

Black Hole Superradiance of Self-Interacting Scalar Fields

Marios Galanis

Stanford University

12/9/2021

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

AstroDark 2021

Why ultralight scalar fields

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Peccei, Quinn '77

Solves the strong CP problem

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$$V \sim \Lambda_{\text{QCD}}^4 \left[1 - \cos \left(\frac{\phi}{f_a} \right) \right]$$

$$\mu_a \simeq 6 \times 10^{-12} \text{ eV} \frac{10^{18} \text{ GeV}}{f_a}$$

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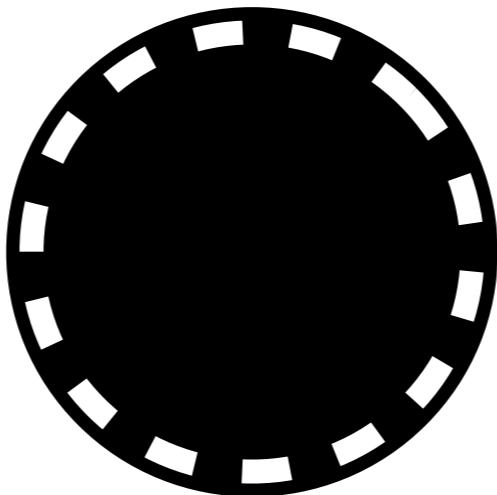
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Can also be the DM!

How to spin down a Black Hole

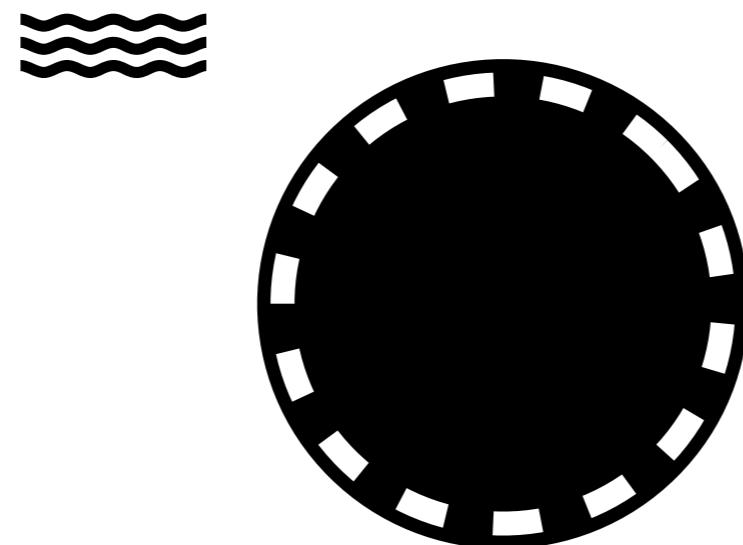


How to spin down a Black Hole

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

Azimuthal number!

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



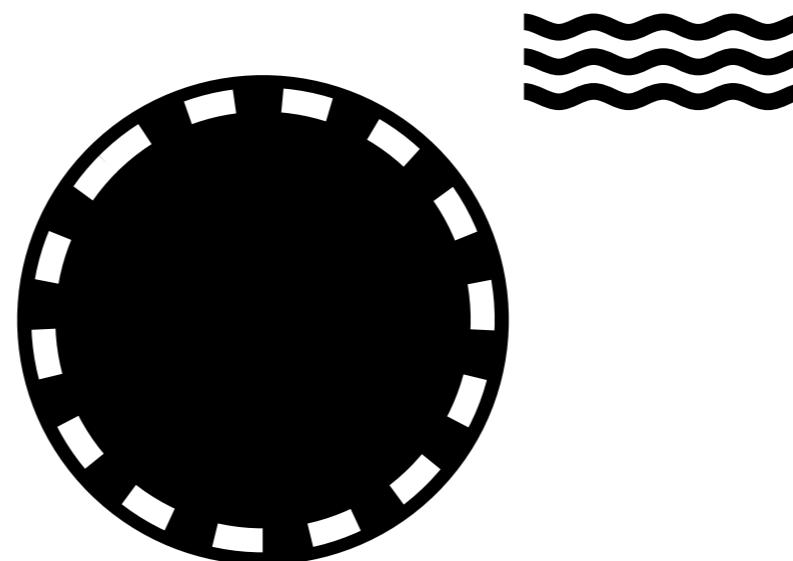
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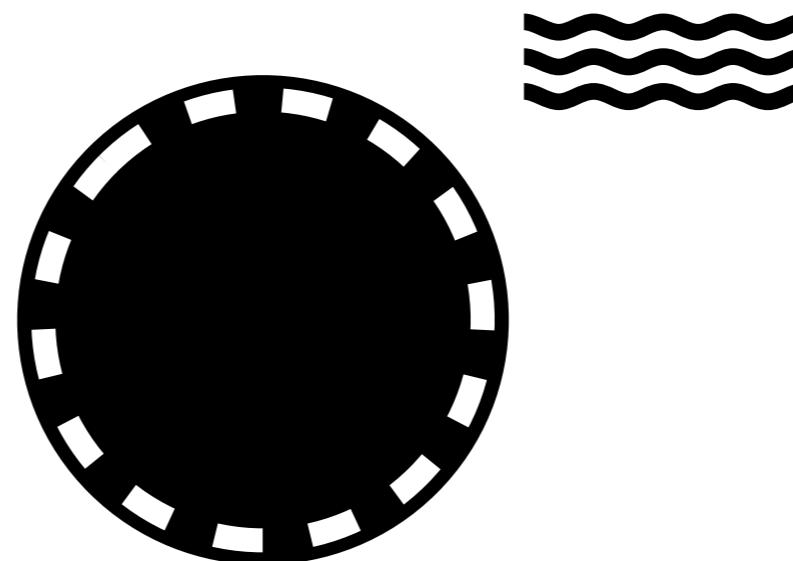
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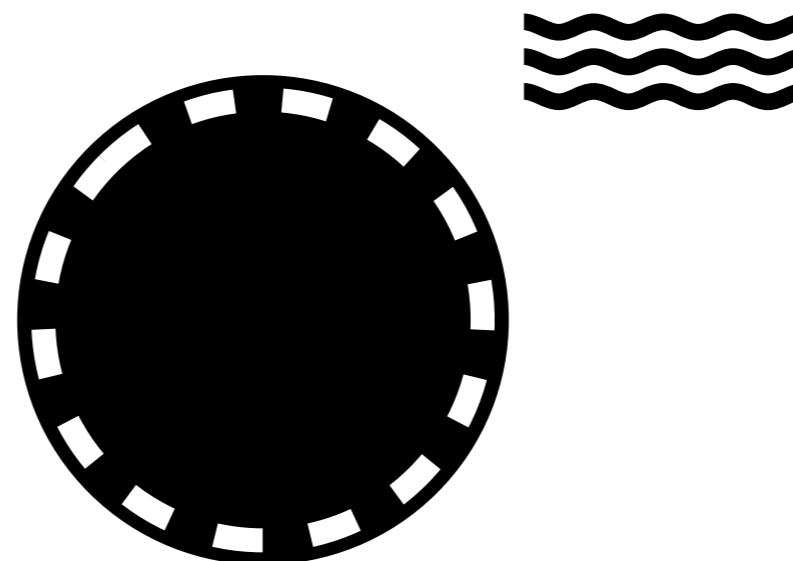
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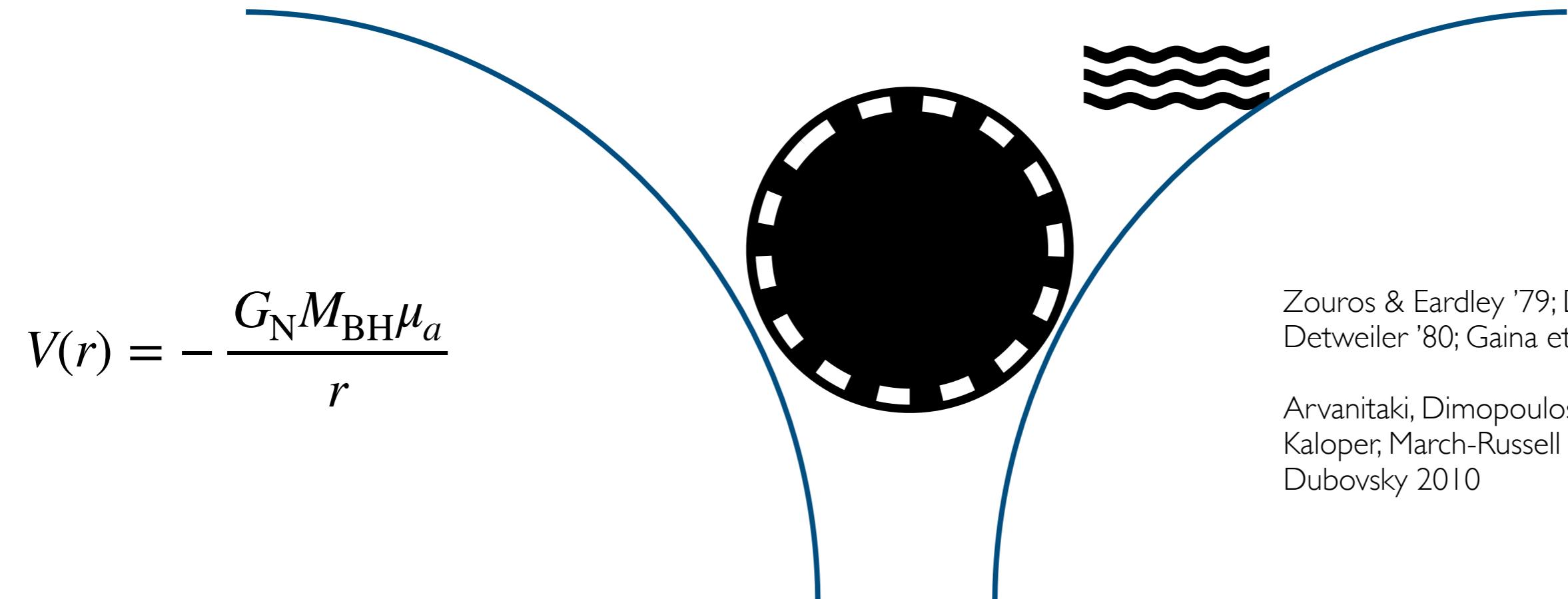
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What if I make the wave bound?



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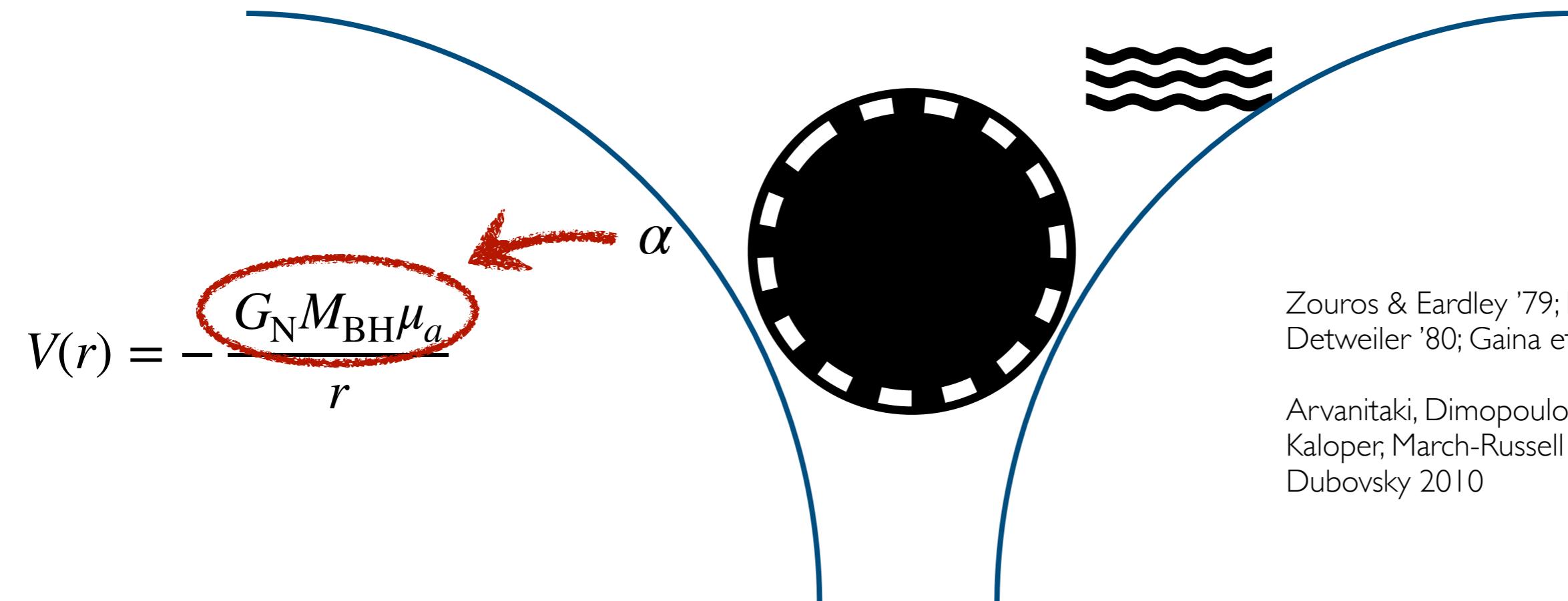
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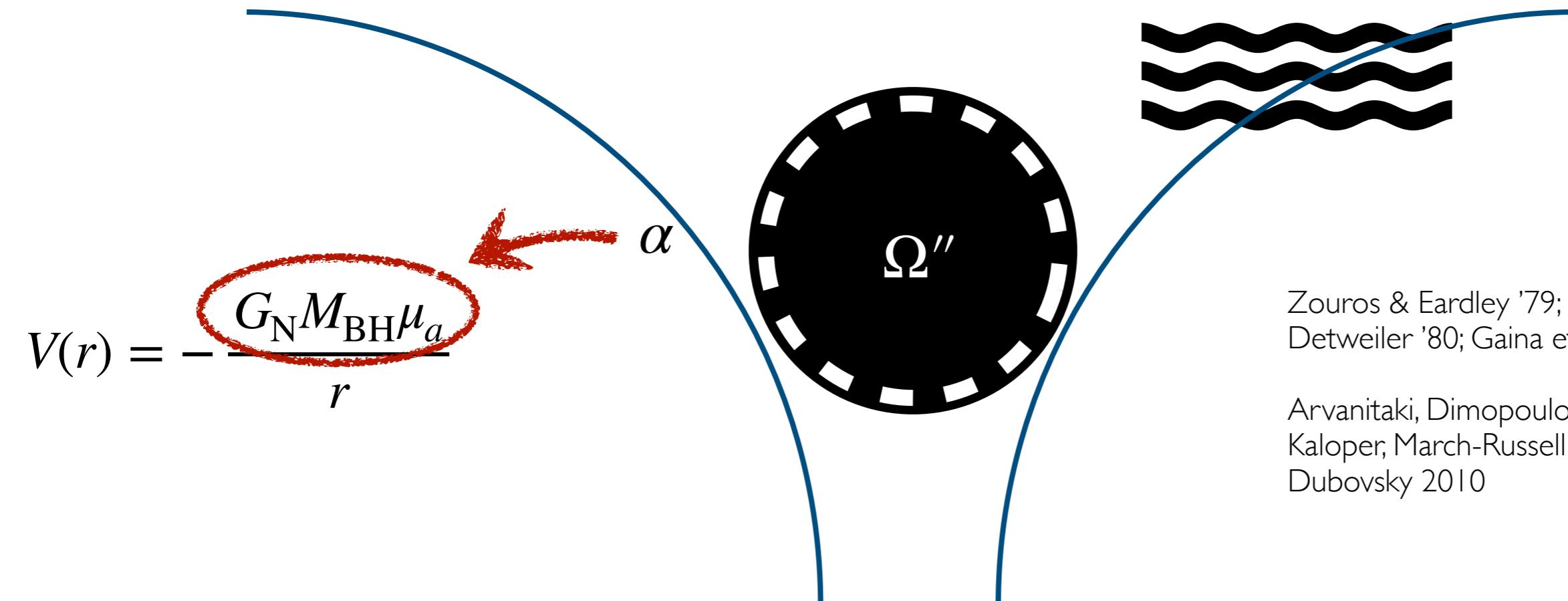
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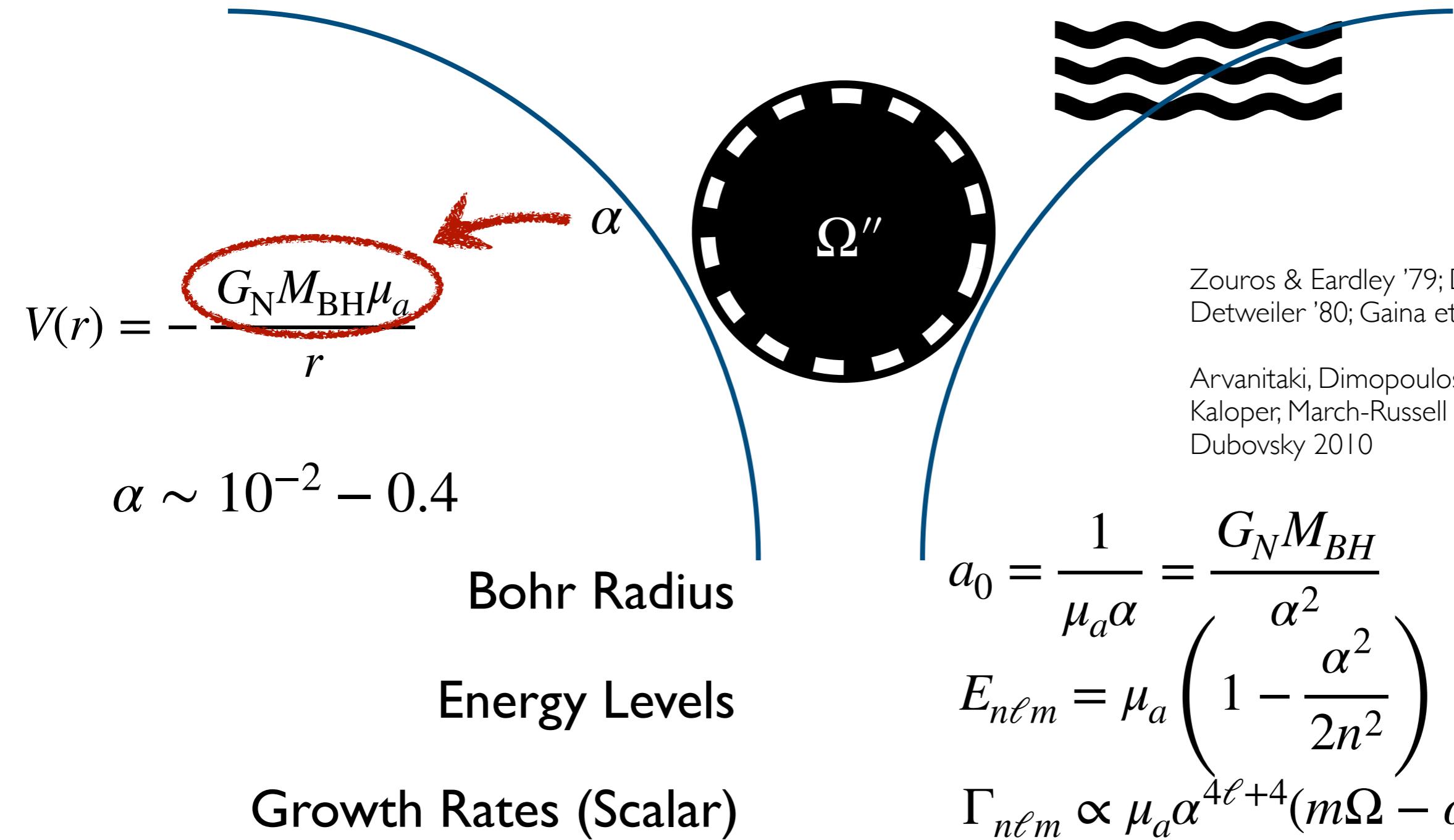
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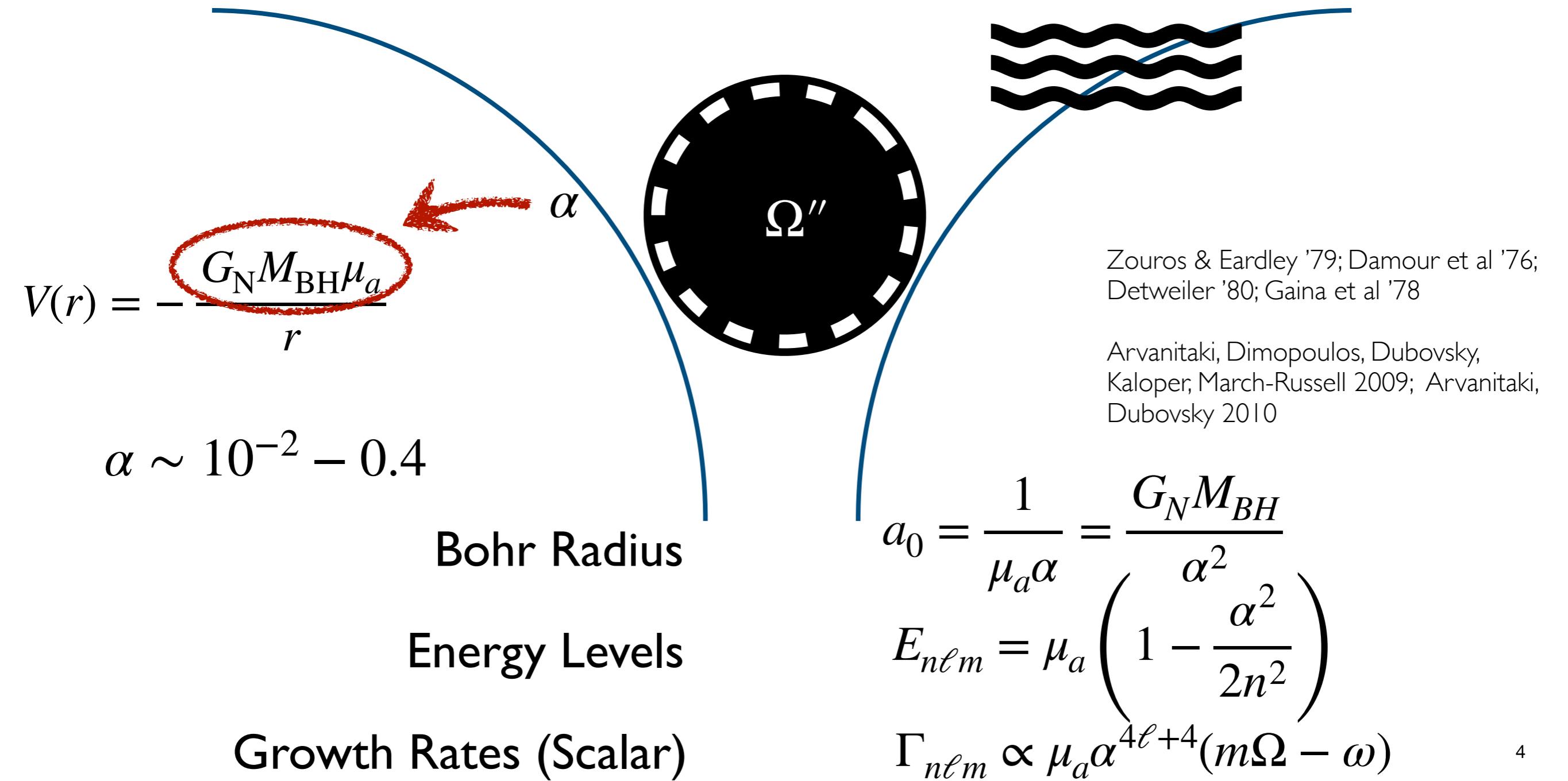
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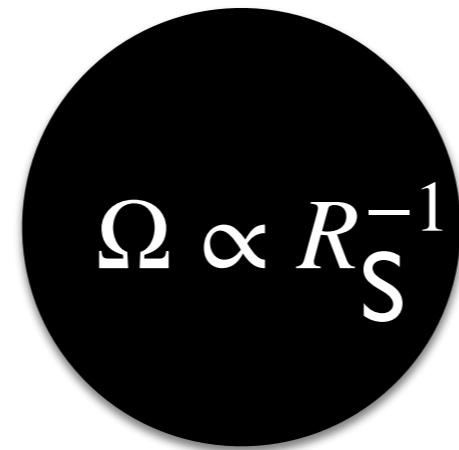
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Numbers to have in mind

