Effects of Superradiance in Active Galactic Nuclei

with Himanshu Verma, Kingman Cheung, Joseph Silk

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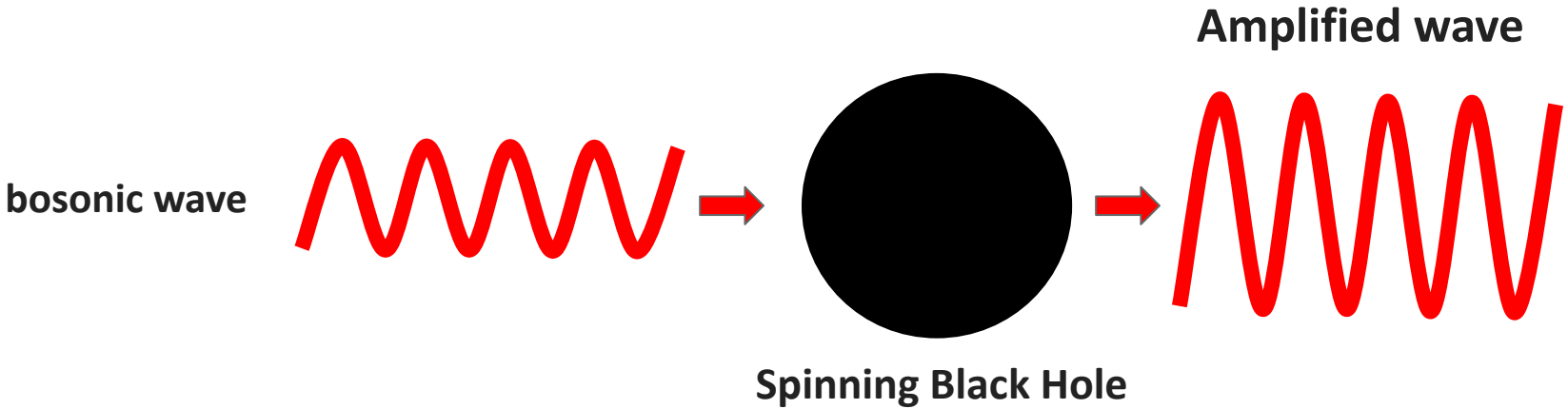
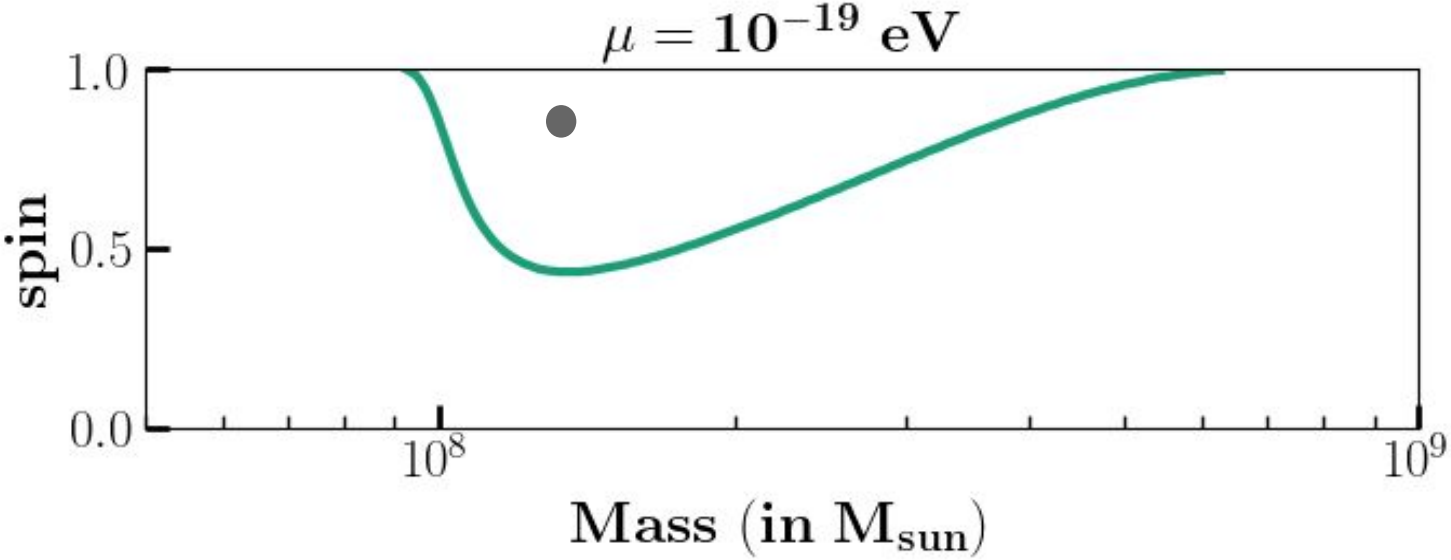
Black Hole Superradiance

- 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

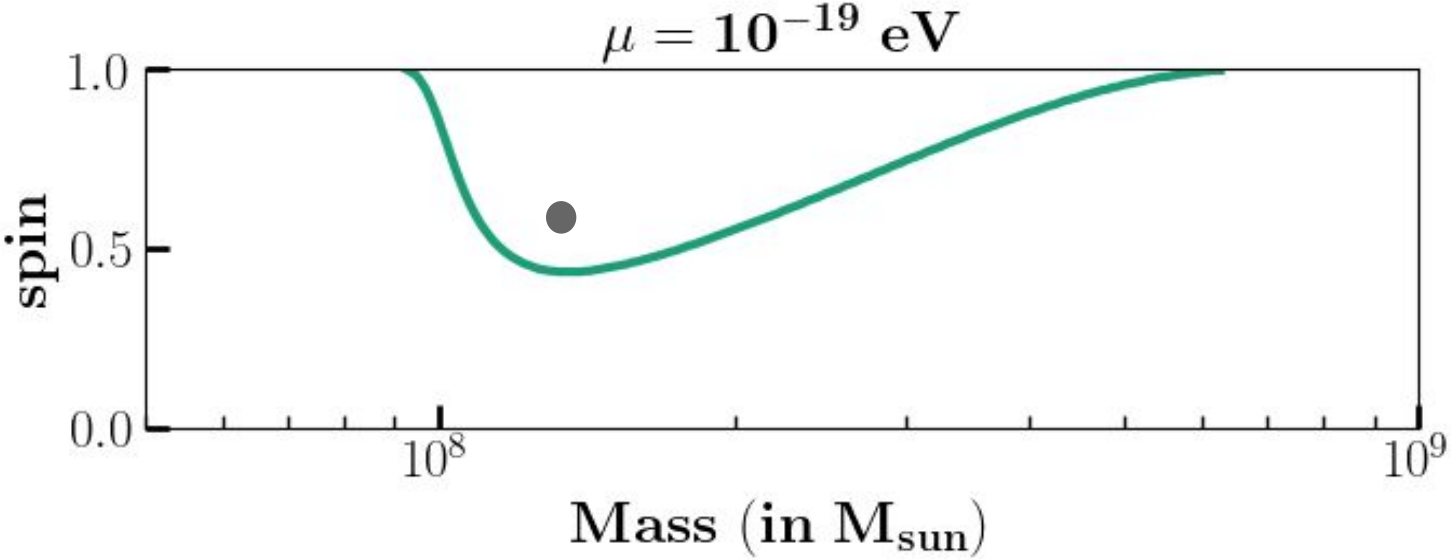


Observational signature of Superradiance: Depletion region



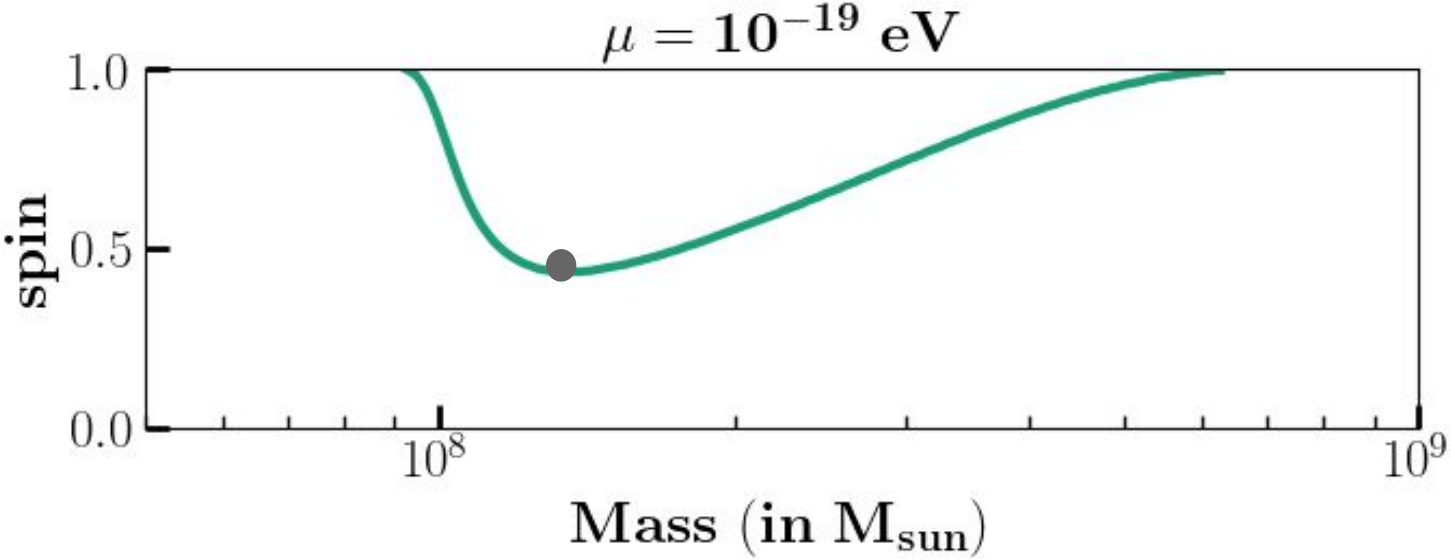
P.Sarmah et al. [2404.09955]

