Continuum Reverberation of Accretion Disks Surrounding Low-Mass-Ratio SMBHBs

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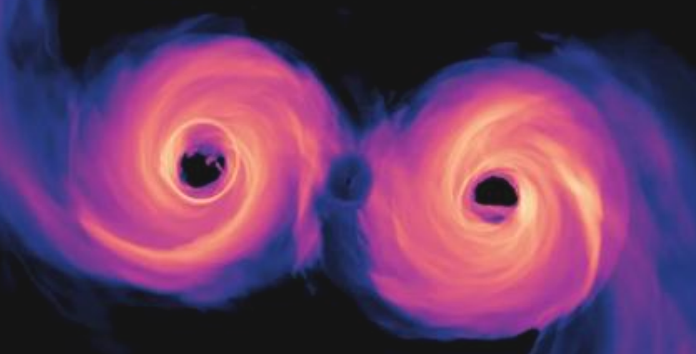


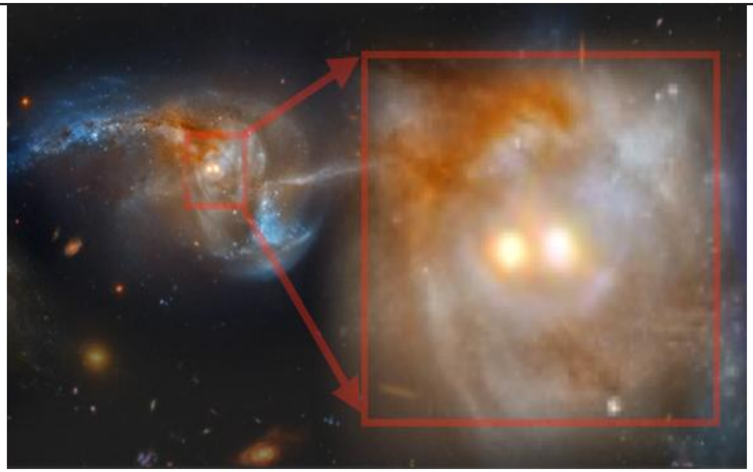
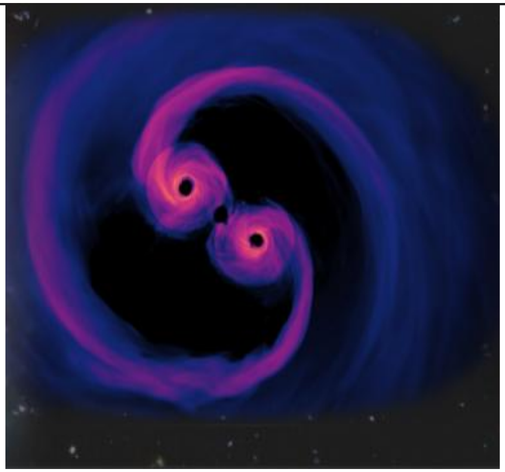
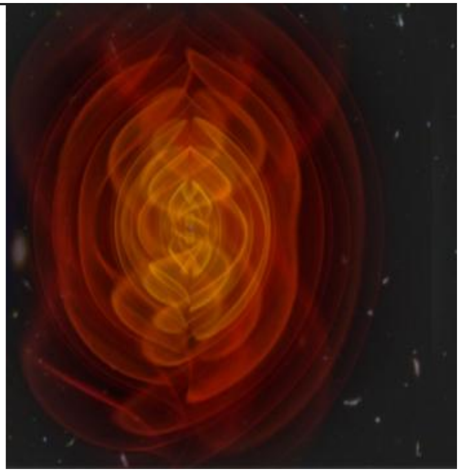
Collaborators： Yi-Xin Fu, Jian-Min Wang, Keith Horne, Juan Hernández-Santisteban, Roberta Vieliute, Rick Edelson, Tingting Liu, Michael Brotherton, Luka Popovic, Andjelka Kovacevic, Shuo Zhai

“VII Conference on AGN and Gravitational Lensing”
Serbia, 2026-07-21

Outline

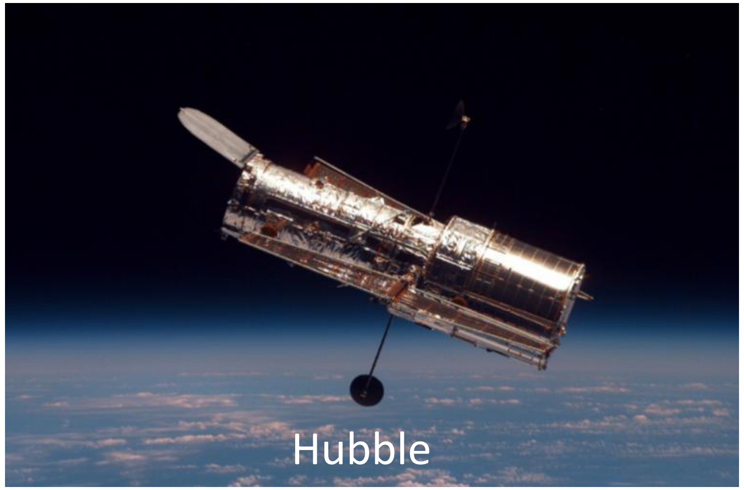
- Brief introduction to SMBHBs
- Continuum reverberation of SMBHB accretion disks
- Application to PG 1302-102
- Future perspective

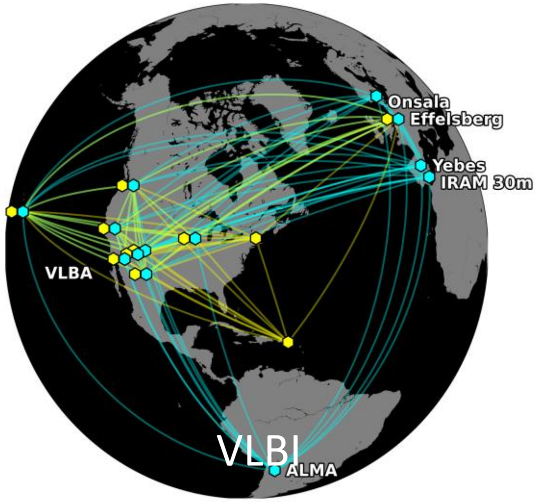
The life history of SMBHBs

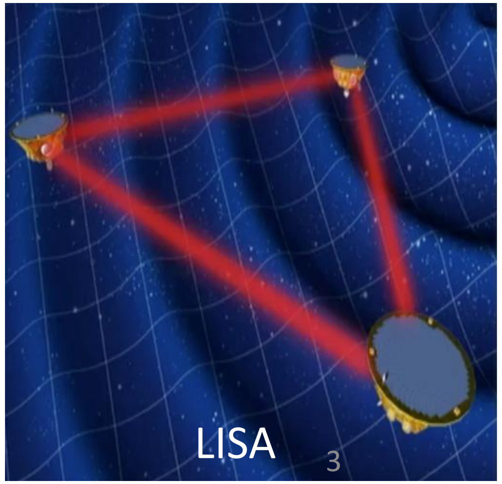





galaxy merger | dual AGN | SMBHB | coalescence

>kpc | ~100pc-kpc | <1pc

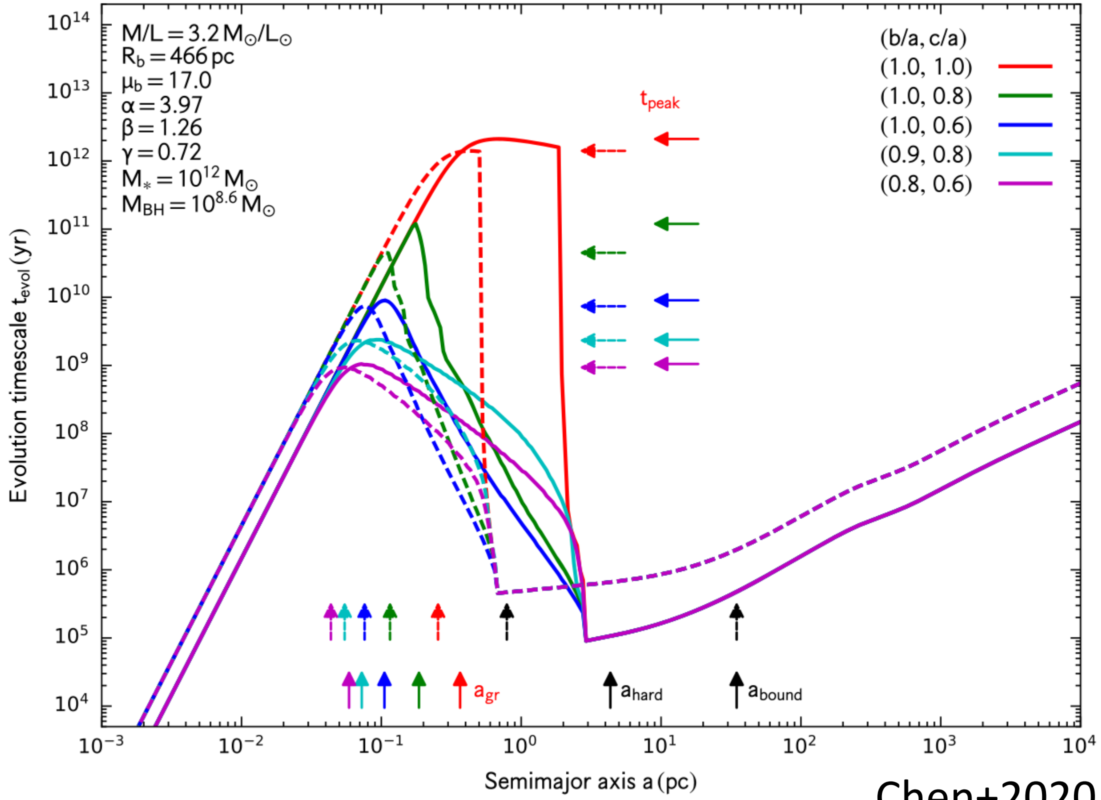






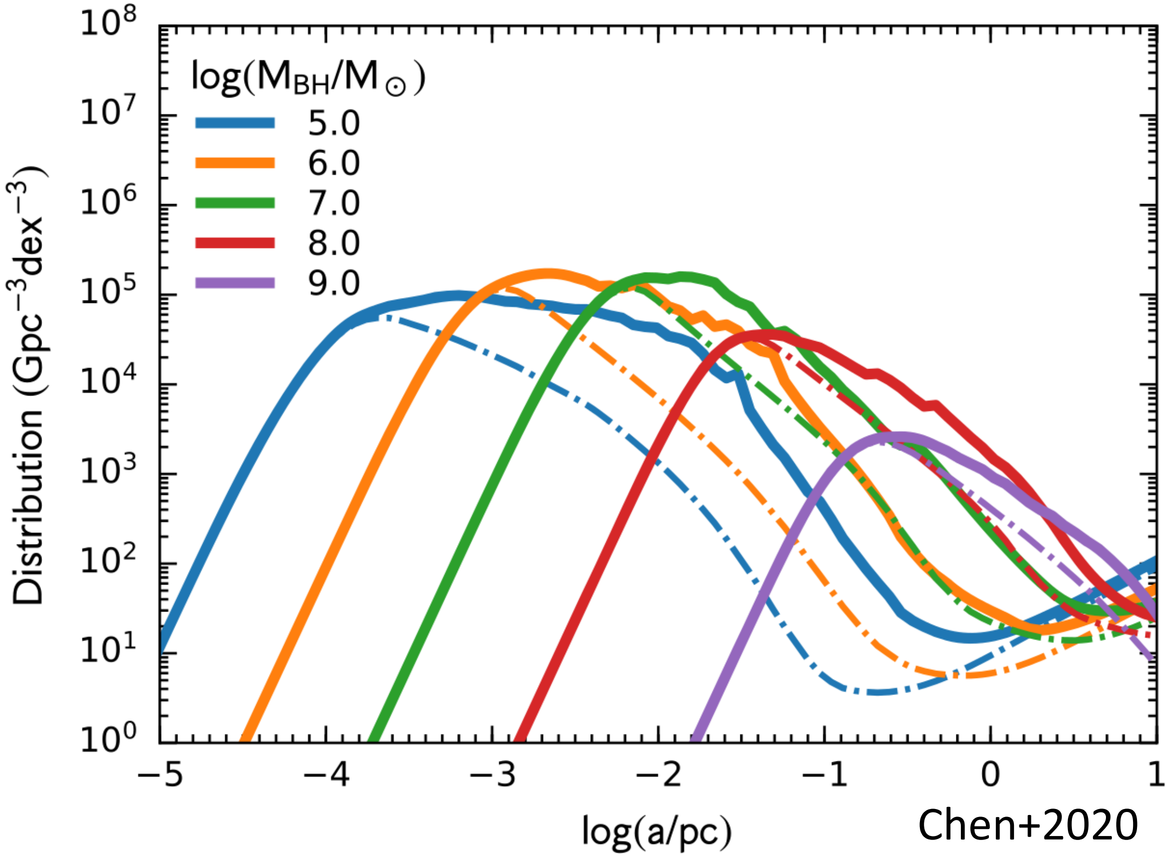
The life history of SMBHBs

Evolution timescale



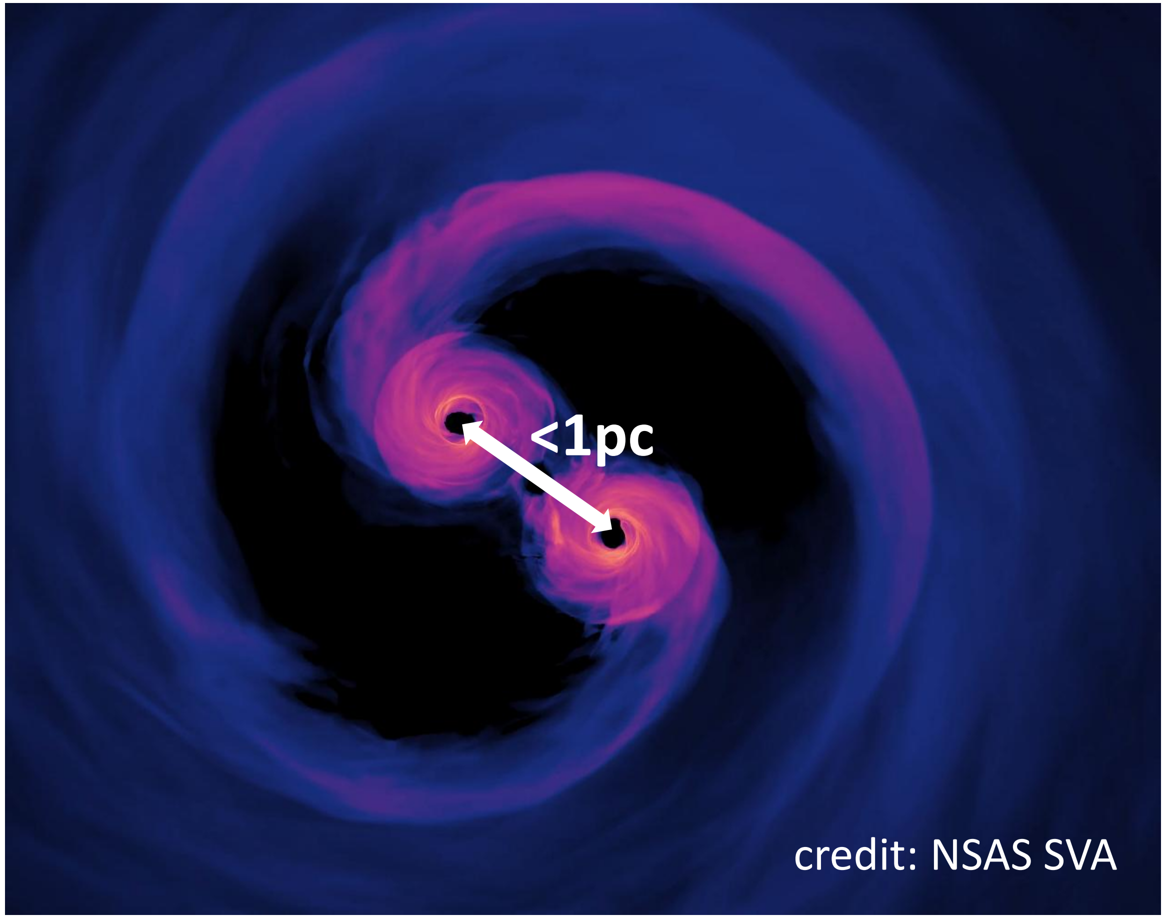
Chen+2020

orbital separation distribution at z=0



Chen+2020

Electromagnetic identification of SMBHBs is challenging...



1pc at z=0.4 (cosmic distance=1Gpc)

