Effects of Superradiance in Active Galactic Nuclei

with Himanshu Verma, Kingman Cheung, Joseph Silk [arXiv: 2404.09955]

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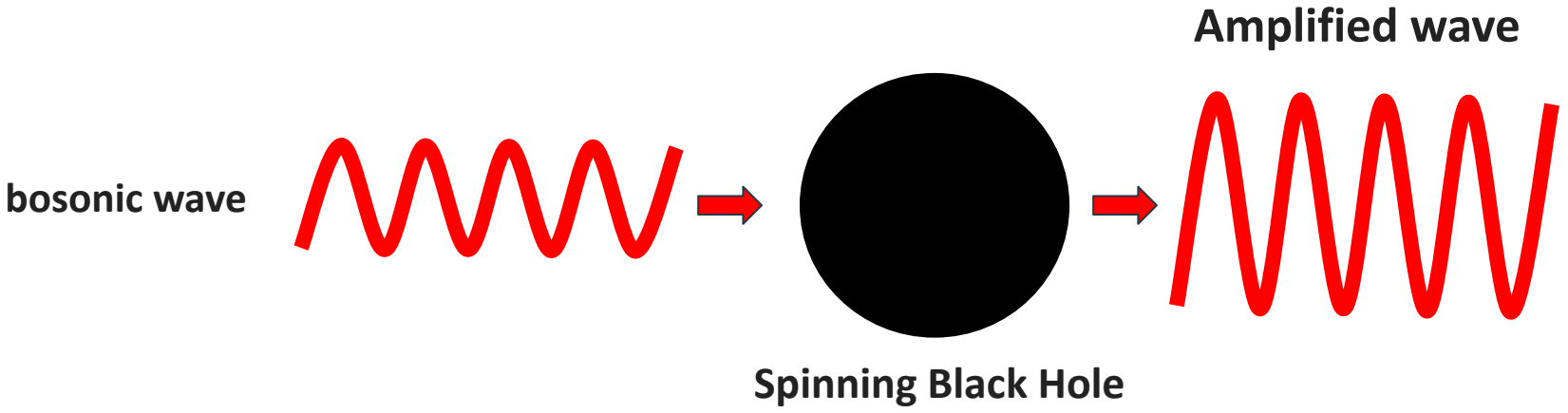
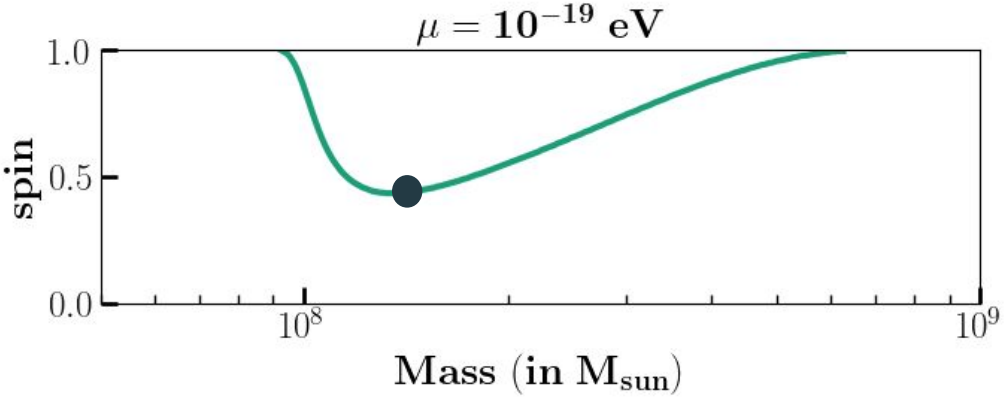
Black Hole Superradiance

- 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

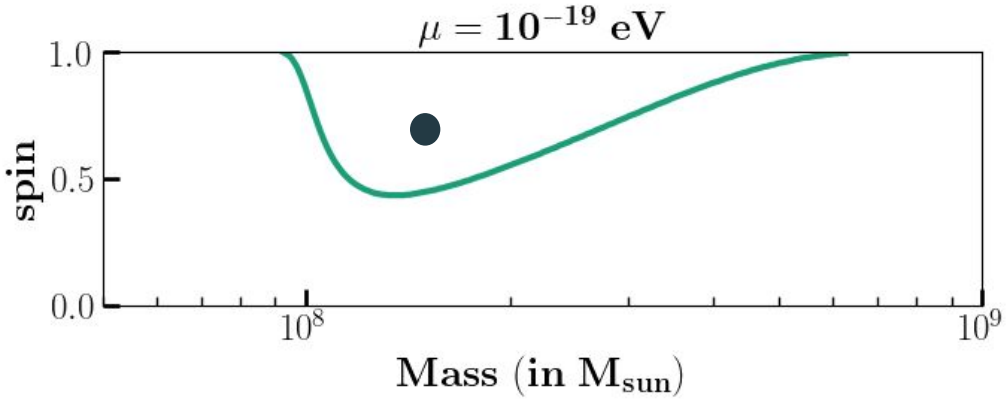


Observational signatures of Superradiance



P.Sarmah et al. [2404.09955]

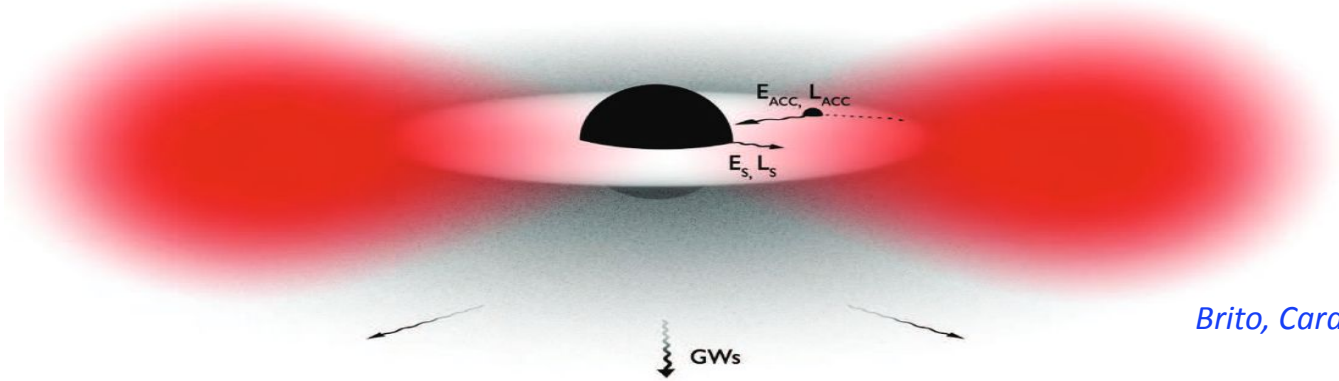
Observational signatures of Superradiance



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)

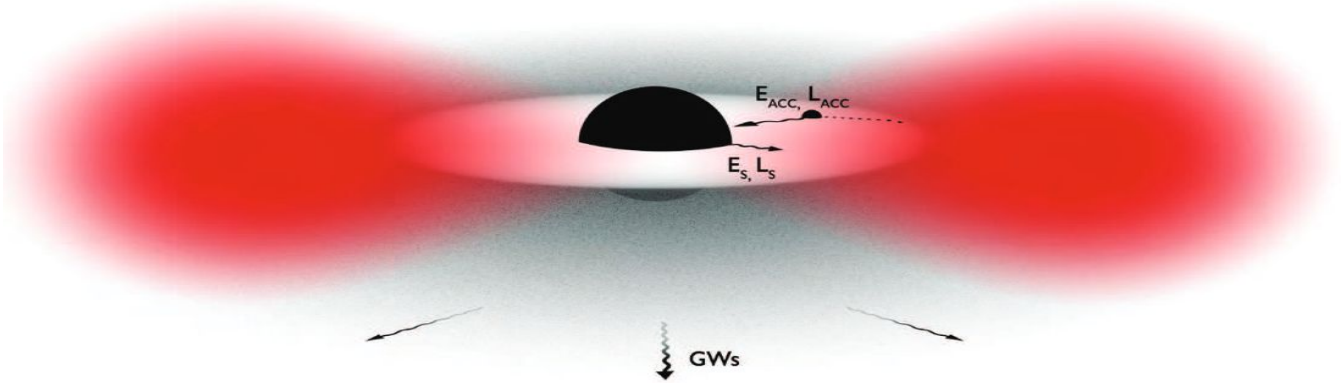


Brito, Cardoso, Pani, 2014 [1411.0686]

- **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

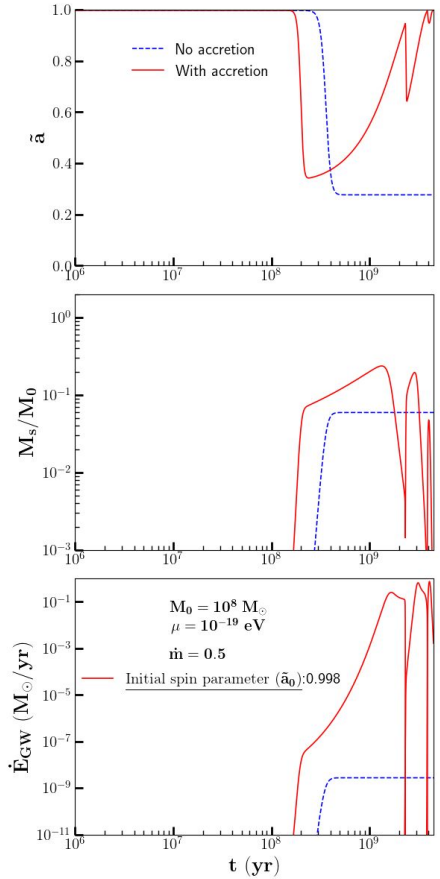
Radiative efficiency

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

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

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

Time evolution of accreting BH + scalar cloud system



P.Sarmah et al. [2404.09955]