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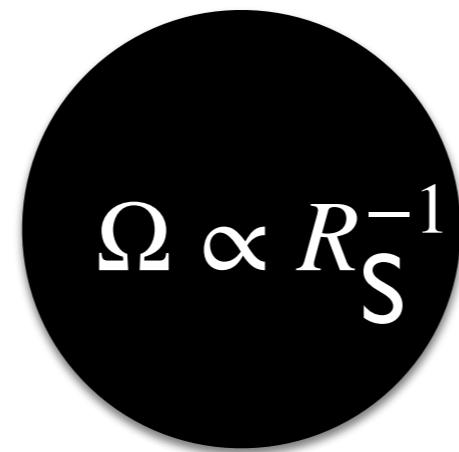
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$$R_S \sim 100 \text{ km}$$

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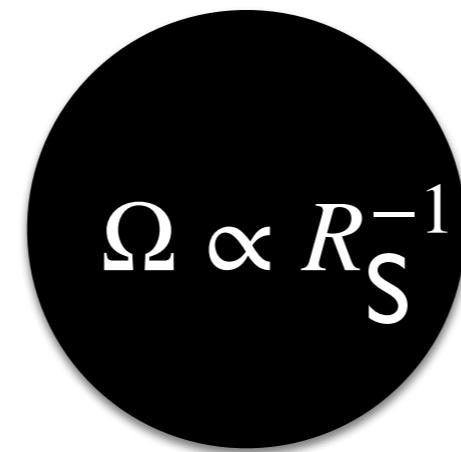
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Sensitive to QCD axions with GUT- to Planck-scale decay constants f_a

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

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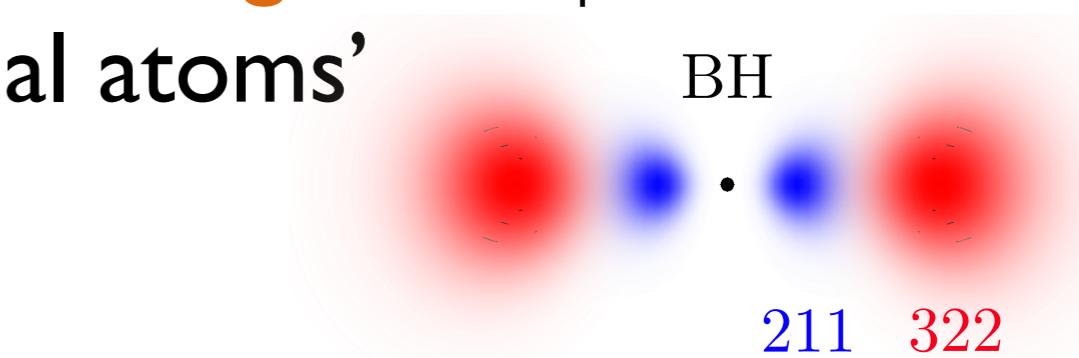
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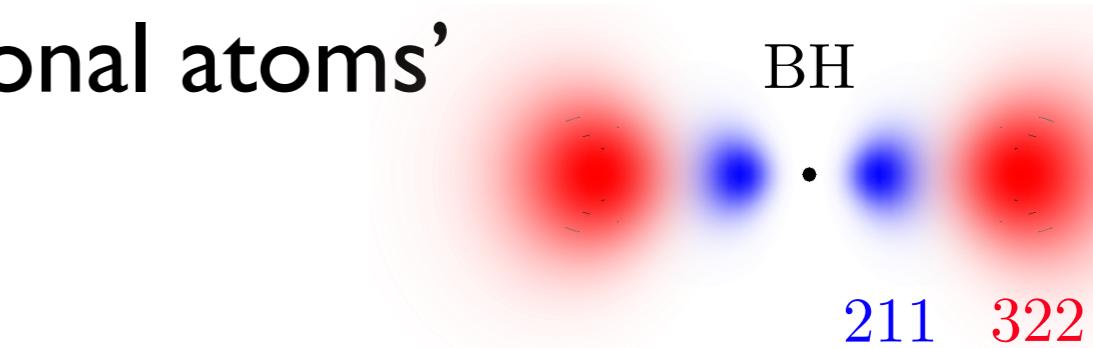
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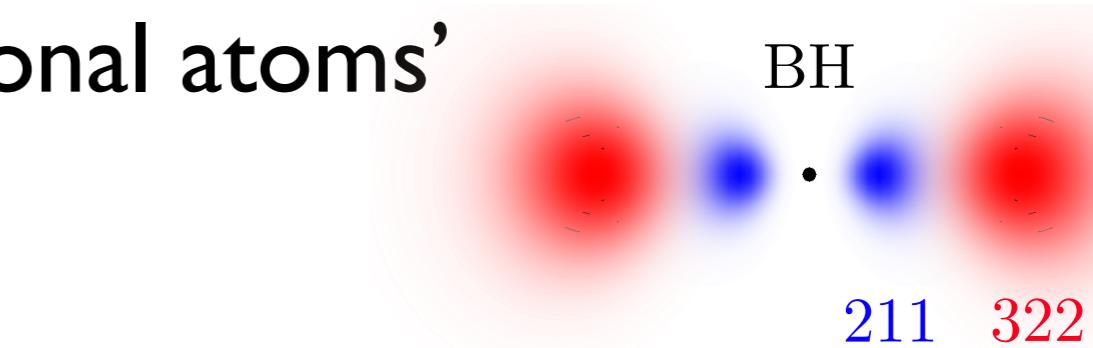
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- Clouds **grow spontaneously** when a rapidly rotating BH is formed, **independent of any** pre-existing (cosmological or otherwise) **abundance**
- Cloud has **O(10%) of the BH's energy**

