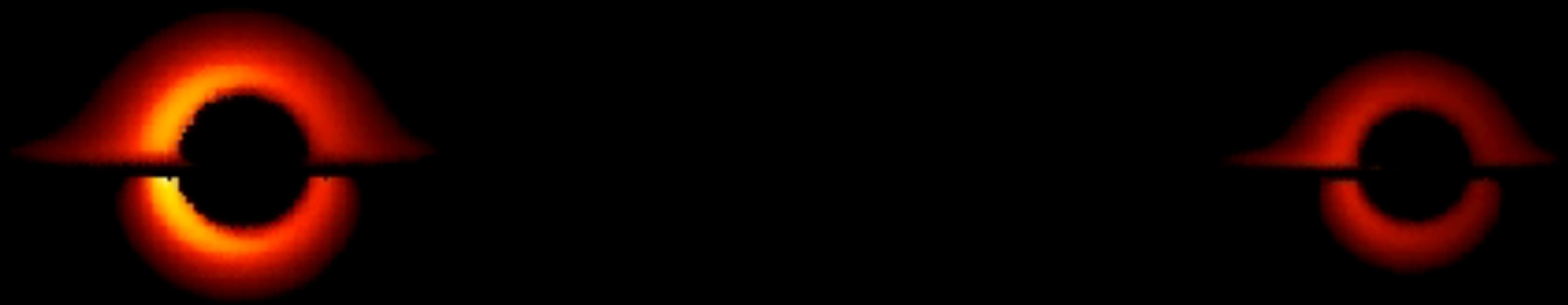
Tell-tale electromagnetic signatures of massive black hole binaries



Jordy Davelaar

Einstein Fellow

PRINCETON UNIVERSITY

NHFP
NASA Hubble Fellowship Program

Black hole binaries

Expected to reside in numerous galactic nuclei (Begelman+ 1980). Potential sources of Gravitational Wave signals that can be seen by PTA and LISA.

Produced by galactic mergers. Interactions with gas and stars migrate the black holes towards each other

Localizing these binaries relies on electromagnetic signatures, but... we dont have a clear signature to look for!

