Title: Jets with a Twist: Magnetized Spherical Accretion onto a Rapidly Spinning BH - VIRTUAL

Speakers: Aretaios Lalakos

Series: Strong Gravity

Date: January 11, 2024 - 1:00 PM

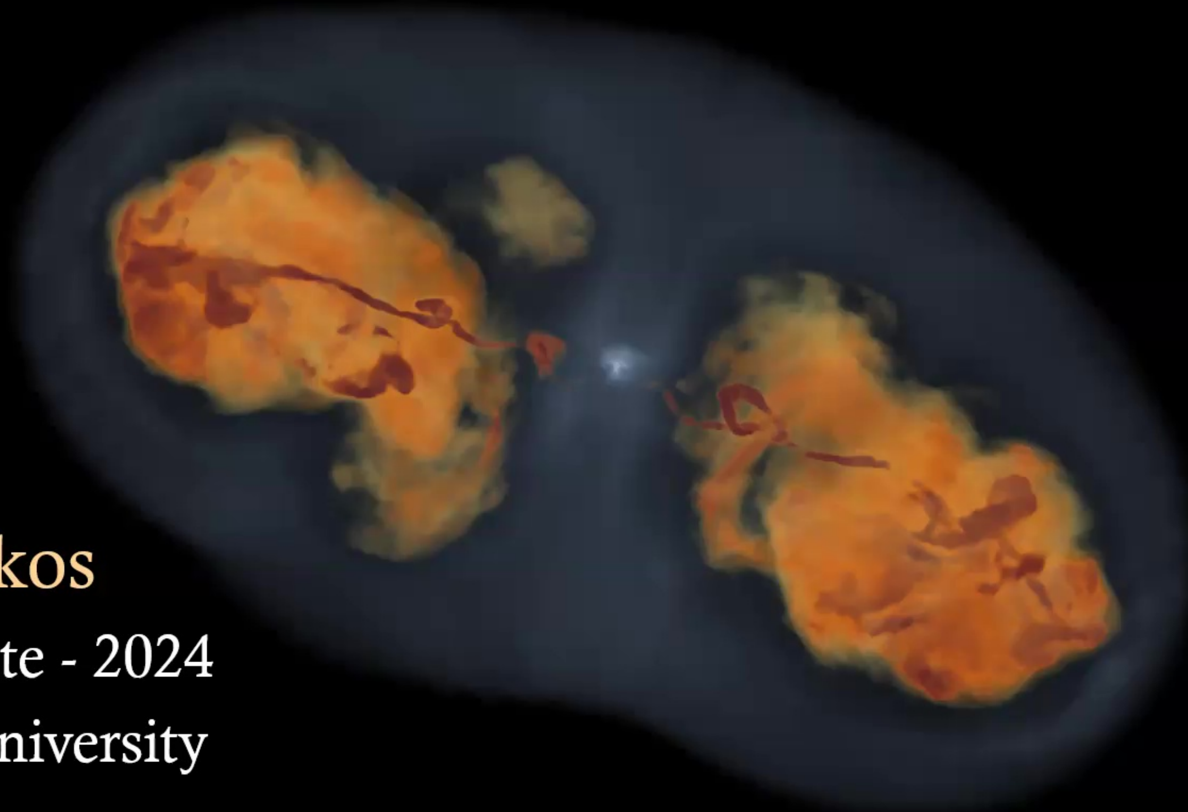
URL: https://pirsa.org/24010071

Abstract: Spinning supermassive black holes (BHs) in active galactic nuclei (AGN) can launch relativistic collimated outflows, or jets, by coiling up the magnetic field lines that cross the event horizon on the scale of BH gravitational radius, Rg. Sustained jet launching and propagation to kpc-scales are thought to require non-zero angular momentum to form an accretion disk, keep the magnetic field lines on the BH, and ensure stable jet propagation. Past 3D general relativistic magnetohydrodynamic (GRMHD) work predicted that absent gas angular momentum, magnetized jets are expected to become unstable to the kink instability already at 800 Rg, i.e., orders of magnitudes smaller distances than the BH sphere of influence, or the Bondi radius, RB (e.g., for Sgr A* and M87, RB~10^[5-6] Rg). This raises the question: Do the jets need gas angular momentum to survive the kink instability and make it out to large distances, outside of Rb? I will present 3D GRMHD simulation results for a rapidly spinning BH immersed into uniform zero angular momentum gas threaded by a weak vertical magnetic field, with the largest simulated Bondi radius to date, RB = 1000 Rg. I will show that the BH accumulates dynamically-important magnetic field, enters the magnetically-arrested disk state, and produces powerful jets that make it out of Rb. I will also show how the jets get twisted into knots and dissipate their energy after the MAD state ends.

Zoom link https://pitp.zoom.us/j/99925612004?pwd=QkhIUmpKRkVKUURpclhPekJST2NIQT09

Journey into the Galaxy

Closing the Feedback Loop by Bridging the Event Horizon and Galaxy Scales



Aris Lalakos

Perimeter Institute - 2024

Northwestern University

NSF

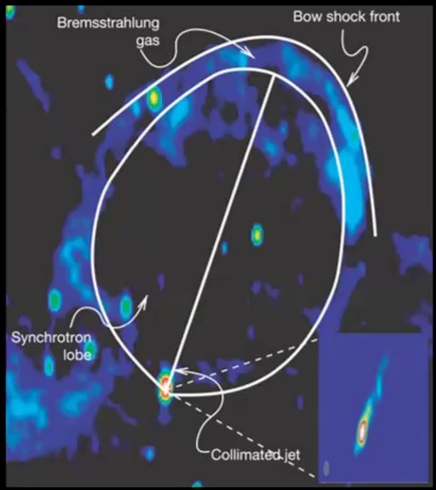
Oak Ridge National Laboratory

CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics

Jets as Cosmic Fountains

- Supermassive BHs ($10^6 - 10^{10}\ M_\odot$): Active Galactic Nuclei (AGN)
- Stellar Mass BHs ($\sim 10\ M_\odot$): GRBs, X-ray Binaries
- Young stellar objects (YSO)/ White dwarf in Binaries

Hercules A (Hubble)



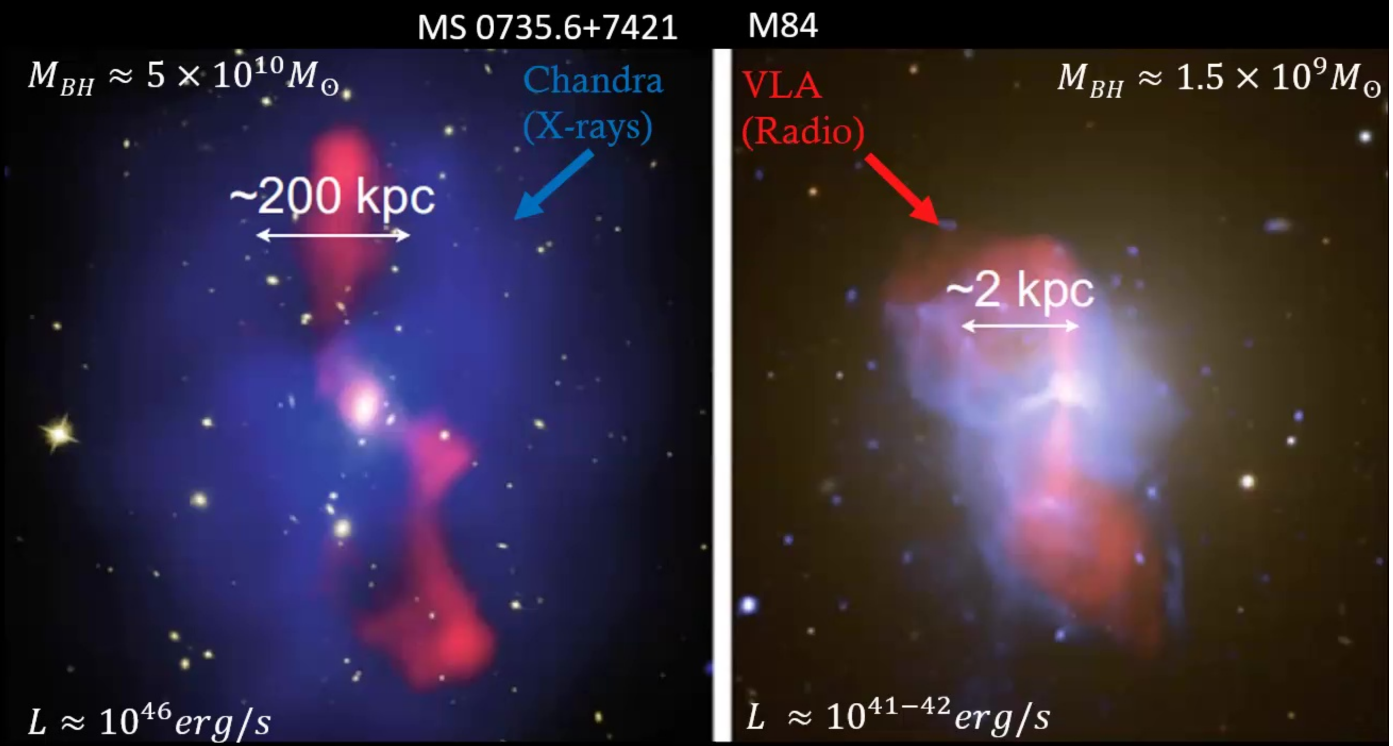
Cyg-X1 (Gallo et al. 2005)

HH 211 (JWST)

R Aquarii (ESO/Schmid et al.)

Feedback is *Crucial!*

Even 1% of the SMBH rest mass energy coupled to the galaxy can unbind its gas!

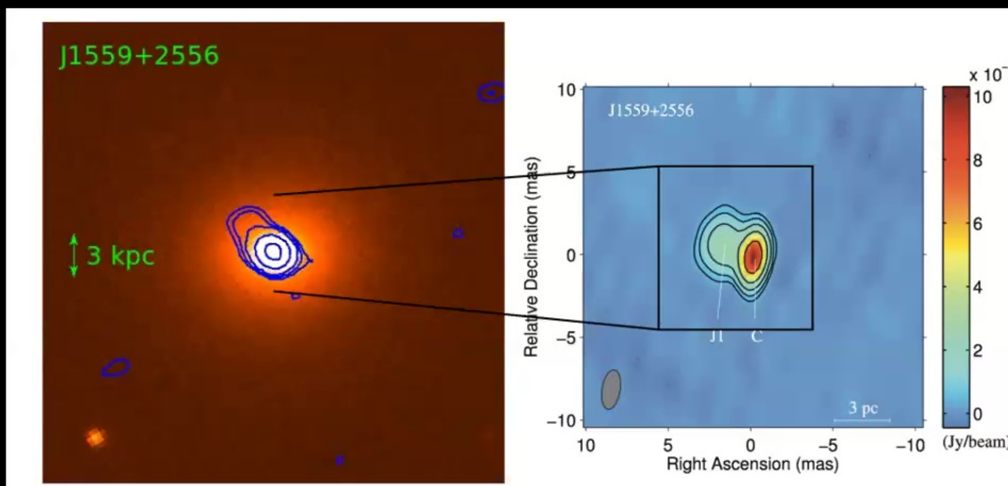


Aris Lalakos lalakos@u.northwestern.edu

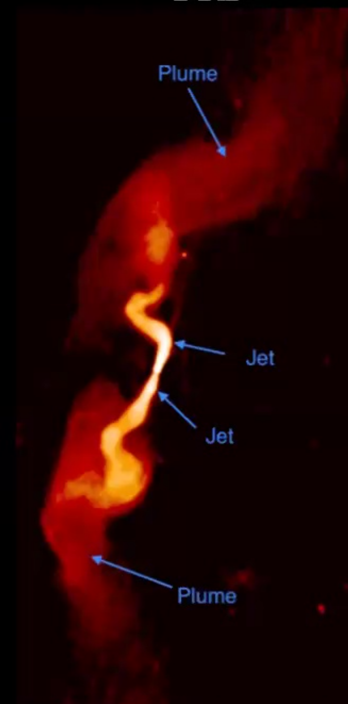
We still don't understand jet morphology

