# Black Hole Superradiance of Self-Interacting Scalar Fields

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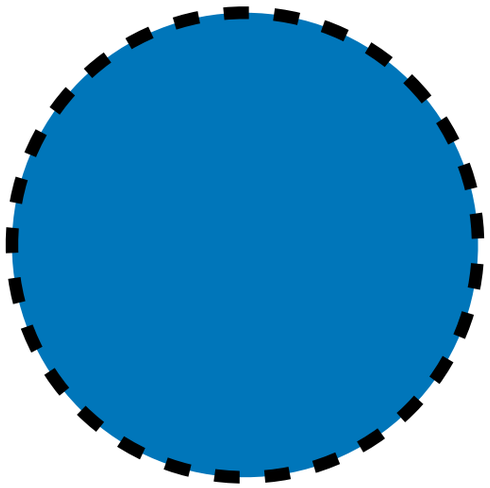
Stanford University

07/30/2021

Based on Phys. Rev. D **103**, 095019, with M. Baryakhtar, R. Lasenby and O. Simon (2021)

CHEW 2021

# How to spin down a rotating cylinder



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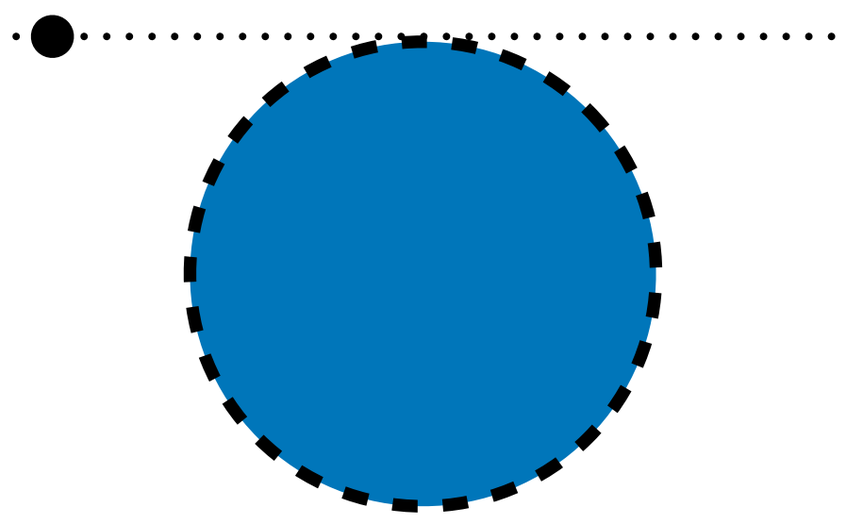
Simple: throw a slow ball tangentially to it

Friction will do the work

$$\Omega_i > v_{\varphi,i}$$



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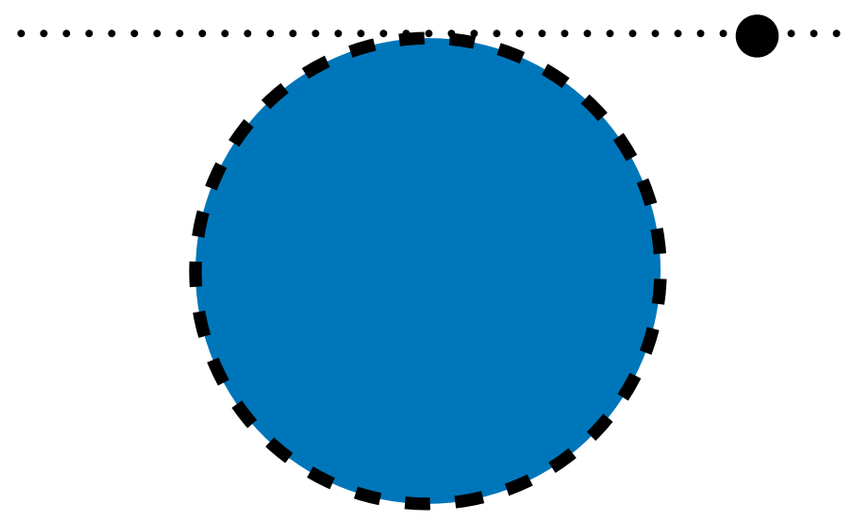

$v_{\varphi,f} > v_{\varphi,i}$

The ball **extracted energy** and **angular momentum** from the cylinder

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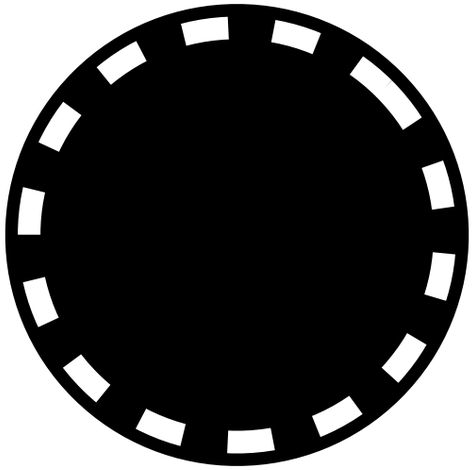

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With waves $\propto e^{-i\omega t + im\phi}$

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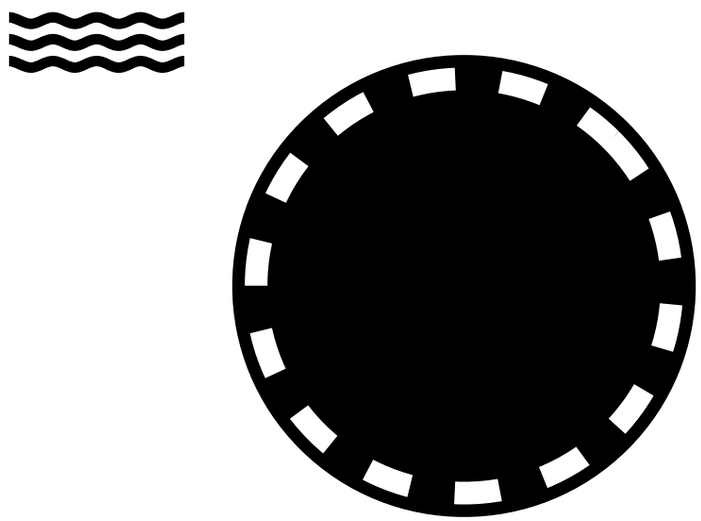

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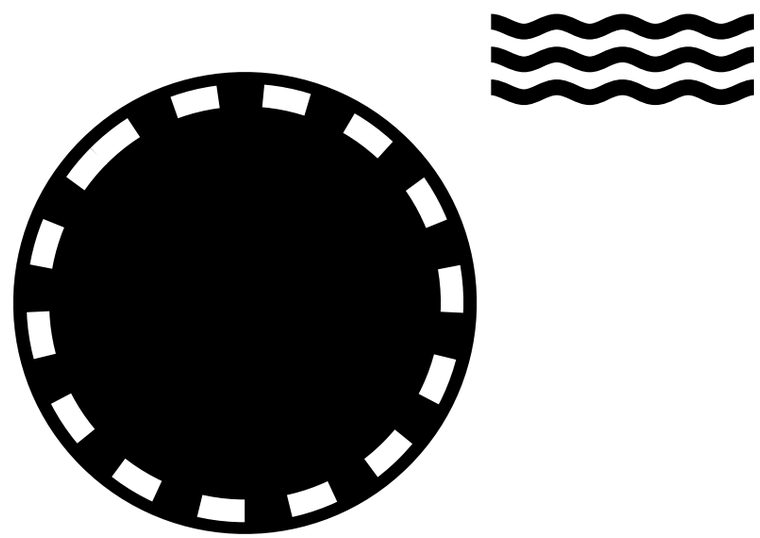

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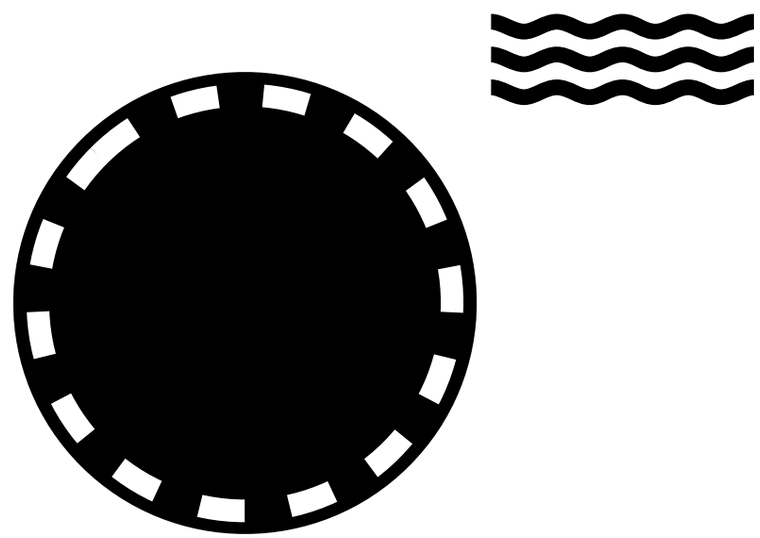

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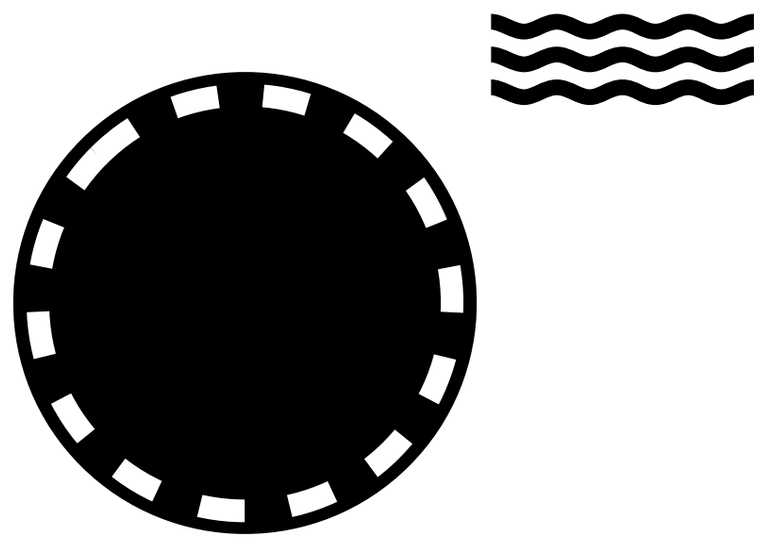

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**The absorbing horizon**

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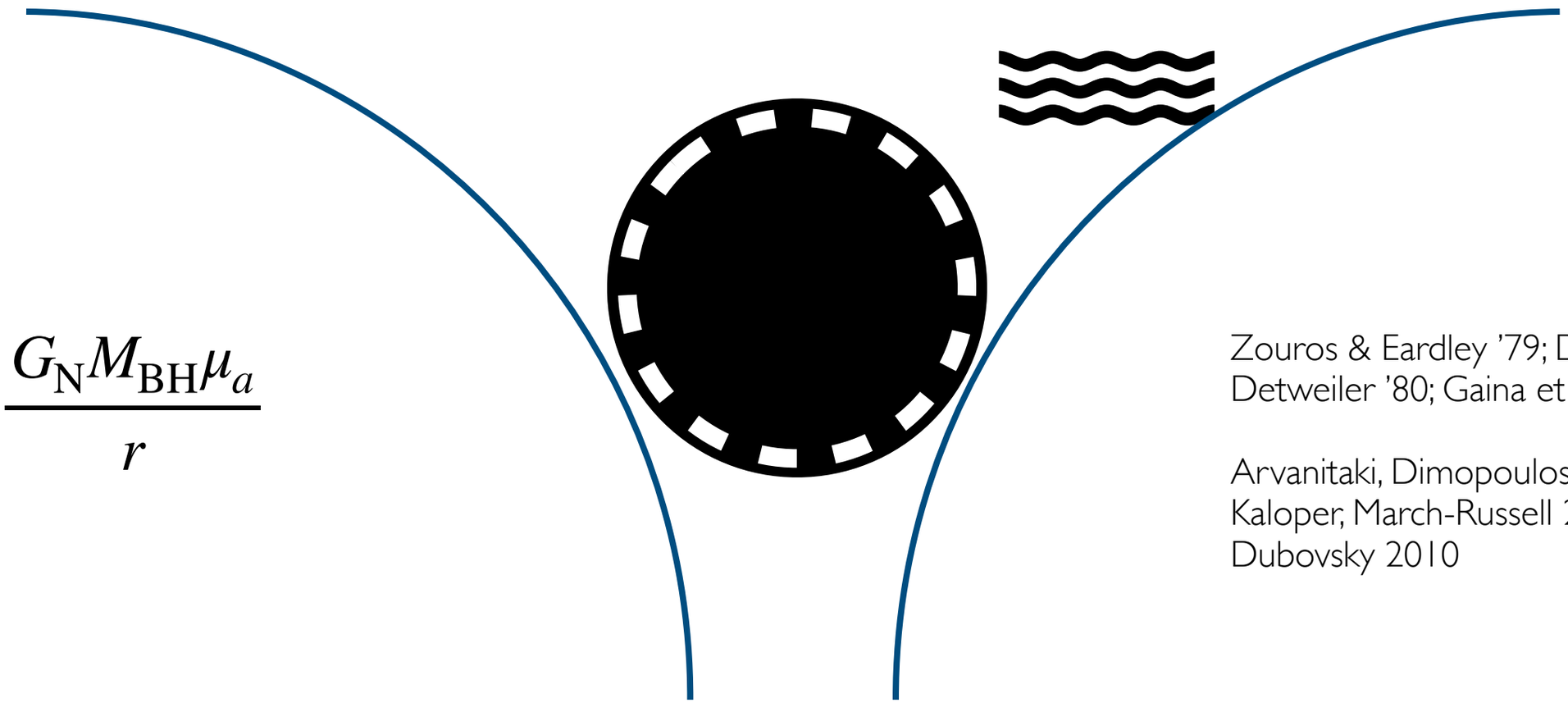

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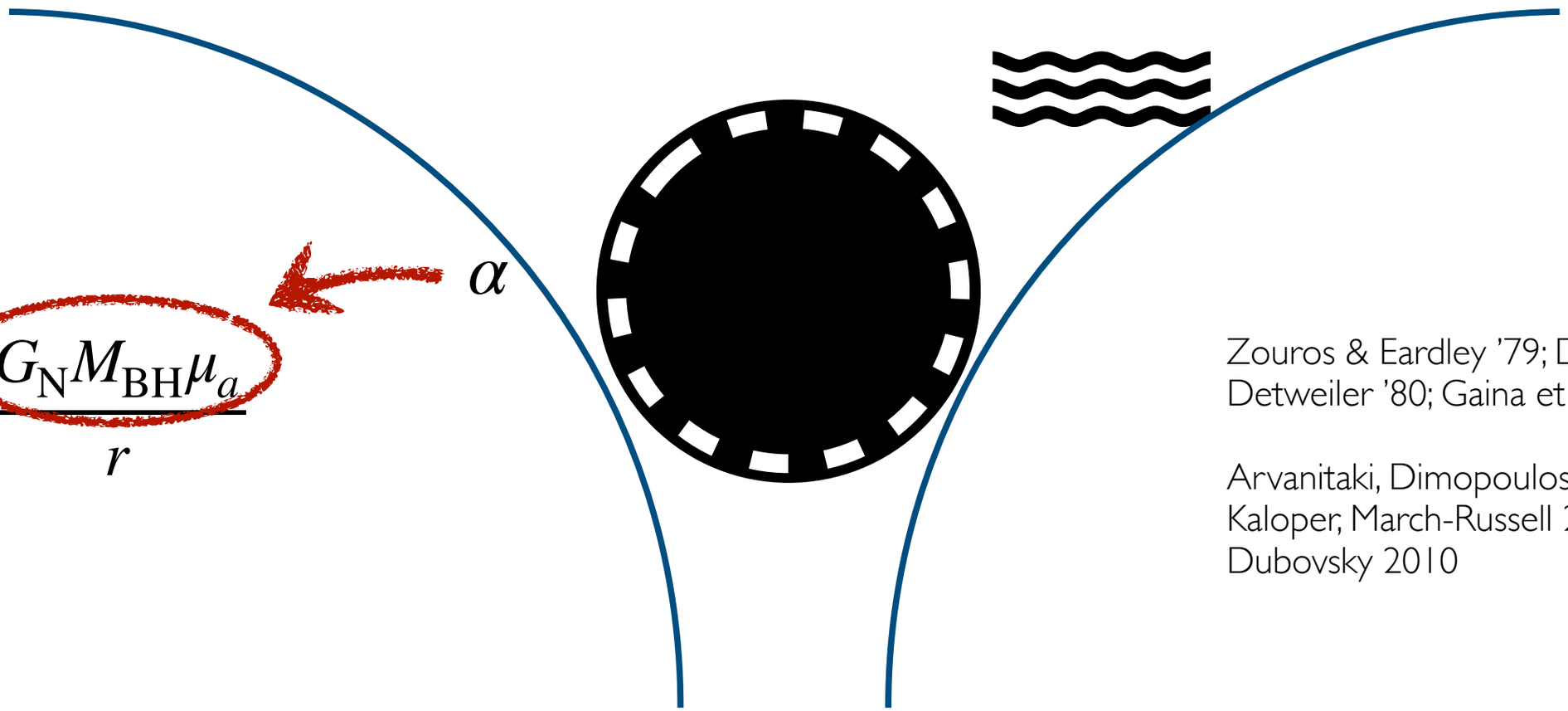


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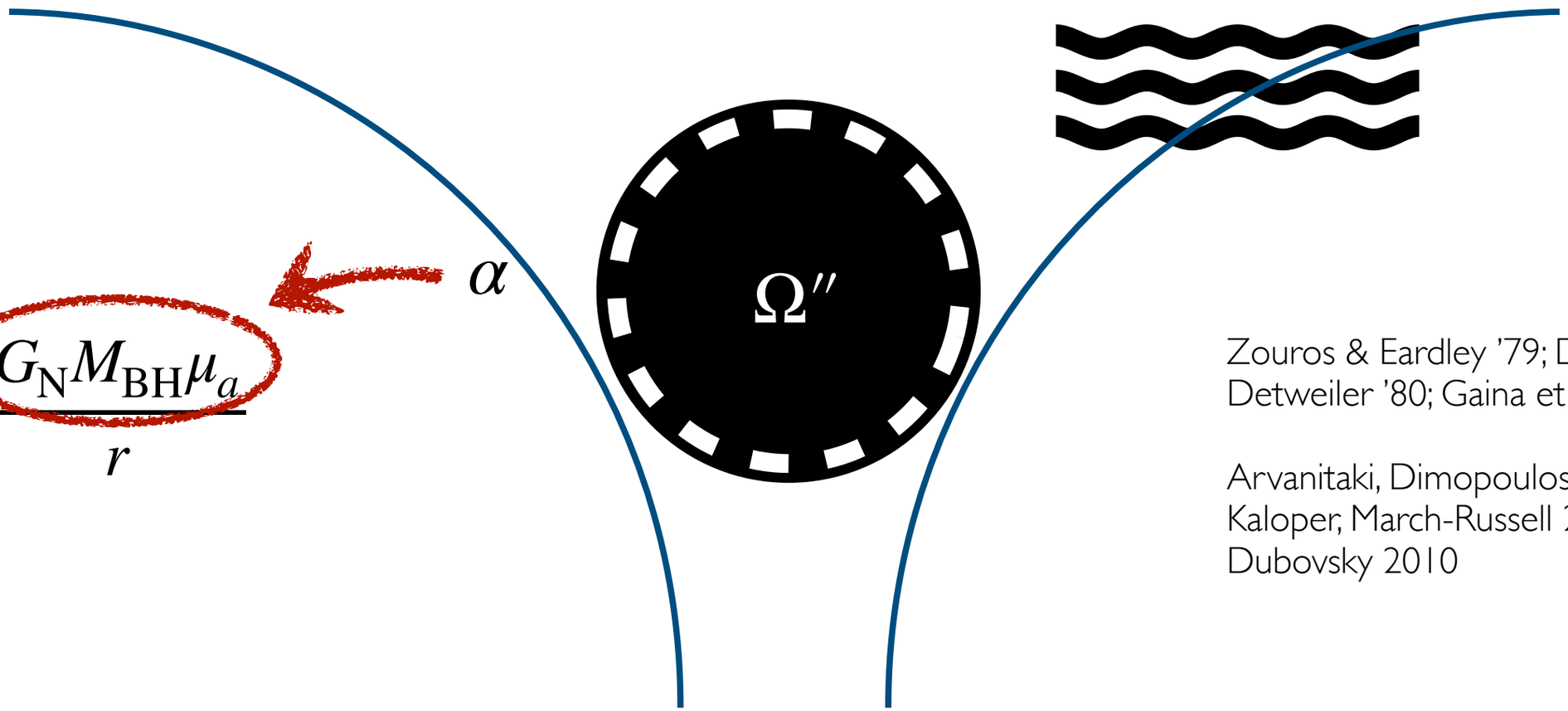


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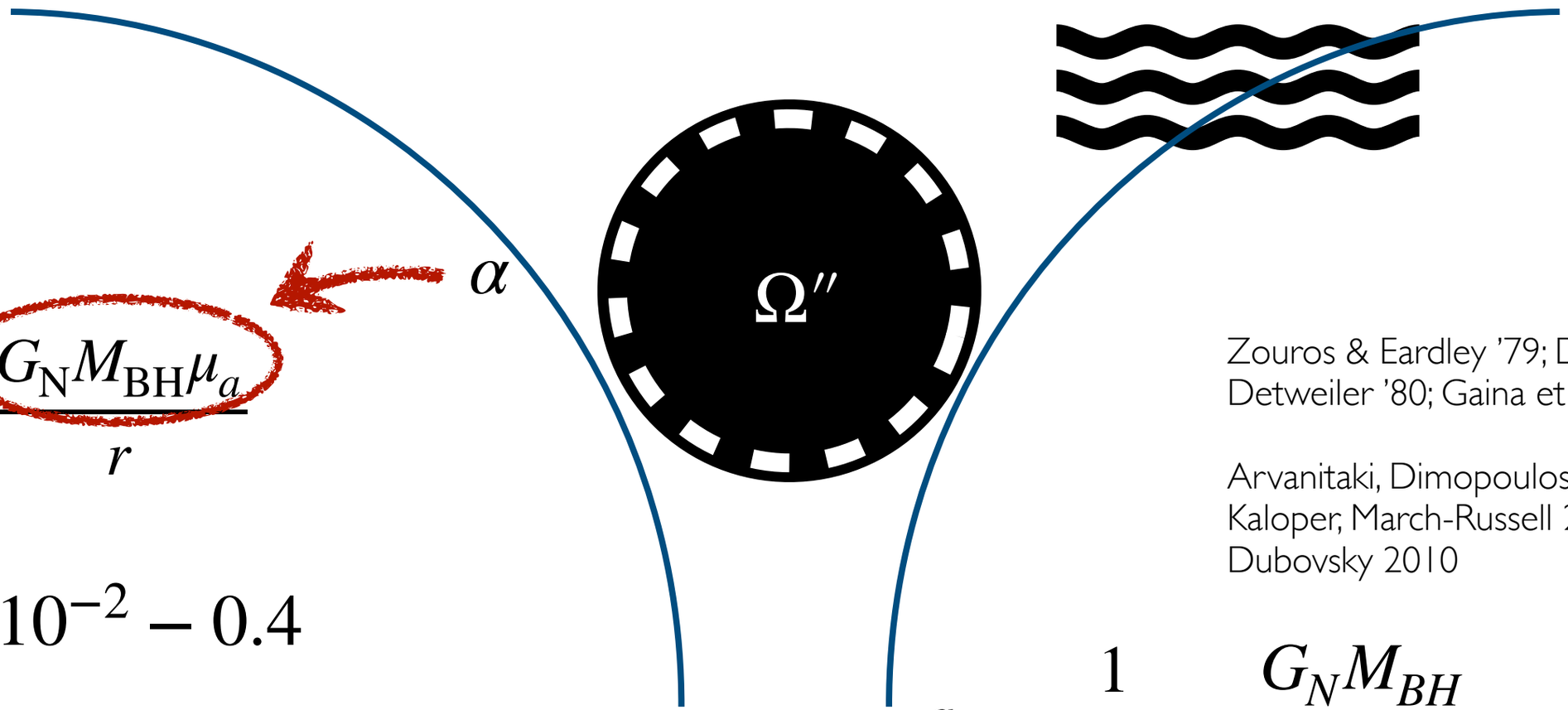


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$$\alpha \sim 10^{-2} - 0.4$$

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Bohr Radius $\quad a_0 = \frac{1}{\mu_a \alpha} = \frac{G_N M_{BH}}{\alpha^2}$

Energy Levels $\quad E_{n\ell m} = \mu_a \left(1 - \frac{\alpha^2}{2n^2}\right)$

Growth Rates (Scalar) $\quad \Gamma_{n\ell m} \propto \mu_a \alpha^{4\ell+4}(m\Omega - \omega)$

