GRAVITATIONAL WAVES: FROM DETECTION TO NEW PHYSICS SEARCHES

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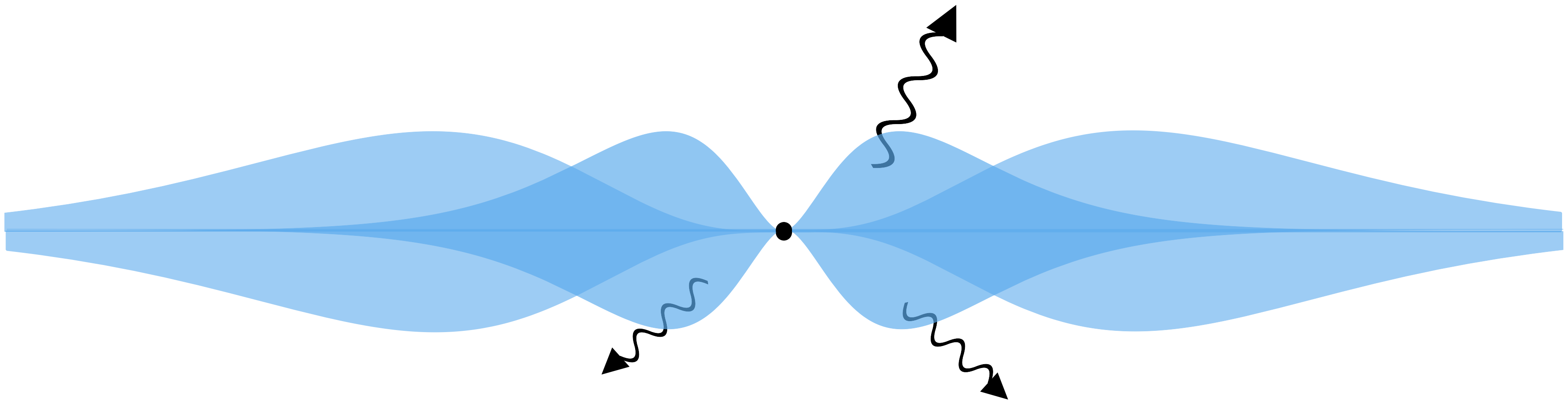
Lecture 3 July 2. 2020

Superradiance and Black Holes

or

How to Extract Energy from Black Holes
and
Discover New Particles



Outline for Today

- Superradiance and rotating BHs
- Gravitational Atoms
- Signs of New Particles
  - Black Hole Spindown
  - Gravitational Wave Signals

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- Rotational, or Zeldovich, superradiance: extraction of an object's rotational energy by an incident wave in the presence of dissipation
- Rotating (Kerr) black holes can superradiance and lose energy and angular momentum

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- Ultralight fields can form macroscopic gravitationally bound states with astophysical black holes, or ``gravitational atoms''
- Bosonic fields can form states with exponentially large occupation values which grow spontaneously through superradiance

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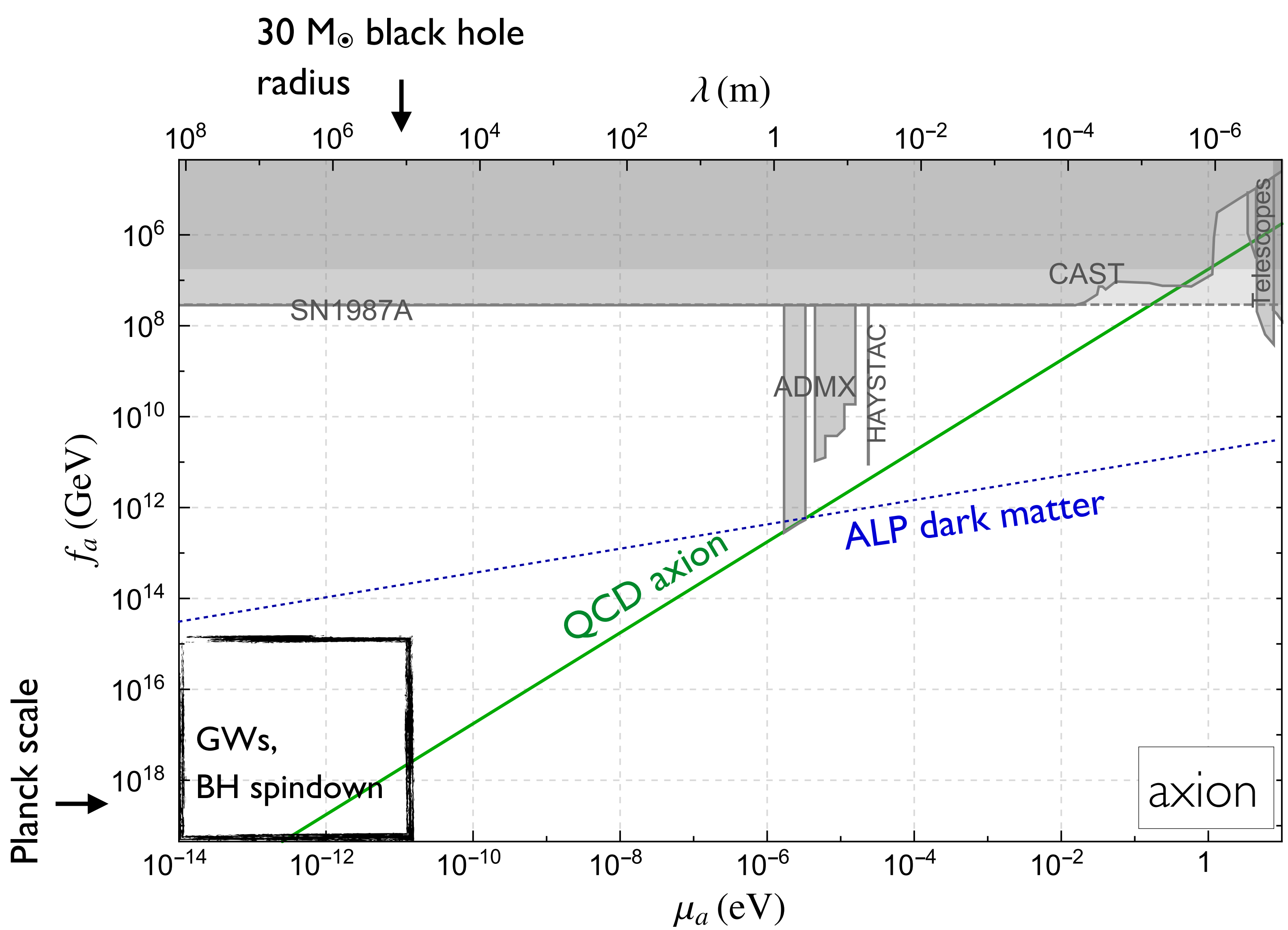
- If there is a light axion (scalar/vector) with compton wavelength comparable to astrophysical BH sizes, it will cause astrophysical black holes to spin down
- The resulting bound states of light particles will source gravitational wave radiation that is observable by LIGO

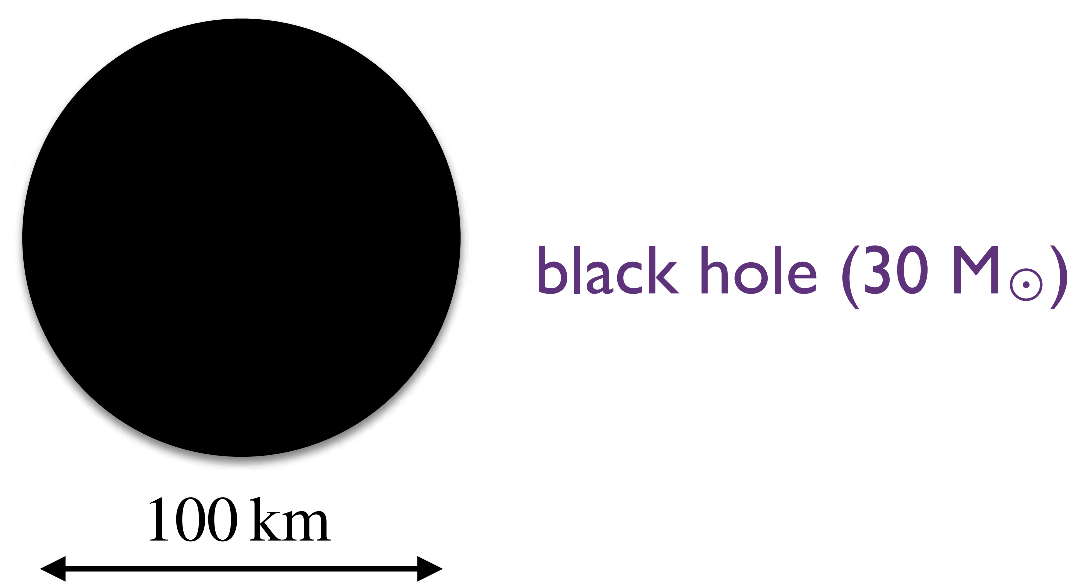
Motivation

- Ultralight scalar particles often found in theories beyond the Standard Model
- E.g. the QCD axion solves the `strong-CP' problem
- As already discussed, ultralight scalars can make up the DM

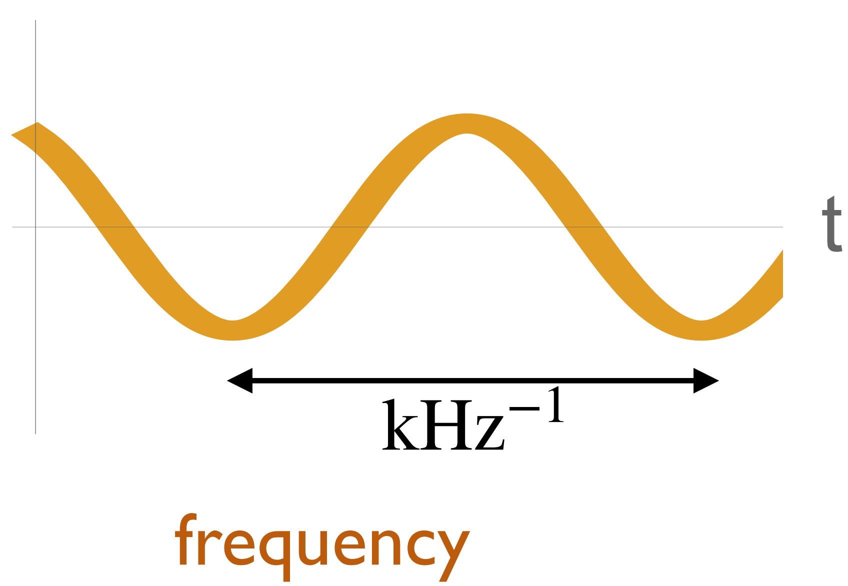


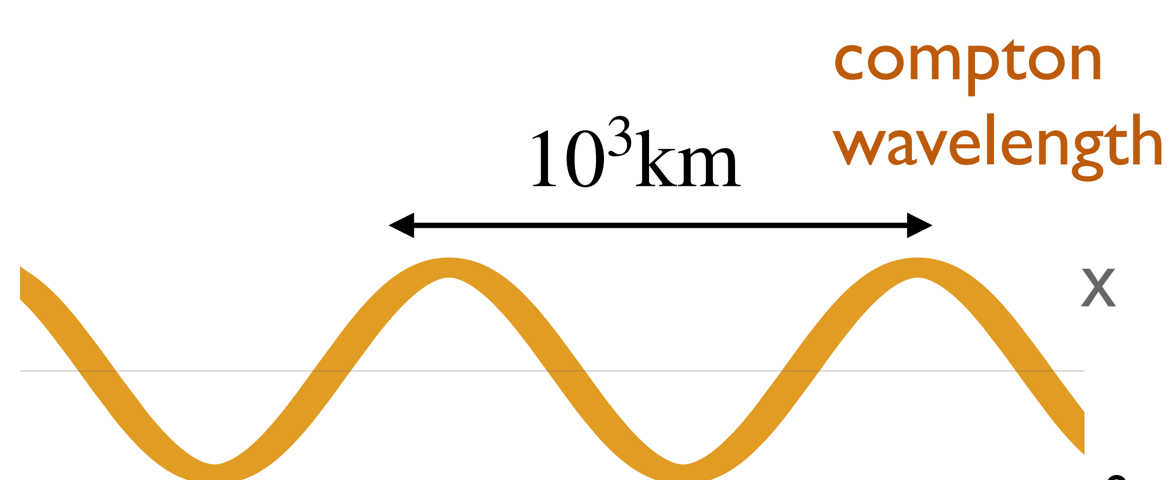
Astrophysical Black Holes and Ultralight Particles

- 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



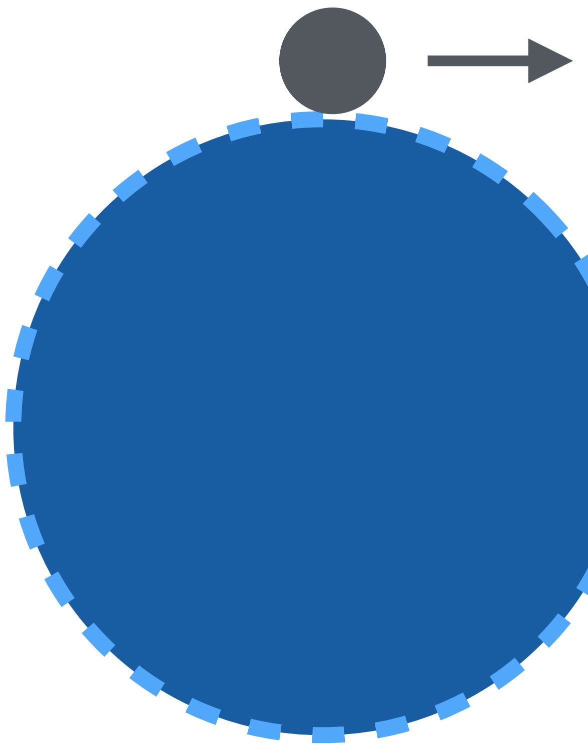
for a 10^{-12} eV particle:





Superradiance: gaining from dissipation

- A an object scattering off a **rotating** cylinder can increase in angular momentum and energy.
- Effect depends on **dissipation**, necessary to change the velocity



Ball incident on cylinder with lossy surface slows down due to friction

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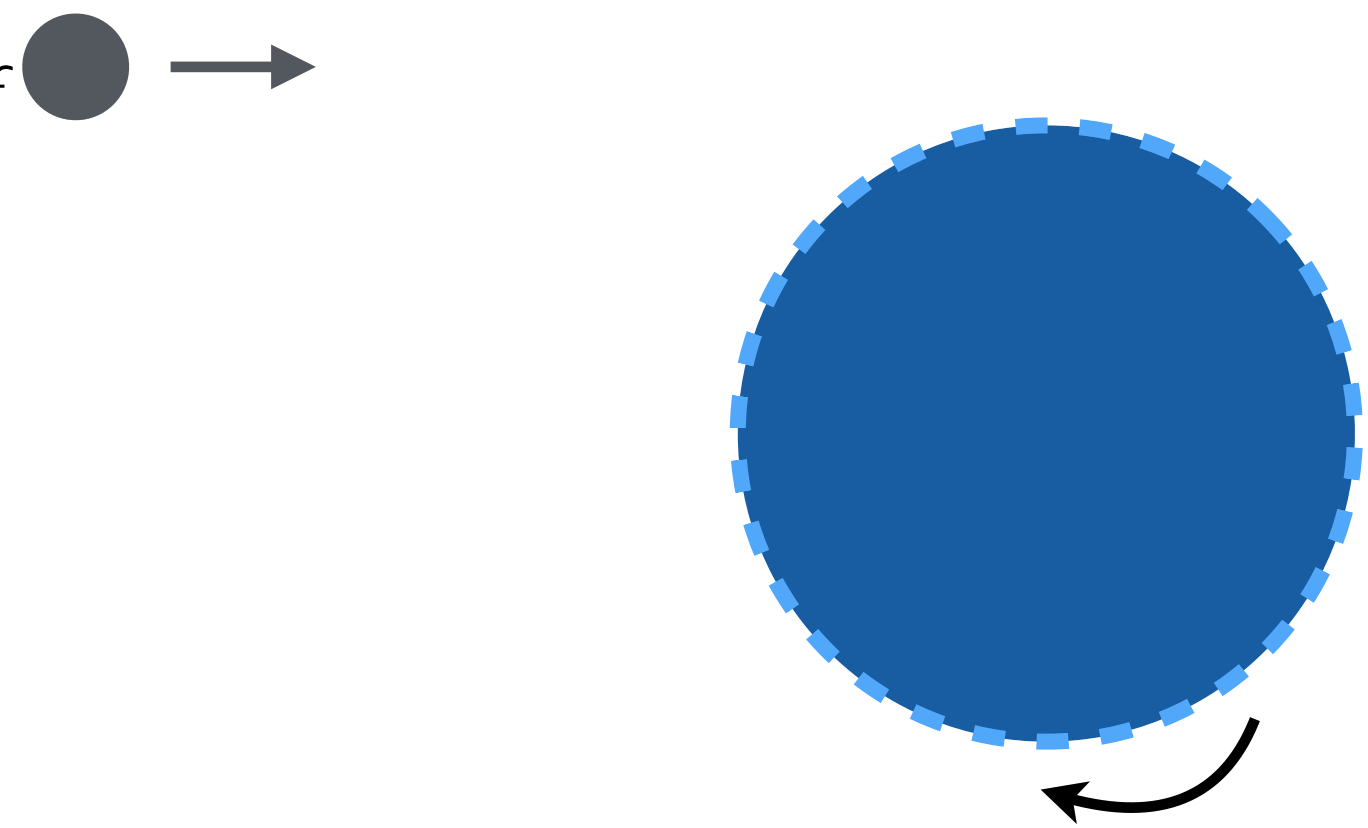

If the cylinder is rotating at angular velocity equal to the angular velocity of the ball about the axis, $\Omega_i = v_{\phi,i}$ the relative velocity at the point of contact is zero: no energy loss

