Tick-Tock: The Imminent Merger of a Supermassive Black Hole Binary

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Supermassive black hole binaries (SMBHs) are a fascinating byproduct of galaxy mergers in the hierarchical universe[1]. In the last stage of their orbital evolution, gravitational wave radiation drives the binary inspiral and produces the loudest siren[2–4] awaiting to be detected by gravitational wave observatories. Periodically varying emission from active galactic nuclei has been proposed as a powerful approach to probe such systems[5–9], although none of the identified candidates are close to their final coalescence such that the observed periods stay constant in time. In this work, we report on the first system with rapid decaying periods revealed by its optical and X-ray light curves, which has decreased from about one year to one month in three years. Together with its optical hydrogen line spectroscopy, we propose that the system is an uneven mass-ratio, highly eccentric SMBH binary which will merge within three years, as predicted by the trajectory evolution model. If the interpretation is true, coordinated, multi-band electromagnetic campaign should be planned for this first binary SMBH merger event observed in human history, together with possible neutrino measurements. Gravitational wave memory from this event may also be detectable by Pulsar Timing Array with additional five-to-ten year observation.

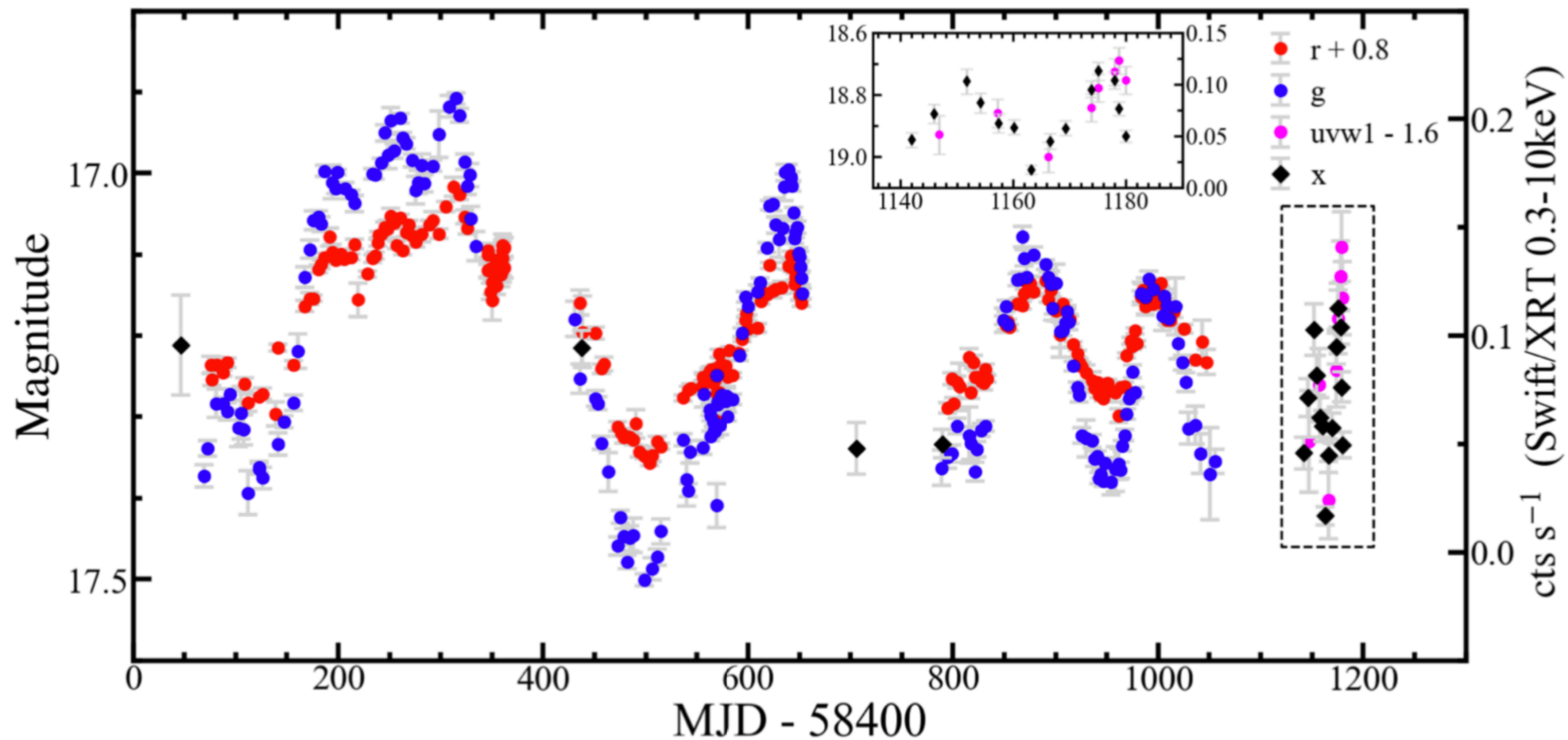
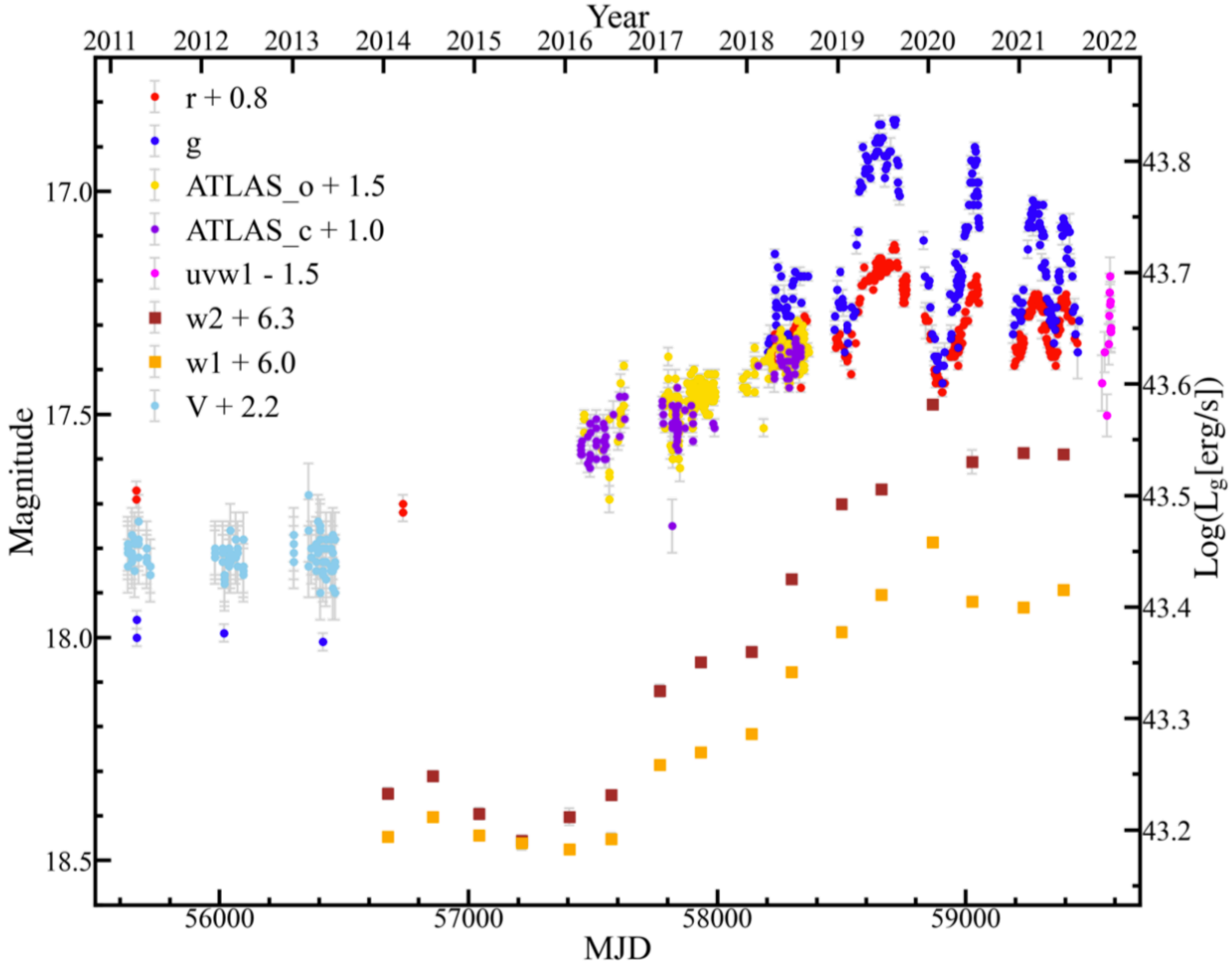


