Multimessenger Modelling of SMBBHs with Eccentric and MAD 3D GRMHD Simulations

Vikram Manikantan (U. Arizona)

with Vasileios Paschalidis and Gabriele Bozzola

16th LISA Symposium

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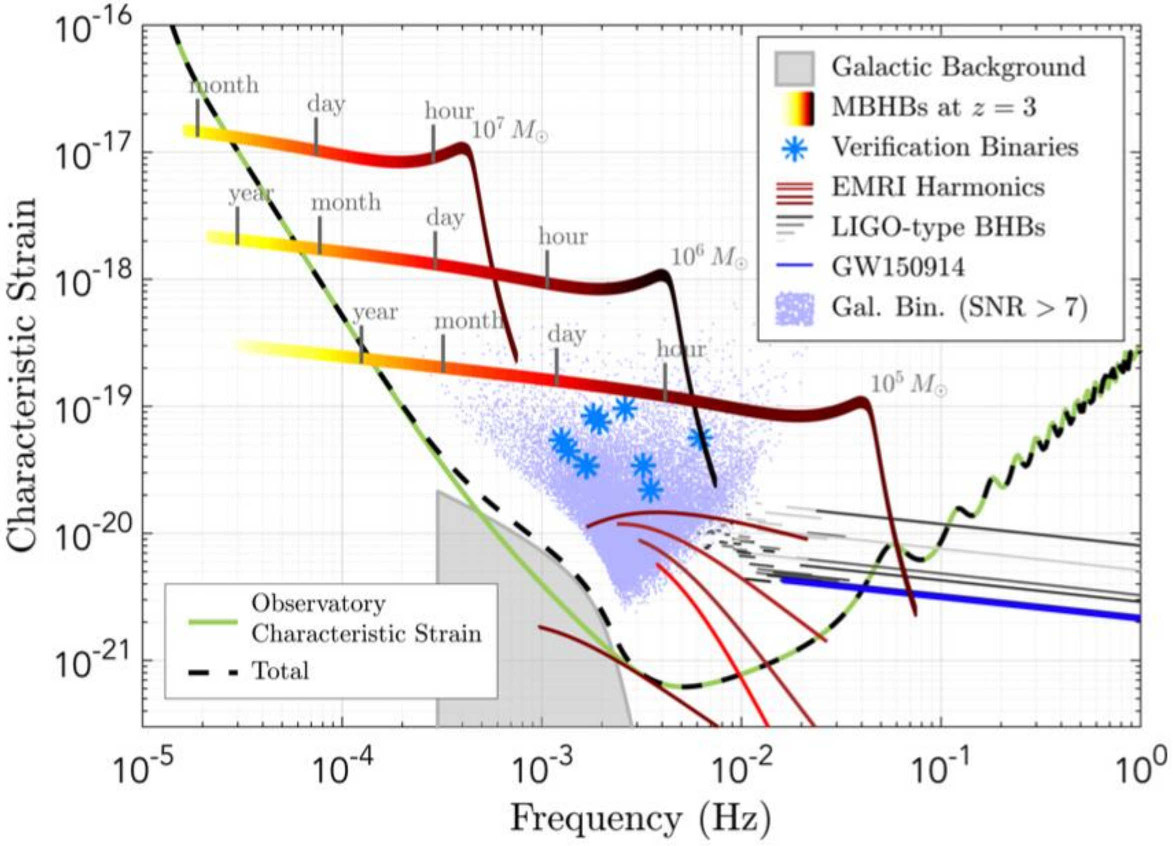
TEXAS ADVANCED COMPUTING CENTER

Astronomy & Steward Observatory

Supermassive Binary Black Holes (SMBBHs) are a key LISA target

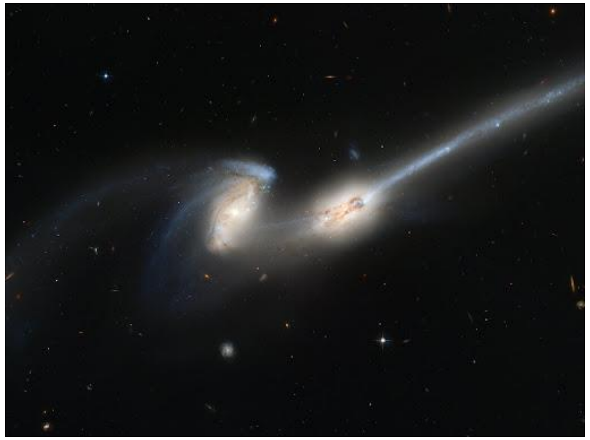
- LISA is sensitive to $10^5 - 10^7$ Msun binaries
- Out to redshifts $z < 20$ at SNR ~200 for 10^6 Msun binaries
- SMBBHs are expected to be ubiquitous and useful multimessenger sources (Begelman+1980, Bogdanovic+2022, Schulz 1986, Holz+2005)
- Modelling of these binaries must start now!



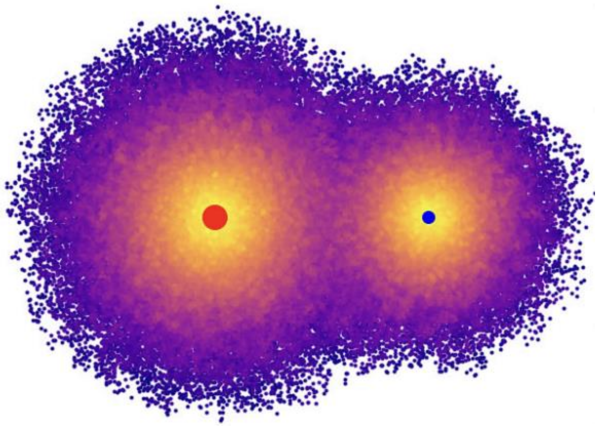
LISA L3 Mission Proposal

SMBBH evolution spans ~10 orders of magnitude

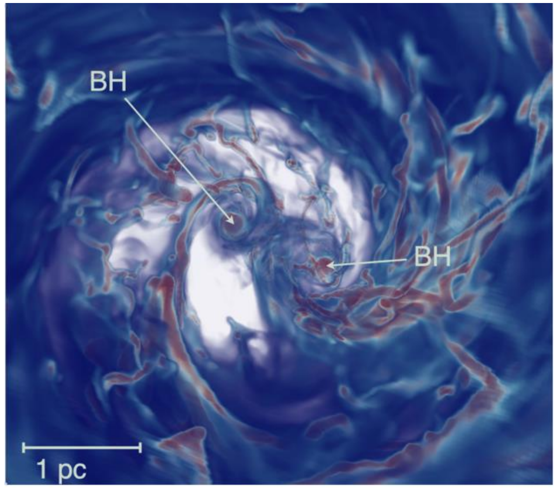
NGC 4676, Credits: NASA/ESA



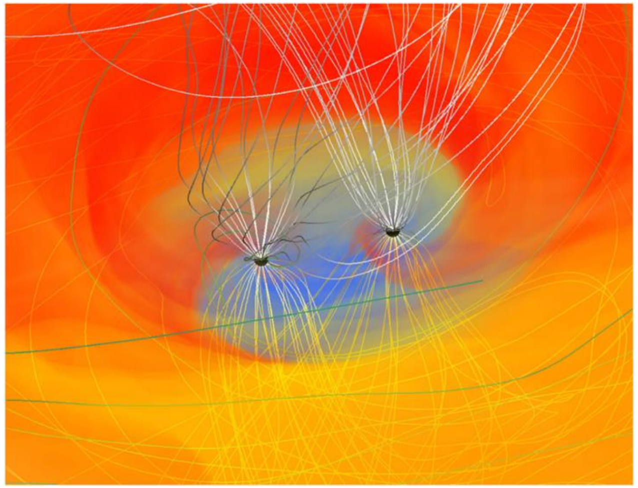
Sobolenko+2021



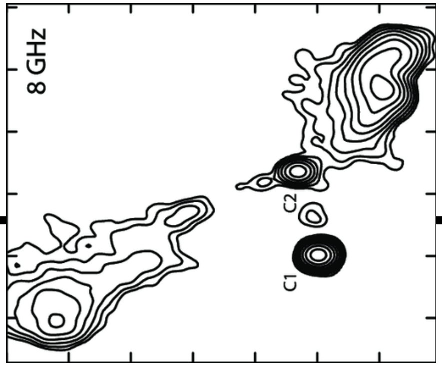
Wang+2025



Gold, Paschalidis+2014



Rodriguez+2009

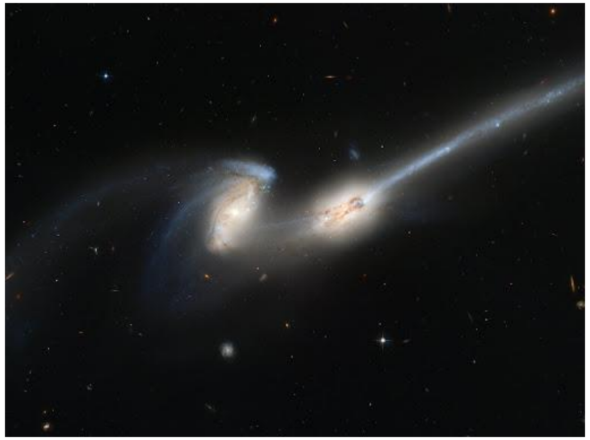


Galactic scales
> 10 kpc

Horizon scales
~ 1 μpc

I study the late-inspiral, gravitational wave regime (final 100 orbits premerger)

NGC 4676, Credits: NASA/ESA



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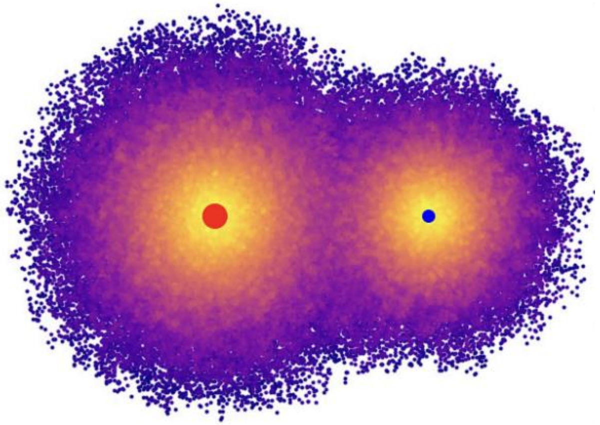

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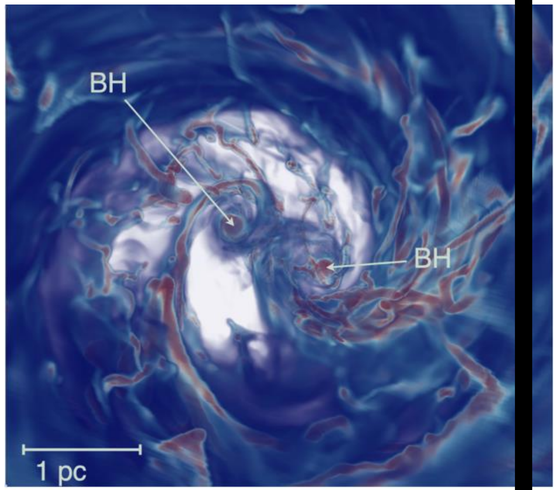
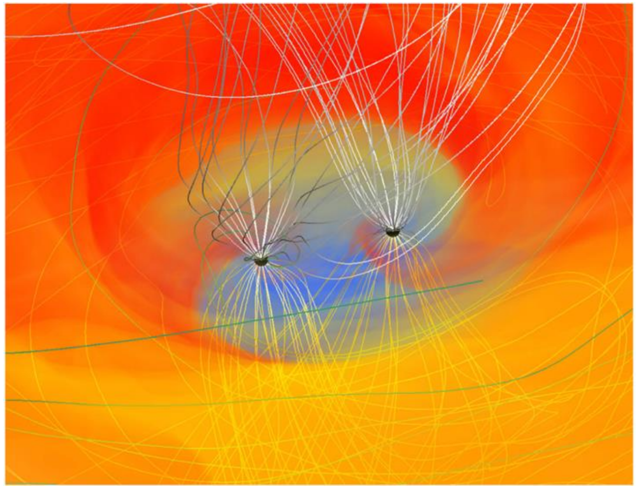


Gold, Paschalidis+2014



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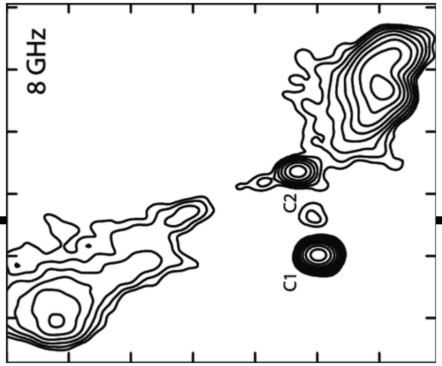


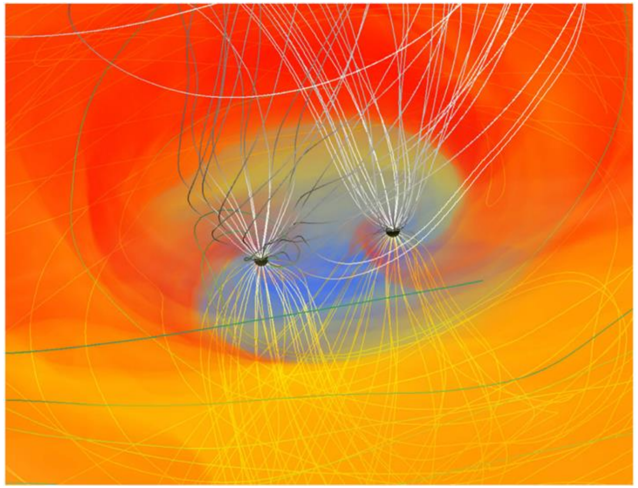
Galactic scales
> 10 kpc

Horizon scales
~ 1 μpc

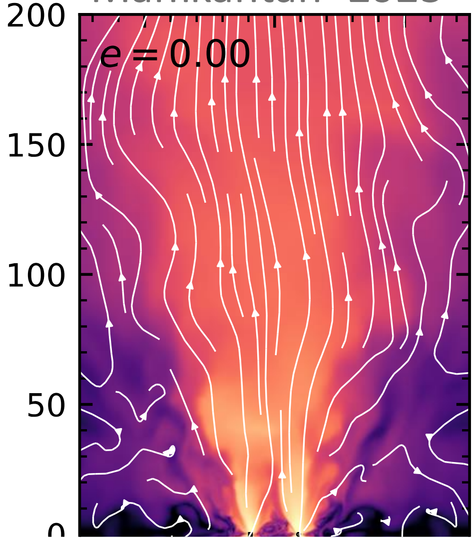
Multiwavelength and Multimessenger modelling of SMBBHs

- Modelling gravitational waves requires evolving Einstein's equations
- Modelling electromagnetic emission requires understanding the magnetized accretion flow and outflows
- Therefore, we run three-dimensional <u>fully general-relativistic magnetohydrodynamic simulations</u> with the Einstein Toolkit

