Effects of Superradiance in Active Galactic Nuclei

with Himanshu Verma, Kingman Cheung, Joseph Silk [arXiv: 2404.09955](under review in MNRAS)

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Postdoctoral fellow

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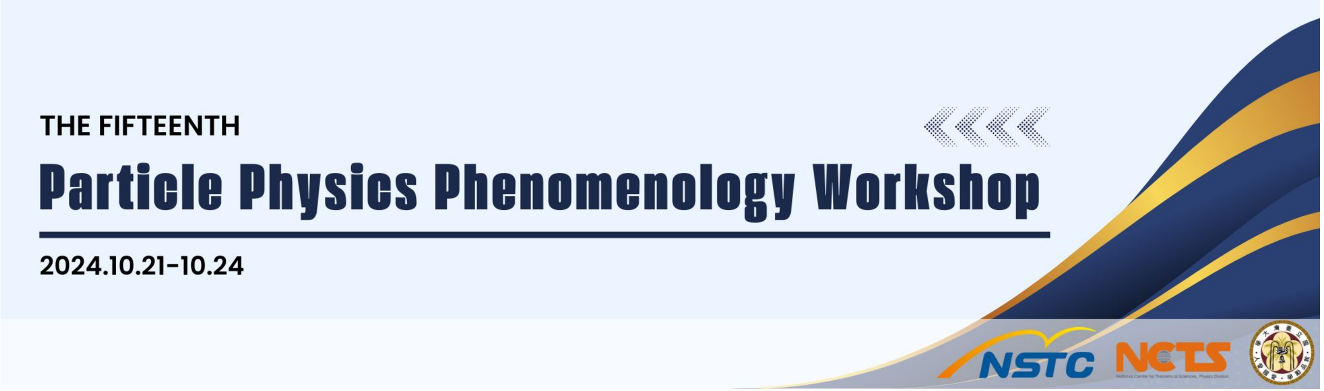
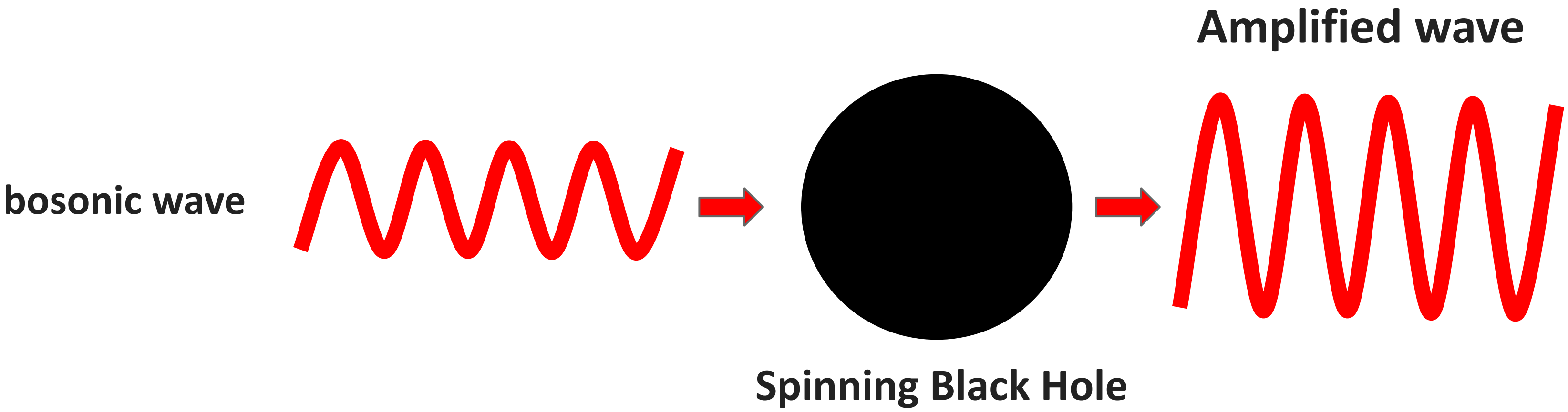


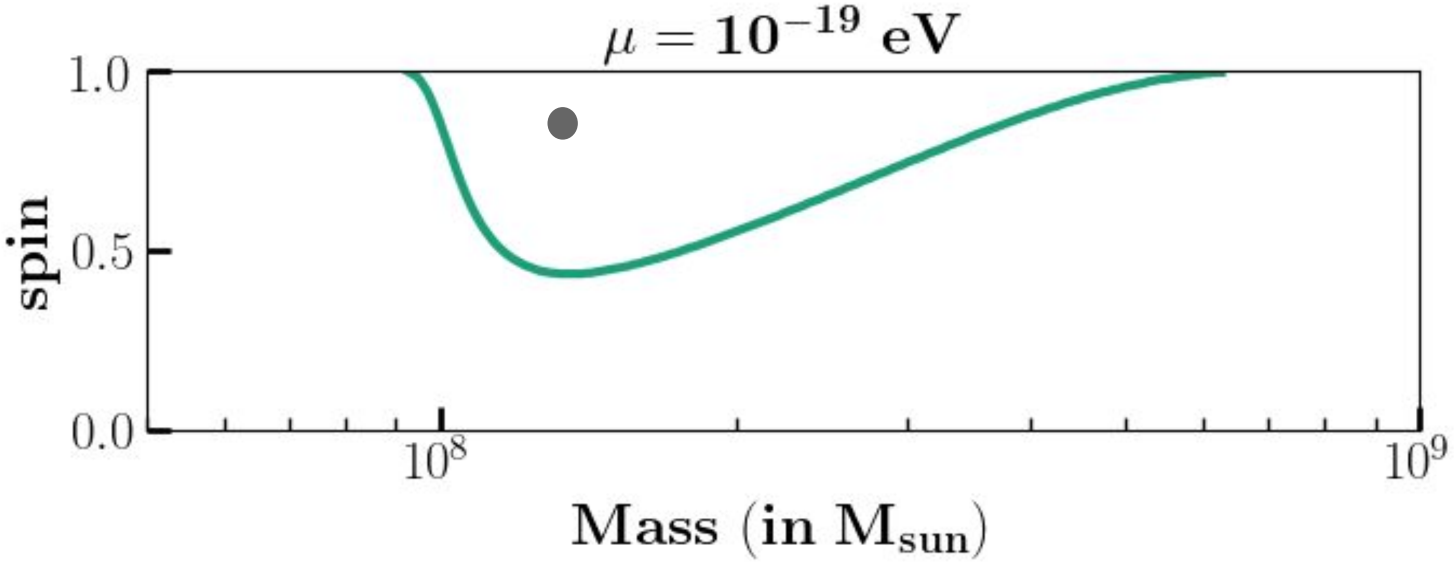
Black Hole Superradiance

- 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

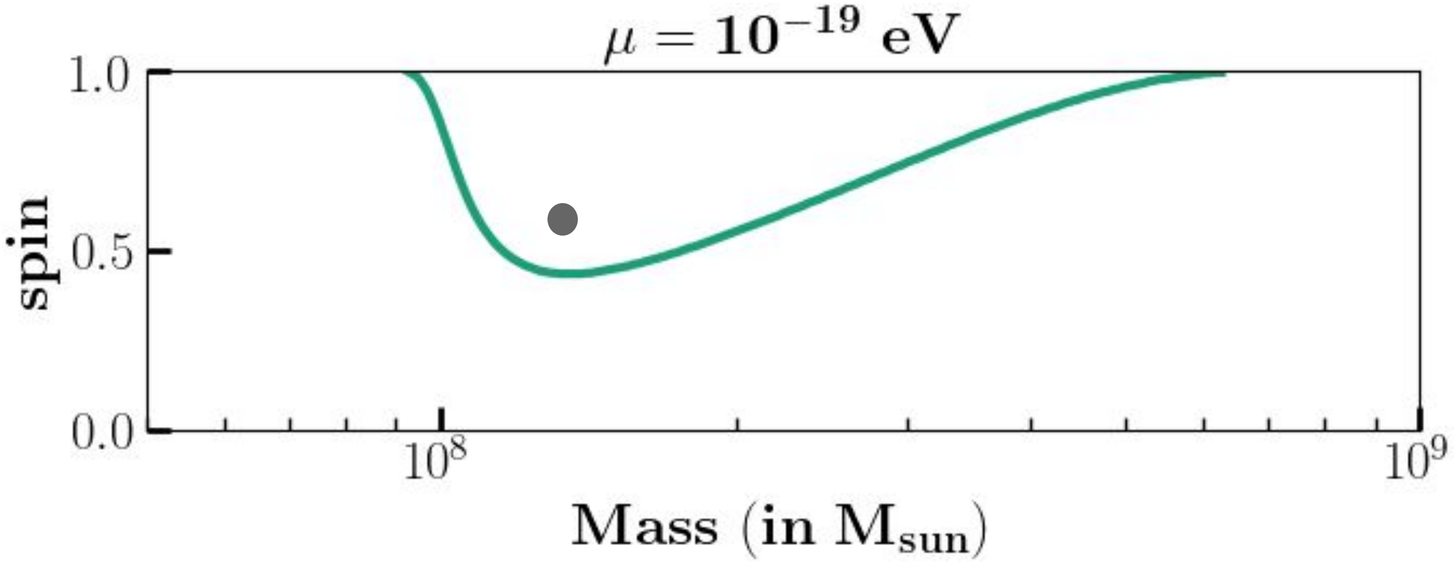


Observational signature of Superradiance: Depletion region



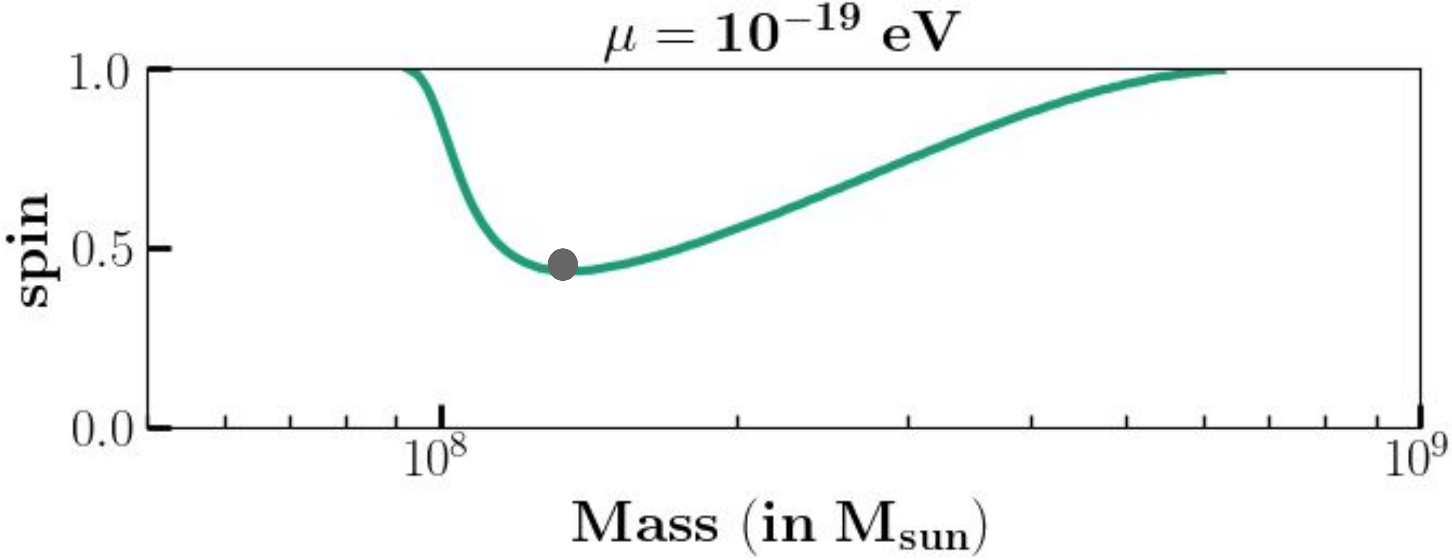
P.Sarmah et al. [2404.09955]

Observational signature of Superradiance: Depletion region



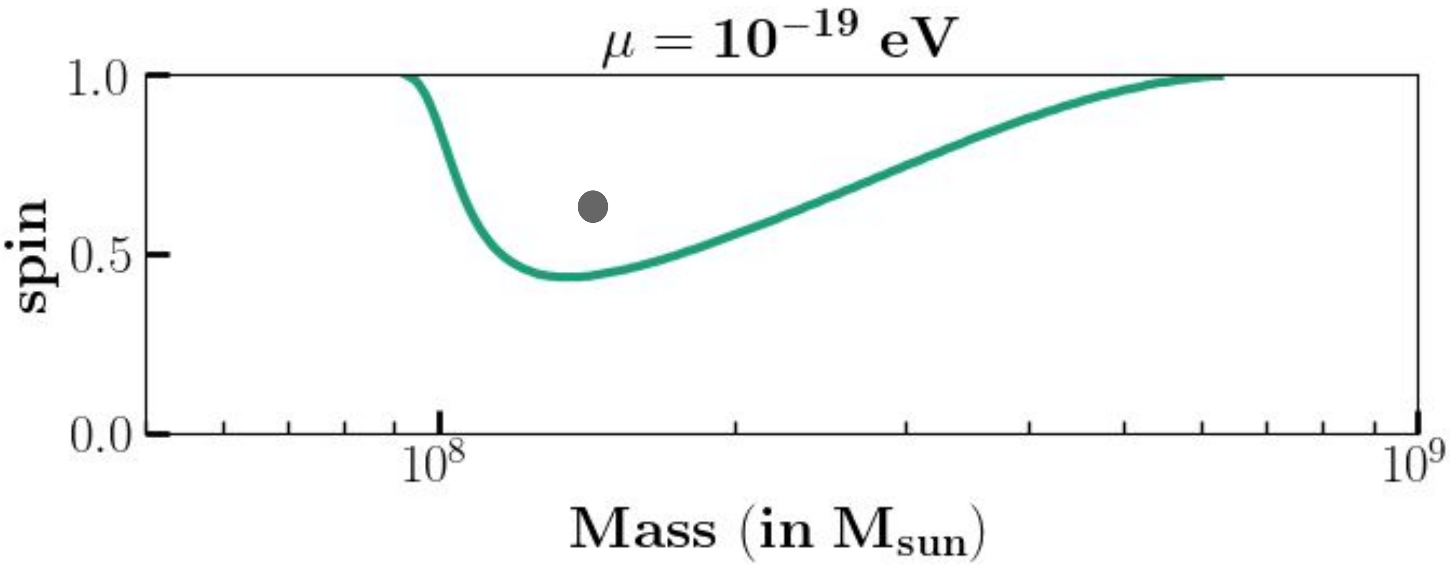
P.Sarmah et al. [2404.09955]