Figure 1: **The optical, UV and X-ray light curves of SDSSJ1430+2303.** The ZTF *g* and *r* band photometric data are shown in blue and red solid circles, with error bars in grey. The black solid diamonds and magenta solid circles represent the XRT count rate in 0.3-10 keV and UVW1 magnitudes from our Swift monitoring, respectively. We have zoomed in the Swift data (the region encircled by dashed box) in the inset for clarity.

- Seyfert 1 galaxy at z=0.08105
- Typical AGN-like narrow emission line ratios
- Unusual blueshifted broad Hα emission
- Oscillation pattern with decaying period in optical luminosity

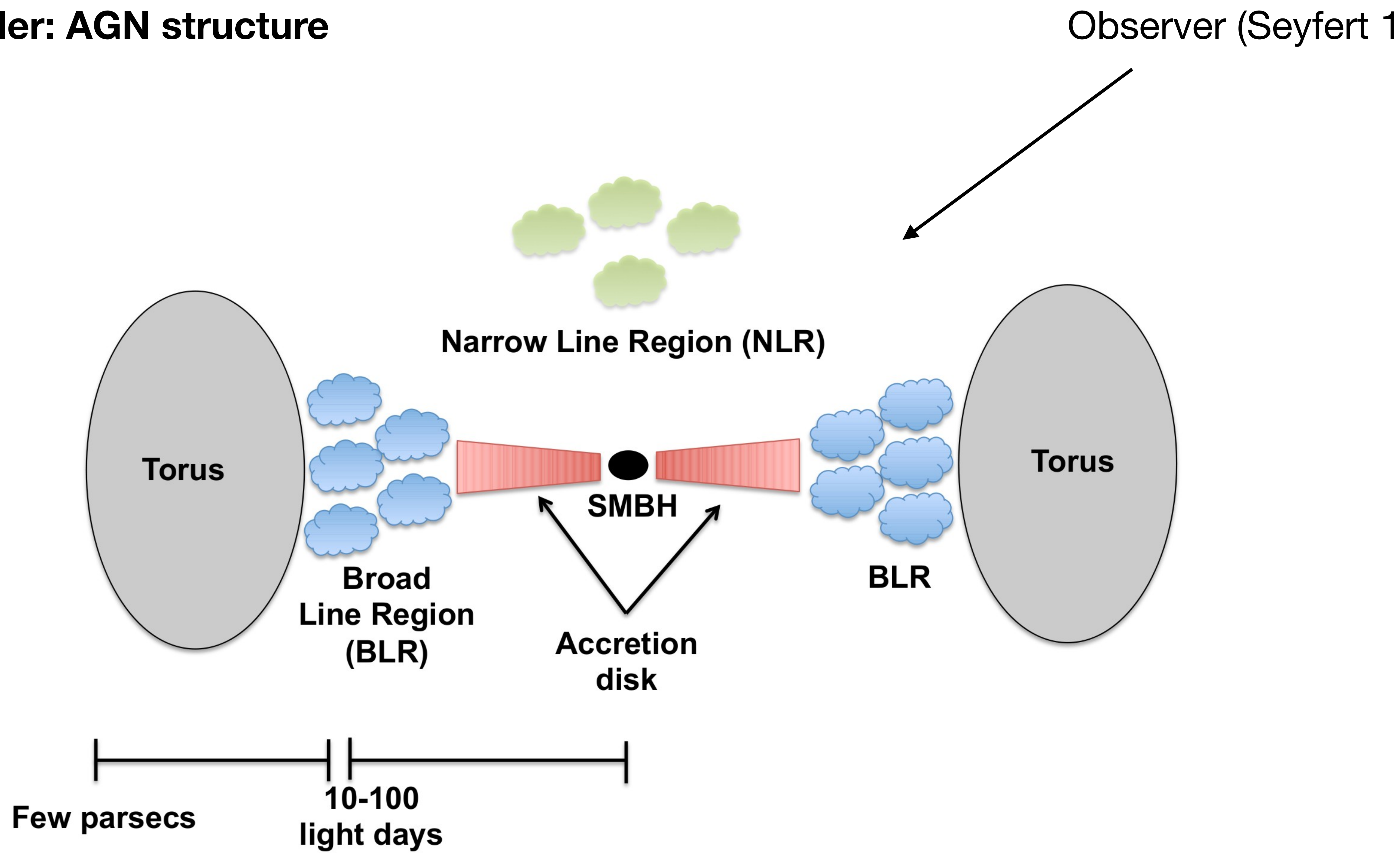


Extended Data Fig. 1: **The long-term optical light curves of SDSSJ1430+2303**. We have gathered useful photometric data in the past decade, spanning from PanSTARRS (2011-2014, g band in blue and r band in red), CRTS (2011-2013, V band in skyblue), ATLAS (2016-2018, c band in blueviolet and o band in gold) to ZTF (2018-2021). All photometry except for CRTS have been calibrated to ZTF reference flux with PSF photometry. The g band monochromatic luminosity (νL_ν) has been also denoted in the vertical axis on the right side. The NEOWISE W1 and W2 data are shown as orange and blue squares, respectively.

Interpretation: secondary BH on an inclined, eccentric trajectory

The chirping flares are not compatible with known disk oscillation/instabilities, which have been tentatively used to explain other recurring AGN variabilities such as quasi-periodic eruptions[24] and quasi-periodic oscillations[25]. The rapid decaying periods, which has decreased from ~ 1 year to ~ 1 month within only three years, also disfavour dissipation mechanisms such as dynamical friction at accretion disk crossings and/or tidal gravitational heating of stars near pericenter passages as the main drivers for orbital evolution (see details in alternative model part in Methods). It appears the only plausible scenario is a secondary black hole orbits around the primary SMBH in an inclined, highly eccentric trajectory. The secondary black hole crosses the accretion disk shortly before and after the pericenter passages, where significant energy and angular momentum are radiated away through gravitational waves (see trajectory model part in Methods), and the induced shock waves at disk-crossings eject plasma balls to produce observed flares in the optical band. Note that the flare luminosity is on the same order of magnitude as the background disk luminosity, indicating that the mass ratio between these two black holes cannot be too extreme. The X-ray emission from hot corona around the SMBH(s) are likely affected by the pericenter passages, where the direct accretion onto black holes are mostly perturbed, but they may be also subject to variations in other circum-single disk conditions.

