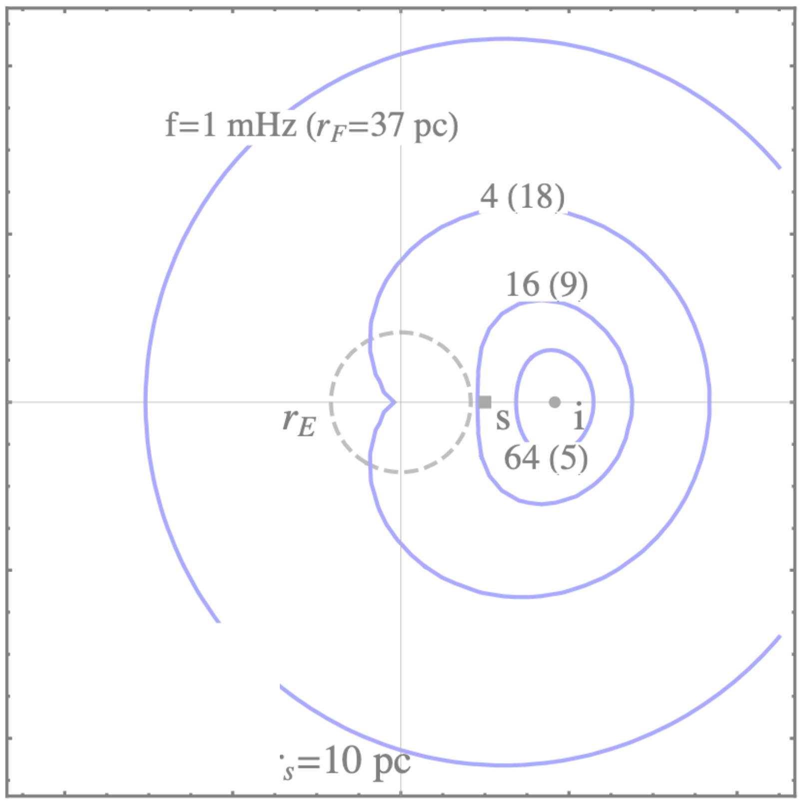
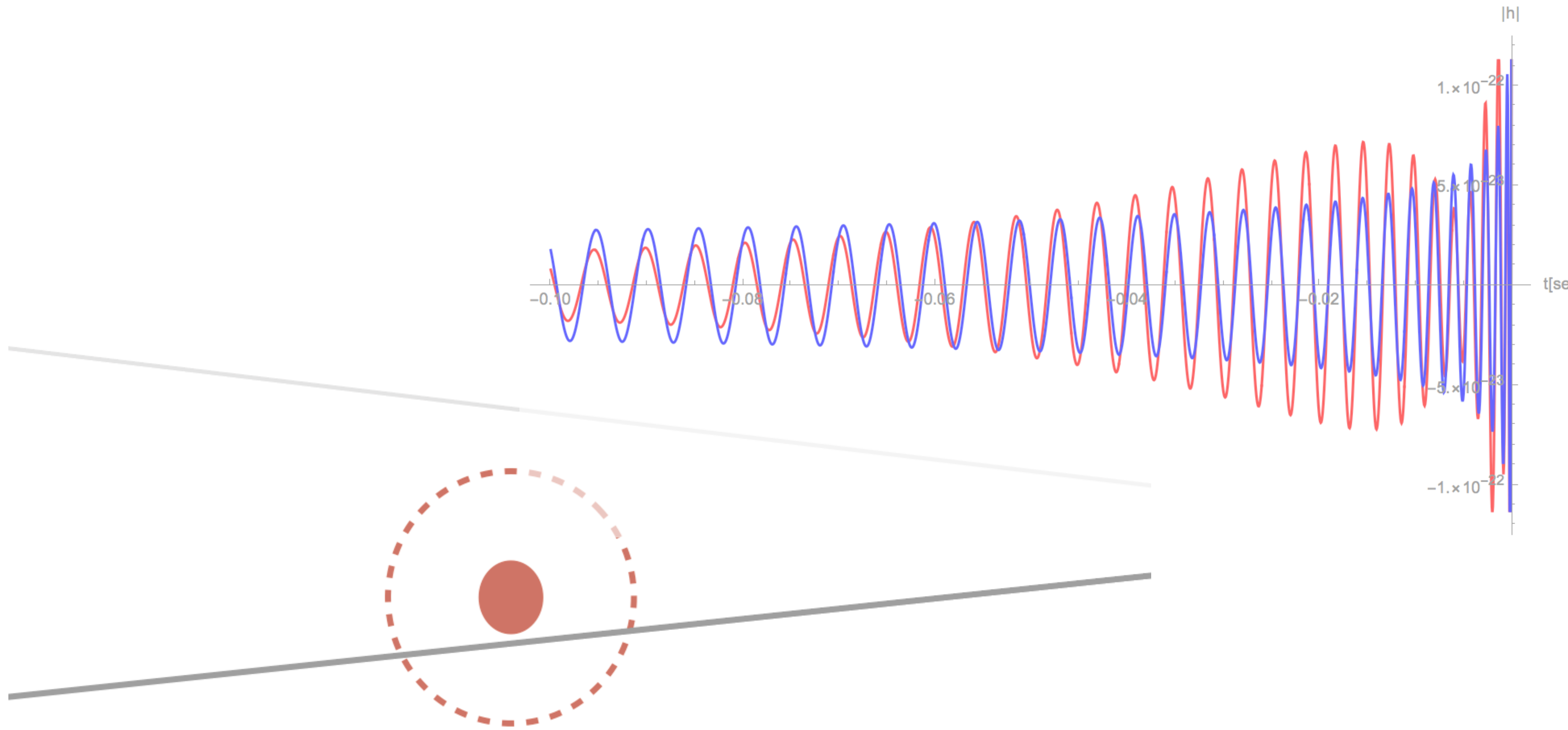
GW phenomenology of dark matter





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

CAU BSM Workshop, 2021 Feb 2

Topics

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

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

3. **Binary environmental effect**
   - DM wave

4. **Parametric resonance**
   - Axions with gravitational Chern-Simons

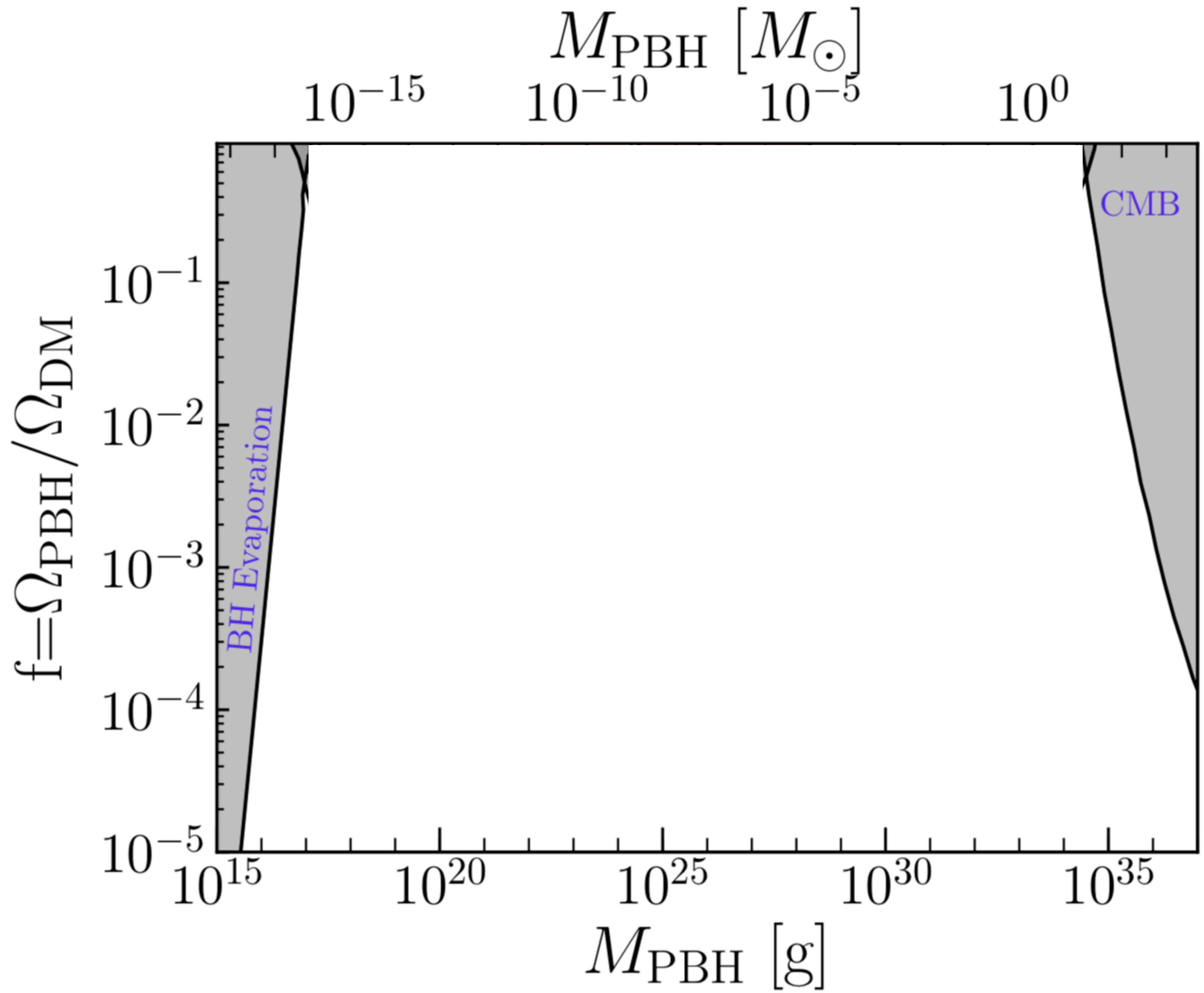
1. Strong lensing : Fringe and Parallax

— Primordial Black Hole DM

S.Jung, C.S.Shin, 1712.01396 PRL(2019)
S.Jung, TaeHun Kim, 1908.00078 PRR(2020)
S.Jung, TaeHun Kim, 1810.04172 JCAP(2020)

PBH DM

A wide mass range is possible btwn two general constraints.