Baldi 2019

FR0



FRI



3C 31

FRII

Cygnus A

FR0 (Ghisellini 2011) - More numerous (5 x FRI) (Stecker 2019)

1) Evolution from FRI/II?
2) Shorter, slower, strongly coupled to the galaxy
3) Some known to be gamma-ray emitters (Paliya 2021) - Ideal laboratories to study dissipative processes

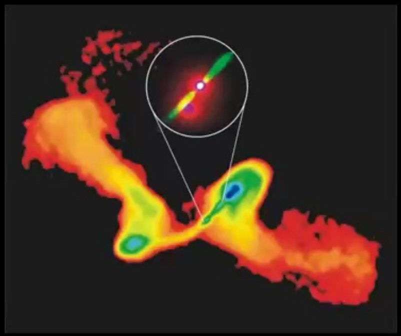
21 cm – 1.4 GHz

Fanaroff Riley (FR) 1974

Aris Lalakos lalakos@u.northwestern.edu

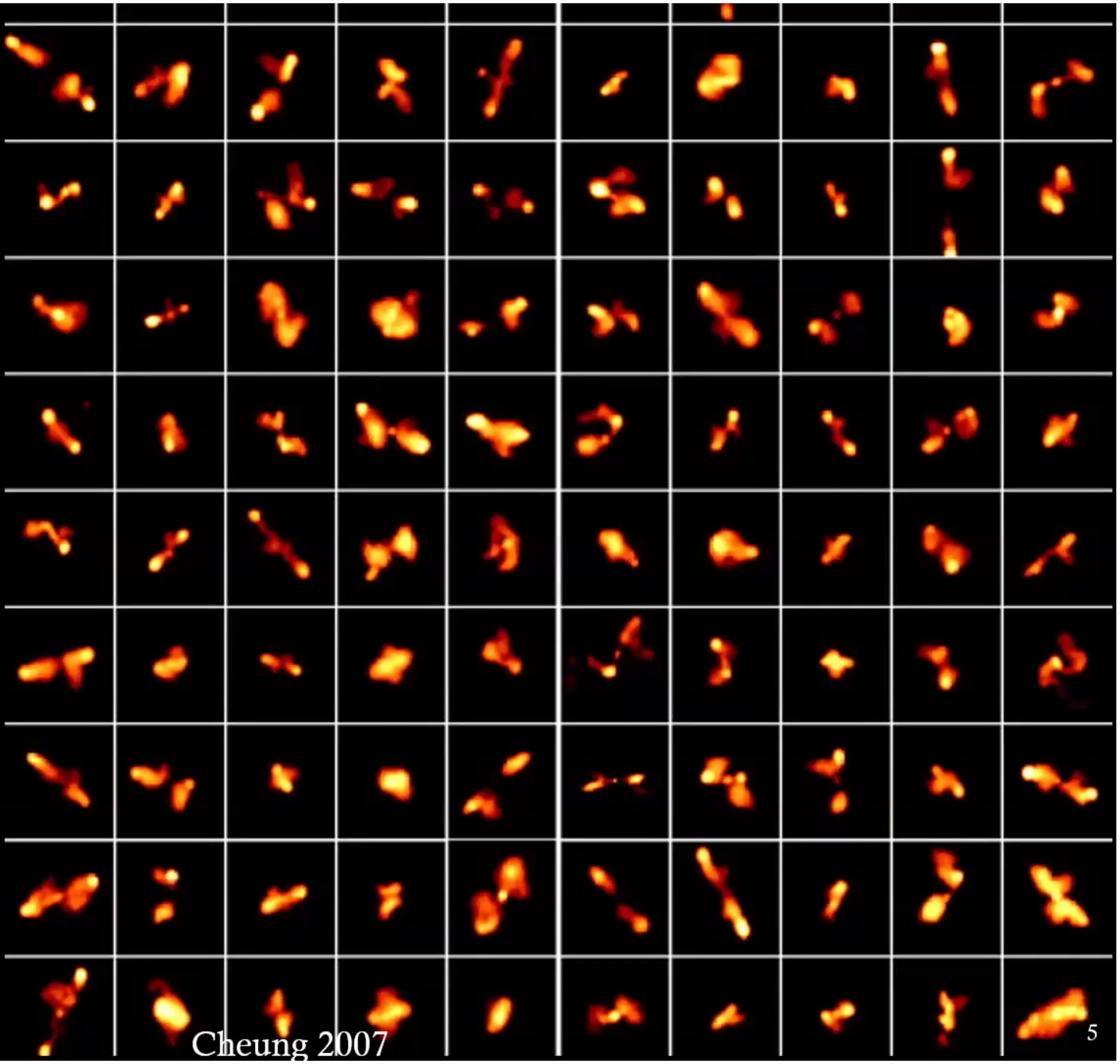
X-shaped Radio Galaxies (XRGs)

- Spin orientation change (Long-time accretion, SMBH Mergers)
- Asymmetries in backflows



HODGES-KLUCK & REYNOLDS, 2011

Aris Lalakos



Cheung 2007

5

First time closing Feedback loop in GRMHD

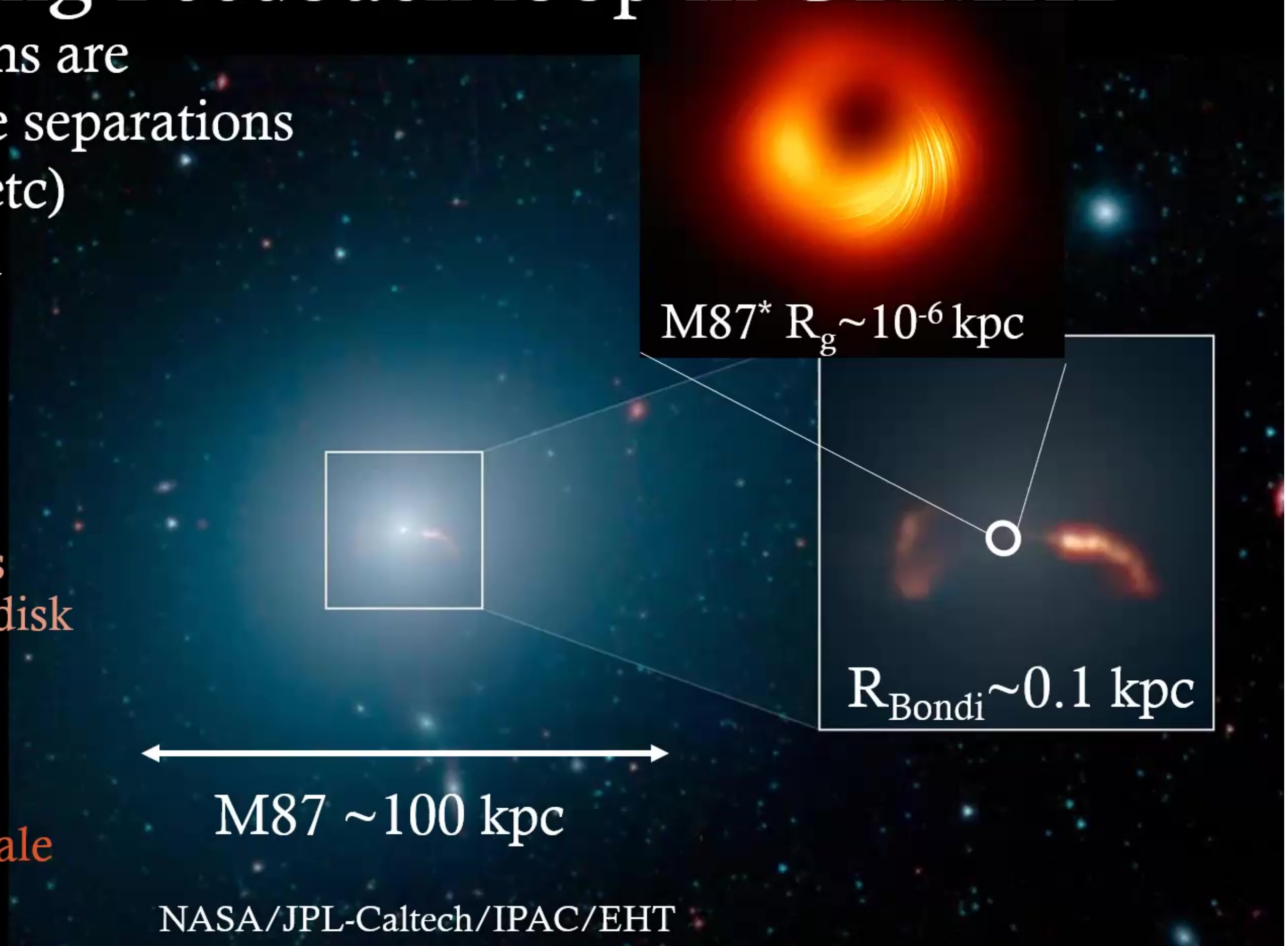
Many Astrophysical systems are riddled with immense scale separations (Collapsars, NSM, AGN, etc)

Magnetic fields are dynamically important EHT: M87* is MAD
→ need BHs to create jets.

>98% of material not consumed! What physics causes this suppression? Is it the jet or disk winds?

- I was the first to close the feedback loop at the largest scale separation in GRMHD

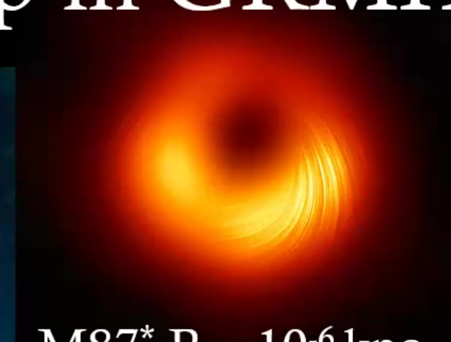
Lalakos et al 2022, **ApJL 936 L5**



Aris Lalakos lalakos@u.northwestern.edu

First time closing Feedback loop in GRMHD

Many Astrophysical systems are riddled with immense scale separations (Collapsars, NSM, AGN, etc)



M87* $R_g \sim 10^{-6}$ kpc

Magnetic fields are dynamically important EHT: M87* is MAD
→ need BHs to create jets.

>98% of material not consumed! What physics causes this suppression? Is it the jet or disk winds?

