Illuminating Black Holes

Binary Dynamics, Accretion, and Tidal Disruption

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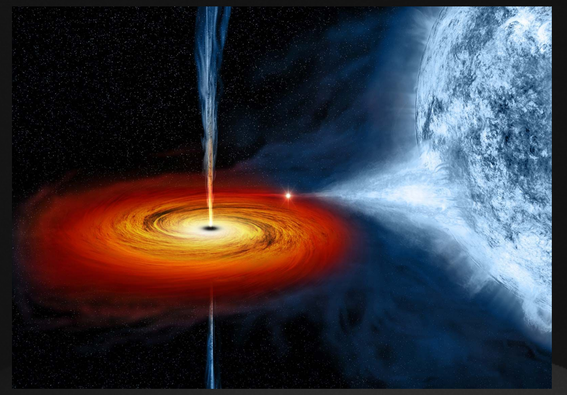
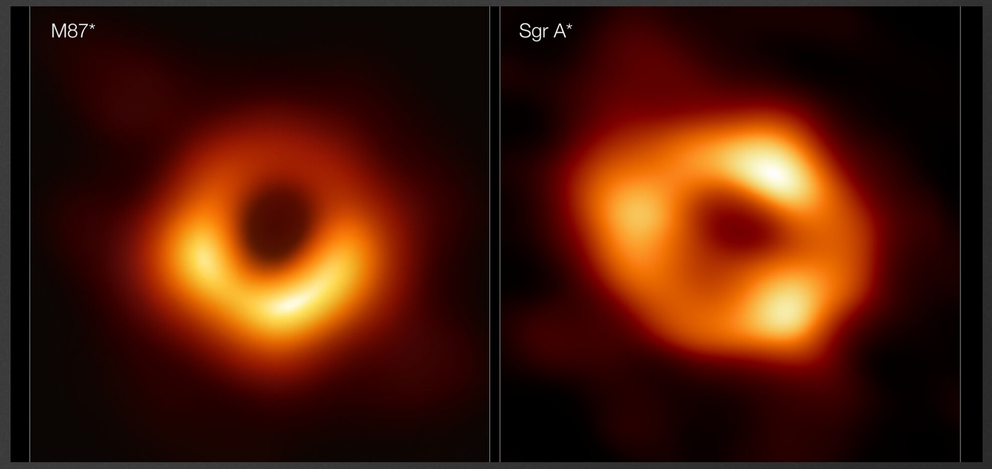
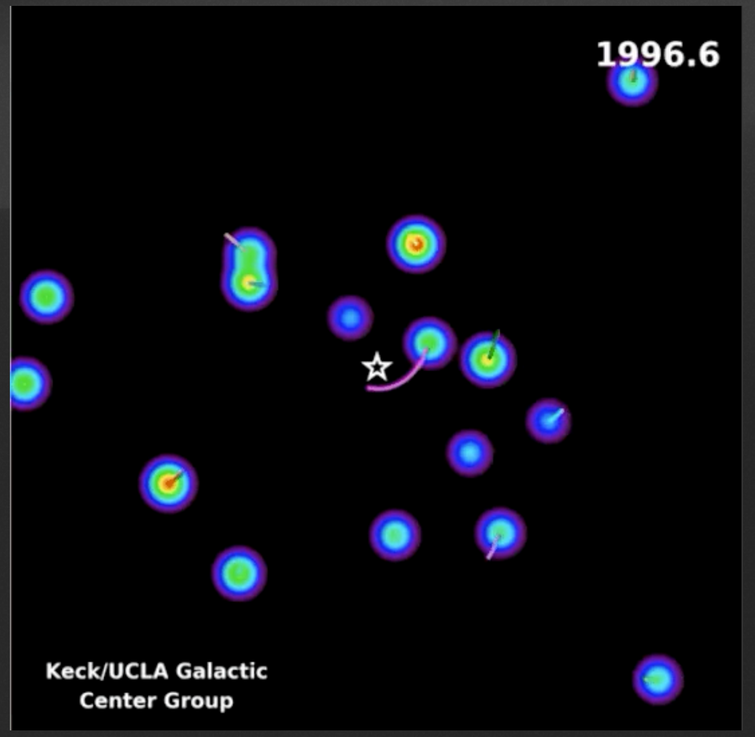
Black Holes are REAL!



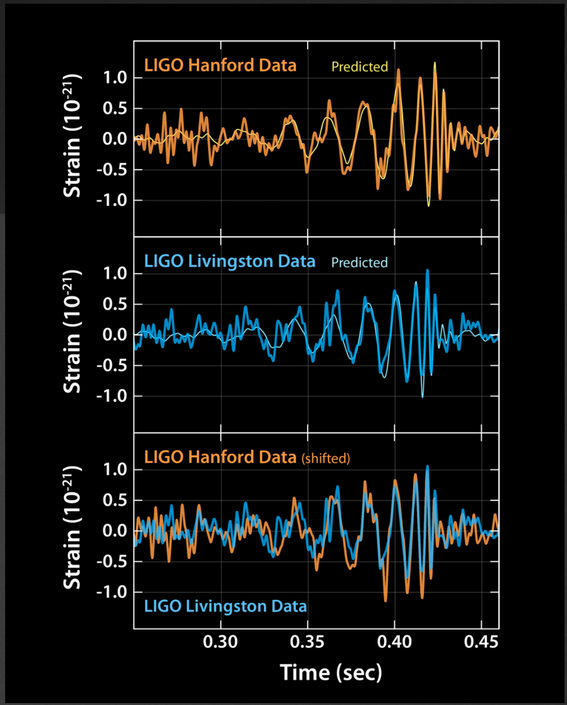
- Cyg X-1, star-stellar mass BH binary
- Dynamical evidence of Sgr A*, supermassive BH
- EHT image

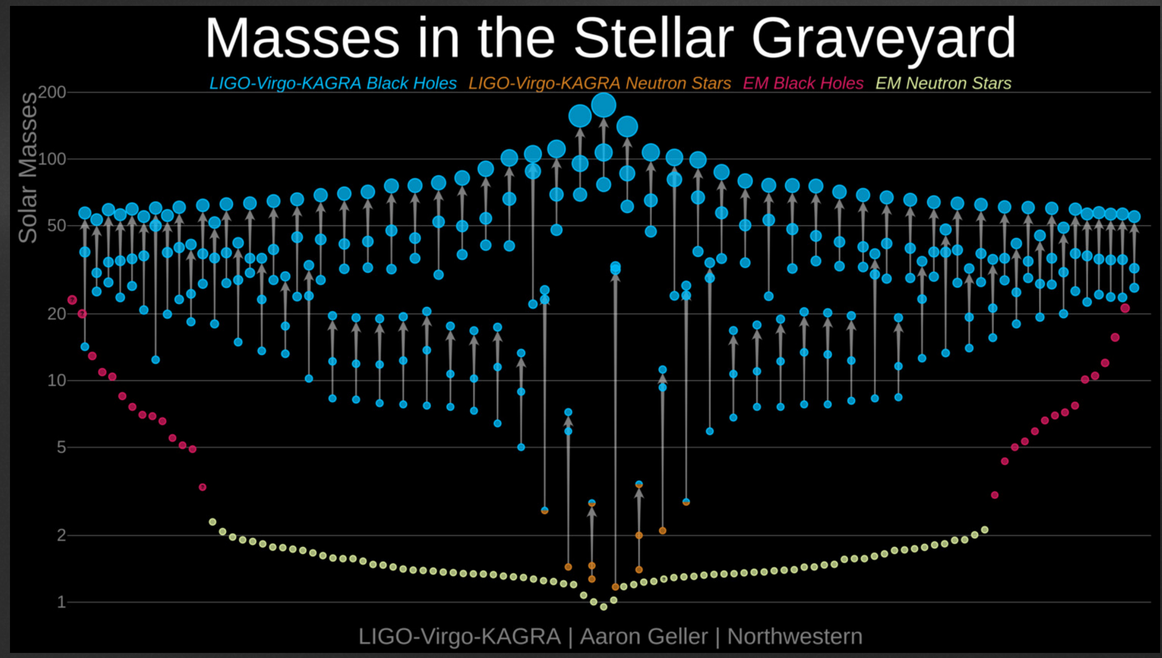




Black Holes are REAL!

- GW from stellar-mass BH binaries





What about massive BH binaries?

- LISA will be able to detect massive BH mergers in 2030s, hopefully.



- Can we do more before LISA’s launch?

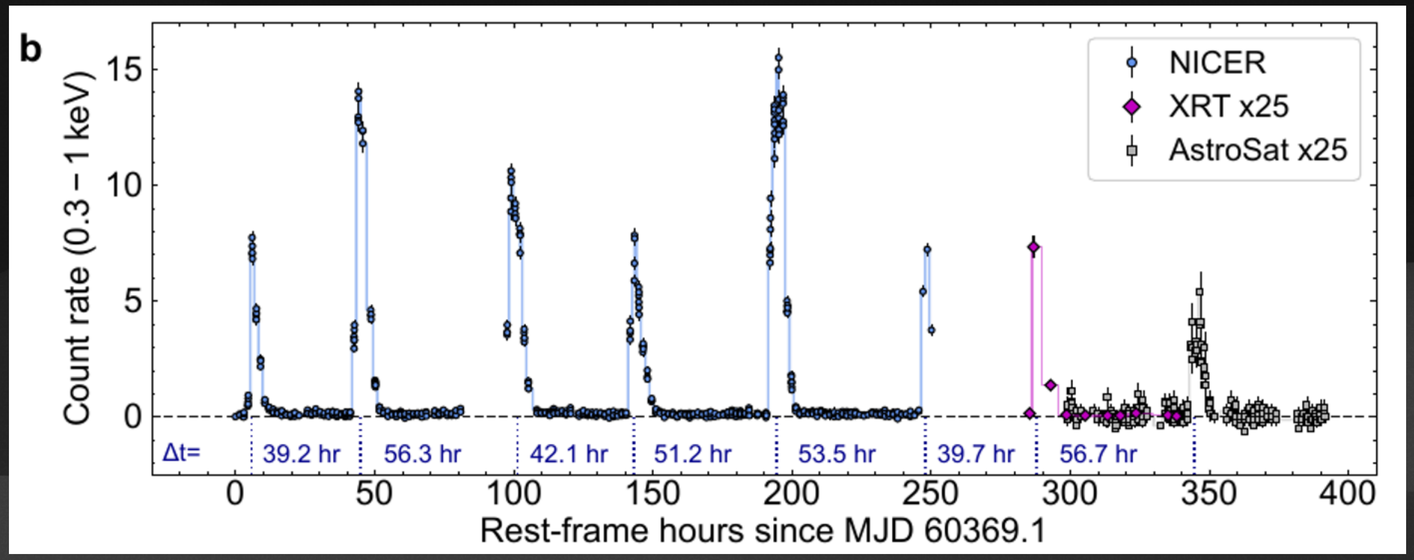
Outline

How to observe SMBH(s) in the binary?

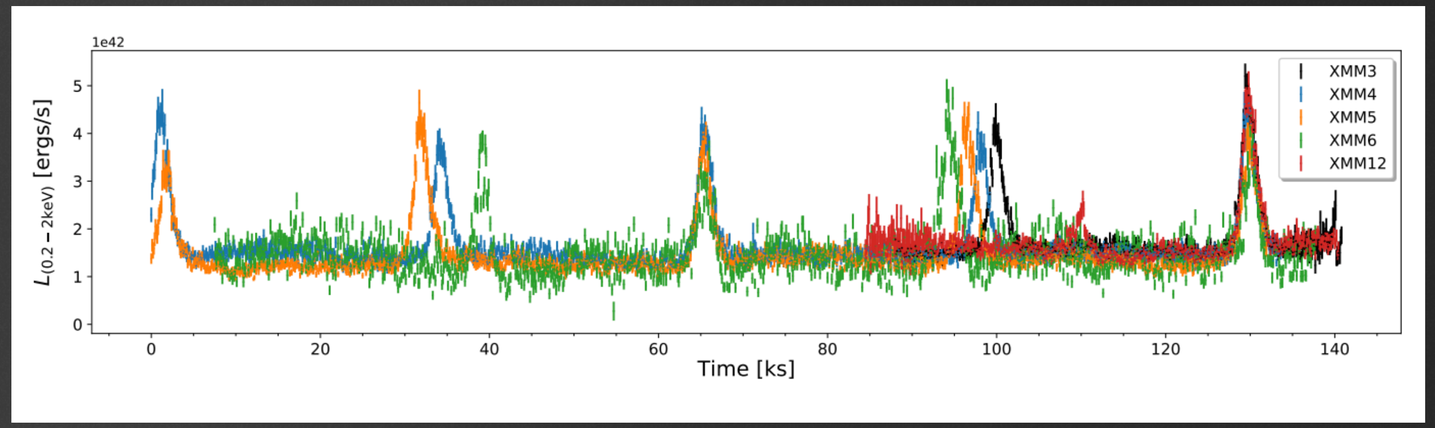
- Quasi Periodic Eruptions
- EMRI: BH-WD Micro-TDE at the galactic center
- Stellar Collisions near a SMBH
- End-to-end TDE simulation

Quasi Periodic Eruptions

repeated X-ray flares.



AT2019qiz
Nicholl et al. (2024)



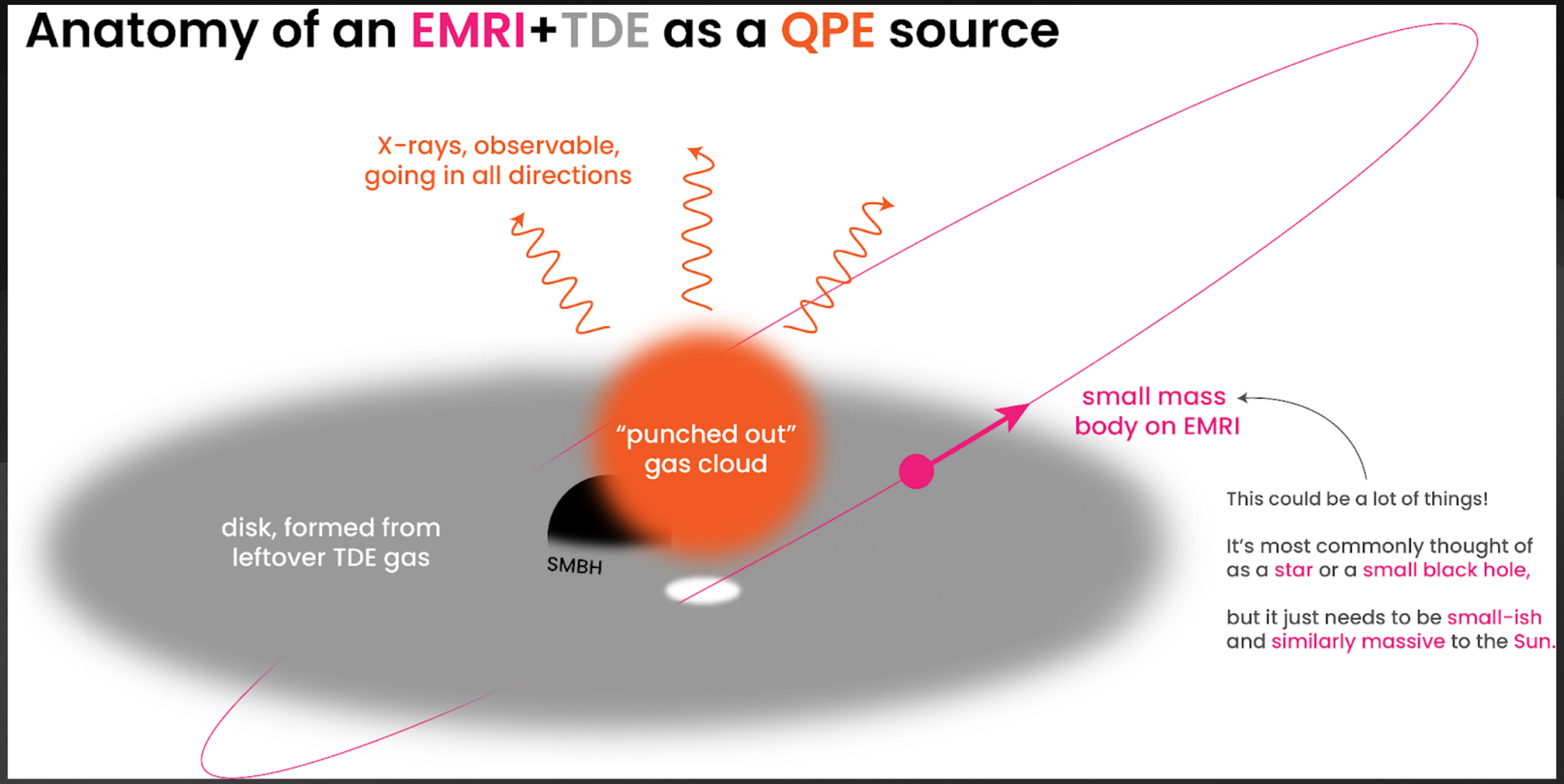
GSN069
Zhou et al. (2024)

A TDE supplies the disk

Debris meets an orbiting secondary.