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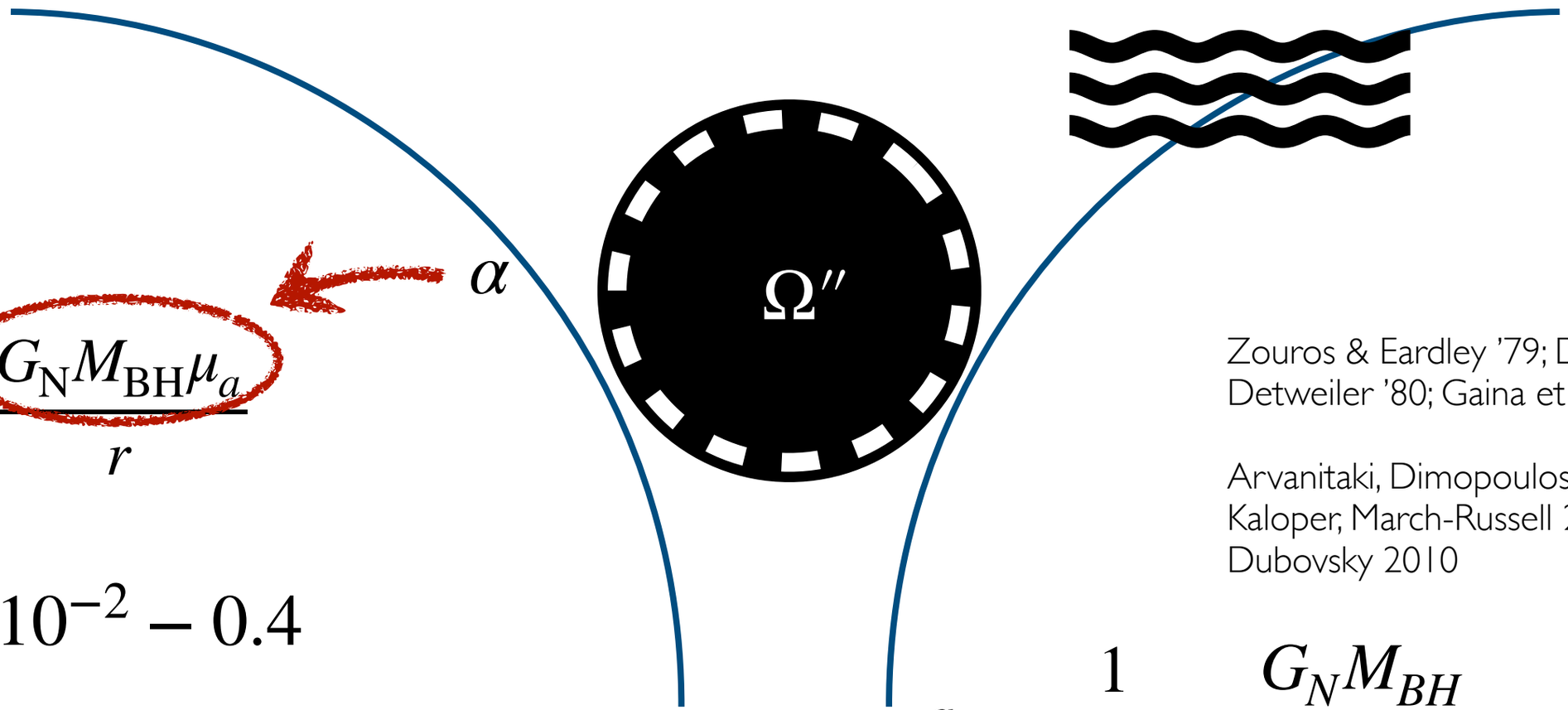


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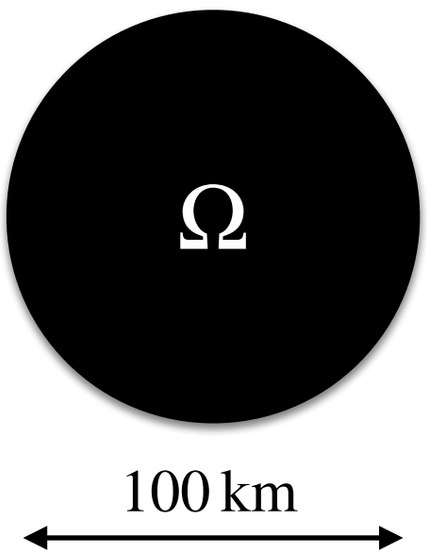
# Numbers to have in mind

$$\boxed{\Omega > \omega/m}$$

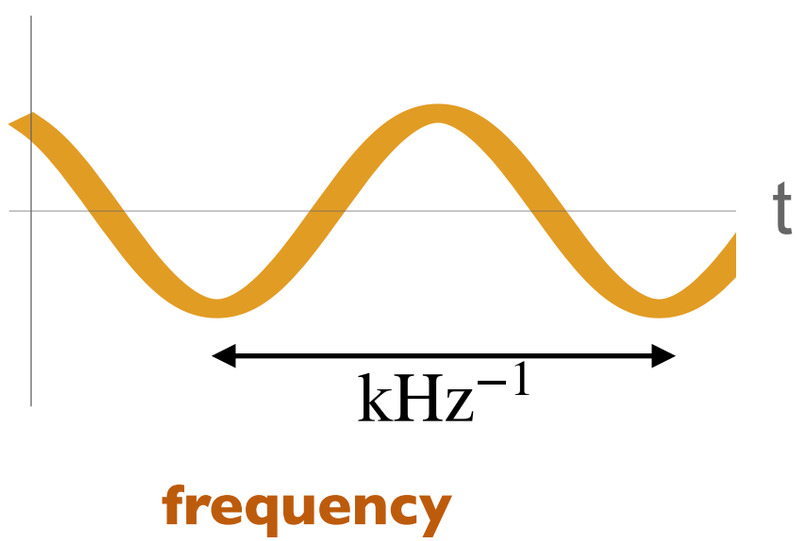


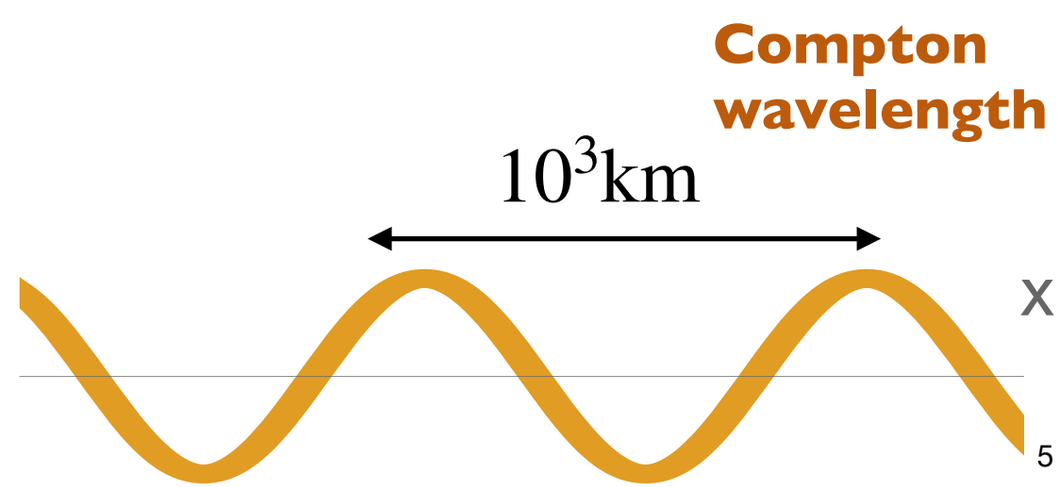

black hole (30 $M_\odot$)

- Set a typical length scale, and are a huge source of energy
- Sensitive to QCD axions with GUT- to Planck-scale decay constants $f_a$

$$\alpha = \mu_a G_N M_{BH} \sim 0.22$$

for a $10^{-12}$ eV particle:



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- **Number of axions increases exponentially** by extracting the BH's energy and angular momentum

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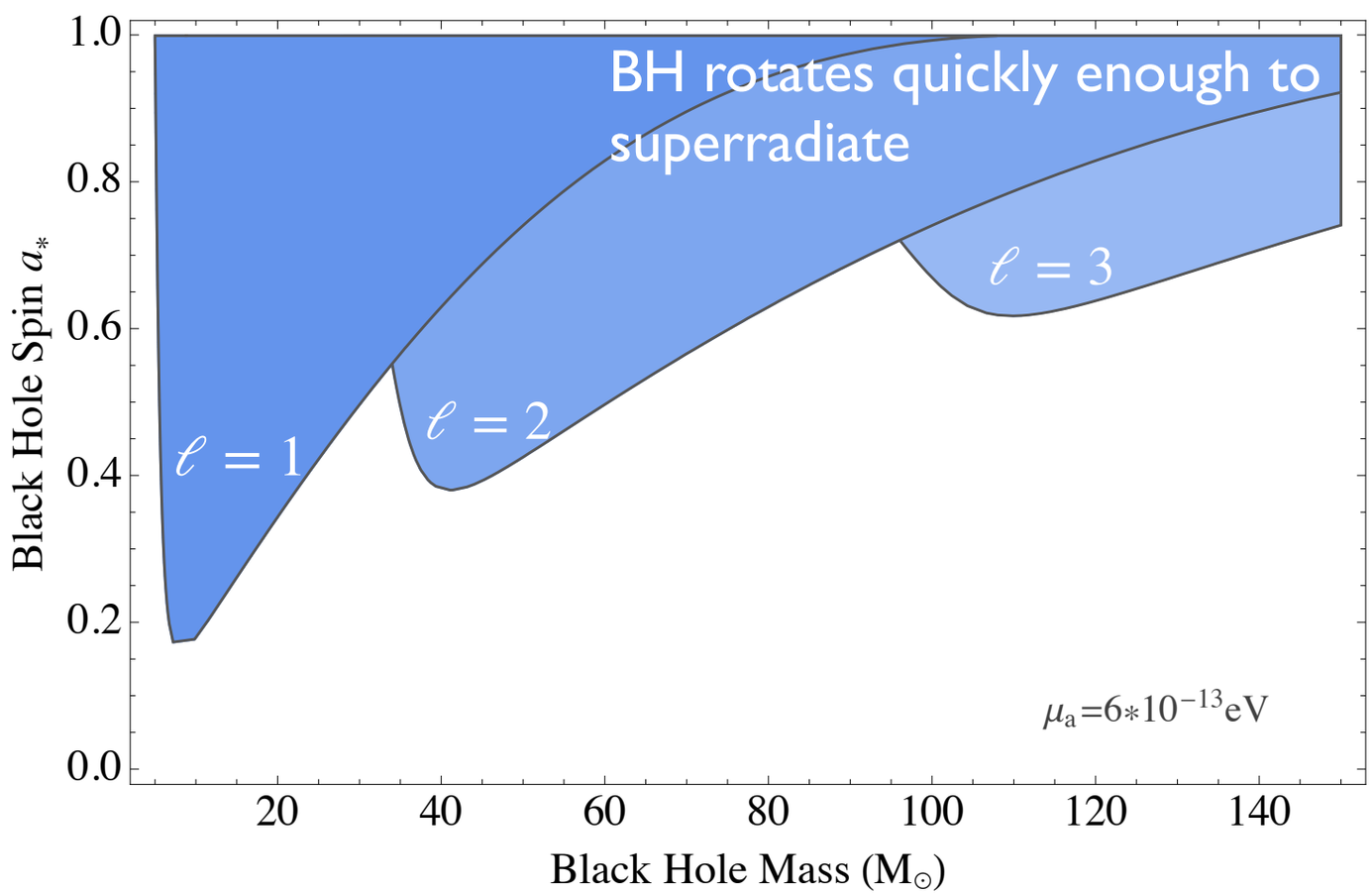

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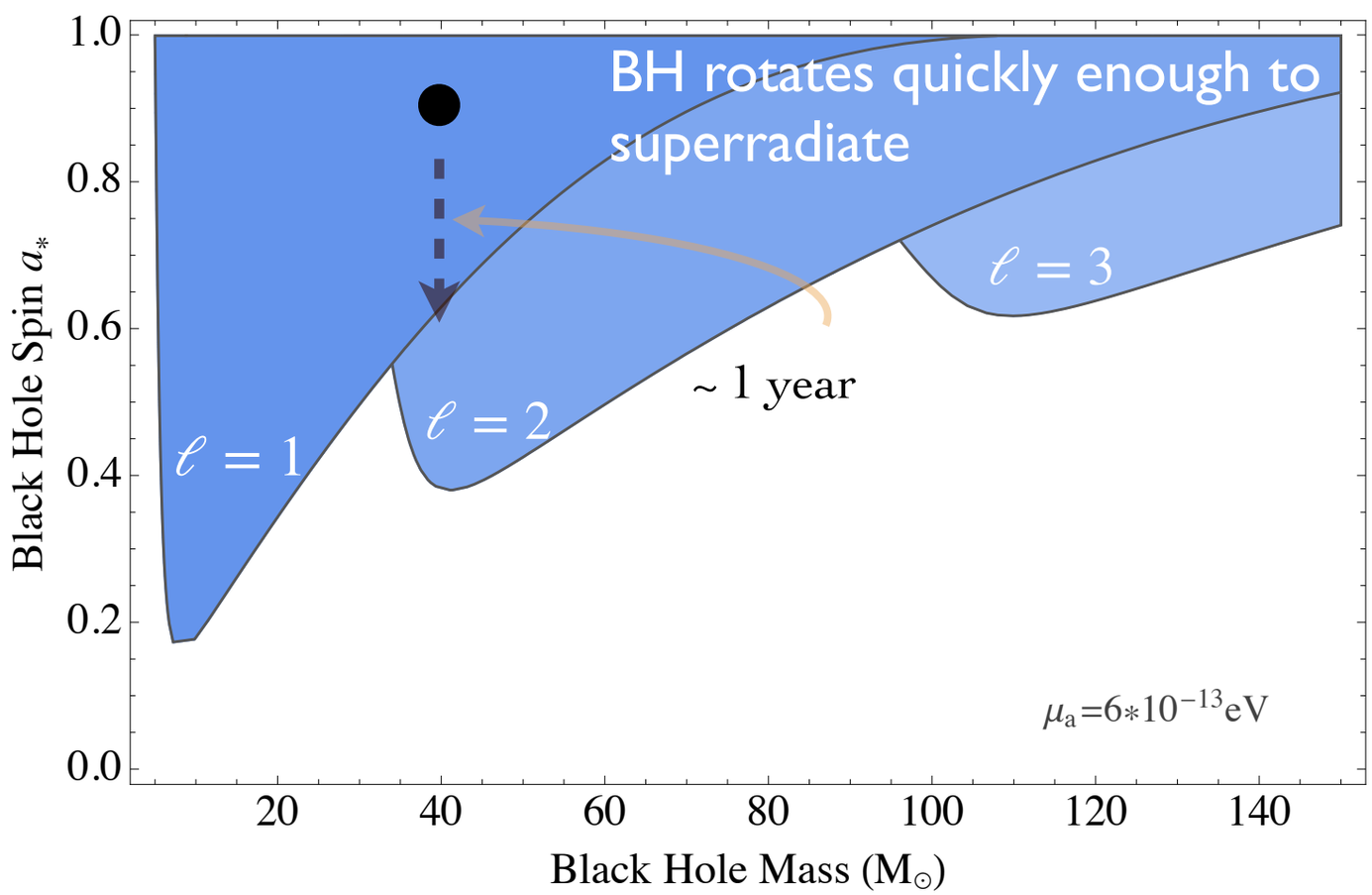

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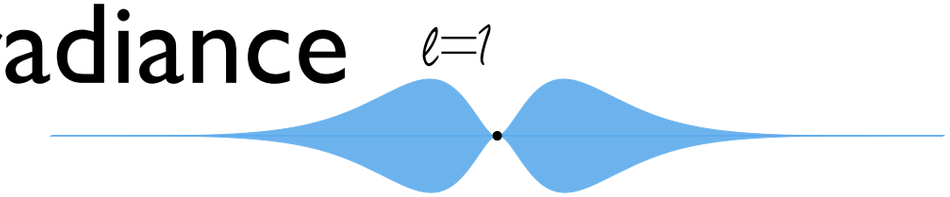


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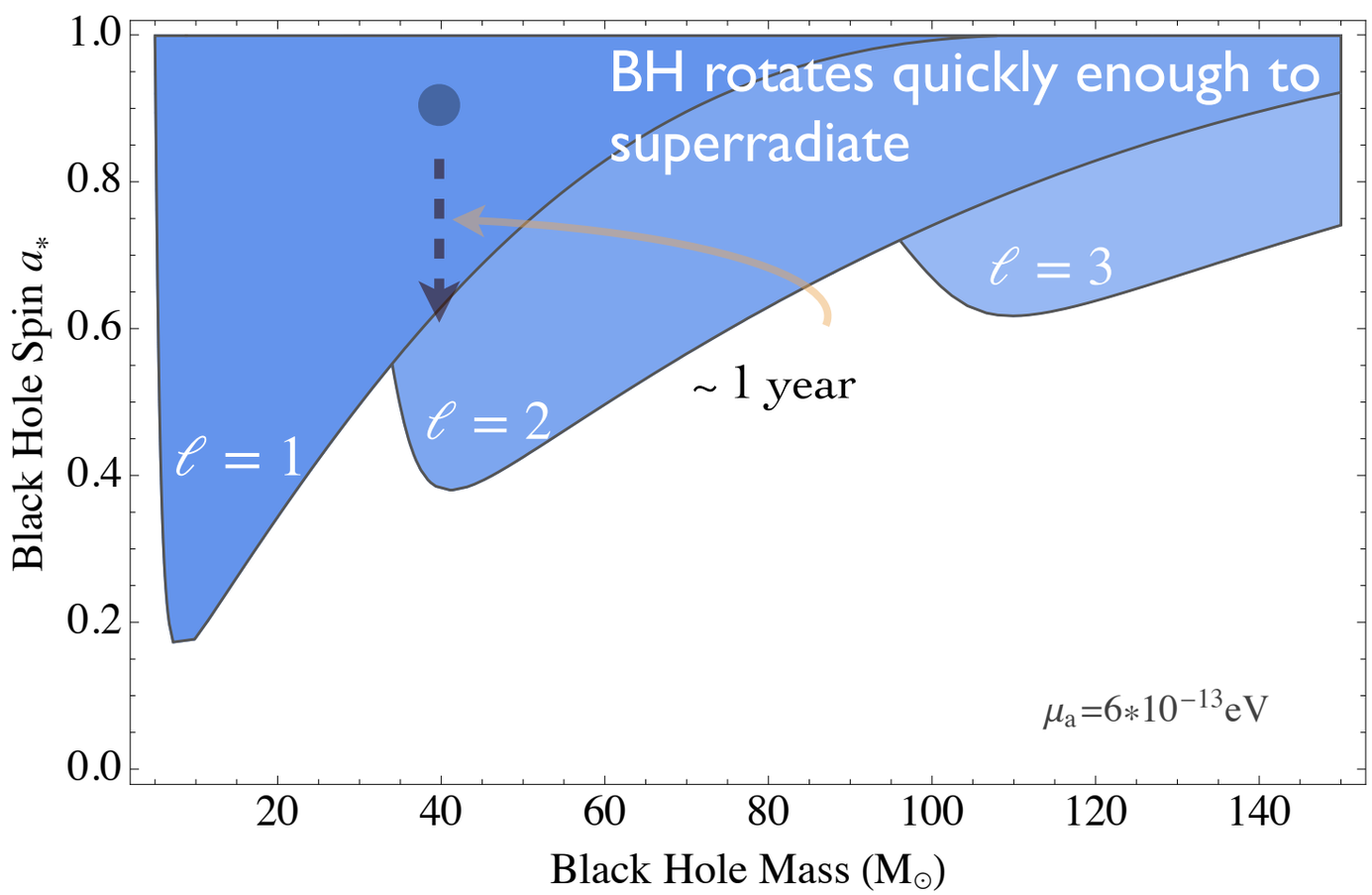

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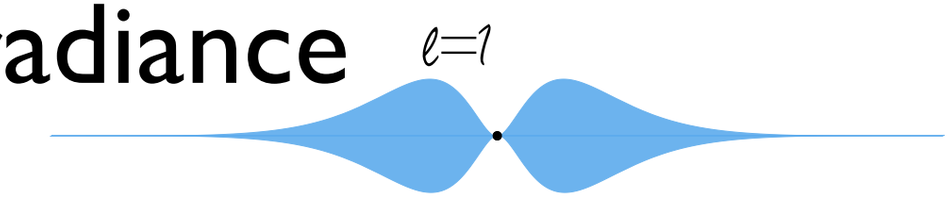


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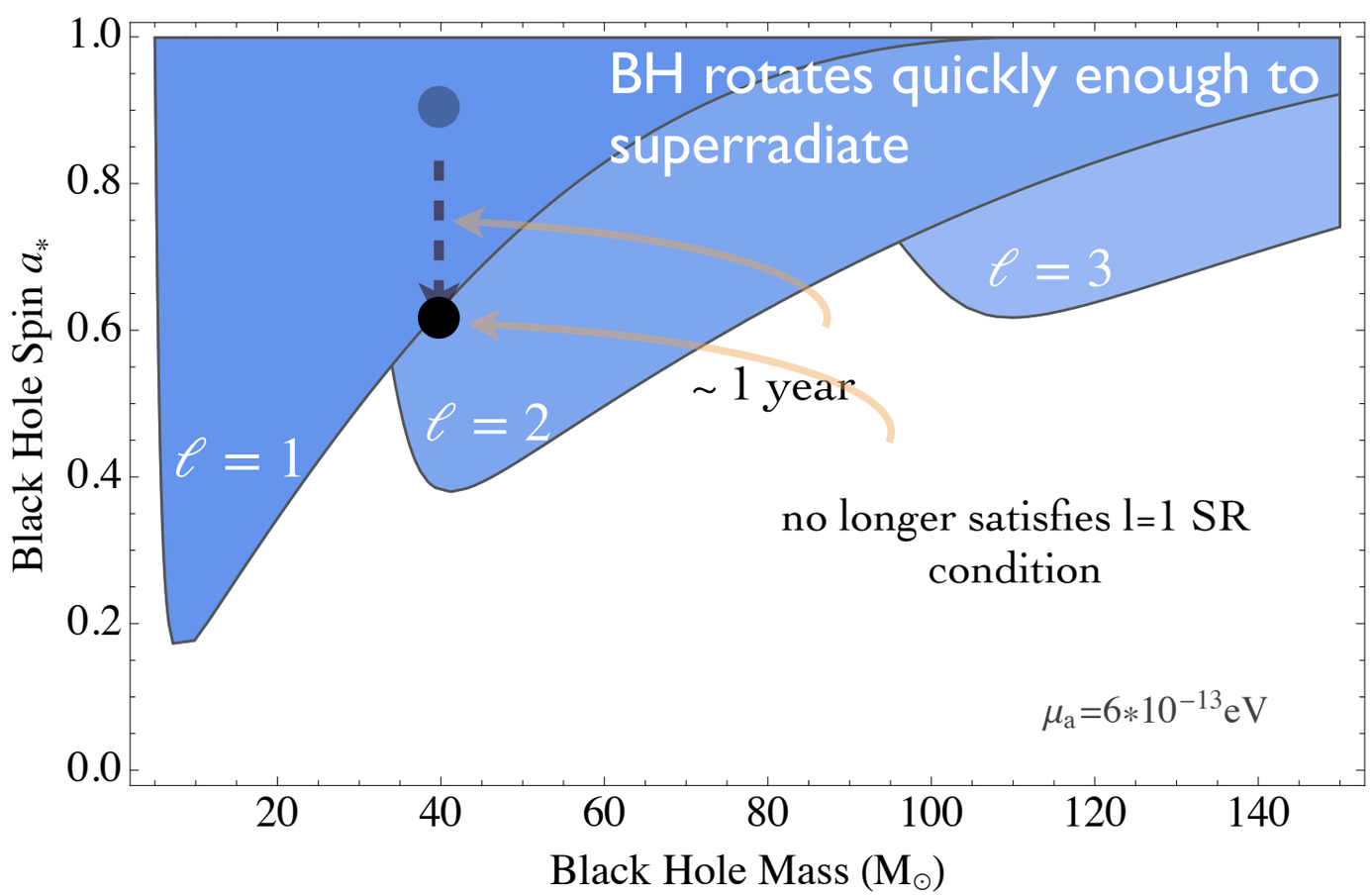


