Prospects for detecting the axion annihilation signal using continuous gravitational-wave searches

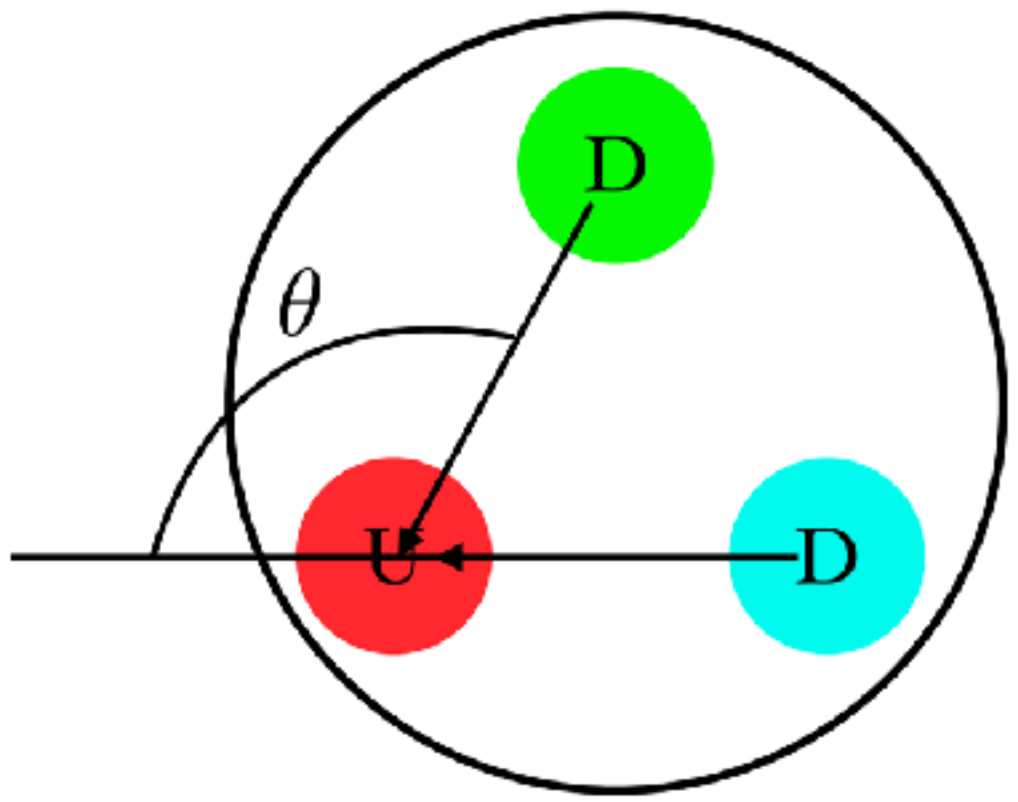
Sylvia J. Zhu (DESY, AEI Hannover)

PRD 102, 063020
https://www.aei.mpg.de/continuouswaves/arxiv200303359

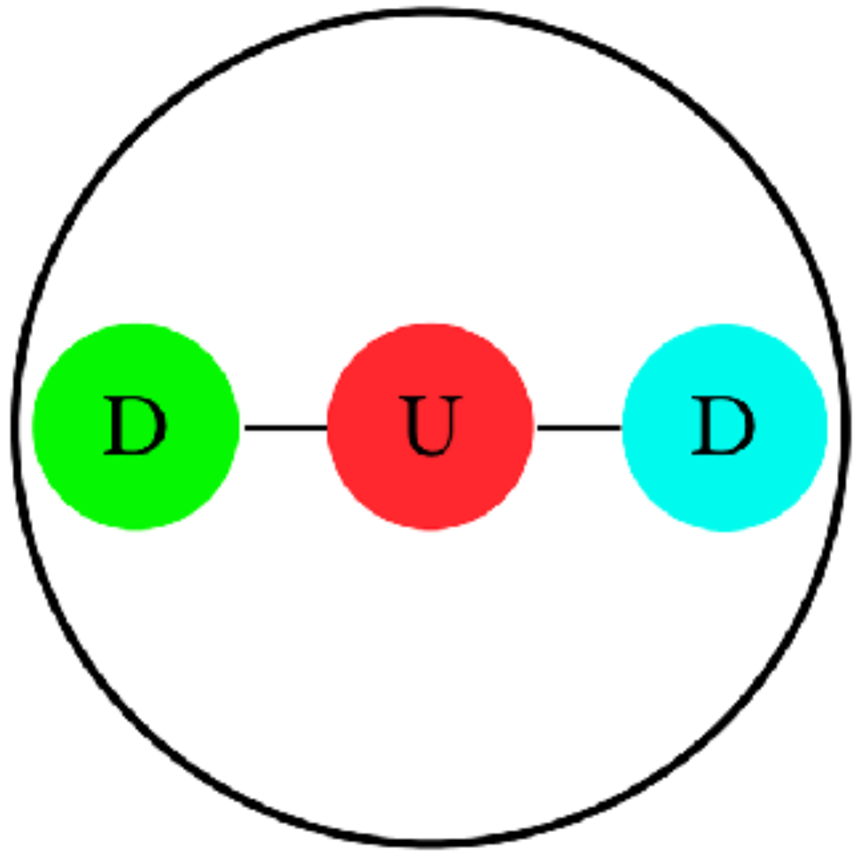
In which I try to convince you I understand what an axion is

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

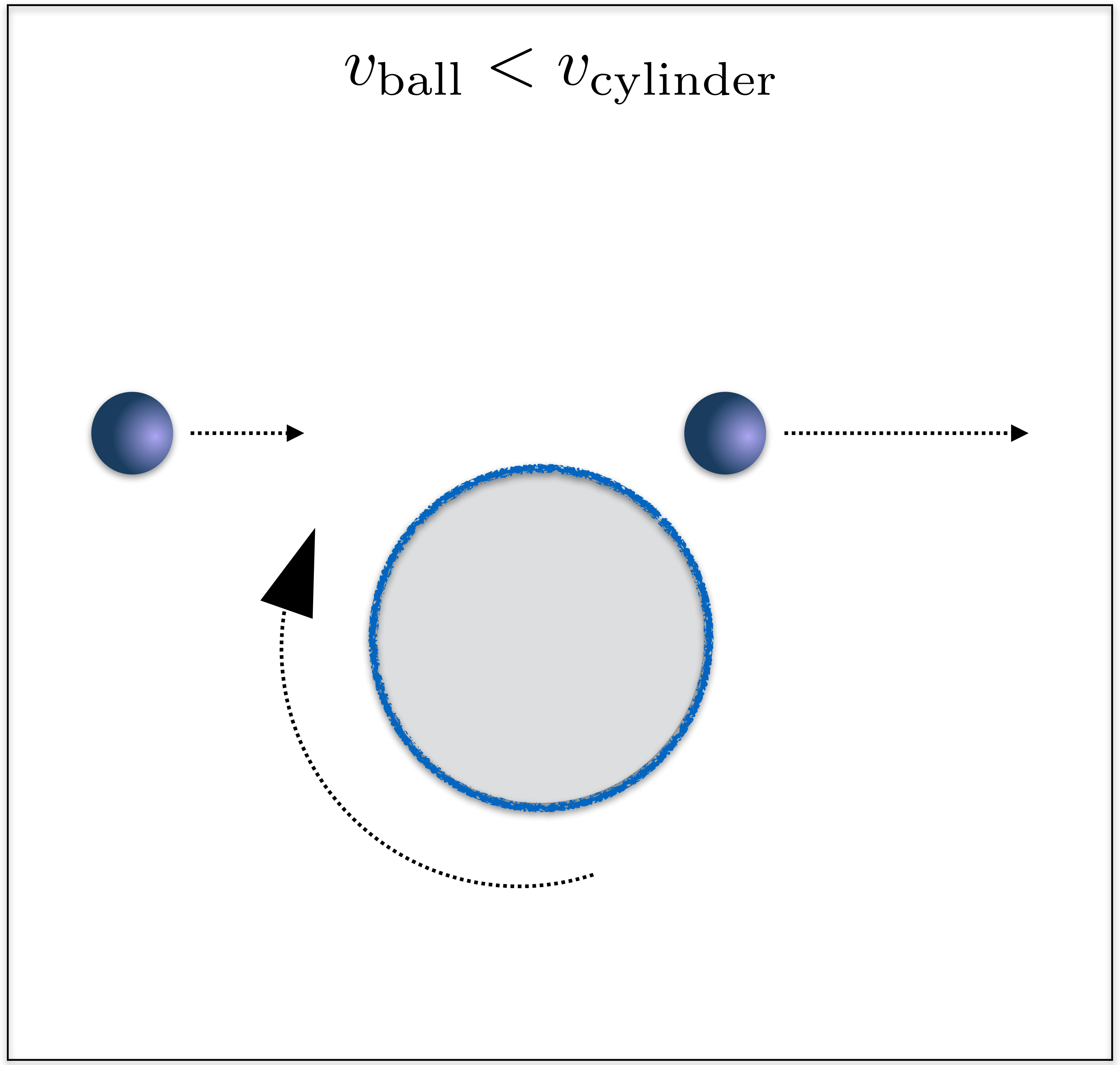


If θ is dynamical, then it will naturally 'relax' to zero → θ is a field and its oscillations give rise to **axions**

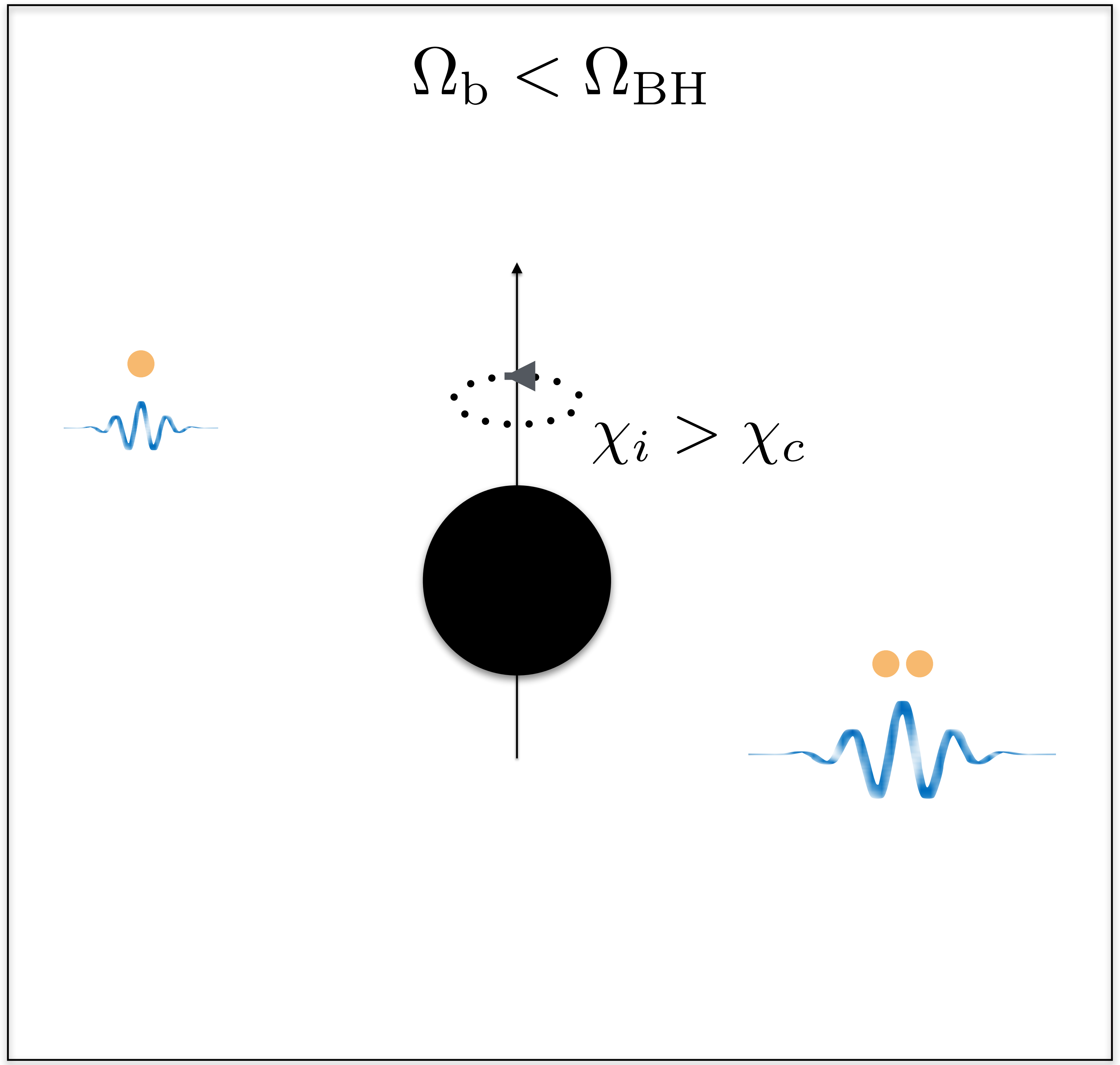
Superradiance instability

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

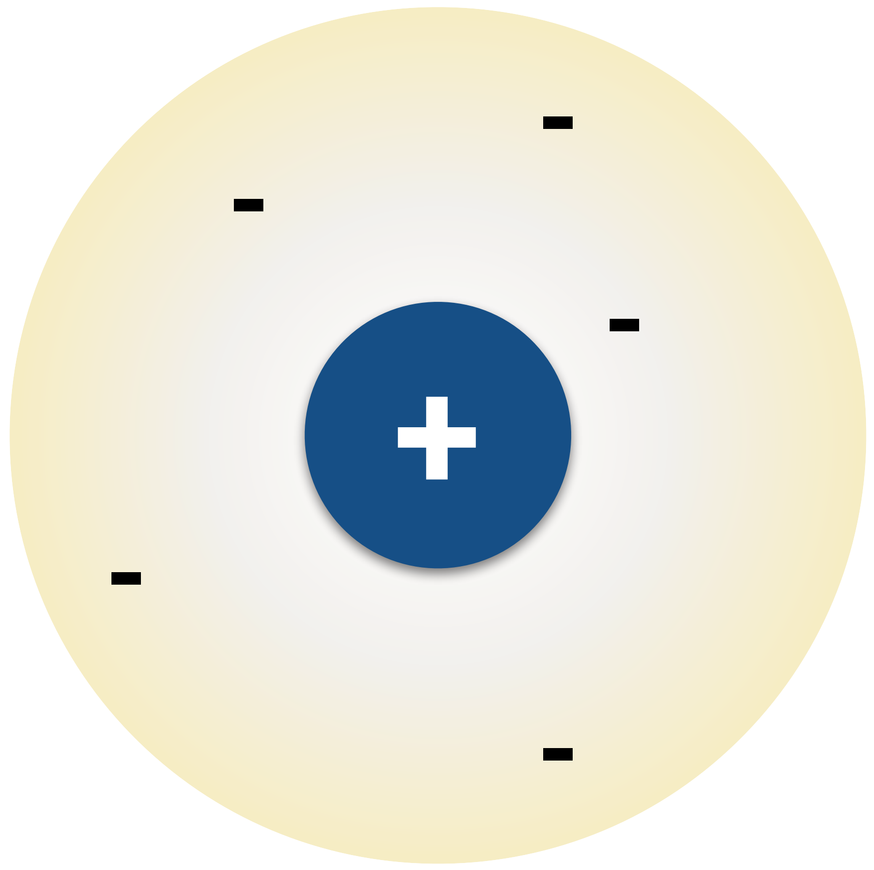
classical analog

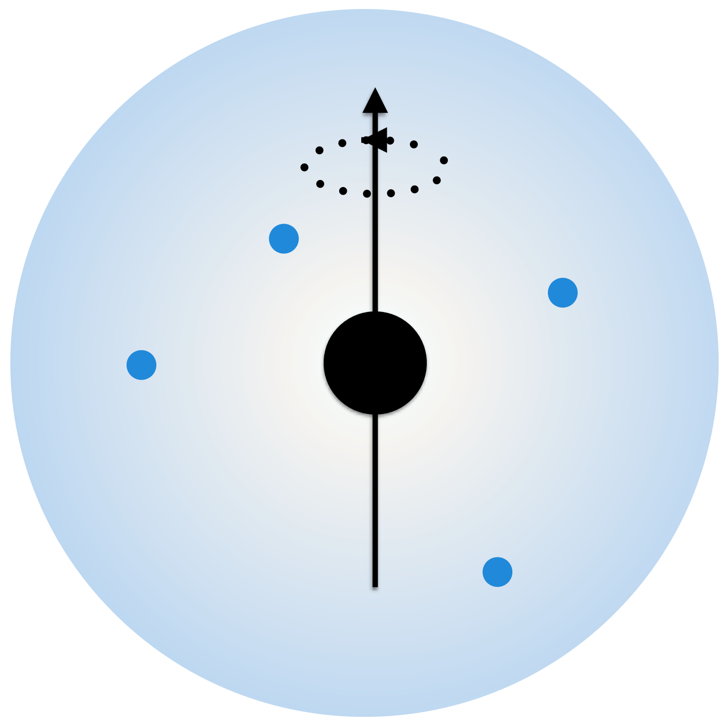


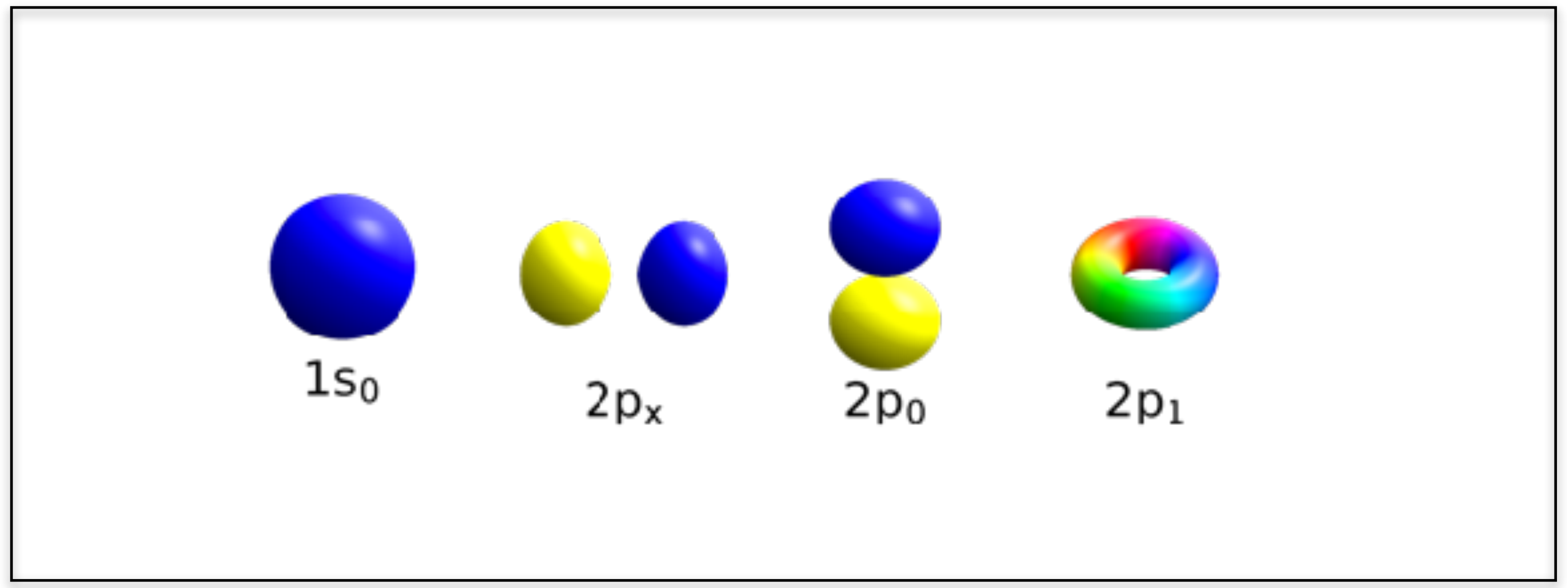
superradiance



Gravitational "atom"

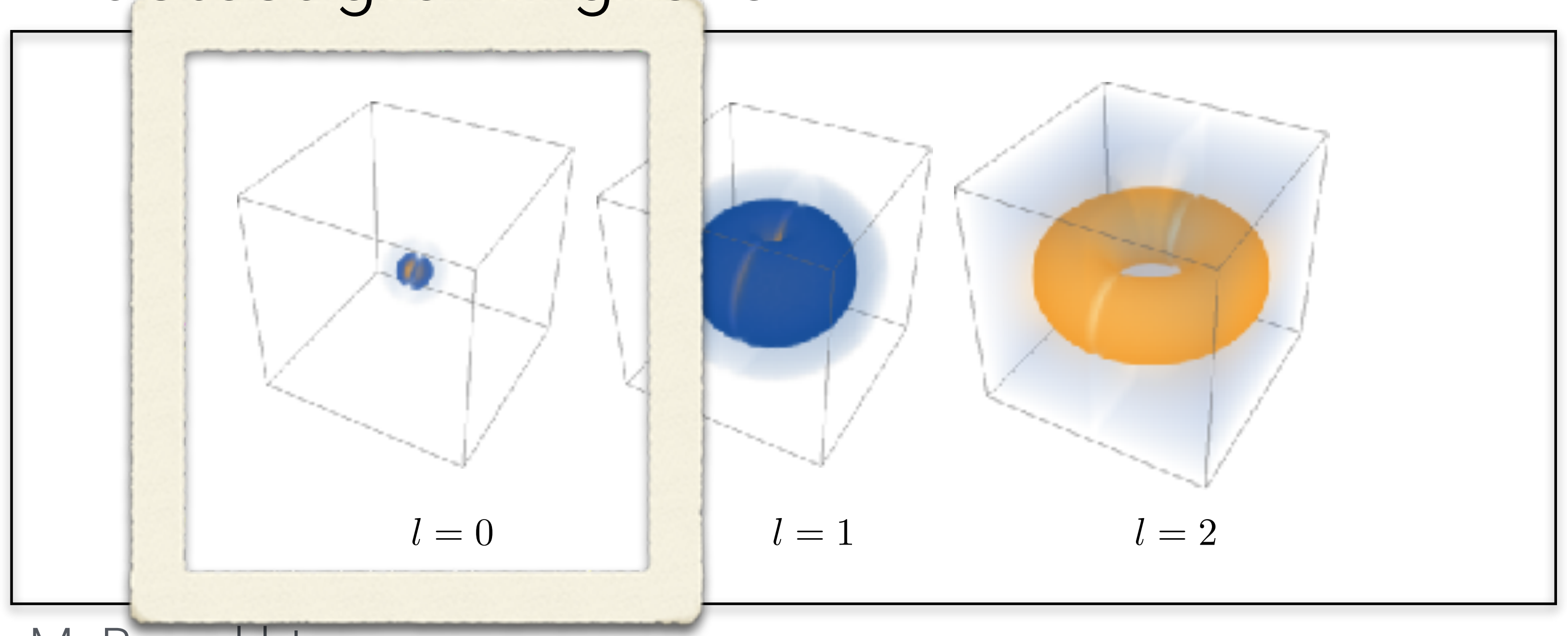






[Wikimedia Commons]

