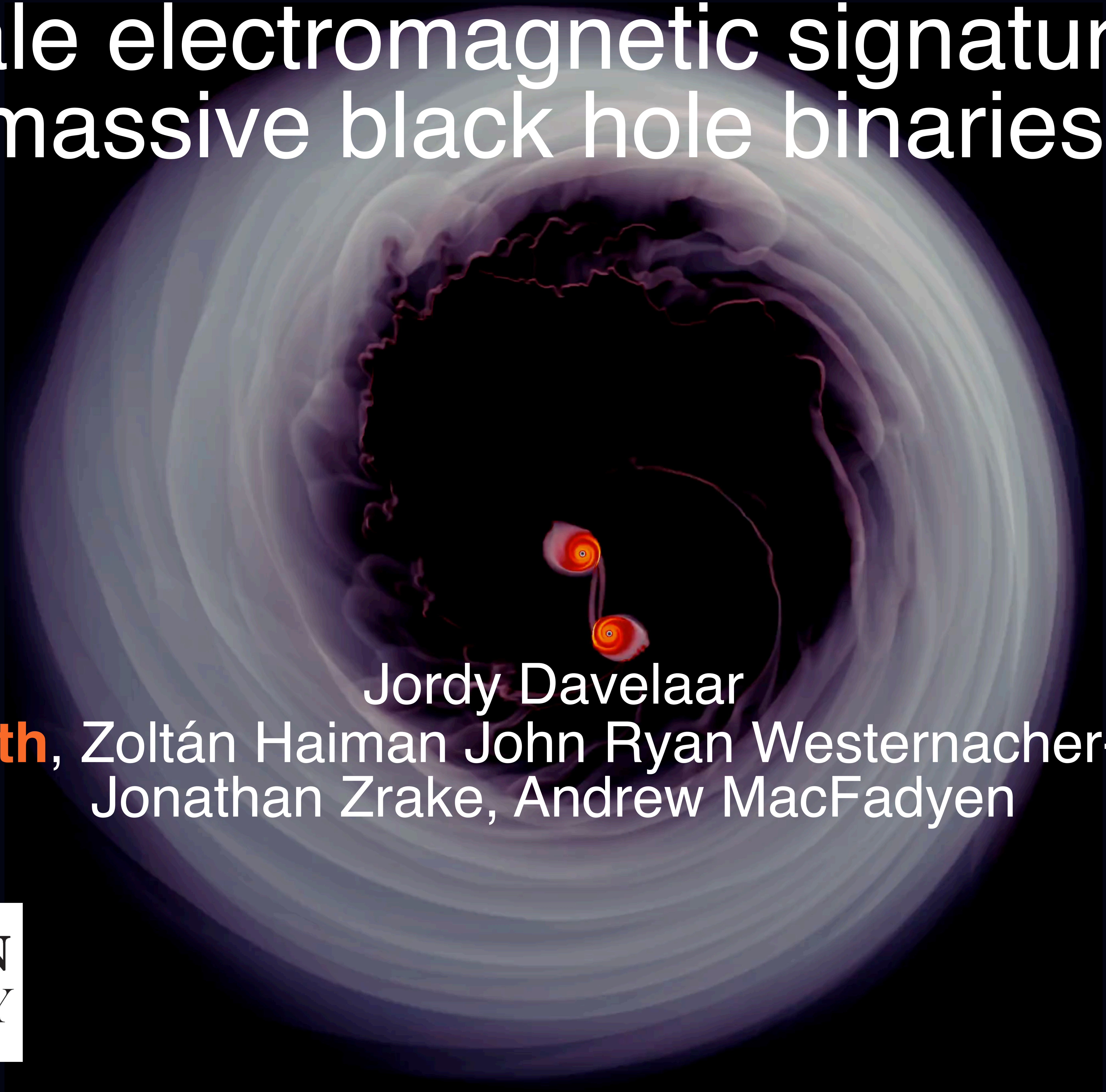
Tell-tale electromagnetic signatures of massive black hole binaries



Jordy Davelaar

Luke Krauth, Zoltán Haiman John Ryan Westernacher-Schneider, Jonathan Zrake, Andrew MacFadyen

PRINCETON UNIVERSITY

NHFP
NASA Hubble Fellowship Program

Massive black hole binaries

Michael Koss/ALMA (ESO/NAOJ/NRAO)/M. Weiss (NRAO/AUI/NSF)

Laser Interferometer Space Antenna

LISA: space-based observatory designed to detect low-frequency gravitational waves (Colpi, et al. 2024)