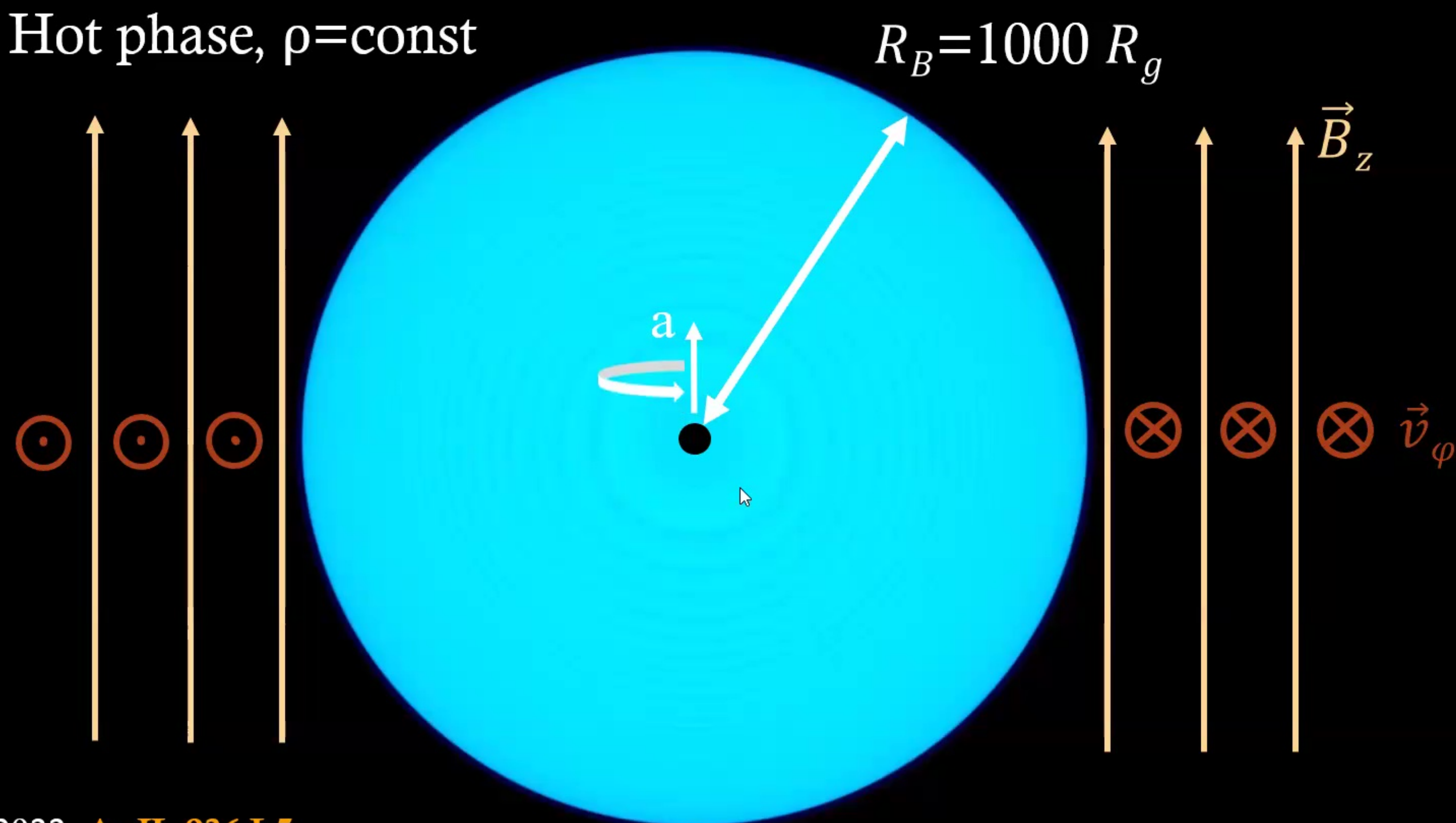
- I was the first to close the feedback loop at the largest scale separation in GRMHD

Lalakos et al 2022, **ApJL 936 L5**

Extremely Timely for current and future missions:

1) ngEHT/ SKA: near-BH jet formation and jet propagation
2) XRISM/ATHENA: Large scale jets induced turbulence and feedback
3) JWST: early BH growth
4) LISA – LVK: GW
5) ICE-CUBE: Neutrino production

Cracking the basics – Simple and controlled IC conditions

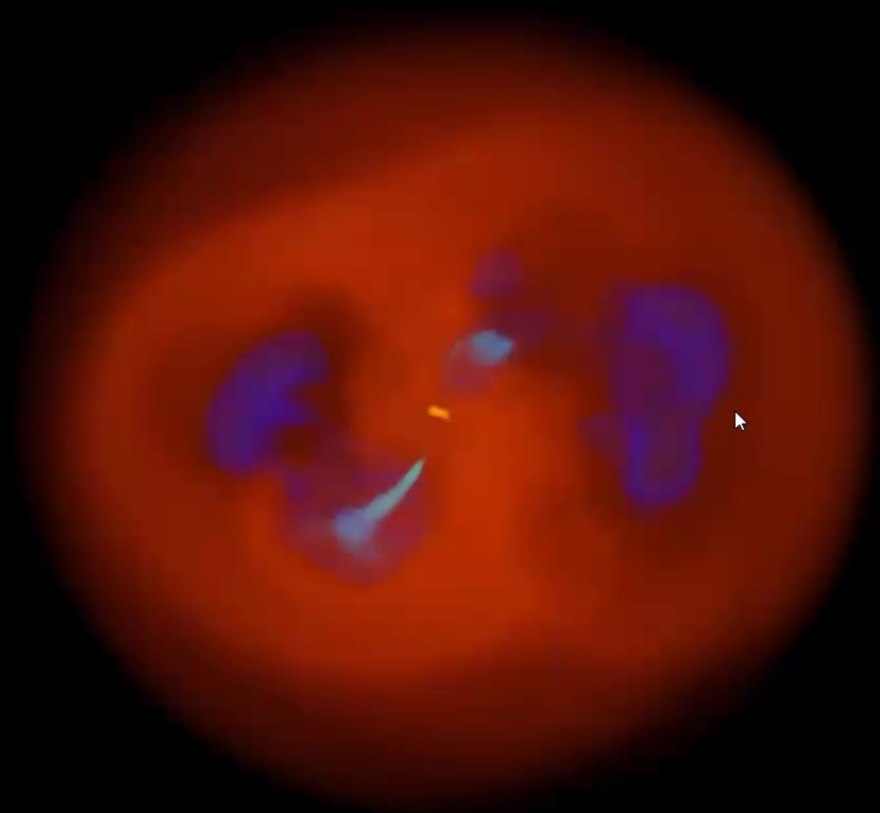


Lalakos et al 2022, ApJL 936 L5

H-AMR: In-house developed GRMHD code (Liska et al. 2022)

Aris Lalakos lalakos@u.northwestern.edu

Red: high-density
Blue: low-density



1/11/2024

Aris Lalakos lalakos@u.northwestern.edu

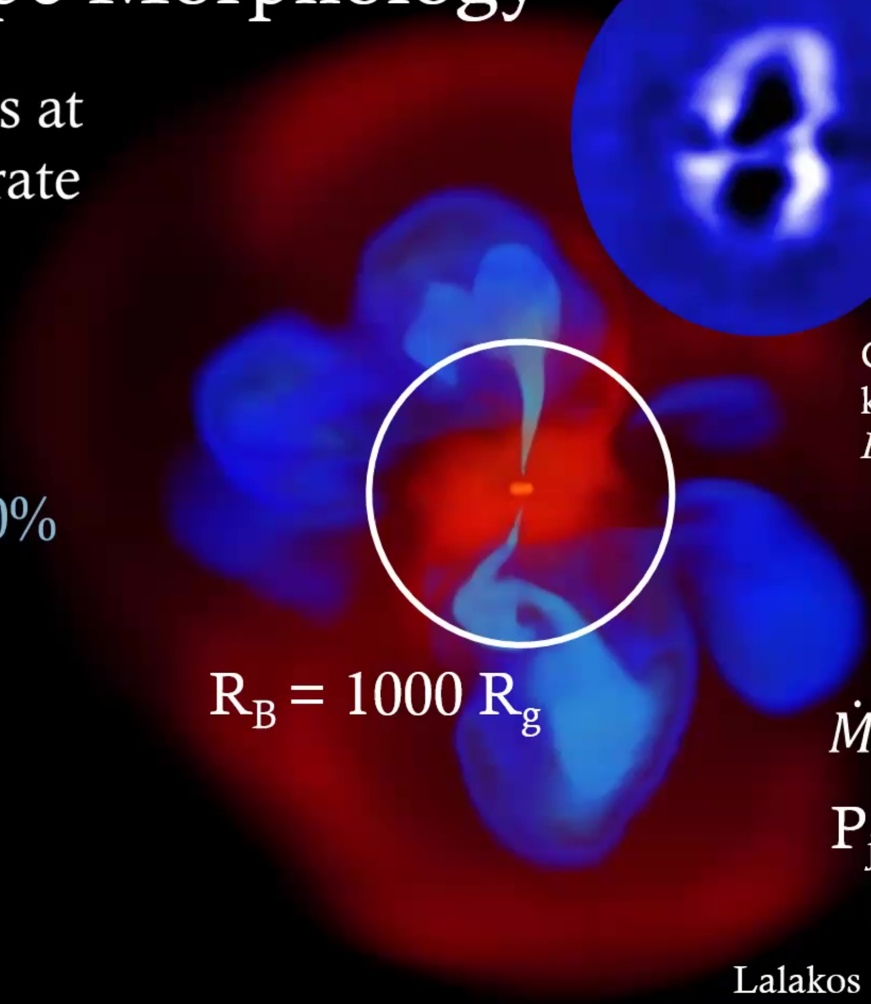
Unexpected X-shape Morphology

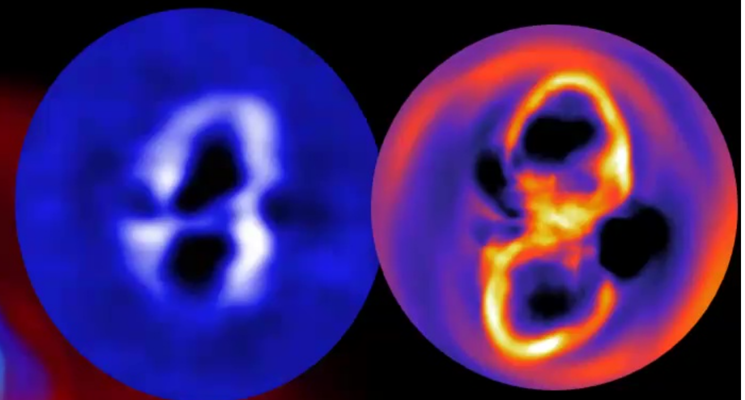
BH mass accretion saturates at 2% of the Bondi accretion rate

steady state=MAD

agreement with upper limit EHT!