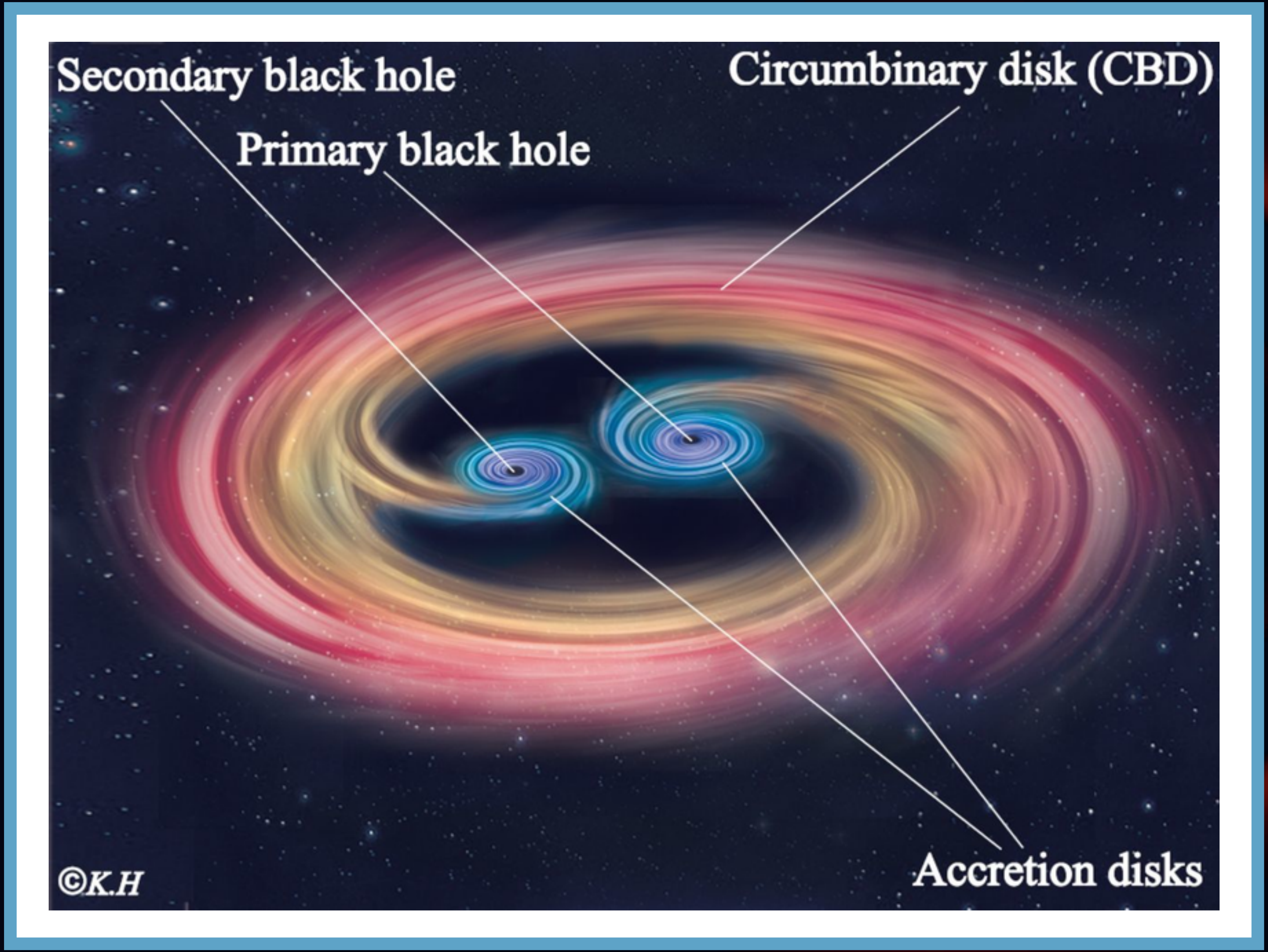
Voggel et al 2021/ESO

Accretion around binaries

Binary system is surrounded by circumbinary disk

Due to gravitational torques accretion material is accreted into the cavity

Forms two minidisks around each black hole.

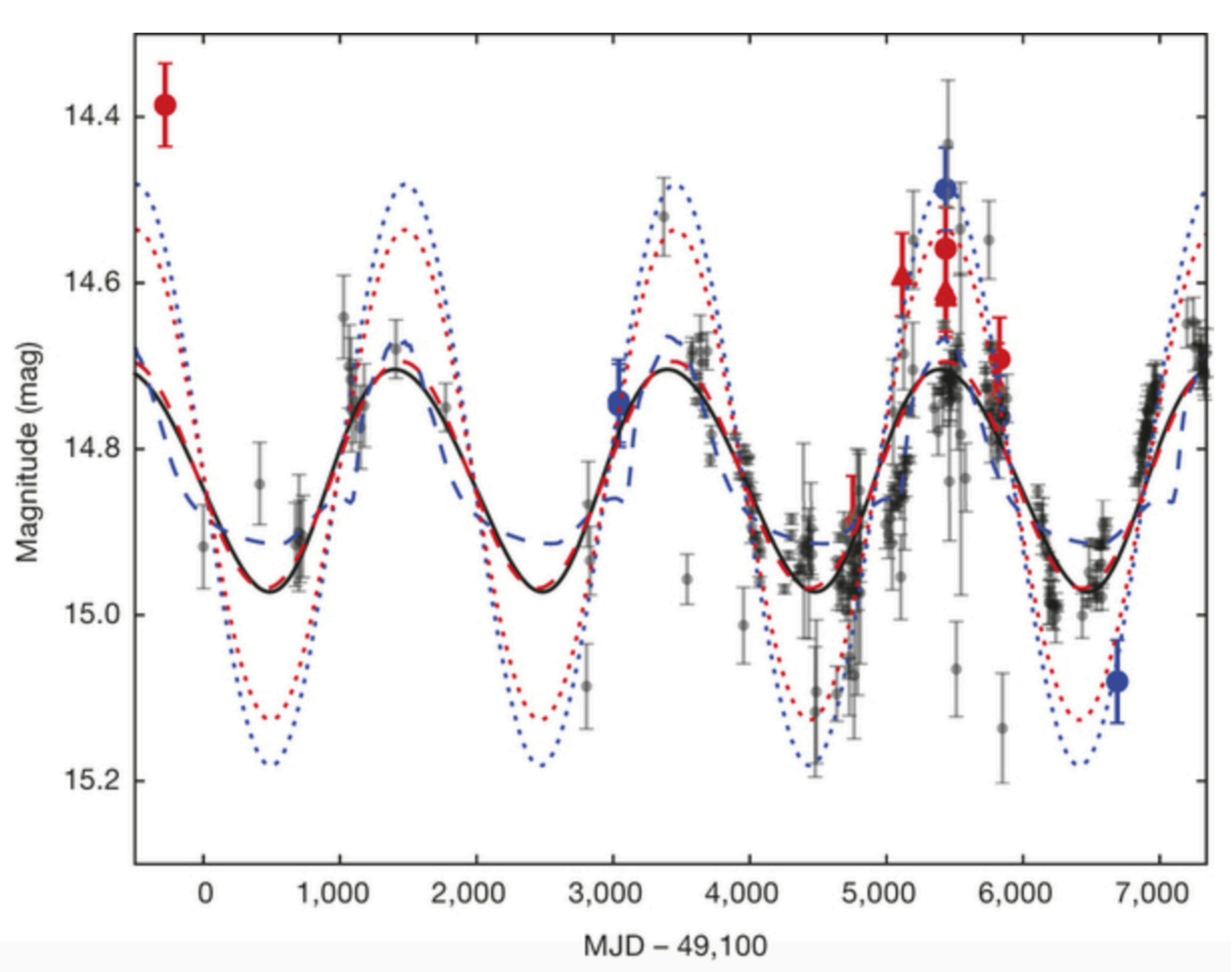


Observational evidence

Currently ~150 candidates found with large time-domain surveys, see e.g. D'Orazio+2015, Graham+2015, Charisi+2016, Lui+2019,2020, Hu+2020

Typically masses of 10^9 solar mass, and orbits of a year.

