Axion and Gravitational Waves from Black Hole Superradiance

Masha Baryakhtar

NYU

February 20, 2020

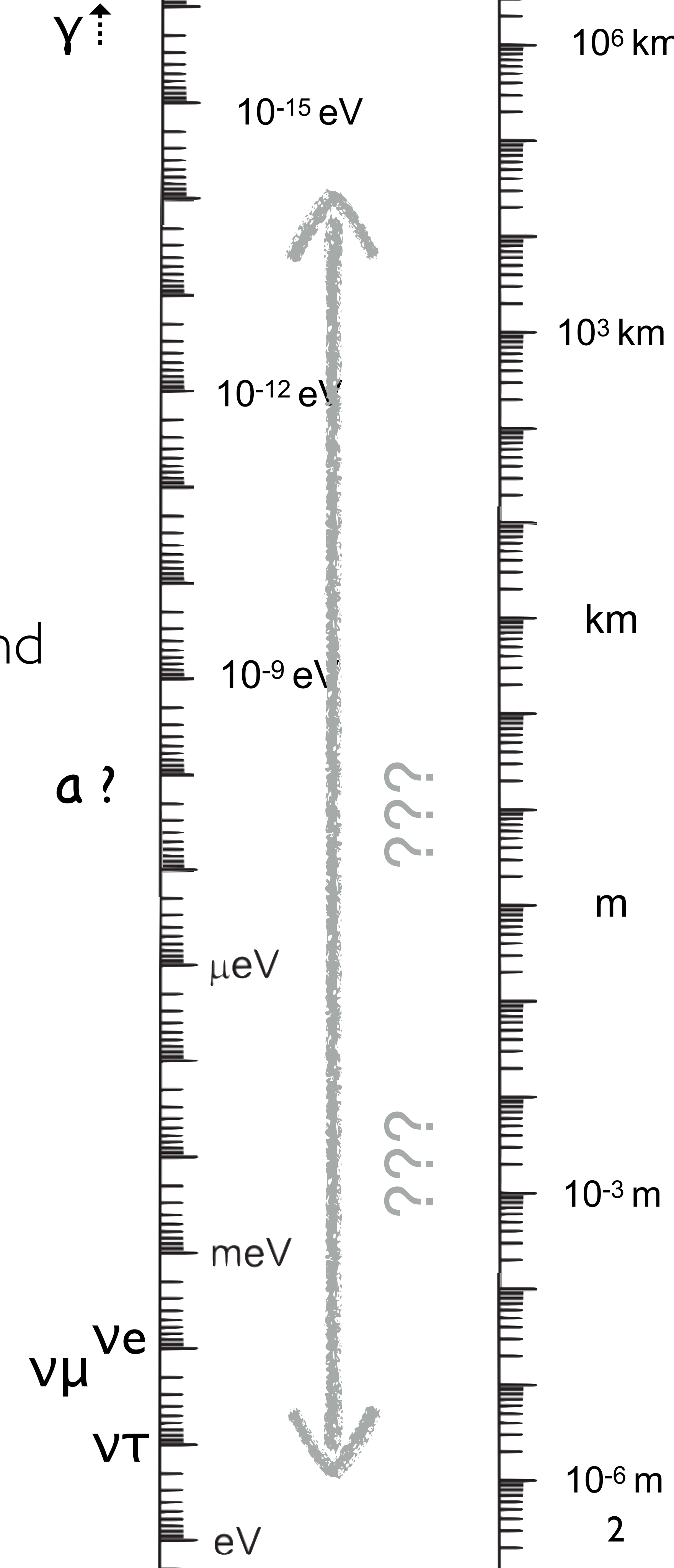
Searching for Axions

- Axions are
  - Solutions to a theoretical puzzle of small numbers— the strong-CP problem— approximately massless particle with mass and couplings fixed by a high scale f_a,

$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

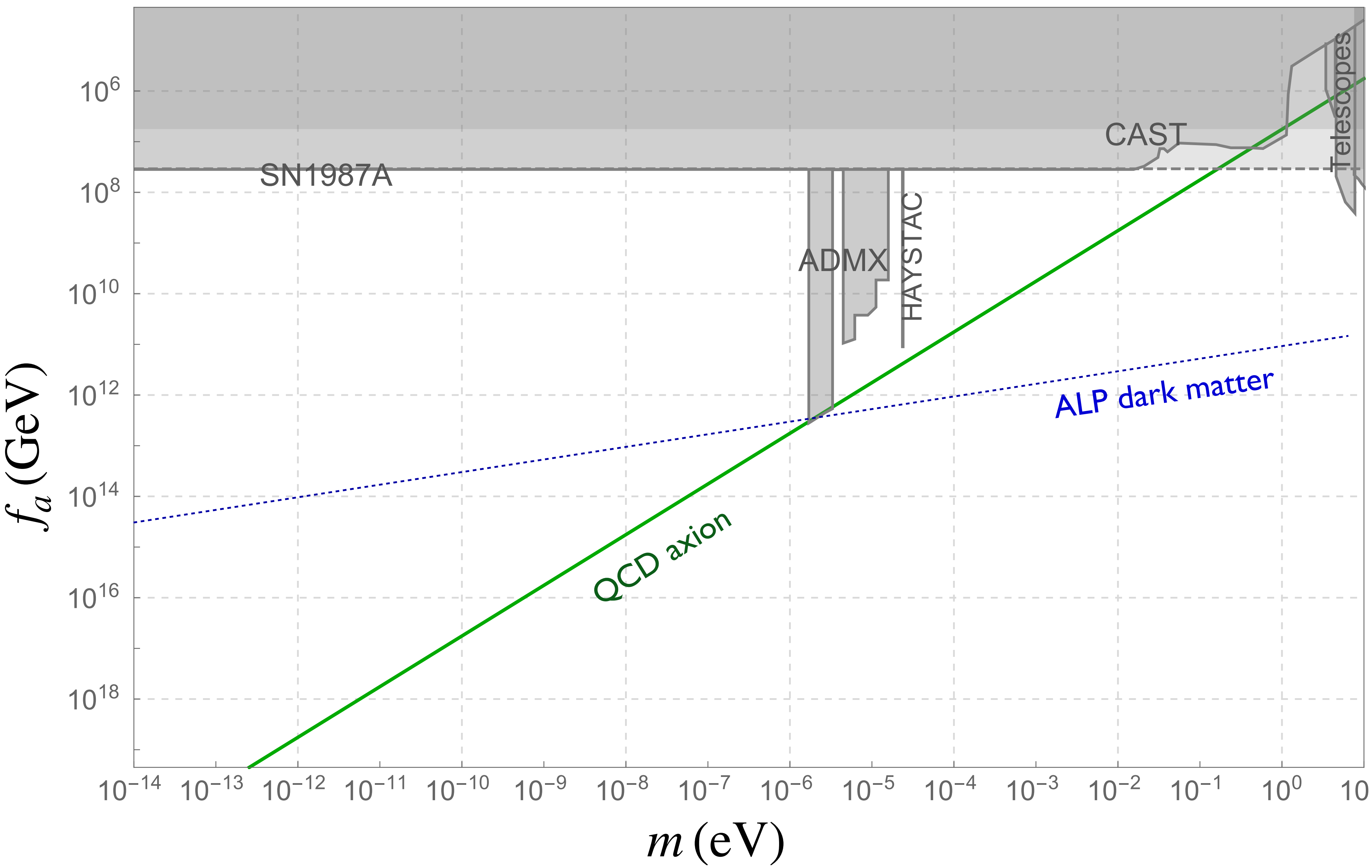
Dark photons and axion like particles

  - Low-energy remnants of complex physics at high scales
  - Candidates for the dark matter of the universe



