Gravitational Waves from Ultralight Bosons

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GEMMA | Lecce, Italy

motivation

gravitational waves can teach us about

astrophysics

cosmology

nuclear matter

gravity

…

how about particle physics?

main message

if an **ultralight boson** exists,
it will spontaneously form clouds
around **spinning black holes**

these clouds will emit potentially
detectable **gravitational waves**,
evidence for a new particle

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DISCLAIMER:
I'M NOT A THEORIST!

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ultralight bosons

simple, **well-motivated** extension of the standard model

a *new* **integer-spin** particle with very **small mass**

$$10^{-20} \lesssim \mu/\mathrm{eV} \lesssim 10^{-9}$$

should **interact very weakly** if at all,
other than gravitationally, hence **hard to detect**

depending on specific mass and other couplings,
could be a viable **dark matter** candidate

the QCD axion

scalar postulated to solve the **strong-CP problem**:
why doesn't the strong force break CP symmetry?

$$\mu_a \sim 6 \times 10^{-13}\,\mathrm{eV}\ \frac{10^{19}\,\mathrm{GeV}}{f_a}$$

where f_a is the Peccei-Quinn symmetry breaking scale

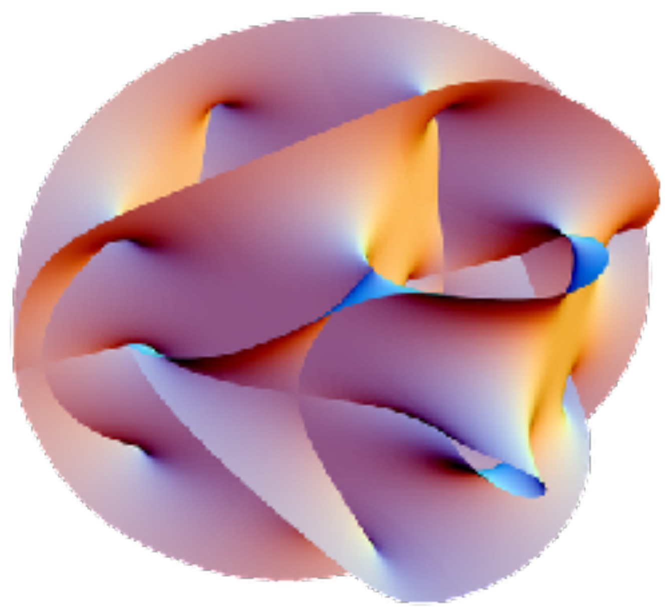
other model-dependent couplings,
e.g. to electromagnetism

$$\mathcal{L}_{a\gamma\gamma} \propto \frac{g_\gamma}{f_a} a\,\vec{E}\cdot\vec{B}$$

string theory predicts many

ultralight bosons

existence of *myriad* axion-like particles is a natural consequence of extra dimensions in **string theory**



QCD axion would be *one* component of this **axiverse**
should expect many of them to be much lighter

$$10^{-33} < \mu/\mathrm{eV} < 10^{-10}$$

mass could populate every decade in this range

how to look for ultralight, weakly-interacting bosons?

(without assuming much about specific properties)

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superradiance

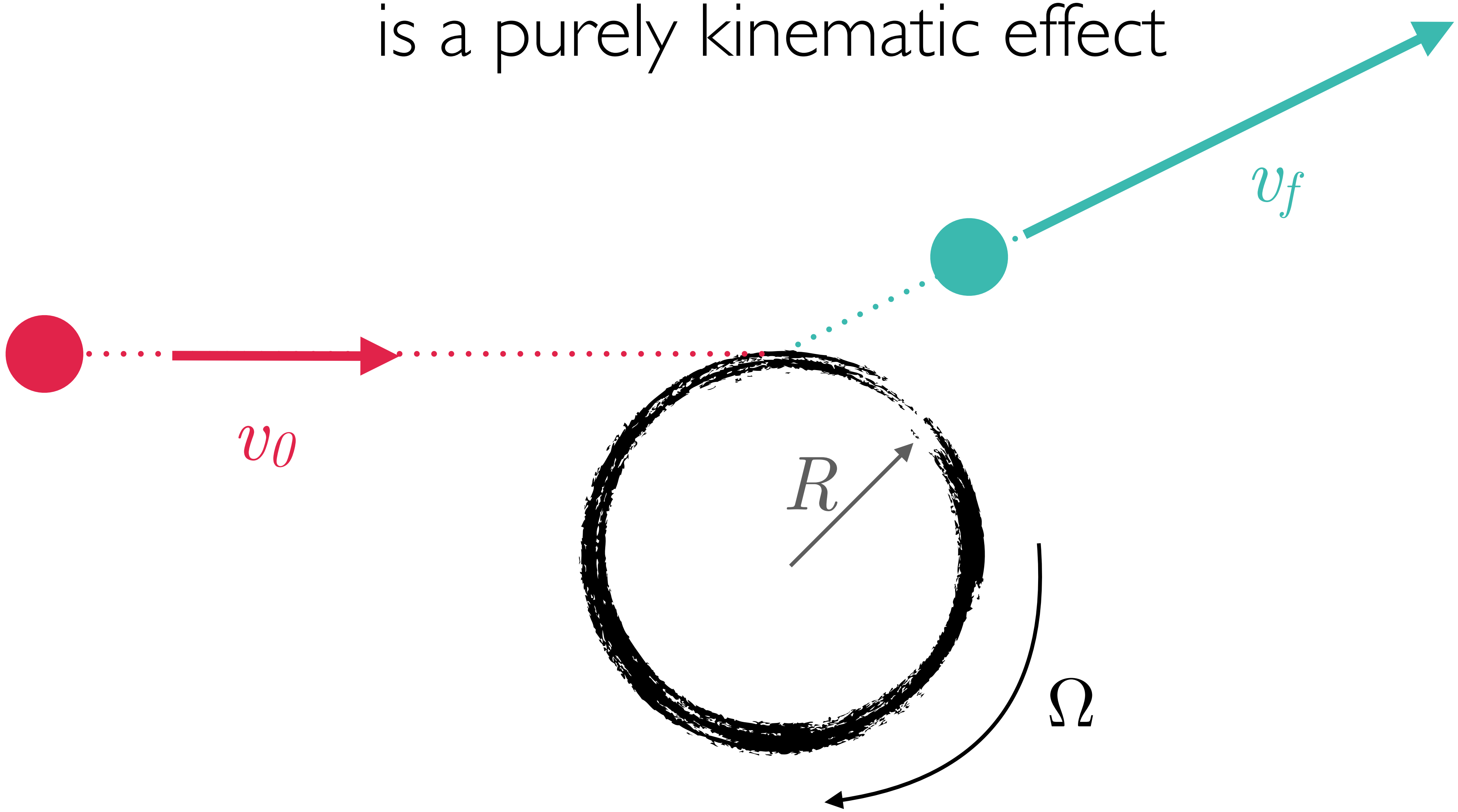
waves may be scattered from a black-hole with an *increased* amplitude

more generally, any wave *enhancement* due to a *dissipative* process

see review by Brito et al. [arXiv:1501.06570]

superradiance

is a purely kinematic effect



$$v_0/R < \Omega \implies v_0 < v_f$$

superradiance

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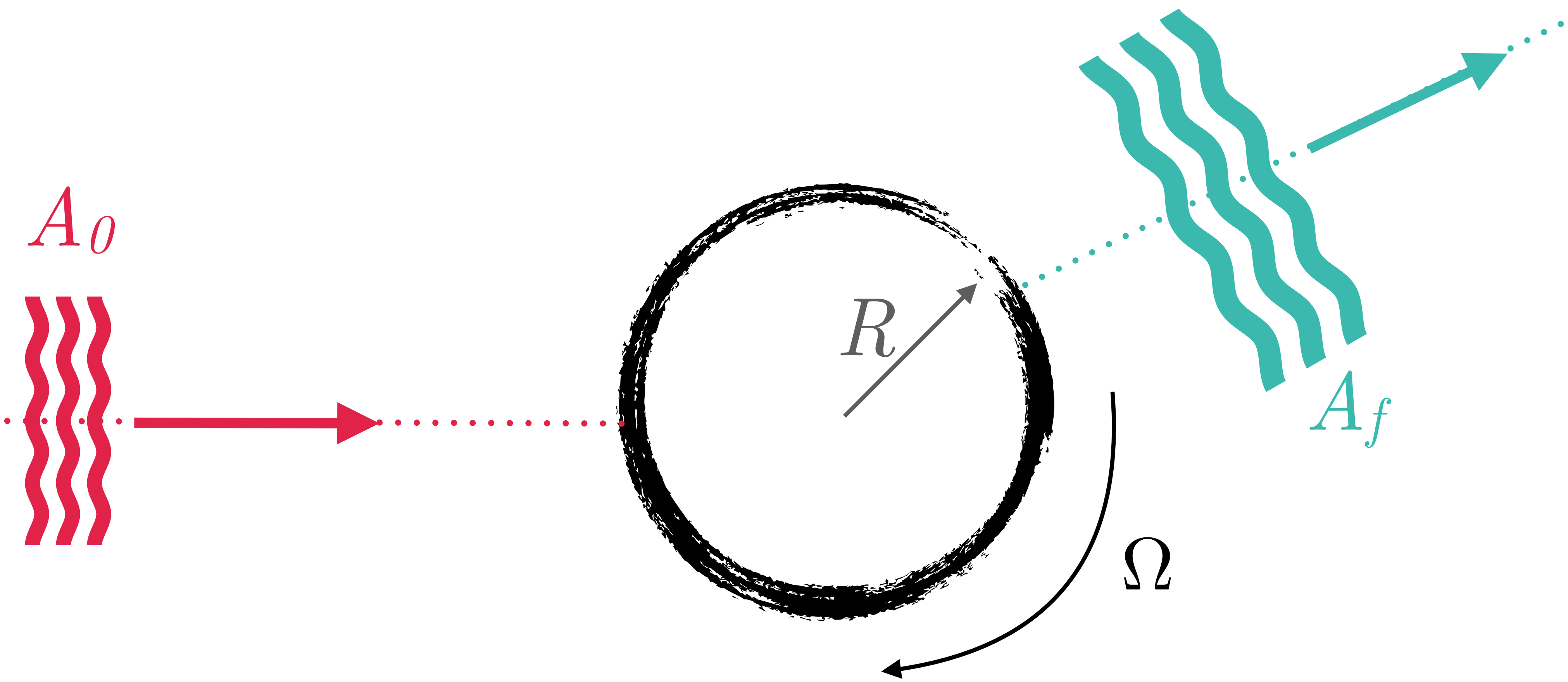


$$\omega_0/m < \Omega \implies A_0 < A_f$$

wave frequency, ω ; azimuthal quantum number, m

superradiance condition

wave is amplified if

$$\omega/m < \Omega$$

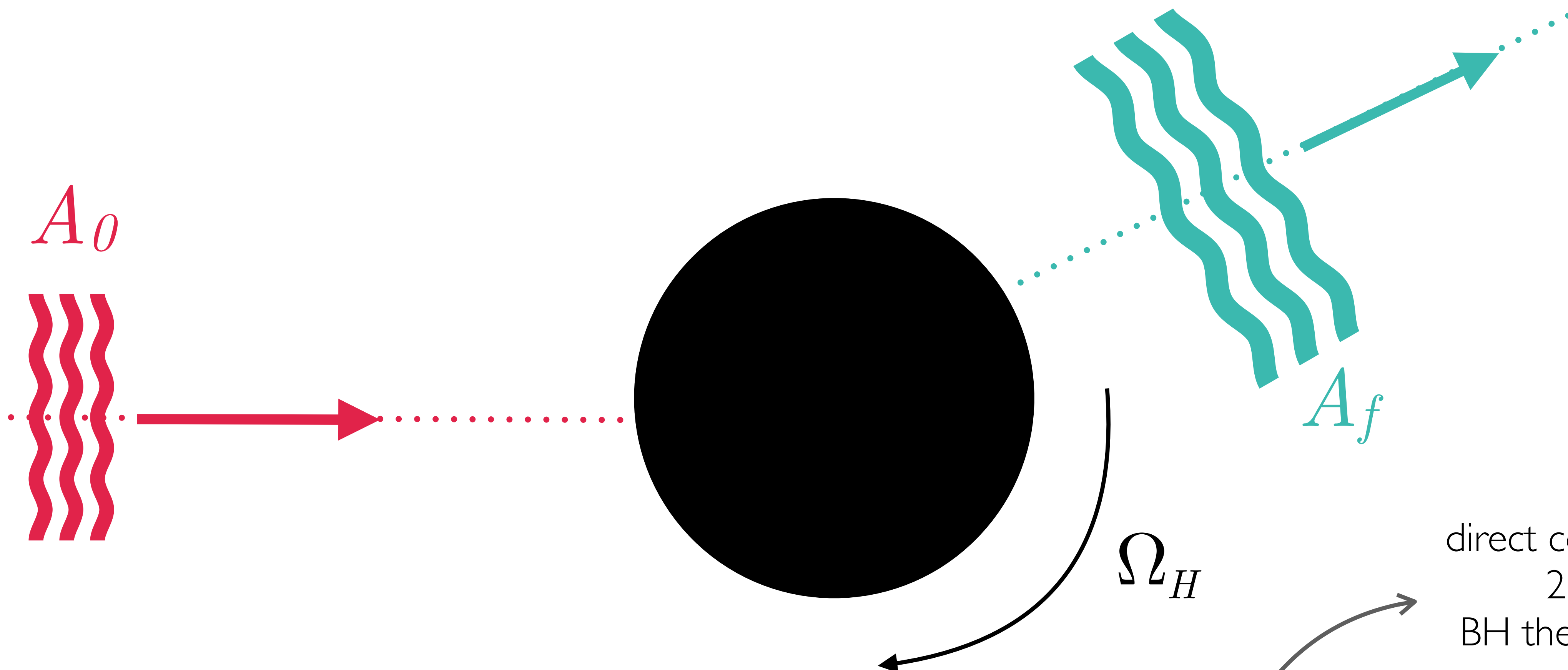
wave frequency, ω ; azimuthal quantum number, m

generic kinematic effect, but **hard to observe**:
need highly spinning central object, with lots of symmetry, and size comparable to incoming wavelength

rotating black-hole

superradiance

wave extracts energy from the ergoregion
(like Penrose process)



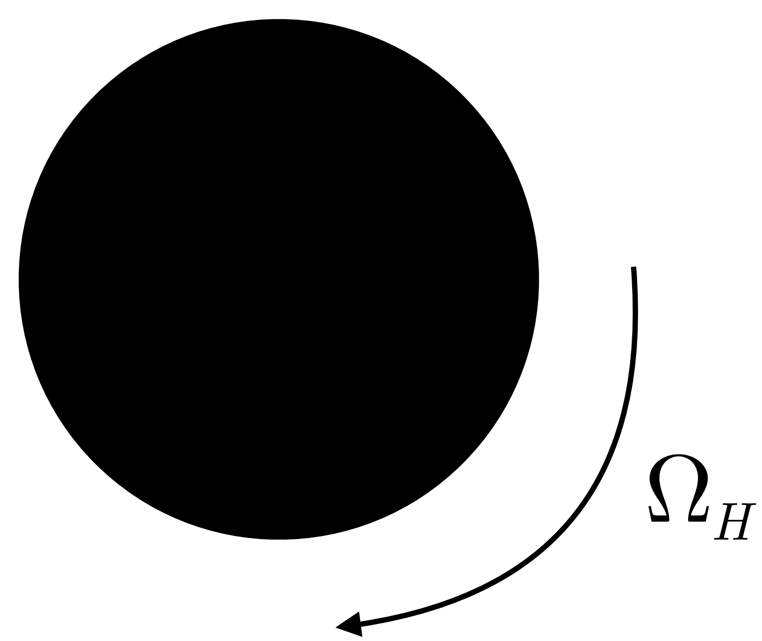
direct consequence of
2nd law of
BH thermodynamics

$$\omega_0/m < \Omega_H \Longrightarrow A_0 < A_f$$

wave frequency, ω ; azimuthal quantum number, m

black-hole bomb

(Teukolsky & Press 1972)