Observational signature of Superradiance: Depletion region



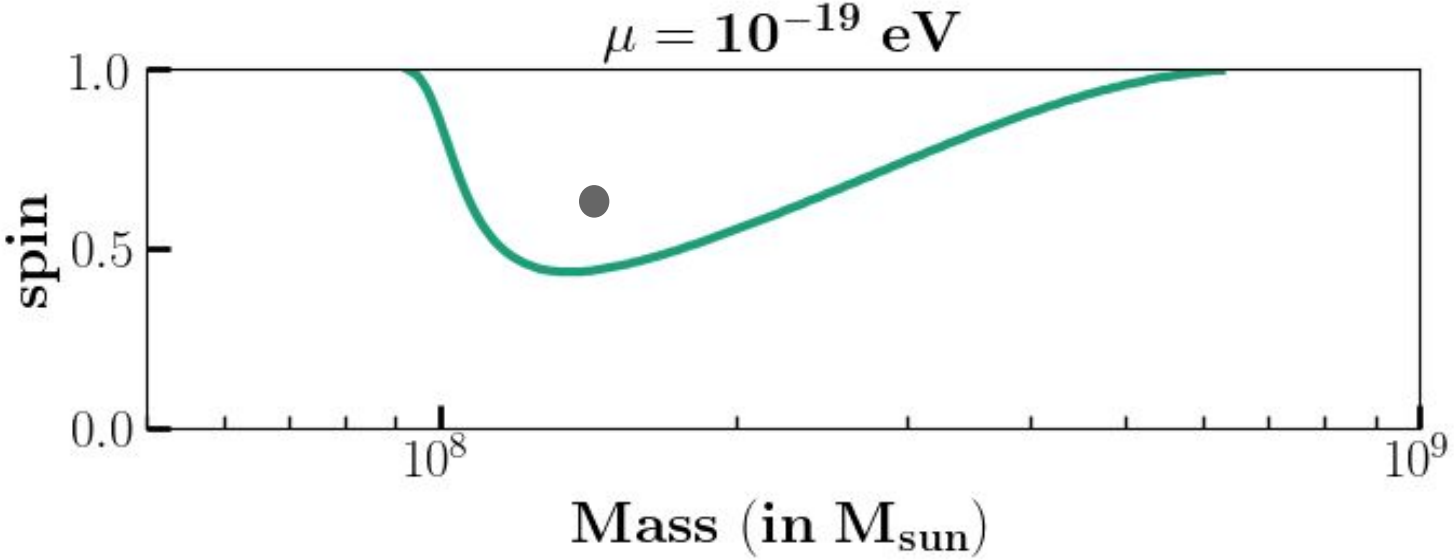
P.Sarmah et al. [2404.09955]

Observational signature of Superradiance: Depletion region



P.Sarmah et al. [2404.09955]

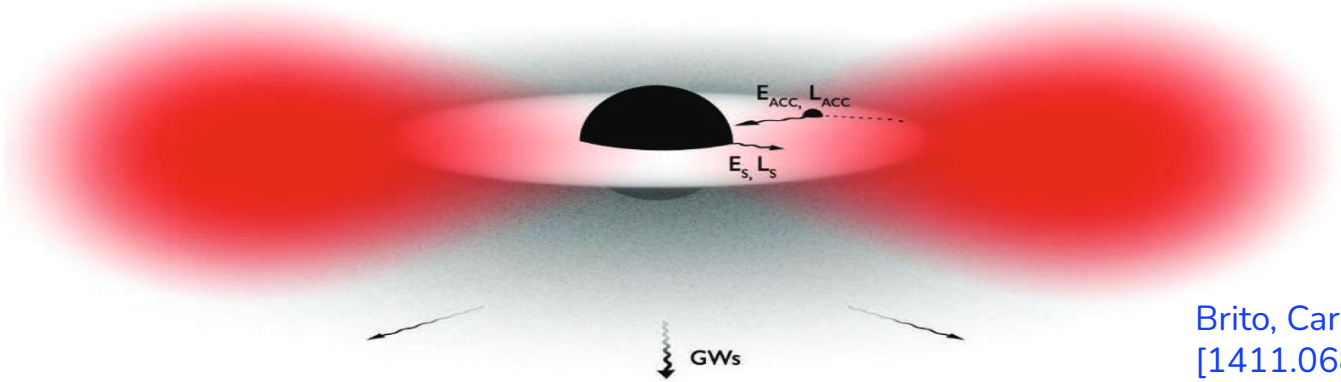
Observational signature of Superradiance



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)

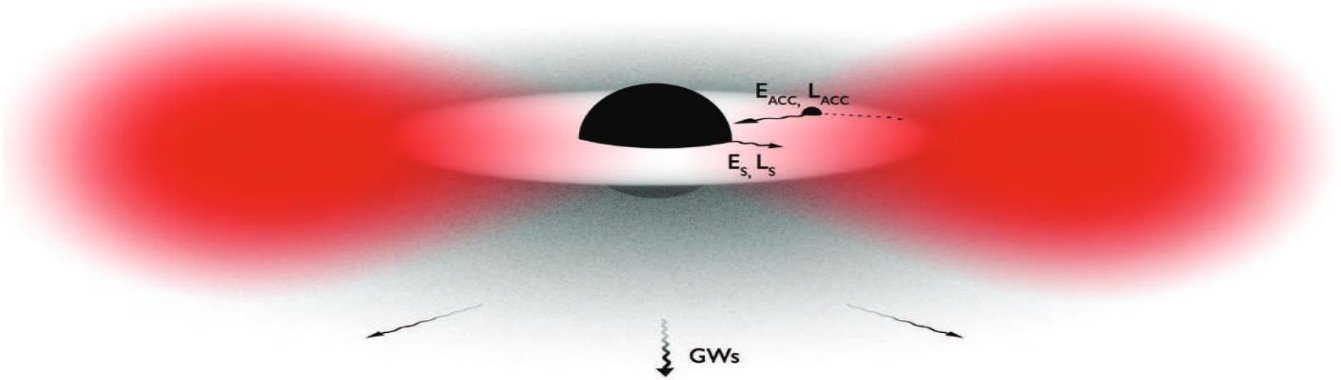


Brito, Cardoso, Pani, 2014 [1411.0686]

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

Question

Can we search for ULSP using the observable characteristics of AGN?



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

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 Model

- **Total Luminosity**

$$L = \epsilon(\tilde{a})\,\dot{M}_{\rm disk}c^2$$

Radiative efficiency

- **Accretion rate parameter**

$$\dot{m} \equiv \frac{\dot{M}_{\rm disk}c^2}{L_{\rm Edd}}$$

$[\dot{m} > 0.01 \text{ for thin accretion disk}]$

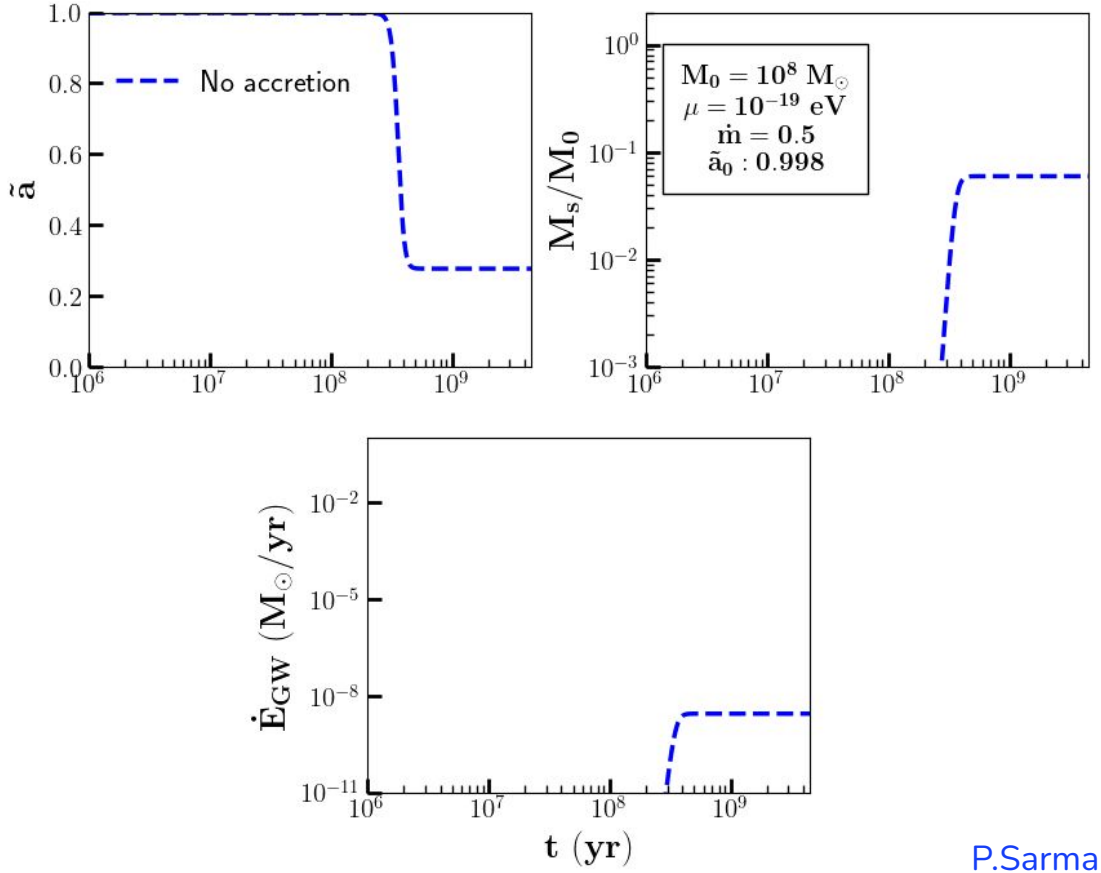
- **Eddington Luminosity**

$$L_{\rm Edd} \approx 1.26 \times 10^{38}\,{\rm erg/s}\,\frac{M}{M_\odot}$$

BH Accretion rate →

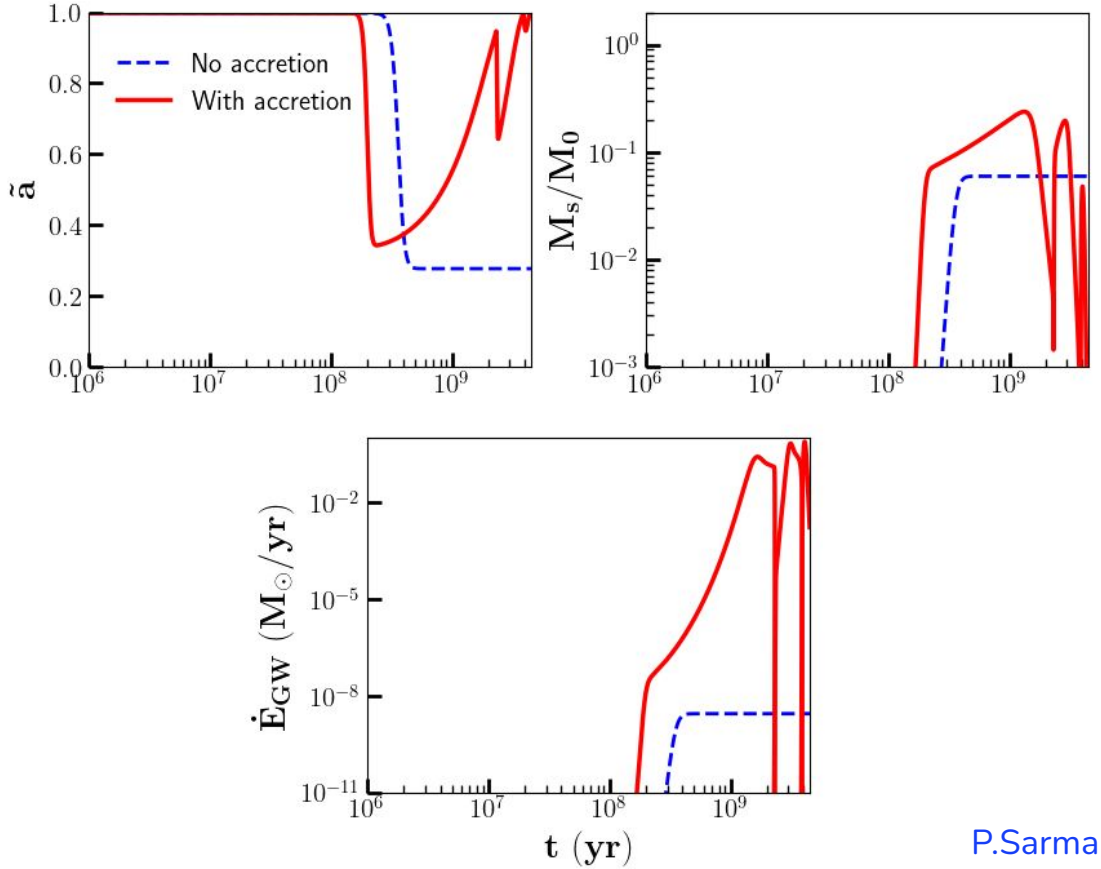
$$\dot{M}_{\rm Acc} = (1-\epsilon(\tilde{a}))\dot{m}\frac{L_{\rm Edd}}{c^2}$$

