Stellar Black Holes Can “Stretch” Supermassive Black Hole Accretion Disks

Kaushik Chatterjee
Postdoc
SWIFAR, Yunnan University
(kaushik@ynu.edu.cn)

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- How do they effect the environment
- What is the modification of the effective temperature
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- What is the change in half-light radius
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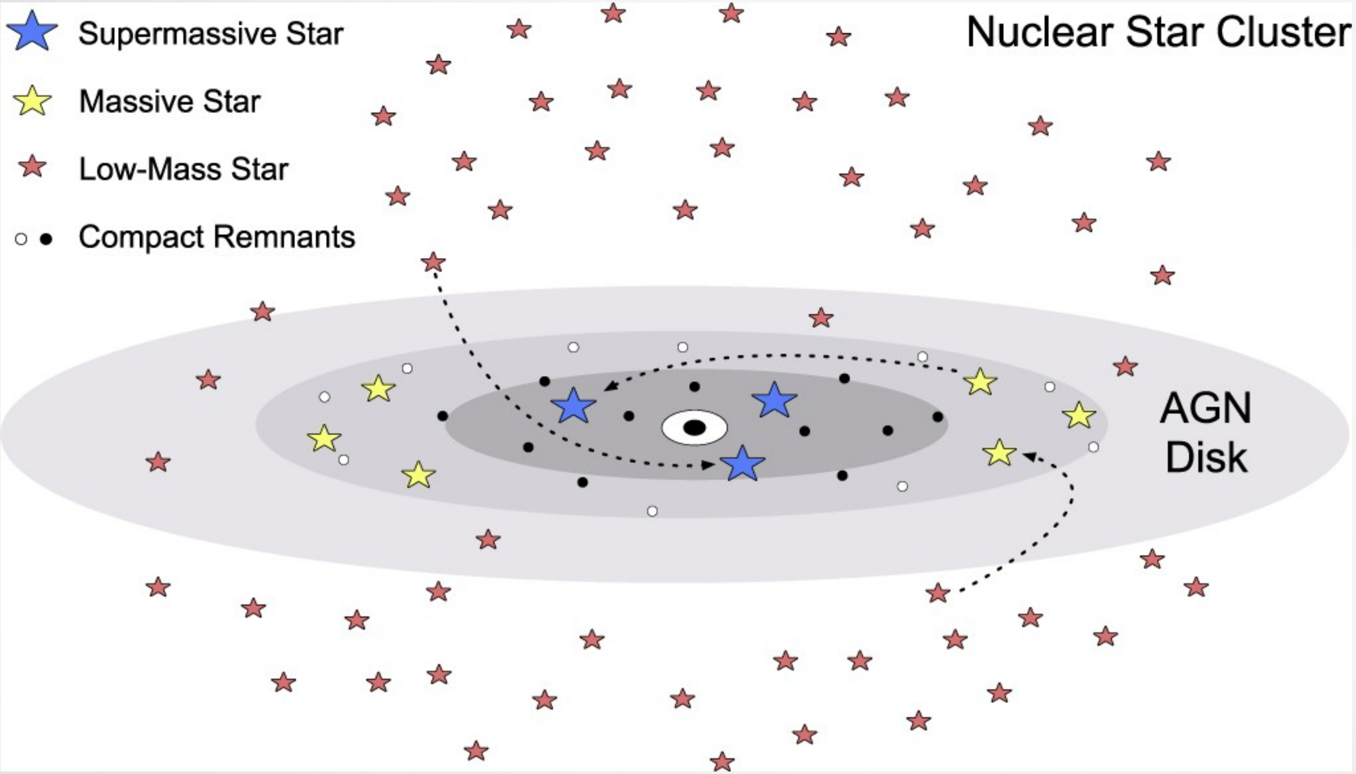
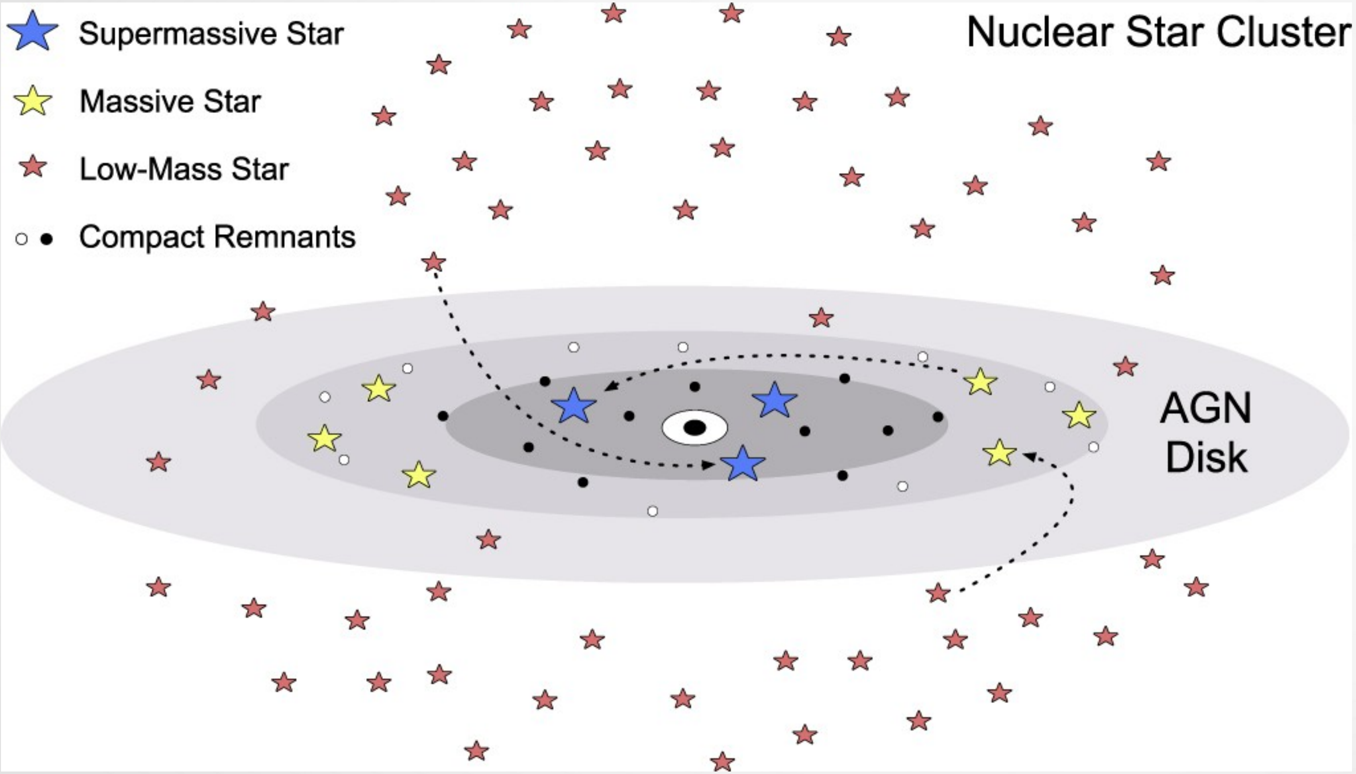
Schematic Diagram



Cantiello et al. (2021)

A schematic showing stellar evolution in the accretion disk of an AGN. Low mass stars can be formed in or accreted by the disk, where they gain mass and eventually evolve to leave behind compact remnants near the center of the disk

Schematic Diagram



Cantiello et al. (2021)

The outer regions of the accretion disk are far from the central supermassive black hole (SMBH), where self-gravity plays a dominant role, and the disk inevitably collapses to form stars.

