Searching for axion clouds with the Levitated Sensor Detector

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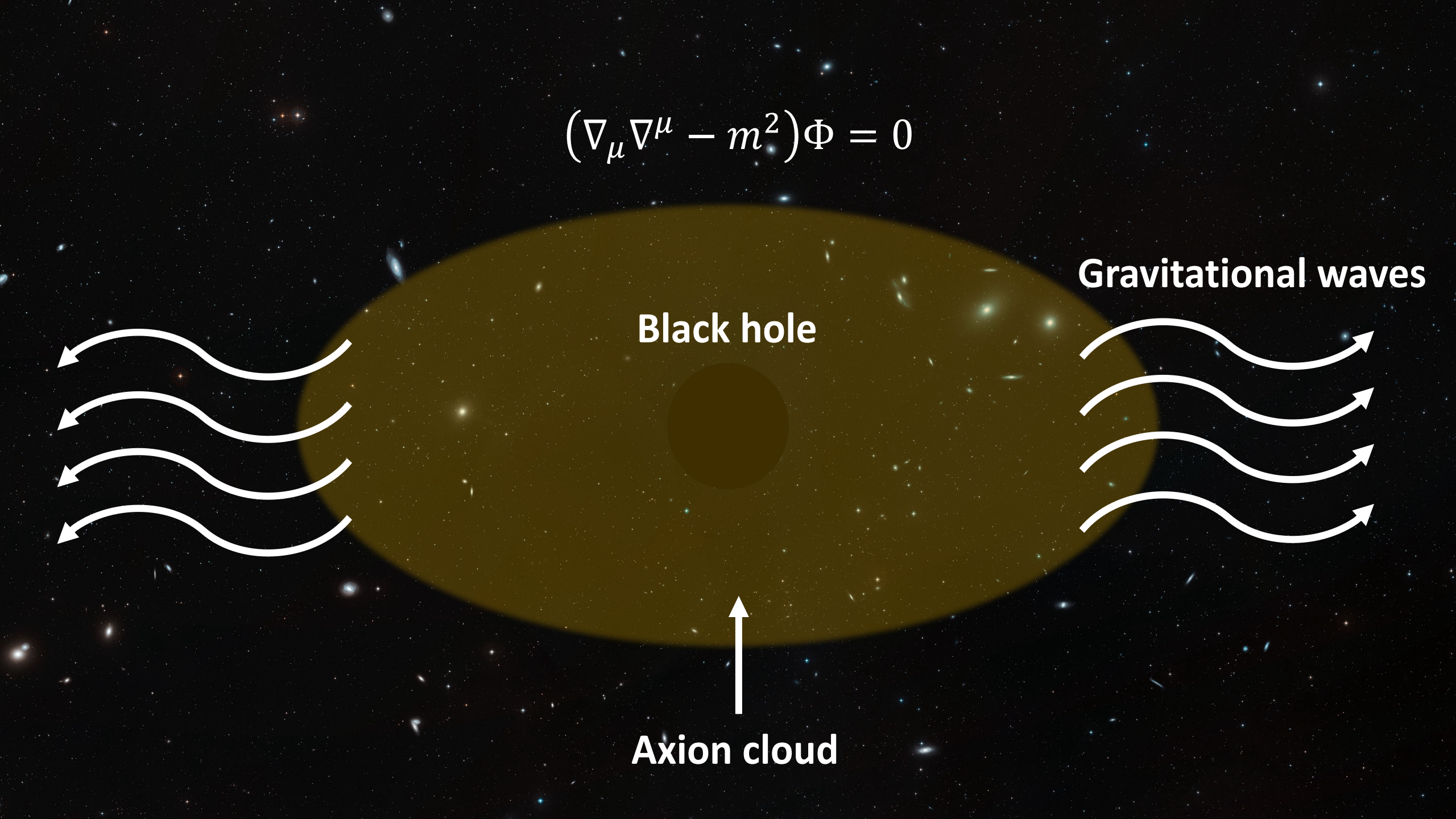
$$\left(\nabla_\mu \nabla^\mu - m^2\right)\Phi = 0$$



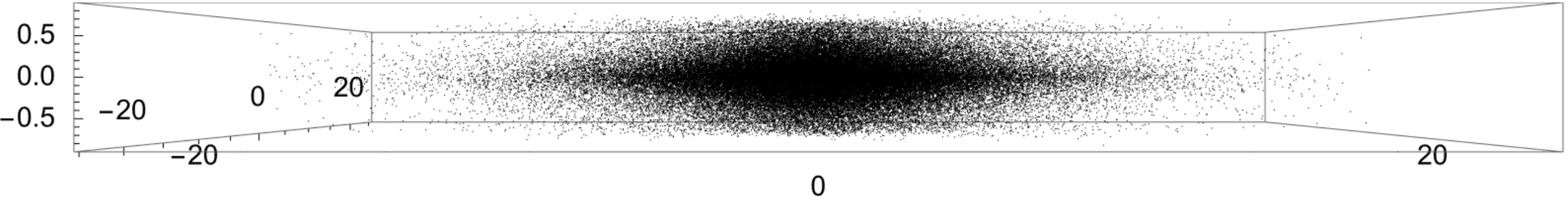
$$\Phi(t, r, \theta, \phi) = e^{-i\omega t} e^{im\phi} R(r) S(\theta)$$

In-going boundary-condition at event horizon $\Longrightarrow \omega = \omega_R + i\omega_I$

