Searching for Mini Extreme Mass Ratio Inspirals with Gravitational-Wave Detectors

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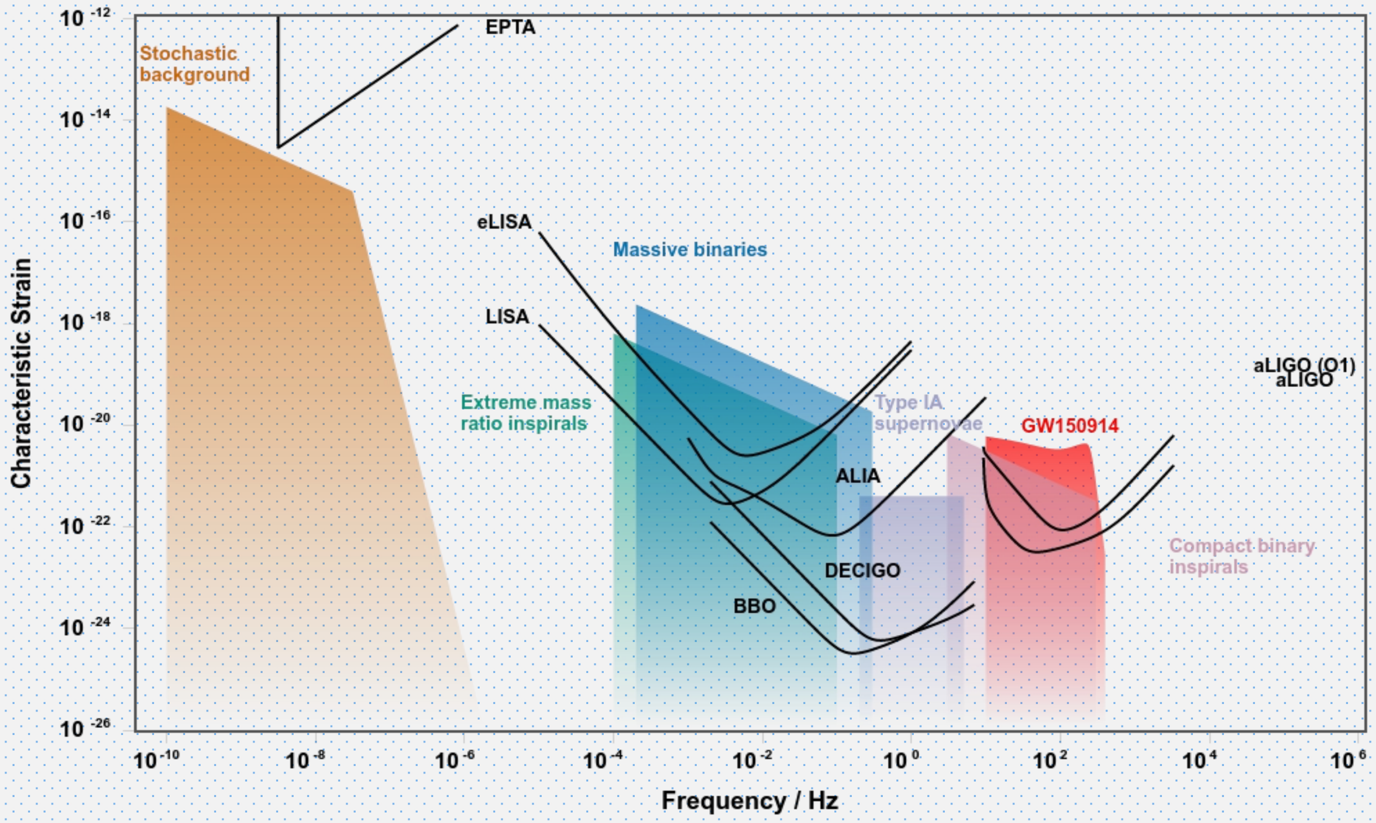
Jun. 8, 2022

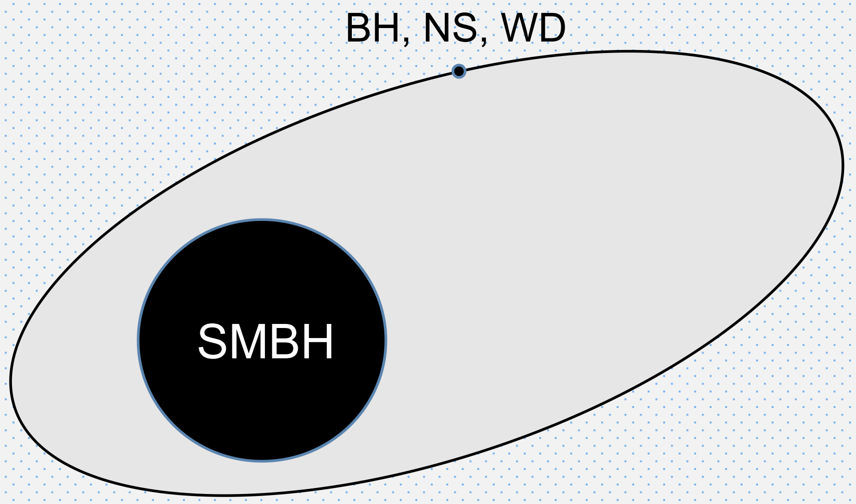
Huaike Guo, Andrew Miller, arxiv:2205.10359

What is an Extreme Mass Ratio Inspiral?

- Binaries in galactic centers
- Extremely small (or large) mass ratios
- Important targets for LISA, Taiji, Tianqin, ...

