



# Searching for gravitational-wave signals from axions

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Sylvia J. Zhu (DESY, AEI Hannover)

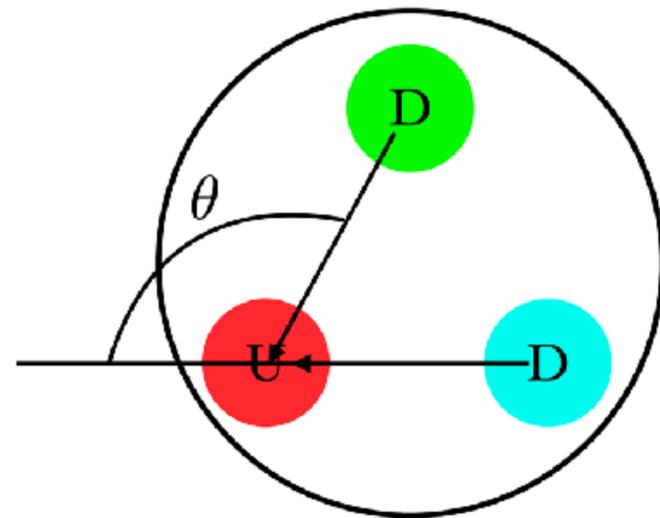
PRD 102, 063020

<https://www.aei.mpg.de/continuouswaves/arxiv200303359>

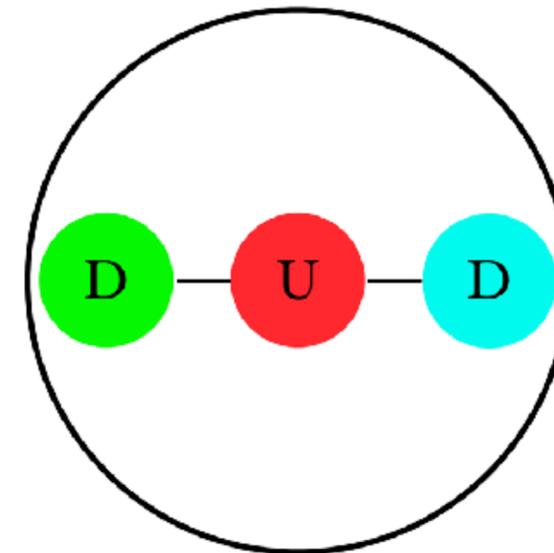
# In which I try to convince you I understand what an axion is

Axions are hypothetical particles that were proposed to solve the *strong CP problem*

The neutron should have an electric dipole moment



... but it does not

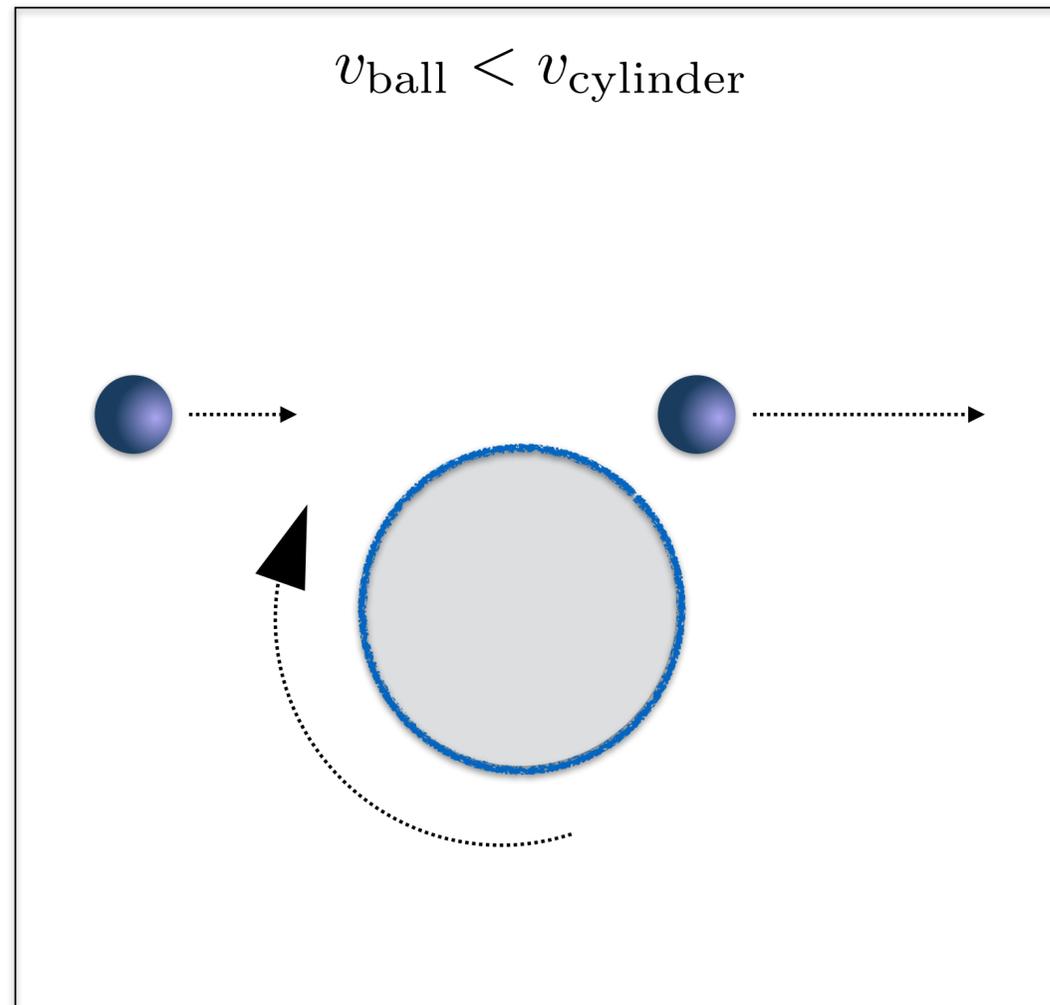


If  $\theta$  is dynamical, then it will naturally 'relax' to zero  $\rightarrow \theta$  is a field and its oscillations give rise to **axions**

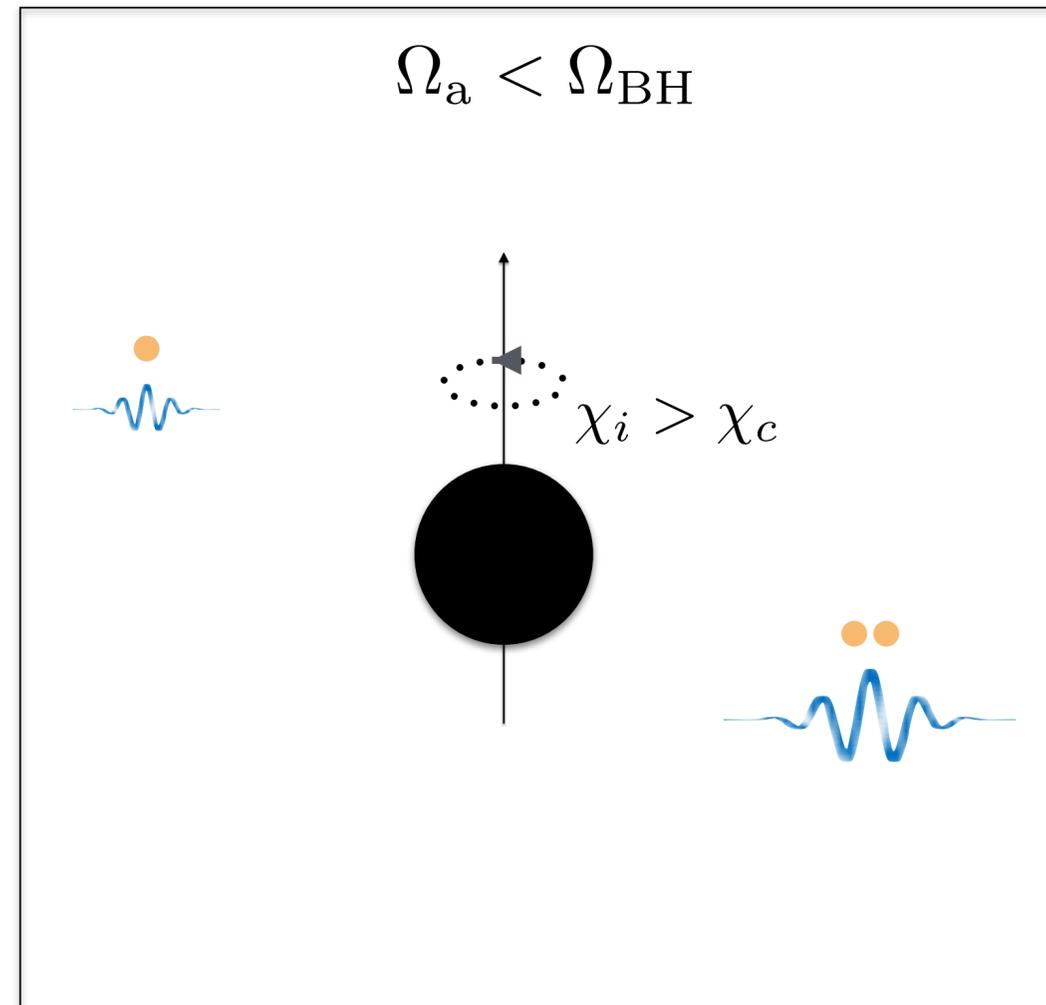
# Superradiance instability

Axions around a black hole can increase in number by extracting black hole spin

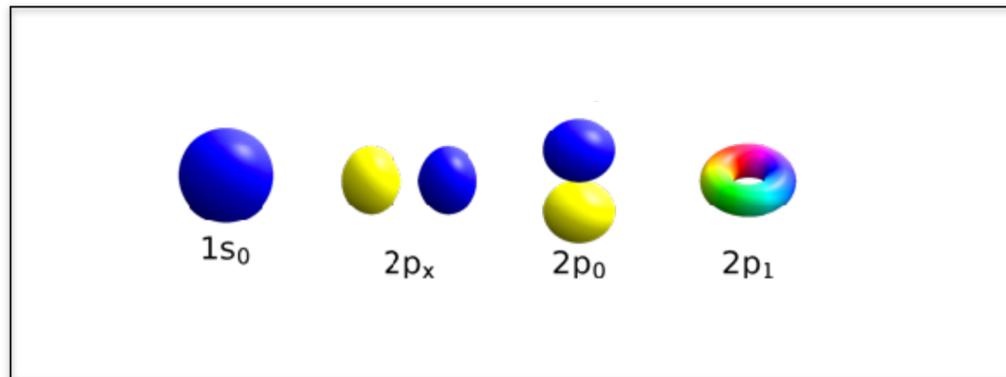
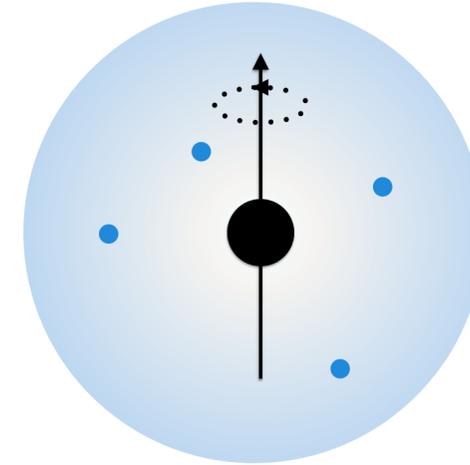
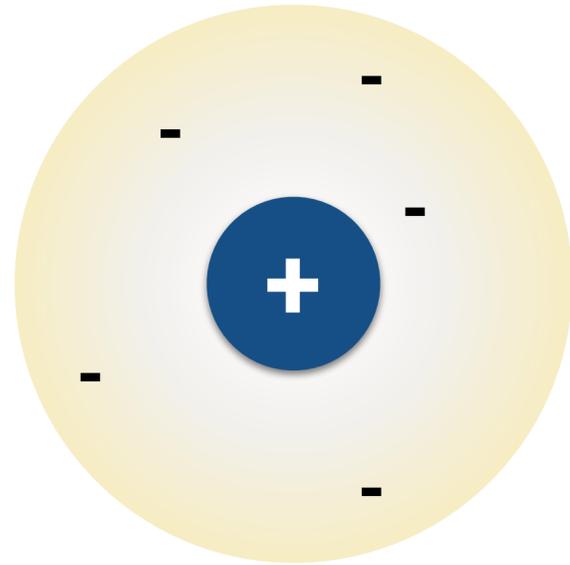
classical analog



superradiance



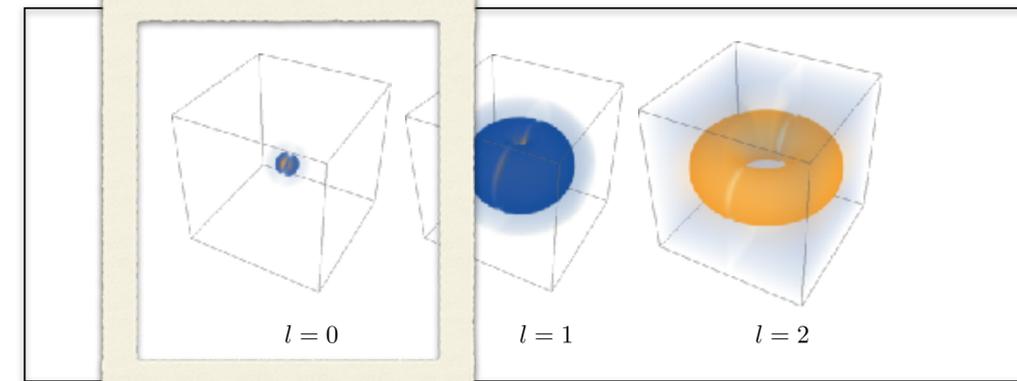
# Gravitational “atom”



[Wikimedia Commons]

$$\alpha \propto q_e q_{\text{nuc}}$$

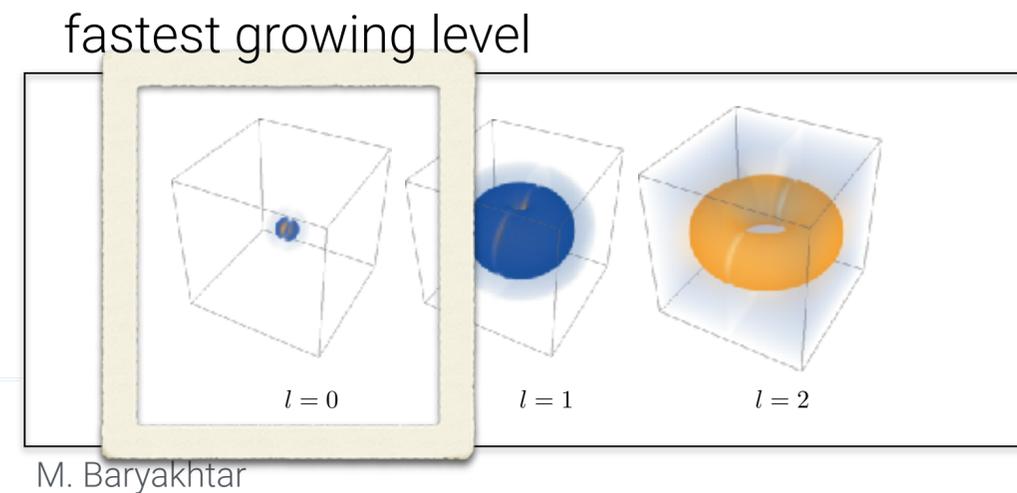
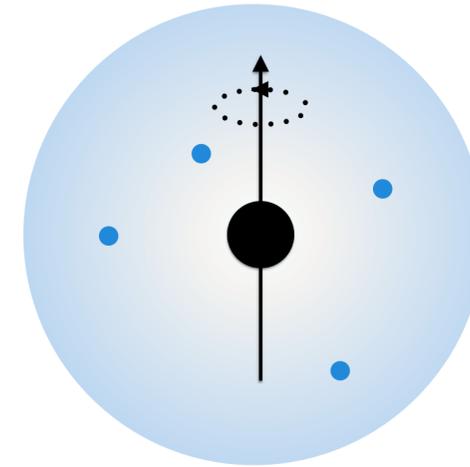
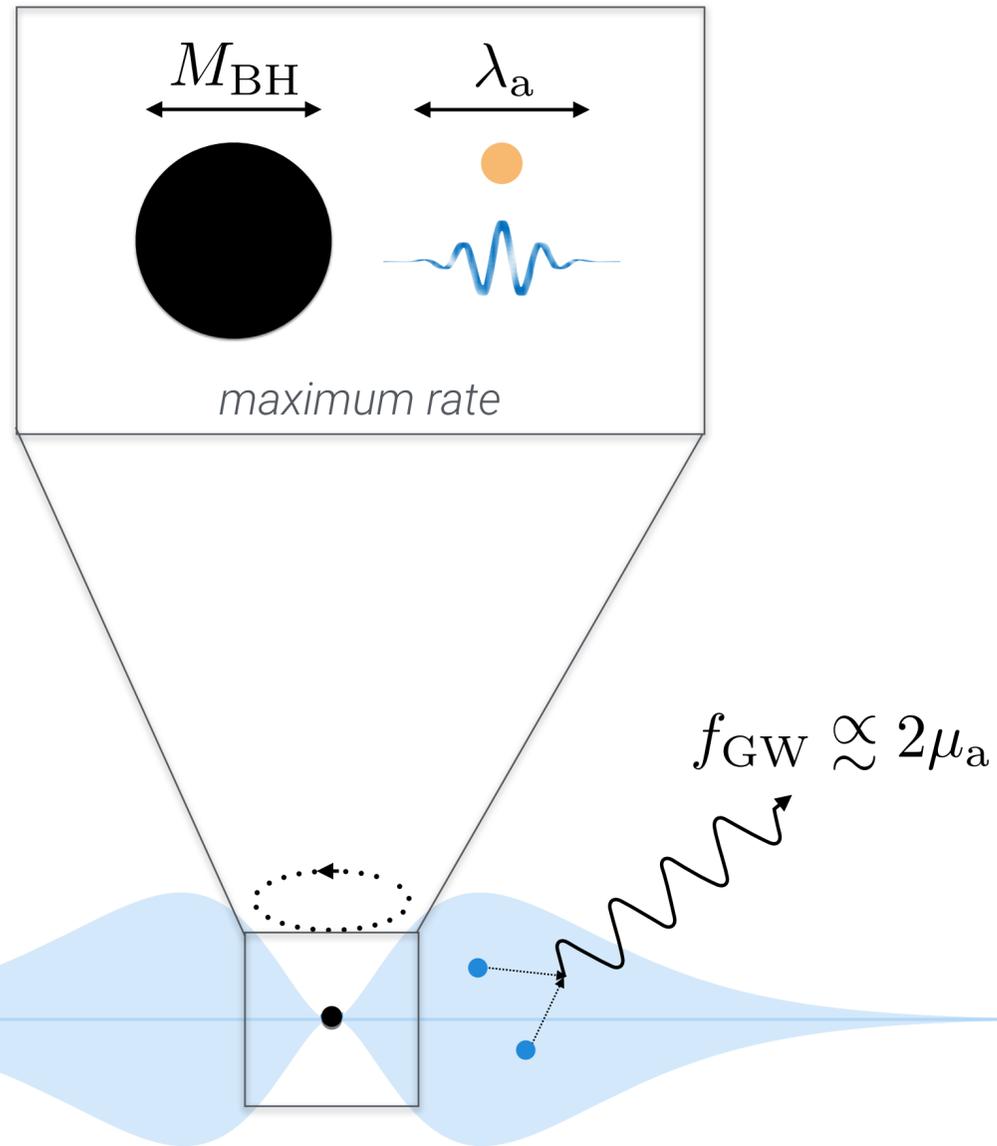
fastest growing level



M. Baryakhtar

$$\alpha \propto \mu_a M_{\text{BH}}$$

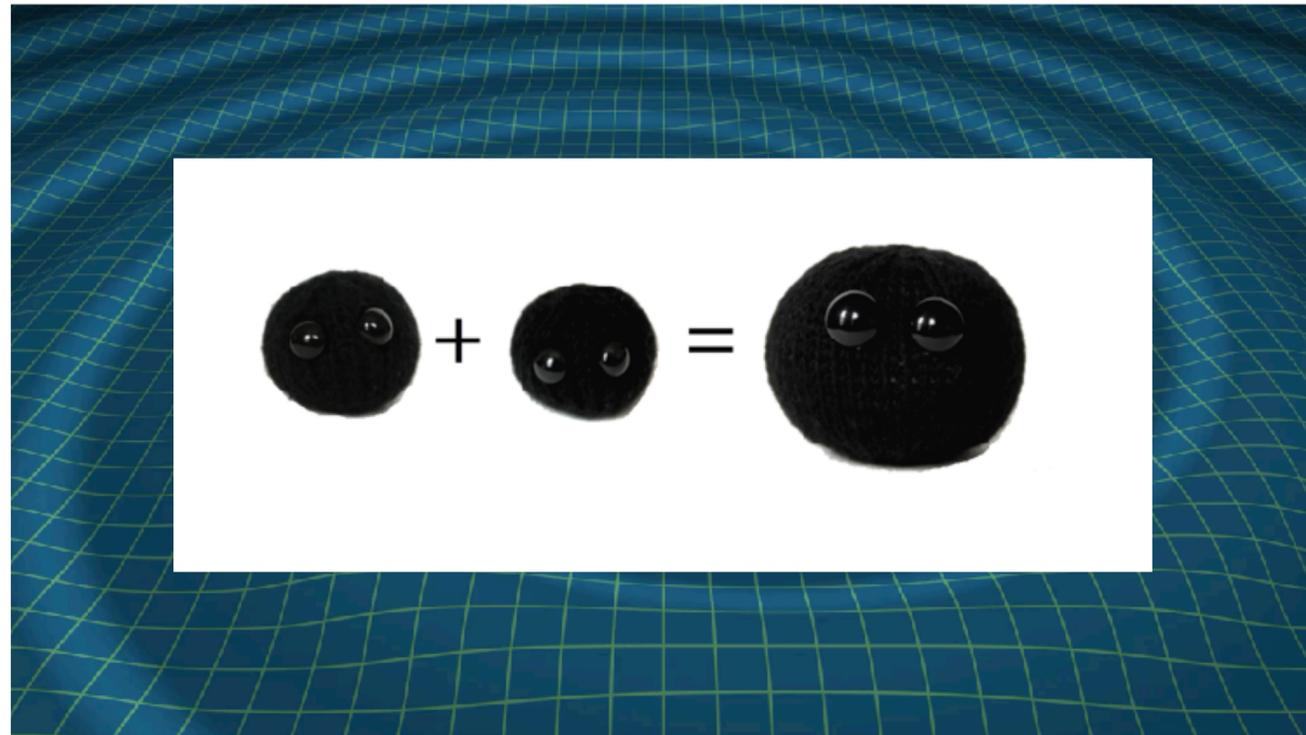
# Gravitational “atom” sources continuous gravitational waves



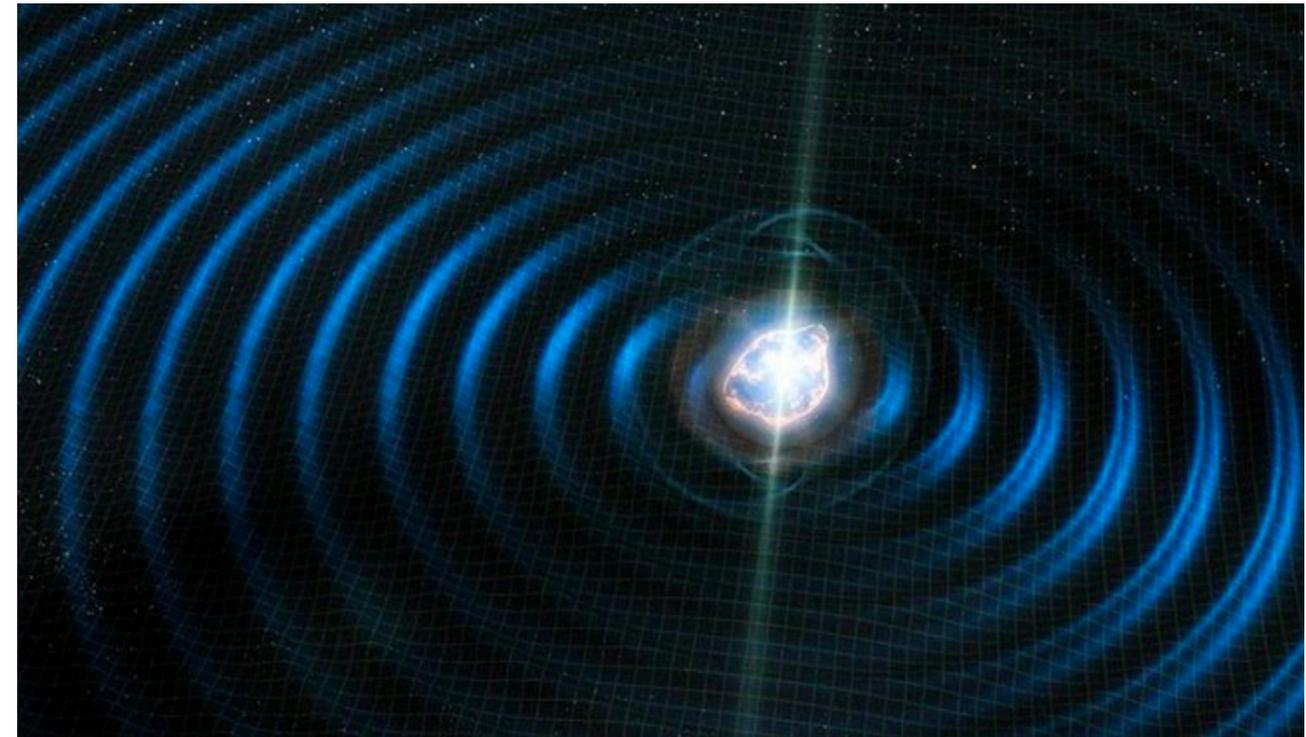
$$\alpha \propto \mu_a M_{\text{BH}}$$

# Some types of gravitational-wave signals

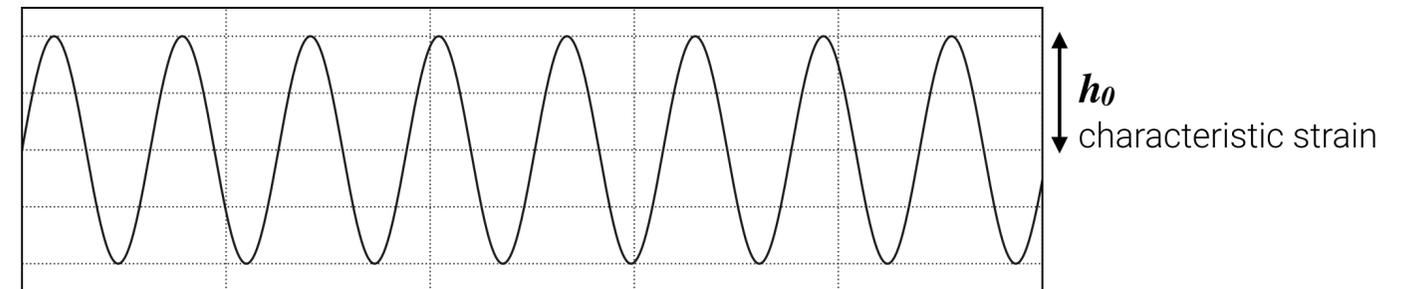
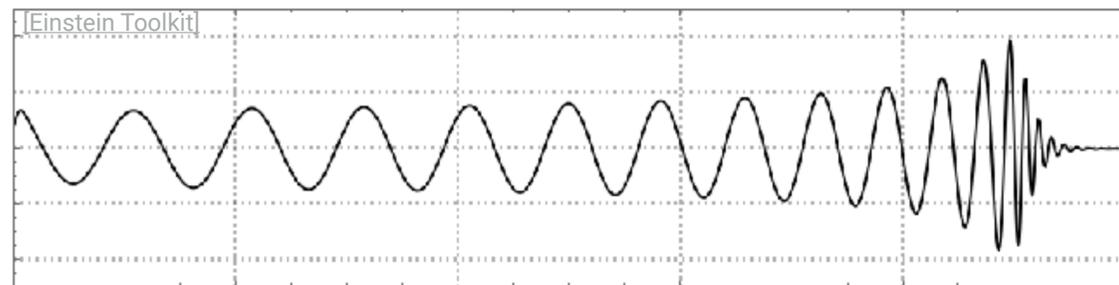
transient signals can be loud ( $h \approx 10^{-21}$ )



continuous signals are very quiet ( $h \approx 10^{-25}$ )

