Effects of Superradiance in Active Galactic Nuclei

arXiv: 2404.09955

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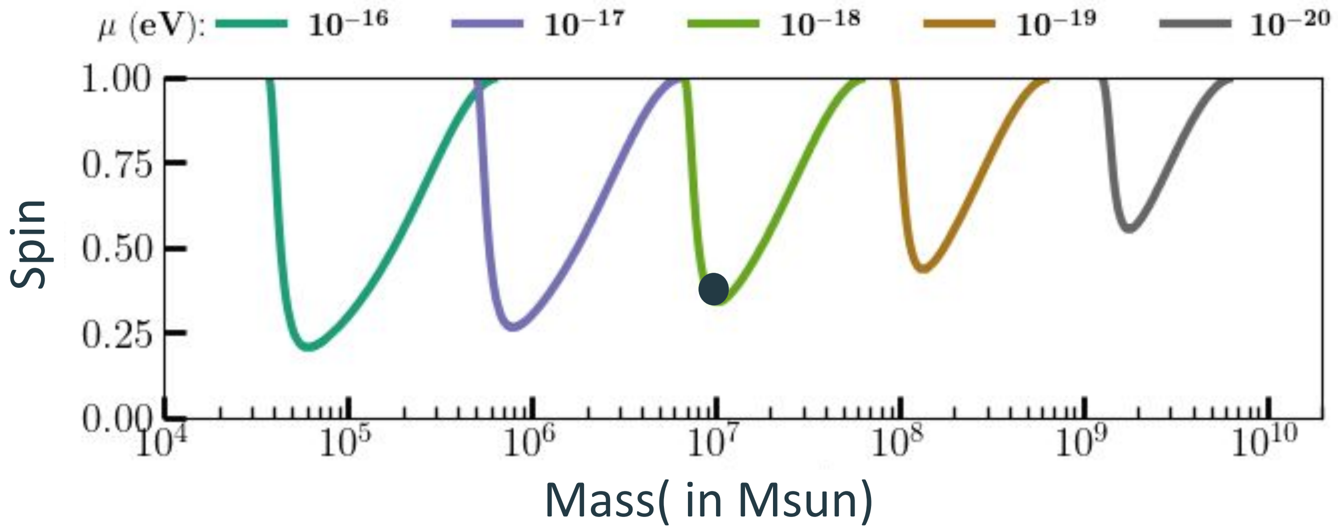
Black Hole as Particle Detector

- Spinning supermassive BH opens a room for ultralight scalar particles to get produced through a phenomenon- ***Superradiance (SR)***
- A bosonic cloud grow near the BH, *draining* the angular momentum of the BH

Observational signatures of Superradiance



P.Sarmah et al. [2404.09955]

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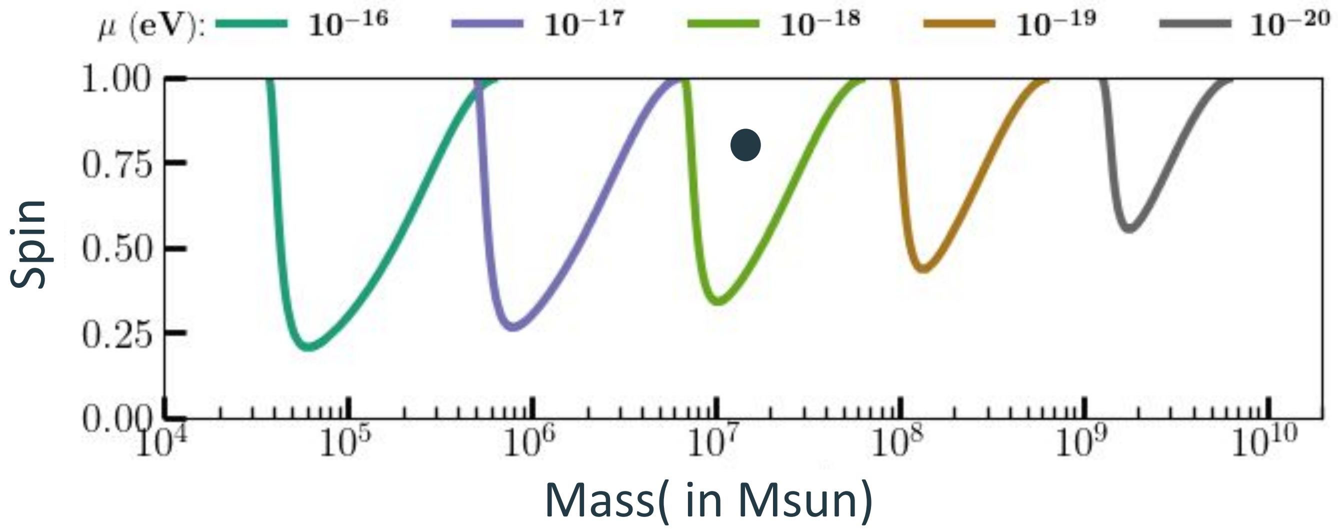
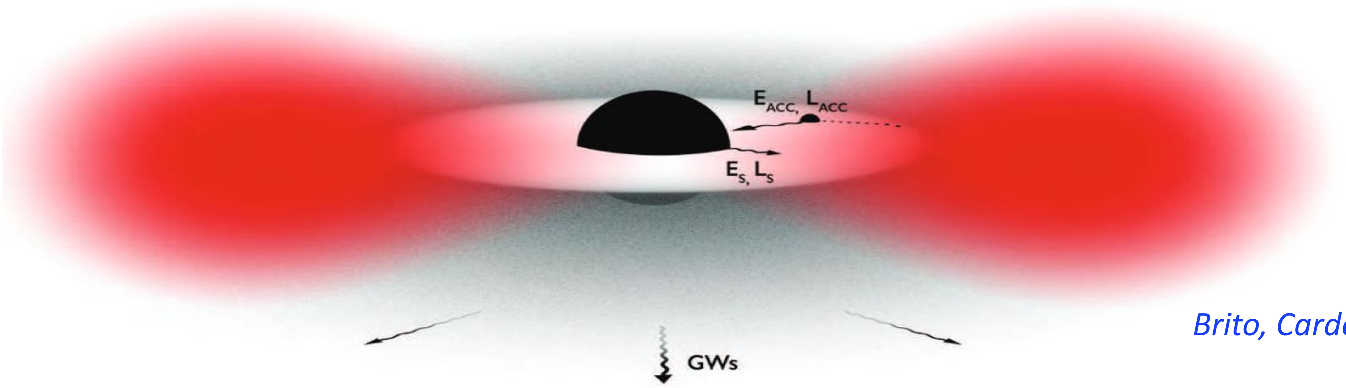