In addition, stars near the center of the galaxy can interact with the SMBH accretion disk, resulting in a loss of orbital energy and angular momentum, and are captured by the accretion disk.

Stars in accretion disks can accrete gas and rapidly evolve into compact objects, such as white dwarfs, neutron stars, and stellar black holes (sBHs).

Timescales

- AGN lifetime ~ 10^7-10^8 year
- The rate of capture of stars ~ 10^{-4}-10^{-3} per year
- Total capture within AGN's lifetime ~ 10^3-10^5

Thus, 10^3-10^5 number of stars get the time to evolve into different types of compact objects, depending on the environment.

Types of Compact Objects formed

1. White Dwarf: However, their evolution takes ~ 1 billion years.

2. Neutron Star: Timescale ~ a few to tens of million years. Their energy output is smaller to be significant with the AGN disk.

3. Black Hole: Timescale ~ a few to tens of million years. They affect the environment significantly.

So, what are the effects?

1. Embedded sBHs can change the effective temperature distribution of the AGN accretion disk by heating in the outer region.

2. The spectral energy distribution (SED) can have a turnover at some wavelength, depending on the distribution of sBHs.

3. The half-light radius can be changed.

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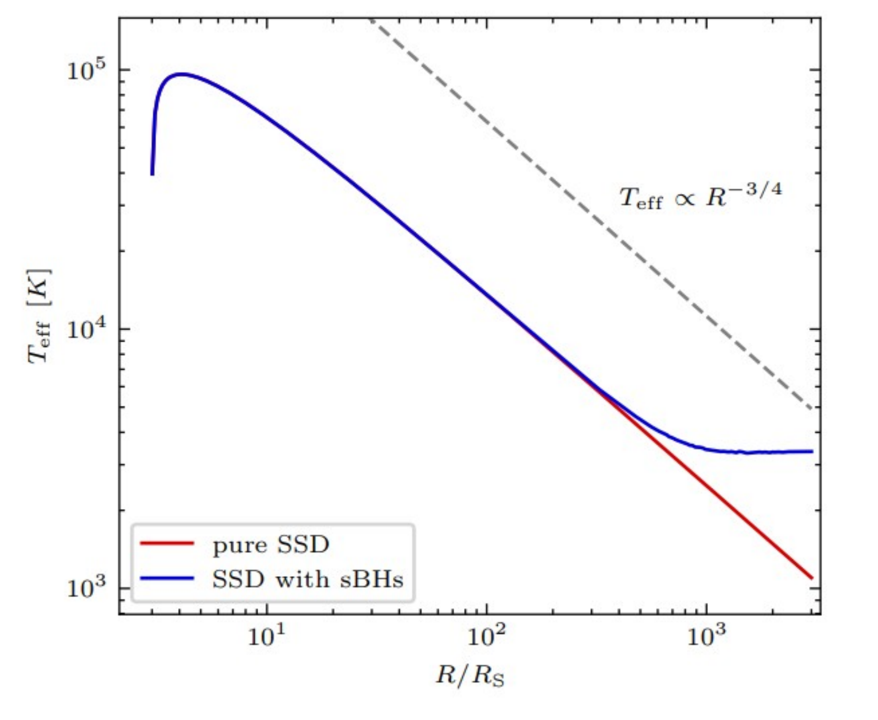
How???

Temperature distribution (Pure SSD)

Suppose, there are no stellar black holes (sBHs).

Temperature distribution of the pure SSD (Shakura Sunyaev Disk):

$$T_{eff} \sim R^{-3/4}$$ (***R*** is the radius of the disk)



So, temperature falls as a power-law (red line) with radial distance.

Temperature distribution (AGN disk embedded with sBHs)

When there are sBHs, present in the AGN disk, they will accrete a small fraction ($\boldsymbol{f_{sBHs}}$) of the gas material, present in the disk.

By this accretion, they will emit some radiation, mainly in X-rays.

AGN disk is optically thick. So, this radiation from the sBHs will mostly be trapped in the disk.

This would heat the disk and increase its temperature.

Now, the temperature distribution in the AGN disk is from the contribution from:

i) heating in the AGN disk itself
ii) heating due to the trapped radiation from sBHs

Suppose, $\boldsymbol{Q_{vis}}$ is the heating rate per unit area due to the AGN disk itself. And $\boldsymbol{Q_{sBHs}}$ is the heating rate in each zone by the sBHs.

When estimating the ratio of heating, they find that in each zone,

$$\boldsymbol{\epsilon} = \boldsymbol{Q_{sBHs}}/(\boldsymbol{Q_{vis}} * \text{ area of the zone}) \propto (\boldsymbol{R}/\boldsymbol{R_s})^3$$

Continued……

Thus, it is noticed that the effect will be much more as we consider more outside part of the disk.

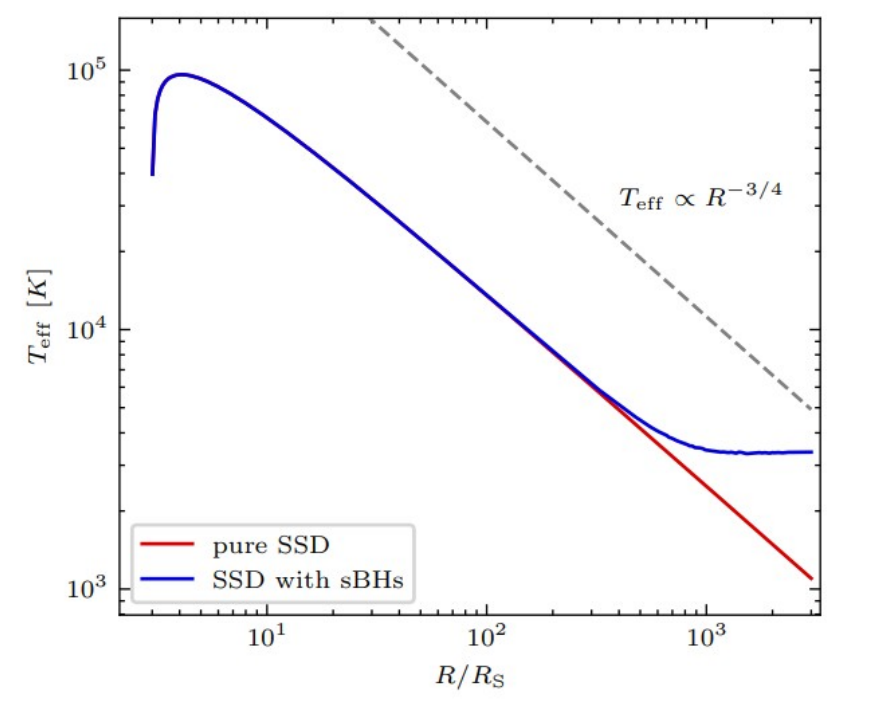
$$\epsilon \propto (R/R_s)^3$$

Physically, we can also think that, since at the closer distances, the effect of the SMBH is very large, the sBHs will have negligible effect at disk regions, close to the SMBH.

