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Stellar Black Holes Can "Stretch" Supermassive Black Hole Accretion Disks

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Oct. 17, 2024

Zhou *et al.* 2024 *ApJL* **966** L9

Outline

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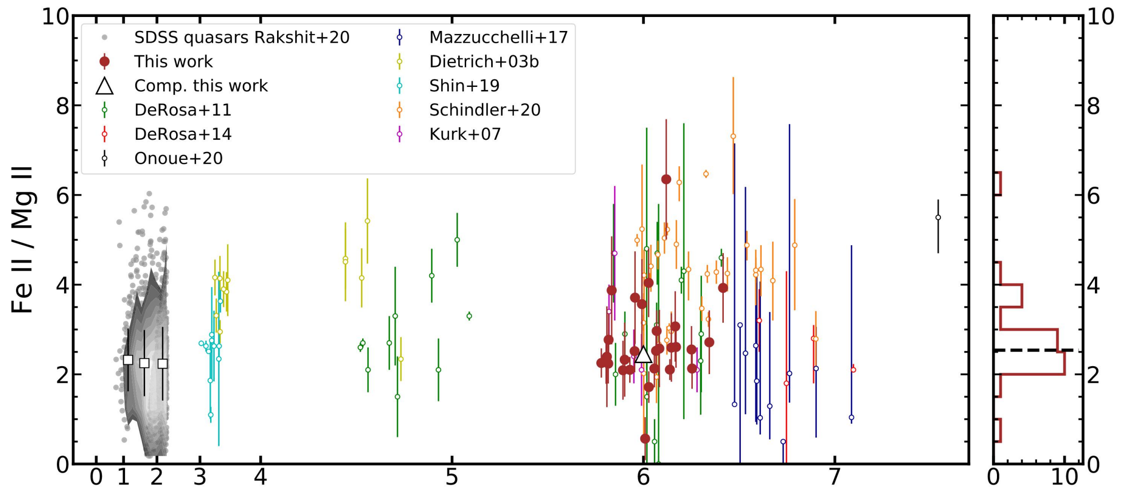
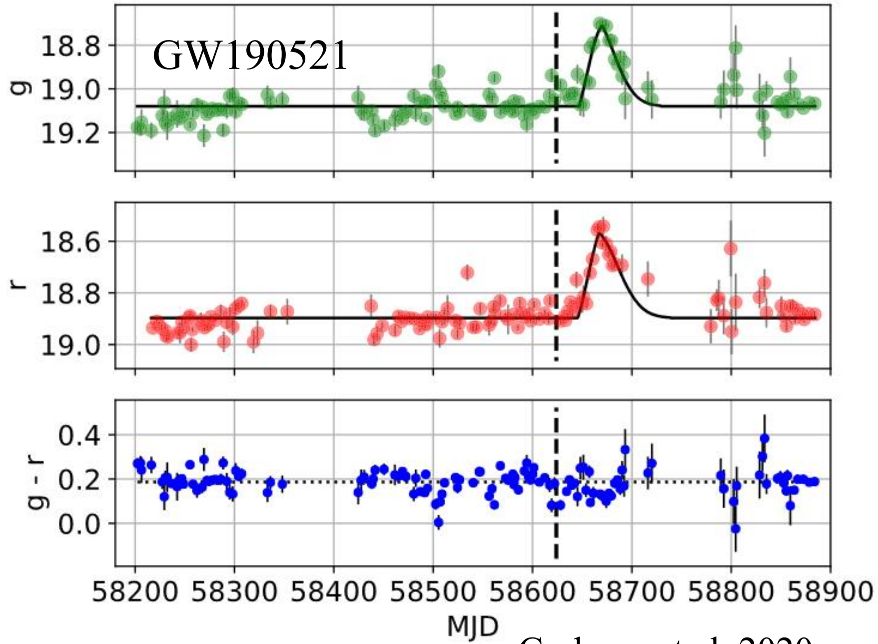
  b. Quasar microlensing
- **Model**
- **Consequences**
  a. Half-light radius
  b. Spectral energy density
- **Conclusions**
- **Future prospect**

Stellar black holes in the AGN accretion disk

- **Self-gravity** plays a dominant role in the outer regions of the AGN accretion disk;
- The **redshift-independent high metal abundance** in quasar broad-line regions;