Gold, Paschalidis+2014

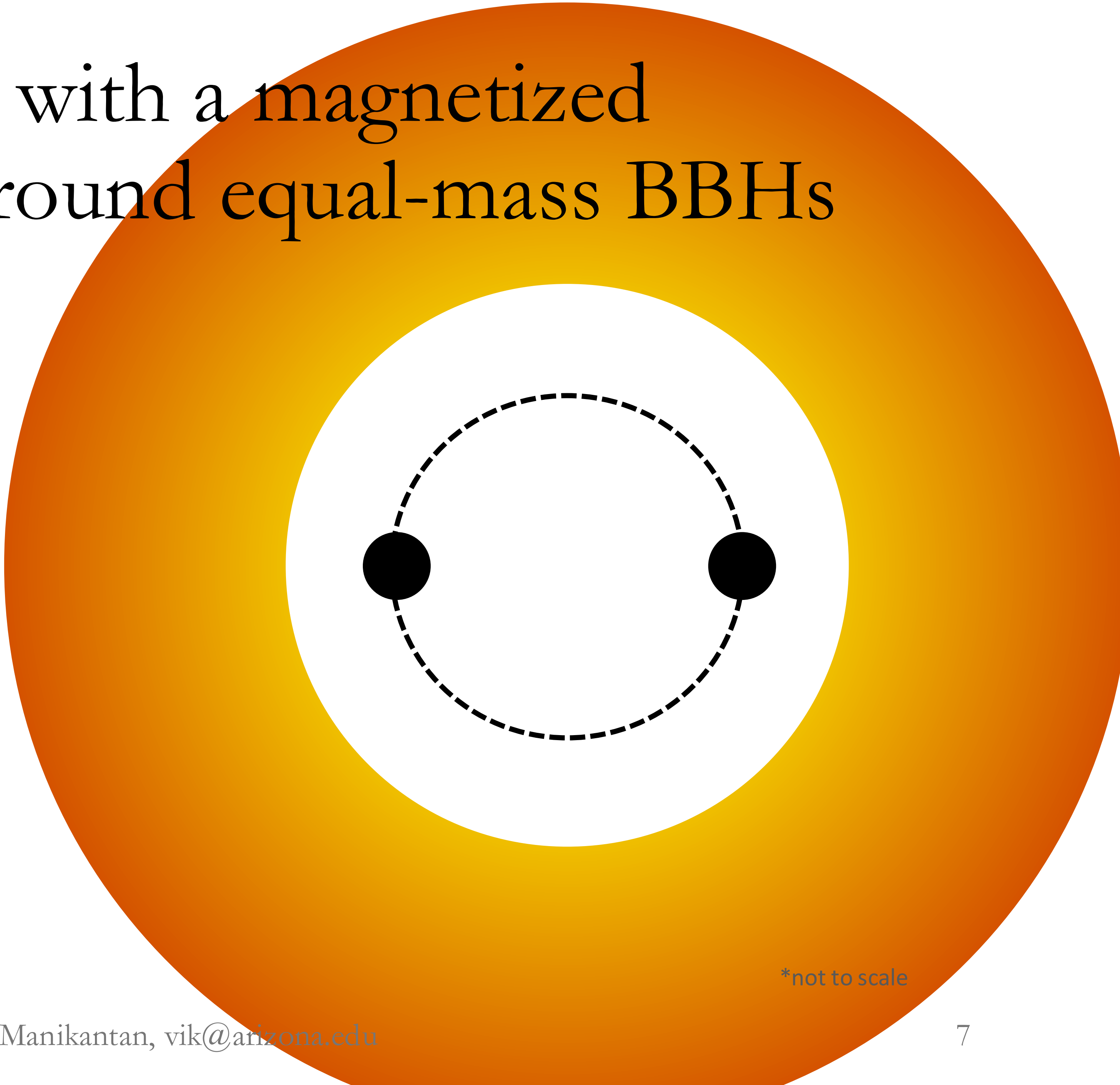


Manikantan+2025



Initialize the system with a magnetized circumbinary disk around equal-mass BBHs

- Binary black holes are equal mass and have no spin
- Major axis of ~20 GM/c^2 (~25 orbits from merger) and ~30 GM/c^2 (~120 orbits from merger)
- Circumbinary disk seeded with an initially poloidal magnetic field



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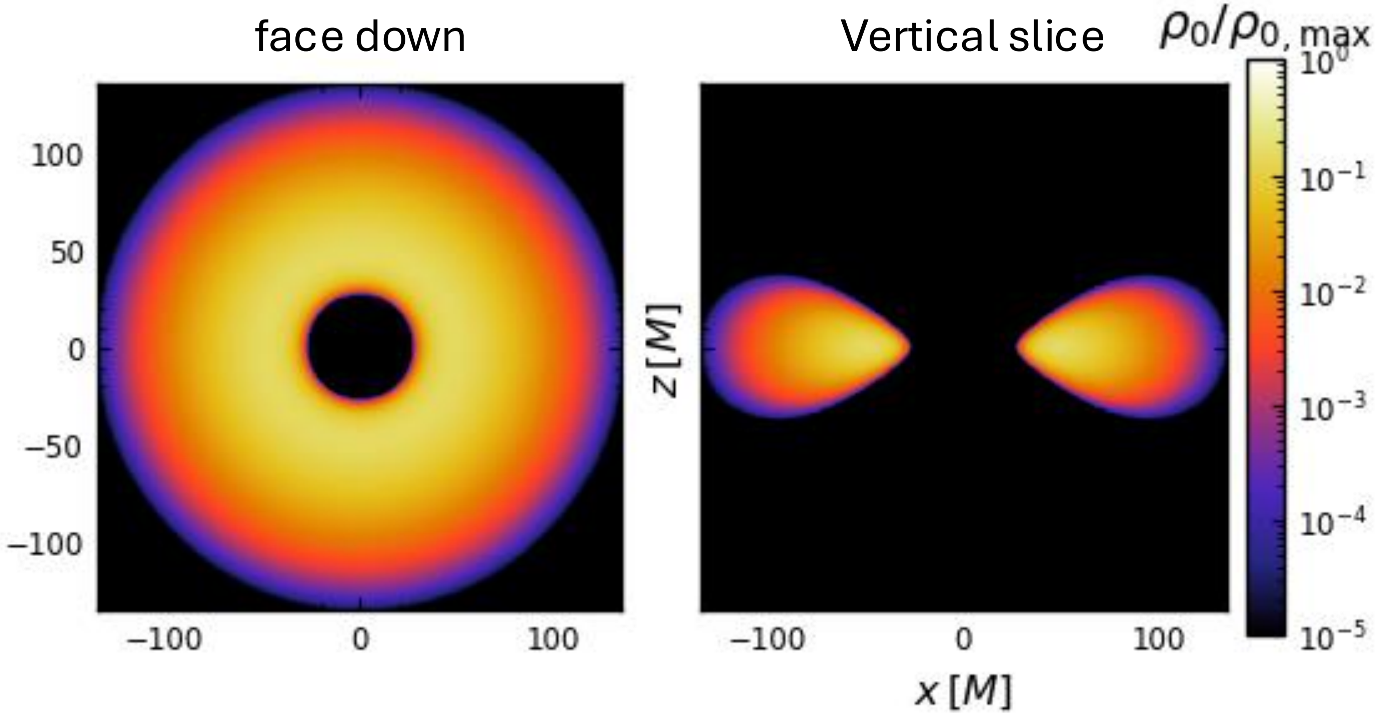
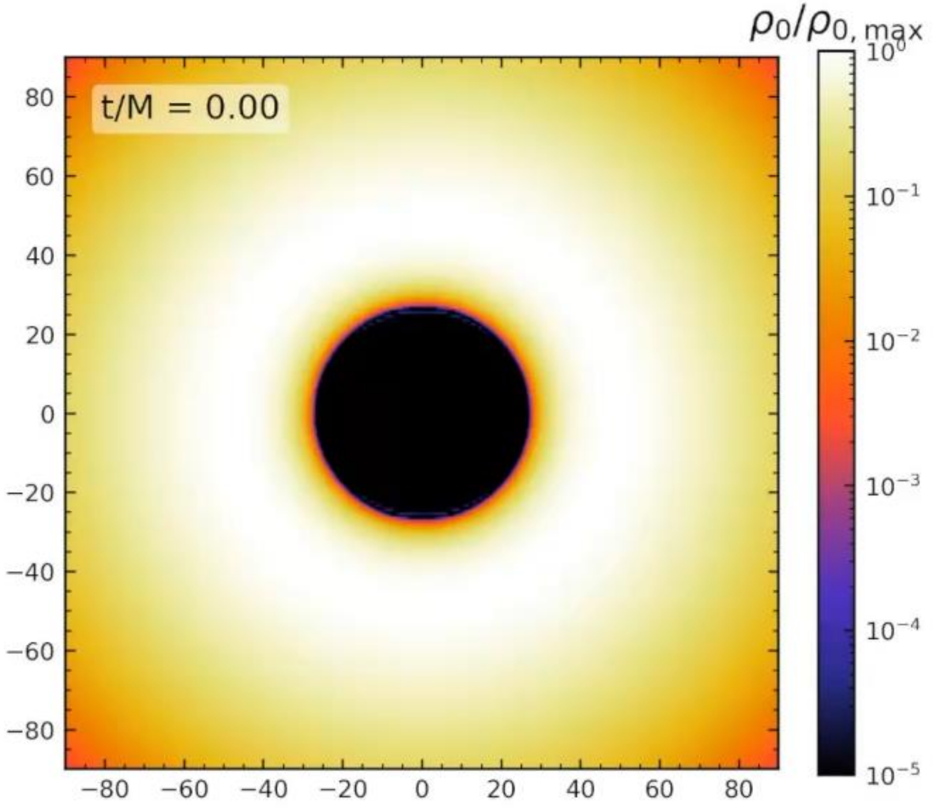


Initializing the system with a circularized circumbinary disk around equal-mass BBHs

- Binary black holes are equal mass and have no spin
- Major axis of ~20 GM/c^2 (~125 orbits from merger) and ~30 GM/c^2 (~120 orbits from merger)
- Circumbinary disk seeded with an initially poloidal magnetic field

Determining Electromagnetic Counterparts from 3D Simulations

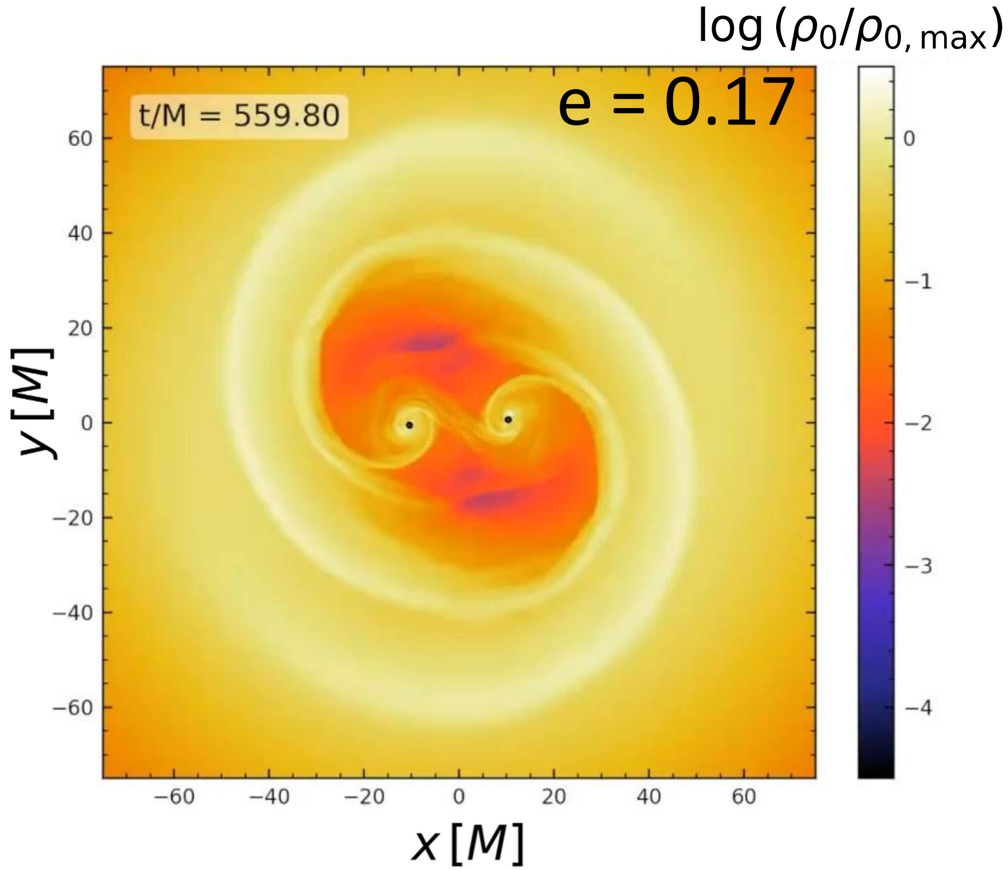
1. What is the accretion rate periodicity?
2. What is the jet luminosity, and does it have a periodicity?
3. Do the black holes host minidisks, and for how long?
4. Is there nonthermal emission from the jet or from magnetic reconnection near the horizons?



Multimessenger Modelling of SMBBHs with 3D GRMHD simulations in this talk

1. **Eccentric binary black holes:**
   1. accrete at at their orbital frequency (unlike quasicircular binaries)
   2. emit smoking gun, quasiperiodic synchrotron emission from their dual jet
2. Binaries at large relativistic separations ($30GM/c^2$):
   1. **develop magnetically arrested minidisks**
   2. host magnetic reconnection events that can power nonthermal flaring

1. Eccentric binary black holes



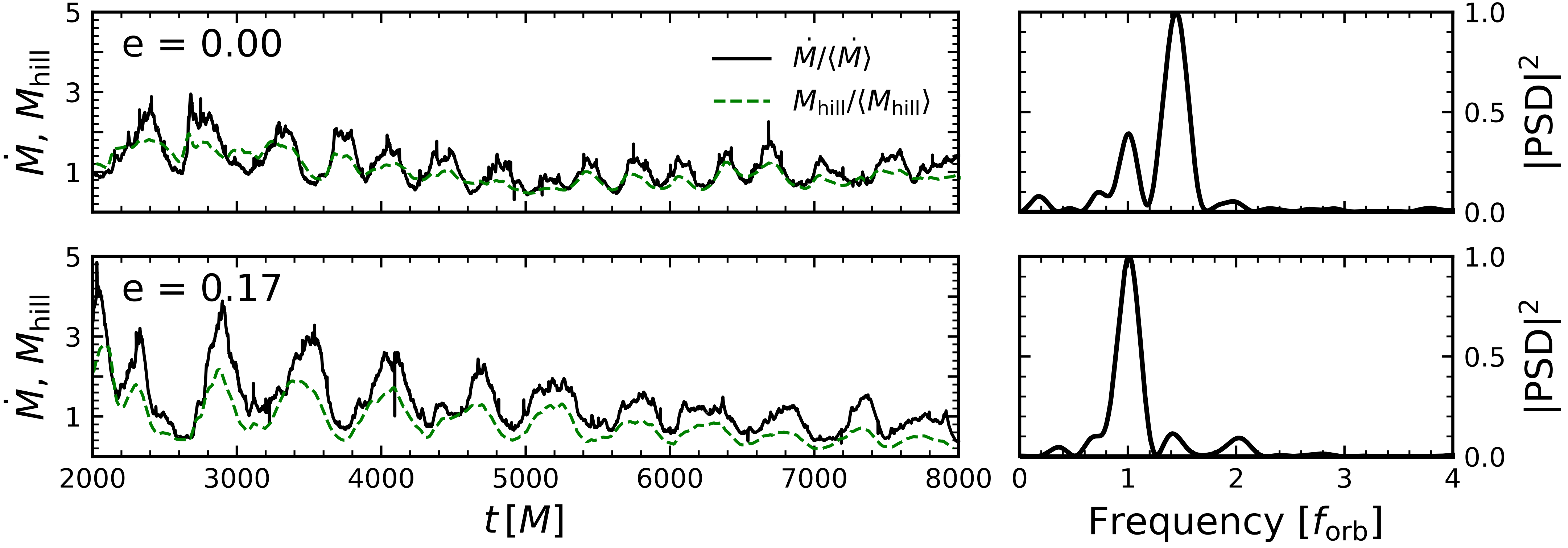
Units

Time: 1M ~ 0.84 $(M_{tot}/10^7 M_\odot)$minutes

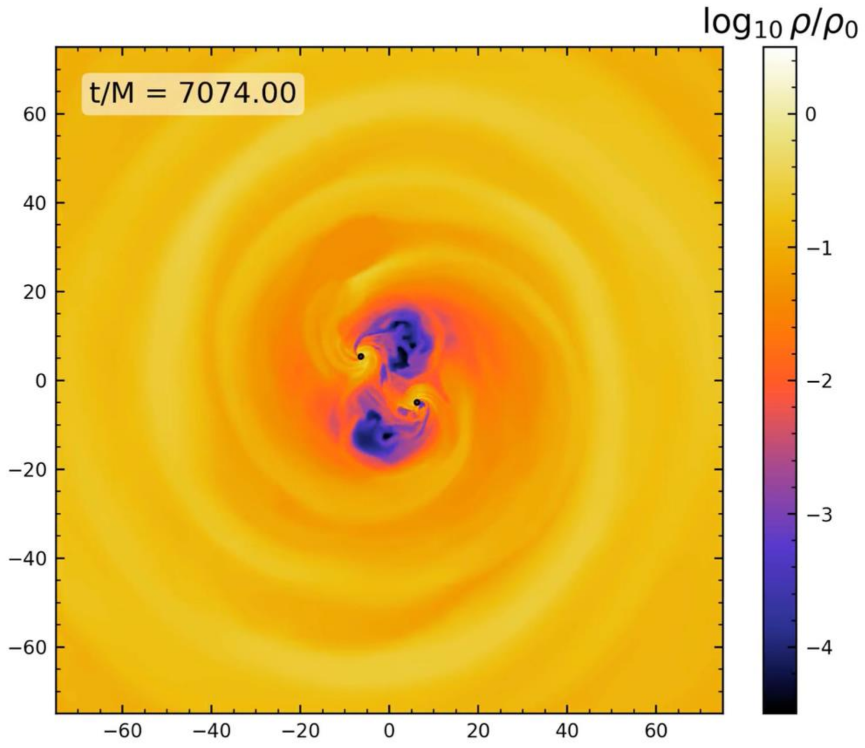
Space: 1M ~ $4 \times 10^{-4}(M_{tot}/10^7 M_\odot)$mpc