Thus, we notice from the right side plot, that after a certain distance (~ 300 R_s), the effective temperature is increasing as we go more outside the disk.

$$2\sigma T^4_{eff,sBHs}(R, \phi) = Q_{vis}(1 + \epsilon)$$

This is how we can get the effective temperature of the AGN disk, embedded with sBHs.



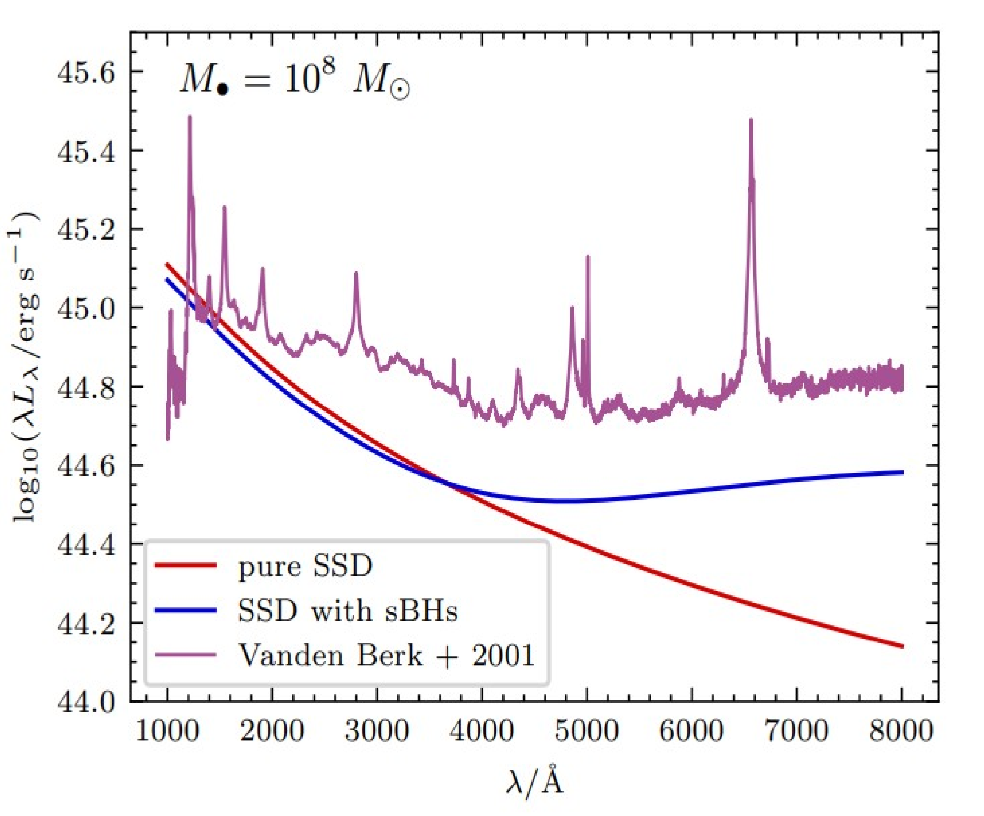
Spectral Energy Distribution (SED)

Case-I: $\boldsymbol{M_{SMBH} = 10^8}$ *Solar Mass* ; $\boldsymbol{f_{sBHS} = 0.1}$

At ~ 3600 Angstrom, the SED of the embedded disk starts to have higher SED, than a pure SSD.

Above ~ 4700 *Angstrom,* the SED of the embedded disk is significantly higher than the pure SSD.

Below ~ 3600 *Angstrom,* the pure SSD has slightly higher SED than the sBHs embedded disk.



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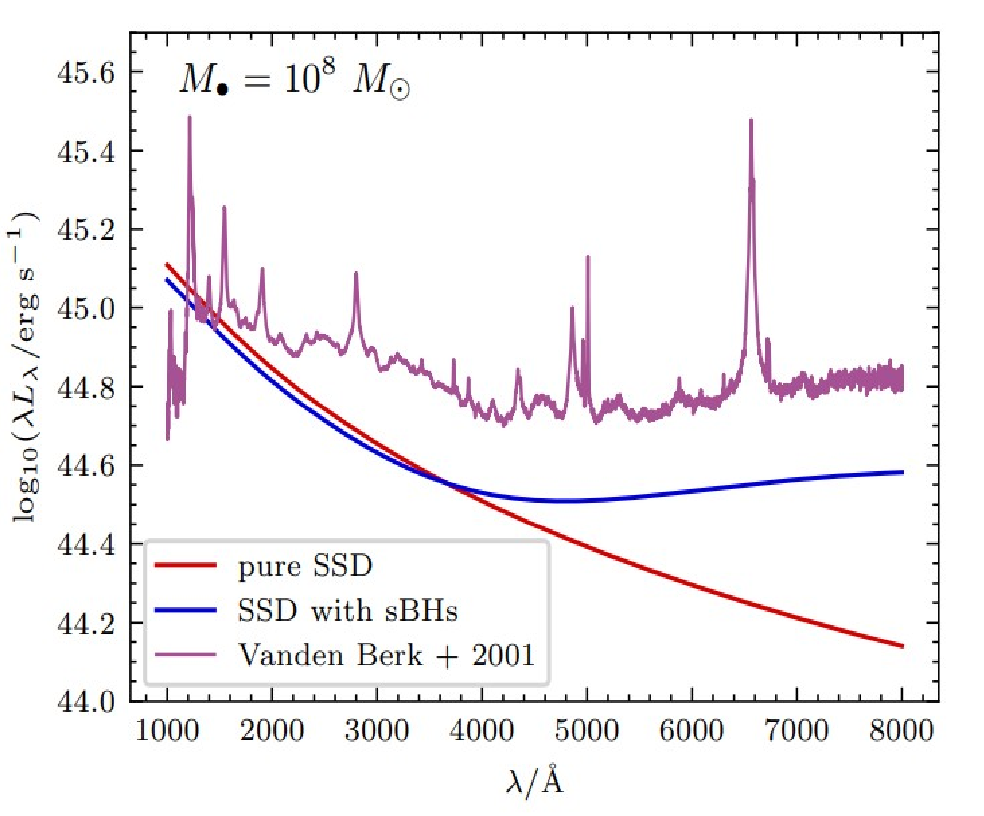
Why?

As discussed earlier, the effect from the accretion in sBHs would make a contribution at only the outer edges of the disk.