Quasi Periodic Eruptions



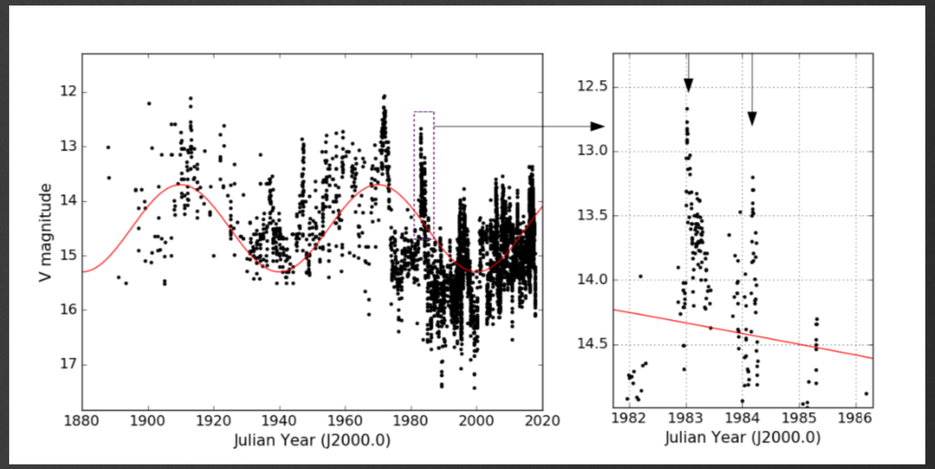
Nicholl et al. (2024)

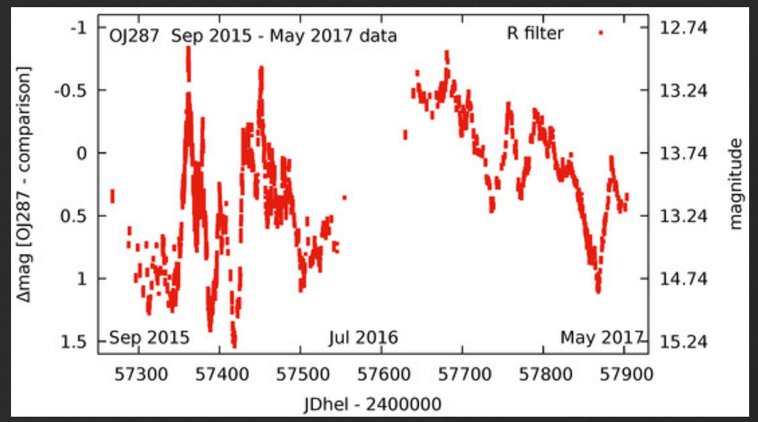
OJ-287

- OJ 287 is a bright blazar at a redshift of z ~ 0.3.
- Its 130 years long optical light curve shows two periodic variations:

I.Quasi-periodic double-peaked high brightness flares with period ~ 12 years

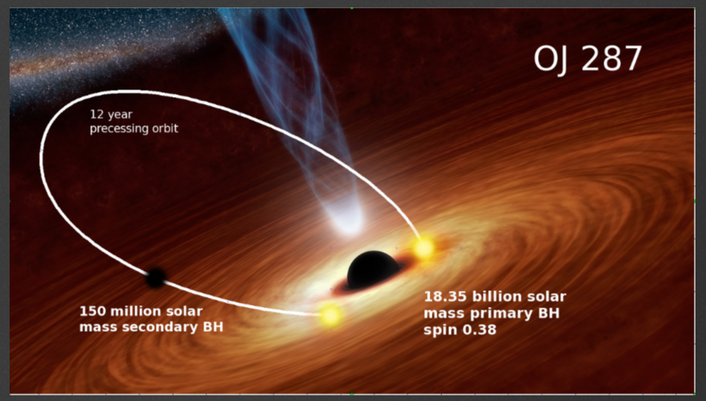
II.Long term variations with 60 years period

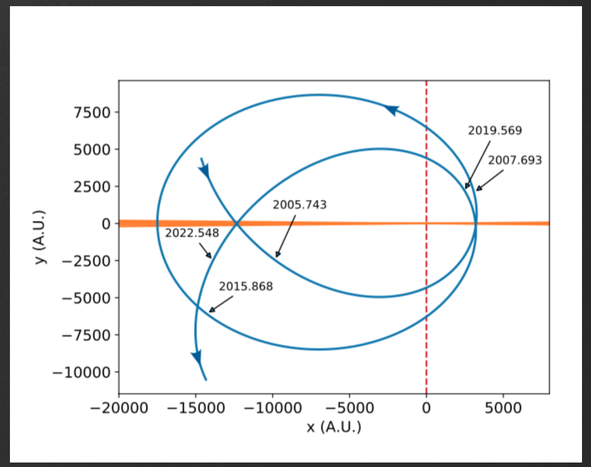


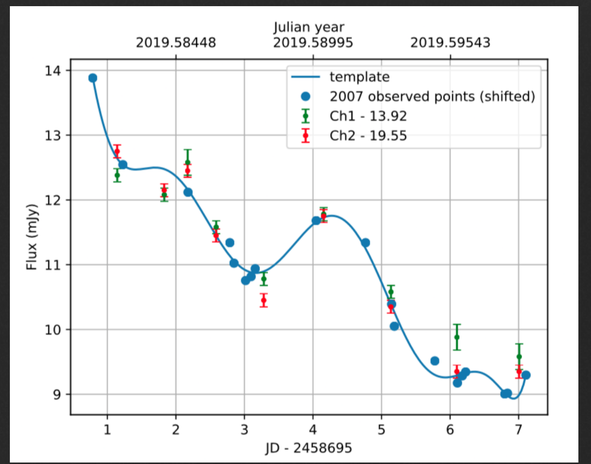


Binary BH model of OJ 287

- Lehto & Valtonen (1996) model: a secondary BH impacts with the accretion disk of the primary.
- Binary-model inference gives a primary mass $\sim 1.8 \times 10^{10}\, M_{\odot}$, mass ratio q~0.01
- eccentricity e~0.66 and spin a~0.4
- flare modelling invokes a cold, optically thick, geometrically thin disk H/R~0.01-0.03

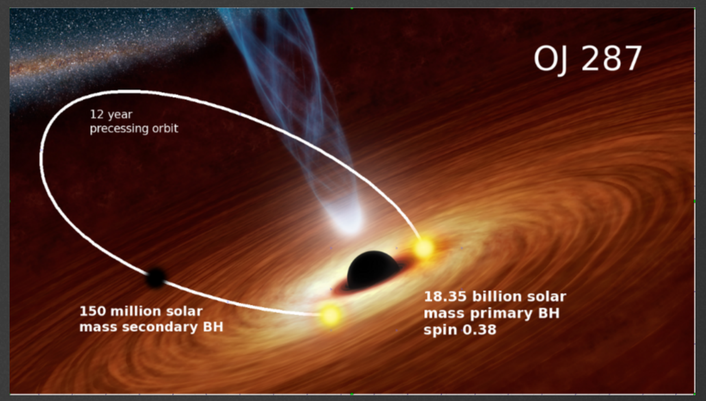


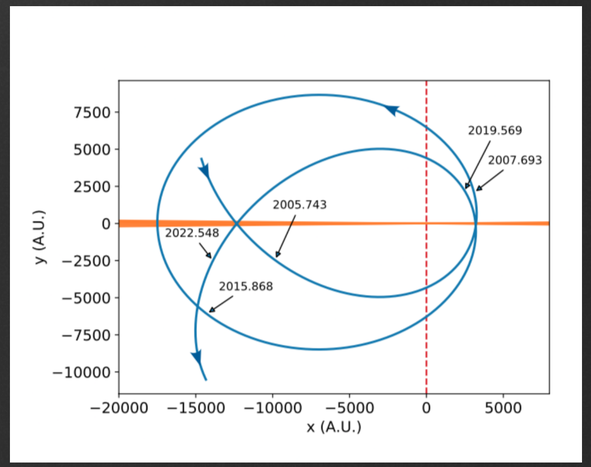


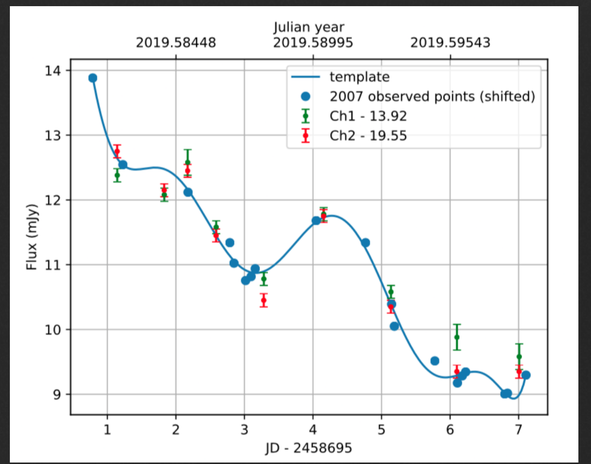


Binary BH model of OJ 287

- Dey et al. (2018) predicted that the next SMBH impact would occur in July 31, 2019.
- Spitzer observations strongly supports the arrival of the predicted flare.
- The predicted July 2022 impact flare could NOT be monitored due to OJ 287’s solar elongation!! (& the demise of Spitzer) arXiv:2308.03017

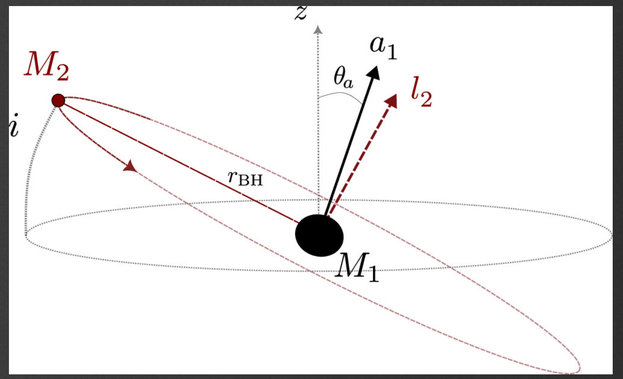


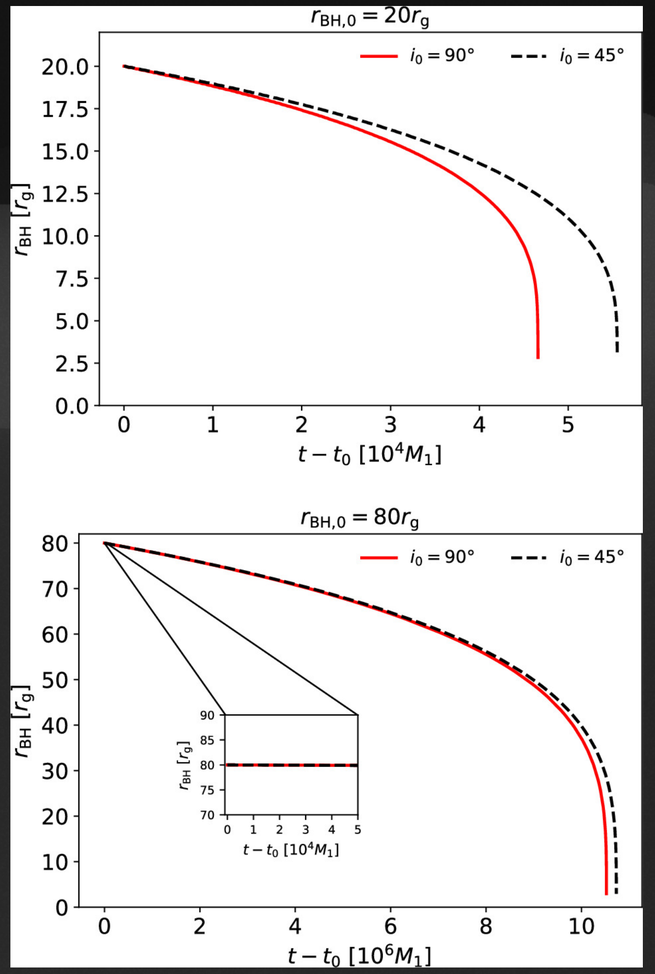




GRMHD simulations of BH-Disk interactions

- 3D GRMHD with Athena++
- Approximate metric as in Combi et al. (2021) + PN trajectories
- The central BH is assumed to be static.
- Start with a Fishbone & Moncrief torus,
- Relax the disk before introducing the perturber

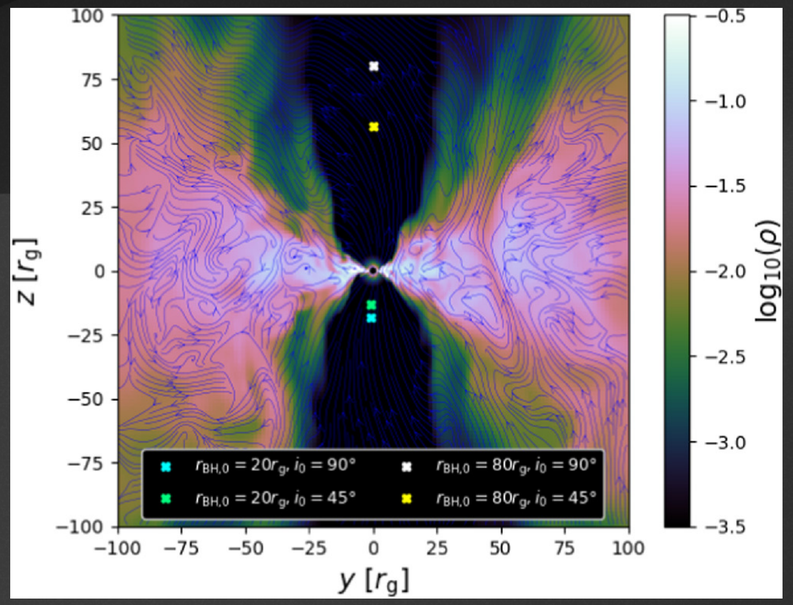


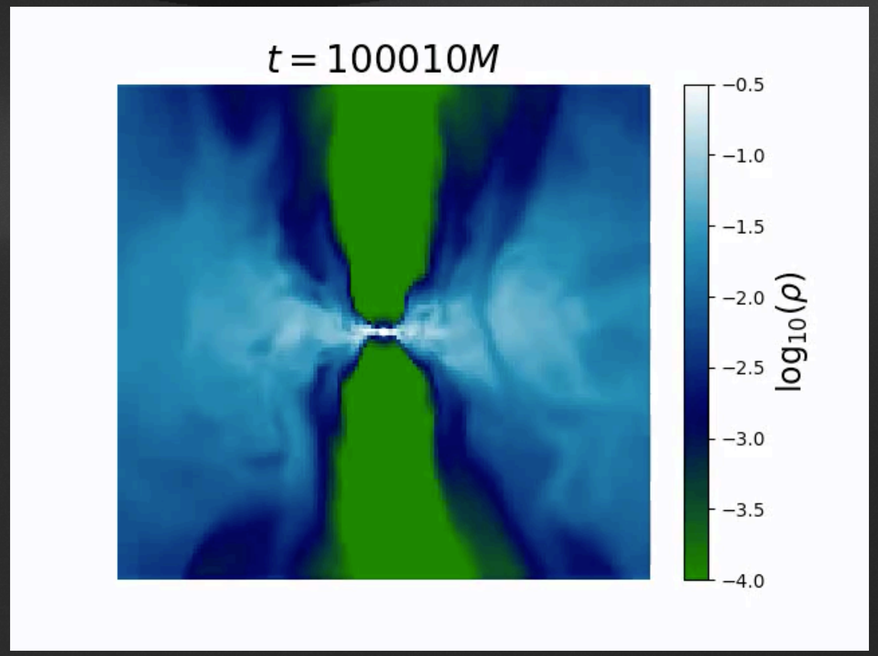


Thick MAD Disk

Sean M. Ressler, Luciano Combi, Xinyu Li, Bart Ripperda, and Huan Yang (2404.02193)

- q=0.1 fixed.

