Multimessenger Emissions from Sources of Gravitational Waves

November 29th-December 3rd 2010

Sao Sebastiao, Brazil

The workshop Multimessenger Emissions from Sources of Gravitational Waves will take place from November 29th to December 3rd 2010, and it will be held at the Maresias Beach Hotel in Sao Sebastiao, Brazil.

The objective of this 5-day workshop is to discuss the state of the art of different aspects of gravitational wave emission, including EM counterparts, supernovae and neutrino emission, different astrophysical sources, numerical simulations, analytical methods and data analysis.

The astrophysics of black hole mergers

1. Pairing massive BHs in galactic nuclei
   from large to small scales, role of gas
2. Electromagnetic signatures of massive BH binaries
   in EM observations or in GW detections
3. [Where do massive BHs come from anyway?]
   protogalaxy formation after the cosmic dark age
4. [Stellar-mass BH binaries]
   in AGN accretion disks with EM signatures

Pairing Massive BHs in Galactic Nuclei

Zoltán Haiman

Columbia University

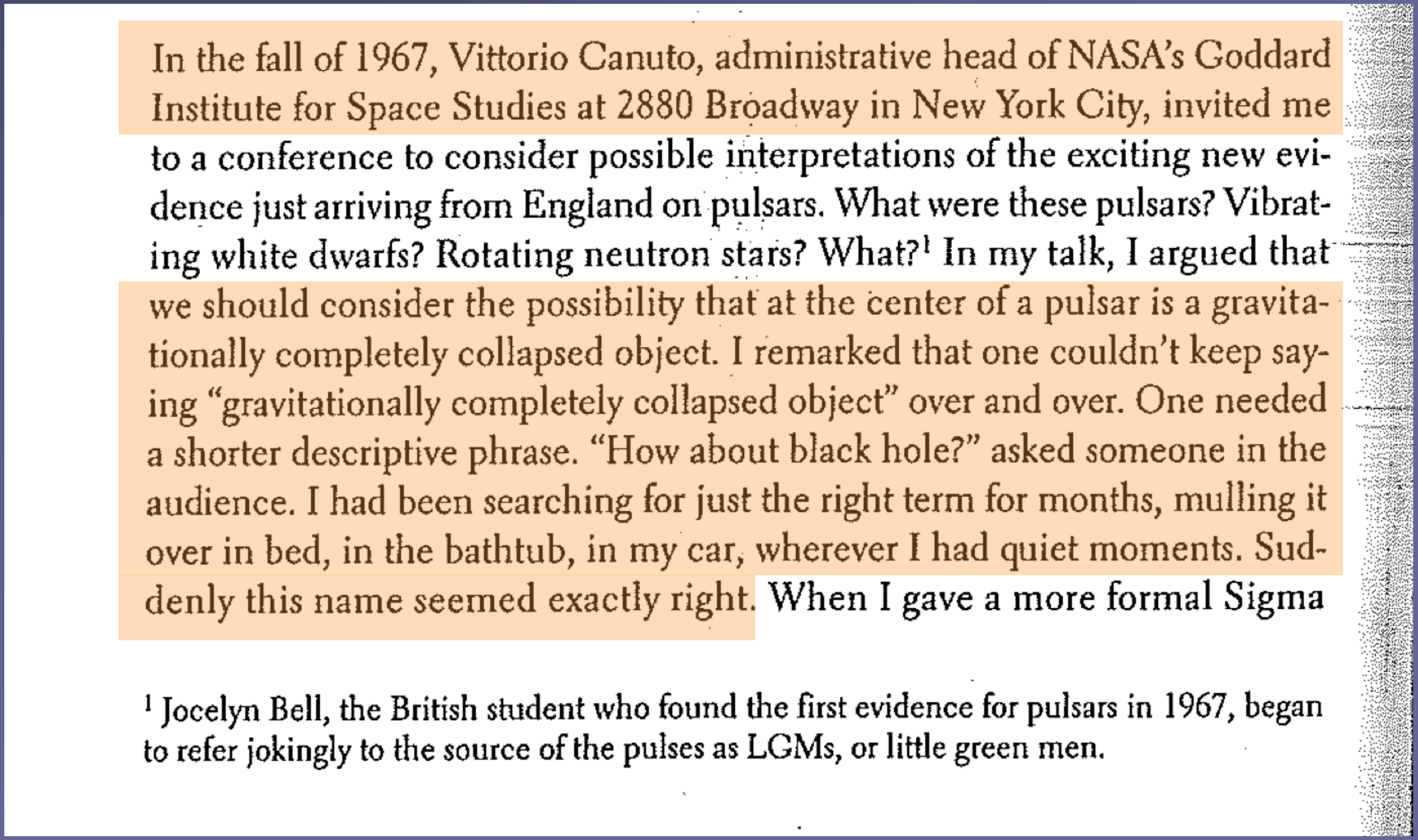
Lecture 1

São Paulo Advanced School on Multi-Messenger Astrophysics *May 29 - June 7, 2023*

John Archibald Wheeler (1911-2008)

(1999 at Princeton University)

"Geons, Black Holes, and Quantum Foam: A Life in Physics" (1998)



In the fall of 1967, Vittorio Canuto, administrative head of NASA's Goddard Institute for Space Studies at 2880 Broadway in New York City, invited me to a conference to consider possible interpretations of the exciting new evidence just arriving from England on pulsars. What were these pulsars? Vibrating white dwarfs? Rotating neutron stars? What?[1] In my talk, I argued that we should consider the possibility that at the center of a pulsar is a gravitationally completely collapsed object. I remarked that one couldn't keep saying "gravitationally completely collapsed object" over and over. One needed a shorter descriptive phrase. "How about black hole?" asked someone in the audience. I had been searching for just the right term for months, mulling it over in bed, in the bathtub, in my car, wherever I had quiet moments. Suddenly this name seemed exactly right. When I gave a more formal Sigma

[1] Jocelyn Bell, the British student who found the first evidence for pulsars in 1967, began to refer jokingly to the source of the pulses as LGMs, or little green men.

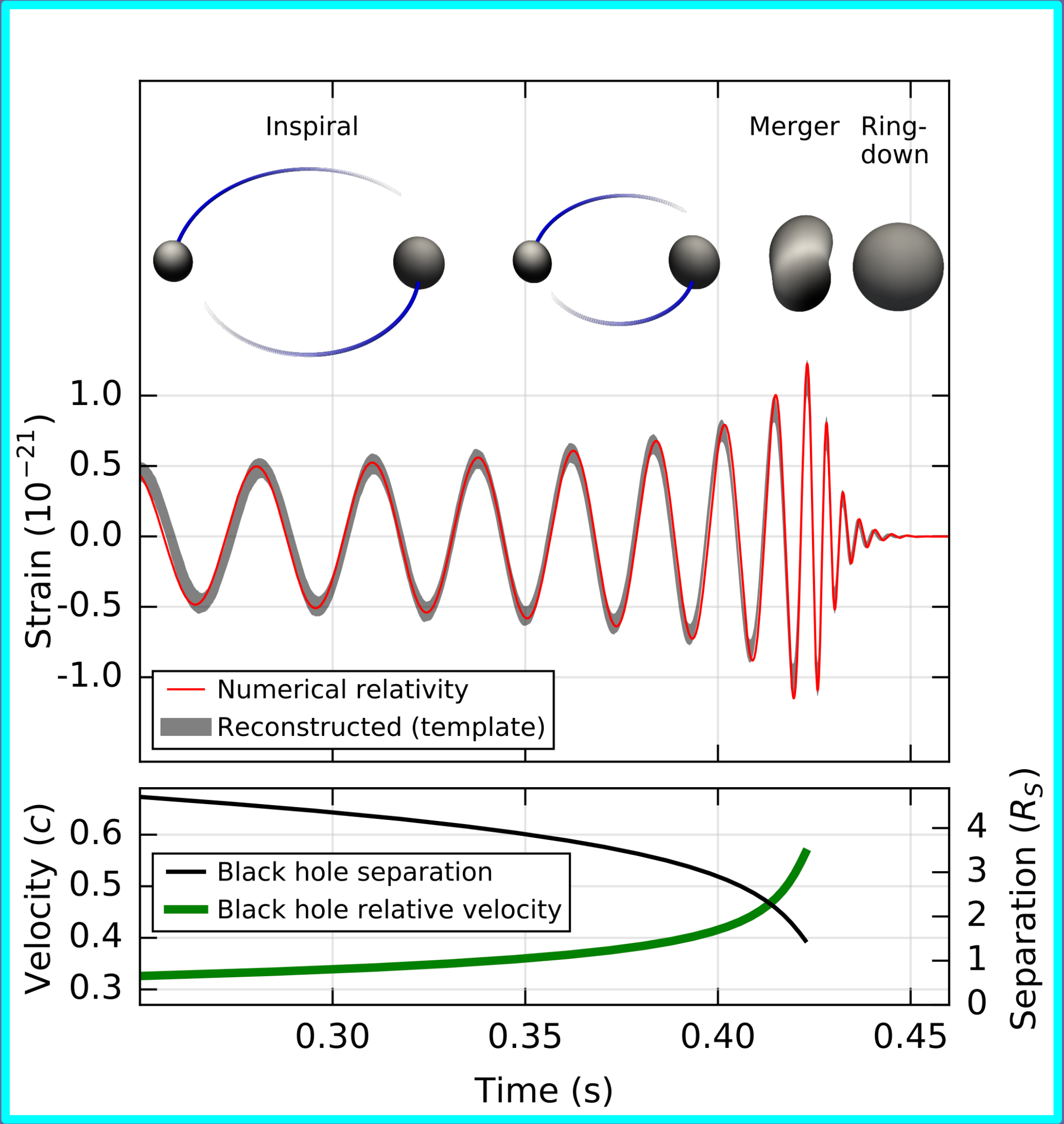
Columbia University

(Broadway & West 112th Street)

Goddard Institute for Space Studies (GISS)

(Broadway & West 112th Street)

Binary BH coalescence



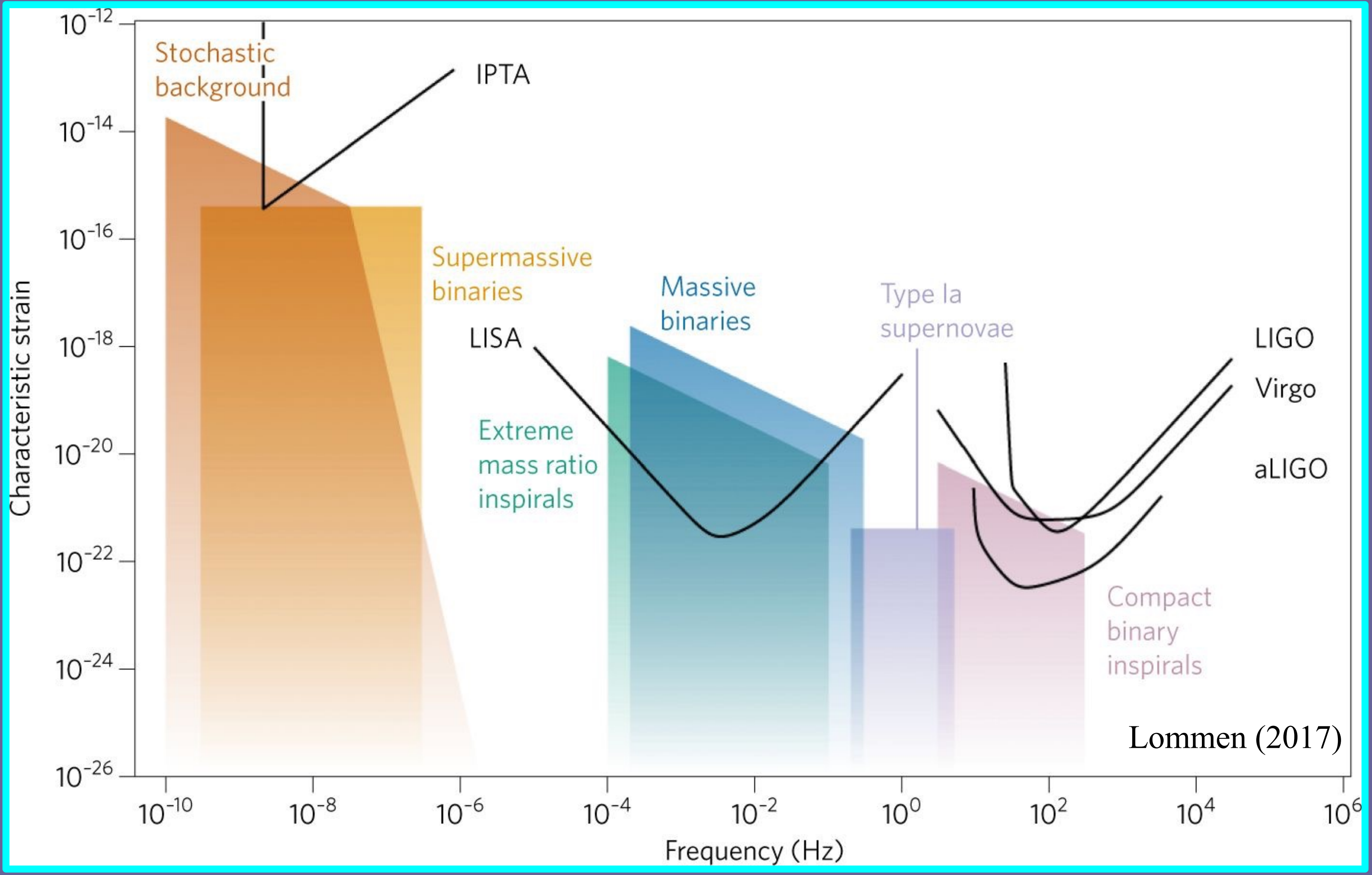
LIGO 2016 – Phys. Rev. Lett.

