

# EM Counterparts for GW sources in Active Galactic Nuclei in the Era of Time-domain Astronomy

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# Outline

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- **Background:** SMBHs, AGNs, TDEs and Time-domain
- **AGN Flares:** occasional or (quasi-)periodic
- **SMBH binary:** our recent work on J1430+2303, SMBHB TDE
- **Summary**

# Supermassive Black Holes (SMBHs)



III. Niklas Elmehed. © Nobel Media.  
Roger Penrose  
Prize share: 1/2



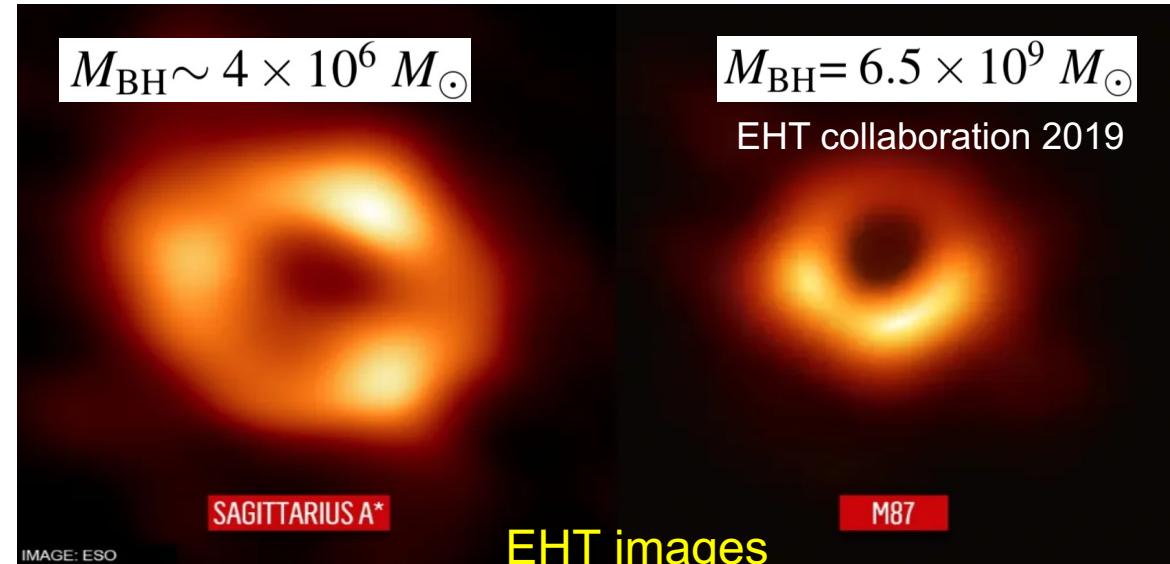
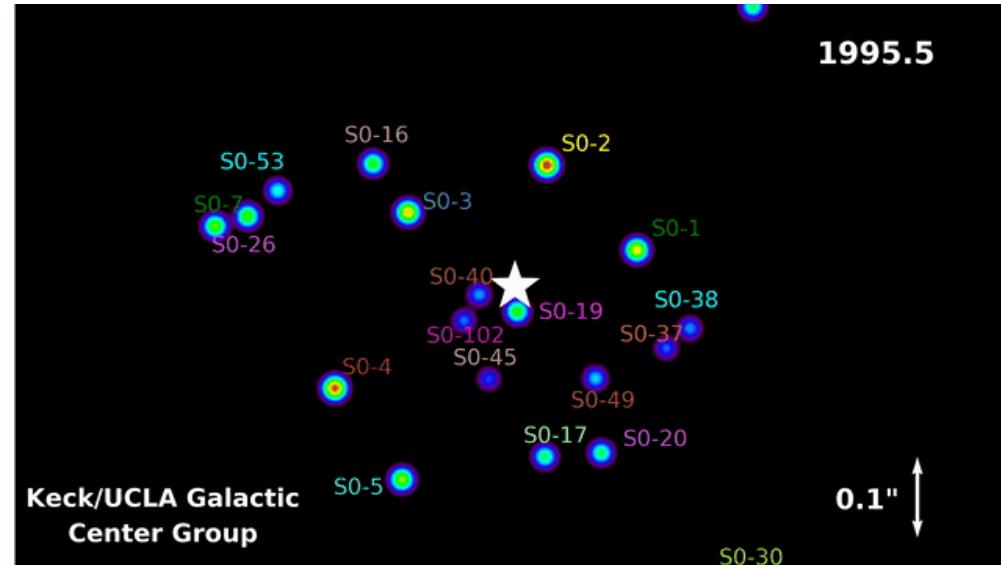
III. Niklas Elmehed. © Nobel Media.  
Reinhard Genzel  
Prize share: 1/4



III. Niklas Elmehed. © Nobel Media.  
Andrea Ghez  
Prize share: 1/4

The Nobel Prize in Physics 2020 was divided, one half awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy."

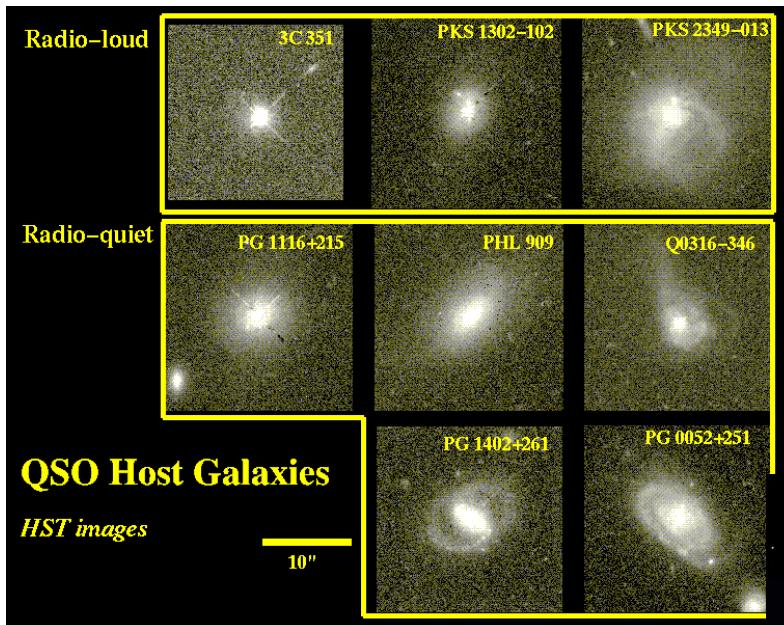
SMBHs are ubiquitous in the centers of massive galaxies



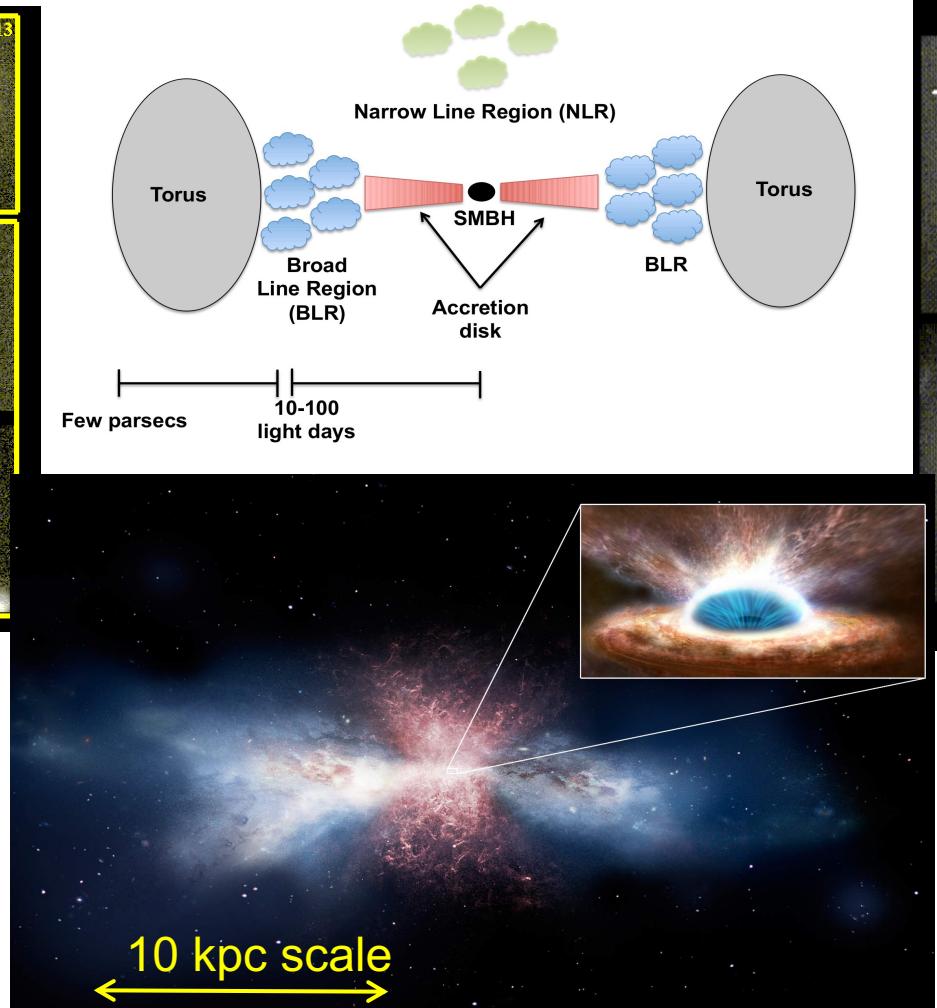
# Active Galactic Nuclei (AGN): accreting SMBH

Bachall+1997

Quasar

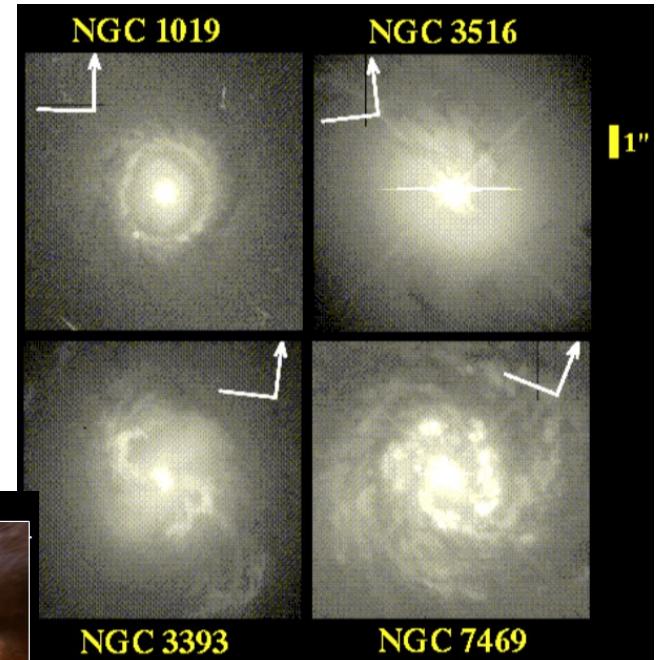


higher luminosity



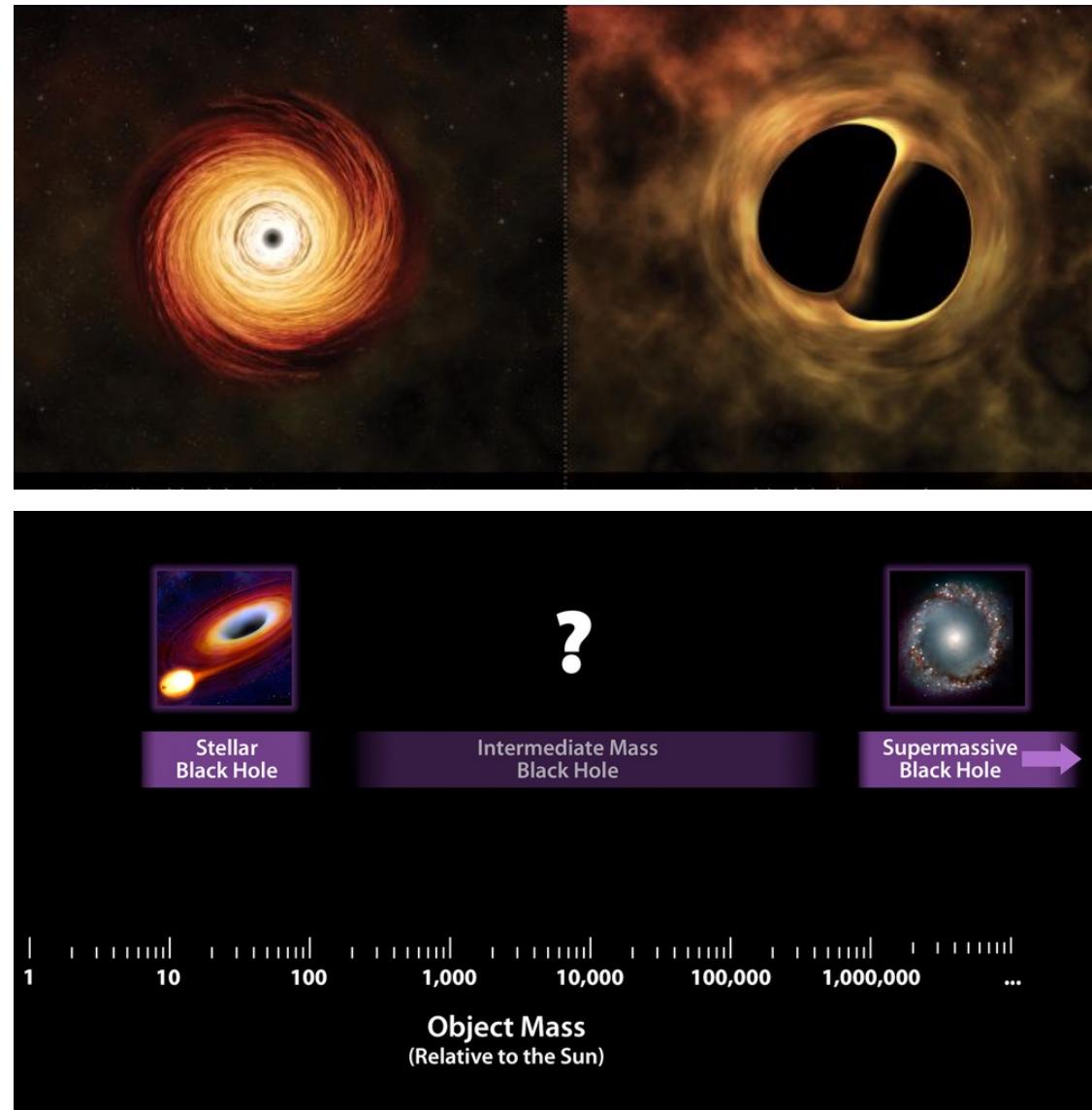
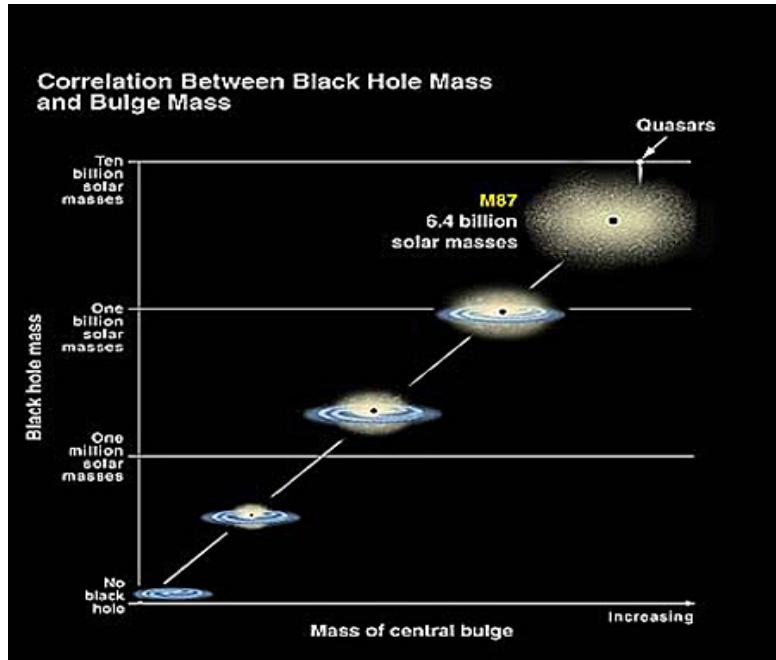
Malkan+1998