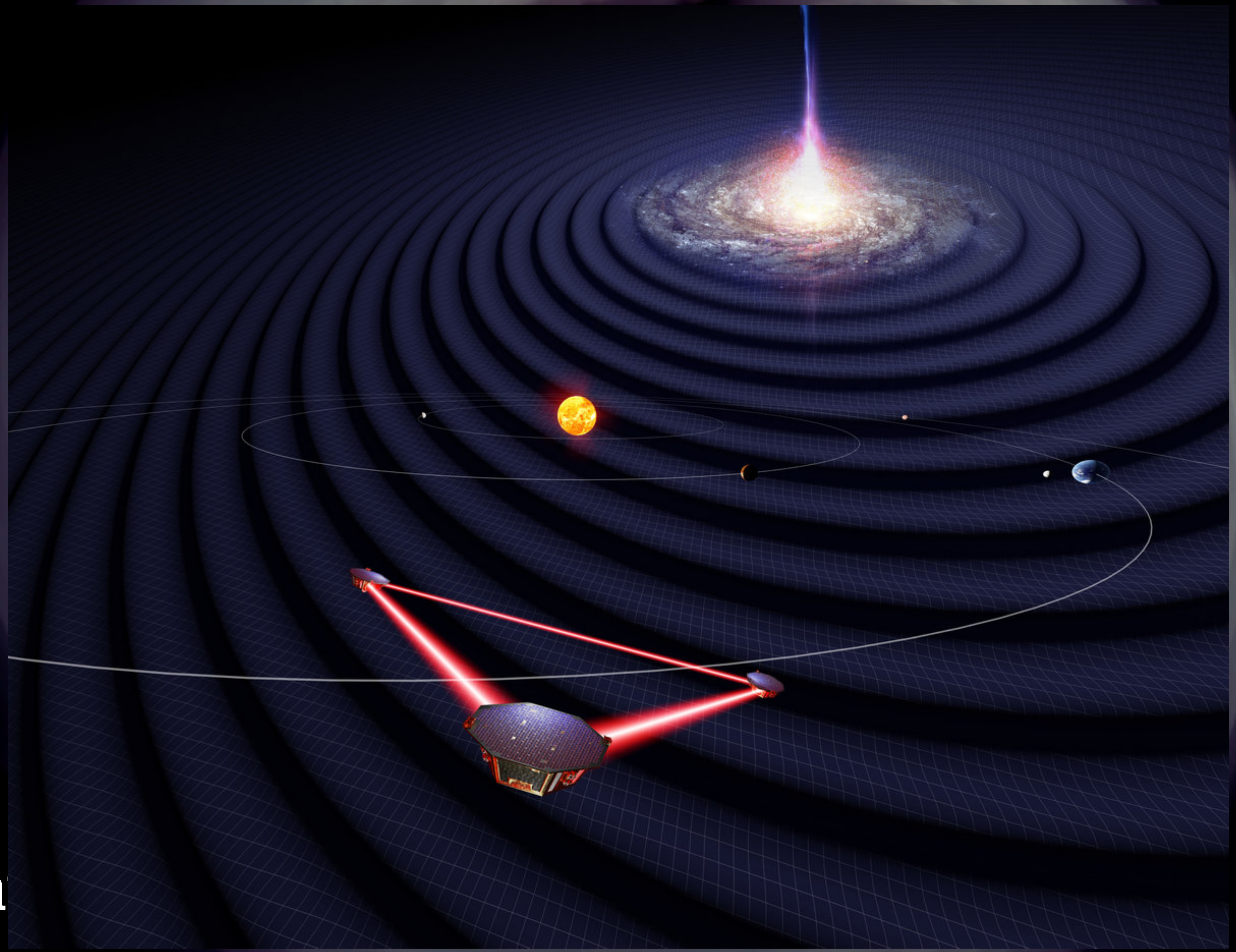
Launching Next Decade

Frequency Range: ~0.1 mHz to ~1 Hz

Targets:

- Wider-separation binaries
- Massive binary black holes
- white dwarf mergers

Unlocking new insights into the low-frequency gravita wave universe

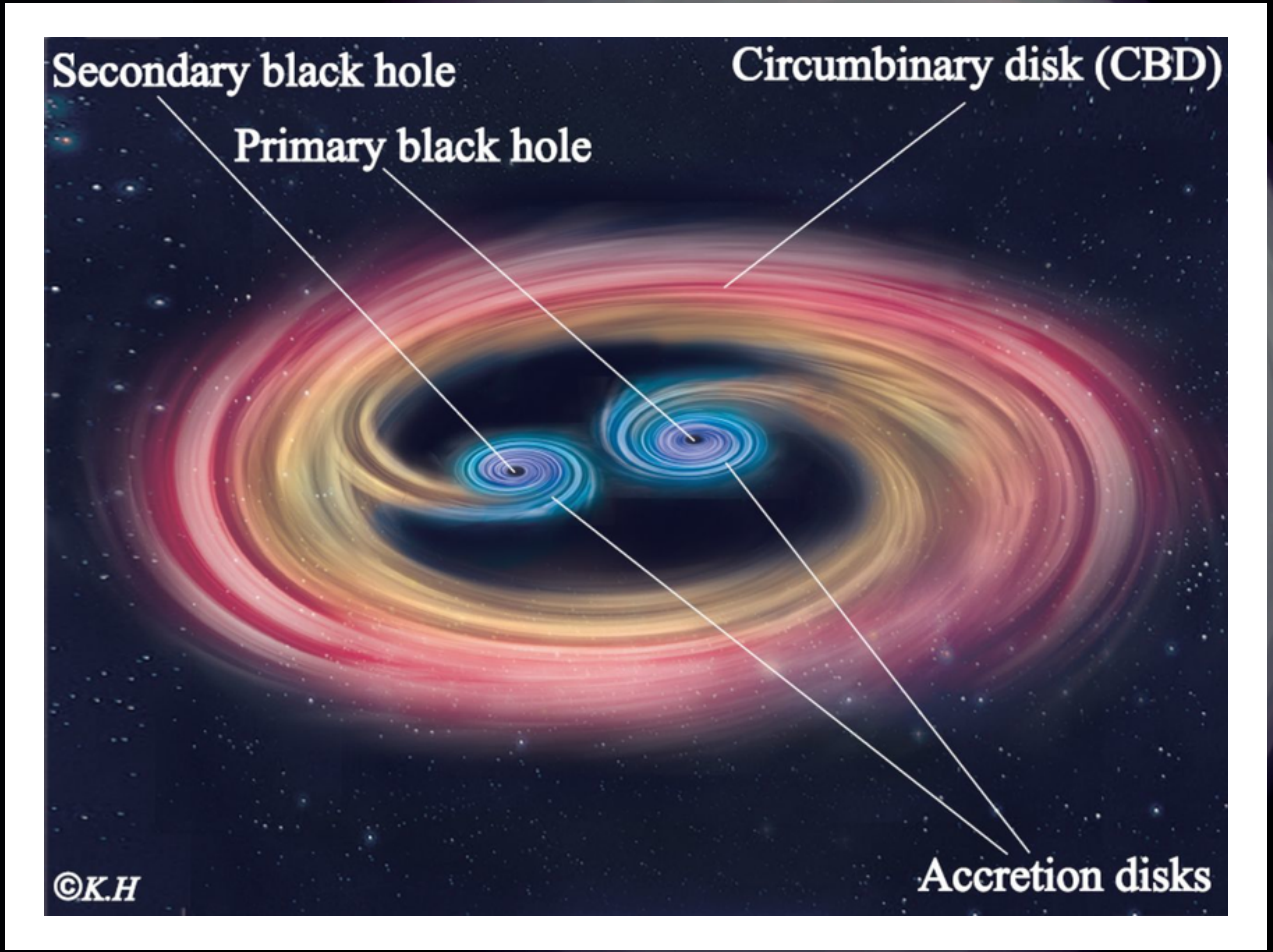


Accretion around binaries

Binary system is surrounded by circumbinary disk. Each black hole has a minidisks.

Question: Does the feeding of the minidisks continue all the way through merging?

Method: Study merging black hole binaries with Newtonian Hydrodynamical GPU-code Sailfish (Westernacher-Schneider et al. 2022)



Hydrodynamical Setup

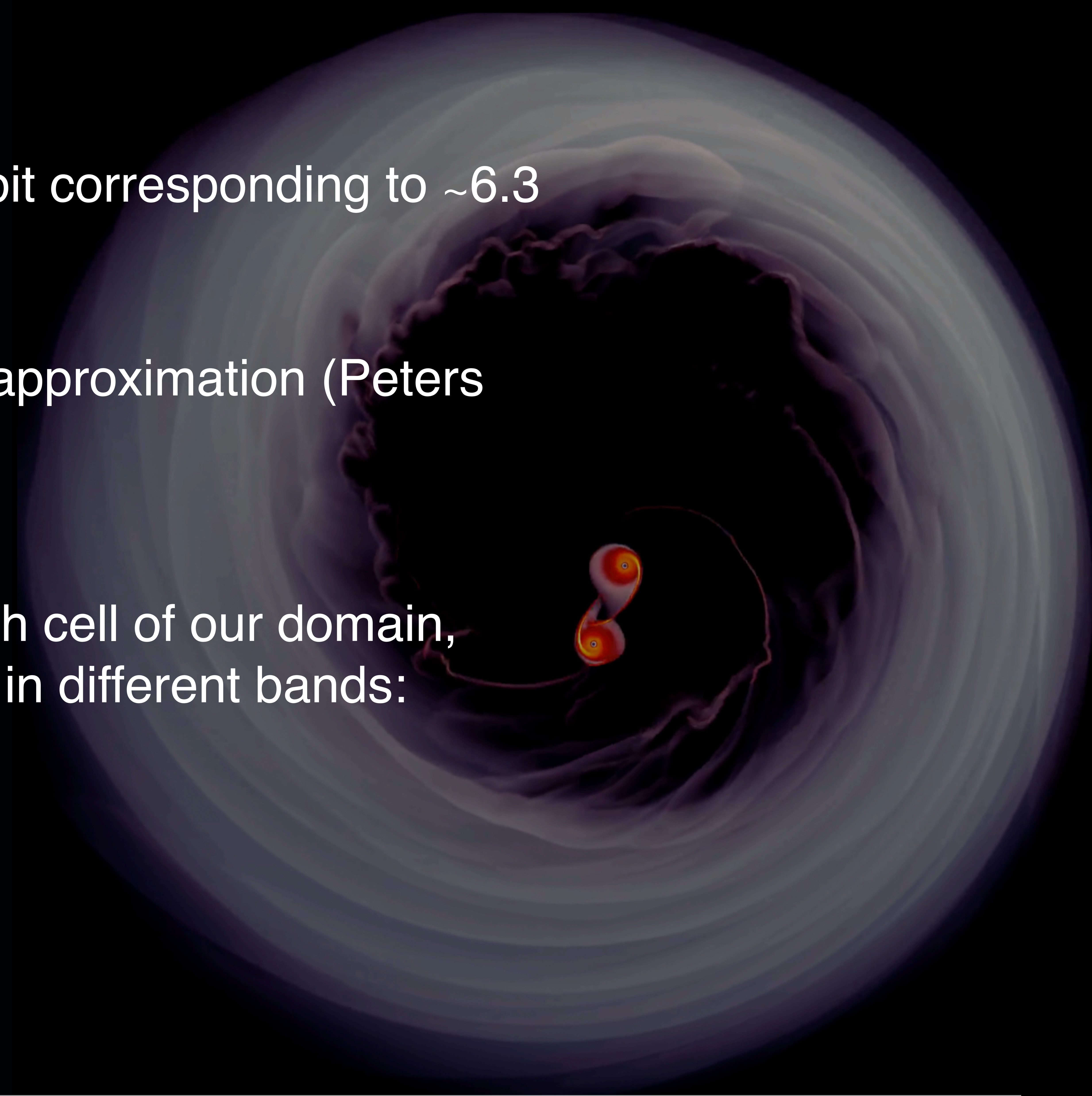
- Evolve for 820 orbits on a fixed circular orbit corresponding to ~6.3 viscous times at $r = a_0$.