fastest growing level

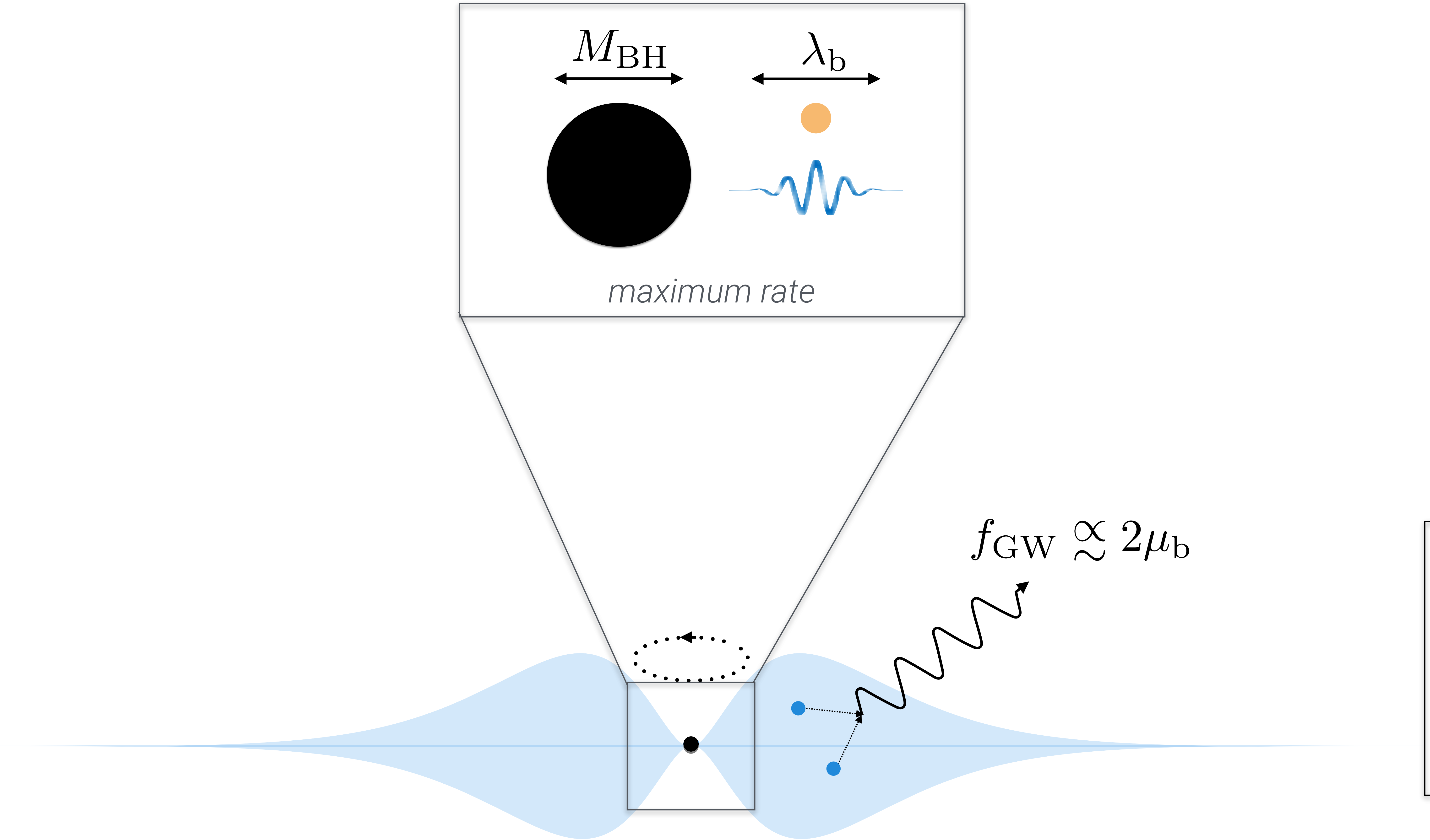


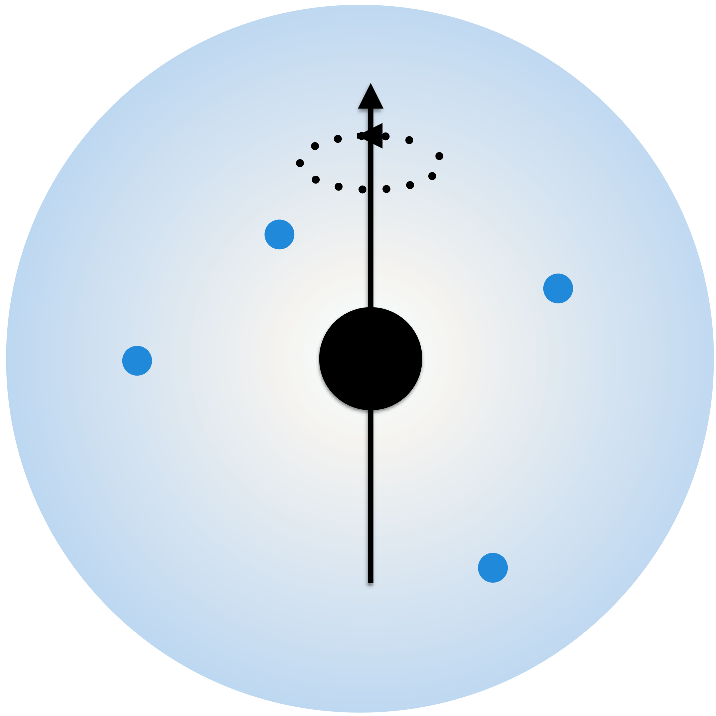
M. Baryakhtar

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

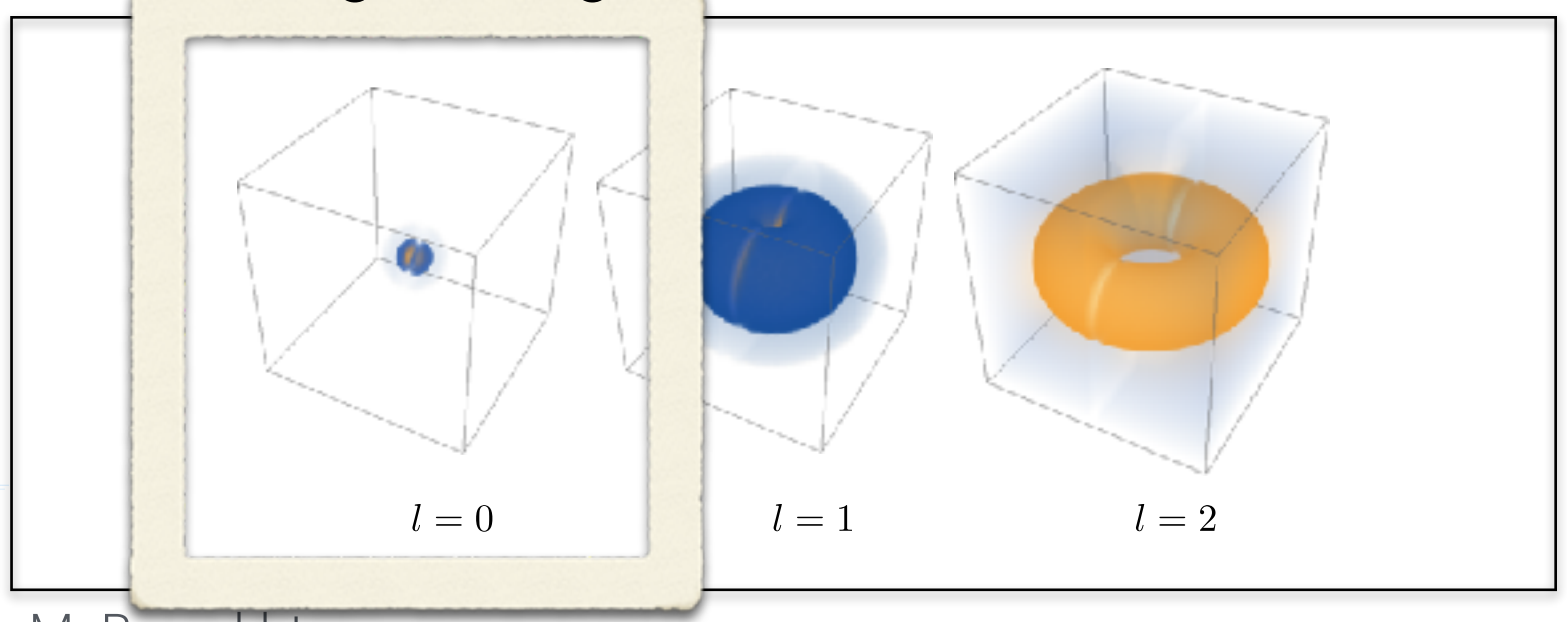
$$\alpha \propto \mu_b M_{\rm BH}$$

Gravitational "atom" sources continuous gravitational waves





fastest growing level

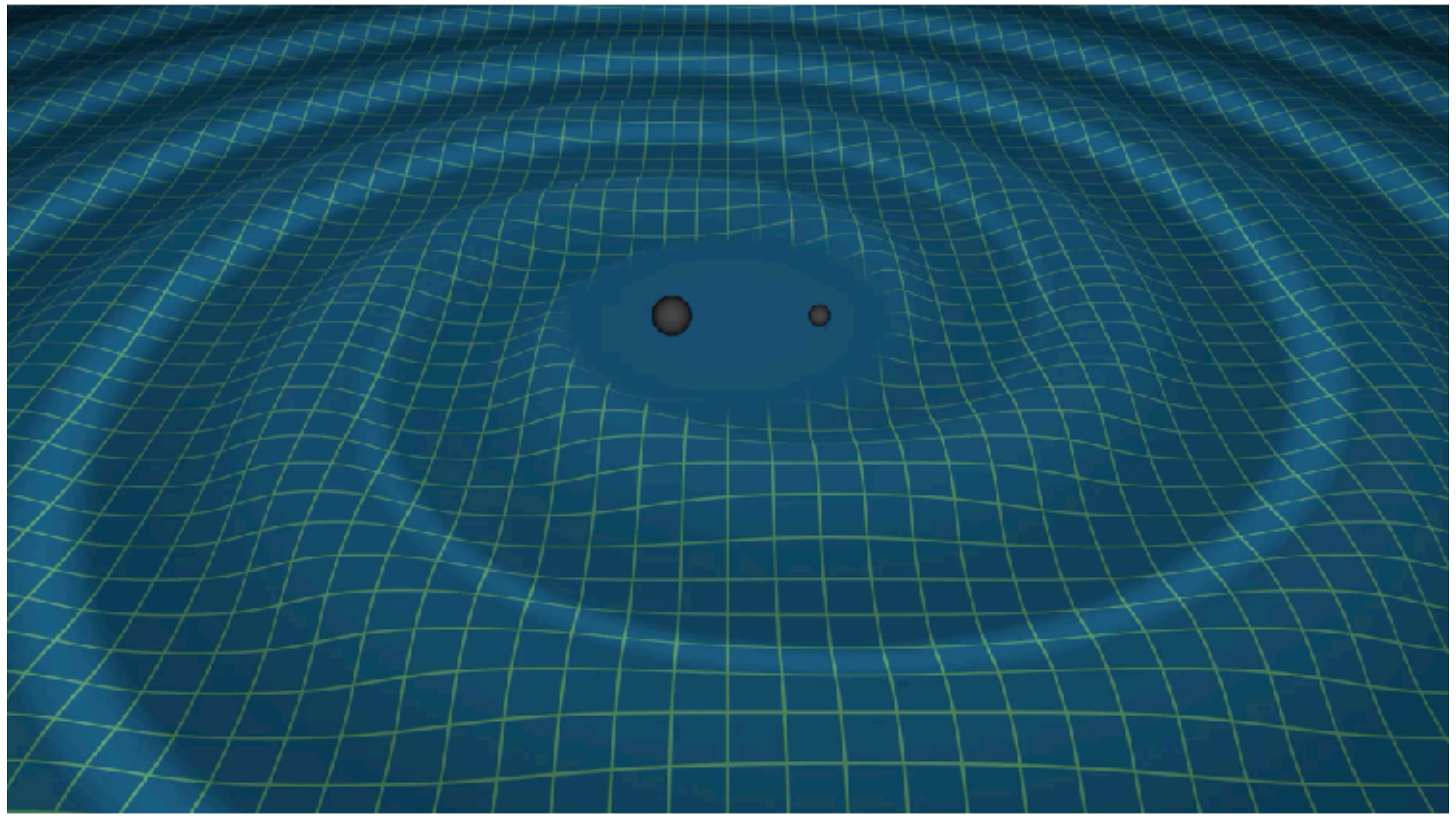


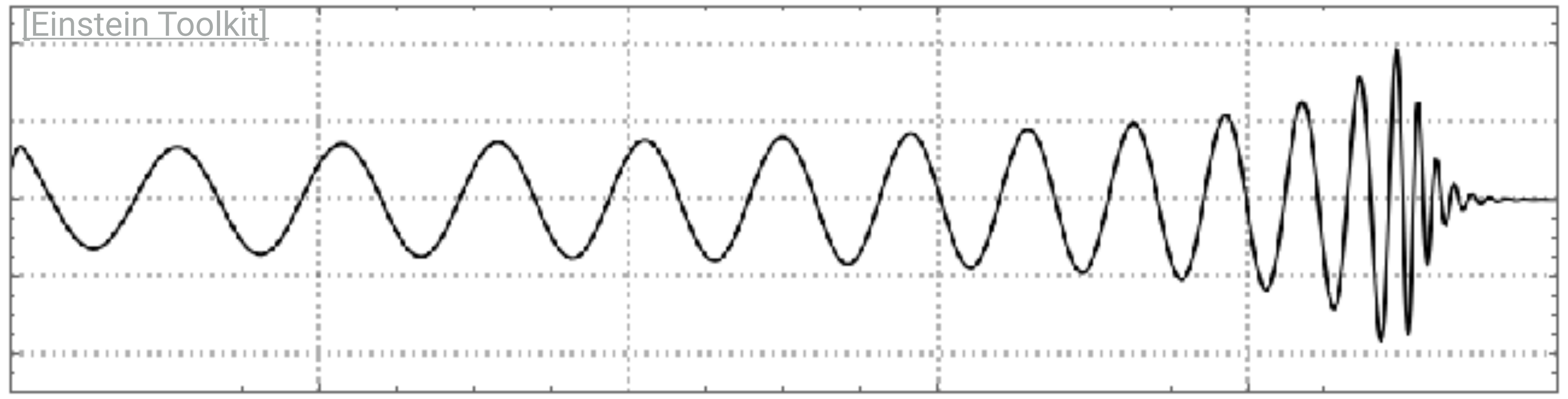
M. Baryakhtar

$\alpha \propto \mu_{\rm b} M_{\rm BH}$

Some types of gravitational-wave signals

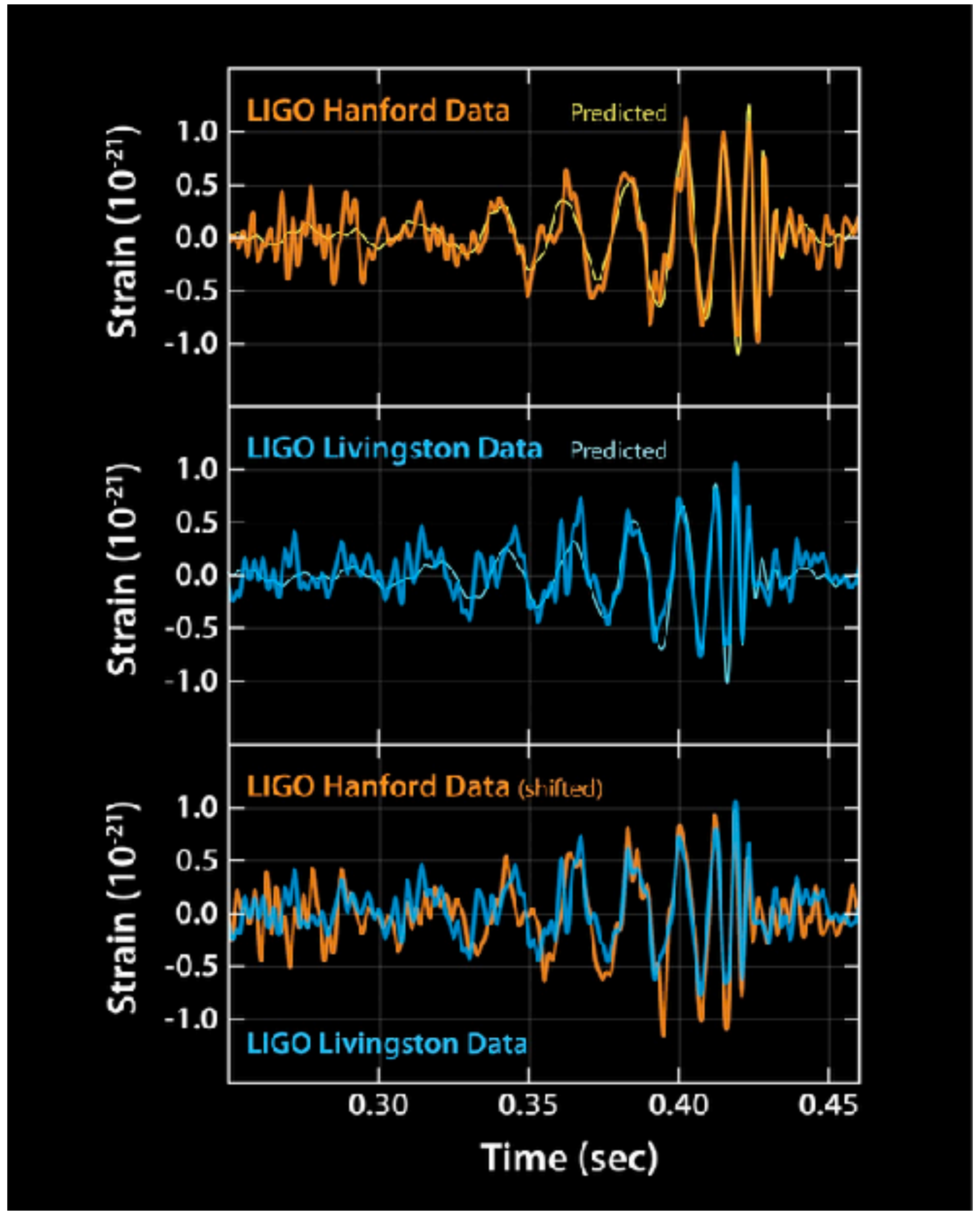
transient signals ($h \lesssim 10^{-21}$)





strain *h*: fractional change in length

binary orbit



[R. Hurt - Caltech/JPL][Caltech/MIT/LIGO Lab]

Some types of gravitational-wave signals

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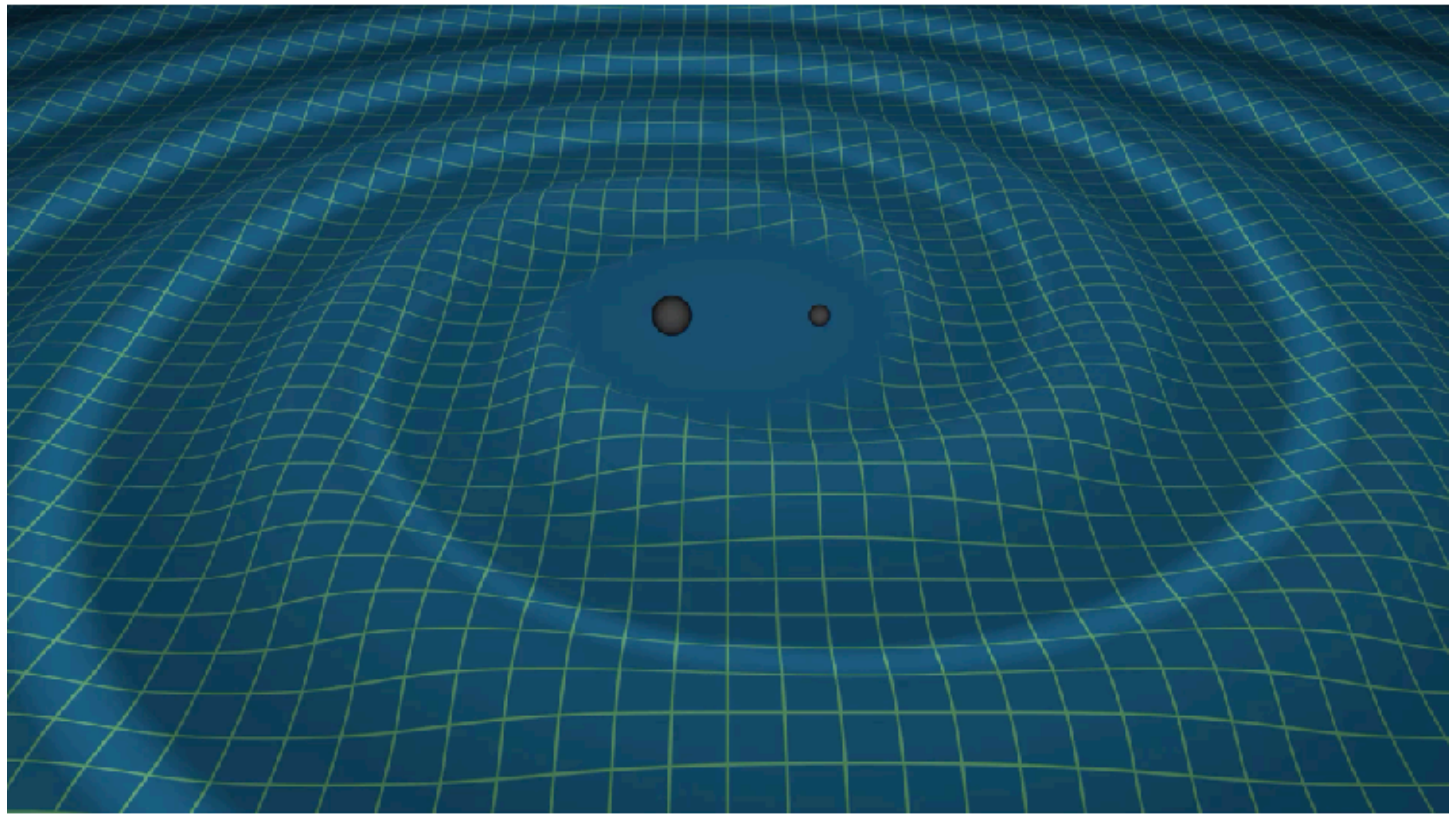
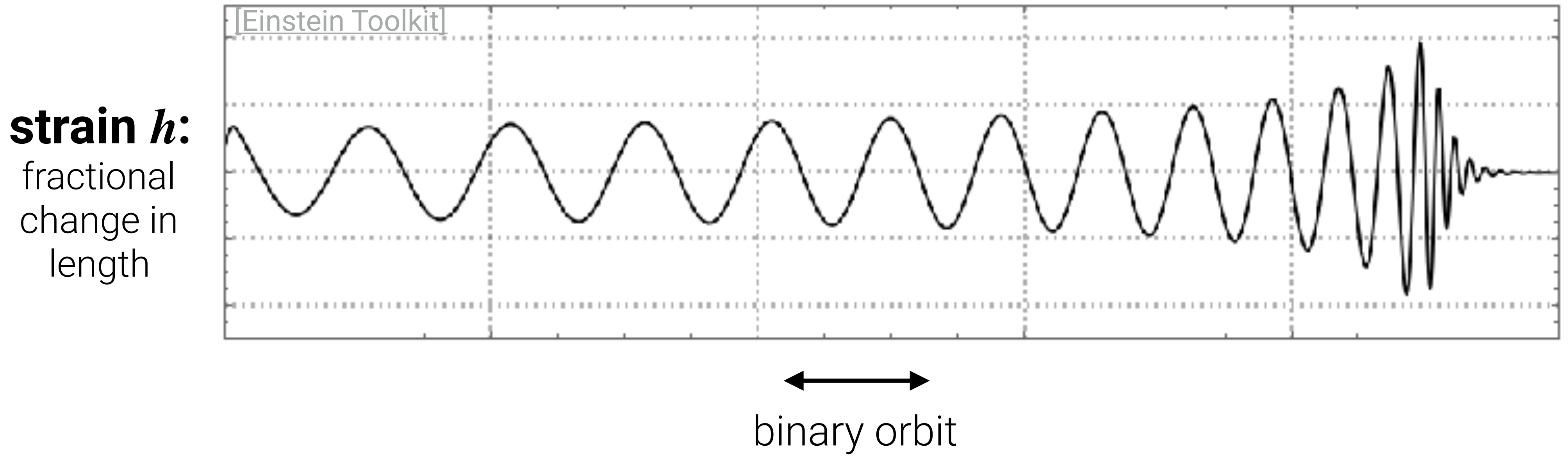
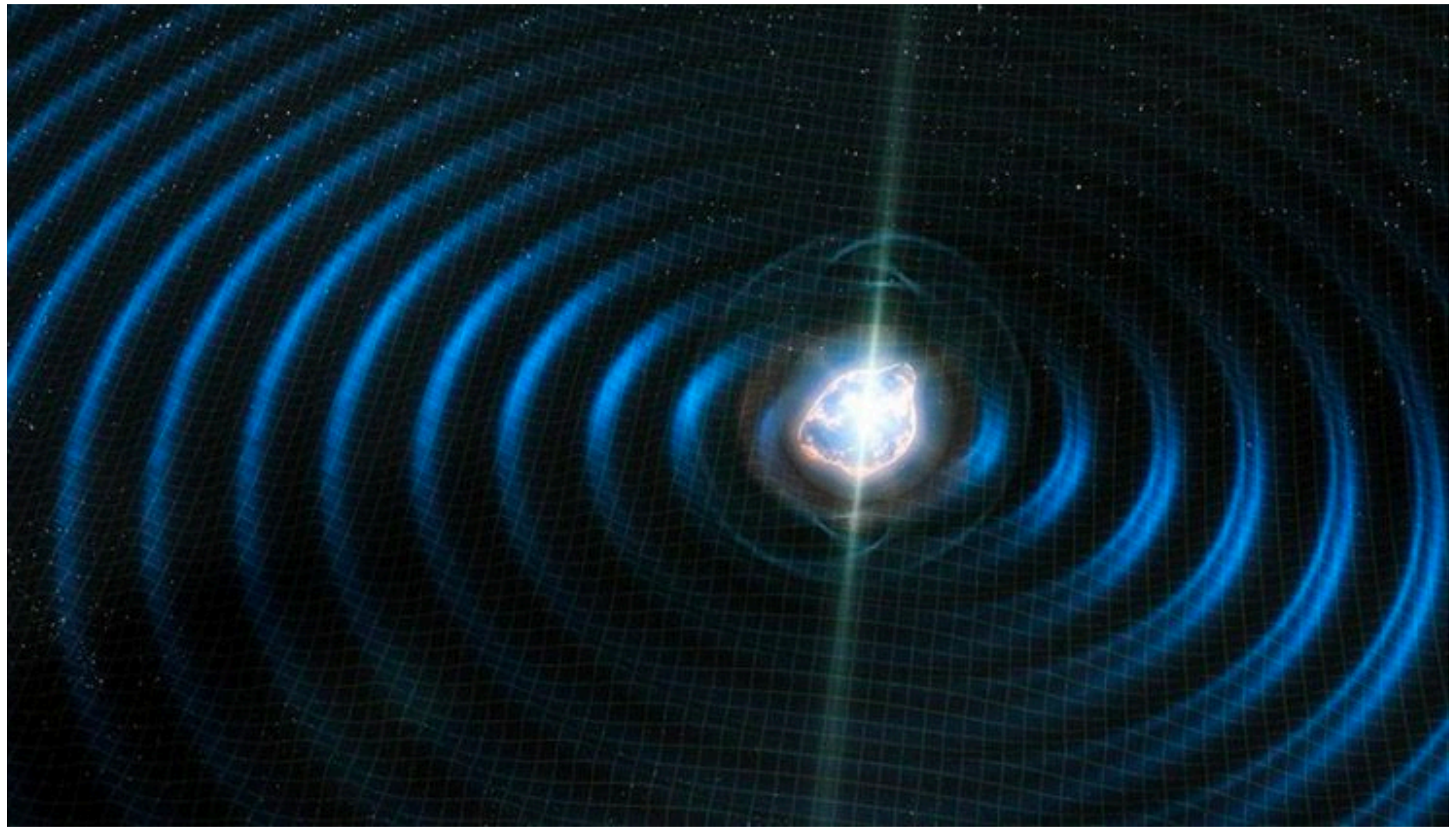
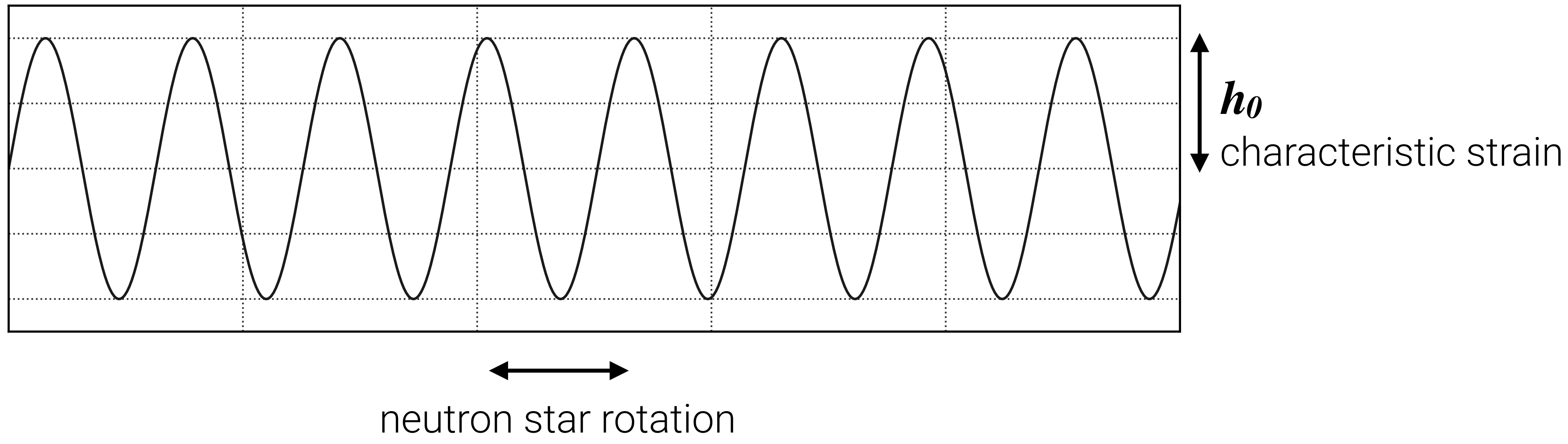


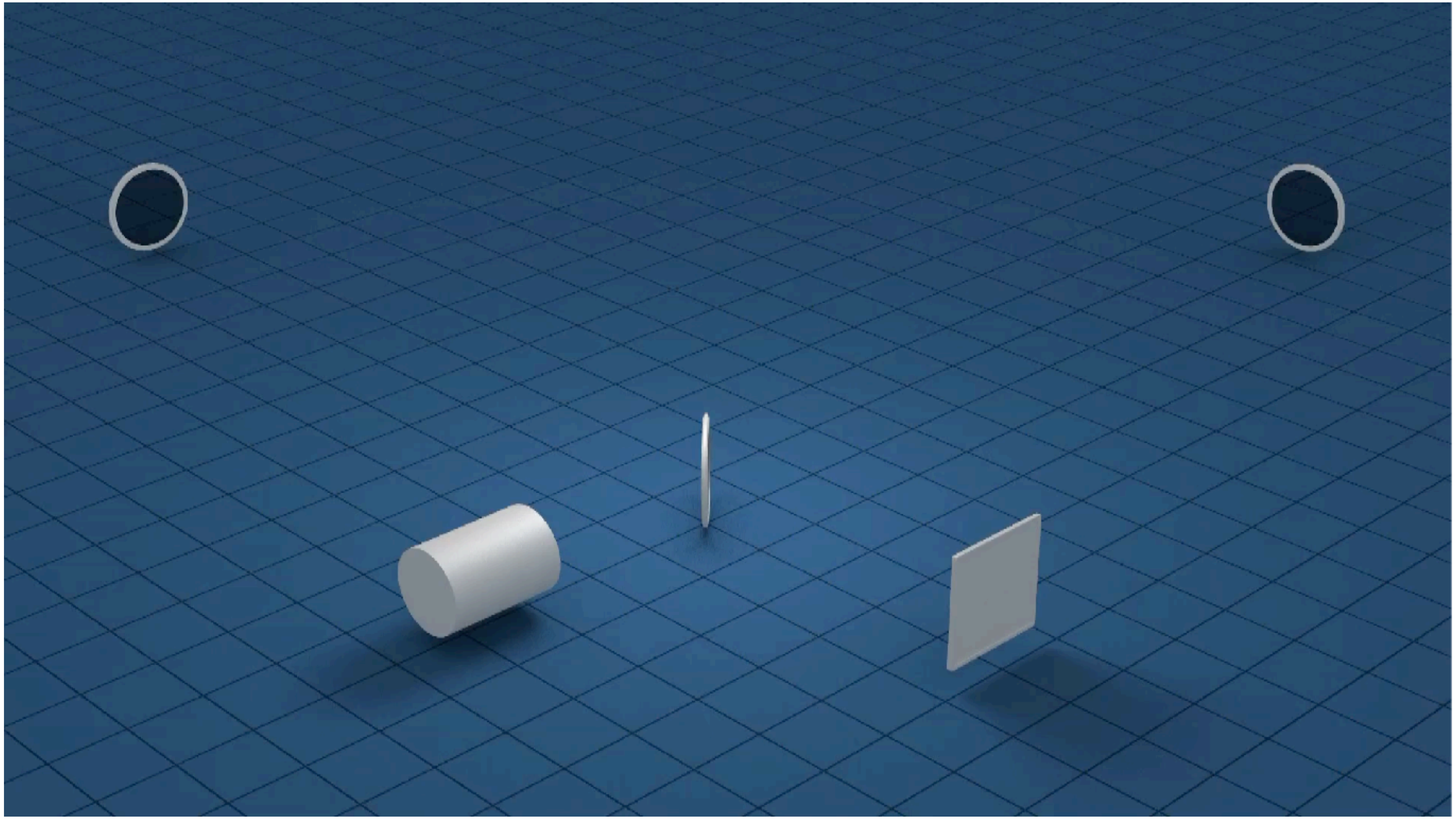


continuous signals ($h \lesssim 10^{-25}$)





Gravitational-wave interferometers

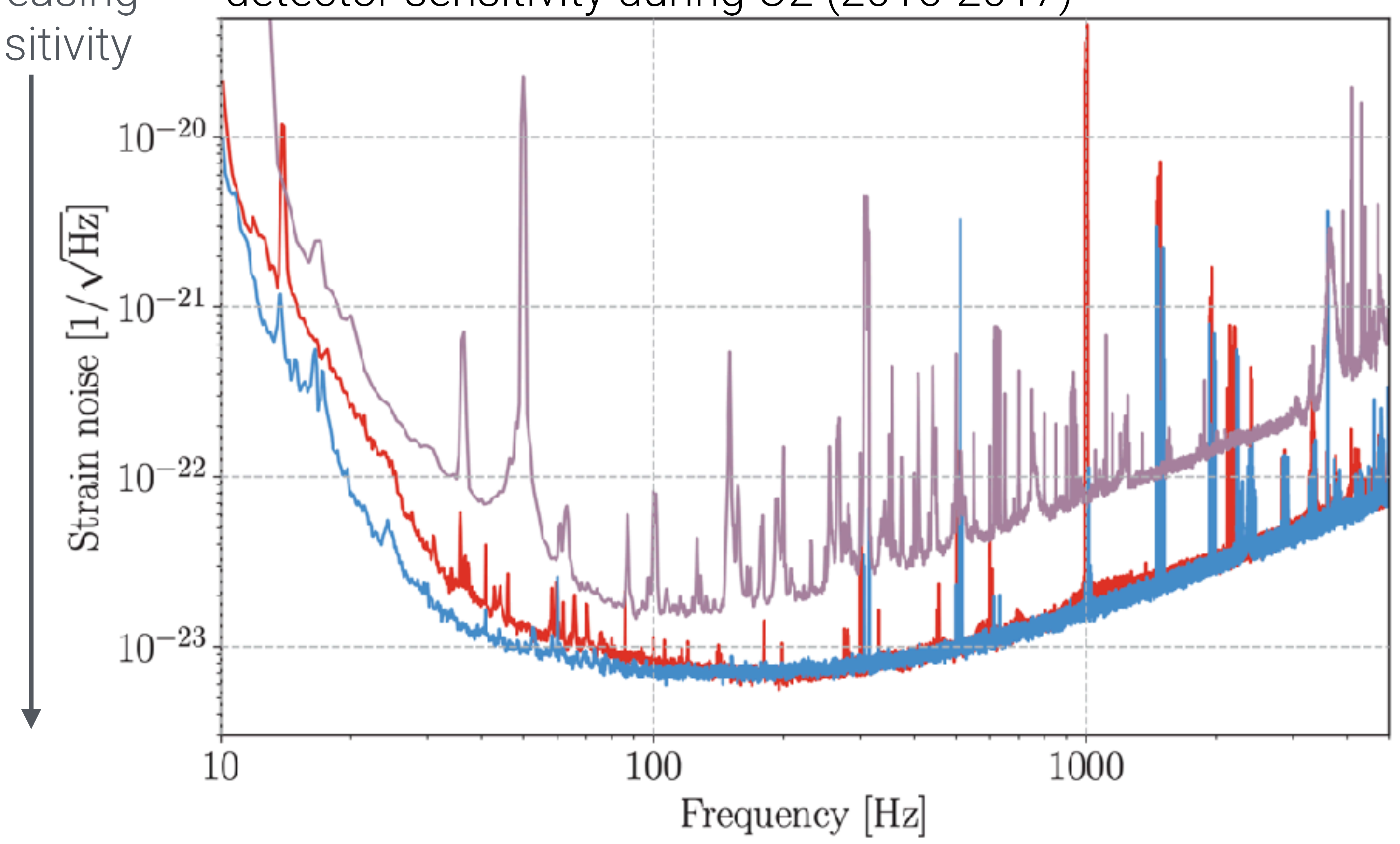


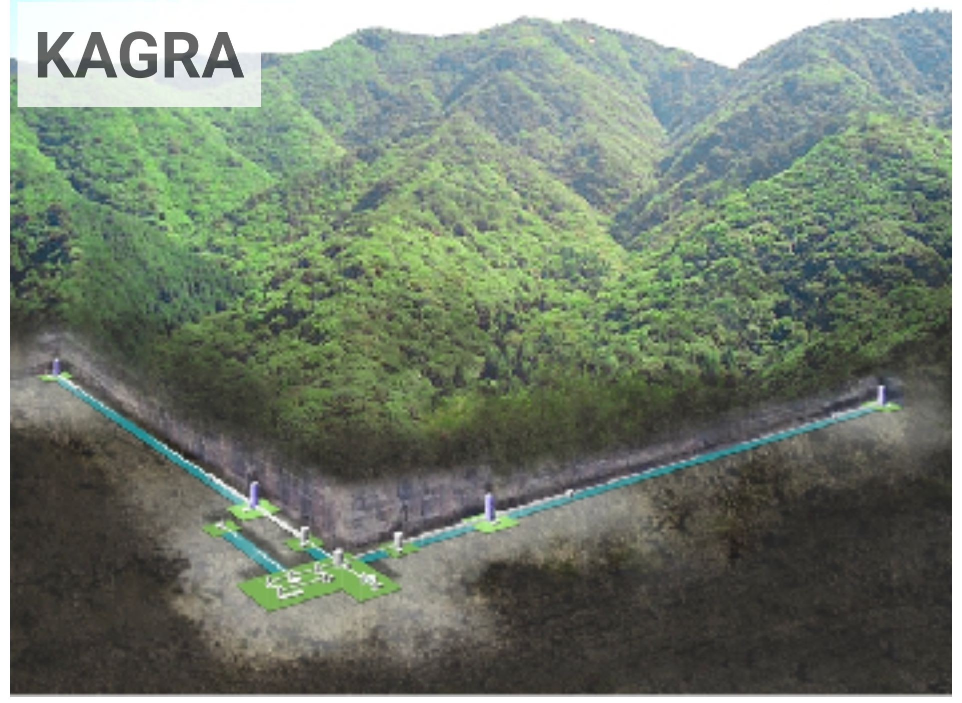
[T. Pyle, Caltech/MIT/LIGO Lab]

Gravitational-wave interferometers

increasing sensitivity

detector sensitivity during O2 (2016-2017)

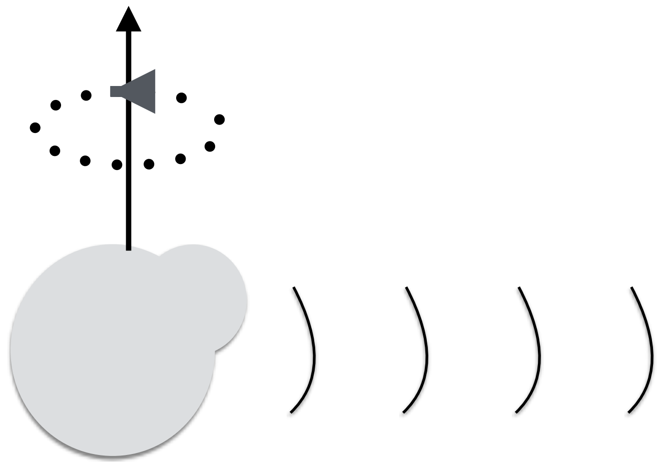


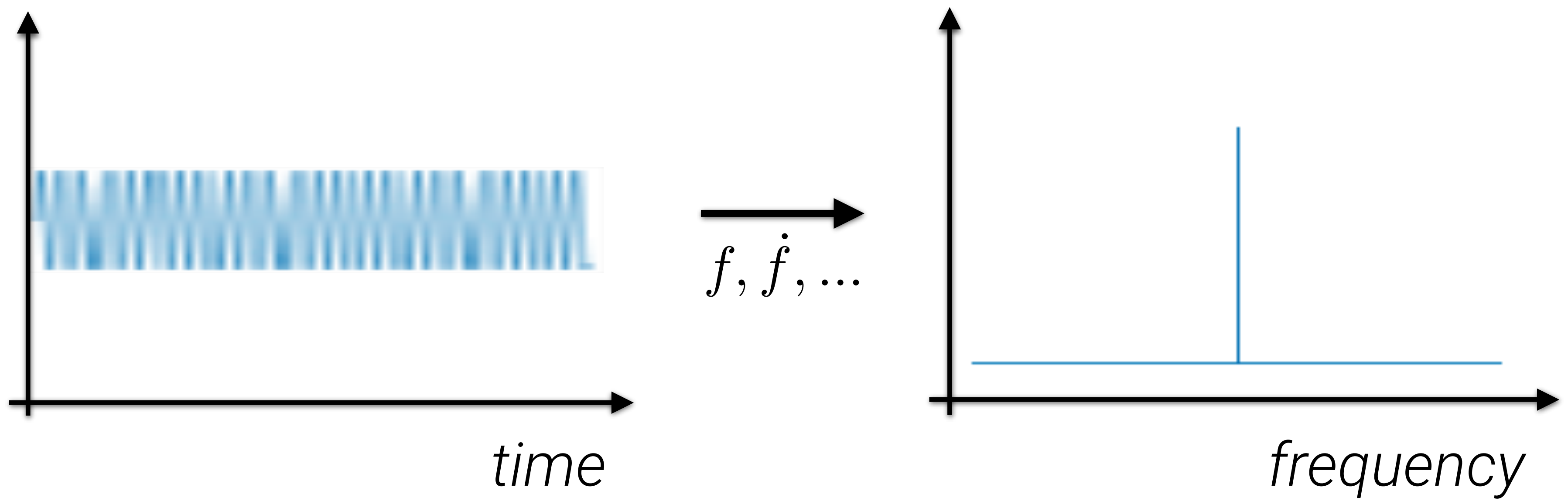


[LIGO, Virgo, and KAGRA collaborations][Abbott et al. (2019)]

