Effects of Superradiance in Active Galactic Nuclei

arXiv: 2404.09955

with Himanshu Verma, Kingman Cheung, Joseph Silk

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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

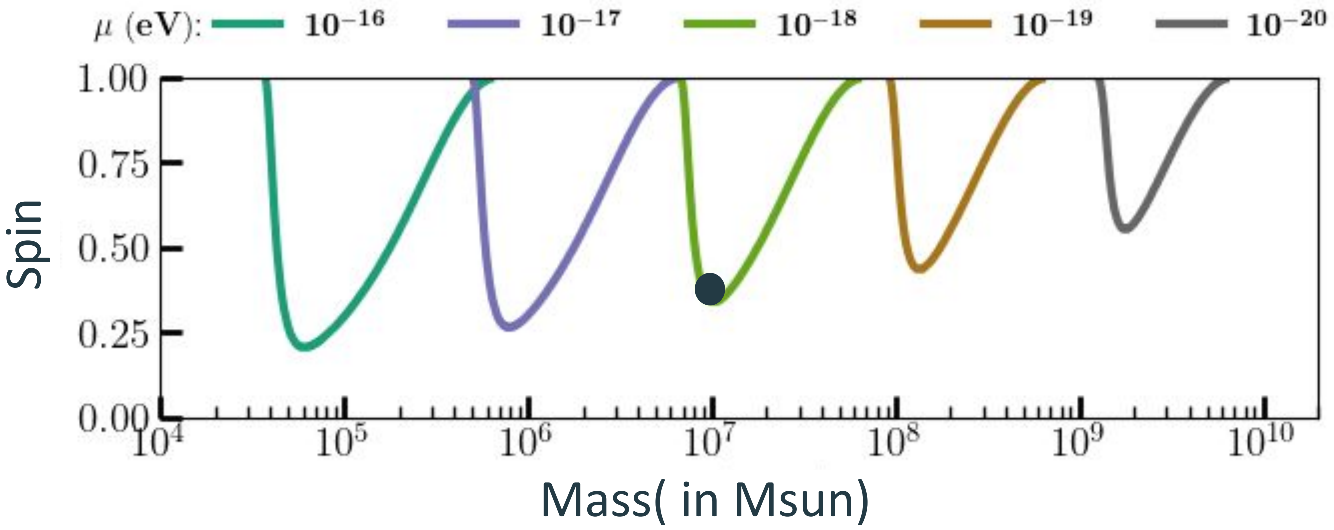
Observational signatures of Superradiance

- 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*

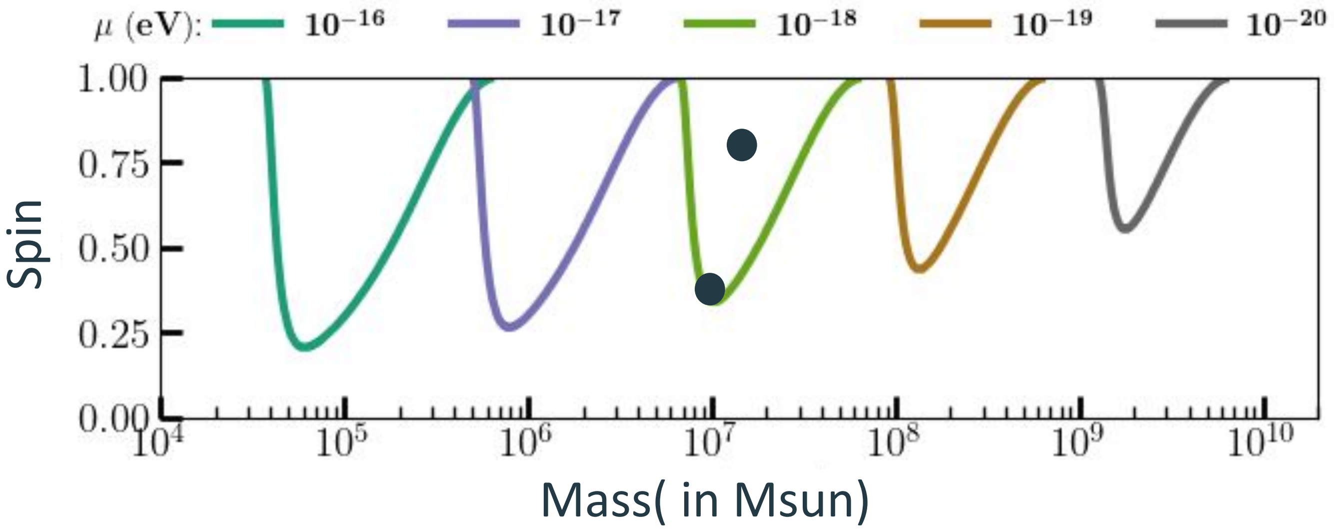
- Depletion region in Regge plane i.e. spin versus mass plane of the BH, *Brito et al. 2014*

Observational signatures of Superradiance



P.Sarmah et al. [2404.09955]

Observational signatures of Superradiance



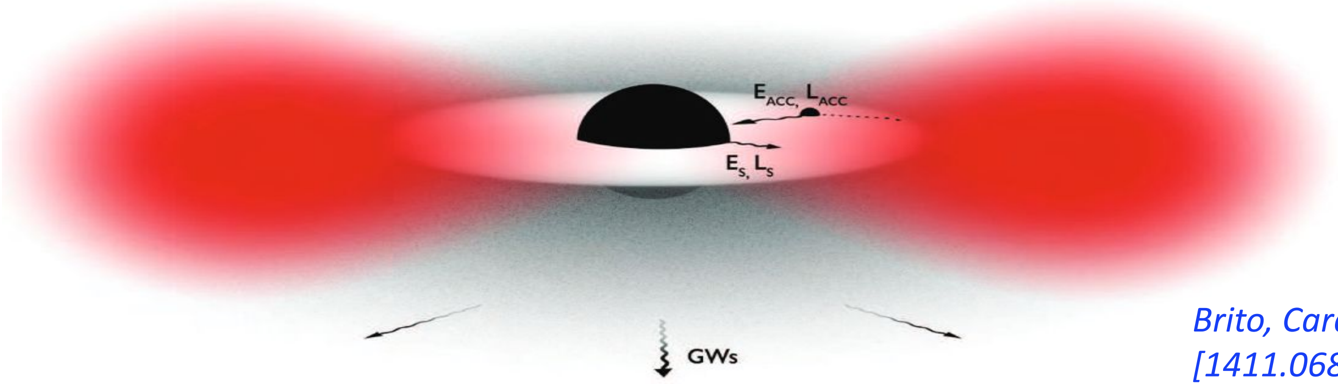
Observation of a BH inside the depletion region in the Regge plane exclude the scalar

P.Sarmah et al. [2404.09955]

Realistic environment for BH Superradiance:

The Active Galactic Nucleus (AGN)

AGN are the bright compact object at the galactic center consisting of a SMBH at its core.