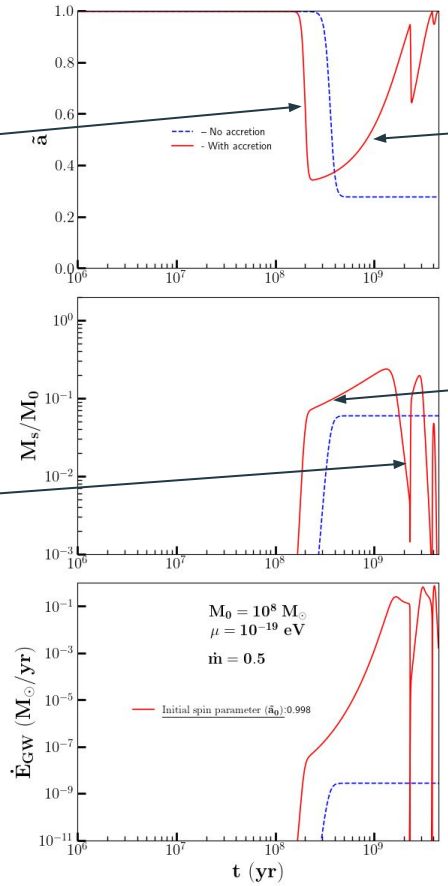
Time evolution of accreting BH + scalar cloud system

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 $F_\lambda(\tilde{a}, r)$

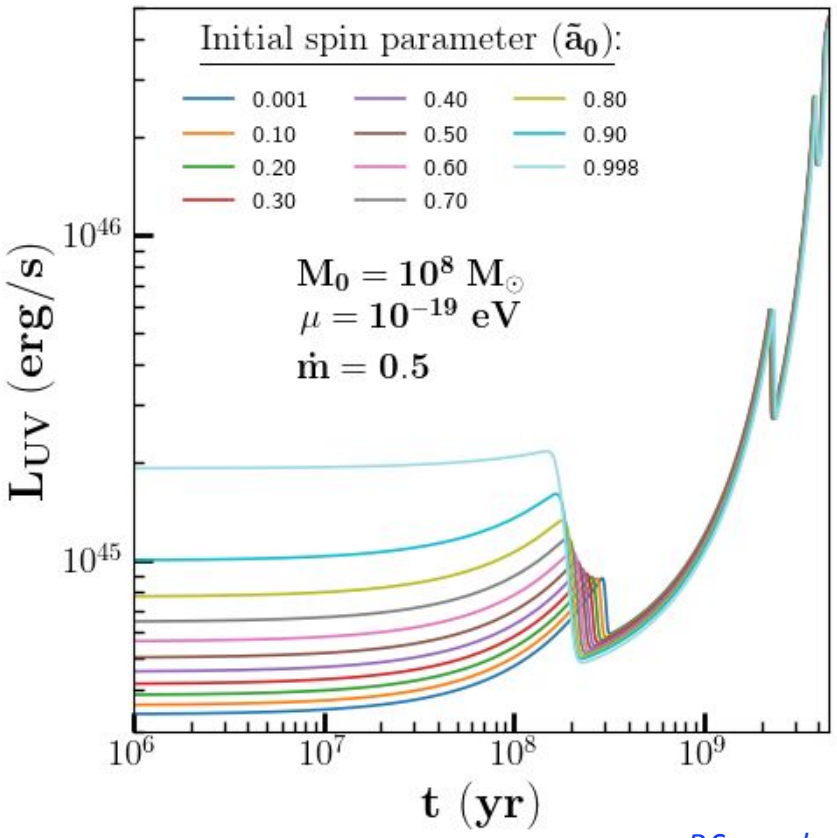
$$L_{\mathrm{X}} = \int_{10^{-4}}^{0.01} F_\lambda d\lambda,$$

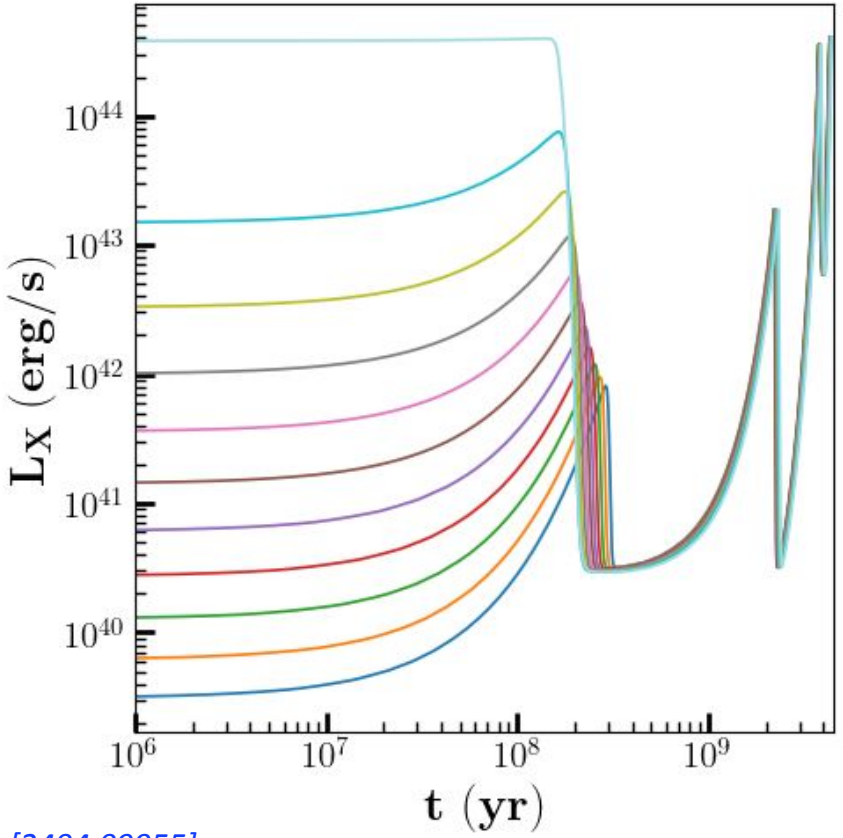
$$L_{\mathrm{UV}} = \int_{0.01}^{0.4} F_\lambda d\lambda,$$

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

P.Sarmah et al. [2404.09955]