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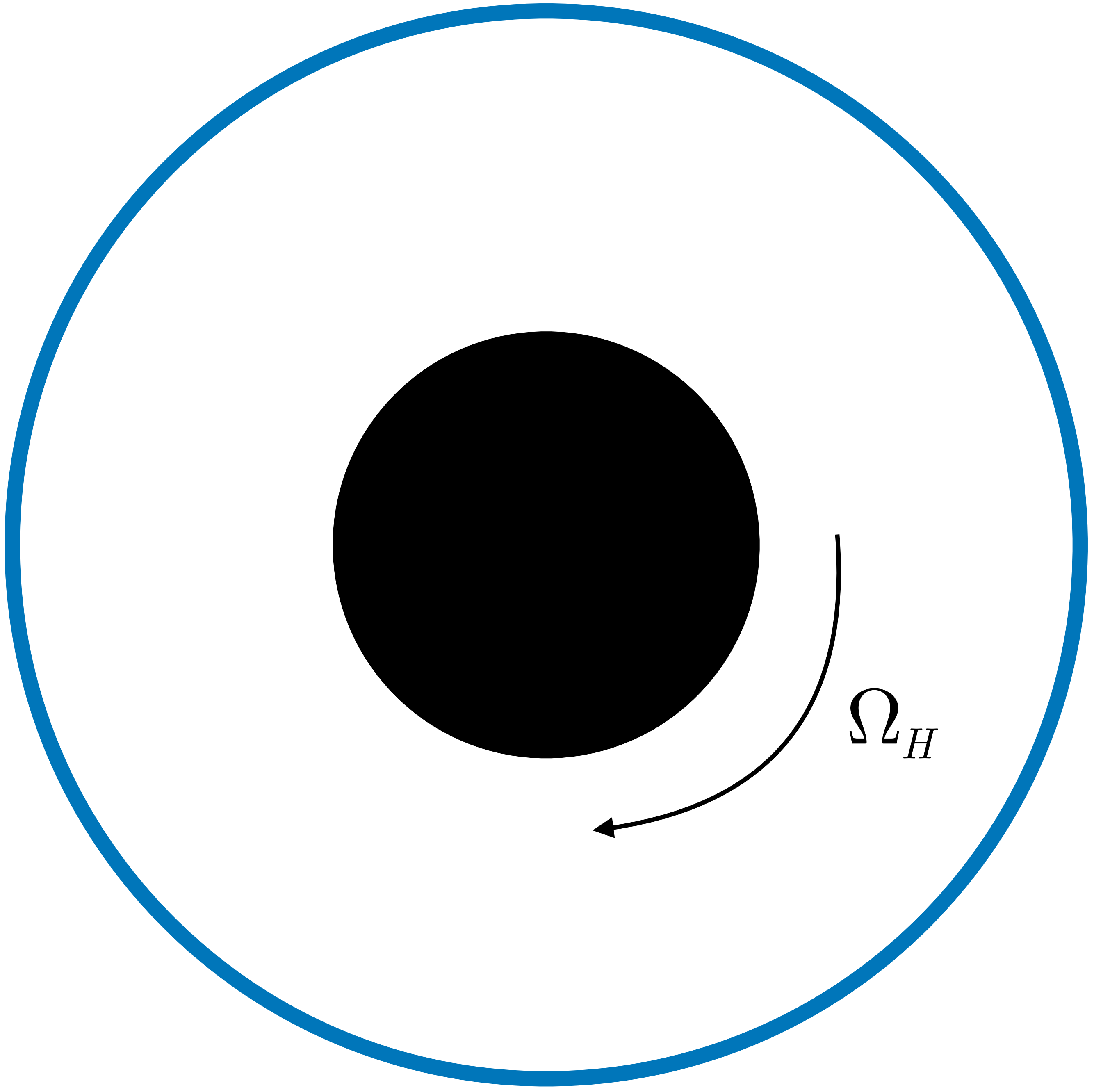

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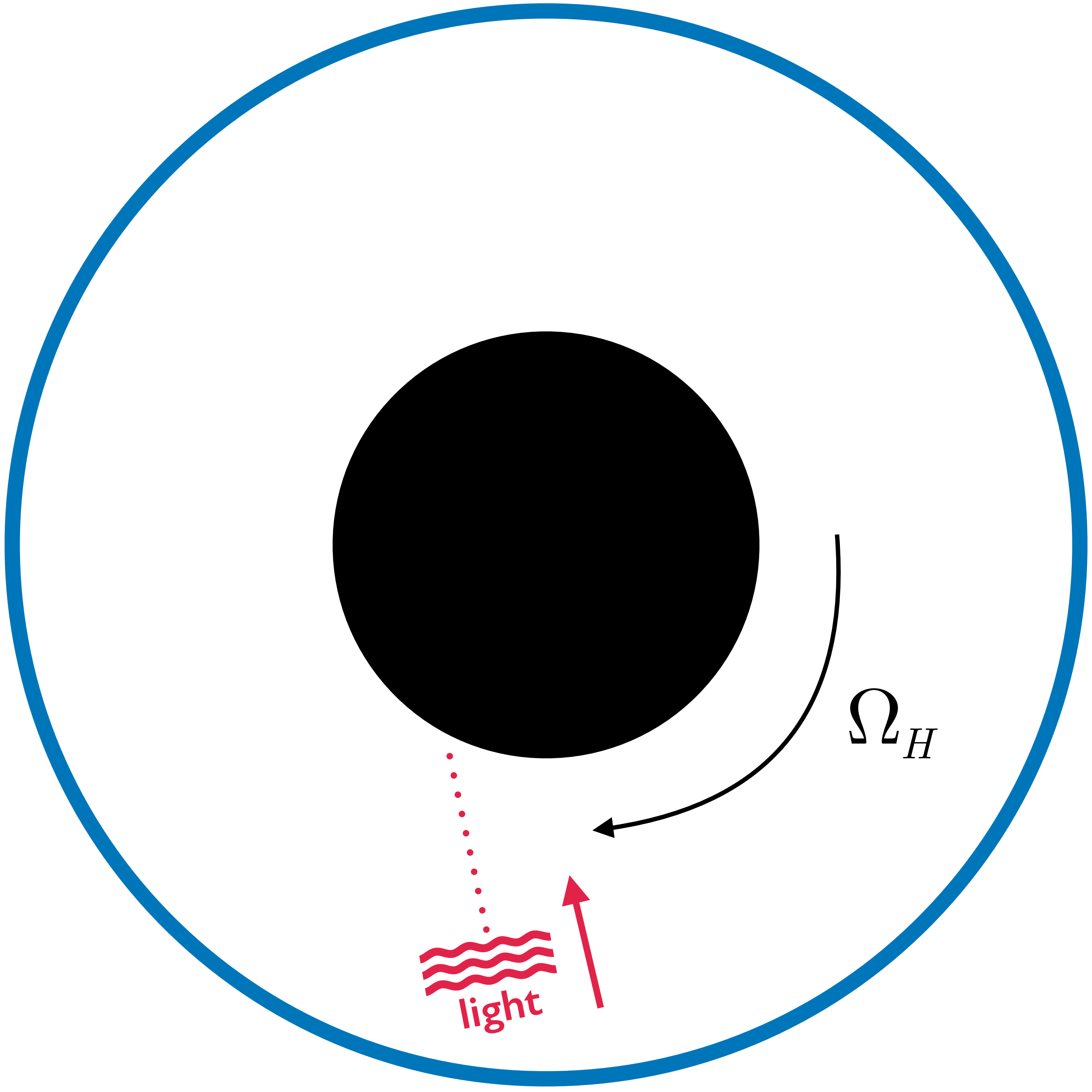
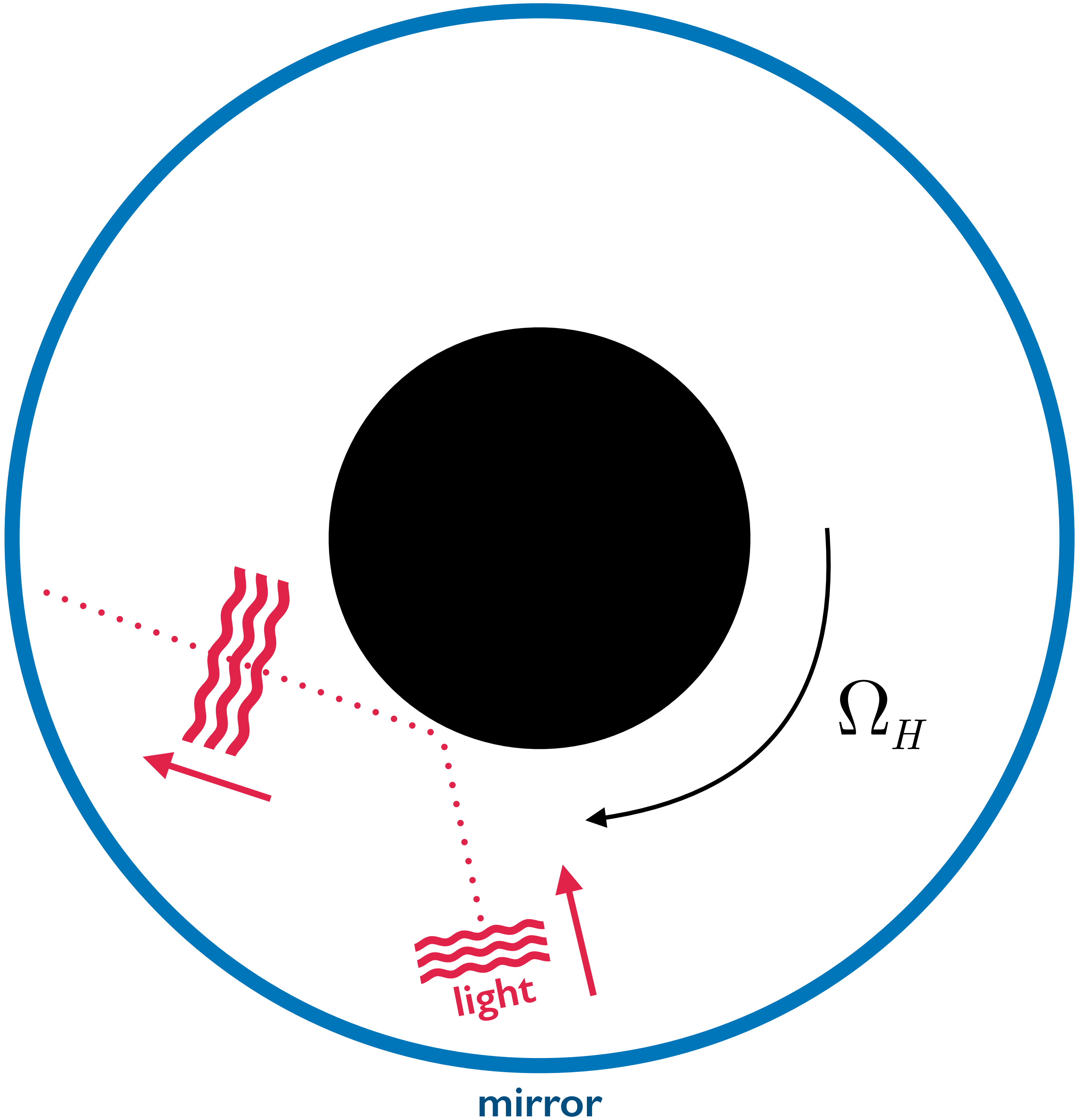


mirror

black-hole bomb

(Teukolsky & Press 1972)



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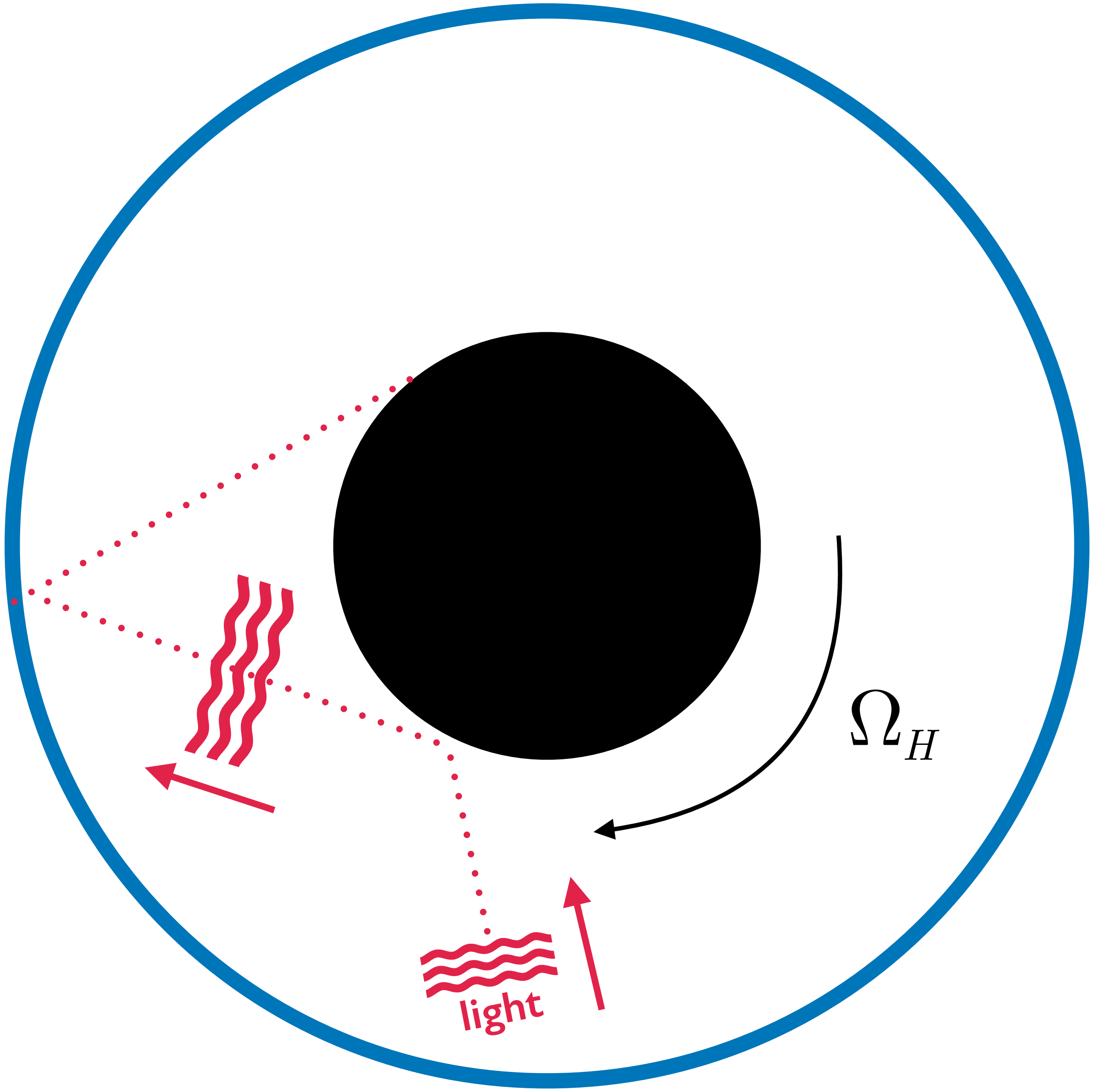