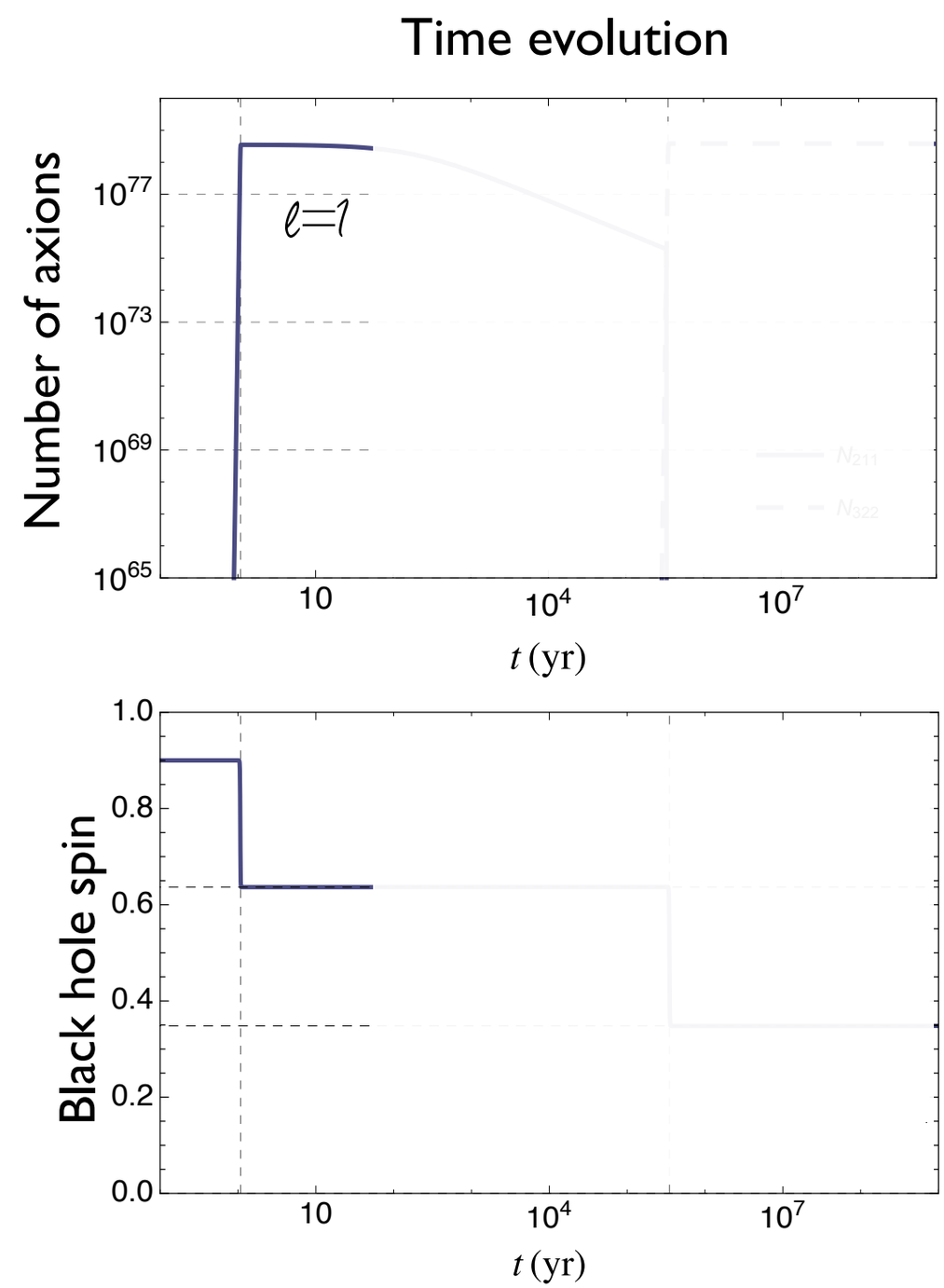

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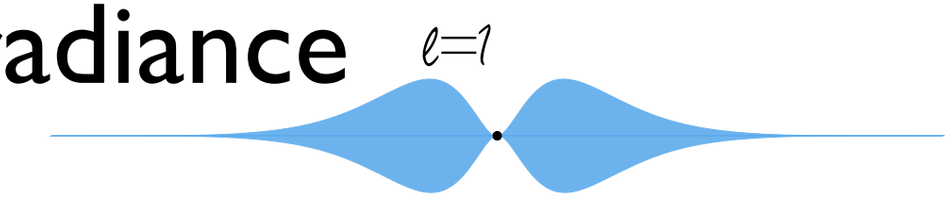


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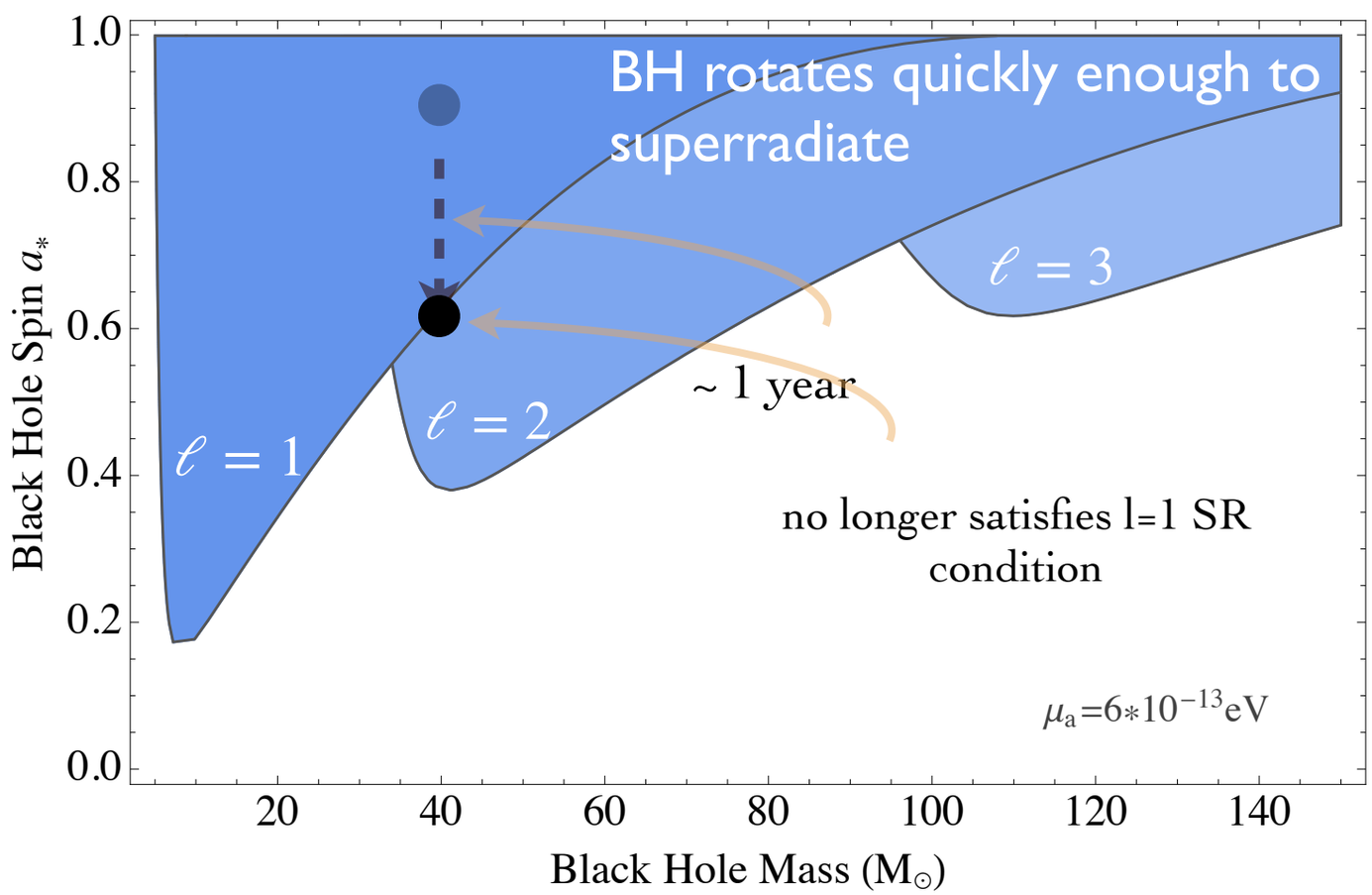


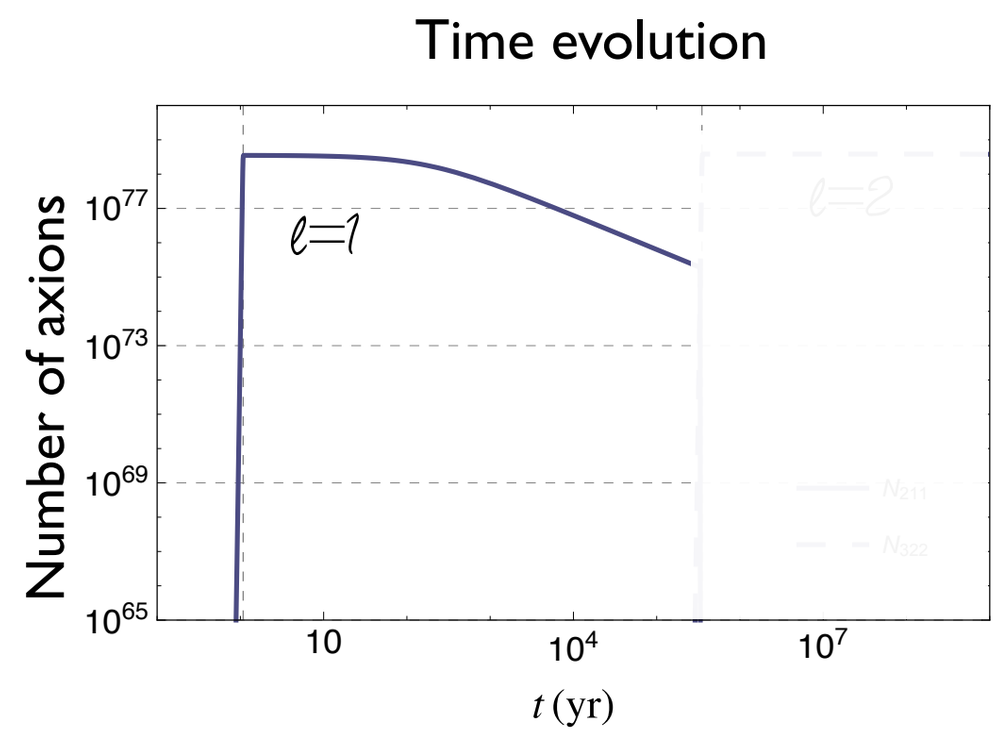


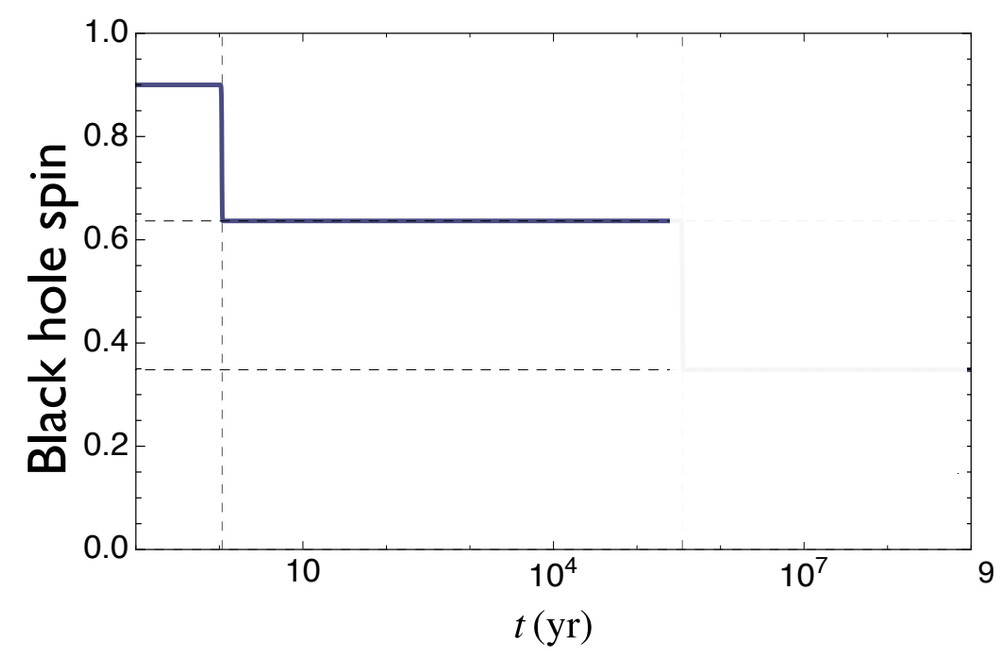

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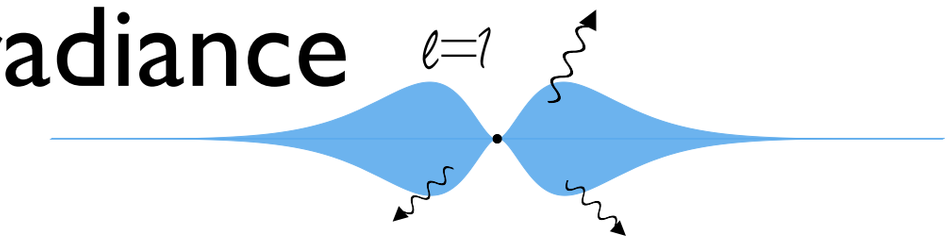


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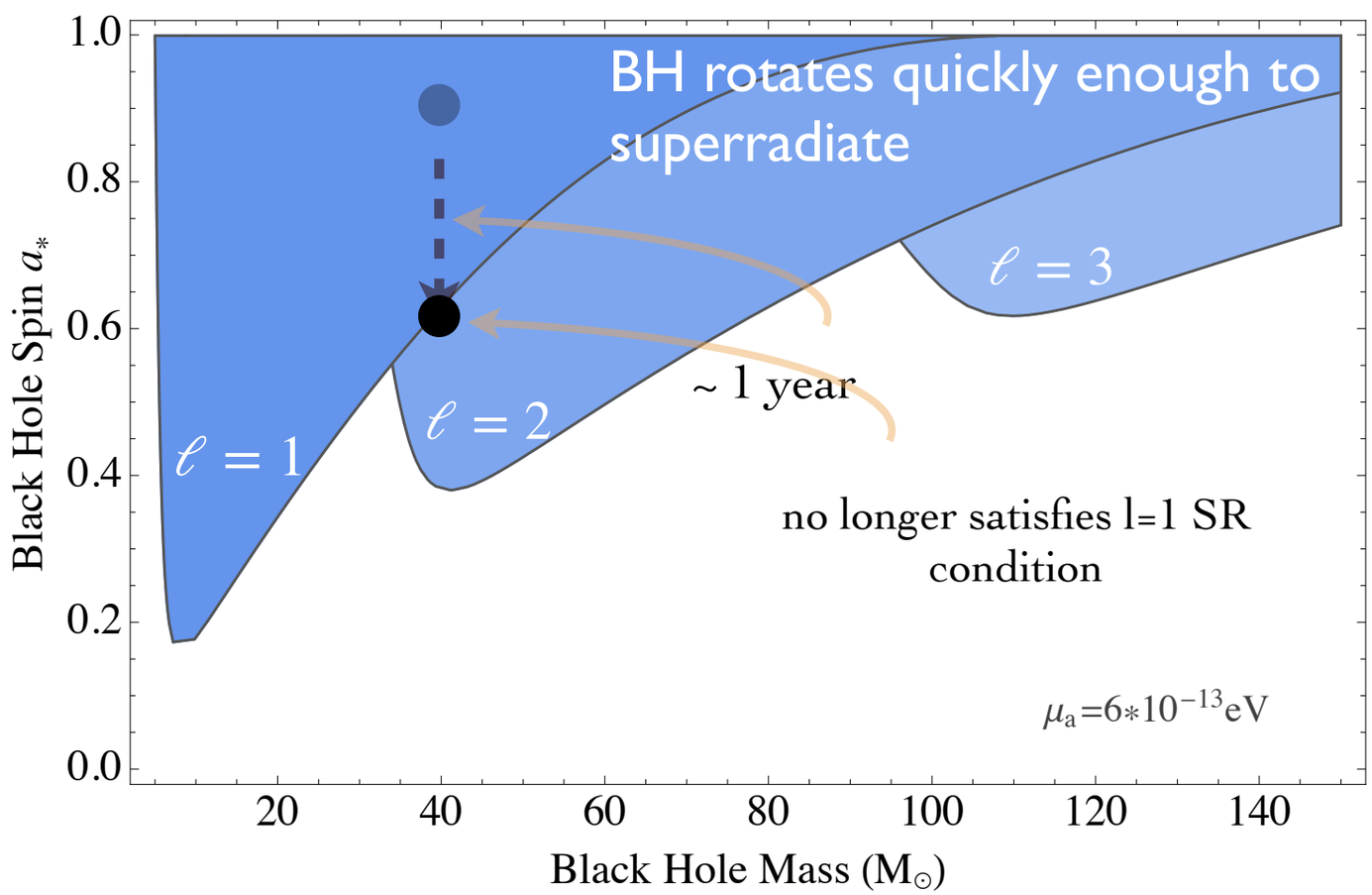


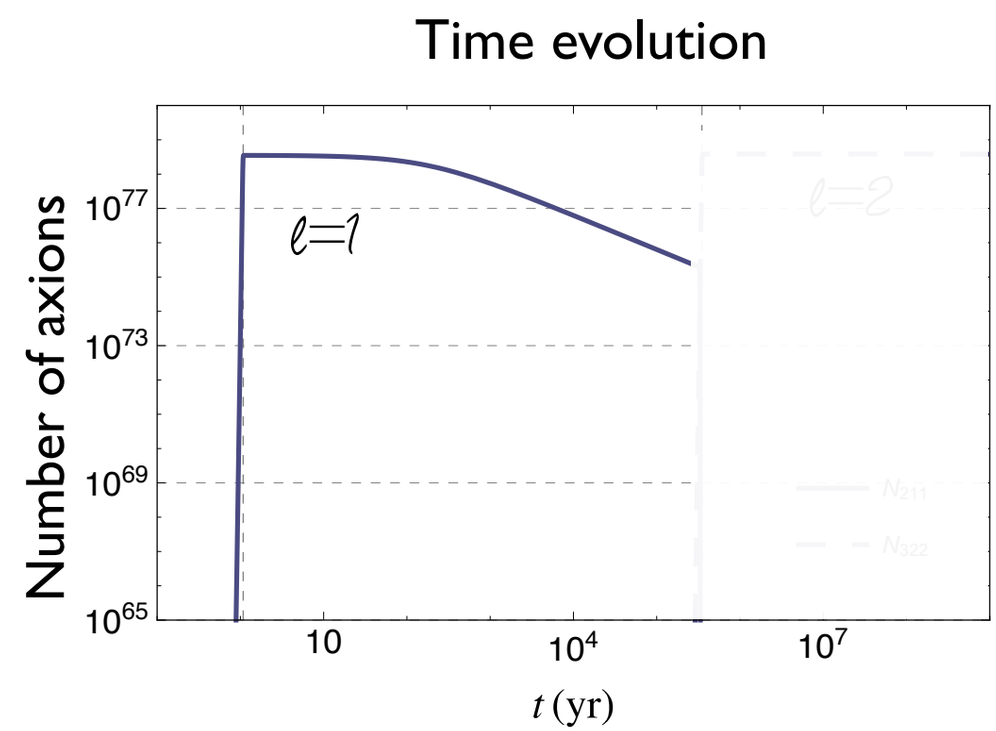


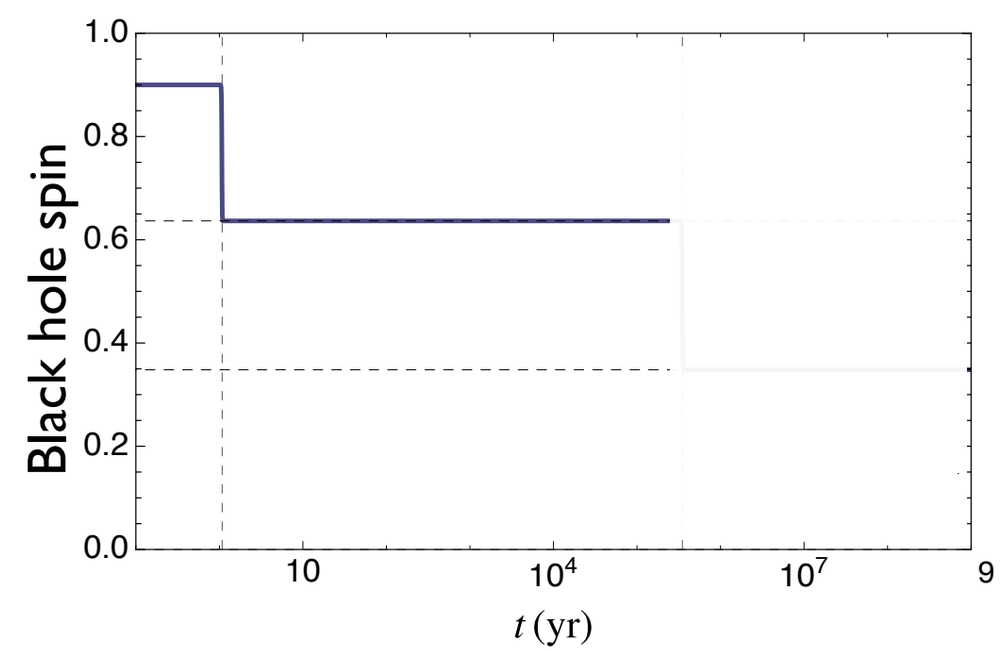

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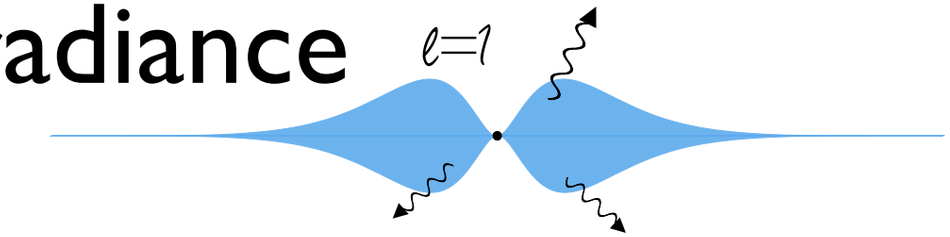


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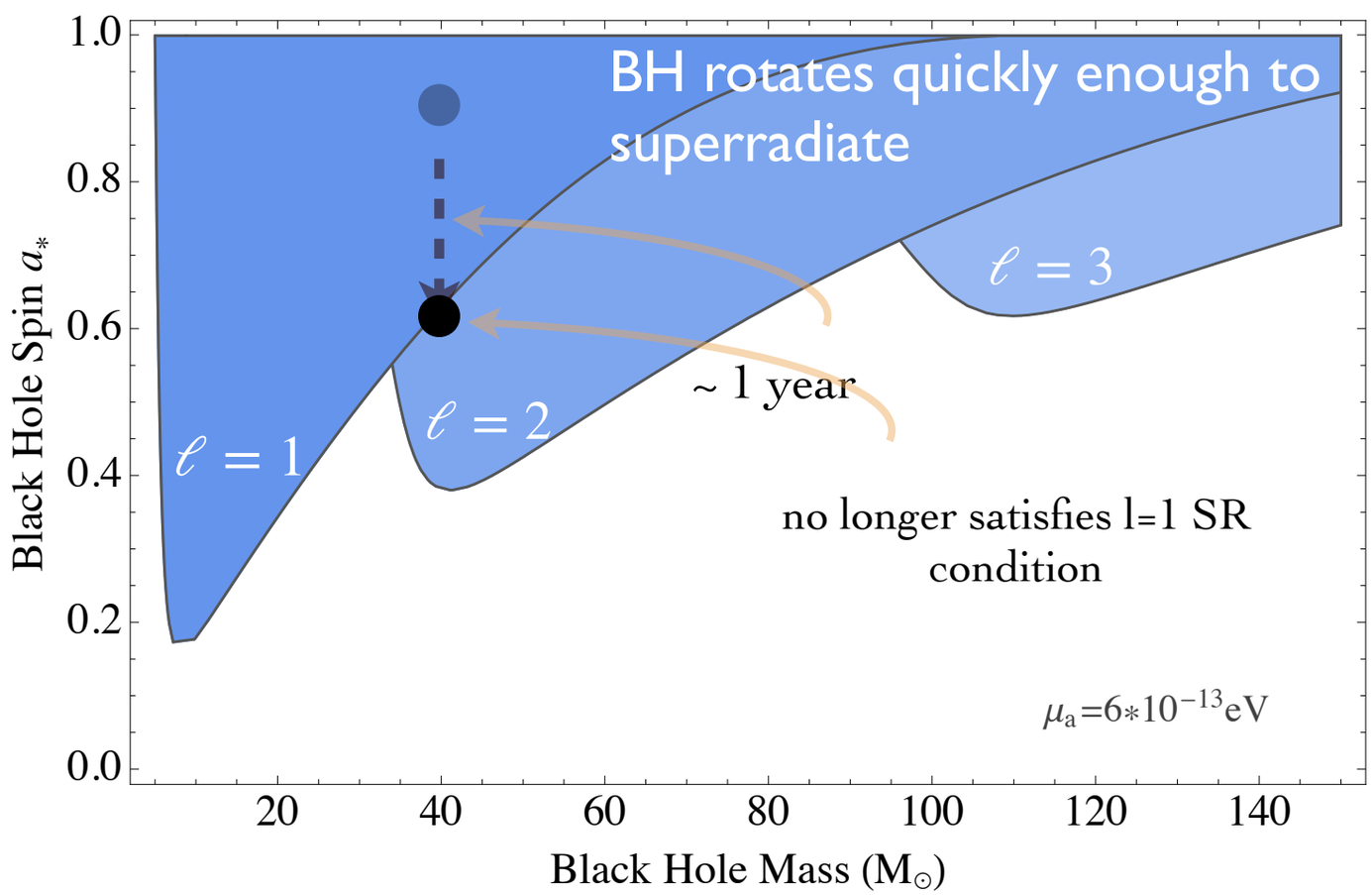


