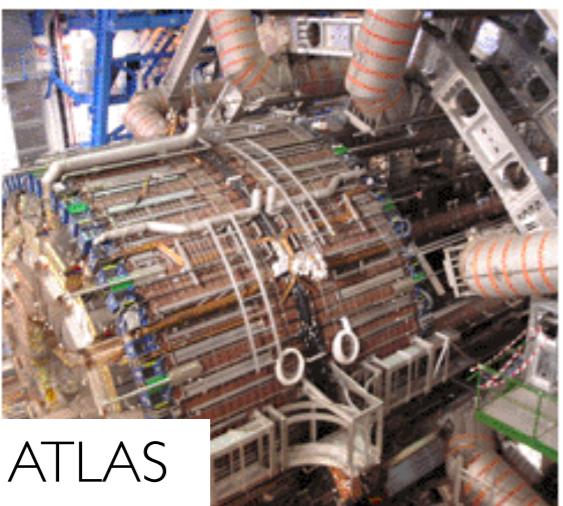


# Searching for Axions and Dark Photons with Black Holes and Gravitational Waves

Masha Baryakhtar  
New York University  
Oct 24 2019

# Searching for New Physics

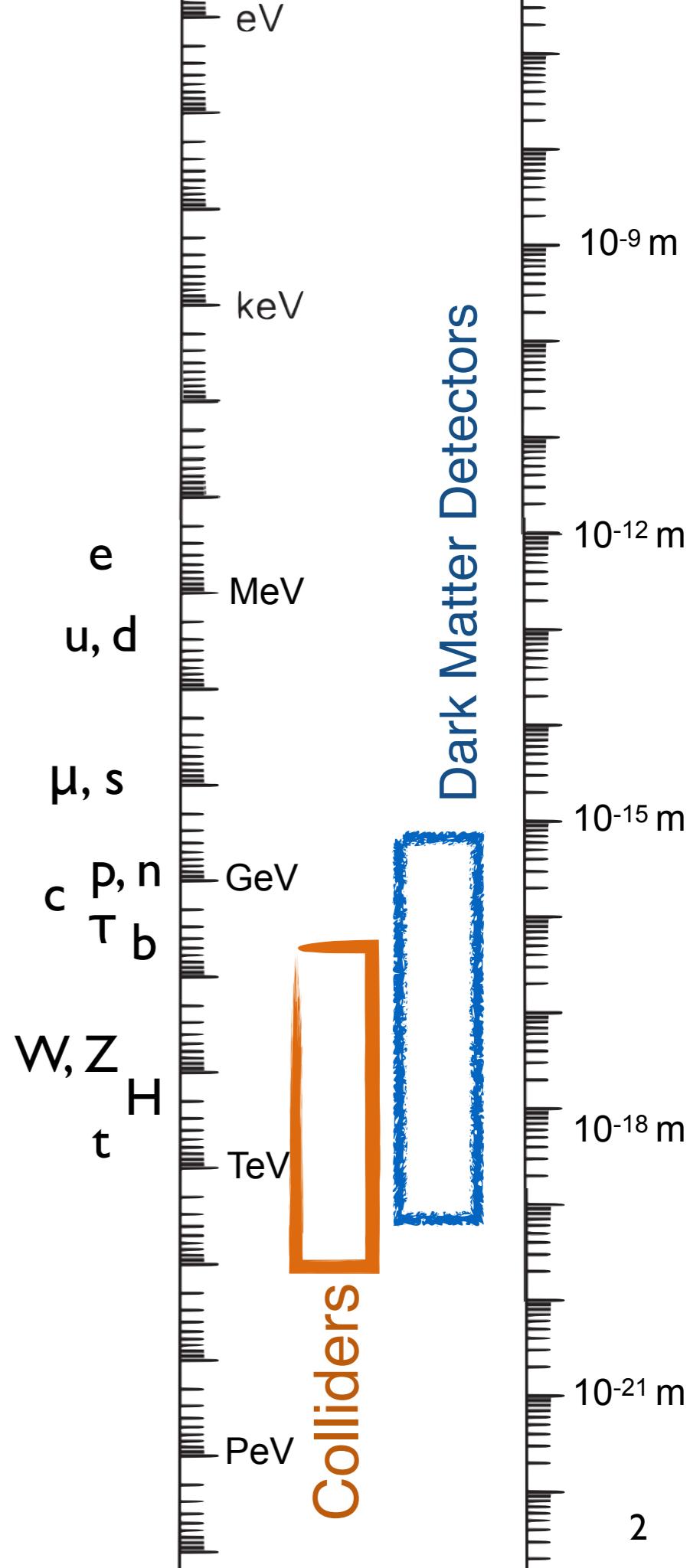
- Most of the standard model lies within several orders of magnitude in mass
- Other scales must appear in a complete theory
  - Planck scale, neutrino masses, dark matter, dark energy...



ATLAS



XENON

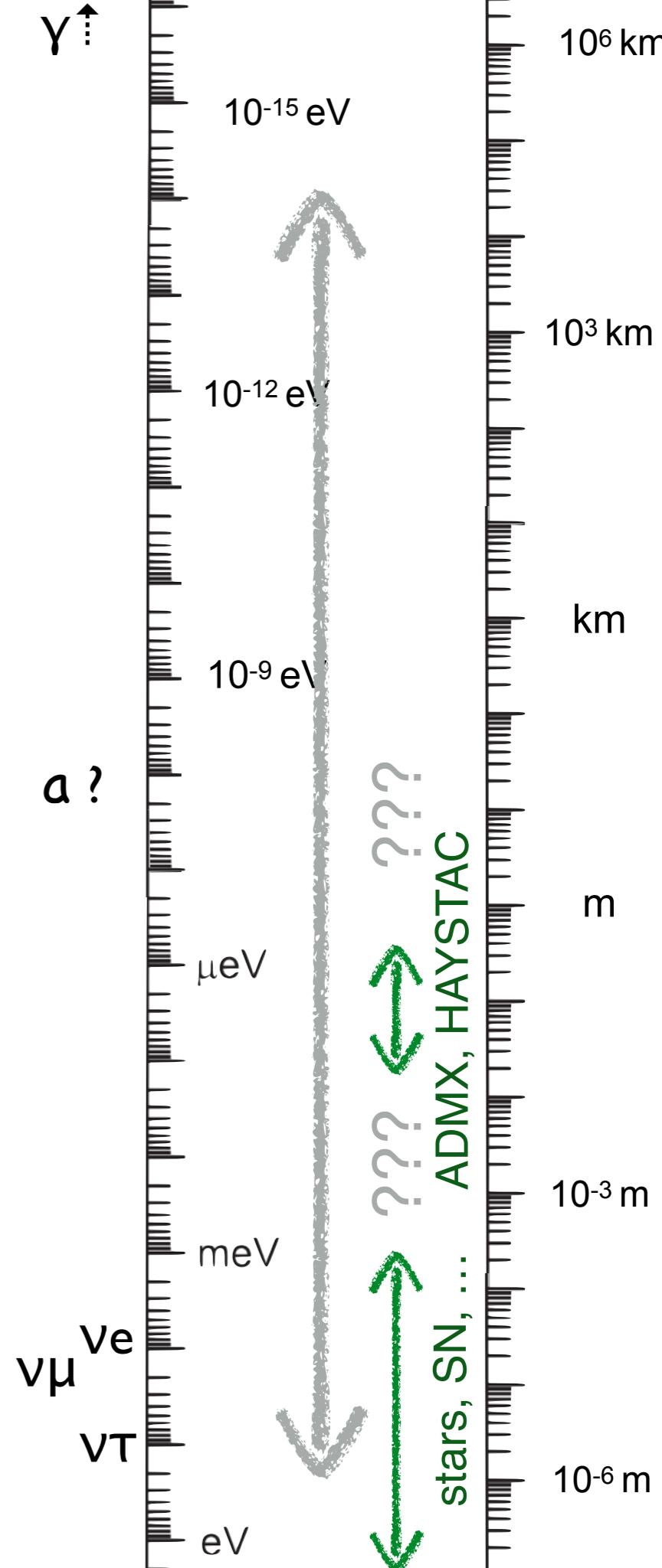


Colliders

Dark Matter Detectors

# Searching for New Physics

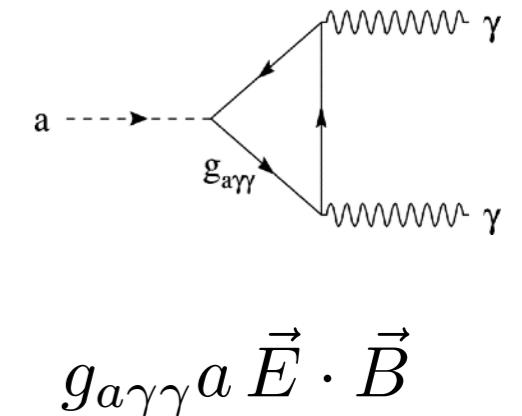
- Most of the standard model lies within several orders of magnitude in mass
- Other scales must enter in a complete theory
- Outstanding problems motivate searches at low energies
- Dark matter, strong-CP problem,...
  - QCD axion
  - Dilatons, moduli, dark photons, ...
  - Very weakly interacting
  - Long wavelength



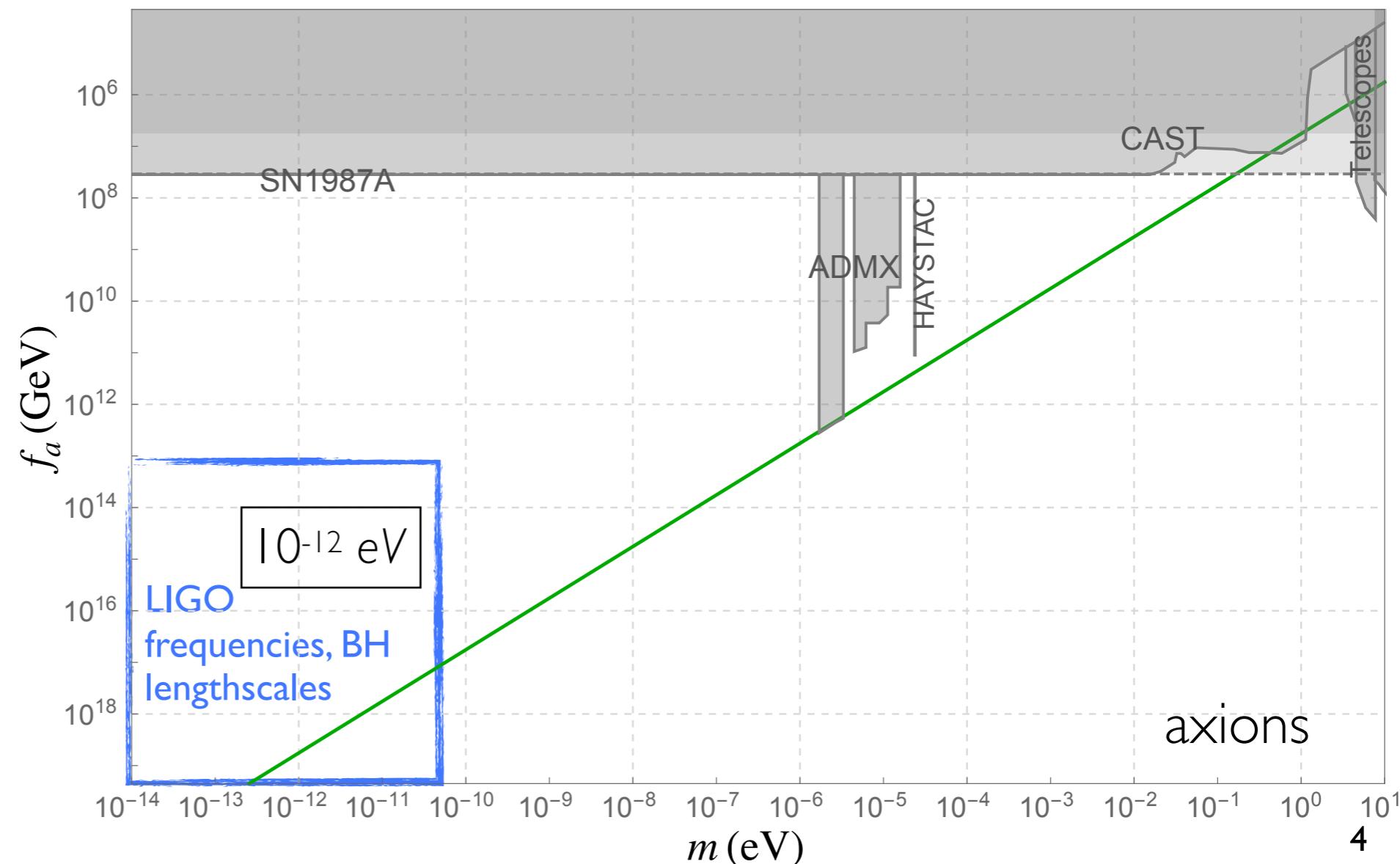
# Searching for axions

- Wide parameter space of weakly coupled, light particles

- Axions generically couple to photons: opens new search strategies with recent technological advances



- ‘High-scale’ axions theoretically motivated: ultraweak couplings and length-scales not accessible in the laboratory

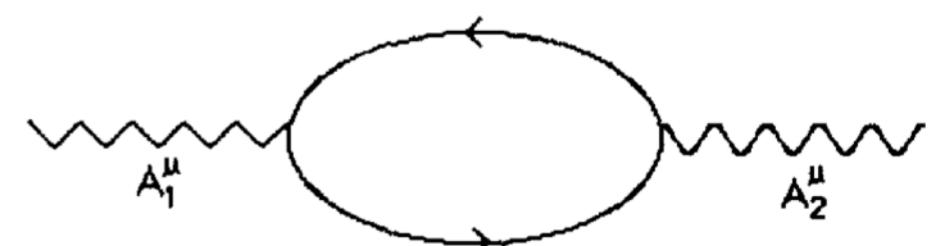
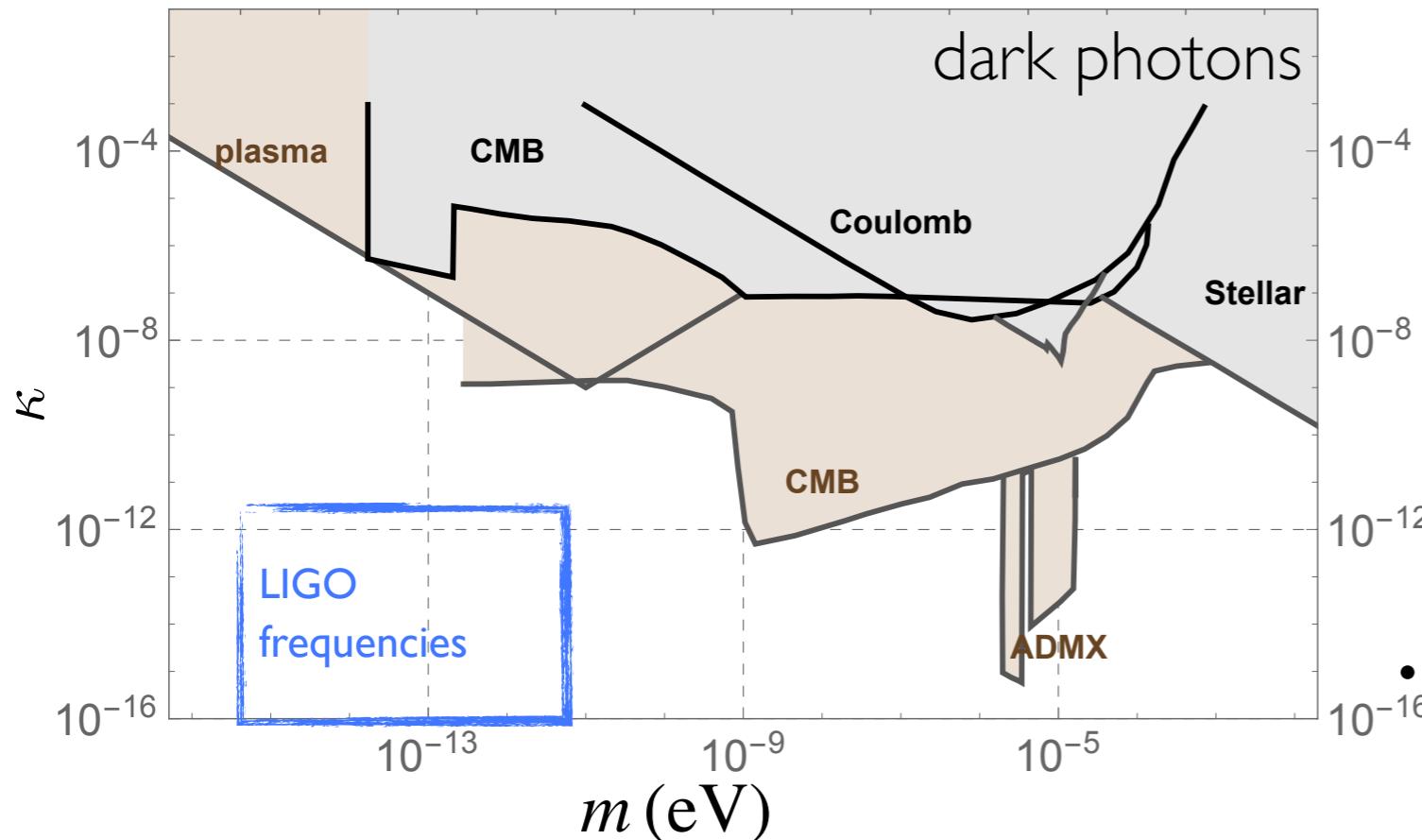


# Cousins of the QCD Axion: Dark Photons

- Gauge fields with an additional index give rise to light dark photons in 4D
  - Cicoli, Goodsell, Jaeckel, Ringwald [1103.3705]
  - Arvanitaki, Craig, Dimopoulos, Dubovsky, March-Russell [0909.5440]
- Long-lived dark matter candidate; produced through inflationary fluctuations at high scales

$$\frac{\rho_{\text{dp}}}{\rho_{\text{cdm}}} \sim \left( \frac{m}{\text{eV}} \right)^{1/2} \left( \frac{H_I}{5 \times 10^{12} \text{GeV}} \right)^2$$

Graham, Mardon, Rajendran [1504.02102]



$$-\frac{1}{4} F'_{\mu\nu}^2 + \frac{\kappa}{2} F_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_A^2 A_\mu'^2$$

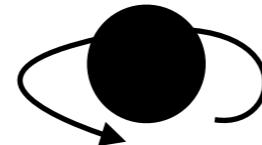
- Dark photons mix with SM photon via kinetic term