However, periodic signatures are degenerate with Quasar red-noise! (Graham et al. 2015b, Vaughan et al. 2016)



D'Orazio+2015

Spikey

Observed by Kepler in 2010, KIC-11606854 (Hu+2020)

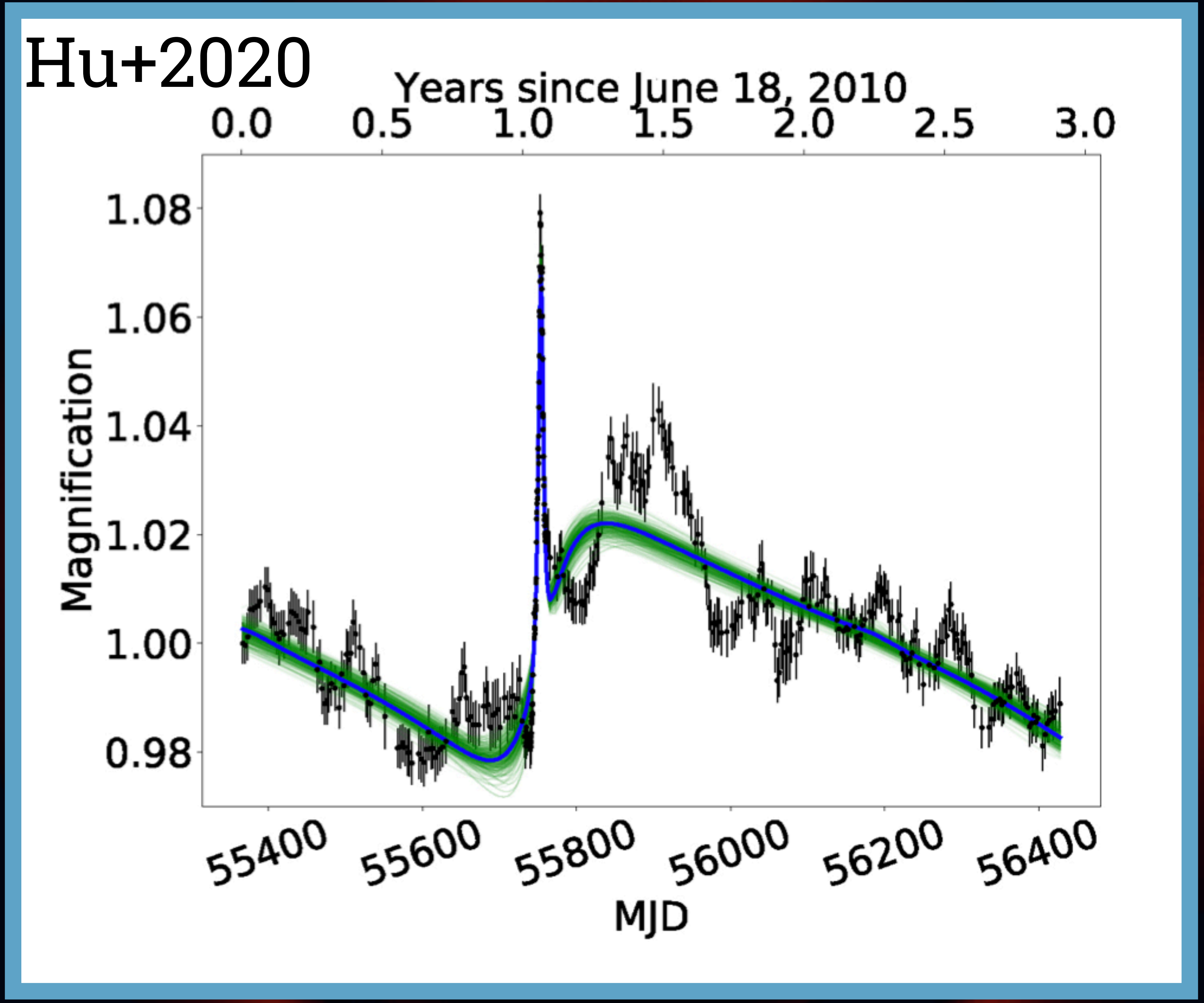
Doppler modulated light curve plus a strong flare when BHs are aligned

Self-lensing model shows remarkably good fit.

Binary with 10^8 solar mass, seen at ~80 degrees

Modeling does not take GR or finite source sizes into account.

Need for more sophisticated models!