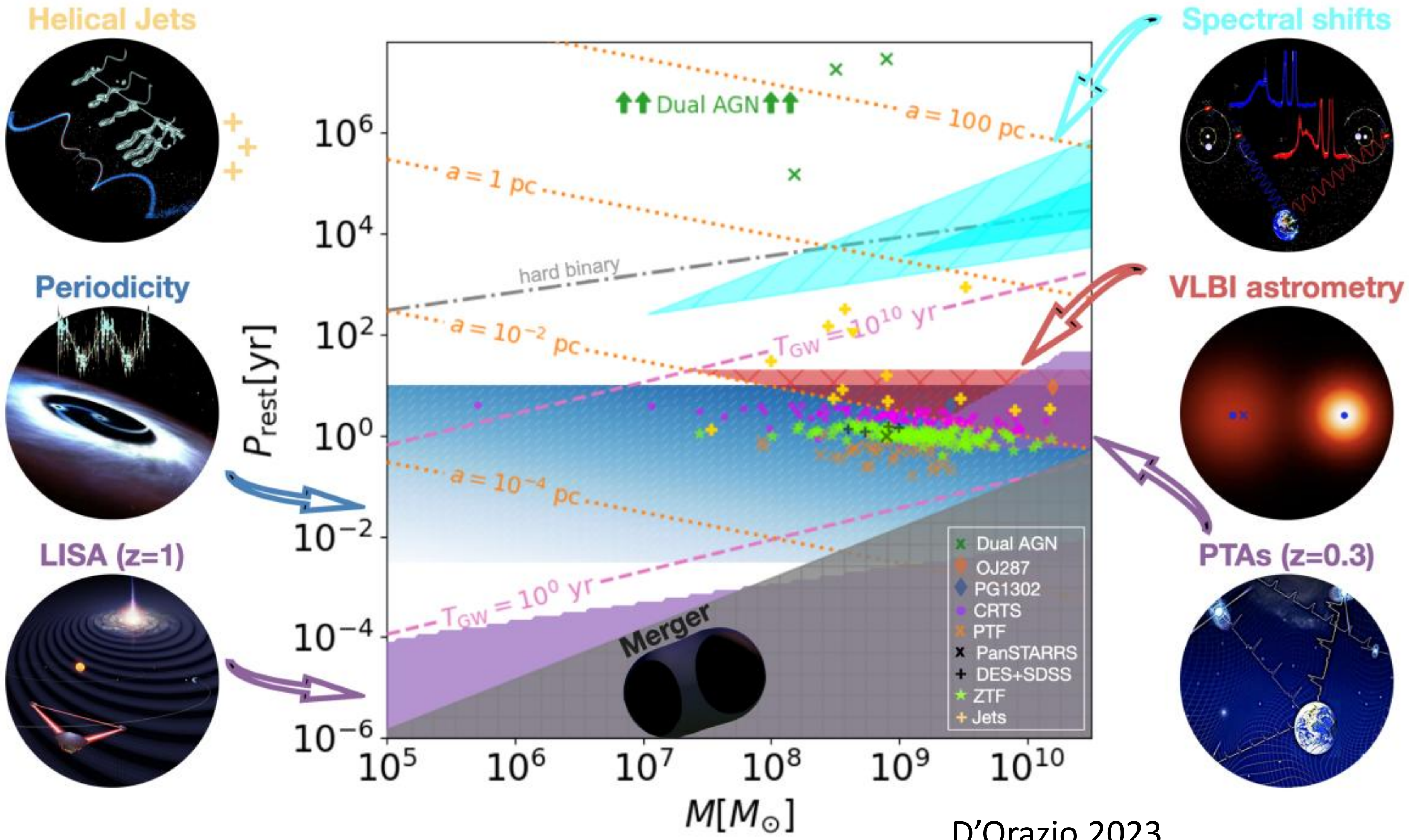
angular size: ~0.2 milli-arcsec

JWST 6m： ~70 milli-arcsec @2μm

ELT 39m： ~10 milli-arcsec @2μm

Many indirect identification methods are proposed

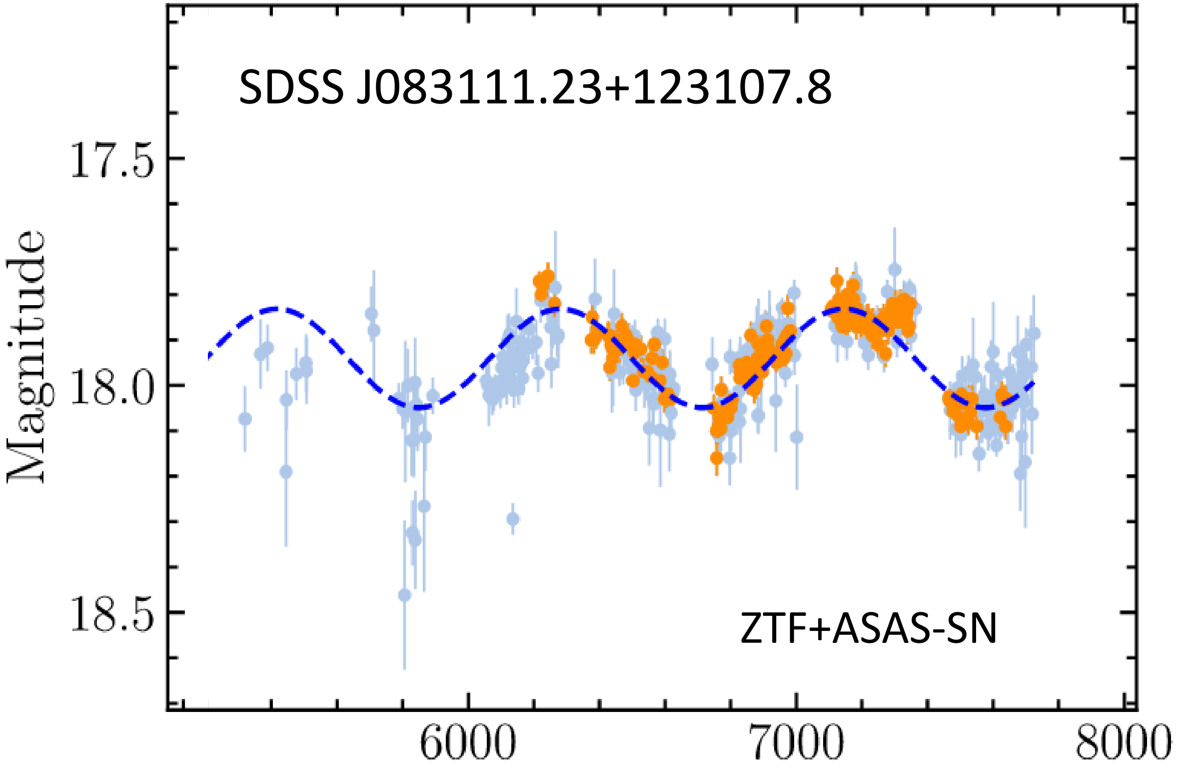
- Periodical variability
- UV deficency
- X-shaped/helical jet
- Broad-line signatures
- Self-lensing variations
- Tidal disruption
- etc

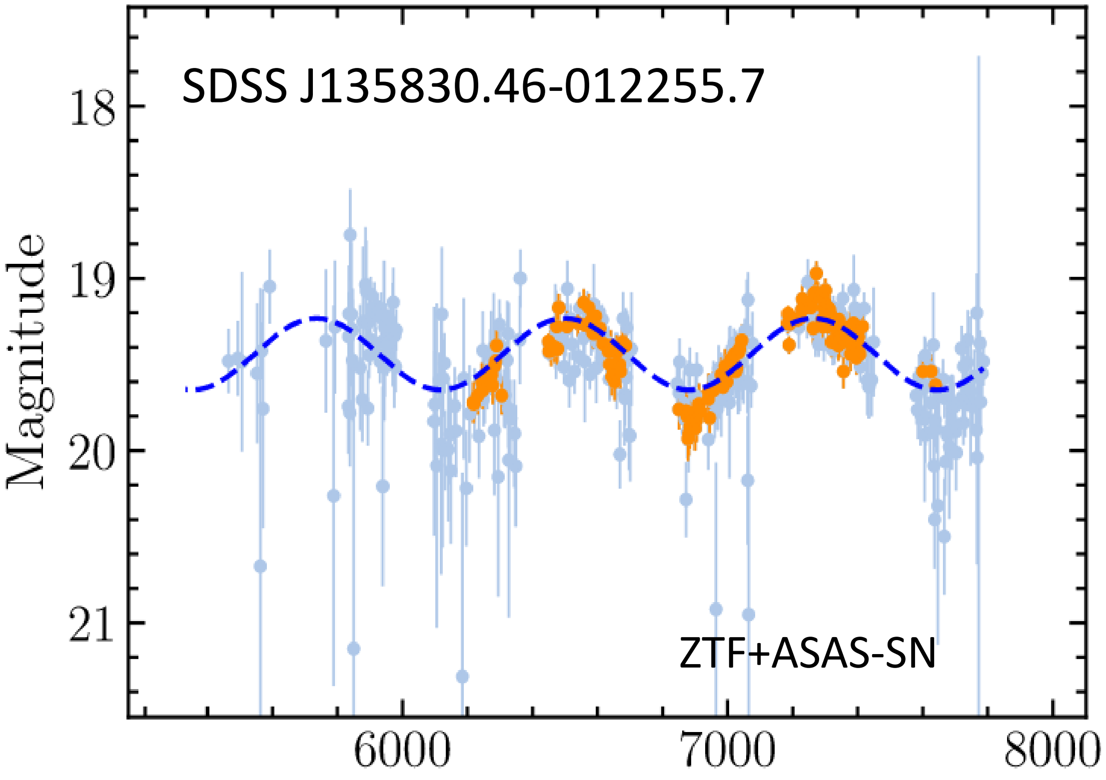


D'Orazio 2023

Periodical searches for SMBHBs

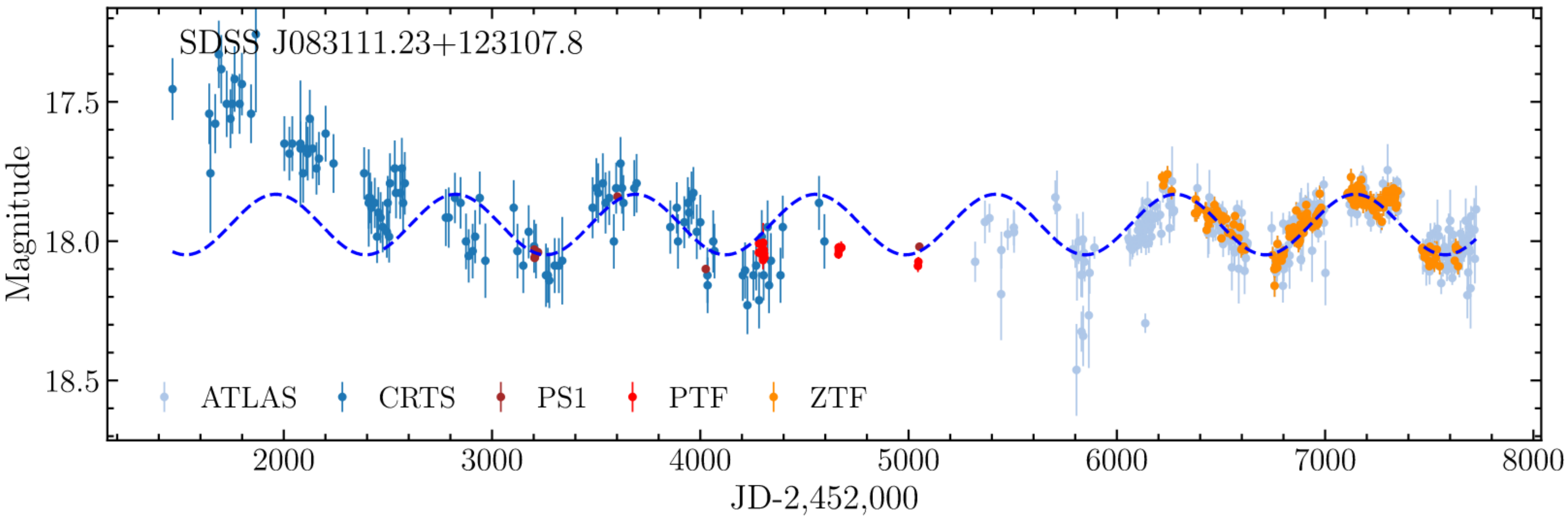
Graham et al. 2015; Charisi et al. 2016; Liu et al. 2019; Chen et al. 2020; Chen et al. 2024