$$\Longrightarrow e^{-i\omega t} = e^{-i\omega_R t} e^{\omega_I t}$$

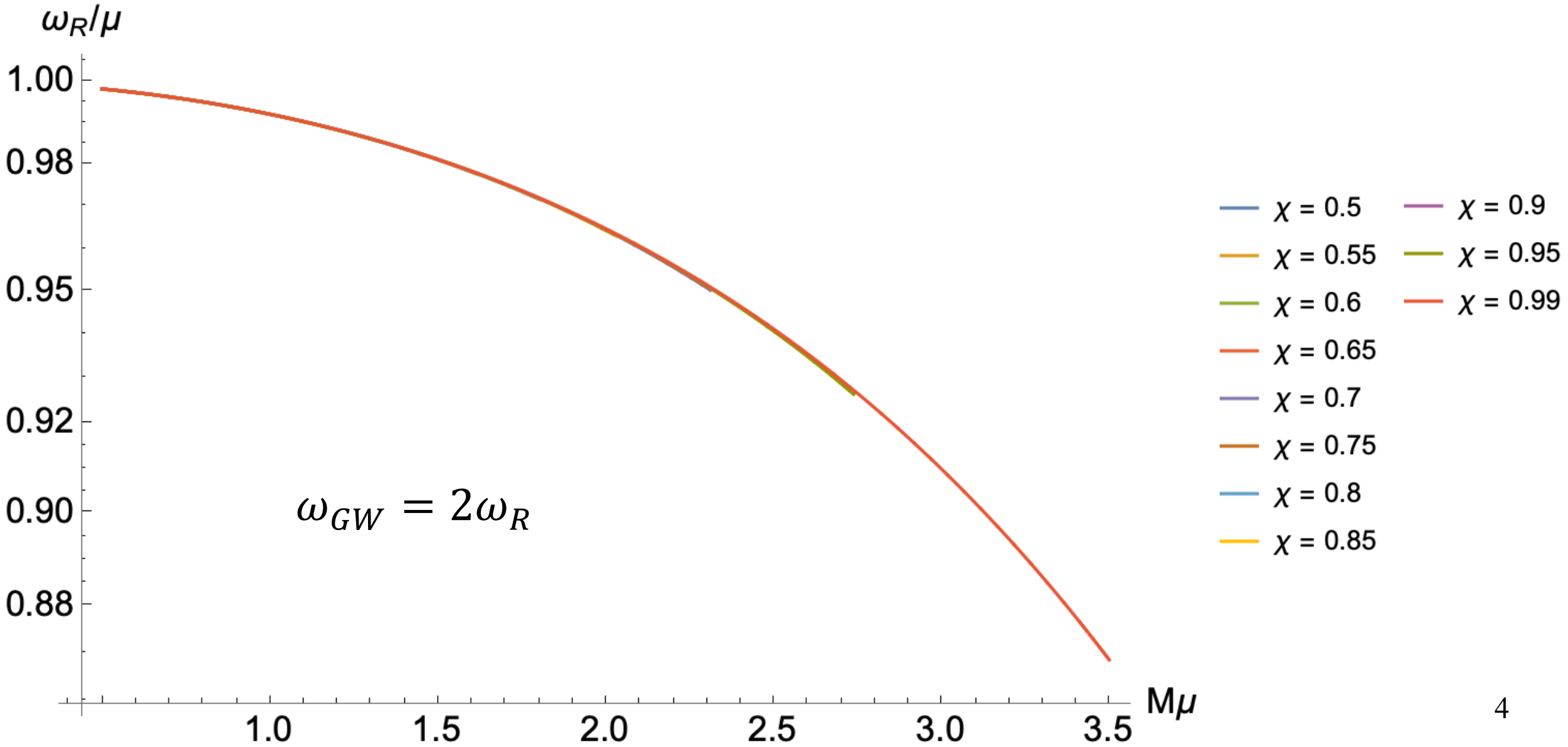
Superradiance condition: $\boxed{\omega_R < m\Omega_H} \Longrightarrow \omega_I > 0$

$$\boxed{f_{GW} = 2\frac{\omega_R}{2\pi}}$$

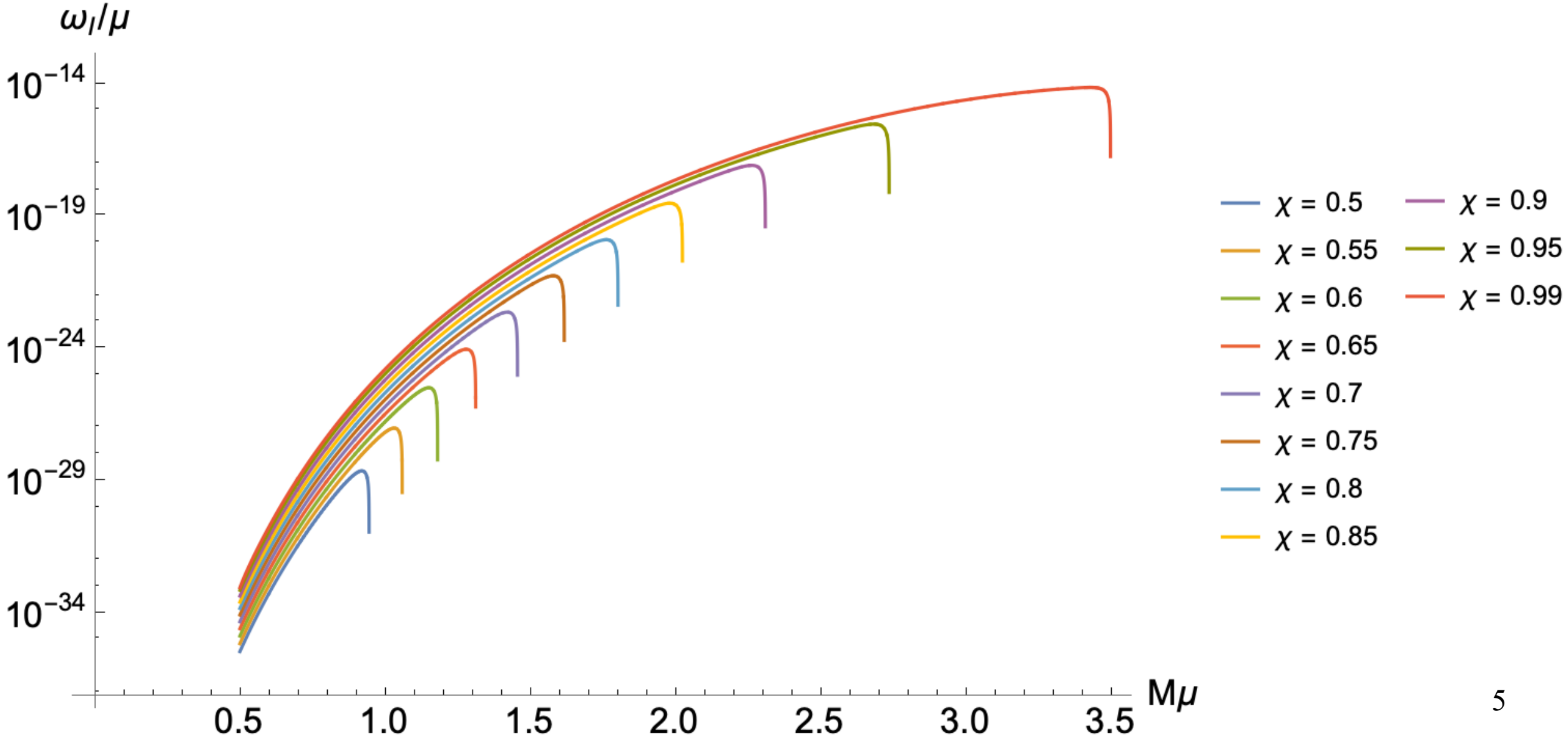


- The Milky Way could have a population of extant axion clouds
  - How many resolvable sources can we expect?
  - How do we characterize the confusion-limited noise foreground?
  - LSD boson mass range: $10^{-11}\ eV$ up to a few $\times 10^{-10}\ eV$

