Multi-band Emission from Star-disk Collision and Implications to Quasi-Periodic Eruptions

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QPEs: Repeating Flares from Galactic Center

1. QPEs are soft X-ray flares repeating every few hours to few days, preferentially from $M_{BH} \sim 10^6 M_\odot$ black holes in quiescent galaxies, estimated $L_{bol} \sim 10^{42}$ergs/s, temperature $k_B T \sim 10^{-1}$ keV. Found by eROSITA, XMM-*Newton*, NICER…

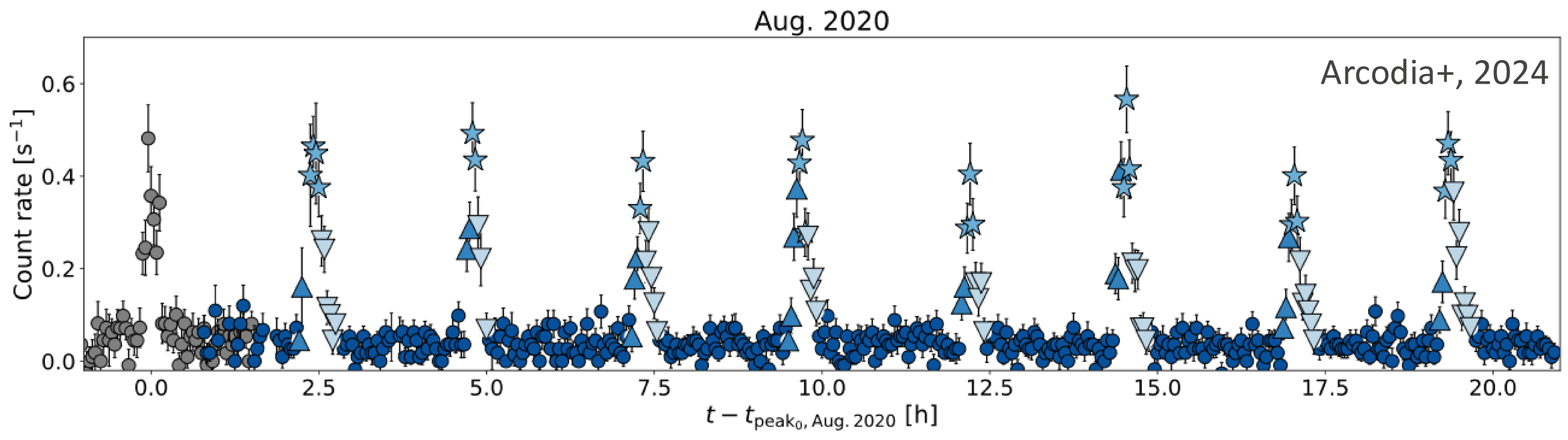


Fig A1: XMM-*Newton* 0.2-2.0 keV light curve for the original 2020 flares of eRO-QPE2

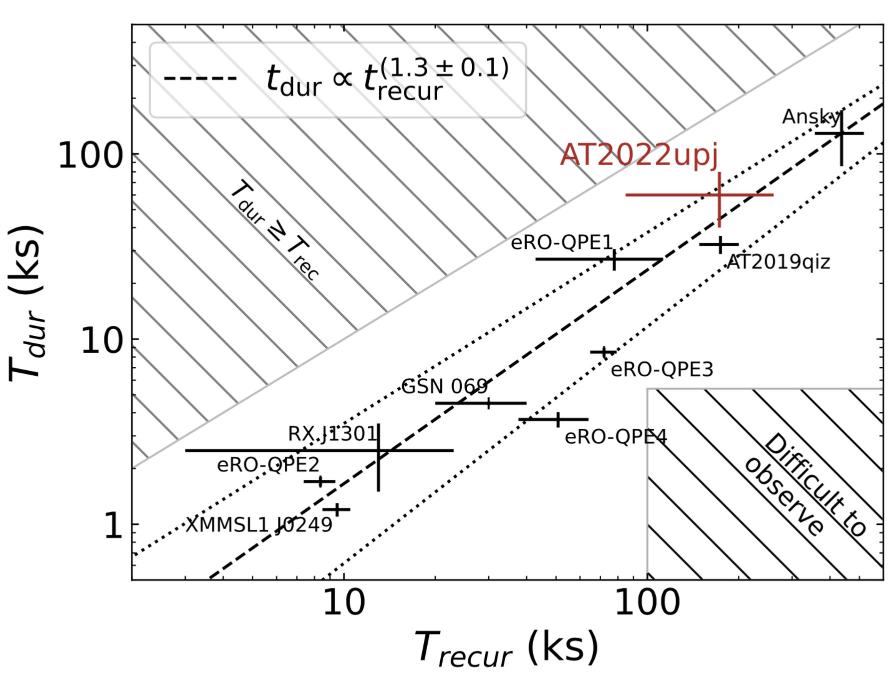


Fig A2: Correlation between flare duration and recurrence time (Chakraborty+ 2024, 2025).

