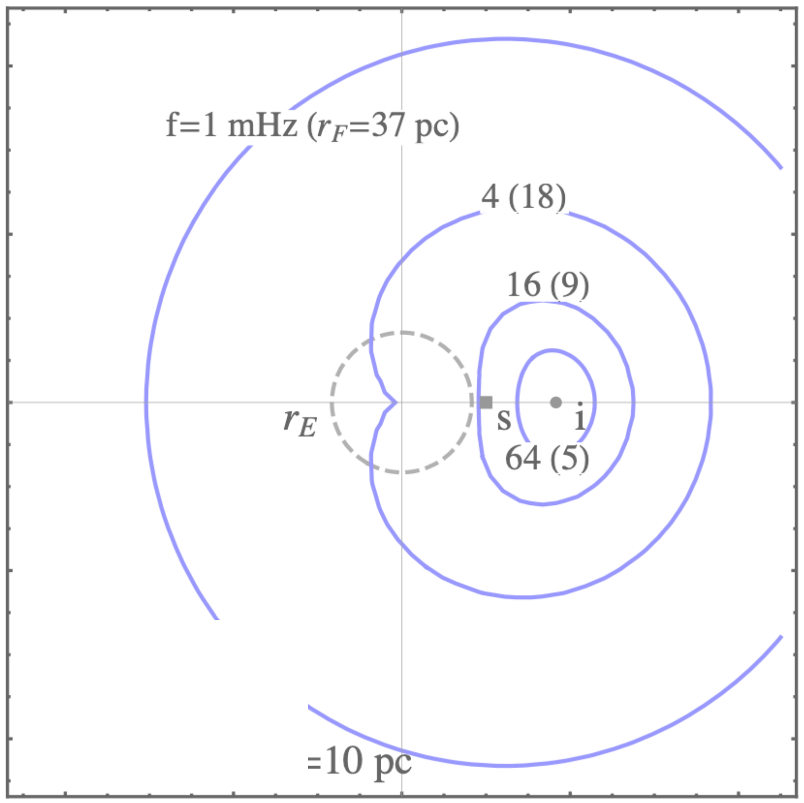
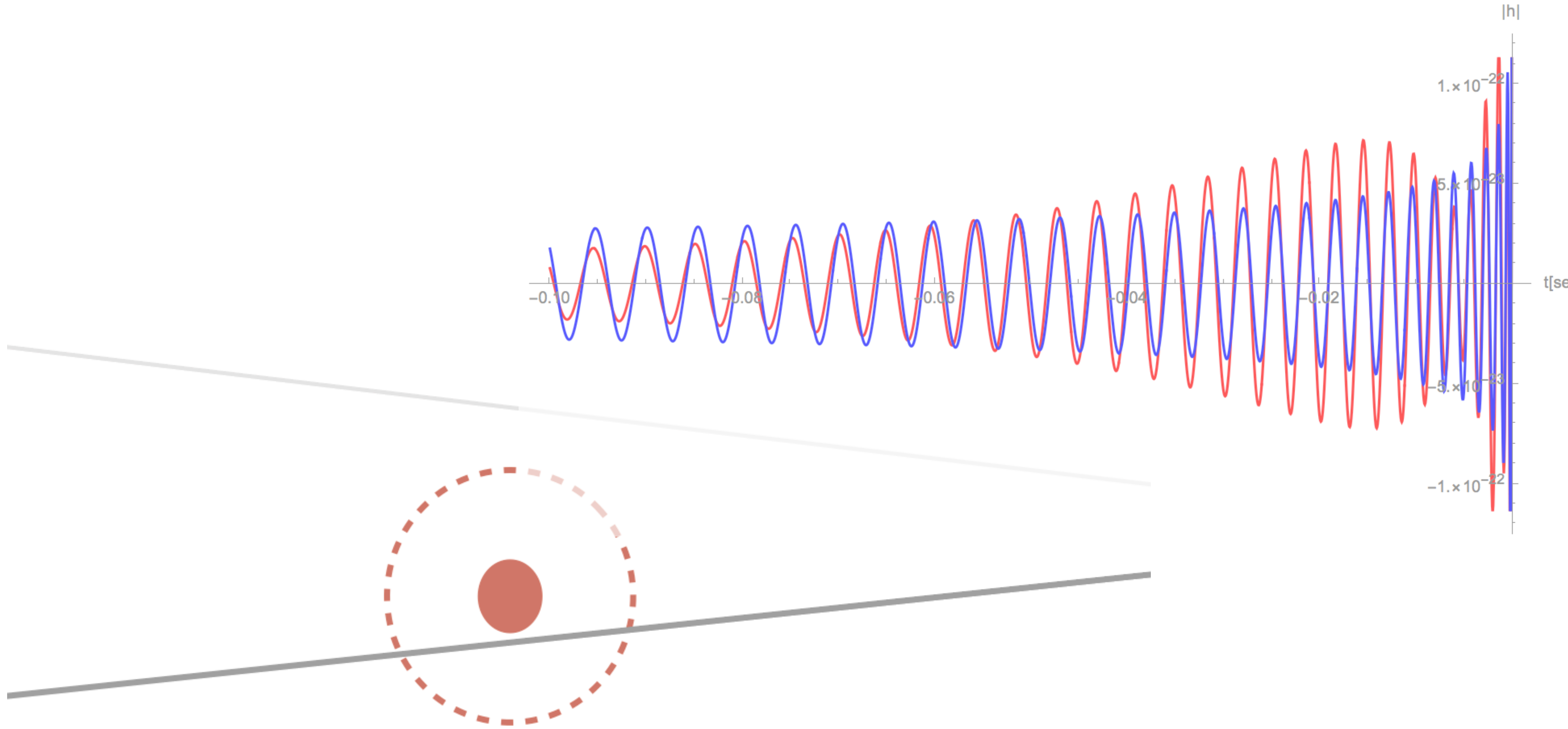
Lensing probes of DM

- Latest developments





Sunghoon Jung

Seoul National University

Works with HanGil Choi, TaeHun Kim, Sungjung Kim, Chanung Park, ChangSub Shin

CAU Workshop, 2022 Feb 10

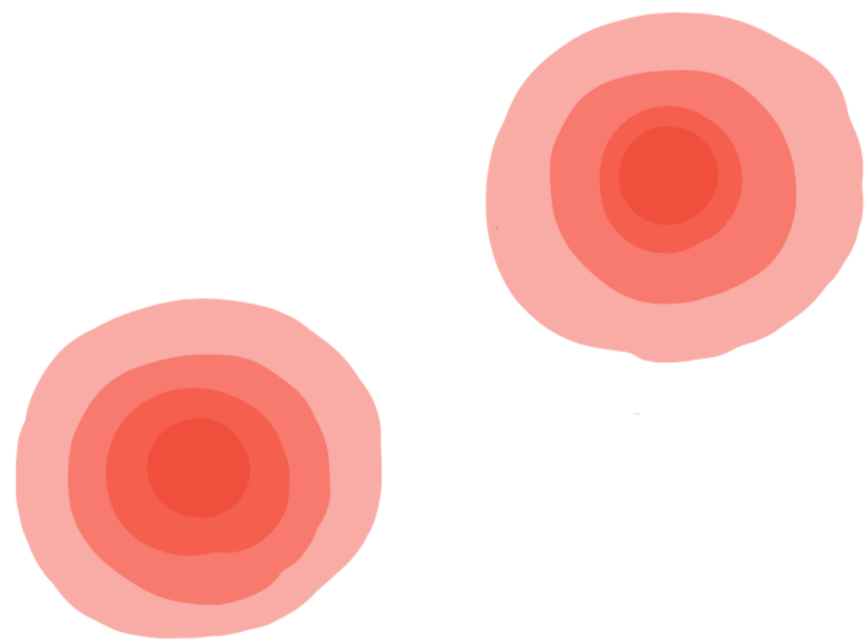
Lensing has been one of the best ways to measure masses (distribution) in the universe. It has been very well studied.

But, recently it turned out that many were still missing, which actually open up important possibilities to probe DM (and DE). GW discovery was one key motivation.

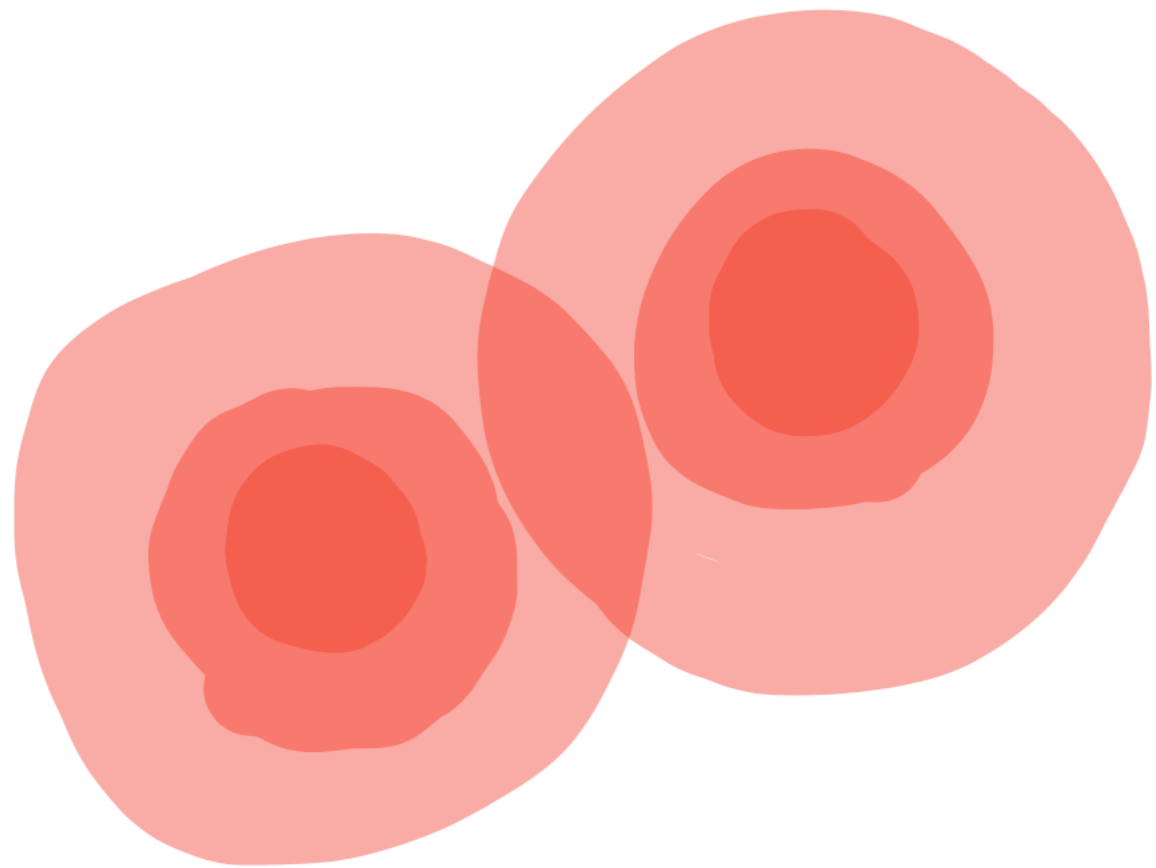
Today, I will talk about latest examples, with systematic and intuitive understandings beyond the traditional lensing.

Lensing is typically characterized by
image location, brightness, time-delay, shape distortion…
containing the info on the DM lens.

But lensing in general turns out to be much more spectacular.



As
f $\downarrow$ or E $\downarrow$ or wavelength $\uparrow$,
(or source bigger,
or detector res worse),



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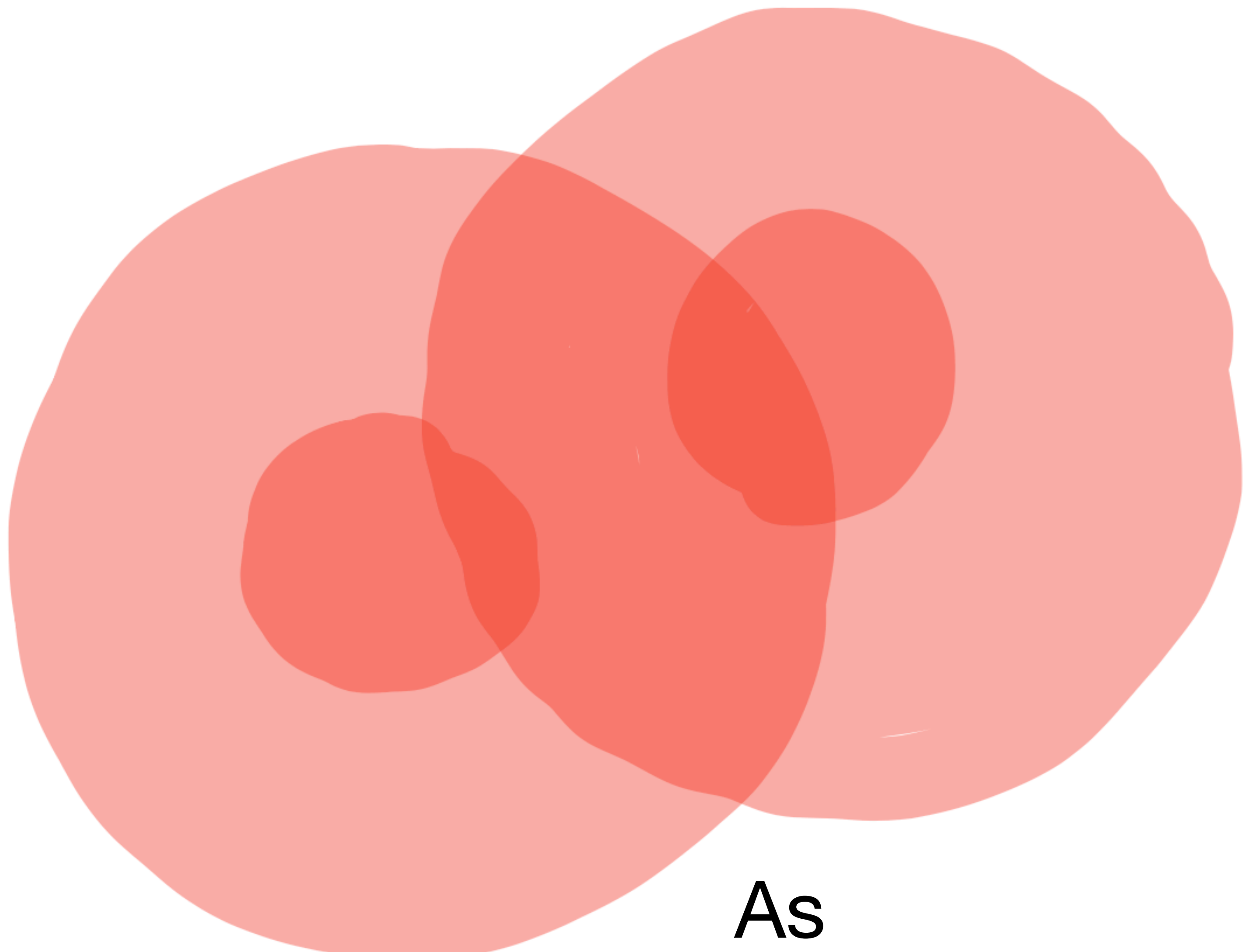