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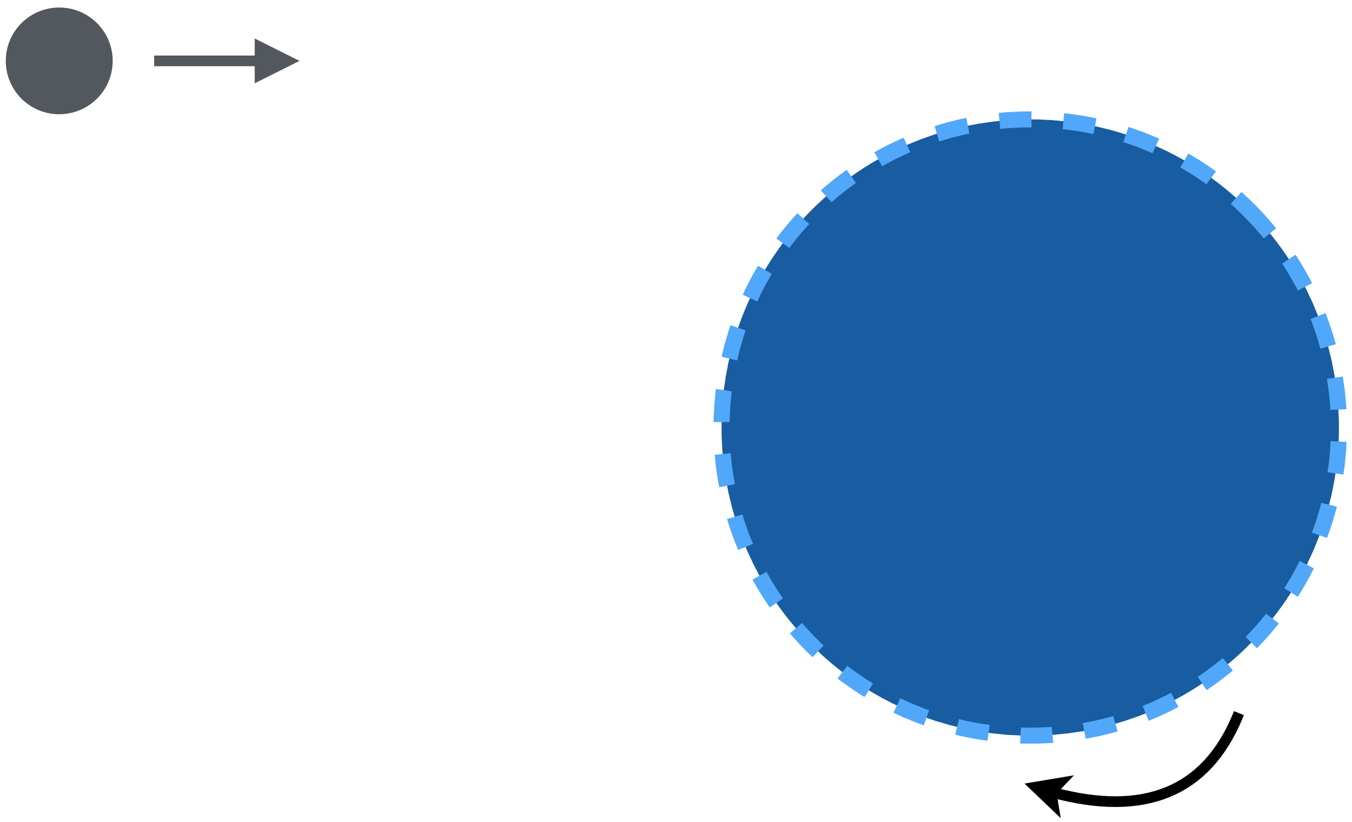


If the cylinder is rotating even faster, $\Omega_i > v_{\phi,i}$

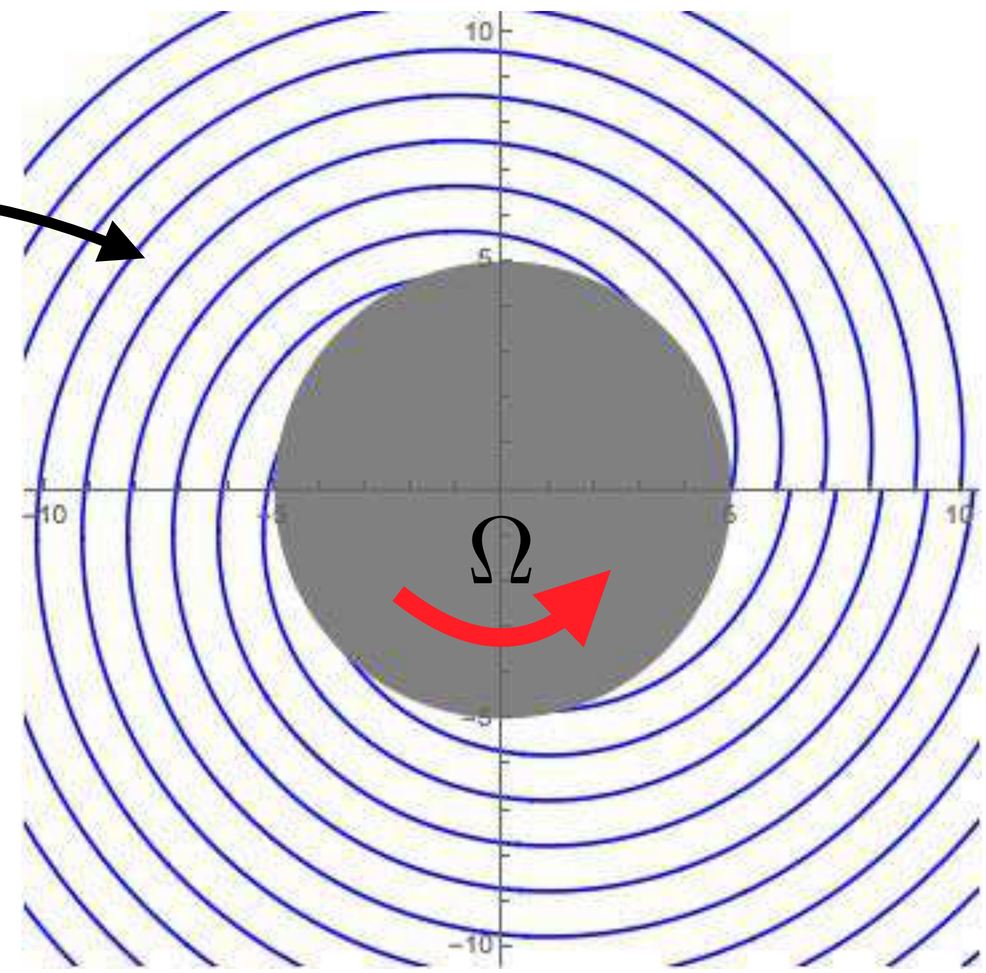
Ball scattering off rapidly rotating cylinder with **lossy** surface speeds up!

Energy increase comes from cylinder slowing down, losing energy and angular momentum

Superradiance: gaining from dissipation

- Scalar perturbations scattering off of rotating cylindrical medium with absorption

$$\Phi = \phi(r)e^{-i\omega t + im\varphi}$$



The amplitude of the field will increase for

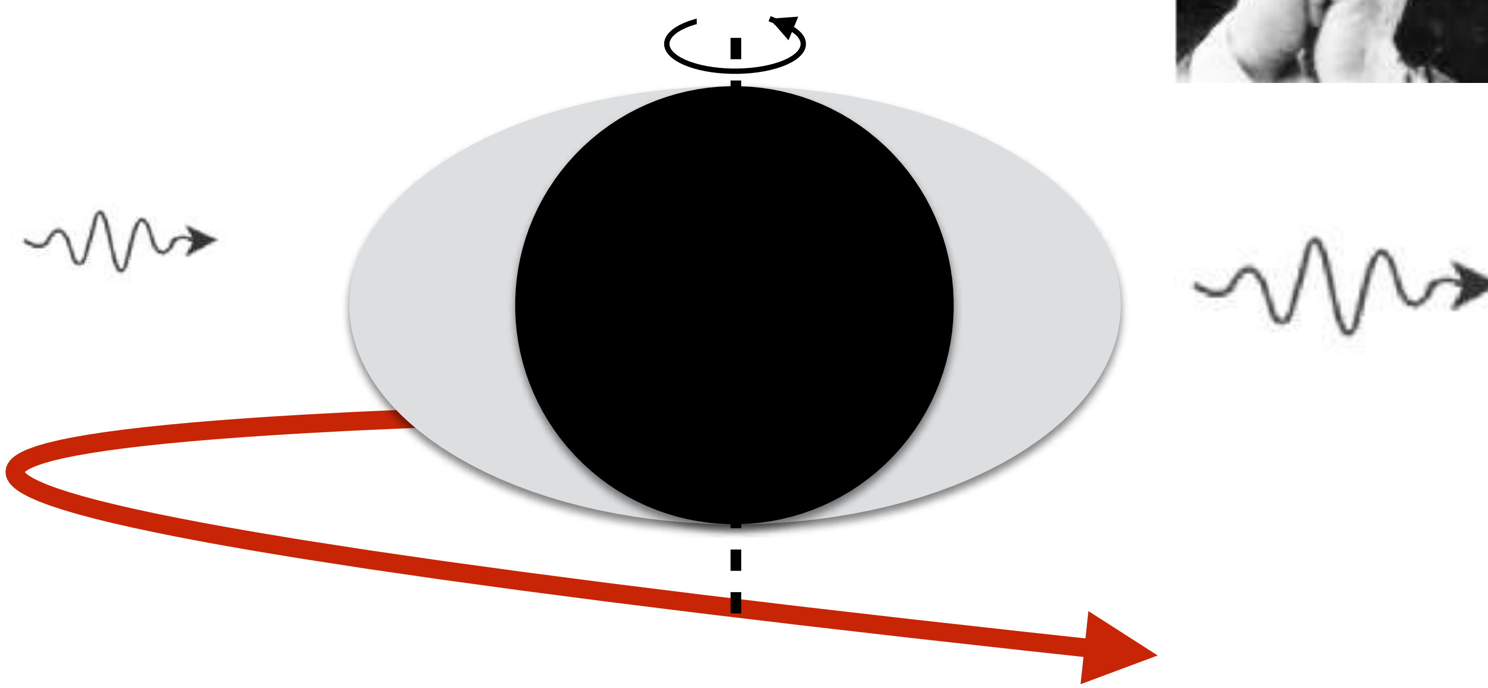
$$v_{\varphi,i} < \Omega_i \rightarrow \boxed{\omega/m < \Omega}$$

superradiance condition

Superradiance: gaining from dissipation

- 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

Gravitational wave amplified when scattering from a rapidly rotating black hole

Numerical GR simulation by Will East

Superradiance condition for Black Holes

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

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What is the `angular velocity' of the BH horizon?

Kerr Metric

$$ds^2 = -\left(1 - \frac{2r_g r}{\Sigma}\right) dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2r_g r a^2}{\Sigma} \sin^2\theta\right) \sin^2\theta d\phi^2 - \frac{4r_g r a}{\Sigma} \sin^2\theta dt d\phi$$

$$r_g \equiv GM, \quad a \equiv \frac{J}{M} \equiv a_* r_g, \quad \Sigma = r^2 + a^2 \cos^2\theta, \quad \Delta = r^2 - 2r_g r + a^2$$

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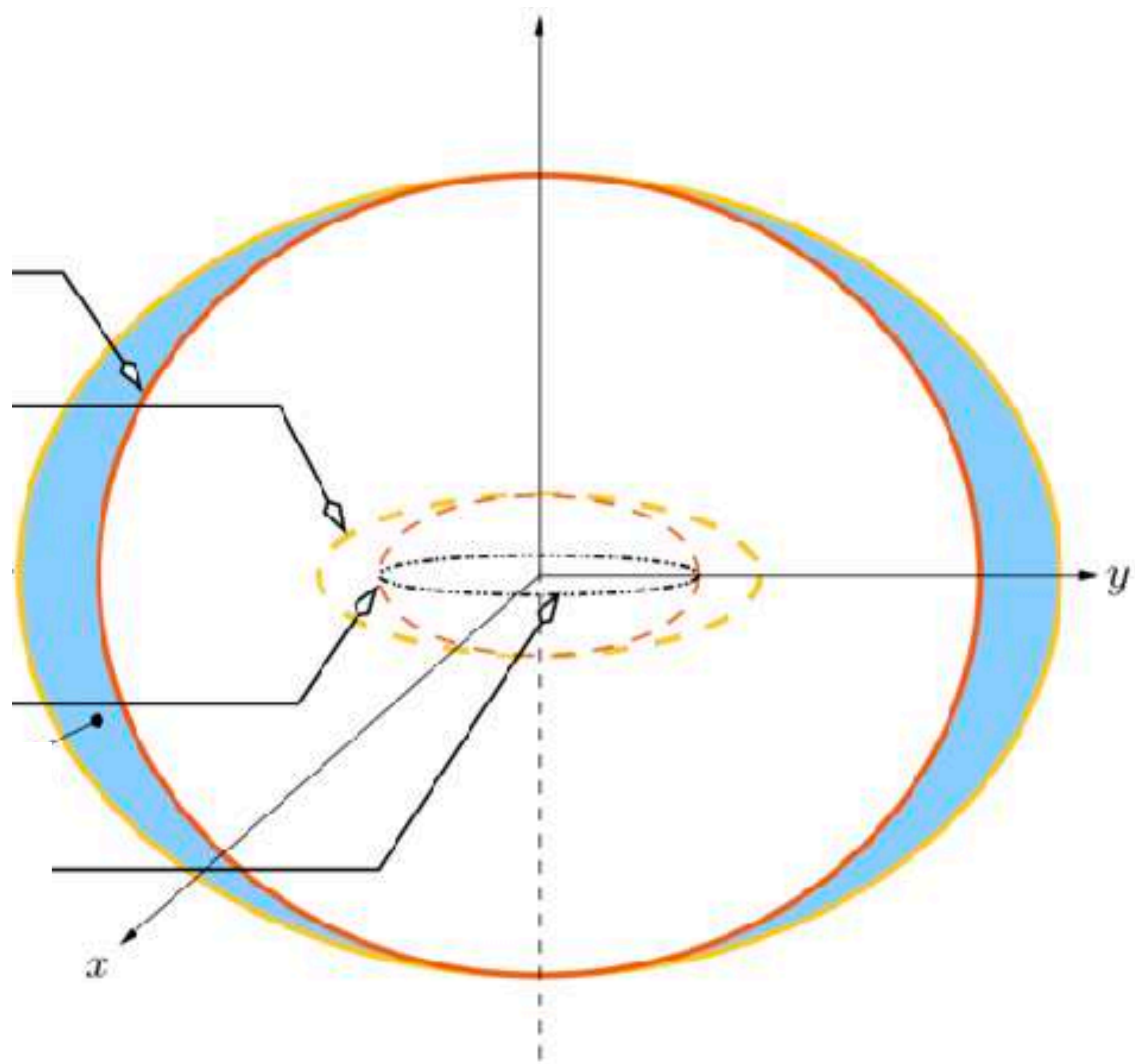

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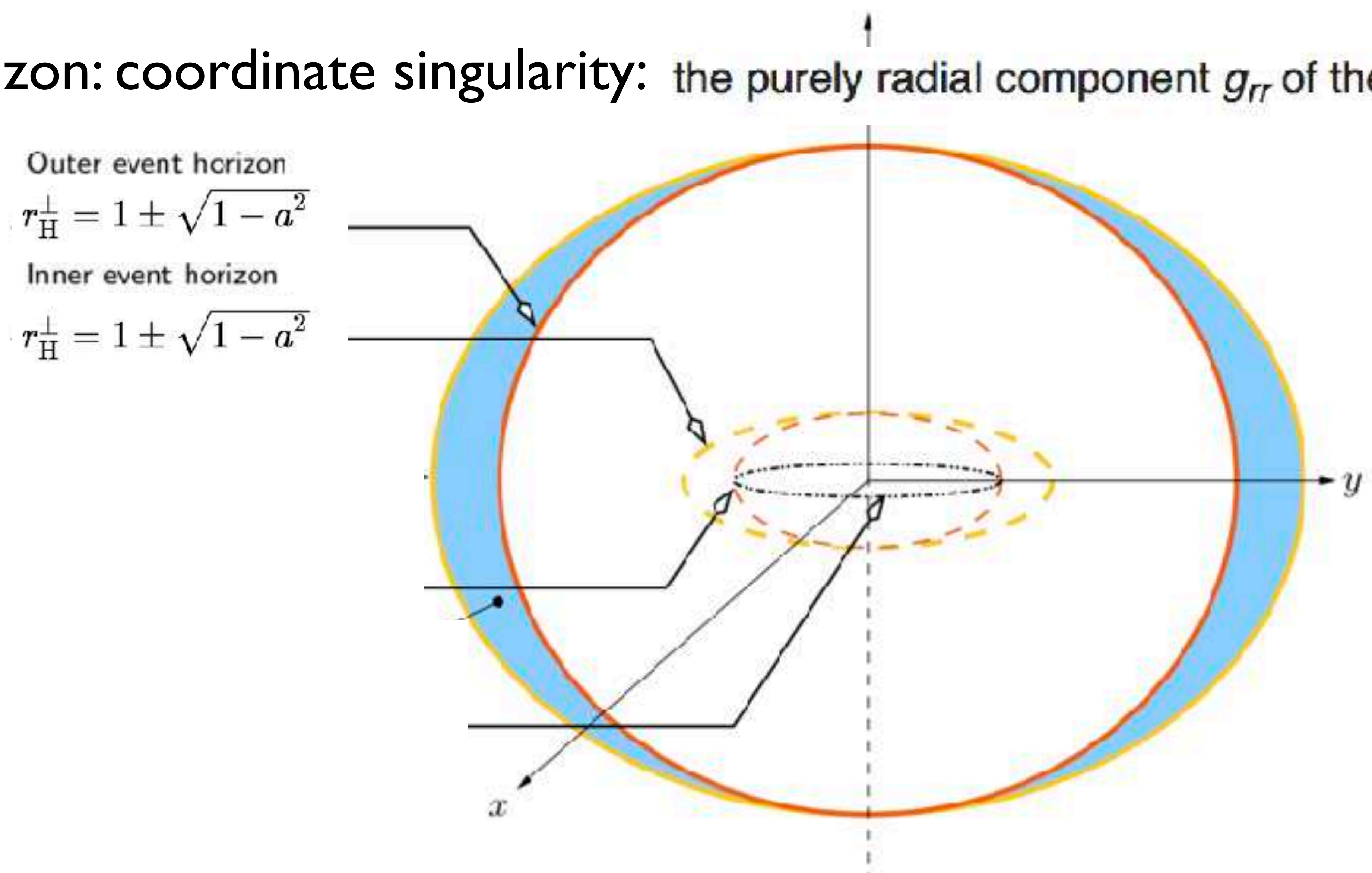
Horizon: coordinate singularity: the purely radial component g_{rr} of the metric goes to infinity