Brito, Cardoso, Pani, 2014 [1411.0686]

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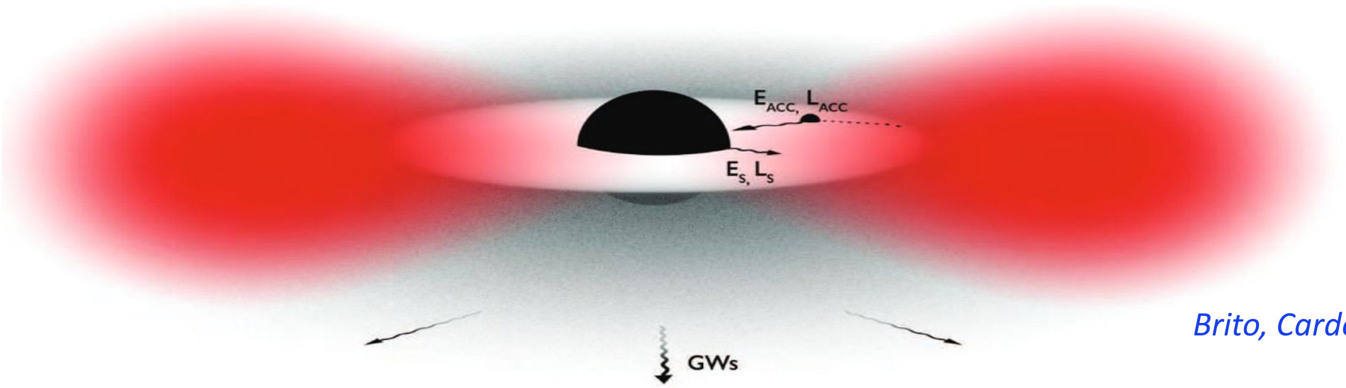
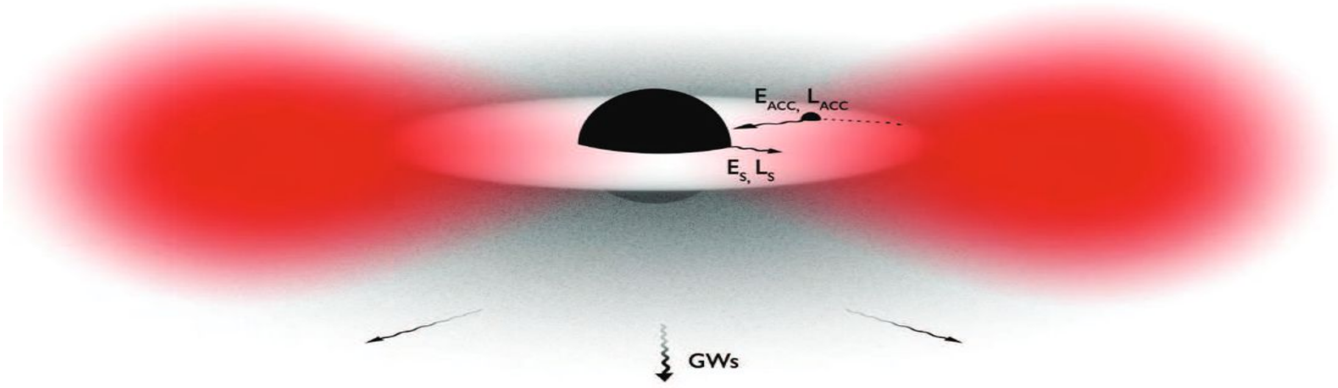


Brito, Cardoso, Pani, 2014 [1411.0686]

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

Question

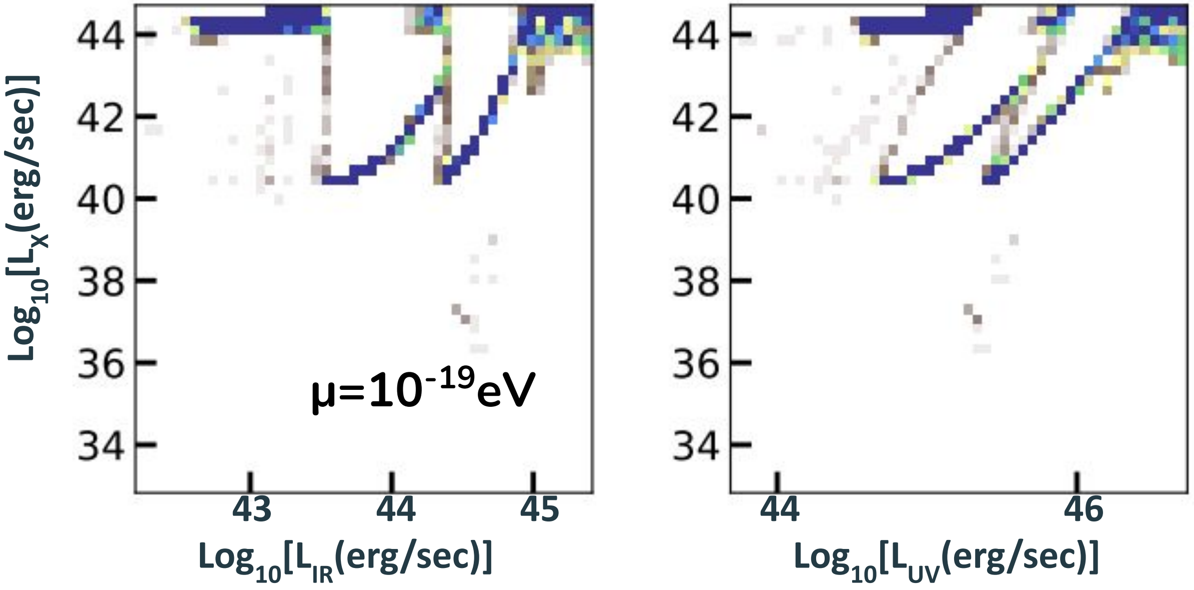
How do the characteristics of AGN alter due to Superradiance history of the BH?



Key Findings

- **Sudden drops** in the time-variation of the band-luminosities and Eddington ratio

- 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

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

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

Characteristics of AGN

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

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

$$L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma_T} \approx 1.26\times10^{38}\,{\rm erg/s}\frac{M}{M_\odot}$$

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

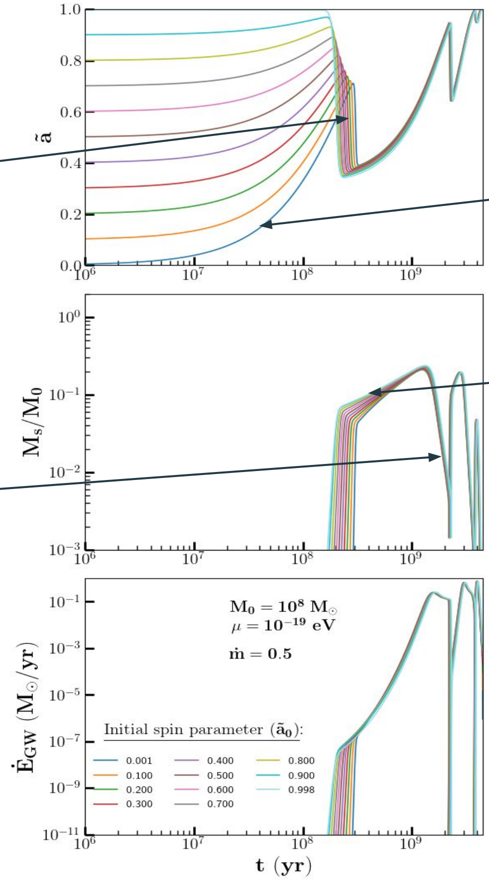
Time evolution of BH + scalar cloud system