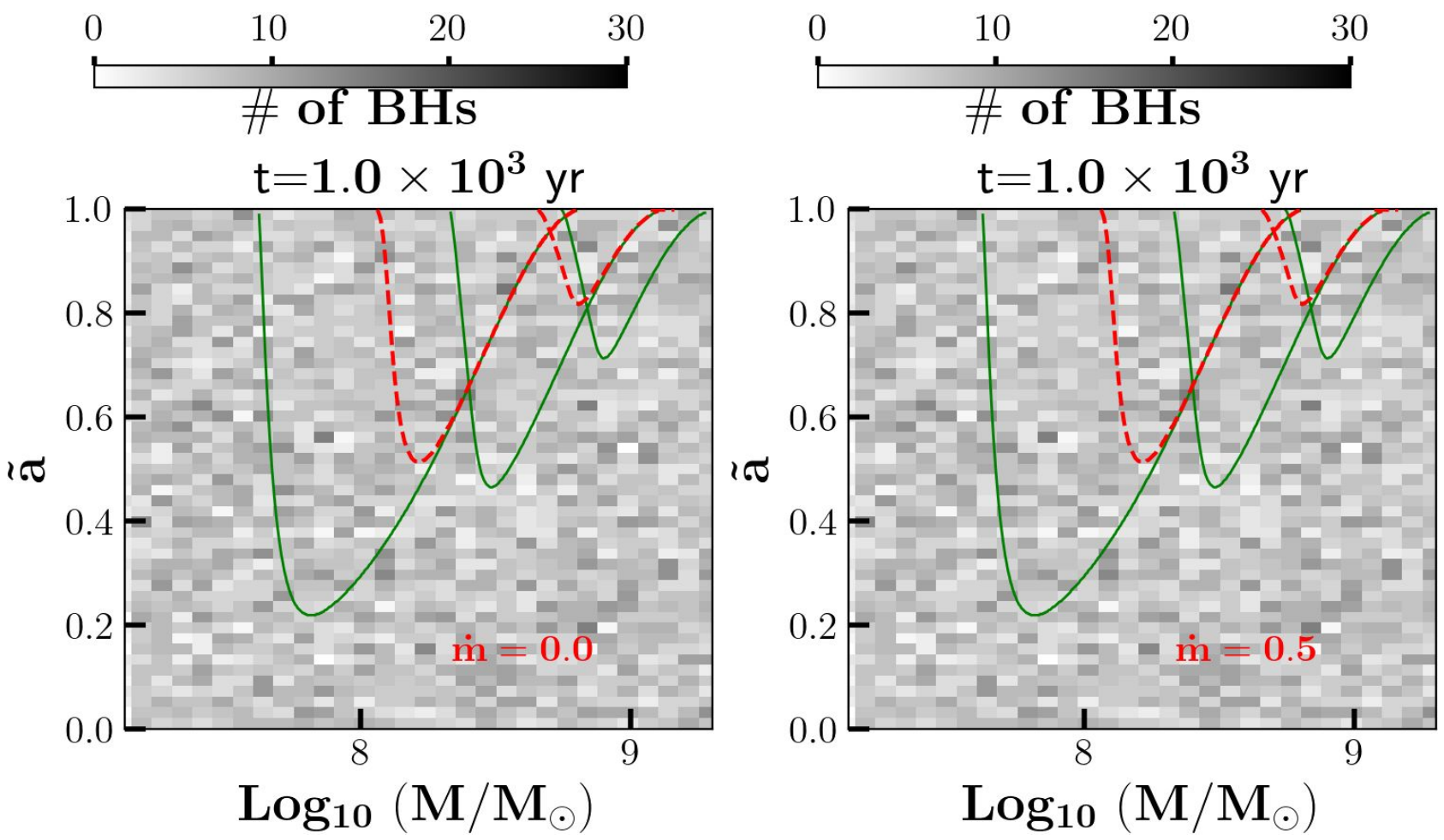
Luminosity in various bands

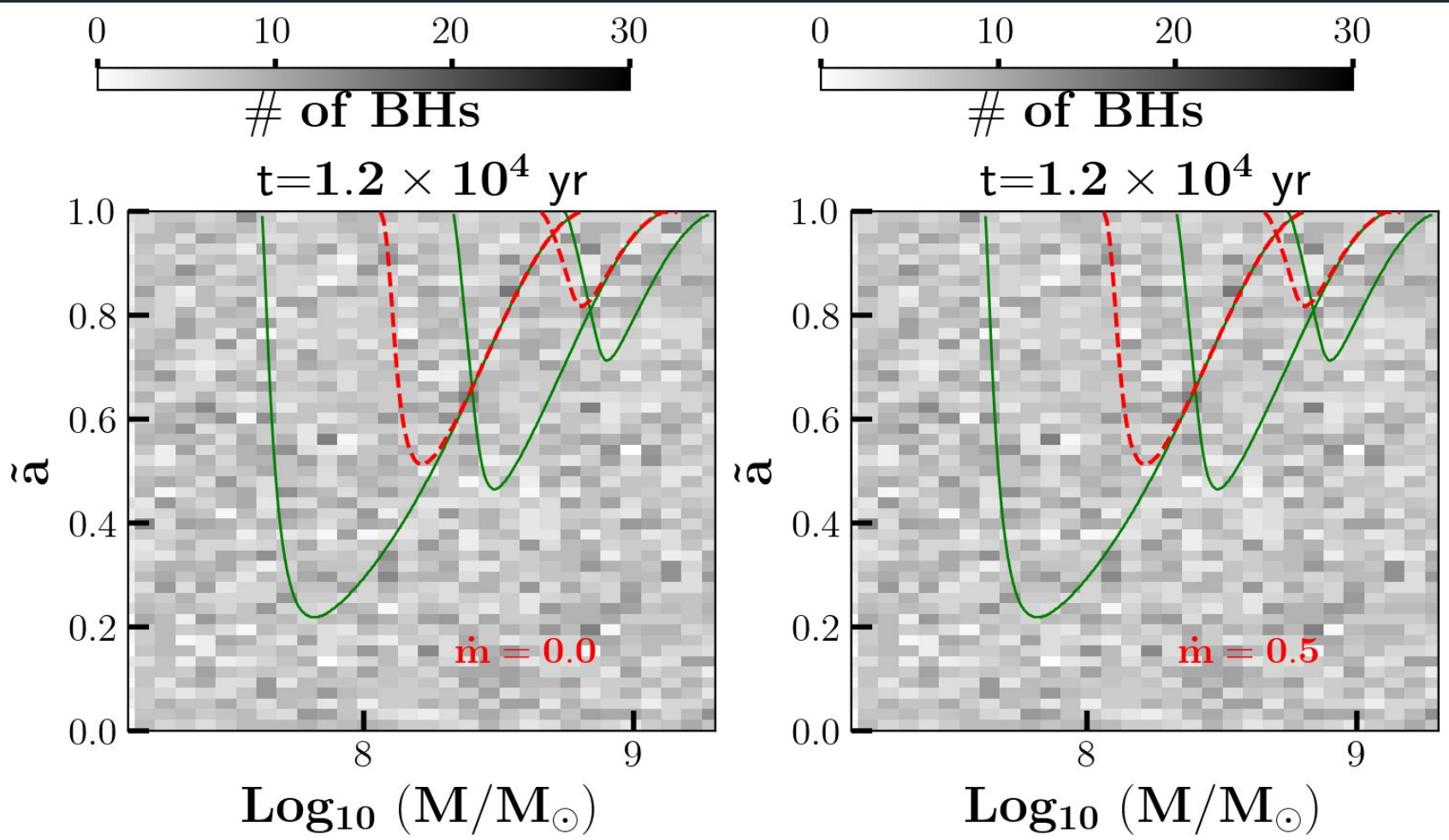


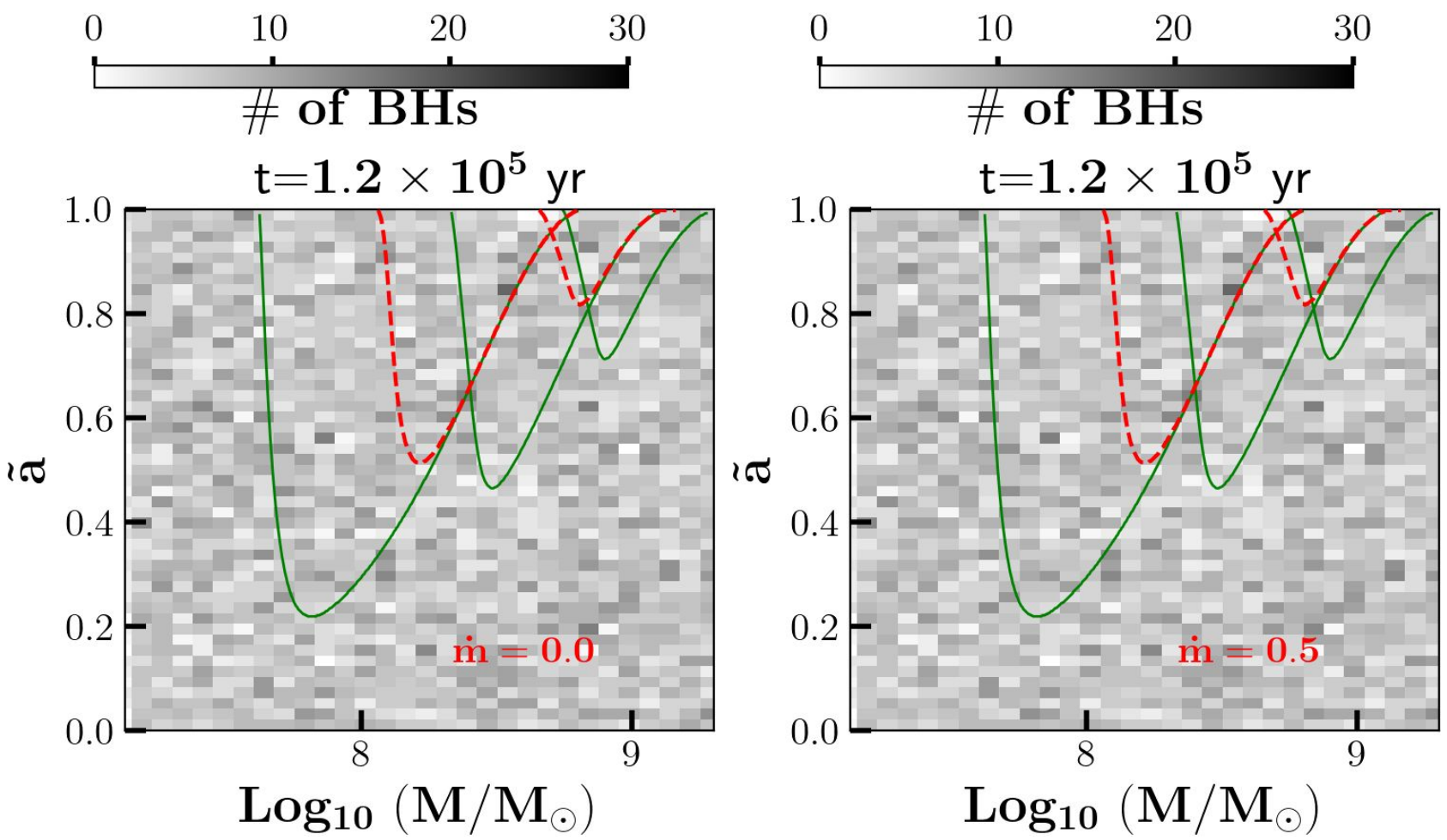


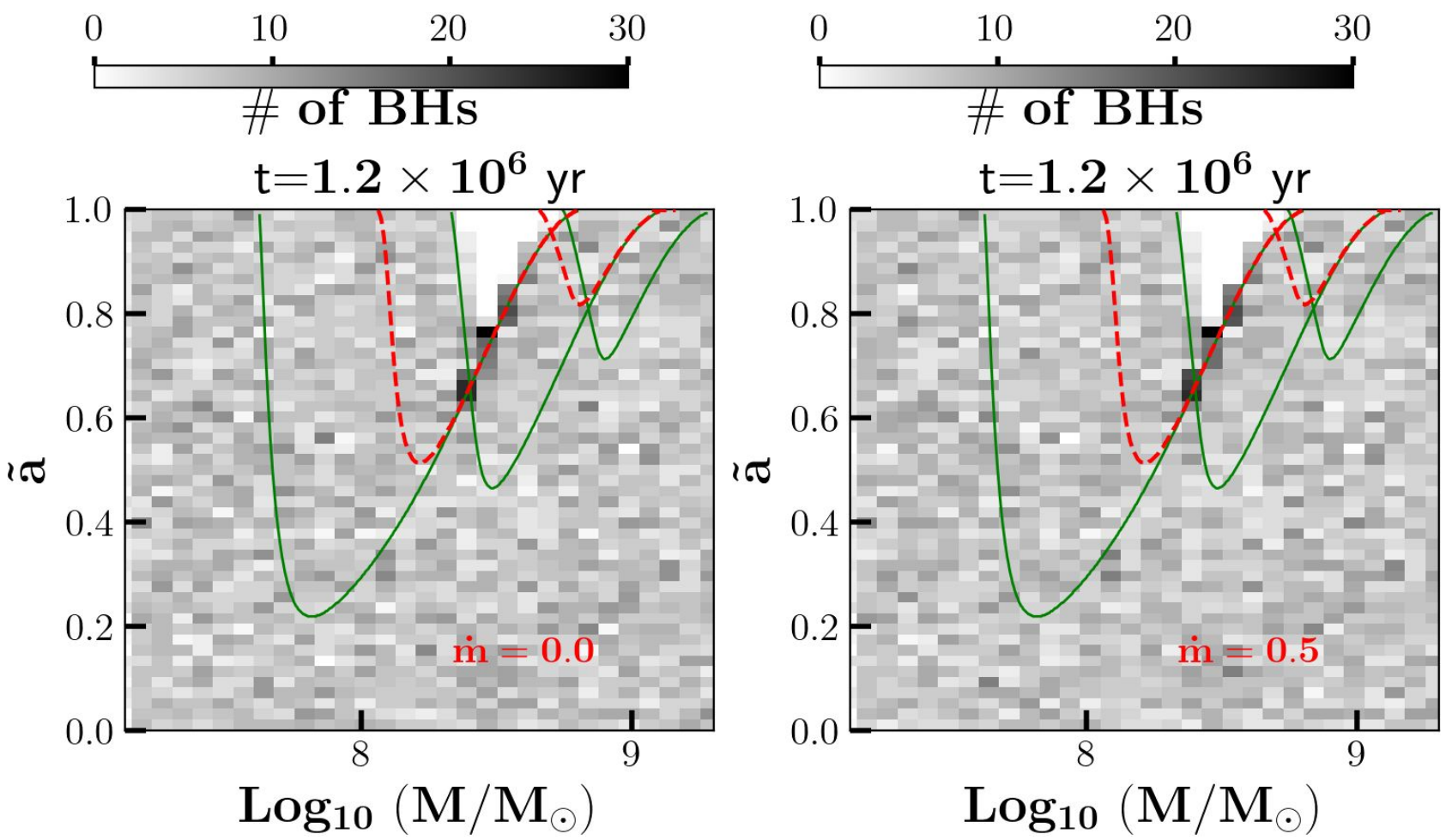
P.Sarmah et al. [2404.09955]

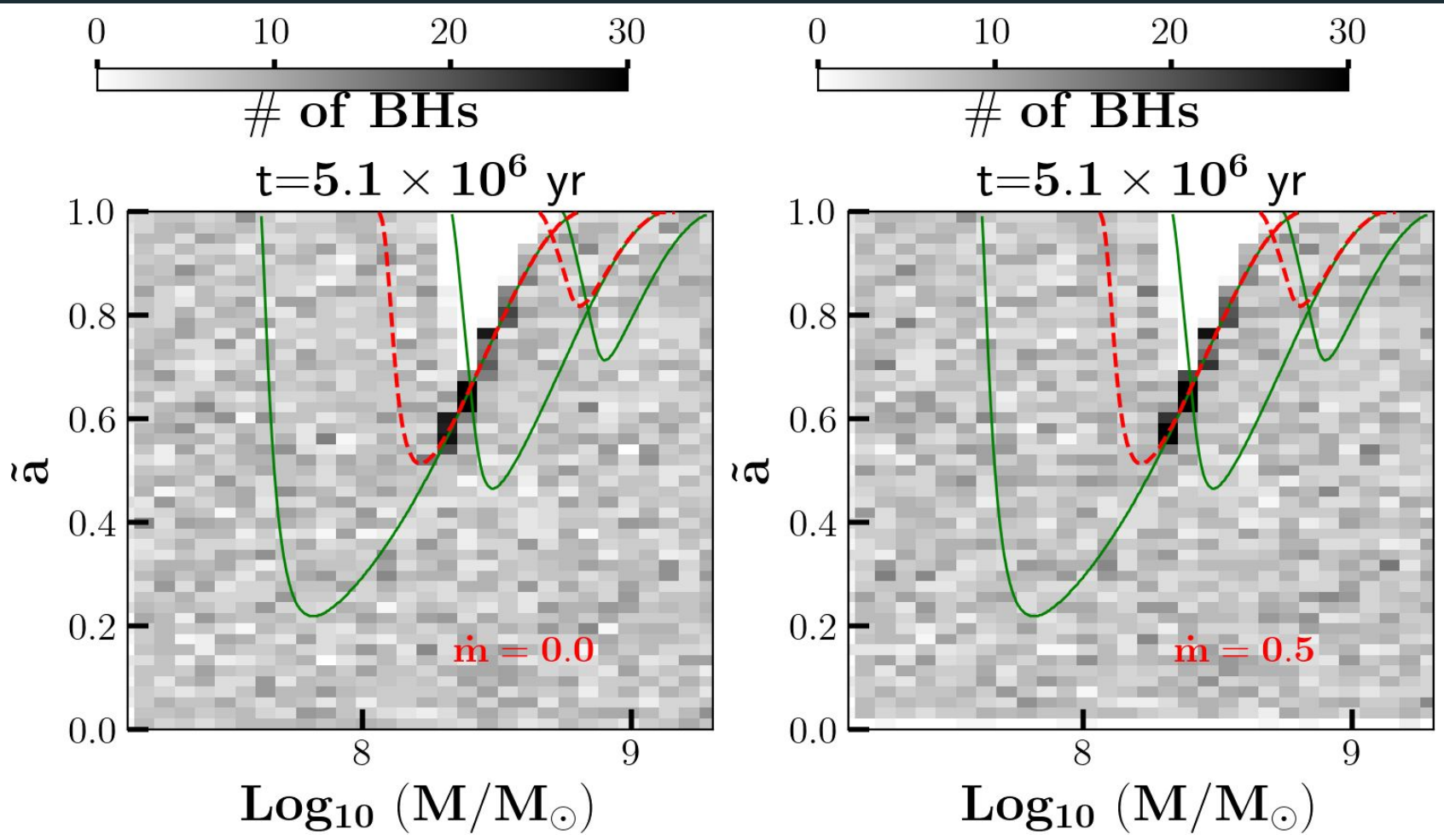
