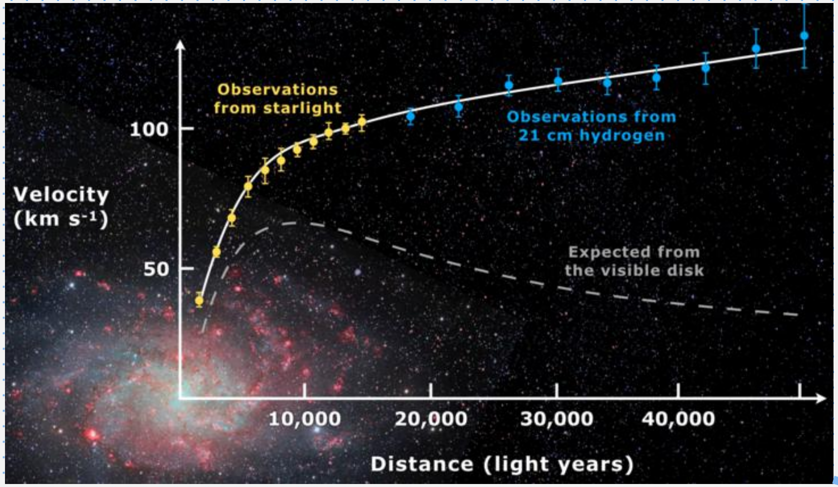
Macroscopic Dark Matter Detection with Extreme Mass Ratio Inspirals

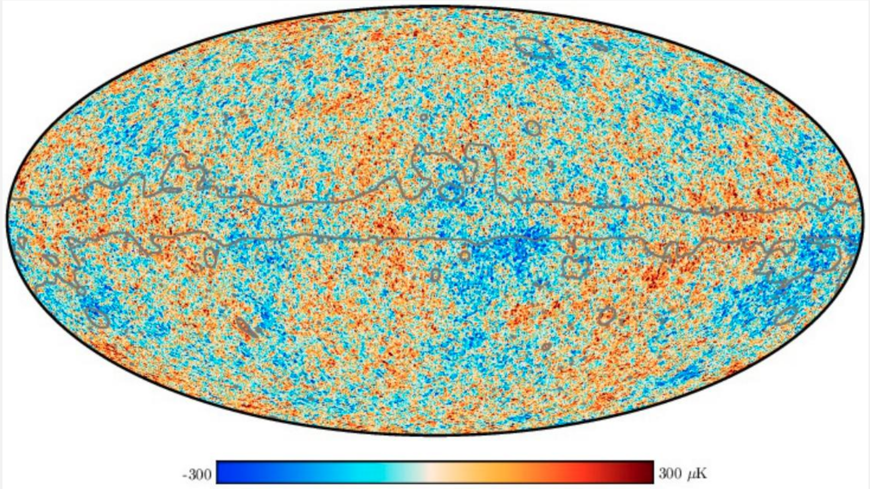
郭怀珂

2022年10月18日

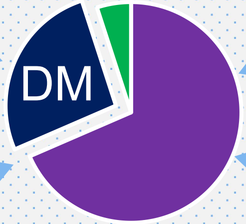
HG, A.Miller, arxiv:2205.10359
HG, J.Shu, Y.Zhao, PRD 99 (2019) 023001
HG, K.Sinha, C.Sun, JCAP 09 (2019) 032

Dark Matter: Observational Evidence



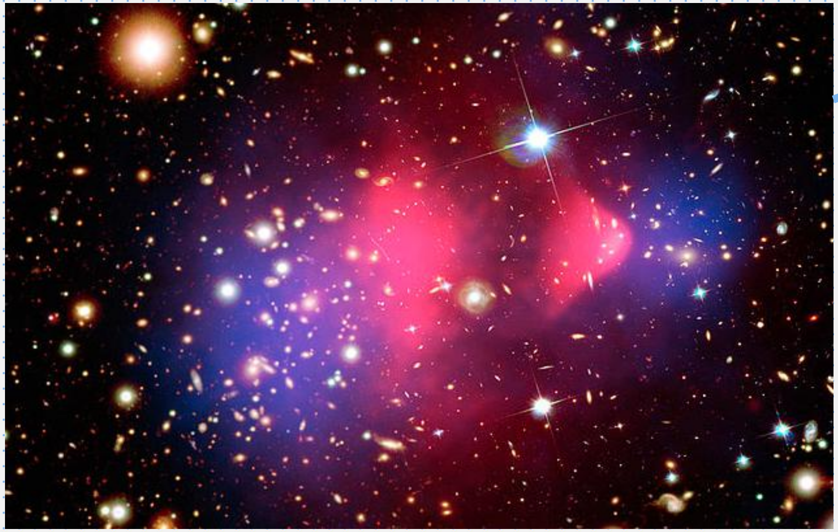


Planck 2018

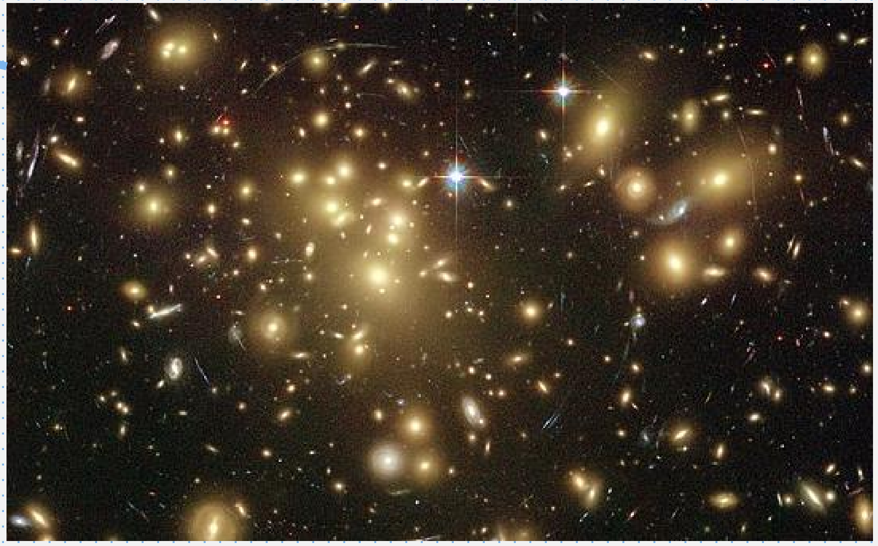


$$\Omega_c = 0.26$$

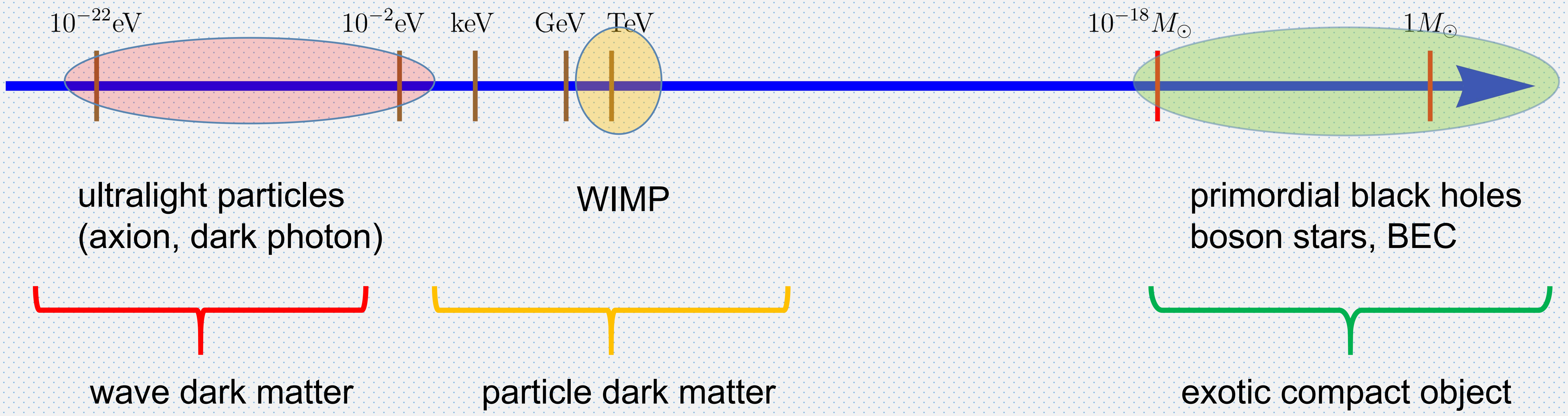
(PDG2022)



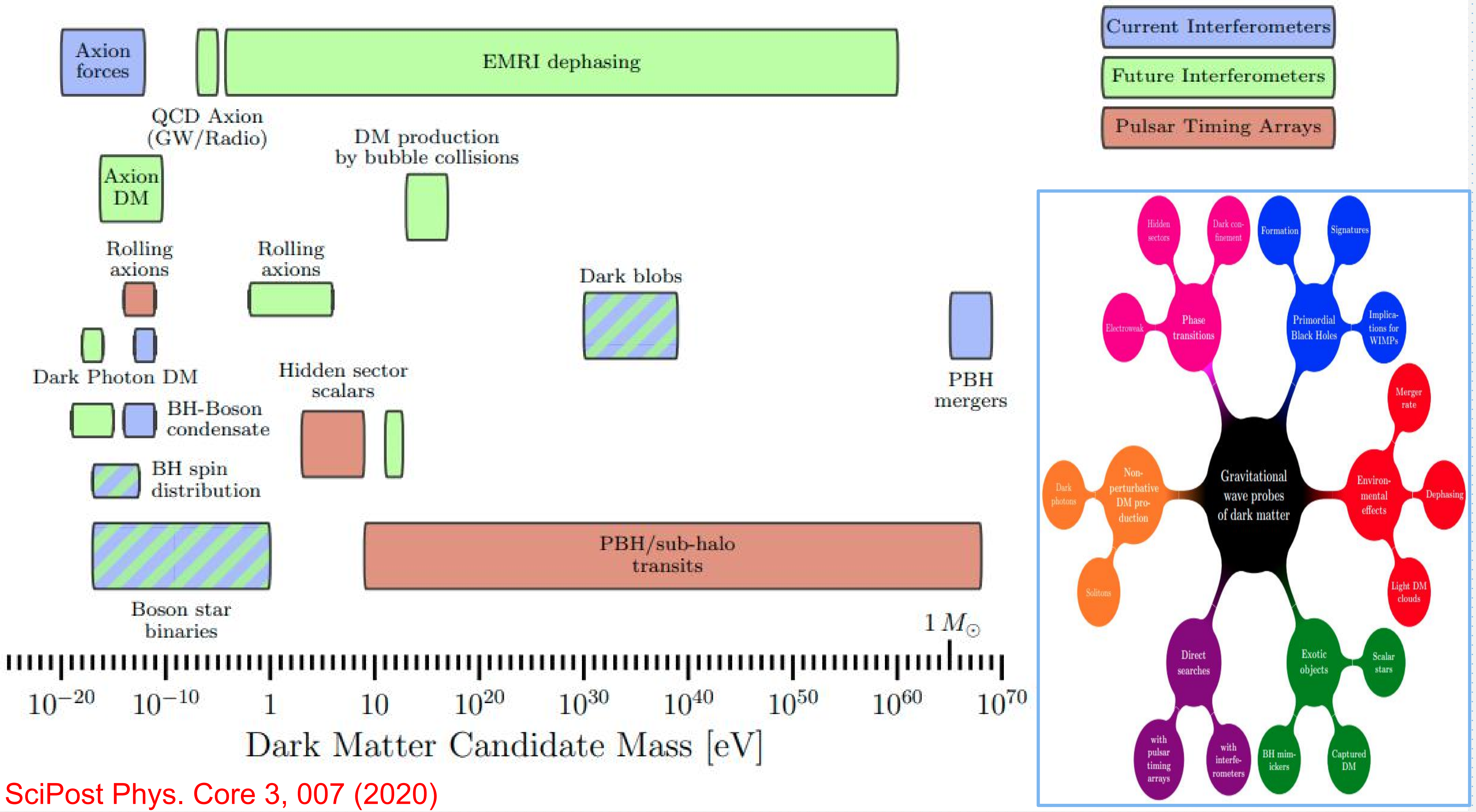
Wikipedia



Dark Matter Candidates



Many can be searched for with gravitational waves (detectors)



SciPost Phys. Core 3, 007 (2020)

Exotic Compact Objects

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

(mass, spin, compactness (mass/radius))

- (Mini) Boson Star (self-interactions or not)
- Solitonic Boson Star (specific potential)
- Oscillaton (real scalar field)
- Proca Star (massive vector)
- Axion Stars (dense or dilute)

See, e.g., Liebling, Palenzuela, Living Rev Relativ (2017) 20:5

PHYSICS REPORTS (Review Section of Physics Letters) 221, Nos. 5 & 6 (1992) 251–350. North-Holland

PHYSICS REPORTS

Nontopological solitons*

T.D. Lee

Department of Physics, Columbia University, New York, NY 10027, USA

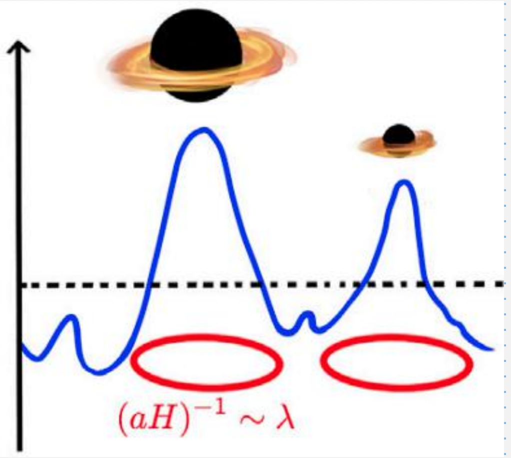
and

Y. Pang

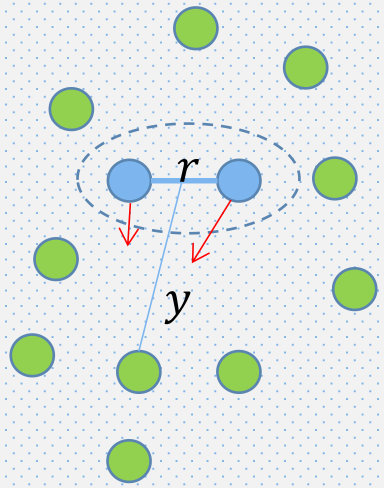
Brookhaven National Laboratory, Upton, NY 11973, USA

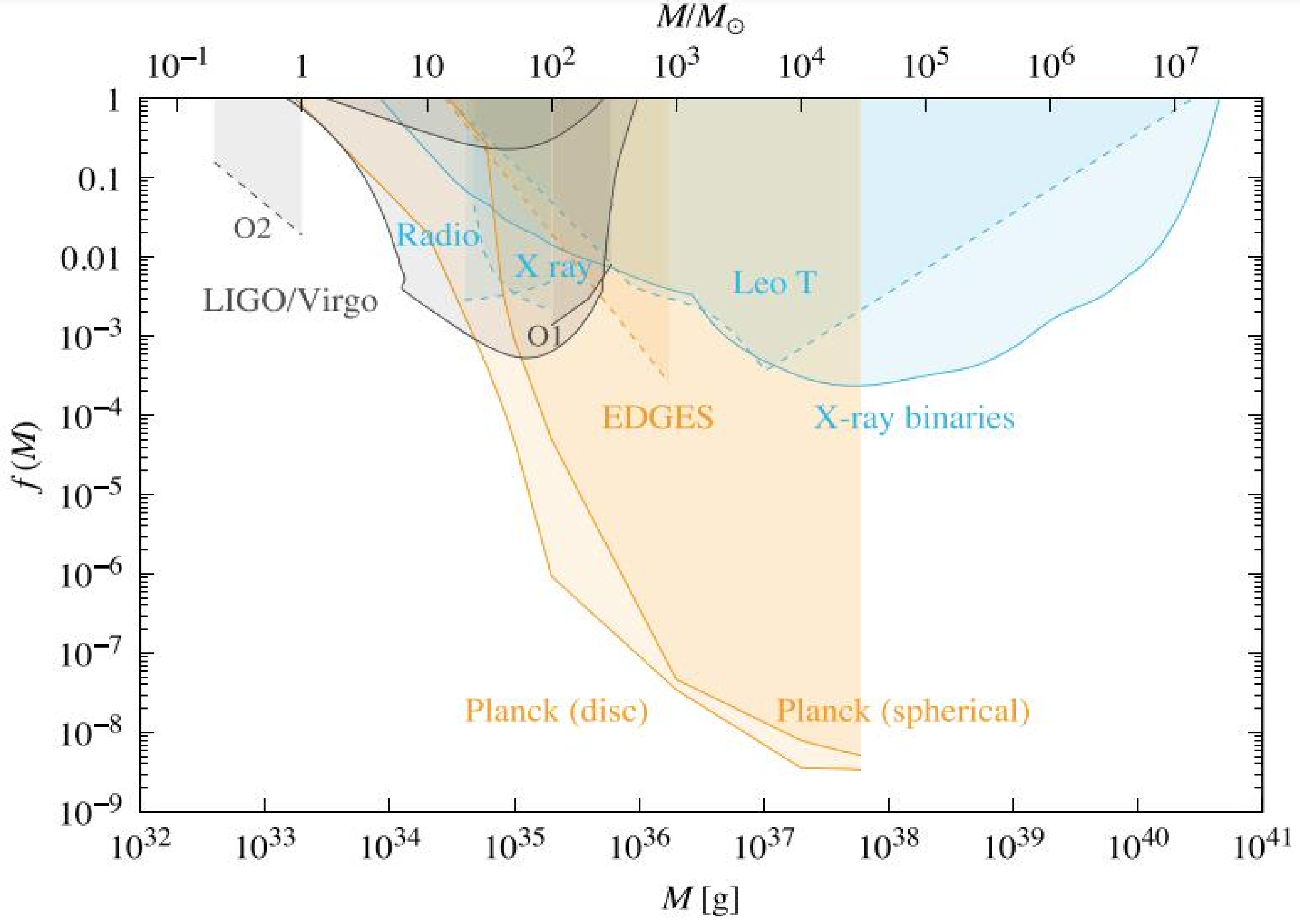
Received May 1992; editor: D.N. Schramm

Primordial Black Holes



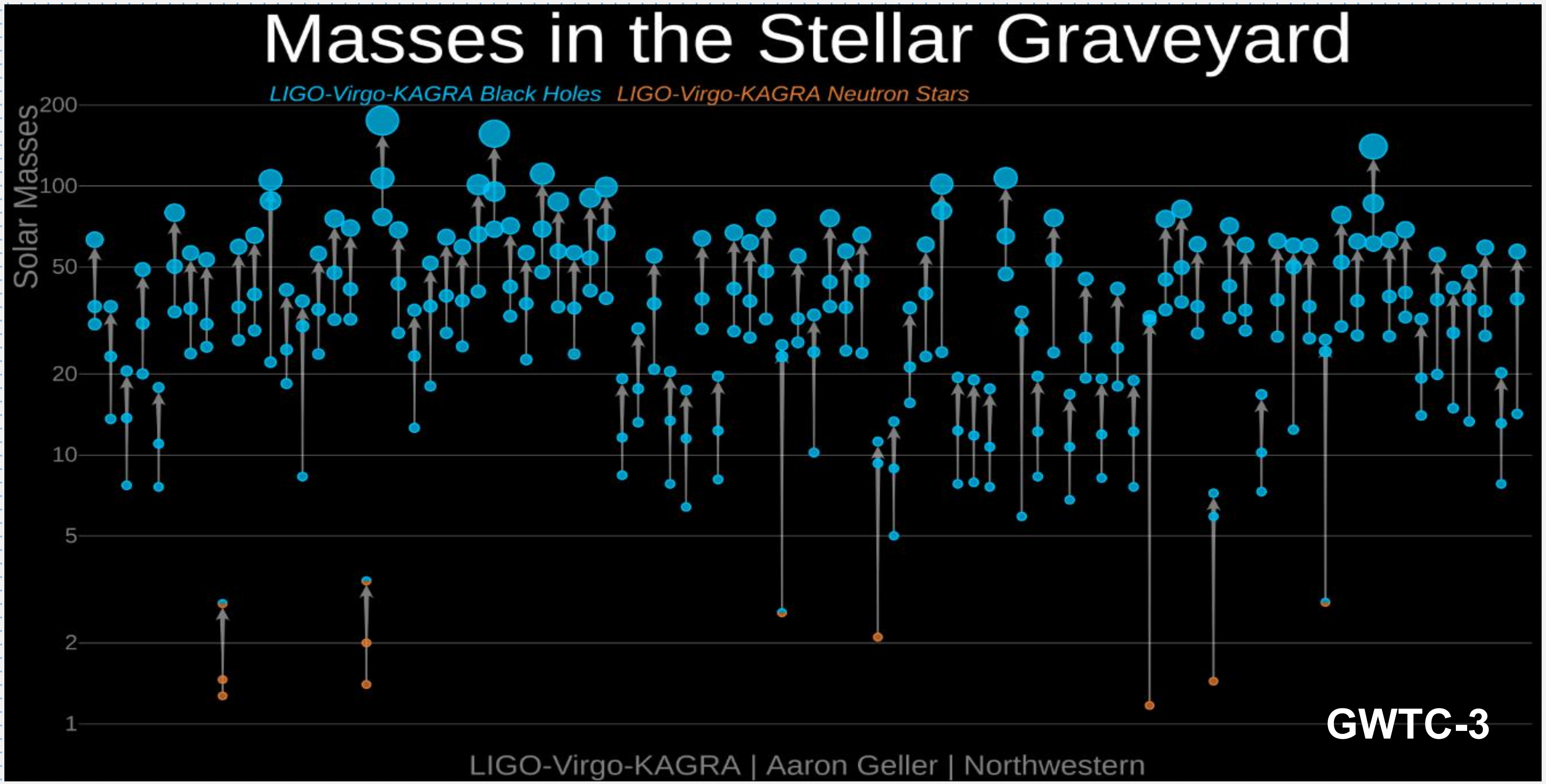
Villanueva-Domingo et al
Front. Astron. Space Sci, 2021.681084