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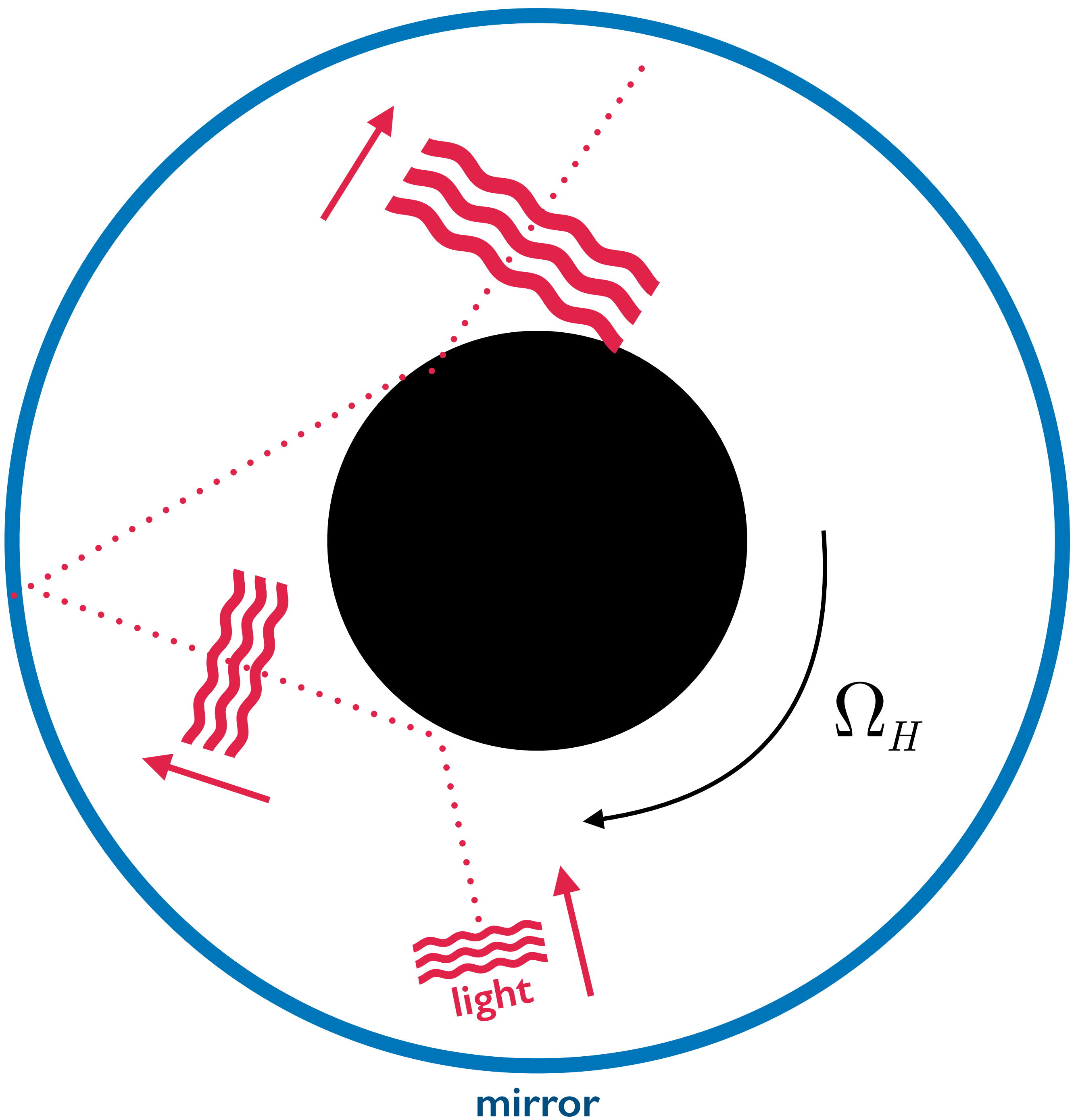

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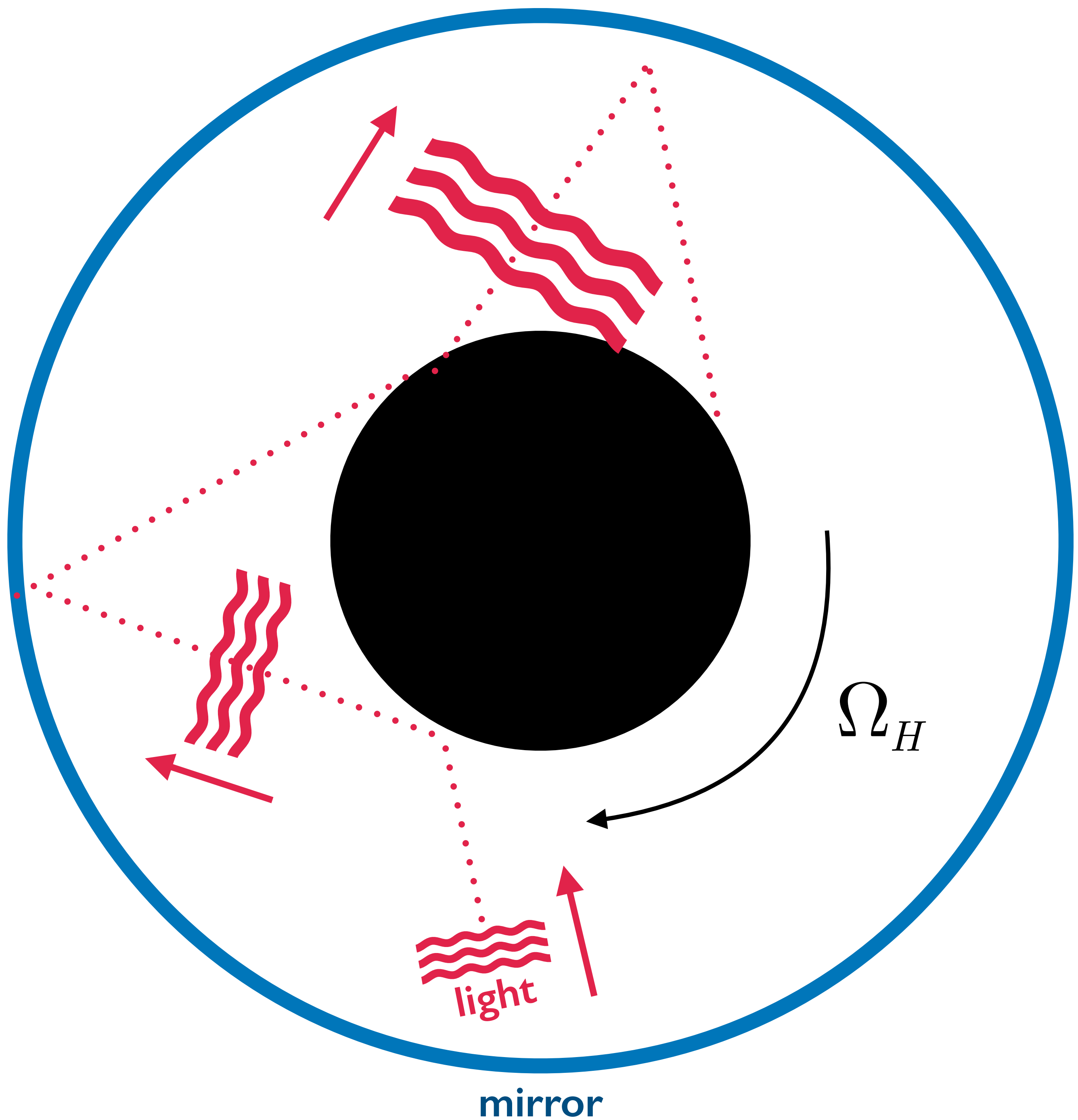

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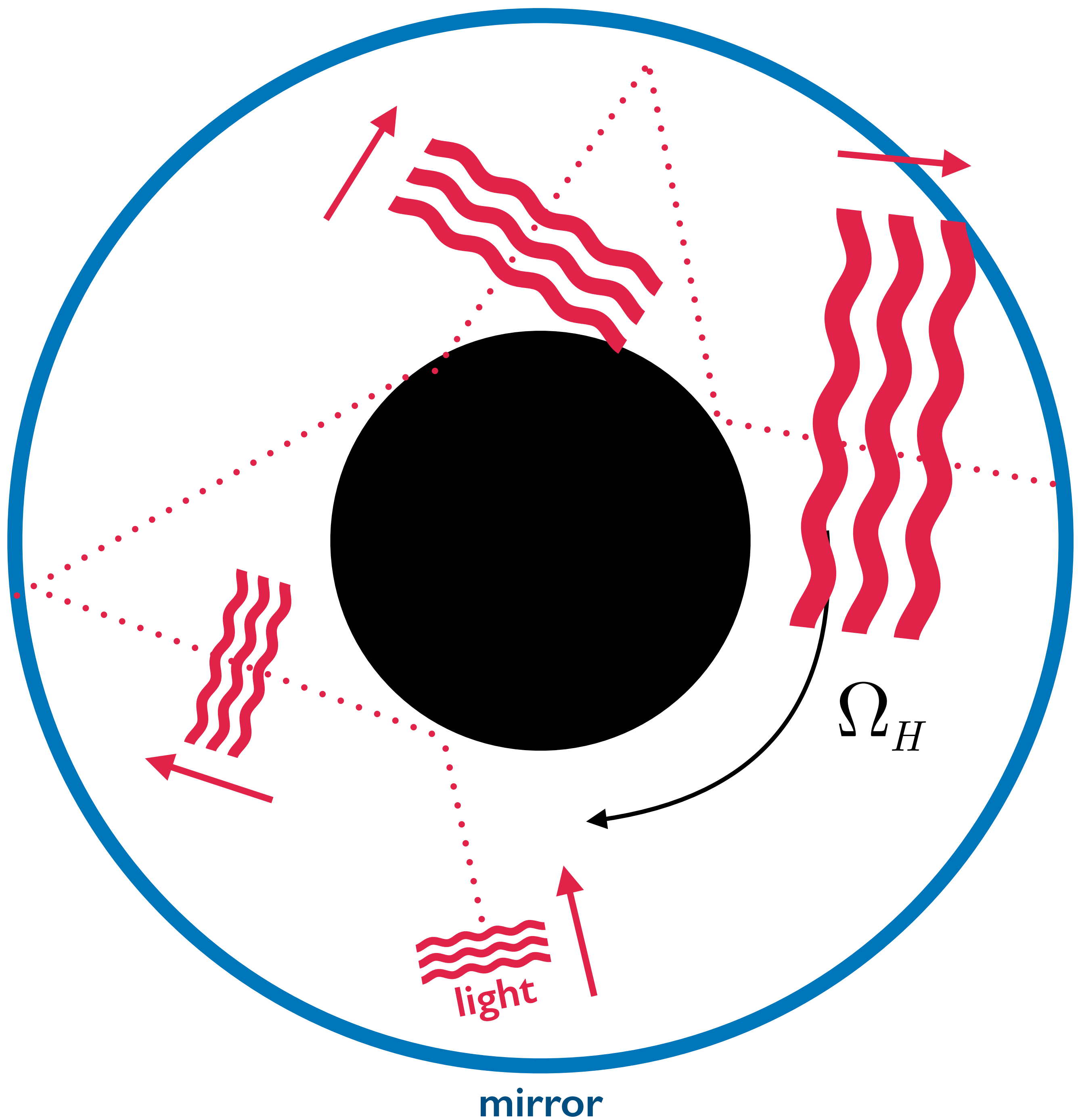

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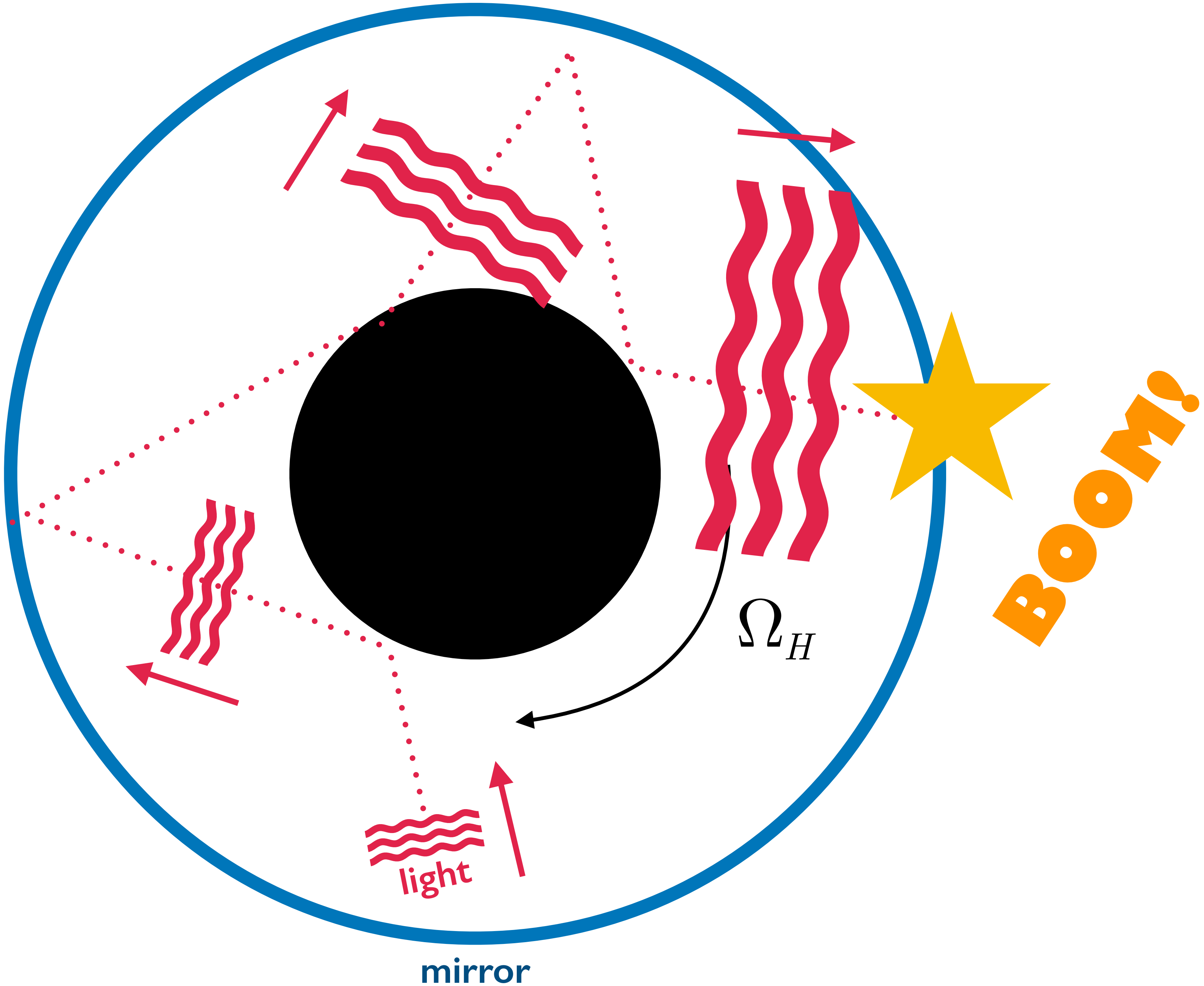
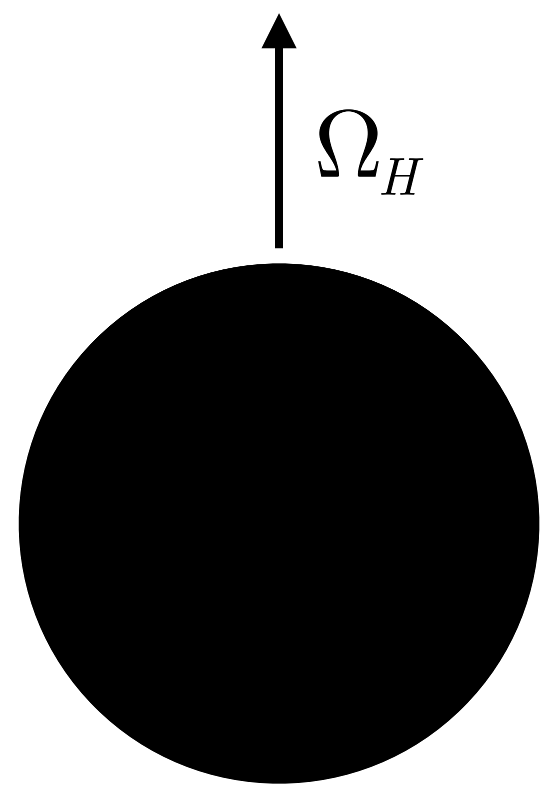