Distribution of SMBHs at the AGN core

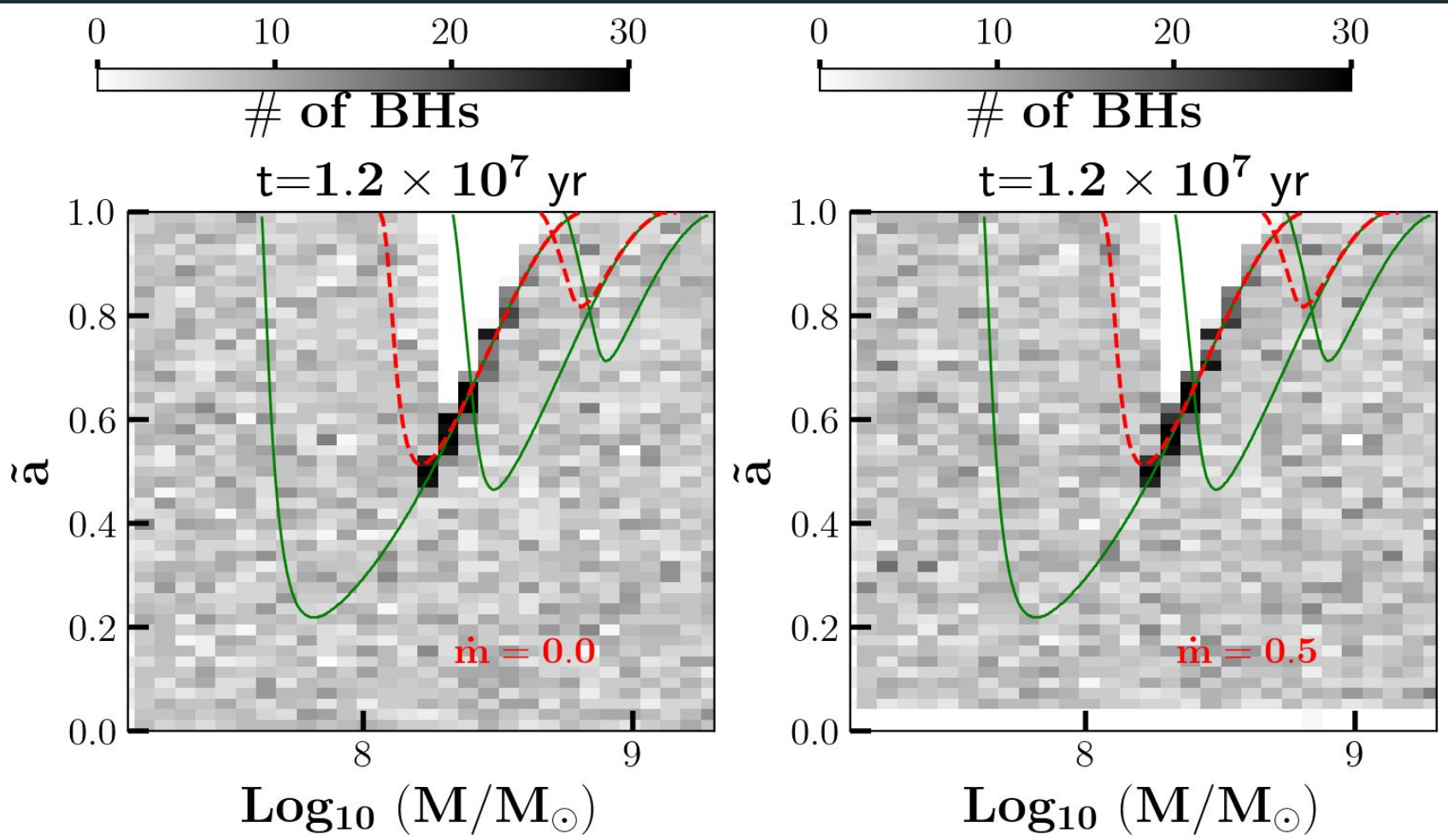

0
10
20
30
# of BHs
t=1.0 × 10³ yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log₁₀ (M/M⊙)
0
10
20
30
# of BHs
t=1.0 × 10³ yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log₁₀ (M/M⊙)