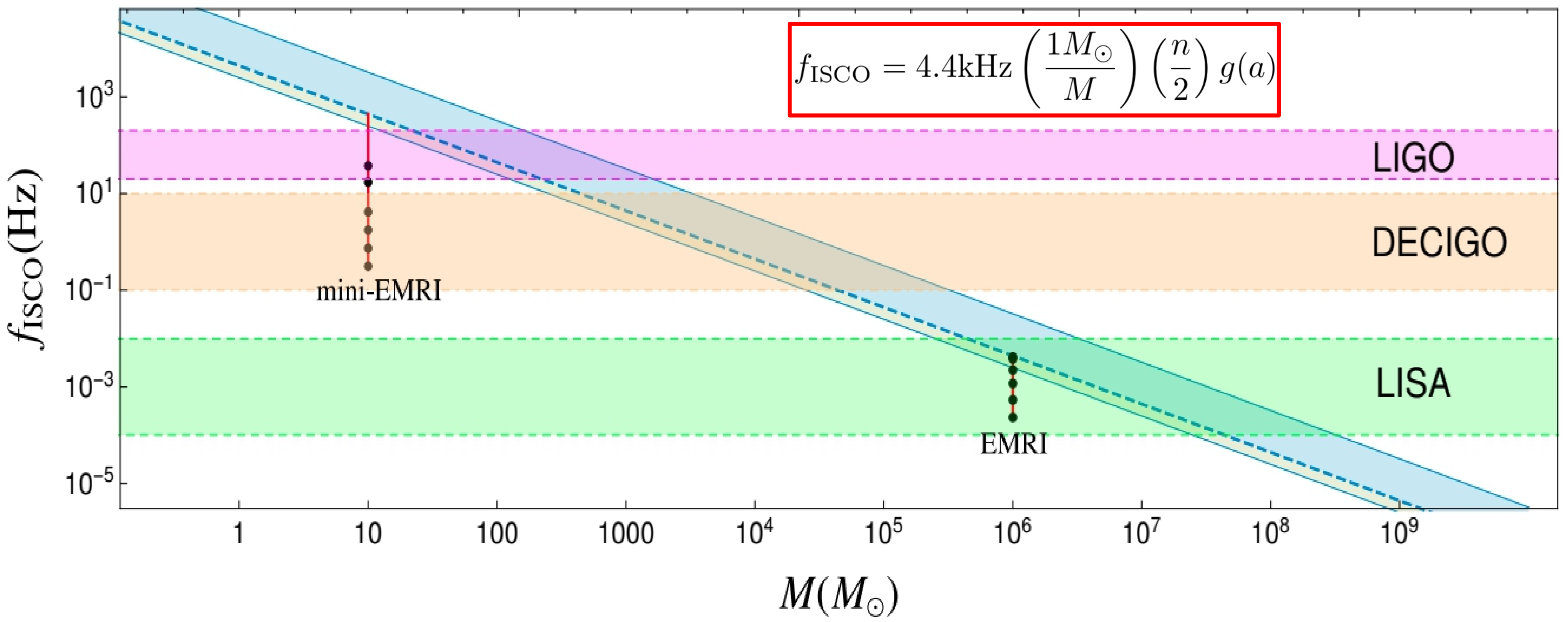


Moore, Cole and Berry, Class. Quantum Grav. 32 (2015) 015014



mass ratio $< 10^{-5}$

What is an Mini Extreme Mass Ratio Inspiral?



Similar systems:

Davoudiasl, Giardino, Phys.Lett.B 768, 198 (2017)

Pan, Lyu, Yang, PRD 105, 083005 (2022)

Barsanti et al PRL 128, 111104 (2022)

Exotic Compact Objects

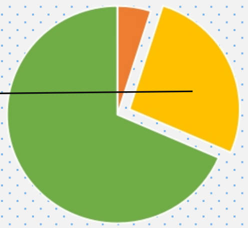
Ordinary

- Neutron Stars
- White Dwarfs
- Black Holes

Exotic

- Neutron Stars
- White Dwarfs
- Black Holes
- Primordial Black Holes
- Boson Stars
- Quark Stars
- ...

?