boson superradiance



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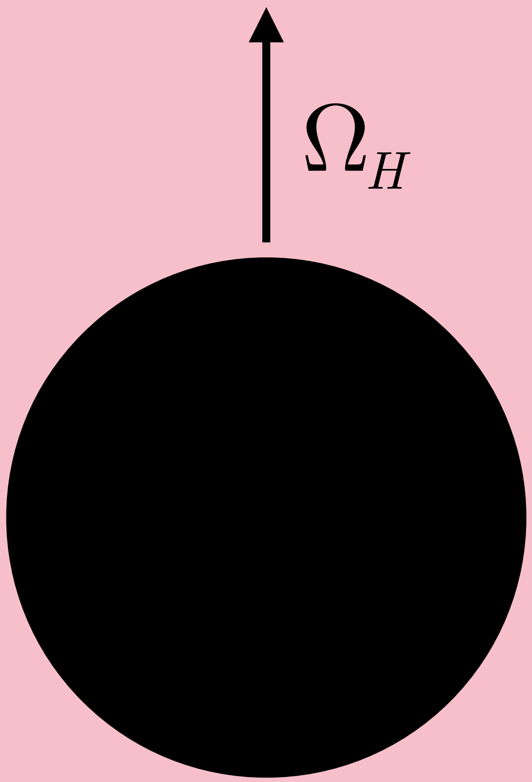
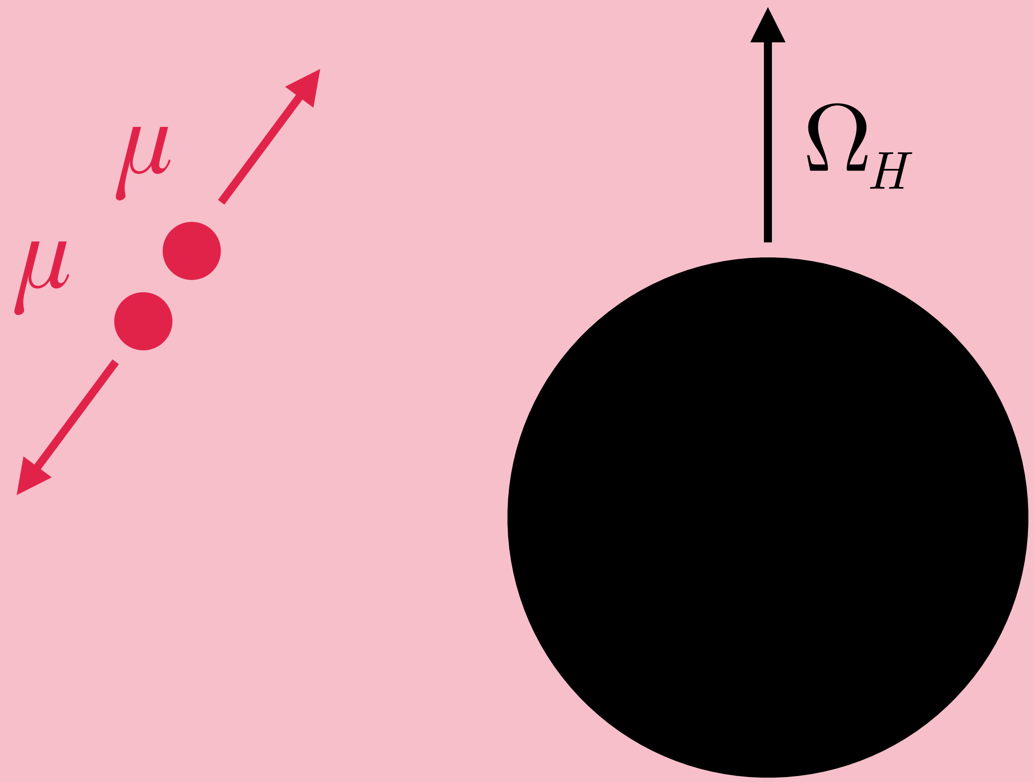


boson field

boson superradiance



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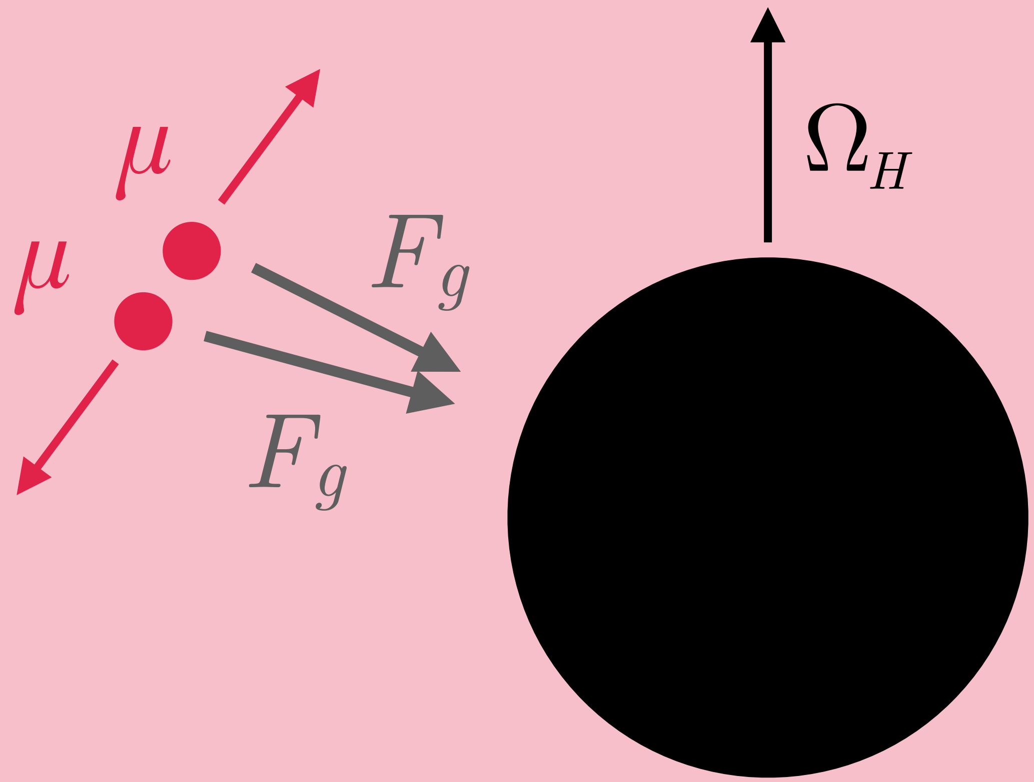

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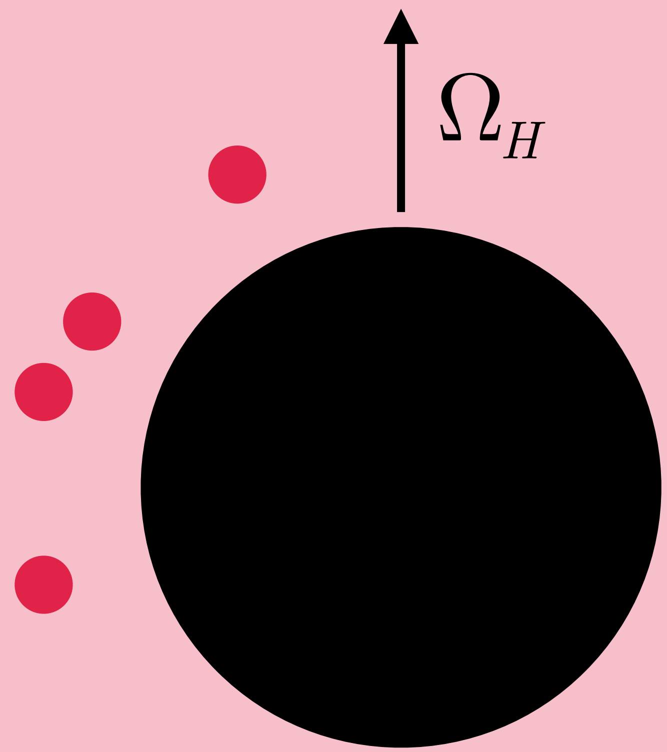

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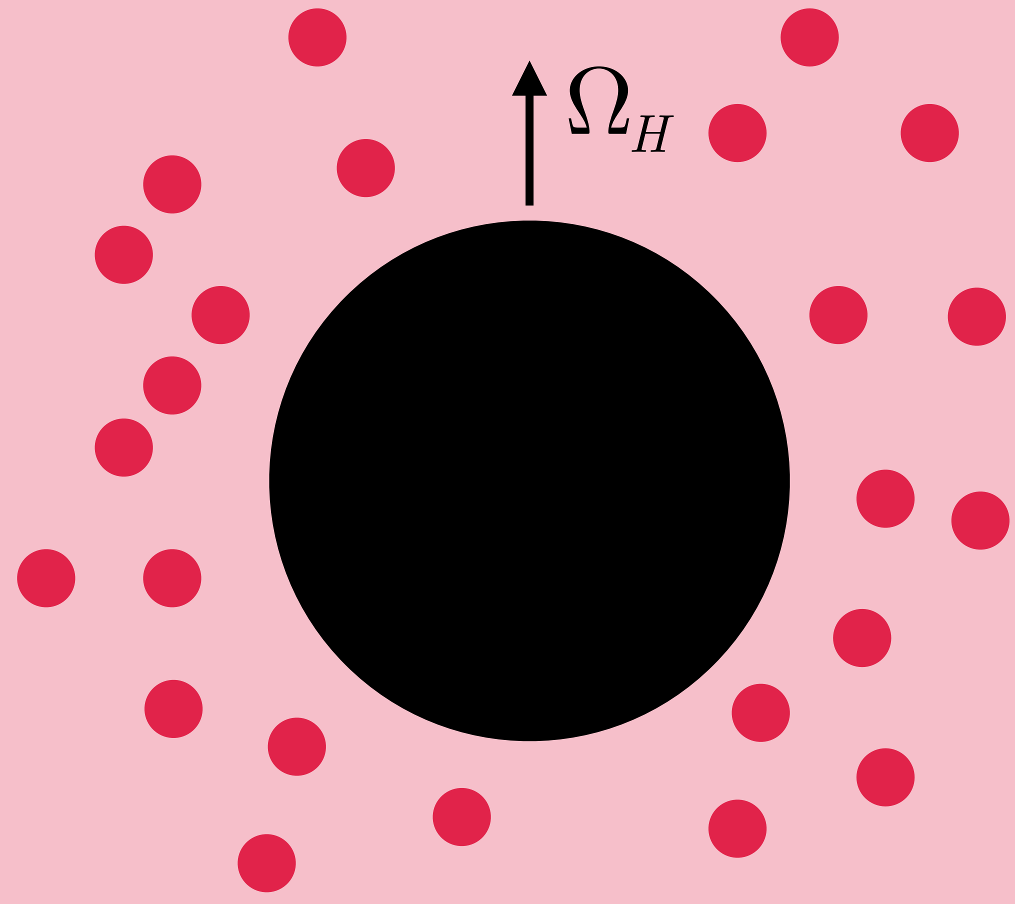
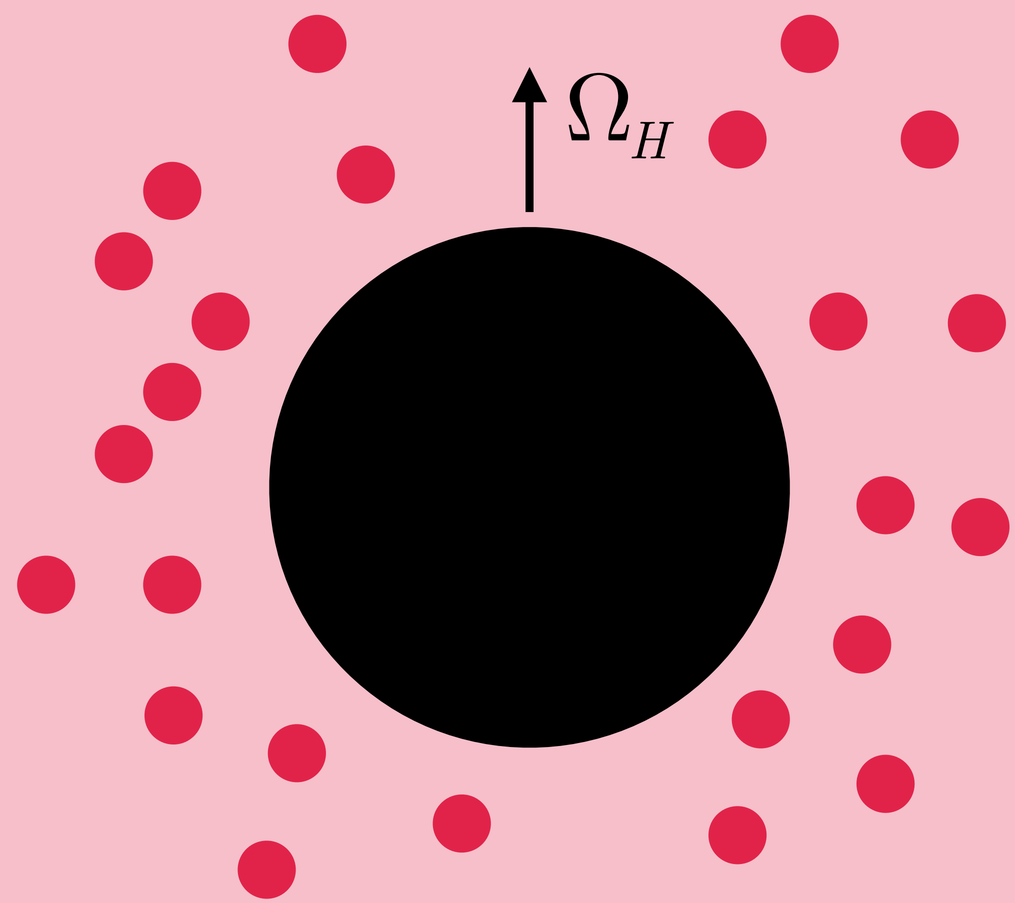


boson field

boson superradiance

mass acts as a "mirror"!



boson field

confinement condition

maximum amplification for

$$\lambda_C \sim 2\pi R$$

boson Compton wavelength, $\lambda_C = h/\mu c$; black-hole radius, R

for **astrophysical black holes**, this gives

$$\mu \sim 10^{-9} - 10^{-20}\ \mathrm{eV}$$

for the QCD axion, this also means f_a~GUT scale

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theoretically interesting!

for the QCD axion, this also means f_a~GUT scale

an atom in the sky

solve Schrödinger equation on Kerr background:

hydrogenic energy levels!

level energy

$$\hbar\omega \simeq \mu c^2 \left(1 - \frac{\alpha^2}{2n^2}\right)$$

cloud radius

$$r_c \sim \frac{n^2}{\alpha^2}\frac{GM}{c^2}$$

with a *Fine-structure constant* given by

$$\alpha = \frac{GM\mu}{\hbar c} = \frac{1}{2}\frac{R_s}{\lambda\!\!\!^{-}_C}$$

Schwarzshild radius

principal quantum number $n = n_r + l + m$

an atom in the sky

solve Schrödinger equation on Kerr background:
hydrogenic energy levels!
but not quite…

bosons *instead of fermions*

system is ***non-Hermitian****,*
with ingoing boundary condition at horizon

for scalar, rate of **level growth** is

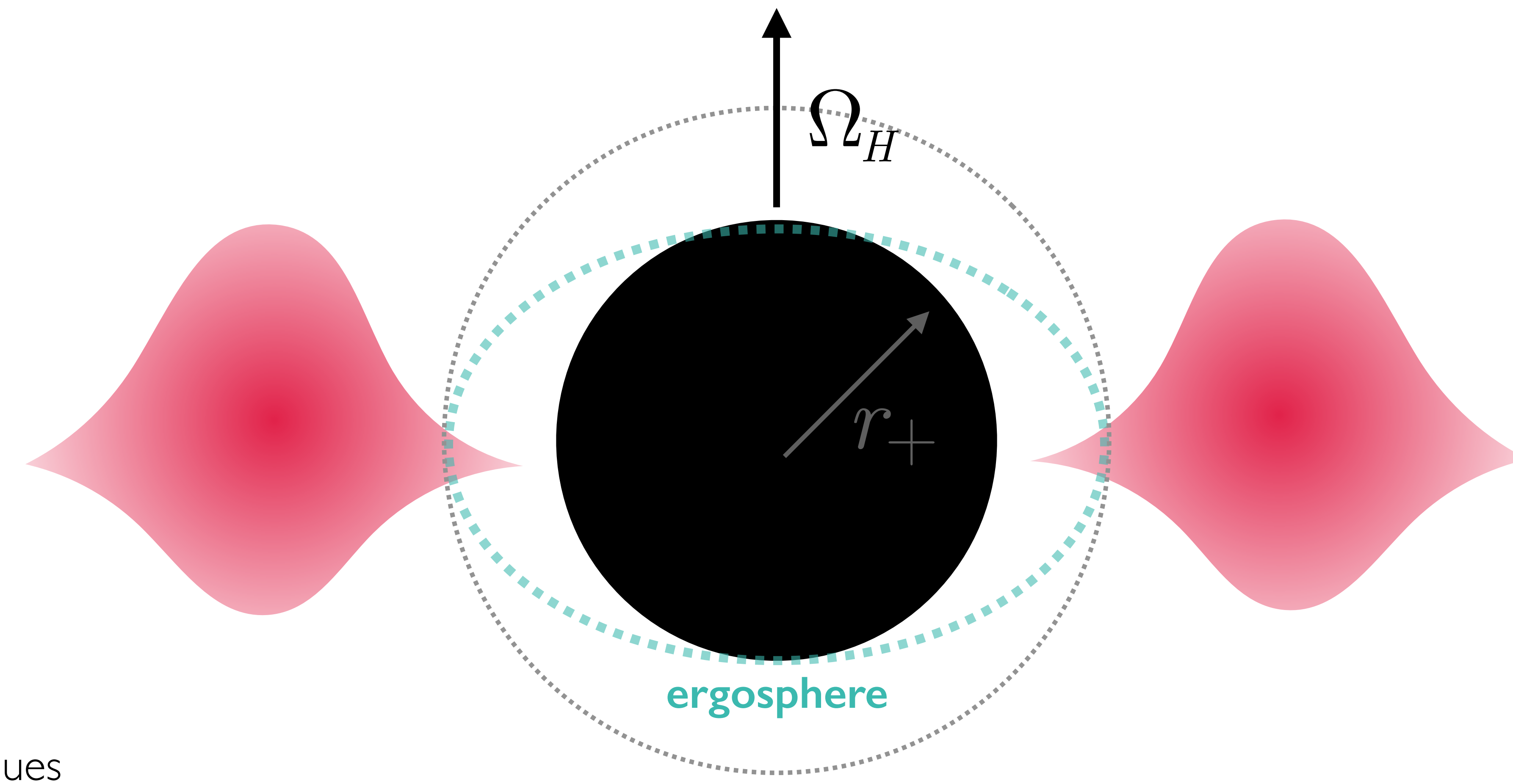
$$\Gamma_{lmn} \propto \mu\, \alpha^{2l+4} r_+ (m\Omega_H - \mu)$$

