Radiation-hydrodynamics of star-disc collisions

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Co-funded by the European Union

MINISTRY OF EDUCATION, YOUTH AND SPORTS

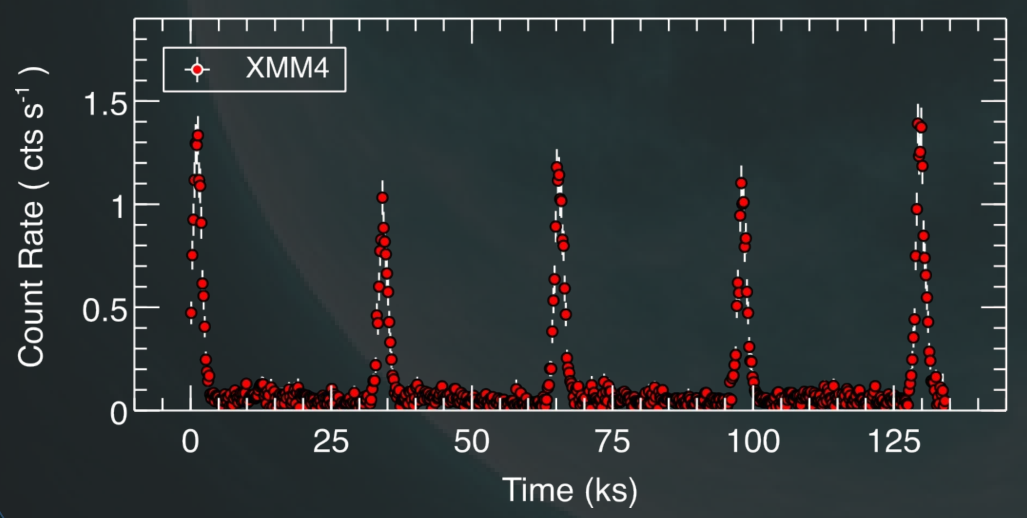
TAKE-AWAY MESSAGE

Star-disc collisions launch two outflows on opposite sides of the disc with different properties: the forward outflow expands faster, contains more mass, carries more energy, and is about twice as luminous as the backward outflow. The asymmetry in outflow properties and luminosity arises naturally from the collision dynamics, offering a possible explanation for the alternating "strong–weak" flare patterns observed in several quasi-periodic eruption sources.

Jankovič, T. et al. 2026

1 Quasi-periodic eruptions

Quasi-periodic eruptions (QPEs) are bright, recurring X-ray flares from galactic nuclei, occurring close to supermassive black holes (SMBHs). They last for about **several minutes to hours, repeat on timescales of hours to days, and reach peak luminosities of 10^{41} –10^{43} erg/s**. Some QPEs show alternating "long–short" recurrence times and "strong–weak" flare amplitudes, while others vary more irregularly. While their physical origin remains uncertain, **star–disc collision model** is one of the most promising models.