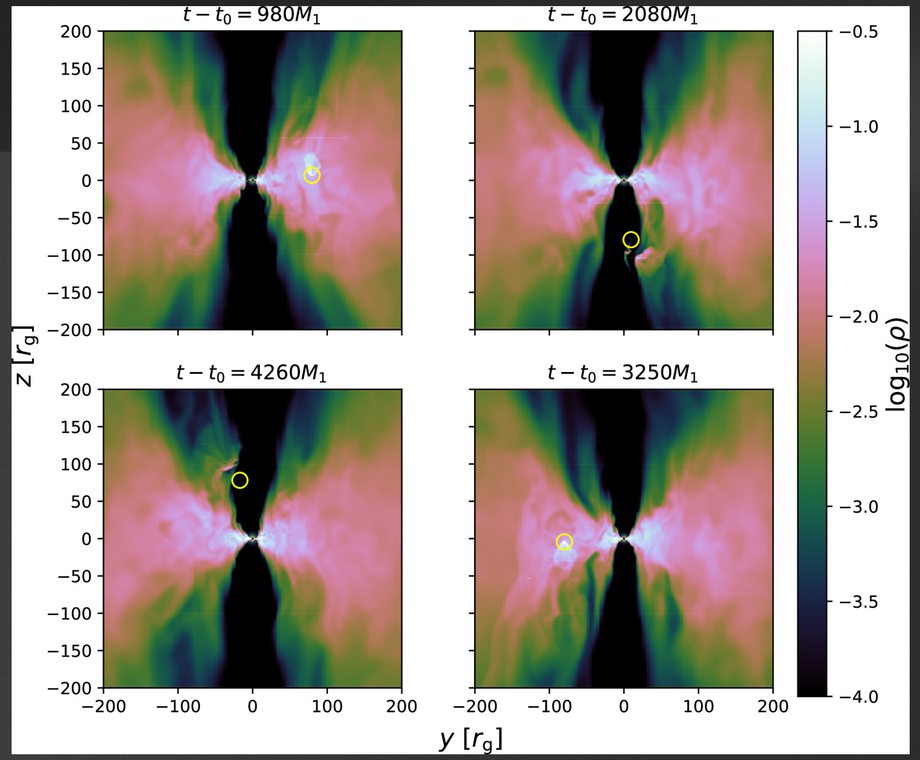


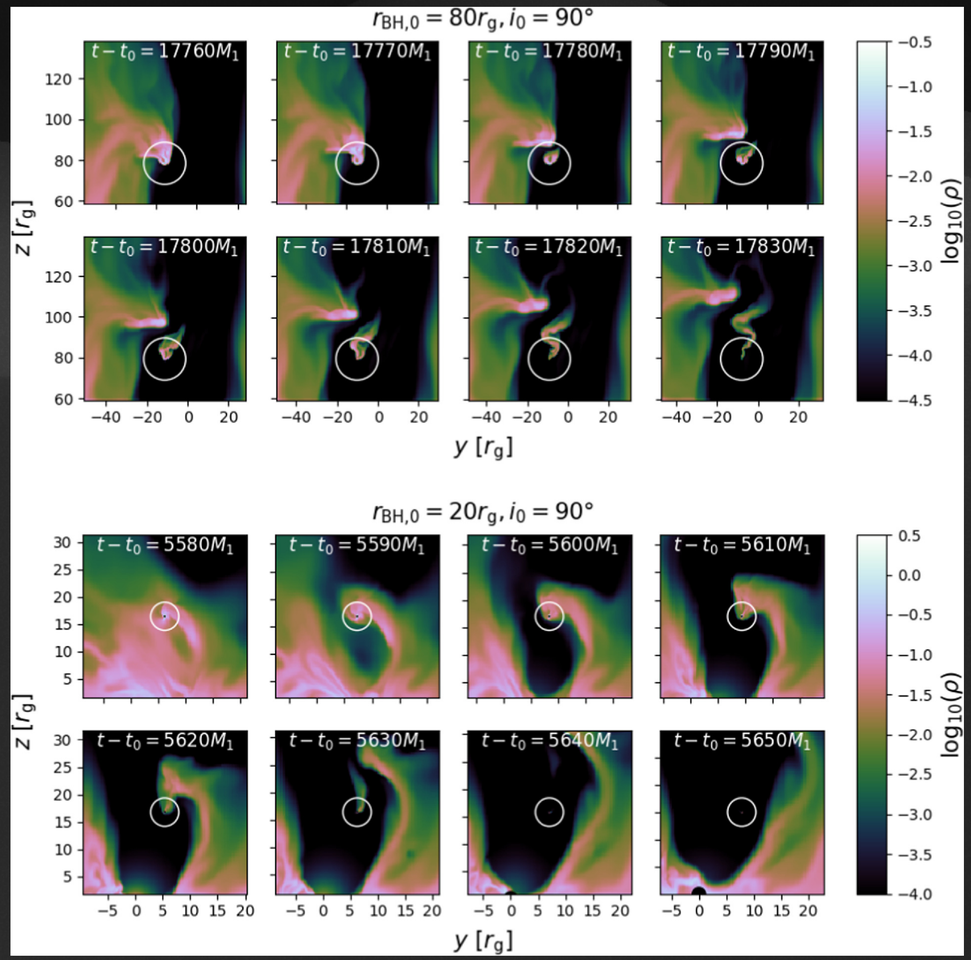


Thick MAD Disk: Morphology

Sean M. Ressler, Luciano Combi, Xinyu Li, Bart Ripperda, and Huan Yang (2404.02193)

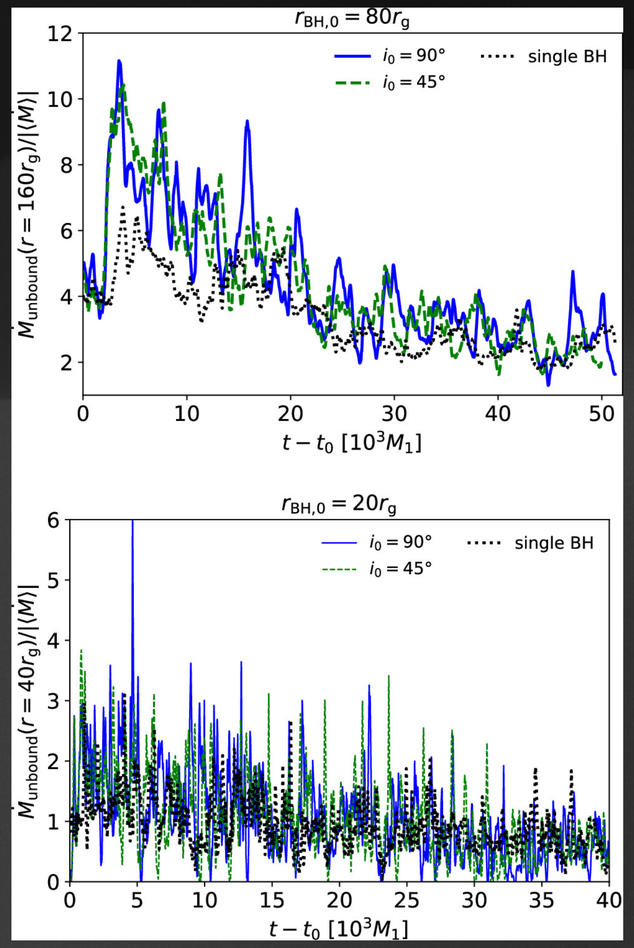
- Bow shock from BHL accretion
- Mass is dragged out by the secondary

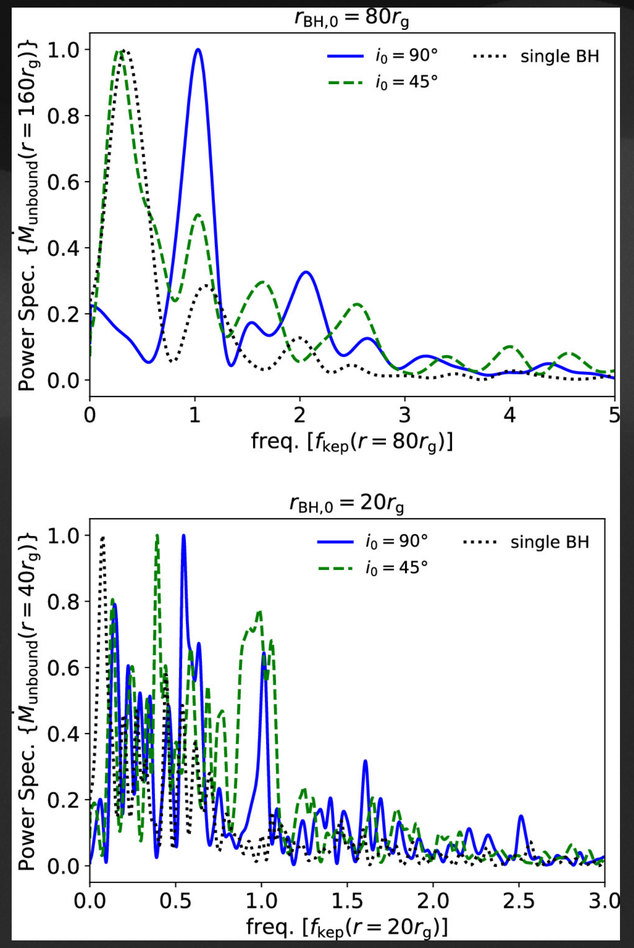




Thick MAD Disk: mass outflow rate

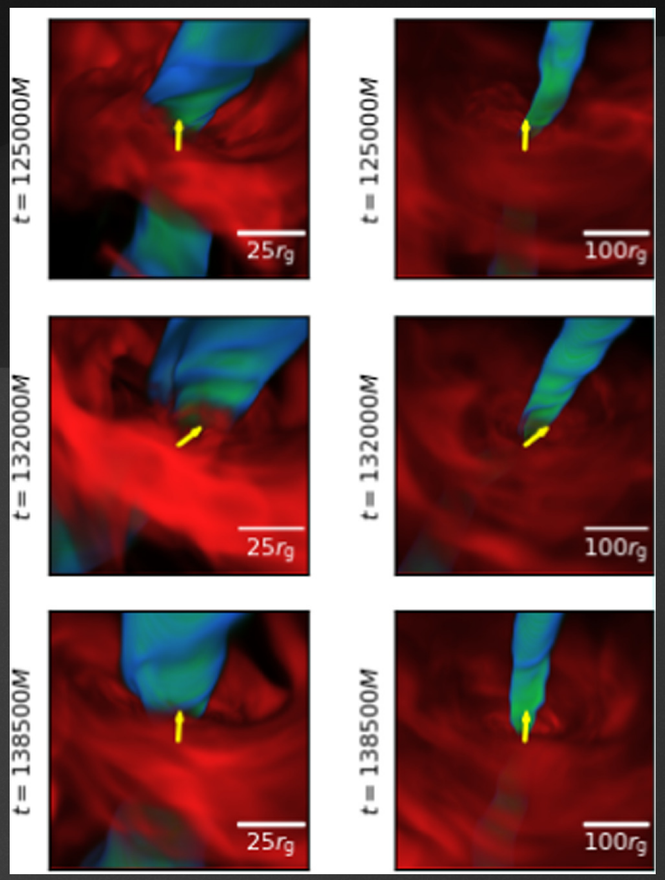
Sean M. Ressler, Luciano Combi, Xinyu Li, Bart Ripperda, and Huan Yang (2404.02193)

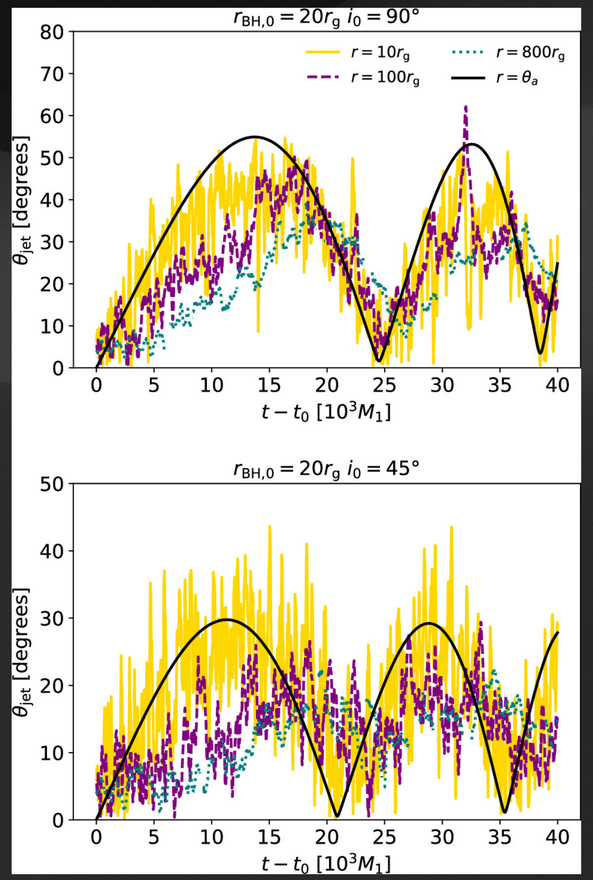




Thick MAD Disk: spin-orbit coupling

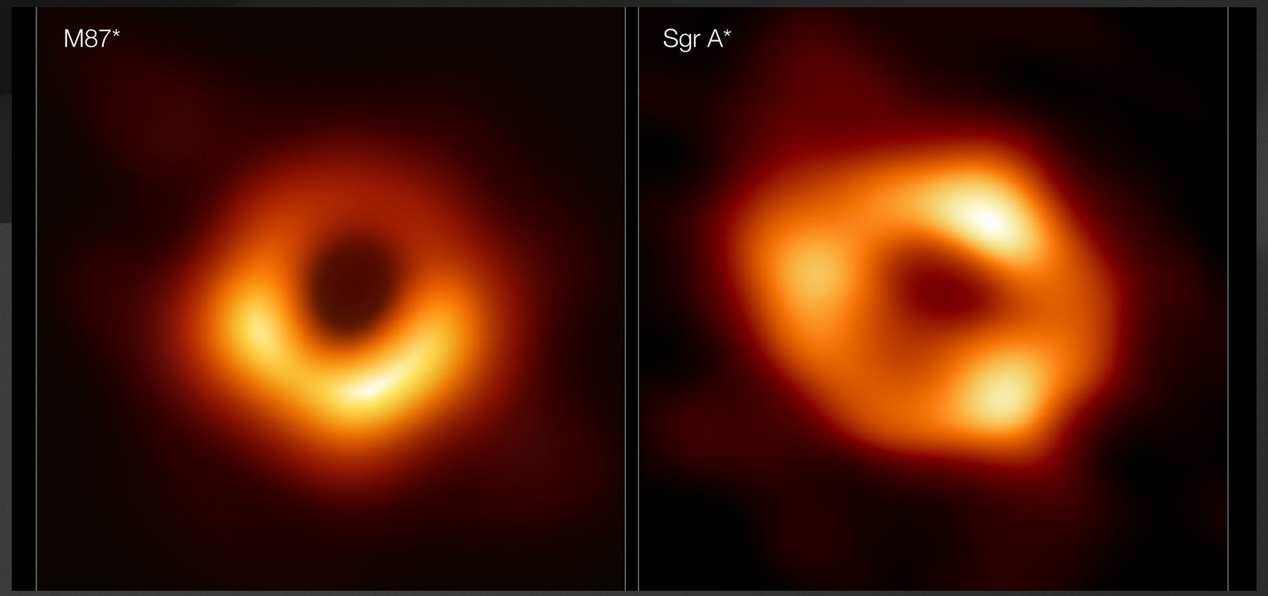
Sean M. Ressler, Luciano Combi, Xinyu Li, Bart Ripperda, and Huan Yang (2404.02193)





How does the system look like?