Outflows efficiency $\eta \sim 150\%$





Chandra (galaxy cluster known as RBS 797)
F. Ubertosi et al 2022

$\dot{M}_{BH} \sim 2\%\ \dot{M}_{Bondi}$

$P_{jets} \sim 10^{44}$ erg/s

Lalakos et al 2022, ApJL 936 L5

Aris Lalakos lalakos@u.northwestern.edu

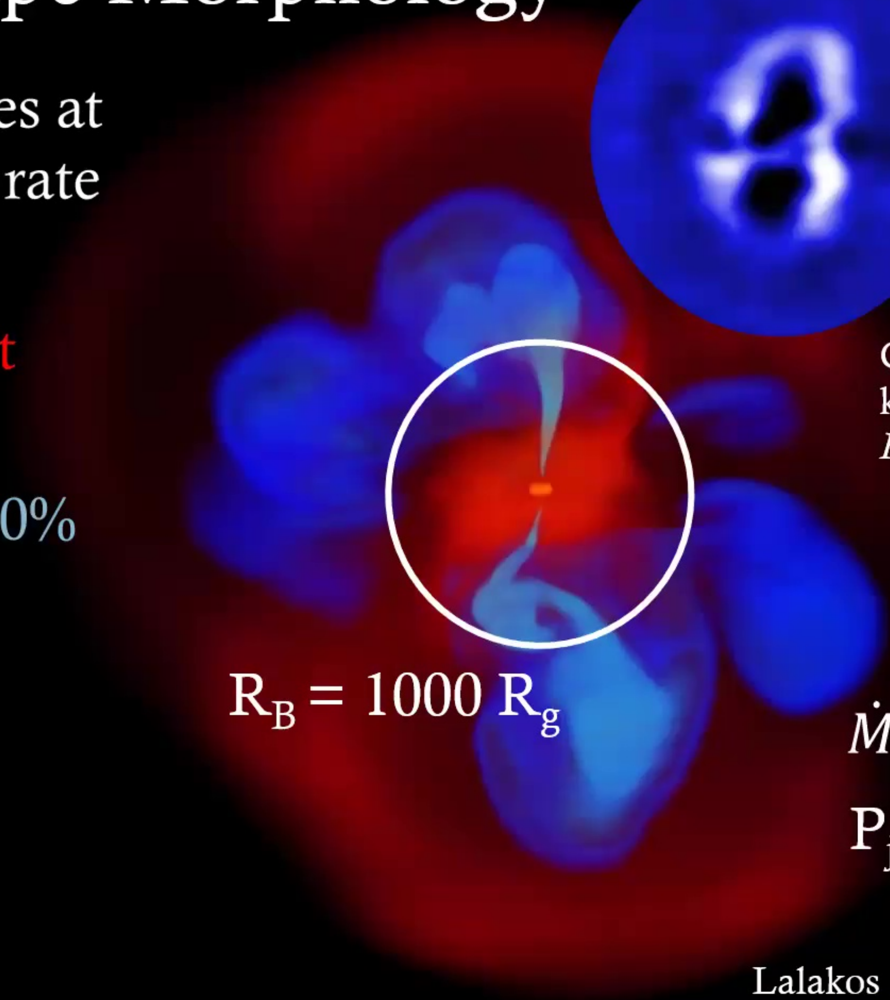
Unexpected X-shape Morphology

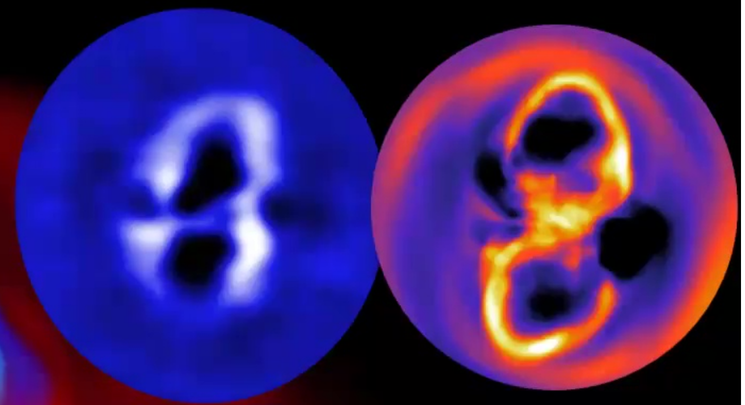
BH mass accretion saturates at 2% of the Bondi accretion rate

steady state=MAD

agreement with upper limit EHT!

Outflows efficiency $\eta \sim 150\%$





Chandra (galaxy cluster known as RBS 797)
F. Ubertosi et al 2022

$\dot{M}_{BH} \sim 2\%\ \dot{M}_{Bondi}$

$P_{jets} \sim 10^{44}$ erg/s

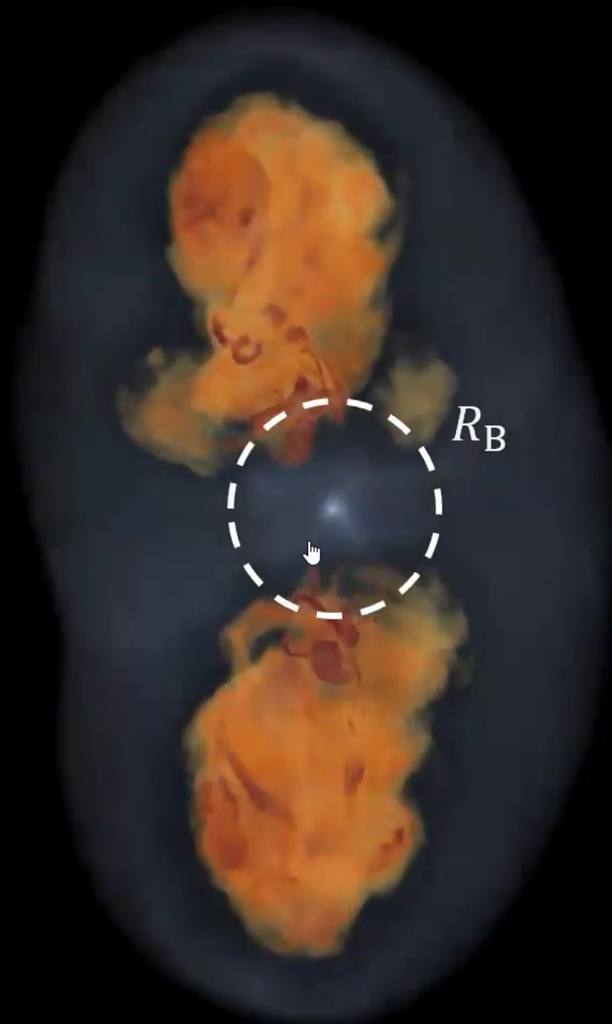
Lalakos et al 2022, ApJL 936 L5

9

Aris Lalakos lalakos@u.northwestern.edu

Red : low-density
Blue: high-density

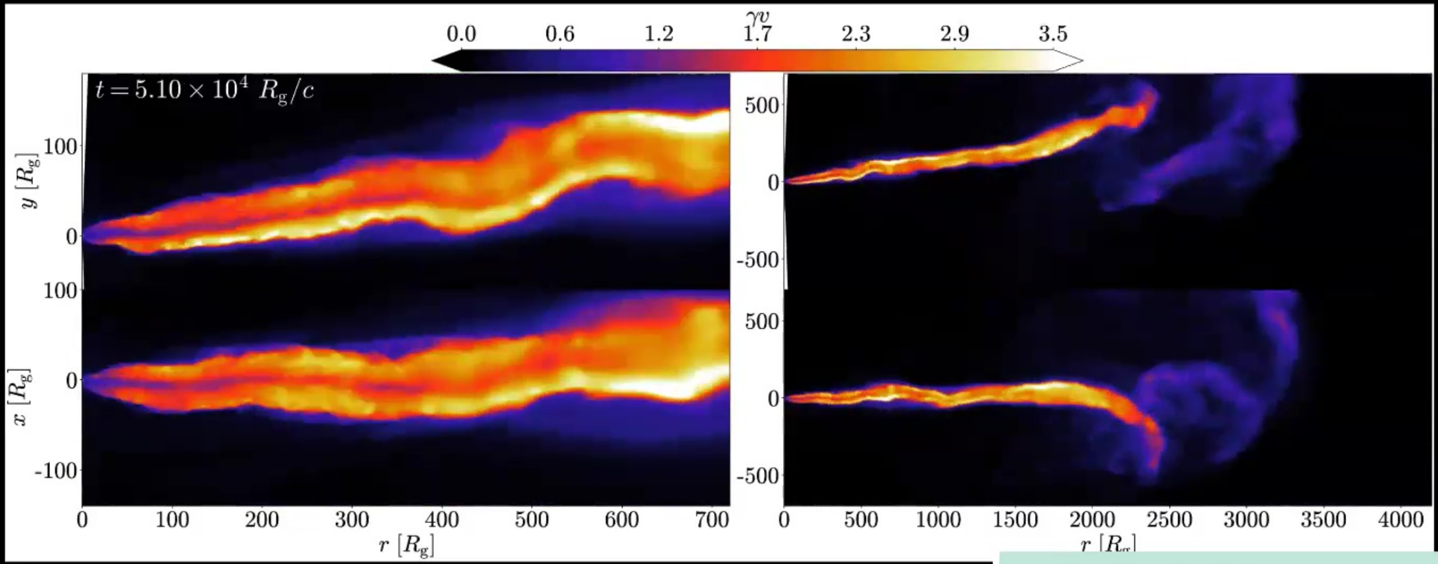
Lalakos et al 2023 arXiv:2310.11487



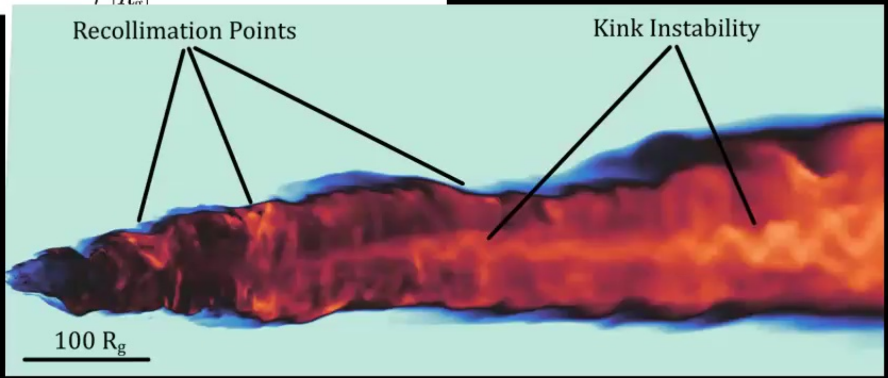
Ressler et al. 2021 + Kwan et al. 2022 showed that zero ang. momentum:
1) Hard time reaching MAD.
2) Jets unstable when $r \geq 800\ R_g$.