Carr, et al, Rep. Prog. Phys. 84 (2021) 116902

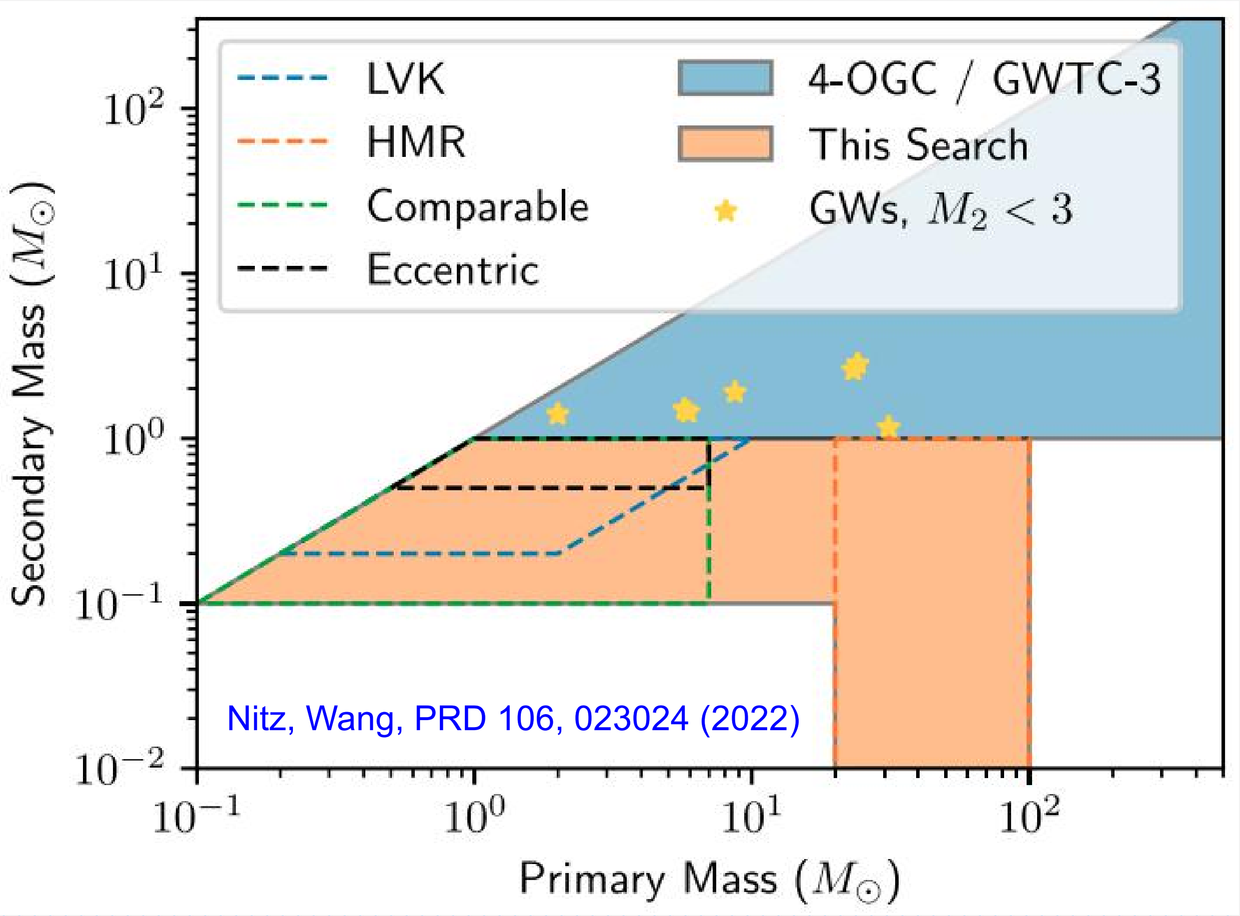
Astrophysical-origin BHs or PBHs?



- Spin distribution, merger rates (stochastic GWs)
- Mass as discriminator

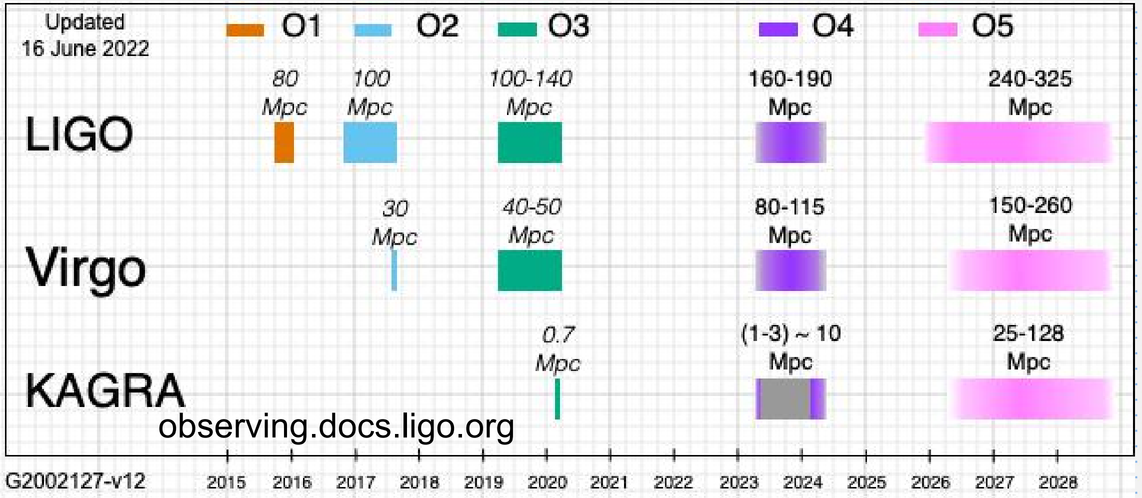
Subsolar PBH Searches

Rising interest in subsolar PBH searches



- Method: matched-filtering
- All assuming ultracompact objects

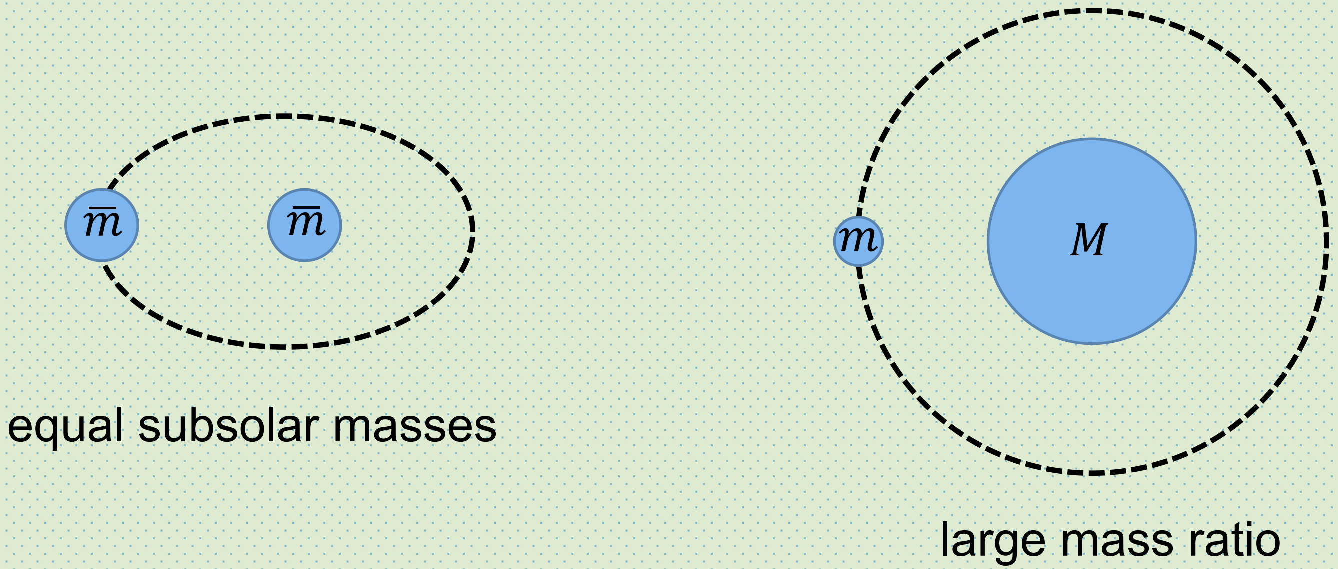
Need to take generic compactness into account for generic ECOs



Lighter?

- Amplitude and SNR are proportional to positive powers of chirp mass (Mc)

Same Chirp Mass Binaries

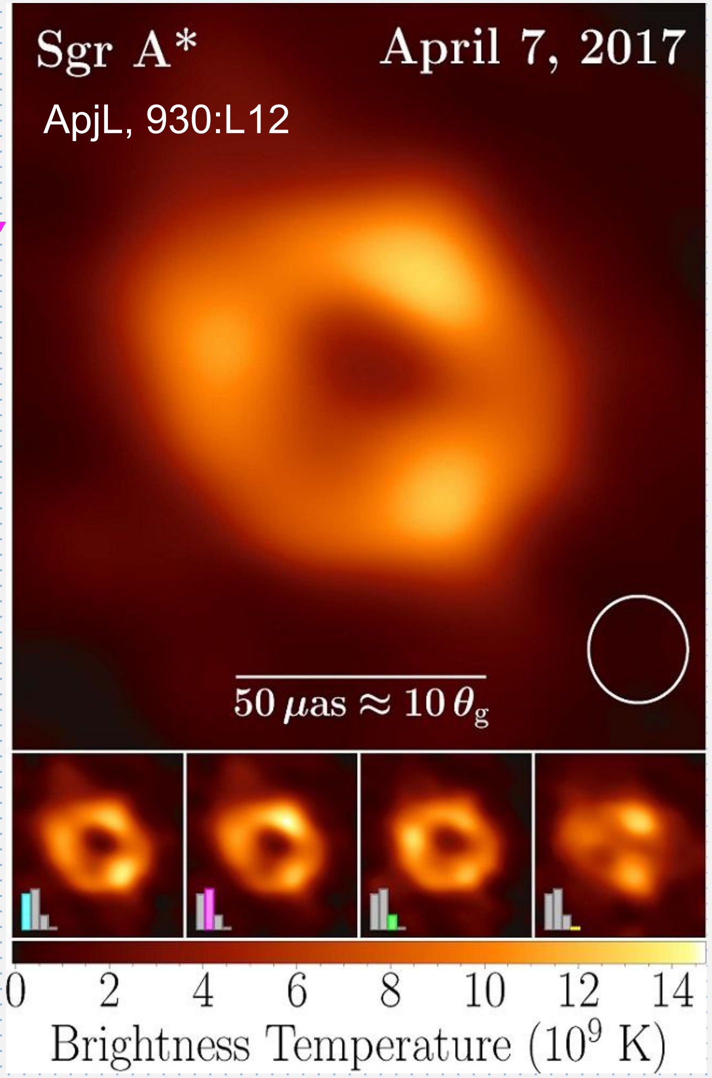


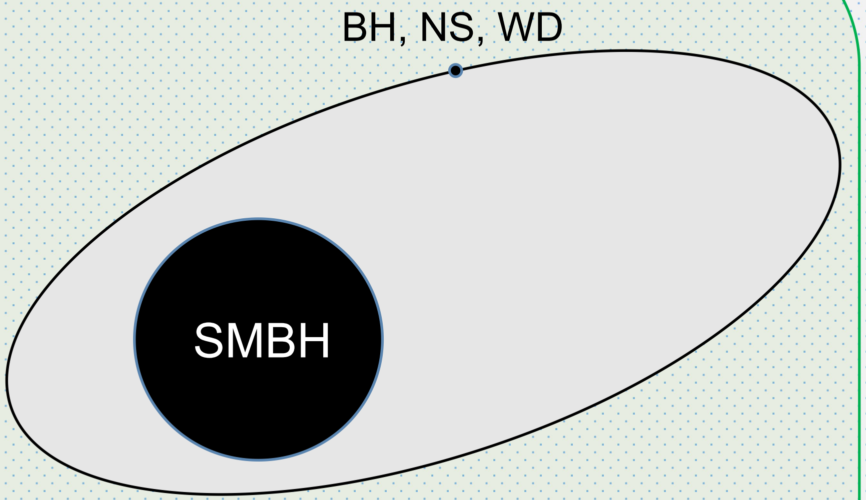
$$\frac{m}{\bar{m}} \approx 2^{-1/3}\left(\frac{\bar{m}}{M}\right)^{2/3} \Rightarrow m \ll \bar{m} \ll M$$

✓ Large mass ratio: probe lighter ECO

The Extreme Mass Ratio Inspiral (EMRI)