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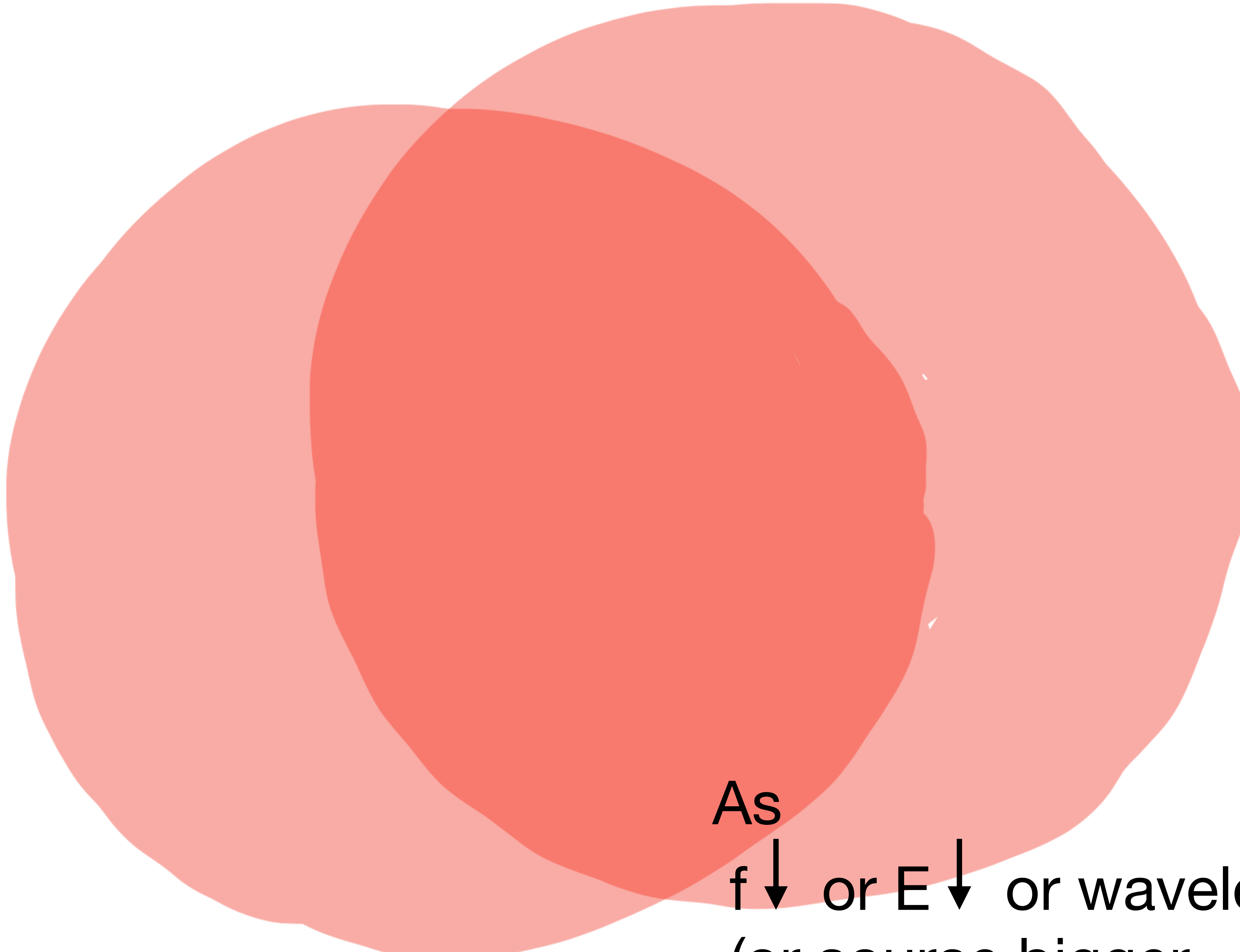

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or detector res worse),

Why and when do images blur and overlap?

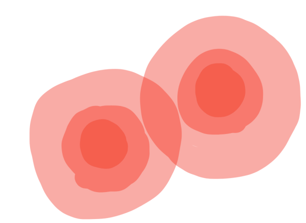
Key fact: Lensing is a path integral.
(clear images = stationary points)

Each case is realized in recently developed DM probes.
I will elaborate physics and applications by using latest examples.

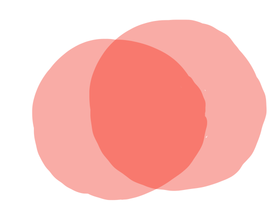
Topics

1. GRB Lensing Parallax:
   filling the last gap in the mass window of PBH DM

2. GW Fringe: allowing LIGO to probe PBH DM



3. Small-Scale Shear:
   unique probe of NFW subhalo $< 10^7$ Msun with GW

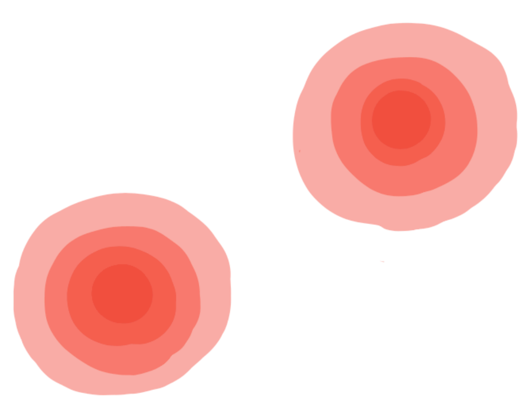


4. DM Focusing: equivalence to the DM lensing by Sun

1. GRB Lensing Parallax:

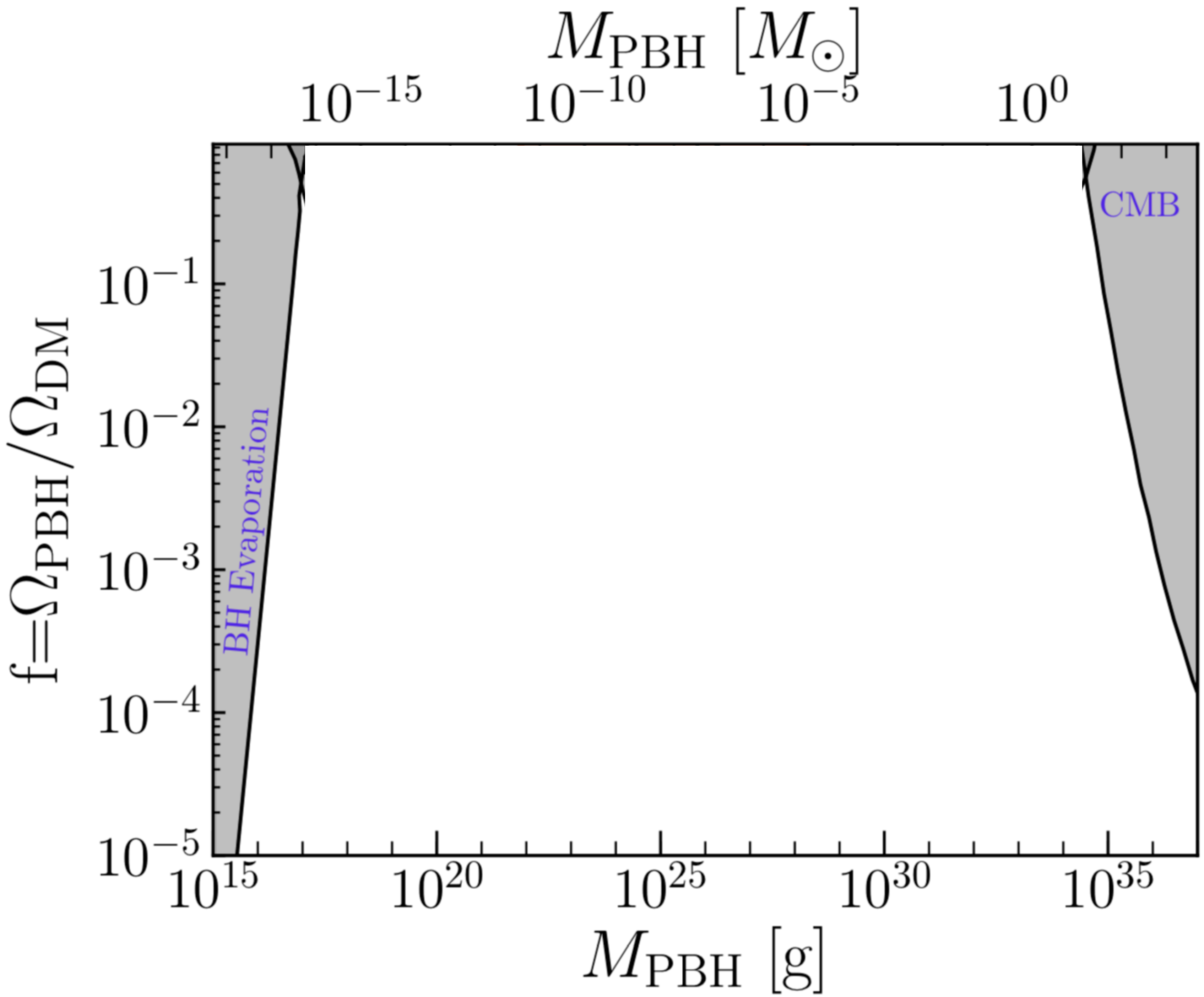
filling the last gap of PBH DM

S.Jung and T.H.Kim
1908.00078 PRR(2020)



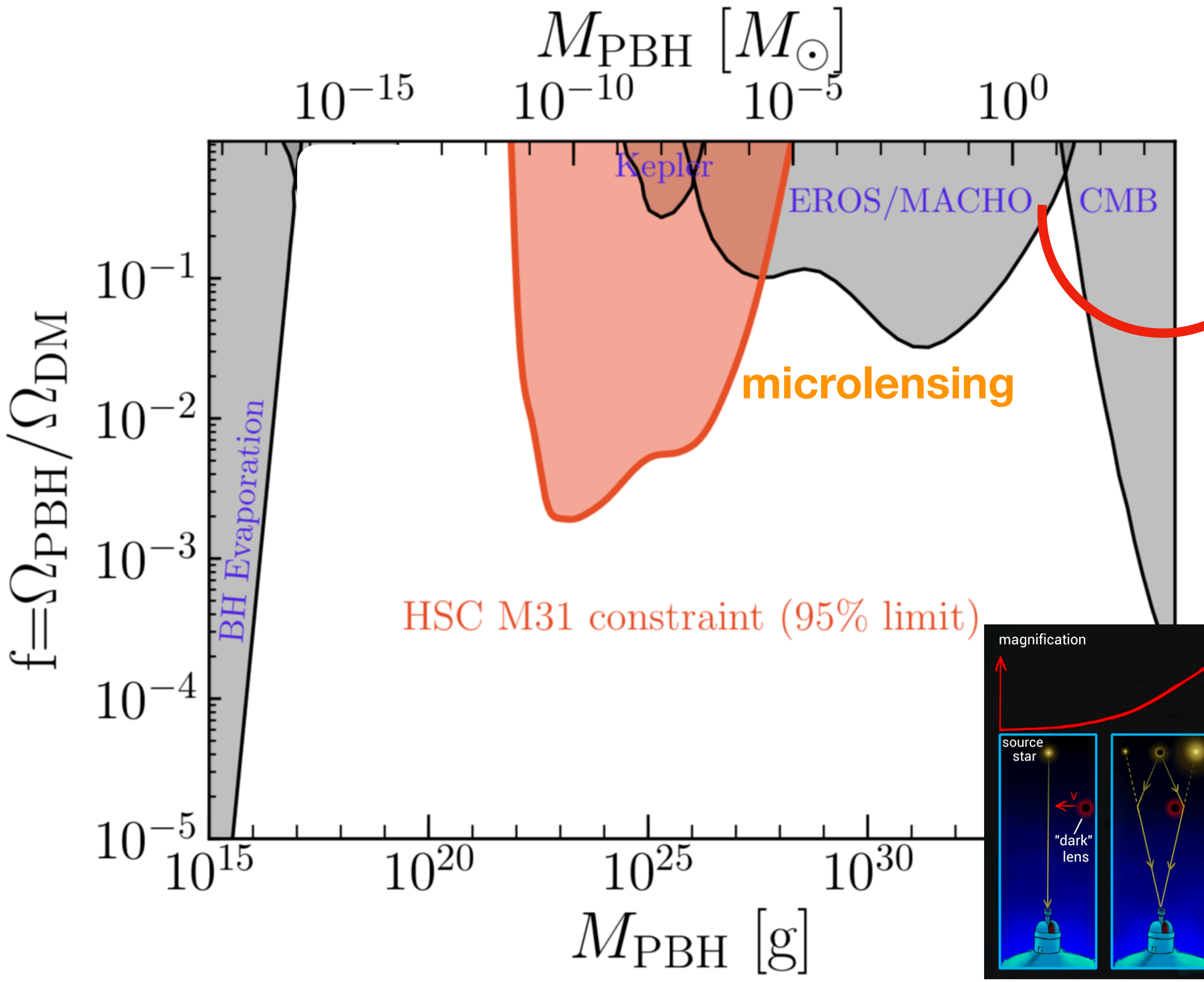
PBH DM

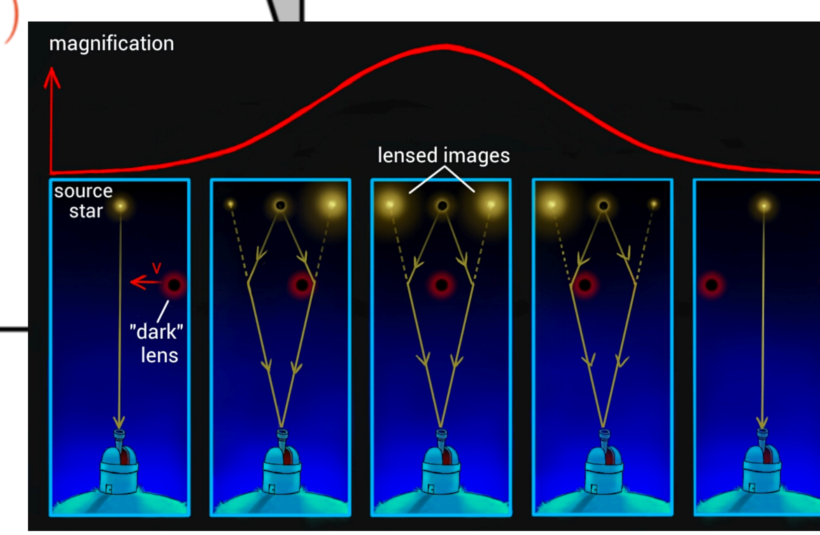
A wide mass range is possible btwn two general constraints.