Observational signature of Superradiance: Depletion region



P.Sarmah et al. [2404.09955]

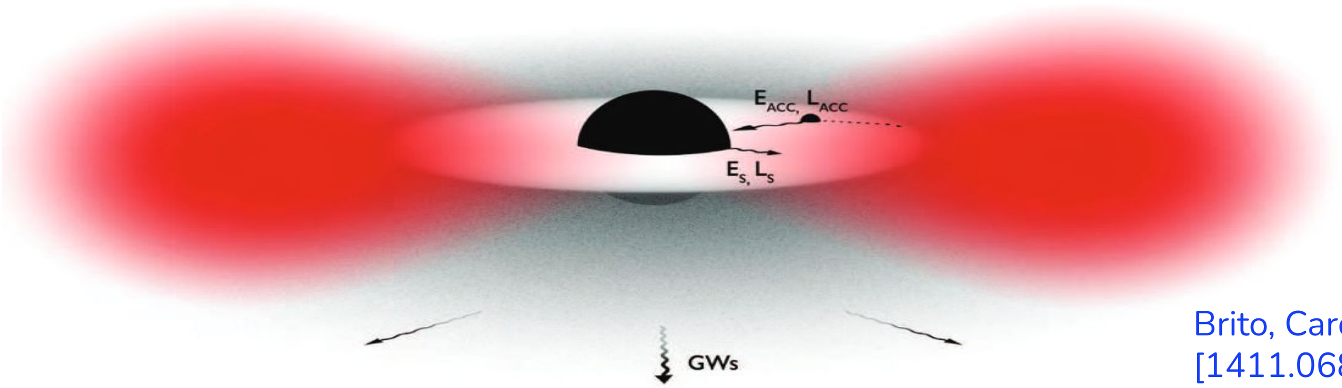
Observational signature of Superradiance: Depletion region



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)

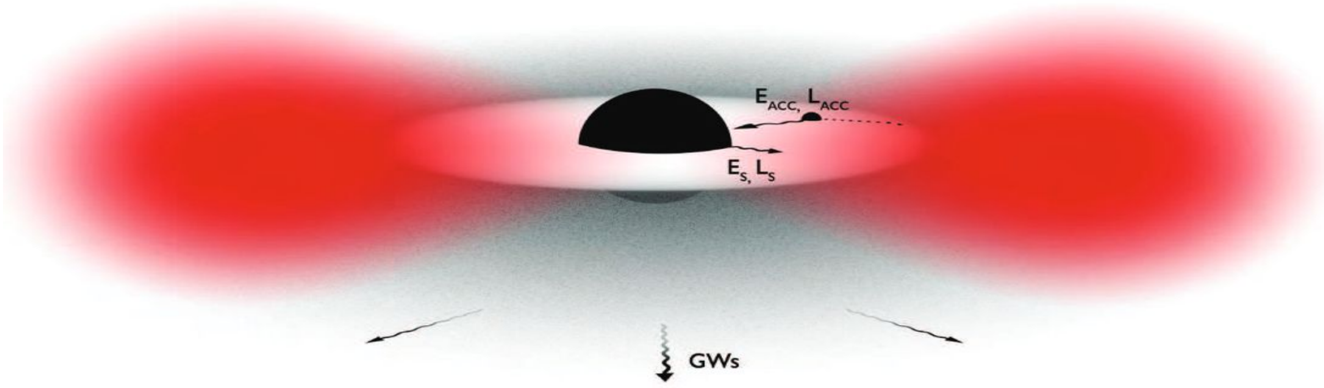


Brito, Cardoso, Pani, 2014
[1411.0686]

- **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

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

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

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

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

Brito, Cardoso, Pani, 2014 [1411.0686]

Accretion Model

- **Total Luminosity**

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

Radiative efficiency

- **Accretion rate parameter**

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

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

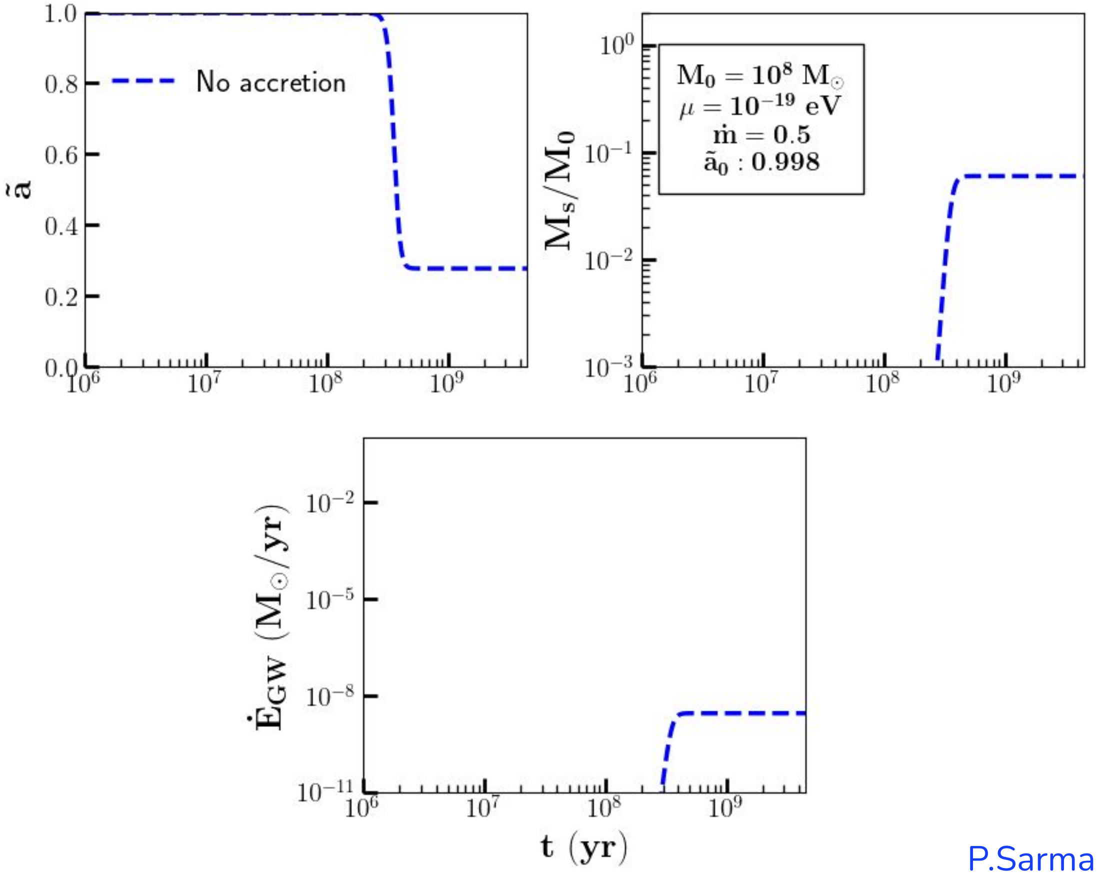
- **Eddington Luminosity**

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

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



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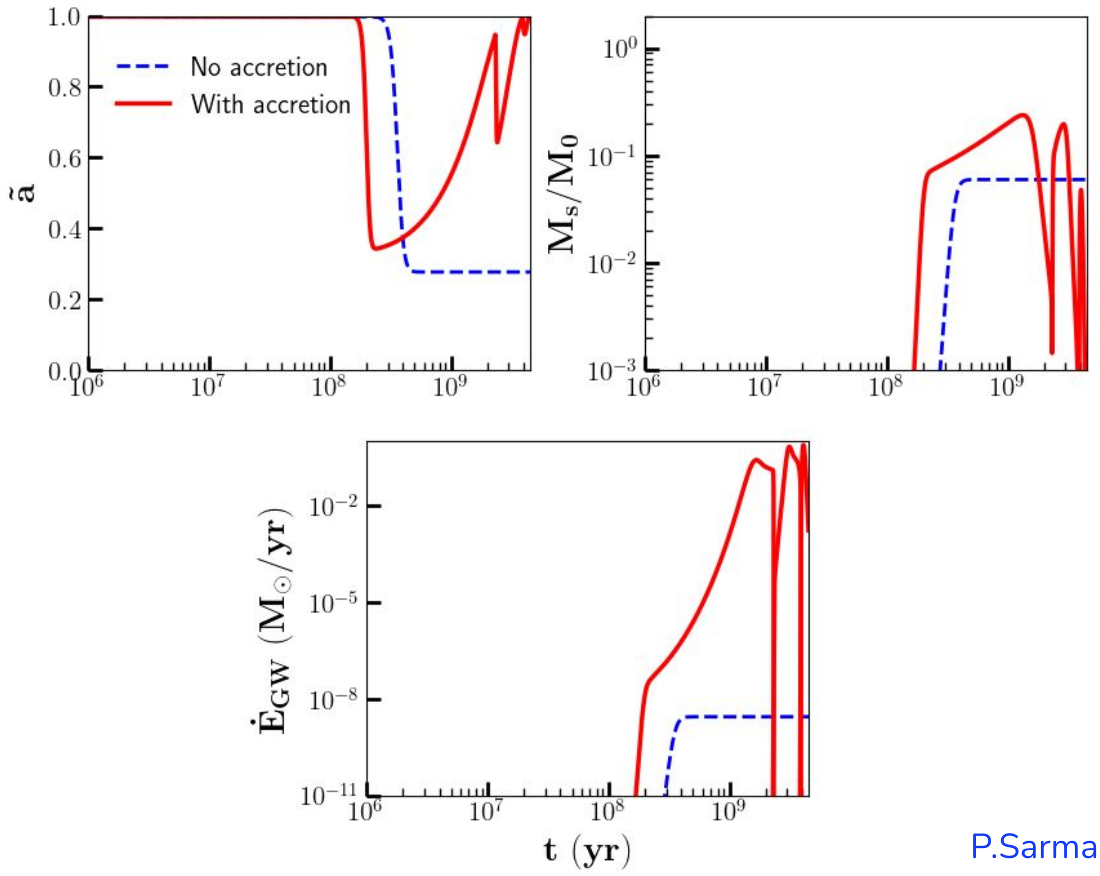

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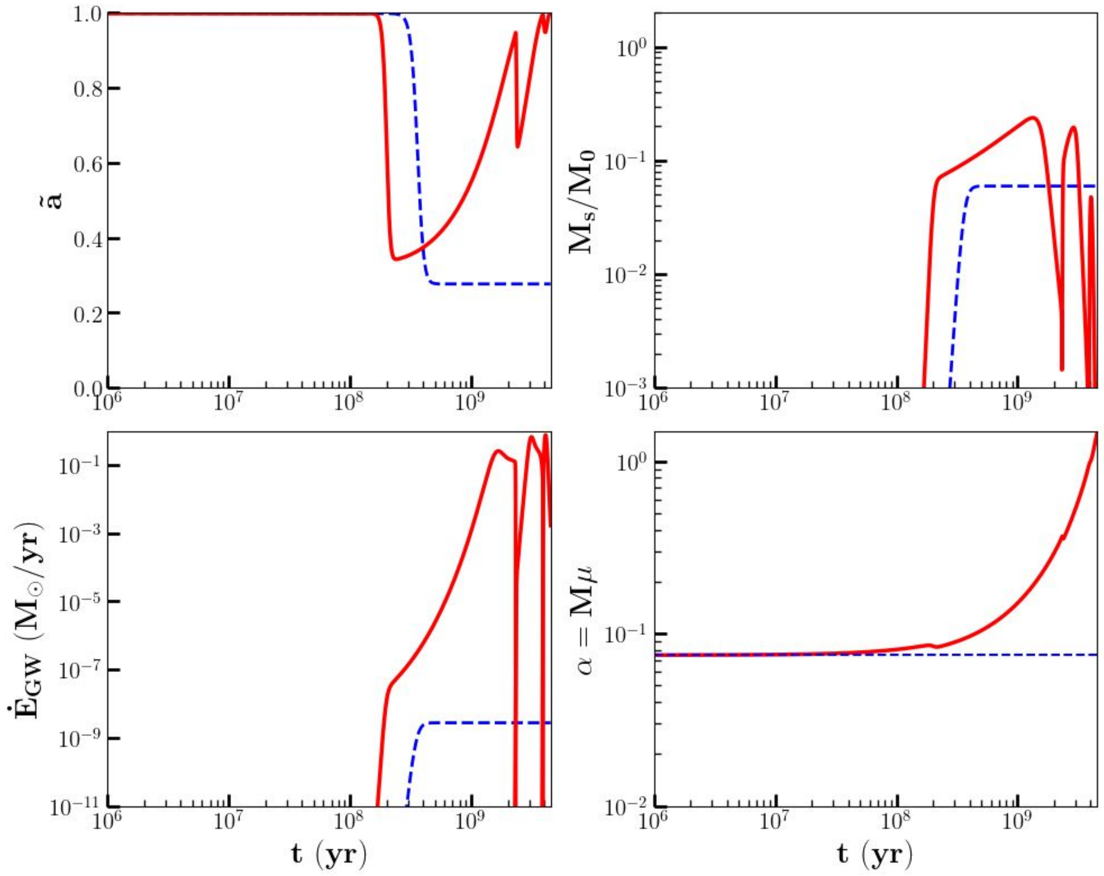
Time evolution of accreting BH + scalar cloud system