Wikipedia



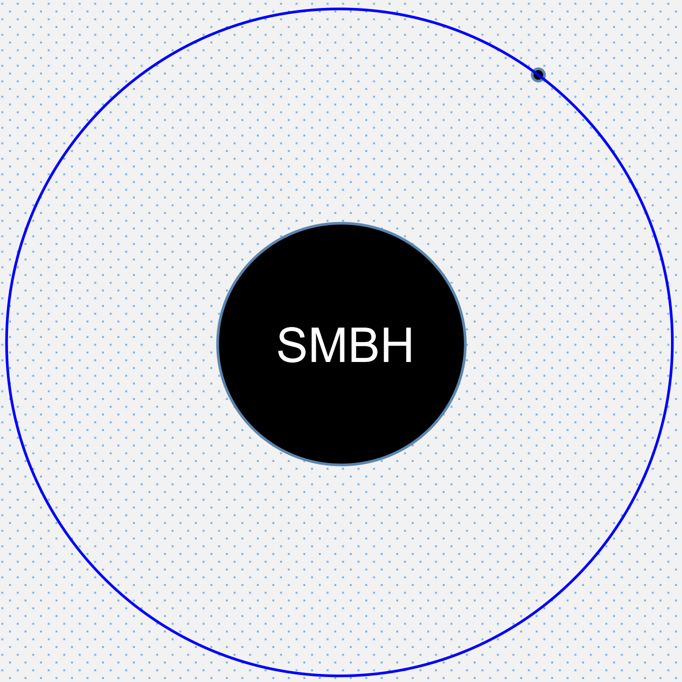


SMBH: $4 * 10^6$ solar mass

BH/NS/WD: O(1-10) solar mass

extreme mass ratio

Typical Frequencies

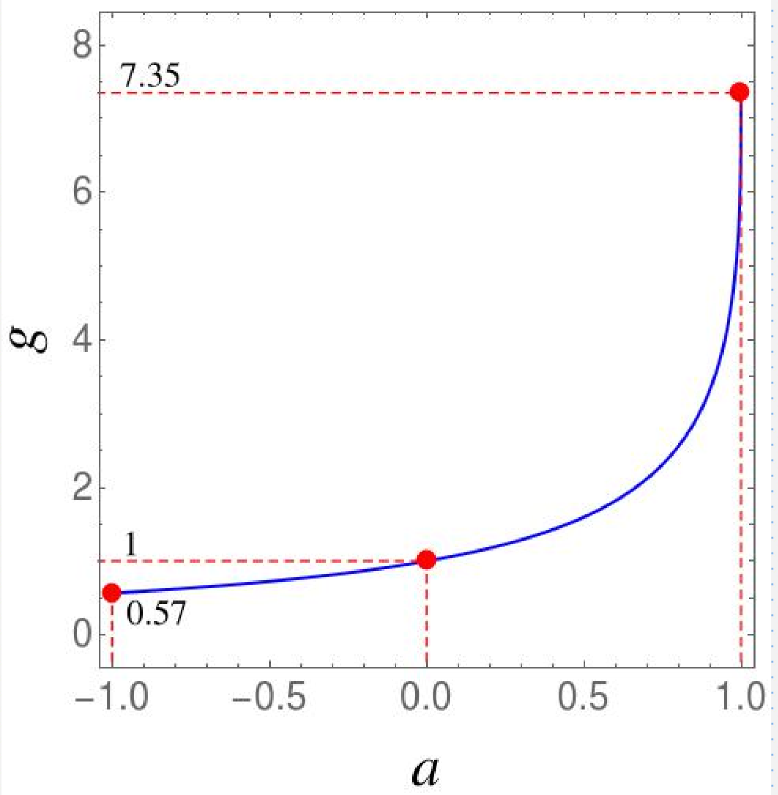


Innermost stable circular orbit

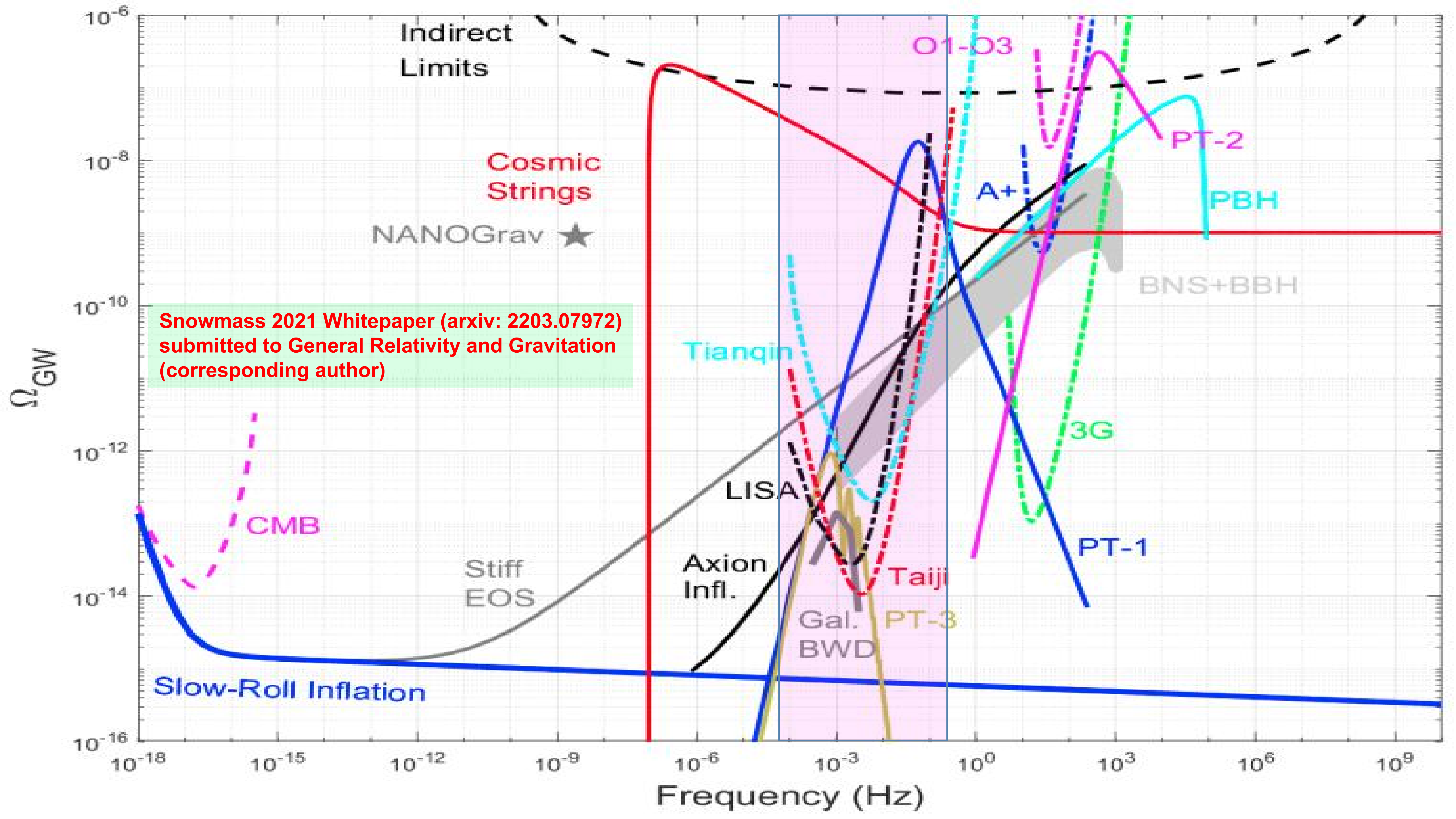
$$f_{\rm ISCO} = 4.4{\rm kHz} \left(\frac{1M_\odot}{M}\right)\left(\frac{n}{2}\right) g(a)$$

Bardeen, Press, Teukolsky, ApJ,178,347, 1972

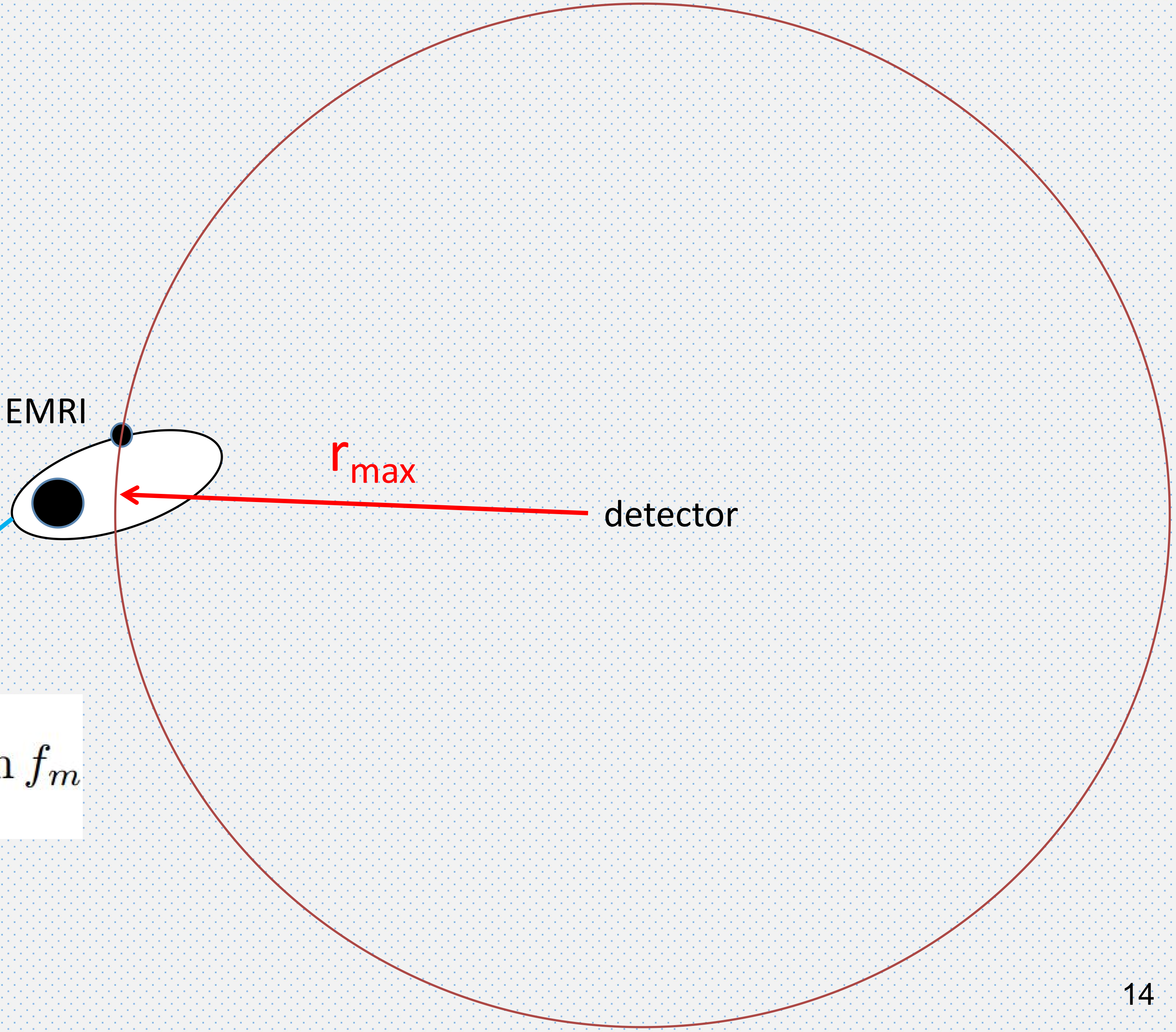
Typical frequency: mili-Hz.



Important target for space-based gravitational wave detectors



Indirect
Limits
Cosmic
Strings
NANOGrav
O1-O3
PT-2
A+
PBH
BNS+BBH
Snowmass 2021 Whitepaper (arxiv: 2203.07972)
submitted to General Relativity and Gravitation
(corresponding author)
Tianqin
3G
LISA
CMB
PT-1
Stiff
EOS
Axion
Infl.
Taiji
Gal.
BWD
PT-3
Slow-Roll Inflation
Ω_{GW}
Frequency (Hz)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}



$$\mathrm{SNR}^2 = \frac{\mathcal{S}^2}{\mathcal{N}^2} = \sum_m \int \left[\frac{h_{c,m}(f_m)}{h_n(f_m)}\right]^2 d\ln f_m$$

Matched-filtering

Noise

Waveforms

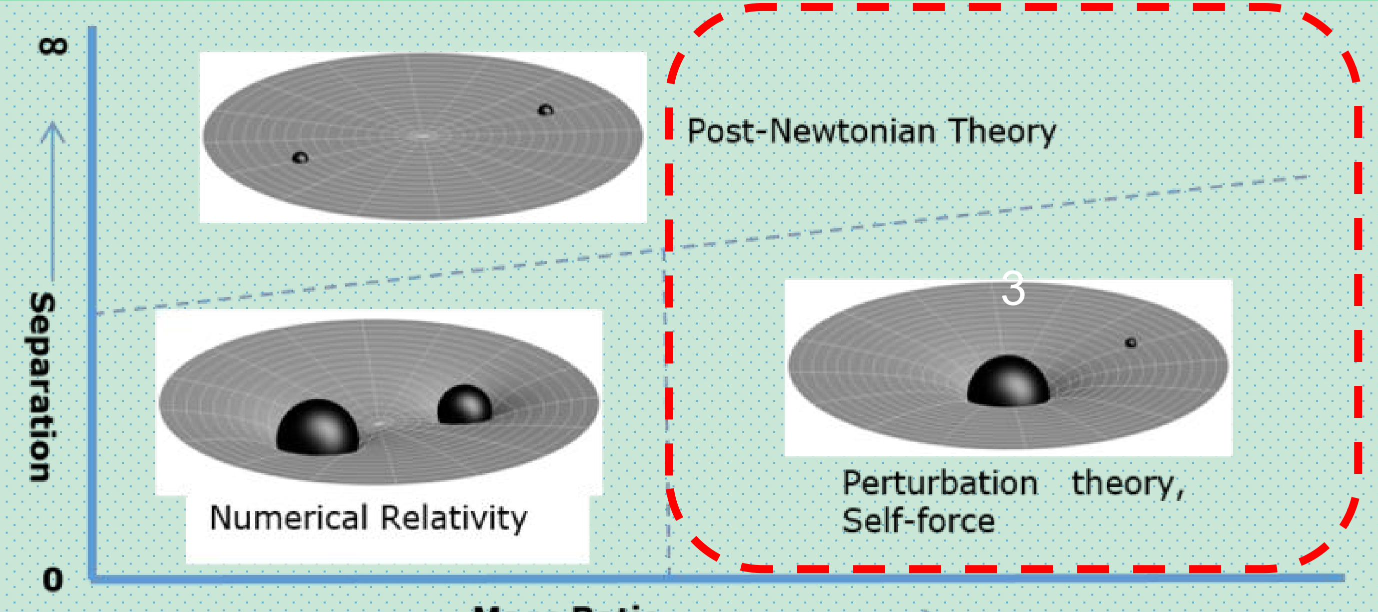
- Post-Newtonian studies in the inspiral stage
- Relativistic effect near ISCO requires numerical calculations
- Extreme mass ratio enables a new perturbation theory

Waveform calculation is still an ongoing effort.

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

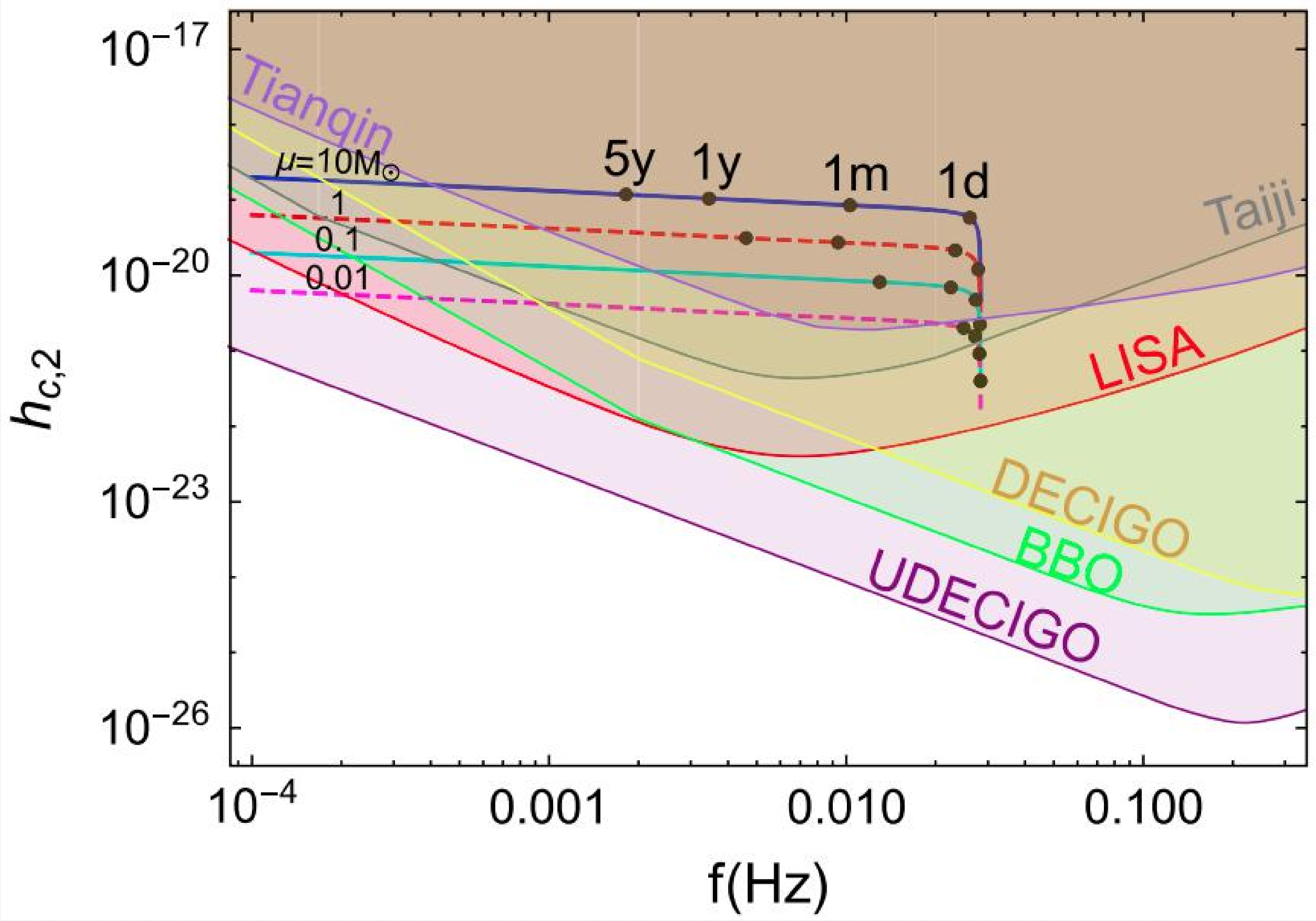
Result consistent with others (LISA review)