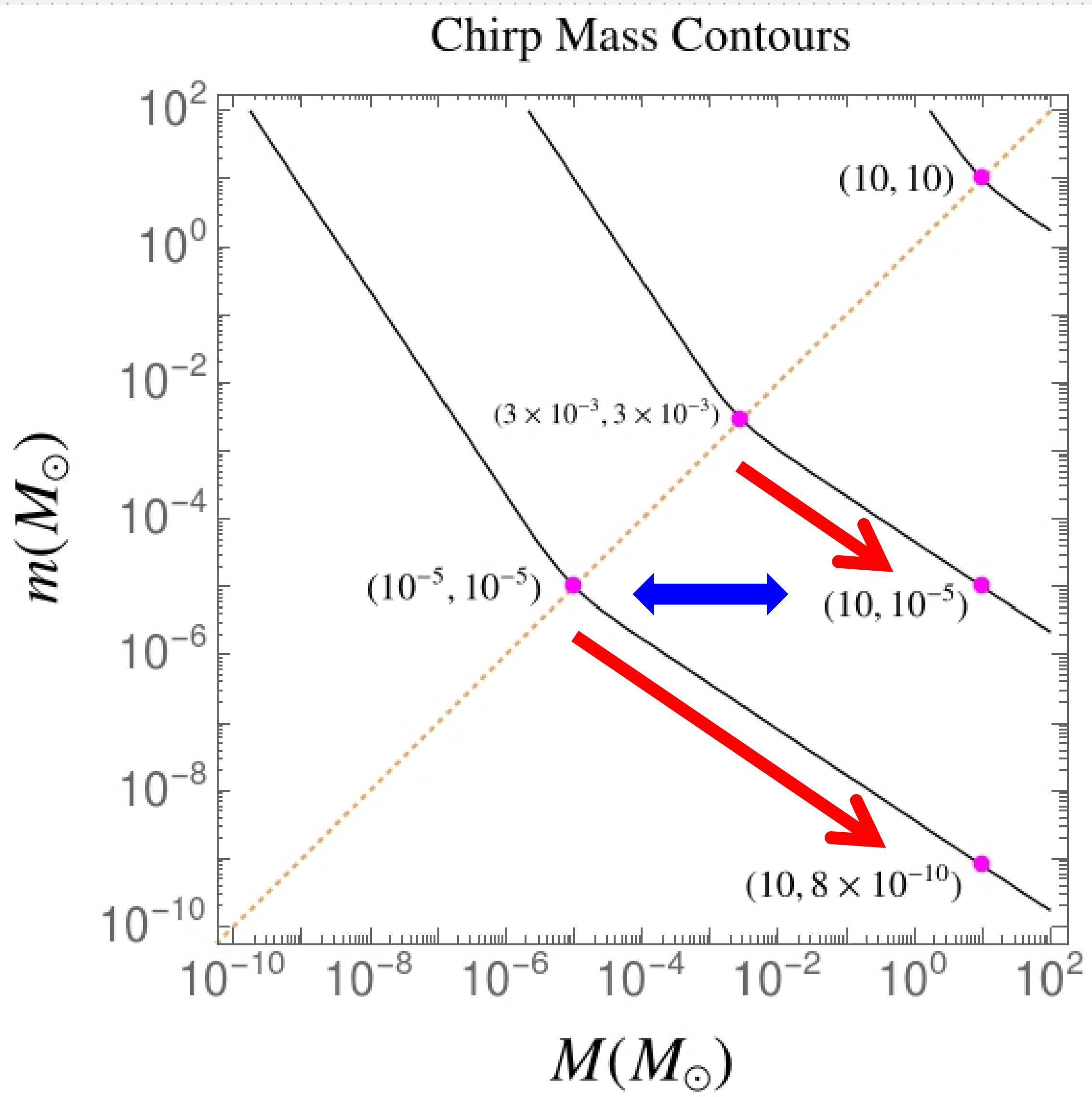


m (mass)
C (compactness = mass/radius)

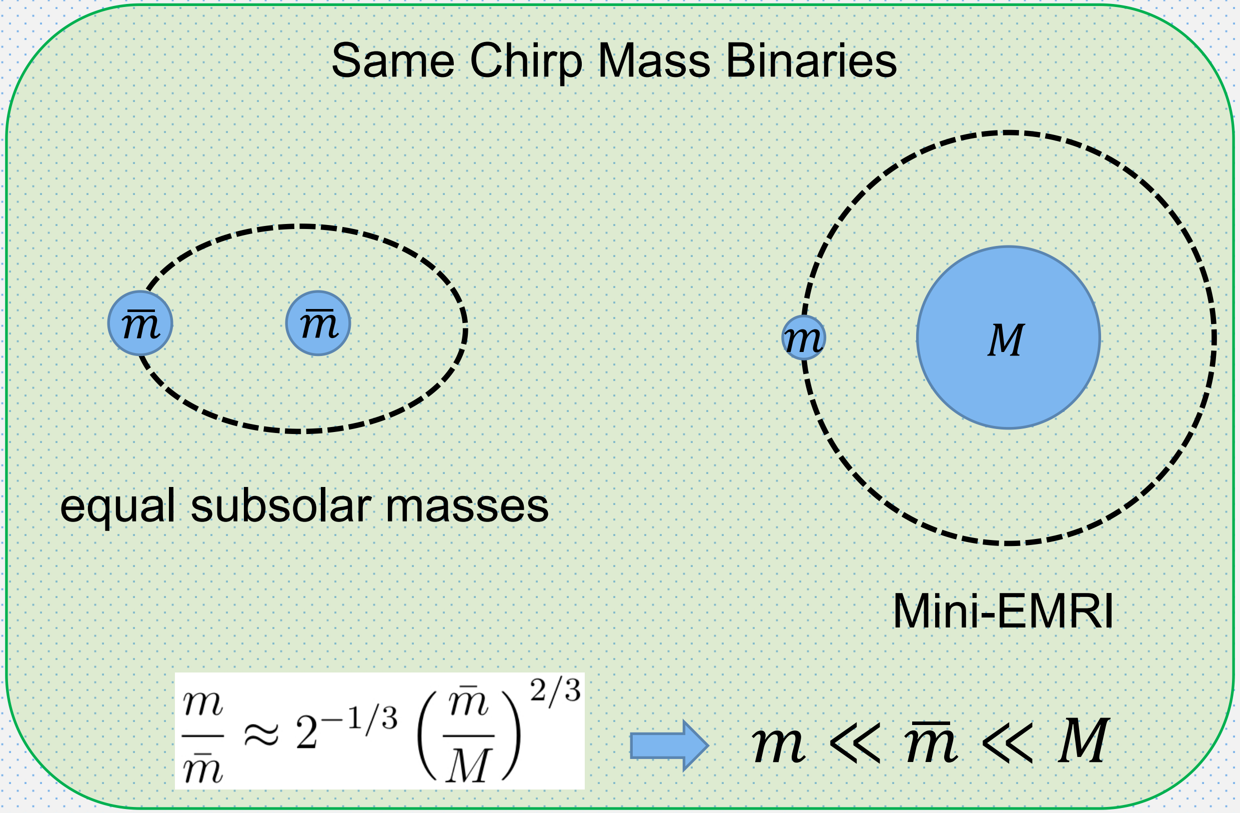
Detection of subsolar ECO would point to new physics.