single level dominates at any given time

$$l = m = 1$$

axion cloud

first dominant mode for scalars



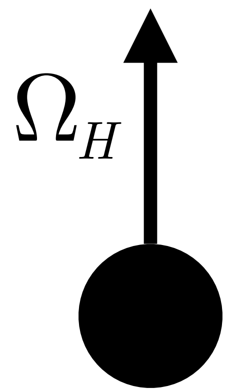
for fiducial values

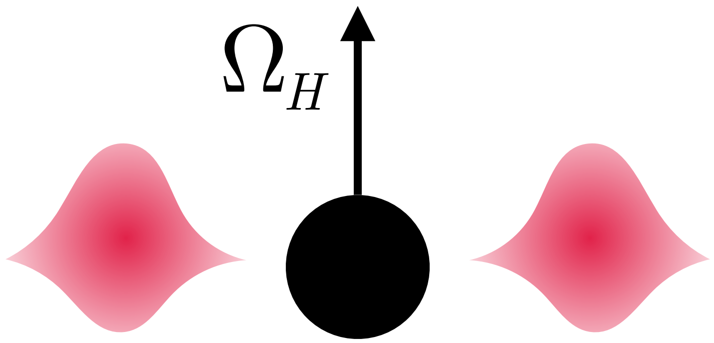
$\alpha \sim 0.5$

$\mu \sim 10^{-11}\mathrm{eV}$

$$\Gamma_{110}^{-1} \sim \mathcal{O}(\text{hours}) \qquad r_c \sim 10 R_s$$

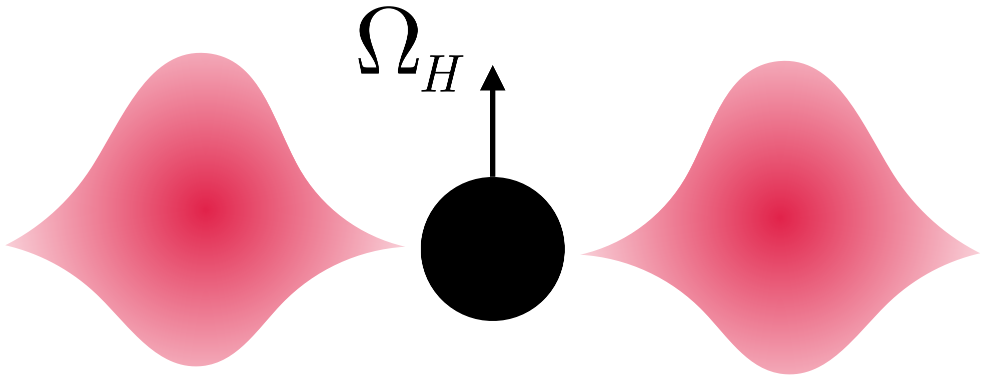
boson field


Ω_H



$$\omega/m < \Omega$$

cloud spontaneously forms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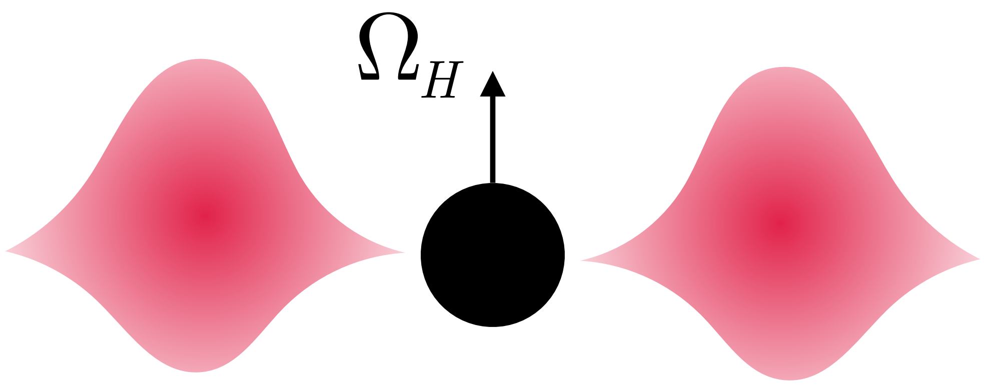
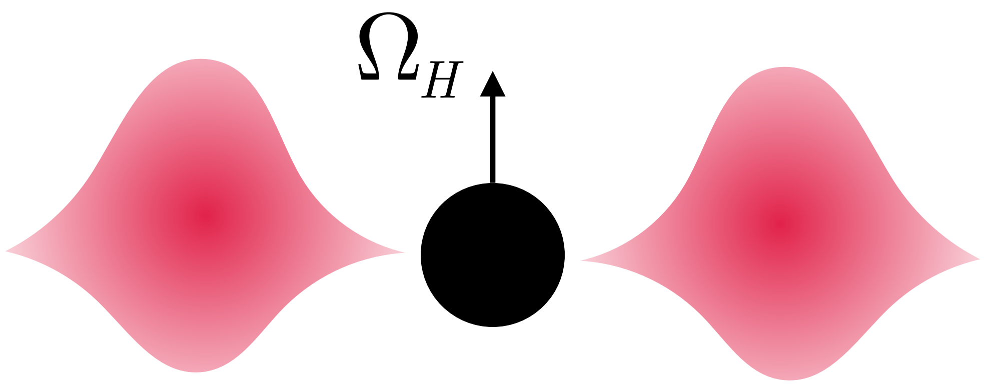


$$\omega/m < \Omega$$

cloud and BH effectively decouple

BH has spun down

(and lost some mass)

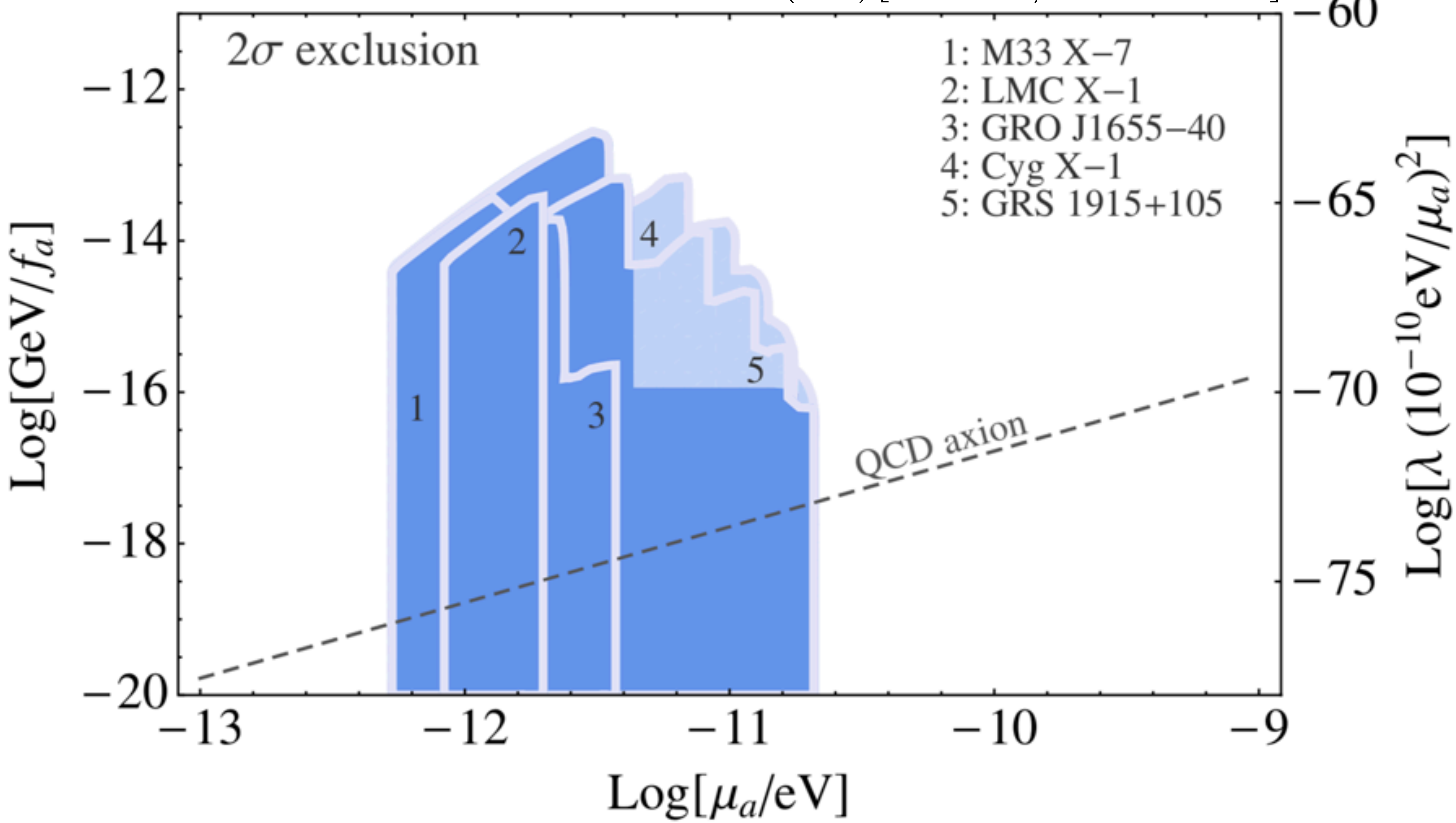


~~$\omega / m < \Omega$~~

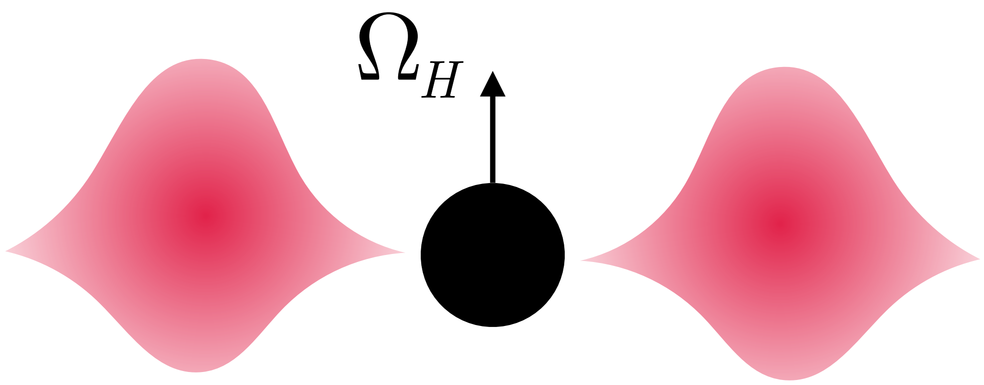
cloud and BH effectively decouple

limits from X-ray binaries

Arvanitaki et al. (2015) [10.1103/PhysRevD.91.084011]



*some of these measurements potentially suffer from strong systematics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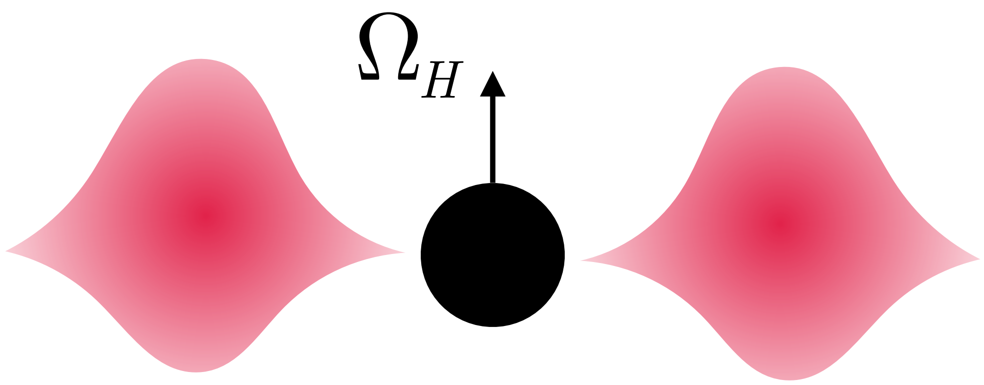
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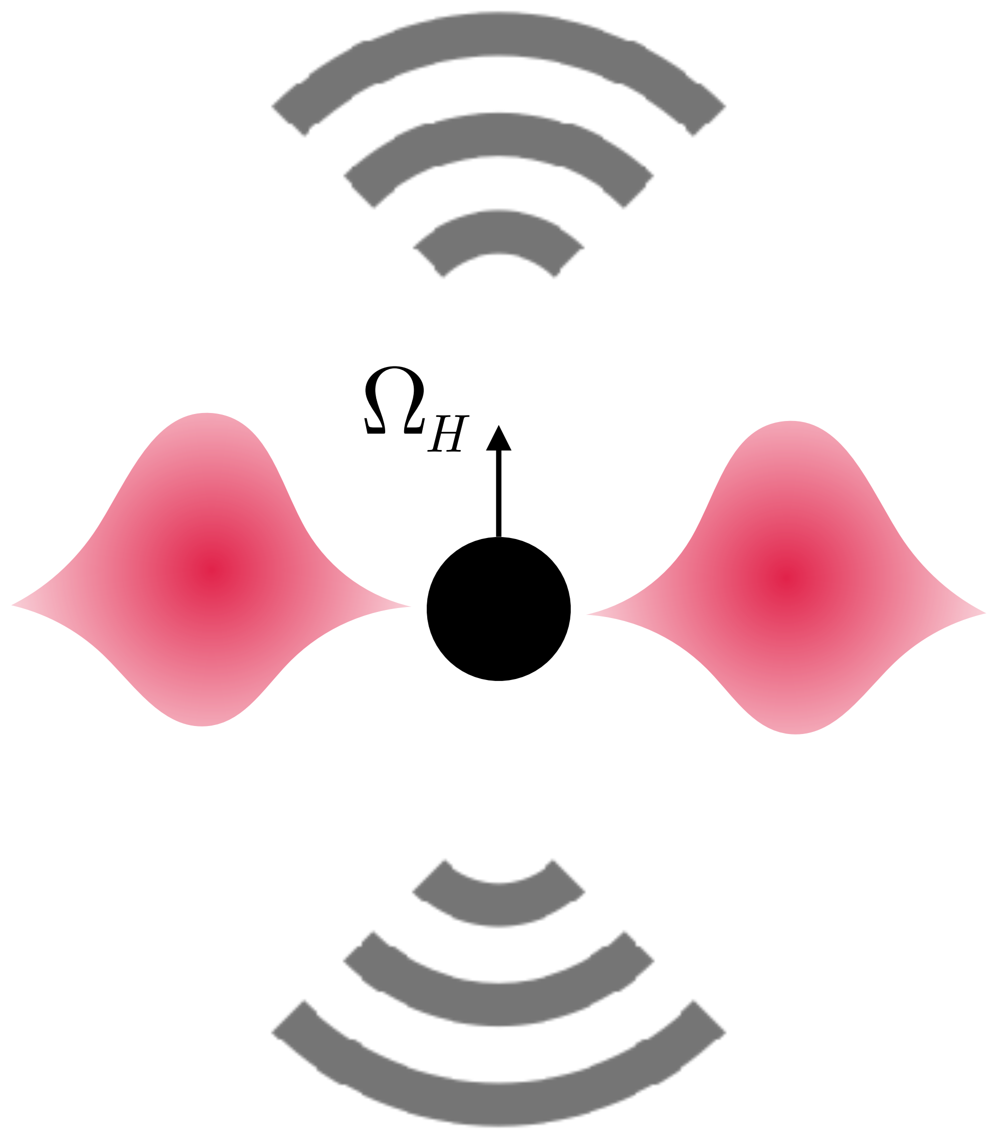
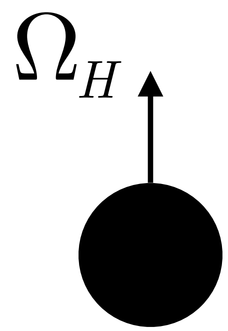


cloud emits GWs!