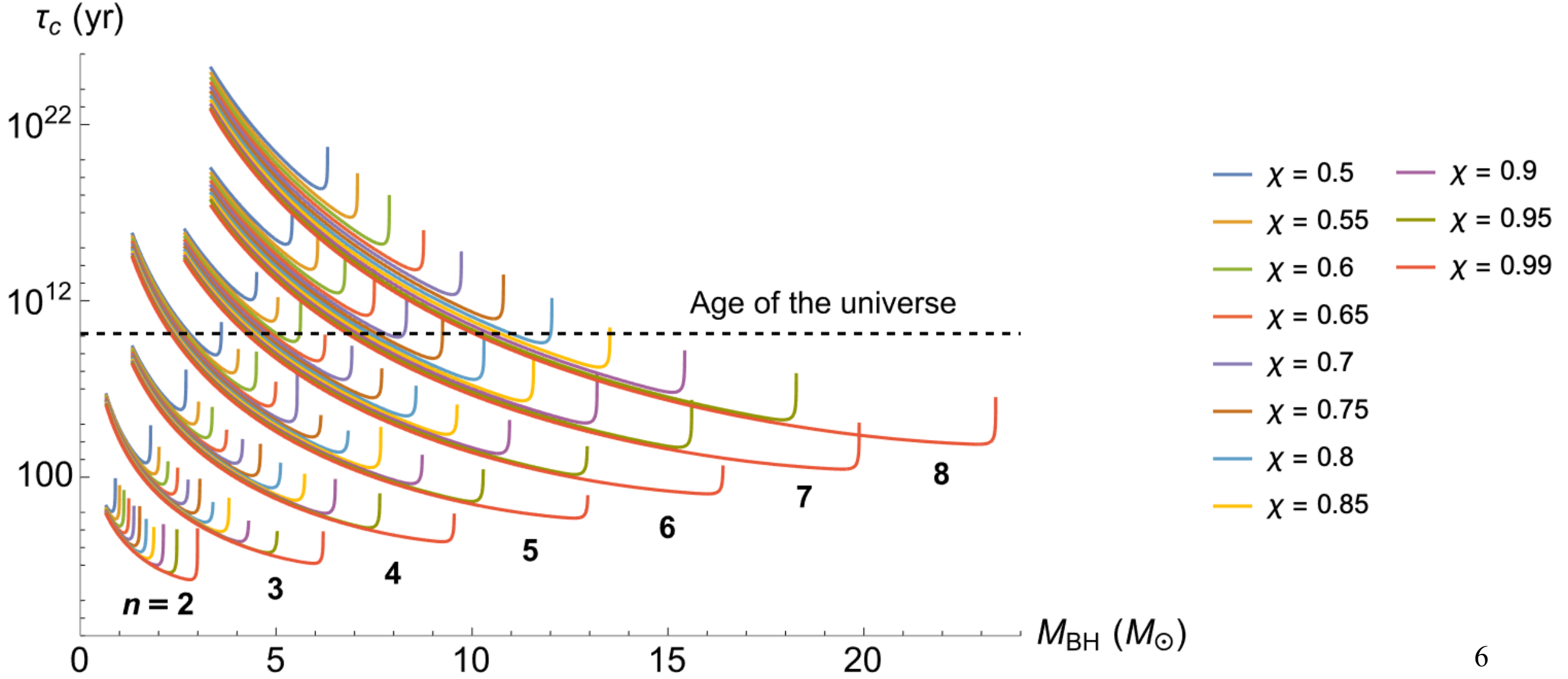
$n = 8,\ m = l = 7$


ω_R/μ
1.00
0.98
0.95
0.92
0.90
0.88
$\omega_{GW} = 2\omega_R$
1.0
1.5
2.0
2.5
3.0
3.5
Mμ
χ = 0.5
χ = 0.55
χ = 0.6
χ = 0.65
χ = 0.7
χ = 0.75
χ = 0.8
χ = 0.85
χ = 0.9
χ = 0.95
χ = 0.99

$n = 8,\ m = l = 7$


ω_I/μ
10^{-14}
10^{-19}
10^{-24}
10^{-29}
10^{-34}
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Mμ
χ = 0.5
χ = 0.55
χ = 0.6
χ = 0.65
χ = 0.7
χ = 0.75
χ = 0.8
χ = 0.85
χ = 0.9
χ = 0.95
χ = 0.99

$$\mu = 3\times10^{-11}\ eV$$



Galactic stellar-origin BH's

- BH mass distribution $\phi(m)$:
  - If a total mass M_{tot} is converted into stars, the number of stars N_m in the interval $(m,\ m\ +\ dm)$ is given by

$$N_m dm = M_{tot}\phi(m)dm$$

- Normalization:

$$\int_{m_{min}}^{m_{max}} \phi(m)\, m dm = 1$$

Galactic stellar-origin BH's

- BH mass distribution assumed to be of Salpeter form

$$\phi(m)dm = Km^{-2.35}dm$$

- Spin distribution:

$$\chi \sim U[0.1,\ 1]$$

Find fastest superradiant bound-state

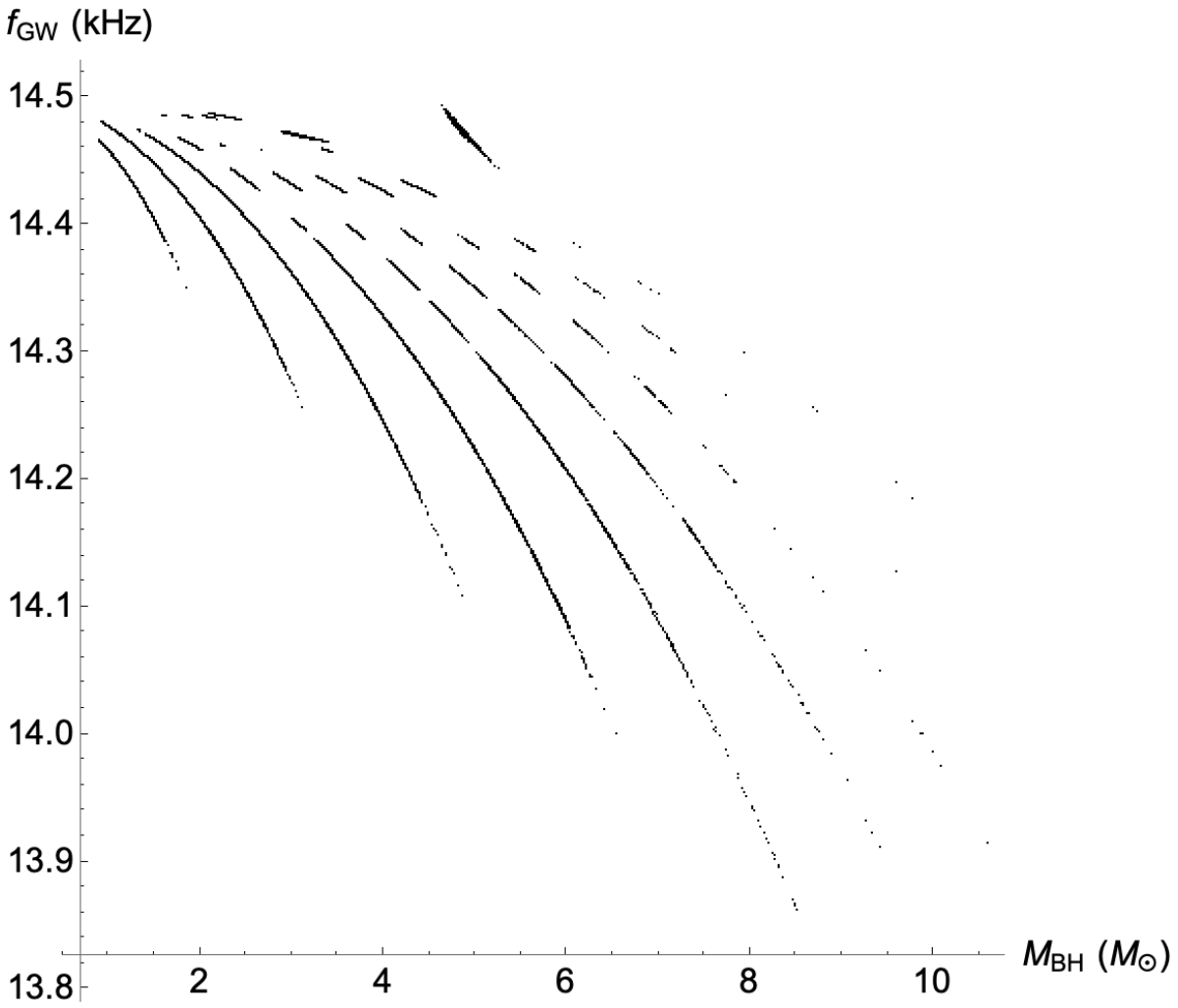
Is $\tau_c <$ BH's age?