Gravitational Superradiance

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

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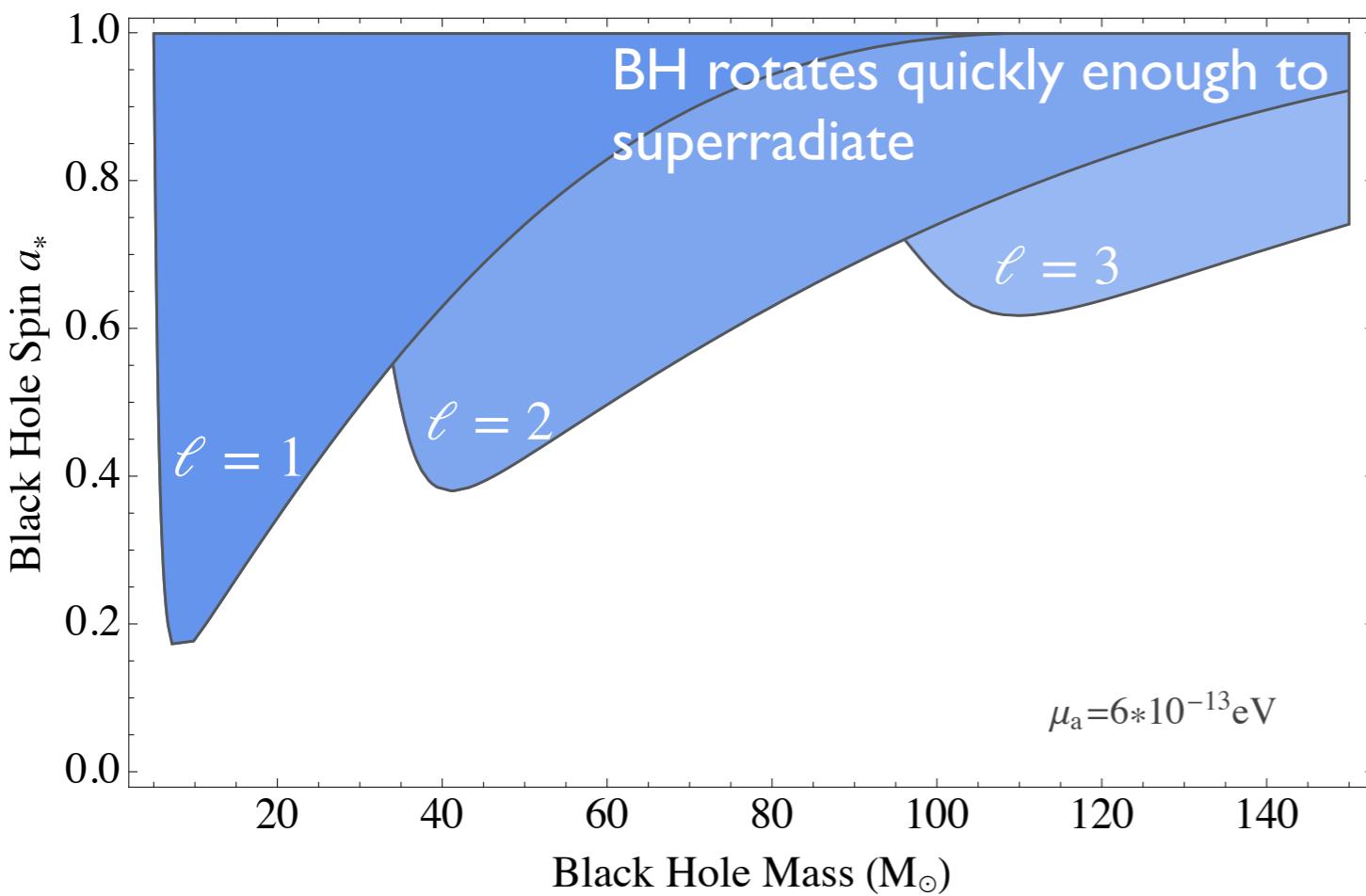
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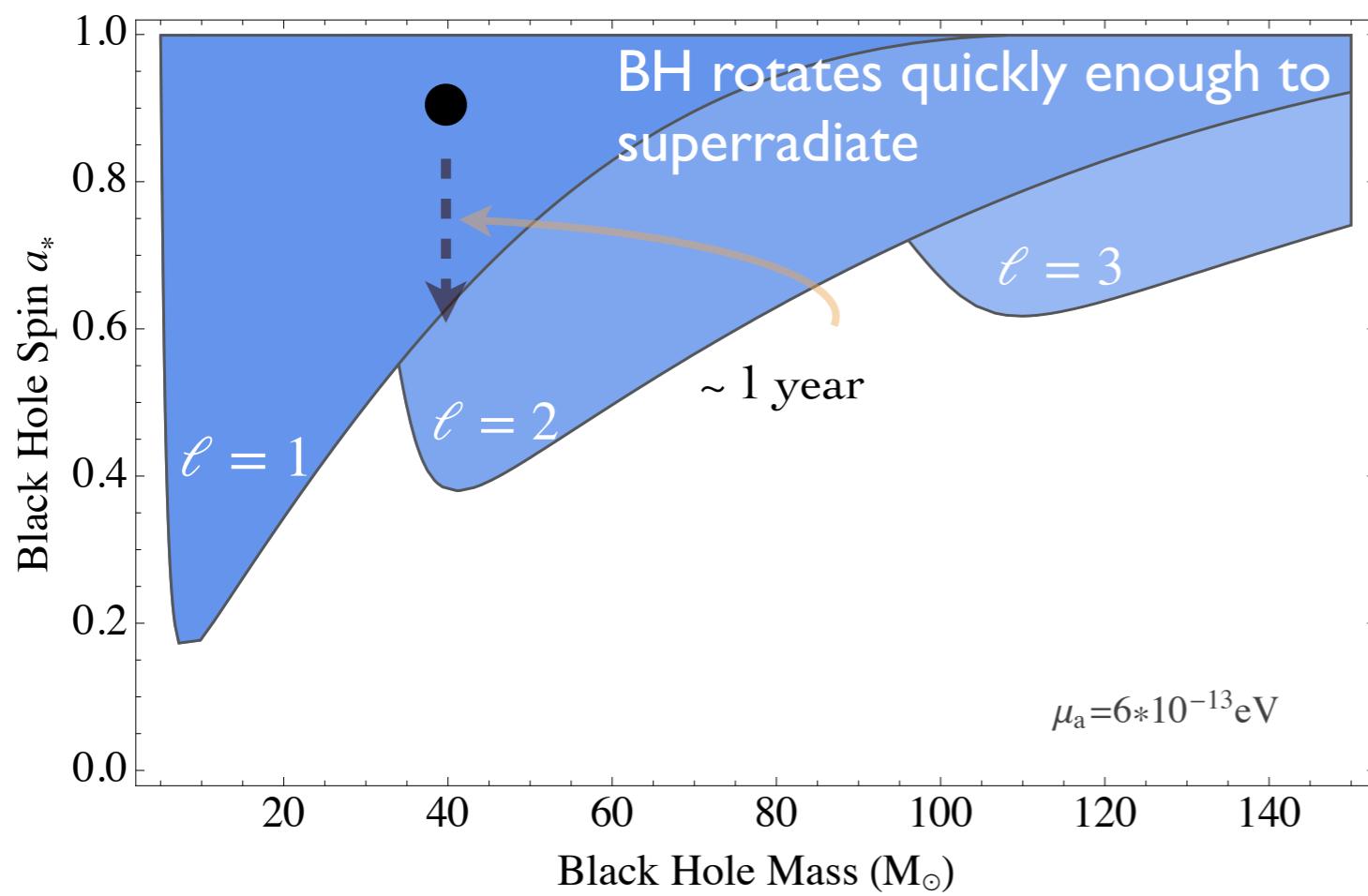
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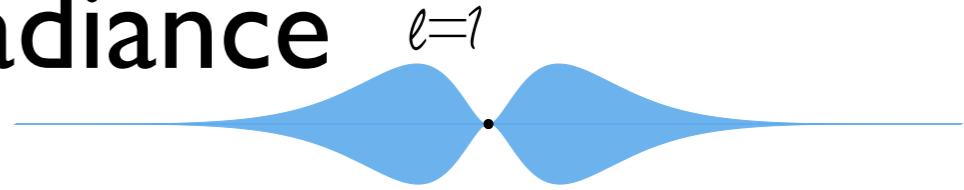
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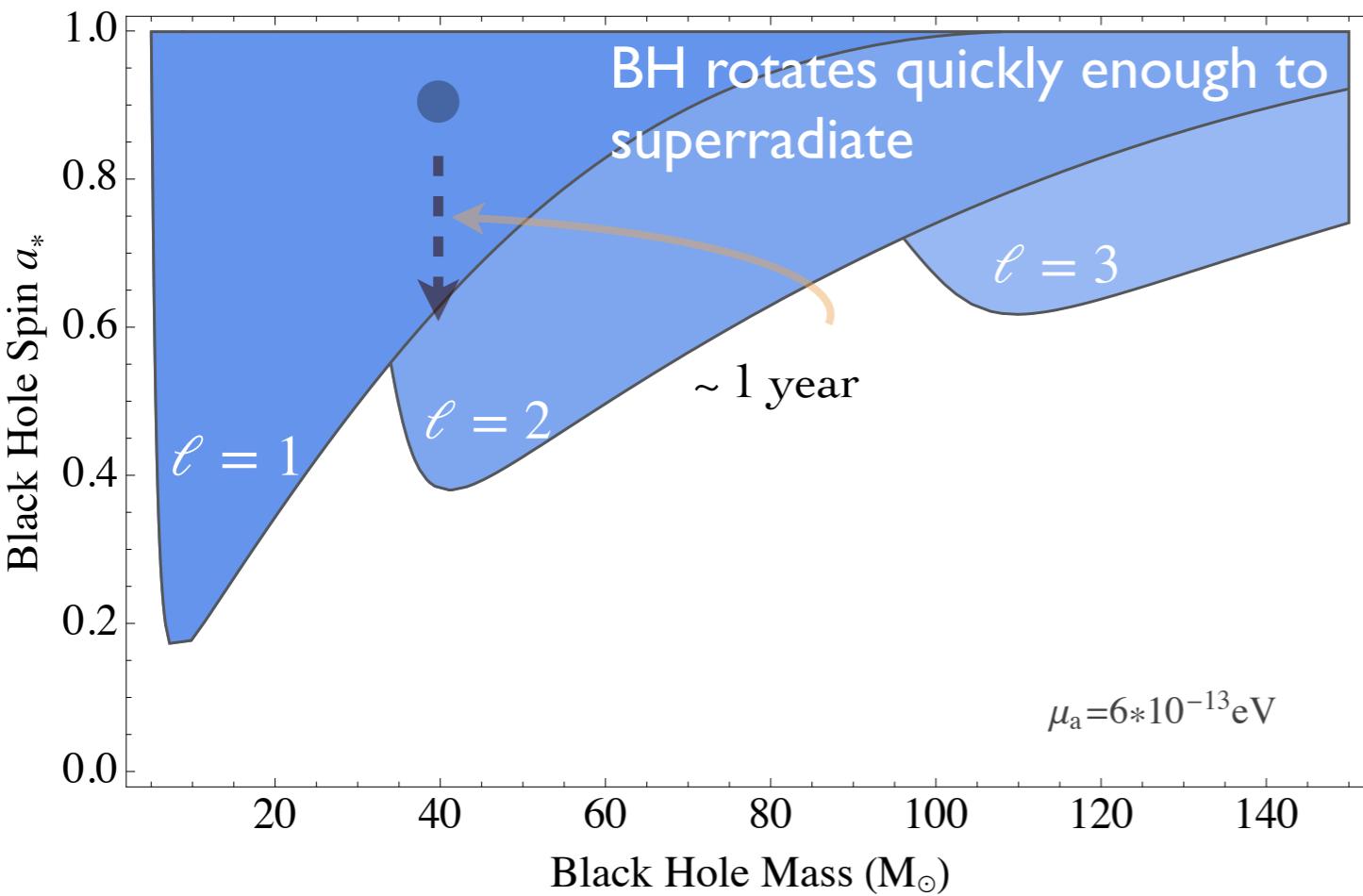
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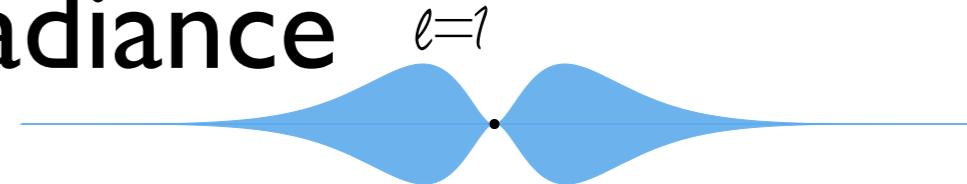
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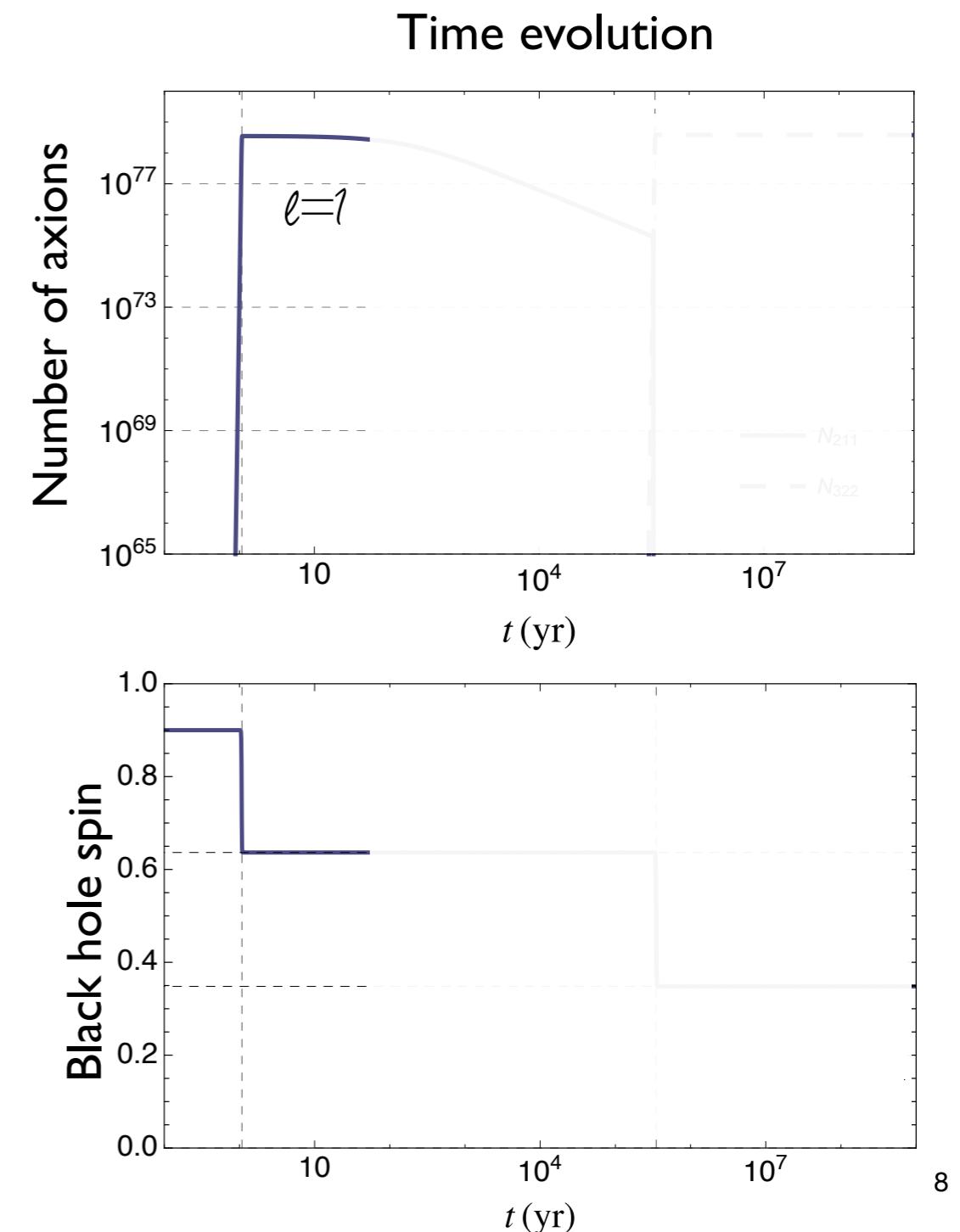
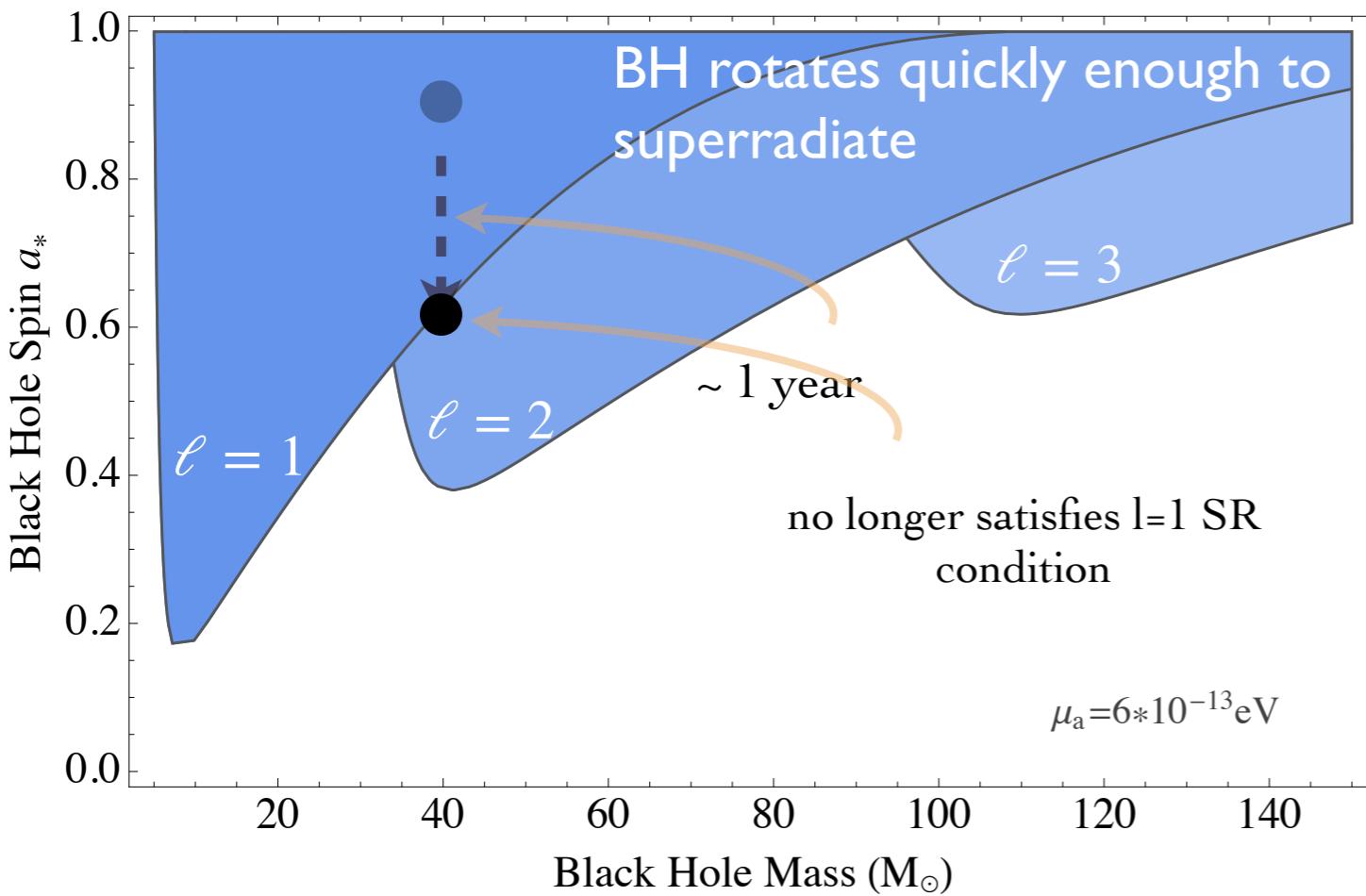
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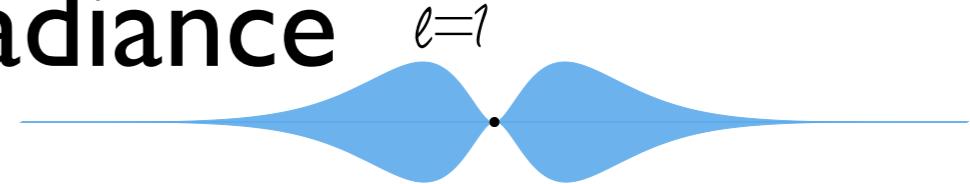
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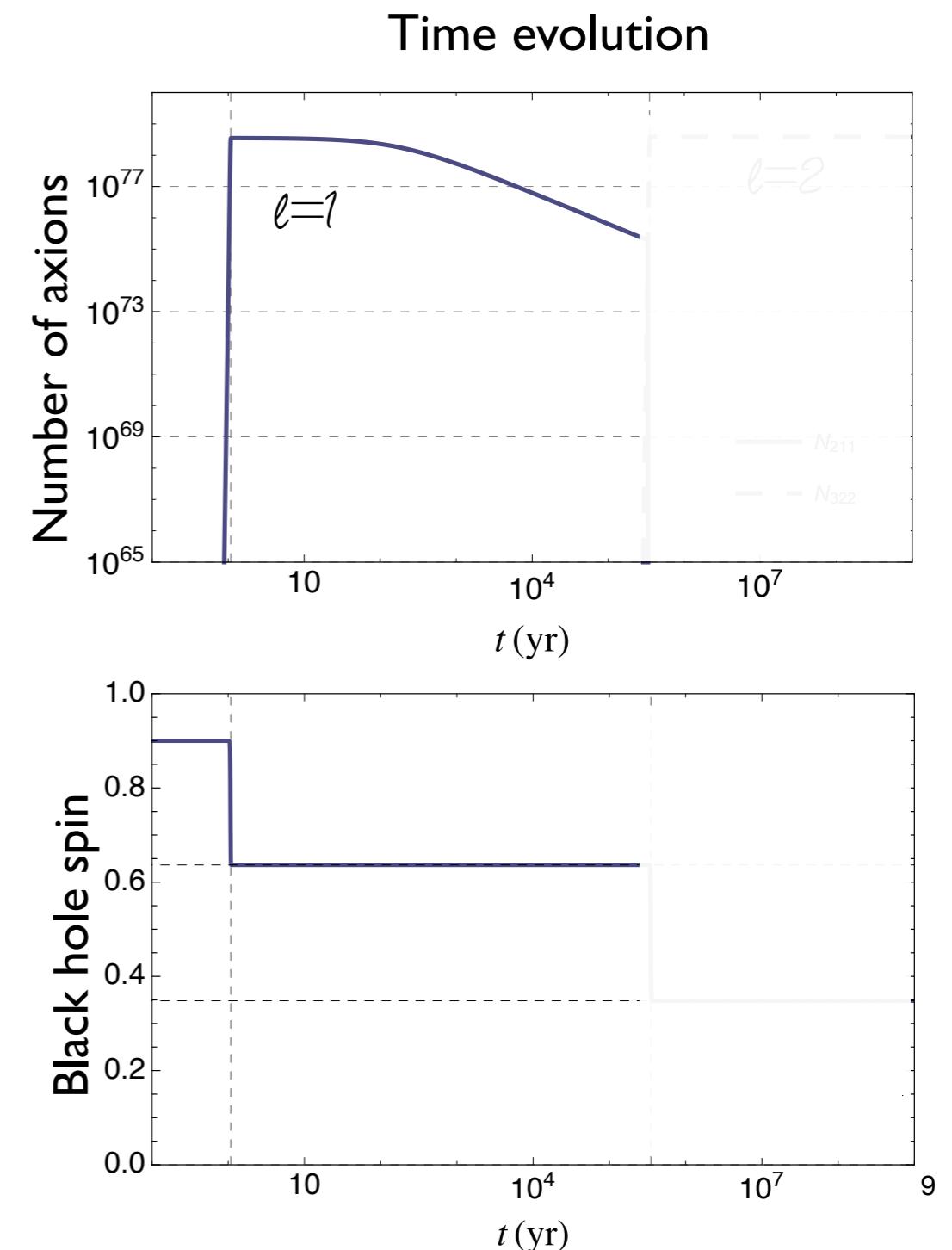
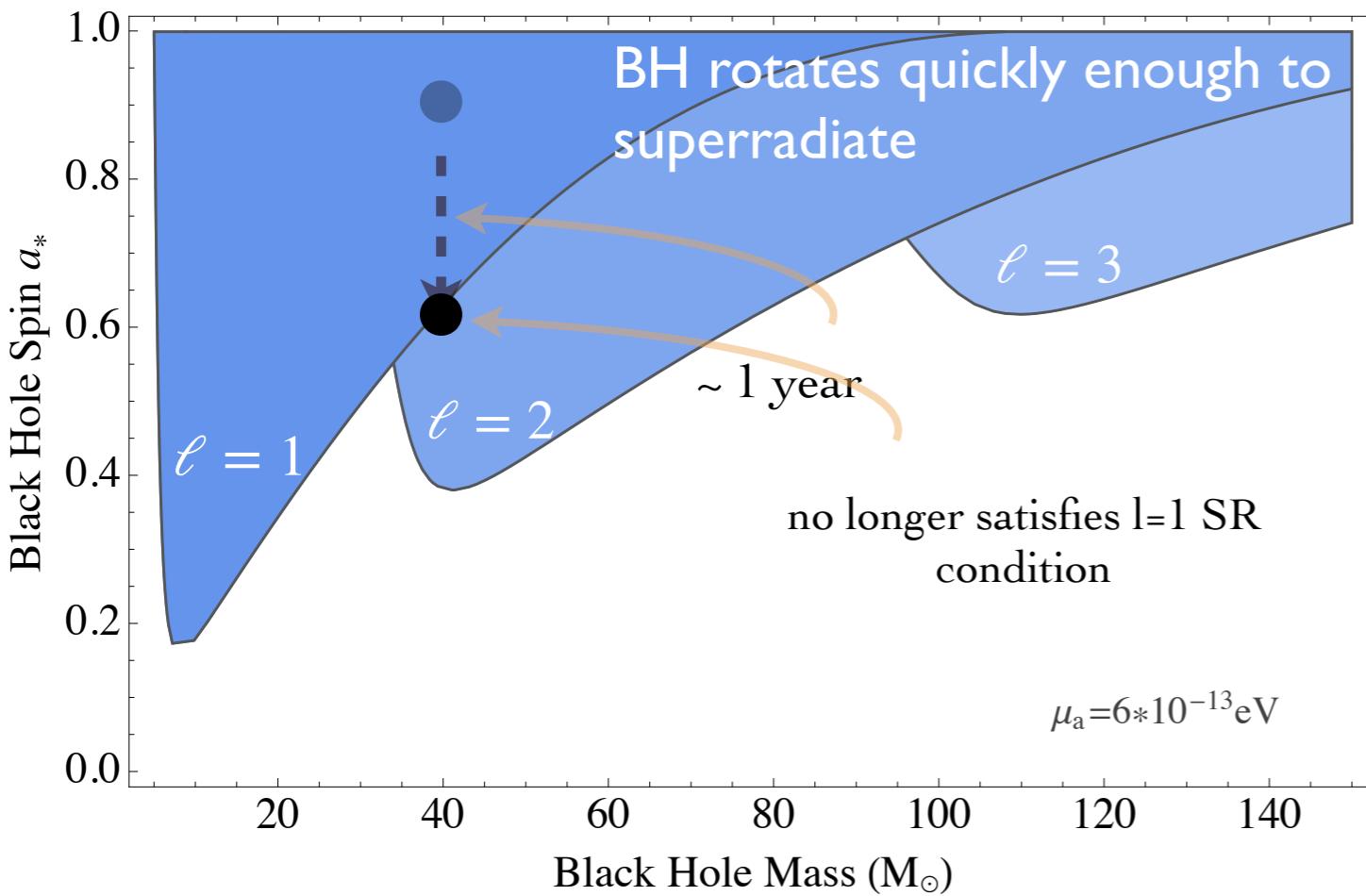
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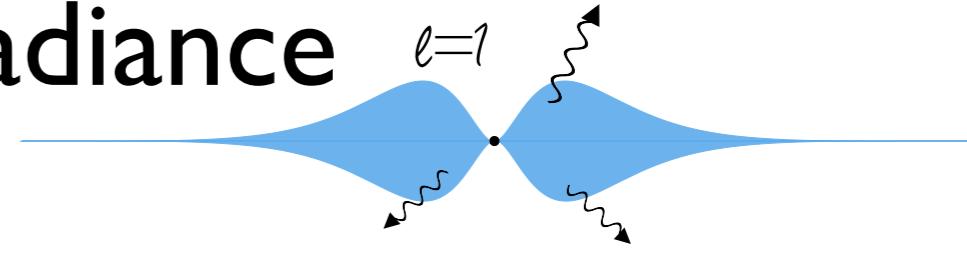
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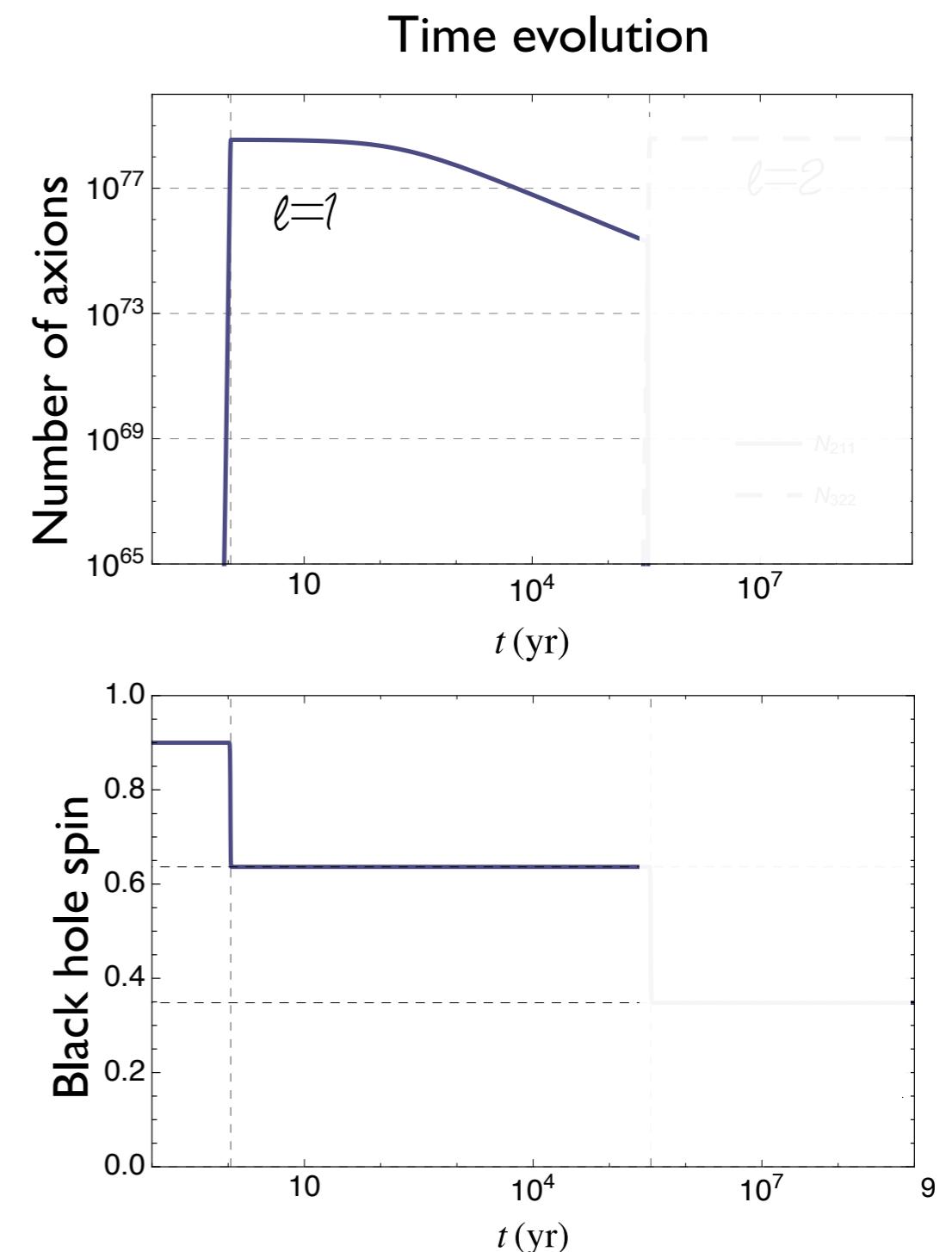
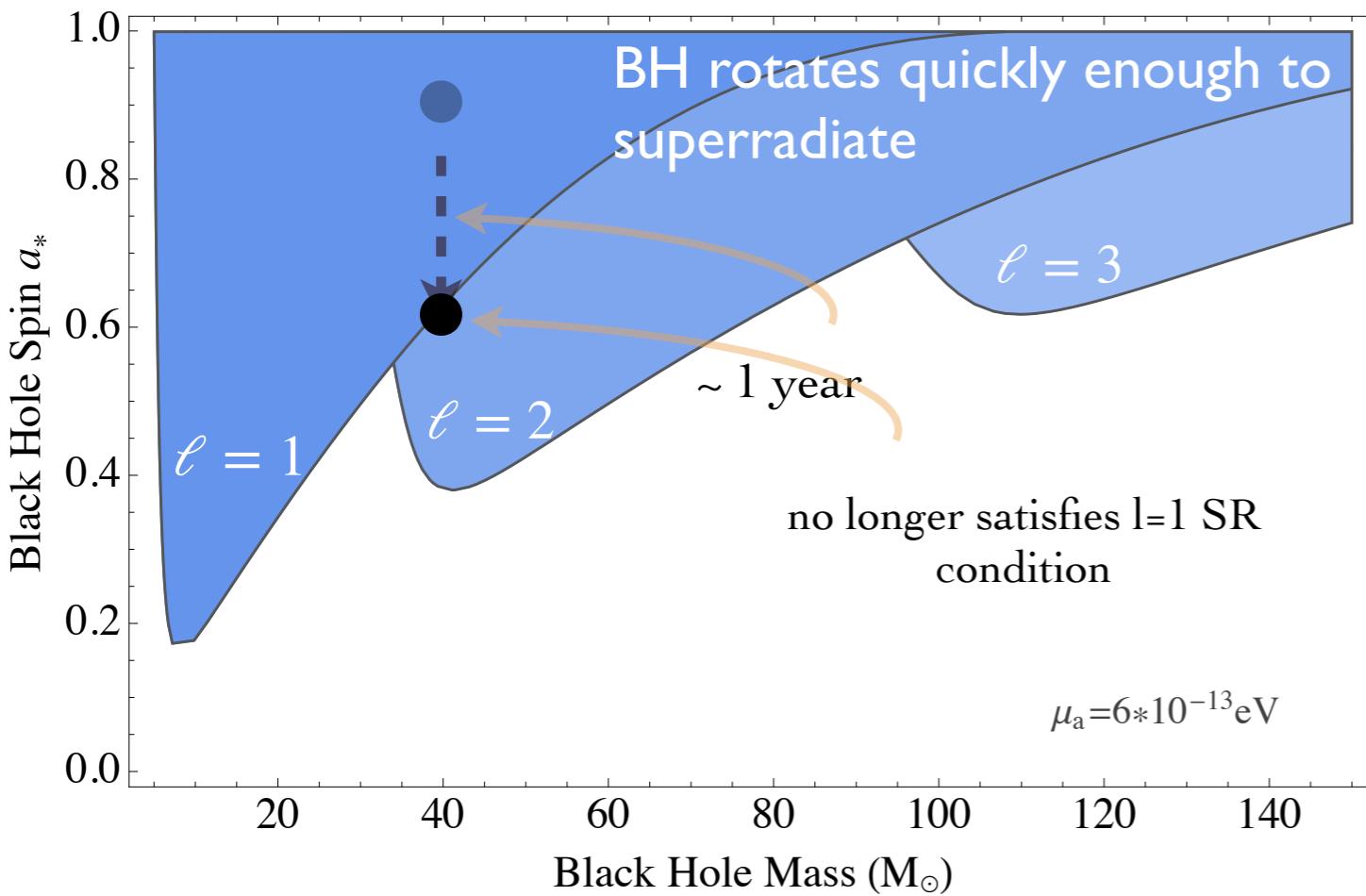
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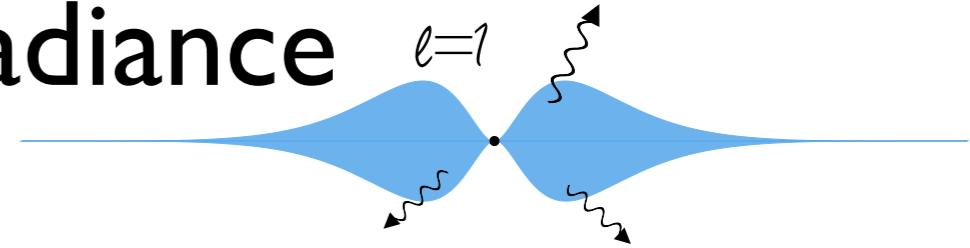
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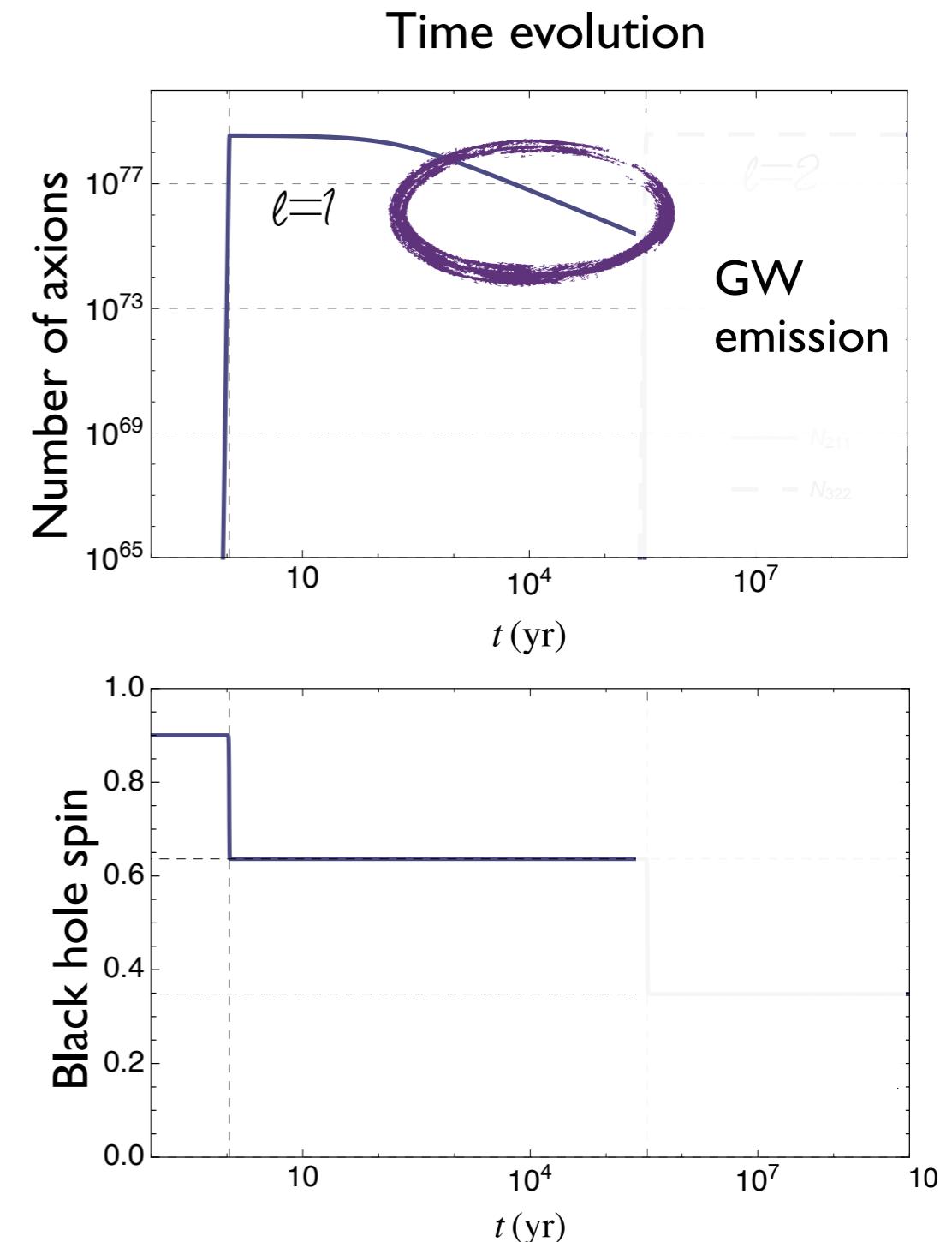
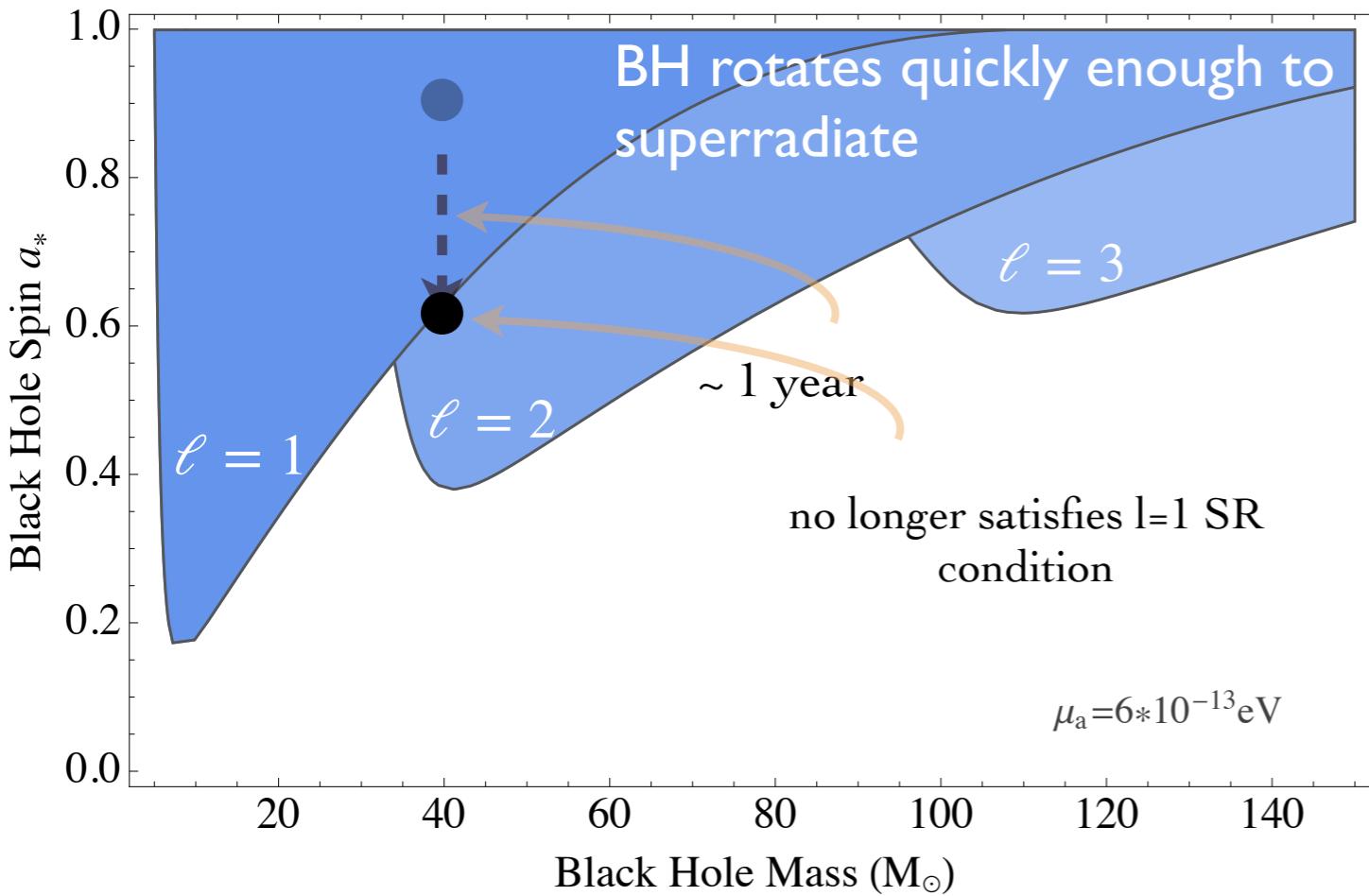