Wang et al. 2022



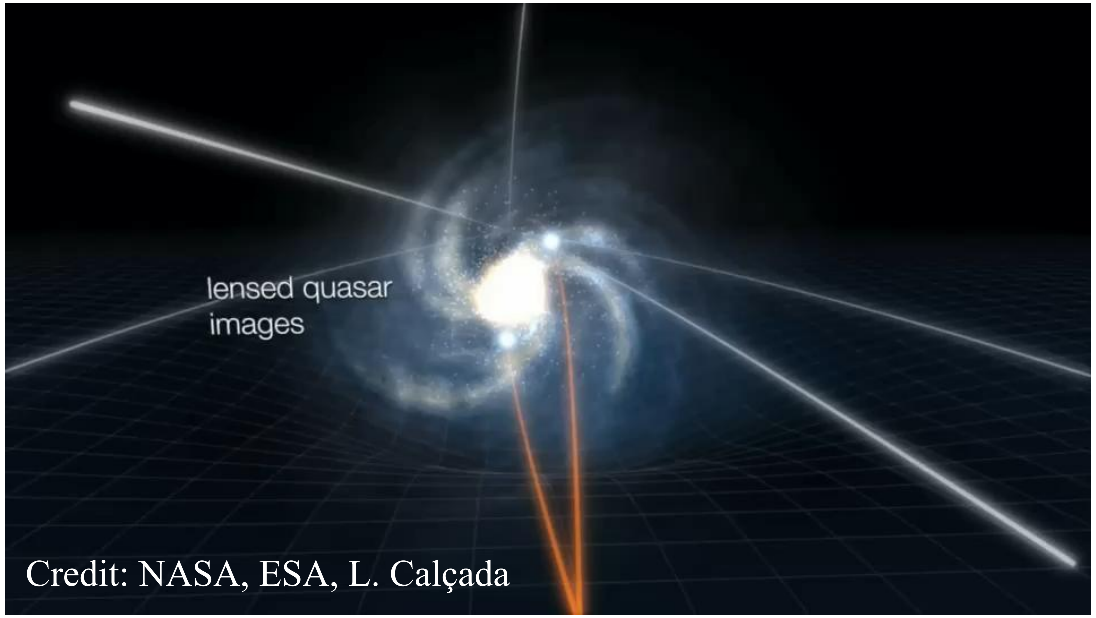
Graham, et al. 2020

- The potential electromagnetic counterpart detected by ZTF for the **gravitational wave emitter**.

Previous works: transient phenomenon (e.g., Cheng & Wang 1999; **talks in this meeting**) or metal enrichment (e.g., Artymowicz et al. 1993) mostly due to stars in AGN disks.

How to observationally infer **stellar black hole distributions** in accretion disks?

Accretion disk measured by microlensing events



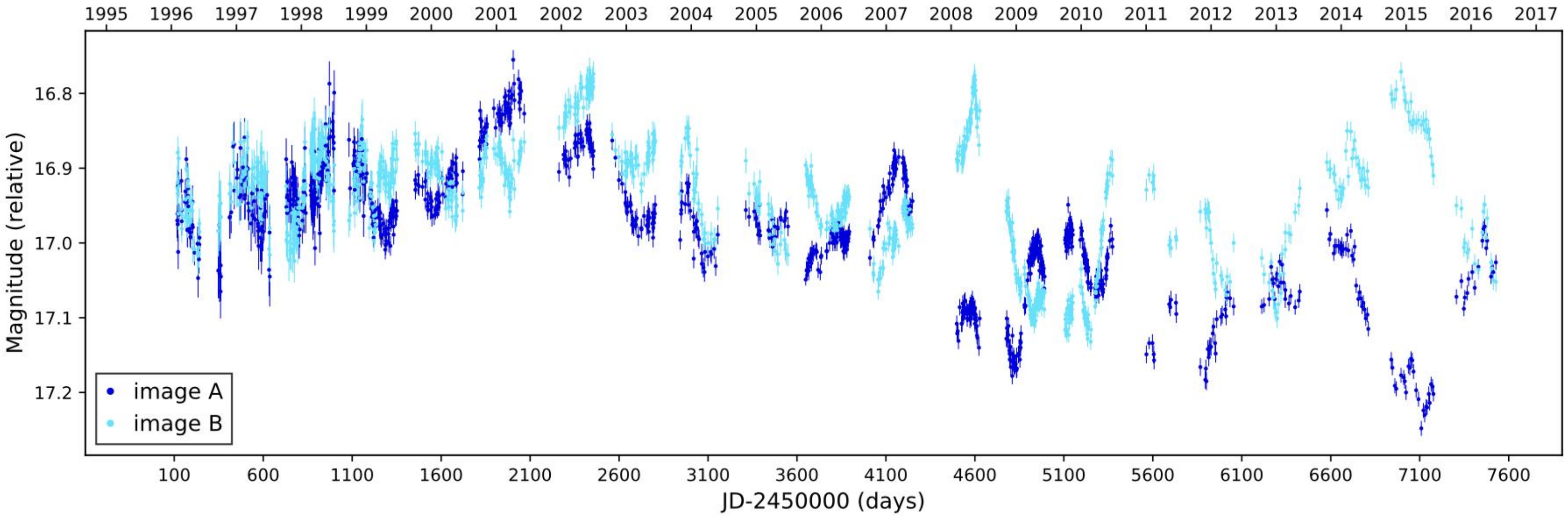
Strong gravitational lensing by a foreground galaxy