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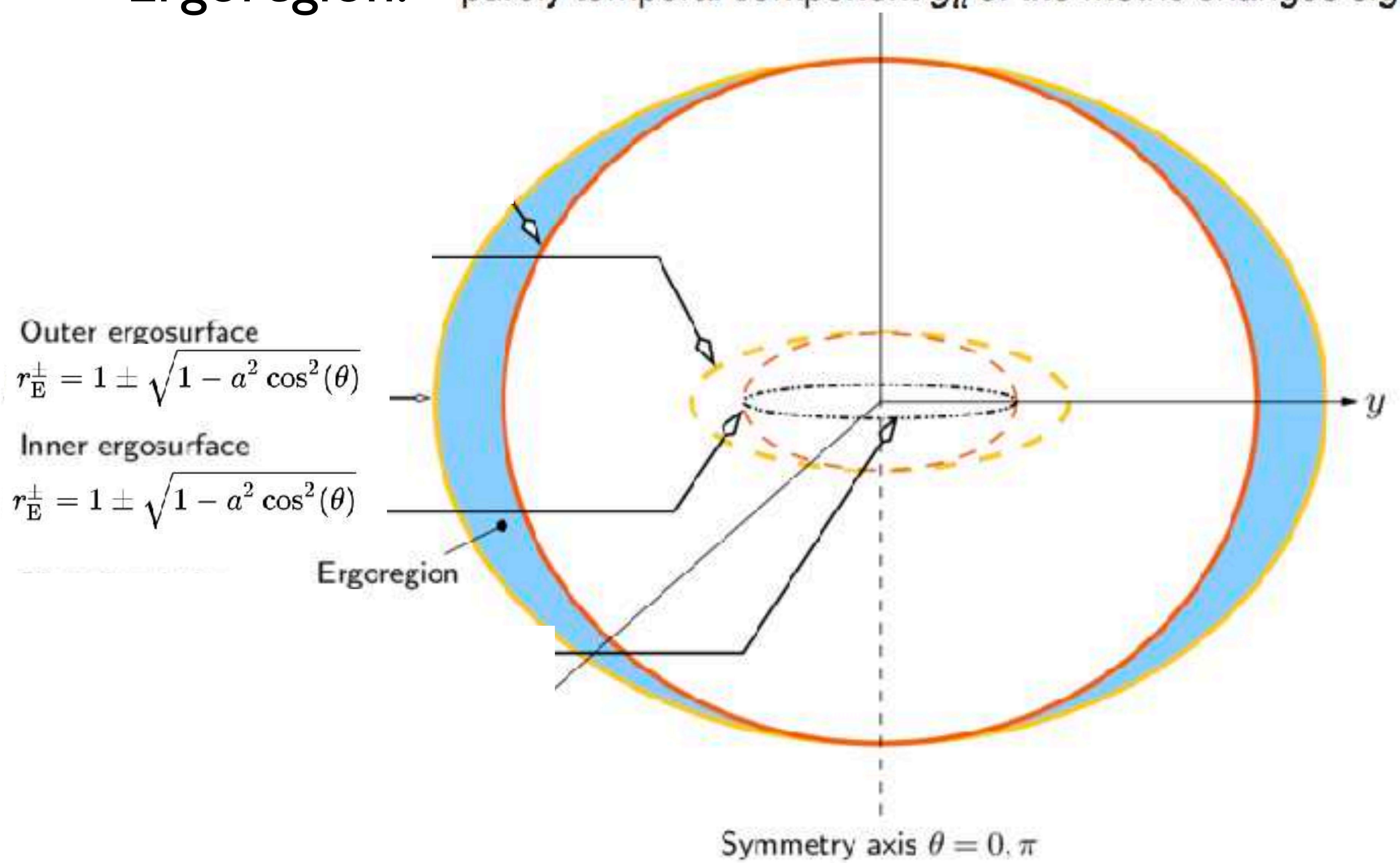
Ergoregion: purely temporal component g_{tt} of the metric changes sign



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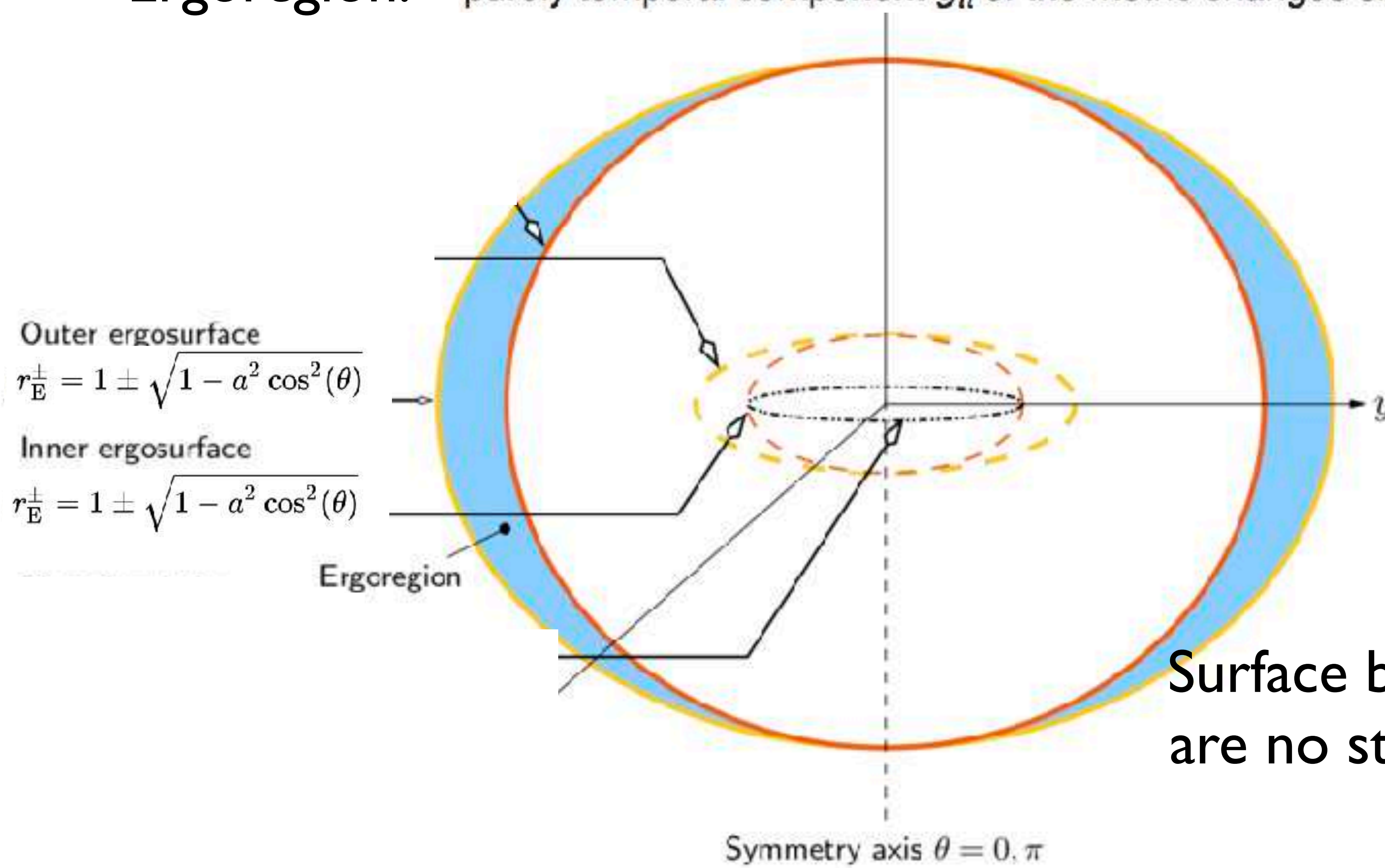

Surface beyond which there are no stationary observers

Superradiance condition for Black Holes

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

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

What is the `angular velocity' of the BH horizon?

`Blackboard'

Superradiance condition for Black Holes

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For a scalar field mode with energy ω and angular momentum m ,

$$\Phi = \phi(r)e^{-i\omega t+im\varphi}$$

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And a Kerr black hole,

$$\frac{\omega}{m} < \frac{1}{2r_g} \frac{a_*}{1 + \sqrt{1 - a_*^2}}$$

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$$\frac{\omega}{m} < \frac{1}{2r_g} \frac{a_*}{1 + \sqrt{1 - a_*^2}}$$

For a nonrelativistic field with mass μ and angular momentum m, the SR condition is

$$\frac{\mu r_g}{m} < \frac{1}{2} \frac{a_*}{1 + \sqrt{1 - a_*^2}} < \frac{1}{2}$$

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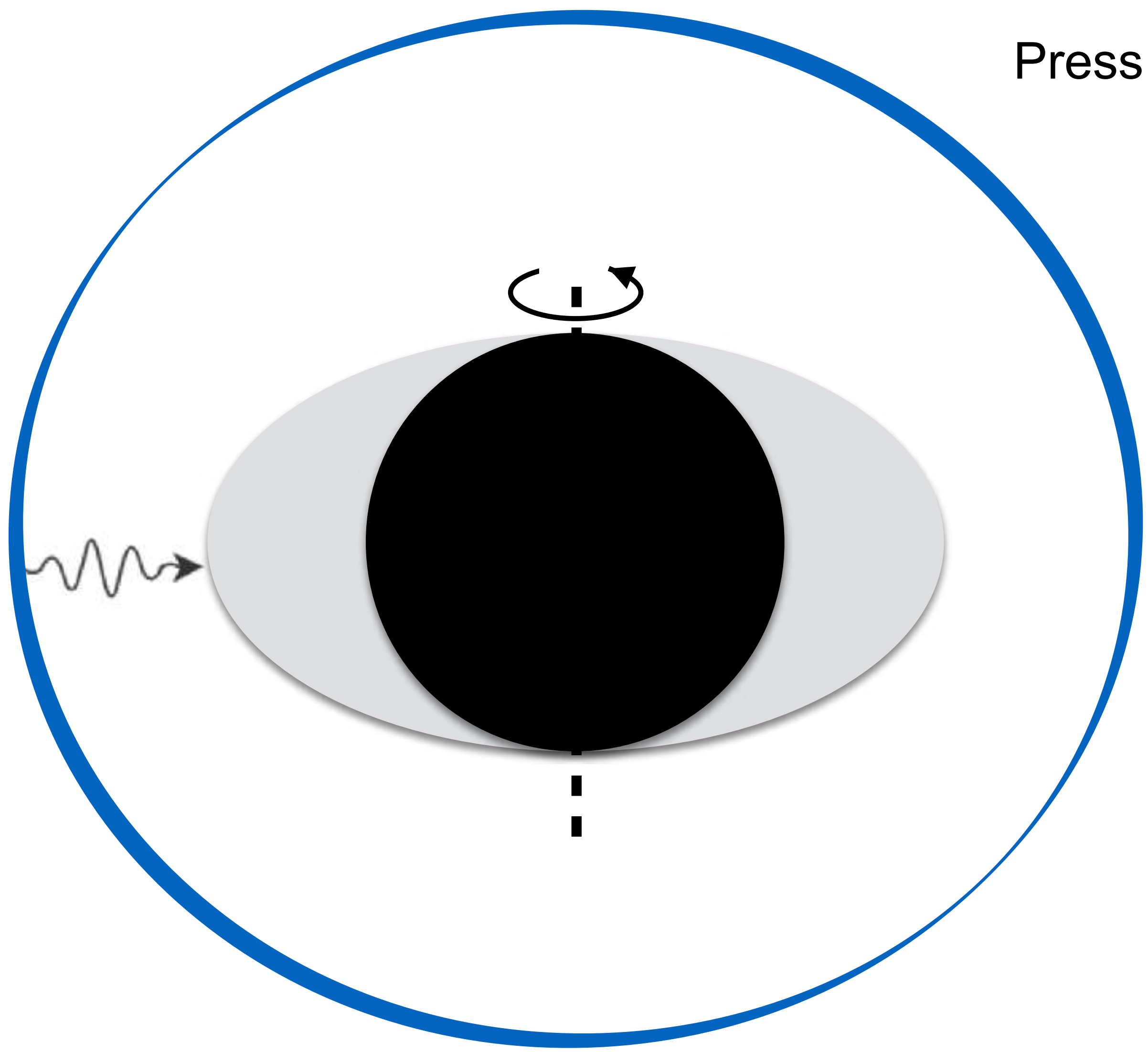
Superradiance

Particles/waves trapped in orbit around the BH repeat this process continuously

Press & Teulkosky



"Black hole bomb" exponential instability when surround BH by a mirror

Kinematic, not resonant condition

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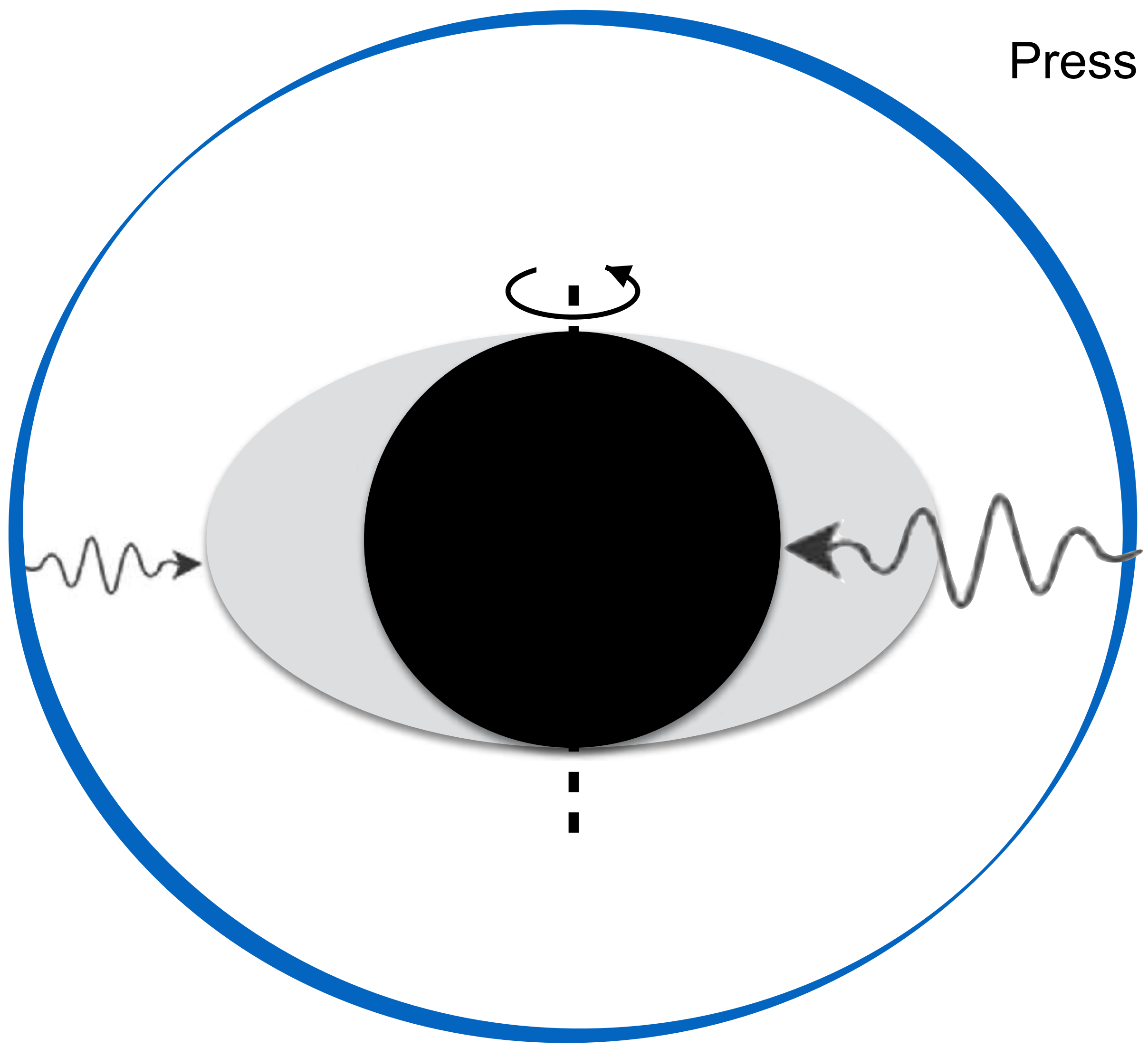

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Superradiance

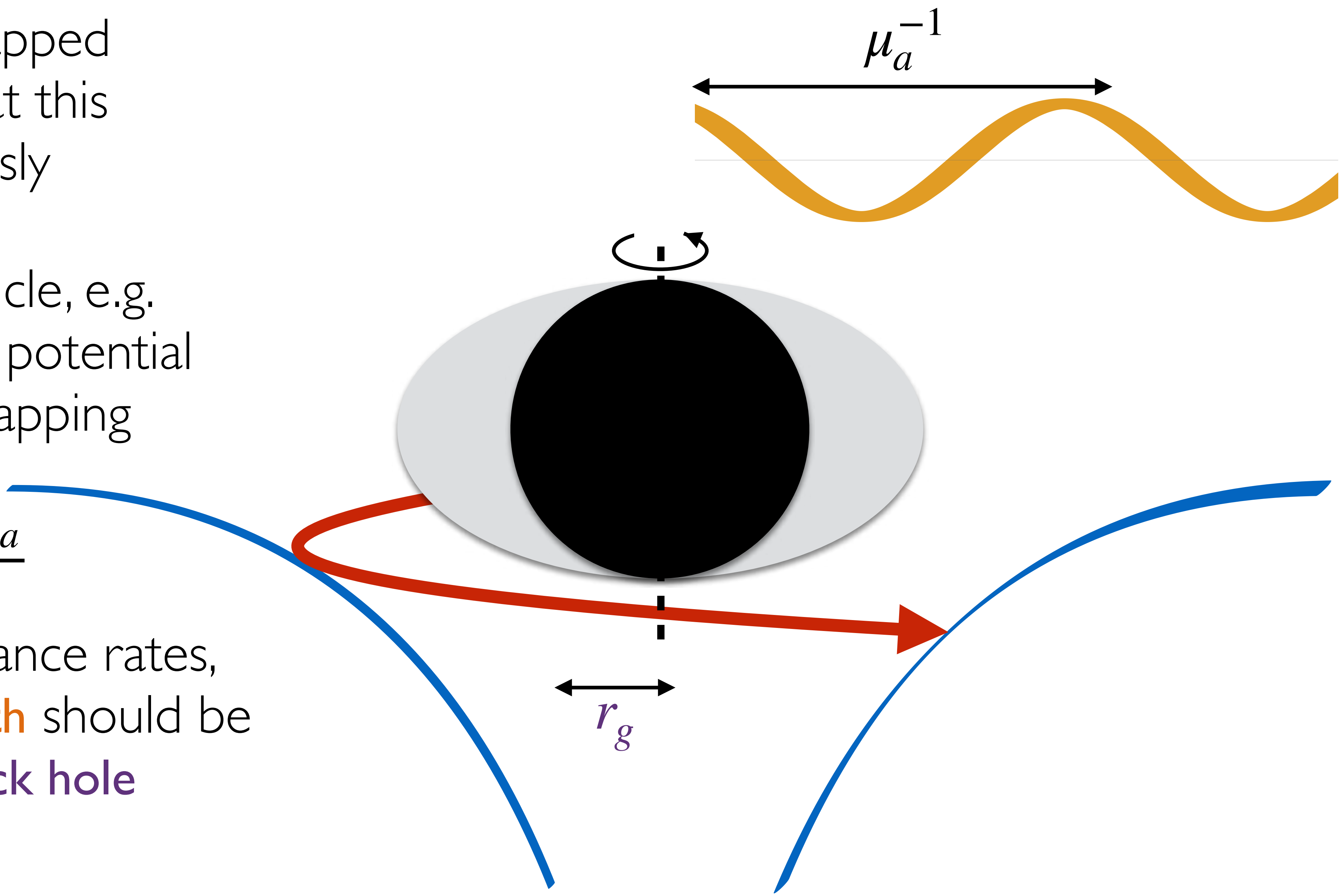
- Particles/waves trapped near the BH repeat this process continuously

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

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

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

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

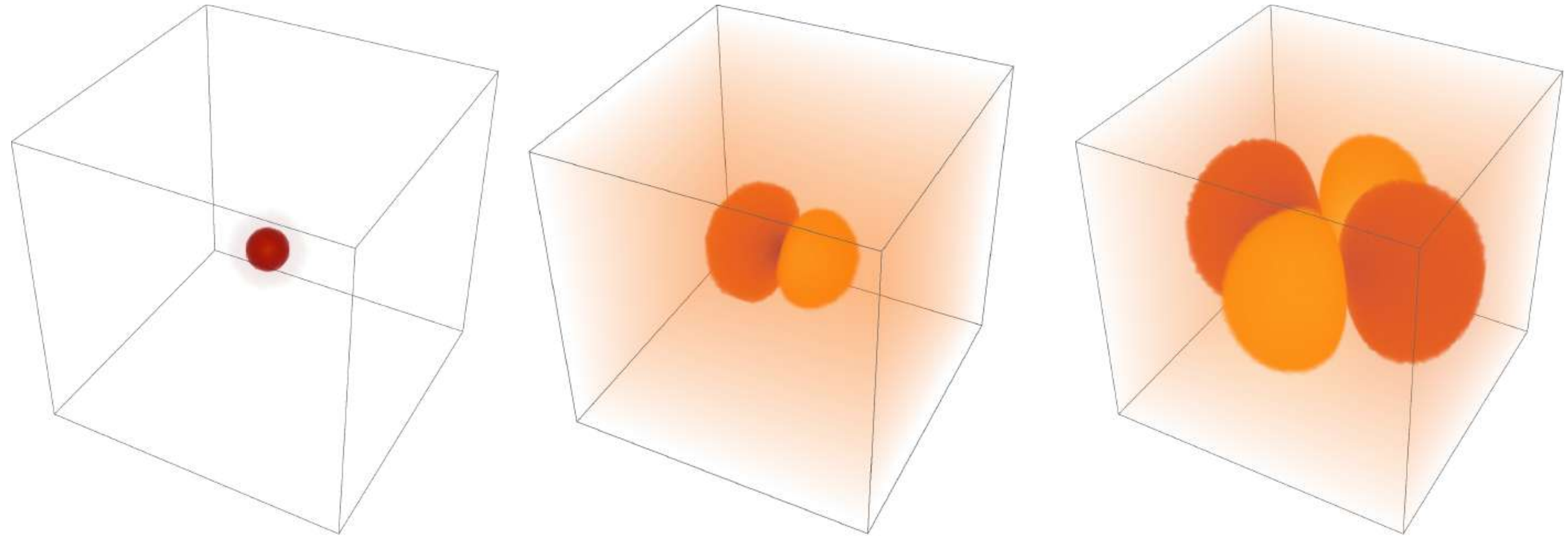


[Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78]
[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010]

Gravitational Atoms?

