Black Holes and Axions: Gravitational Waves and Axionic Beacons

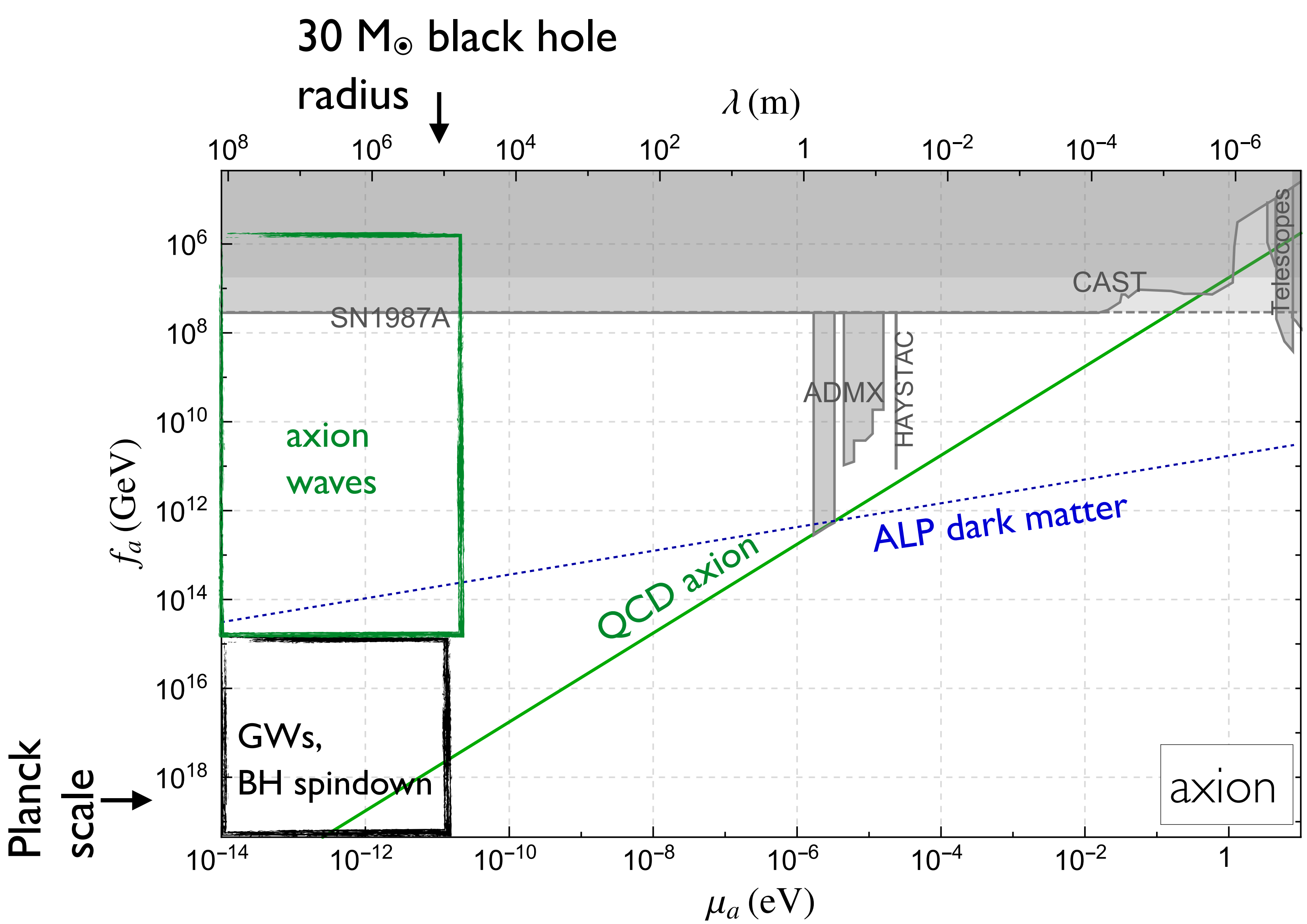
Masha Baryakhtar

New York University/University of Washington

January 26, 2020

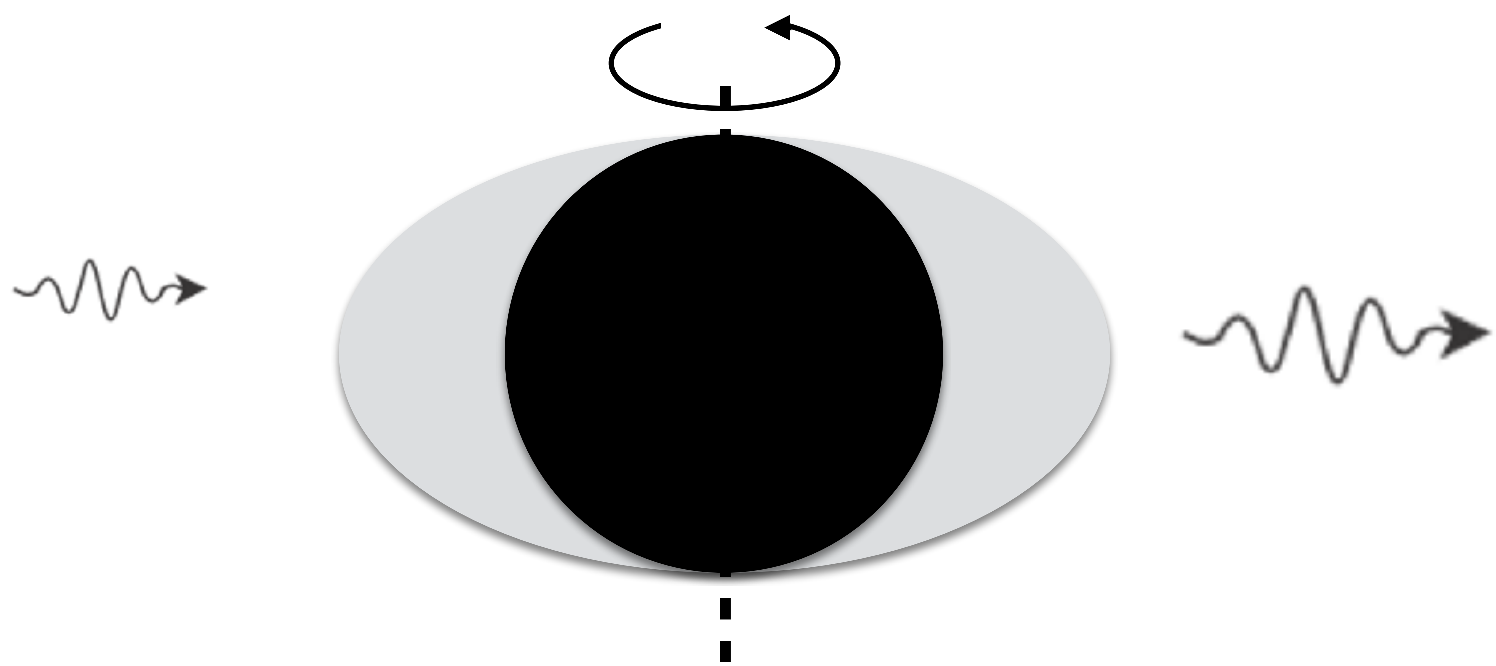
Ultralight Axions and Black Holes

- Rotating black holes can source `clouds' of weakly coupled bosons through **superradiance**, independently of cosmological abundance
- High-scale axions with **gravitational** interactions **spin down BHs** and **source GWs**
- Lower-scale axions with **self-interactions** source **axion waves**



Superradiance

- A wave scattering off a rotating object can increase in amplitude by extracting angular momentum and energy.
- Growth proportional to probability of absorption when rotating object is at rest: **dissipation** necessary to increase wave amplitude



Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

Zel'dovich; Starobinskii; Misner

Superradiance

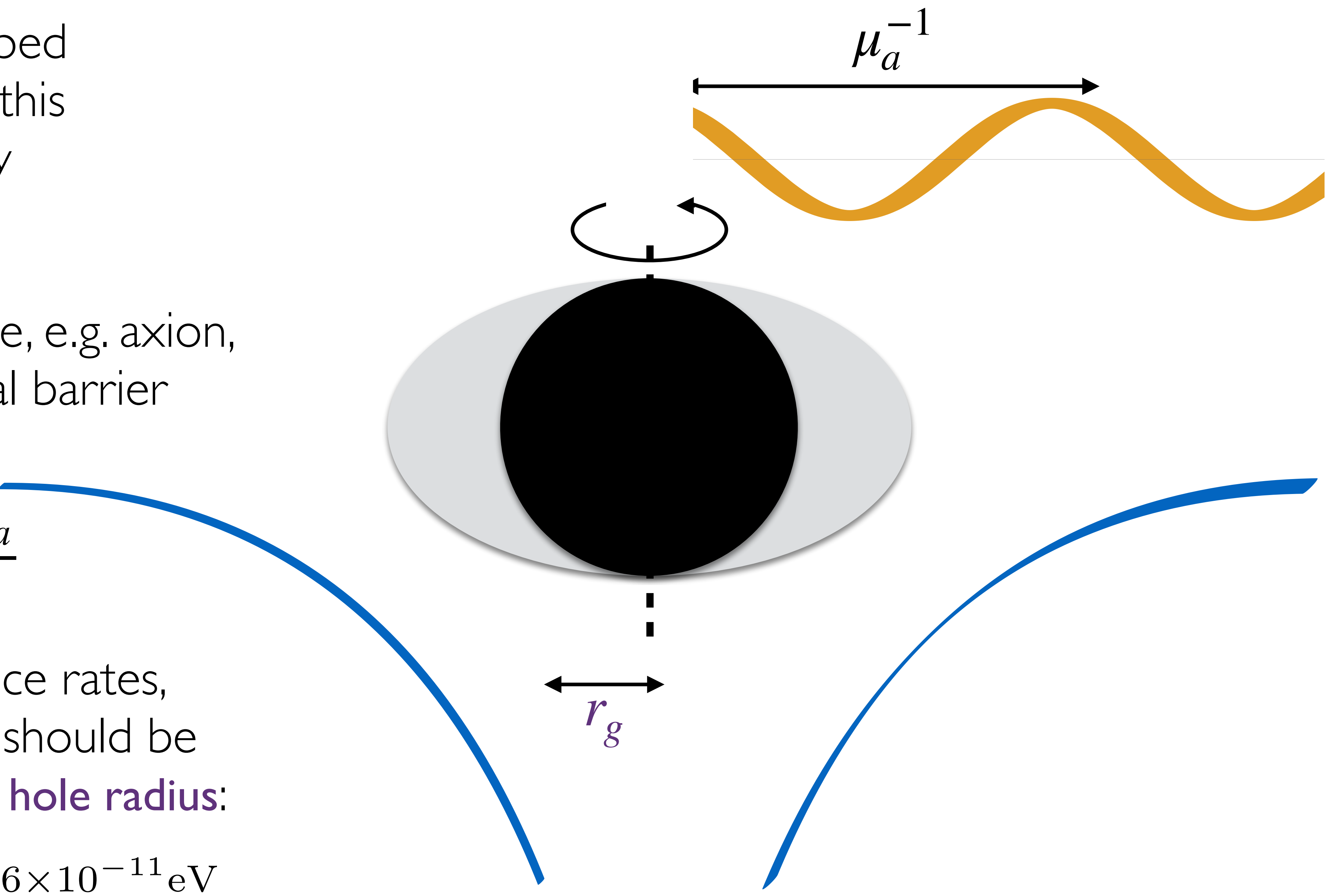
- Particles/waves trapped near the BH repeat this process continuously

- For a massive particle, e.g. axion, gravitational potential barrier provides trapping

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

- For high superradiance rates, compton wavelength should be comparable to black hole radius:

$$r_g \lesssim \mu_a^{-1} \sim 3\,\mathrm{km}\,\frac{6\times10^{-11}\mathrm{eV}}{\mu_a}$$

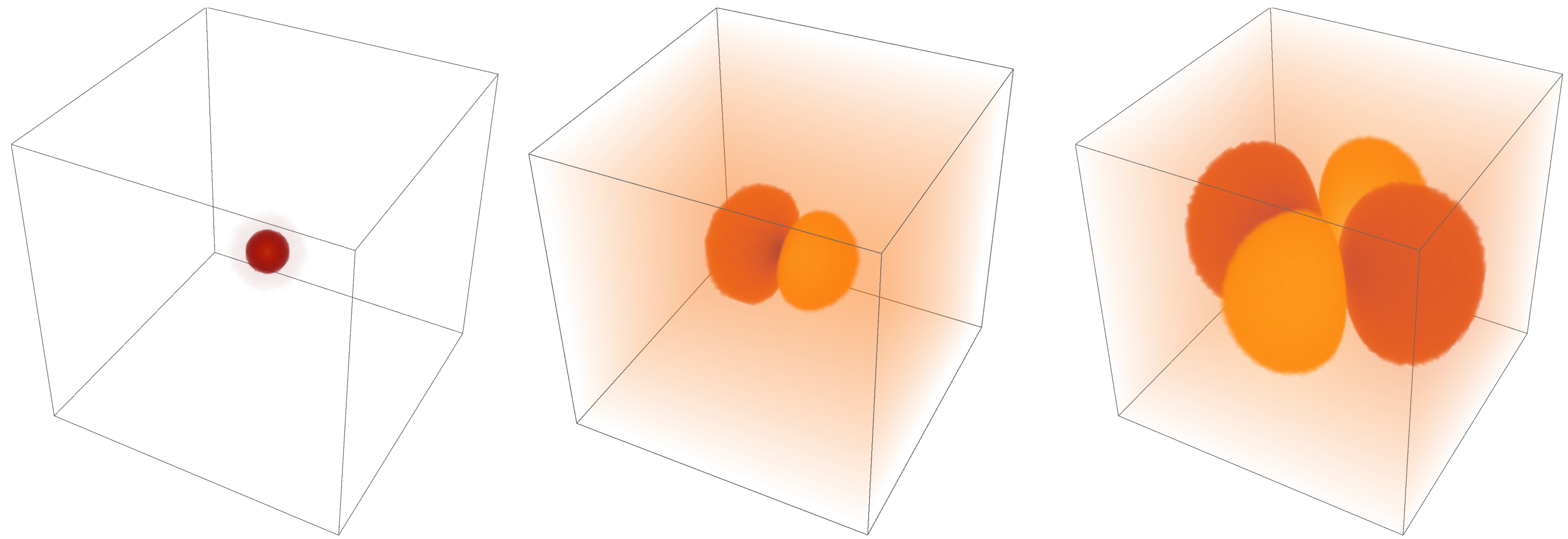


Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78
Tool to search for axions: Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010

Gravitational Atoms

Axion
Gravitational Atoms

$$V(r) = -\frac{G_{\rm N} M_{\rm BH} \mu_a}{r}$$



$n = 1, \ell = 0, m = 0$ $\quad$ $n = 2, \ell = 1, m = 1$ $\quad$ $n = 3, \ell = 2, m = 2$

Gravitational potential similar to hydrogen atom

`Fine structure constant`

$$\alpha \equiv G_{\rm N} M_{\rm BH} \mu_a \equiv r_g \mu_a$$

Radius

$$r_c \simeq \frac{n^2}{\alpha\, \mu_a} \sim 4 - 400 r_g$$

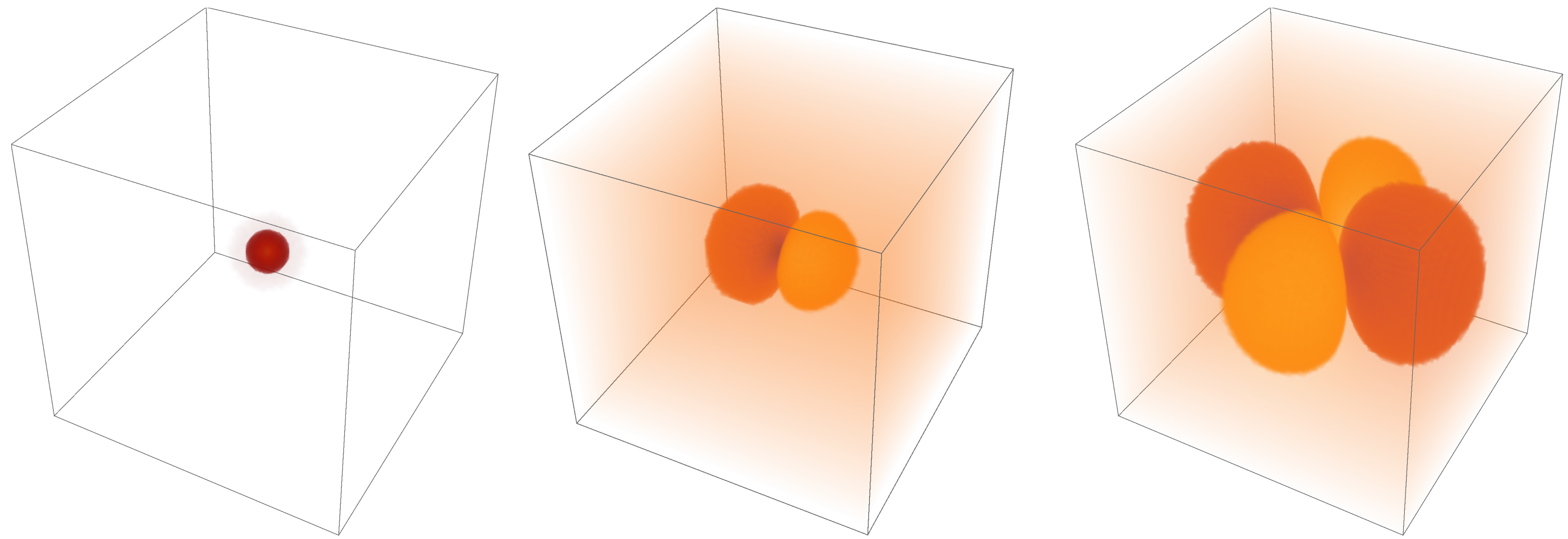
Occupation number

$$N \sim 10^{75} - 10^{80}$$

Gravitational Atoms

Axion
Gravitational Atoms

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$



$n = 1, \ell = 0, m = 0$ $\quad$ $n = 2, \ell = 1, m = 1$ $\quad$ $n = 3, \ell = 2, m = 2$

Gravitational potential similar to hydrogen atom

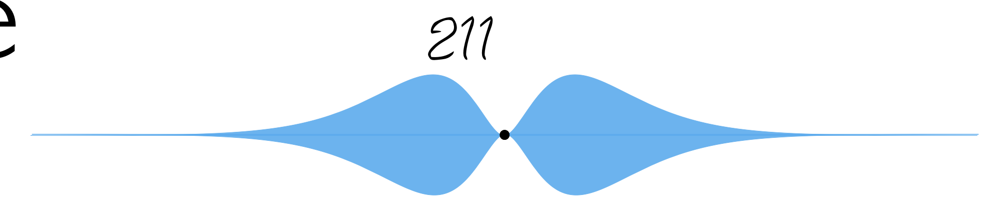
`Fine structure constant`	Radius	Occupation number
$\alpha \equiv G_N M_{BH} \mu_a \equiv r_g \mu_a$	$r_c \simeq \frac{n^2}{\alpha\, \mu_a} \sim 4 - 400 r_g$	$N \sim 10^{75} - 10^{80}$

Boundary conditions at horizon give imaginary frequency:

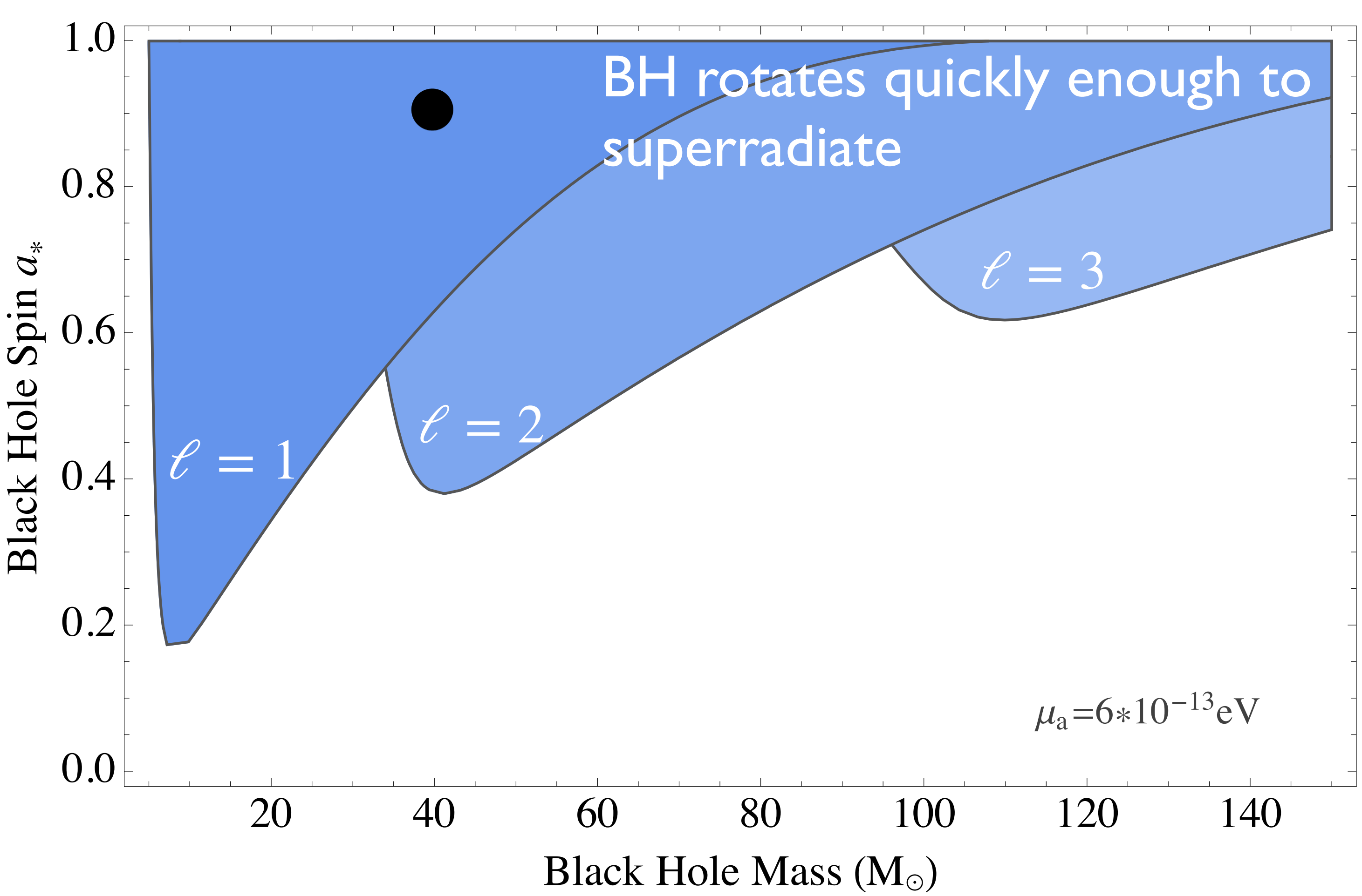
$$E \simeq \mu \left(1 - \frac{\alpha^2}{2n^2}\right) + i\Gamma_{sr}$$

exponential growth of particle number in states satisfying superradiance condition

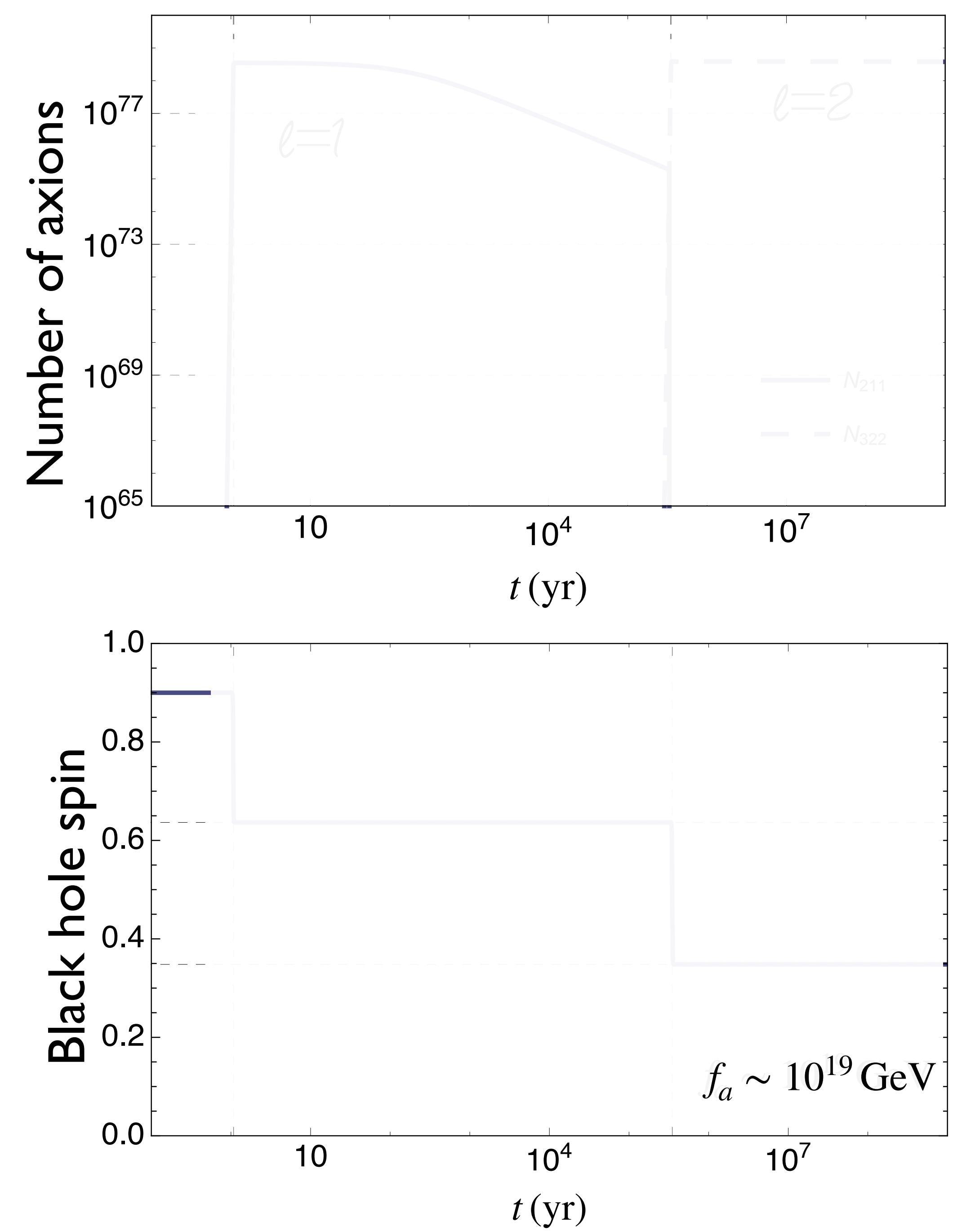
Superradiance



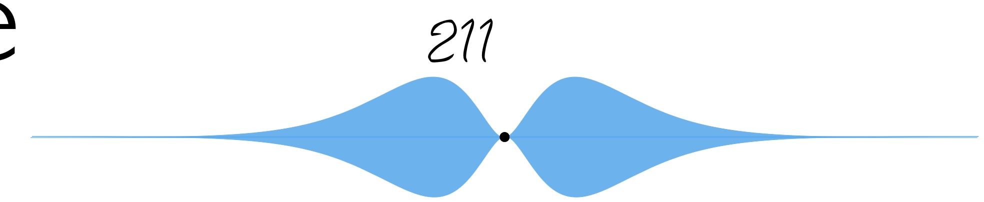
- If new light axions exist, fast-spinning black holes will superradiate: lose energy and angular momentum to exponentially growing bound states of axions



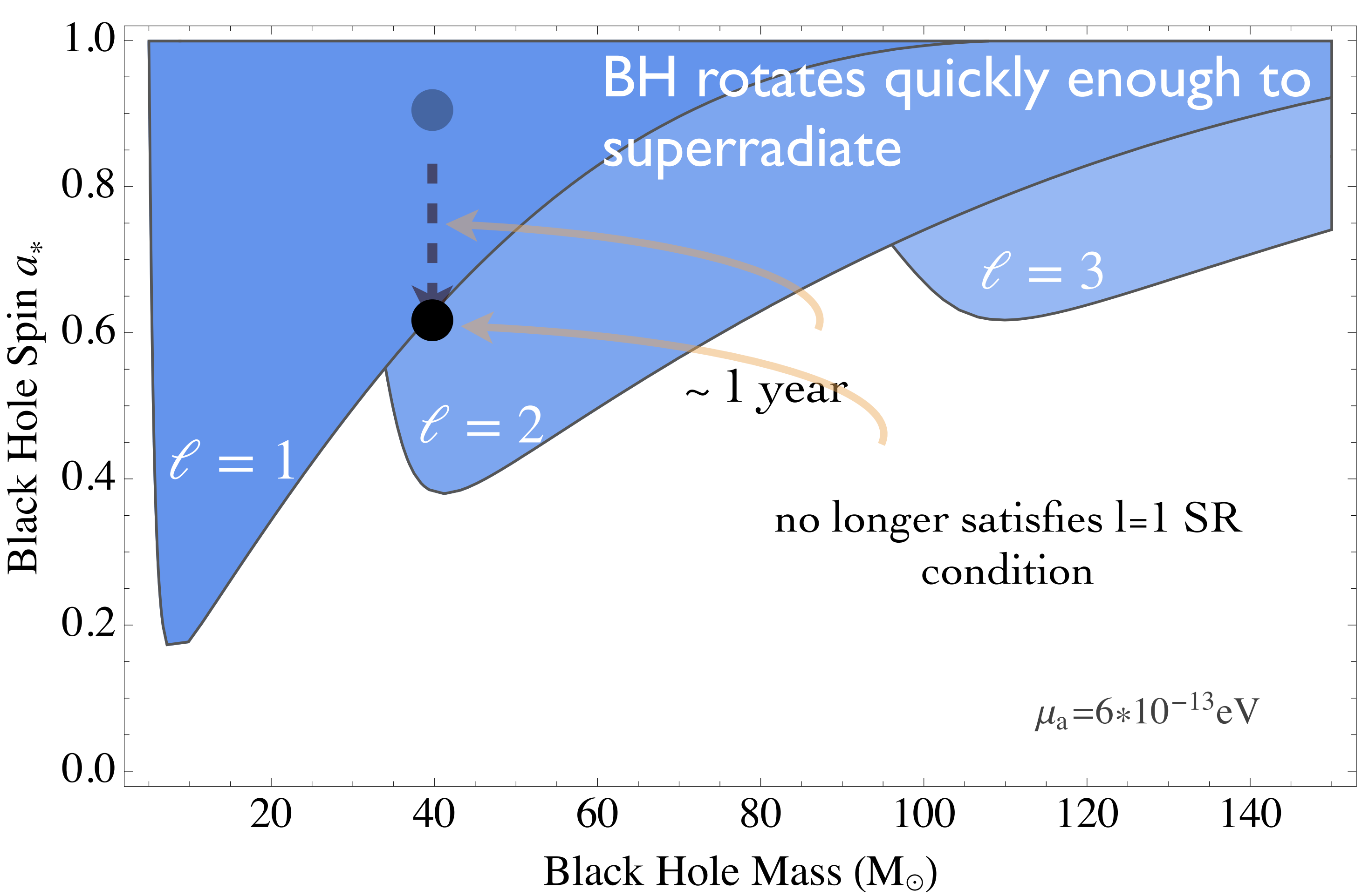
Time evolution



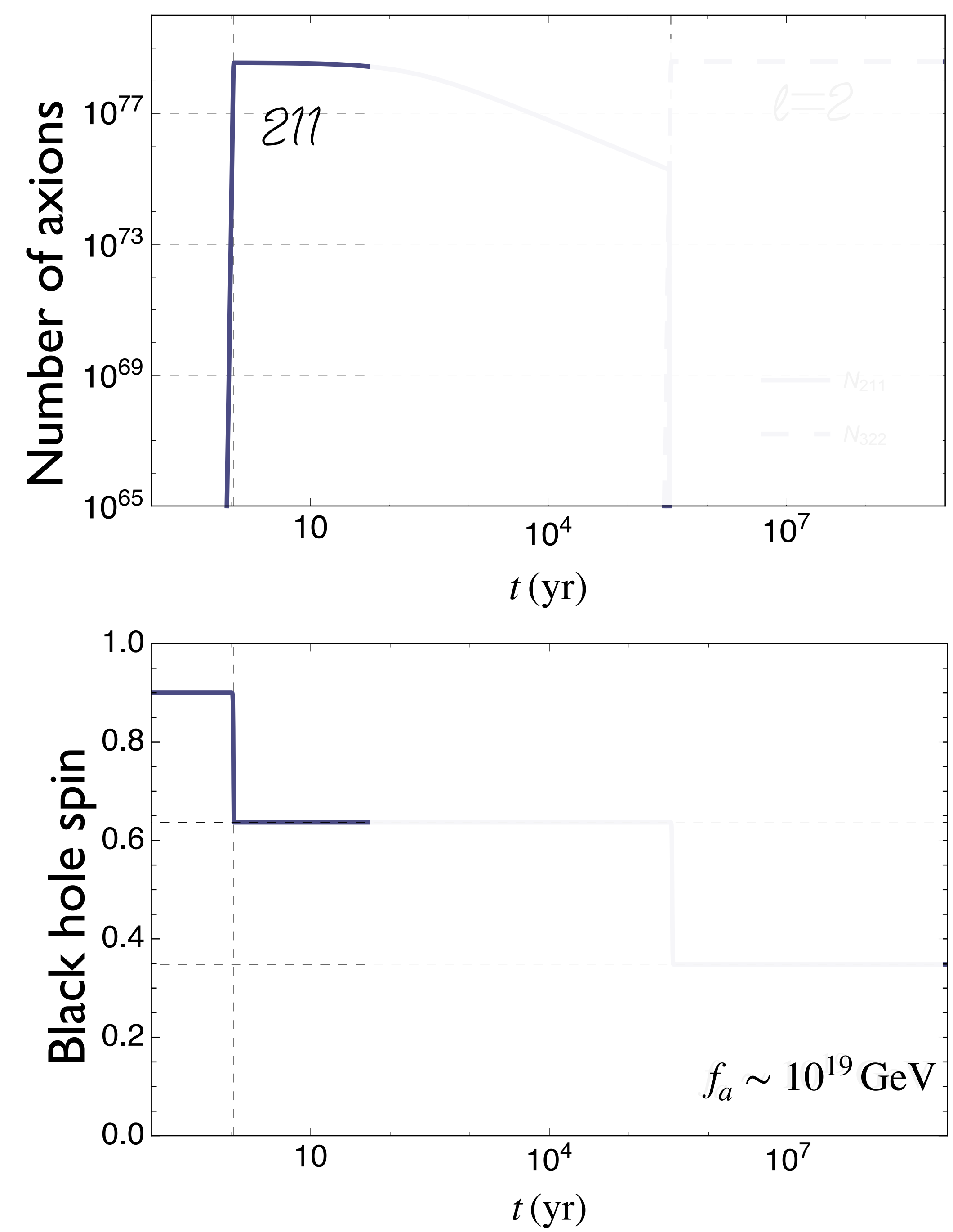
Superradiance



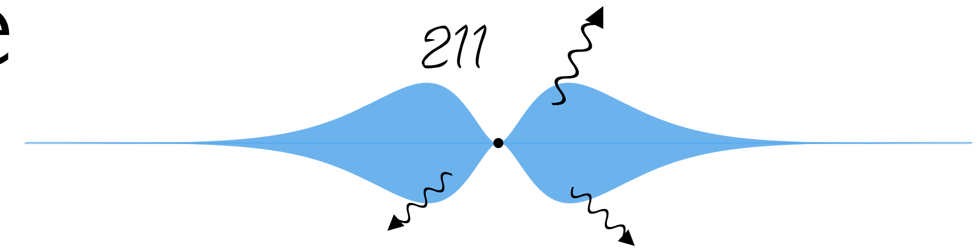
- If new light axions exist, fast-spinning black holes will superradiate: lose energy and angular momentum to exponentially growing bound states of axions



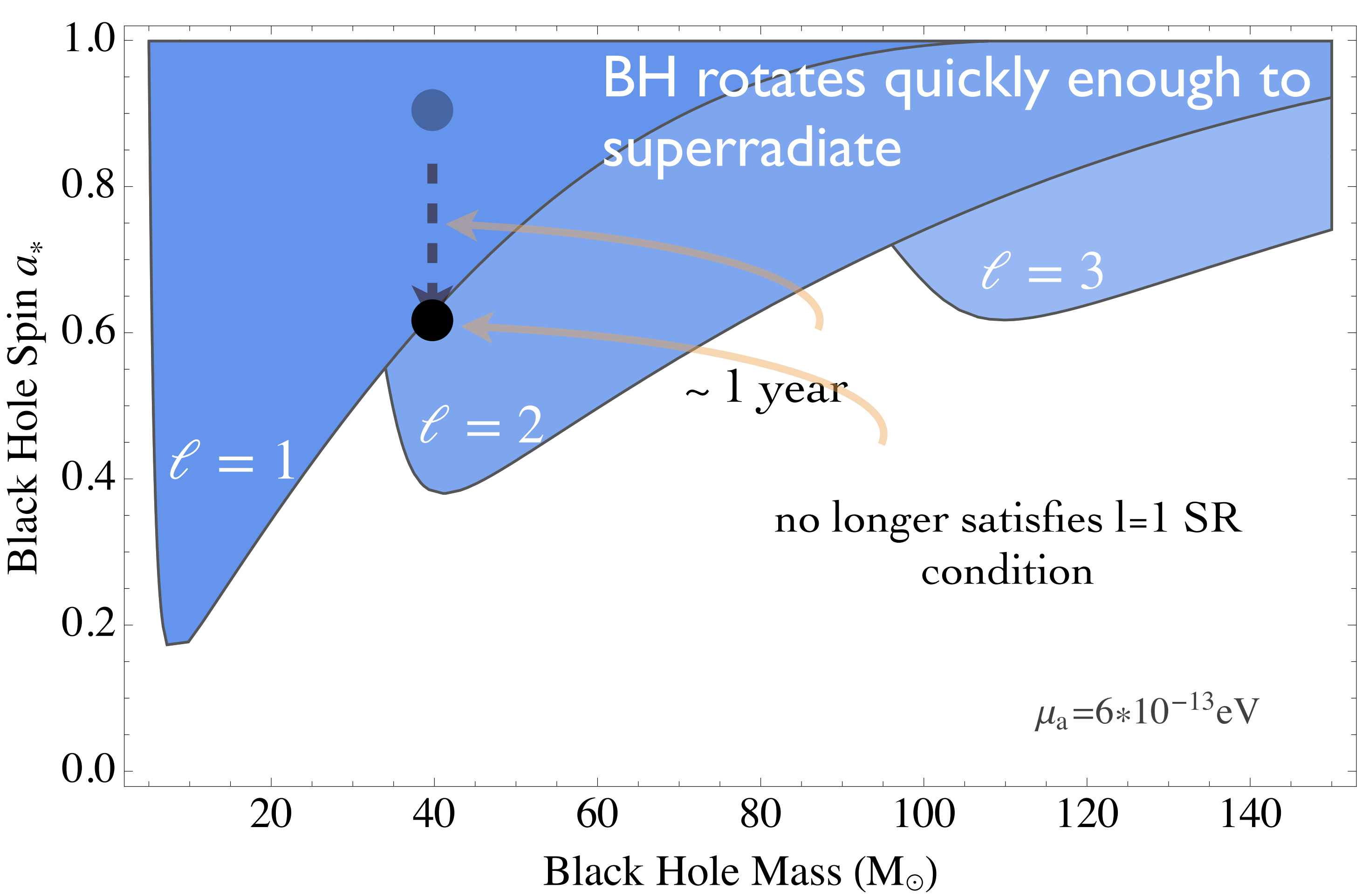
Time evolution



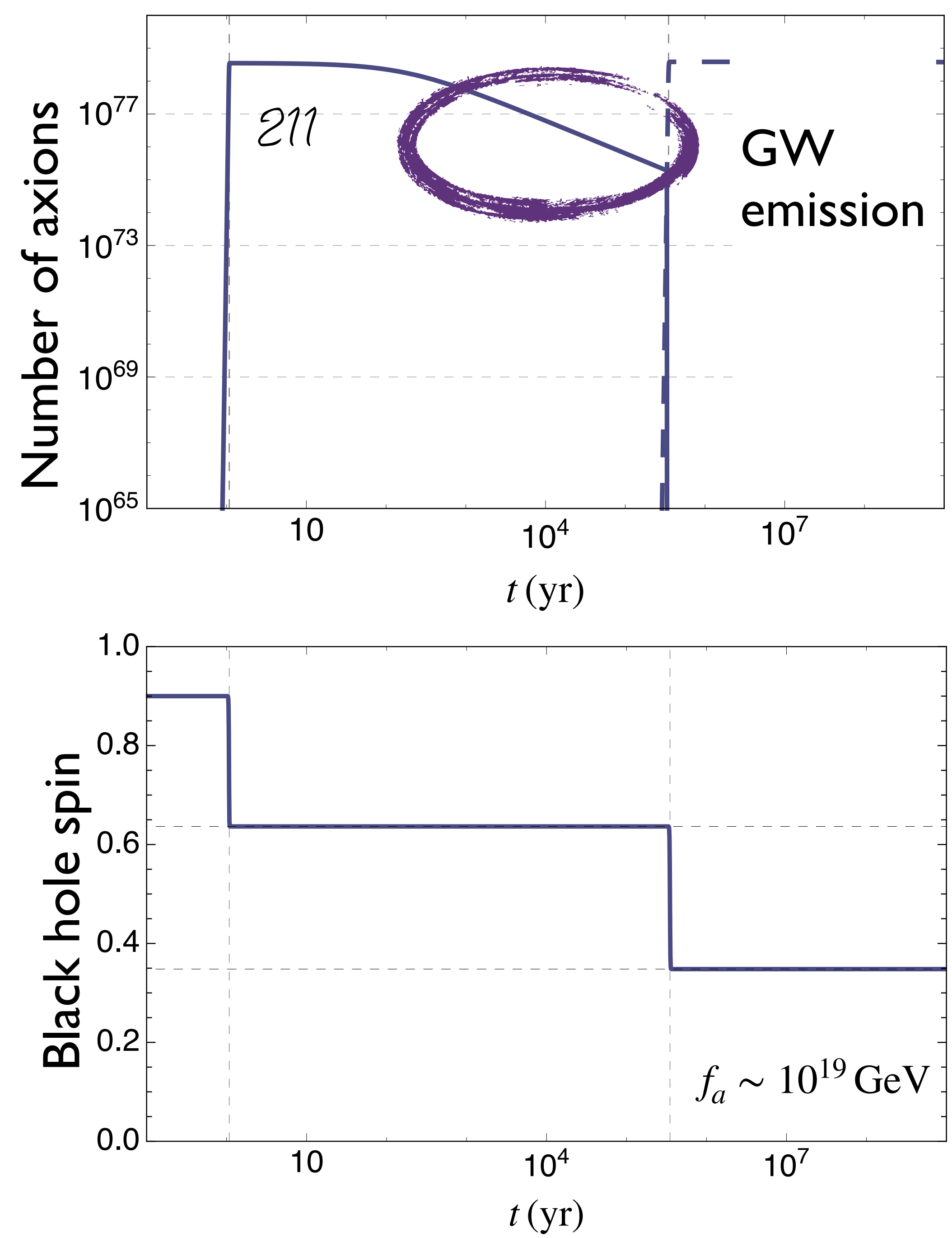
Superradiance



- Large energy density in the cloud, with time dependence set by the axion mass
- Sources monochromatic gravitational wave radiation
- Axion cloud depletes on long timescales through GW emission