PBH DM

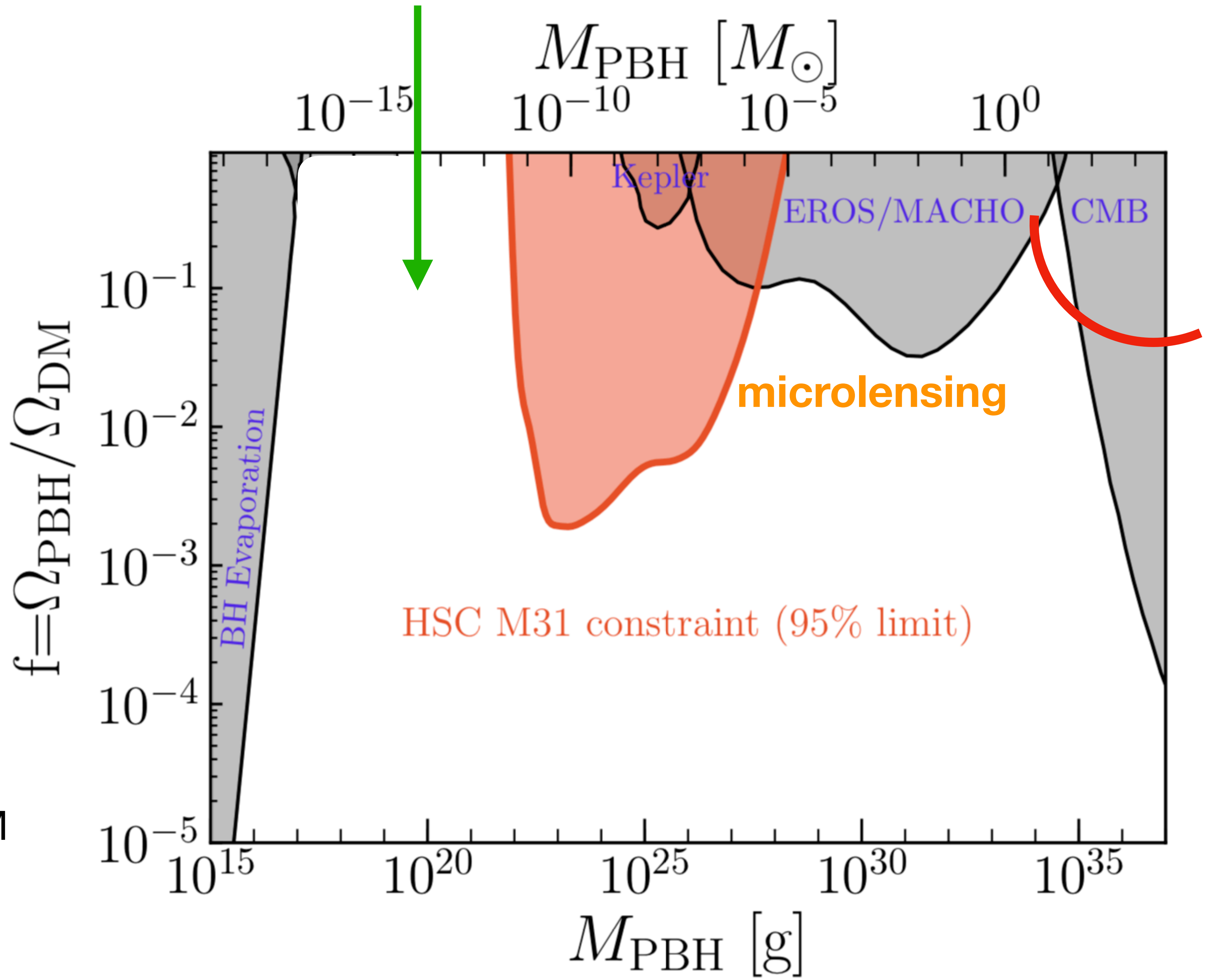
A large portion was probed by (micro)lensing.





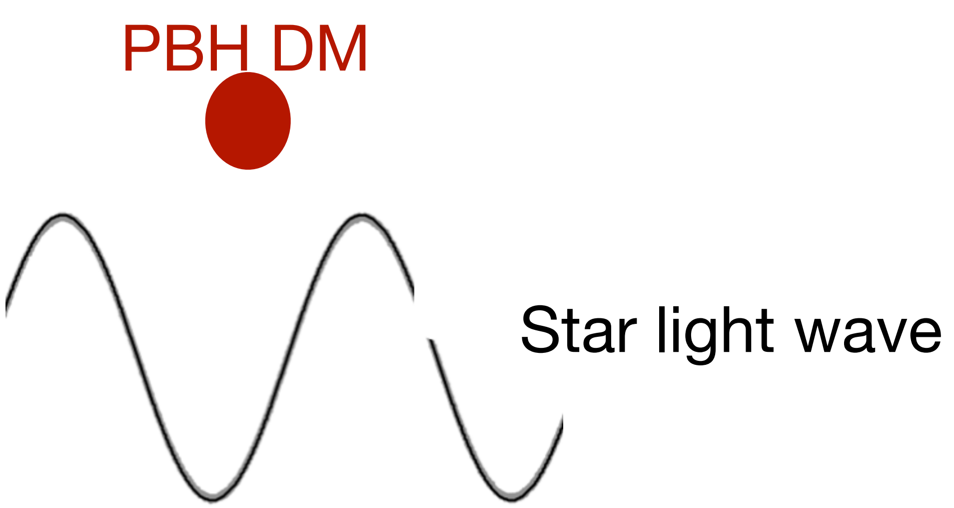
The last gap

No possible lensing probes of the lightest PBH DM.



Rsch ~ 10 fm
lightest PBH DM

Difficulties with (micro)lensing



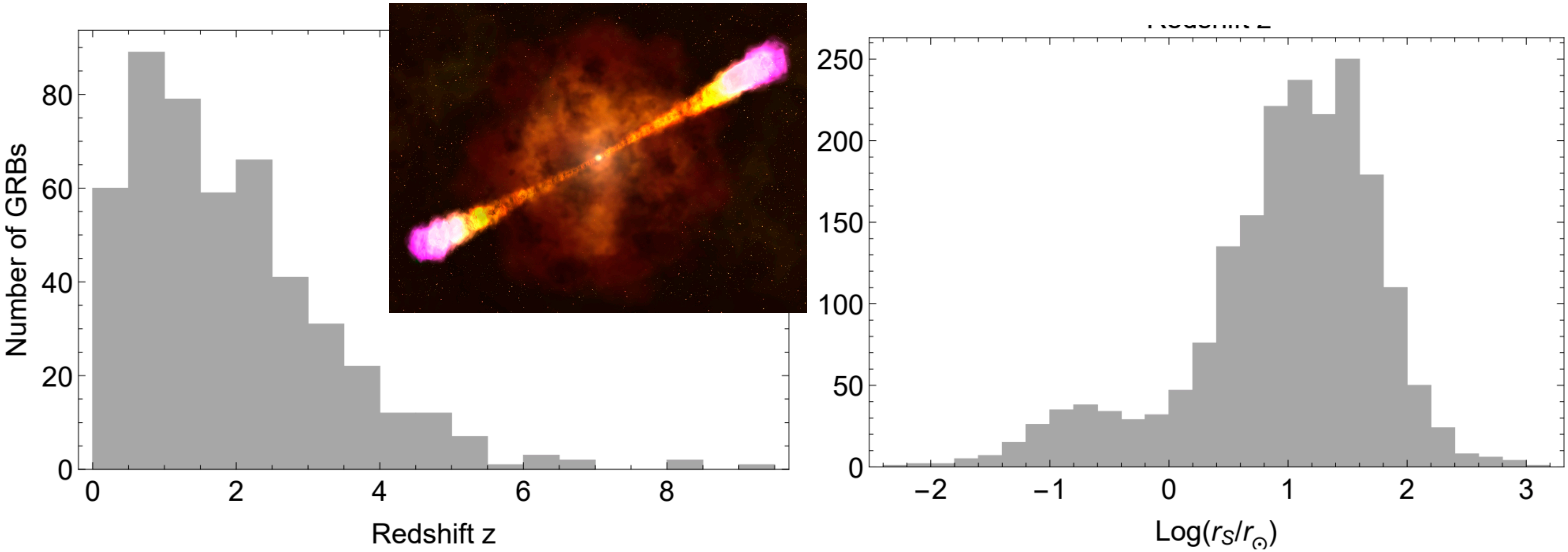
- Two inherent difficulties with “(micro)lensing of nearby stars”:
- 1. IR/optical wavelength is long > PBH R_sch is small.

Difficulties with (micro)lensing

- Two inherent difficulties with "(micro)lensing of nearby stars":

- 1. IR/optical wavelength is long > PBH R_sch is small.
  2. Nearby stars appear large > nearby PBH r_E is small.

GRB lensing as a new probe

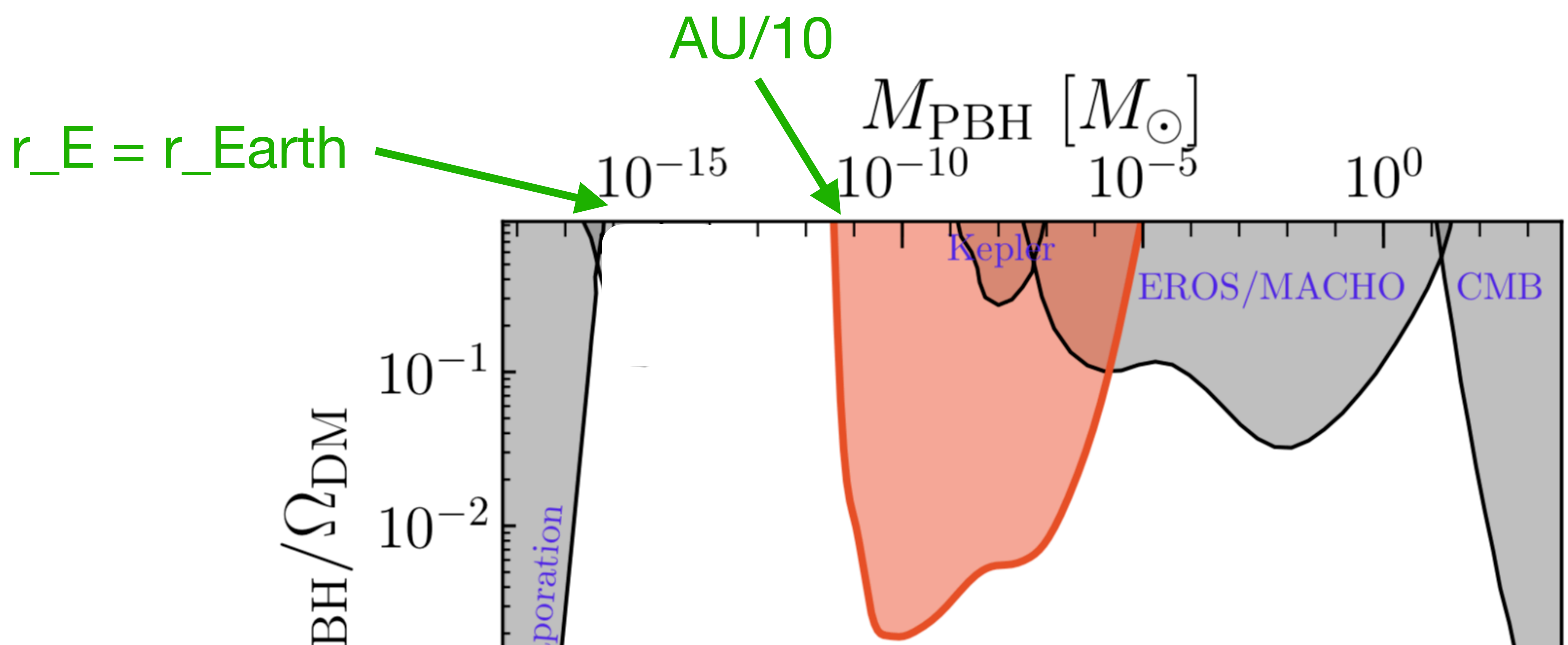


- Gamma-Ray Burst is a candidate to overcome both:

  1. At far distance, GRB appears small < PBH r_E large.
  2. Gamma-ray wavelength is small(est) < PBH r_Sch.

  N.B. At cosmo distance, it also probes a larger part of the Universe.

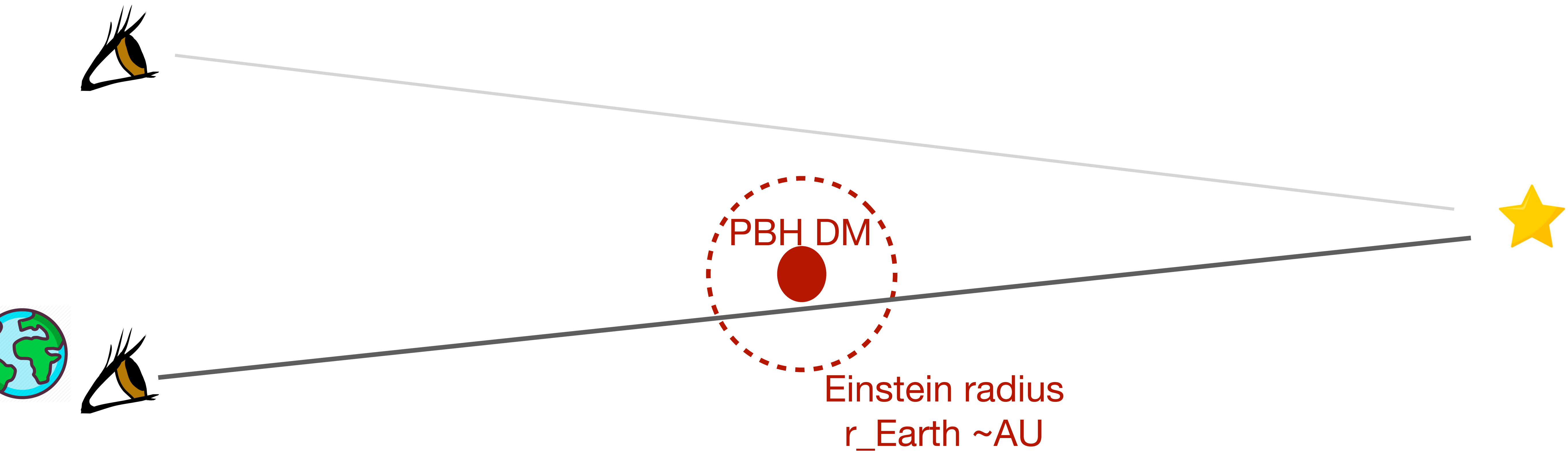
GRB Lensing Parallax



- But GRB is a short pulse. How can we tell it's lensed?!
- The Einstein radius of this mass range *happens* to be the astrophysical scale accessible to us : r_E = r_Earth ~ AU !