Superradiance-dominated phase

Accretion-dominated phase

Attractor phase

GW-dominated phase



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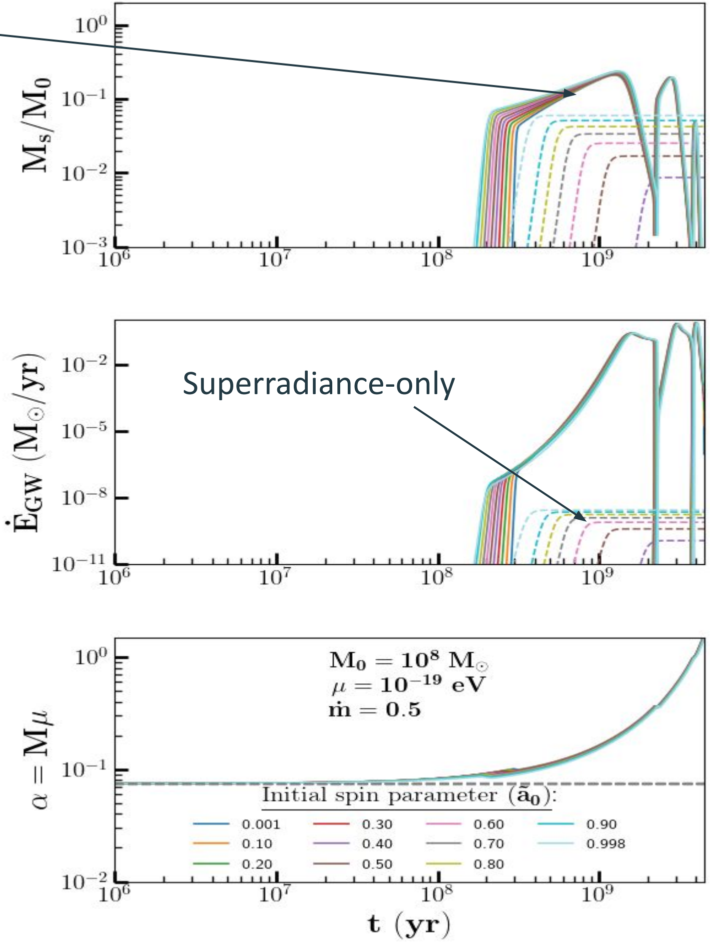
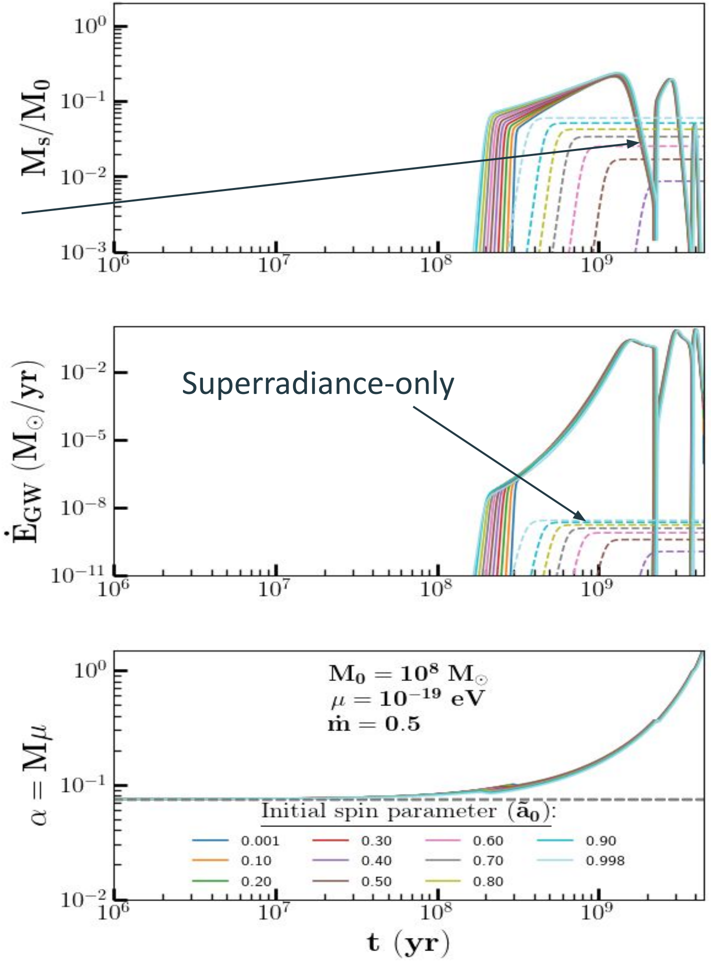
Attractor phase



- **Attractor phase**: spin hovering slightly above critical spin for an extended duration, consequently, scalar cloud continues to grow and exceeds 10% of the BH mass

P.Sarmah et al. [2404.09955]

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]

Time Variation in the AGN Characteristics due to Superradiance

Luminosity in various bands

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

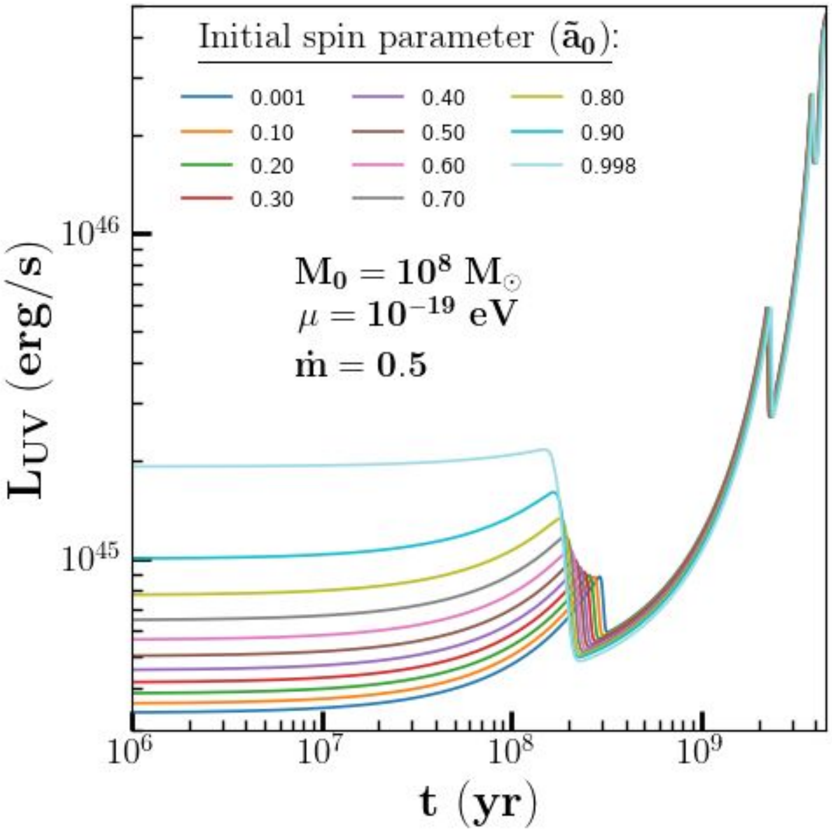
$$L_{\mathrm{X}} = \int_{10^{-4}}^{0.01} F_\lambda d\lambda,$$

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

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

P.Sarmah et al. [2404.09955]