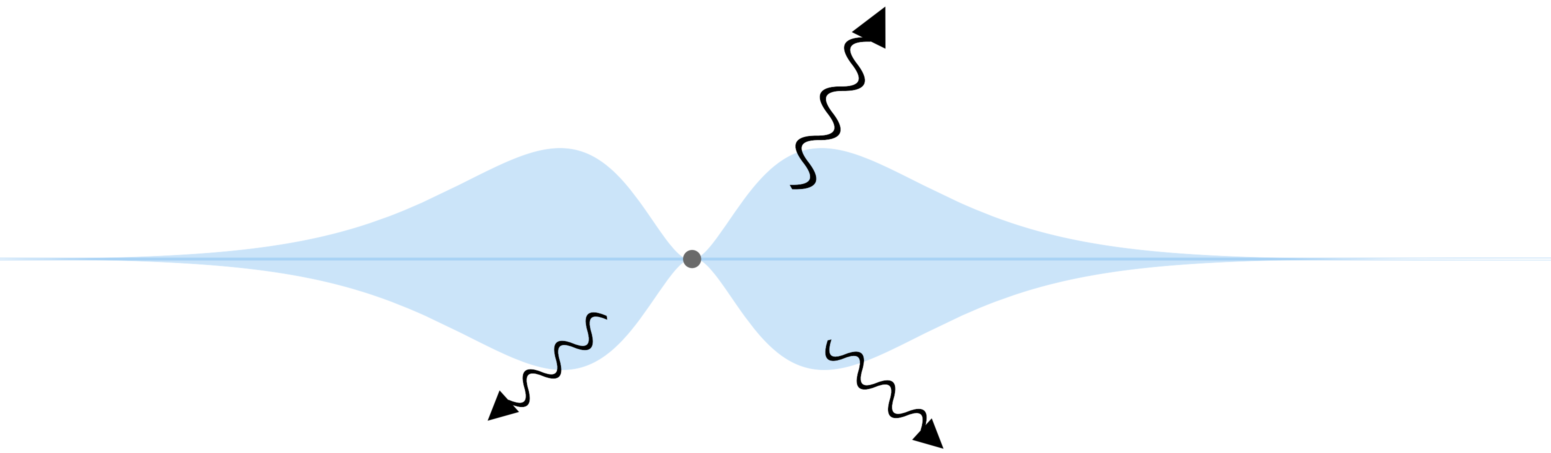


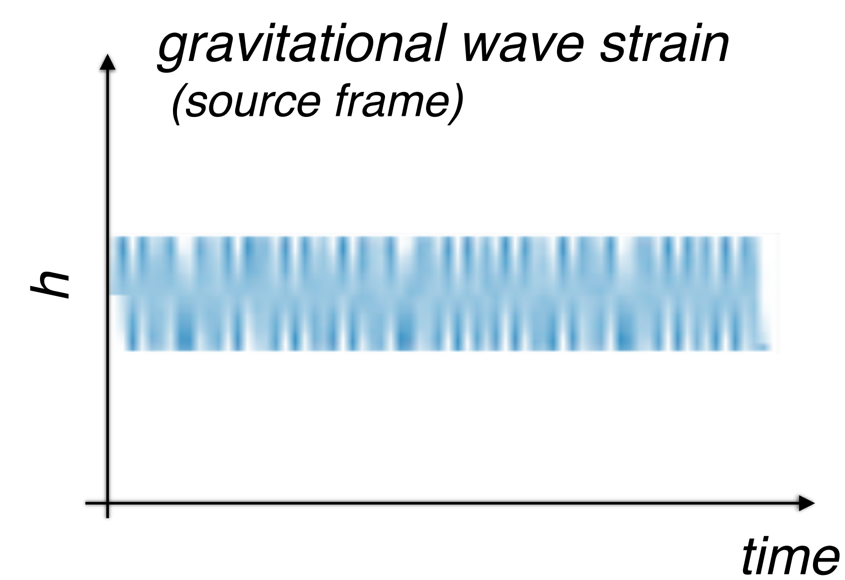
Time evolution



Gravitational Wave Searches for Axions

Gravitational Wave Signals

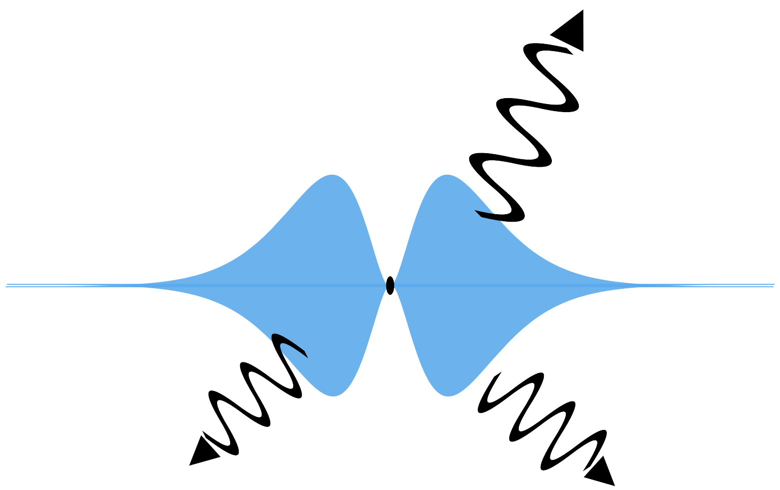


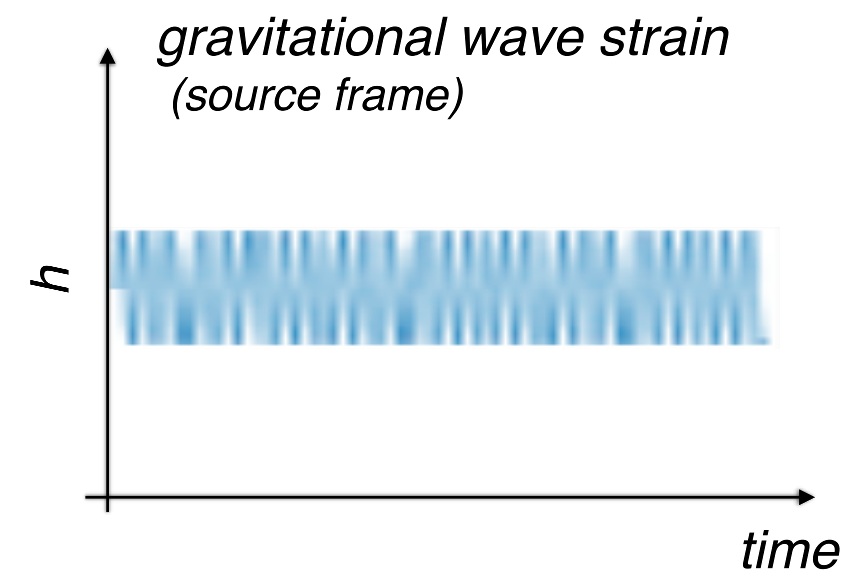


- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to 10,000 — can be observed and studied in detail

Arvanitaki, **MB**, Huang (2015)
Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
Brito et al (2017)
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2020)

Gravitational Wave Signals





- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
    - Event rates up to 10,000 — can be observed and studied in detail

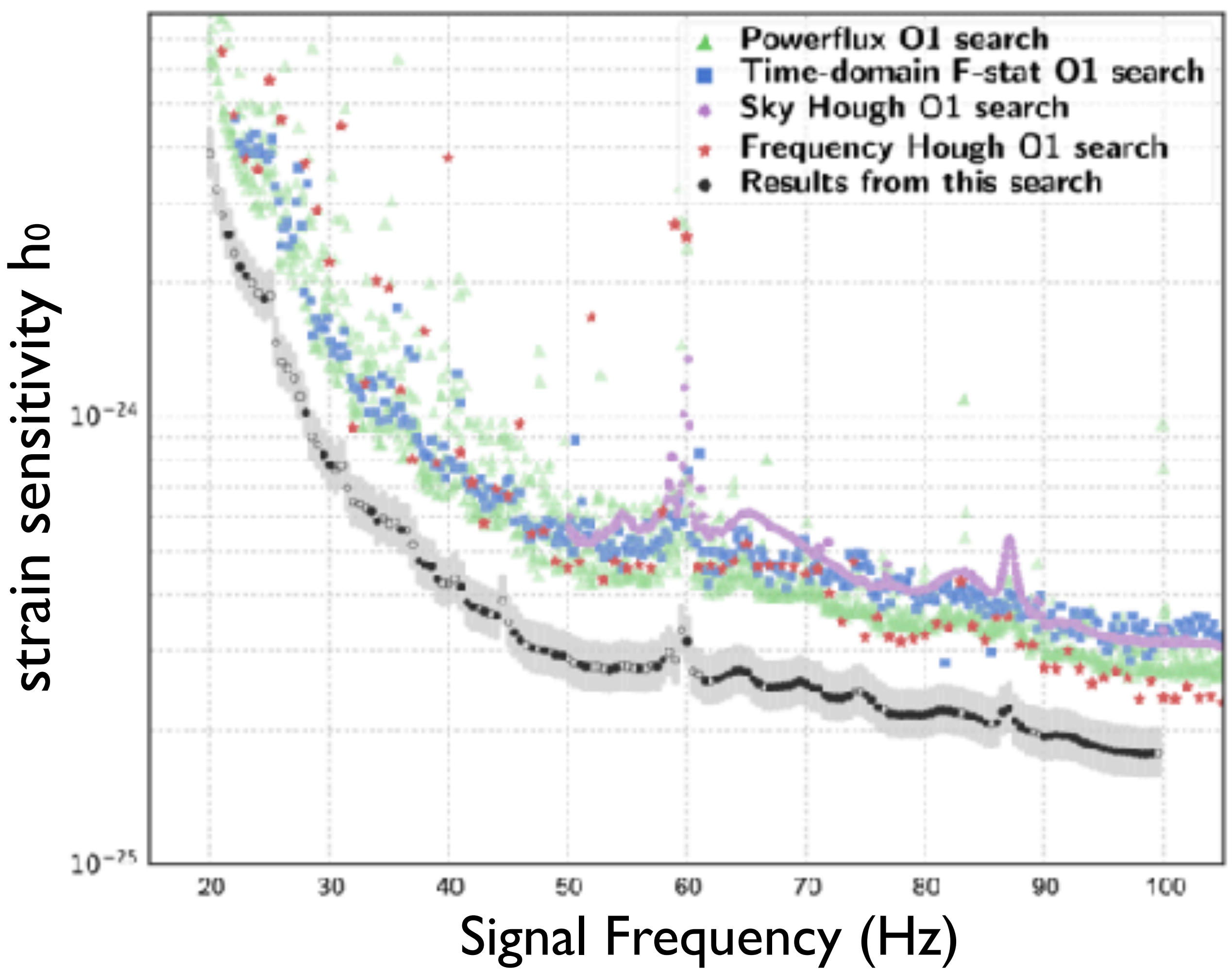
- **Loud, short signals** last for ~ days - months, observable from BBH or NS-NS merger events
    - Event rates <1/year at design aLIGO sensitivity, up to 100's at future observatories

Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
Isi, Sun, Brito, Melatos (2019)

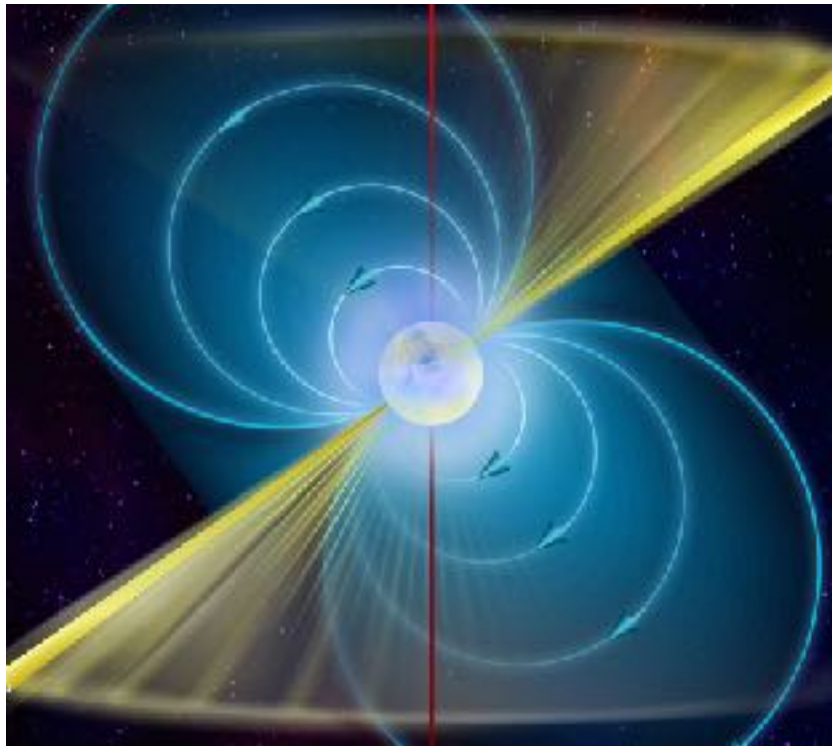
Gravitational Wave Searches

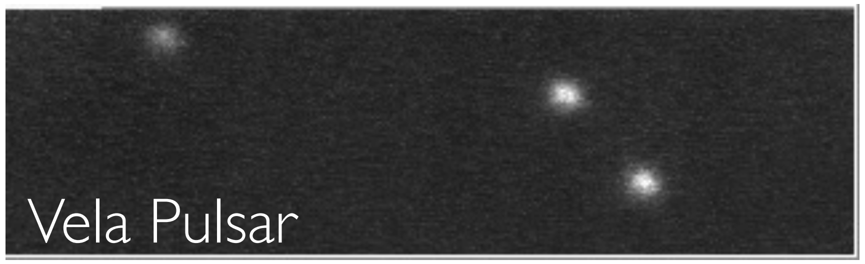
- Current searches for gravitational waves from asymmetric rotating neutron stars ongoing
- Targeted as well as all-sky searches, reaching to very weak signals with large computational efforts

All-Sky O1 Upper Limits



Abbott et al PRD 96, 122004 (2017)

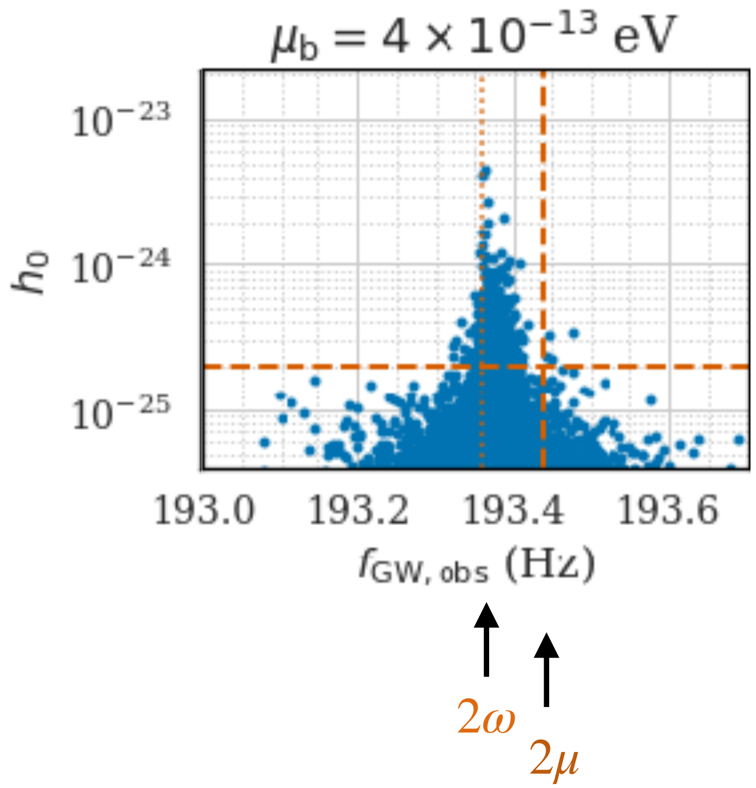




Cambridge University Lucky Imaging Group

Gravitational Wave Signals

- Up to 10^8 black holes born in the Milky Way over age of universe
- Each can potentially grow a cloud of axions and subsequently source gravitational waves

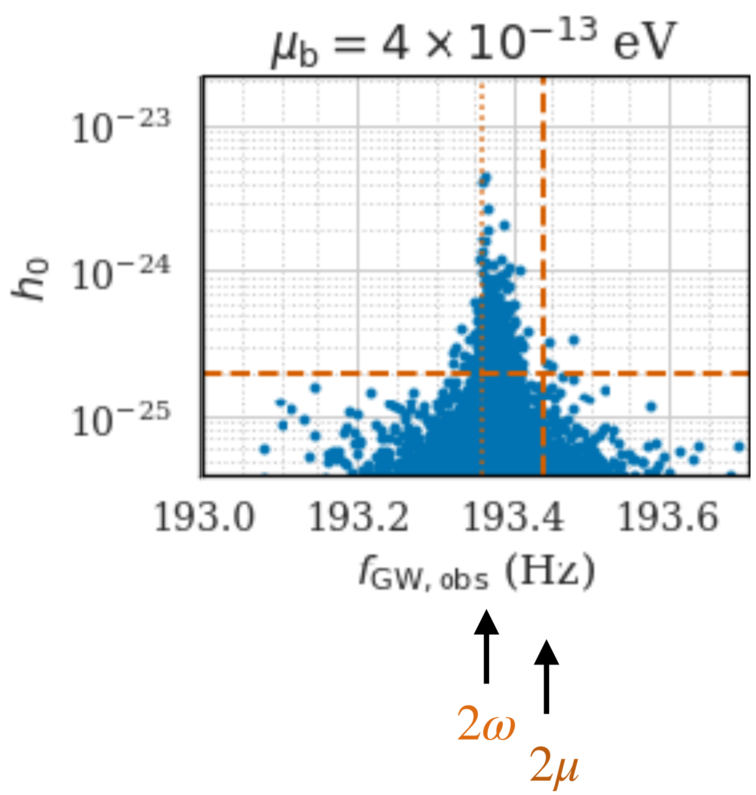


- Signals clustered at frequency ~twice the axion mass
- Binding energy (constant) and doppler shift (time-dependent) change frequency at LIGO
- Heavier black holes produce larger signals, lower frequencies

Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

Gravitational Wave Signals

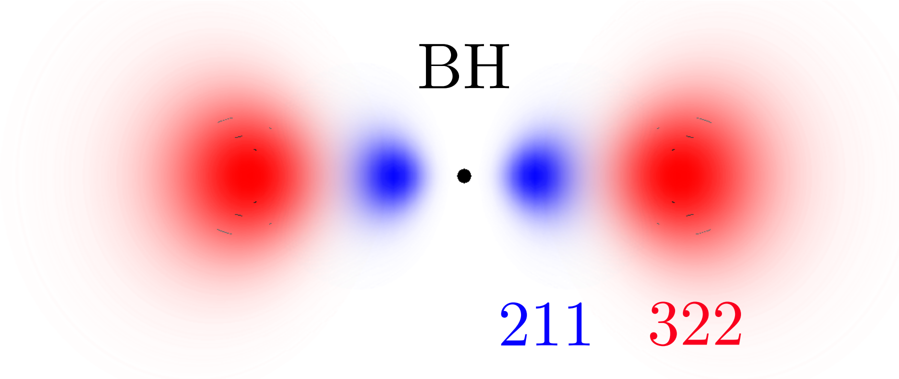
- Up to 10^8 black holes born in the Milky Way over age of universe
- Each can potentially grow a cloud of axions and subsequently source gravitational waves