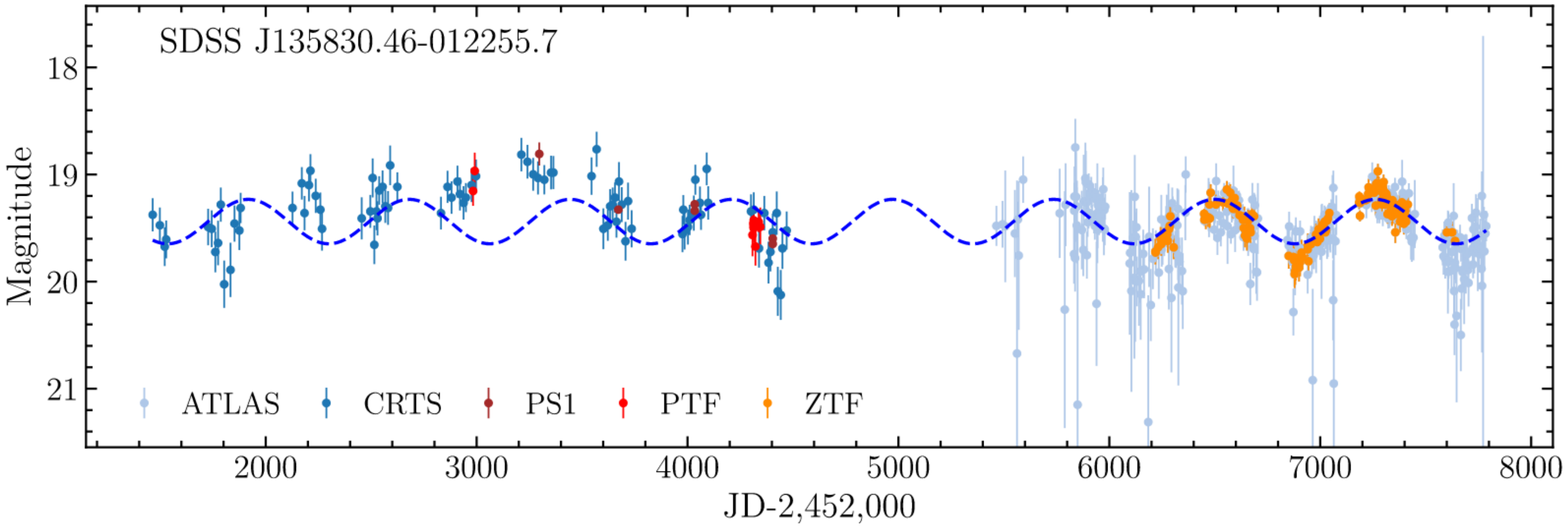




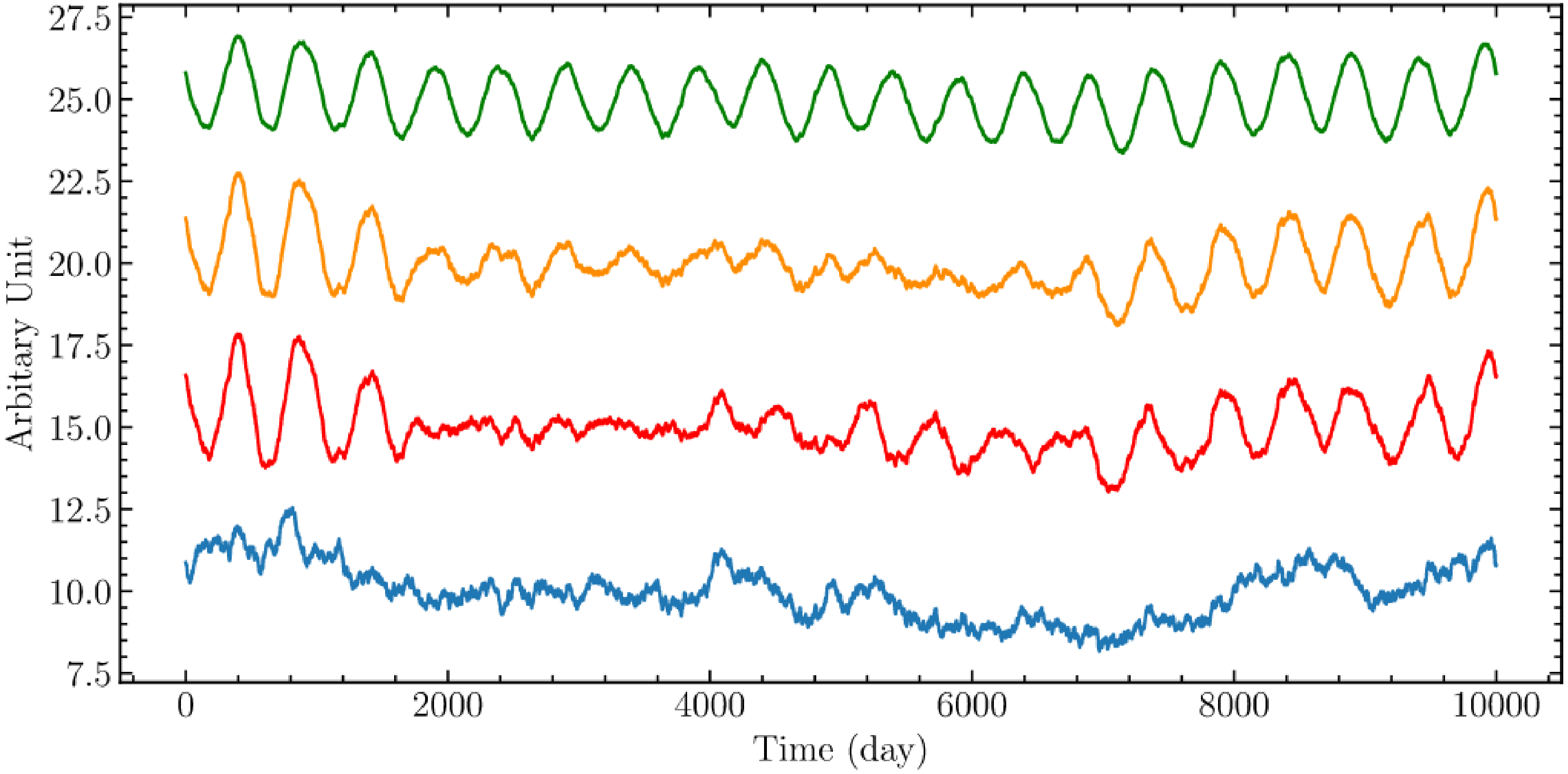
Chen et al. (LYR) 2024

Periodical searches for SMBHBs

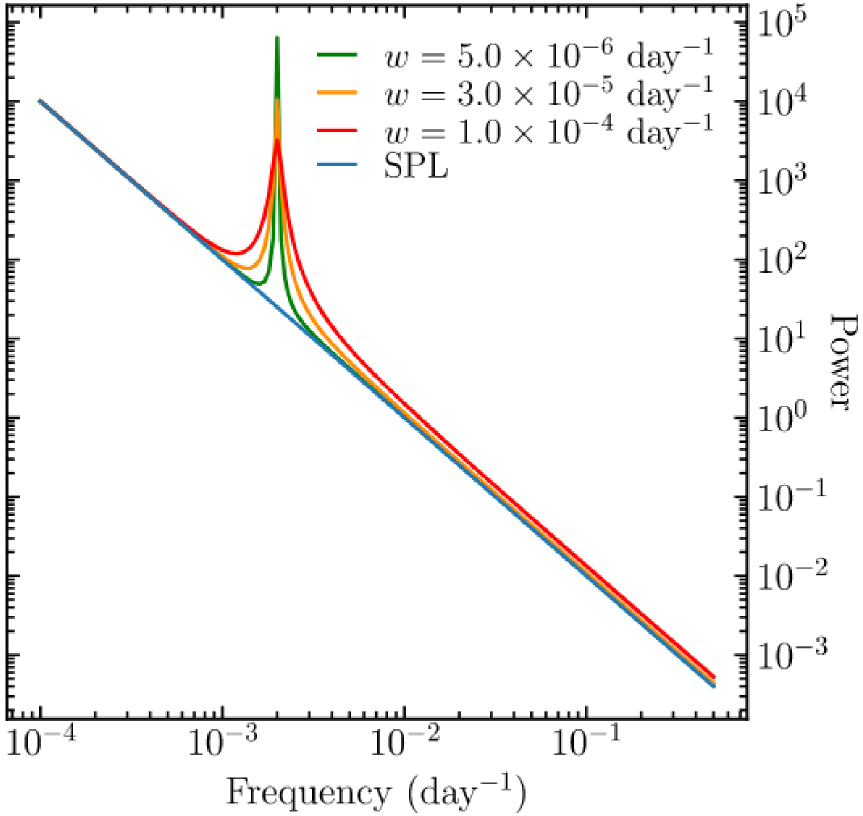




Explanation: quasi-periodical + red-nosie variability

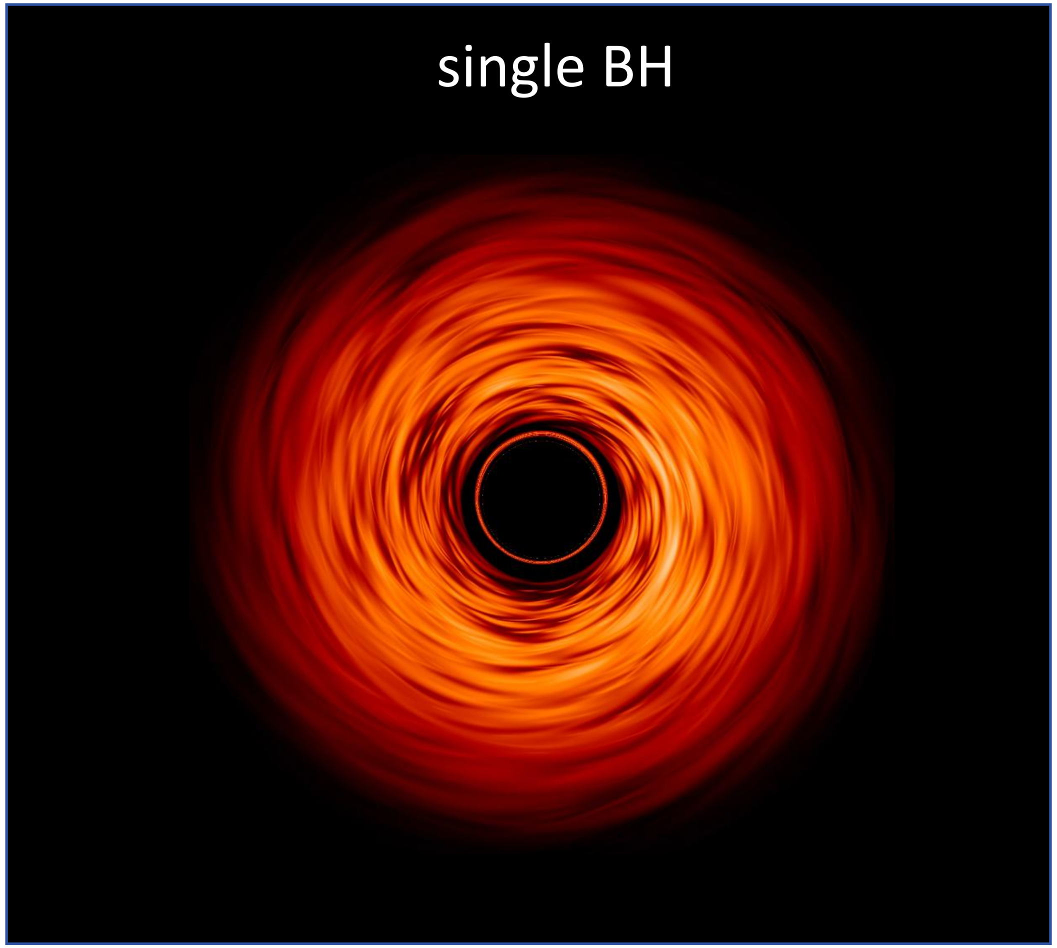


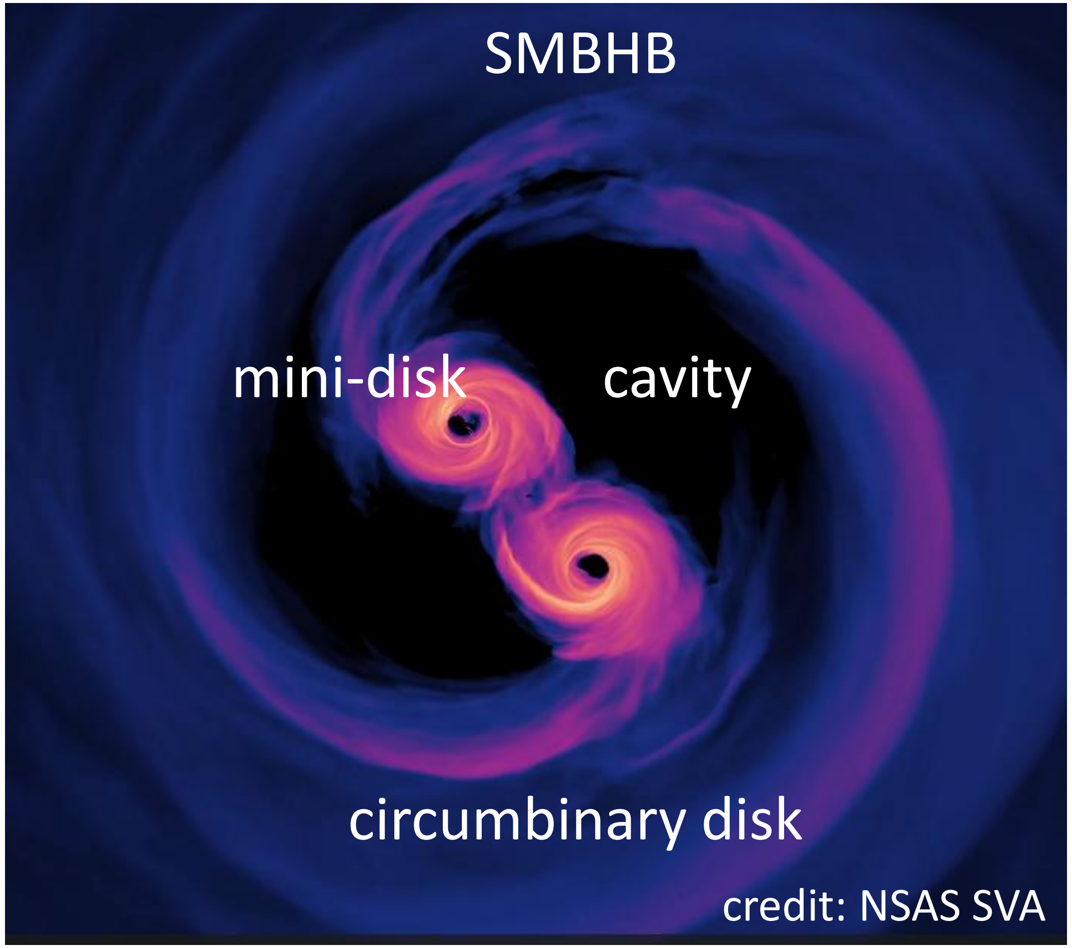
light curves



power spectral density

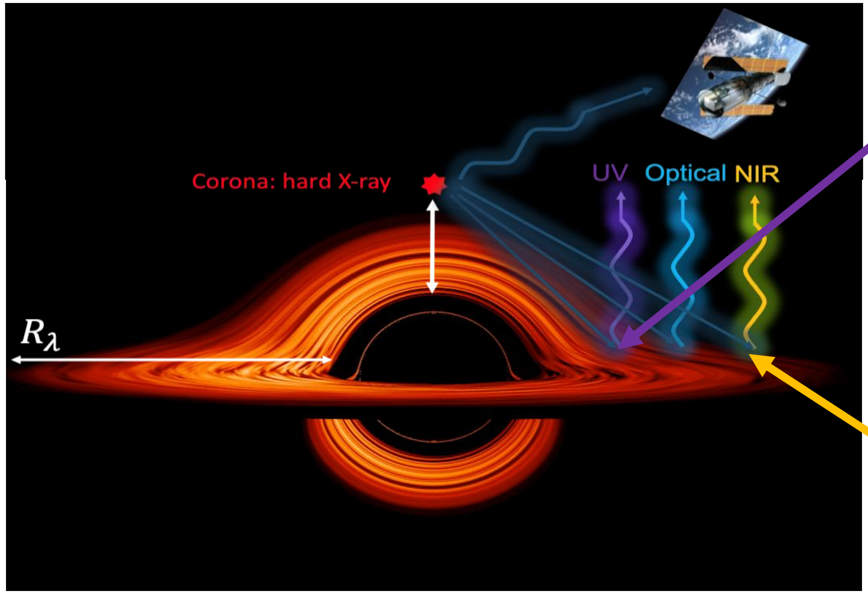
Basic concept: accretion disks surrounding SMBHBs



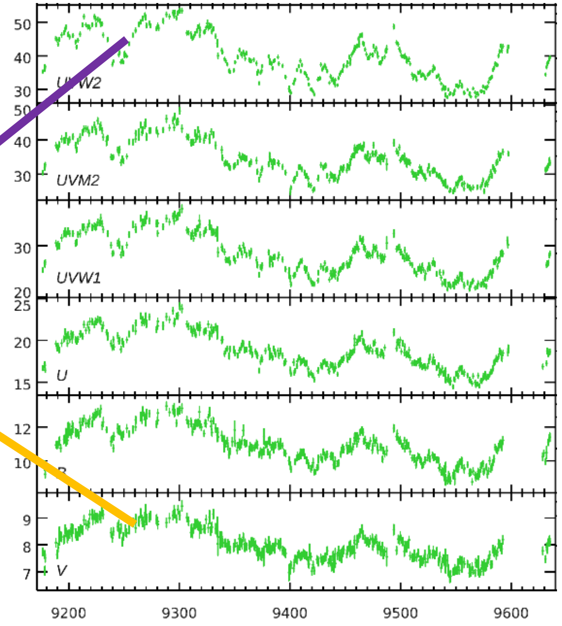


Reverberation Mapping: measuring disk structure

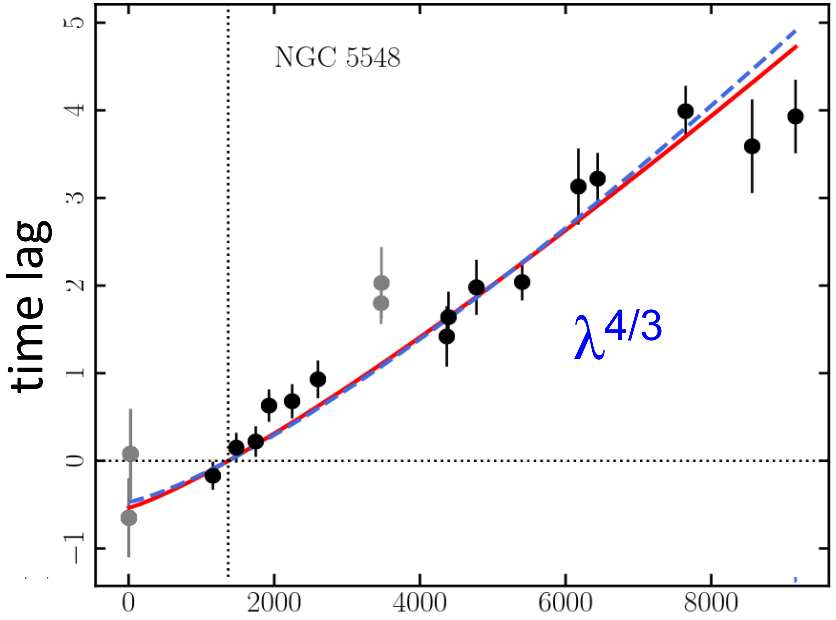
$$X(\lambda, t) = \int_0^\infty \psi(\lambda, \tau) X_b(t - \tau) d\tau \qquad \psi(\lambda, \tau) \equiv A(\lambda) \int_\Sigma \frac{\partial B(\lambda, T)}{\partial T} \frac{\partial T}{\partial L_b} \delta(\tau_d - \tau) r d\theta dr$$



accretion disk + lamp-post



light curves



wavelength

Reverberation mapping: measuring disk structure

viscous energy

$$Q_{\rm vis} = \frac{3GM\dot{M}}{4\pi r^3}\left(1 - \sqrt{\frac{r_{\rm ISCO}}{r}}\right)$$

lamp-post illumination

$$Q_{\rm lp}(r,t) = \frac{2(1-a)L_b(t-\tau_1)}{4\pi(r^2+h^2)}\cos\theta_{\rm inc}$$

thermal balance

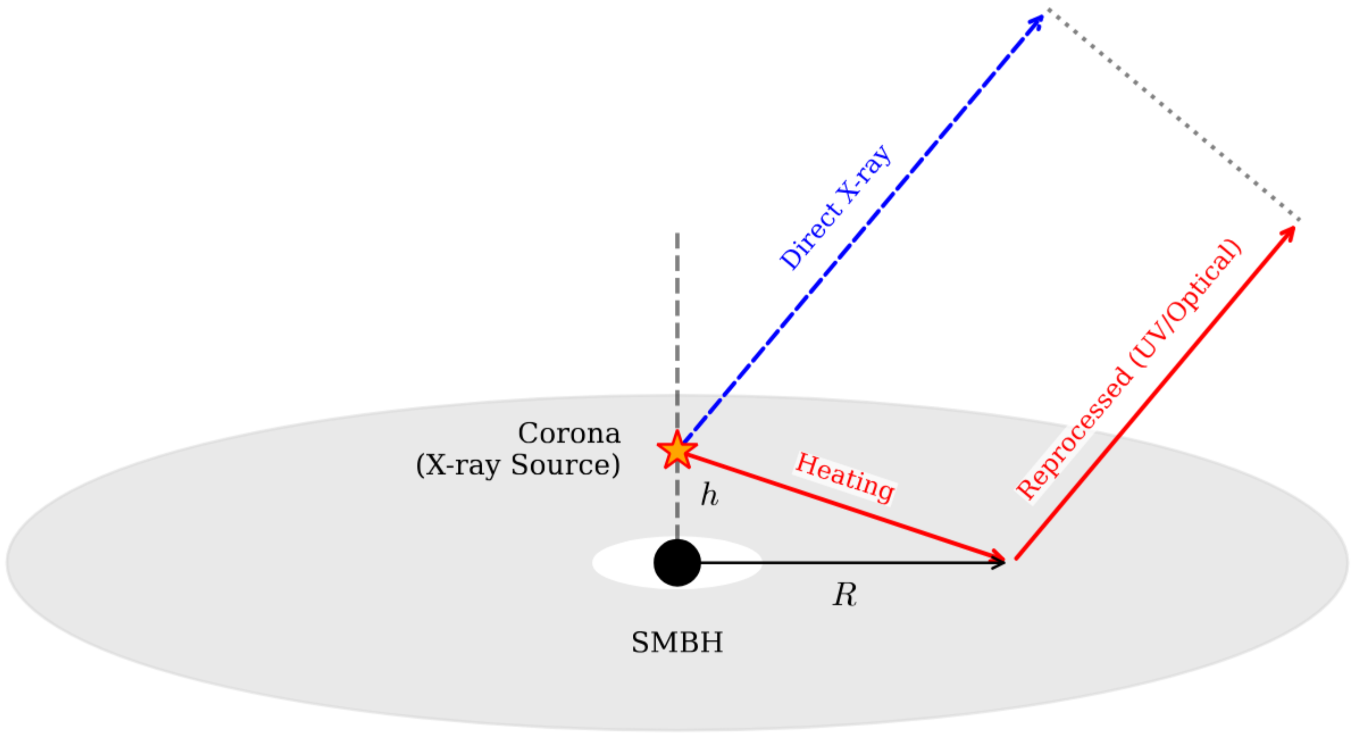
$$2\sigma T^4(r,t) = Q_{\rm vis}(r) + Q_{\rm lp}(r,t)$$

temperature profile

$$T(r) \propto r^{-3/4}$$

time lag

$$\tau_{\rm d}(r,\theta) = \frac{1}{c}(\sqrt{r^2+h^2} - r\cos\theta\sin i + h\cos i) \sim r/c$$



Reverberation mapping: measuring disk structure

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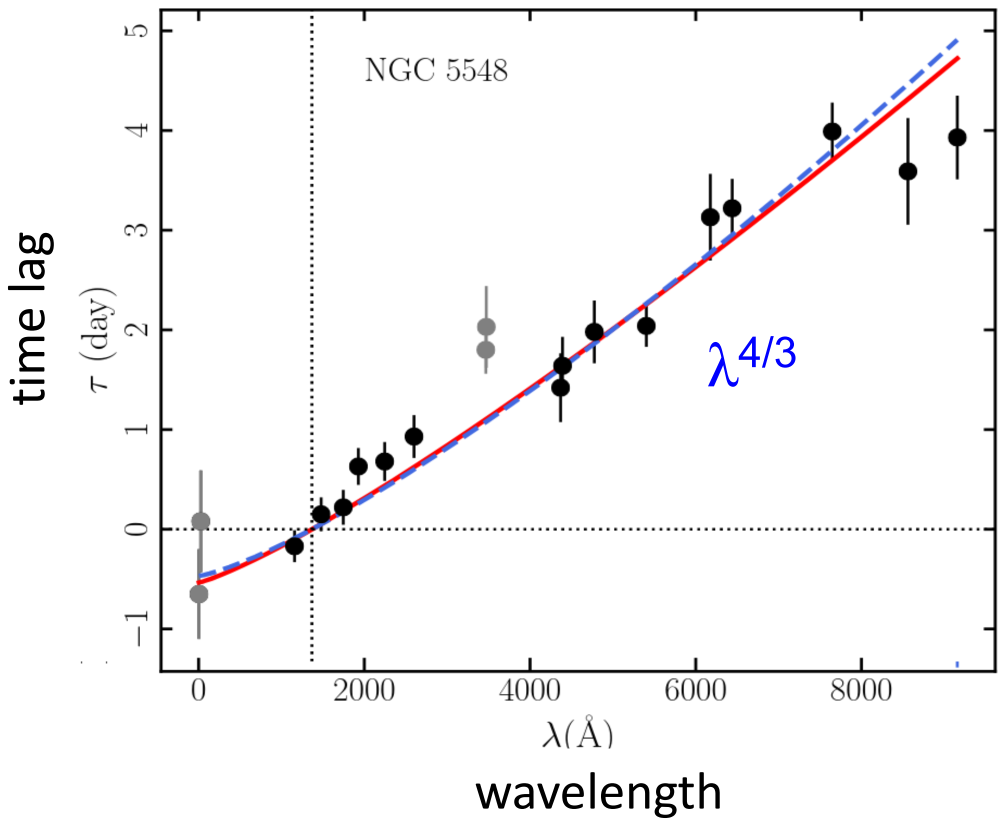
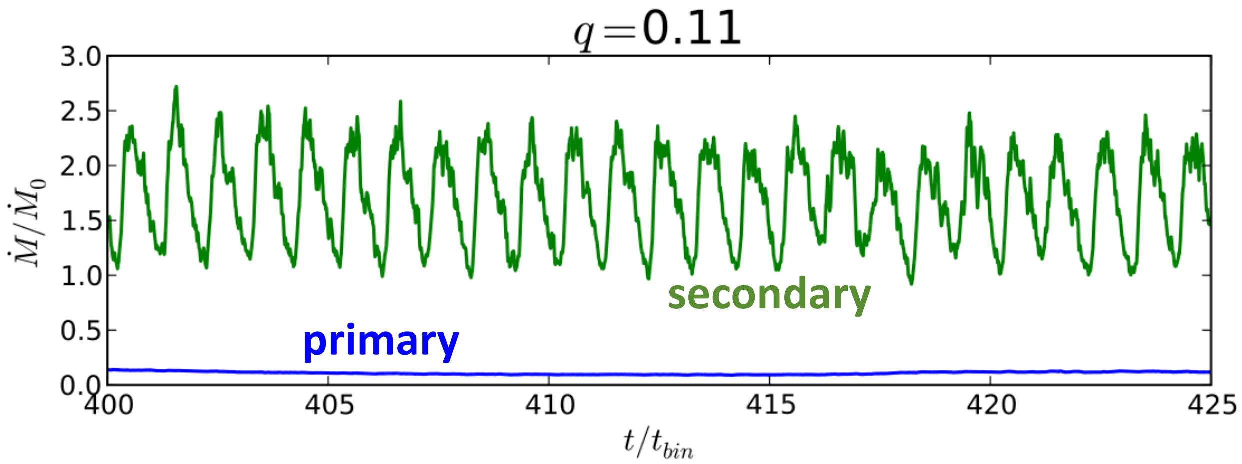
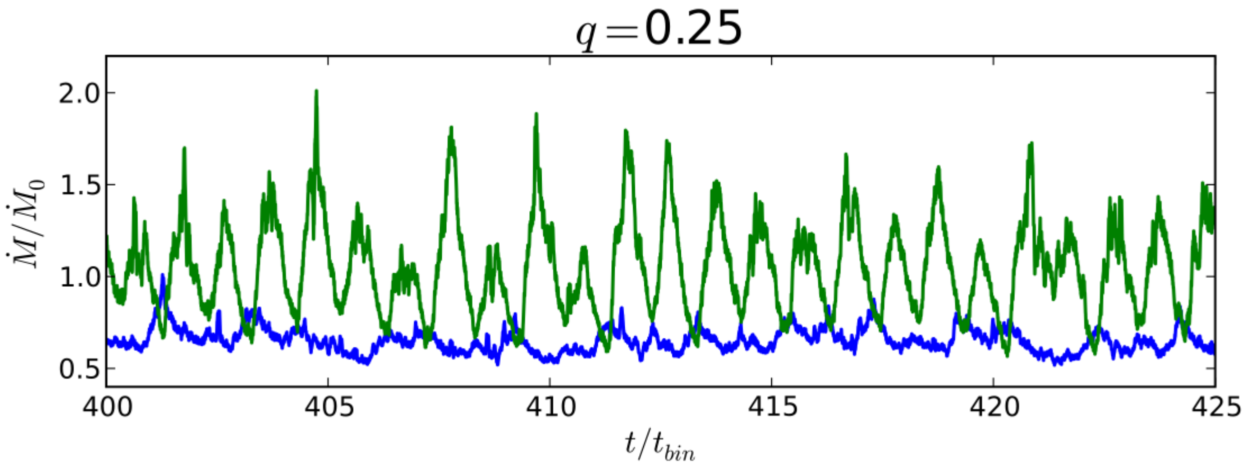