General-relativistic ray tracing (GRRT)

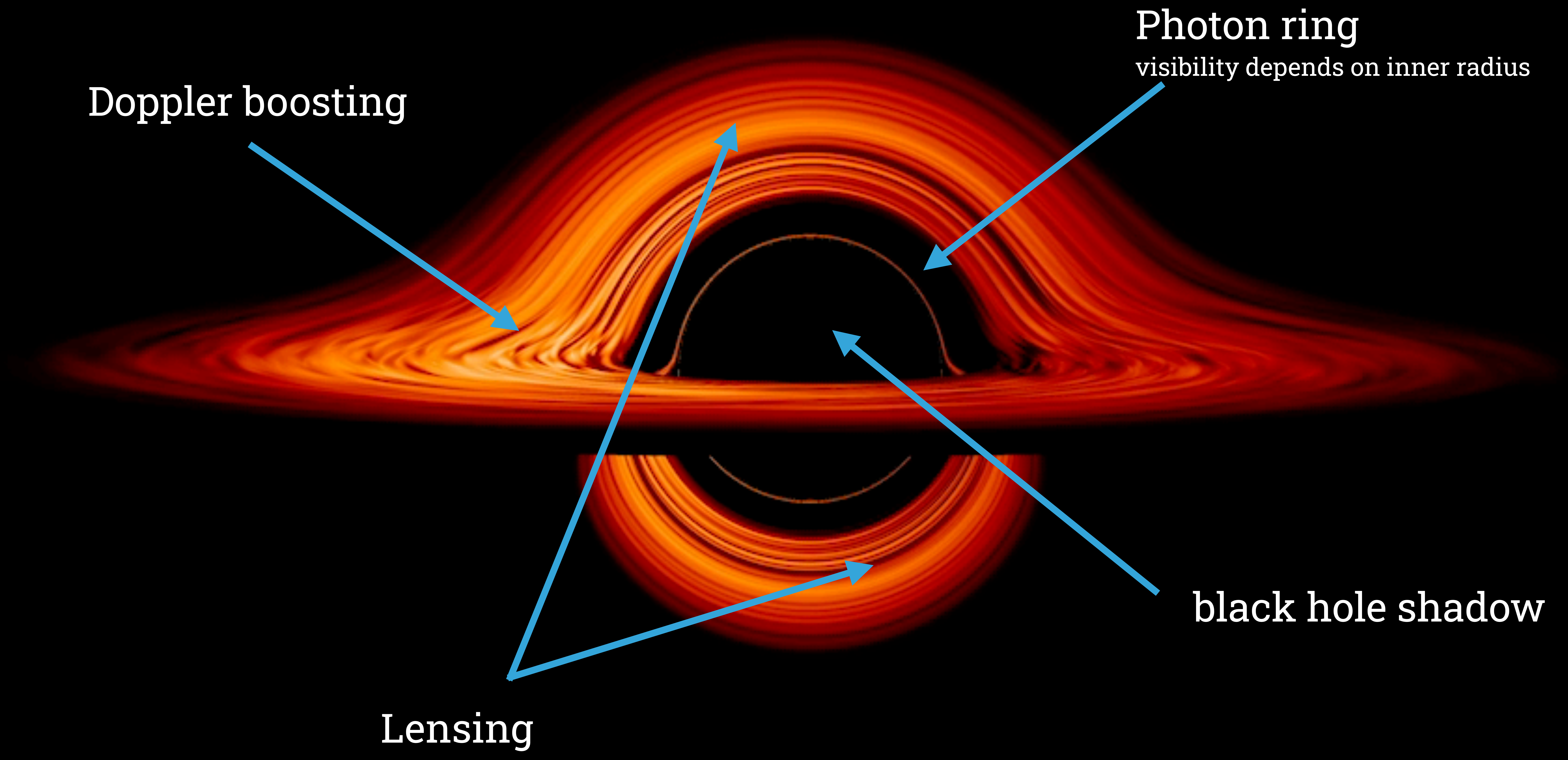
RAPTOR; geodesic integrator and radiation transport code
Code papers: Bronzwaer,et al. 2018, 2020, Davelaar et al 2018

Camera at the edge of the domain. Each pixel is assigned a wave vector and solve the geodesic equation

$$\frac{dx^\alpha}{d\lambda} = k^\alpha,$$
$$\frac{dk^\alpha}{d\lambda} = -\Gamma^\alpha_{\ \mu\nu} k^\mu k^\nu.$$