Up to 1000s of signals observable with Advanced LIGO searches

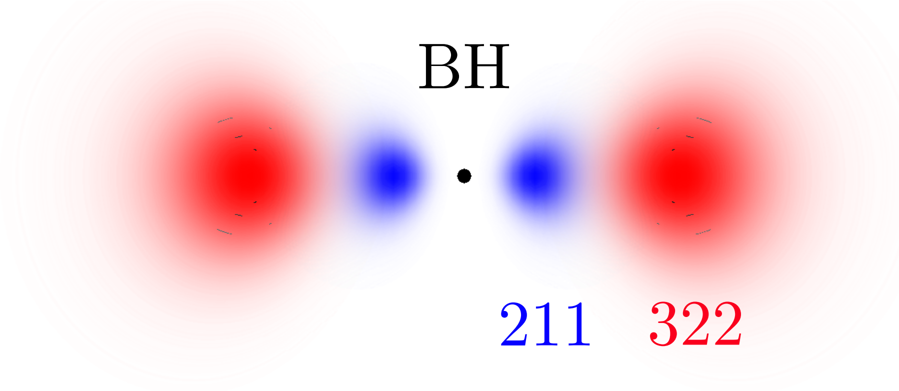
- Signals clustered at frequency ~twice the axion mass
- Binding energy (constant) and doppler shift (time-dependent) change frequency at LIGO
- Heavier black holes produce larger signals, lower frequencies

Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)



Self interactions and Axionic Beacons

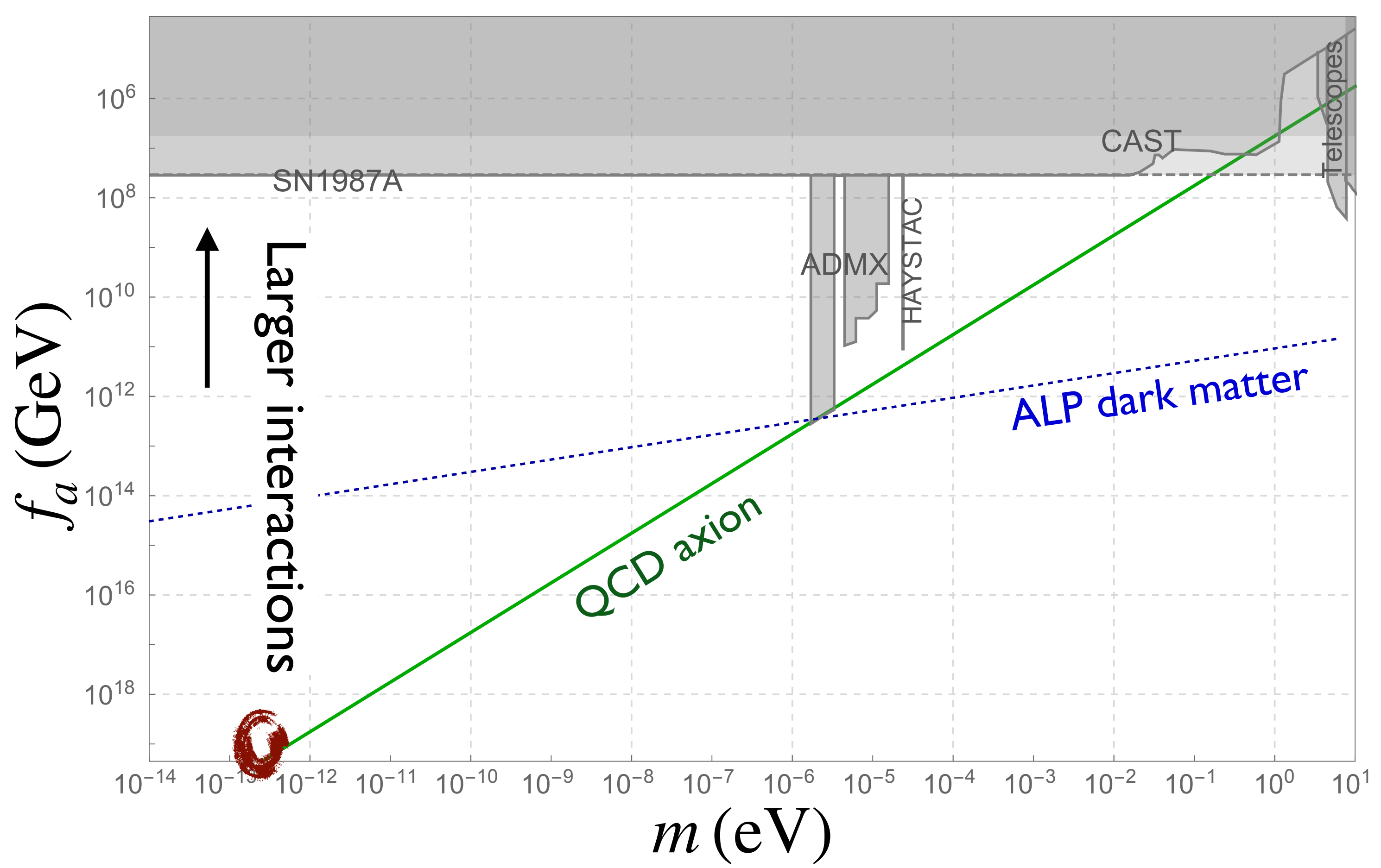
Self-Interactions



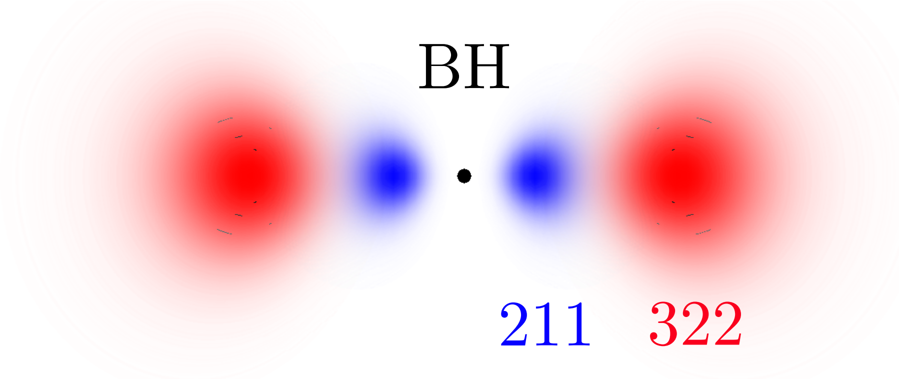
- So far, have focused on gravitational signatures of the axion (light spin-0 particle)

MB, M. Galanis, R. Lasenby, O. Simon, *2011.11646*

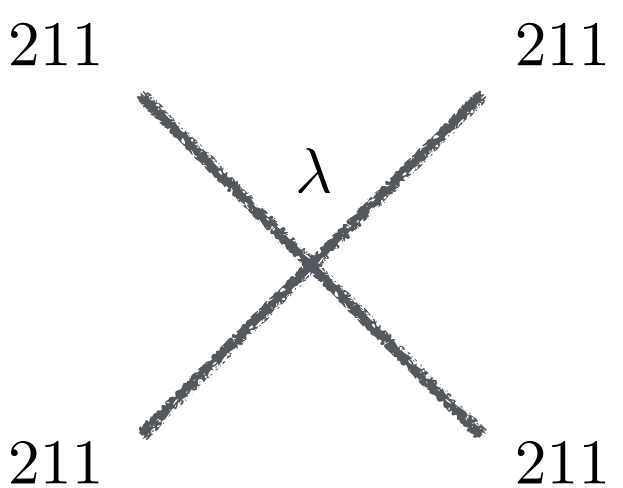
- What new effects arise when axion self-interactions become important?



Self-Interactions

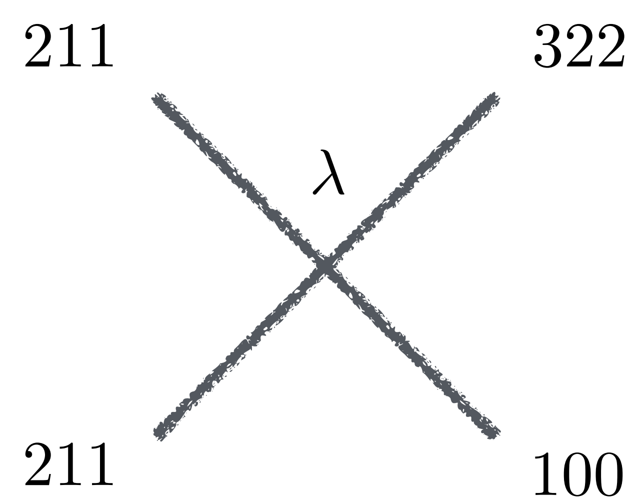


Self-energy:



- What new effects arise when axion self-interactions become important?

Level interactions:



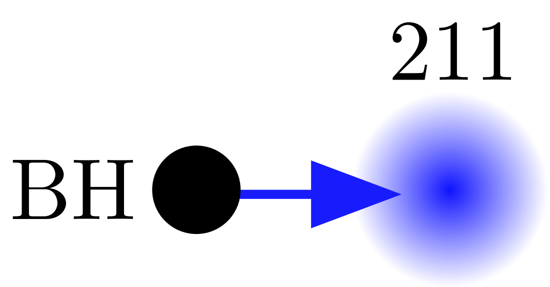
$$\lambda \sim \frac{\mu^2}{f_a^2}$$

for typical pseudoGoldstone bosons

Arvanitaki, Dubovsky 2010
Yoshino, Kodama 2012
Gruzinov 2016
Fukuda, Nakayama 2020

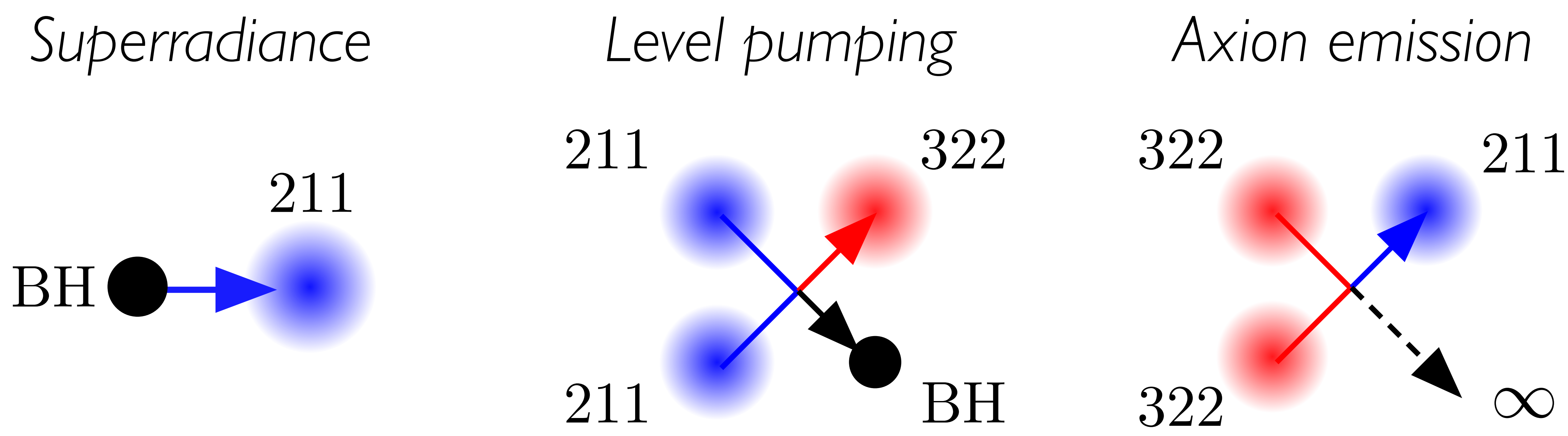
Self-Interactions

Superradiance



- What new effects arise when axion self-interactions become important?

Self-Interactions

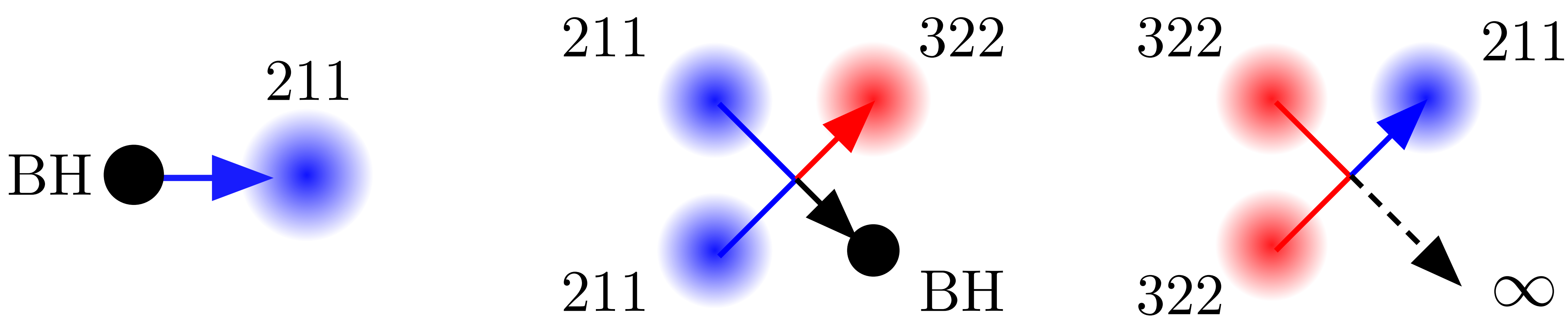


- What new effects arise when axion self-interactions become important?

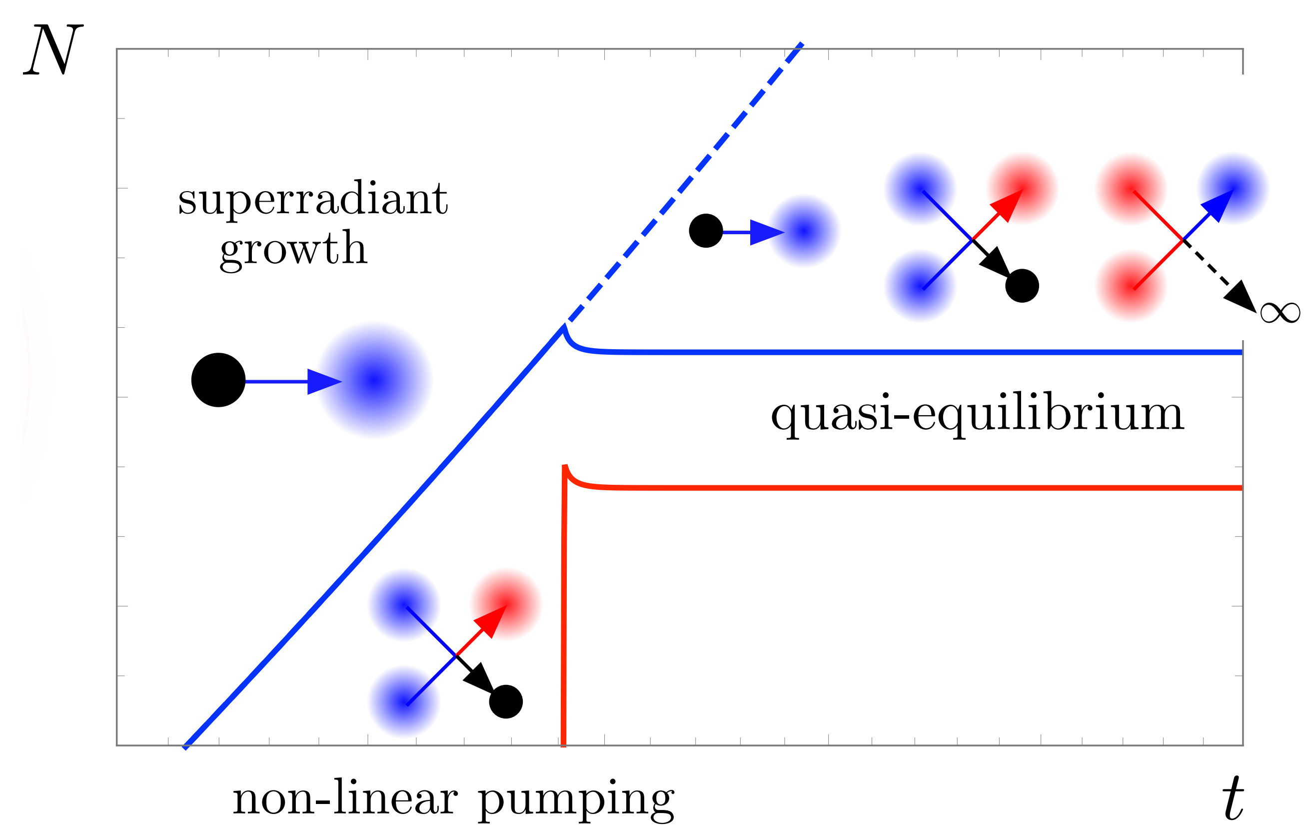
    - Black hole energy sources the cloud through superradiance
    - Second level populated through self-interactions
    - Non-relativistic axion waves carry energy to infinity

Self-Interactions

Superradiance *Level pumping* *Axion emission*

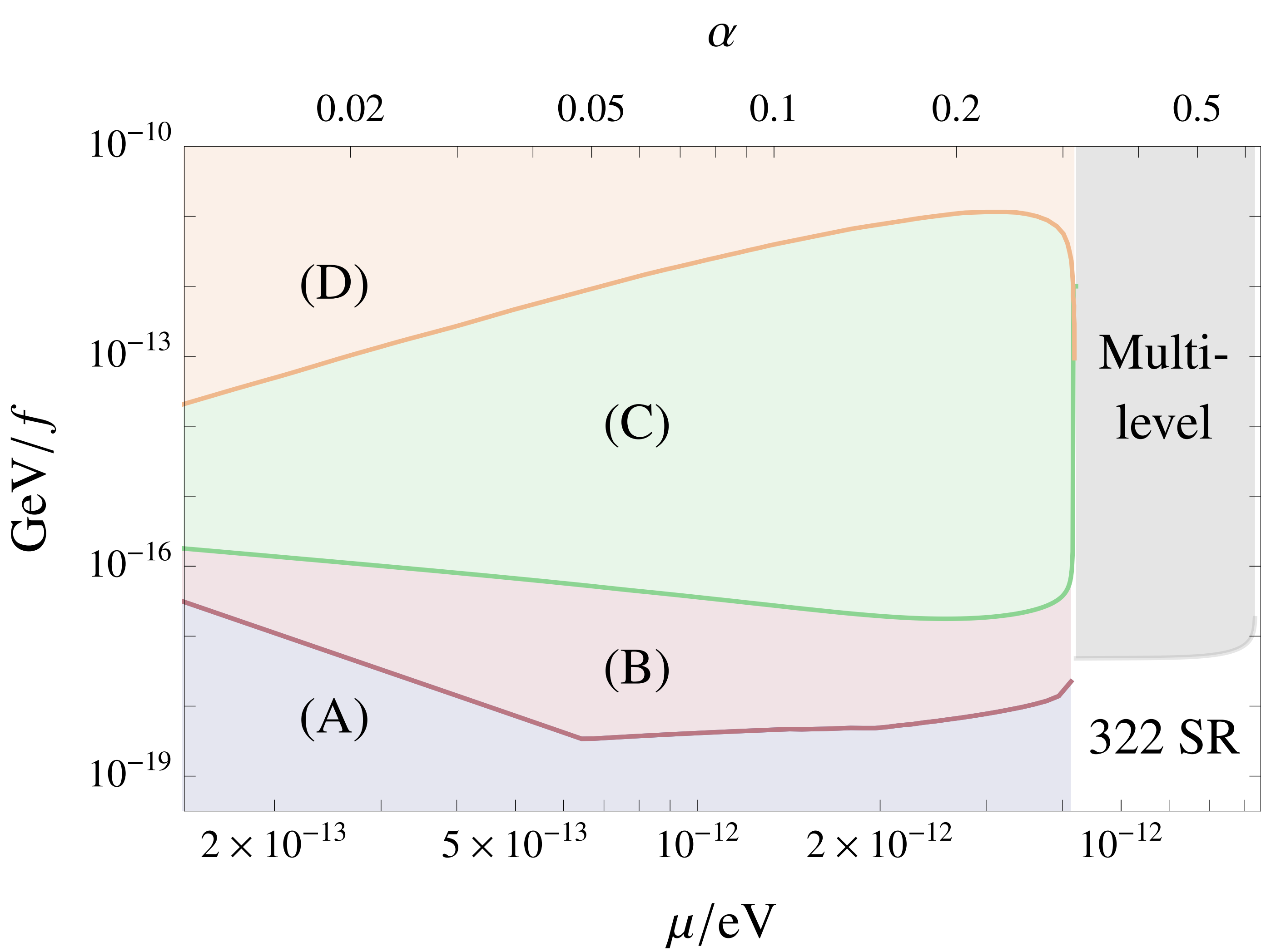


- At large self-interactions, emission to infinity and into black hole saturates superradiant growth early and leads to quasiequilibrium of two levels



Self-Interactions

A range of dynamics for different axion self-interactions with different observational implications