Observation of a BH inside the depletion region in the Regge plane exclude the scalar

P.Sarmah et al. [2404.09955]

Realistic environment for BH Superradiance:

The Active Galactic Nucleus (AGN)

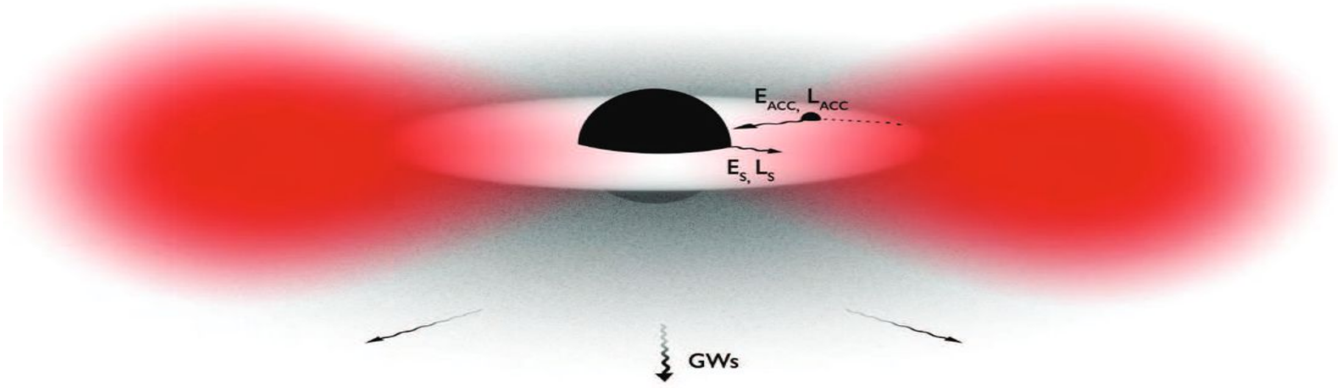


Brito, Cardoso, Pani, 2014 [1411.0686]

- **Key points:** Role of accretion in adding mass and angular momentum to the BH
- 2 competing process: Spin up- accretion, Spin down- Superradiance

Question

How do the characteristics of AGN alter due to Superradiance history of the BH?



Key Findings

As the accreting SMBH spins down due to superradiance:

- **Sudden drops** in the time-variation of the luminosities of AGNs in various wavelength bands.
- Observation of **depletion regions** in various planes of band-luminosities and f_{Edd} and **accumulation** of AGN along the boundaries of the depletion region.

Superradiance in a nutshell

- *Condition of Superradiance(SR):*

$$\omega_R < m\Omega,$$

ω_R,Ω= angular velocity of the particle and BH

- *Consequence of Superradiance*: Growth of scalar cloud, BH loses mass and angular momentum.

  - Angular momentum lost till :$\tilde{a} \sim \tilde{a}_{critical} = 4\alpha m/(m^2 + \alpha^2)$,

gravitational fine structure constant - $\alpha \sim GM\mu$

Brito et al., 2015b particle detector, 906

Luminosity, Eddington Ratio of AGN

- *Total Luminosity :* $L = \epsilon(\tilde{a})\dot{M}_{\rm disk}c^2$

Fanidakis et al, 2011, MNRAS, 410, 53

Radiative efficiency

$$\dot{m} \equiv \dot{M}_{\rm disk}c^2/L_{\rm Edd} \qquad L = \epsilon(\tilde{a})\dot{m}L_{\rm Edd}$$

$$L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma_T} \approx 1.26 \times 10^{38}\,{\rm erg/s}\,\frac{M}{M_\odot}$$

- *Eddington Ratio:* $f_{\rm Edd} \equiv L/L_{\rm Edd}$, $\quad f_{\rm Edd} = \epsilon(\tilde{a})\dot{m}$

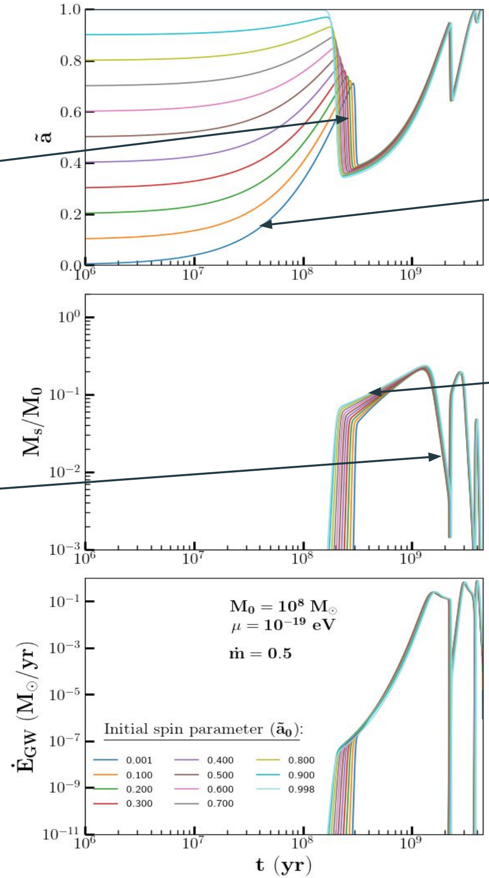
Time evolution of accreting BH + scalar cloud system

Superradiance-dominated phase

Accretion-dominated phase

Attractor phase

GW-dominated phase



P.Sarmah et al. [2404.09955]