Axion
Gravitational Atoms

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



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

$$ds^2 = -\left(1 - \frac{2r_g r}{\Sigma}\right) dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2r_g r a^2}{\Sigma}\sin^2\theta\right)\sin^2\theta d\phi^2 - \frac{4r_g r a}{\Sigma}\sin^2\theta dt d\phi \quad \& \quad (D^2 - \mu^2)\varphi = 0$$

$$\left(\frac{\partial^2}{\partial t^2} - \vec{\nabla}^2 + \mu^2 - \frac{2GM\mu^2}{r}\right)\varphi = 0.$$

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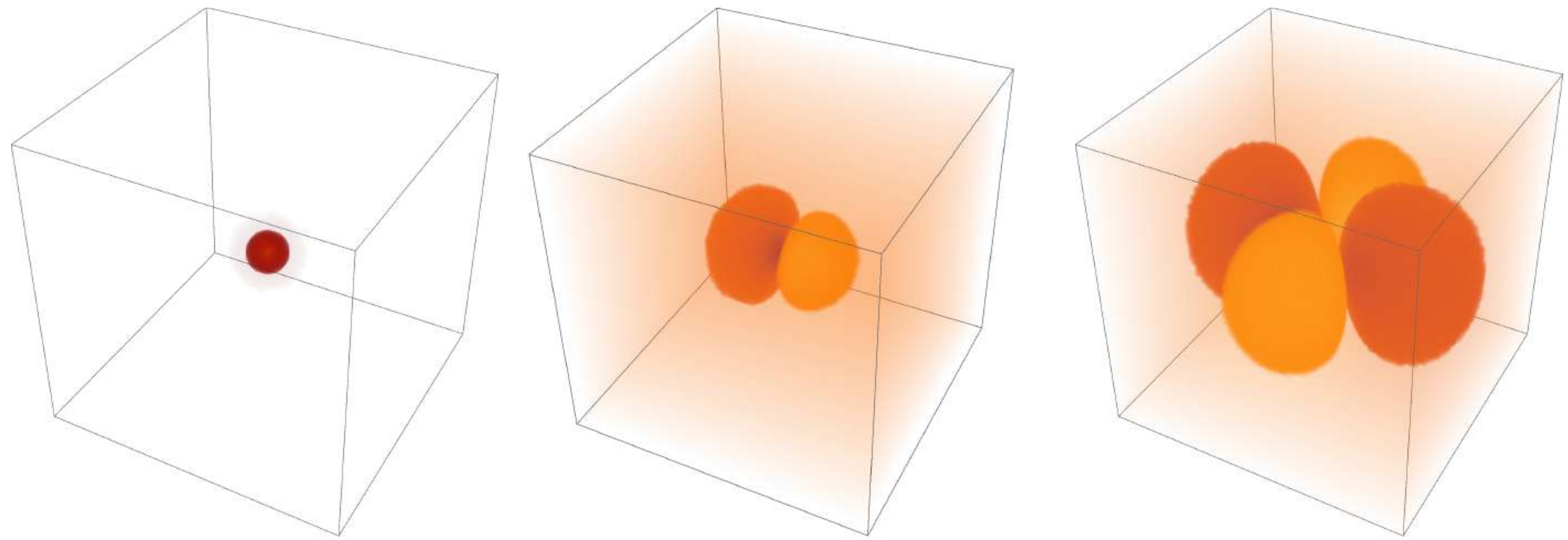

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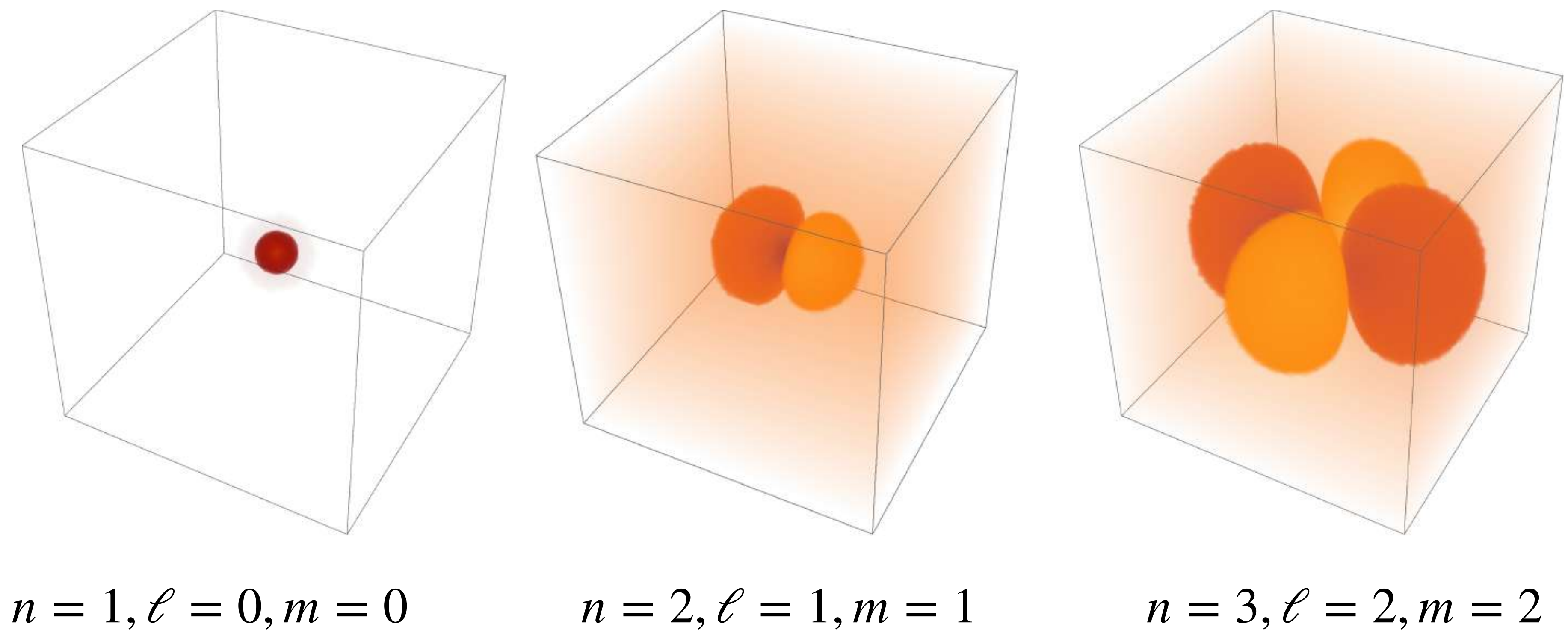
$$\left(\frac{\partial^2}{\partial t^2} - \vec{\nabla}^2 + \mu^2 - \frac{2GM\mu^2}{r}\right)\varphi = 0. \quad \& \quad \varphi = \frac{1}{\sqrt{2\mu}}(\psi e^{-i\mu t} + \mathrm{c.c})$$

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[\frac{-\hbar^2}{2\mu}\nabla^2 + V(\mathbf{r},t)\right]\Psi(\mathbf{r},t)$$

Gravitational Atoms

Axion
Gravitational Atoms



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

Gravitational potential similar to hydrogen atom

`Fine structure constant`

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

Constraint on α from SR condition: $$\frac{\alpha}{m} < \frac{1}{2}\frac{a_*}{1+\sqrt{1-a_*^2}} < \frac{1}{2}$$

Gravitational Atoms

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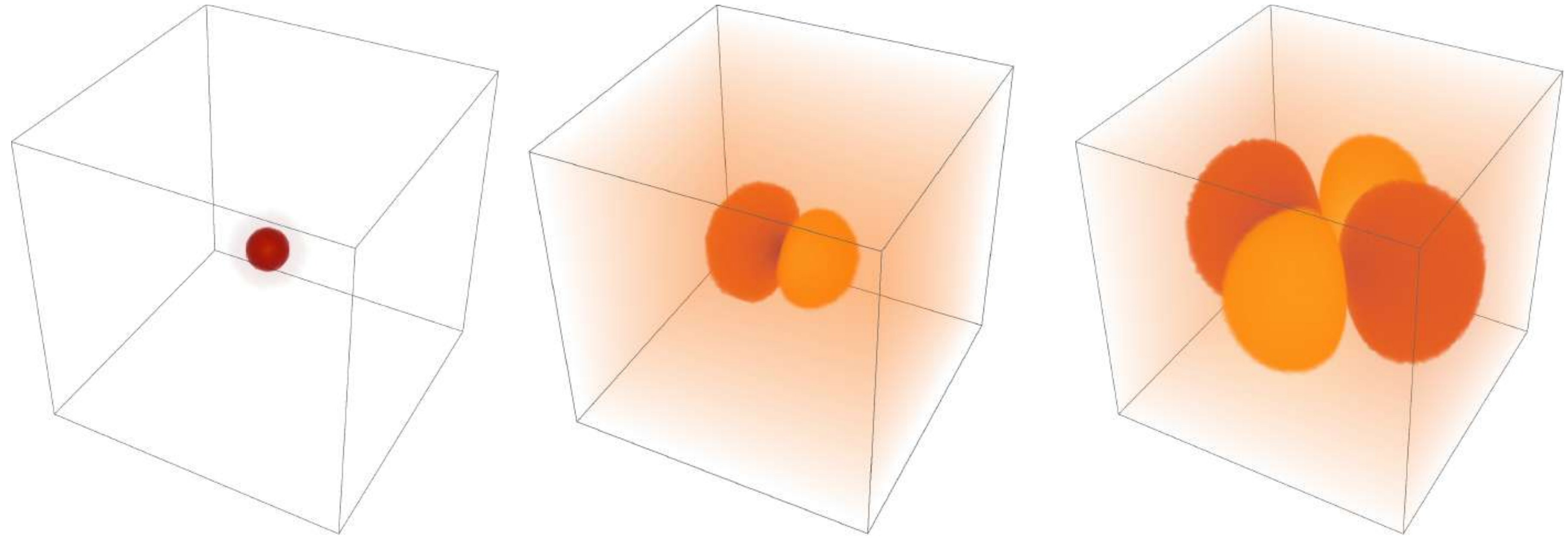

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`Fine structure constant`

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

Radius

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

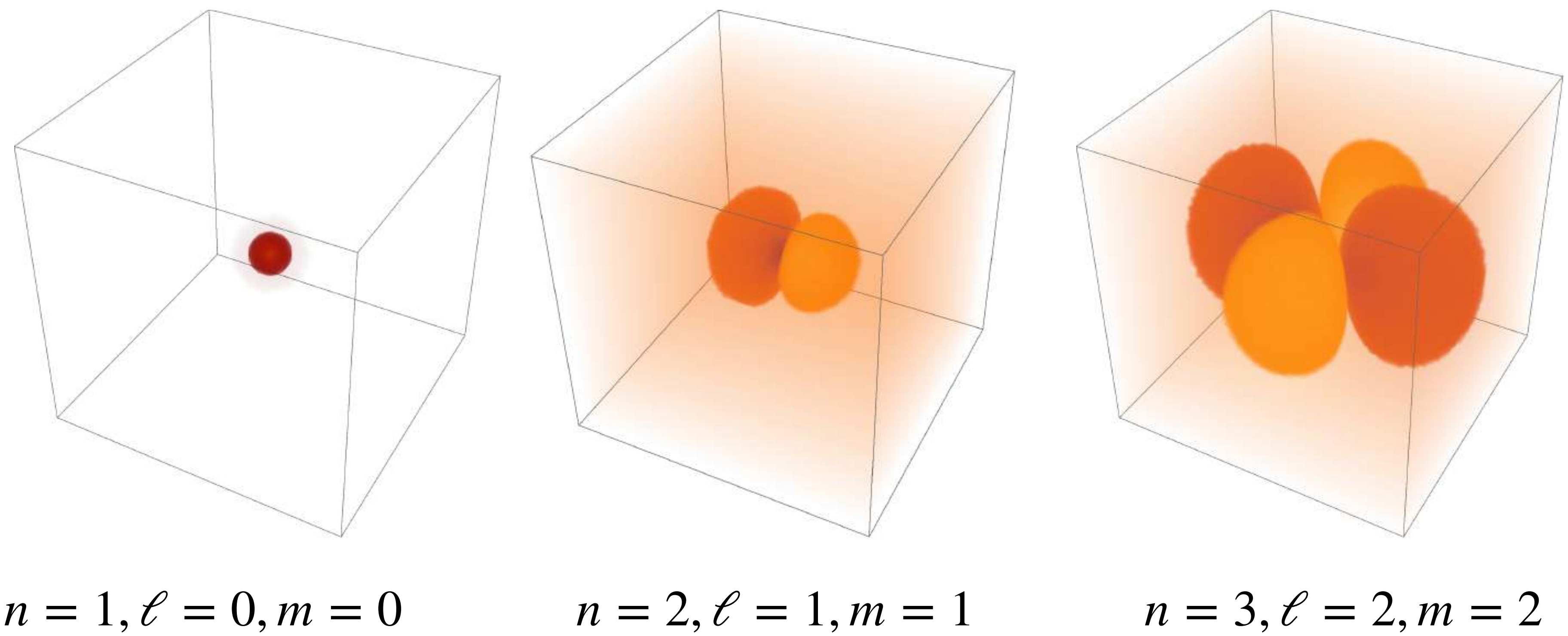
Occupation number

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

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 Timescales

$$\alpha = G_{\rm N} M_{\rm BH} \mu_a = r_g \, \mu_a \lesssim \frac{m}{2} a_*$$

BH lightcrossing time	r_g	.01 ms
Particle wavelength	$\mu^{-1} = \dfrac{r_g}{\alpha}$	.1 ms
Cloud size	$r_c \sim \dfrac{n}{\alpha^2} r_g$	ms
Superradiance time		
Annihilation time		

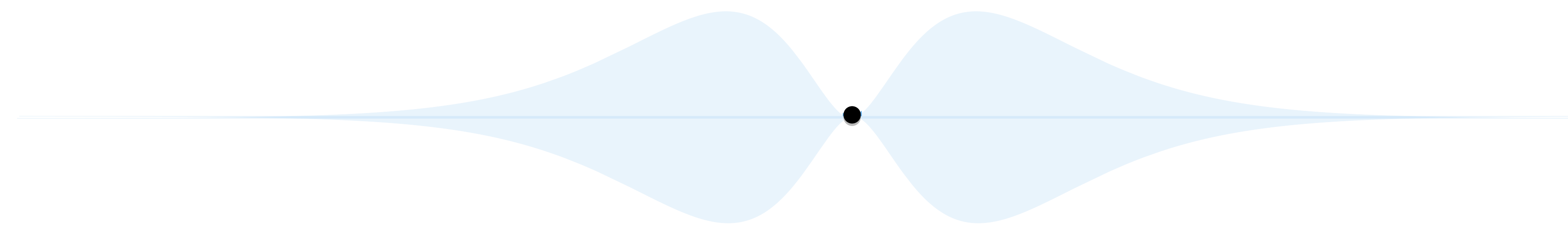
Superradiance Timescales

$$\alpha = G_{\rm N} M_{\rm BH} \mu_a = r_g \mu_a \lesssim \frac{m}{2} a_*$$

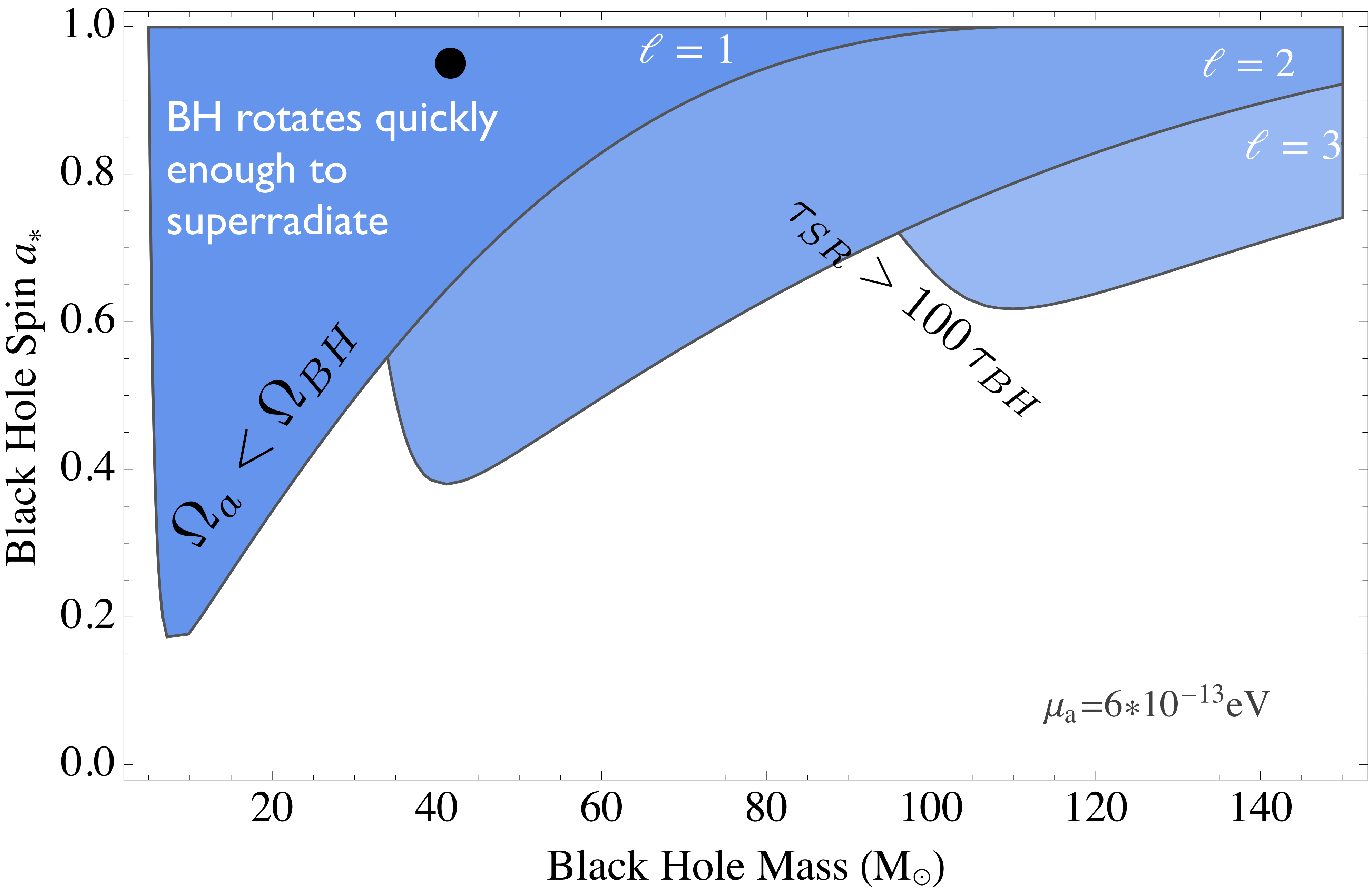
BH lightcrossing time	r_g	.01 ms
Particle wavelength	$\mu^{-1} = \frac{r_g}{\alpha}$	.1 ms
Cloud size	$r_c \sim \frac{n}{\alpha^2} r_g$	ms
Superradiance time	$\tau_{\rm sr} \sim \frac{c_{n\ell m}}{(m\Omega_{BH} - \mu) r_+} \frac{1}{\alpha^{4\ell+2j+5}} r_g$	100 s
Annihilation time		