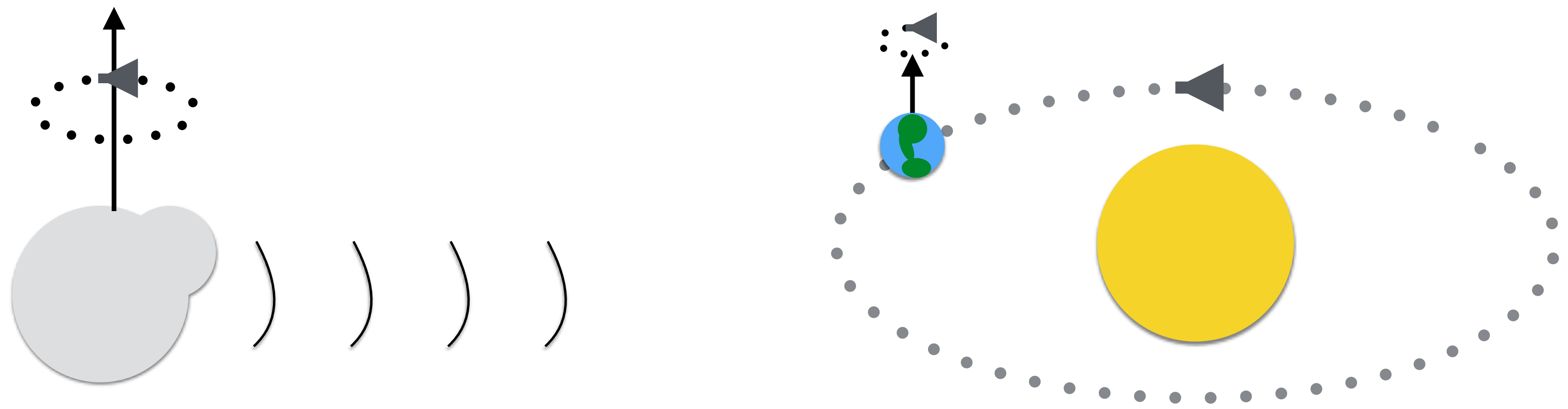
Searching for continuous gravitational waves

the waveform at the **source**:

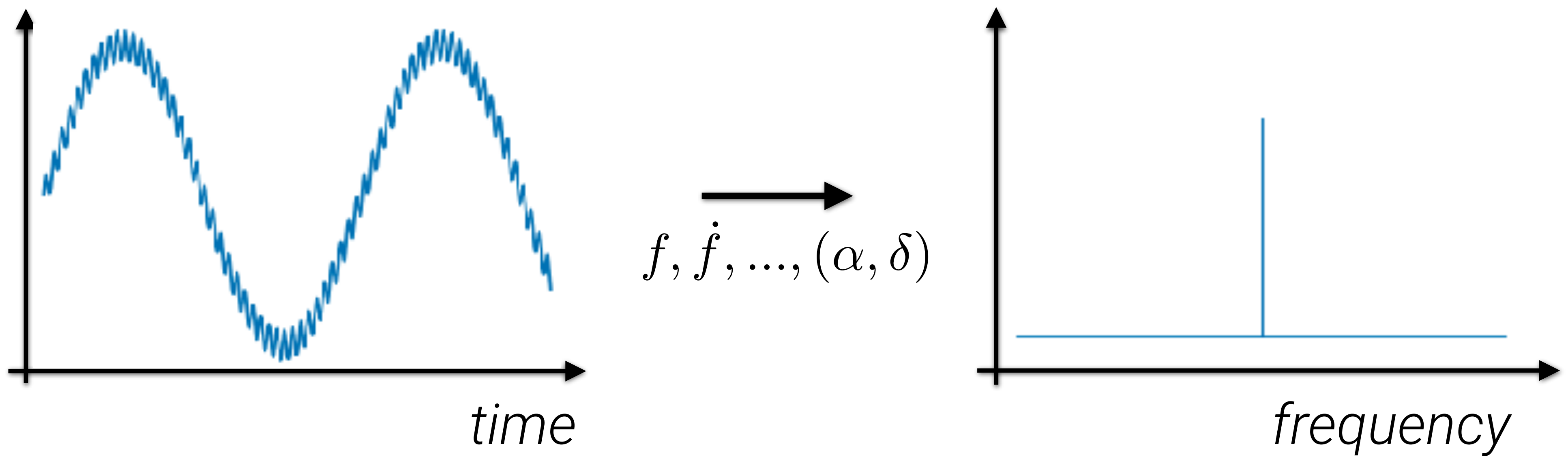




the waveform at the **detector**:

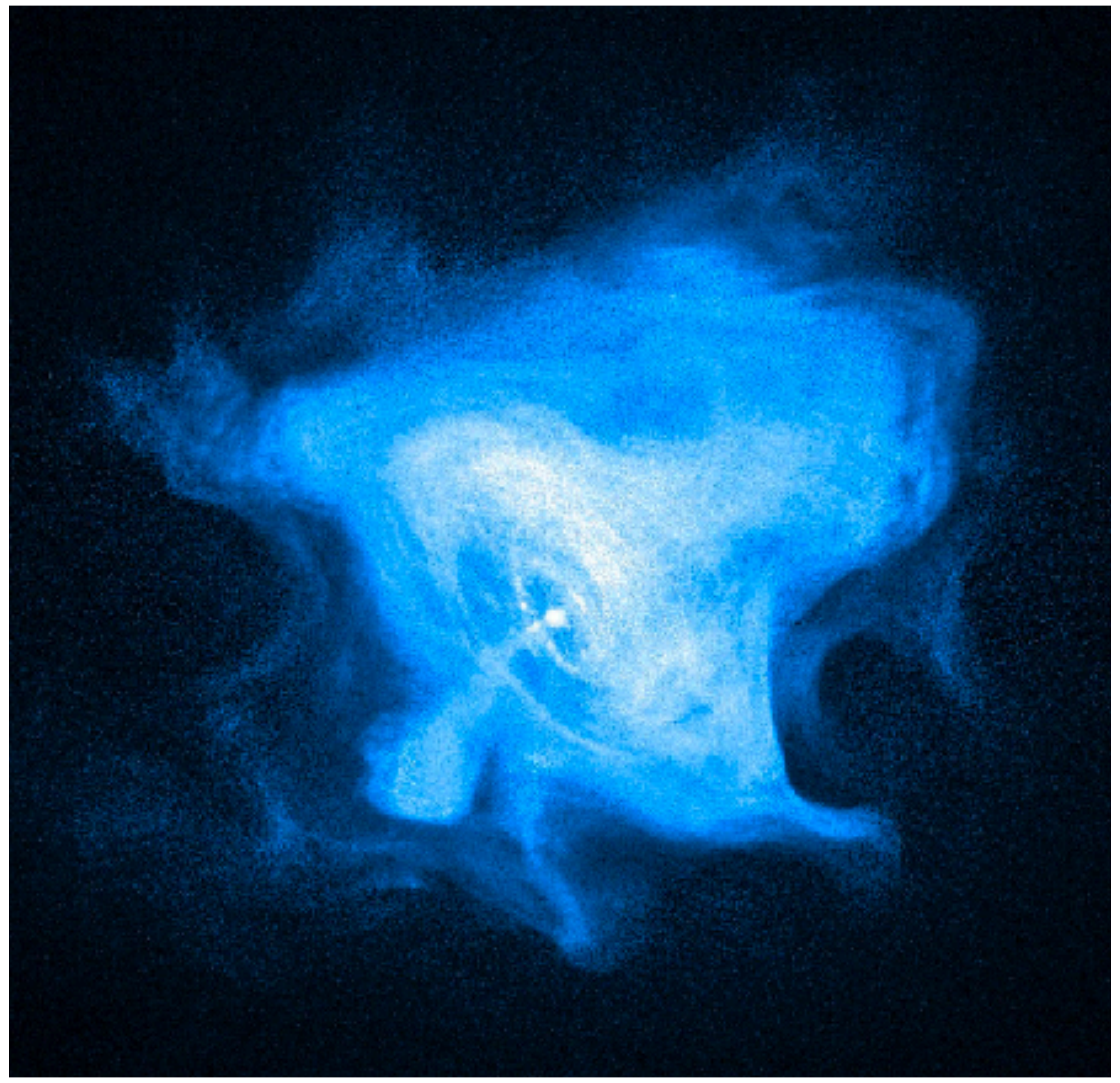


demodulate the signal for ~every point in the sky

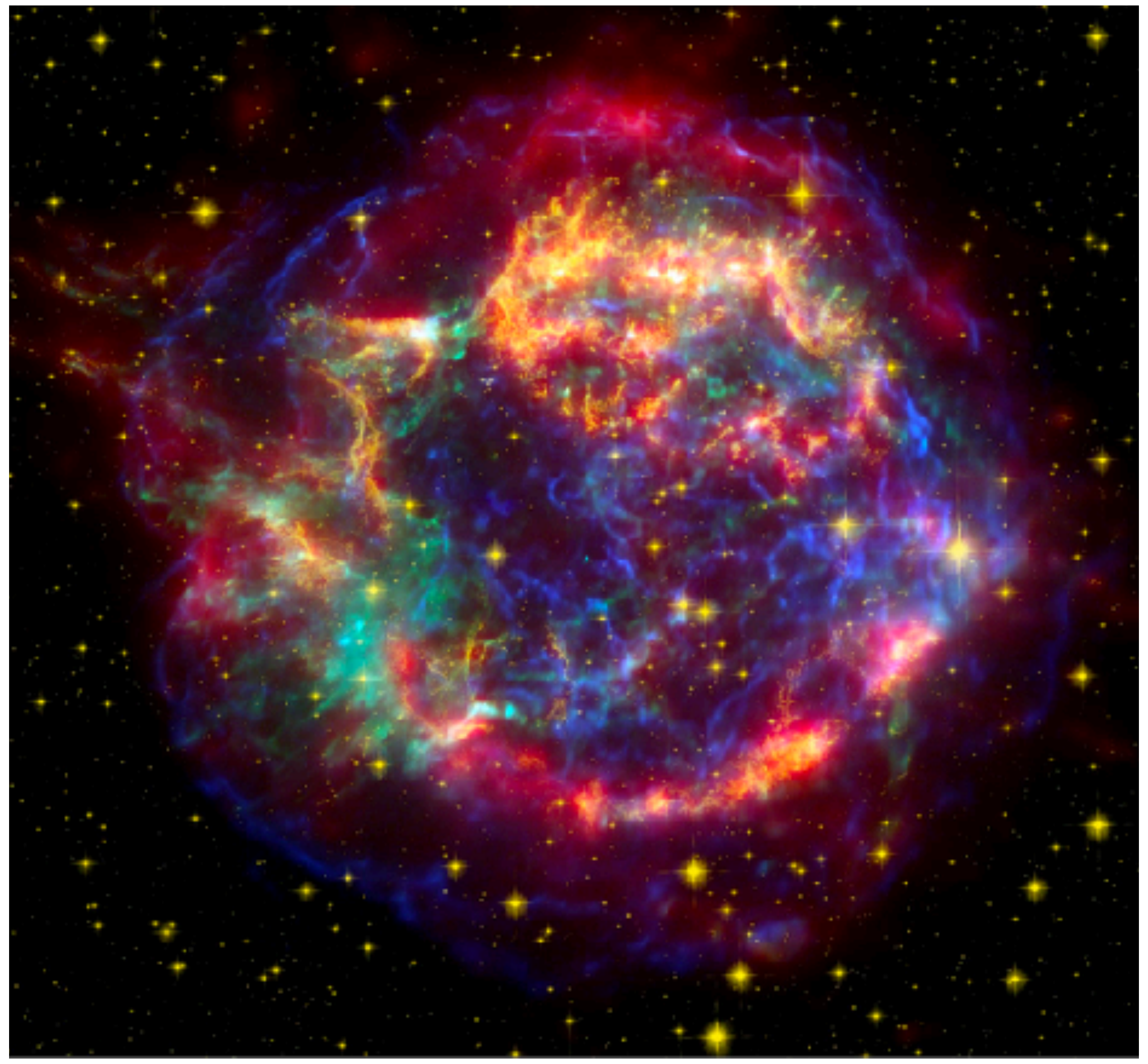


Types of searches

targeted search
known pulsars



directed search
known neutron stars



all-sky search
minimal assumptions

¯_(ツ)_/¯

computational cost

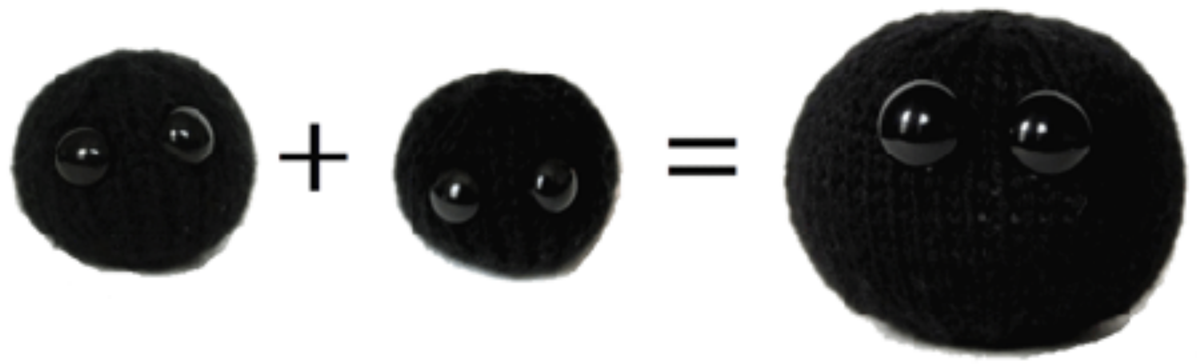
search sensitivity

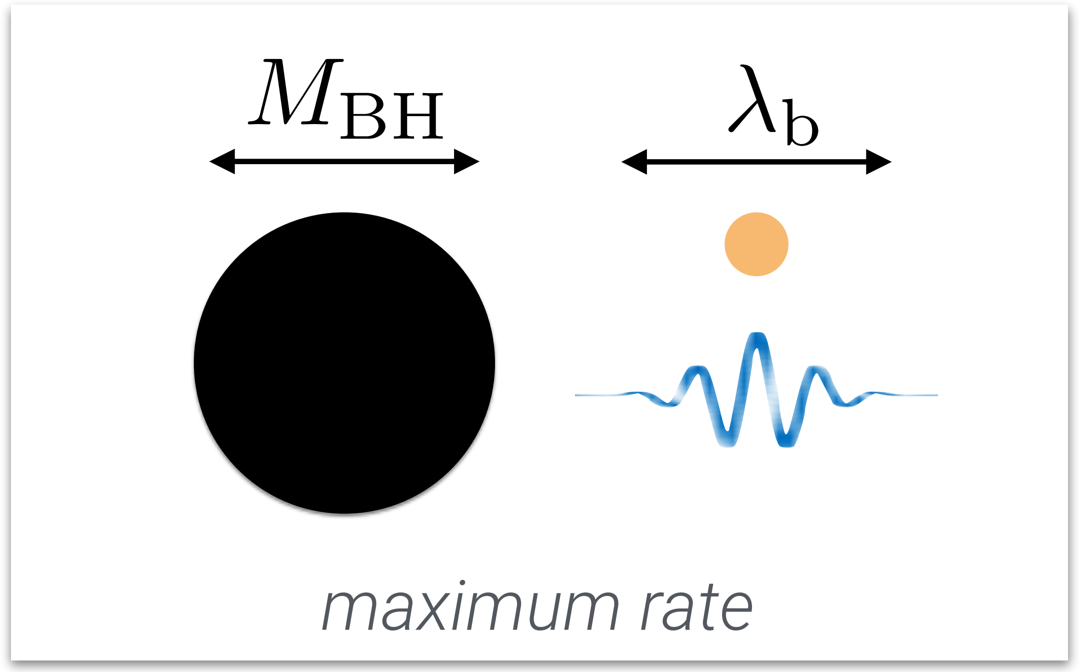
[NASA/CXC/SAO/F.Seward et al.][Courtesy NASA/JPL-Caltech]

Types of searches

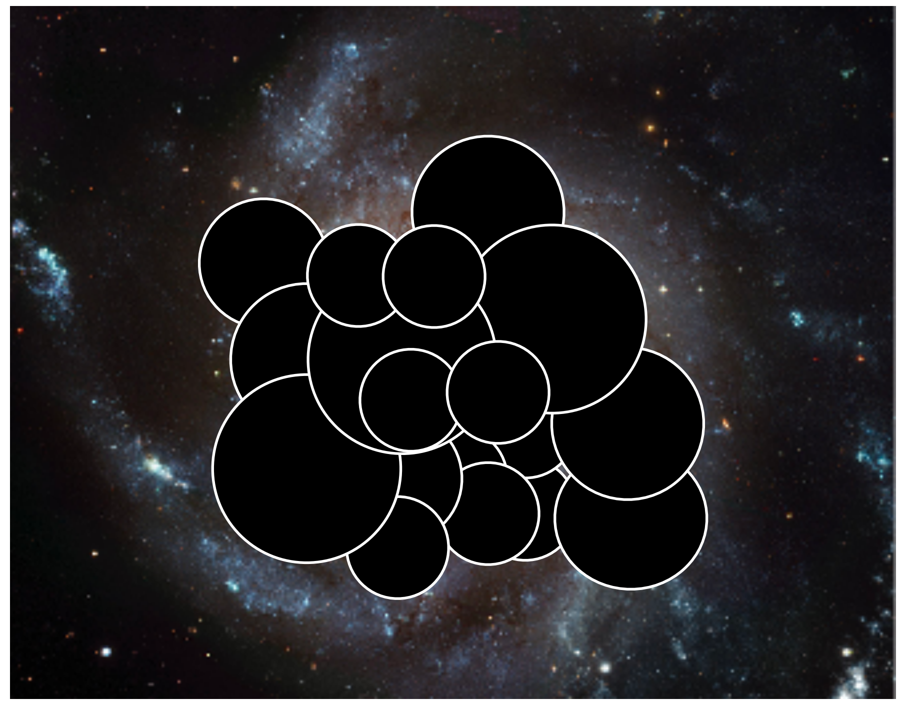
targeted search
known black hole
+
known boson mass

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)



[Christopher Berry, Dawn Finney][ESA/Hubble]

What to do with search results?

Detect a signal → Find the boson 

Detect no signal :(

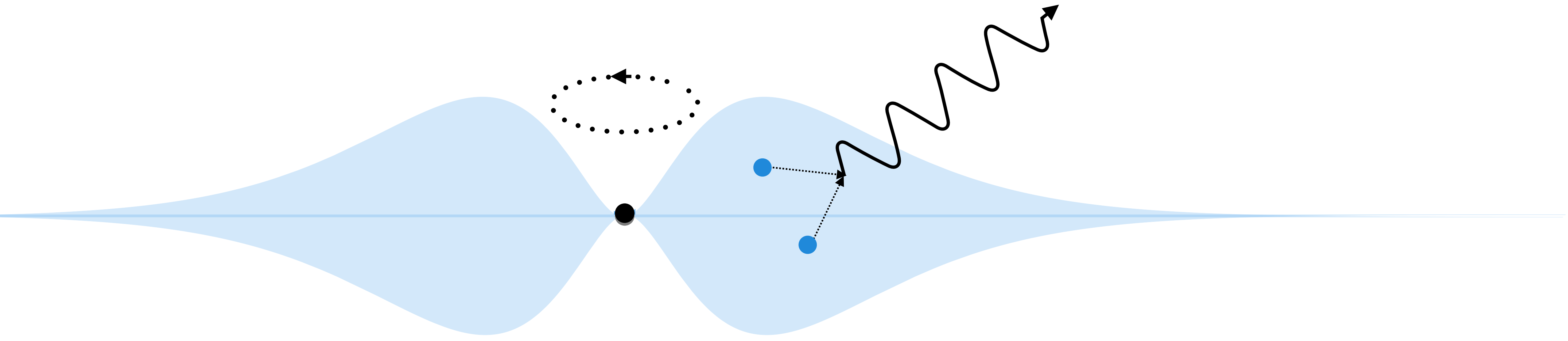
- Because the boson doesn't exist?
- Because the black holes don't result in a detectable signal?
  - Are they too old?
  - Too young?
  - Spinning too slowly?
  - The wrong mass?

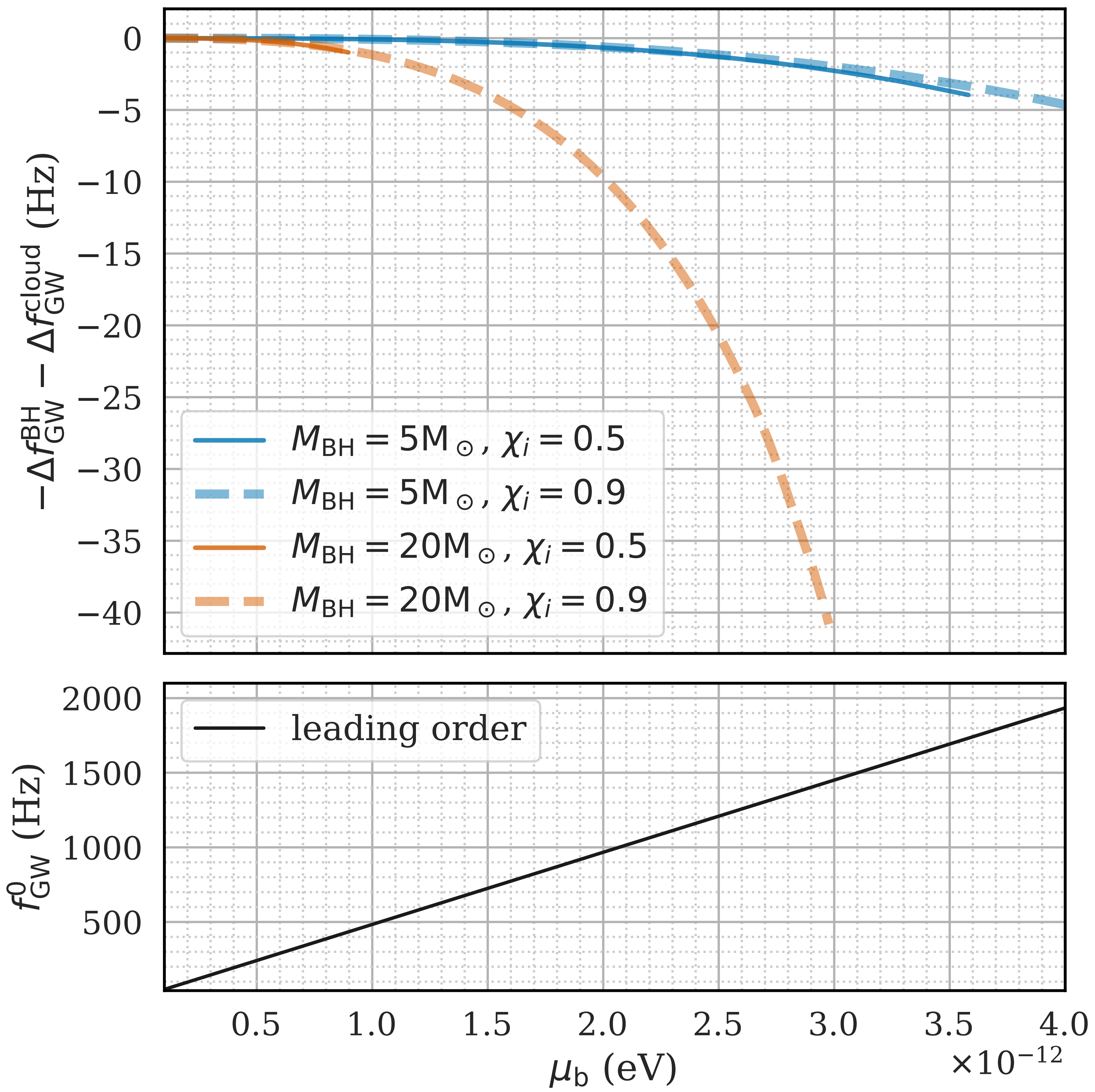
Gravitational “atom” sources continuous gravitational waves

$\alpha \propto \mu_{\rm b} M_{\rm BH}$ **larger α:** (note: spin-0 particles)

$h_{0,\rm peak} \propto \alpha^7$ - louder signals

$f_{\rm GW} \lesssim 2\mu_{\rm b}$

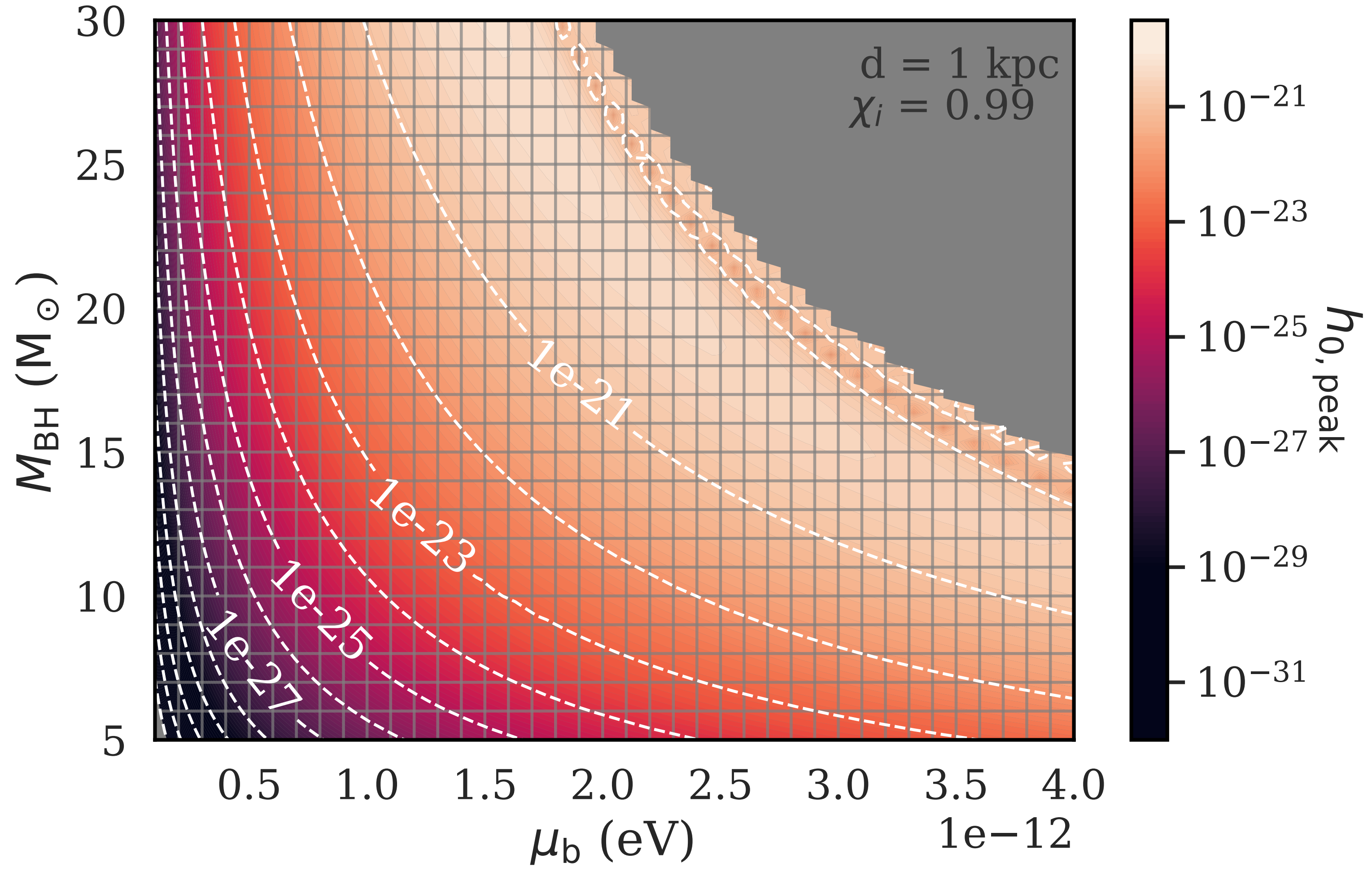




What kind of signals do we expect?

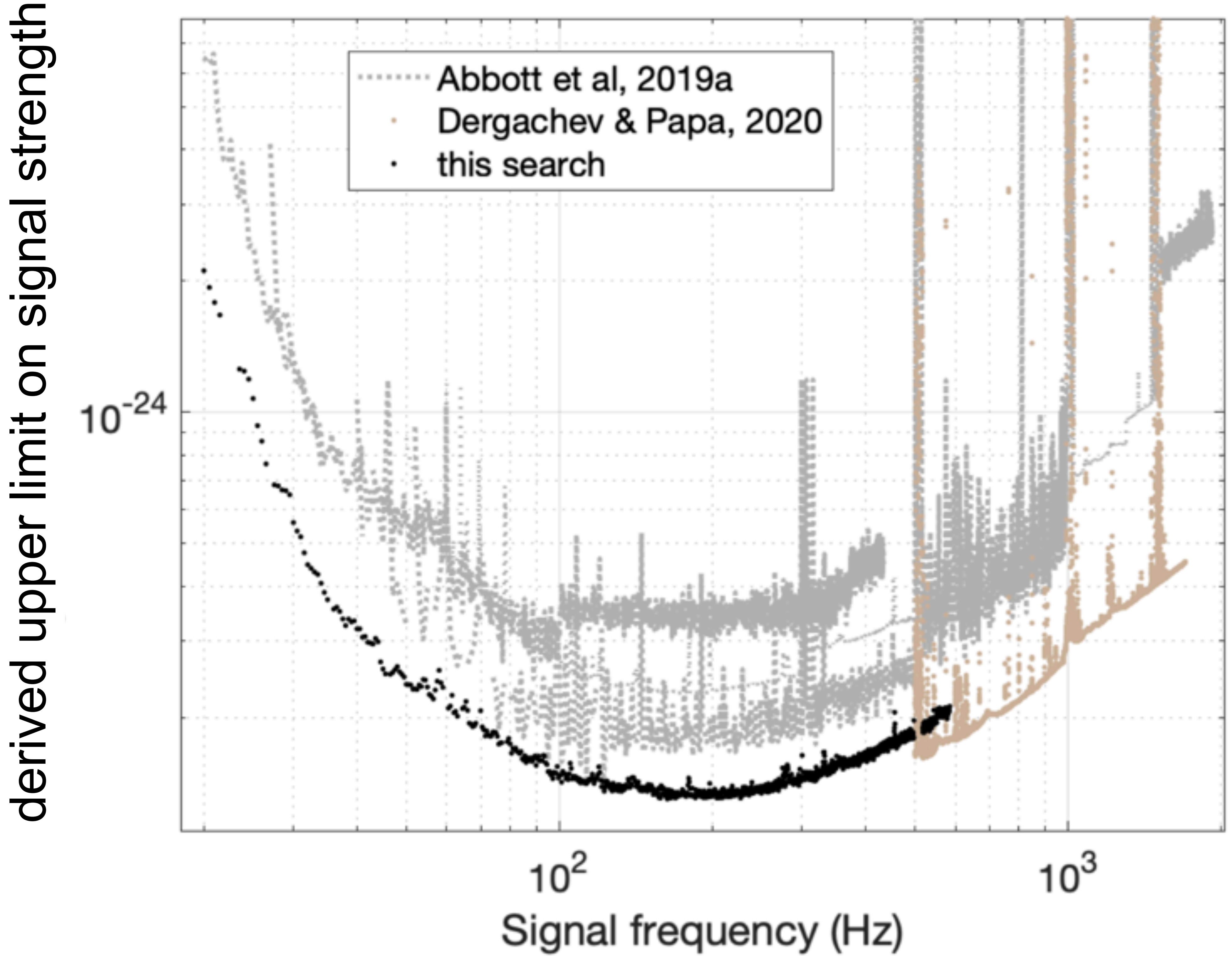
$\alpha \propto \mu_b M_{BH}$ determines most of the signal properties

signal strength



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

recent all-sky search results



Gravitational “atom” sources continuous gravitational waves

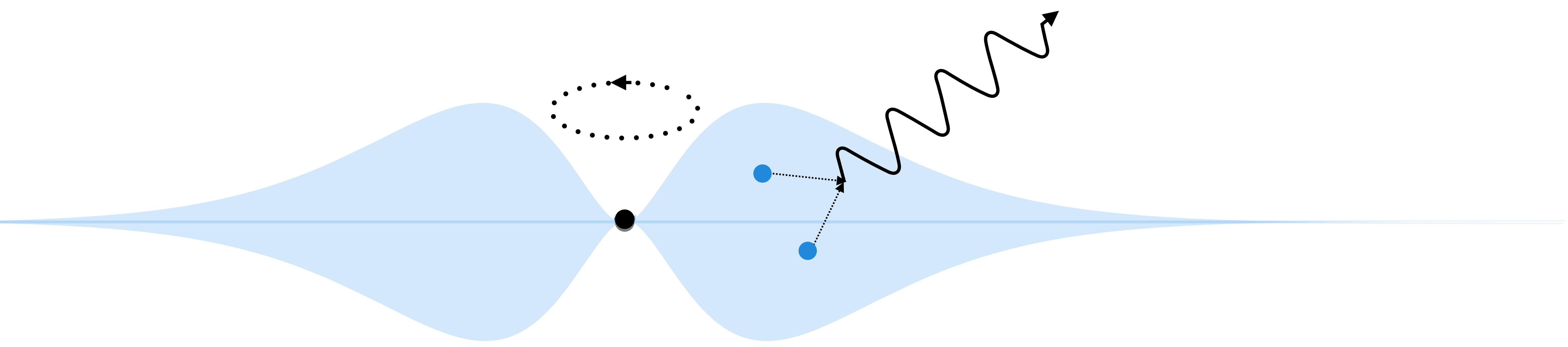
$\alpha \propto \mu_{\rm b} M_{\rm BH}$ **larger α:** (note: spin-0 particles)