Time evolution of BH + scalar cloud system



P.Sarmah et al. [2404.09955]

Time evolution of accreting BH + scalar cloud system

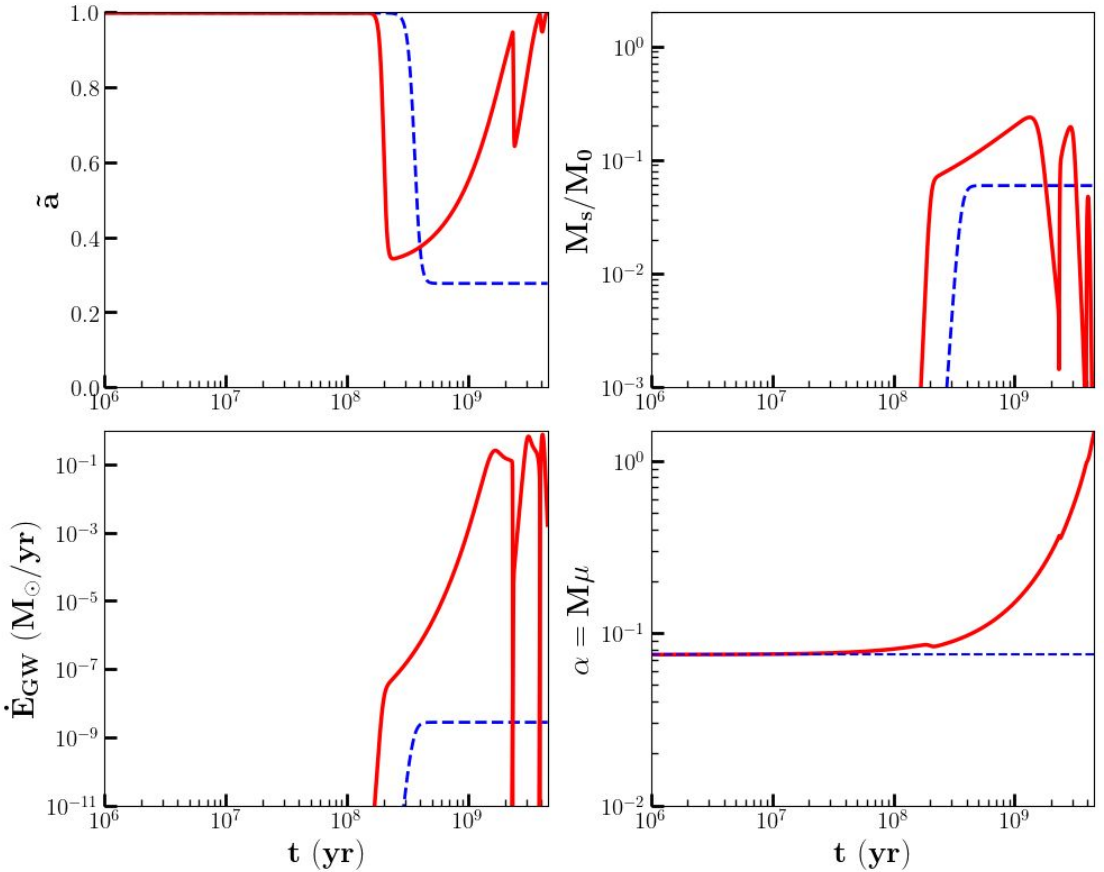


P.Sarmah et al. [2404.09955]

Time evolution of accreting BH + scalar cloud system

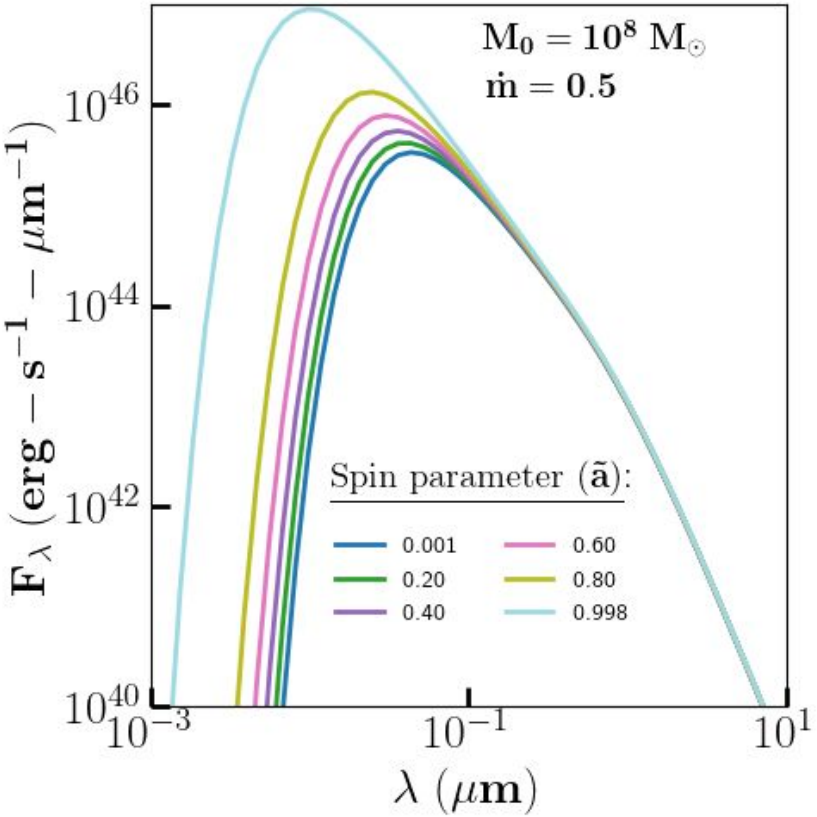
$dE_{GW}/dt \sim (Ms/M)^2\, \alpha^{4l+10}$

Yoshino H., Kodama H.'14



Continuum Spectrum of AGN

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



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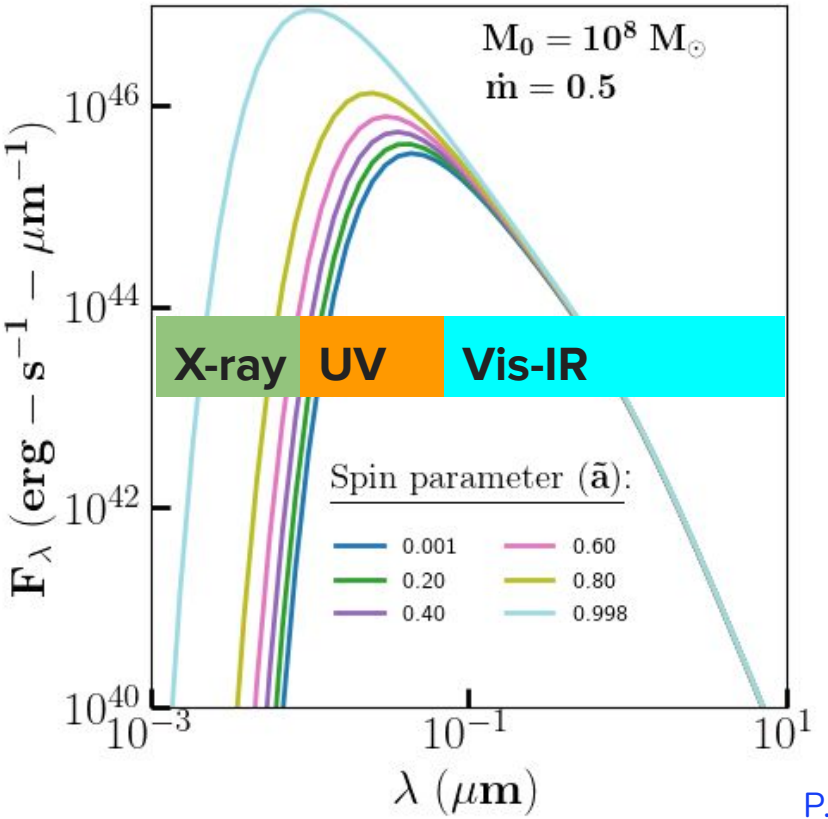
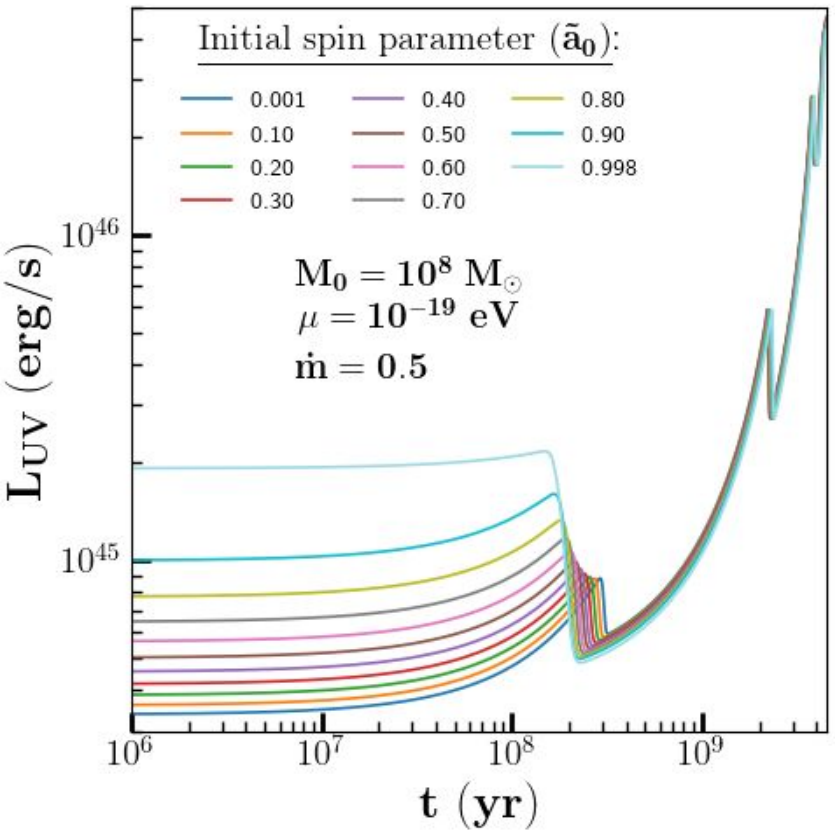
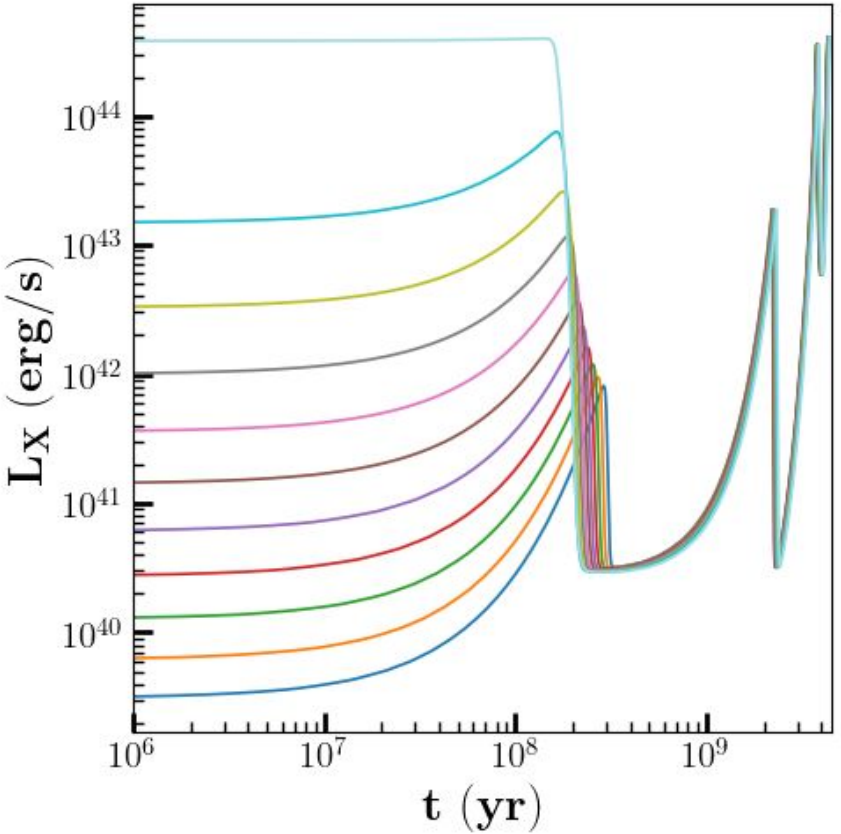