dimensionless waveform is independent of total mass*

**redshifted chirp mass M(1+z)*

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Multi-band Gravitational Waves



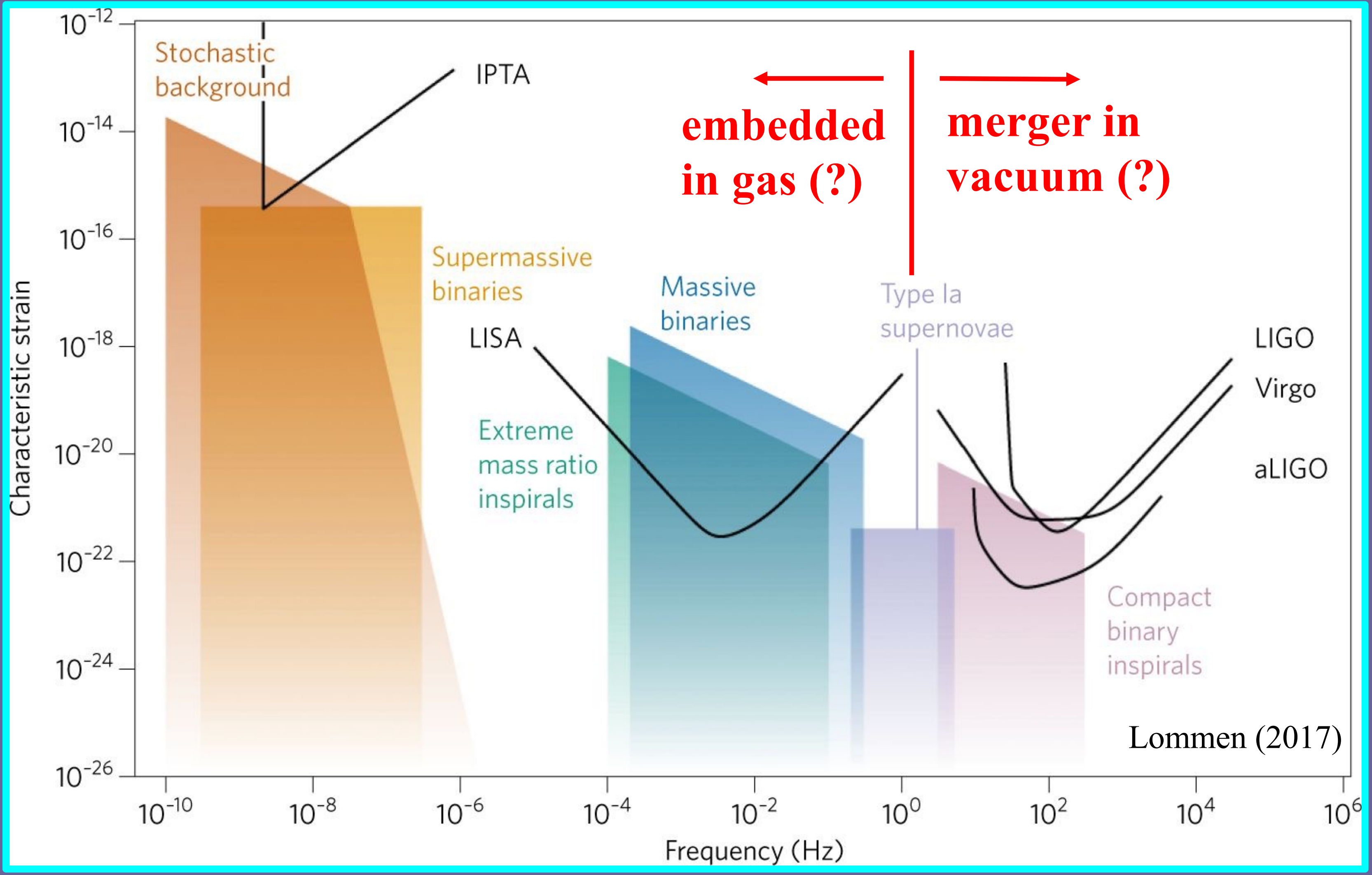
Lommen (2017)

$(10^{8}$-$10^{10})M_\odot$
pulsar timing

$(10^{4}$-$10^{7})M_\odot$
LISA

$(10$-$10^{2})M_\odot$
LIGO

Multi-band Gravitational Waves



embedded in gas (?)

merger in vacuum (?)

Lommen (2017)

$(10^8$-$10^{10})M_\odot$
pulsar timing

$(10^4$-$10^7)M_\odot$
LISA

$(10$-$10^2)M_\odot$
LIGO

Science from Multi-Messenger Astrophysics

- **Astronomy and astrophysics**

— *Accretion physics*: EM emission w/known BH parameters + distorted GWs
— *Environments of massive BH mergers:* quasar/galaxy co-evolution
— *Assembly of the first BHs in the 'dark age'*: mergers (GW) vs. accretion (EM)
— *Are there intermediate-mass BHs? Where/how do they form?*
— *Formation mechanism and fate of stellar-mass binaries*
— *Physics of mass transfer in double white-dwarfs*
— *Mapping the structure of the Milky Way through DWDs*

- **Fundamental physics and cosmology**

— *Dark Energy:* Hubble diagrams from standard sirens (& current H_0 tension)
— *Non-GR gravity:* compare $d_L(z)$ from GWs vs photons
delay between arrival time of photons and gravitons
(propagation effects, *extra dimensions*, graviton mass)
— *Lorentz violations:* frequency-dependence in delay $hf = \gamma mc^2$
— *Inflation:* Non-minimal inflation through GW background slope (cf. CMB)
— *Dark matter:* intermediate-mass ratio mergers (DM spikes)
— *NS equation of state:* mergers involving NSs

- **EM counterparts can also help with confidence of GW detection**

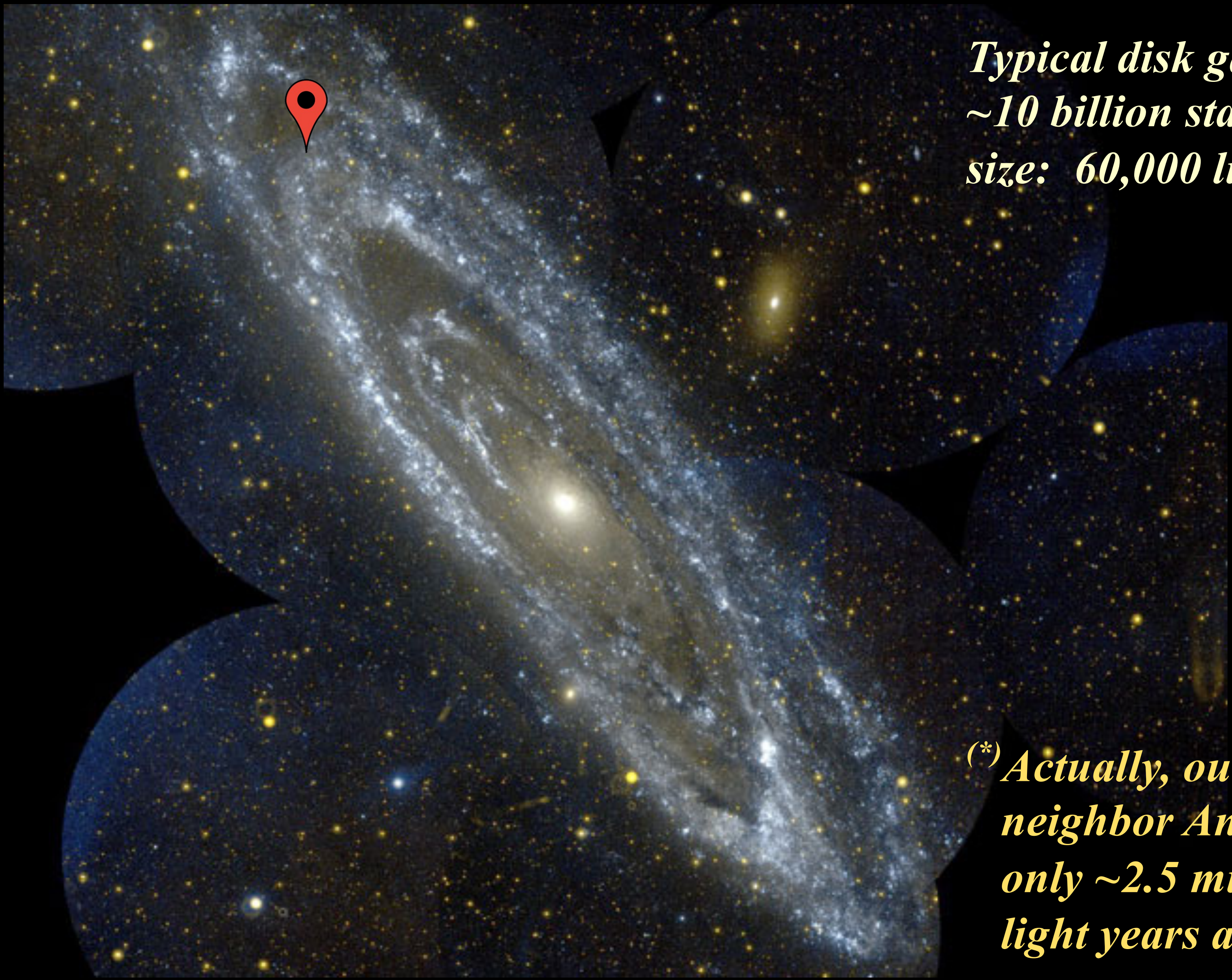
— known EM source position helps break GW parameter degeneracies

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**

   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

The Milky Way(*)