+

Microlensing by stars within the foreground galaxy

↓

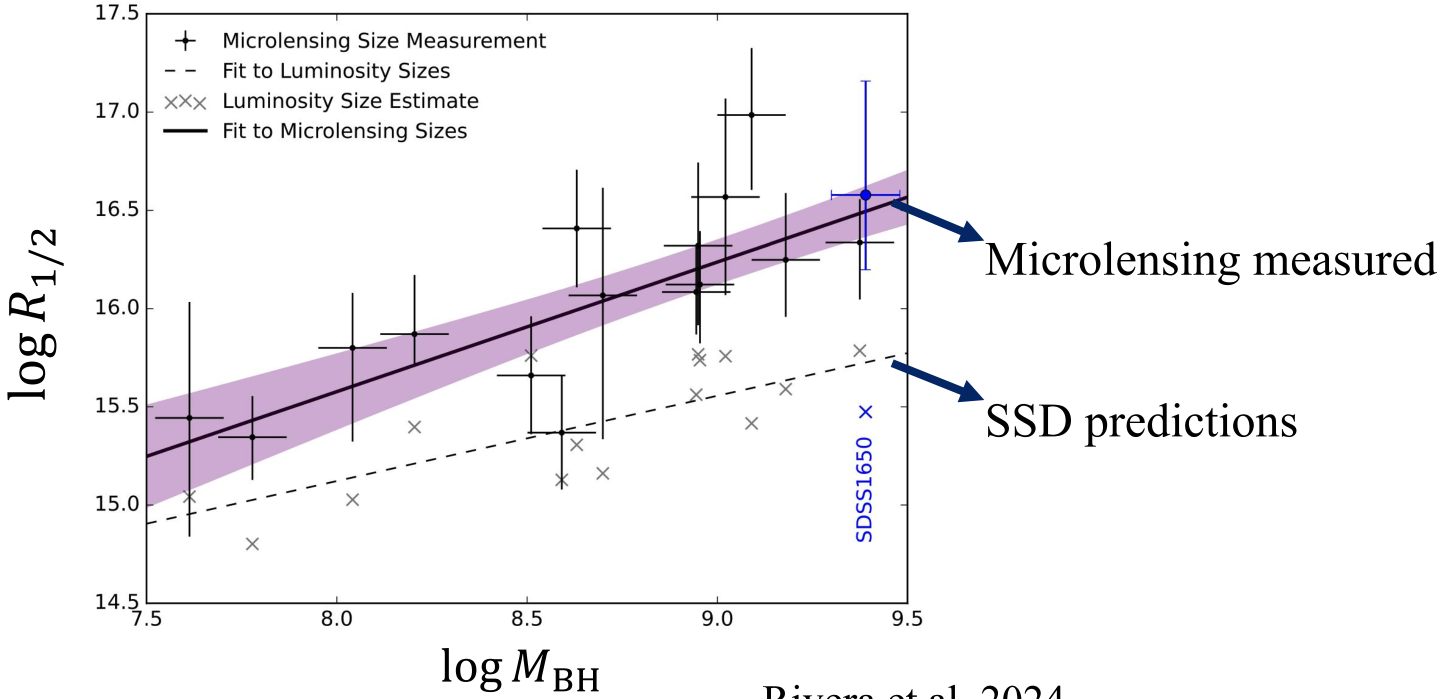
Resolve the **AGN accretion disk luminosity profile**



Fian et al. 2021

Half-light radius: the radius corresponding to **half of the monochromatic luminosity** for a given wavelength which can be measured by microlensing effectively.

The microlensing measured half-light radii are **2-4 times larger** than the SSD predictions.



Rivera et al. 2024

The excess of half-light radius may be caused by **the additional contribution of stellar black holes (sBHs)** in the accretion disk.

Model

- The total accretion rate for the embedded sBHs: $f_{\mathrm{sBHs}}\dot{M}_{\mathrm{tot}}$
- The total number of sBHs: $N_{\mathrm{sBHs}} = \dfrac{f_{\mathrm{sBHs}}\dot{M}_{\mathrm{tot}}}{\dot{M}_{\mathrm{sBH,Edd}}}$, $\quad N(R) = 2\pi R \Delta R \dfrac{N_{\mathrm{sBHs}}}{\pi(R_{\mathrm{out}}^2 - R_{\mathrm{in}}^2)}$,
- The area $\Delta S(R,\phi)$ in the AGN disk has two sources of heating:
  a) the **local viscous heating** Q_{vis}^{+} in the AGN disk;
  b) the **sBHs accretion** $Q_{\mathrm{sBHs}}^{+}/\Delta S(R,\phi)$.

$$\epsilon = Q_{\mathrm{sBHs}}^{+}/(Q_{\mathrm{vis}}^{+}\Delta S(R,\phi)) \propto (R/R_{\mathrm{S}})^3,$$