# Outline

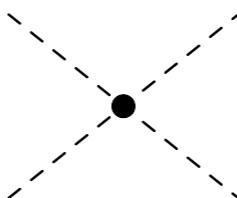
- Black Hole Superradiance



- Gravitational Signatures

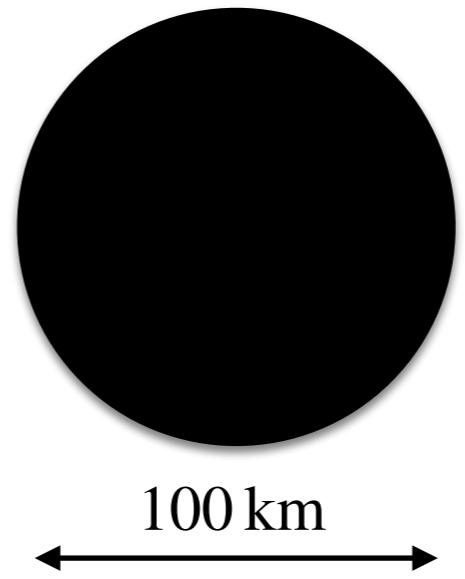


- Axion Self-Interactions

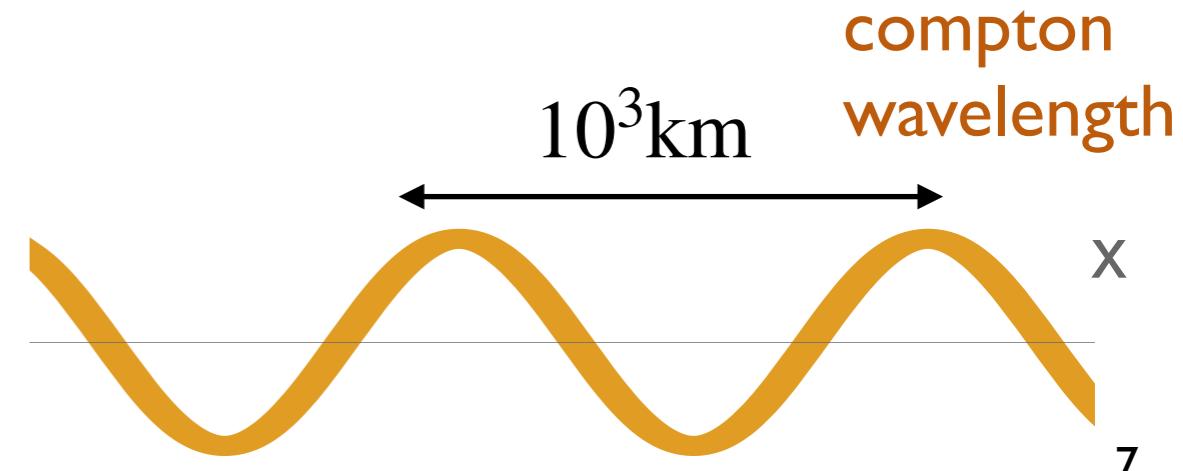
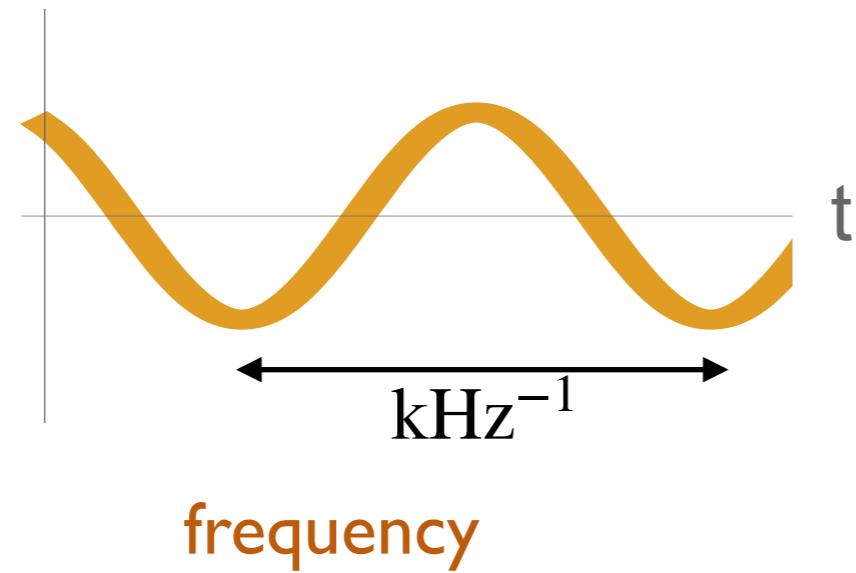


# Astrophysical Black Holes and Ultralight Particles

- 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  $f_a$

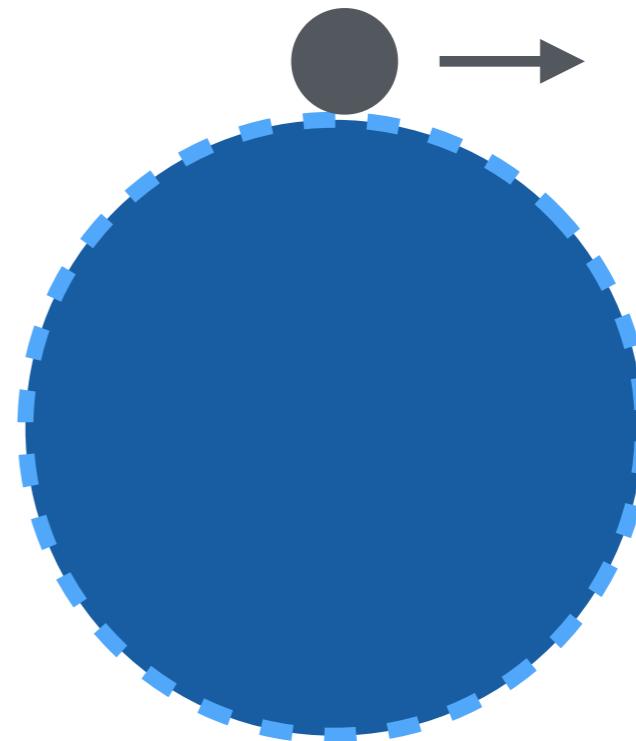


black hole ( $30 M_\odot$ )



# Superradiance

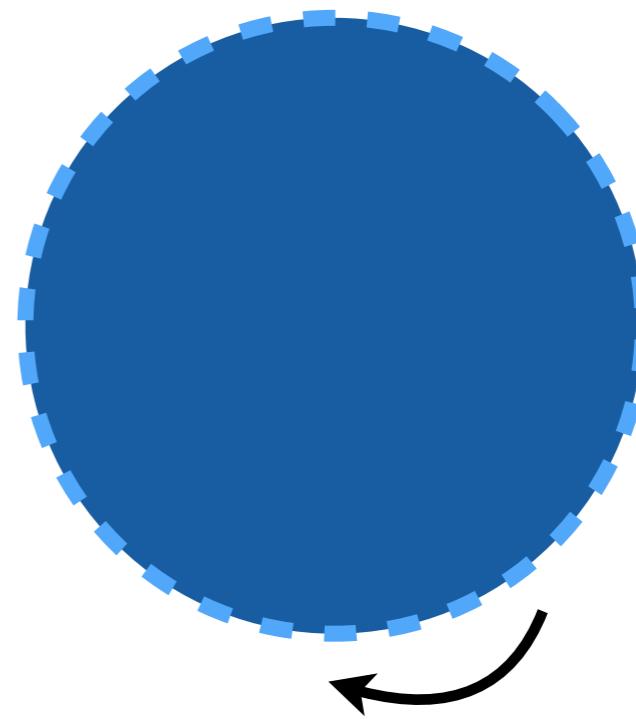
- A ball scattering off a rotating cylinder can increase in angular momentum and energy.
- Effect depends on dissipation, necessary to change the velocity



Ball scattering off cylinder with lossy surface slows down

# Superradiance

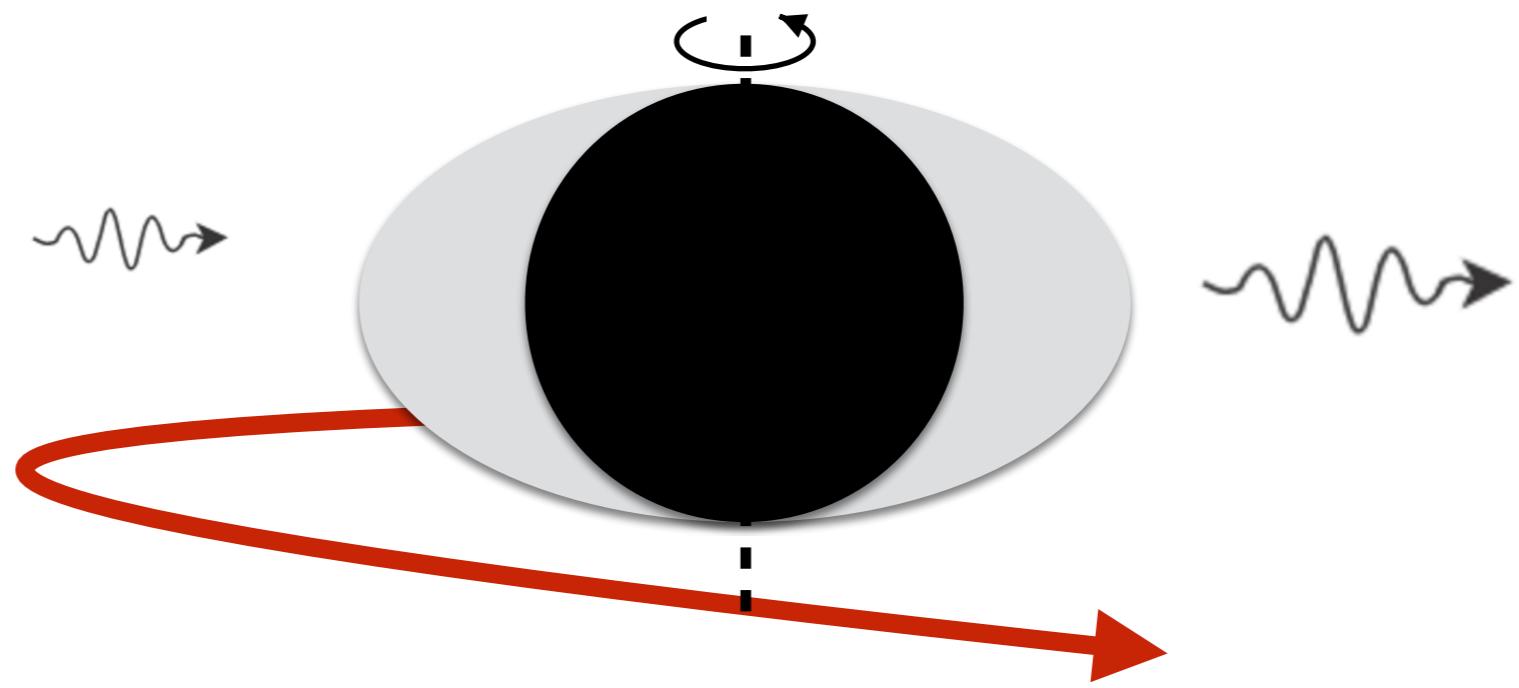
- A ball scattering off a rotating cylinder can increase in angular momentum and energy.
- Effect depends on dissipation, necessary to change the velocity



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

# 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 change the wave amplitude



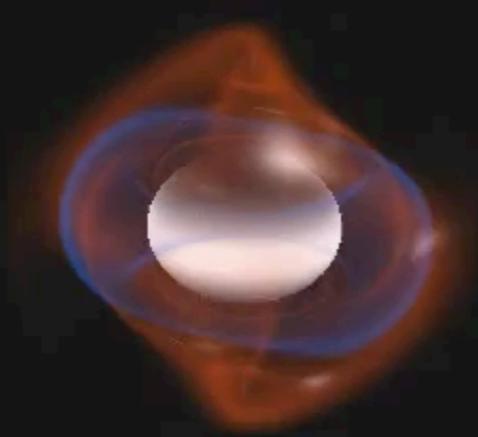
**Superradiance condition:**

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

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

# Gravitational Wave Signals

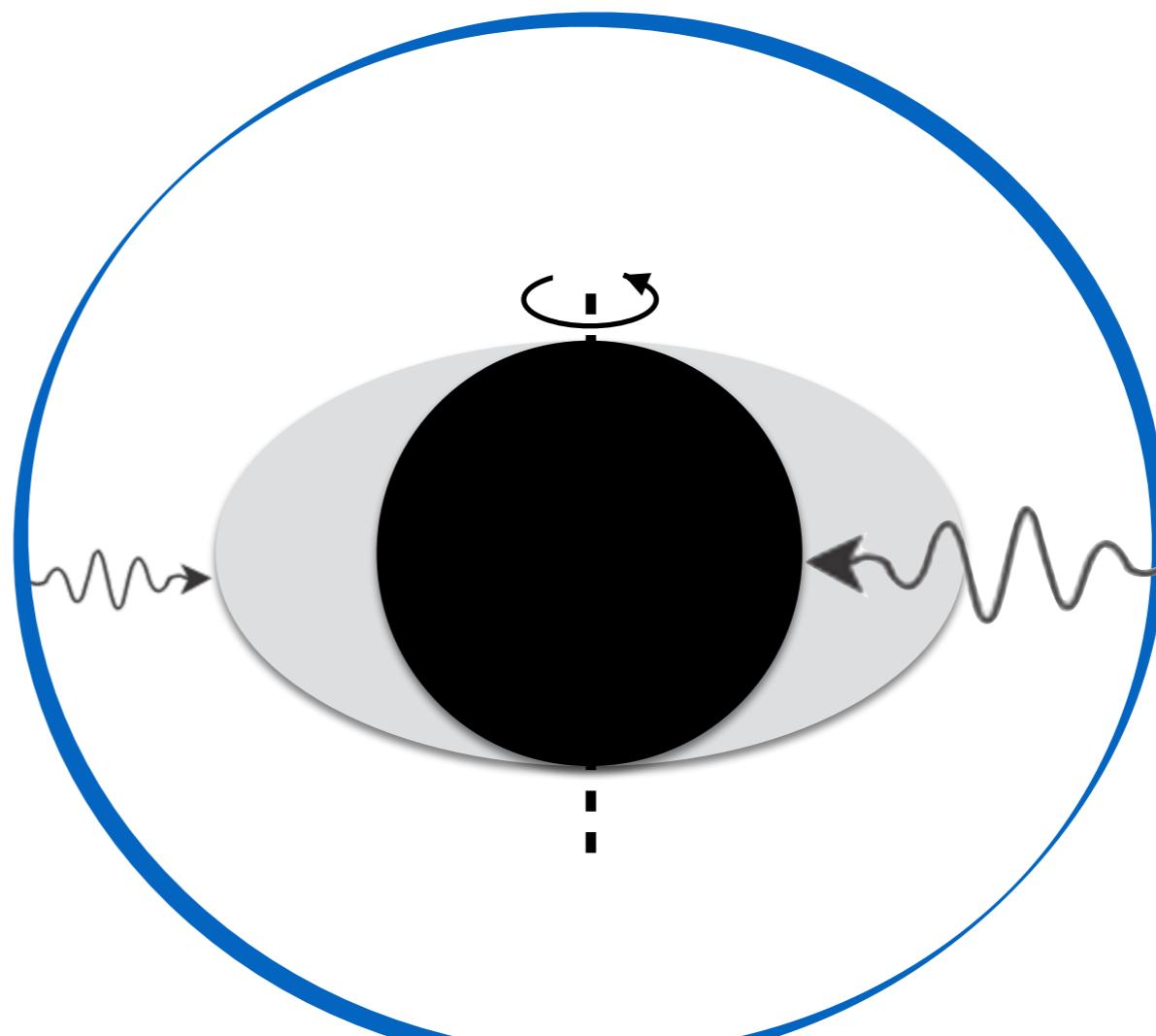
Gravitational waves scattering from a rapidly rotating black hole



Numerical GR simulation by Will East

# Superradiance

- Particles/waves trapped near the BH repeat this process continuously
- “Black hole bomb”: exponential instability when surround BH by a mirror
- Kinematic, not resonant condition



**Superradiance condition:**

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

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

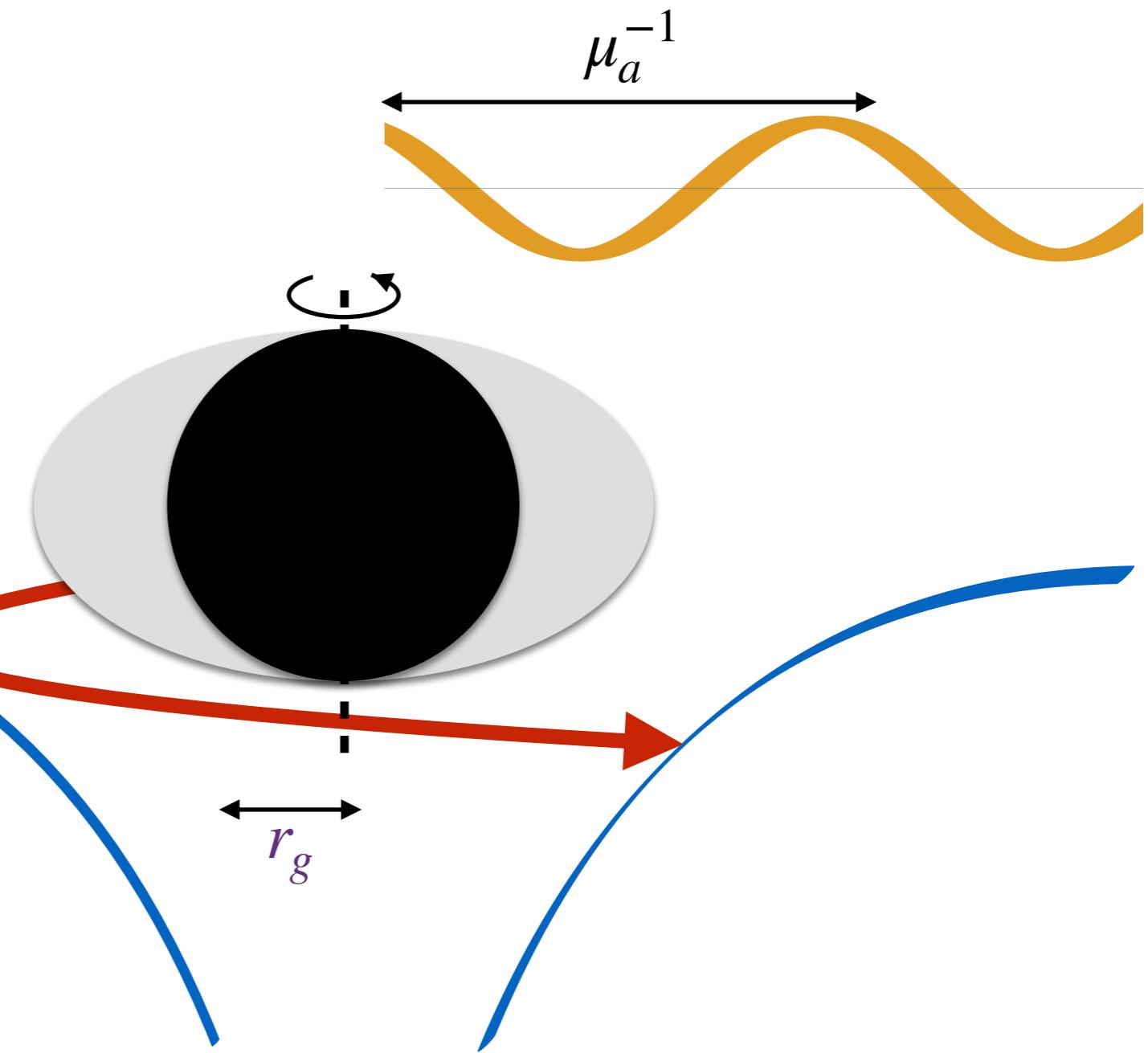
# Superradiance

- For a massive particle, e.g. axion, gravitational potential barrier acts as “mirror”

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

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

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



[Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78]

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010]

# Superradiance

$V(r) = -\frac{G_N M_{\text{BH}} \mu_a}{r}$	Hydrogen atom	Gravitational ‘atom’
‘Fine structure constant’	$\alpha_{\text{em}}$	$\alpha = G_N M_{\text{BH}} \mu_a \equiv r_g \mu_a$
Radius	$r_B = \frac{n^2}{\alpha_{\text{em}} m_e}$	$r_c \sim \frac{n^2}{\alpha \mu_a} \sim 4 - 400 r_g$

# Superradiance

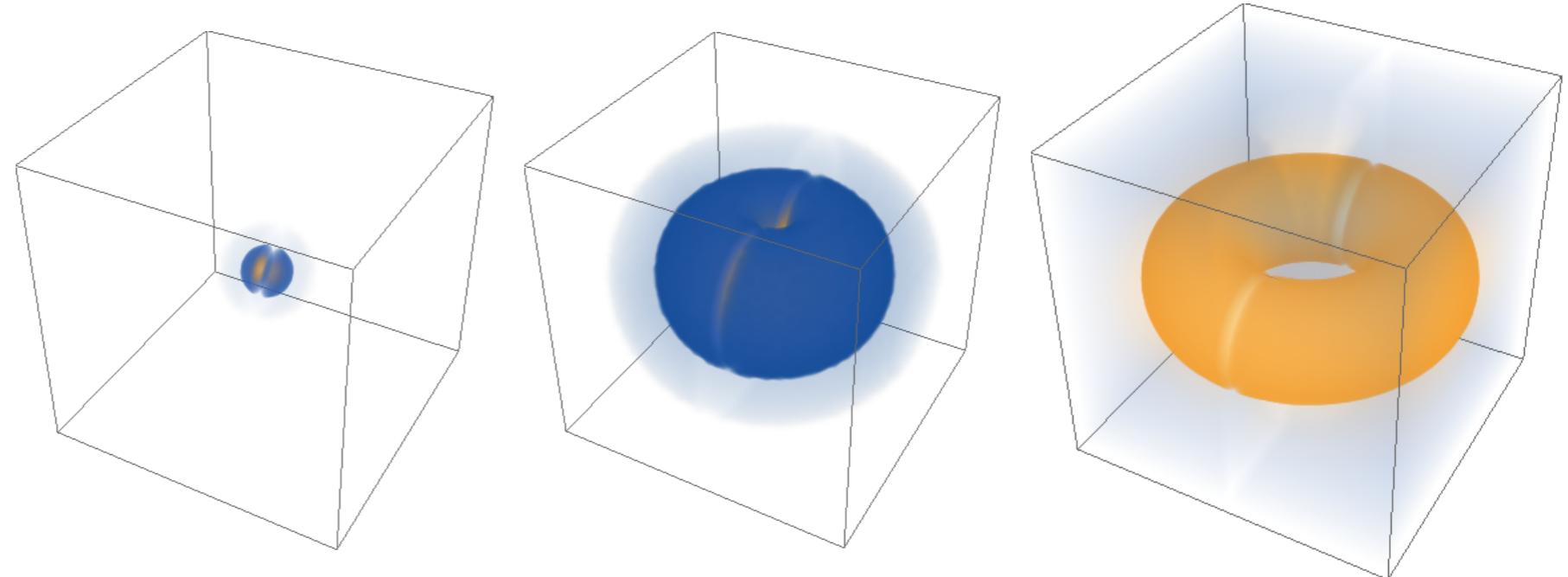
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Occupation number	$N = 1$	$N \sim 10^{75} - 10^{80}$
Boundary conditions	regular at origin	ingoing at horizon
Energy levels	$m_e \left( 1 - \frac{\alpha_{\text{em}}^2}{2n^2} \right)$	$\mu_a \left( 1 - \frac{\alpha^2}{2n^2} + i\Gamma_{sr} \right)$