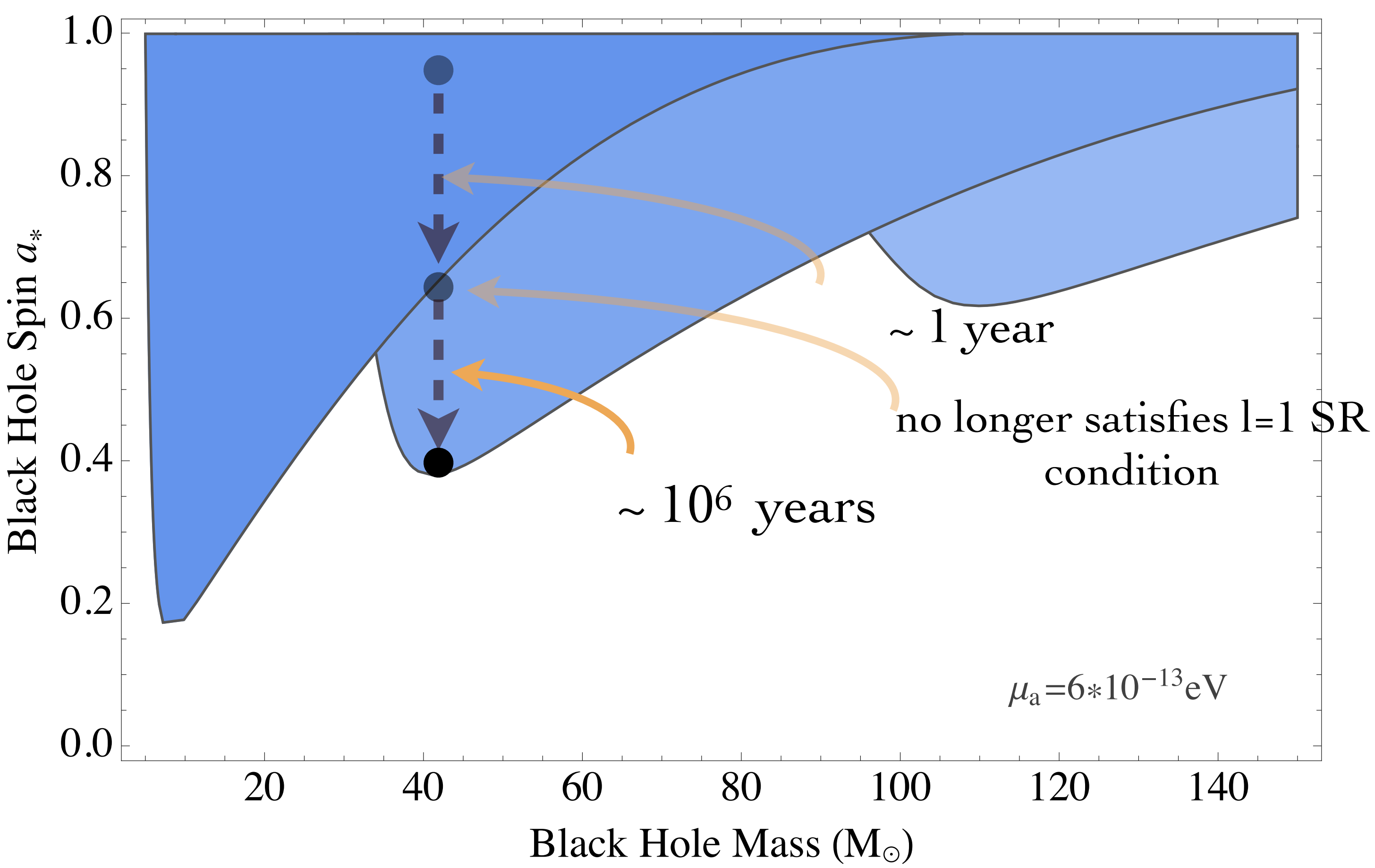
- (A) 'gravitational superradiance': GW annihilations, spindown
- (B) small self-interactions: GW annihilations & transitions, spindown
- (C) moderate self-interactions: reduced occupation numbers: weak GWs, spindown, axion waves
- (D) large self-interactions: no spindown, axion waves

MB, M. Galanis, R. Lasenby, O. Simon, *2011.11646*

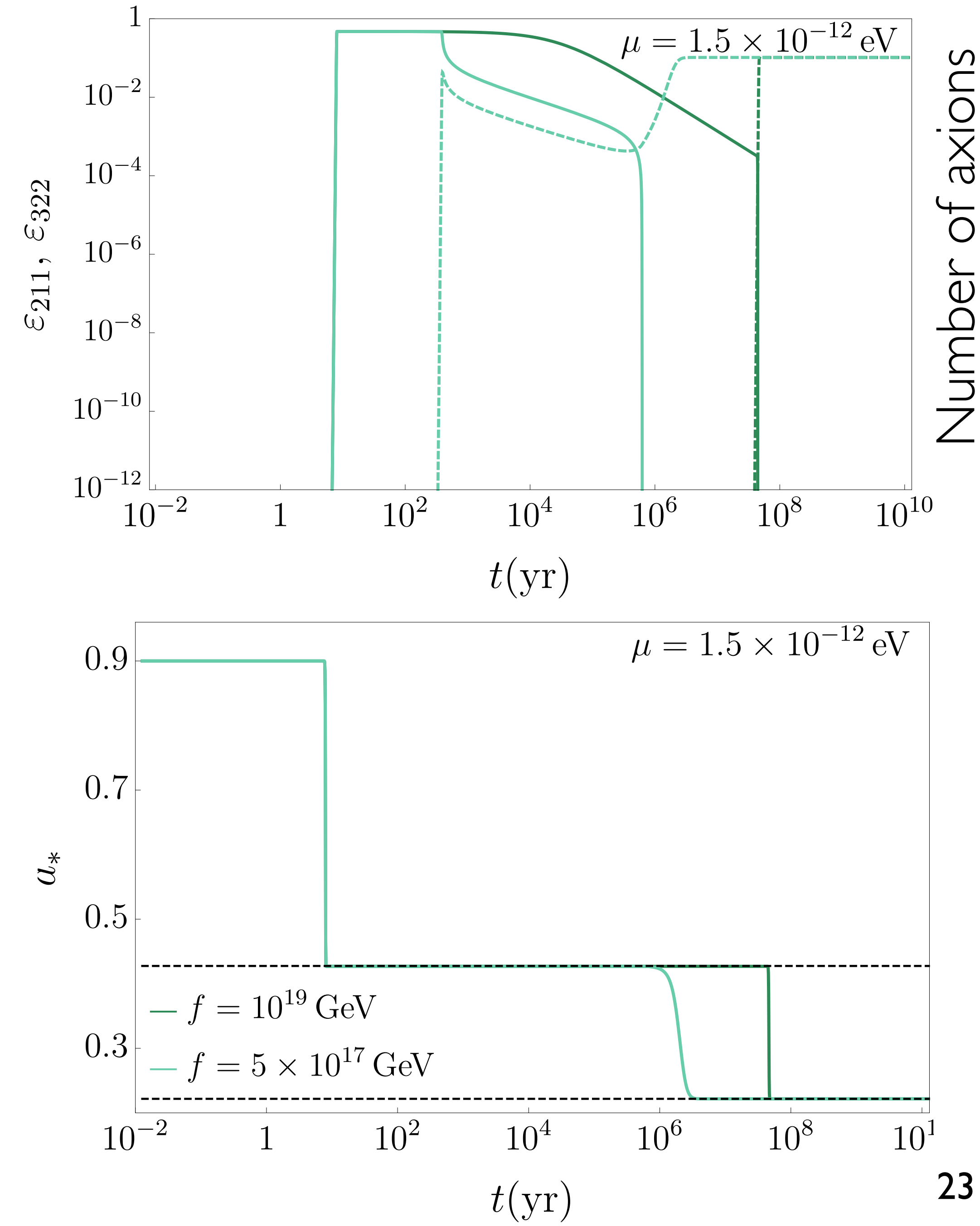
Self-Interactions

Gravitational superradiance:

- BH spins down: next level formed; annihilations to GWs deplete first level
- Next level has a superradiance rate exceeding age of BH



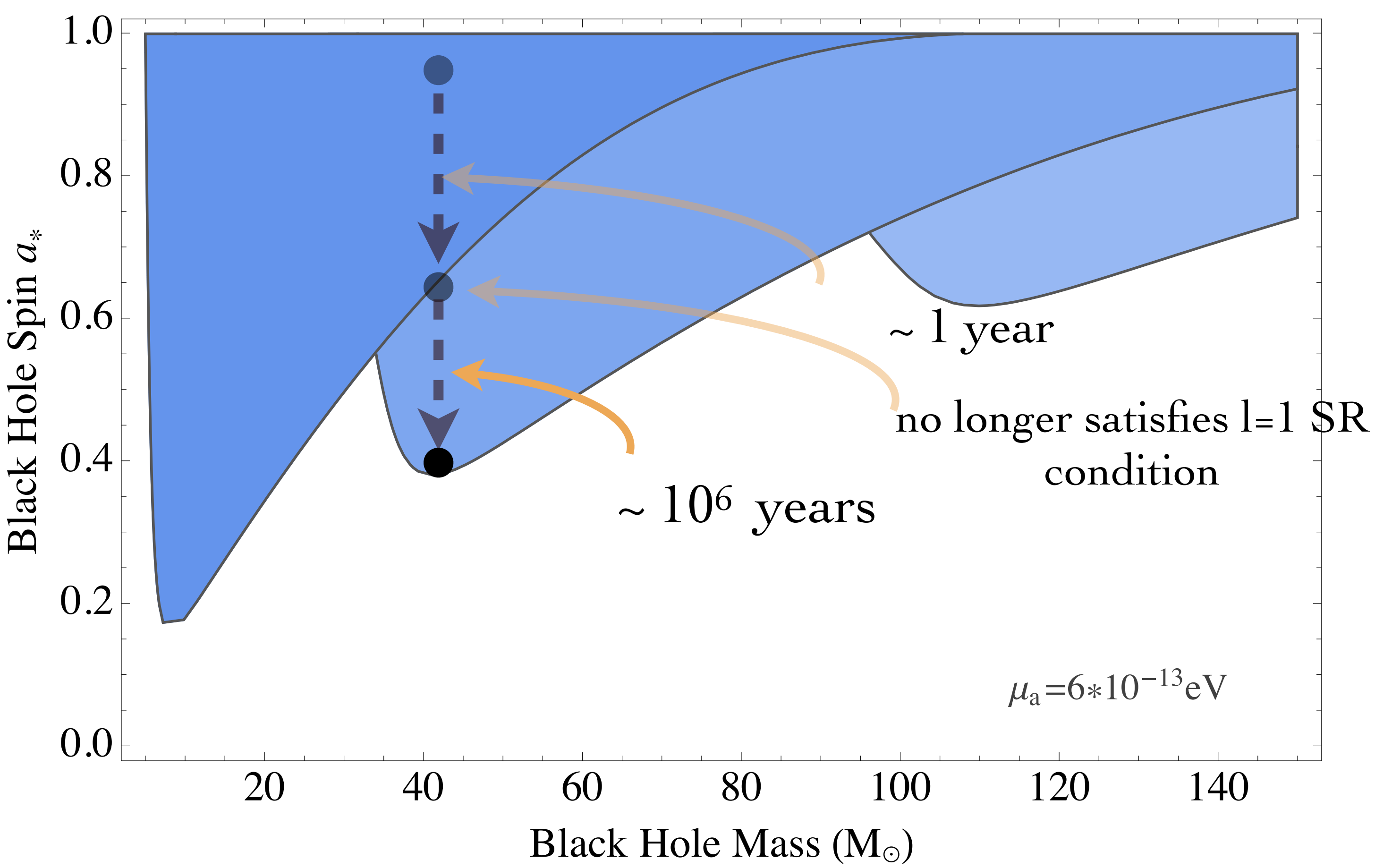
Time evolution



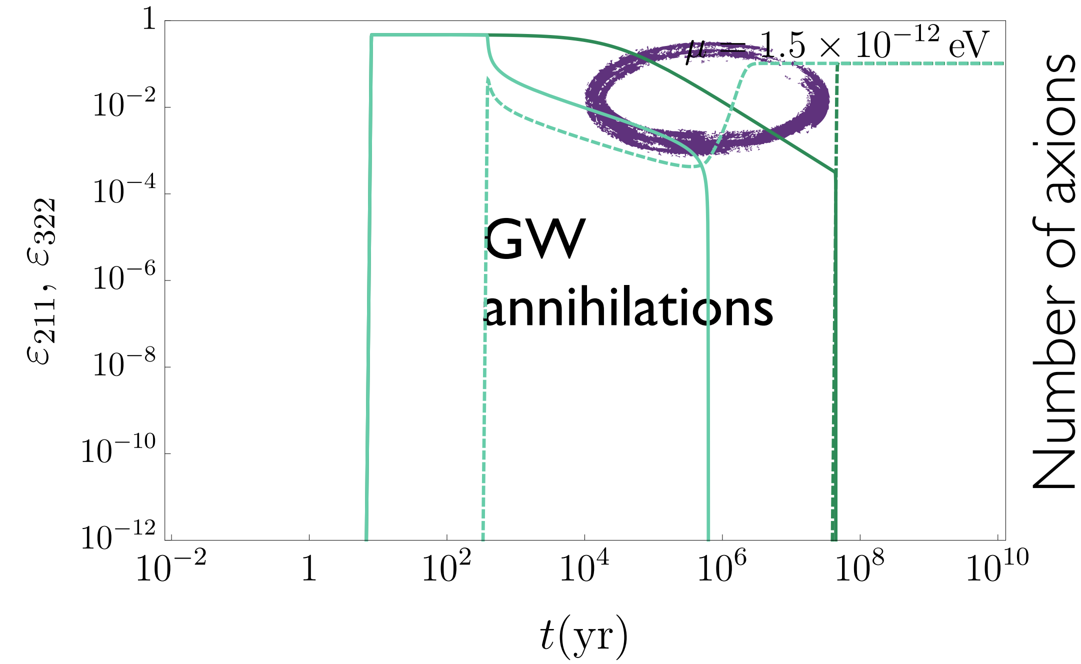
Self-Interactions

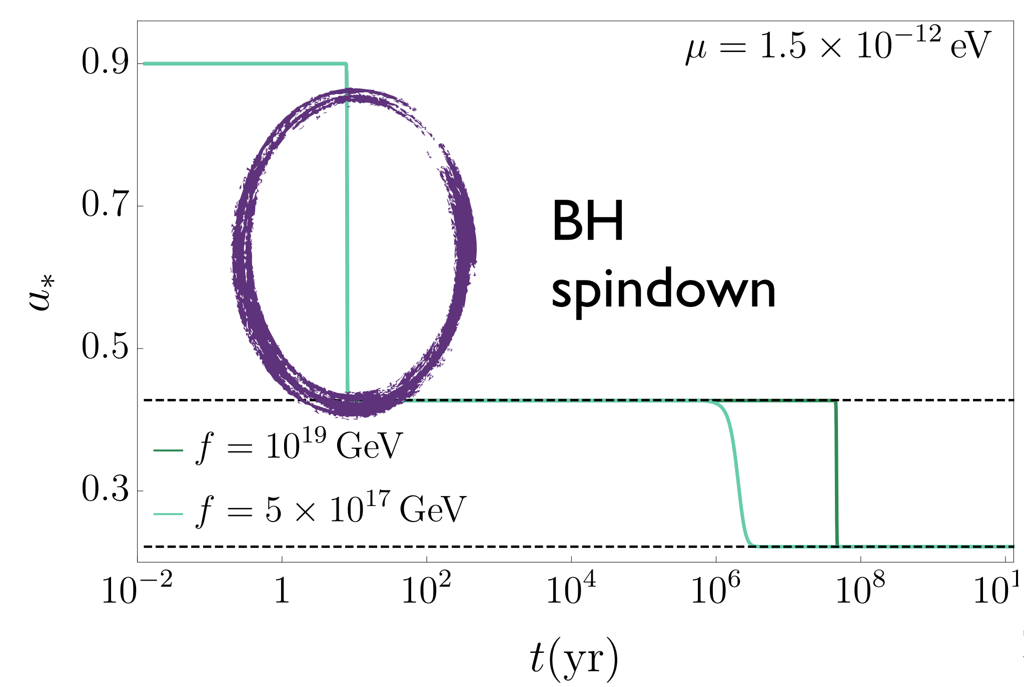
Gravitational superradiance:

- BH spins down: next level formed; annihilations to GWs deplete first level
- Next level has a superradiance rate exceeding age of BH