Aris Lalakos lalakos@u.northwestern.edu

Jets can survive out to larger distances than expected



1. Kink instability twists jets into a helical shape and dissipates magnetic energy.
2. Linear stability (Bromberg et al. 2016) fails to capture non-linear external kink.
3. Most of magnetic energy dissipated to heat! Connection to non-thermal particle emission and multimessenger phenomena (UHECRs and neutrinos)

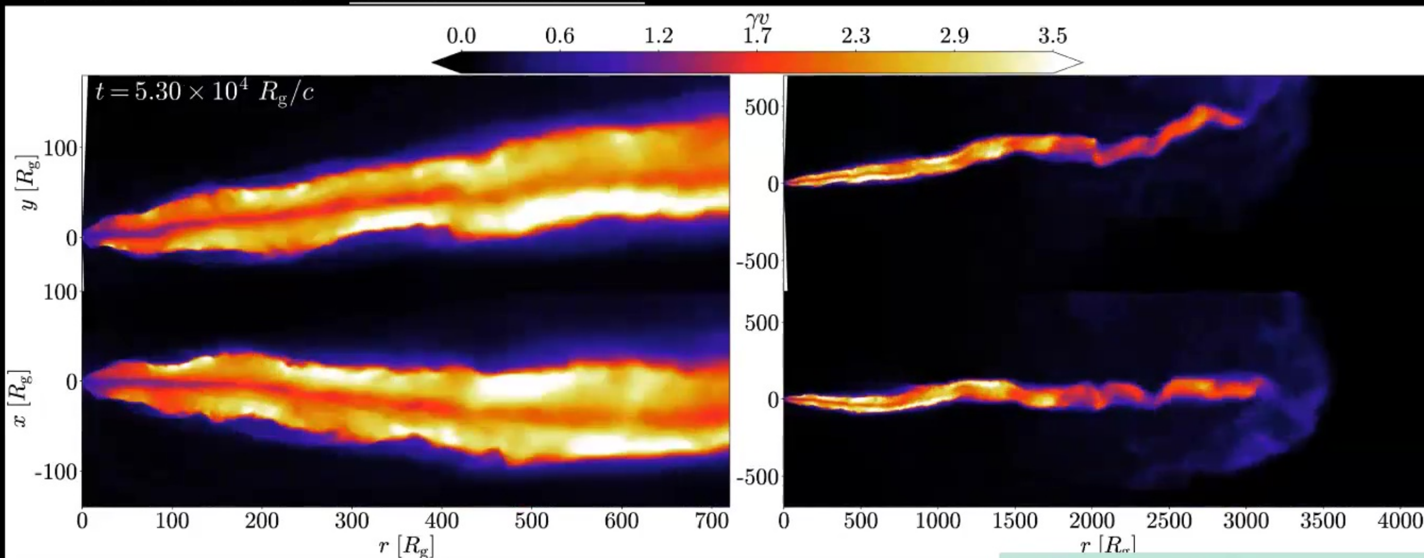


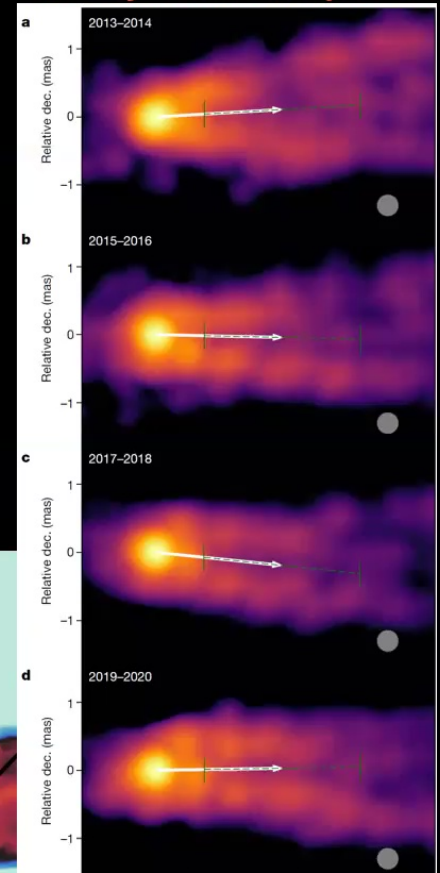
Aris Lalakos lalakos@u.northwestern.edu

Jets can survive out to larger distances than expected

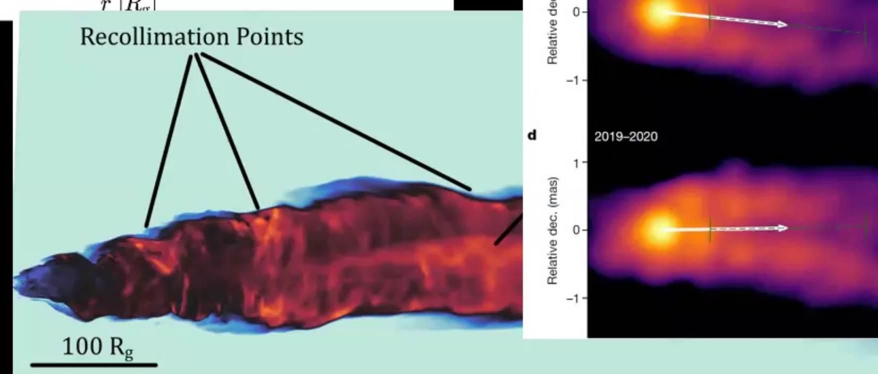
Lalakos et al 2023 arXiv:2310.11487

MAD jets inherently wobble





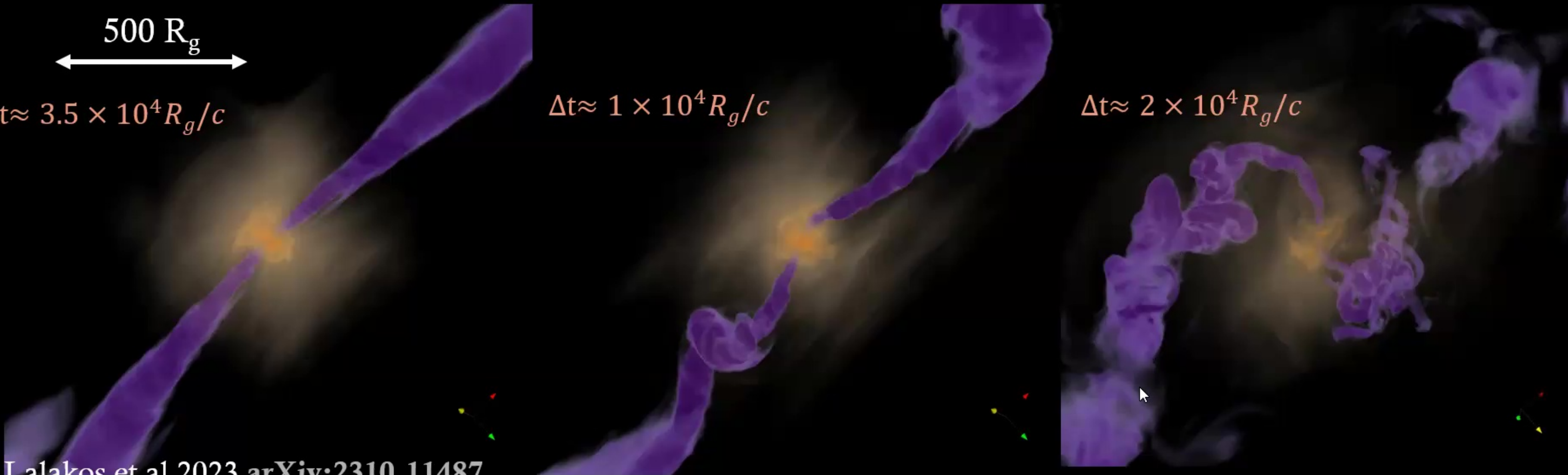
1. Kink instability twists jets into a helical shape and dissipates magnetic energy.
2. Linear stability (Bromberg et al. 2016) fails to capture non-linear external kink.
3. Most of magnetic energy dissipated to heat! Connection to non-thermal particle emission and multimessenger phenomena (UHECRs and neutrinos)



Aris Lalakos lalakos@u.northwestern.edu

Cui 2023 (precession) 11

The MAD, the BAD, and the RAD



Lalakos et al 2023 arXiv:2310.11487

- Jets escape out of R_B
- $\dot{M}_{BH} = 2\% \dot{M}_B$

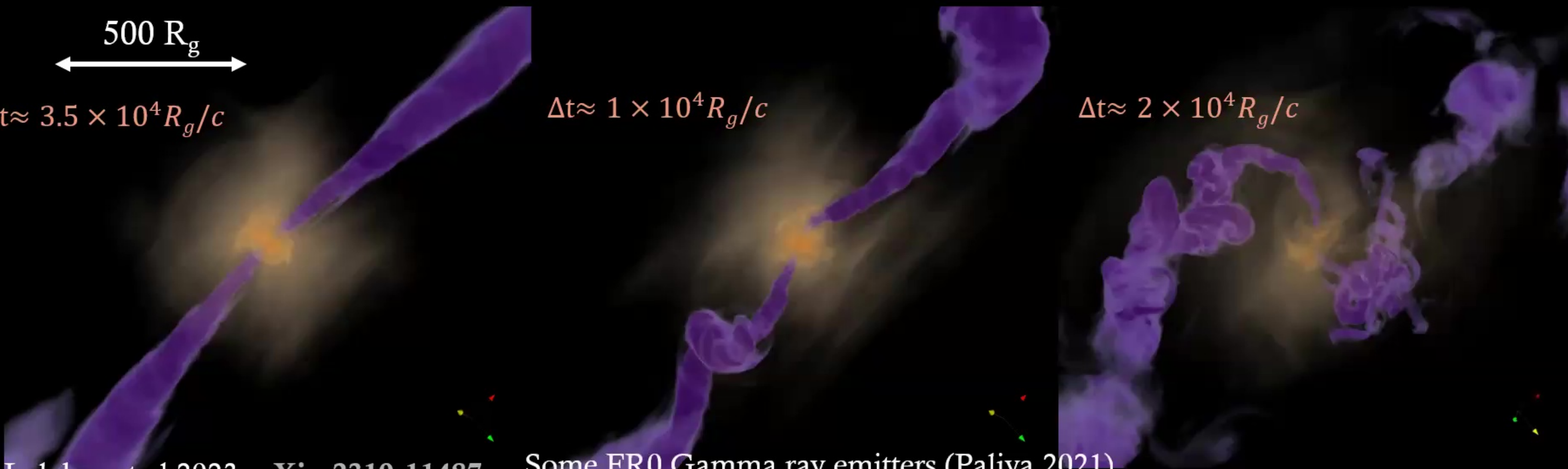
MAD jets rather than disk winds do most feedback!

(Barely A) Disk rapidly precesses
jets fall apart
- $\dot{M}_{BH}$ = 5-10% $\dot{M}_B$

- Rocking Accretion Disk flips 90-180°
Jets 15 x weaker
- can reach $\dot{M}_{BH} = 2\% \dot{M}_B$

Aris Lalakos lalakos@u.northwestern.edu

The MAD, the BAD, and the RAD

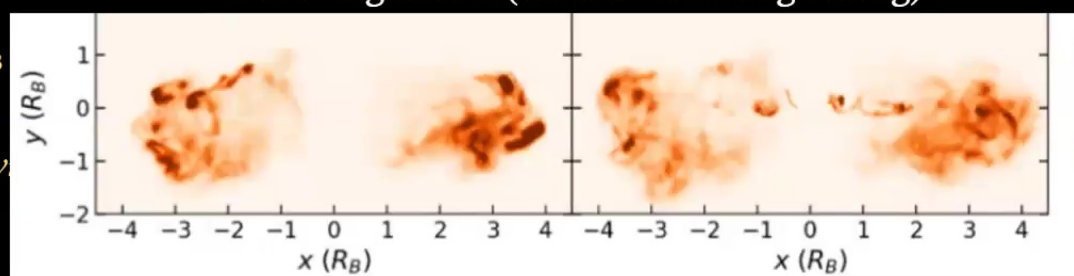


Lalakos et al 2023 arXiv:2310.11487

Some FR0 Gamma ray emitters (Paliya 2021)
Jet disintegration? (Credit Haocheng Zhang)