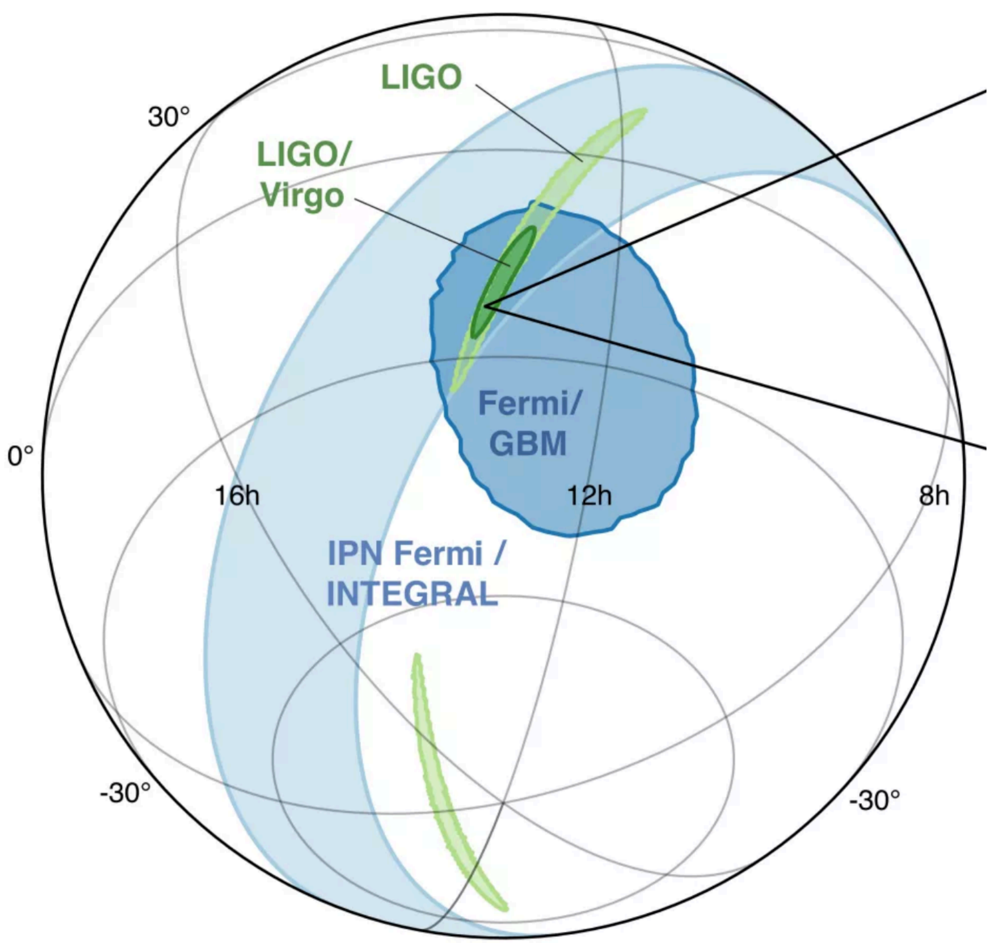


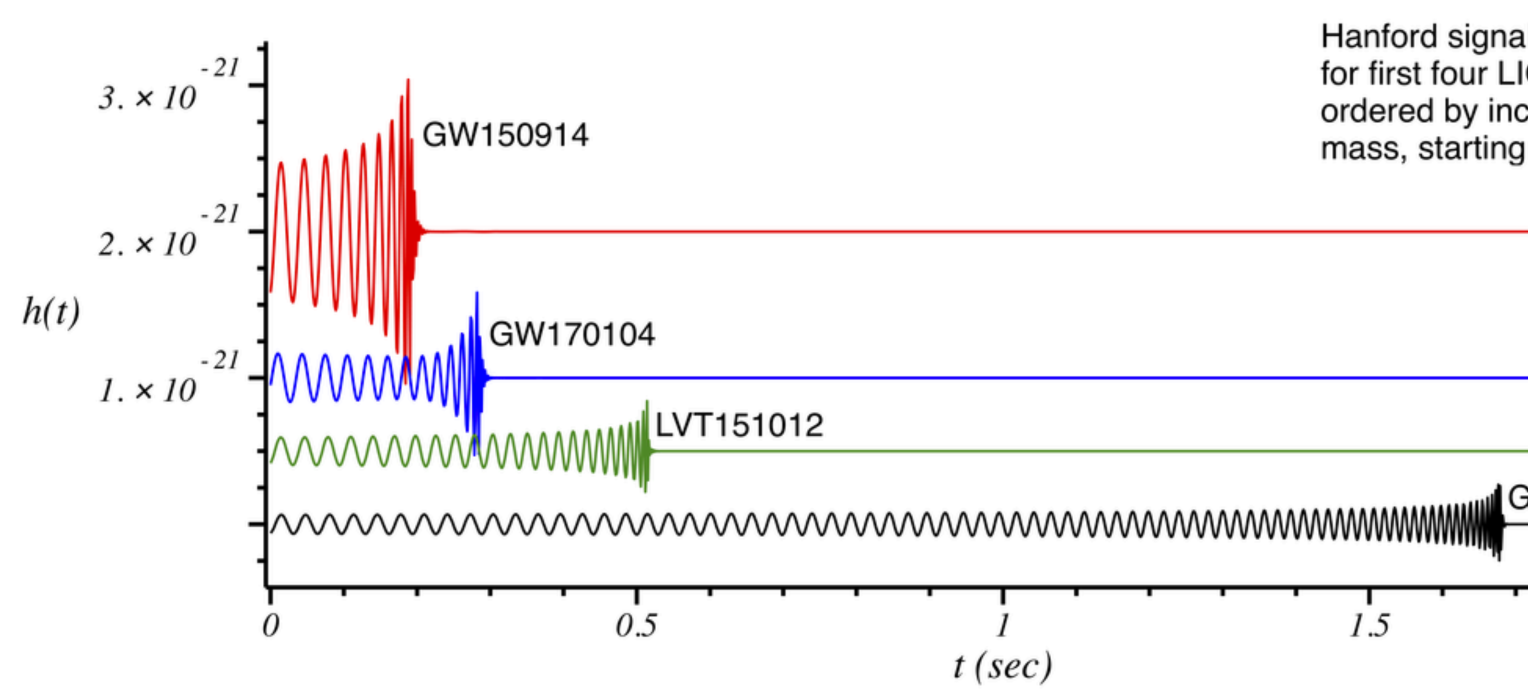
‘GW lensing’ observation seems very unlikely at LIGO!

LIGO can see only with

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

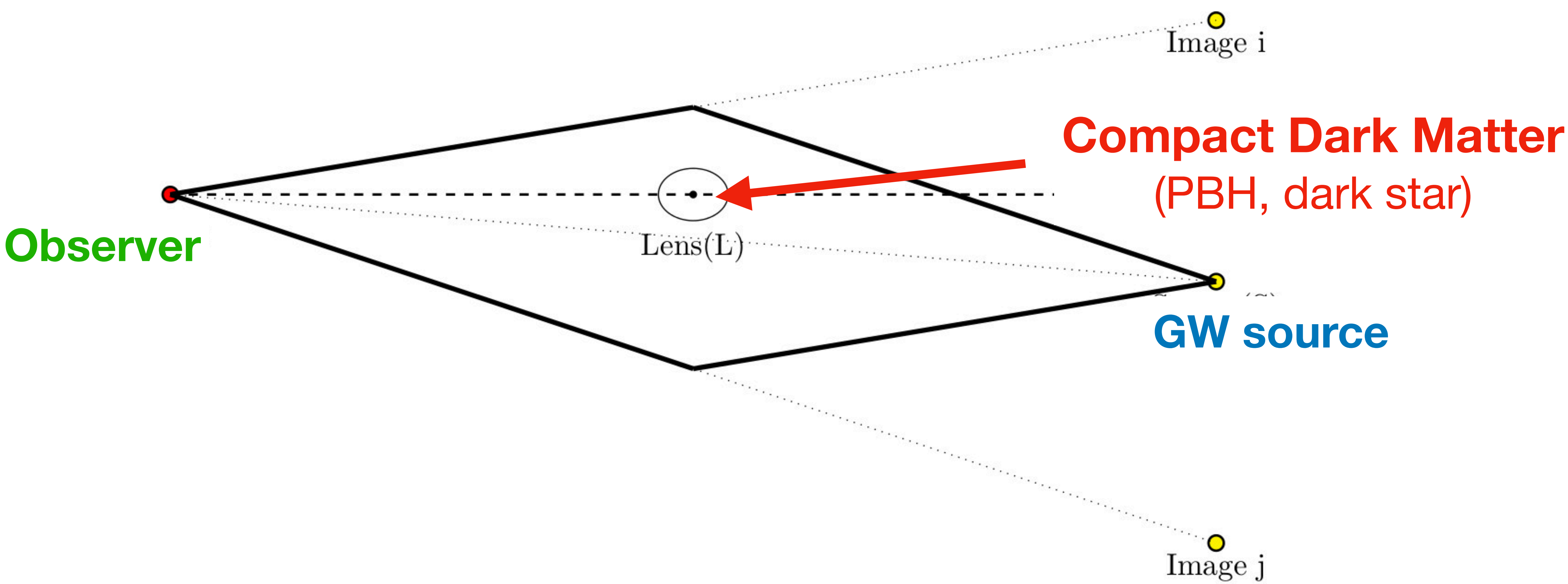
(2) measurement time < 1 sec ~ 1 min (let alone days)





Time-delayed images

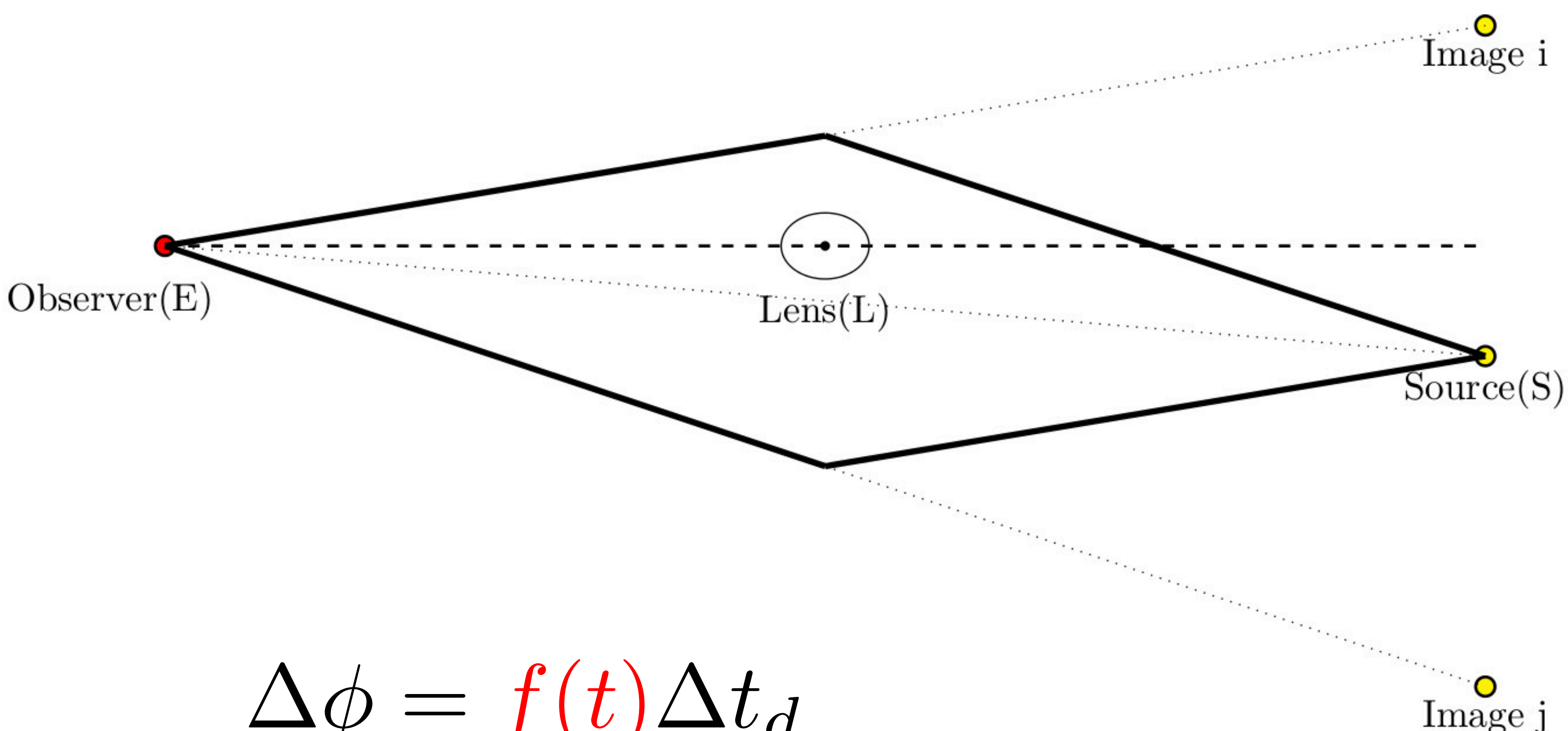
Consider time-delayed lensed images of GW.



