New physics out of the shadow

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Based on:

gr-qc/2205.07787`

astro-ph/2205.06238

astro-ph/2112.06932

In collaboration with:

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The system considered:

A rotating, supermassive BH surrounded by a boson cloud.

The cloud would experience the phenomenon of superradiance: enhanced energy and angular momentum transferred from the BH to the cloud, thanks to the absorbing boundary condition (the event horizon)

Zeldovich, Press, Teukolsky (1970)

Superradiance occurs for $\omega_+ > \omega/m$

BH angular velocity at EH

$\omega \sim \mu$: Boson frequency

m : Azimuthal number

One candidate: a light boson field

Motivation: Light bosons might be DM candidates.

Examples:

- Fuzzy DM
- Dark Energy
- String- or QCD-axion and ALPs
- Vector DM, dark/hidden photons

However, a light boson field might not need be DM or DE

Massless bosons

$$S = \frac{1}{2}\int \mathrm{d}^4x\,\sqrt{-g}\,g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

There is an additional shift symmetry $\phi \to \phi + c$

The symmetry is lost whenever a potential is added, such a quadratic mass term $\sim \mu^2\phi^2/2$

The symmetry is broken at some level, at least by QG effects that spoil all continuous global symmetries.

Nearly-massless boson ➜ shift symmetry is "approximate"

Giving a small mass to the boson

An important example is the periodic potential, for which a residual discrete shift symmetry exists $\phi \to \phi + 2\pi n F$

This model has two parameters: mass m and energy scale F

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu\phi\partial_\nu\phi + V(\phi)\right]$$

$$V(\phi) = \mu^2 F^2 (1 - \cos\phi/F)$$

String-inspired particle models predict numbers of these type of fields (Svrcek&Witten hep-th/0605206, Cicoli+ 2110.02964)
Important applications in cosmology (Arvanitaki+ 0905.4720)

Giving a small mass to the boson

$$V(\phi) = \mu^2 F^2 (1 - \cos\phi/F)$$

$$\mu^2 F^2 = M_{\rm Pl}^2 \Lambda^2 e^{-S}$$

ReducedPlanck mass $M_{\rm Pl} = 1/\sqrt{8\pi G} \approx 2.435 \times 10^{18}\,{\rm GeV}$

Instanton action $S \sim 2\pi/\alpha_{\rm SM}$

Instanton-suppressing energy scale by SUSY Λ

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Instanton-suppressing energy scale by SUSY Λ

$F = 10^{17}\,{\rm GeV}$

$\Lambda \sim M_{\rm Pl}$ (No suppression) → $S \sim 230$

$\Lambda \sim 10^{11}\,{\rm GeV}$ (Gravity-mediated SUSY breaking) → $S \sim 200$