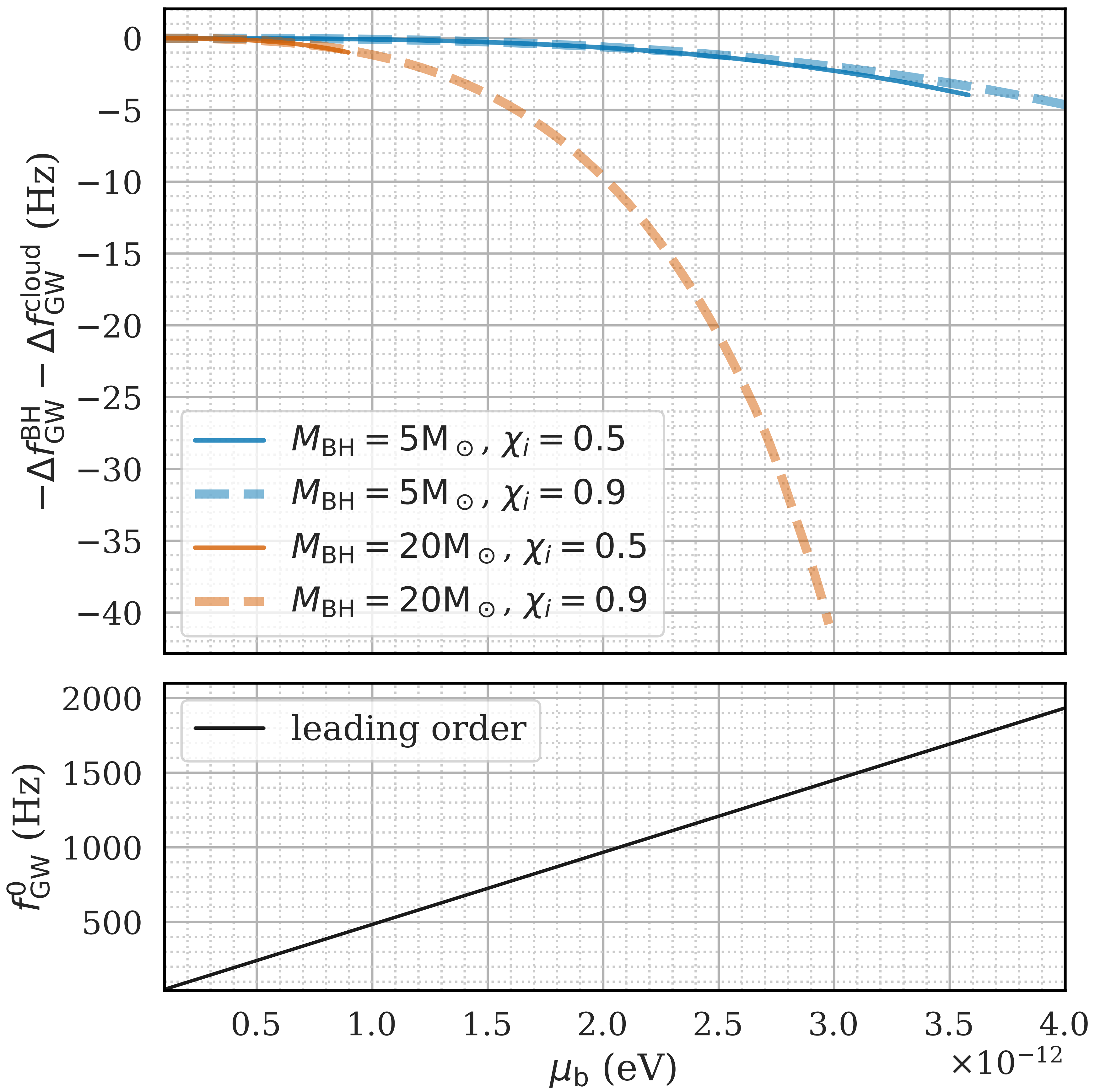
$h_{0,\rm peak} \propto \alpha^7$ - louder signals, but

$\tau_{\rm GW} \propto \alpha^{-15}$ - shorter signal timescales

$\chi_c \approx \dfrac{4\alpha}{1+4\alpha^2}$ - requires faster spinning BHs

$f_{\rm GW} \propto\approx 2\mu_{\rm b}$





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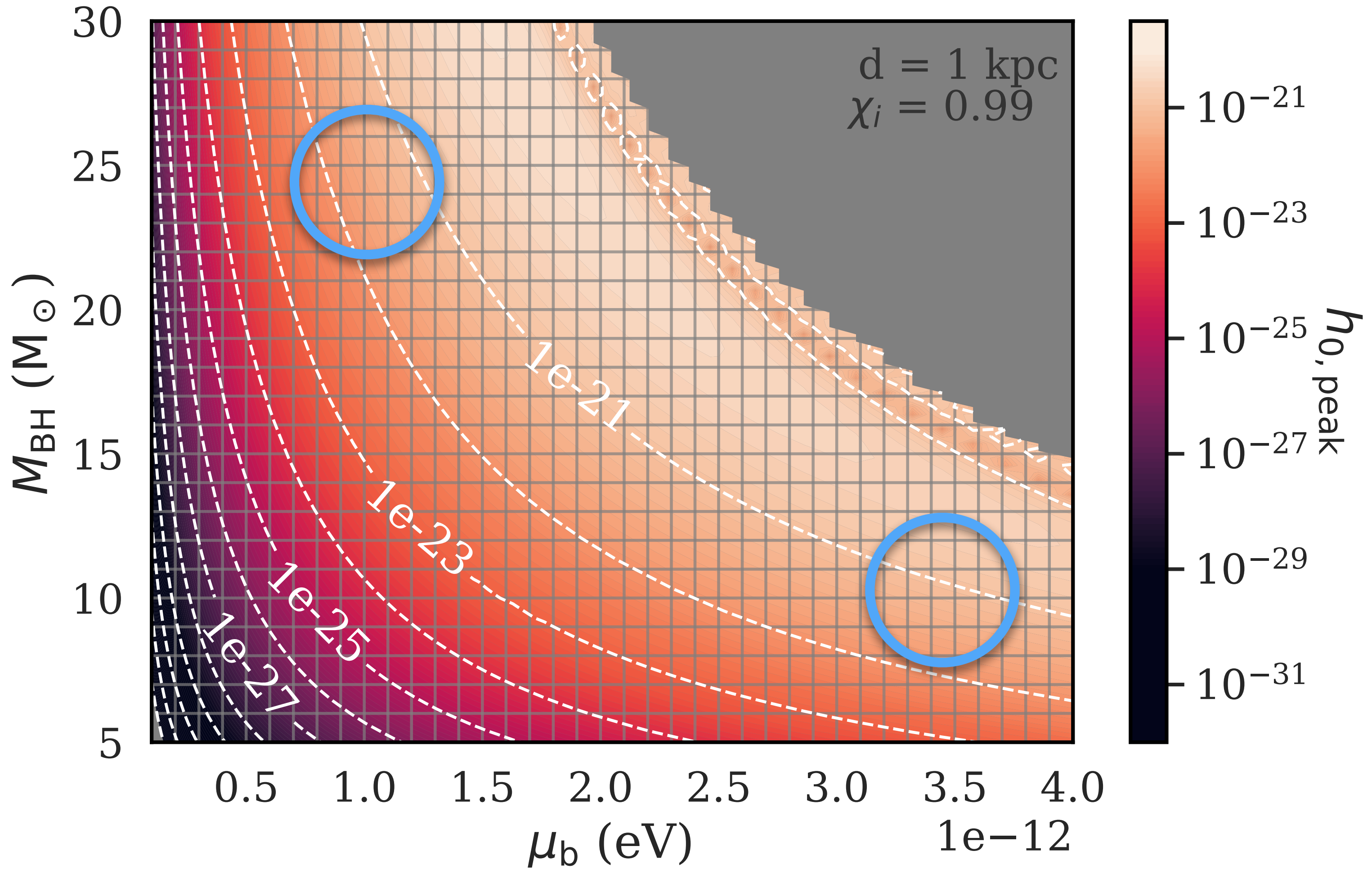
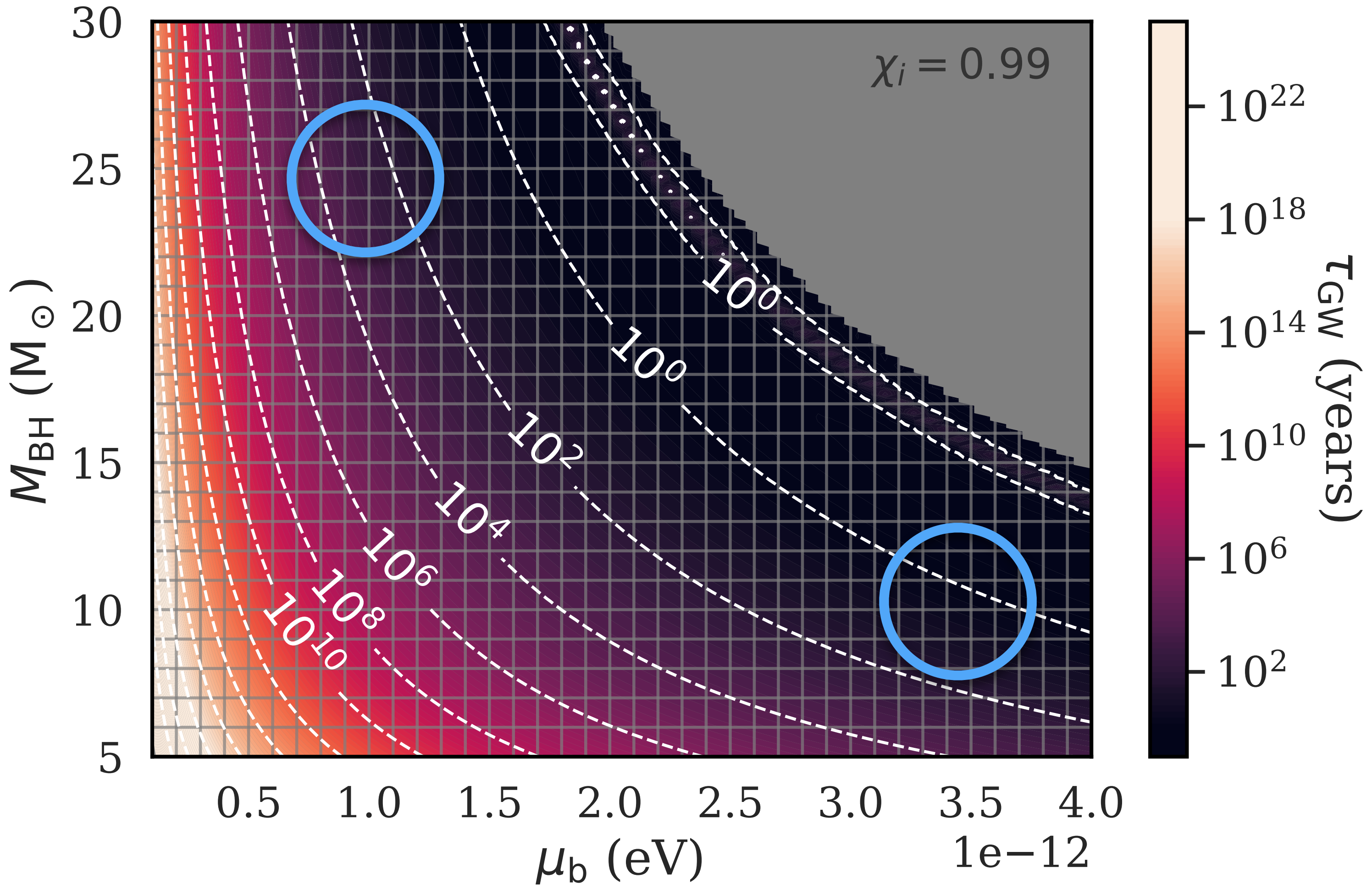


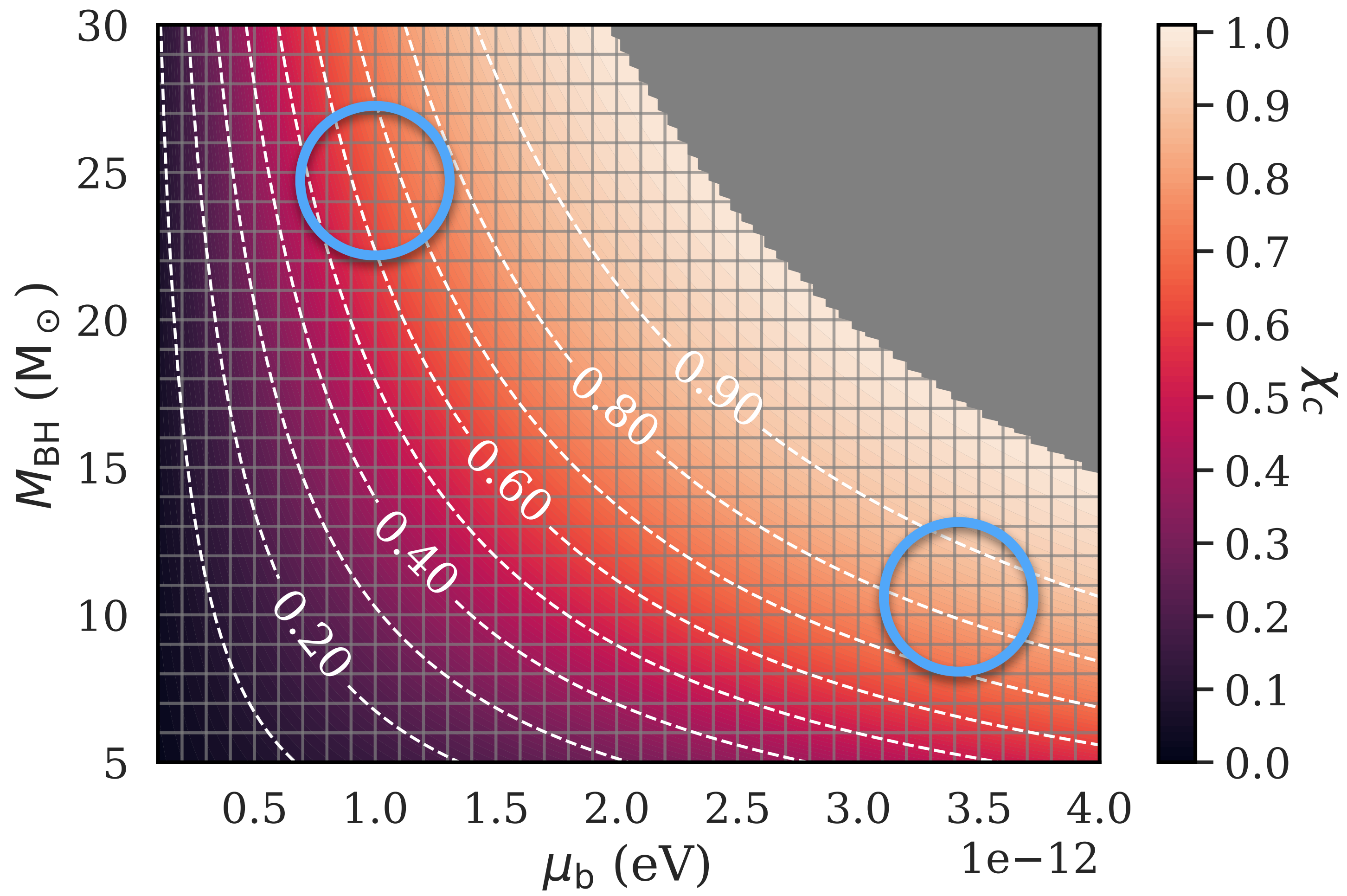
$$h_{0,\rm peak} \propto \alpha^7$$

signal duration



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

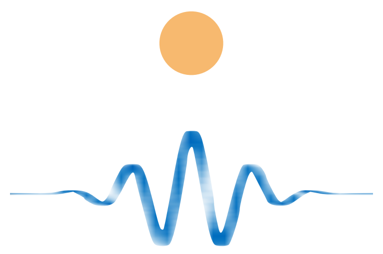
whether the system forms



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

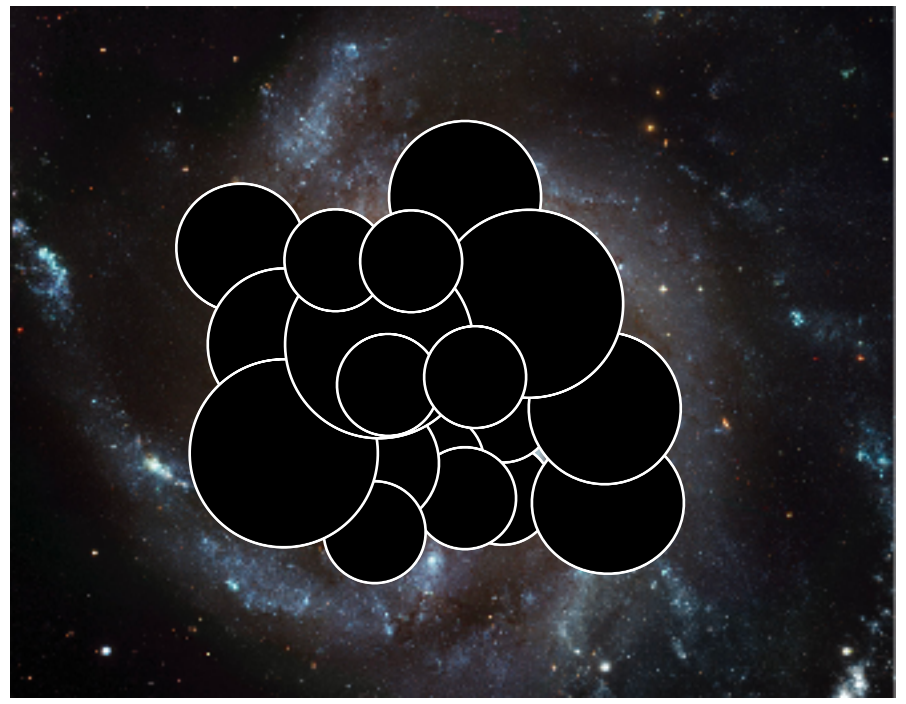
Calculate the signal from every black hole

{μ_b}



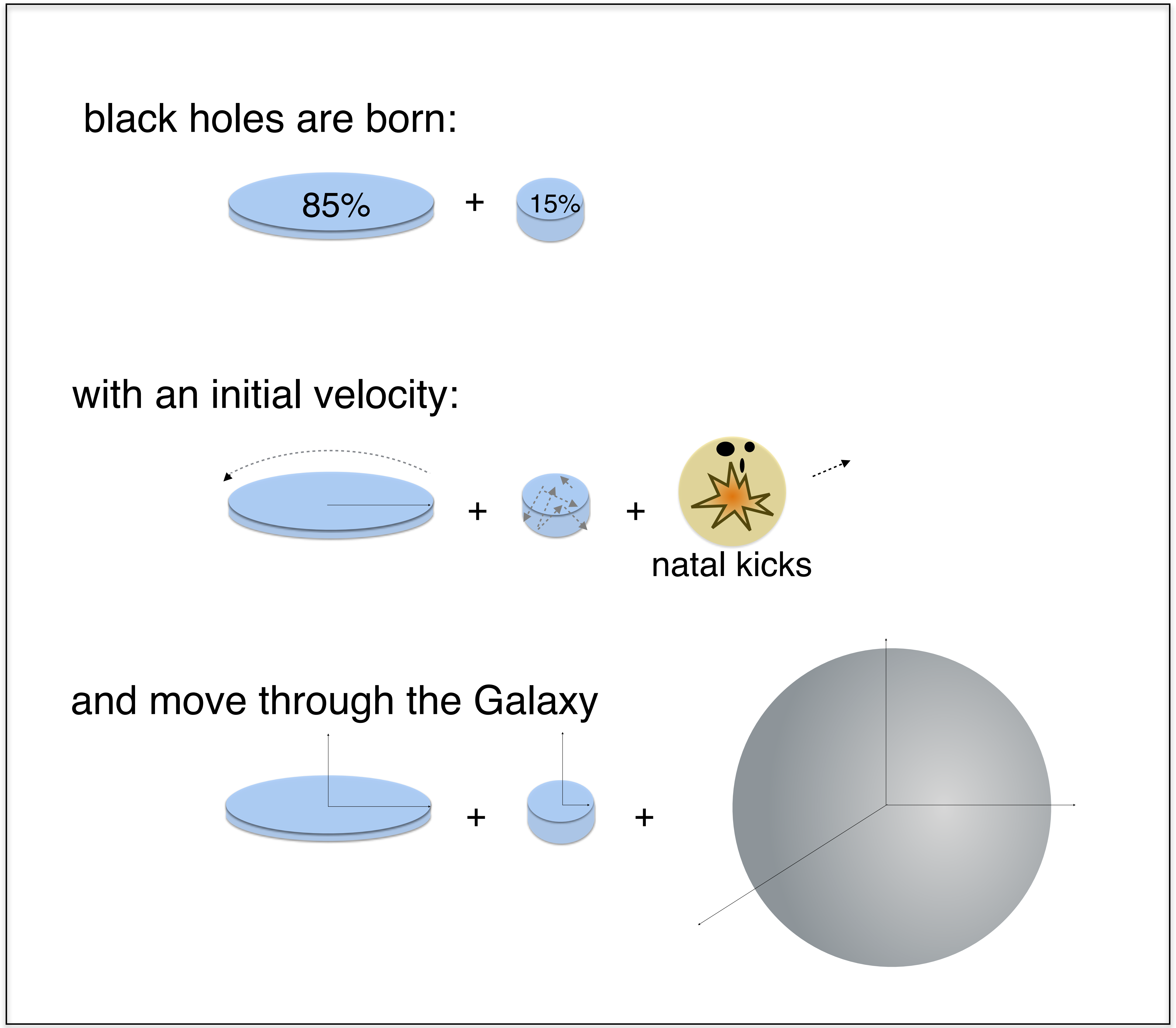
x

{10^8 black holes}



Simulate 10^8 isolated black holes in the Galaxy

galaxy = disk + bulge + halo



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

mass: power-law distribution

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

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

spin: uniform distribution

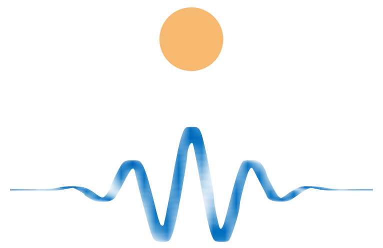
$$\chi_i \in [0, 1]$$

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

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

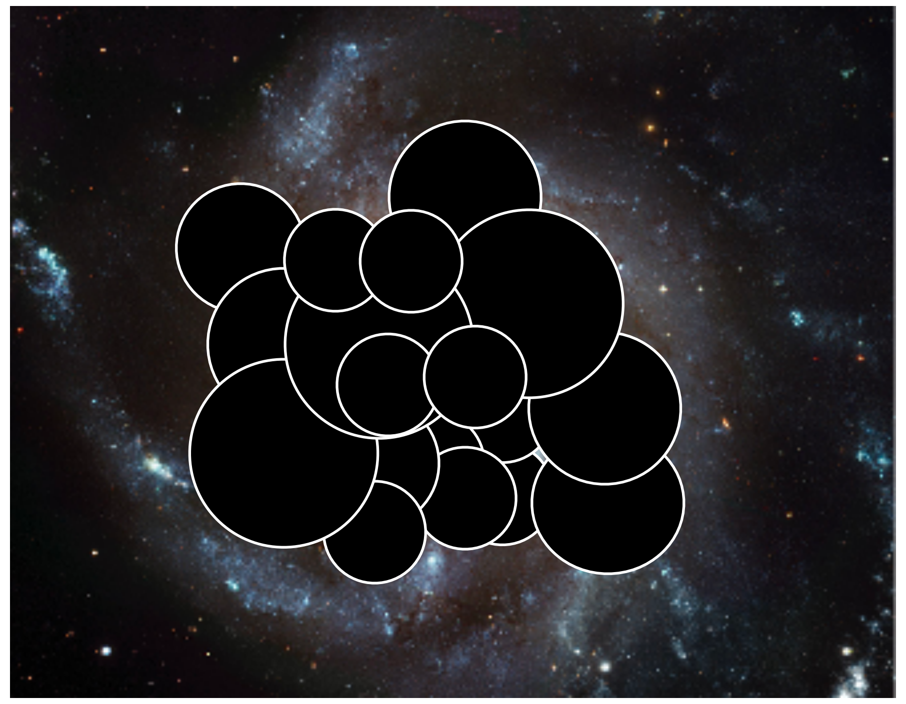
Calculate the signal from every black hole

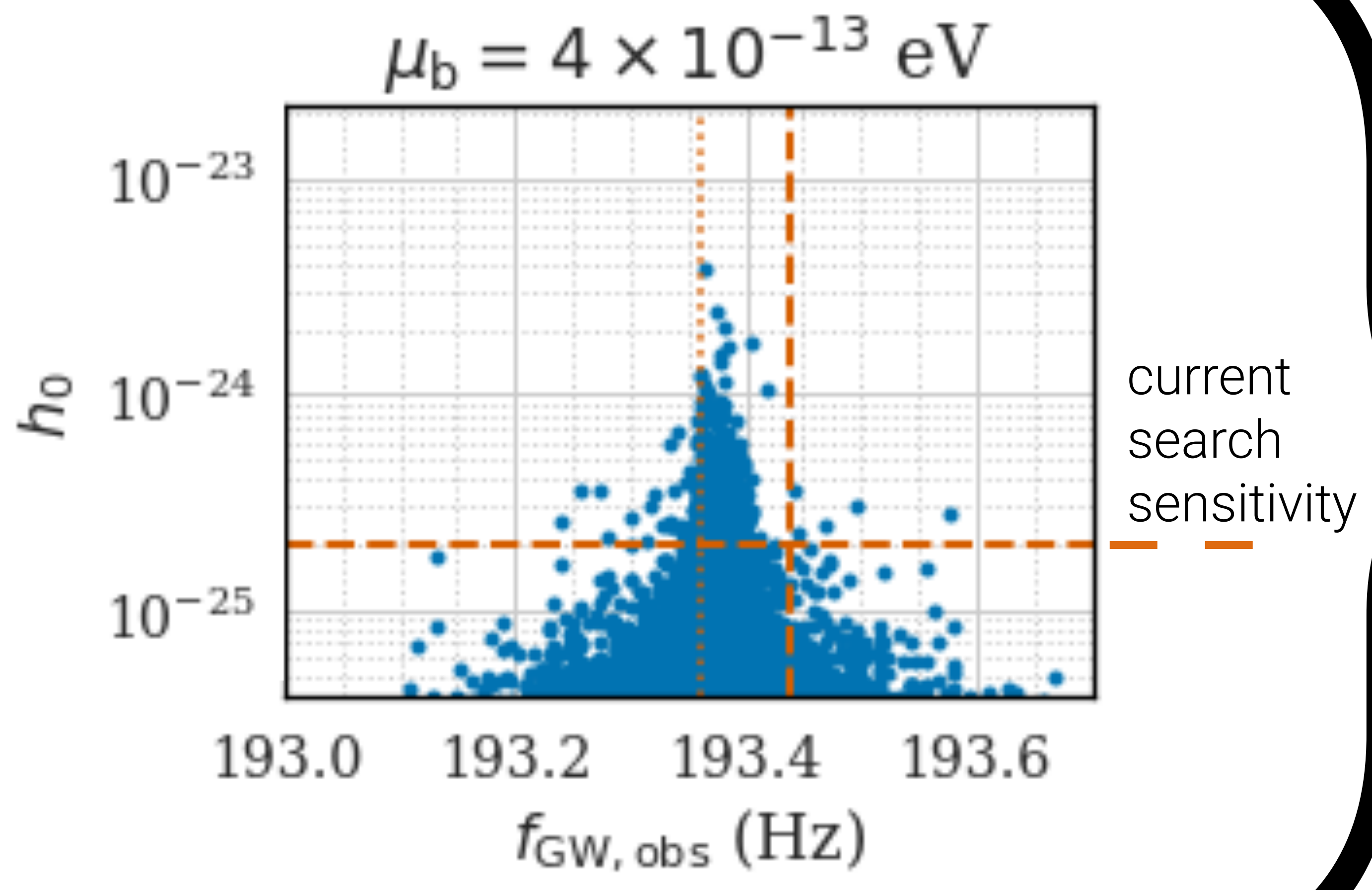
$\{\mu_b\}$



x

$\{10^8$ black holes$\}$

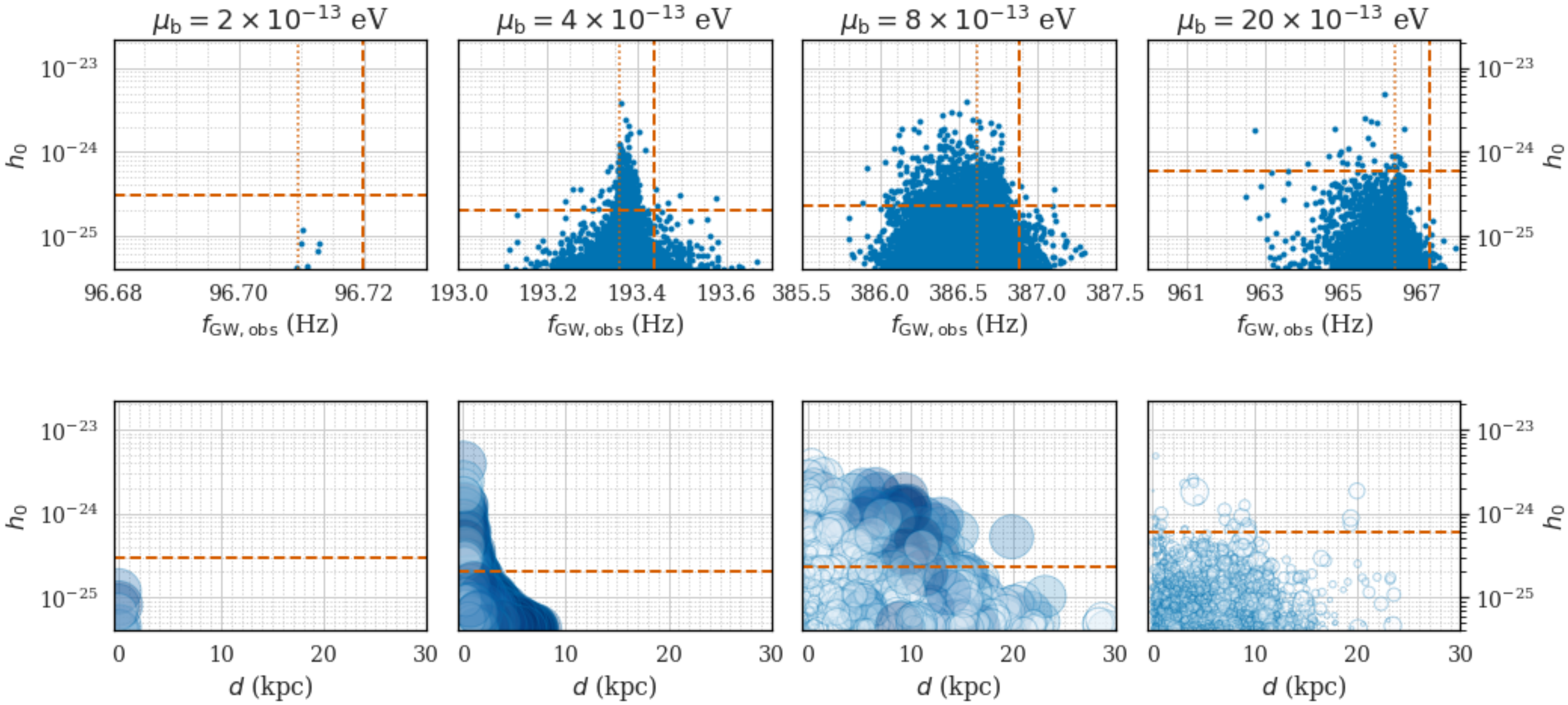




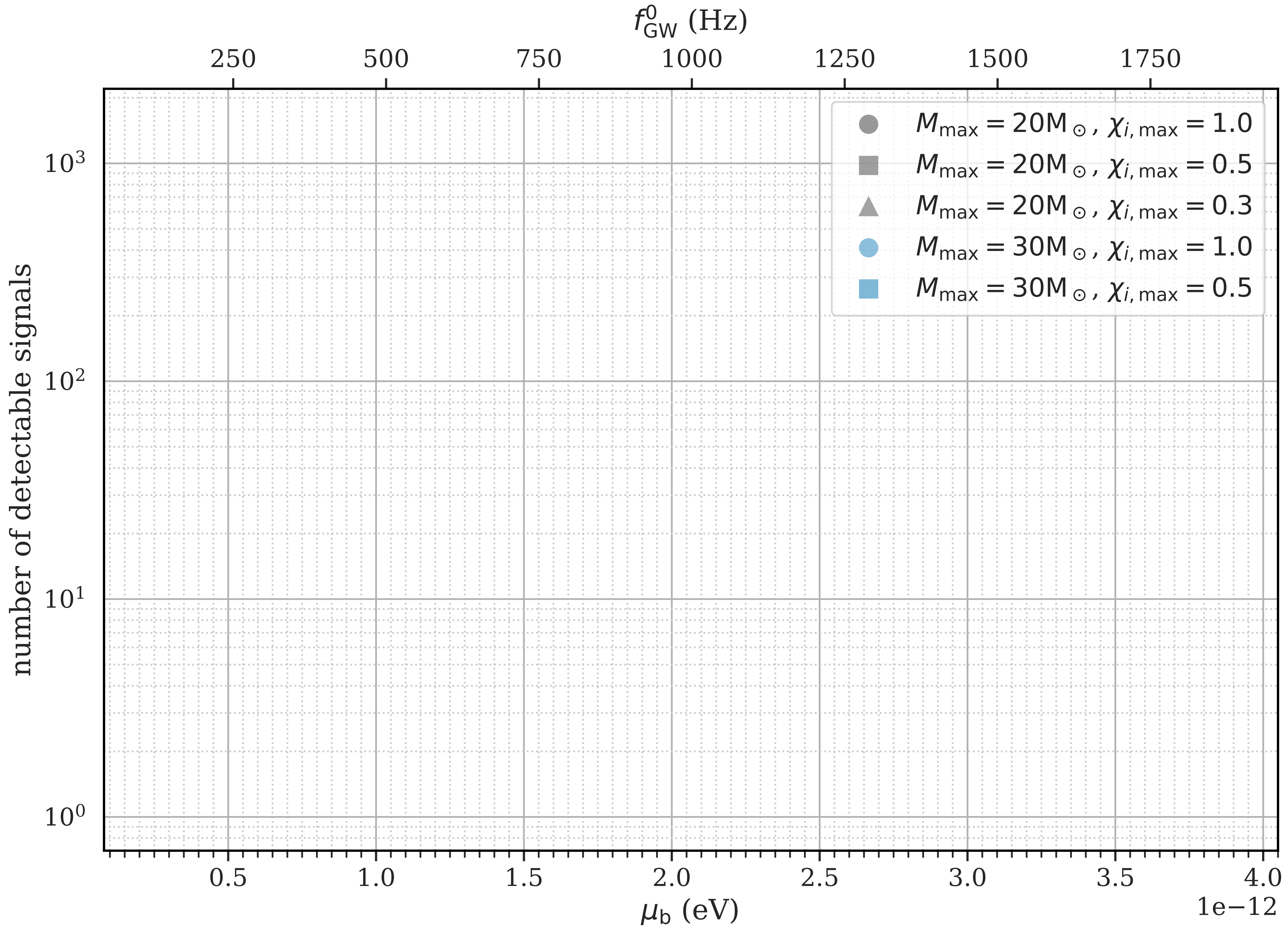
What do the ensemble signals look like?

gravitational-wave signals:

black hole properties:



What are the current detection prospects?