- Inspiral implemented with the quadrupole approximation (Peters 1964):

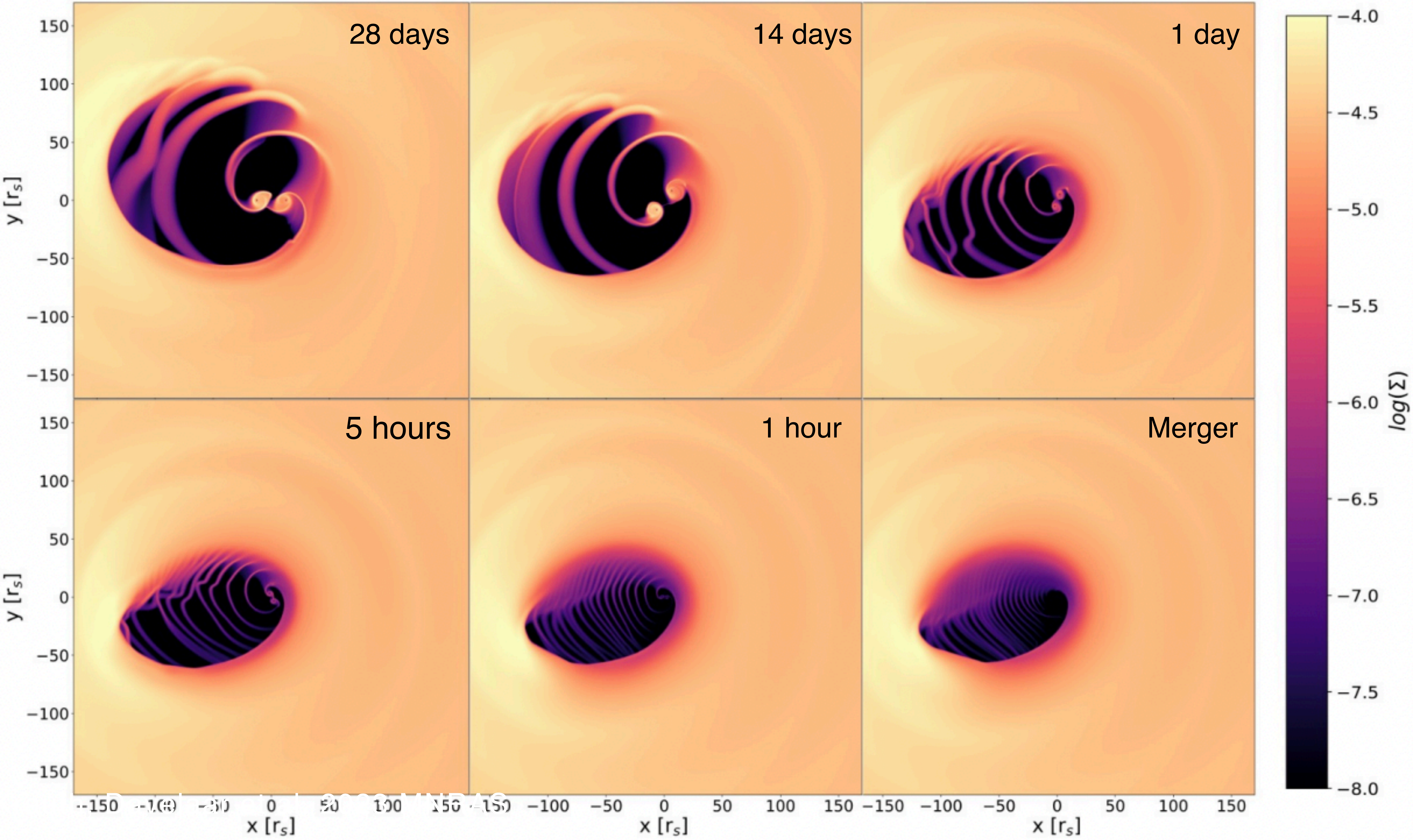
$$a(t) = a_0(1 - t/\tau)^{1/4}$$

- We assume black-body emission from each cell of our domain, which allows us to compute the luminosity in different bands:

$$dL = \pi dA \int_{\nu_1}^{\nu_2} \frac{2h\nu^3/c^2}{exp\left(\frac{h\nu}{kT_{eff}}\right) - 1} d\nu$$