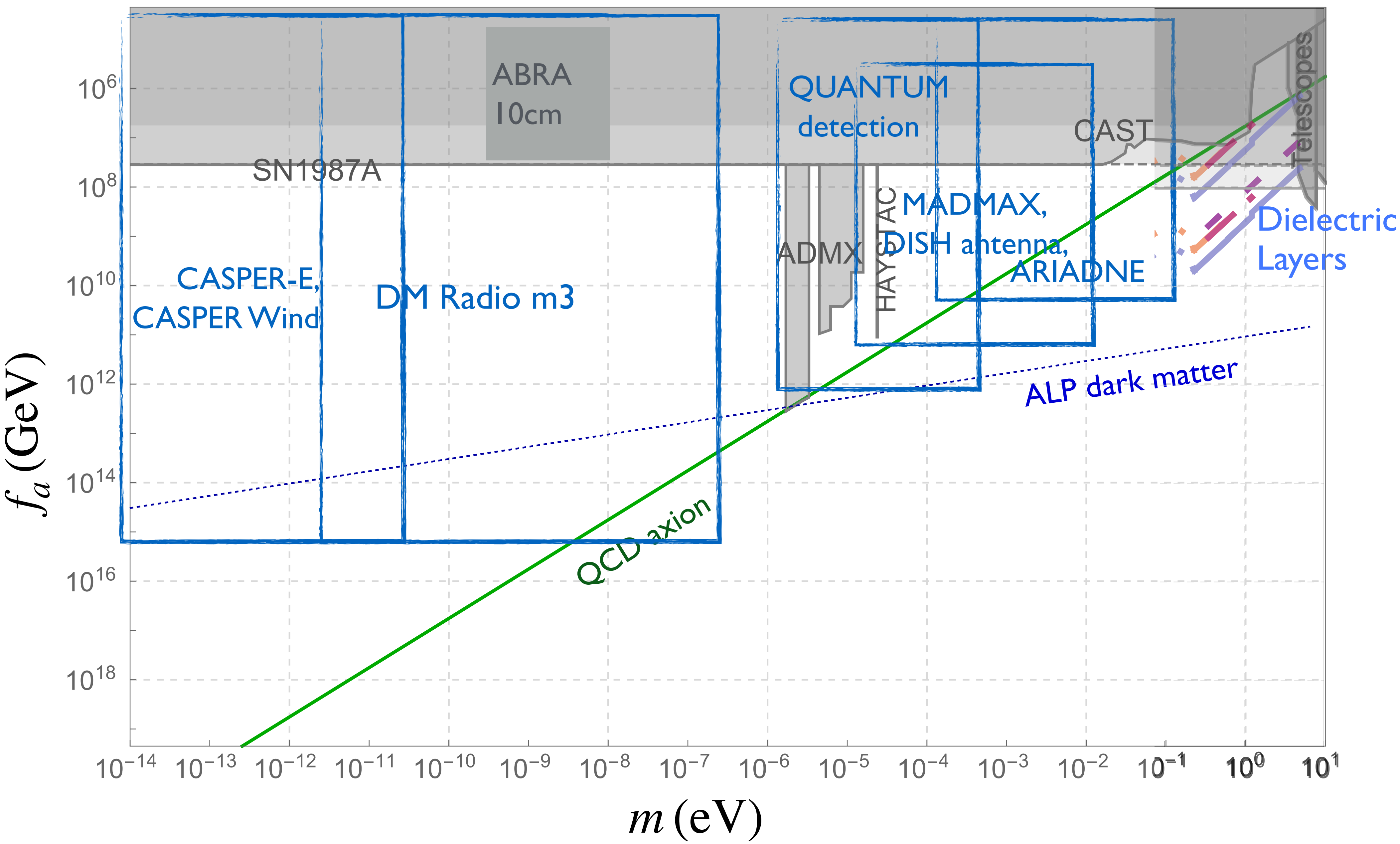
Searching for Axions

- Very well-motivated parameter space, very difficult to search for

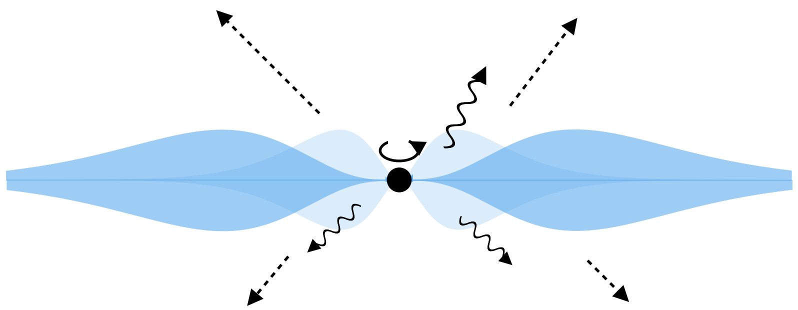


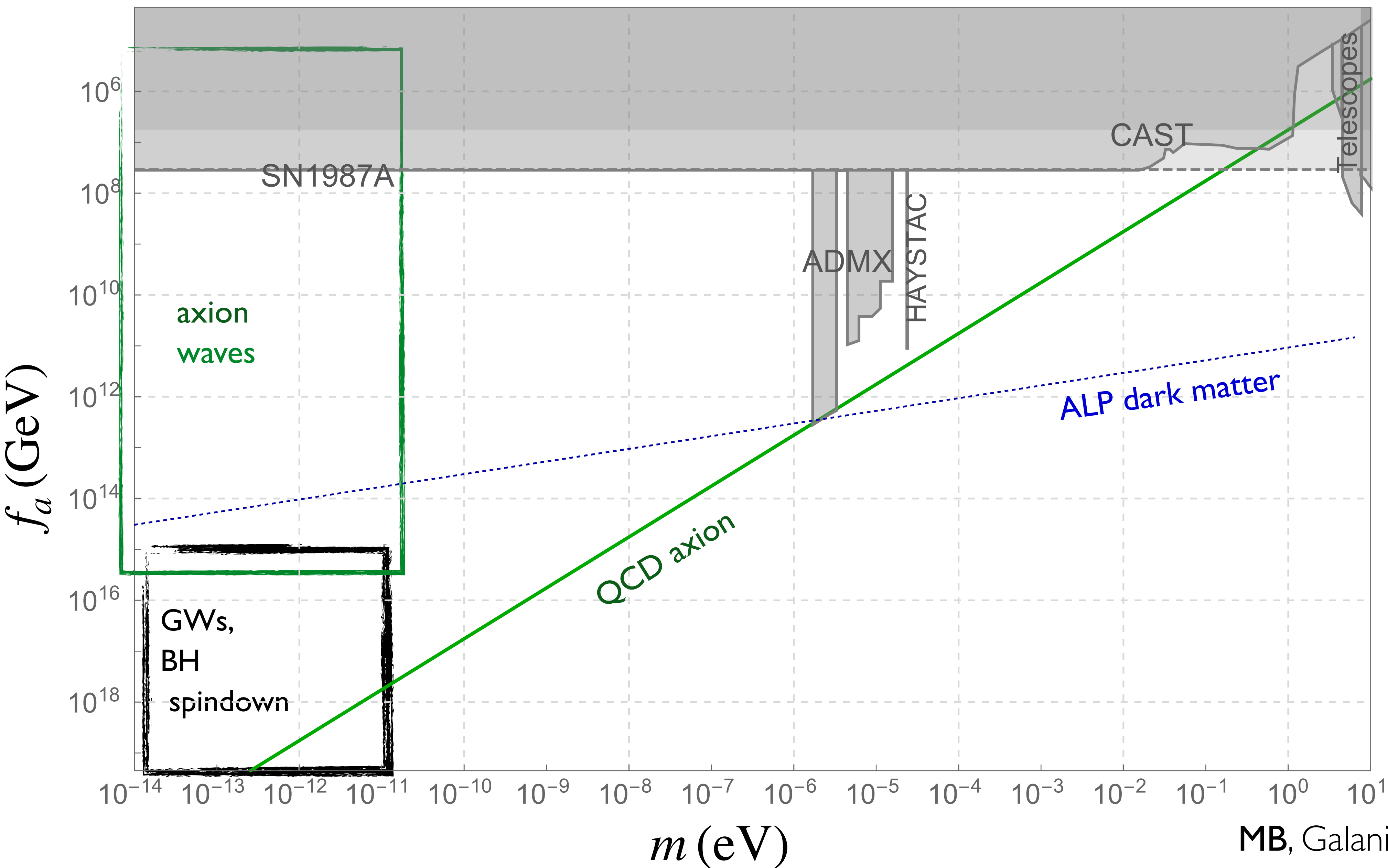
Searching for Axions

- A lot of progress in the last <10 years
- Many great search strategies being developed and implemented!



Searching for Axions



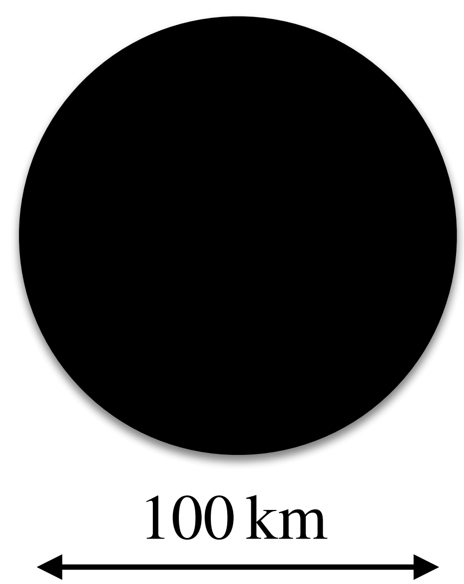


- Rotating black holes can source `clouds' of weakly coupled bosons
- Self-interactions between axions change dynamics and emit axion waves detectable in the lab

MB, Galanis, Lasenby, Simon (*in prep*)
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (*in prep*)
Arvanitaki, **MB**, Lasenby, Dimopoulos, Dubovsky, PRD 2017
Arvanitaki, **MB**, Huang, PRD 2015

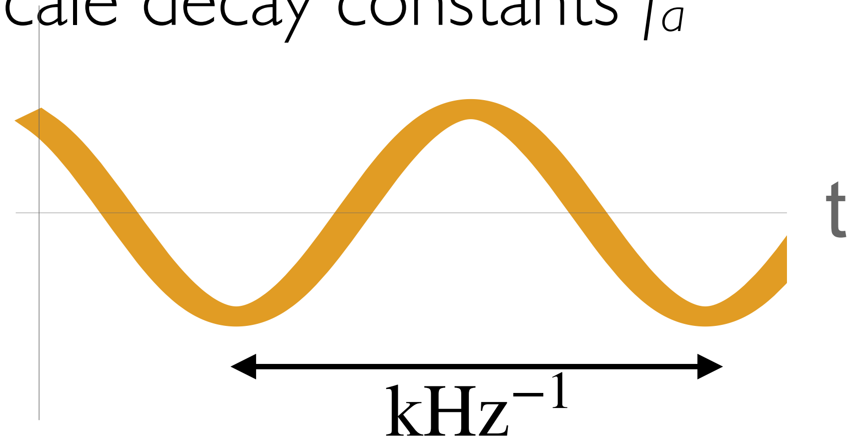
Astrophysical Black Holes and Ultralight Particles

- Moving to the opposite side of the mass spectrum: 'particle' does not fit in a laboratory
- Black holes in our universe provide nature's laboratories to search for light particles
- Set a typical length scale, and are a huge source of energy
- Sensitive to QCD axions with GUT- to Planck-scale decay constants f_a

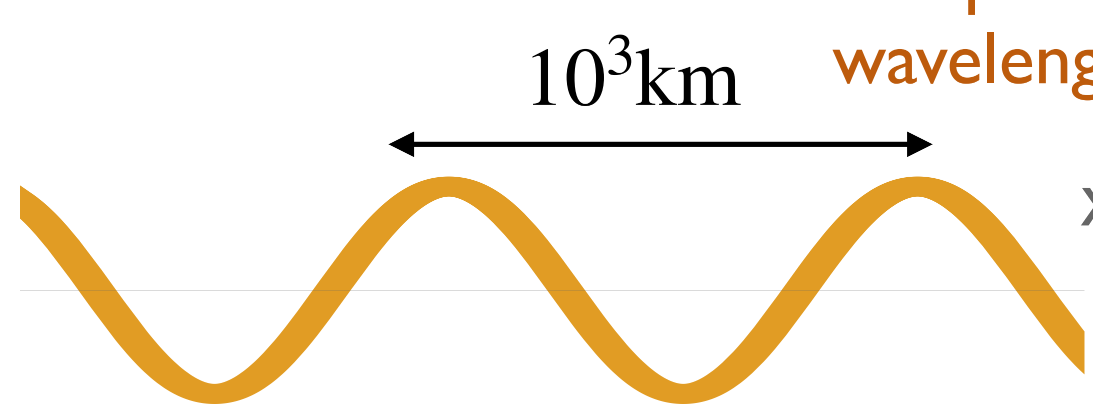


black hole (30 $M_\odot$)

for a 10^{-12} eV particle:



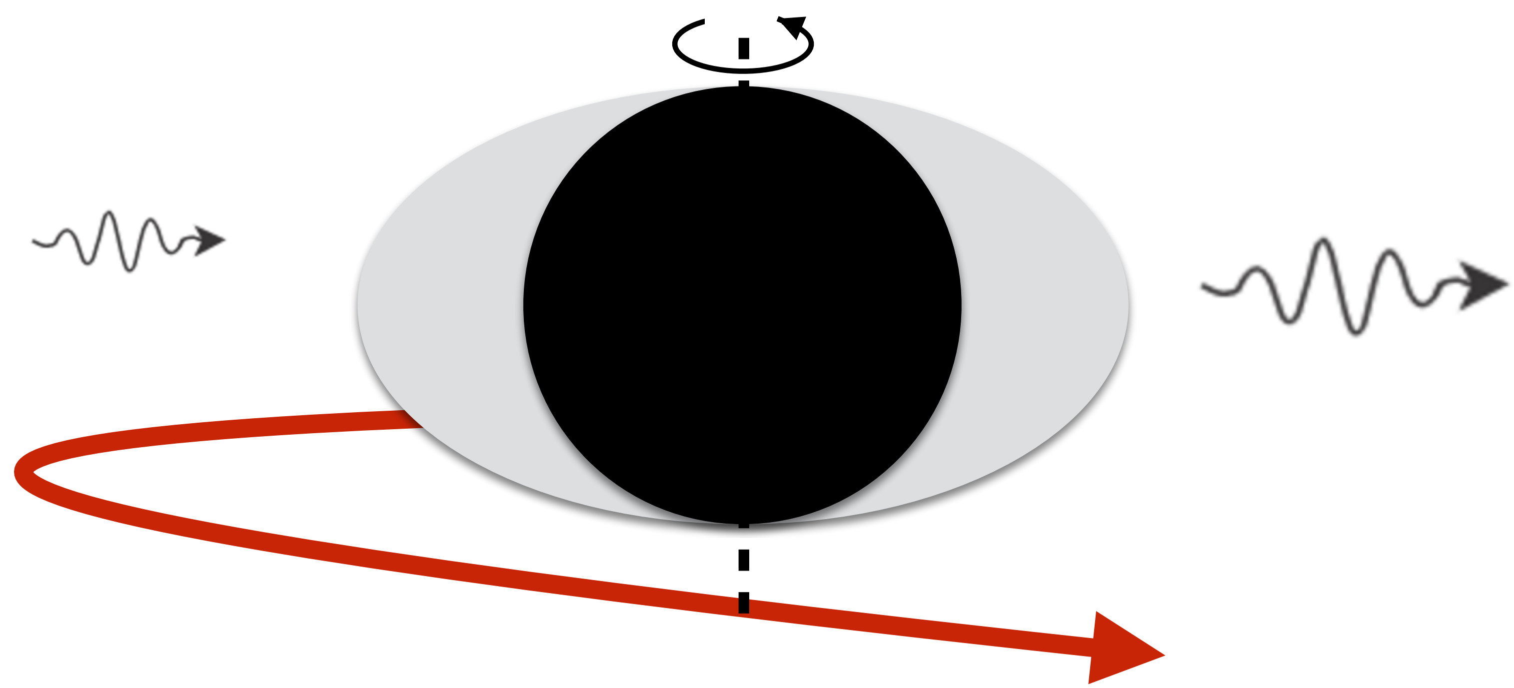
frequency



compton wavelength

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: **disspiation** necessary to increase wave amplitude



Superradiance condition:

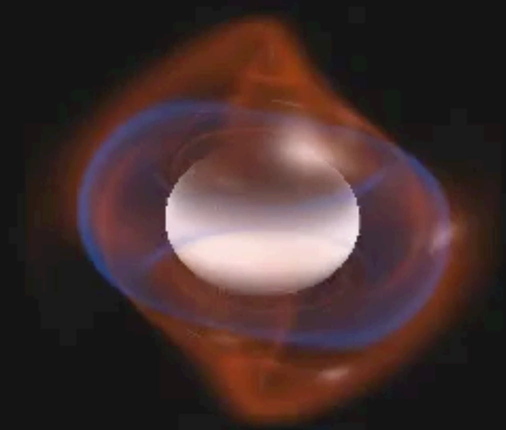
Angular velocity of wave slower than angular velocity of BH horizon,