Luminosity in various bands



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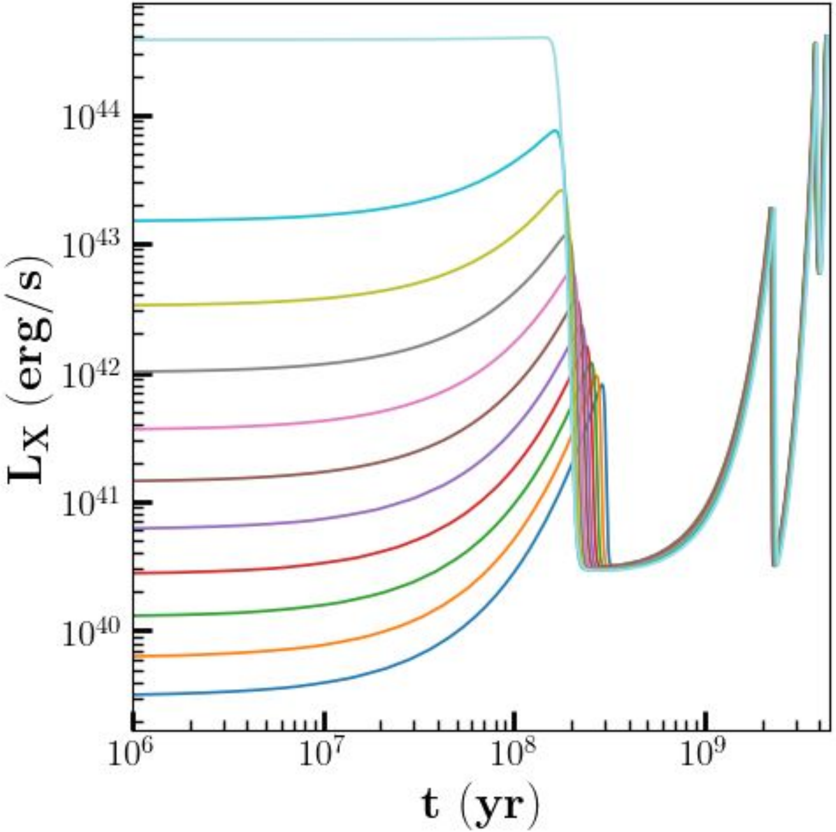

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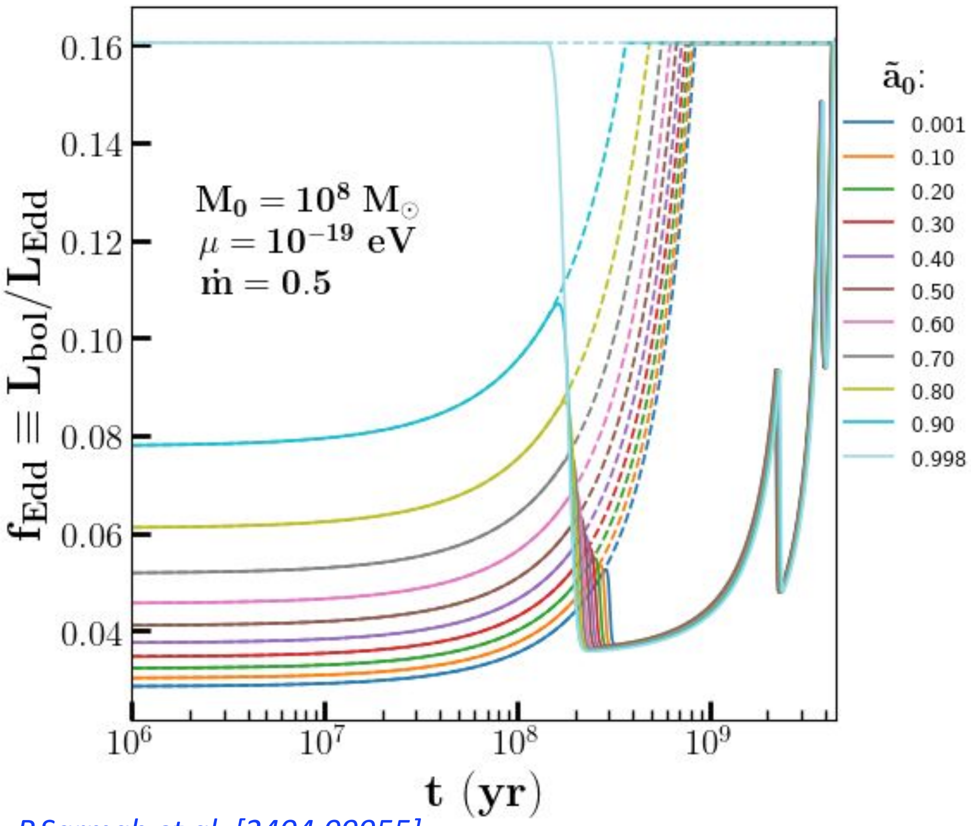
Eddington Ratio

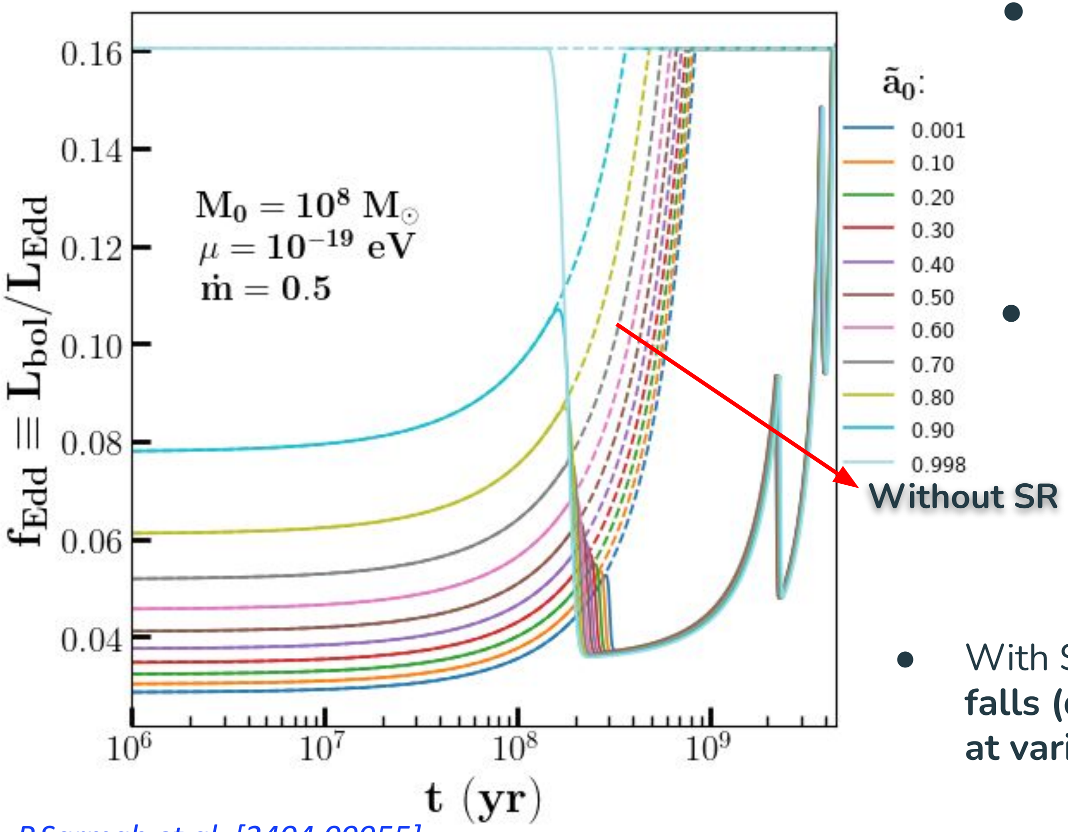


- **sudden drops** at the time-scales corresponding to various modes of superradiant growth.