Some (less compact) plenatary mass might be also form mini-EMRIs

Advantages



- Amplitude and SNR are proportional to positive powers of Mc.
- Mini-EMRI can probe much lighter ECOs



Waveforms

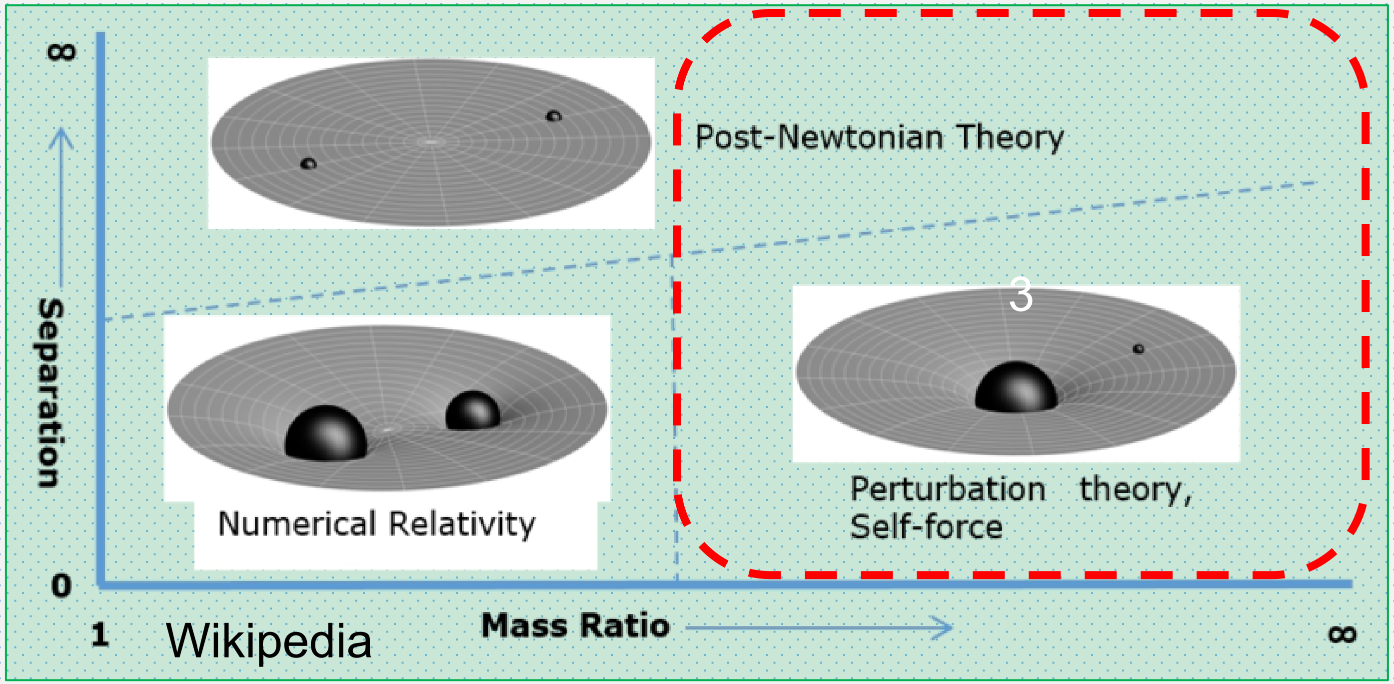
- Post-Newtonian studies in the inspiral stage
- Relativistic effect near ISCO requires numerical calculations
- Extreme mass ratio enables a new perturbation theory

Waveform calculation is still an ongoing effort.

Numerical result available for circular orbit
Finn, Thorne, PRD 62, 124021

Result consistent with others (LISA review)