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

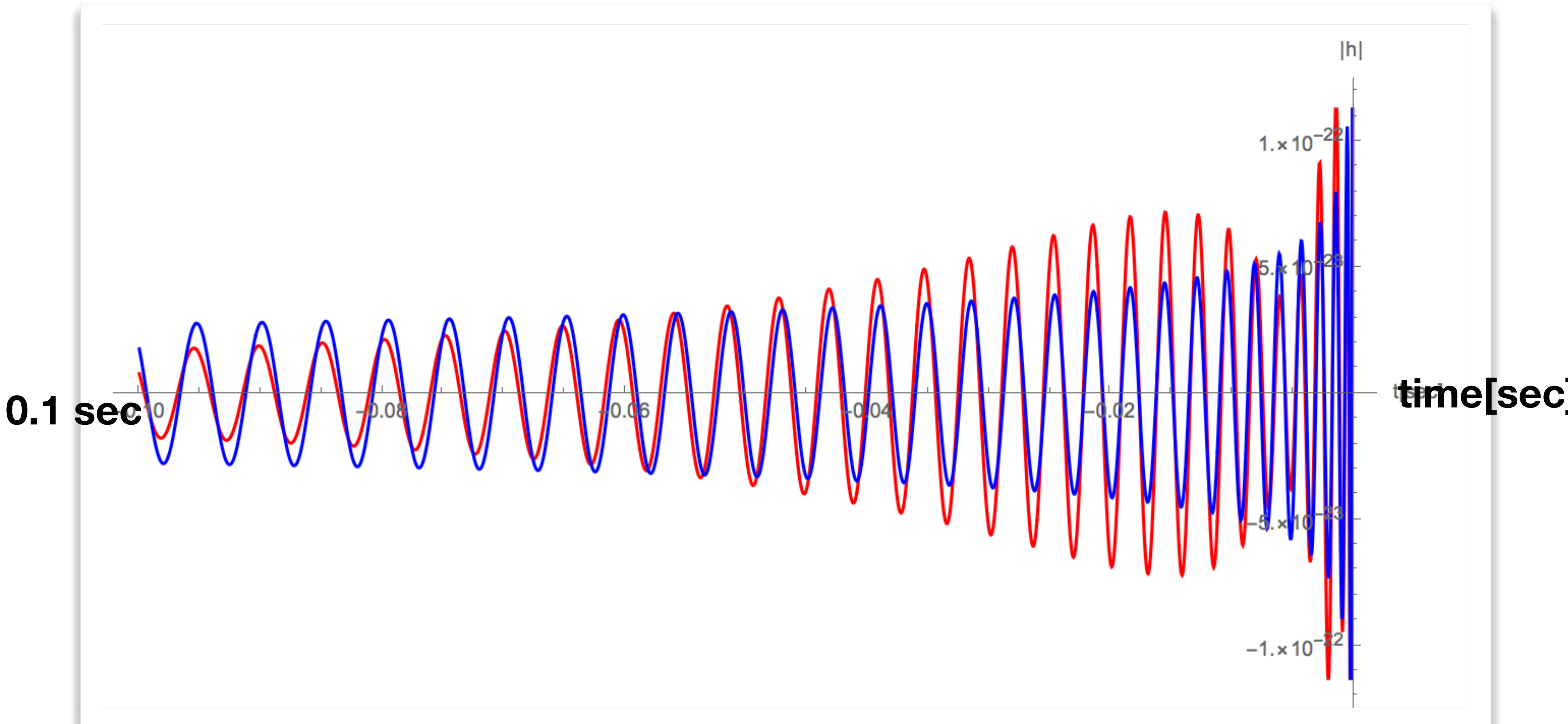
GW lensing Fringe

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



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

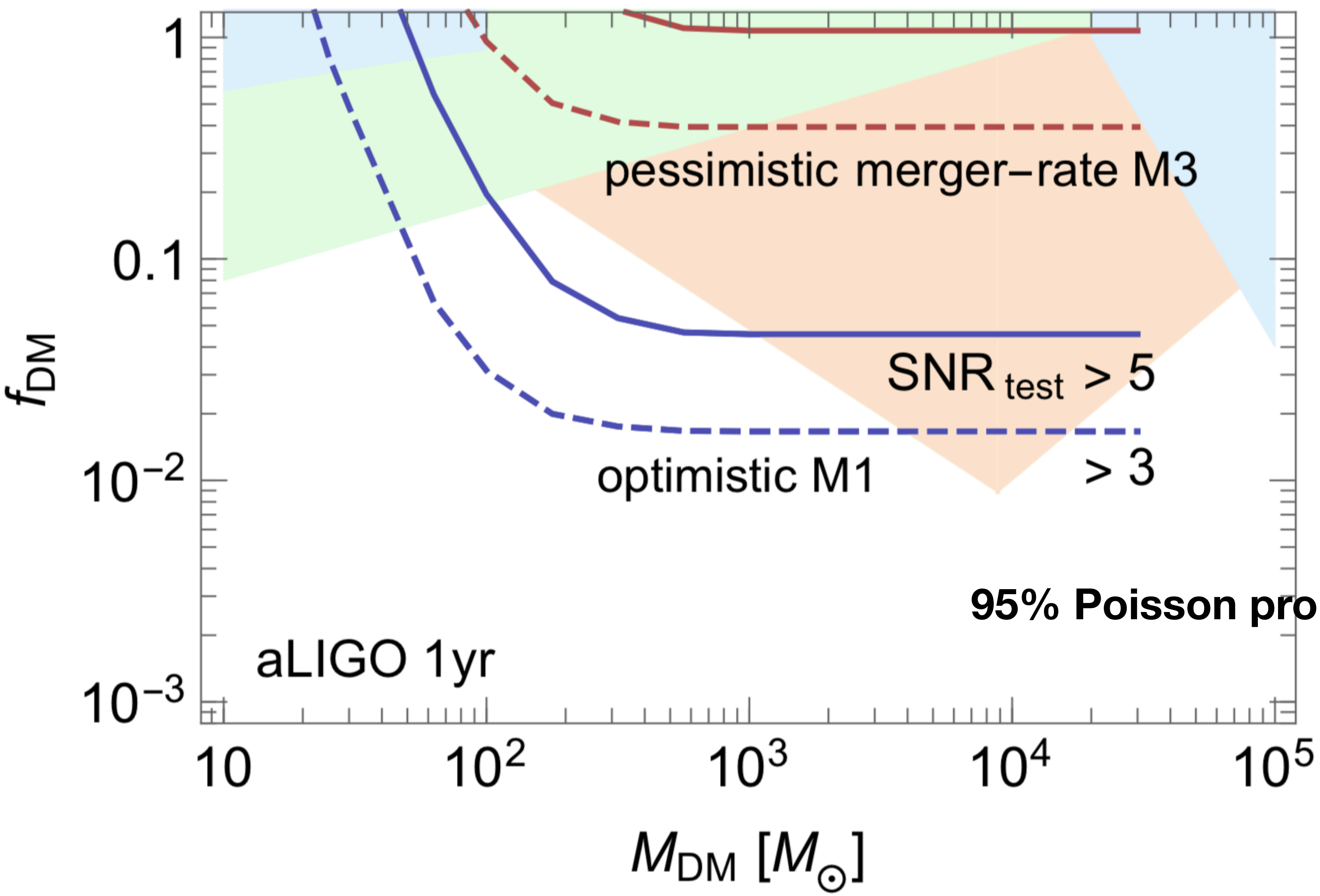
“GW Fringe”



NS-NS merger lensed by 100 Msun PBH.