$\Lambda \sim 10^{4}\,{\rm GeV}$ (Gauge-mediated SUSY breaking) → $S \sim 170$

Dark sector with massive boson fields

Consider a real scalar field ϕ of mass μ

The boson cloud around a BH of mass M peaks at

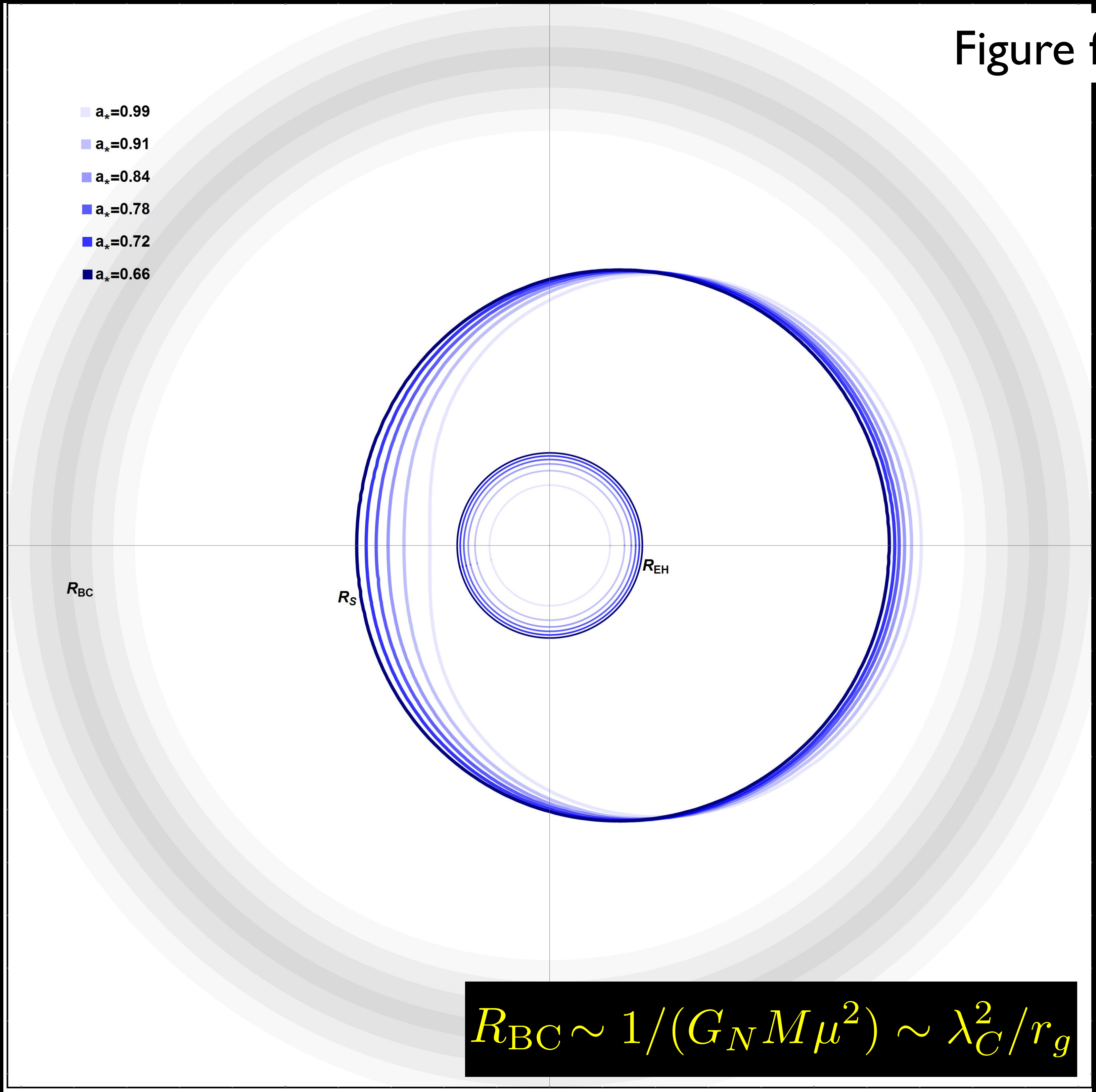
$$R_{\rm BC} \sim 1/(G_N M \mu^2) \sim \lambda_C^2/r_g$$

$\lambda_C \equiv \hbar/(\mu c)$ Compton wavelength

$r_g \equiv G_N M/c^2$ Gravitational radius

Efficient superradiance occurs for $\alpha \equiv \dfrac{r_g}{\lambda_C} \lesssim 1$

Figure from Rittick Roy



$$R_{\rm BC} \sim 1/(G_N M \mu^2) \sim \lambda_C^2/r_g$$

Shadow evolution of a Kerr black hole for different values of the spin parameter a_*. R_{EH} denotes the radius of the event horizon, R_S denotes the size of the shadow and R_{BC} denotes the radius at which ultralight bosons accumulate after extracting energy and angular momentum from the black hole via a process called quasi-Hawking process. As the black hole spins down, it's event horizon and shadow evolve. The boson cloud is ~100 times the event horizon radius and hence not to scale.

Competing effects

1) Accretion (e.g. Barausse+ 1404.7149)

$$\dot{M}_{\rm acc} \approx 0.02 f_{\rm Edd} \frac{M(t)}{10^6 M_\odot} M_\odot\,{\rm yr}^{-1} \qquad \dot{J}_{\rm acc} \propto \dot{M}_{\rm acc}$$

e.g. $f_{\rm Edd} \lesssim 1$ for AGNs; $f_{\rm Edd} \sim 10^{-9}$ for SgrA*

2) GW emission (e.g. Yoshino&Kodama 1312.2326)

$$\dot{E}_{\rm GW} \sim \frac{484 + 9\pi^2}{23040} \left(\frac{N_B \mu}{M}\right)^2 (G_N M \mu)^{14}$$

3) Superradiance evolution of the boson cloud $\dot{N}_B = \Gamma N_B$

$$\Gamma = \frac{(G_N M \mu)^9}{24 G_N M} \left(a - \frac{2\mu M r_+}{m}\right)$$