Gravitational Superradiance



Up to **thousands of observable signals** above current LIGO upper limits — lack of observation can disfavor a range of axion masses

Zhu, Baryakhtar, Papa, Tsuna, Kawanaka, Eggenstein (2020)

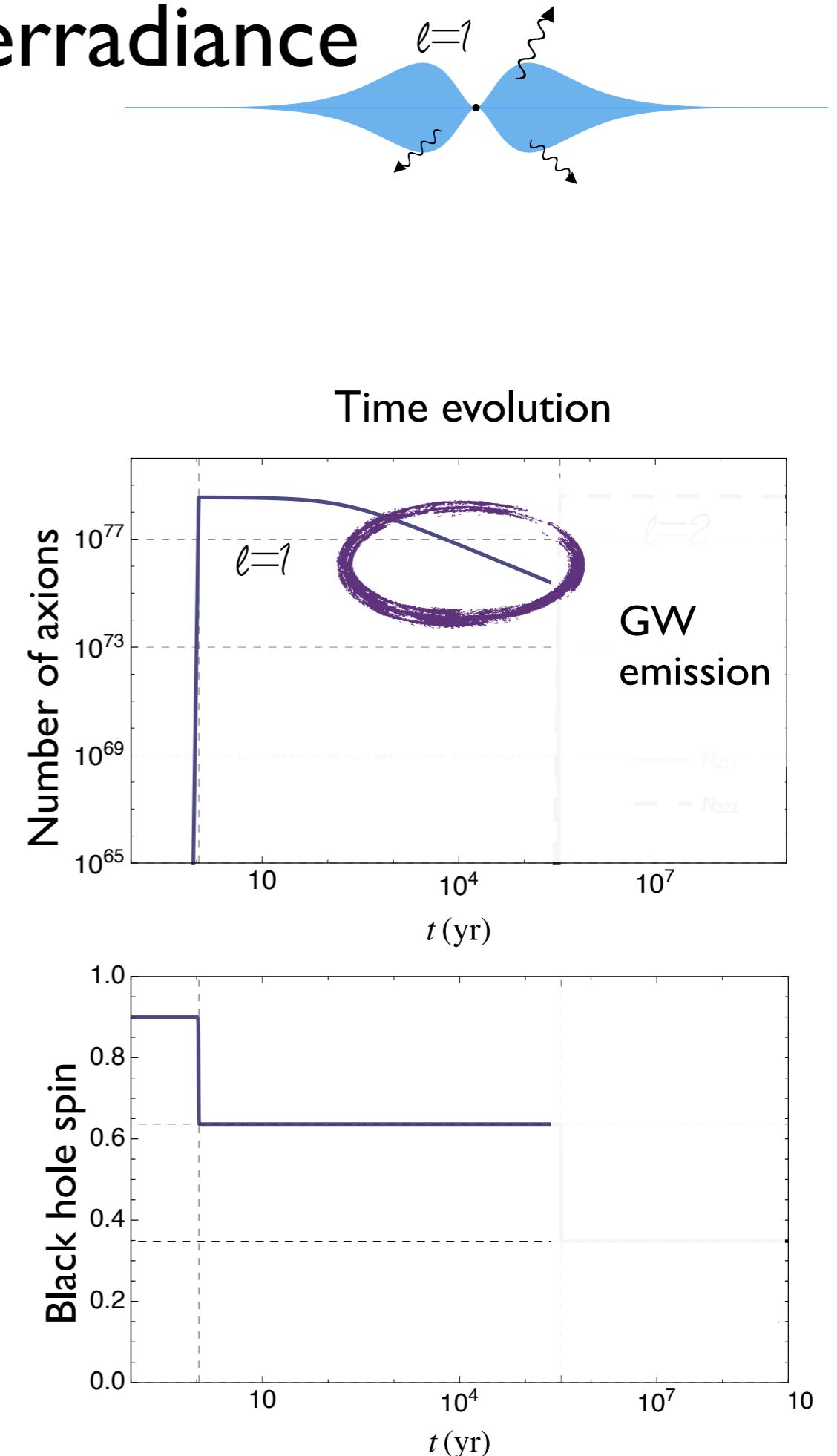
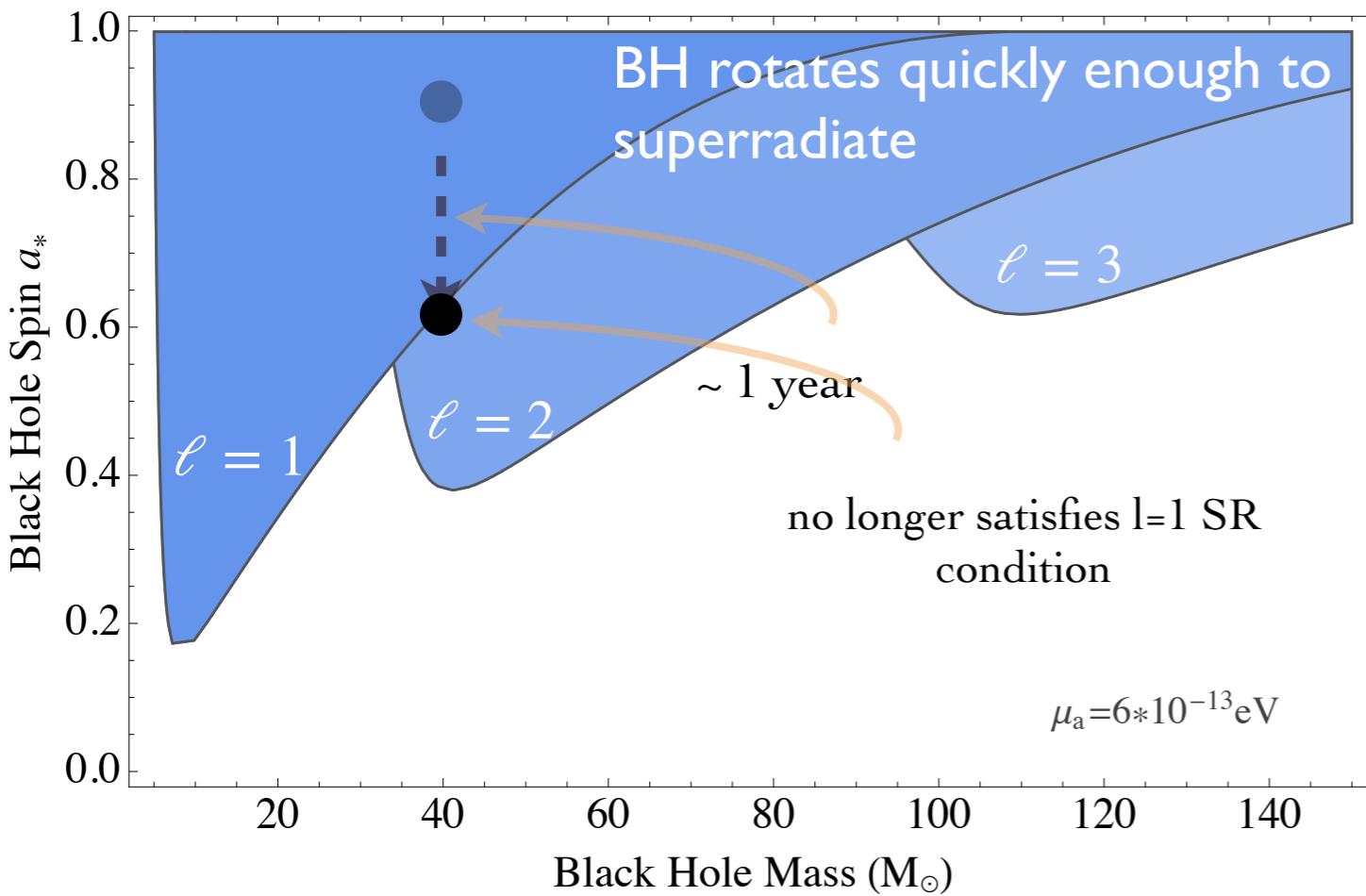