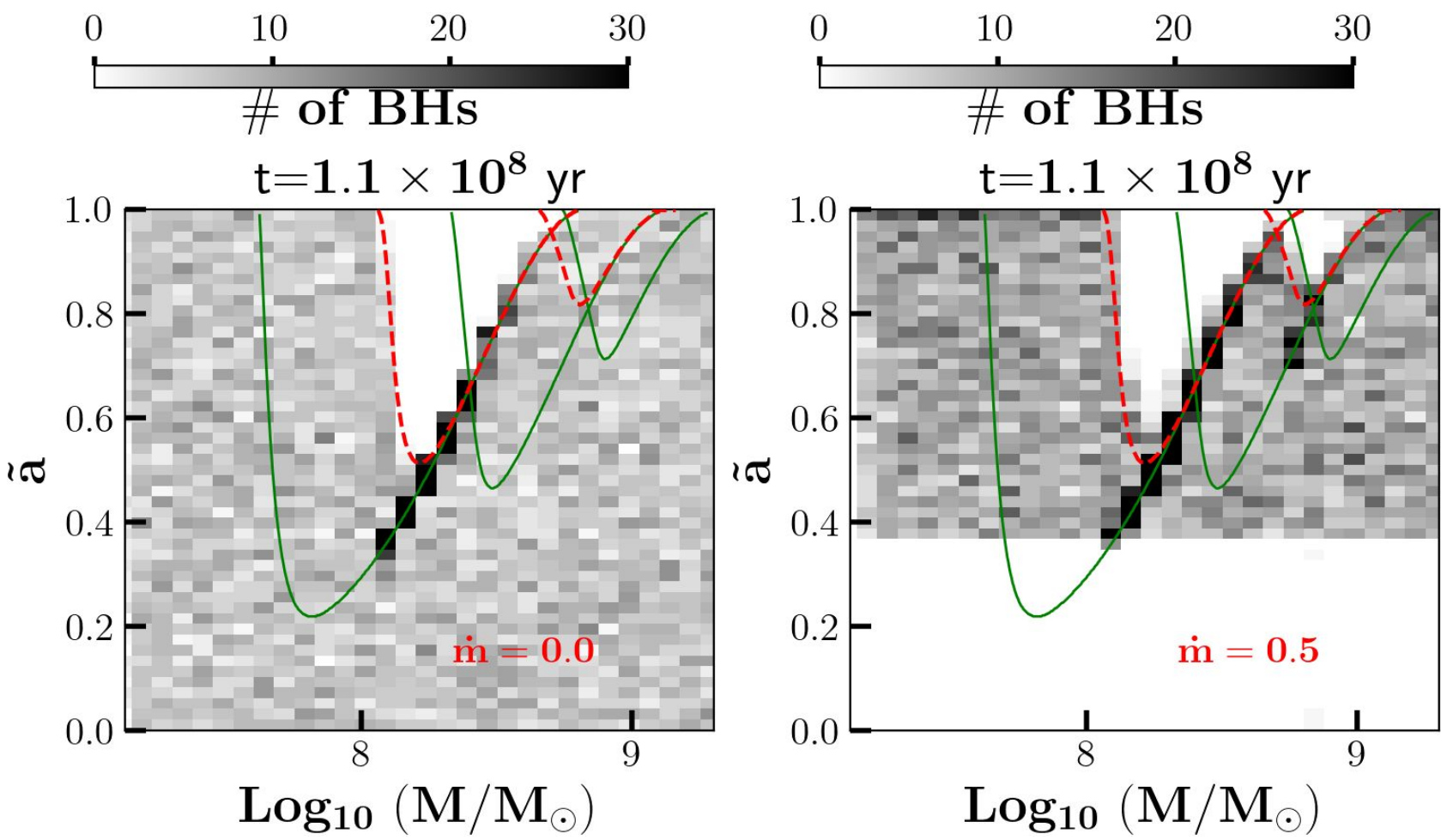

0
10
20
30
# of BHs
t=1.2 × 10^4 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^4 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)

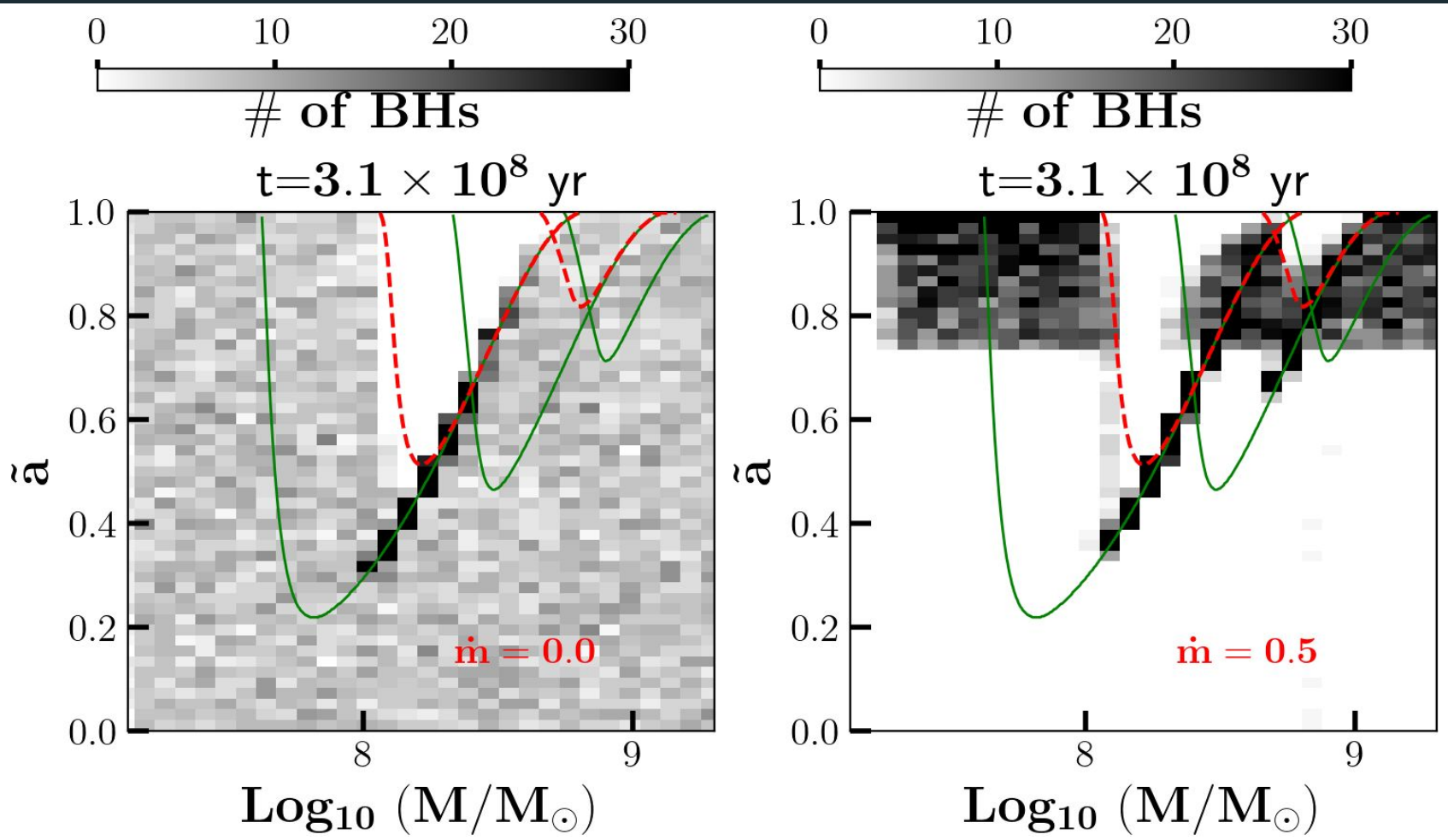

0
10
20
30
# of BHs
t=1.2 × 10^5 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^5 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)