Seyfert Galaxies



# How do SMBHs form and grow?

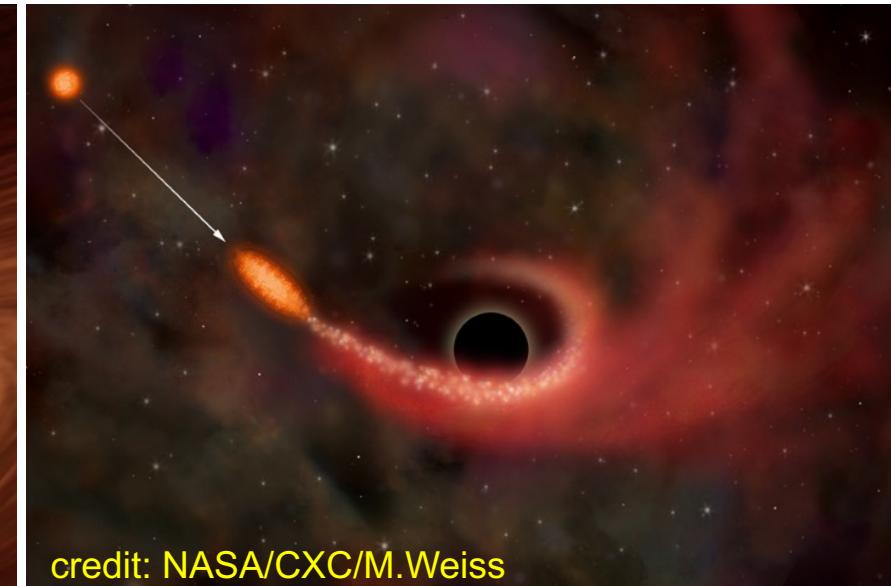
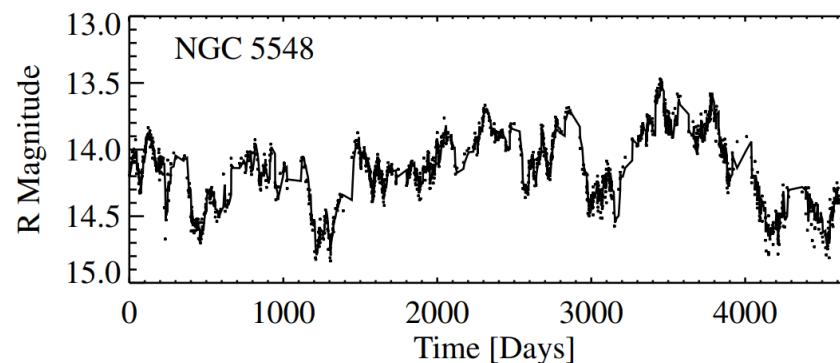
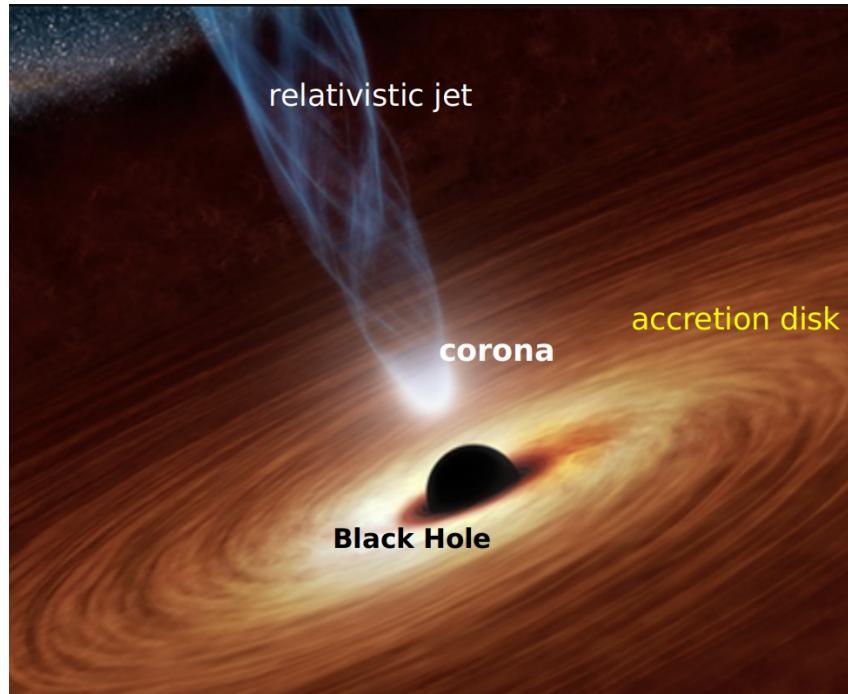
- SMBHs must grow from smaller seeds via accretion/merger, but how?
- Do IMBHs exist and serve as SMBH seeds?
- What drives the coevolution of SMBHs and their host galaxies?



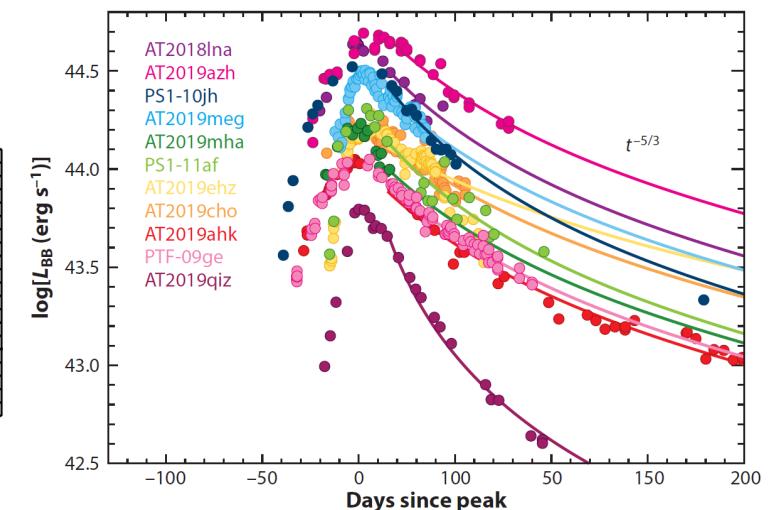
# SMBHs beyond local universe: AGN and TDE

- **AGN:** persistent, relatively steady gas accretion
- **TDE:** transient and rare accretion of disrupted stellar material

**variability study** becomes one of the most powerful approach to study SMBH in the golden time-domain era

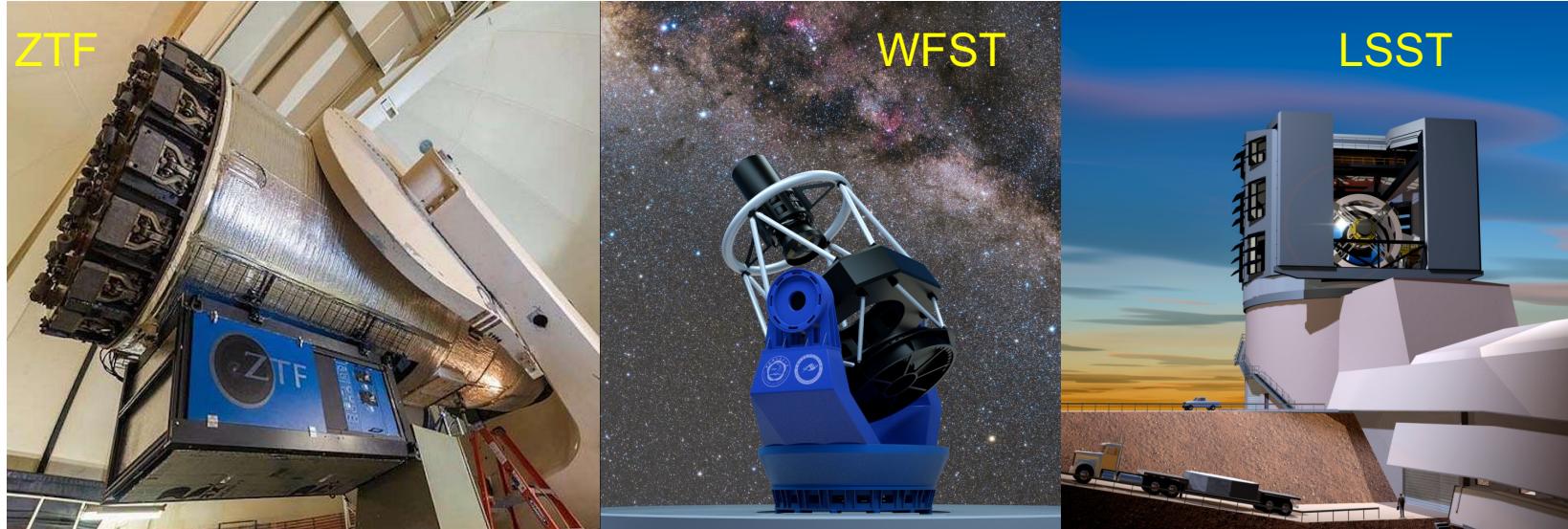
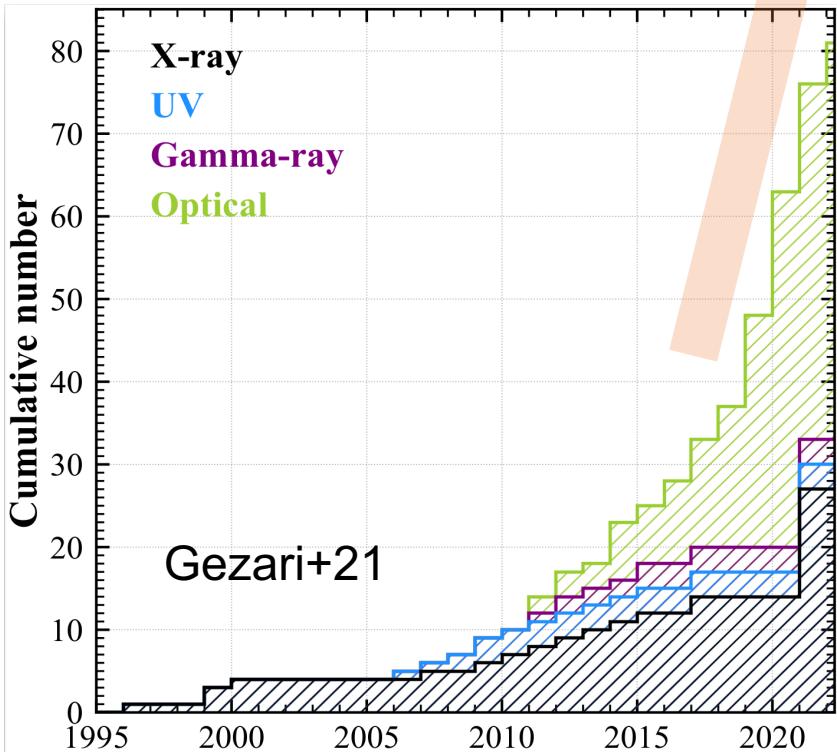


credit: NASA/CXC/M.Weiss



# 2020s as a golden optical time-domain era

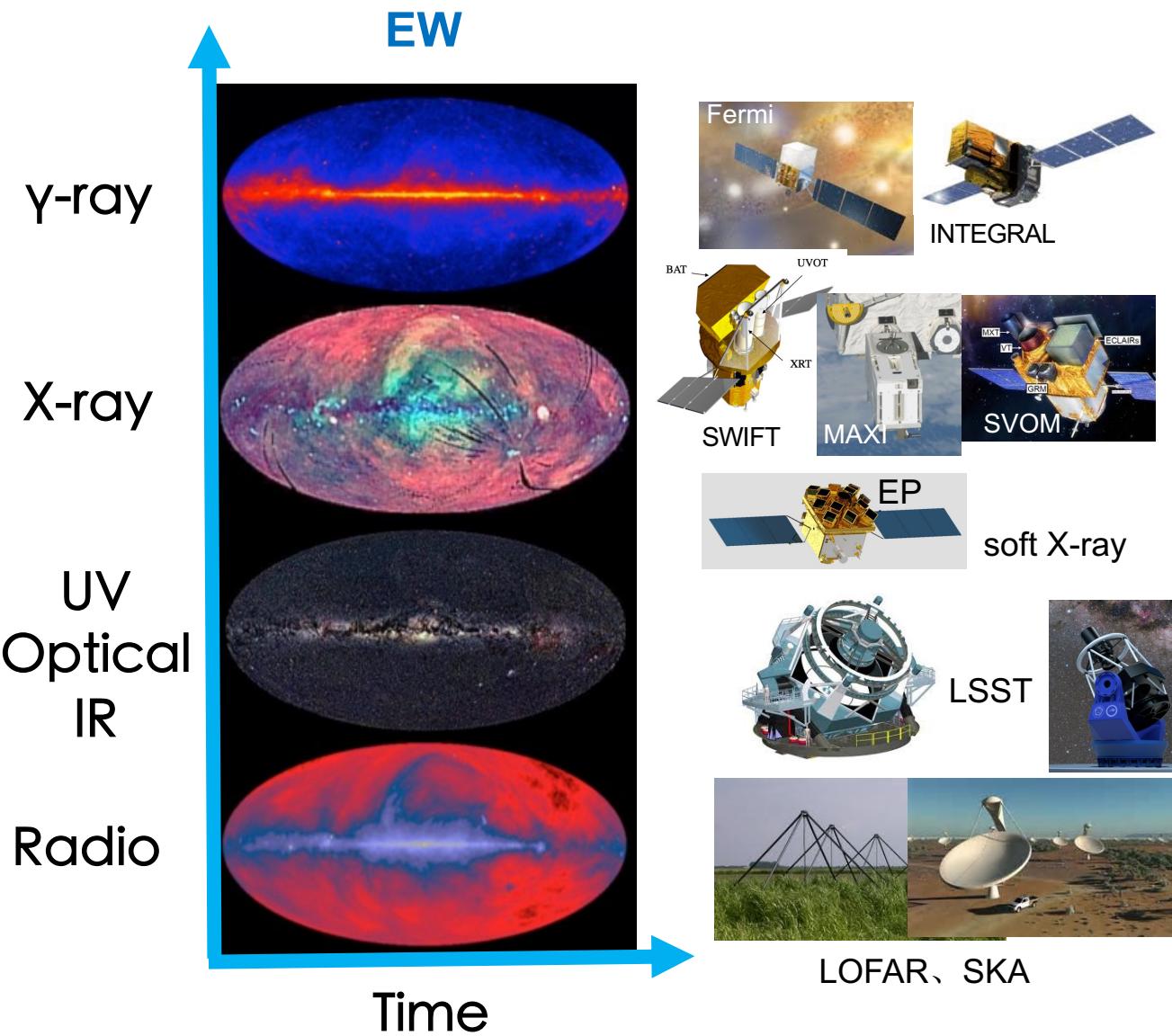
TDE number grows rapidly in the past decade, particularly since ZTF (2018-)