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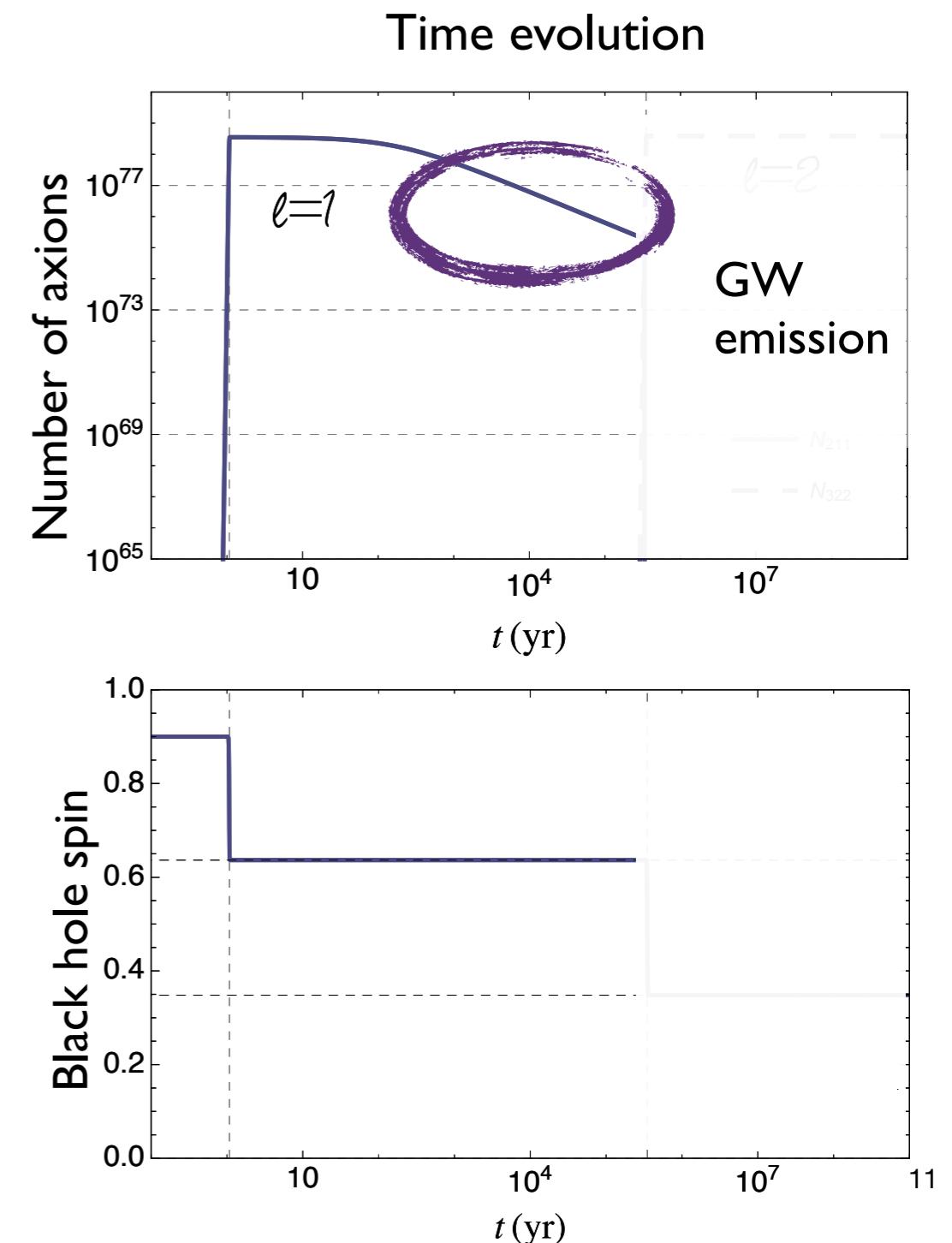
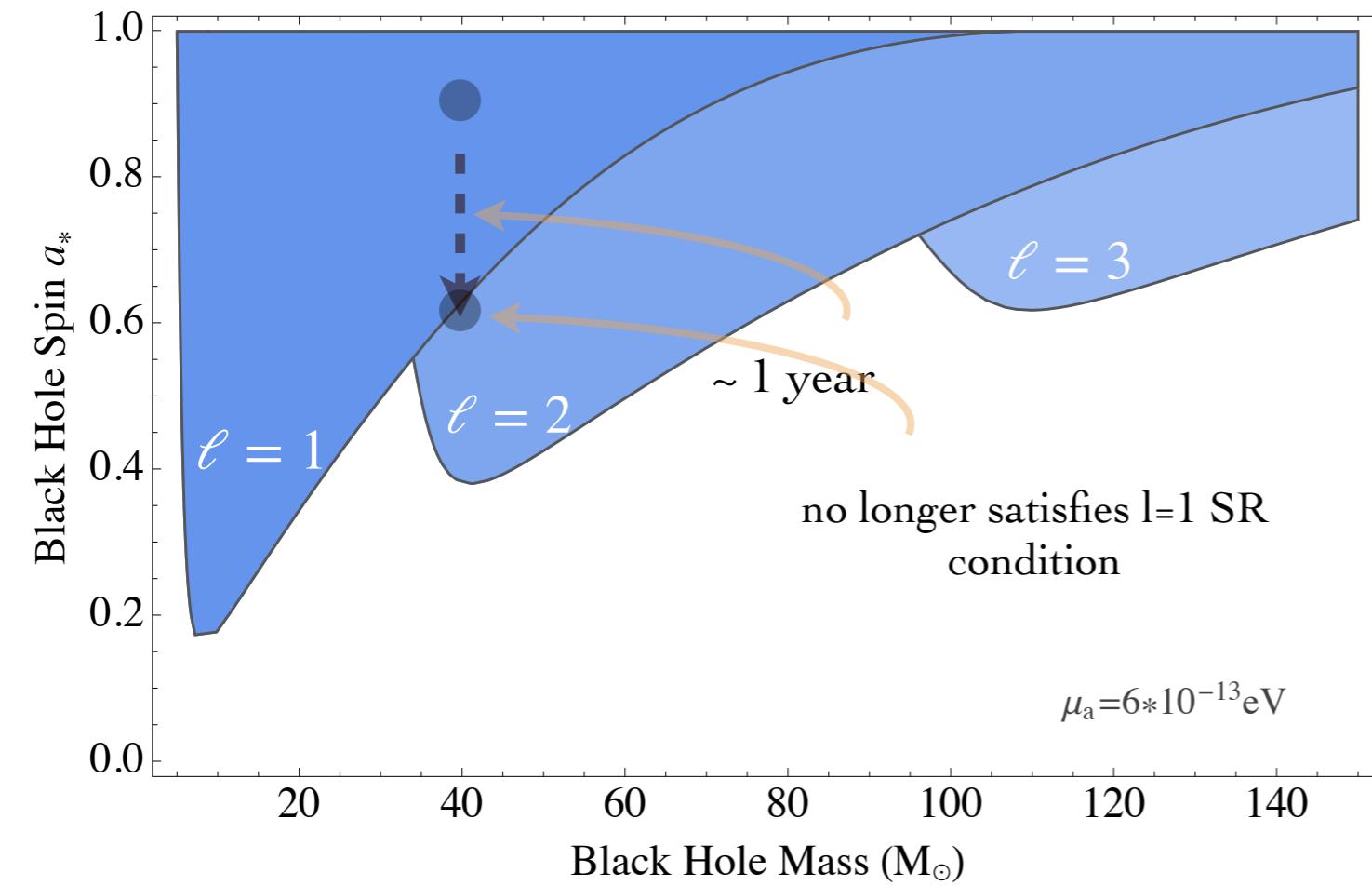
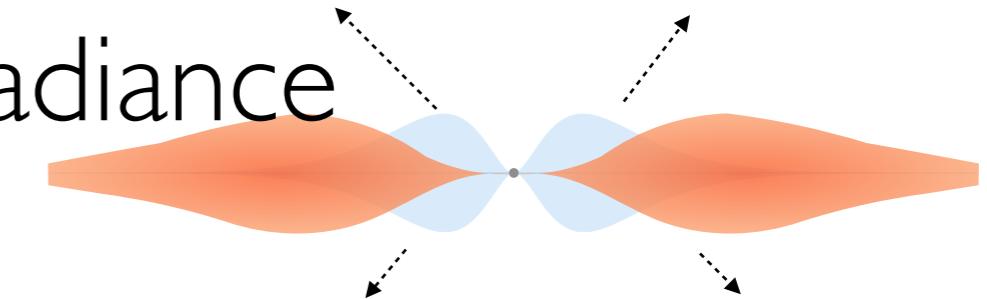
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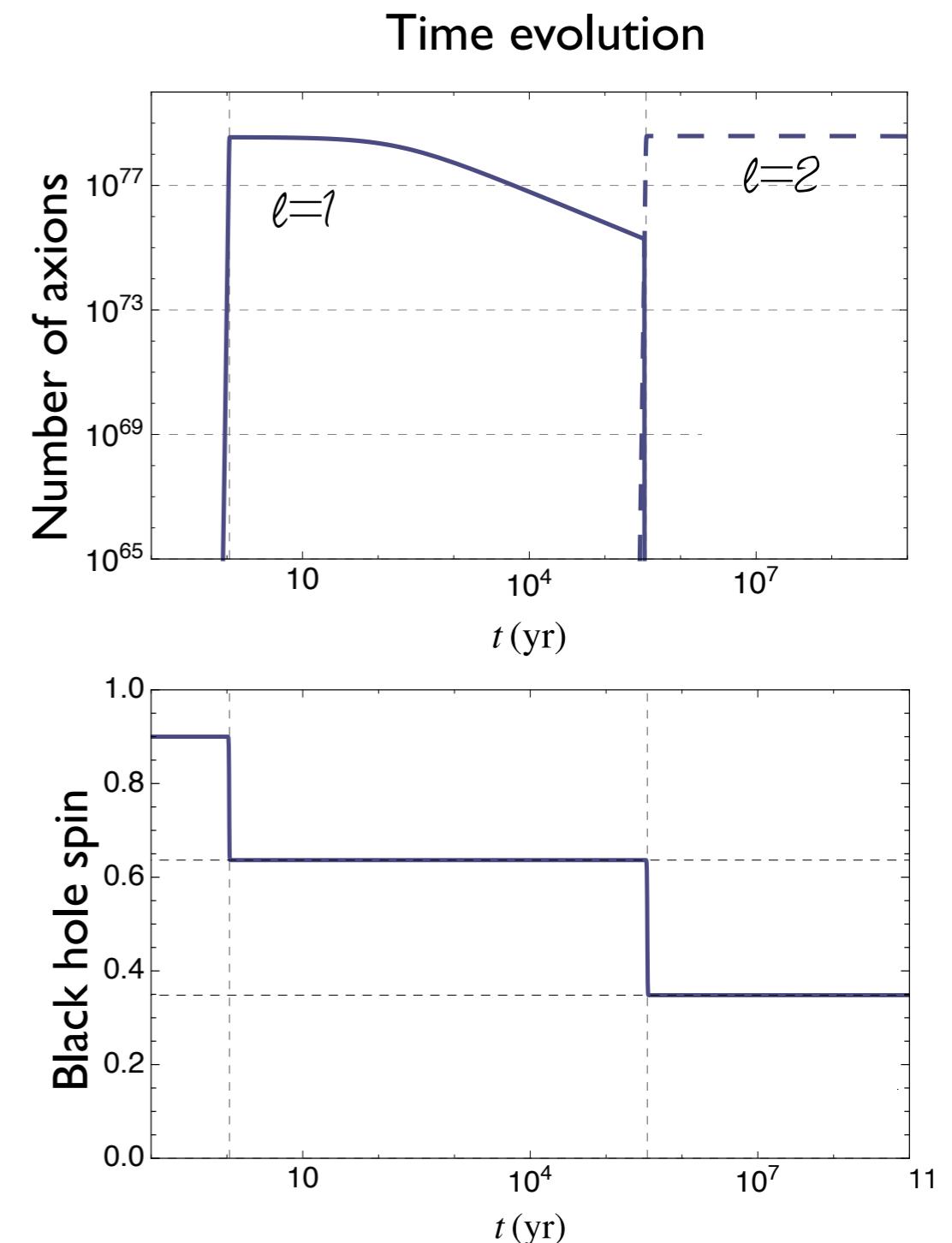
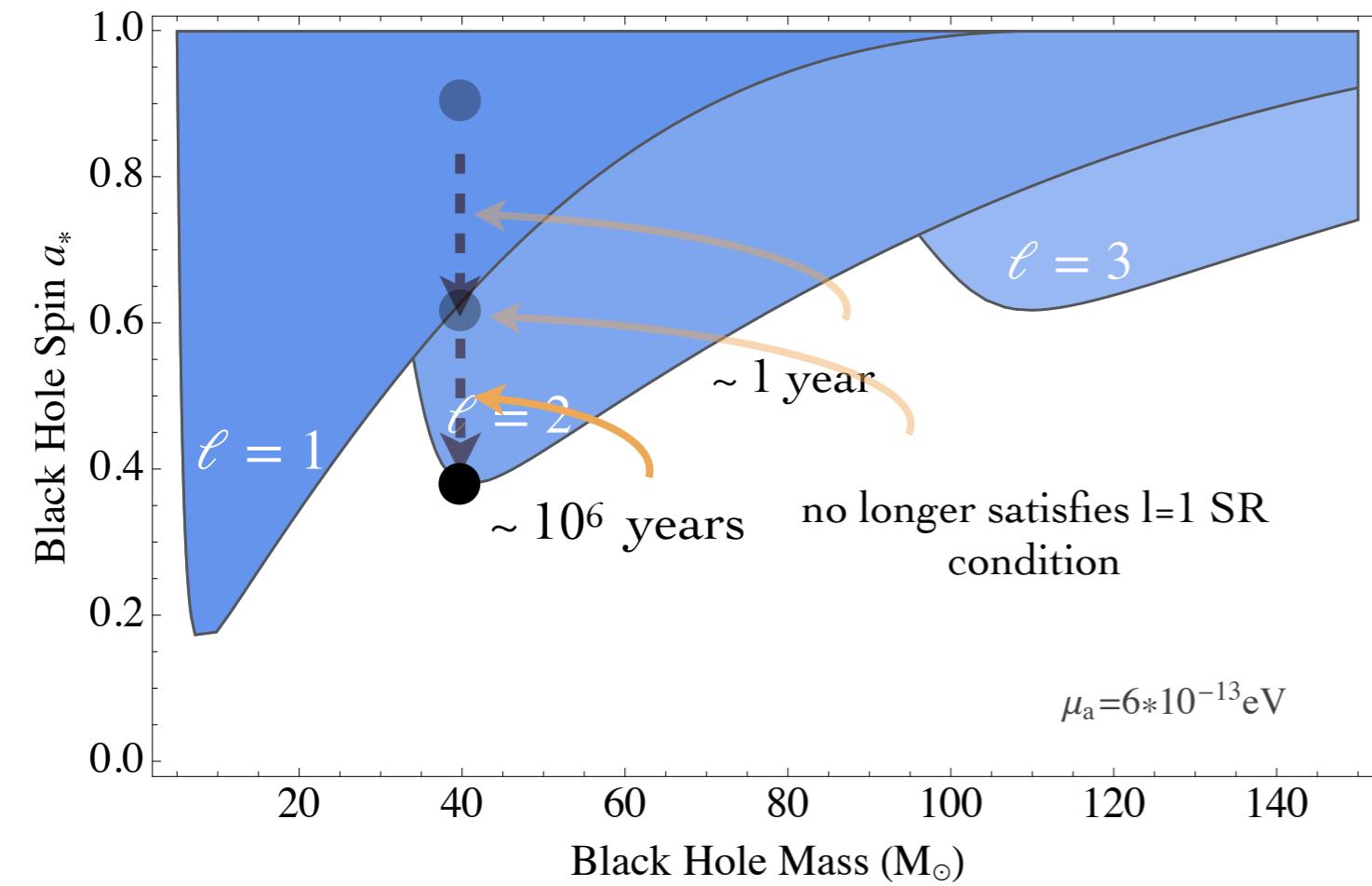
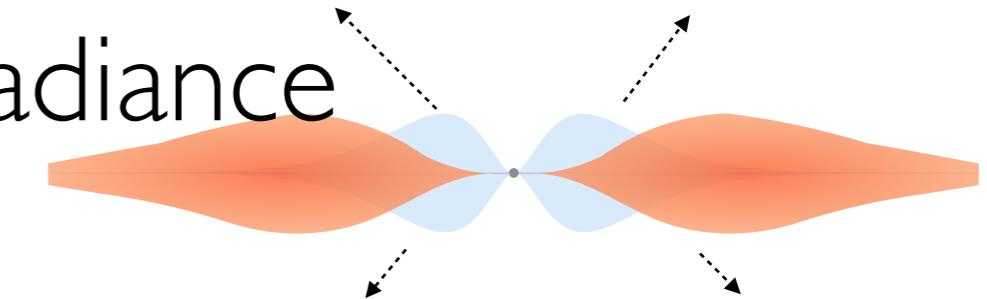
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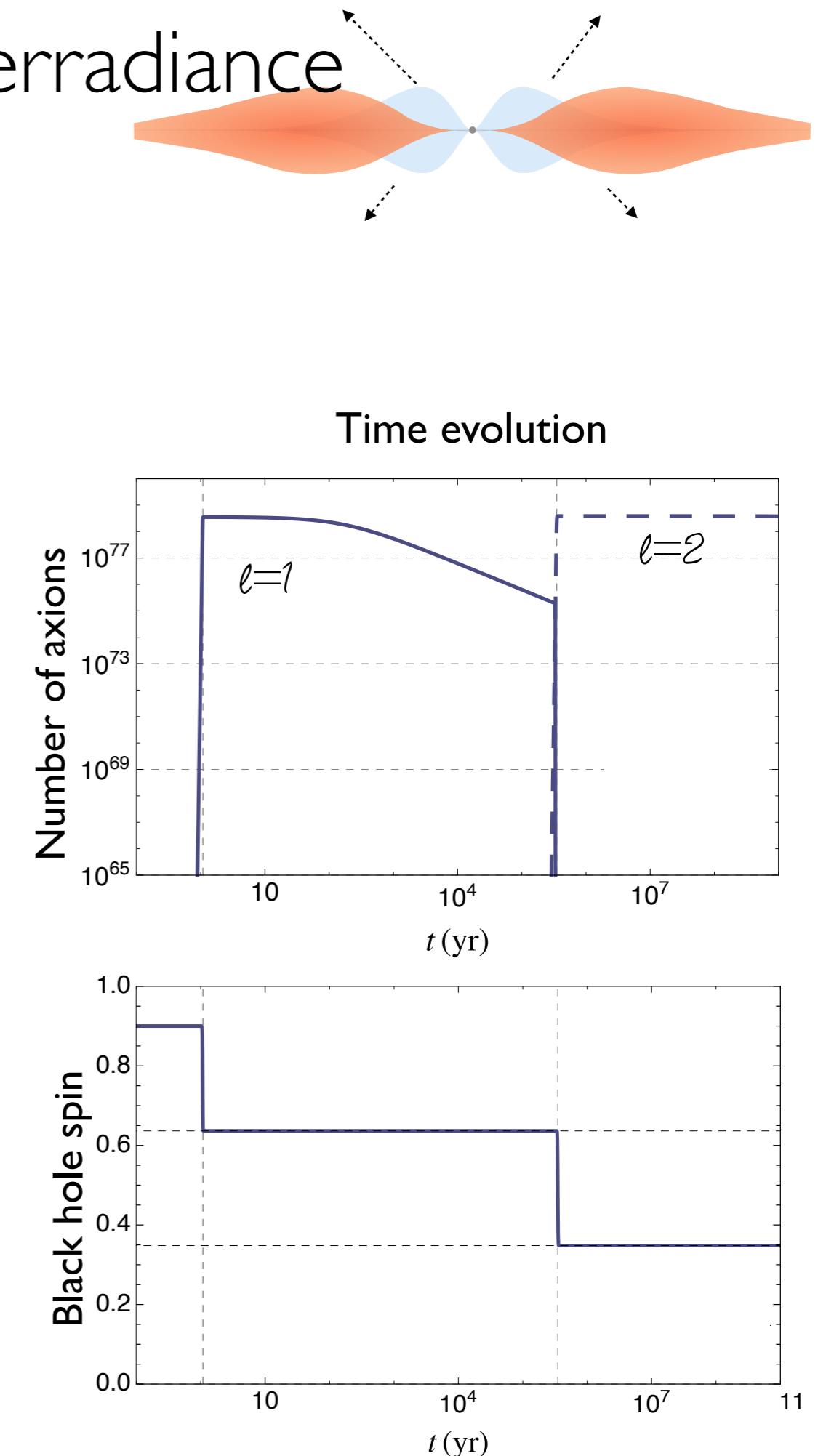
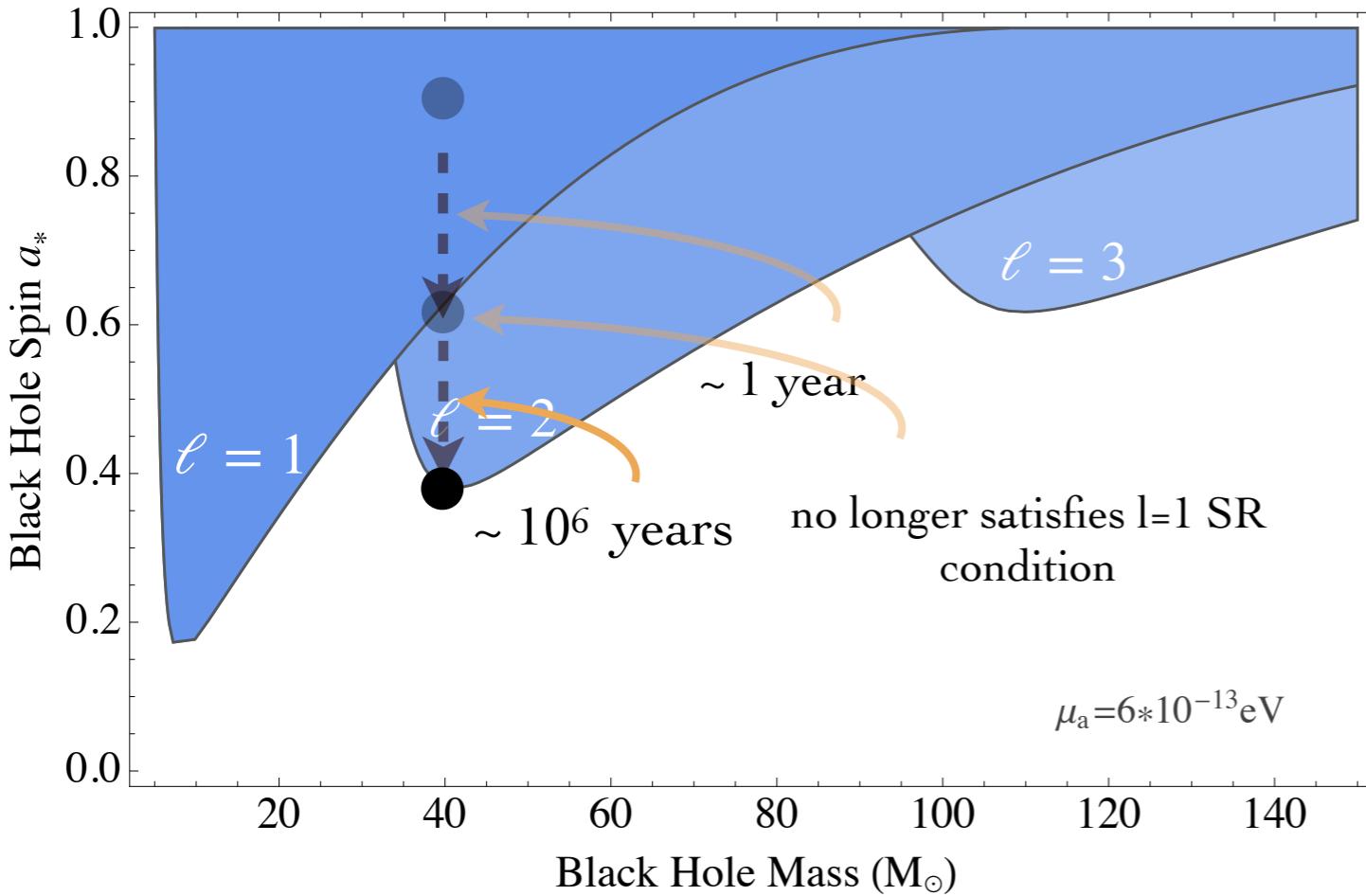


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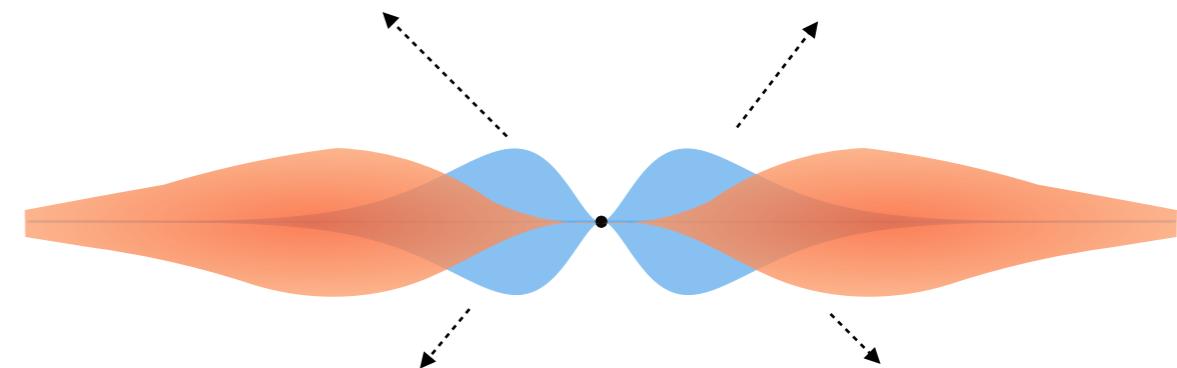
Gravitational Superradiance