M_{PBH} [g]

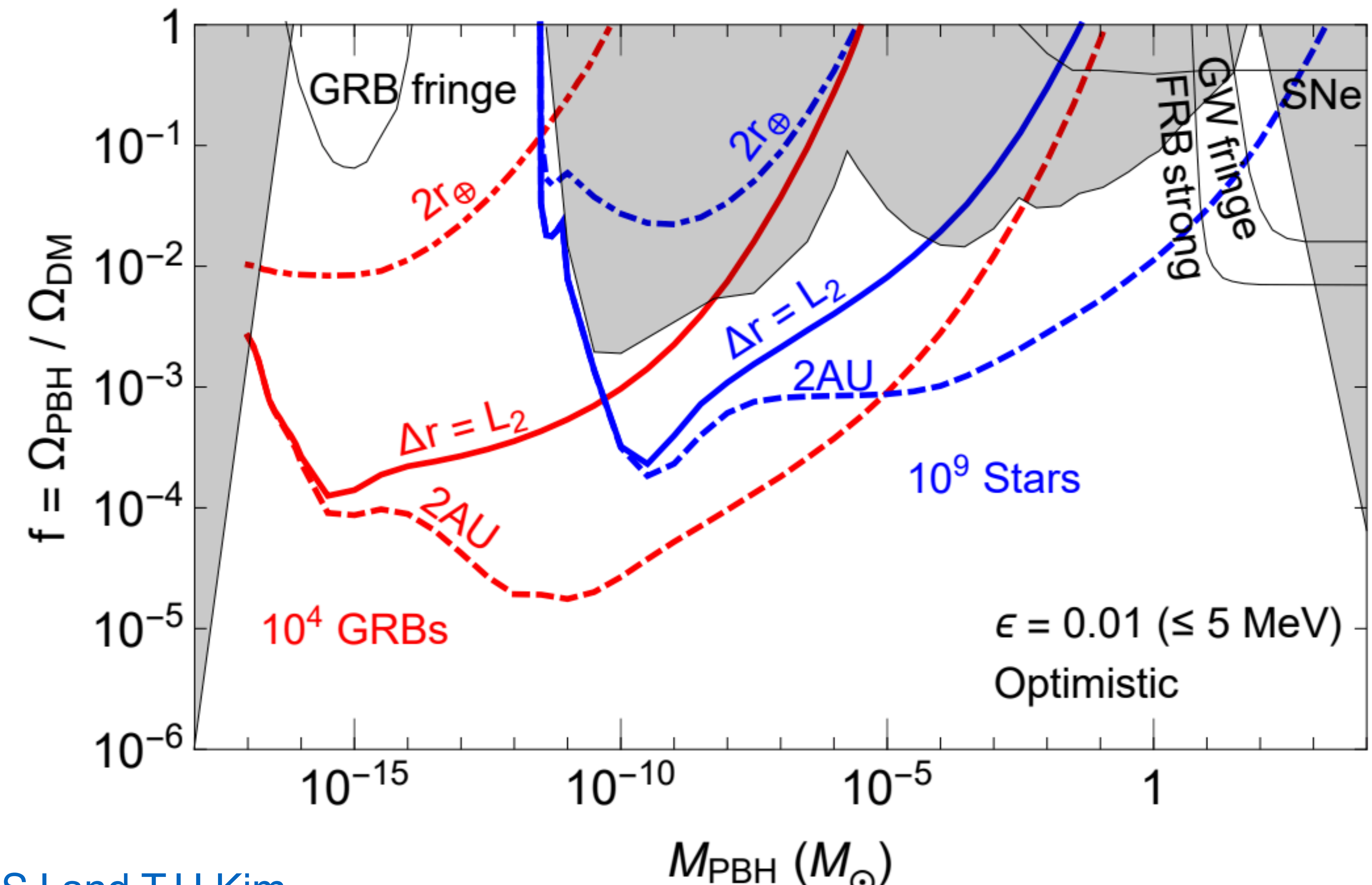
GRB Lensing Parallax



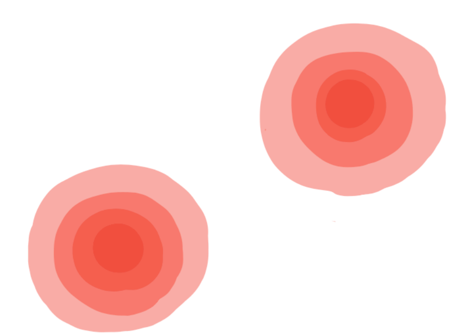
- GRB pulses observed by spatially separated detectors can measure different lensing magnifications.

SJ and T.H.Kim
1908.00078 PRR(2020)

GRB Lensing Parallax



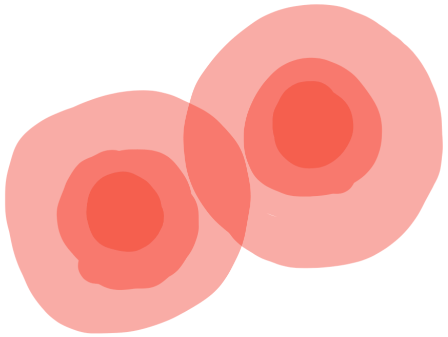
SJ and T.H.Kim
1908.00078 PRR(2020)



2. GW Fringe:

allowing LIGO to probe PBH DM

S.Jung and C.S.Shin
1712.01396 PRL(2019)

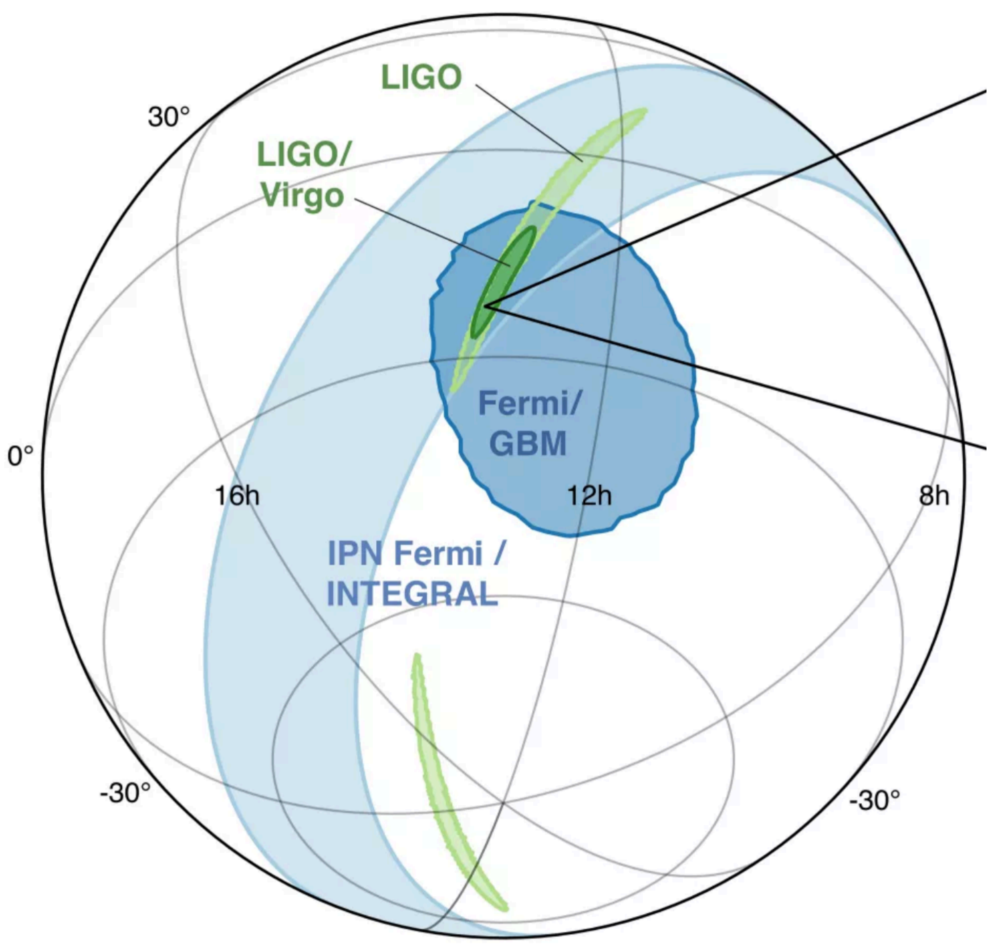


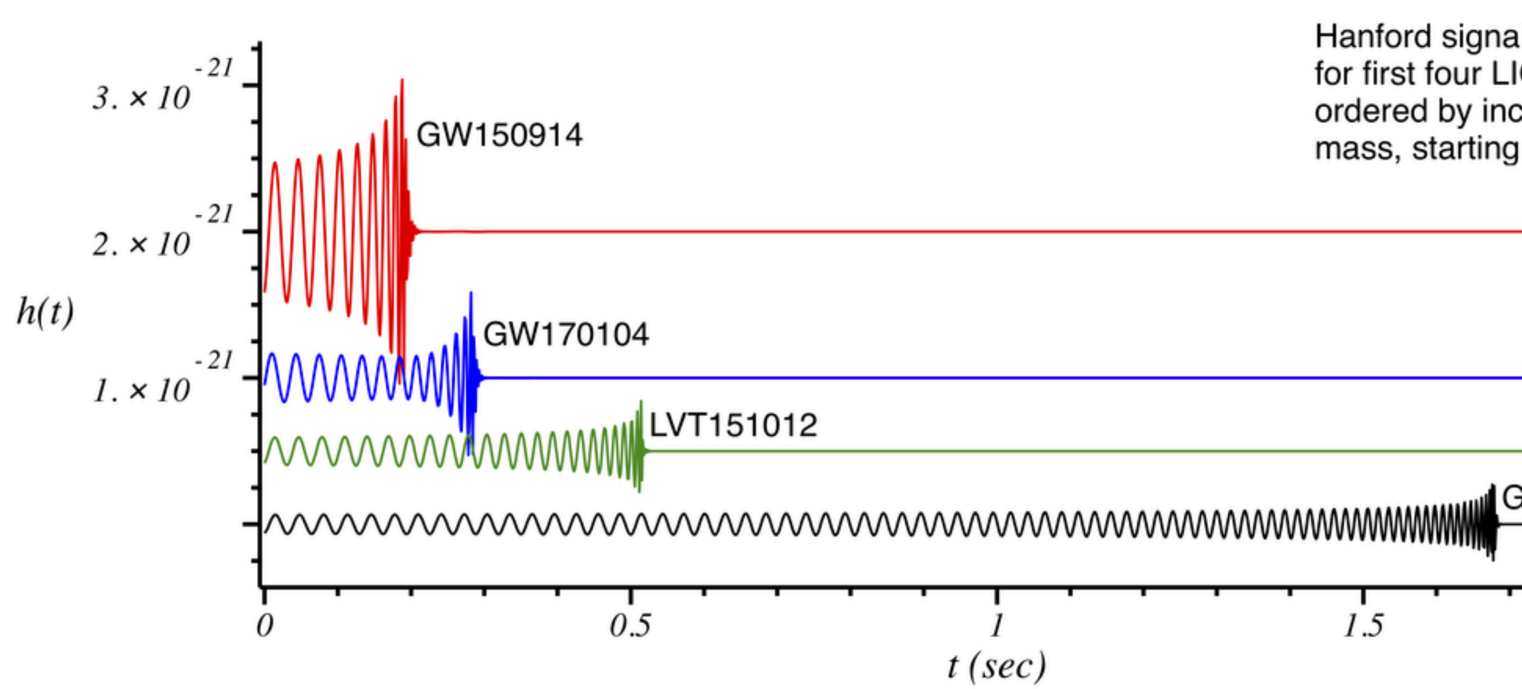
‘GW lensing’ observation seems very unlikely at LIGO!

LIGO can see only with

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

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





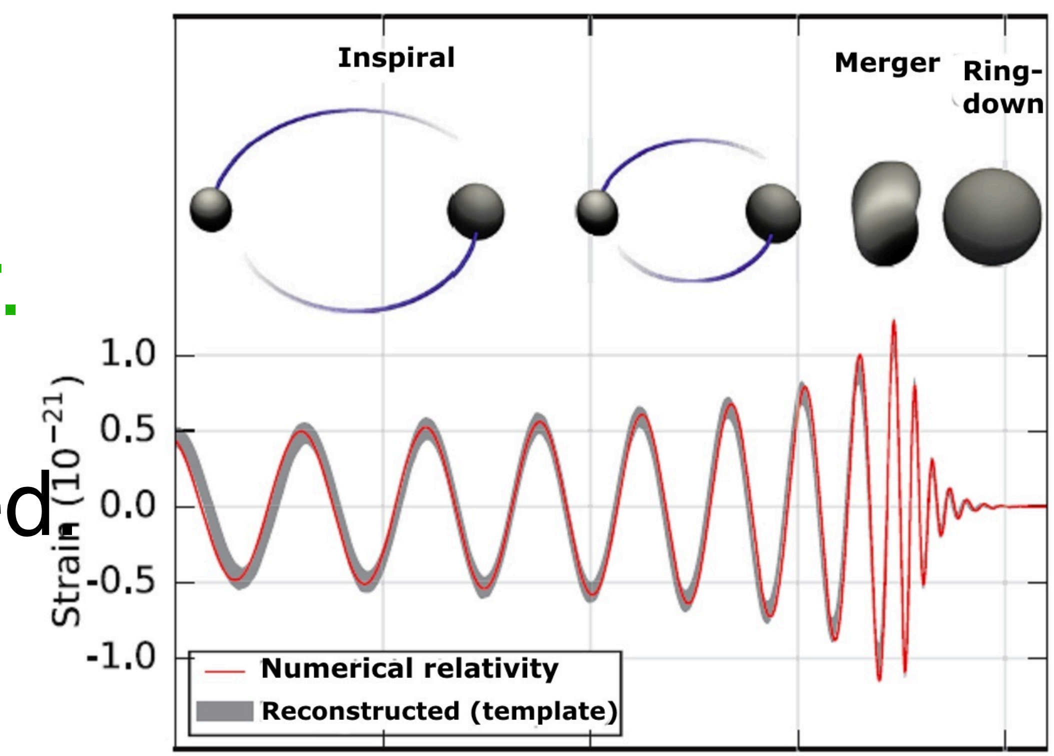
GW vs. light

Even though they follow the same null geodesics,,,

- GW chirps.
  - It provides characteristic lensing pattern, extremely useful in detection as well as DM info extraction.

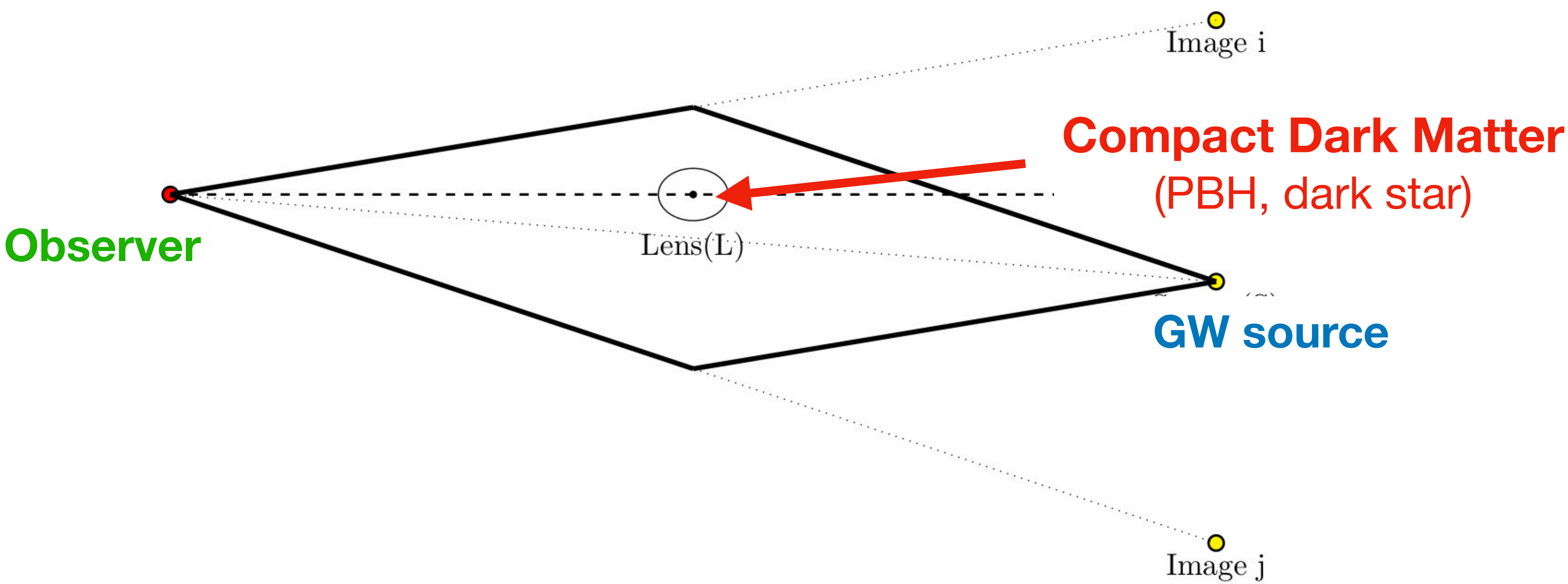
- GW angular resolution is much worse.
  - New observables.