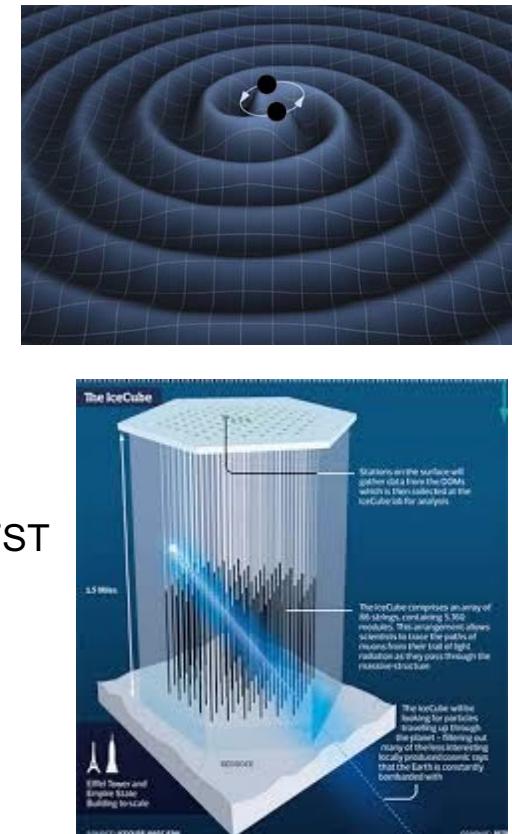
Survey	D	FOV	filter	mag	TDE	Time
ZTF	1.2	47	g,r	20.5	15/yr	2018-
WFST	2.5	6.55	ugriz	23.0	100/yr	2023-
LSST	8.4	9.6	ugrizy	24.7	1000/yr	2024-

Wide-field, fast, deep surveys

# 2020s-: not only time-domain but also a **multi-messenger** Era

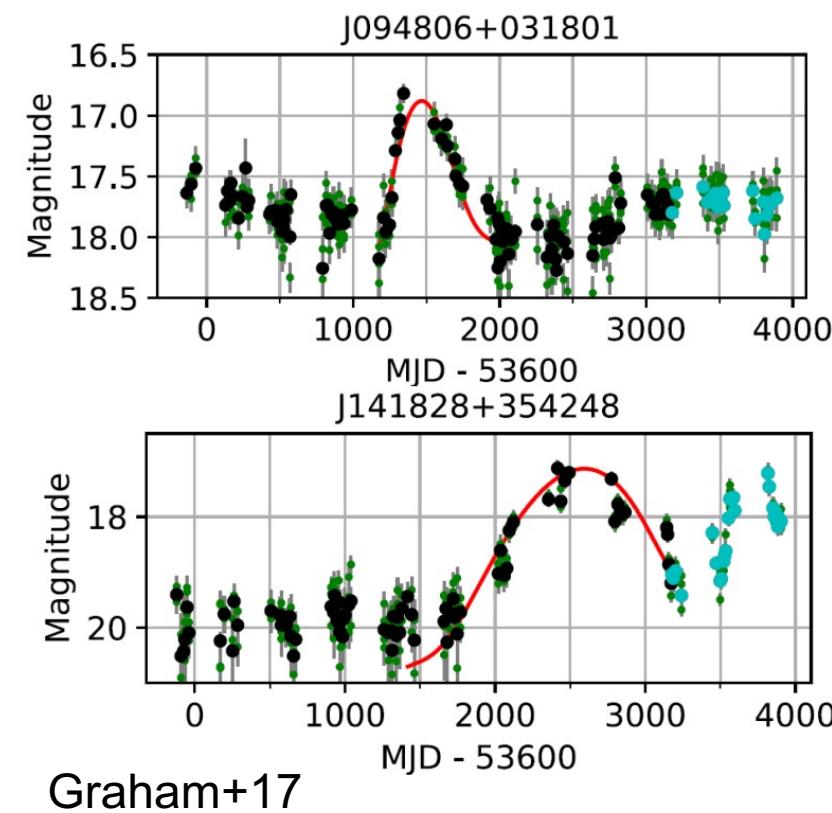
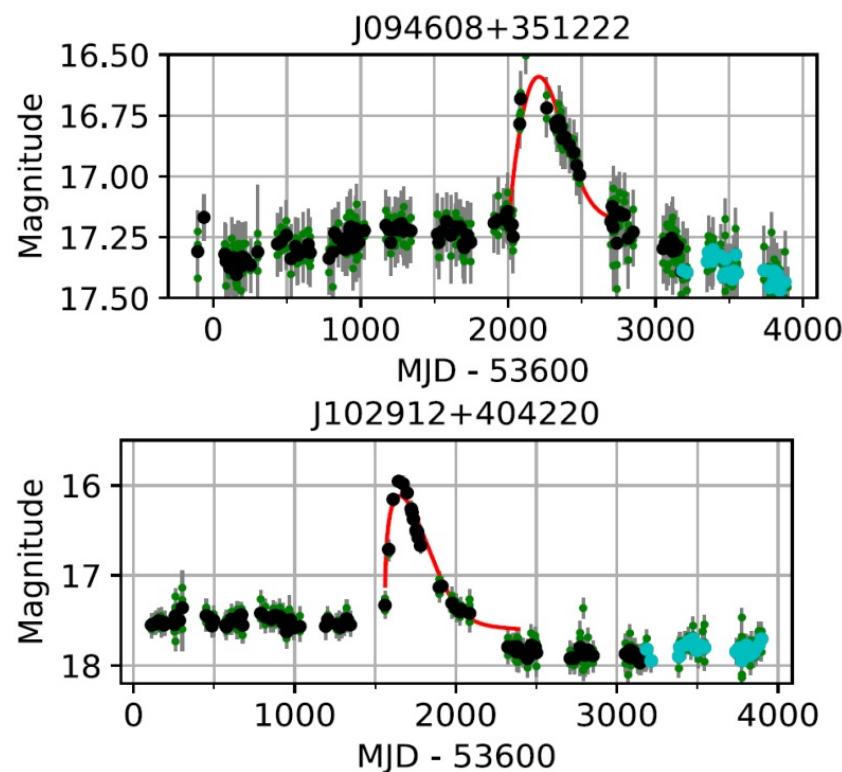


**multi-messenger**  
GW and Neutrino



# Diverse flares in AGNs: challenge standard accretion disk

- accretion disk instability
- sporadic gas accretion
- TDE in AGN
- nuclear supernova
- stellar-mass BH binary merger in accretion disk



EW signal (photometric and spectral) is insufficient for diagnosis, leading to **Ambiguous Nuclear Transient** (ANT; e.g., Hinkle+21, Holoiien+22)

# Diverse flares in AGNs: challenge standard accretion disk

PHYSICAL REVIEW LETTERS 124, 251102 (2020)

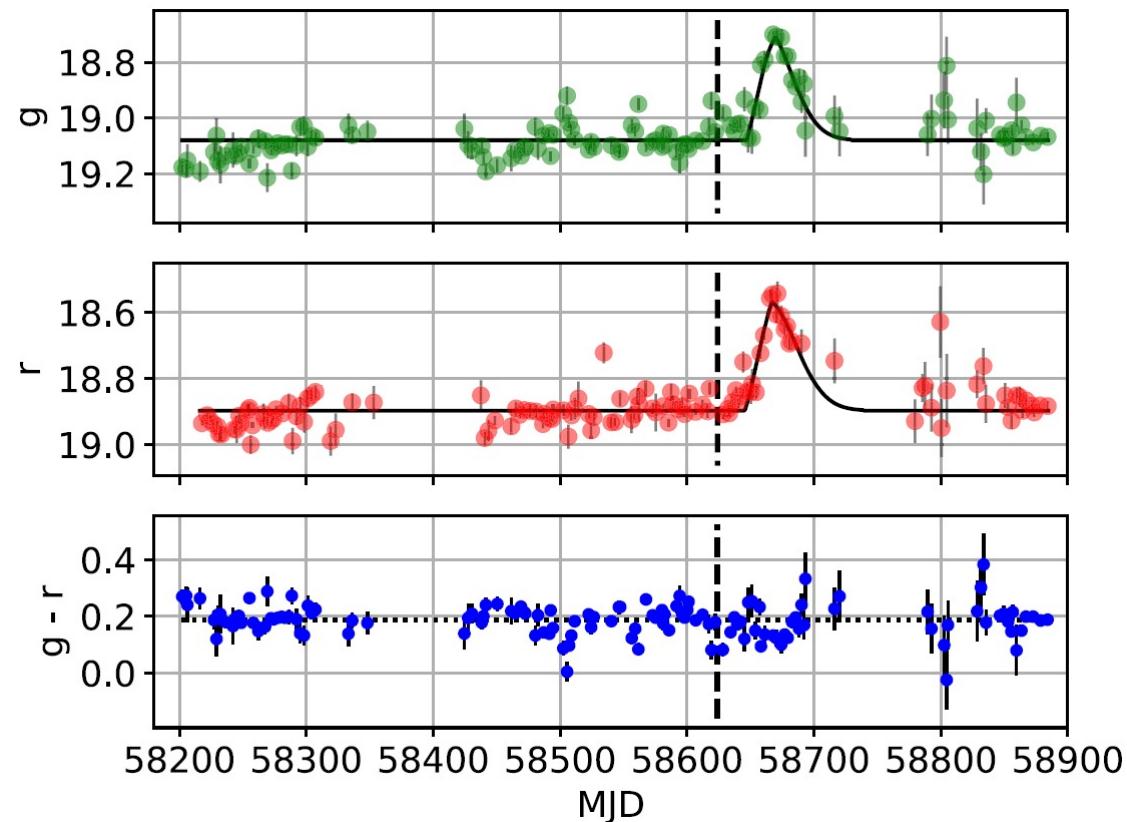
Editors' Suggestion

Featured in Physics

- accretion disk instability
- sporadic gas accretion
- TDE in AGN
- nuclear supernova
- stellar-mass BH binary merger in accretion disk

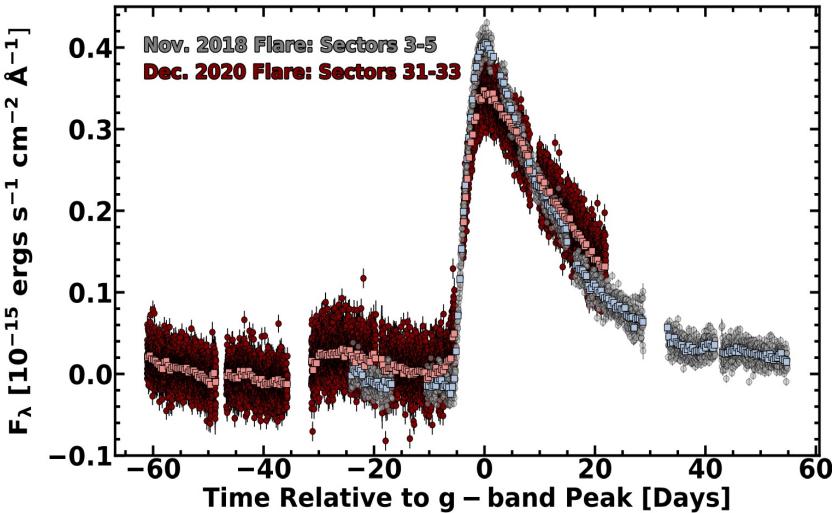
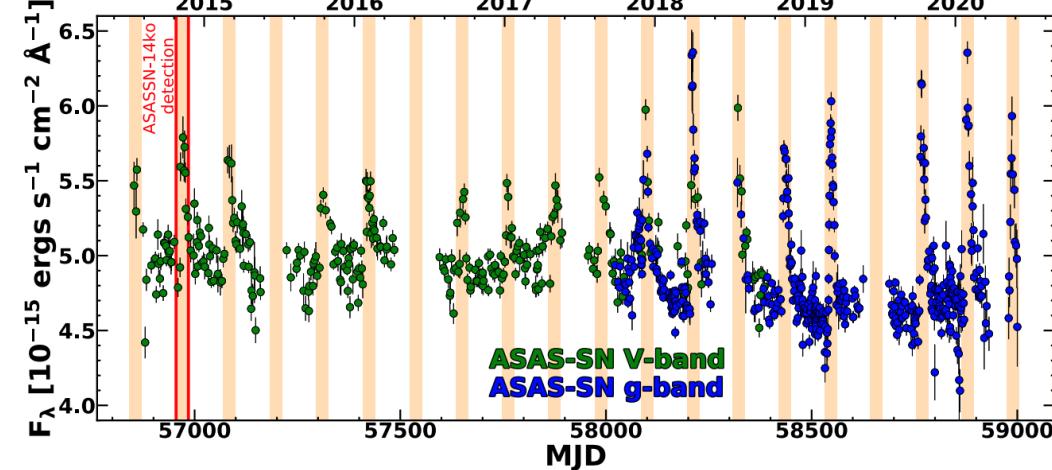
GW may helps!

Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g<sup>\*</sup>

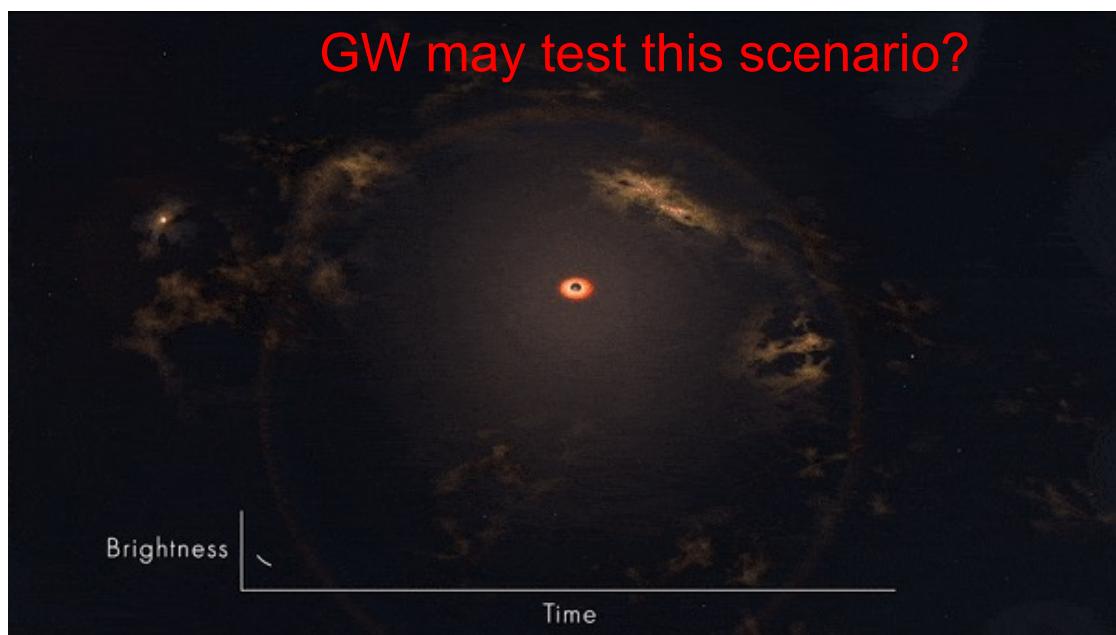
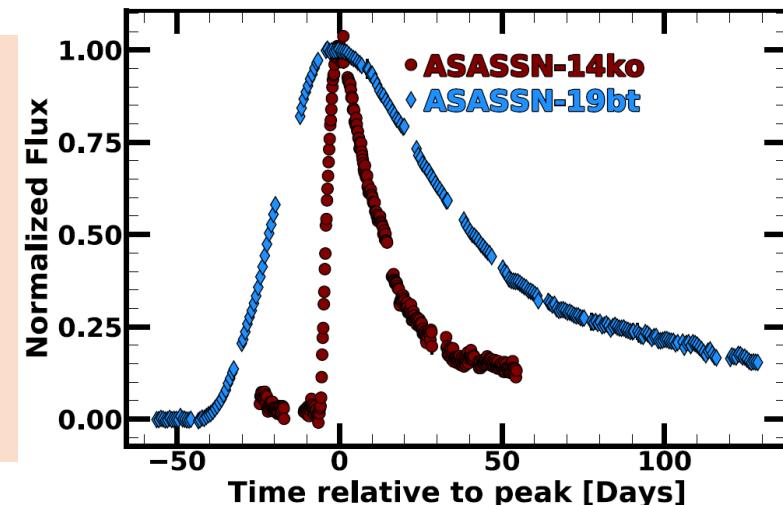