Outer side means the emission energy is less, which corresponds to higher wavelength. Thus, at higher wavelengths, the effects are more.

At small distances, the effect is very less. From the region, closer to the SMBH, the emission energy is higher that corresponds to lower wavekengths.Thus, not much effect at lower wavelengths.

However, some part of the AGN disk material goes on to accrete onto sBHs, instead of going onto the SMBH. Thus, the overall profile is a little less in case of sBHs embedded disk compared to a pure SSD.



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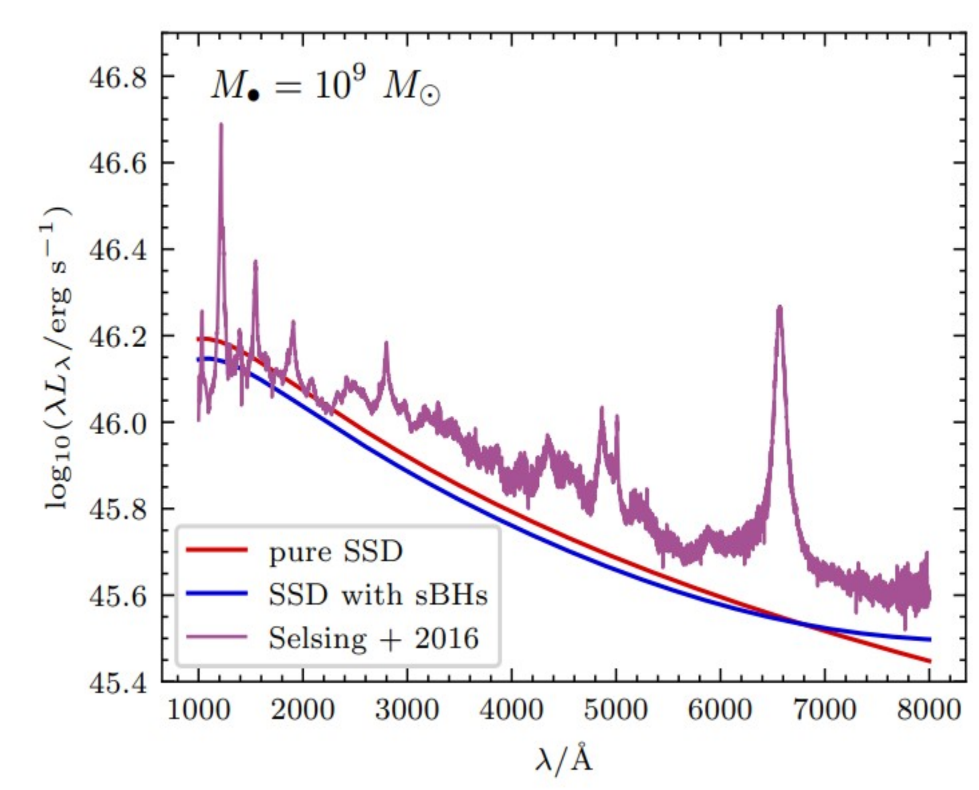
Case-II: M_{SMBH} **= 10⁹** *Solar Mass* ; f_{sBHS} **= 0.1**

At ~ 7000 Angstrom, the SED of the embedded disk starts to have higher SED, than a pure SSD.

Above ~ 8000 *Angstrom,* the SED of the embedded disk is significantly higher than the pure SSD.

Below ~ 7000 *Angstrom,* the pure SSD has slightly higher SED than the sBHs embedded disk.



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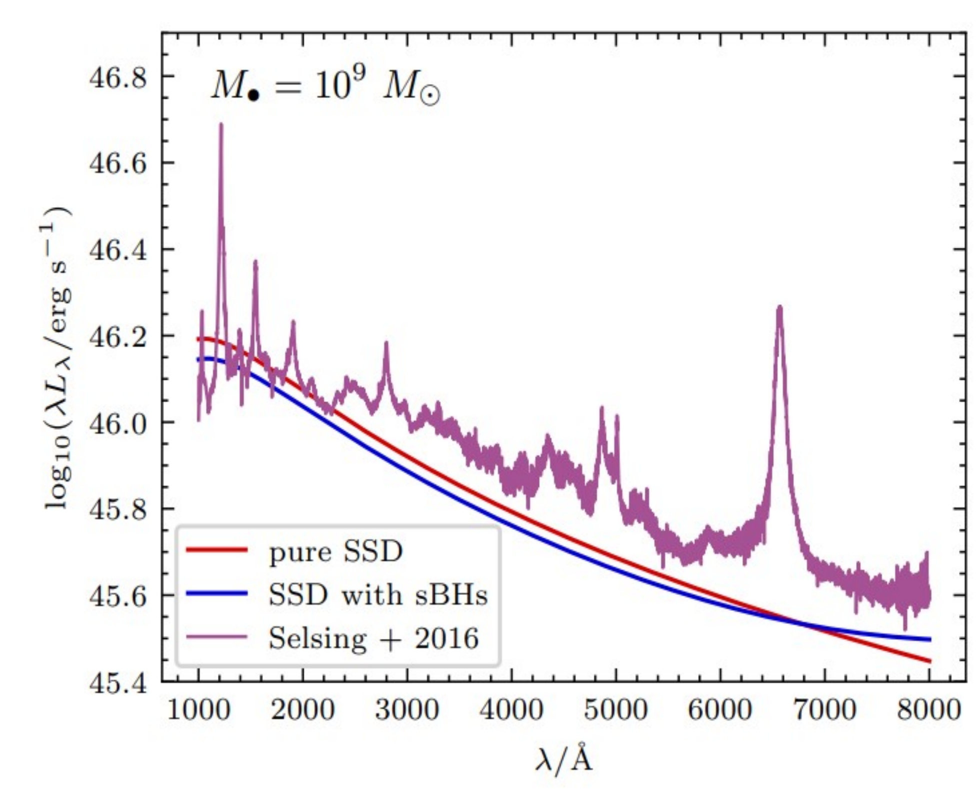
Why?