Luminosity in various bands

Using Novikov-Thorne model of the accretion disk, get the spin-dependant flux $\boldsymbol{F_\lambda}$ ***(ã ,r)***

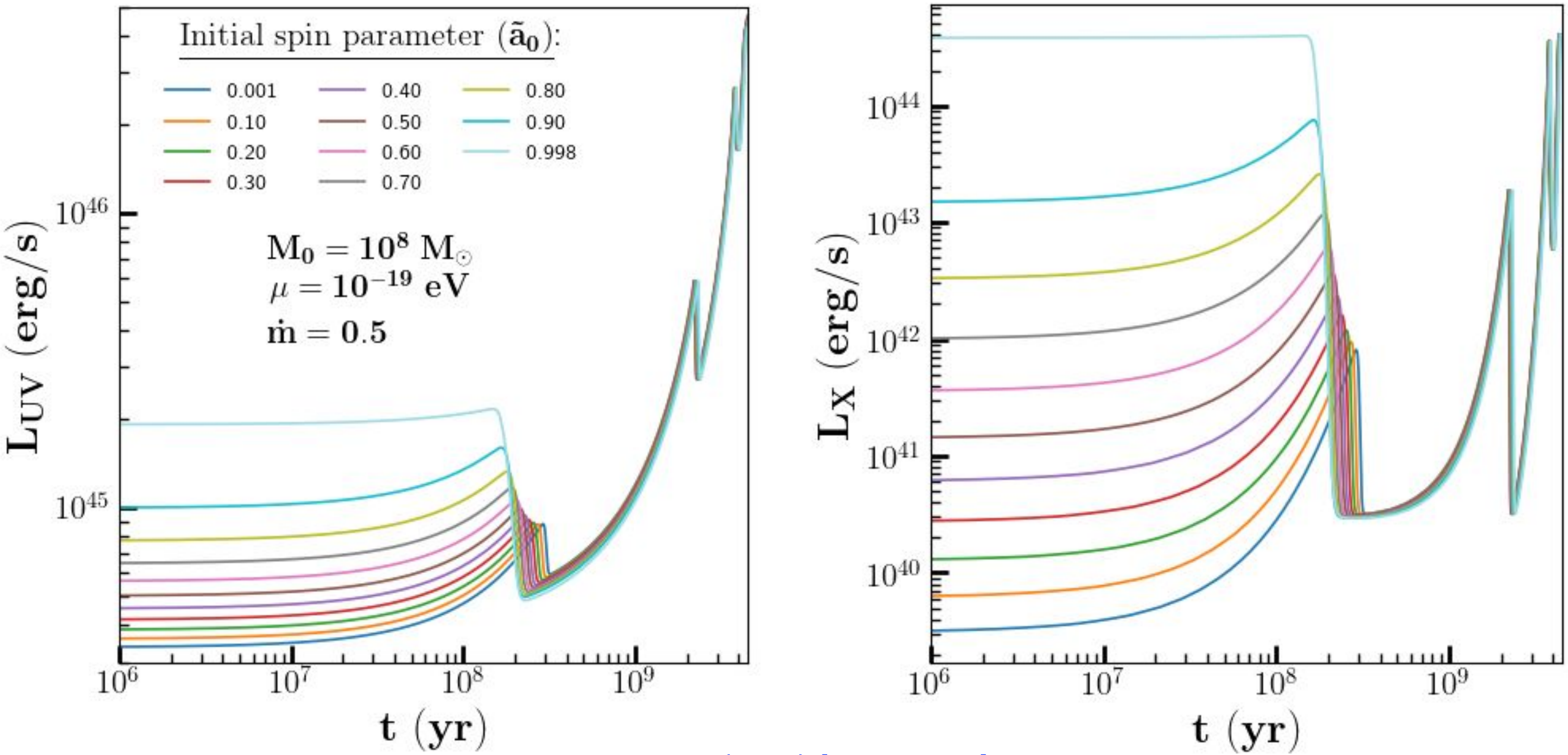
$$L_{\mathrm{X}} = \int_{10^{-4}}^{0.01} F_\lambda d\lambda,$$

$$L_{\mathrm{UV}} = \int_{0.01}^{0.4} F_\lambda d\lambda,$$

$$L_{\mathrm{Vis-IR}} = \int_{0.4}^{100} F_\lambda d\lambda,$$

P.Sarmah et al. [2404.09955]