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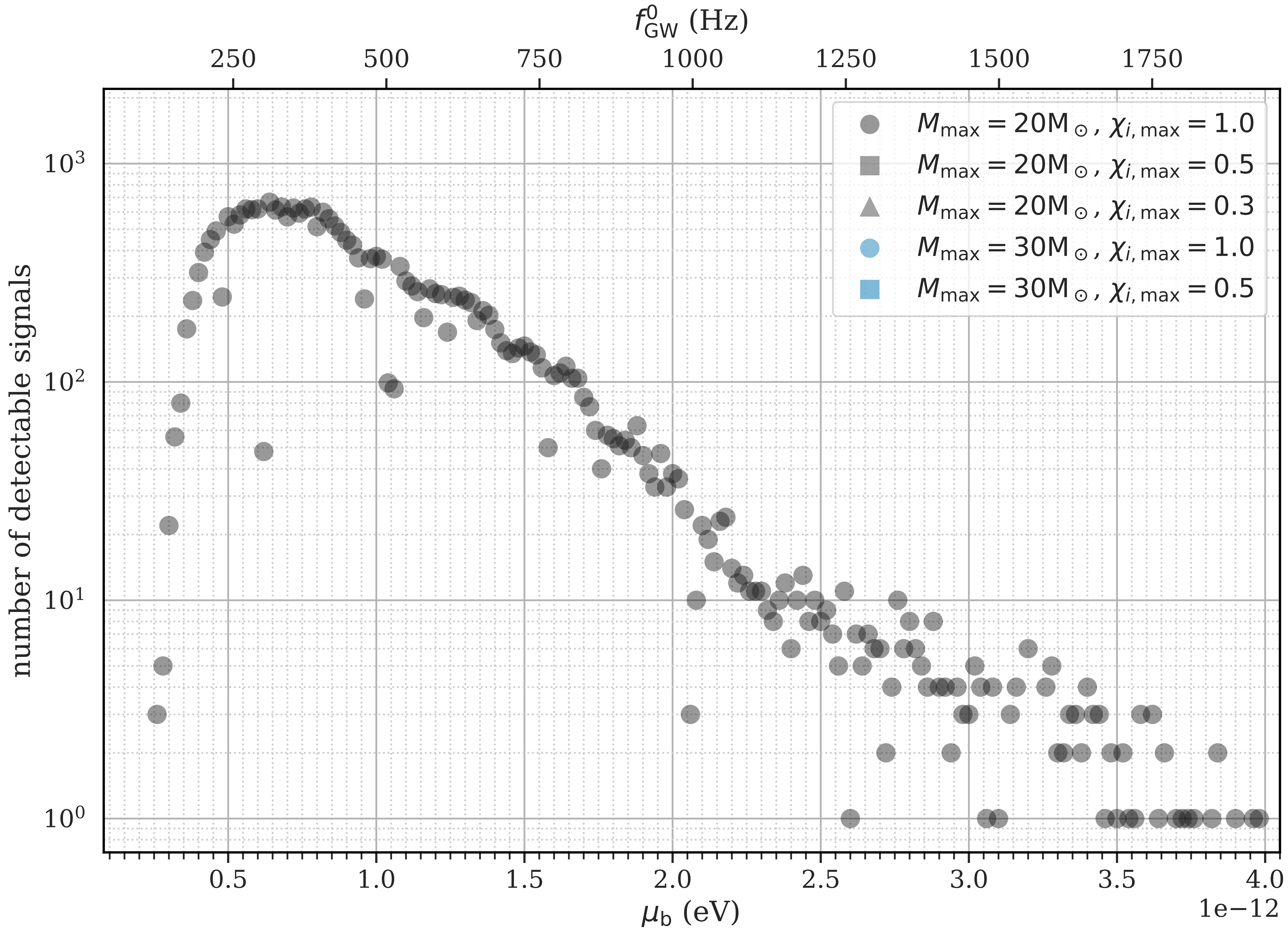

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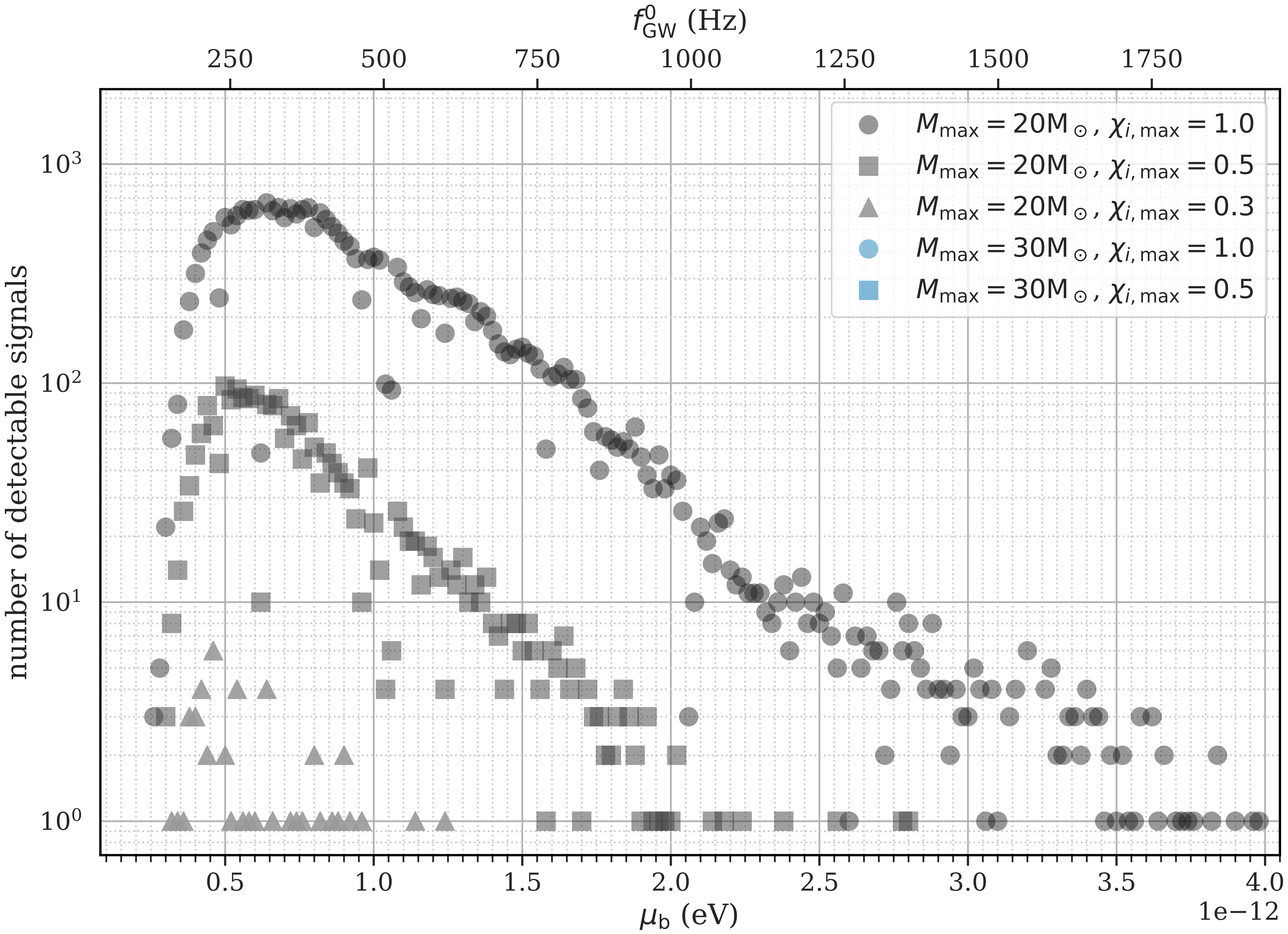

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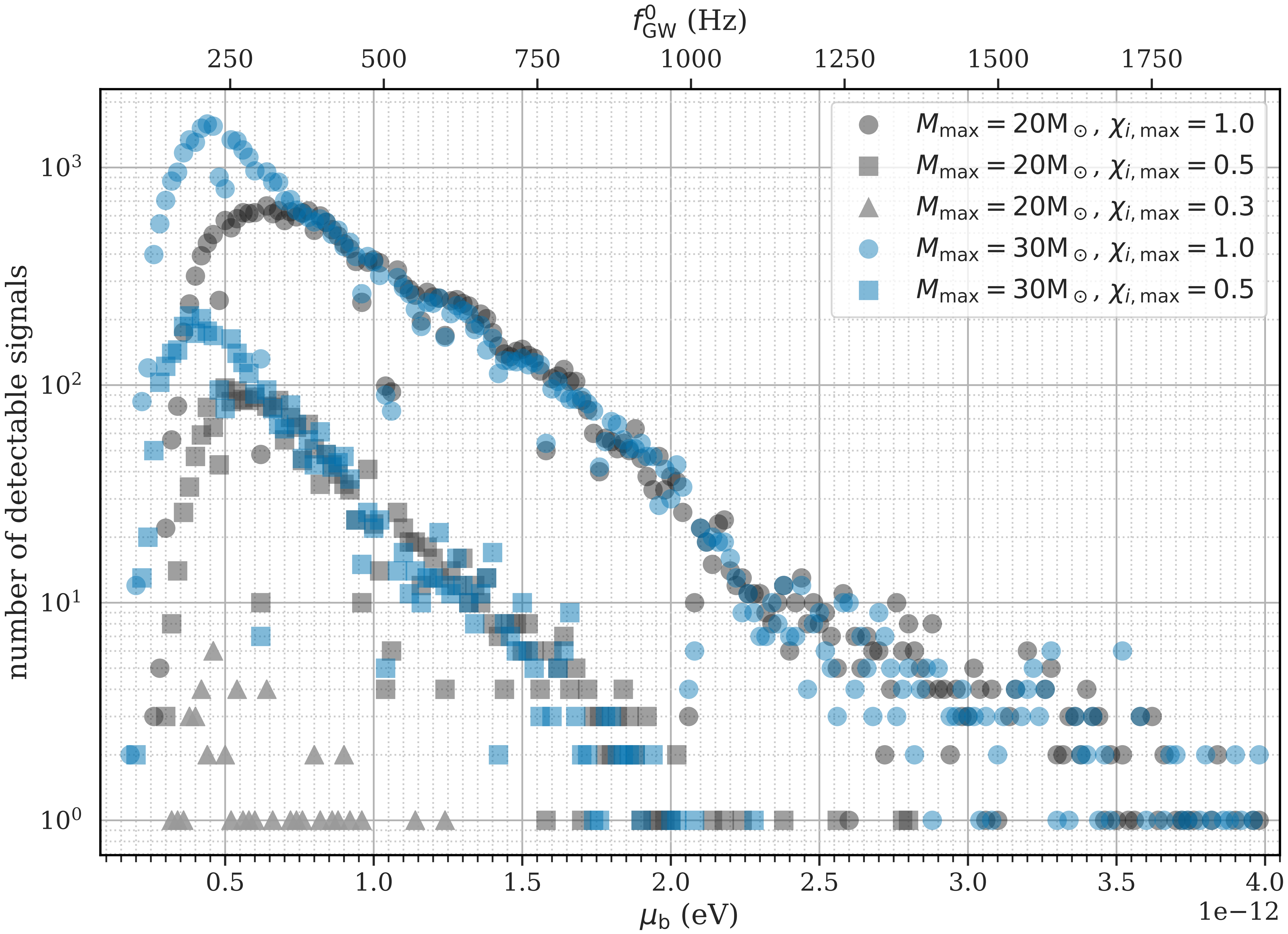
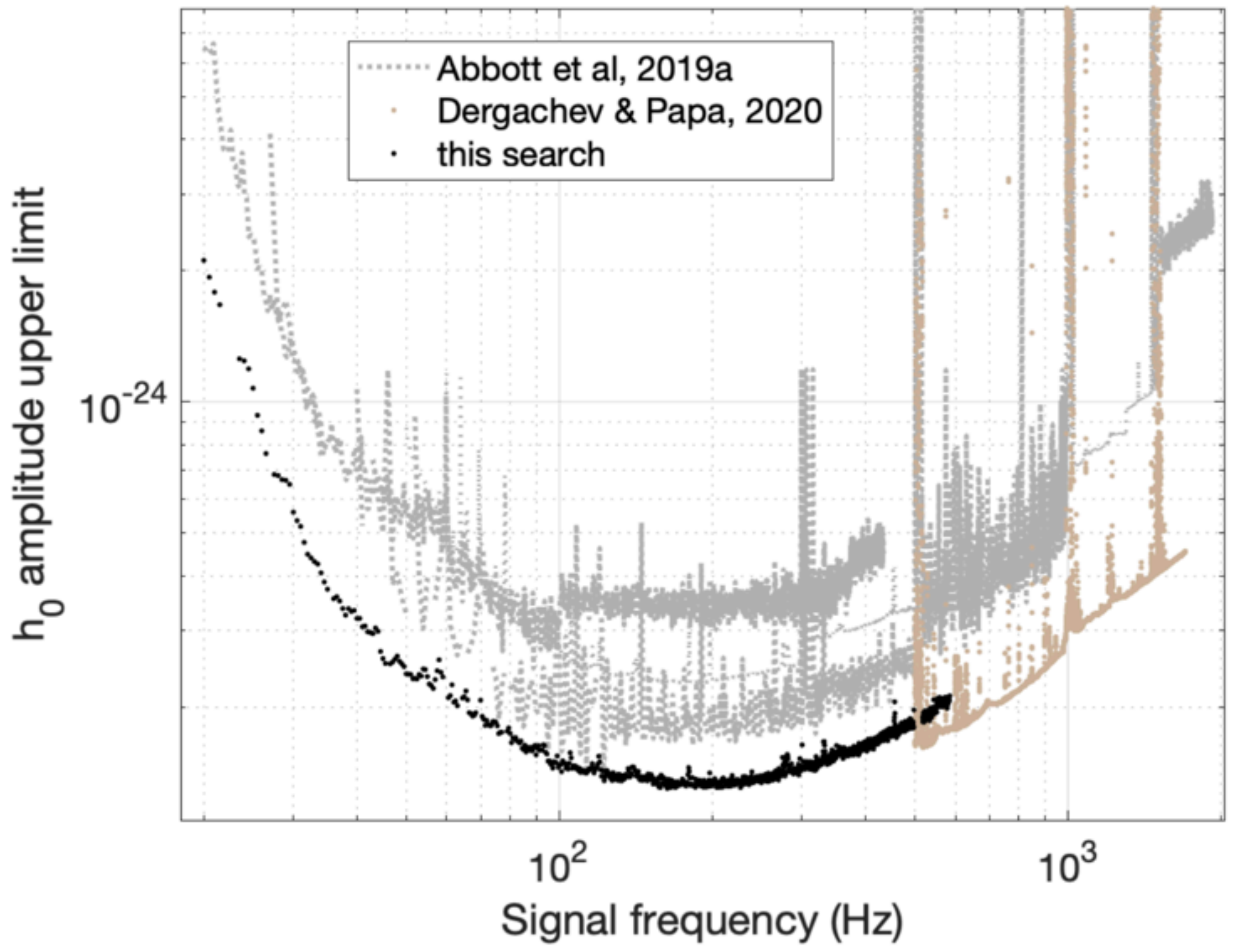


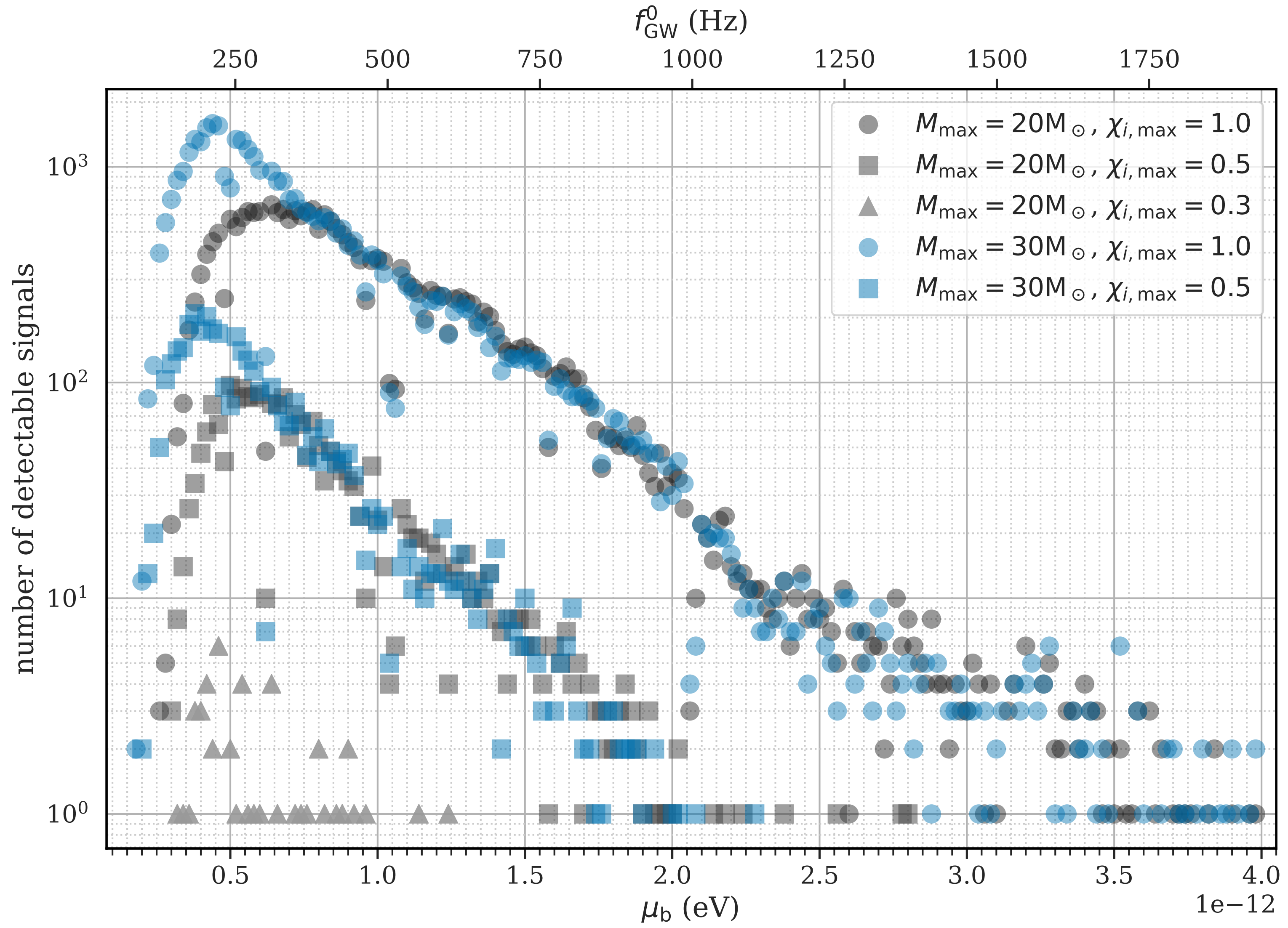
Interpreting null results (upper limits) — boson clouds

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

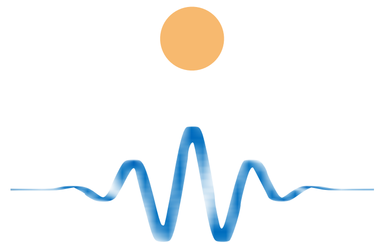
upper limit on gravitational-wave signal strength



expectations on number of detectable signals



range of disfavored boson masses



Thanks

PRD 102, 063020

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

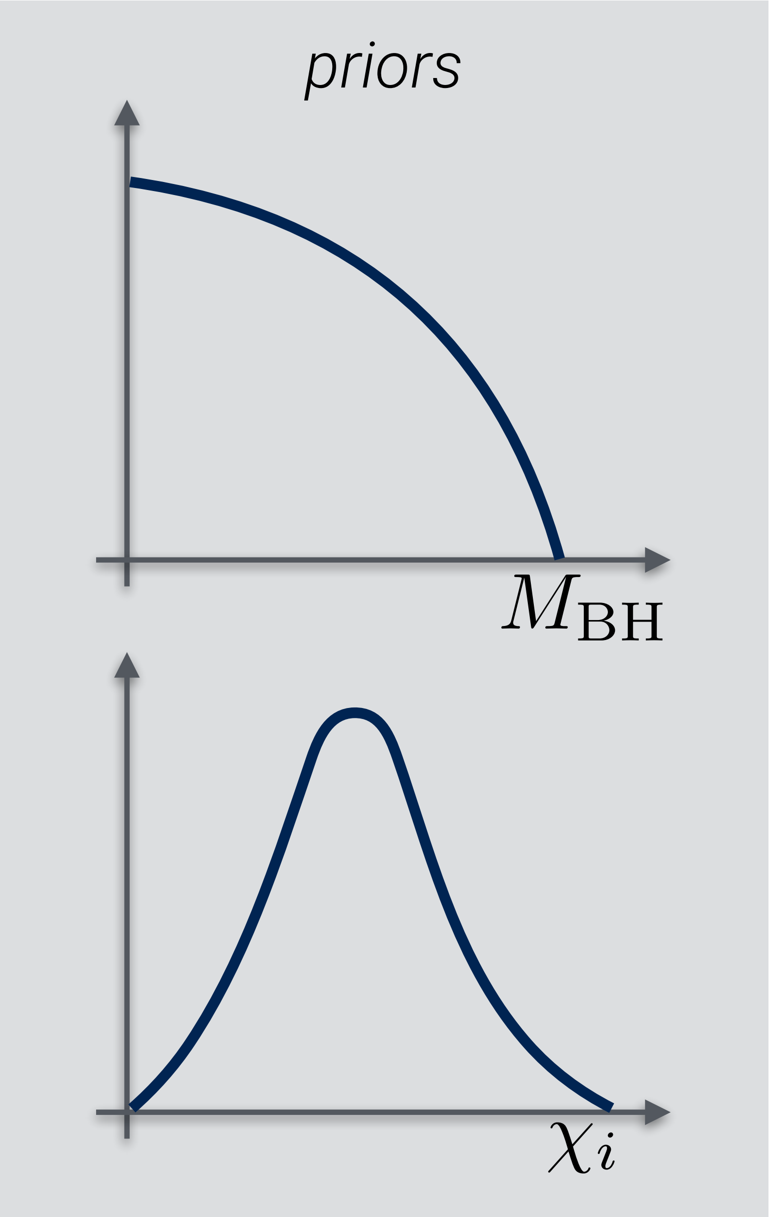
extra slides

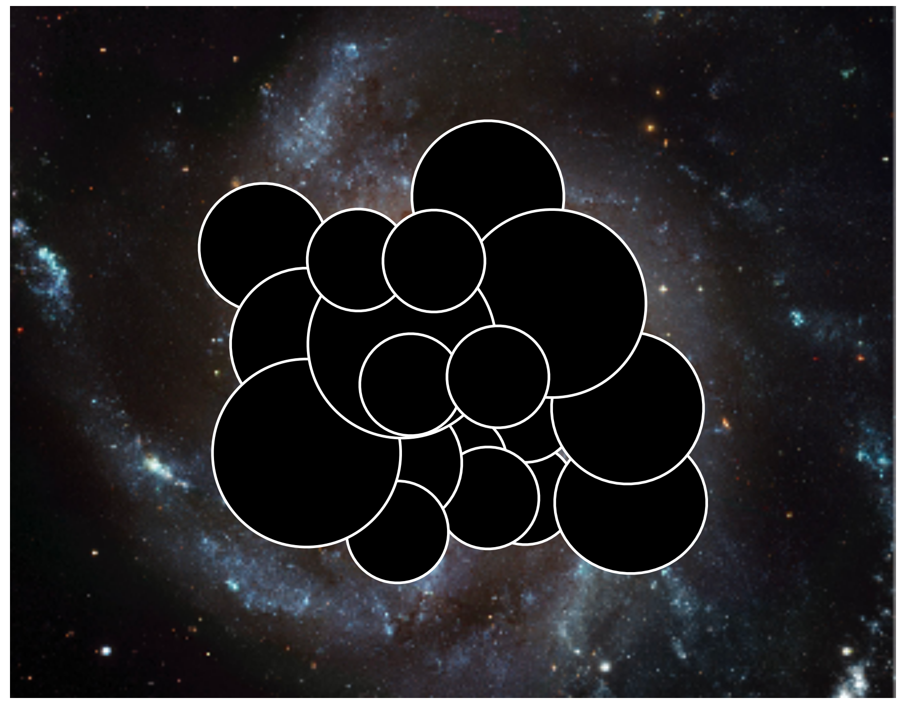
Recent searches using GWs

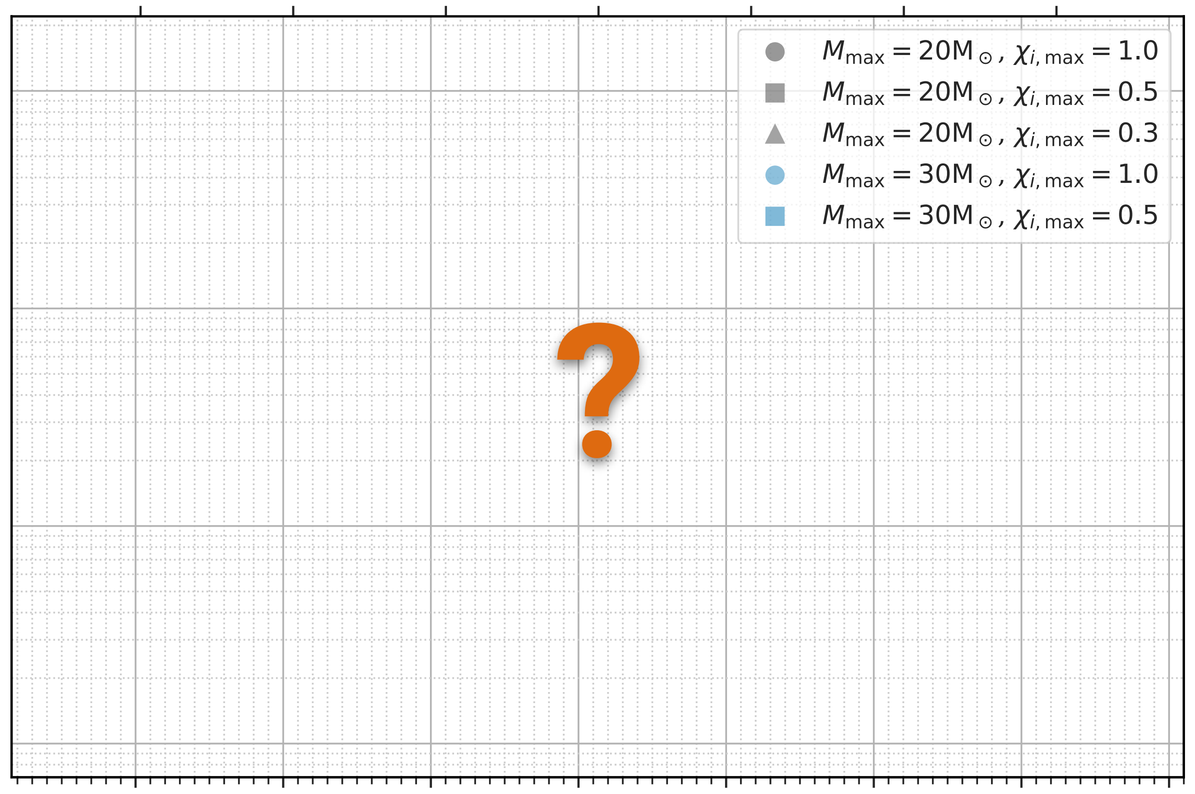
Some recent searches (non exhaustive list!!)