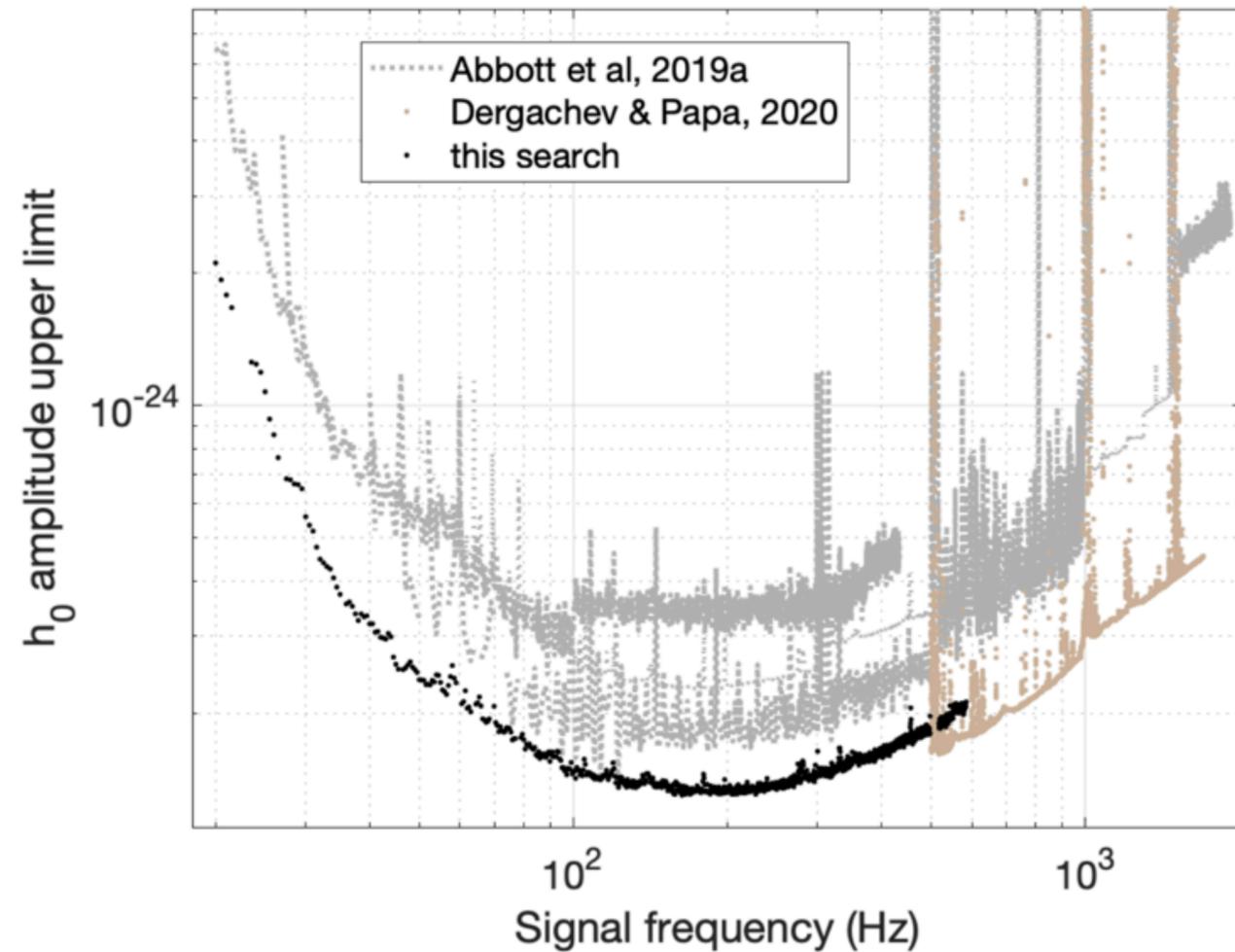


**strain  $h$ :**  
fractional  
change in  
length

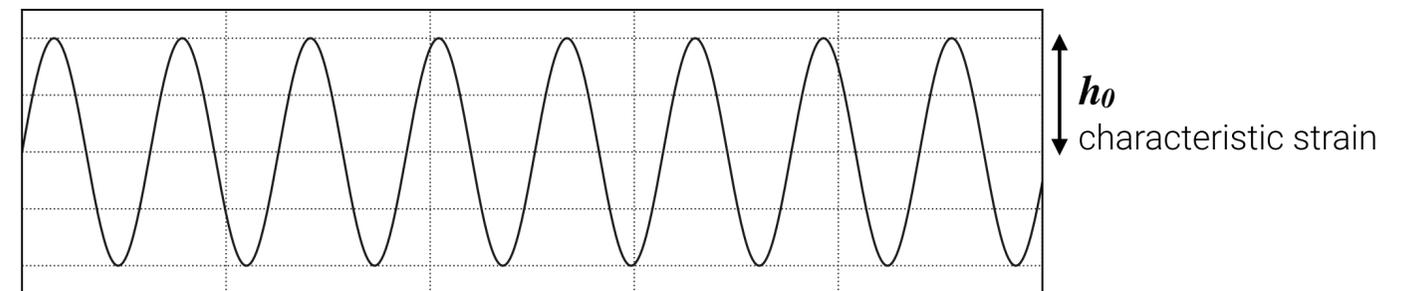
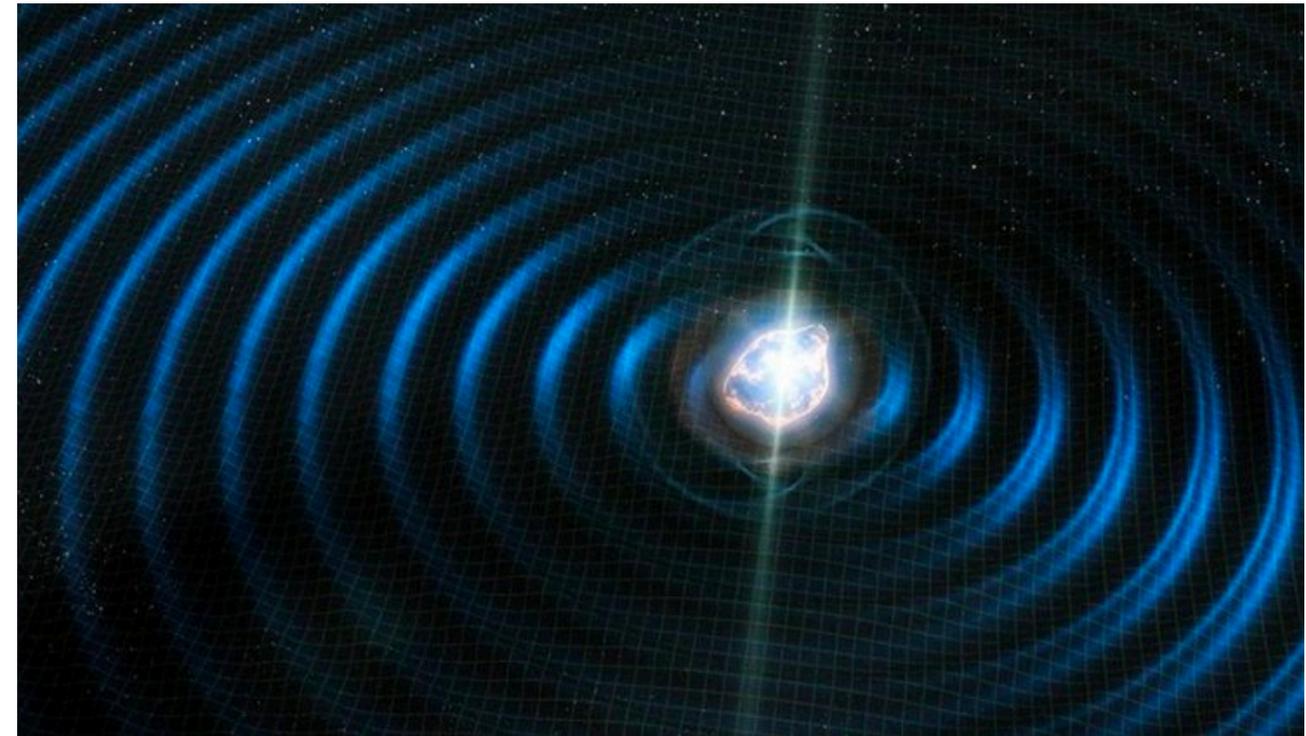


# Some types of gravitational-wave signals

## recent example of a search

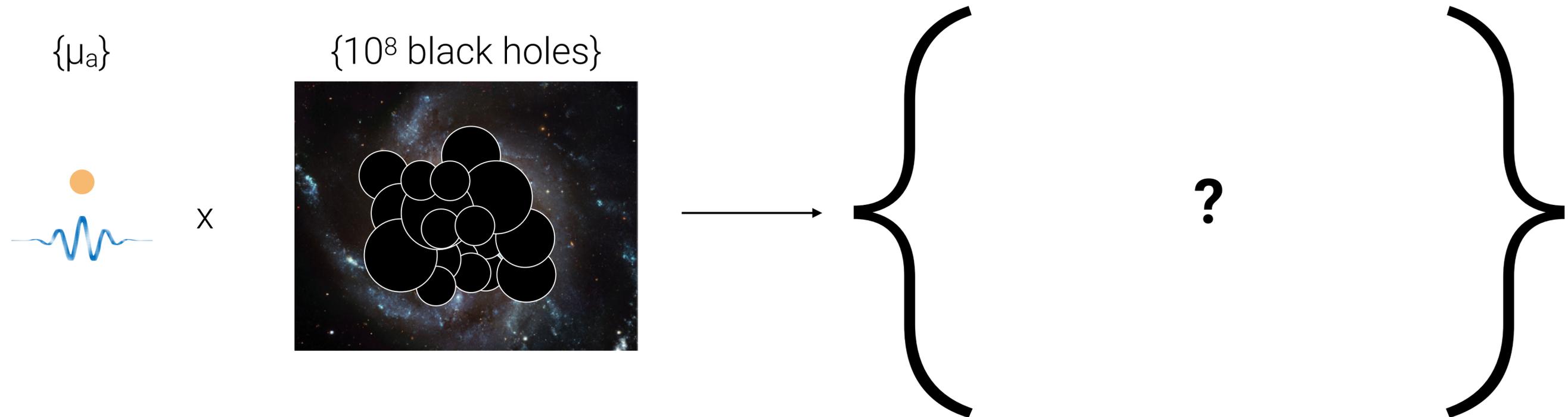


continuous signals are very quiet ( $h \lesssim 10^{-25}$ )



# Searching for the axion annihilation signal

The axion can have any mass within a large range ( $\sim 10^{-13}$  eV to  $10^{-1}$  eV).  
It will (try to) interact with **all black holes**.



To search for axions, we search for the **ensemble axion annihilation signal** from **all black holes in the Galaxy**

# What to do with search results?

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Detect a signal  $\longrightarrow$  Find the axion



Detect no signal :(

Because the axion doesn't exist?

Because the black holes don't result in a detectable signal?

Are they too old?

Too young?

Too far away?

Spinning too slowly?

The wrong mass?

# Gravitational “atom” sources continuous gravitational waves

$\alpha \propto \mu_a M_{\text{BH}}$  **larger  $\alpha$ :** (note: spin-0 particles)

$h_{0,\text{peak}} \propto \alpha^7$

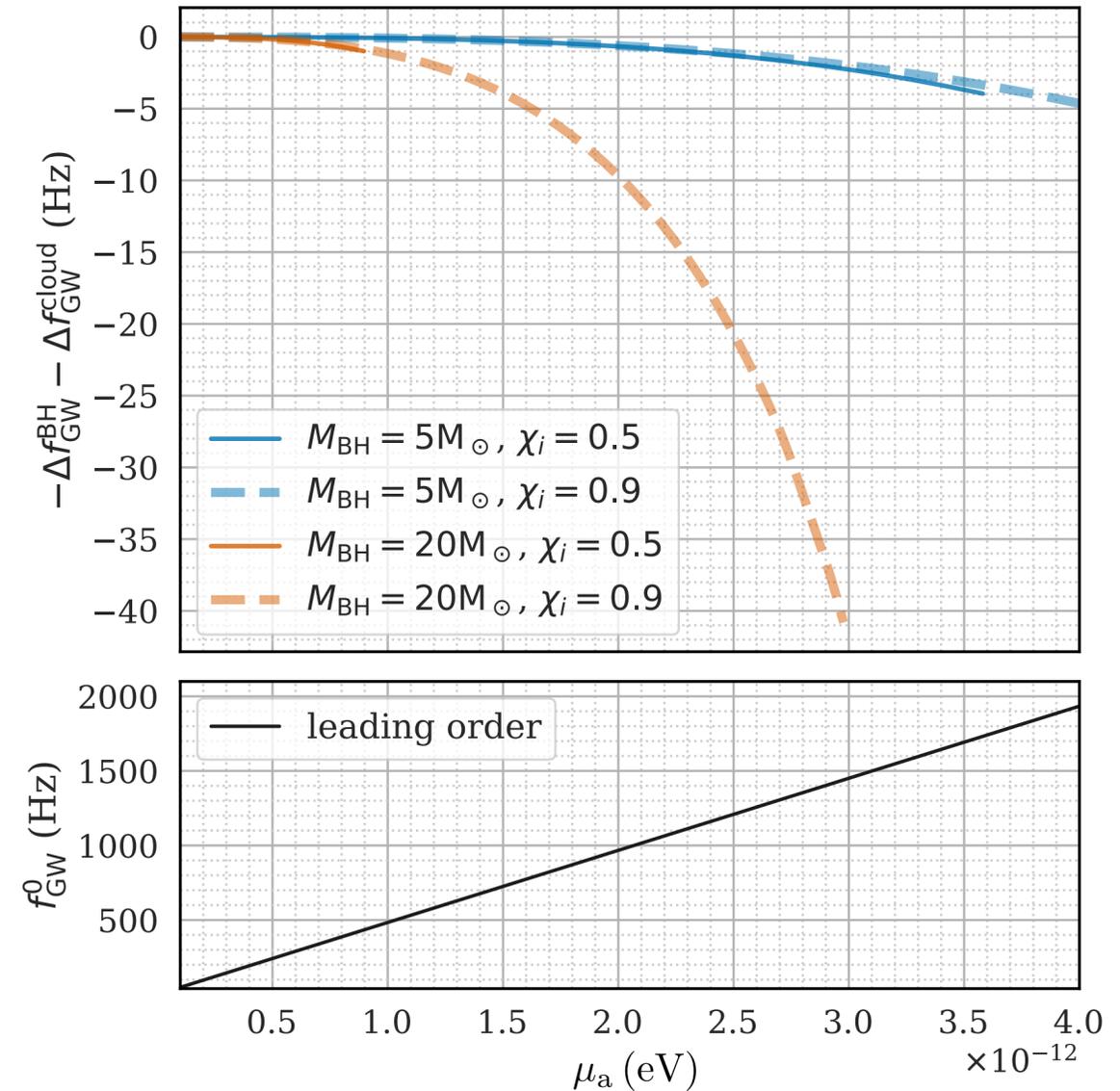
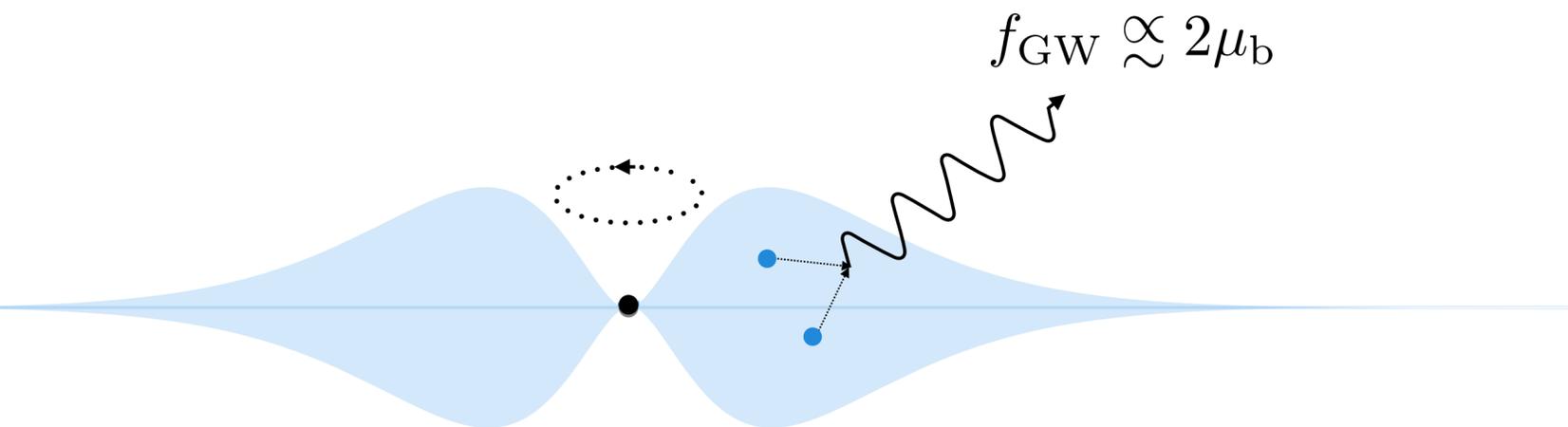
- louder signals, but

$\tau_{\text{GW}} \propto \alpha^{-15}$

- shorter signal timescales

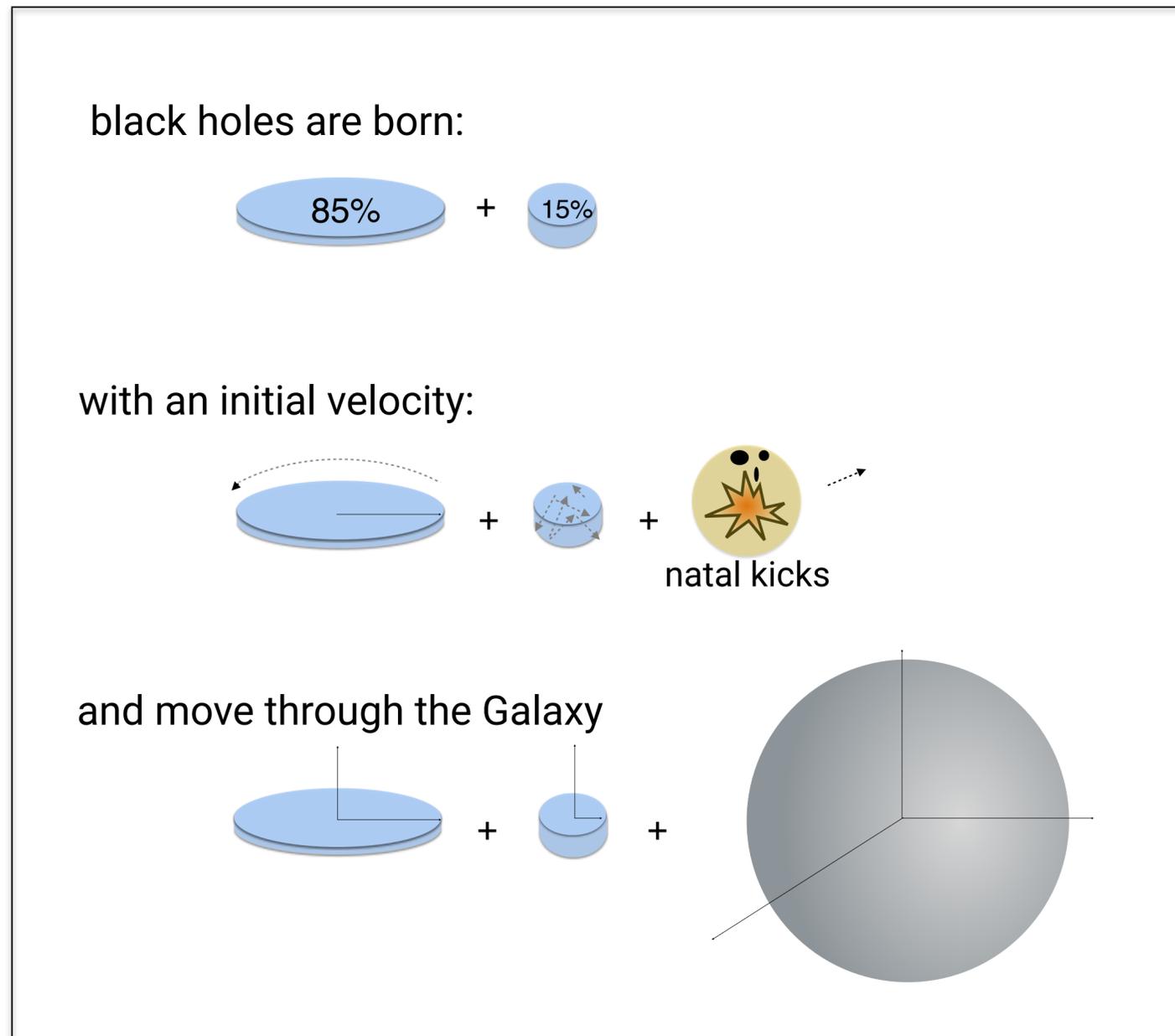
$\chi_c \approx \frac{4\alpha}{1 + 4\alpha^2}$

- requires faster spinning BHs



# Simulate $10^8$ isolated black holes in the Galaxy

galaxy = disk + bulge + halo



[Tsunaga, Kawanaka, and Totani, MNRAS 477 (2018)]

mass: power-law distribution

$$M_{\text{BH}} \in [5M_{\odot}, 20M_{\odot}]$$

$$M_{\text{BH}} \in [5M_{\odot}, 30M_{\odot}]$$

spin: uniform distribution

$$\chi_i \in [0, 1]$$

“optimistic”

$$\chi_i \in [0, 0.5]$$

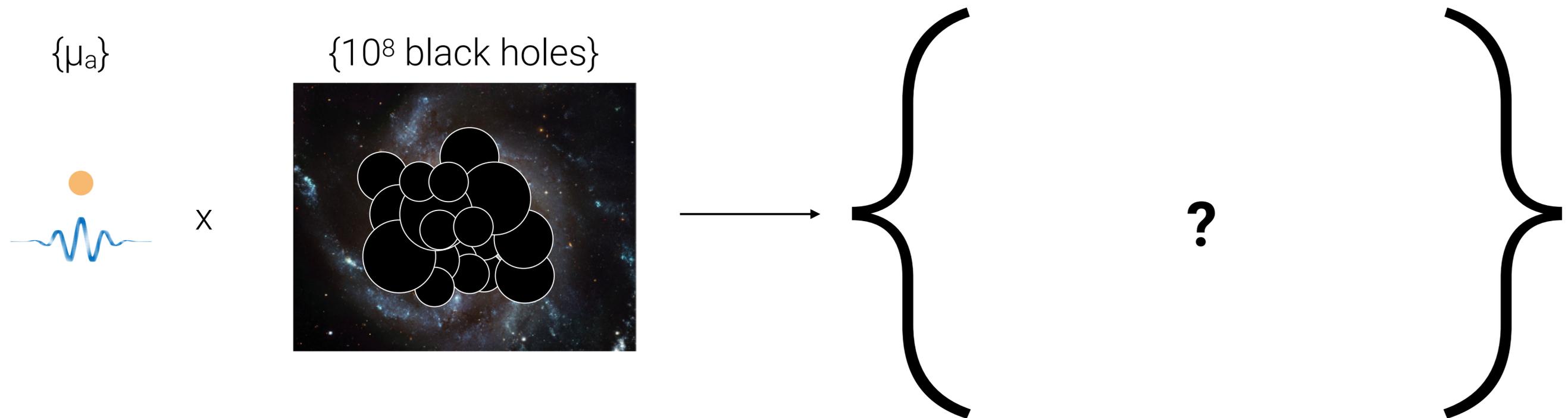
“moderate”

$$\chi_i \in [0, 0.3]$$

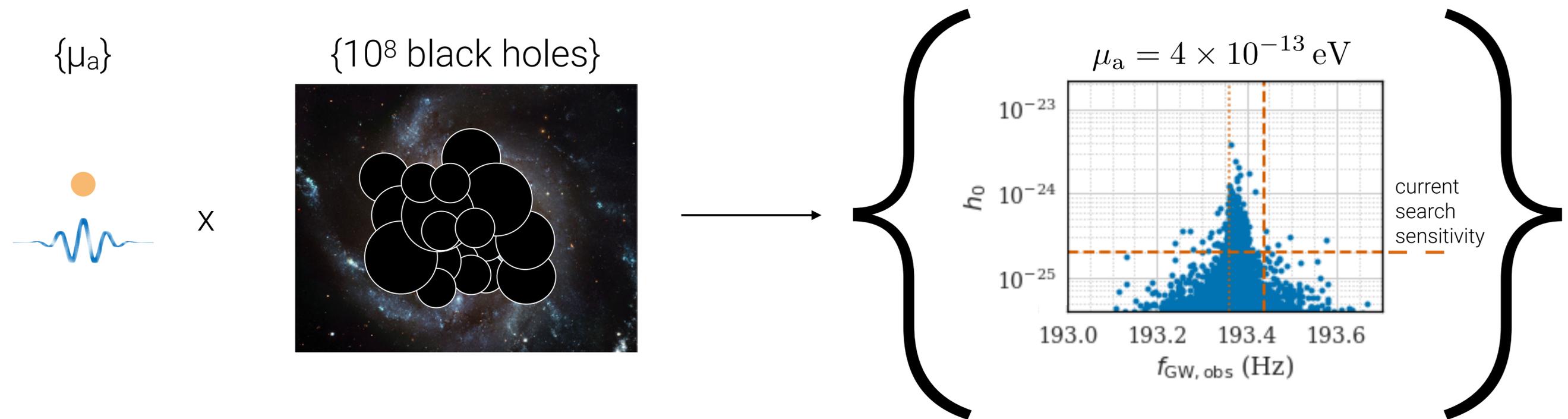
“pessimistic”

# Calculate the signal from every black hole

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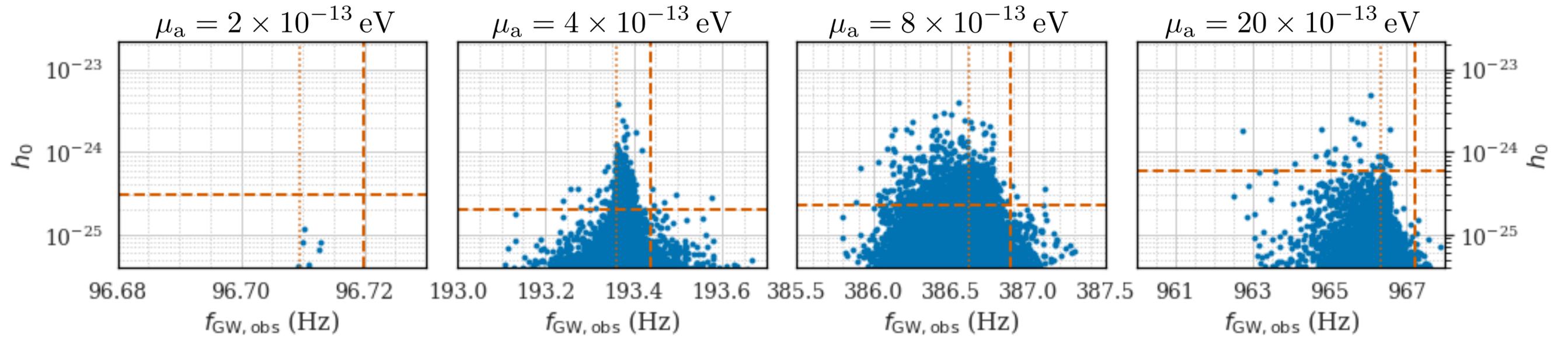