As the geodesic is computed, solve the radiation transport equation

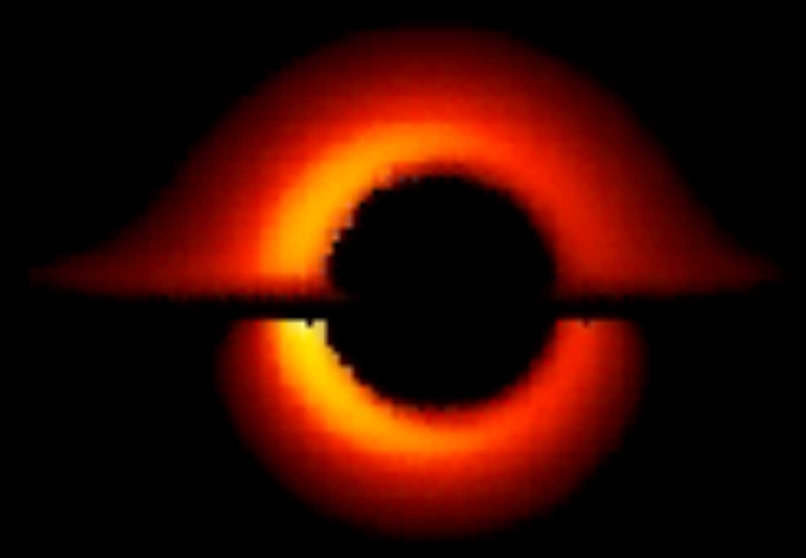
$$\frac{d}{d\lambda}\left(\frac{I_\nu}{\nu^3}\right) = \frac{j_\nu}{\nu^2} - \nu\alpha_\nu\left(\frac{I_\nu}{\nu^3}\right)$$

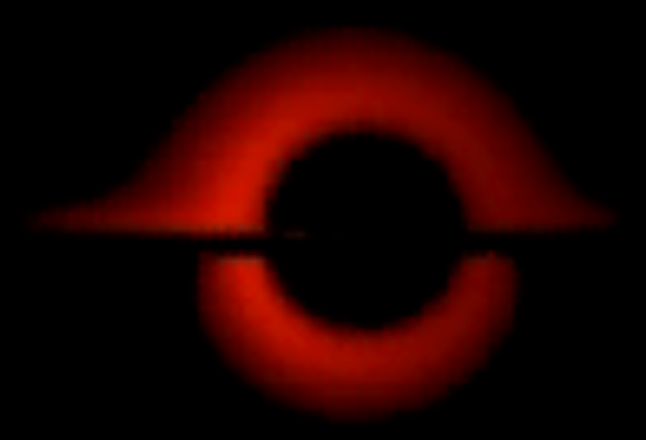


Credit: Jeremy Schnittman

Self-lensing model

Viewing angle 87 degrees
Binary separation 100 gravitational radii
Equal mass binary
Optically thick - no photon ring
X-ray image