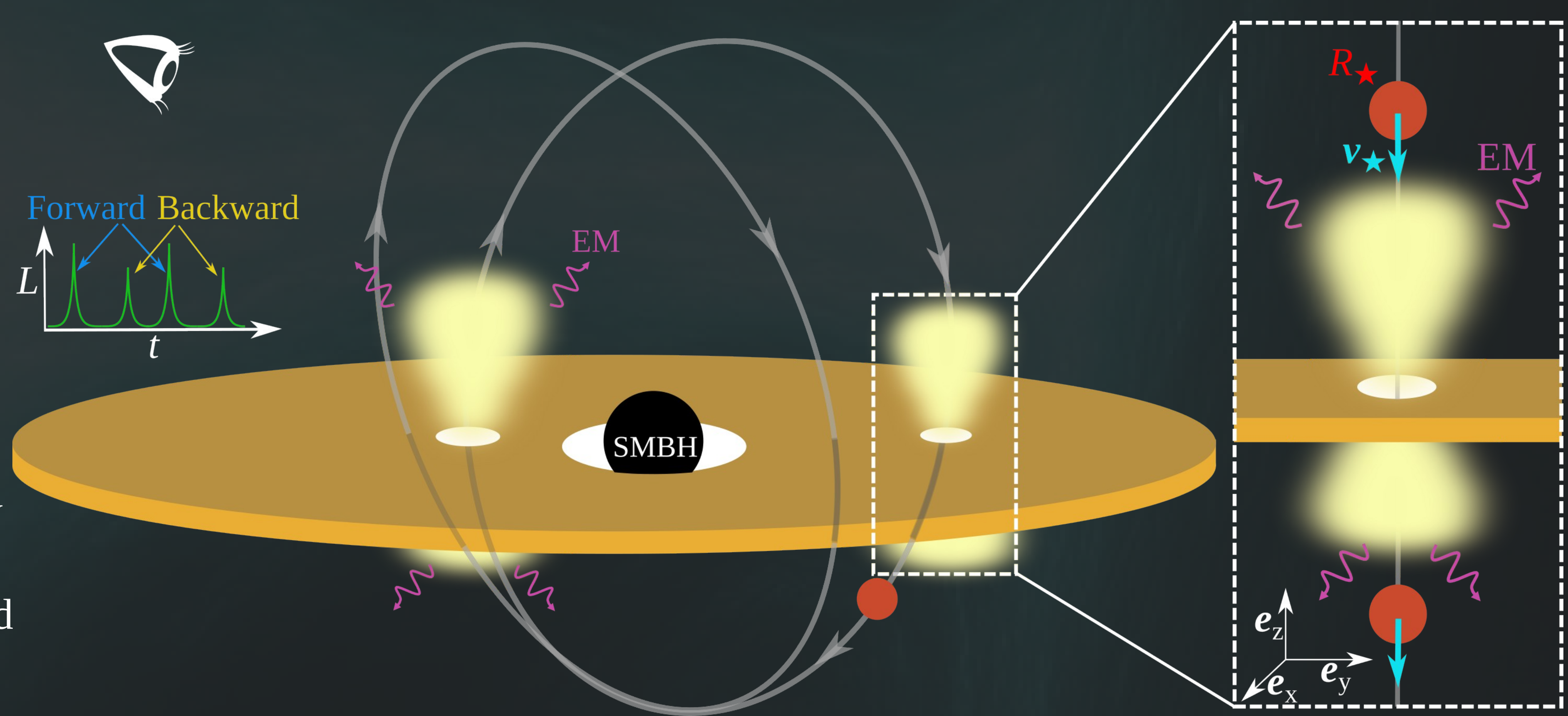


X-ray lightcurve of QPE GSN069 (Miniutti, G. et al. 2024).

2 Star-disc collisions model

In this model, a star (red circle) is brought close to an SMBH (black circle) and follows an inclined orbit (grey trajectories) through the accretion disc (orange cylinder), crossing it twice per orbit. Each crossing shocks the gas and launches dense, initially optically thick ejecta, which expand until radiation escapes as a QPE flare. This model naturally explains the alternating "long-short" patterns of QPEs due to a moderately eccentric orbit of the star. The observed "strong-weak" pattern could arise due to one collision appearing brighter and the other dimmer to an observer.

The inset on the right zooms into the collision region, highlighting the initial setup of our simulation: a local section of the disc and a star moving perpendicularly toward the disc.