Reminder: AGN structure



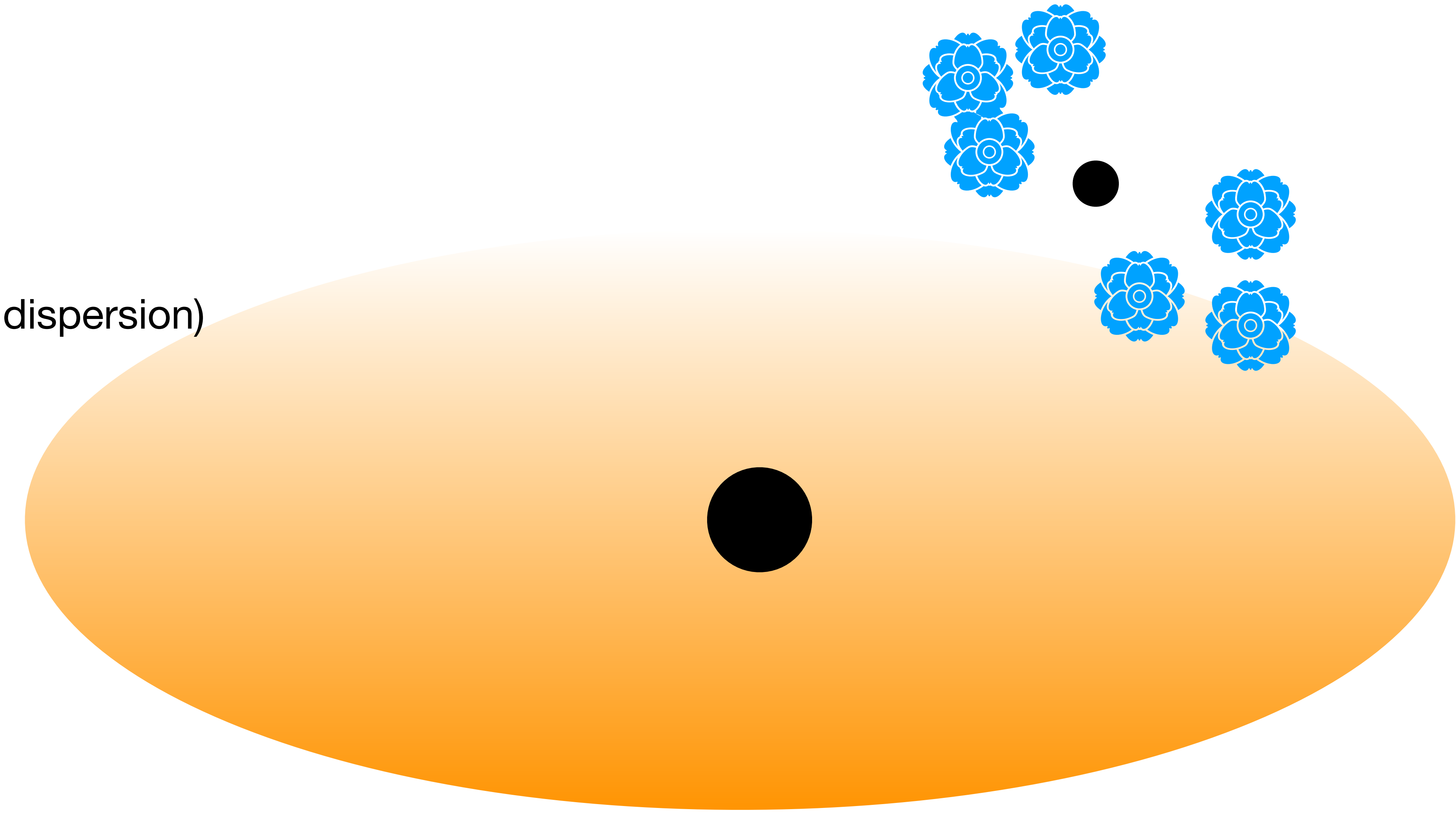
The whole picture

$$M_1 \simeq 2 \cdot 10^8 \, M_\odot$$

(estimated from galaxy velocity dispersion)

$$M_2 \simeq 4 \cdot 10^7 \, M_\odot$$

(estimated from Hα)



As a black hole collides with an accretion disk, it kicks out certain amount of gas within radius $R_a = C_{\rm BH} G M_{\rm BH}/v_{\rm rel}^2$ ($C_{\rm BH}$ is a dimensionless constant of order unity) which later on expands and radiates when the plasma ball becomes optically thin.