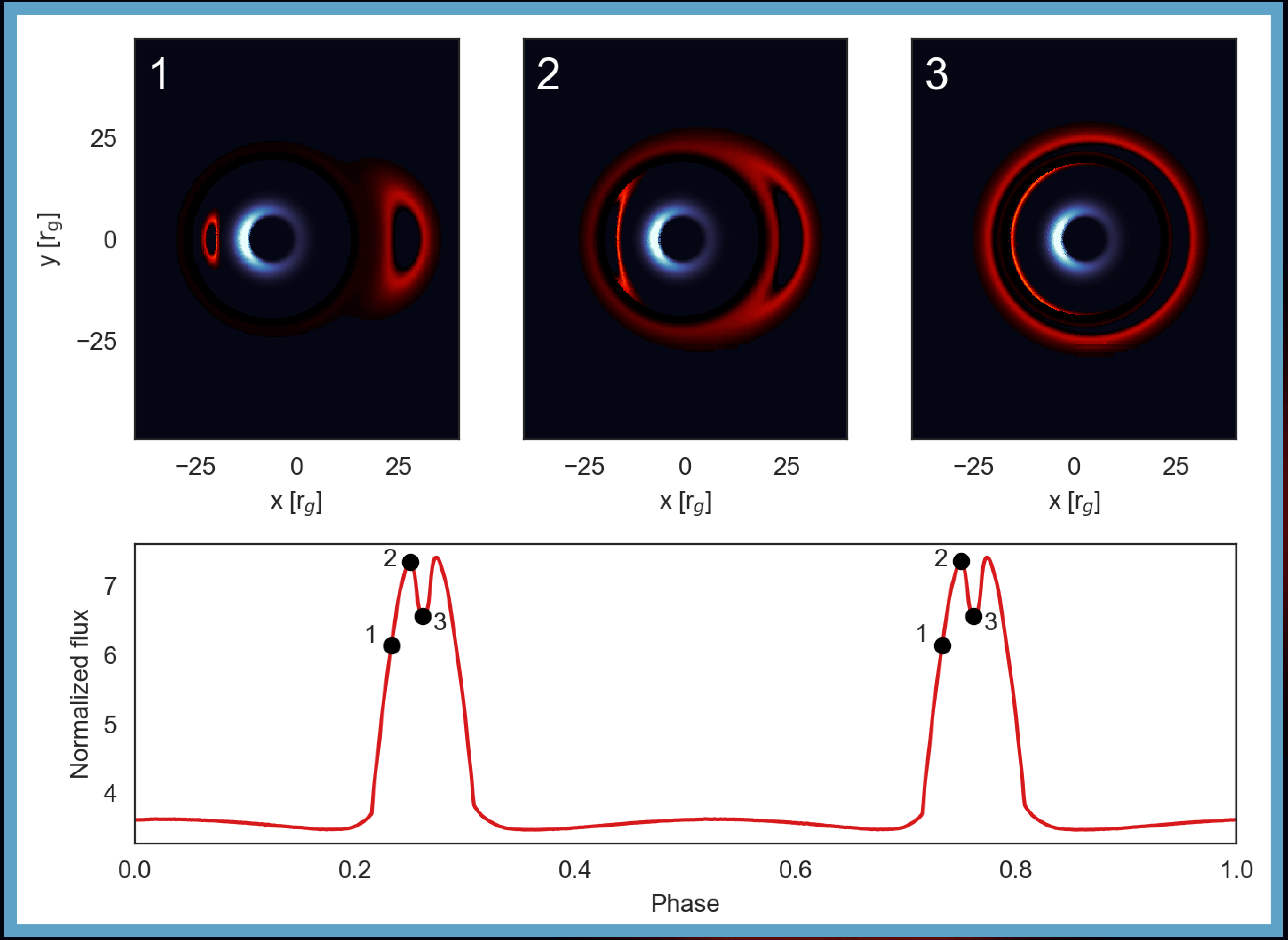


Davelaar & Haiman 2022 PRL & PRD

A shadow in disguise

Viewing angle 90 degrees
Binary separation 100 gravitational radii
Equal mass binary
X-ray image

Lens focal point moves over spatially varying emission morphology, which is imprinted in the observed light curve