# Calculate the signal from every black hole

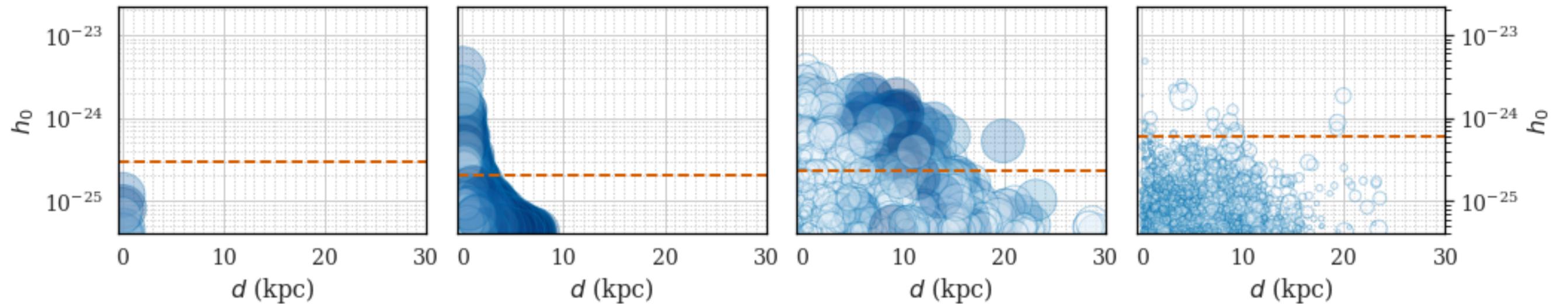


# What do the ensemble signals look like?

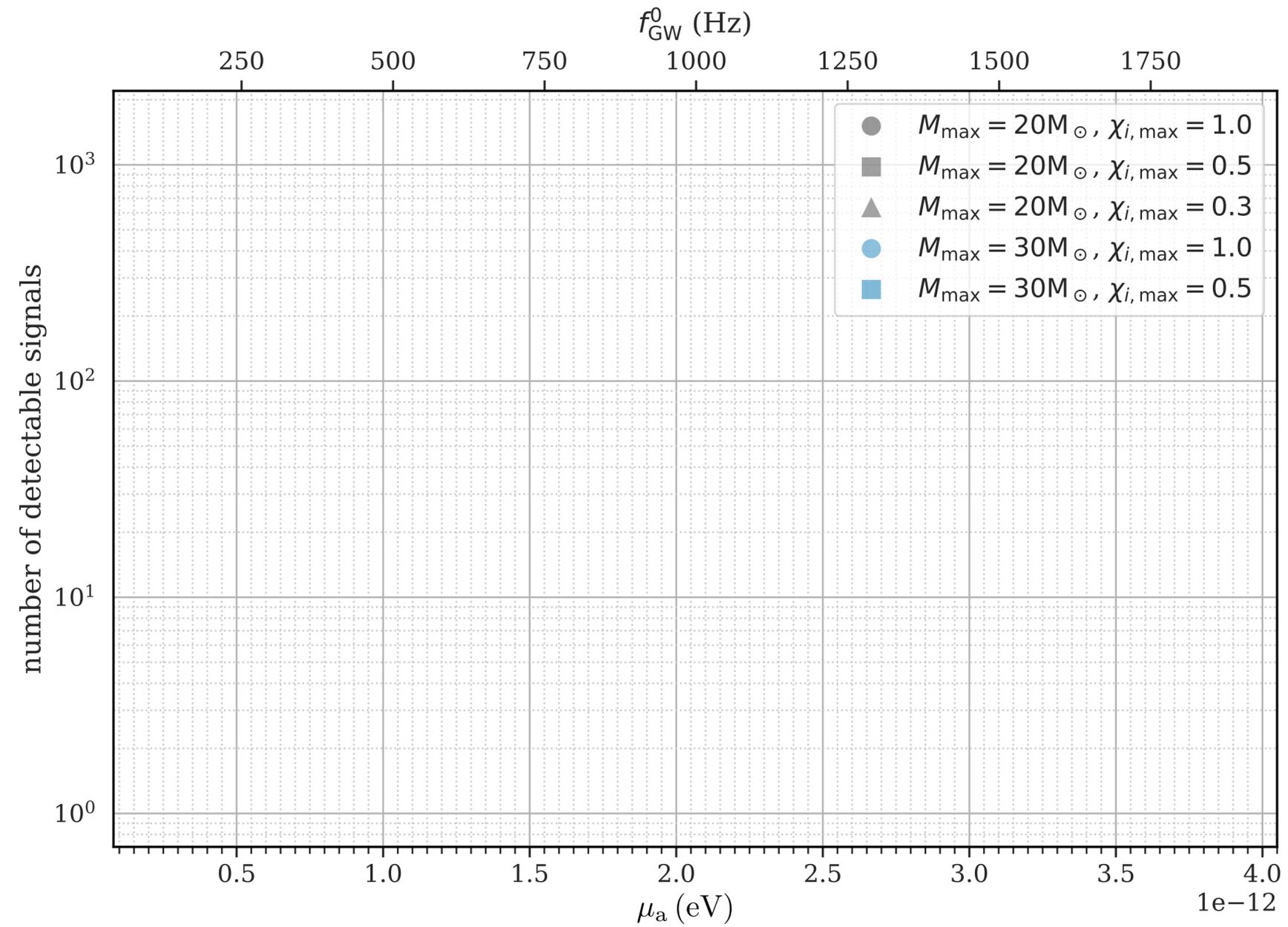
gravitational-wave signals:



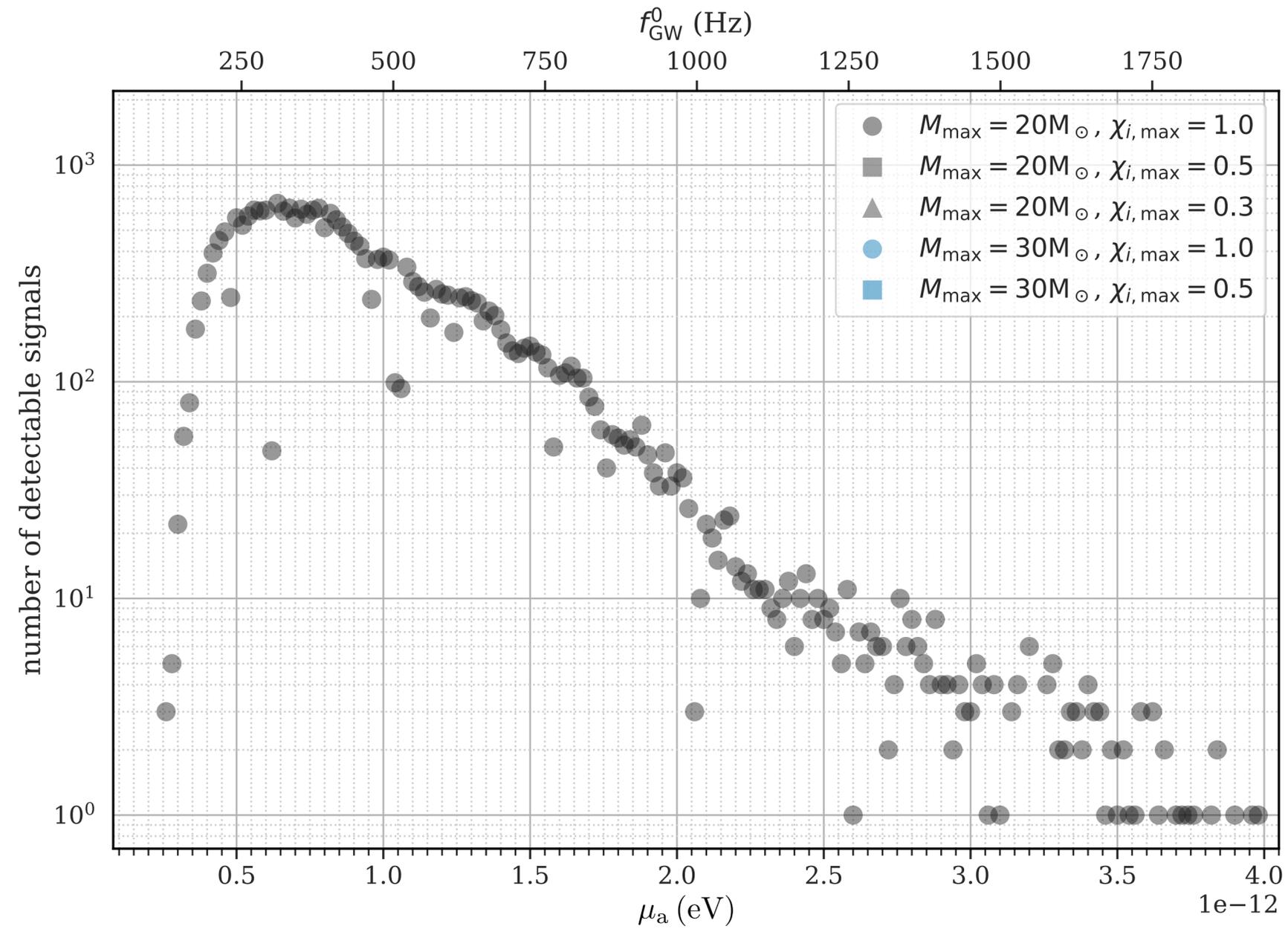
black hole properties:



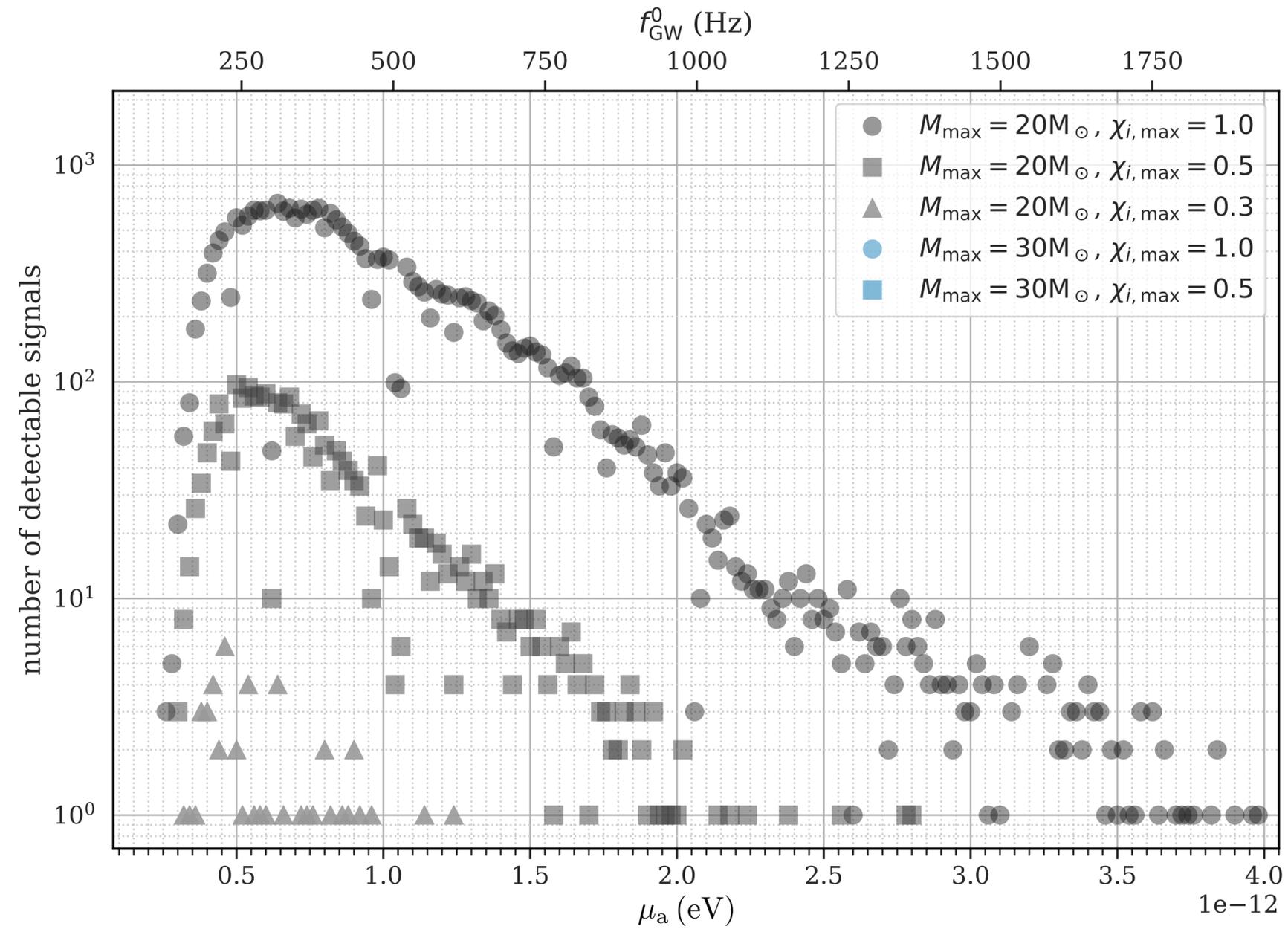
# What are the current detection prospects?



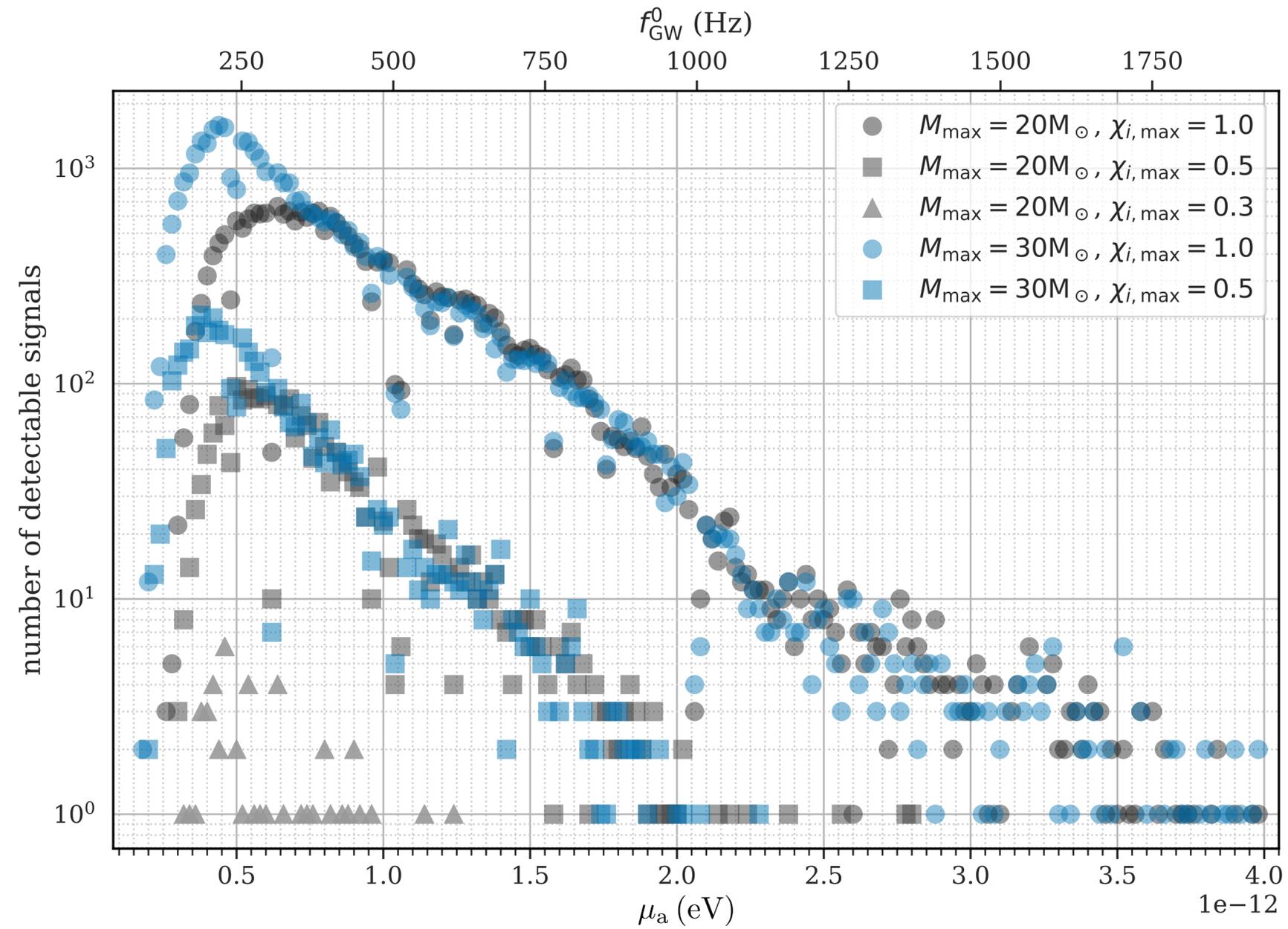
# What are the current detection prospects?



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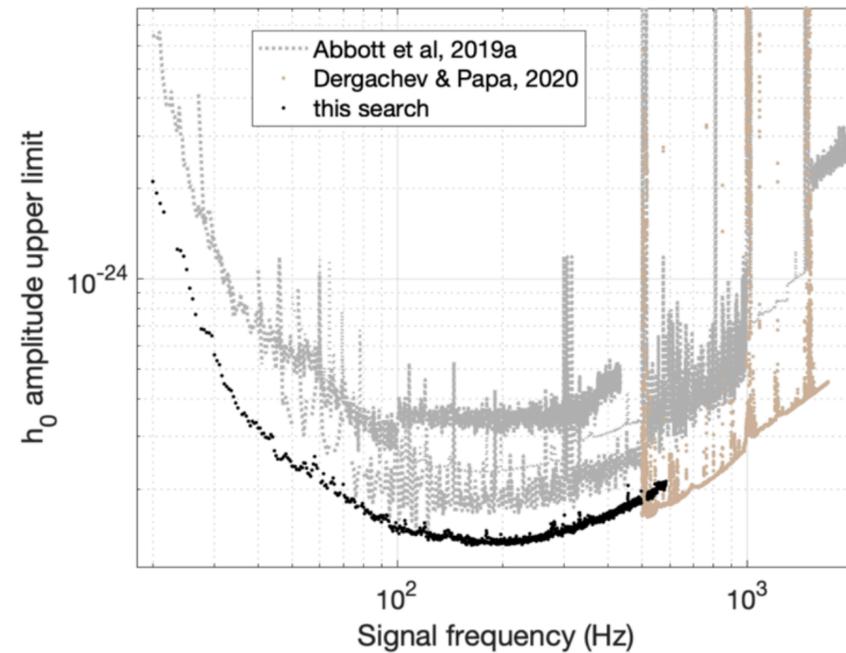
# What are the current detection prospects?



# Interpreting null results for boson clouds

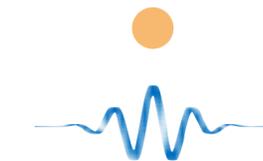
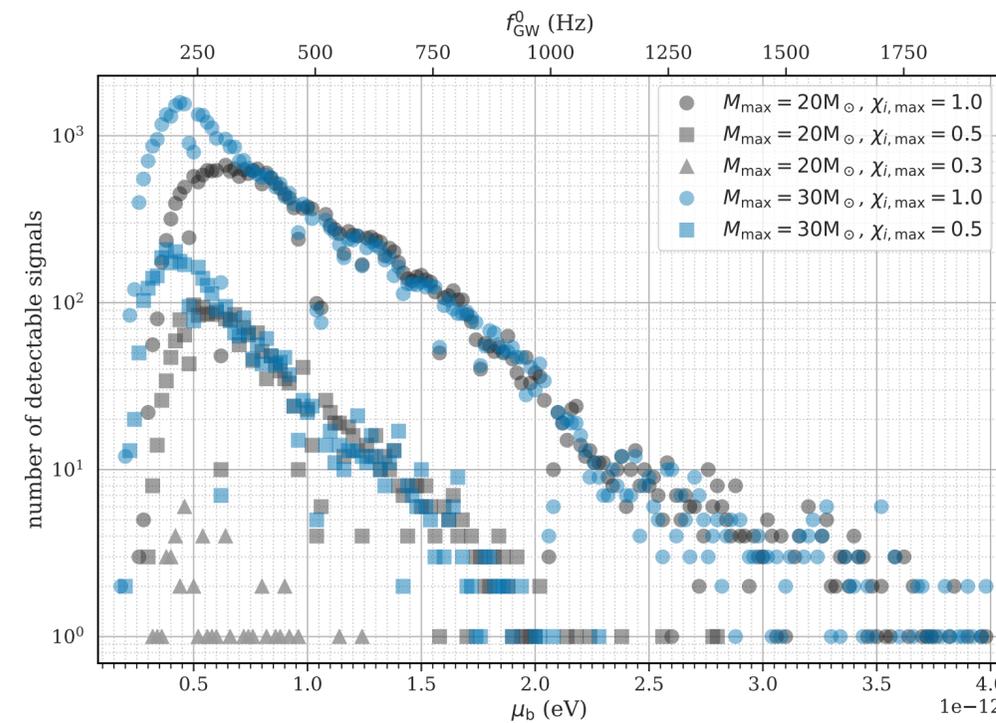
We now have a framework for robustly defining boson mass exclusion/disfavorment (??) regions

continuous gravitational-wave search sensitivities



range of disfavored boson masses

expectations on number of detectable signals



# Thanks

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[PRD 102, 063020](#)

<https://www.aei.mpg.de/continuouswaves/arxiv200303359>

# extra slides

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# Recent searches using GWs

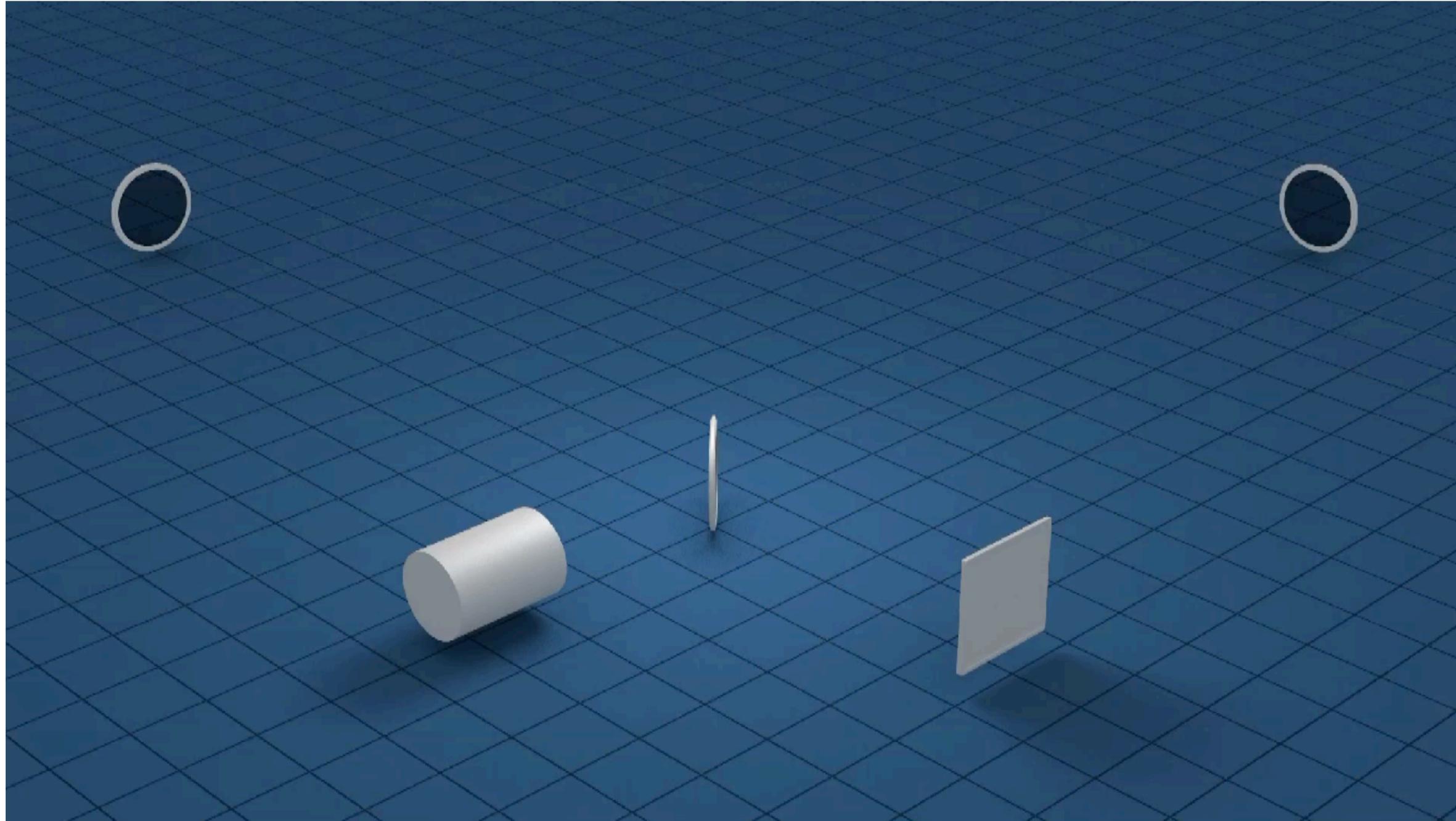
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Some recent searches (non exhaustive list!!)

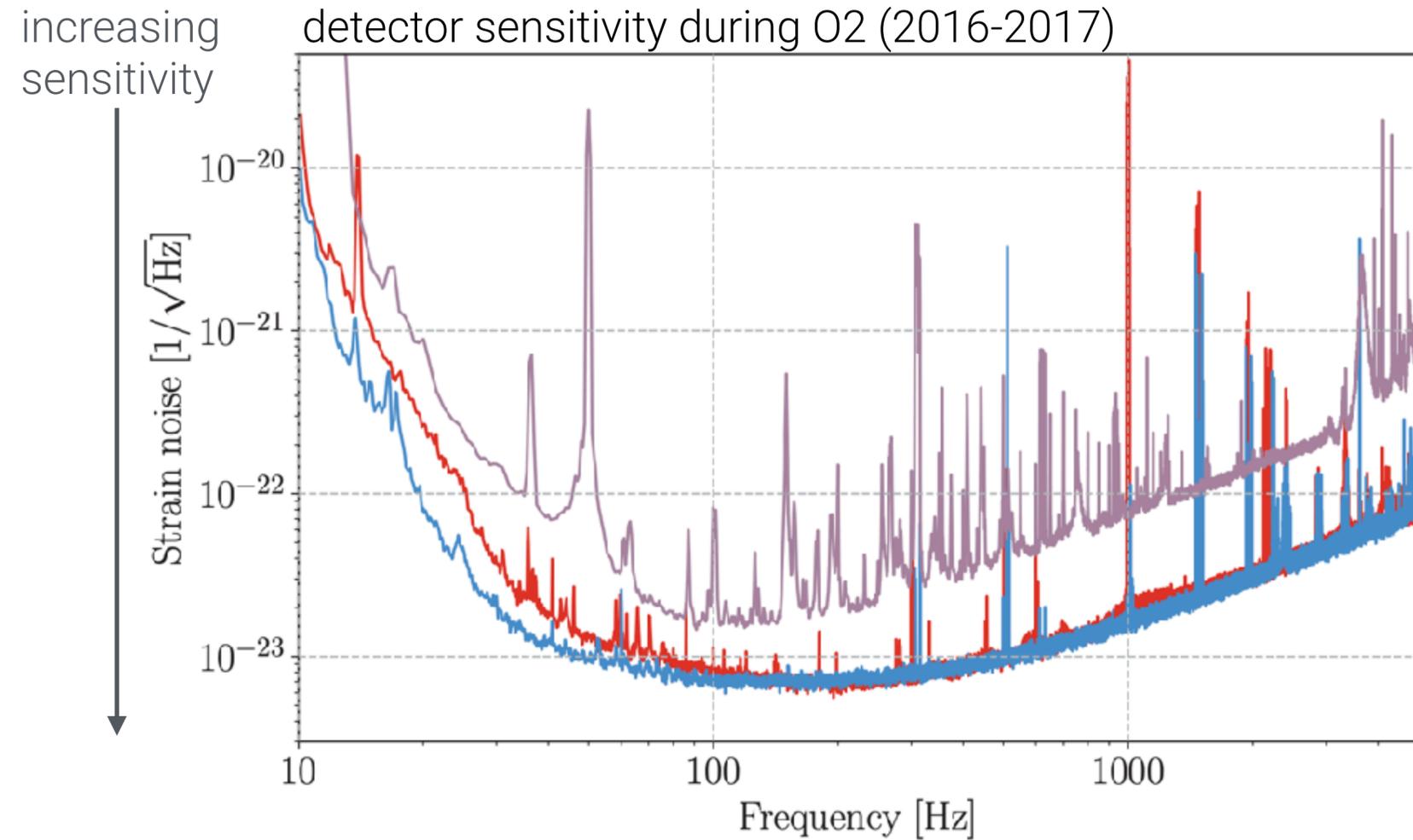
- Directed search for signal from a single BH: [Isi et al., PRD 99 \(2019\)](#); [Ling et al., PRD 101 \(2020\)](#)
- Search for the stochastic background: [Tsukada et al., PRD 99 \(2019\)](#)
- All-sky search: [Palomba, ..., A. Miller, et al., PRL 123 \(2019\)](#)
- Indirect constraints from spinning black holes: [Ng et al., arXiv:1908.02312](#)

# Gravitational-wave interferometers

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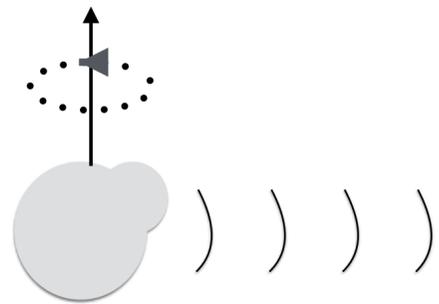