- GW wavelength is much longer.
  - New developments beyond traditional lensing became needed.



Time-delayed images

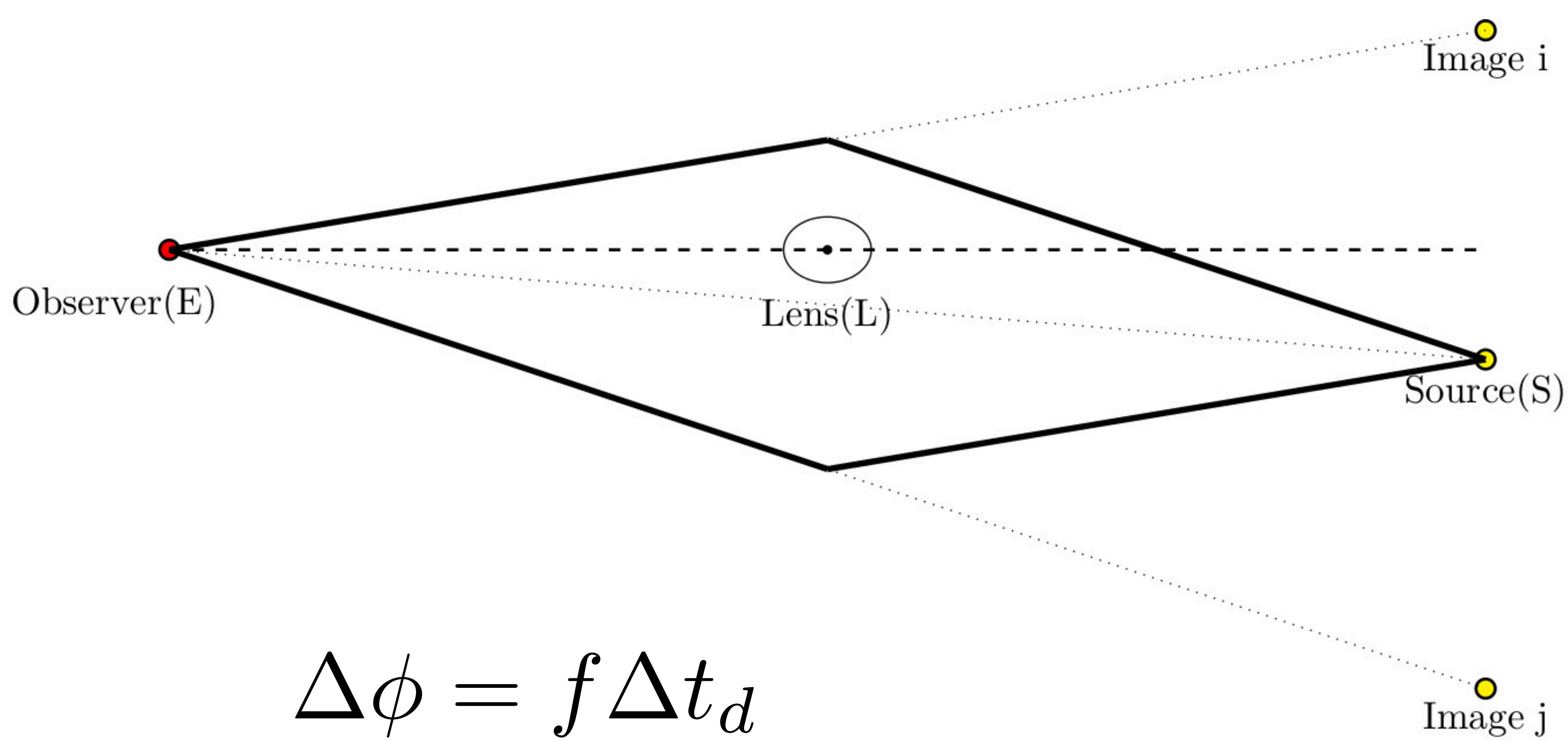
Consider time-delayed lensed images of GW.



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

Interfered images

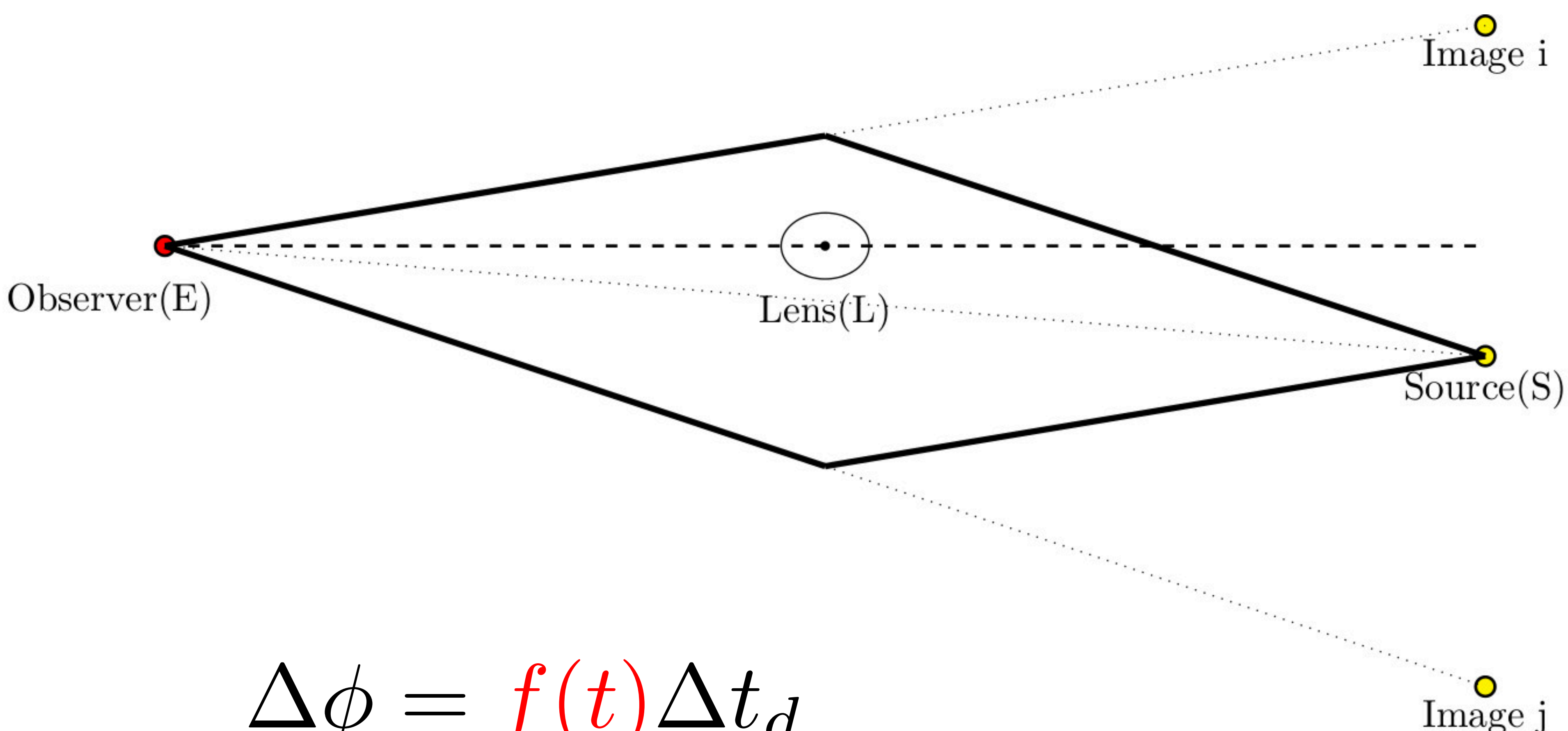
Unresolved GW images rather superpose and “interfere” in our observation.



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

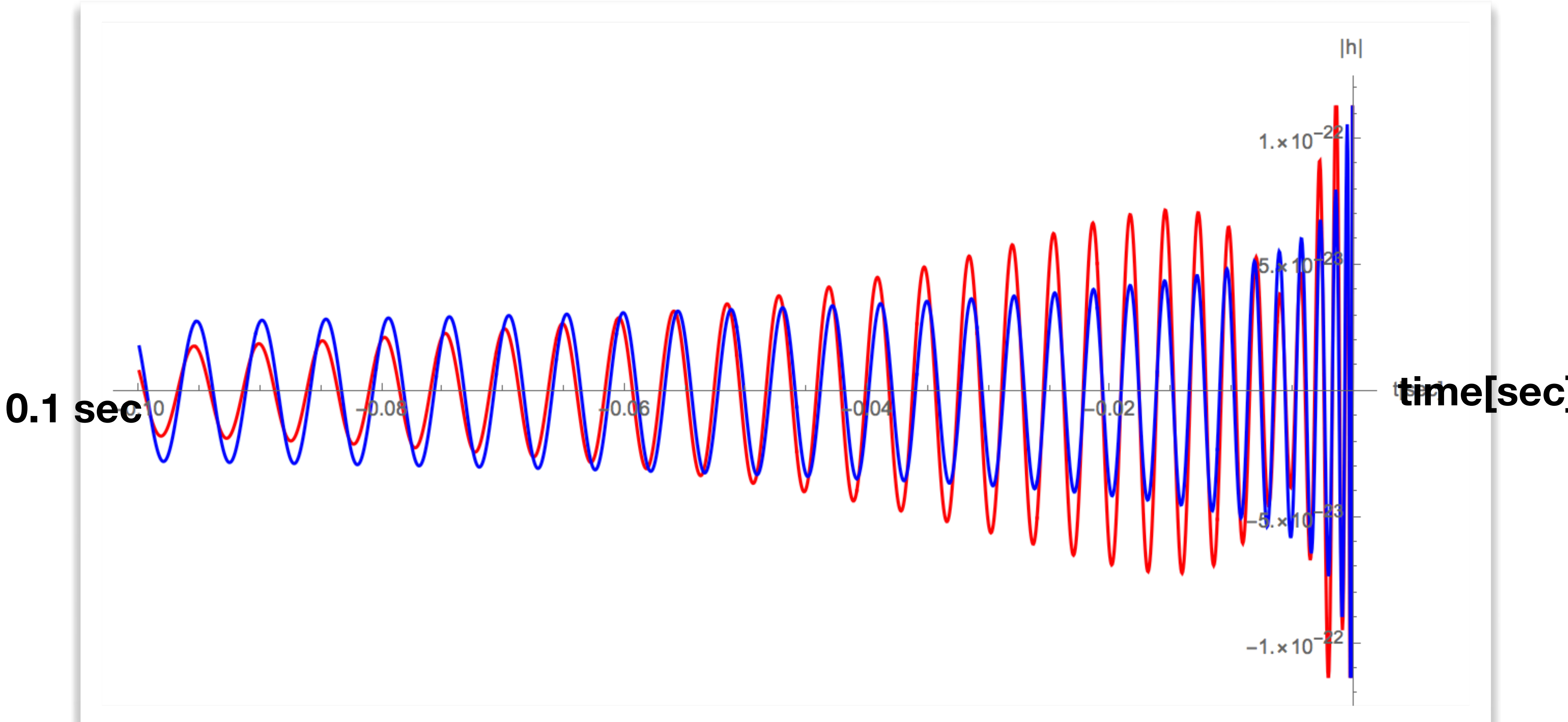
GW lensing Fringe

It is the *GW chirping* that makes the interference observable — sweeping the interference pattern over a range of freq.



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

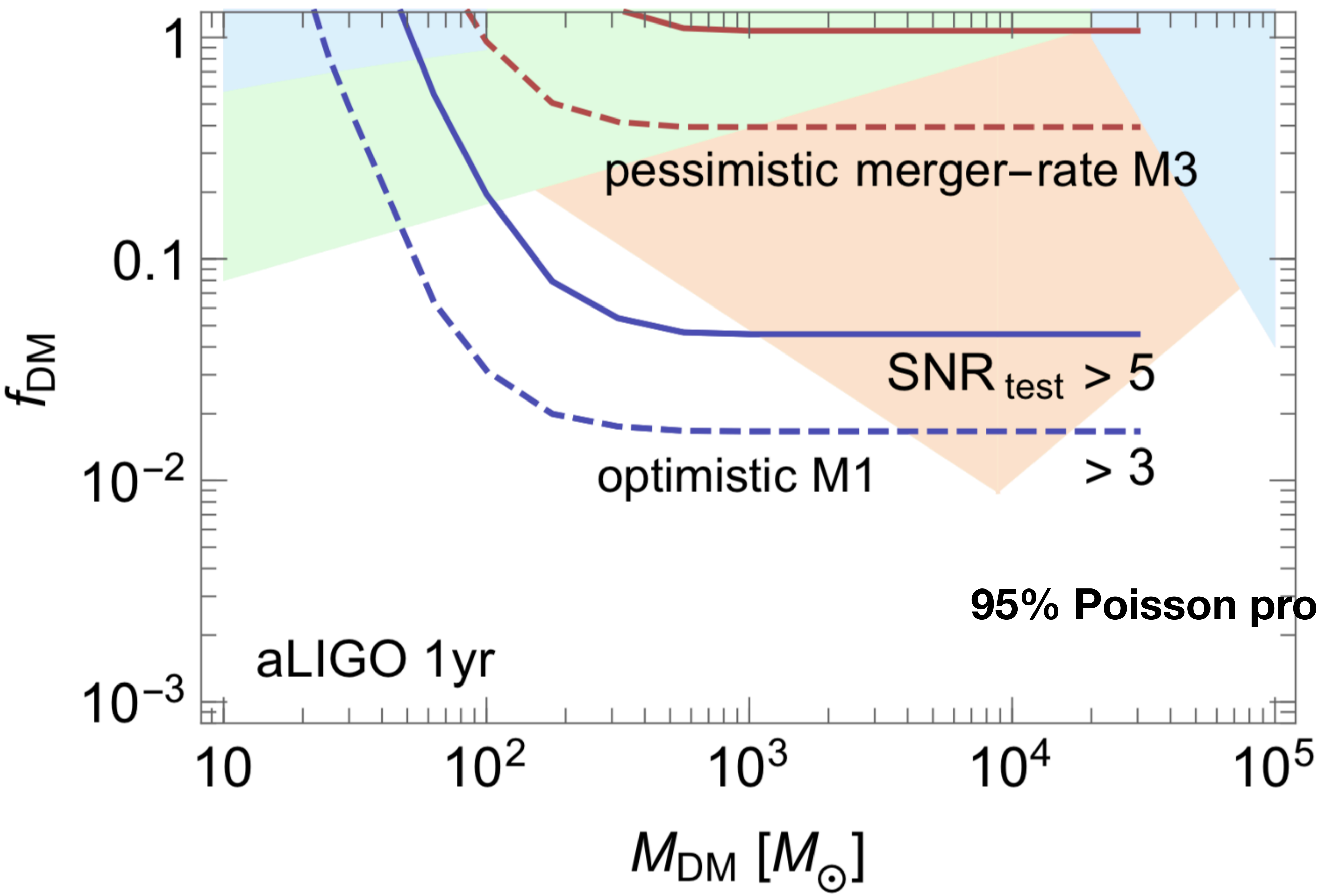
“GW Fringe”



NS-NS merger lensed by 100 Msun PBH.