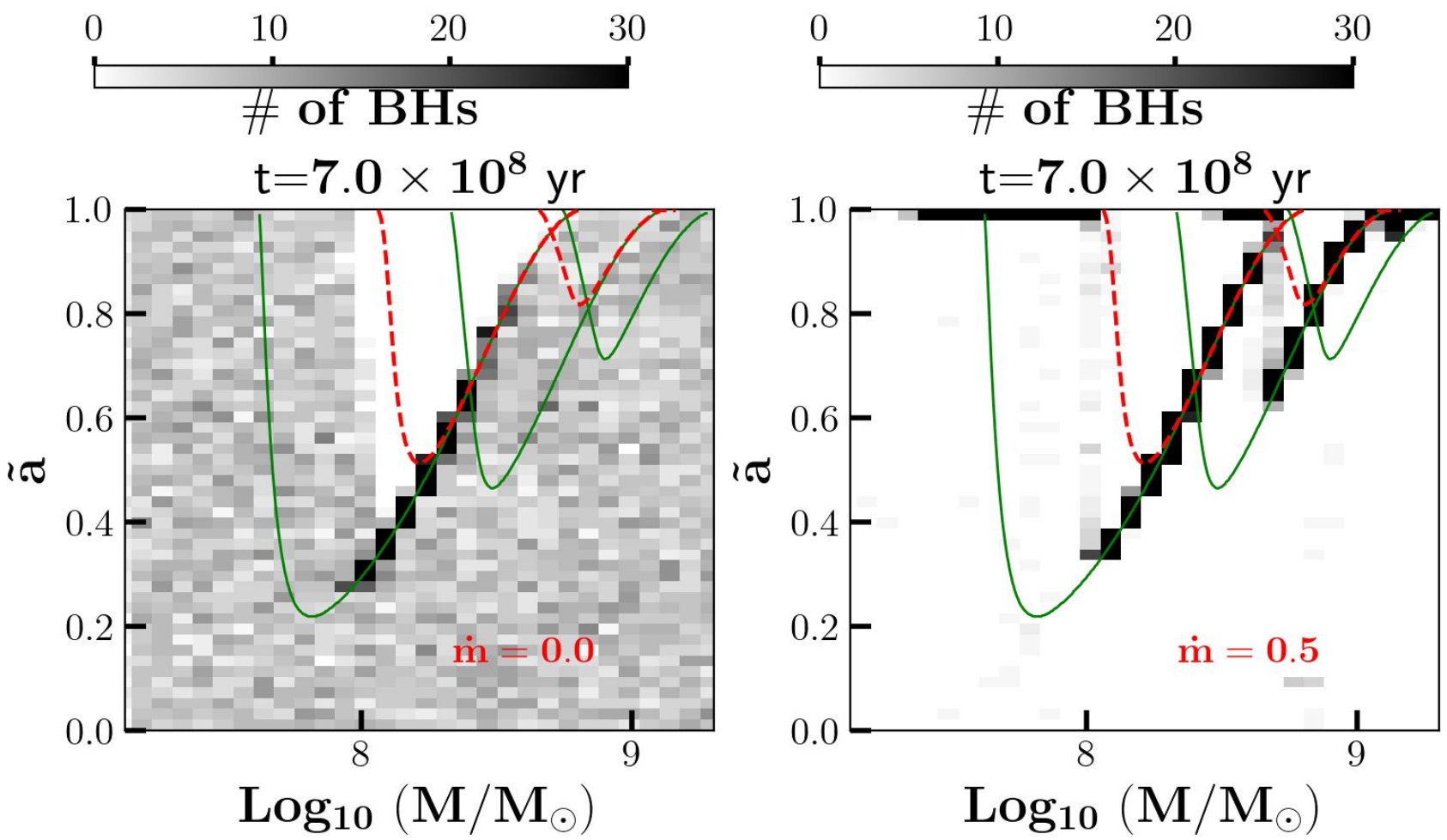

0
10
20
30
# of BHs
t=1.2 × 10^6 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^6 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)


0
10
20
30
# of BHs
t=5.1 × 10^6 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=5.1 × 10^6 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)

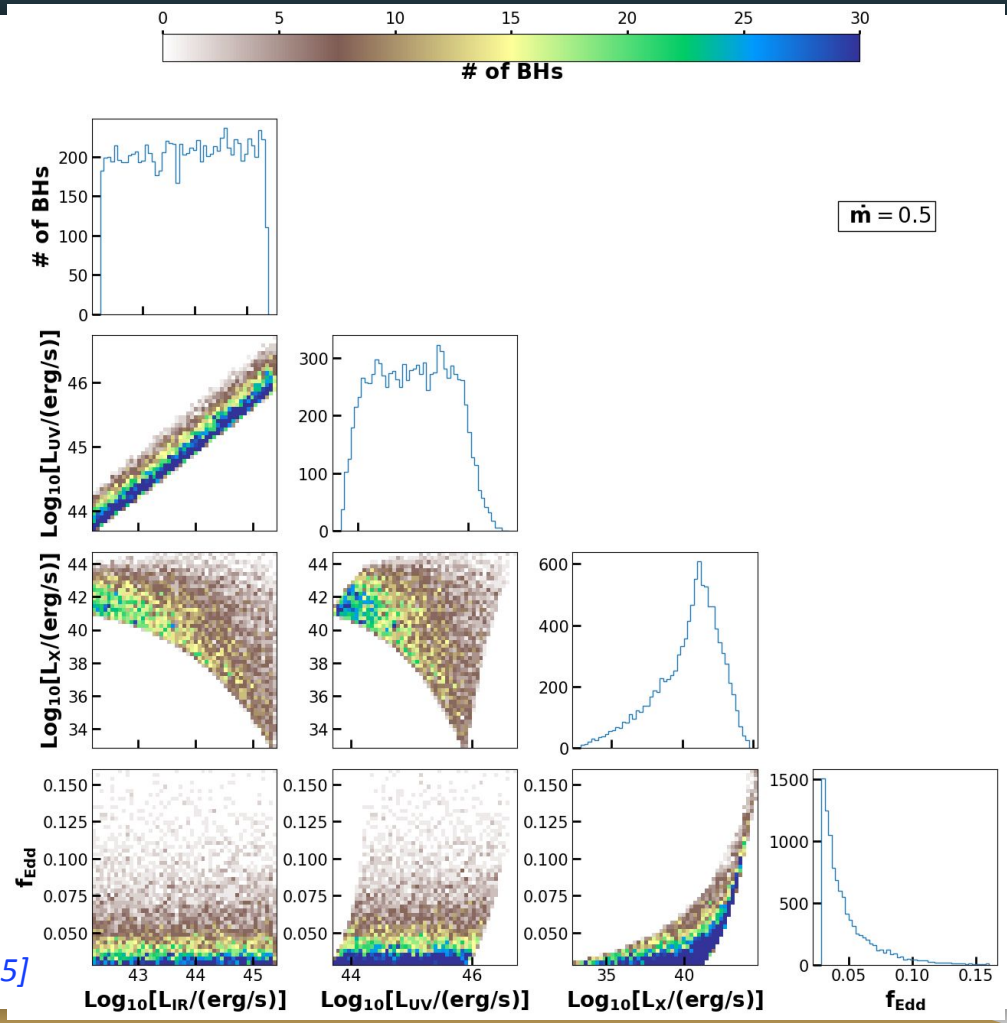

0
10
20
30
# of BHs
t=1.2 × 10^7 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^7 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)


0
10
20
30
# of BHs
t=1.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)

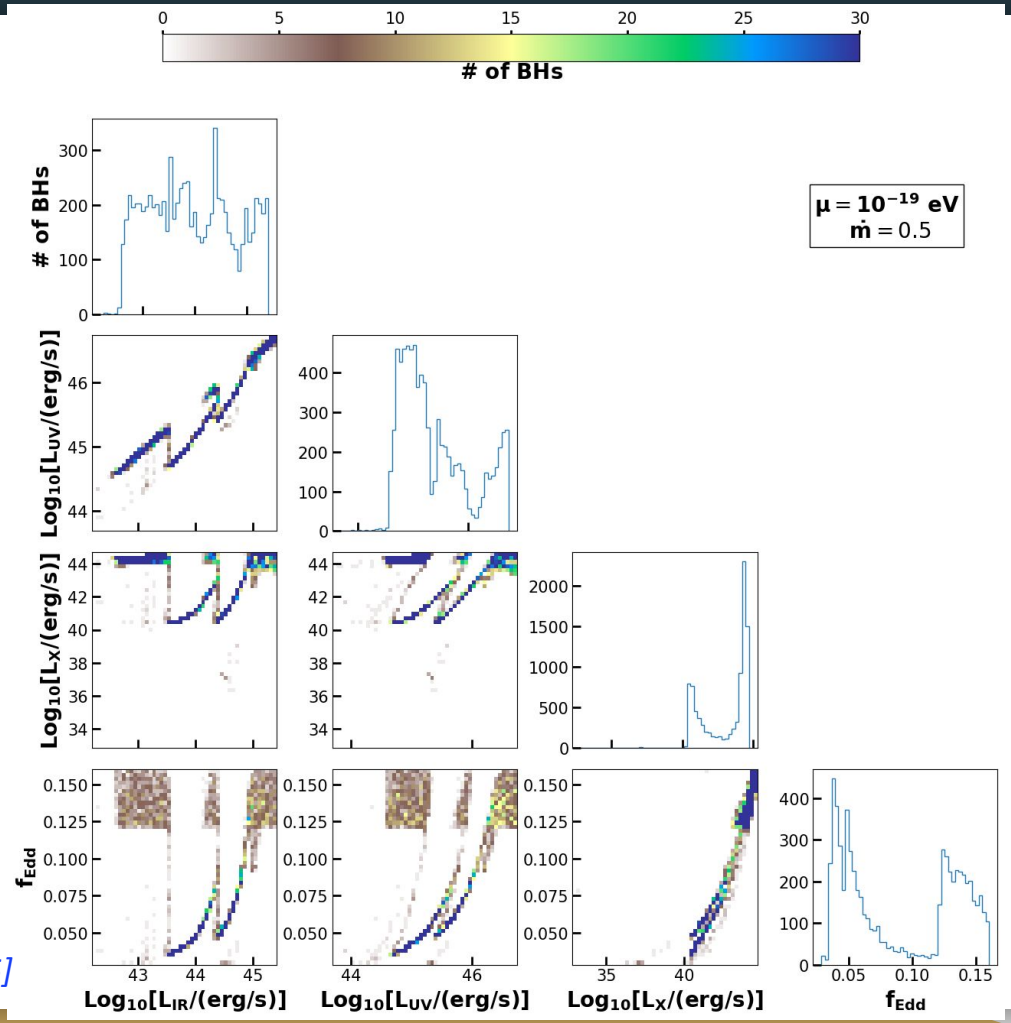

0
10
20
30
# of BHs
t=3.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=3.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)


0
10
20
30
# of BHs
t=7.0 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=7.0 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
8
9
Log10 (M/M⊙)

Distribution of AGN Characteristics



P.Sarmah et al. [2404.09955]



P.Sarmah et al. [2404.09955]

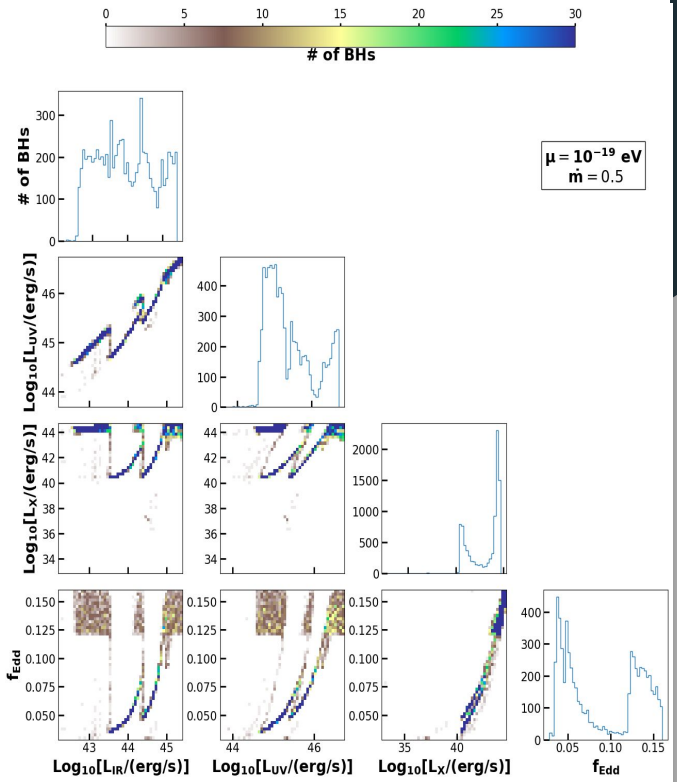
Summary

- 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.