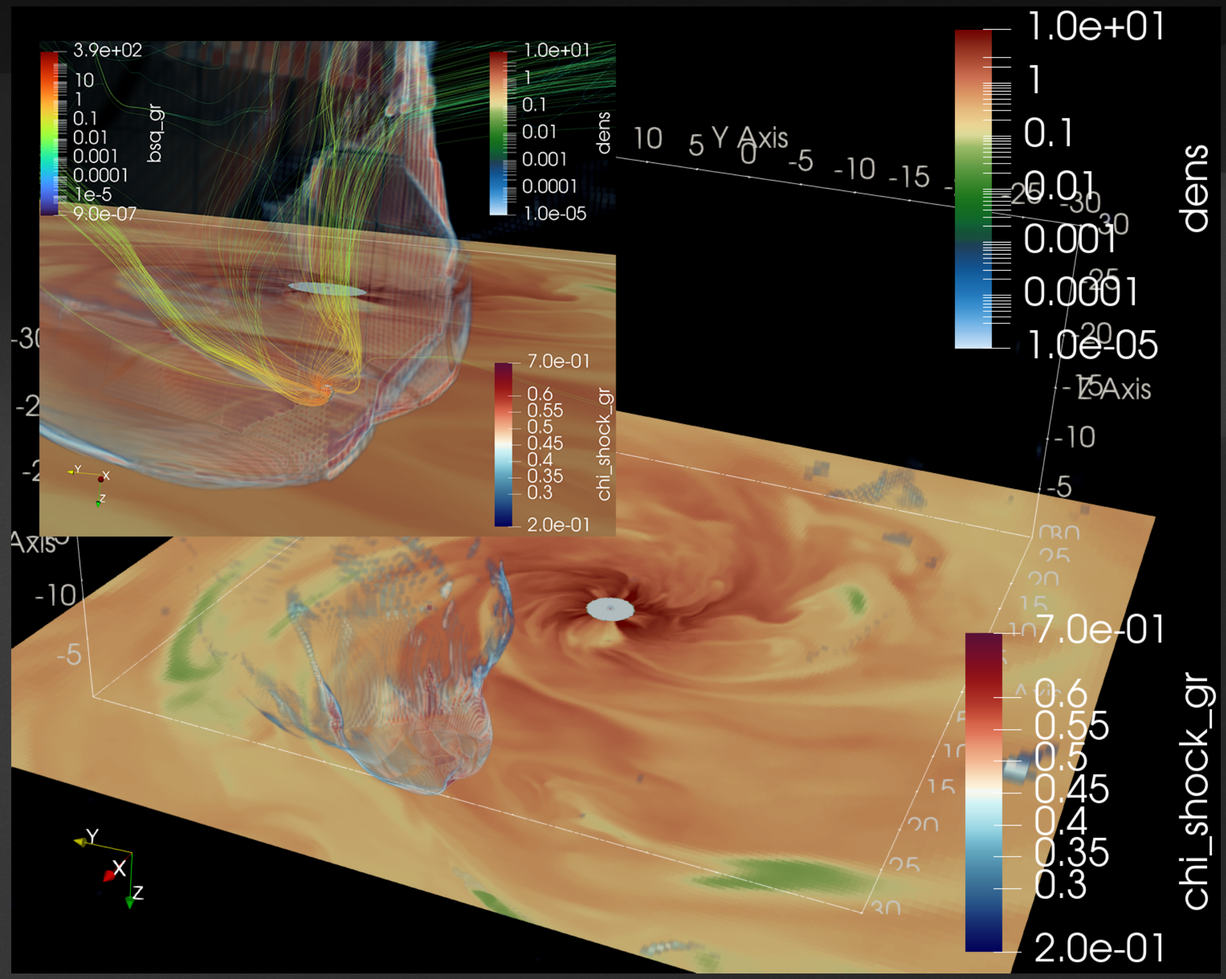
Hongxuan Jiang, Xinyu Li et al. (2603.10792)





Thick MAD Disk: lensing flares

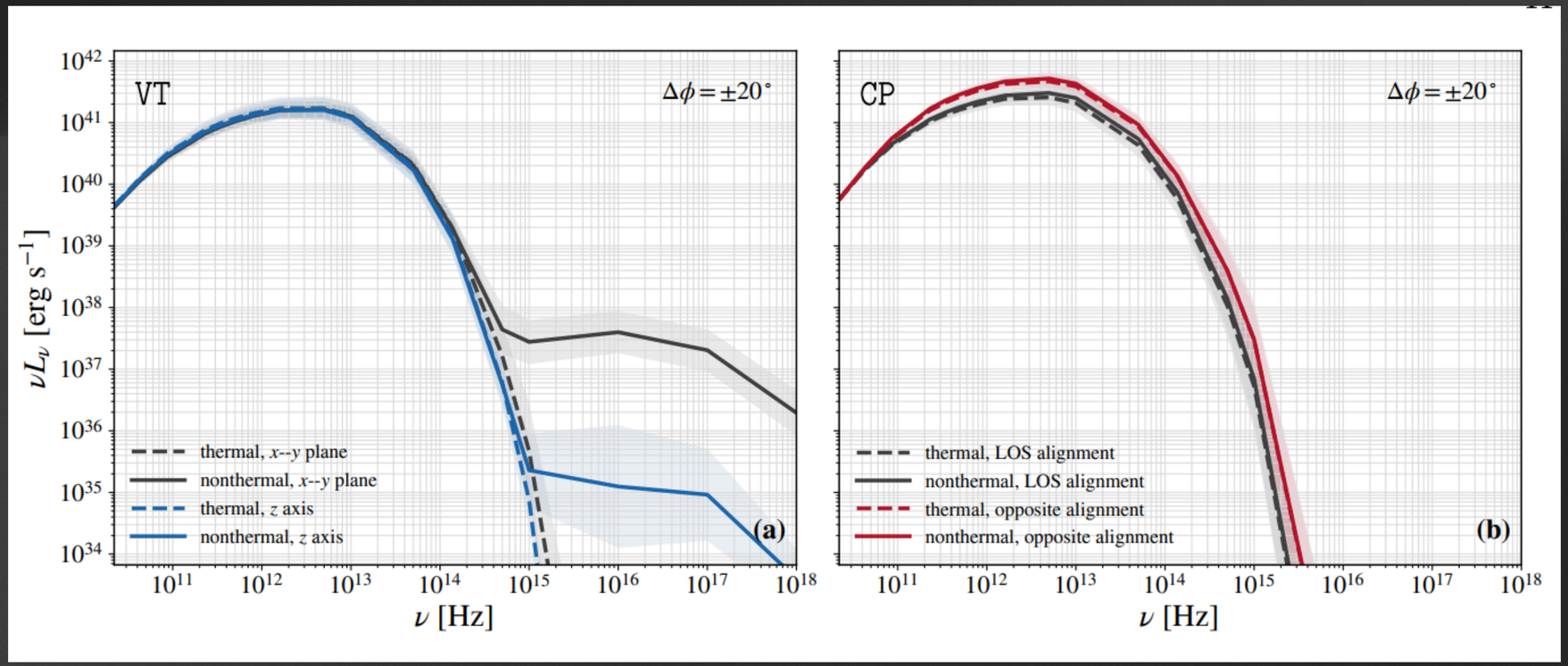
Hongxuan Jiang, Xinyu Li et al. (2603.10792)



Thick MAD Disk: lensing flares

Hongxuan Jiang, Xinyu Li et al. (2603.10792)

- GRRT code BHOSS for post-processing
- Shock produces non-thermal electrons, but not observable



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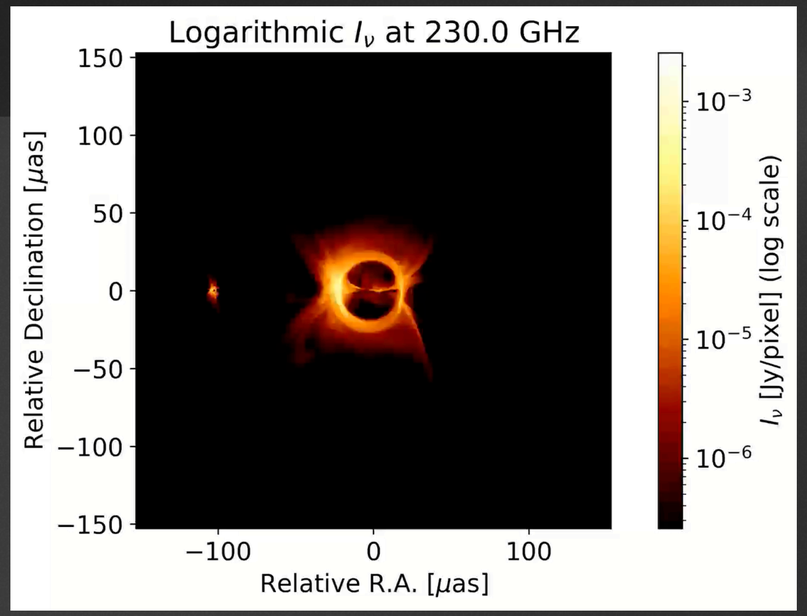
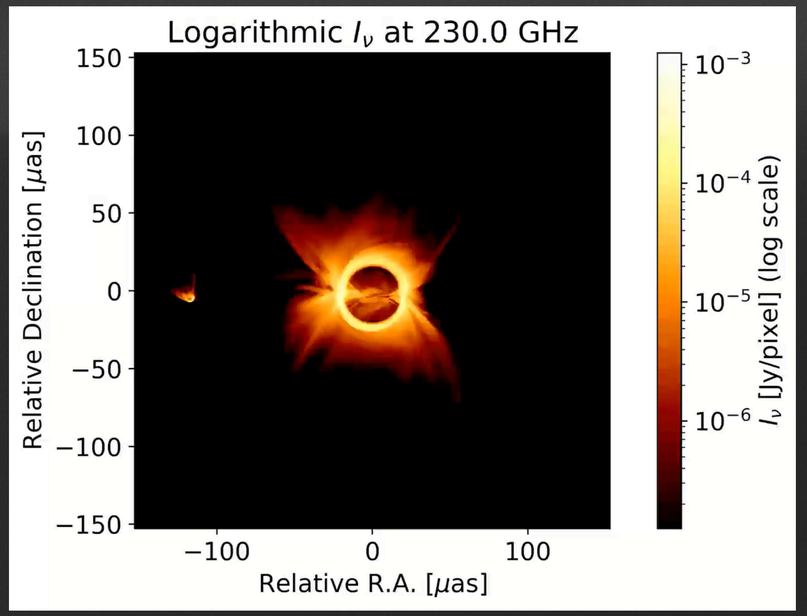
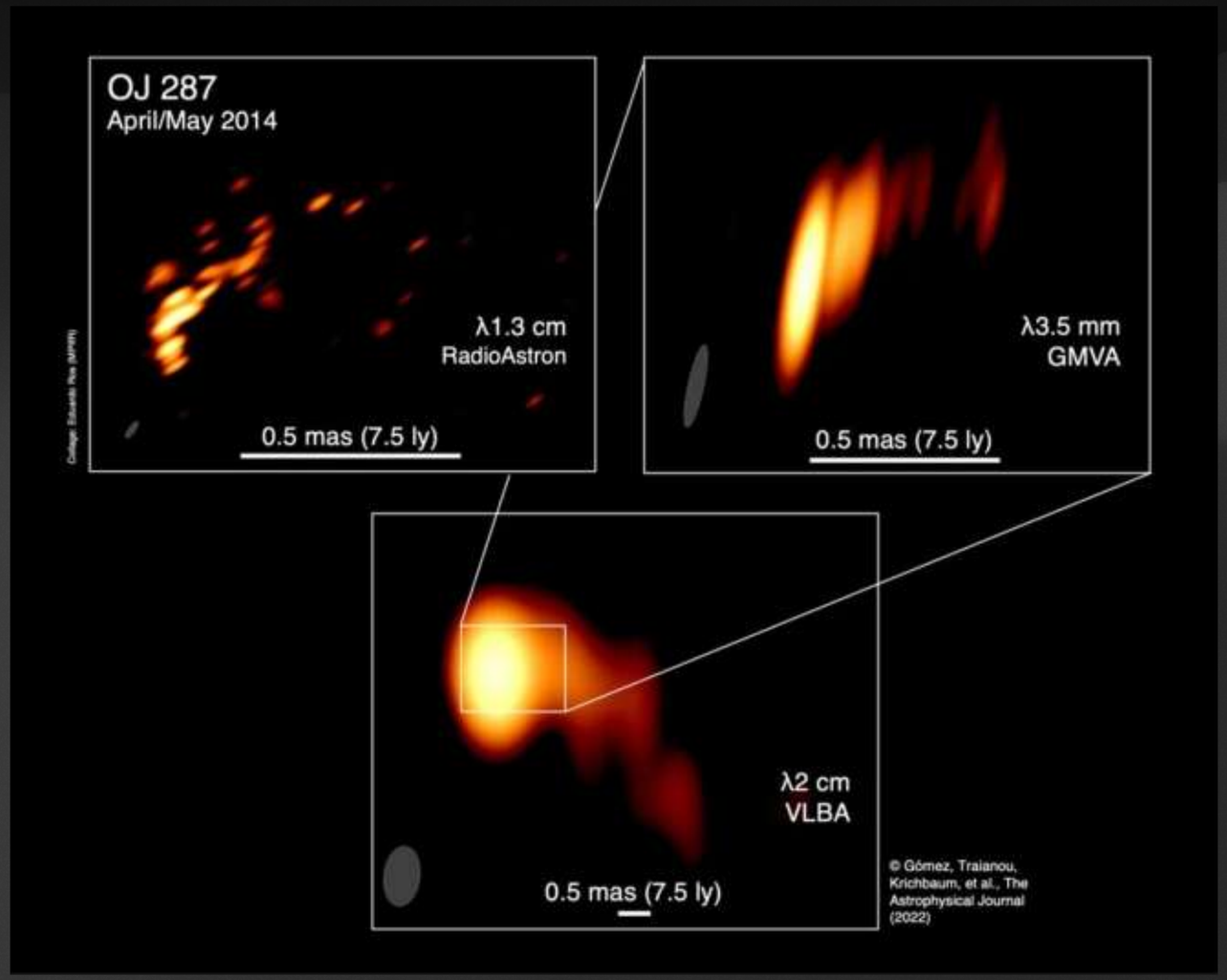