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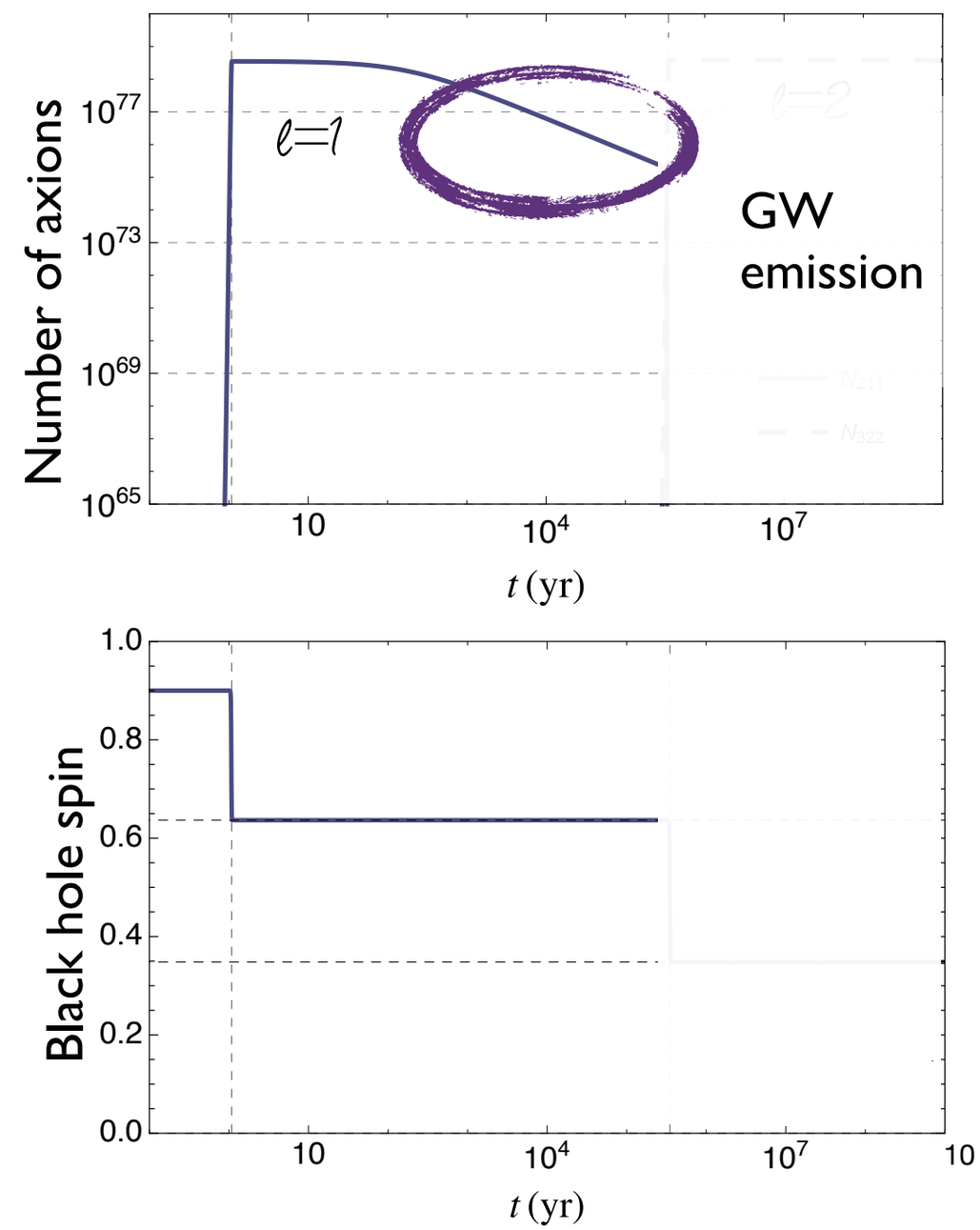

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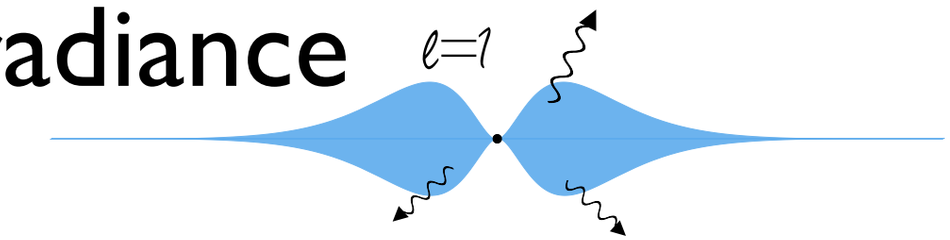


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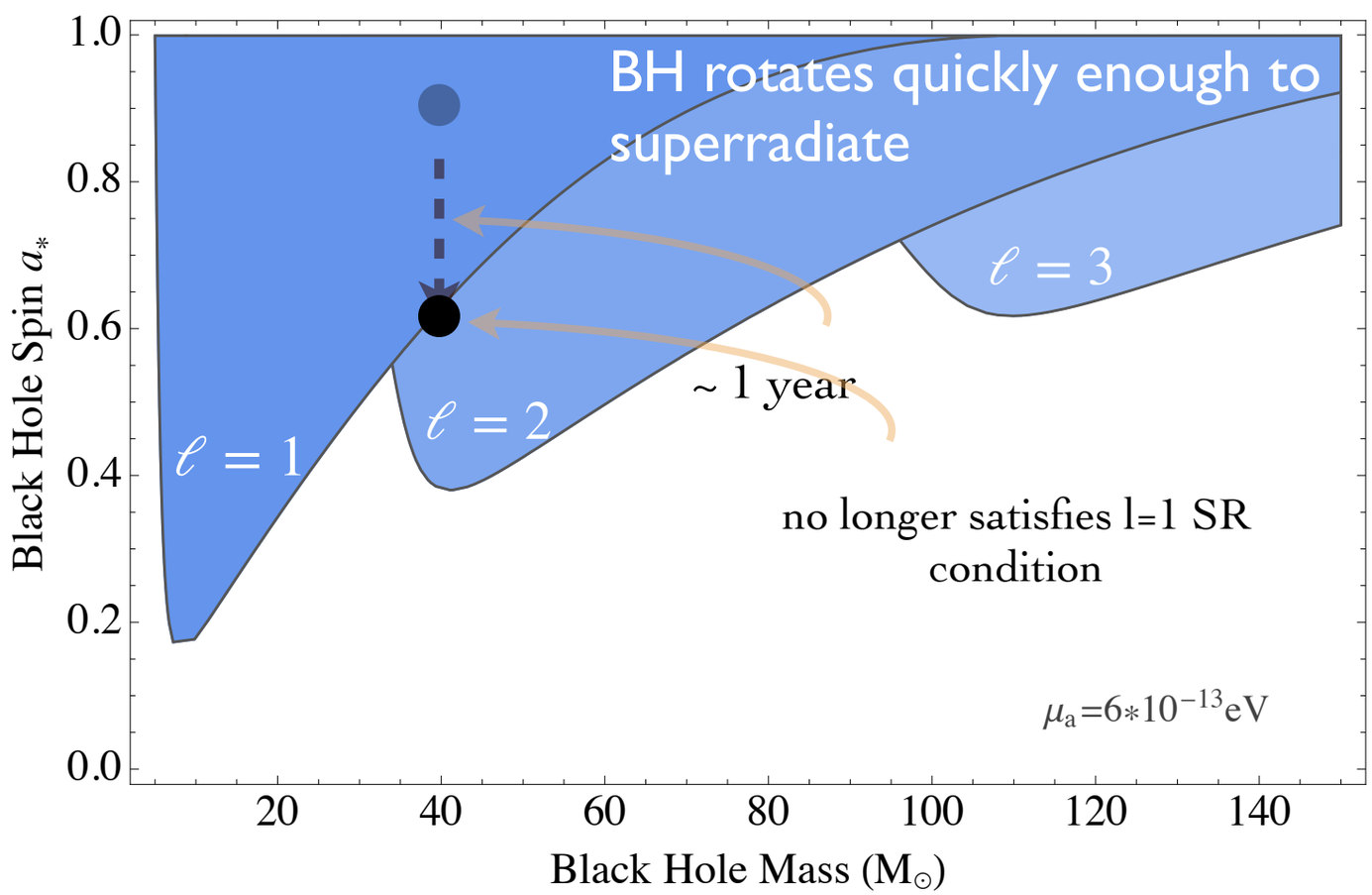


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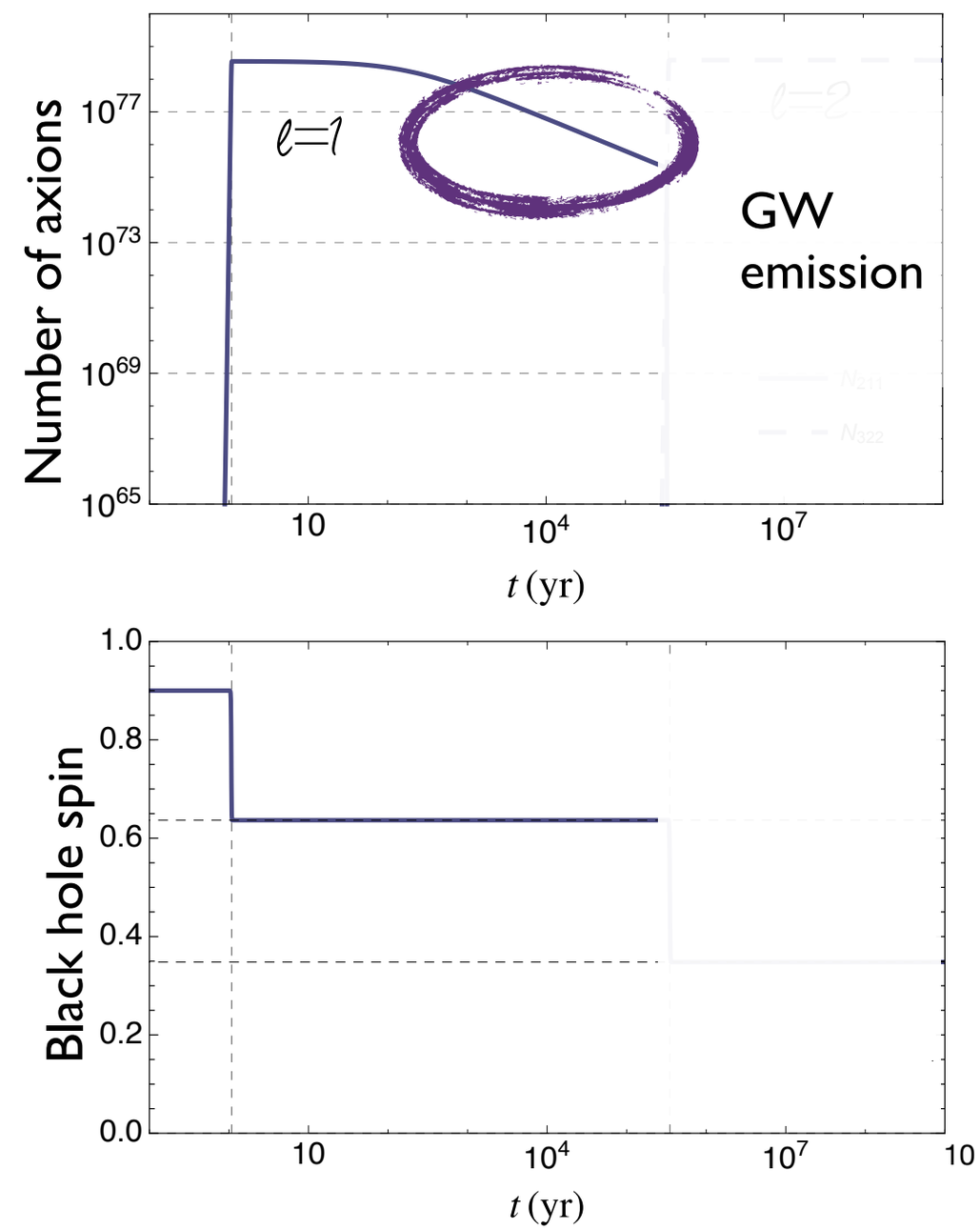

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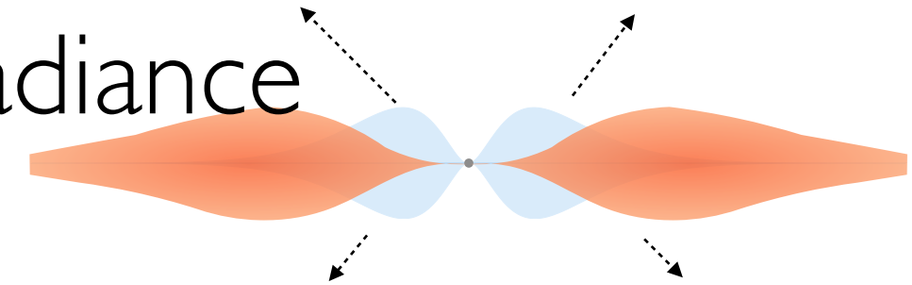

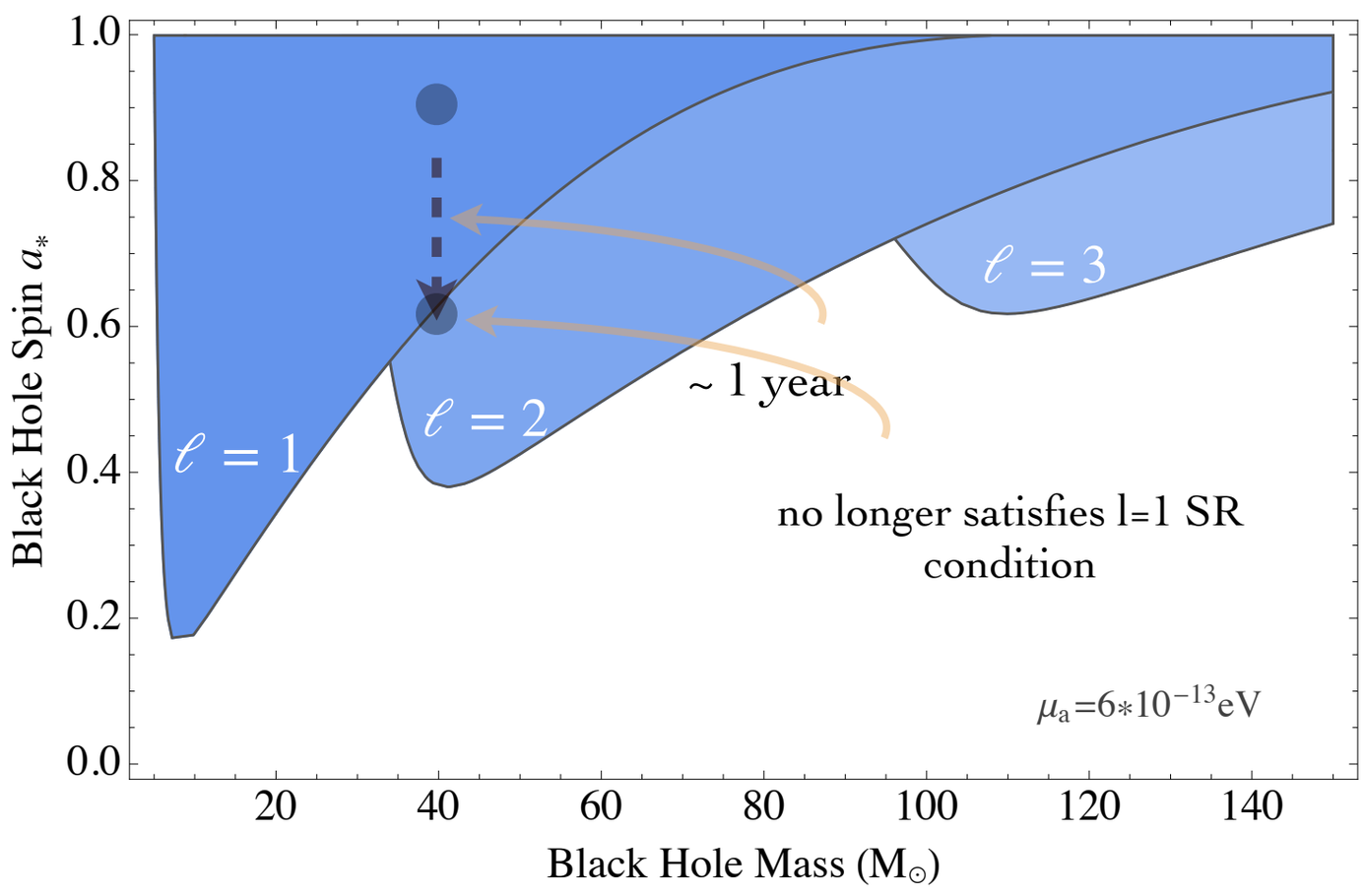


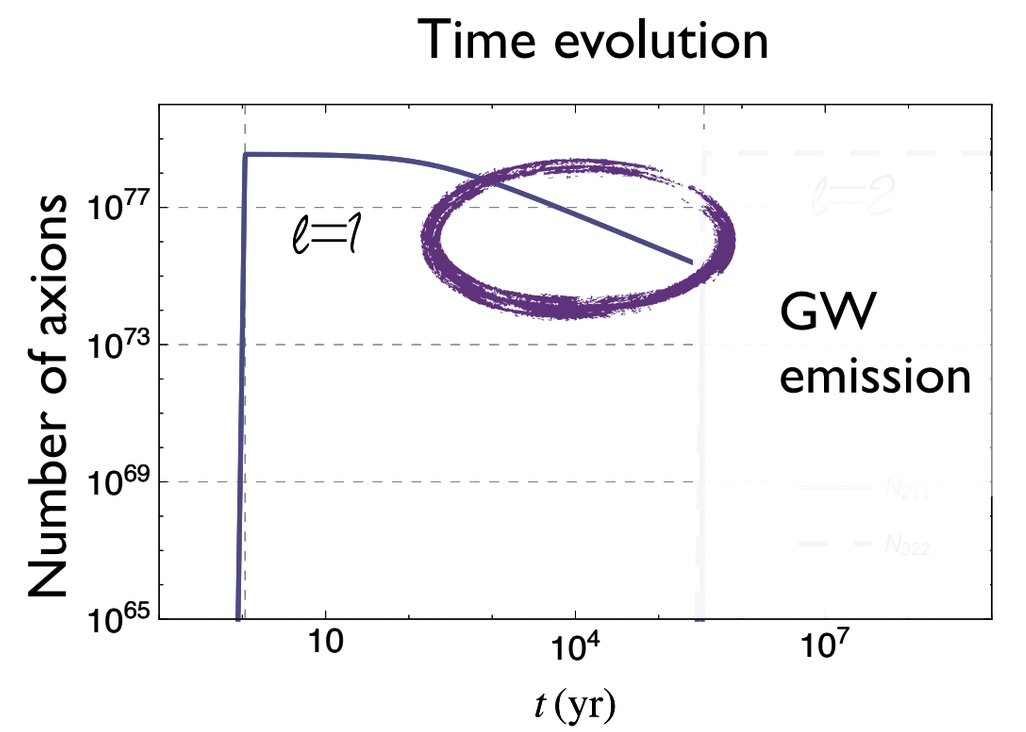


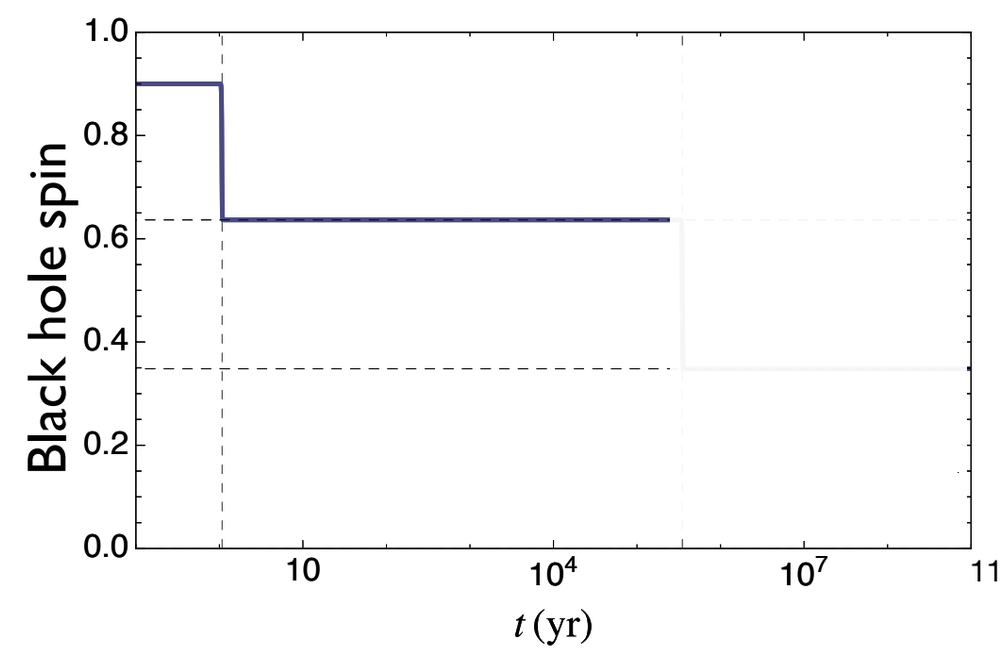

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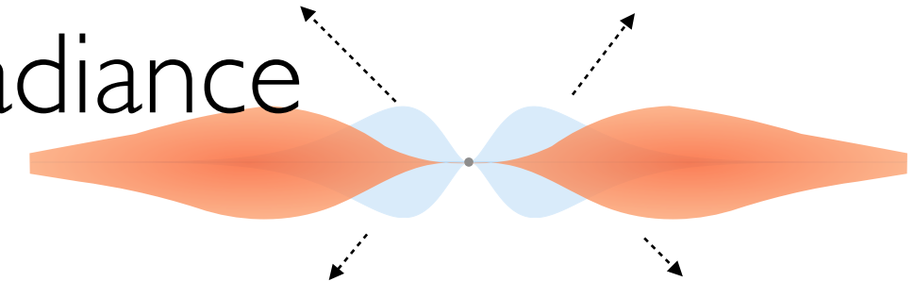