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

PBH DM fraction

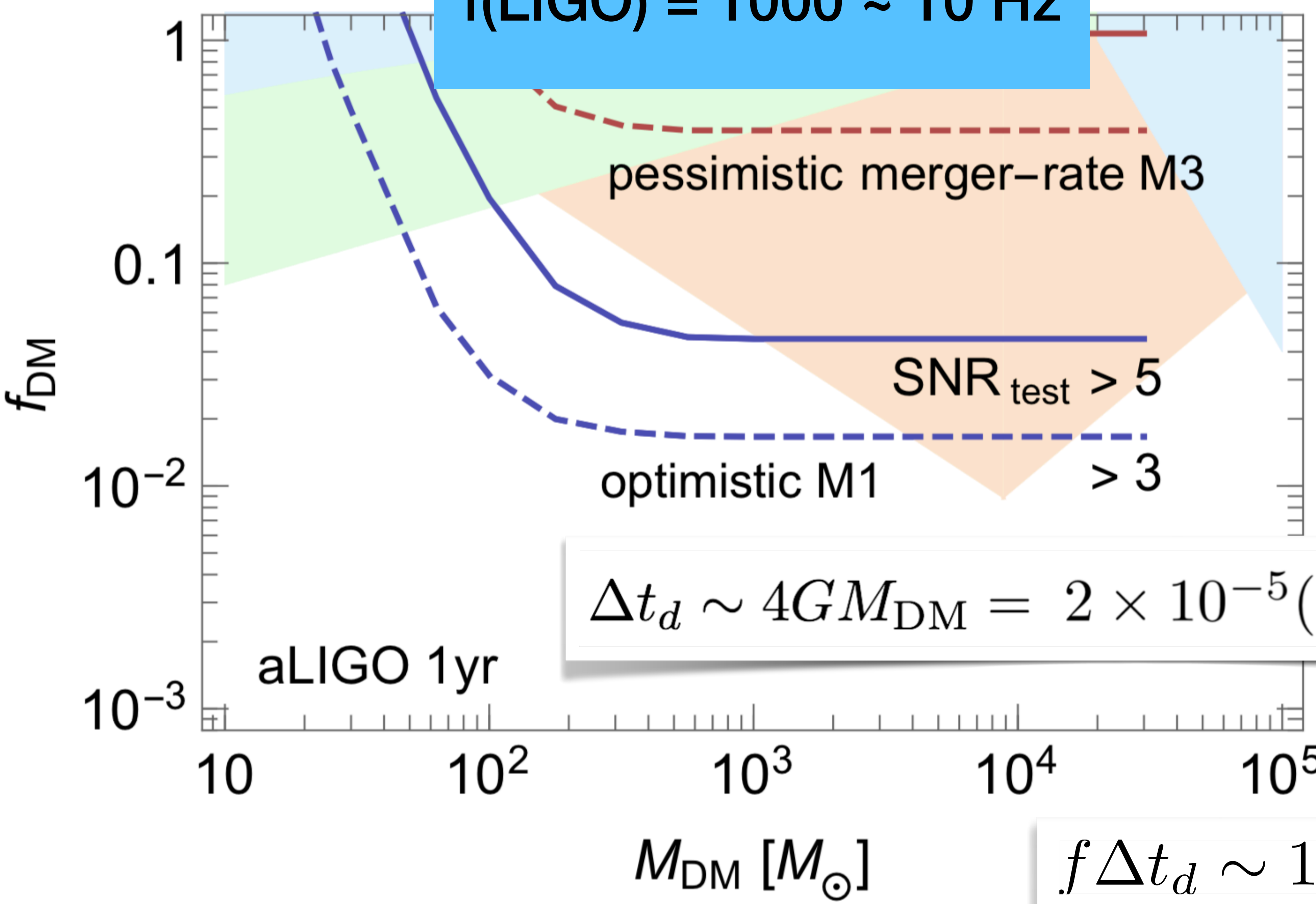


95% Poisson prob of >=1 detection

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

PBH DM fraction

f(LIGO) = 1000 ~ 10 Hz

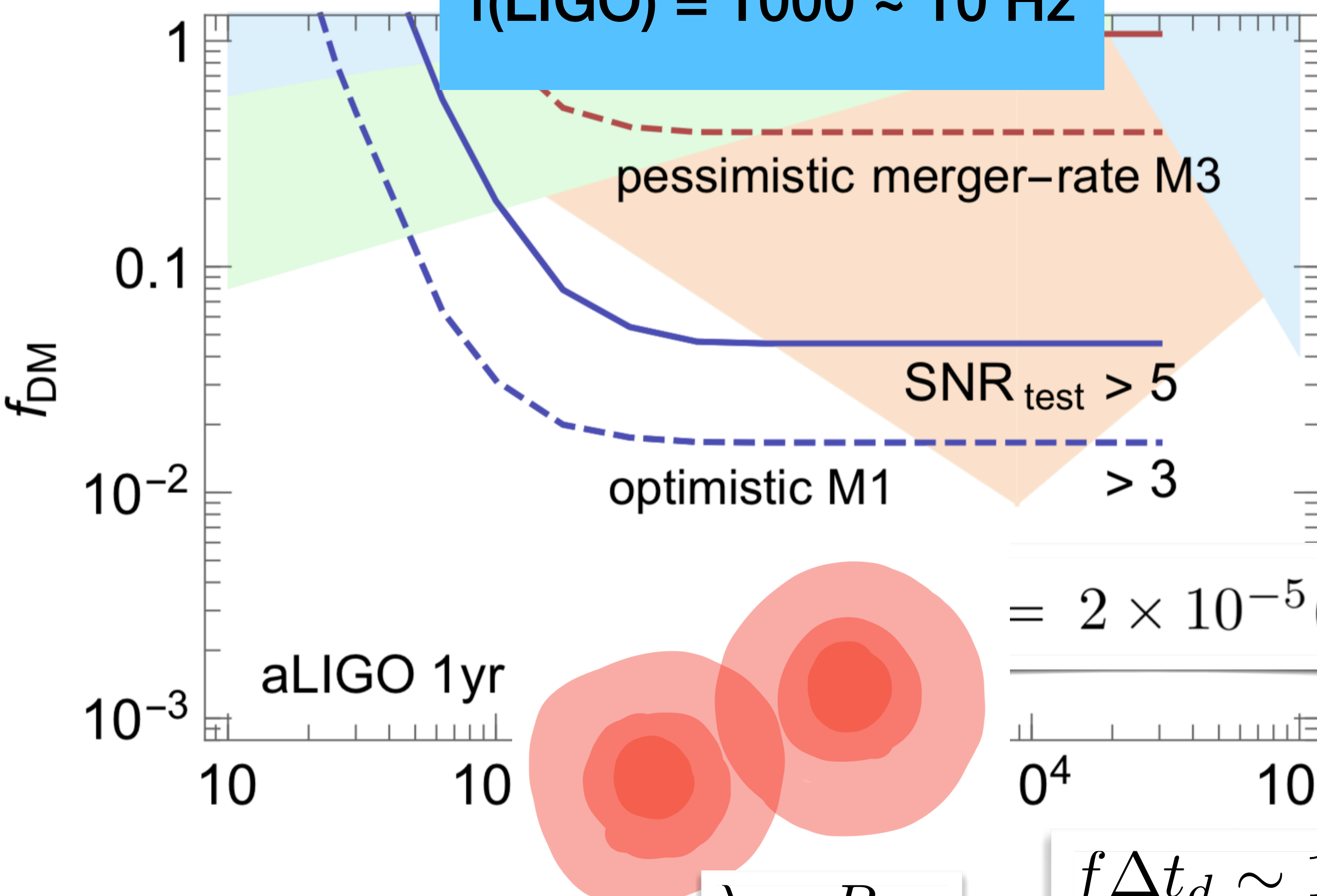


$$\Delta t_d \sim 4GM_{\rm DM} = \; 2\times 10^{-5}(M_{\rm DM}/M_\odot) \; {\rm sec}$$

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

PBH DM fraction

f(LIGO) = 1000 ~ 10 Hz



$= 2 \times 10^{-5} (M_{DM}/M_\odot)$ sec

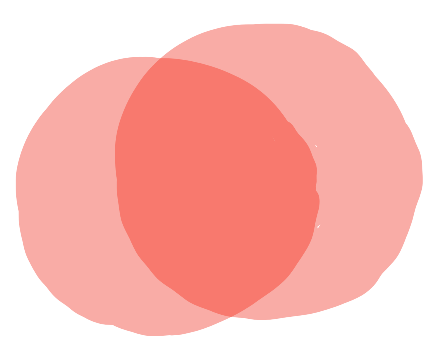
$\lambda \sim R_{Sch}$

$f \Delta t_d \sim 1+$

3. Small-Scale Shear:

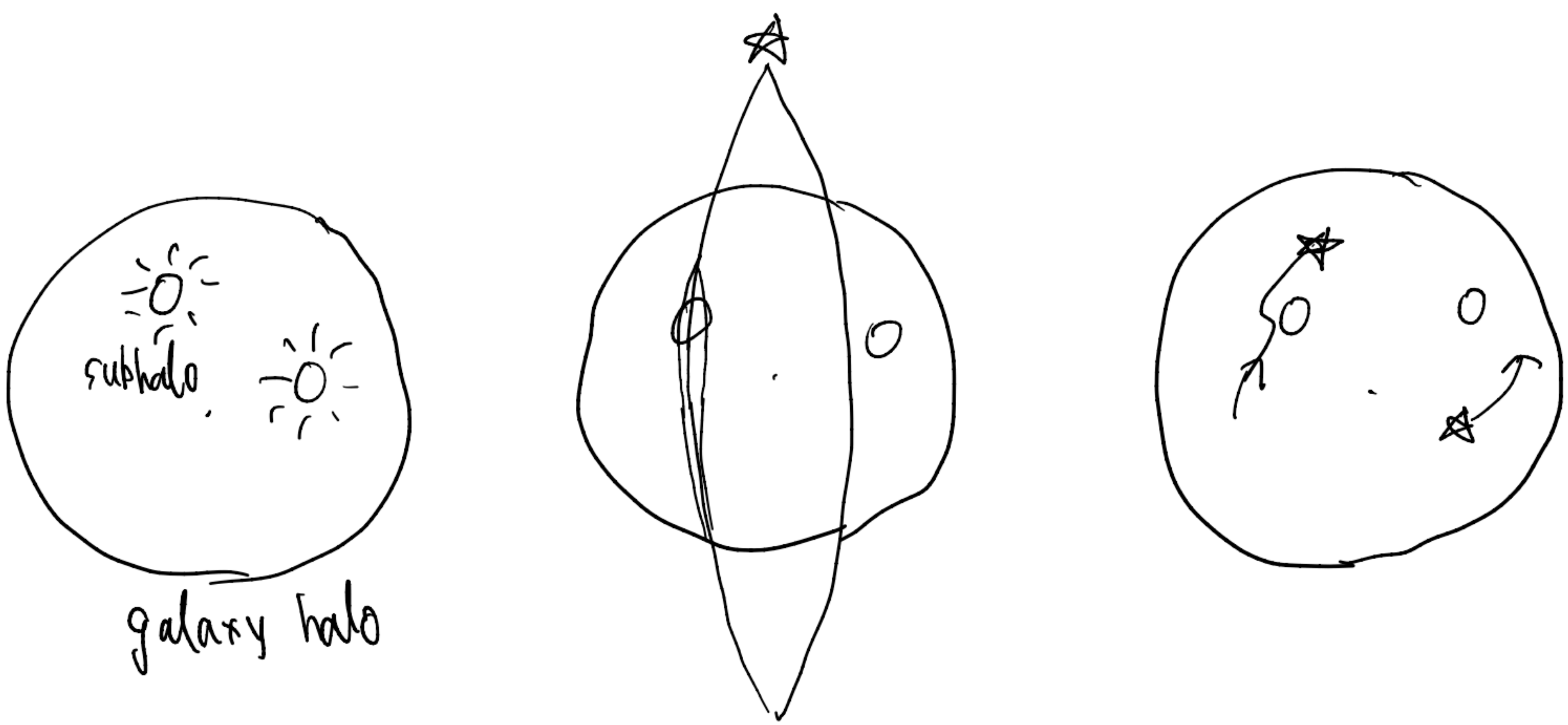
small invisible NFW subhalos < 10^7 Msun with GW

H.G.Choi, C.U.Park, and S.Jung
2103.08618 PRD(2021)