Flux into horizon: $\Gamma_{\rm sr}^{\rm scalar} \sim \int_{r=r_g} \psi^* \psi \cdot dA$

Superradiance: a stellar black hole history



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



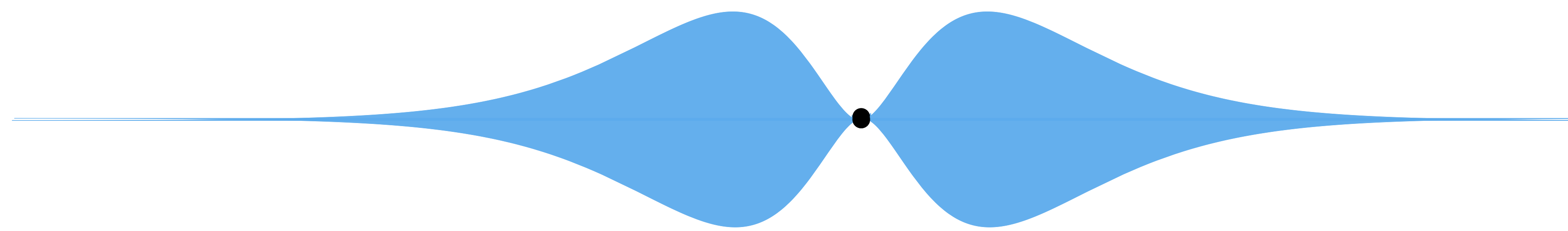
BH lightcrossing time

0.2 msec (60 km)

Particle wavelength

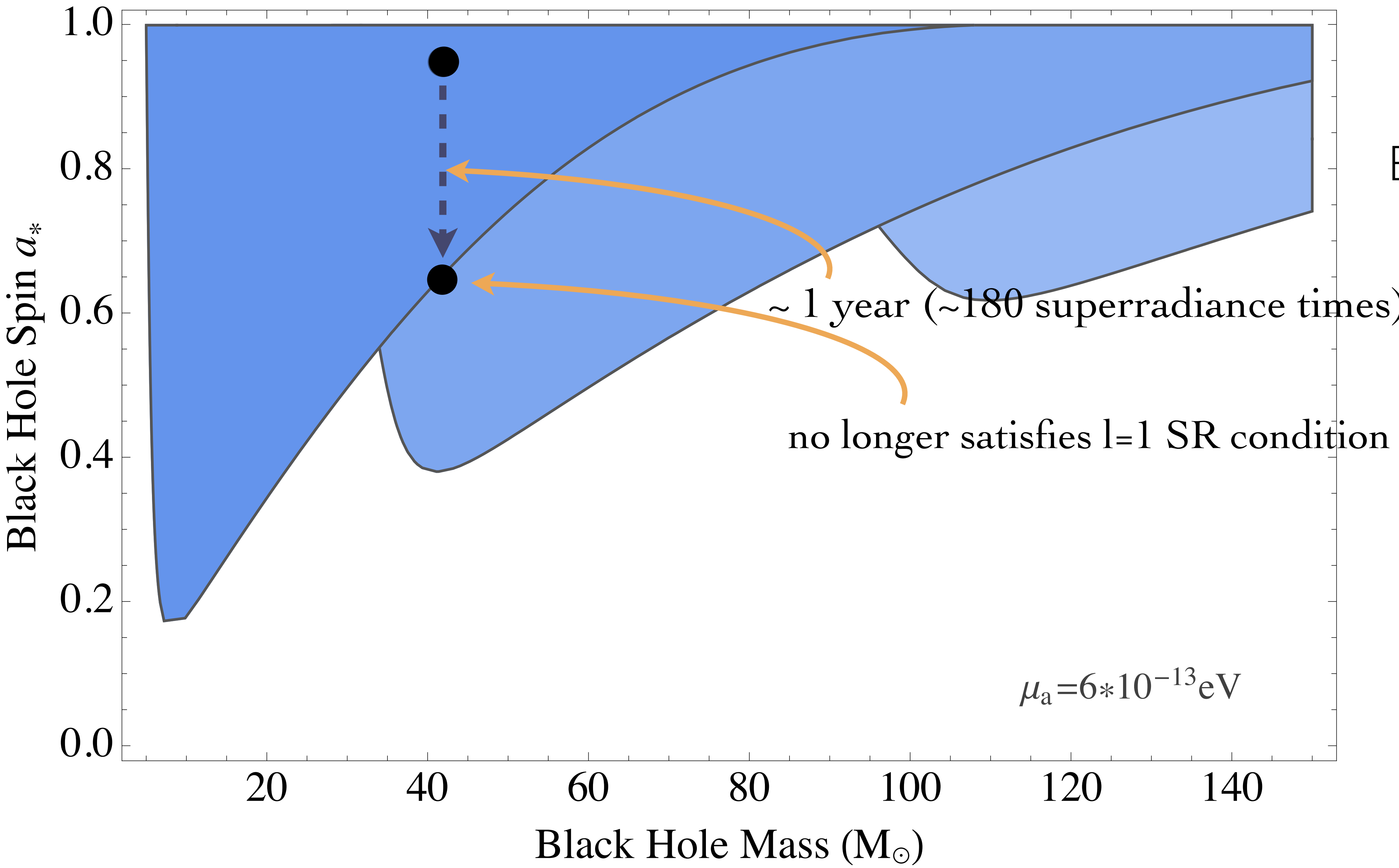
1 msec (300 km)

Superradiance: a stellar black hole history



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)

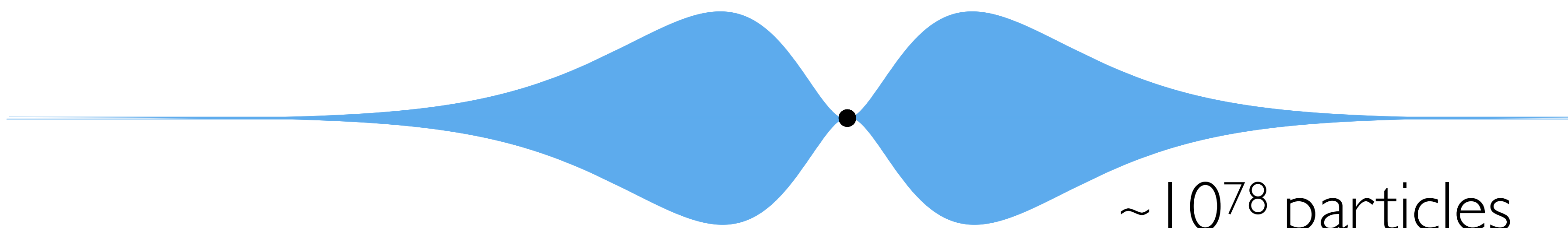
BH lightcrossing time

0.2 msec (60 km)

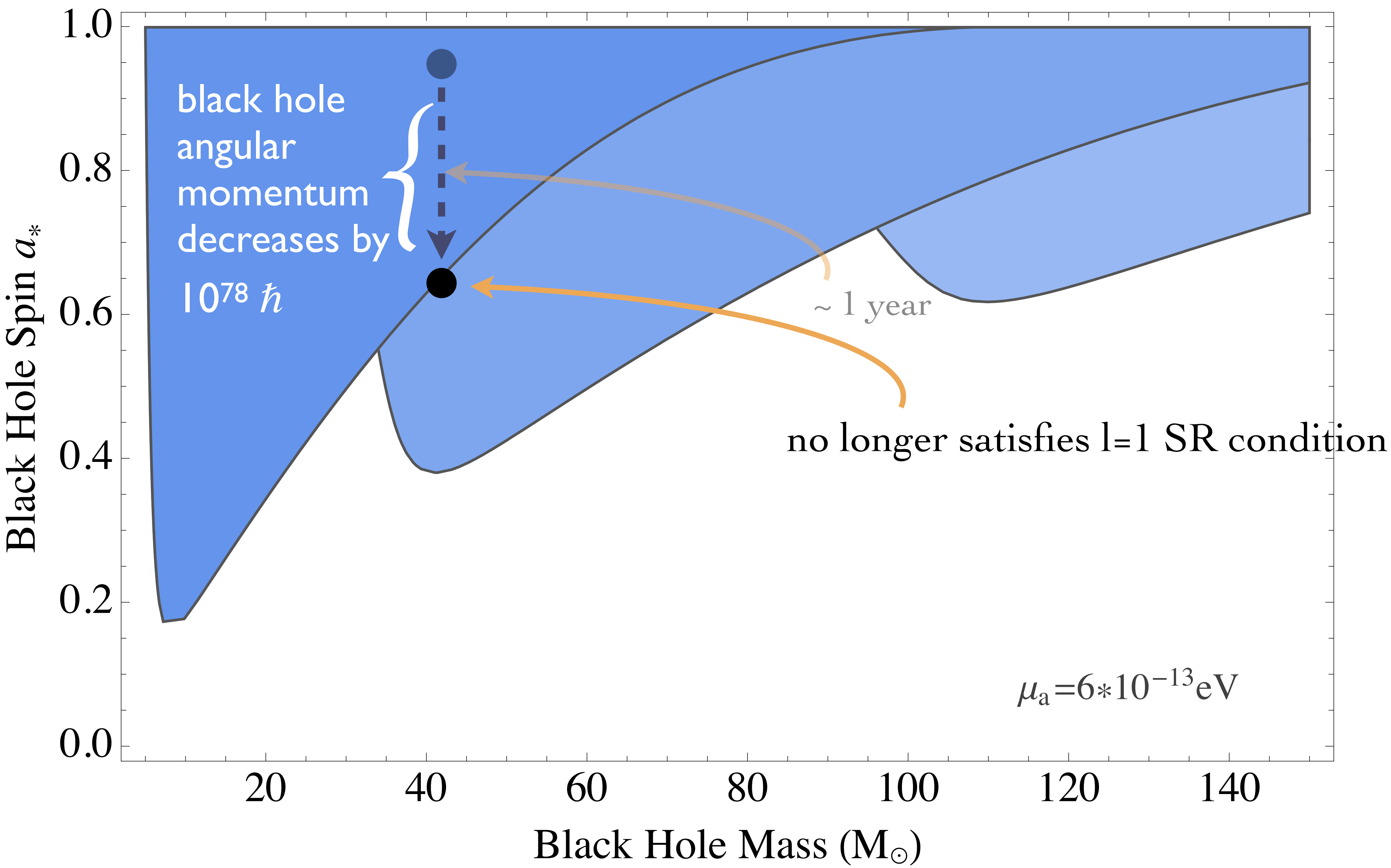
Particle wavelength

1 msec (300 km)

Superradiance: a stellar black hole history



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



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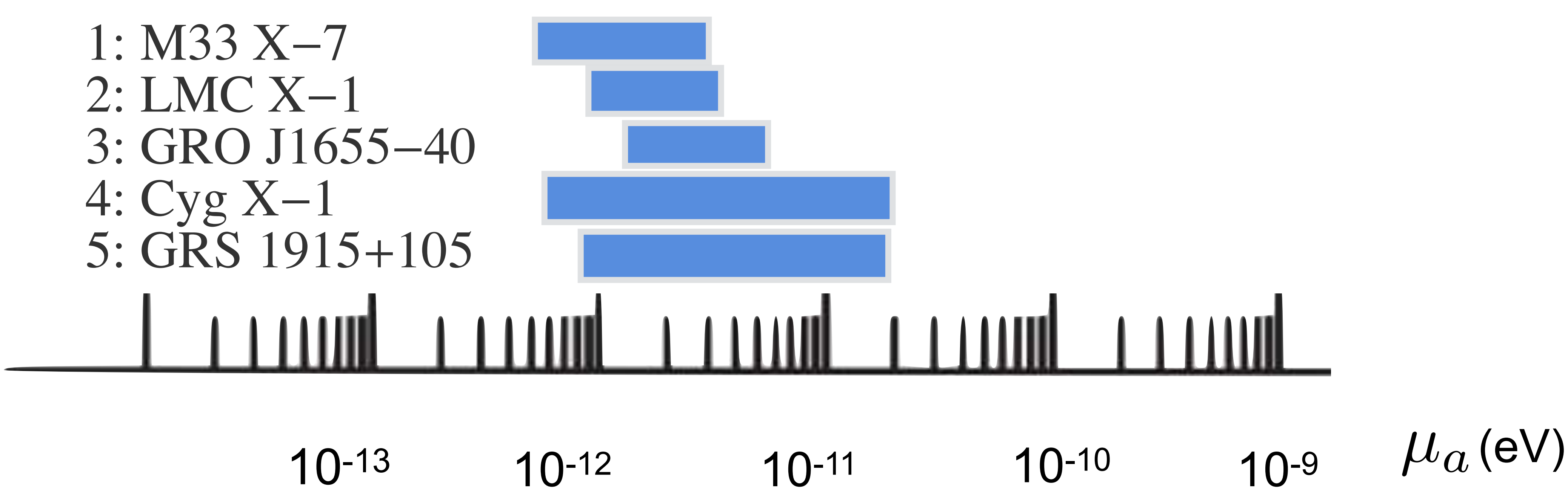
- The resulting bound states of light particles will source gravitational wave radiation that is observable by LIGO

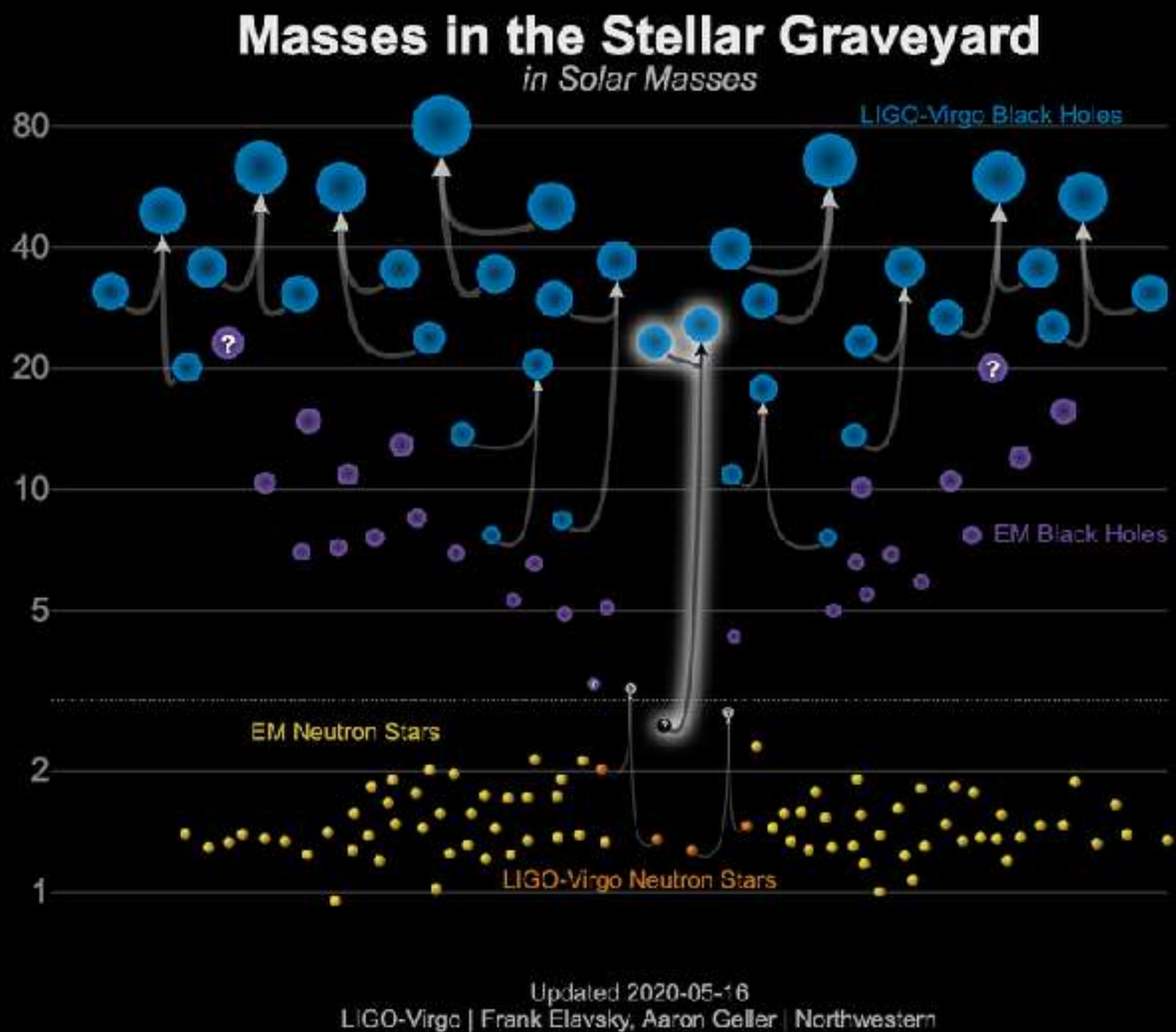
Black Hole Spins

Five currently measured black holes combine to set limit:

$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$$



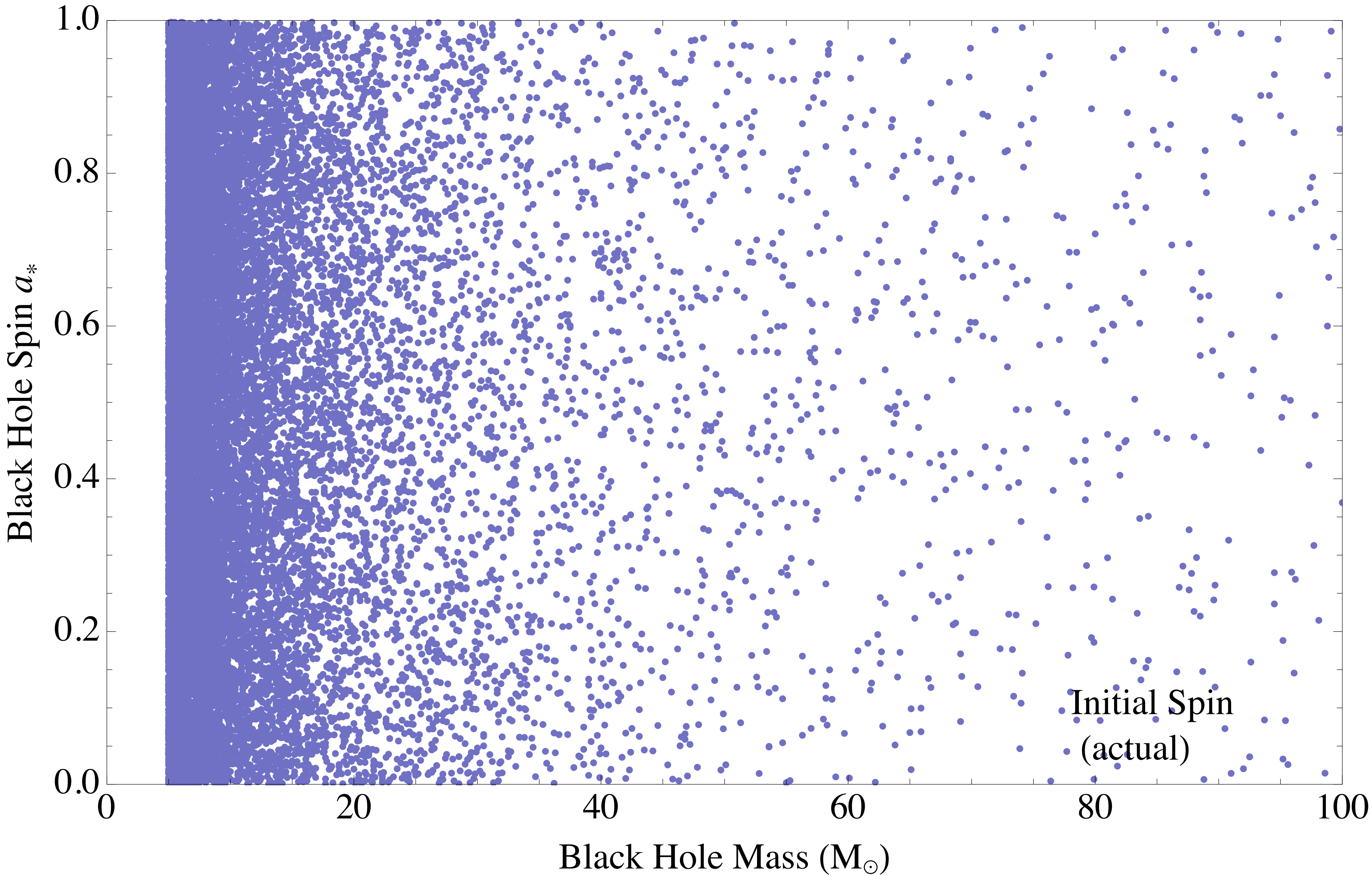
Many BH-BH mergers detected



Each detection comes with a measurement of the initial black hole masses, and, to a lesser extent, spins

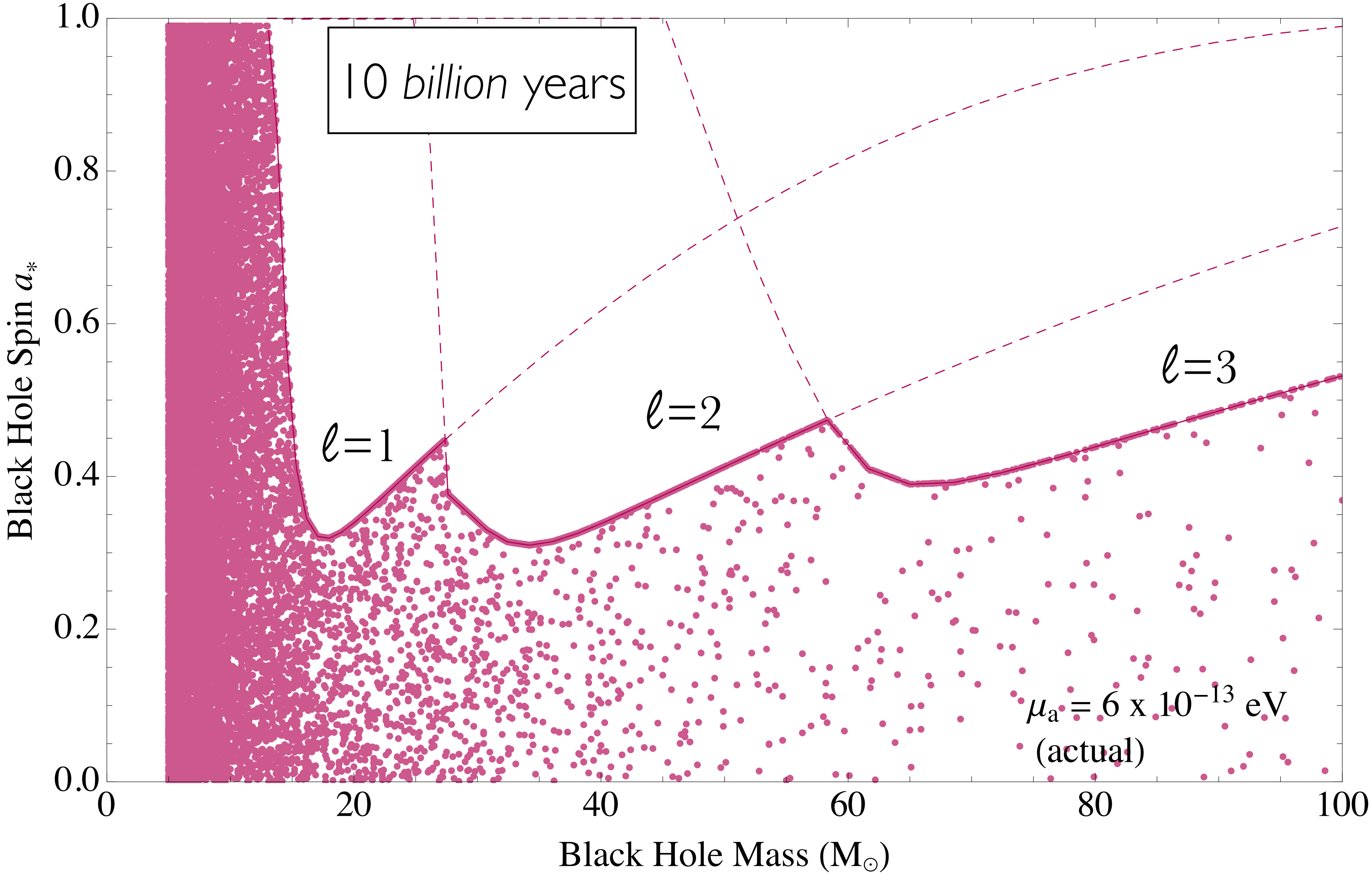
Black Hole Spins
at LIGO

9-240 BBHs/Gpc^3/yr. : 1000s of BHs merging in low-redshift universe



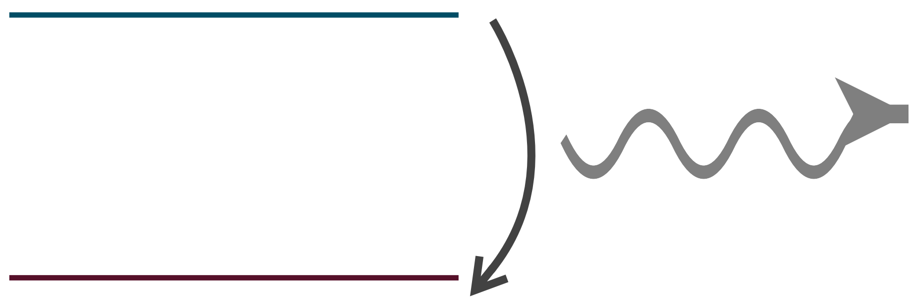
Black Hole Spins
at LIGO

If light axion exists, many initial BHs would have low spin due to superradiance, limited by age and radius of binary system

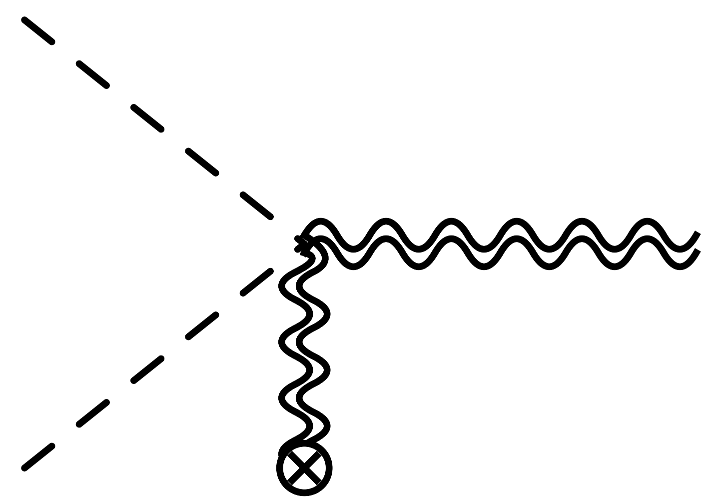


Gravitational Wave Signals

- Transitions between levels

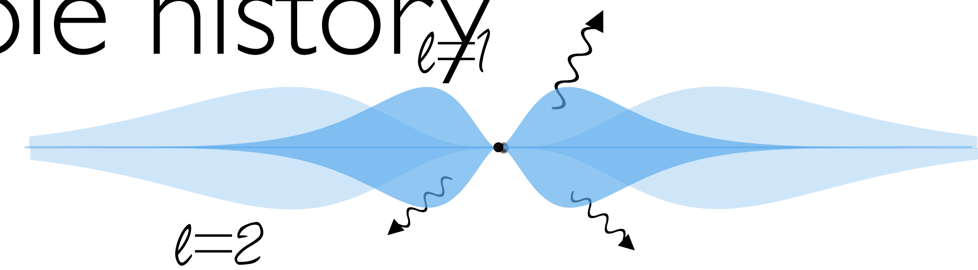


- Annihilations to gravitons

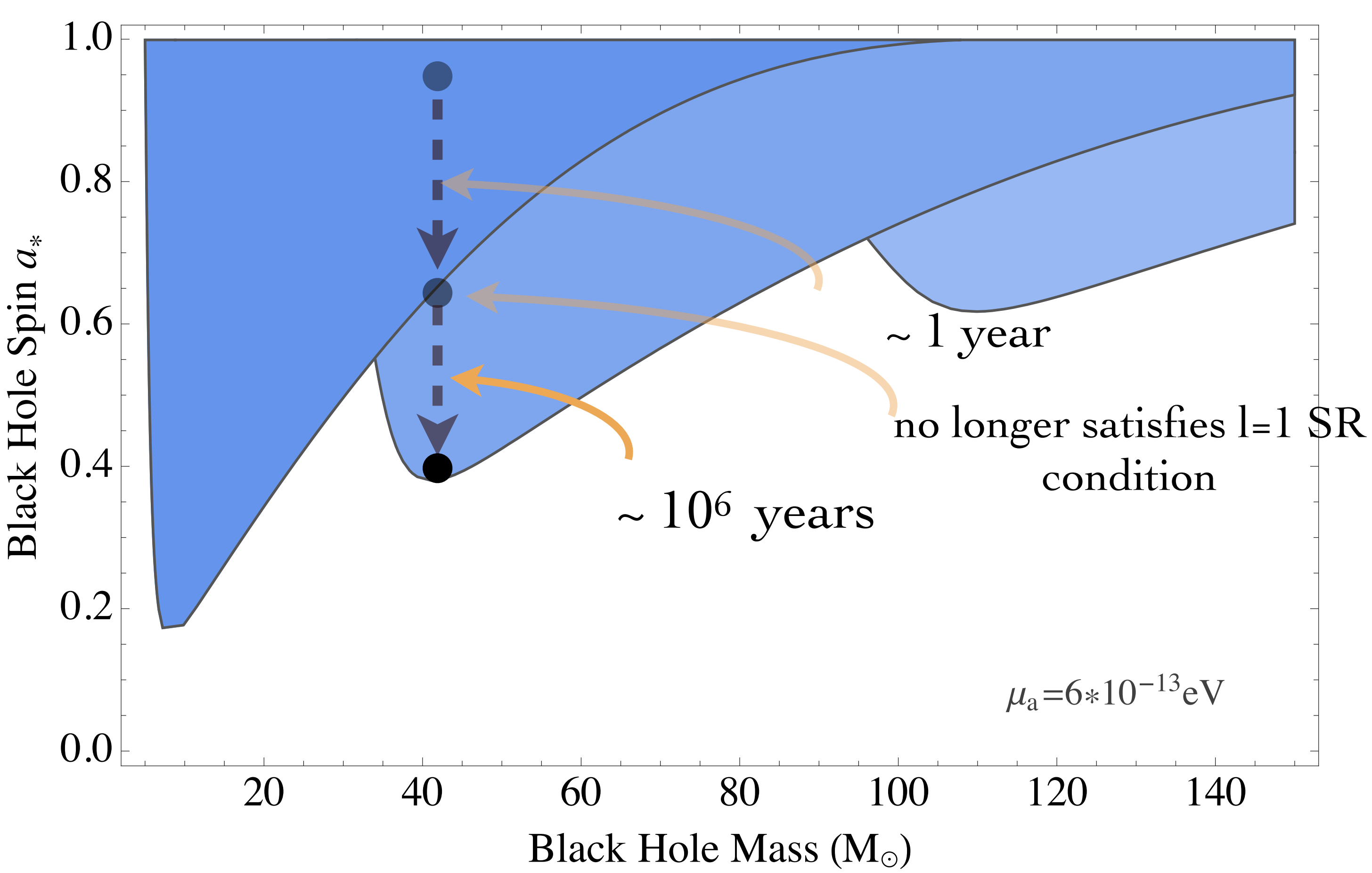


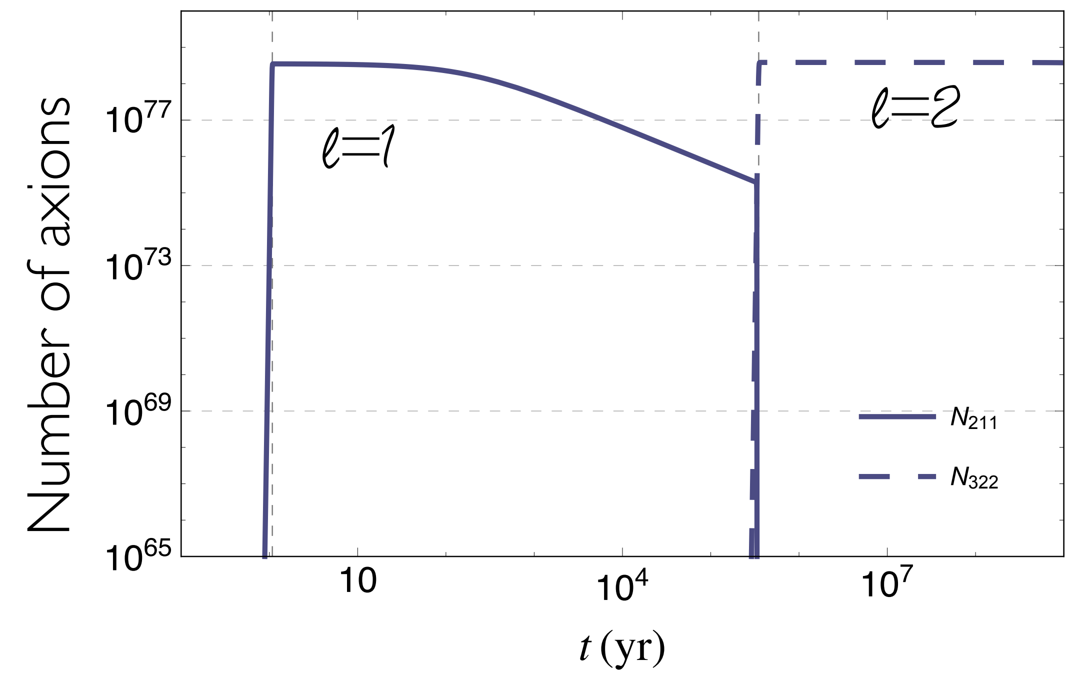
    - Signals coherent, monochromatic, last hours to millions of years

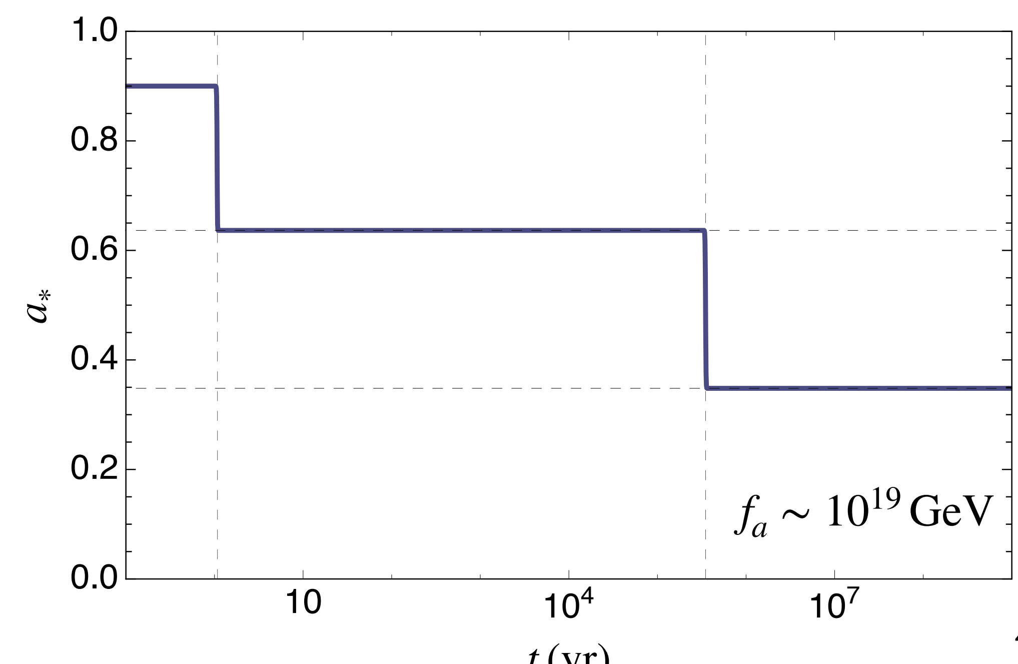
Superradiance: a stellar black hole history