OJ-287


OJ 287
April/May 2014
λ1.3 cm
RadioAstron
0.5 mas (7.5 ly)
λ3.5 mm
GMVA
0.5 mas (7.5 ly)
λ2 cm
VLBA
0.5 mas (7.5 ly)
© Gómez, Traianou, Krichbaum, et al., The Astrophysical Journal (2022)

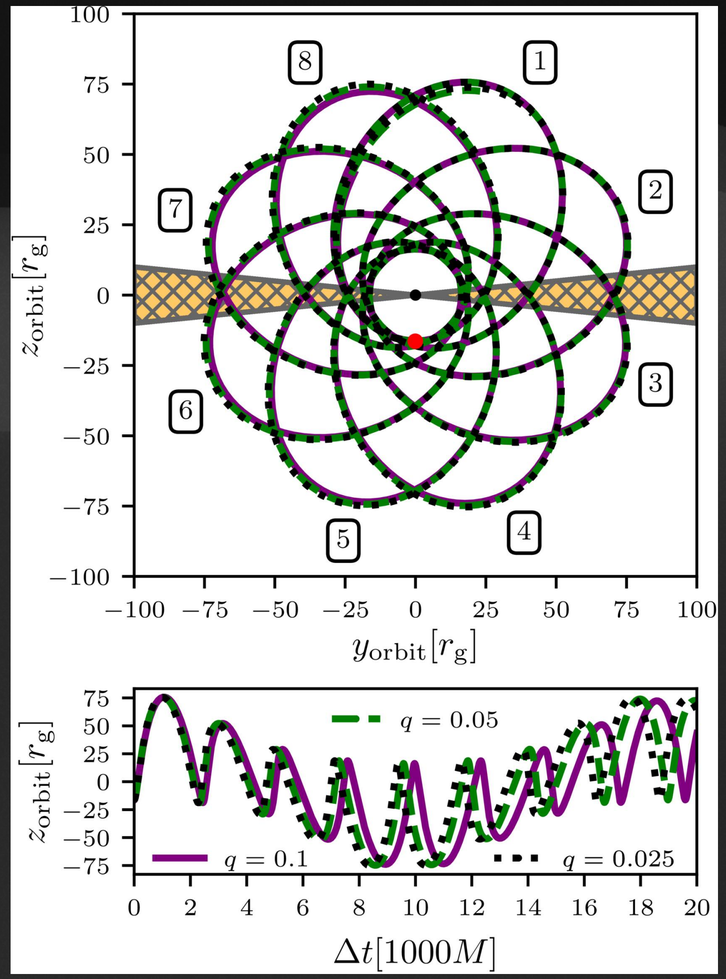
Thick MAD Disk: summary

- the overall effects of the secondary on the primary accretion flow are small and hard to confirm the secondary from EM light curve
- the spin–orbit coupling can cause the spin direction of the primary to significantly change, observations of precession in thick AGN disks would be strong evidence for the presence of a secondary black hole companion
- Self-lensing flares can be observed if we have an EHT with ten times better resolution.

Thin Disk: OJ-287 like system

Sean M. Ressler, Luciano Combi, Bart Ripperda, Xinyu Li (2509.18241)

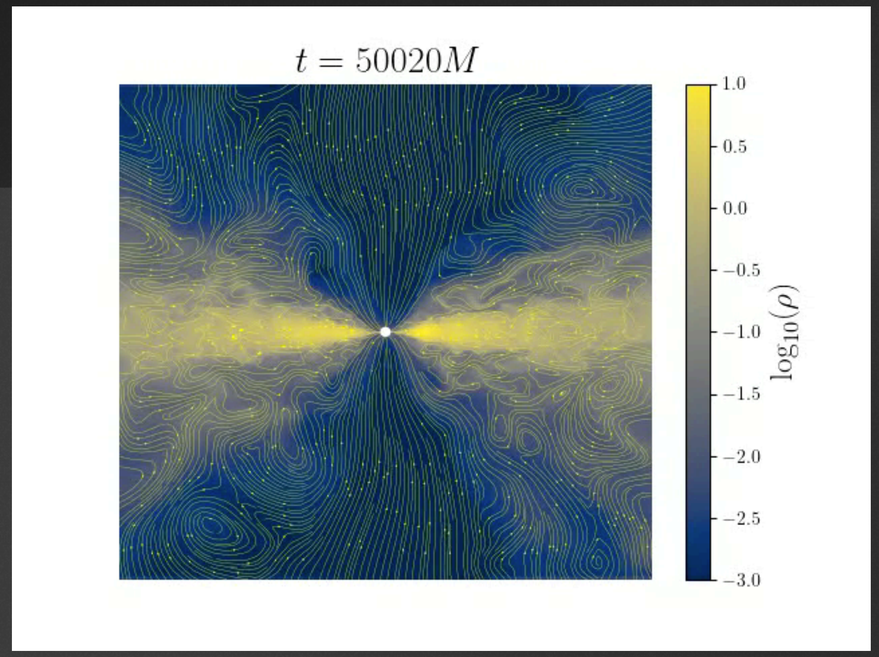
- Adding a cooling term to keep the disk thin
- H/R=0.1, q=0.1, 0.05, 0.025

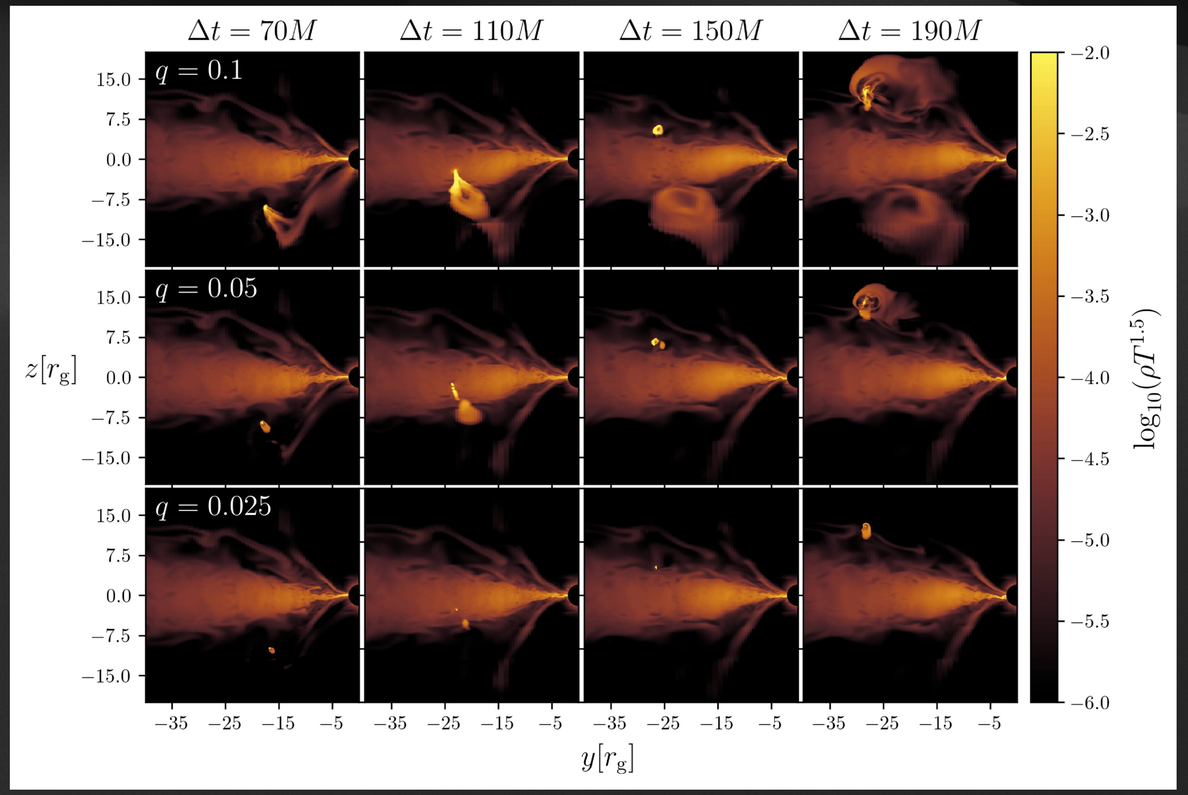


Thin Disk: morphology

Sean M. Ressler, Luciano Combi, Bart Ripperda, Xinyu Li (2509.18241)

- Jets from the boosted secondary

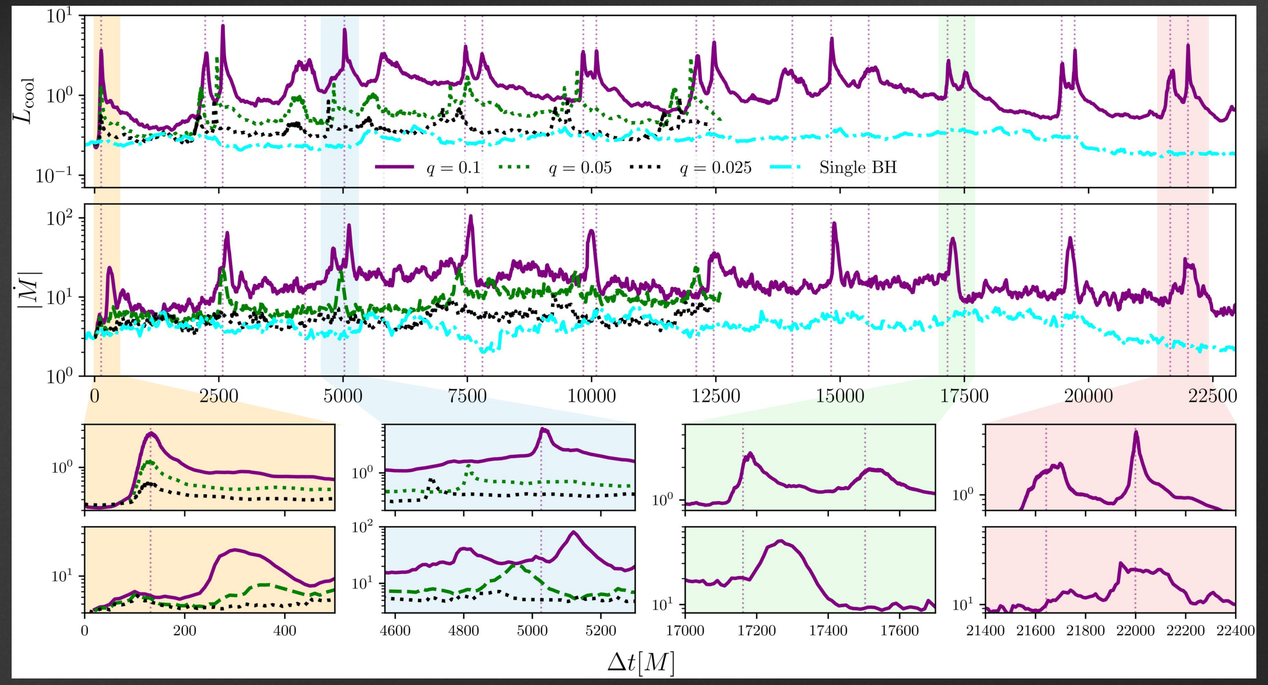




Thin Disk: light curve

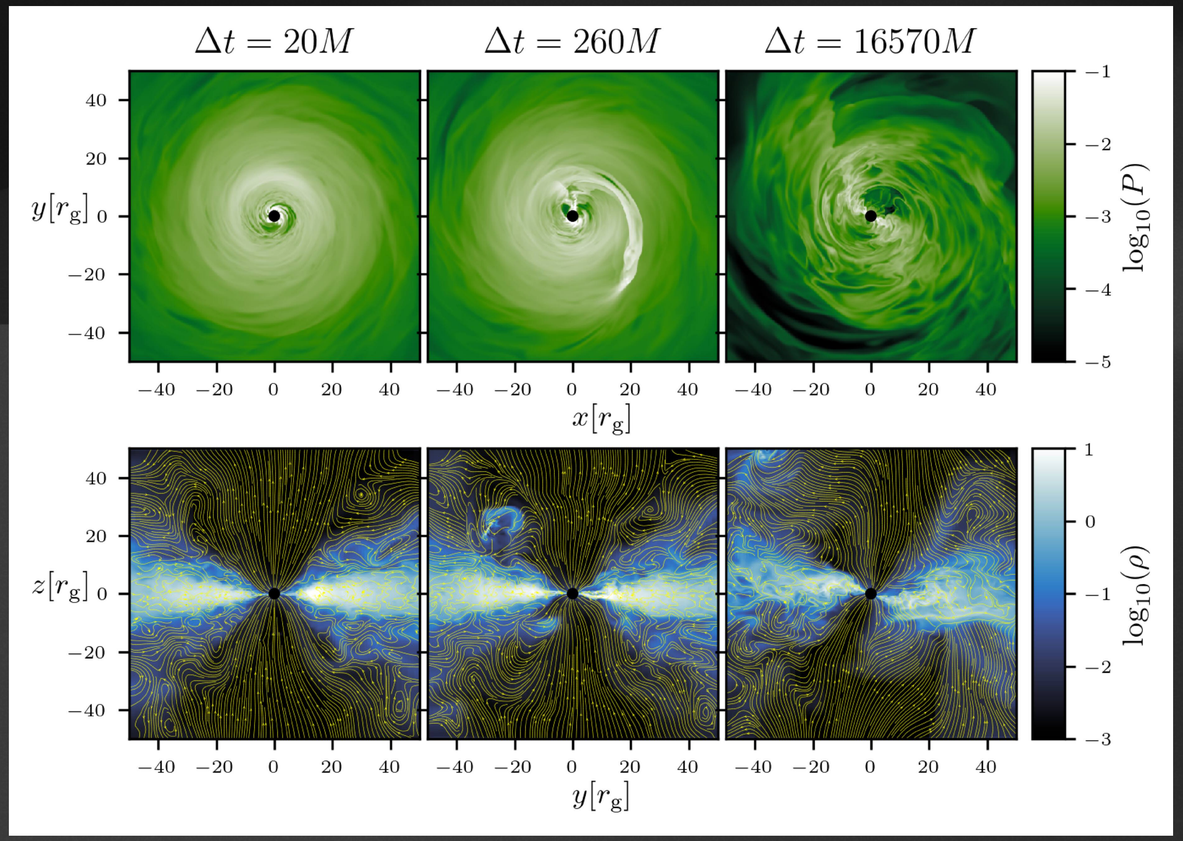
Sean M. Ressler, Luciano Combi, Bart Ripperda, Xinyu Li (2509.18241)