dominant mode: n=2

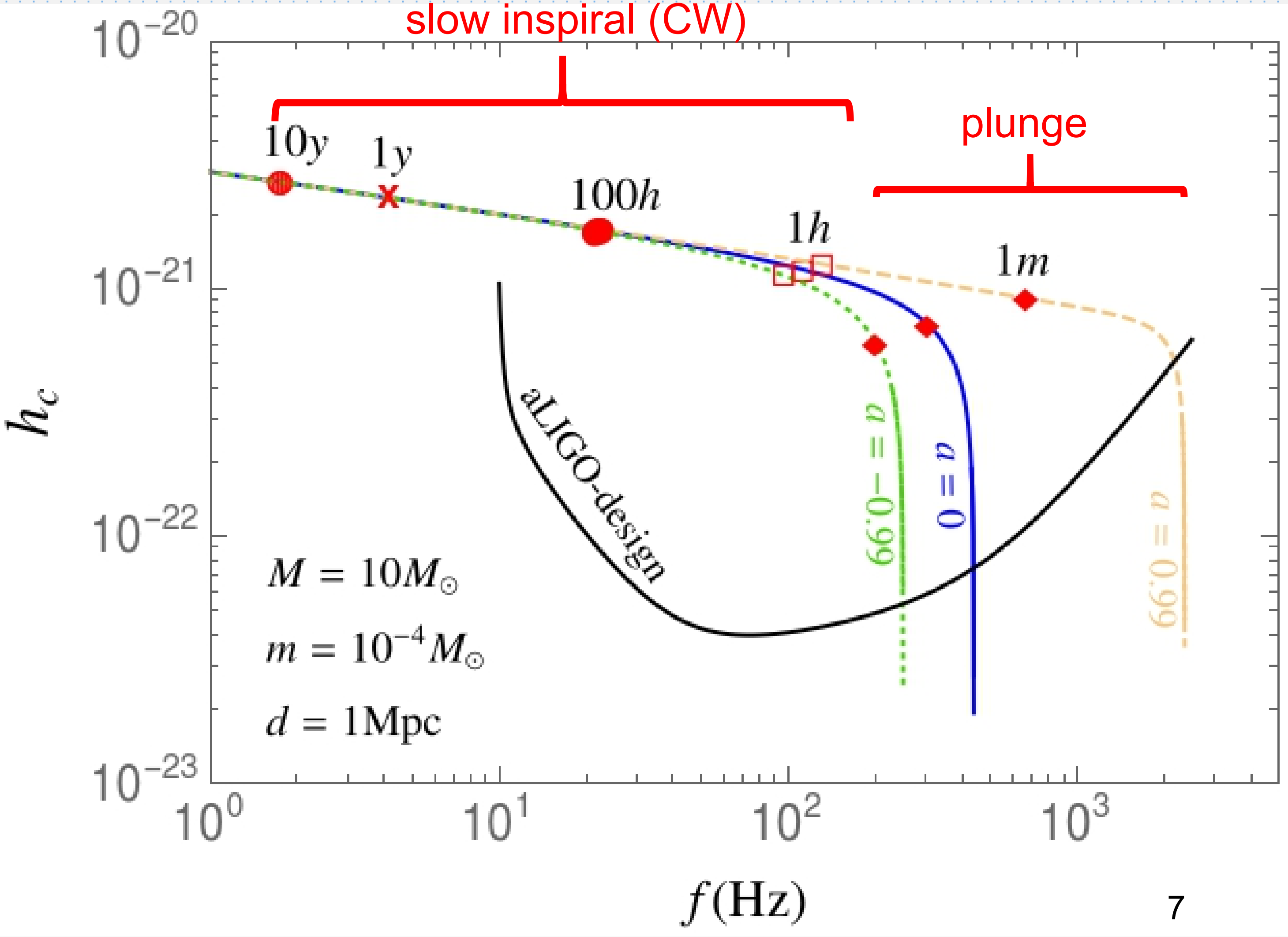


Wikipedia

Signal Properties

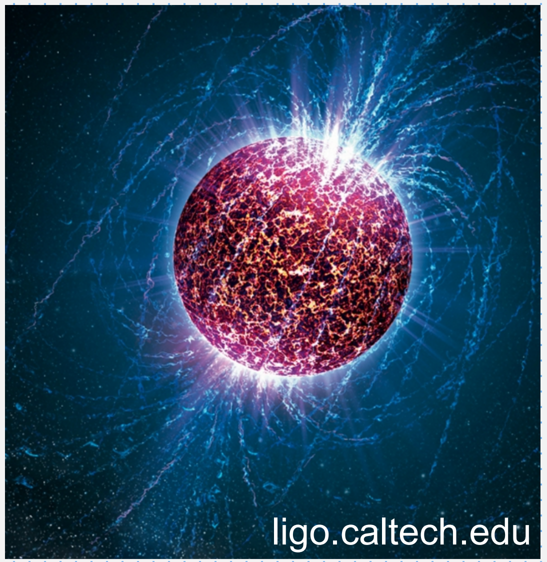
- Signal is long-lasting within detector band
- 2 stages: inspiraling and plunging
- ECO can be tidally disrupted

Tidal radius: $r_{\text{tidal}} = \frac{(m^2 M)^{1/3}}{C}$



Search Strategies

- Signal is similar to continuous waves from neutron stars
- Search strategies can be employed for mini-EMRIs



✓ targed searches (known black holes, neutron stars as the heavier object)

✓ all-sky searches (blind searches)

Search Techniques

Coherent Searches

- The optimal method (better sensitivity)
- However, long duration, gaps, non-Gaussian noise
- Computationally challenging (especially all-sky)

Incoherent Searches

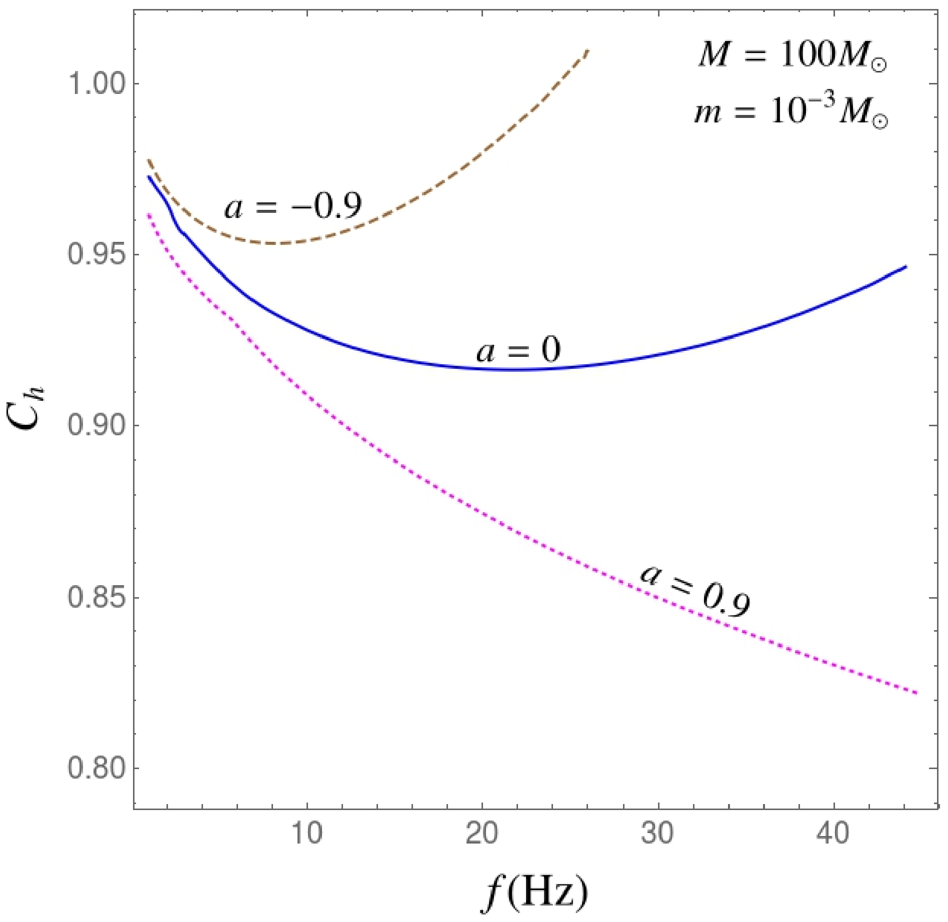
- Reduced sensitivity
- Mature and robust methods
- Computationally feasible