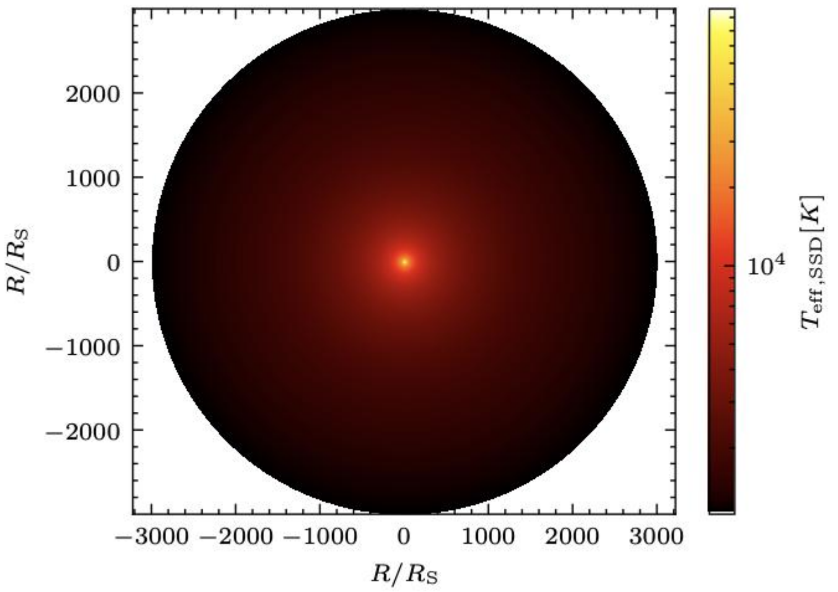
➢ **Pure SSD**

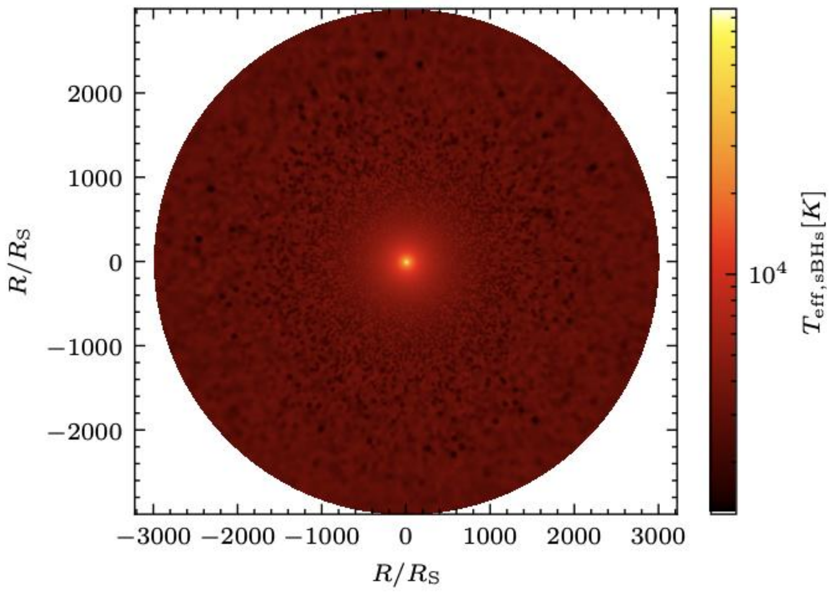
$$2\sigma T_{\mathrm{eff,\,SSD}}^4(R) = Q_{\mathrm{vis}}^{+}$$

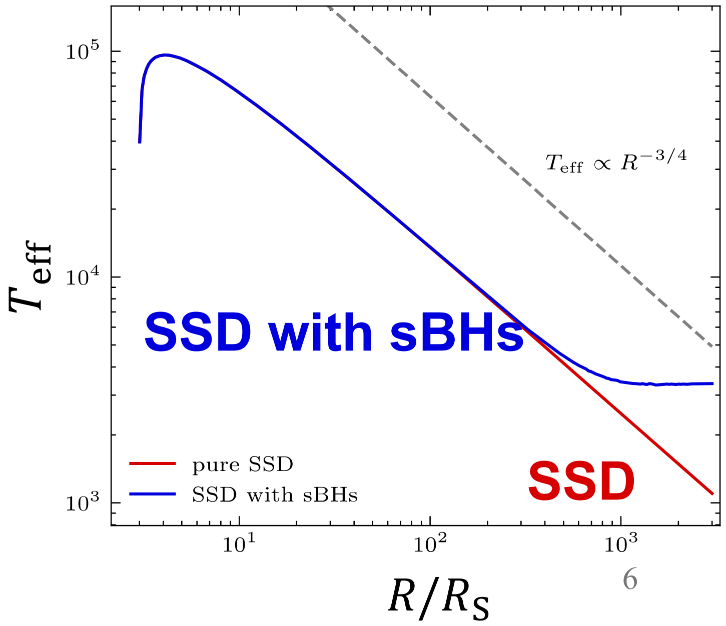
➢ **SSD with sBHs**

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

$M_{\mathrm{SMBH}} = 10^8\,M_\odot, M_{\mathrm{sBH}} = 50\,M_\odot,$
$f_{\mathrm{sBHs}} = 0.1$