1. What is the accretion rate and periodicity?

Quasicircular binaries accrete at $\sim 1.4\ f_{orb}$
Eccentric Binaries Accrete at their Orbital Frequency



1. Eccentric binary black holes



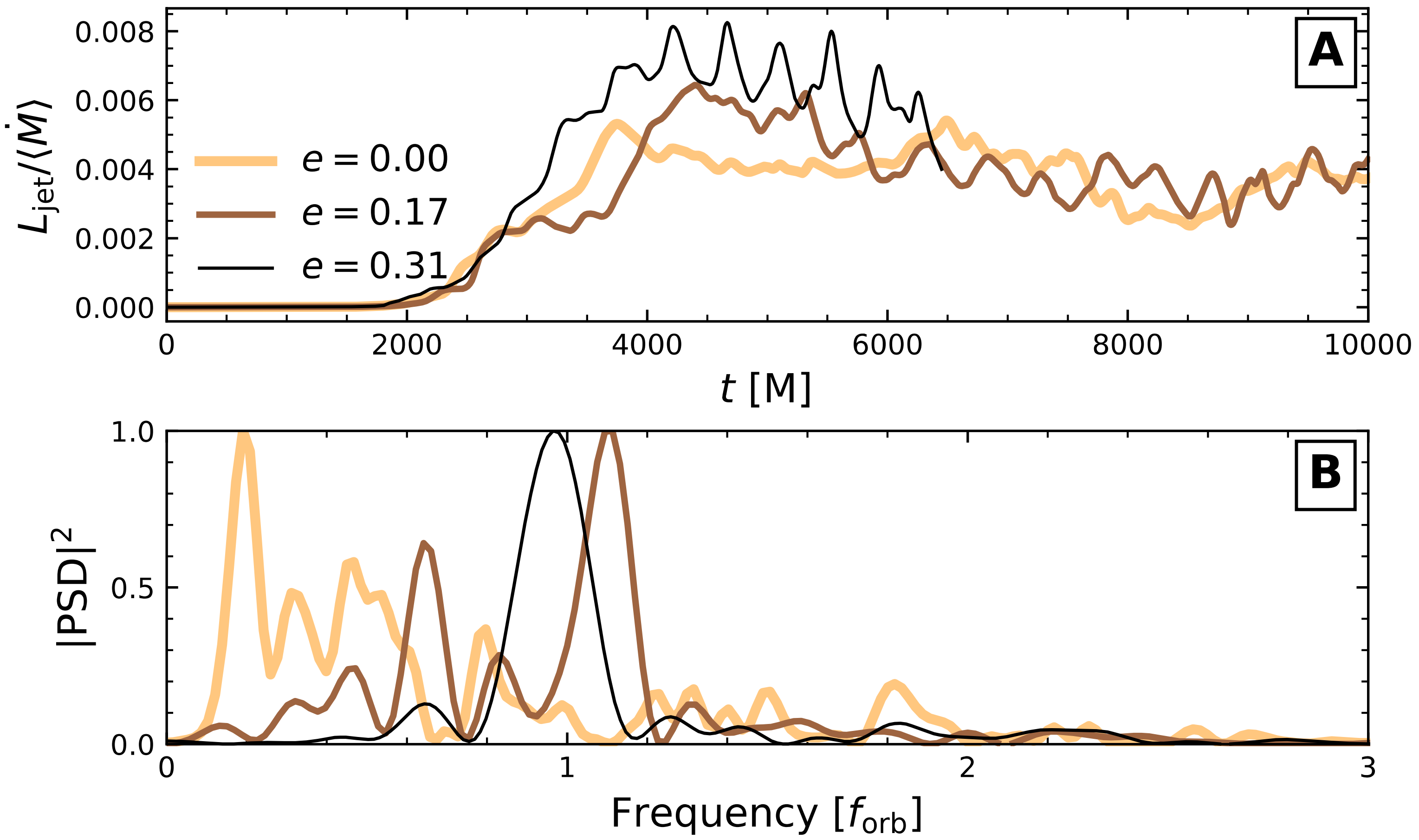
1. What is the accretion rate and periodicity? At the orbital frequency (as opposed to 1.4x for quasicircular)
2. What is the jet luminosity, and does it have a periodicity?

Units

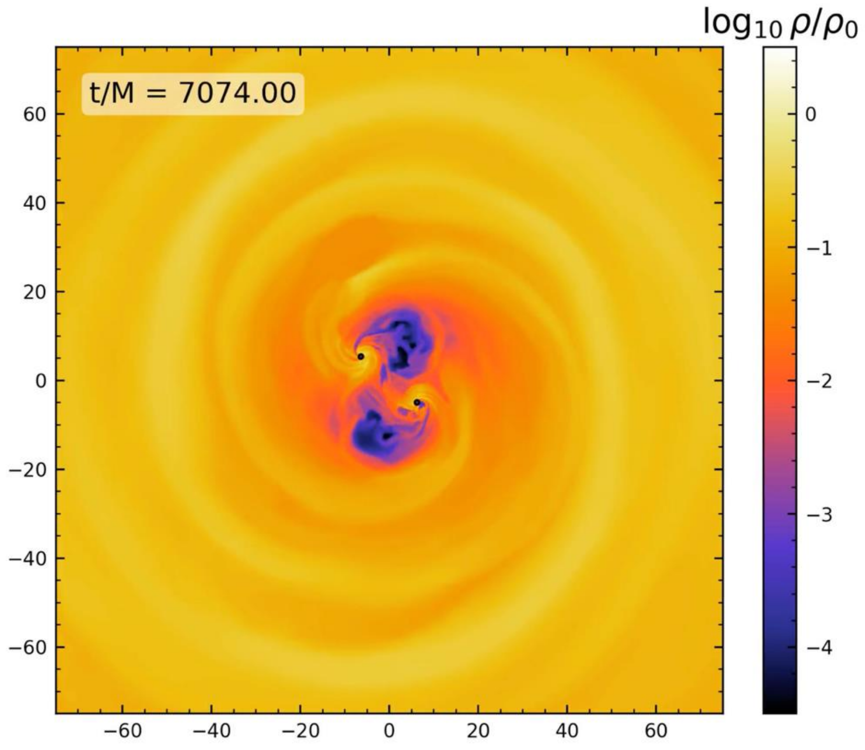
Time: 1M ~ 0.84 $(M_{tot}/10^7 M_\odot)$minutes

Space: 1M ~ $4 \times 10^{-4}(M_{tot}/10^7 M_\odot)$mpc

Eccentric binaries have jets with variability on their orbital period



1. Eccentric binary black holes



Units

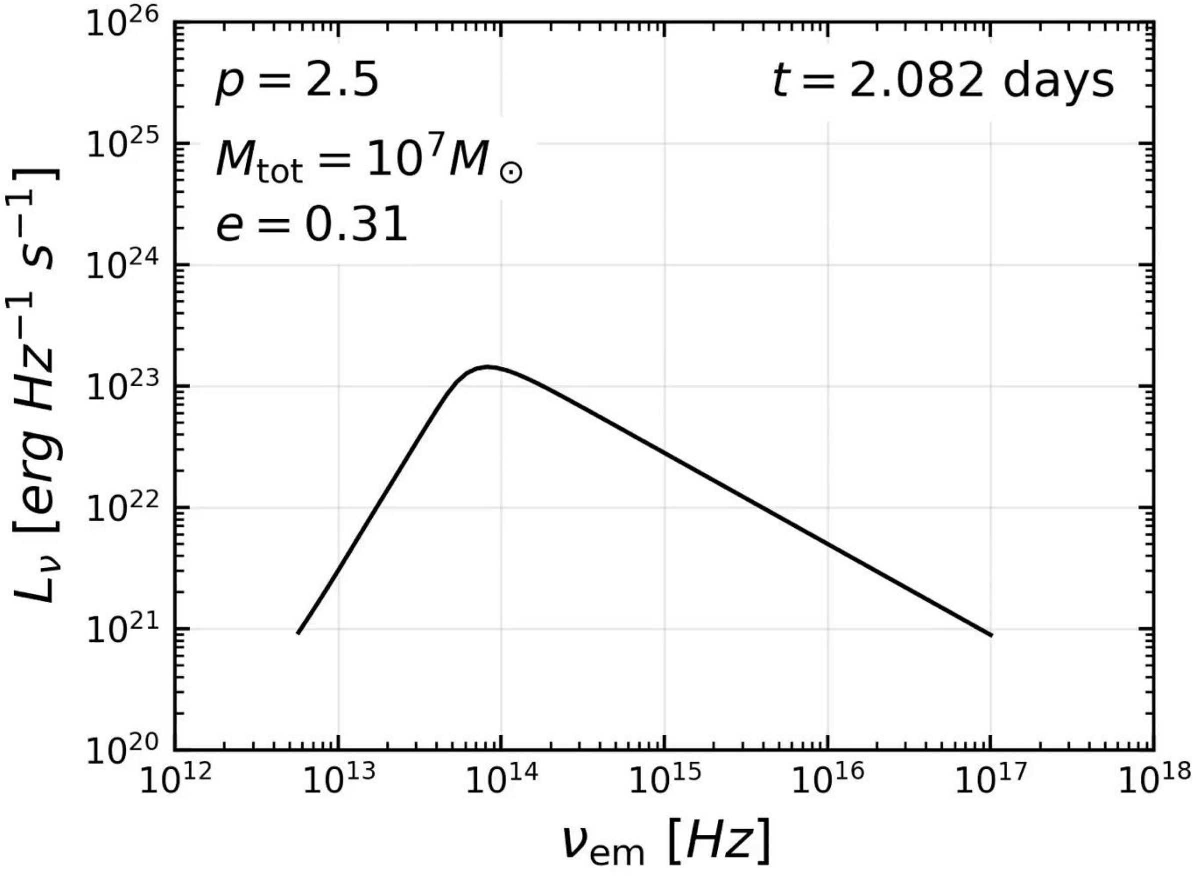
Time: 1M ~ 0.84 $(M_{tot}/10^7 M_\odot)$minutes

Space: 1M ~ $4 \times 10^{-4} (M_{tot}/10^7 M_\odot)$mpc

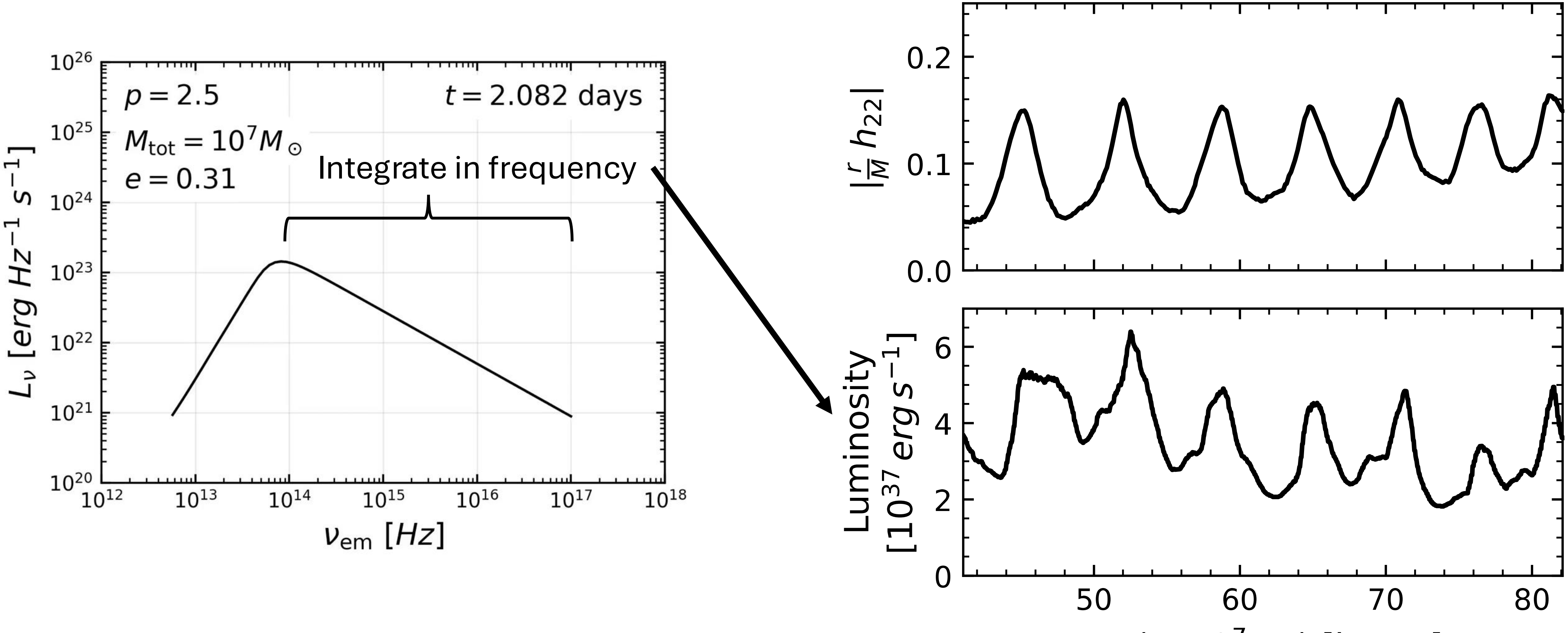
1. What is the accretion rate and periodicity? At the orbital frequency (as opposed to 1.4x for quasicircular)
2. What is the jet luminosity, and does it have a periodicity? Yes, at the orbital frequency (no clear periodicity for quasicircular binary)
3. What does nonthermal emission from the jet look like? Is it periodic?

We perform a radiative transfer of the jet synchrotron emission, which we find to be variable on the orbital period

- Looking down the barrel of the jet (i.e. blazar)
- Powerlaw electron distribution in equipartition with the magnetic field energy density
- Assumptions:
    1. Fast-light
    2. Non-relativistic
    3. height > 50 M
    4. 10% Eddington
    5. 10% radiative efficiency

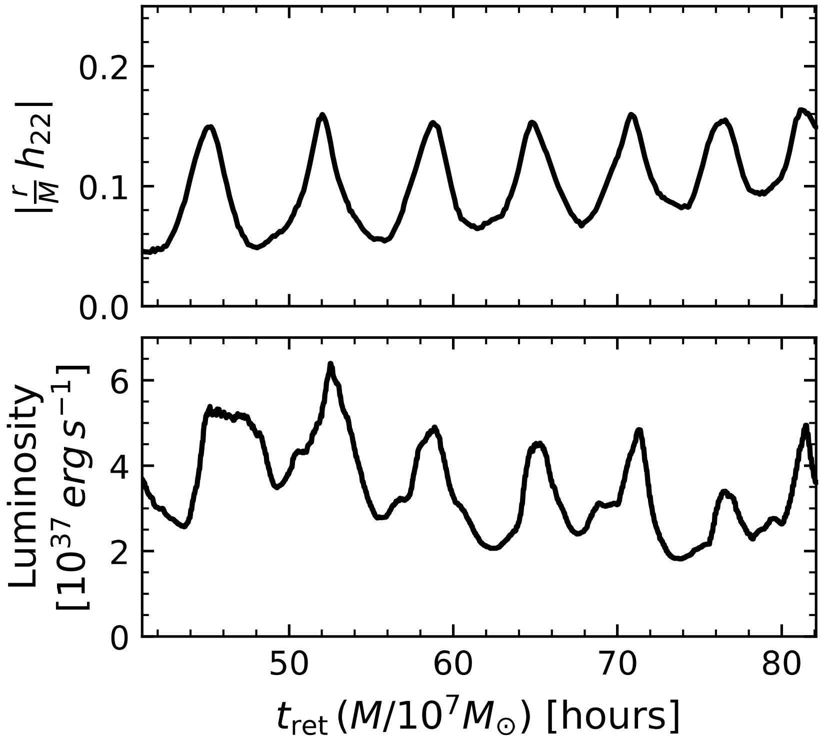


Integrated luminosity is sharply peaked and coincident with GW bursts



Eccentric binary black holes are identifiable from their smoking gun quasiperiodic synchrotron emission

1. **Eccentric binary black holes (Manikantan+2025a,b):**
   1. accrete at at their orbital frequency (unlike quasicircular binaries)
   2. emit smoking gun, quasiperiodic synchrotron emission from their dual jet at their orbital frequency
   3. EM bursts are coincident with GW bursts
   4. Now developing a model to use on candidate SMBBHs