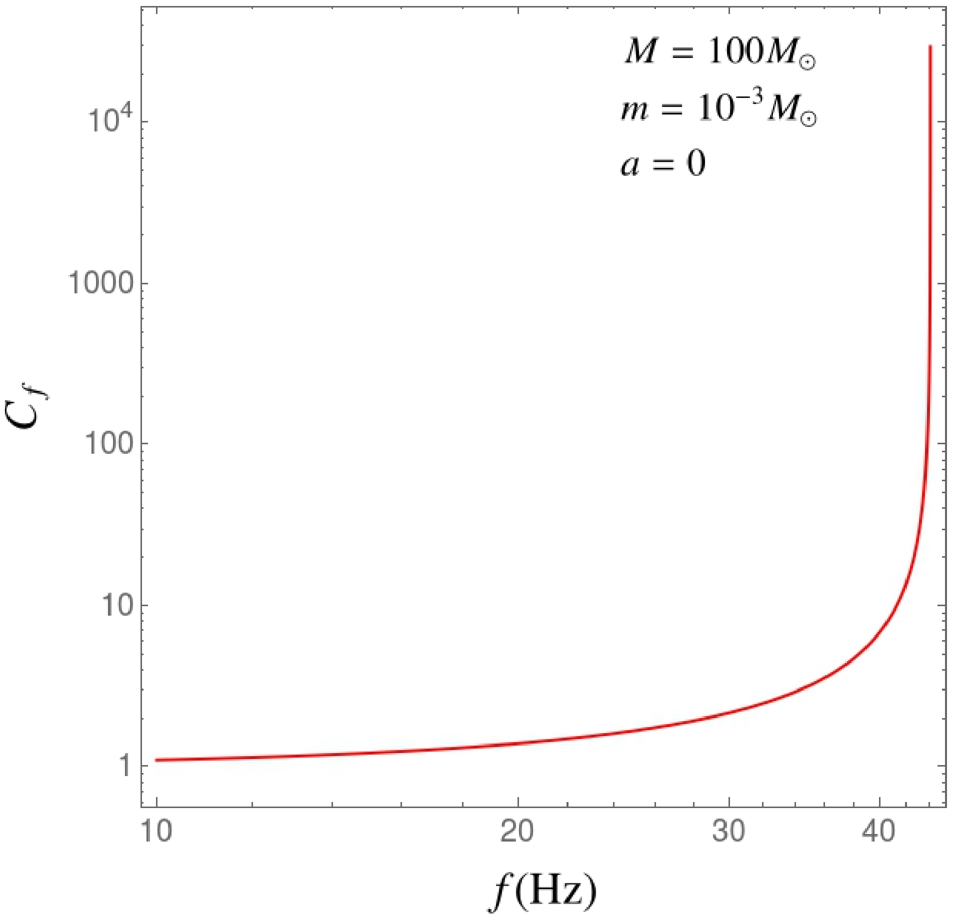
We employ the mature incoherent search methods

Inputs

$$h_0 = \frac{4}{d}\left(\frac{GM_c}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}\boxed{C_h(a,f)}$$

$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} f^{11/3}\boxed{C_f(a,f)}$$