# Superradiance

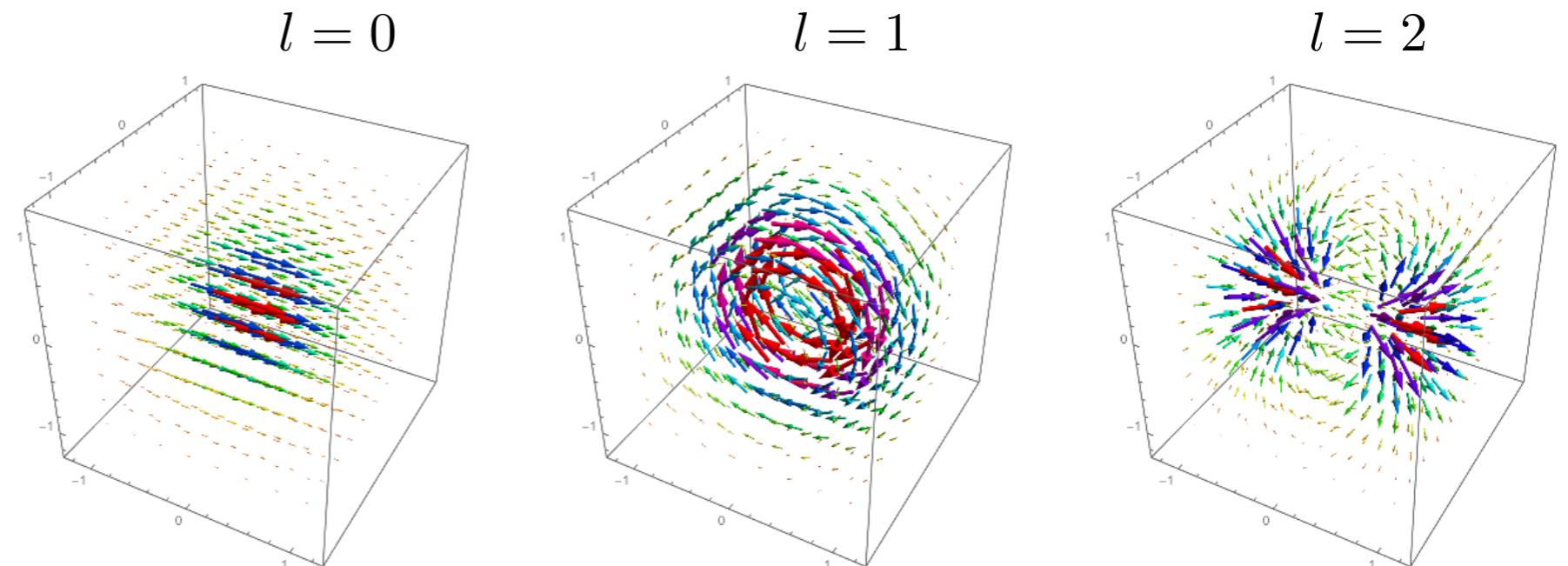
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Energy levels	$m_e \left( 1 - \frac{\alpha_{\text{em}}^2}{2n^2} \right)$	$\mu_a \left( 1 - \frac{\alpha^2}{2n^2} + i\Gamma_{sr} \right)$
Superradiance condition:	$\frac{\mu_a}{m} < \Omega_{BH}$	(m = magnetic quantum number)
	$\Gamma_{sr} > 0$	: growing mode

# Superradiance

Axion  
Gravitational Atoms



Dark Photon  
Gravitational Atoms



$j = 1, l = 0$

$j = 1, l = 1$

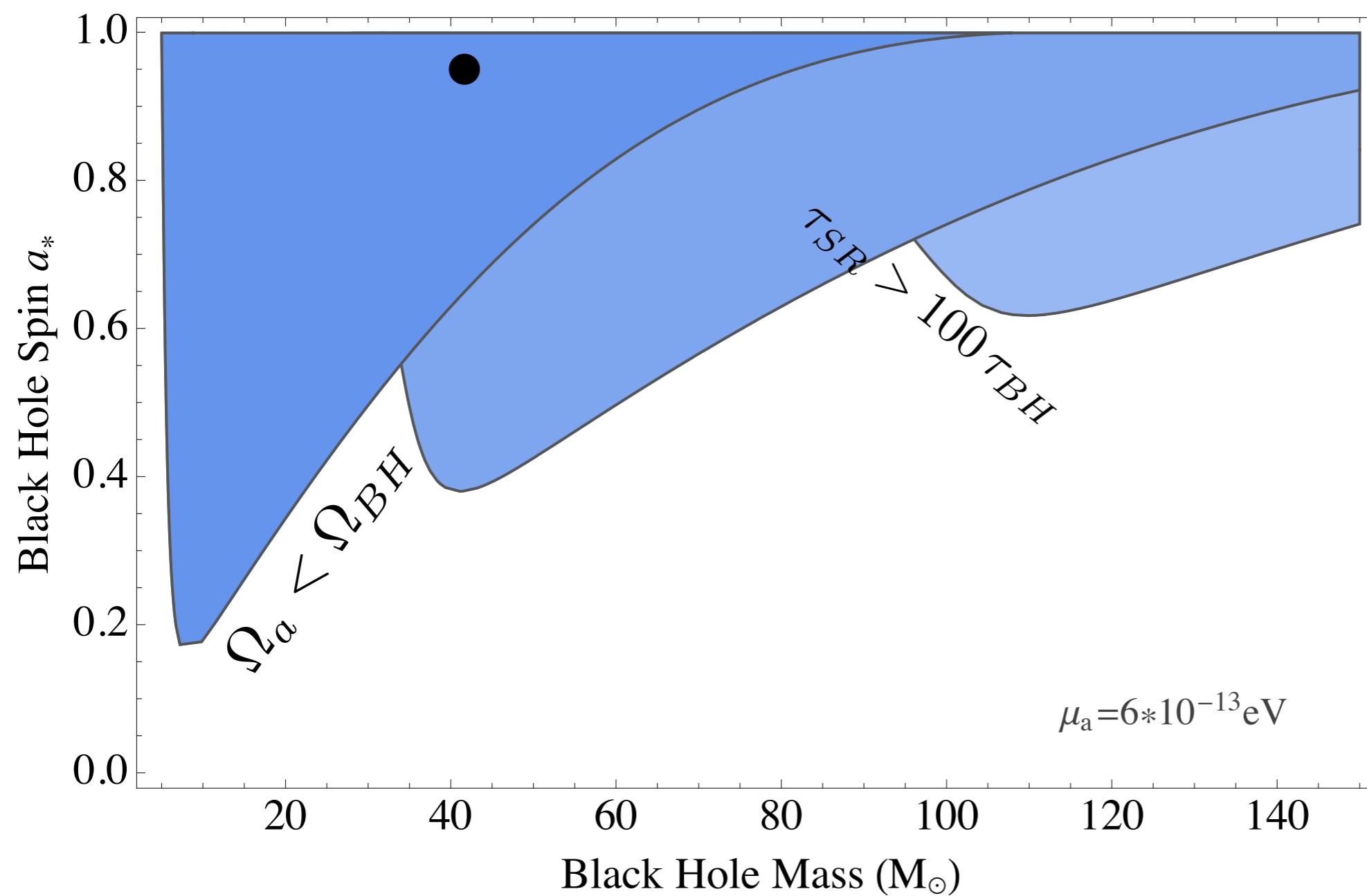
$j = 1, l = 2$

Hydrogen-like radial profile, vector spherical harmonic angular:  
localized closer to the black hole for the same total angular momentum

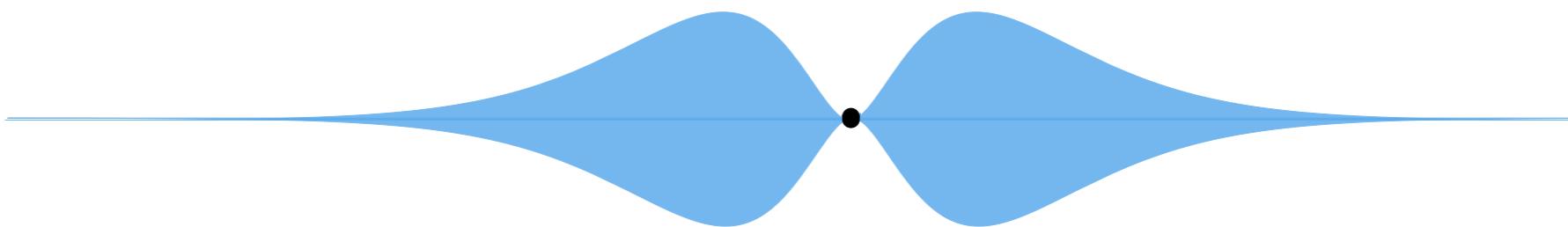
**MB**, R. Lasenby, M. Teo

# Superradiance: a stellar black hole history

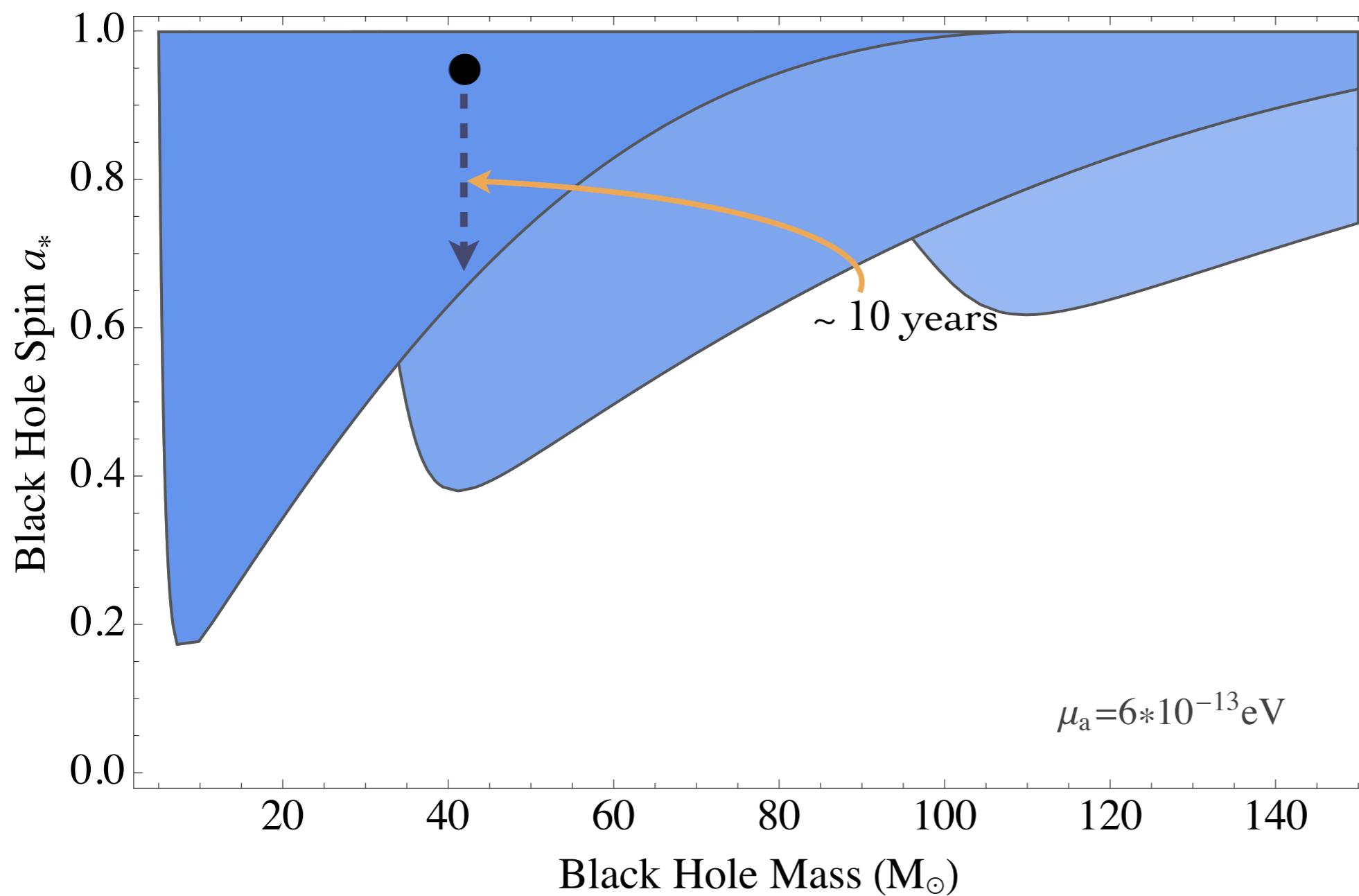
A black hole is born with spin  $a^* = 0.95$ ,  $M = 40 M_\odot$ .



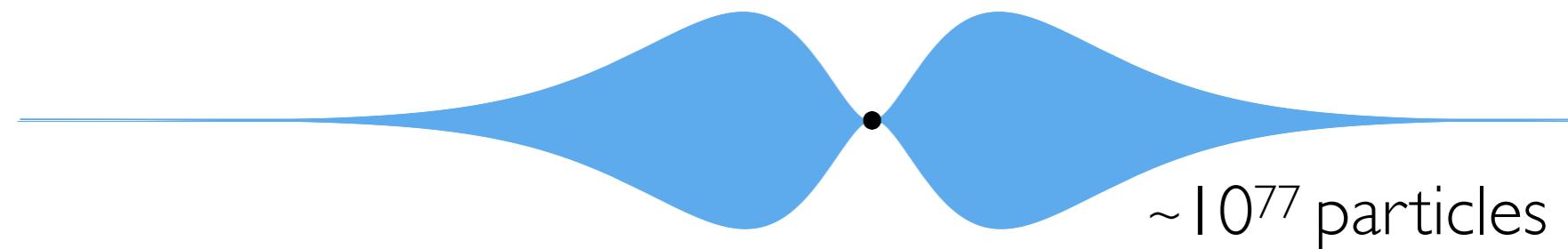
# Superradiance: a stellar black hole history



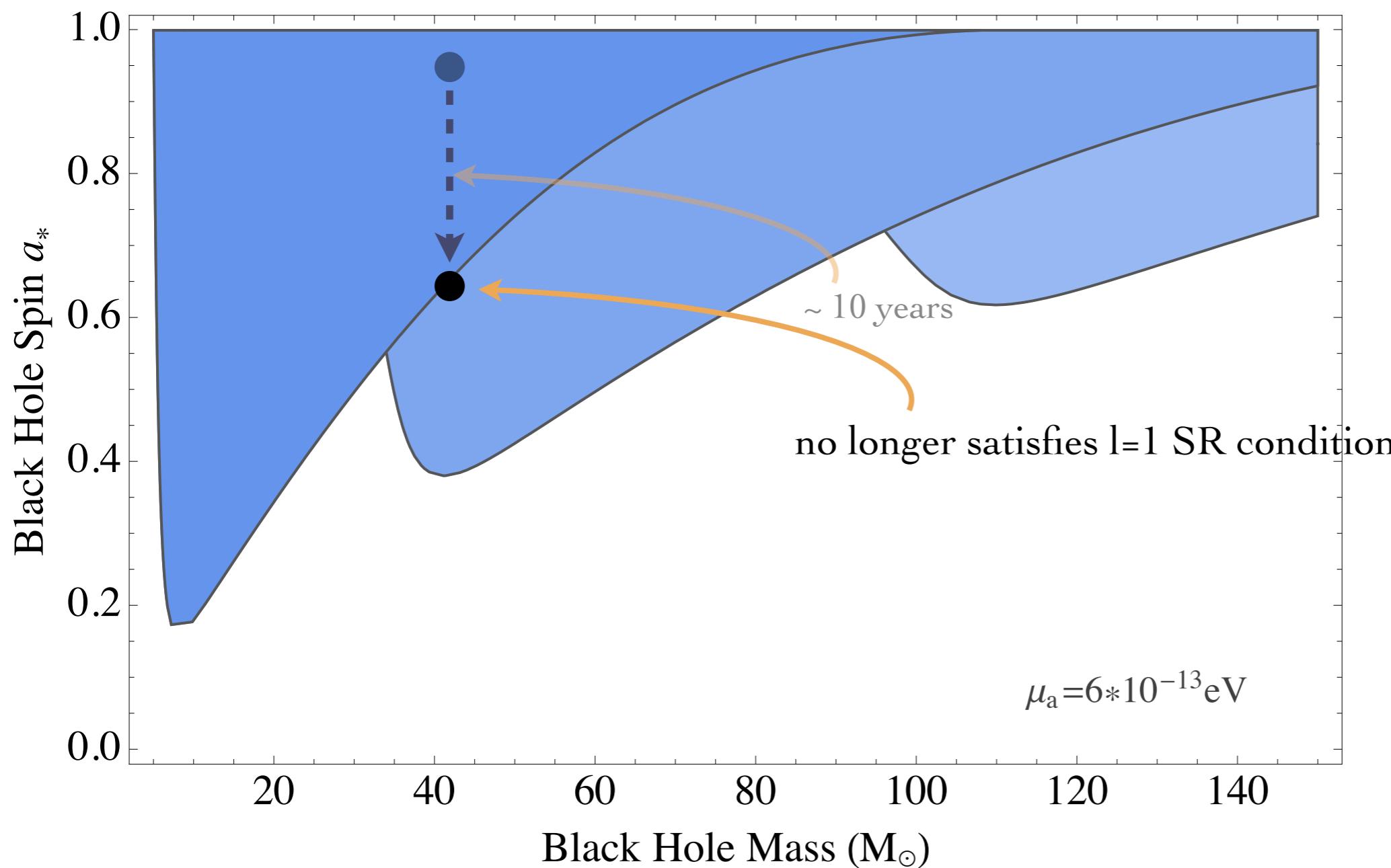
BH spins down and fastest-growing level is formed



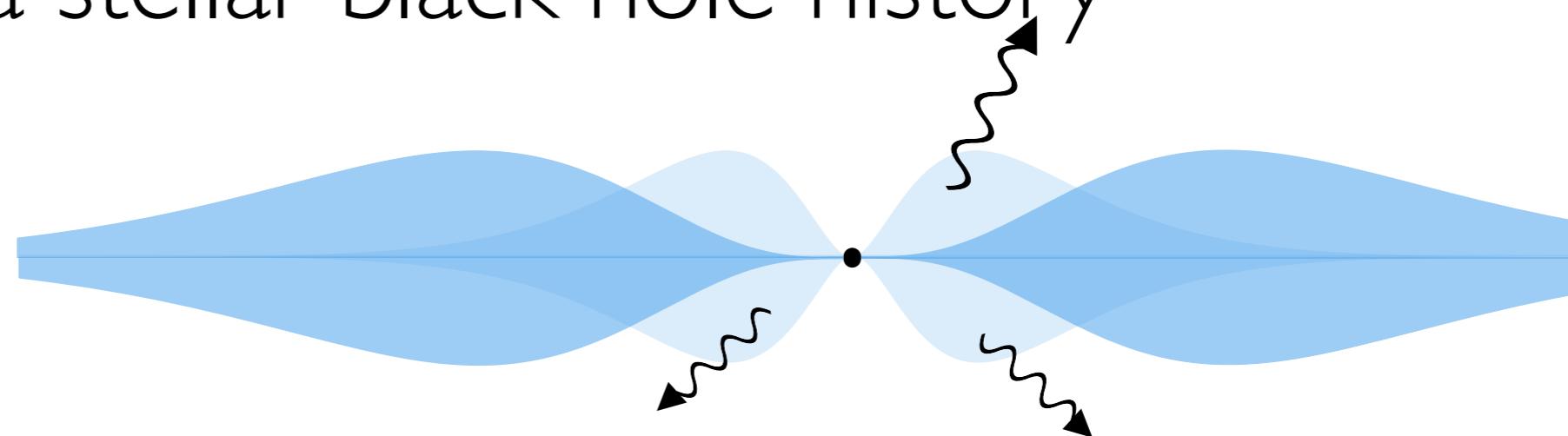
# Superradiance: a stellar black hole history