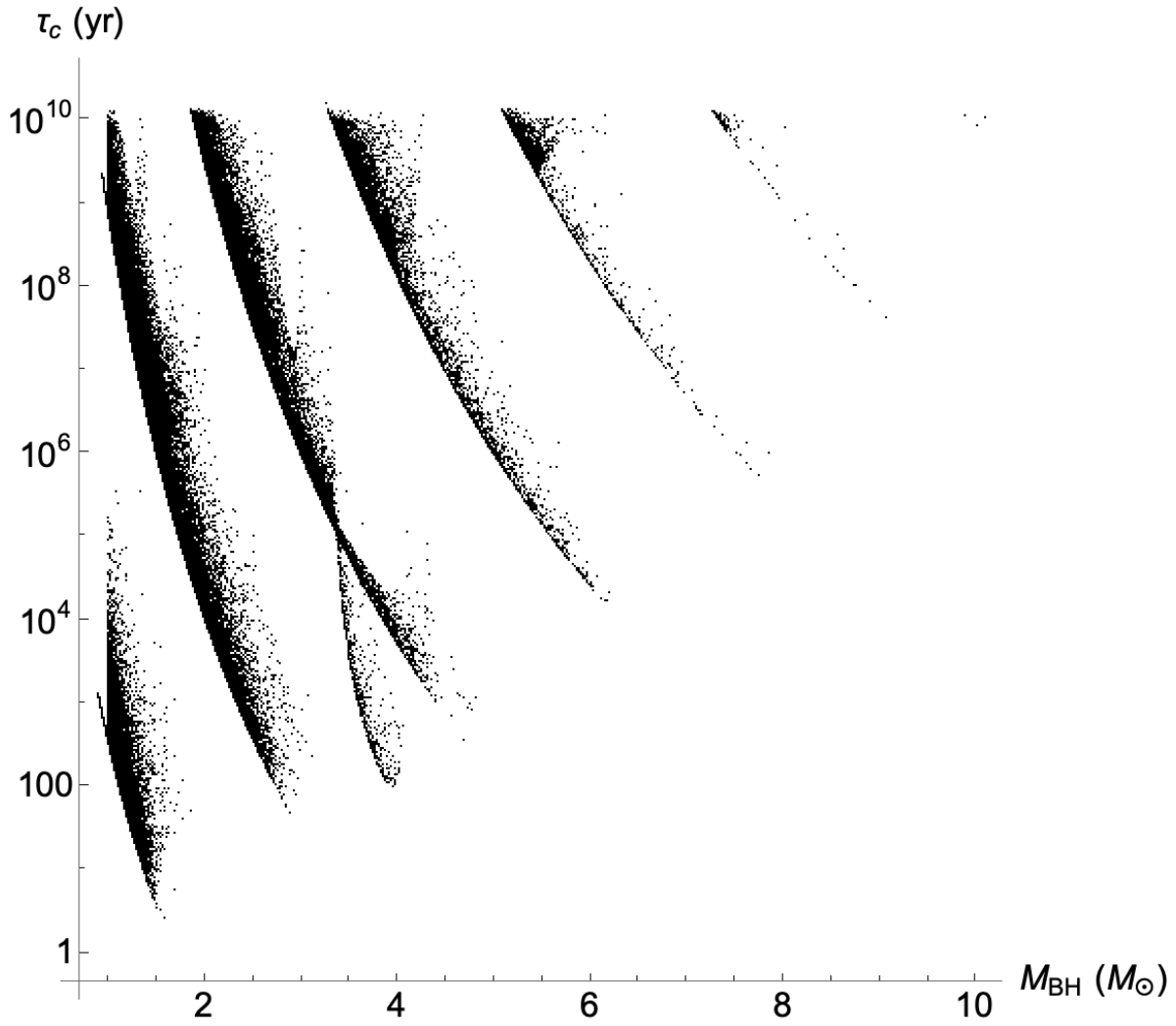
Is $\tau_{GW} >$ Time remaining to the present?