Multimessenger Modelling of SMBBHs with 3D GRMHD simulations in this talk

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   1. accrete at at their orbital frequency (unlike quasicircular binaries)
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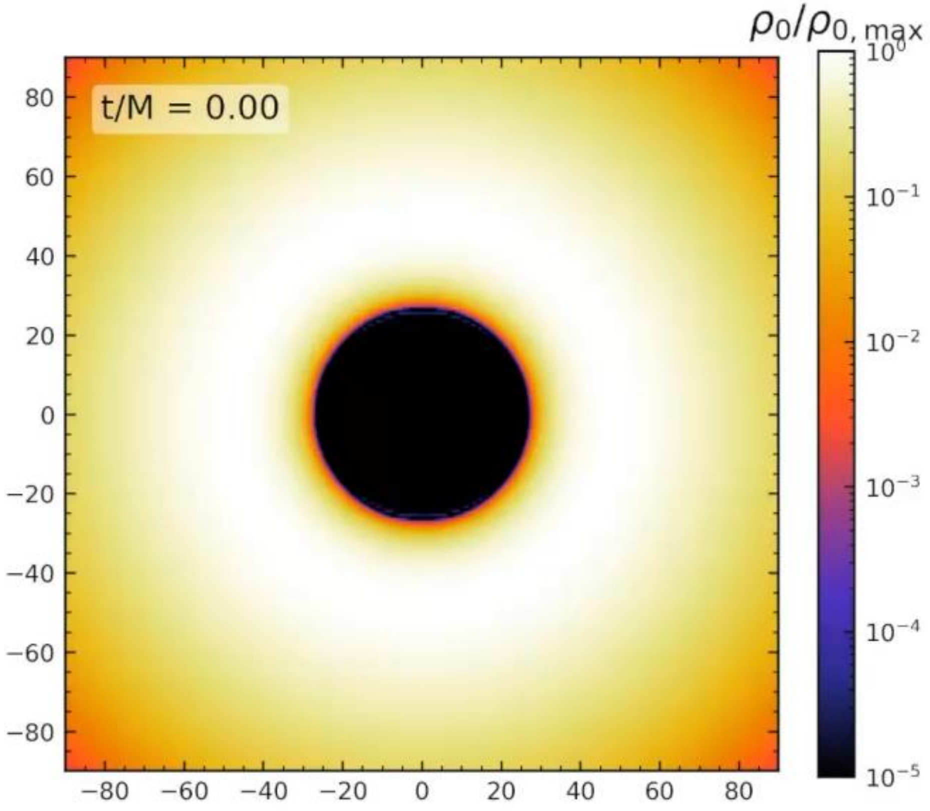
2. Binaries at large relativistic separations ($30GM/c^2$):
   1. develop magnetically arrested minidisks
   2. host magnetic reconnection events that can power nonthermal flaring

2. Binaries at large relativistic separations

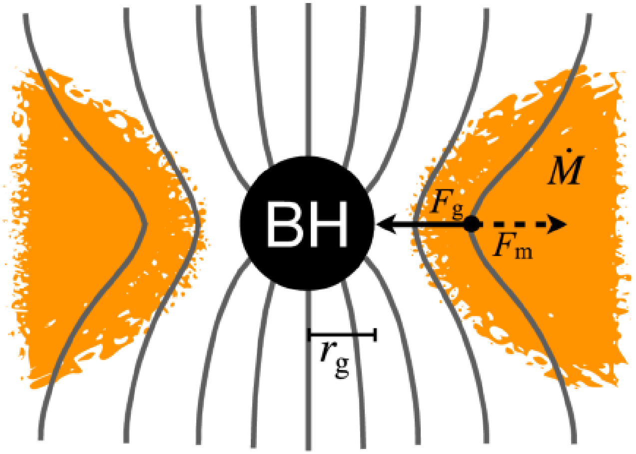


- Separation of 30 GM/c^2 (~100 orbits from merger, longest simulation yet in full GR + MHD)

1. Do the black holes host minidisks, and for how long?
2. What is the accretion rate and periodicity?
3. Is there nonthermal emission from the jet or from magnetic reconnection near the horizons?

Magnetically arrested disks are common end-states in BH accretion

- Magnetic flux accumulates on the horizon and regulates accretion (Narayan+2003)
- Magnetically arrested disks (MAD) are a common end state in single BH accretion (Jacquemin+2022, Begelman+2022, Gottlieb+2023, Lalakos+2024)
- Magnetic reconnection can power flares in infrared and X-ray (Dexter+2020, Scepi+2022)
- Can binary black holes have magnetically arrested disks? Yes! (this work)

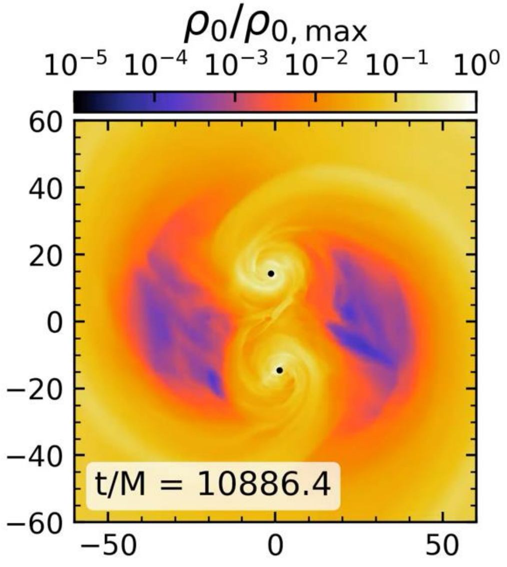


Hada+2024

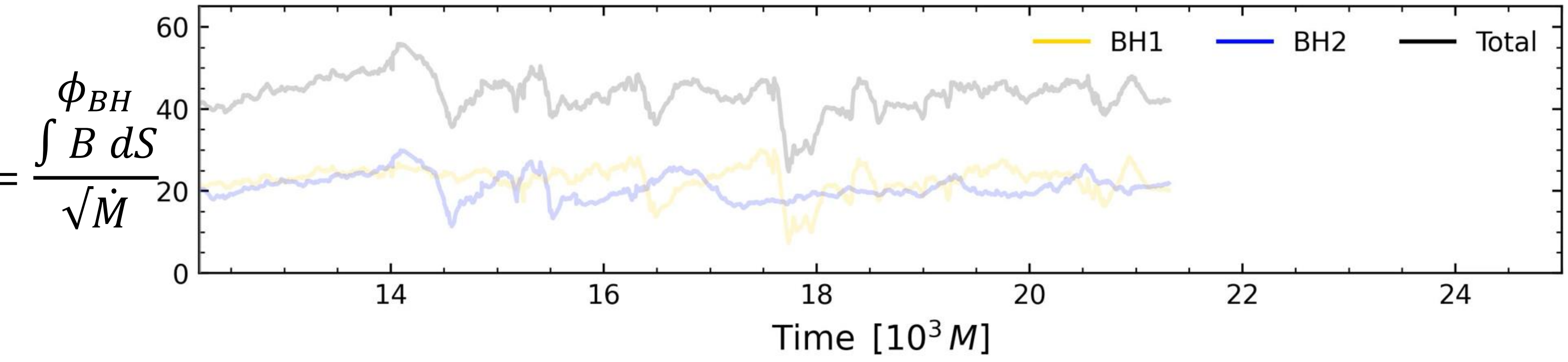
$$\boxed{\phi_{BH} = \frac{\int B\, dS}{\sqrt{\dot{M}}}}$$

(how much magnetic field is threading the BH horizon)

BBH minidisks become magnetically arrested



- Minidisks bring magnetic flux to the horizons and saturate the horizons
- Flux erupts from the horizon, proceeds through the minidisk and into the cavity
- ϕ_{BH} oscillates with flux eruption events
- Open-source diagnostic tool QuasiLocalMeasuresMHD to measure the black hole magnetic flux (github.com/arizona-relativity)

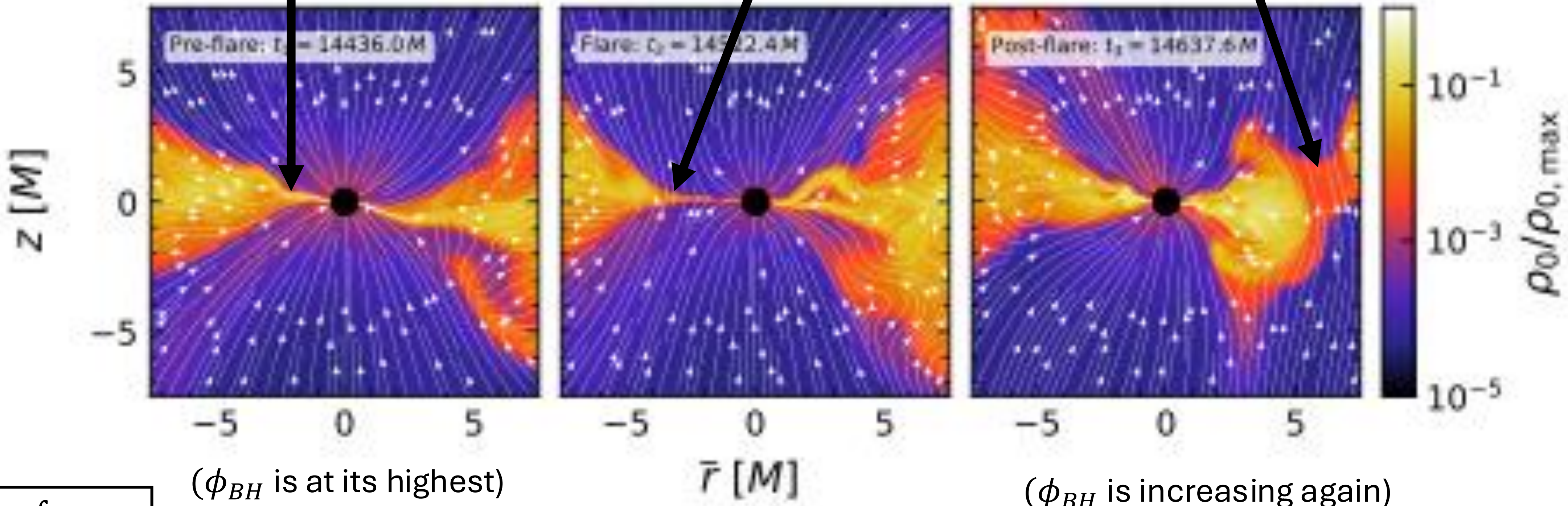


Forming a magnetic flux bundle at the horizon

Magnetic field lines are squeezing at the equator

Eventually, they reconnect to form a bundle, powering nonthermal flares

The bundle of magnetic flux moves away from the BH



(ϕ_{BH} is at its highest)

(ϕ_{BH} is at its lowest)

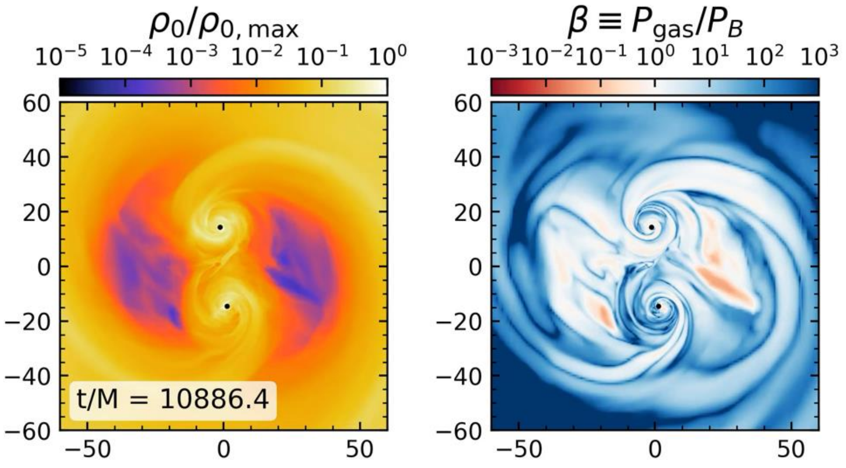
(ϕ_{BH} is increasing again)

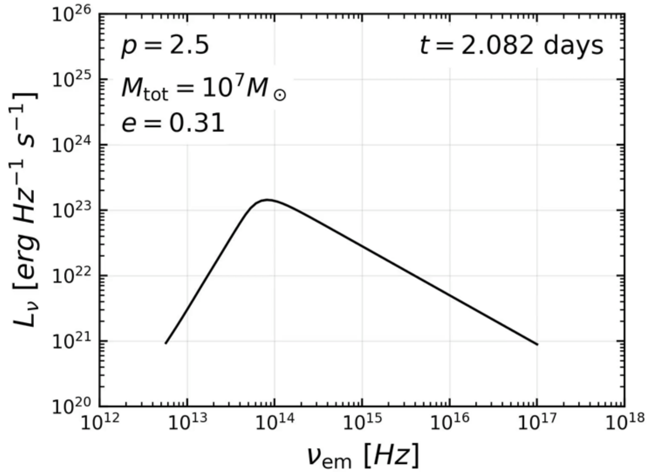
$$\boxed{\phi_{BH} = \frac{\int B\, dS}{\sqrt{\dot{M}}}}$$

Vikram Manikantan, vik@arizona.edu

Multimessenger emission from eccentric binary black hole and magnetically arrested minidisks

- Eccentric black hole binaries will launch **jets variable on the orbital timescale** with **observable smoking gun quasiperiodic synchrotron emission** (ApJL, 984 L47 and PRD, 112, 043004)
- Binary black holes at large relativistic separations will form **magnetically arrested minidisks** with expected flaring in infrared and X-ray bands (PRD 112, 103050)





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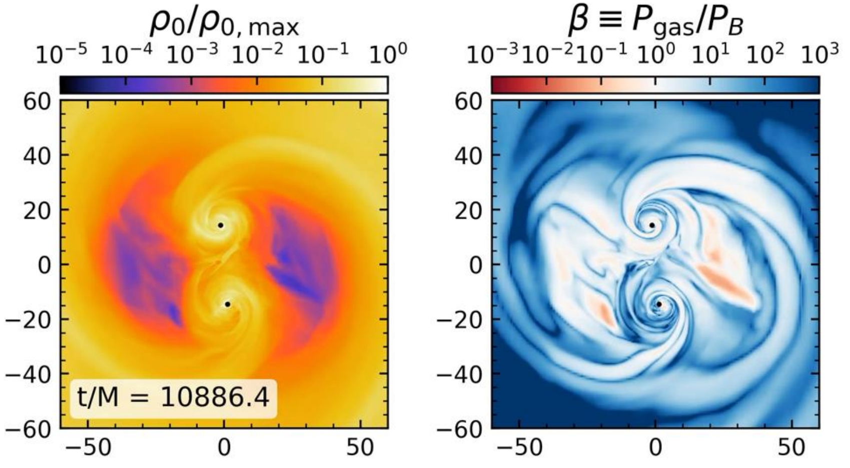
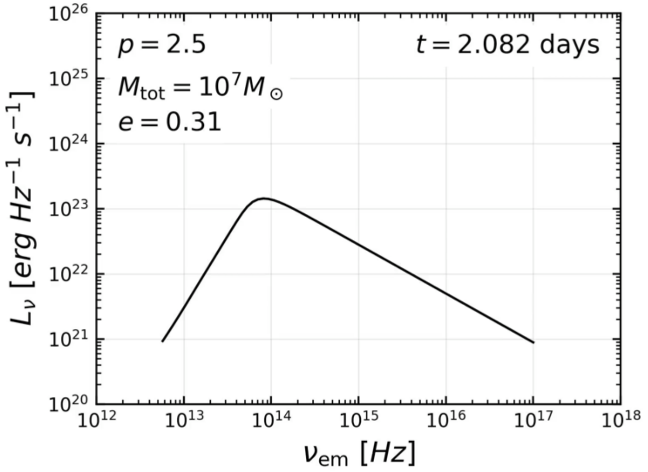
Multimessenger emission from eccentric binary black hole and magnetically arrested minidisks

1. **Eccentric binary black holes:** (ApJL, 984 L47 and PRD, 112, 043004)
    1. accrete at at their orbital frequency (unlike quasicircular binaries)
    2. emit smoking gun, quasiperiodic synchrotron emission from their dual jet at their orbital frequency
    3. EM bursts are coincident with GW bursts
    4. Now developing a model to use on candidate SMBBHs
2. **Binaries at large relativistic separations (30GM/c²):** (PRD 112, 103050)
    1. develop magnetically arrested minidisks
    2. host magnetic reconnection events that can power nonthermal flaring in infrared and x-ray