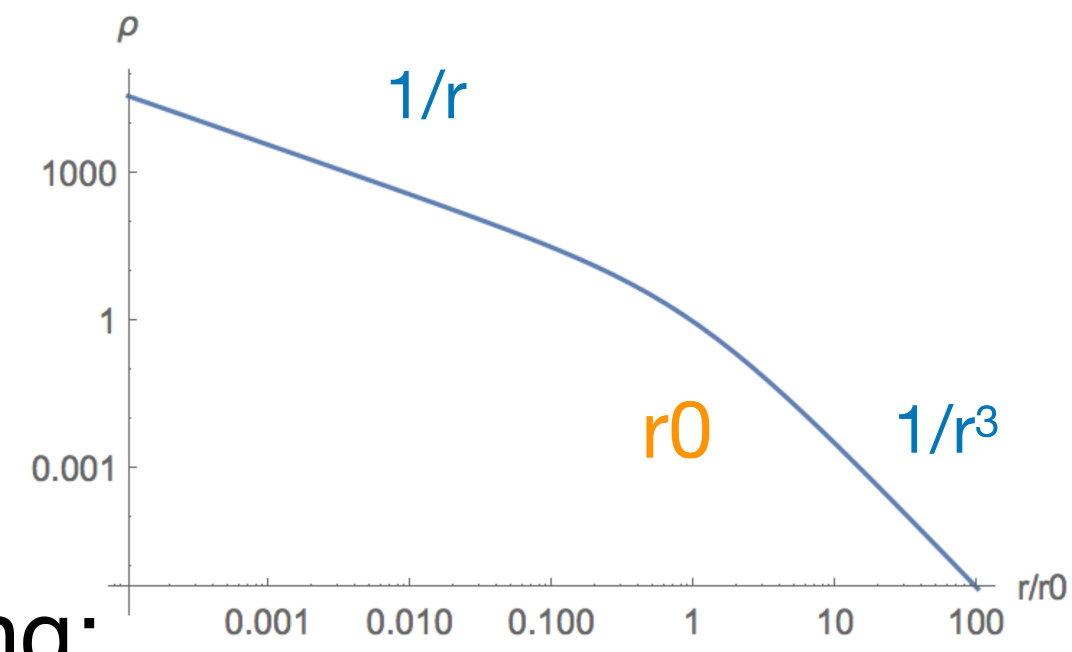


Small-scale subhalos never seen

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



NFW subhalo



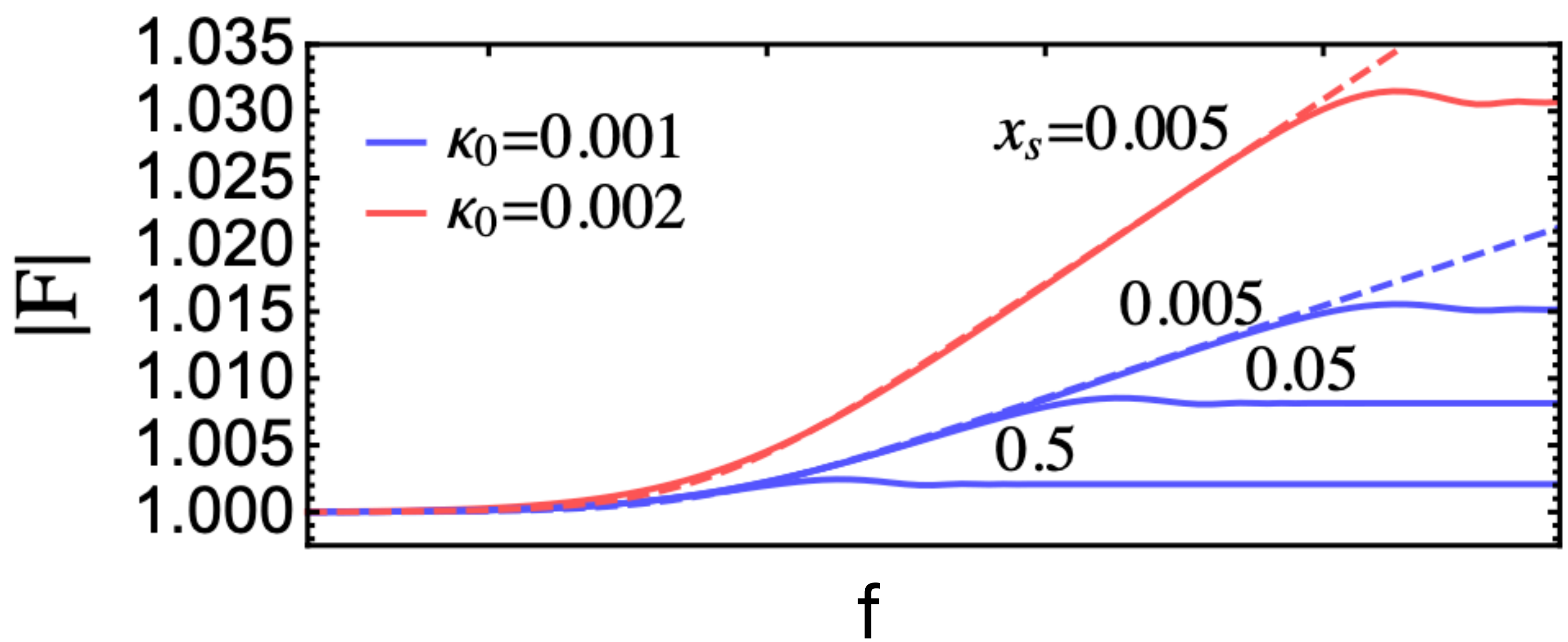
- CDM prediction.
- Diffuse over a length scale r0.
- Too diffuse to induce strong lensing: Einstein radius (or surface density) is exponentially small.

$$r_0 \simeq 2\ \mathrm{kpc}\left(\frac{M_{\mathrm{NFW}}}{10^9 M_\odot}\right)^{0.41}$$ = 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, possible only with GW scale coincidence and its chirping.
- Although weak and single-imaged, lensing does change brightness, as a function of the GW frequency — diffractive lensing.



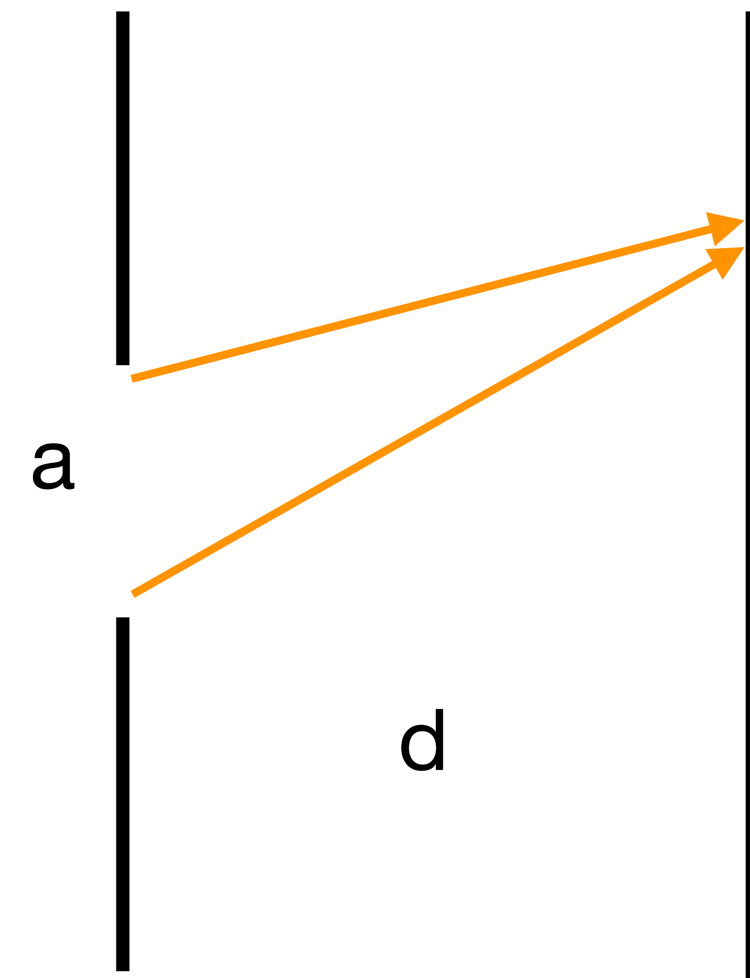
Analogy with single-slit diffraction

- 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

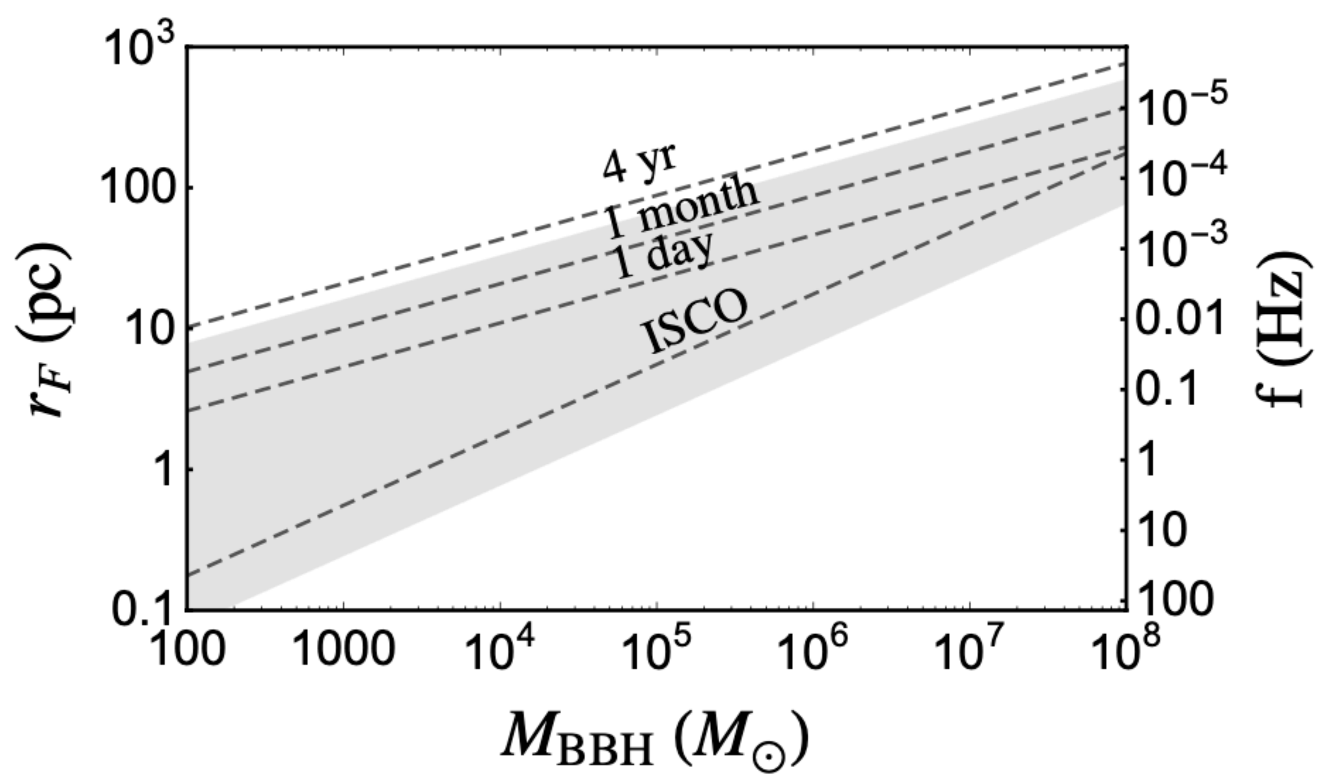


- Shadow quickly sharpens with the frequency when rF ~ a. Exactly same happens for the NFW shadow with GW.

GW diffractive lensing by NFW

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

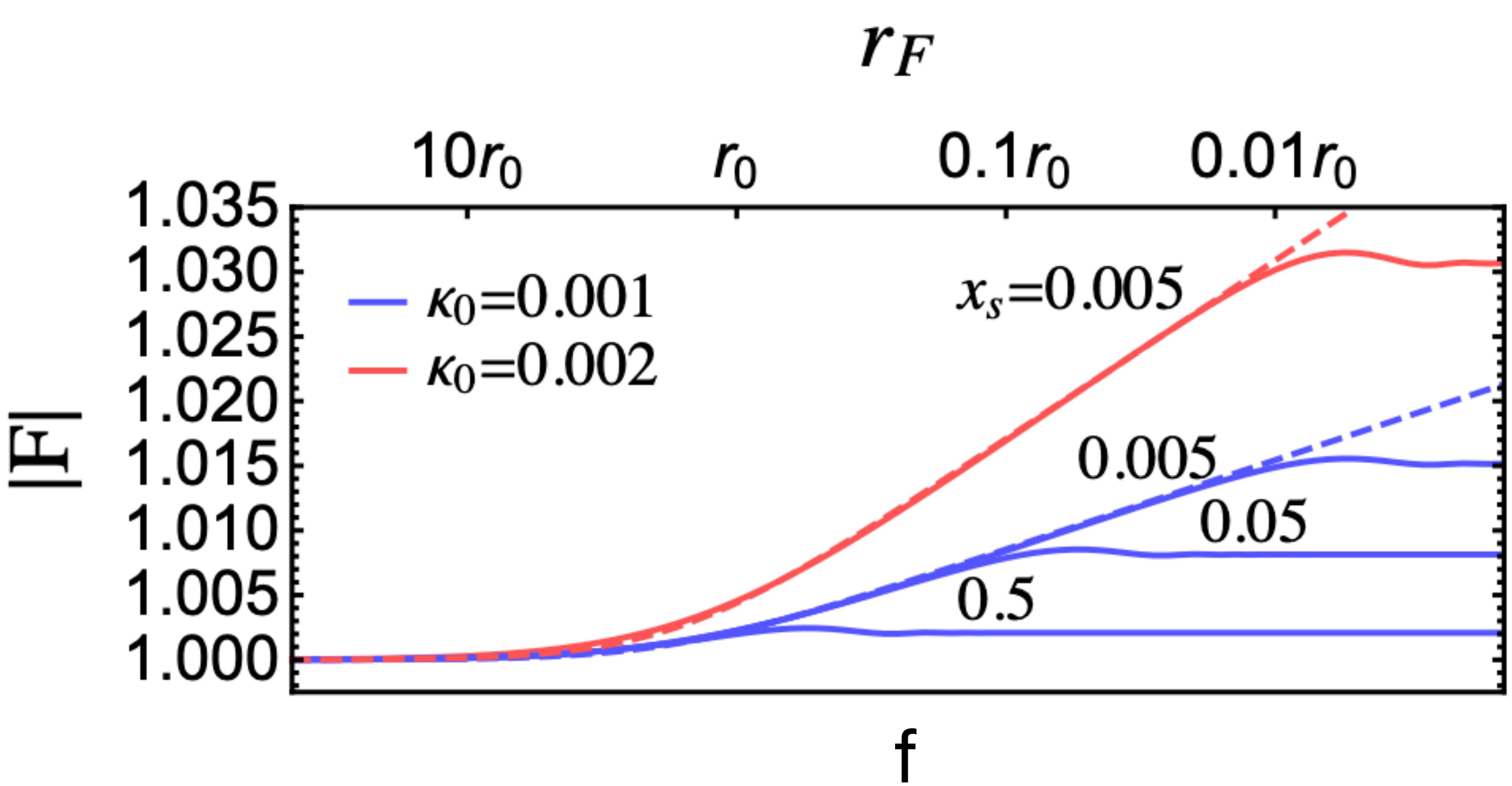
$$r_F \simeq 1.76 \text{ pc} \sqrt{\frac{1}{1+z_l}\left(\frac{d_{\rm eff}}{\rm Gpc}\right)\left(\frac{\rm Hz}{f}\right)}.$$



Observable signal of NFW

- The freq-dep amplitude is the observable signal of NFW!

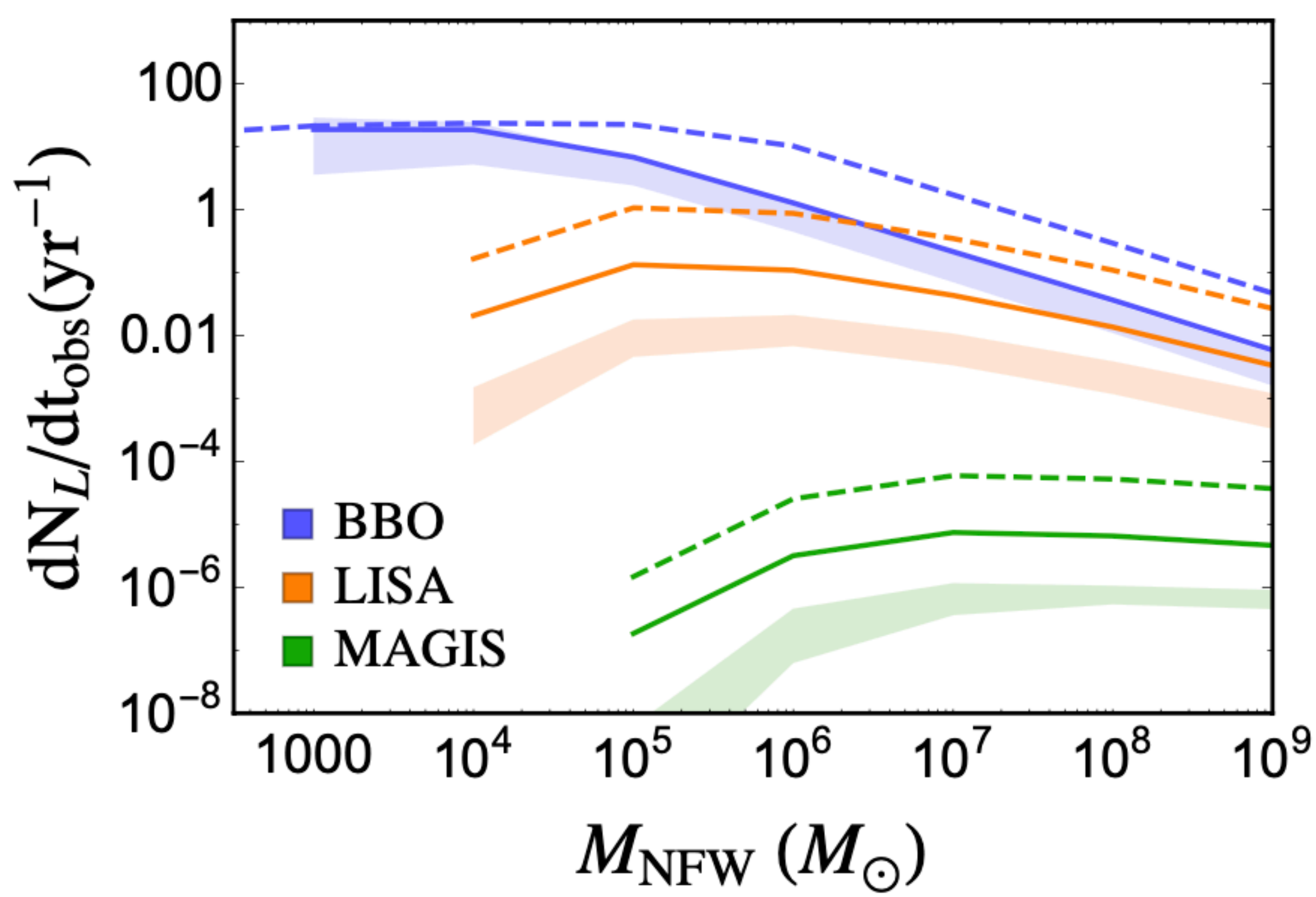
(NFW shadow becomes clearer with the GW chirping.)

