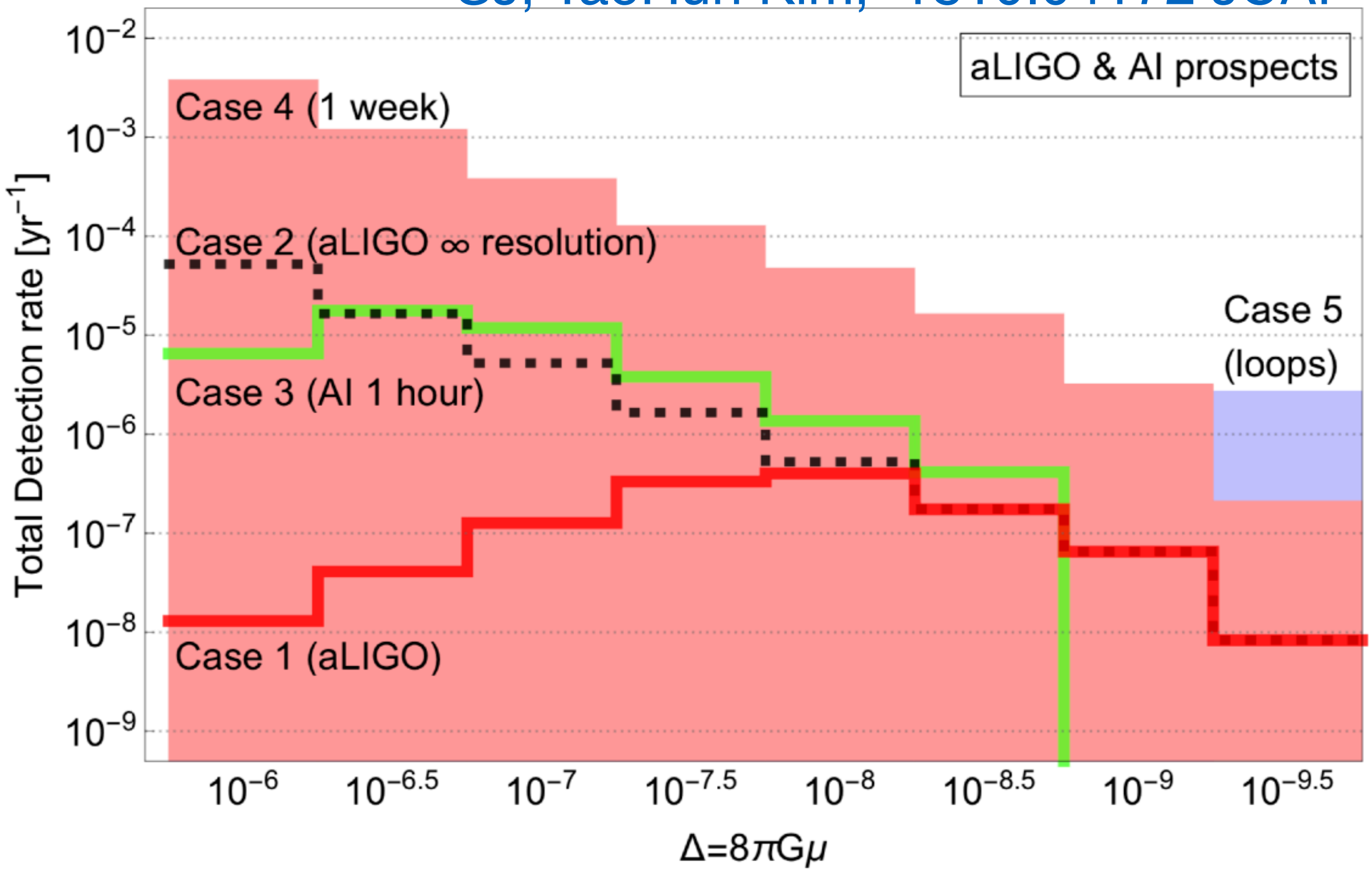
Aside 2: cosmic strings

- GW fringe from *three* rays (2 geo + 1 diffracted).
- Unexplored range of string tension < 10^-6.
  Both global and gauged strings.