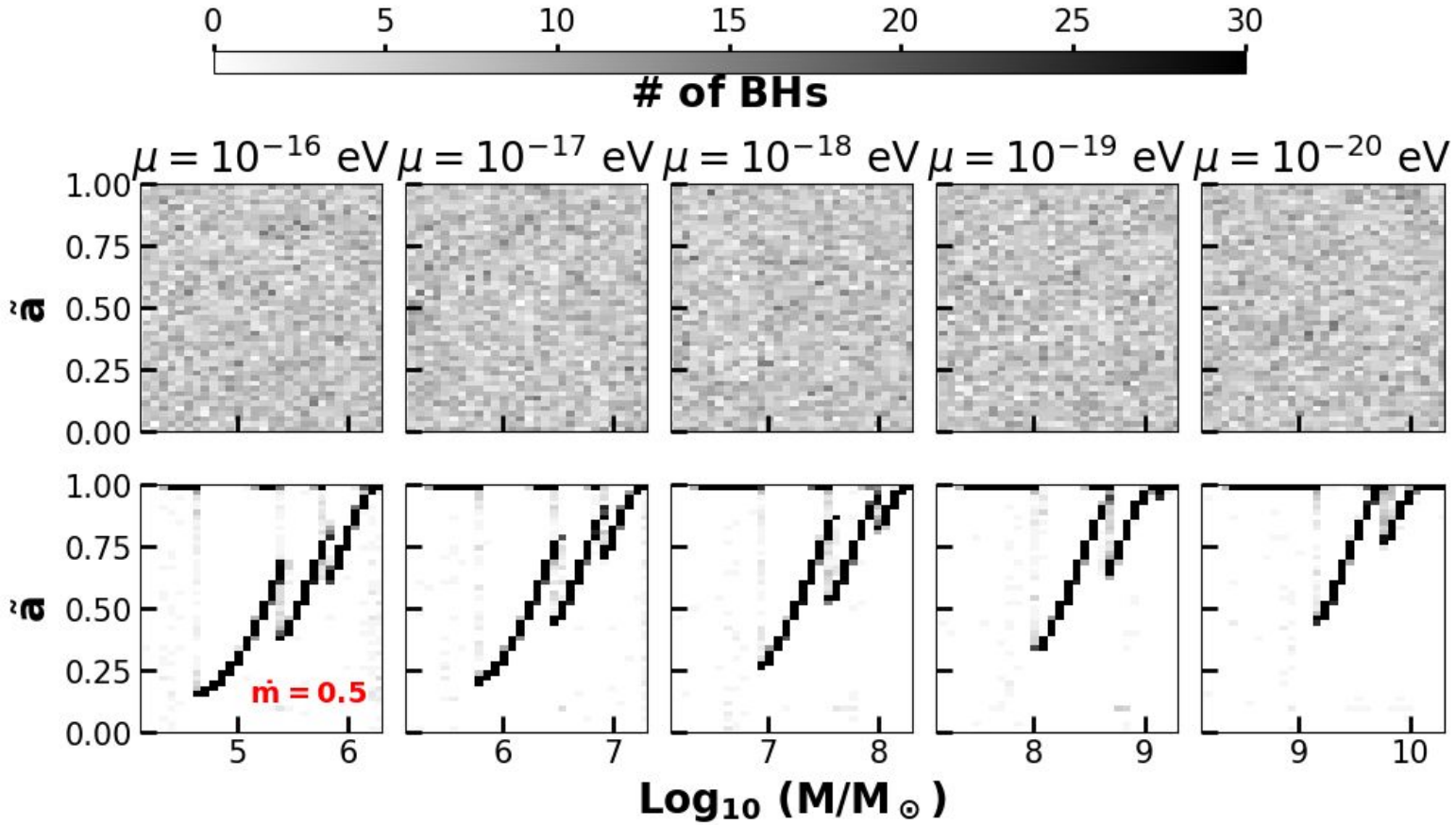
- **Multiple dips** in the luminosity evolution corresponding to timescales of dominant modes of superradiance.

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



Thank you!

Questions?
Comments?
Suggestion?



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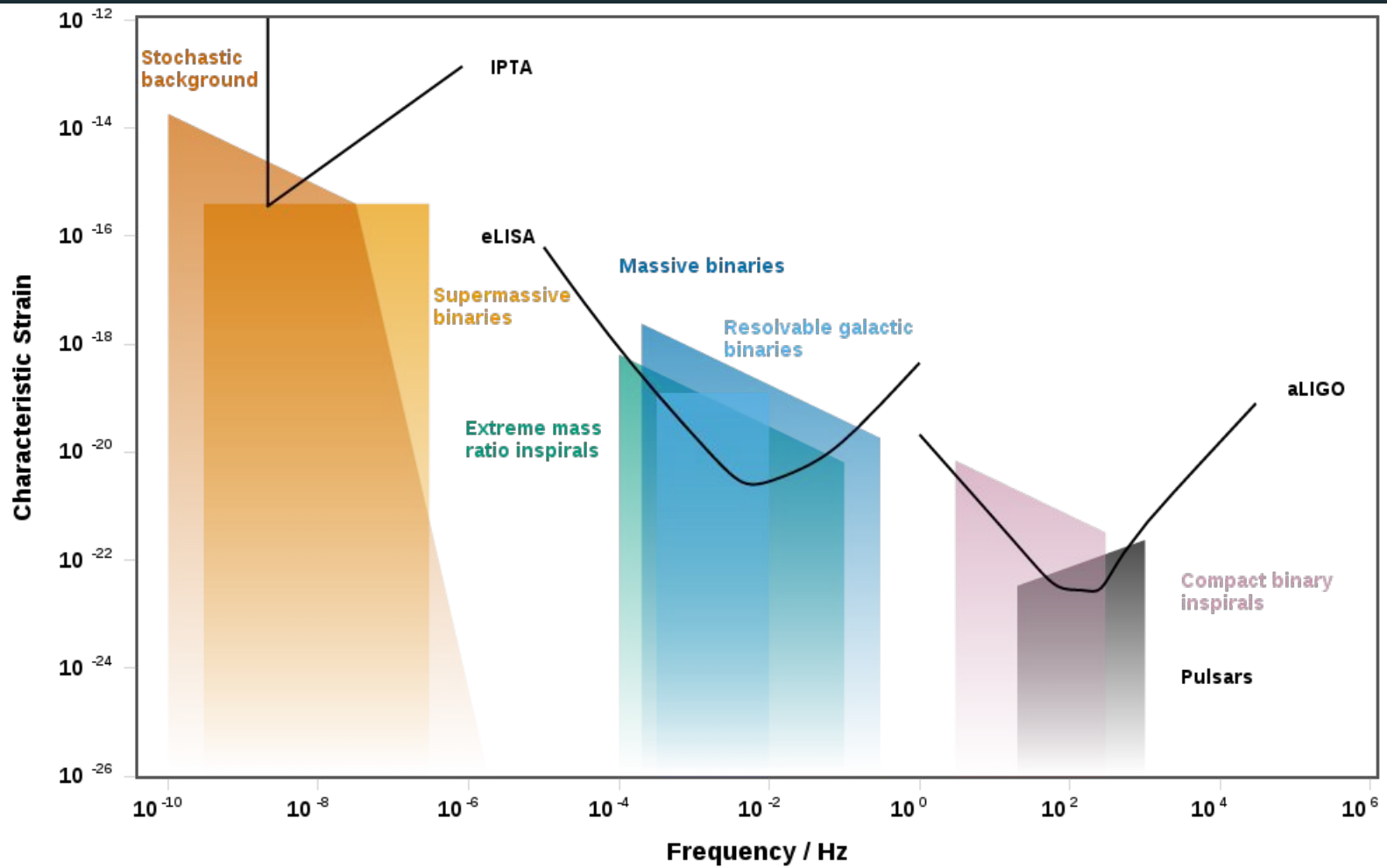

Characteristic Strain
Frequency / Hz
Stochastic background
IPTA
eLISA
Massive binaries
Supermassive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
aLIGO
Compact binary inspirals
Pulsars