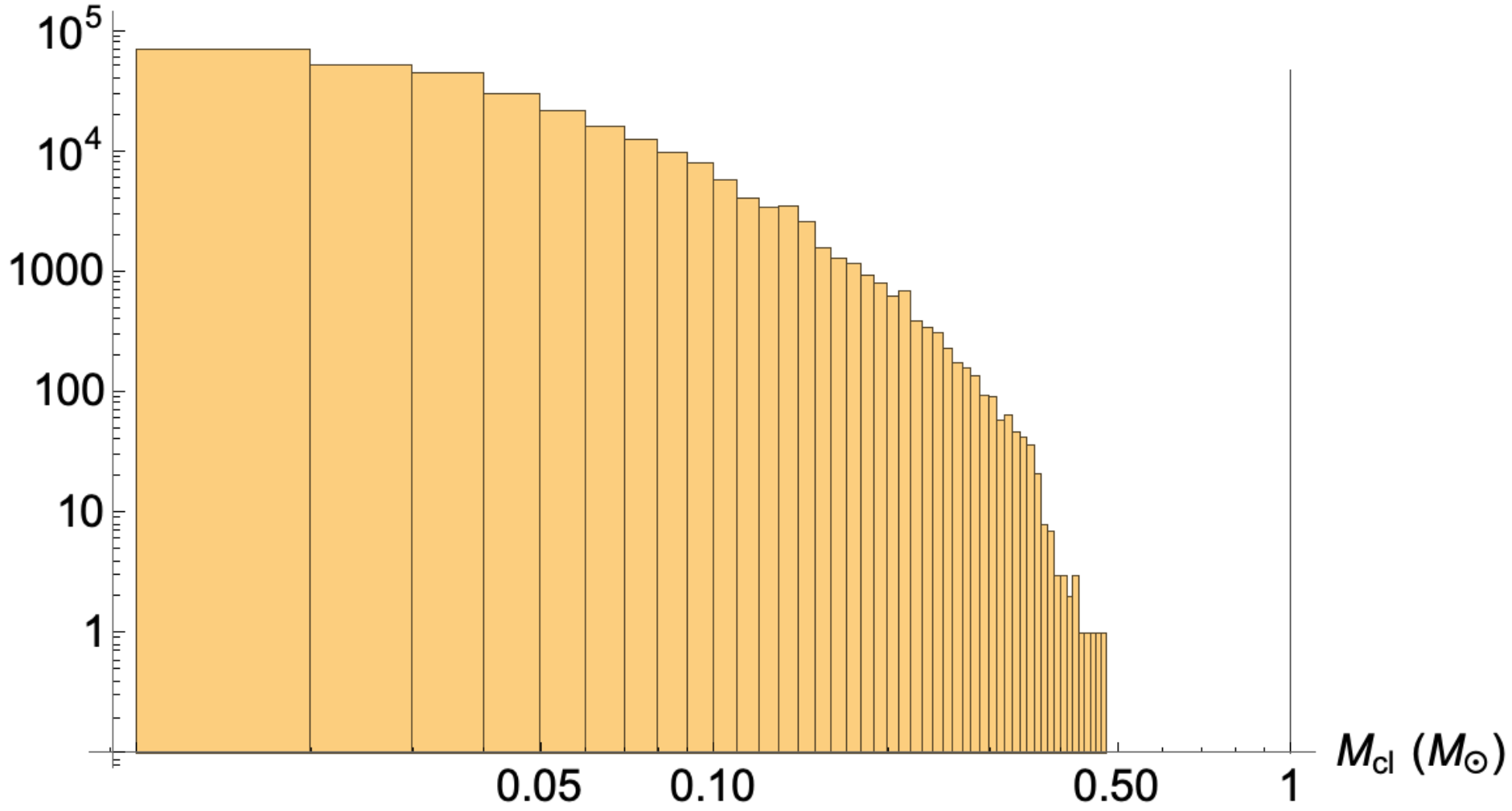
If yes, cloud still present today

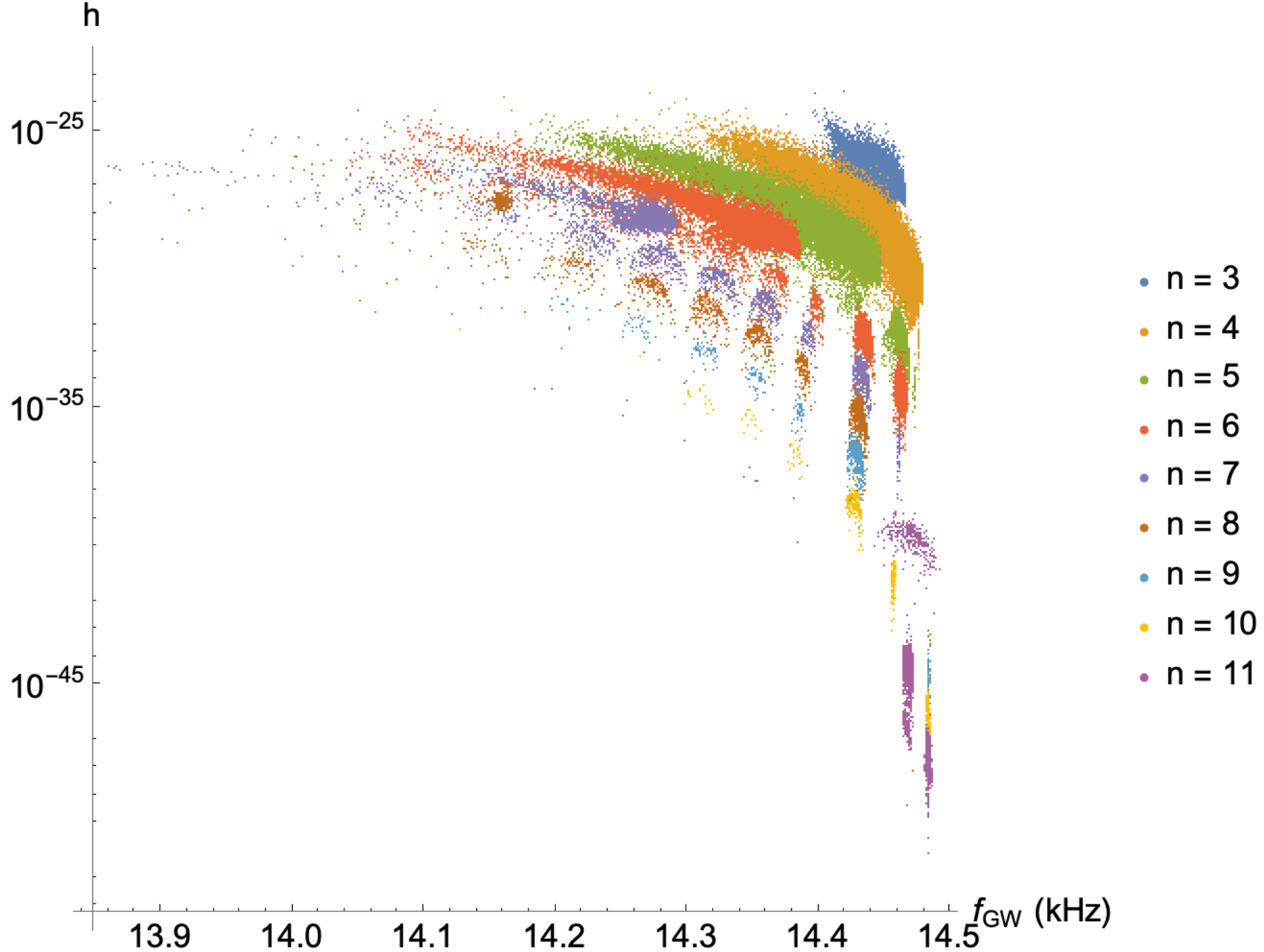
If no, a new cloud begins to grow

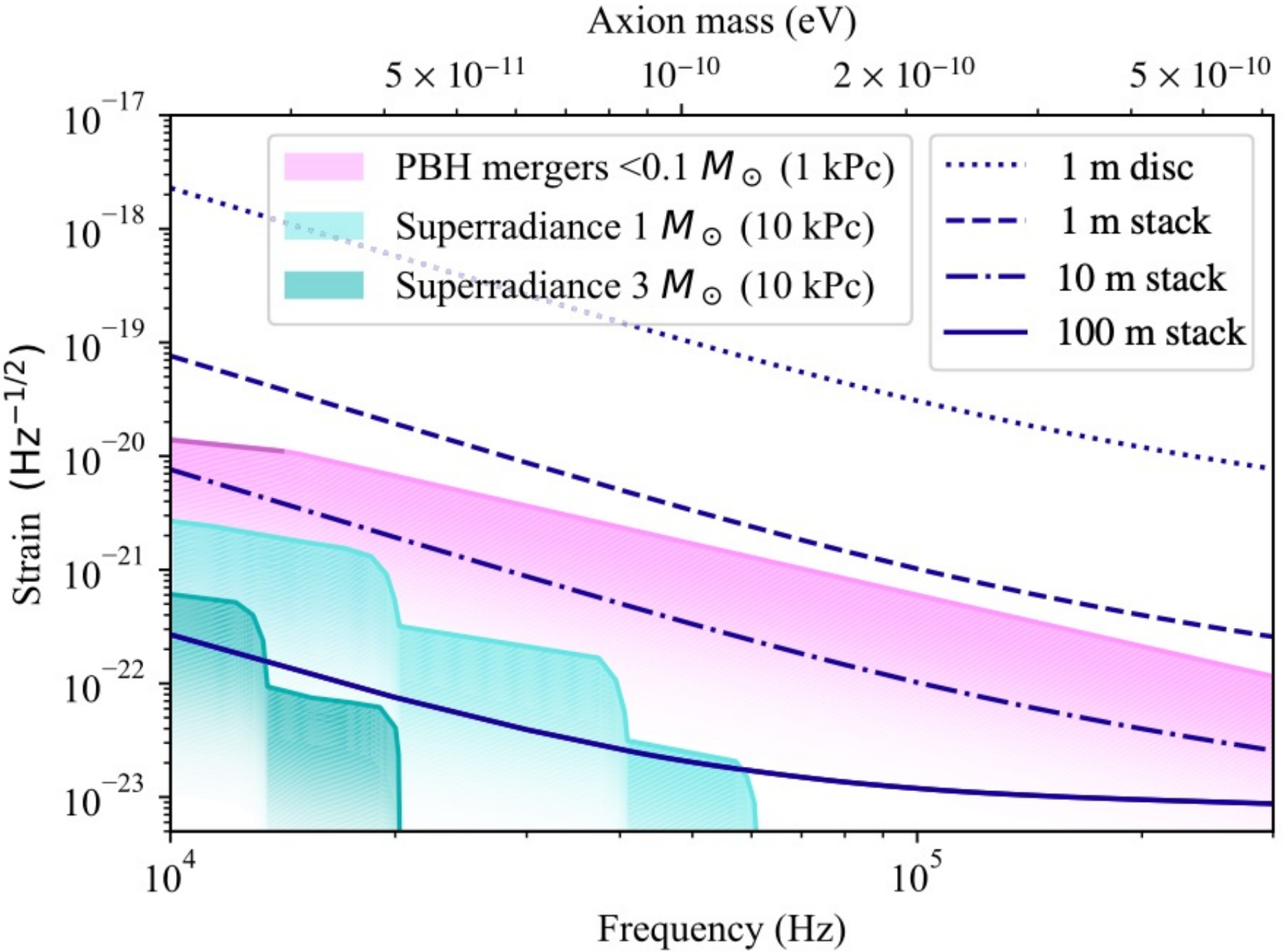
$\mu = 3\times10^{-11}\ eV$



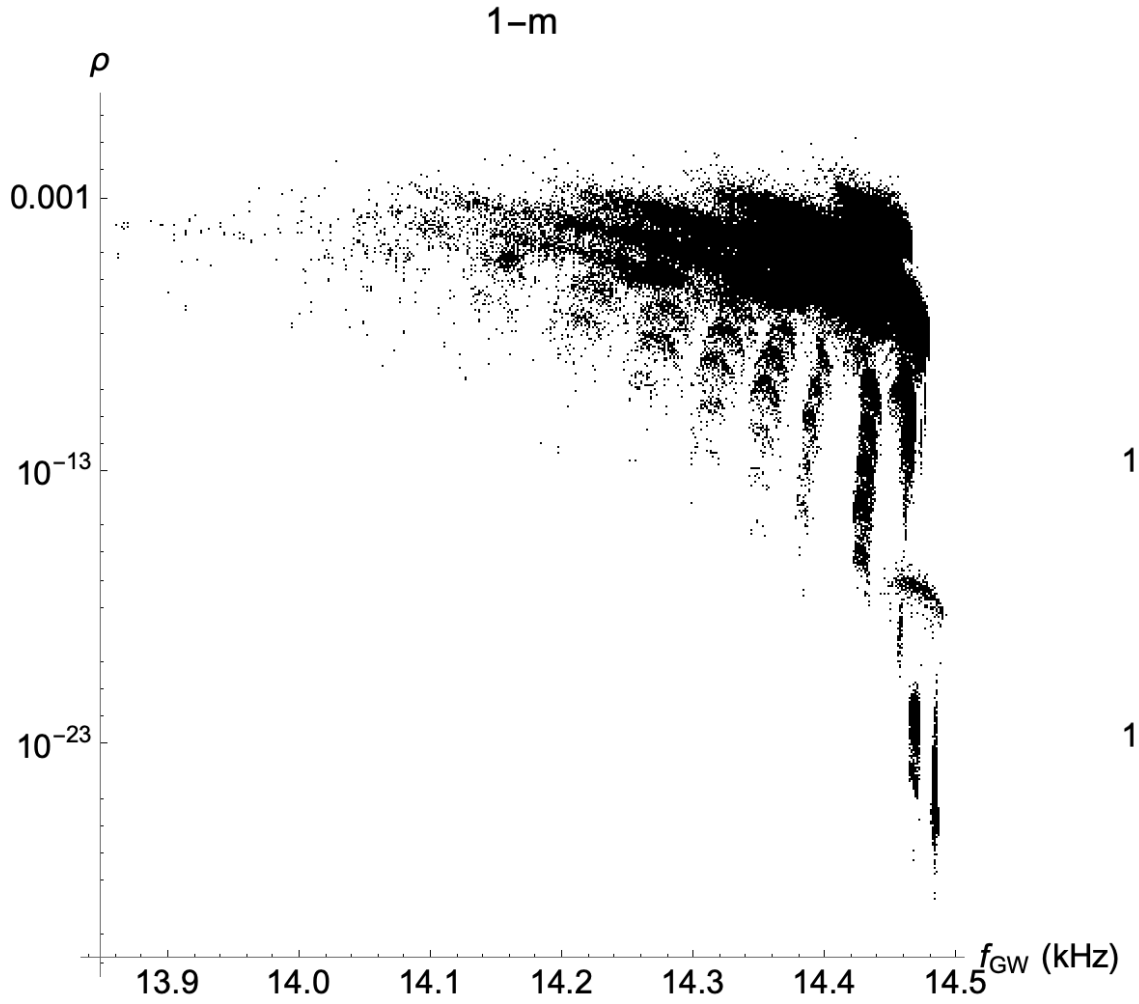


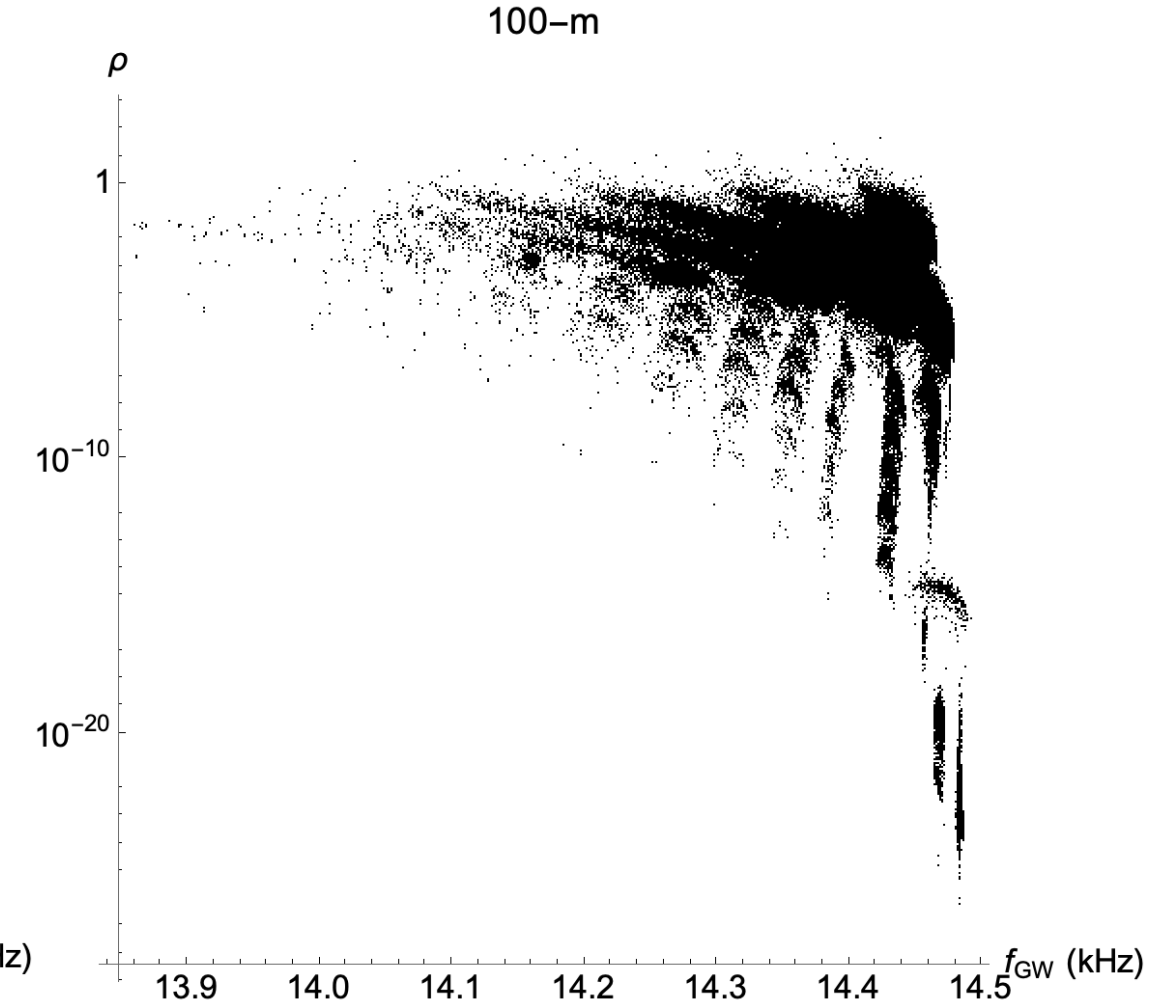

10^5
10^4
1000
100
10
1
0.05
0.10
0.50
1
M_{cl} $(M_\odot)$