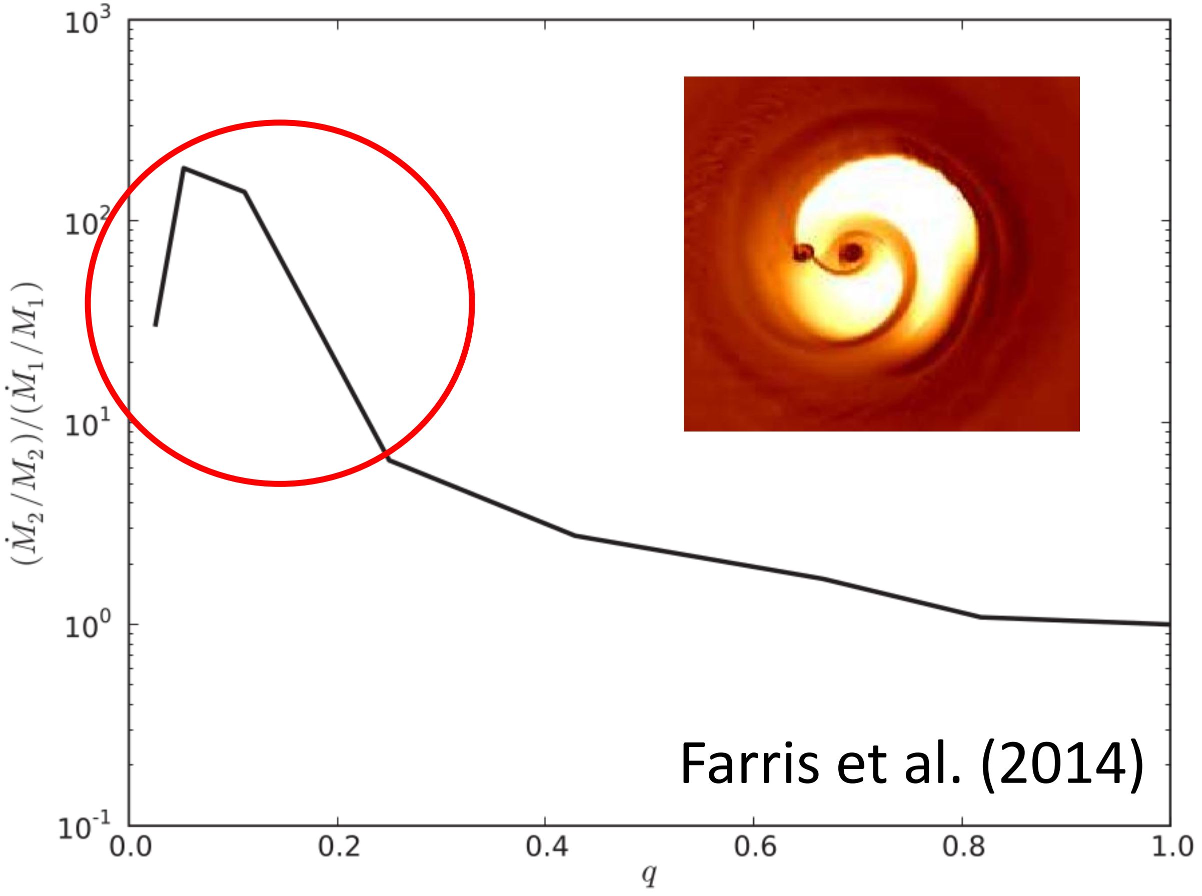
Low-mass-ratio SMBHBs: secondary BH is more active

variations of accretion rates





ratio of accretion rates

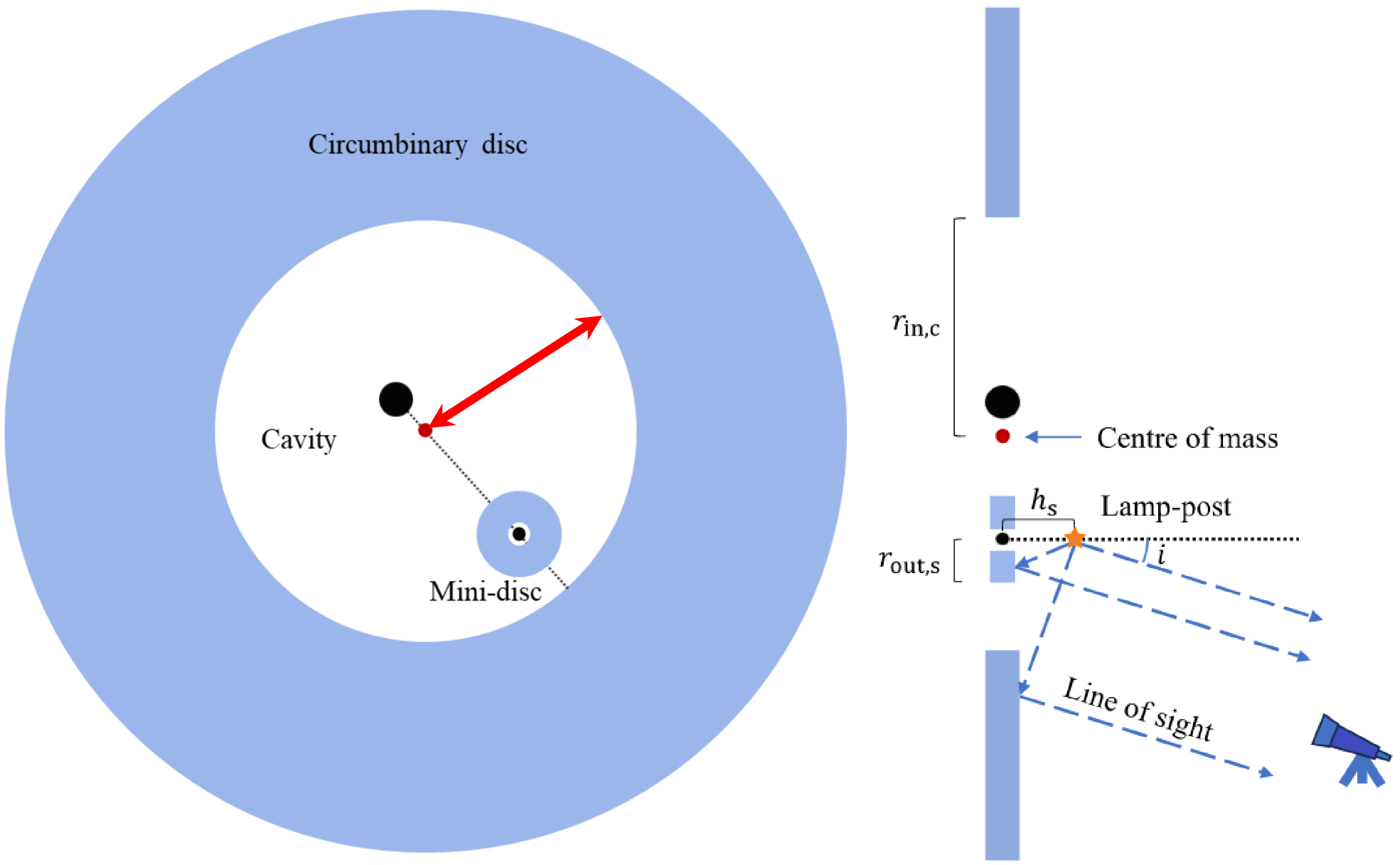


Low-mass-ratio SMBHBs model

- mass ratio q ≤ 0.25
- circular Keplerian orbit
- only secondary BH is active
- circular cavity

  size: ~2a
- mini-disk is truncated

  size: a fraction of Roch lobe
- lamp-post scenario



Low-mass-ratio SMBHBs model

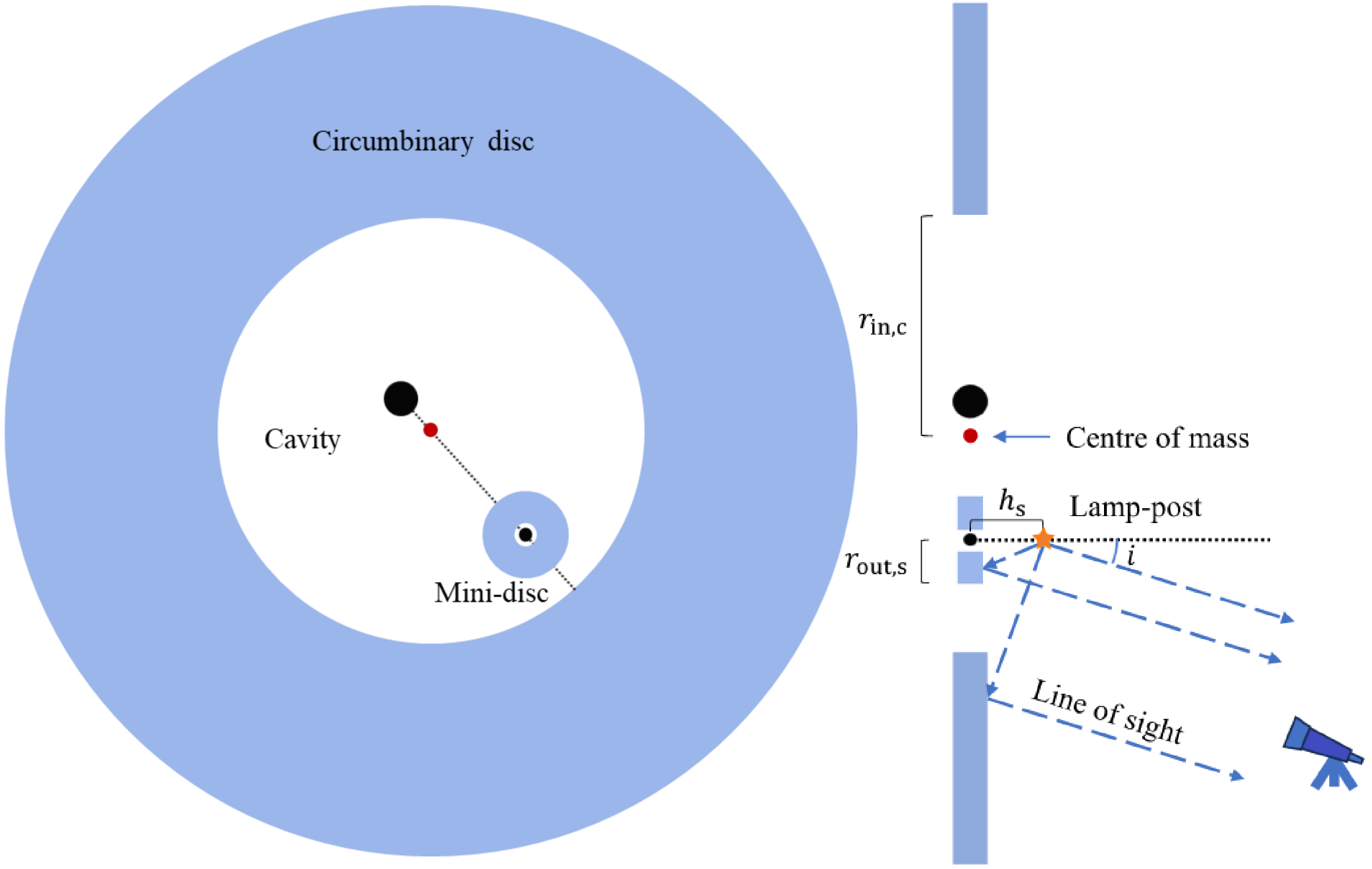
Disk surfuce temperature:

$$T^4(t,\boldsymbol{r}) = T^4_{\rm vis}(\boldsymbol{x}) + T^4_{\rm b}(t-\tau,\boldsymbol{r})$$

$$T^4_{\rm vis} = \begin{cases} \dfrac{3GM_{\rm s}\dot{M}_{\rm s}}{8\pi\sigma r^3}\left(1-\sqrt{\dfrac{r_{\rm in,s}}{r}}\right) \\ \dfrac{3GM_{\rm t}\dot{M}_{\rm c}}{8\pi\sigma r_{\rm c}^3} \end{cases}$$

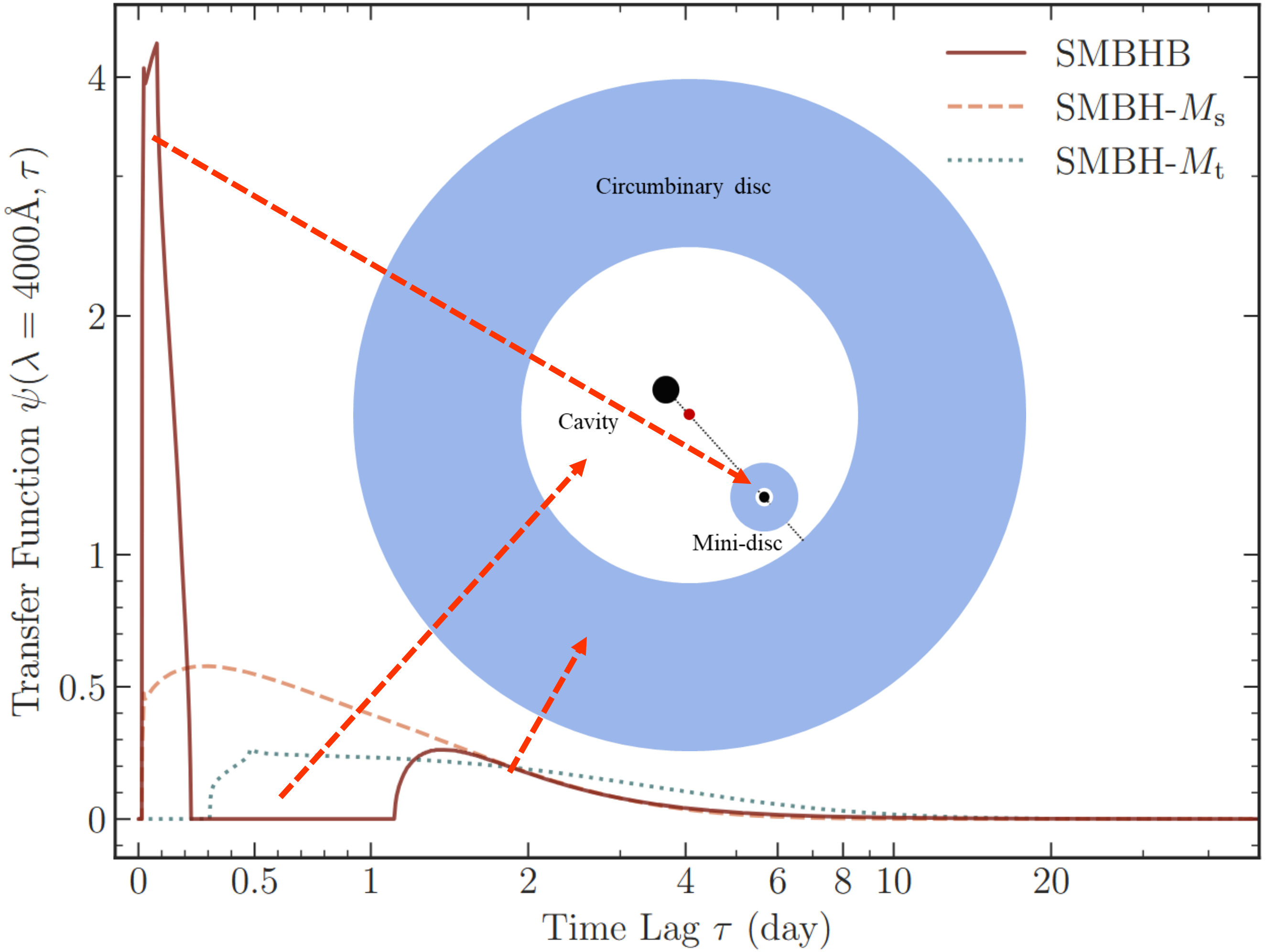
$$T^4_{\rm b}(t-\tau_{\rm s}) = \frac{L_{\rm b}(t-\tau_{\rm s})(1-a)h_{\rm s}}{4\pi\sigma} \times \begin{cases} \left(r^2+h_{\rm s}^2\right)^{-3/2} \\ \left(d_{\rm c}^2+h_{\rm s}^2\right)^{-3/2} \end{cases}$$

$$\psi(\lambda,\tau) \equiv A(\lambda)\int_\Sigma \frac{\partial B(\lambda,T)}{\partial T}\frac{\partial T}{\partial L_{\rm b}}\delta(\tau_{\rm d}-\tau) r{\rm d}\theta{\rm d}r$$



Low-mass-ratio SMBHBs: two-mode trasfer function

Parameter	Unit	Value
$M_{\rm t}$	$10^8\ {\rm M}_\odot$	5.25
$M_{\rm p}$	$10^8\ {\rm M}_\odot$	5
$M_{\rm s}$	$10^8\ {\rm M}_\odot$	0.25
q	–	0.05
$a_{\rm B}$	$R_{\rm g,t}$	300
$P_{\rm B}$	day	977
$\dot{M}_{\rm c}$	$\dot{M}_{\rm Edd,c}$	0.1
$\dot{M}_{\rm s}$	$\dot{M}_{\rm Edd,s}$	2.1
L_μ	$\eta\dot{M}_{\rm s}c^2$	$f_{\rm b}$
a	–	0.1
$h_{\rm s}$	$R_{\rm g,s}$	6
$r_{\rm s,in}$	$R_{\rm g,s}$	6
$r_{\rm s,out}$	$r_{\rm R,s}$	0.1
$r_{\rm c,in}$	$a_{\rm B}$	$(1+q)^{-1}+(q/3)^{1/3}$
$r_{\rm c,out}$	$R_{\rm g,t}$	10^5
$\theta_{\rm s}$	degree	0
i	degree	30
$T_{\rm GW}$	yr	3×10^5