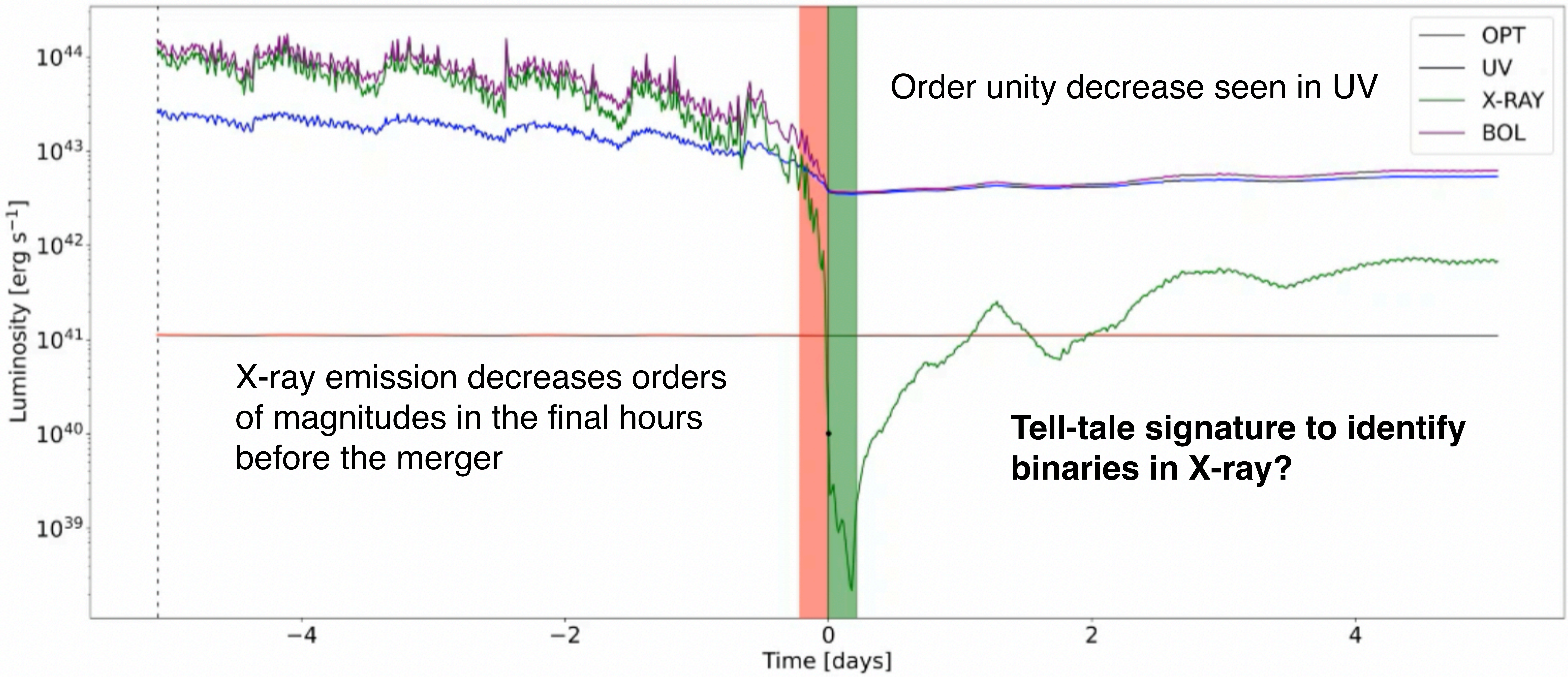


Simulation results



28 days
14 days
1 day
5 hours
1 hour
Merger
y [r_s]
x [r_s]
$log(\Sigma)$

Light curves



Accretion driven signal

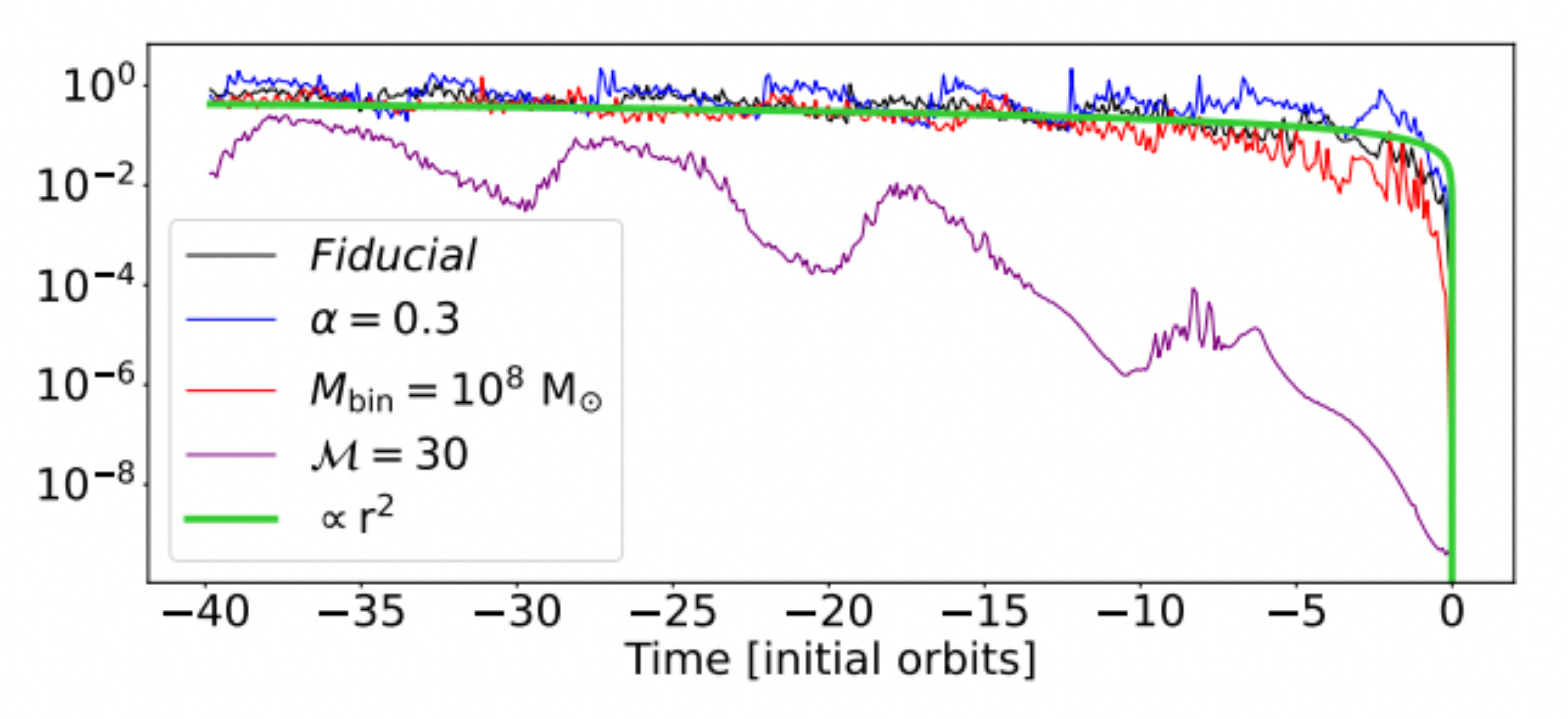
As the binary shrinks the tidal truncation radius shrinks

$$r_{\mathrm{tidal}} \approx 0.4 a_{\mathrm{bin}}$$