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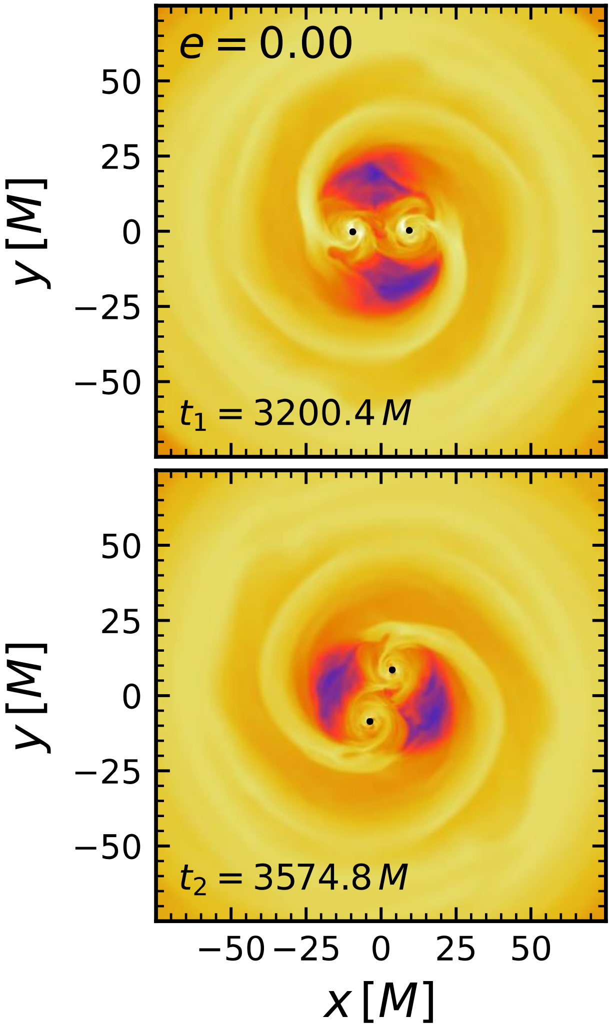
Back up slides

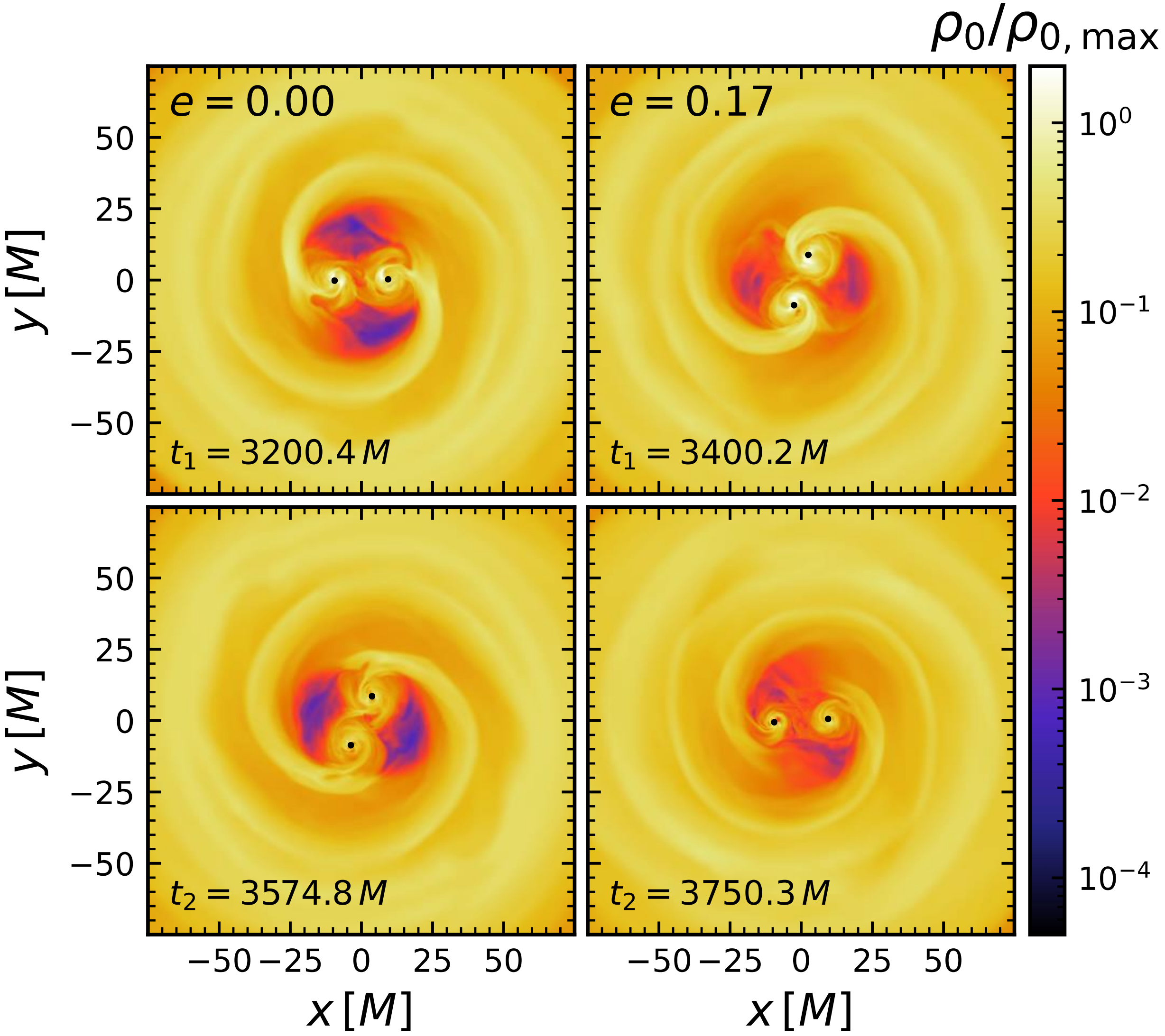
Quasicircular binaries form minidisks

- Tidal streams circularize around BBH
- Form minidisks and then accrete
- Quasicircular binary has persistent structure

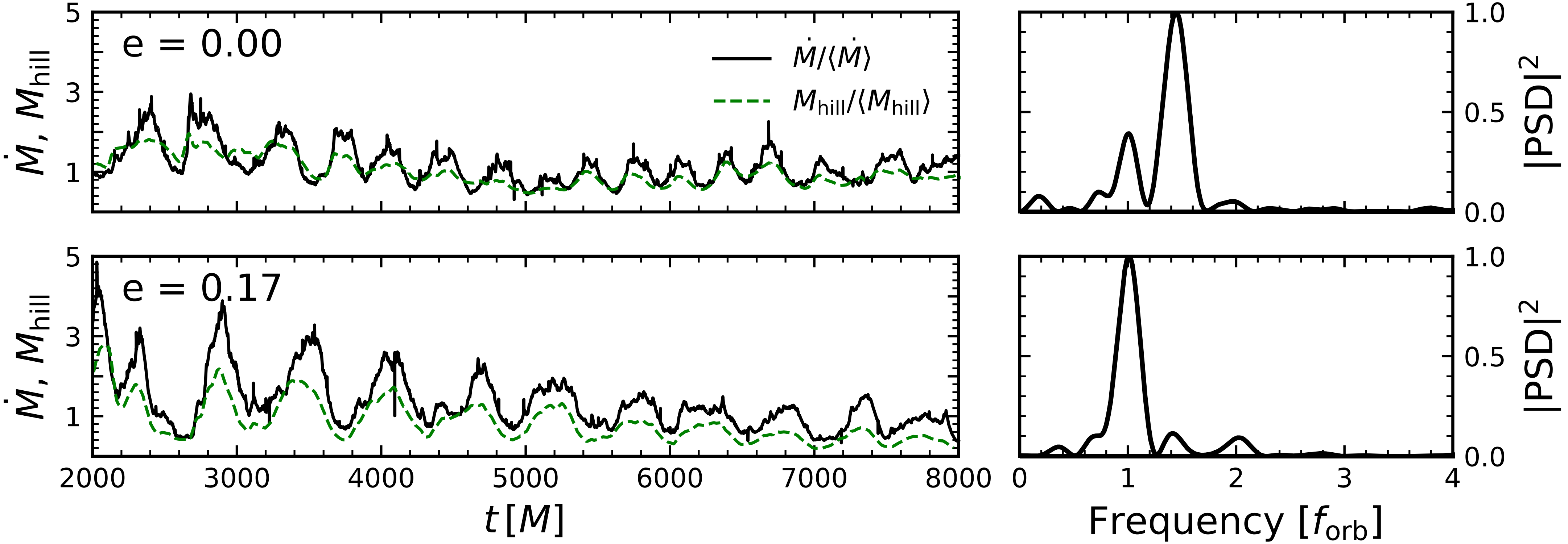


Eccentric Binaries don't Sustain Minidisks

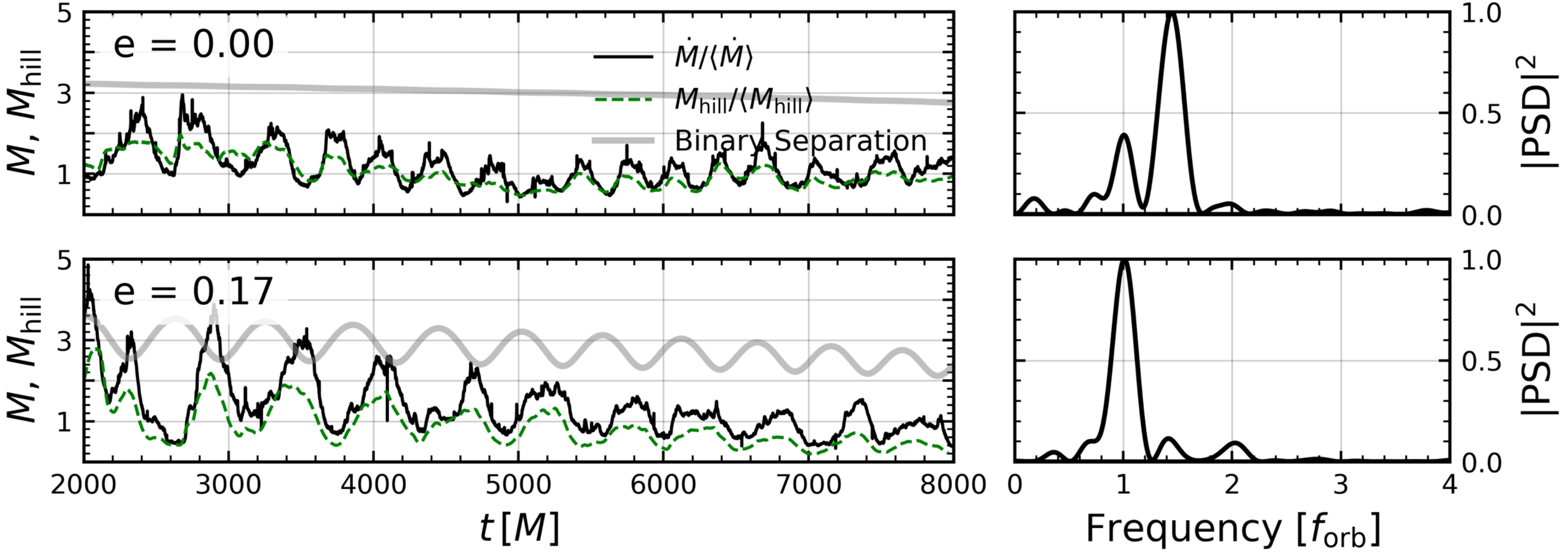
- Tidal streams circularize around BBH
- Form minidisks and then accrete
- Quasicircular binary has persistent structure
- Eccentric Binaries don't sustain minidisks (at these separations)



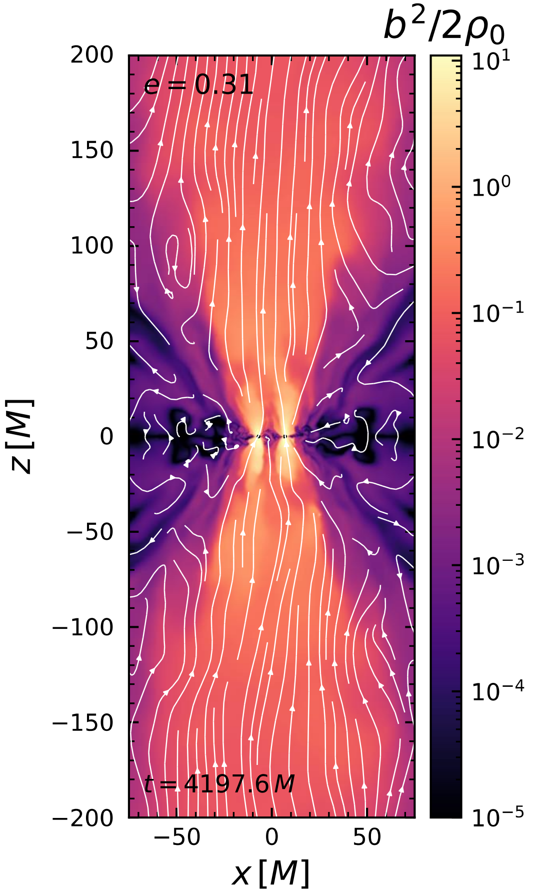
Quasicircular binaries accrete at ~1.4 f_{orb}
Eccentric Binaries Accrete at their Orbital Frequency

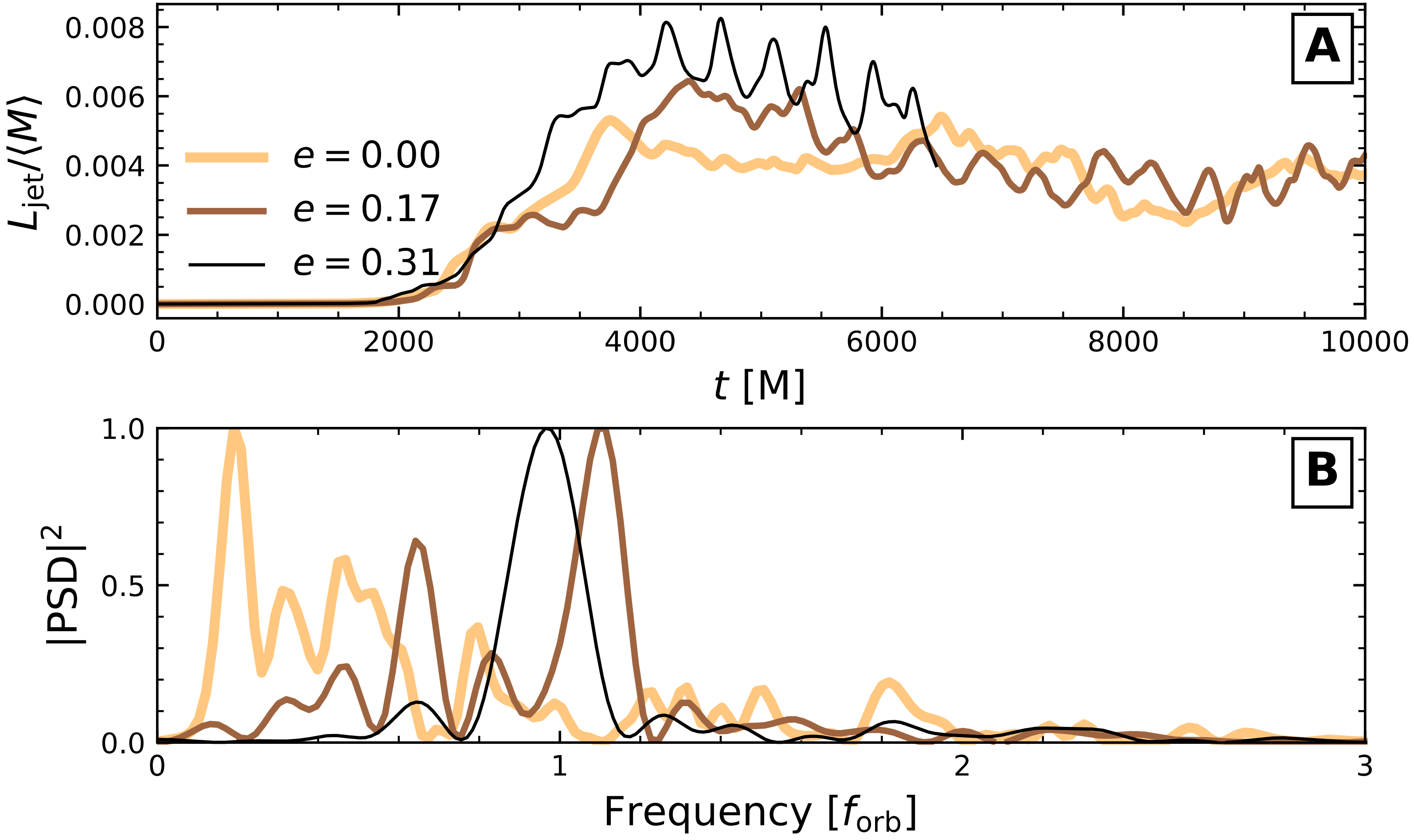


Accretion is Driven By Pericenter Approach



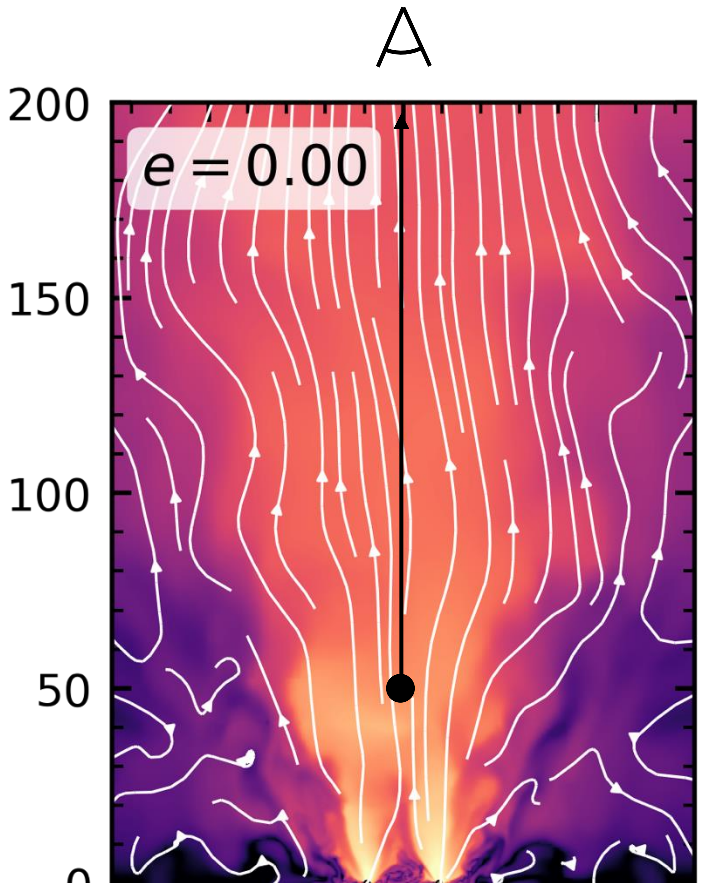
Eccentric binaries have jet variability on the orbital period