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

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

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

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

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

Observational signatures of Superradiance

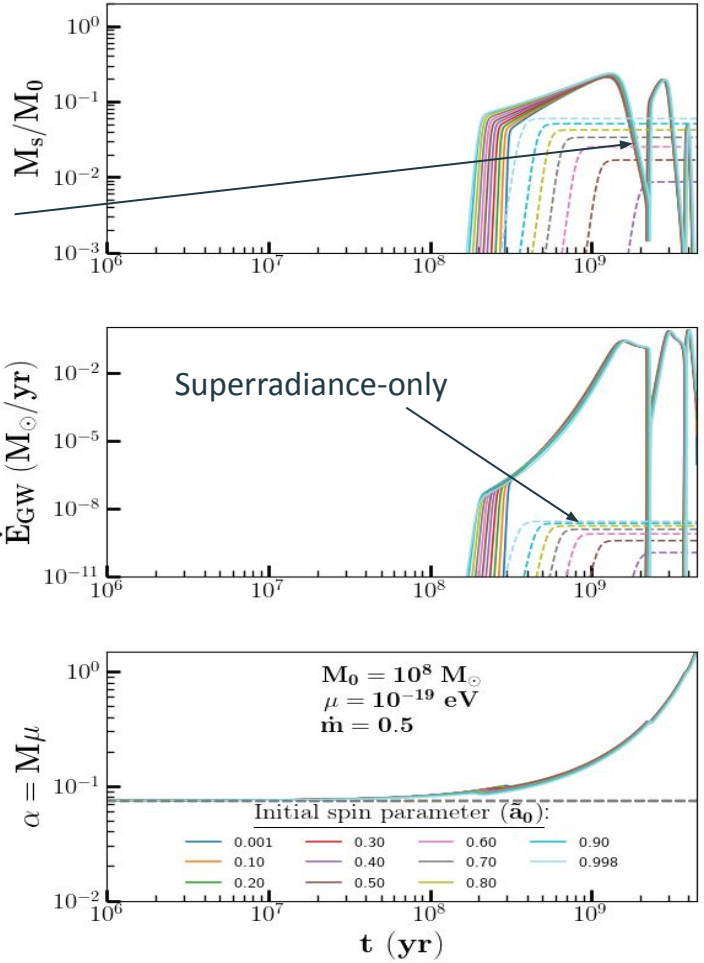
- Interesting signatures of gravitational wave emission emitted from the annihilation of scalars in the cloud around the BH, *Arvanitaki et al. 2015b*
- Scalar cloud affecting the black hole images, *Davoudiasl & Denton 2019, Saha et al. 2022*
- Depletion region in Regge plane i.e. spin versus mass plane 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

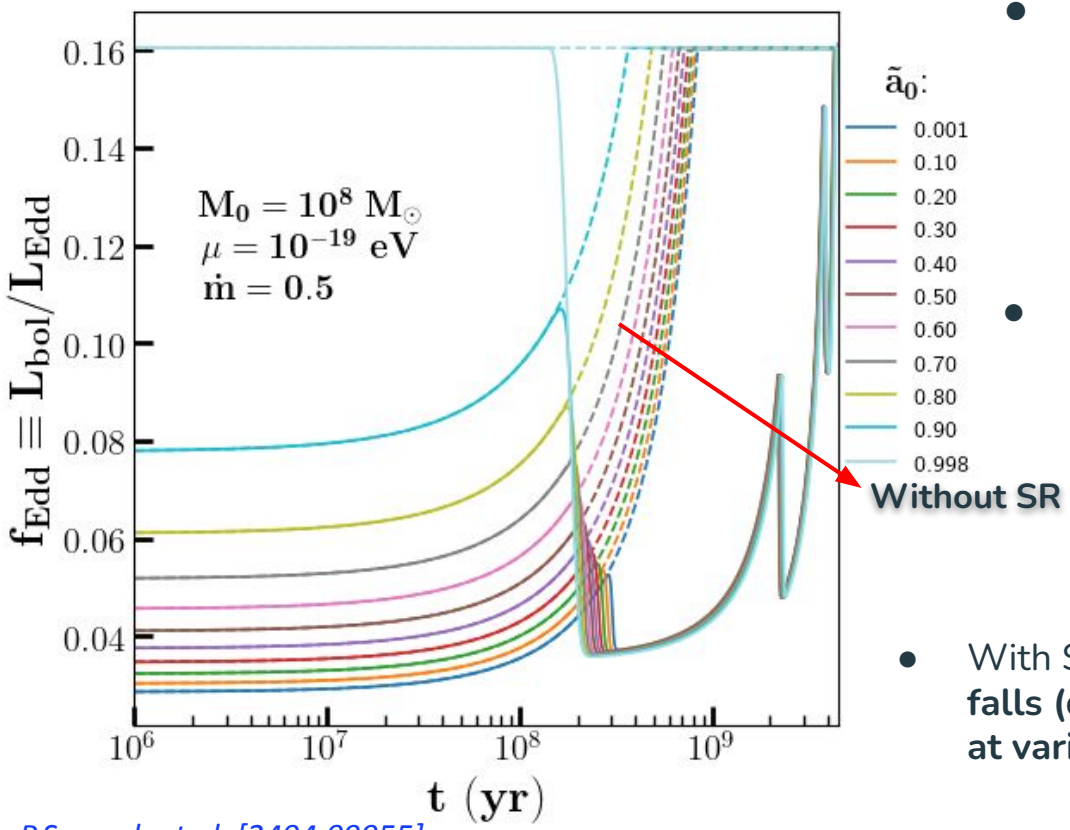
$$dE_{GW}/dt \sim (M_s/M)^2 \, \alpha^{4l+10}$$

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, $\mathbf{f_{Edd}}$ **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]

Time evolution of BH + scalar cloud system

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

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

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

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

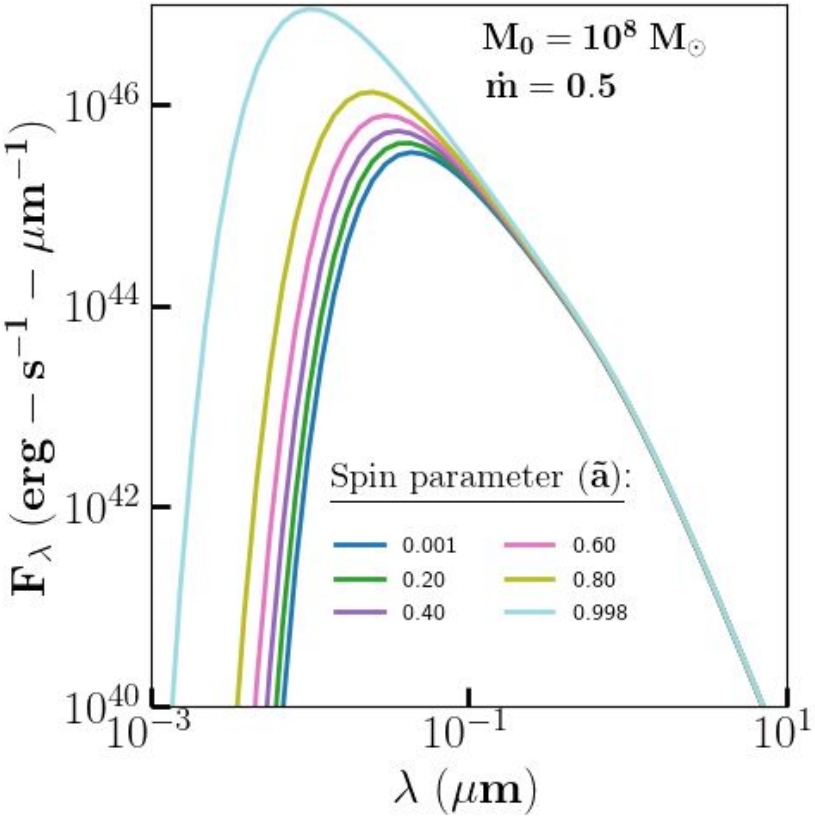
Accretion disk around Kerr BH: Novikov-Thorne model

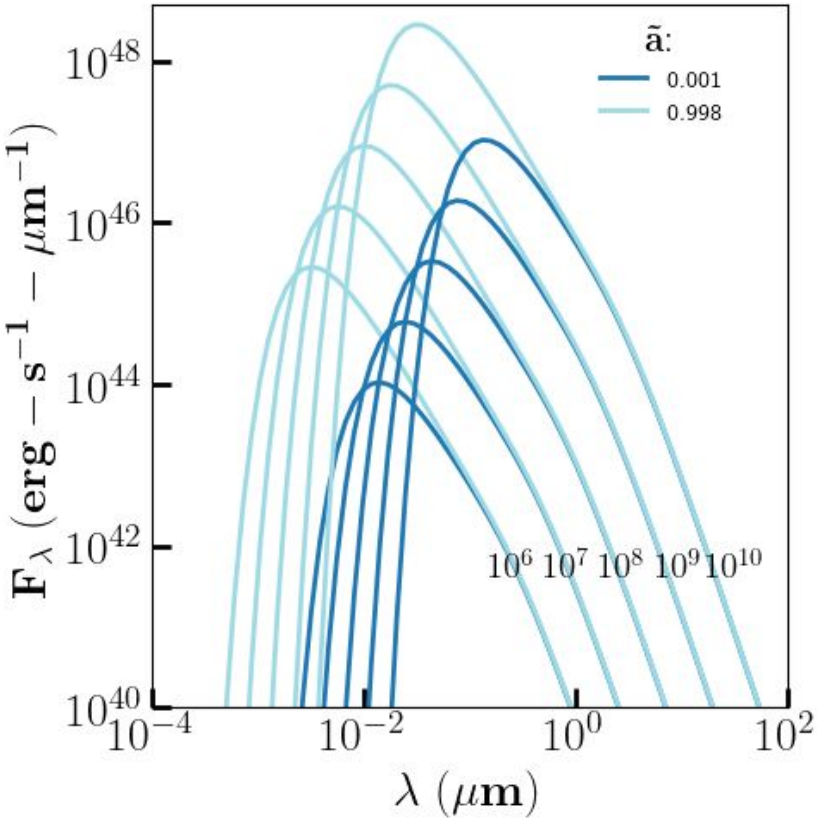
$$F(r) = 7 \times 10^{26} \frac{\text{erg}}{\text{s cm}^2} \dot{m} \frac{M_\odot}{M} \left(\frac{M}{r}\right)^3 \mathcal{B}^{-1} C^{-1/2} Q$$

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]