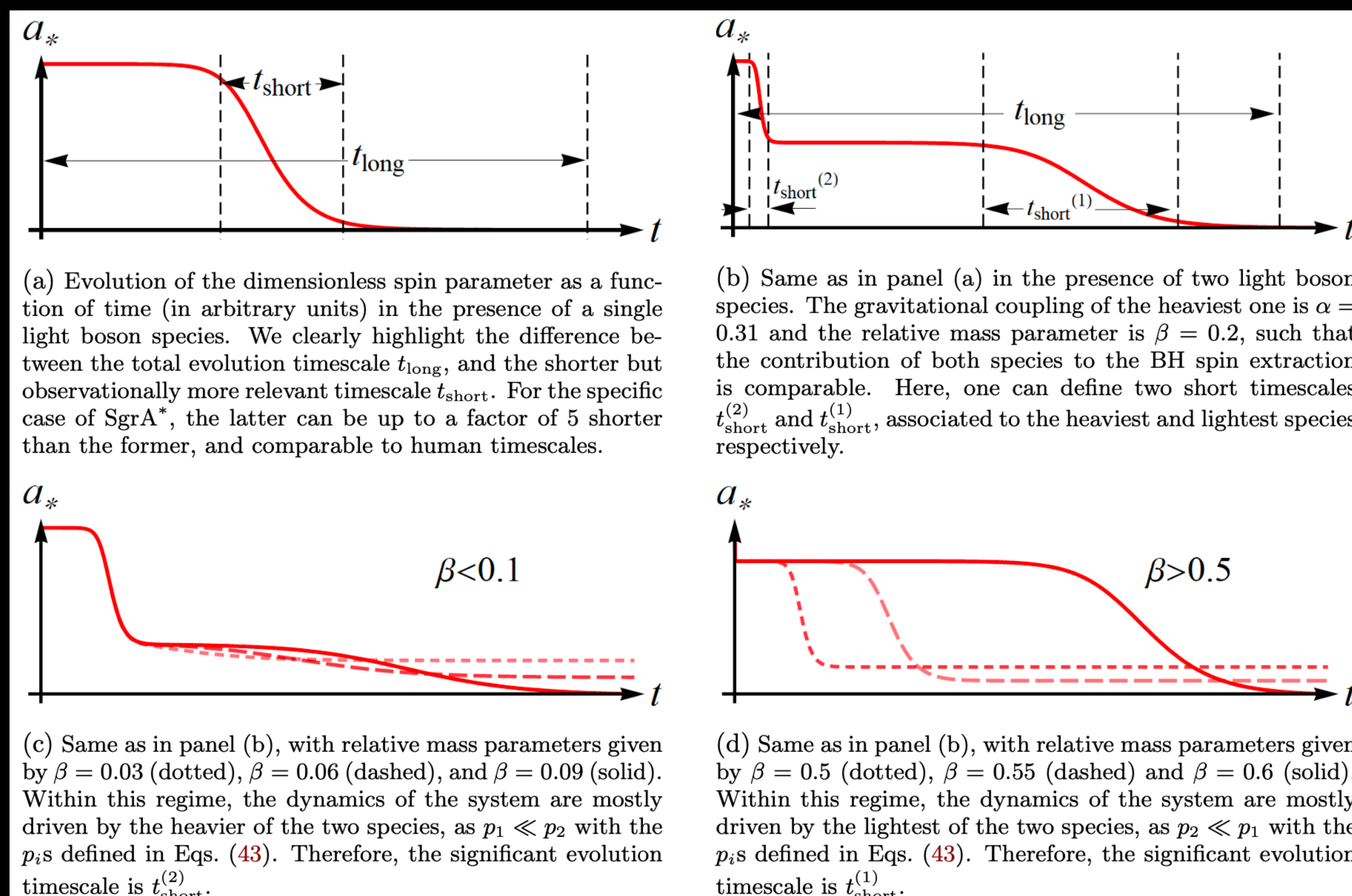
Superradiance halts when

$$a_{\rm crit} \approx \frac{2\mu M r_+}{m}$$

Superradiance with two boson fields

Two boson fields of mass μ_1 and μ_2, with $\boxed{\beta = 1 - \mu_1/\mu_2}$

$$\mathcal{L} \supset \frac{\mathcal{R}}{16\pi G_N} - \frac{1}{2}(\nabla\phi_1)^2 - \frac{1}{2}(\nabla\phi_2)^2 - \frac{1}{2}\mu_1^2\phi_1^2 - \frac{1}{2}\mu_2^2\phi_2^2$$



(a) Evolution of the dimensionless spin parameter as a function of time (in arbitrary units) in the presence of a single light boson species. We clearly highlight the difference between the total evolution timescale $t_{\rm long}$, and the shorter but observationally more relevant timescale $t_{\rm short}$. For the specific case of SgrA*, the latter can be up to a factor of 5 shorter than the former, and comparable to human timescales.