If every other quantities are fixed,

$$T_{eff,sBHs} \propto M^{-1/4}_{SMBH}$$

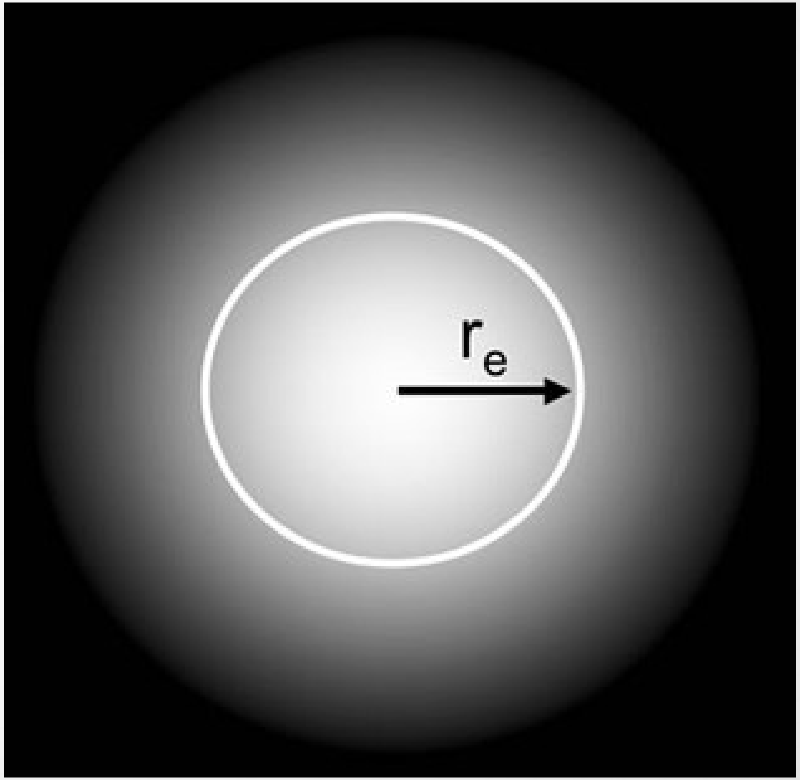
Thus, with mass of the SMBH being increased, the effective temperature due to the accreting sBHs in the disk would have less effect. Thus, the sBHs would start to affect the temperature even more outside part of the disk. This corresponds to higher wavelength than the previous case



Half light radius

The sizes of galaxies are difficult to measure since they don’t possess clearly defined boundaries. Most galaxies simply get fainter and fainter in their outer regions, and the apparent size of the galaxy depends almost entirely on the sensitivity of the telescope used and the length of time for which the object is observed.

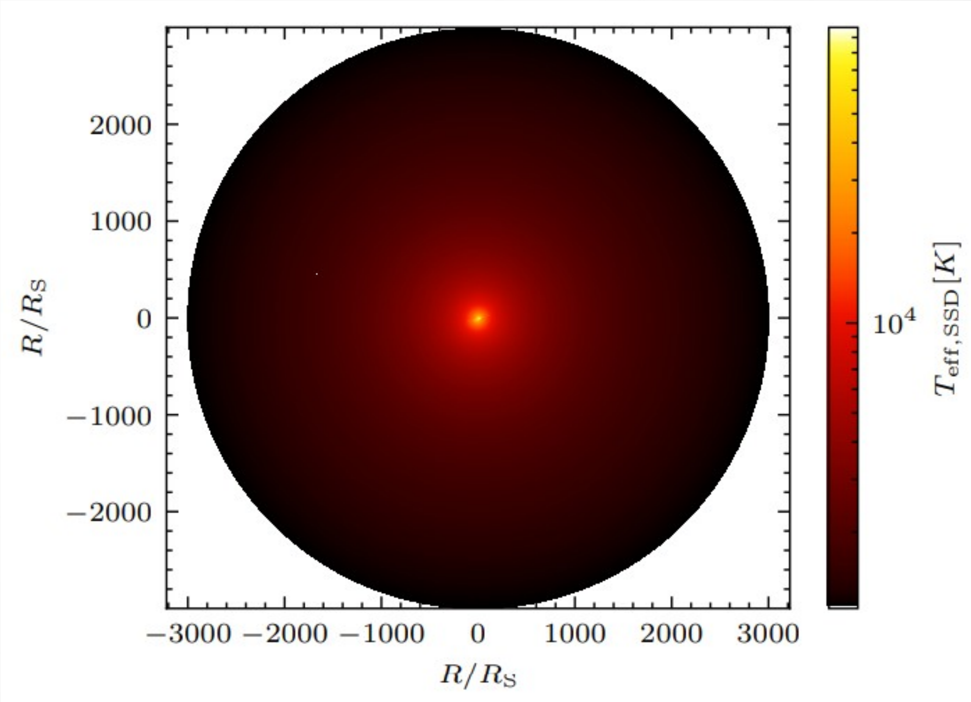
To overcome this ambiguity, astronomers define the ‘half-light’, or ‘effective’ radius (re) as the radius within which half of the galaxy’s luminosity is contained.



Face-on view of the disk

Pure SSD

The luminosity is highest at the centre and as we see outward, it is decreasing.



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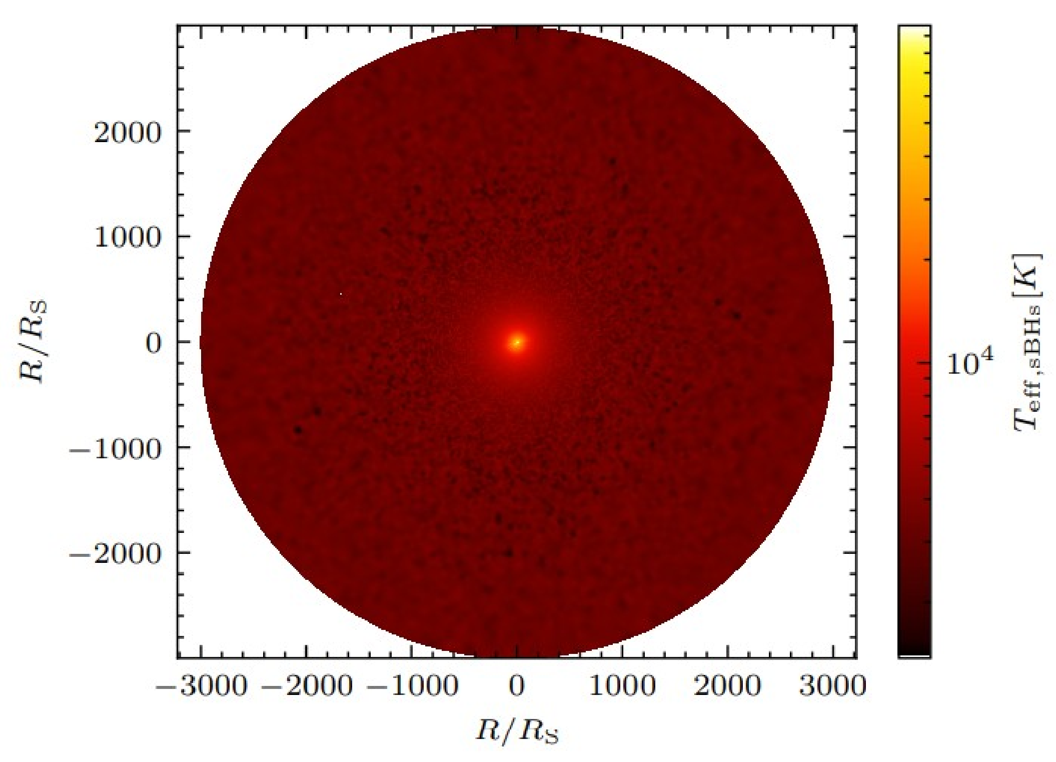
<u>SBHs embedded SSD</u>

Unlike the pure SSD case, here the outer part of the disk would be illuminated due to combined accretion of the AGN disk material by the embedded sBHs. Thus, the outer part has more luminosity than the pure SSD.