- Jets escape out of R_B
- $\dot{M}_{BH} = 2\% \, \dot{M}_B$

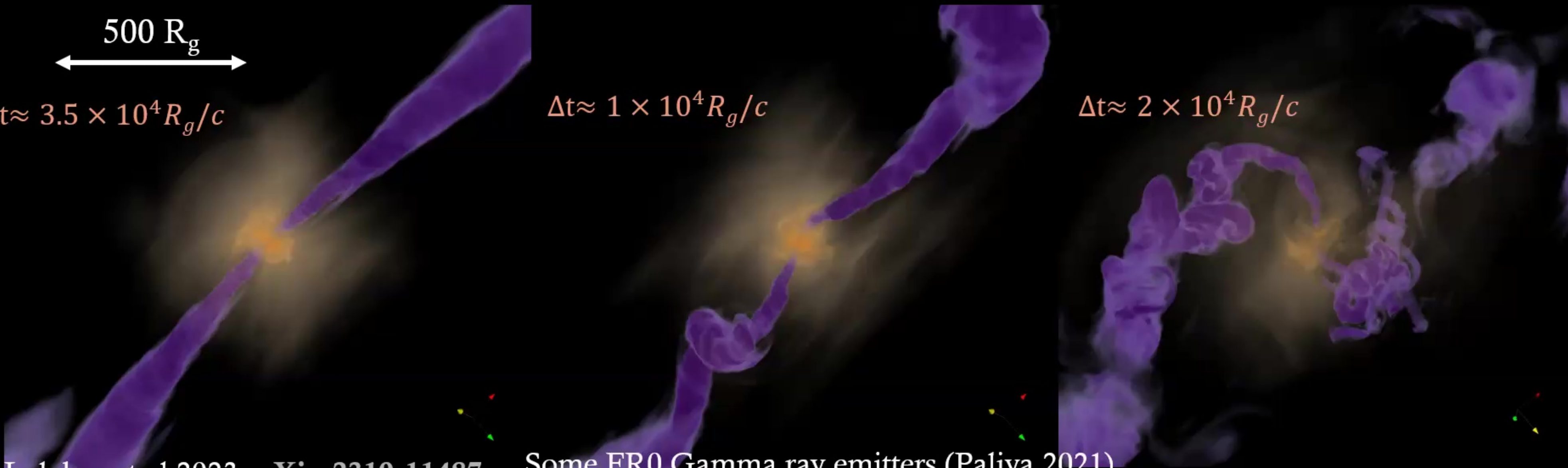
MAD jets rather than disk w
most feedback!



Accretion Disk flips 90-180°
Jets 15 x weaker
n reach $\dot{M}_{BH} = 2\% \, \dot{M}_B$

Aris Lalakos lalakos@u.northwestern.edu

The MAD, the BAD, and the RAD

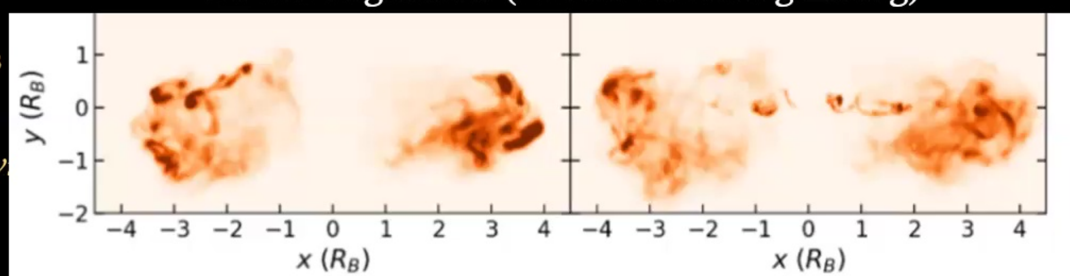


Lalakos et al 2023 arXiv:2310.11487

Some FR0 Gamma ray emitters (Paliya 2021)
Jet disintegration? (Credit Haocheng Zhang)

- Jets escape out of R_B
- $\dot{M}_{BH} = 2\% \, \dot{M}_B$

MAD jets rather than disk w
most feedback!



Accretion Disk flips 90-180°
Jets 15 x weaker
n reach $\dot{M}_{BH} = 2\% \, \dot{M}_B$

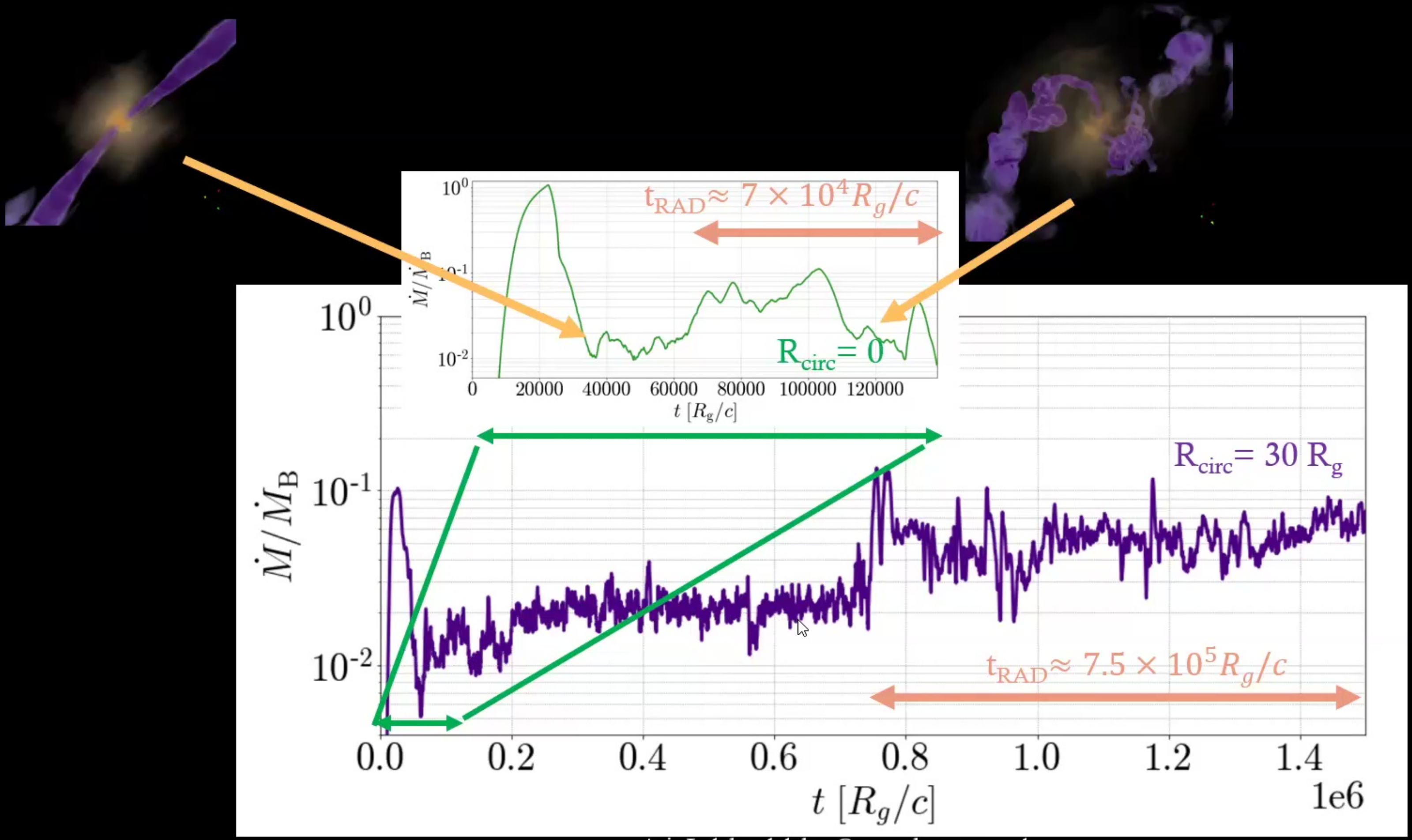
Is this caused by the lack of Gas Angular Momentum?

Aris Lalakos lalakos@u.northwestern.edu

12

RADs angular momentum starved?

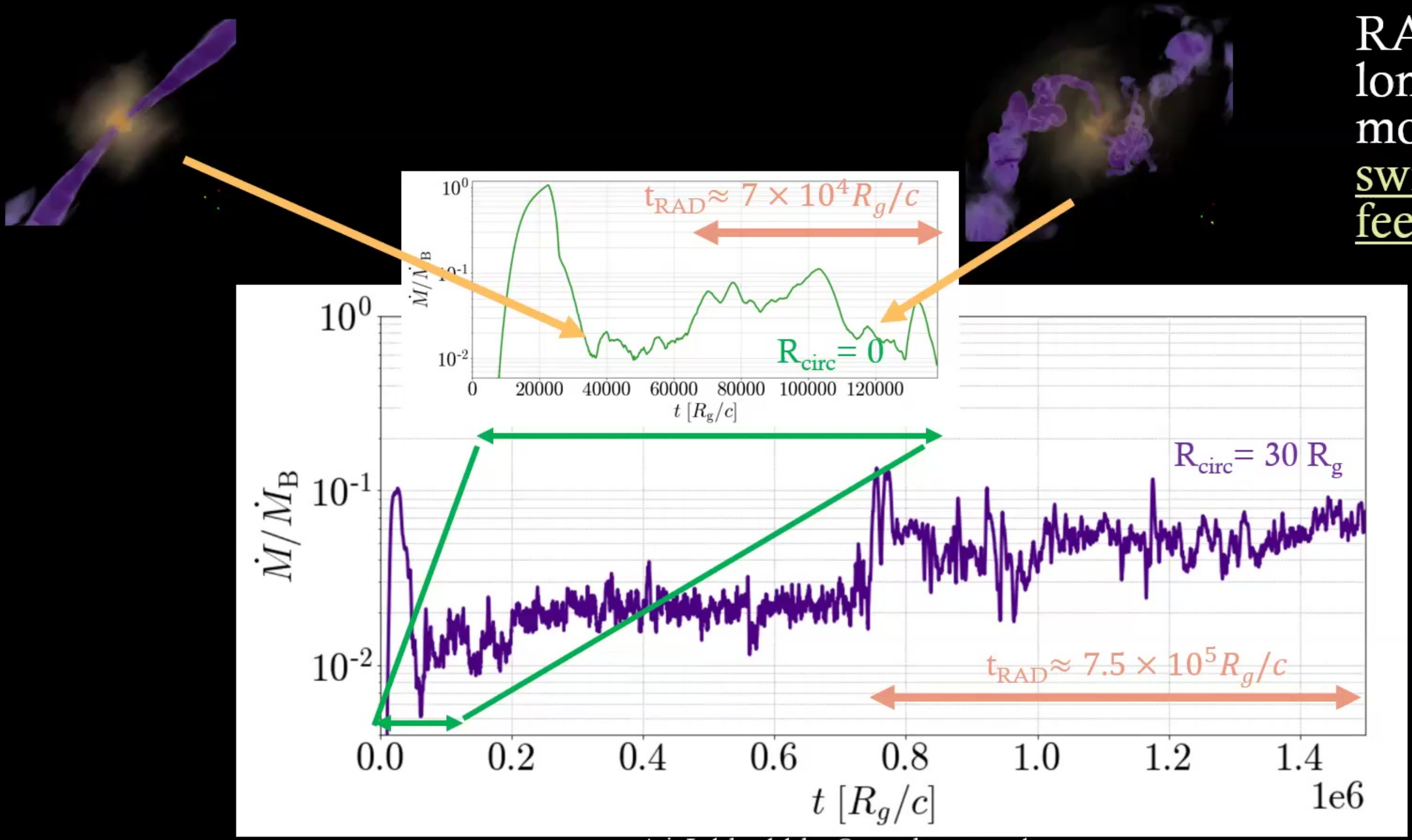
Lalakos et al 2023 (in prep)



Aris Lalakos lalakos@u.northwestern.edu

RADs angular momentum starved?

