Dark Interactions: New perspectives
for theory and experiment

Bounds on ultralight bosons from the Event Horizon Telescope observation of Sgr A*

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Based on arXiv:2208.03530
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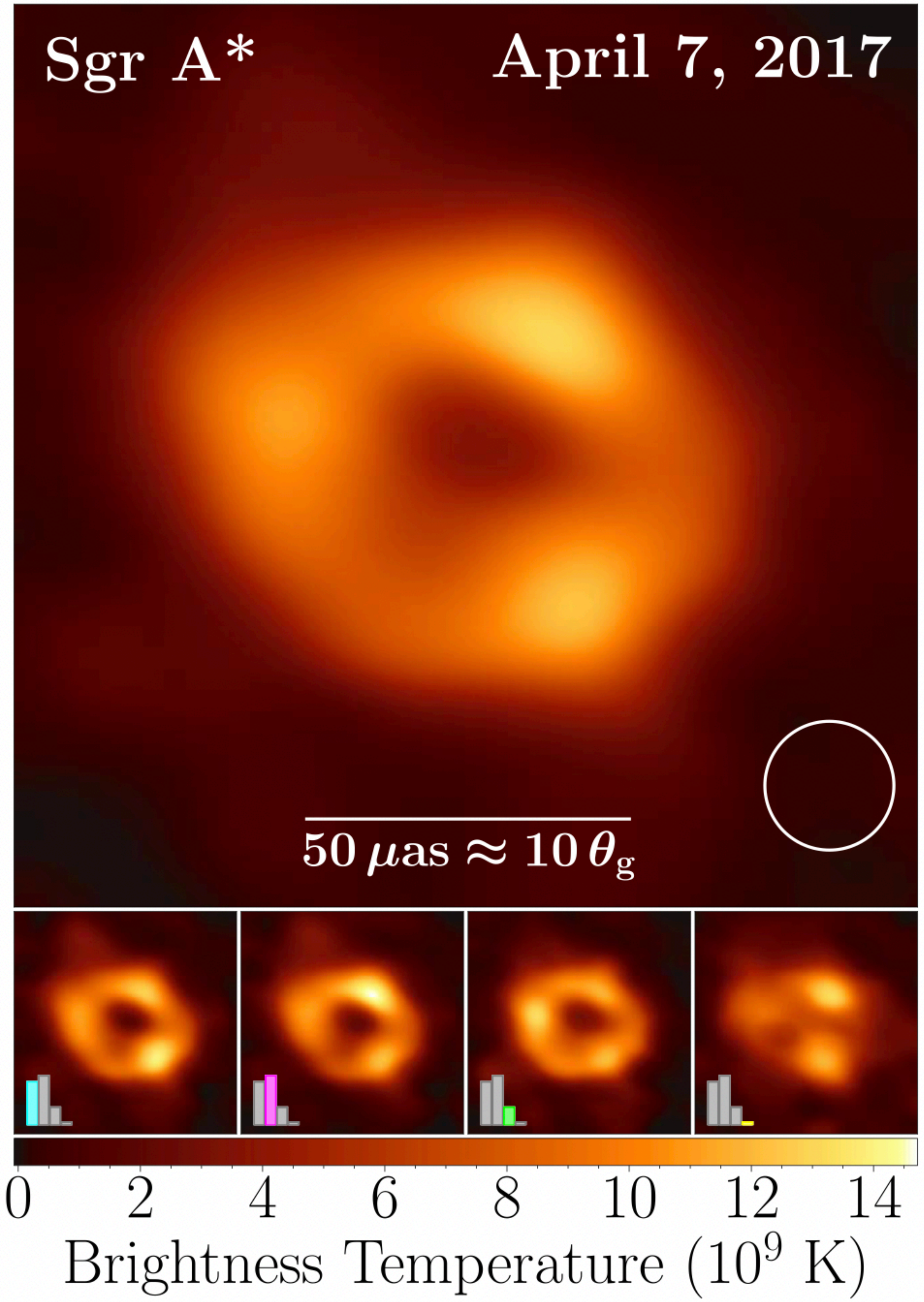
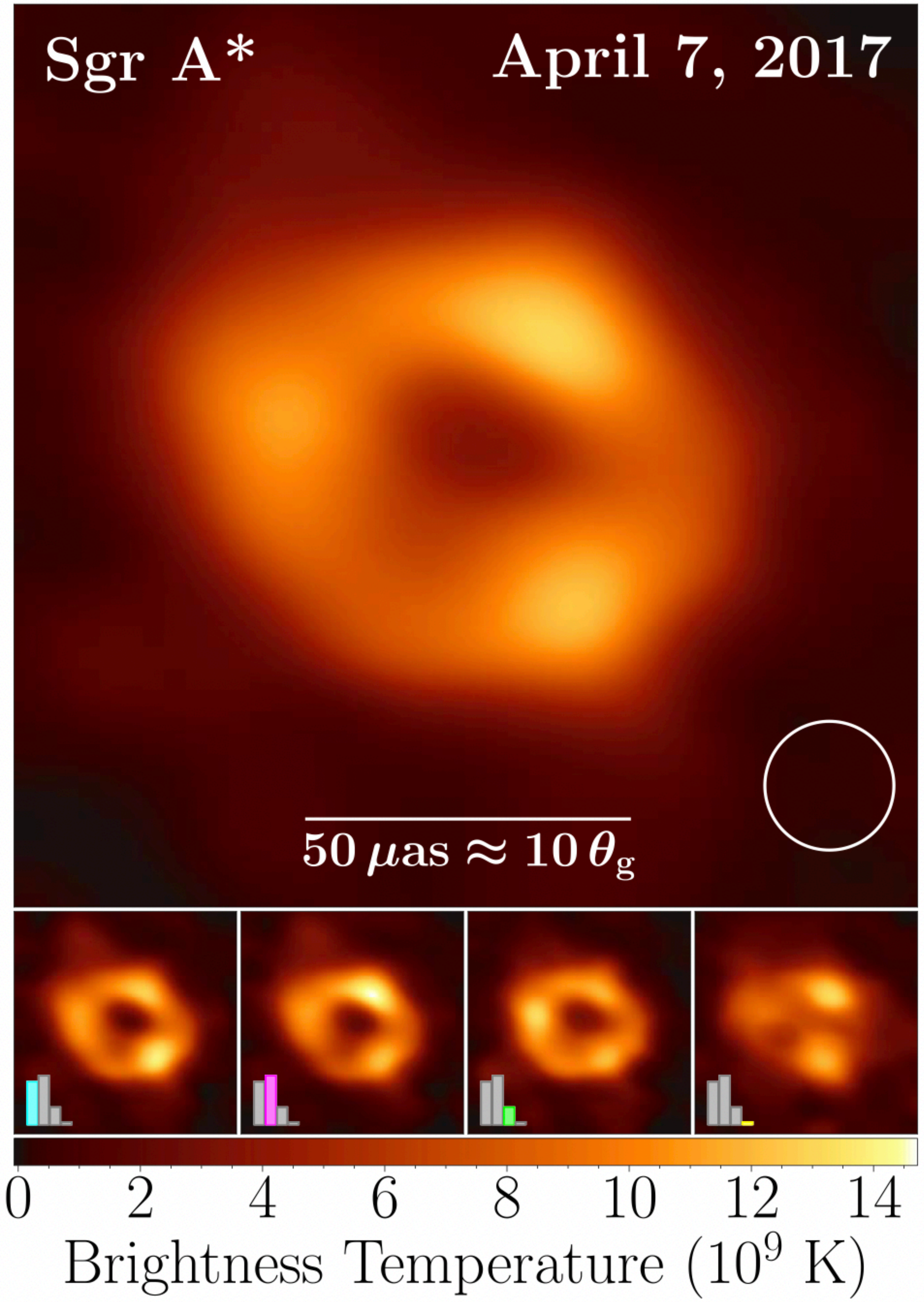
Event Horizon Telescope Observations