Luminosity in various bands



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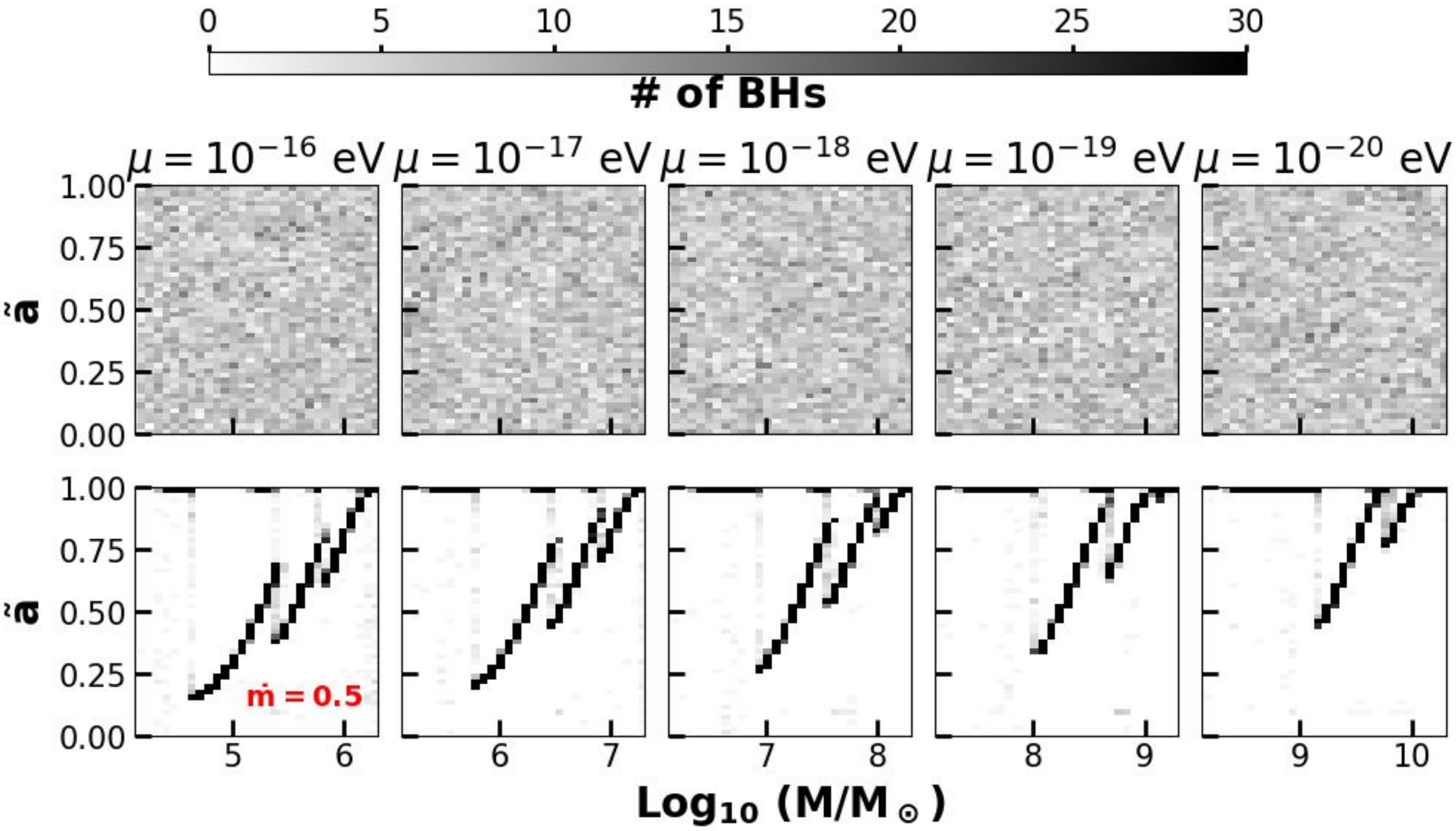
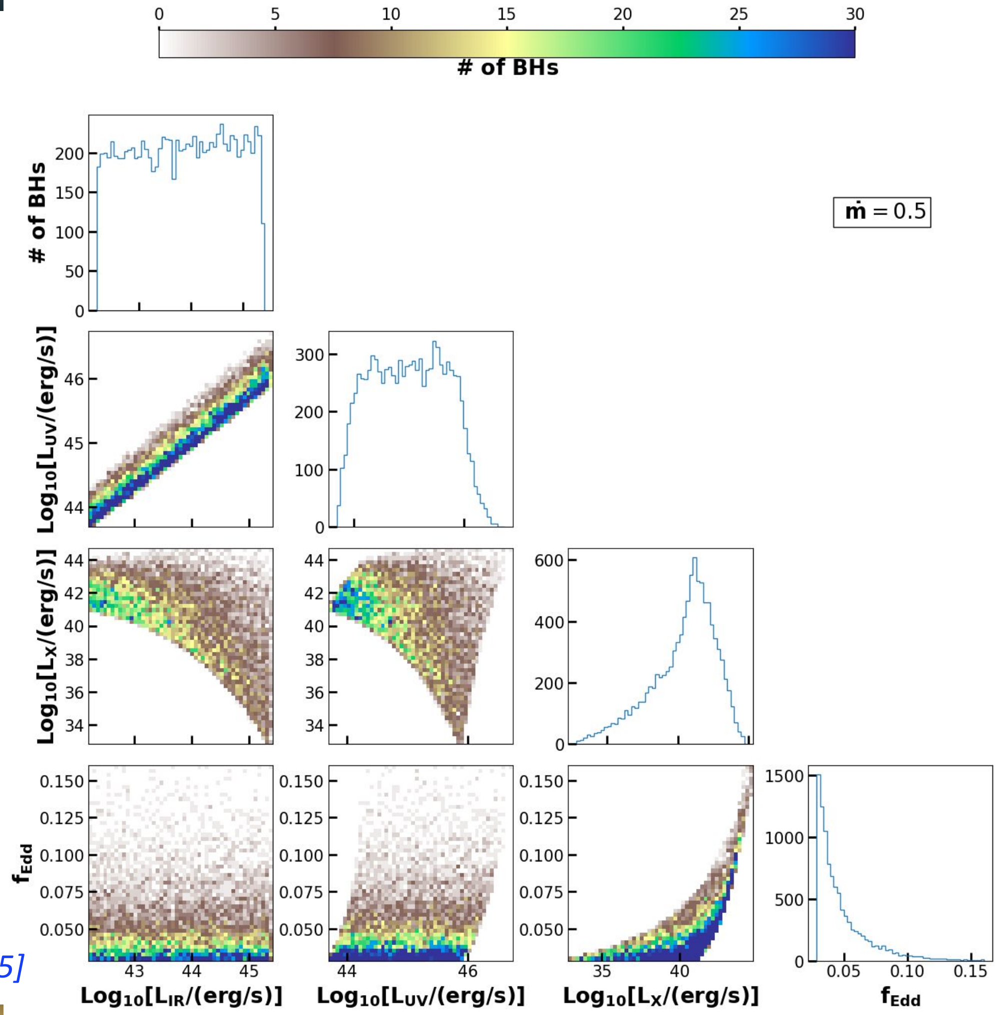
Distribution of SMBHs at the AGN core



P.Sarmah et al. [2404.09955]