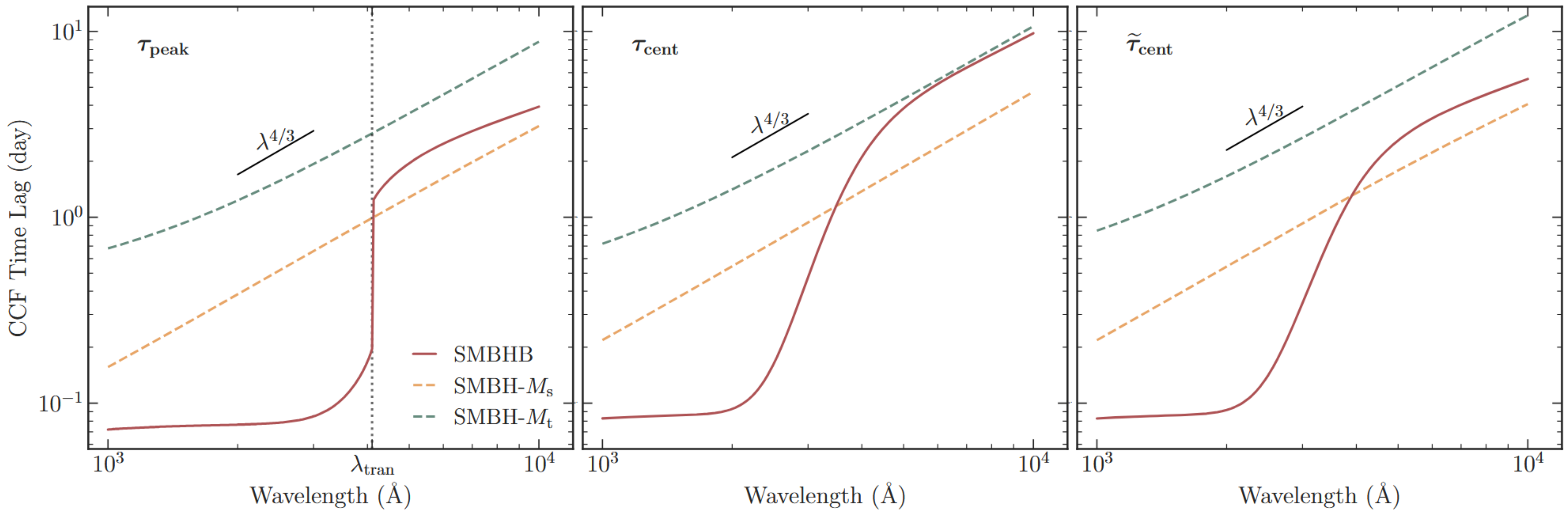


Low-mass-ratio SMBHBs: τ-λ relation

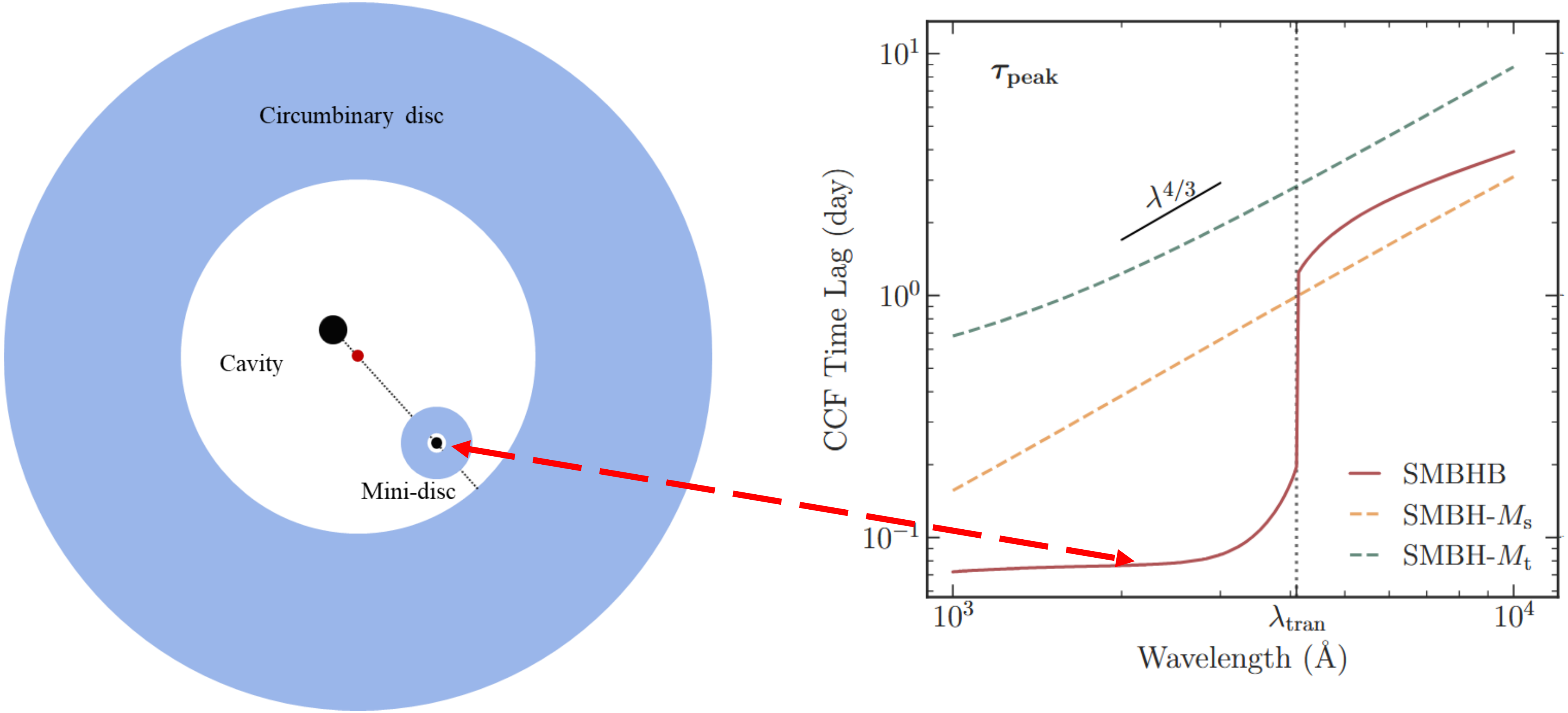
$$\tau_{\rm peak} \equiv \arg\max \psi_{\otimes}(\lambda, \tau)$$

$$\tau_{\rm cent} = \frac{\int_0^\infty \tau \psi_{\otimes}(\lambda, \tau) \mathrm{d}\tau}{\int_0^\infty \psi_{\otimes}(\lambda, \tau) \mathrm{d}\tau}$$

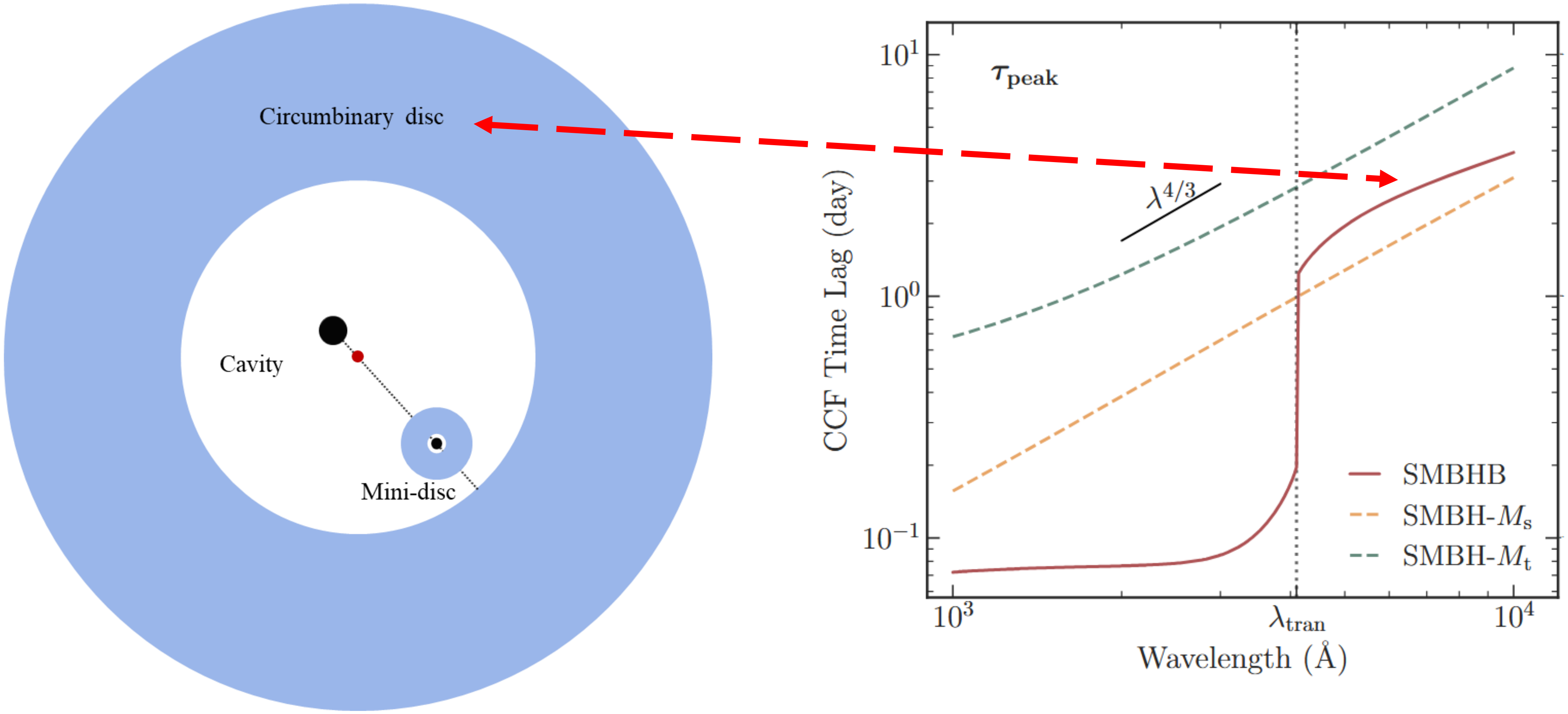
$$\tilde{\tau}_{\rm cent} = \frac{\int_{>80\%} \tau \psi_{\otimes}(\lambda, \tau) \mathrm{d}\tau}{\int_{>80\%} \psi_{\otimes}(\lambda, \tau) \mathrm{d}\tau}$$



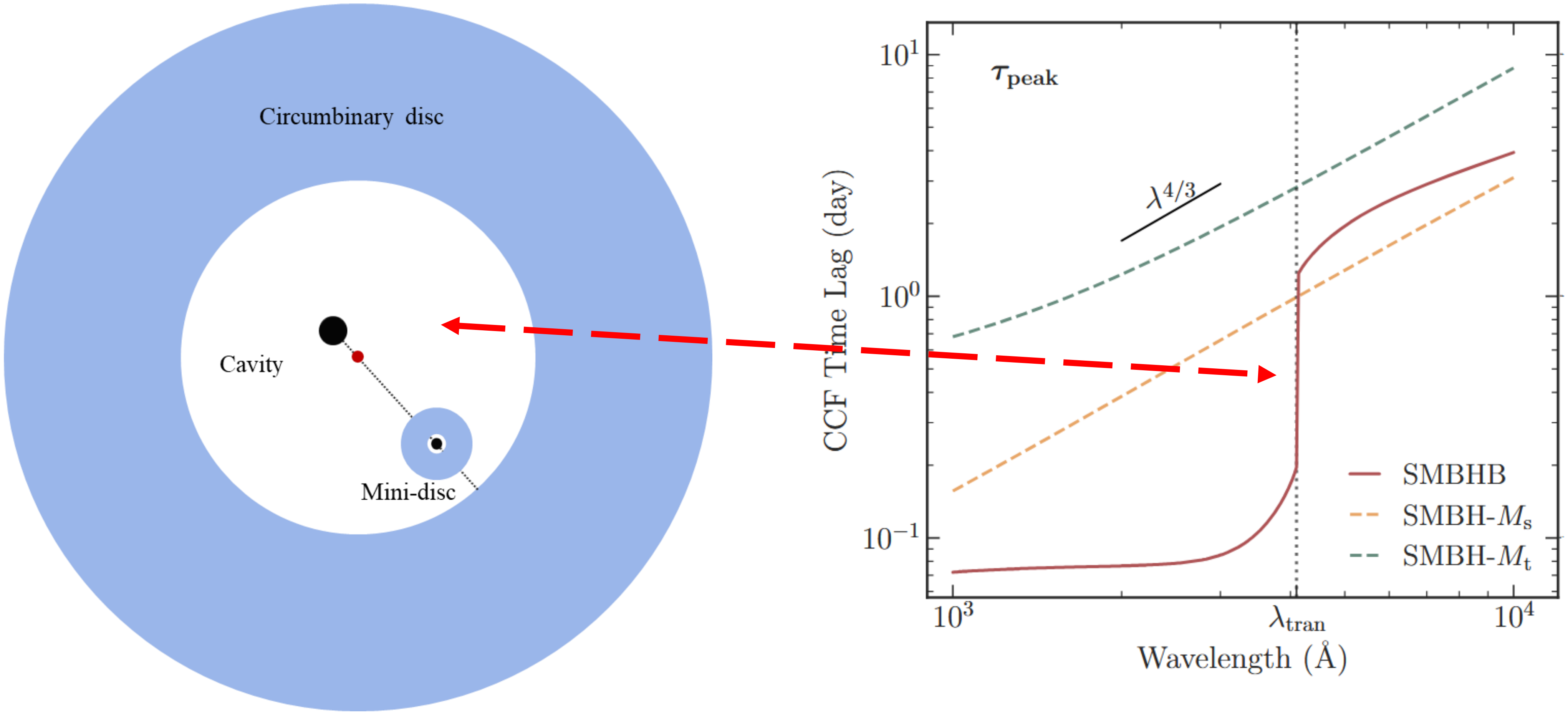
Low-mass-ratio SMBHBs: τ-λ relation



Low-mass-ratio SMBHBs: τ-λ relation



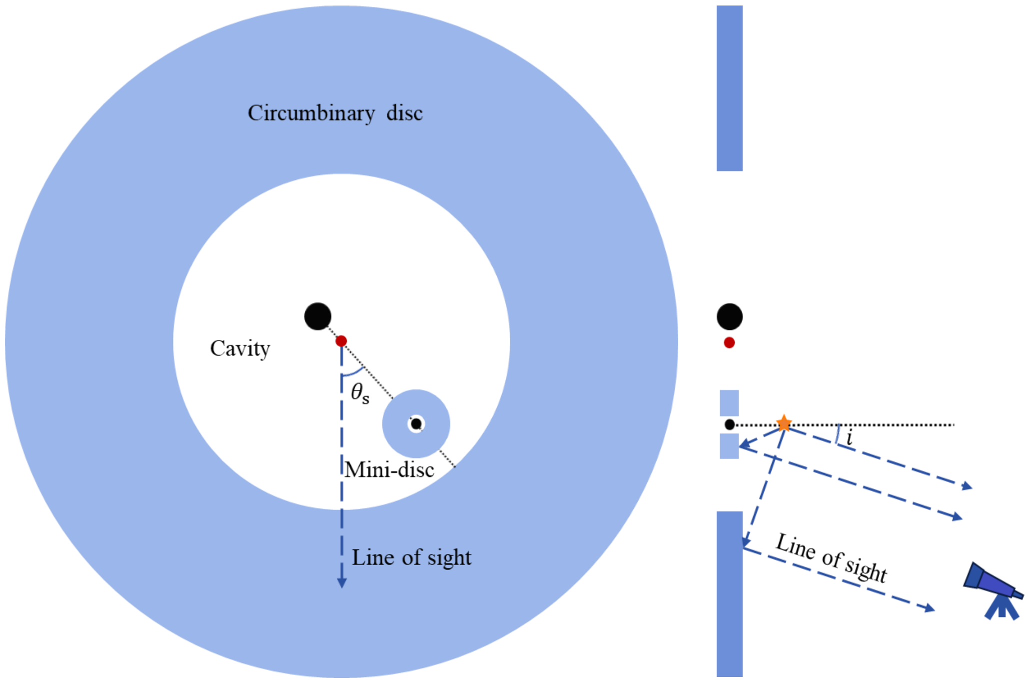
Low-mass-ratio SMBHBs: τ-λ relation

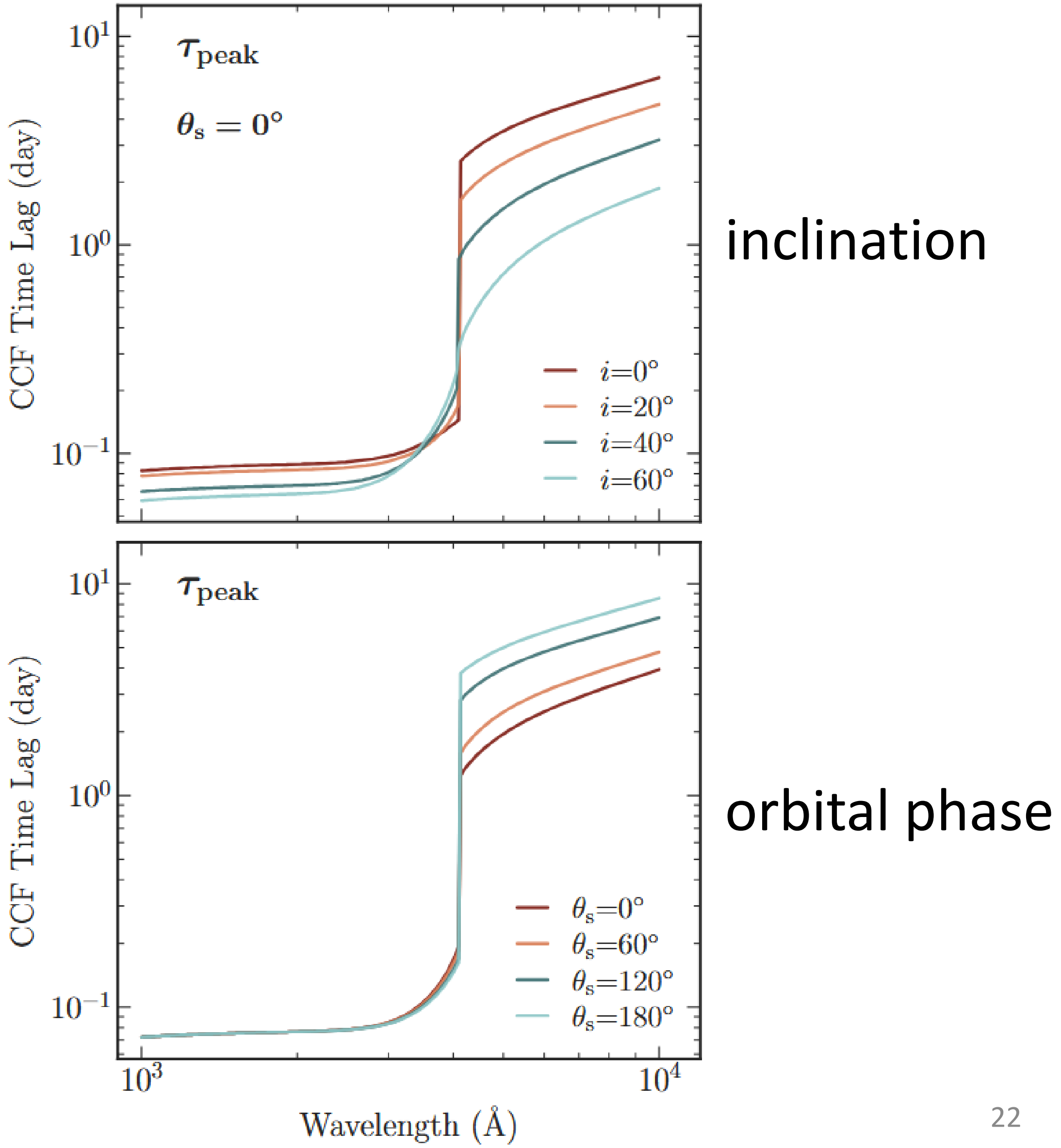


Low-mass-ratio SMBHBs: τ-λ relation

Inclination & orbital phase

- change relation shape
- mainly affect optial time lag
- τ-λ transition is retained