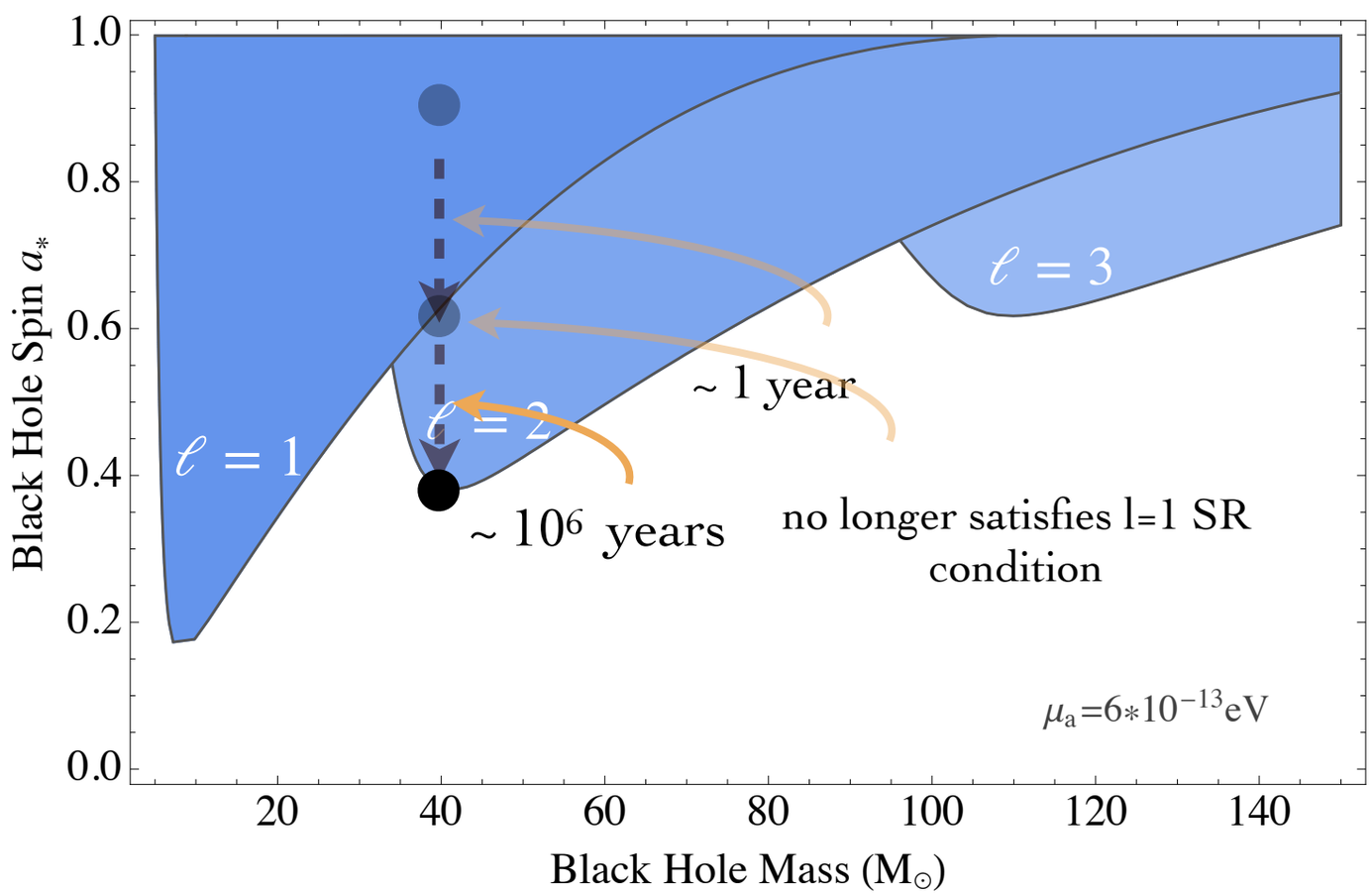


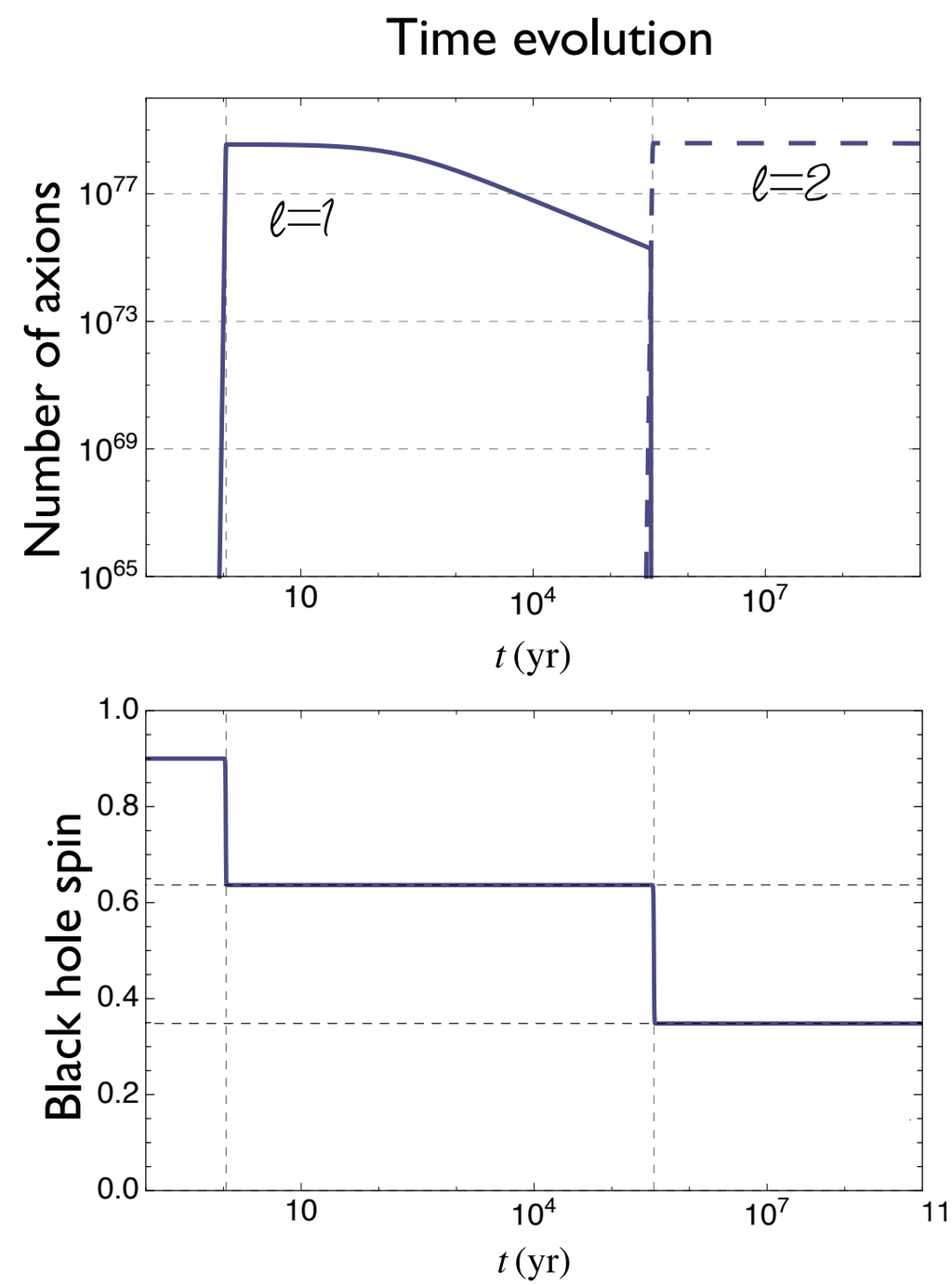

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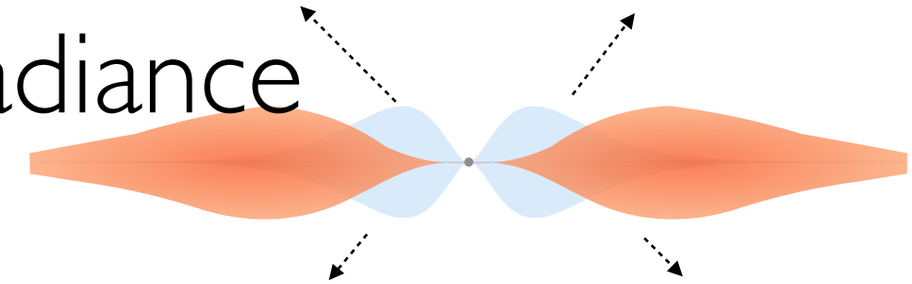
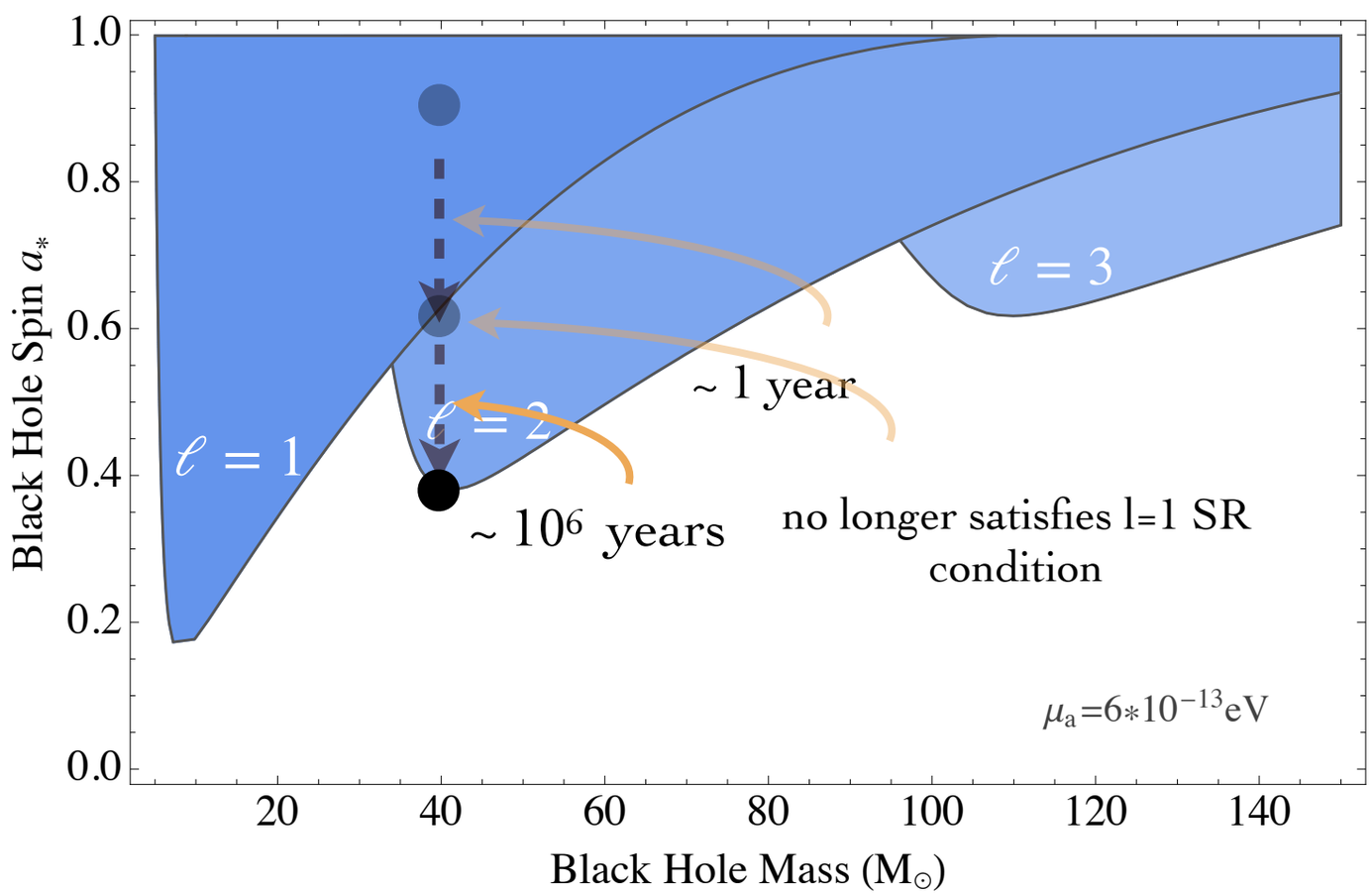
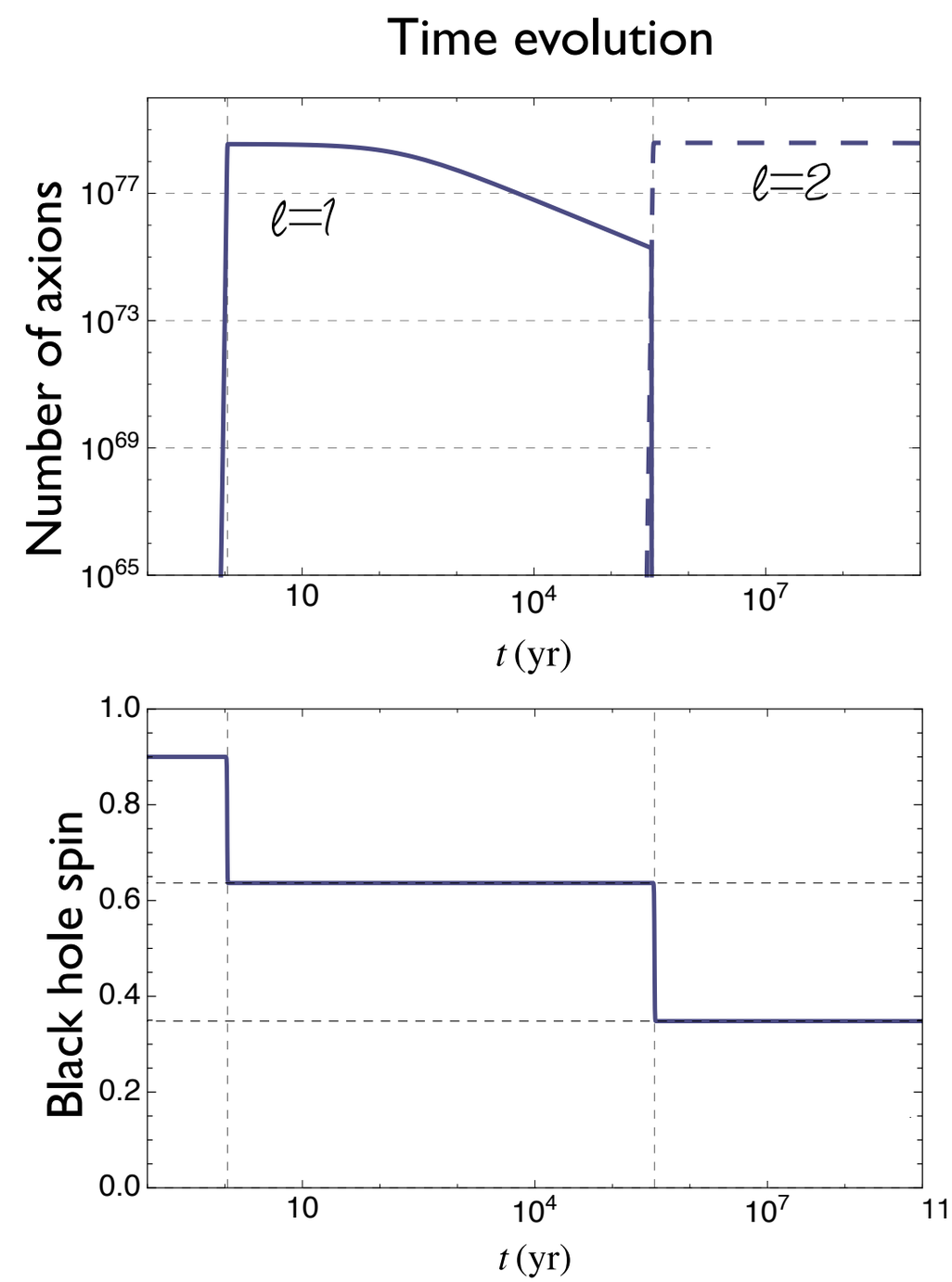
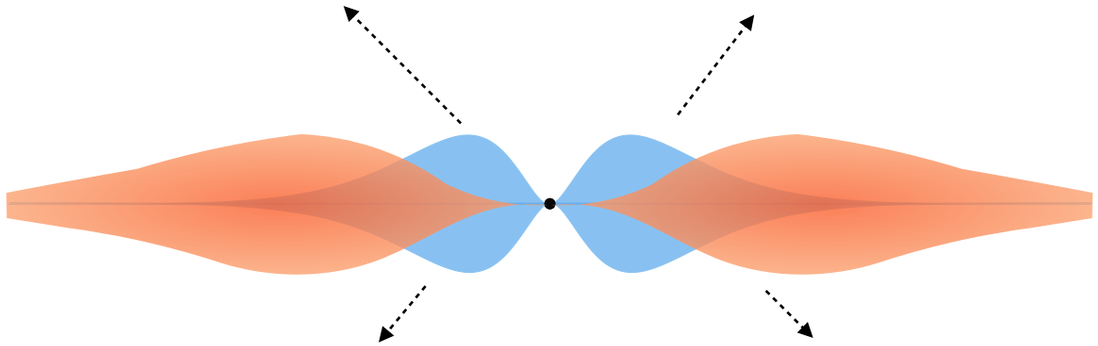


- Bound state with higher angular momentum grows exponentially
- Growth parametrically longer due to angular momentum barrier: less overlap with black hole, less efficient energy extraction



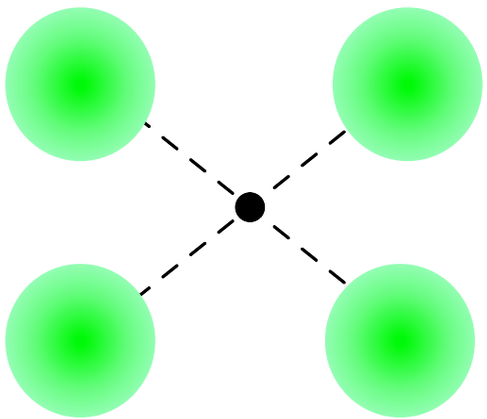
# Self-Interactions



M. Baryakhtar, **MG**, R. Lasenby, O. Simon 2021

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

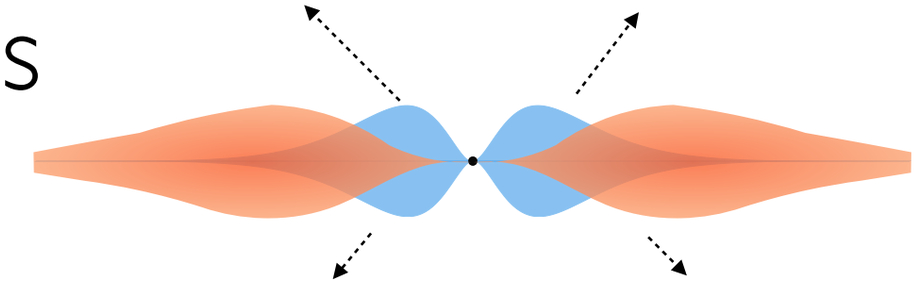
- What new effects arise when axion self-interactions become important?



Fukuda, Nakayama JHEP01(2020)128
A. Gruzinov, 1604.06422

$$\text{Free real scalar field} + \frac{\lambda}{4!}\phi^4 \qquad \lambda \to \frac{\mu_a^2}{f_a^2}$$

# Self-Interactions



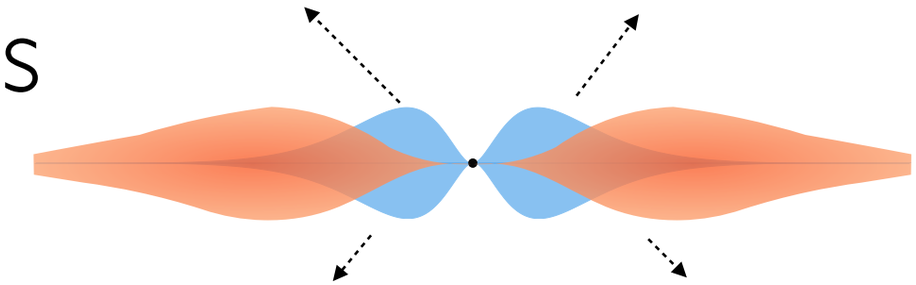
M. Baryakhtar, **MG**, R. Lasenby, O. Simon 2021

Larger self-interactions:

- Black hole energy sources the cloud through superradiance

A. Gruzinov, 1604.06422

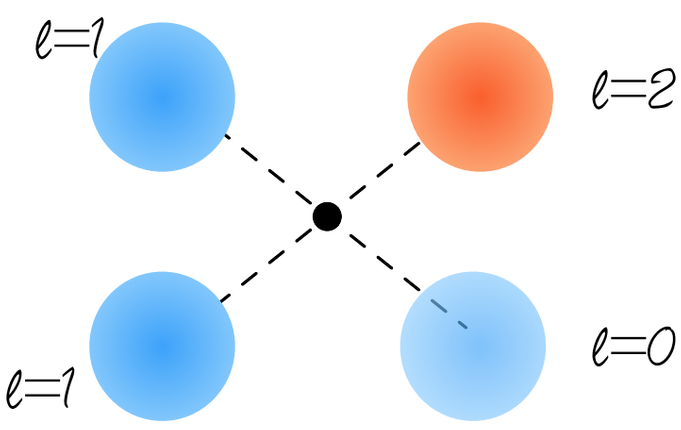
# Self-Interactions



M. Baryakhtar, **MG**, R. Lasenby, O. Simon 2021

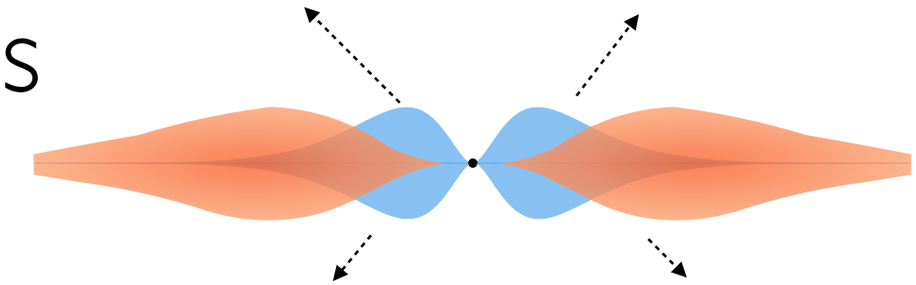
Larger self-interactions:

- Black hole energy sources the cloud through superradiance
- Second level populated through self-interactions




A. Gruzinov, 1604.06422

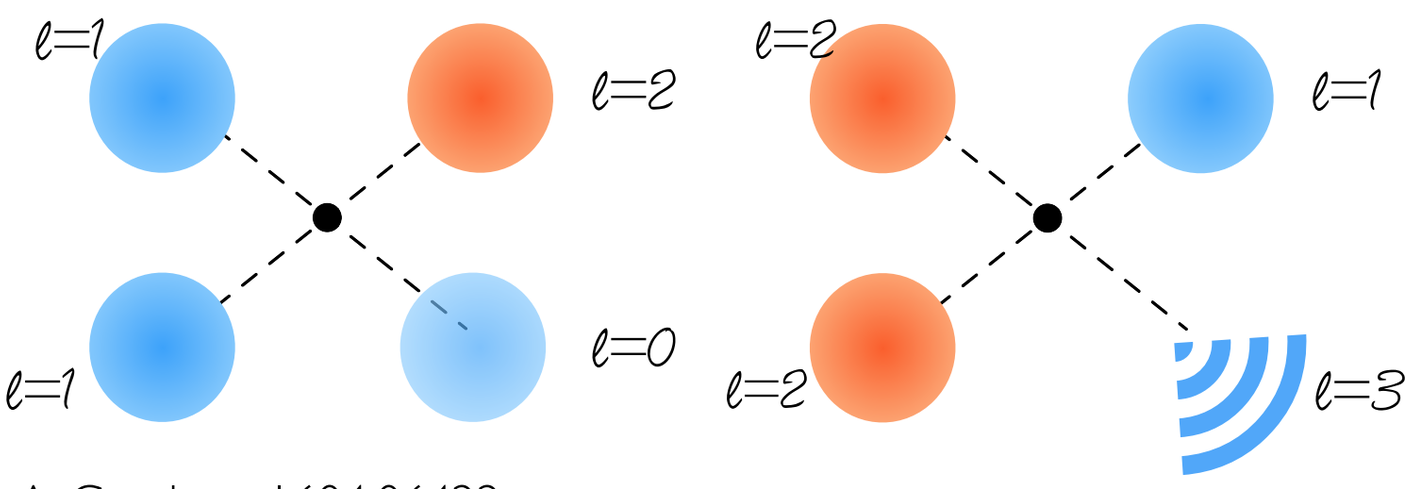
# Self-Interactions



M. Baryakhtar, **MG**, R. Lasenby, O. Simon 2021

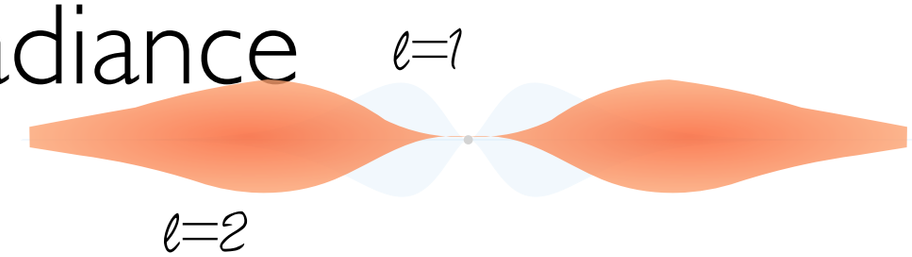
Larger self-interactions:

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




A. Gruzinov, 1604.06422

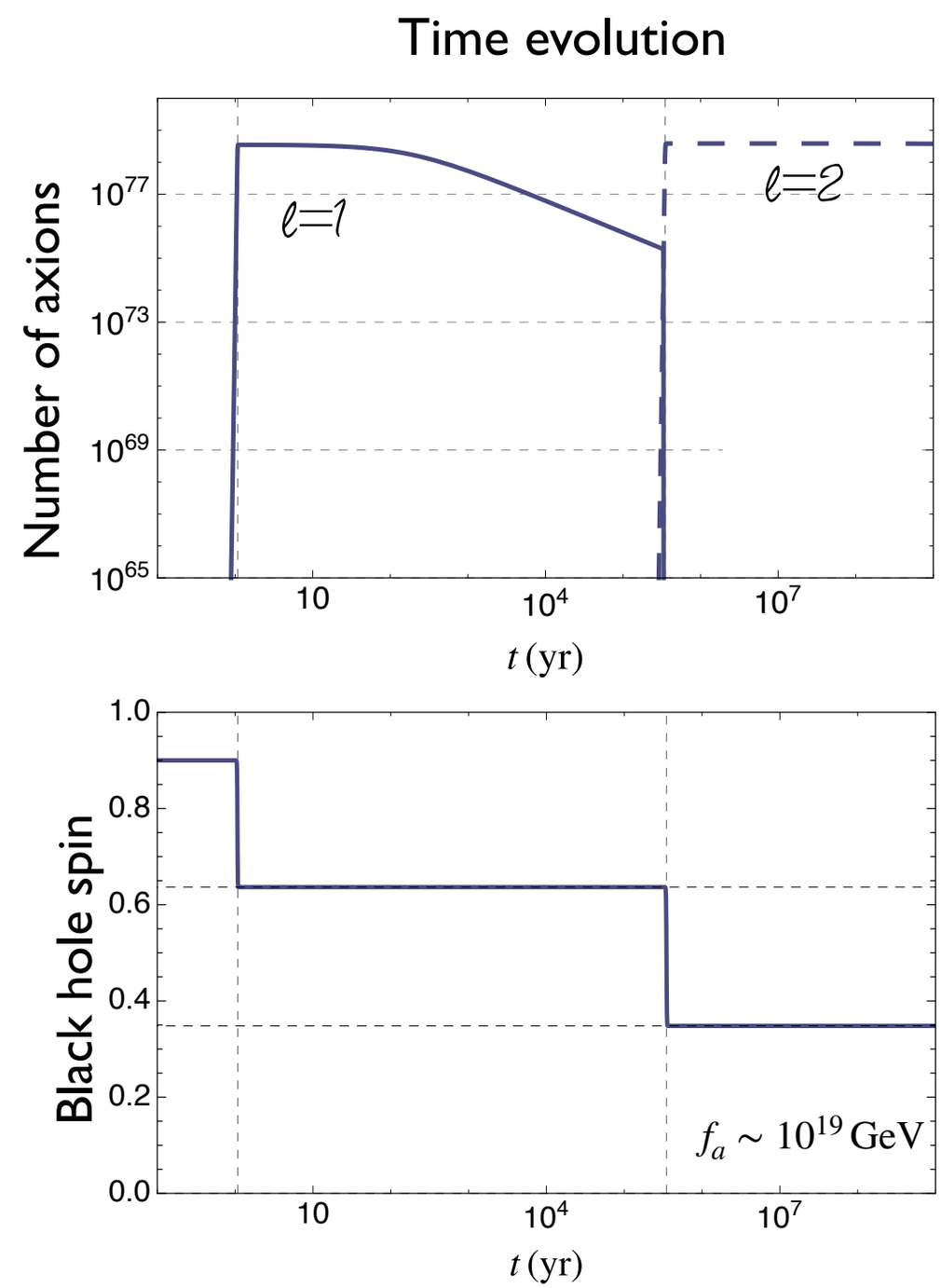
# Gravitational Superradiance



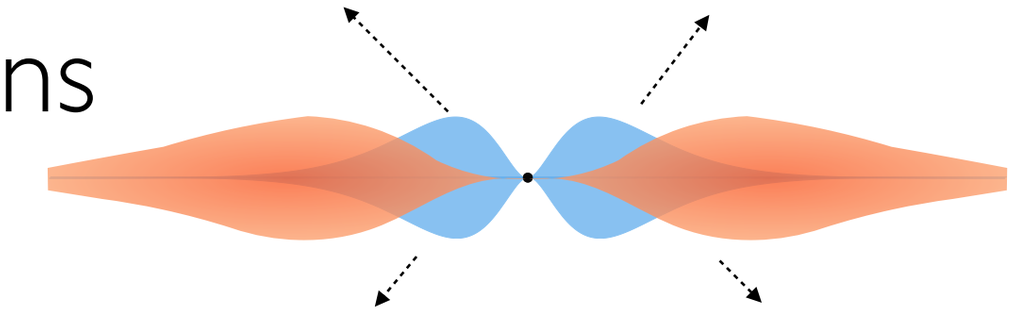

Gravitational self-interactions $f_a \sim M_{\rm Pl}$

M. Baryakhtar, **MG**, R. Lasenby, O. Simon 2021

- One bound state at a time
- Gravitational radiation



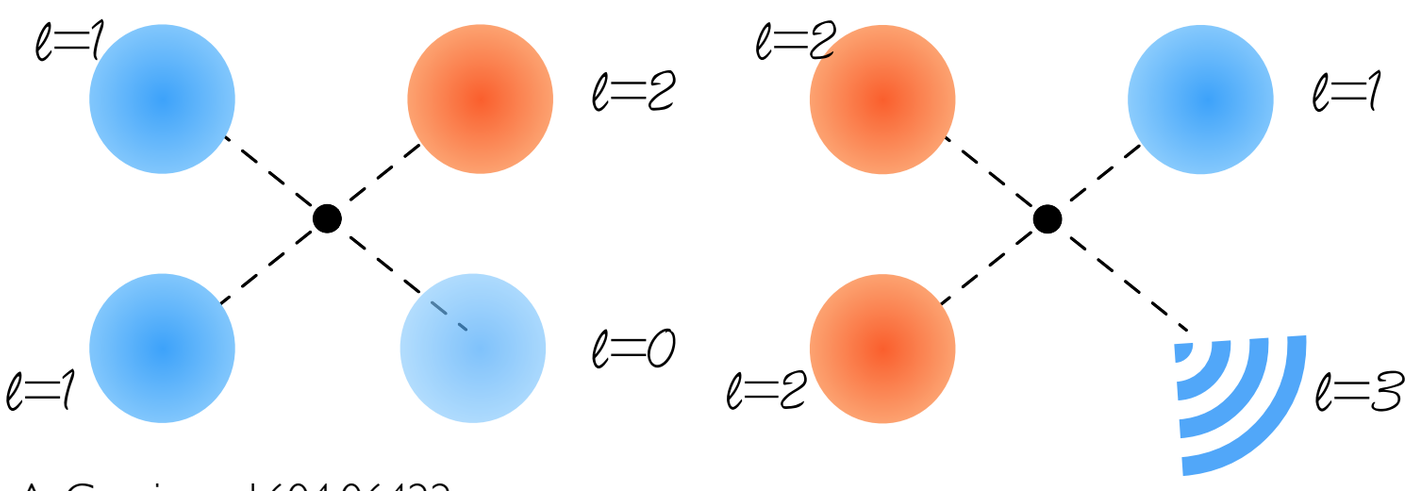
# Self-Interactions



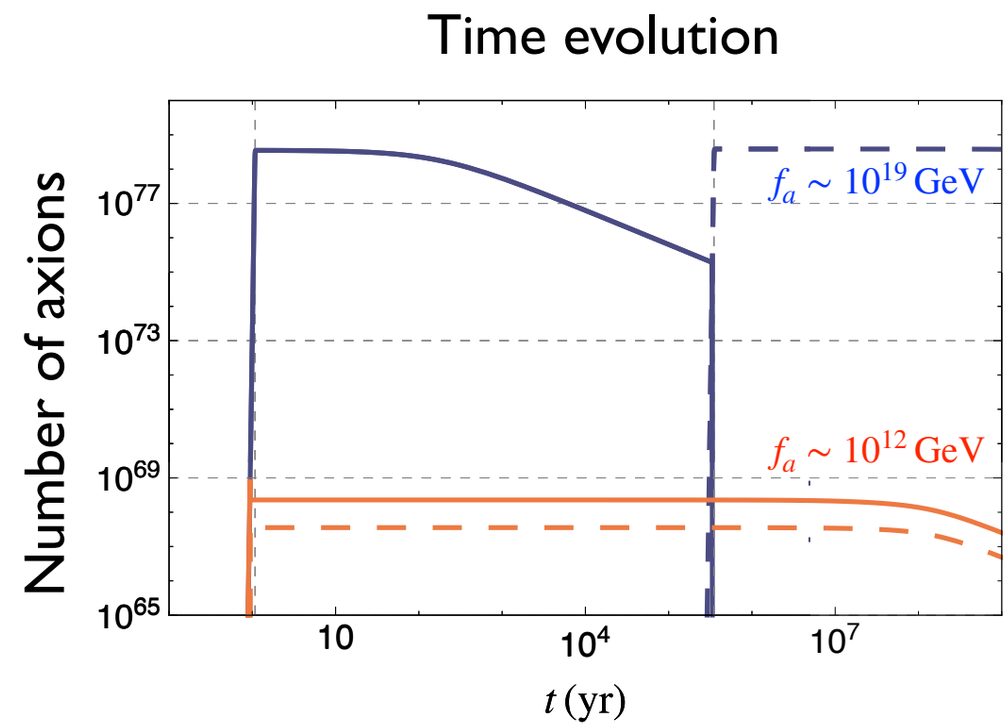
Larger self-interactions: $f_a \sim 10^{12}\mathrm{GeV}$

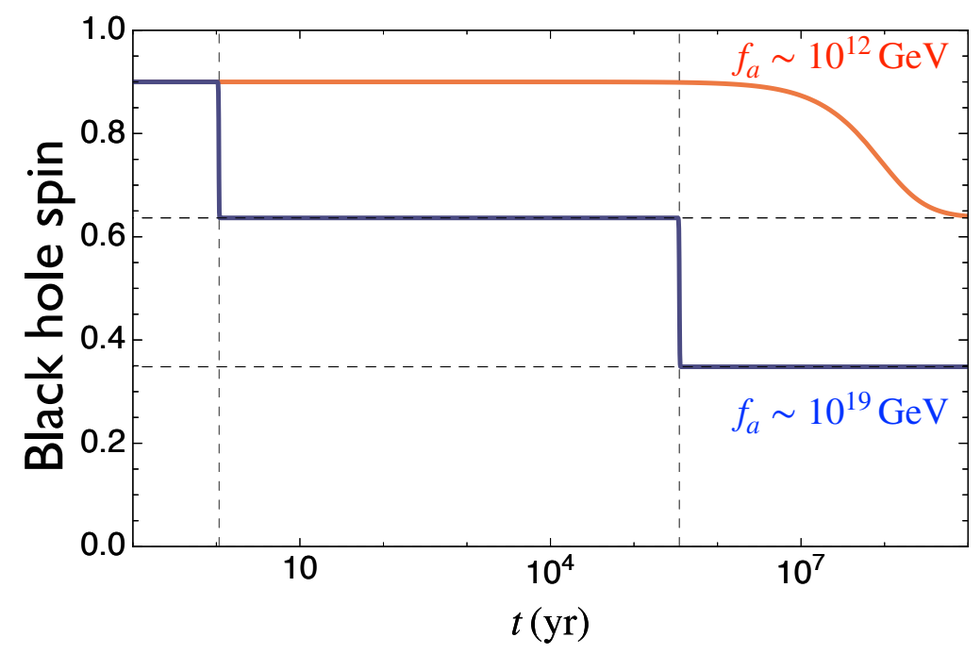
M. Baryakhtar, **MG**, R. Lasenby, O. Simon 2021

- Two levels populated simultaneously
- Axion radiation

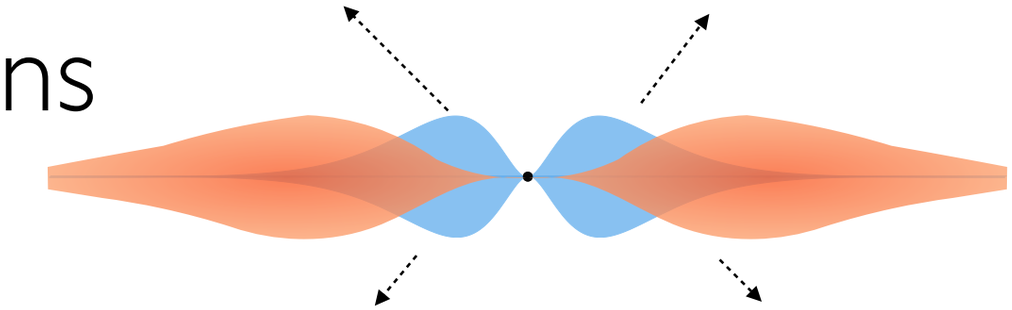



A. Gruzinov, 1604.06422



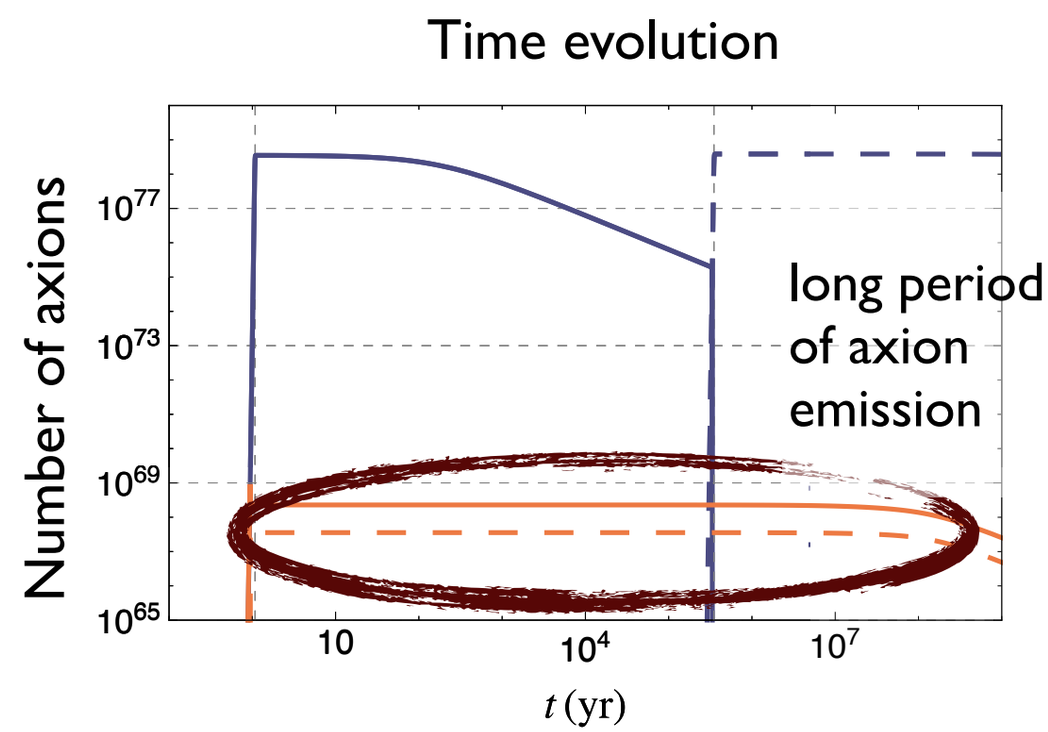
# Self-Interactions

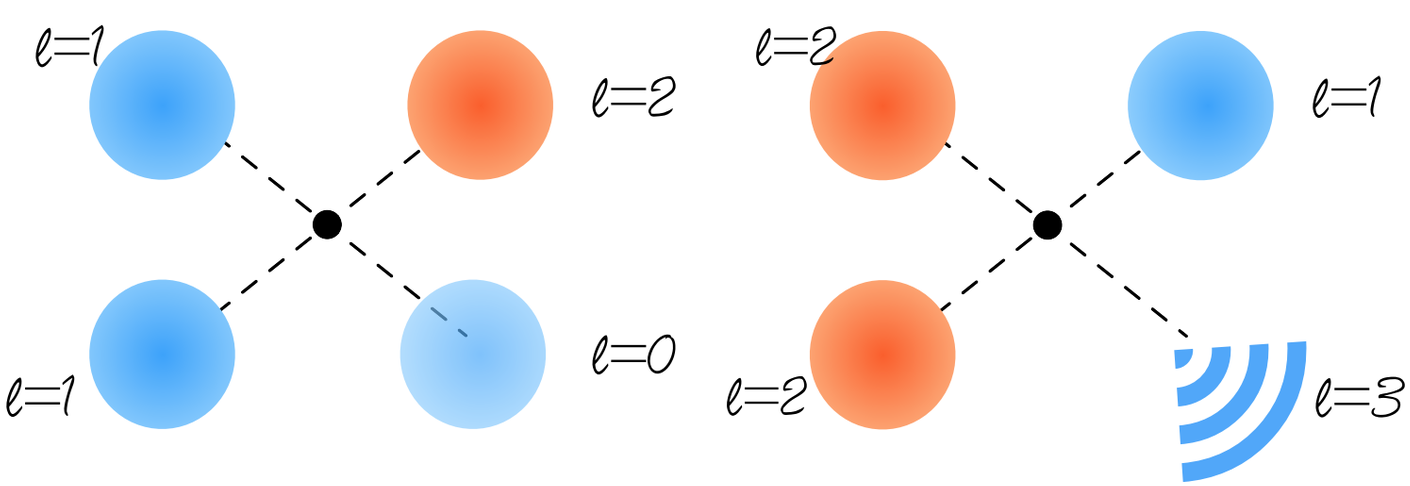


Larger self-interactions: $f_a \sim 10^{12}\mathrm{GeV}$

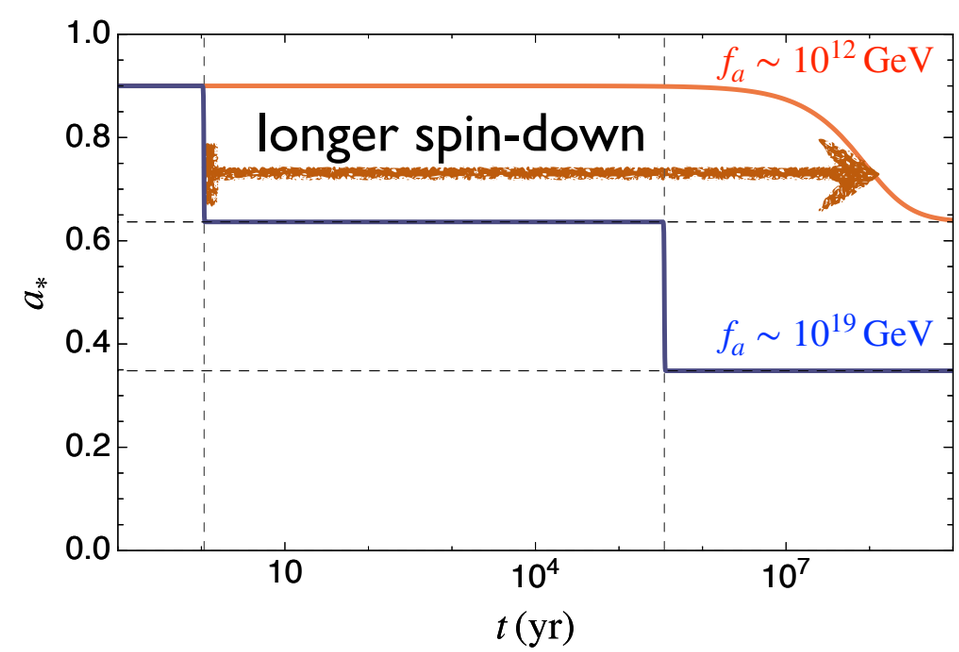
M. Baryakhtar, **MG**, R. Lasenby, O. Simon 2021

- Quasi-equilibrium with constant energy emission in scalar waves over ~ Hubble time
- Black hole spin-down time increased
- New gravitational wave emission: transitions



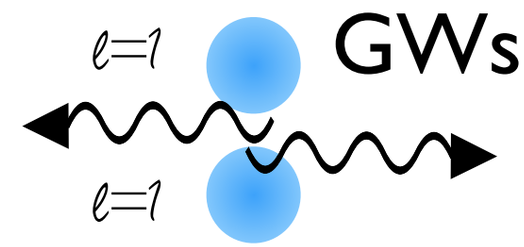




A. Gruzinov, 1604.06422

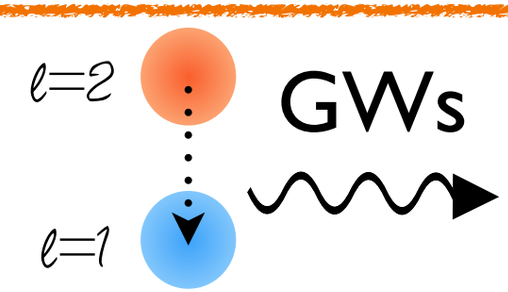


# Signatures

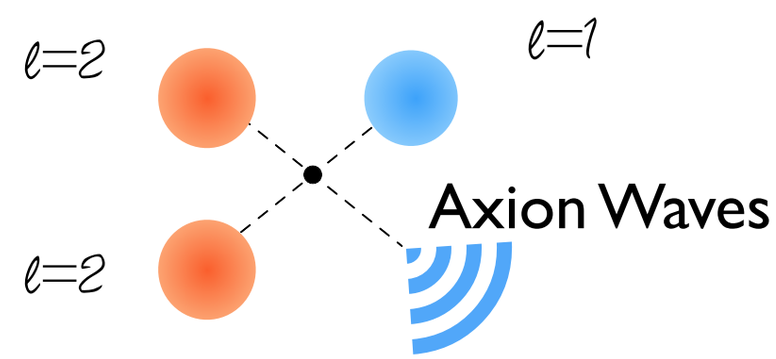
- Gravitational Waves from Annihilations




- Gravitational Waves from Transitions




- Axion Waves

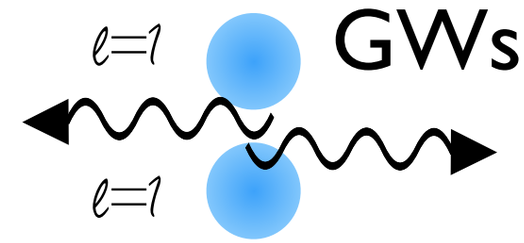



# Constraints

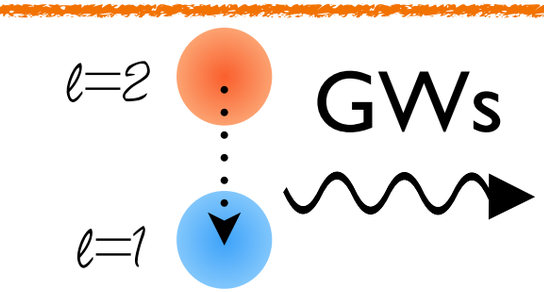
- Black Hole Spindown

# Signatures

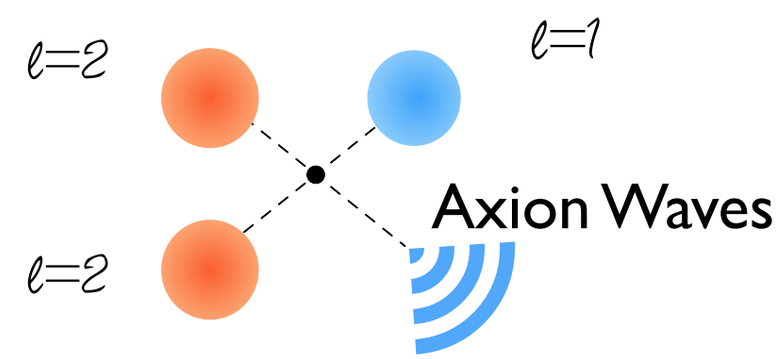
- Gravitational Waves from Annihilations




- Gravitational Waves from Transitions




- Axion Waves



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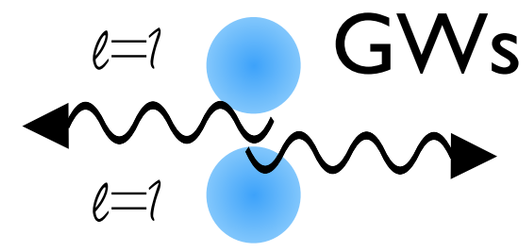


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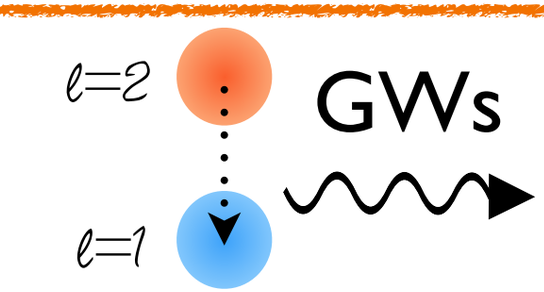


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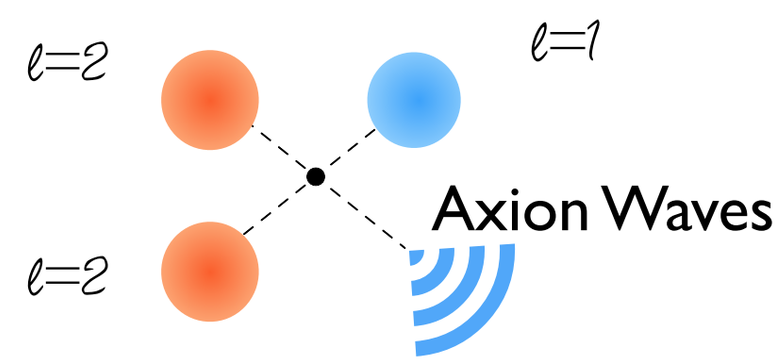
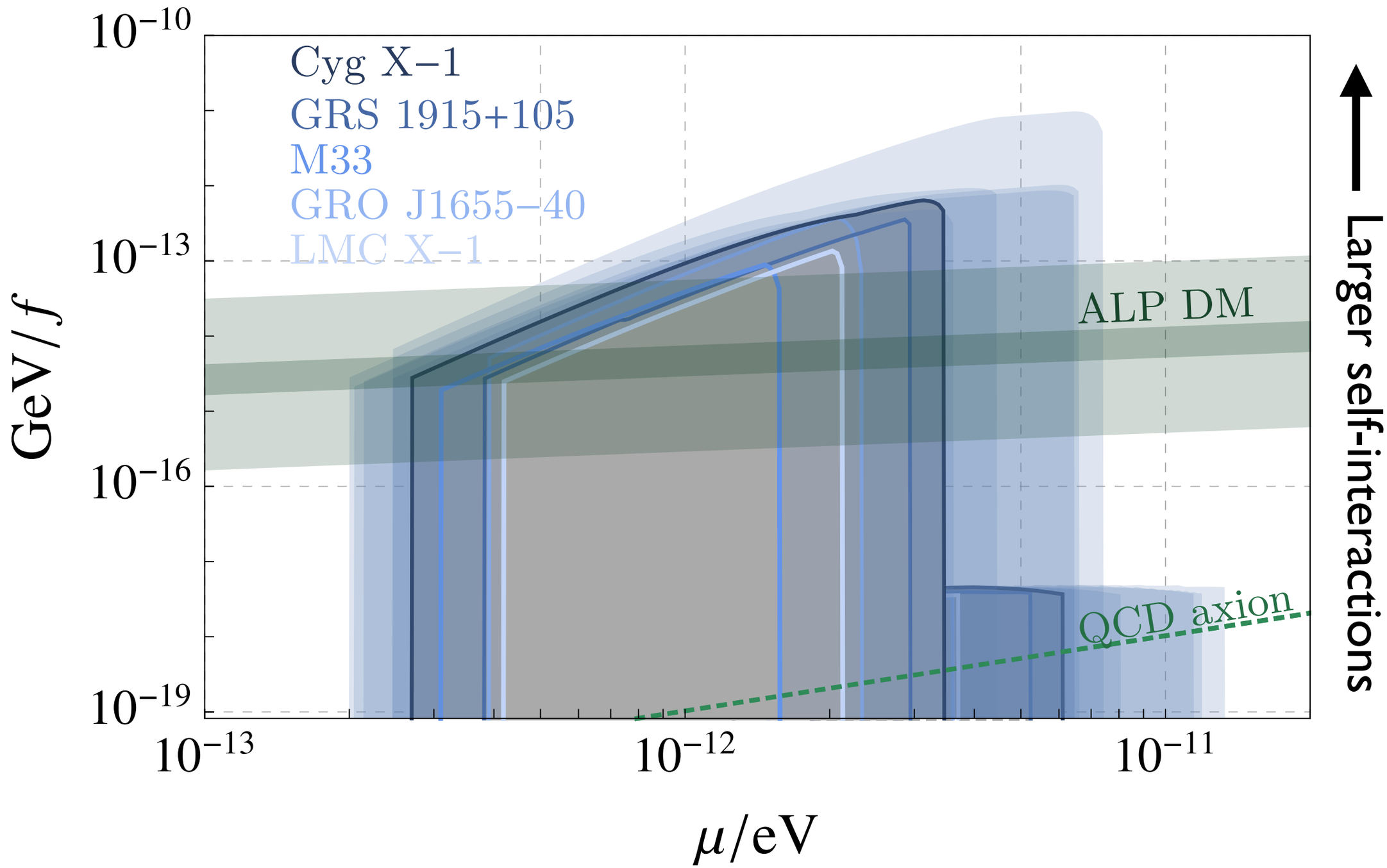