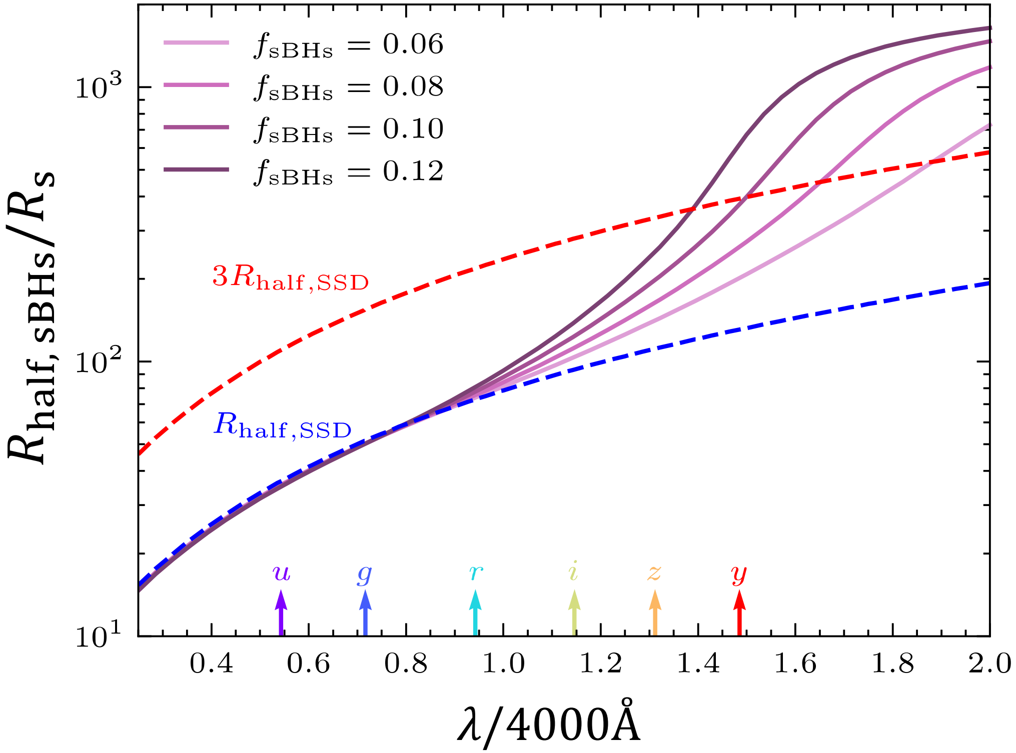
Consequence 1: Half-light radius

- **Equally densely distributed**

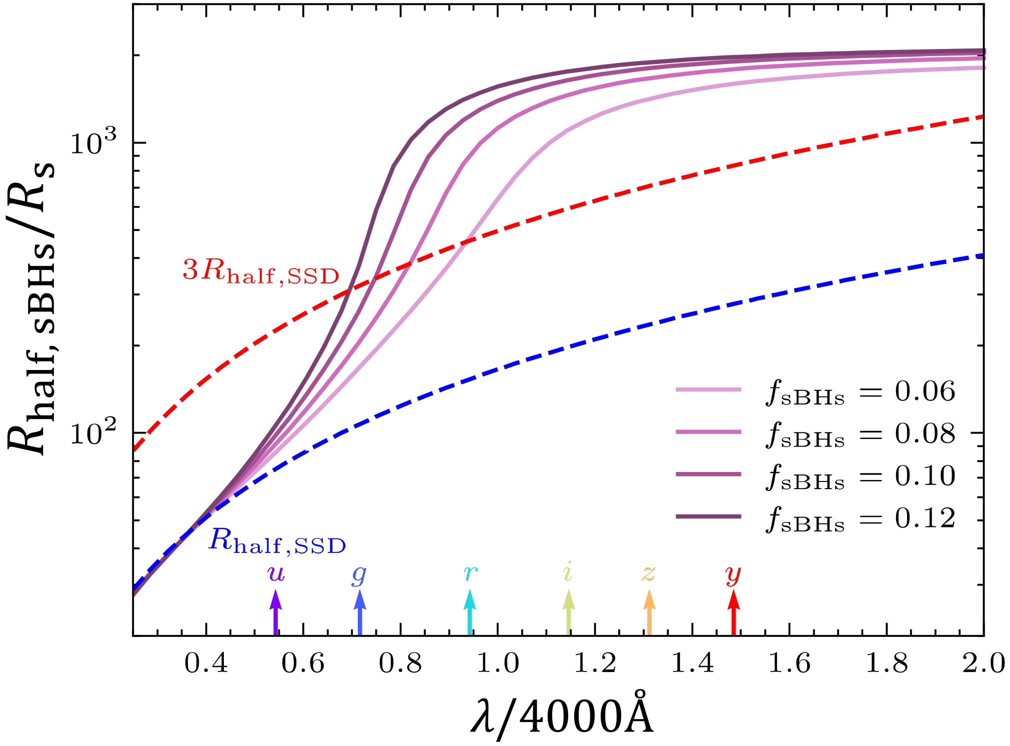
$$\epsilon = Q^{+}_{\rm sBHs}/(Q^{+}_{\rm vis}\Delta S(R,\,\phi)) \propto (R/R_{\rm S})^3,$$

$$T_{\rm eff,sBHs} \propto M_{\bullet}^{-1/4}\dot{m}_{\rm tot}^{1/4}(R/R_{\rm S})^{-3/4}(1+\epsilon)^{1/4}$$