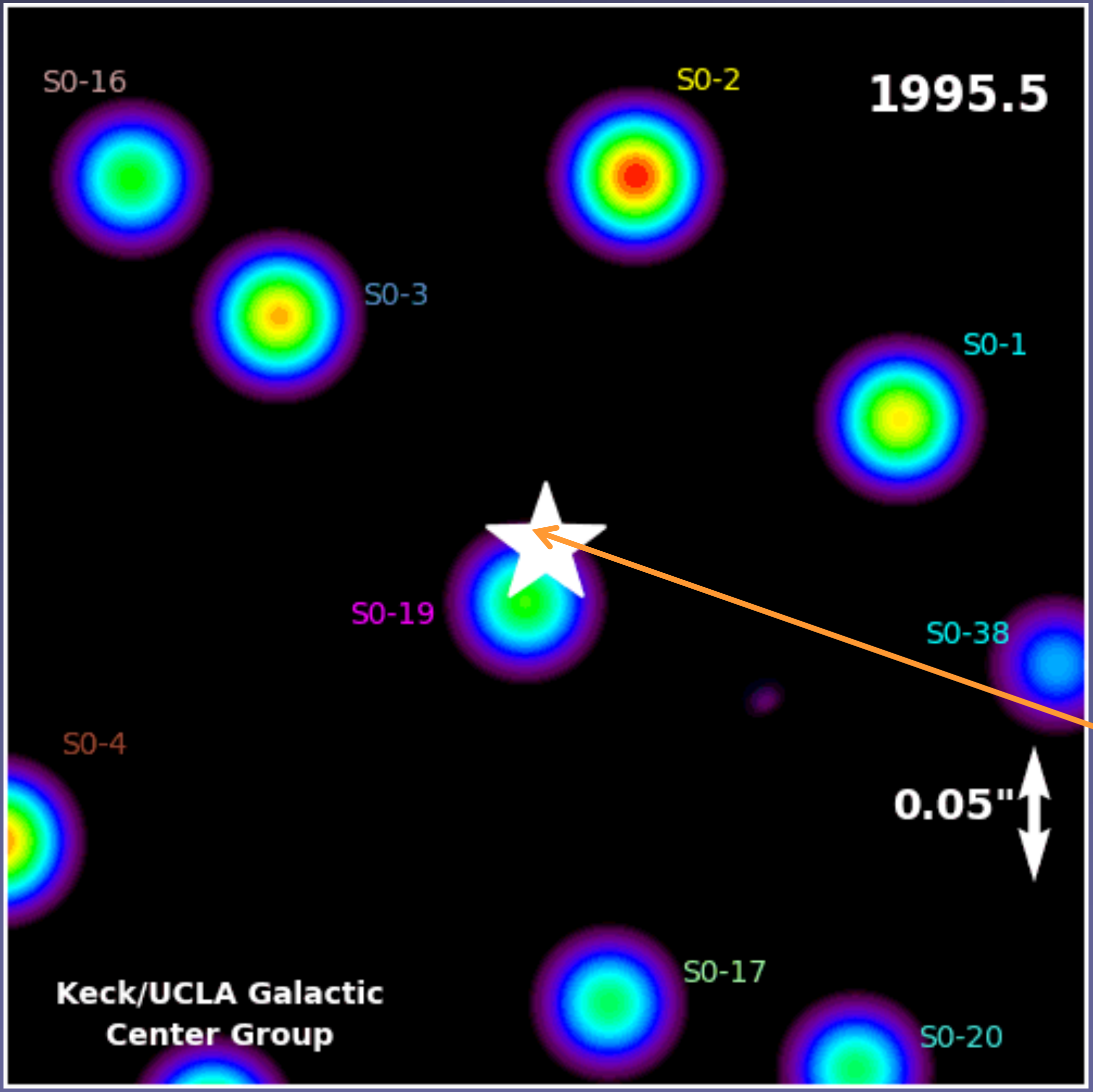


Typical disk galaxy
~10 billion stars
size: 60,000 light yr

(*) Actually, our neighbor Andromeda only ~2.5 million light years away

credit: GALEX survey

An Image of the Galactic Center



by Keck telescope, Hawaii

0.05” = a person (1.8m) in New York, viewed from São Paulo

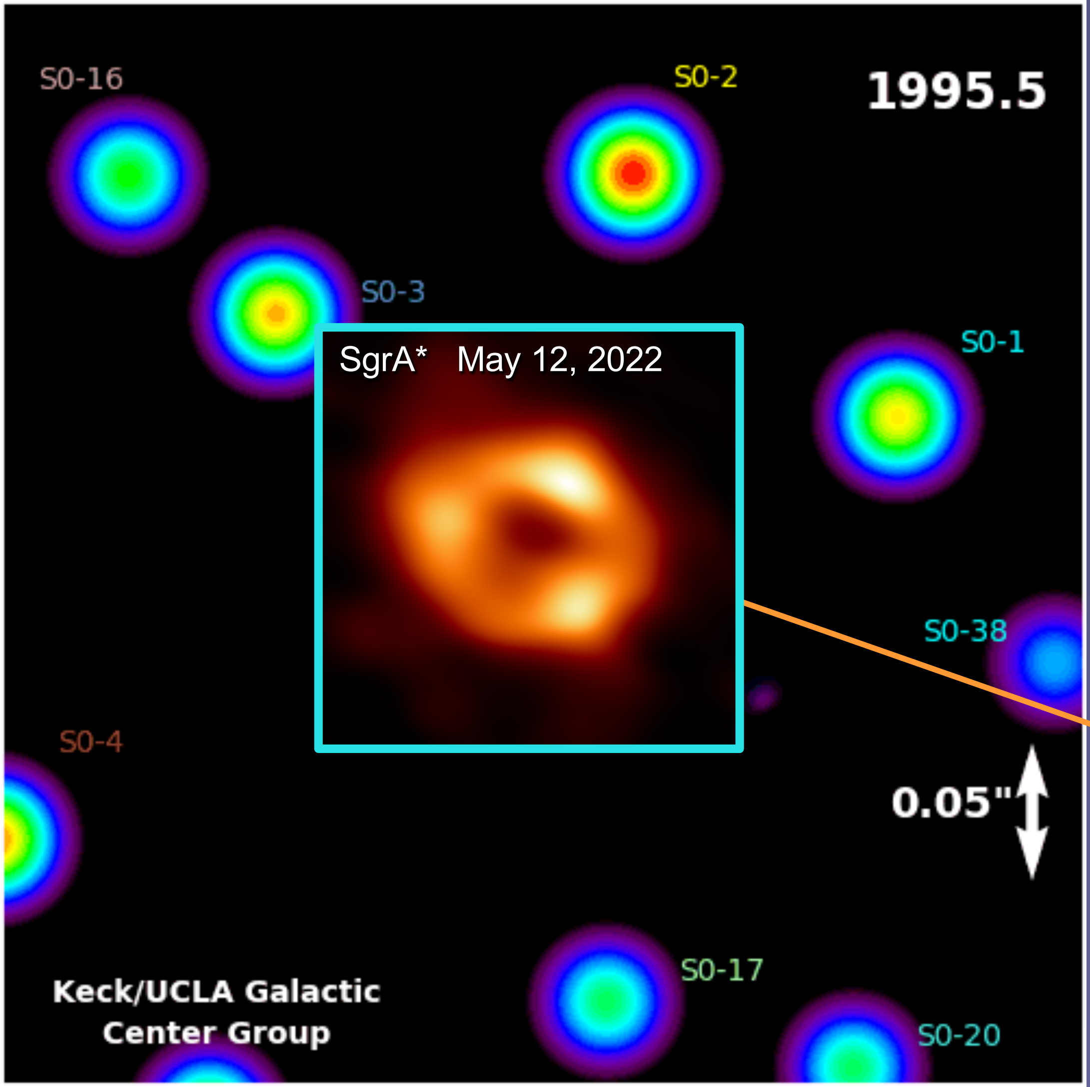
$$M_{BH} = \text{const} \times rv^2/G$$

$$M_{BH} \approx (4 \pm 0.5) \times 10^6\, M_\odot$$

BH!

**Credit: Andrea Ghez
UCLA**

An Image of the Galactic Center



by Keck telescope, Hawaii

0.05” = a person (1.8m) in New York, viewed from São Paulo

$$M_{BH} = \text{const} \times rv^2/G$$

$$M_{BH} \approx (4 \pm 0.5) \times 10^6 M_\odot$$

BH!

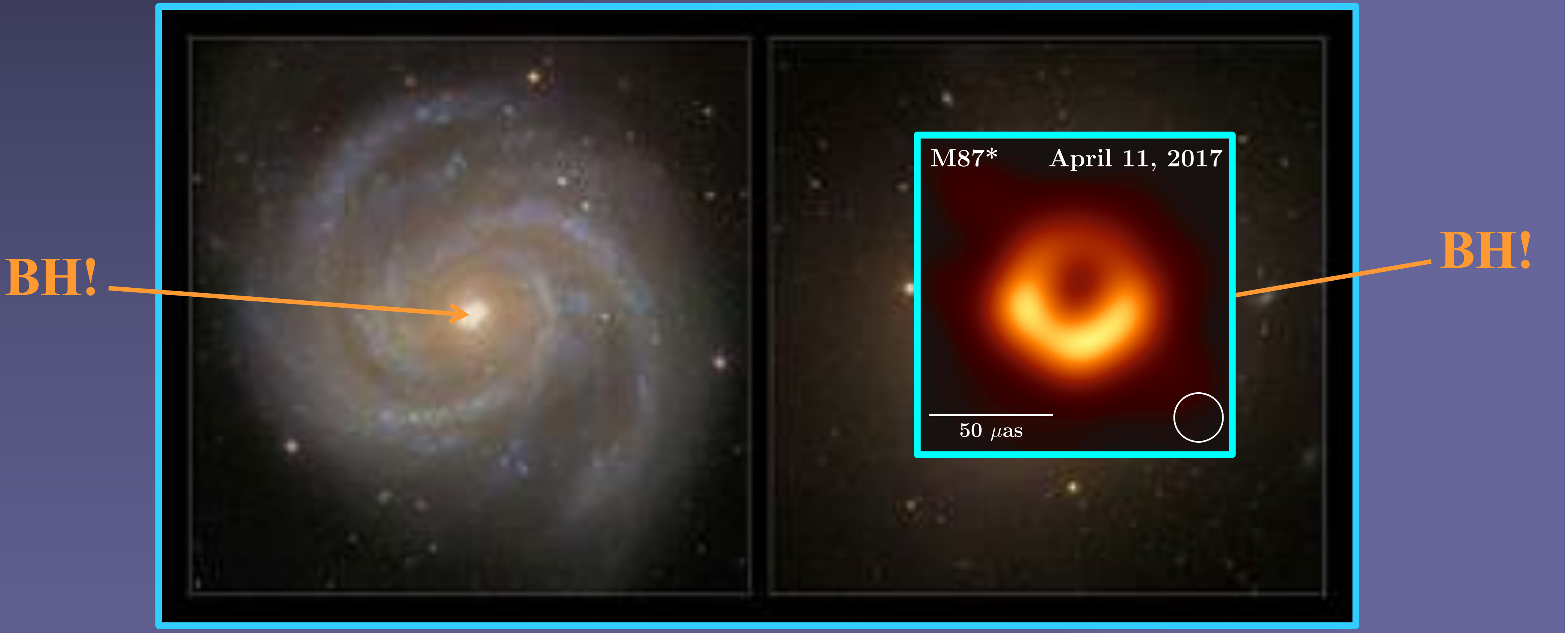
Credit: Andrea Ghez
UCLA

What about other galaxies?

Credit: Galaxy Zoo / Sloan Digital Sky Survey

- Measure **Doppler shift** of combined light of many stars or gas
- Black holes are present **in every galaxy** where we can detect them. From M_{BH}= const × rv^2/G: $M_{BH} \approx 10^6\, M_\odot - 10^9\, M_\odot$
- About 100 examples known in nearby universe

What about other galaxies?