Synchrotron Radiative Transfer of Jet Emission

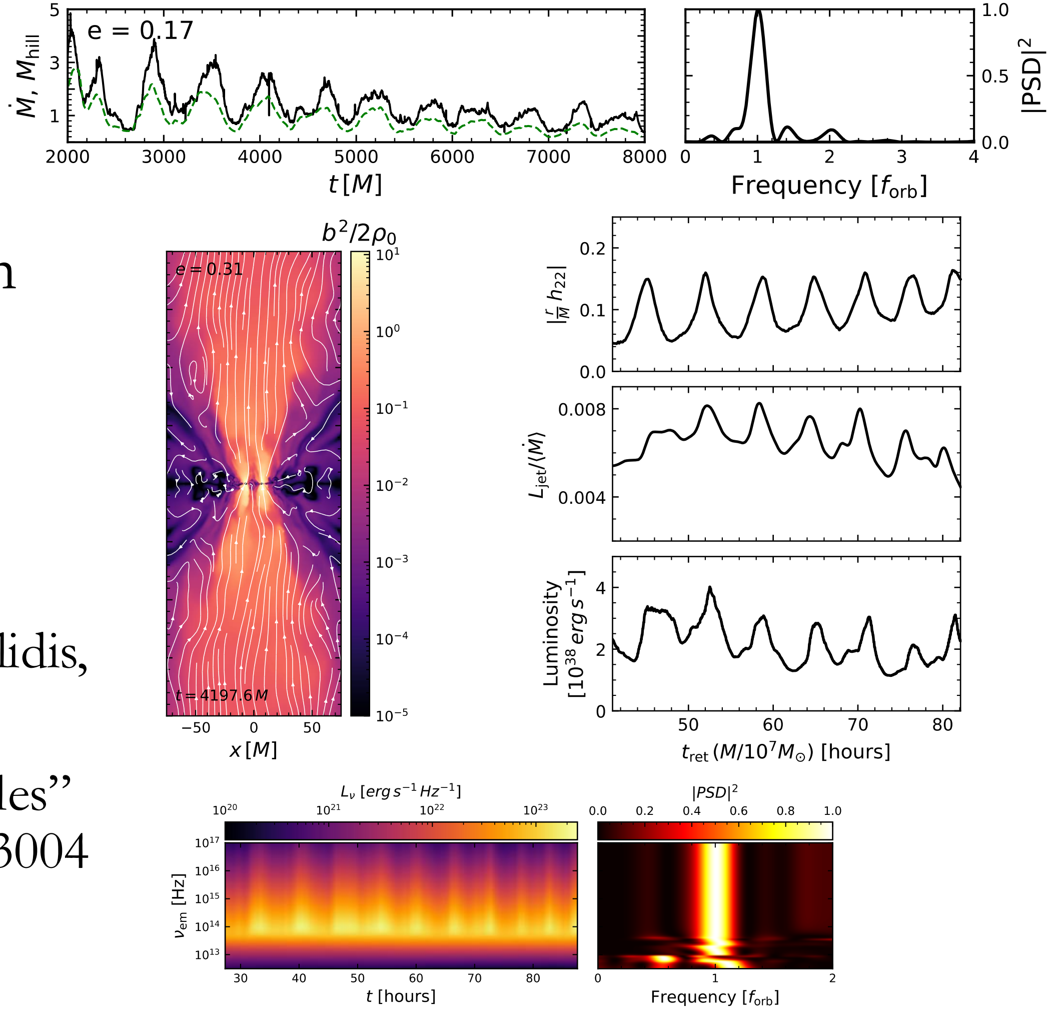
- Looking down the barrel of the jet (i.e. blazar)
- Powerlaw electron distribution in equipartition with the magnetic field energy density
- Assumptions:
  1. Fast-light
  2. Non-relativistic
  3. height > 50 M
  4. 10% Eddington
  5. 10% radiative efficiency



Eccentric SMBBHs are Uniquely Identifiable

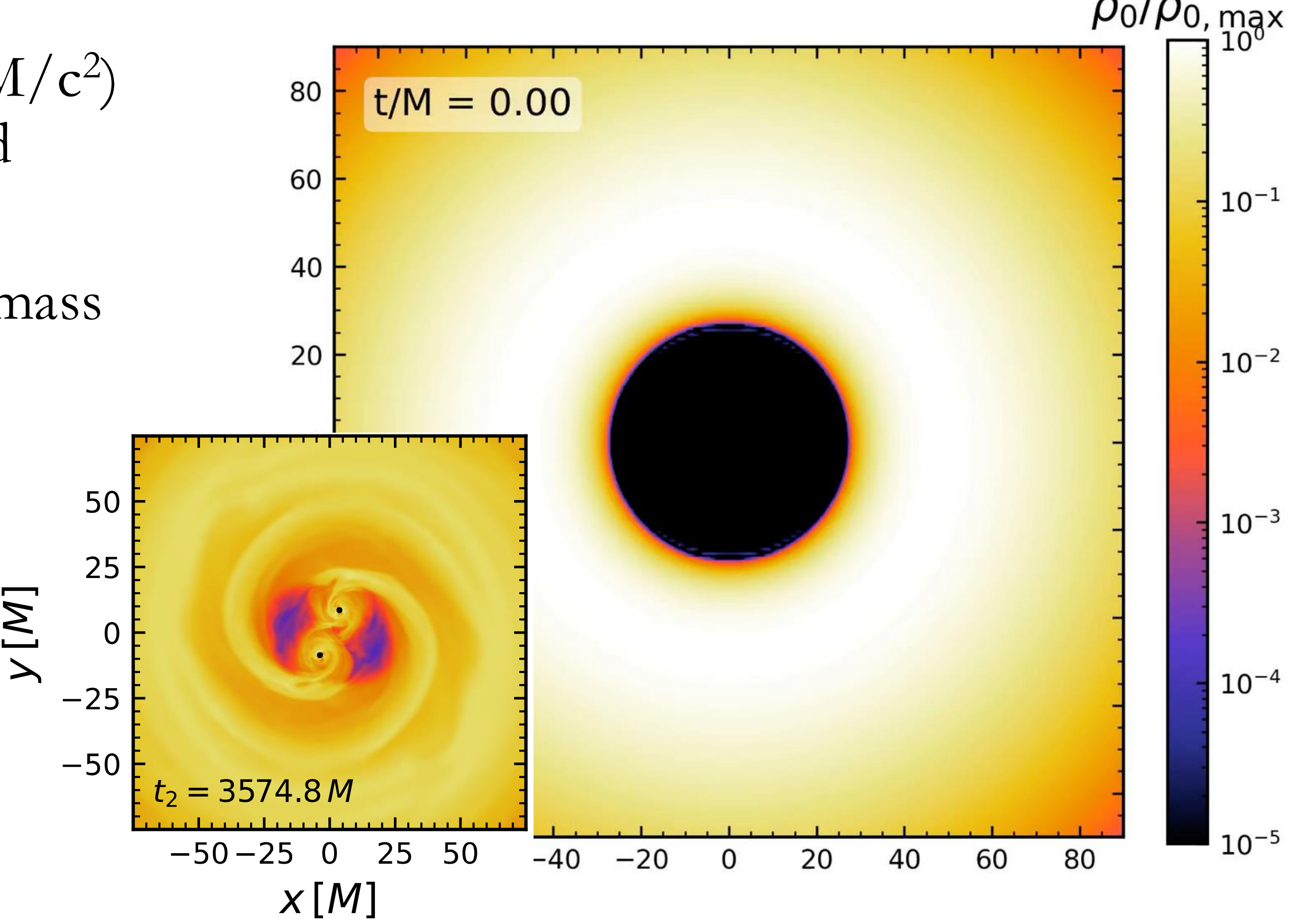
- Eccentric BBHs accrete at $\sim f_{orb}$
- Their jets are variable on $\sim f_{orb}$
- This variability is reflected in their synchrotron emission
- Coincident GW and EM bursts

- "Coincident Multi-messenger Bursts from Eccentric Supermassive Binary Black Holes" Manikantan, Paschalidis, Bozzola, ApJL, 984 L47
- "Effects of Eccentricity on Accreting Binary Black Holes" Manikantan, Paschalidis, Bozzola, Phys. Rev. D 112, 043004

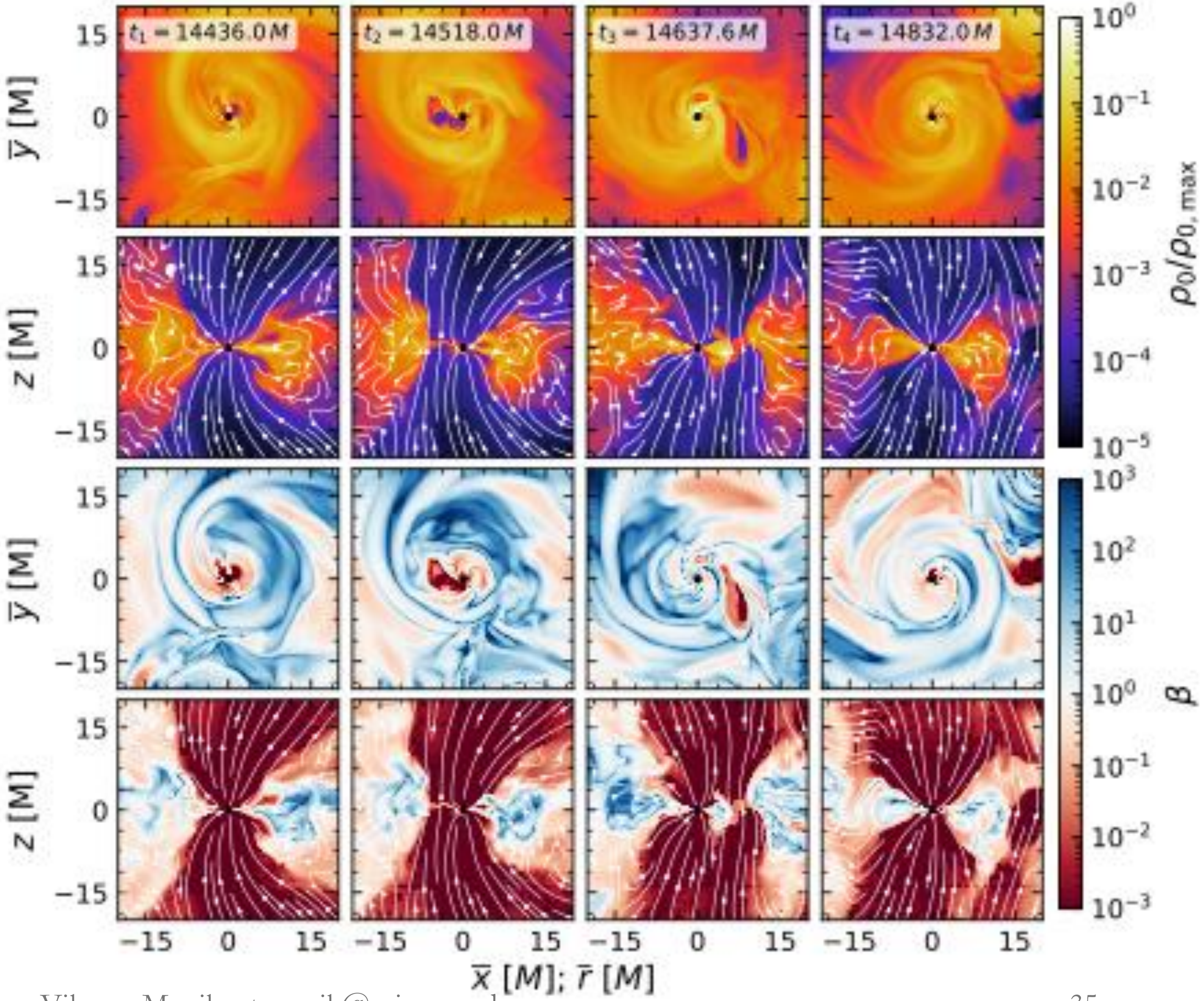


BBHs at large relativistic separations form large minidisks

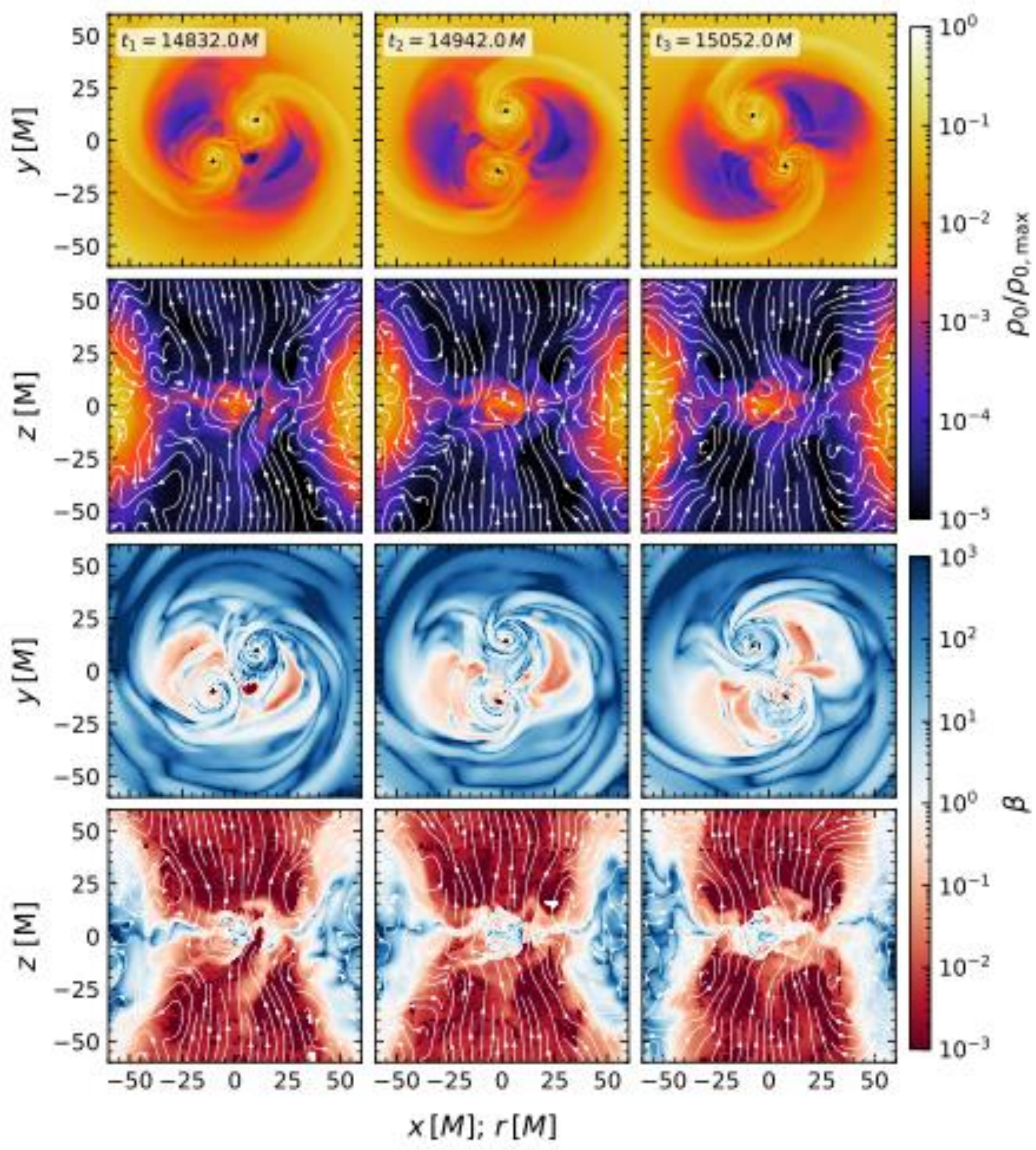
- Largest binary separation ($\sim$30 GM/c^2) studied in full general relativity and MHD
- Nonspinning, quasicircular, equal mass
- Initialize with a magnetized circumbinary disk
- Tidal streams circularize to form minidisks
- Minidisks accrete onto each BH