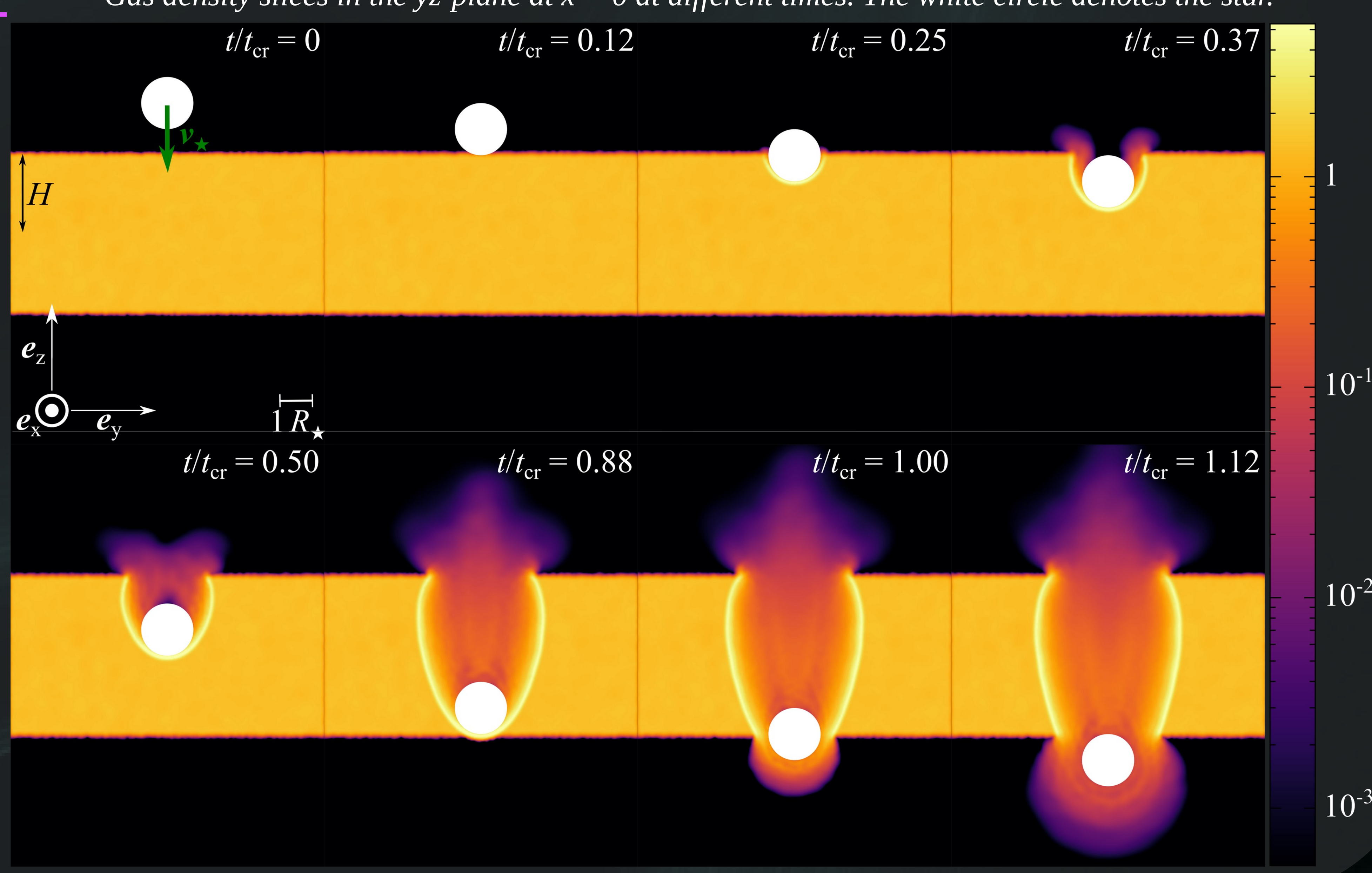
3 Radiation-hydrodynamics simulation

Using the SPH code Phantom (Price, D. et al. 2018), we perform a **radiation-hydrodynamics simulation of a star crossing a local section of an accretion disc**. The disc is initially stationary and uniform, with height $H = 3\,R_\odot$ and density $\rho_d = 3.8\times10^{-8}$ g cm^{-3} and . The star is modelled as a solid sphere with radius $R_\star = 1\,R_\odot$ moving perpendicularly toward the disc with velocity $v_\star = 0.1c$. The mass of gas directly intercepted by the star is therefore $M_d = 1.2\times10^{-7}\,M_\odot$. Radiation transport is treated via flux-limited diffusion approximation. Time is normalized to the disc-crossing time $t_{cr} = 2(H+R_\star)/v_\star = 3$ min.