Time evolution

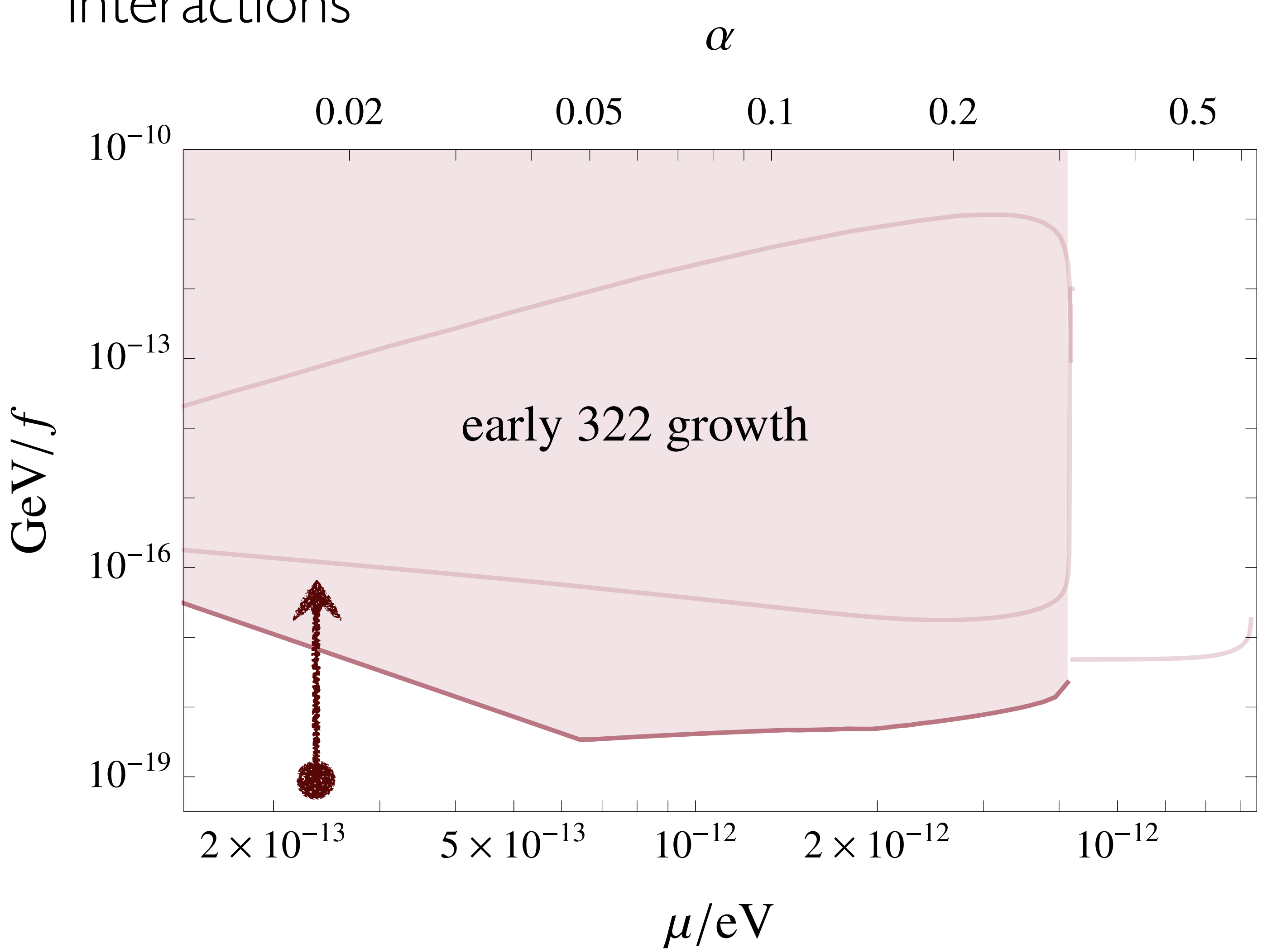




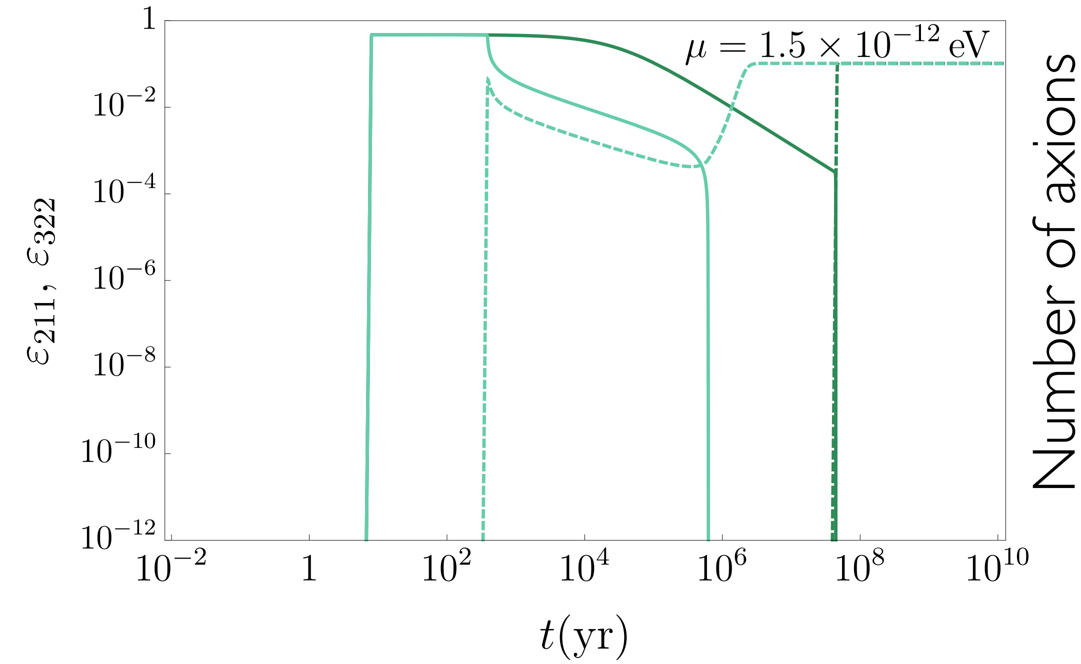
Self-Interactions

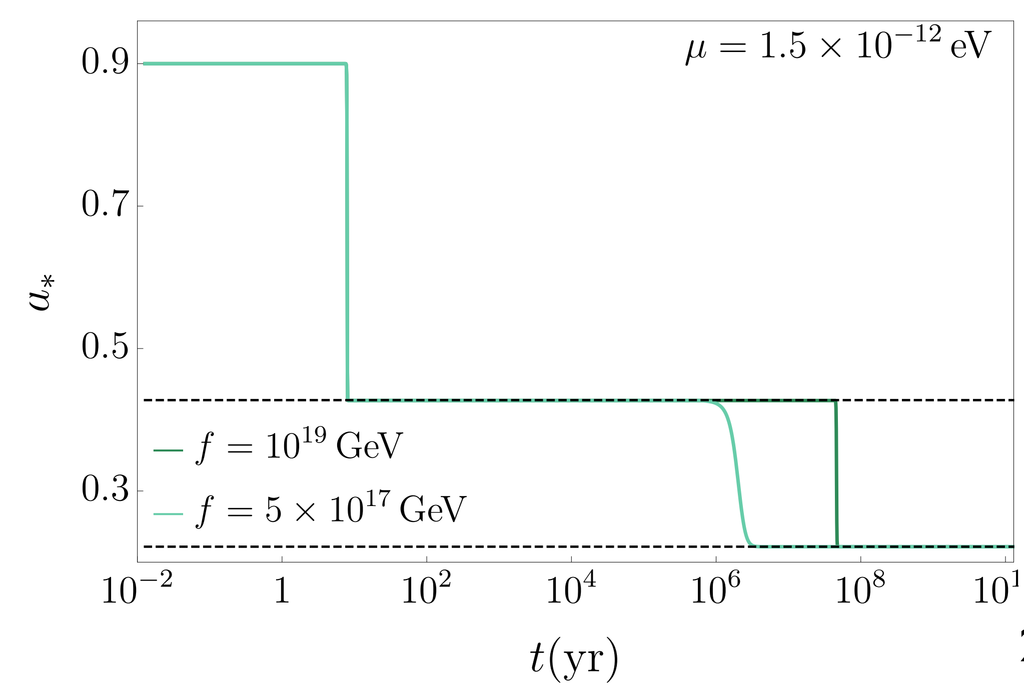
Small self-interactions:

- Black hole energy sources the first level cloud (211) through superradiance
- Second level (322) populated through self-interactions



Time evolution

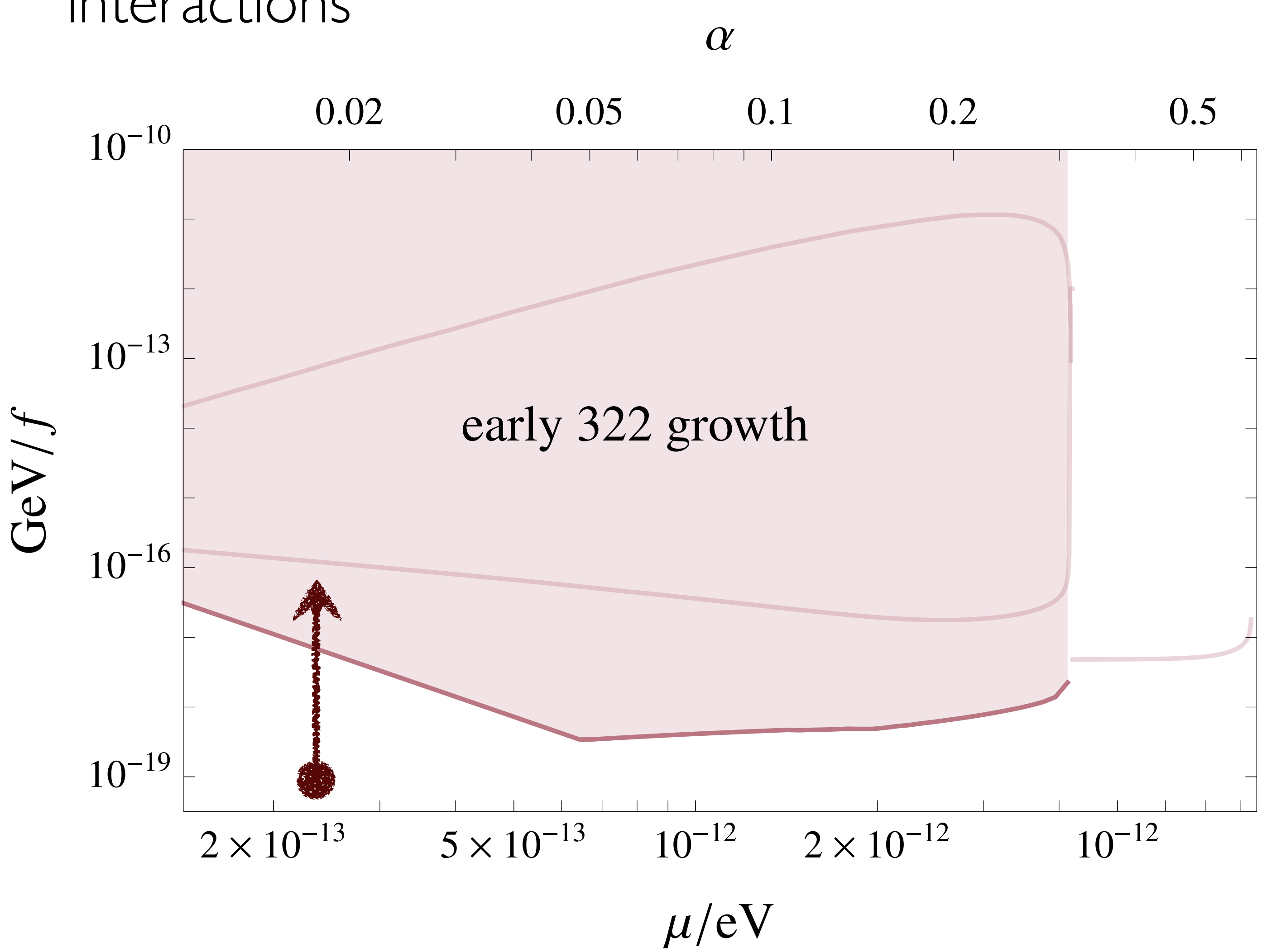




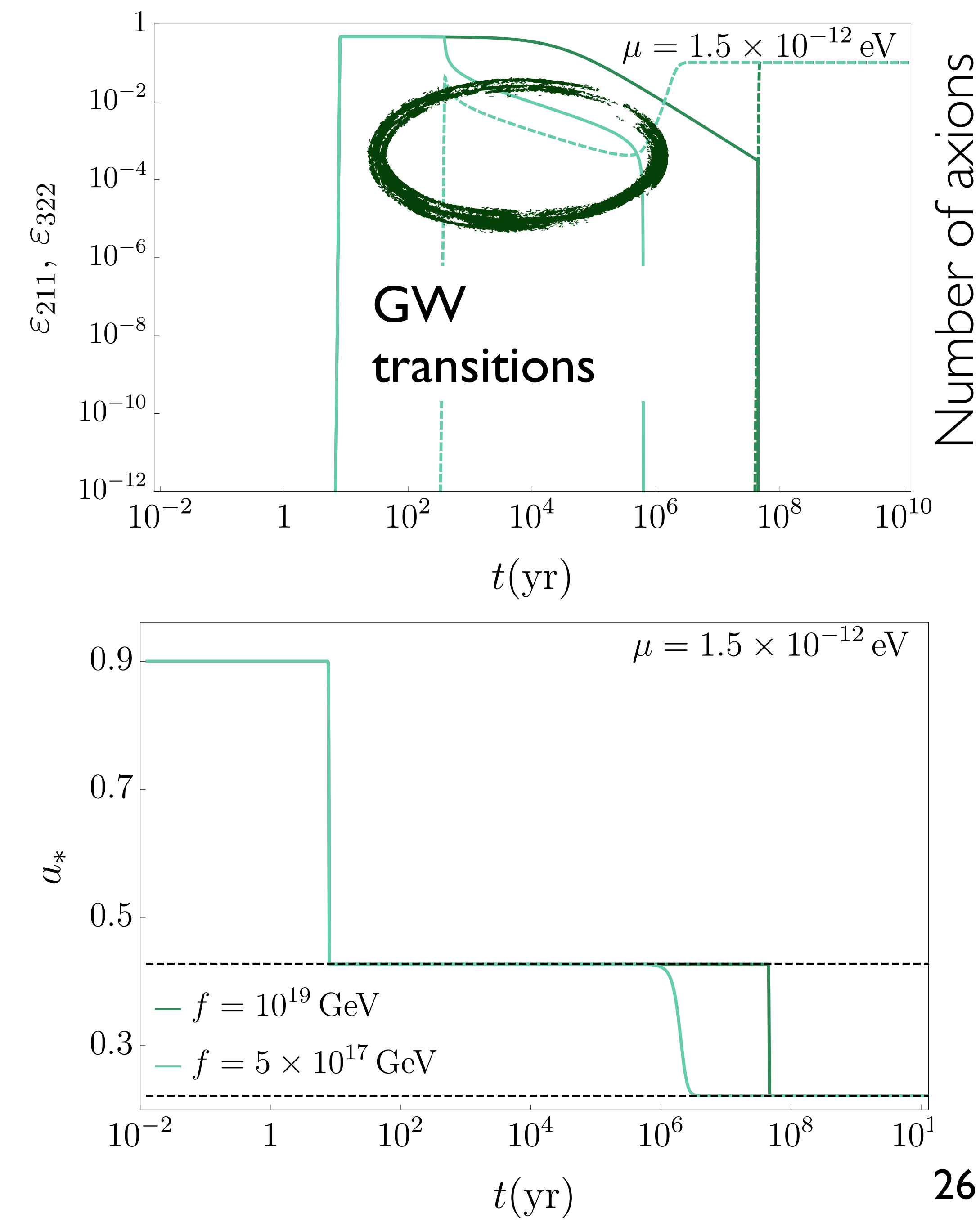
Self-Interactions

Small self-interactions:

- Black hole energy sources the first level cloud (211) through superradiance
- Second level (322) populated through self-interactions



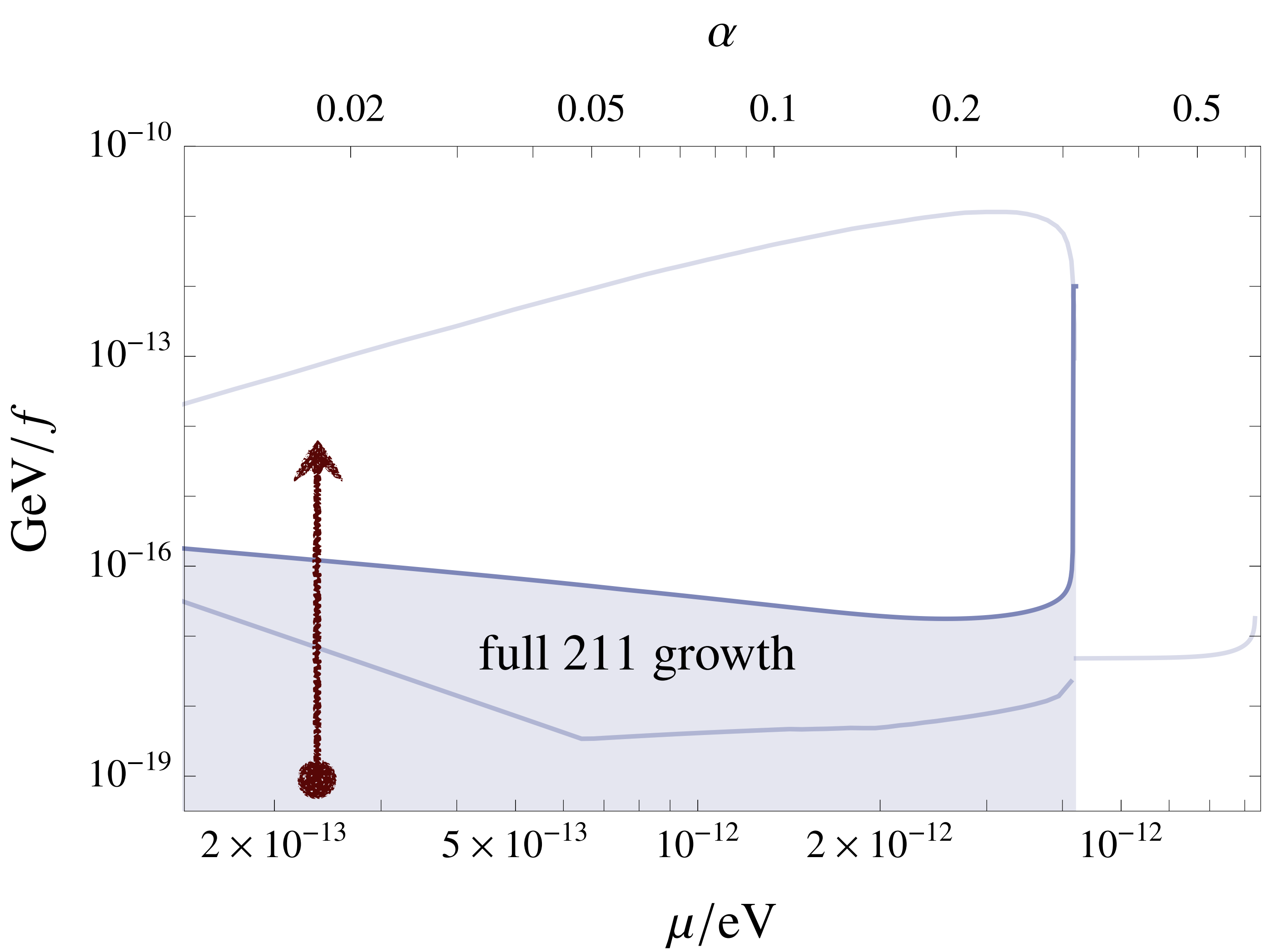
Time evolution



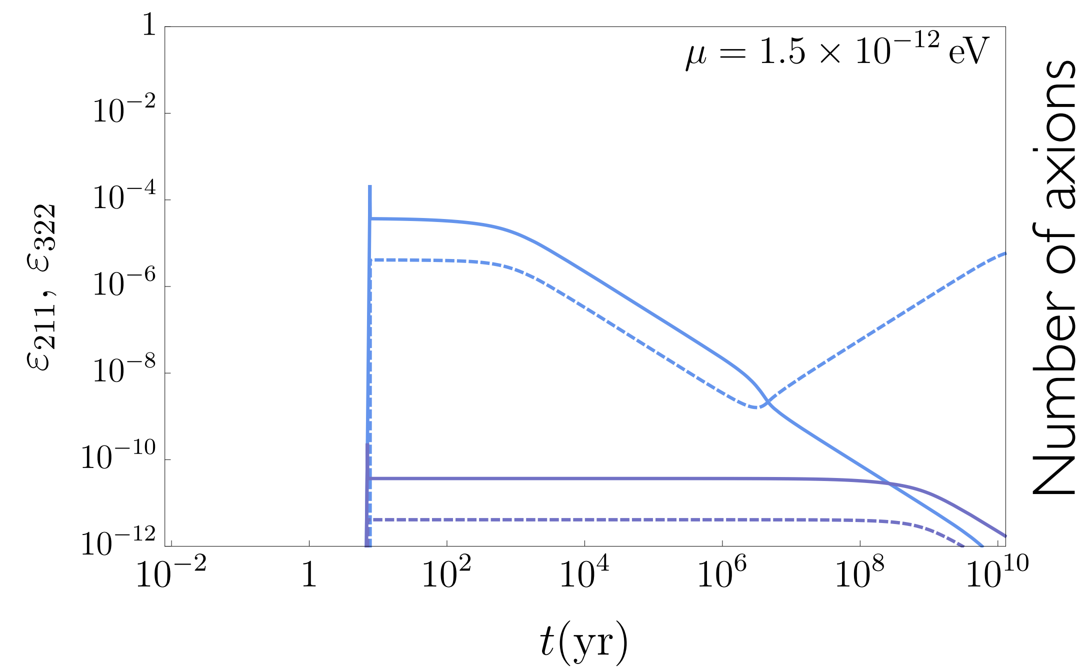
Self-Interactions

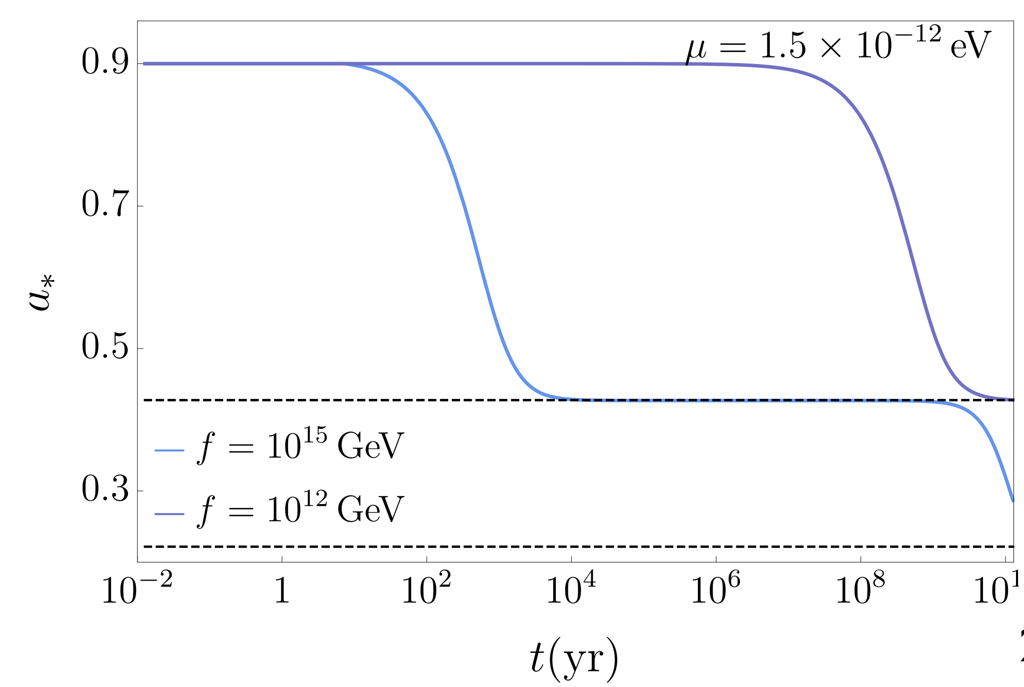
Moderate self-interactions:

- New energy loss mechanisms (into the BH and waves to infinity)
- 211 no longer grows to maximum