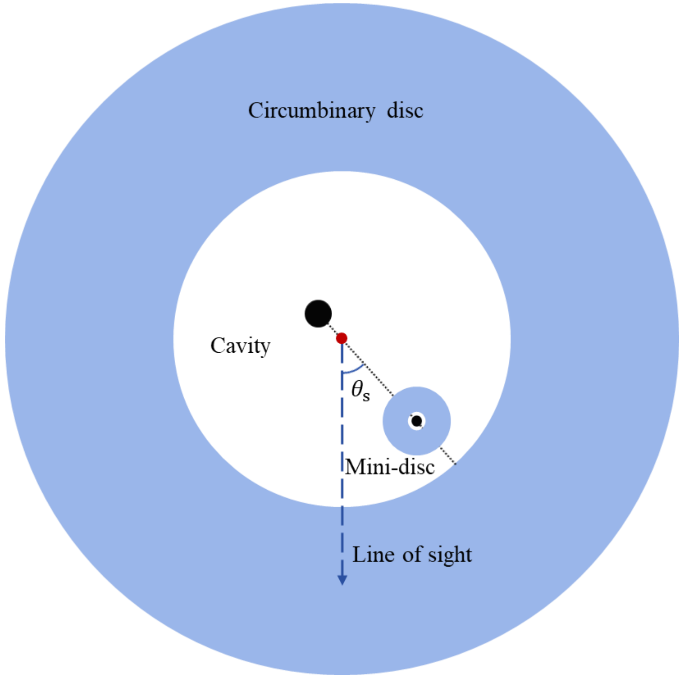


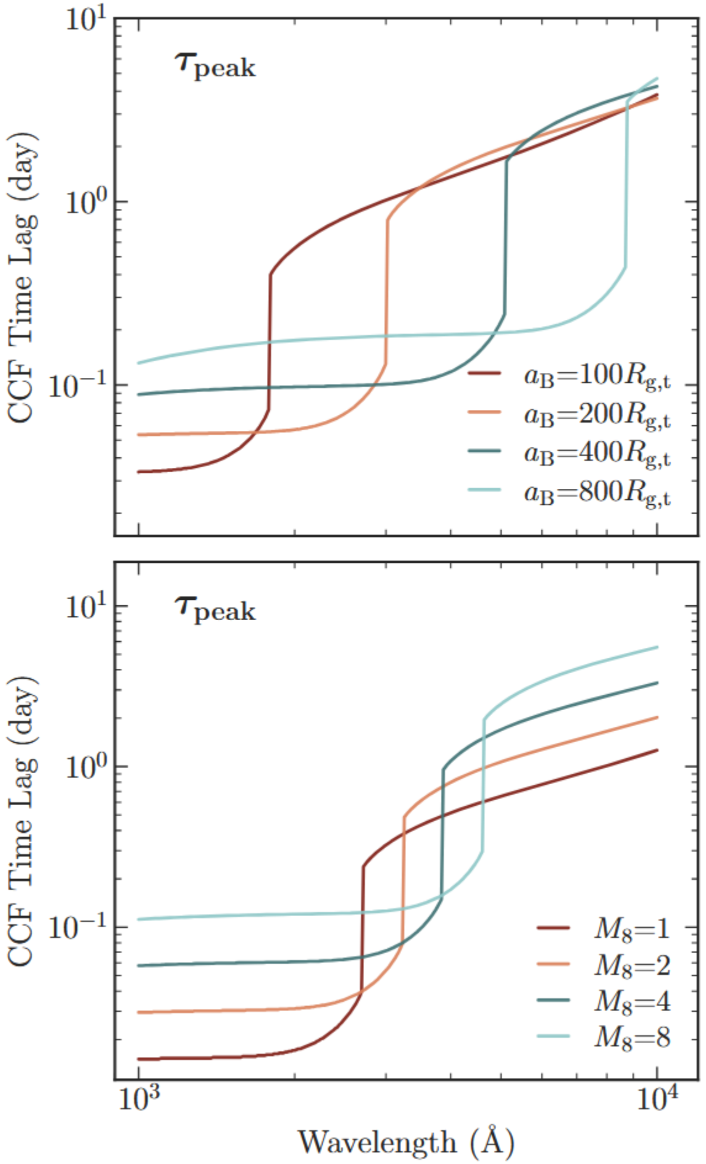


Low-mass-ratio SMBHBs: τ-λ relation

orbital separation & total mass

- change cavity size
- change transition wavelength

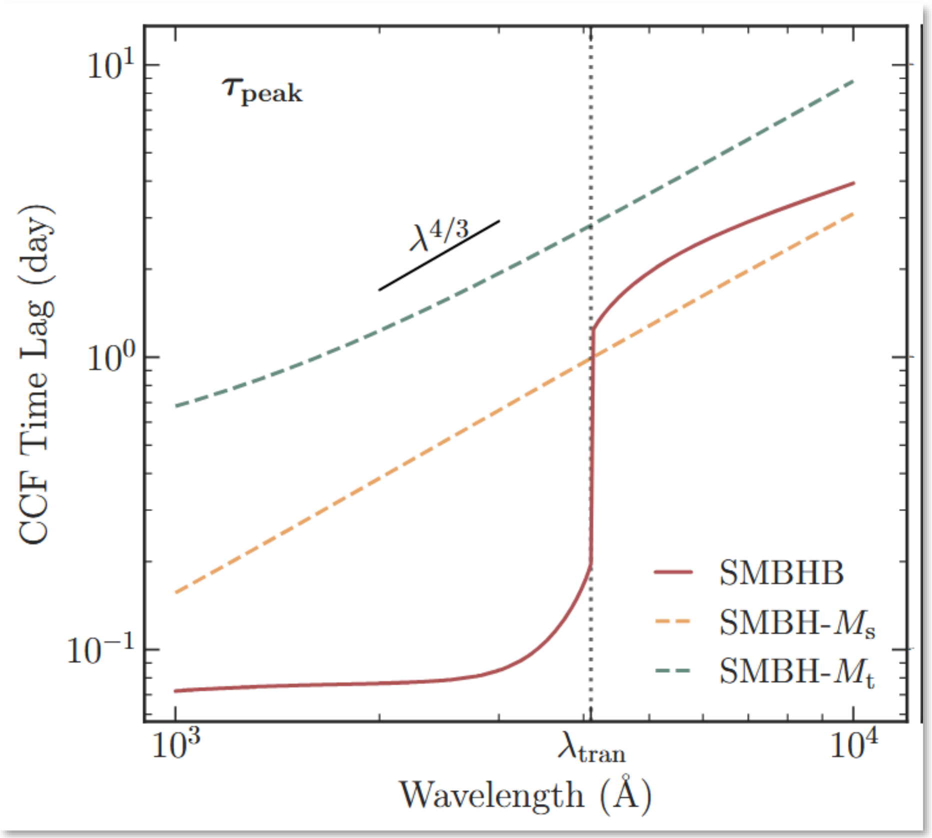




orbital separation

total mass

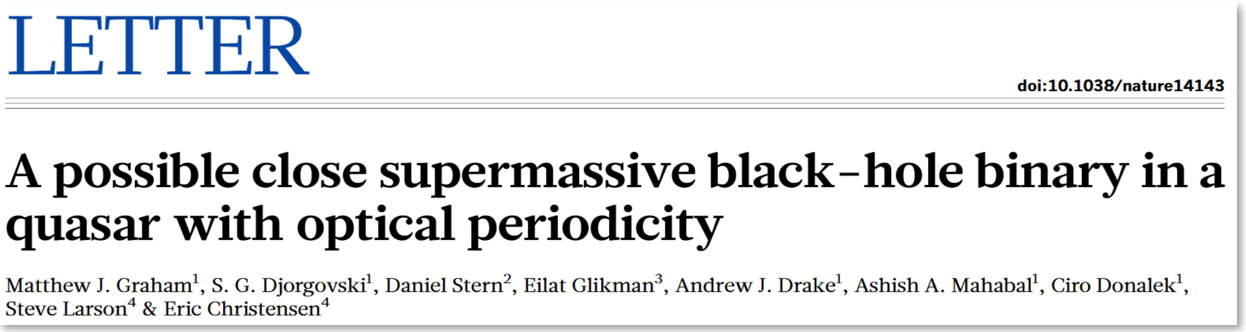
Low-mass ratio SMBHBs: τ-λ relation



$$\lambda_{\rm tran} \approx \boxed{2700} f^{-1/4}\left(\frac{M_{\rm t}}{10^8 M_\odot}\right)^{1/4}\left(\frac{\dot{m}_{\rm c}}{0.1}\right)^{-1/4}\left(\frac{a_{\rm B}}{100 R_{\rm g,t}}\right)^{3/4} \text{Å}$$

$$\approx \boxed{8600} f^{-1/4}\left(\frac{M_{\rm t}}{10^8 M_\odot}\right)^{-1/4}\left(\frac{\dot{m}_{\rm c}}{0.1}\right)^{-1/4}\left(\frac{P_{\rm B}}{\rm yr}\right)^{1/2} \text{Å}$$

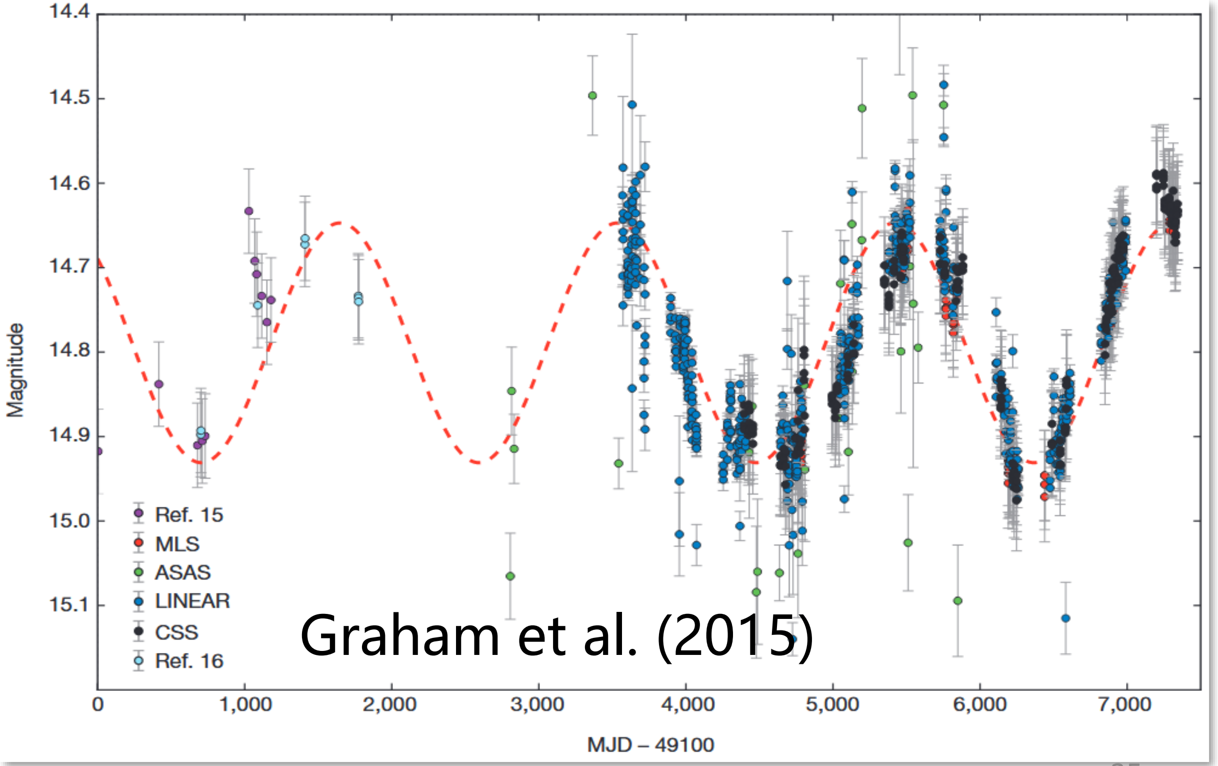
Application to PG 1302-102


LETTER

doi:10.1038/nature14143

A possible close supermassive black-hole binary in a quasar with optical periodicity

Matthew J. Graham[1], S. G. Djorgovski[1], Daniel Stern[2], Eilat Glikman[3], Andrew J. Drake[1], Ashish A. Mahabal[1], Ciro Donalek[1], Steve Larson[4] & Eric Christensen[4]



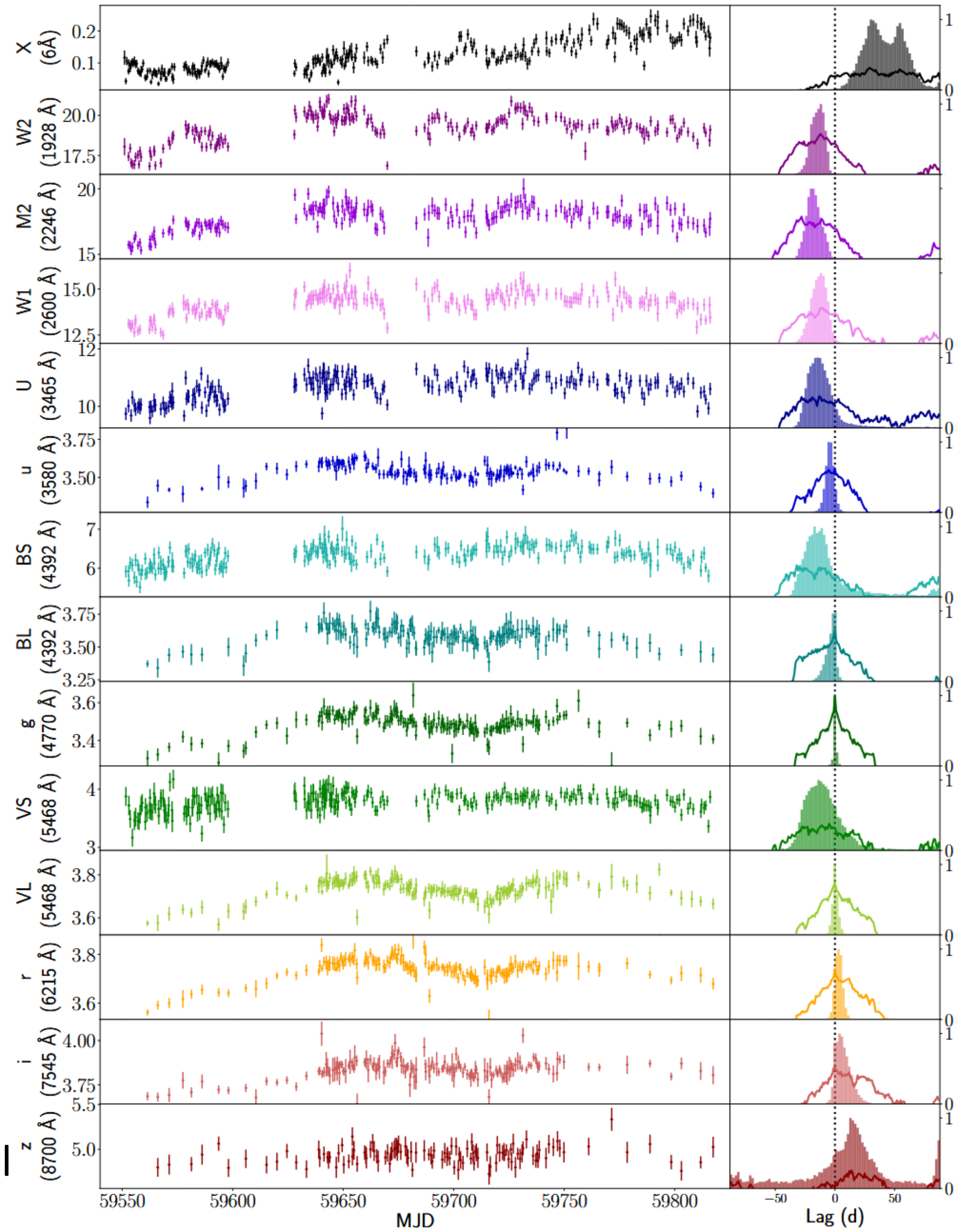
Graham et al. (2015)

Basic properties

- Catalina Sky Survey
- Lincoln Near-Earth Asteroid Research
- z = 0.2784
- Magnitude V = 15.0
- Period 1884 days

UV

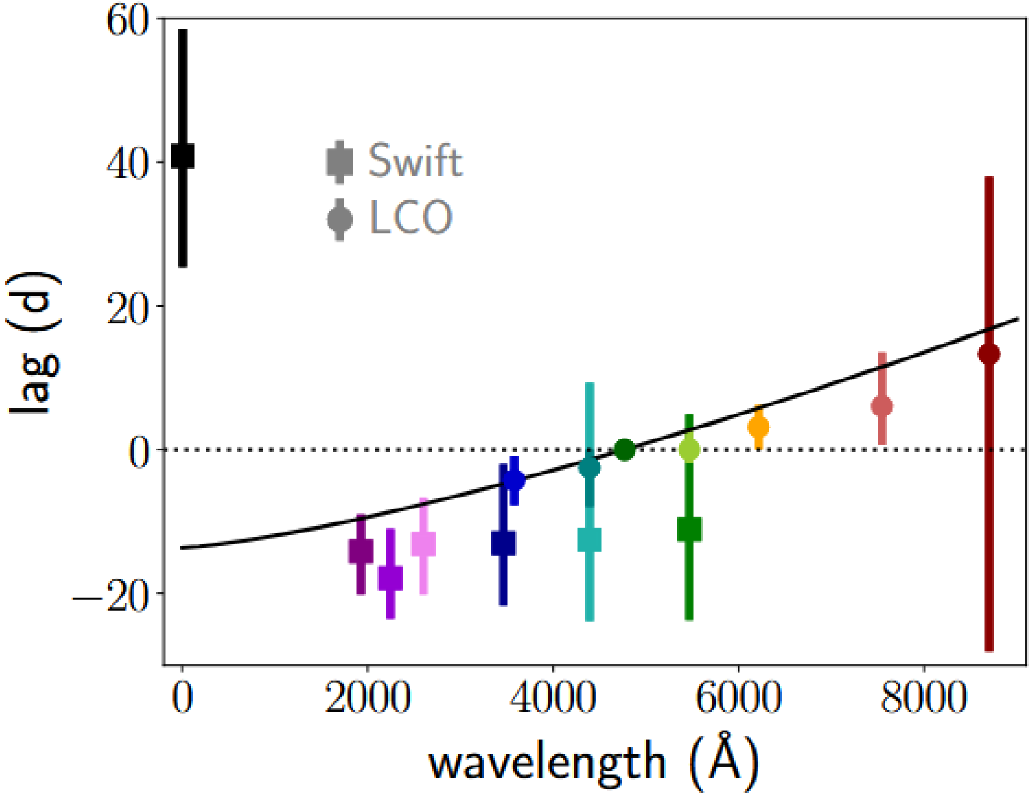
optical



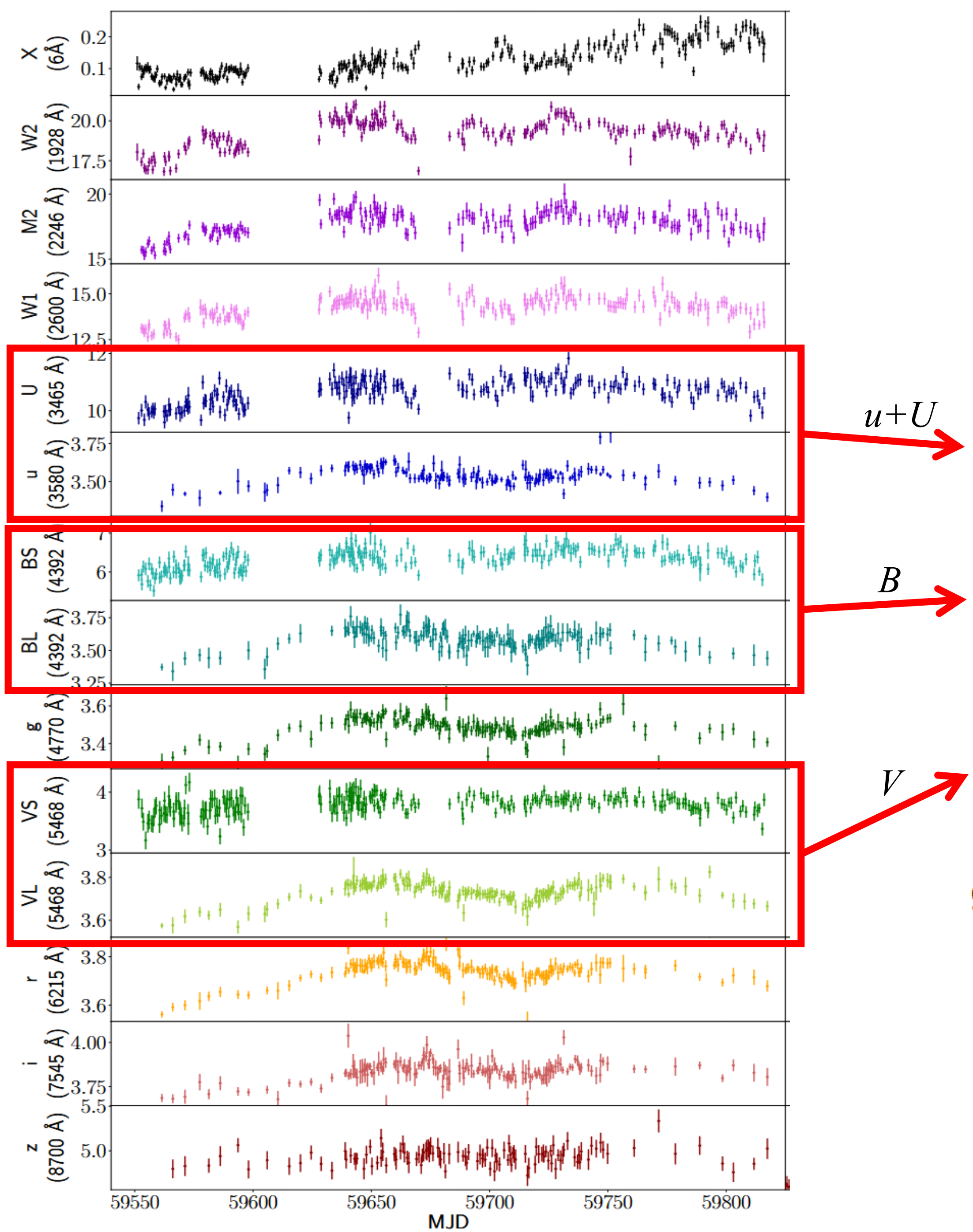
The Astrophysical Journal, 964:167 (8pp), 2024 April 1
https://doi.org/10.3847/1538-4357/ad23e2