Lalakos et al 2023 (in prep)

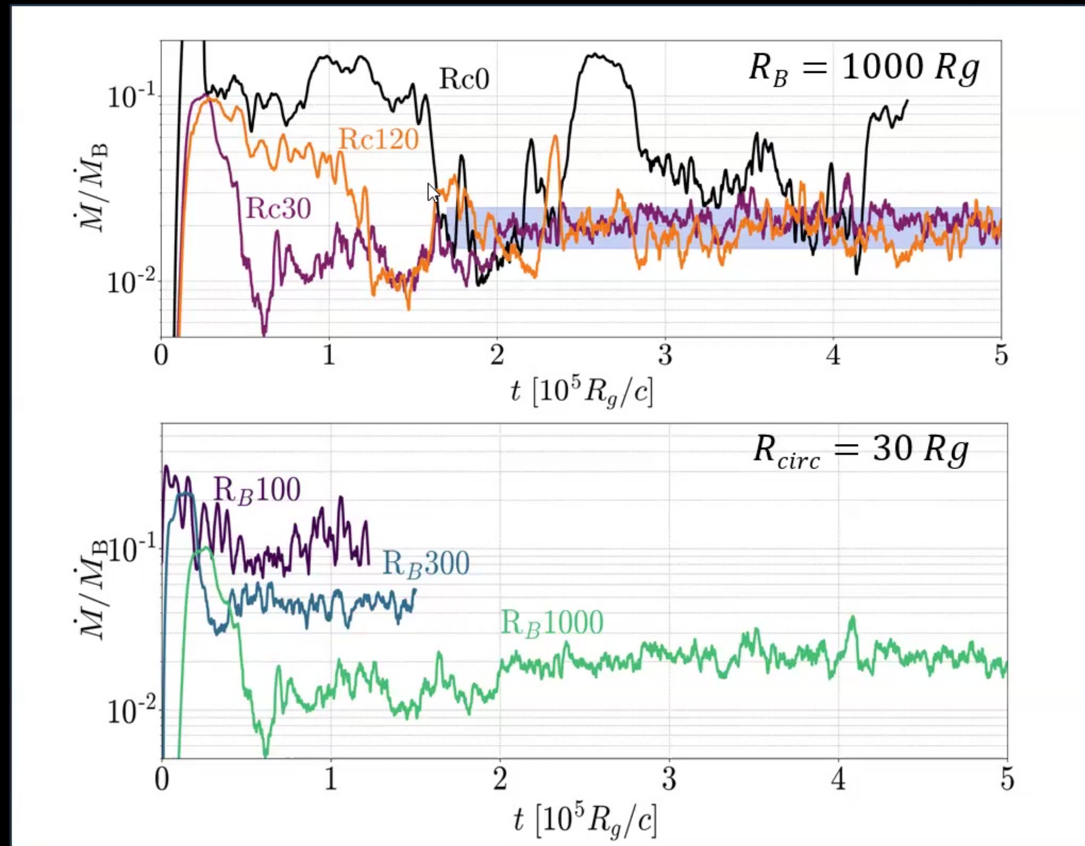


RAD: Δt ~ 10 x longer with ang. mom. On-off switch from feedback!

Aris Lalakos lalakos@u.northwestern.edu

Rotation does not affect what BH consumes when MAD

Lalakos et al 2023 (in prep)

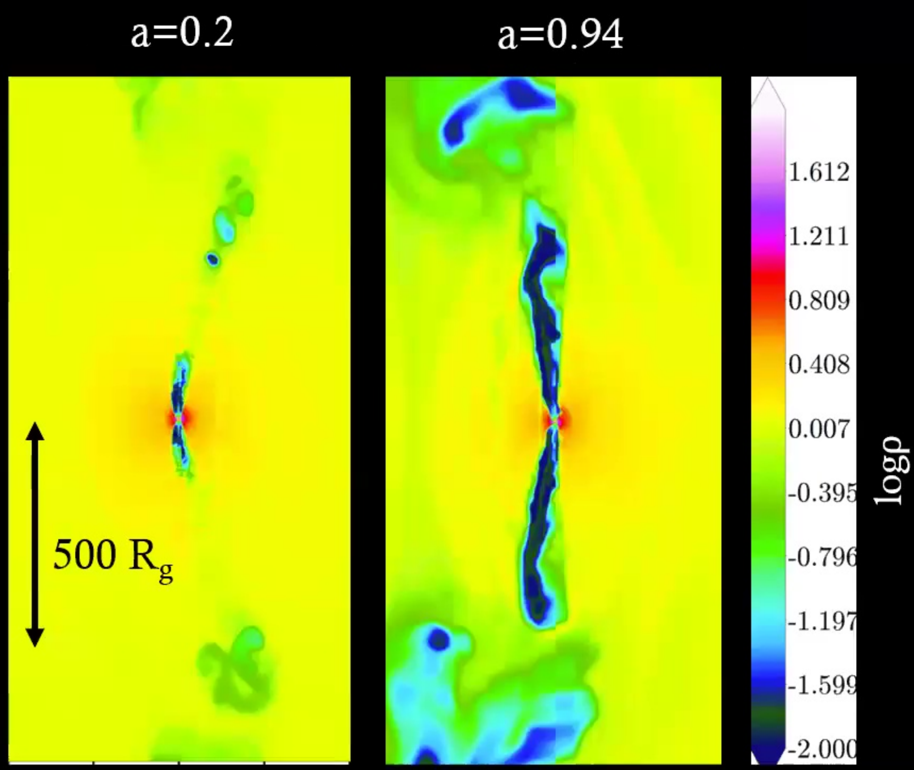


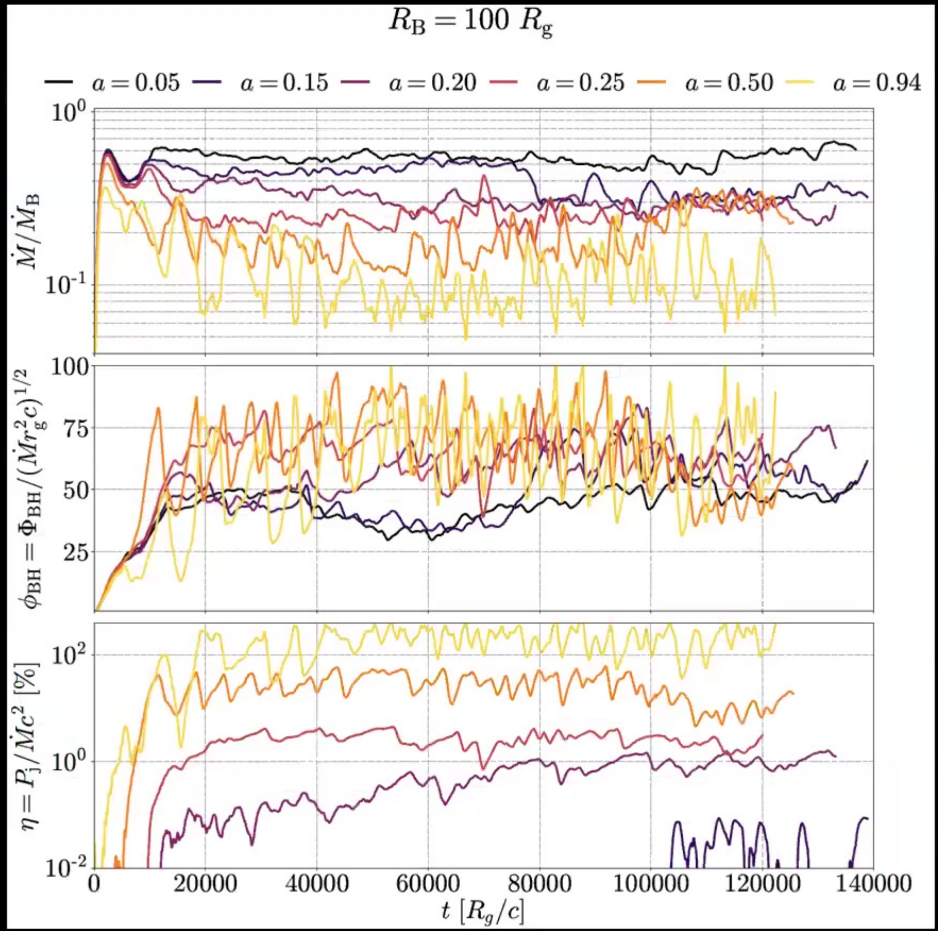
- Angular momentum (size of the disk) does not affect the suppression of mass accretion *when MAD* – jets do!

- The mass accretion scaling: $\langle \dot{M} \rangle / \dot{M}_B \sim (R_B/R_g)^{-(0.5-0.7)}$

Critical spin - quenched jets

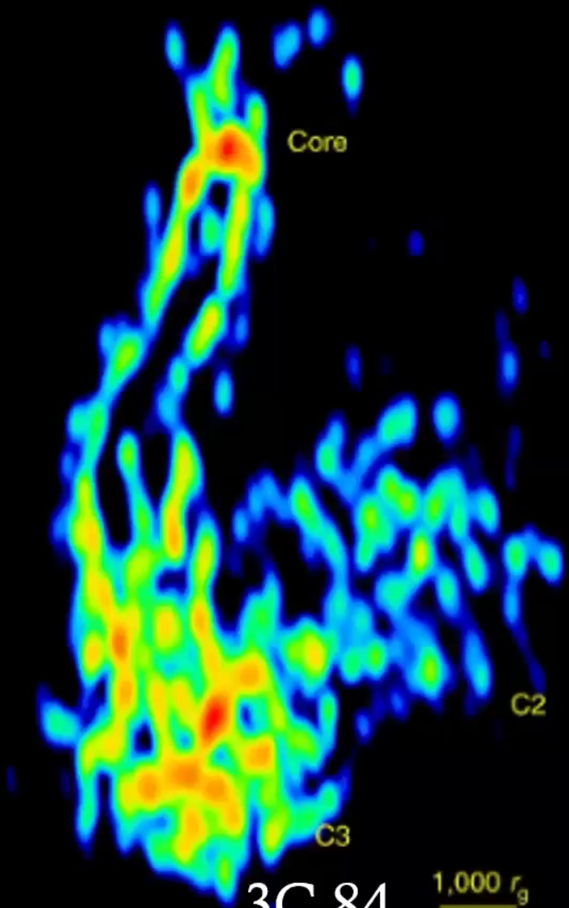
Lalakos et al 2023 (in prep)





Aris Lalakos lalakos@u.northwestern.edu

Mystery of 3C 84 – Cylindrical jets near BH?



3C 84
Giovannini et al. 2018

3C 84 Restarted (2003) activity shows cylindrical shaped jets (year 2017) of width ~100-200 R_g within a distance of ~350 R_g

What makes the jets so wide?

- A rapid jet width expansion within 100 R_g?
- Is it Disk winds?

And why does the jet collimate into a cylinder?