- Event Horizon Telescope (EHT) : A large telescope array consisting of a global network of radio telescopes.
- Revealed the first direct image of a black hole (M87*) in 2019.
- Recently, revealed the image of Sagittarius A* (Sgr A*), a supermassive black hole at the center of the Milky Way galaxy.

Pic Credit: Event Horizon Telescope Collaboration ApJL 930 L12 (2022)

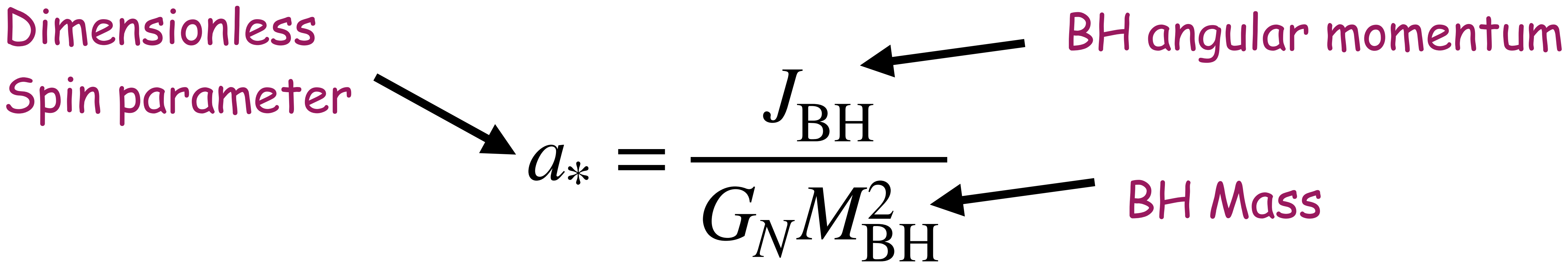
Event Horizon Telescope Observations



- Mass $M = 4.0^{+1.1}_{-0.6} \times 10^6 M_\odot$

Agrees with the mass measurements by other observations.

- EHT can infer the spin of the BHs.



Dimensionless Spin parameter

BH angular momentum

BH Mass

$$a_* = \frac{J_{\rm BH}}{G_N M_{\rm BH}^2}$$

- $a_* = 0.5$ and $a_* = 0.94$ passed all the EHT tests for Sgr A*.

Pic Credit: Event Horizon Telescope Collaboration ApJL 930 L12 (2022)

What can we learn about particle physics using Sgr A*?

- Rotating black holes can source clouds of light bosonic particles (masses $\lesssim 10^{-10}$ eV) around themselves through a process known as Superradiance (independent of the cosmic density of light bosonic particle).
- Superradiance can be used as a tool to search for new light particles.

M. Baryakhtar, et al. 2017 & 2021, H. Davoudiasl et al. 2019, M. J. Stott 2020, C.Unal et al. 2021, D. Baumann et al. 2022, and others