$M_{\rm SMBH} = 10^8\,M_\odot, M_{\rm sBH} = 50\,M_\odot$

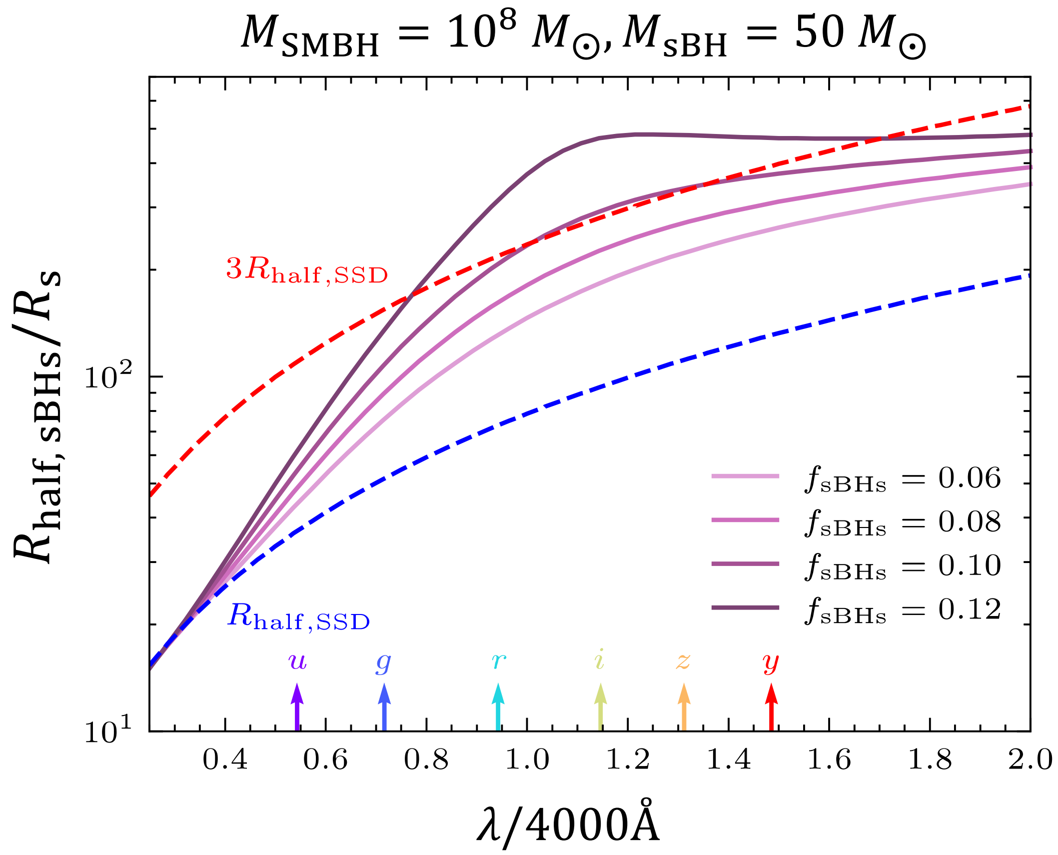


$M_{\rm SMBH} = 10^7\,M_\odot, M_{\rm sBH} = 50\,M_\odot$



The presence of accreting sBHs significantly alters **the half-light radius–wavelength relation** by increasing the half-light radius of the long-wavelength emission.