cloud dissipates

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GW emission mechanisms

boson annihilation

two axions annihilate into a graviton

level transitions

axions switch energy levels like in hydrogen atom

bosenova

axion nonlinearities lead to sudden cloud collapse

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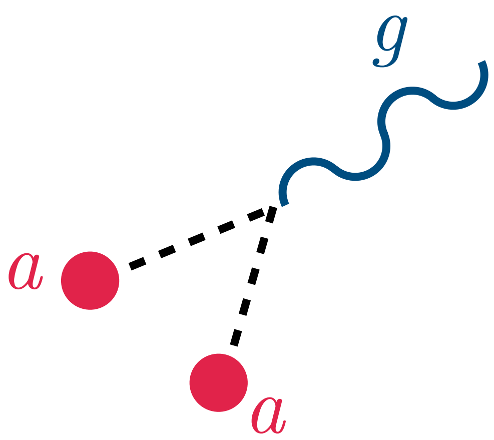


boson annihilation

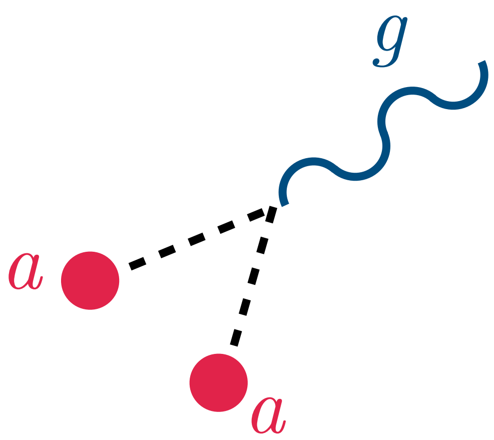
axions annihilate into gravitons, producing **coherent GWs**

macroscopically, this is just due to the **stress-energy of the cloud**

$$f_{\mathrm{GW}} \approx 2\mu/\hbar \simeq 290\,\mathrm{Hz}\left(\frac{\mu}{6\times10^{-13}}\right)$$

$$h_0 \sim 4\times10^{-22}\left(\frac{\alpha}{0.1}\right)^8\left(\frac{\mathrm{kpc}}{d}\right)\left(\frac{\mathrm{Hz}}{f}\right)$$

Arvanitaki et al. (2015) [10.1103/PhysRevD.91.084011]
Brito et al. (2017) [10.1103/PhysRevD.96.064050]



boson annihilation

the signal can **last very long**

$$T_{\mathrm{GW}} \approx 2 \times 10^{7}\mathrm{yr} \left(\frac{\mathrm{Hz}}{f}\right) \left(\frac{0.1}{\alpha}\right)^{14}$$

(*much* longer than superradiance timescale)

and is expected to have a slight **spin-up**

$$\dot{f}_{\mathrm{GW}} \sim 10^{-15} \frac{\mathrm{Hz}}{\mathrm{s}} \left(\frac{f}{\mathrm{Hz}}\right) \left(\frac{M_{\mathrm{Pl}}}{f_a}\right)^{2} \left(\frac{10^{3}\mathrm{yr}}{T_{\mathrm{GW}}}\right)$$

(due to self interactions)

Arvanitaki et al. (2015) [10.1103/PhysRevD.91.084011]
Brito et al. (2017) [10.1103/PhysRevD.96.064050]

axion search space

LIGO

$$10^{-14} \lesssim \mu/\mathrm{eV} \lesssim 10^{-11}$$

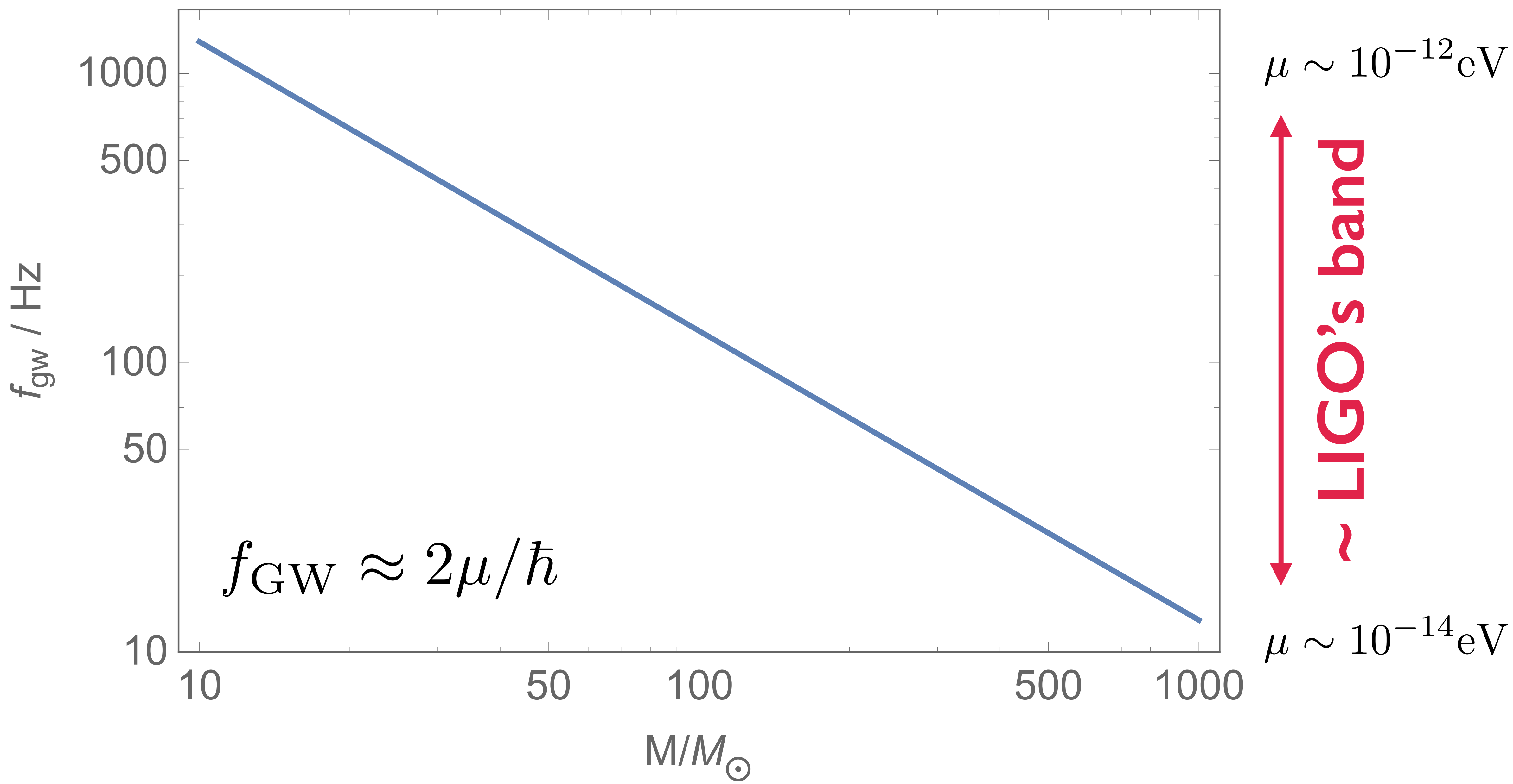
LISA

$$10^{-19} \lesssim \mu/\mathrm{eV} \lesssim 10^{-15}$$

directed CW searches

“continuous (gravitational) waves”

look for signals from a particular BH



Isi, Sun, Brito (in prep.)

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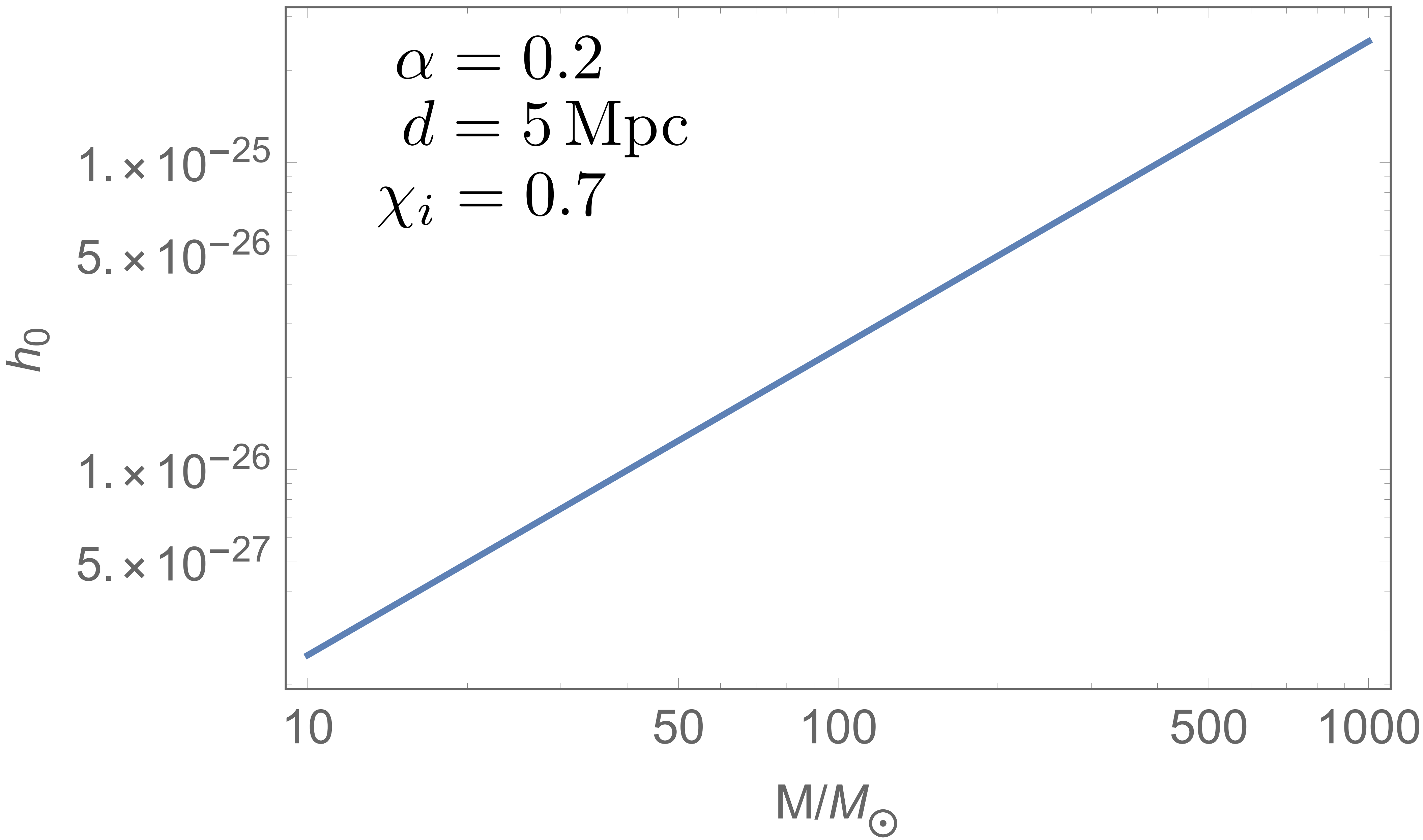

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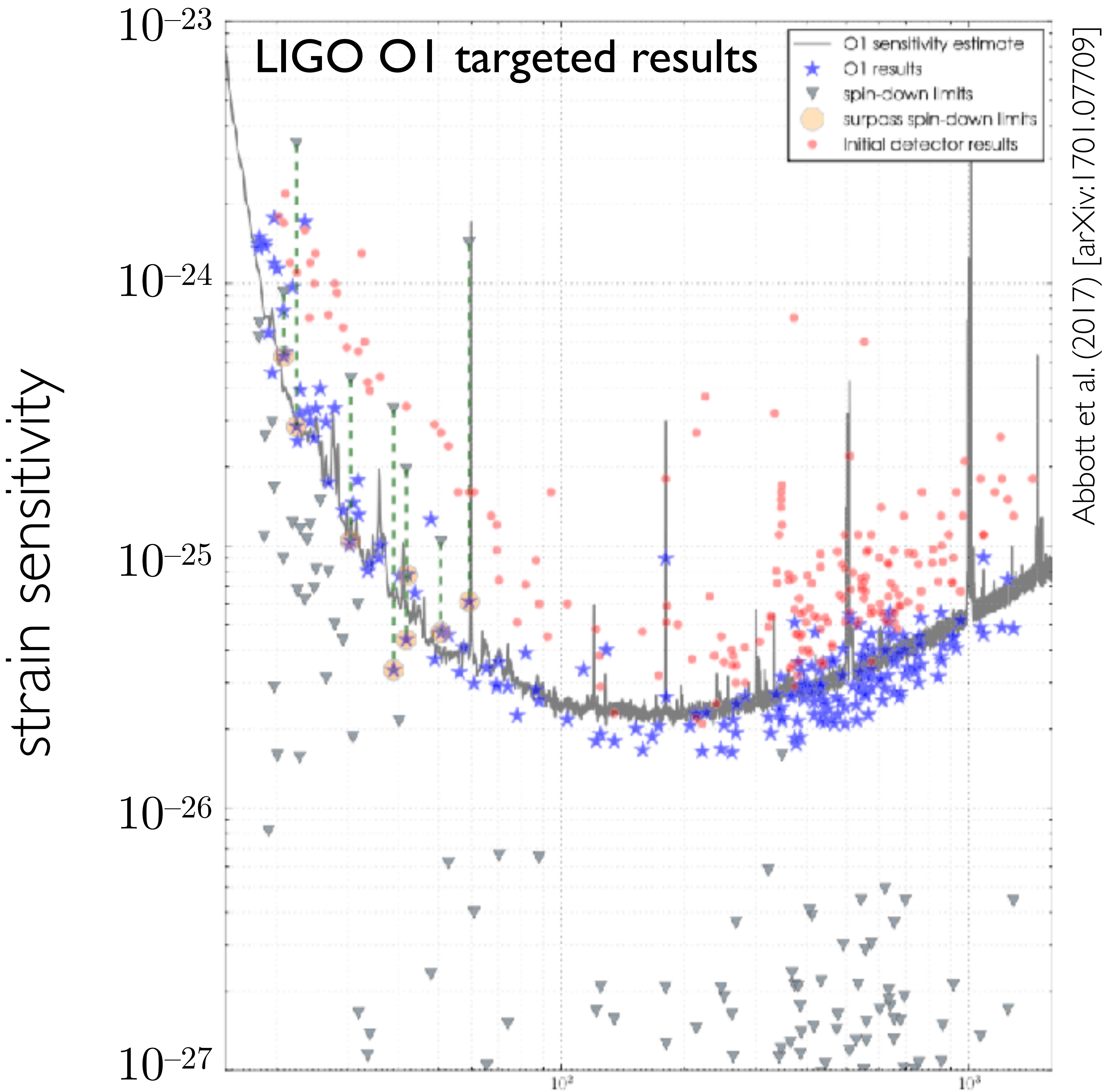
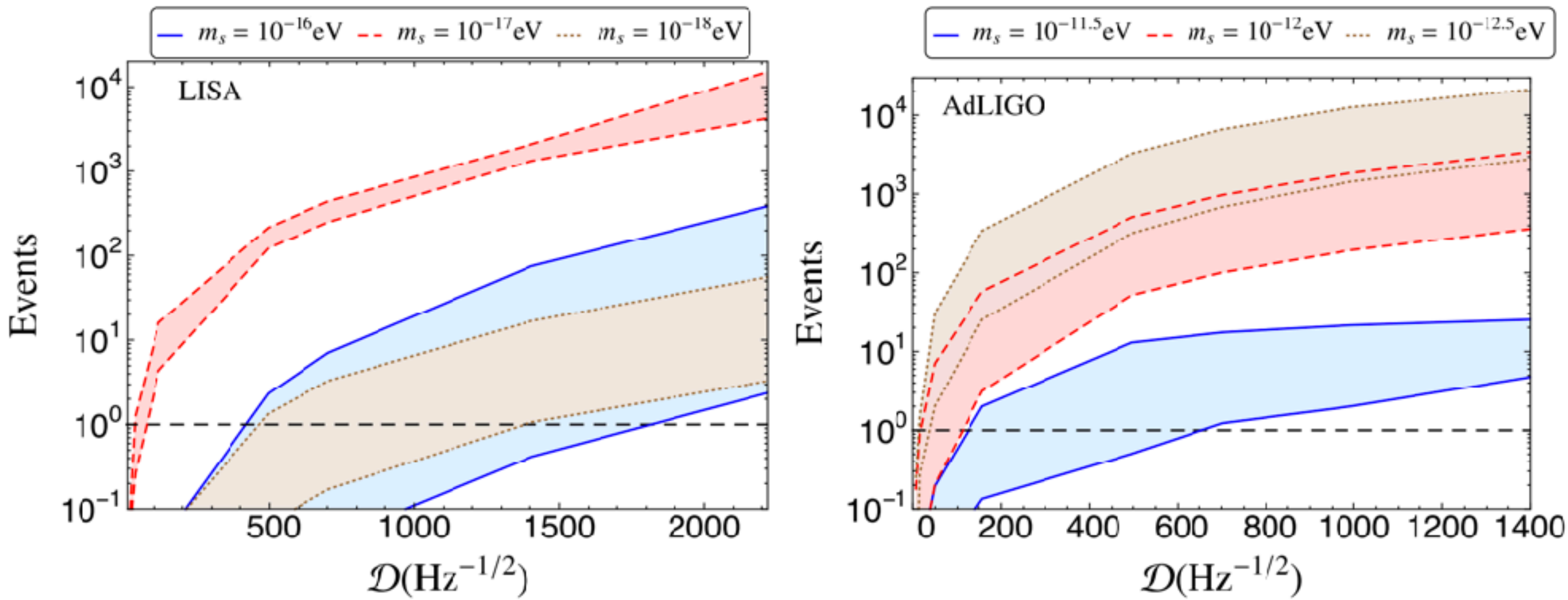