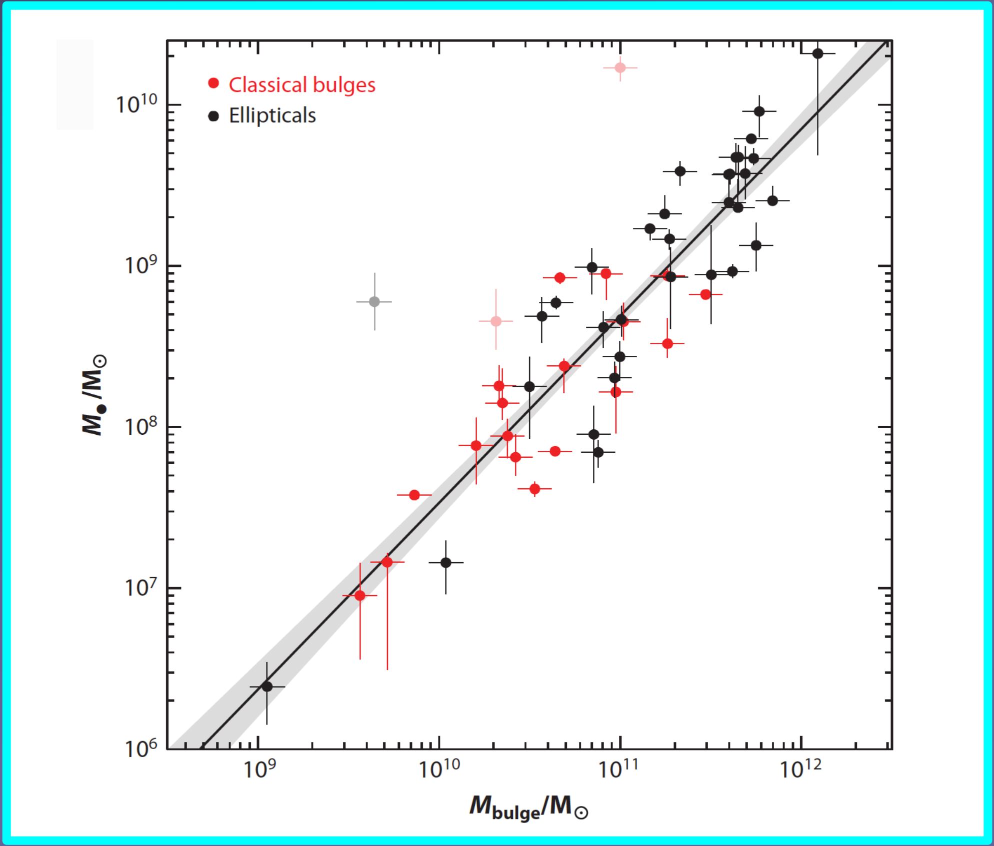


Credit: Galaxy Zoo / Sloan Digital Sky Survey

- Measure **Doppler shift** of combined light of many stars or gas
- Black holes are present **in every galaxy** where we can detect them. From $M_{BH} = \text{const} \times rv^2/G$: $M_{BH} \approx 10^6 M_\odot - 10^9 M_\odot$
- About 100 examples known in nearby universe

Massive BHs in Centers of Most Galaxies

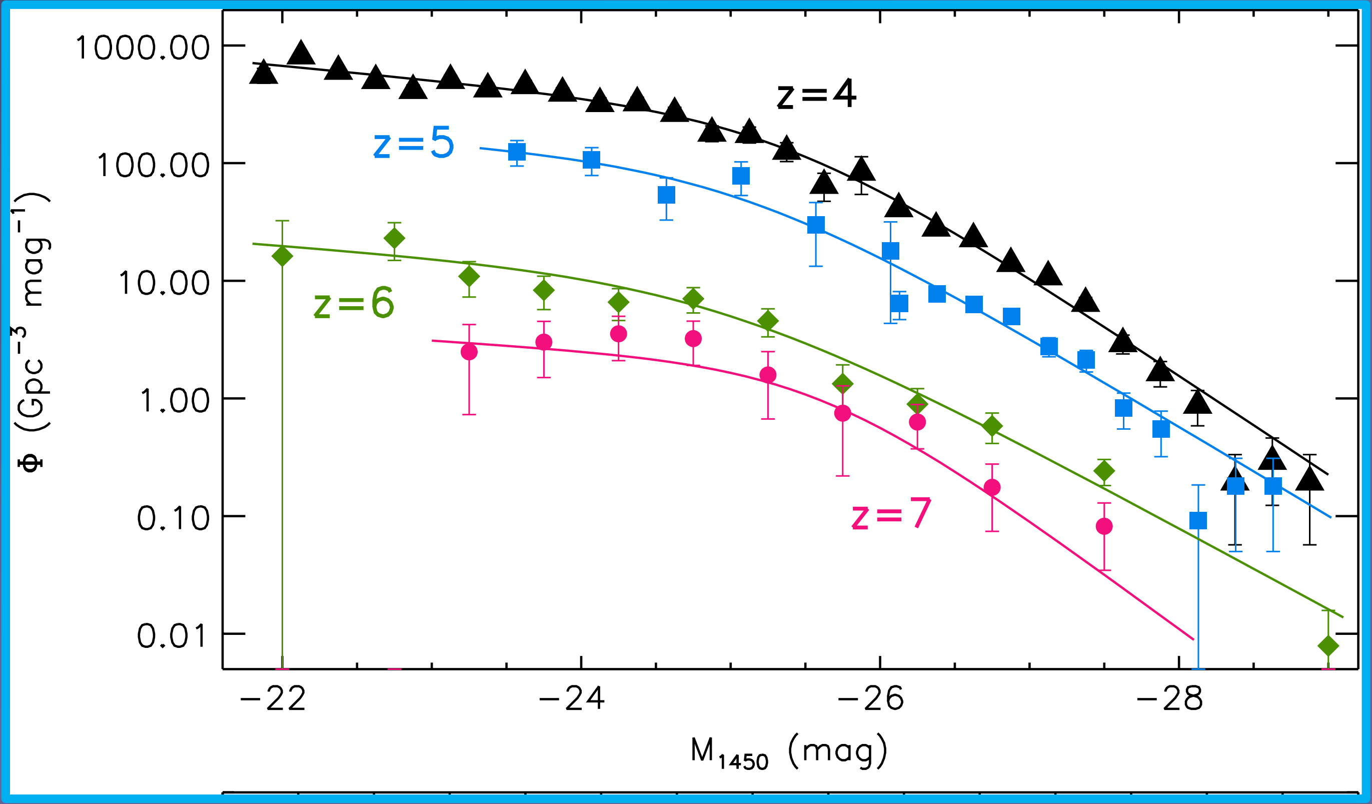
- Mass of nuclear BH measured in few dozen nearby galaxies
- BH mass correlates with mass of galaxy



Kormendy & Ho (ARA&A 2013)

Massive BHs in Early Galaxies

Quasars with $M_{BH} = 10^{8\text{-}10}\ M_\odot$ seen out to z=7.54 (t=700 Myr)



Matsuoka et al.(2023; arXiv:2305.11225)

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**

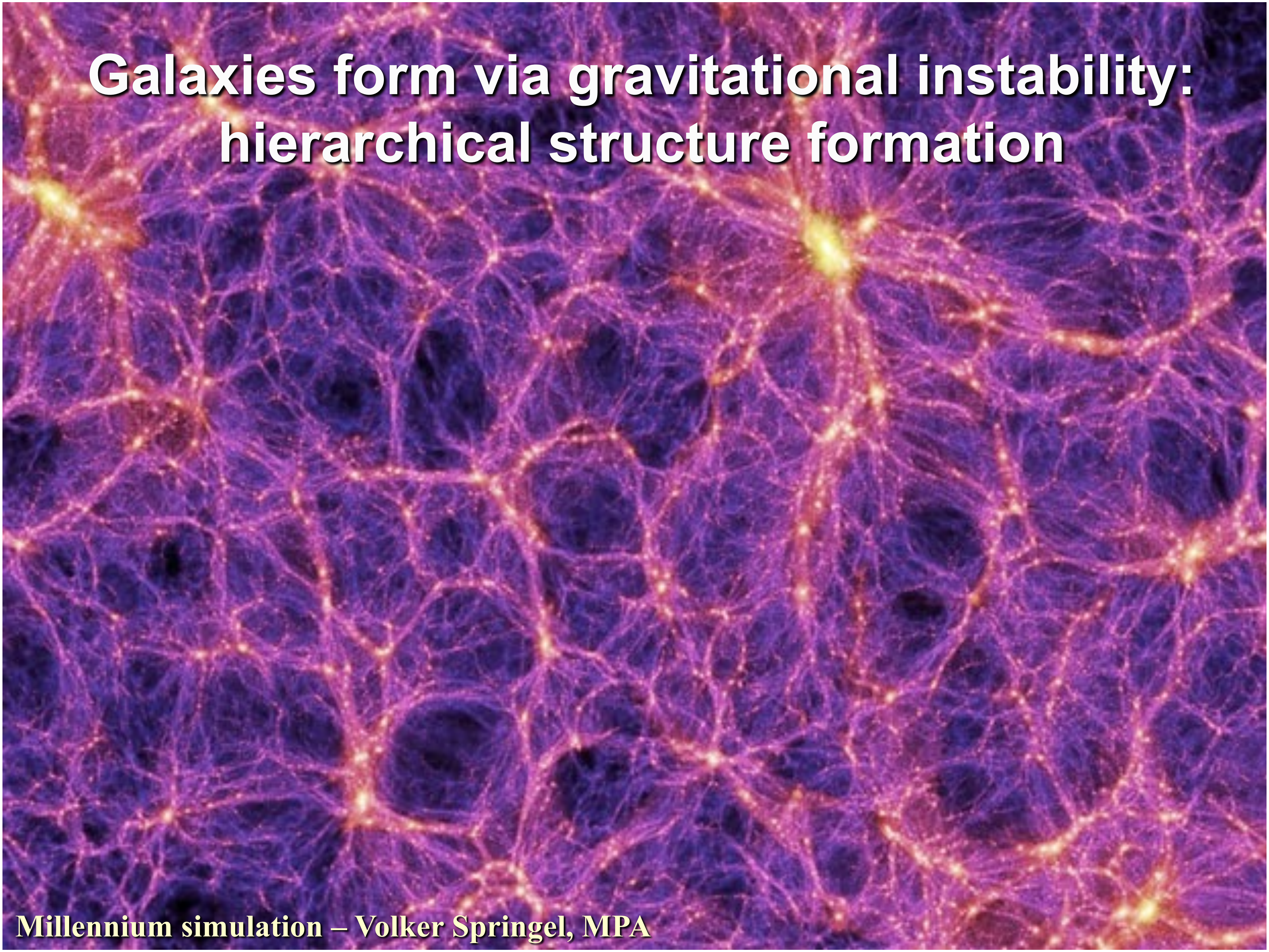
    - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**
   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

Galaxies form via gravitational instability: hierarchical structure formation



Millennium simulation – Volker Springel, MPA

Galaxies Collide and Merge

Arp 271 (credit: ESO)

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**
   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

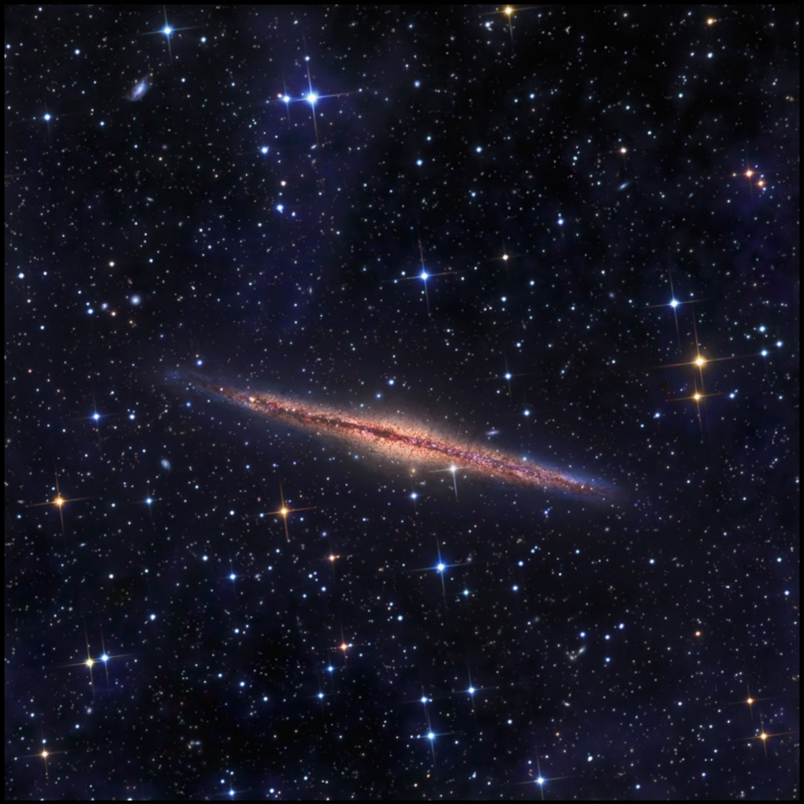
SMBH binaries <u>with gas disks</u> should be common