Distribution of AGN Characteristics



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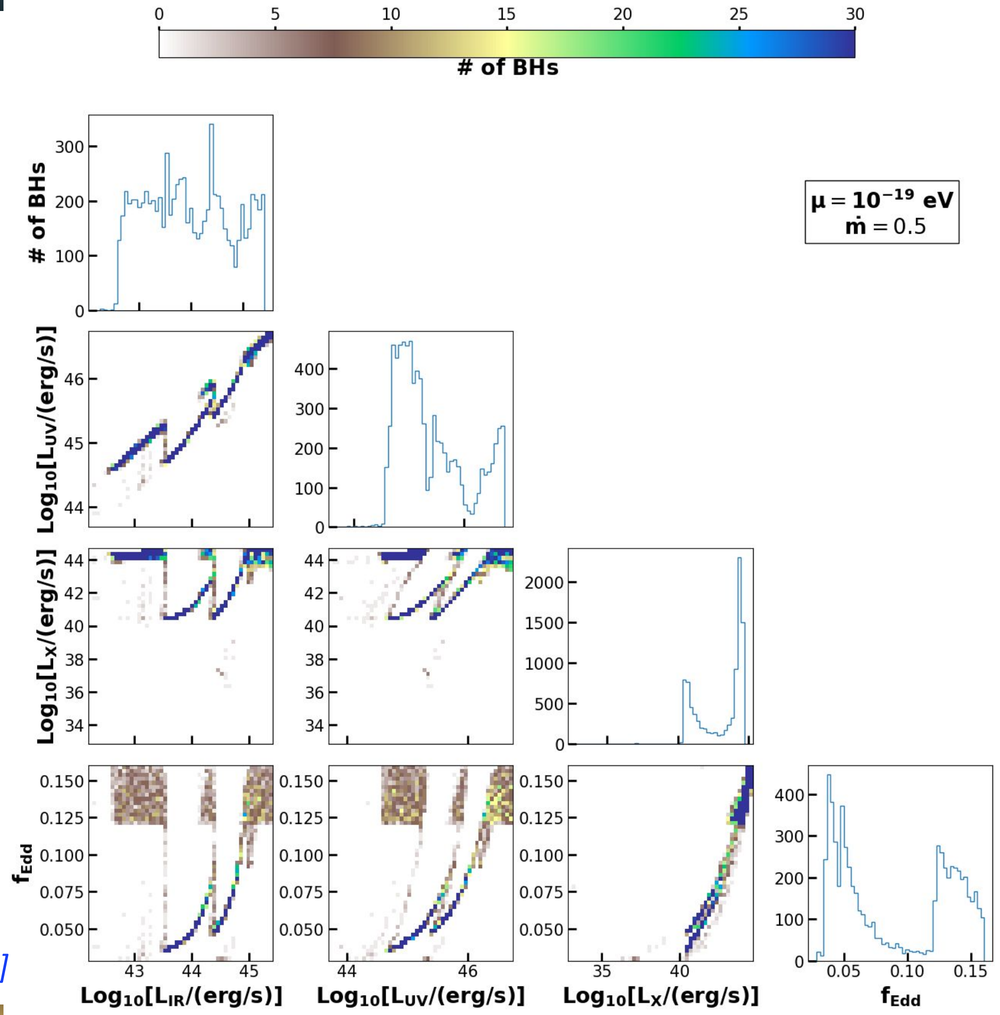

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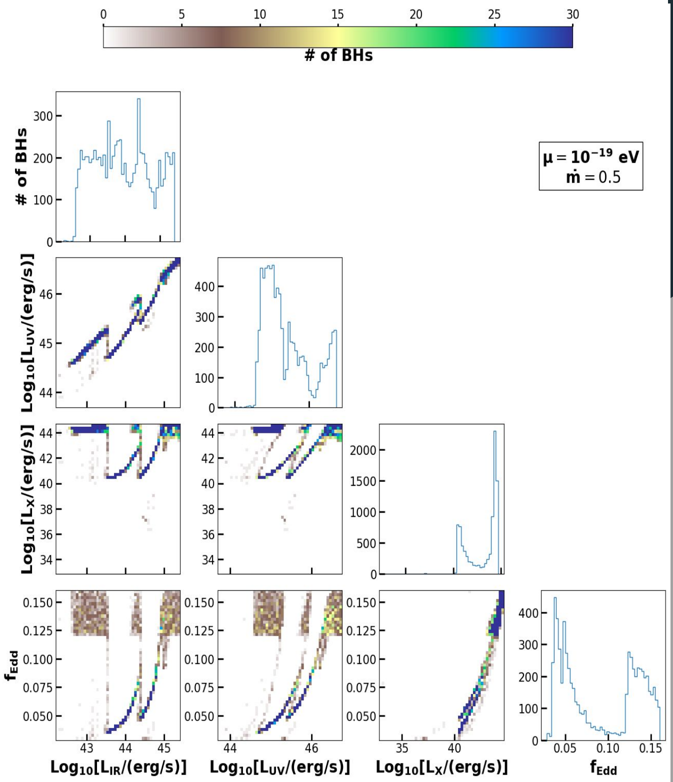
Summary

- Accreting SMBH undergoing Superradiance at the core of AGN leads to-

  Enhanced growth of scalar cloud and GW emission rate and appearance of higher modes within the age of the universe.

- **Multiple dips** in the luminosity evolution corresponding to timescales of dominant modes of superradiance.

- Observation of **depletion regions** in various planes of band-luminosities and f_{Edd} and **accumulation** of AGN along the boundaries of the depletion region.