# Predictable recurring optical outburst: partial TDE?

**ASASSN-14ko** (Payne+21,22)

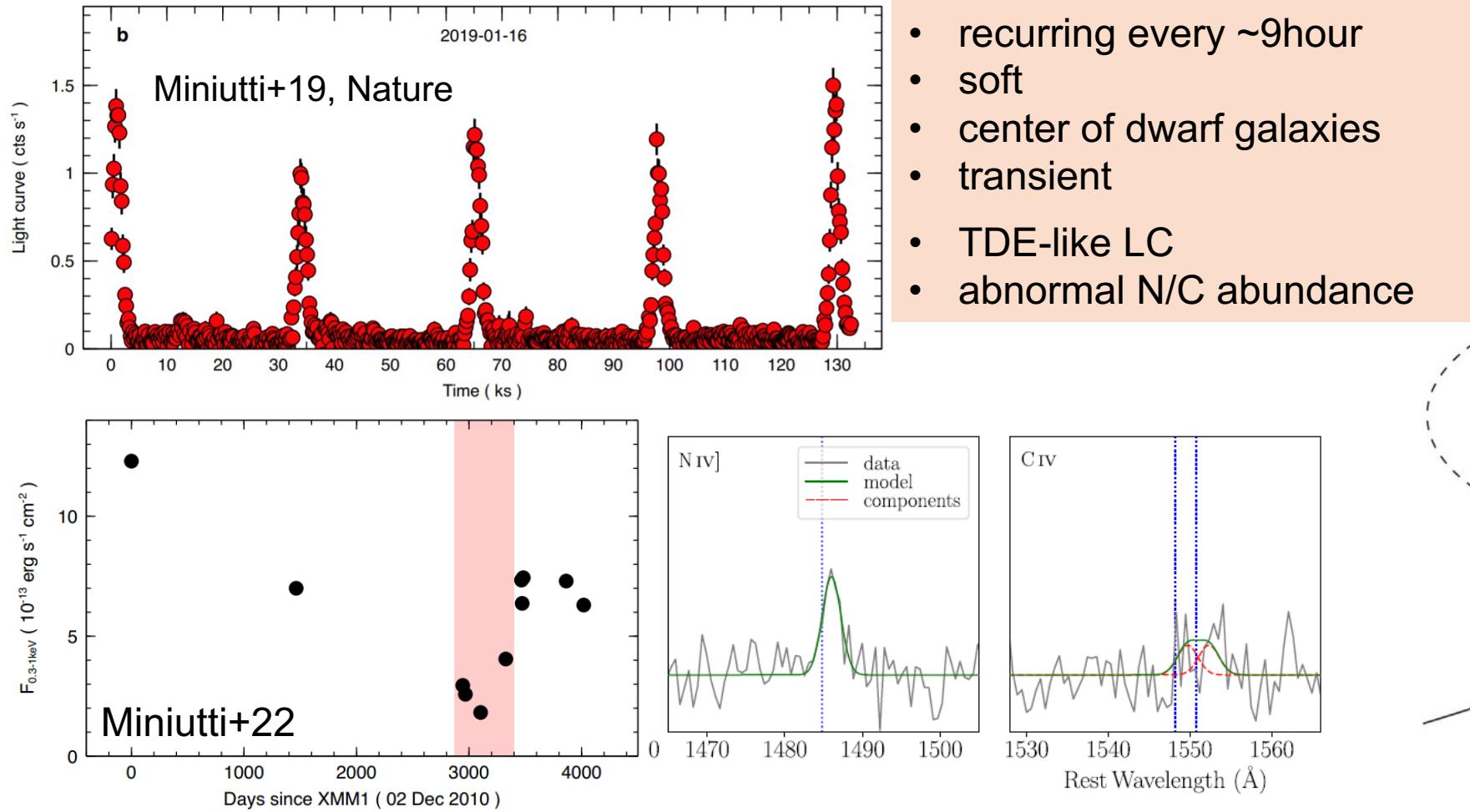


- $P_0 = 114.2 \pm 0.4$  days  
 $\dot{P} = -0.0017 \pm 0.0003$
- peak luminosity varies
  - LC shapes not identical
  - compressed TDE LC
  - Seyfert 2

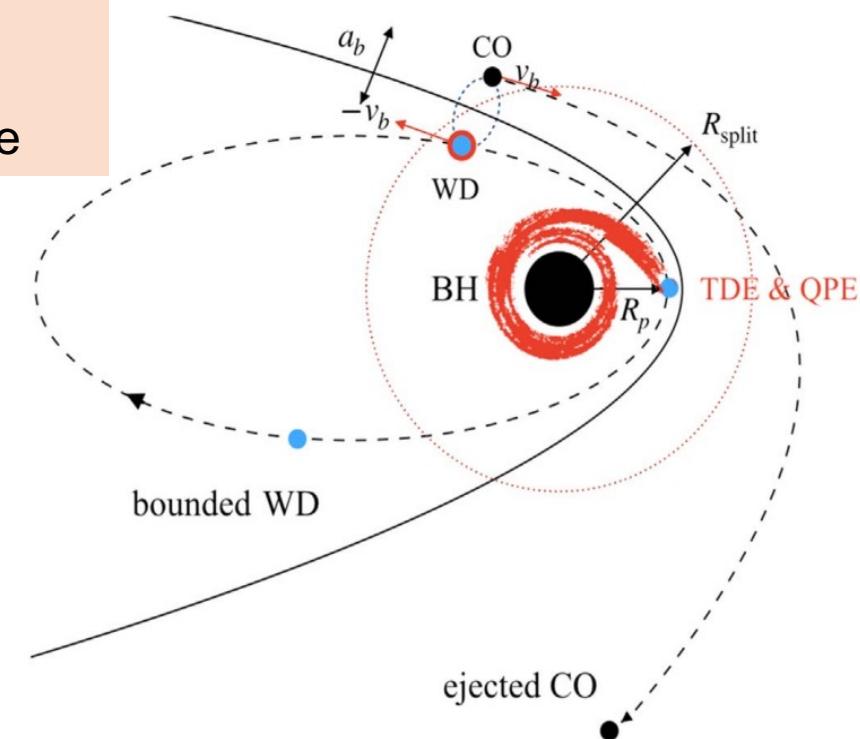


GW may test this scenario?

# X-ray quasi-periodic eruption (QPE): IMBH TDE?

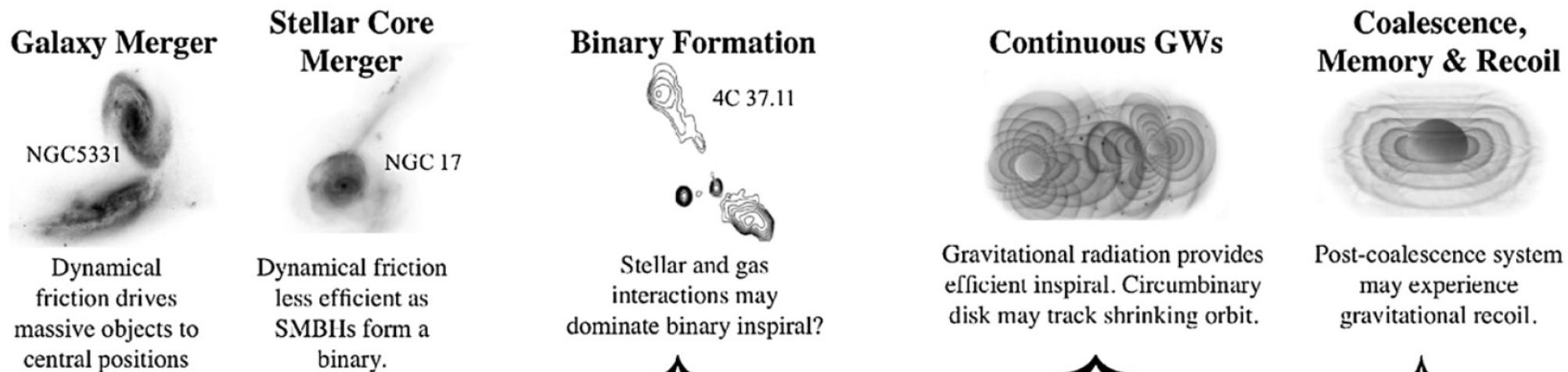


a plausible model:  
WD-IMBH EMRI system

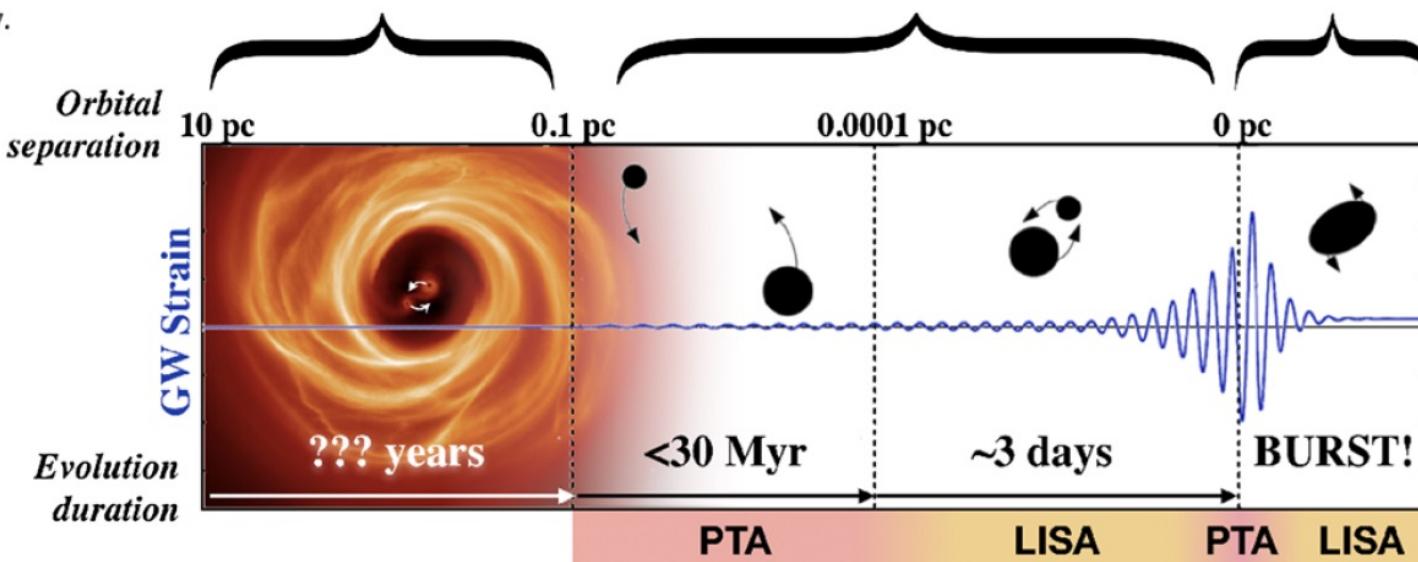


**Wang+22**

# SMBH binary



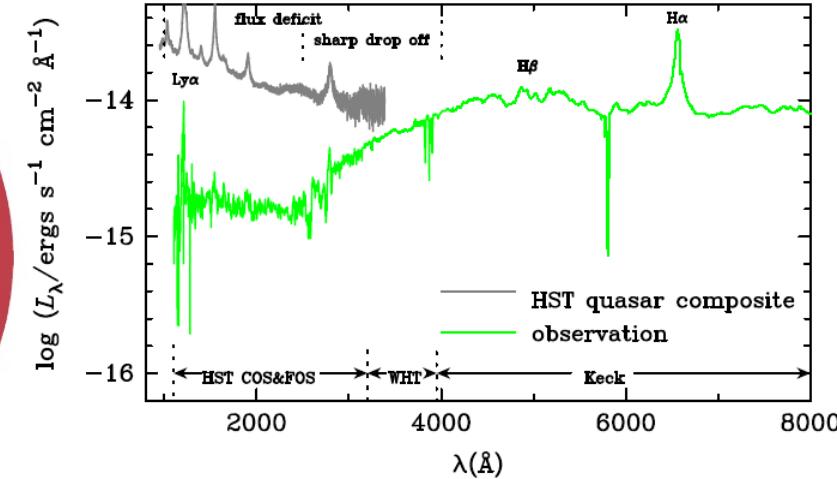
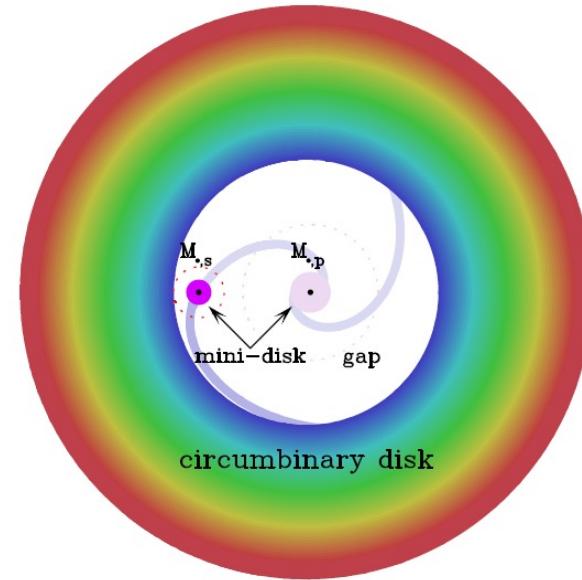
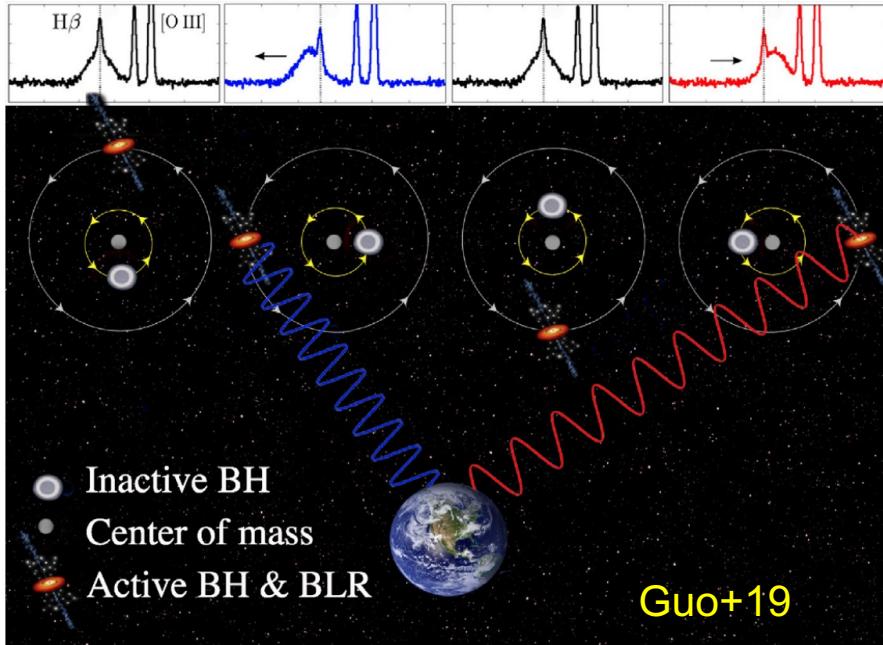
## The Lifecycle of Binary Supermassive Black Holes



spatially unresolvable (even VLBI)