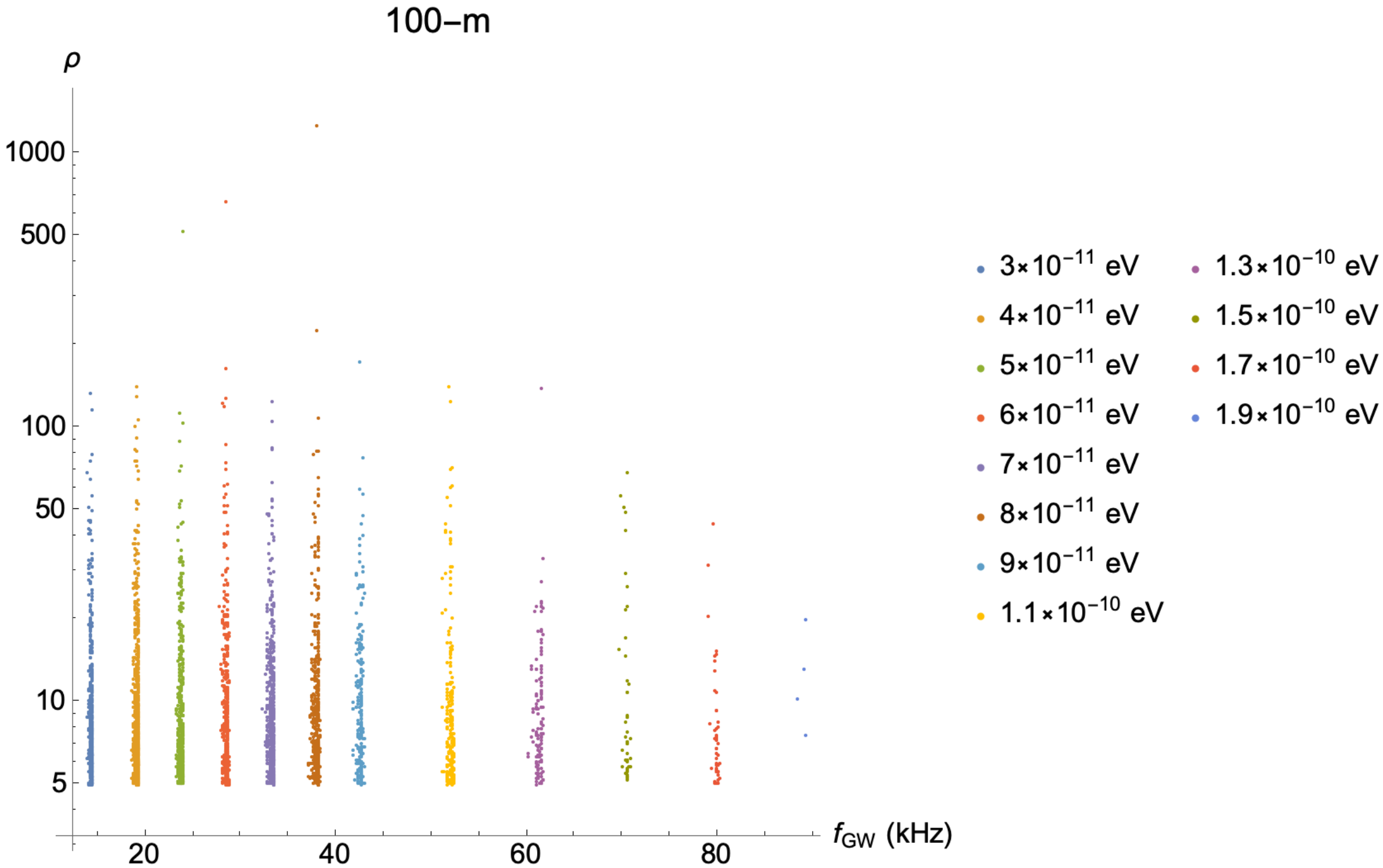

h
10^{-25}
10^{-35}
10^{-45}
13.9
14.0
14.1
14.2
14.3
14.4
14.5
f_{GW} (kHz)
n = 3
n = 4
n = 5
n = 6
n = 7
n = 8
n = 9
n = 10
n = 11


Axion mass (eV)
5×10^{-11}
10^{-10}
2×10^{-10}
5×10^{-10}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
Strain $(\mathrm{Hz}^{-1/2})$
PBH mergers <0.1 $M_\odot$ (1 kPc)
Superradiance 1 $M_\odot$ (10 kPc)
Superradiance 3 $M_\odot$ (10 kPc)
1 m disc
1 m stack
10 m stack
100 m stack
10^4
10^5
Frequency (Hz)

$$\rho = \frac{h\sqrt{T_{obs}}}{\sqrt{S_n(f)}}$$






100−m
ρ
1000
500
100
50
10
5
20
40
60
80
f_{GW} (kHz)
3×10^{-11} eV
4×10^{-11} eV
5×10^{-11} eV
6×10^{-11} eV
7×10^{-11} eV
8×10^{-11} eV
9×10^{-11} eV
1.1×10^{-10} eV
1.3×10^{-10} eV
1.5×10^{-10} eV
1.7×10^{-10} eV
1.9×10^{-10} eV