# Gravitational-wave interferometers

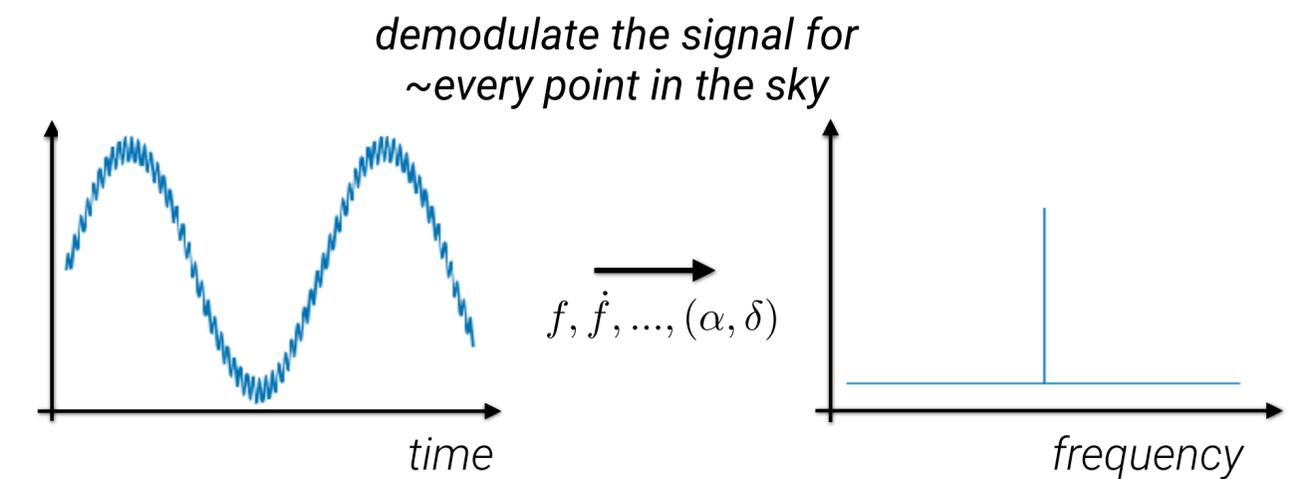
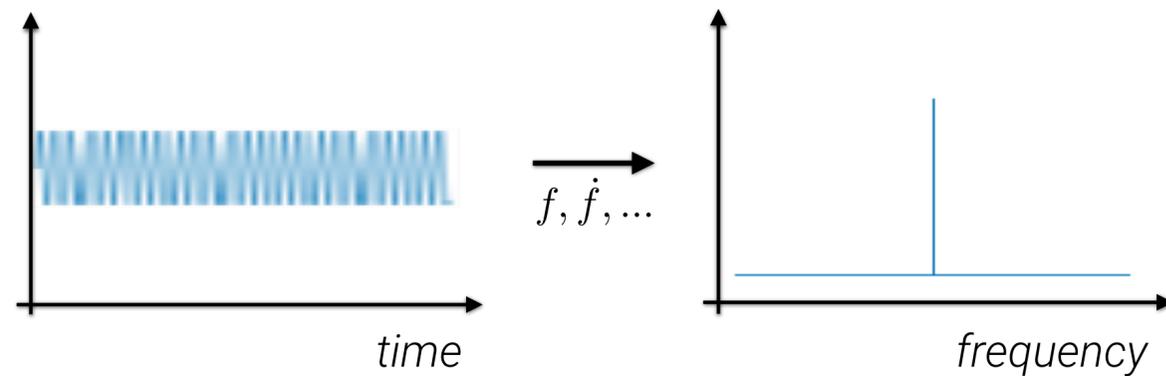
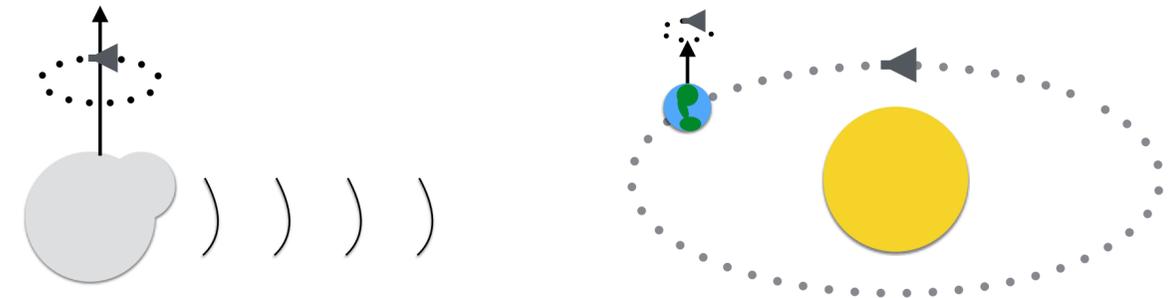


# Searching for continuous gravitational waves

the waveform at the **source**:

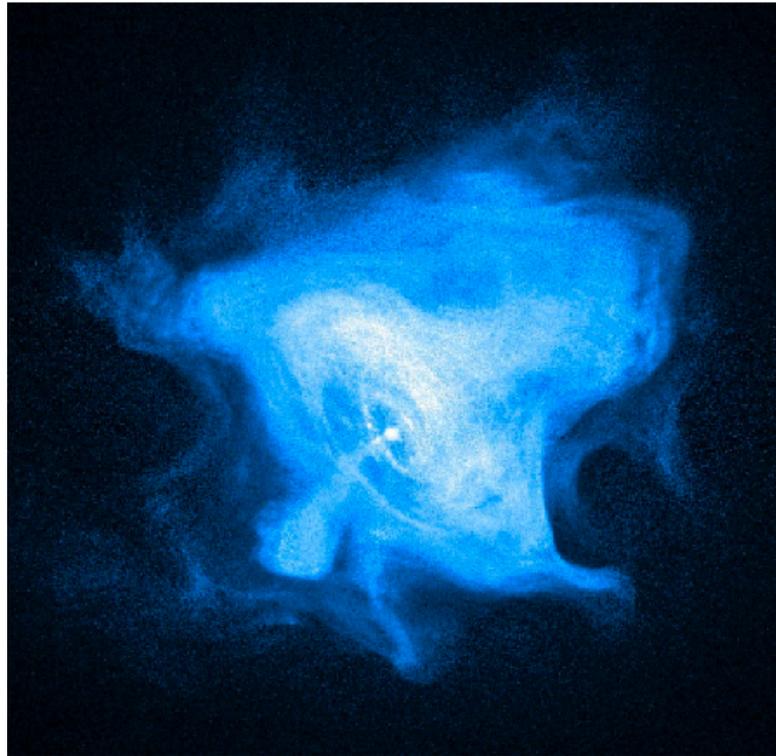


the waveform at the **detector**:

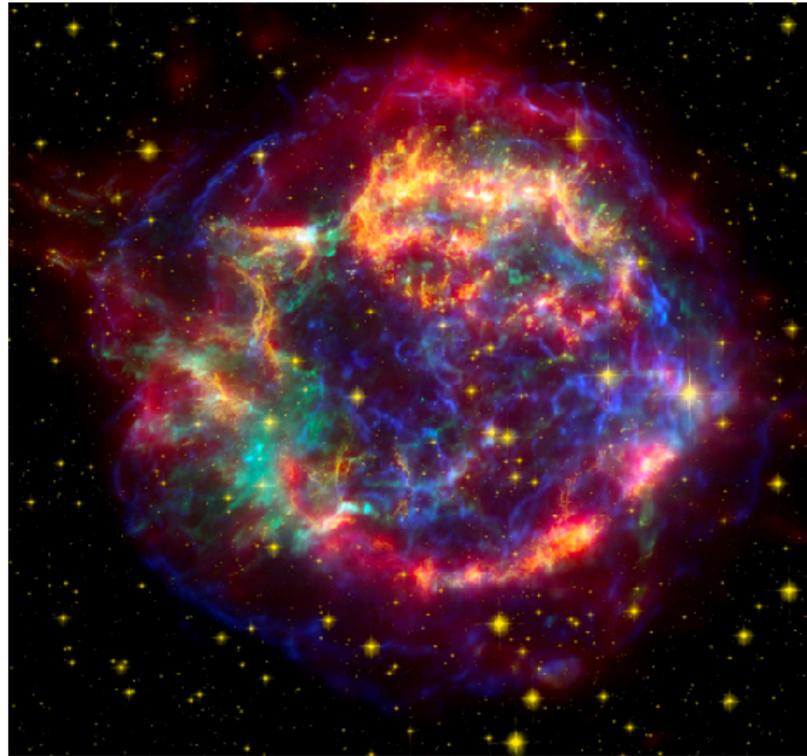


# Types of searches

targeted search  
**known pulsars**

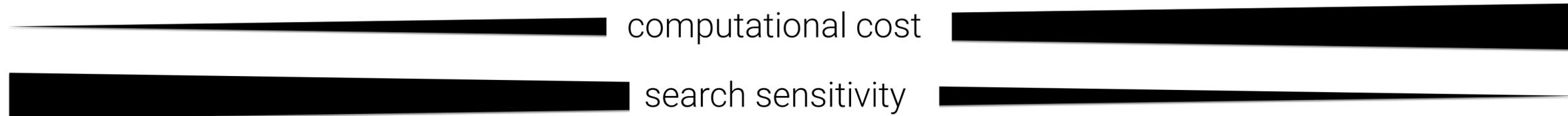


directed search  
**known neutron stars**



all-sky search  
**minimal assumptions**

~(ツ)~



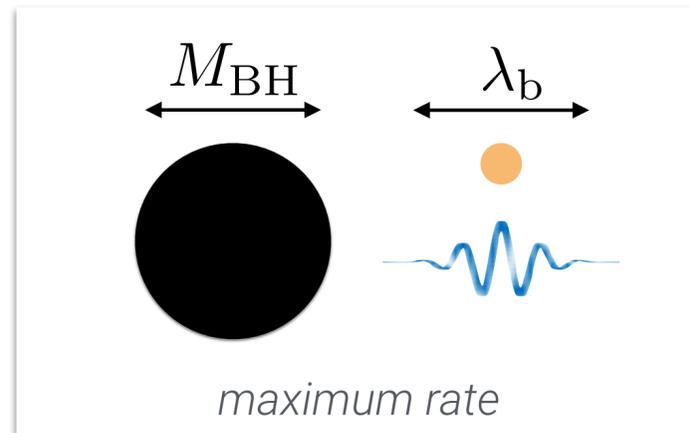
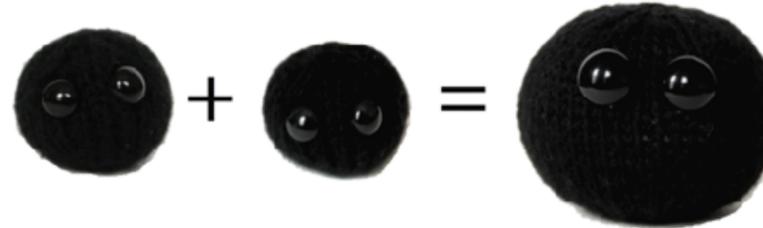
# Types of searches

targeted search  
**known black hole**  
+  
**known boson mass**



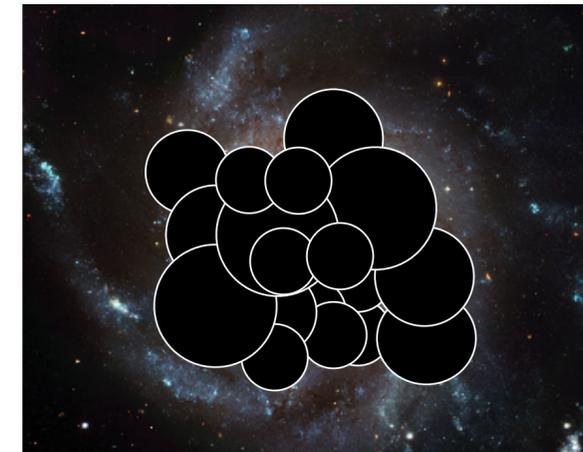
directed search  
**known black hole**  
+  
**unknown boson mass**

e.g., [Isi et al., PRD 99 \(2019\)](#)



all-sky search  
**minimal assumptions on**  
**black hole positions or**  
**boson mass**

e.g., [Palomba et al., PRL 123 \(2019\)](#)



# Gravitational “atom” sources continuous gravitational waves

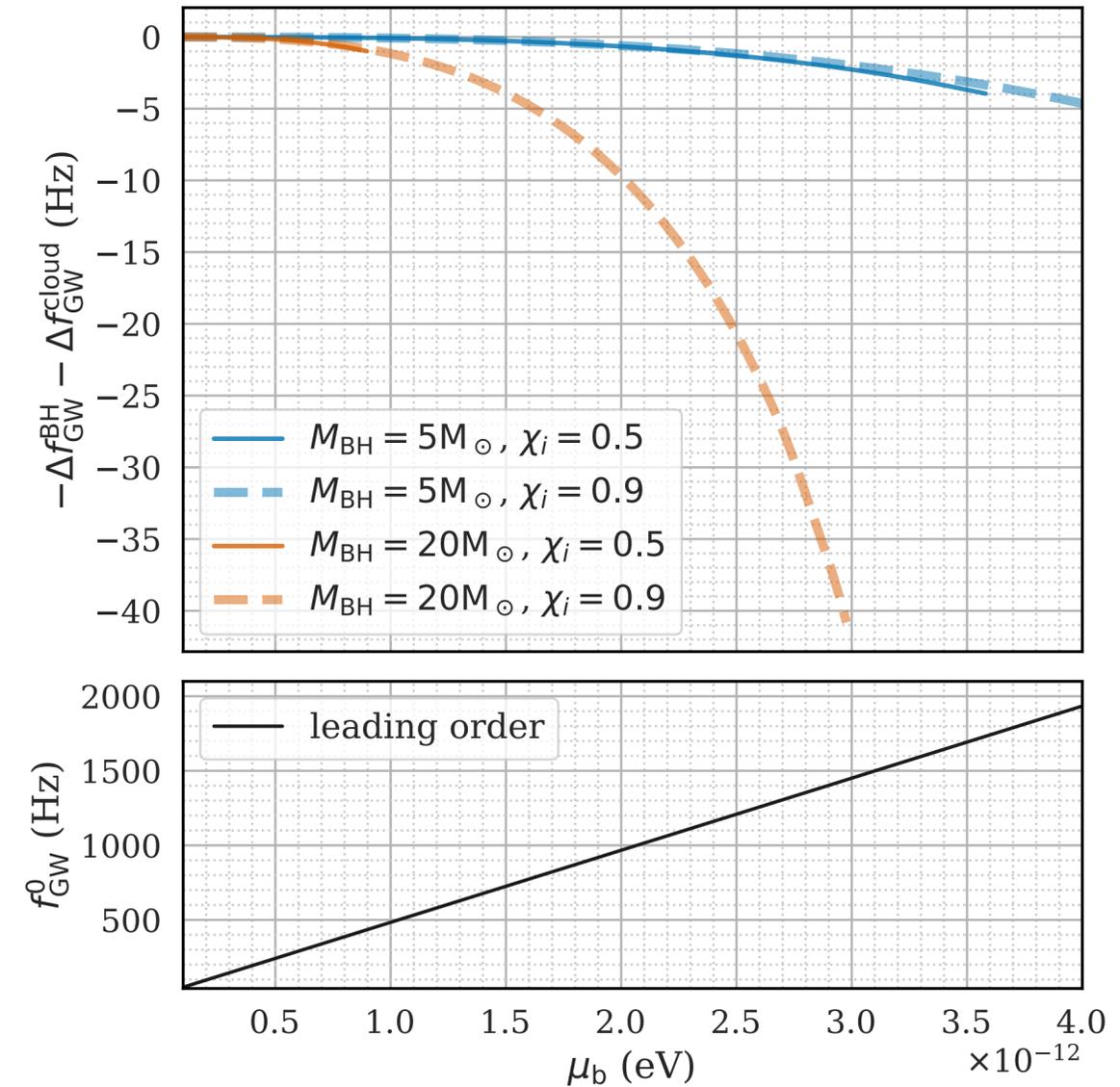
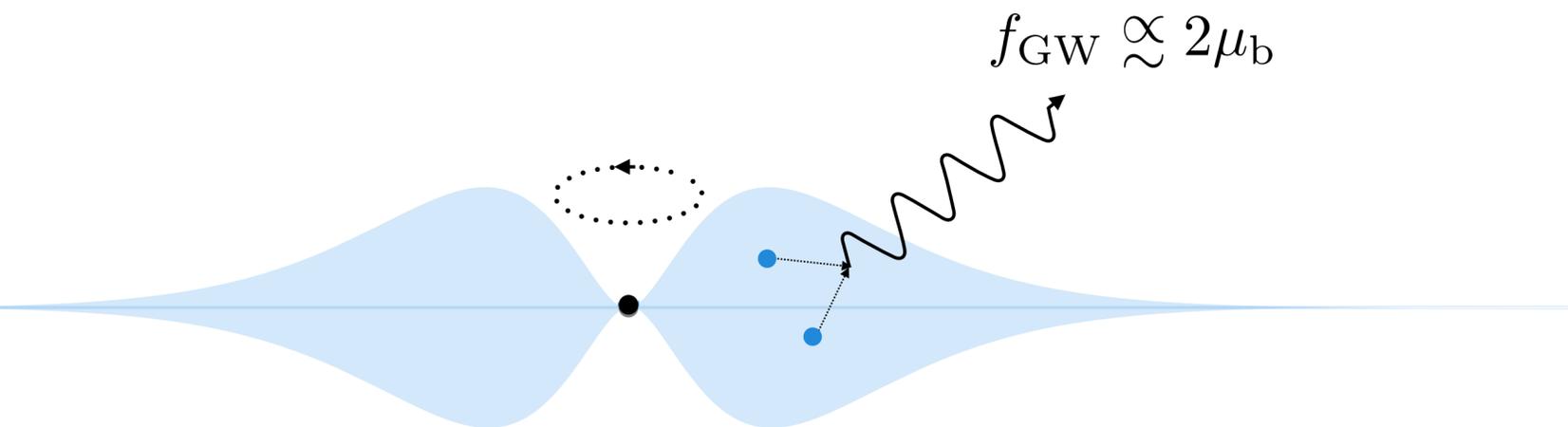
$$\alpha \propto \mu_b M_{\text{BH}}$$

**larger  $\alpha$ :**

(note: spin-0 particles)

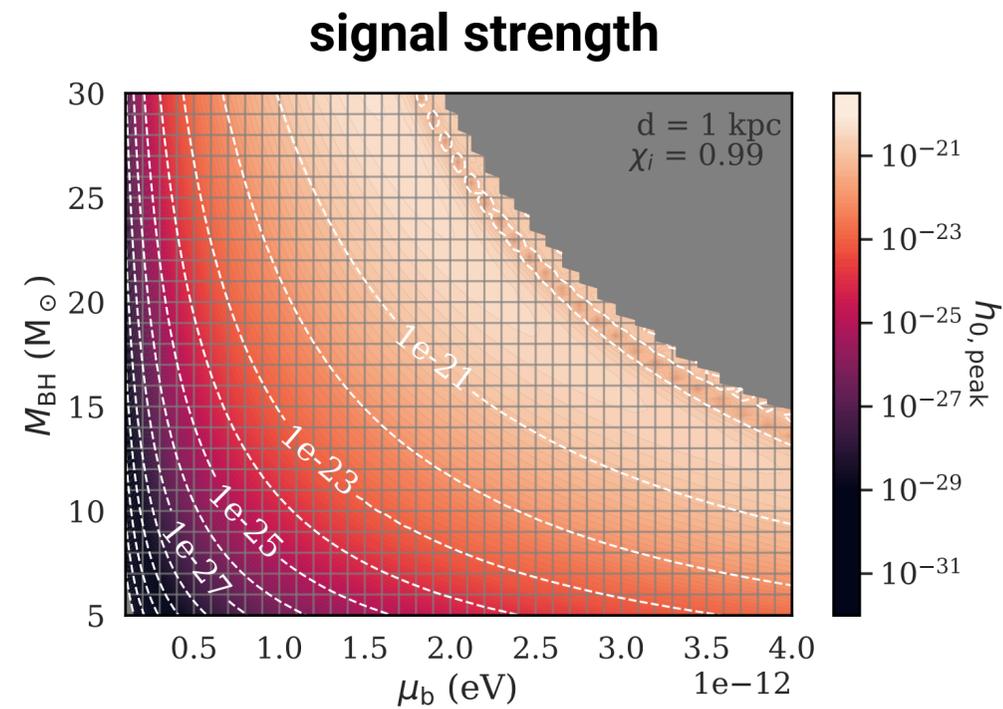
$$h_{0,\text{peak}} \propto \alpha^7$$

- louder signals



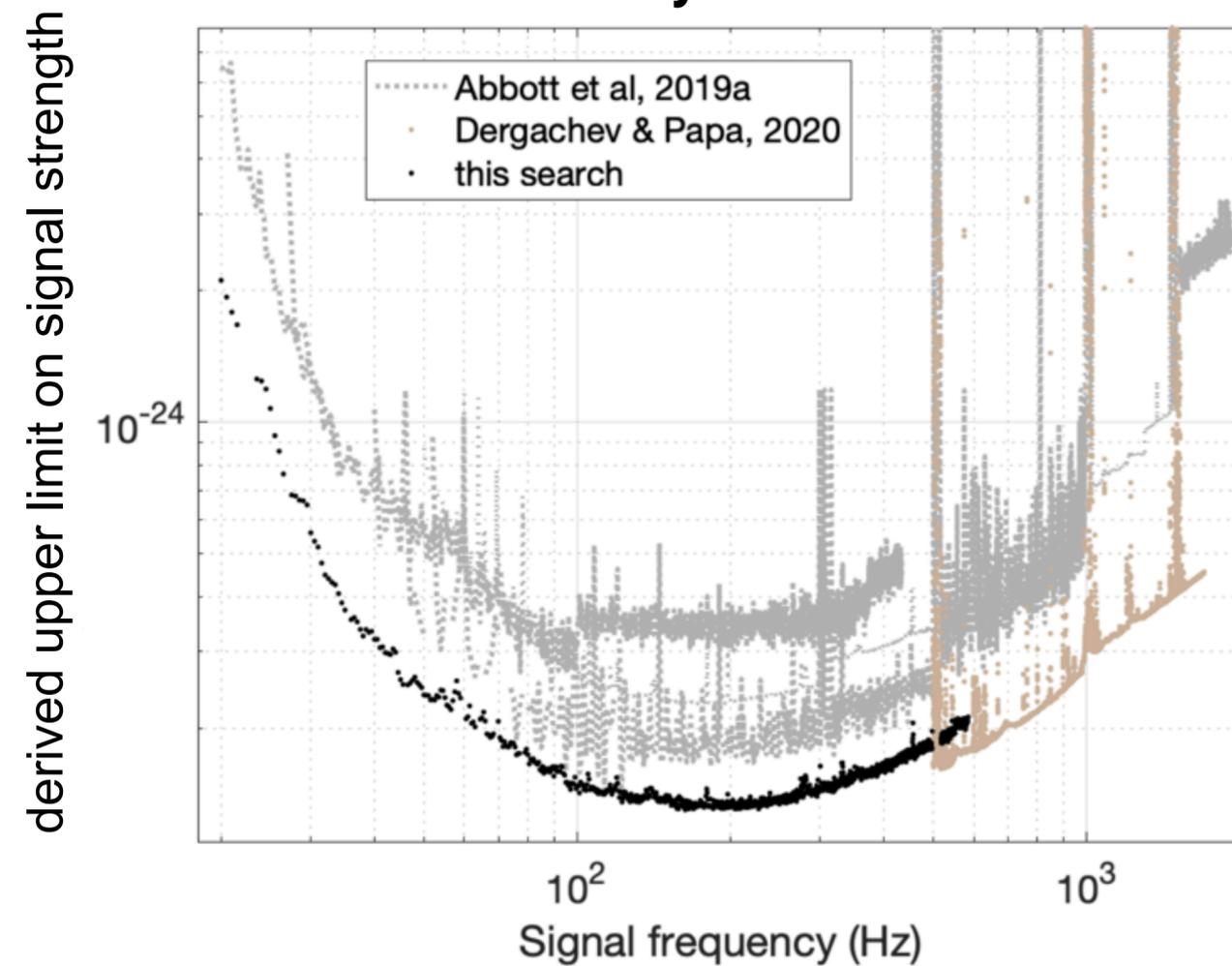
# What kind of signals do we expect?

$\alpha \propto \mu_b M_{\text{BH}}$  determines most of the signal properties



$$h_{0,\text{peak}} \propto \alpha^7$$

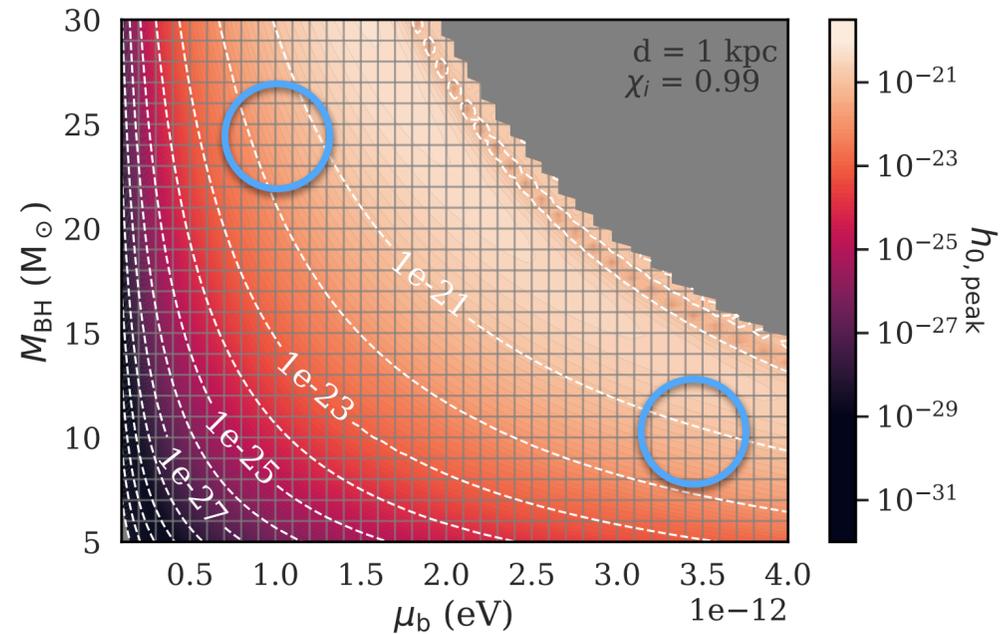
## recent all-sky search results



# What kind of signals do we expect?

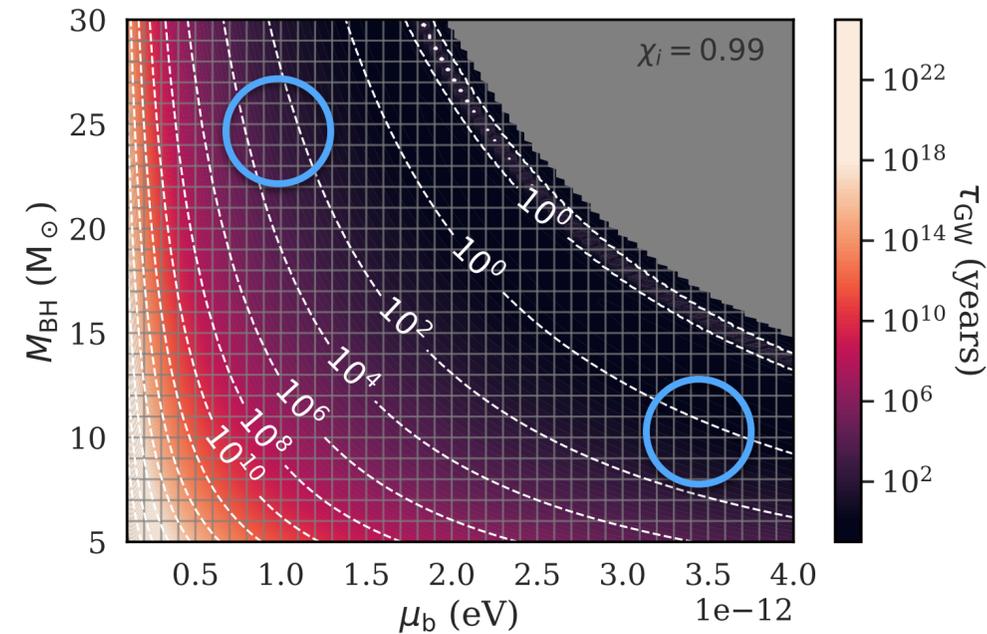
$\alpha \propto \mu_b M_{\text{BH}}$  determines most of the signal properties