# Indirect indicators of sub-pc SMBHB

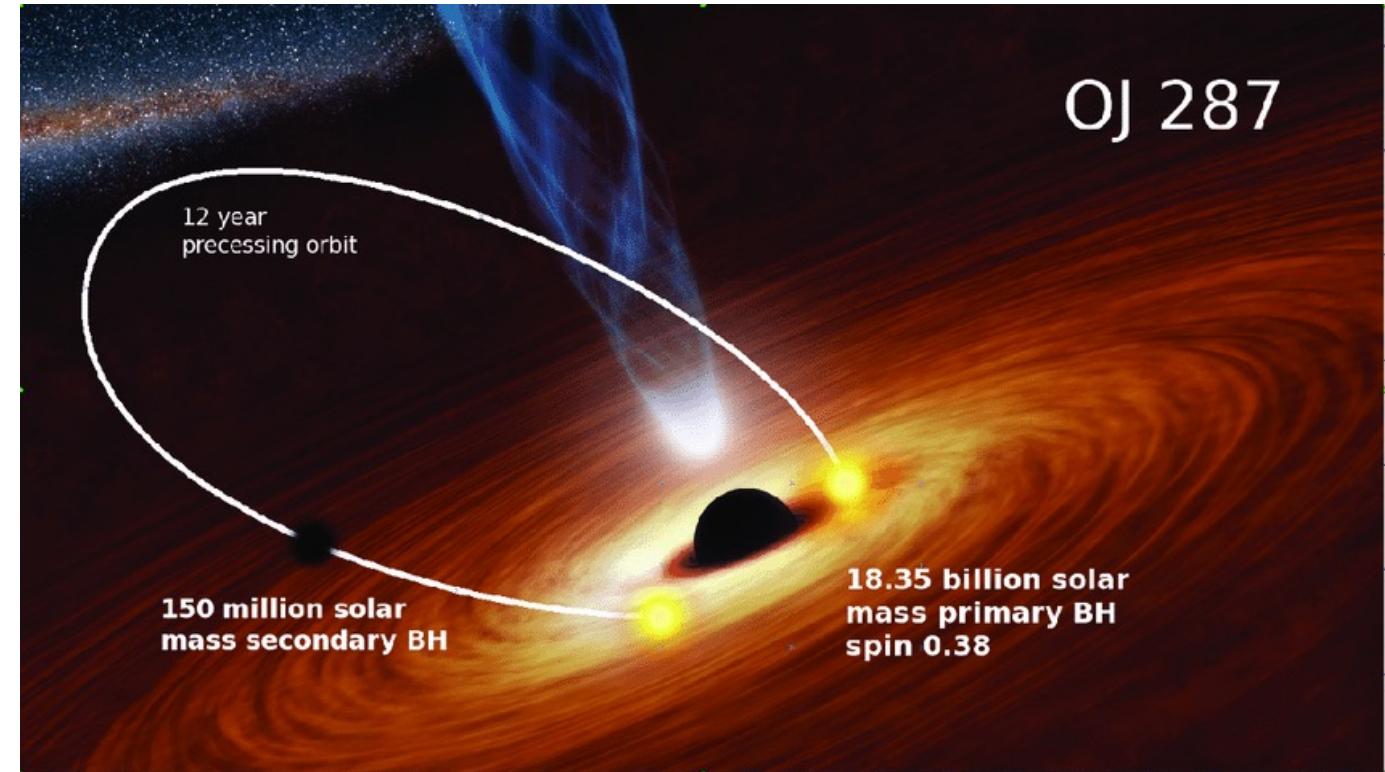
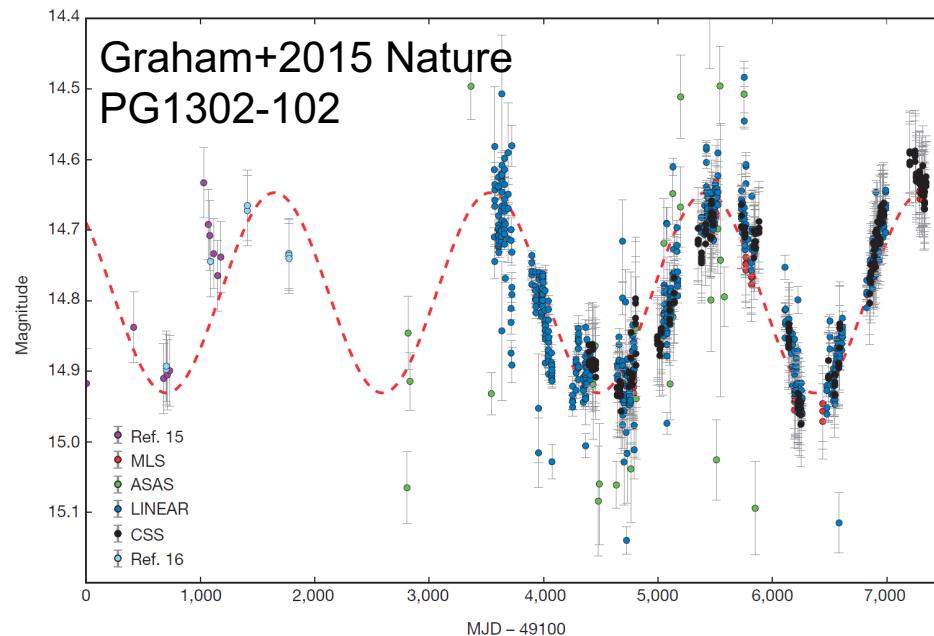
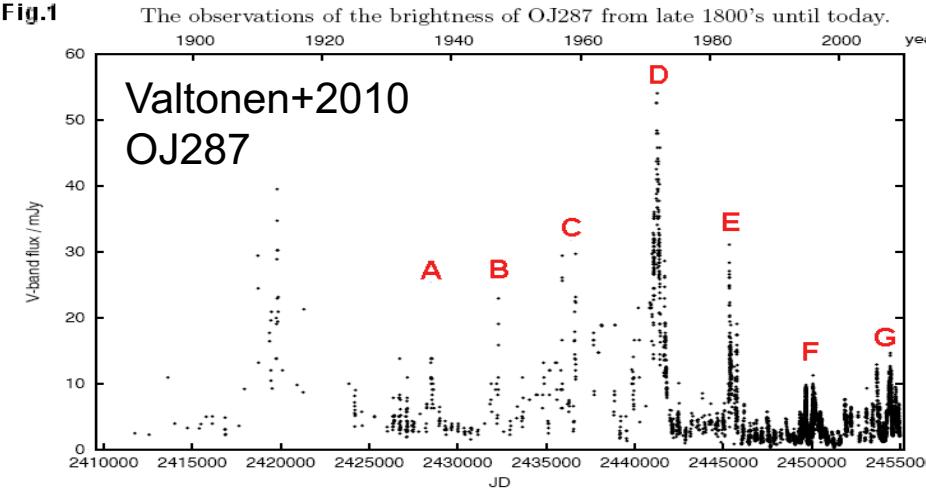
- Broad-line velocity shift
- deficits in the optical-to-UV continuum



many candidates, but no confirmed sub-pc SMBHB yet

# Periodicity as evidence for SMBH binary

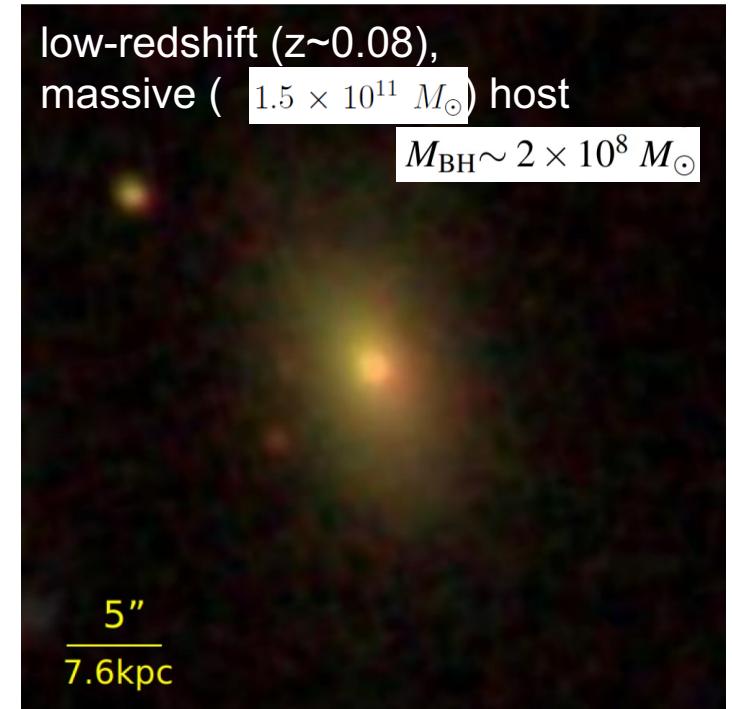
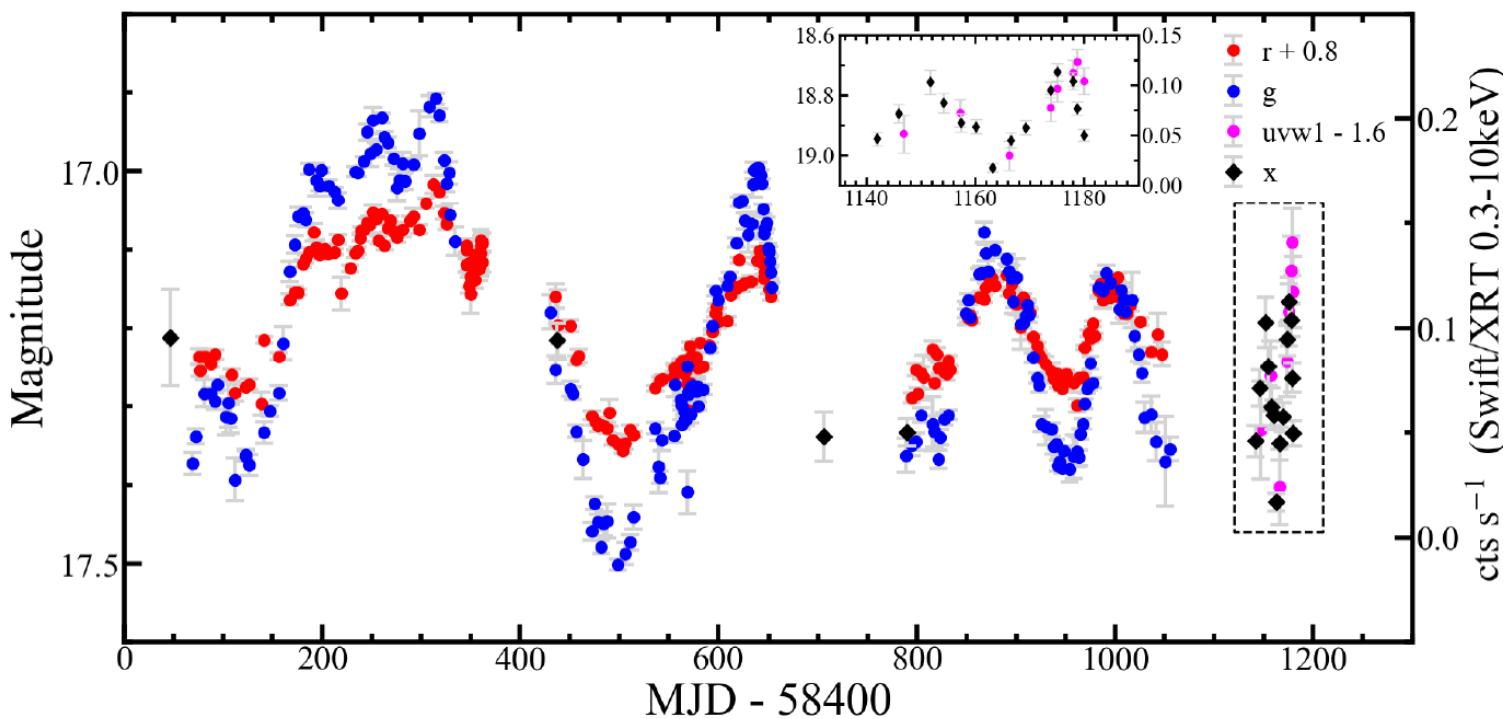
Fig.1



Graham2015b,Liu2016,Charisi2016,Zheng2016,Chen2020...

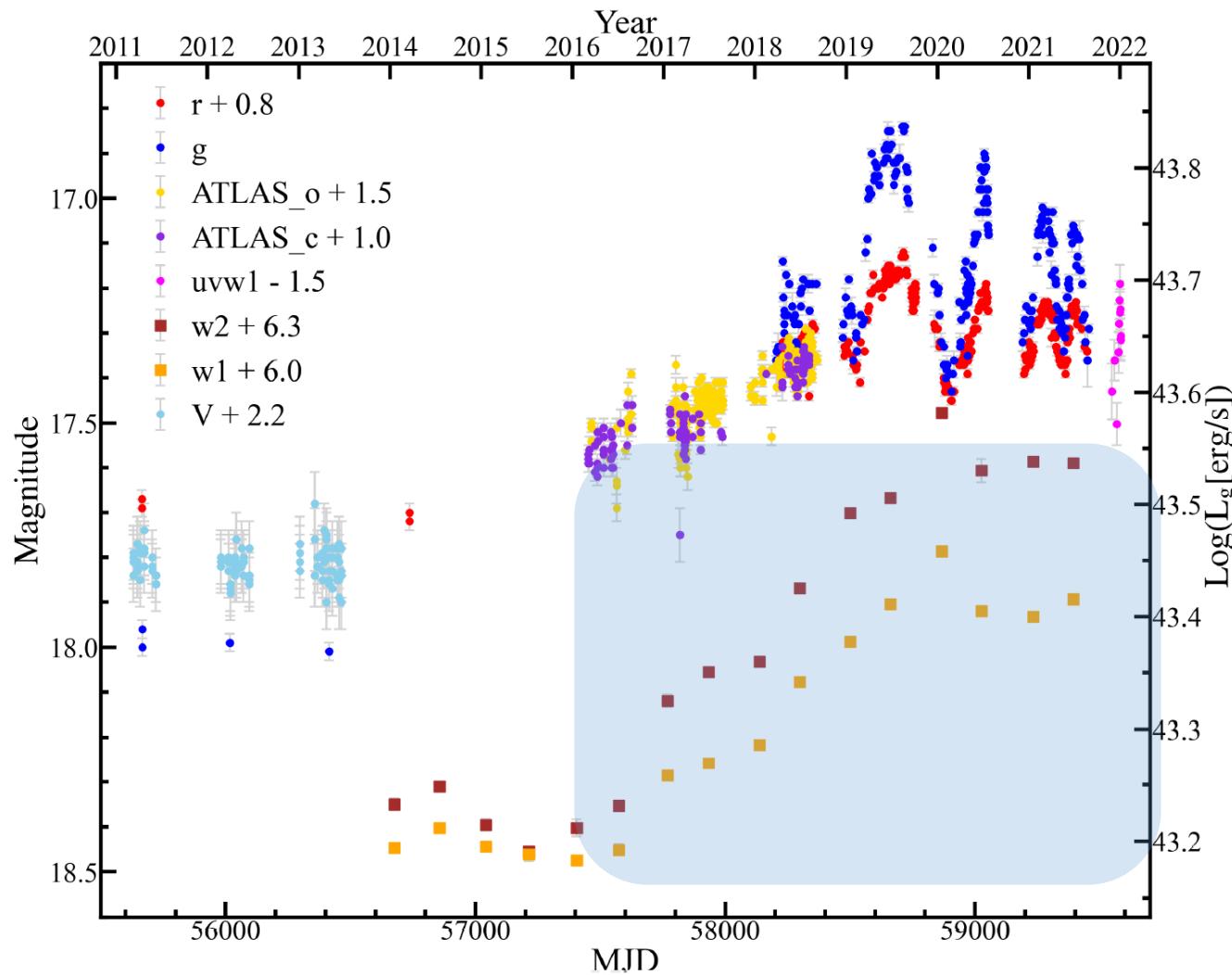
Still no candidates close to final coalescence with decreasing period