- 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



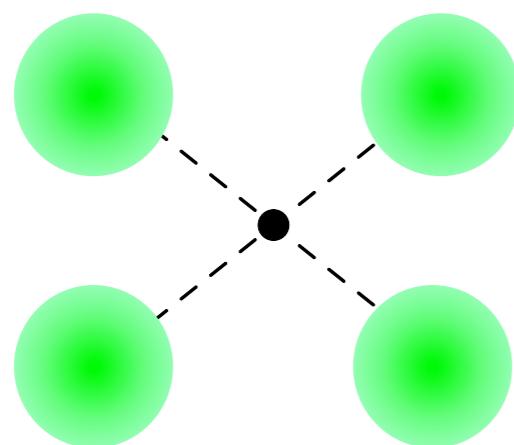
Self-Interactions

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



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

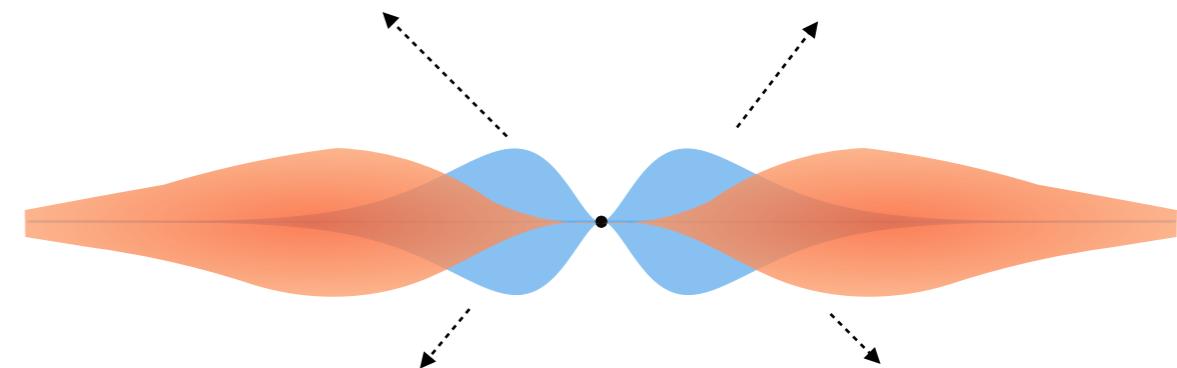
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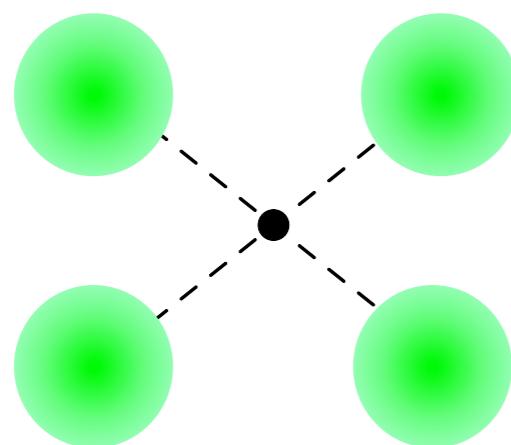
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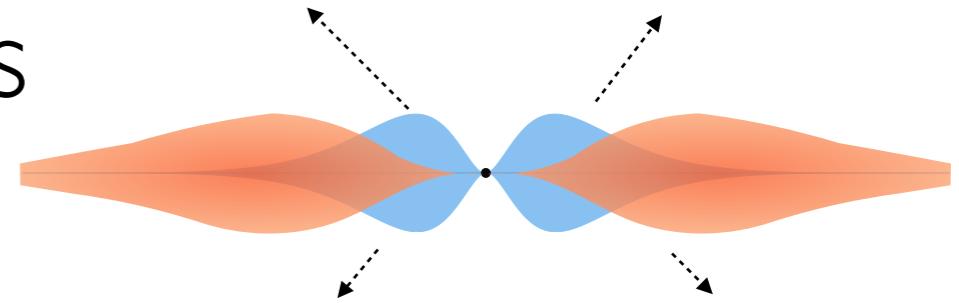


Arvanitaki, Dubovsky 2011

A. Gruzinov, 1604.06422

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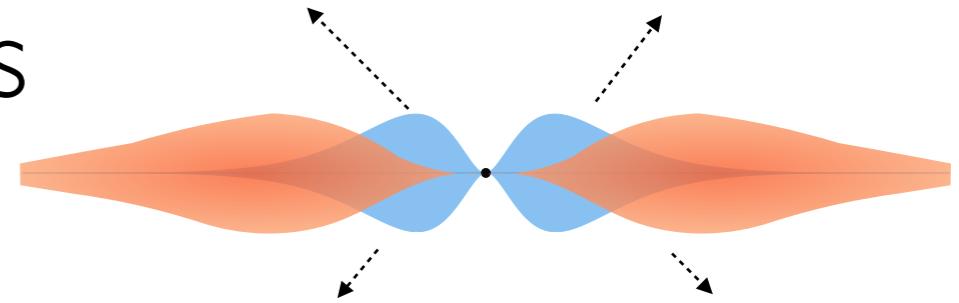


Larger self-interactions:

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

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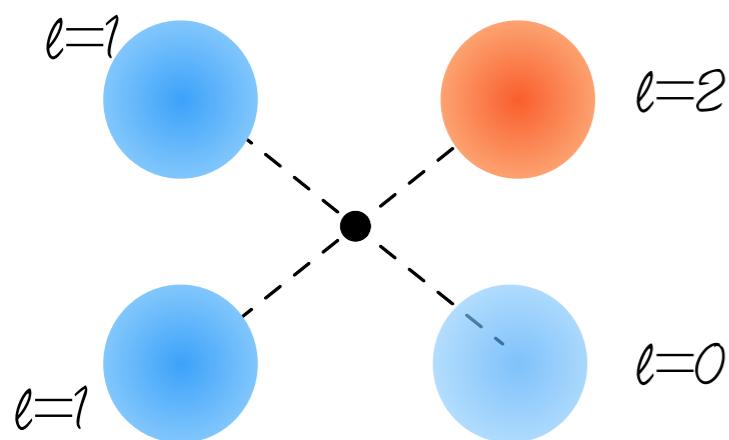
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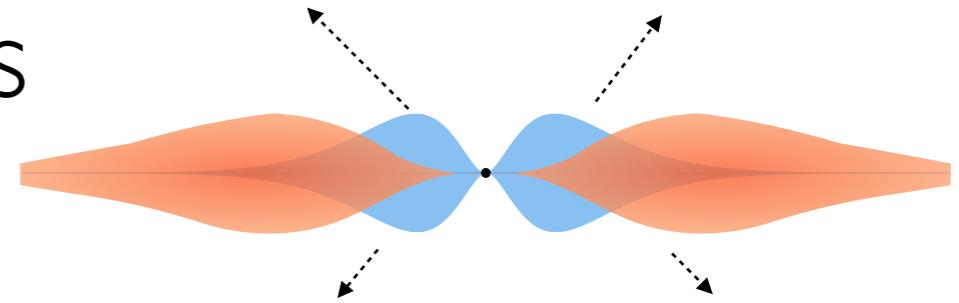
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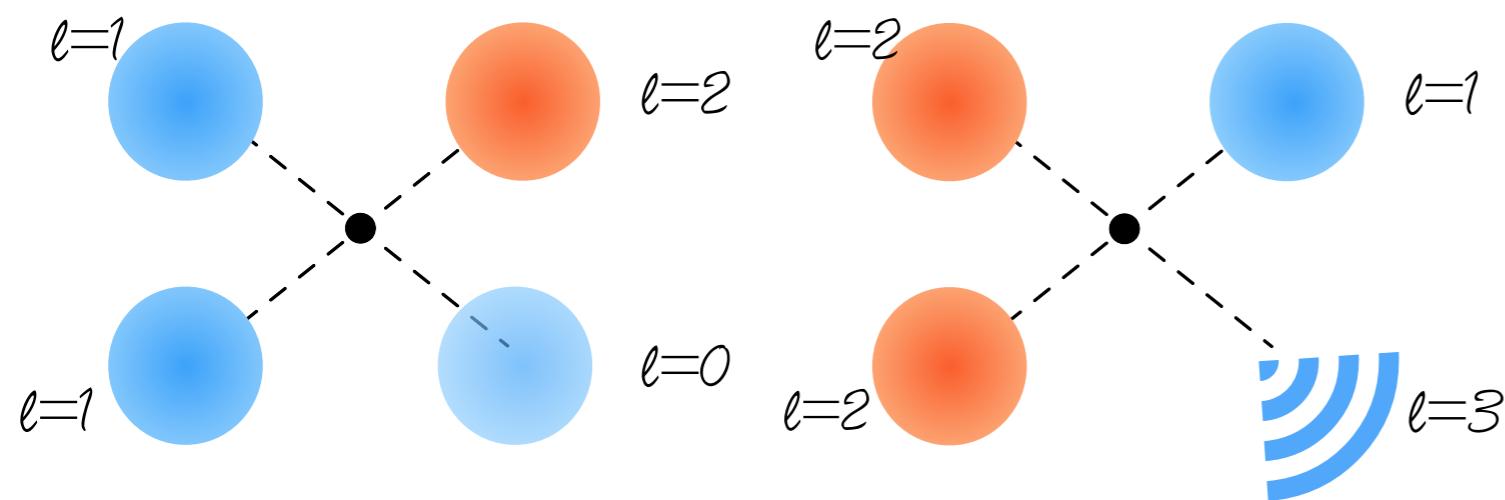
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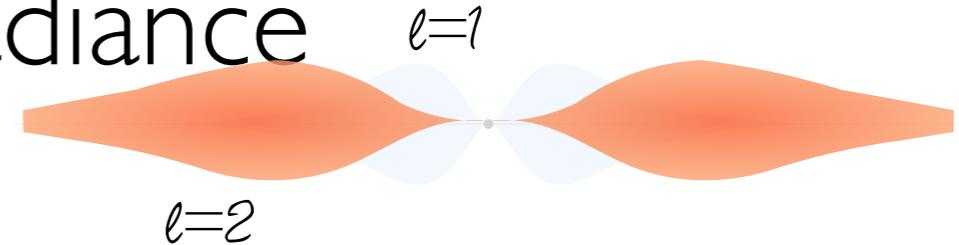
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- Non-relativistic axion waves carry energy to infinity



A. Gruzinov, 1604.06422

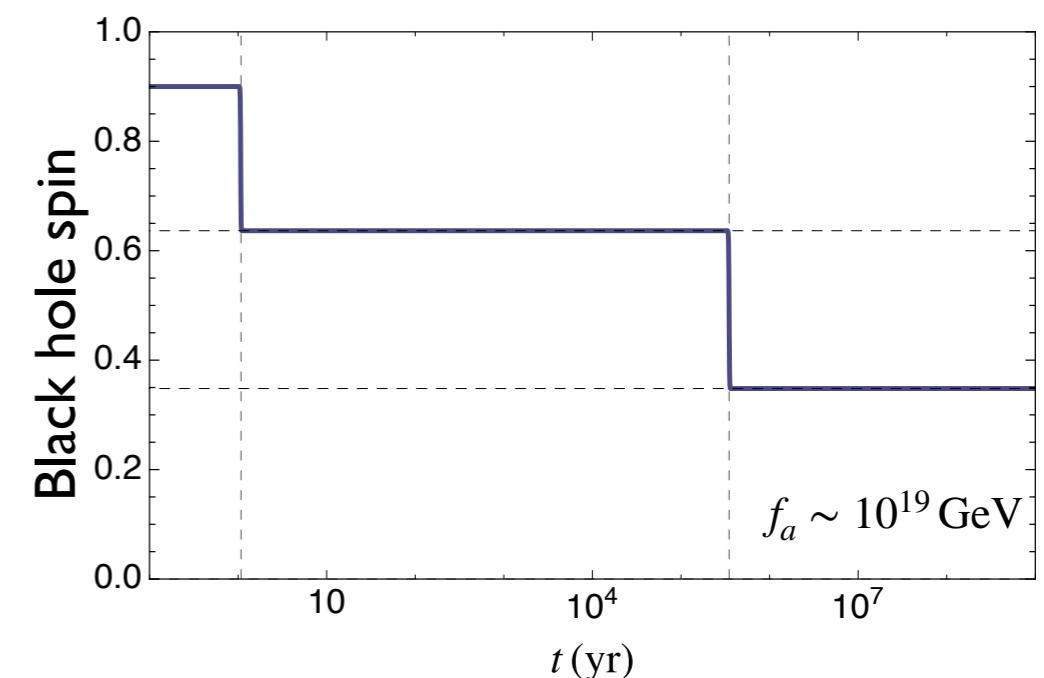
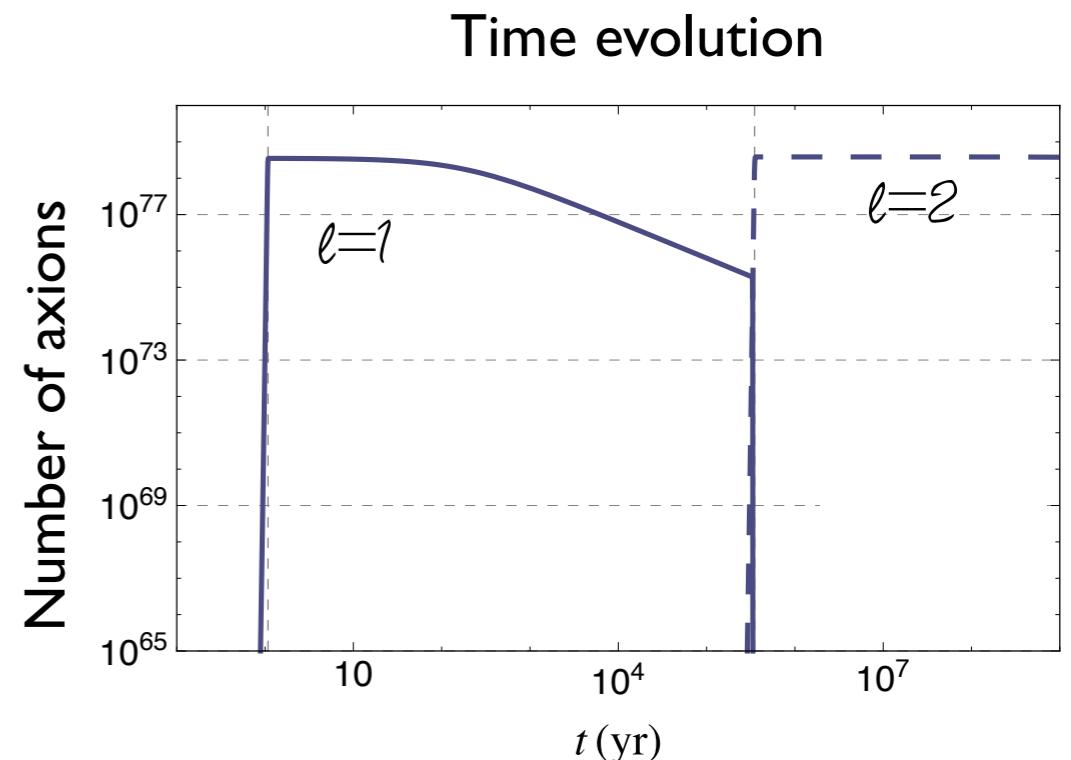
Gravitational Superradiance



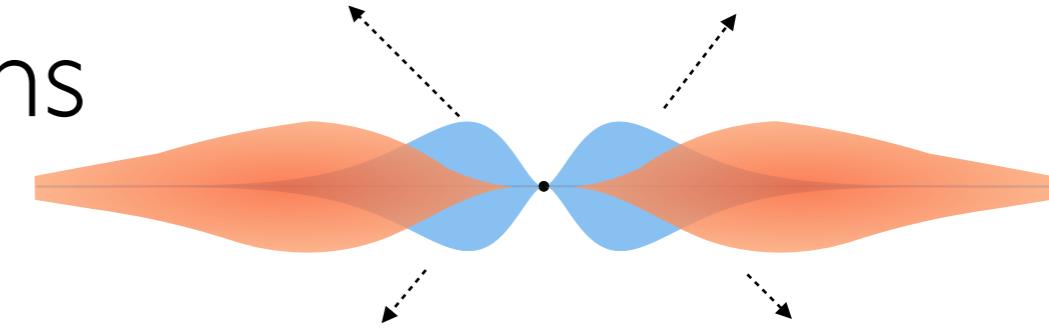
Gravitational self-interactions $f_a \sim M_{\text{Pl}}$

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

- One bound state at a time
- Gravitational radiation



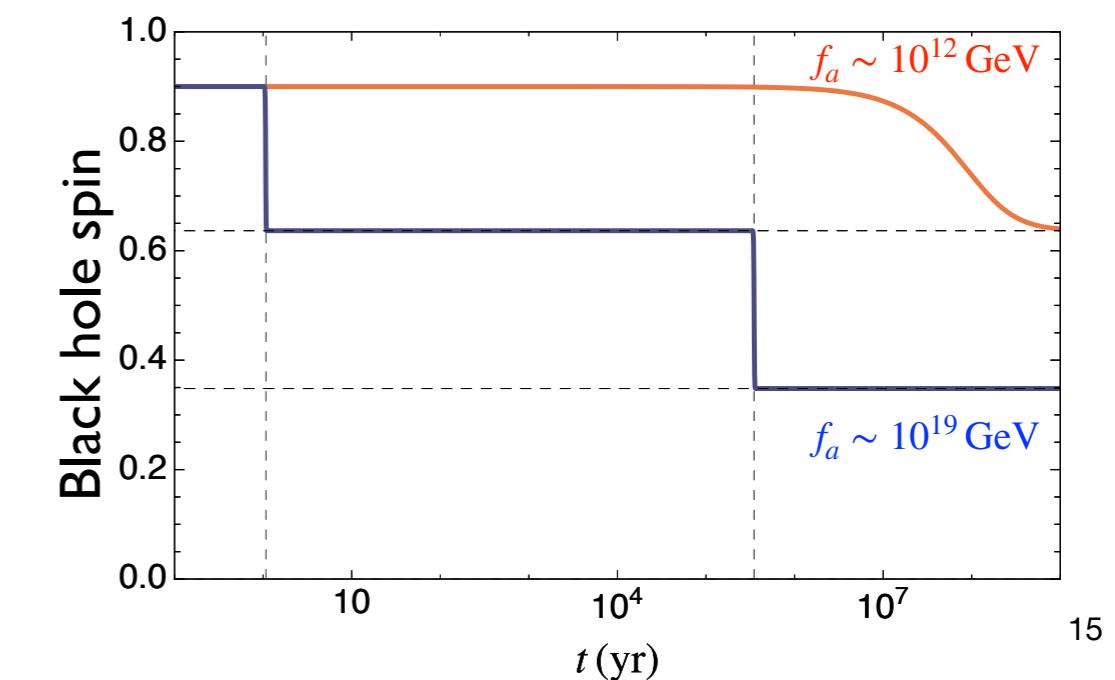
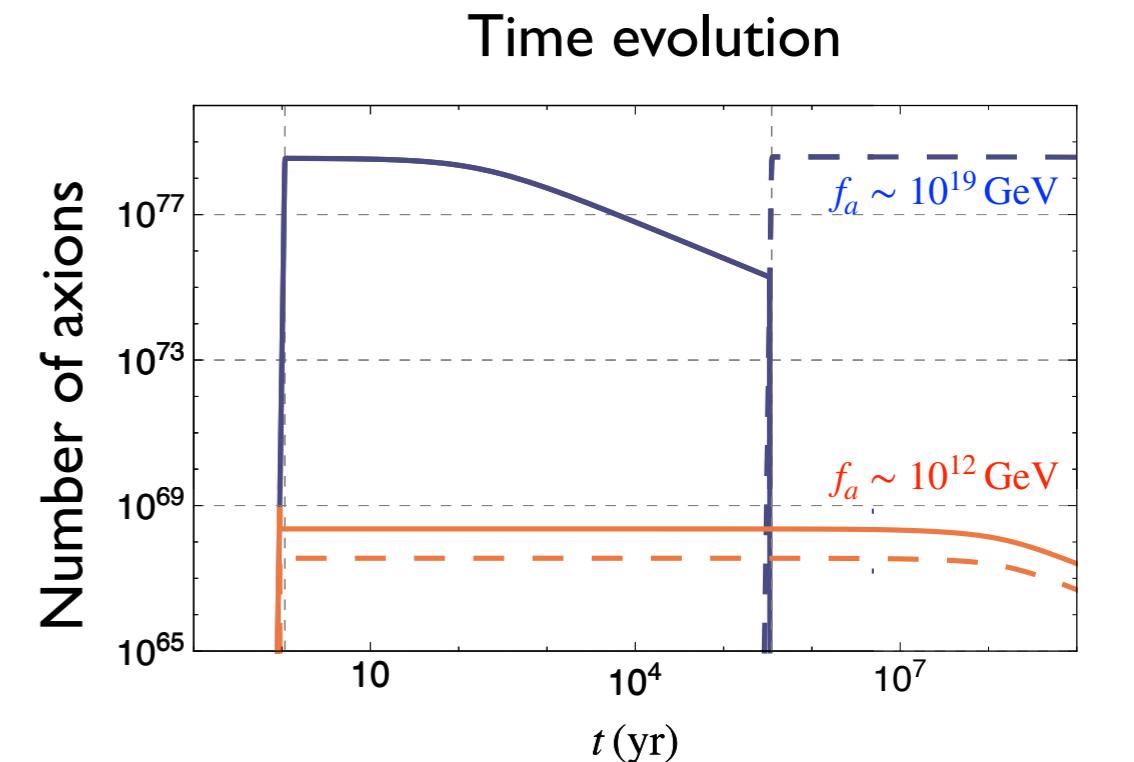
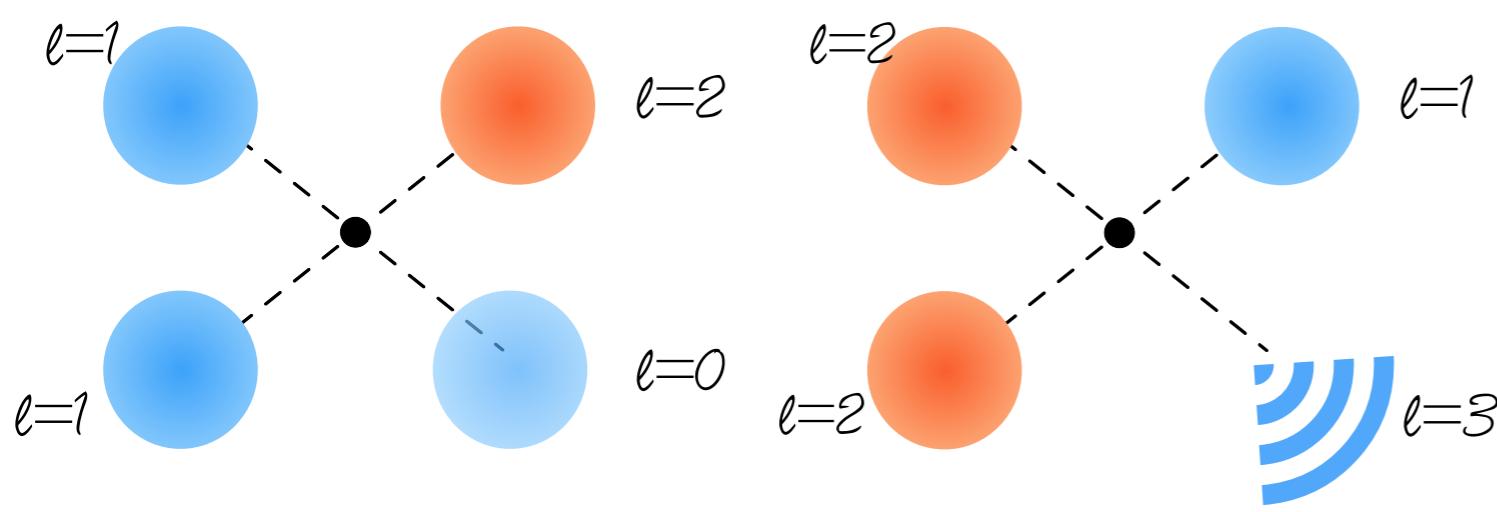
Self-Interactions