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

P.Sarmah et al. [2404.09955]

Eddington Ratio



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

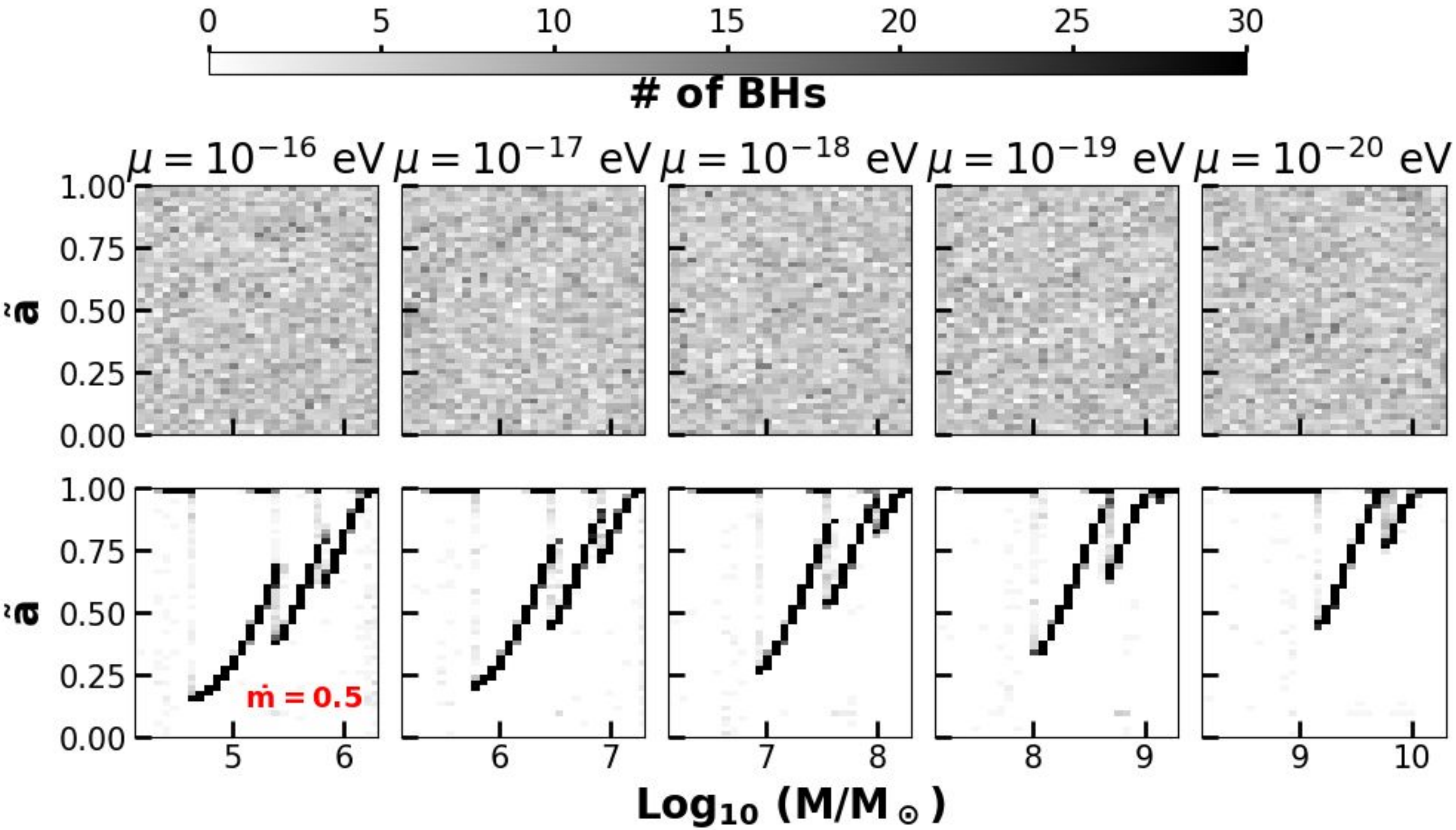
$$f_{Edd} = \epsilon(\tilde{a})\dot{m}.$$

- Without scalar field, $\mathbf{f_{Edd}}$ **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.**

P.Sarmah et al. [2404.09955]

Distribution of SMBHs at the AGN core



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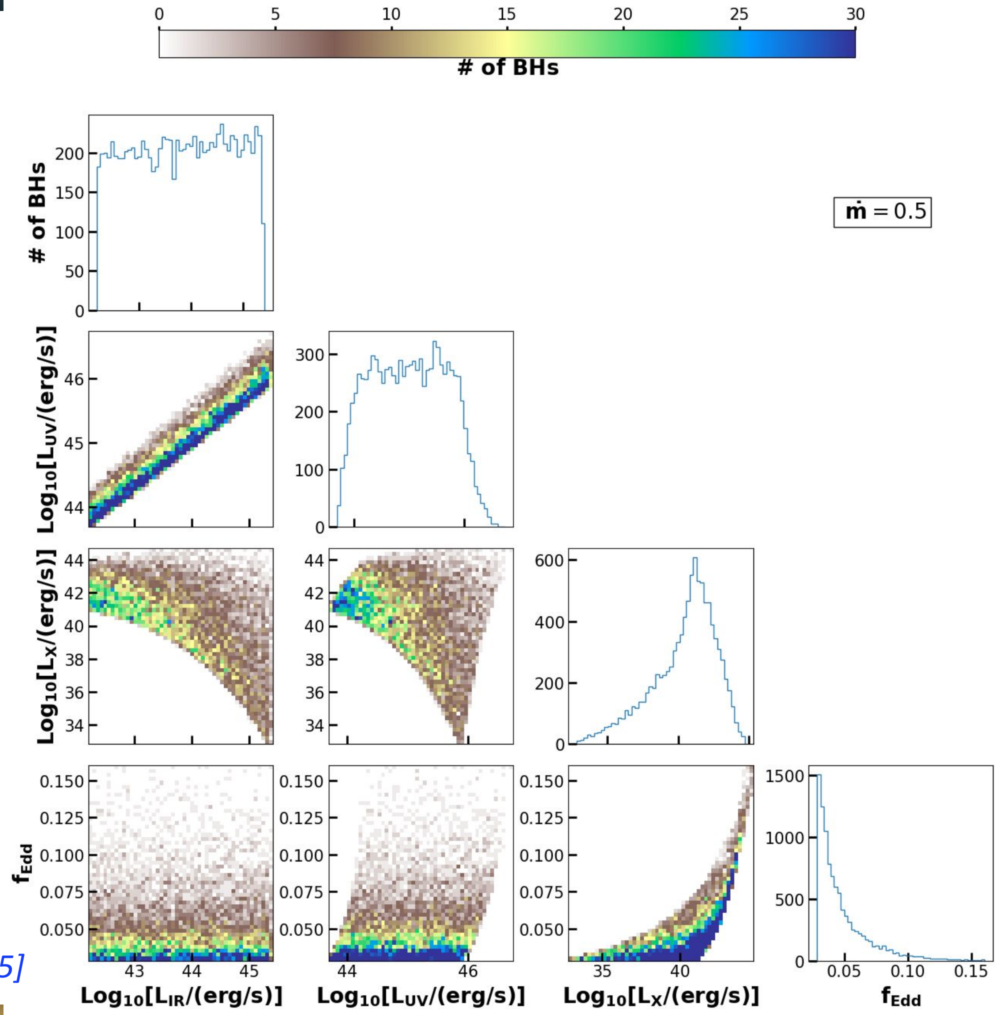
Distribution of AGN Characteristics