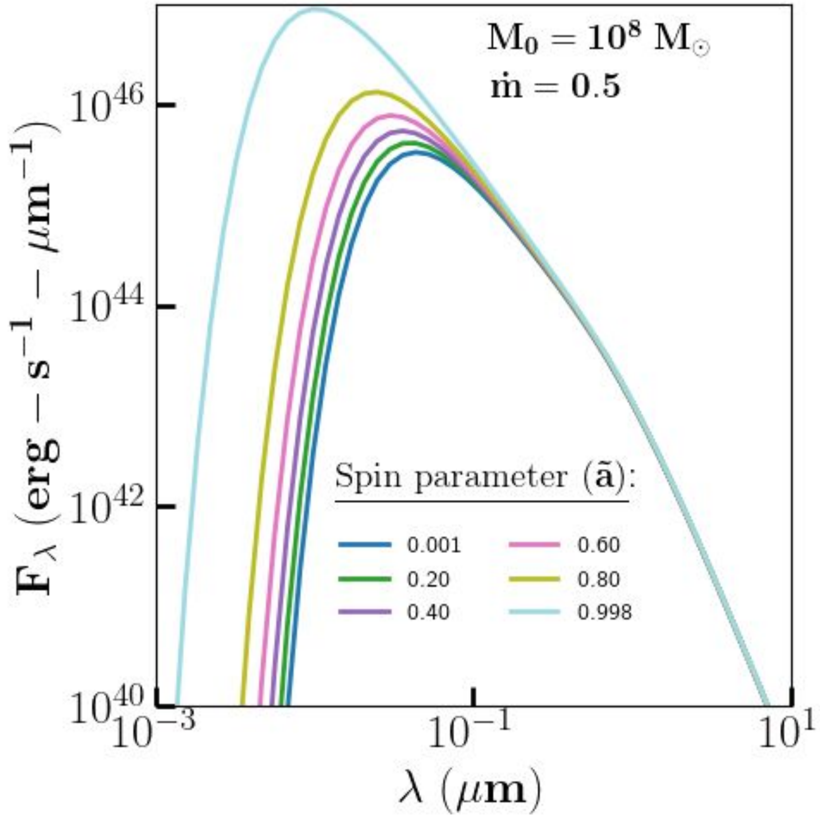


$dE_{GW}/dt \sim (Ms/M)^2 \, \alpha^{4l+10}$

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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Continuum Spectrum of AGN

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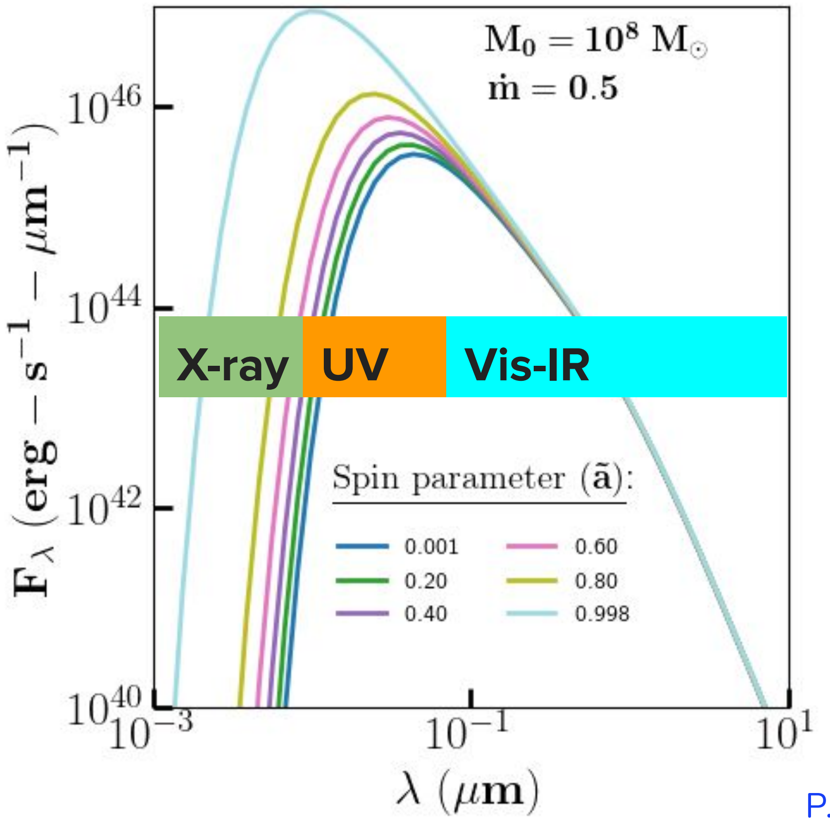
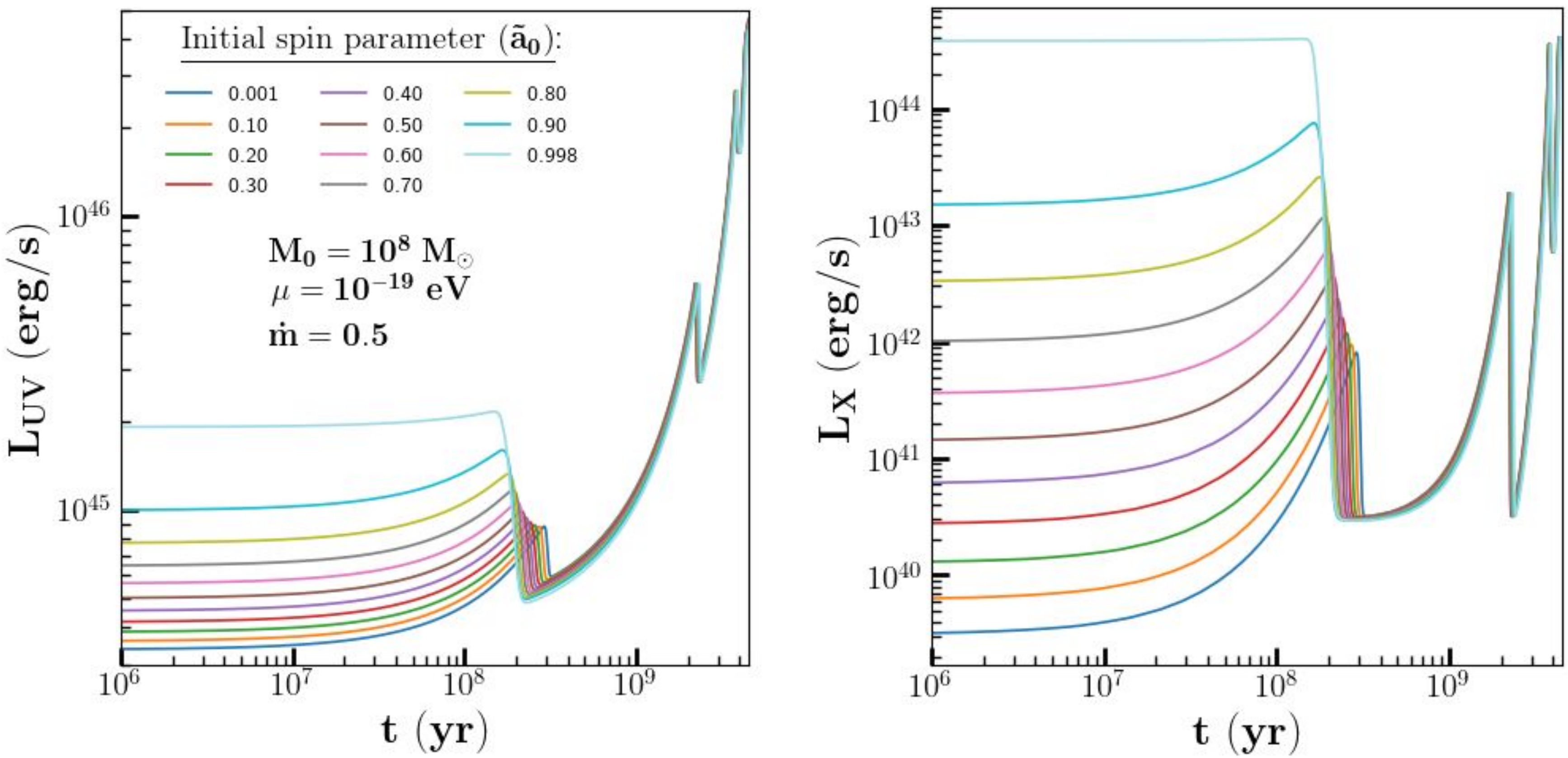


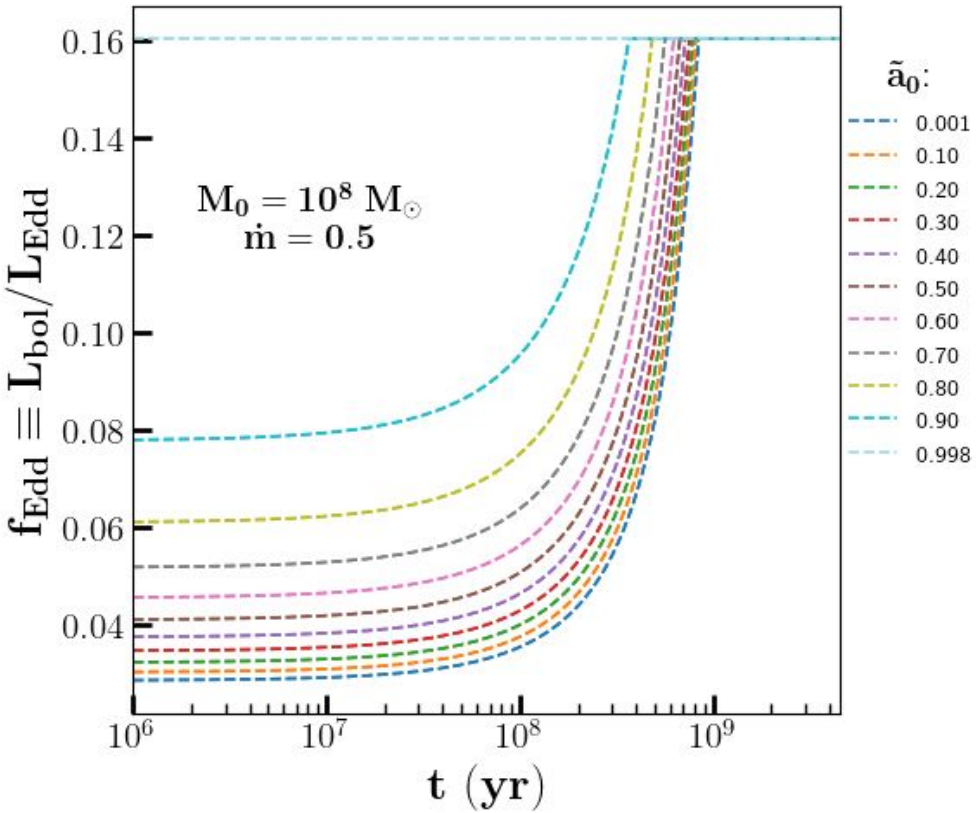
P.Sarmah et al. [2404.09955]

Luminosity in various bands



P.Sarmah et al. [2404.09955]

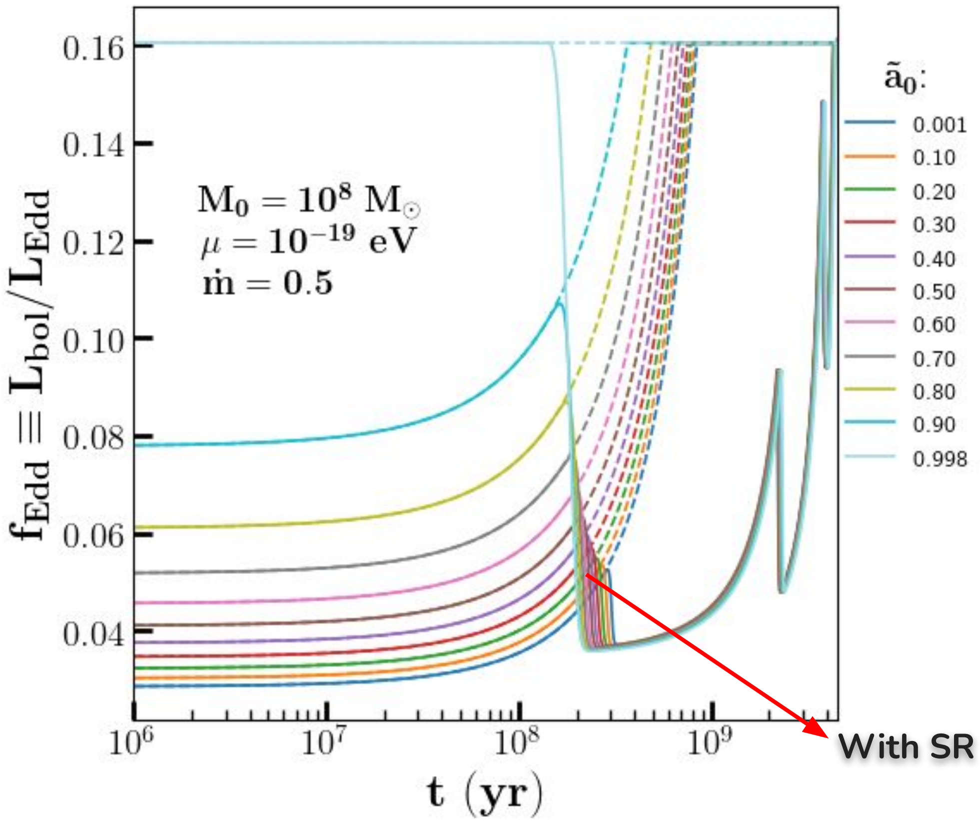
Eddington Ratio



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

P.Sarmah et al. [2404.09955]