signal strength



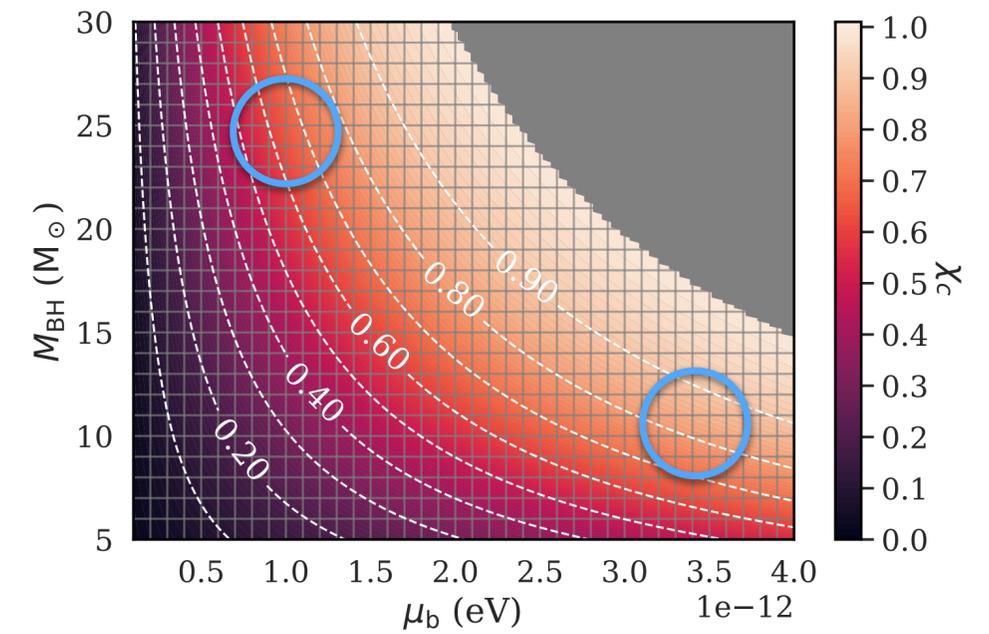
$$h_{0,\text{peak}} \propto \alpha^7$$

signal duration



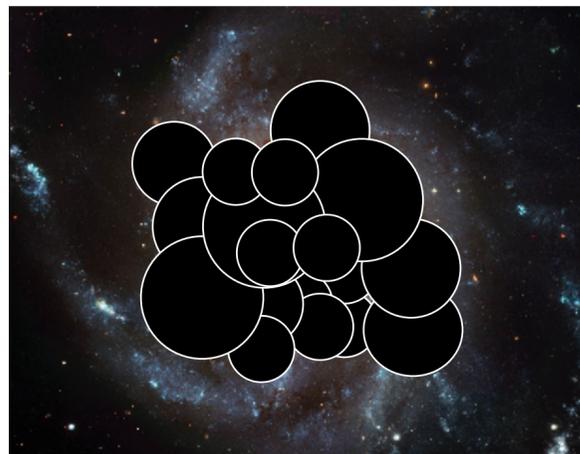
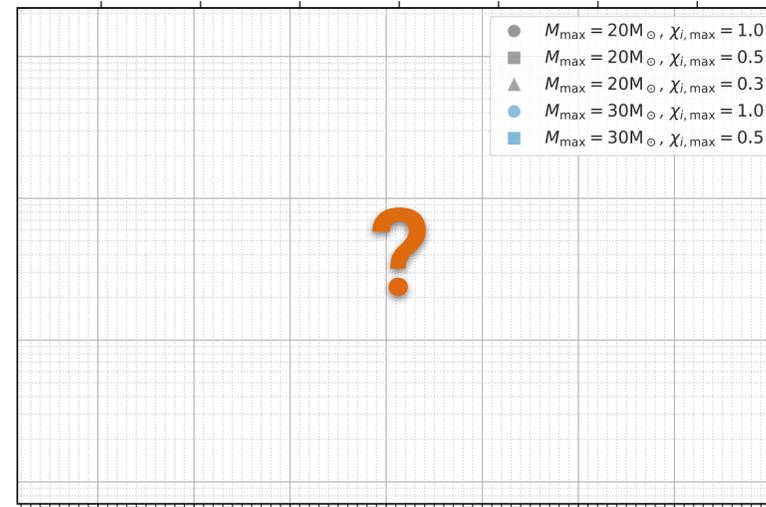
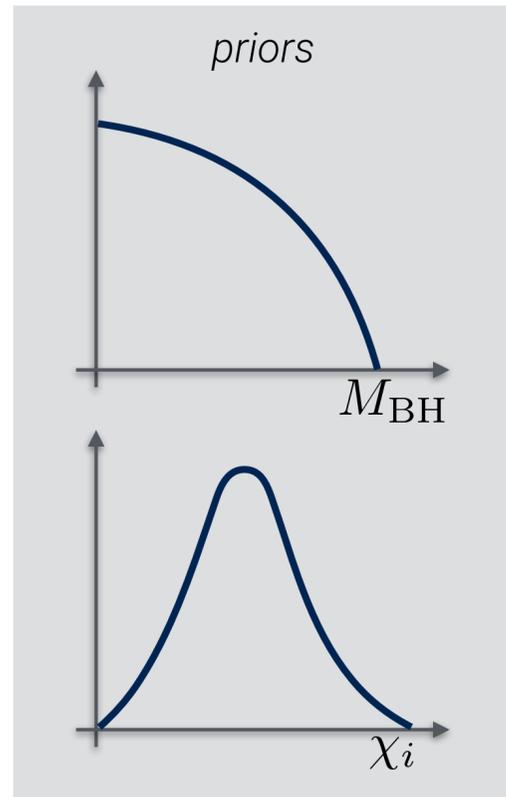
$$\tau_{\text{GW}} \propto \alpha^{-15}$$

whether the system forms

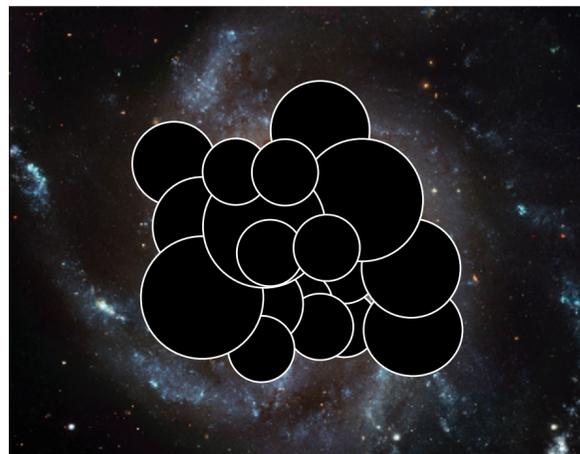
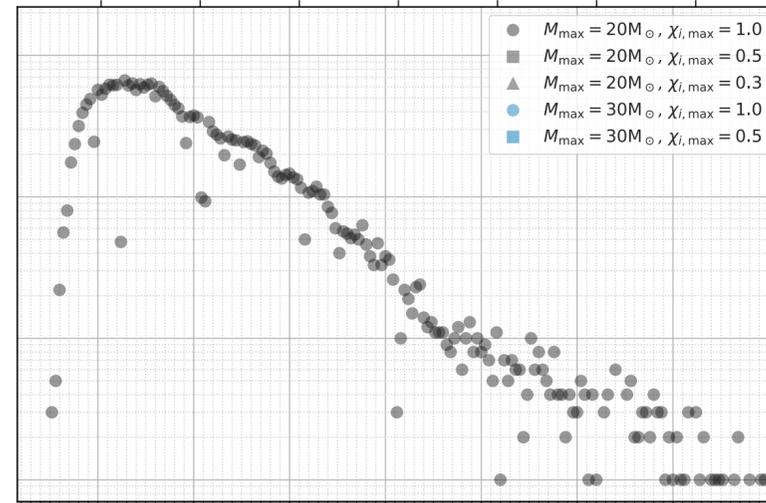
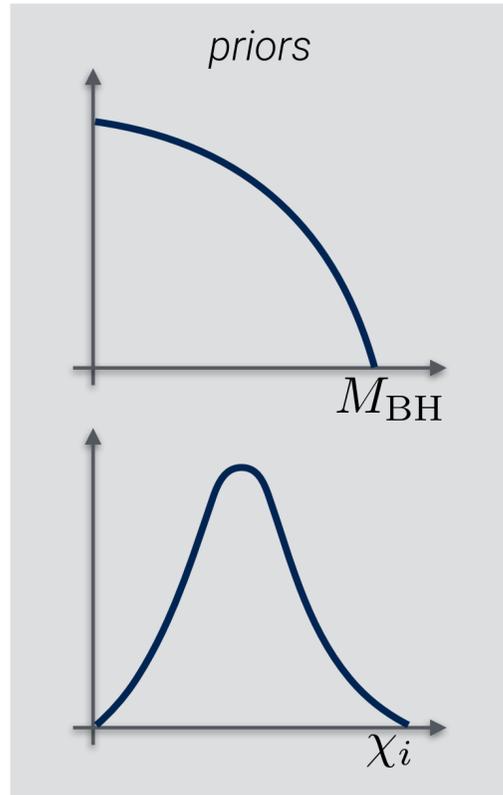


$$\chi_c \approx \frac{4\alpha}{1 + 4\alpha^2}$$

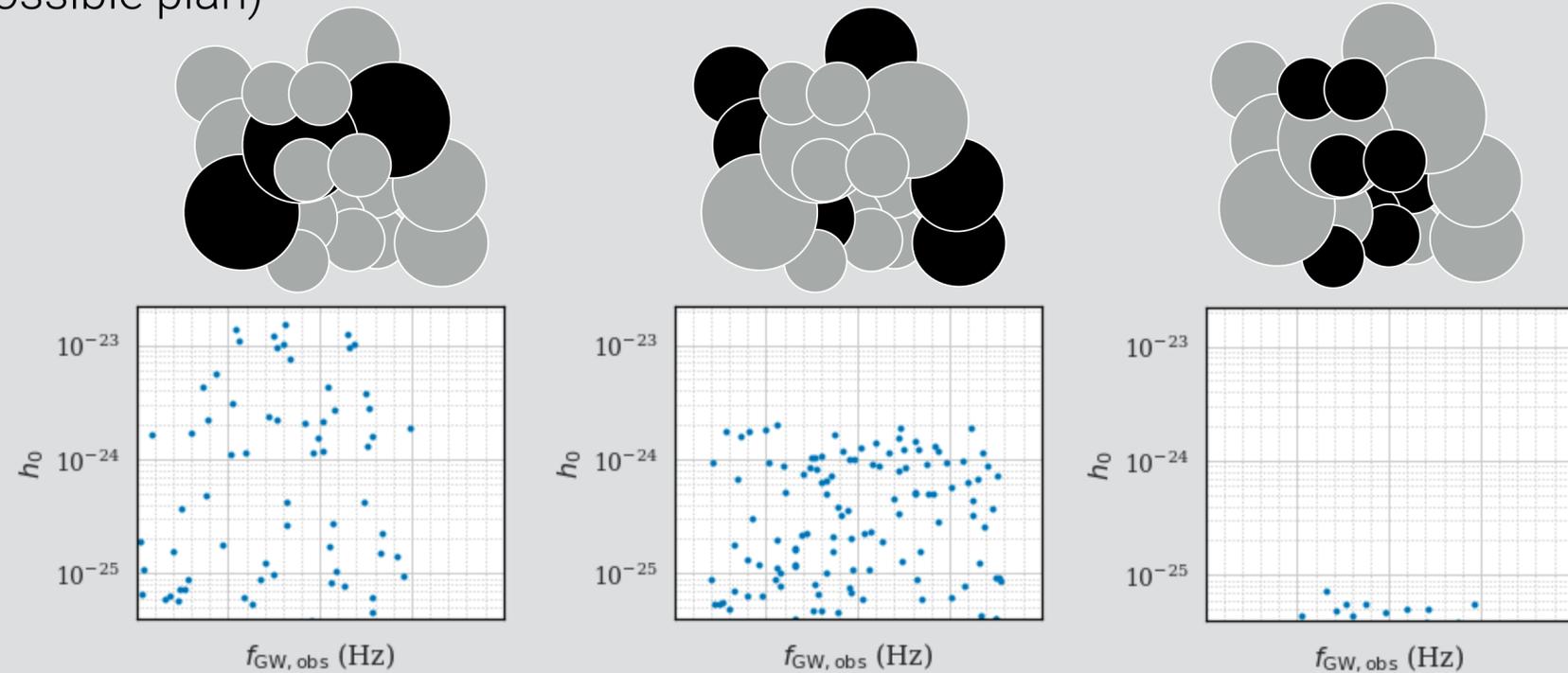
# Interpreting null results (upper limits) – boson clouds (speculating)



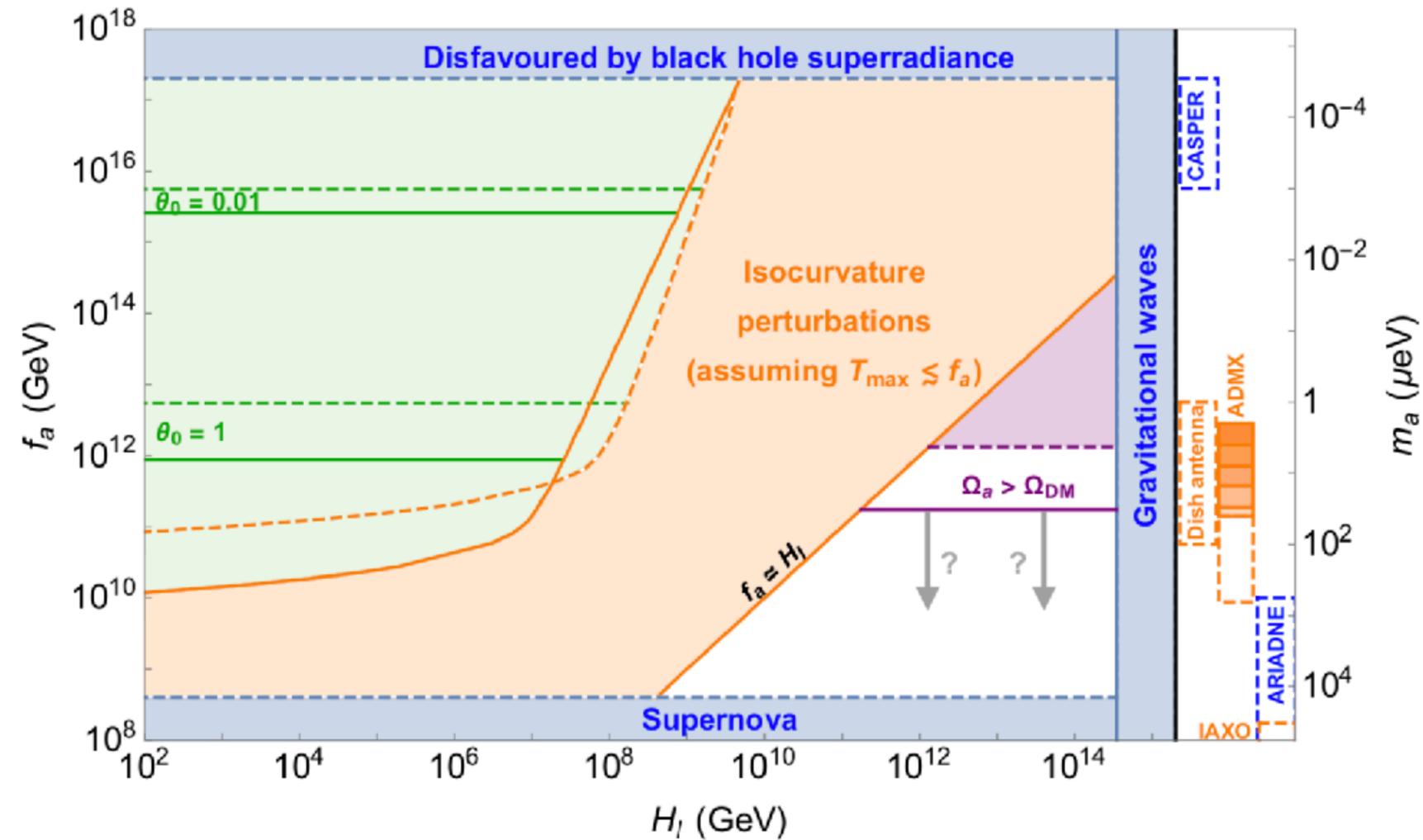
# Interpreting null results (upper limits) – boson clouds (speculating)



(possible plan)



# the QCD axion can take a wide range of masses



# The ensemble signal

2 bosons annihilate -> gravitational waves

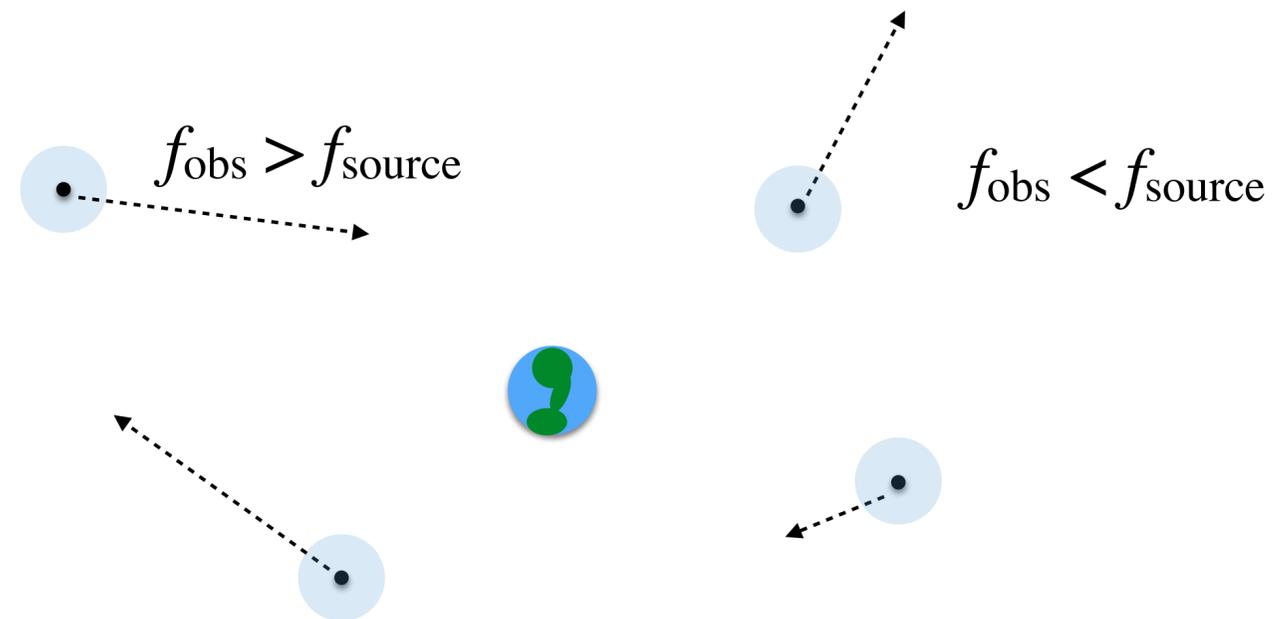
black holes are moving towards or away from us

all\* black holes will have radiating clouds  
(i.e., all black holes with the right properties)

**inherent signal frequency** depends almost entirely on **boson mass**  $f_{\text{source}}$

**observed signal frequency** will be **Doppler shifted** due to this motion  $f_{\text{obs}}$

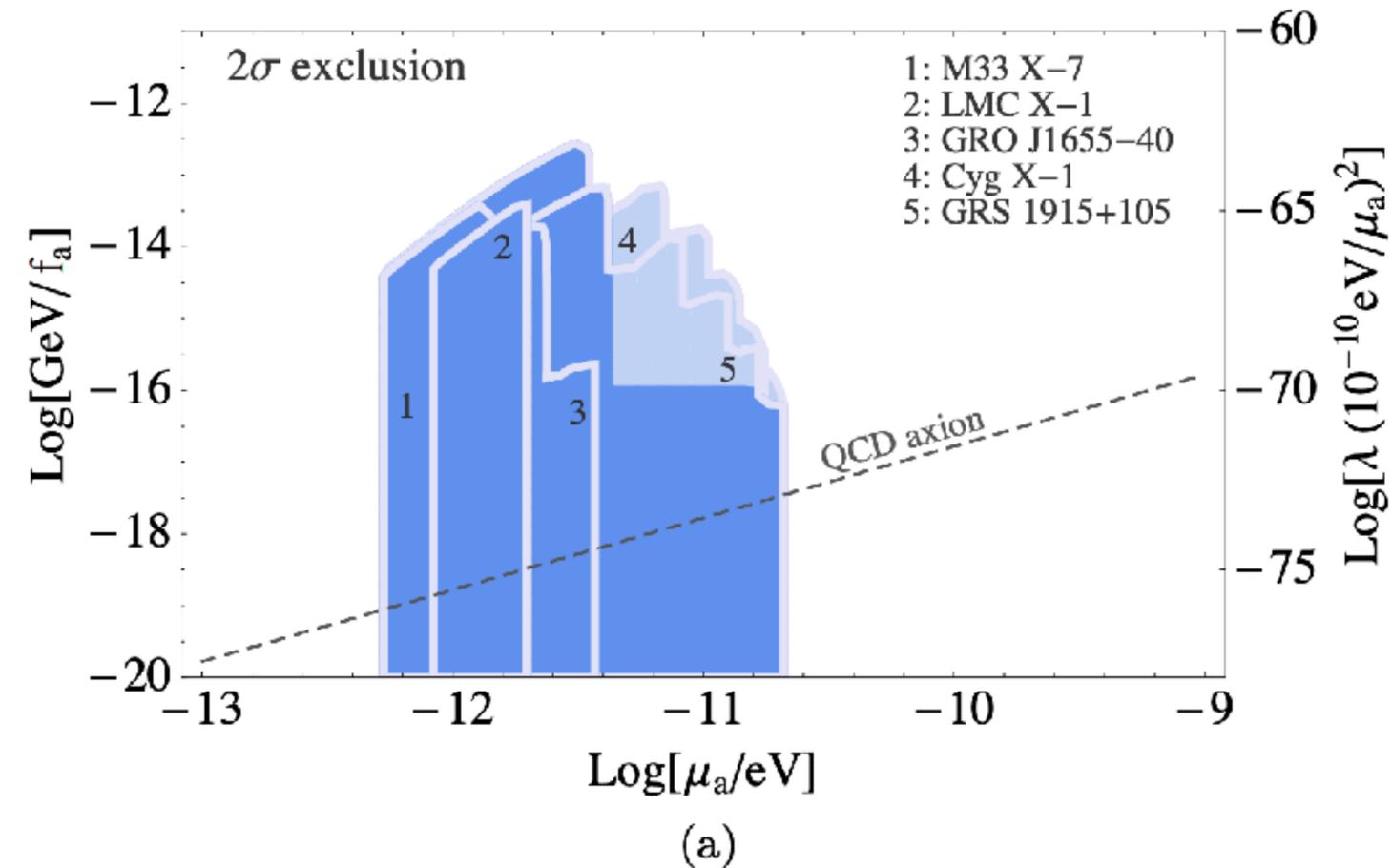
we should be looking for the **ensemble signal** produced by all the boson clouds near us



# Mass and self coupling

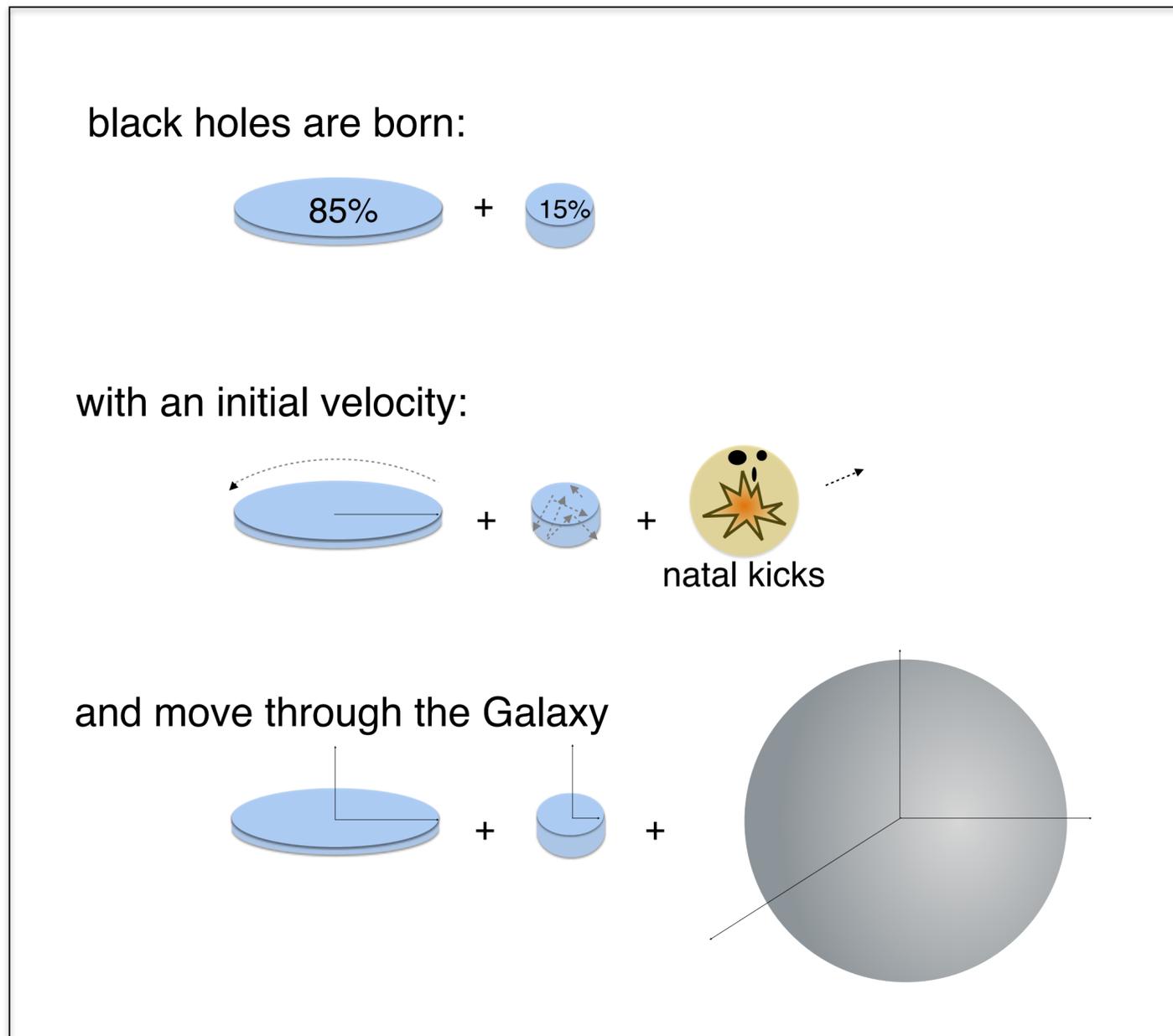
We are interested in particles for which the self coupling is not so strong that cloud collapses as a bosonova.

e.g., the regions here are determined based on observations of spinning black holes

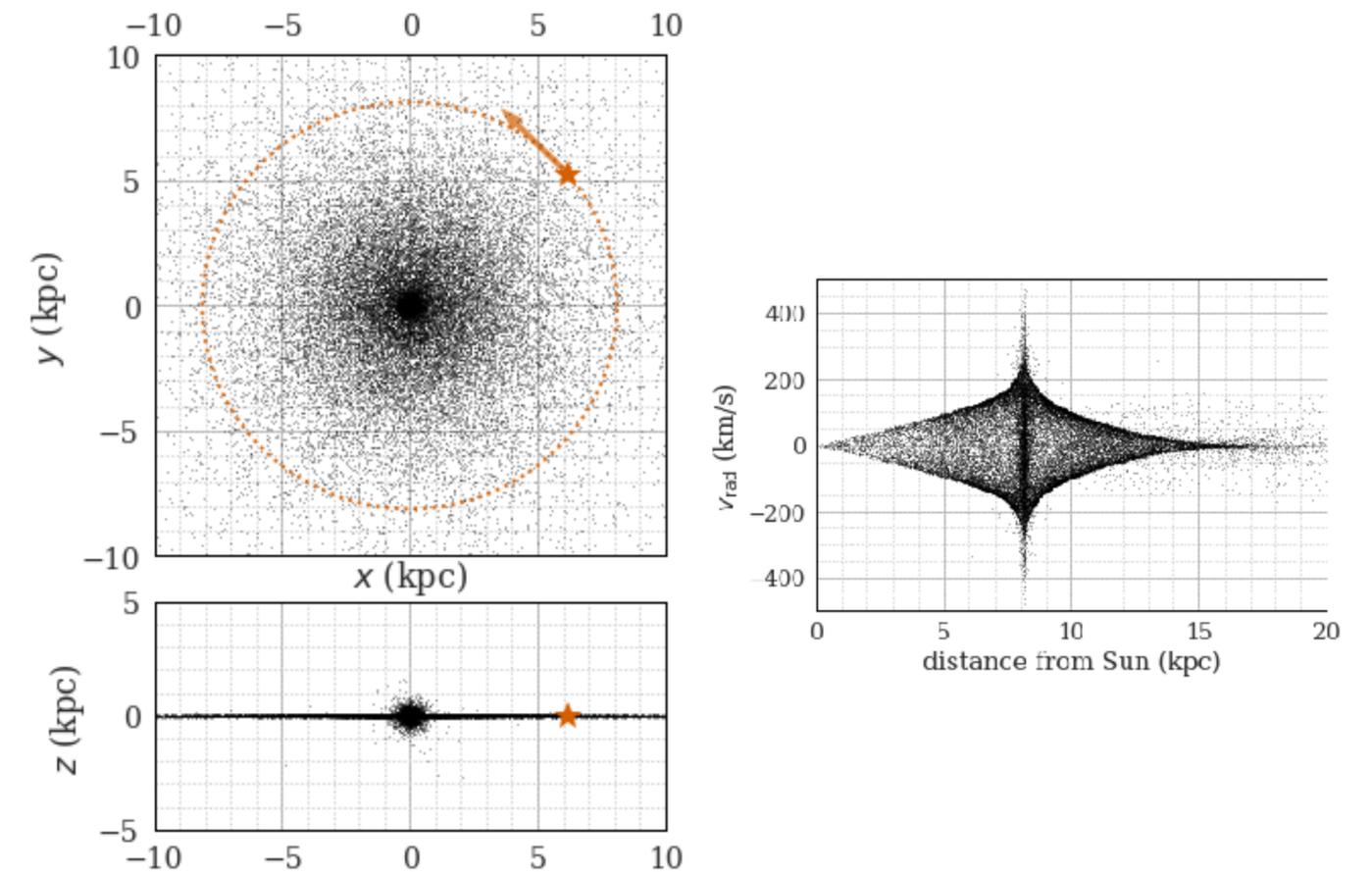


# $10^8$ isolated black holes in the Galaxy

galaxy = disk + bulge + halo (see D. Tsuna et al. 2018)