- 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

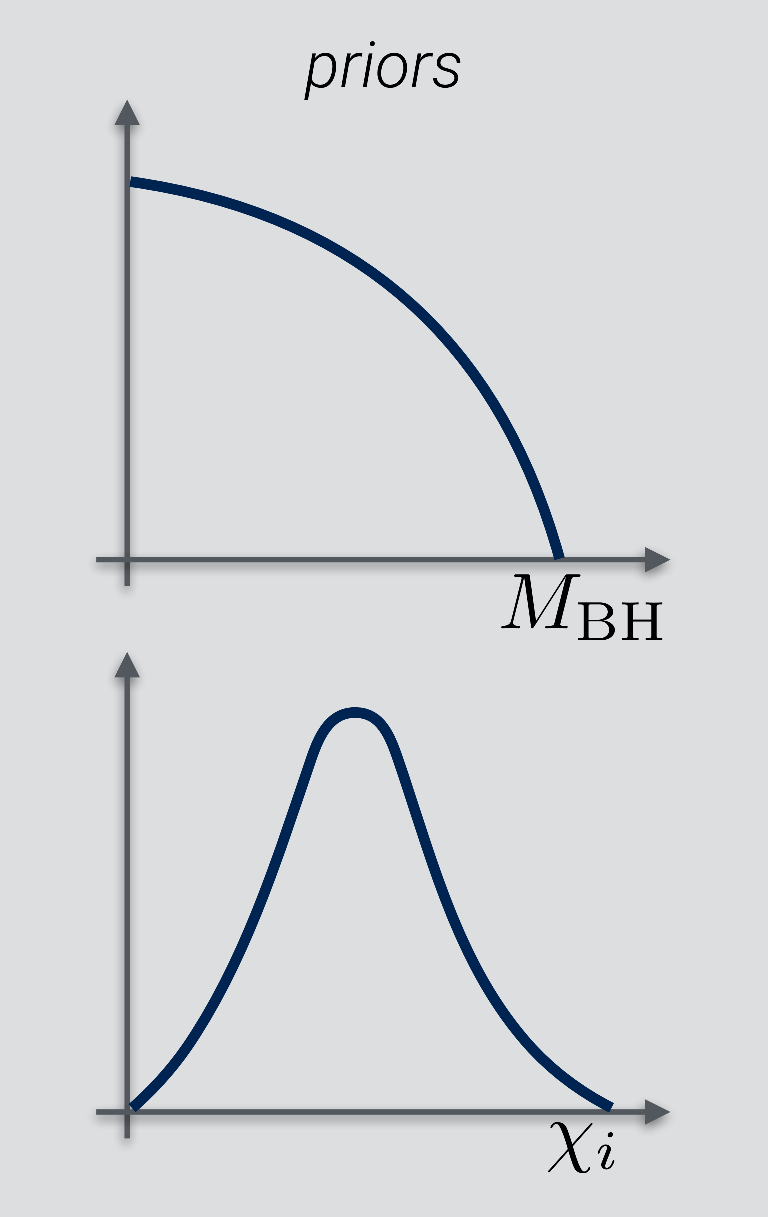
Interpreting null results (upper limits) — boson clouds (speculating)

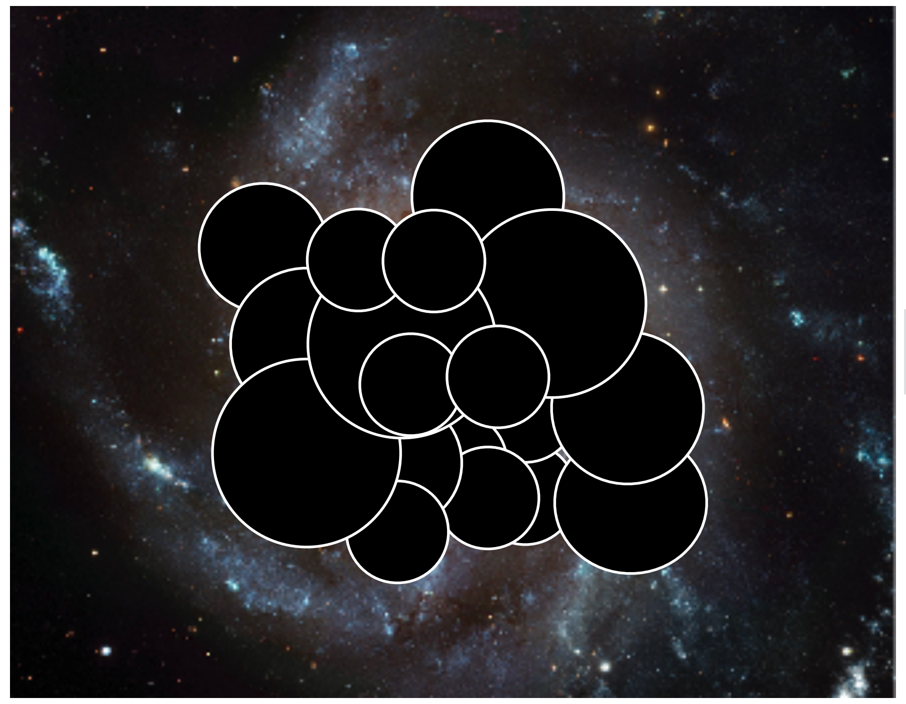


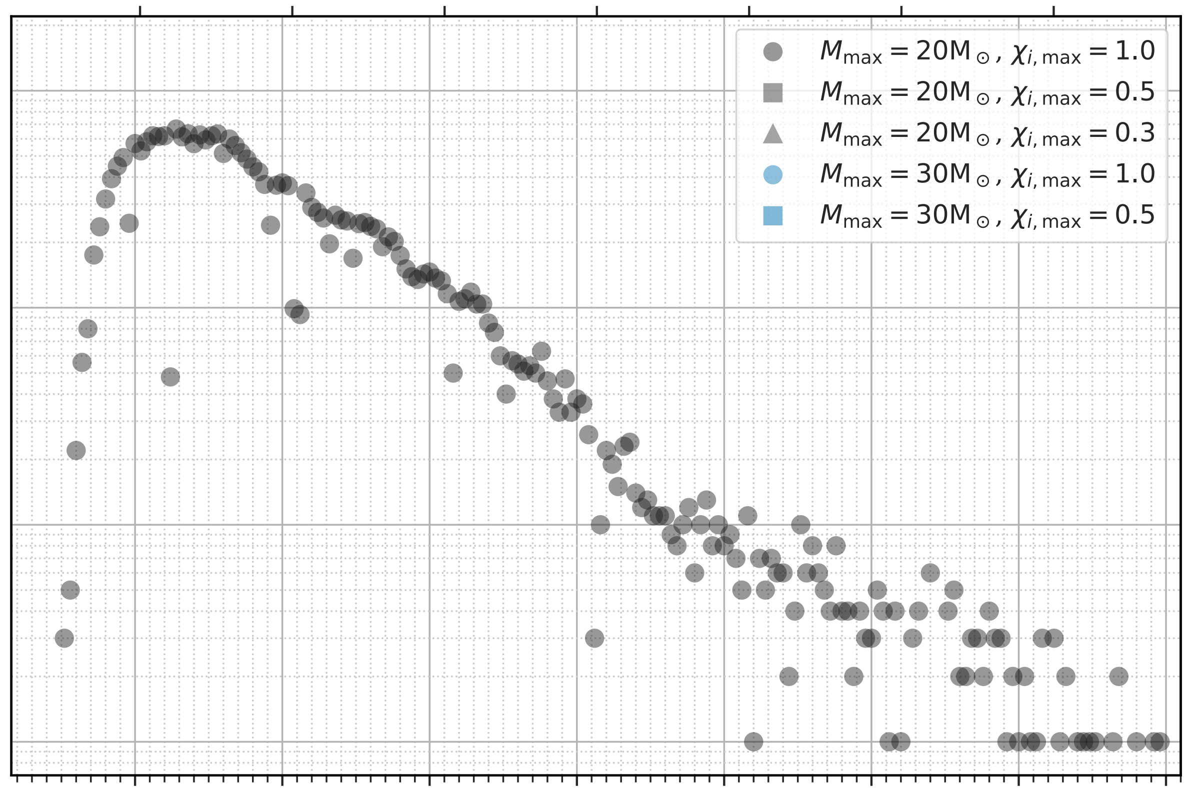


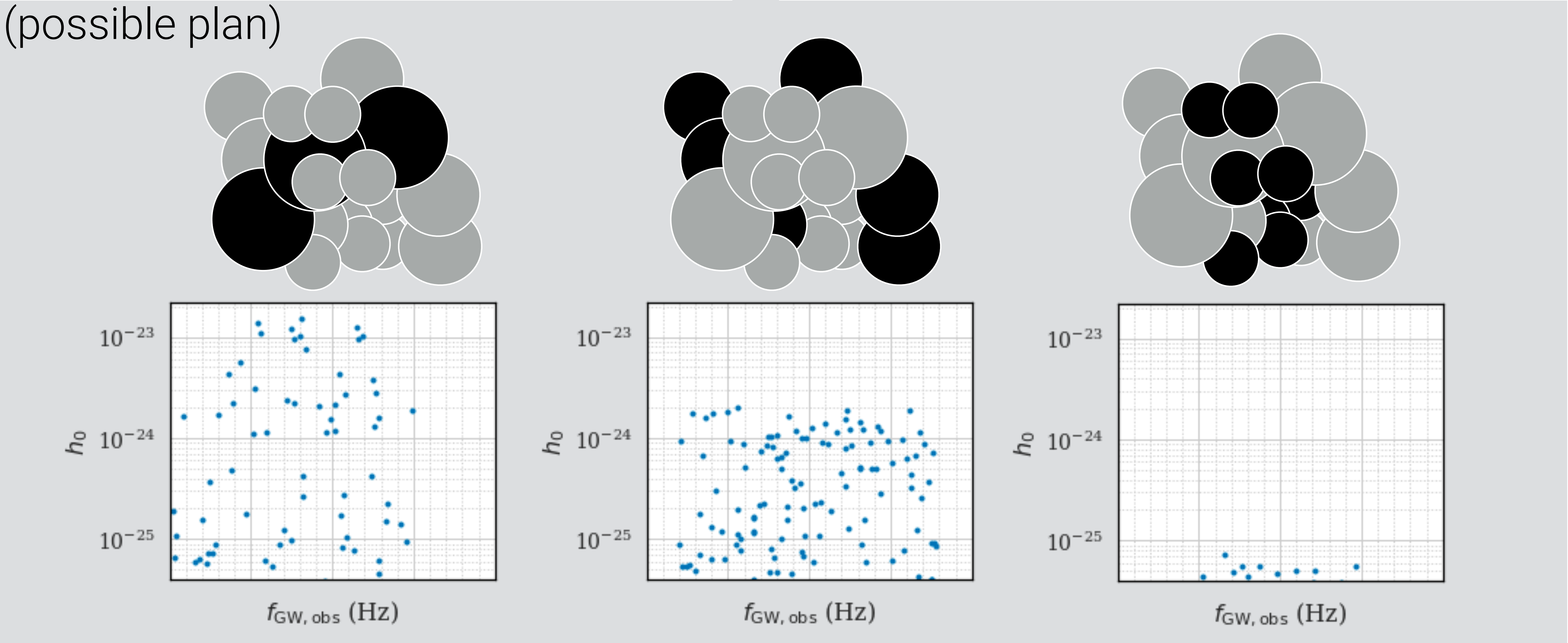


Interpreting null results (upper limits) — boson clouds (speculating)

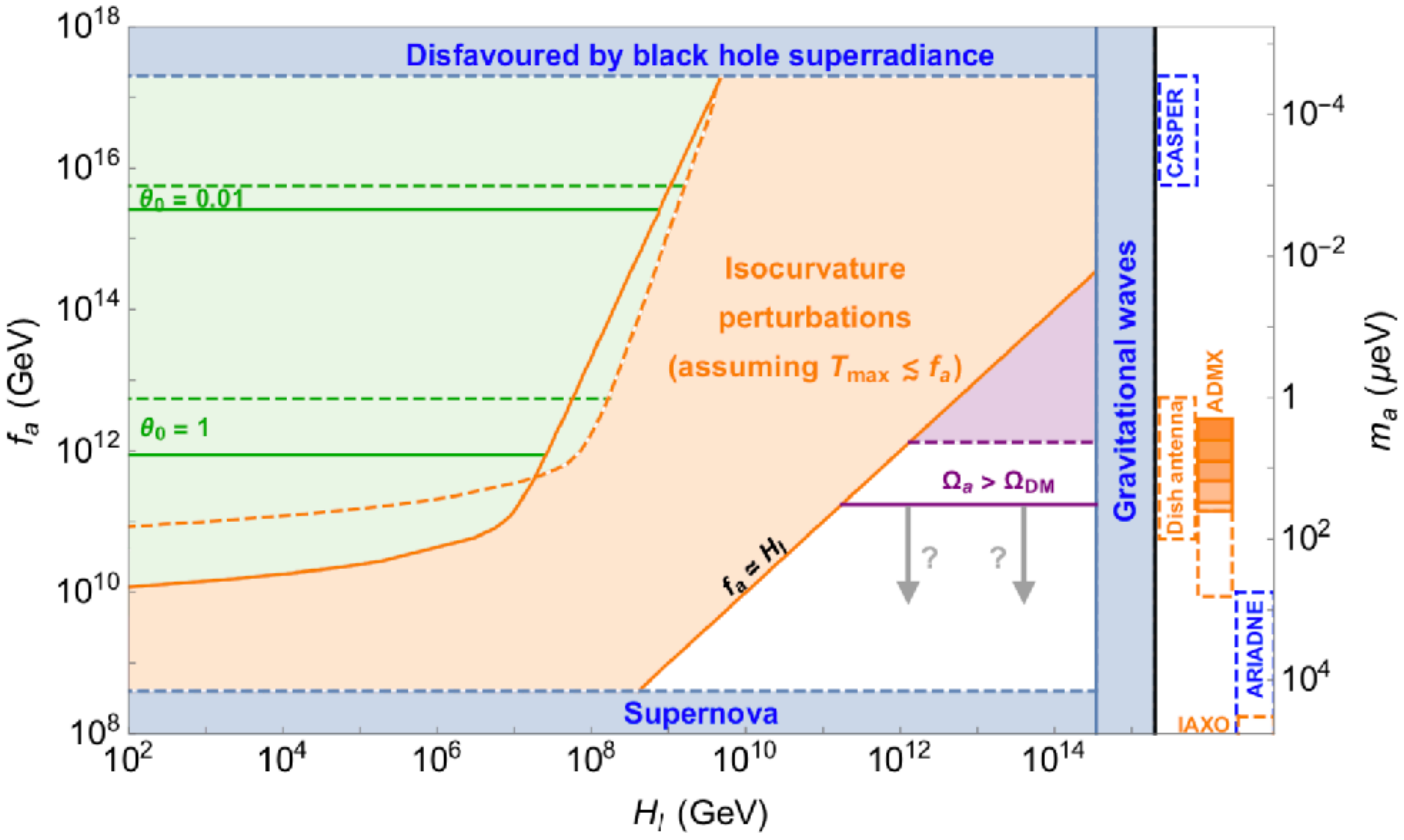








the QCD axion can take a wide range of masses



[di Cortona et al., JHEP 2016]

The ensemble signal

2 bosons annihilate -> gravitational waves

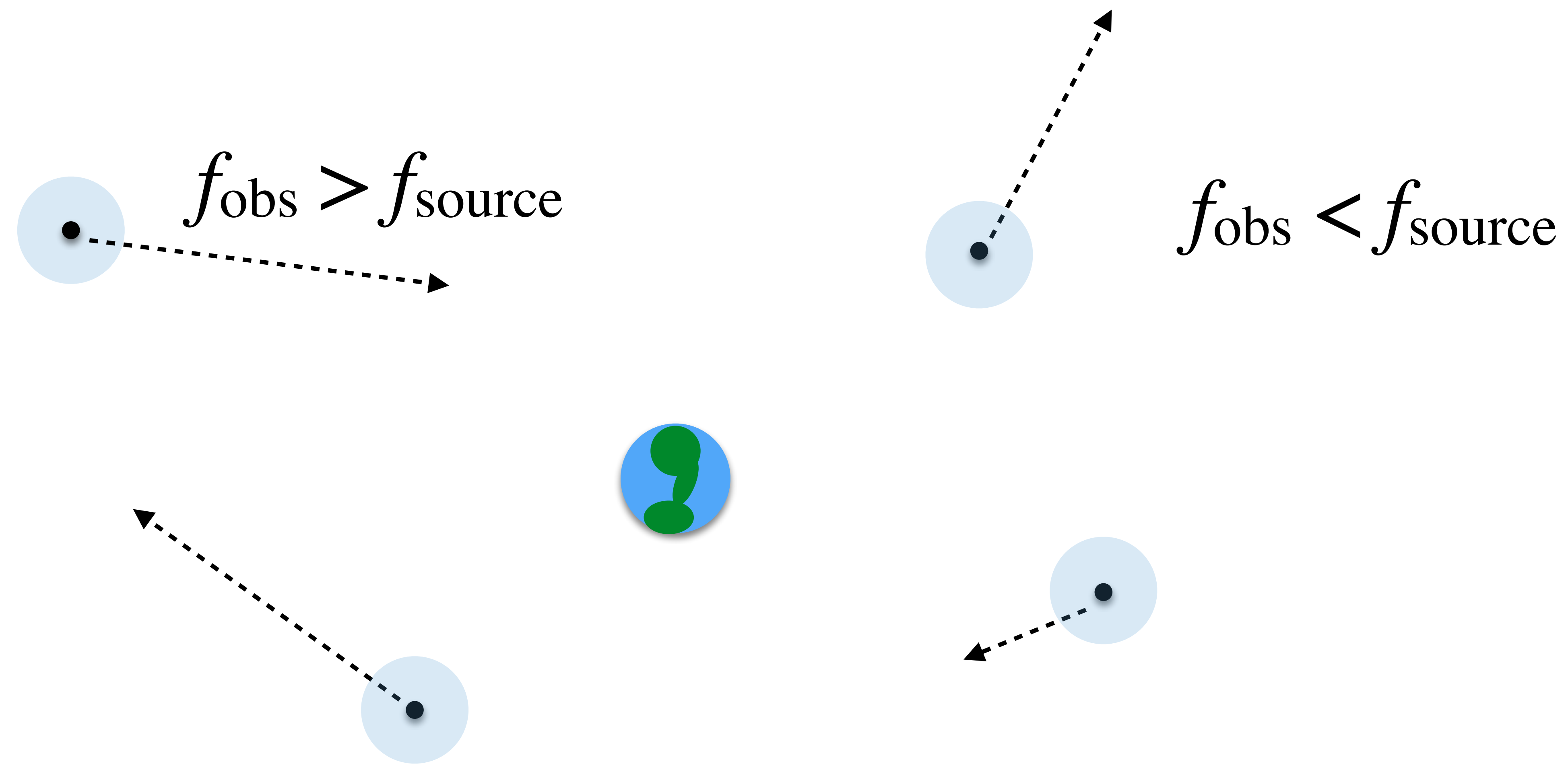
inherent signal frequency depends almost entirely on **boson mass** f_{source}

black holes are moving towards or away from us

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

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

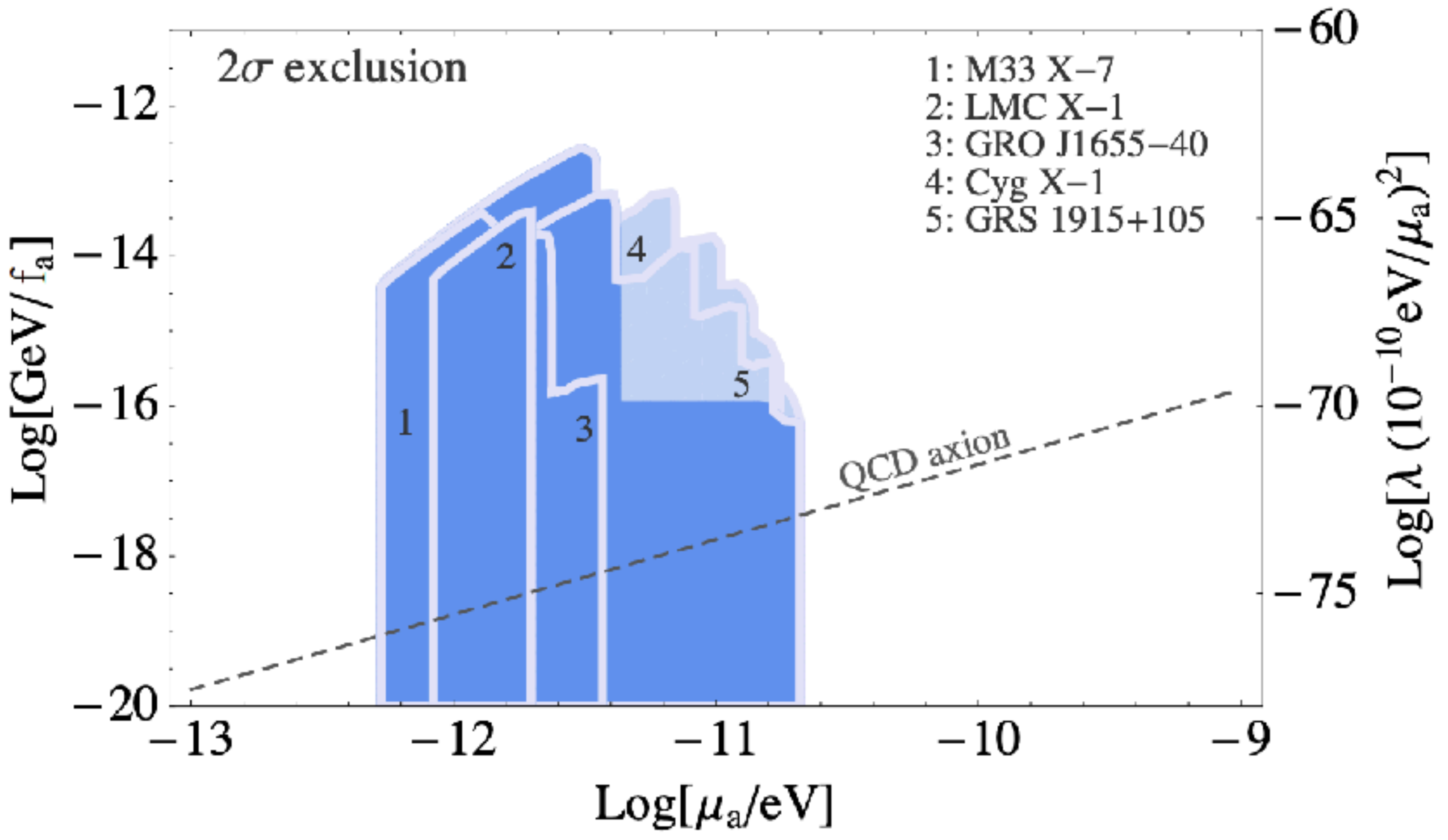
we should be looking for the **ensemble signal** produced by all the boson clouds near us



Mass and self coupling

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

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

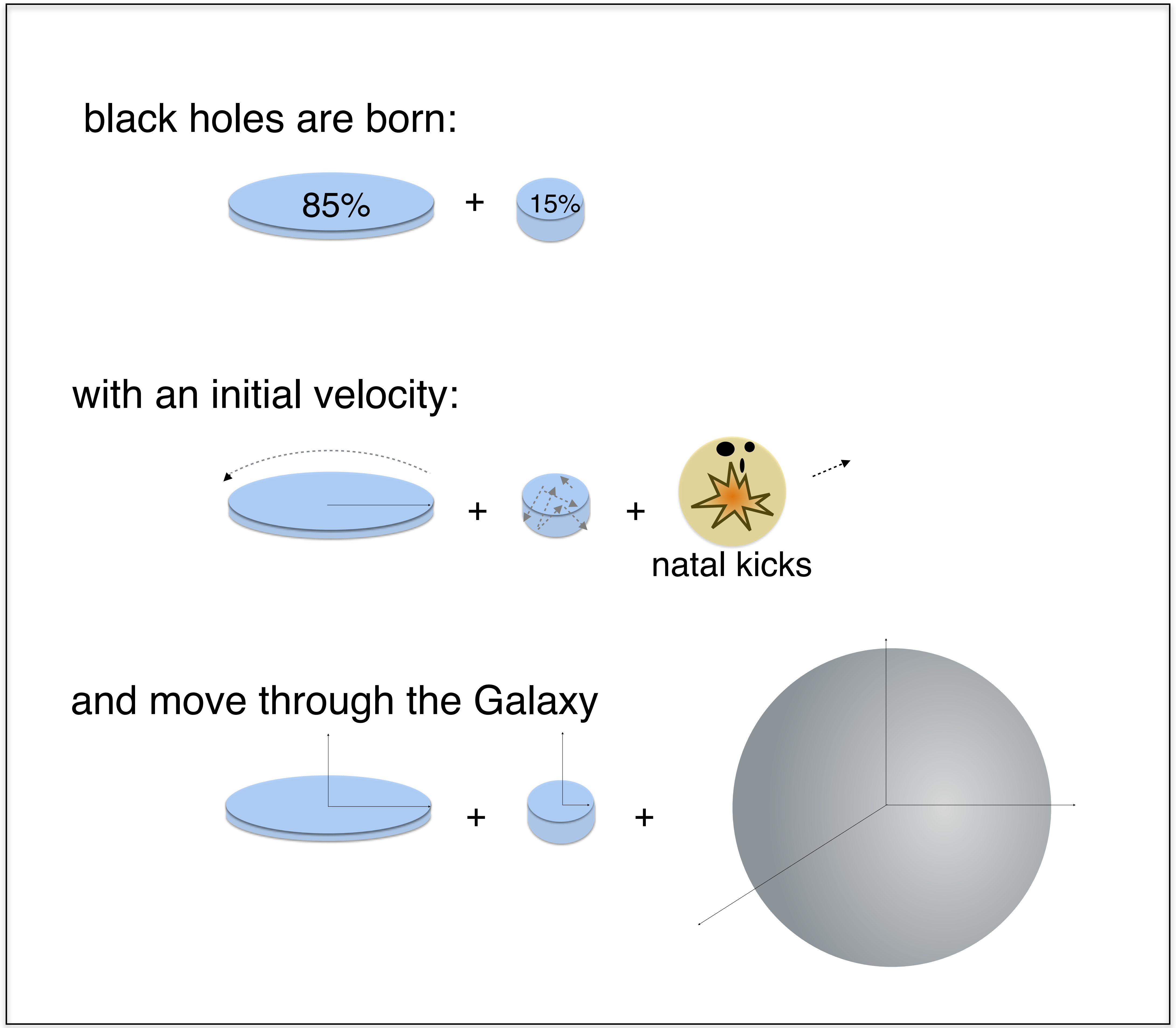


(a)

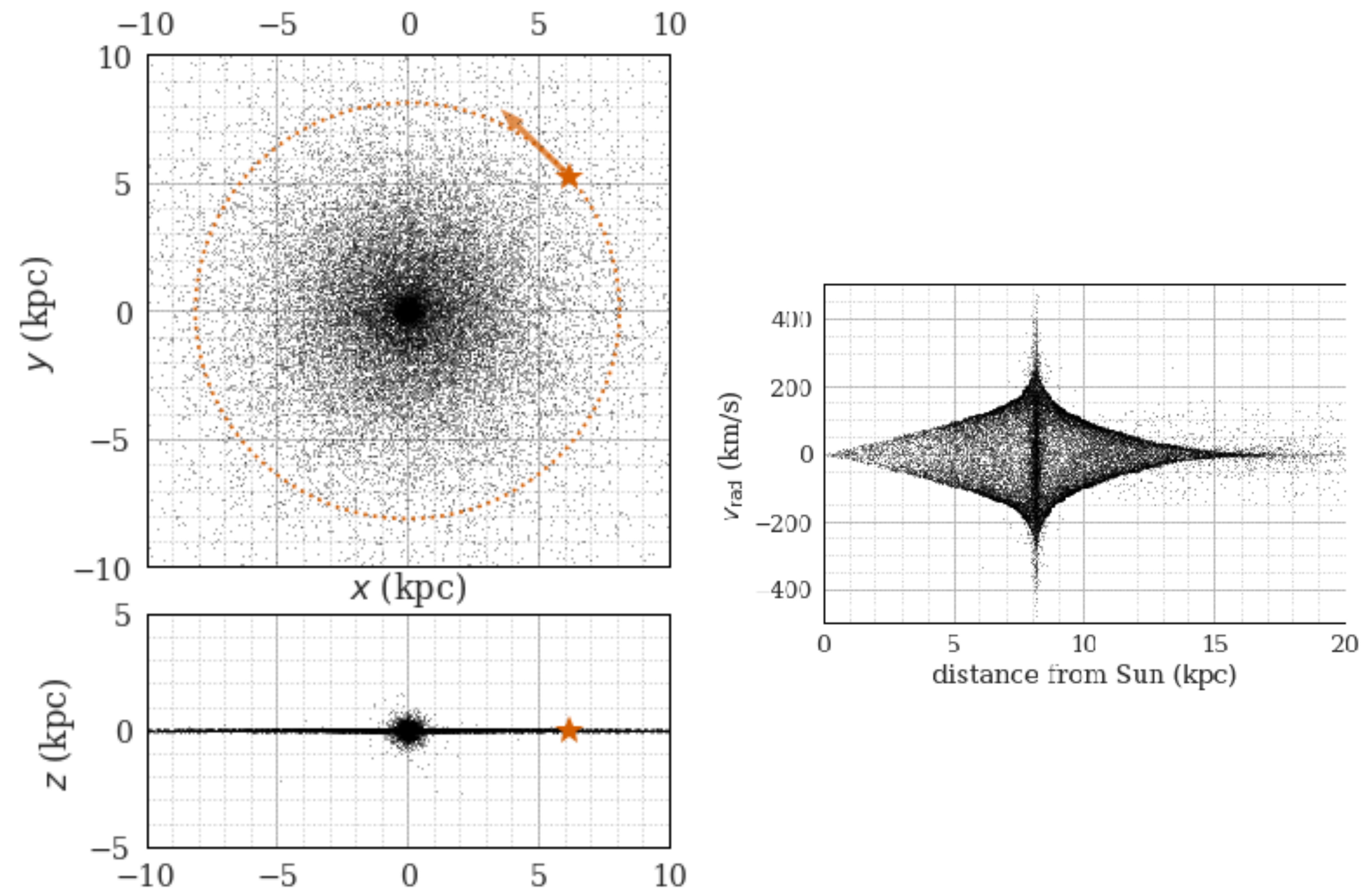
[Arvanitaki, Baryakhtar, and Huang, PRD 91 (2015)]

10^8 isolated black holes in the Galaxy

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

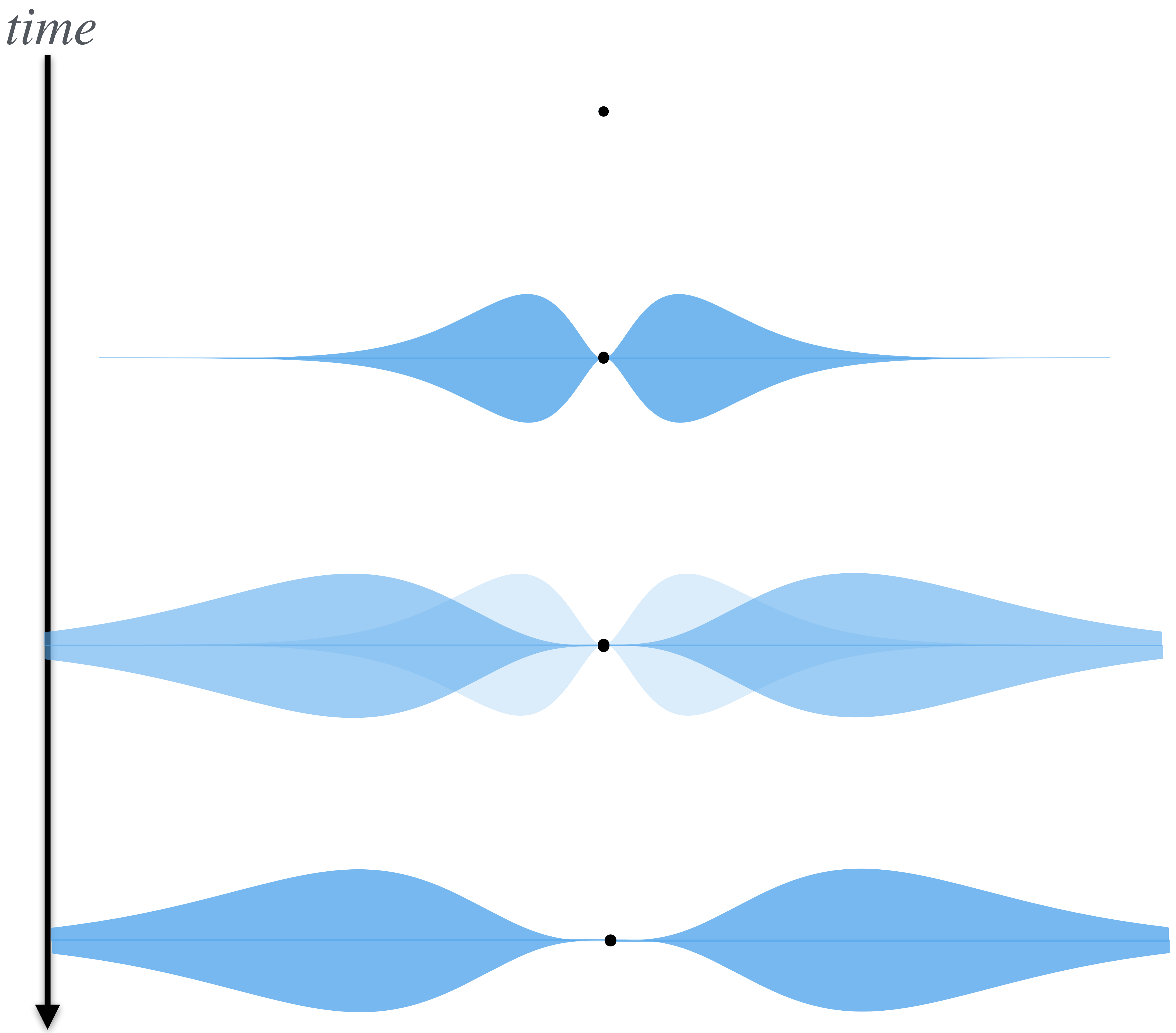


final black hole spatial properties



formation of the second cloud level

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



$\chi = \chi_i$

$\chi = \chi_{c,1} < \chi_i$

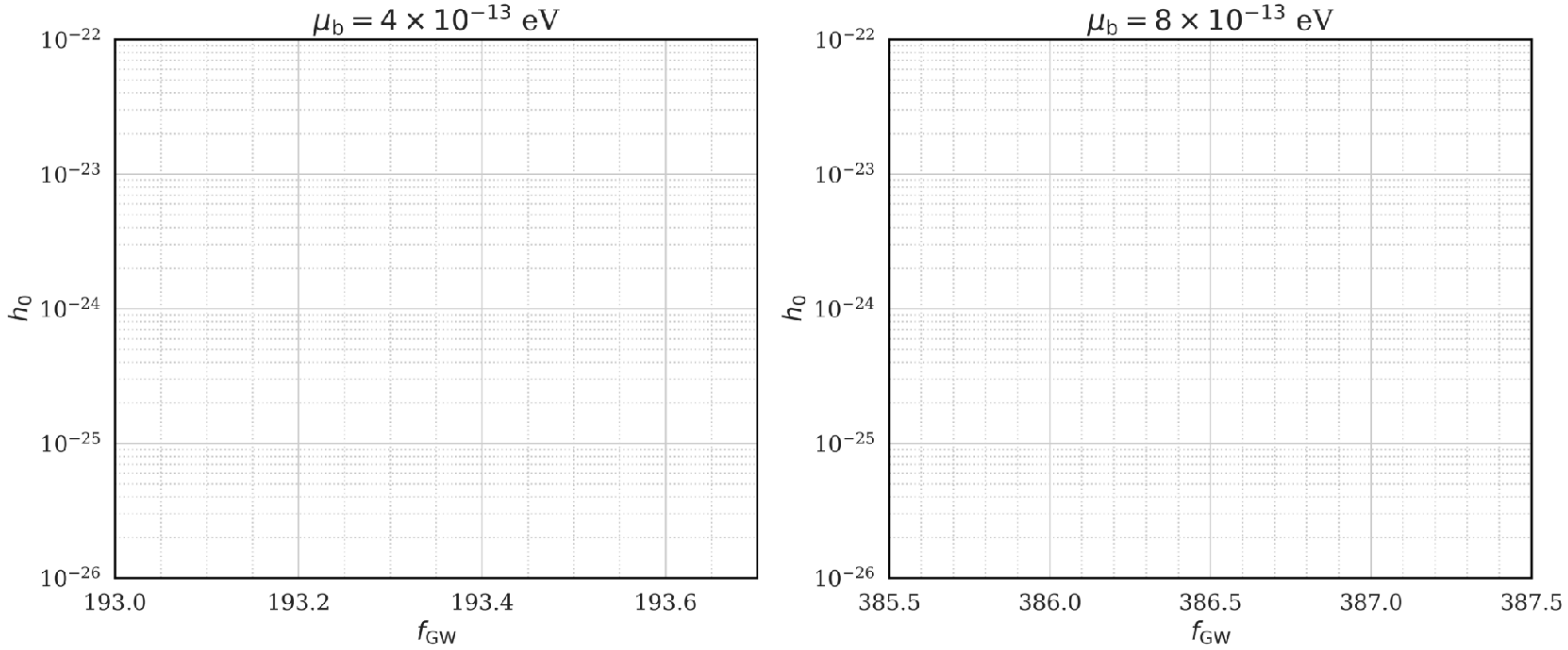
$\tau_{\mathrm{growth},1}$

$\chi \to \chi_{c,2} < \chi_{c,1}$

$\tau_{\mathrm{growth},2} \gg \tau_{\mathrm{growth},1}$

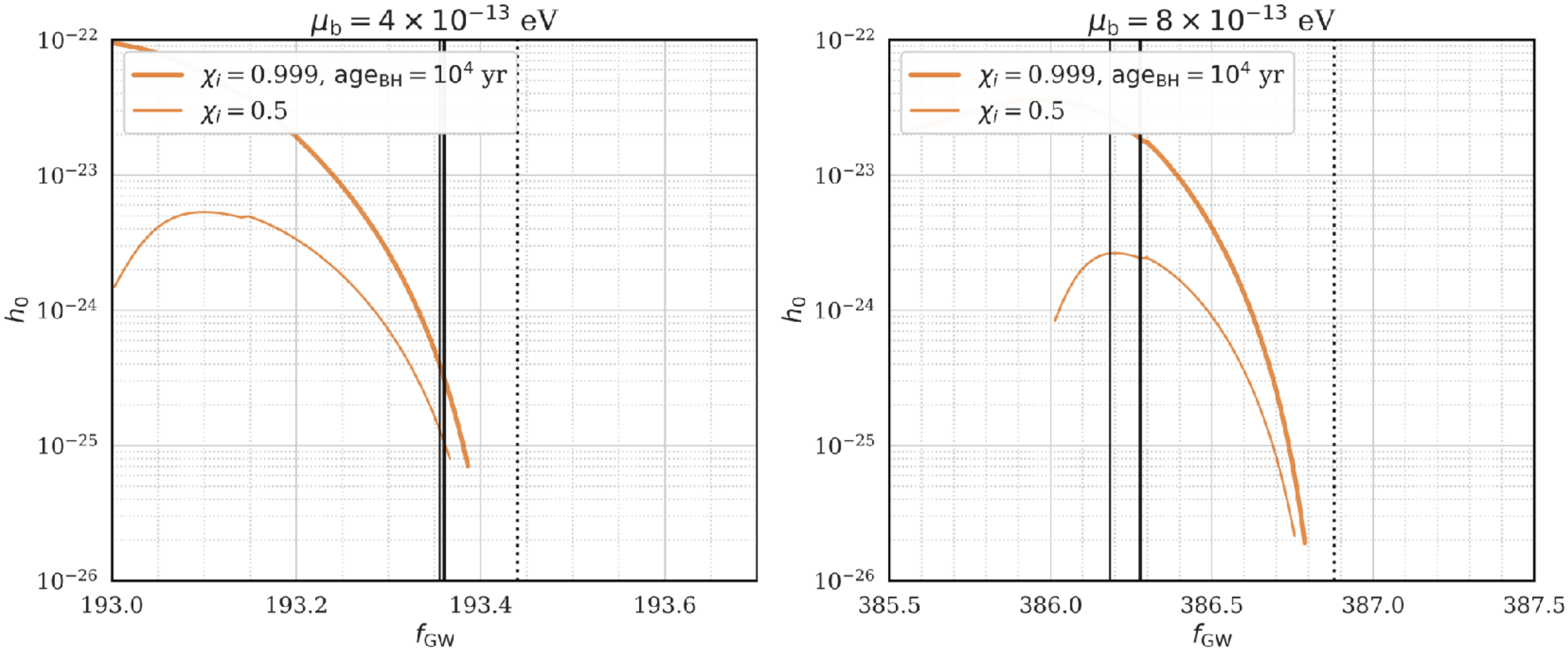
$\chi = \chi_{c,2}$

What do the ensemble signals look like?