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







Gravitational Wave Signals

- Gravitational wave strain emitted from a time-varying energy density

$$h_{ij} = \frac{2G}{r}\frac{d^2 I_{ij}}{dt^2}, \quad I_{ij} = \int T_{00} x^i x^j d^3x$$

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$$\phi = \frac{1}{\sqrt{2\mu}} \sum_i \sqrt{N_i} \left(\psi^i e^{-i\omega t} + \psi^{i*} e^{i\omega t} \right)$$

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Blackboard estimate for annihilations

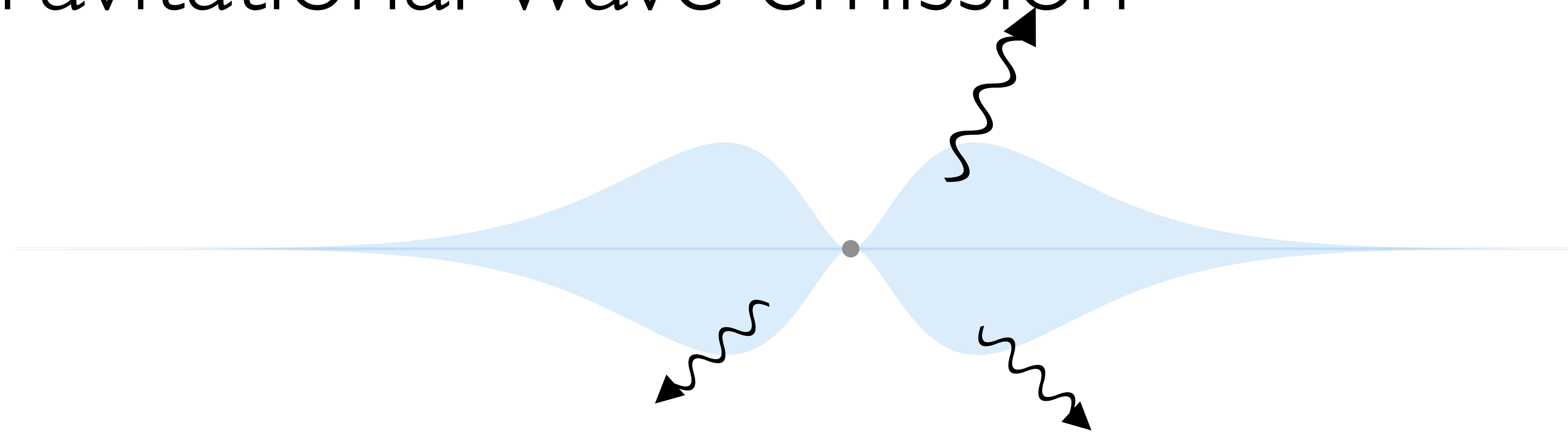
Superradiance Timescales

$$\alpha = G_{\rm N} M_{\rm BH} \mu_a = r_g \mu_a \lesssim \frac{m}{2} a_*$$

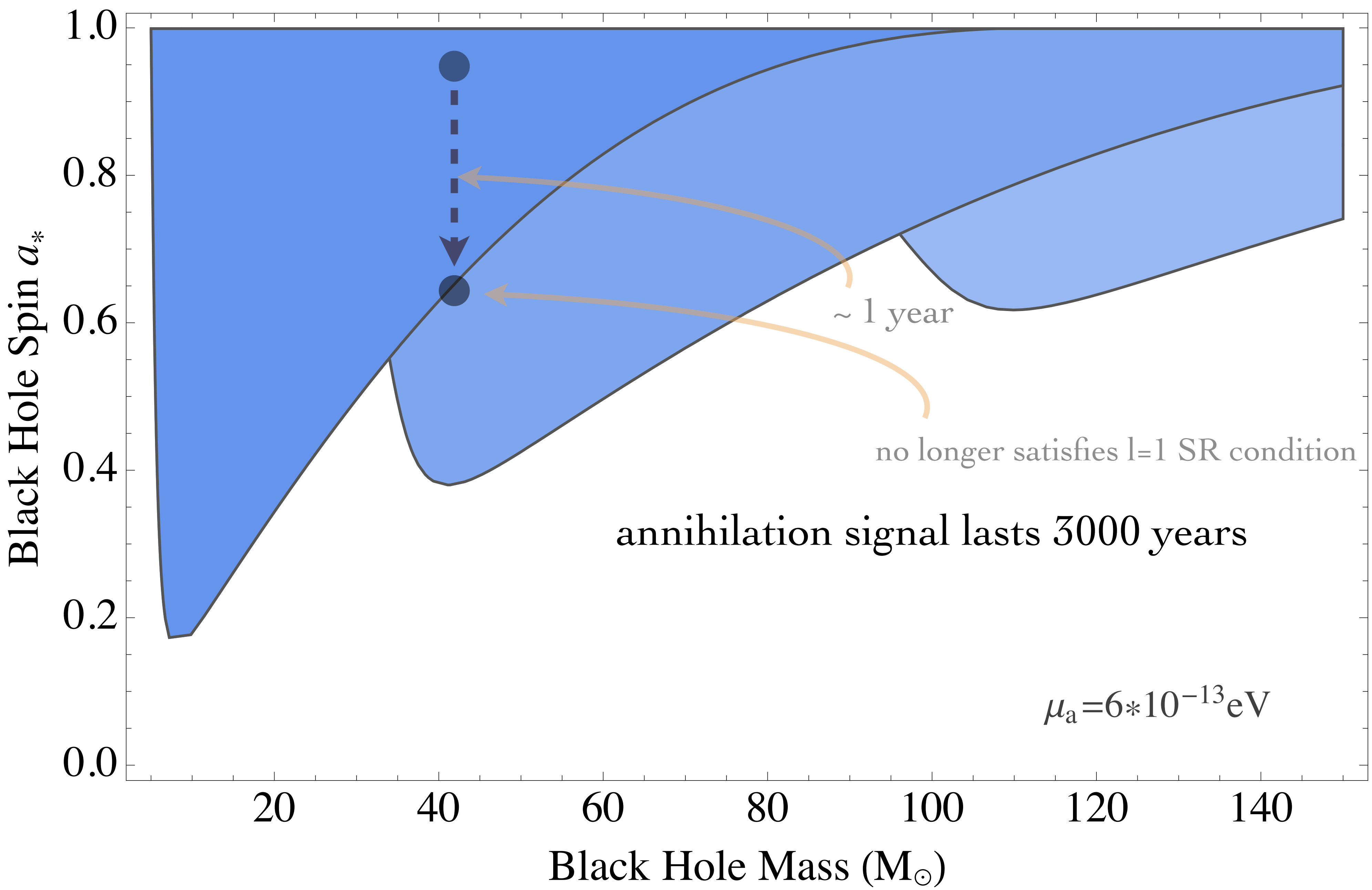
BH lightcrossing time	r_g	.01 ms
Particle wavelength	$\mu^{-1} = \frac{r_g}{\alpha}$	.1 ms
Cloud size	$r_c \sim \frac{n}{\alpha^2} r_g$	ms
Superradiance time	$\tau_{\rm sr} \sim \frac{c_{n\ell m}}{(m\Omega_{BH} - \mu) r_+} \frac{1}{\alpha^{4\ell+2j+5}} r_g$	100 s
Annihilation time	$\tau_{ann} \propto \frac{1}{\alpha^{4\ell+11}} r_g$	.1 year

Gravitational Wave Power: $P_{GW} \sim G_N \omega^2 \overline{T}_{ij}(\omega, k) \overline{T}^*_{ij}(\omega, k)$

Superradiance: gravitational wave emission



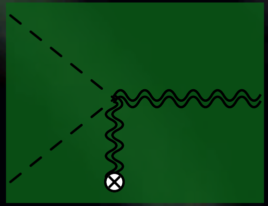
Cloud of axions sources coherent, monochromatic gravitational waves

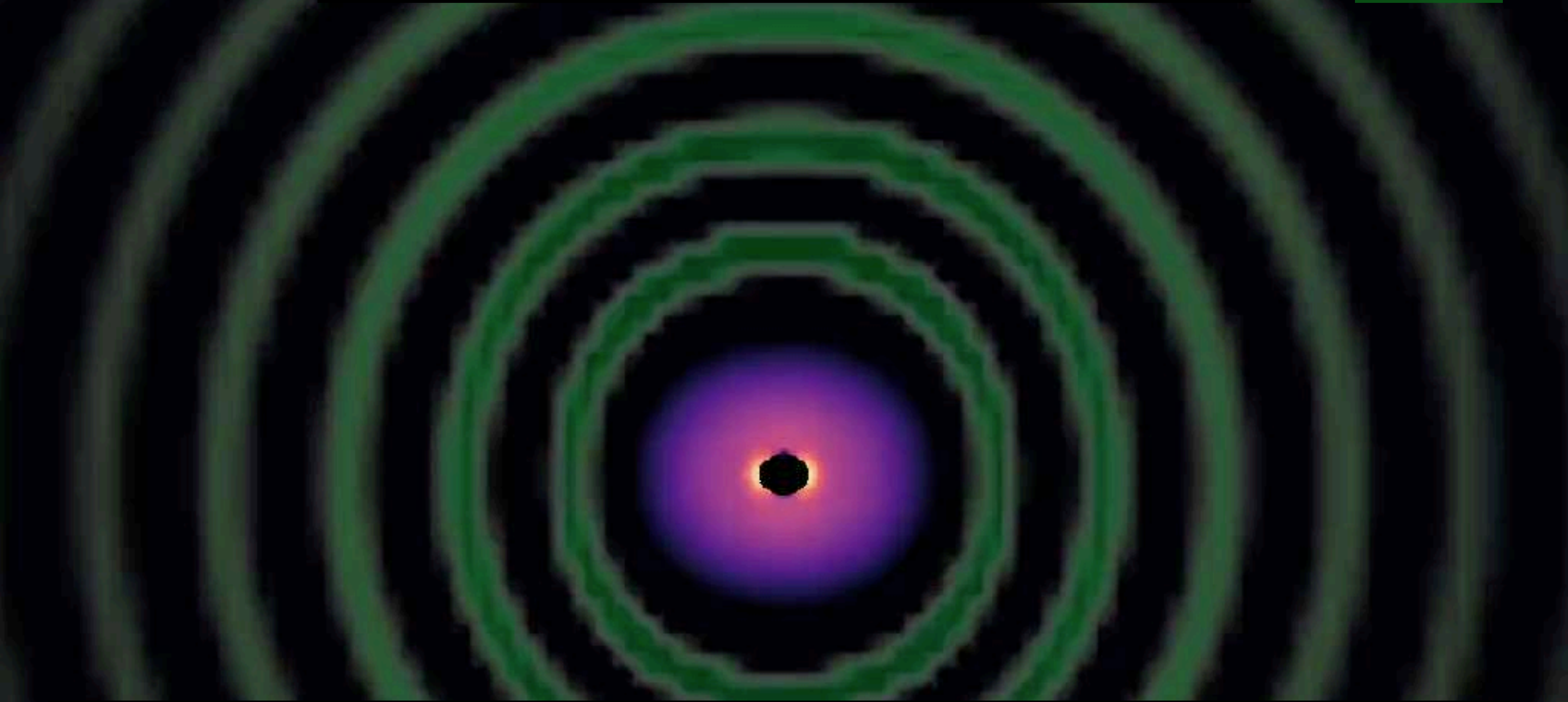


Gravitational wave frequency is set by twice the axion energy

Emission can be observed in LIGO continuous wave searches

Gravitational Wave Signals





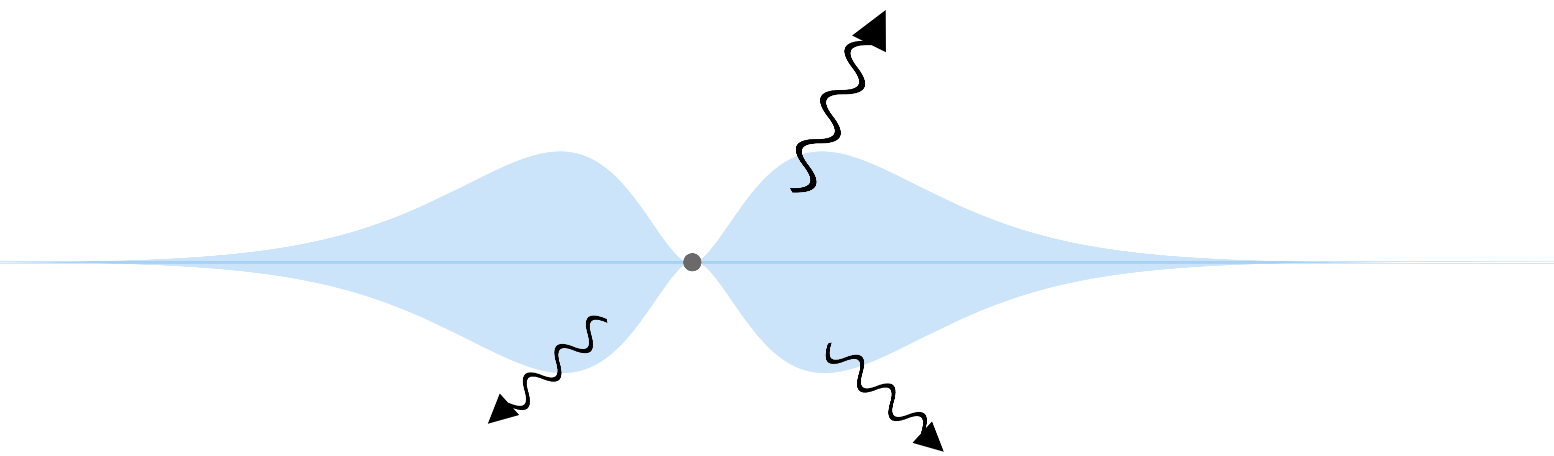
Time-varying energy density sources gravitational waves:

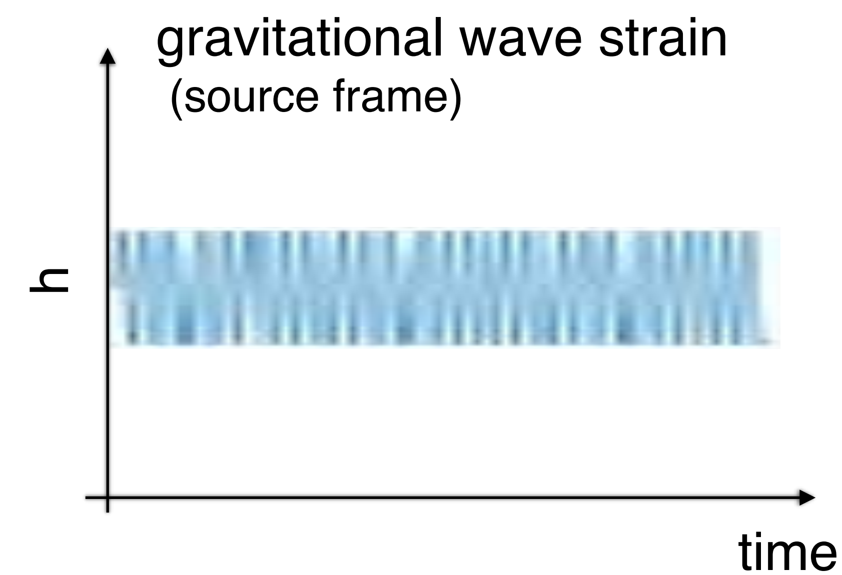
two bosons annihilating into gravitational waves

- coherent and monochromatic:
- fit into searches for long, continuous, monochromatic gravitational waves ("mountains" on neutron stars)

Numerical GR simulation by Will East

Gravitational Wave Signals

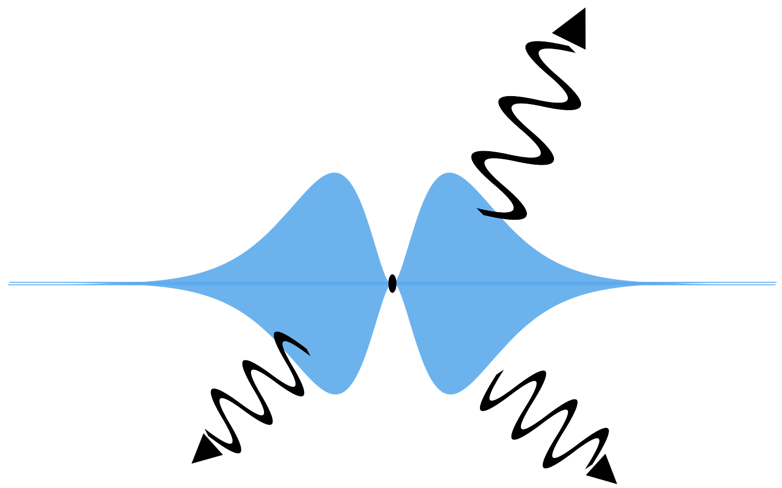


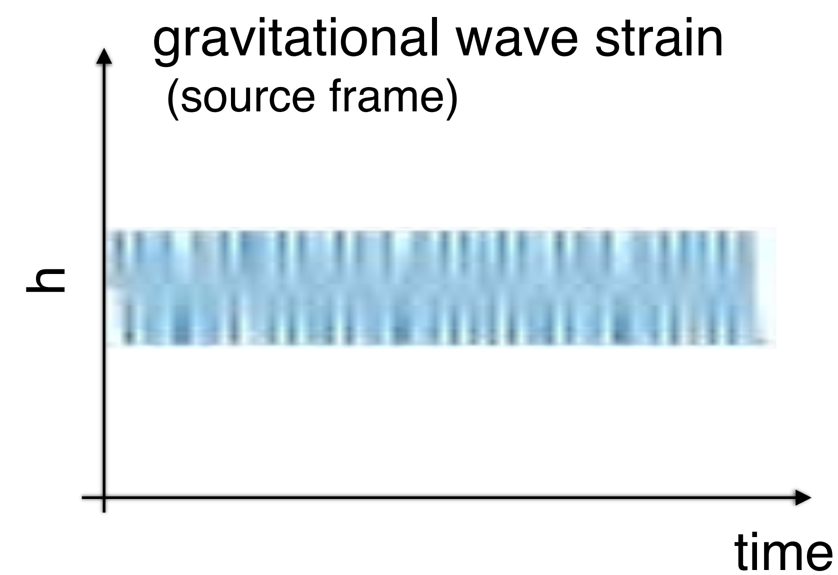


- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to 10,000 — can be observed and studied in detail

Arvanitaki, **MB**, Huang (2015)
Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
Brito et al (2017)