Figs. from Nunez et al. 2017

SJ, TaeHun Kim, 1810.04172 JCAP



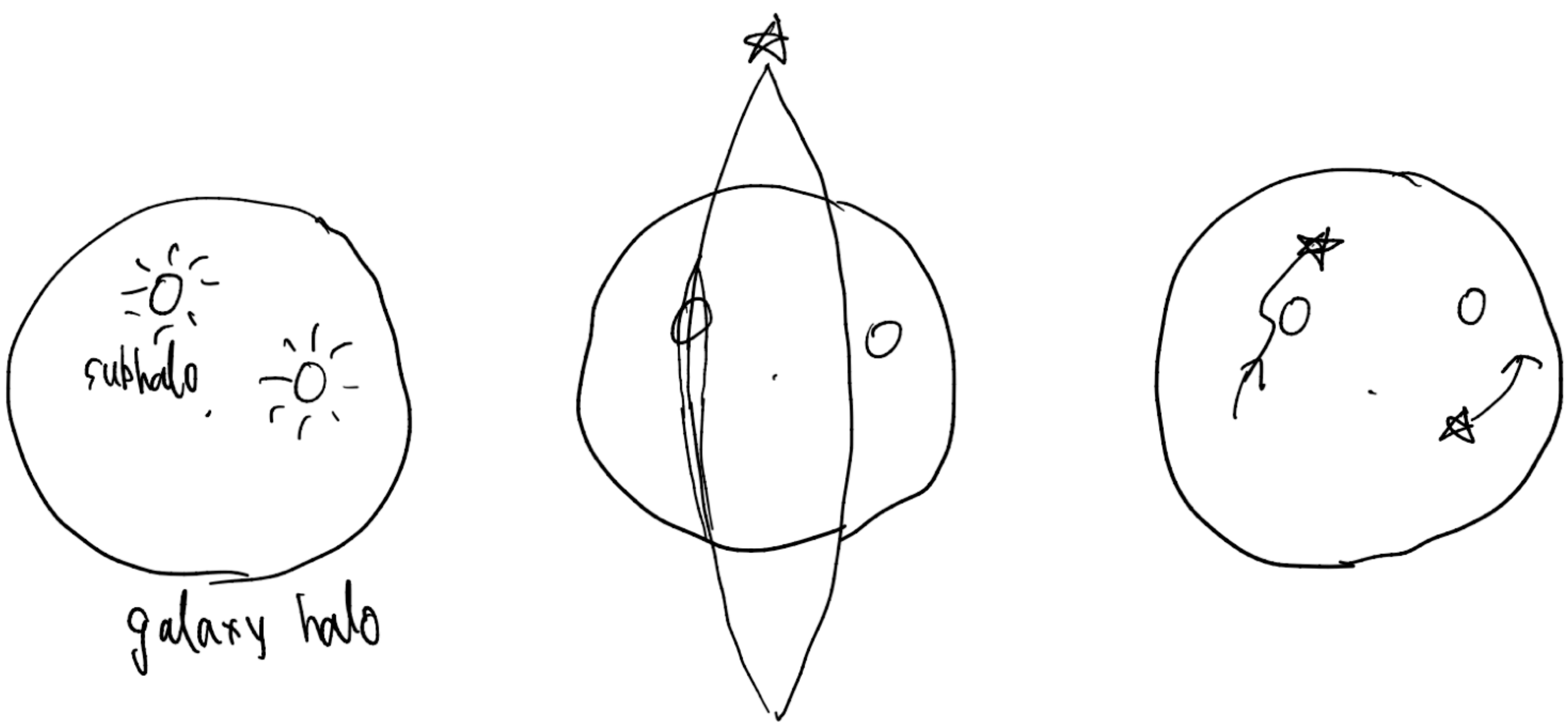
2. Diffraction by small-scale shear

— Diffuse NFW subhalos

Han Gil Choi, Chanung Park, SJ, 2103.08618 PRD

Small-scale subhalos never seen

- 10^7 Msun is visibility lower limit
  from luminous satellites, milli-lensing pert, star kinematics!



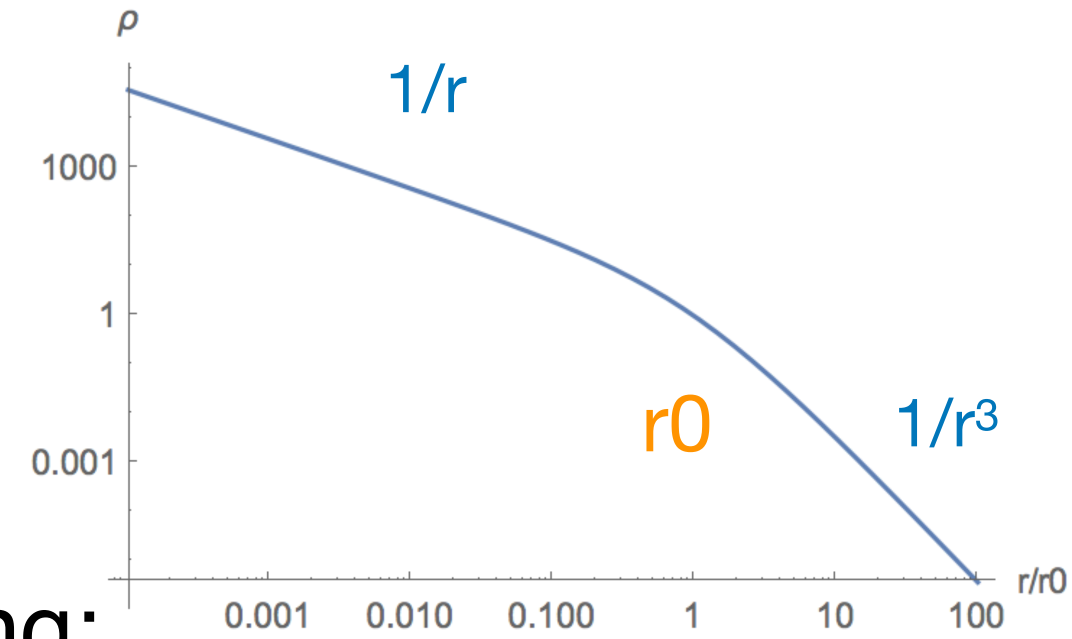
Small-scale subhalos never seen

- 10^7 Msun is visibility lower limit
  from luminous satellites, milli-lensing pert, star kinematics.

Below this range,

- No baryons, keeping pristine DM nature.
- Answers to CDM small-scale puzzles?
  Light thermal DM (WDM, fuzzy) free-streaming here?