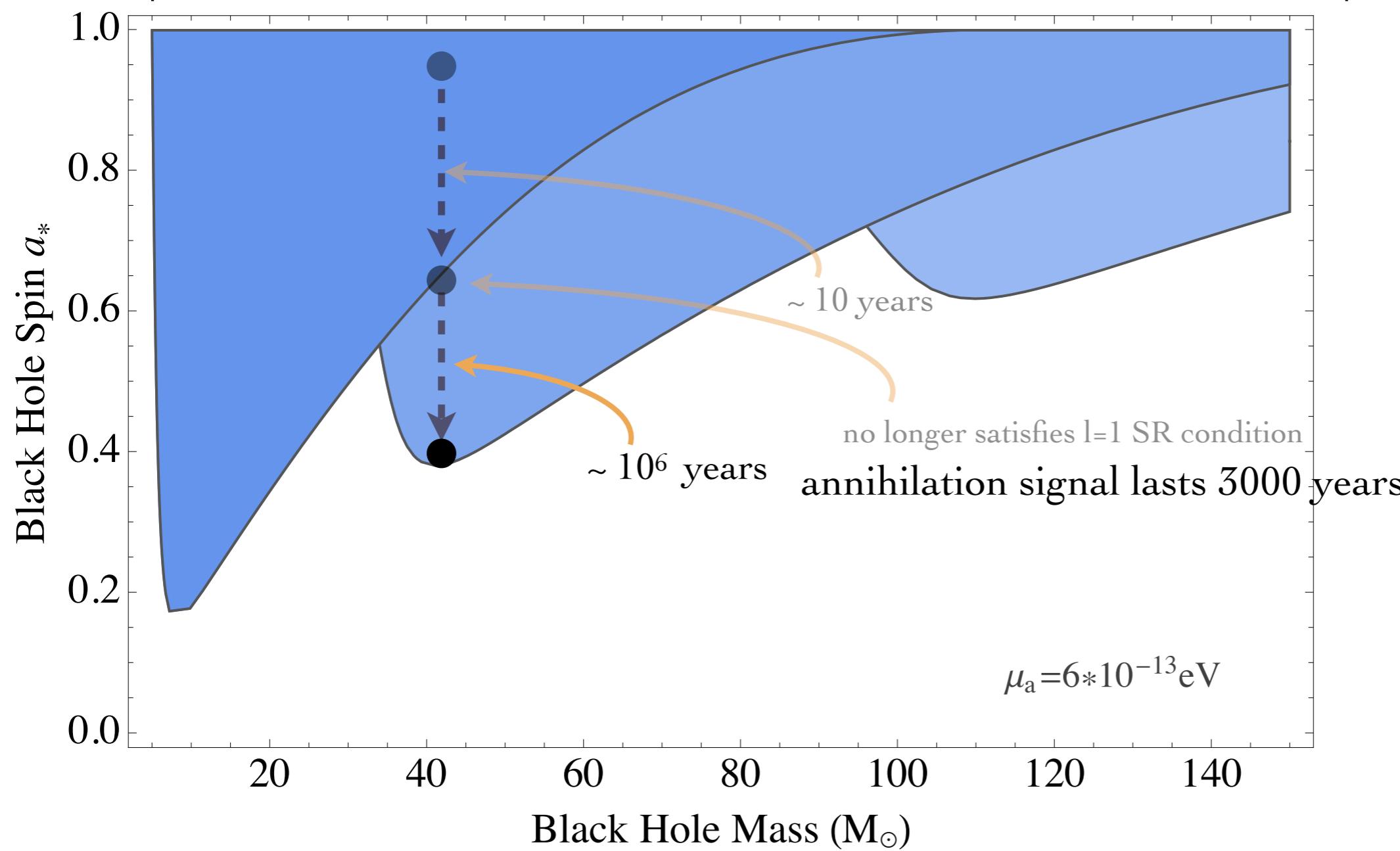
Once BH angular velocity matches that of the level, growth stops



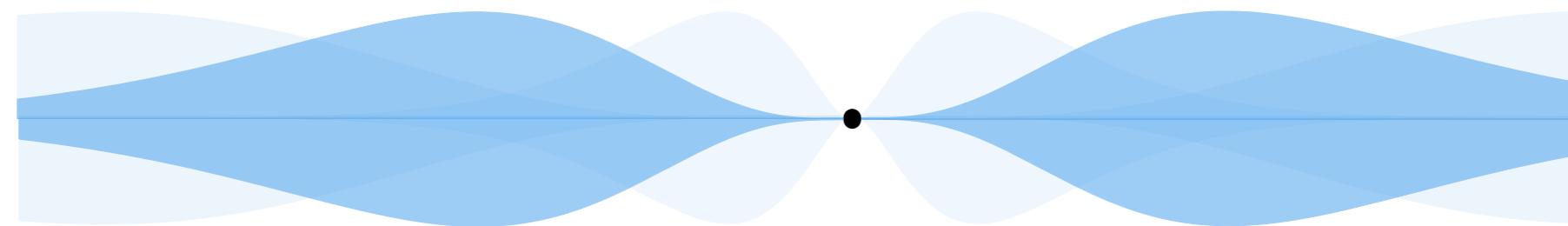
# Superradiance: a stellar black hole history



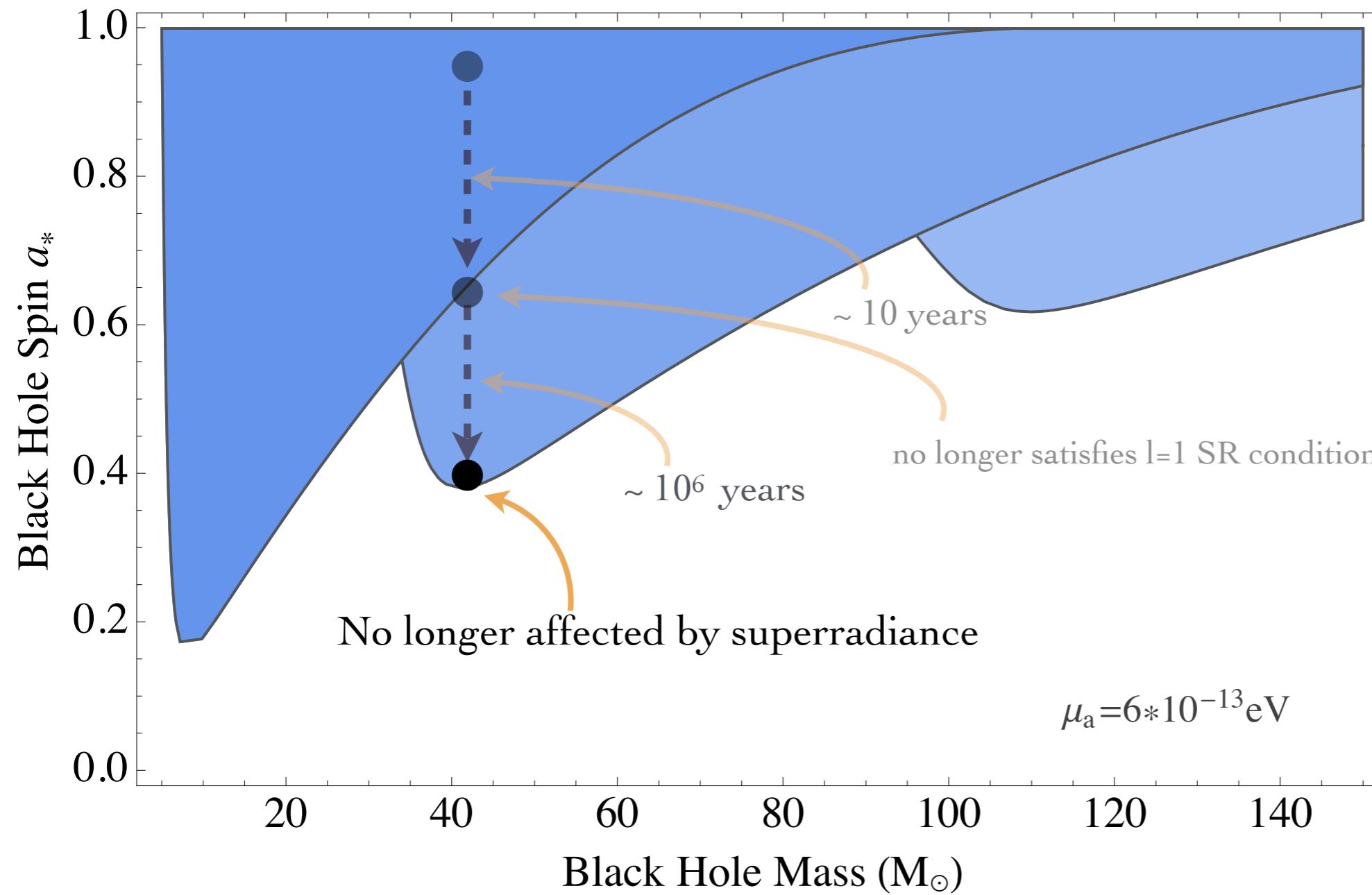
BH spins down: next level formed; annihilations to GWs deplete first level



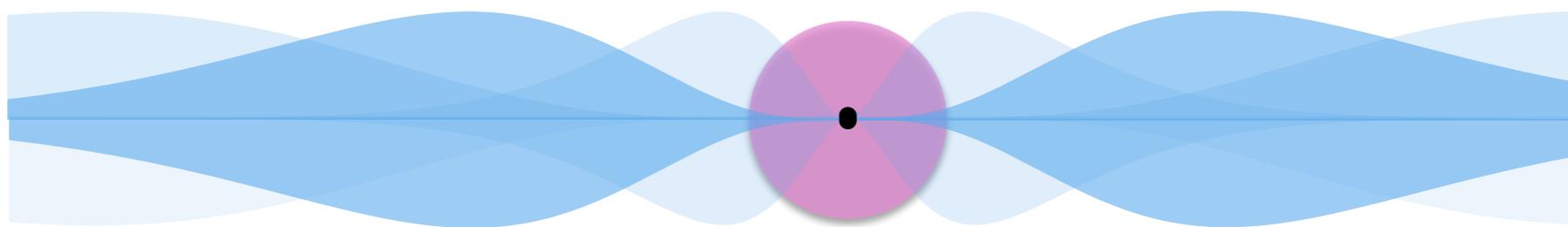
# Superradiance: a stellar black hole history



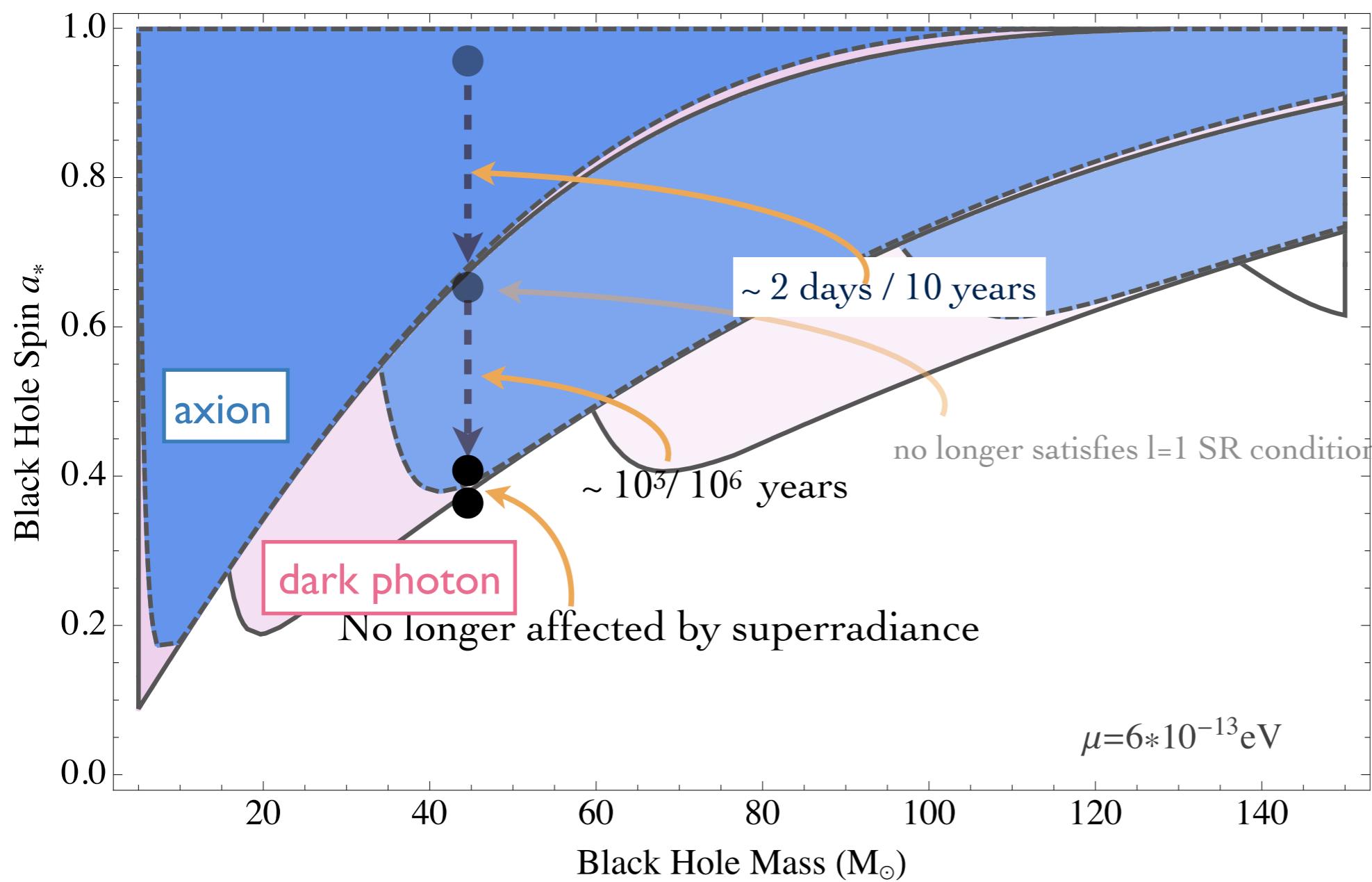
Next level has a superradiance rate exceeding age of BH



# Superradiance: a stellar black hole history



Dark photons: cousins of the axion, have spin-1 like our photon (but with a mass)



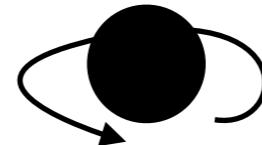
Dark photons can have higher total angular momentum  $j$  for a given orbital angular momentum  $I$

# Outline

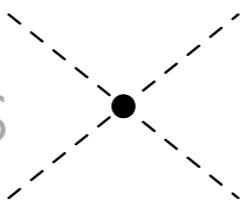
- Black Hole Superradiance



- Gravitational Signatures



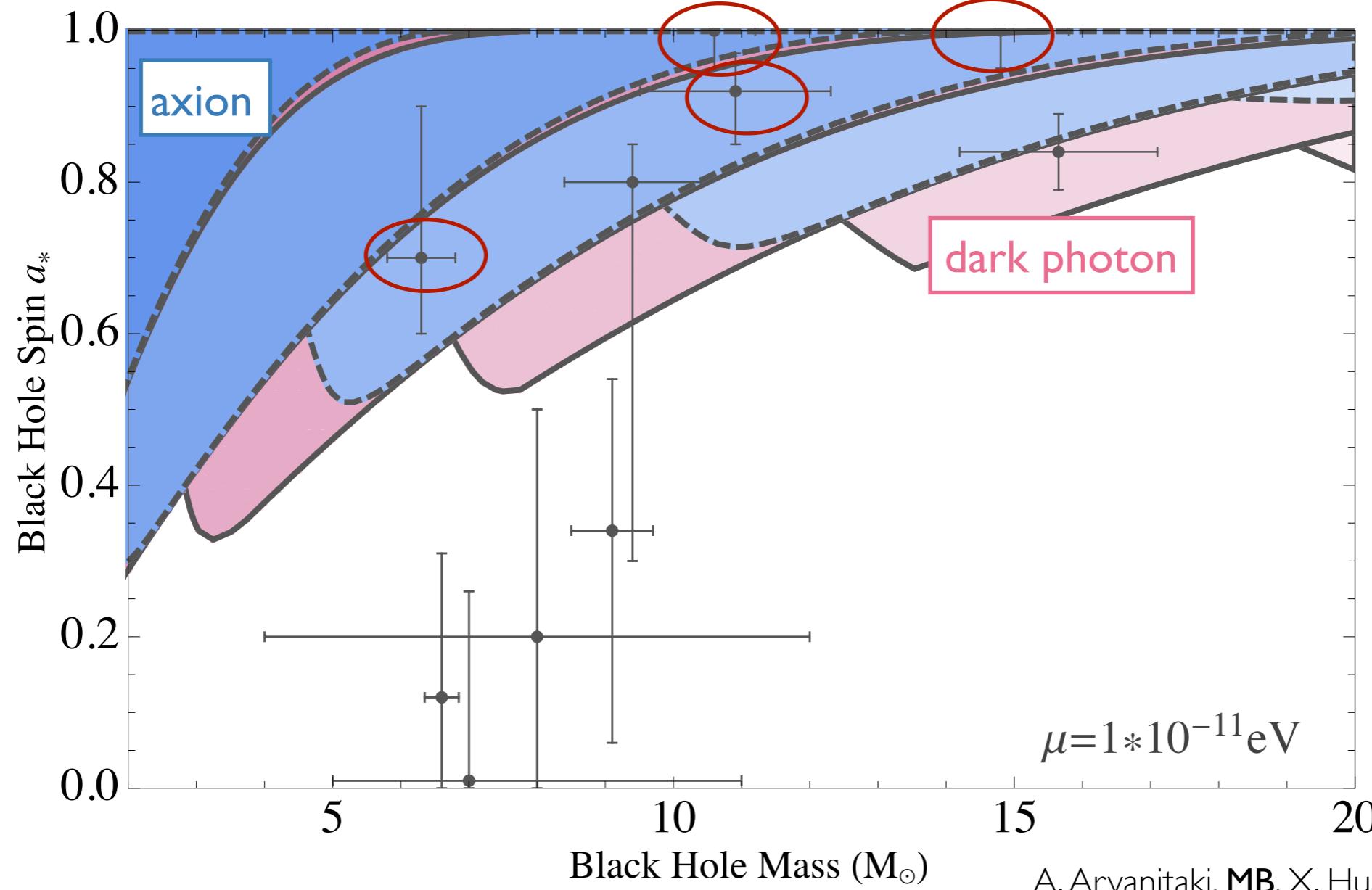
- Axion Self-Interactions



# Black Hole Spins

Black hole spin and mass measurements from X-ray binaries:

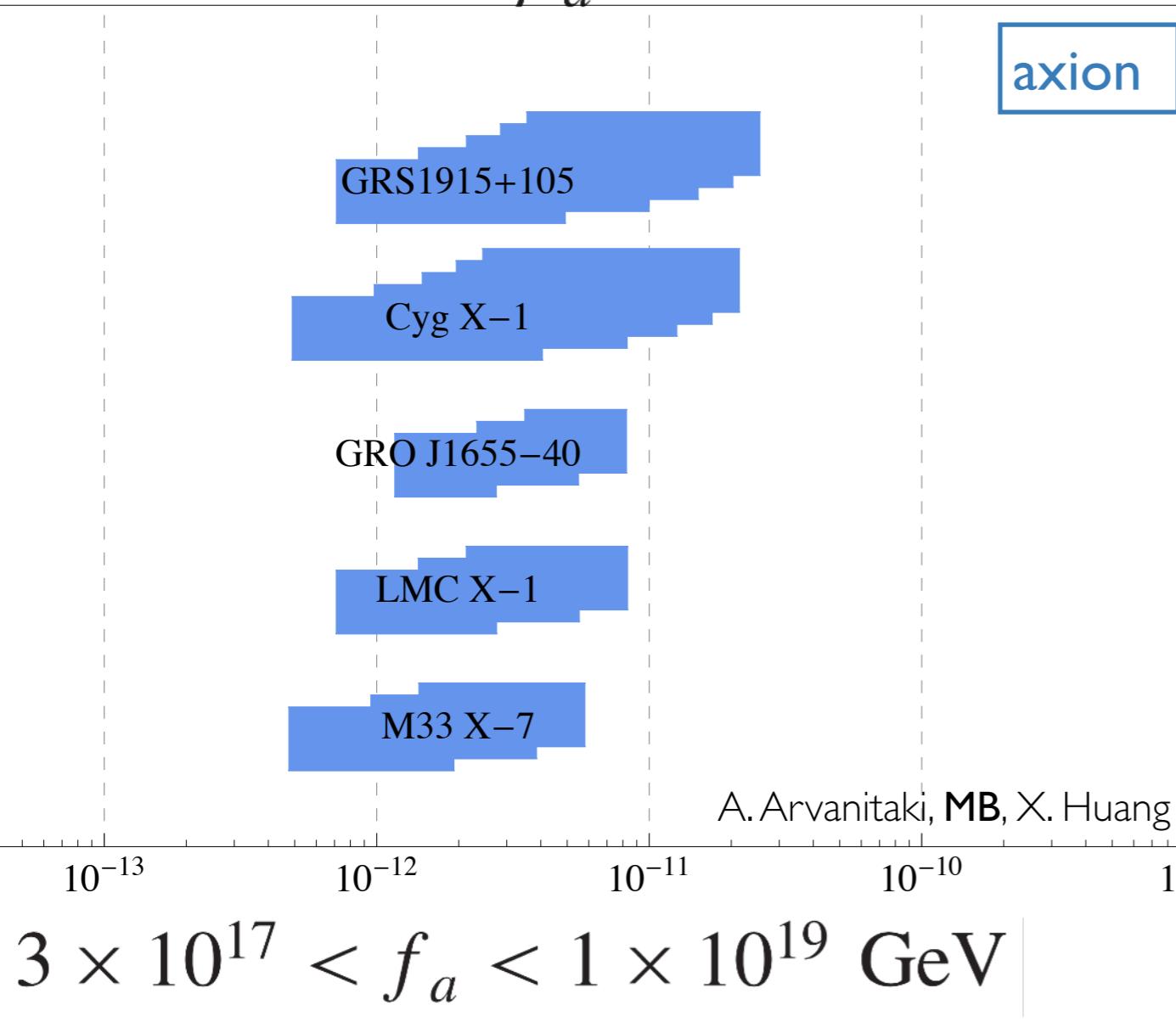
Several black holes disfavor axion and dark photon at  $10^{-11}$  eV



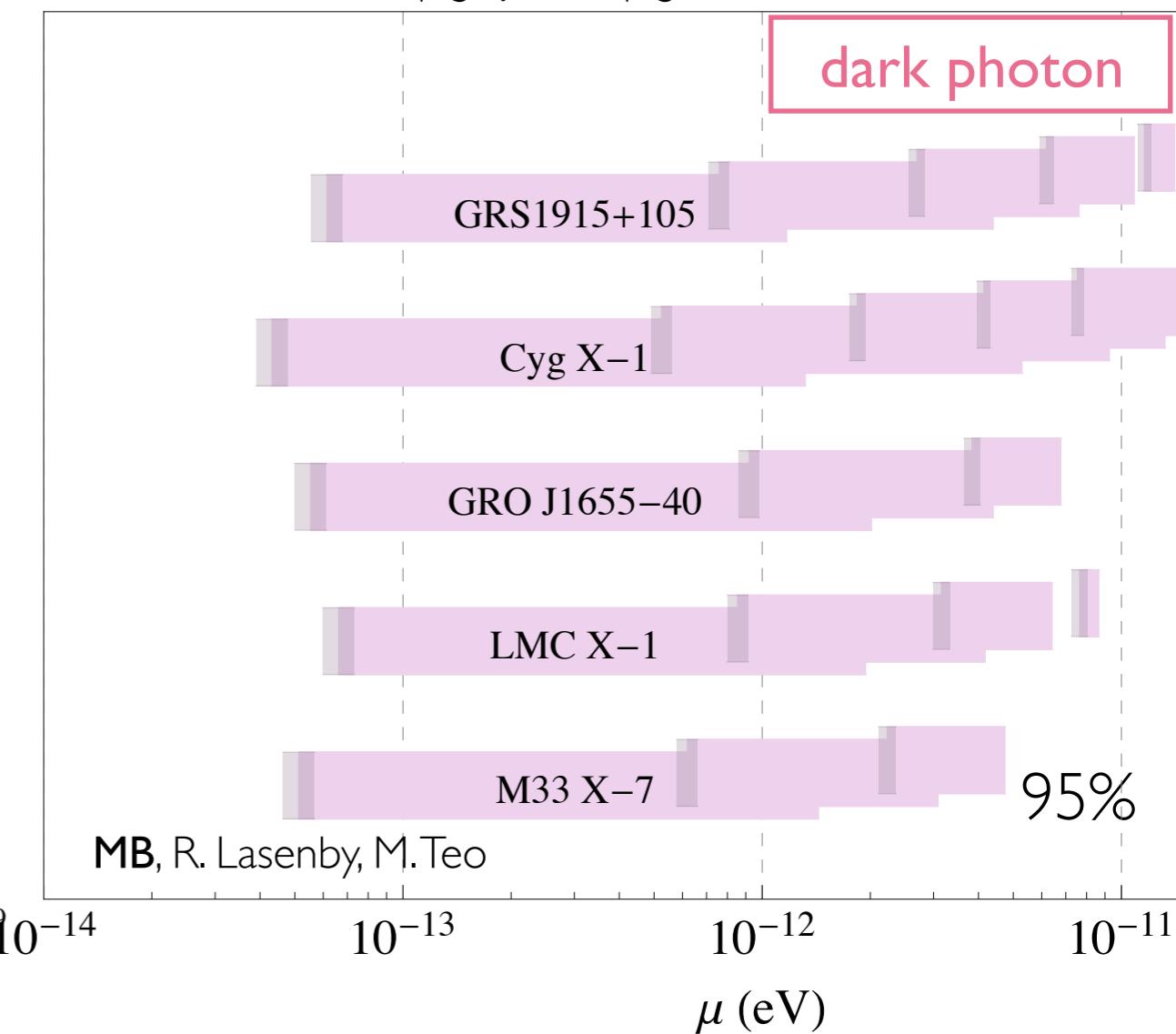
# Black Hole Spins

Five stellar black holes and four SMBHs combine to disfavor the range:

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

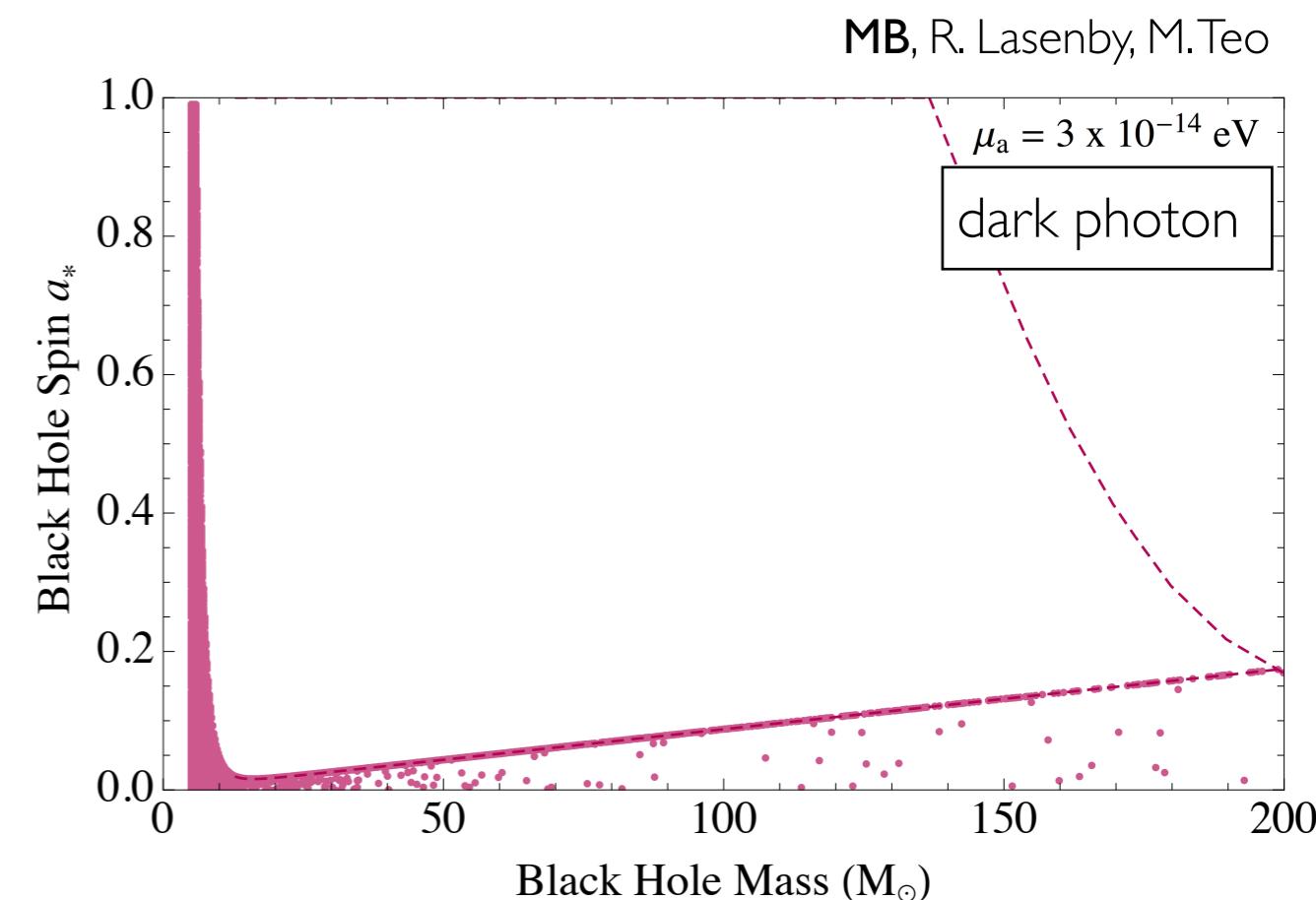
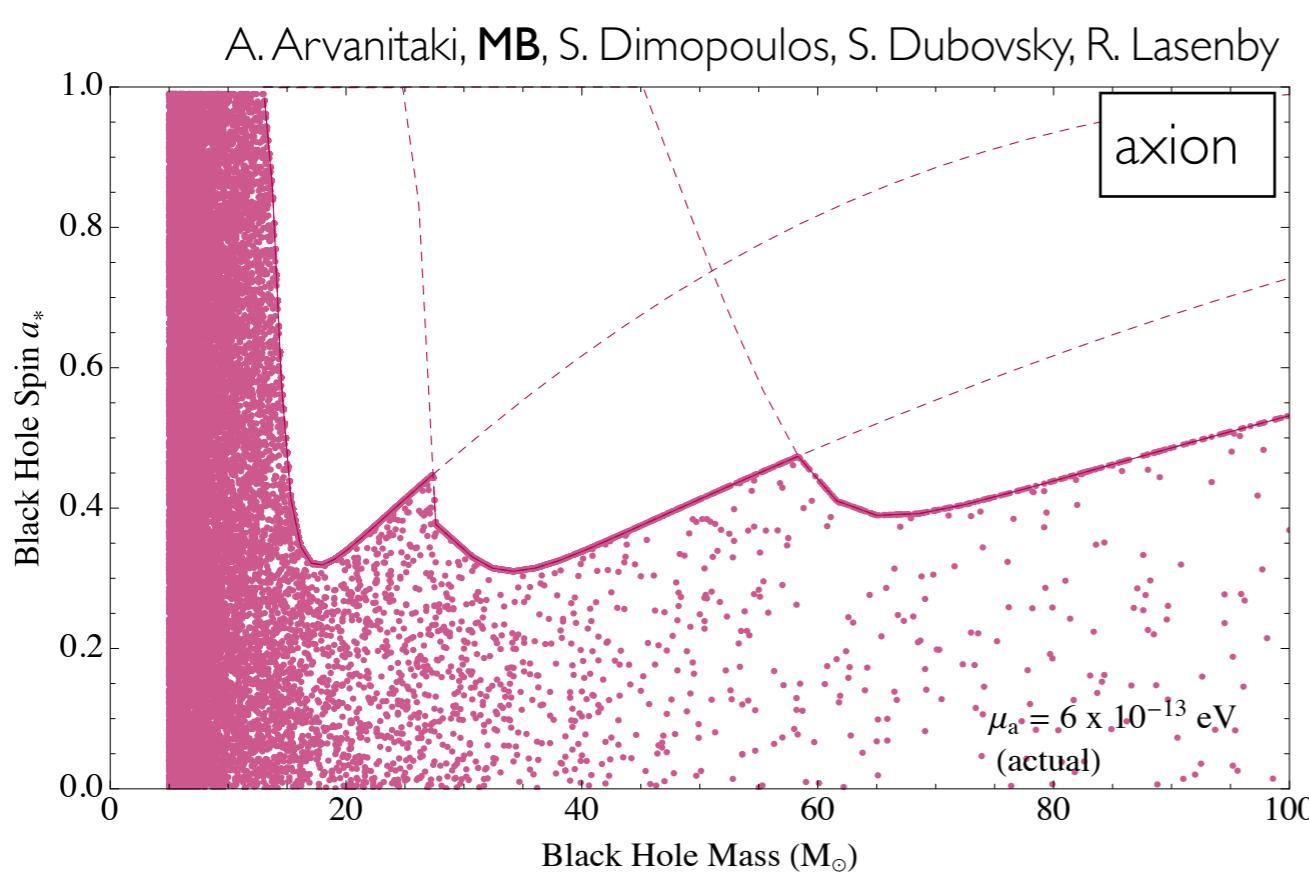


$$2 \times 10^{-11} \gtrsim \mu_V \gtrsim 5 \times 10^{-14} \text{ eV}$$



# Black Hole Spins at LIGO

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



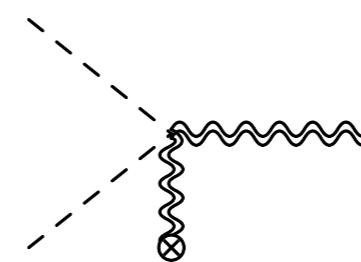
With  $\sim 100$ - $300$  spin measurements, possible to see statistical evidence for light boson in the mass range  $10^{-11} - 10^{-13} \text{ eV}$

# Gravitational Wave Signals

- Transitions between levels

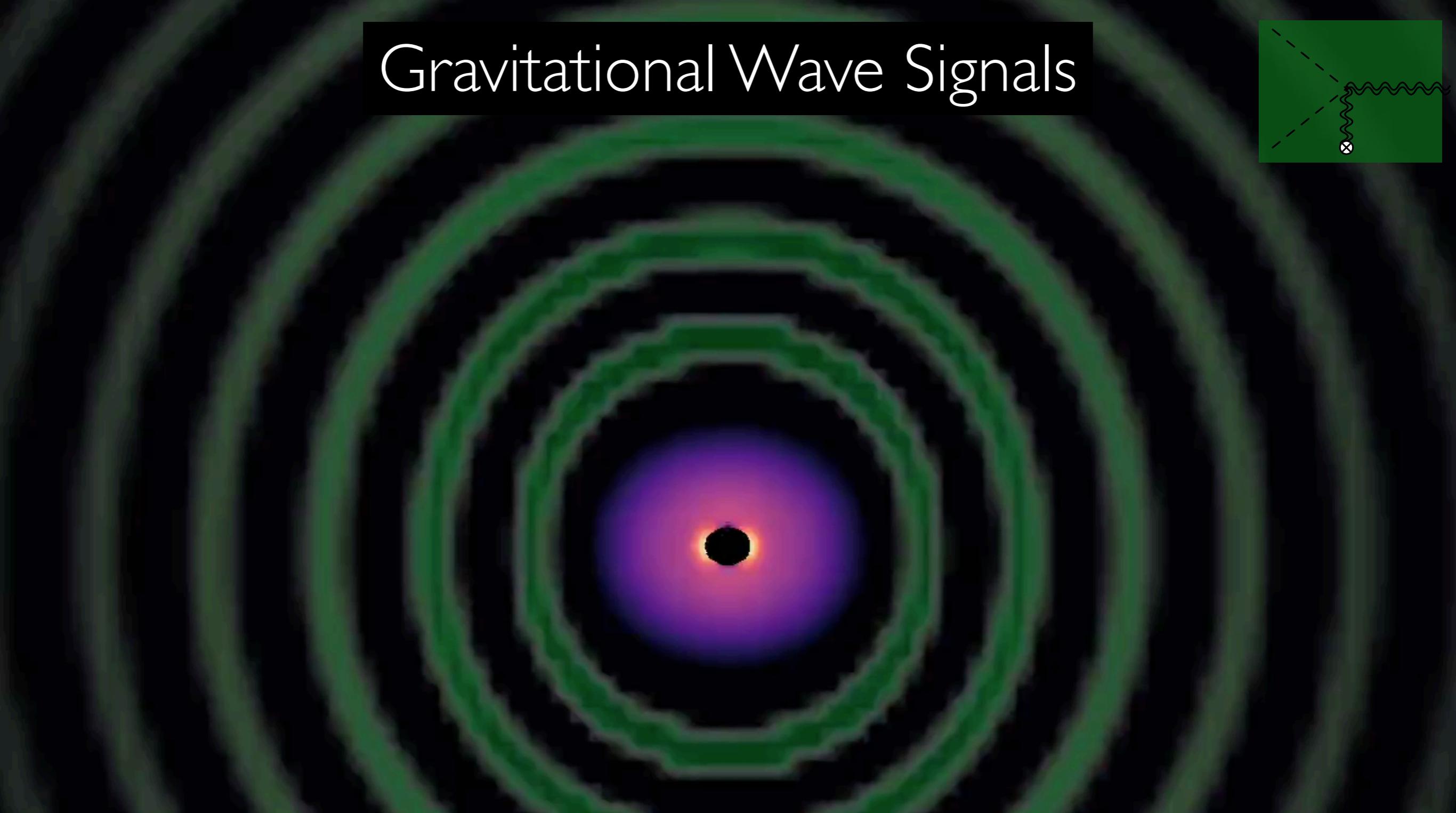
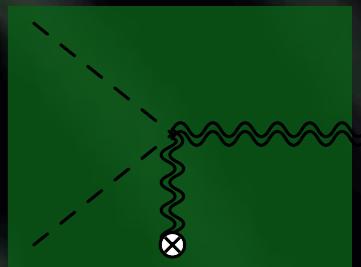