For each collision of the secondary BH on the disk, a total amount of energy $\delta E = \frac{1}{2}\Sigma\pi R_a^2 v_{\rm rel}^2$ is deposited into the shocked gas which subsequently eject from the disk, with

$$\delta E = 2.5 \times 10^{50} \text{ ergs } C_{\rm BH}^2 \left(\frac{0.3}{\alpha}\right)\left(\frac{0.1\dot{M}_{\rm Edd}}{\dot{M}}\right)\left(\frac{M_2}{4\times 10^7 M_\odot}\right)^2\left(\frac{r}{20M}\right)^{2.5}\delta^{-2},$$

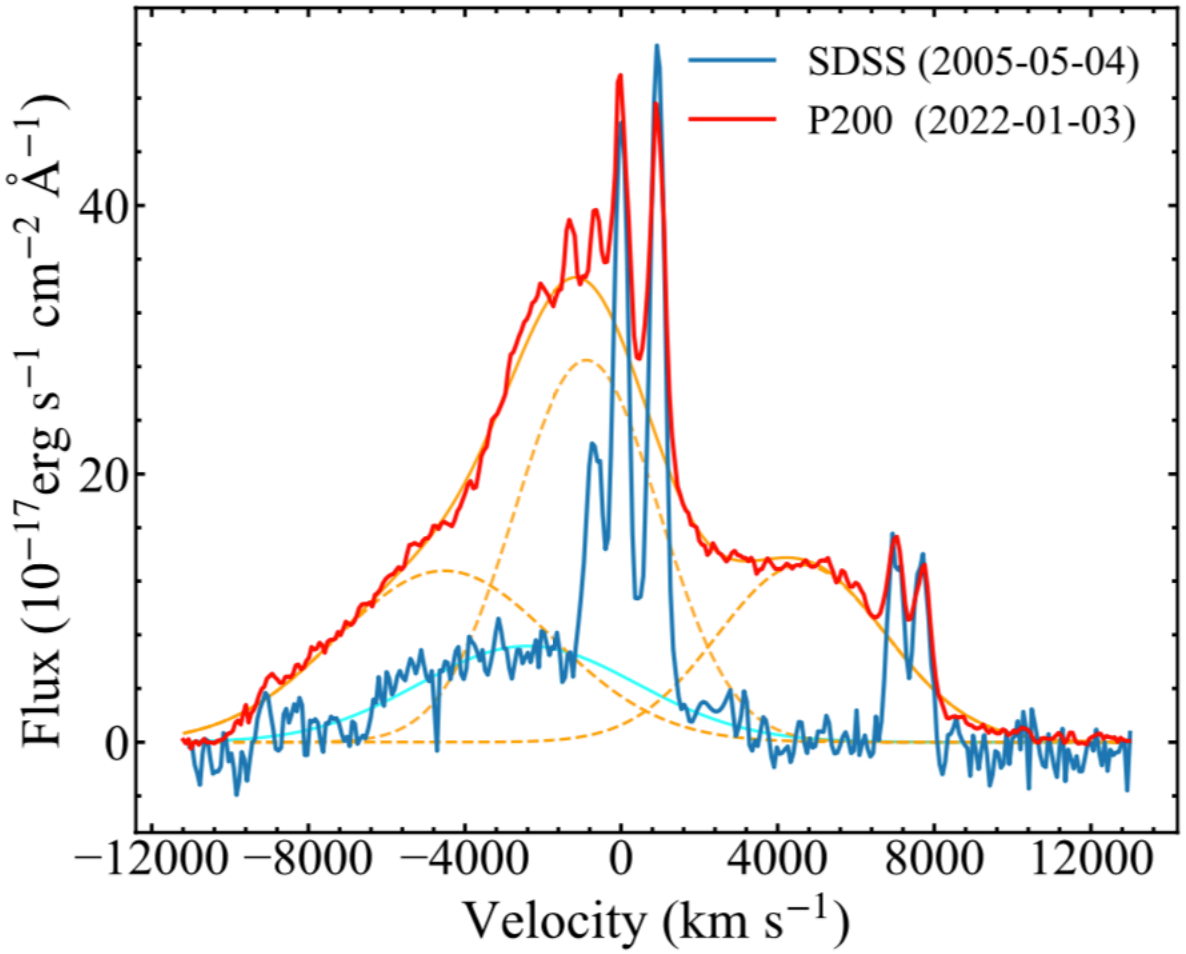


Figure 2: **The spectroscopic profile change around Hα region.** The broad Hα in SDSS spectra (blue, taken in 2005) is blueshifted with velocity of ~ 2400 km s^{-1} (cyan line). The very recent spectra from P200/DBSP obtained on 2022 Jan. 3 (red) has shown a complex velocity structure, which can be fitted with three Gaussians (orange dashed lines), including a significantly redshifted (~ 4600 km s^{-1}) and a blueshifted (~ 4000 km s^{-1}) component.

- BLR clouds carried by the secondary MBH
- Hα blueshift reflects the velocity of the secondary
- As the MBHs approach, BLR clouds scatter around, creating complex velocity structure