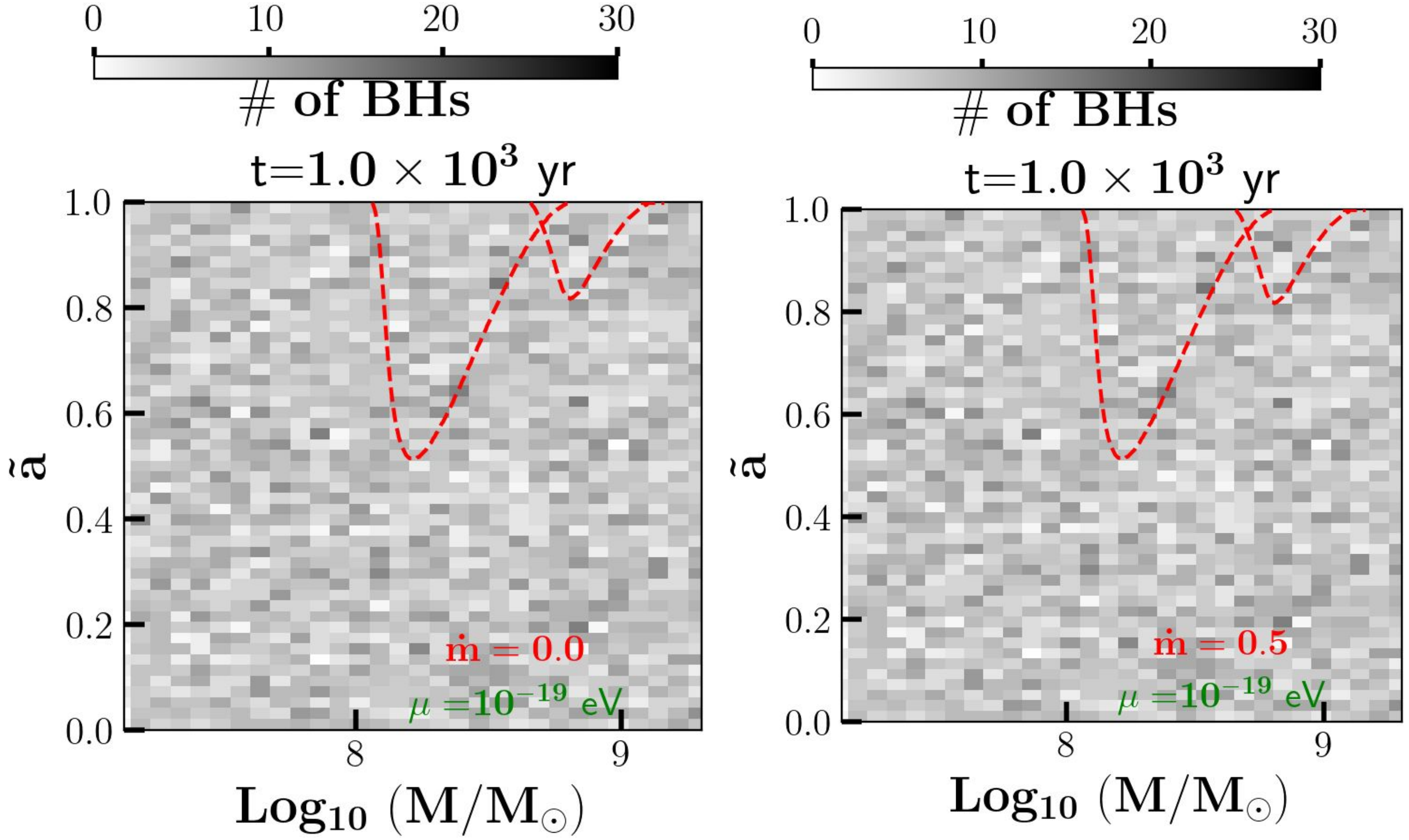
Eddington Ratio

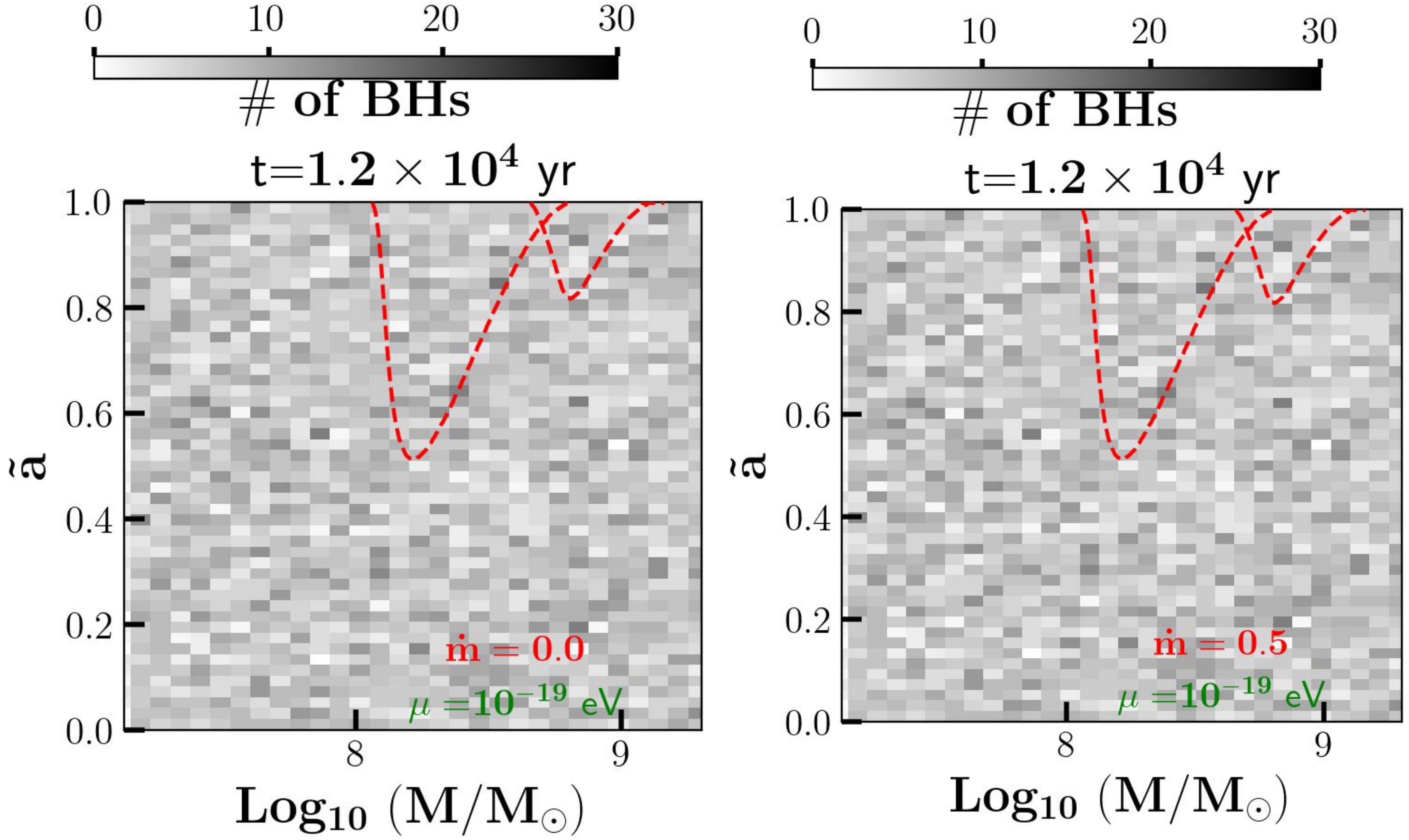


- With SR, no longer monotonically increasing, falls (due to SR) and rise (due to accretion) at various epochs.

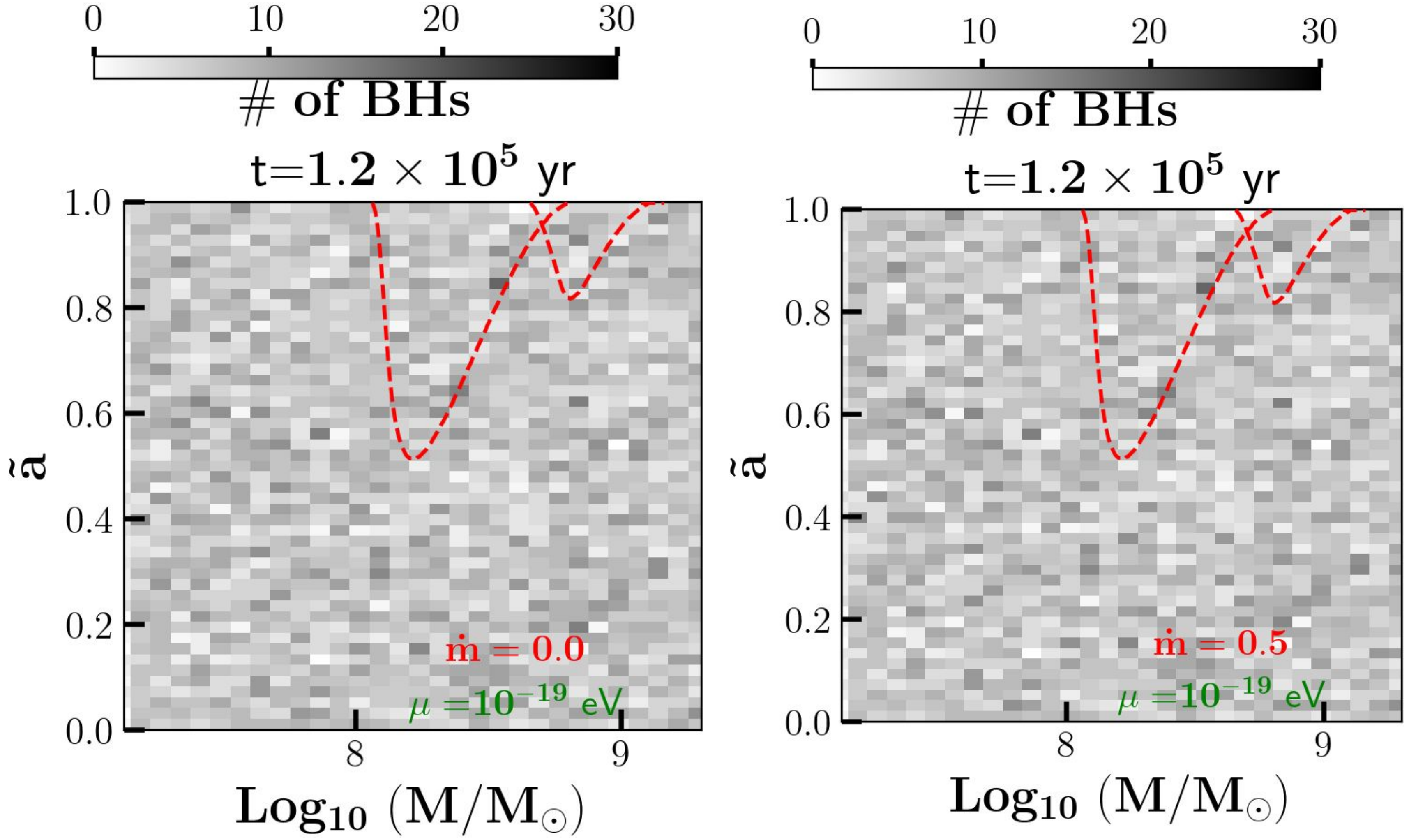
P.Sarmah et al. [2404.09955]

Distribution of SMBHs at the AGN core

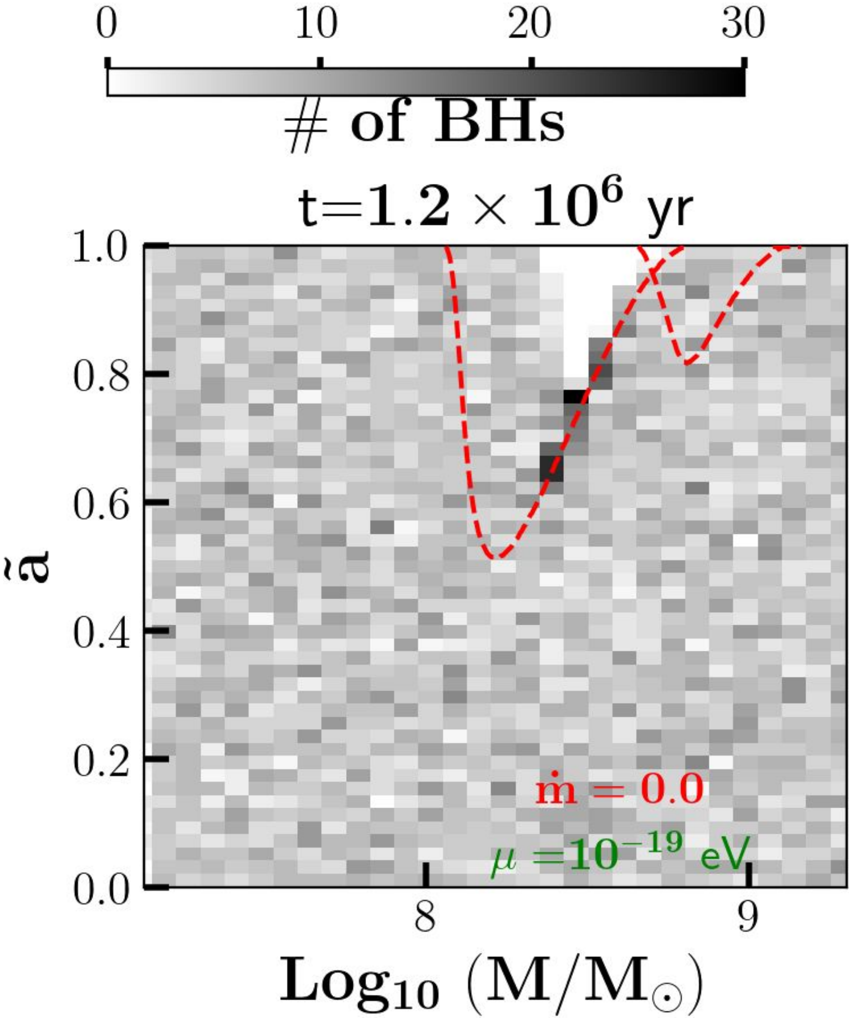

0
10
20
30
# of BHs
t=1.0 × 10^3 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M☉)
0
10
20
30
# of BHs
t=1.0 × 10^3 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M☉)