LIGO O1 targeted results
O1 sensitivity estimate
O1 results
spin-down limits
surpass spin-down limits
Initial detector results
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
strain sensitivity
GW frequency (Hz)
Abbott et al. (2017) [arXiv:1701.07709]

all-sky CW searches

look for signals from anywhere in the sky



$$\mathcal{D}(f) \equiv \sqrt{S_n(f)}/h_{\rm thr}$$

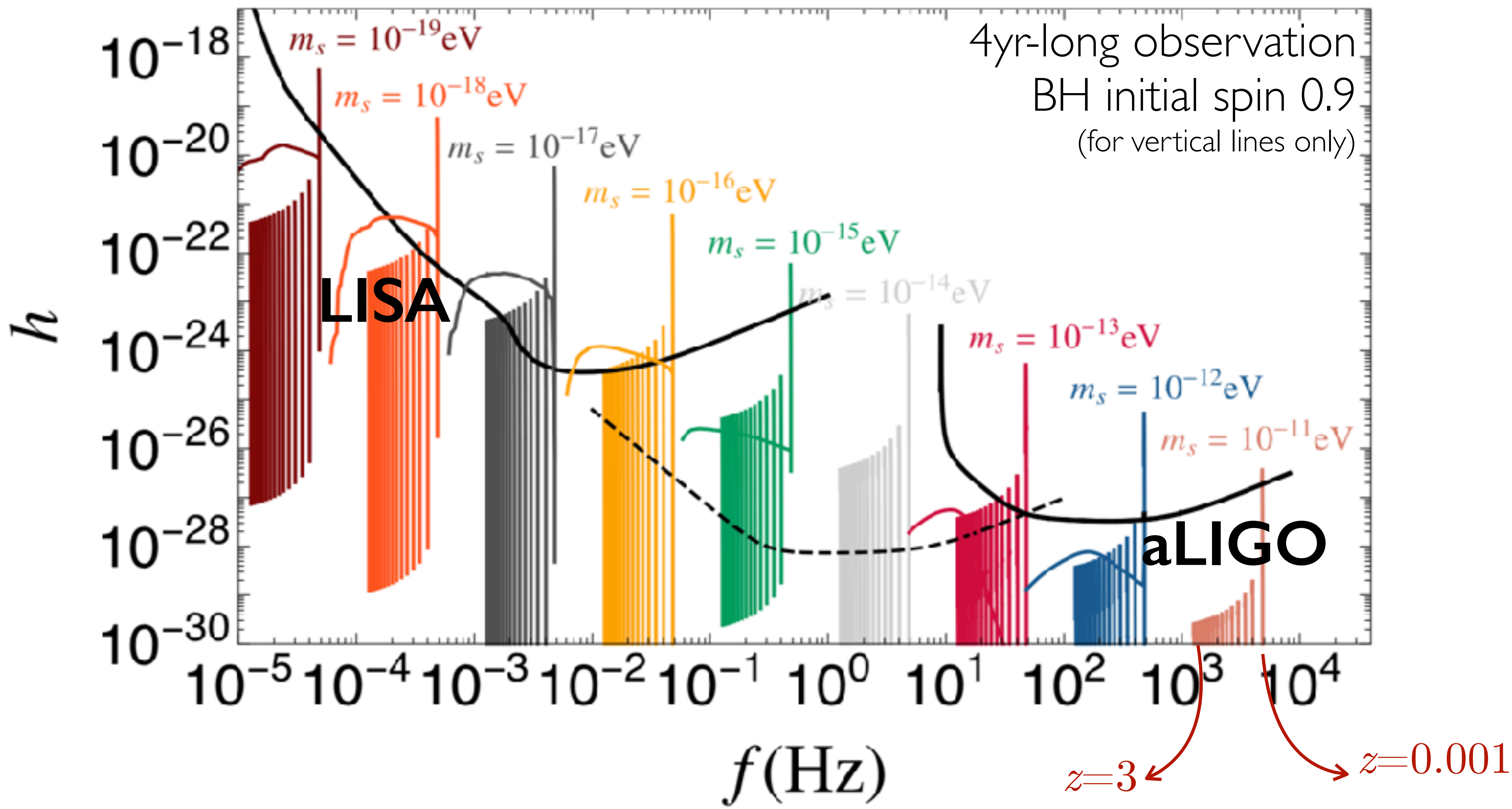
strain needed for detection

(band-width corresponds to different BH population models)

Brito et al. (2017) [10.1103/PhysRevD.96.064050]

stochastic background

look for *unresolvable* signals from anywhere in the sky



Brito et al. (2017) [10.1103/PhysRevLett.119.131101]

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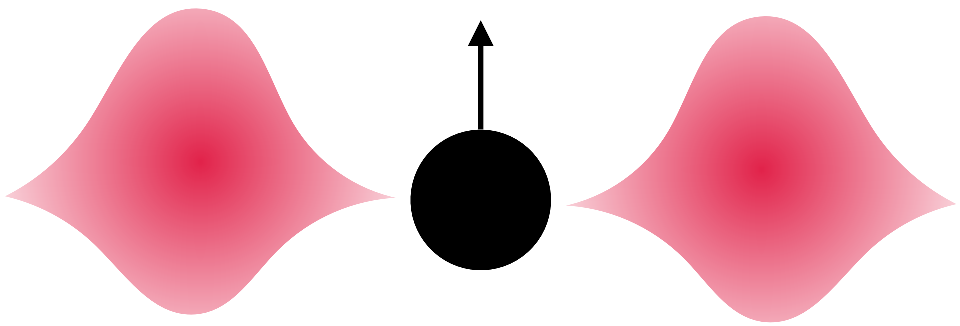
thank you!



learn more

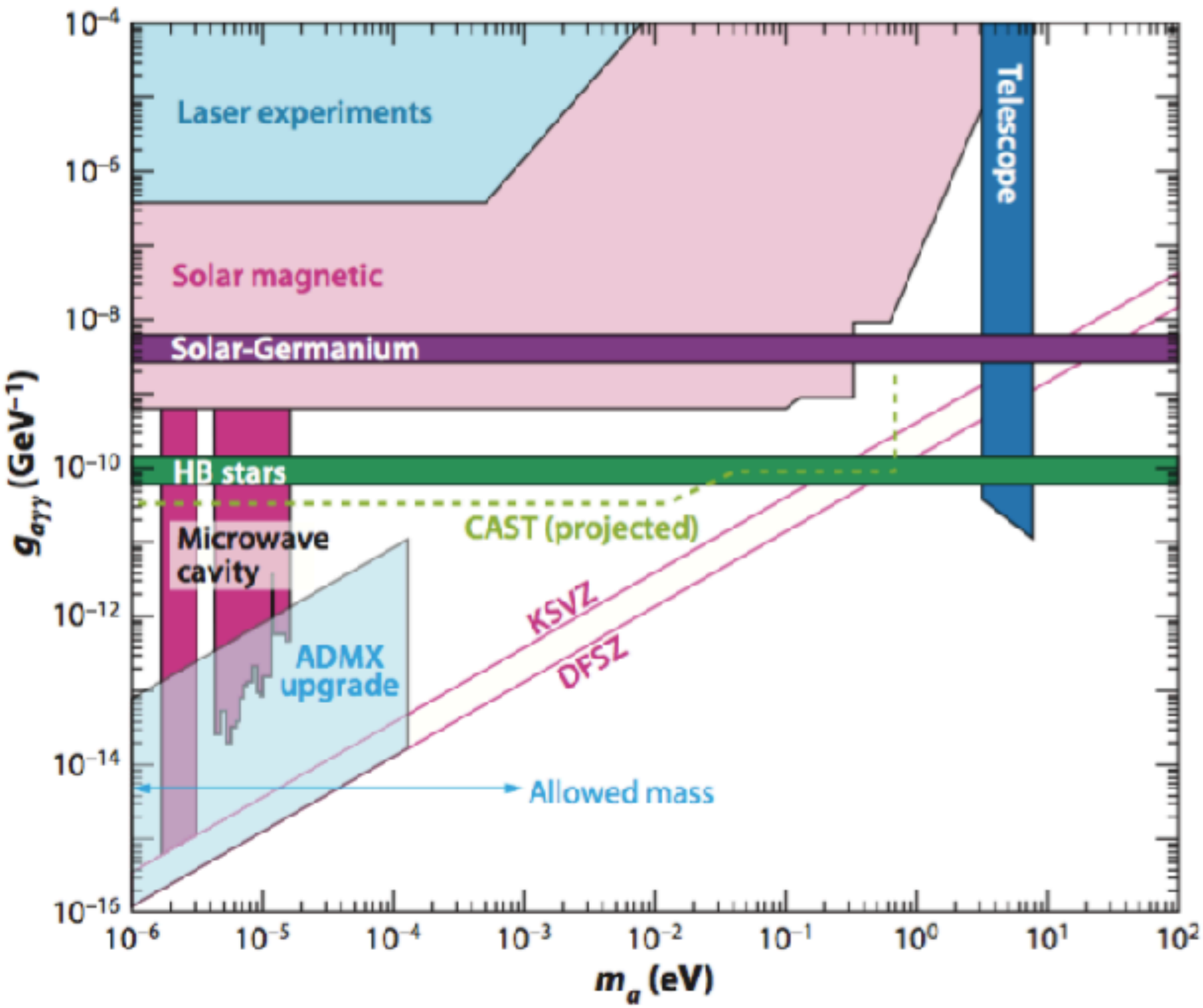
Arvanitaki & Dubovsky (2011) [arXiv:1004.3558]

Arvanitaki et al. (2015) [arXiv:1411.2263]

Brito et al. (2017) [arXiv:1706.05097]

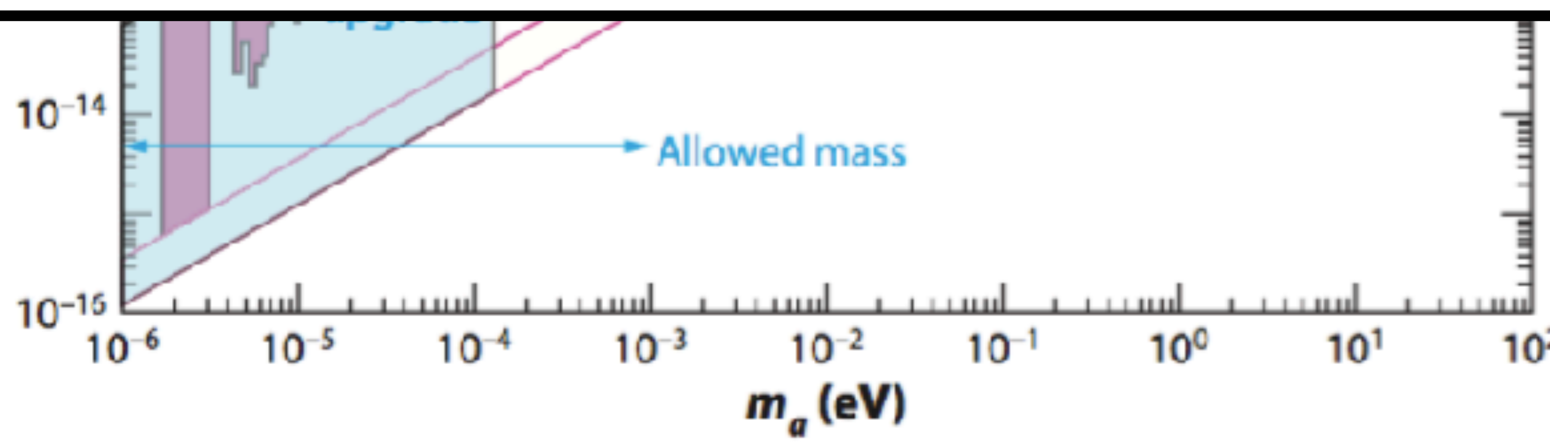
extra

model-dependent
constraints

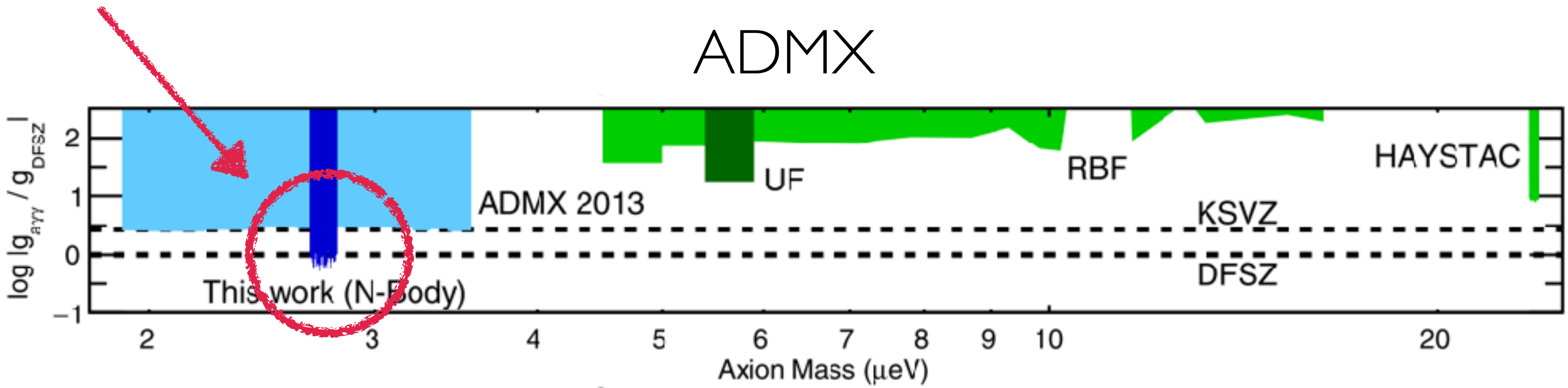


Feng (2010) [doi: 10.1146/annurev-astro-082708-101659] model-dependent

constraints



ADMX



Du et al. (2018) [10.1103/PhysRevLett.120.151301] a dark matter candidate:

the QCD axion

for the QCD axion to be a viable **cold dark matter** candidate it must satisfy **more constraints** than needed to solve the strong-CP problem