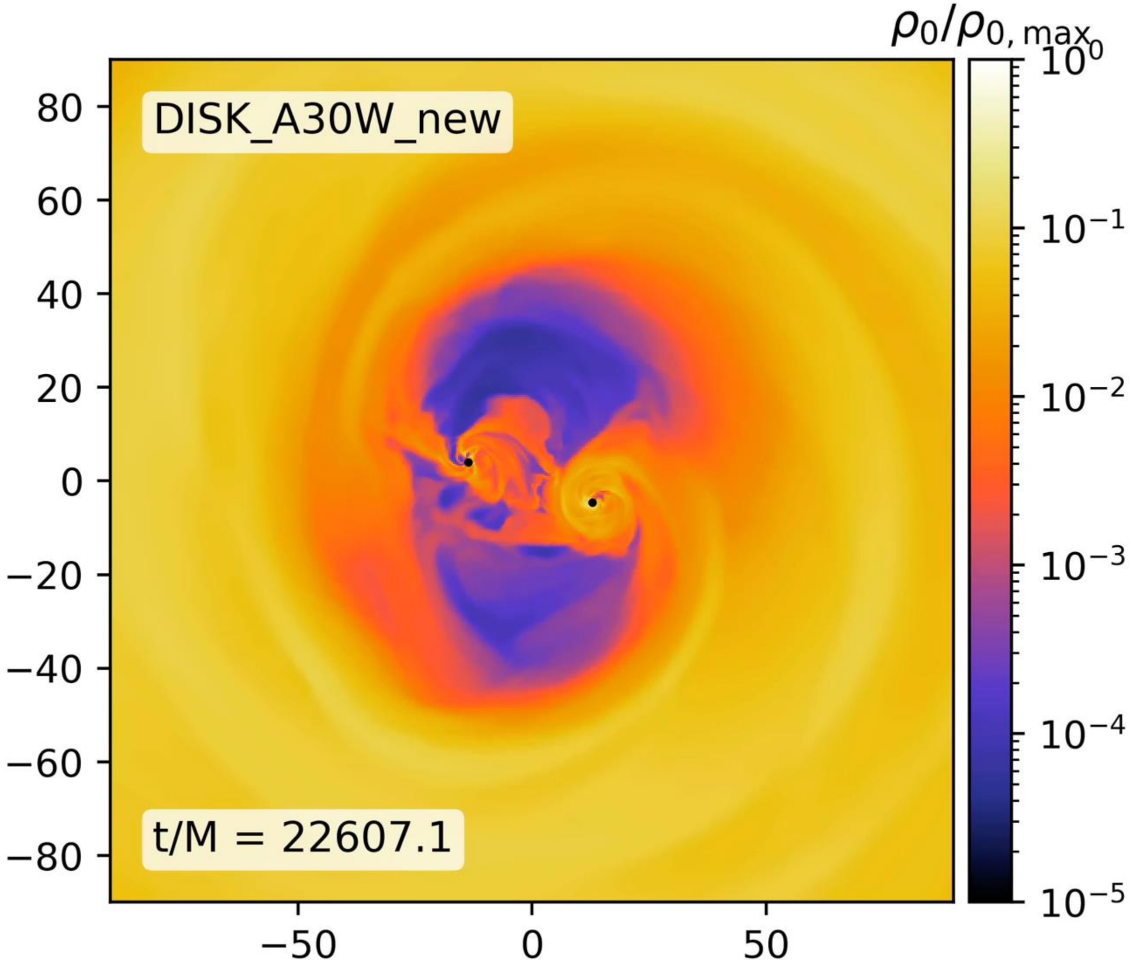
Journey through the minidisk



…into the cavity

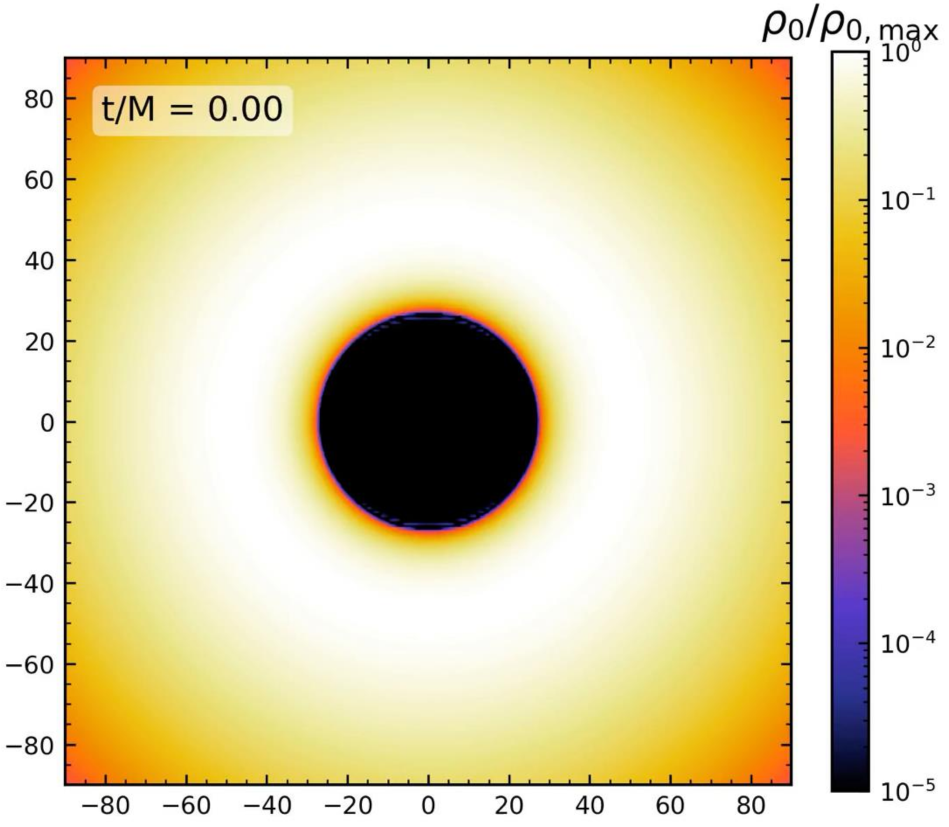


Late evolution of 30M binary



Multimessenger emission from eccentric binaries and magnetically arrested minidisks

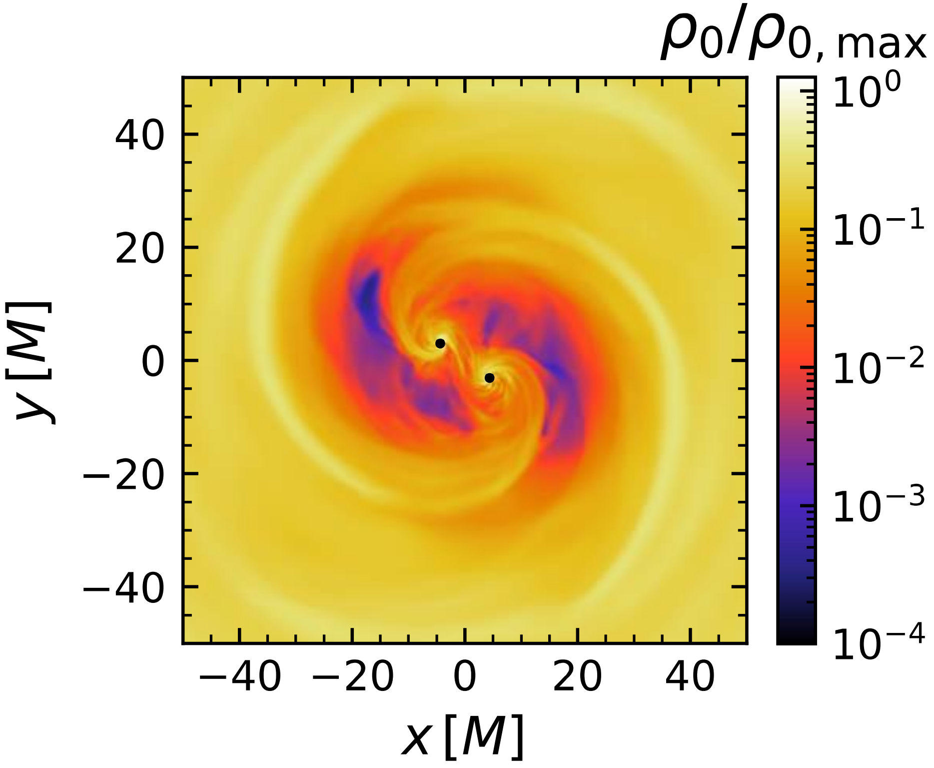
- Binary black holes at separation d/M > 30 will form large minidisks
- With enough magnetic flux, they will become magnetically arrested minidisks
- Significant implications for the evolution of the accretion flow and for observable signatures of SMBBHs



Phys. Rev. D 112, 103050

Goal: Understand the Effect of **Eccentricity** on Relativistically Separated Binary Black Holes

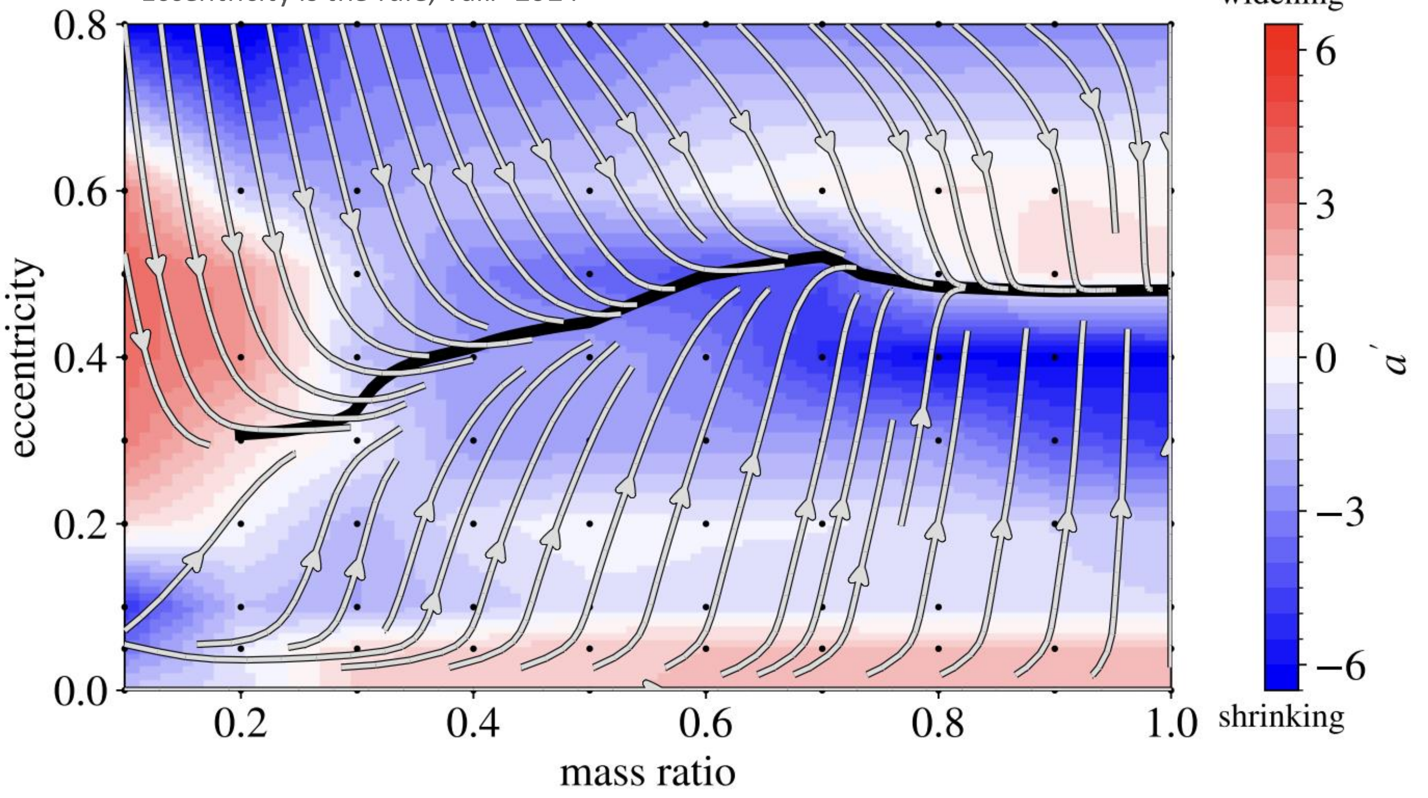
- Einstein Toolkit: Full general relativity (LeanBSSN) & Ideal Magnetohydrodynamics (IllinoisGRMHD)
- Eccentricities: e = 0.00, 0.17, 0.31 (Roedig+2011, Ryu+2018, Siwek+2024)
- Initial major axis: a = 20 M
- Equal mass, non-spinning BBH
- Seed circumbinary disk with poloidal magnetic field



Eccentricity is expected to be common

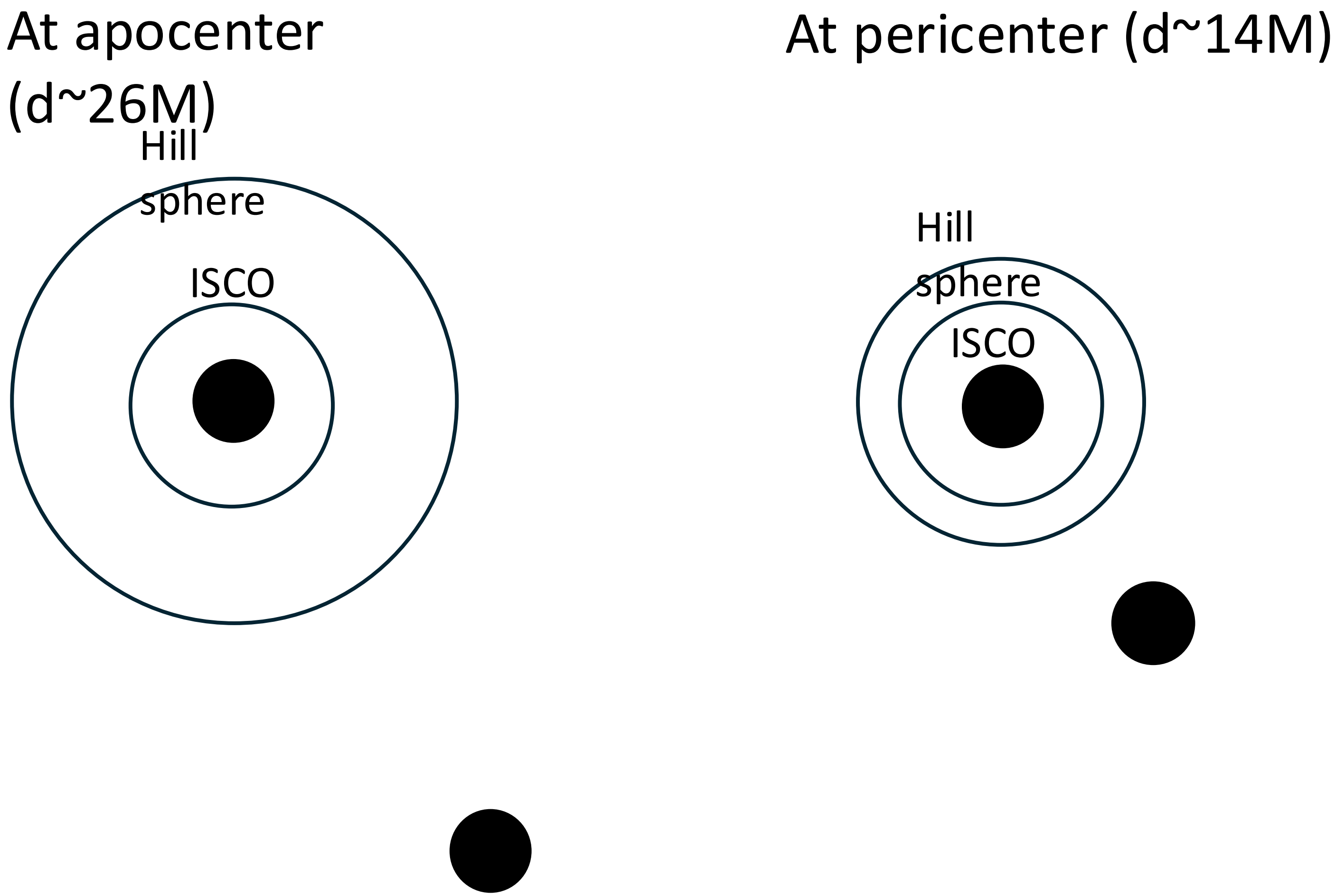
- Galaxy mergers are eccentric; SMBBHs preserve that eccentricity (Gualandris+2022)
- CBD-binary interactions induce long-term eccentricity (Valli+2024)
- SMBBH eccentricity is the norm, and up to e=0.5 (Siwek+2024)