dominant mode: n=2



Wikipedia

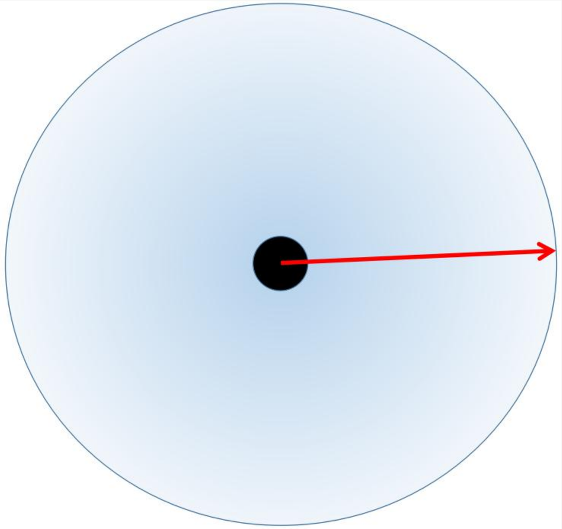
GW Amplitude

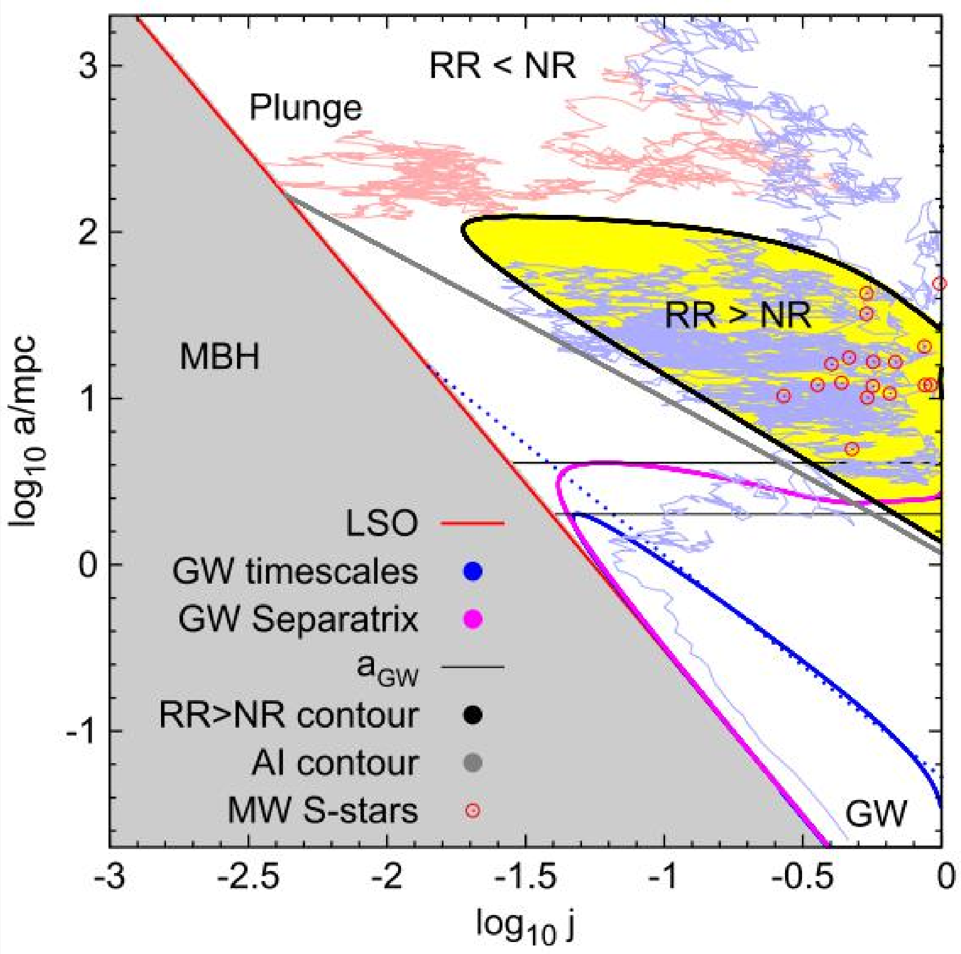


HG, Jing Shu, Yue Zhao, Phys. Rev. D 99, 023001

EMRI Rate

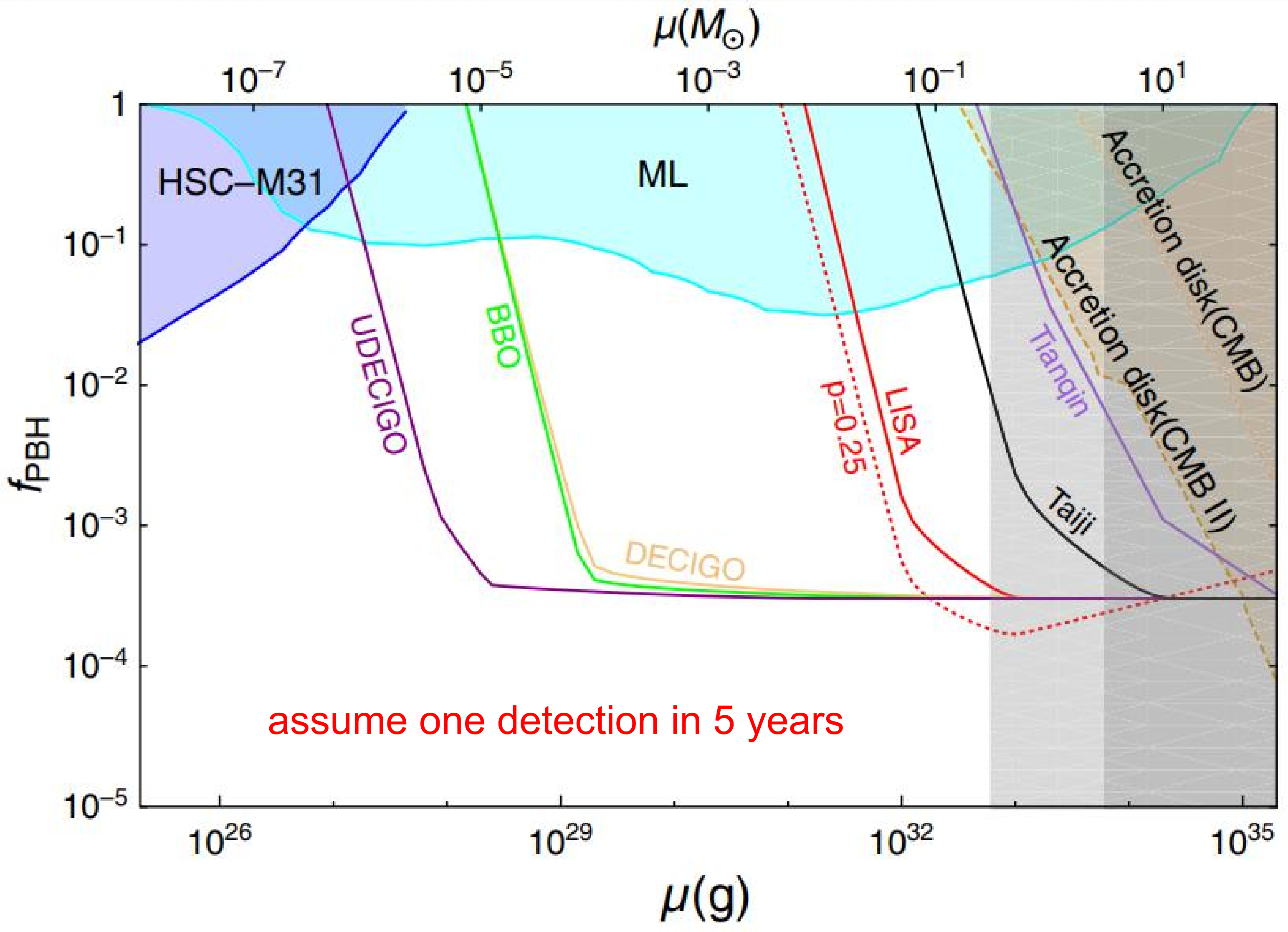
$$\Gamma = \int \mathcal{R}(M,\mu)\left(\frac{dn(M,z)}{dM}dM\right)(p(s,z)ds)\left(\frac{dV_c}{dz}dz\right)$$





Babak et al, PRD 95, 103012 (2017)

Constraining PBH Dark Matter

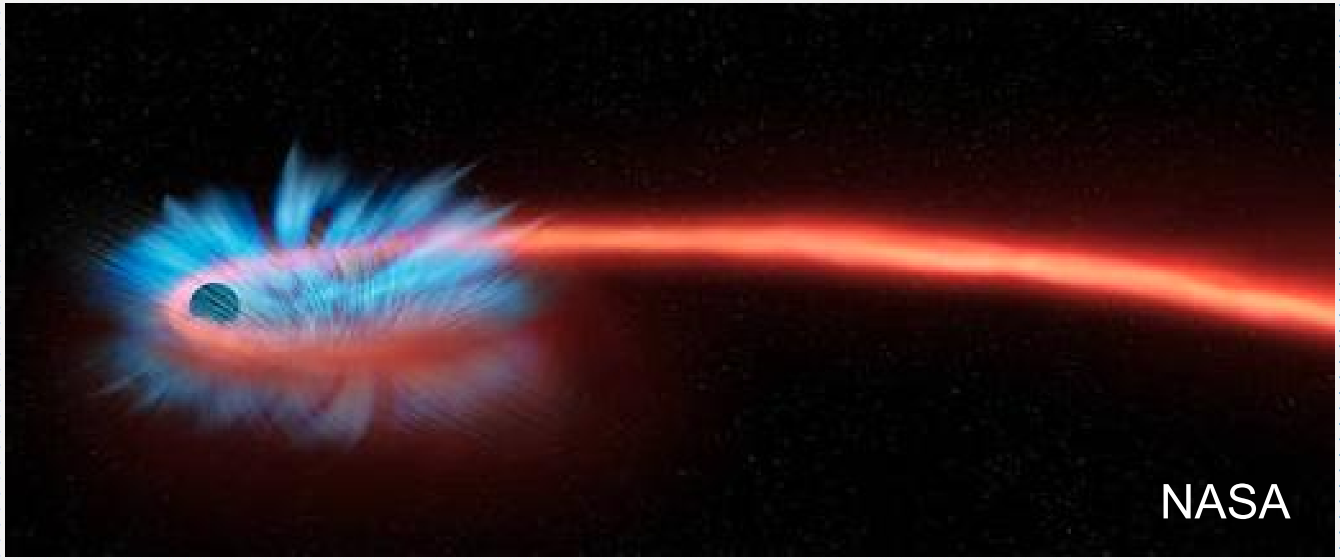


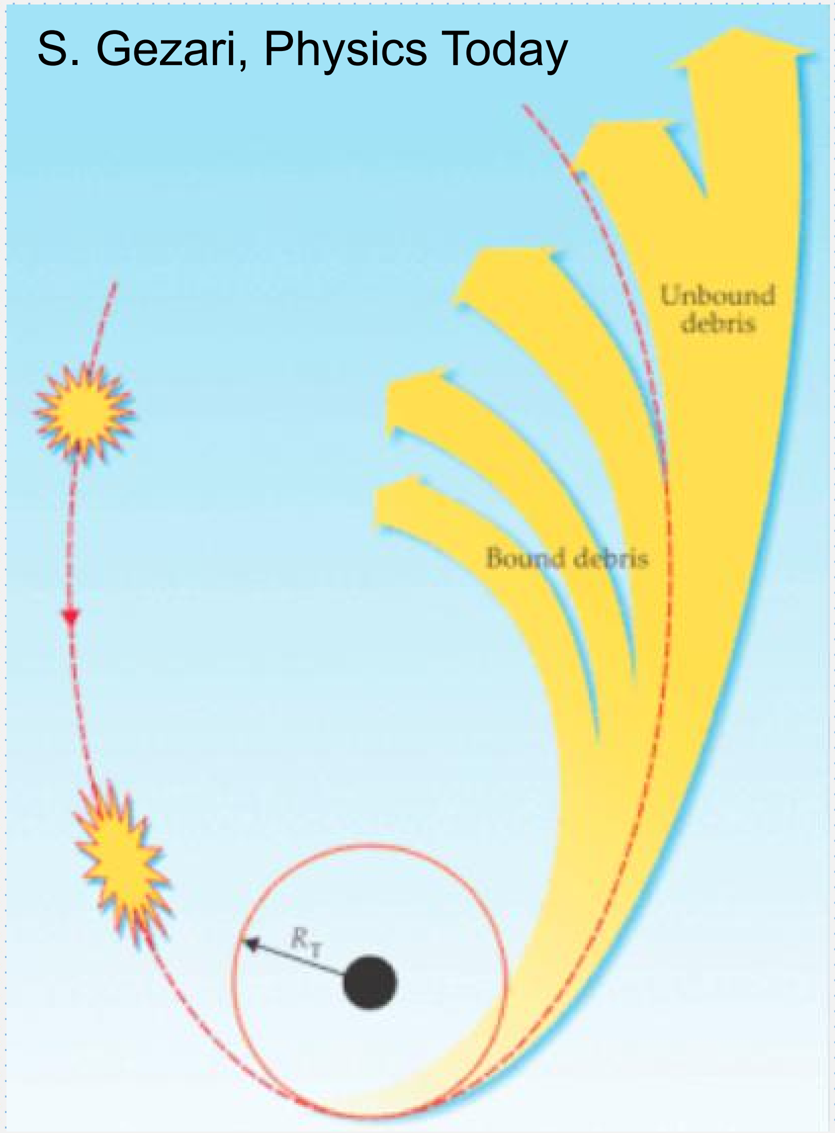
HG, Jing Shu, Yue Zhao, Phys. Rev. D 99, 023001

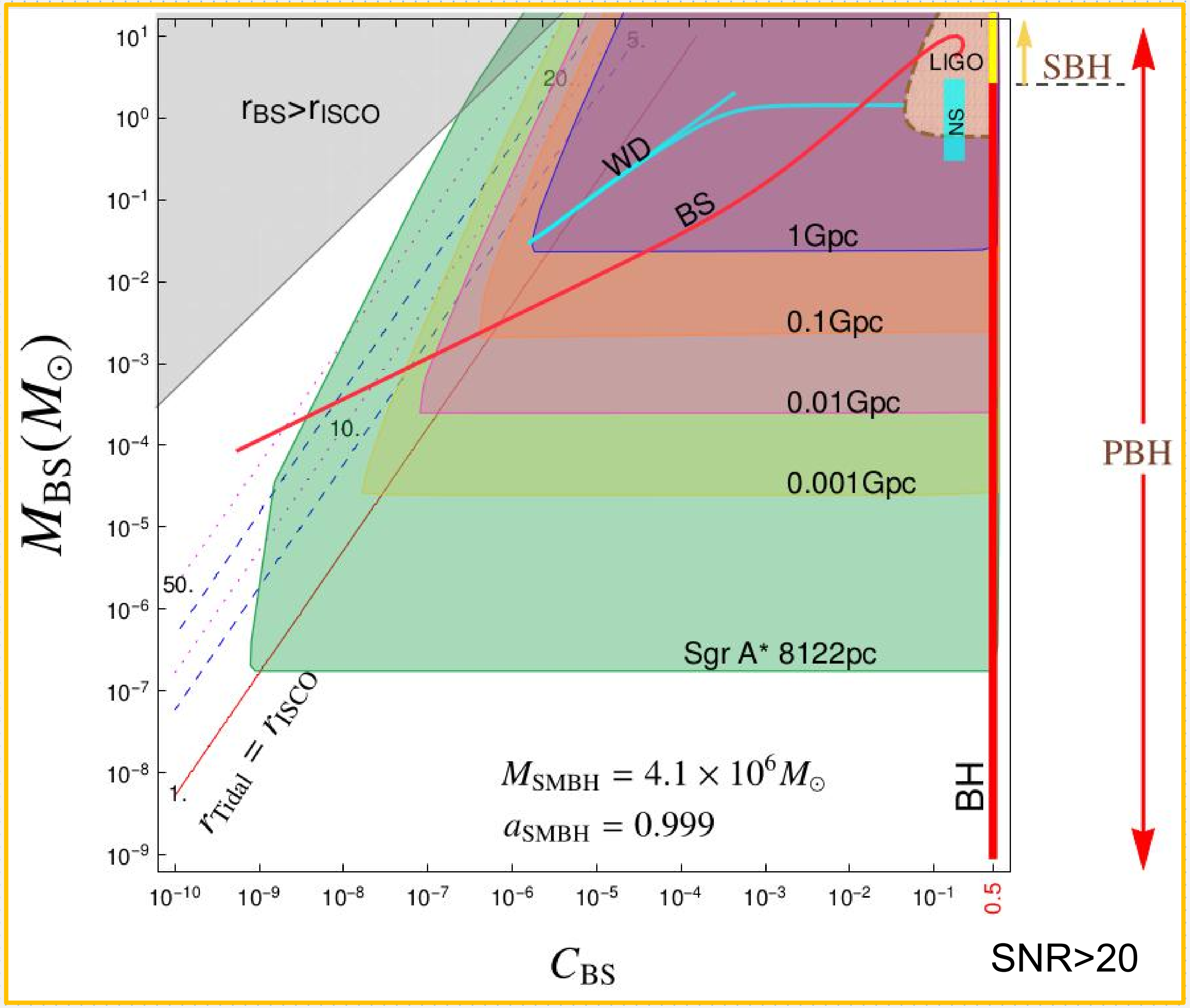
Tidal Disruption

Signal will be cut-off when tidal disruption occurs

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

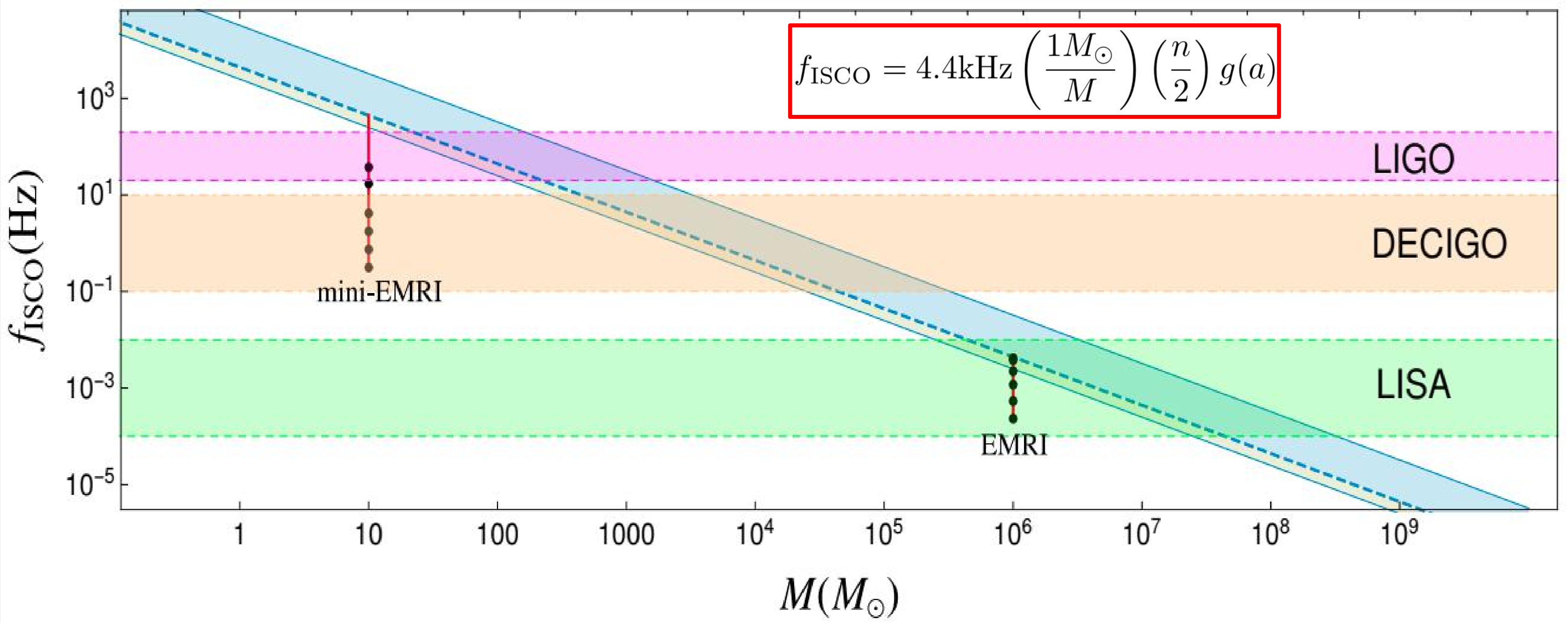






HG, Kuver Sinha, Chen Sun, JCAP 09 (2019) 032

LIGO can detect non-standard EMRIs



Similar systems:

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

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

Barsanti et al PRL 128, 111104 (2022)

Benefits of mini-EMRIs

- Ideal system for searches of subsolar exotic compact objects (ECOs)