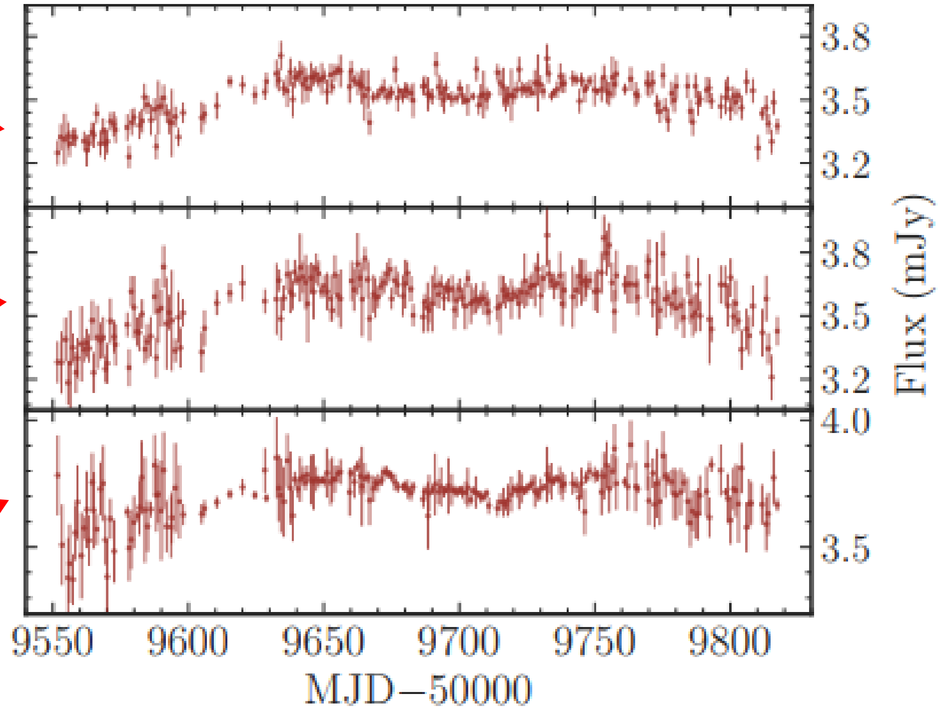
Intensive Swift and LCO Monitoring of PG 1302–102: Active Galactic Nucleus Disk Reverberation Mapping of a Supermassive Black Hole Binary Candidate

Liu et al. (2024)



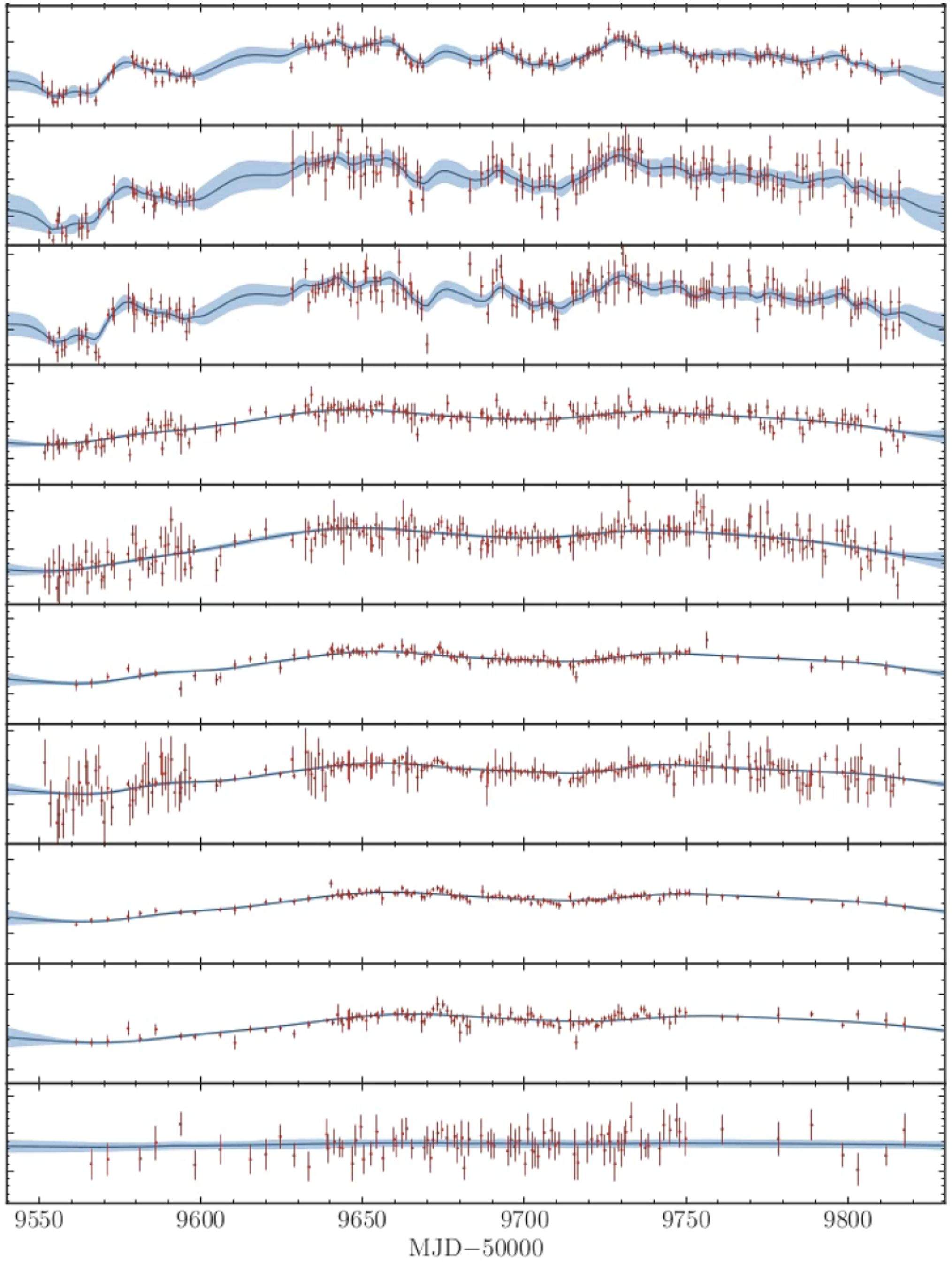
Light-curve combination





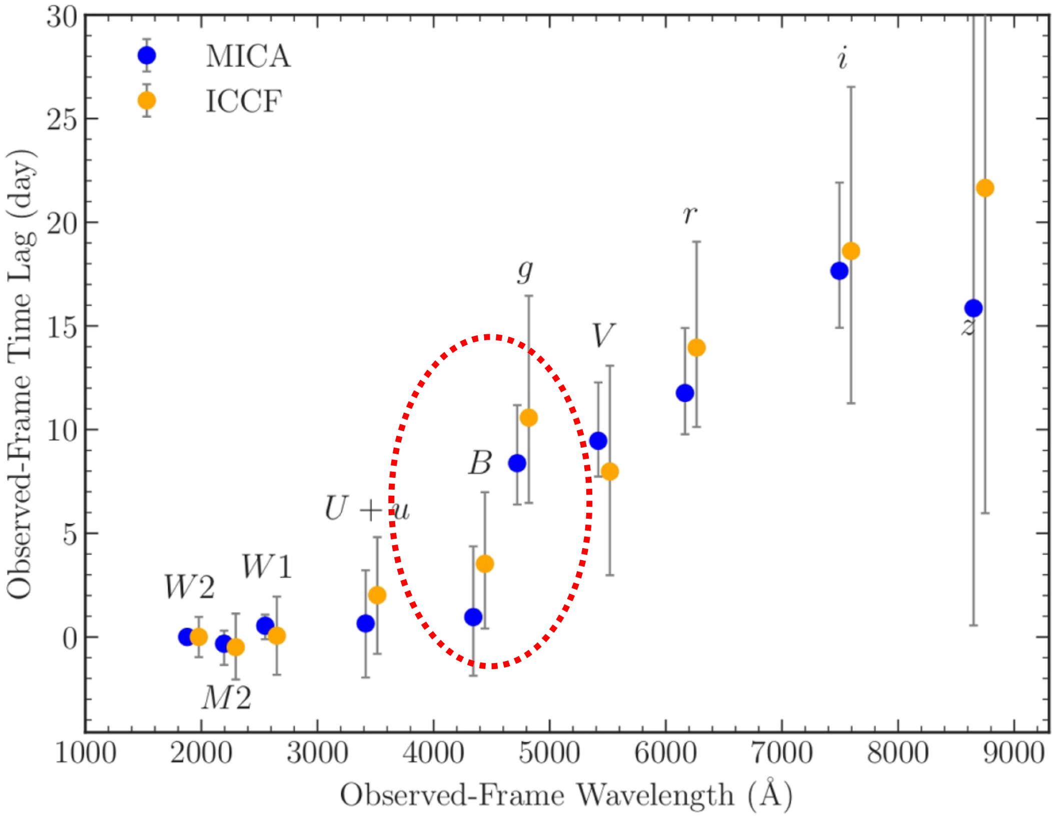
UV

optical

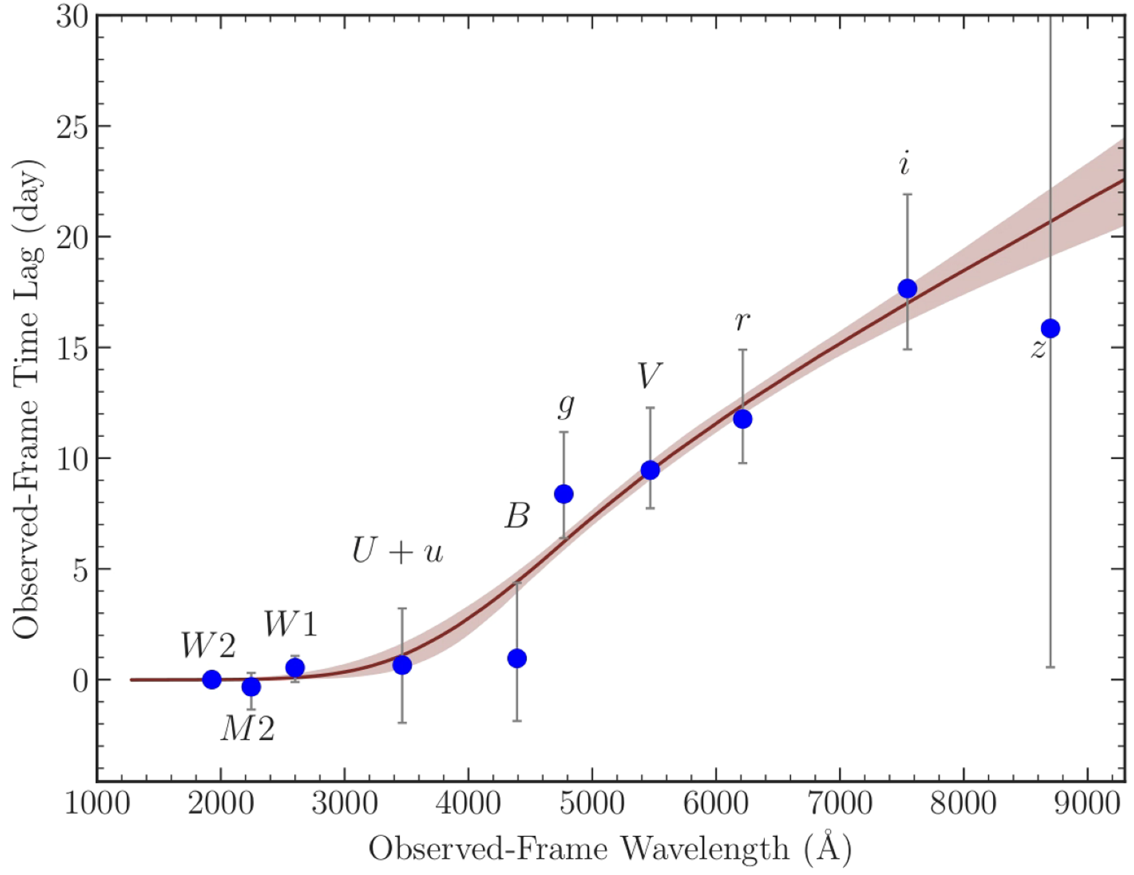


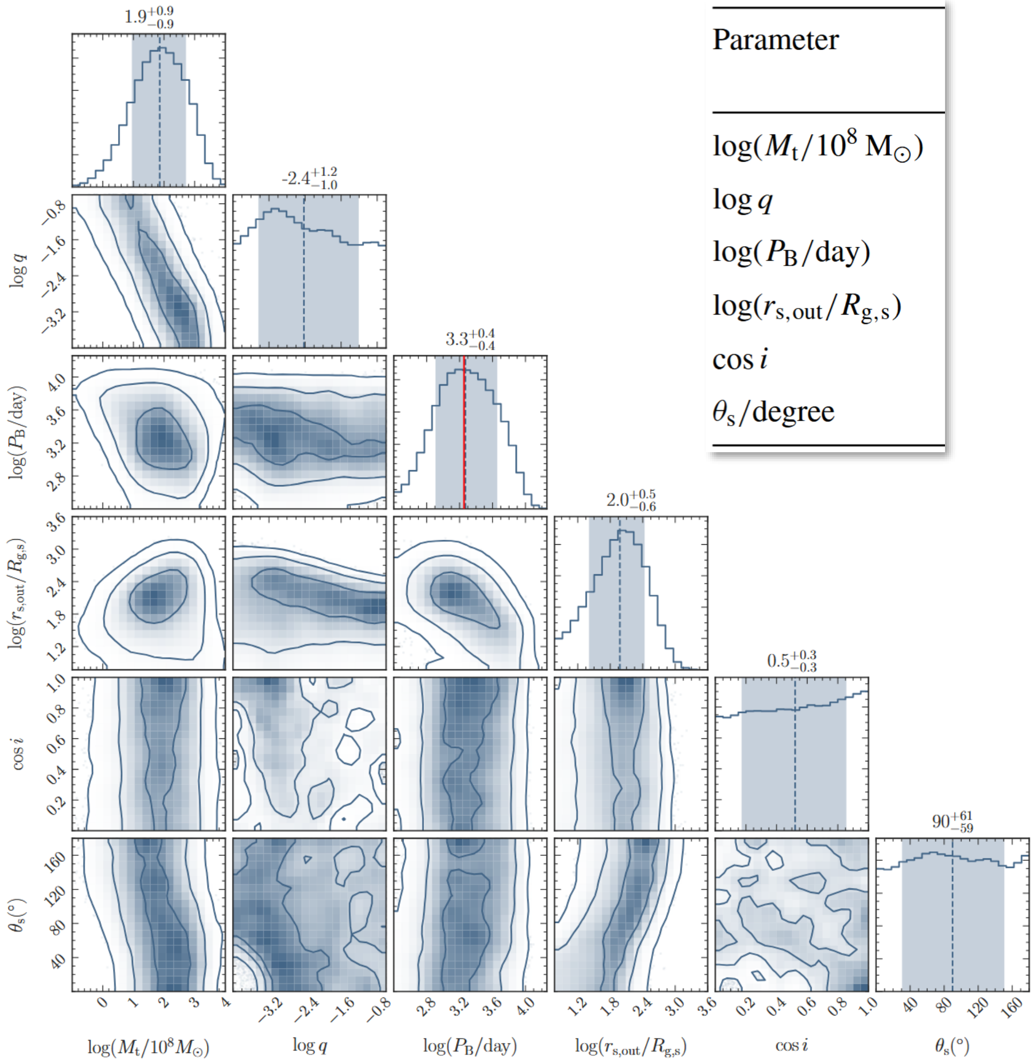
Time-lag measurement

- ICCF
- MICA (with a Gaussian transfer function)



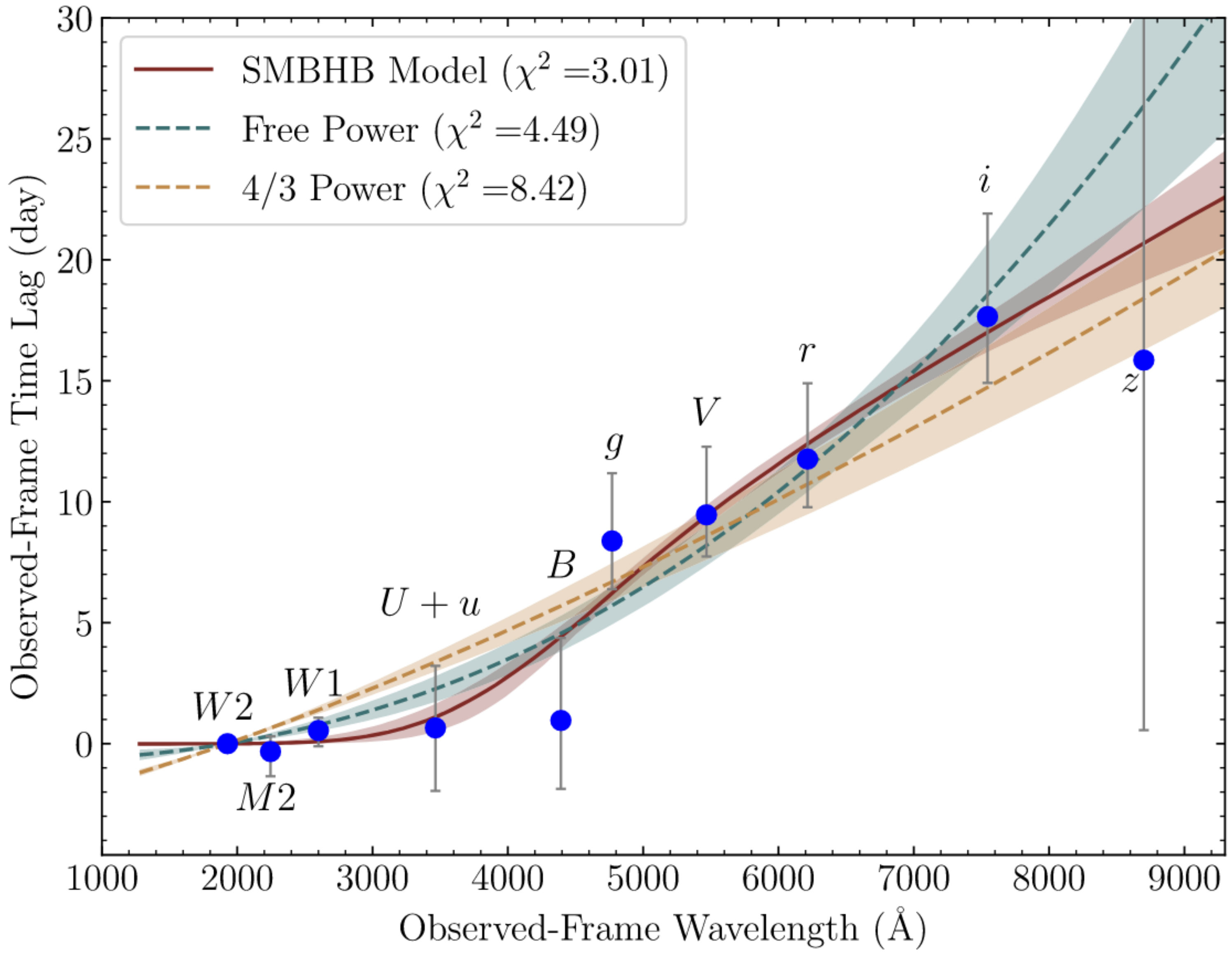
SMBHB model fits to time lag - wavelength relation