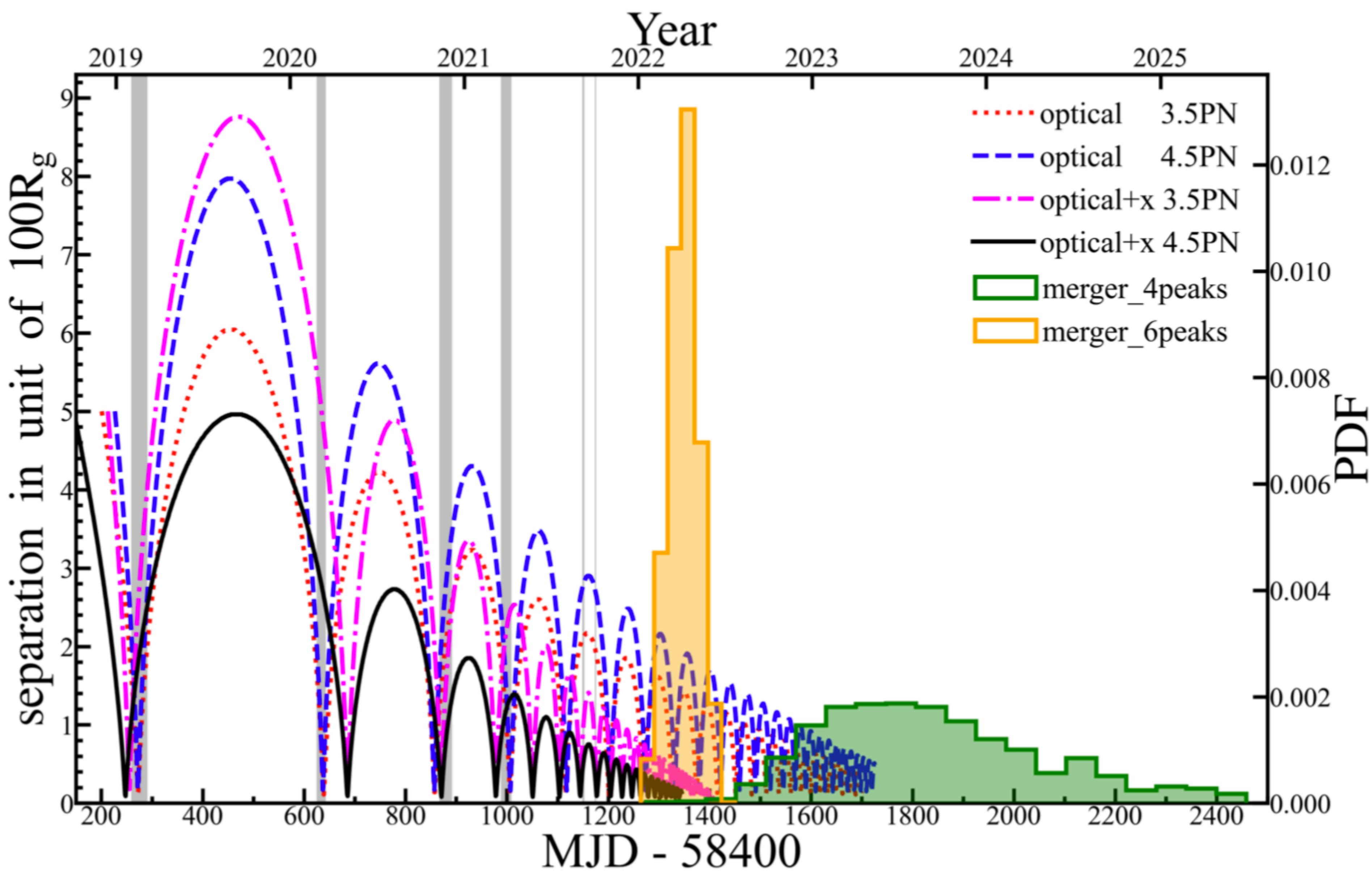
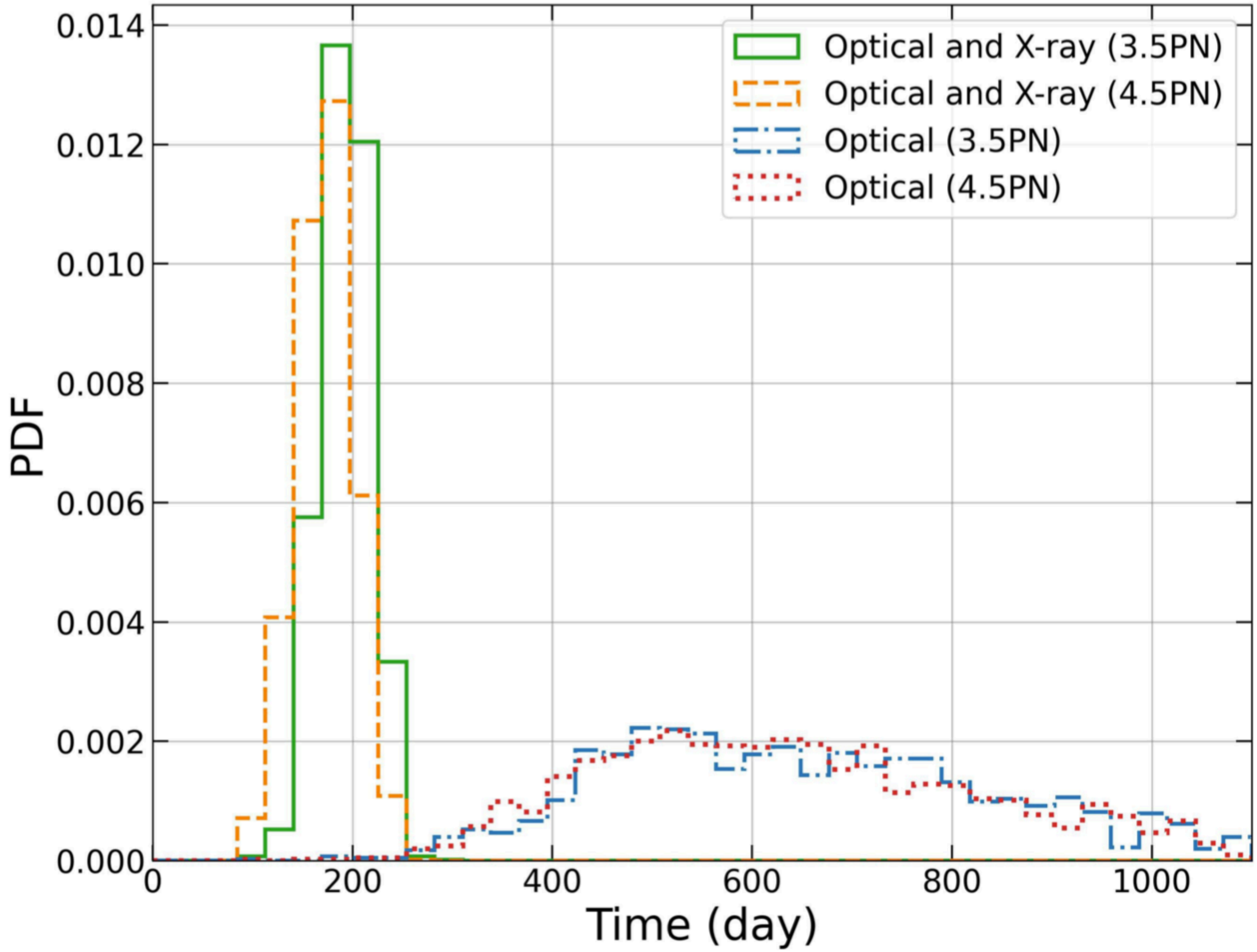