NFW subhalo



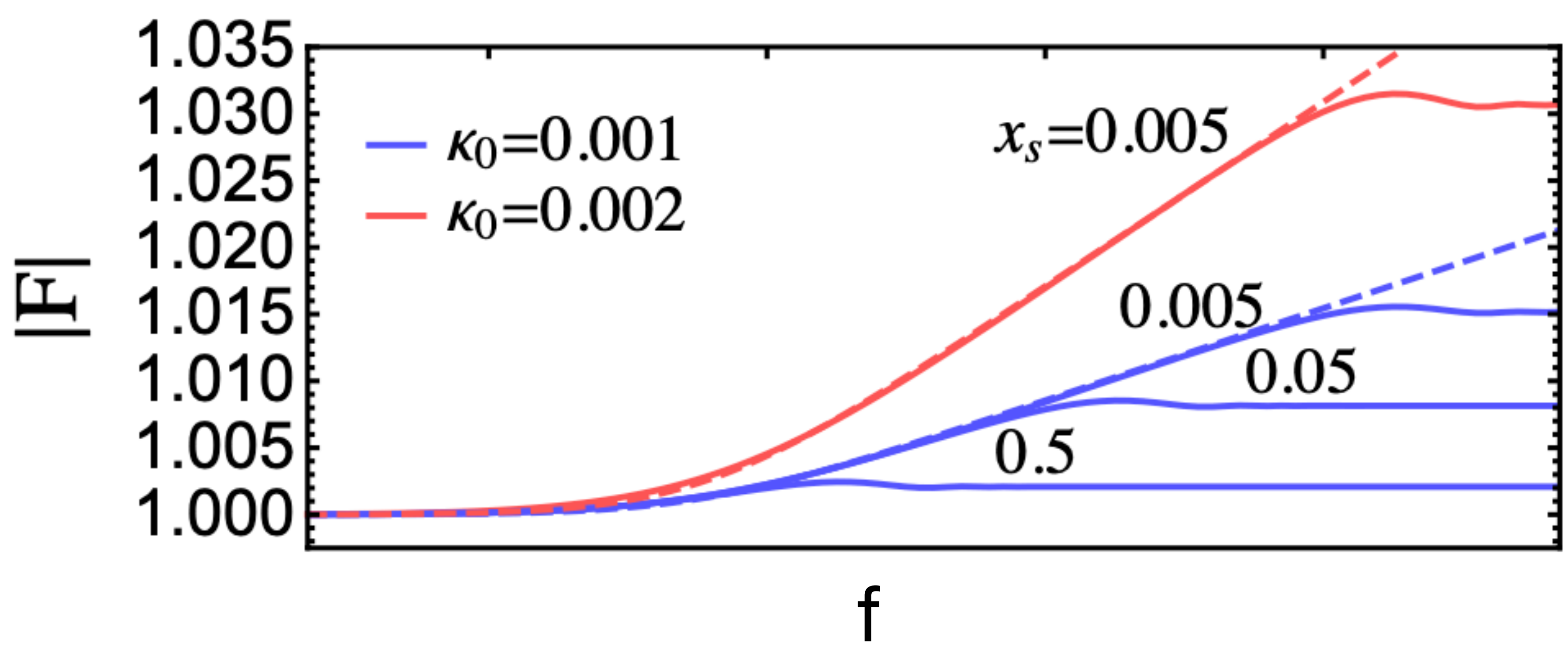
- CDM prediction.
- Diffuse over a length scale r0.
- Too diffuse to induce strong lensing:
  Einstein radius (or surface density) is exponentially small.

$$r_0 \simeq 2 \text{ kpc} \left(\frac{M_{\rm NFW}}{10^9 M_\odot} \right)^{0.41}$$ = 1 - 100 pc for 10 - 10^7 Msun

$$r_E \lesssim r_0 \exp(-100)$$

Single-imaged lensing: diffraction

- But NFW can still induce observable lensing effects, uniquely on GW.



H.G.Choi, C.Park, SJ, 2103.08618 PRD

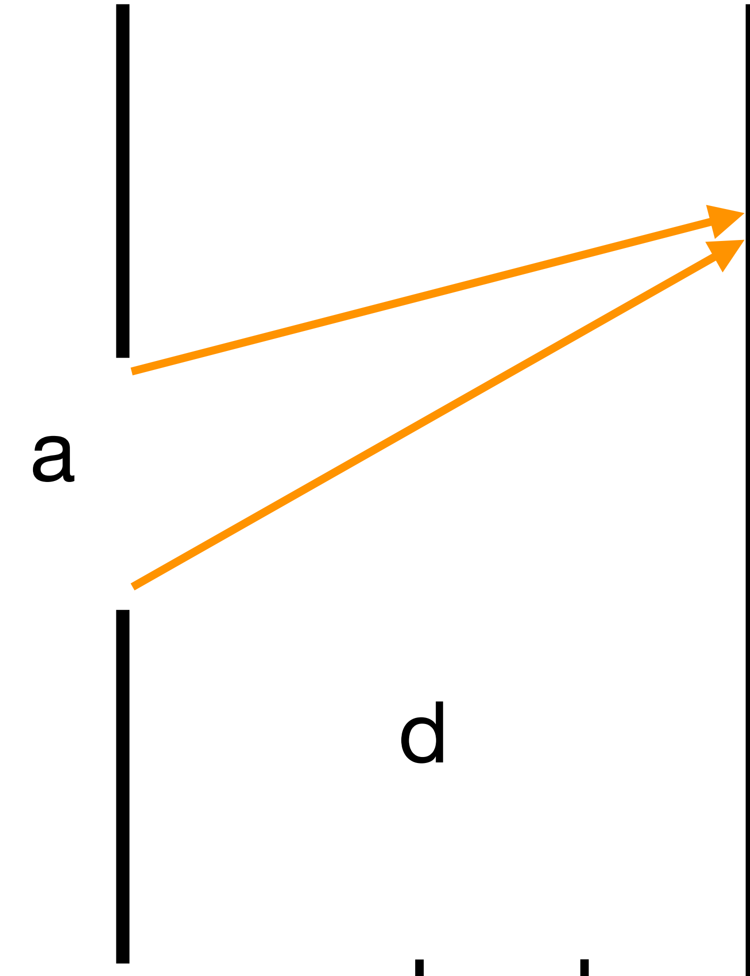
Analogy with single-slit diffraction

- Slit shadow is blurred when the phase variation is small.

$$\Delta\phi = 2\pi \frac{\sqrt{a^2+d^2}-d}{\lambda} \sim \frac{\pi a^2}{\lambda d} = \left(\frac{a}{r_F}\right)^2 \lesssim 1$$