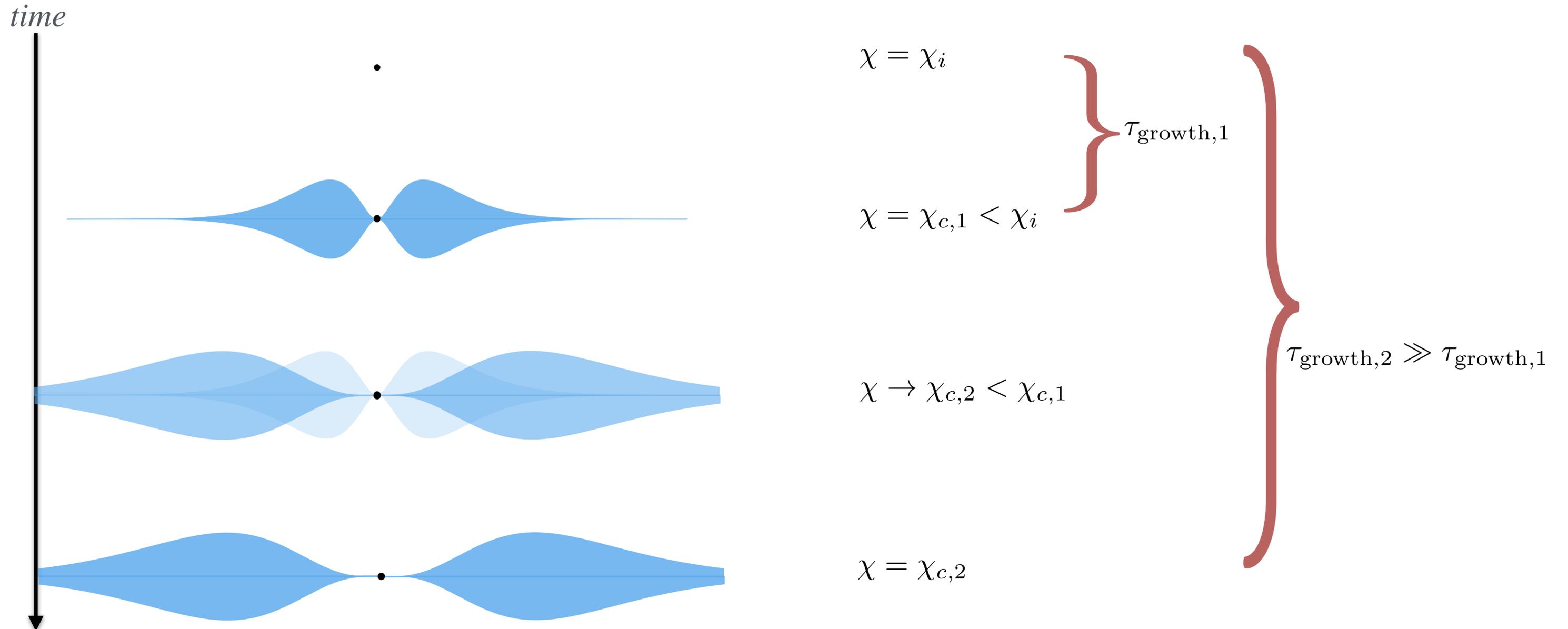


final black hole spatial properties

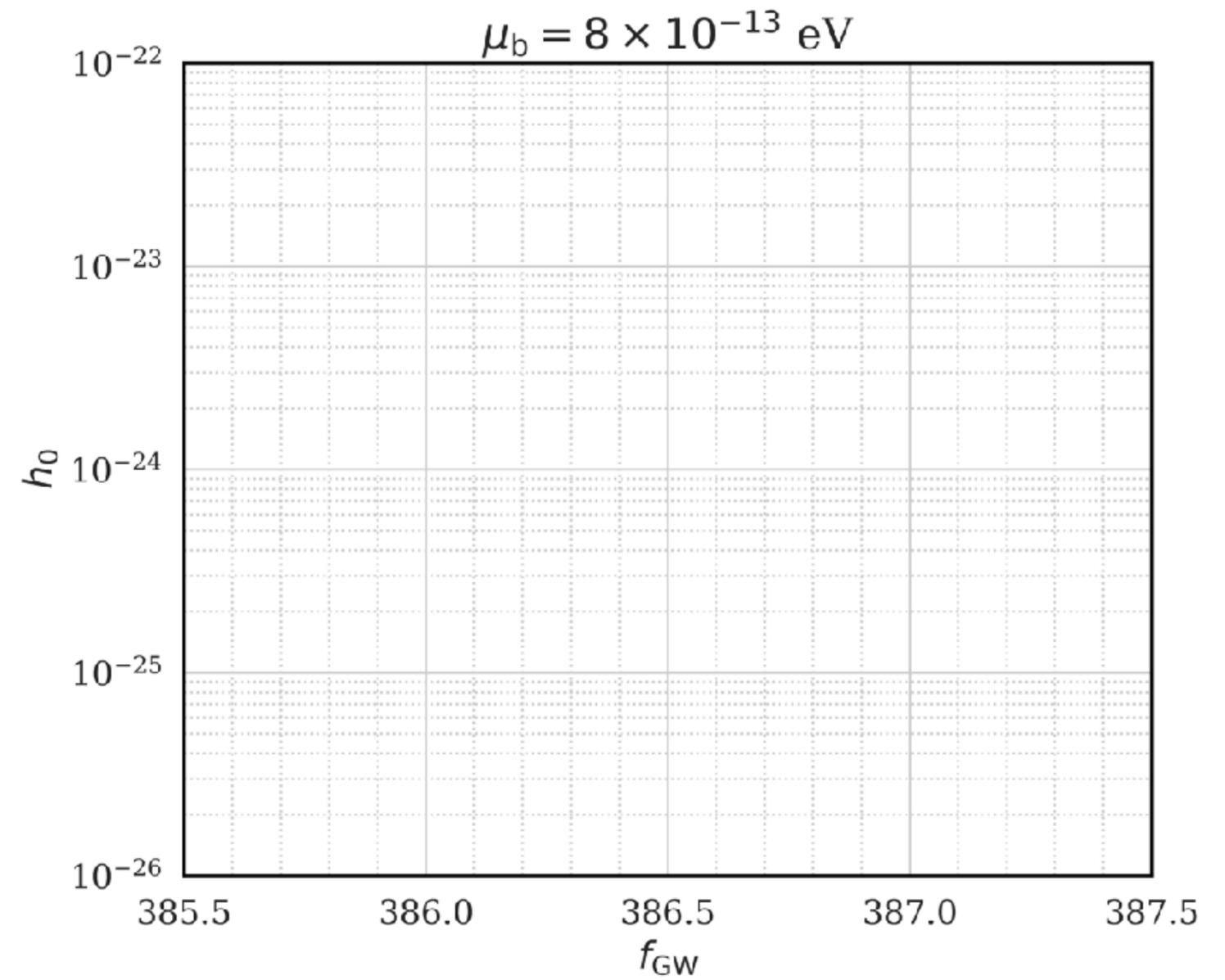
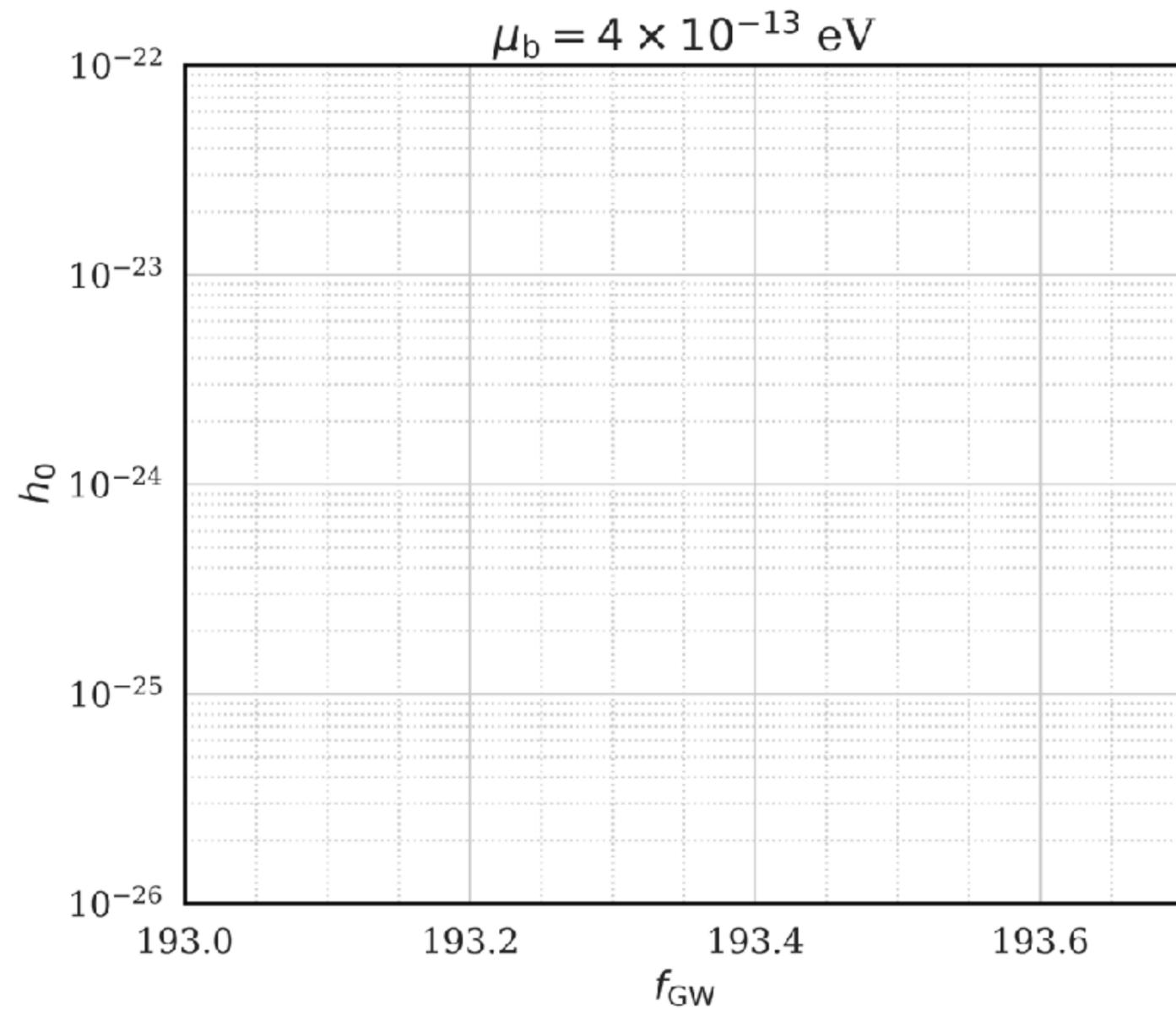


# formation of the second cloud level

When the second level fully forms, the first level falls back into the black hole and emission ceases.

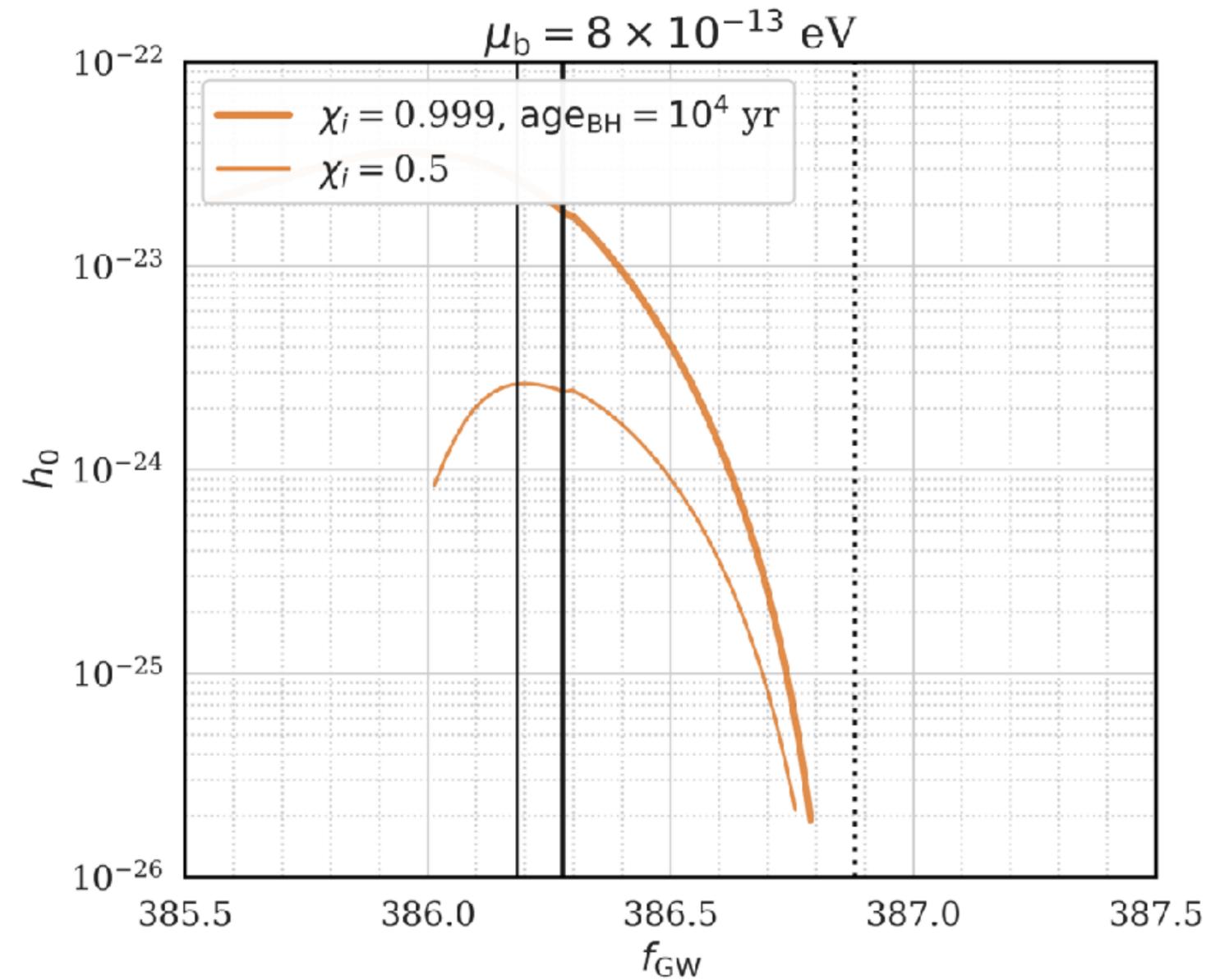
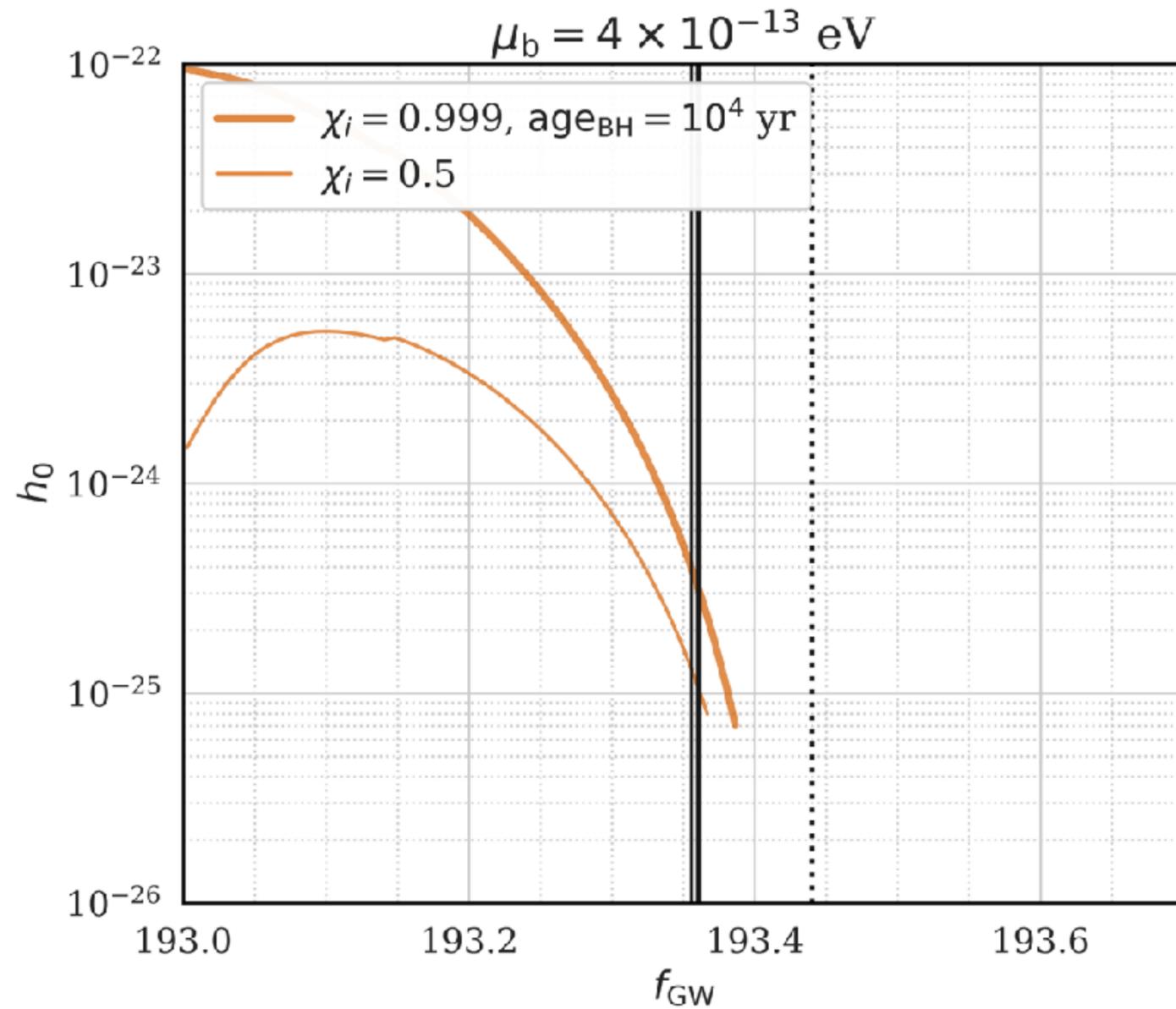


# What do the ensemble signals look like?



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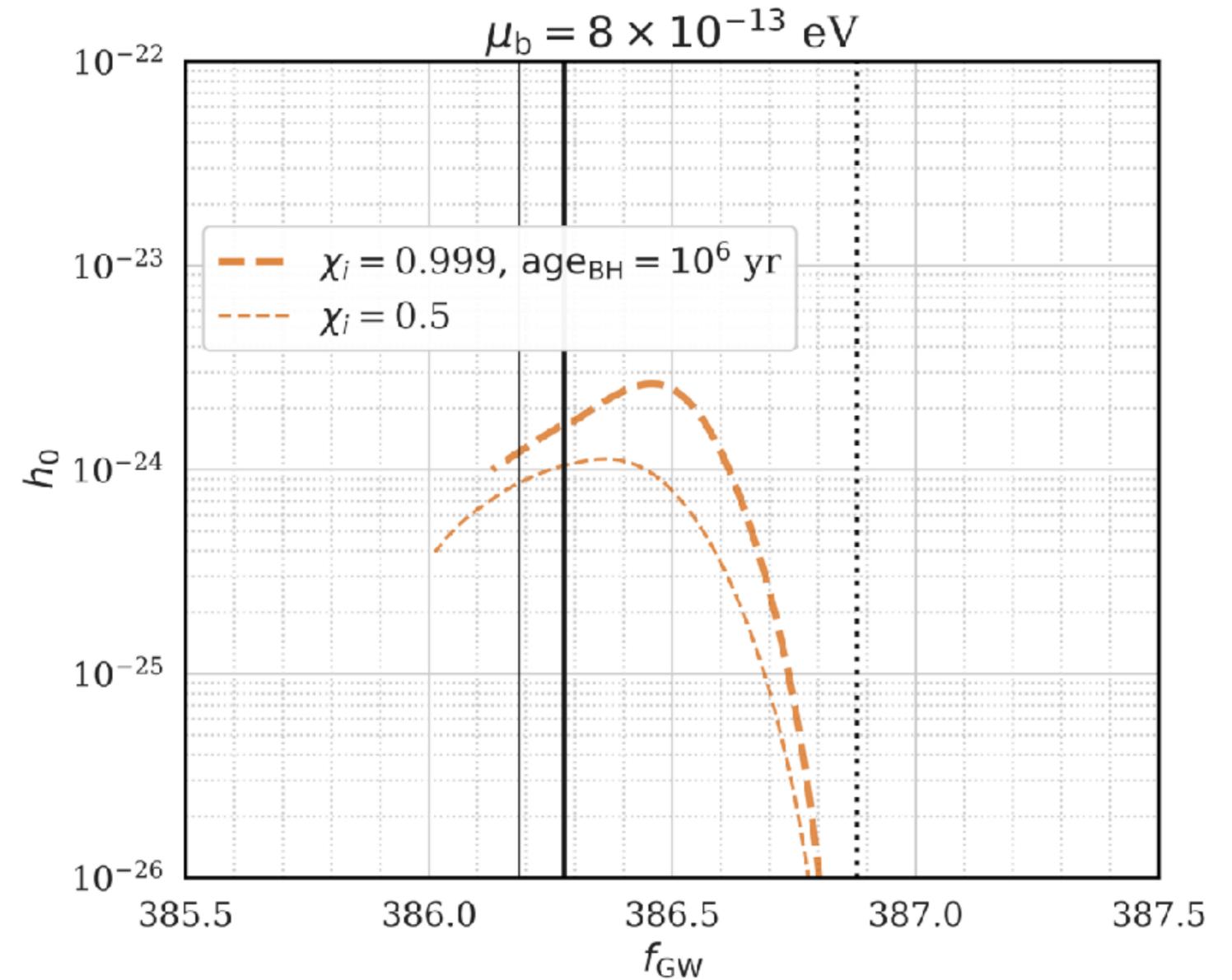
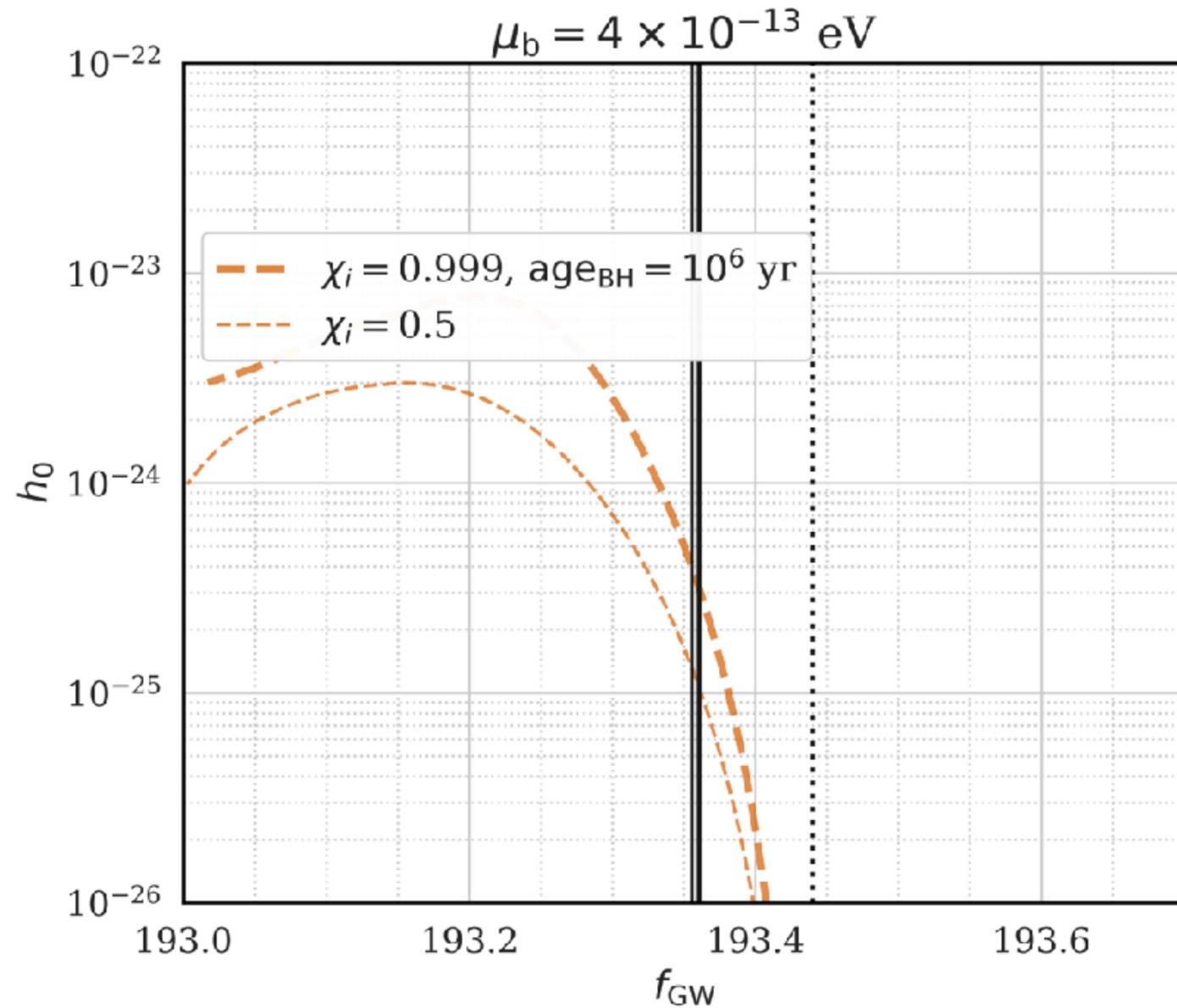
The orange curves define the envelopes of the potential signals over a wide range of boson masses.



The black solid vertical lines show  $\min f_{\text{GW}}$  given  $M_{\text{BH}} = 20M_{\odot}$ ; the dotted line shows the rest mass frequency.