PRL (2019), SJ, CSShin

PBH DM fraction

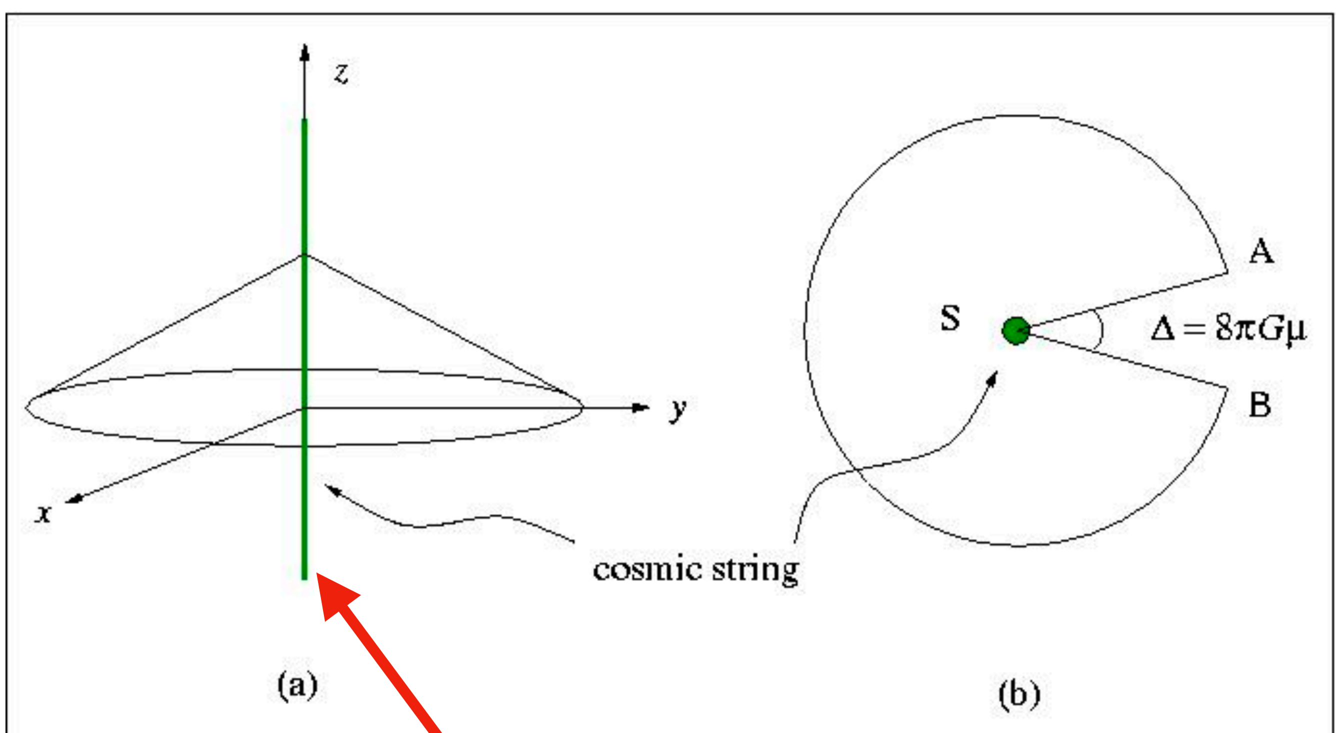


95% Poisson prob of >=1 detection

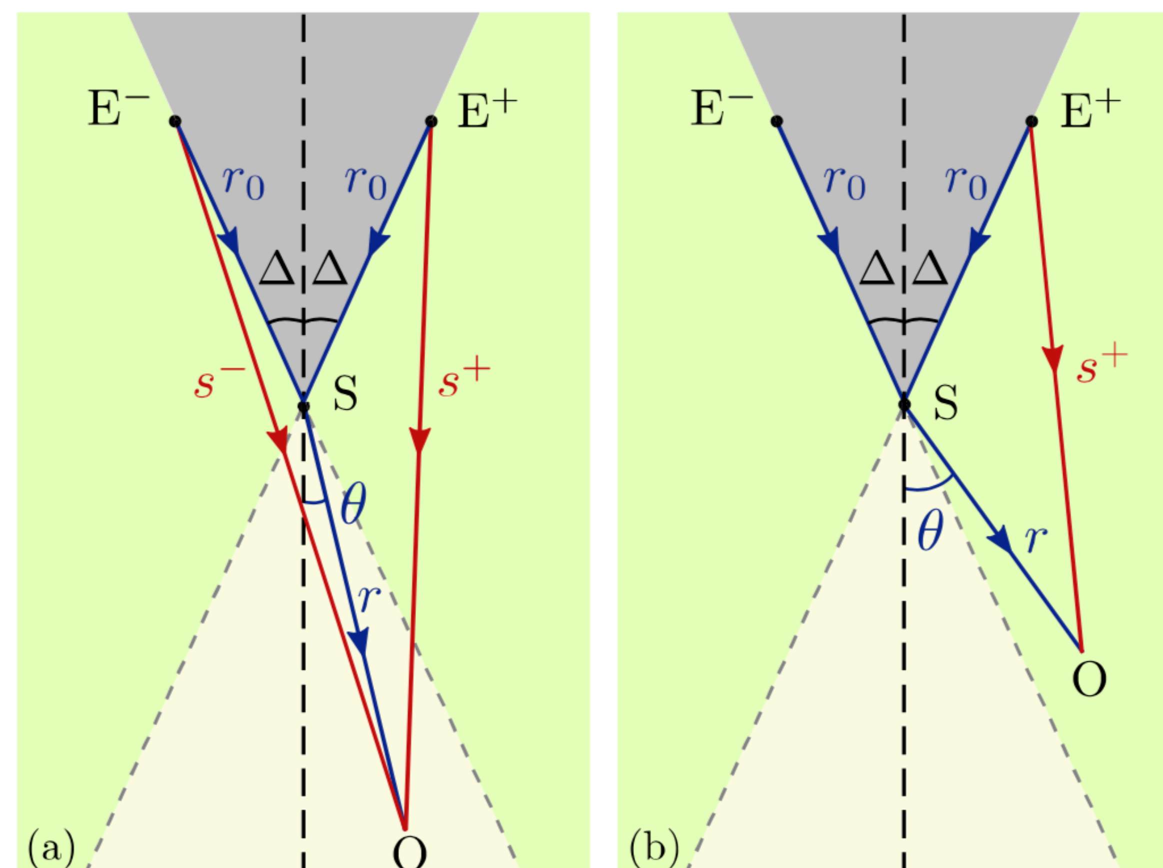
PRL (2019), SJ, CSShin

Aside: GW fringe from cosmic strings

- 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

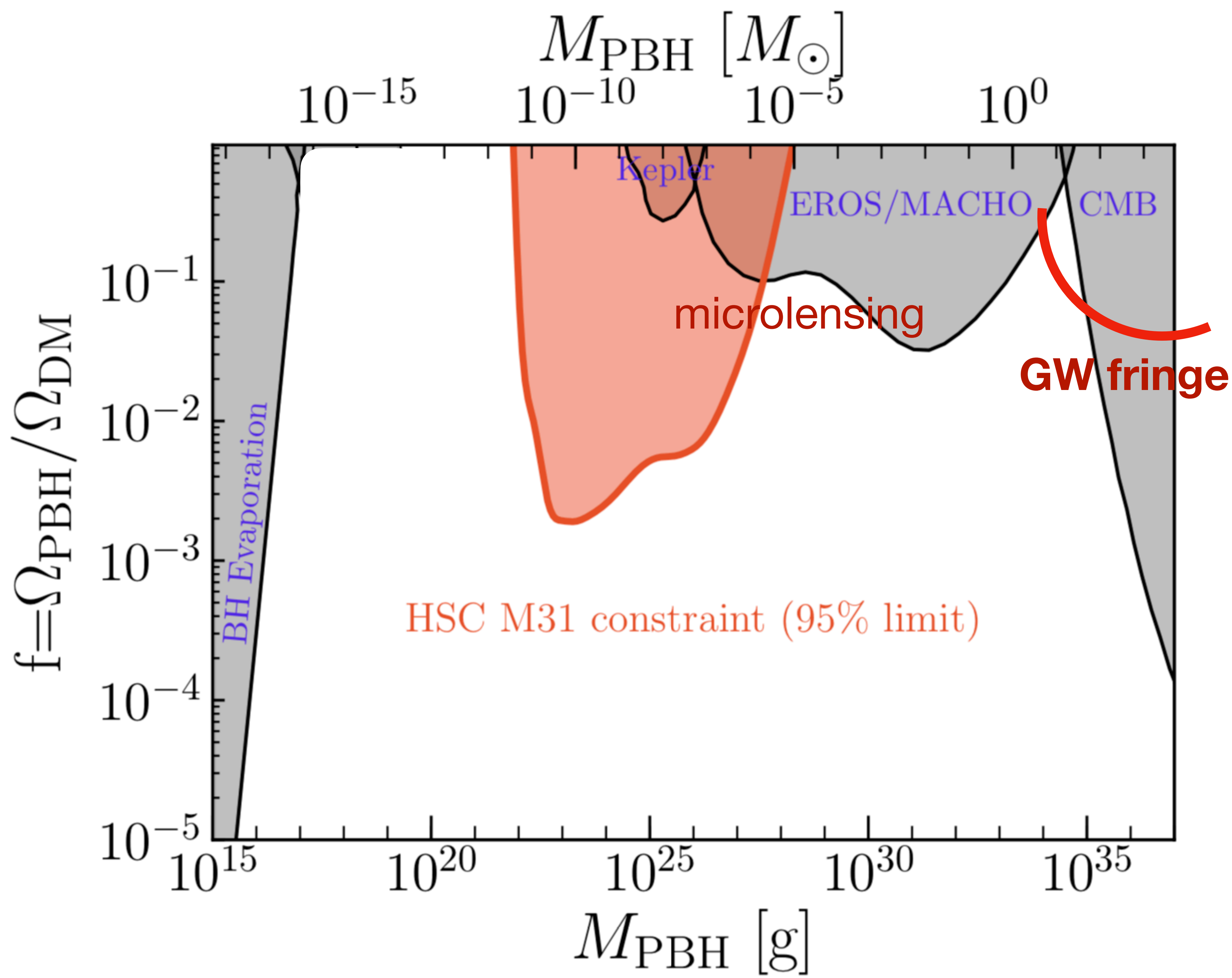


Figs. from Nunez et al. 2017

SJ, TaeHun Kim, JCAP(2020)

PBH DM

- Search status. A wide mass range probed by lensing.

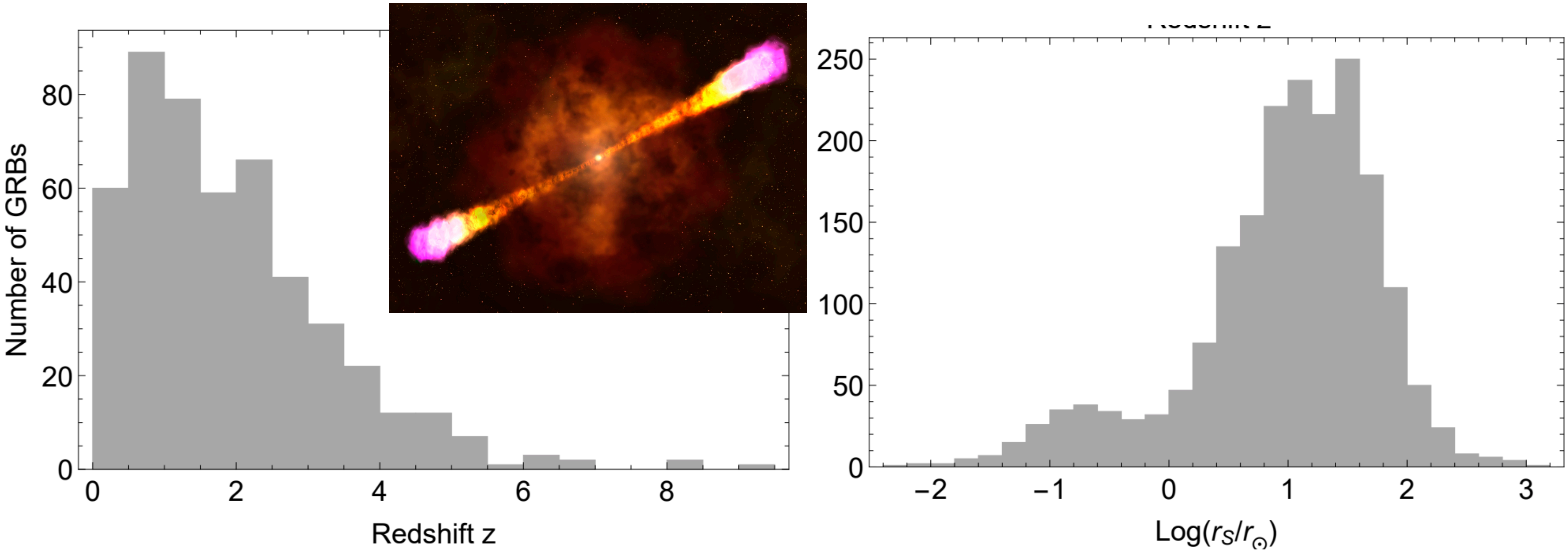


Limitations with (micro)lensing

- 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

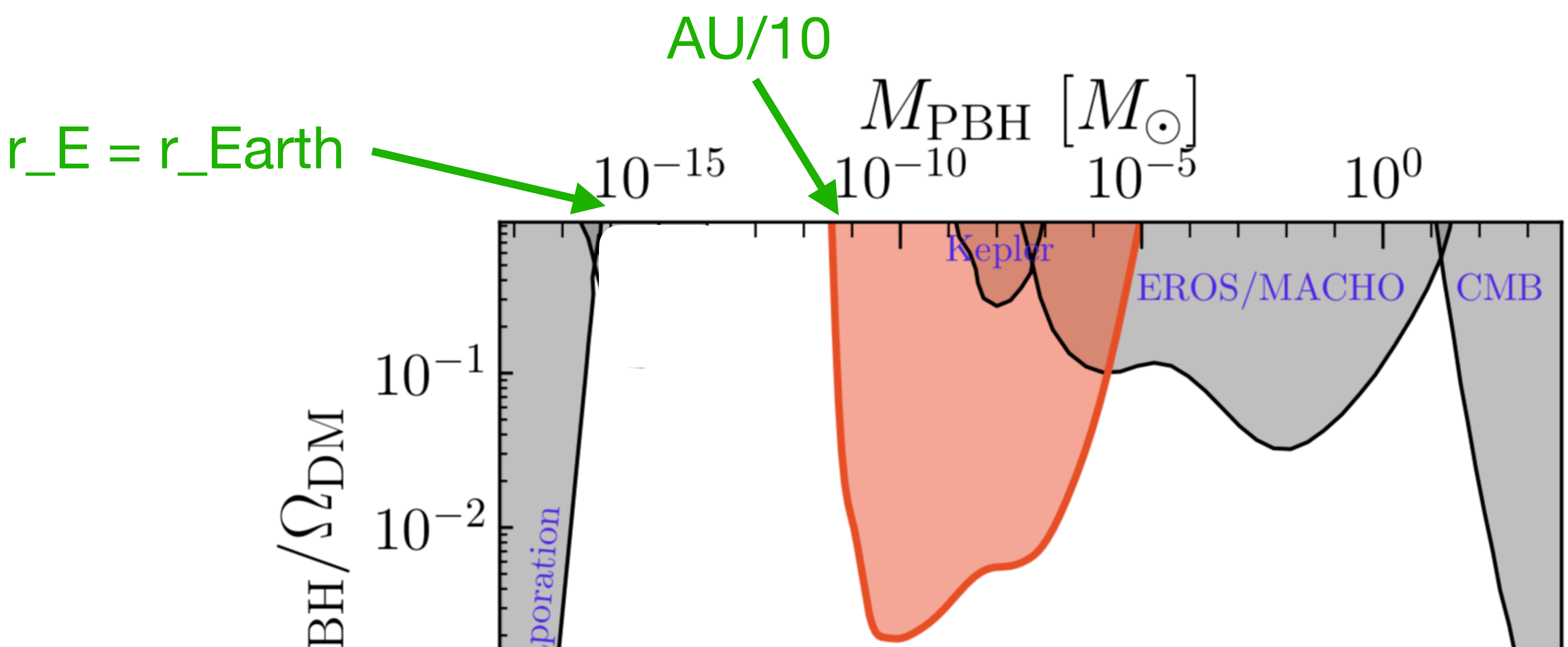


- Gamma-Ray Burst can overcome both:

  1. At cosmo 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

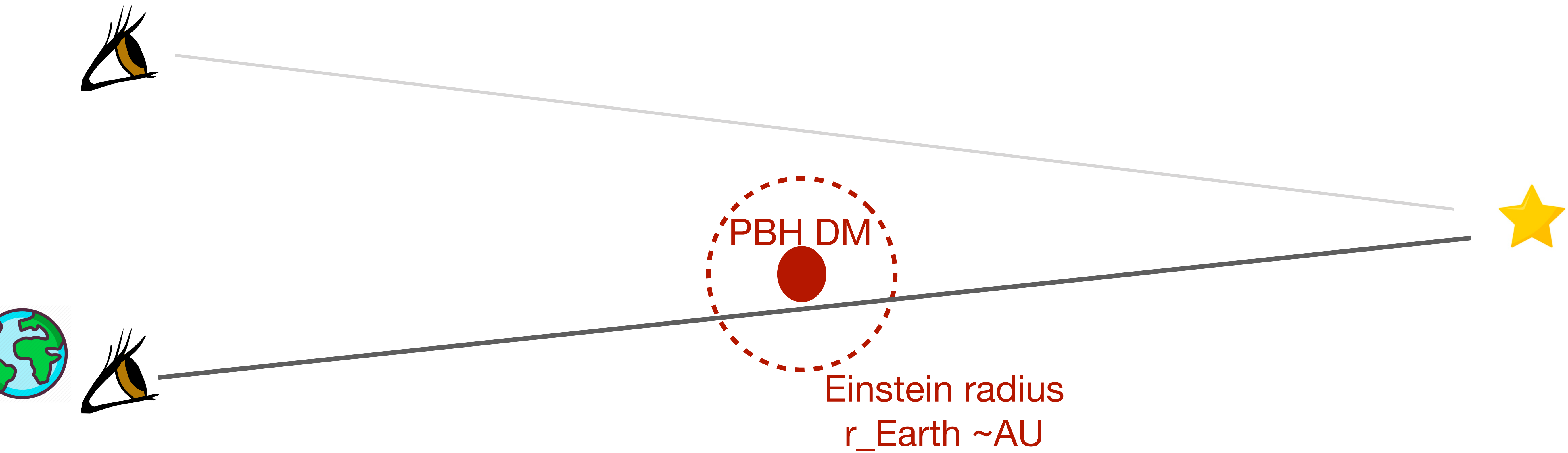


- But GRB is a short pulse. How can we tell it's lensed?!
- The Einstein radius of this mass range *happens* to be the astrophysical scale accessible to us : r_Earth ~ AU !