# Constraints

- Black Hole Spindown

# Black Hole Spin-down Constraints

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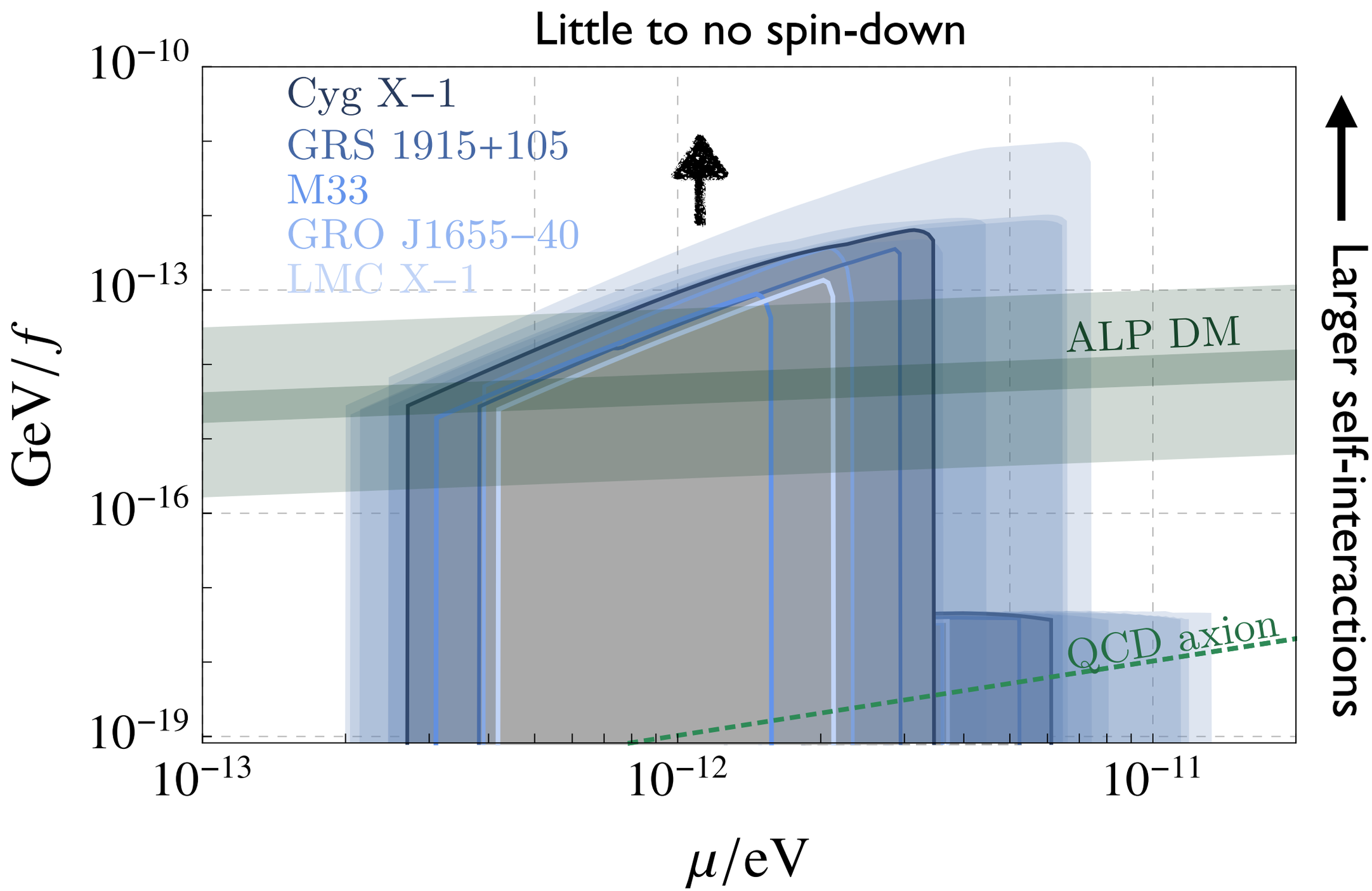
# Black Hole Spin-down Constraints

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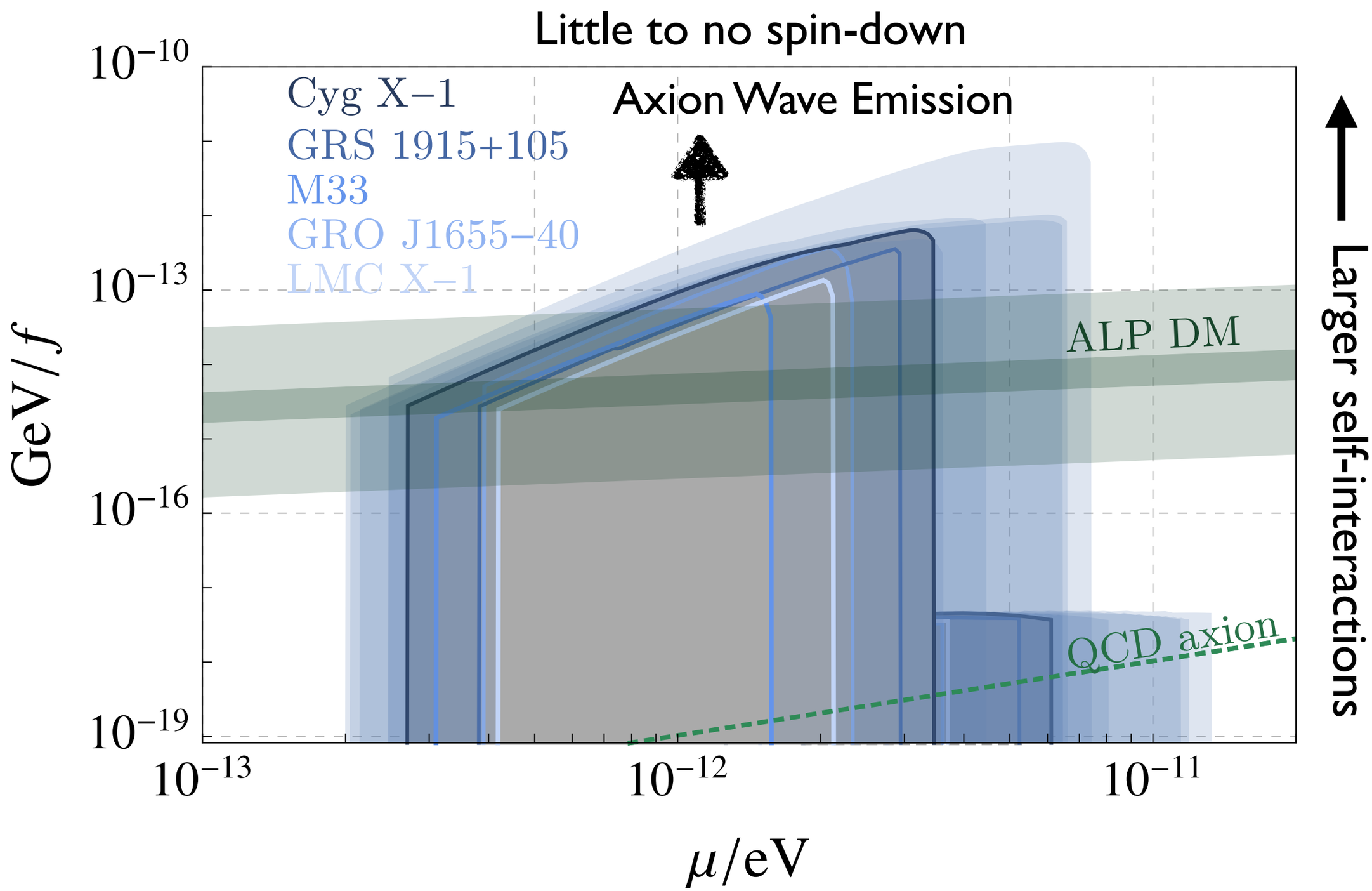
# Black Hole Spin-down Constraints

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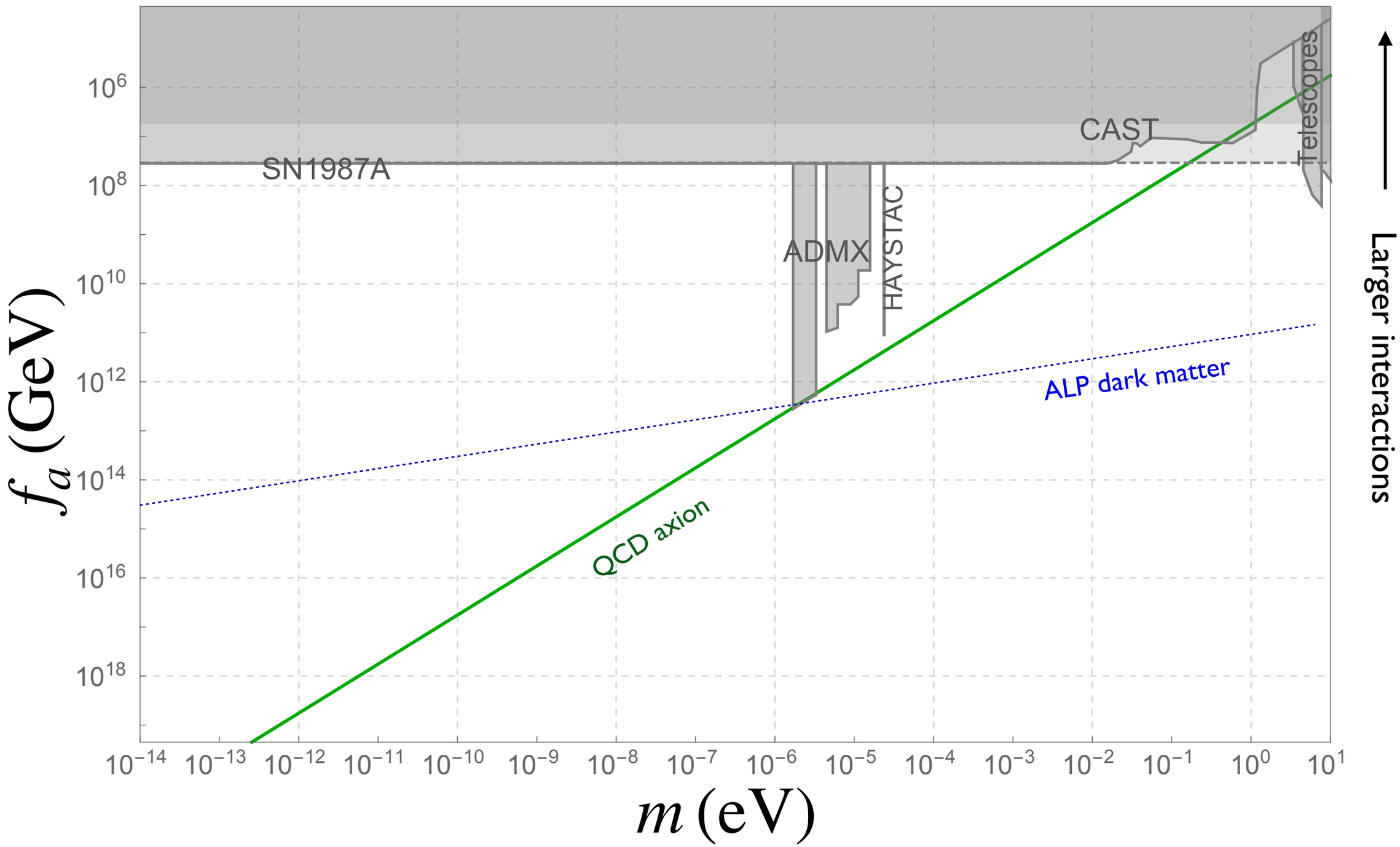
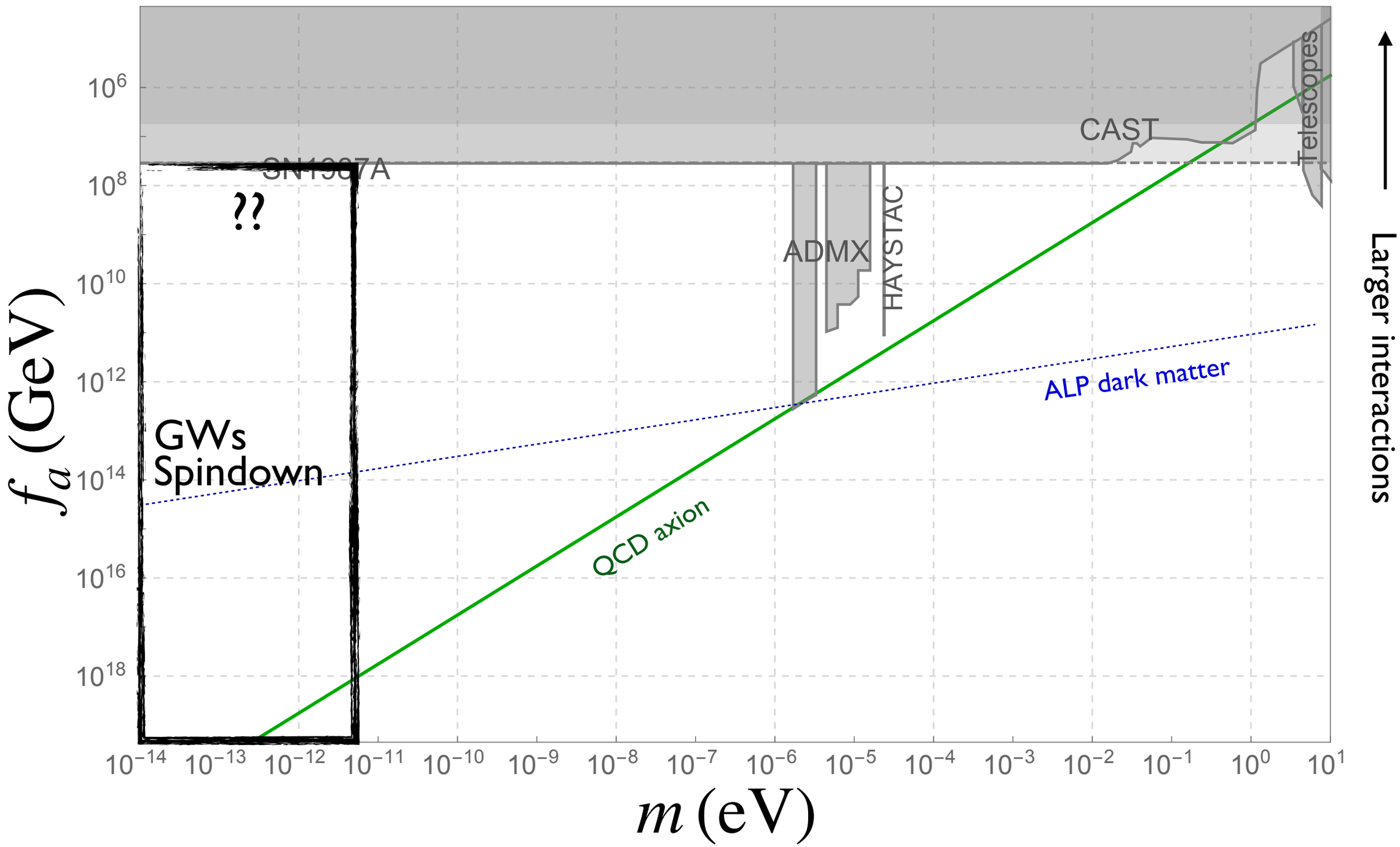
# Axion Parameter Space



# Axion Parameter Space

## Before



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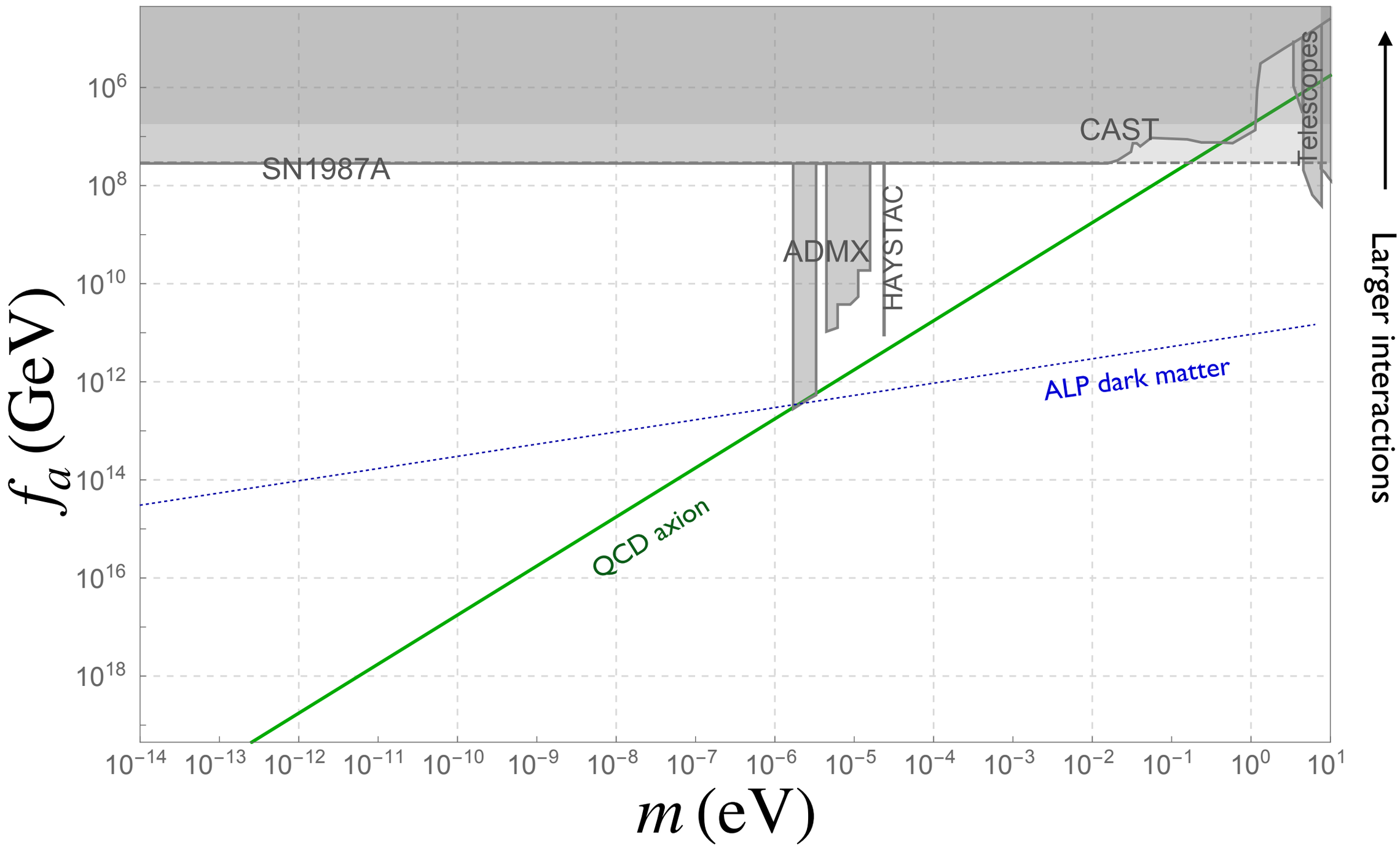
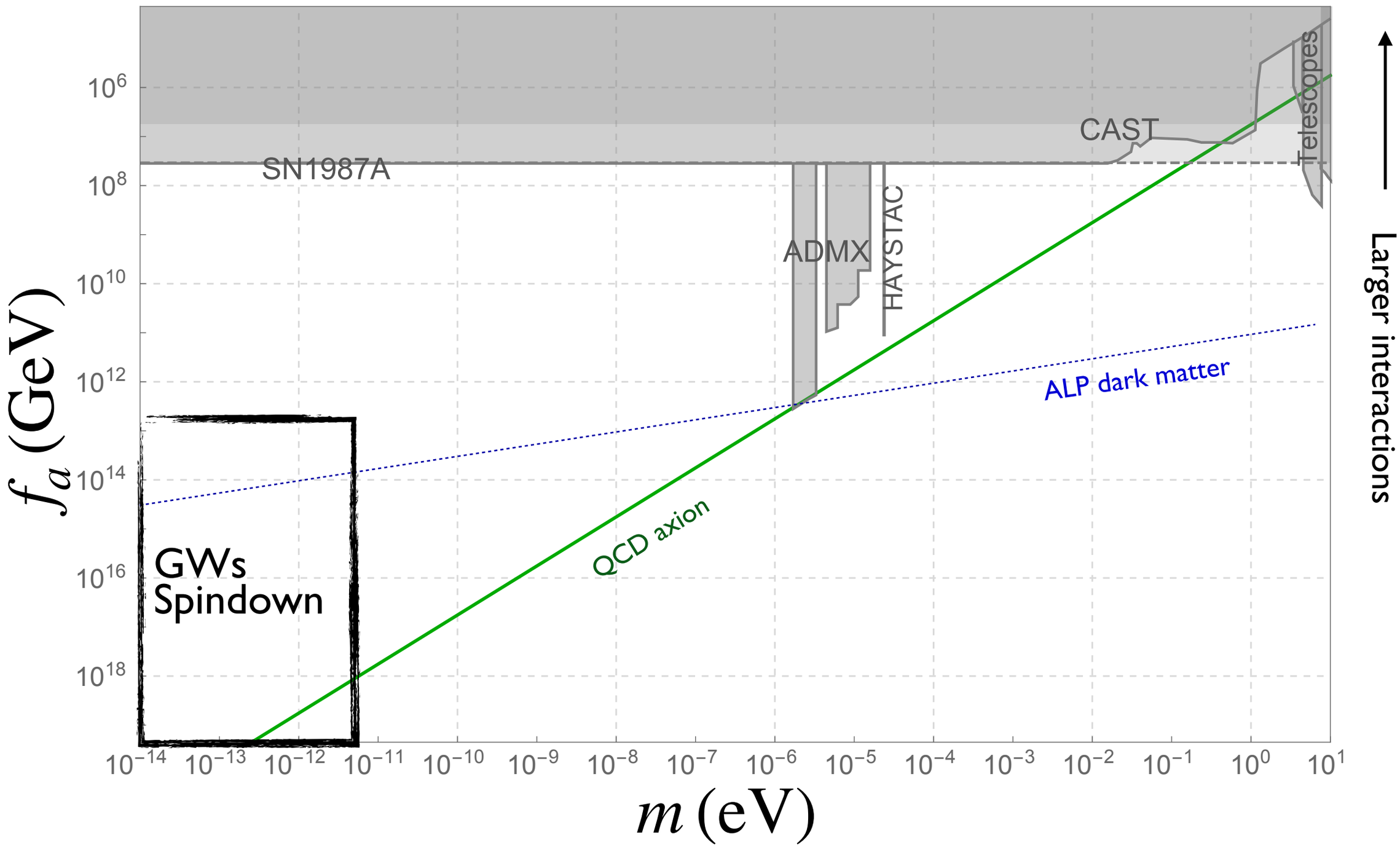


# Axion Parameter Space

## Our Result



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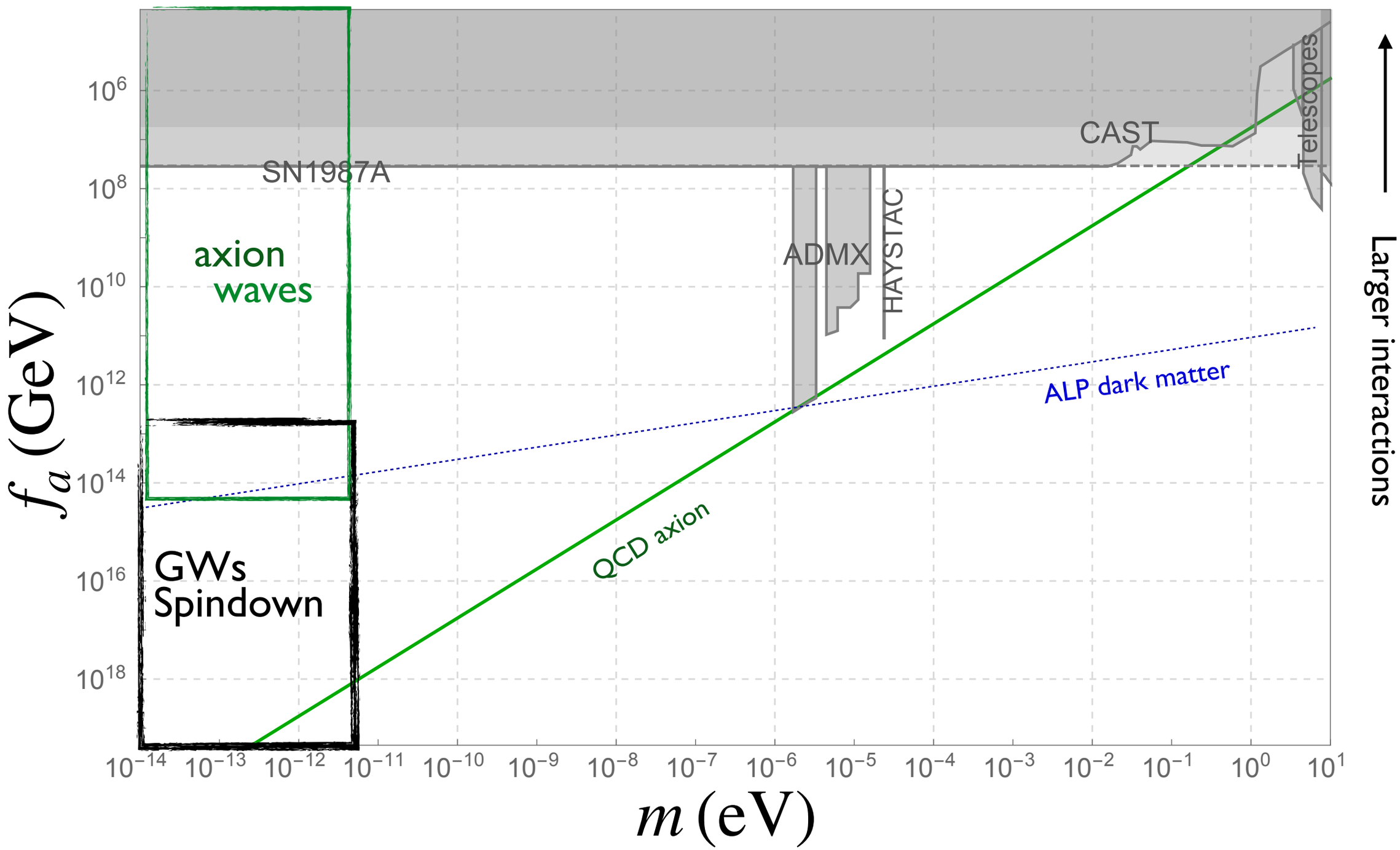