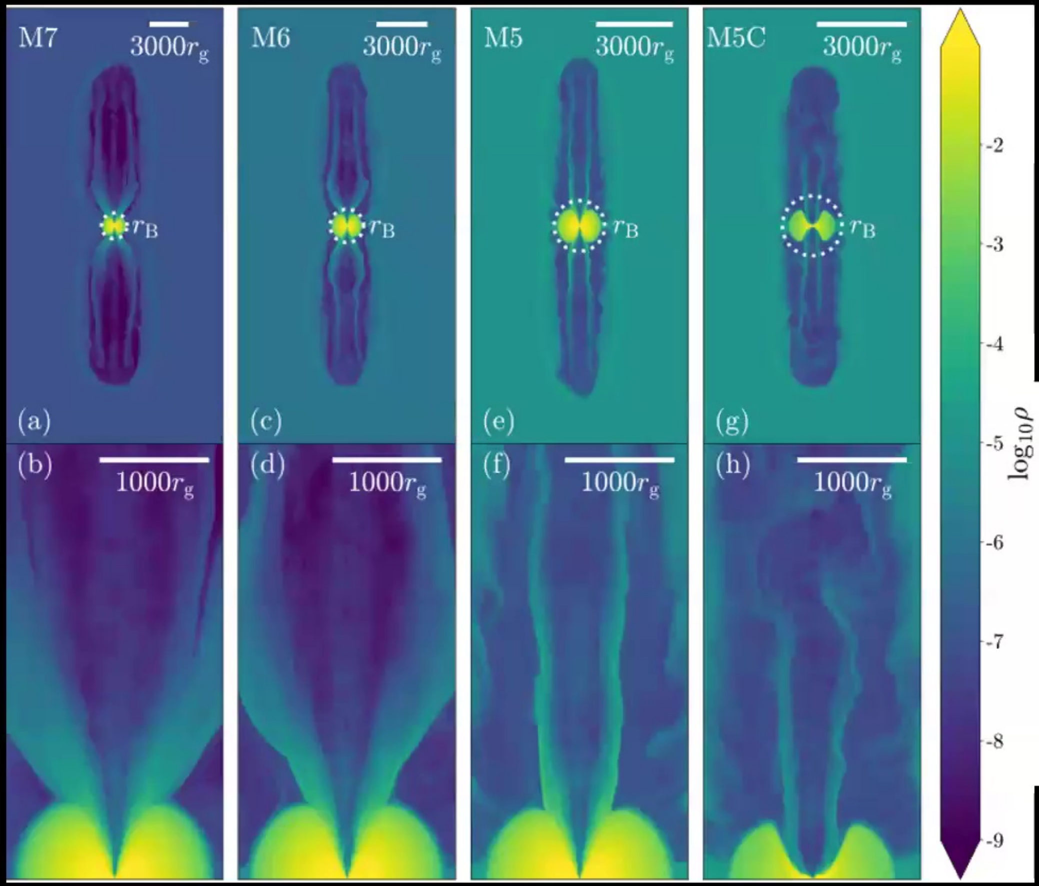
Valeriia Rohoza

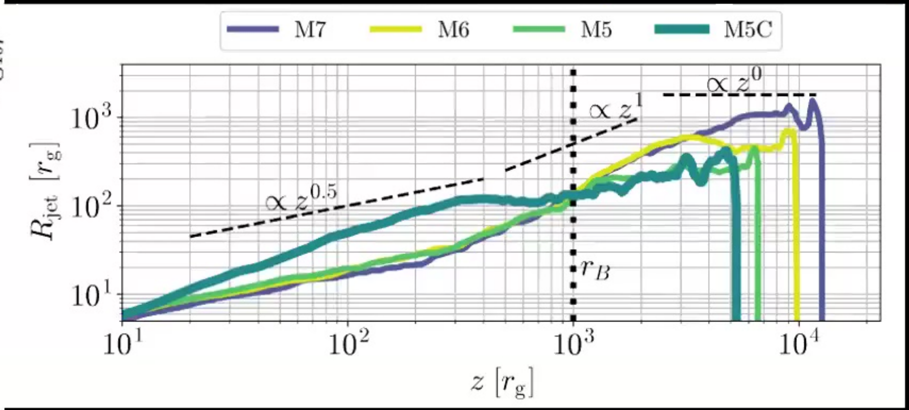
Rohoza, Lalakos et al 2023
arXiv:2311.00018

Does disk cooling affect the jets?

Valeriia Rohoza

Rohoza et al 2023
arXiv:2311.00018



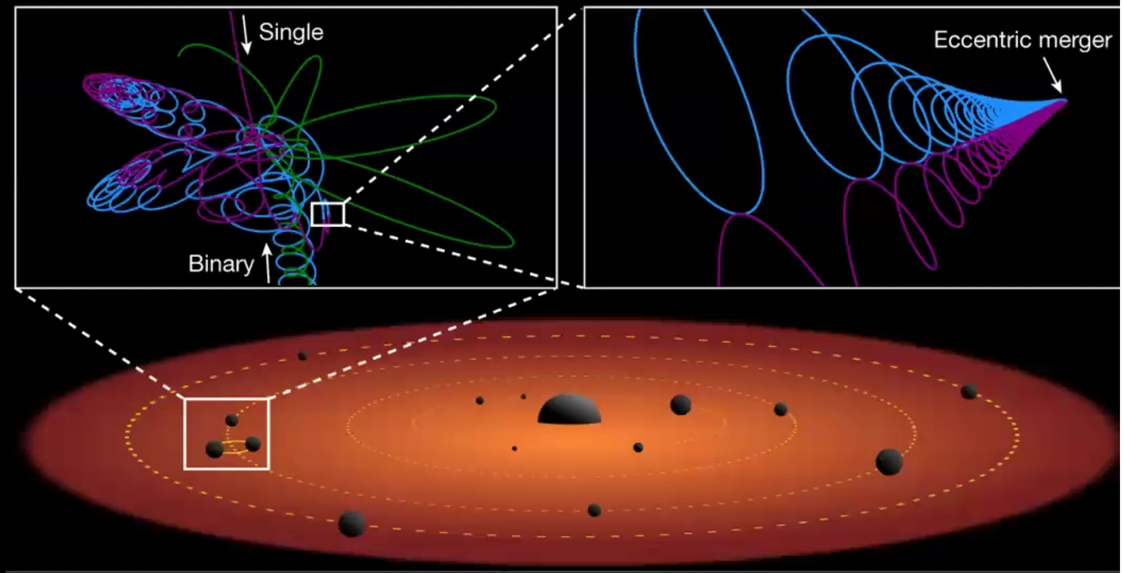


Aris Lalakos lalakos@u.northwestern.edu

Super Eddington accretion on stellar mass BHs in AGN disks and first BHs

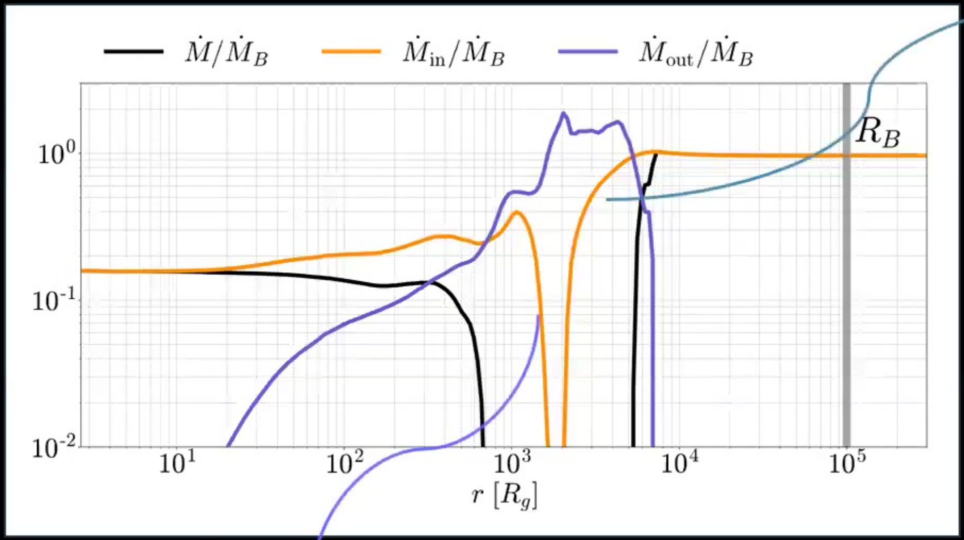
- Massive stars forming in AGN disk (rich environment) → possible merger (LVK detection?) (Tagawa et al. 2022)
- Can jets breakout of dense AGN disk? Transient emission?

- Estimates: $\dot{M}_{BH} \geq 10^6\ \dot{M}_{Edd}$!
- Important for Early MBHs
- Mechanical feedback crucial but what about radiation ?



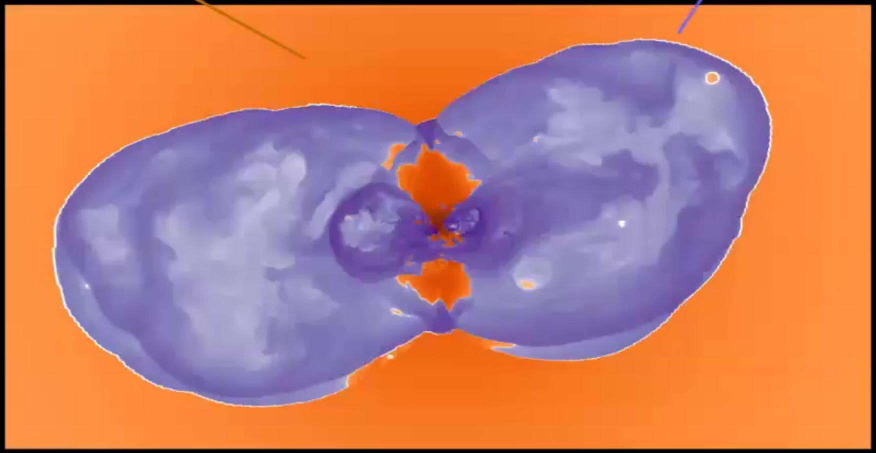
Samsing et al. 2022 (Nature)

Net accretion even with feedback



Bow shocks stop inflow

Outflows remove more mass than accreted!



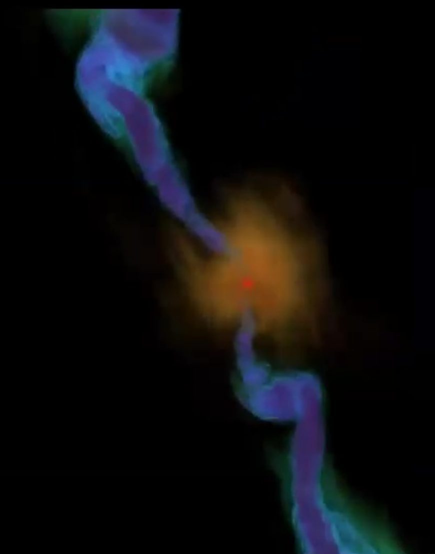
AL + Hui Li (in prep)

Summary

- Largest scale separation $R_B = 1000\,R_g$ and longest durations
  Necessary to CLOSE the feedback loop!
- RADs are Persistent and as dynamically important as MADs with unstable and weak jets – FR0s !

Next goals :

1) Realistic scales $R_B = 10^{5\text{-}6}\,R_g$ w/ radiation on-the-fly
2) Super Eddington?
   - Growth of early BHs (JWST),
   - Quasars and TDEs,
   - sBHs in AGN disks (LVK) / jet breakout and EM emission.



Aris Lalakos lalakos@u.northwestern.edu