$M_{\rm PBH}$ [g]

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

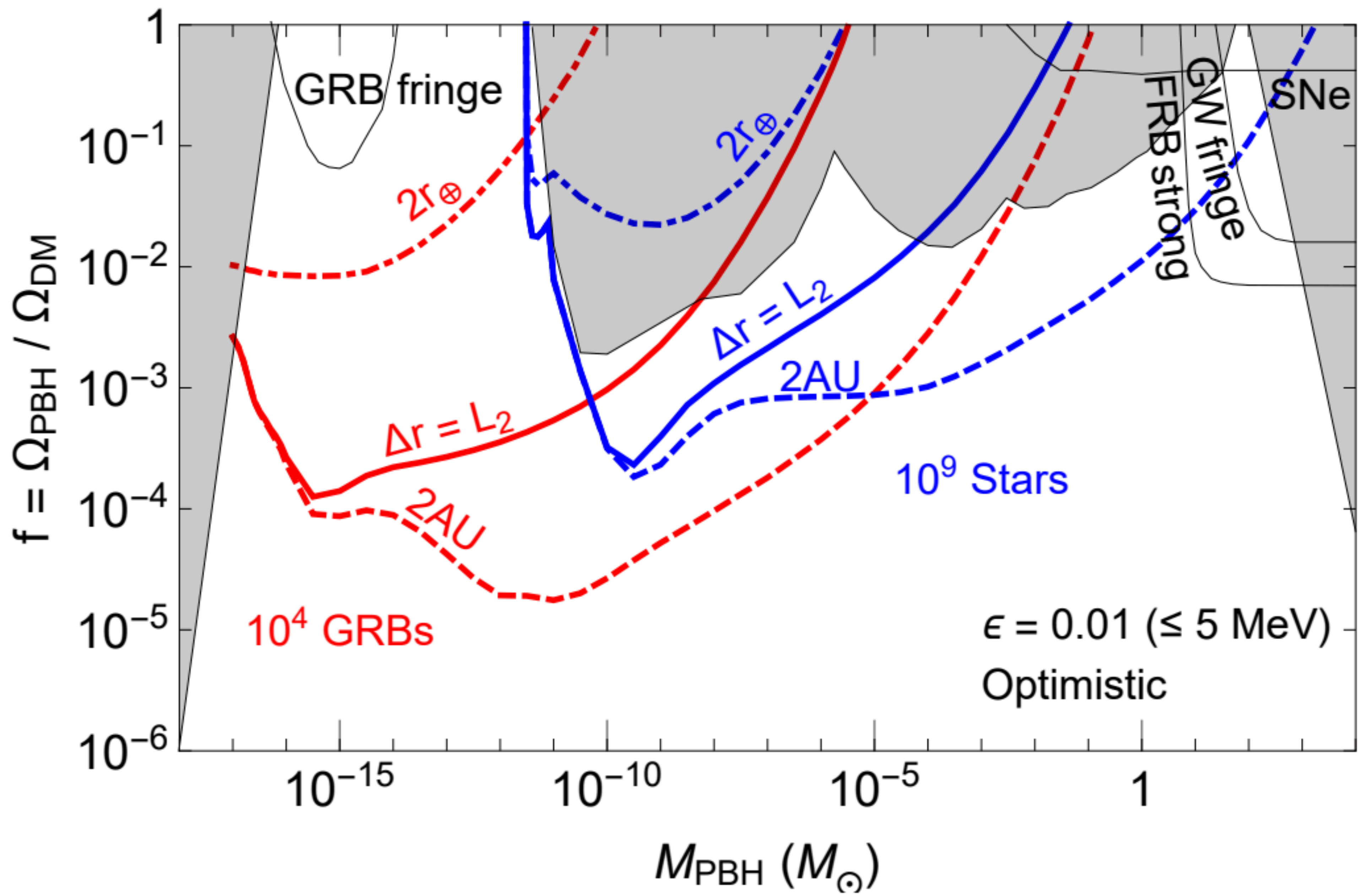
GRB Lensing Parallax



- GRB 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)

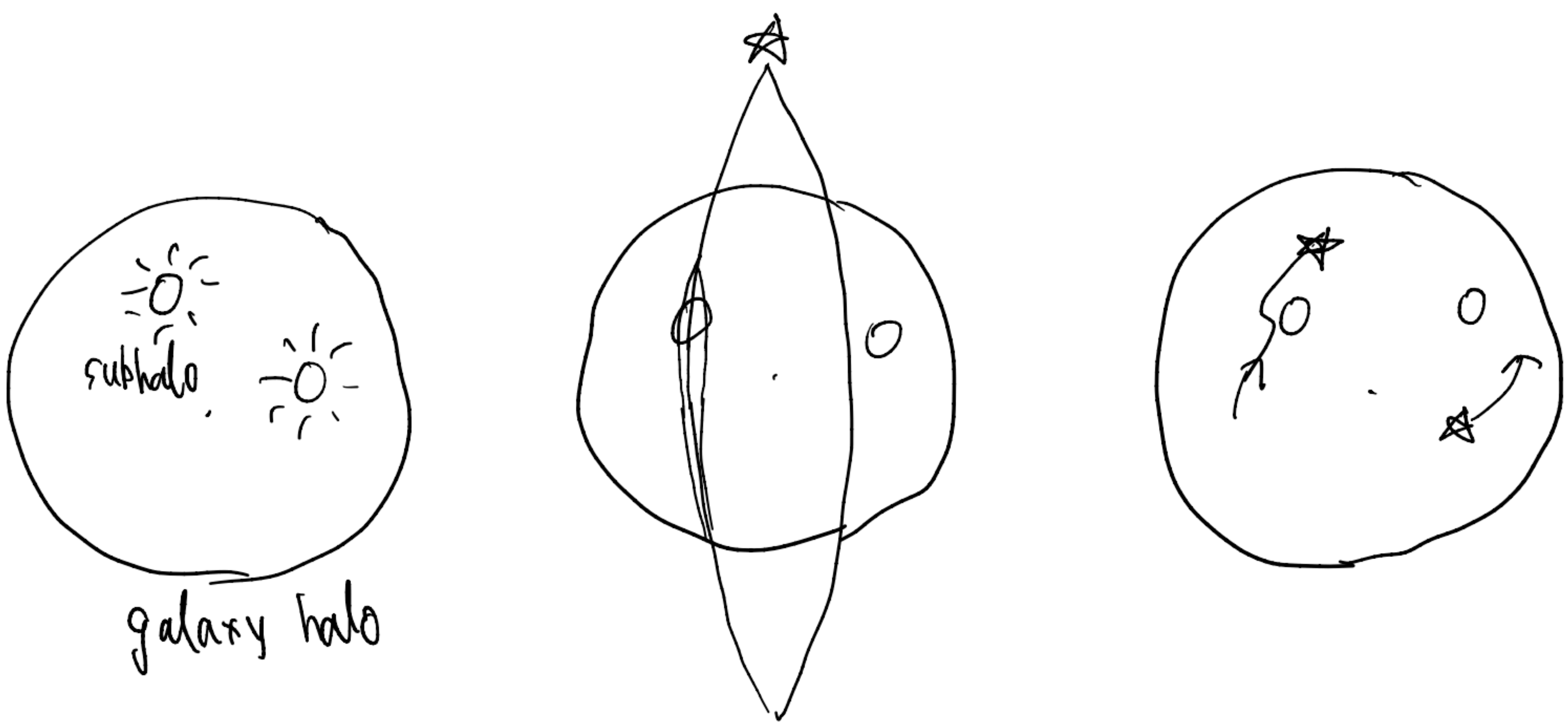
2. Diffraction by small-scale shear

— Diffuse NFW subhalos

Han Gil Choi, Chanung Park, SJ, To appear soon

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

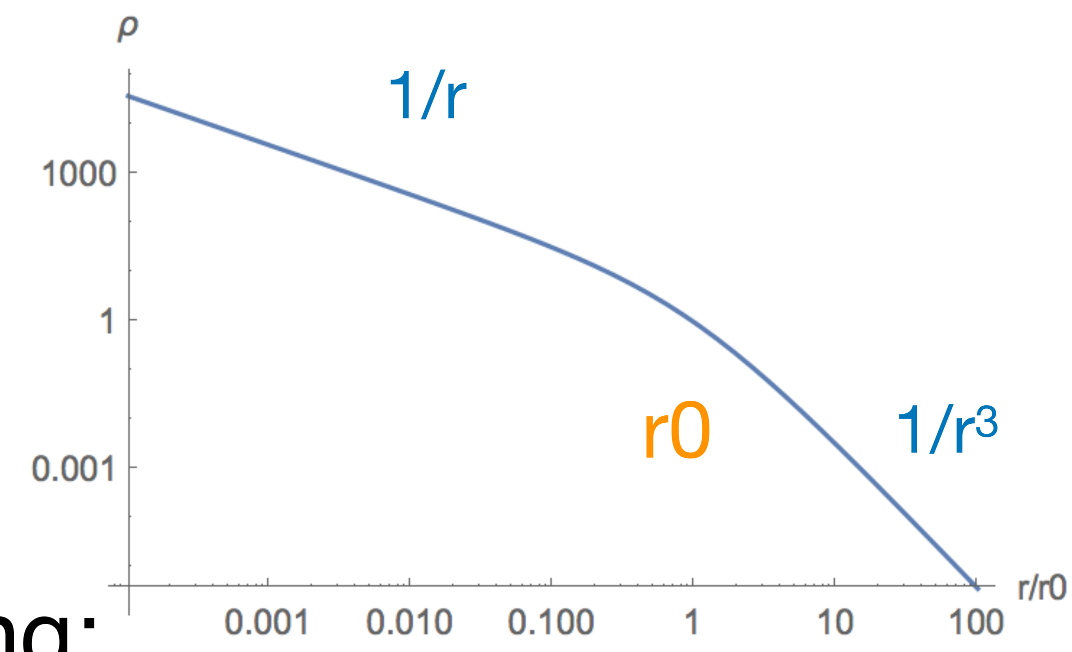
- 10^7 Msun is visibility lower limit
  from luminous satellites, milli-lensing pert, star kinematics.