# Chirping flares in SDSSJ1430+2303

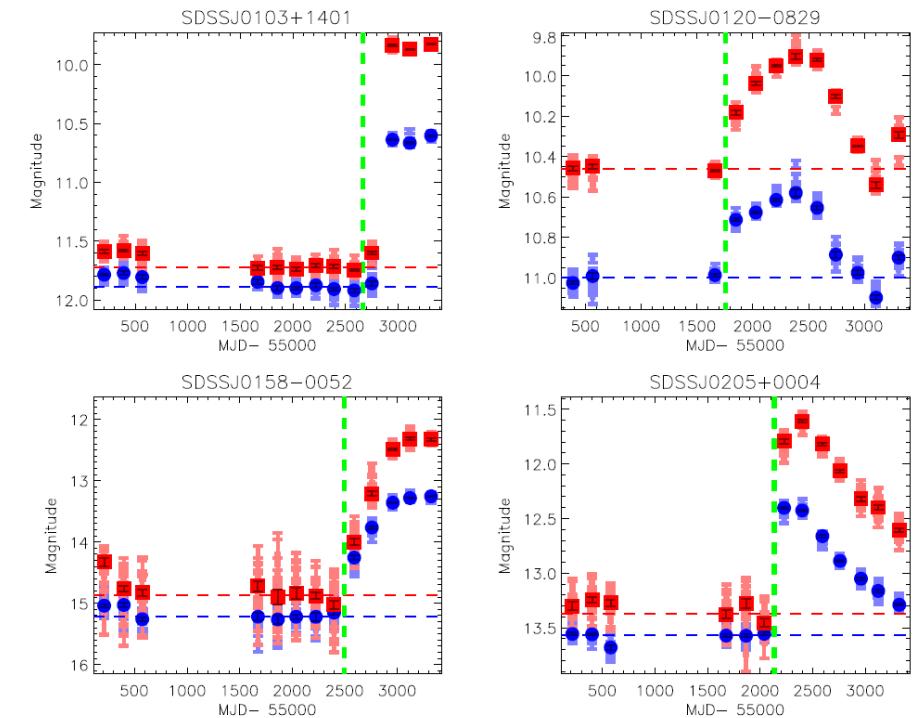


period decreasing from  $\sim 1$  yr to  $\sim 3$ (or 1) month within 3 years, a SMBH binary approaching merger?

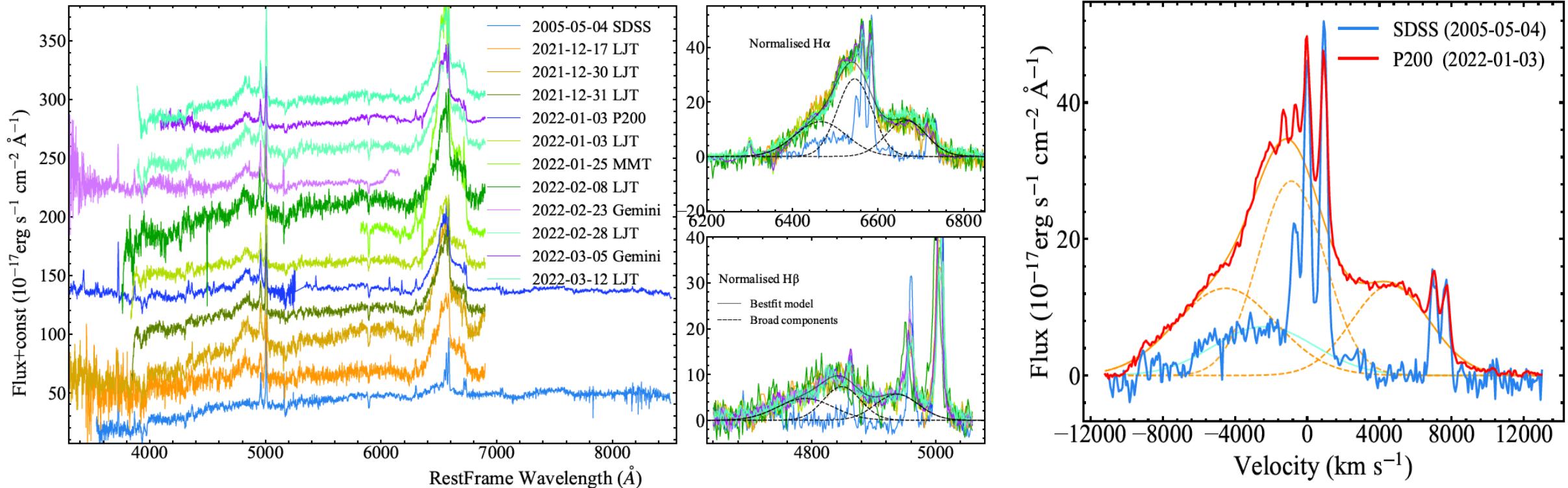
# Chirping flares in SDSSJ1430+2303



initially noticed due to its mid-infrared outburst (MIRONG, Jiang+21)



# spectral evolution: changing-look AGN

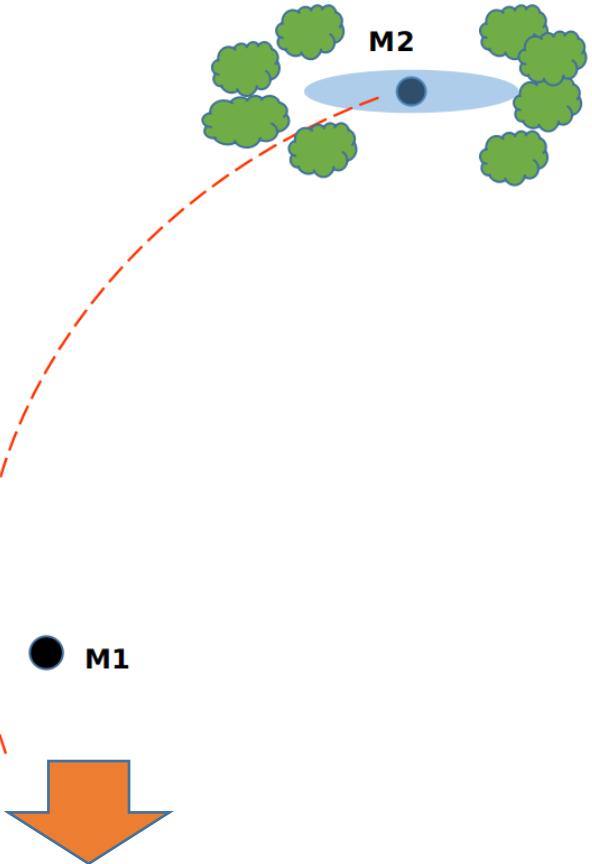


2005: blueshifted (-2400km/s) broad H $\alpha$ ,  $M_{\text{BH}} \sim 4 \times 10^7 M_{\odot}$

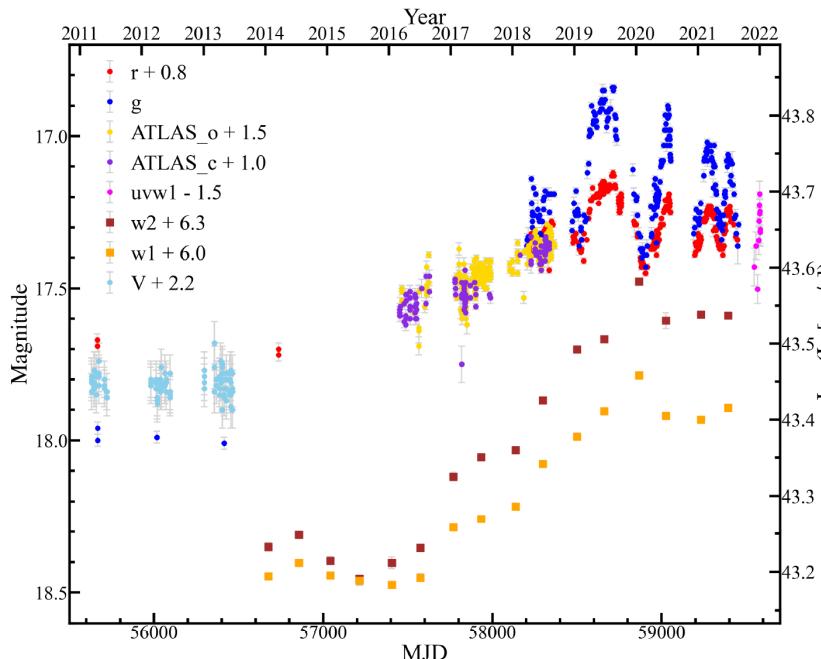
2022: double-peaked (-4000 and 4600km/s)

as an independent evidence

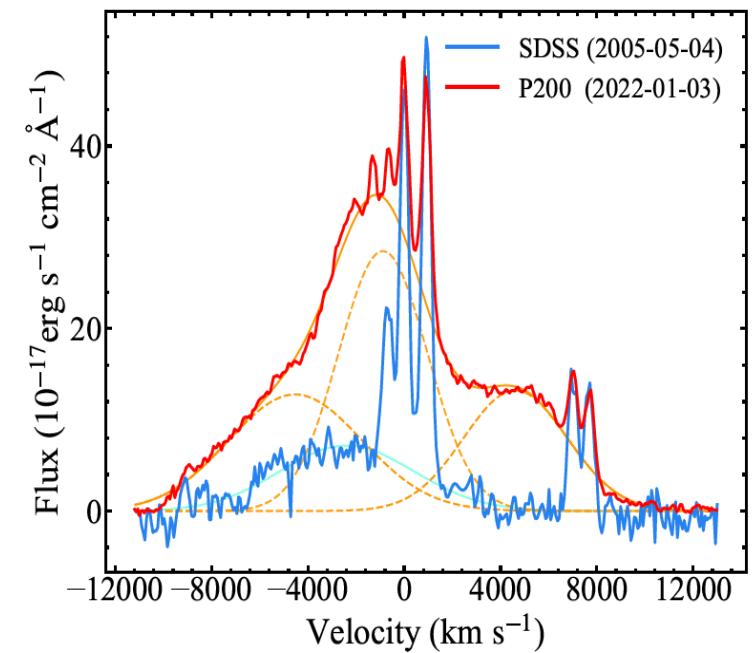
# First encounter around 2014-2016



**outburst:** the gas captured by primary BH and being accreted

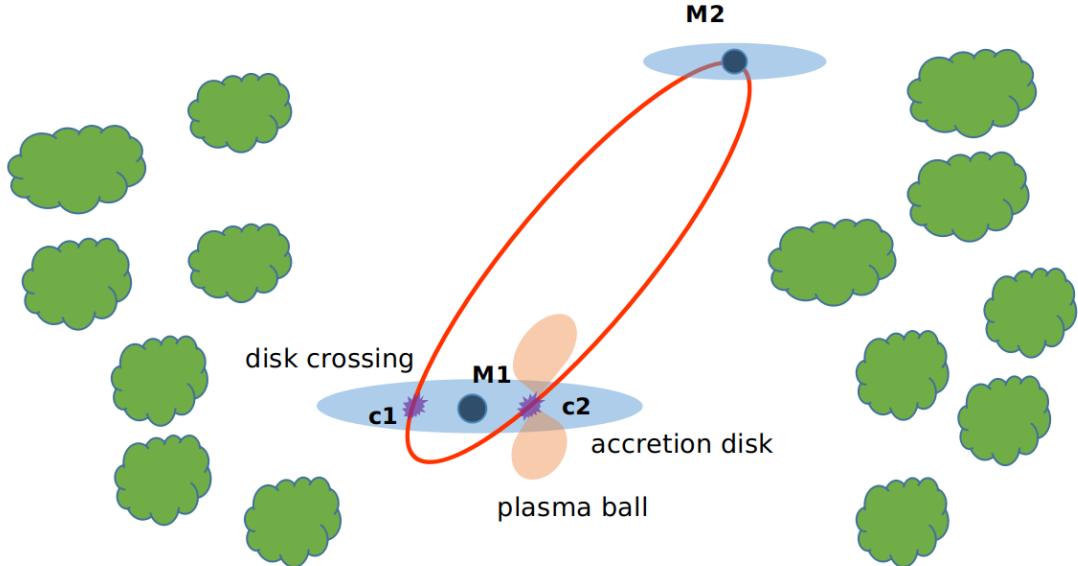


**high-velocity H $\alpha$  component:** unbounded gas



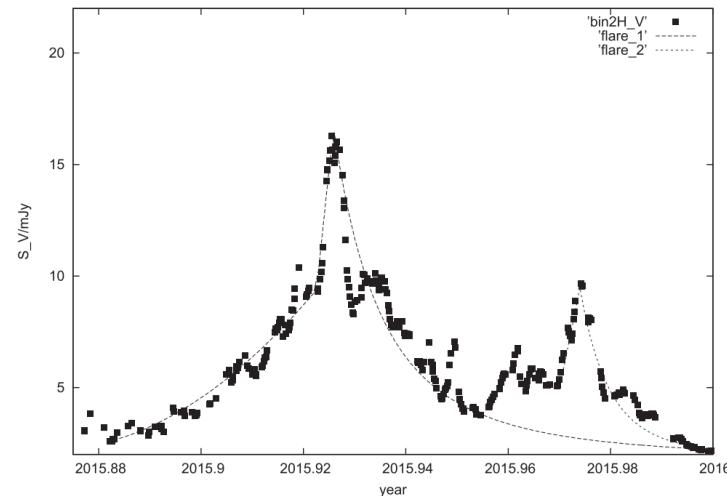
BLR clouds tidally disturbed and scattered by the primary SMBH