P.Sarmah et al. [2404.09955]

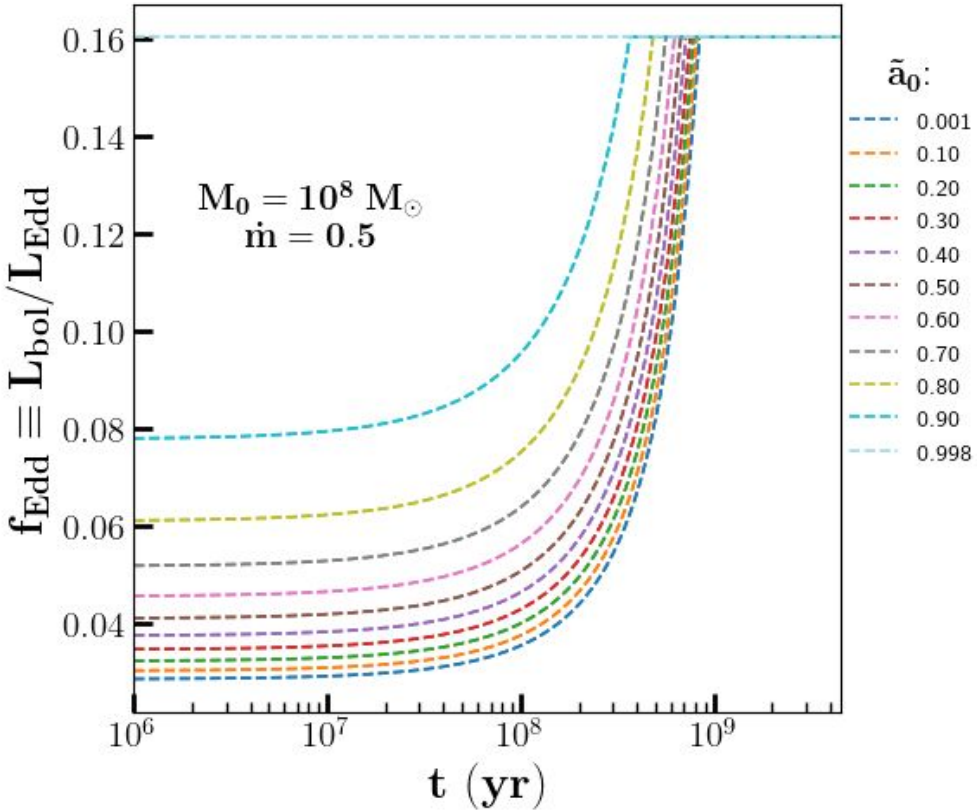
Luminosity in various bands





P.Sarmah et al. [2404.09955]

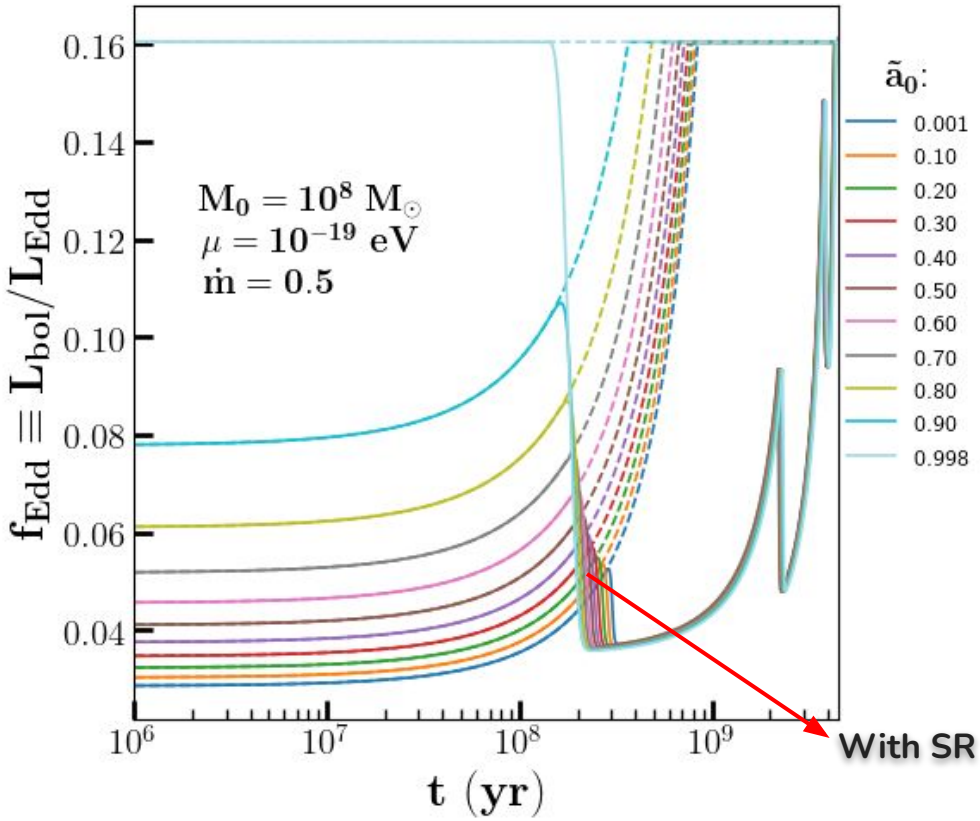
Eddington Ratio



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

P.Sarmah et al. [2404.09955]