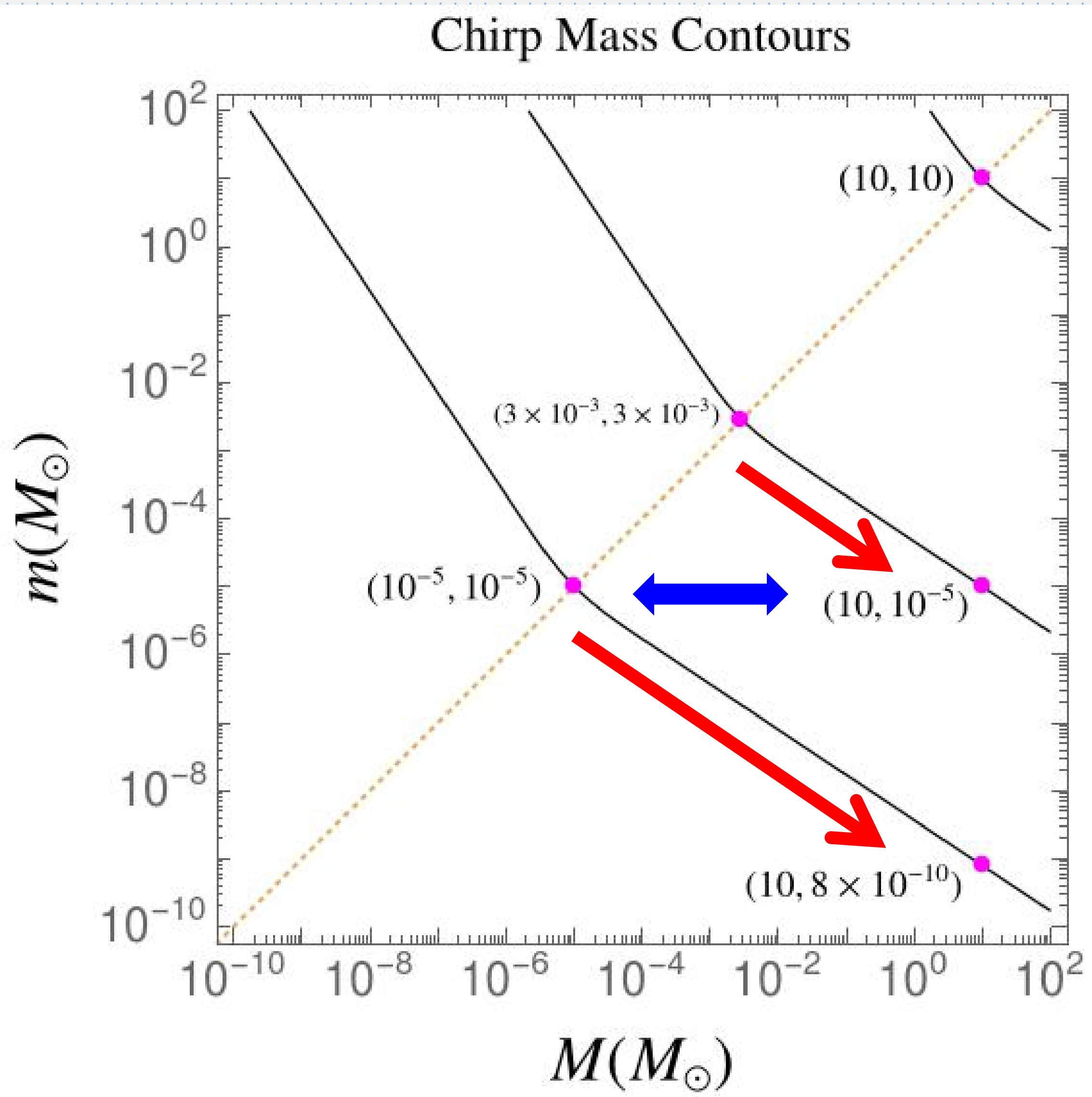
  Probe much smaller ECOs

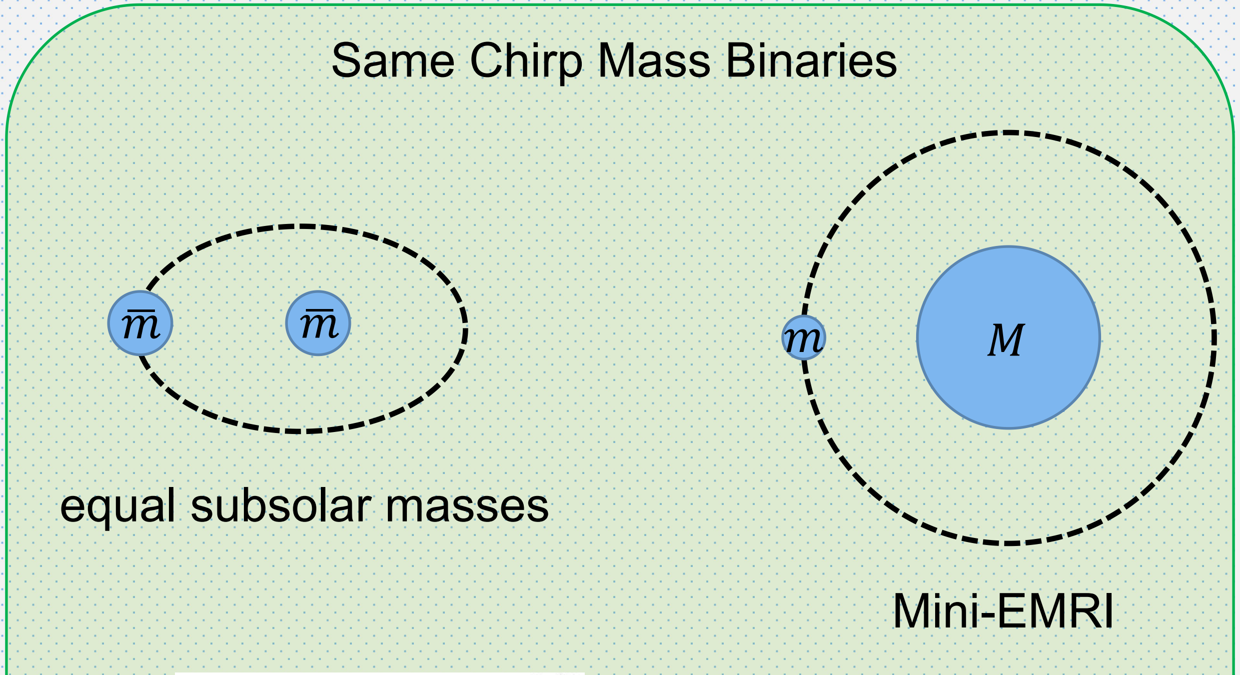
- Distinguish ECOs from ordinary compact objects
- Prepare for searches at furture space-based detectors (data analysis, waveforms)

Some plenatary masses can also form mini-EMRIs:
equally exiciting to detect and track (tidal disruption).

Will remain agnostic about formation mechanisms, merger rate (model independent)

Advantage of mini-EMRIs: Probe lighter ECO

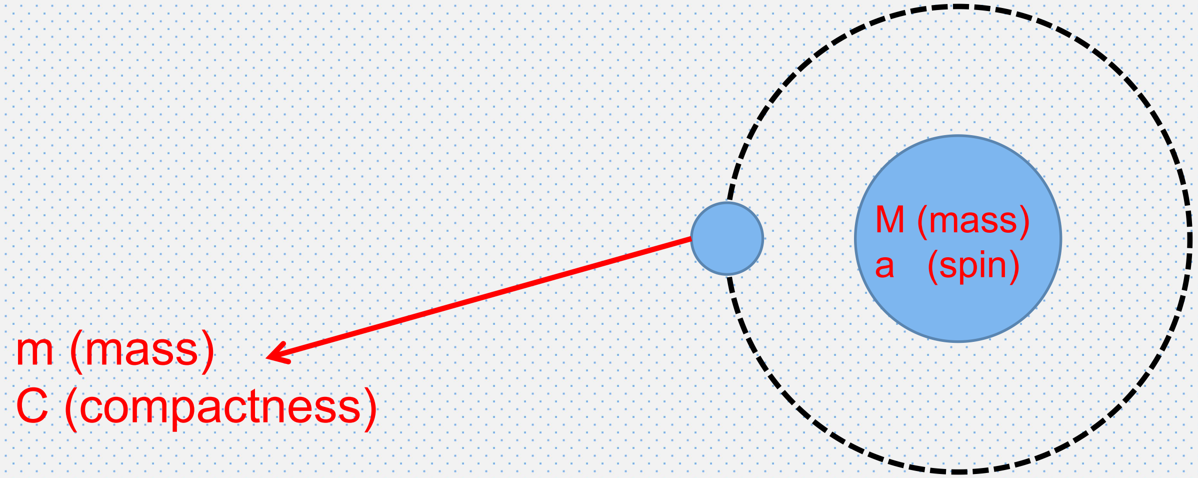




$$\frac{m}{\bar{m}} \approx 2^{-1/3}\left(\frac{\bar{m}}{M}\right)^{2/3} \Rightarrow m \ll \bar{m} \ll M$$

mini-EMRIs: this study

- Consider the heavier one to be ultra compact (such as BH, PBH)
- Allow a less compact light one, described by compactness (C=mass/radius)

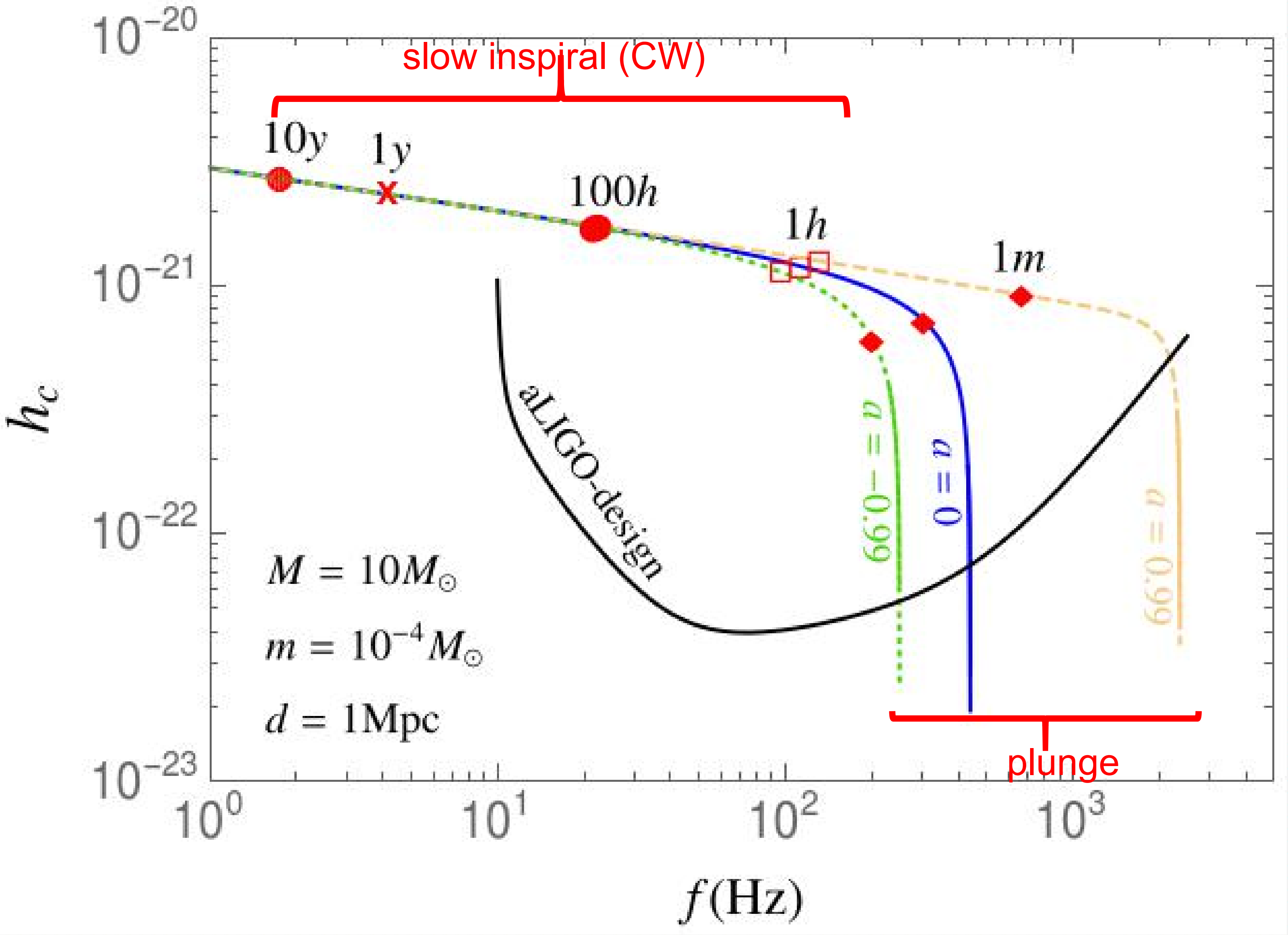


$m \lesssim \mathcal{O}(10^{-2}) M_\odot$

$M \lesssim \mathcal{O}(1000) M_\odot$

(detectable by LIGO)

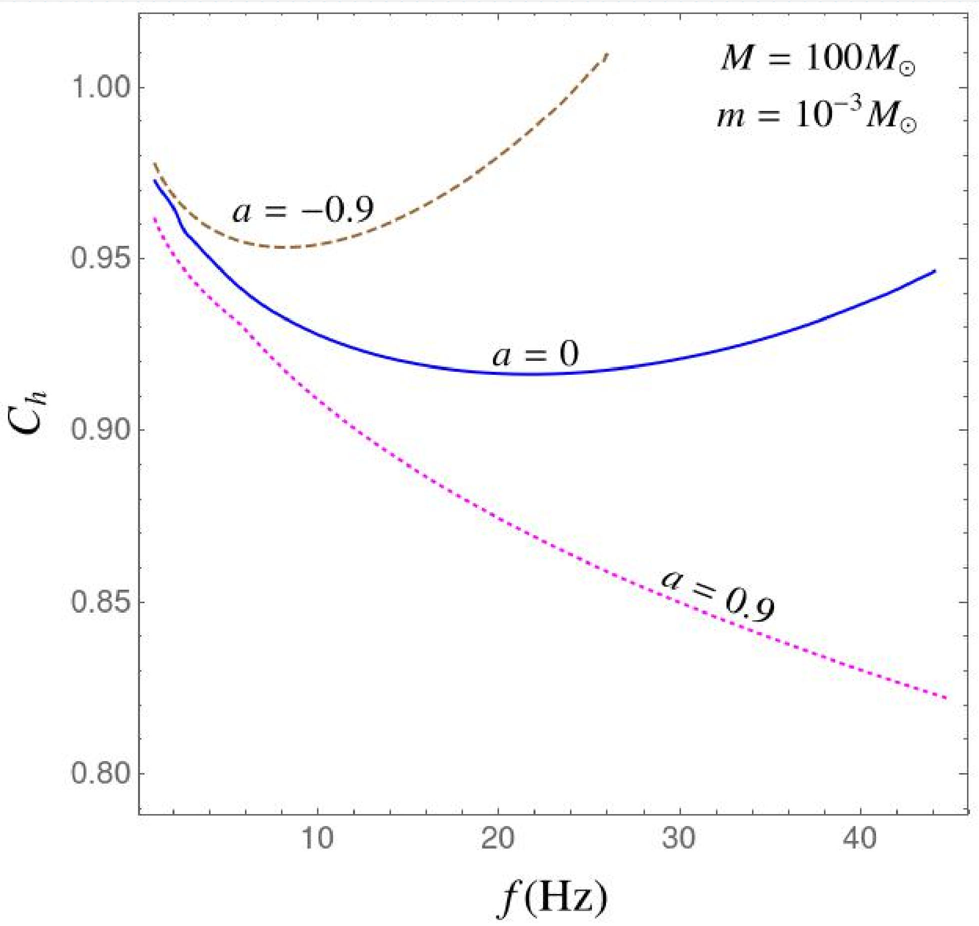
There can be many variants

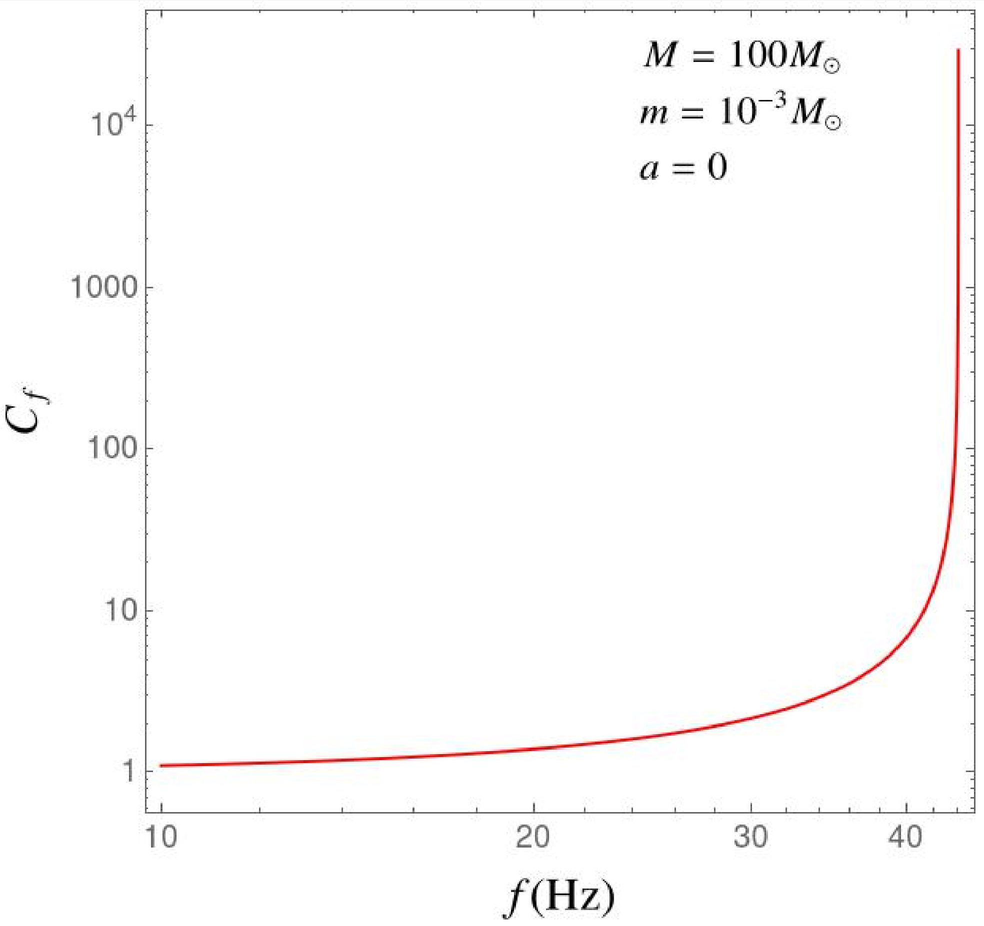


HG, A.Miller, arxiv:2205.10359

Relativistic Effects

$$h_0 = \frac{4}{d}\left(\frac{GM_c}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3} C_h(a, f) \qquad \dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} f^{11/3} C_f(a, f)$$





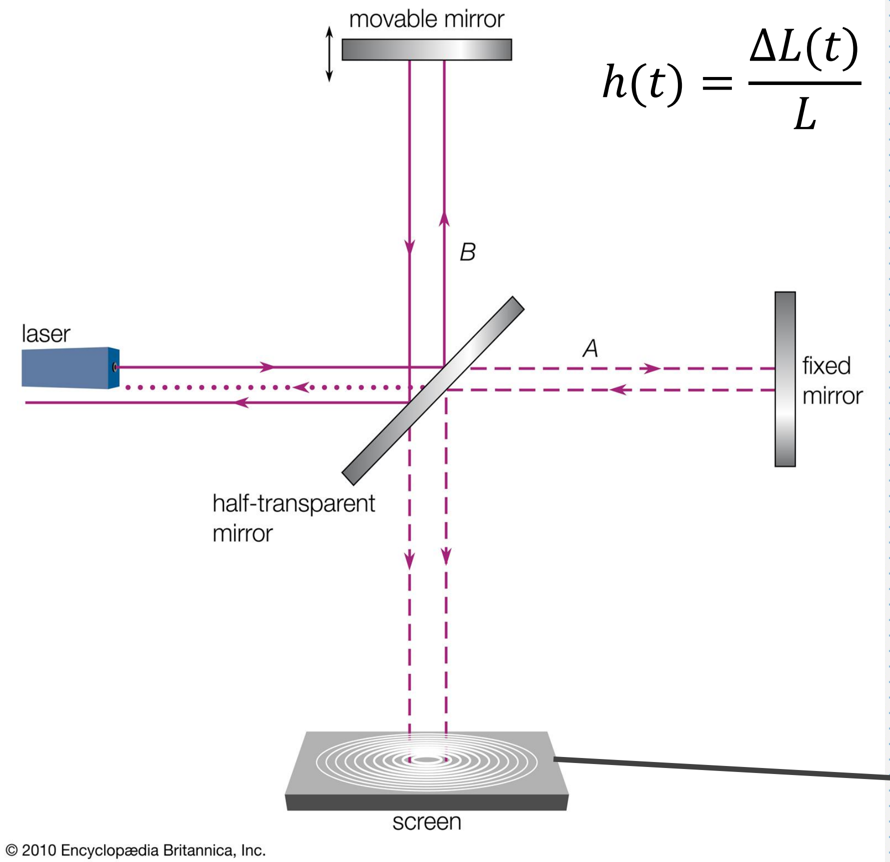
HG, A.Miller, arxiv:2205.10359

Signal Properties

- Signal is long-lasting (hours, days, months) within detector band
- 2 stages: inspiraling and plunging
- Frequency is slowly varying during the inspiral stage (quasi-monochromatic)
- Need to take tidal disruption of ECO into account

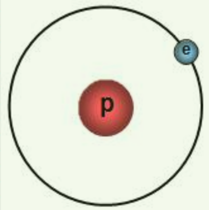
Now need a detection method (data analysis) for mini-EMRI searches