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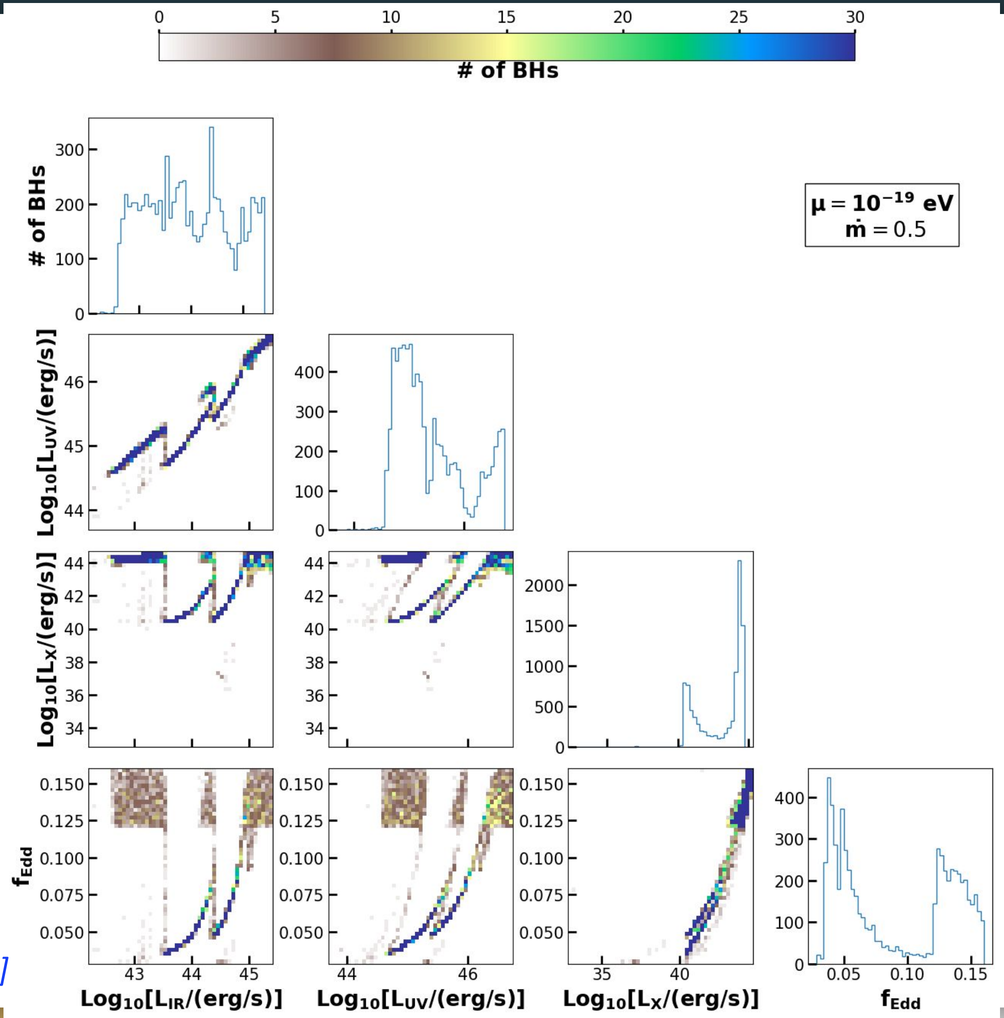


P.Sarmah et al. [2404.09955]

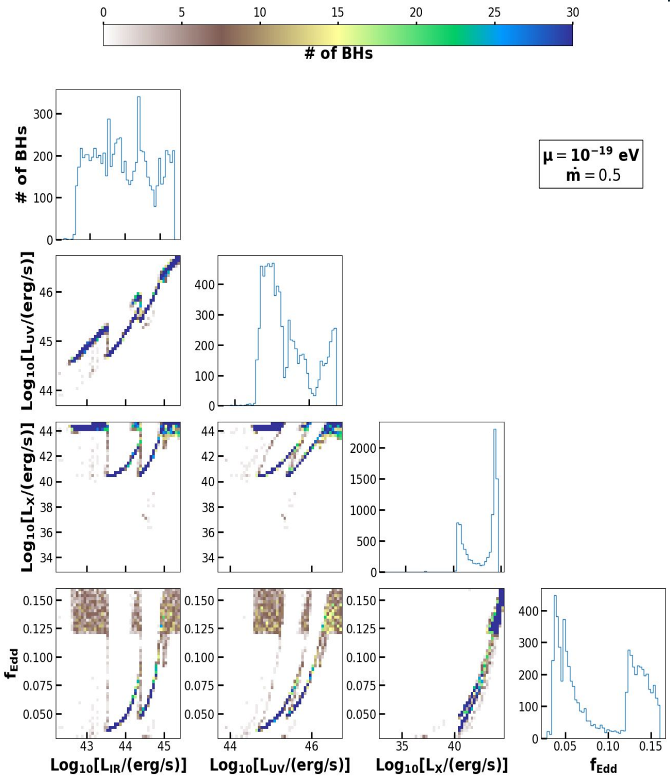
Summary

- 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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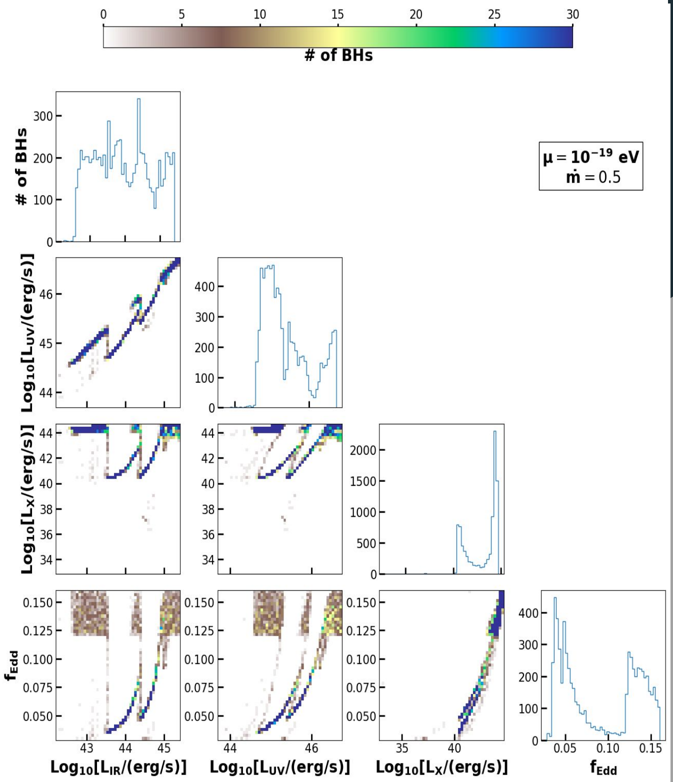


This depletion in the AGN characteristics could be searched in Sloan Digital Sky Survey(SDSS), and expected to improve with Dark Energy Spectroscopic Instrument(DESI) with higher precision in the AGN characteristics.

Thank you!

Questions?
Comments?
Suggestion?