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



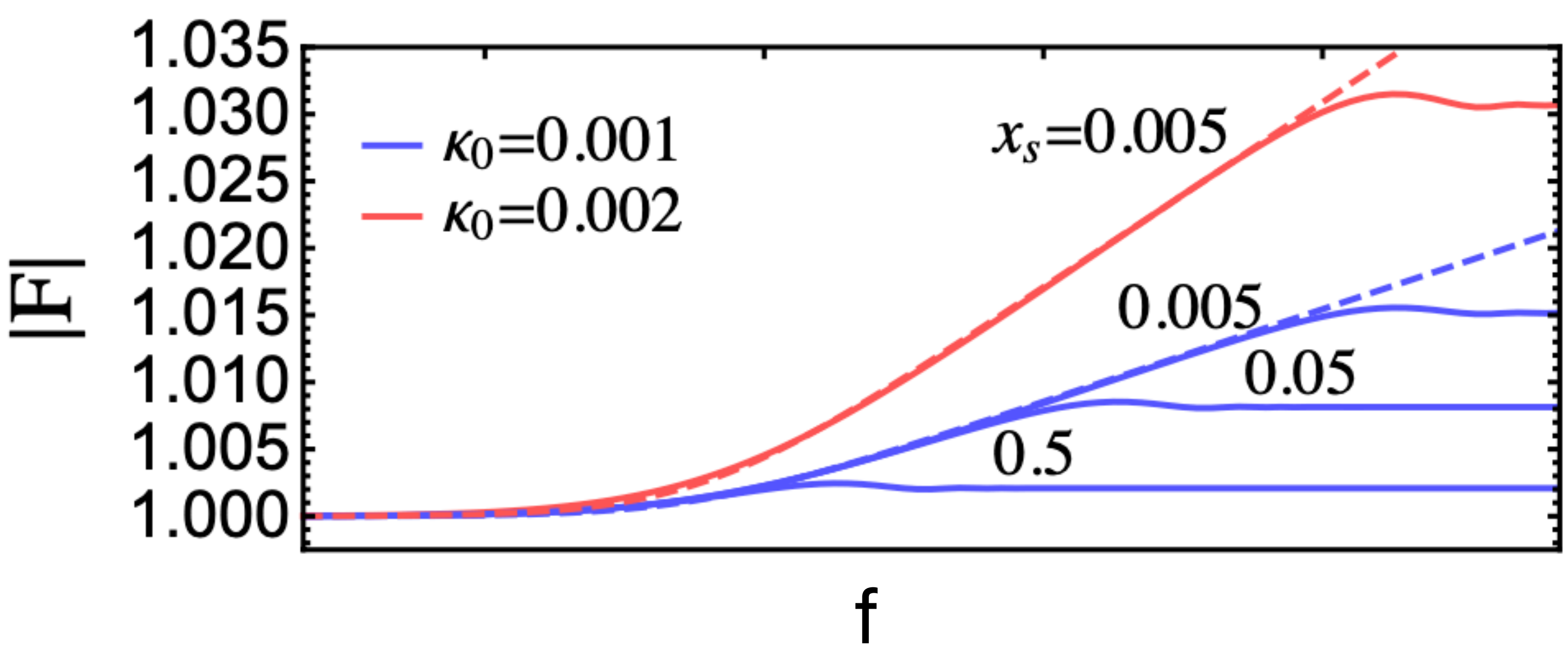
- CDM prediction.
- Diffuse over a length scale r0.
- Too diffuse to induce strong lensing: Einstein radius (or surface density) is exponentially small.

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

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

Single-imaged lensing: diffraction

- But still NFW can induce weak lensing amplification.

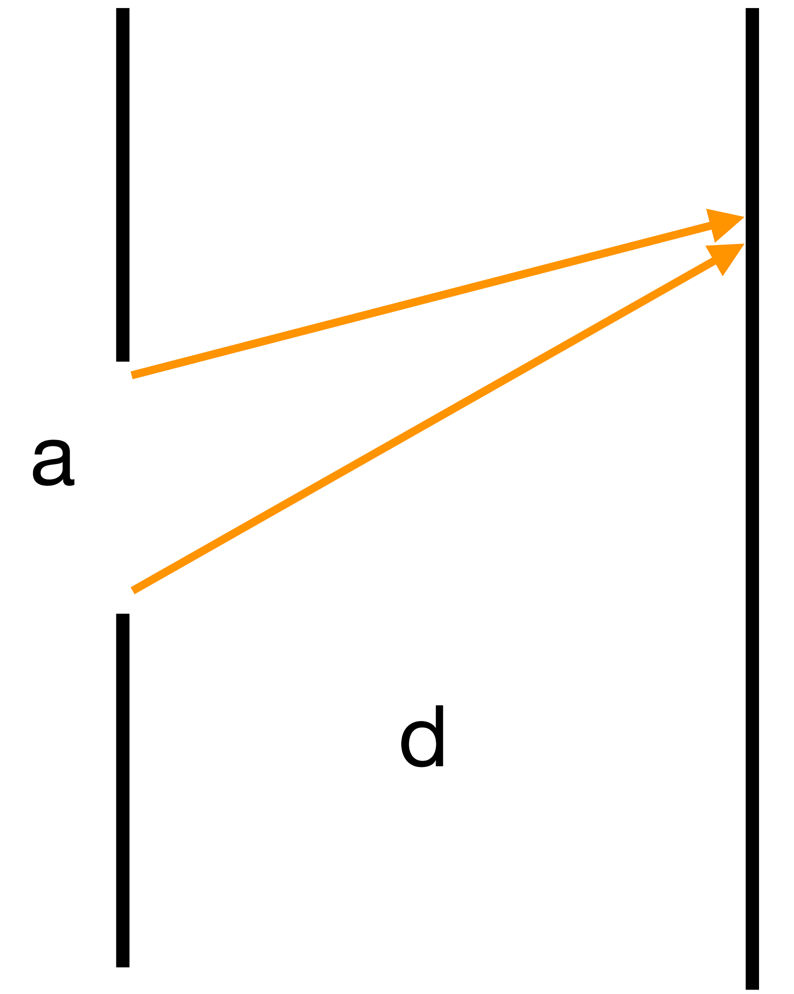


To appear soon, H.G.Choi, C.Park, SJ

Analogy with single-slit diffraction

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

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



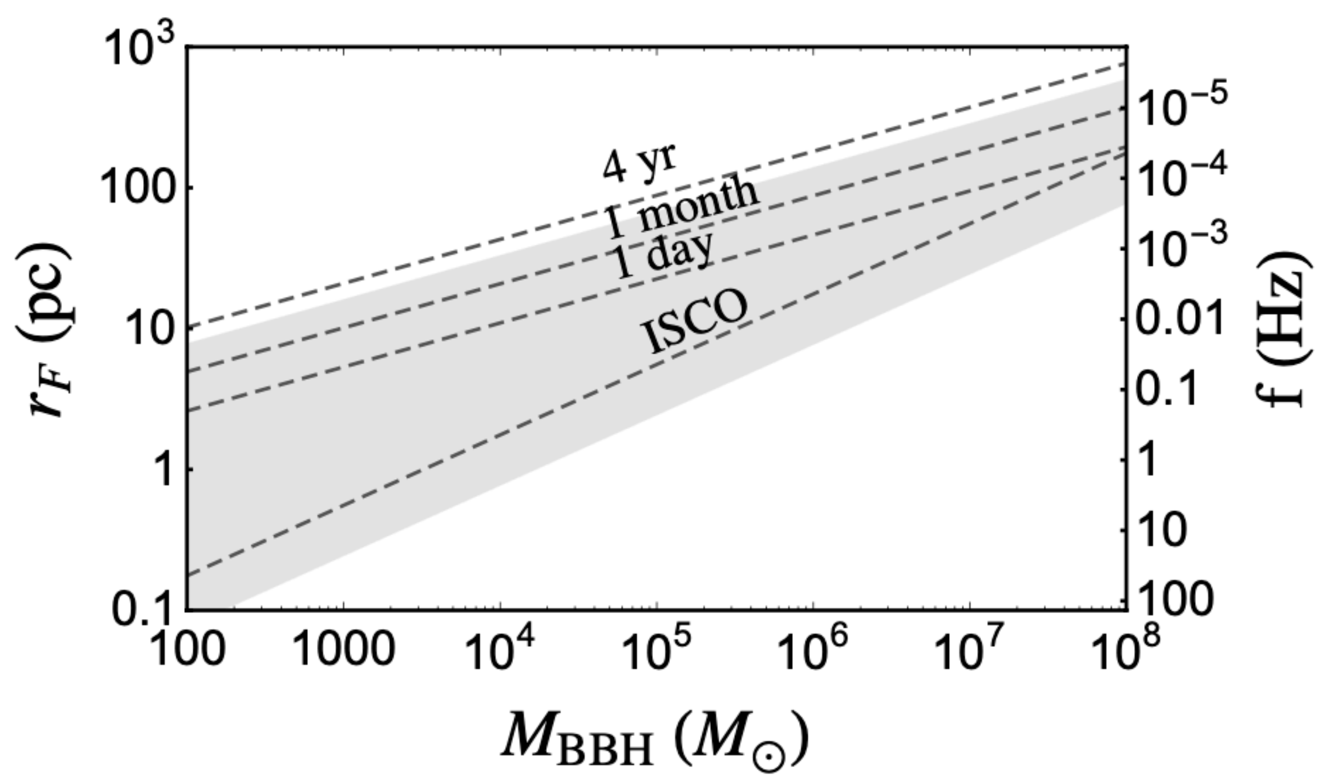
$$r_F \equiv \sqrt{\frac{d_{\rm eff}}{\pi f(1+z_l)}}$$

a: characteristic lensing scale = r0, rs, rE

Single-imaged lensing: diffraction

- What happens fortunately is that r0 happens to coincide with the Fresnel length of GW diffraction around NFW!

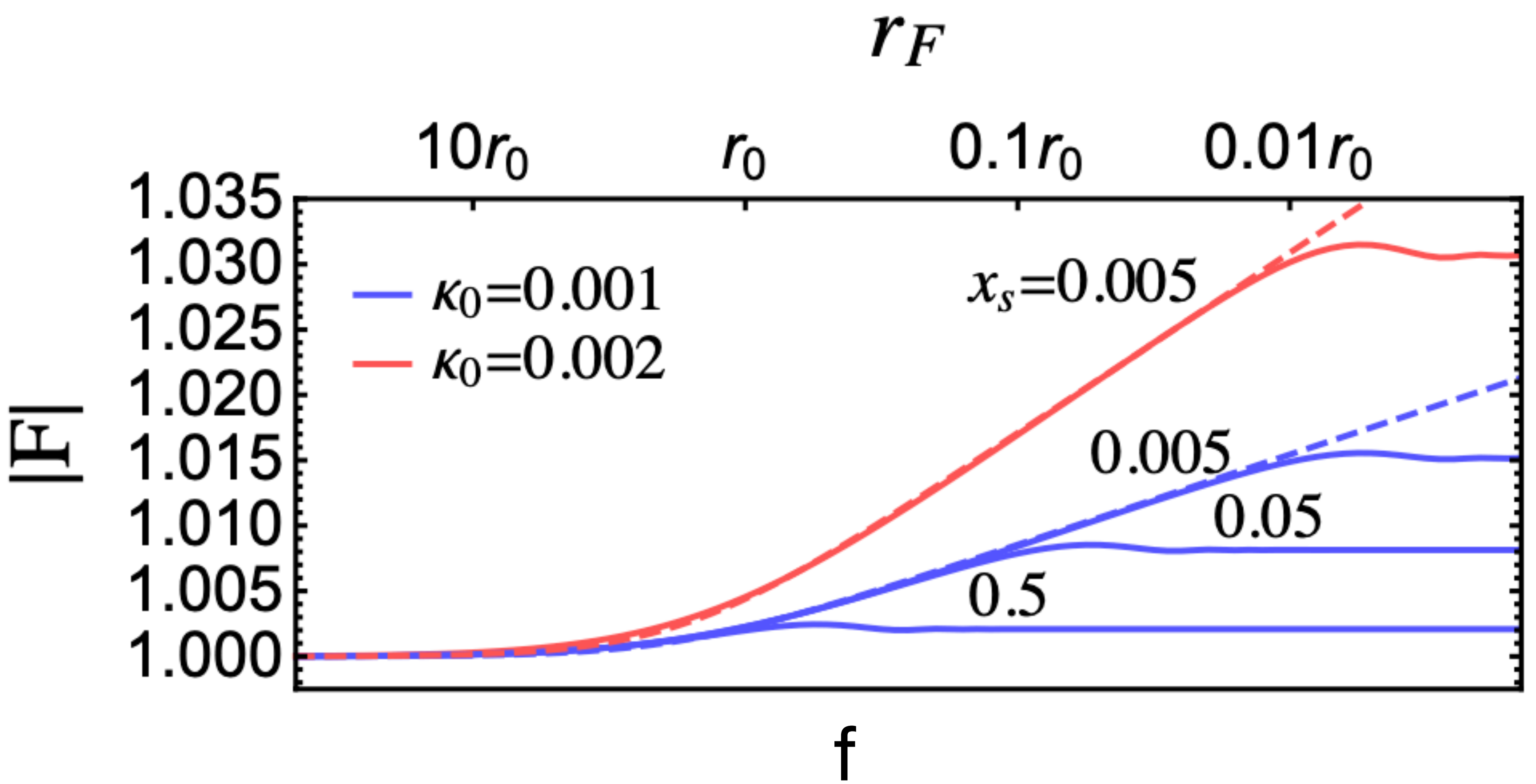
$$r_F \simeq 1.76 \text{ pc} \sqrt{\frac{1}{1+z_l}\left(\frac{d_{\rm eff}}{\rm Gpc}\right)\left(\frac{\rm Hz}{f}\right)}.$$



To appear soon, H.G.Choi, C.Park, SJ

Observable signal of NFW

- Diffraction changes with frequency chirping. (shadow becomes clearer)
- f-dep lensing is the observable signal of NFW!