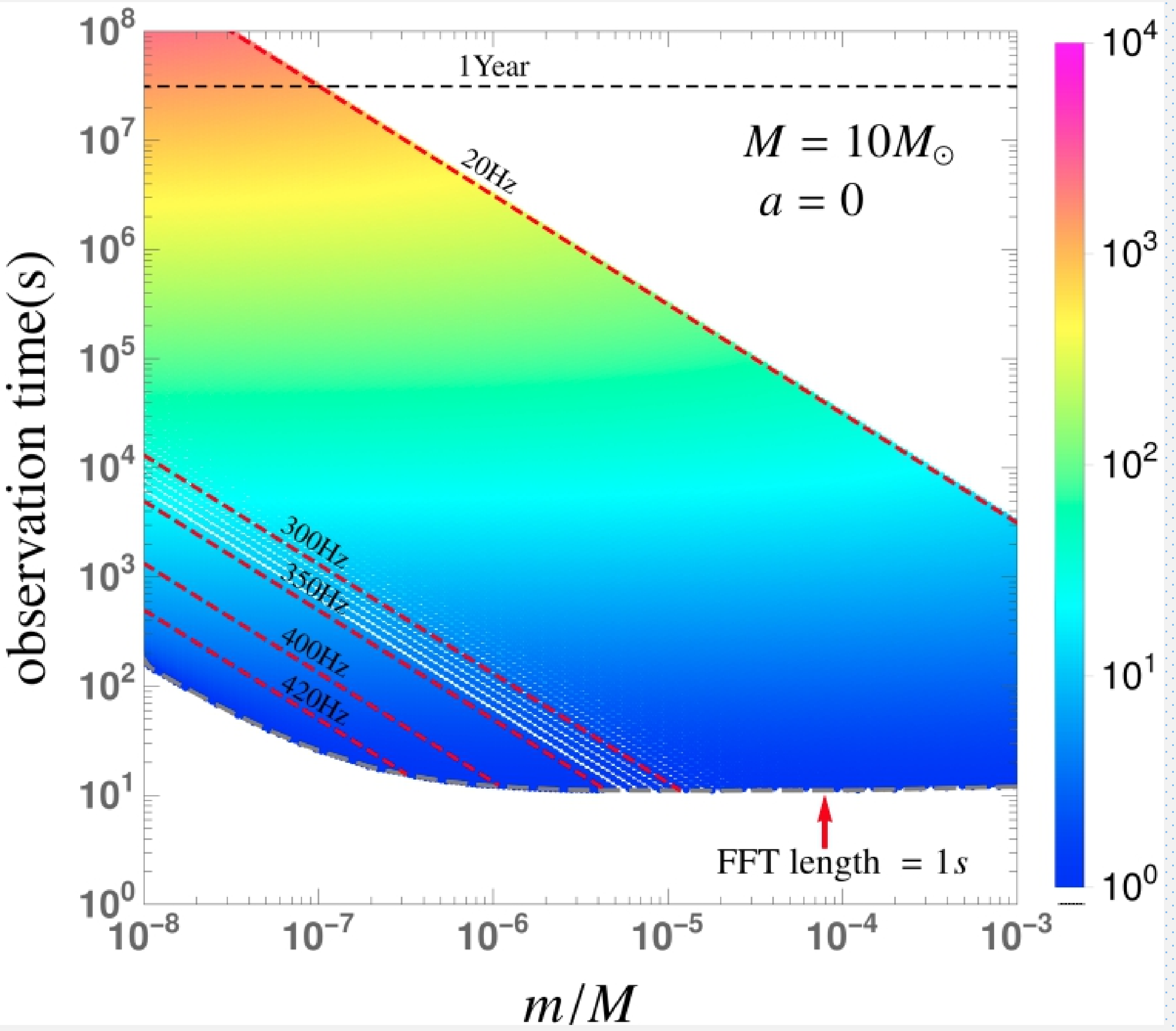


Incoherent Search Method

- Break data into chunks (length TFFT)
- Fast fourier transform each chunk
- Detect excess powers in time-frequency map
- Combine the powers incoherently (Hough transform)

TFFT: contain signal power in 1 frequency bin

Example: a 10hz band



Distance Reach

$$T_{FFT} = \frac{1}{\sqrt{df/dt}}$$

amplitude: f-independent coefficient

time of each segment

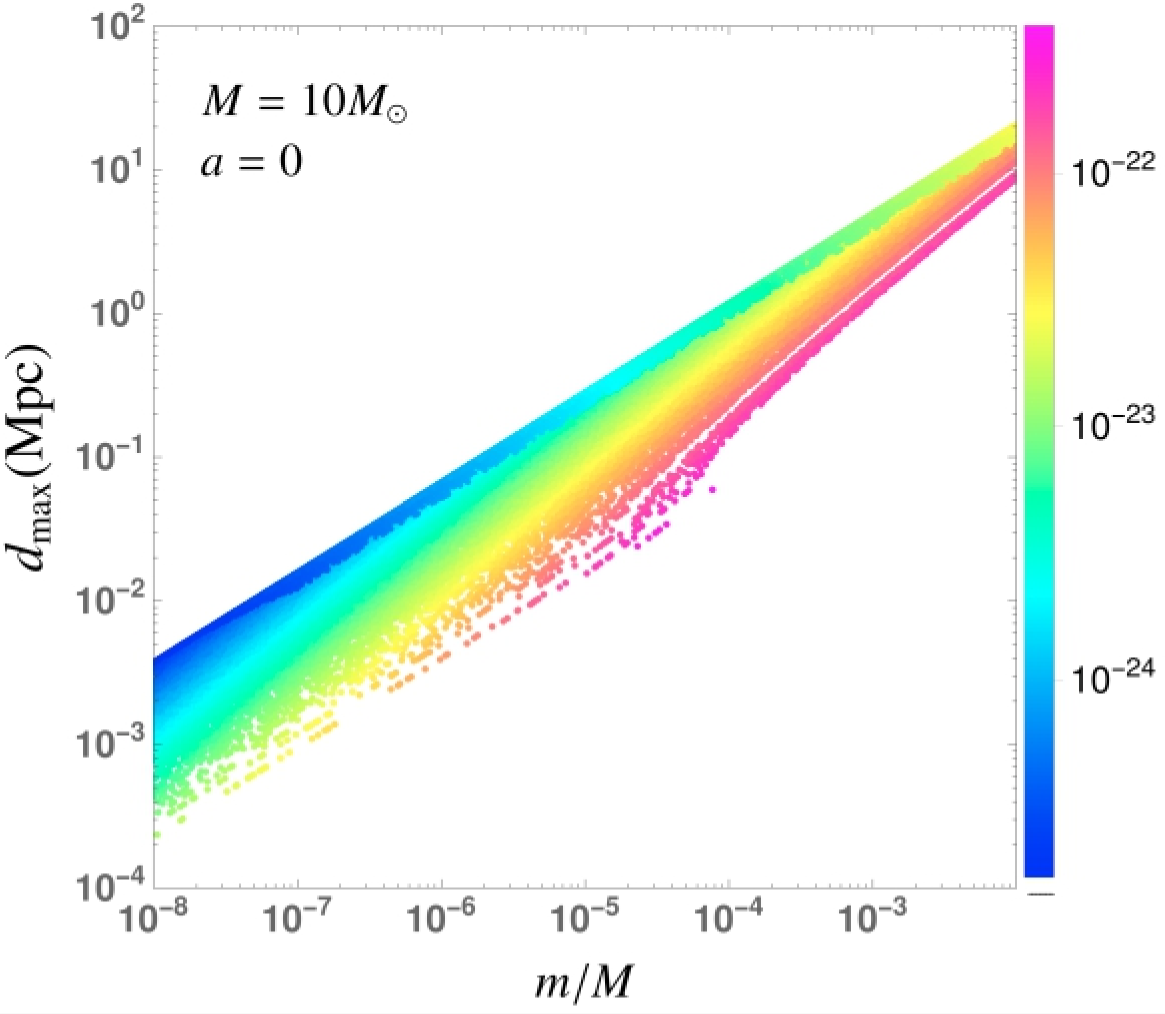
$$d_{\max} = 0.995\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi}{c}\right)^{2/3}\frac{T_{\rm FFT}}{\sqrt{T_{\rm obs}}}\left(\sum_i \frac{\mathcal{F}_i^2}{S_n(f_i)}\right)^{1/2}\left(\frac{p_0(1-p_0)}{Np_1^2}\right)^{-1/4}\sqrt{\frac{\theta_{\rm thr}}{\left(CR_{\rm thr}-\sqrt{2}\,{\rm erfc}^{-1}(2\Gamma)\right)}}$$