Gravitational Wave Signals





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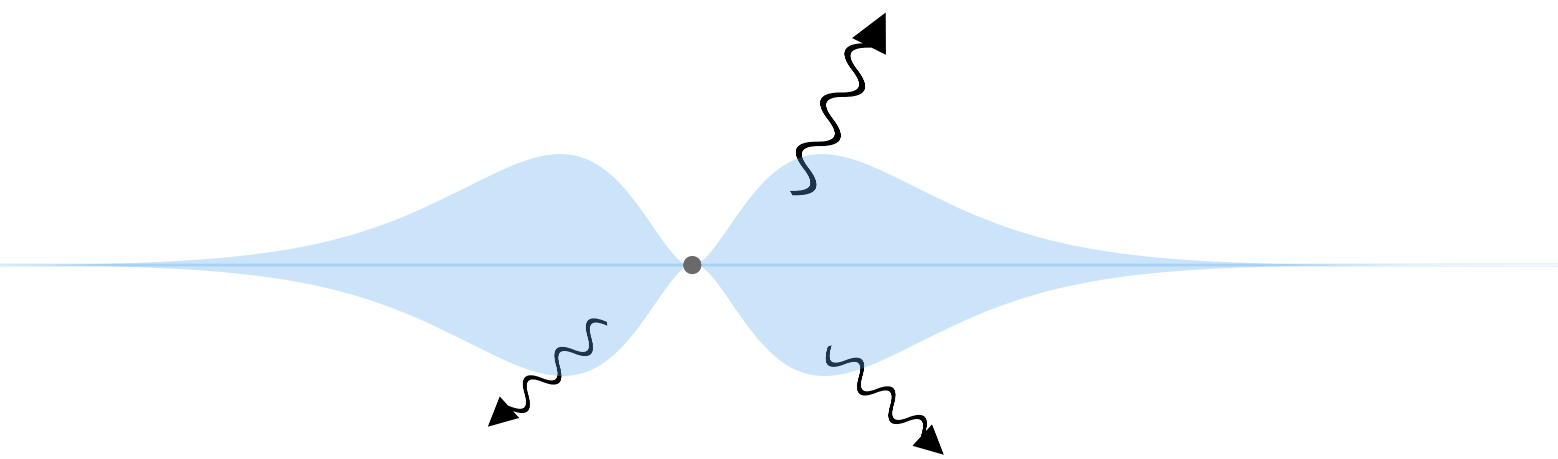
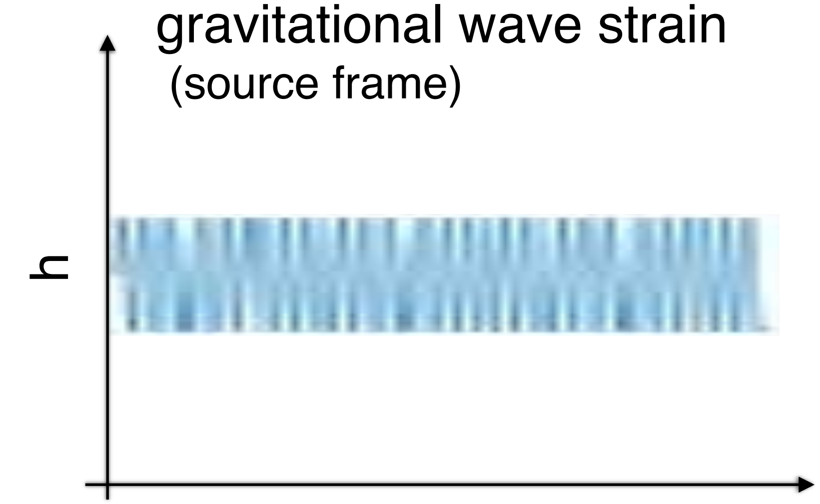
- **Loud, short signals** last for ~ days - months, observable from BBH or NS-NS merger events
  - Event rates <1/year at design aLIGO sensitivity, up to 100's at future observatories

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

Gravitational Wave Signals





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Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2020)

what are the near-term prospects of detection?

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Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
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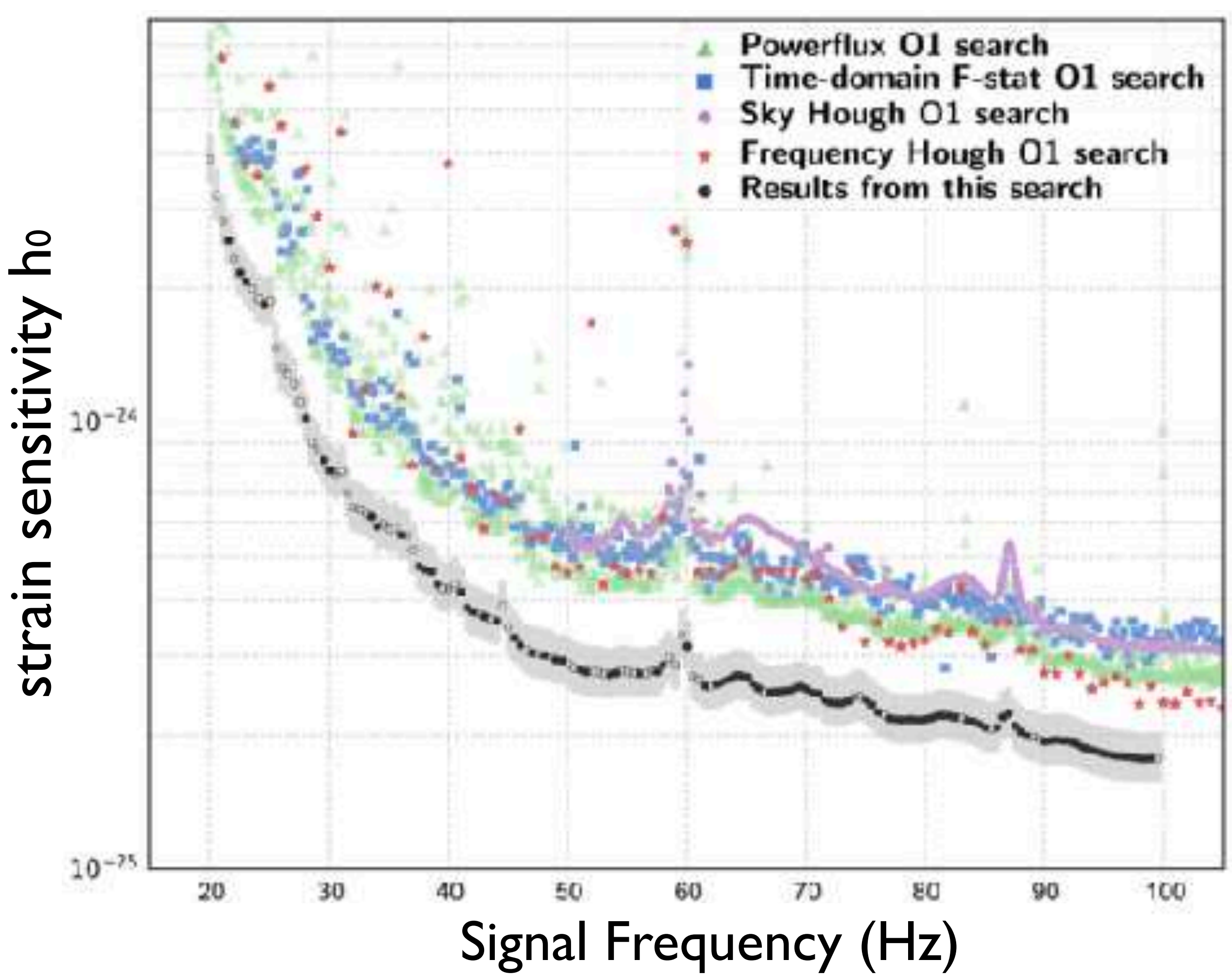
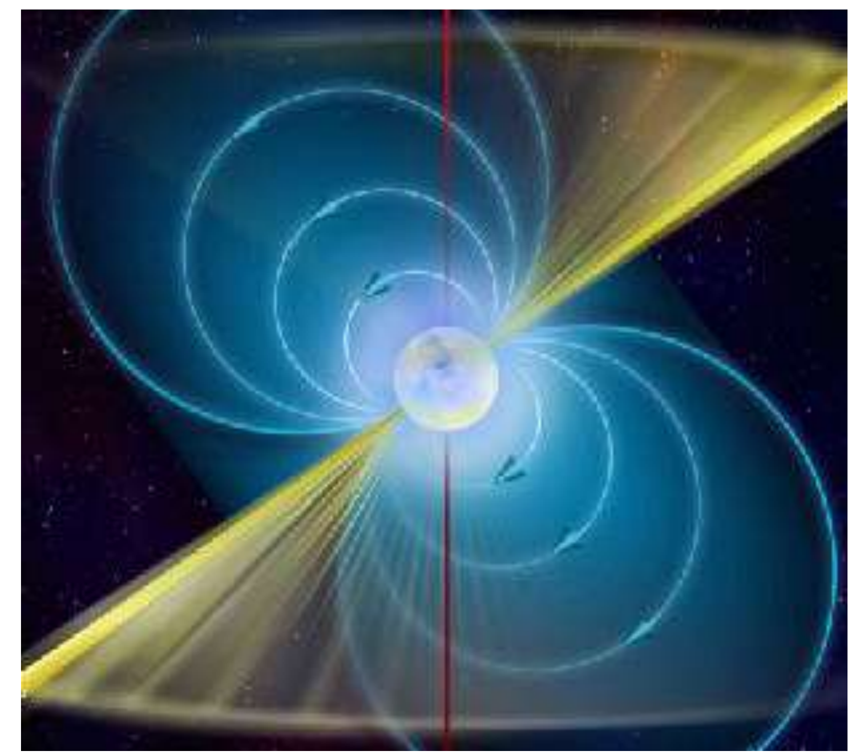
Gravitational Wave Searches

- 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

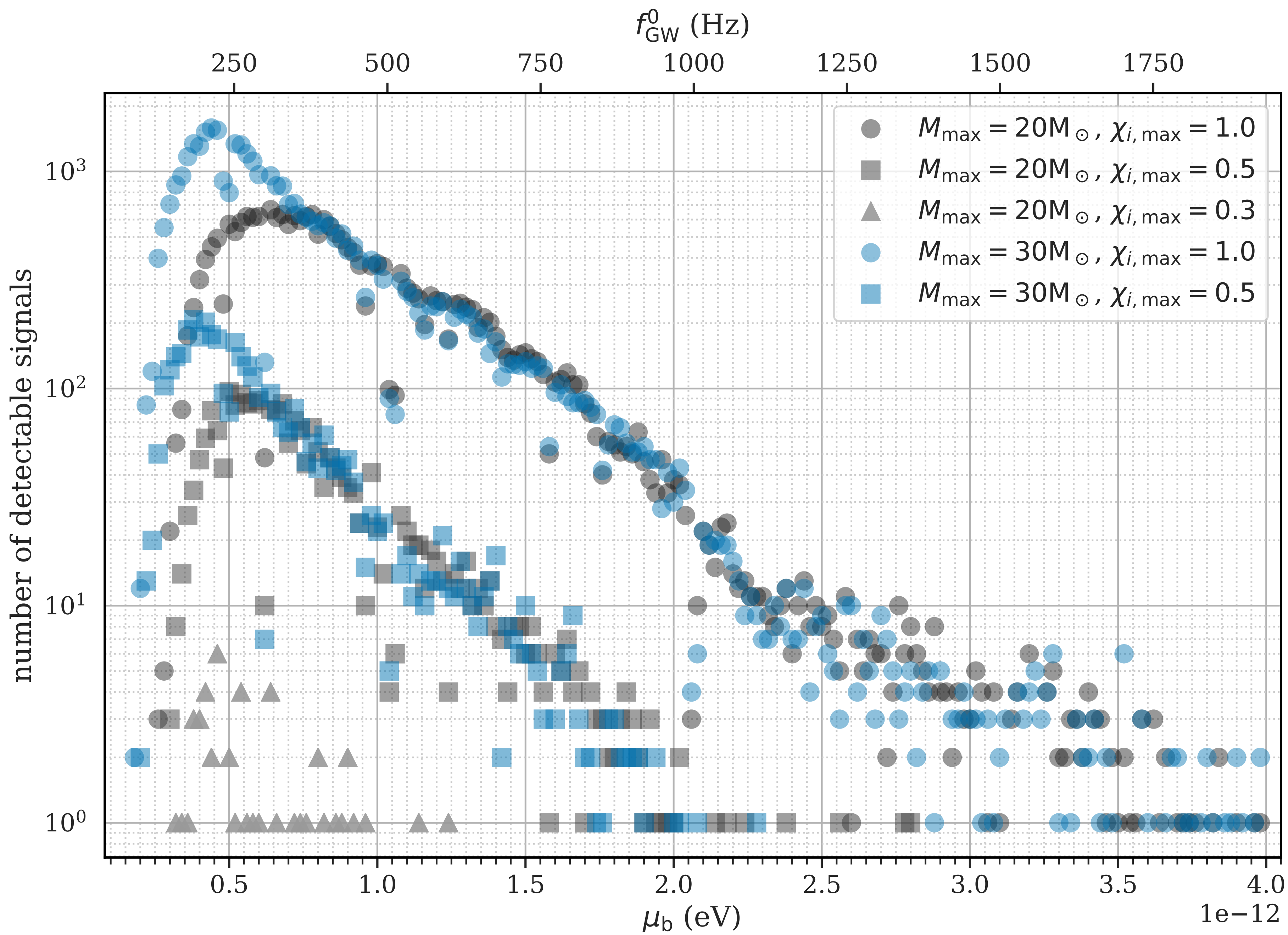


Abbott et al PRD 96, 122004 (2017)



Cambridge University Lucky Imaging Group

Gravitational Wave Signals

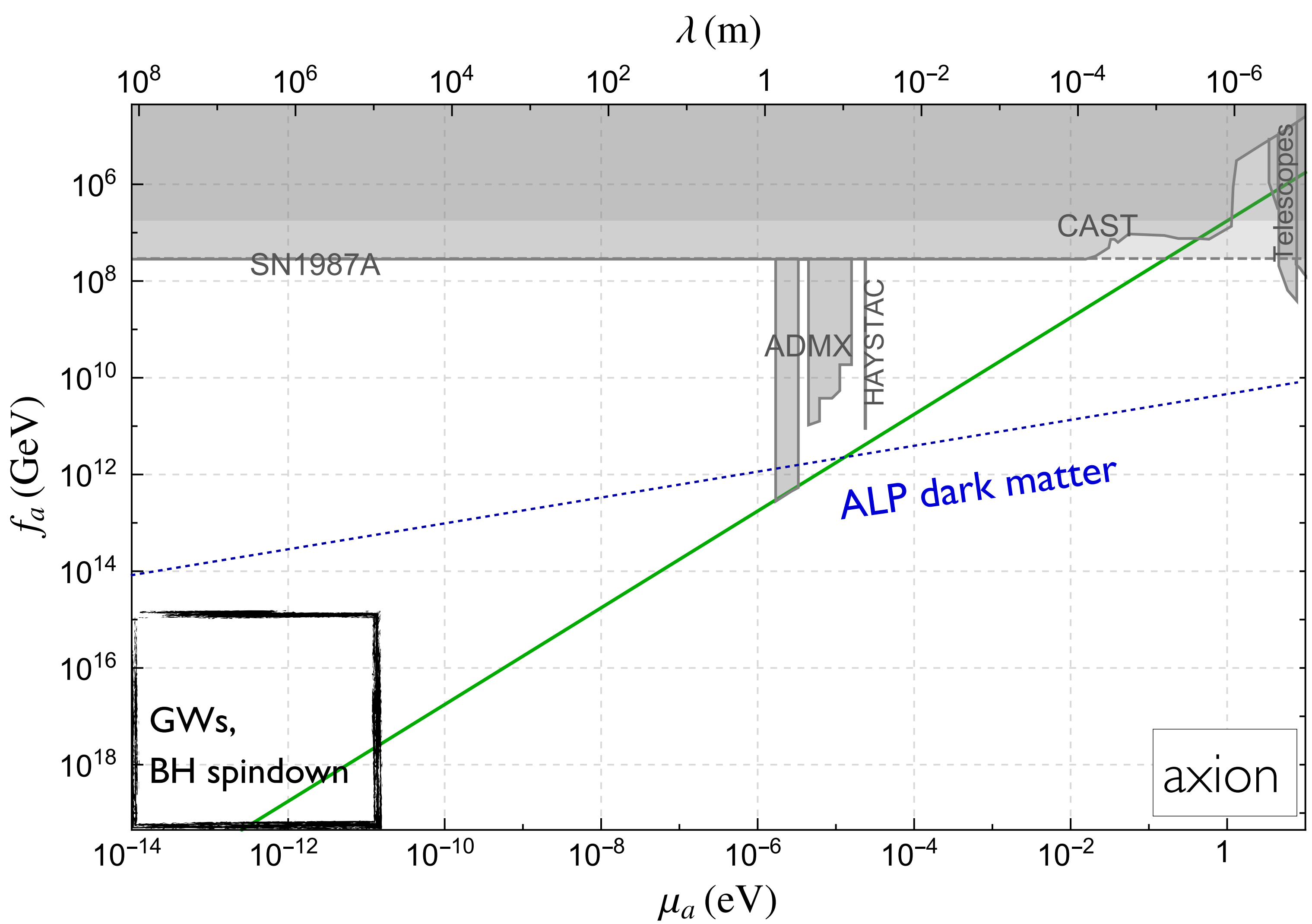


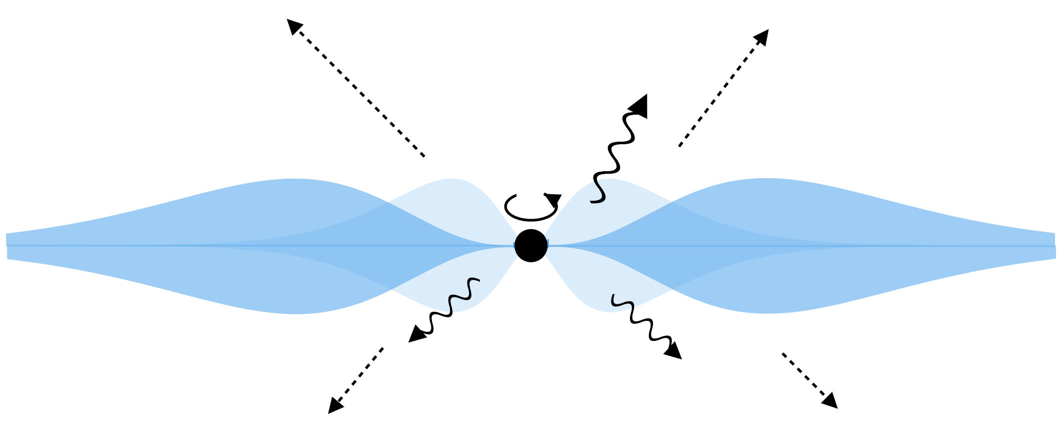
- **Weak, long signals** last for ~ million years, visible from our galaxy
- Very sensitive to number of rapidly rotating black holes
- Weak dependence on mass distribution except at low axion masses

- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- See also papers by Brito et al on stochastic searches for these signals when many signals are present

New Physics with Gravitational Waves

- If ultralight axions (bosons) exist, 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





GRAVITATIONAL WAVES: FROM DETECTION TO NEW PHYSICS SEARCHES

- Detection at LIGO and physics of LIGO
- Pulsar timing for GWs and ultralight scalar DM
- Axion clouds around black holes and GWs

Potentially new discoveries await!