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

Zel'dovich; Starobinskii; Misner

Superradiance

Gravitational waves scattering from a rapidly rotating black hole



Numerical GR simulation by Will East

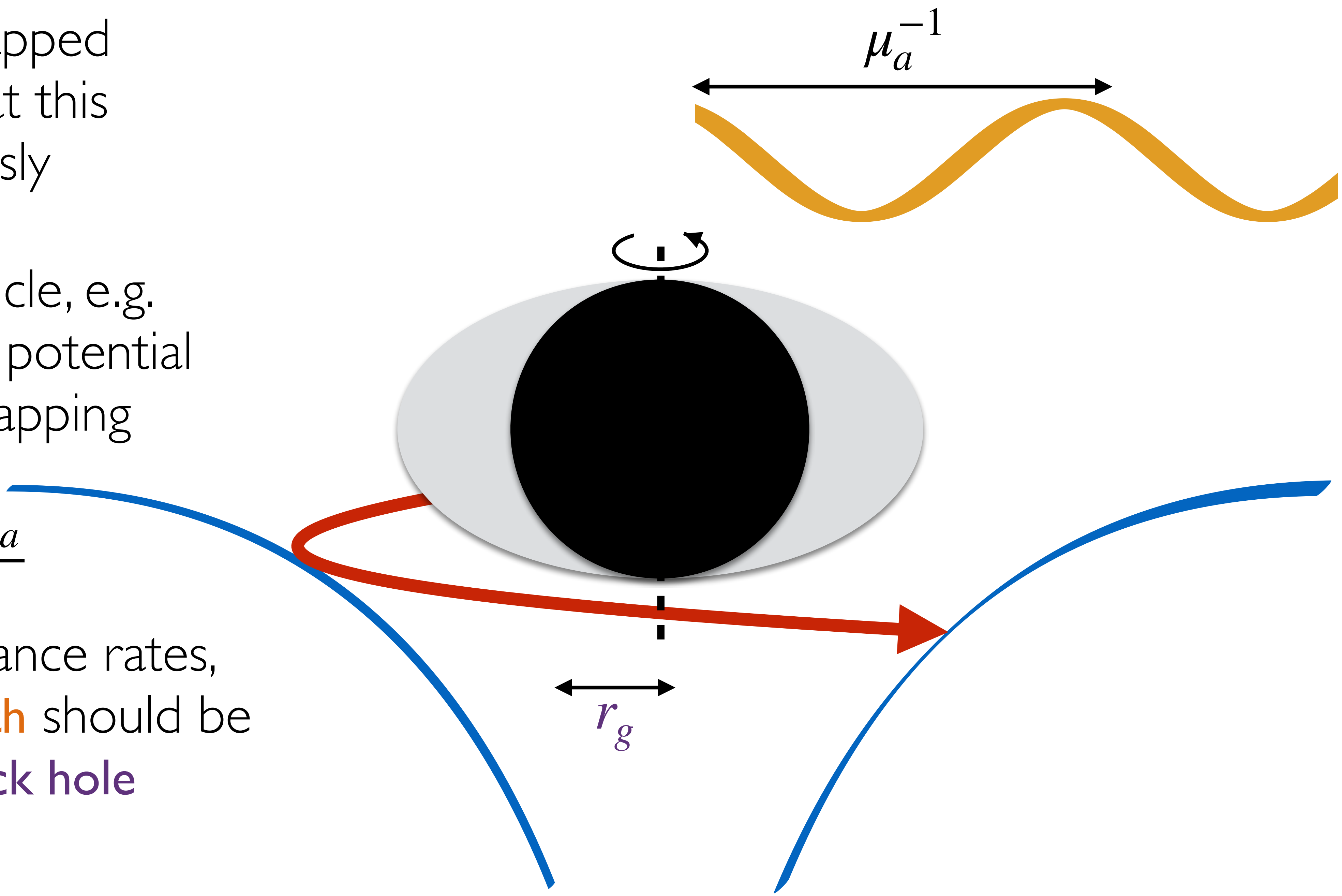
Superradiance

- 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:

$$r_g \lesssim \mu_a^{-1} \sim 3\,\mathrm{km}\,\frac{6\times 10^{-11}\mathrm{eV}}{\mu_a}$$

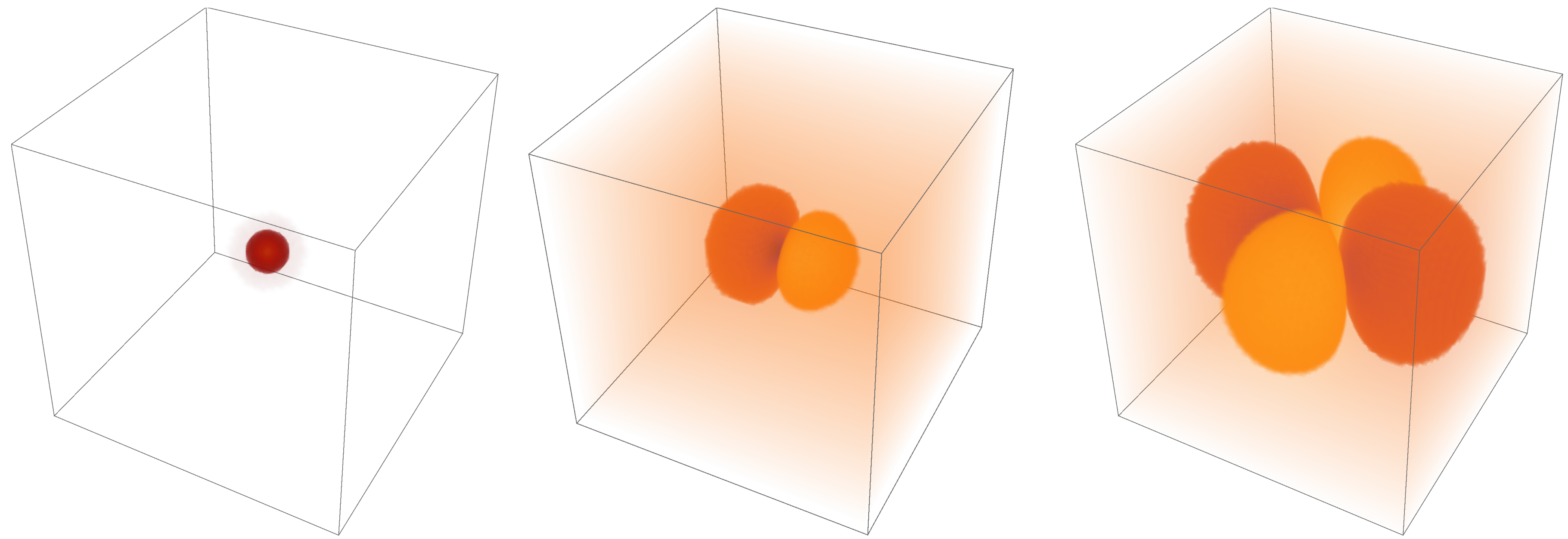


[Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78] Press & Teukolsky
[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010]

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

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

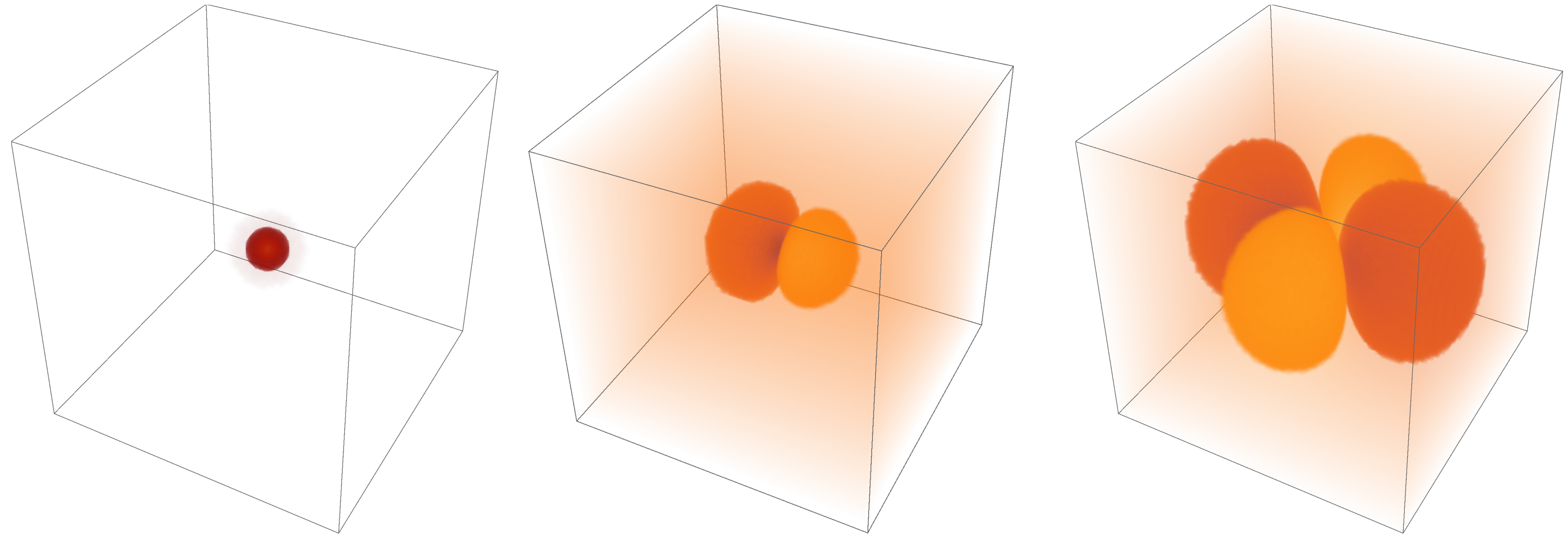
Occupation number

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

Gravitational Atoms

Axion
Gravitational Atoms

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



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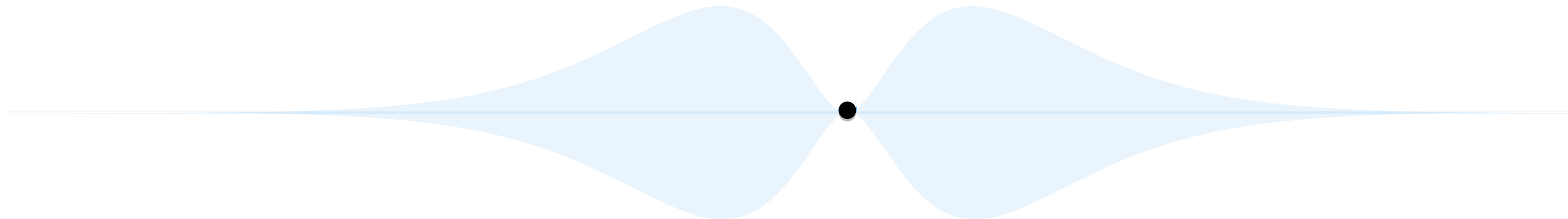
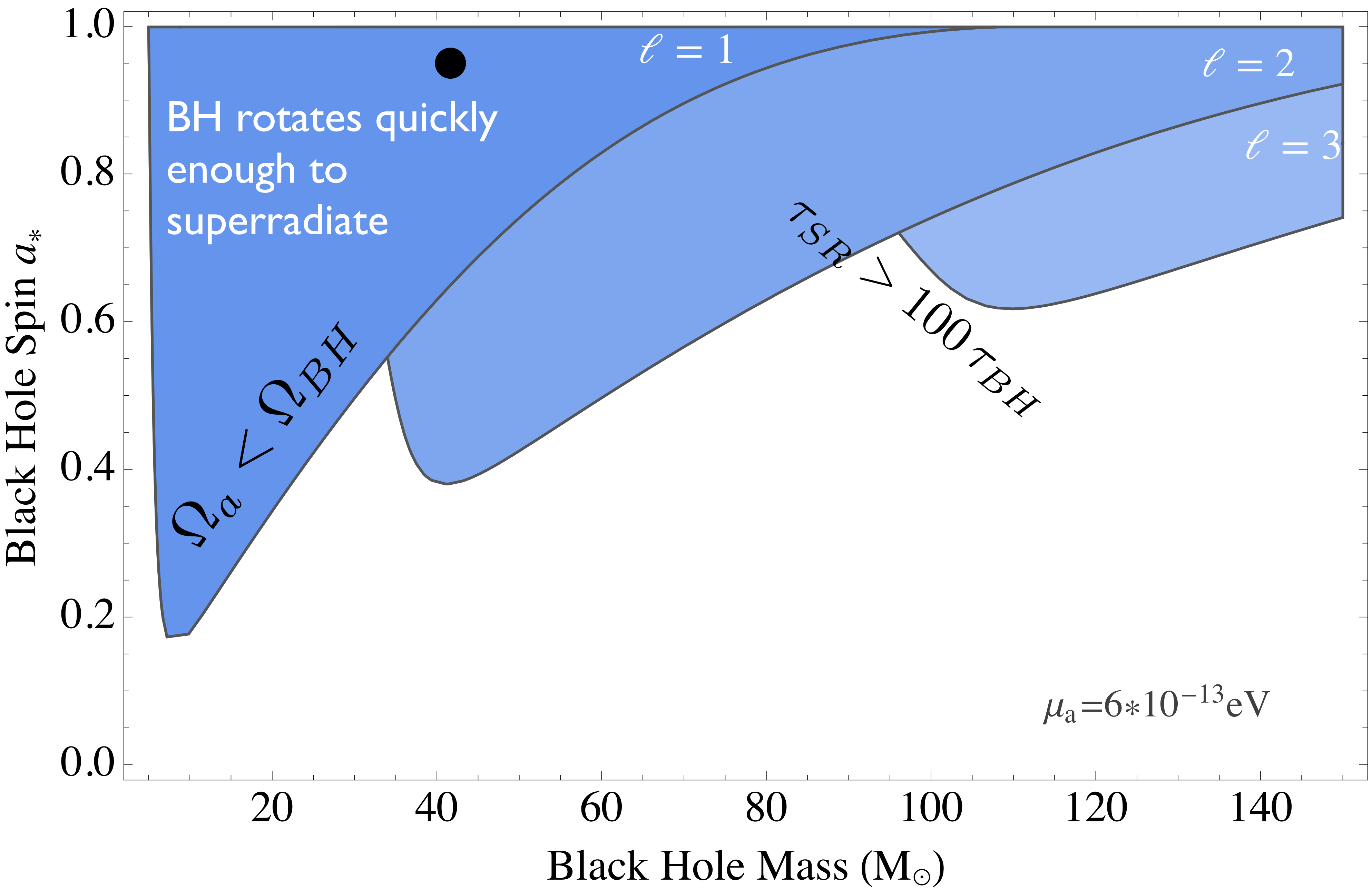
Boundary conditions at horizon give imaginary frequency: **exponential growth for rapidly rotating black holes**

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

Superradiance: a stellar black hole history



A black hole is born with spin a* = 0.95, M = 40 M⊙.