(b) Same as in panel (a) in the presence of two light boson species. The gravitational coupling of the heaviest one is $\alpha = 0.31$ and the relative mass parameter is $\beta = 0.2$, such that the contribution of both species to the BH spin extraction is comparable. Here, one can define two short timescales $t^{(2)}_{\rm short}$ and $t^{(1)}_{\rm short}$, associated to the heaviest and lightest species respectively.

(c) Same as in panel (b), with relative mass parameters given by $\beta = 0.03$ (dotted), $\beta = 0.06$ (dashed), and $\beta = 0.09$ (solid). Within this regime, the dynamics of the system are mostly driven by the heavier of the two species, as $p_1 \ll p_2$ with the p_is defined in Eqs. (43). Therefore, the significant evolution timescale is $t^{(2)}_{\rm short}$.

(d) Same as in panel (b), with relative mass parameters given by $\beta = 0.5$ (dotted), $\beta = 0.55$ (dashed) and $\beta = 0.6$ (solid). Within this regime, the dynamics of the system are mostly driven by the lightest of the two species, as $p_2 \ll p_1$ with the p_is defined in Eqs. (43). Therefore, the significant evolution timescale is $t^{(1)}_{\rm short}$.

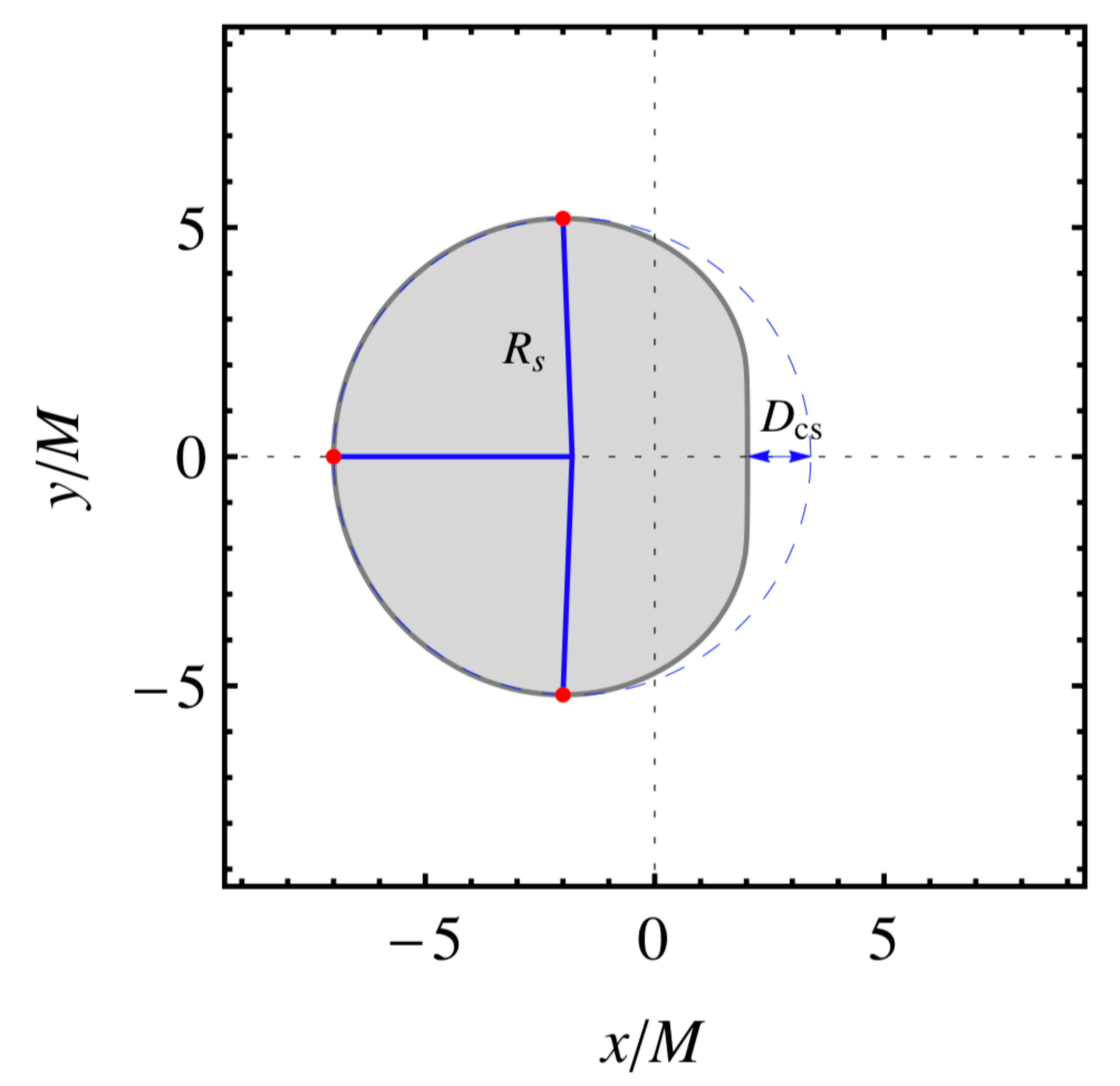
Roy, Vagnozzi, **LV** 2112.06932

Application to Sgr A*

$$\Delta R_{\rm Abs} \approx 13\,\mu{\rm as}\left(\frac{\Delta R}{6\sqrt{3}}\right)\left(\frac{M}{4.2\times10^6 M_\odot}\right)\left(\frac{8.5\,{\rm kpc}}{D}\right)$$

$$\chi = \frac{y_{\rm max} - y_{\rm min}}{x_{\rm max} - x_{\rm min}}$$

Transition thick-thin for $\lambda \sim {\rm mm}$ (Doeleman+2001)



β	$t_{\rm long}$ (yrs)	$\Delta\chi$	$\Delta R_{\rm Abs}$ (μas)
10^{-3}	73	0.06	0.62
0.01	97	0.06	0.61
0.03	172	0.06	0.57
0.05	233	0.06	0.54

TABLE I: Total evolution timescale $t_{\rm long}$, net change in the axis ratio $\Delta\chi$, and net change in the angular size of the BH shadow $\Delta R_{\rm Abs}$ as a function of the relative mass parameter β. These values have been computed for the specific case of SgrA*, located at a distance $D = 8\,{\rm kpc}$ away from us and with a mass of $M = 4.2 \times 10^6 M_\odot$. While the total evolution timescale for all the cases reported exceeds typical human timescales, the shorter but observationally more relevant timescale $t_{\rm short}$ is $\sim 16\,{\rm yrs}$ for all cases reported in the Table.