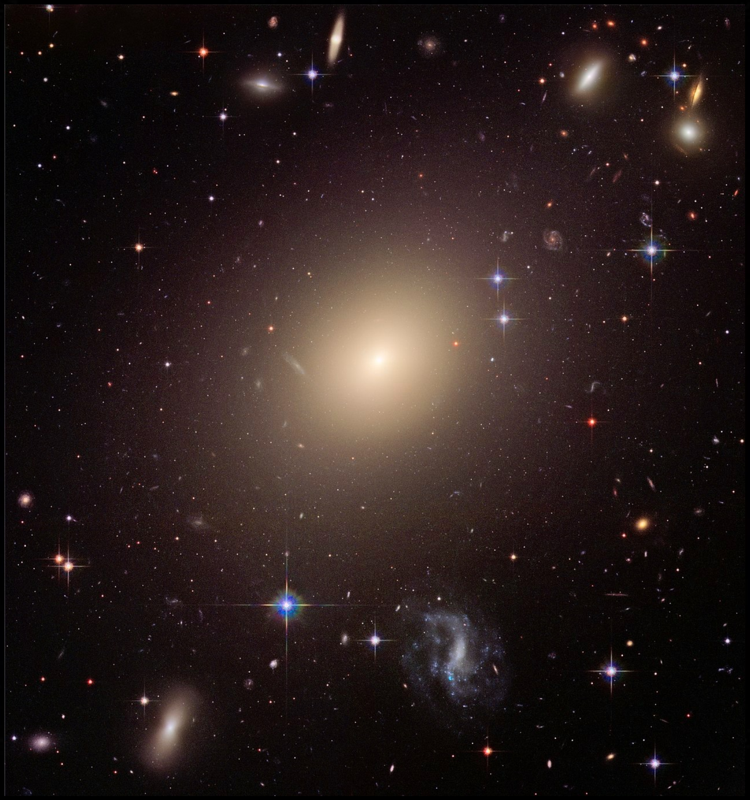
1. **Most galaxies contain SMBHs**
   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

3. **Most galaxies contain gas**
   - $M_{bh} \lesssim 10^{7.5}$ $M_\odot$ SMBHs are in gas-rich disk galaxies
   - $M_{bh} \gtrsim 10^{7.5}$ $M_\odot$ SMBHs are in “dry” ellipticals, but still with gas

Spiral vs Elliptical galaxies

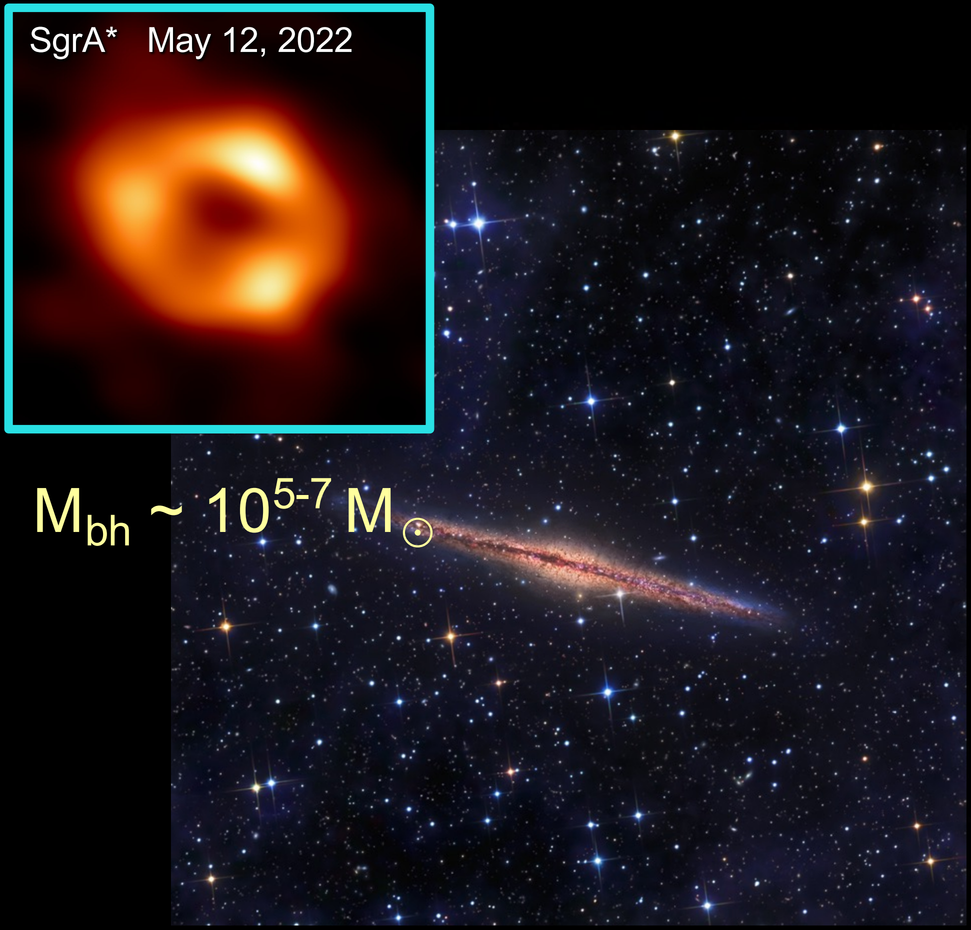




spiral galaxy NGC 891
similar to our Milky Way

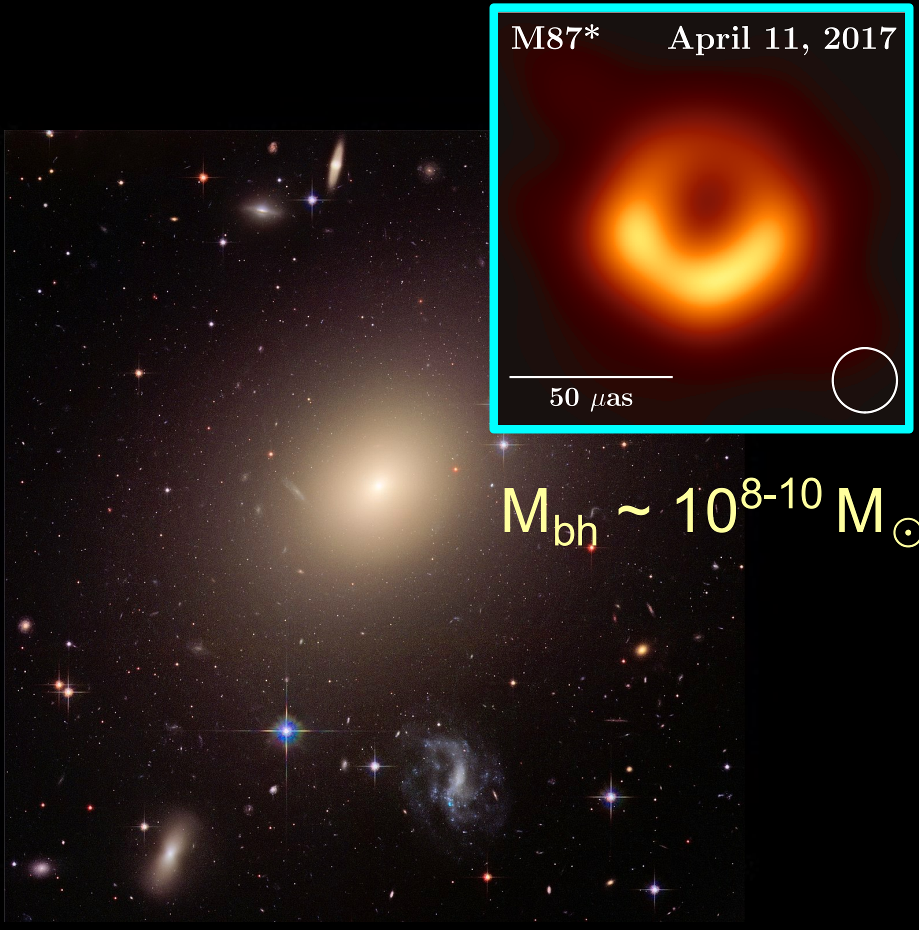
giant elliptical galaxy
at center of Abell S0740

Spiral vs Elliptical galaxies



$M_{bh} \sim 10^{5\text{-}7}\, M_\odot$

spiral galaxy NGC 891
similar to our Milky Way



$M_{bh} \sim 10^{8\text{-}10}\, M_\odot$

giant elliptical galaxy
at center of Abell S0740

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**
   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

3. **Most galaxies contain gas**
   - $M_{bh} \lesssim 10^{7.5}$ $M_\odot$ SMBHs are in gas-rich disk galaxies
   - $M_{bh} \gtrsim 10^{7.5}$ $M_\odot$ SMBHs are in "dry" ellipticals, but still with gas

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**
   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

3. **Most galaxies contain gas**
   - $M_{bh} \lesssim 10^{7.5}$ $M_\odot$ SMBHs are in gas-rich disk galaxies
   - $M_{bh} \gtrsim 10^{7.5}$ $M_\odot$ SMBHs are in "dry" ellipticals, but still with gas

4. **Both SMBHs and gas are driven rapidly to nucleus (< kpc)**
   - gas torqued by merger (misaligned stellar vs. gaseous bars)
   - SMBHs by dynamical friction on stars and dark matter