# Flare model: accretion disk impact



an uneven mass-ratio (5:1), highly eccentric ( $e>0.9$ ) SMBH binary

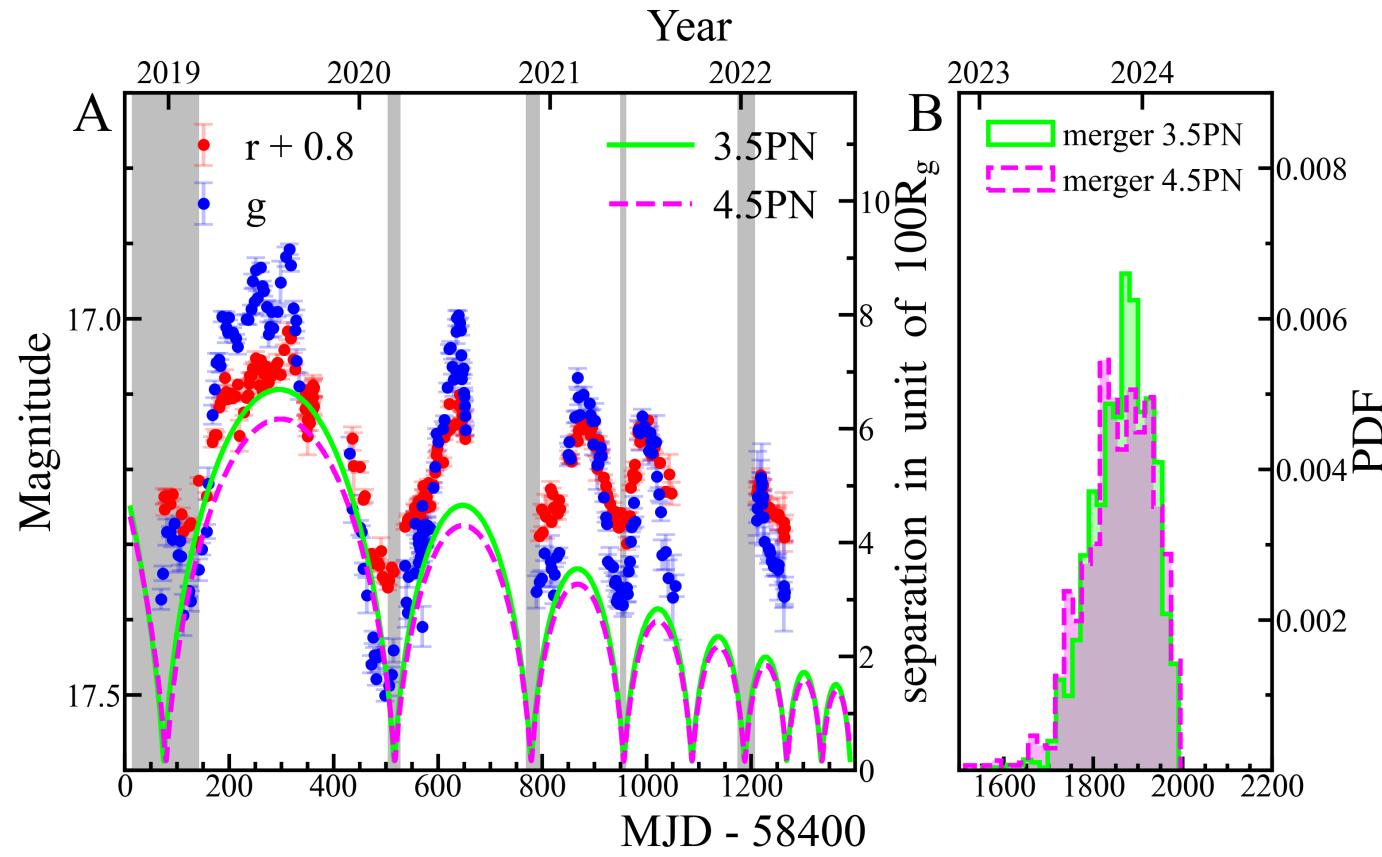
- The secondary SMBH crosses the accretion disk shortly before and after the pericenter passages
- ejected plasma balls induced by disk crossing produce observed optical flares (similar to SNe)
- significant energy and angular momentum radiated away through GWs, leading to orbit decay



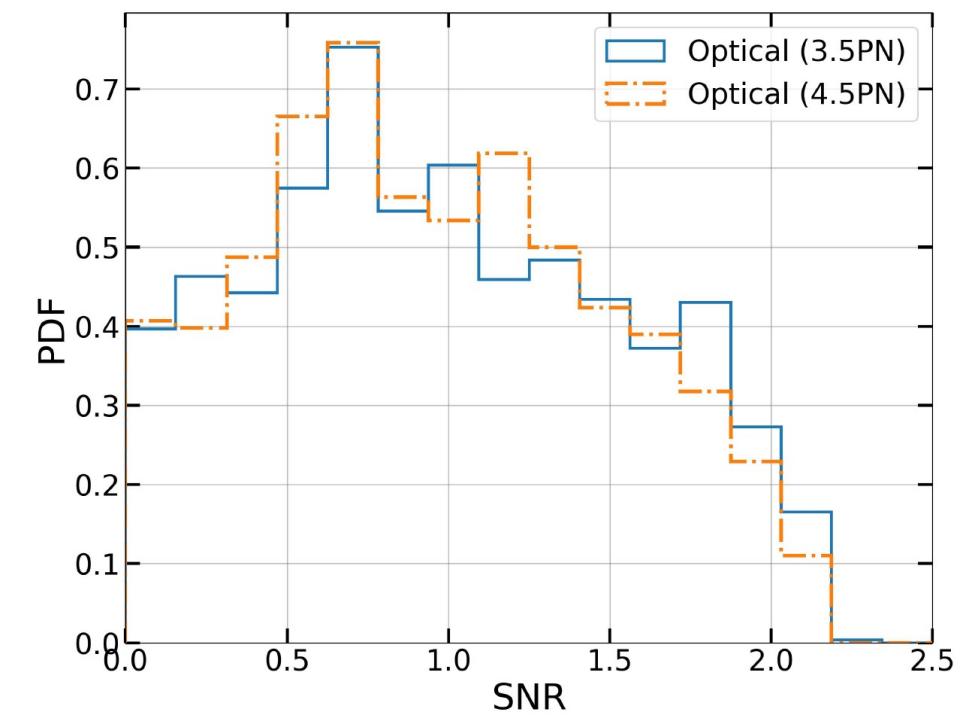
OJ287 flare model  
(Lehto+96, Ivanov+98,  
Pihajoki+2016...)

Valtonen+2019

# predicted merger time

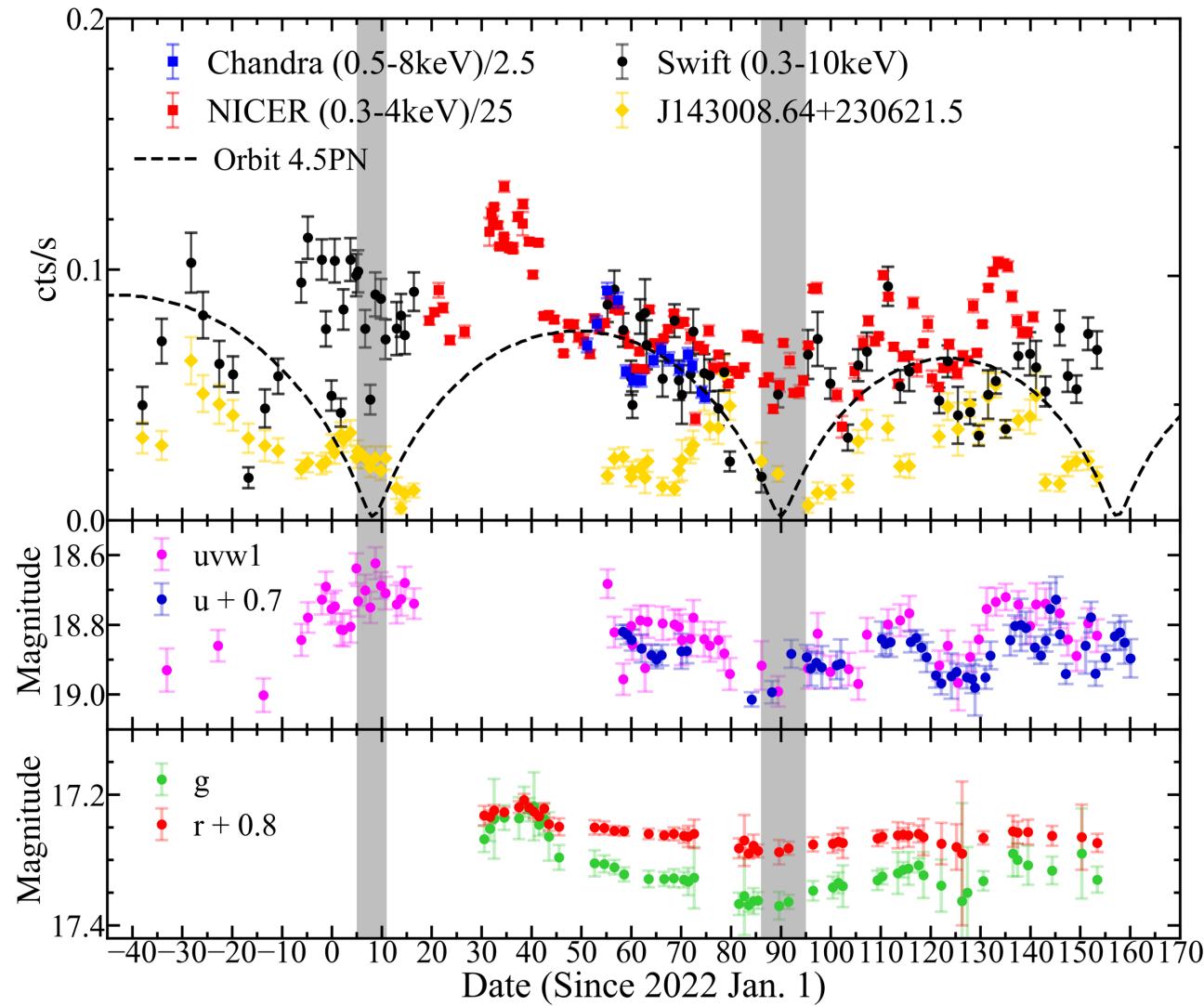


expected SNR for the **gravitational memory effect** as observed using PTA



see Chen+2022 (arxiv:2204.00749)  
for a more realistic calculation

# Multi-wavelength light curves



Swift: every 1-3 day since 2021 Nov.23

NICER: daily since Jan.20

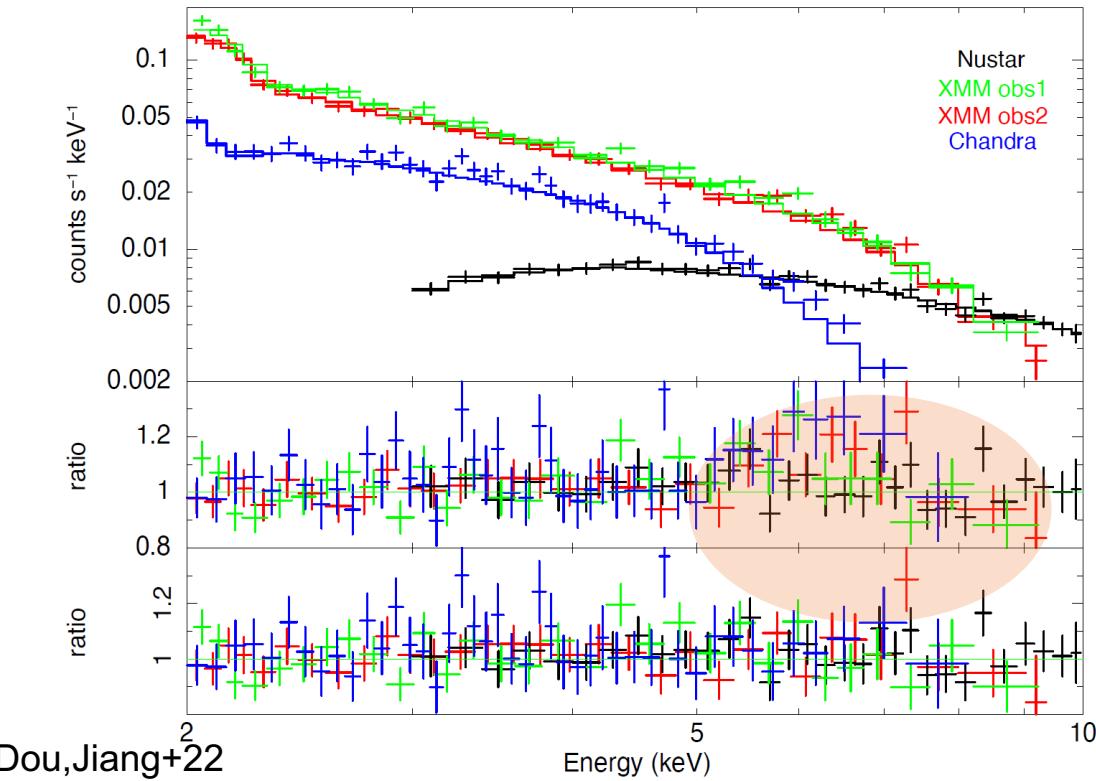
Chandra: 15\*4ks (Feb.21-Mar.16)

XMM-Newton: 50ks (Dec.31)+75ks (Jan.19)  
+100ks (June 29)

NuSTAR: 100ks (Feb.2-6)

# X-ray Spectral Fitting (Joint XMM+NuSTAR+Chandra)

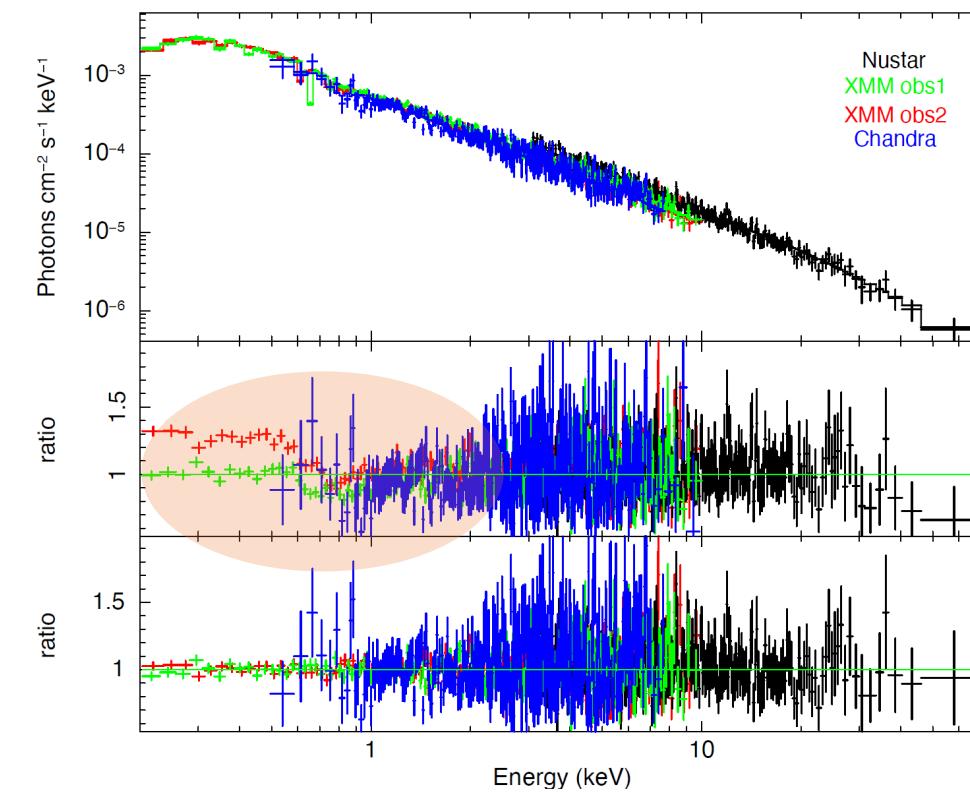
- powerlaw (+ Gaussian Fe Ka) fitting



Dou,Jiang+22

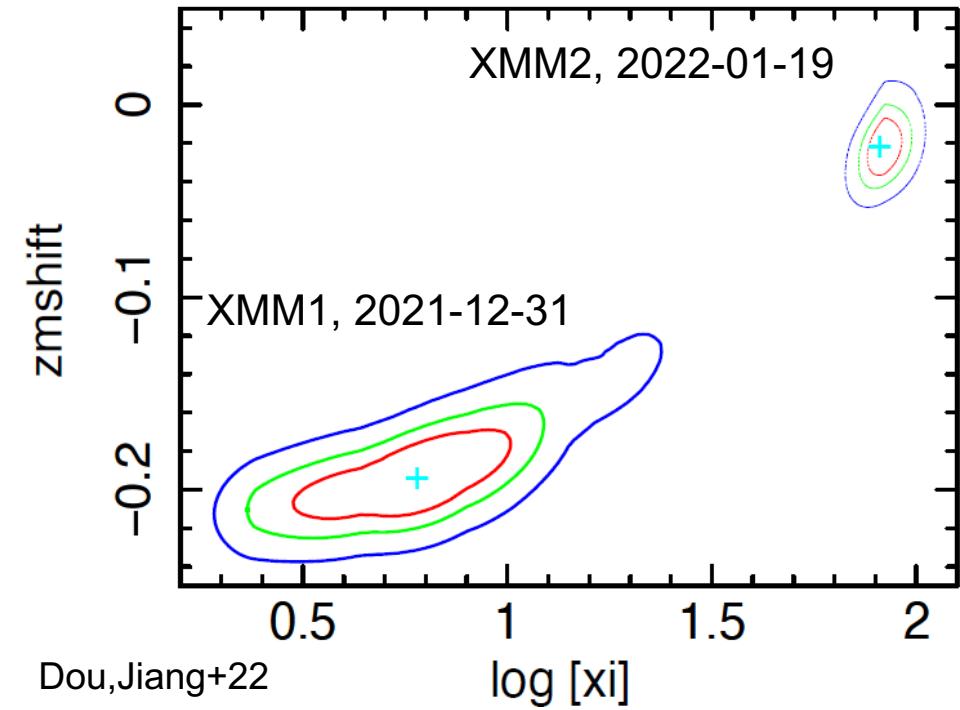
Broad Fe Ka detected though its **velocity shift or profile change (smoking-gun evidence)** not yet measurable due to poor S/N