2. They show tight correlation between flare duration and recurrence time. But the correlation between timing and black hole mass is weak (e.g. Nicholl+ 2024)

3. Some QPE shows long-short alteration between the flares (e.g. Miniutti + 2019, 2023). Two candidates are discovered after previous TDE. 2 years secular evolution suggest potential disk precession.

Results (almost) Reproduce Observed Soft X-ray Flares!

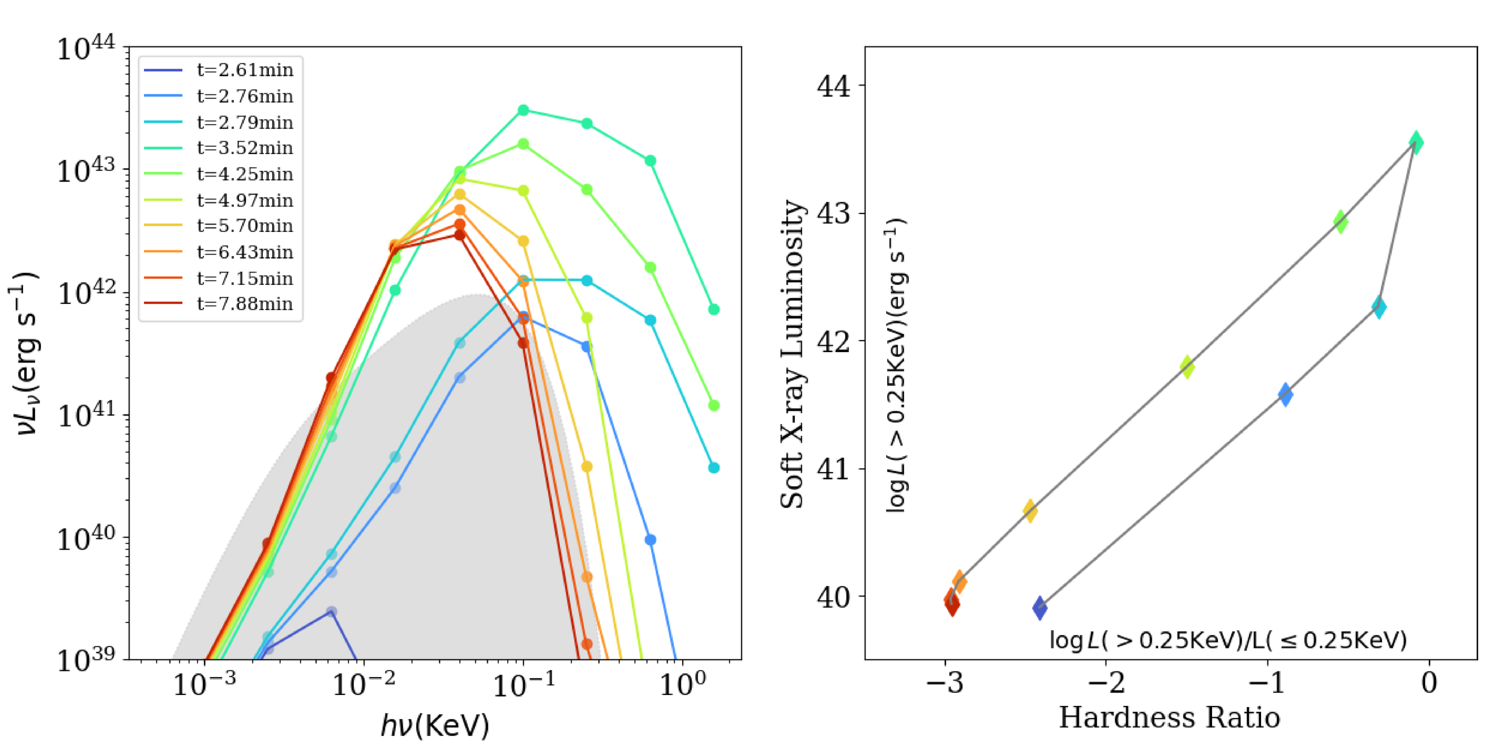


Fig C1 Left: Ejecta cooling SEDs (colored lines) from fiducial model of 0.1c solar type star collides with $\Sigma_{\rm disk} \sim 10^4 {\rm g/cm^{-2}}$ disk. Grey shaded region is a simple thin disk spectrum assuming $M_{\rm BH} = 10^6 M_\odot$, $\dot{M} = 0.1\,\dot{M}_{\rm Edd}$ Schwarzschild BH. Right: hardness-luminosity cycle including disk SED.