The total Luminosity is set by the total emitting surface area

$$L \propto r_{\mathrm{disk}}^2 \propto r_{\mathrm{tidal}}^2 \propto a_{\mathrm{bin}}^2 \propto (1 - t/\tau)^{1/2}$$

As the binary shrinks, the minidisk starve, and the X-ray luminosity plummets



Krauth, Davelaar et al. 2023 MNRAS

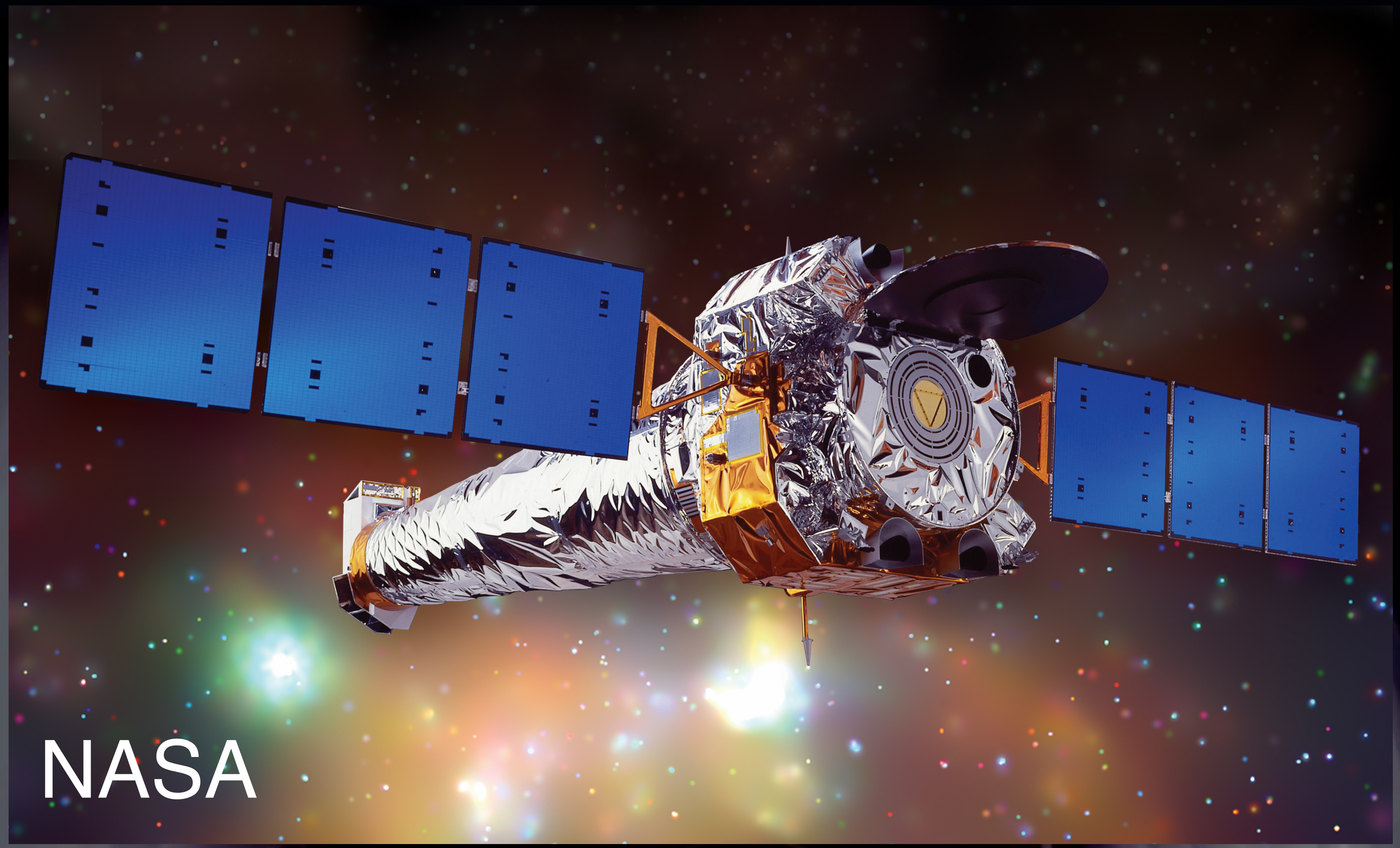
A needle in a hay stack?