$$r_F \equiv \sqrt{\frac{d_{\rm eff}}{\pi f(1+z_l)}}$$ Fresnel length

a: characteristic lensing scale = r0, rs, rE

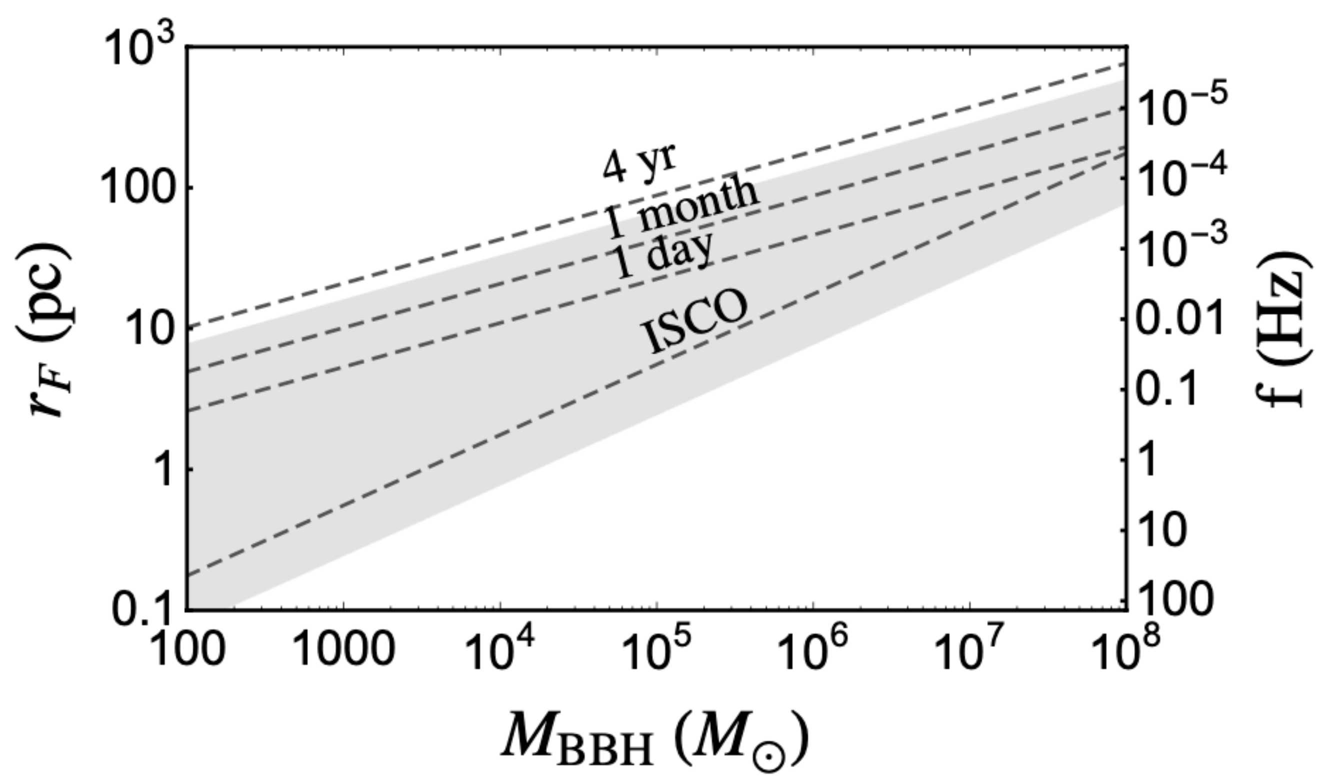


- Shadow varies prominently with the frequency only when the frequency is right to make rF ~ a.

Single-imaged lensing: diffraction

- A scale coincidence:
  NFW r0 happens to coincide with the rF of GW diffraction!

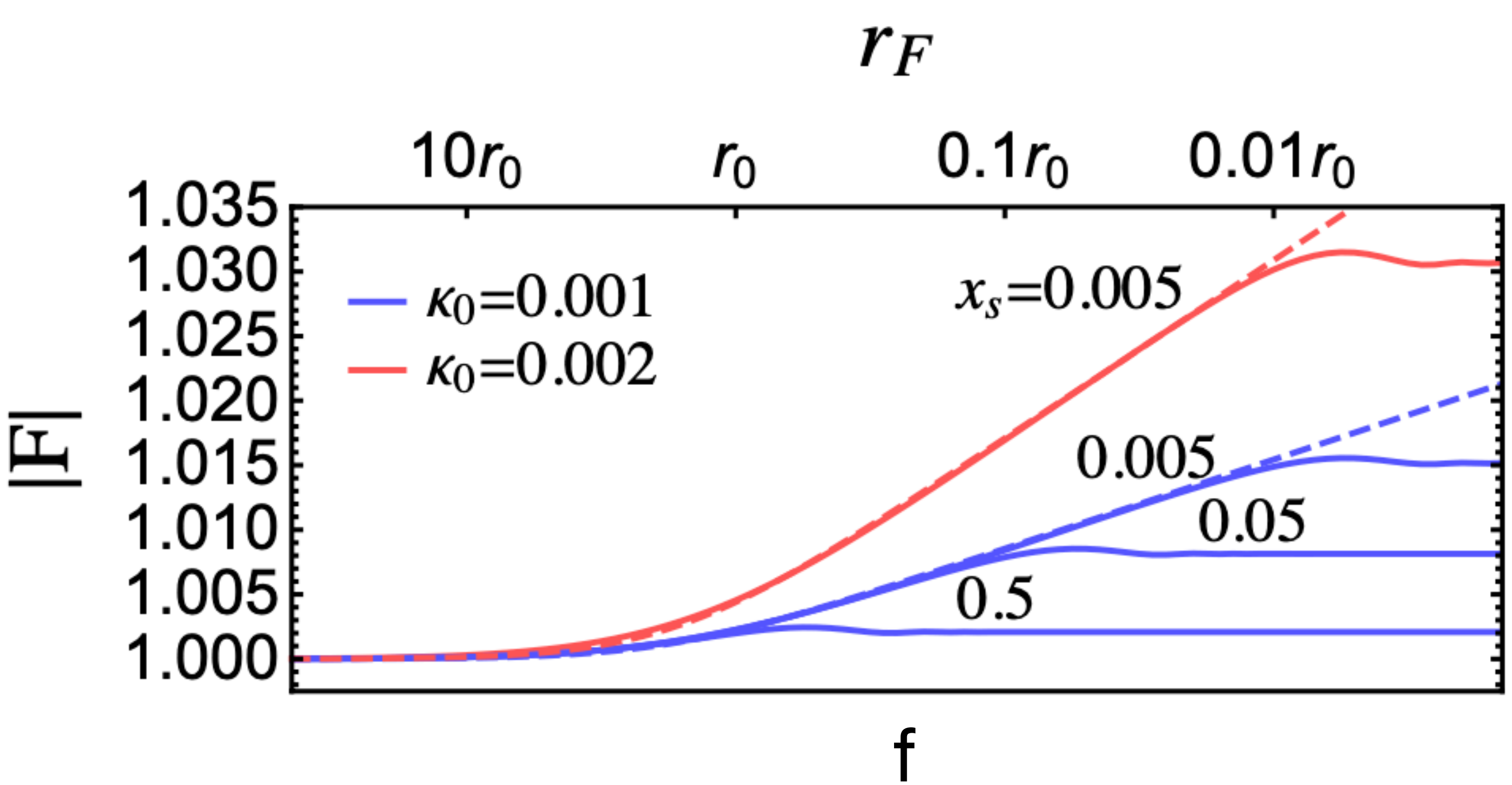
$$r_F \simeq 1.76 \text{ pc} \sqrt{\frac{1}{1+z_l}\left(\frac{d_{\rm eff}}{\rm Gpc}\right)\left(\frac{\rm Hz}{f}\right)}.$$