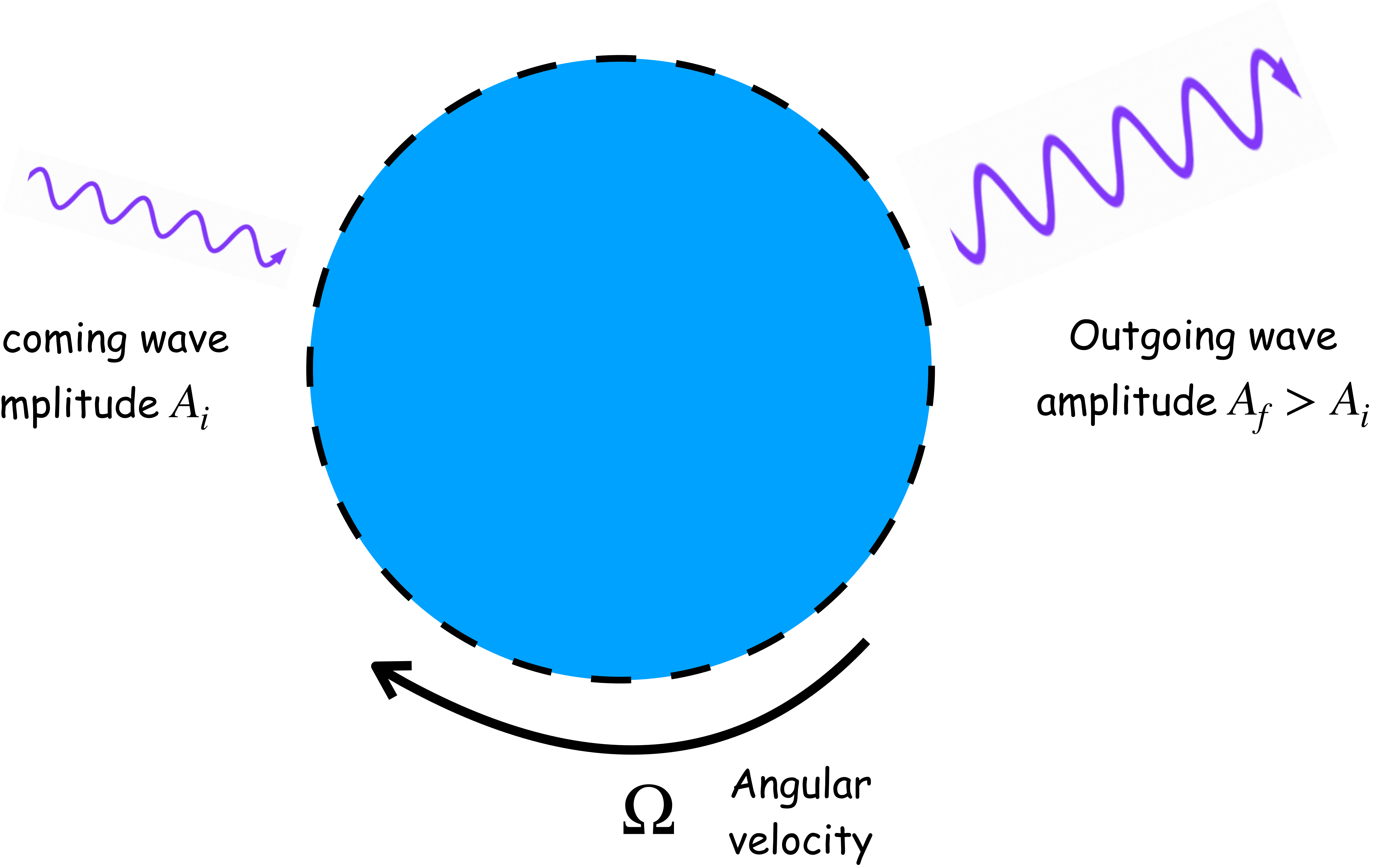
Superradiance (SR)

- Incident wave on a rotating dissipative surface will grow in amplitude by extracting energy and angular momentum if