Eddington Ratio



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

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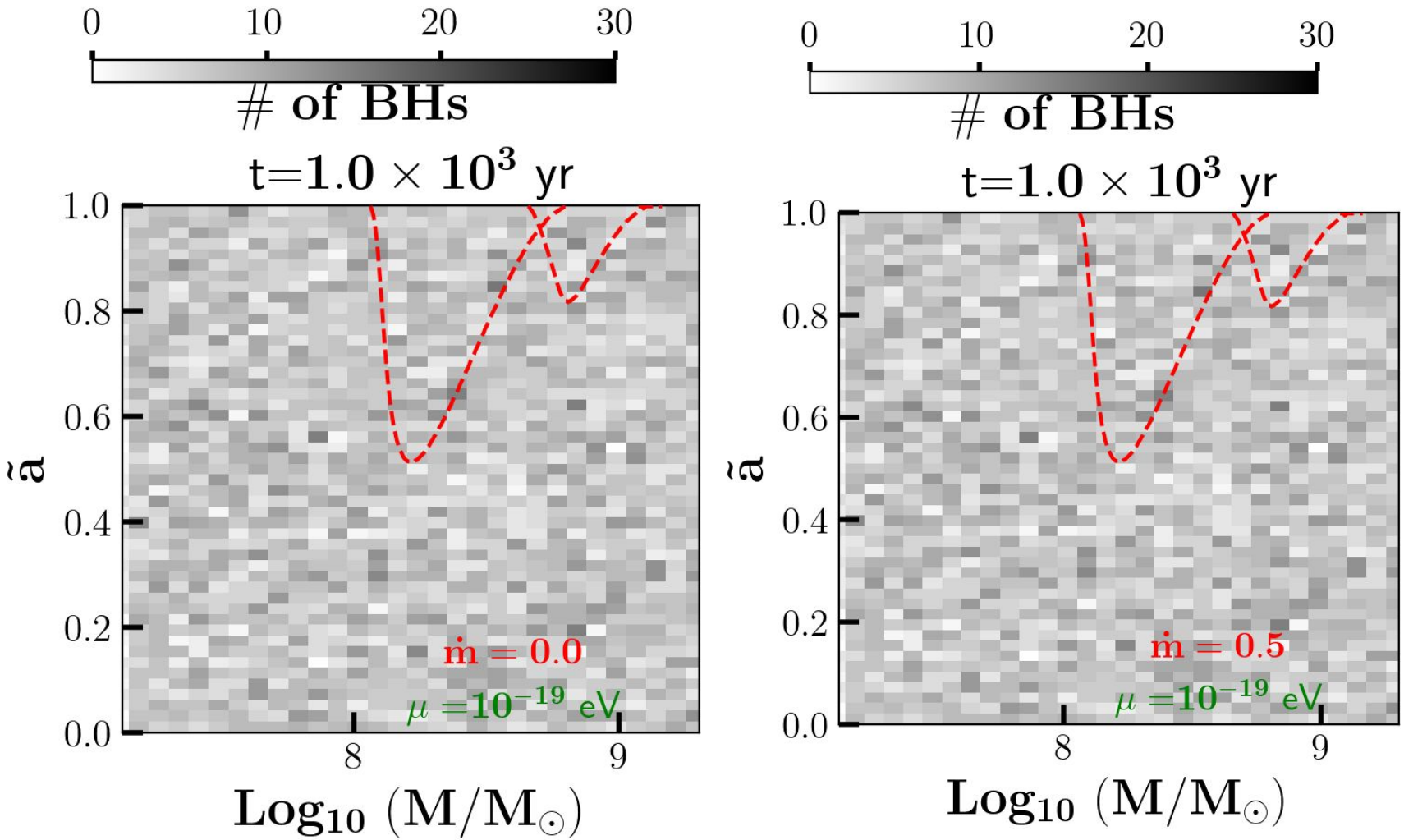
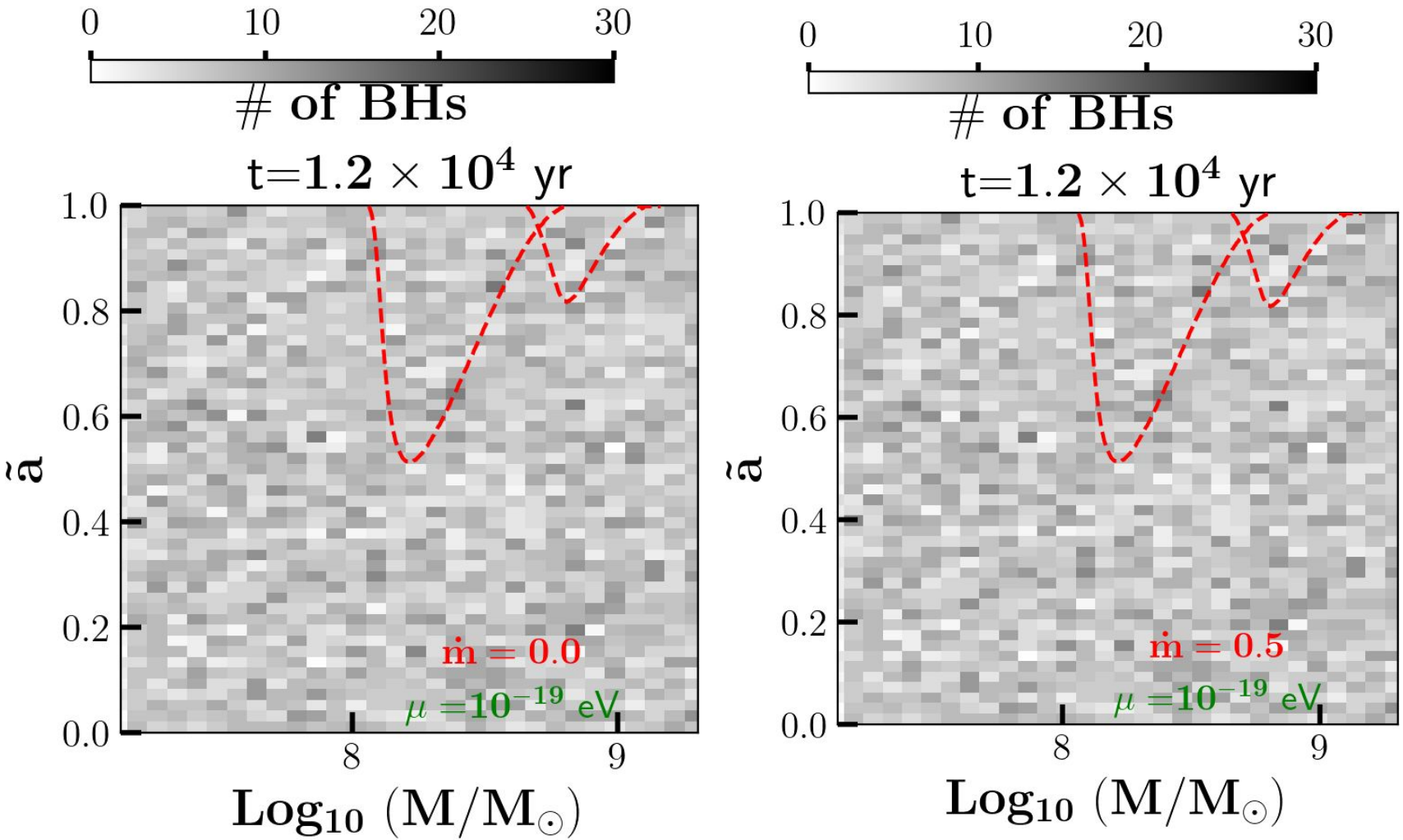
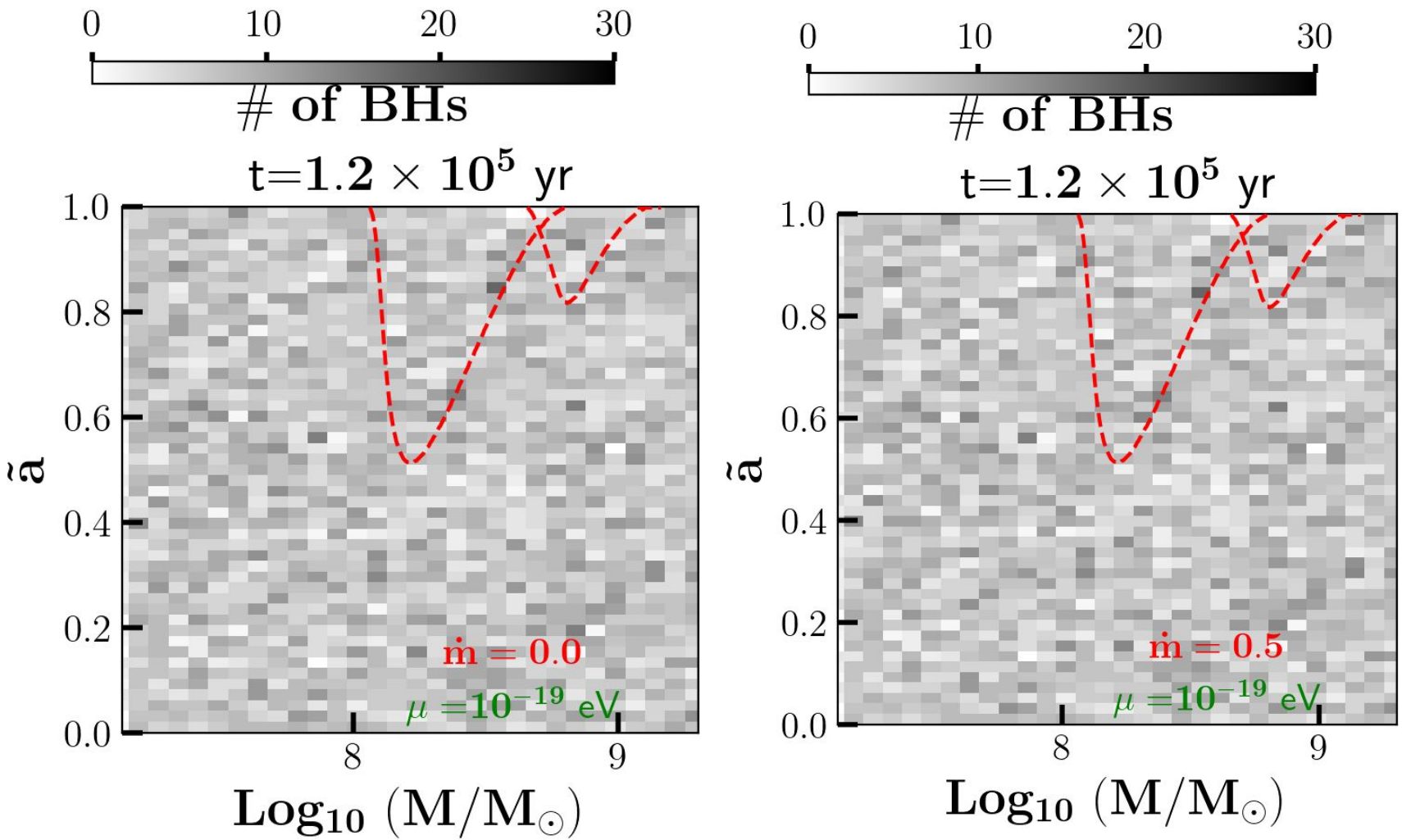
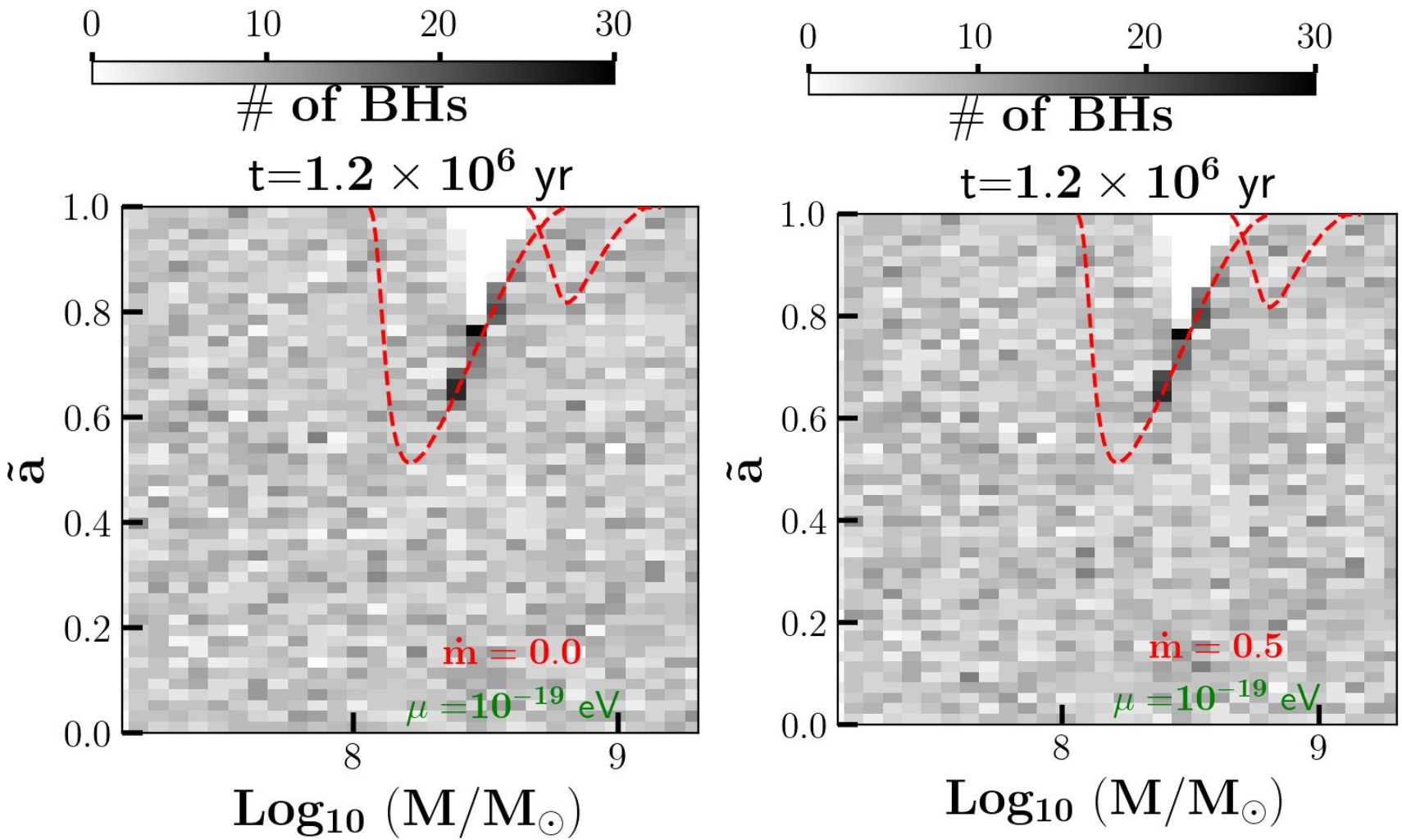
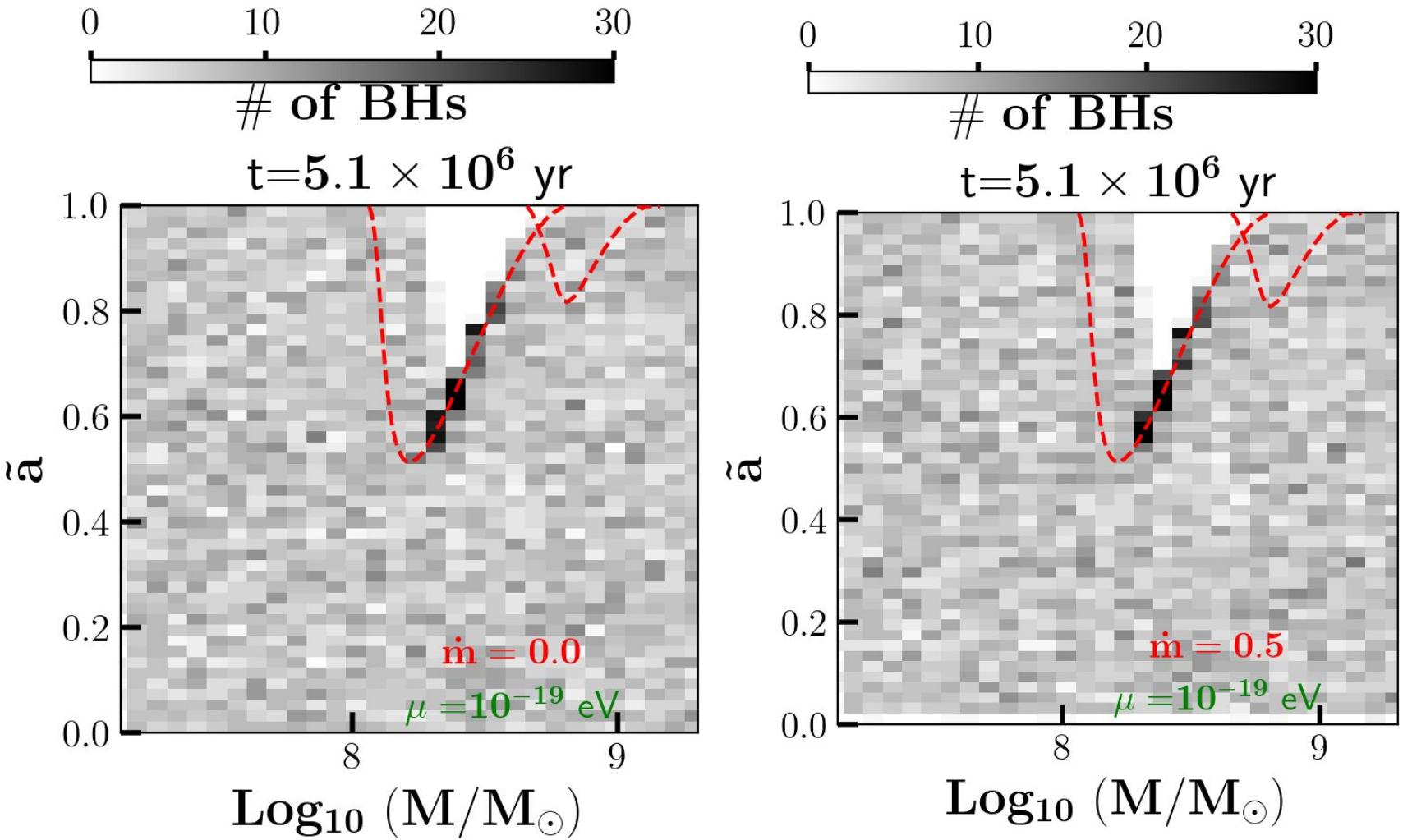
Distribution of SMBHs at the AGN core