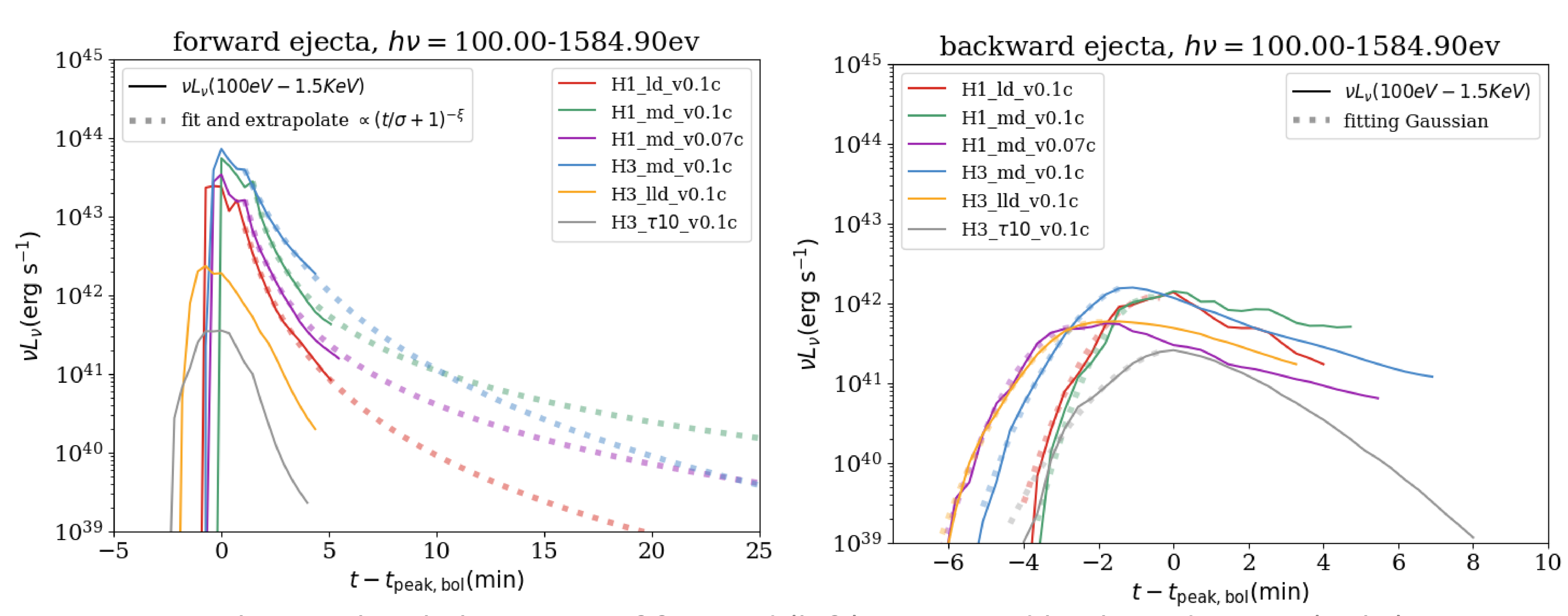


Fig C2: 0.1keV-1.6keV light curves of forward (left) ejecta and backward ejecta (right)

1. Can reproduce short duration flares (duration < hour), but only one ejecta is energetic enough to be observed.

2. Thicker disk, higher collision velocity increases soft X-ray opacity.

3. Soft X-ray flux emerges because opacity of those groups are lower than frequency-integrated opacity. Bound-free opacity is important and leads to strong thermalization, unless the ejecta is overionized.