Time evolution

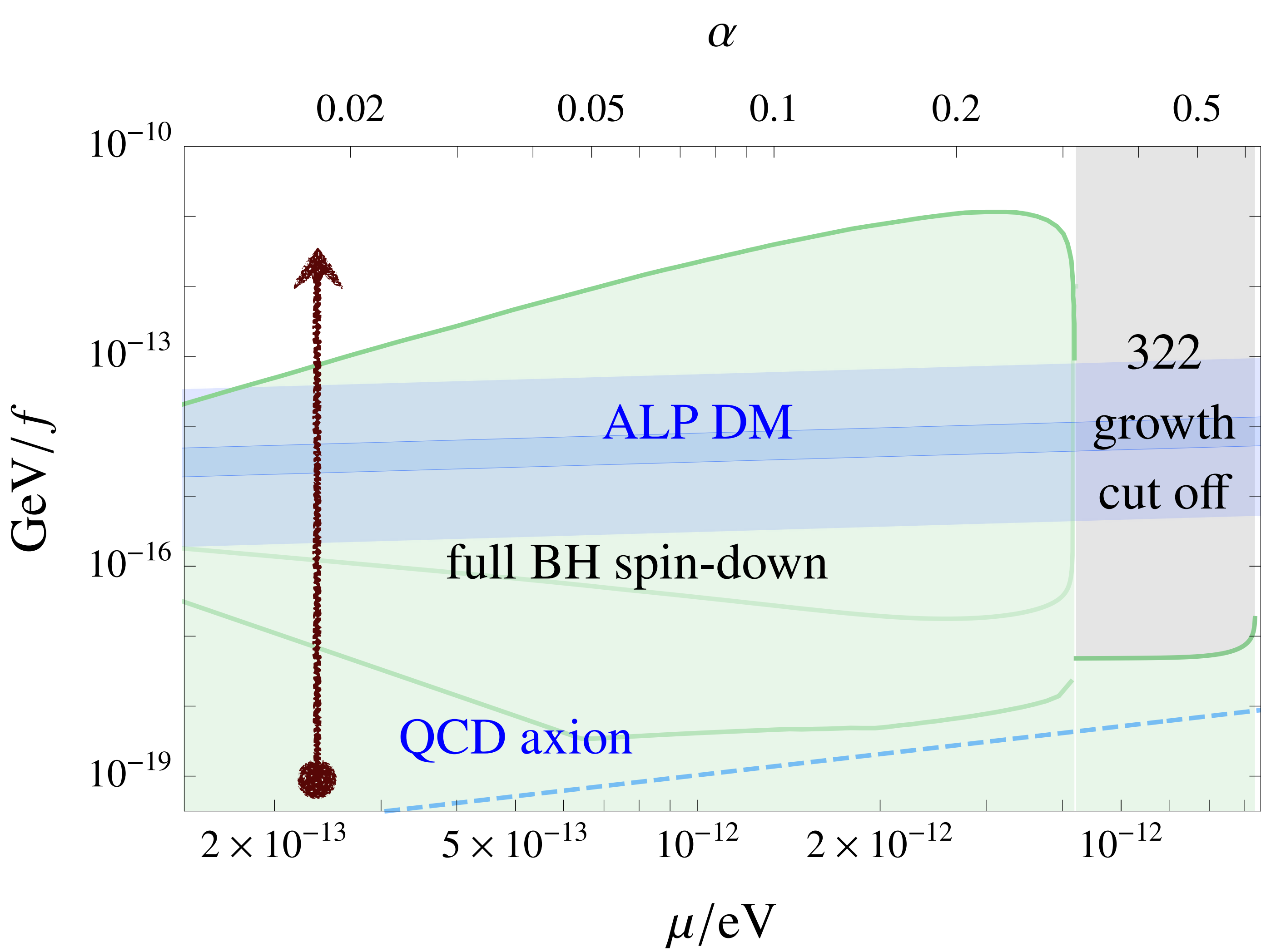




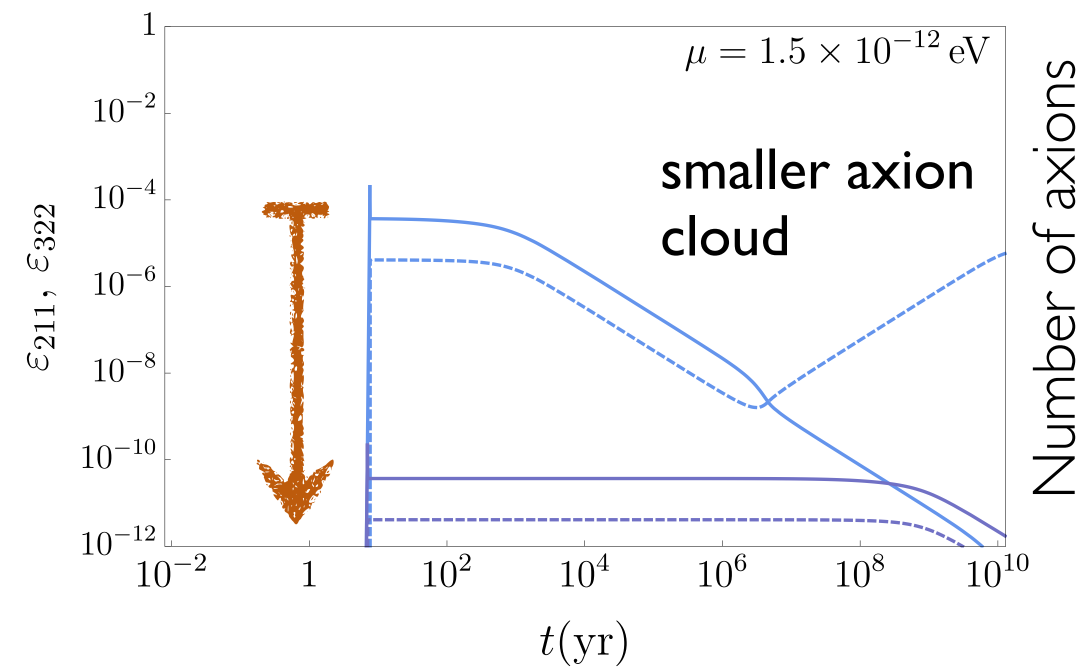
Self-Interactions

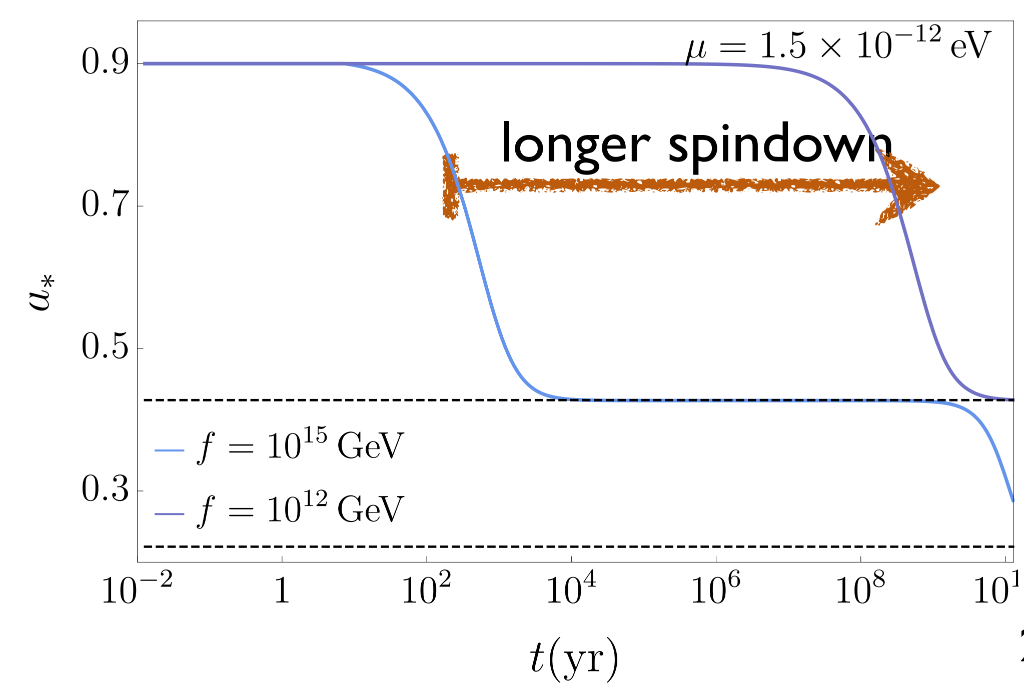
Large self-interactions:

- Smaller axion cloud parametrically slows the spindown of the black hole, equiliubrium can last longer than the age of the universe



Time evolution

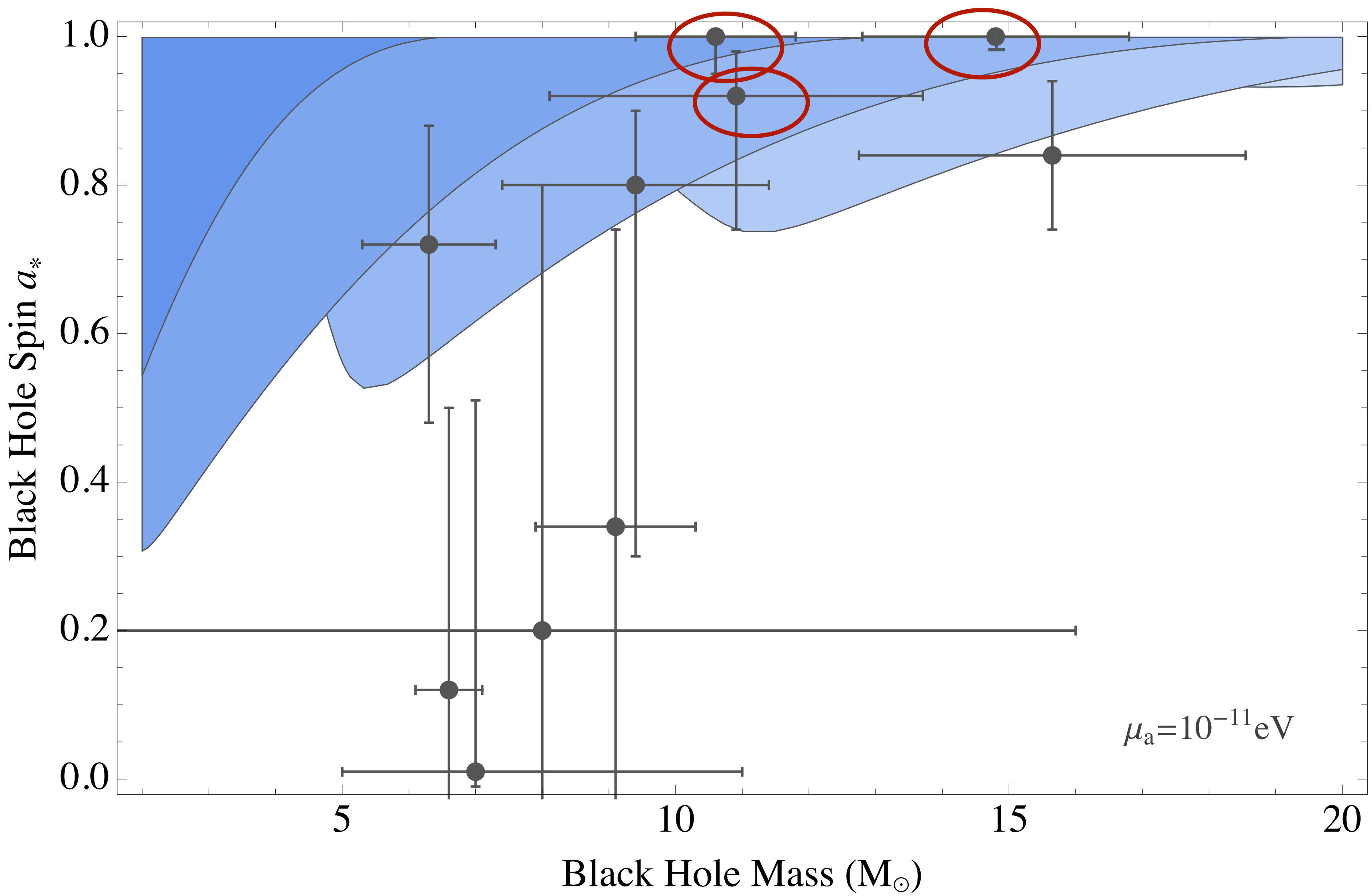




Black Hole Spins

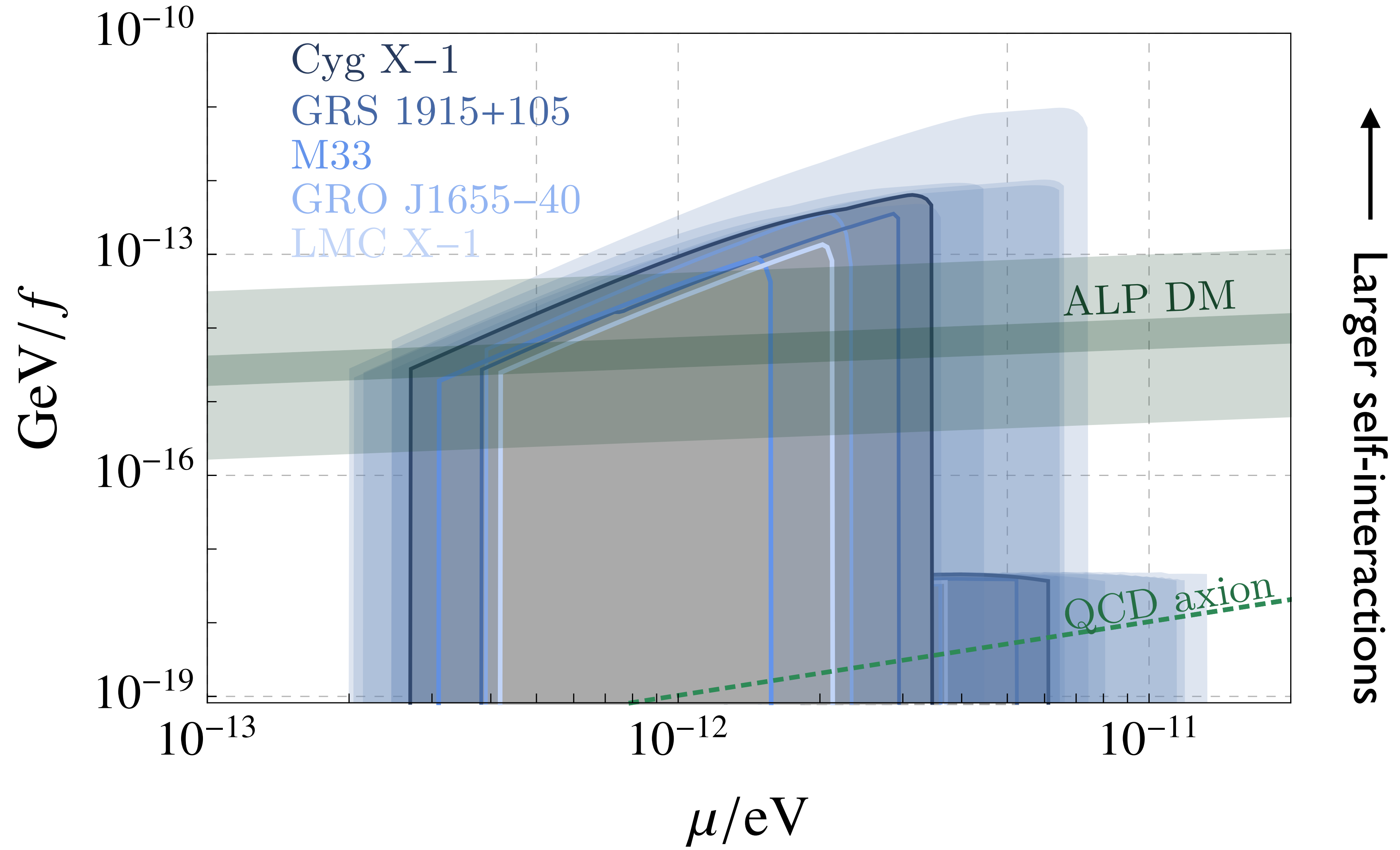
Black hole spin and mass measurements can be used to constrain axion parameter space

Black hole spins measured in X-ray binaries



Black Hole Spins

Five currently measured black holes combine to set limit:



MB, M. Galanis, R. Lasenby, O. Simon, *2011.11646*

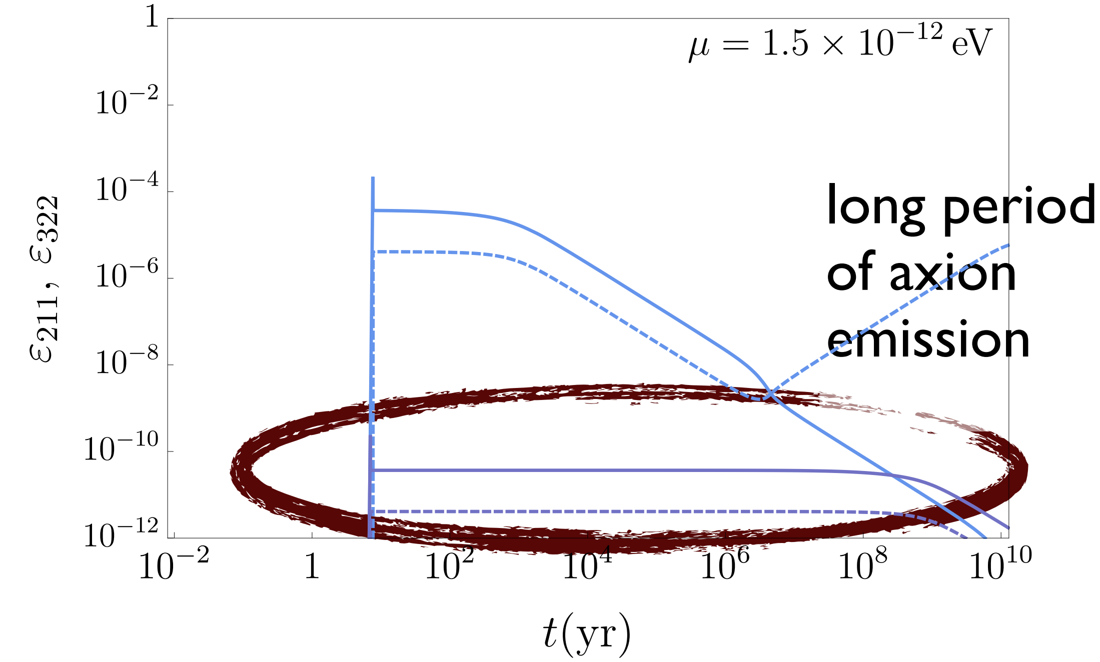
- As self-interactions increase, the number of axions in each level is bounded and spin extraction from the black hole slows

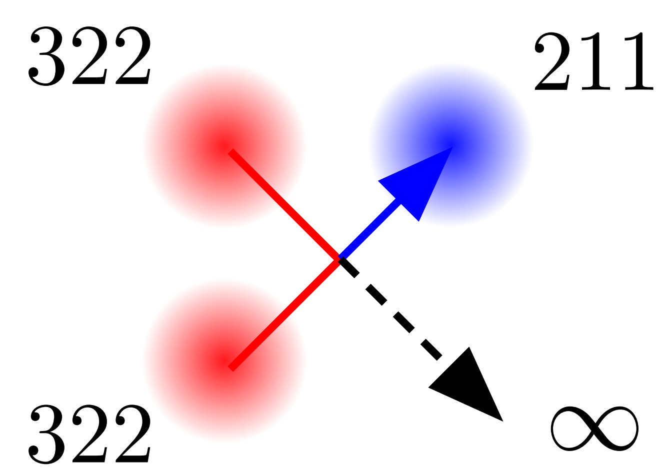
Self-Interactions

Large self-interactions:

- Black hole energy slowly converted to axions
- Cloud size constant over time
- Non-relativistic (but faster than DM!), coherent axion waves emitted at constant amplitude throughout black hole lifetime

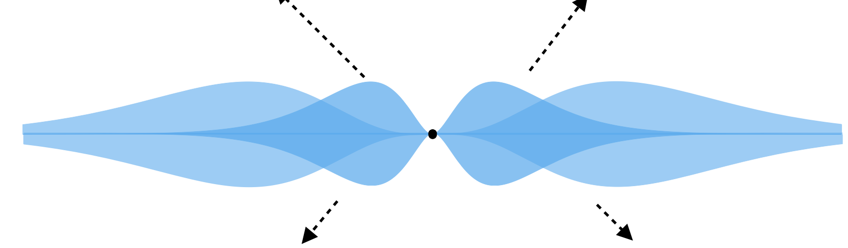
Time evolution





Axions emitted to infinity with $v \simeq \alpha/6$

Axionic Beacons



A new source of axions in the universe

- Almost monochromatic signal; similar to axion DM

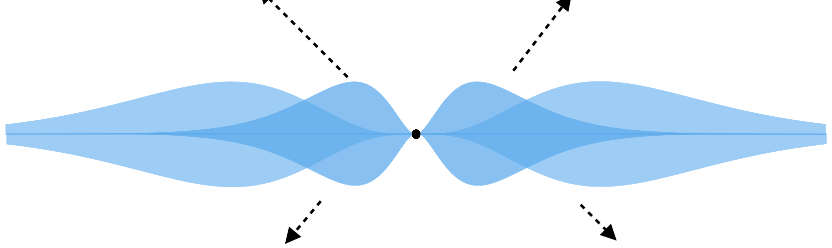
$$\rho_{\varphi,\mathrm{Earth}} \lesssim 10^{-2}\,\mathrm{GeV}\,\mathrm{cm}^{-3}\left(\frac{\mathrm{kpc}}{r}\right)^2\left(\frac{f_a}{10^{16}\,\mathrm{GeV}}\right)^2$$

- Fractional field amplitude independent of self interactions, comparable to laboratory search targets

$$\theta \simeq 10^{-19}\left(\frac{10^{-12}\,\mathrm{eV}}{\mu}\right)\left(\frac{\alpha}{0.1}\right)^3\left(\frac{10\,\mathrm{kpc}}{r}\right)$$

- Signal does not decouple at small fa in lab experiments!