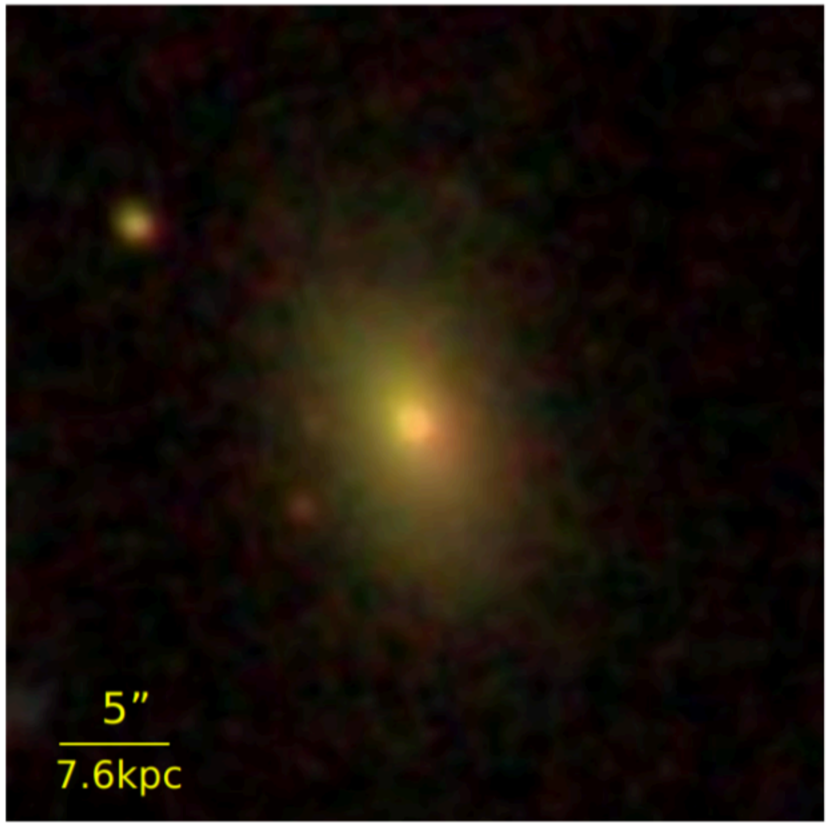
Figure 3: **The evolution of the binary separation from trajectory model and predicted merger time.** The separations (in unit of $100R_g$ of the primary SMBH) inferred from different scenarios (with or without X-ray peaks, 3.5PN or 4.5PN, see details in Methods) are shown in red dotted, blue dashed, magenta dot-dashed and black lines, respectively. The observed peak times suggested by light curves are denoted with grey shadow regions. The possibility distribution function (PDF) of merger time (4.5PN) predicted from optical plus X-ray peaks is shown with orange histogram while that without X-ray peaks is shown in green histogram.