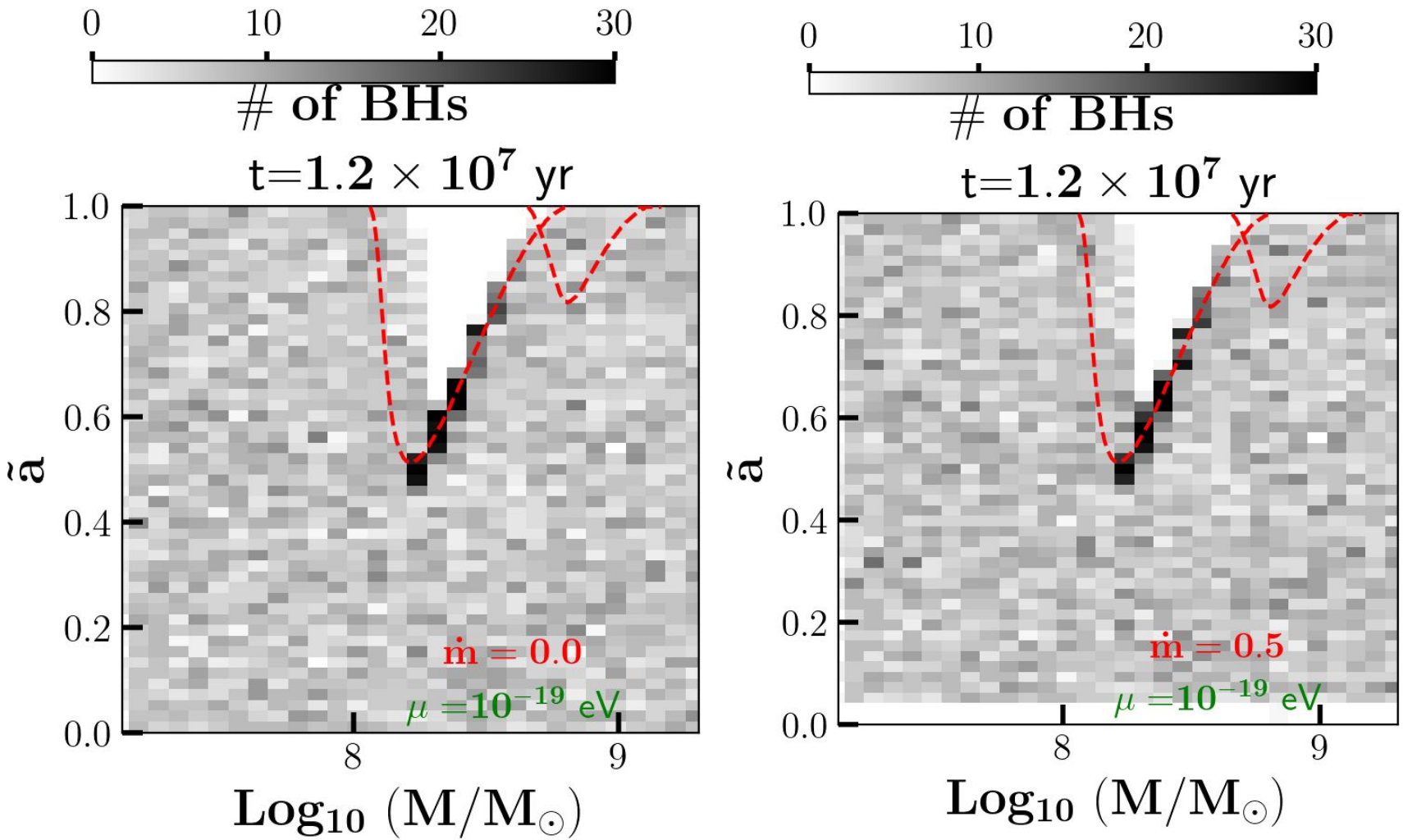

0
10
20
30
# of BHs
t=1.0 × 10³ yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10⁻¹⁹ eV
8
9
Log₁₀ (M/M⊙)
0
10
20
30
# of BHs
t=1.0 × 10³ yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10⁻¹⁹ eV
8
9
Log₁₀ (M/M⊙)