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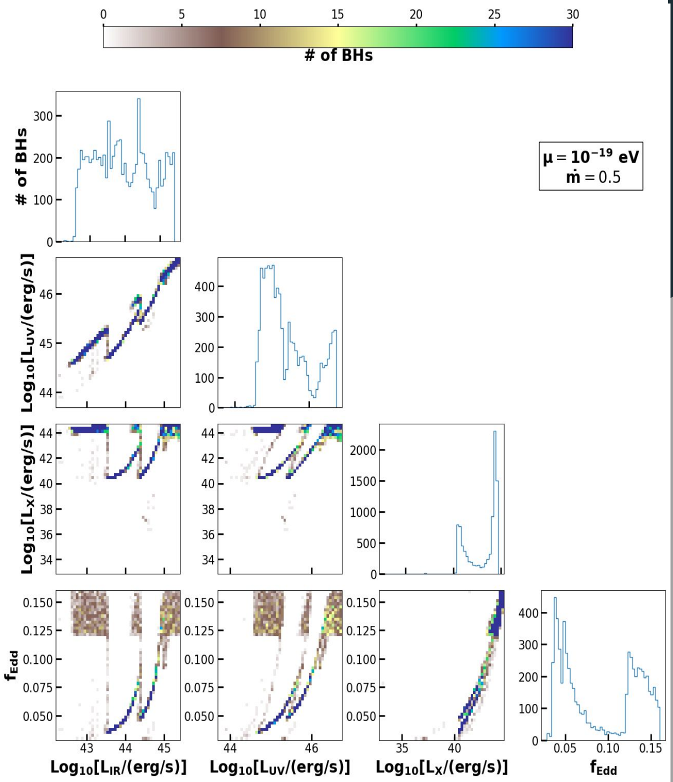
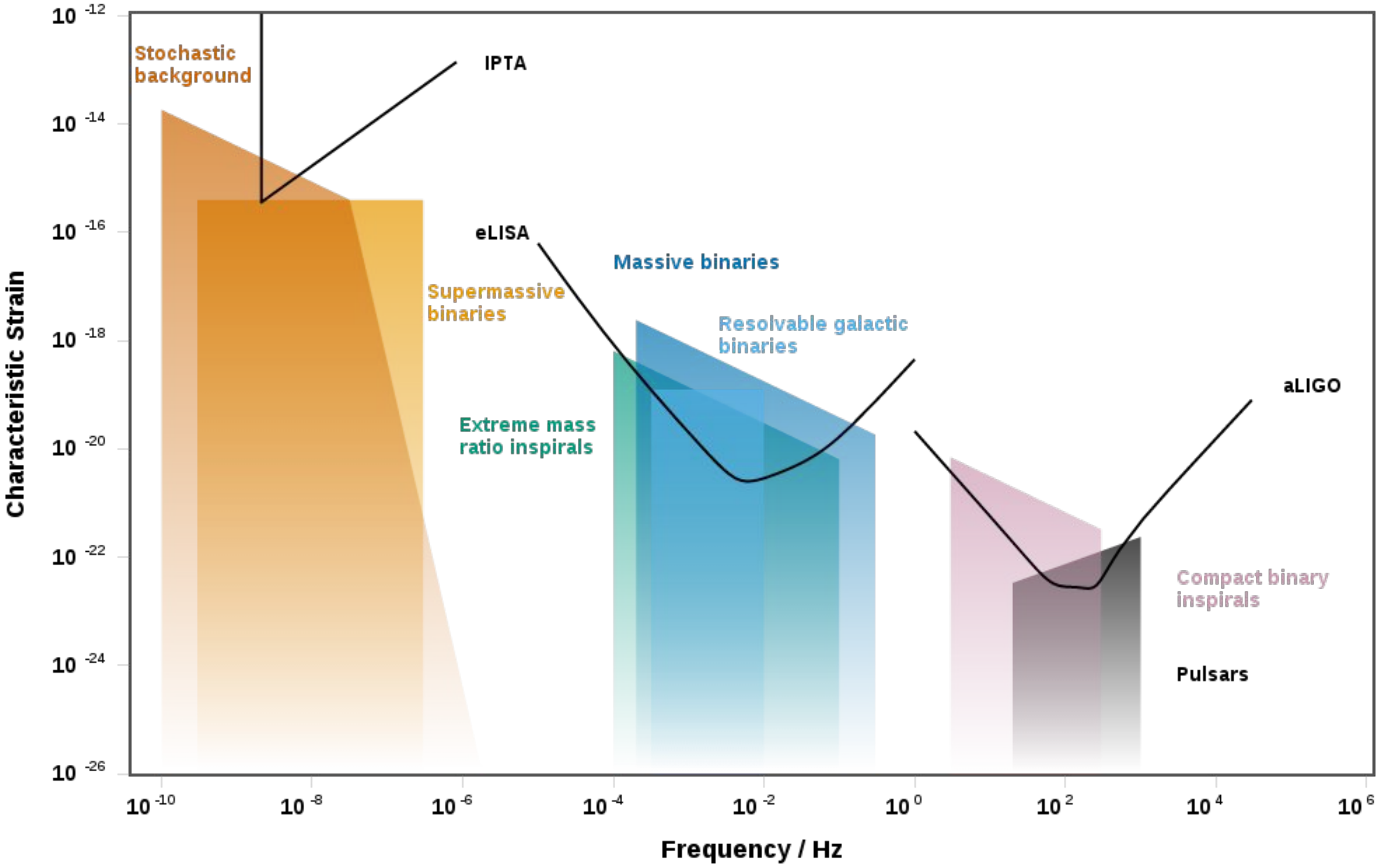


This depletion in the AGN characteristics could be searched in Sloan Digital Sky Survey(SDSS), and expected to improve with Dark Energy Spectroscopic Instrument(DESI) with higher precision in the AGN characteristics.

Thank you!

Questions?
Comments?
Suggestion?