THE ASTROPHYSICAL JOURNAL, 471:115–142, 1996 November 1

TRANSFORMATIONS OF GALAXIES. II. GASDYNAMICS IN MERGING DISK GALAXIES

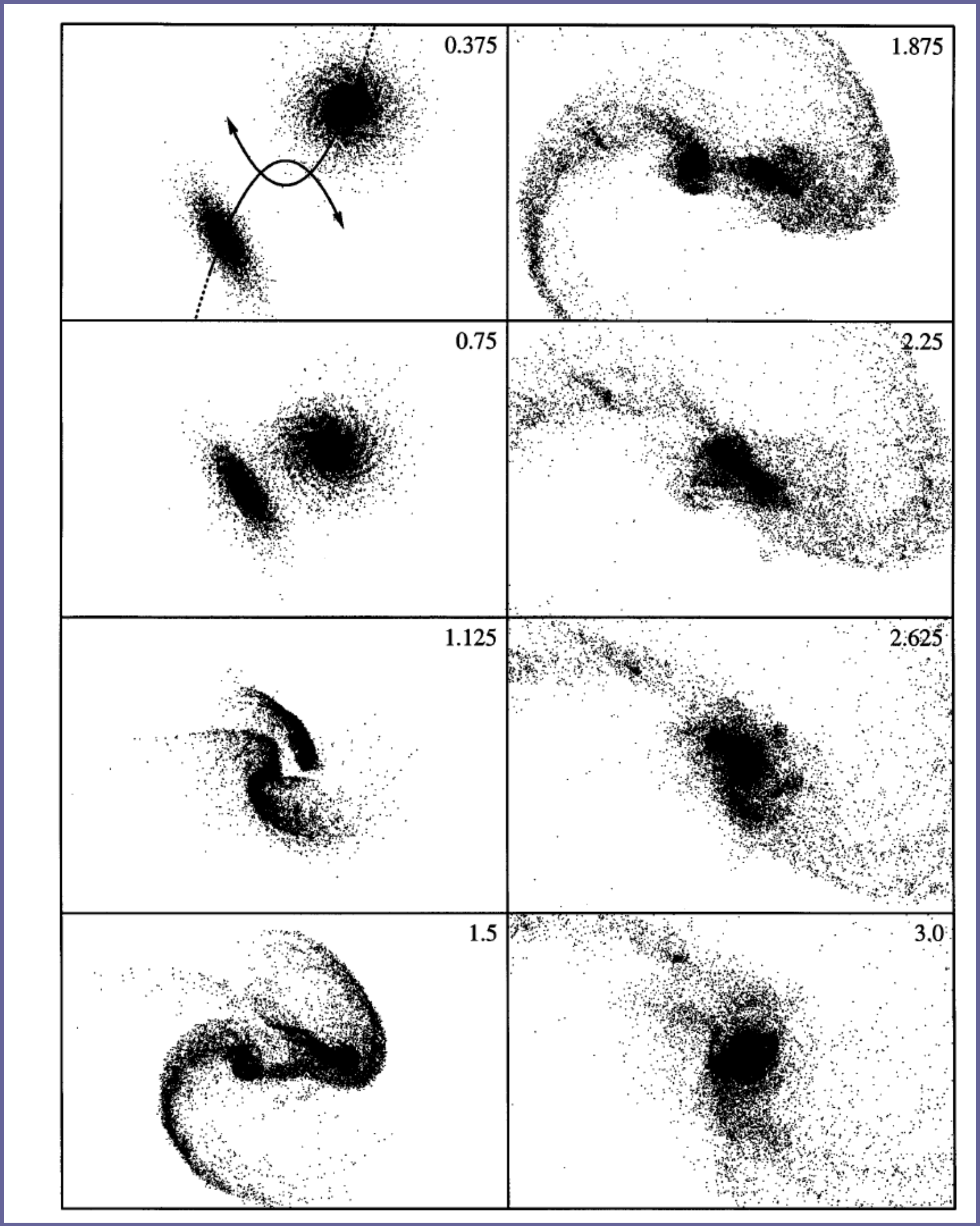
JOSHUA E. BARNES
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI; barnes@zeno.ifa.hawaii.edu
AND
LARS HERNQUIST[1]
Board of Studies in Astronomy and Astrophysics, U.C. Santa Cruz, Santa Cruz, CA 95064; lars@helios.ucsc.edu
Received 1995 February 27; accepted 1995 October 3

ABSTRACT

In mergers of disk galaxies, gas plays a role quite out of proportion to its relatively modest contribution to the total mass. To study this behavior, we have included gasdynamics in self-consistent simulations of collisions between equal-mass disk galaxies. The large-scale dynamics of bridge- and tail-making, orbit decay, and merging are not much altered by the inclusion of a gaseous component. However, tidal forces during encounters cause otherwise stable disks to develop bars, and the gas in such barred disks, subjected to strong gravitational torques, flows toward the central regions where it may fuel the kiloparsec-scale starbursts seen in some interacting disk systems. Similar torques on the gas during the final stages of a collision yield massive gas concentrations in the cores of merger remnants, which may be plausibly identified with the molecular complexes seen in objects such as NGC 520 and Arp 220. This result appears insensitive to the detailed microphysics of the gas, provided that radiative cooling is permitted. The inflowing gas can dramatically alter the *stellar* morphology of a merger remnant, apparently by deepening the potential well and thereby changing the boundaries between the major orbital families.

Subject headings: galaxies: interactions — galaxies: structure — hydrodynamics — methods: numerical

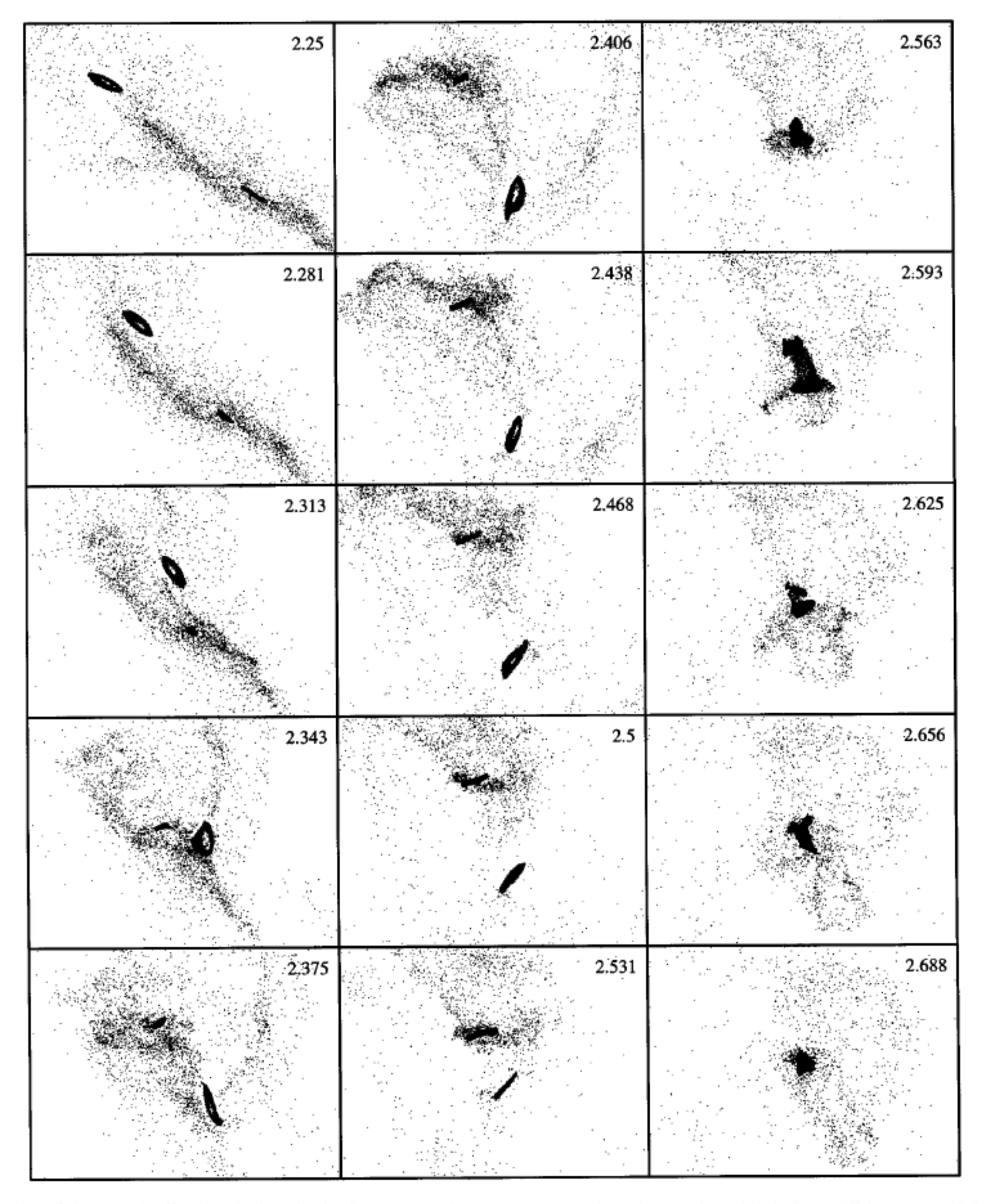
Stellar distribution



← 100kpc →

[t]=250 Myr

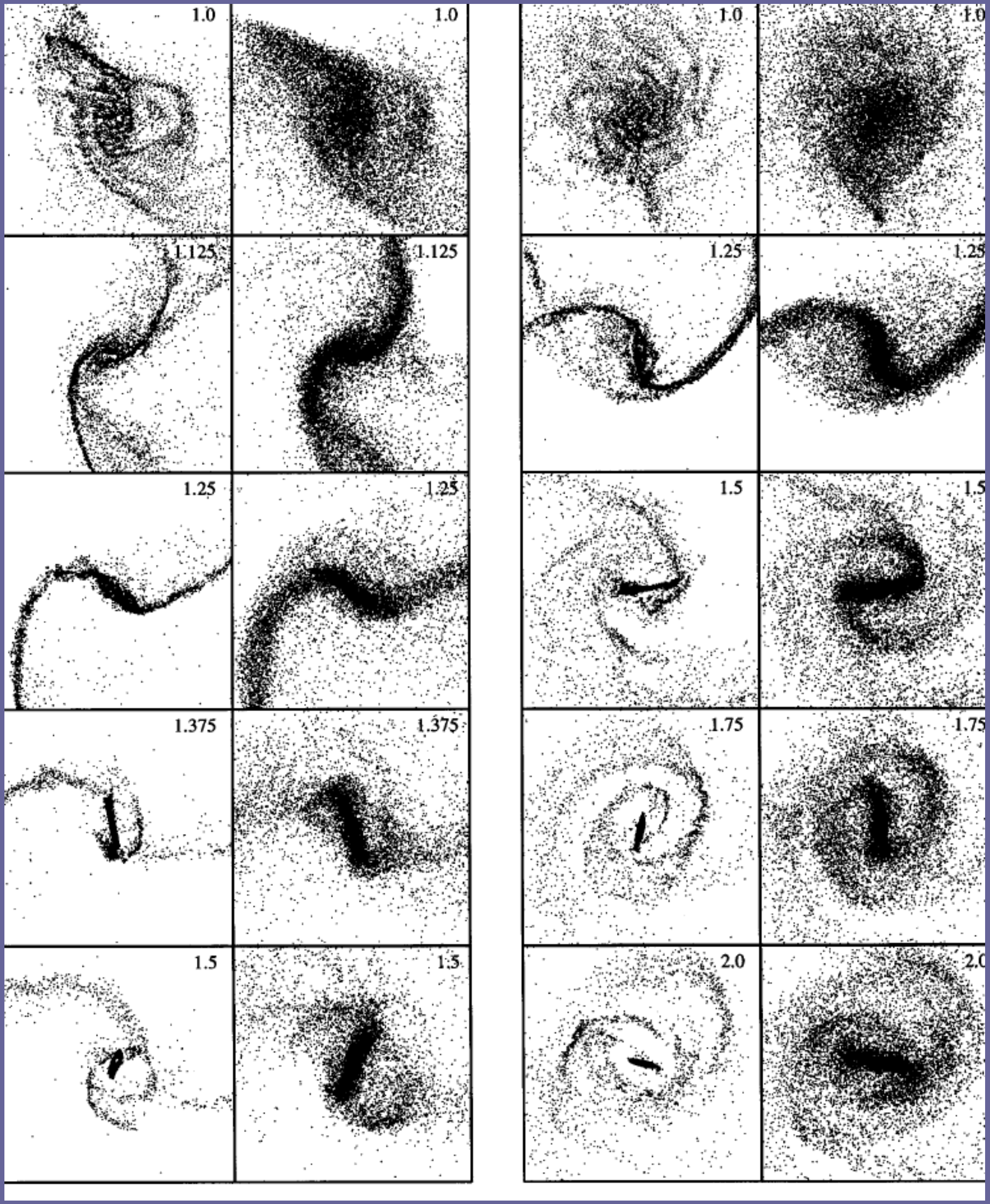
Gas distribution



← 10kpc →

[t]=250 Myr

Misaligned bars



Torques on the gas:

- *Until 1st passage: direct gravity of the other galaxy: gas spin transferred to orbit*
- *After 1st passage: phase difference between gaseous and stellar bars, gas spin transferred to stellar disk*