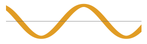


BH lightcrossing time

0.2 msec (60 km)

Particle wavelength

1 msec (300 km)



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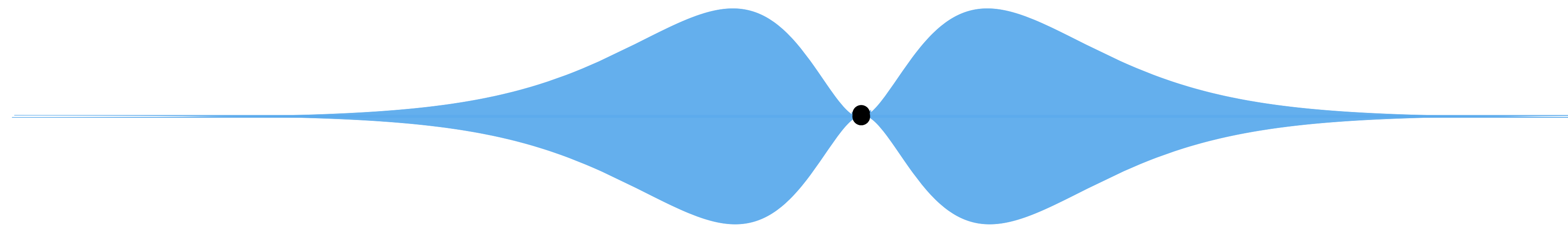
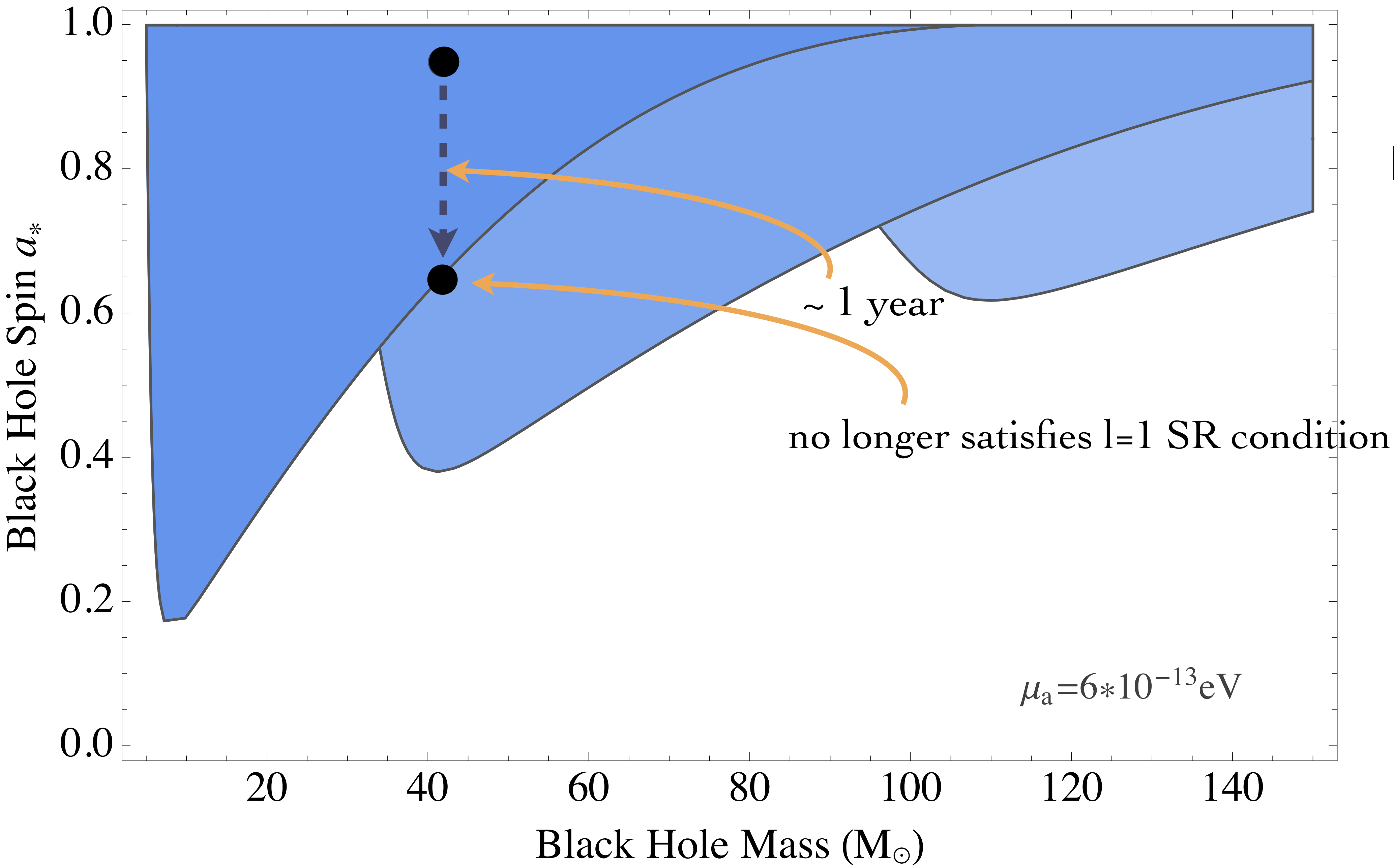


BH spins down and fastest-growing level is formed

Once BH angular velocity matches that of the level, growth stops



Cloud radius

6 msec (2000 km)

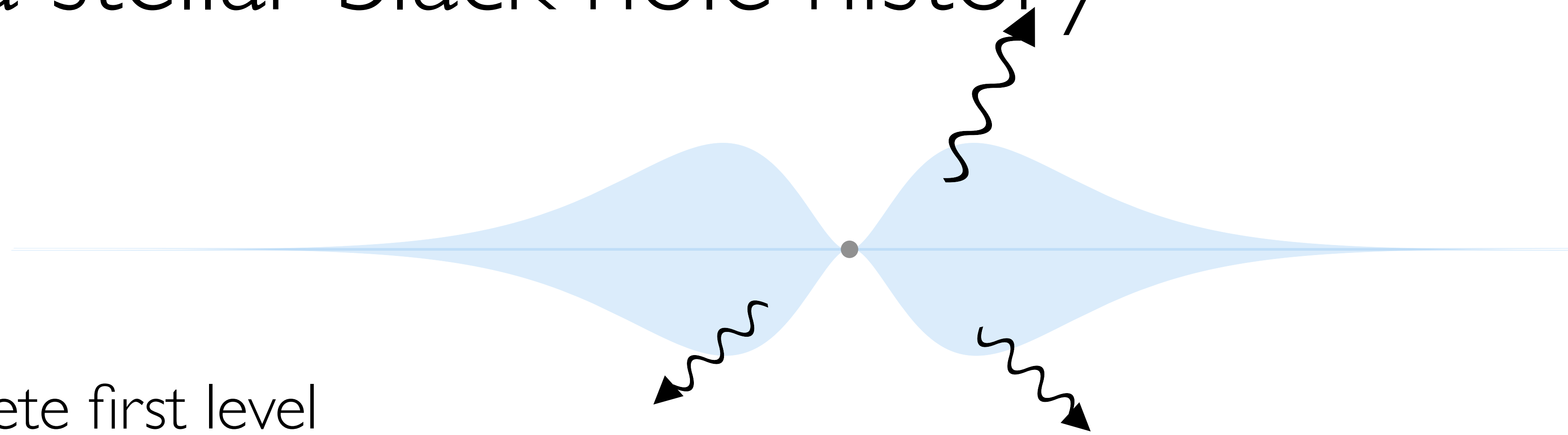
BH lightcrossing time

0.2 msec (60 km)

Particle wavelength

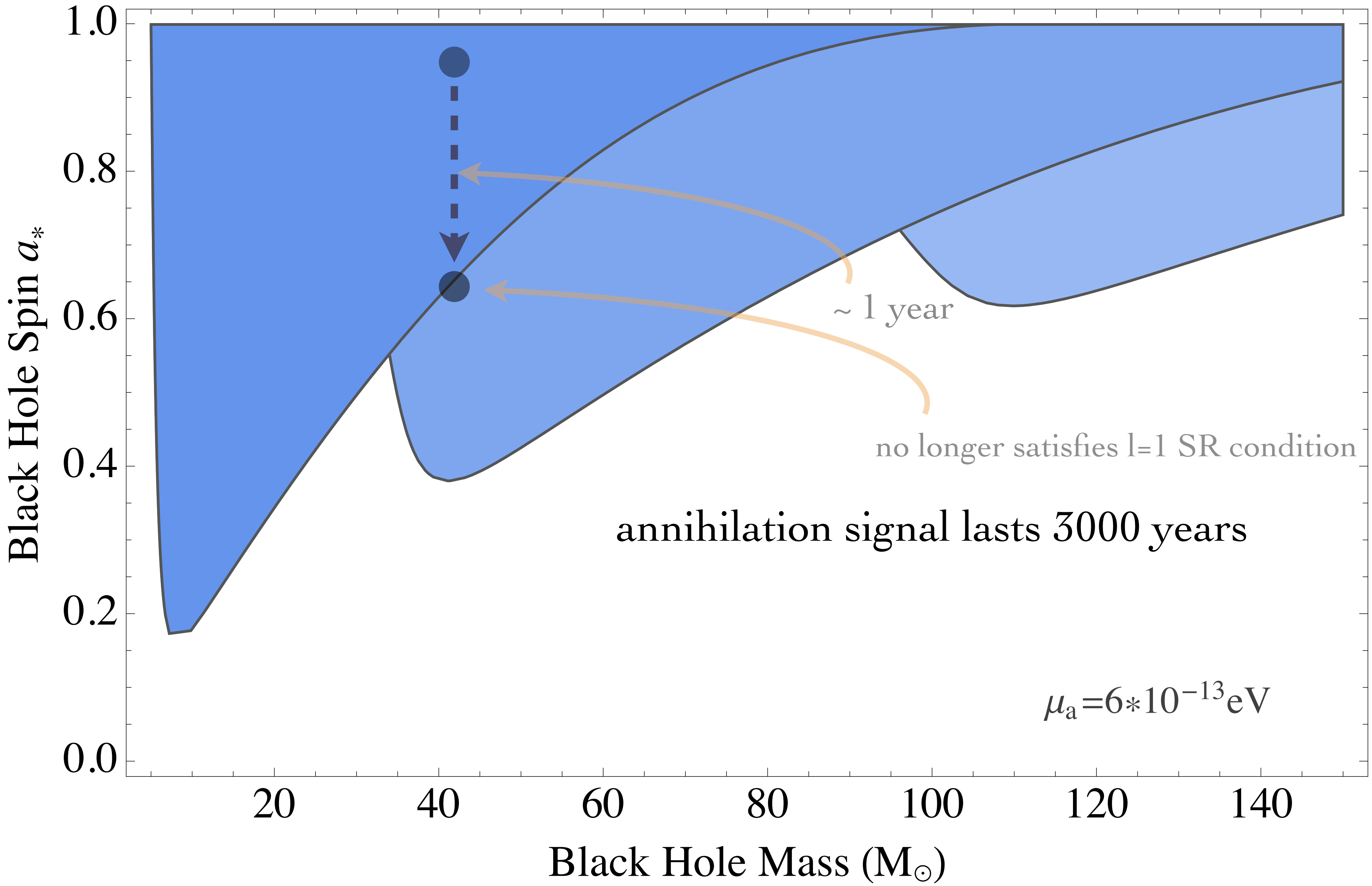
1 msec (300 km)