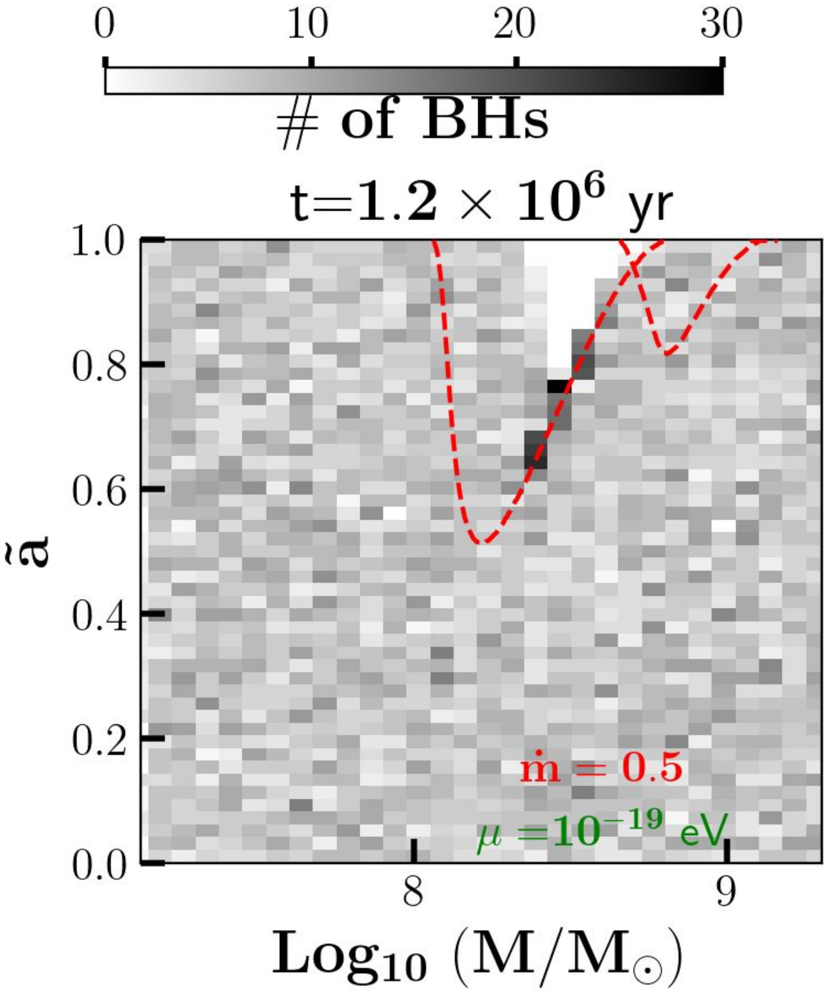


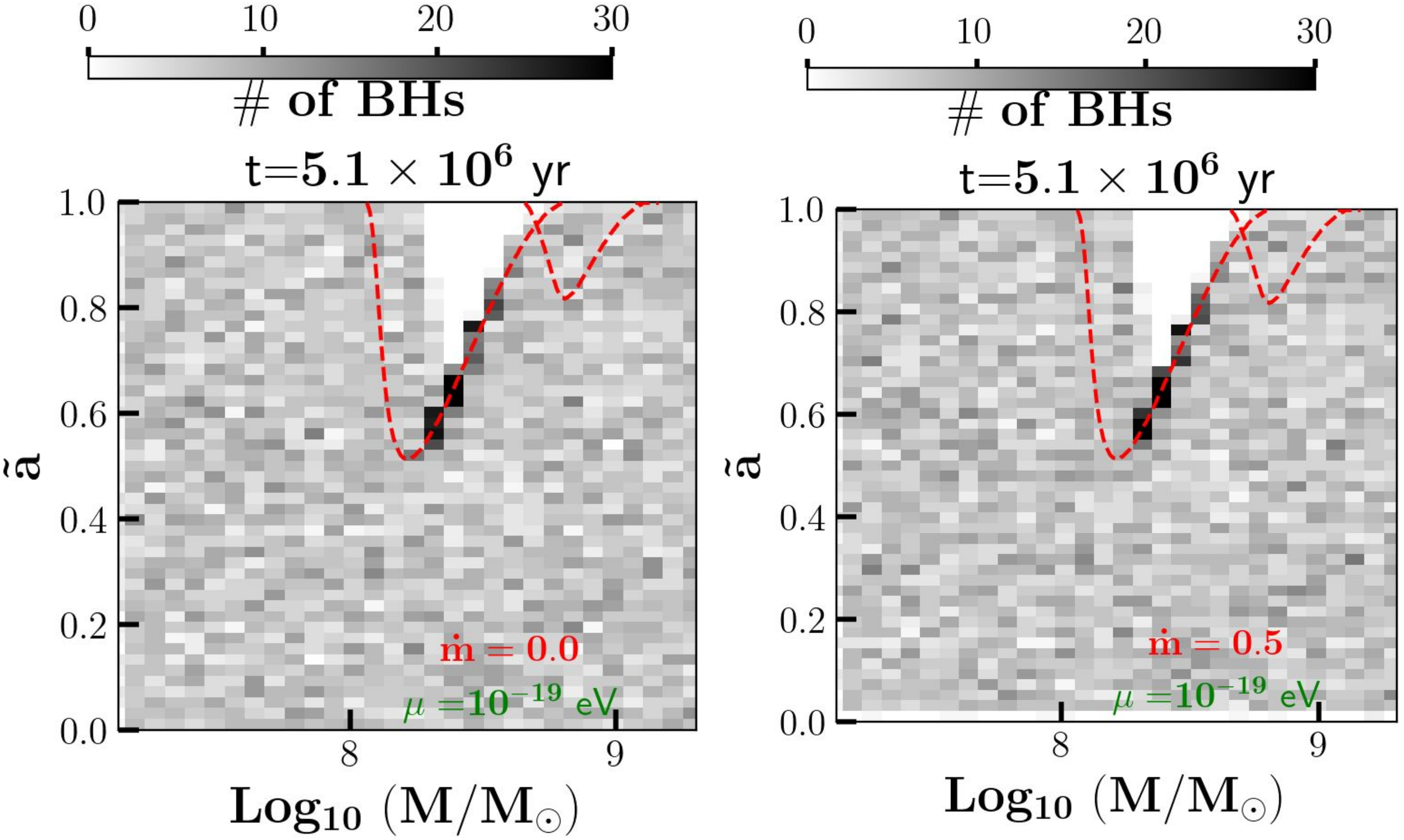
0 10 20 30
# of BHs
t=1.2 × 10^4 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^-19 eV
8 9
Log10 (M/M⊙)
0 10 20 30
# of BHs
t=1.2 × 10^4 yr
ã
ṁ = 0.5
μ =10^-19 eV
8 9
Log10 (M/M⊙)



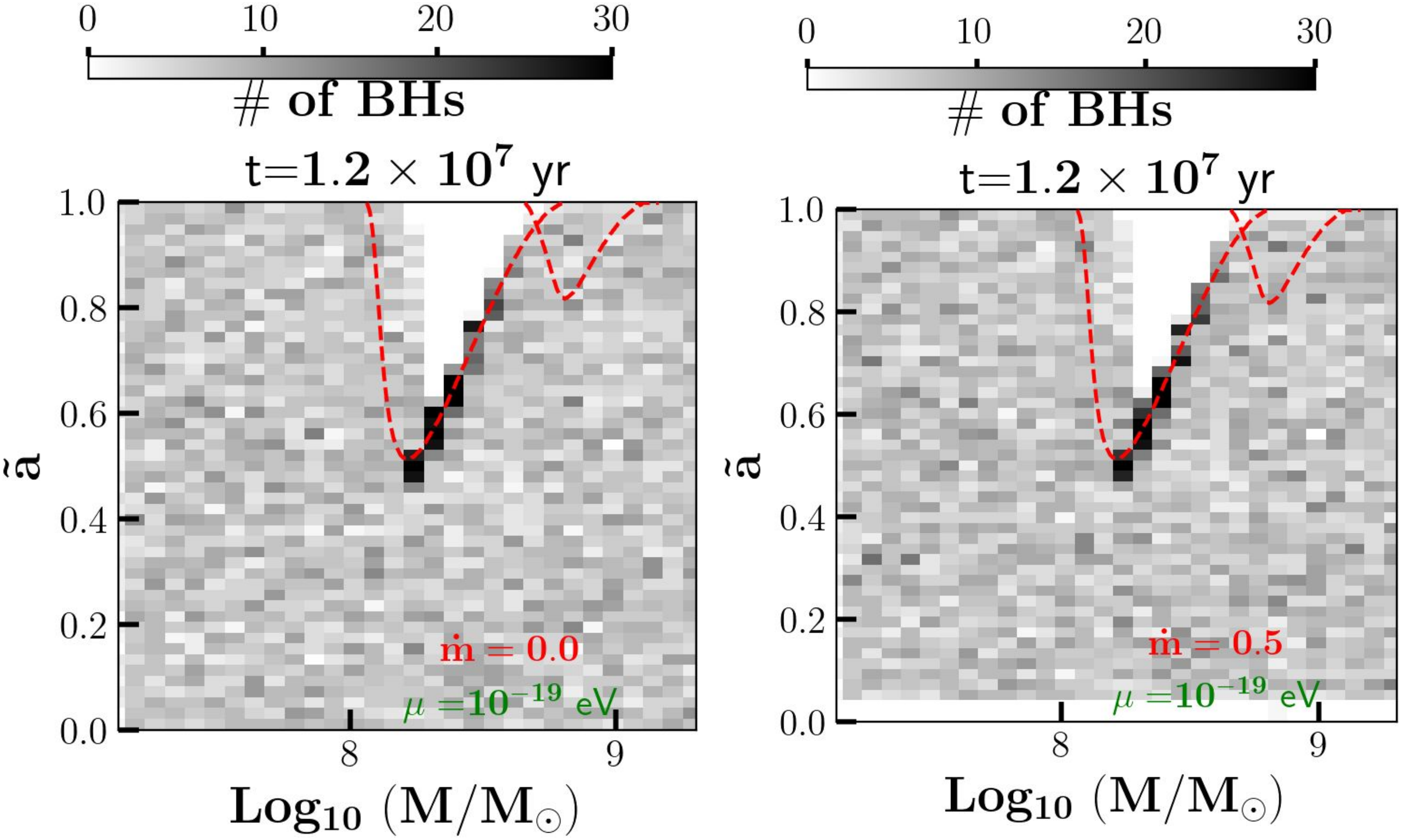
0 10 20 30
# of BHs
t=1.2 × 10^5 yr
ã
1.0 0.8 0.6 0.4 0.2 0.0
8 9
Log10 (M/M⊙)
ṁ = 0.0
μ =10^-19 eV
0 10 20 30
# of BHs
t=1.2 × 10^5 yr
ã
1.0 0.8 0.6 0.4 0.2 0.0
8 9
Log10 (M/M⊙)
ṁ = 0.5
μ =10^-19 eV


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⊙)

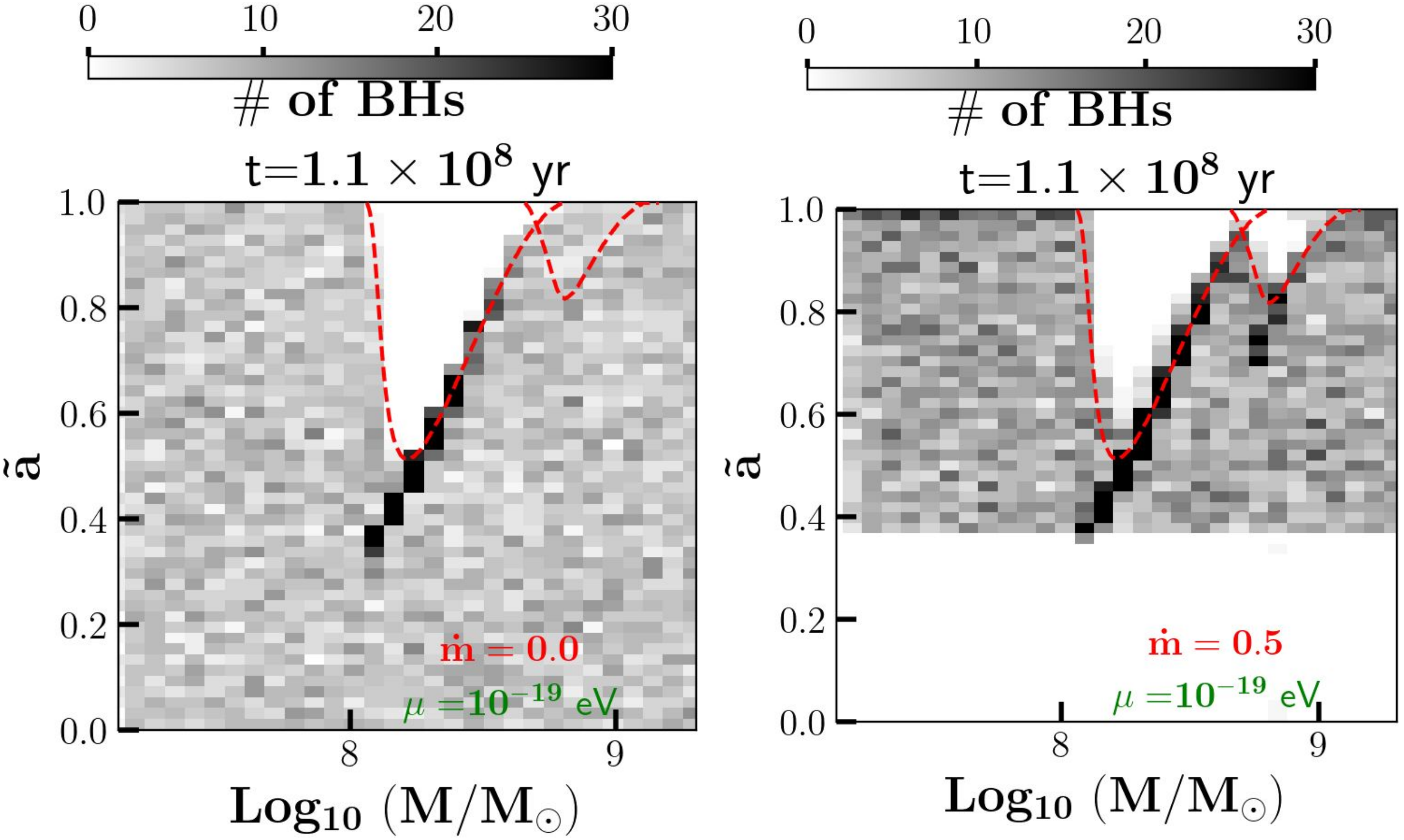

0
10
20
30
# of BHs
t=1.2 × 10^6 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)