Possible signatures of SR instability in AGN

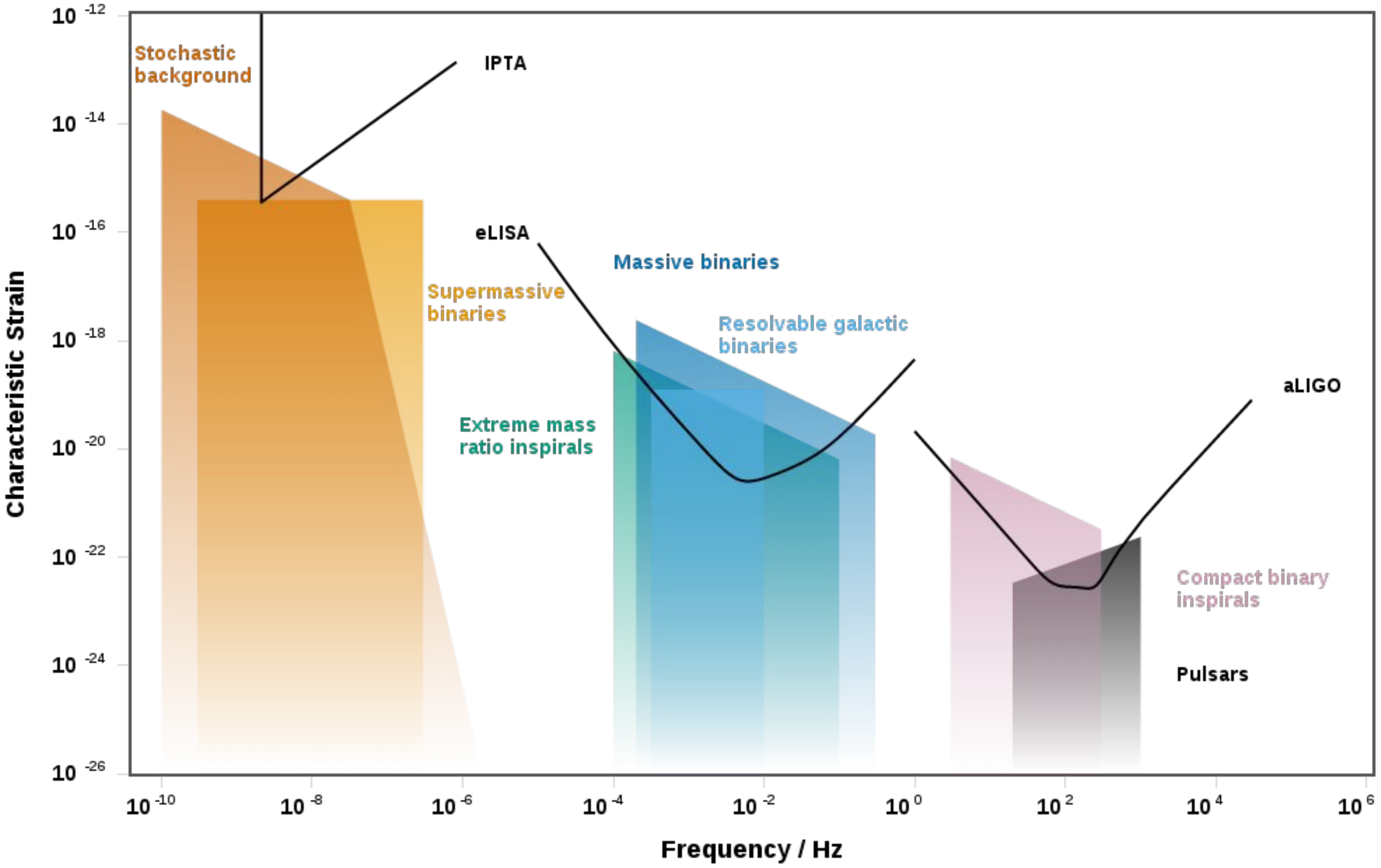
- **Galactic Outflow**: massive depletion of gas from the galaxy itself, is a link that connects the center black hole to its host galaxy.

- 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.



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

Time evolution of BH + scalar cloud system

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

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

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

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

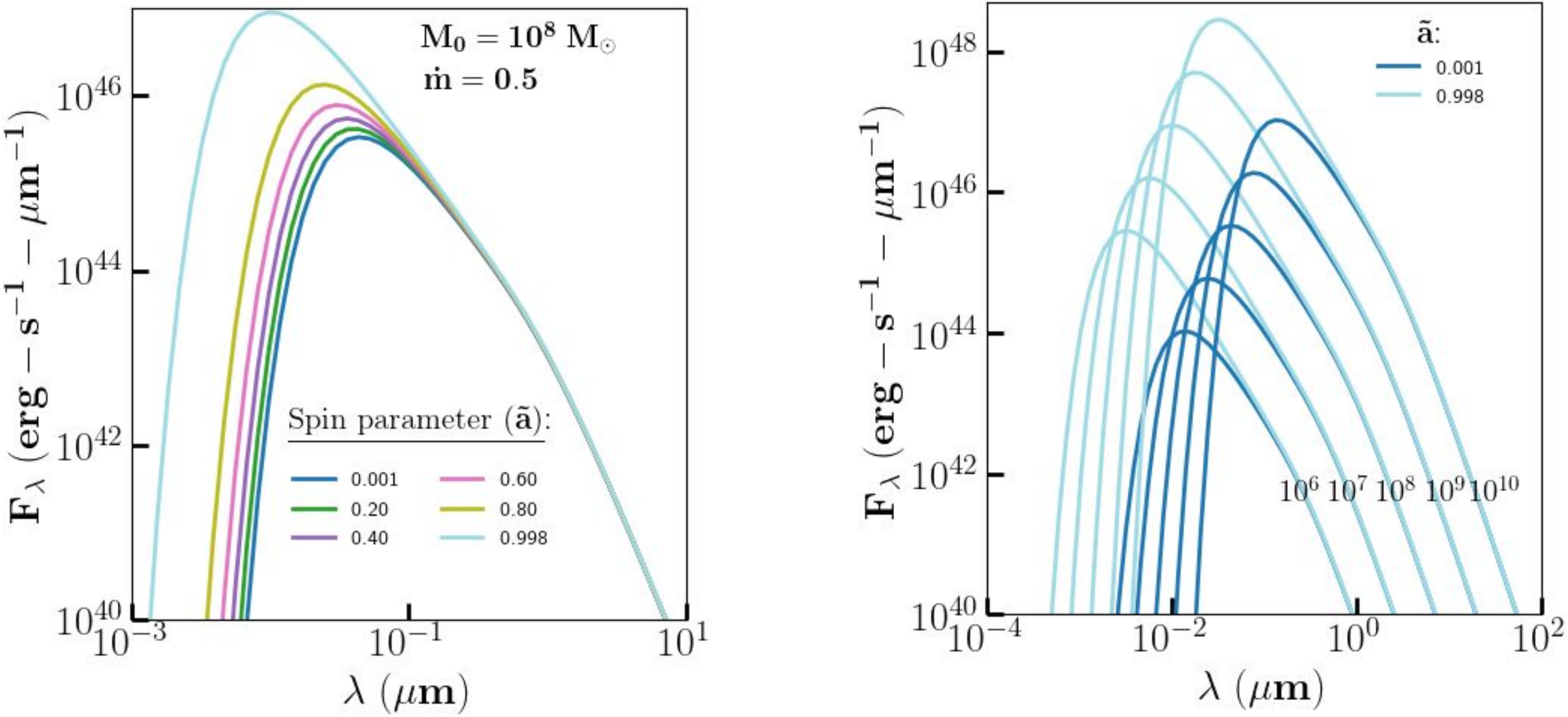
Accretion disk around Kerr BH: Novikov-Thorne model

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

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]

Accretion disk around Kerr BH: Novikov-Thorne model

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$$f_\lambda(r) = \frac{\pi}{f_{\text{col}}^4} B_\lambda(f_{\text{col}} T_s(r)),$$

where B_λ is the Planck function for blackbody radiation given by,

$$B_\lambda(r) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T_s(r)}} - 1}.$$

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

To search for the depletion region, This would require precise measurements of mass and spin of the BH.
Such measurements is most plausible when the BH is in realistic ambience from where one gets radiation coming from the surrounding of the BH and then through spectroscopic measurements one gets the information of spin and mass.