Superradiance: a stellar black hole history



Annihilations to GWs deplete first level

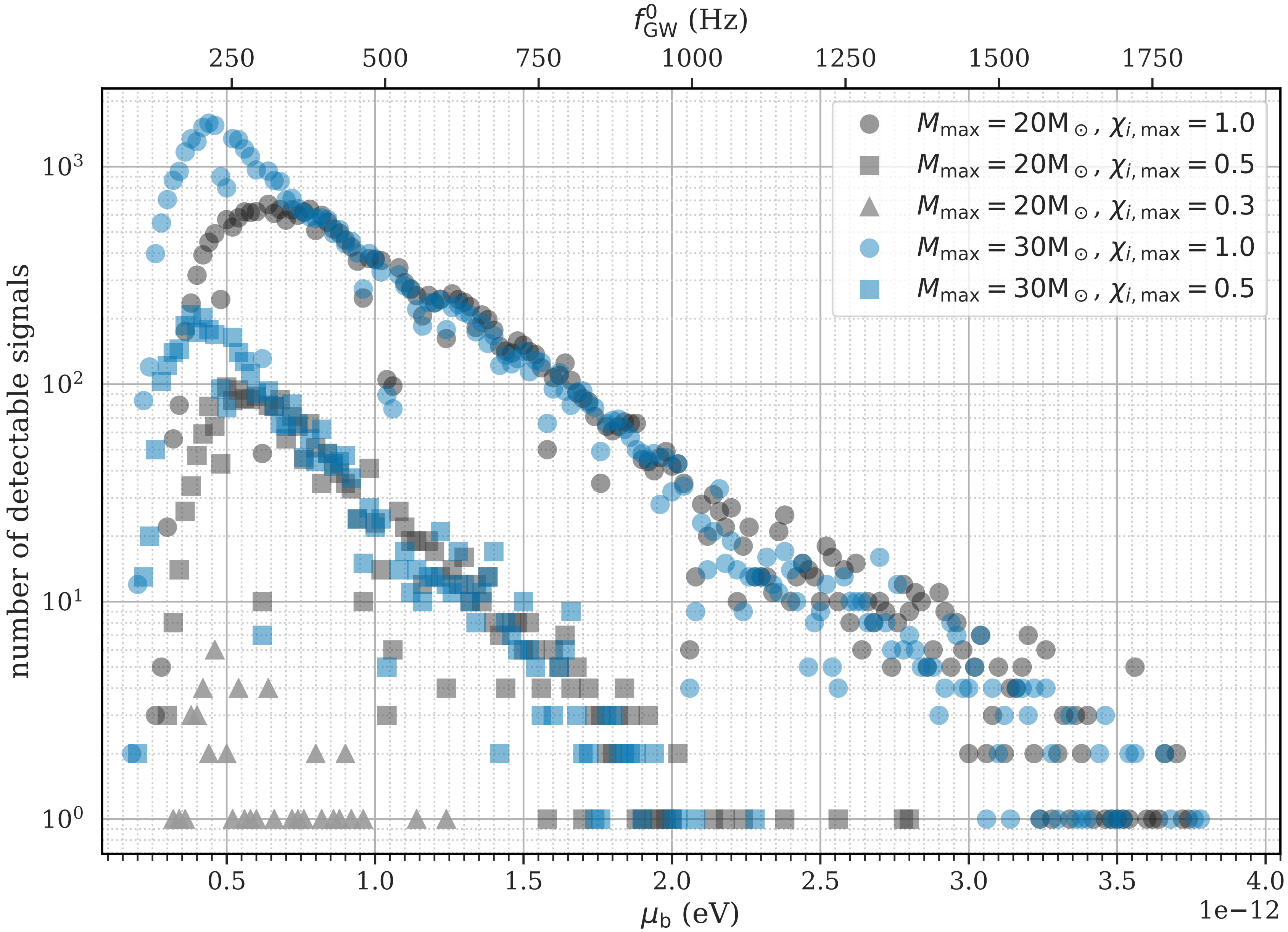
Gravitational waves can be observed in LIGO continuous wave searches



Signals fall into ongoing searches for gravitational waves from asymmetric rotating neutron stars

Up to thousands of observable signals

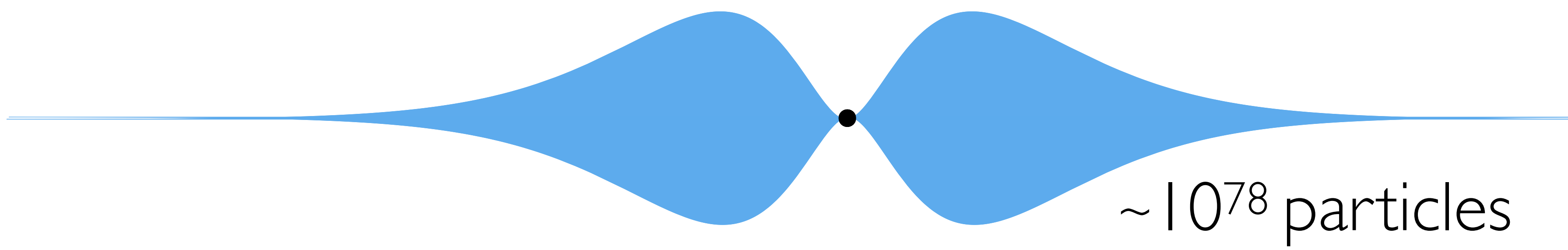
Gravitational Wave Signals



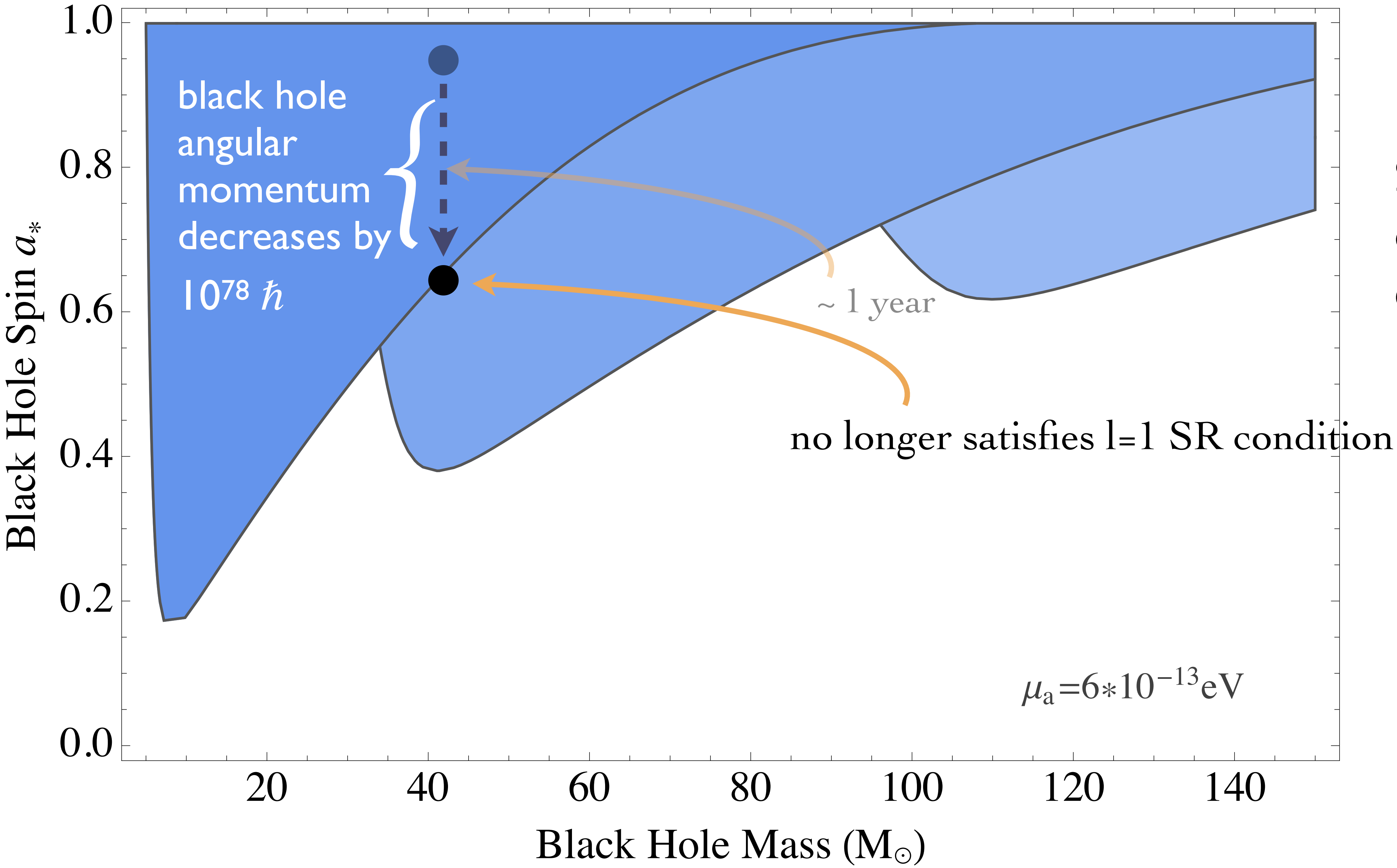
S. J. Zhu, **MB,** M. A. Papa, D. Tsuna, N. Kawanaka, H.B. Eggenstein *(in prep)*

- **Weak, long signals** last for ~ million years, visible from our galaxy
- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- Can disfavor axions of mass ~10^{-12} eV with assumptions on BH mass distribution