$$\boxed{\frac{\omega}{m} < \Omega}$$

m = azimuthal angular momentum quantum number

- After scattering growth in amplitude



Incoming wave amplitude A_i

Outgoing wave amplitude $A_f > A_i$

Ω Angular velocity

Zel'dovich, 1971, Misner 1972

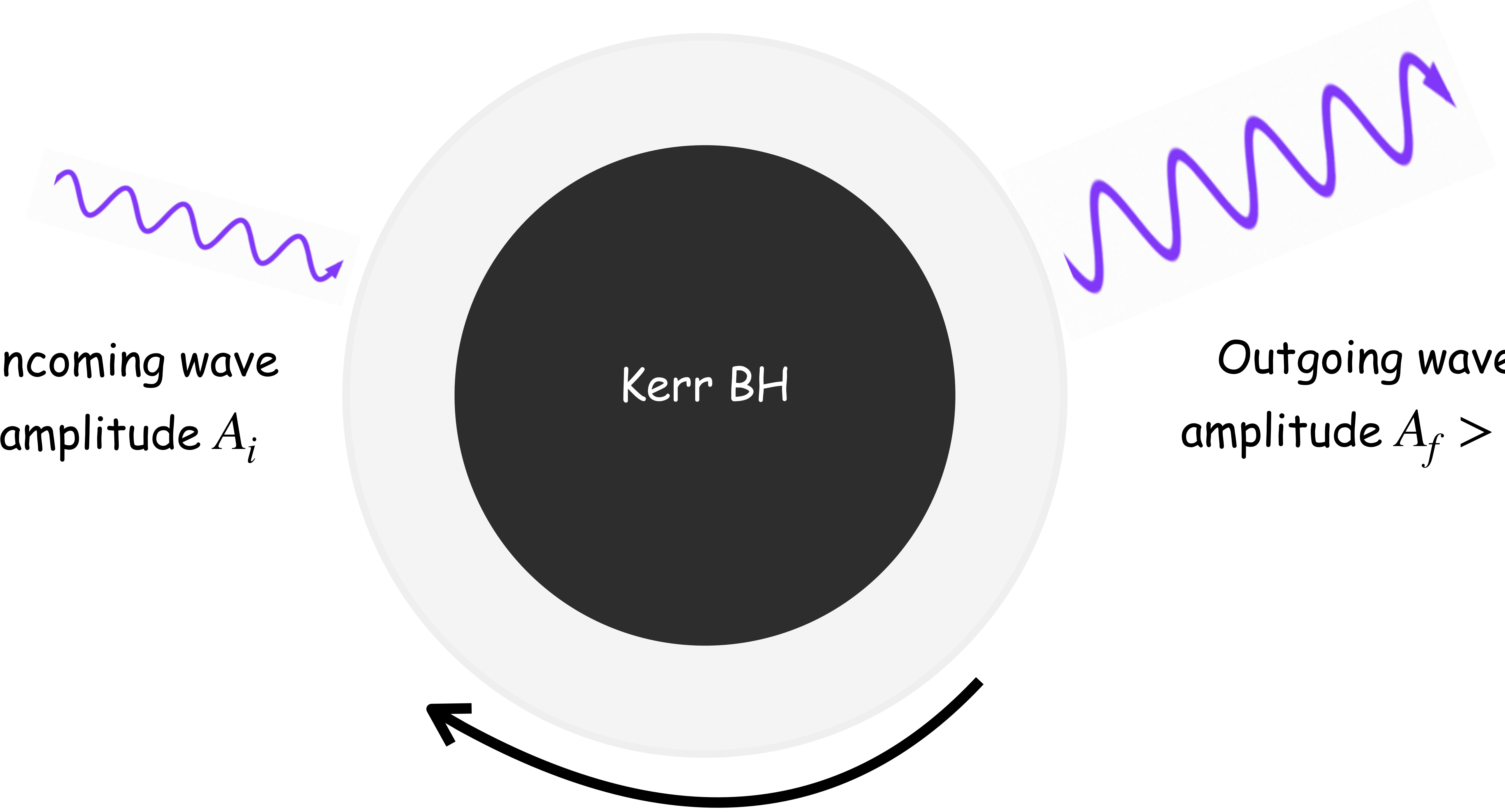
Black Hole Superradiance

- Superradiance can occur for rotating Black holes : Kerr BHs

$$\boxed{\frac{\omega}{m} < \Omega_H}$$

m = azimuthal angular momentum quantum number

- After scattering growth in amplitude



Incoming wave amplitude A_i

Kerr BH

Outgoing wave amplitude $A_f > A_i$

Ω_H Angular velocity Of BH horizon

Zeldovich, 1971; Misner 1972; Press and Teukolsky ,1972-74;

Review: Brito, Cardoso & Pani 2015

BH Superradiance for massive particle

- Motion will be confined due to gravitational potential of massive particle: A bound state around BH