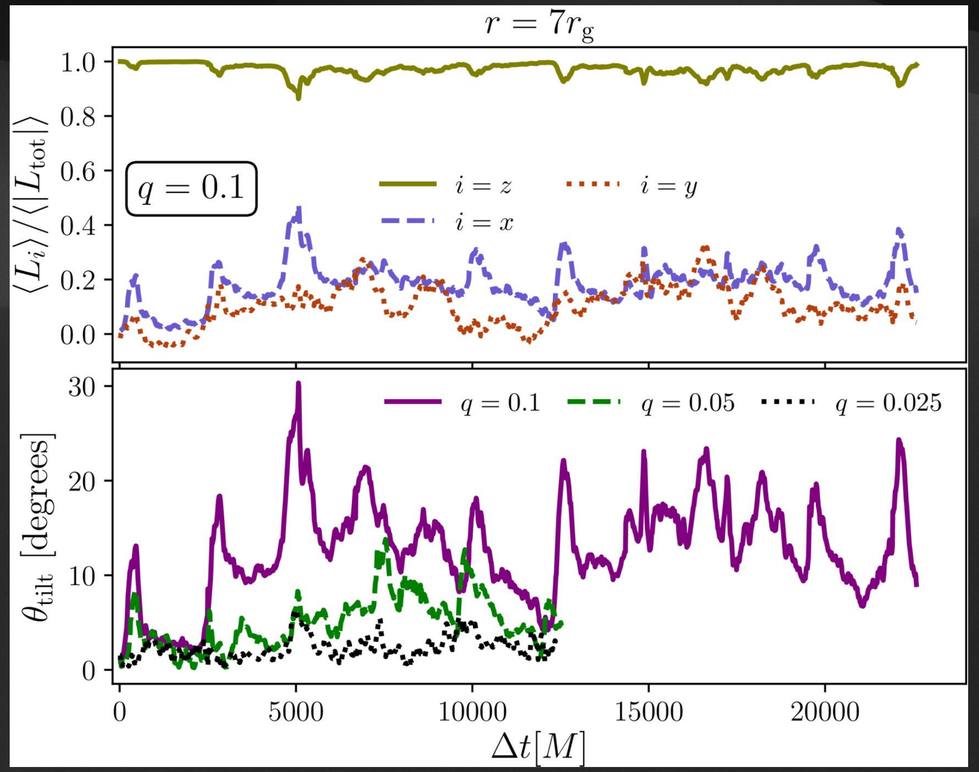
- Each impact of the secondary with the disk results in a spike.
- Short timescale variabilities exhibit observed features.



Thin Disk: disk tilt

Sean M. Ressler, Luciano Combi, Bart Ripperda, Xinyu Li (2509.18241)





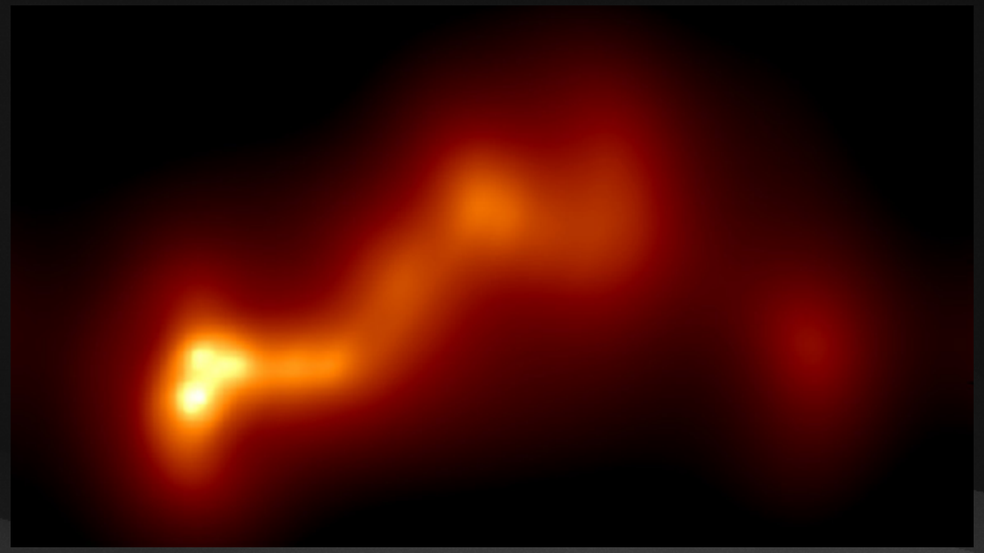
Thin Disk: takeaway

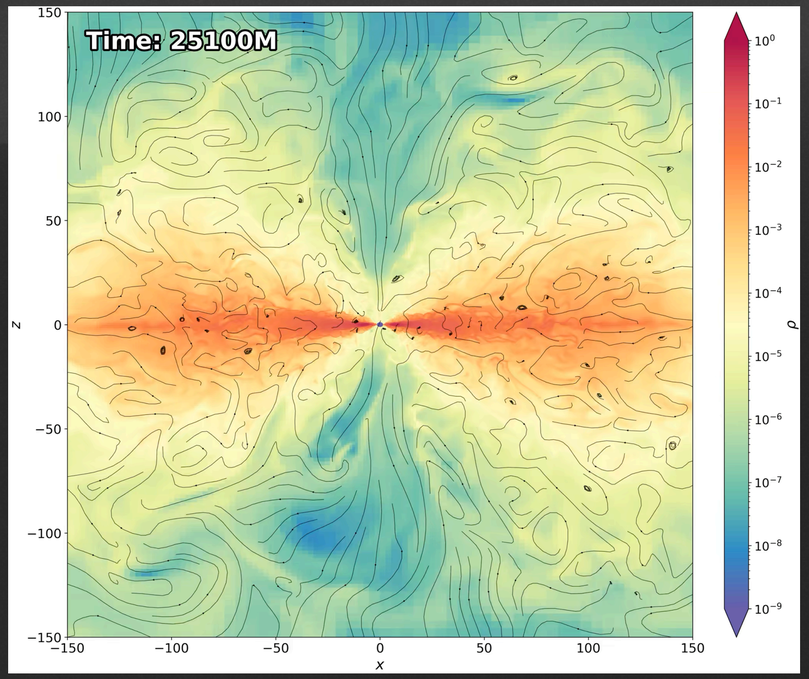
Sean M. Ressler, Luciano Combi, Bart Ripperda, Xinyu Li (2509.18241)

- We confirm the basic paradigm that impacts of the secondary on the disk can generate enough power to outshine the quiescent emission.
- The secondary also causes spiral shocks to form in the disk, enhanced accretion events, overall heating of the flow, and stochastic tilting of the disk.

Jet from OJ-287

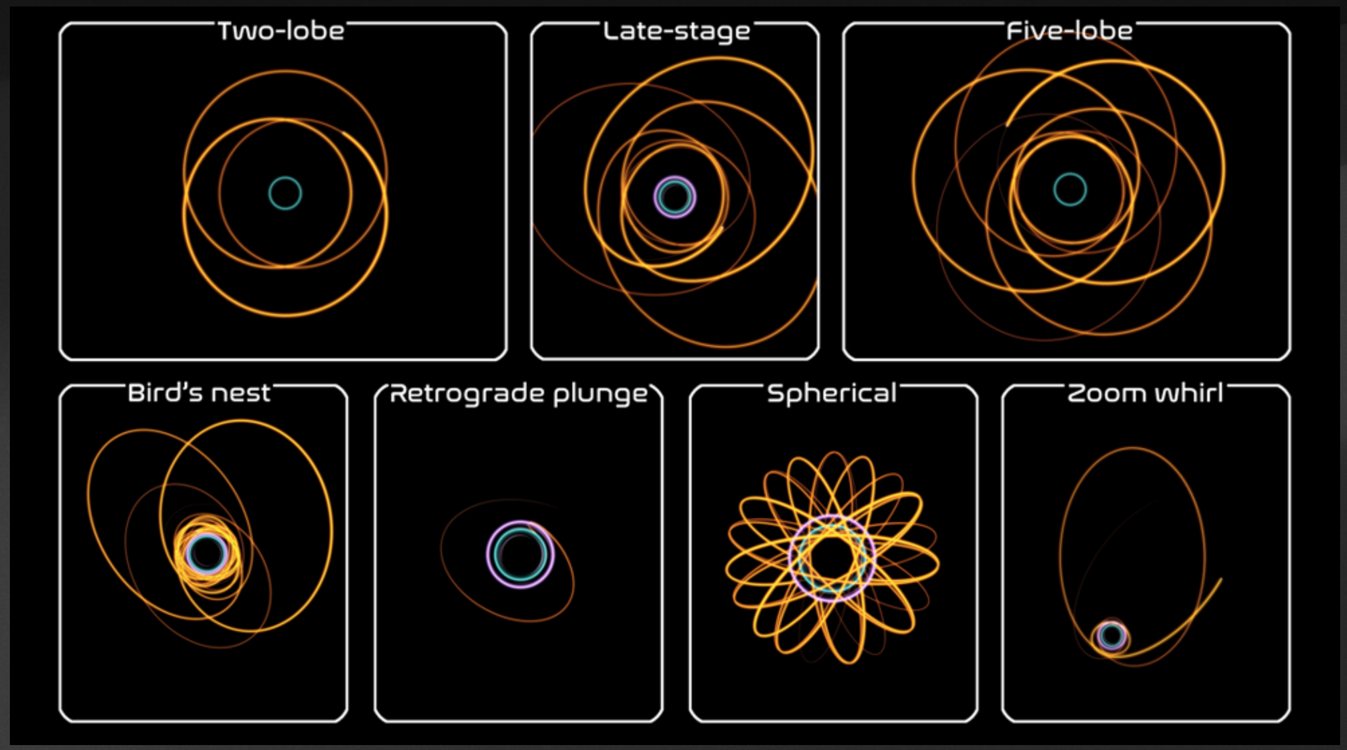
- Is the wiggling jet caused by the secondary?
- A thin disk + Kerr black hole + radiative transfer simulation is on the way.
- Jet + QPE connection might provide stronger support.





EMRIs: a stellar-mass secondary

A compact object spirals into a massive BH.

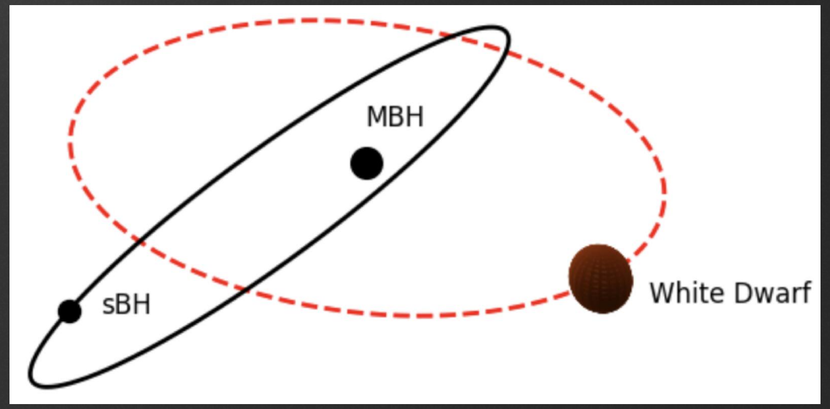


NASA/LISA

Micro-TDE between EMRI and WD

Xinyu Li, Houyi Sun, Yuan-Chuan Zou, Huan Yang (2501.13702)

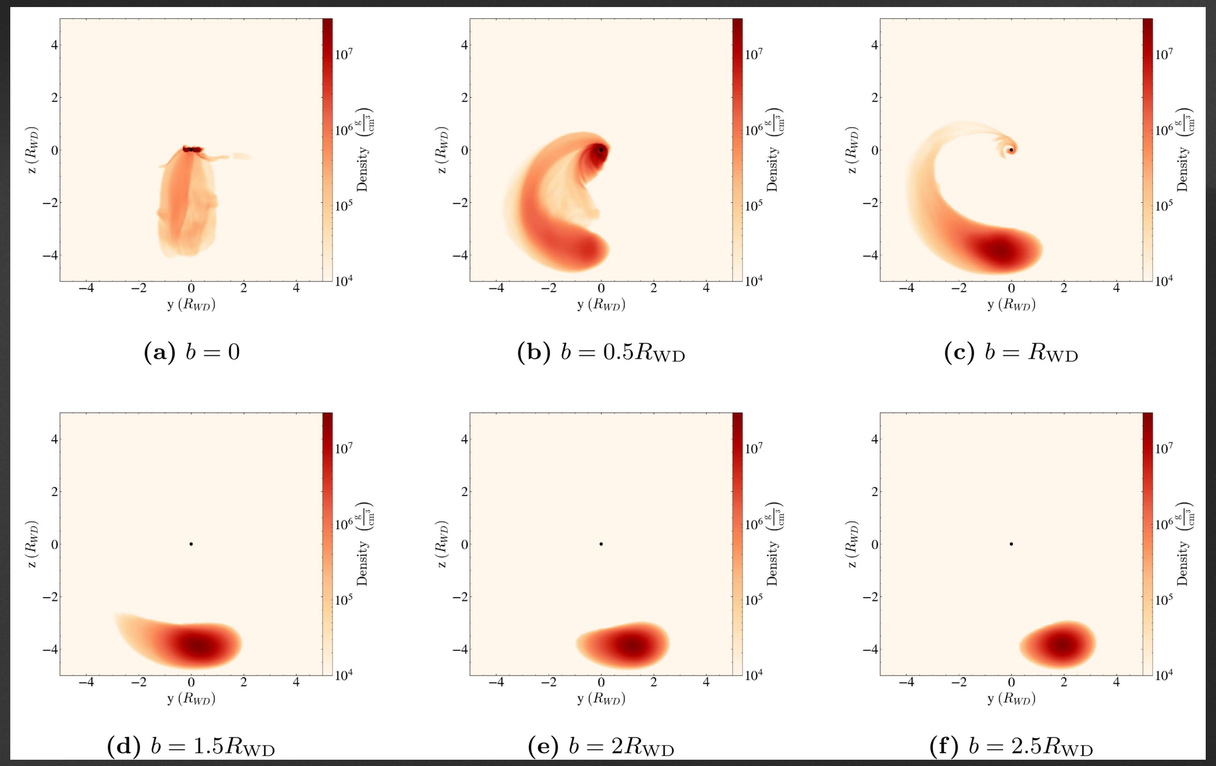
- A stellar-mass BH on highly eccentric orbit around a massive BH within 100 gravitational radius.
- A WD around the MBH may closely encounter with the sBH, v~0.1c.
- The event rate is calculated a few times per year within $z \leq 3$.



Micro-TDE between EMRI and WD

Xinyu Li, Houyi Sun, Yuan-Chuan Zou, Huan Yang (2501.13702)

- The WD will be tidally disrupted by the sBH.
- Hydrodynamical simulations.