- **Trapped in the same radius**



$$N(R) \propto (R/R_{\rm S})^{\beta}$$

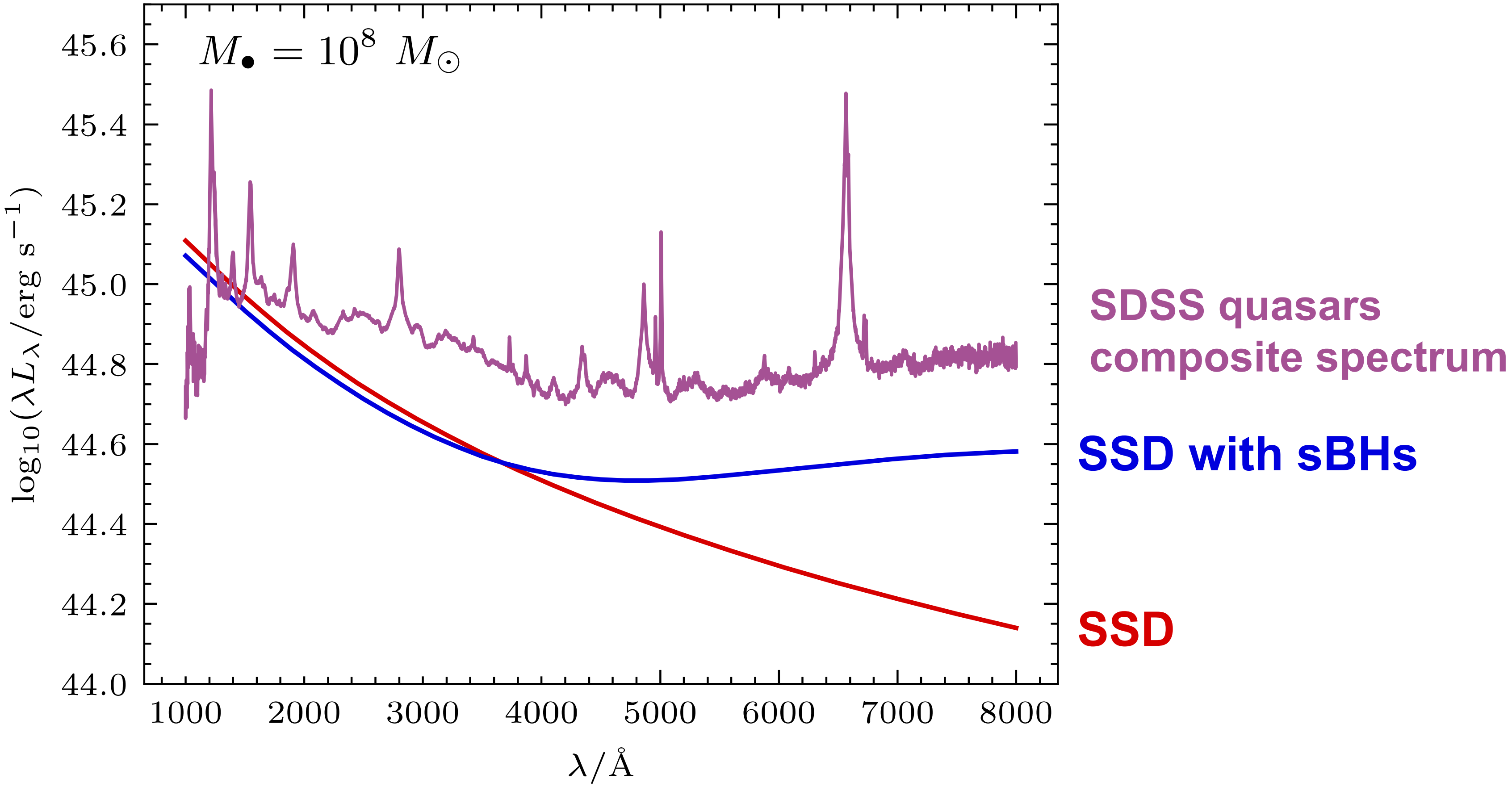
$$\epsilon = Q^+_{\rm sBHs}/(Q^+_{\rm vis}\Delta S(R,\phi)) \propto (R/R_{\rm S})^{\beta+1}$$

$$\beta \downarrow \longrightarrow R_{\rm critical} \downarrow \longrightarrow \lambda_{\rm critical} \downarrow$$

The dependence of the half-light radius with wavelength can **probe the sBH distribution in the AGN accretion disk**.

Consequence 2: Spectral energy density (SED)

$M_{\mathrm{SMBH}} = 10^8\ M_\odot, M_{\mathrm{sBH}} = 50\ M_\odot,\ f_{\mathrm{sBHs}} = 0.1$