- Leads to superradiant instabilities

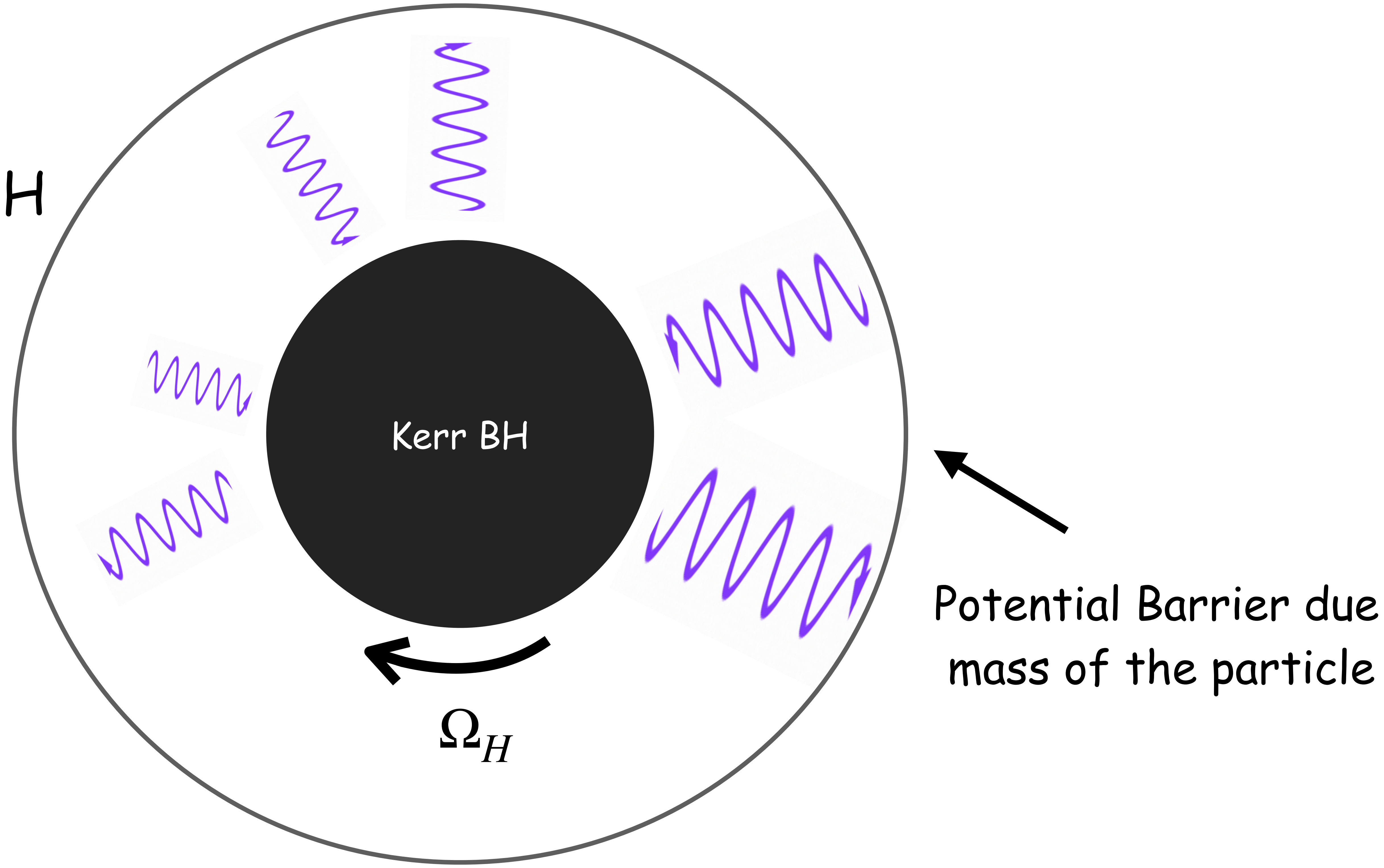
- The growth of superradiant instabilities is maximal when

$$\lambda_c \sim r_g = G_N M_{\mathrm{BH}}$$

Compton wavelength of Massive particle

Gravitational radius of BH

- As a result, BH spin depletes



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Scalar Ultra-light Bosons

- A massive scalar field (Φ) obeys the Klein-Gordon (KG) equation of motion in a spacetime defined by the metric $g^{\mu\nu}$

$$(g^{\mu\nu}\nabla_\mu\nabla_\nu - \mu_S^2)\Phi = 0$$

Scalar particle mass

- Solutions of the Klein-Gordon equation admit quasi-bound state with complex eigenfrequencies

For the dominant mode:
$|nlm\rangle = |211\rangle$

$$\omega_{nlm} = \omega_{nlm}^R + i\Gamma_{nlm}$$

n = principle quantum number
l = angular momentum quantum number
m = azimuthal angular momentum quantum number

superradiant instability growth rate

- Superradiant instability growth rate for the dominant mode: $\boxed{\Gamma_{211} = \frac{1}{48} a_* r_g^8 \mu_S^9}$

Detweiler 1980;
Baumann et al. 2019

Similarly, we can get the growth rate for vector and tensor bosonic particles

Constraints on Ultra-light Bosons

Conditions for BH spin depletion via superradiance:

1. Condition for superradiance: $\boxed{\omega < m\,\Omega_H}$

$$\Omega_H = \frac{1}{2r_g}\frac{a_*}{1+\sqrt{1-a_*^2}}$$

2. Second condition: the timescale for energy extraction via superradiance should be smaller than the timescale for BH accretion

$$\boxed{\tau_{\rm SR} < \tau_{\rm BH}}$$

$$\tau_{\rm SR} = \frac{\ln N_{\rm max}}{\Gamma_{nlm}}$$

$N_{\rm max}$ = maximum occupation number of the cloud after the BH spin downs by $\Delta a_* = 1 - a_*$

$$N_{\rm max} = \frac{G_N M_{\rm BH}^2 \Delta a_*}{m}$$

- For the timescale for BH accretion, we chose $\tau_{\rm BH} = 5 \times 10^9\, yr$

Constraints on Ultra-light Bosons (ULBs)

Since the spin of Sgr A* has not been completely depleted via superradiance, we can use the two conditions to constrain the ultra-light boson mass.

Mass and spin parameter

for Sgr A*

$M = 4.0 \times 10^6 M_\odot$

$a_* = 0.5$ and $a_* = 0.94$

For the dominant mode of scalar Ultra-light bosons, the constraints region is:

$$\left(\frac{48 \ln N_{\rm max}}{a_* \, r_g^8 \tau_{\rm BH}}\right)^{1/9} < \mu_S < \Omega_H$$

This work's result arXiv:2208.03530

Constrained mass range for scalar ULBs

Constraints on ULB masses

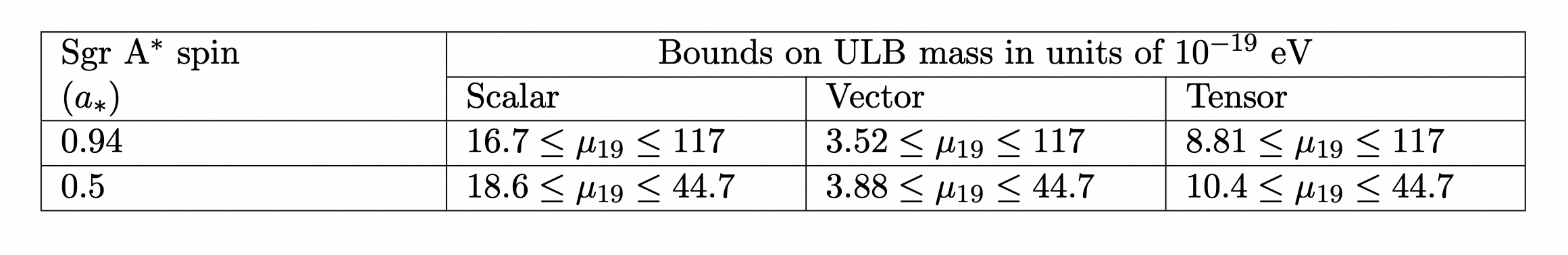
Constraints on ULB masses with spins 0, 1 and 2 (scalar, vector and tensor)

This work's results
arXiv:2208.03530

Light shaded region $a_* = 0.94$

Dark shaded region $a_* = 0.5$

$$\mu_{19} = \frac{\mu_b}{10^{-19}\,\mathrm{eV}}$$



Sgr A* spin (a_*)	Bounds on ULB mass in units of 10^{-19} eV		
	Scalar	Vector	Tensor
0.94	$16.7 \leq \mu_{19} \leq 117$	$3.52 \leq \mu_{19} \leq 117$	$8.81 \leq \mu_{19} \leq 117$
0.5	$18.6 \leq \mu_{19} \leq 44.7$	$3.88 \leq \mu_{19} \leq 44.7$	$10.4 \leq \mu_{19} \leq 44.7$

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Self-interacting Scalar ULBs

- Self-interaction may lead to the collapse of the scalar cloud developed through superradiance.
- The cloud will collapse when the number of particles in the cloud reaches $N_{\rm BOSE}$.