Observable signal of NFW

- freq-dep lensing (diffractive lensing) is the observable signal of NFW!

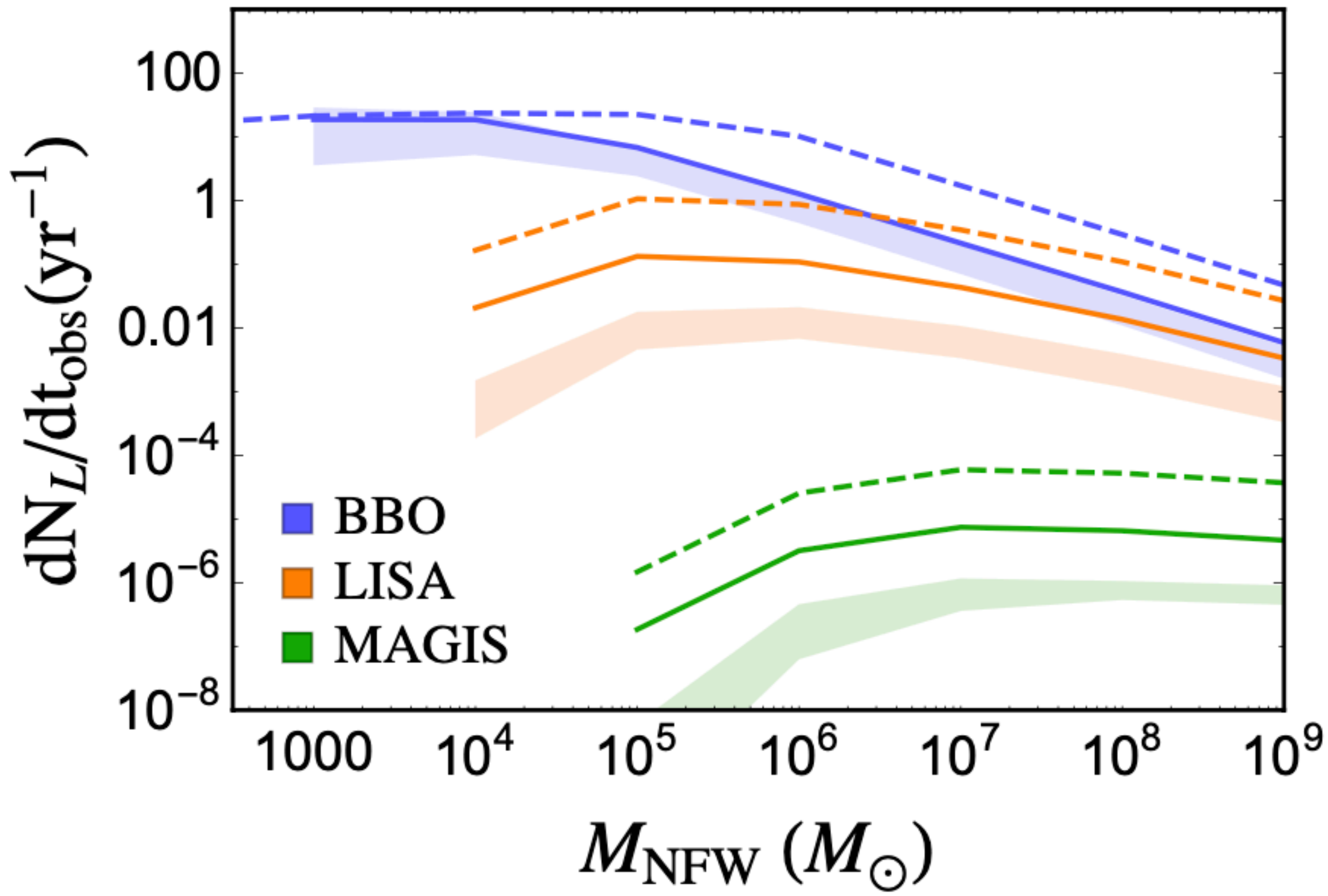
  (NFW shadow becomes clearer (only) at GW frequencies.)



$$F(w) \simeq 1 + \overline{\kappa}(r = \frac{r_F}{\sqrt{2}})$$

Gauss thm applied to the region within rF.