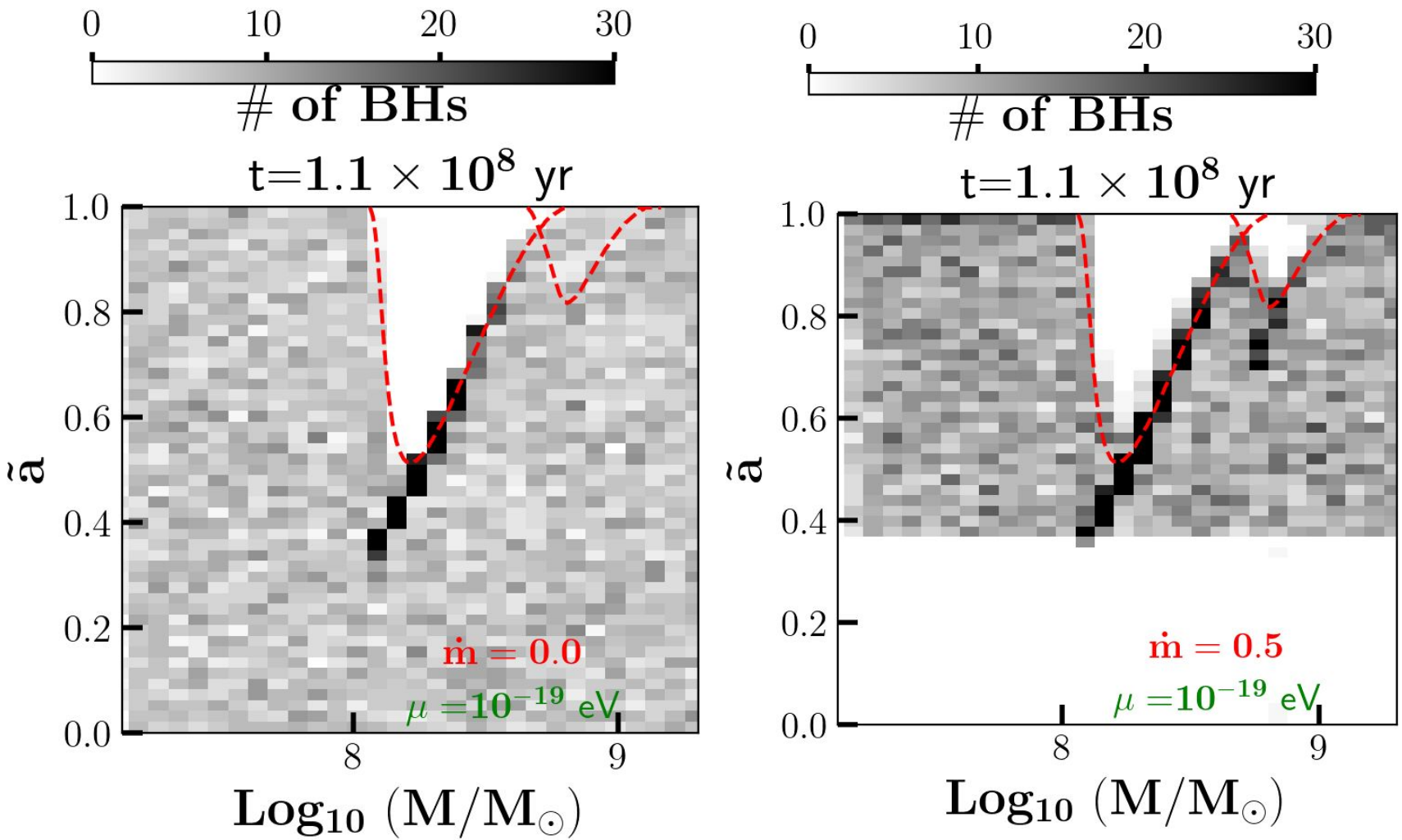

0
10
20
30
# of BHs
t=1.2 × 10^4 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^4 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)

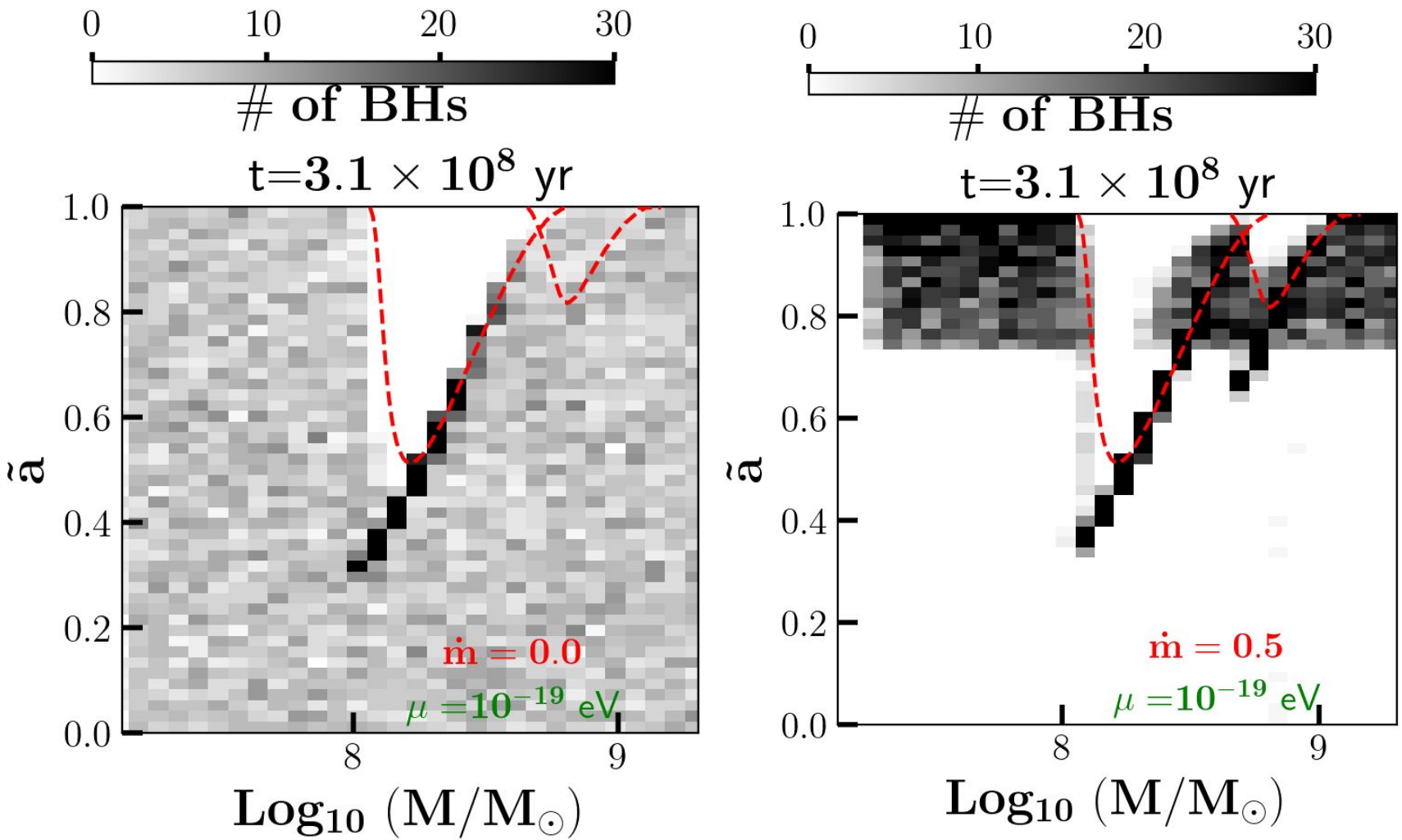

0
10
20
30
# of BHs
t=1.2 × 10^5 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^5 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)

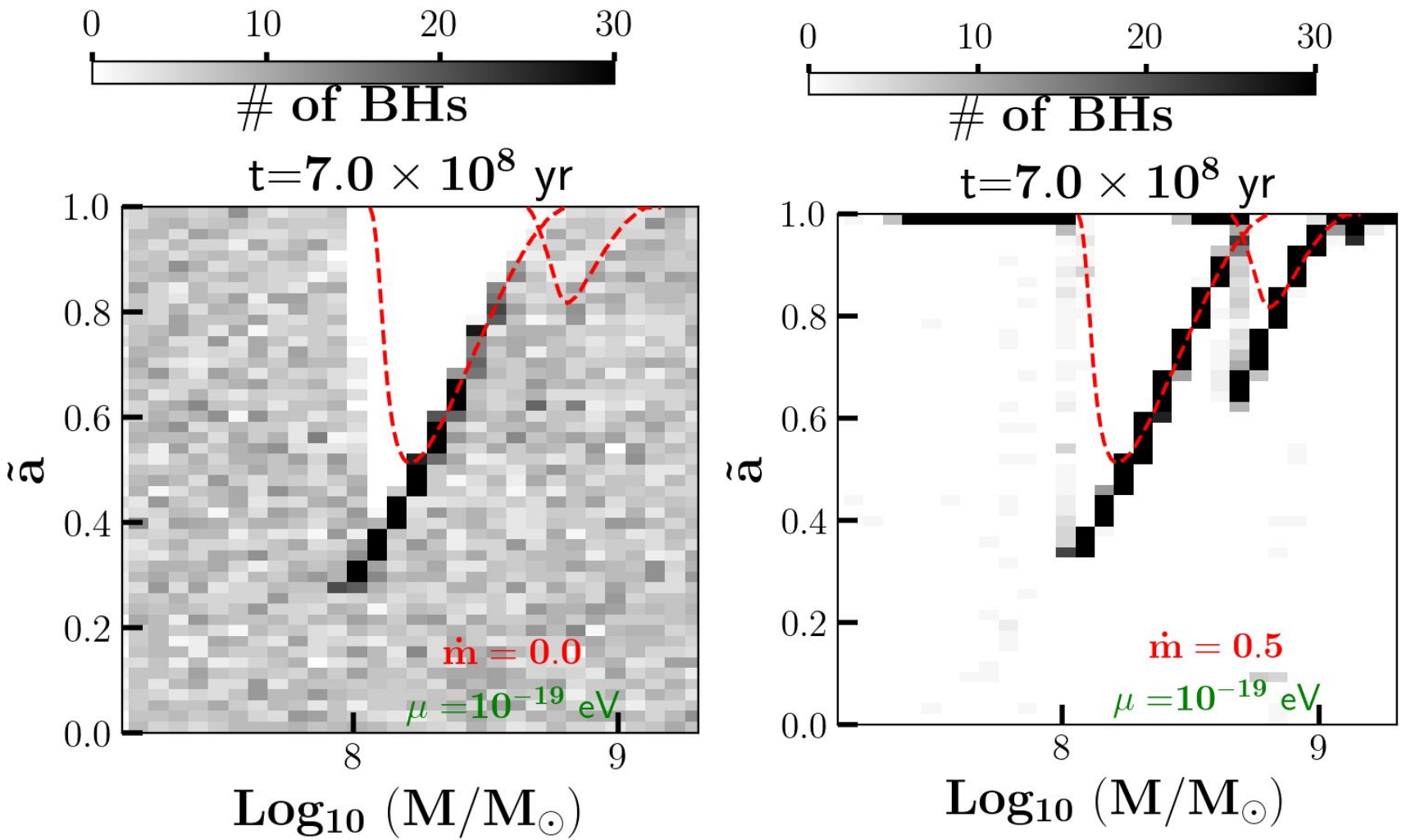

0
10
20
30
# of BHs
t=1.2 × 10^6 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^6 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)


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
μ =10^−19 eV
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
μ =10^−19 eV
8
9
Log10 (M/M⊙)

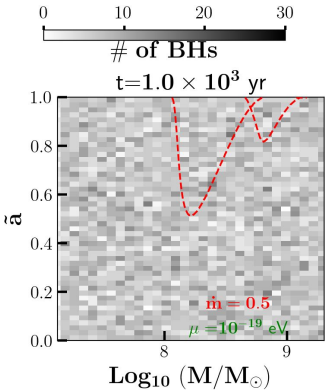

0
10
20
30
# of BHs
t=1.2 × 10^7 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.2 × 10^7 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)

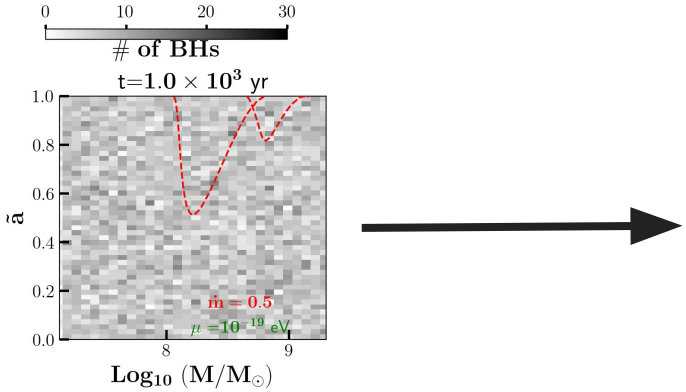

0
10
20
30
# of BHs
t=1.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=1.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)