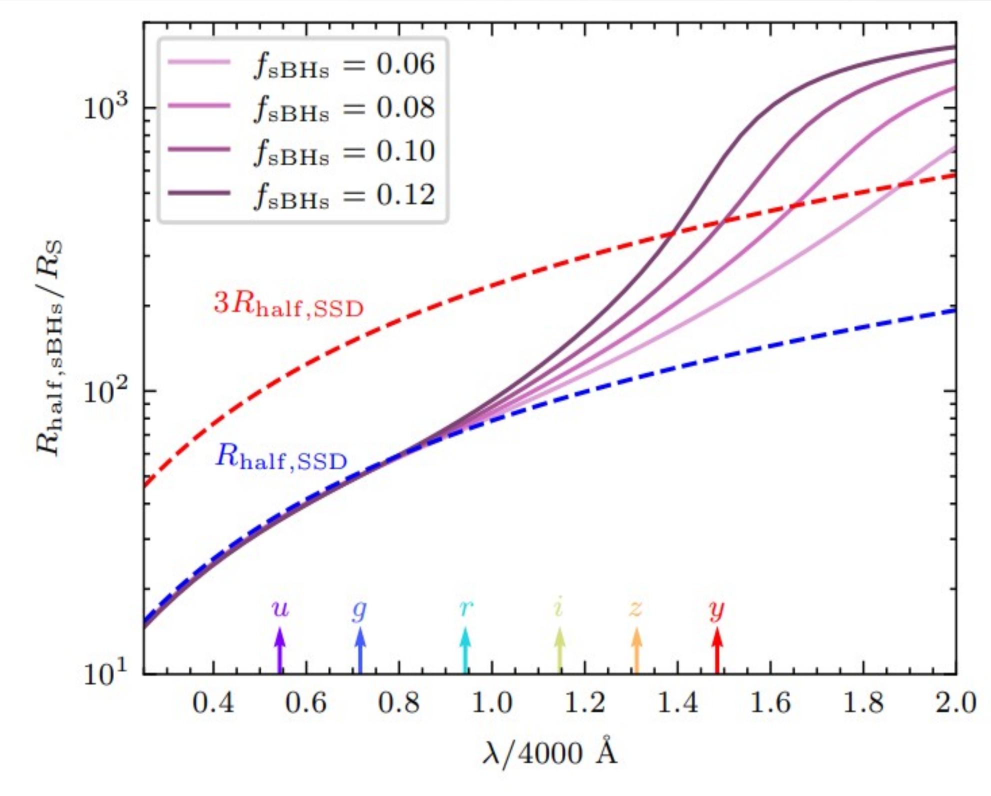
Change in the half-light radius

Case-I: $M_{SMBH} = 10^8$ *Solar Mass* ; f_{sBHs} = changing

As seen in the case of temperature distribution and the SED, for this mass of the SMBH, the contribution would start to effect from ~ 3600 Angstrom.

The half-light radius would start to increase after this wavelength. After ~ 4700 Angstrom, it would be much higher than pure SSD.

For changing f_{sBHs} the effect would also change. When f_{sBHs} increases, it would increase the accretion to the sBHs, which would heat the disk more at the outer side and the outer regions would be more illuminated. Thus half-light radius would increase more. Vice-versa.



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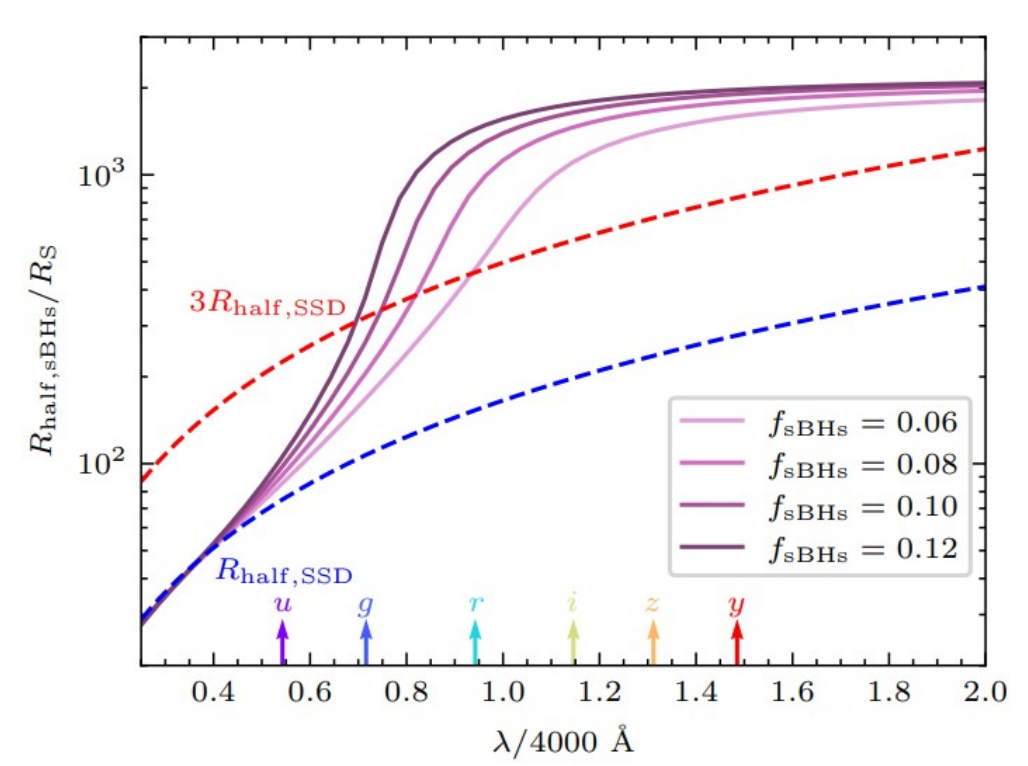
Case-II: ***M_{SMBH}* = 10^7** *Solar Mass* ; ***f_{sBHs}* =** changing

As the mass of the SMBH is decreased, the effect of sBHs would start to contribute at a lower wavelength.

For this mass of the SMBH, the contribution would start to effect from ~ 2000 Angstrom. The half-light radius would start to increase after this wavelength. After ~ 3000 Angstrom, it would be much higher than pure SSD.

Here, the effect for changing ***f_{sBHs}*** would be same as the previous case. When ***f_{sBHs}*** increases, it would increase the accretion to the sBHs, which would heat the disk more at the outer side and the outer regions would be more illuminated. Thus half-light radius would increase more. Vice-versa.