Detection prospects



3-sigma likelihood

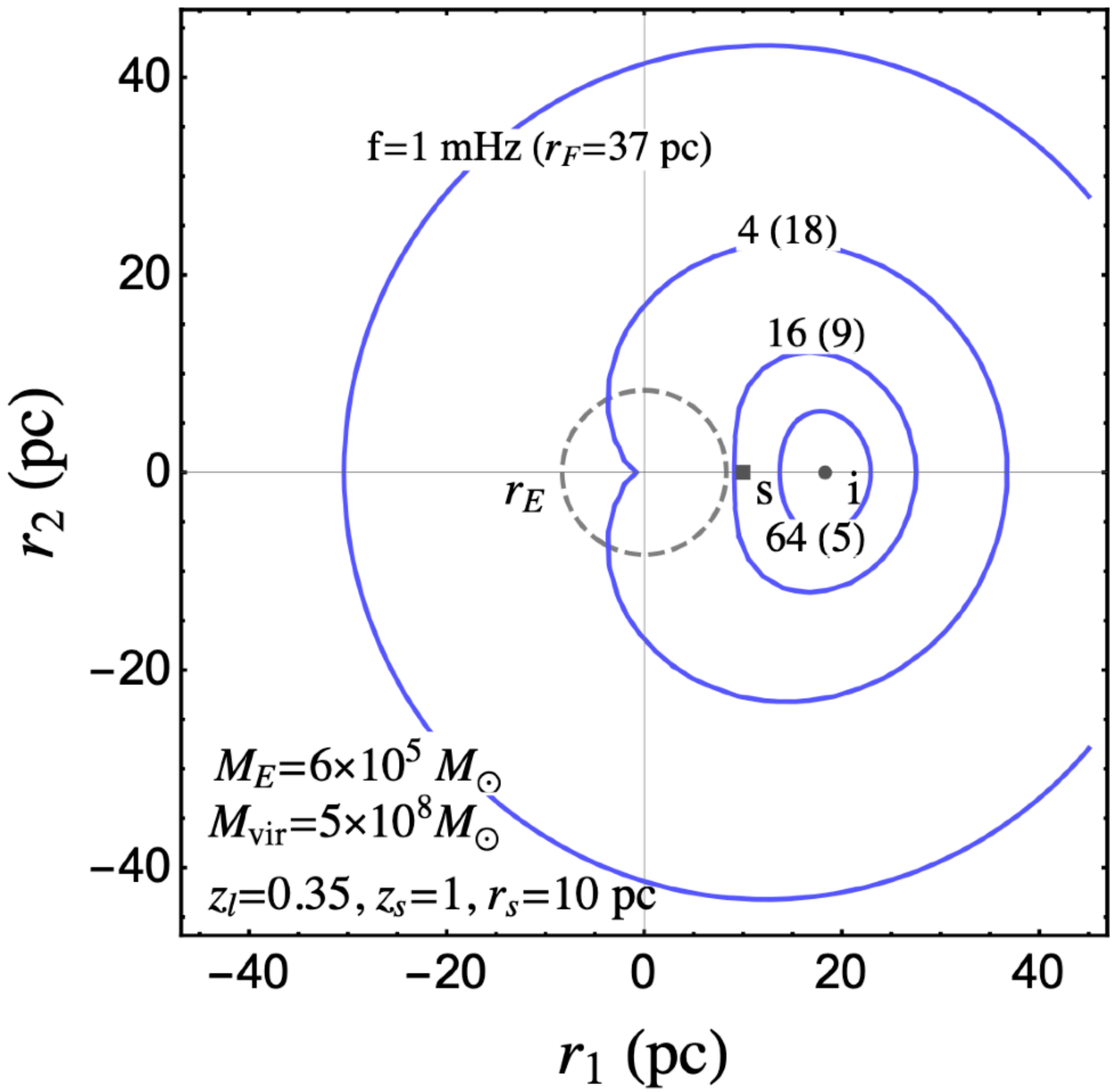
- BBO can detect *individual* invisible NFW with O(10) events/yr; LISA marginally; and MAGIS/ET unlikely.

- Limiting: small merger rates, large SNR > 1/gamma(r0) ~1000

H.G.Choi, C.Park, SJ, 2103.08618 PRD

Peeling off layers of a subhalo

- We can do further more: GW chirping probes the mass profile at a successively smaller-scale.



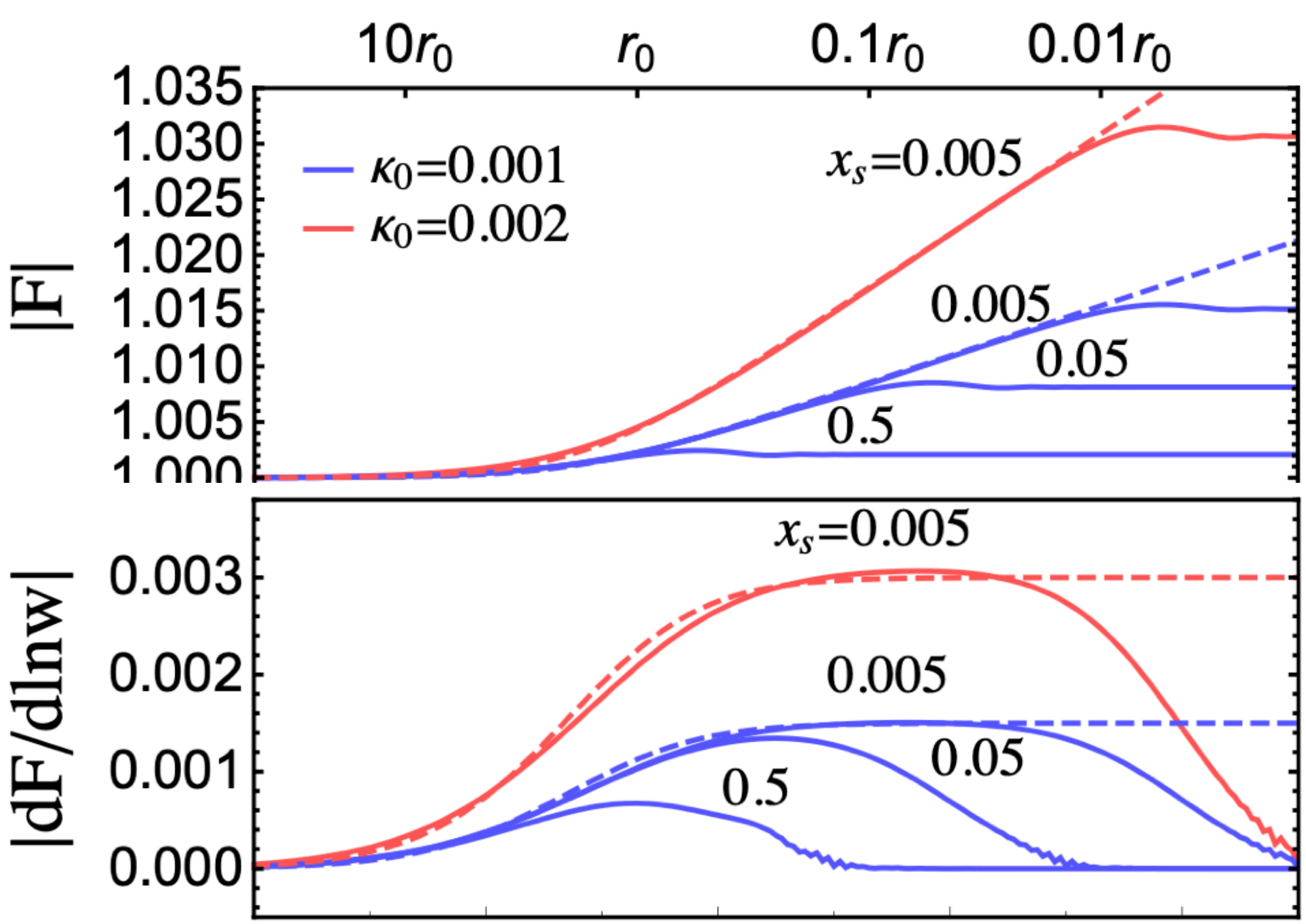
$$F(w) \simeq 1 + \overline{\kappa}(r = \frac{r_F}{\sqrt{2}})$$