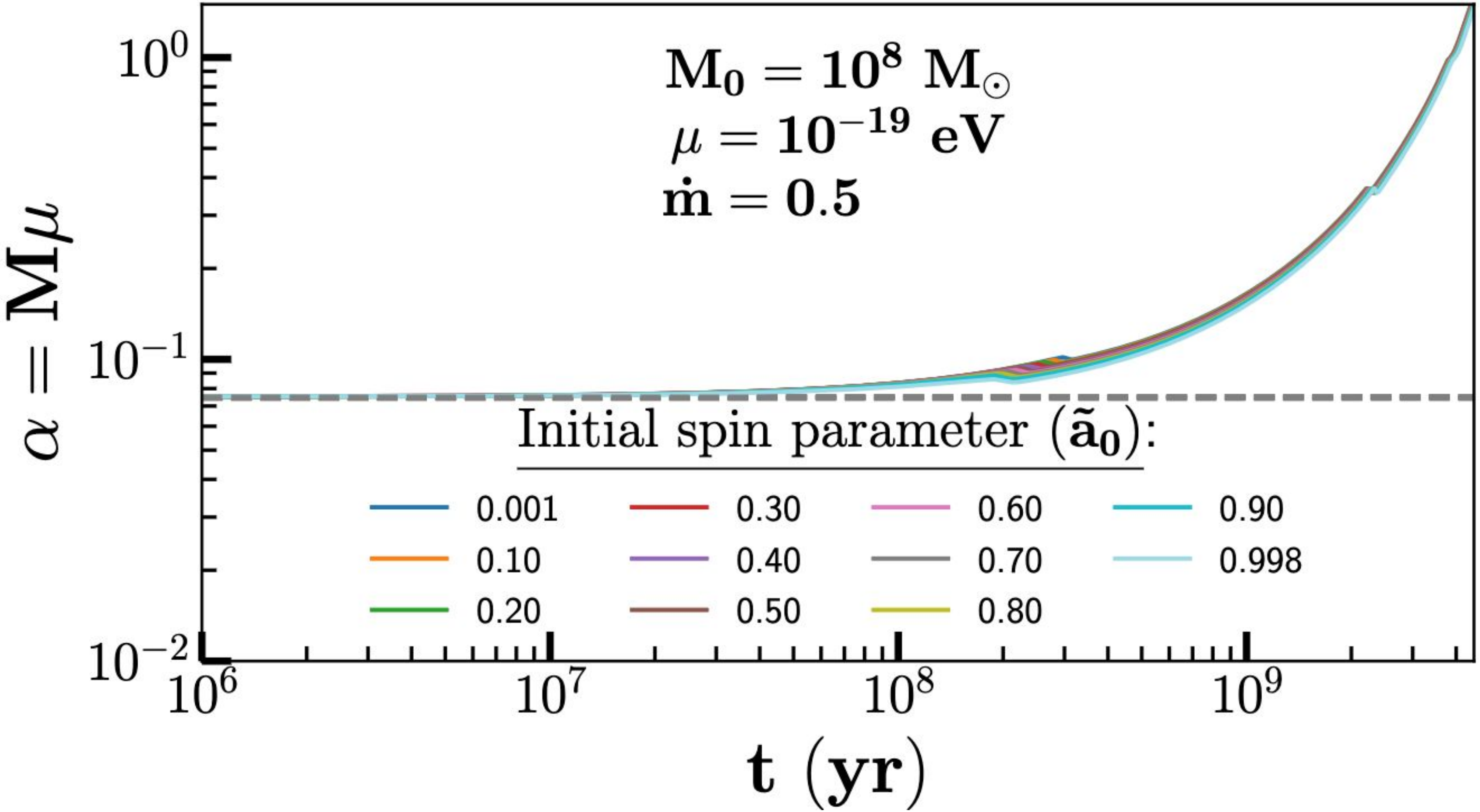
Best example for this case where we get SMBH in a realistic ambience is -AGN.

For isolated BH- Bh image

$$ds^2 = -\left(1 - \frac{2Mr}{\rho^2}\right) dt^2 - \frac{4Mra}{\rho^2} \sin^2\theta dt d\phi + \frac{\rho^2}{\Delta} dr^2 + \rho^2 d\theta^2 + \left(r^2 + a^2 + \frac{2Mra^2 \sin^2\theta}{\rho^2}\right) \sin^2\theta d\phi^2,$$

where $\rho^2 = r^2 + a^2 \cos^2\theta$ and $\Delta = r^2 + a^2 - 2Mr$. Here spin a c

Added by Himanshu



Luminosity in various bands

Remove vis ir plot

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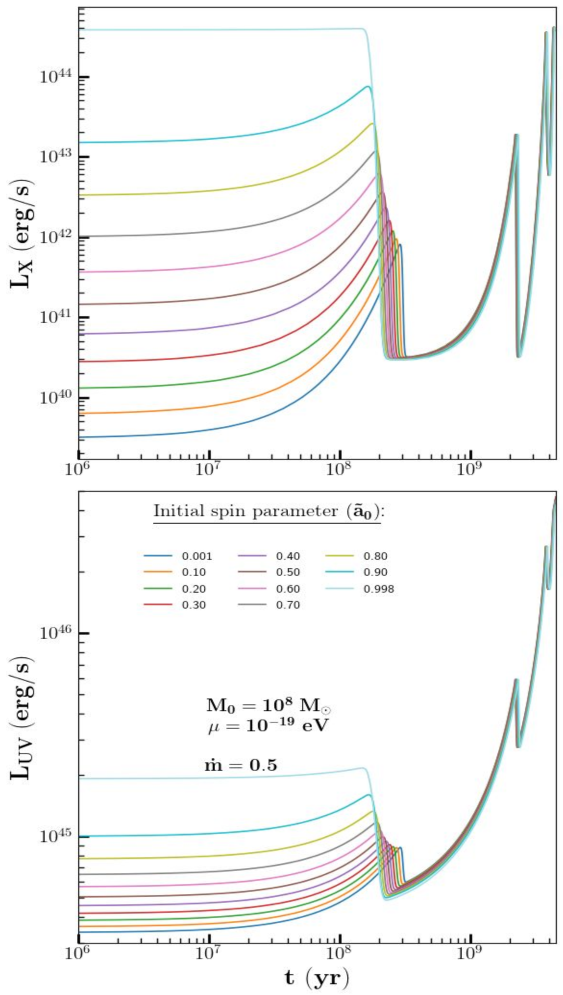

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