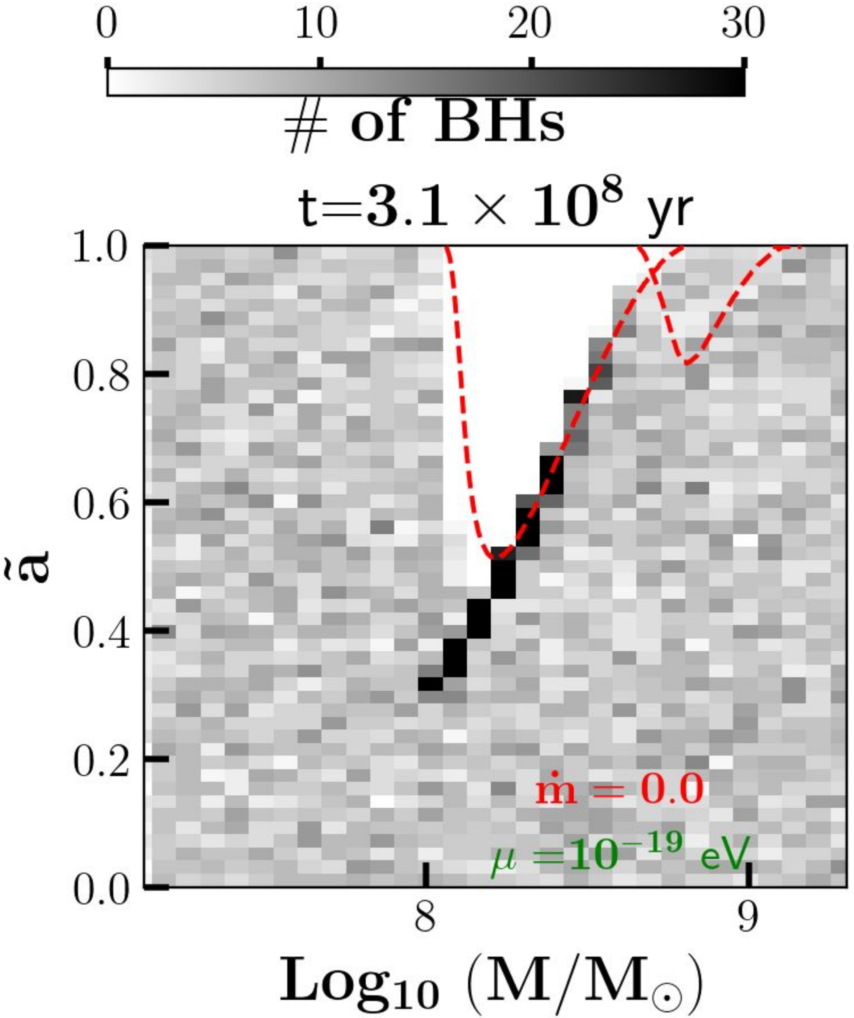
0 10 20 30
# of BHs
t=5.1 × 10^6 yr
ã
Log10 (M/M⊙)
ṁ = 0.0
μ =10^−19 eV
0 10 20 30
# of BHs
t=5.1 × 10^6 yr
ã
Log10 (M/M⊙)
ṁ = 0.5
μ =10^−19 eV



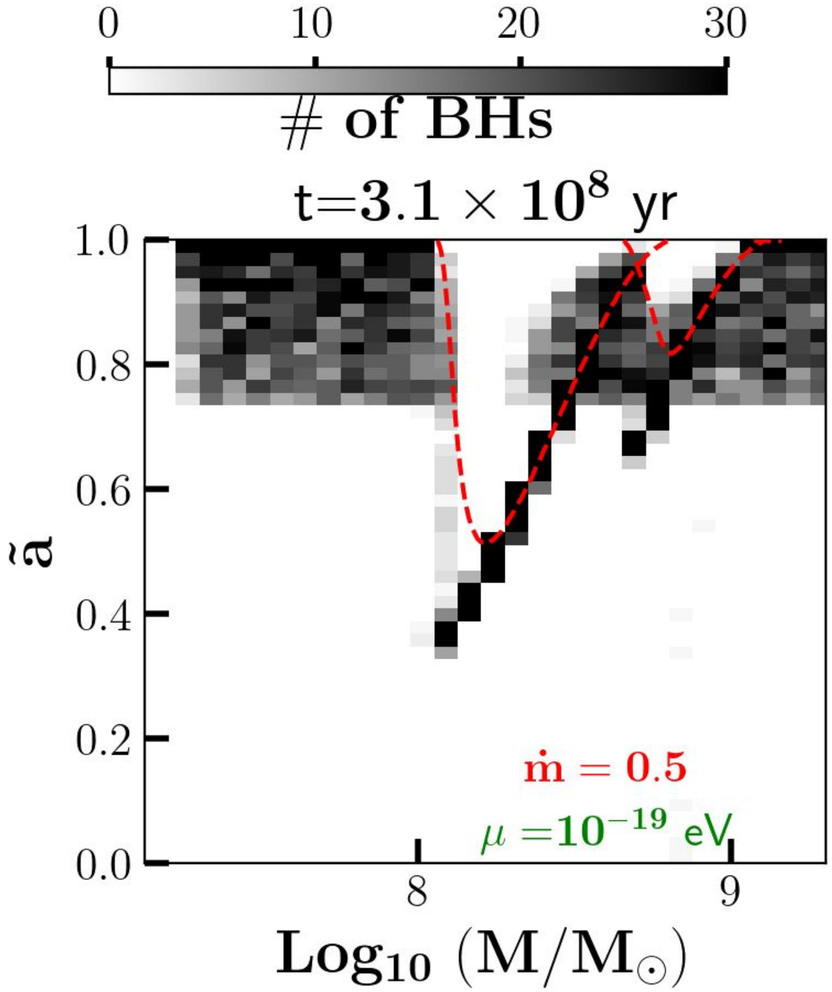
0
10
20
30
# of BHs
t=1.2 × 10^7 yr
ã
1.0
0.8
0.6
0.4
0.2
0.0
8
9
Log10 (M/M☉)
ṁ = 0.0
μ =10^-19 eV
0
10
20
30
# of BHs
t=1.2 × 10^7 yr
ã
1.0
0.8
0.6
0.4
0.2
0.0
8
9
Log10 (M/M☉)
ṁ = 0.5
μ =10^-19 eV



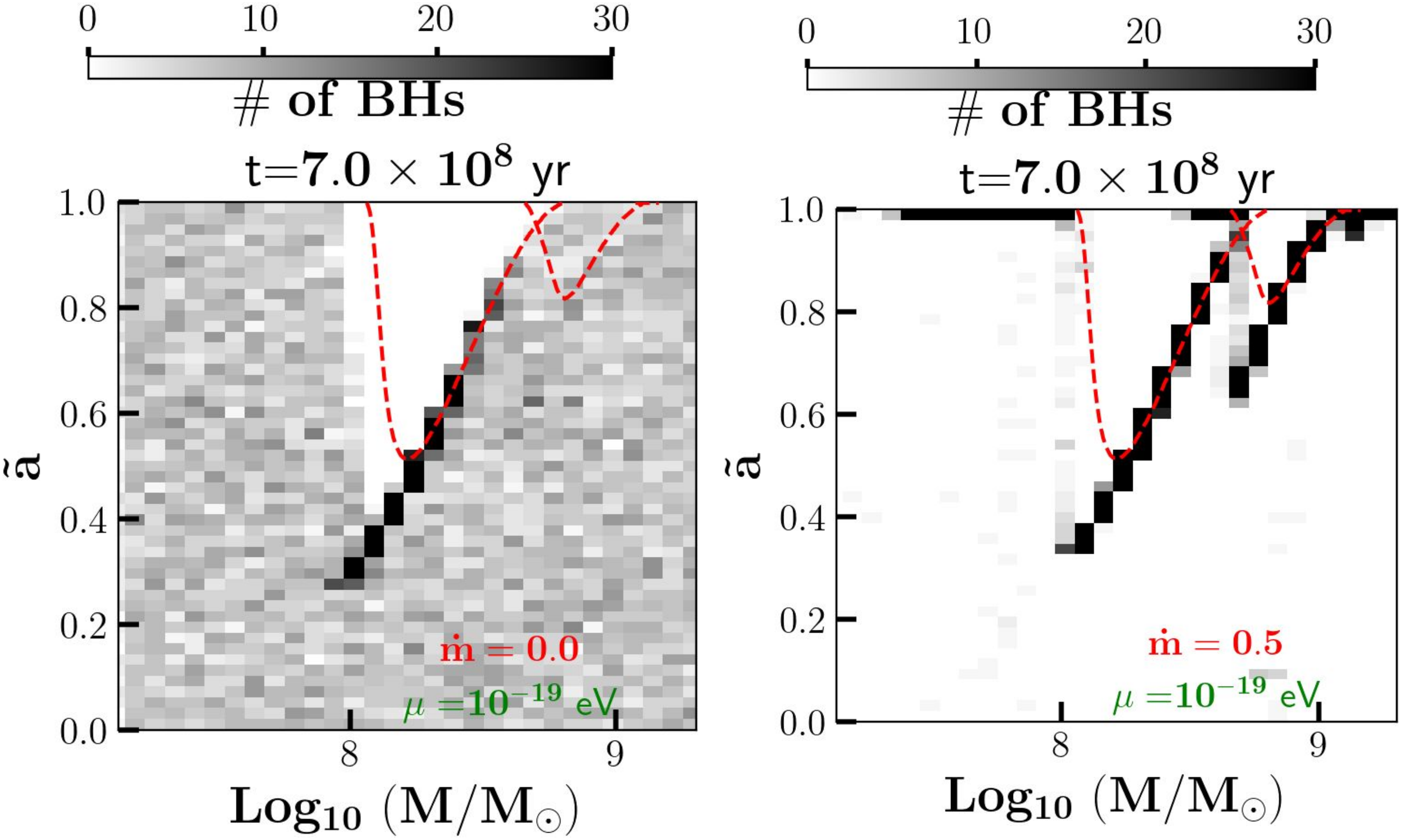
0
10
20
30
# of BHs
t=1.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
8
9
Log10 (M/M⊙)
ṁ = 0.0
μ =10^−19 eV
ṁ = 0.5



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⊙)

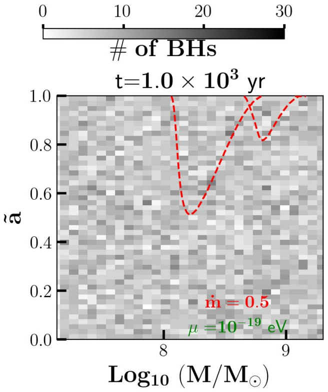


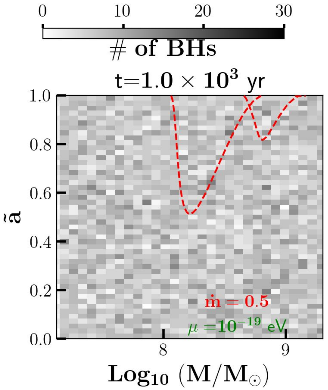
0
10
20
30
# of BHs
t=3.1 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.5
μ =10^−19 eV
8
9
Log10 (M/M⊙)