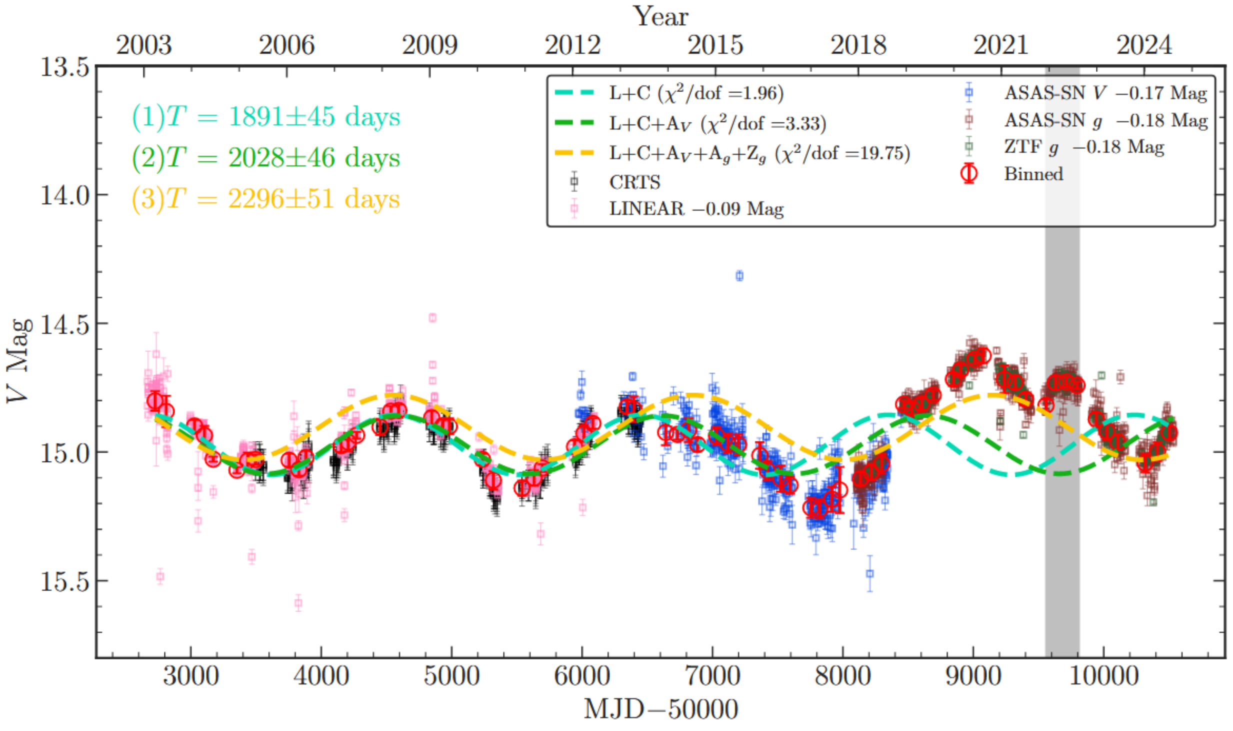
Parameter
$\log(M_t/10^8\ M_\odot)$
$\log q$
$\log(P_B/\mathrm{day})$
$\log(r_{s,out}/R_{g,s})$
$\cos i$
θ_s/degree

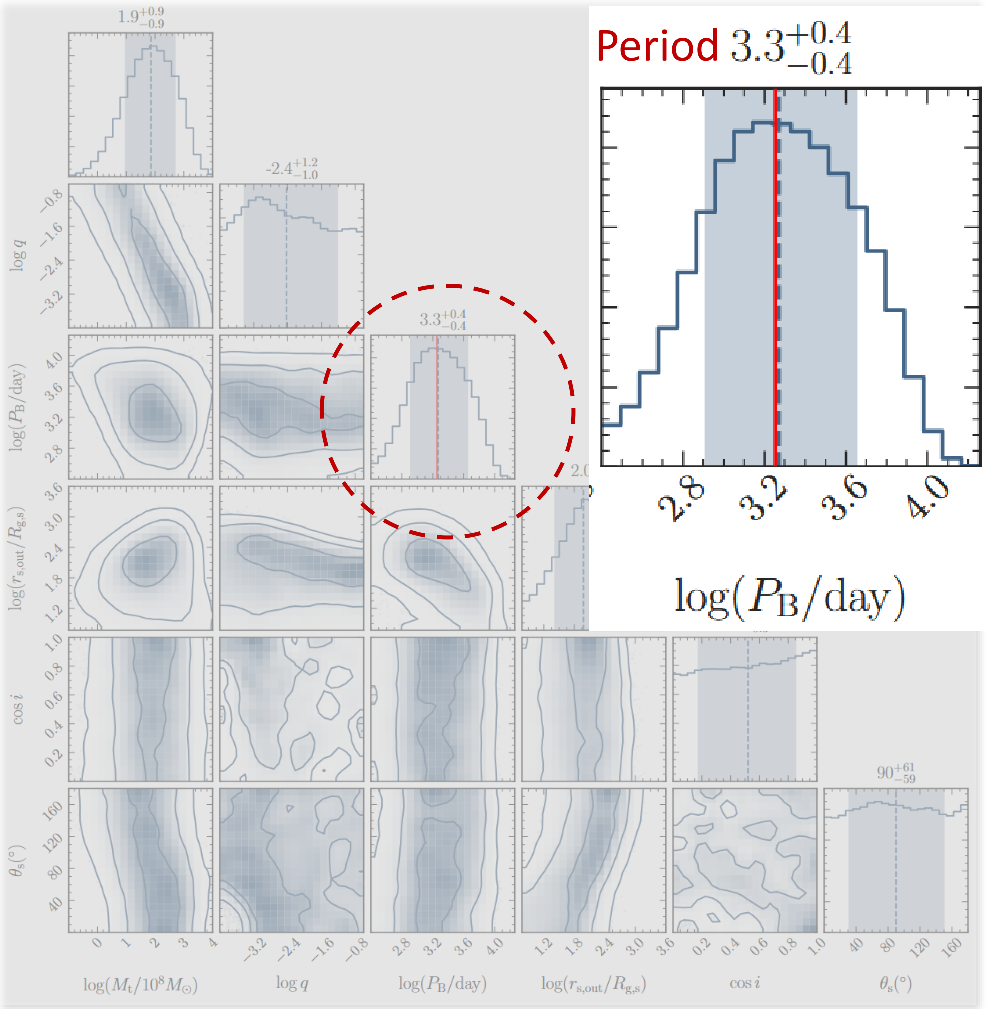
SMBHB model fits to time lag - wavelength relation



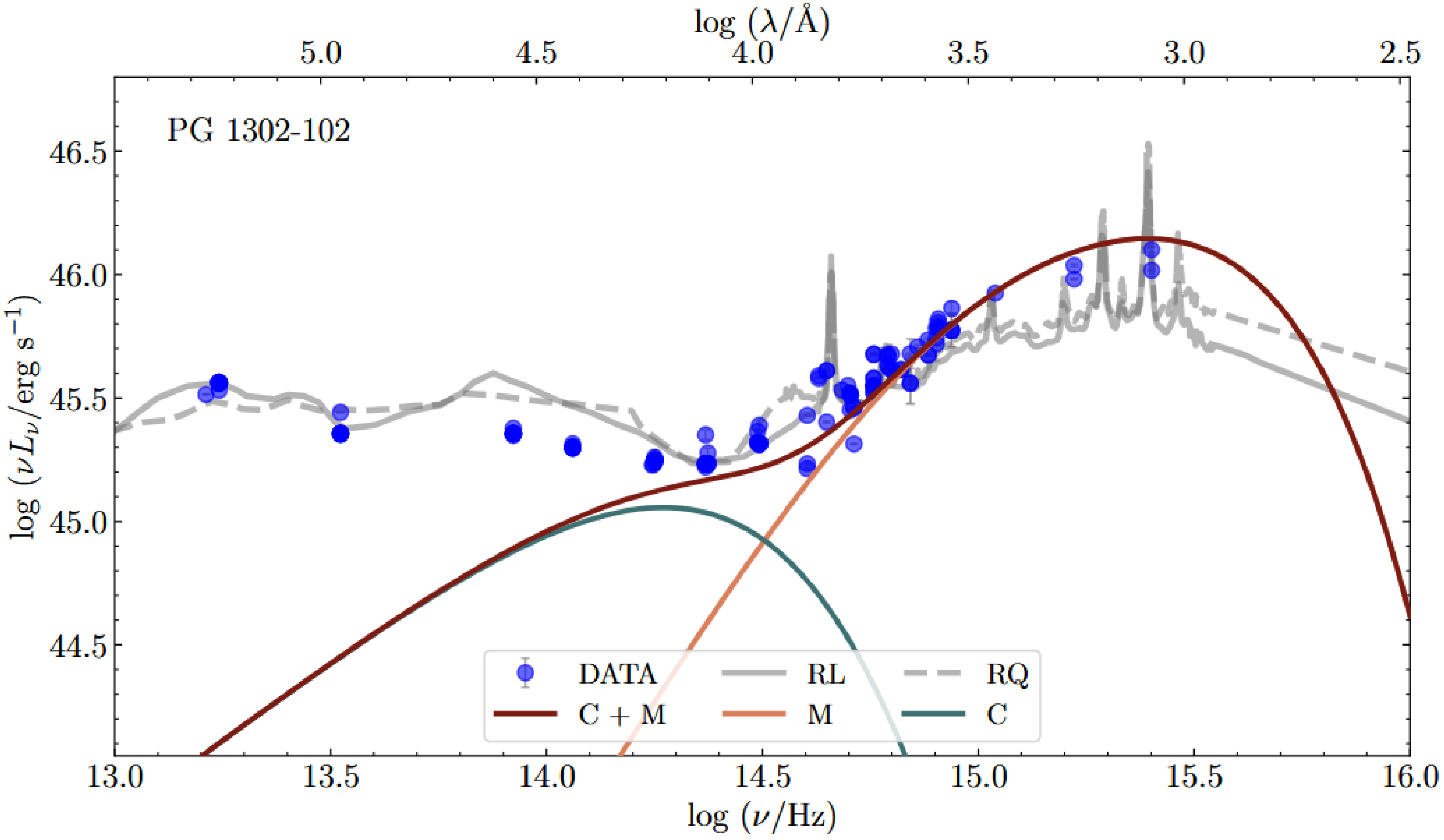
SMBHB model fits to time lag - wavelength reation

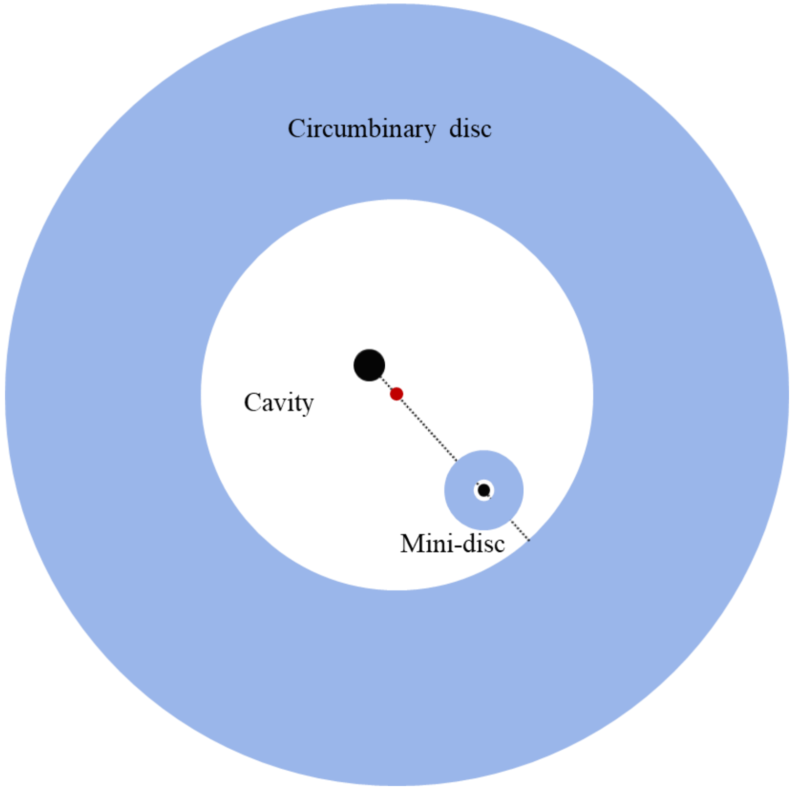
orbital period: $\log\left(\frac{P_B}{\mathrm{day}}\right) = 3.3 \pm 0.4$ (~2000 days)





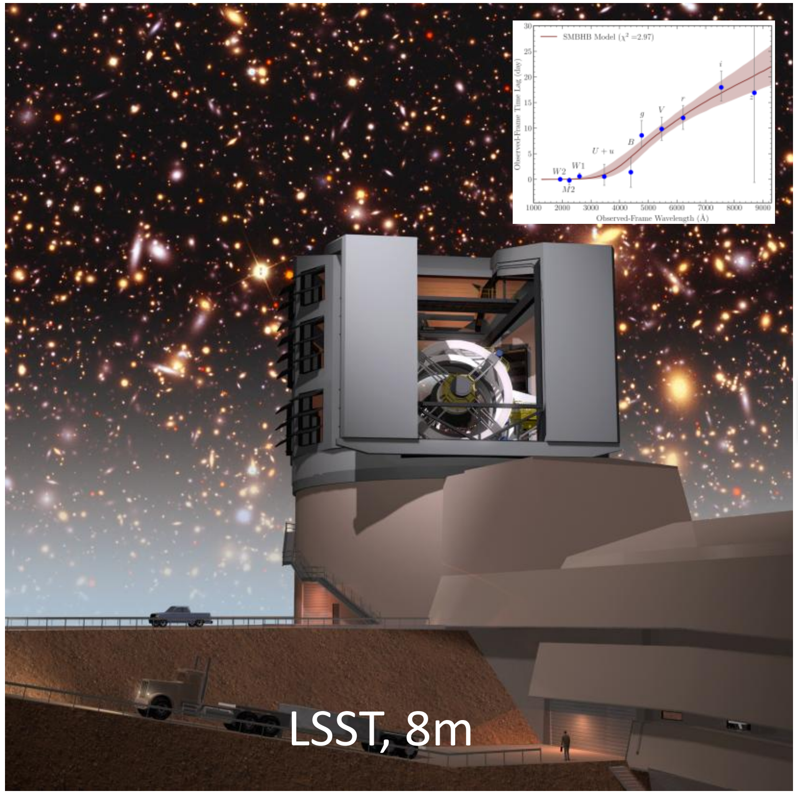
SMBHB model fits to time lag - wavelength relation



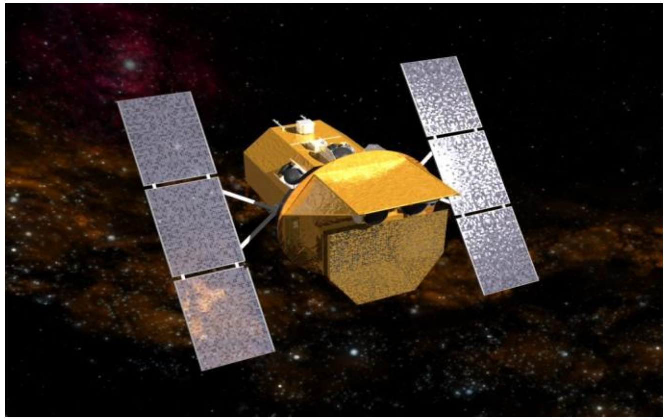


Future perspective

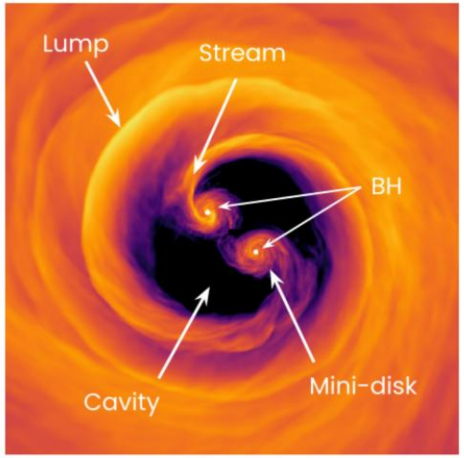
LSST 6 bands DDF: candidate sample

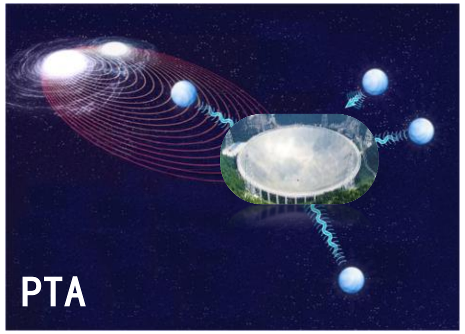


Dedicated observations



Synergy with PTA

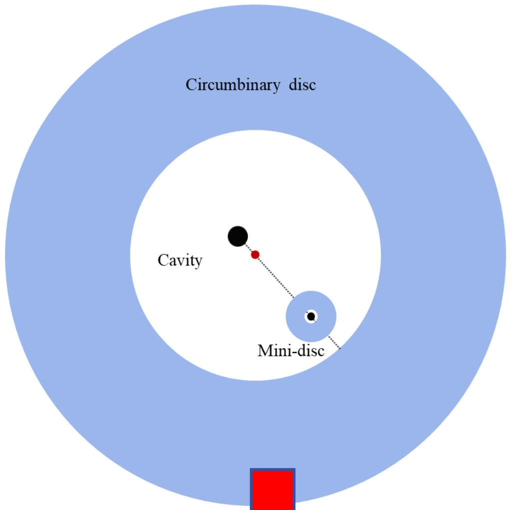




Summary

- A new method for identifying SMBHBs: continuum reverberation mapping
- Application to PG 1302-102
- Future improvements:

  Continuum RM signature when both BHs are active.



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Continuum reverberation mapping of accretion discs surrounding supermassive black hole binaries: observational signatures

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