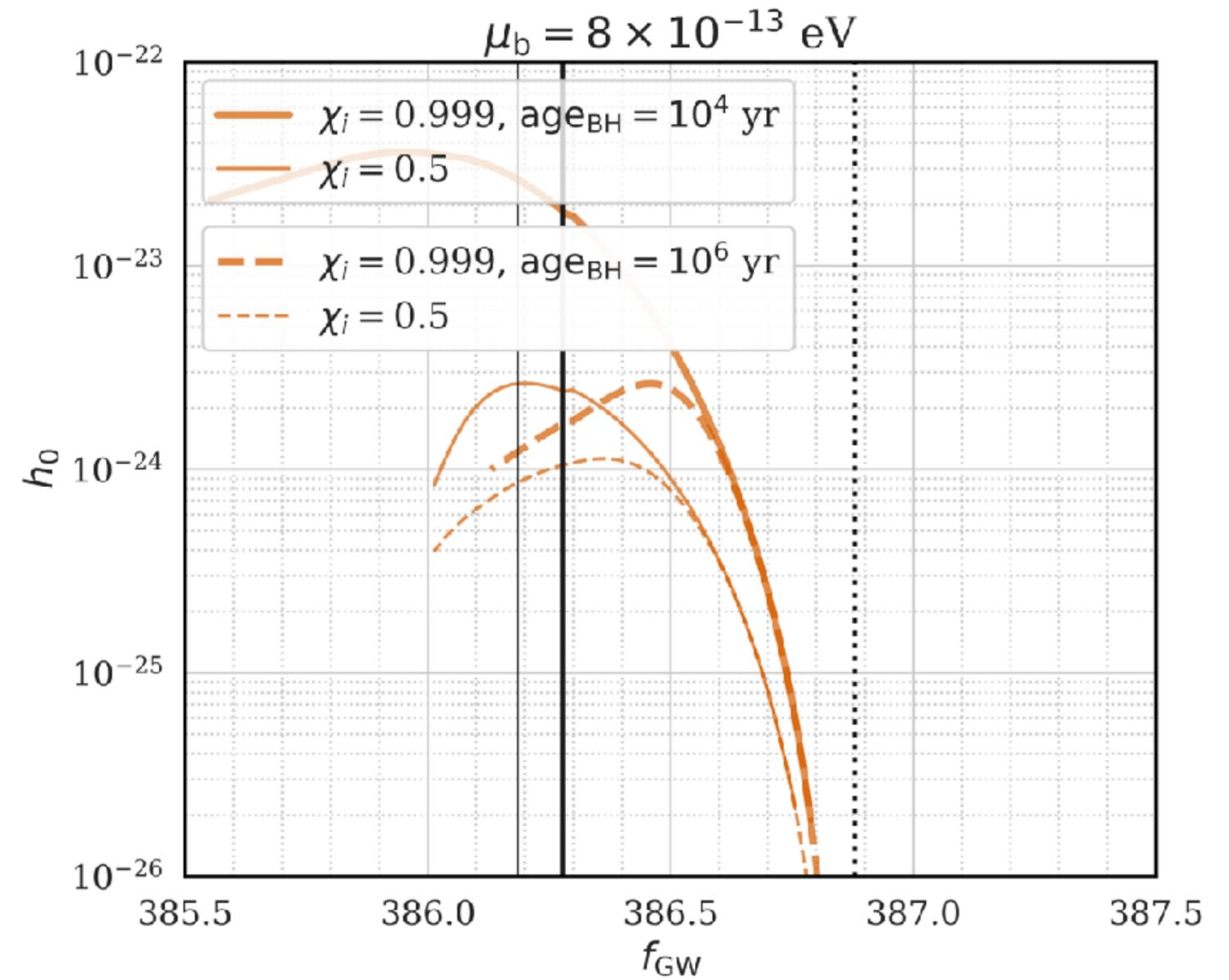
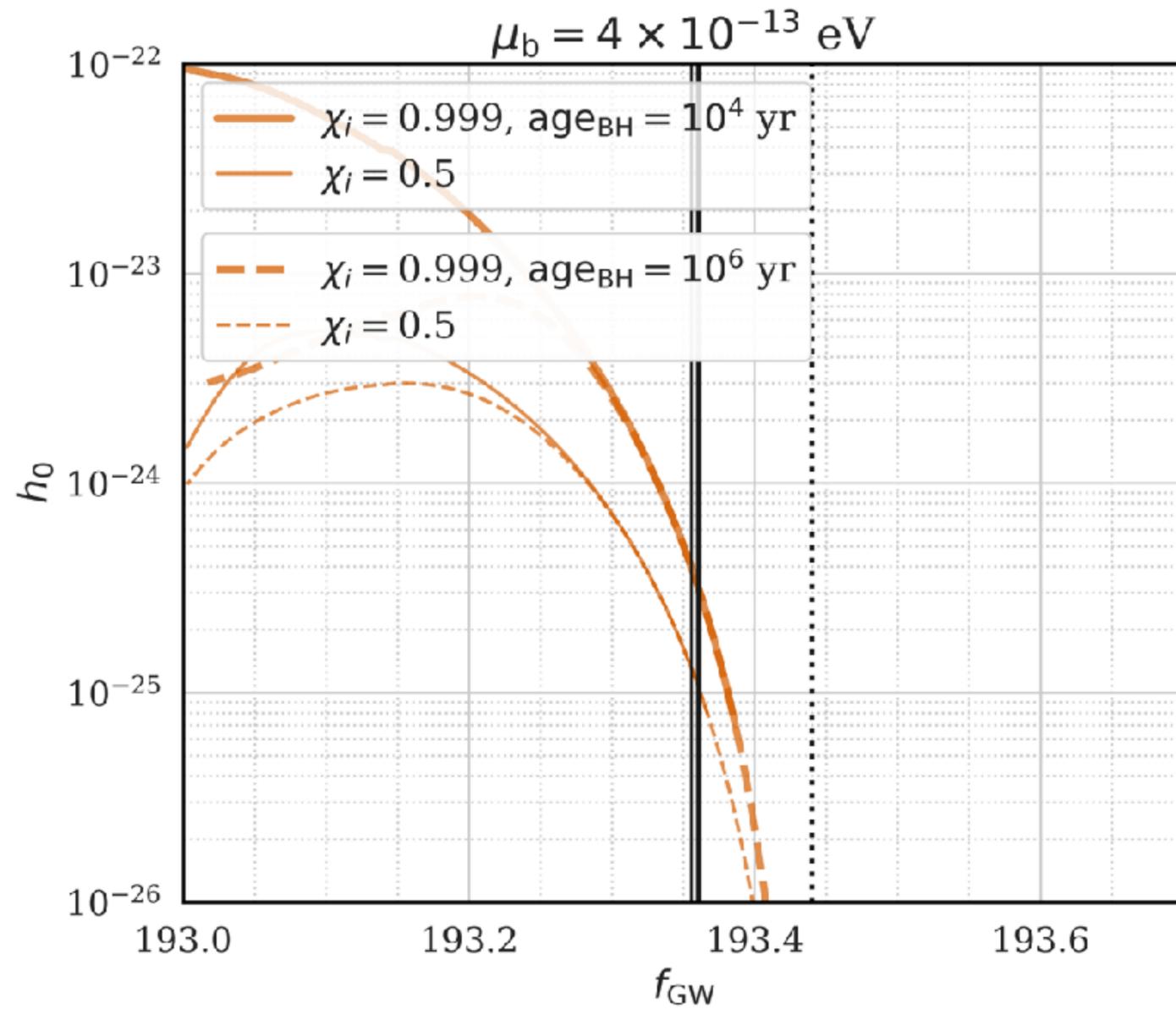
# What do the ensemble signals look like?

Signals get quieter as black holes age => envelopes drop



The black solid vertical lines show  $\min f_{\text{GW}}$  given  $M_{\text{BH}} = 20M_{\odot}$ ; the dotted line shows the rest mass frequency.

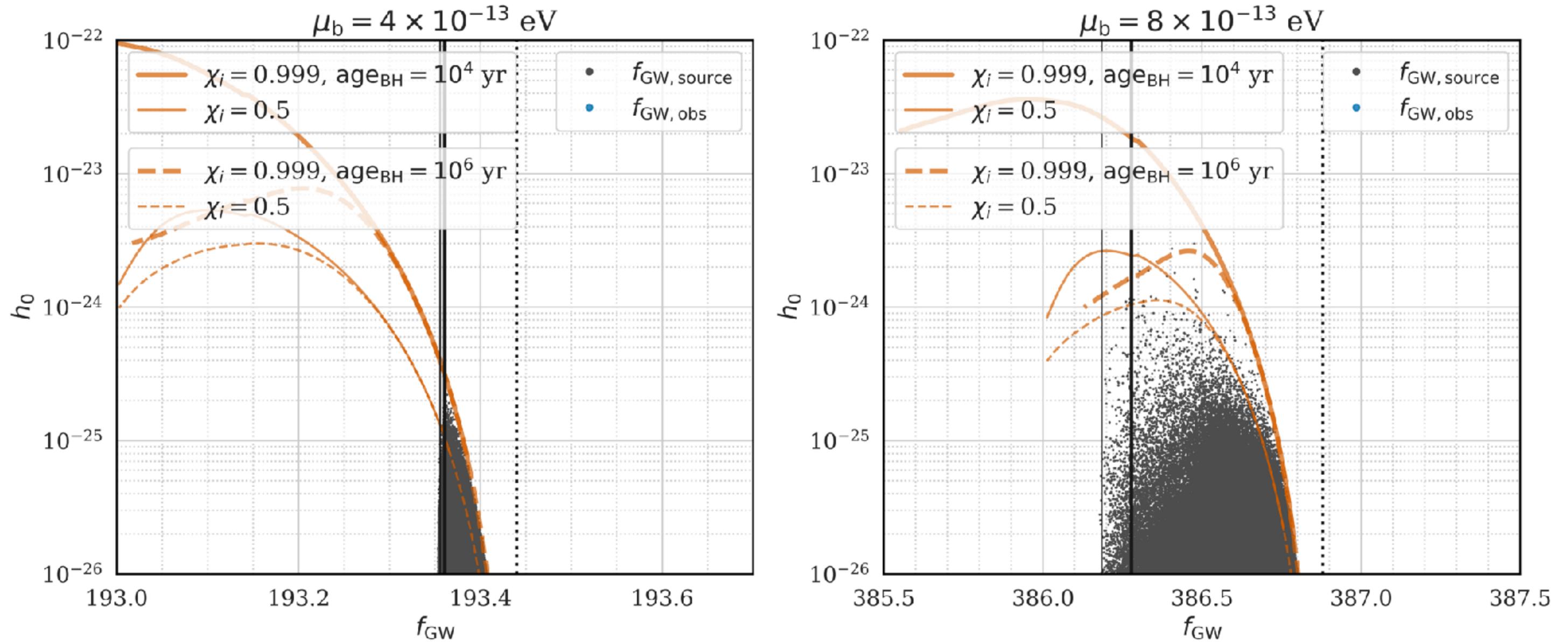
# What do the ensemble signals look like?



The black solid vertical lines show  $\min f_{\text{GW}}$  given  $M_{\text{BH}} = 20M_{\odot}$ ; the dotted line shows the rest mass frequency.

# What do the ensemble signals look like?

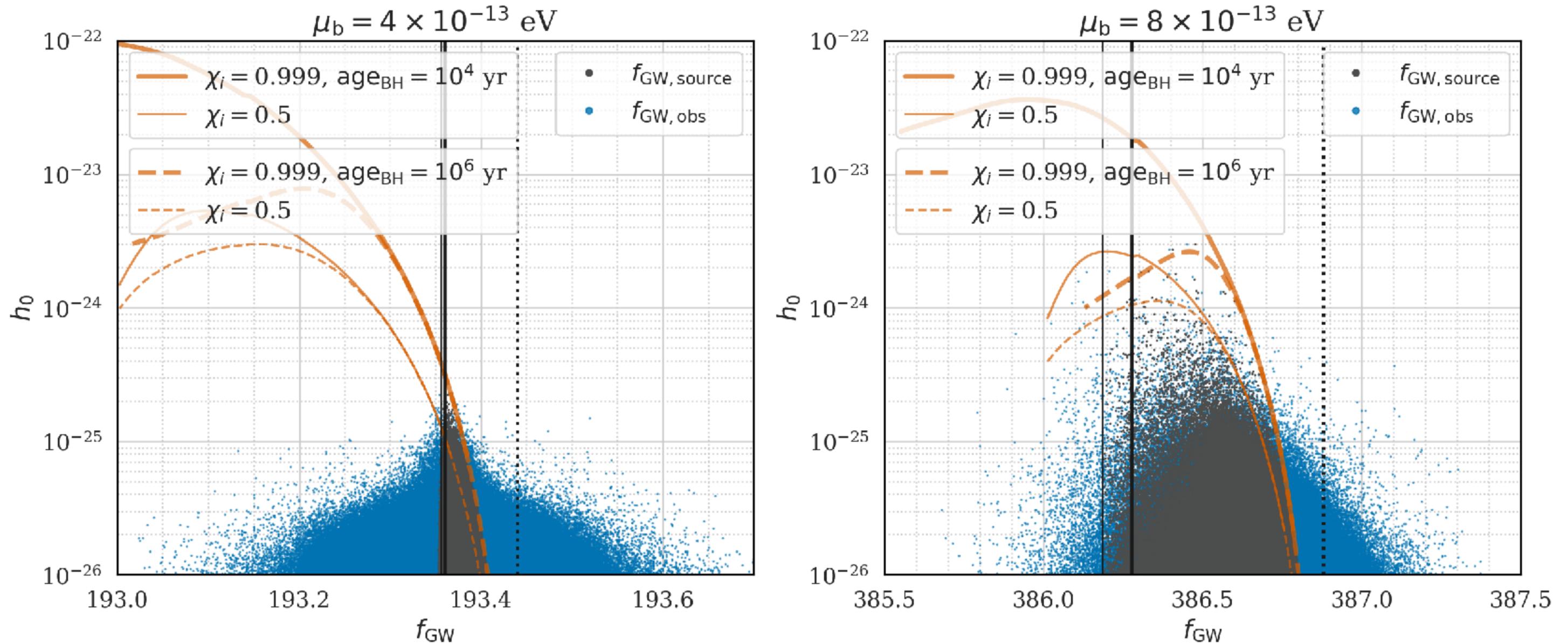
The signals w/ their source frequencies fill in the regions defined by the envelopes and vertical lines.



The black solid vertical lines show  $\min f_{\text{GW}}$  given  $M_{\text{BH}} = 20M_{\odot}$ ; the dotted line shows the rest mass frequency.

# What do the ensemble signals look like?

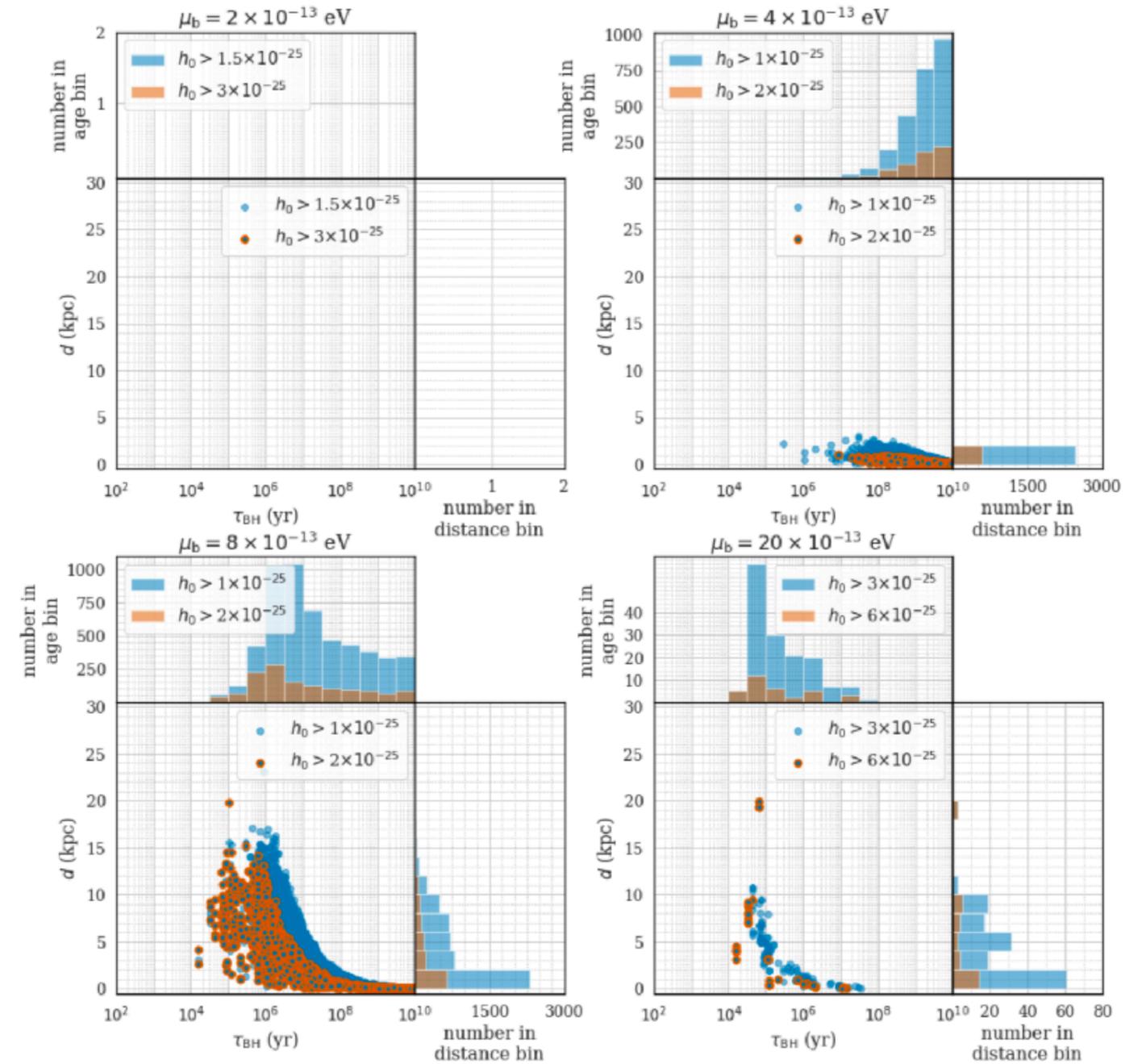
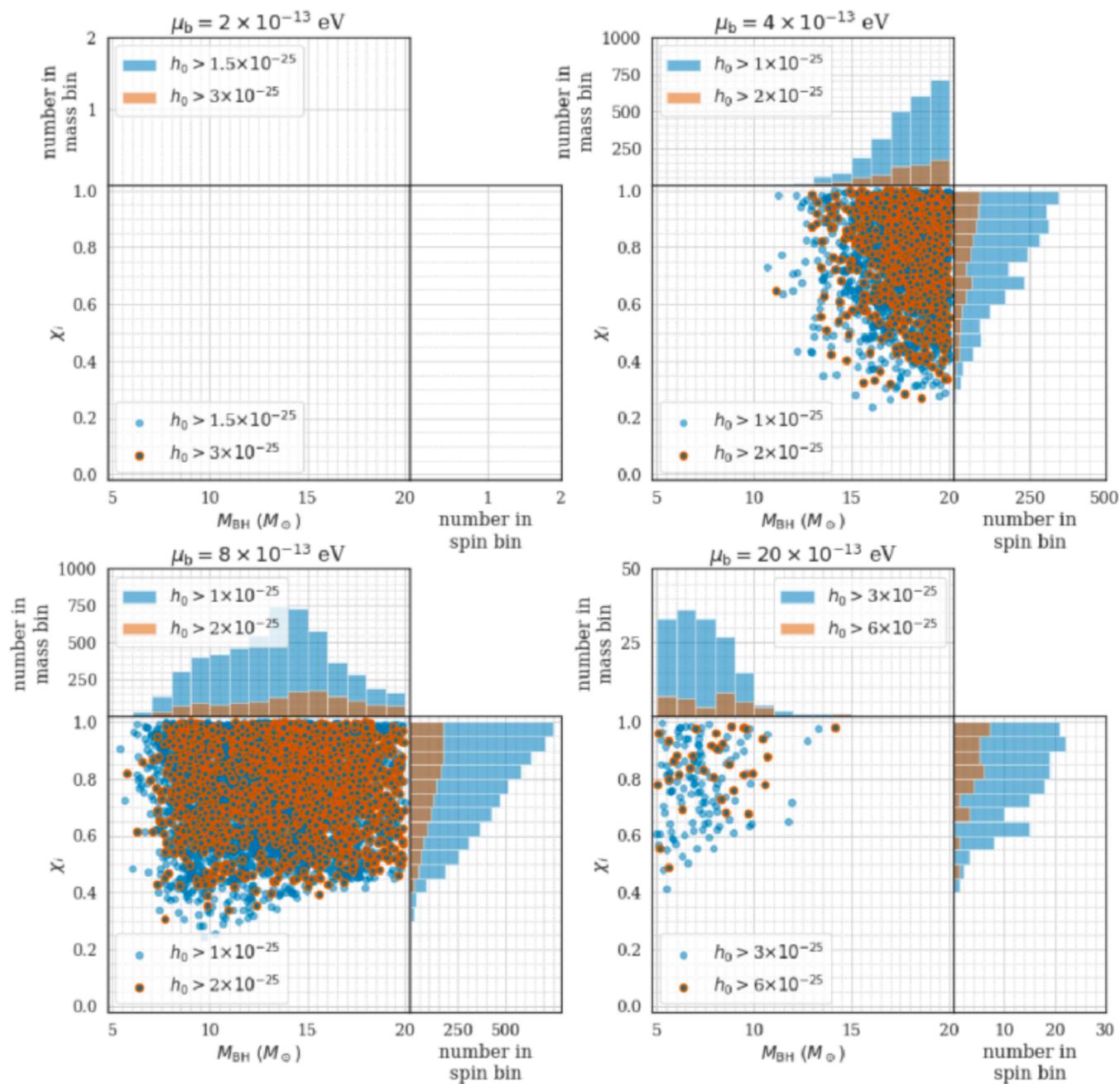
The black hole velocities add a large Doppler shift and "smear out" the distribution.



The black solid vertical lines show  $\min f_{\text{GW}}$  given  $M_{\text{BH}} = 20M_{\odot}$ ; the dotted line shows the rest mass frequency.

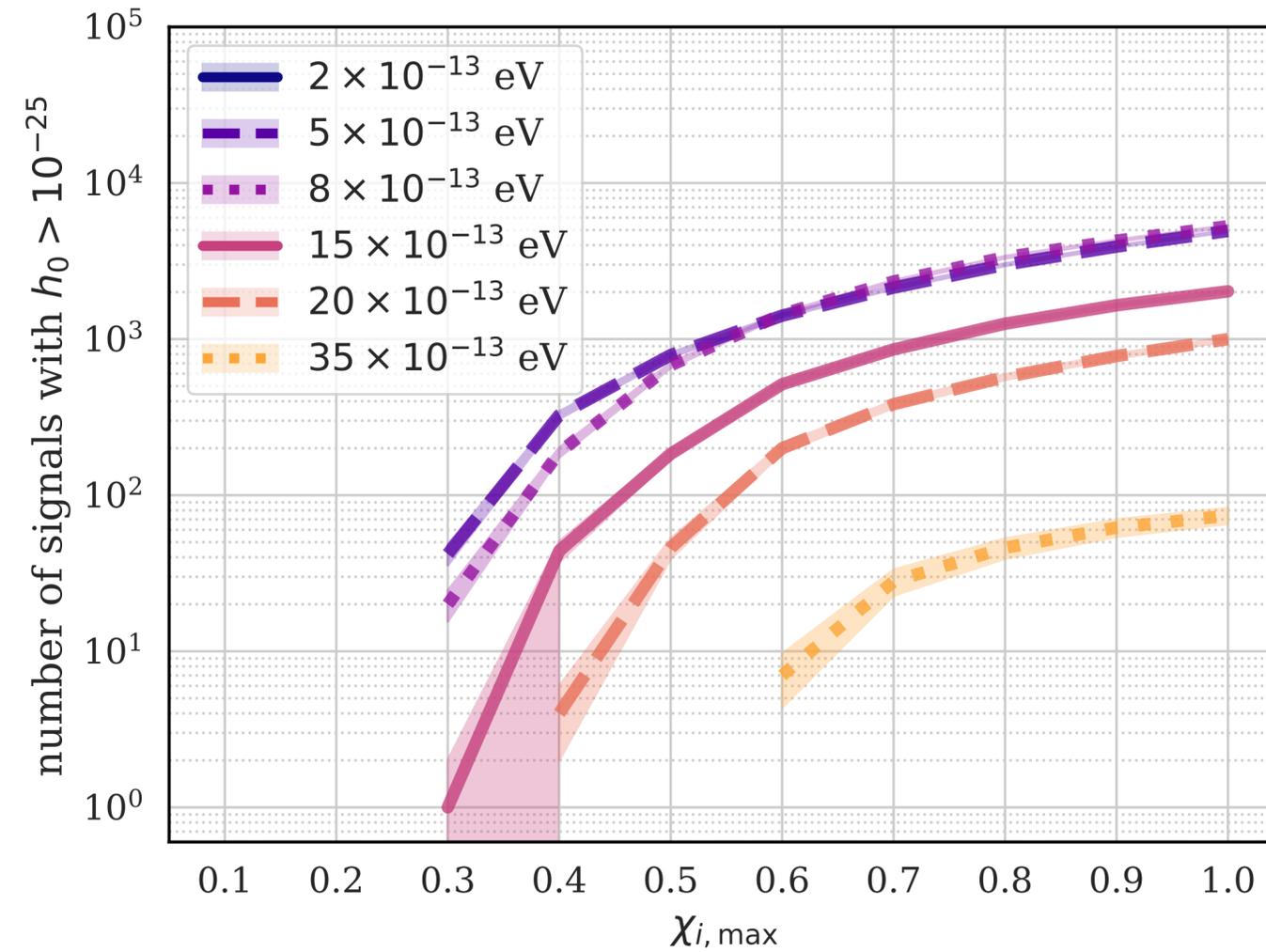
# Which black holes produce ~detectable signals?

The “relevant” black holes depend on the boson mass, through both the signal properties and the detector sensitivity



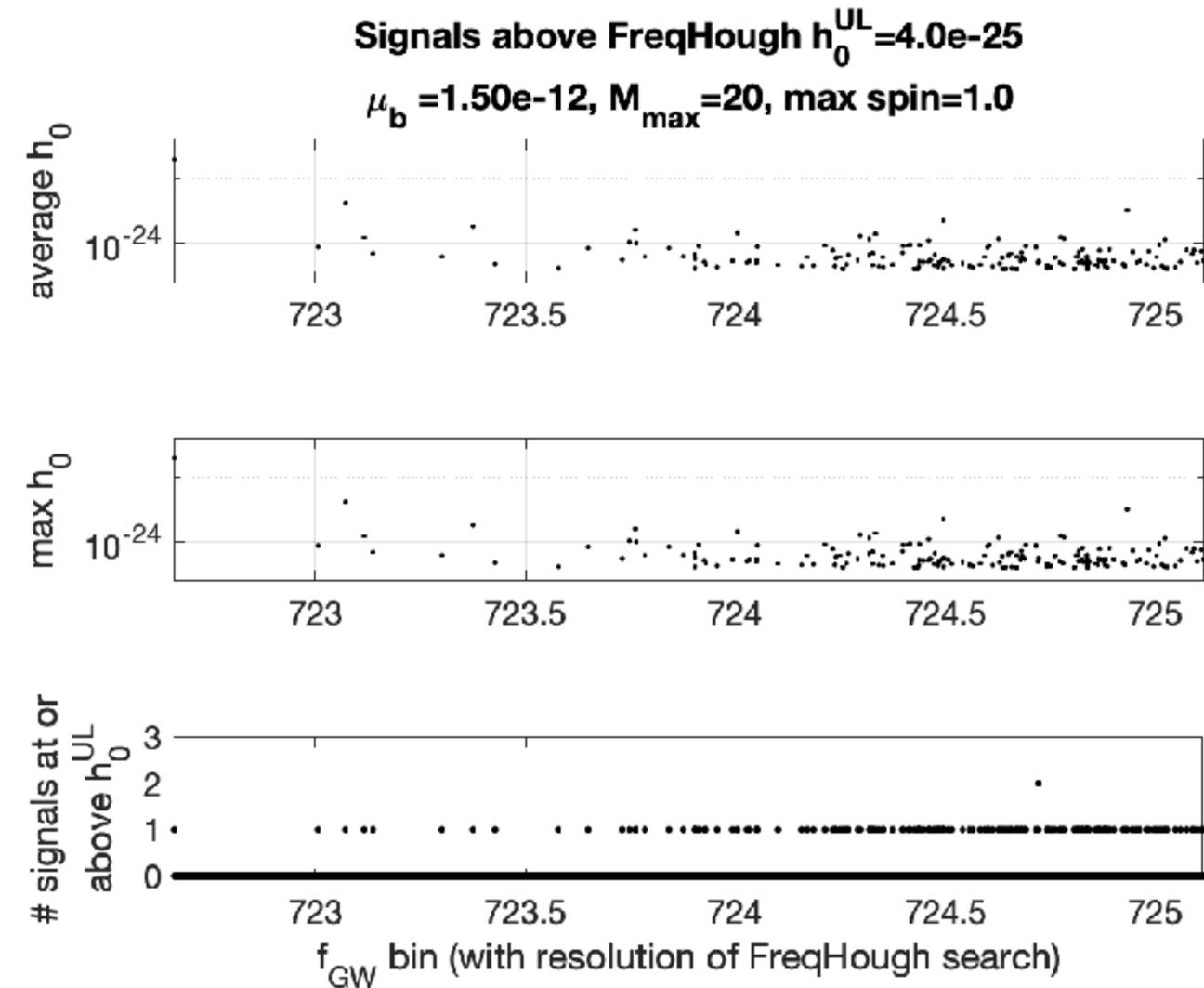
# Varying spin

For our BH population, initial spins of  $>0.3$  are needed to produce  $\sim$ detectable signals