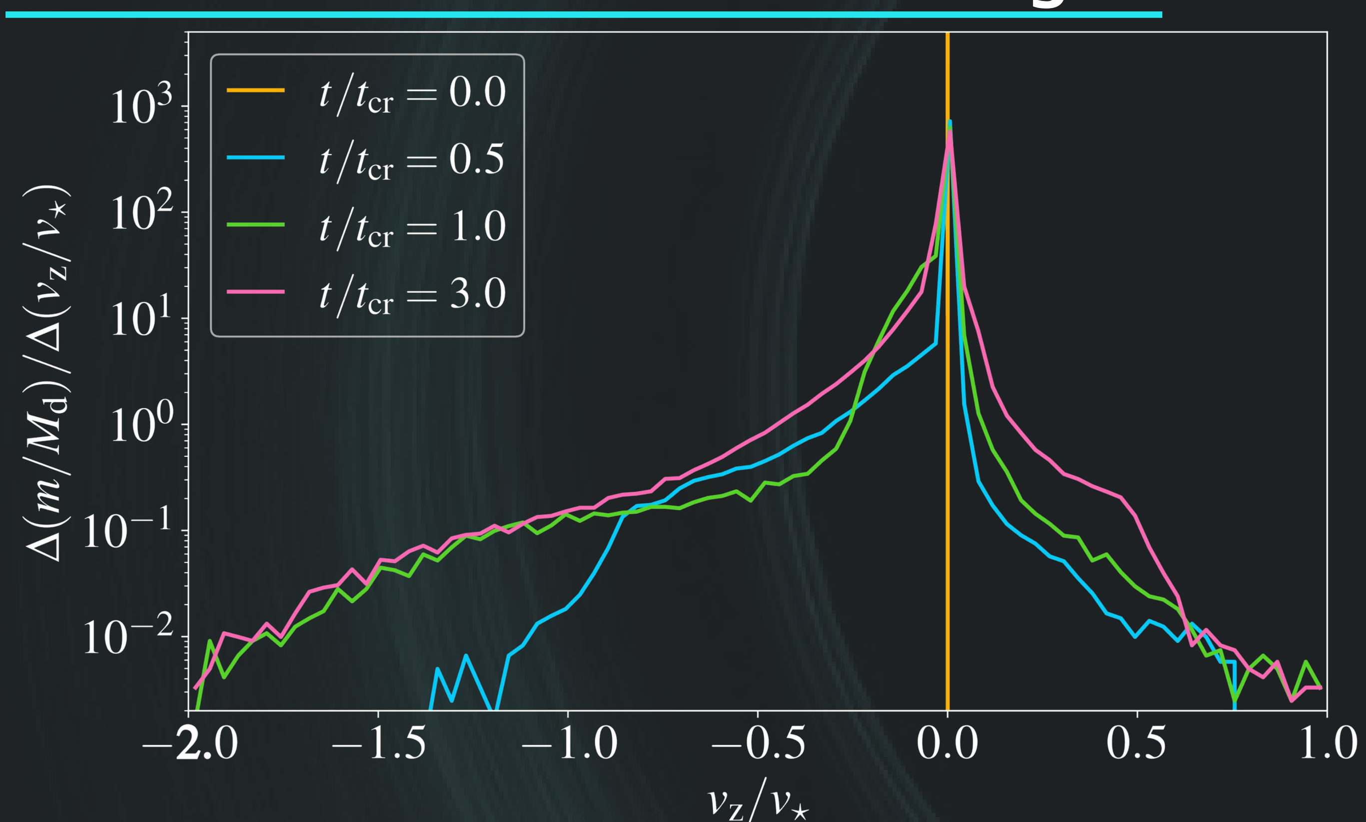
The star collides supersonically with the disc and forms a **radiation-pressure-dominated bow shock**, increasing the gas density, temperature, and radiation energy. Shocked gas then flows around the star and converges in its wake, forming a **secondary shock that redistributes momentum and energy**. When the shocks reach the outer disc boundaries, radiation trapped in the post-shock gas escapes into a lower-pressure region, triggering shock breakout. The upper and lower breakouts launch distinct ejecta components. Because the **momentum and energy are redistributed asymmetrically** around the star, the two outflows differ in mass, velocity, and luminosities.