SMBH binaries with gas disks should be common

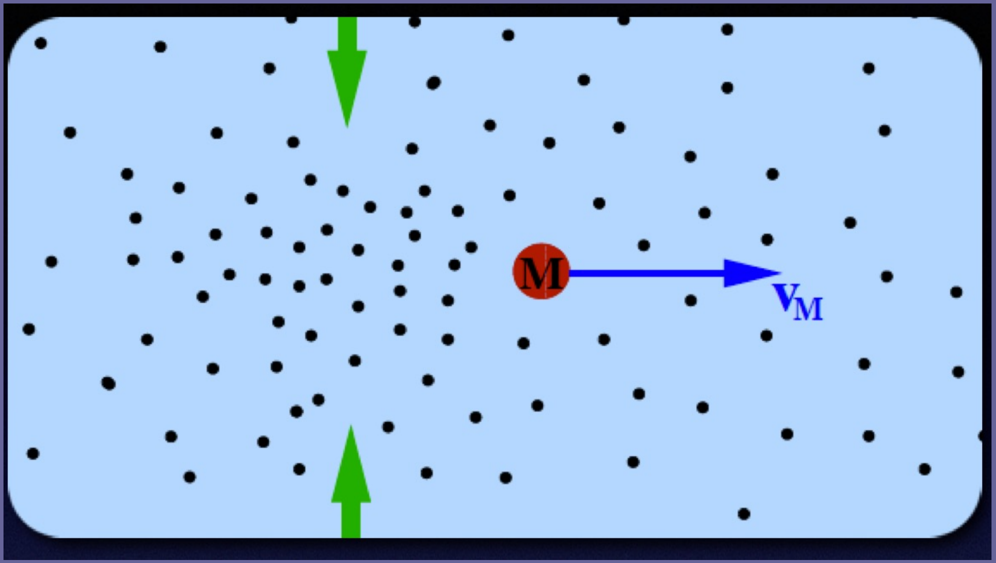
1. **Most galaxies contain SMBHs**
   - SMBH mass 10^{6}-$10^{10}\,M_{\odot}$ correlates with host galaxy (~0.1%)

2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

3. **Most galaxies contain gas**
   - $M_{bh} \lesssim 10^{7.5}\,M_{\odot}$ SMBHs are in gas-rich disk galaxies
   - $M_{bh} \gtrsim 10^{7.5}\,M_{\odot}$ SMBHs are in "dry" ellipticals, but still with gas

4. **Both SMBHs and gas are driven rapidly to nucleus (< kpc)**
   - gas torqued by merger (misaligned stellar vs. gaseous bars)
   - SMBHs by dynamical friction on stars and dark matter

Dynamical friction



(Frank van den Bosch, Yale Univ)

**Chandrasekhar formula:
(1943)**

$$\frac{d\mathbf{v}_M}{dt} = -16\pi^2 \ln\Lambda G^2 m(M+m)\frac{1}{v_M^3}\int_0^{v_M} v^2 f(v)dv\,\mathbf{v}_M$$

$$\frac{d\mathbf{v}_M}{dt} = -\frac{4\pi\ln(\Lambda)G^2\rho M}{v_M^3}\left[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}e^{-X^2}\right]\mathbf{v}_M$$

$$F_{dyn} \approx C\frac{G^2M^2\rho}{v_M^2}$$

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**
   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

3. **Most galaxies contain gas**
   - $M_{bh} \lesssim 10^{7.5}$ $M_\odot$ SMBHs are in gas-rich disk galaxies
   - $M_{bh} \gtrsim 10^{7.5}$ $M_\odot$ SMBHs are in "dry" ellipticals, but still with gas

4. **Both SMBHs and gas are driven rapidly to nucleus (< kpc)**
   - gas torqued by merger (misaligned stellar vs. gaseous bars)
   - SMBHs by dynamical friction on stars and dark matter

SMBH binaries with gas disks should be common

1. **Most galaxies contain SMBHs**
   - SMBH mass 10^6-10^{10} $M_\odot$ correlates with host galaxy (~0.1%)

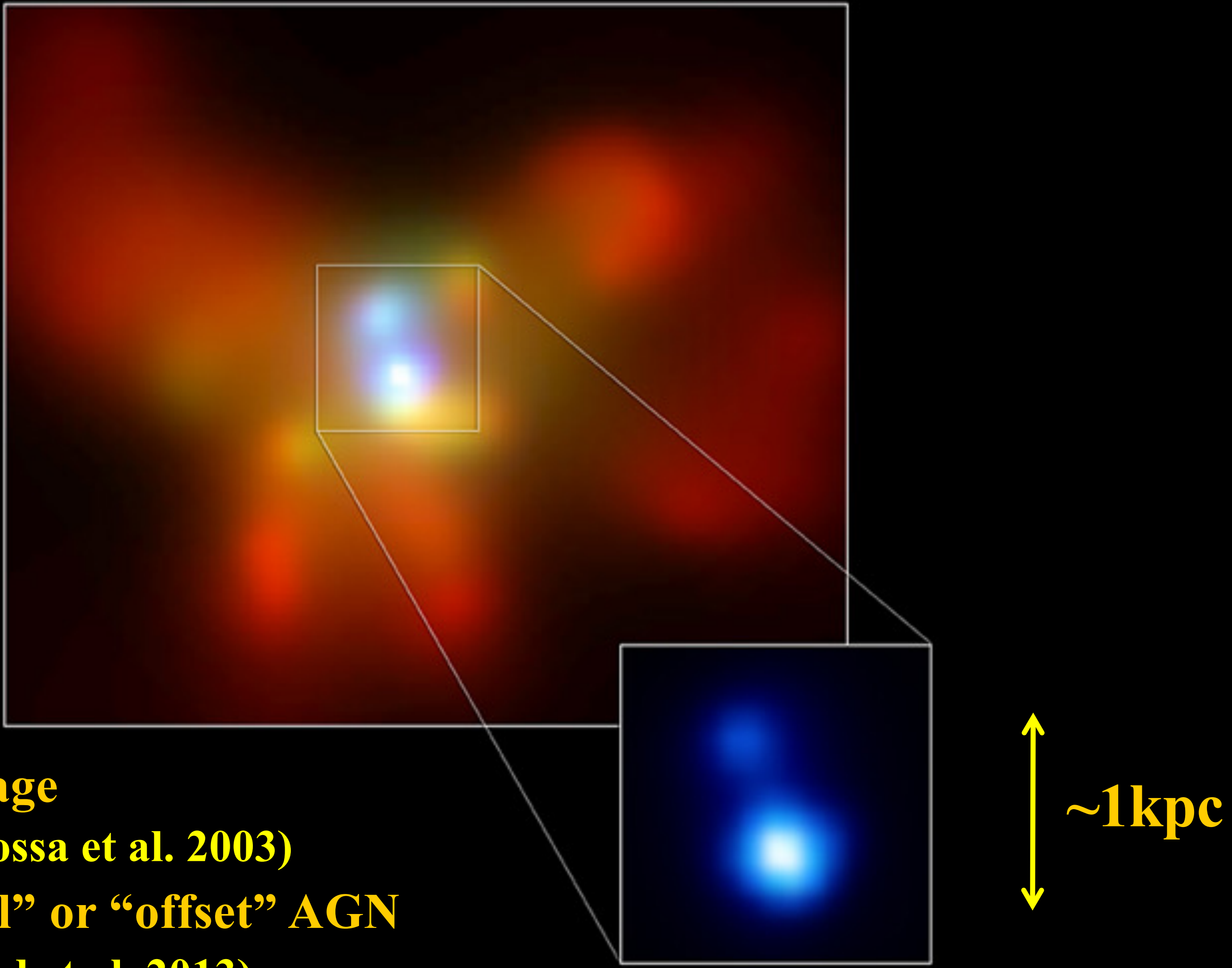
2. **Galaxies experience several mergers**
   - typically several major mergers per Hubble time

3. **Most galaxies contain gas**
   - $M_{bh} \lesssim 10^{7.5}$ $M_\odot$ SMBHs are in gas-rich disk galaxies
   - $M_{bh} \gtrsim 10^{7.5}$ $M_\odot$ SMBHs are in “dry” ellipticals, but still with gas

4. **Both SMBHs and gas are driven rapidly to nucleus (< kpc)**
   - gas torqued by merger (misaligned stellar vs. gaseous bars)
   - SMBHs by dynamical friction on stars and dark matter

→ common outcome: pair of SMBHs with circumbinary gas disk

Active BH pairs in galactic nuclei



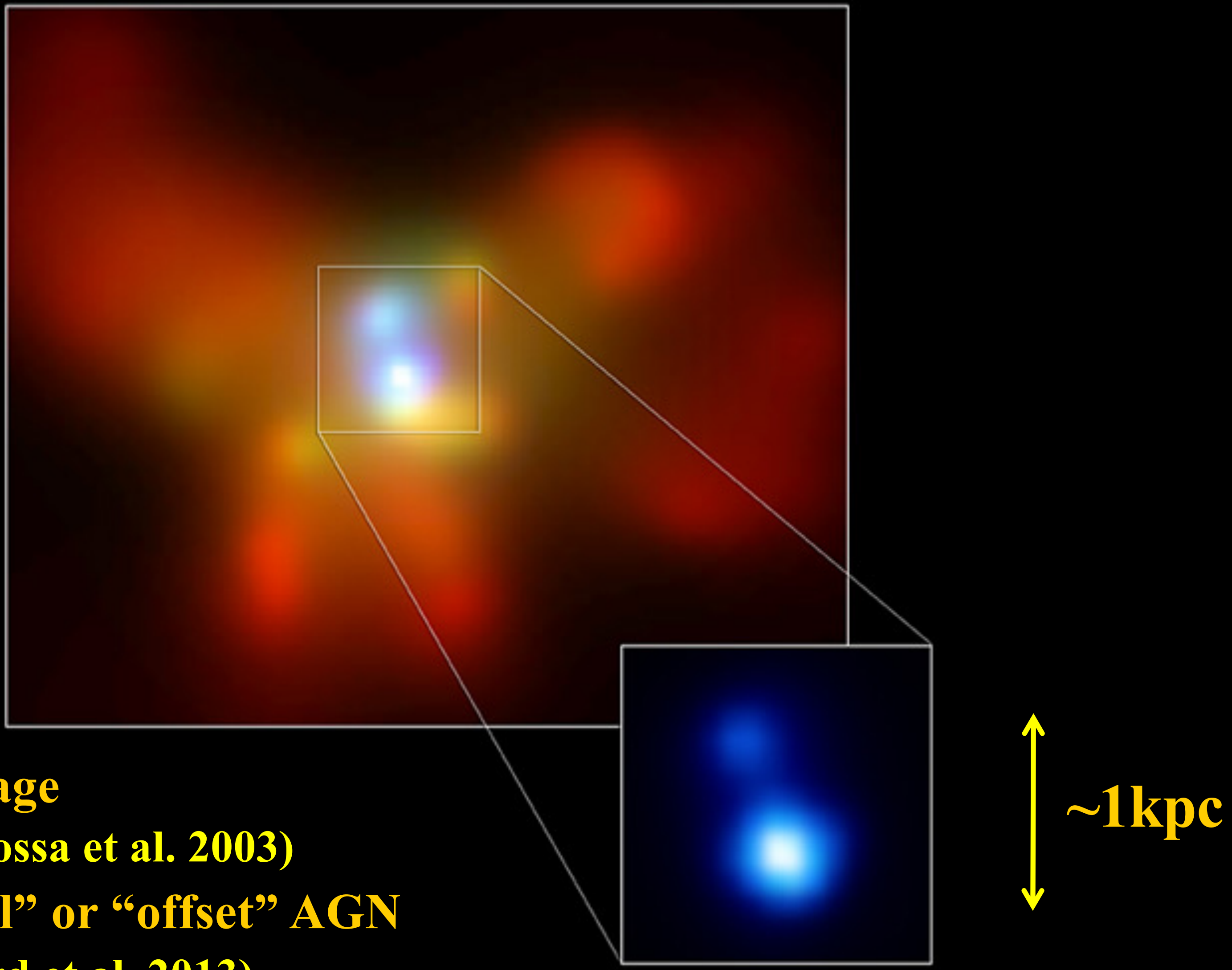
- Chandra X-ray image of NGC 6240 (Komossa et al. 2003)
- Many ~10kpc “dual” or “offset” AGN in optical (Comerford et al. 2013)
- 7.3pc double AGN in radio galaxy 0402+379 by VLBA (Rodriguez et al. 2006)