Axionic Beacons



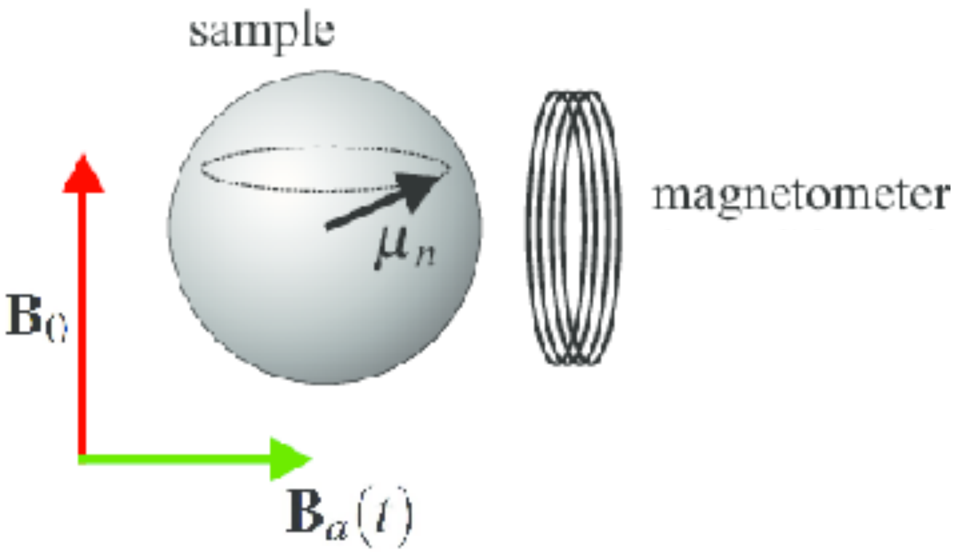
A new source of axions in the universe

- Black hole energy slowly and constantly converted to axion waves

- Can be detected directly if axions couple to the Standard Model

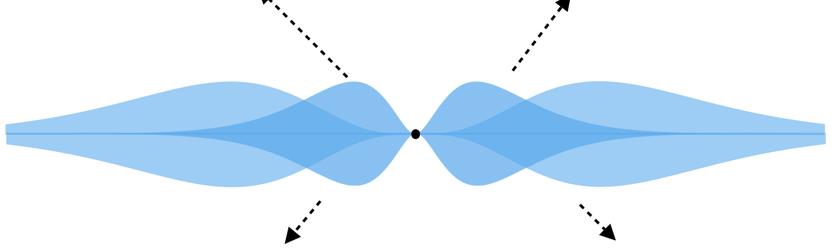
$$H_n \supset g_n \sigma \cdot (\nabla a + \dot{a} v_n)$$
$$\simeq B_a \cdot \mu_n$$

- Axion field gradient acts like a magnetic field on particle spins



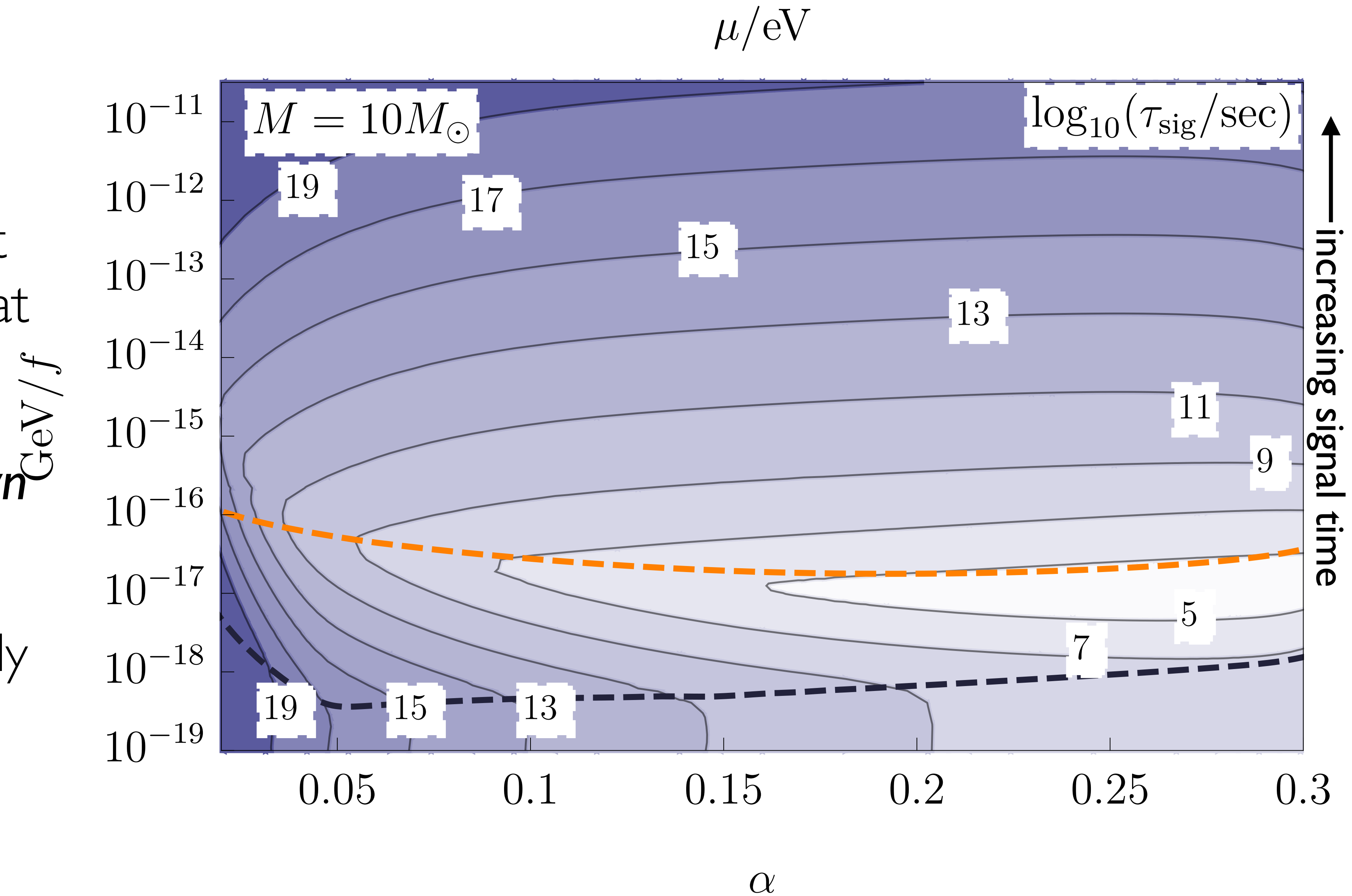
CASPEr Budker, Graham, Ledbetter, Rajendran, Sushkov (2014)
Kimball et al (2017)

Axionic Beacons

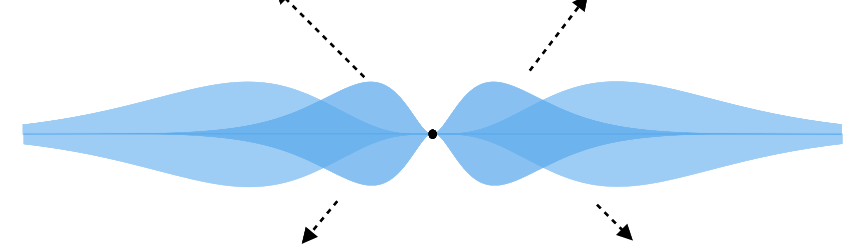


Black hole energy constantly converted to axion waves

- Signal strength independent of self interaction strength at small f_a
- Signal ***constant over spindown time***
- Spindown time parametrically longer at large couplings

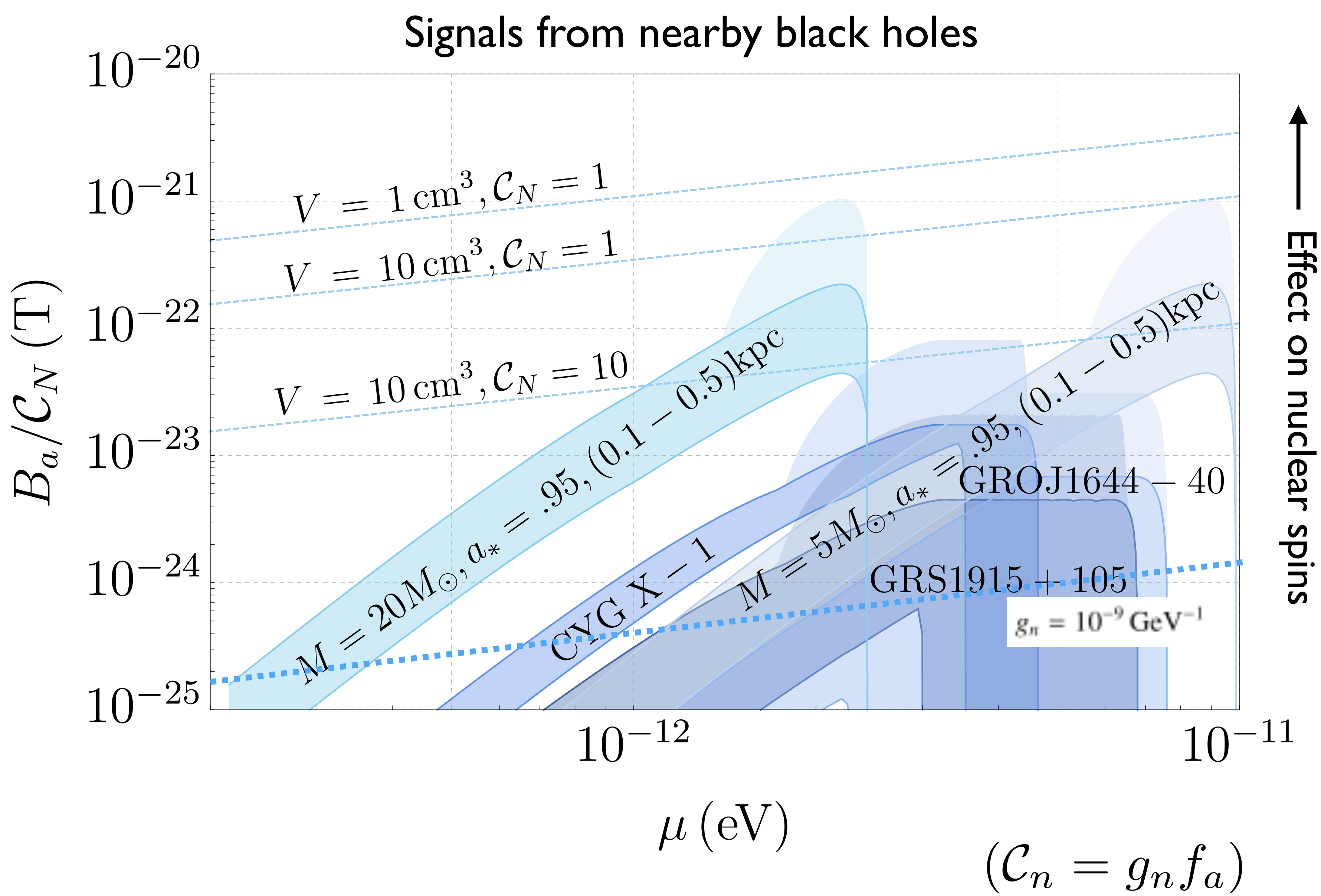


Axionic Beacons

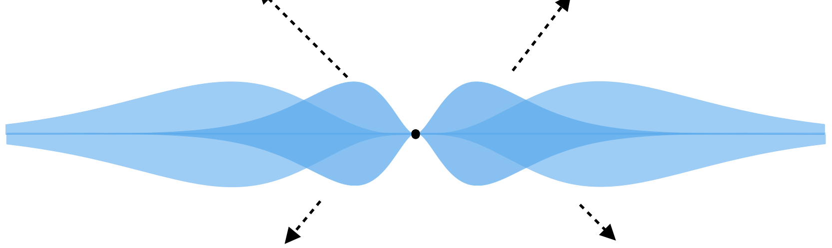


Black hole energy constantly converted to axion waves

- Signal strength ***constant in time***, independent of self interaction strength at small f_a
- Axion waves observable in axion dark matter experiments (CASPER…)
- Requires different data analysis strategies (*c.f.* LIGO continuous waves search)

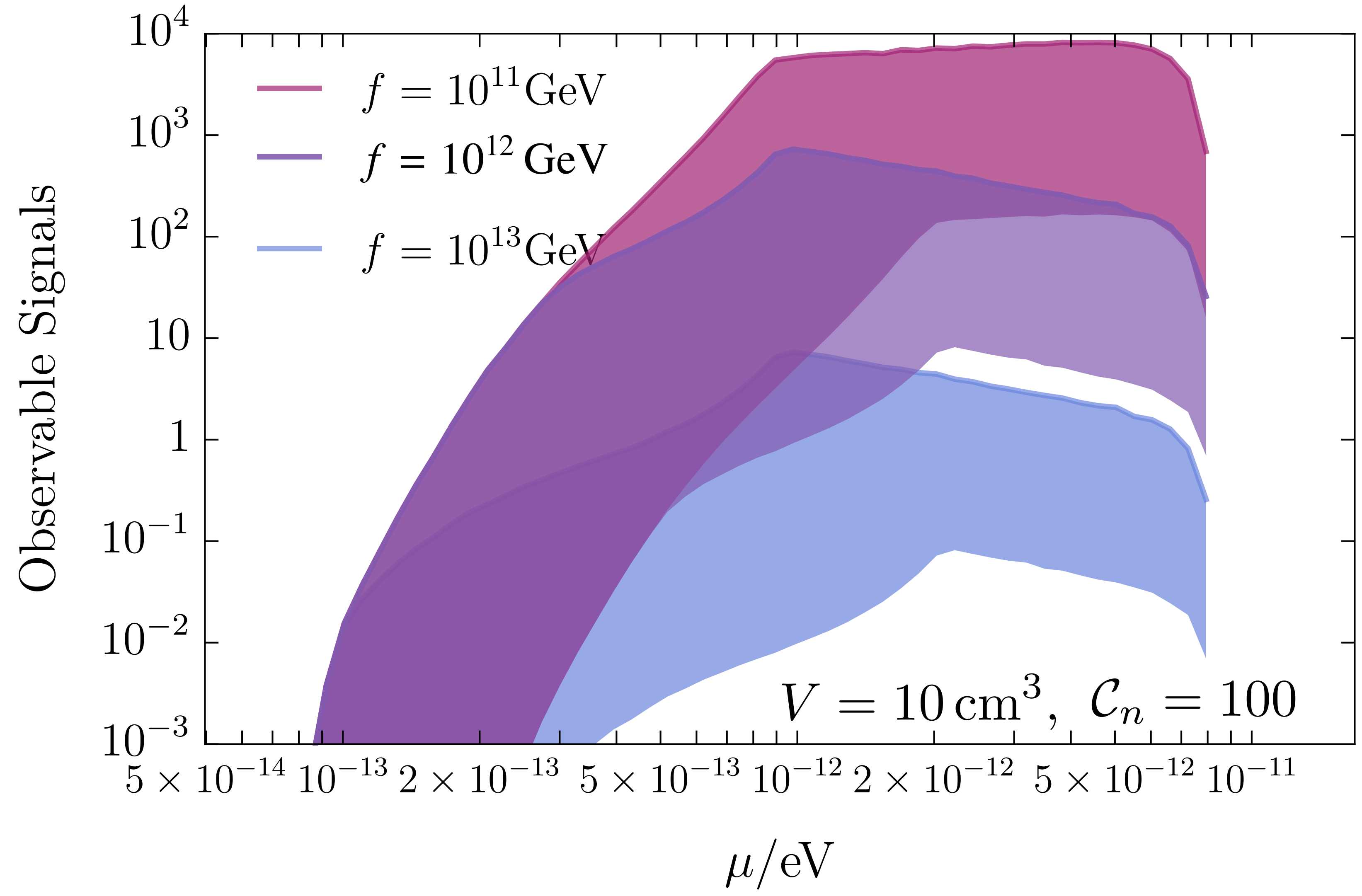


Axionic Beacons

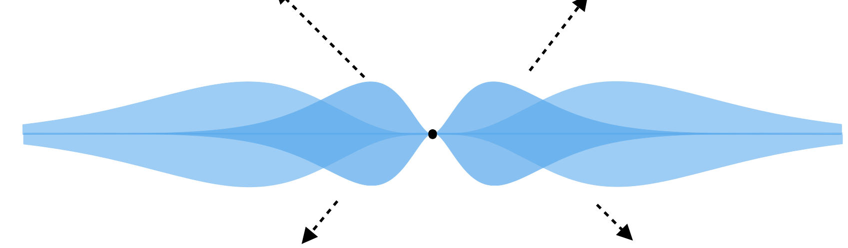


Black hole energy constantly converted to axion waves

- Signal strength ***constant in time***, independent of self interaction strength at small *fa*
- Axion waves observable in axion dark matter experiments (CASPER…)
- Open axion parameter space can give many potential signals

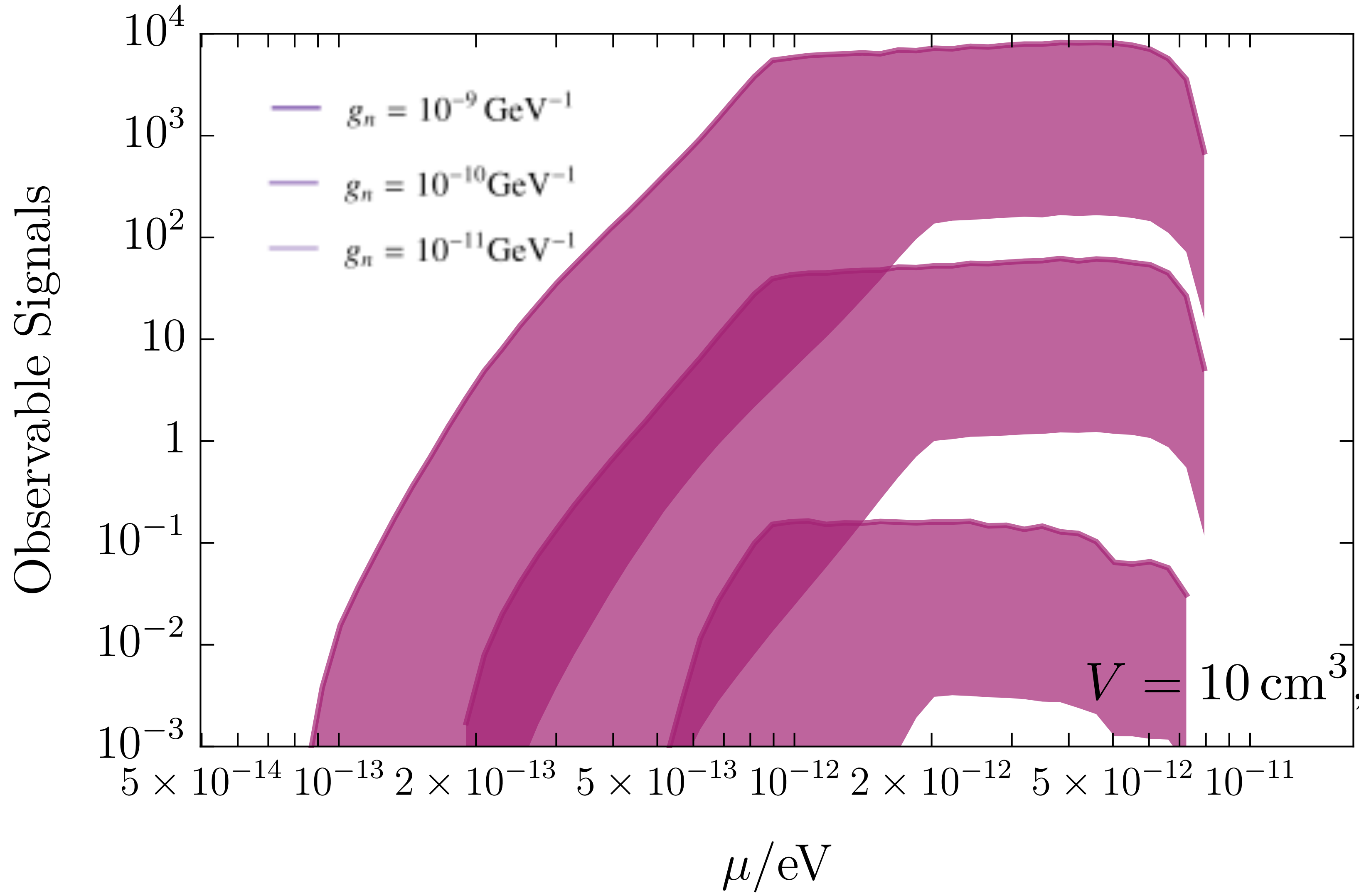


Axionic Beacons



Black hole energy constantly converted to axion waves

- Signal strength ***constant in time***, independent of self interaction strength at small f_a
- Axion waves observable in axion dark matter experiments (CASPER…)
- Requires different data analysis strategies (*c.f.* LIGO continuous waves search)



Gravitational Atoms and Axionic Beacons

- In the presence of ultralight axions, black holes spin down, converting their energy to axion clouds
- Axion clouds produce monochromatic GW radiation; we are looking for these signals in LIGO data
- Self-interactions of axions slow down energy extraction from black holes and populate the universe with axion waves