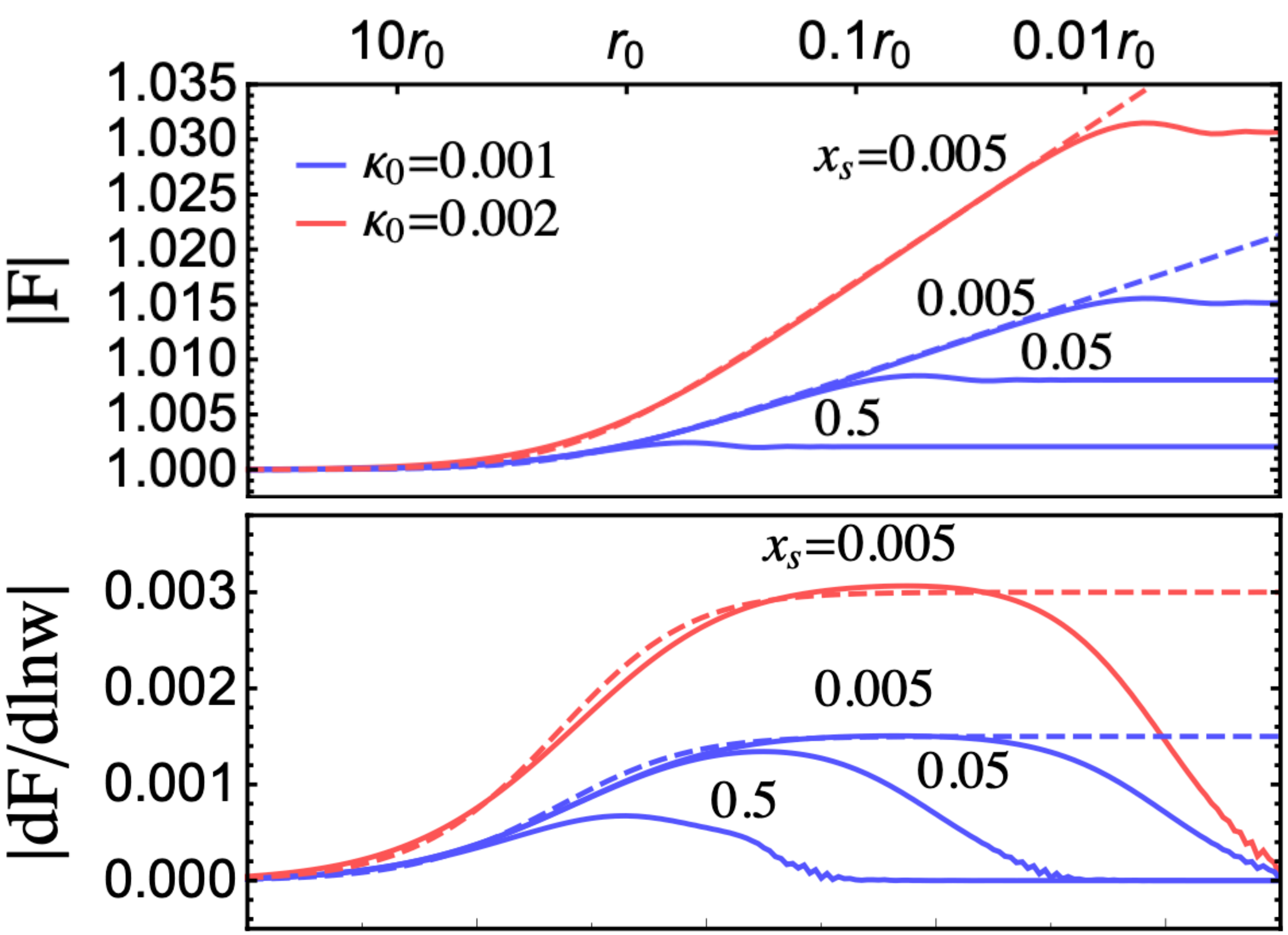
Let's further understand various features in Fig.

To appear soon, H.G.Choi, C.Park, SJ

Shear causes the f-dependence

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

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



NB: Birkhoff thm

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

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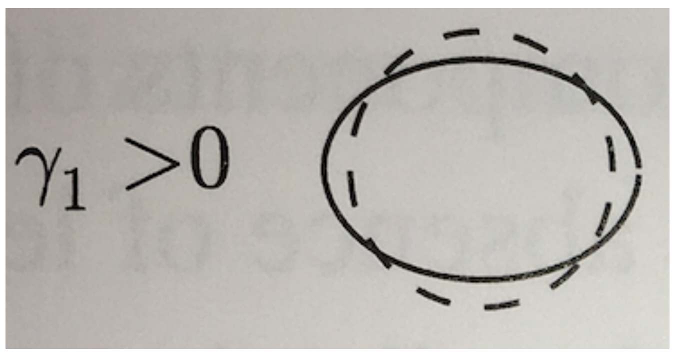
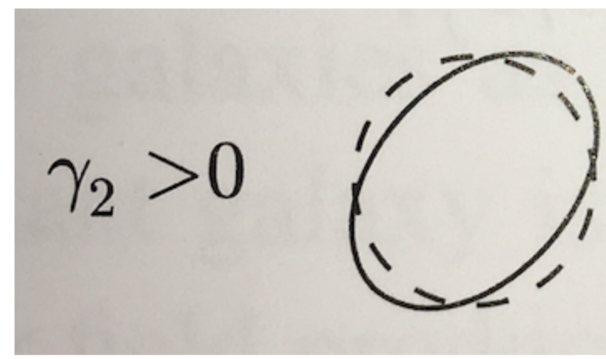
Shear from mass variation

- 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.)

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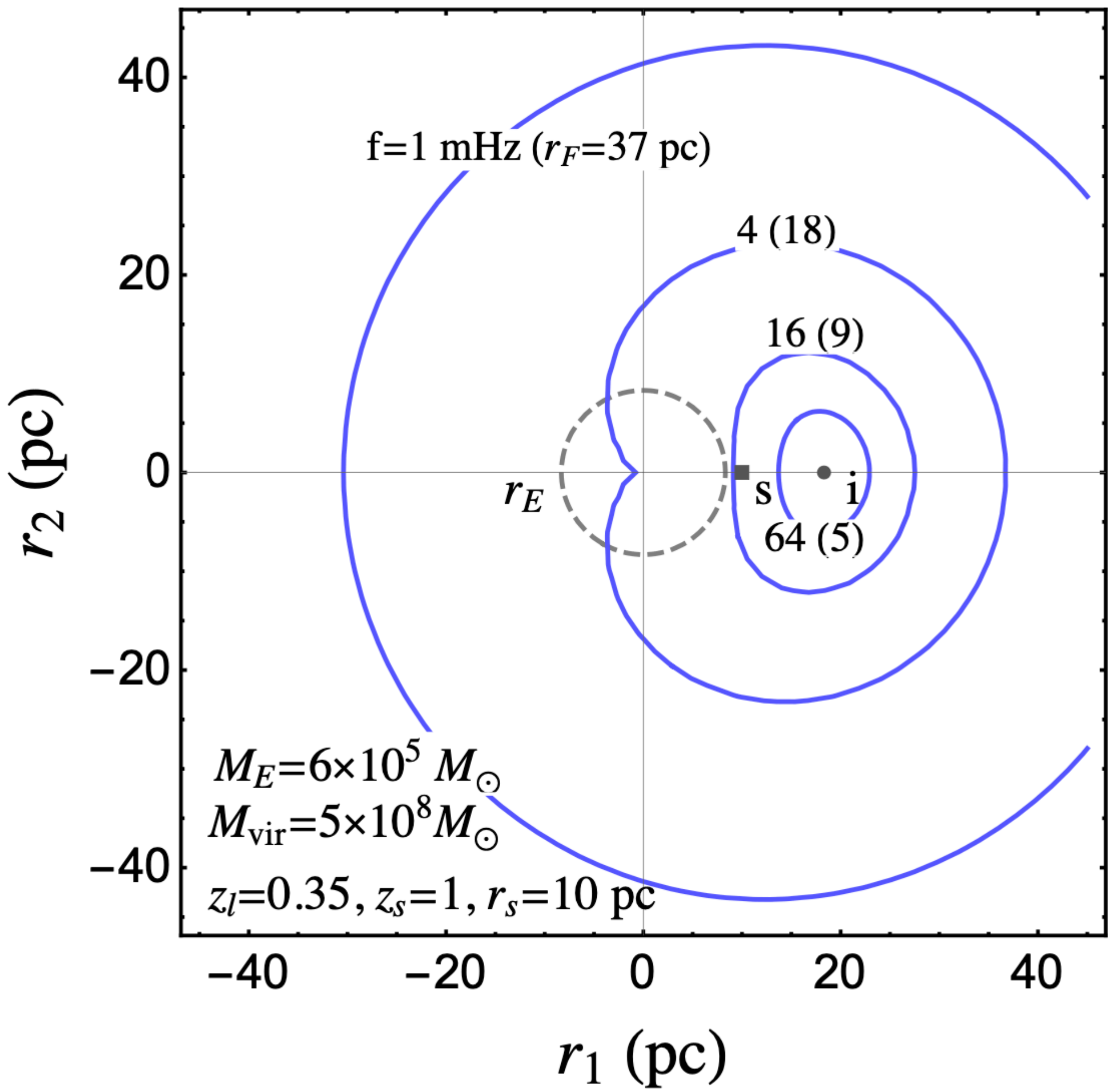
Peeling off layers of a subhalo

- GW chirping probes the mass profile at a successively smaller-scale.



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

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

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

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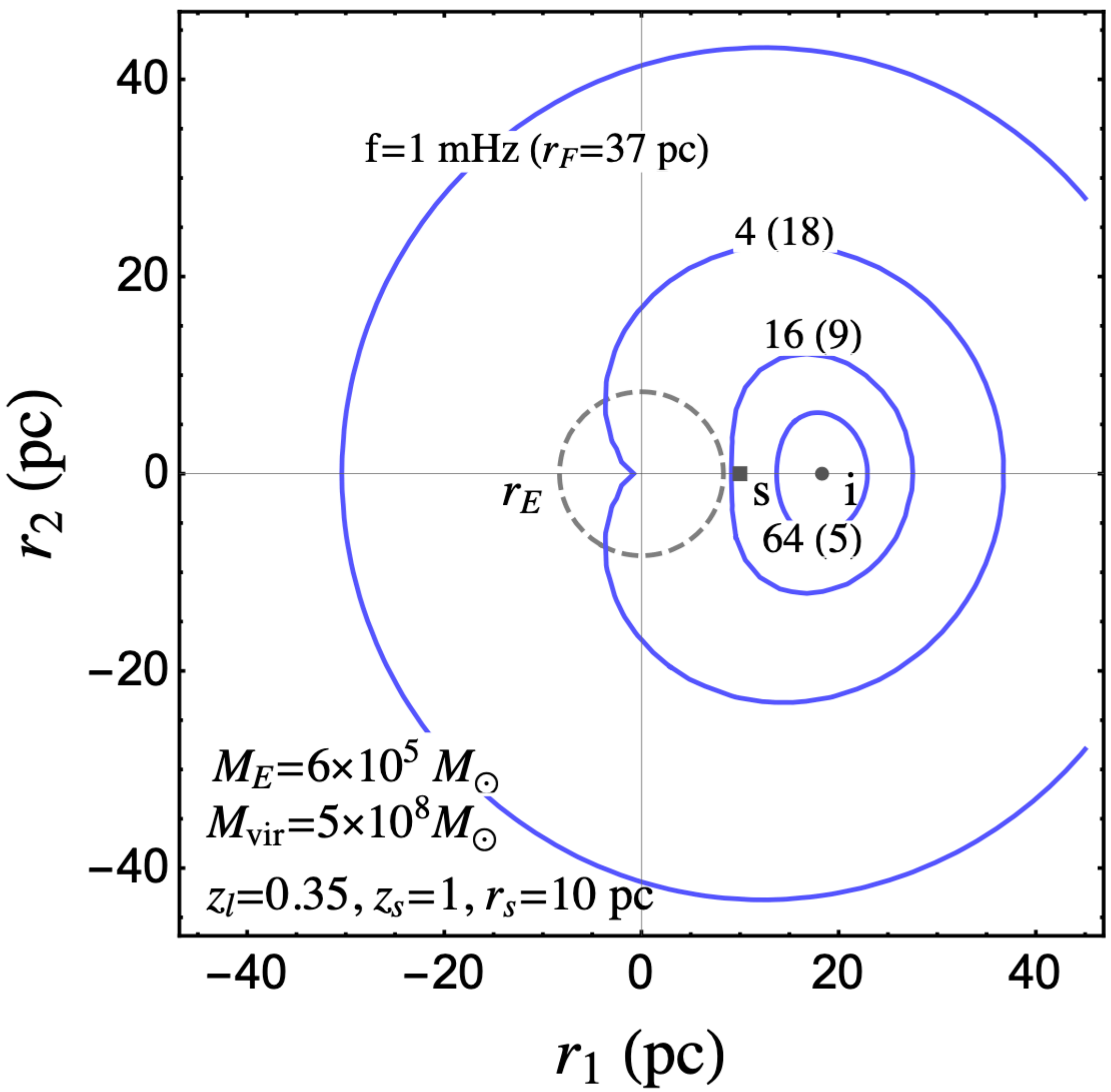
rF ~ rs

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



- From path integral viewpoint,

  blue circle is a boundary of an image w/ O(1) phase variation.