Superradiance: a stellar black hole history

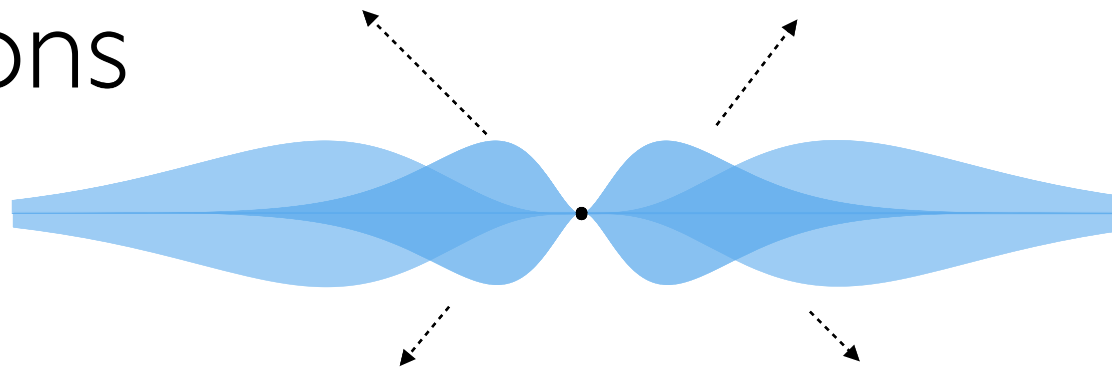


Cloud can carry up to a few percent of the black hole mass: huge energy density



Self-interactions of axions in the cloud can become important

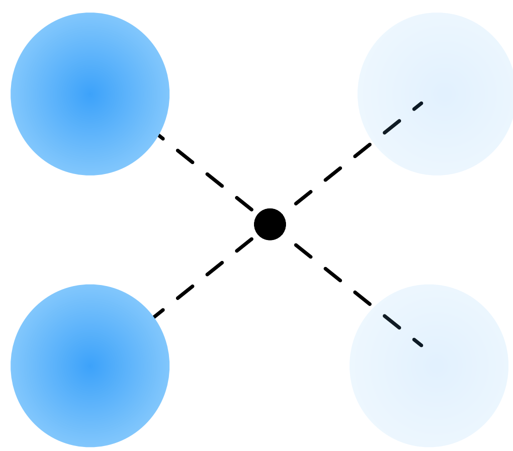
Self-Interactions

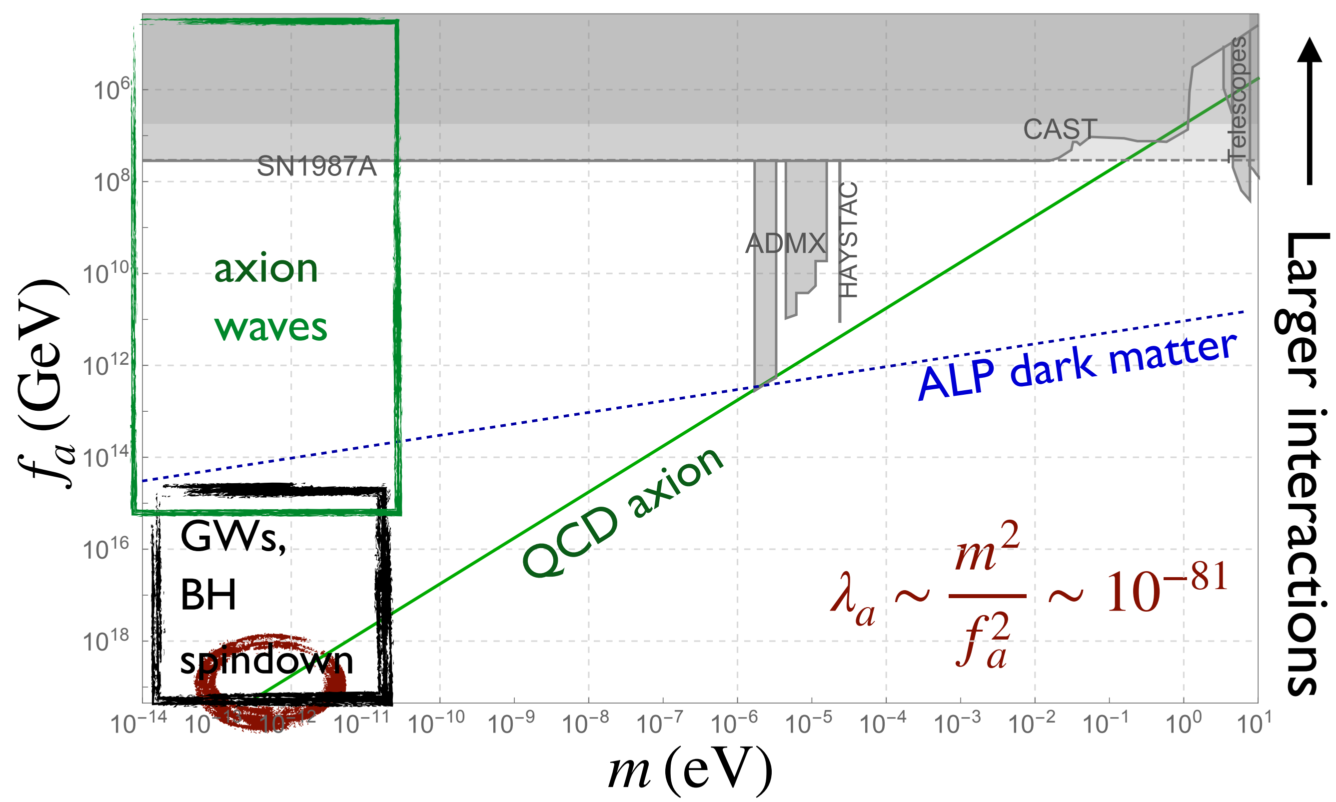


Self-interactions through quartic coupling in axion potential

MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

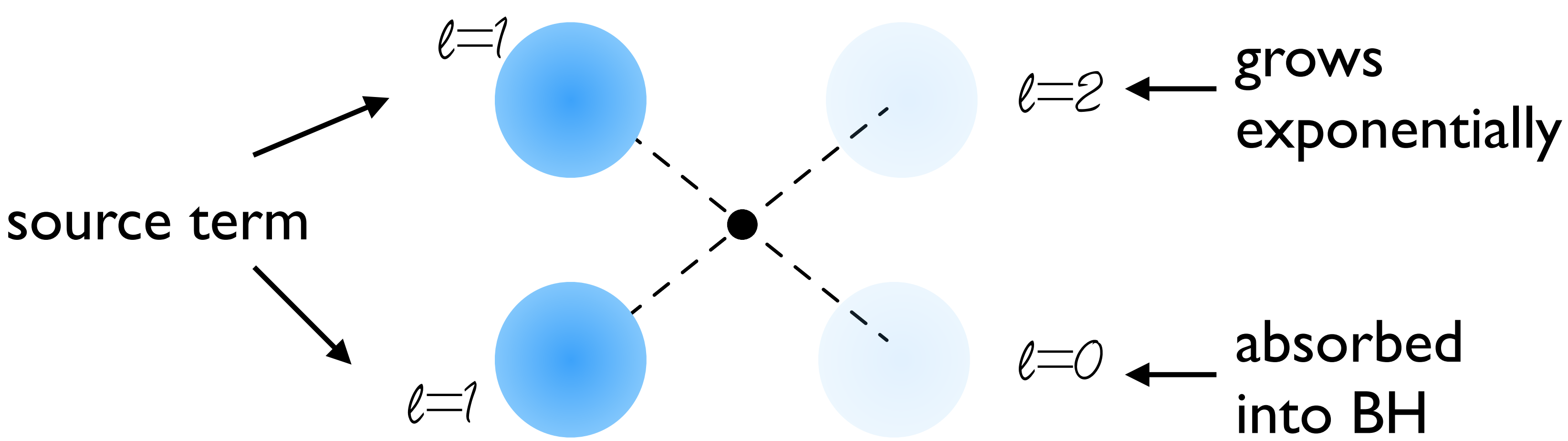
A. Gruzinov, 1604.06422





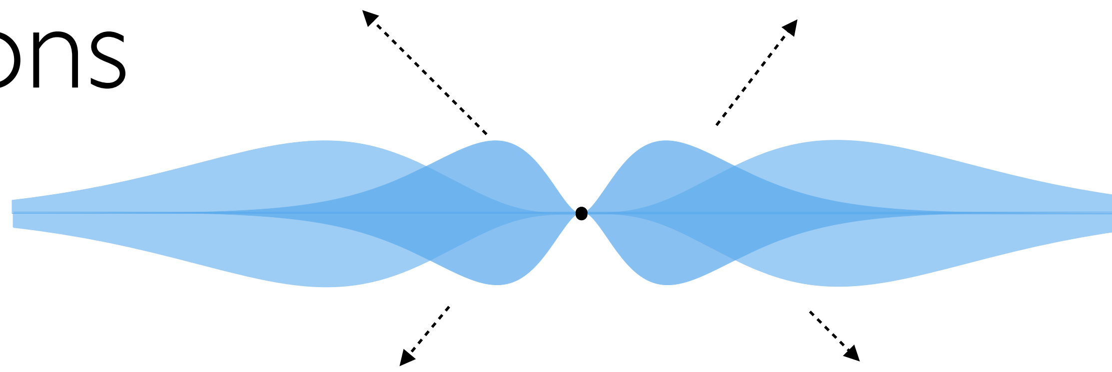
Self-Interactions: gaining from dissipation part II

Self-interactions through quartic coupling in axion potential



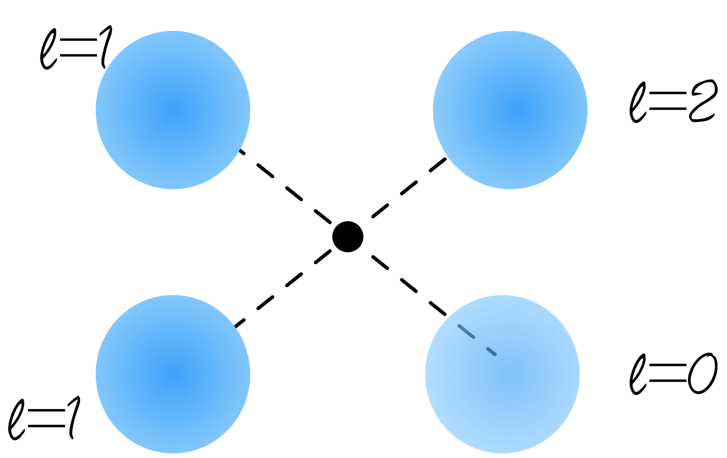
- Two particles with angular momentum 1 produce one with angular momentum 2 and one with angular momentum 0
- The angular momentum 0 `forced oscillation' is absorbed into the black hole
- **Dissipation** through absorption drive **exponential growth** of second level

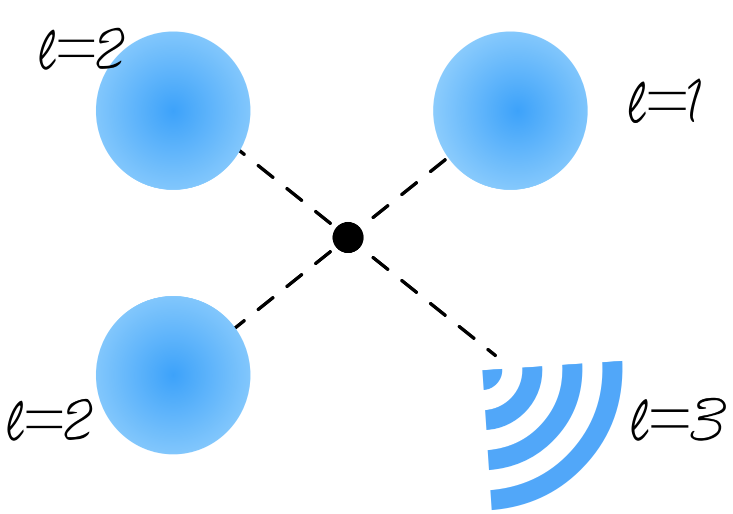
Self-Interactions



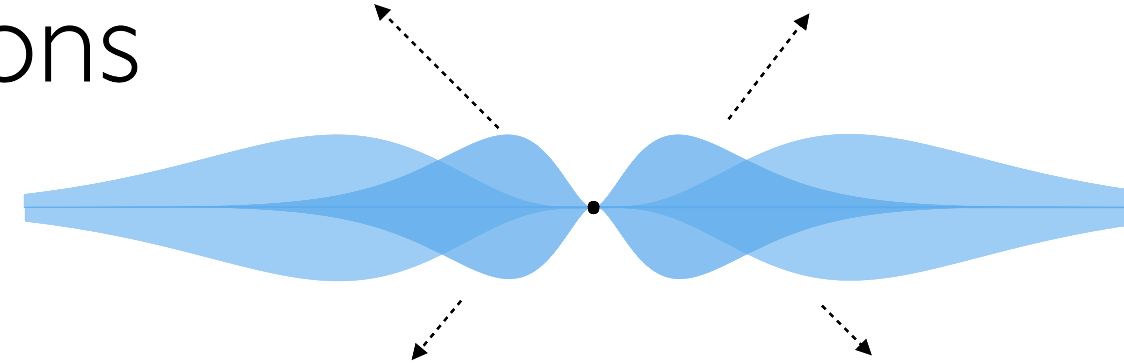
Equilibrium reached at large self-interactions

- Once level 2 is populated, `reverse' process sends particles to infinity
- Processes reach quasi-equilibrium





Self-Interactions



MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

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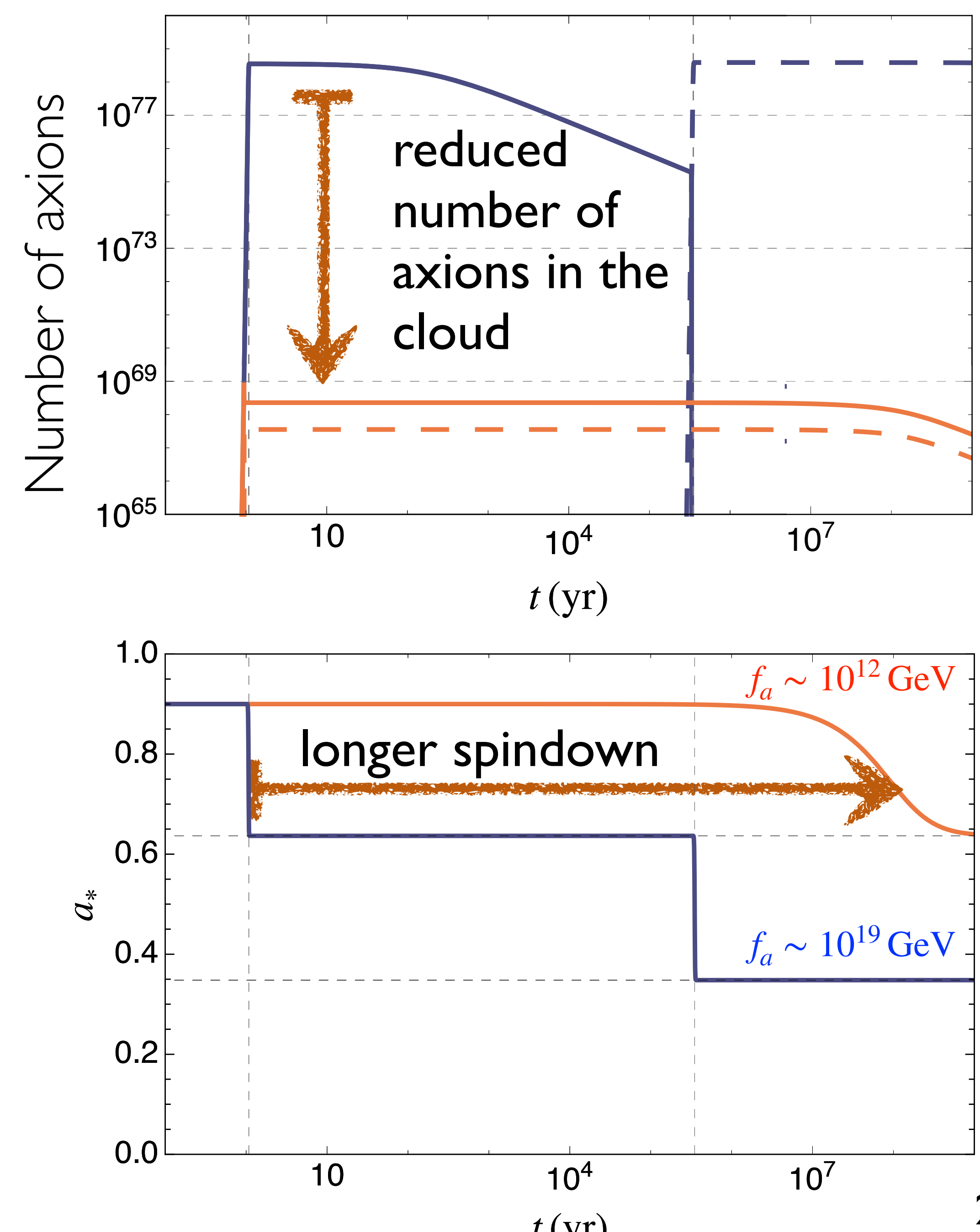
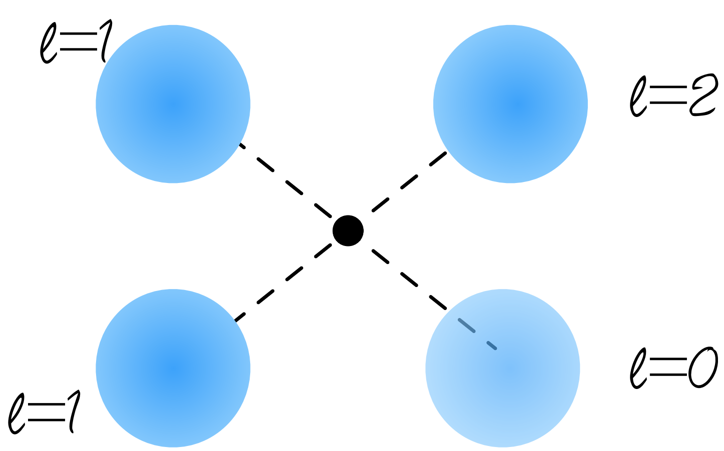
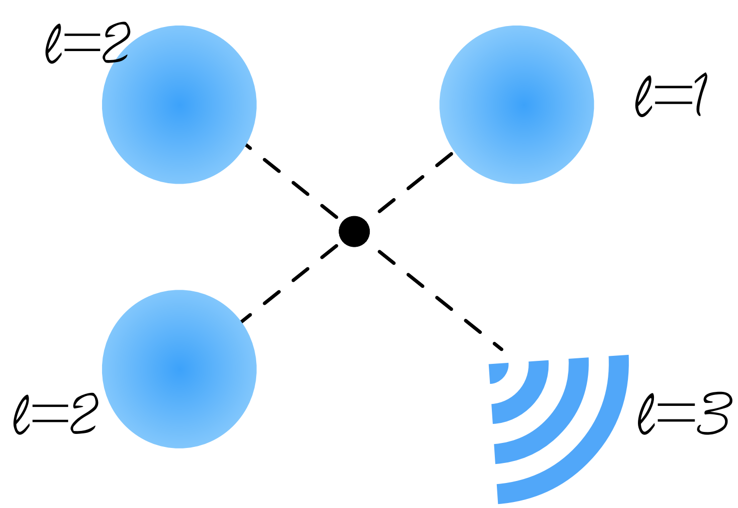
Time evolution