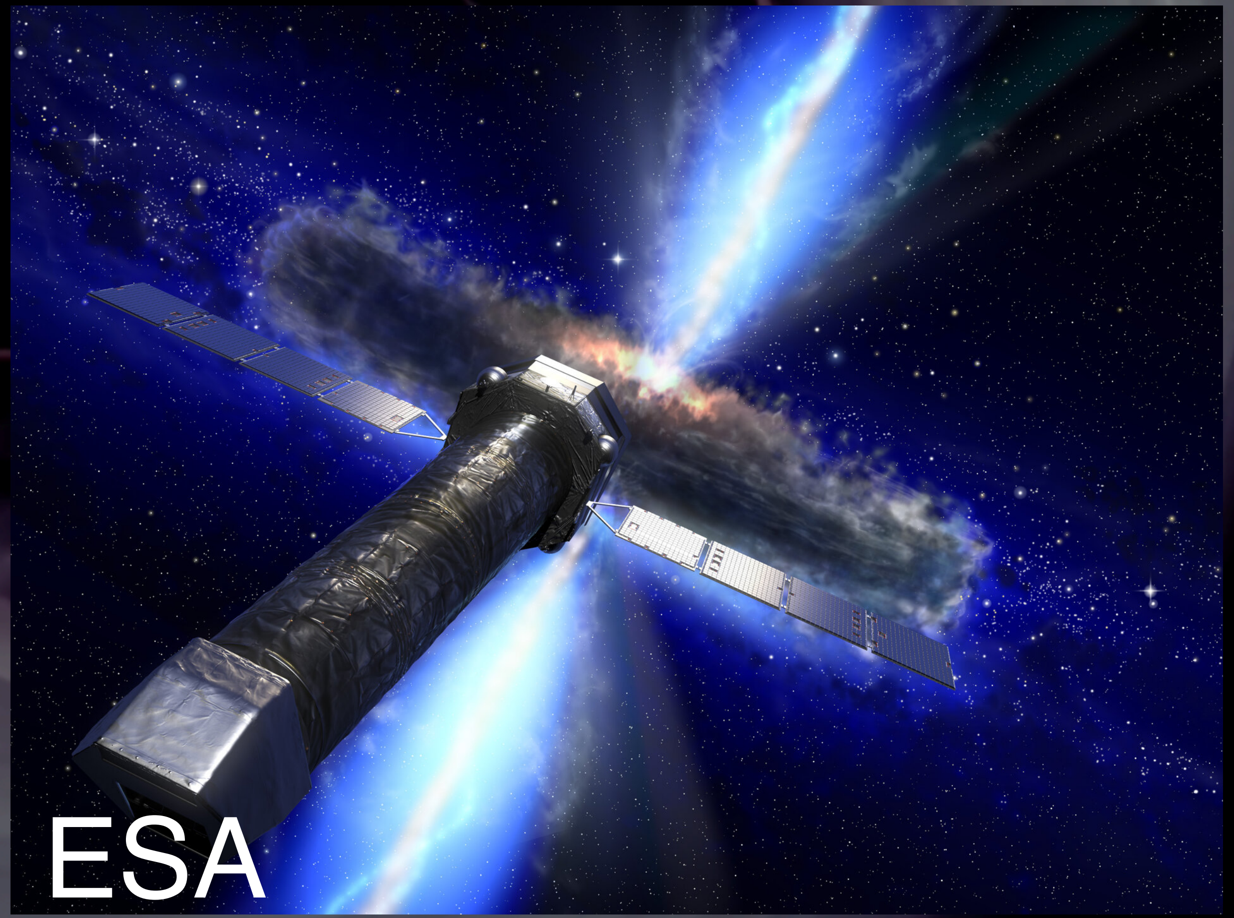
Observational constraints for our fiducial model:

- Lynx: $z < 1$ for X-rays < 10 keV
- Athena: $z < 1$ for X-rays < 2 keV, or $z < 0.5$ for X-rays 2-10 keV
- Peaks ~2 keV 10 hours prior to merger, and decreases to merger

Compare maps to archival data, e.g. Chandra, XMM Newton,…

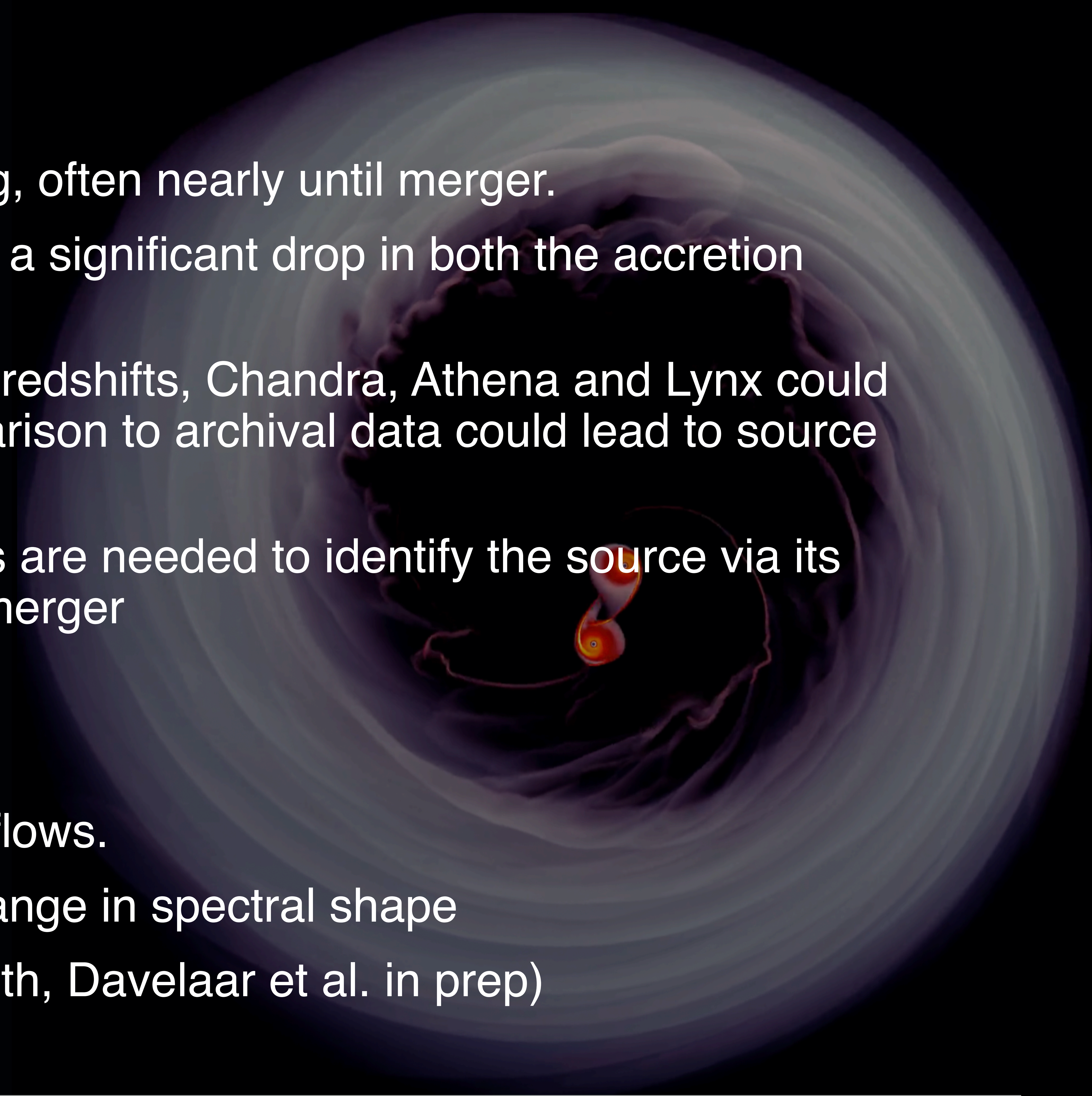
X-ray's could be crucial in finding the hosts of merging black hole binaries in the era of LISA!





Krauth, Davelaar et al. 2023 MNRAS

Summary



- Minidisks persist well past this nominal decoupling, often nearly until merger.
- Minidisks are eventually disrupted, which leads to a significant drop in both the accretion rates and the X-ray luminosity.
- Within ≈10 hrs and for certain binary masses and redshifts, Chandra, Athena and Lynx could perform a full search of the LISA error box, comparison to archival data could lead to source detection.
- Our results suggest that as few as two data points are needed to identify the source via its disappearing thermal X-ray emission just before merger

Caveats:

- Newtonian 2D hydro… No B fields, no 3D, no outflows.
- Non-thermal X-ray emission might take over? Change in spectral shape
- Does this survive for unequal masses? (yes! Krauth, Davelaar et al. in prep)