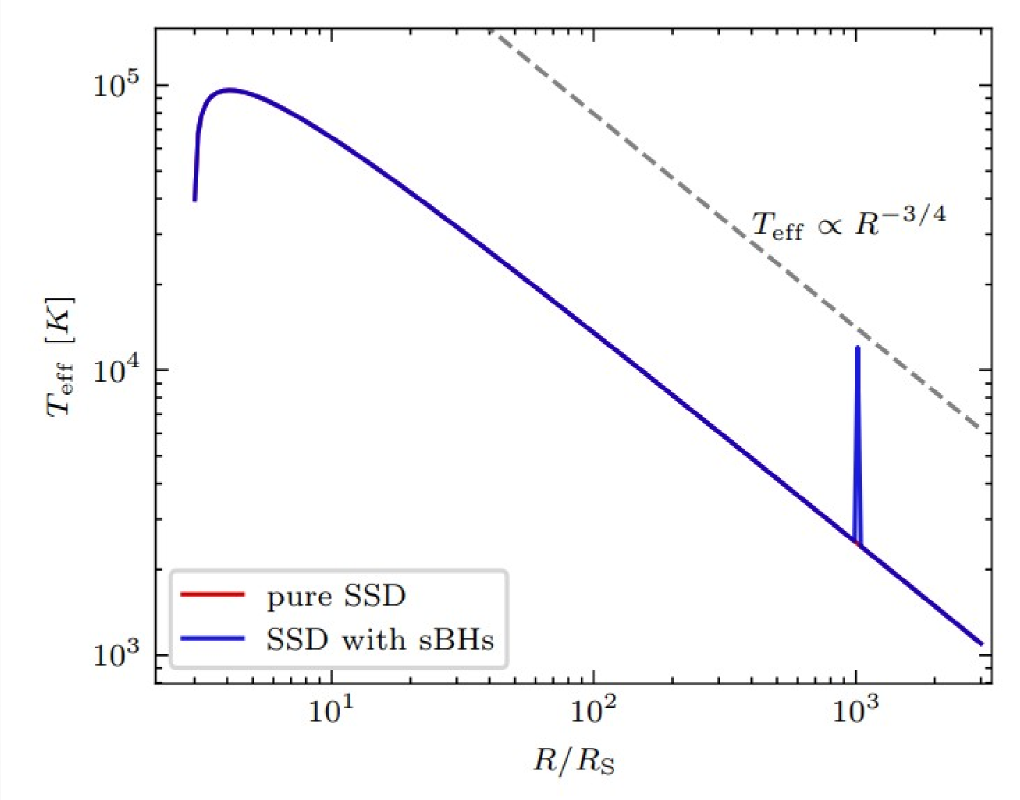
Boundary Condition

Up to now, the sBHs were considered to be distributed in the whole disk from $\boldsymbol{R_{in} = 3R_S}$ to $\boldsymbol{R_{out} = 3000R_s}$

What happens, if it is considered that all the sBHs are embedded in a particular distance, let's say at ~ $\boldsymbol{1000R_S}$

sBHs embedded at ~ ***1000R$_S$***

Here, only at the distance 1000 R_S, the effect would be felt. Thus we see a narrow spike at this distance in the plot.



Temperature Distribution

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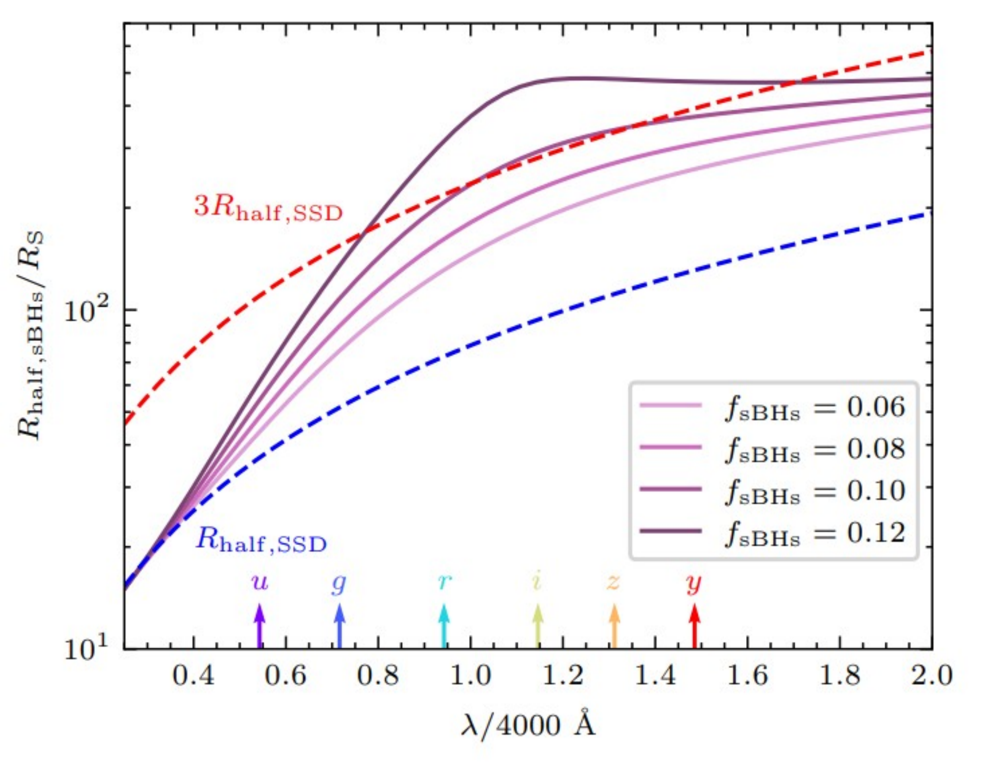
The half-light radius would start to change at the wavelength, that is in correspondence with the distance ***1000R$_S$***. This is ~**1000 Angstrom**, as can be seen from the plot.

The case of different f_{sBHs} would be the same as the previous cases.



Half-Light Radius

So, why the term ‘stretch’ in the title?

When there are embedded sBHs in the AGN disk, the

i) temperature of the outer part of the disk increases

ii) half-light radius increases

Together these effects makes it feel like the outer region is bigger now, as it emits more.

Thus, it is used like a metaphor!

Conclusions

1. Embedded sBHs can cause the effective temperature of the outer regions to be significantly higher than that of the pure SSD.

2. Compared to a pure SSD, an SSD embedded with sBHs produces a redder SED, which may contribute significantly to the spectral slope change around 5000 Angstrom for AGNs with low ($\lesssim$ 108 M⊙) SMBH masses.

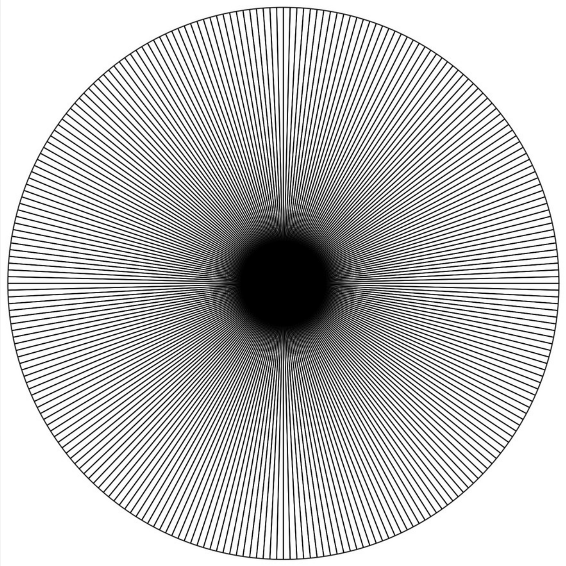
3. The dependence of the half-light radius with wavelength for an SSD embedded with sBHs significantly differs from that of a pure SSD. With suitable sBH distributions, the model half-light radius is consistent with microlensing observations.