- Annihilations to gravitons



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

# Gravitational Wave Signals

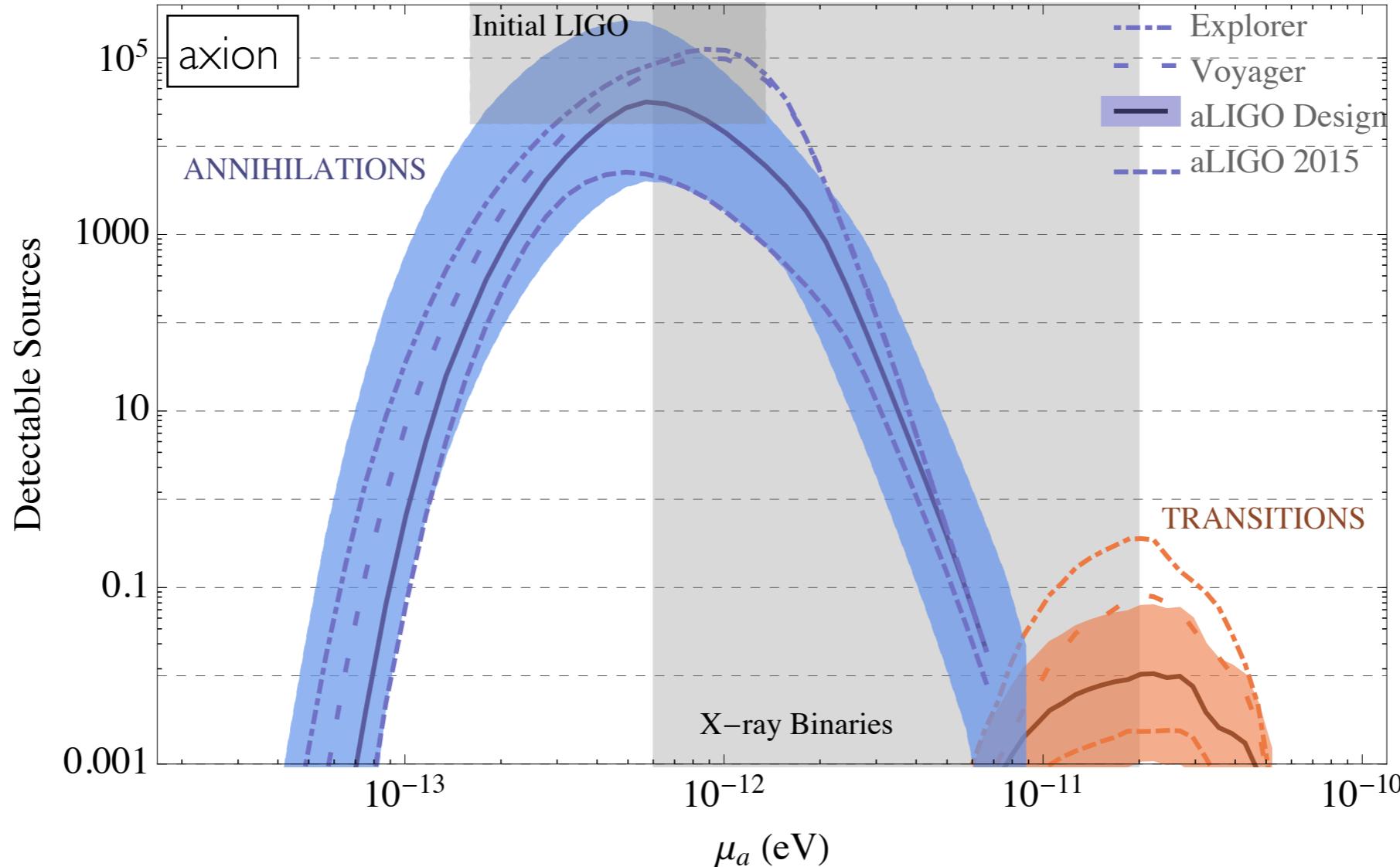


Time-varying energy density sources gravitational waves:  
two bosons annihilating into gravitational waves

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

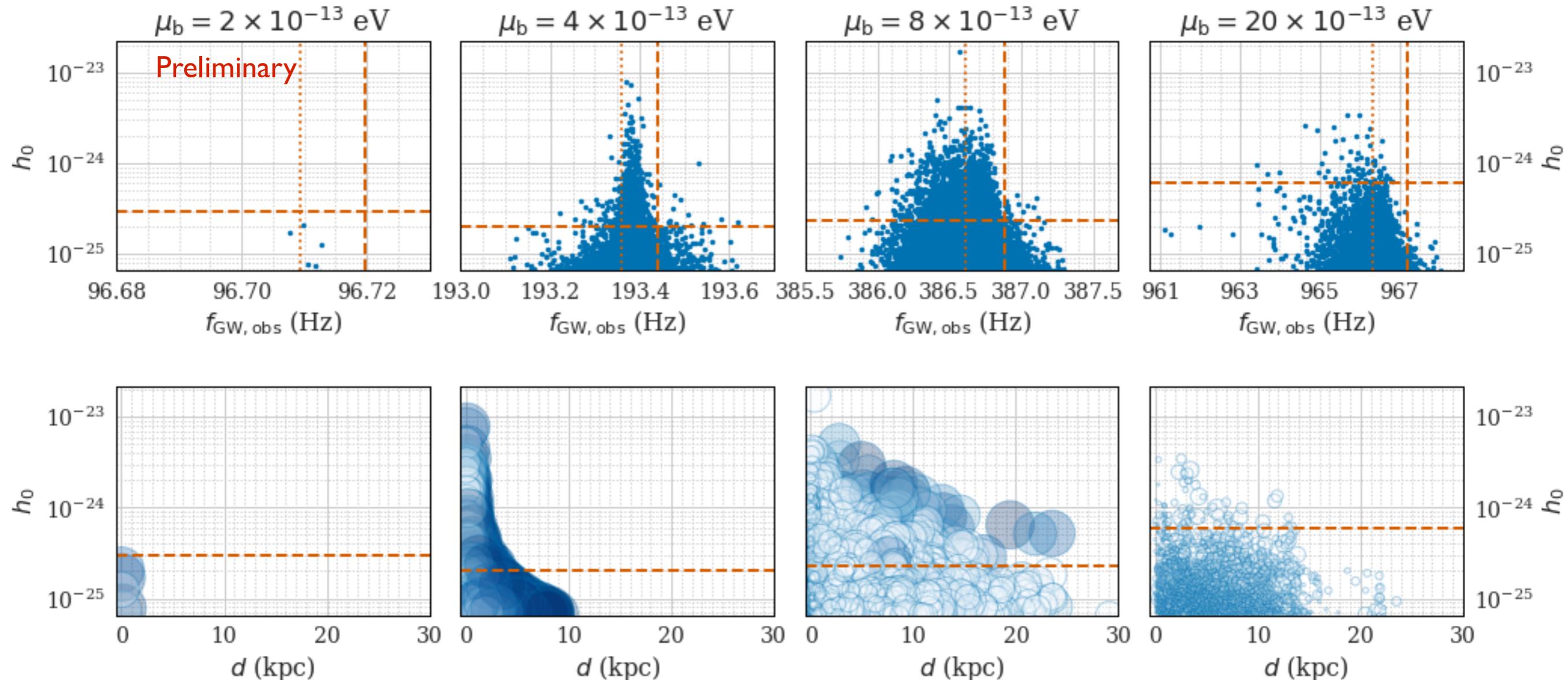
# Gravitational Wave Signals

A. Arvanitaki, **MB**, S. Dimopoulos, S. Dubovsky, R. Lasenby



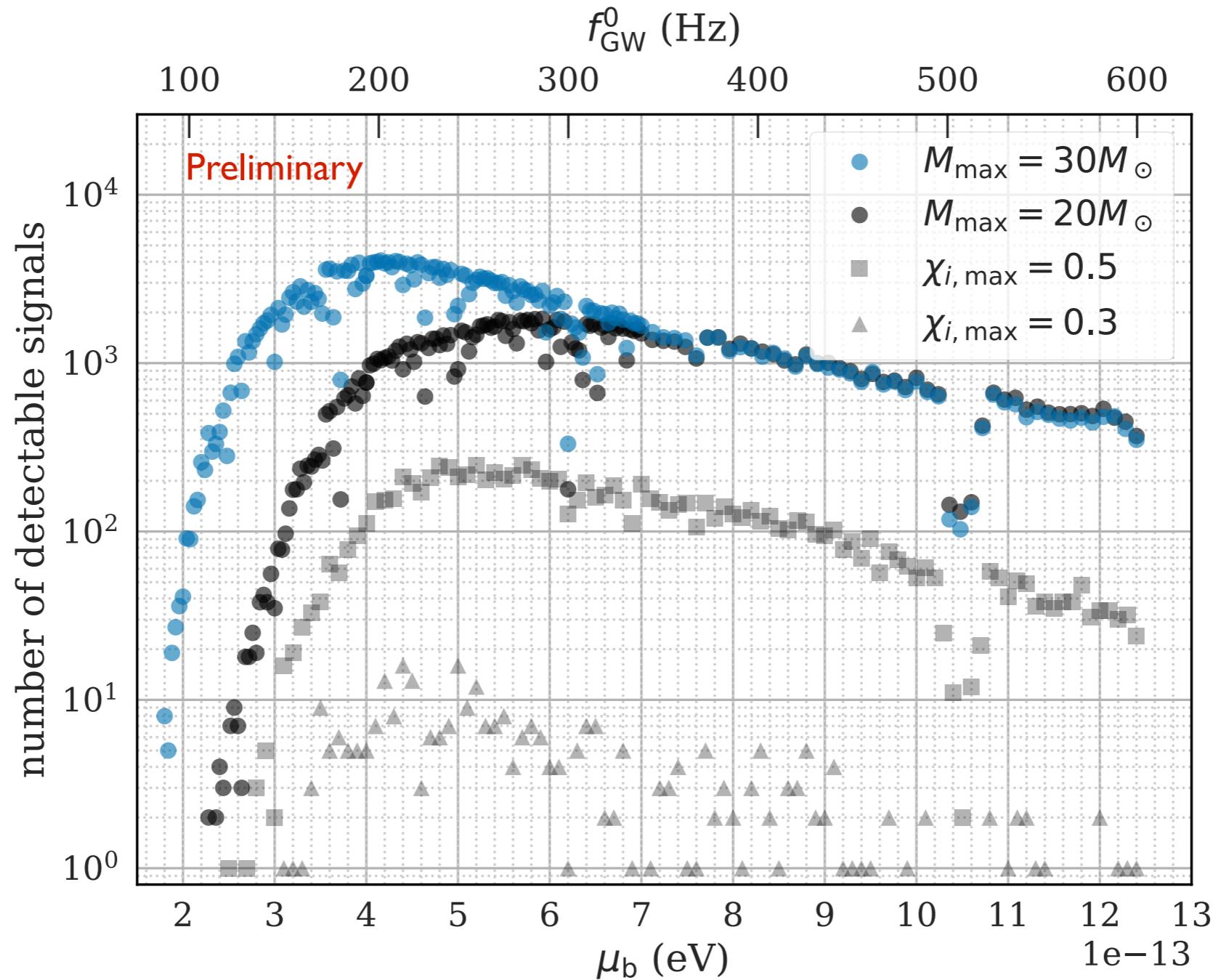
- **Weak, long signals** last for  $\sim$  million years, visible from our galaxy, limited by LIGO noise floor
- Event rates up to 10,000 — can be observed and studied in detail
- Searches ongoing with O1/O2 data:
  - S.J. Zhu, D.Tsuna, M.A. Papa, **MB**, N. Kawanaka, HB Eggenstein
  - S.D'Antonio, C. Palomba, P.Astone, S. Frasca, G. Intini, I. La Rosa, P. Leaci, M.Mastrogiovanni, A. Miller, F. Muciaccia, O.J. Piccinni, A. Singal

# Gravitational Wave Signals



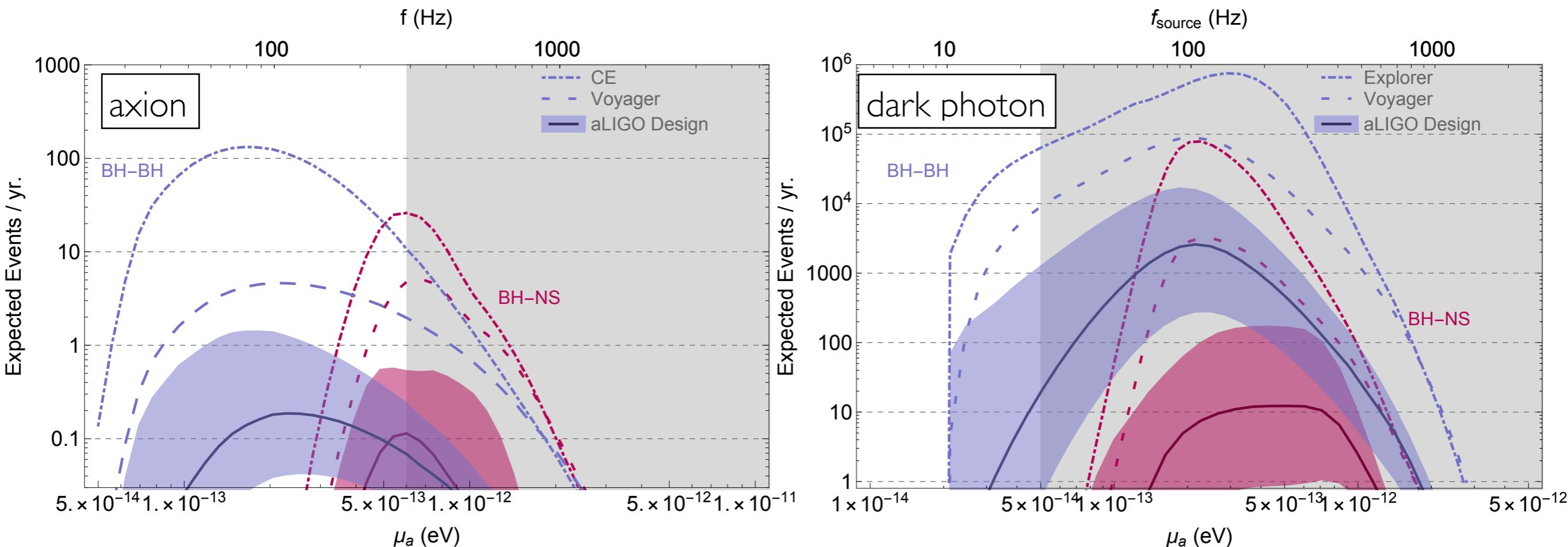
- **Weak, long signals** last for  $\sim$  million years, visible from our galaxy, limited by LIGO noise floor
- Event rates up to 10,000 — can be observed and studied in detail
- Searches ongoing with OI data

# Gravitational Wave Signals



- Up to 1000 events expected in Advanced LIGO Run I, tens to hundreds with moderate spin distributions
- Expect to set exclusion on axion masses using LIGO data

# Gravitational Wave Signals



A. Arvanitaki, **MB**, S. Dimopoulos, S. Dubovsky, R. Lasenby (2017)

**MB**, R. Lasenby, M. Teo (2018)

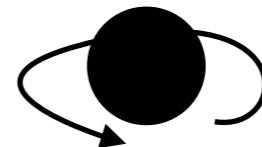
- **Short, bright signals** — directed follow-up searches to recently born BHs from 10-1000 Mpc away
- Measure BH mass, spin, and particle mass: fully study gravitational atom
- Especially promising at future GW observatories, methods investigations ongoing
  - M. Isi, L. Sun, R. Brito, A. Melatos (2019)

# Outline

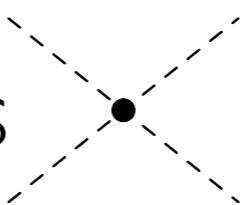
- Black Hole Superradiance



- Gravitational Signatures



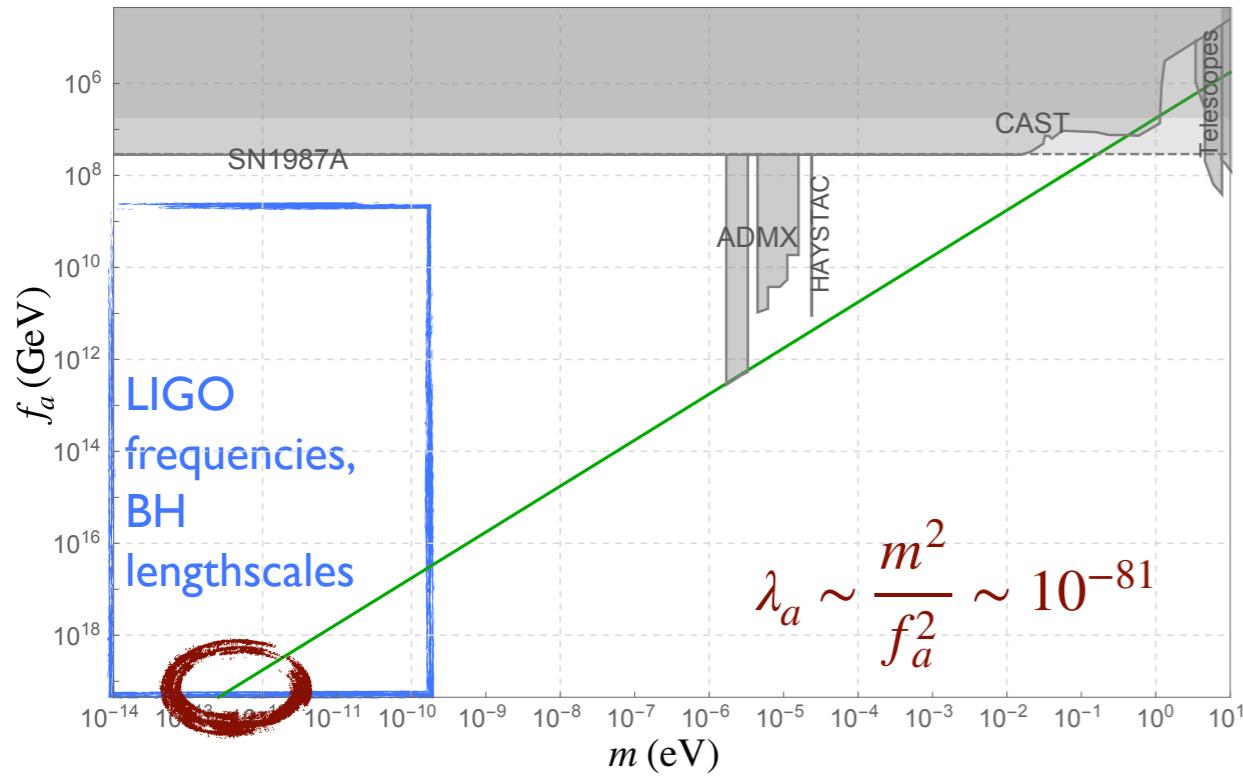
- Axion Self-Interactions



# Self-Interactions

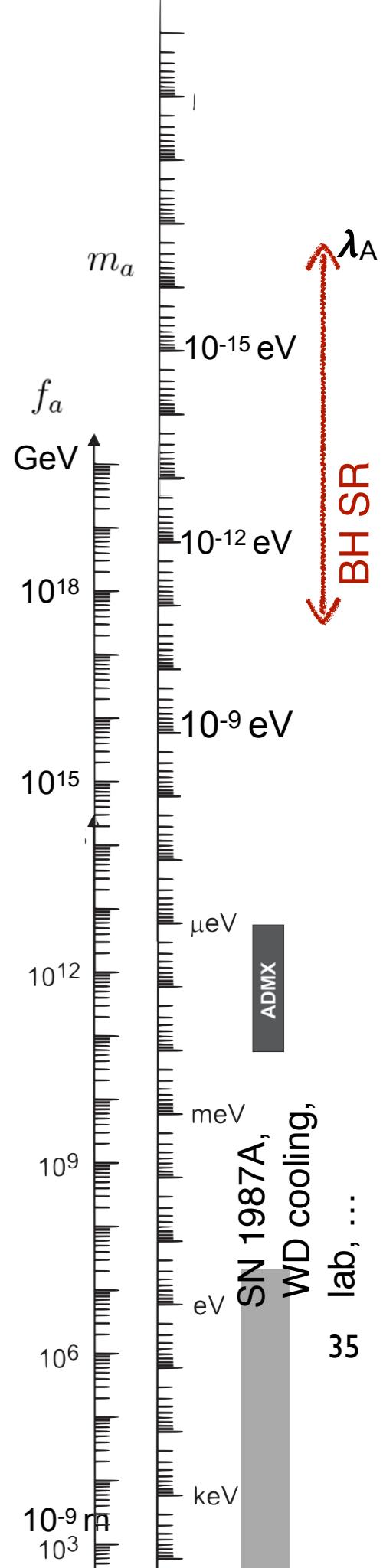
- So far focused on gravitational picture: effects of gravitational atom and gravitational waves
- For QCD axion at these scales,  $f_a \sim M_{Pl}$
- Are there corrections or new effects when including the quartic self-interaction?