- warm absorbed relativistic reflection disk model



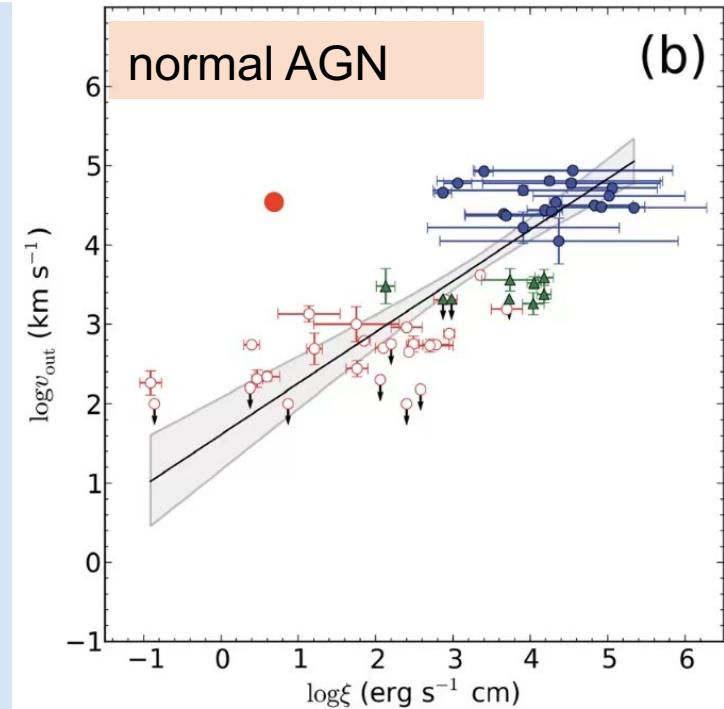
obvious **warm absorber** with rapid variation

# Dramatically changed warm absorber



~0.2c to ~0.02c within 19 days

- velocity anti-correlated with ionization, inconsistent with the predictions from radiatively-driven or MHD- driven winds in normal AGNs
- In the SMBH scenario, the velocity could be simply associated with either the orbital motion of the secondary SMBH or the gas kicked out during the disk crossing



$$v_{out} \propto \xi^{0.5} \text{ or } v_{out} \propto \xi$$

King+03; Fukumura+10

# X-ray signals expected upon the final coalescence

## → WHAT HAPPENS WHEN TWO SUPERMASSIVE BLACK HOLES MERGE?

1 Supermassive black holes sit at the core of **massive galaxies**

2 When massive galaxies merge, the black holes at their cores spiral towards one other, eventually **coalescing and becoming one**

3 We expect supermassive black hole mergers to release both **gravitational waves** and light, in particular **X-rays**

6 After the merger, it is possible that a corona of hot, X-ray emitting gas will form and **jets of particles** may be launched at speeds close to the speed of light

5 During the merger, some of the X-ray emission is expected to be modulated at a **frequency** commensurate to that of the gravitational waves produced by the black holes

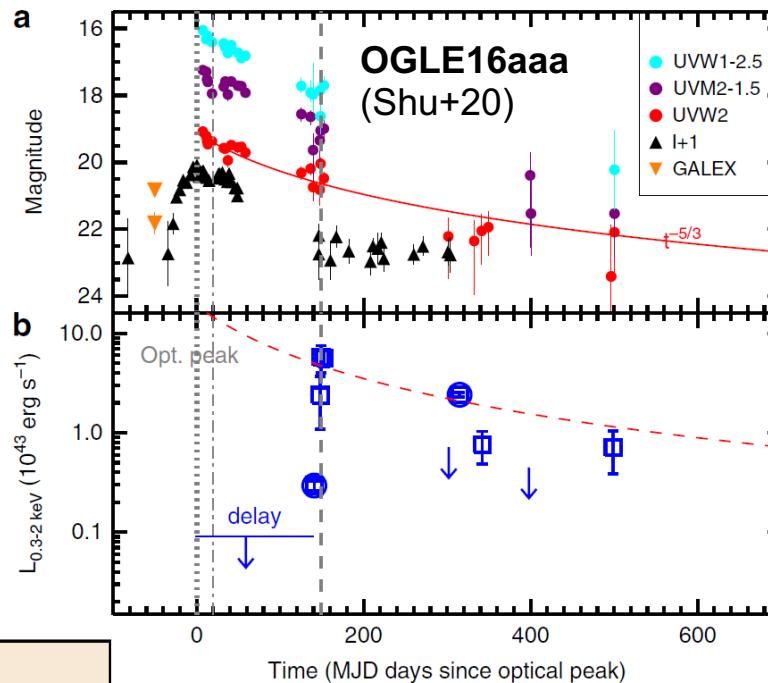
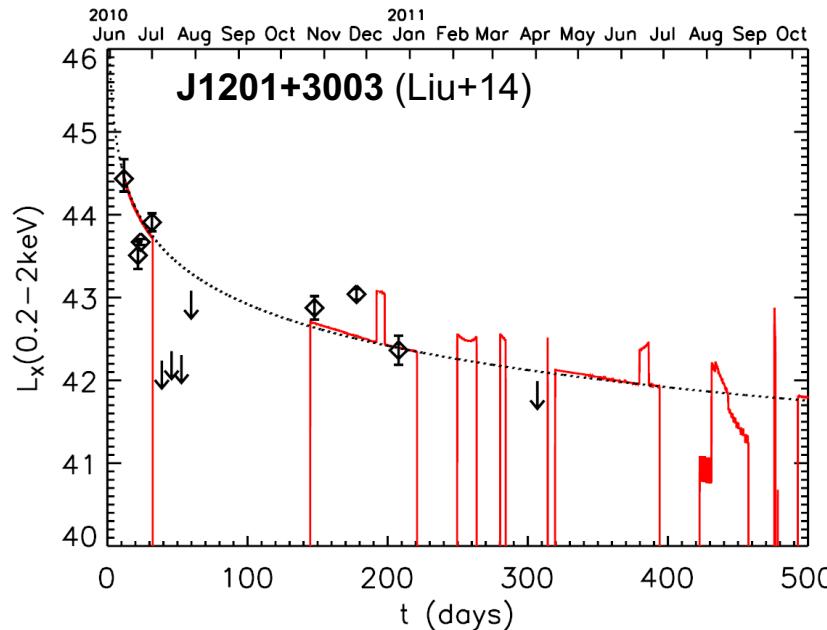
4 The **X-ray** emission comes from the **hot gas** surrounding and accreting onto the merging black holes



We have never observed merging supermassive black holes – we do not yet have the facilities for such observations. Combining the observing power of two future ESA missions, Athena and LISA, would allow us to study these cosmic clashes and their mysterious aftermath for the first time. First, we need LISA to detect the gravitational waves and tell us where to look in the sky; then we need Athena to observe with high precision in X-rays to see how the mighty collision affects the gas surrounding the black holes.

Also Tianqin

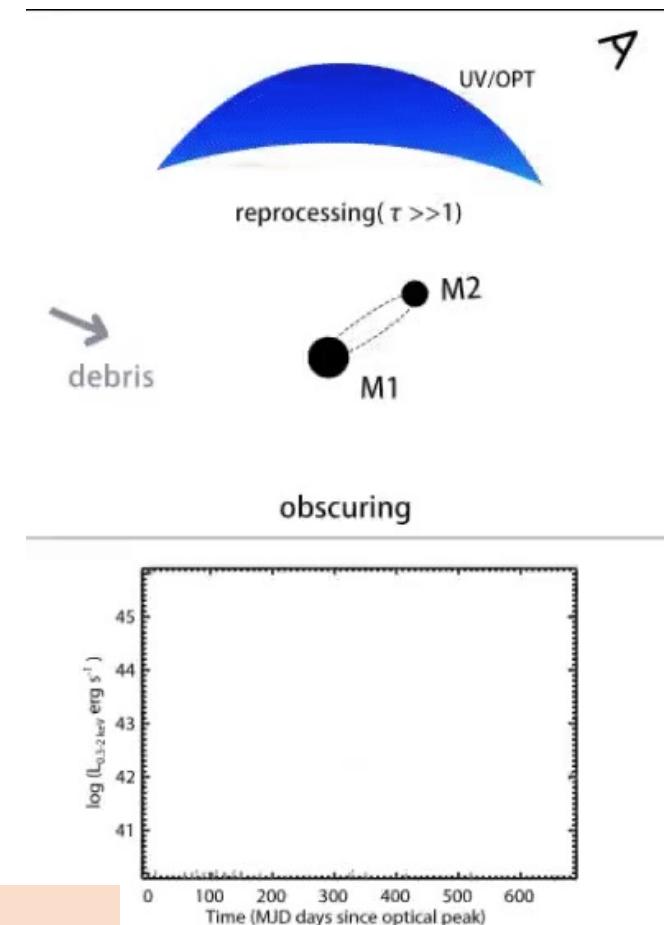
# TDE as a unique probe of normal SMBHB



**Table 3 SMBHB model parameters for OGLE16aaa and J1201 + 3003.**

Parameter	OGLE16aaa	J1201 + 3003
BH mass ( $M_{\odot}$ )	$10^6$	$10^7$
Eccentricity $e$	0.4 [0.4, 0.6]	0.3 [0.1, 0.5]
Penetration factor $\beta$	4.5 [3.0, 6.0]	1.3 [1.3, 1.6]
Mass ratio $q$	0.25 [0.05, 0.9]	0.08 [0.04, 0.09]
Orbital period $T_{\text{orb}}$ (days)	150 [140, 160]	150 [140, 160]
Initial phase $\phi$	$1.7\pi$	$1.5\pi$

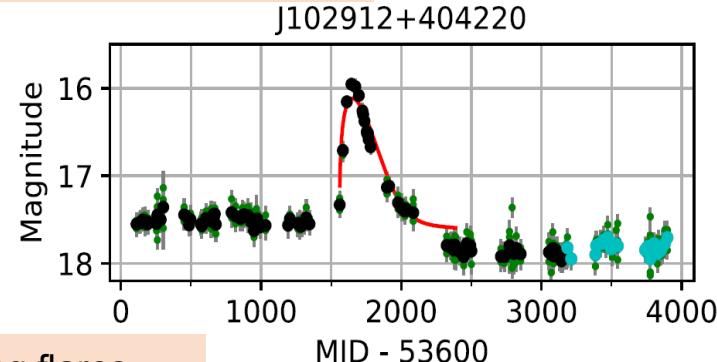
$$a_b \simeq 0.6 \text{ mpc}$$



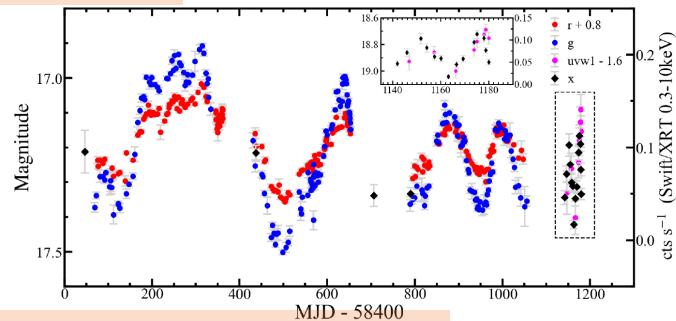
Upon final coalescence, these inactive SMBHB are also prime sources for Tianqin

# Summary and Prospects

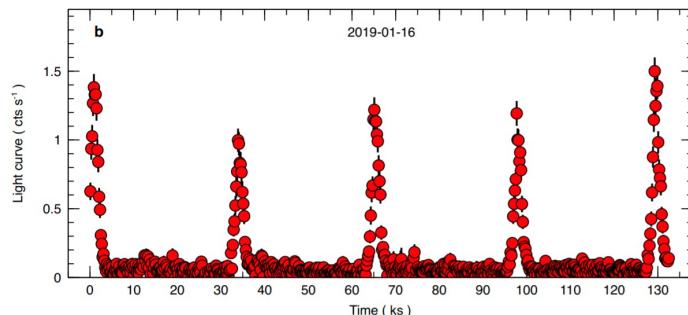
peculiar AGN outburst



chirping flares



Quasi-periodic eruption



## Time-domain surveys (2010s-)



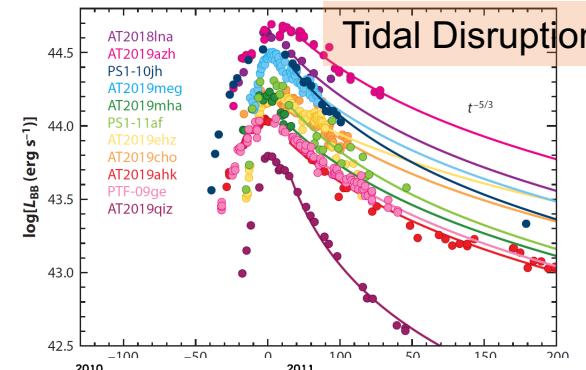
- SMBH+Star
- SMBH binary
- SMBHB+star

**GW sources**

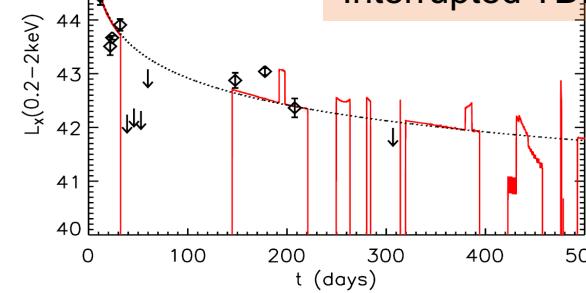
Can Tianqin detect their GW radiation and thus test their nature?

Promising to understand these mysterious EM sources in a blooming multi-messenger era

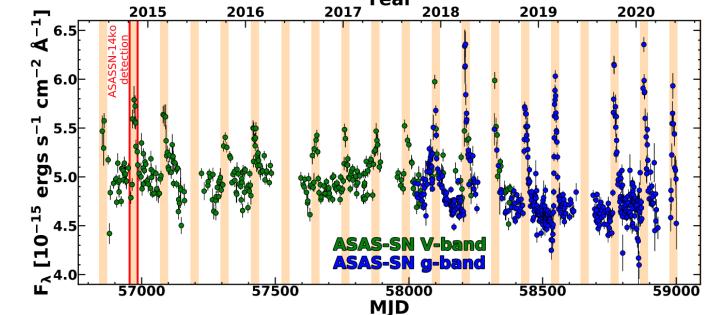
Tidal Disruption Event



Interrupted TDE



predictable recurring flares



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# Thank you!

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