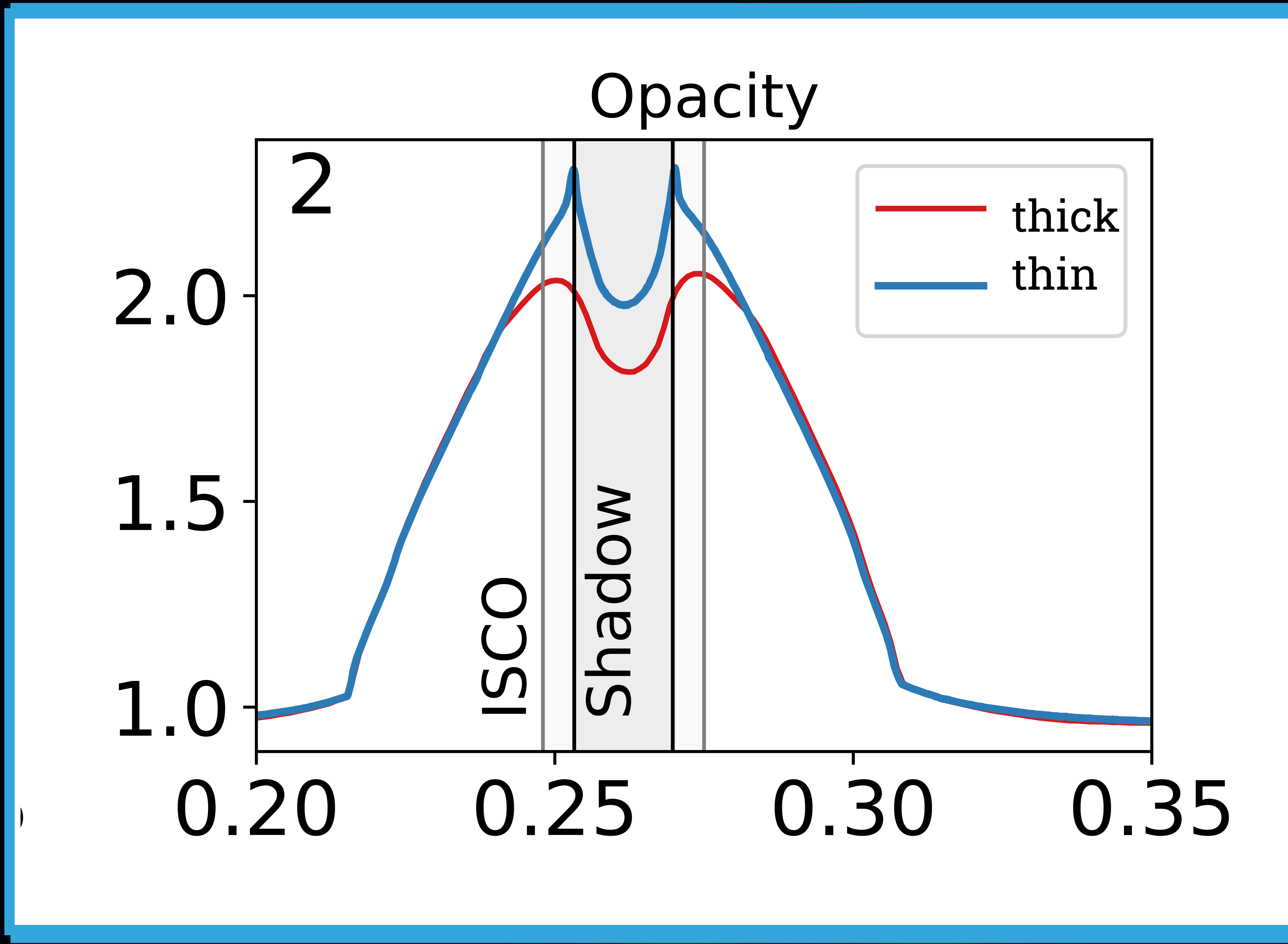


A shadow in disguise

Duration exactly matches the time it takes the lens to move over the black holes apparent size, the “black hole shadow” (Falcke+2000)

Shadow size is tightly constraint by GR if you know the mass of the black hole.

Possible to find black hole shadows that are unresolvable by current VLBI arrays such as the EHT.