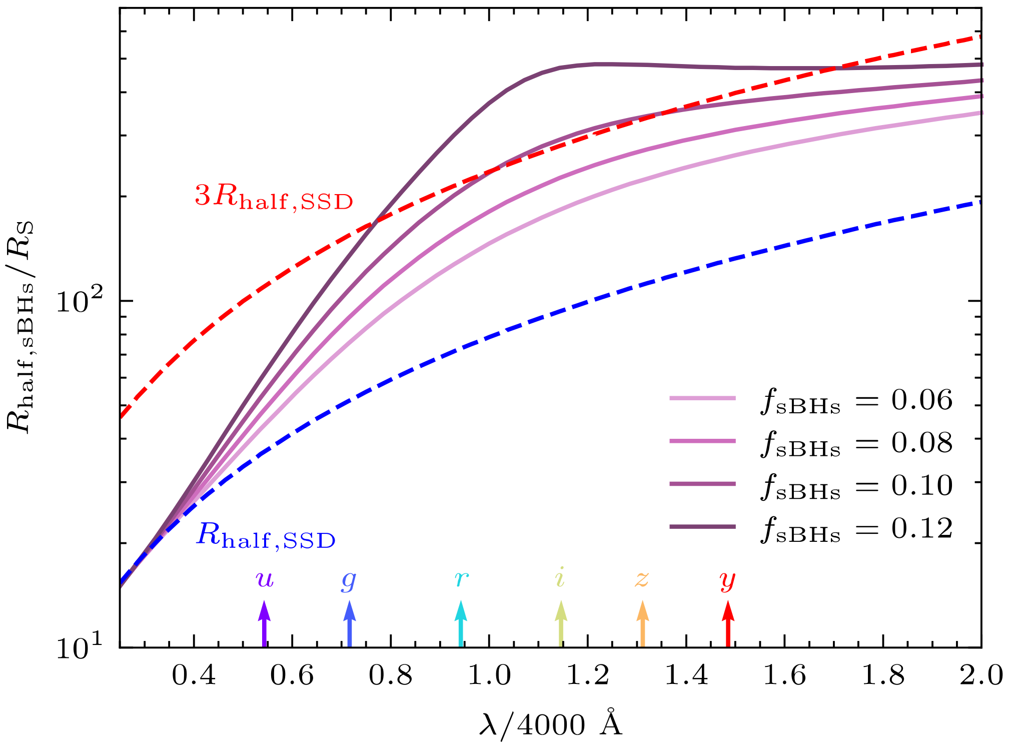


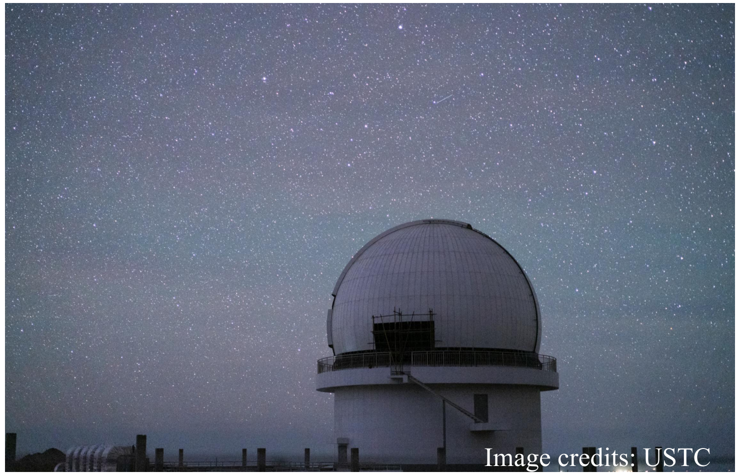
When the wavelength is approximately larger than 5000 Å, **the SED of the SSD with sBHs is significantly larger than that of the pure SSD** when the SMBH mass is ~ $10^8\ M_\odot$, and the spectral slope in this wavelength range is almost consistent with the composite spectrum.

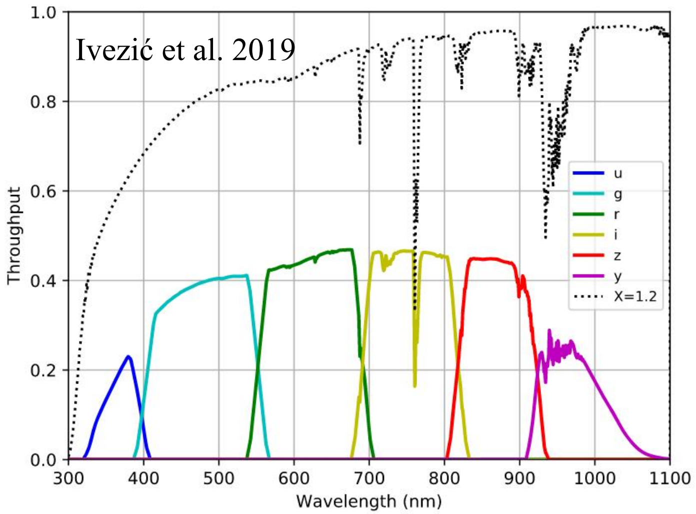
Conclusions

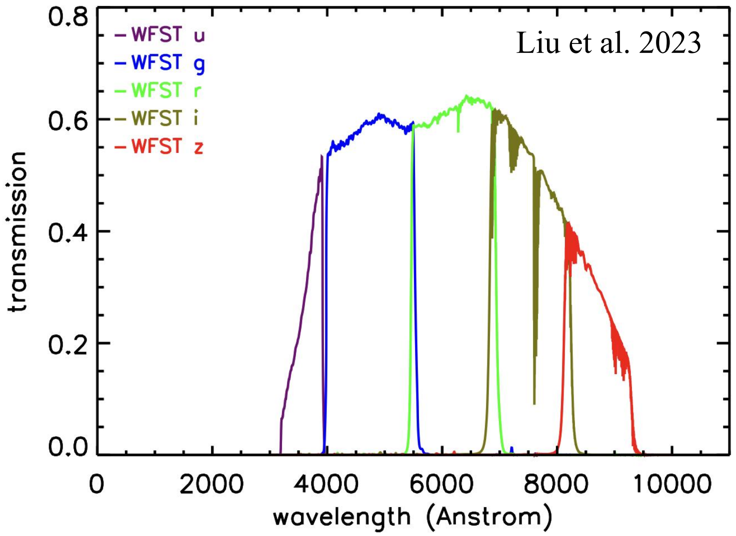
- Embedded sBHs can cause the **effective temperature distribution** to be significantly different from that of the pure SSD;
- Compared to a pure SSD, an SSD embedded with sBHs produces **a redder SED**;
- **The dependence of the half-light radius with wavelength** for an SSD embedded with sBHs significantly differs from that of a pure SSD;
- The dependence of the half-light radius with wavelength can **probe the sBH distribution in the AGN accretion disk**.

Future prospect: LSST & WFST









The LSST and WFST can measure the half-light radii of some lensed quasars in **multiple bands**, which can probe the distributions of accreting sBHs in AGN accretion disks.

Conclusions

- Embedded sBHs can cause the **effective temperature distribution** to be significantly different from that of the pure SSD;
- Compared to a pure SSD, an SSD embedded with sBHs produces **a redder SED**;
- **The dependence of the half-light radius with wavelength** for an SSD embedded with sBHs significantly differs from that of a pure SSD;
- The dependence of the half-light radius with wavelength can **probe the sBH distribution in the AGN accretion disk**.

Thanks!