- Potentially a range of axions with different masses and  $f_a$



$$\mu^4 e^{-S} \left( 1 - \cos \left( \frac{\phi}{f} \right) \right)$$

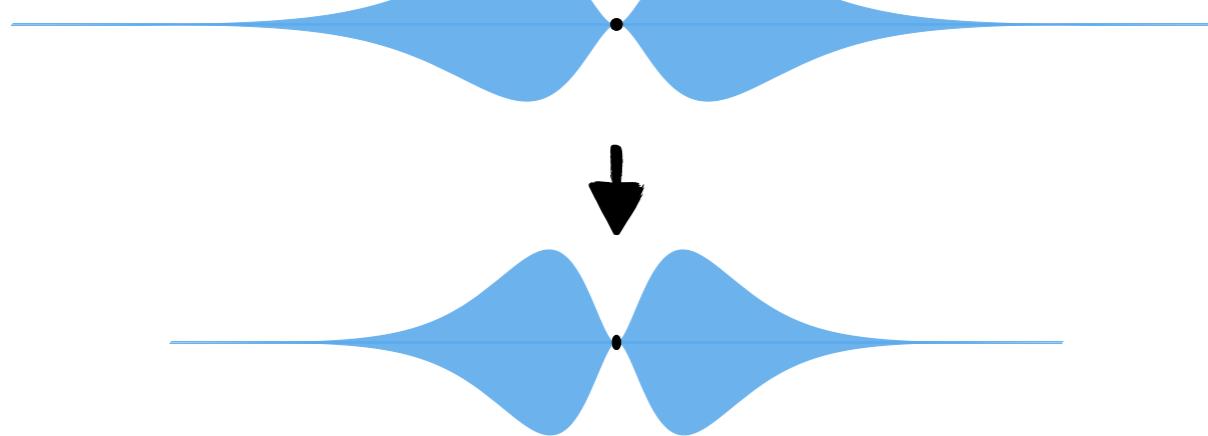
$$V(a) = V_0 + \frac{1}{2} m_a^2 a^2 + \frac{\lambda_a}{4!} a^4 + \dots$$



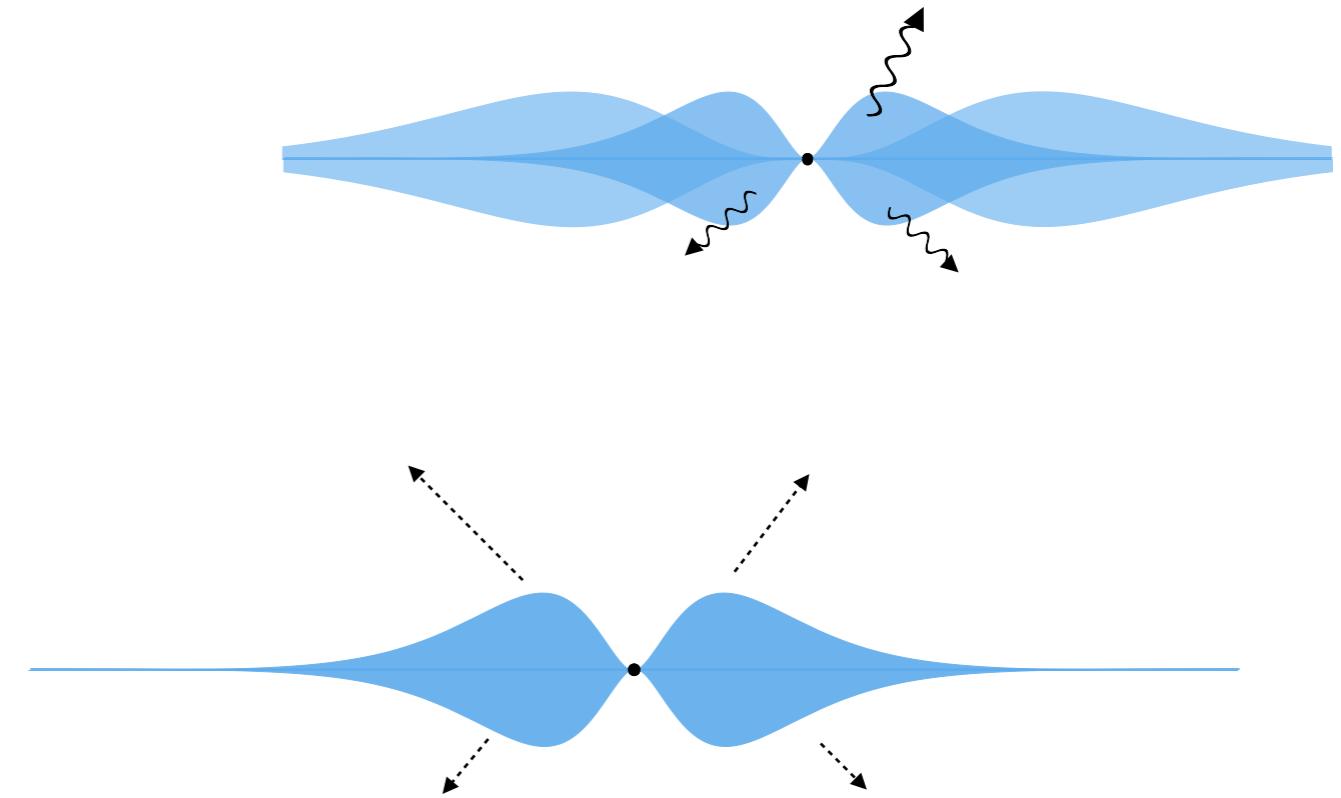
# Self-Interactions

- Self-coupling numerically small, but with large number of axions, self-energy can be important
- Attractive self energy can make the cloud shrink and perhaps collapse

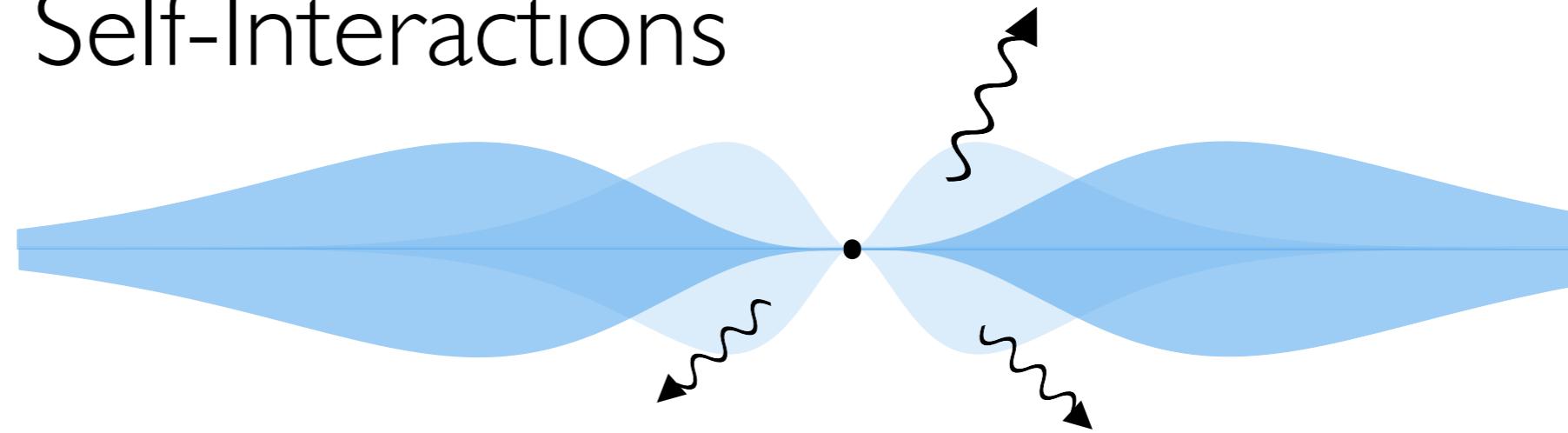
- Quartic coupling can ‘source’ semi-relativistic axion waves and populate multiple levels simultaneously, giving rise to transition signals



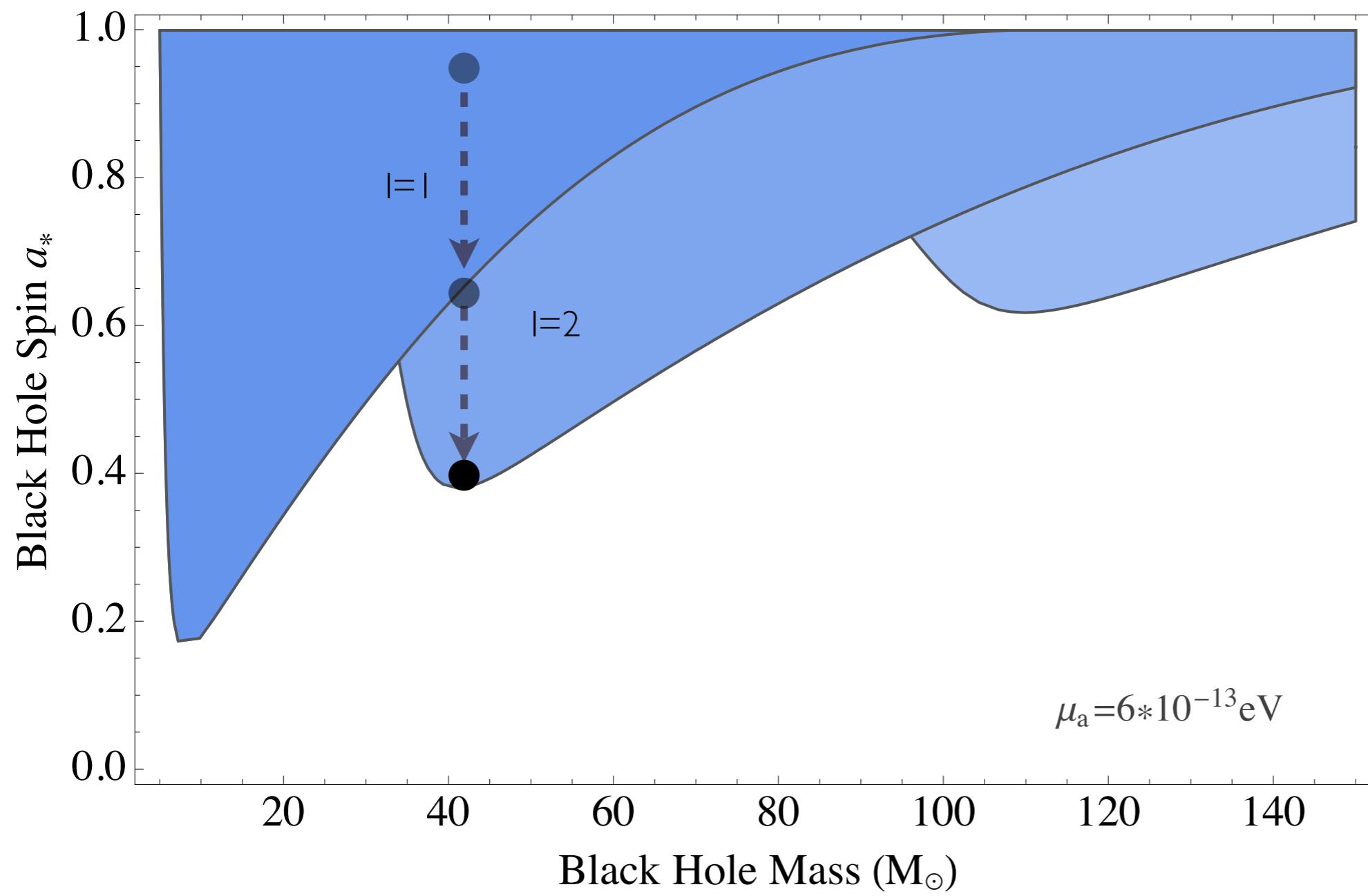
$$V(R) \simeq N \frac{l(l+1)+1}{2\mu_a r^2} - N \frac{\alpha}{r} + \frac{N^2}{32\pi f_a^2 r^3}$$



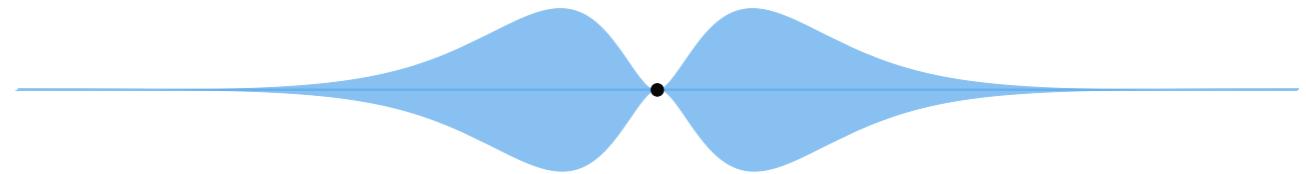
# Self-Interactions



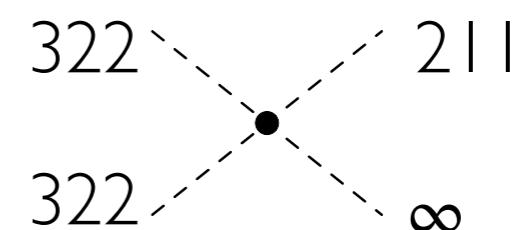
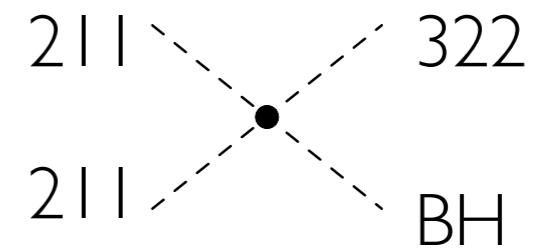
Gravitational picture: one level occupied at a time



# Self-Interactions



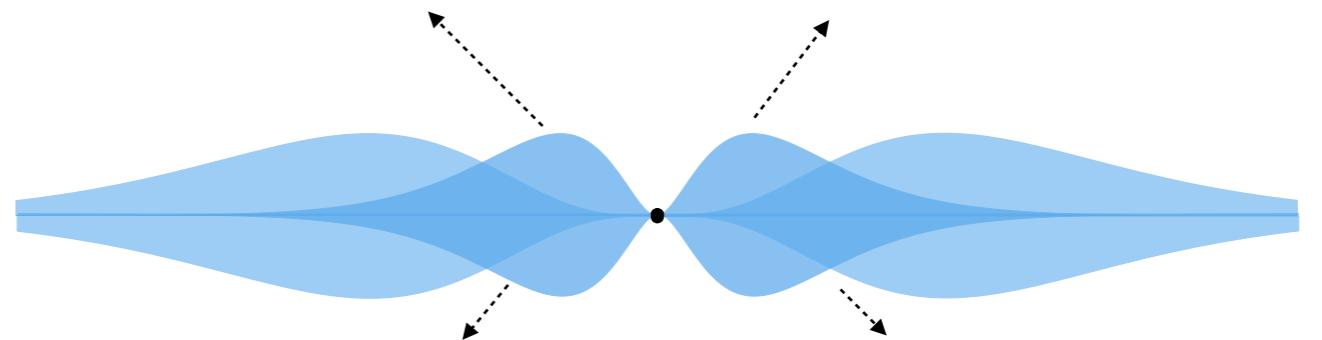
- Axions of one level can act as a source for axions in another, unpopulated level
- Angular momentum conserved; energy conserved with BH sink or radiation off to infinity



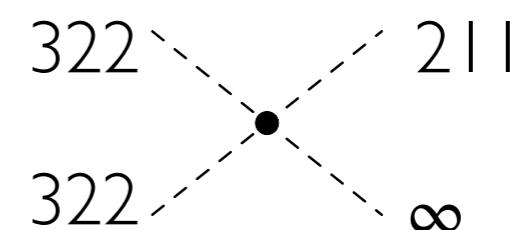
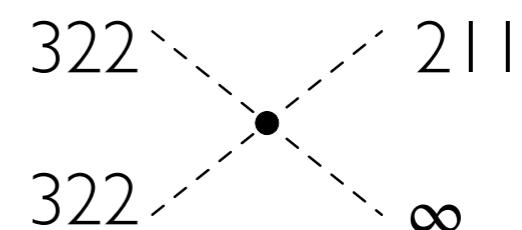
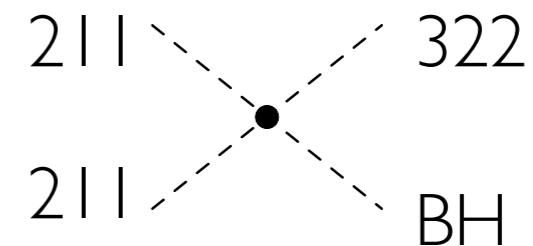
A. Gruzinov, 1604.06422

**MB**, Marios Galanis, Robert Lasenby, Olivier Simon, 19xx.xxxxxx.

# Self-Interactions



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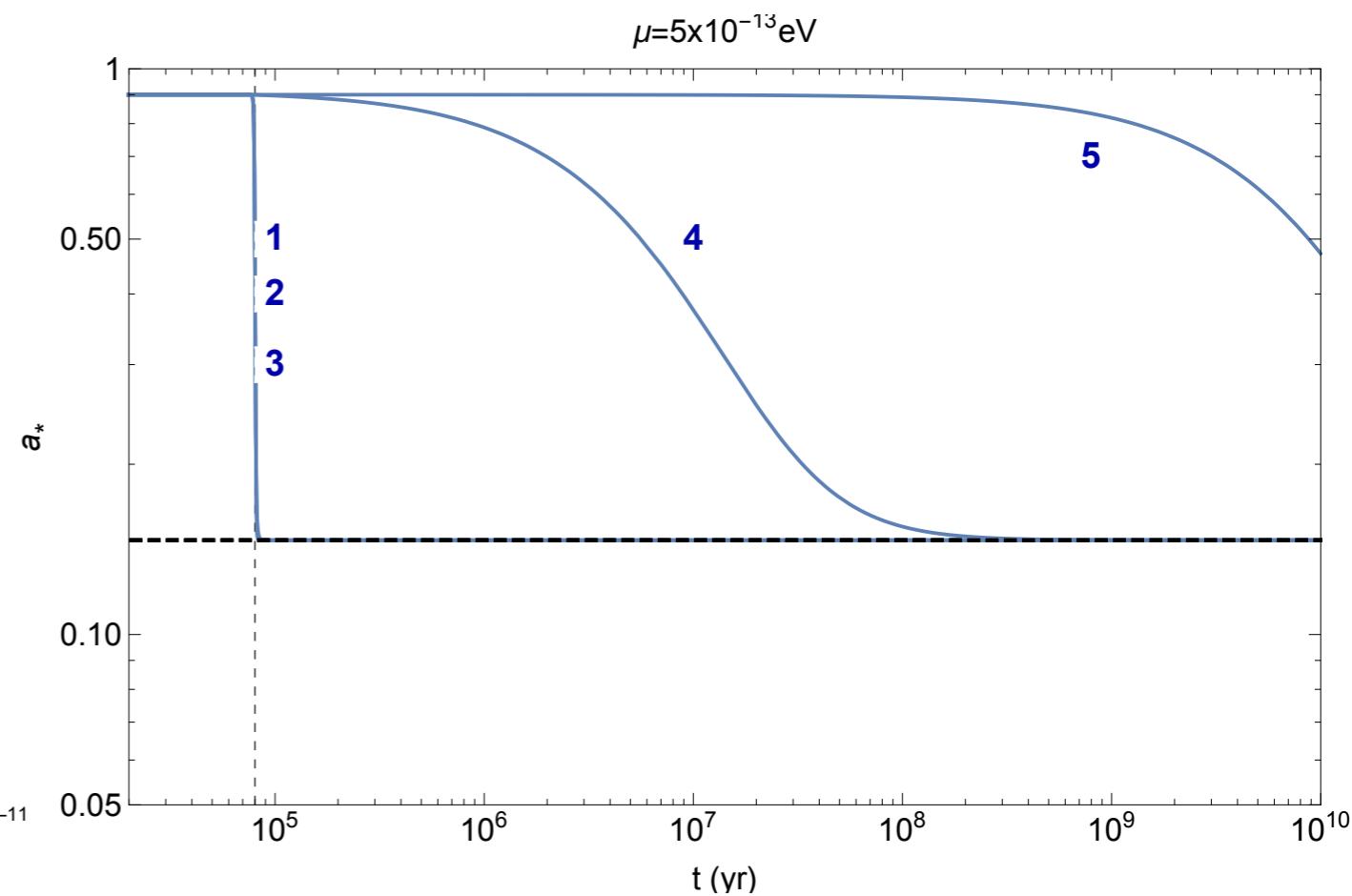
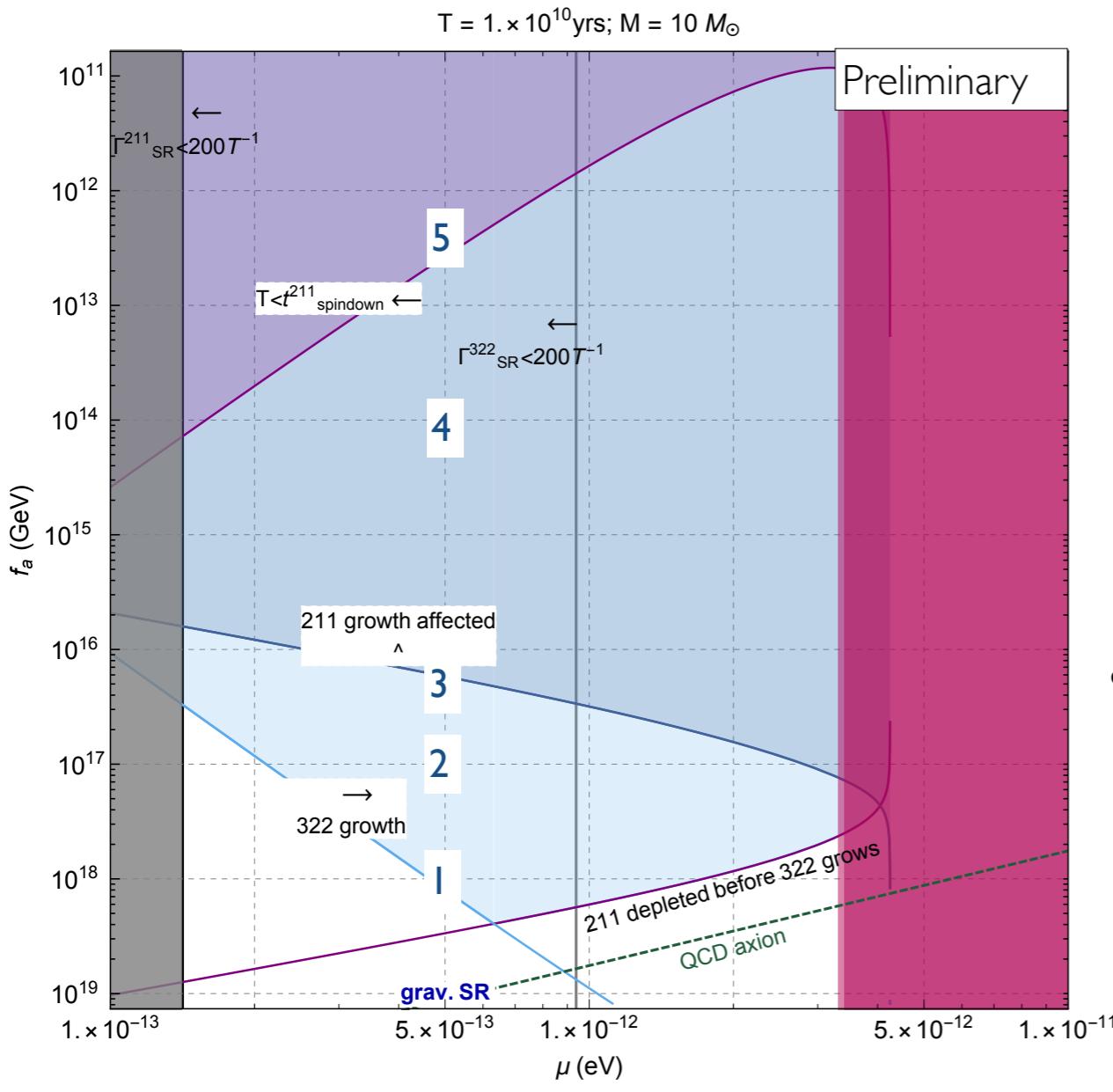