(a) $b = 0$ **(b)** $b = 0.5R_{\rm WD}$ **(c)** $b = R_{\rm WD}$

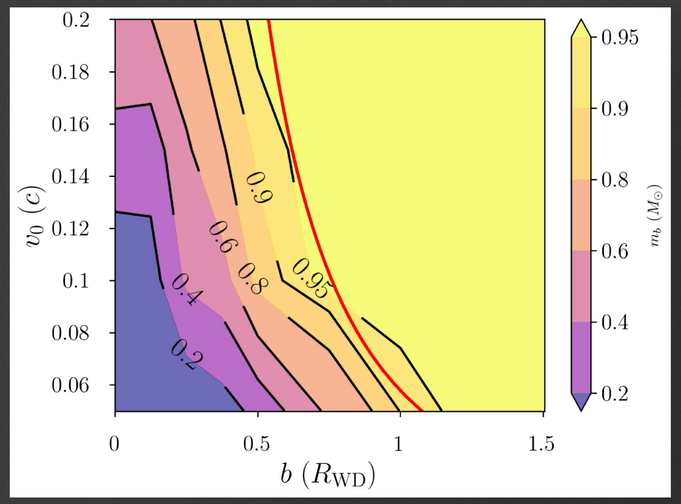
(d) $b = 1.5R_{\rm WD}$ **(e)** $b = 2R_{\rm WD}$ **(f)** $b = 2.5R_{\rm WD}$

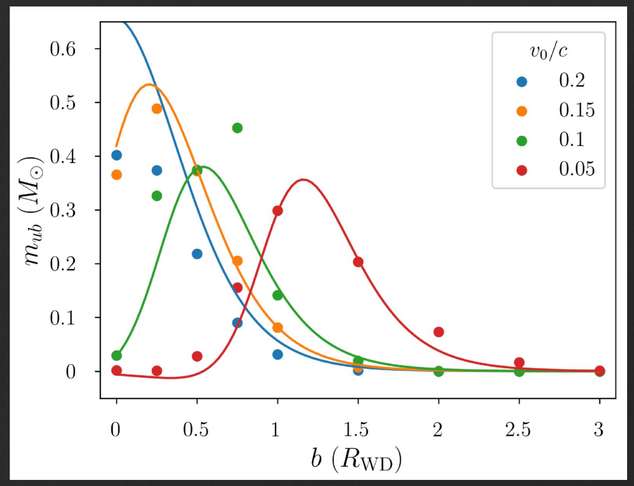
Micro-TDE between EMRI and WD

Xinyu Li, Houyi Sun, Yuan-Chuan Zou, Huan Yang (2501.13702)

Fate of the WD material:

- Accreted onto the sBH -> X-ray burst
- Remain bound
- Unbound from the sBH-WD system, may accrete onto the MBH -> late optical flare





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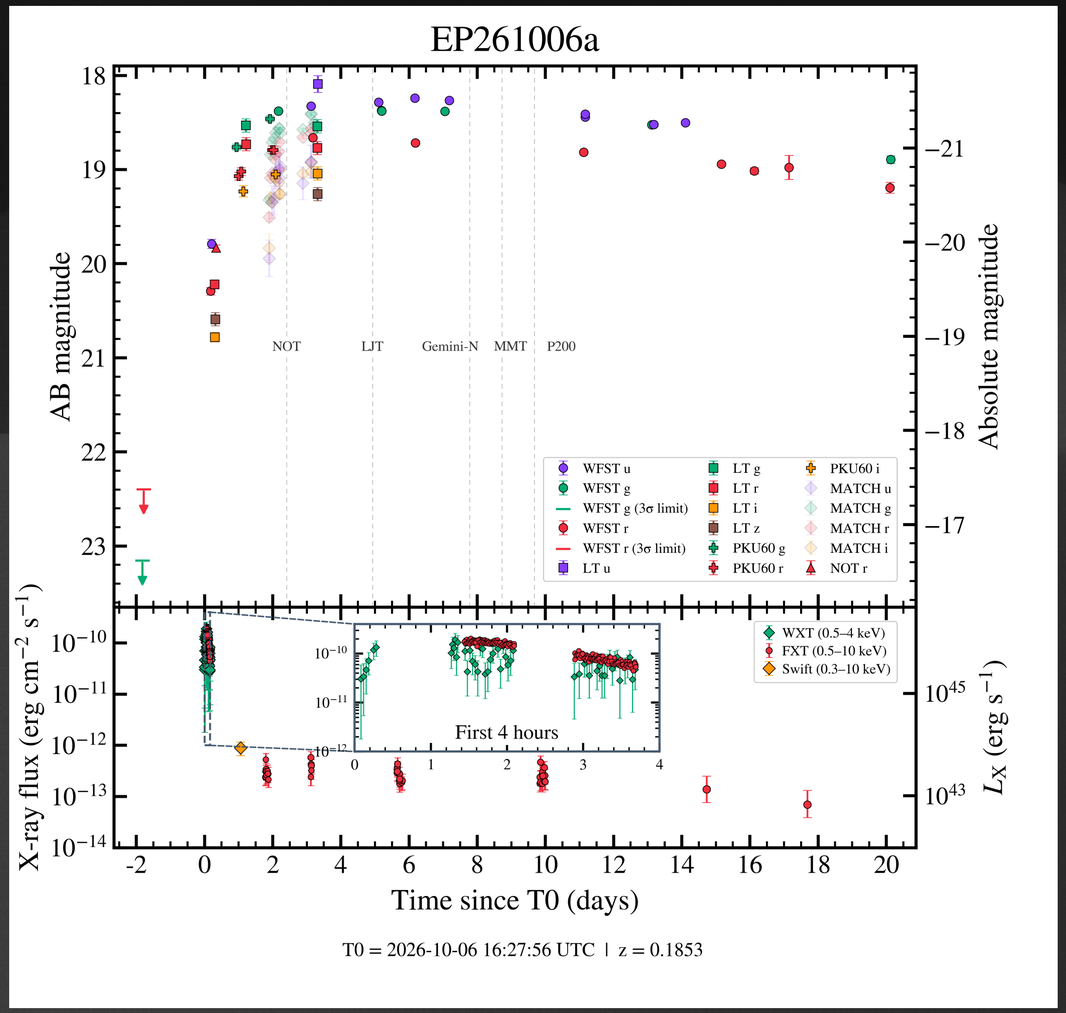
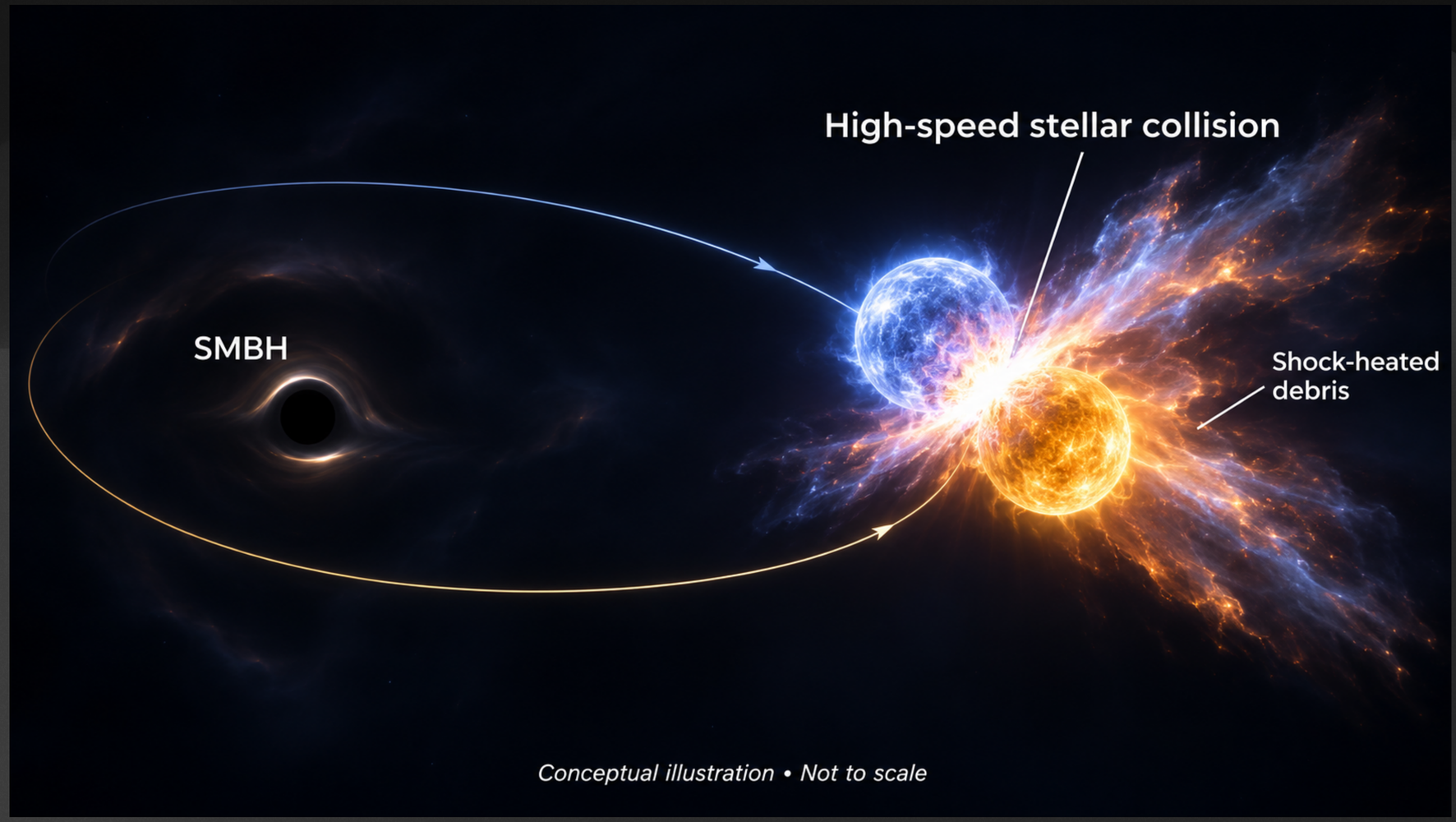
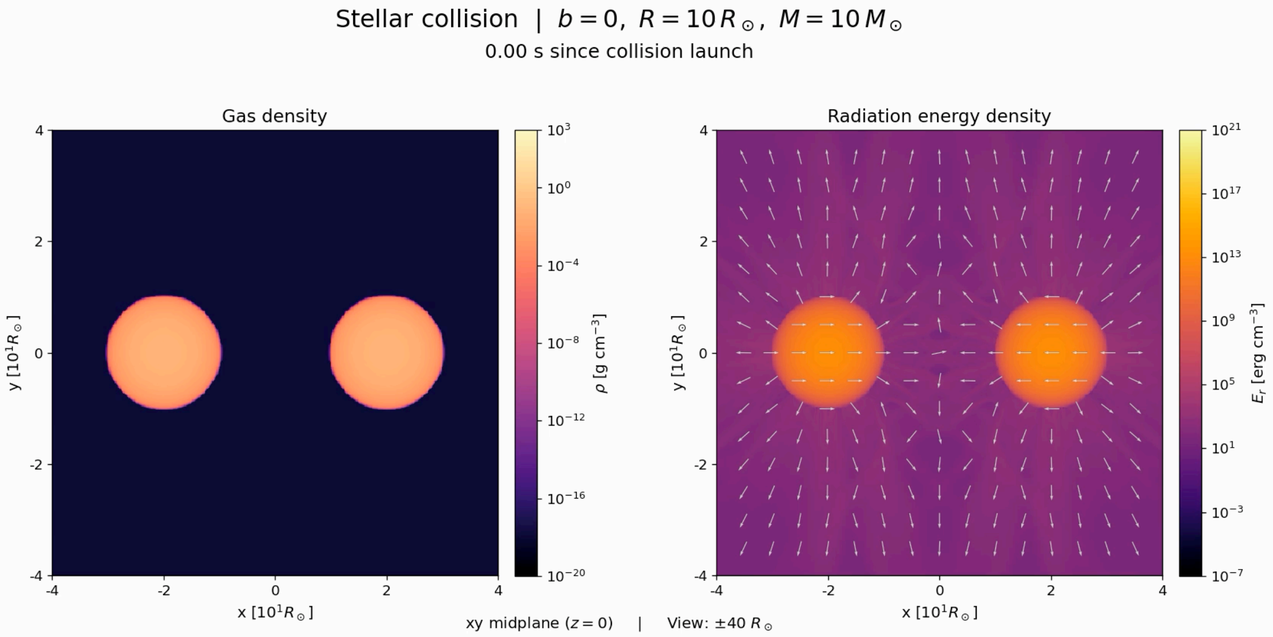


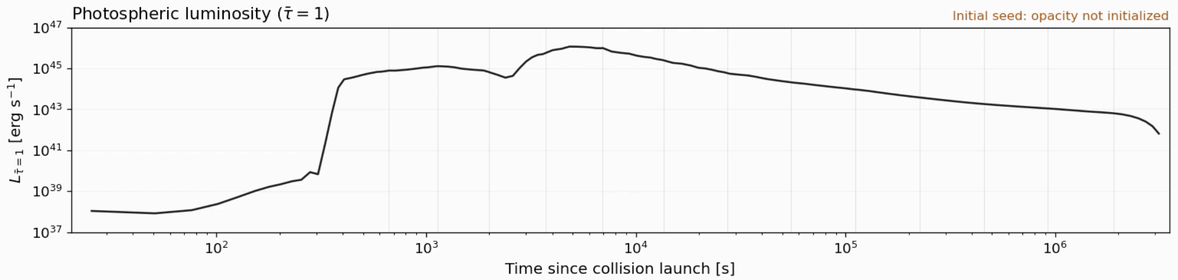
- High X-ray luminosity up to 10^{46} erg/s and rapid fading in a day.
- Rising and long-lasting optical emission.