What do the ensemble signals look like?

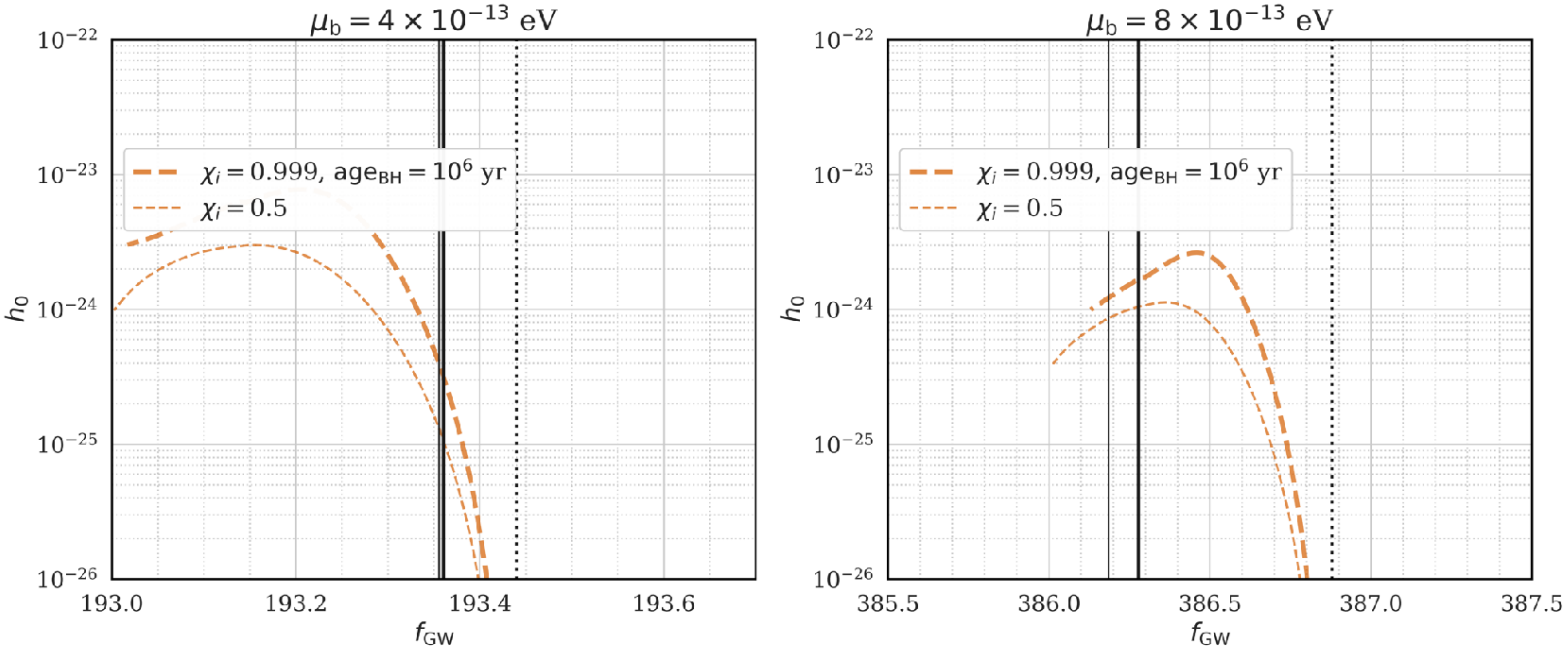
The orange curves define the envelopes of the potential signals over a wide range of boson masses.



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

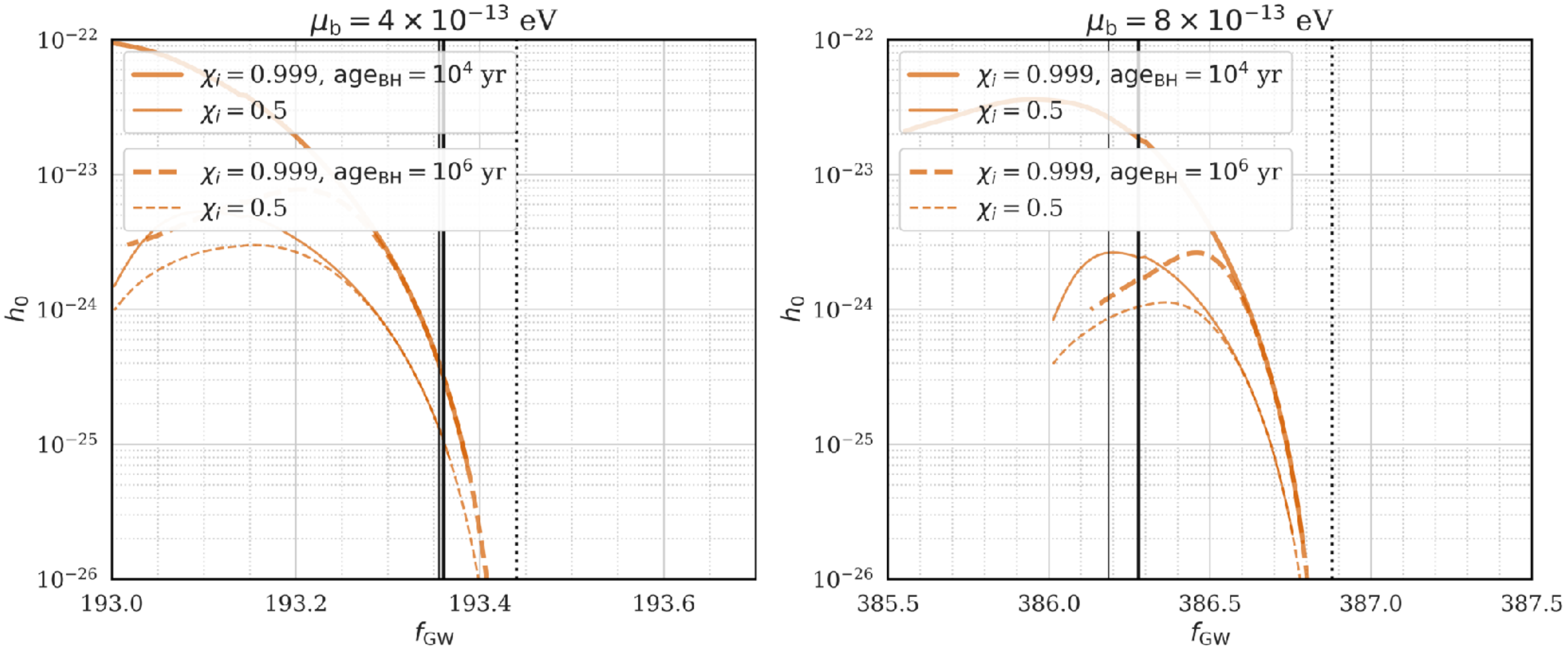
What do the ensemble signals look like?

Signals get quieter as black holes age => envelopes drop



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

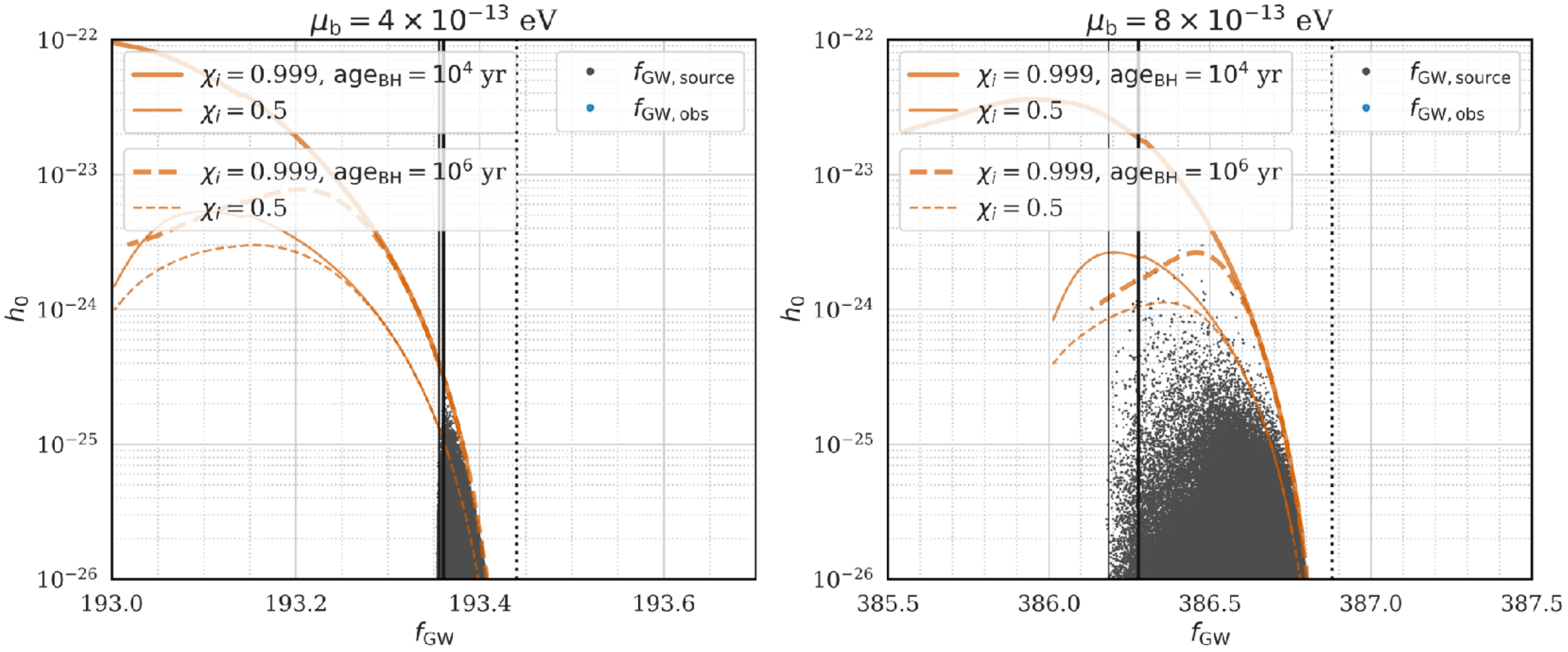
What do the ensemble signals look like?



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

What do the ensemble signals look like?

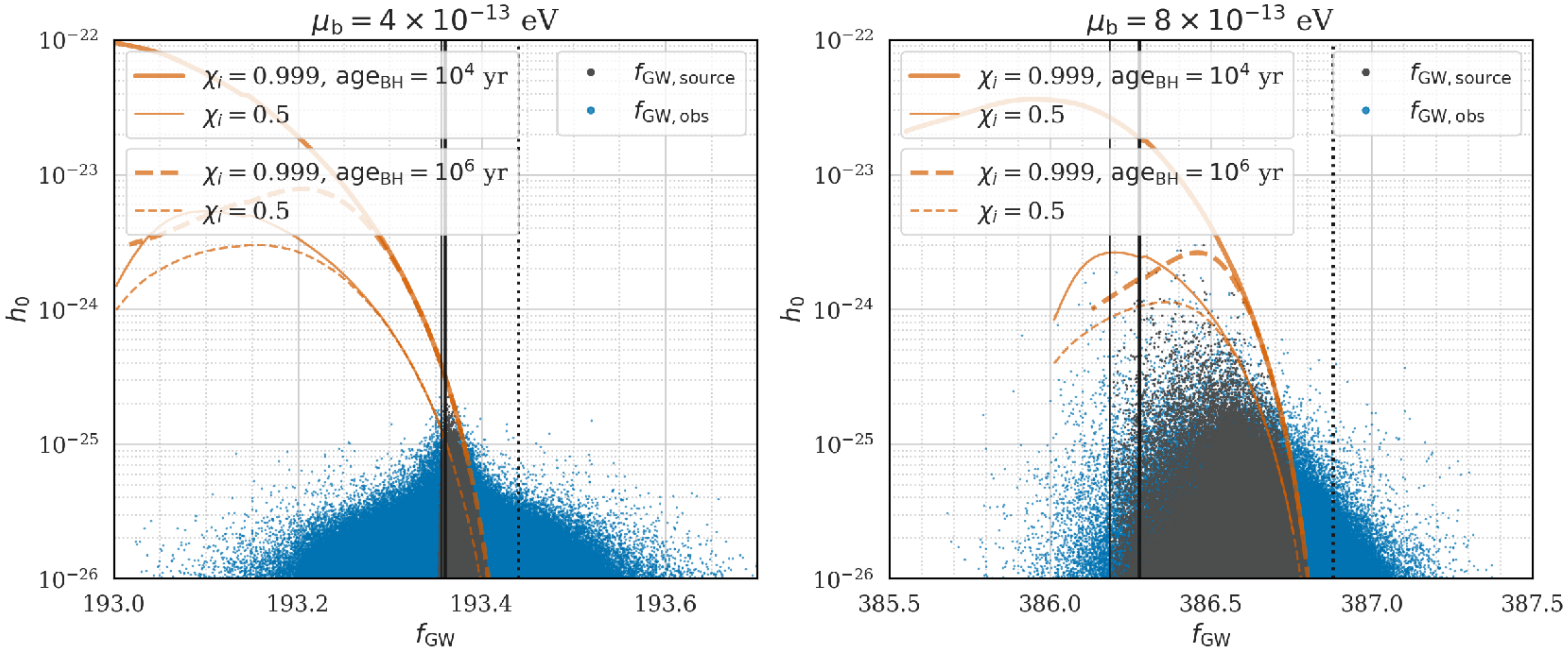
The signals w/ their source frequencies fill in the regions defined by the envelopes and vertical lines.



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

What do the ensemble signals look like?

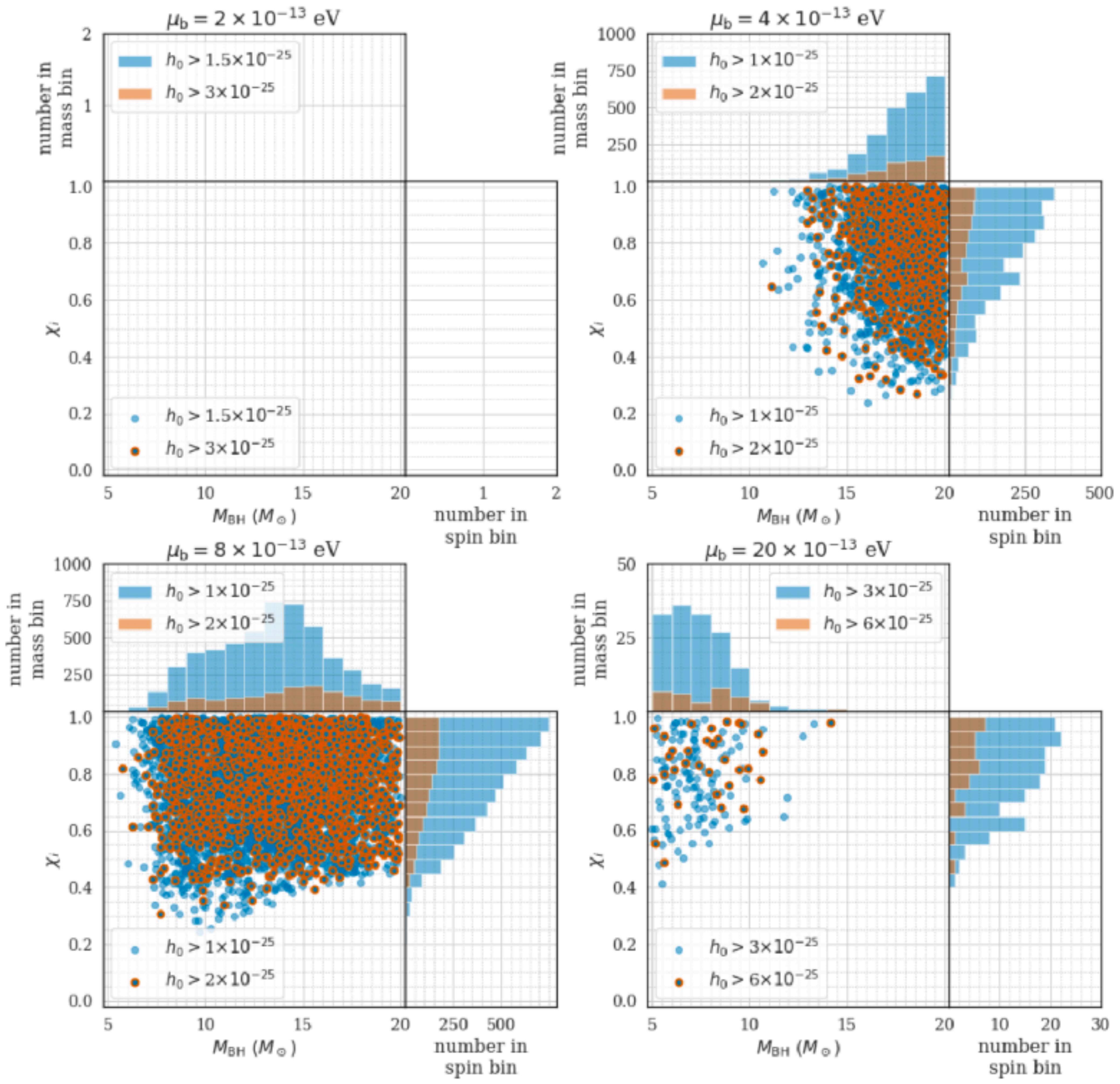
The black hole velocities add a large Doppler shift and "smear out" the distribution.

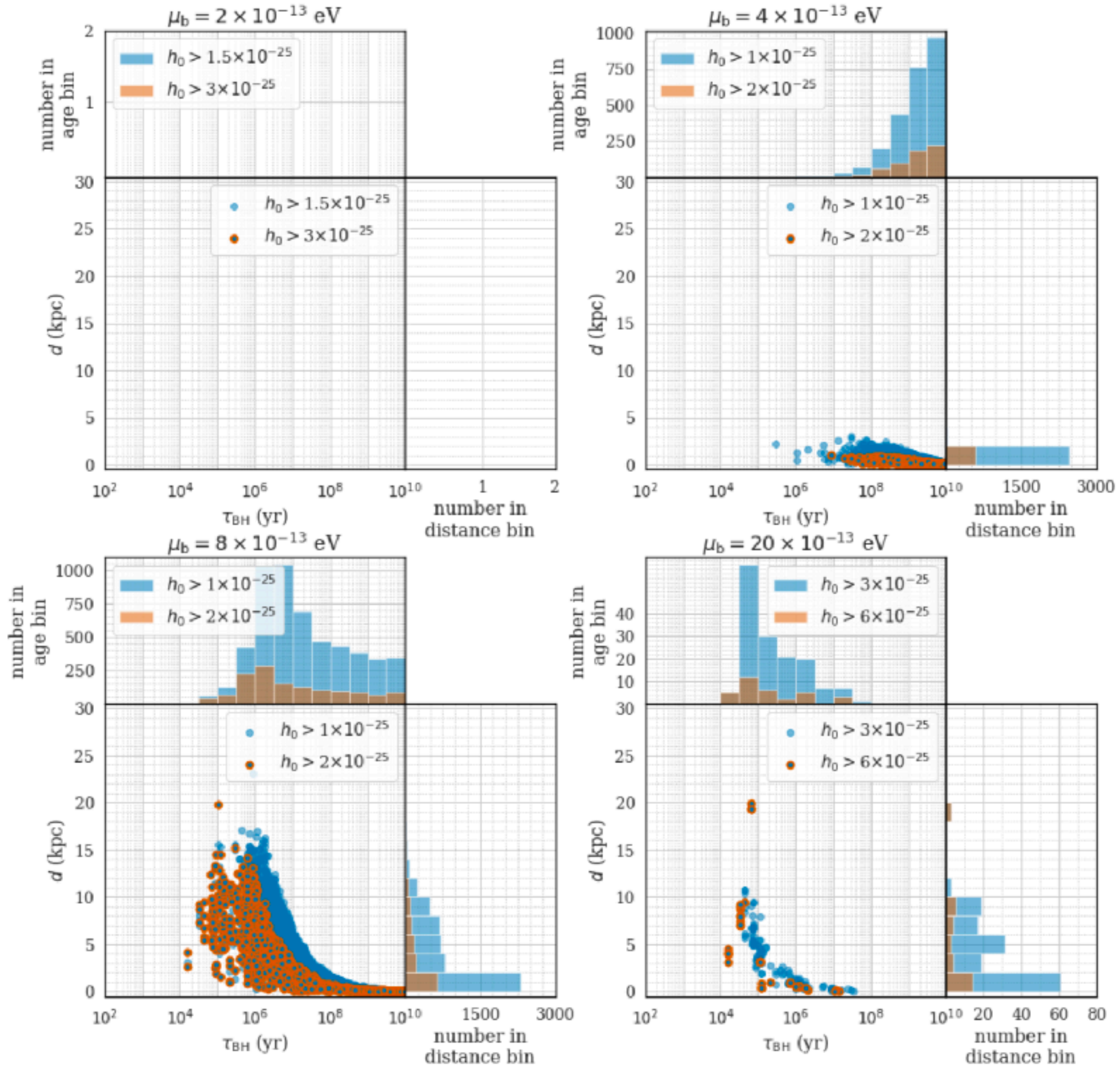


The black solid vertical lines show min f_{GW} given M_{BH} = 20M$_\odot$; the dotted line shows the rest mass frequency.

Which black holes produce ~detectable signals?

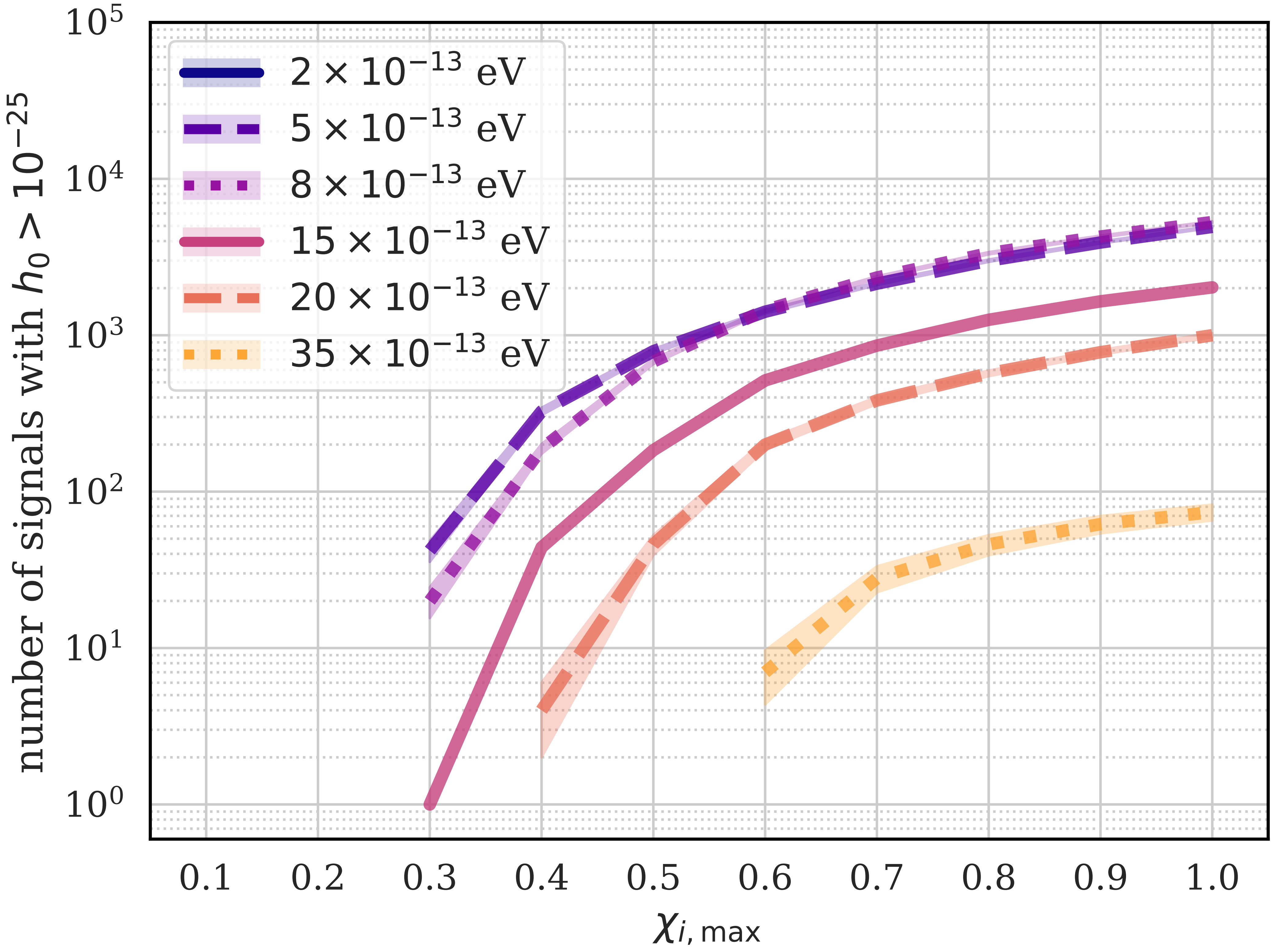
The “relevant" black holes depend on the boson mass, through both the signal properties and the detector sensitivity