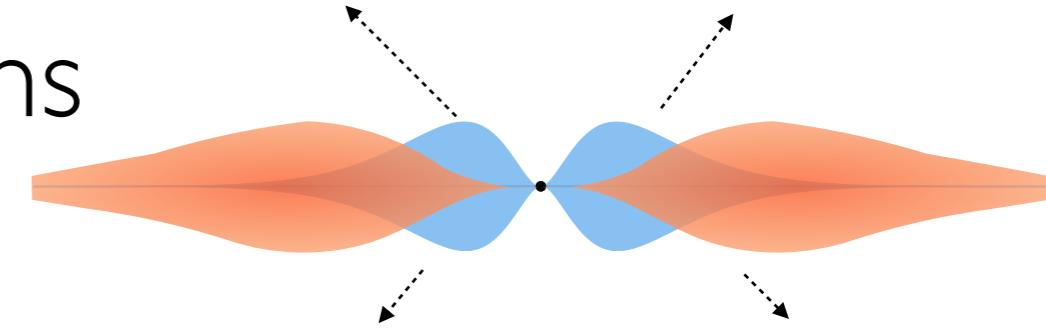
Larger self-interactions: $f_a \sim 10^{12} \text{ GeV}$

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

- Two levels populated simultaneously
- Axion radiation



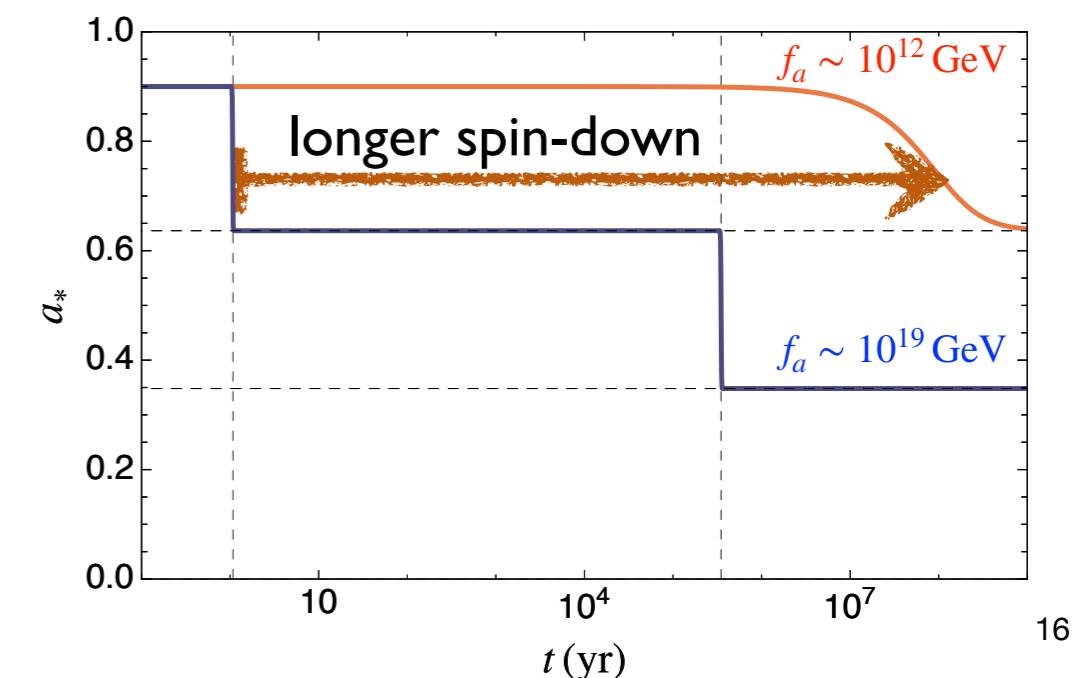
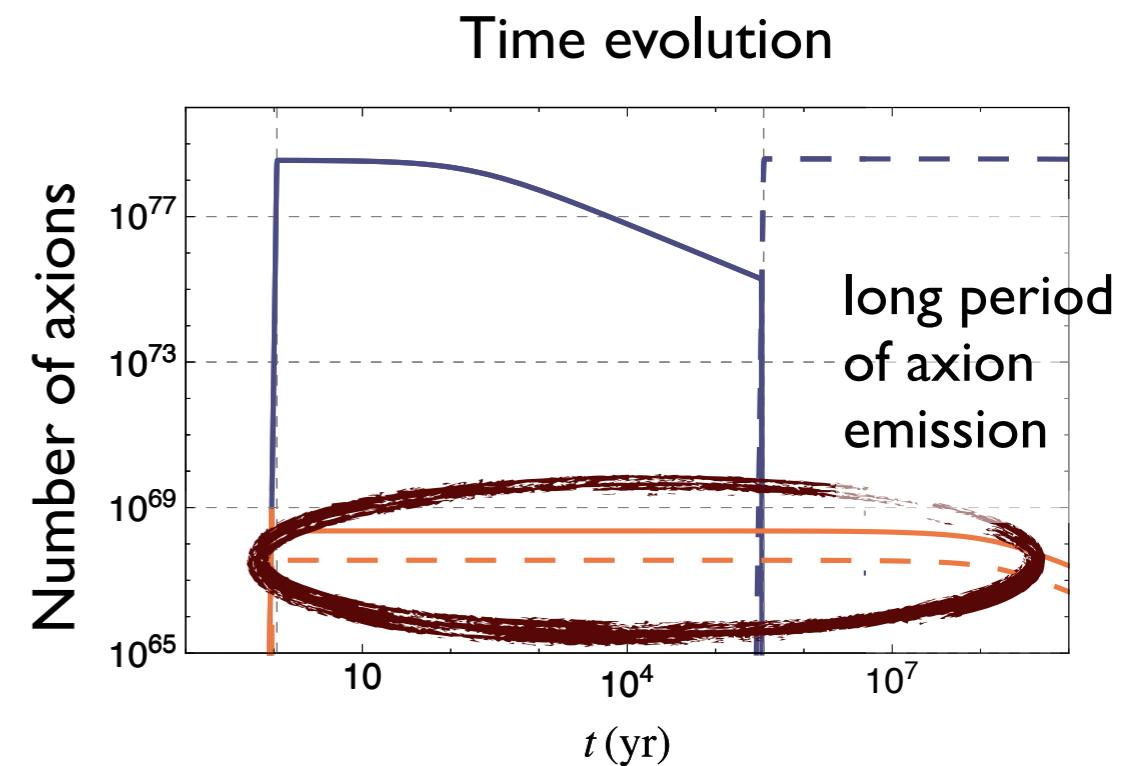
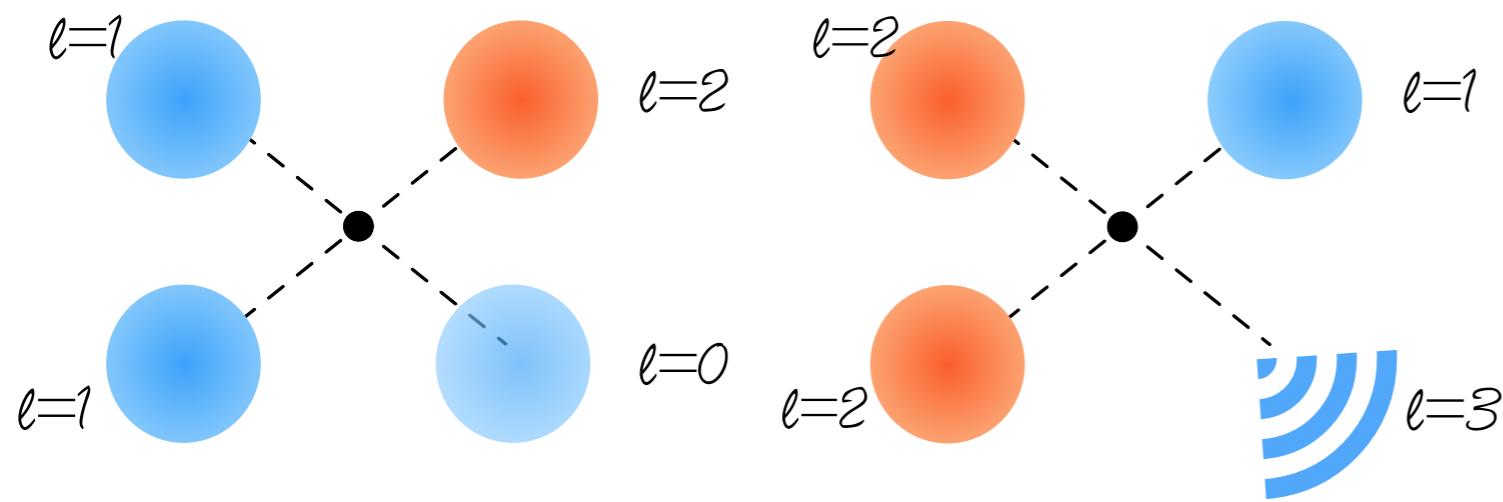
Self-Interactions



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

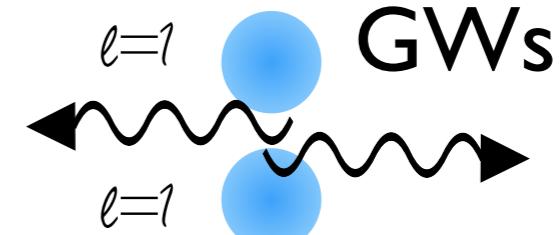
M. Baryakhtar, MG, R. Lasenby, O. Simon 2021

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

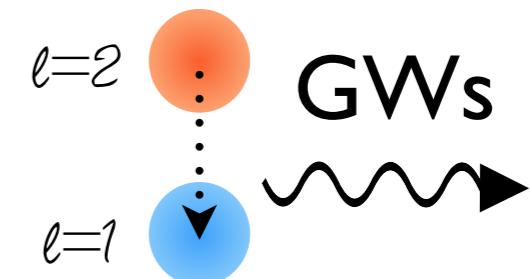


Signatures

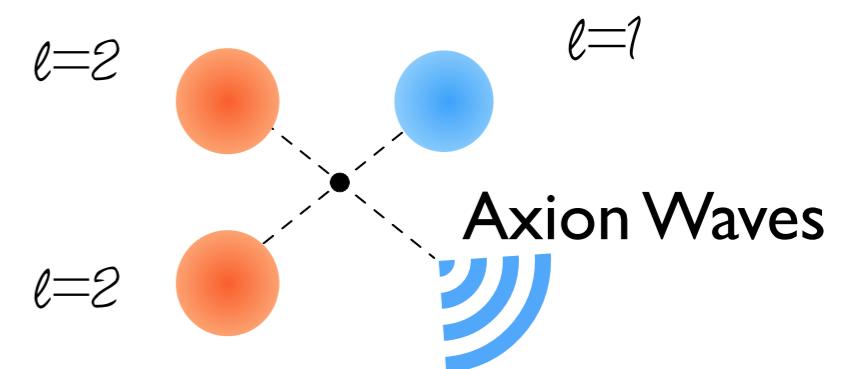
- Gravitational Waves from Annihilations



- Gravitational Waves from Transitions



- Axion Waves

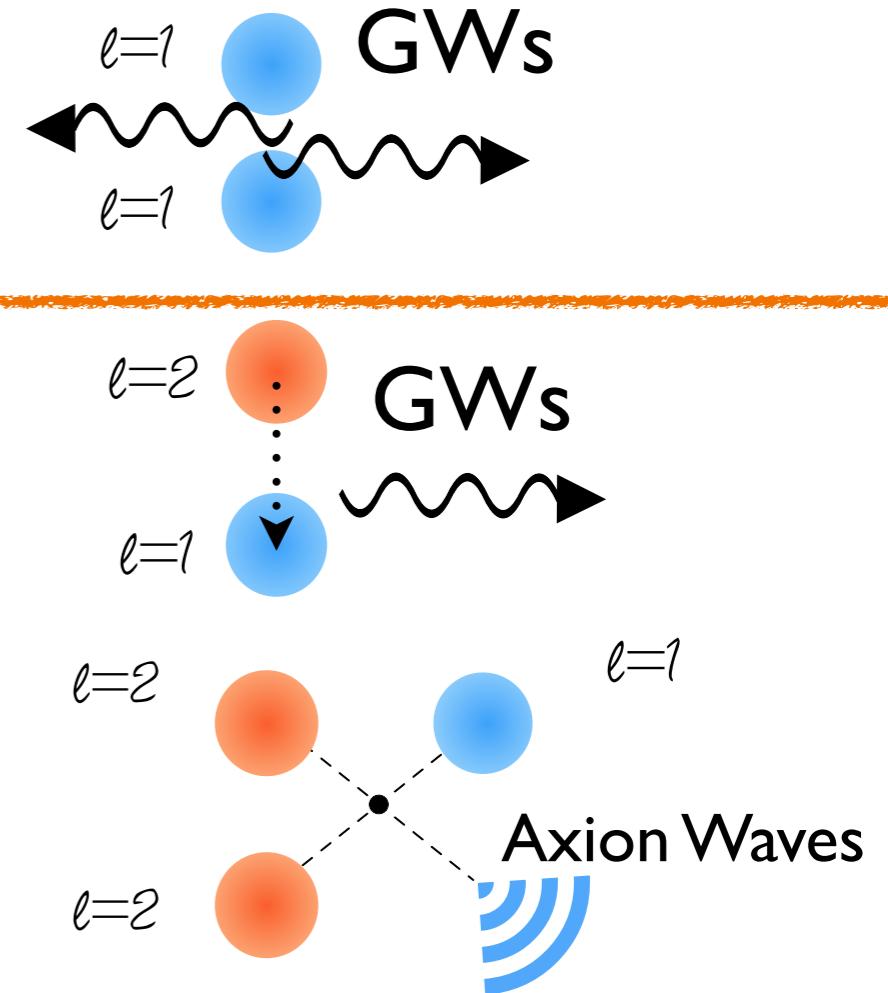


Constraints

- Black Hole Spindown

Signatures

- Gravitational Waves from Annihilations



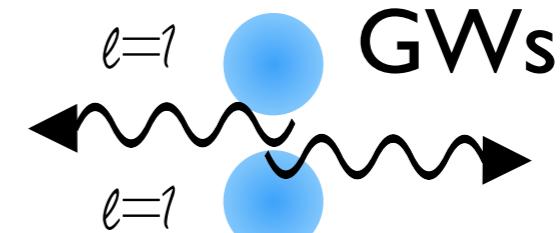
- Axion Waves

Constraints

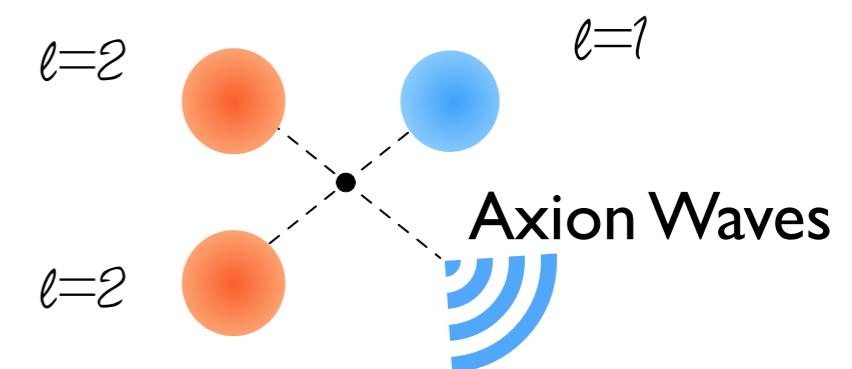
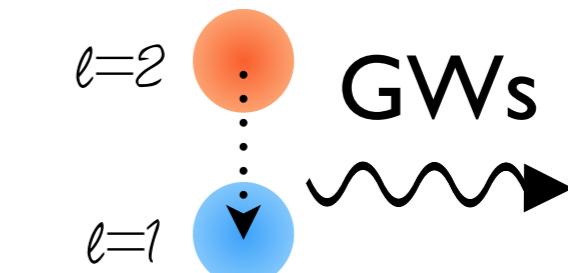
- Black Hole Spindown