Michelson Interferometer



~6000km

10^-15m



10^-15m

signal

noise

$$h(t) = D_{ij} h_{ij}^{TT}(t) + n(t)$$

LALSuite

Searches at LIGO

CBC

short within LIGO band

BH-BH, BH-NS, NS-NS

Bursts

short, non-inspiral

Transient ↑

Persistent ↓

Continuous Waves

const frequency or very slowly varying, long lasting

Stochastic

random, from all directions, like a noise

Searches at LIGO

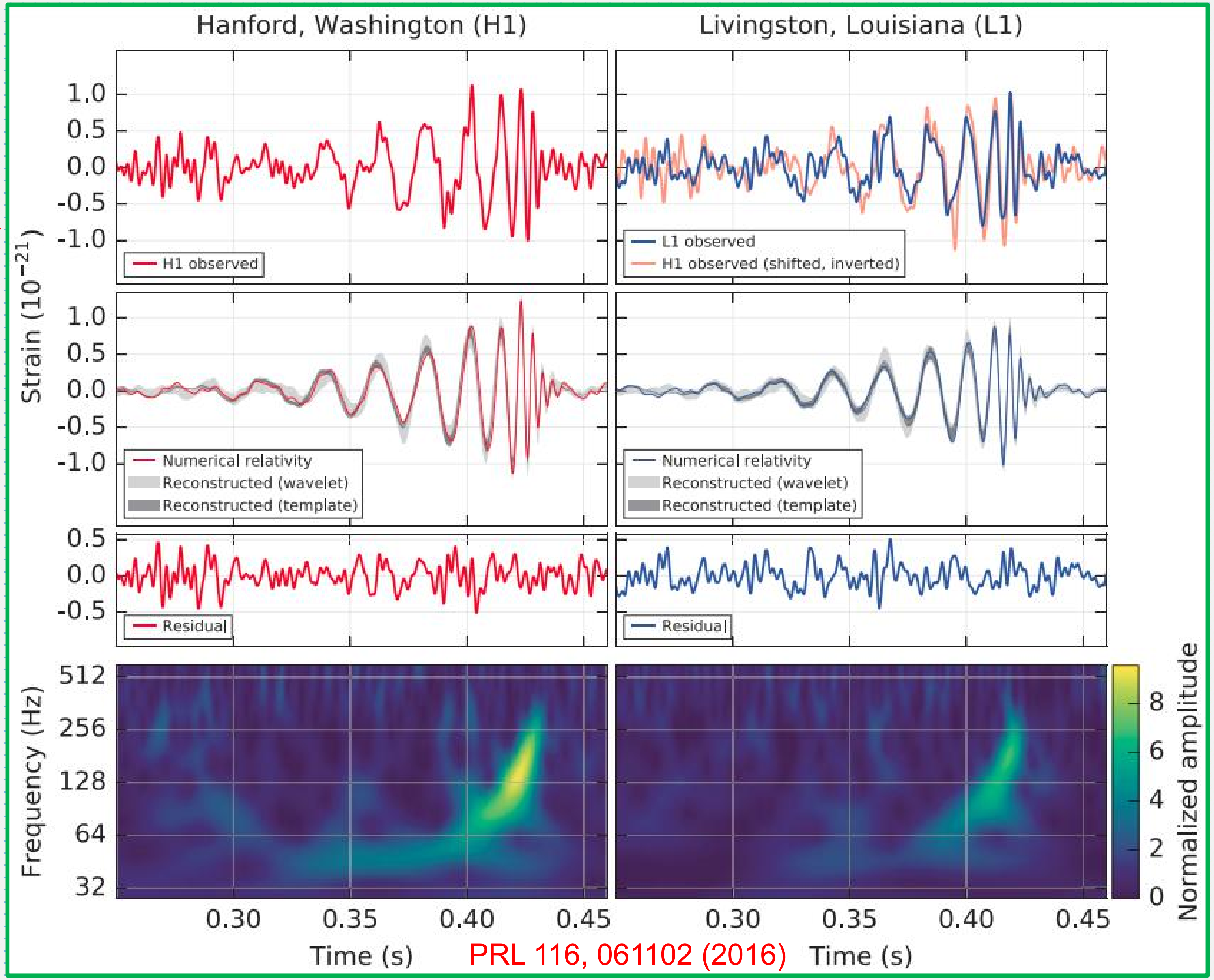
CBC

short within LIGO band

BH-BH, BH-NS, NS-NS

Transient

Persistent



PRL 116, 061102 (2016)

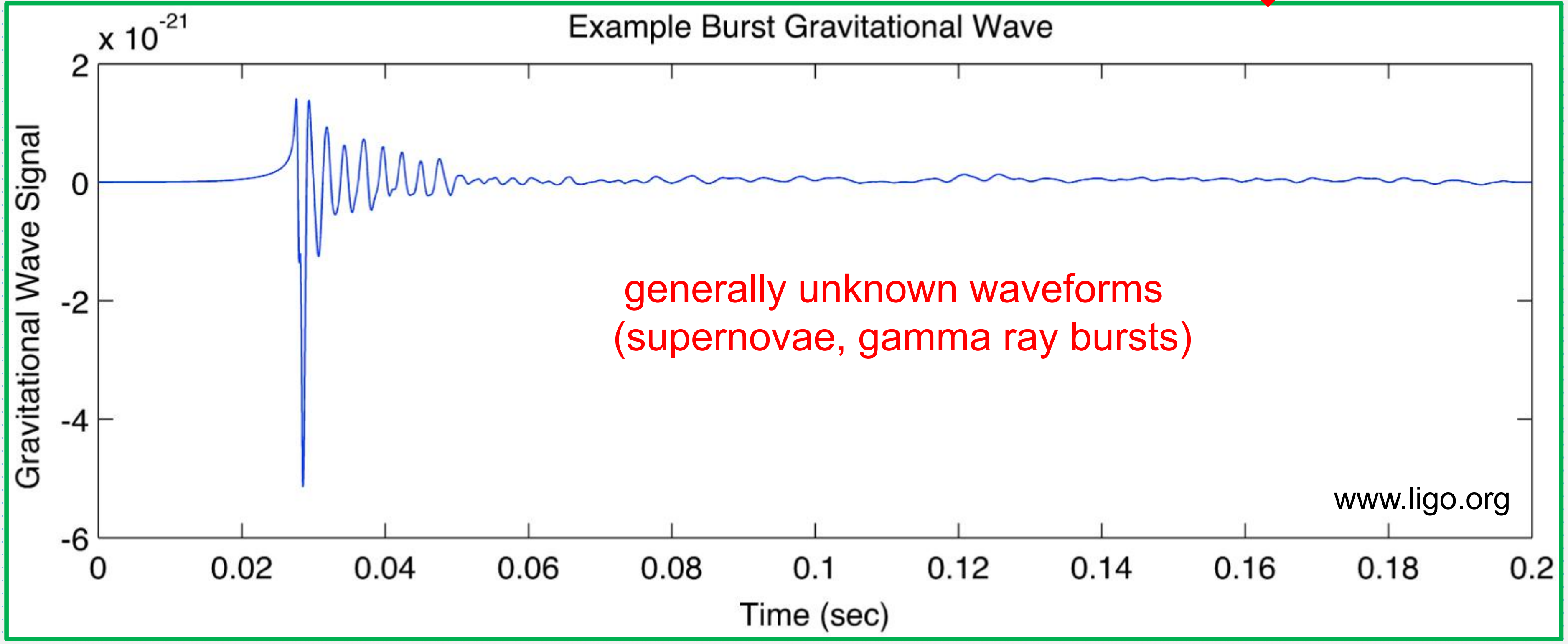
Searches at LIGO

Transient

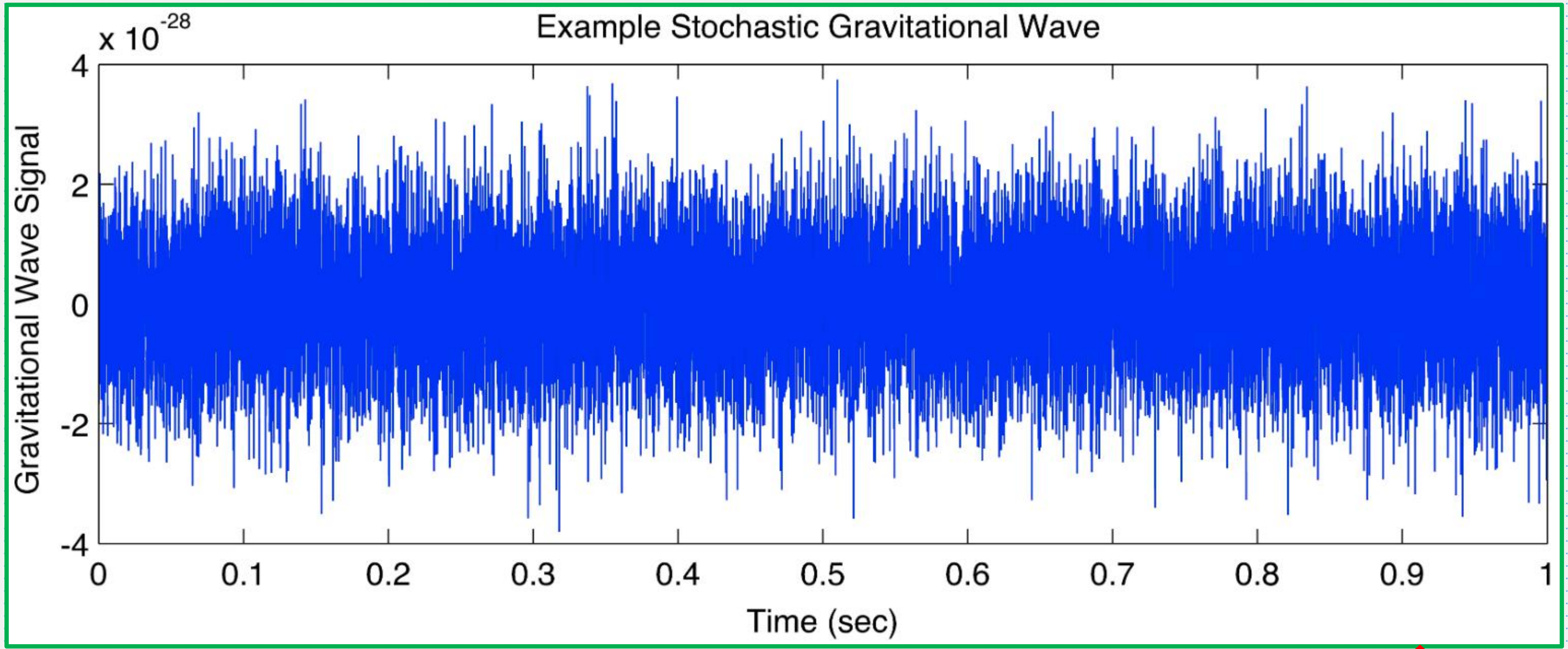
Persistent

Bursts

short, non-inspiral



Searches at LIGO



Transient

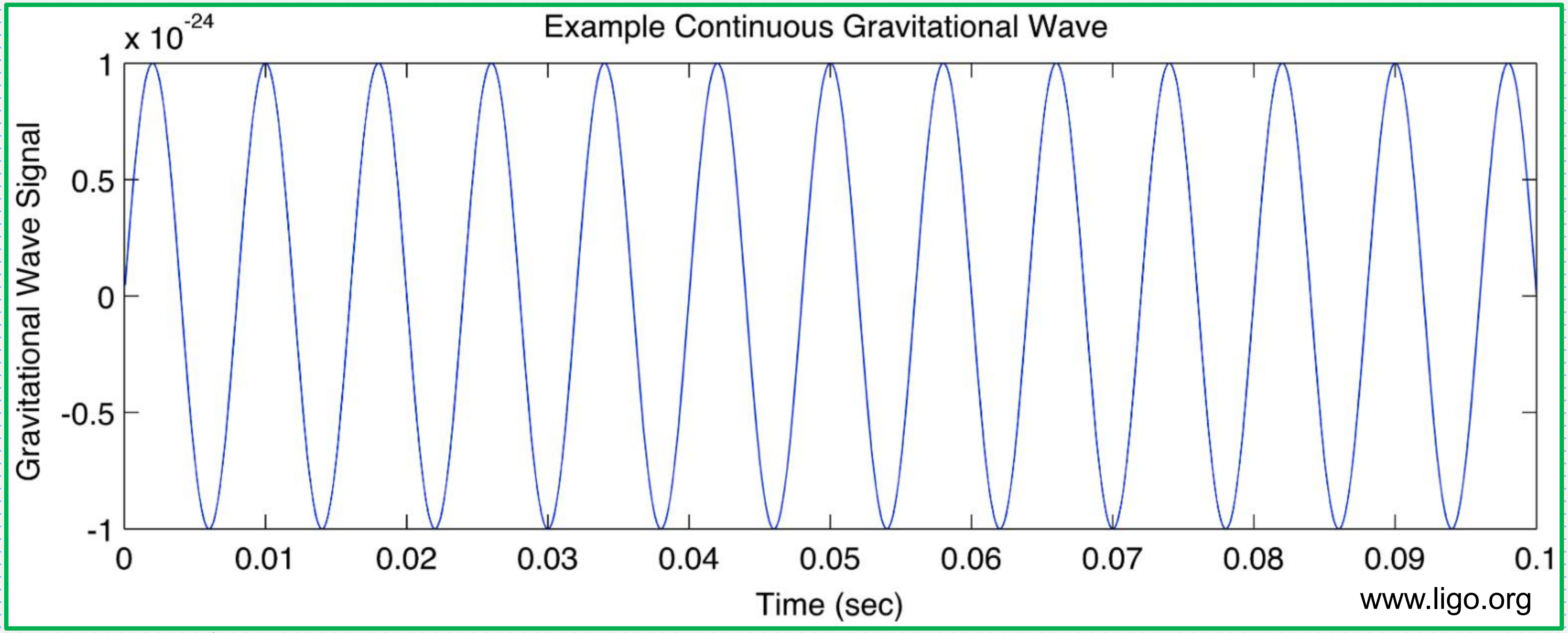
Persistent

astrophysical, or cosmological origins

Stochastic

random, from all directions, like a noise

Searches at LIGO



Transient ⇧

Persistent ⇩

Continuous Waves

const frequency or very slowly varying, long lasting

main target: neutron stars (also dark photon etc)

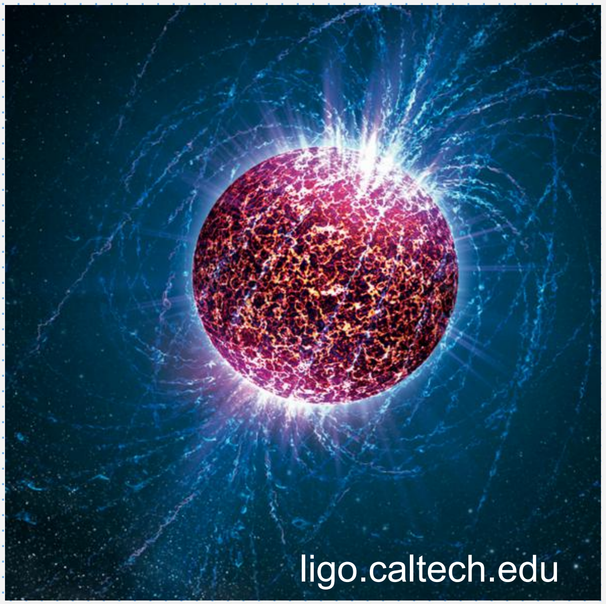
Continuous Wave Signals

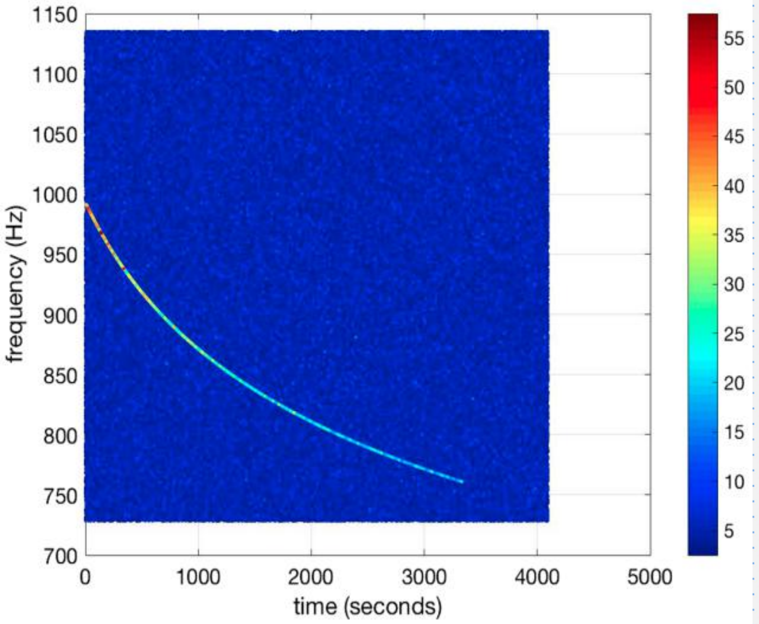
- Signal is long-lasting (almost forever)
- Modelled as plane wave
- Frequency slowly decreasing due to energy loss

$$f(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \cdots$$

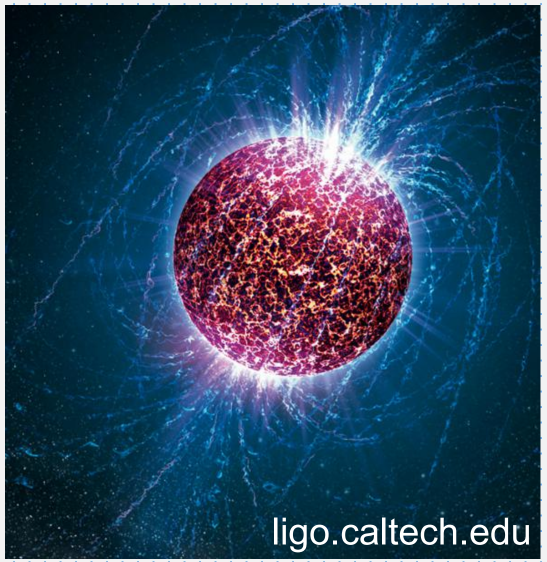
generally assumed small ($\ddot{f}_0$)

spin-down ($\dot{f}_0$)





Search Strategies



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

↓

- ✓ targeted searches (known black holes, neutron stars as the heavier object)
- ✓ all-sky searches (blind searches)

Search Techniques

Coherent Searches (matched-filtering)

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

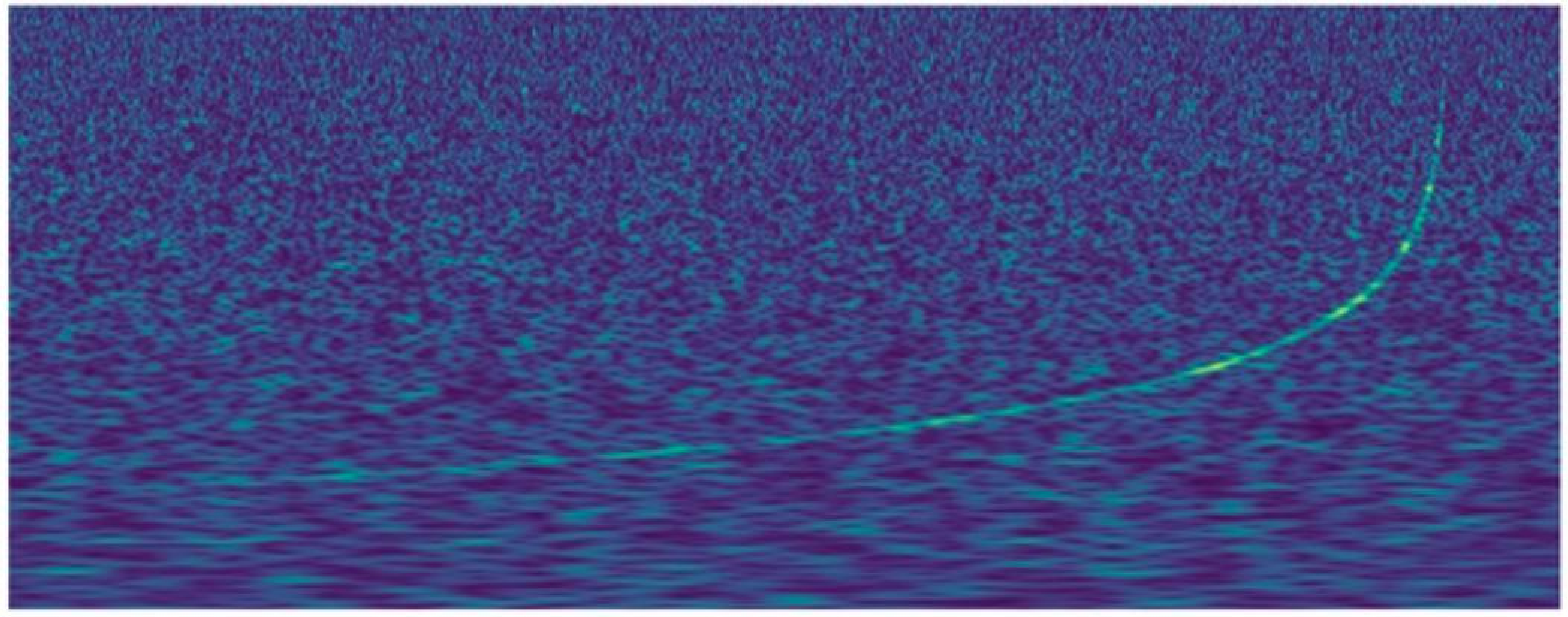
maching learning might be needed
(Zhang et al, PRD105(2022)123027)