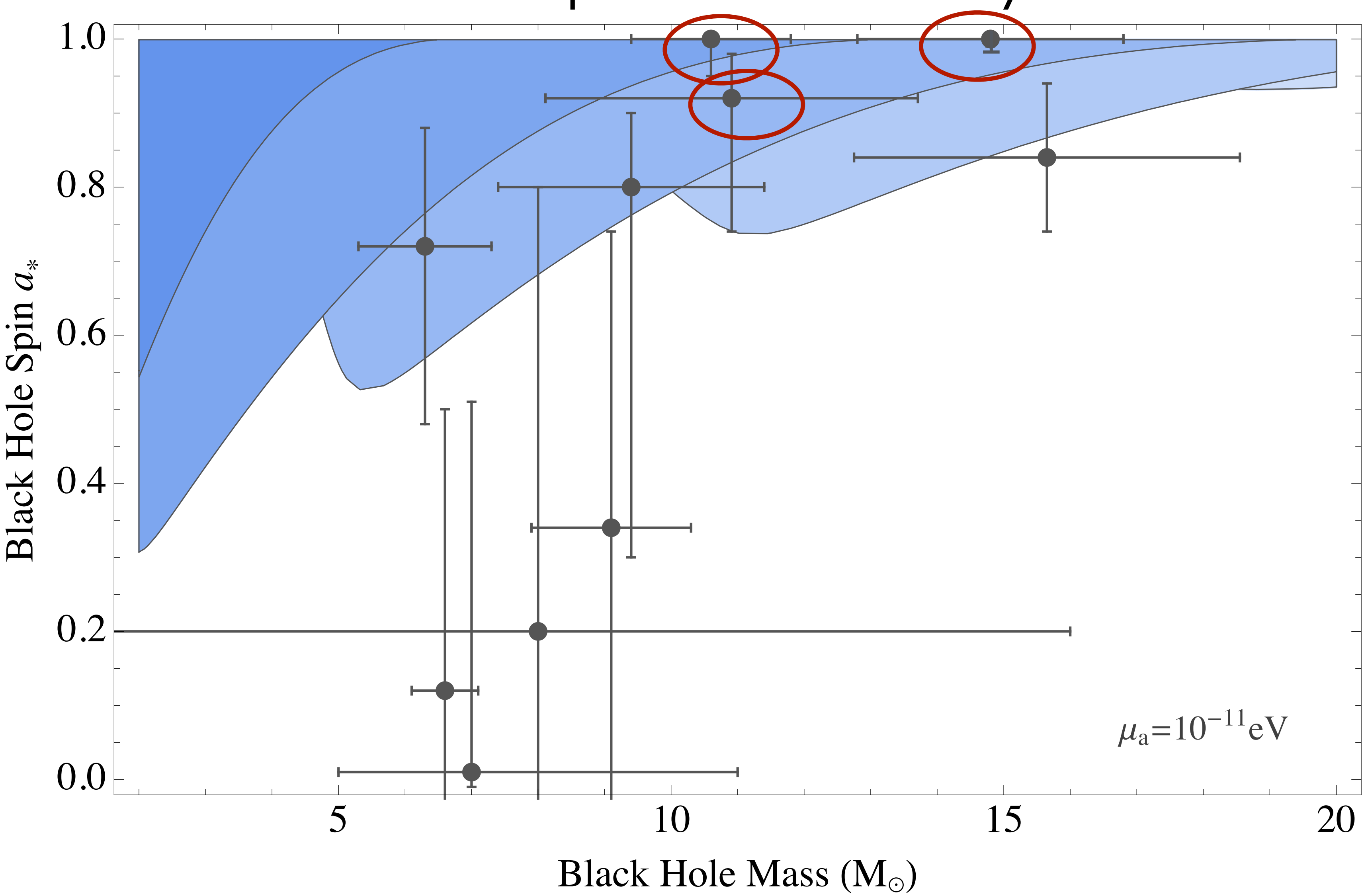




Black Hole Spins

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

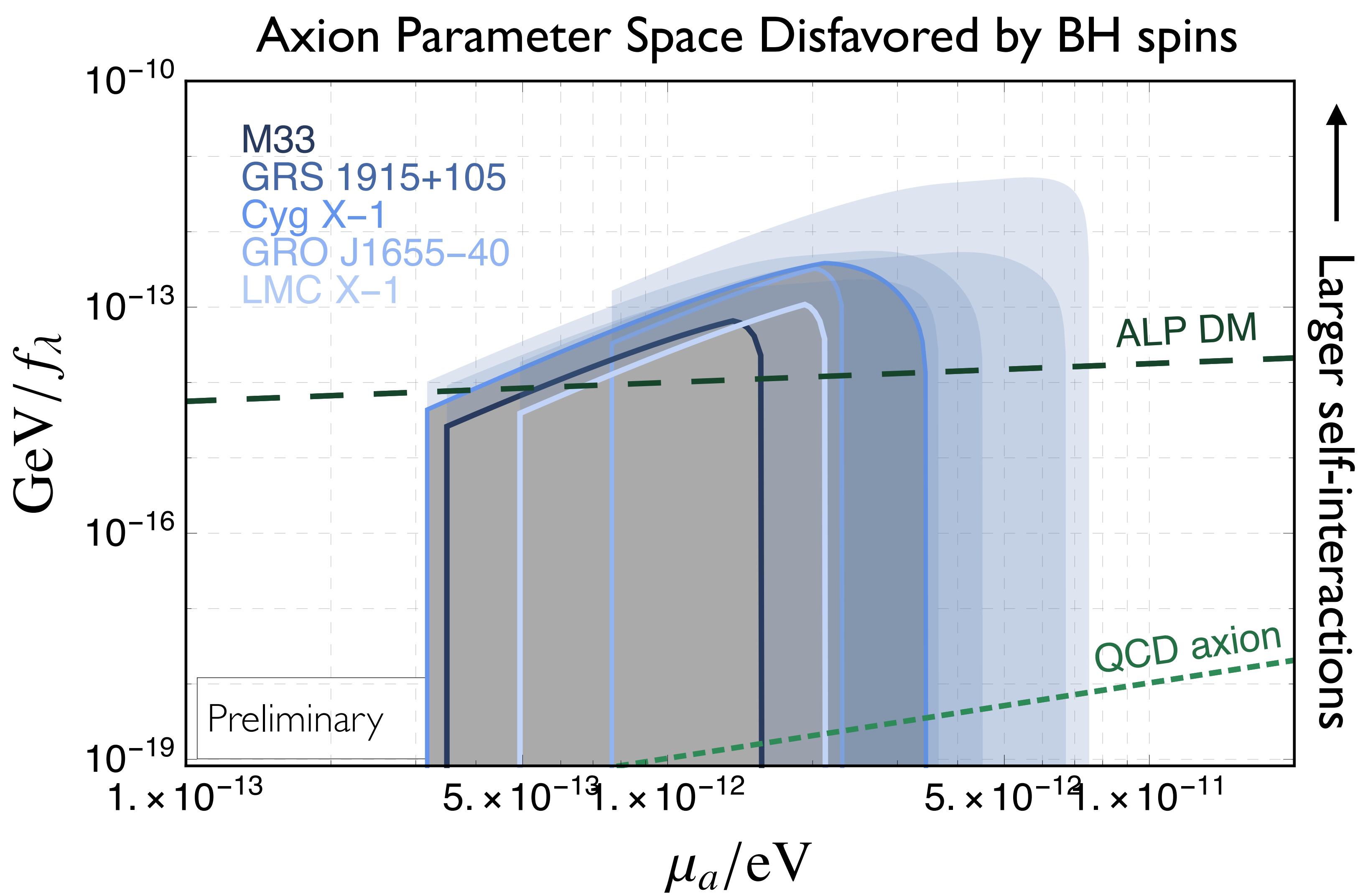
Black hole spins measured in X-ray binaries



A. Arvanitaki, **MB**, X. Huang

Black Hole Spins

Five currently measured black holes combine to set limit:



MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

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

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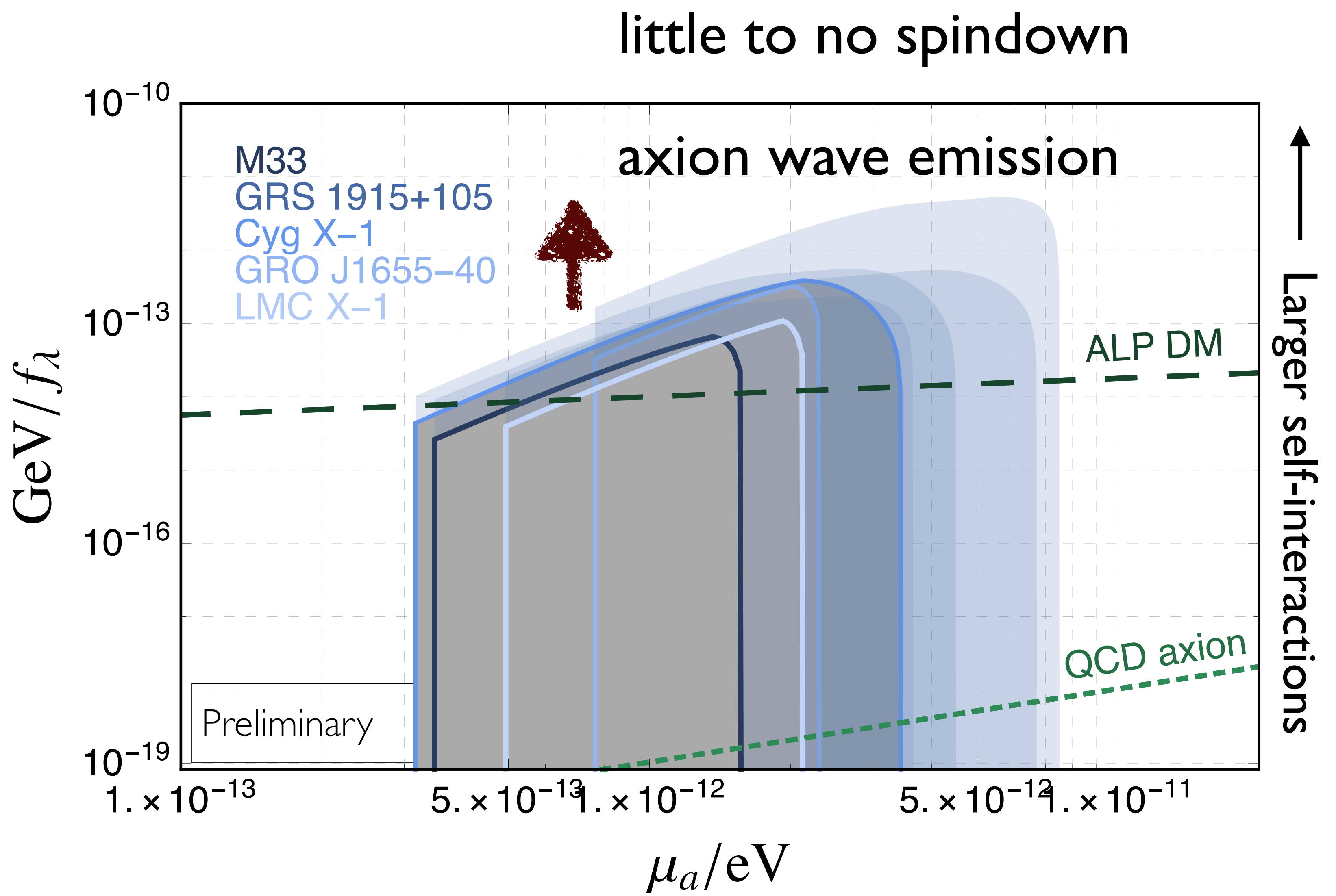