Signatures

- Gravitational Waves from Annihilations



- Gravitational Waves from Transitions
- Axion Waves

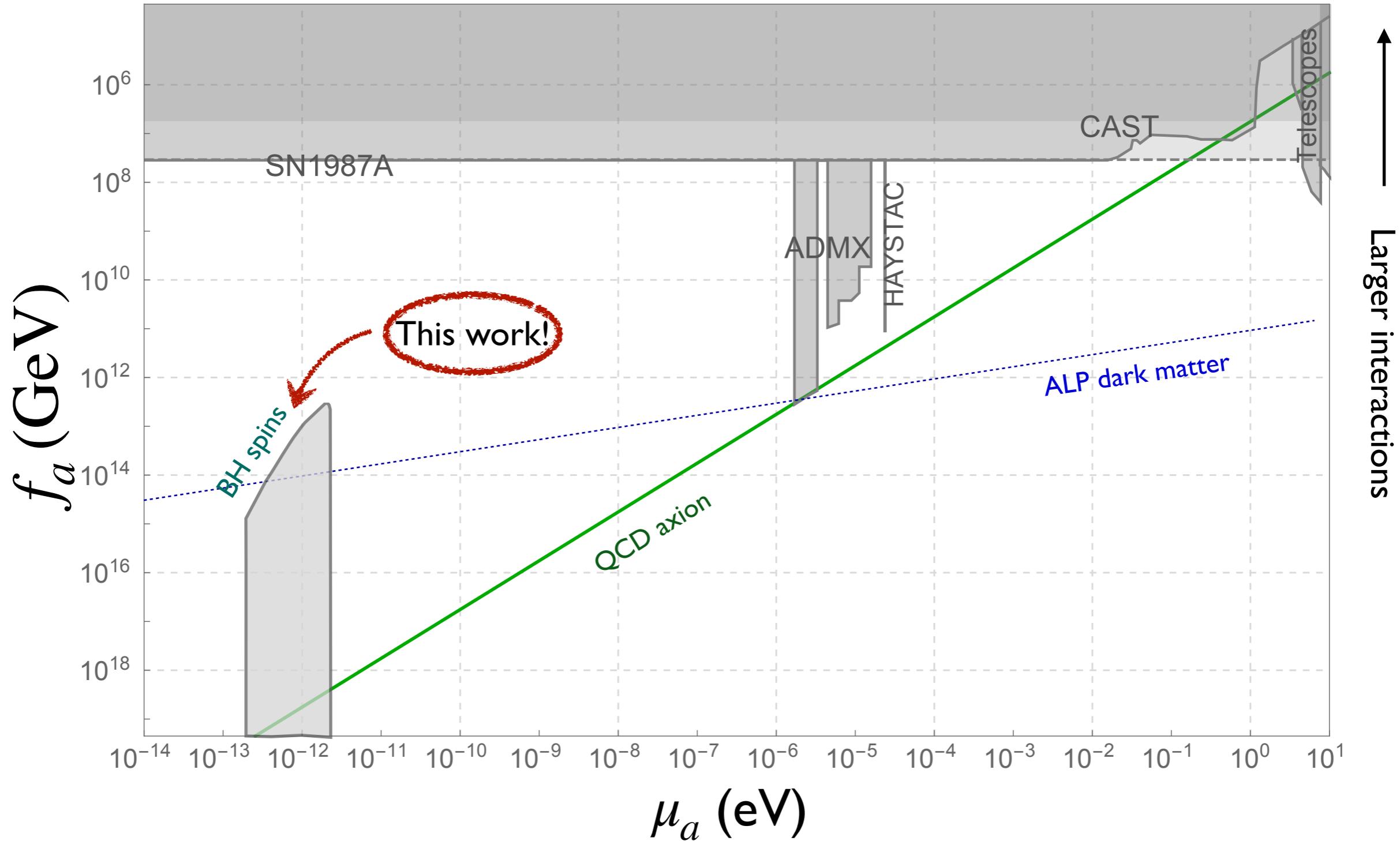


Constraints

- Black Hole Spindown

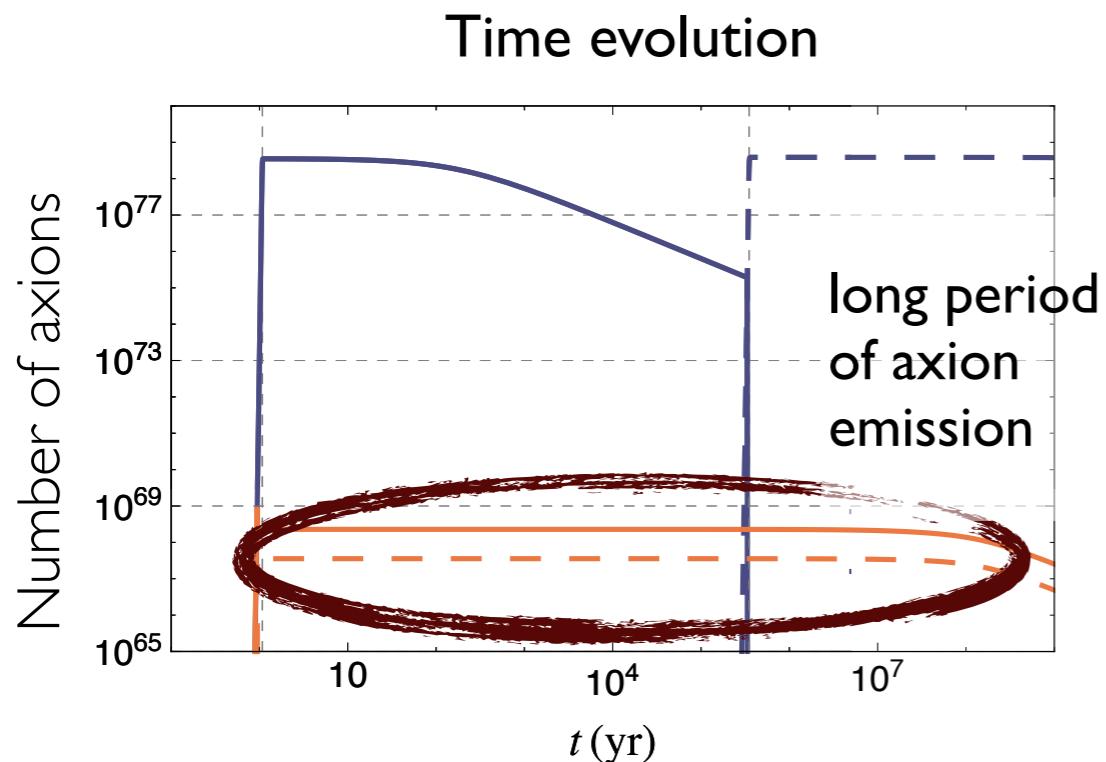
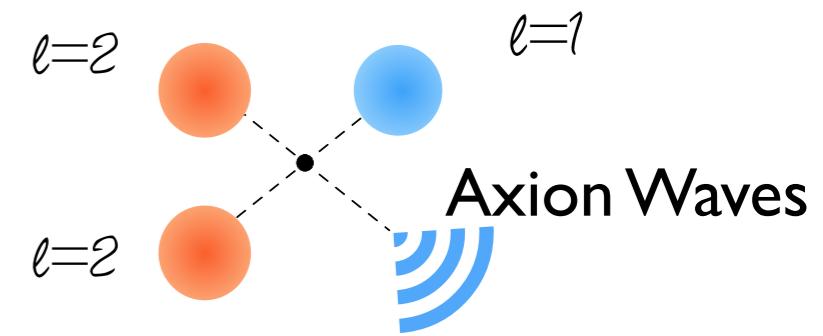
Axion Parameter Space

Our Result



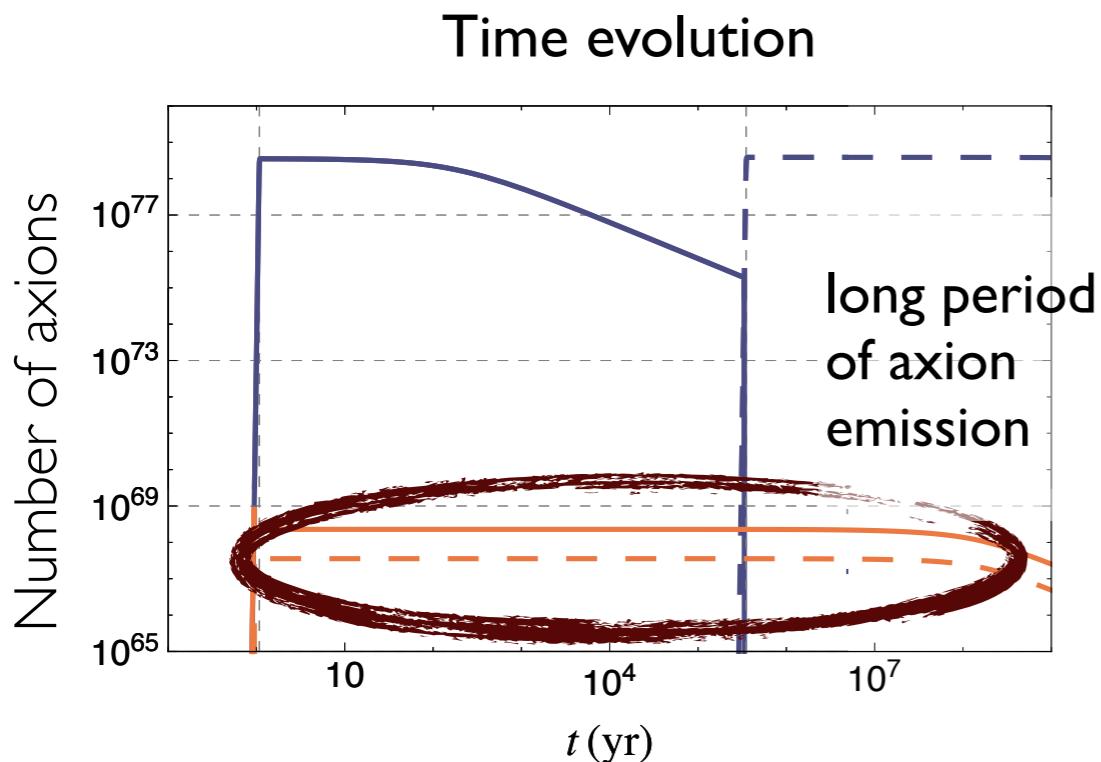
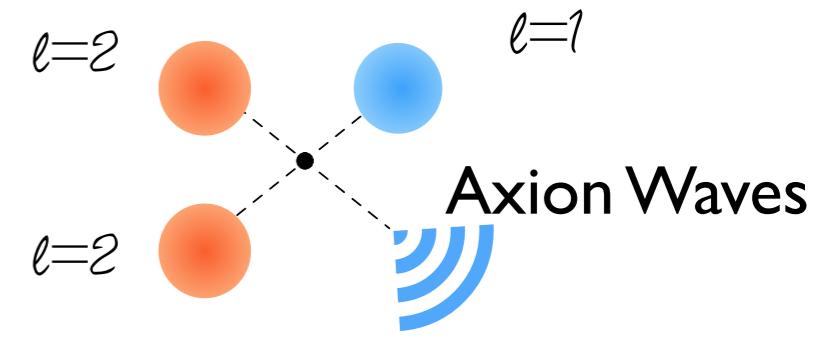
Axion Wave Emission

- Black Hole spins down slowly, emitting axion waves



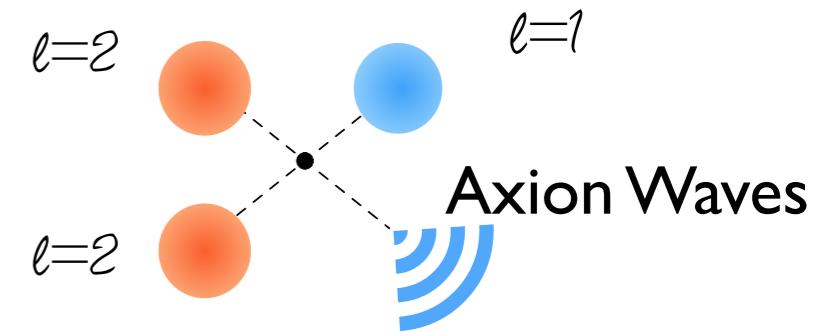
Axion Wave Emission

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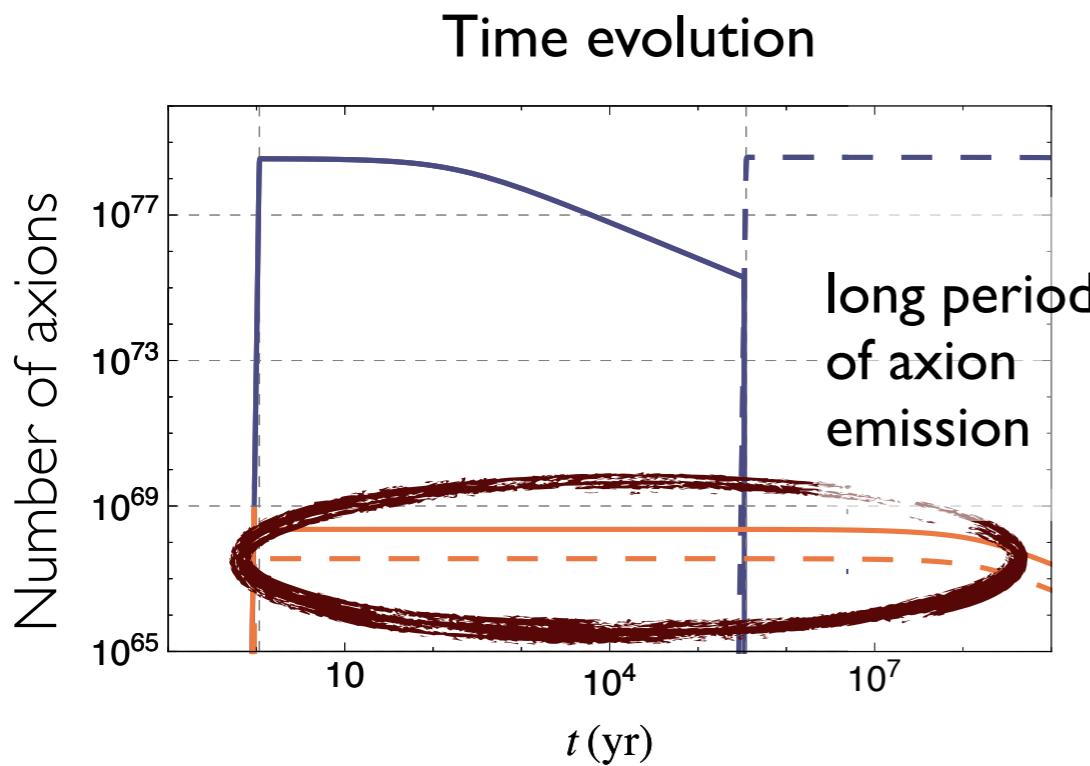


- Directly detectable if coupled to the SM

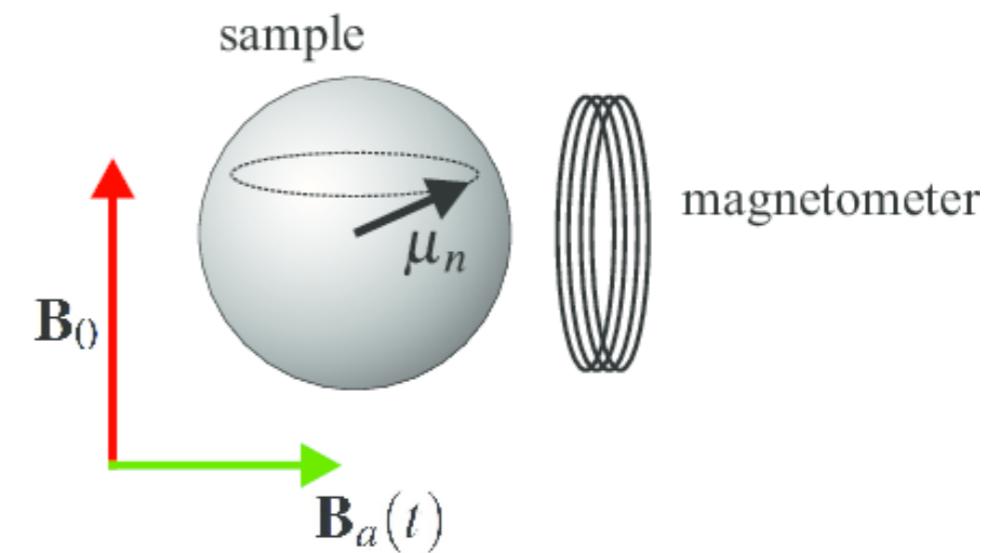
Axion Wave Emission



- Black Hole spins down slowly, emitting axion waves
- Axion field gradient acts like a magnetic field on particle spins



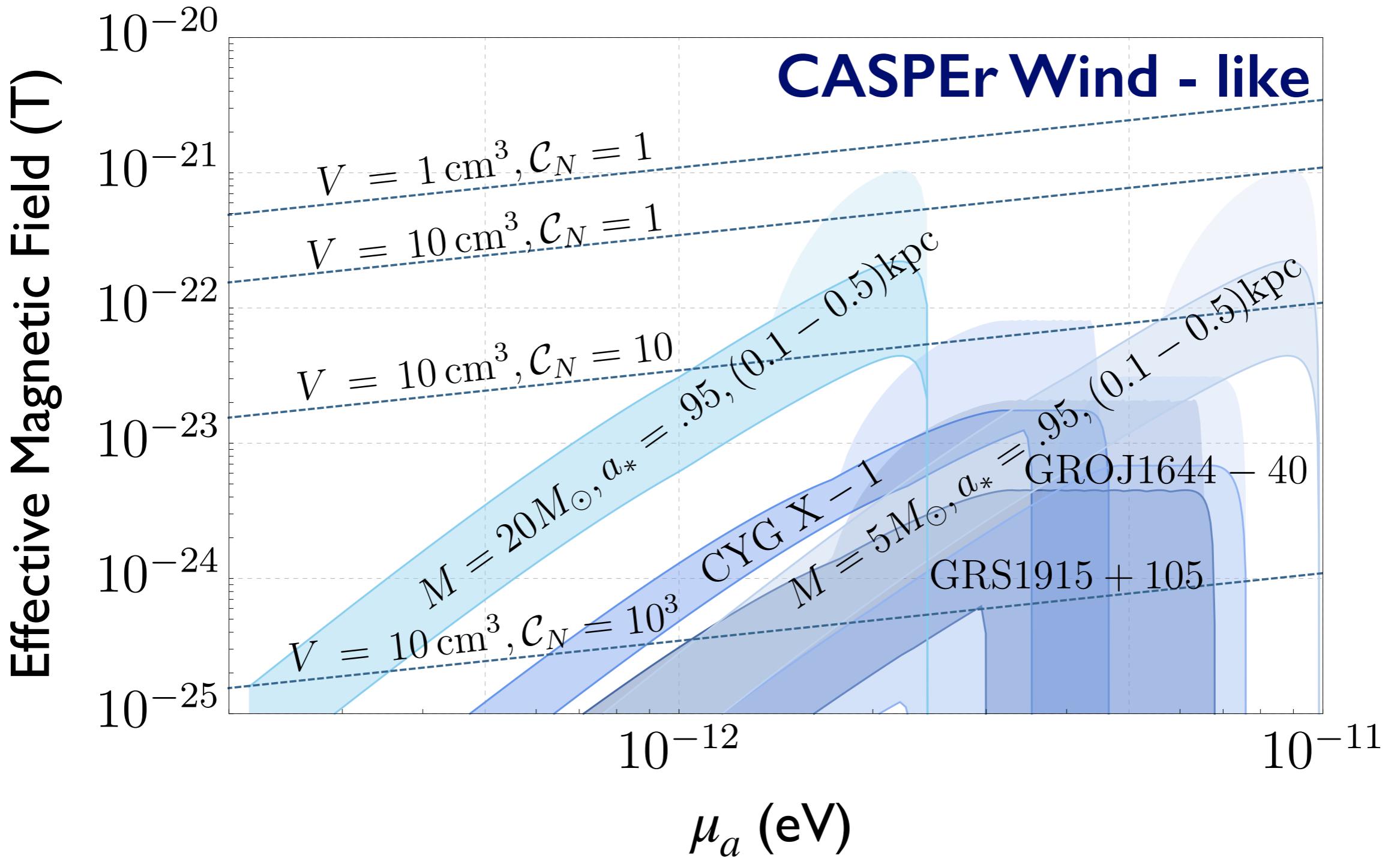
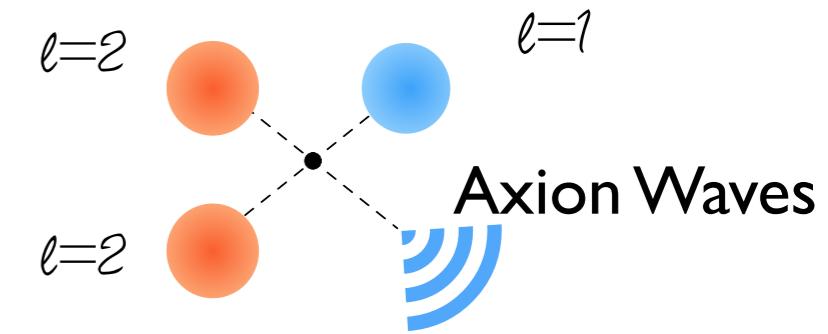
$$H_n \supset C \frac{\nabla a}{f_a} \cdot \vec{\sigma}_N$$



- Directly detectable if coupled to the SM

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

Axion Wave Emission

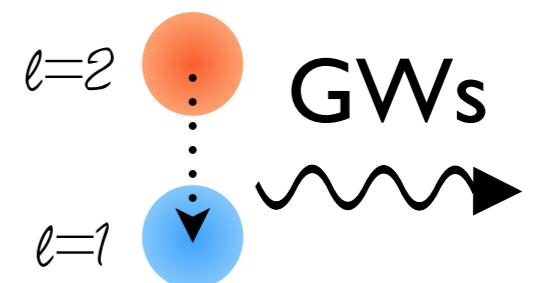


Conclusions

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

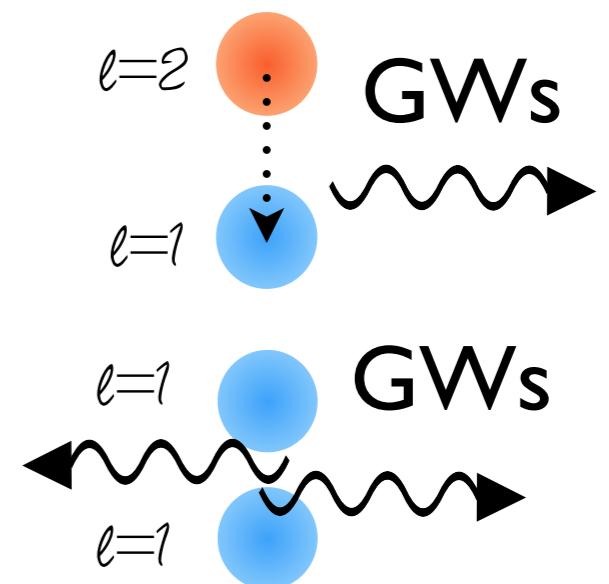
Conclusions

- Self-Interactions **dramatically affect** the evolution of the cloud
- Novel **GW transition signatures**: can be probed by **aLIGO + future observatories**



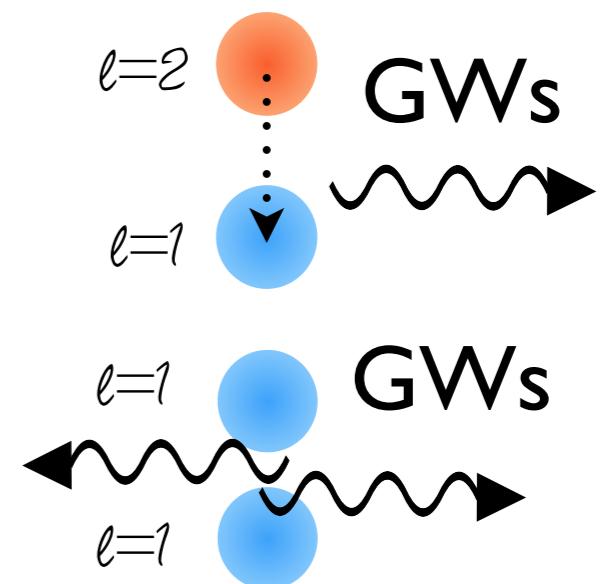
Conclusions

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- Novel **GW transition signatures**: can be probed by **aLIGO + future observatories**
- **GW annihilation signatures** are suppressed but still observable by **aLIGO**



Conclusions

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