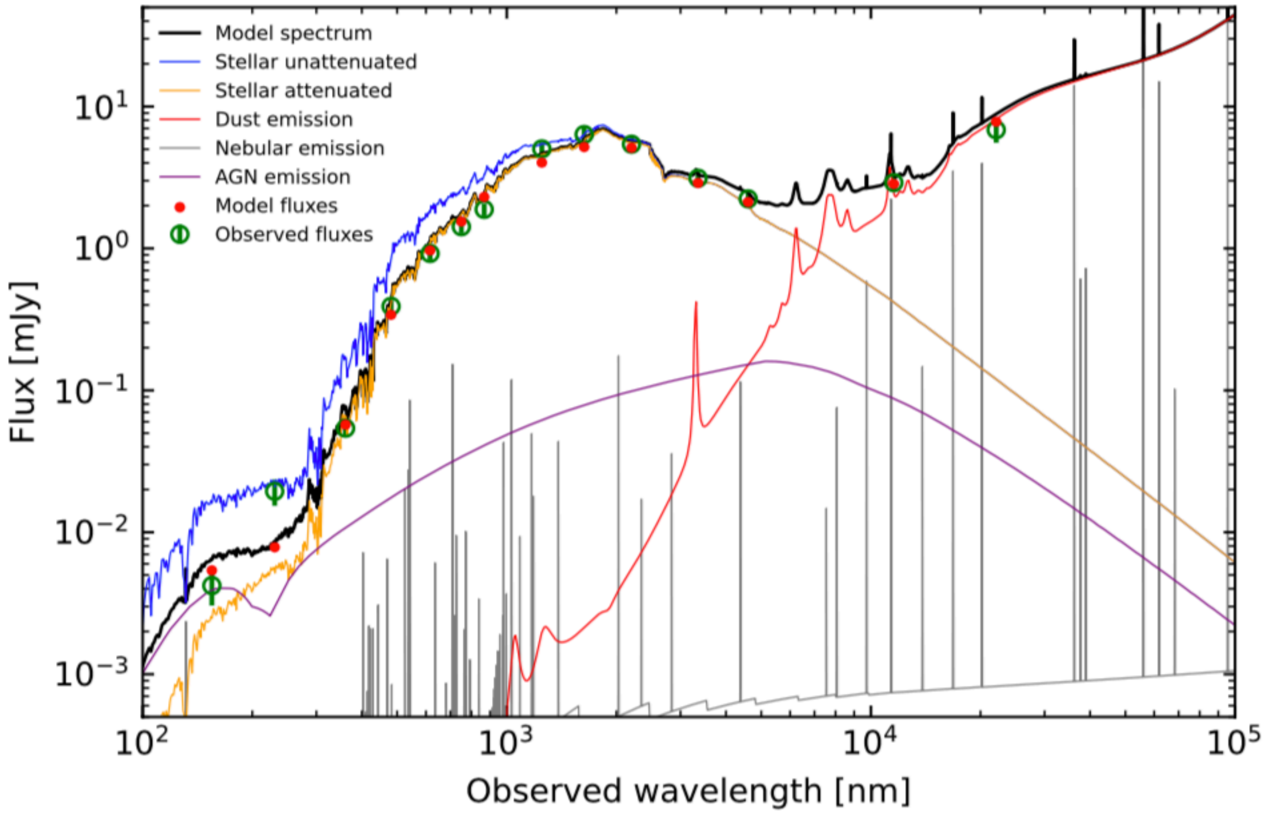
- From 3 milli-pc to 0.6 milli-pc in 3 years



Extended Data Fig. 9: **The posterior distribution of merger time**. The starting point corresponds to the peak time of the second X-ray flare. They are as inferred from the trajectory models, assuming $3.5\mathrm{PN}/4.5\mathrm{PN}$ and with/without using the X-ray data. In general the six-peak cases predict imminent merger within one year, and the merger time for four-peak cases is less than three years.

Host galaxy





Extended Data Fig. 5: **Optical image and broad spectral energy distribution (SED) of the host galaxy of SDSSJ1430+2302.** Left: the SDSS *gri* composited image. Right: the broadband SED (in flux density per unit frequency in observer's rest frame) fitting with CIGALE.

- Typical elliptical galaxy
- No visible morphological features, but consistent with long delay times

Alternative models

- The companion is a star or a dense gas clump which captures gas every time it hits the accretion disk
  - Would not capture enough gas to explain the periodic signal
- The companion is a star that is partially disrupted every time it hits the accretion disk
  - Orbital decay due to GW radiation would be too slow, cannot explain period
- The companion is a stellar-mass BH binary
  - Not enough energy to explain the flairs
- Disk activities, i.e., oscillations and/or instabilities (like quasi-periodic oscillations in other systems)
  - Much faster period evolution than QPOs

EM signal: towards the merger

- Orbital period increases and will become shorter than dissipation timescale: optical flares will fade away
- Total optical luminosity will increase due to repeated heating of the disk by shock waves
- The gas within the inner region of the disk will be heated and become ‘puffed-up’, no longer being geometrically thin; will mask iron emission line
- May expect luminosity variation in X-ray
- Infall of gas into the final BH: on timescale of years
- Possible jet launch, neutrino signal