sum over all segments

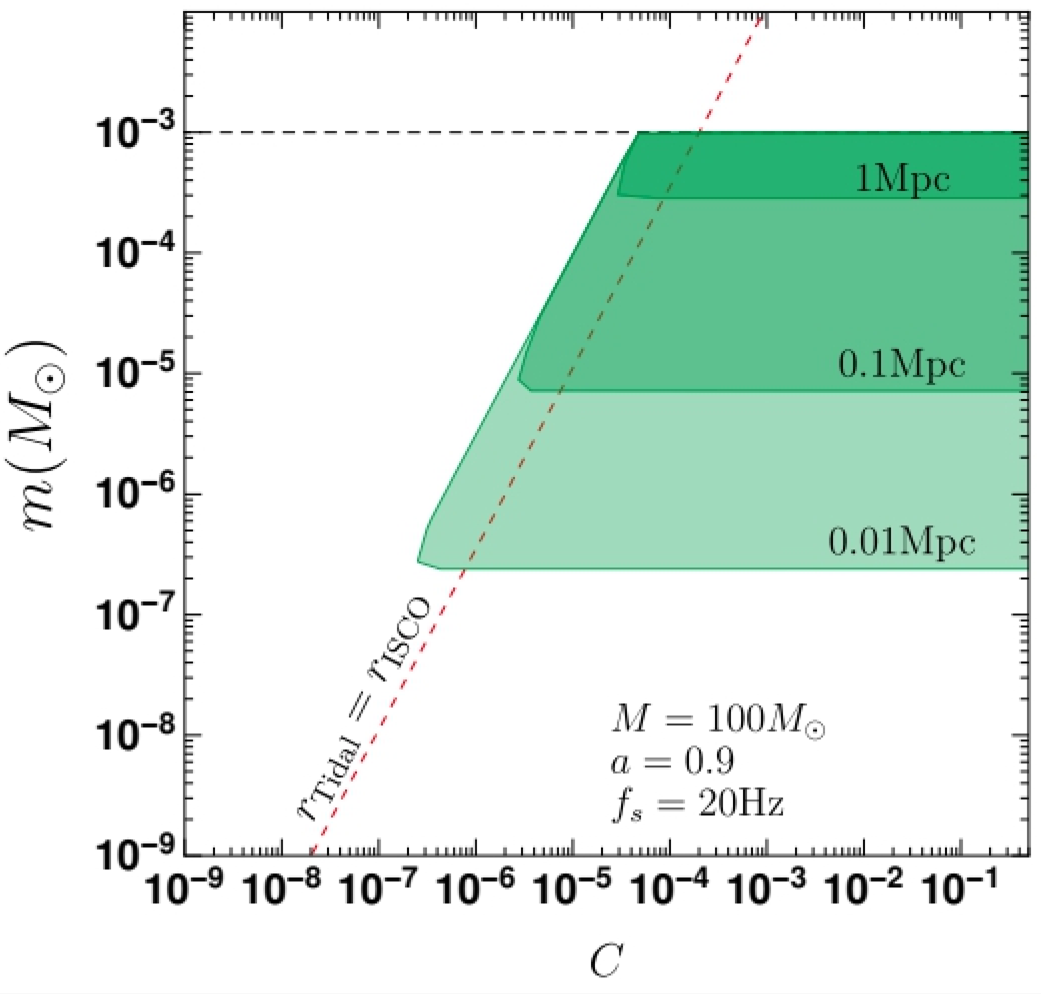
total observation time: set as 1 year

Miller et al, Phy.Dark.Univ.32 (2021) 100836

Results



$M = 10M_\odot$
$a = 0$
$d_{\max}(\mathrm{Mpc})$
m/M
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-22}
10^{-23}
10^{-24}



$m(M_\odot)$
C
1Mpc
0.1Mpc
0.01Mpc
$r_{\mathrm{Tidal}} = r_{\mathrm{ISCO}}$
$M = 100M_\odot$
$a = 0.9$
$f_s = 20\mathrm{Hz}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Summary

- LIGO can detect EMRI (mini version)
- mini-EMRIs allow searching for much lighter (subsolar) ECOs
- Strageties/Methods of CW searches can be directly applied here
- mini-EMRIs discoverable up to O(kpc - 10Mpc)