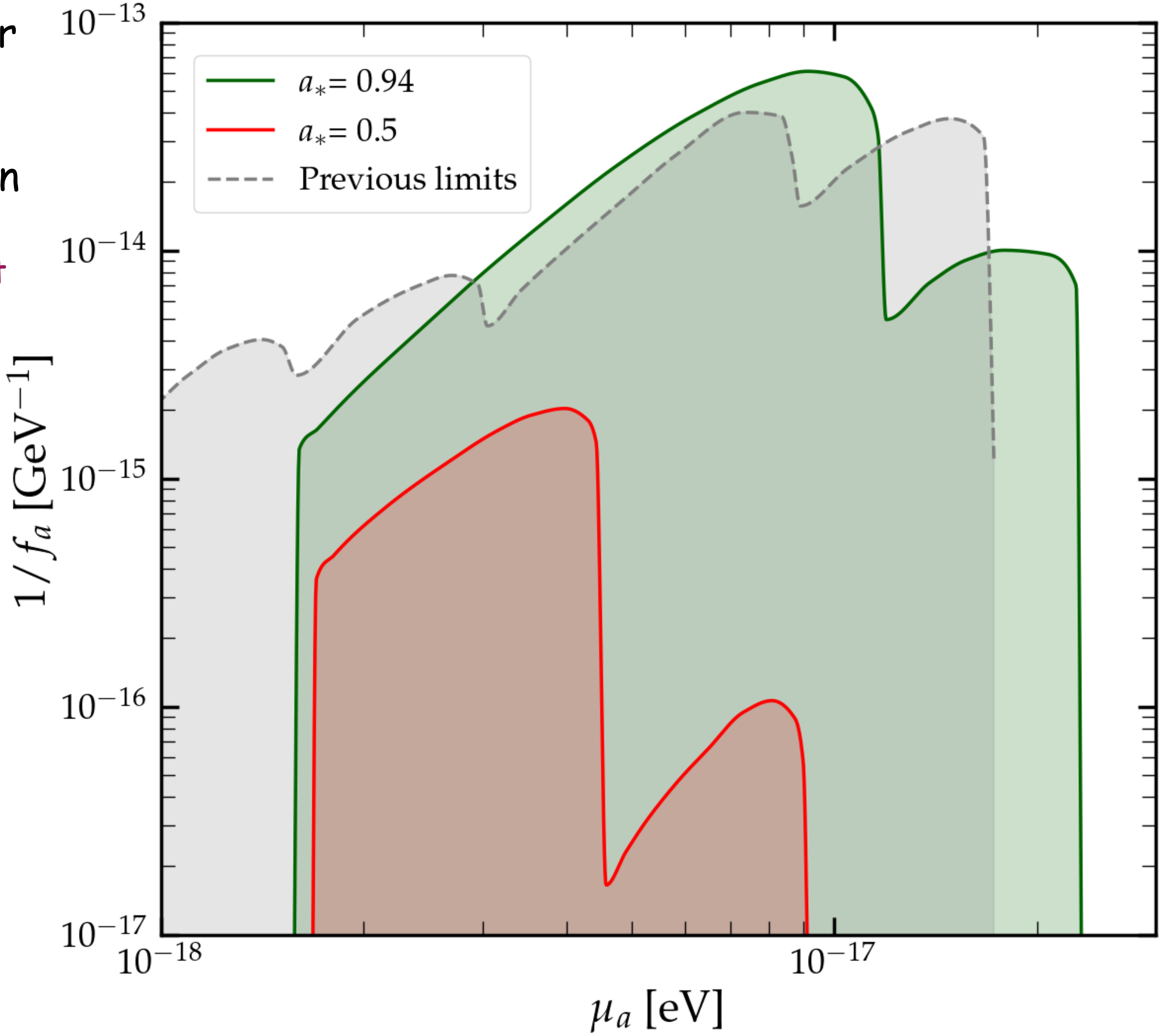
Axion decay constant

$$N_{\rm BOSE} = c \times 10^{94} \frac{n^4}{r_g \mu_a} \frac{M_{\rm BH}}{10^9 M_\odot} \frac{f_a}{M_P}$$

Axion mass

Superradiance can spin down the BH only if the superradiance rate is large, i.e., if

$$\Gamma_{nlm} \tau_{\rm BH} \frac{N_{\rm BOSE}}{N_{\rm max}} > \ln N_{\rm BOSE}$$



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Summary

- Recently, EHT revealed the first image of Sgr A* black hole.
- Using the EHT measurements for Sgr A* spin parameter, we constrain the masses of ultra-light bosonic particles with spins 0, 1, and 2 (scalar, vector, and tensor).
- For ultralight axion, we probe a new region of its decay constant.

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Thank you for your attention!

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