Star-disc collisions launch two outflows on opposite sides of the disc that are inherently asymmetric.

Gas density slices in the yz-plane at x = 0 at different times. The white circle denotes the star.



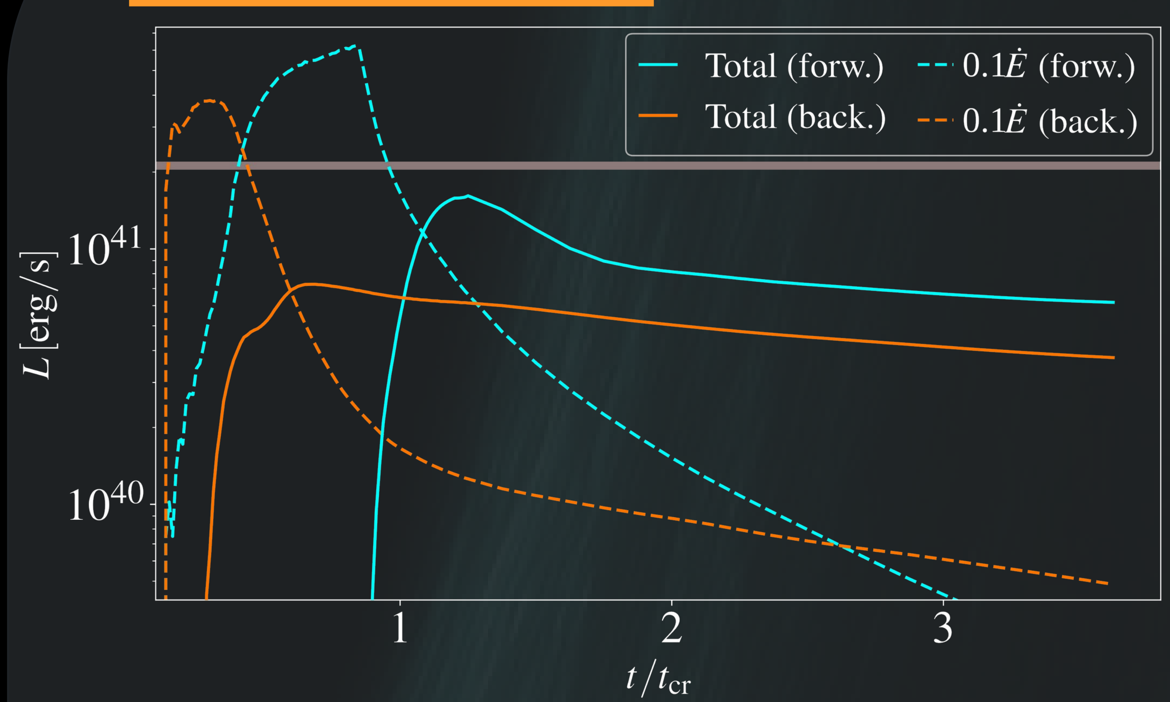
4 Momentum of the shocked gas



Mass-weighted distribution of v_z at different times for the shocked gas.

The **forward-ejected gas carries more momentum and energy** than the backward-ejected gas and experiences stronger shock heating. This is because the star injects momentum mainly along its direction of motion, and the forward-expelled gas originates closer to the stellar tip, where the shocks are strongest.

5 Lightcurves



~2x higher forward L due to higher shock heating rate

adiabatic losses

$L \sim \eta \dot{E}_0$

shock heating rate

Luminosity L of the forward (solid blue line) and backward (solid orange line) outflow. The dashed blue and orange lines denote shock heating rate $\dot{E}$ scaled by a factor 0.1.

The **forward outflow is about twice as luminous** as the backward outflow, with a more pronounced early peak due to forward shock breakout. Since adiabatic losses are similar for both outflows, the luminosity asymmetry mainly reflects stronger shock heating in the forward ejecta. This intrinsic asymmetry provides a **natural explanation for the observed "strong–weak" QPE flare pattern.**