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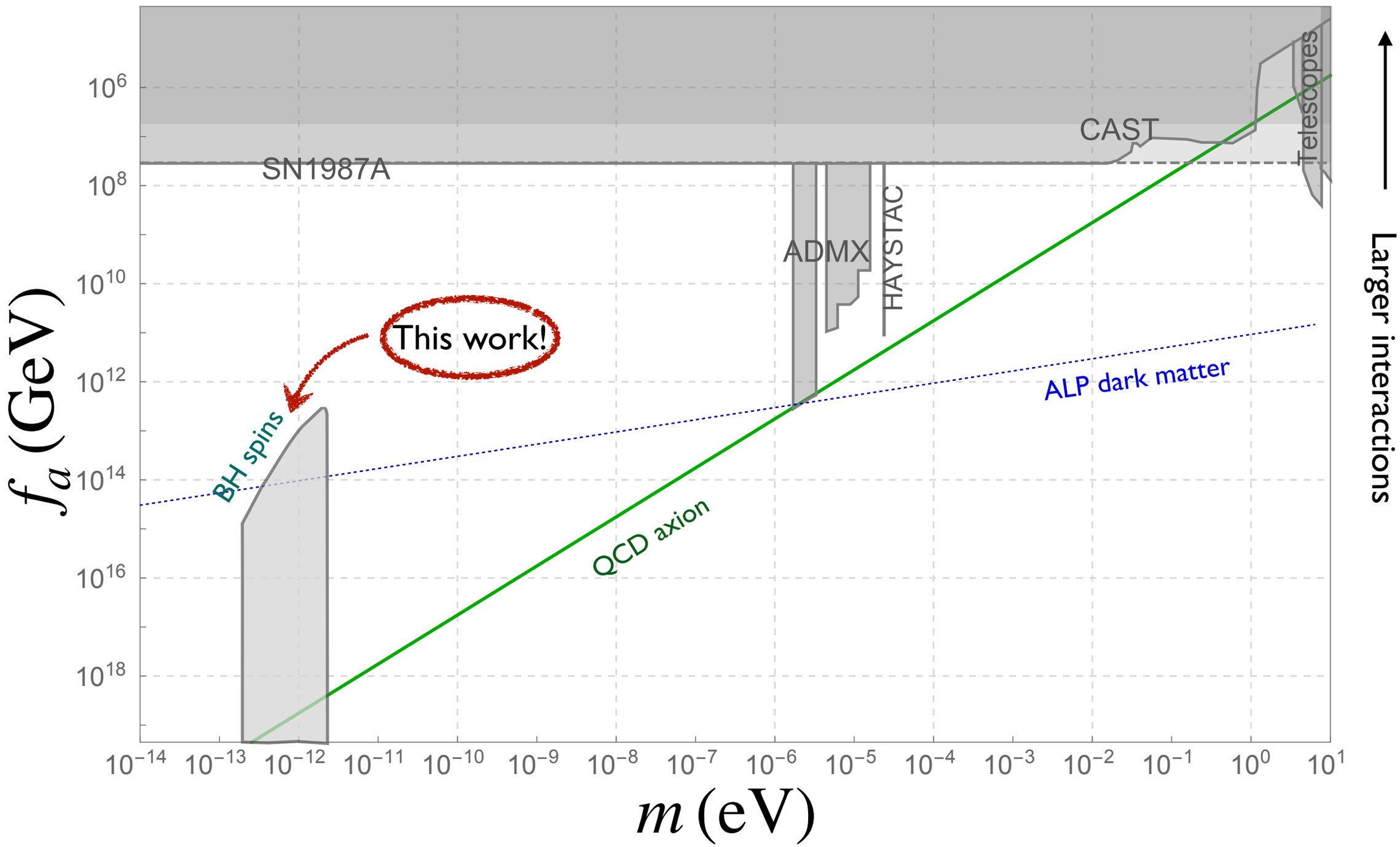
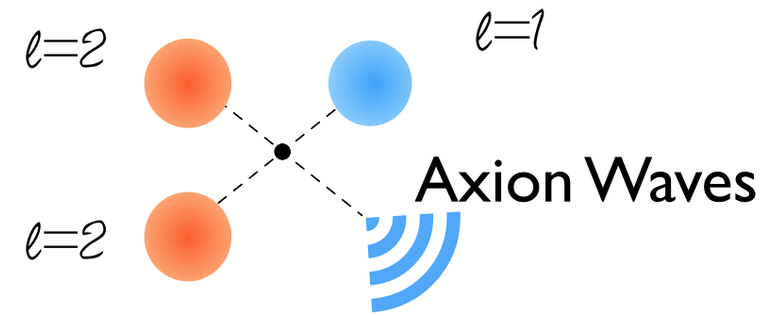
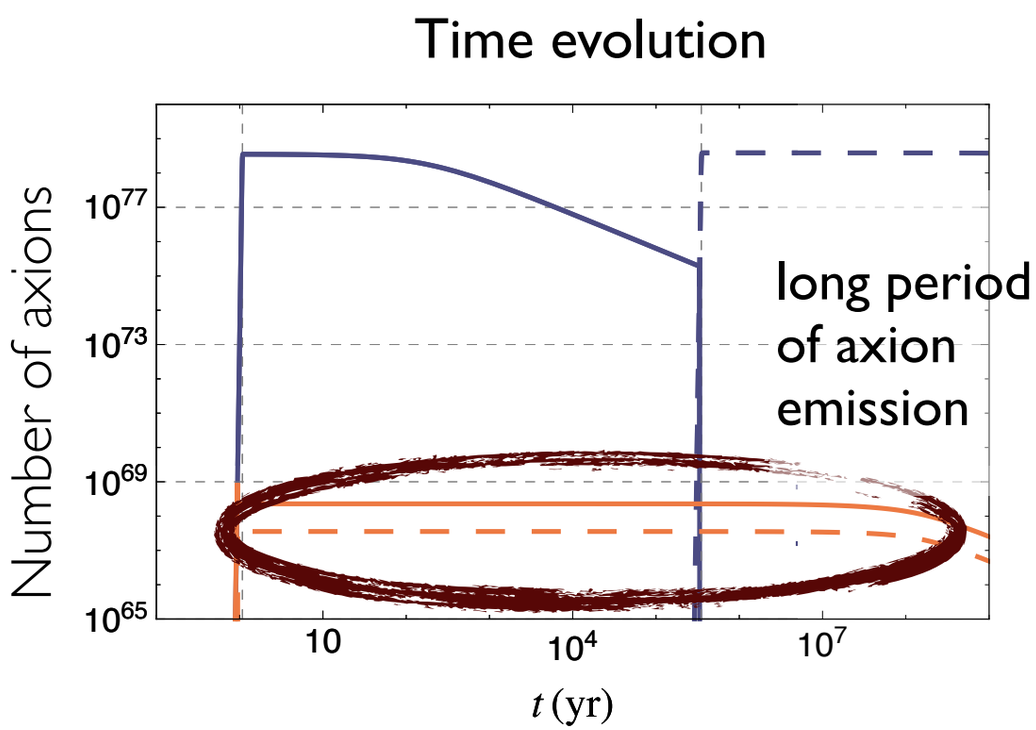


# Axion Wave Emission




- Black Hole spins down slowly, emitting axion waves



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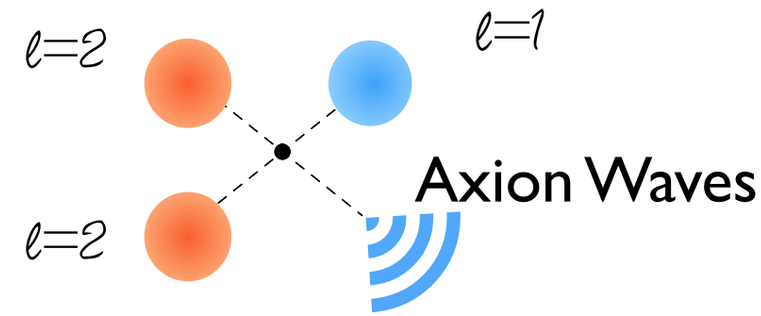


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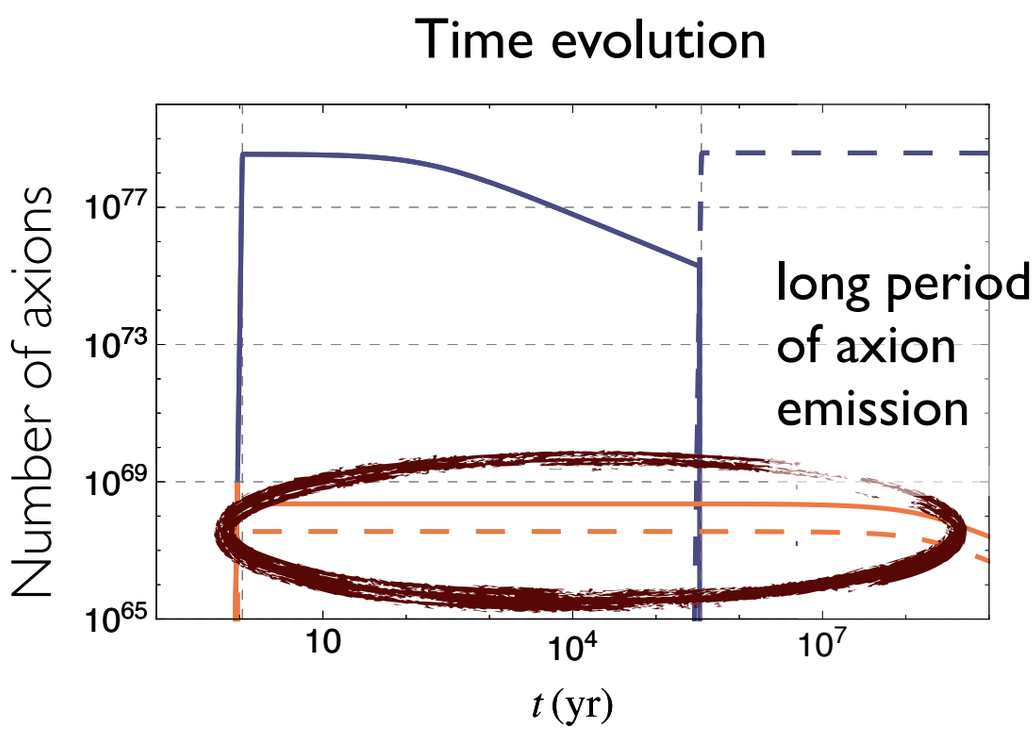


- Directly detectable if coupled to the SM

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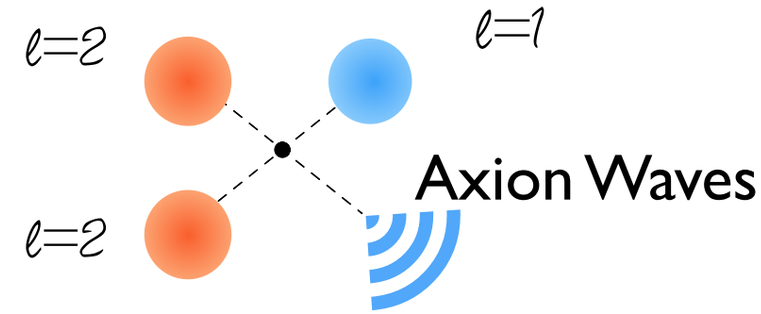
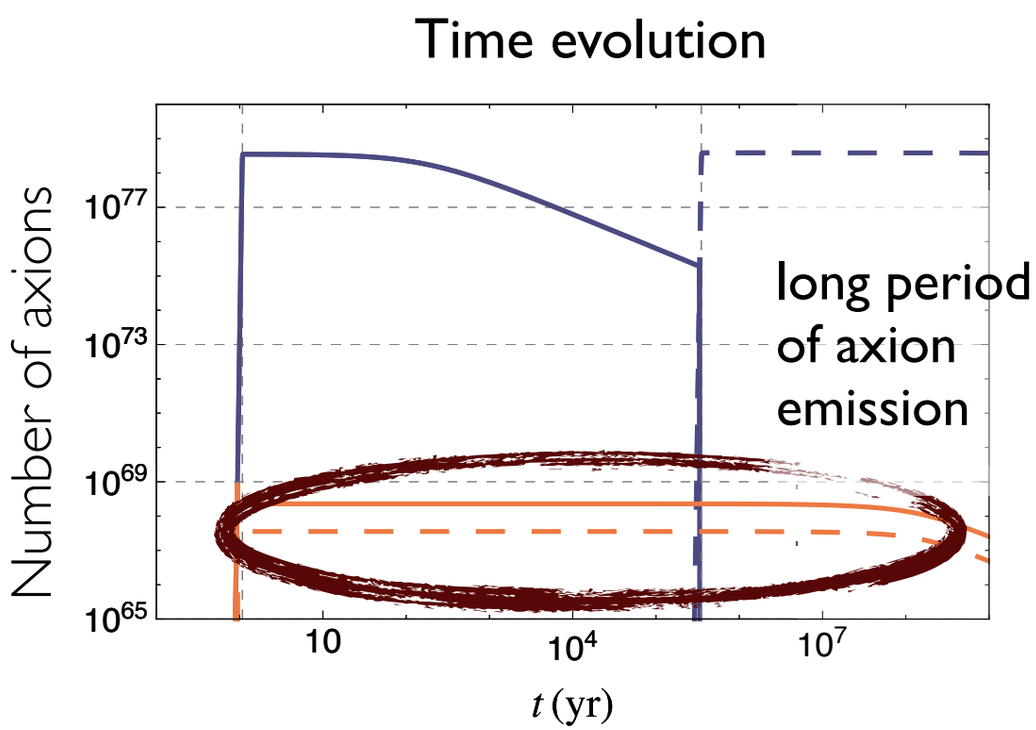
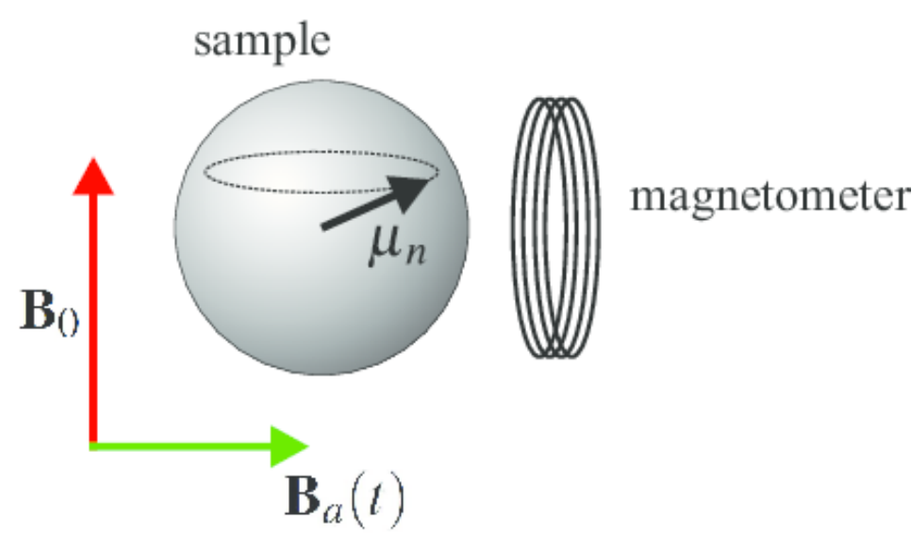



- Black Hole spins down slowly, emitting axion waves

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




$$H_n \supset C \frac{\vec{\nabla} a}{f_a} \cdot \vec{\sigma}_N$$




CASPEr Wind Experiment (2014)
Kimball et al (2017)

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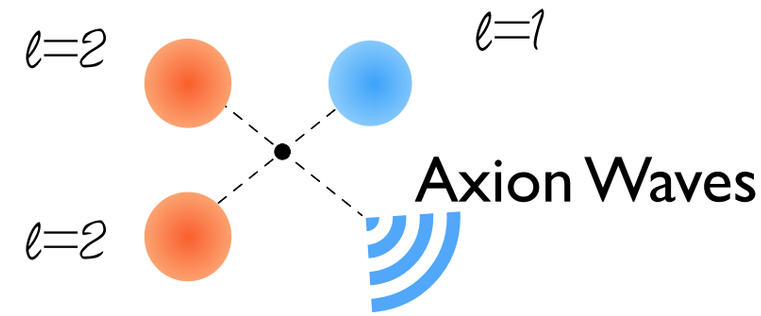
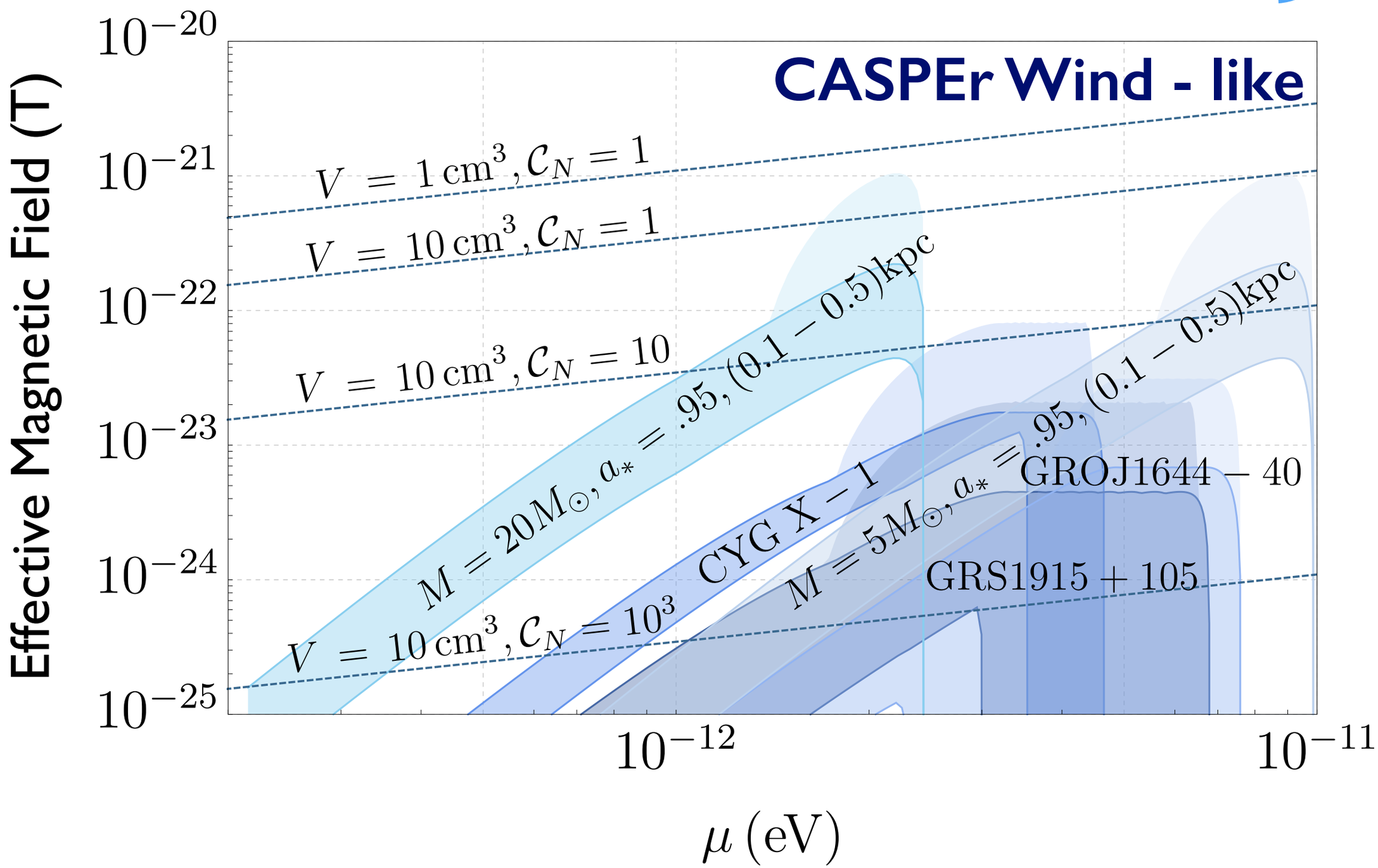
# Axion Wave Emission

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# Conclusions

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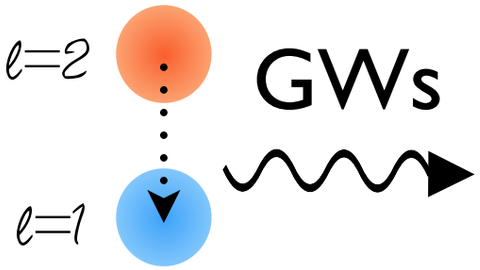

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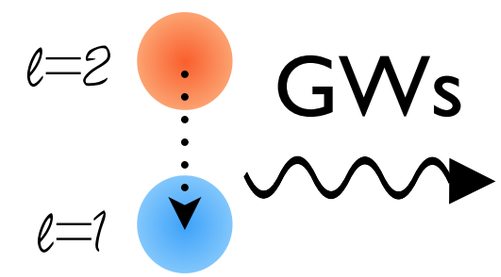
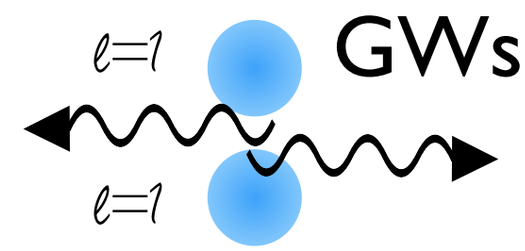



- **GW annihilation signatures** are suppressed but still observable by **aLIGO**



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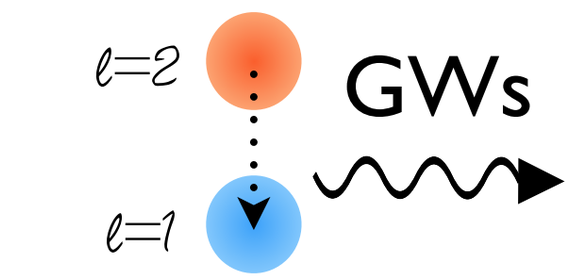


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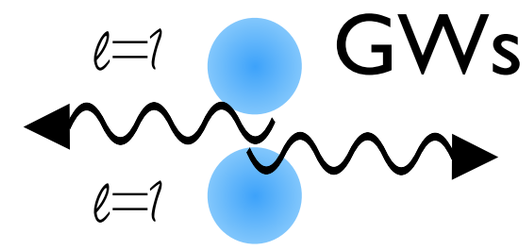
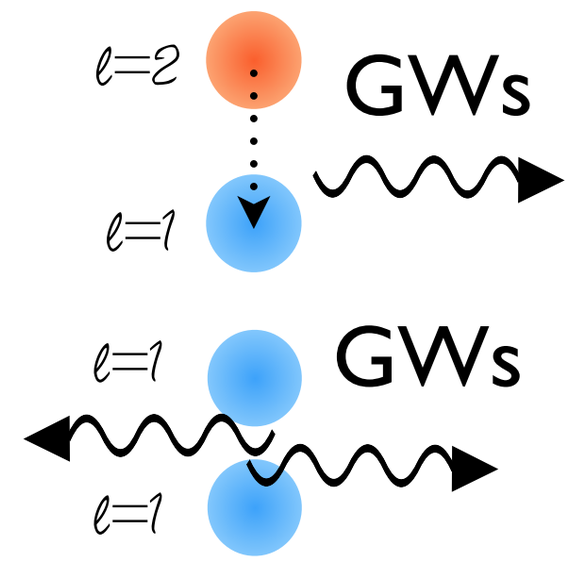



- **Constraints** from spin measurements are **modified** and do not apply for appreciable self-interactions

# Conclusions

- Self-Interactions **dramatically affect** the evolution of the cloud

- Novel **GW transition signatures**: can be probed by **aLIGO + future observatories**




- **GW annihilation signatures** are suppressed but still observable by **aLIGO**

- **Constraints** from spin measurements are **modified** and do not apply for appreciable self-interactions

- Instead Black Holes emit **axion radiation** which can be detected by upcoming experiments, such as **CASPEr-Wind**