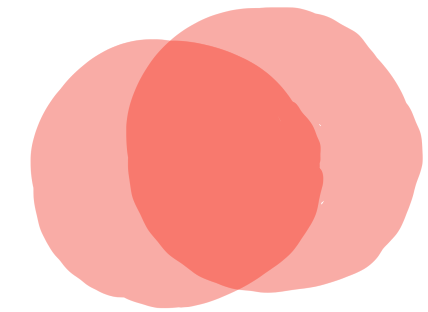


$$F(w) \simeq 1 + \overline{\kappa}(r = \frac{r_F}{\sqrt{2}})$$

Gauss thm applied to the region within rF.

Detection prospects





3-sigma likelihood

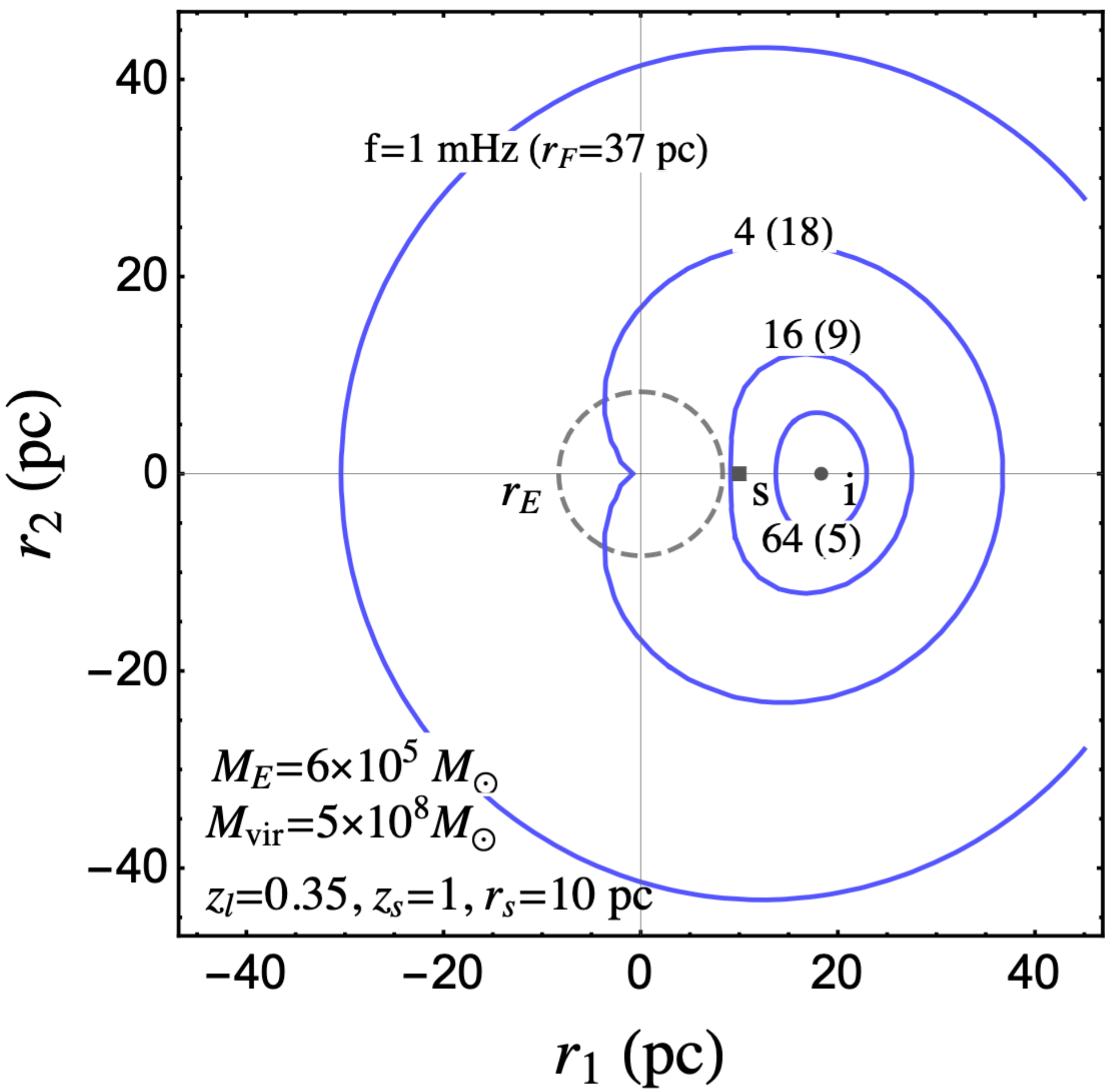
- BBO can detect *individual* invisible NFW with O(10) events/yr; LISA marginally; and MAGIS/ET unlikely.

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

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

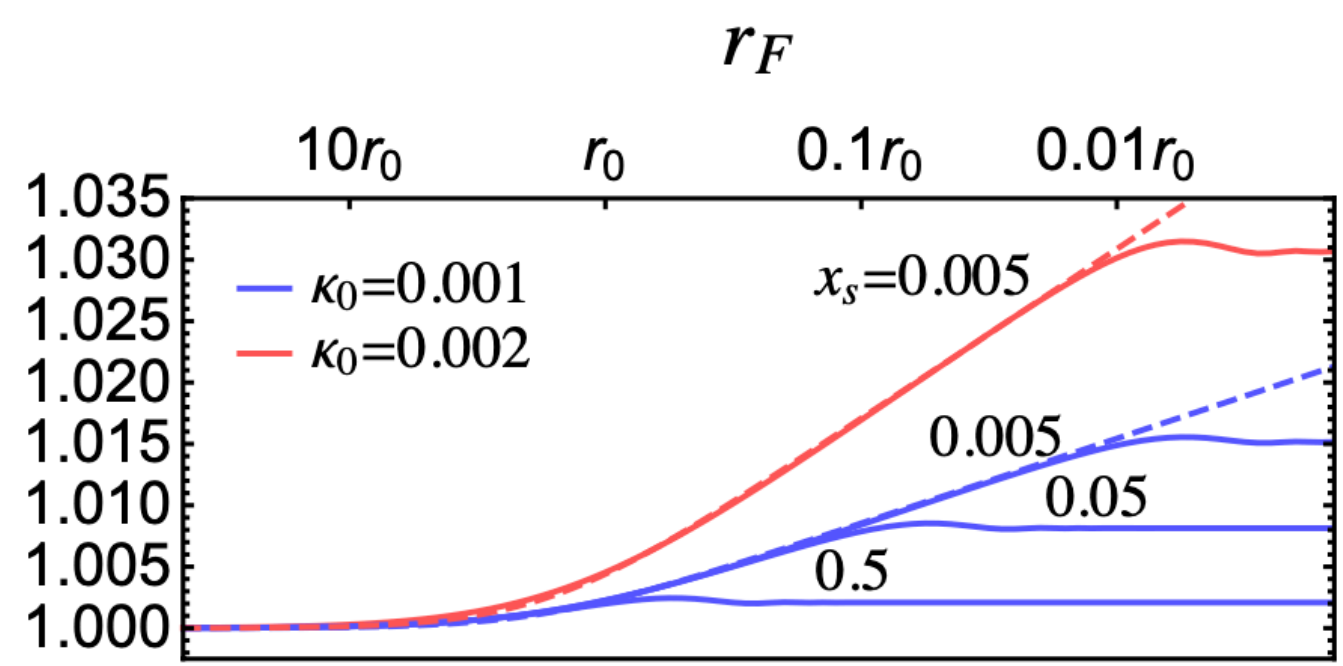
Peeling off subhalo profiles

- Furthermore, GW chirping probes the mass profile at a successively smaller-scale. Shear of the profile measures it.



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

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

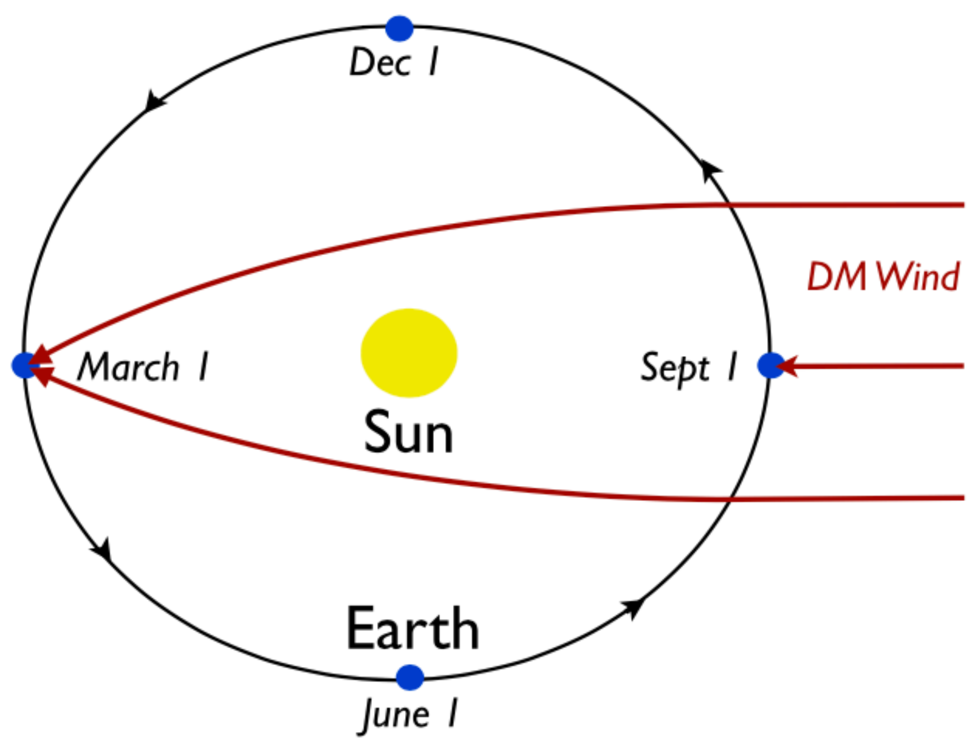


4. DM Focusing:

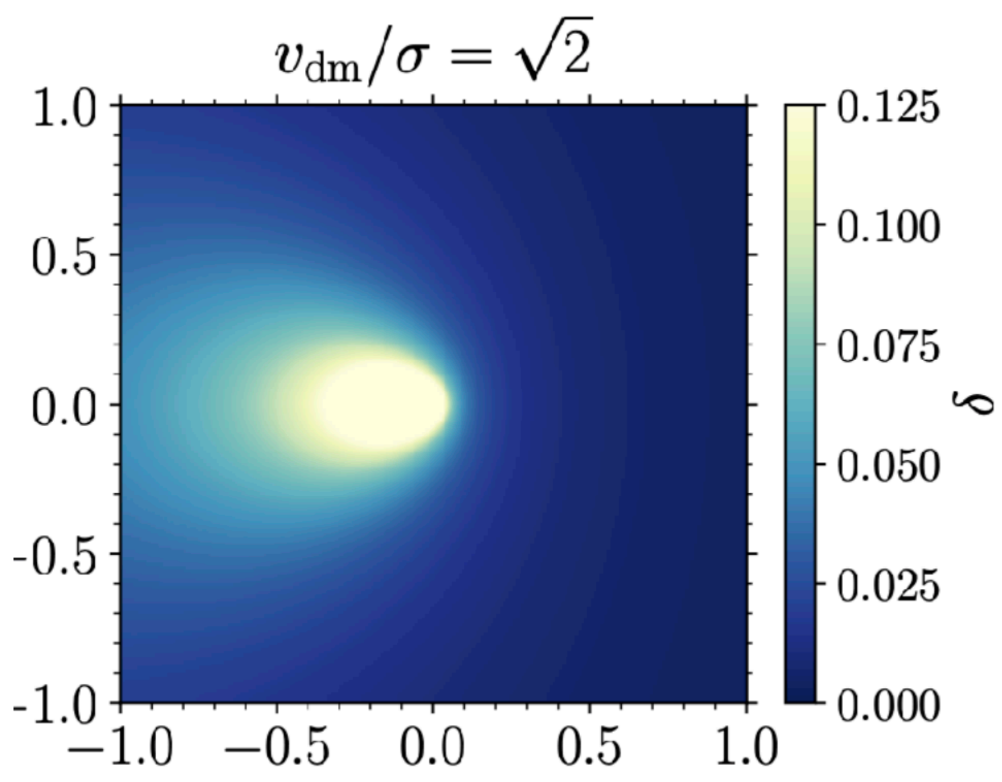
equivalence to the DM lensing by Sun

H.G.Choi, S.Kim, and SJ
To appear soon

DM focusing by Sun



S.K.Lee et al. PRL 2014



Hyungjin Kim et al. 2112.05718

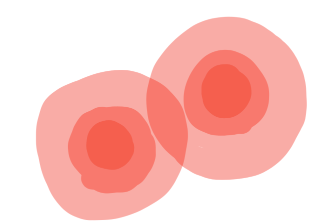
- Solved by Liouville theorem for particle-like DM,
  or Coulomb scattering w/ Schrodinger eq for wave-like DM.

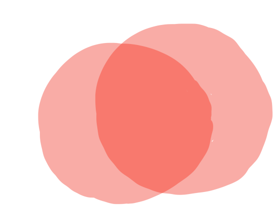
- Equivalent to lensing; always useful technically and theoretically

H.G.Choi, S.Kim, and SJ
To appear soon

Summary

1. GRB Lensing Parallax: clearly distinct images reveal the smallest PBH DM 

2. GW Fringe: time-varying (chirping) interference of PBH images at LIGO 

3. Small-Scale Shear: images of small invisible NFW become sharper with the GW chirping 

4. DM Focusing: equivalence to the lensing provides deeper insights and useful technical tools

Thank you