Flares from a Star Colliding with a Low Luminosity Disk

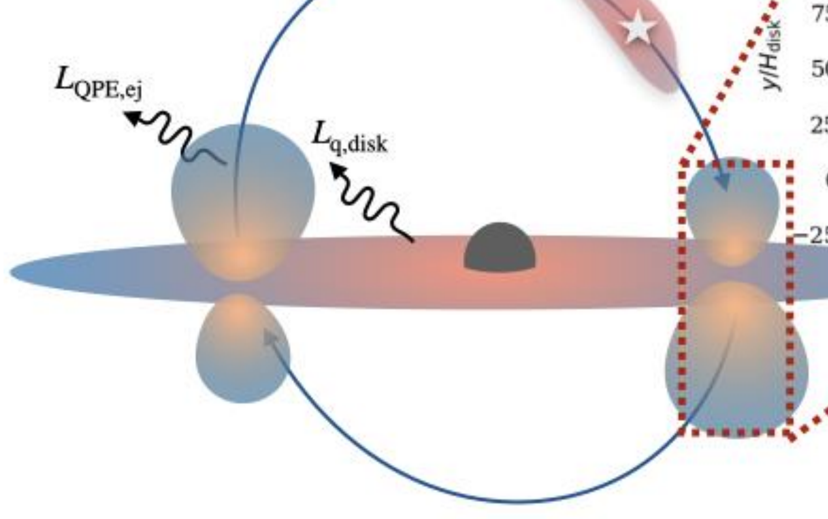


Fig B1: Schematic of star-disk collision. The eject expands and cools, producing observable flares

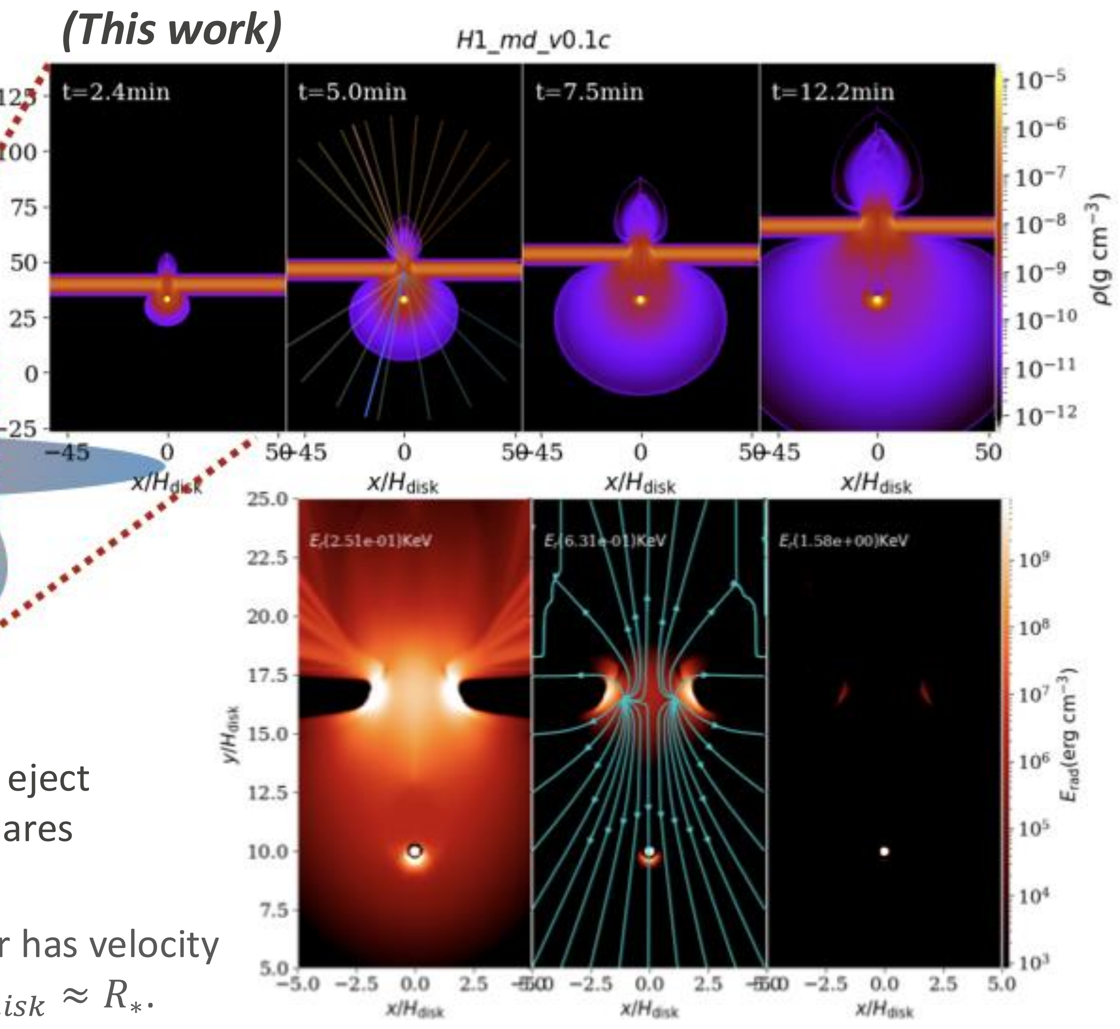


Fig B2 [Top]: Gas density snapshots, the star has velocity $v_* = 0.1c$, the assumed disk is thin with $H_{disk} \approx R_*$.