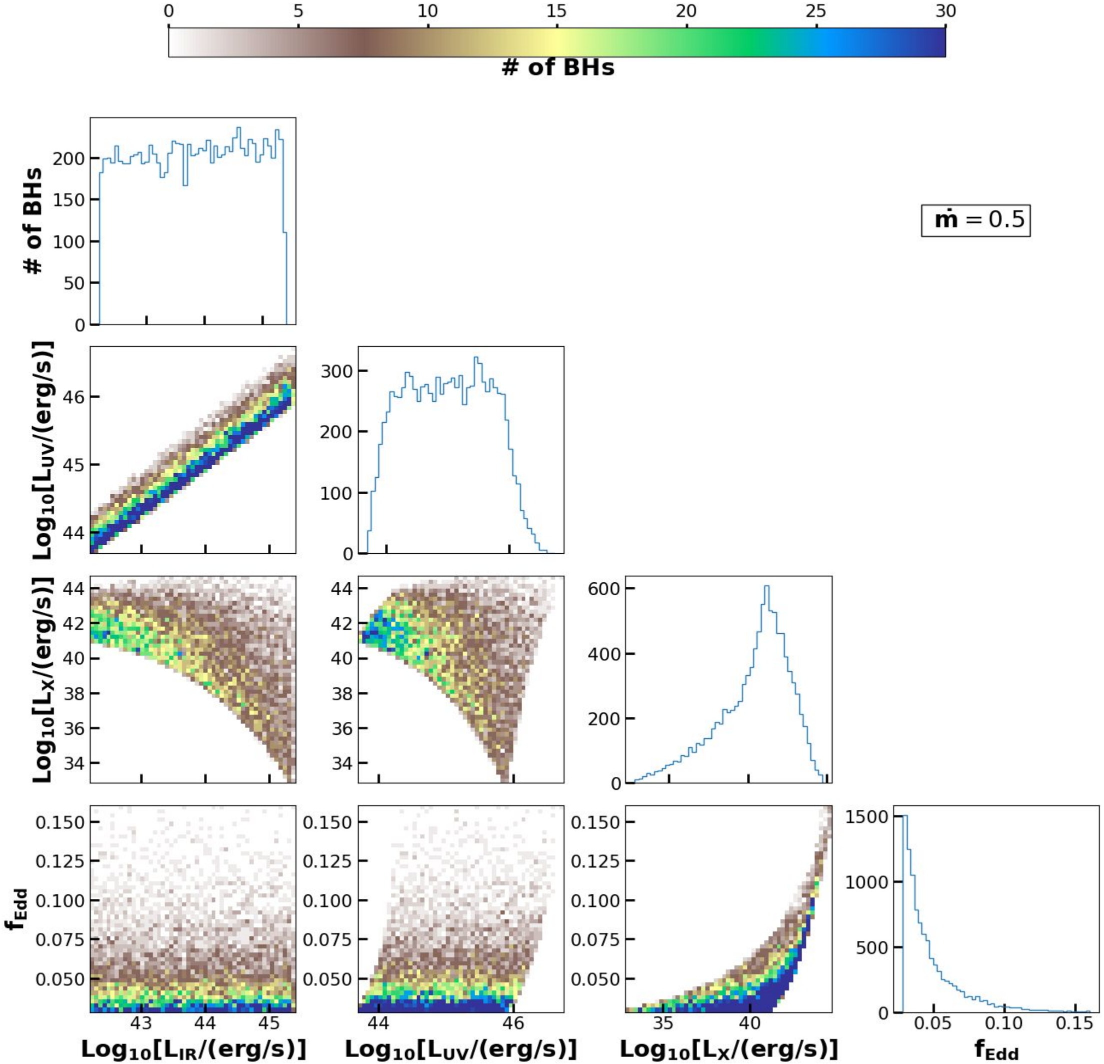
0 10 20 30
# of BHs
t=7.0 × 10^8 yr
1.0
0.8
0.6
0.4
0.2
0.0
ã
ṁ = 0.0
μ =10^−19 eV
8
9
Log10 (M/M⊙)
0 10 20 30
# of BHs
t=7.0 × 10^8 yr
ṁ = 0.5
μ =10^−19 eV
Log10 (M/M⊙)

Distribution of AGN Characteristics

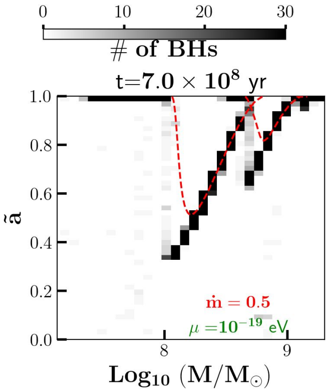

0
10
20
30
# of BHs
t=1.0×10^3 yr
1.0
0.8
0.6
0.4
0.2
0.0
$\tilde{a}$
$\dot{m} = 0.5$
$\mu = 10^{-19}$ eV
8
9
$\mathrm{Log_{10}}\,(\mathrm{M/M_\odot})$

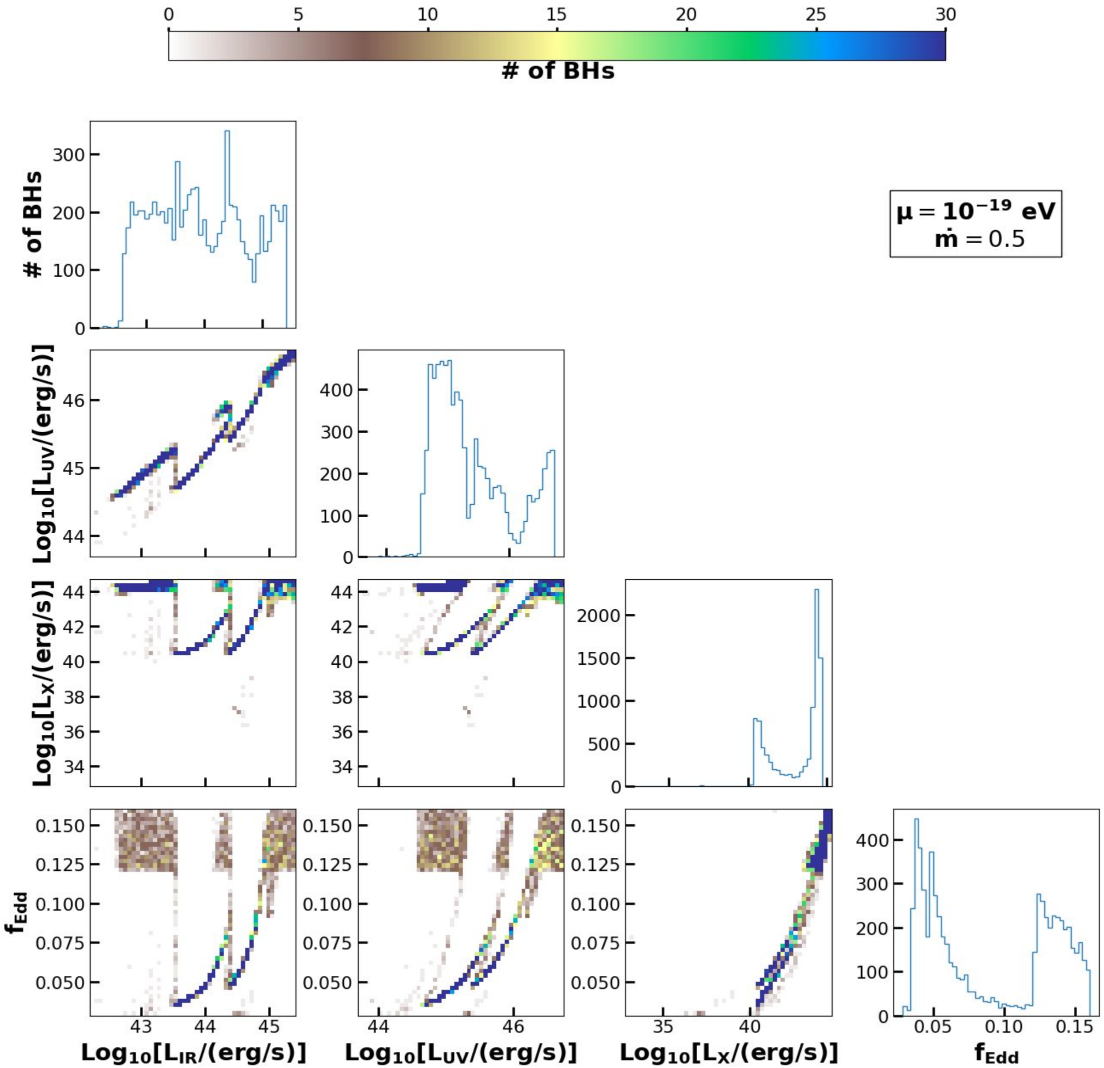


# of BHs
t=1.0 × 10³ yr
ṁ = 0.5
μ = 10⁻¹⁹ eV
ã
Log₁₀ (M/M☉)



# of BHs
ṁ = 0.5
Log₁₀[L_UV/(erg/s)]
Log₁₀[L_X/(erg/s)]
f_Edd
Log₁₀[L_IR/(erg/s)]





P.Sarmah et al. [2404.09955]

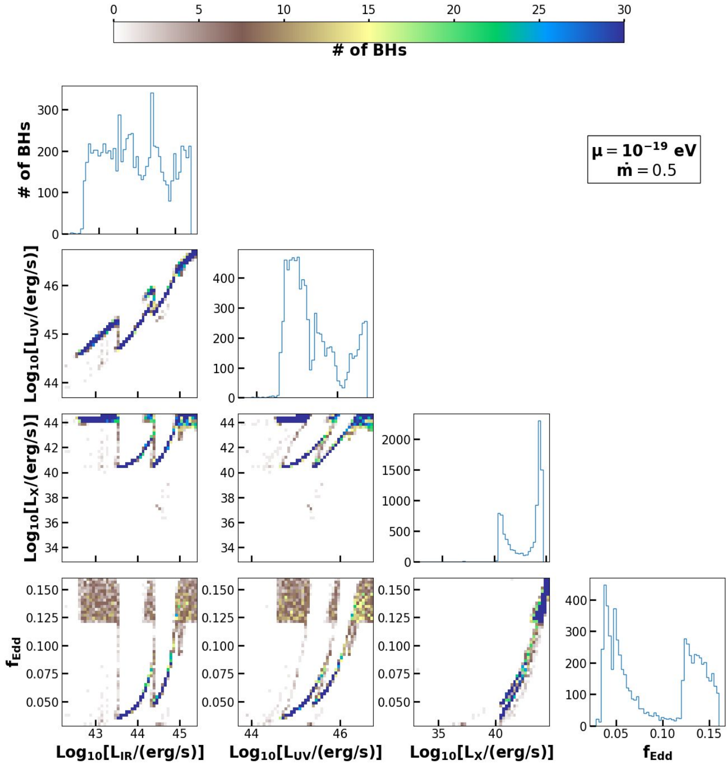
Summary

- 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?

Luminosity in various bands

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

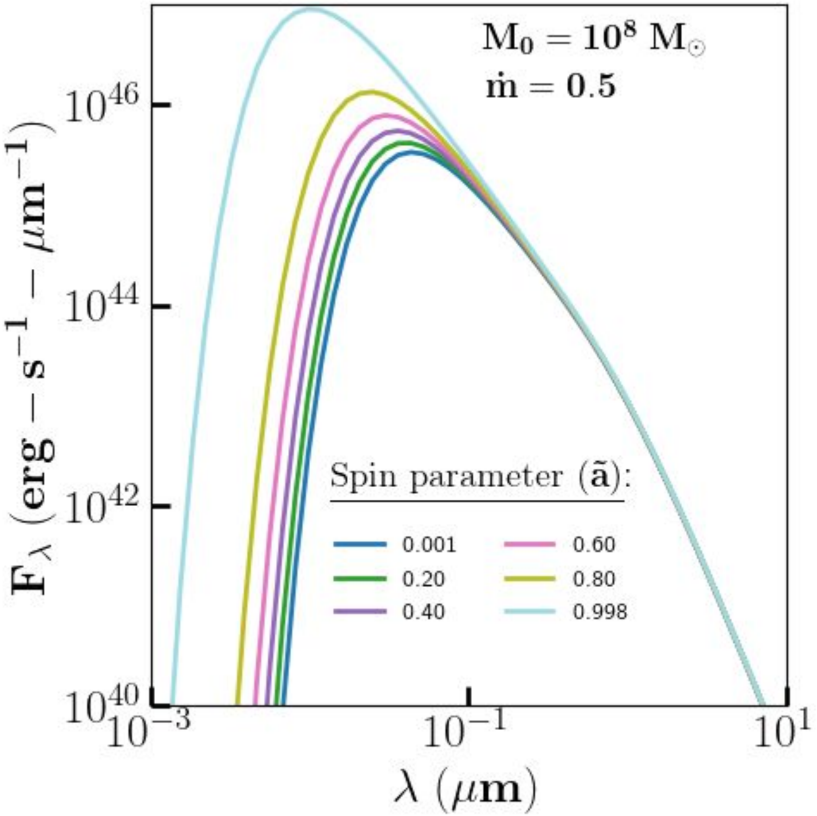
$$L_{\mathrm{UV}} = \int_{0.01}^{0.4} F_\lambda d\lambda,$$

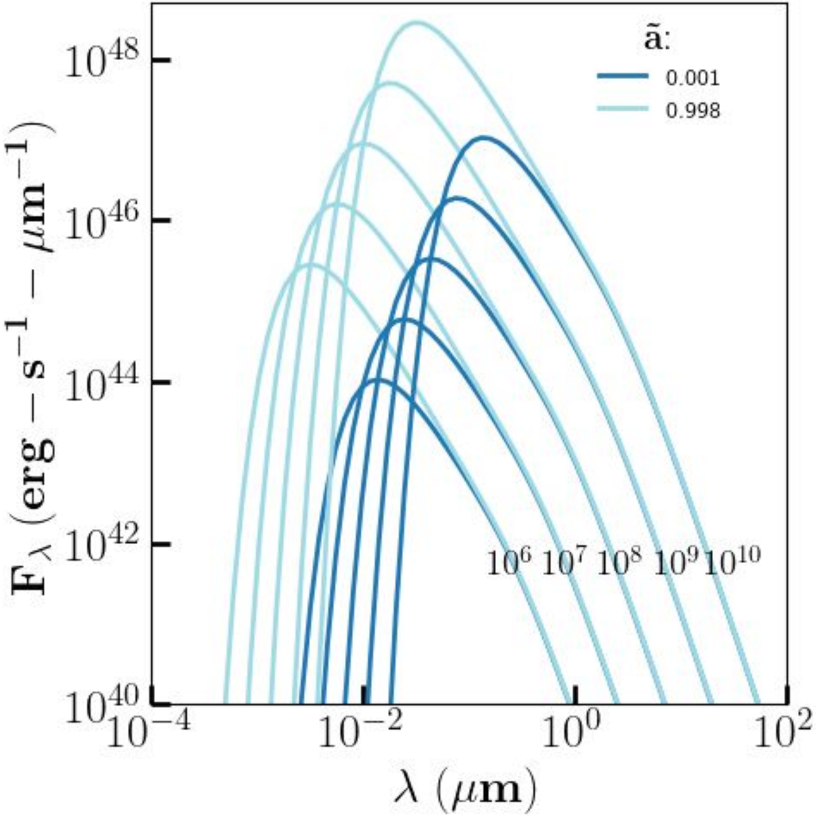
$$L_{\mathrm{Vis-IR}} = \int_{0.4}^{100} F_\lambda d\lambda,$$

P.Sarmah et al. [2404.09955]