Eccentricity is the rule; Valli+2024

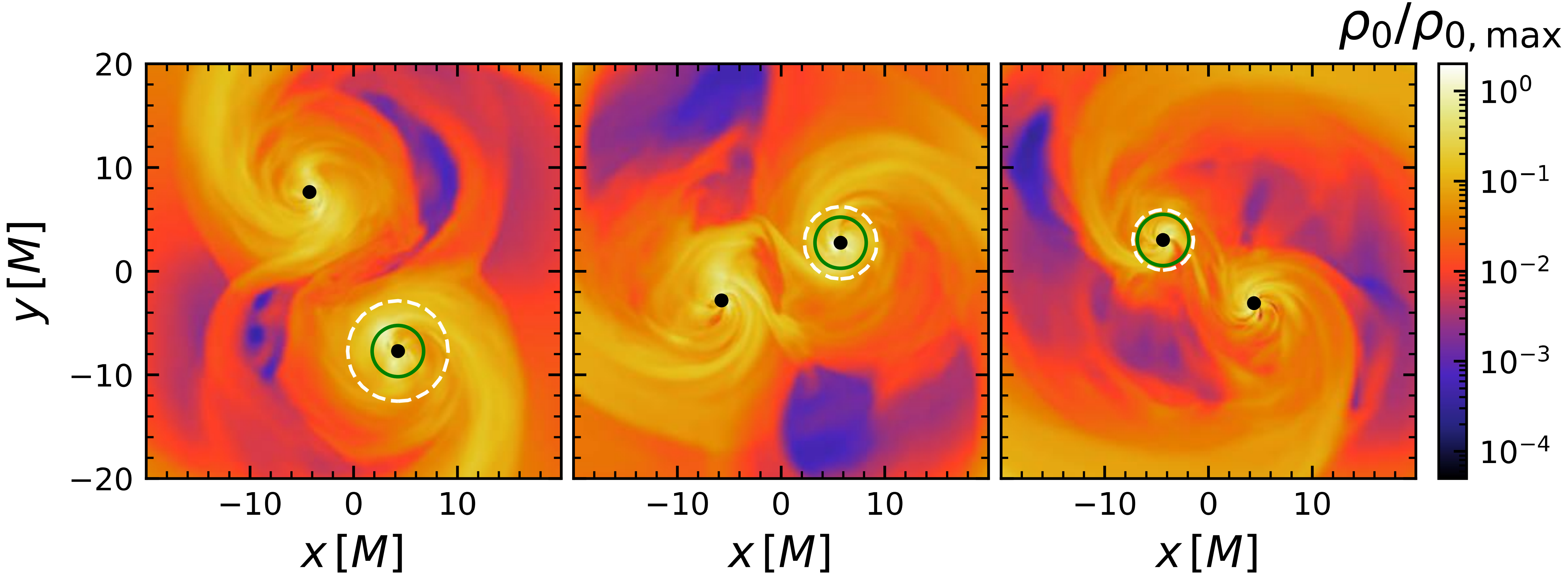


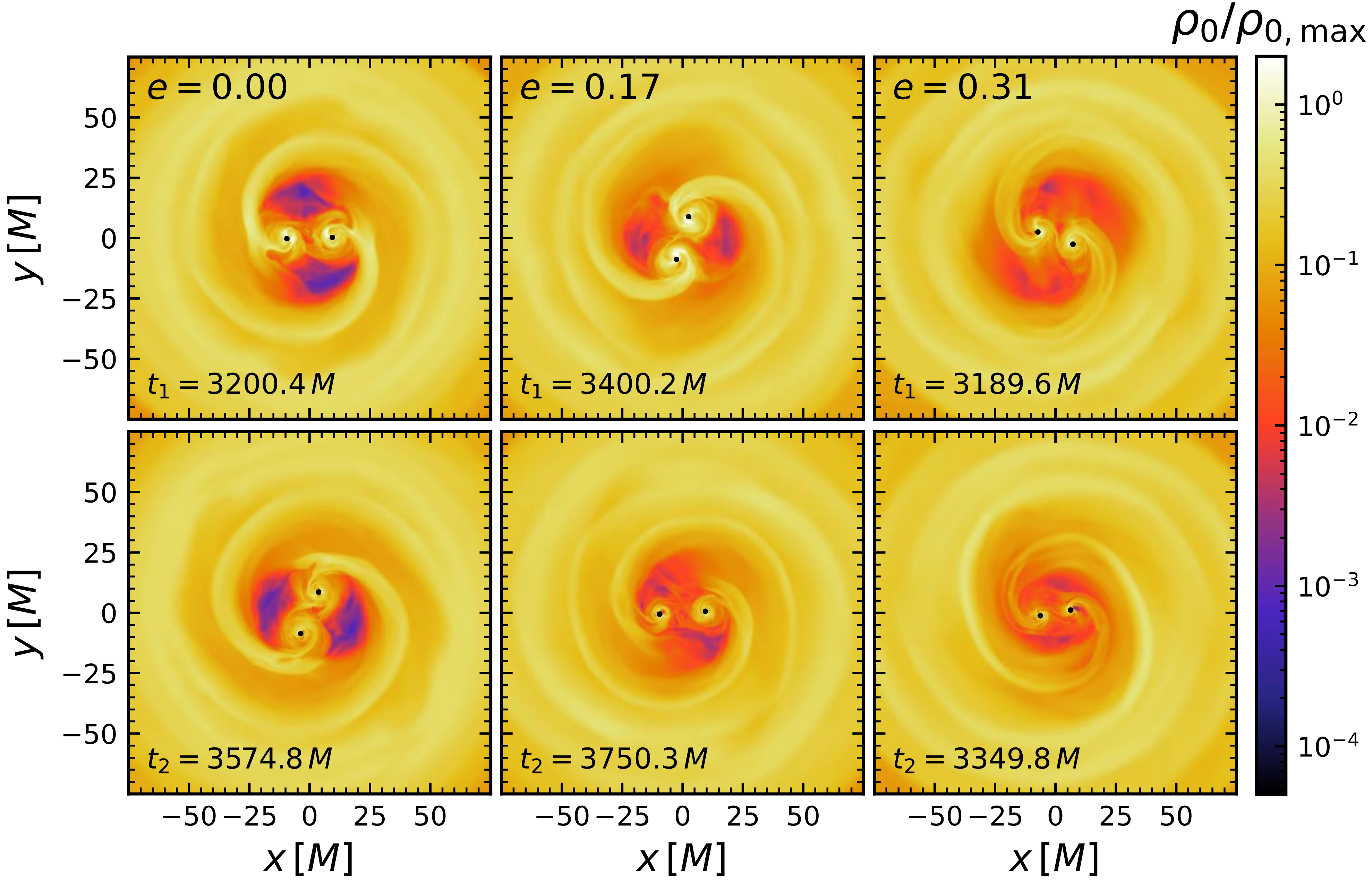
Accretion is Driven By Pericenter Approach

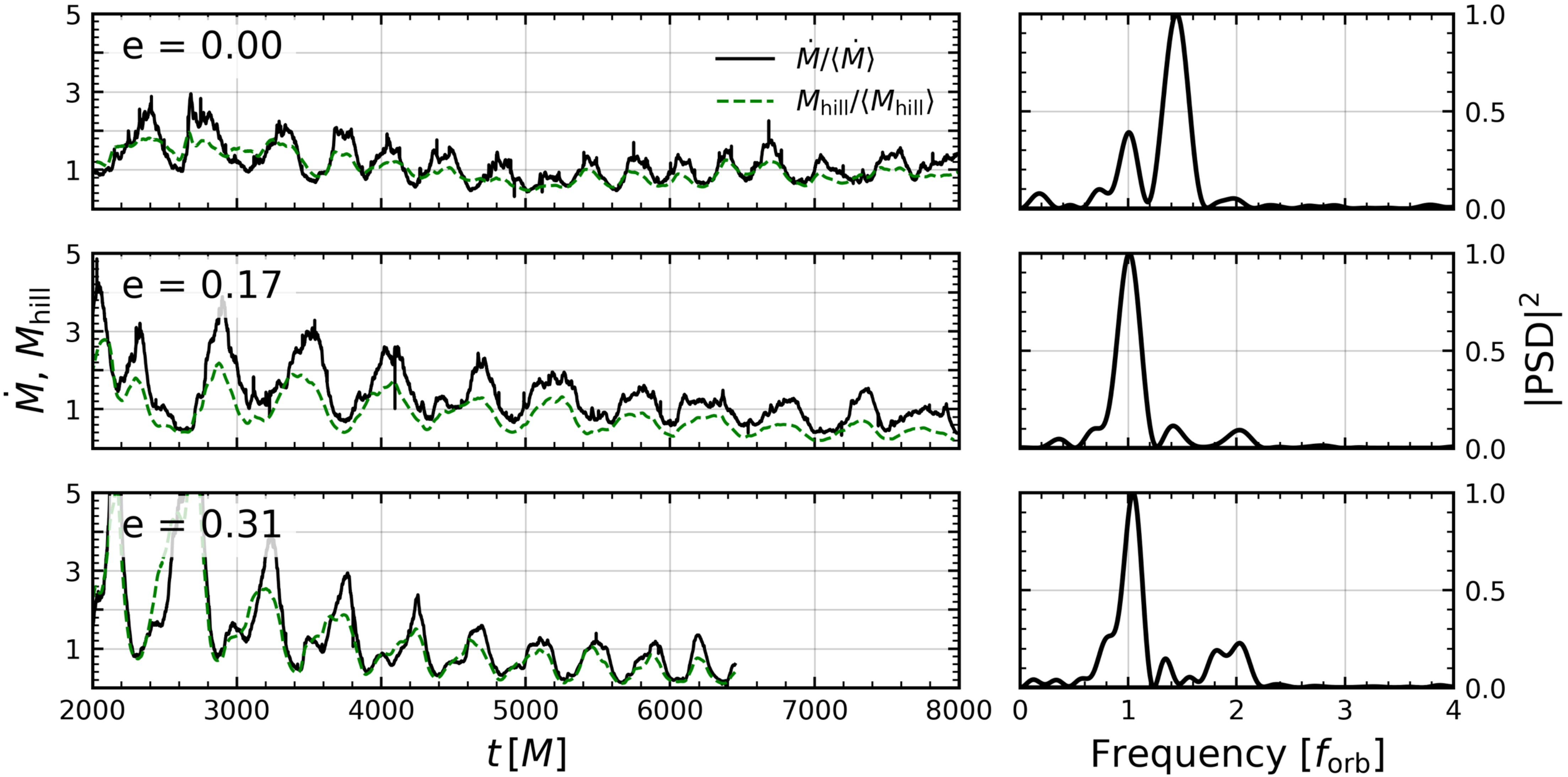
- ISCO: plunging radius
- Hill sphere-ISCO ratio determines presence of minidisks



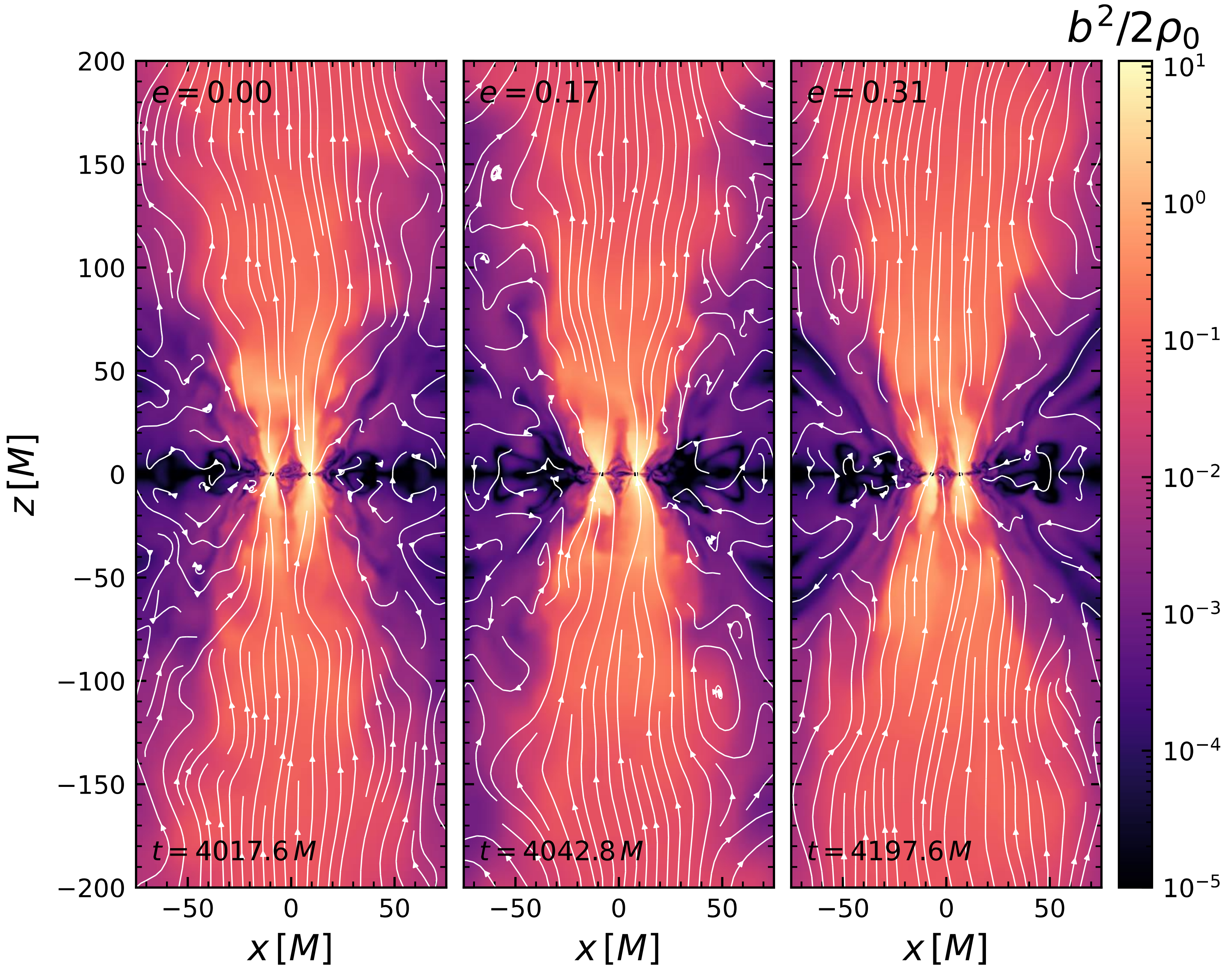
Accretion is Driven By Pericenter Approach




$\rho_0/\rho_{0,\max}$
$e = 0.00$
$e = 0.17$
$e = 0.31$
$t_1 = 3200.4\,M$
$t_1 = 3400.2\,M$
$t_1 = 3189.6\,M$
$t_2 = 3574.8\,M$
$t_2 = 3750.3\,M$
$t_2 = 3349.8\,M$
$y\,[M]$
$x\,[M]$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}



e = 0.00
e = 0.17
e = 0.31
$\dot{M}/\langle\dot{M}\rangle$
$M_{\rm hill}/\langle M_{\rm hill}\rangle$
$\dot{M}$, $M_{\rm hill}$
$t\,[M]$
Frequency [$f_{\rm orb}$]
$|\rm PSD|^2$


$b^2/2\rho_0$
$e = 0.00$
$e = 0.17$
$e = 0.31$
$t = 4017.6\,M$
$t = 4042.8\,M$
$t = 4197.6\,M$
$z\,[M]$
$x\,[M]$
200
150
100
50
0
−50
−100
−150
−200
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

Time-dependent SED are Variable