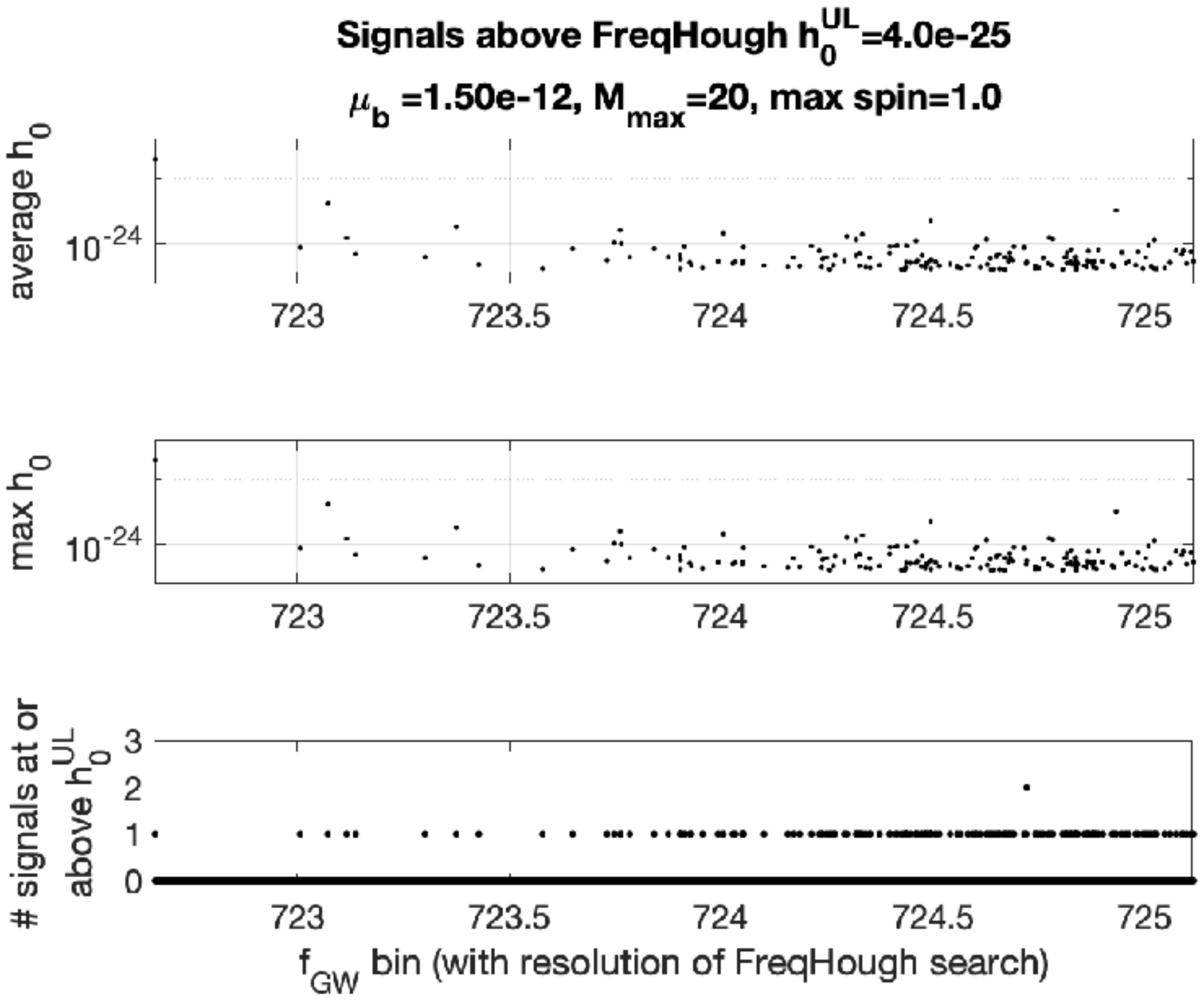
Varying spin

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



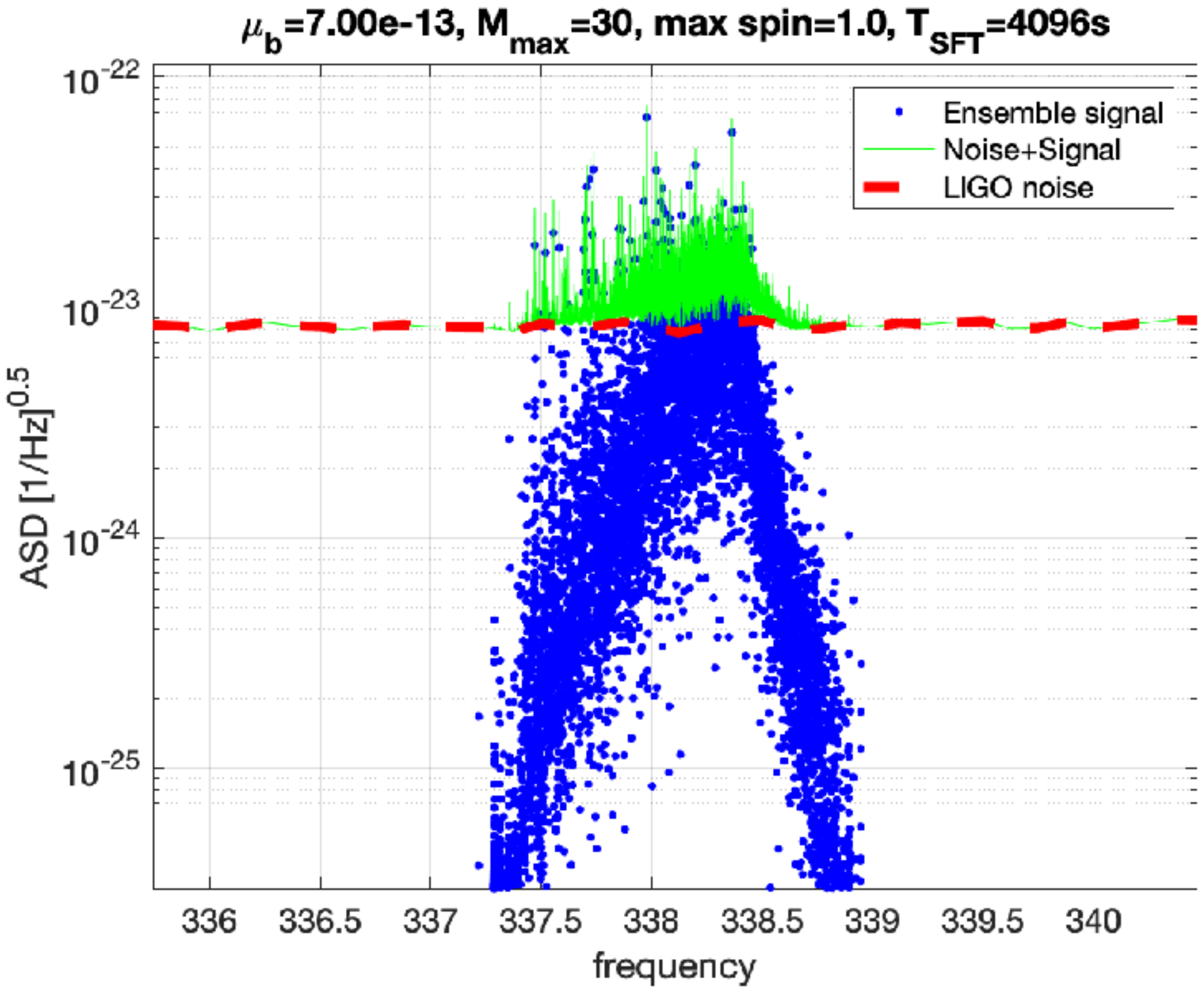
Concerns about signal density

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



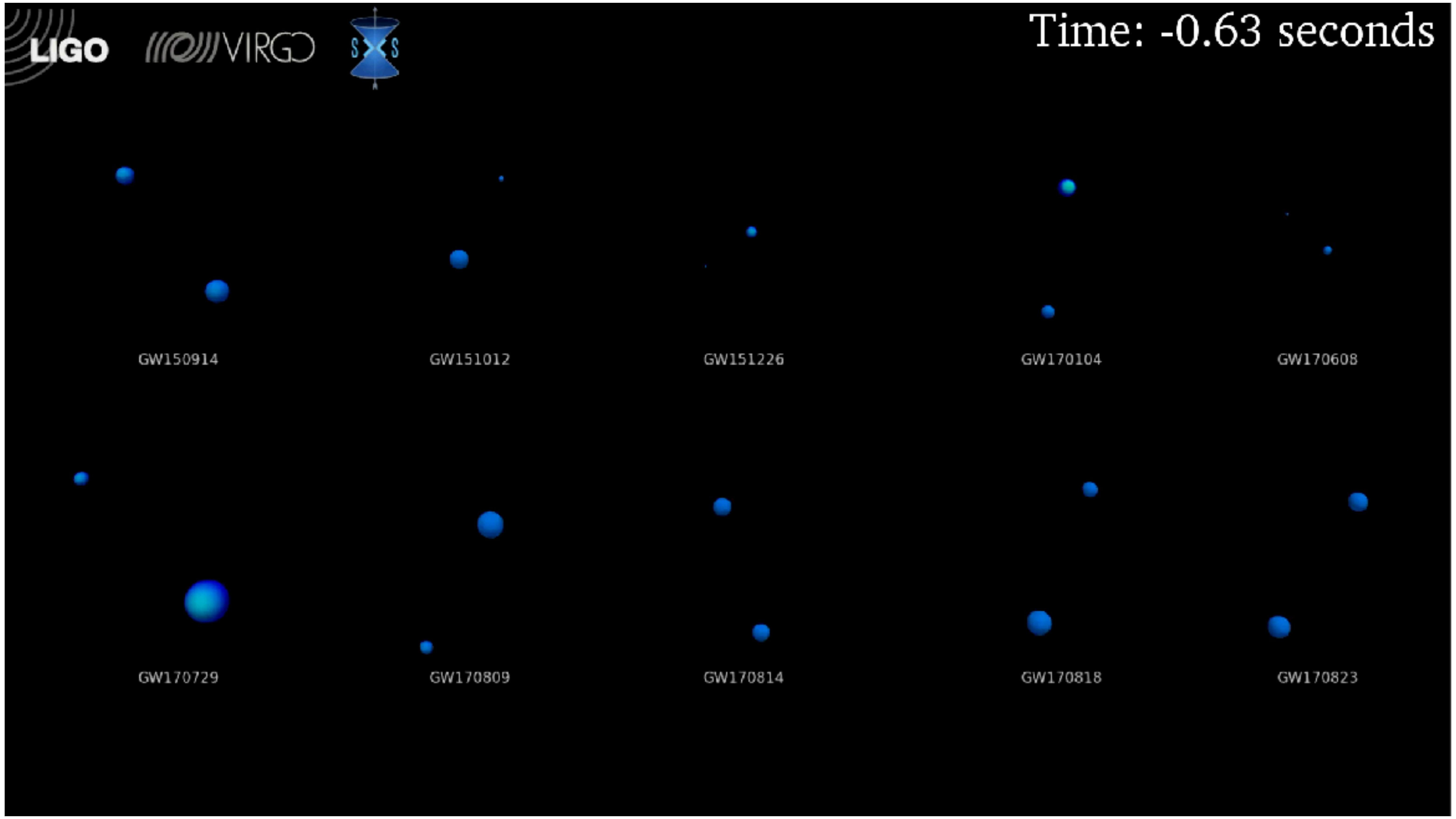
Concerns about signal density

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



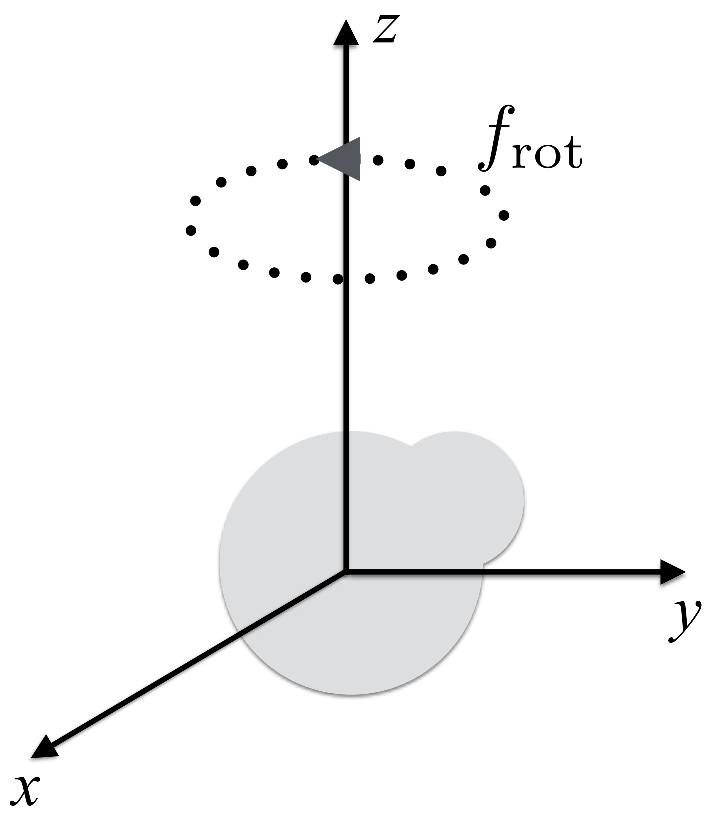
[Teresita Ramirez/Geoffrey Lovelace/SXS Collaboration/LIGO-Virgo Collaboration]

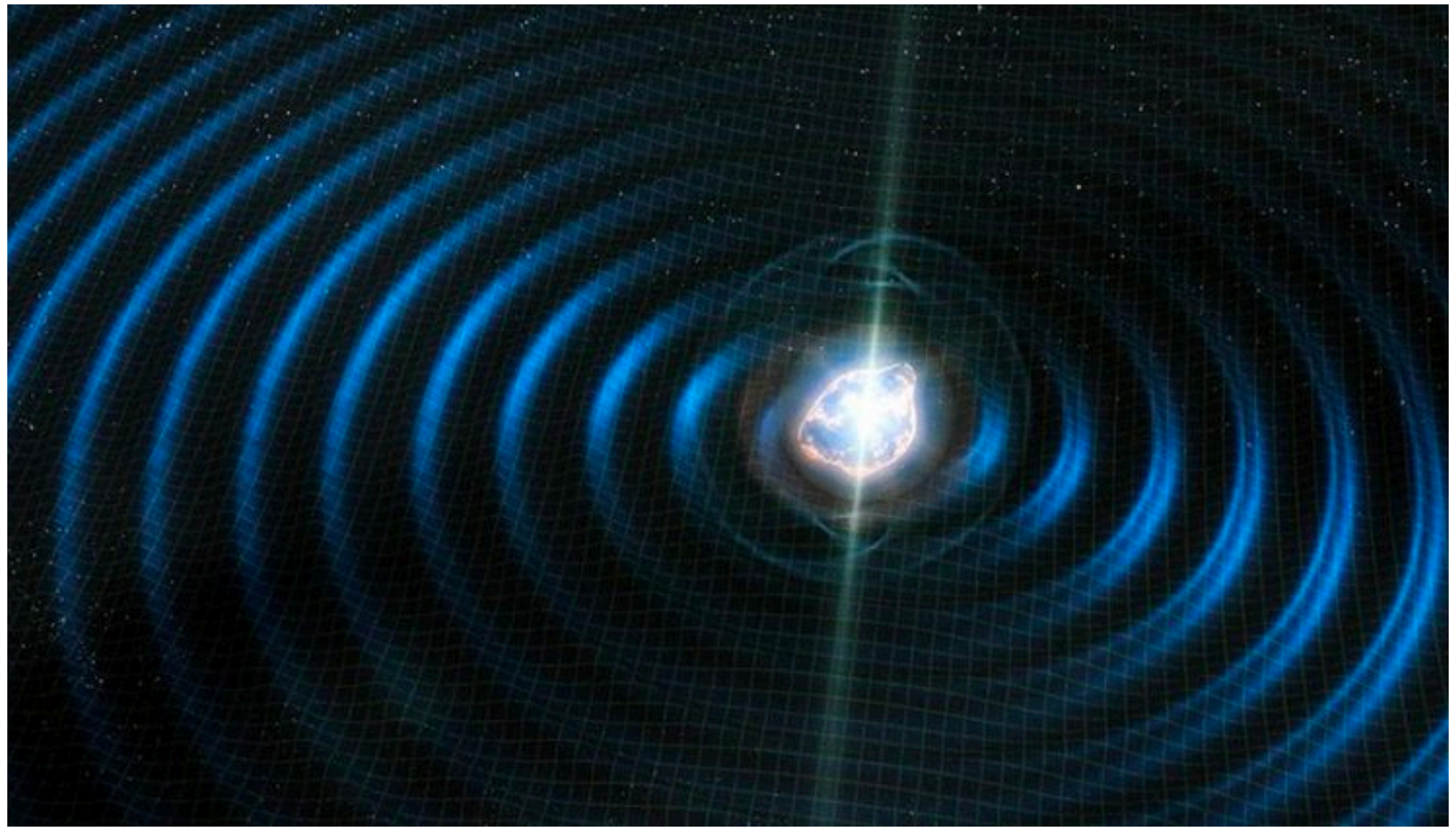
Continuous gravitational waves

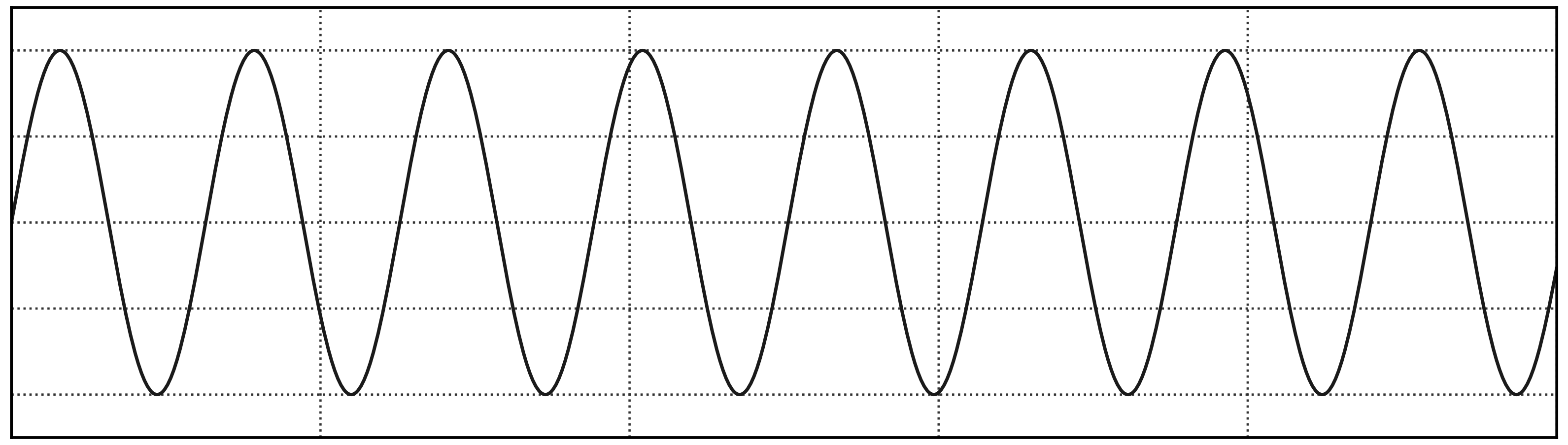
A changing mass quadrupole produces gravitational waves

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

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







h₀
characteristic strain

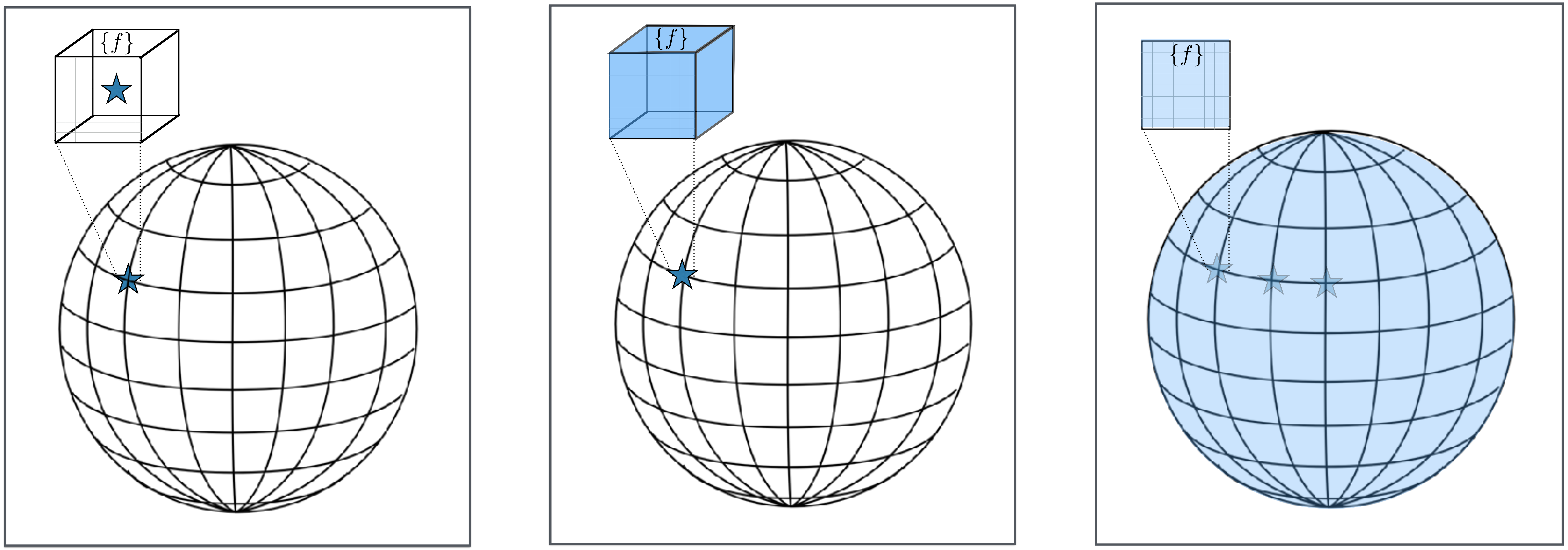
neutron star rotation

Types of searches

targeted search
known pulsars

directed search
known neutron stars

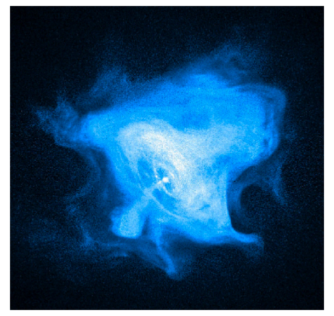
all-sky search
minimal assumptions



computational cost

search sensitivity

Interpreting null results (upper limits) — neutron stars



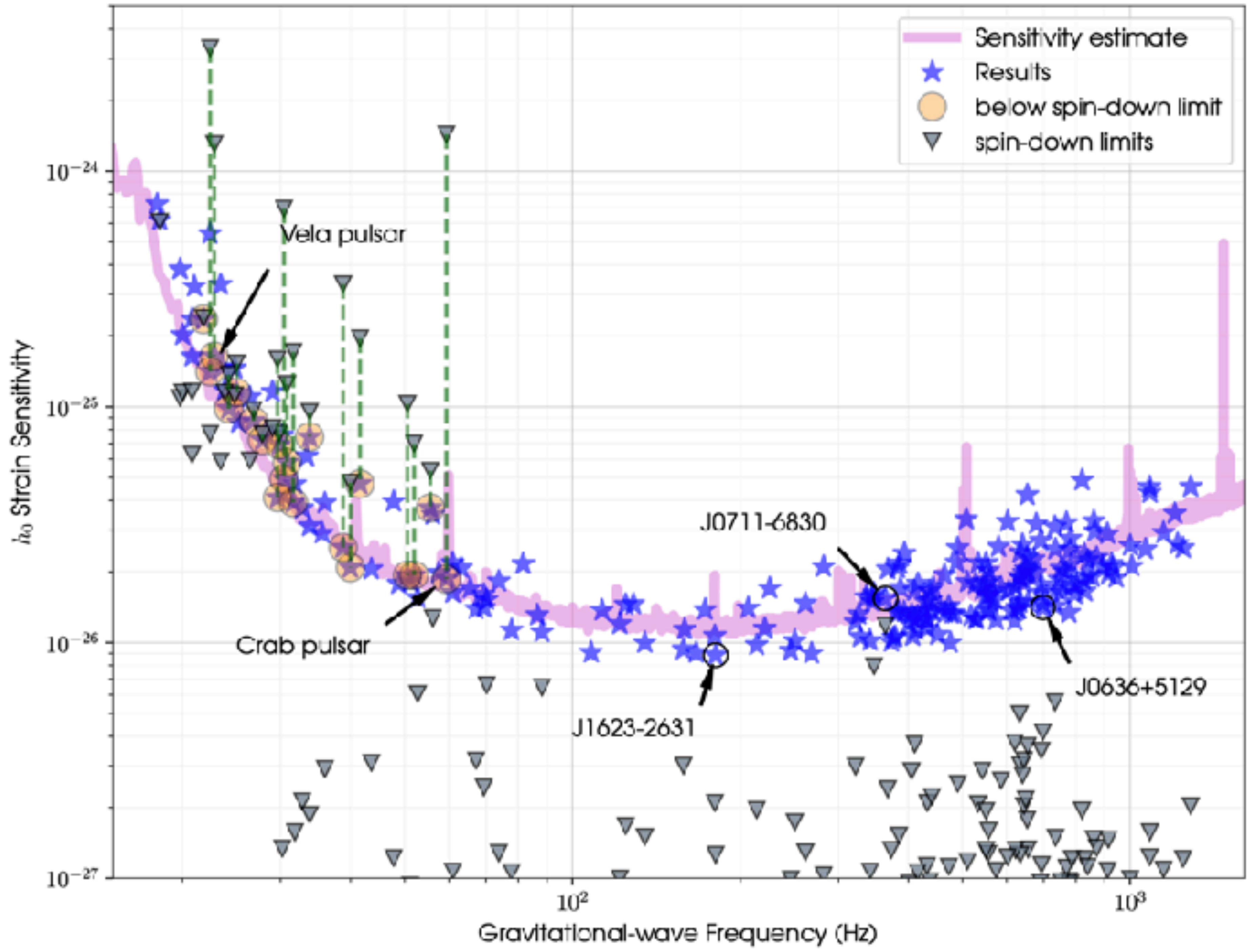
$$h_0 = \frac{4\pi G I_{zz}}{c^4}\frac{f_{\rm GW}^2 \epsilon}{d}$$

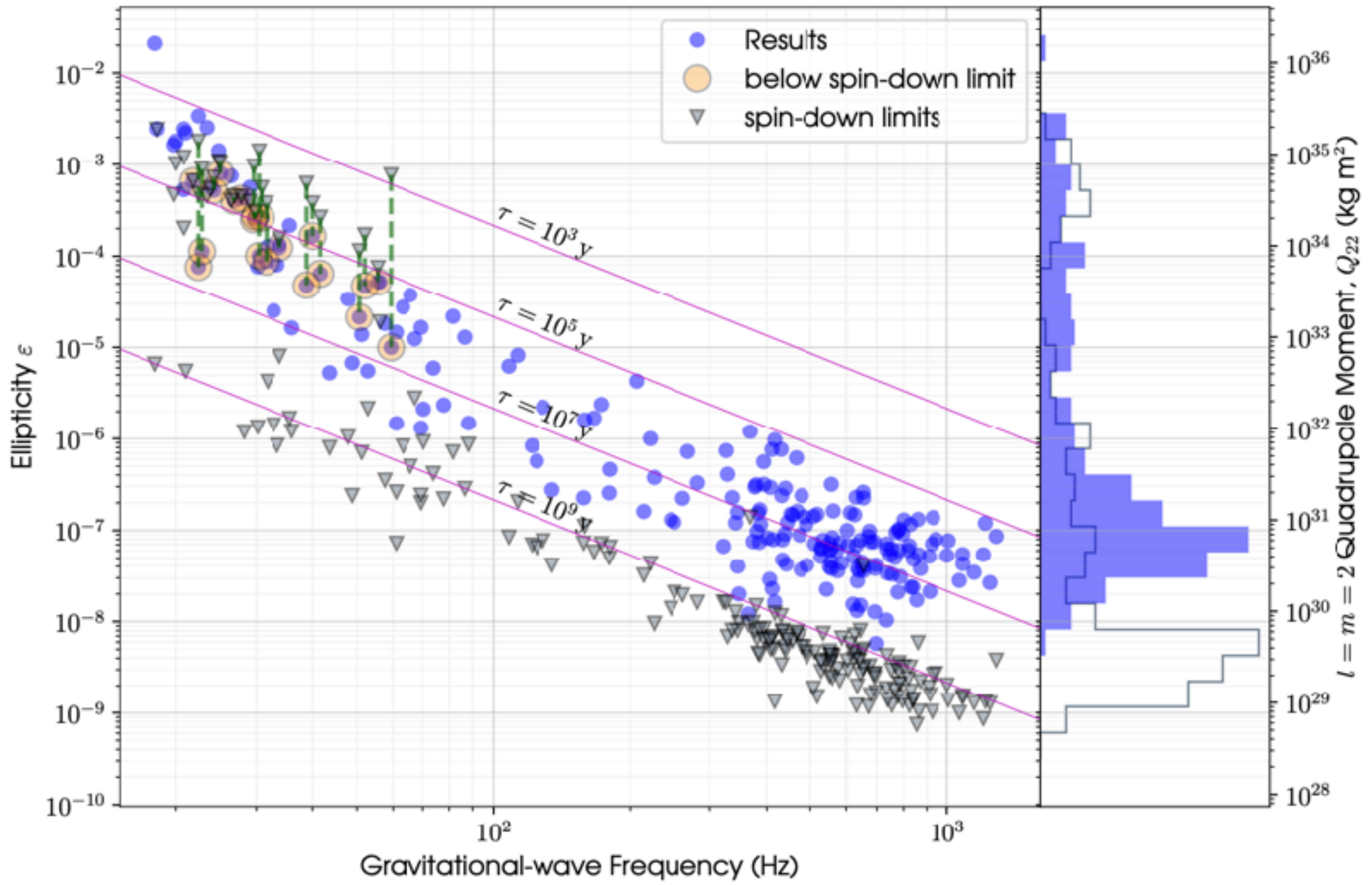
2x rotation frequency $f_{\rm rot}$

ellipticity $\frac{|I_{xx} - I_{yy}|}{I_{zz}}$

distance from detector

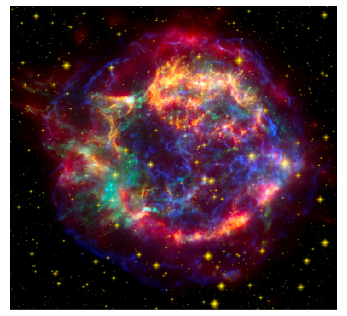
upper limit on gravitational-wave signal strength directly translates to upper limit on neutron star ellipticity (~max mountain height)





[LIGO and Virgo Collaborations, ApJ 879 (2019)]

Interpreting null results (upper limits) — neutron stars



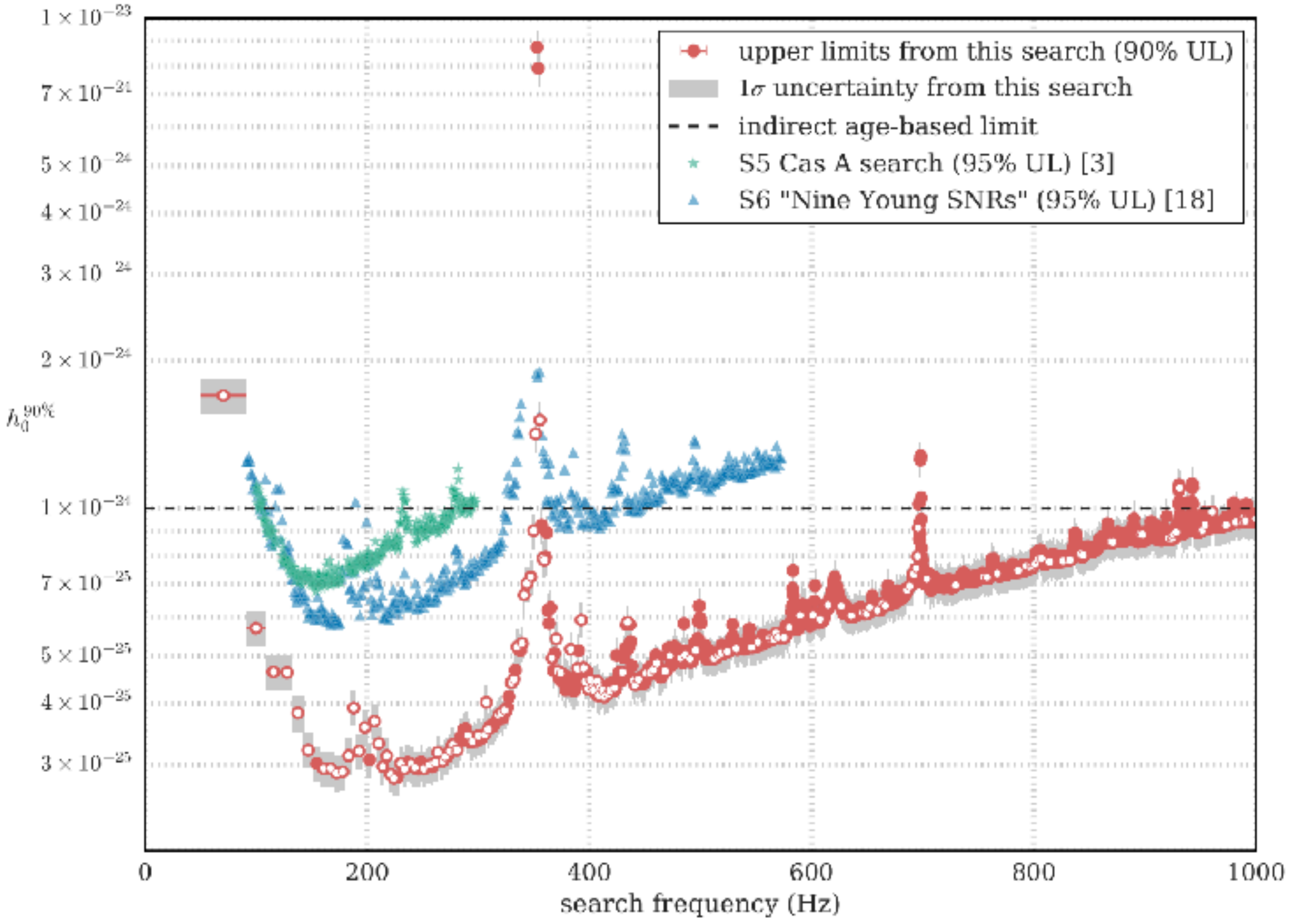
$$h_0 = \frac{4\pi G I_{zz}}{c^4} \frac{f_{\mathrm{GW}}^2 \epsilon}{d}$$

2x rotation frequency f_{rot}

ellipticity $\frac{|I_{xx} - I_{yy}|}{I_{zz}}$

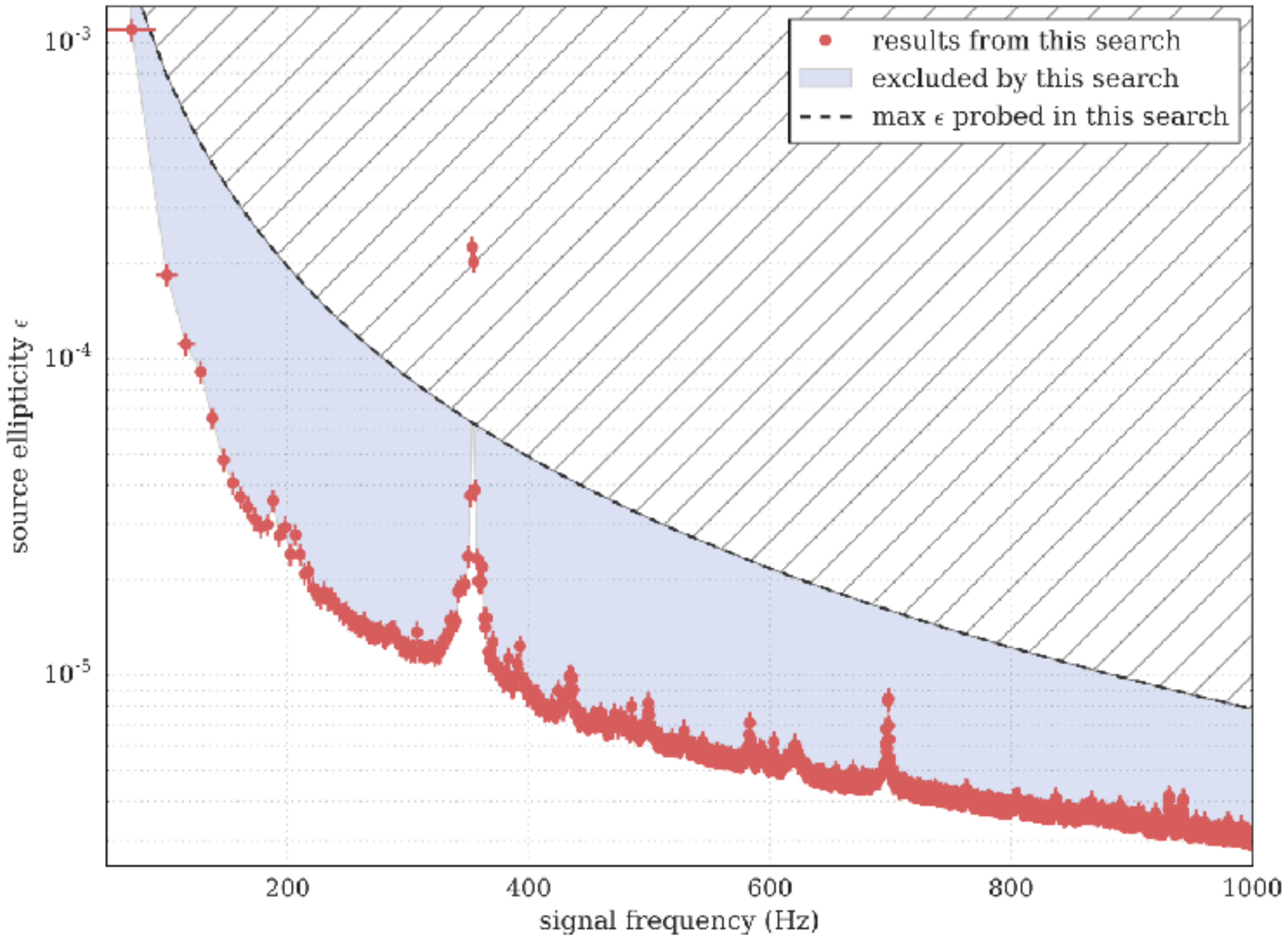
distance from detector

upper limit on gravitational-wave signal strength



translates to, assuming f_{GW},

upper limit on neutron star ellipticity (~max mountain height)



[Zhu et al., PRD 94 (2016)]