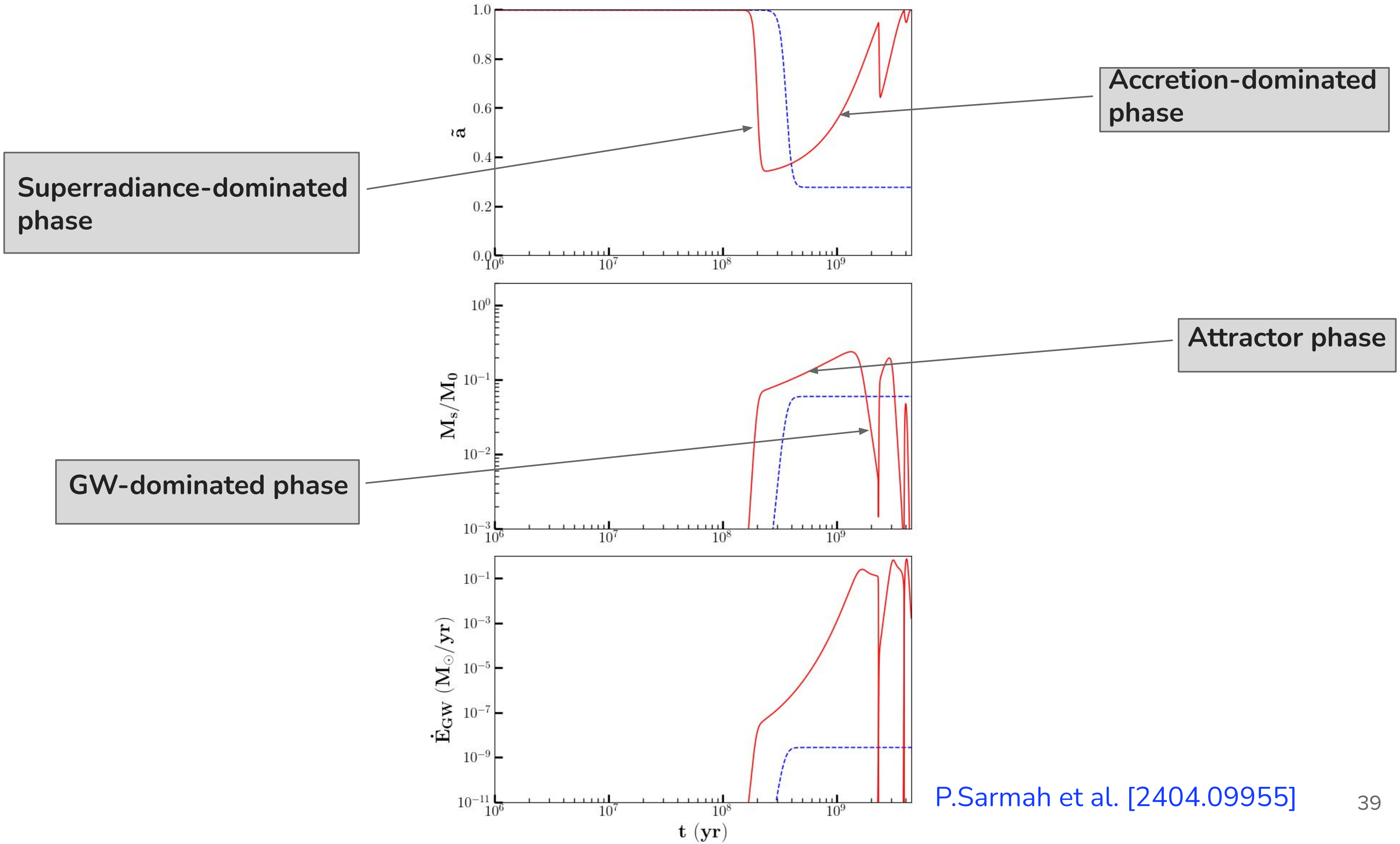
Continuum Spectrum of AGN

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





P.Sarmah et al. [2404.09955]



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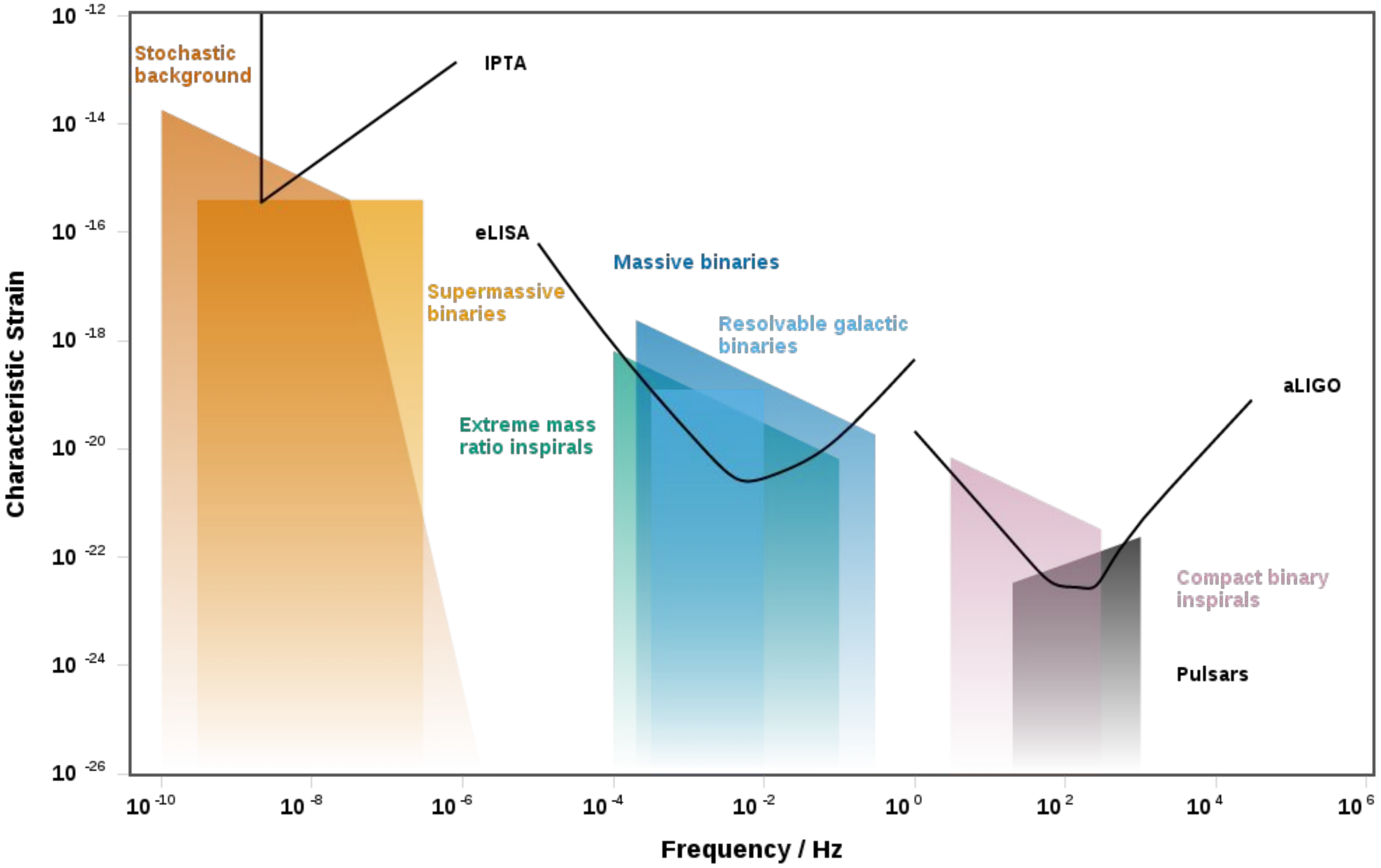
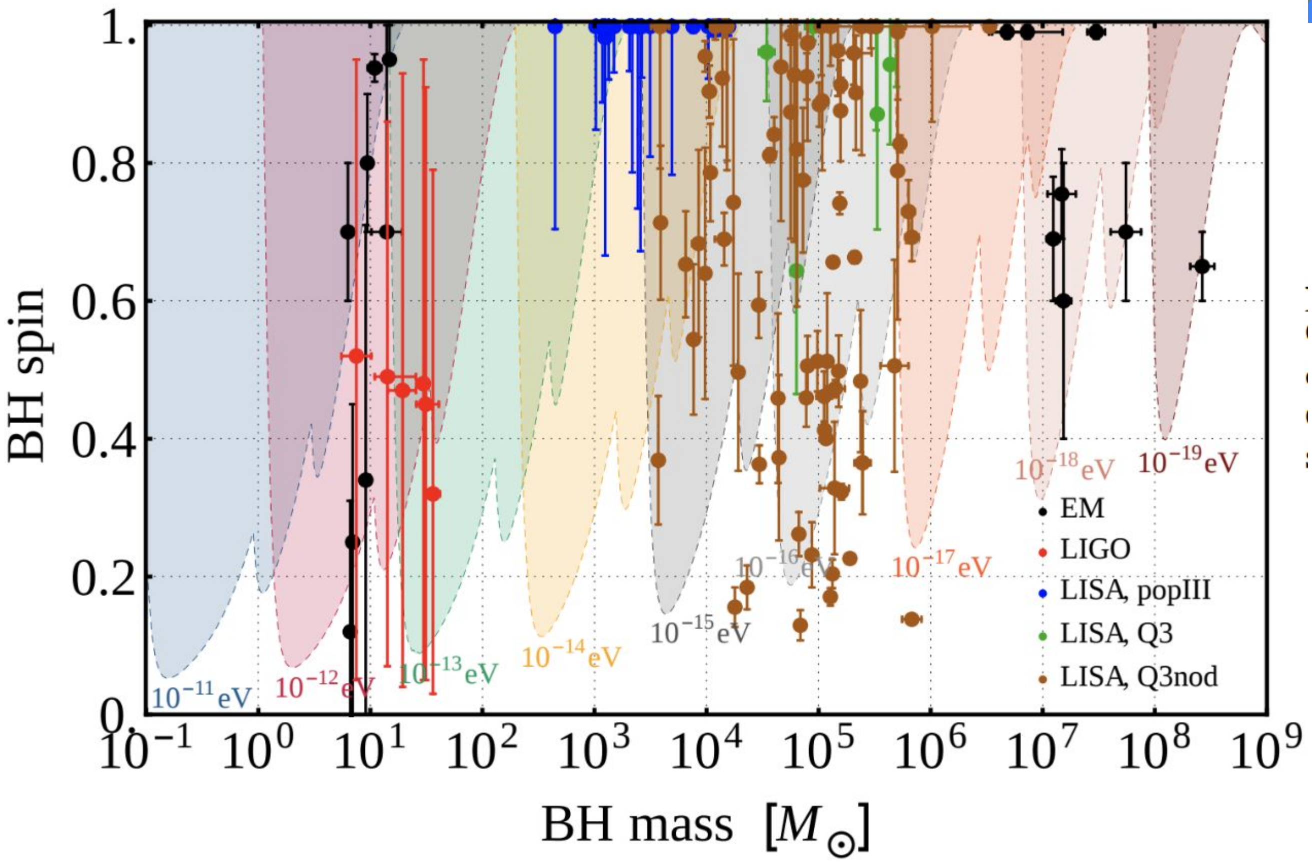


Stochastic background
IPTA
eLISA
Massive binaries
Supermassive binaries
Resolvable galactic binaries
aLIGO
Extreme mass ratio inspirals
Compact binary inspirals
Pulsars
Characteristic Strain
10 -12
10 -14
10 -16
10 -18
10 -20
10 -22
10 -24
10 -26
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6
Frequency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

RB, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani, '17



Superradiance in a Black Hole

- 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

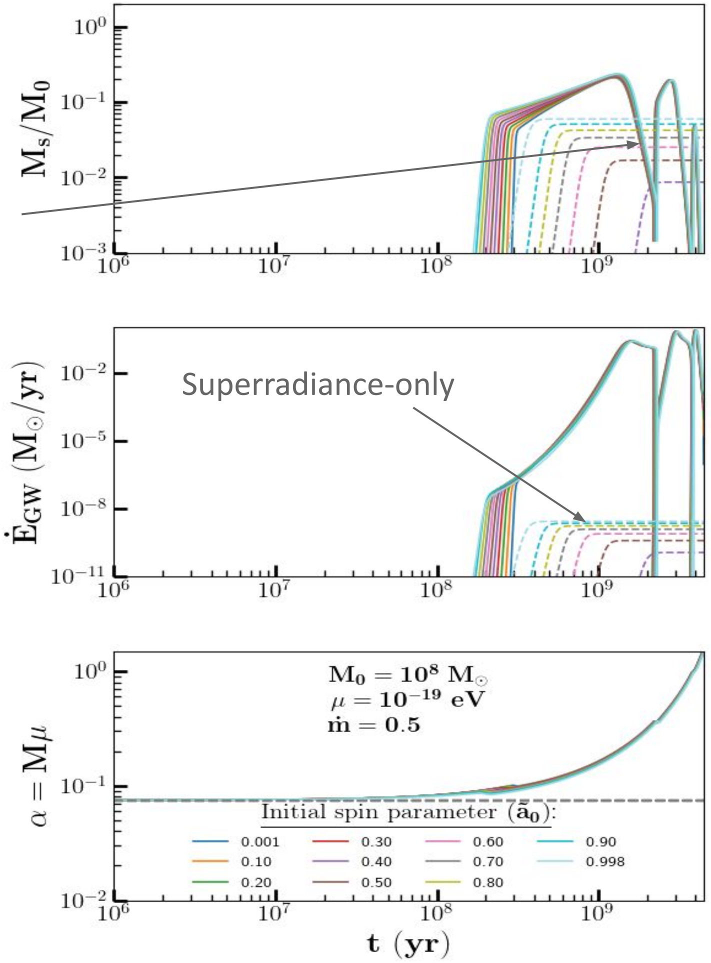
Observational signatures of Superradiance

- 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]

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.

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

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