Summary

- 100-m instrument could see $\mathcal{O}(10^1 - 10^3)$ individual sources for boson masses $\lesssim 2\times10^{-10}\ eV$
- An optimistic upper limit
  - Salpeter mass distribution might be ‘realistic’ if there is a population of $1 - 3\ M_\odot$ isolated ‘rogue’ BH’s
  - Still need to characterize the confusion foreground
- The foreground could be detectable by 1-m and 10-m instruments even if resolved sources are not

LSD COLLABORATION

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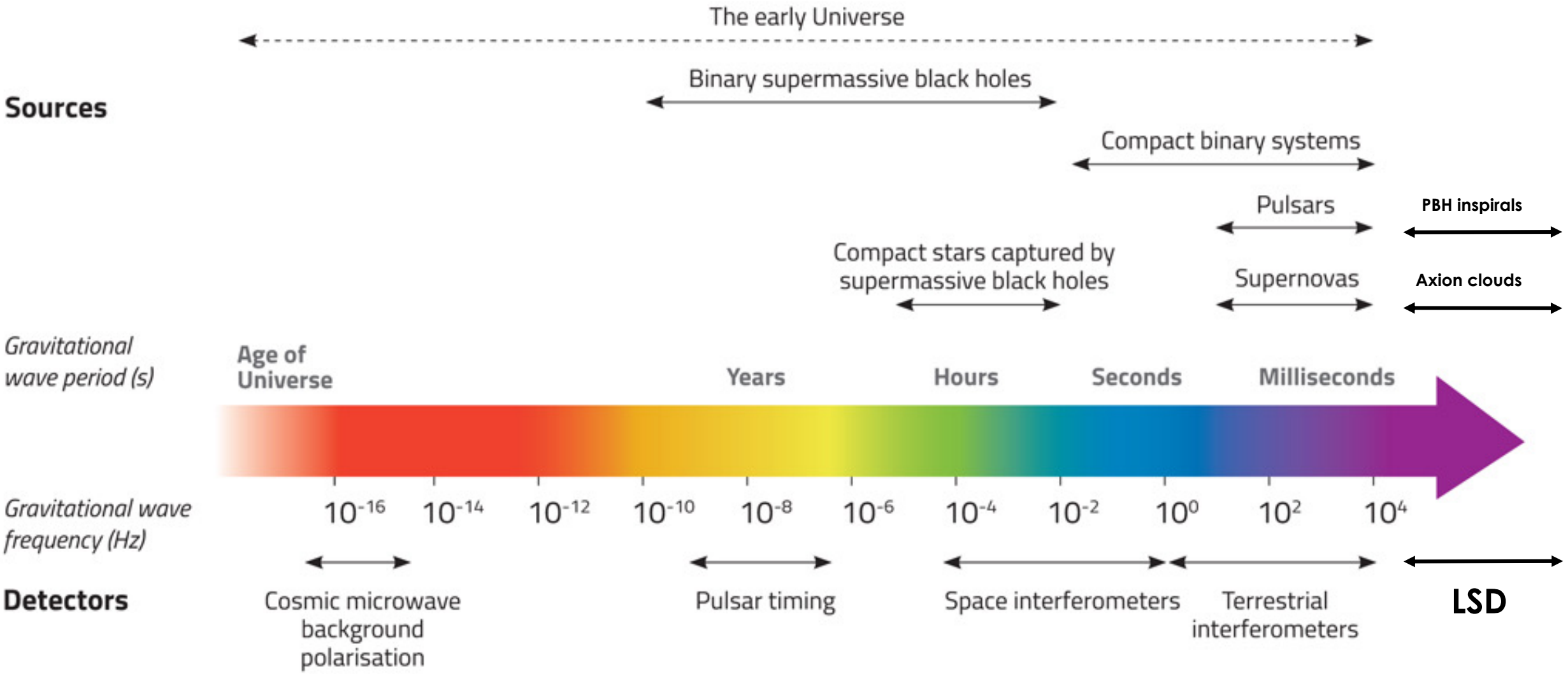
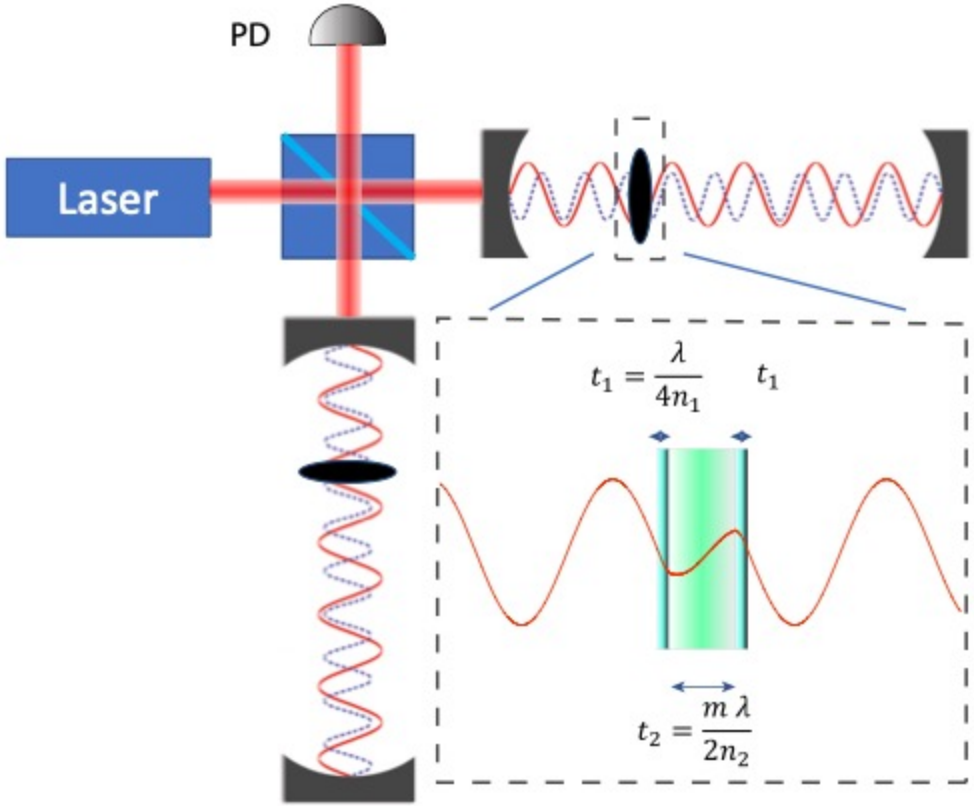

The early Universe
Sources
Binary supermassive black holes
Compact binary systems
Pulsars
PBH inspirals
Compact stars captured by supermassive black holes
Supernovas
Axion clouds
Gravitational wave period (s)
Age of Universe
Years
Hours
Seconds
Milliseconds
Gravitational wave frequency (Hz)
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4}
Detectors
Cosmic microwave background polarisation
Pulsar timing
Space interferometers
Terrestrial interferometers
LSD



- GW sensors: Optically-trapped hexagonal NaYF disks
- Resonant detection of GW's
  - Widely-tunable trapping frequency
- 10 kHz – a few hundred kHz
- 1-m prototype in development at Northwestern