Incoherent Searches

- Reduced sensitivity
- Mature and robust methods
- Computationally feasible

We employ the mature incoherent search methods

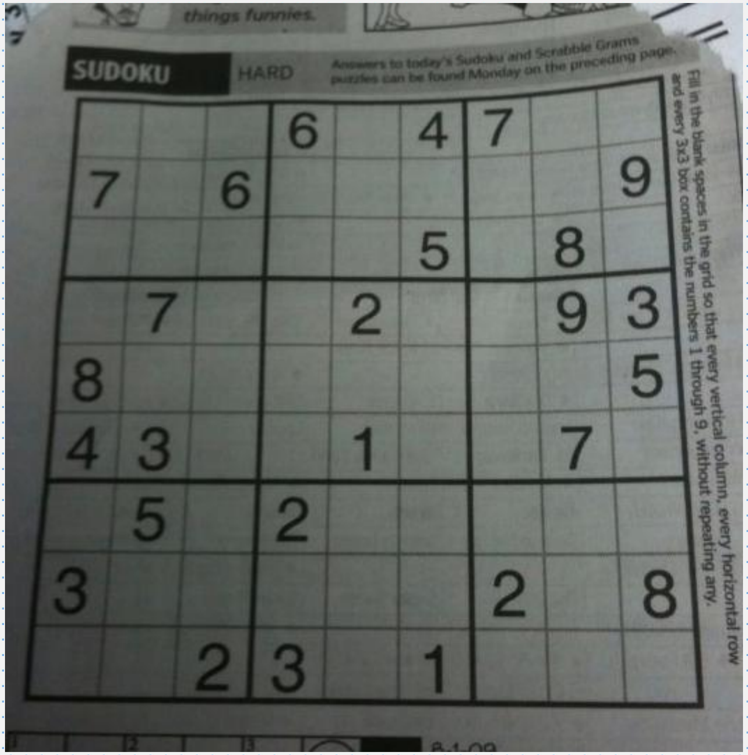
Detecting a long chirp

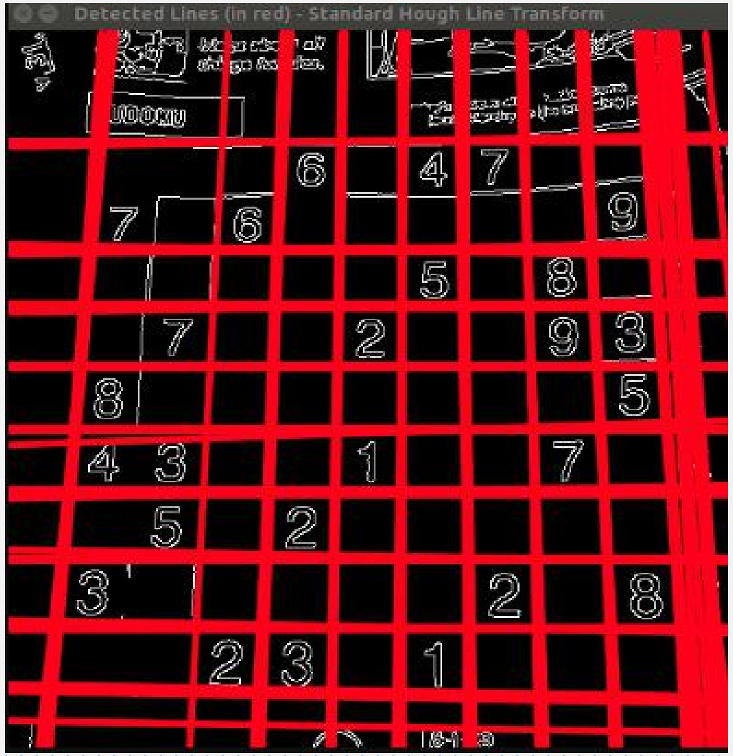


with digital image processing technique (Hough transform)

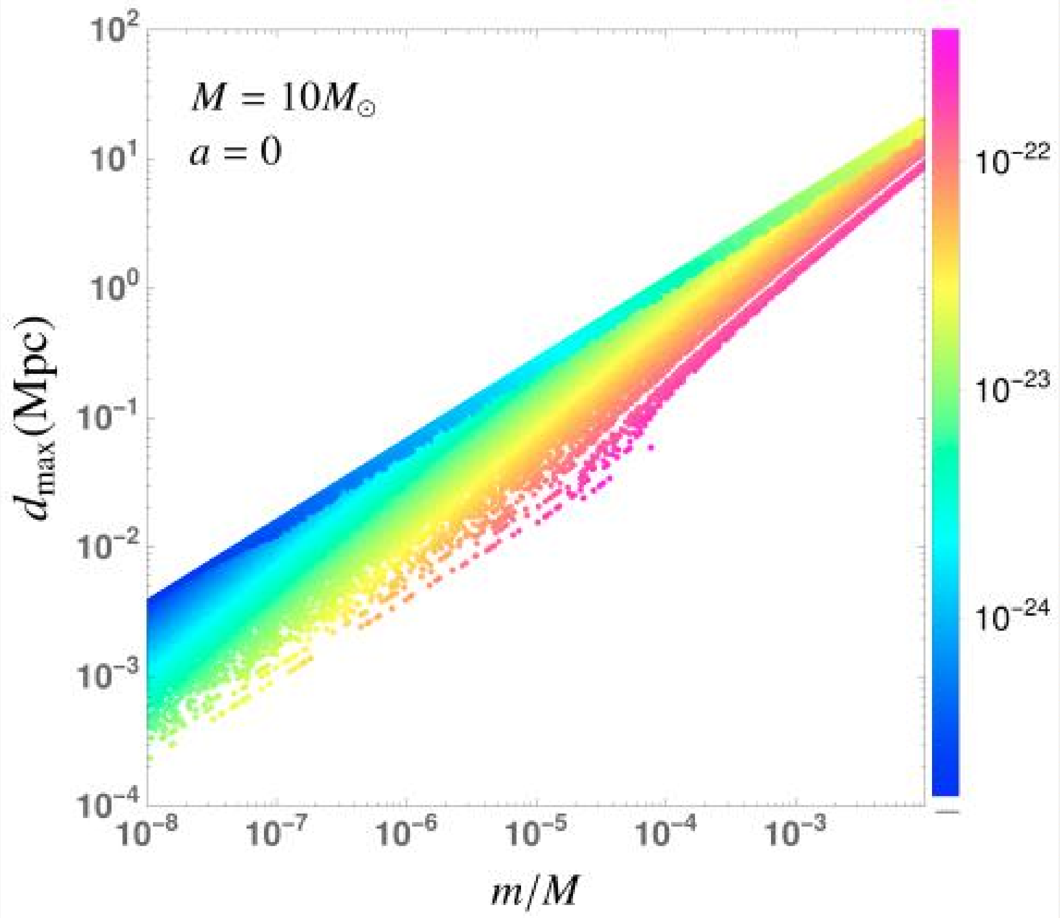
Hough Transform

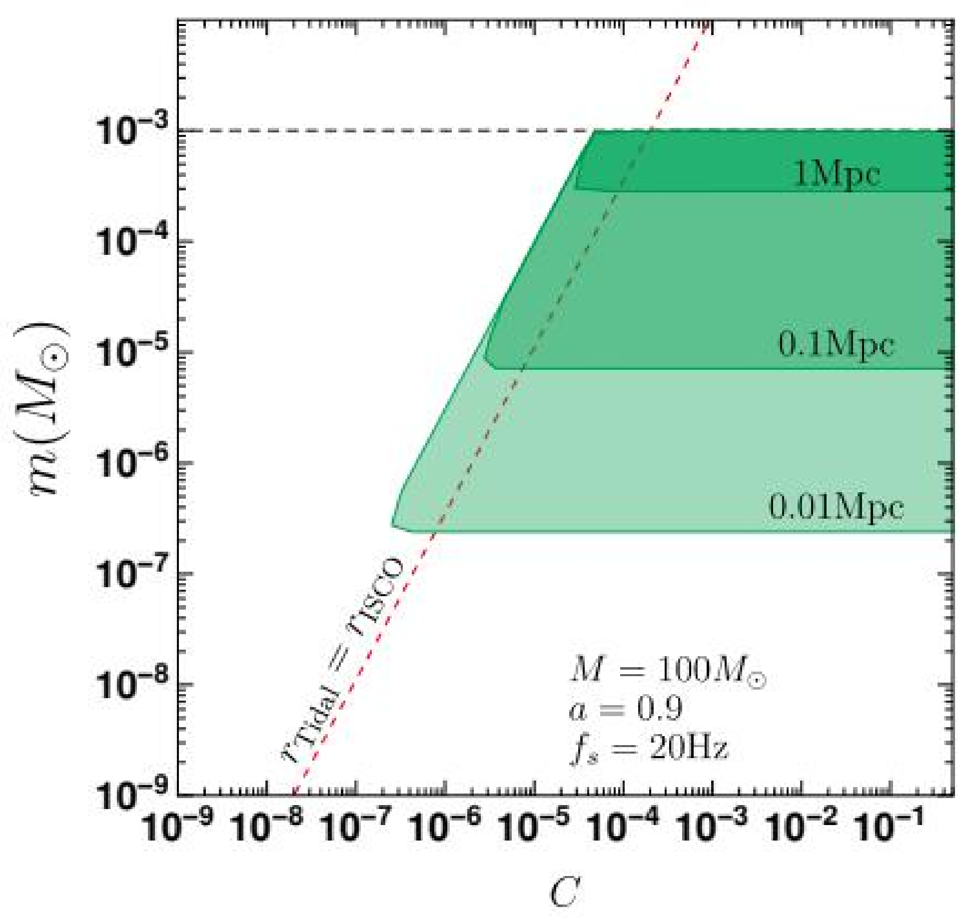
- Feature (pattern) identification algorithm in images
- Detect lines





Results



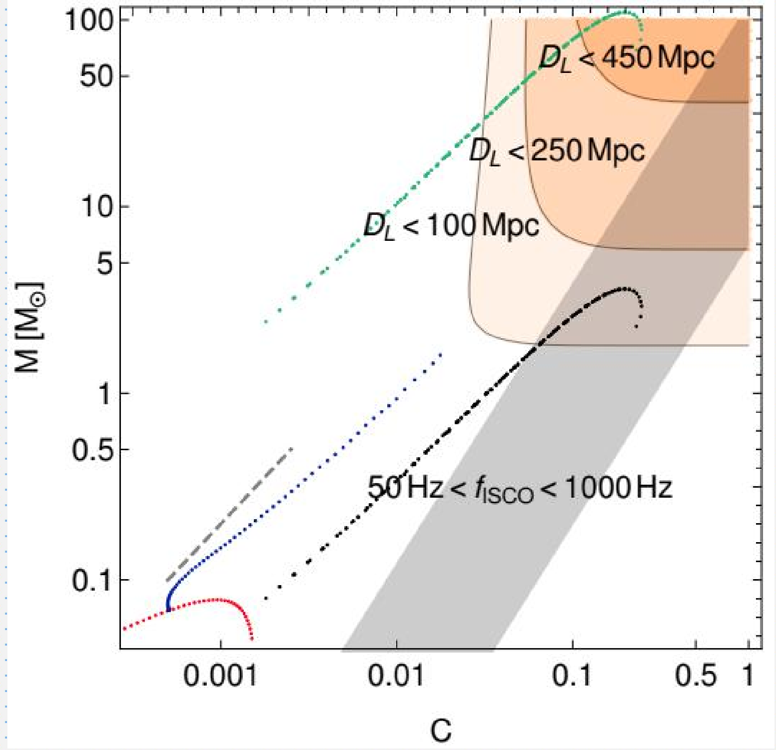


HG, A.Miller, arxiv:2205.10359

Can be optimized: 10Hz band, starting frequency (fs) ...

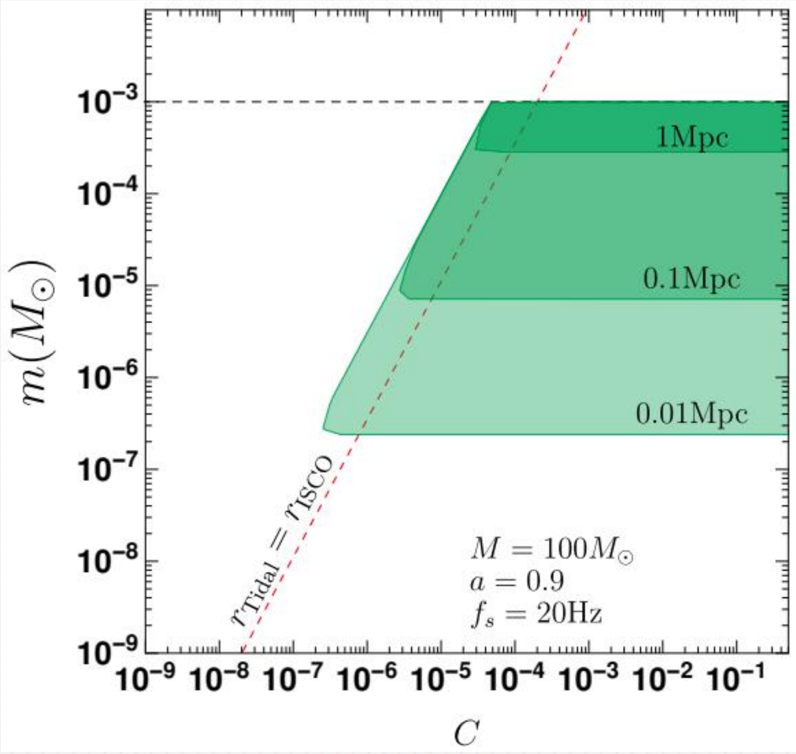
Varieties of EMRIs

LIGO (CBC)



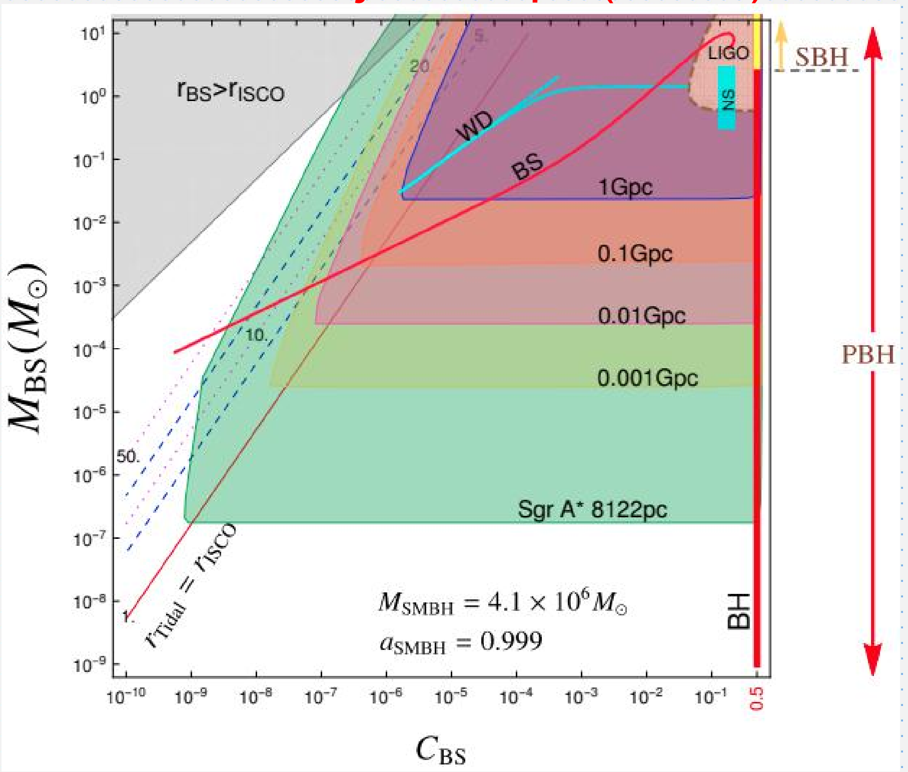
HG, Sinha, Sun, Vagie, JCAP 10 (2021) 028

LIGO ("mini-EMRI")



HG, A. Miller, arxiv:2205.10359

LISA, Taiji, Tianqin (EMRI)



HG, Sinha, Sun, JCAP 09 (2019) 032
HG, Shu, Zhao, PRD 99 (2019) 023001

Summary

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

The Extreme Mass Ratio Inspiral (EMRI)

- Maximal frequency might be different (ISCO)
- Correspondingly, tetector sensitivity might be different
- Relativistic effects might differ