A. Gruzinov, 1604.06422

**MB**, Marios Galanis, Robert Lasenby, Olivier Simon, 19xx.xxxxxx.

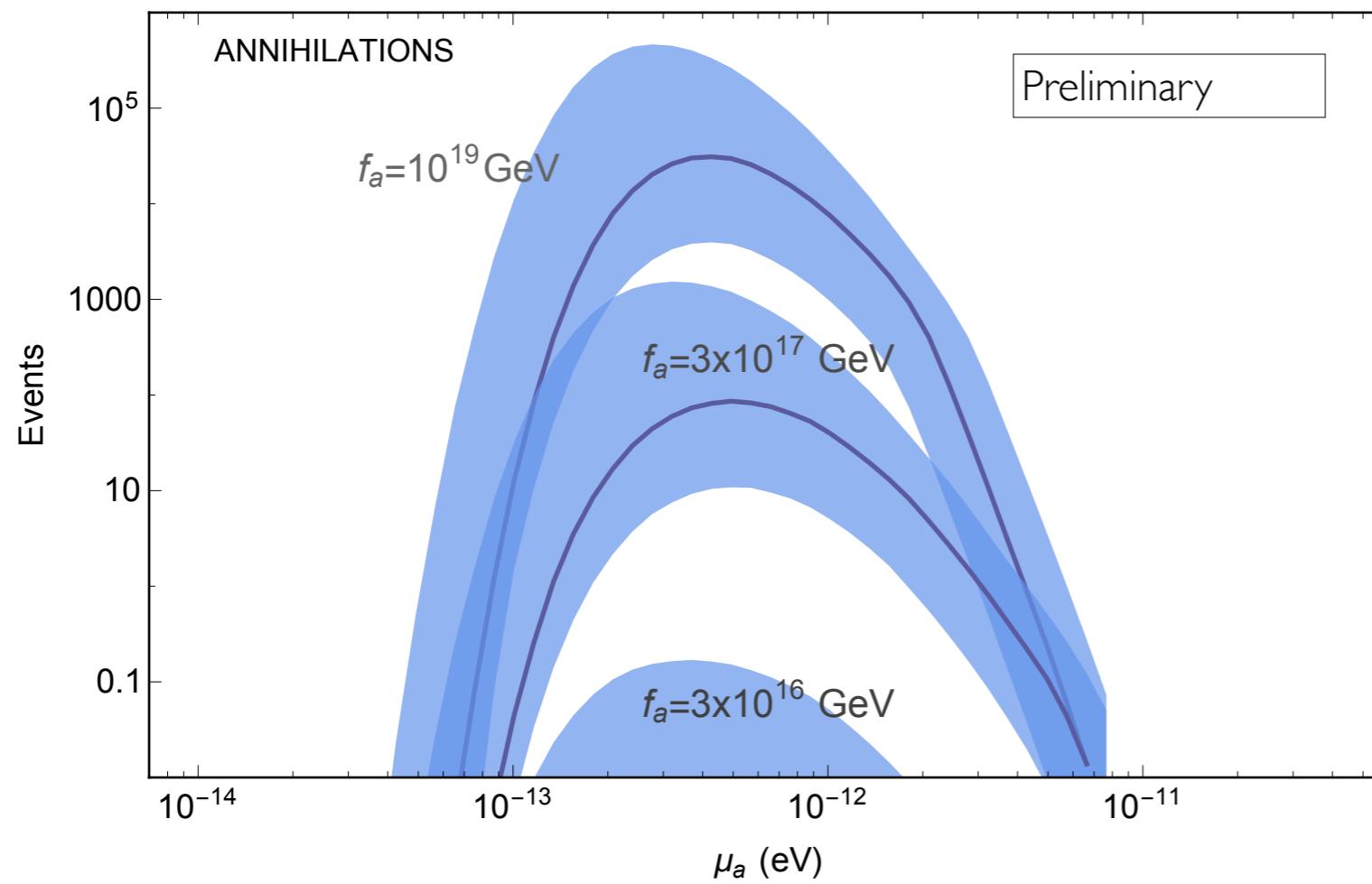
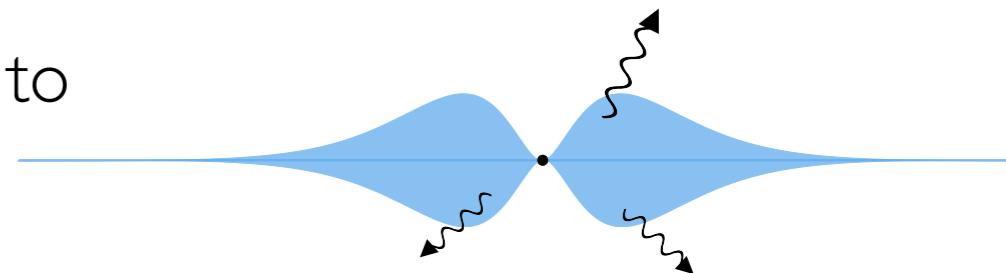
# Self-Interactions

- As self-coupling increases, the primary level may never reach its maximum value, affecting spin down of the black hole



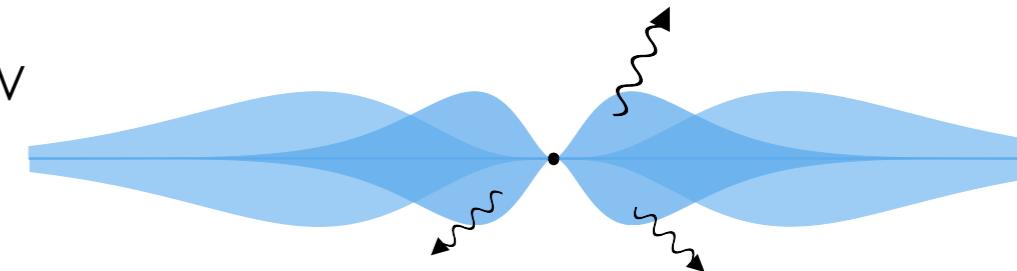
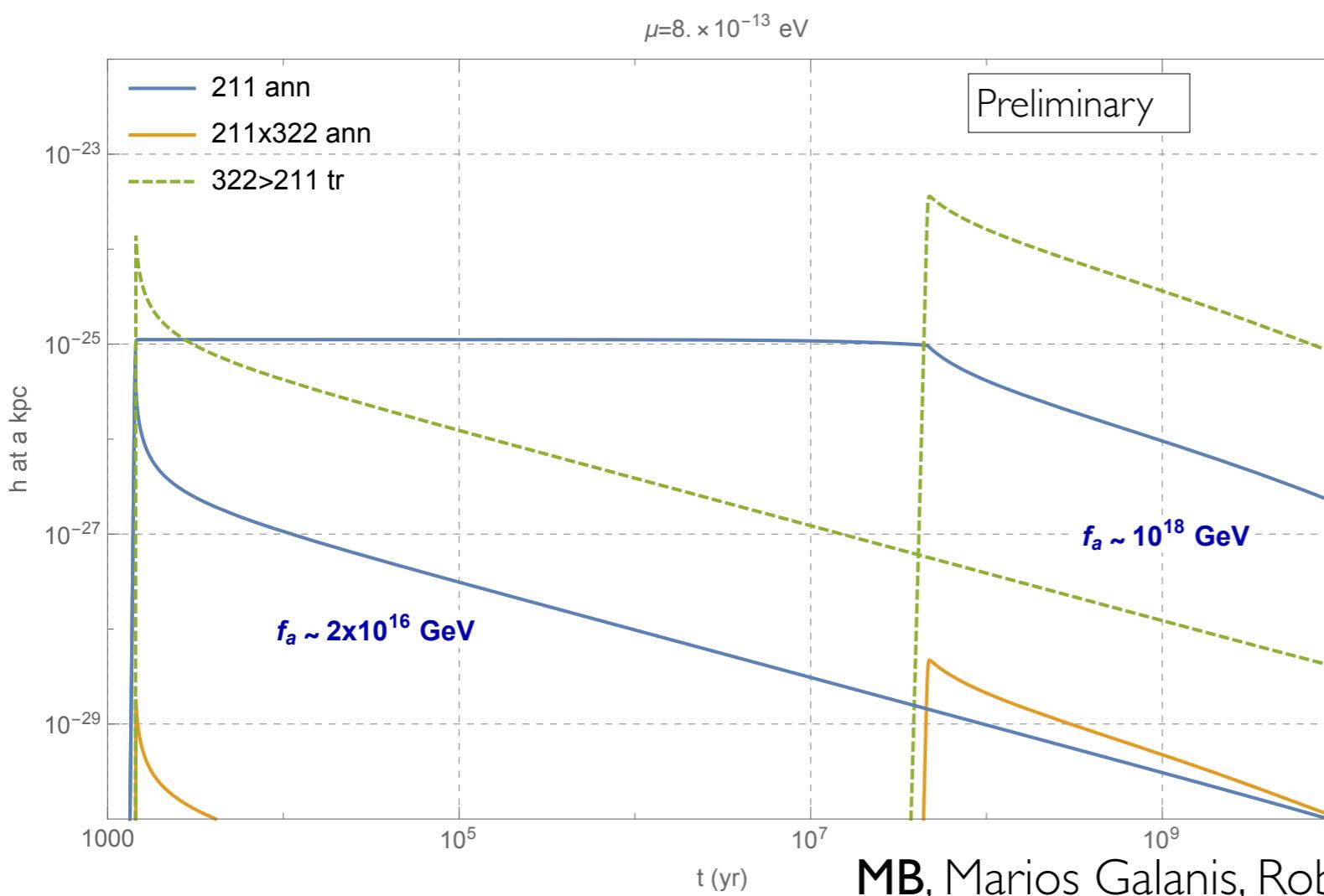
# Self-Interactions

- Evolution of first level capped at smaller value due to self interactions
- Gravitational wave annihilation power suppressed at high  $f_a$

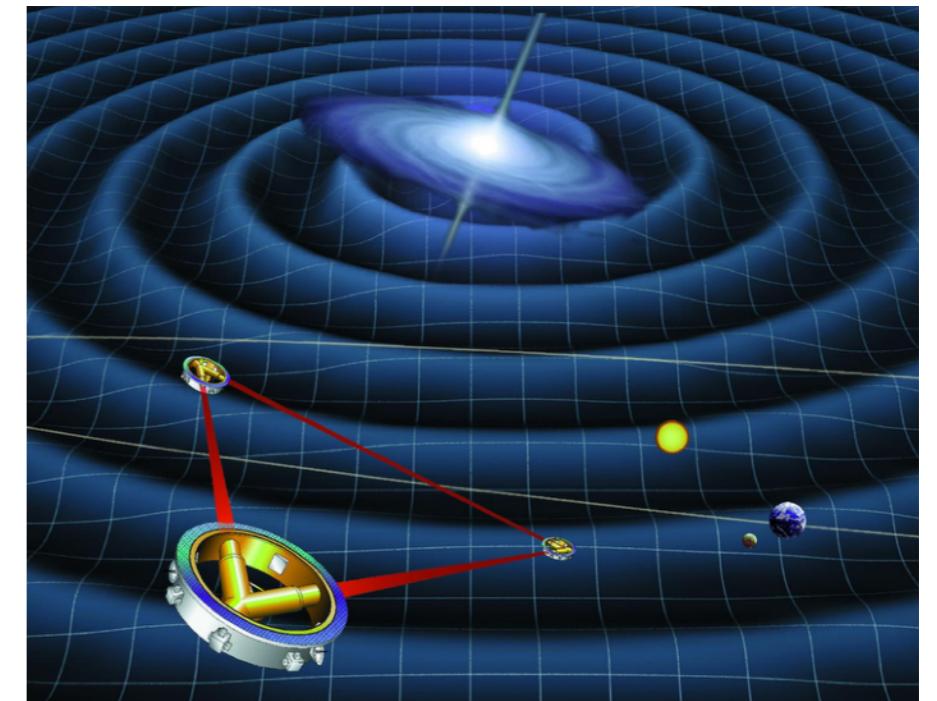


# Self-Interactions

- Two (or more) levels populated simultaneously: new signatures
  - Gravitational transitions between two levels: larger power than annihilations

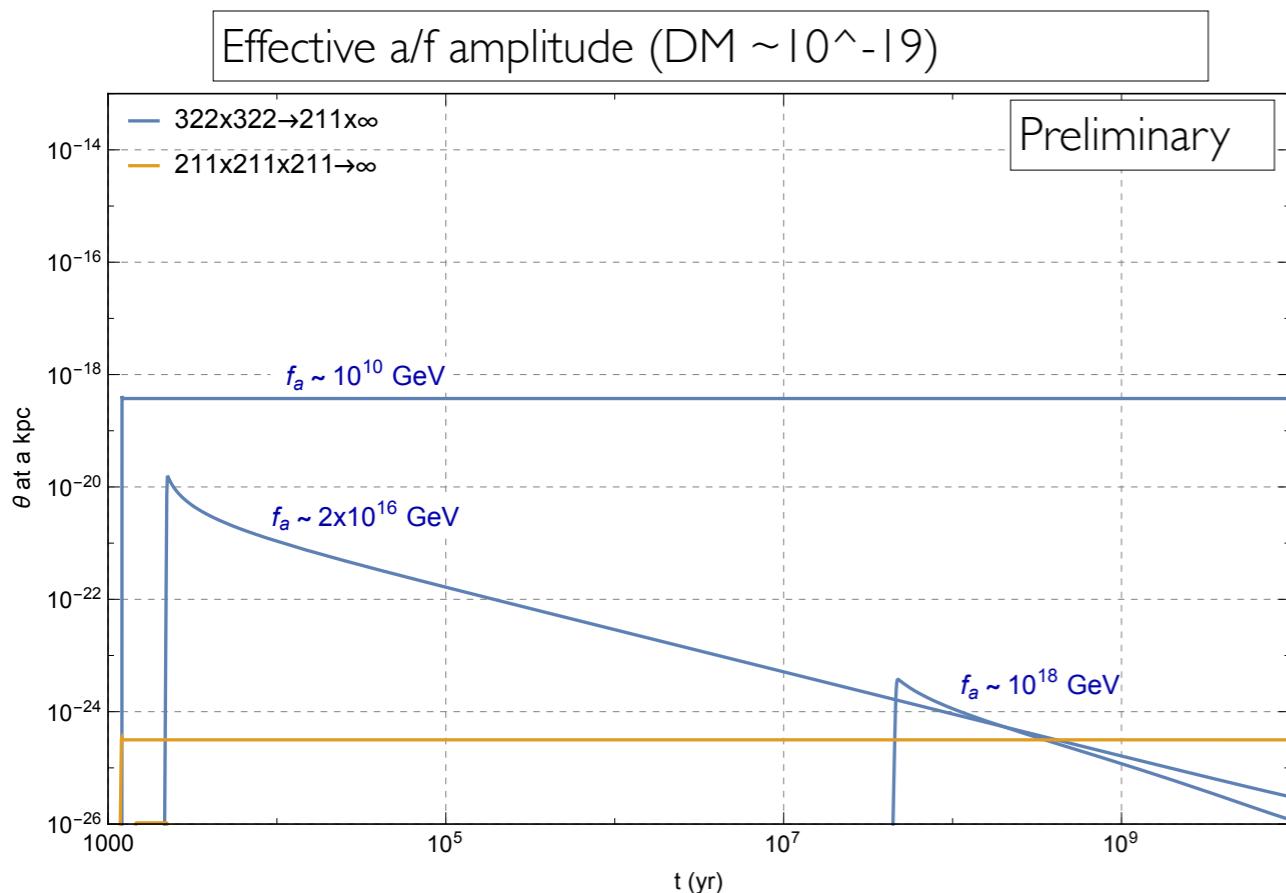
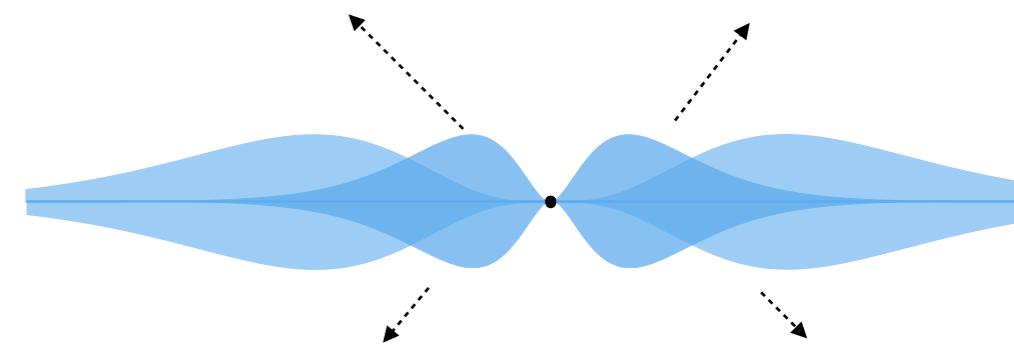


- mHz - 100 Hz frequencies
  - most promising for future detectors: LISA, ...



# Self-Interactions

- Emission of scalar radiation from the cloud:  
axion waves
- Scalar radiation is long-lasting and coherent,  
may be observable in dark matter  
experiments
- Requires different data analysis strategies (e.g.  
LIGO continuous waves search)



# Conclusions

- BH spin measurements already exclude previously open parameter space
- Ongoing continuous gravitational wave searches will be able to exclude or discover light bosons
- Future detectors can see the growth of a gravitational atom in real time
- Self-interactions suppress cloud growth and produce new signatures: GW transition signals and axion flux at dark matter detectors
- A lot of new exciting directions are being developed!