$$r_F \equiv \sqrt{\frac{d_{\rm eff}}{\pi f(1+z_l)}}$$

Shear causes the f-dependence

- Remarkably, the slope is the *shear* of NFW *at r ~ rF* !

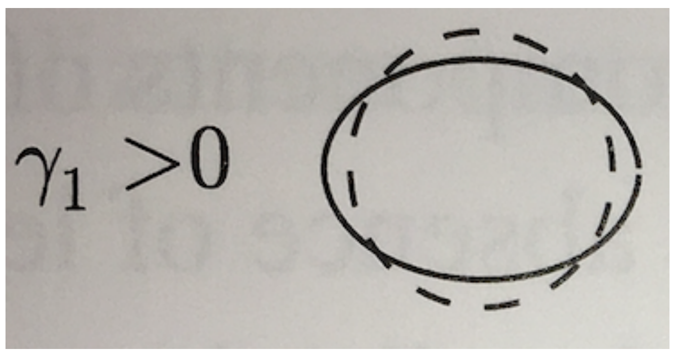
$$\frac{dF(w)}{d\ln w} \simeq \gamma(r = \frac{r_F}{\sqrt{2}})$$

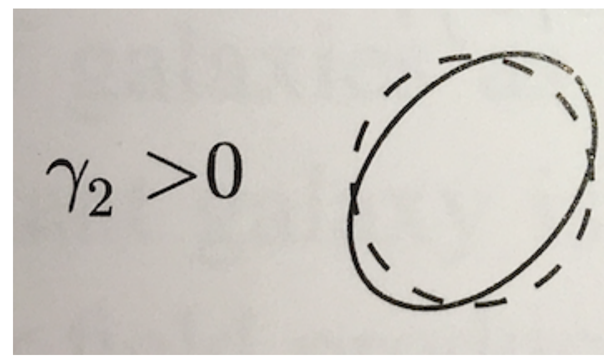


H.G.Choi, C.Park, SJ, 2103.08618 PRD

Shear from mass variation

- Usually responsible for asymmetric distortions of images.





$$\gamma_1 = \frac{1}{2}\left(\frac{d^2\psi}{dx^2} - \frac{d^2\psi}{dy^2}\right)$$

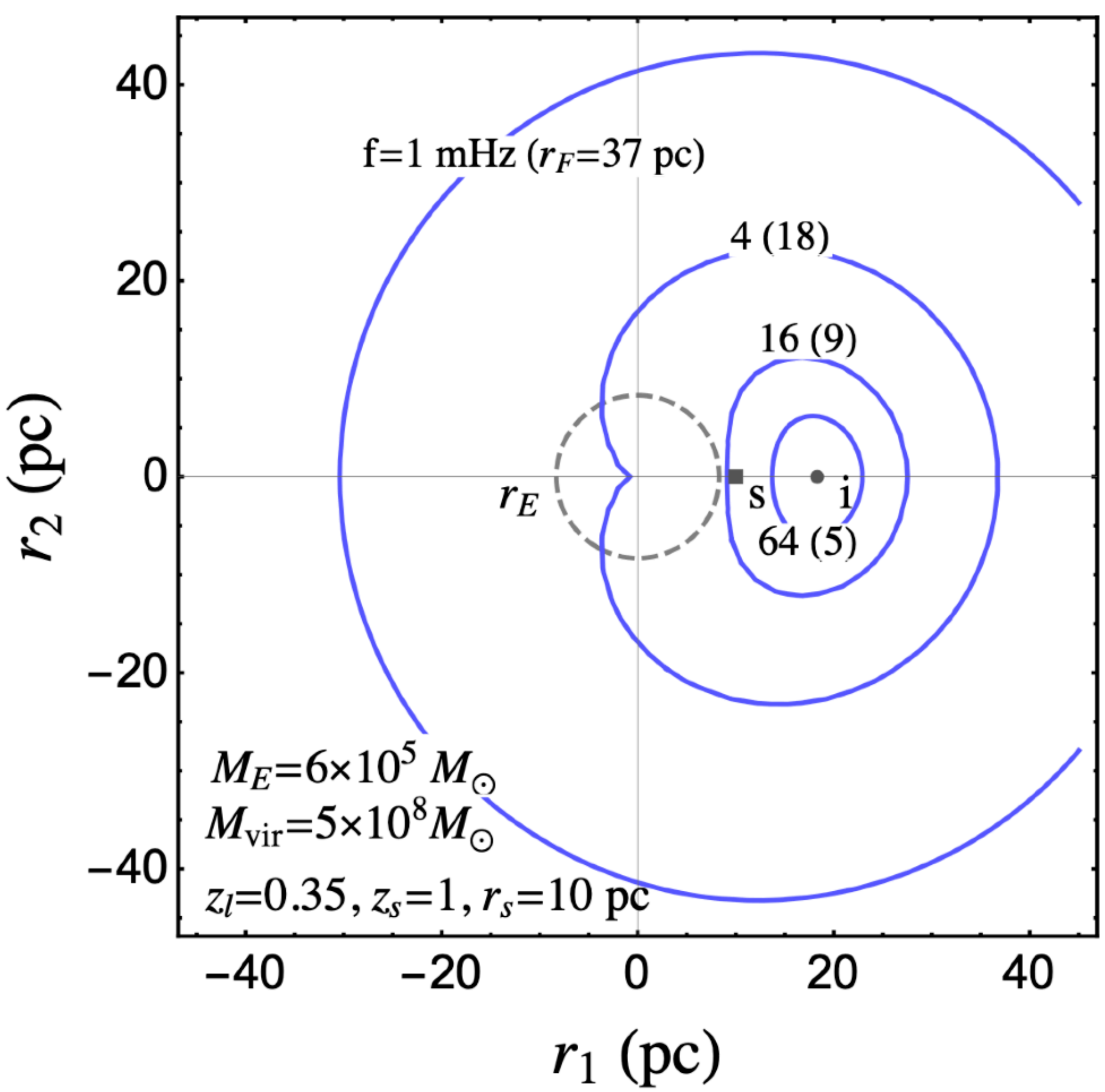
- But can also be thought of as measuring mass variation!