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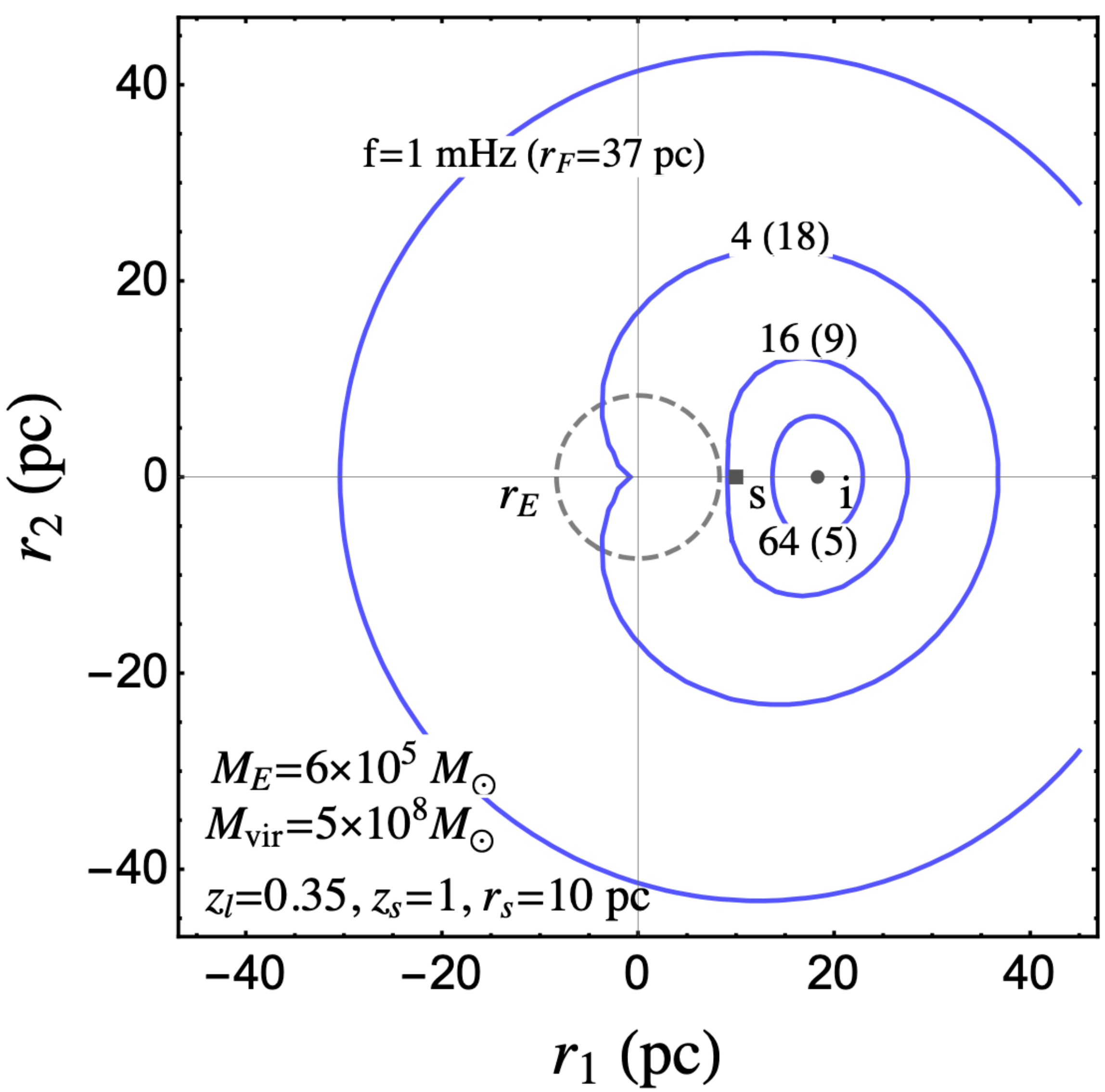
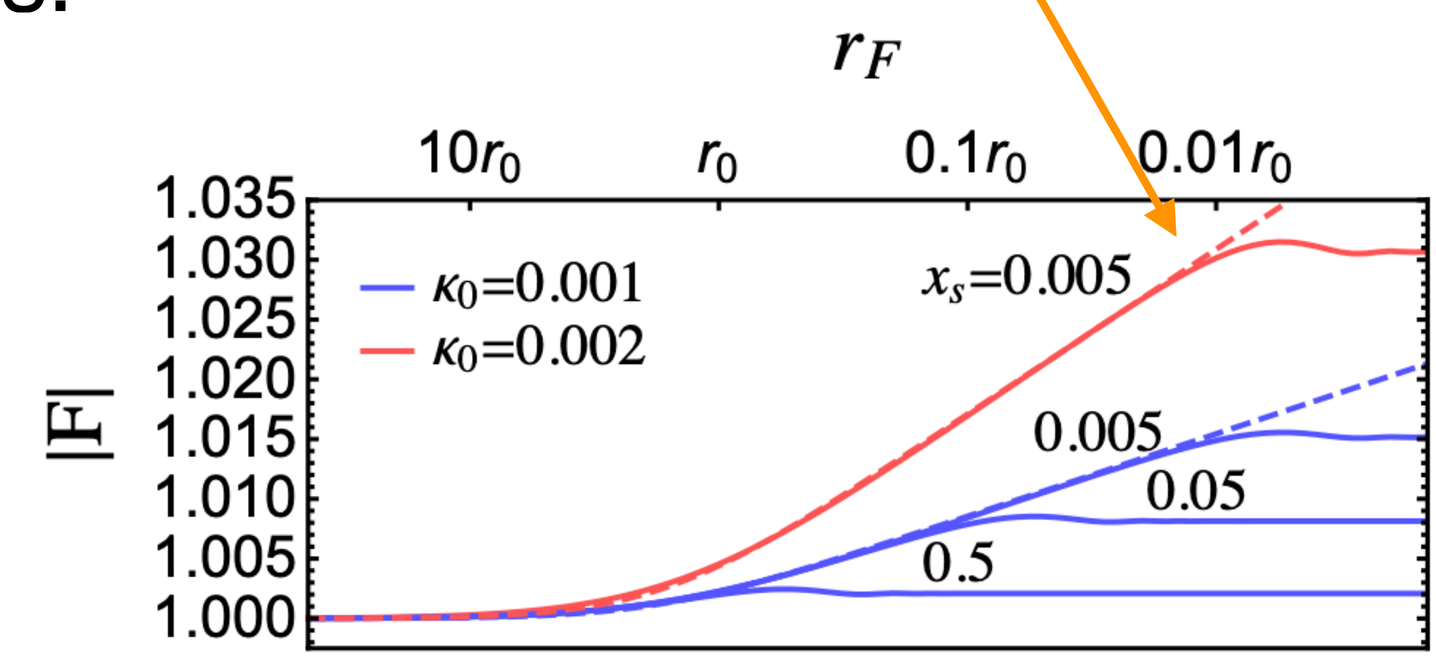
rF ~ rs

- As rF falls below rs, the wave begins to well locate the source away from the lens.





And it's also where diffraction ends.

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

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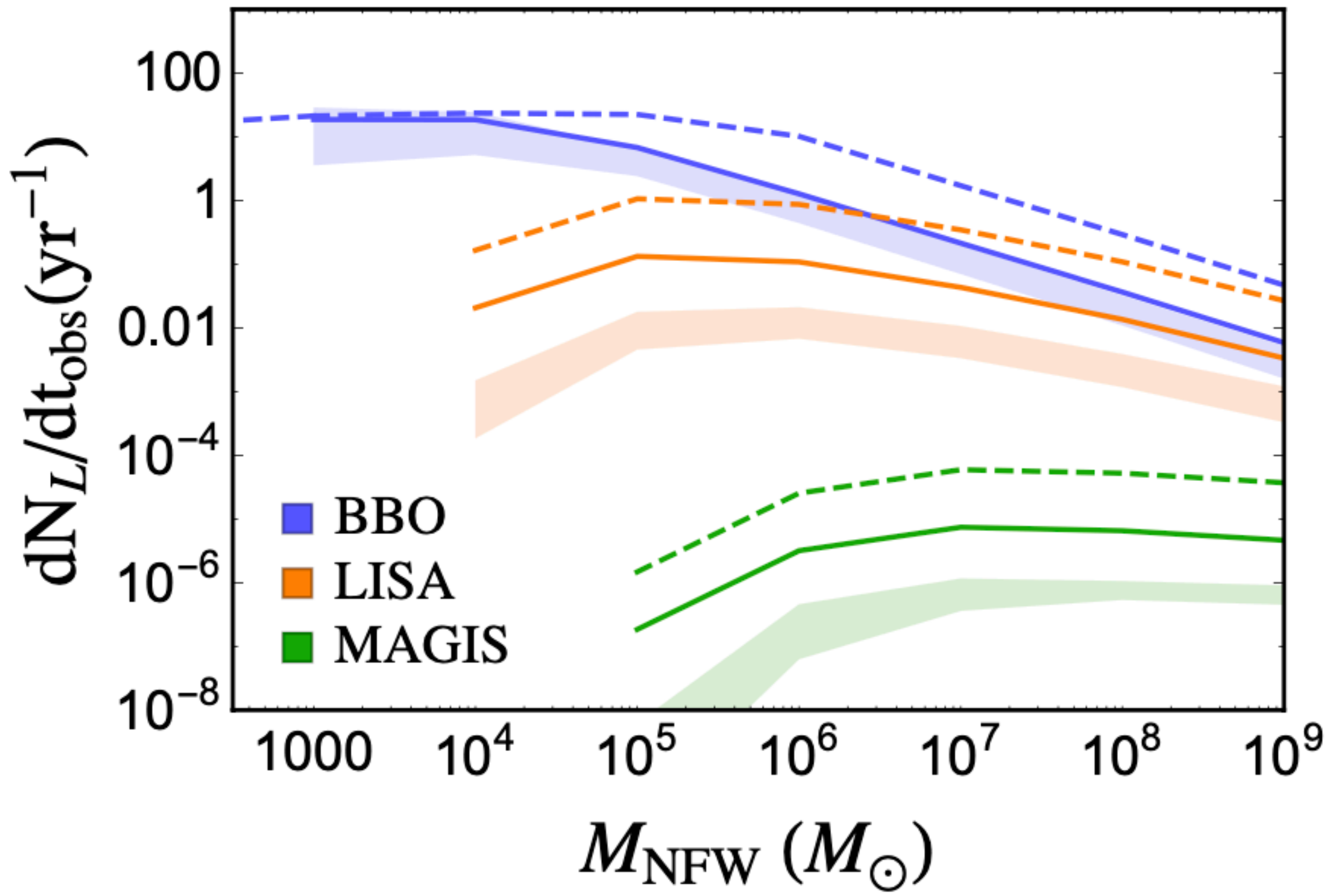
Detection prospects



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

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Thank you