Stochastic background
IPTA
eLISA
Massive binaries
Supermassive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
aLIGO
Compact binary inspirals
Pulsars
Characteristic Strain
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Frequency / Hz

Superradiance in a nutshell

- The metric around a rotating BH parameterized in terms of BH mass M and spin a= ã M, ã dimensionless spin parameter

$\Box \Phi + \mu^2 \Phi = 0$

$\Phi = S_{lm}(\Theta)\psi(r)/r \exp(-i\omega t + im\varphi)$

- Energy eigenvalue $\sim \omega_R + i\,(m\Omega - \omega_R)$

Brito et al., 2015b, particle detector, 906

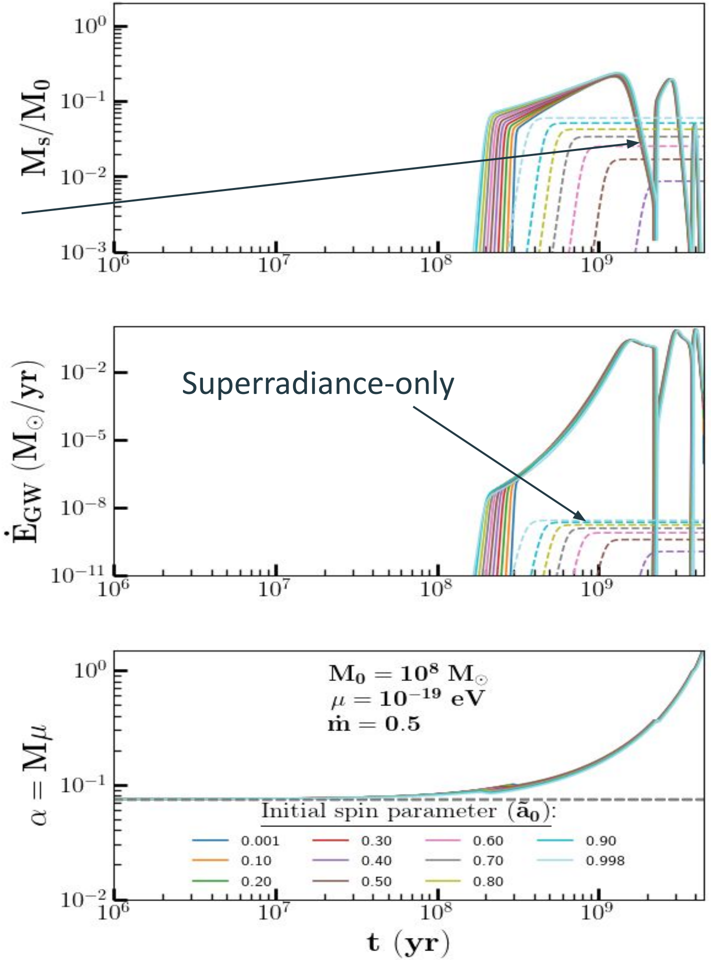
Observational signatures of Superradiance

- Interesting signatures of gravitational wave emission emitted from the annihilation of scalars in the cloud around the BH, *Arvanitaki et al. 2015b*

- Scalar cloud affecting the black hole images, *Davoudiasl & Denton 2019, Saha et al. 2022*

- Depletion region in Regge plane i.e. spin versus mass plane of the BH, *Brito et al. 2014*

GW-dominated phase

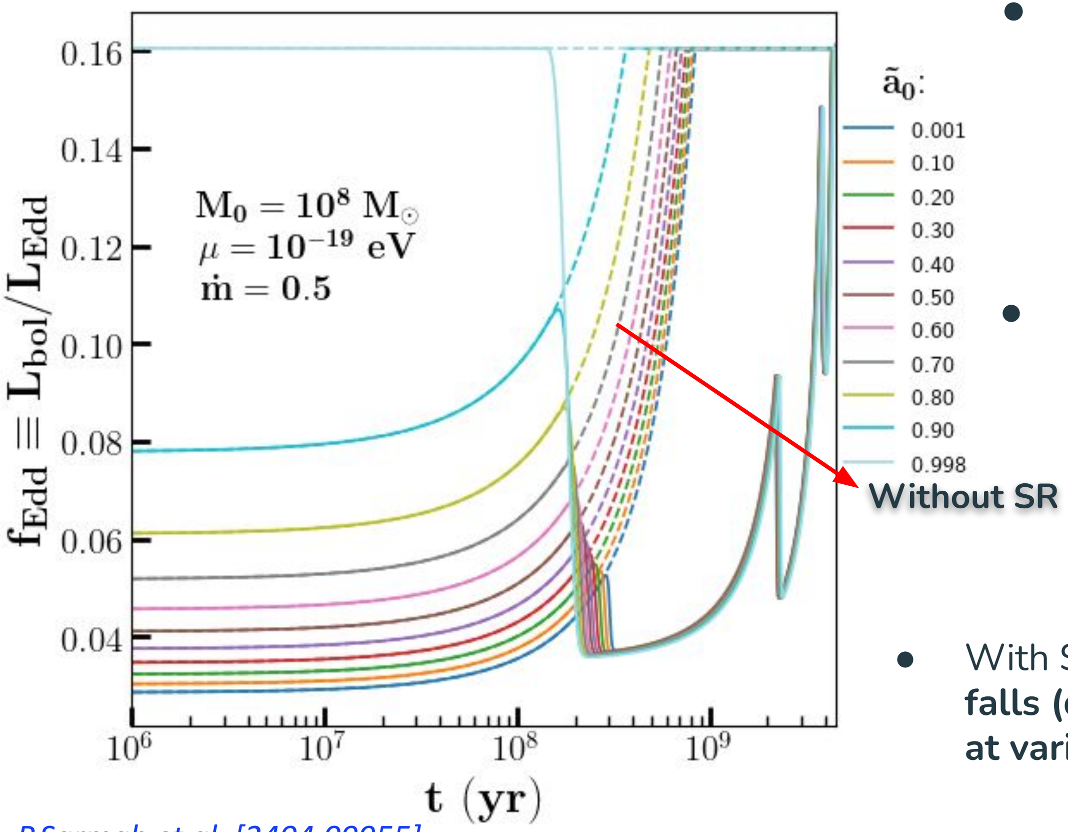


- **GW-dominated phase:** observe an eight-order increase in the peak GW emission rate when accretion is present compared to an isolated BH
$dE_{GW}/dt \sim (M_s/M)^2\ \alpha^{4l+10}$

Yoshino H., Kodama H.'14

P.Sarmah et al. [2404.09955]

Eddington Ratio



- **sudden drops** at the time-scales corresponding to various modes of superradiant growth.

$$f_{\rm Edd} = \epsilon(\tilde{a})\dot{m}.$$

- Without scalar field, f_{Edd} **monotonically increases with time due to accretion.**

- With SR, no longer monotonically increasing, **falls (due to SR) and rise (due to accretion) at various epochs.**

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Possible signatures of SR instability in AGN

- **Galactic Outflow**: massive depletion of gas from the galaxy itself, is a link that connects the center black hole to its host galaxy.
- Radiation-driven outflow is quantified by the momentum transferred by radiation to the gas, which in turn depends on the luminosity (L/c).