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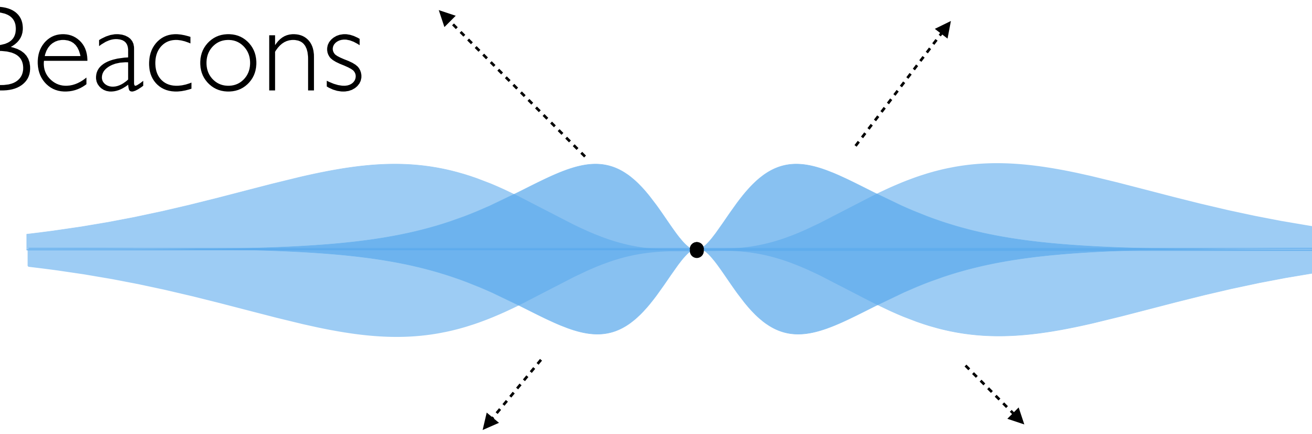
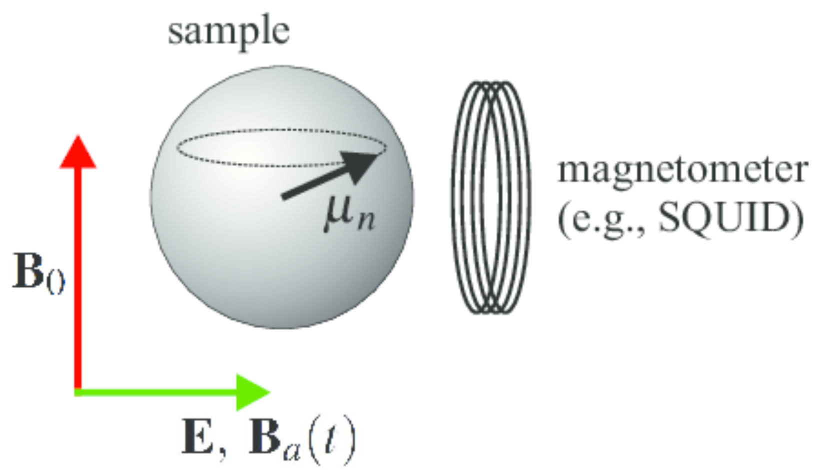
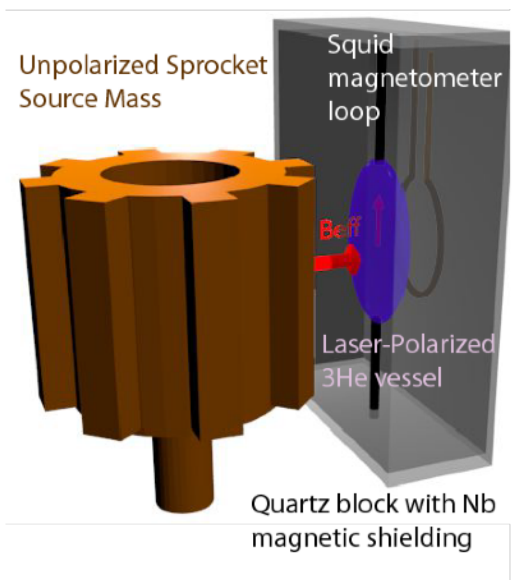
Axionic Beacons



Black hole energy constantly converted to axion waves during equilibrium

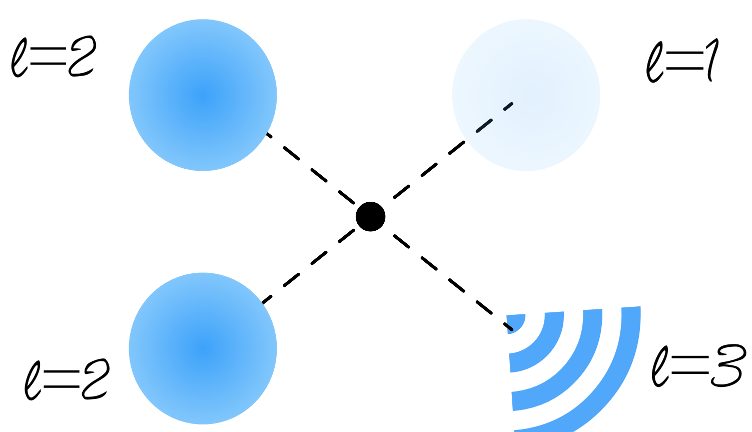




- A new source of axions in the laboratory
- Can be detected directly if axions couple to nuclear spins, photons

$$H_n \supset \frac{\hat{g}_{aNN}}{f_a} \vec{\nabla} a \cdot \vec{\sigma}_N$$

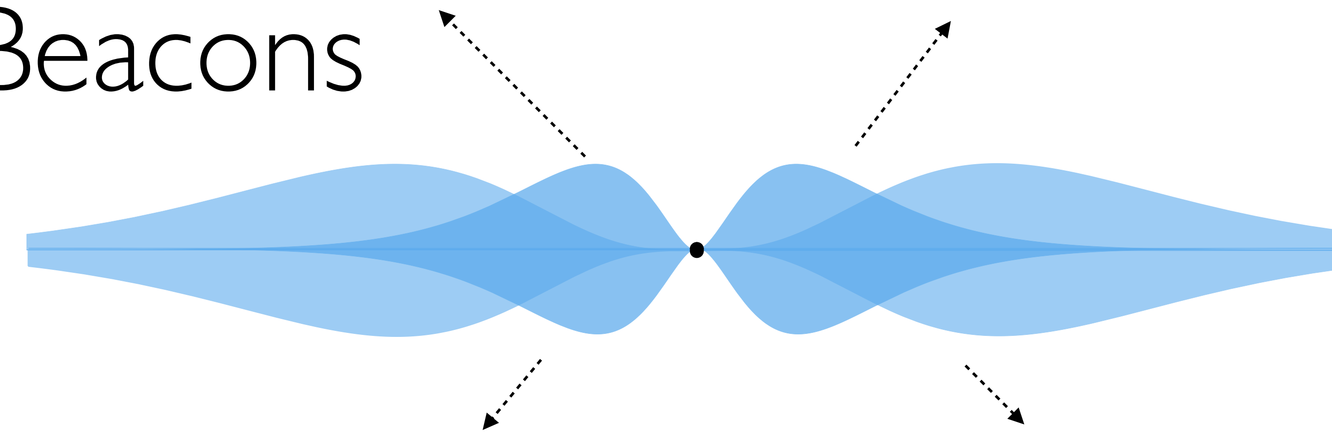
$$\frac{a}{f_a} \sim 10^{-18} \left(\frac{10^{-11} eV}{\mu} \right) \left(\frac{\alpha}{0.25} \right)^3 \frac{kpc}{r}$$



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

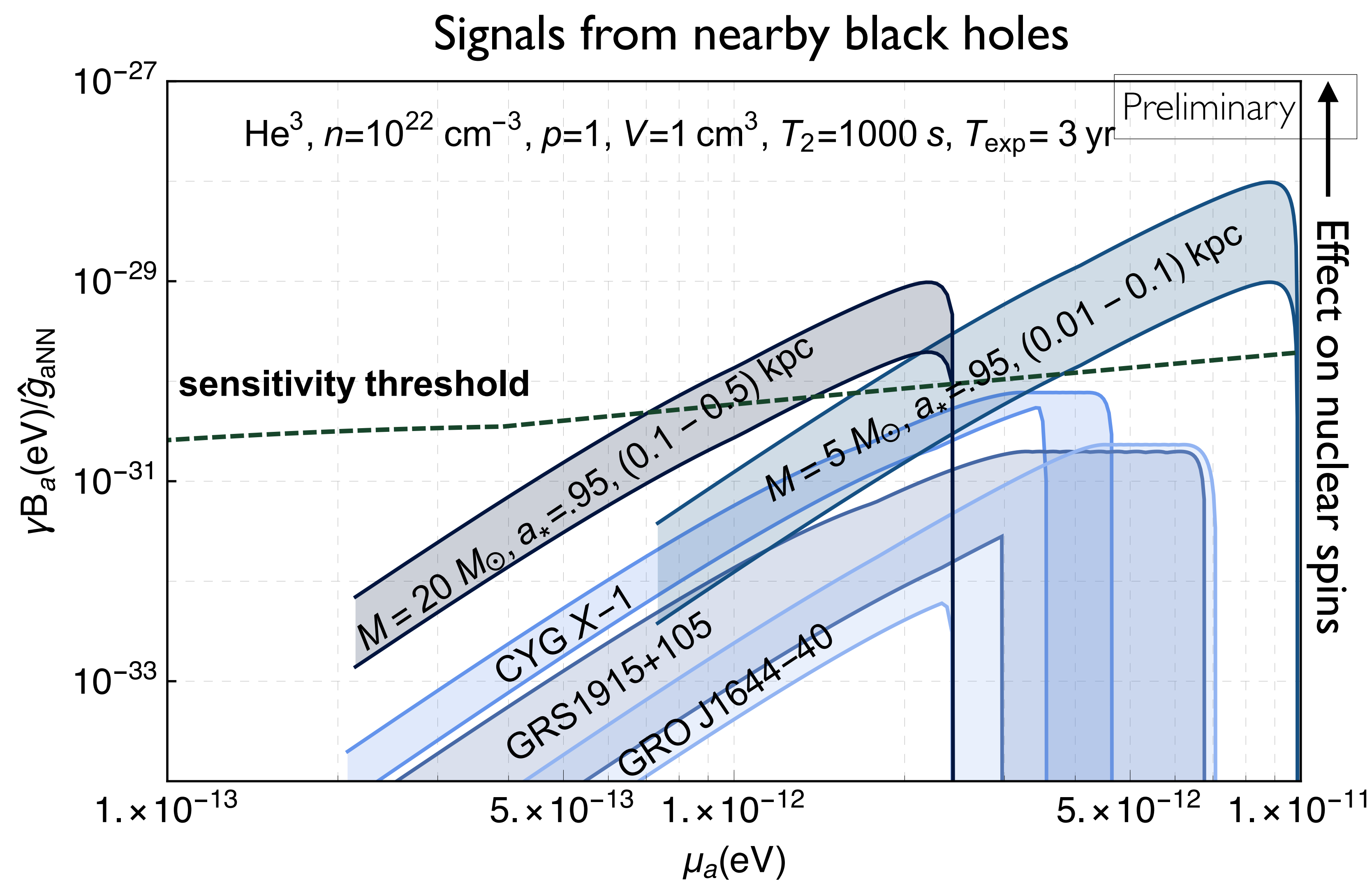
ARIADNE Arvanitaki, Geraci (2014)
ARIADNE collaboration (2017)

Axionic Beacons



Black hole energy constantly converted to axion waves during equilibrium

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



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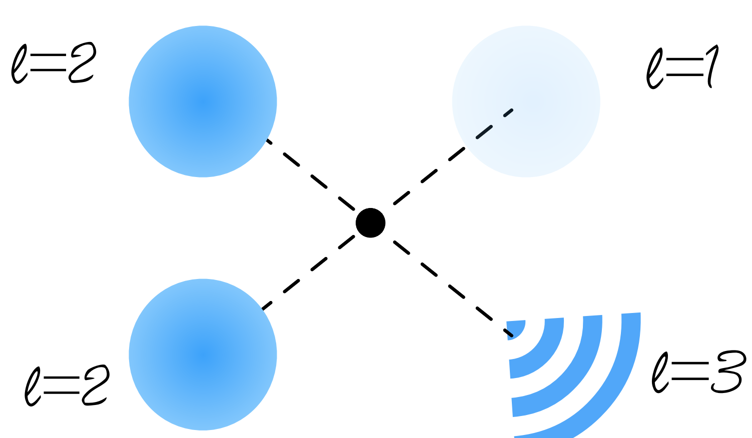

Axions around Black Holes Send Waves to the Lab

- In the presence of ultralight axions, black holes spin down. Measurement of high spin black holes places exclusion limits; LIGO will provide more data points
- Axion clouds produce monochromatic wave 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