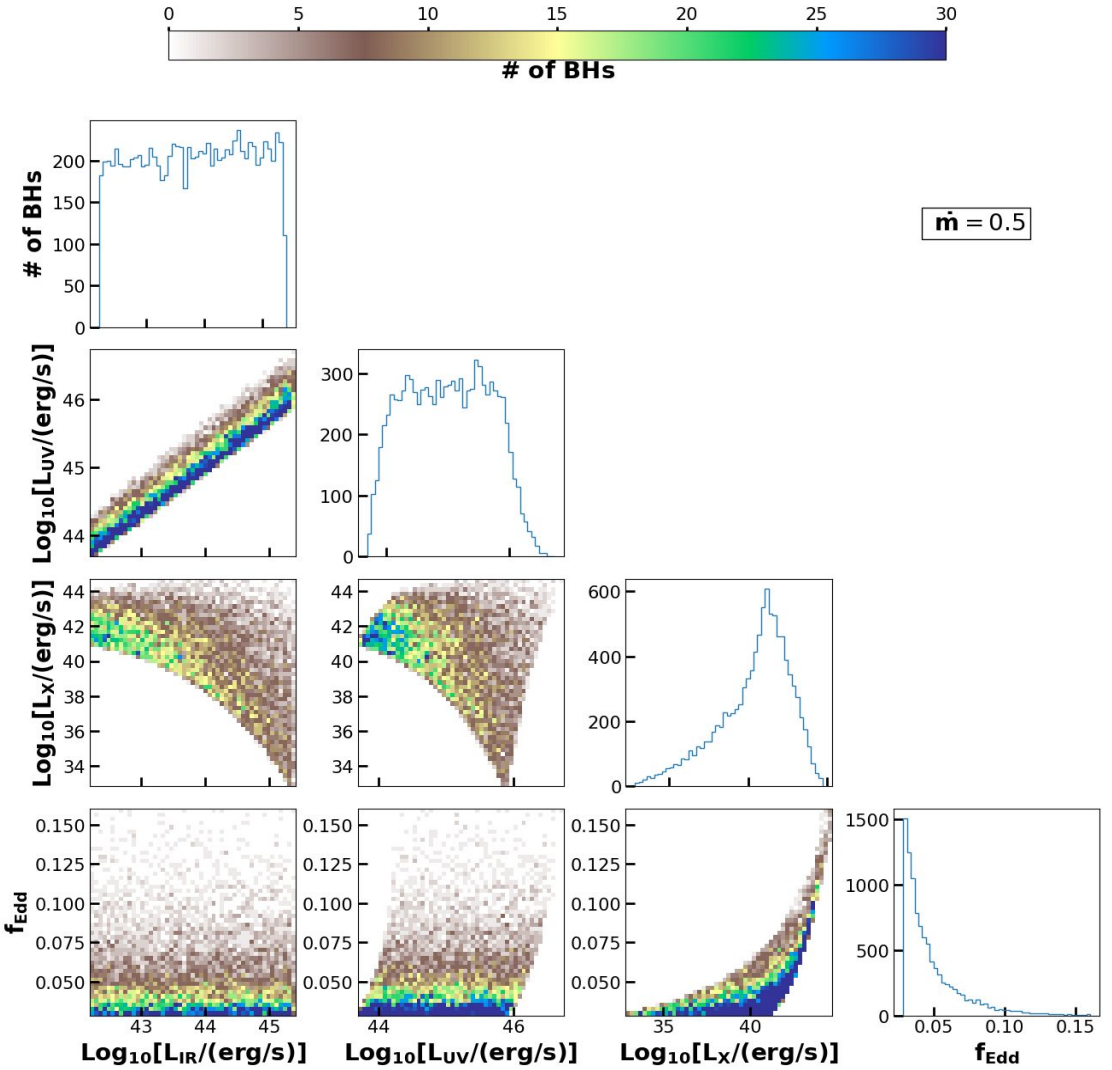

0
10
20
30
# of BHs
t=3.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=3.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)

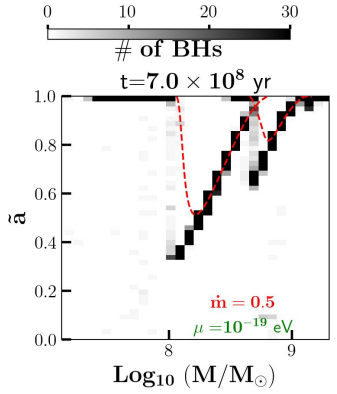

0
10
20
30
# of BHs
t=7.0 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0
10
20
30
# of BHs
t=7.0 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)

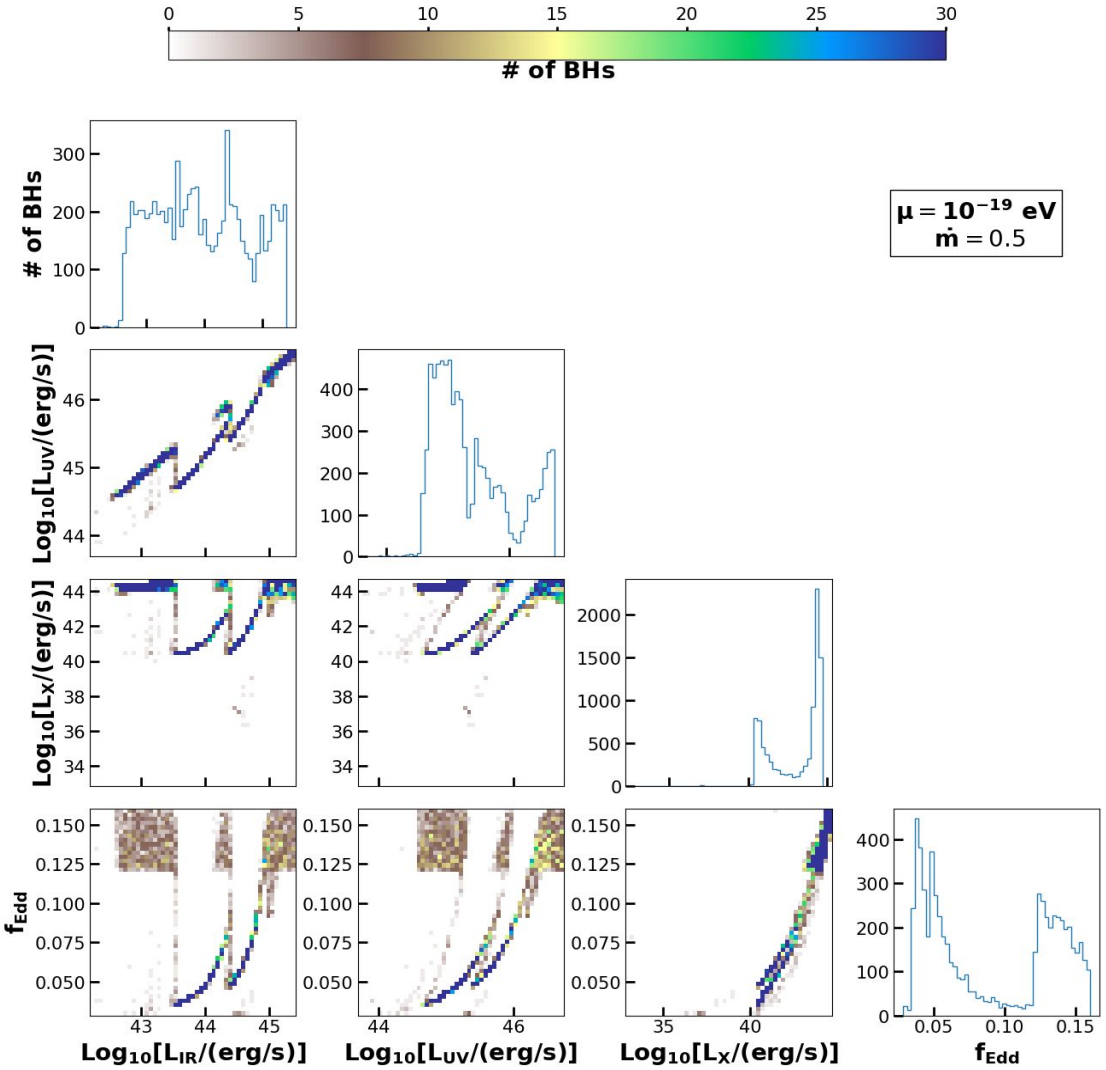
Distribution of AGN Characteristics


0
10
20
30
# of BHs
t=1.0 × 10^3 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^-19 eV
8
9
Log10 (M/M⊙)


0
10
20
30
# of BHs
t=1.0 × 10^3 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^-19 eV
8
9
Log10 (M/M⊙)


0
5
10
15
20
25
30
# of BHs
ṁ = 0.5
# of BHs
Log10[LUV/(erg/s)]
Log10[LX/(erg/s)]
fEdd
Log10[LIR/(erg/s)]
Log10[LUV/(erg/s)]
Log10[LX/(erg/s)]
fEdd





P.Sarmah et al. [2404.09955]

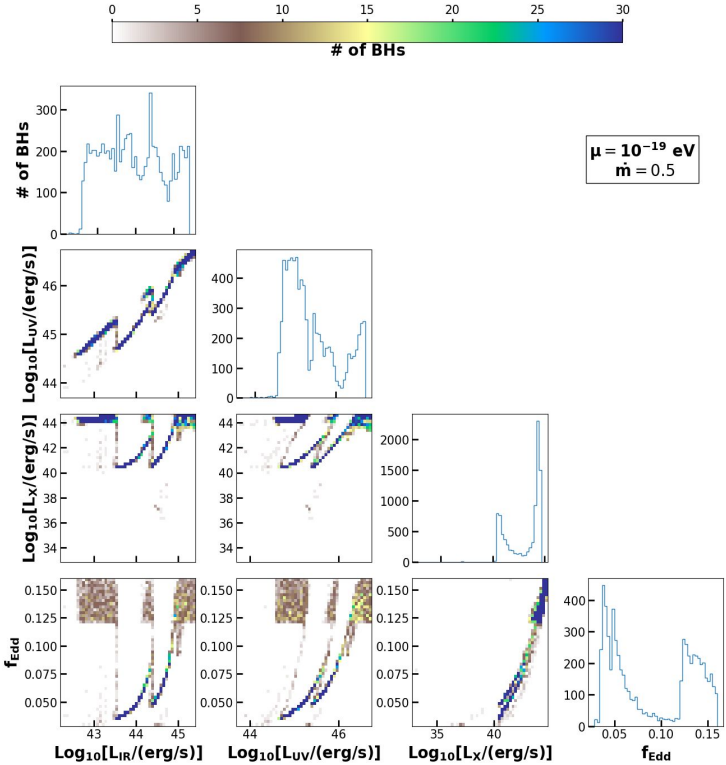
Summary

- 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?