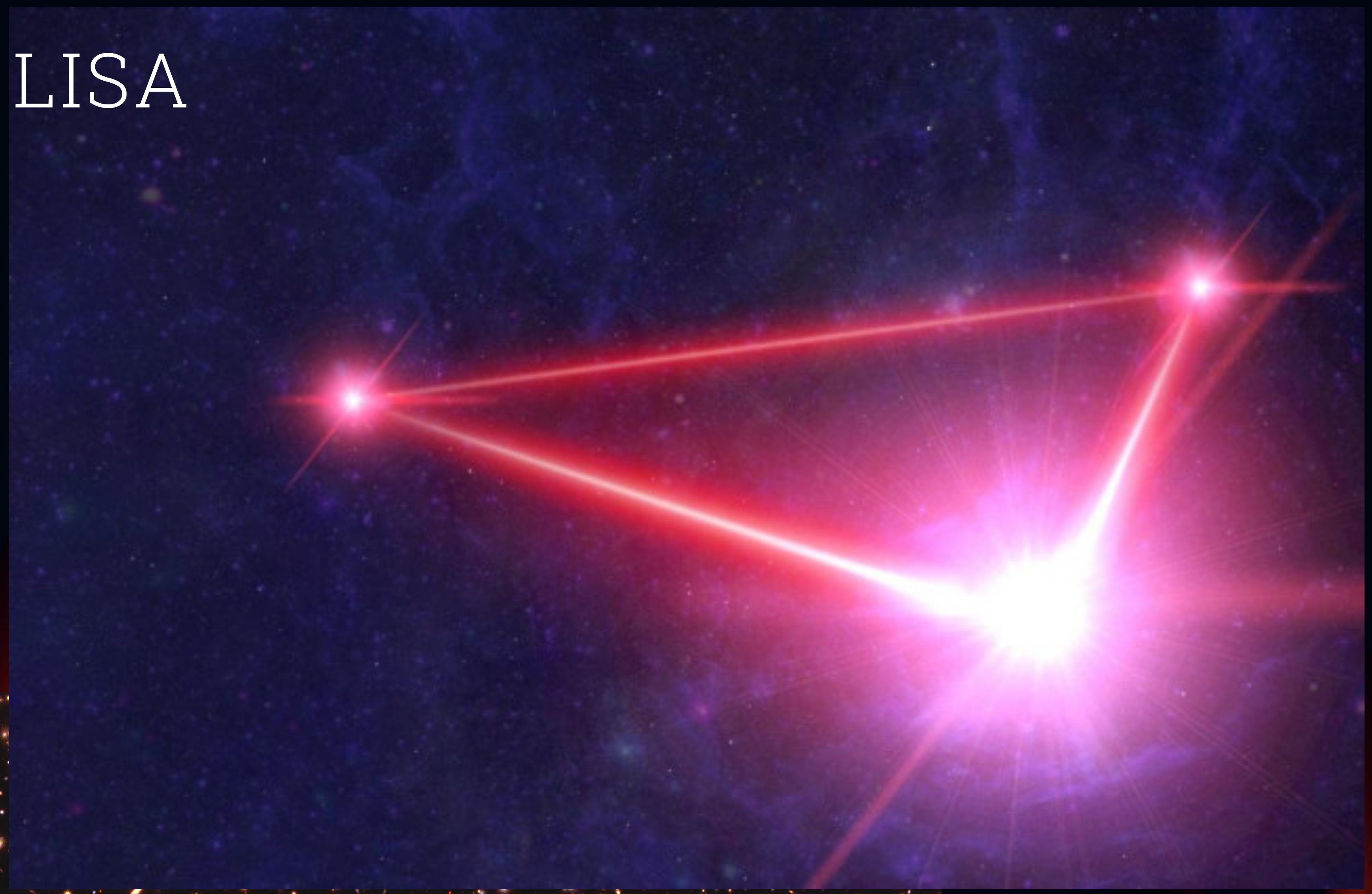
Search strategies

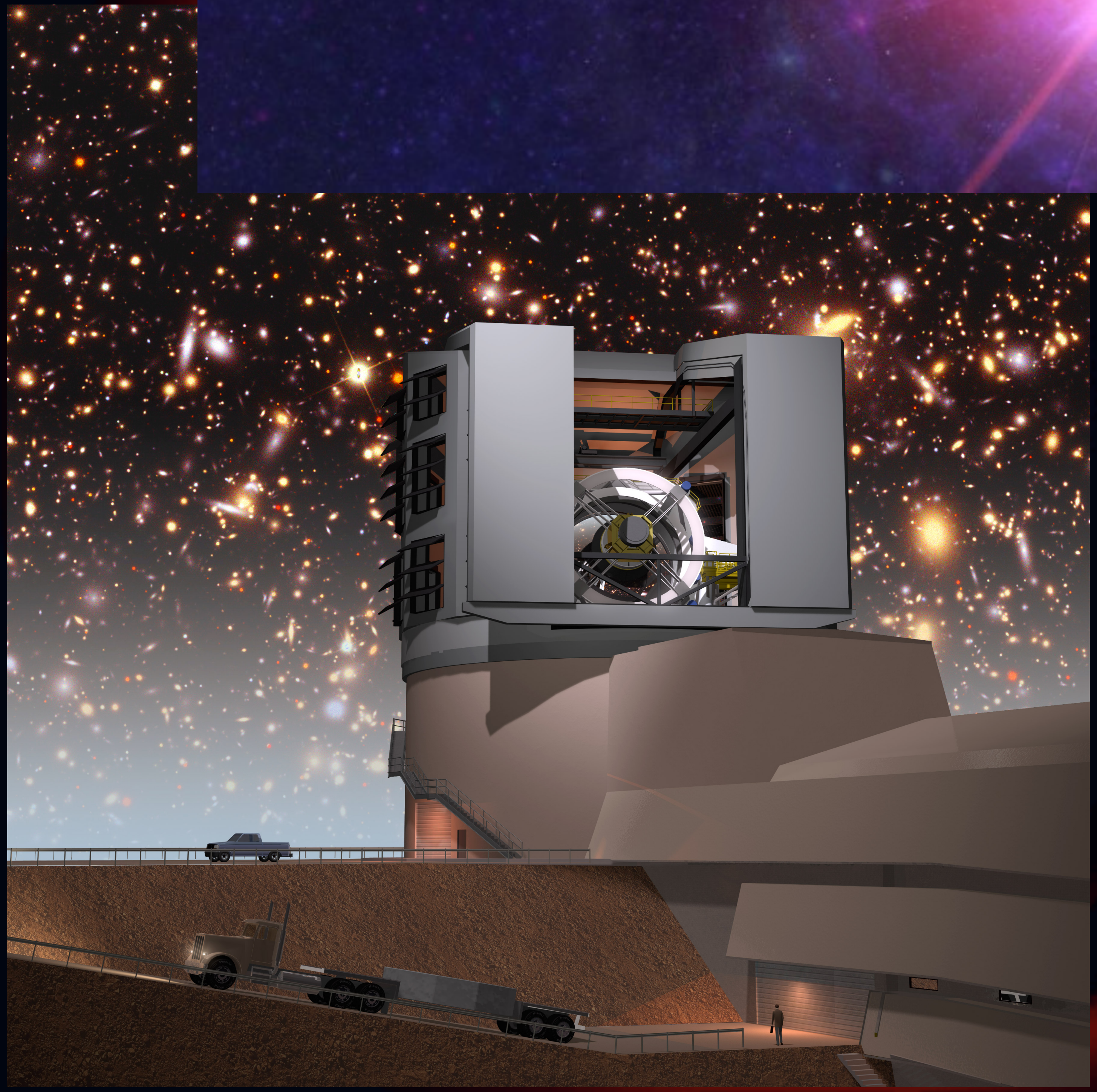
How to find this dip?

Window of inclination is small, for typical black hole in current data; 10^9 M_{sun} BHs period is typically a year, dip lasts ~days and inclination window is couple of degrees at most.

~1 % probability of finding the dip in current data

- Follow up on current candidate, ~150 sources
- Find new sources with VRO's LSST, 100 million AGN targets -> might find dozens of dips (Park, Xin, Davelaar + 2024 in prep)
- pre-merger EM emission of LISA sources


LISA


Rubin Observatory

Summary and outlook

SLFs can be used to confirm presence of black hole binaries if the viewing angle is favorable.

We used GRRT to study how our binary parameters alter the shape and spacing of the SLFs

Inside the SLF we found evidence for a dipping-feature that correlates with the apparent size of the black hole on the sky (the black hole shadow)

This might open new ways to find evidence for black hole shadows currently out or reach by VLBI