Stellar Collisions near a SMBH



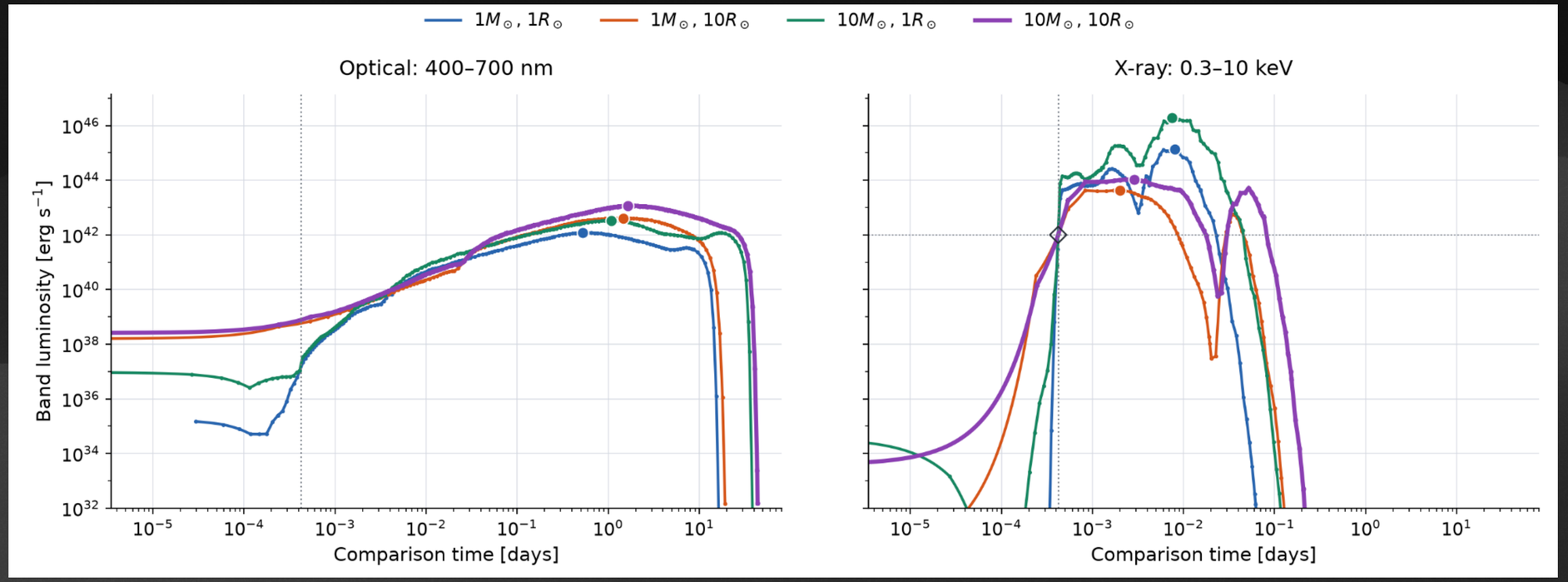
Stellar Collisions near a SMBH

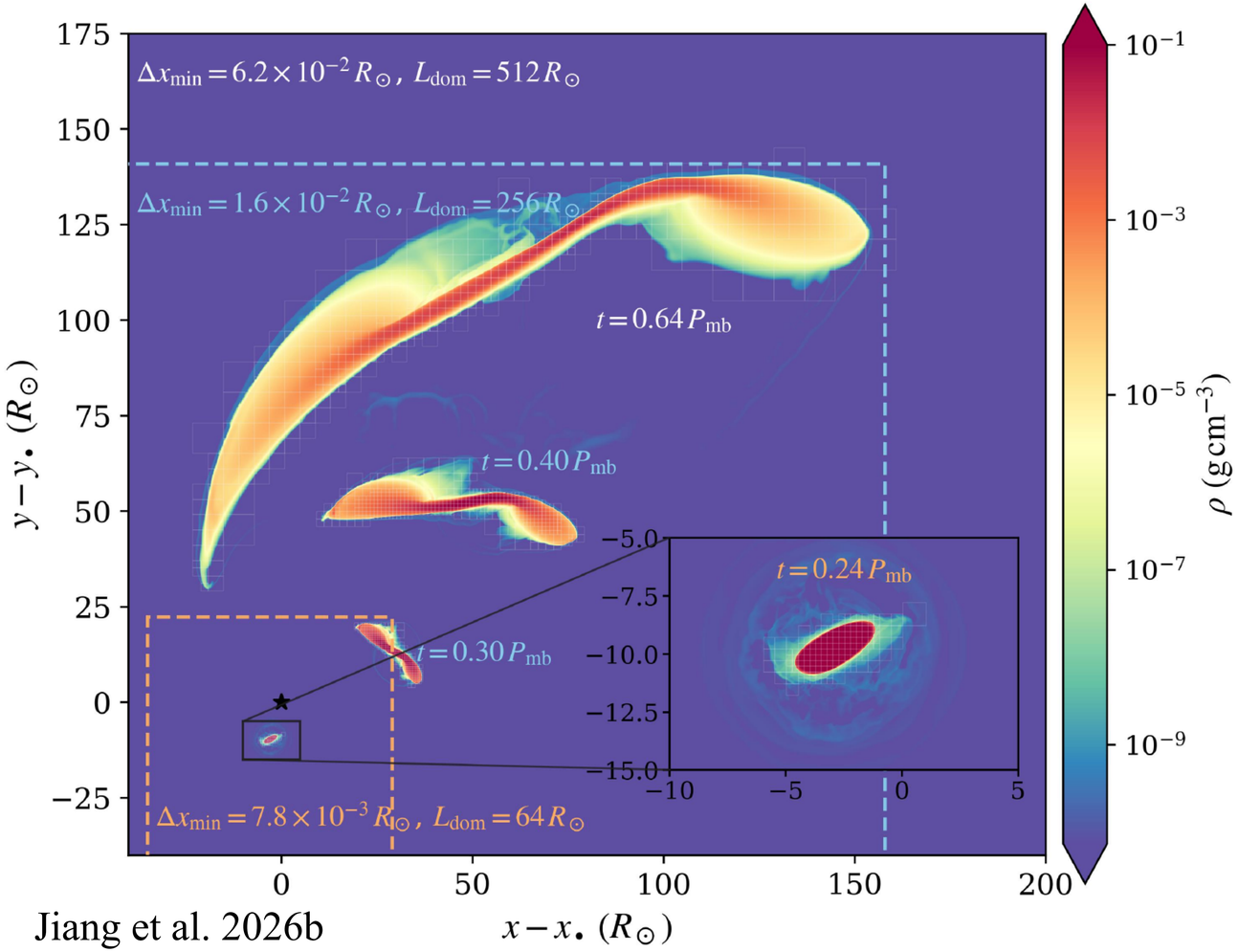




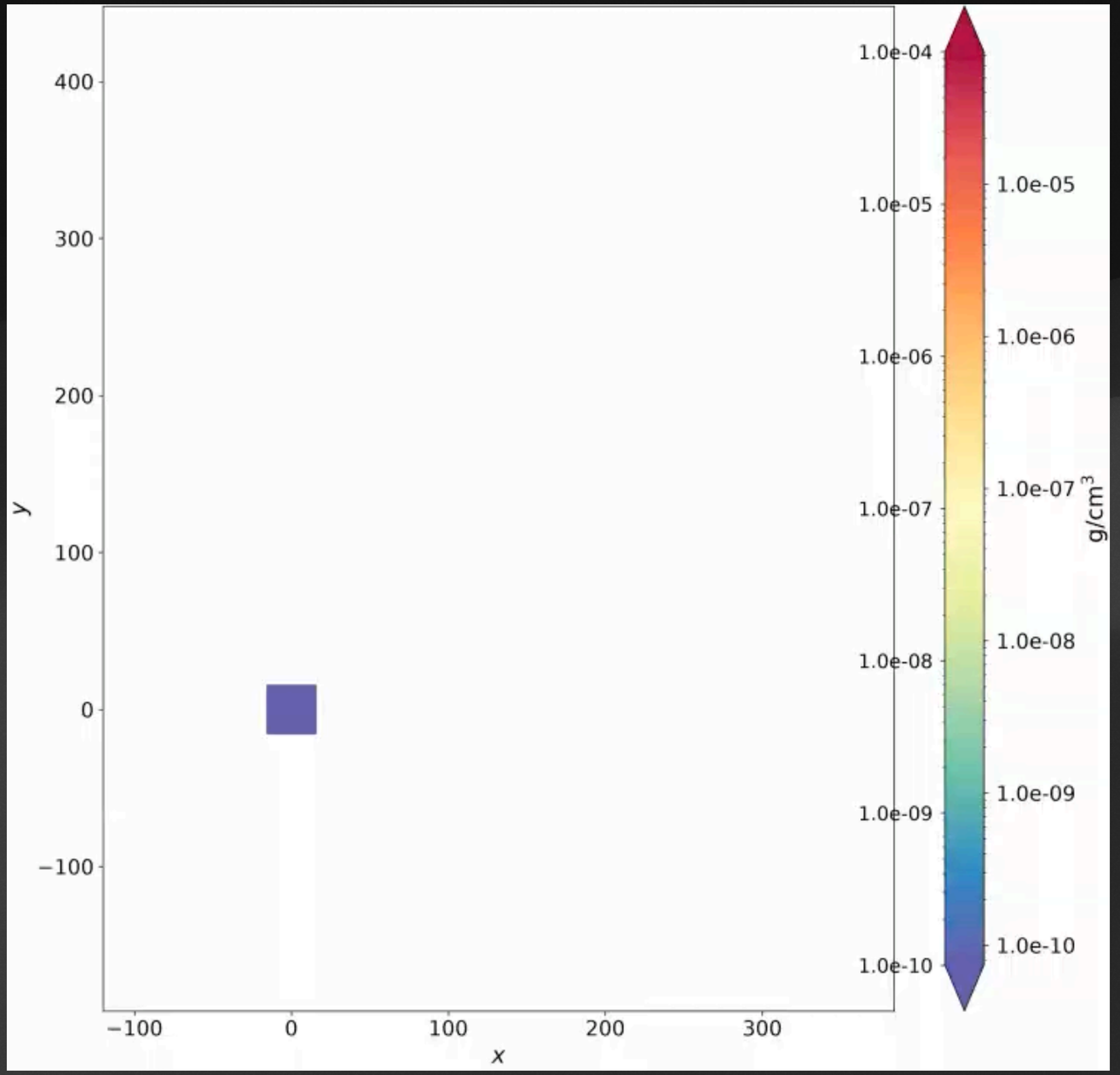
- Stars near the SMBH (<100 rg) with 0.1c

Stellar Collisions near a SMBH

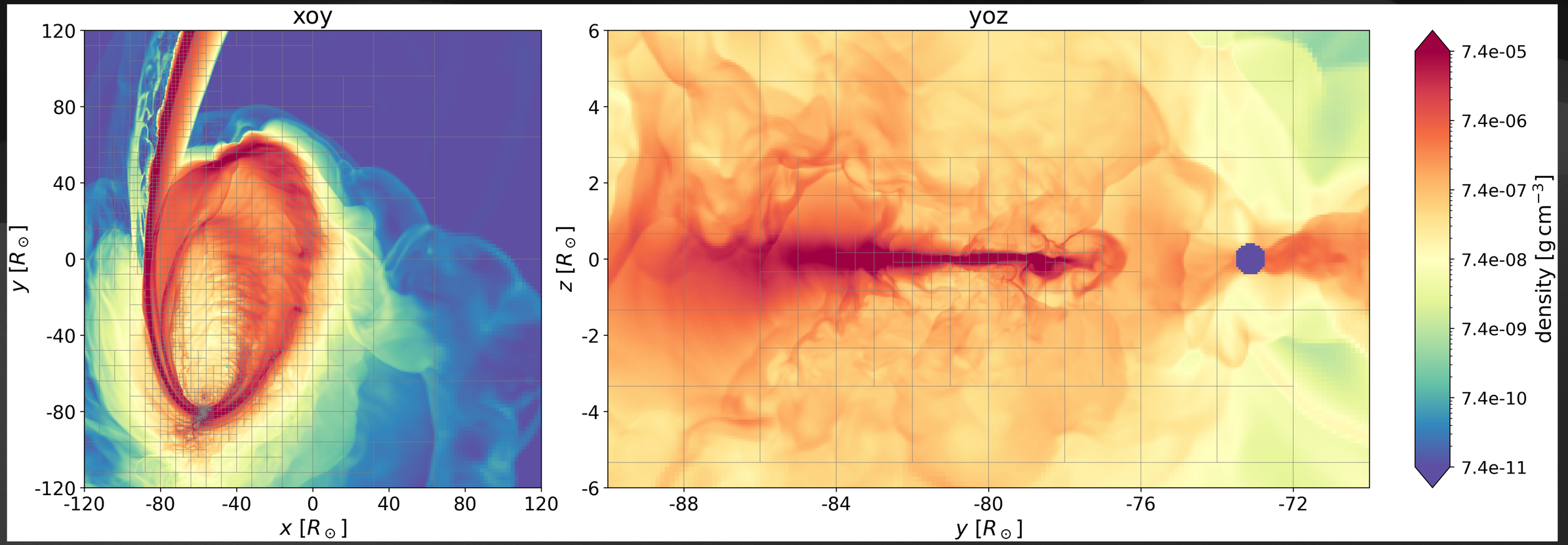




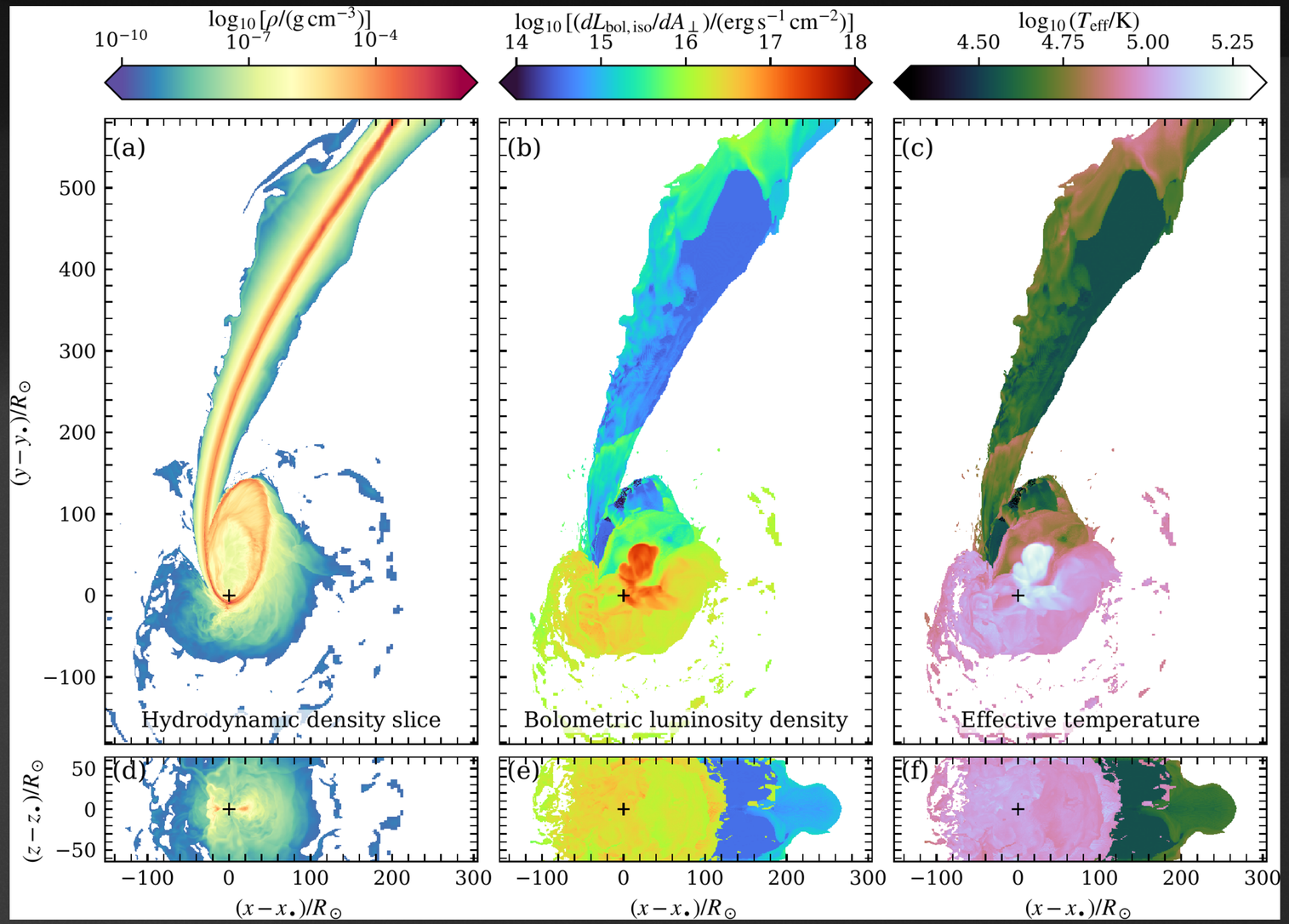
Jiang et al. 2026b


400
300
200
100
0
−100
y
−100
0
100
200
300
x
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
g/cm^3

Nozzle Shock



Radiative Post-Processing



Summary

How to illuminate binary system with SMBH(s)?

- QPE from BH-disk interactions
  - thick disk: jet precession from spin-orbit coupling, lensing flares
  - thin disk: reproduce OJ-287 observed features
- Micro-TDE between EMRI and WD
  - X-ray burst + late optical flare
- High speed stellar collision near SMBH
  - Fast fading X-ray and rising optical emission
- TDE simulations

Looking forward to collaborations and computational resources.