for instance, **cannot be too light** or would have been produced in too much abundance, **cannot be too heavy** or it would affect evolution of heavy stars

these constraints imply

$$10^{12}\,\mathrm{GeV}\,\theta_i^{-2} \gtrsim f_a \gtrsim 10^9\,\mathrm{GeV}$$
$$6\,\mu\mathrm{eV}\,\theta_i^2 \lesssim m_a \lesssim 6\,\mathrm{meV}$$

with ϑ_i some constant less than one

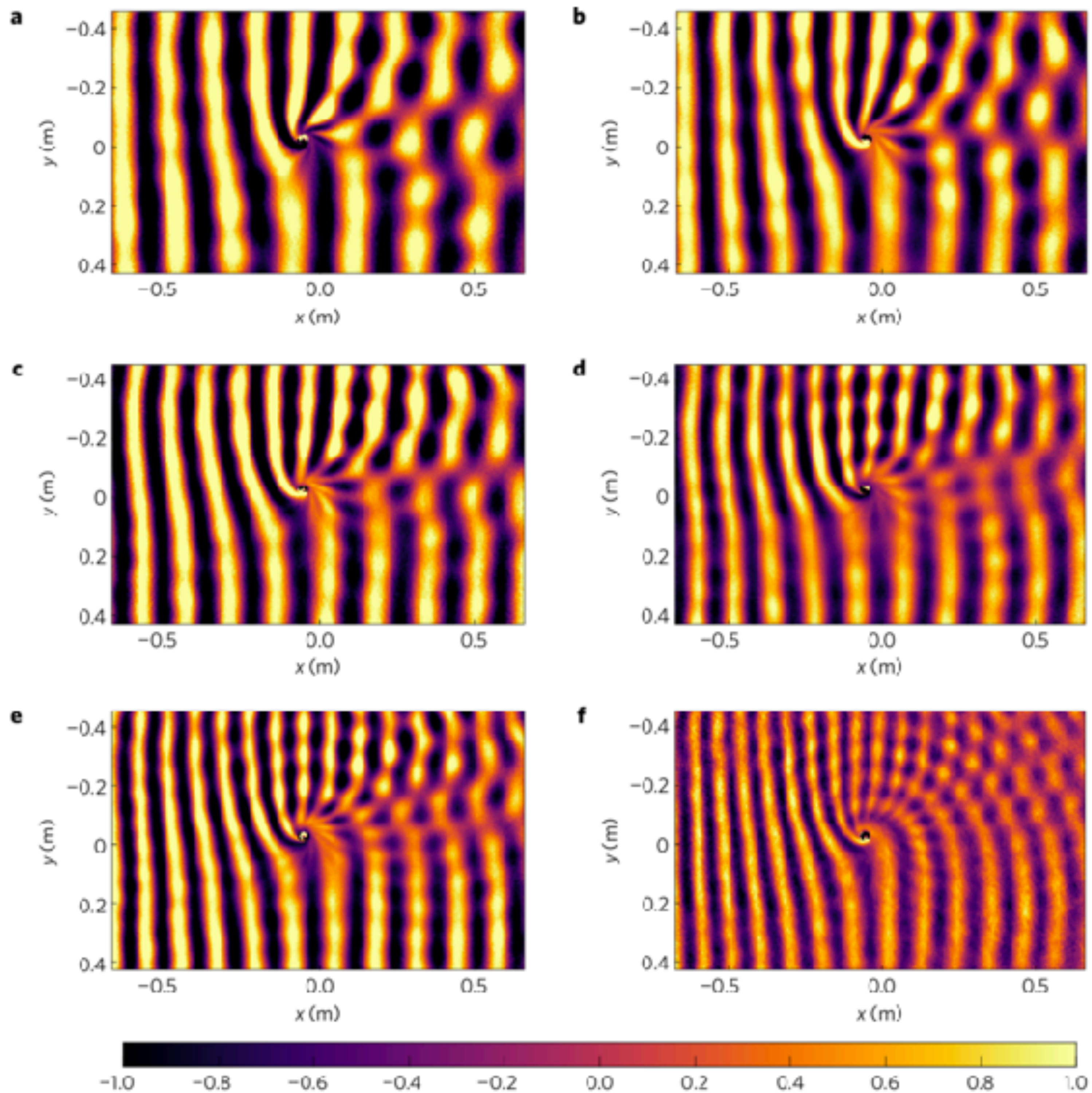
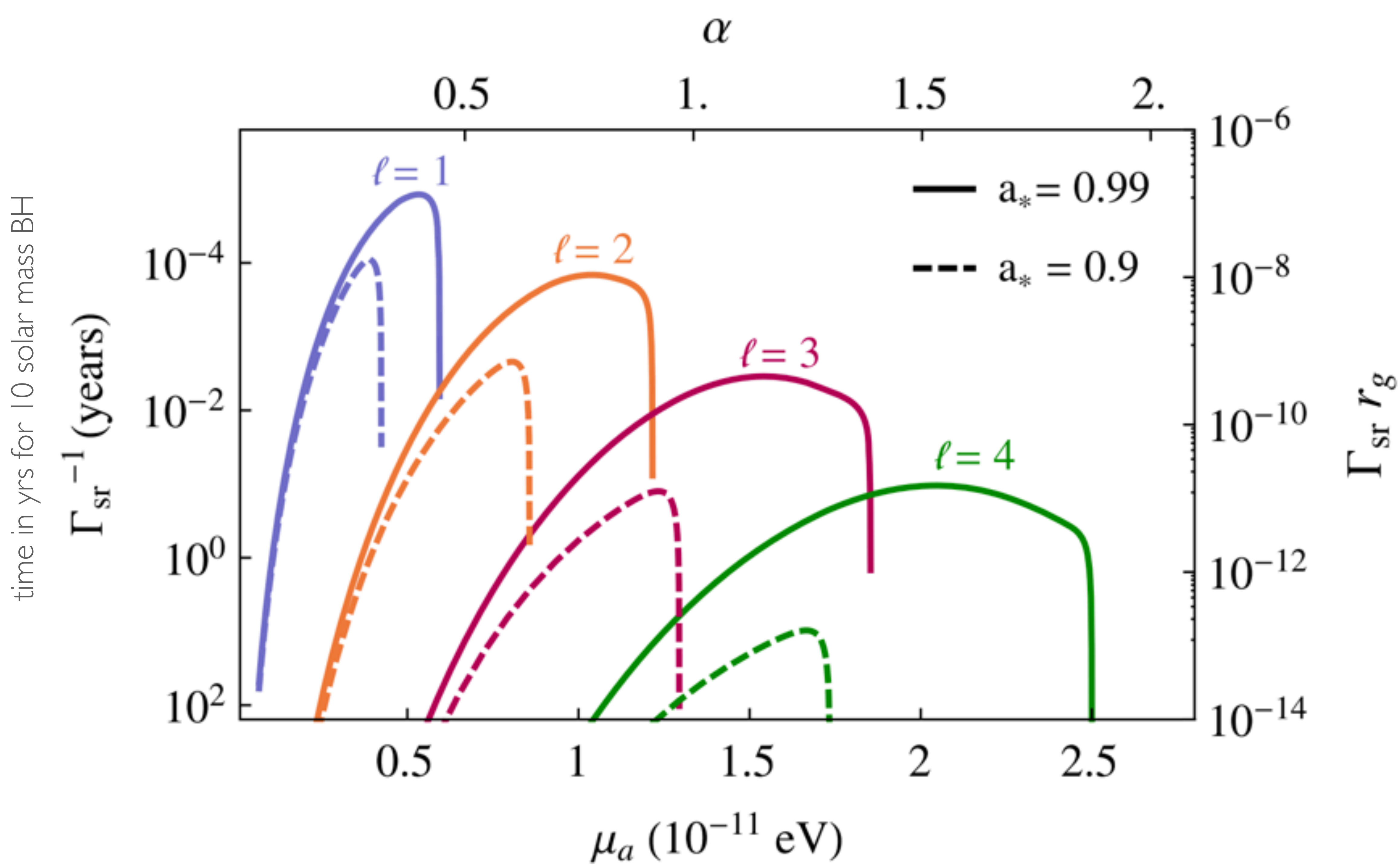


Figure 1 | Wave characteristics of the surface perturbation ξ, filtered at a single frequency, for six different frequencies. a–f, The frequencies are 2.87 Hz (**a**), 3.04 Hz (**b**), 3.27 Hz (**c**), 3.45 Hz (**d**), 3.70 Hz (**e**), and 4.11 Hz (**f**). The horizontal and vertical axis are in metres (m), while the colour scale is in millimetres (mm). The patterns show the interfering sum of the incident wave with the scattered wave. The waves are generated on the left and propagate to the right across the vortex centred at the origin.

Torres et al. (2018) [10.1038/nphys4151]

level growth



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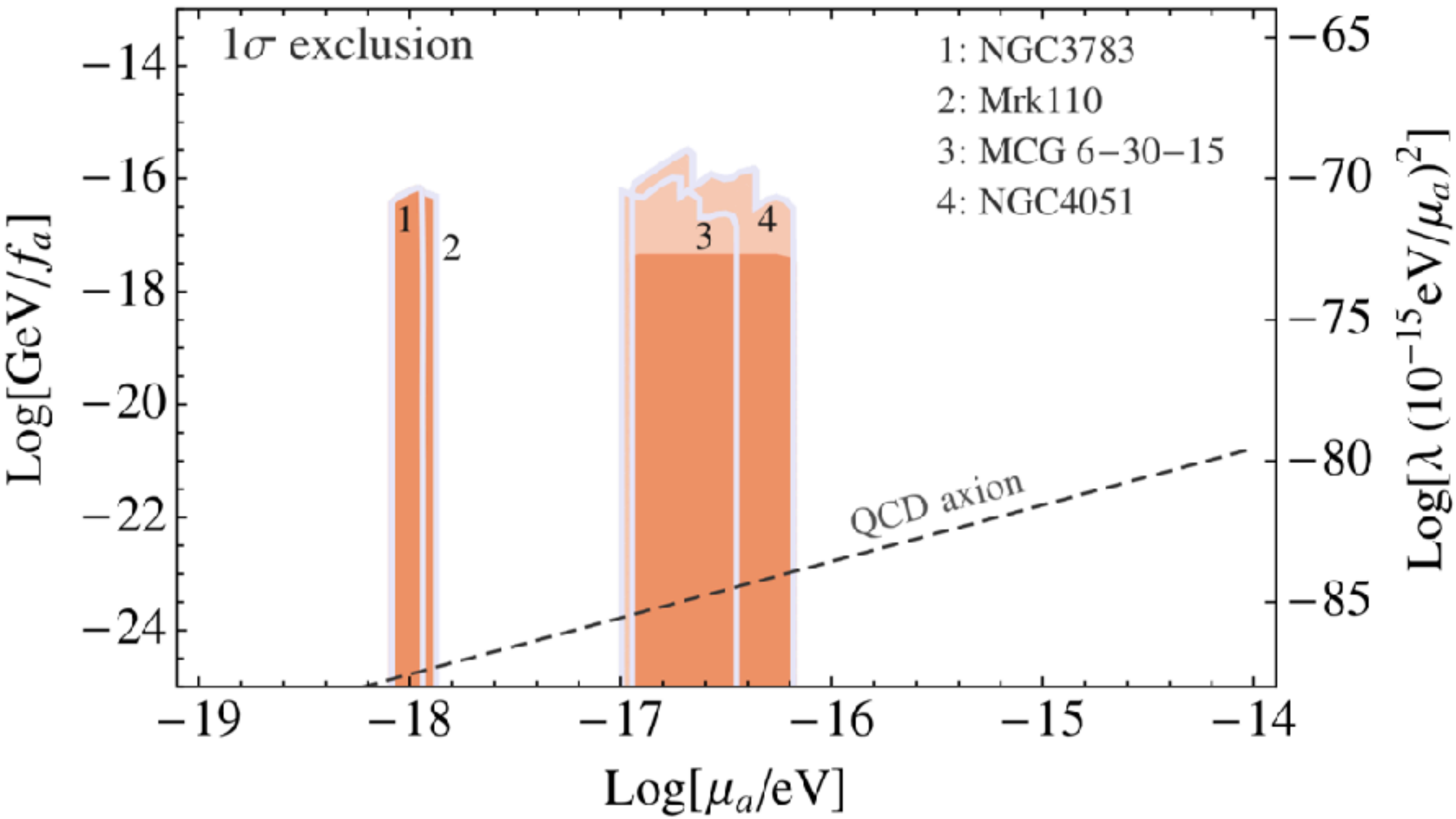

*some of these measurements potentially suffer from strong systematics

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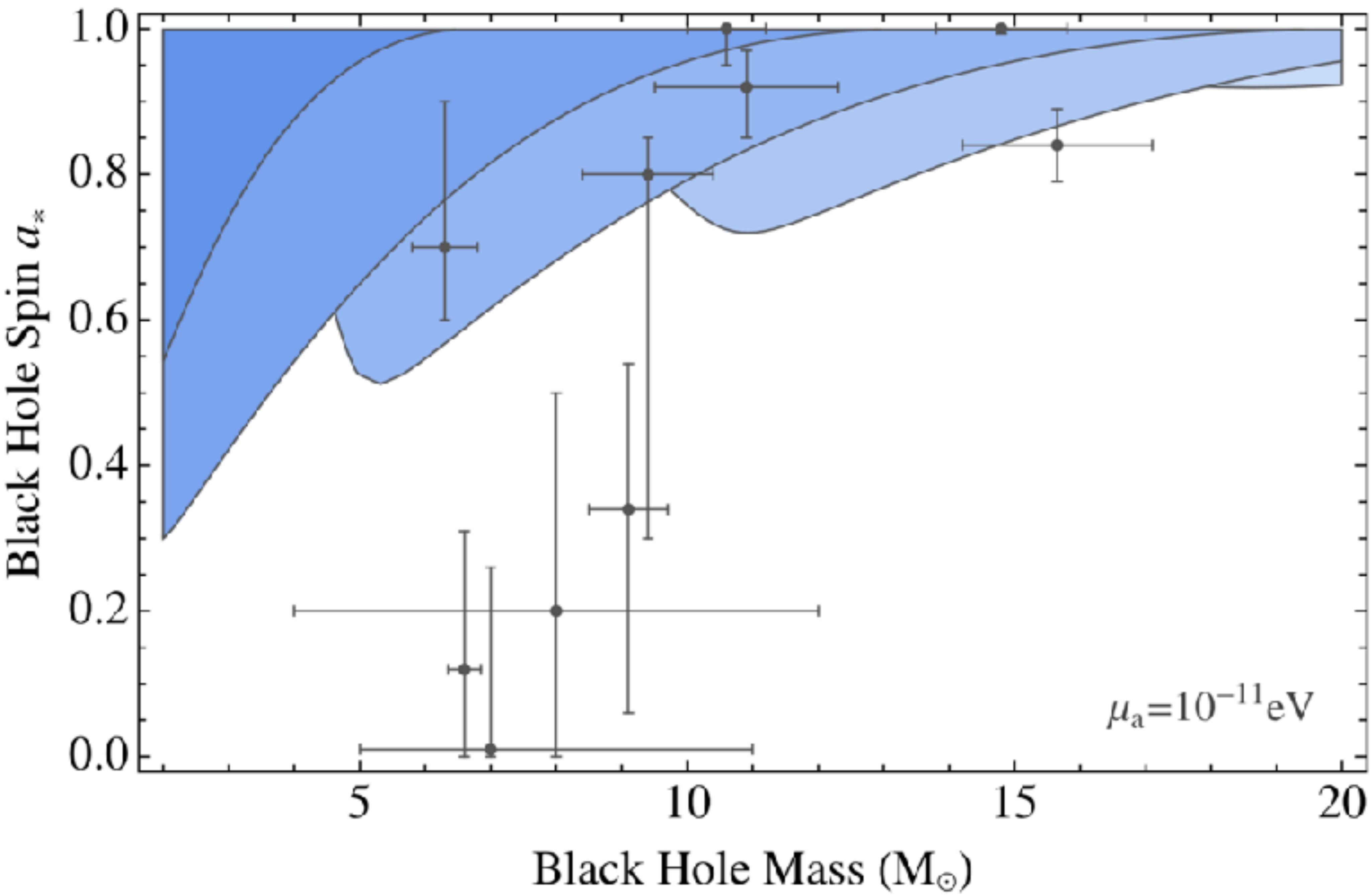

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