Application to Sgr A*

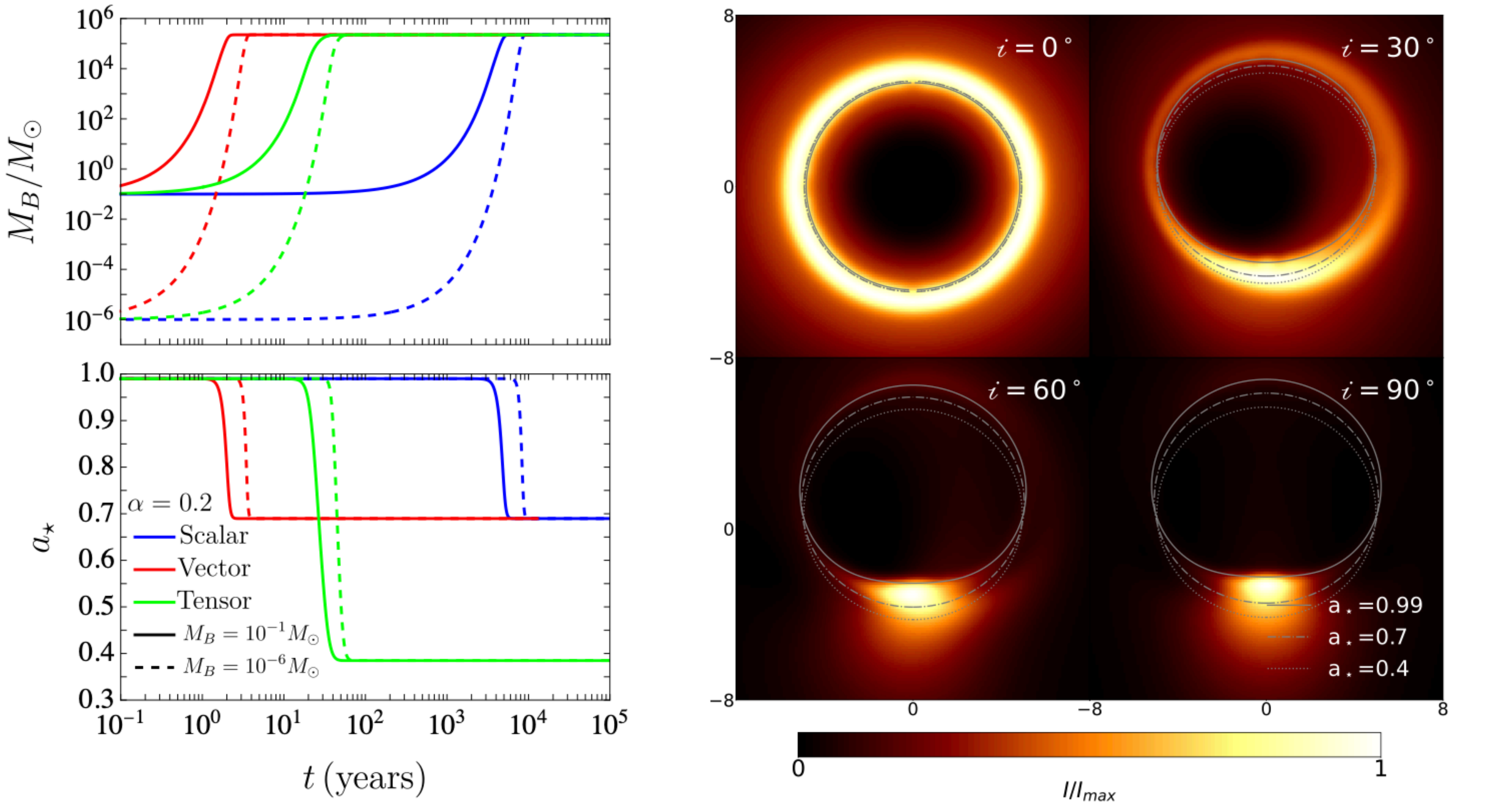


Fig. 14 Left panel: the evolution of the mass of the boson cloud M_B (top) and of the dimensionless BH spin parameter a_* (bottom), as a function of time in years for (initial) $\alpha = 0.2$ and for different choices of the bosonic nature: scalar field (red), vector field (blue), tensor field (green), with the set of quantum numbers as given in the text. The initial mass of the boson cloud is $M_B = 10^{-1} M_\odot$ (solid line) and $M_B = 10^{-6} M_\odot$ (dashed line). We assume an initial BH mass $M = 4.3 \times 10^6 M_\odot$ and initial spin $a_* = 0.99$. Right panel: evolution of shadow contours (gray lines) during different stages of superradiance for a vector with initial $\alpha = 0.2$ and a BH viewed at different inclination angles. The background depicts the intensity map with an initial value of $a_* = 0.99$. The coordinate origin is taken to be the BH location and the axes are specified in units of the initial gravitational radius.

Chen, Roy, Vagnozzi, **LV**, 2205.06238

Fundamental Physics Opportunities with the Next-Generation Event Horizon Telescope

Dimitry Ayzenberg, Lindy Blackburn, Richard Brito, Silke Britzen, Avery E. Broderick, Raúl Carballo-Rubio, Vitor Cardoso, Andrew Chael, Koushik Chatterjee, Yifan Chen, Pedro V. P. Cunha, Hooman Davoudiasl, Peter B. Denton, Sheperd S. Doeleman, Astrid Eichhorn, Marshall Eubanks, Yun Fang, Arianna Foschi, Christian M. Fromm, Peter Galison, Sushant G. Ghosh, Roman Gold, Leonid I. Gurvits, Shahar Hadar, Aaron Held, Janice Houston, Yichao Hu, Michael D. Johnson, Prashant Kocherlakota, Priyamvada Natarajan, Héctor Olivares, Daniel Palumbo, Dominic W. Pesce, Surjeet Rajendran, Rittick Roy, Saurabh, Lijing Shao, Shammi Tahura, Aditya Tamar, Paul Tiede, Frédéric H. Vincent, Luca Visinelli Zhiren Wang, Maciek Wielgus, Xiao Xue, Kadri Yakut, Huan Yang, Ziri Younsi

2312.02130

Can we detect the evolution of a BH shadow?

YES in principle. In more detail:

1. Observationally-favored conditions

(SMBHs in the light mass window and close)

2. Improvements in VLBI angular resolution

(Sub- μas angular resolution, slightly below space-based VLBI, see Fish+ 1903.09539)