Frequency Hough in CW Searches

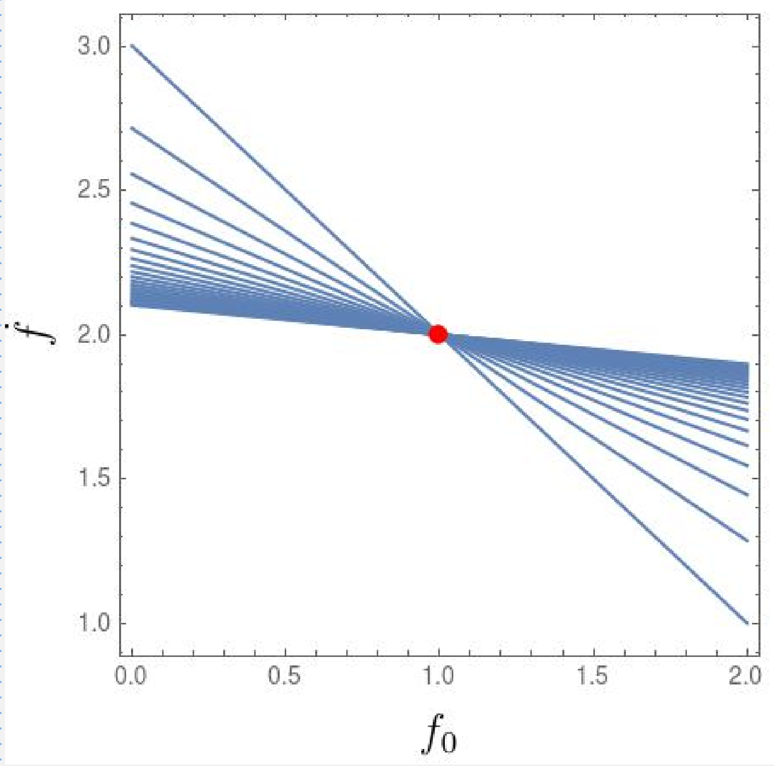
fixed unknowns

$$f(t) = f_0 + \dot{f}_0 (t - t_0)$$

$$\dot{f} = -\frac{f_0}{(t - t_0)} + \frac{f}{(t - t_0)}$$

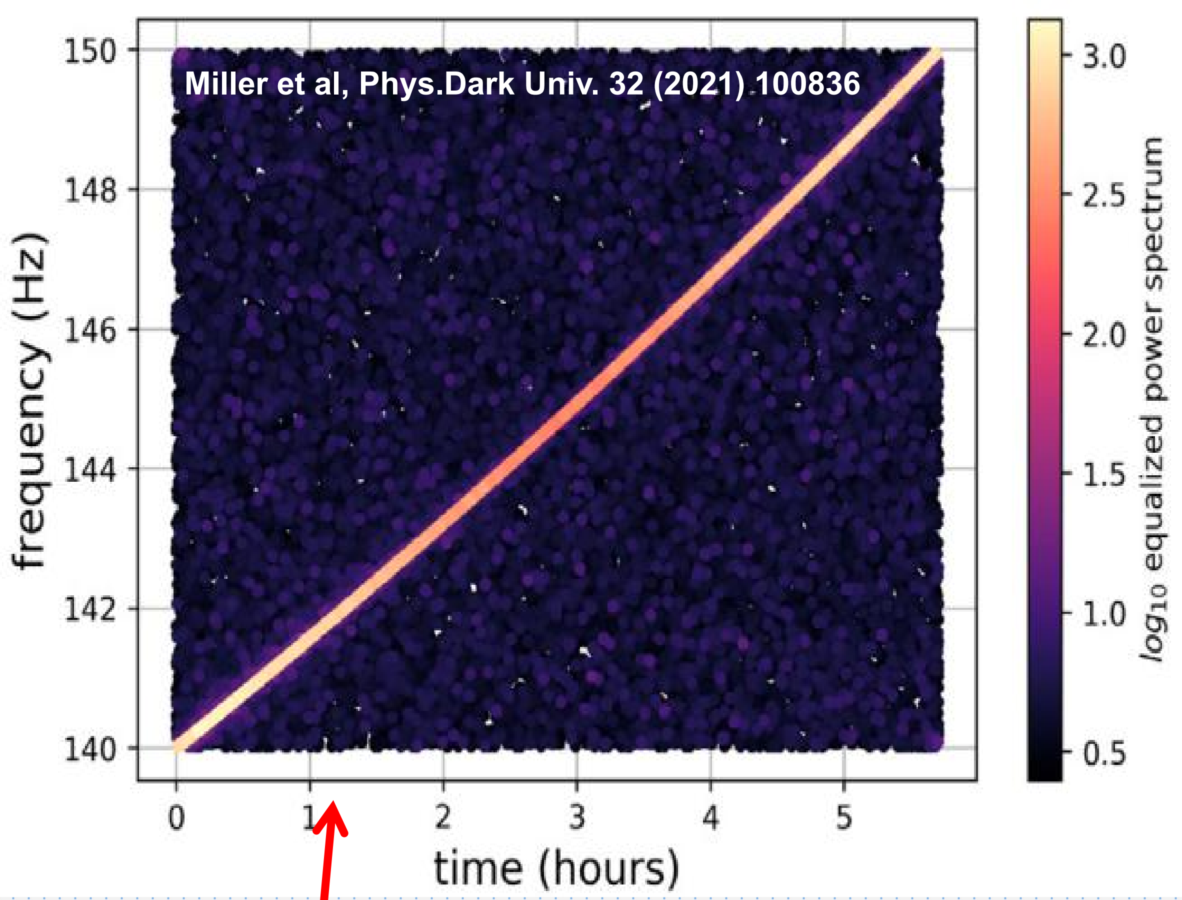
f1 at t1 - t0
f2 at t2 - t0
f3 at t3 - t0
...

line 1
line 2
line 3
...



Generalized frequency Hough for generic dependence
Miller et al, PRD98, 102004 (2018)

Time Frequency Map



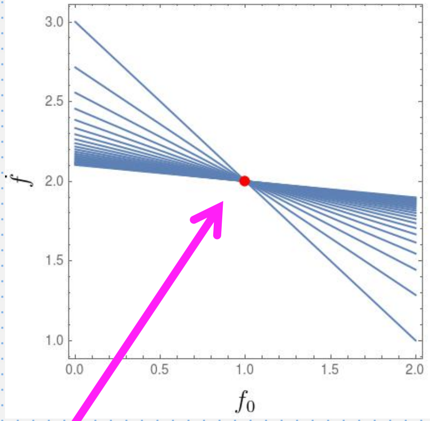
32s for each bin on time axis

Signal is contained within one frequency bin

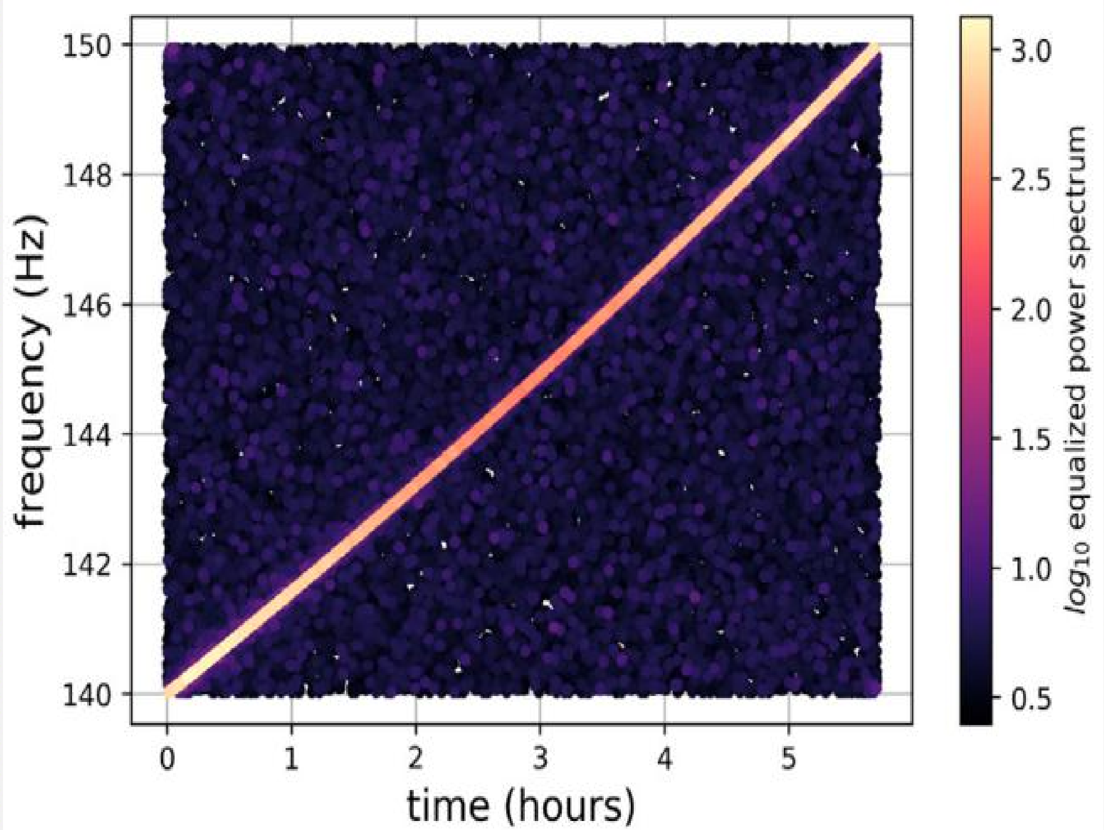
- Signal manifests itself as excess power
- Excess powers identified as peaks
- All peaks from this plot form a peak map

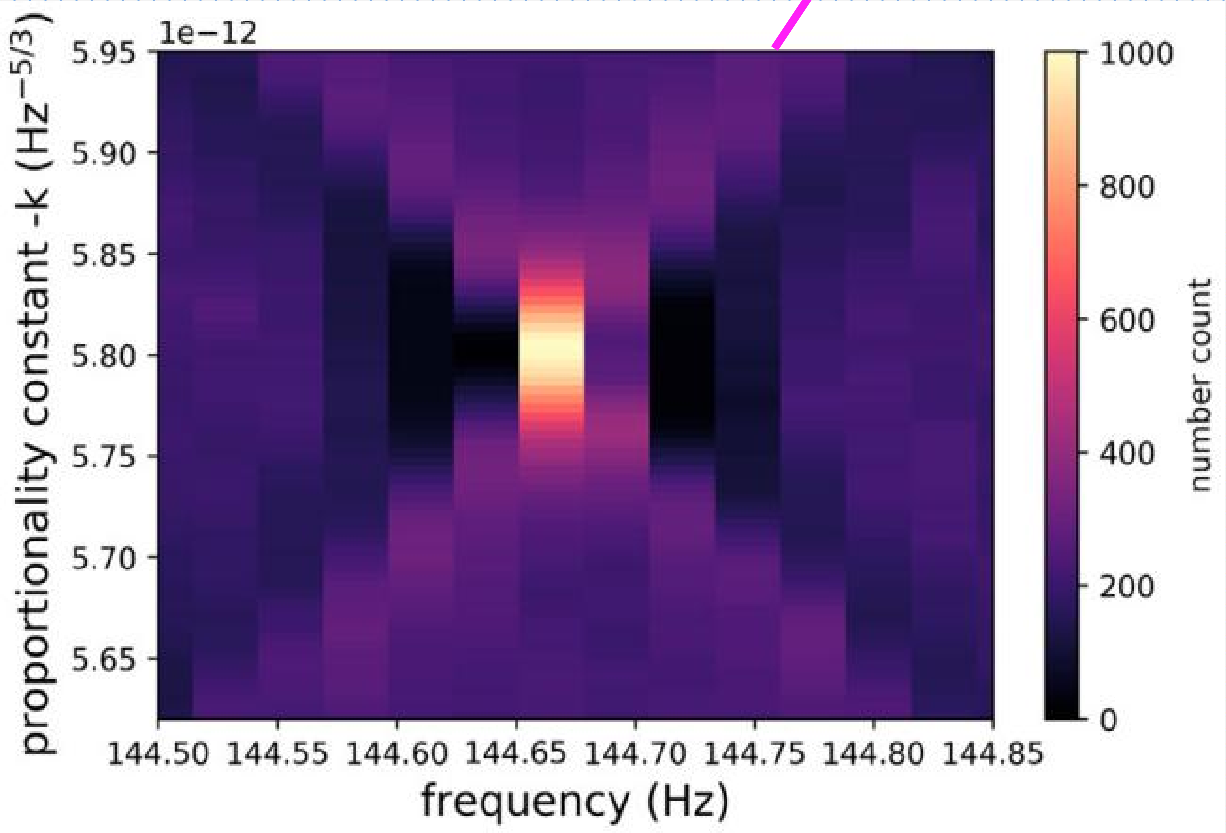
Hough Transform

- System parameters best fit as highest number counts (candidates)
- Coincidence check (candidate vetoes)
- Final candidates transformed into sensitivity estimation (statistical)



number counts





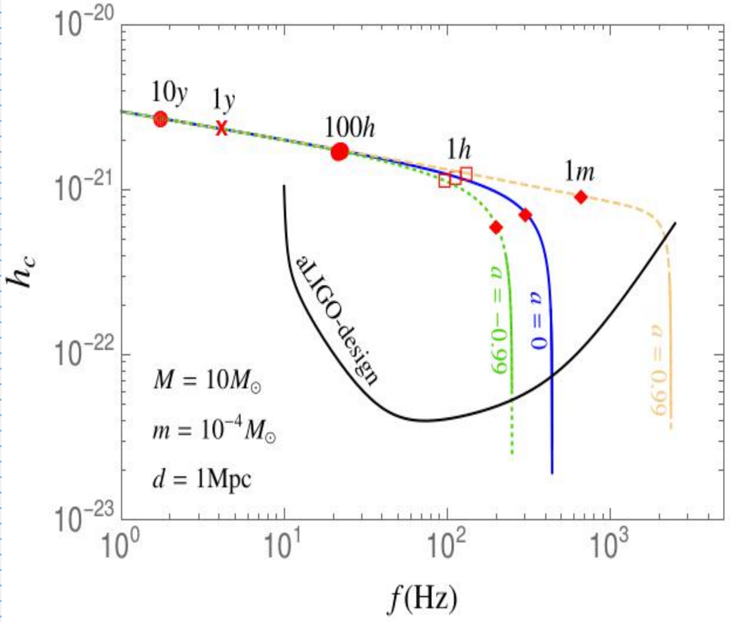
Miller et al, Phys.Dark Univ. 32 (2021) 100836

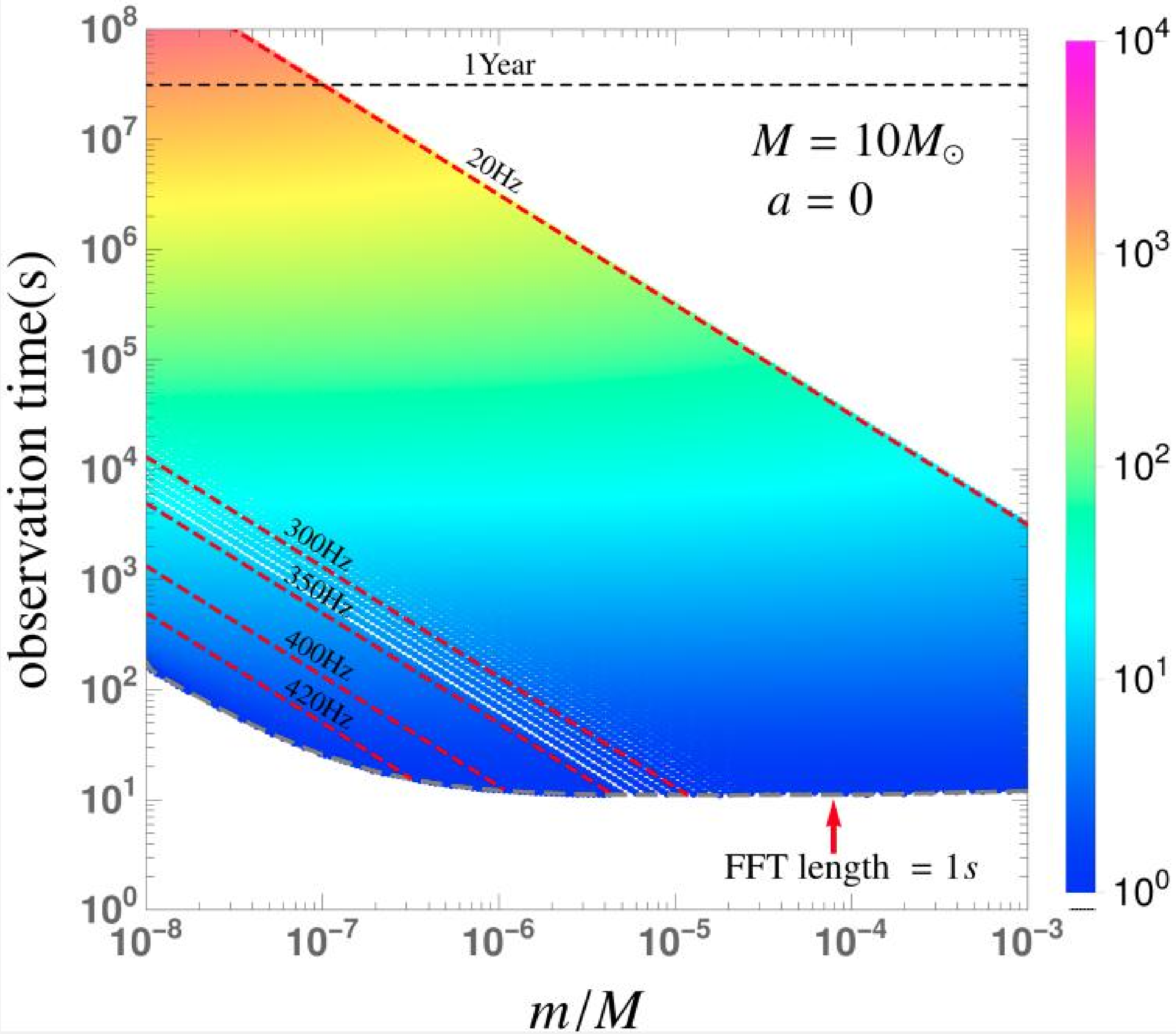
Details of SFTs

Example: 10hz band

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

signal power in 1 frequency bin





Distance Reach

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

amplitude: f-independent coefficient

time of each segment

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

sum over all segments

total observation time: set as 1 year

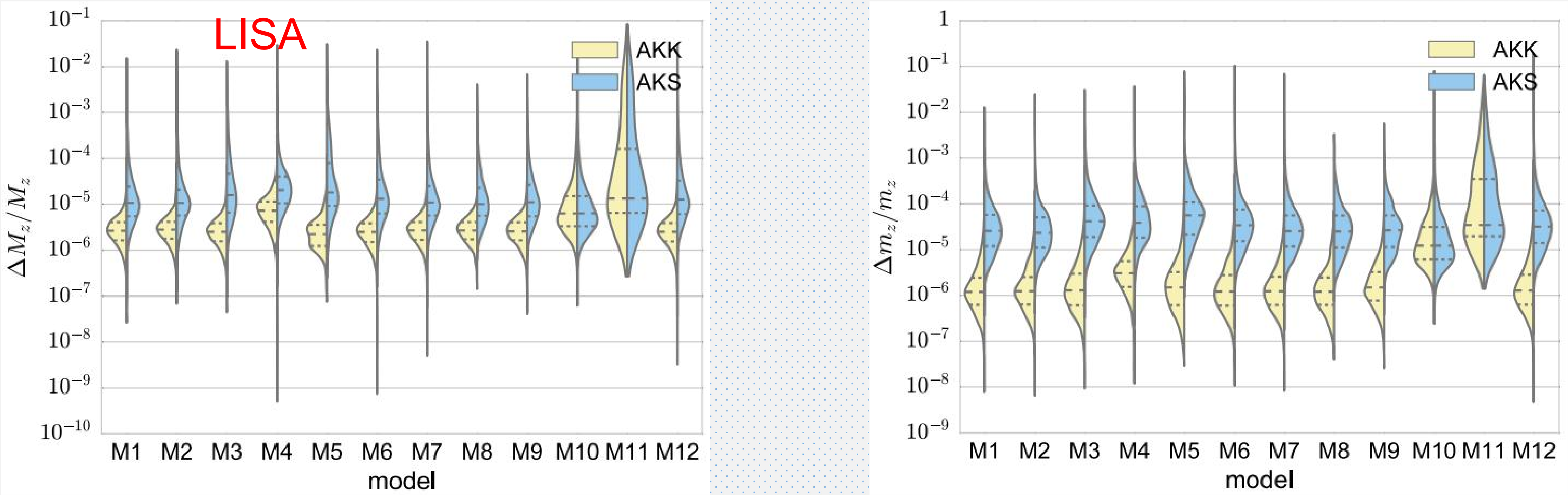
Miller et al, Phy.Dark.Univ.32 (2021) 100836
Astone et al, PRD90, 042002 (2014)
Miller et al, PRD98, 102004 (2018)

Parameter Estimation

- Once detected, parameters of EMRI can be measured very precisely (matched filtering)

  Babak et al, PRD 95, 103012 (2017), Barsanti et al, PRL128,111104 (2022)

- Unambiguous claim on the detection of subsolar ECOs



Babak et al, PRD 95, 103012 (2017)