[Lower]: Radiation energy from multi-group simulation with group of $h\nu = 0.25keV, 0.63keV, 1.58keV$. The streamlines shows the velocity field. The shock compresses disk gas, converting kinetic energy to radiation.

1. Setting recurrence time (orbital period of the star:)

$$T_{\rm QPE} \sim 2\pi/\left(\frac{R_{\rm orb}^3}{GM_{BH}}\right)^{1/2} = 8.6\ {\rm hr}\left(\frac{M_{BH}}{10^6 M_\odot}\right)\left(\frac{R_{\rm orb}}{100 r_g}\right)^{1.5}$$

2. Energy Budget:

$$\text{(Shocked Mass):}\ M_{\rm ej} \sim \pi R_*^2 \Sigma_{\rm disk} = 7.6\times10^{-7} M_\odot \left(\frac{\Sigma_{\rm disk}}{10^5 {\rm g\ cm^{-2}}}\right)\left(\frac{R_*}{R_\odot}\right)^2$$

$$\text{(Kinetic Energy):}\ E_{\rm ej} \approx \frac{1}{2} M_{\rm ej} v_{\rm ej}^2 = 6.8\times10^{45} {\rm erg}\left(\frac{\Sigma_{\rm disk}}{10^5 {\rm g\ cm^{-2}}}\right)\left(\frac{R_*}{R_\odot}\right)^2\left(\frac{v_{\rm ej}}{0.1c}\right)^2$$

3. Setting flare duration (ejecta diffusion time):

$$t_{\rm diff} \approx \left(\frac{\kappa M_{\rm ej}}{4\pi c v_{\rm ej}}\right)^{1/2} \approx 11\ {\rm min}\left(\frac{R_*}{R_\odot}\right)\left(\frac{\Sigma_{\rm disk}}{10^5 {\rm g\ cm^{-2}}}\right)^{1/2}\left(\frac{v_{\rm ej}}{0.1c}\right)^{-1/2}$$

4. Thin, low luminosity disk*:

Scale height comparable to star size (parameterized in simulations)

$$\text{Temperature:}\ k_B T_Q \approx k_B \left(\frac{3GM_\bullet \dot{M}}{8\pi\sigma R_{\rm isco}^3}\right)^{1/4} \simeq 59\,{\rm eV}\,\frac{\dot{m}_{-1}^{1/4}}{M_{\bullet,6}^{1/4}}\left(\frac{R_{\rm isco}}{4R_g}\right)^{-3/4}$$

(Linial & Metzger 2022)

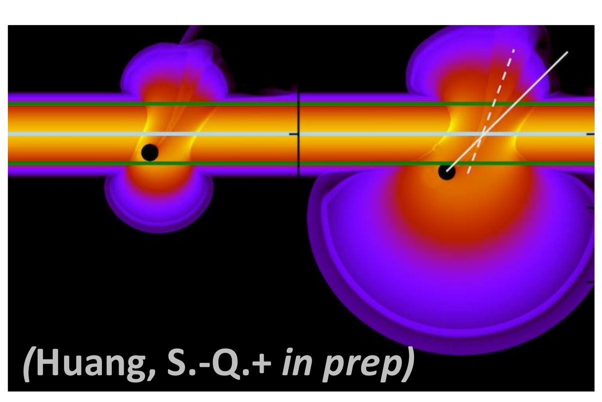
*not modeled in simulation

But… and Future Directions

1. In simulations, the bow shock breakout emission from disk dominates the soft X-ray luminosity. The rising timescale is shorter, and luminosity is higher than the observed flares. Mechanisms to prolong the breakout signal?

2. Simulations *cannot* explain the long duration events, and the fact that luminosities of long and short QPEs are similar.

3. Star's response to repeating interactions with disk, tidal potential, and possibly the TDE(s) (in case of an EMRI star + relic TDE disk).



D1. An inclined encounter finds larger backward ejecta mass and volume.

4. Disk rotation. Impacts to disk. Bow shock and ejecta morphology in 3D.

5. More detailed (time-dependent) Monte Carlo radiation transfer calculation to understand ionization state and X-ray spectra.

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