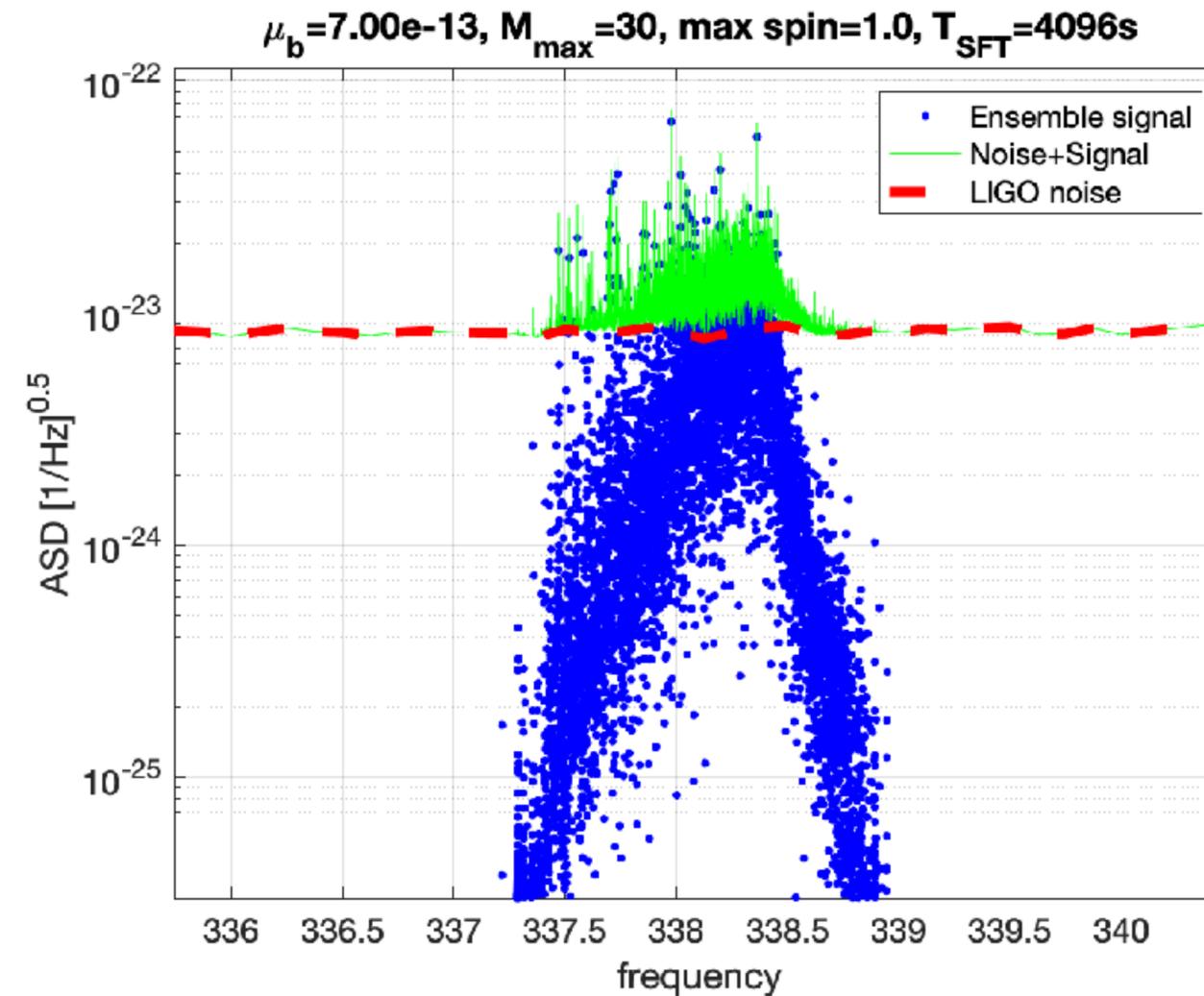
# Concerns about signal density

Searches can turn up multiple signals per frequency bin => signal confusion



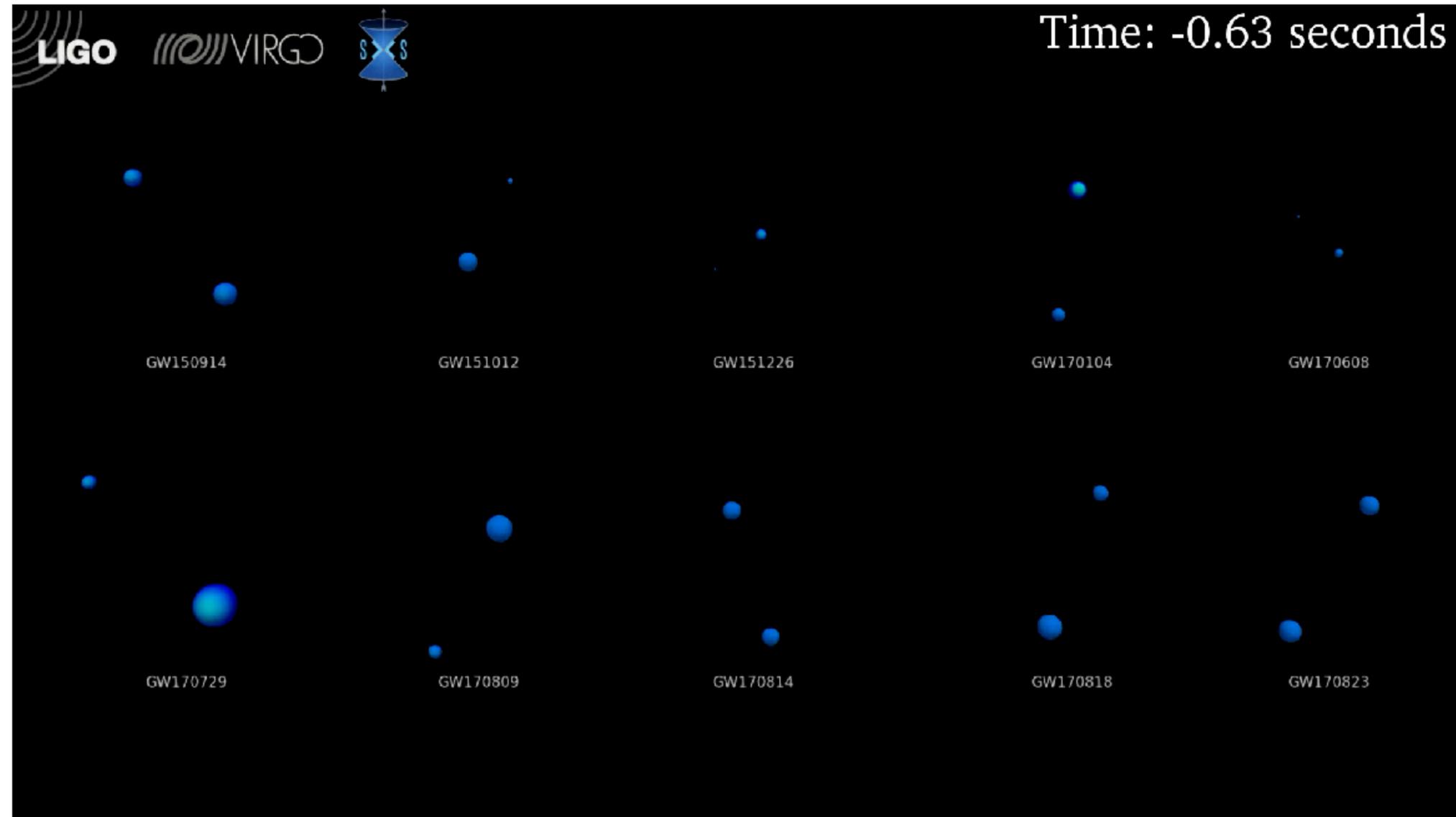
# Concerns about signal density

A dense signal background can affect the noise floor beyond what typical CW searches expect



# sources of transient gravitational waves

A changing mass quadrupole produces gravitational waves

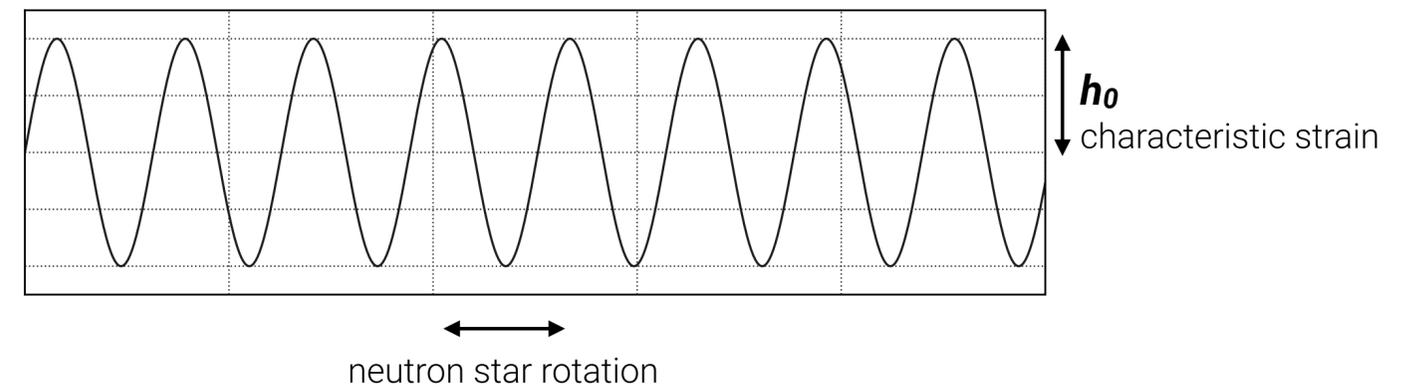
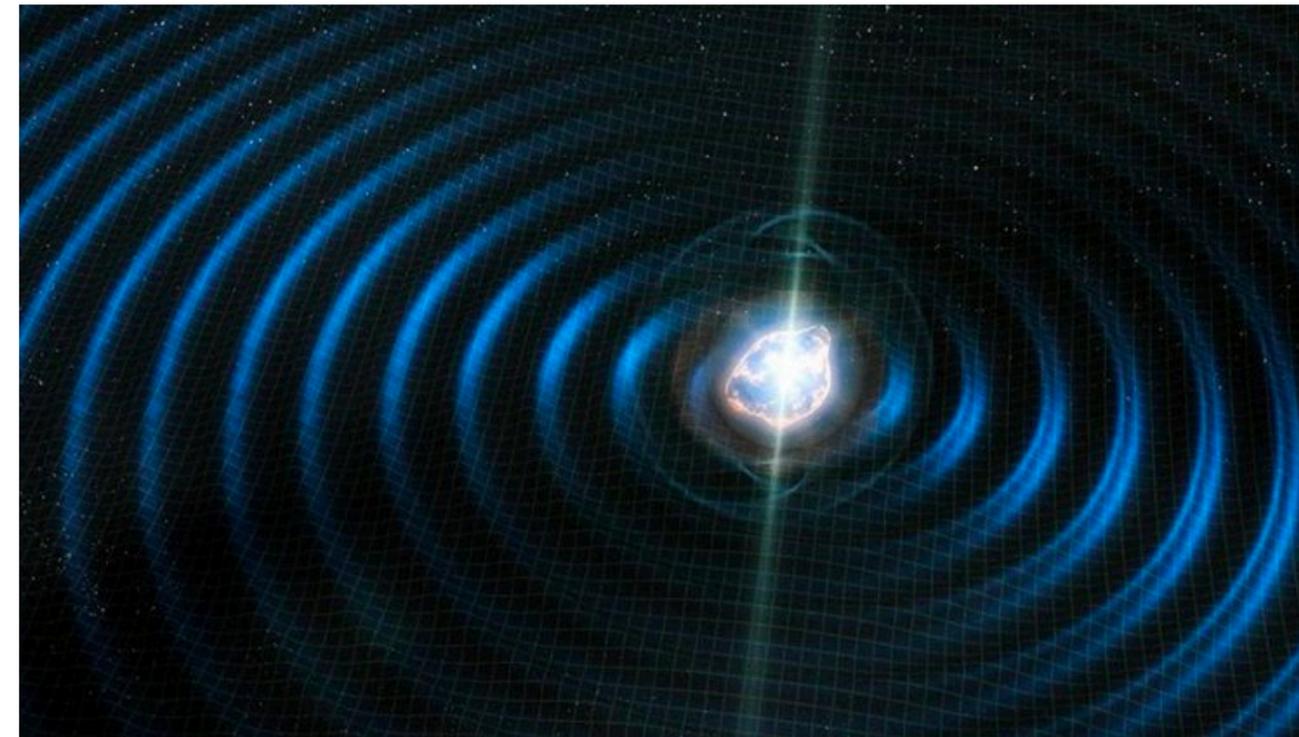
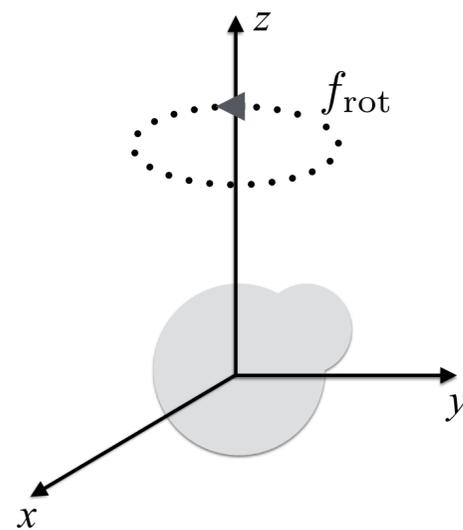


# Continuous gravitational waves

A changing mass quadrupole produces gravitational waves

$$h_0 = \frac{4\pi G I_{zz}}{c^4} \frac{f_{\text{GW}}^2 \epsilon}{d}$$

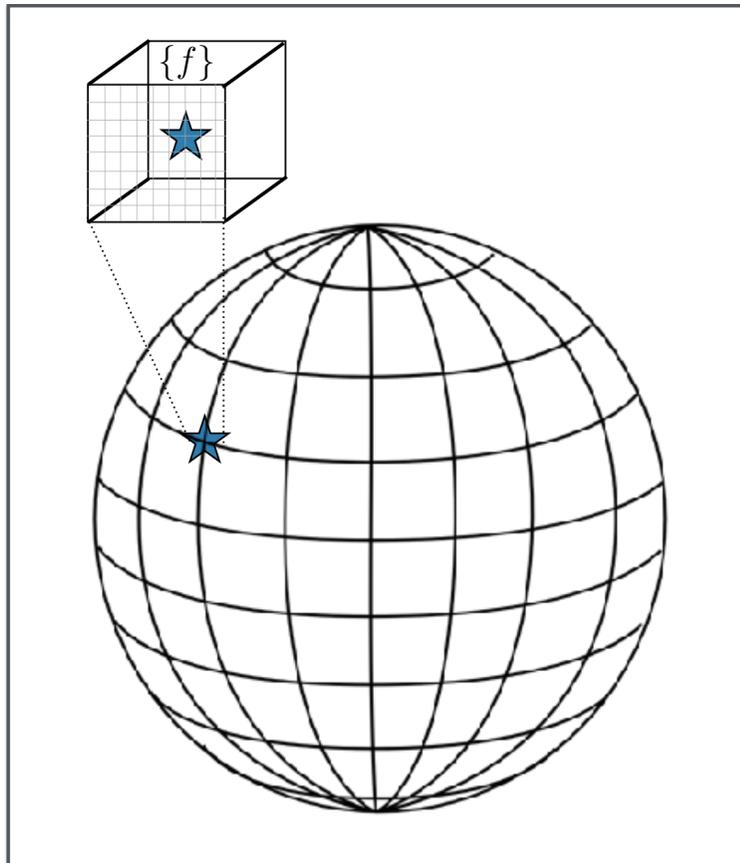
2x rotation frequency  $f_{\text{rot}}$  (pointing to  $f_{\text{GW}}^2$ )  
 ellipticity  $\frac{|I_{xx} - I_{yy}|}{I_{zz}}$  (pointing to  $\epsilon$ )  
 distance from detector (pointing to  $d$ )



# Types of searches

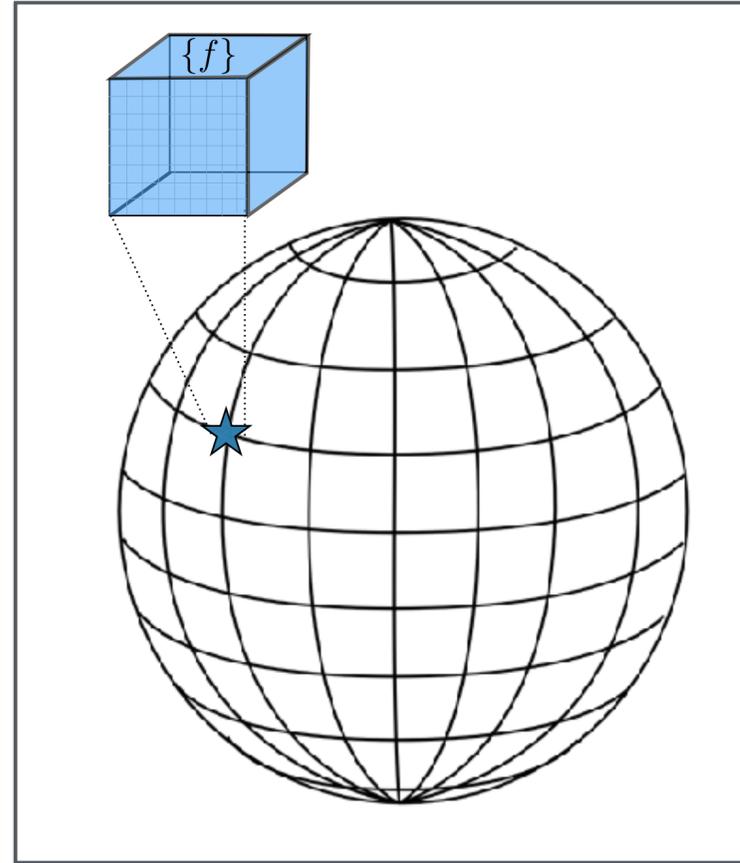
## targeted search

known pulsars



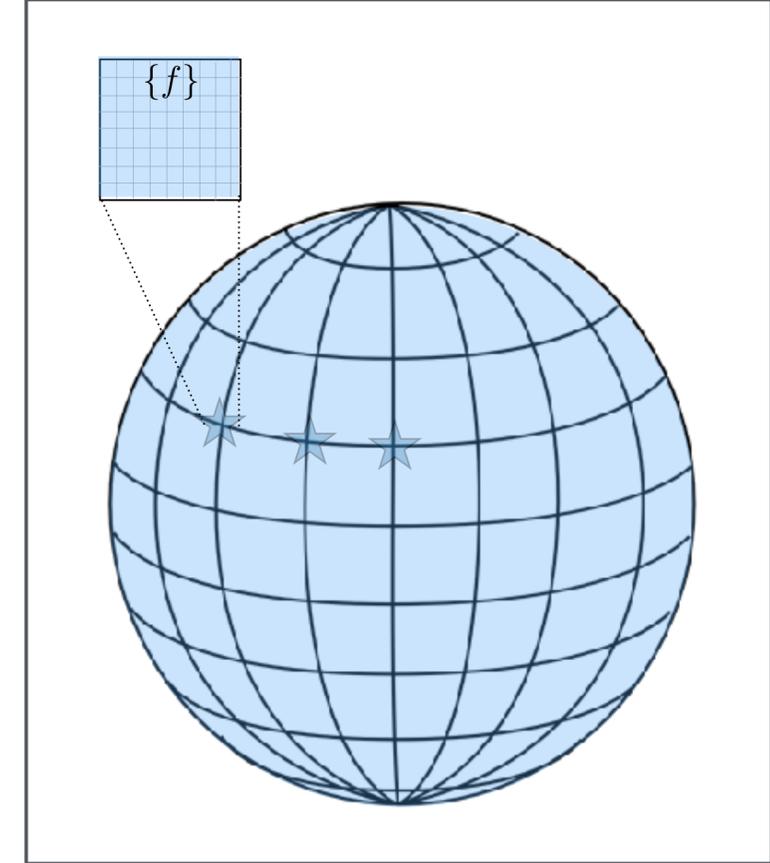
## directed search

known neutron stars



## all-sky search

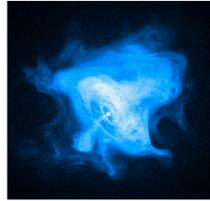
minimal assumptions



computational cost

search sensitivity

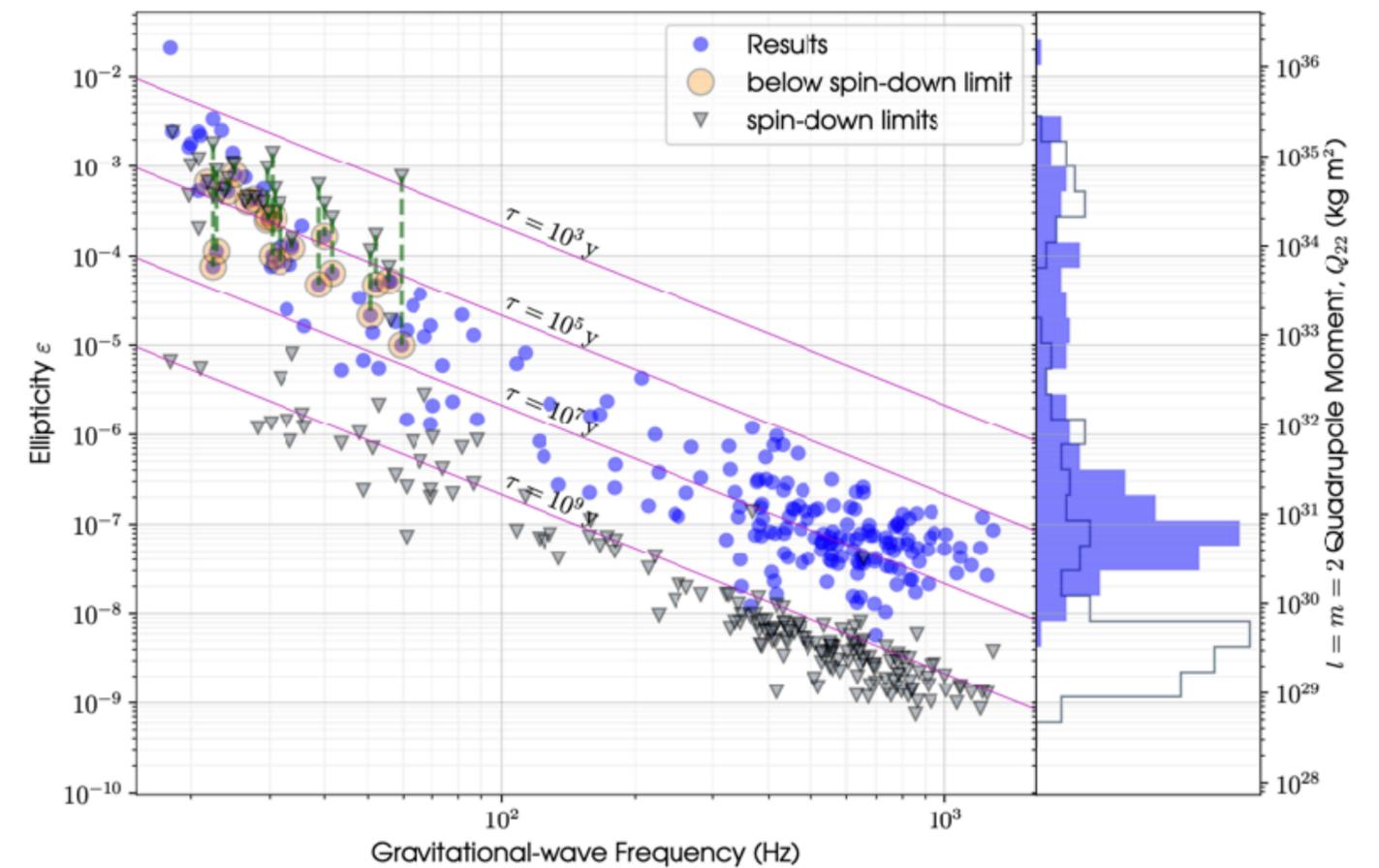
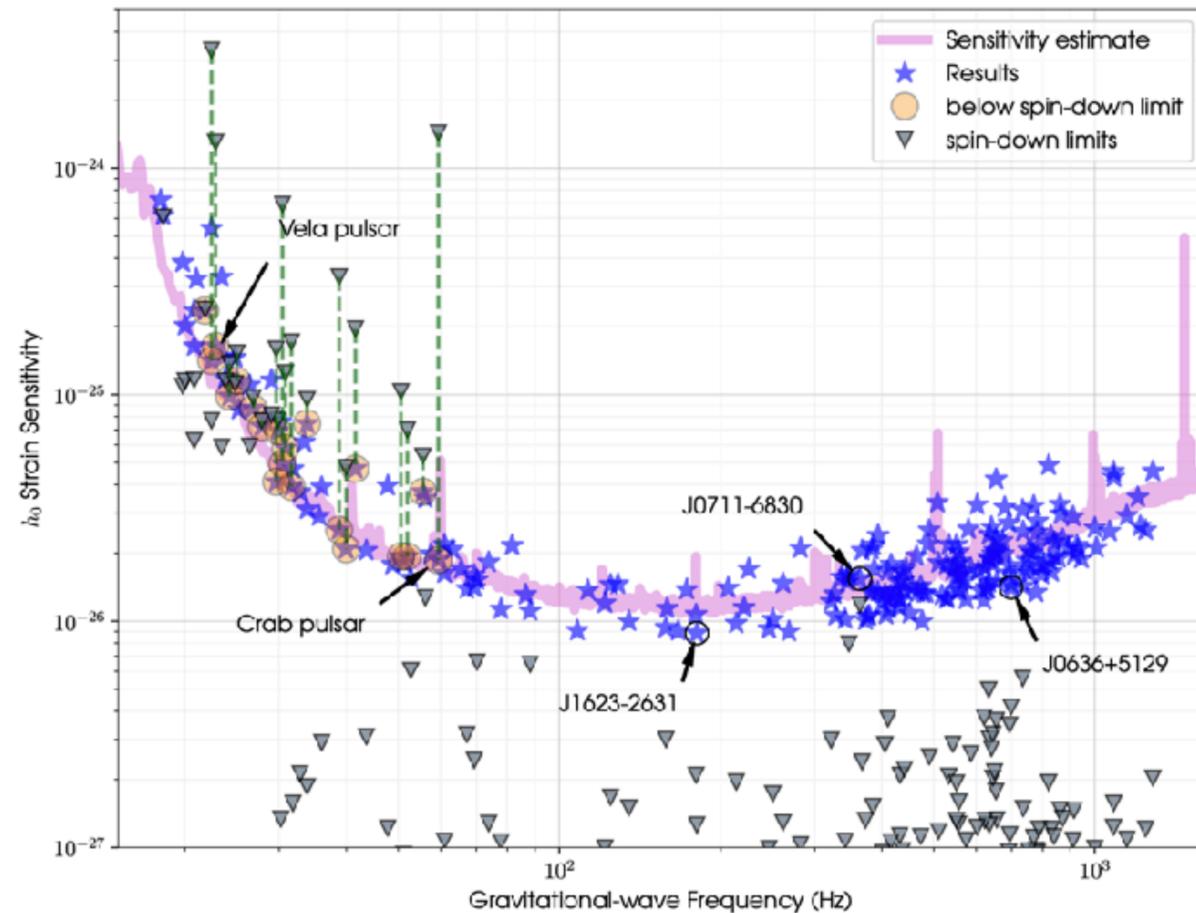
# Interpreting null results (upper limits) – neutron stars



$$h_0 = \frac{4\pi G I_{zz}}{c^4} \frac{f_{\text{GW}}^2 \epsilon}{d}$$

2x rotation frequency  $f_{\text{rot}}$   
 ellipticity  $\frac{|I_{xx} - I_{yy}|}{I_{zz}}$   
 distance from detector  $d$

upper limit on gravitational-wave signal strength directly translates to upper limit on neutron star ellipticity (~max mountain height)



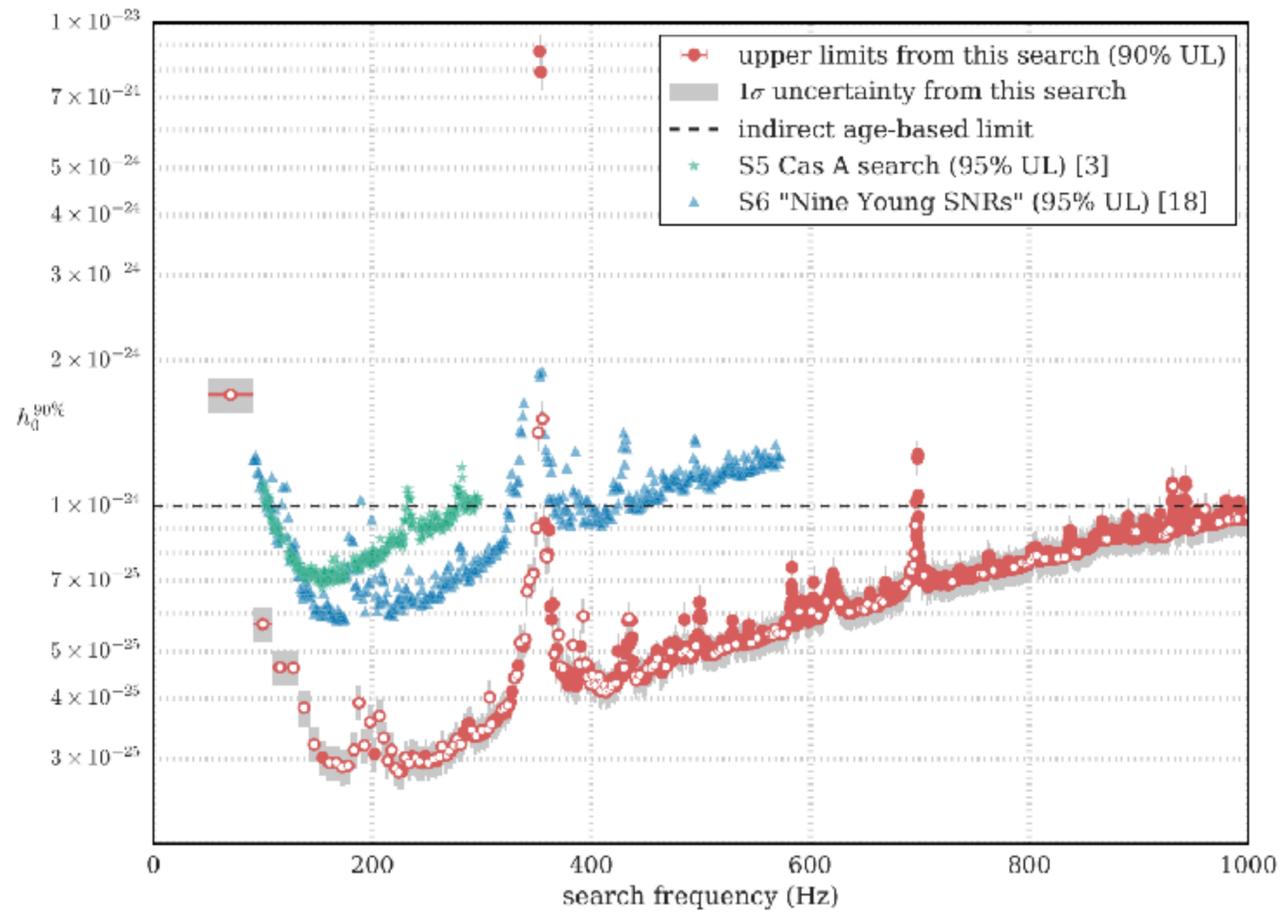
# Interpreting null results (upper limits) – neutron stars



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2x rotation frequency  $f_{\text{rot}}$   
 ellipticity  $\frac{|I_{xx} - I_{yy}|}{I_{zz}}$   
 distance from detector  $d$

upper limit on gravitational-wave signal strength



translates to,  
assuming  $f_{\text{GW}}$ ,

upper limit on neutron star ellipticity ( $\sim$ max mountain height)