Possible signatures of SR instability in AGN

- **Ly-α emission line and Ly-α forest of quasars**: continuous ionization of the neutral gas in the vicinity of a bright UV source leading to a weakened **Ly-α** forest.

- In the presence of superradiance, the rate at which gas was previously ionized would be lower because of sudden drops in the luminosity.

Time evolution of BH + scalar cloud system

$$\frac{dM}{dt} = -\sum_{nlm} 2M_s^{nlm}\omega_I^{nlm} + \dot{M}_{\rm Acc} \ ,$$

$$\frac{dJ}{dt} = -\sum_{nlm} \frac{2}{\mu} m M_s^{nlm}\omega_I^{nlm} + \dot{J}_{\rm Acc} \ ,$$

$$\frac{dM_s^{nlm}}{dt} = 2M_s^{nlm}\omega_I^{nlm} - \dot{E}_{\rm GW}^{nlm} \ ,$$

$$\frac{dJ_s^{nlm}}{dt} = \frac{2}{\mu} m M_s^{nlm}\omega_I^{nlm} - \frac{1}{\mu} m \dot{E}_{\rm GW}^{nlm} \ ,$$

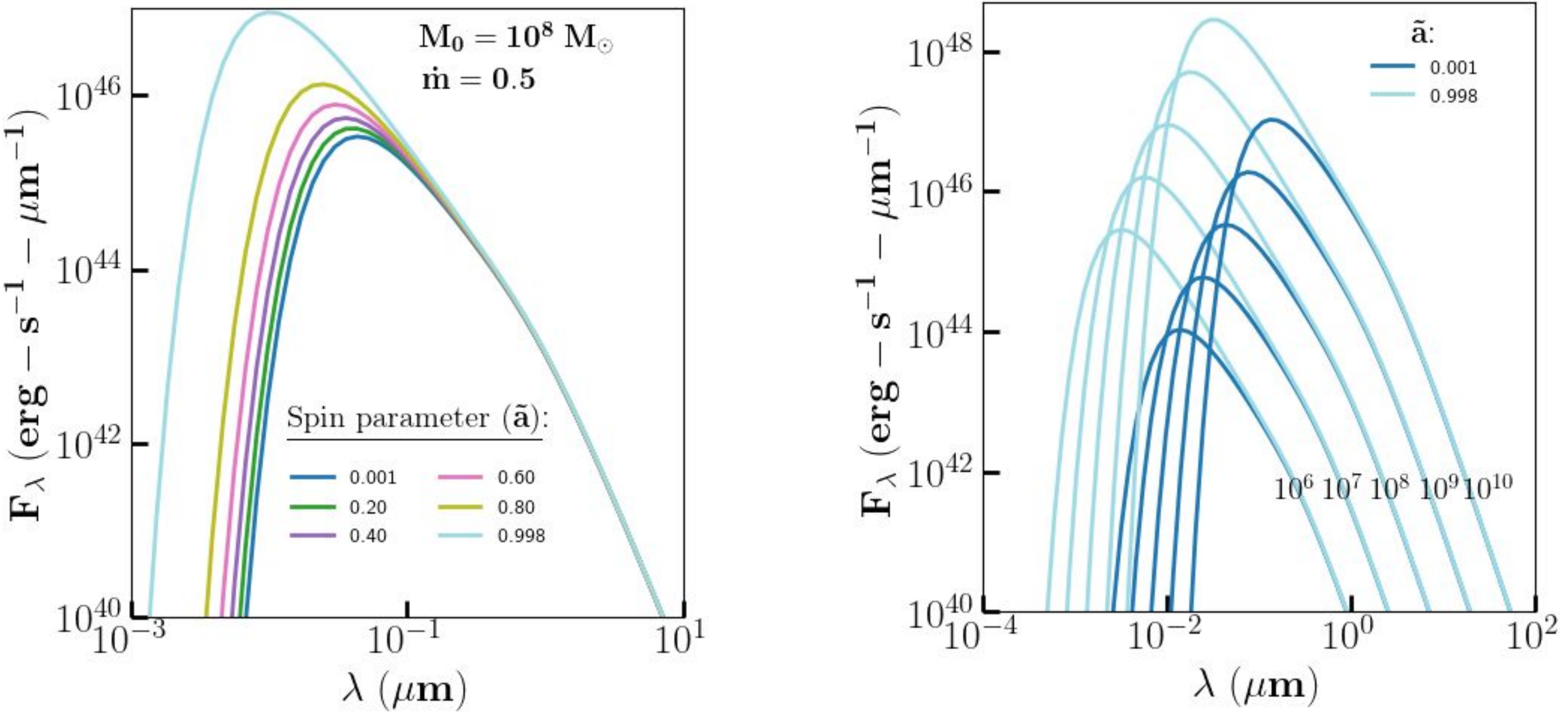
Accretion disk around Kerr BH: Novikov-Thorne model

$$F(r) = 7 \times 10^{26} \frac{\text{erg}}{\text{s cm}^2} \dot{m} \frac{M_\odot}{M} \left(\frac{M}{r}\right)^3 \mathcal{B}^{-1} \mathcal{C}^{-1/2} \mathcal{Q}$$

where *B*, *C*, *Q* are functions of BH spin ã and radius r

Spectrum is obtained by integrating the flux, assuming the flux coming from local Black body

$$F_\lambda = 2 \int f_\lambda(r) r\, dr\, d\phi = 4\pi \int f_\lambda(r) r\, dr$$



- Most visible effects in the X-ray and UV band luminosities of AGNs, least effect in Vis-IR: higher energetic photons come from the inner part

P.Sarmah *et al.* [2404.09955]