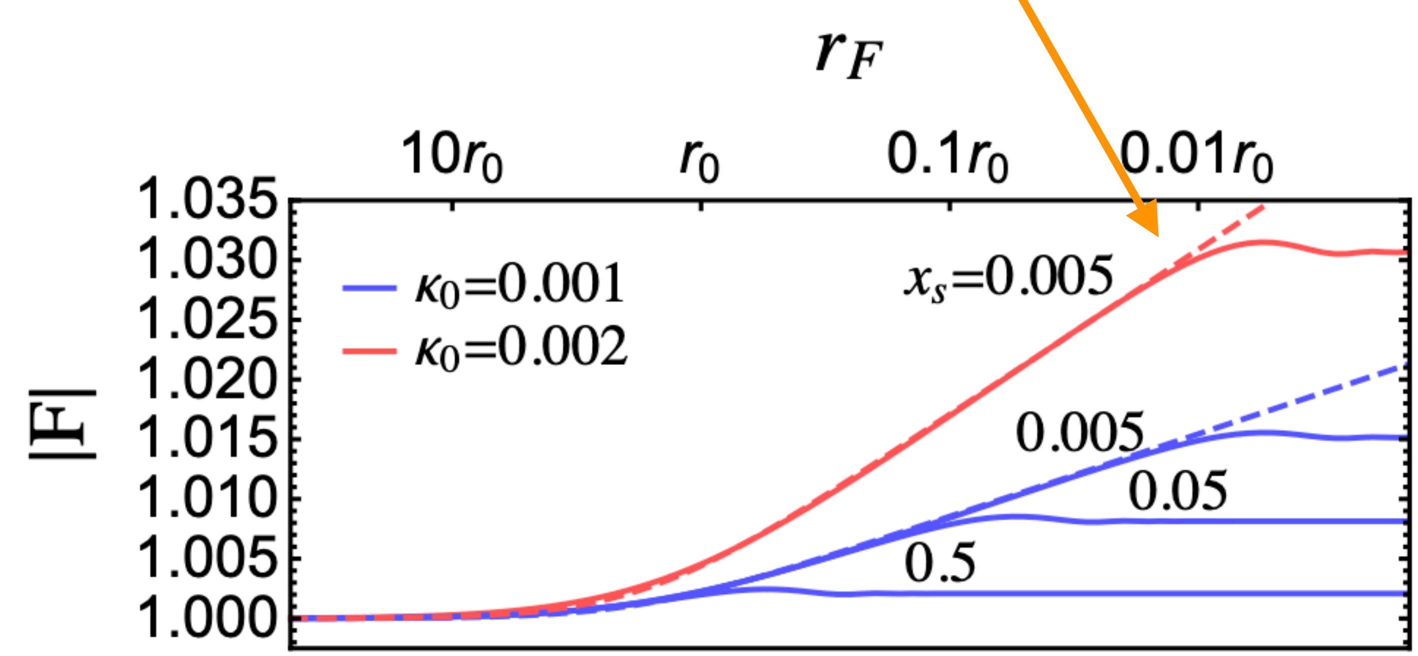
$$\gamma(x) = \overline{\kappa}(x) - \kappa(x)$$

(After all, asymmetry exists only when varying.)

End of diffraction 1: rF ~ rs

- As rF falls below rs, the wave begins to well locate the source away from the lens. (slit becomes clearly imaged)





It is indeed where diffraction ends.

$$\Delta\phi = w\hat{T}_d \simeq w\frac{x_s^2}{2} = \left(\frac{r_s}{r_F}\right)^2 \gtrsim 1$$

End of diffraction 2: Multi-image interference

- For rs < rE,

  the slit size is fixed by another scale — the time-delay btwn would-be multi imaes, or Einstein radius rE.

$$r_F^2 \gtrsim r_E^2 \qquad\qquad 2\pi f \Delta T_{ij} \lesssim 1$$

$$\Delta T_{ij} \sim 4M_E = r_E^2/d_{\rm eff}$$

$$r_E^2/r_F^2 = (4Md_{\rm eff})/(\lambda d_{\rm eff}/\pi) = 4\pi M/\lambda \lesssim 1$$

A new phase: Strong diffraction

- Inside (rs<) rF<rE, wave properties remain important down to near a *caustic* (e.g. xs=0) , where images have small relative time delays.

$$\Delta\hat{T}_d = 2x_E x_s + \mathcal{O}(x_s^2)$$

$$r_F \gtrsim 2\sqrt{r_E r_s}.$$

- This strong diffraction inside rE produces a blurred Einstein ring (rather than a blurred image).

Summary

1. **Strong lensing**
   - Fringe: solar-mass PBH DM & cosmic string
   - Parallax: complete coverage of PBH DM

2. **Diffraction by small-scale shear**
   - Diffuse NFW subhalo

A lot to explore and realize to learn about dark matter!

Thank you