Thank you!

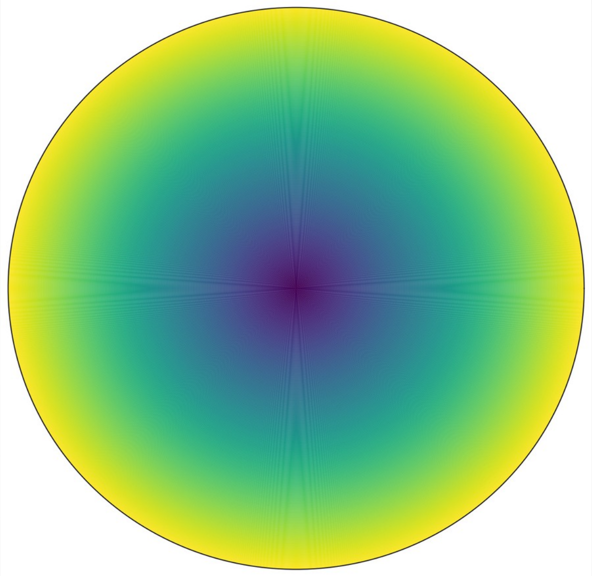
Extra Slides

If needed!

What are zones?



Cut into 256 equal areas of angular separation



Cut into 256 equal areas along radial distance

Some Equations

$$Q^+_{\rm vis} = \frac{3GM_\bullet \dot{M}_\bullet}{8\pi R^3} f_r, \quad (1)$$

where G, $M_\bullet$, and R are the gravitational constant, the SMBH mass, and the radius of the AGN accretion disk, respectively; the factor $f_r = 1-(3R_{\rm S}/R)^{1/2}$, where $R_{\rm S} = 2GM_\bullet/c^2$ is the Schwarzschild radius of the SMBH; the mass accretion rate to the SMBH $\dot{M}_\bullet = (1-f_{\rm sBHs})\dot{M}_{\rm tot}$. Meanwhile, the total heating rate due to sBHs per unit area depends upon their distribution on the AGN accretion disk. We divide the accretion disk from the inner boundary $R_{\rm in}$ to the outer boundary $R_{\rm out}$ into 256 equal rings on a logarithmic scale. For simplification, it is straightforward to assume that sBHs are equally densely distributed in each ring; the sBH number on each ring $N(R)$ is

$$N(R) = 2\pi R \Delta R \frac{N_{\rm sBHs}}{\pi(R^2_{\rm out} - R^2_{\rm in})}, \quad (2)$$

where $N_{\rm sBHs}$ is the total number of sBHs in the AGN accretion disk. As a result, most accreting sBHs reside in the outer regions of the AGN accretion disk. Note that real sBH distributions can be more complicated than this, as we discuss in Section 4.1. Each ring is further divided into 256 equal zones along the azimuthal direction, i.e., $\Delta\phi = 2\pi/256$. Hence, the size of each zone is comparable to the scale height of the AGN accretion disk. The sBHs in each zone will then be able to heat the gas within the zone isotropically. The heating rate in each zone is simply

$$Q^+_{\rm sBHs} = N(R,\phi) L_{\rm sBH}, \quad (3)$$

where $N(R,\phi)$ and $L_{\rm sBH}$ are the number of sBHs in a zone and the bolometric luminosity of each accreting sBH. We assume that all sBHs accrete at the Eddington limit[1], and $L_{\rm sBH}$ equals to the Eddington luminosity of an sBH, which is $L_{\rm sBH,Edd} = 1.26 \times 10^{38} M_{\rm sBH}/M_\odot$ [erg s^{-1}], where $M_{\rm sBH}$ and $M_\odot$ are the sBH mass and the solar mass, respectively. Here, the radiative efficiency of 10% is assumed. We stress that

Some Equations

Gilbaum & Stone (2022), we assume that sBHs accrete at the Eddington limit. Then, the total number of sBHs is

$$N_{\rm sBHs} = \frac{f_{\rm sBHs}\dot{M}_{\rm tot}}{\dot{M}_{\rm sBH,Edd}}, \tag{4}$$

where $\dot{M}_{\rm sBH,Edd}$ is the Eddington accretion rate of an sBH, i.e., $\dot{M}_{\rm sBH,Edd} = 10L_{\rm sBH,Edd}/c^2$.

The heating due to sBHs plays an important role in the outer disk zones. Indeed, it is evident that the ratio

$$\epsilon = Q^+_{\rm sBHs}/(Q^+_{\rm vis}\Delta S(R,\phi)) \propto (R/R_{\rm S})^3, \tag{5}$$

where $\Delta S(R,\phi) = R\Delta\phi\Delta R$ is the area of each zone. For the case of sBHs embedded in an AGN accretion disk, the effective temperature profile of the AGN disk can be obtained by considering the balance between the heating rate and the disk surface cooling rate. We consider perfect blackbody radiation at each radius. Hence, the effective temperature $T_{\rm eff,sBHs}$ is

$$2\sigma T^4_{\rm eff,sBHs}(R,\phi) = Q^+_{\rm vis}(1+\epsilon), \tag{6}$$

Microlensing observations can constrain the AGN disk sizes. Microlensing observations essentially measure the half-light radius (Mortonson et al. 2005). The half-light radius can be estimated as follows. We consider perfect blackbody radiation at each radius and a face-on viewing angle. The local monochromatic luminosity can be expressed as

$$dL_{\nu,\rm sBHs} = \pi B_\nu(T_{\rm eff,sBHs})Rd\phi dR, \tag{7}$$

where $B_\nu(T_{\rm eff,sBHs}) = 2h\nu^3/(c^2e^{h\nu/kT_{\rm eff,sBHs}} - c^2)$ is the Plank function, and h, ν and k are the Planck constant, frequency and the Boltzmann constant, respectively. The half-light radius $R_{\rm half,sBHs}$ at wavelength $\lambda(= c/\nu)$ satisfies

$$\int_{R_{\rm in}}^{R_{\rm half,sBHs}}\int_0^{2\pi} dL_{\nu,\rm sBHs} = \frac{1}{2}\int_{R_{\rm in}}^{R_{\rm out}}\int_0^{2\pi} dL_{\nu,\rm sBHs}. \tag{8}$$

The half-light radius of a pure SSD ($R_{\rm half,SSD}$) can be calculated following the same methodology. The spectral energy distribution (SED) is $L_{\nu,\rm sBHs} = \int_{R_{\rm in}}^{R_{\rm out}}\int_0^{2\pi} dL_{\nu,\rm sBHs}$.