Active BH pairs in galactic nuclei

cf. sphere of influence:

$$r = GM/\sigma^2$$

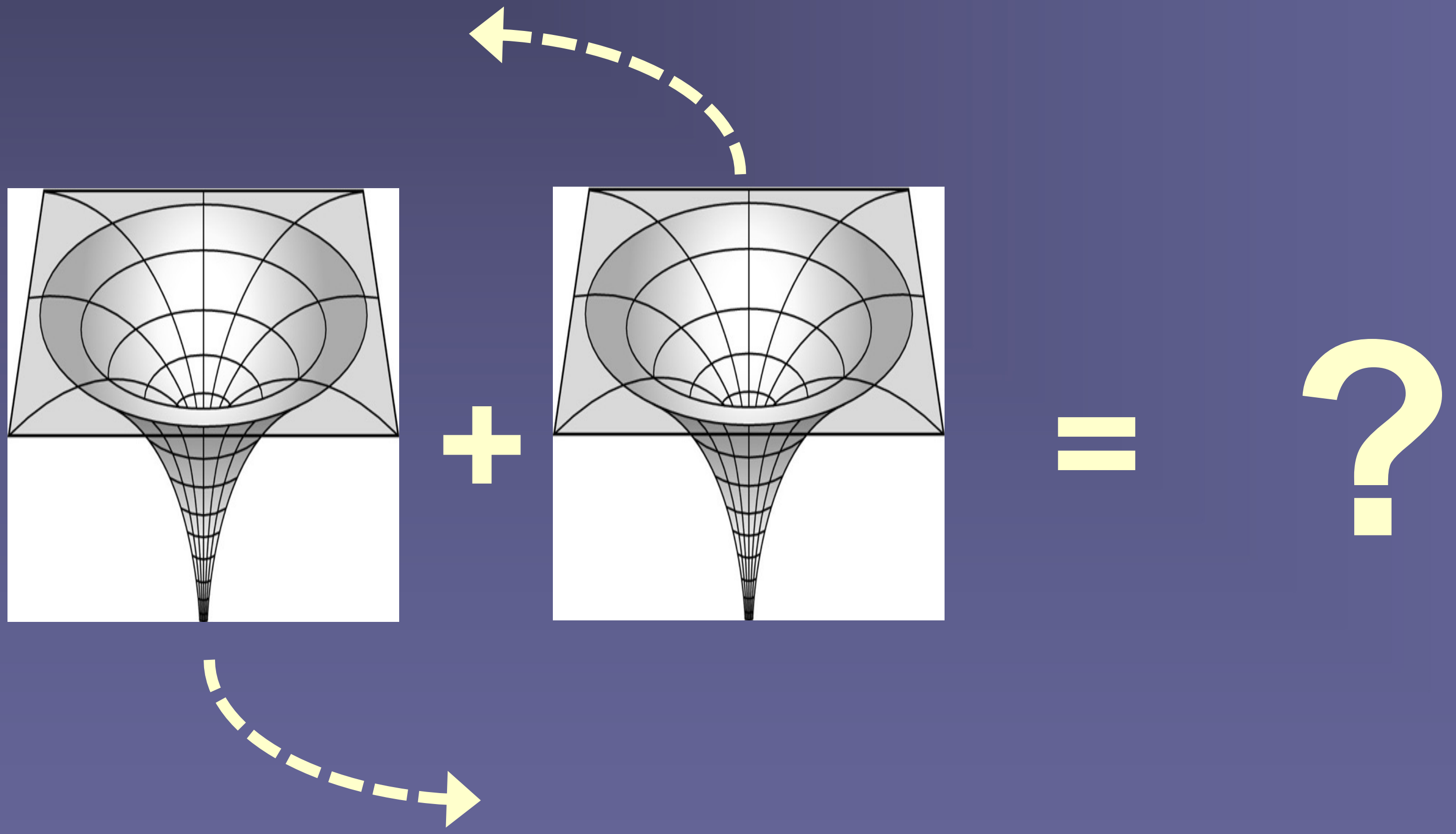
$$= \mathbf{10pc}\ M_8 \sigma_{200}^{-2}$$



- **Chandra X-ray image of NGC 6240 (Komossa et al. 2003)**
- **Many ~10kpc “dual” or “offset” AGN in optical (Comerford et al. 2013)**
- **7.3pc double AGN in radio galaxy 0402+379 by VLBA (Rodriguez et al. 2006)**

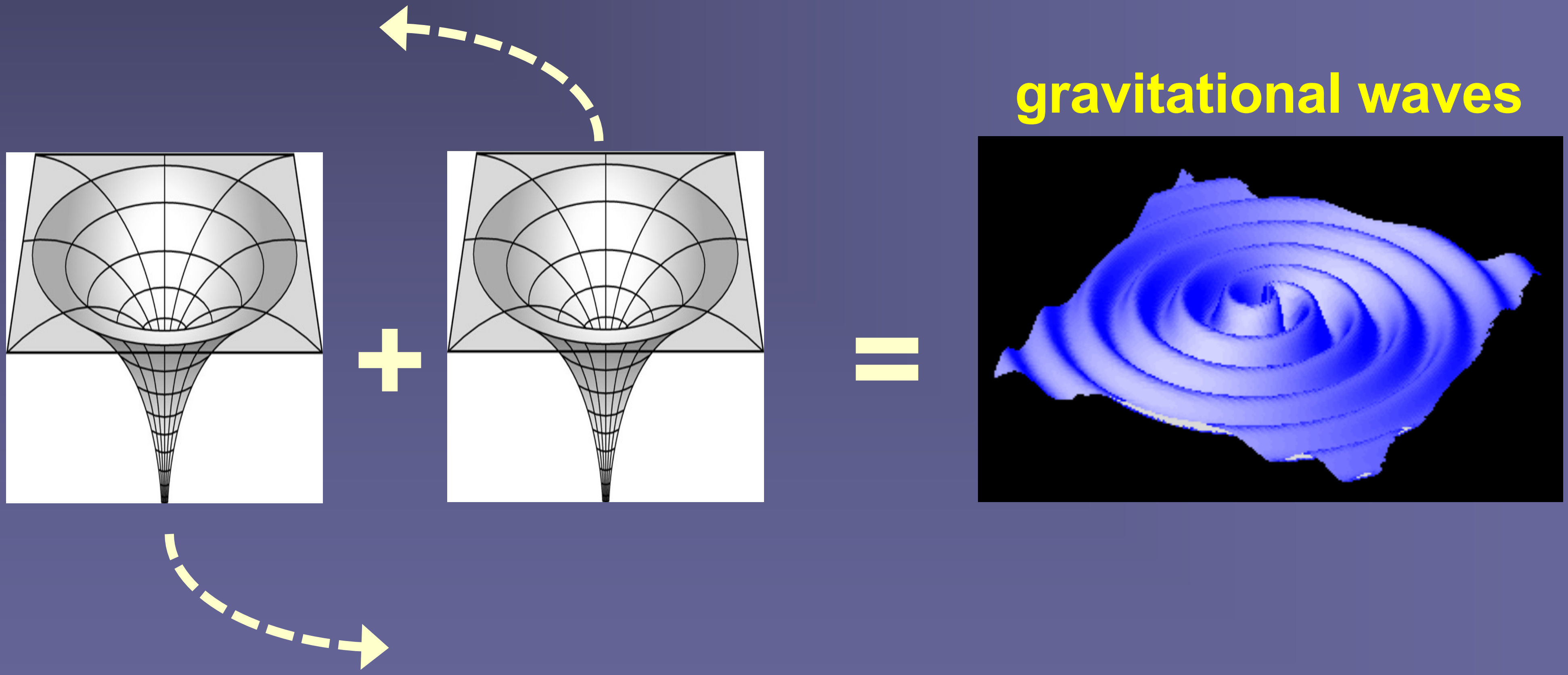
But… do BHs actually merge?

unclear w/out gas/stars – binary may stall



But… do BHs actually merge?

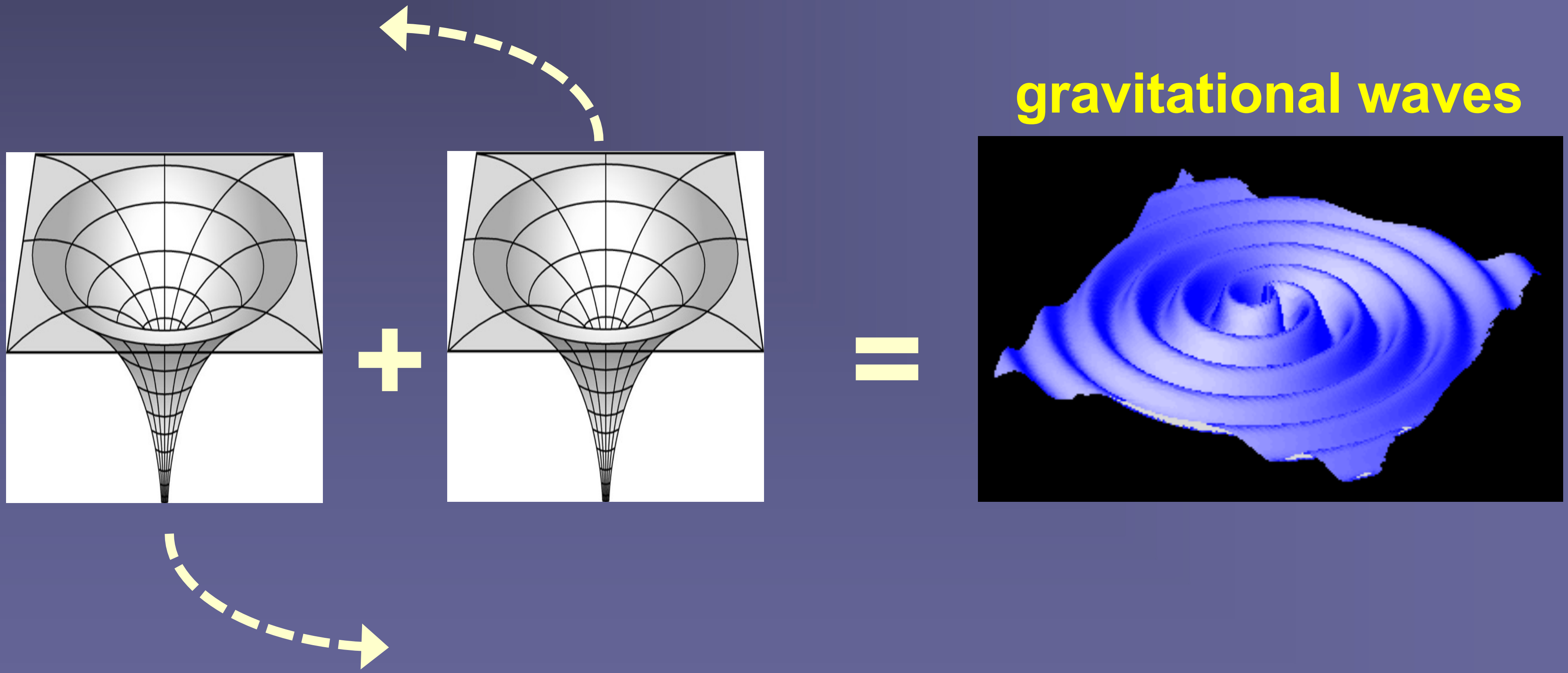
unclear w/out gas/stars – binary may stall



gravitational waves

But… do BHs actually merge?

unclear w/out gas/stars – binary may stall

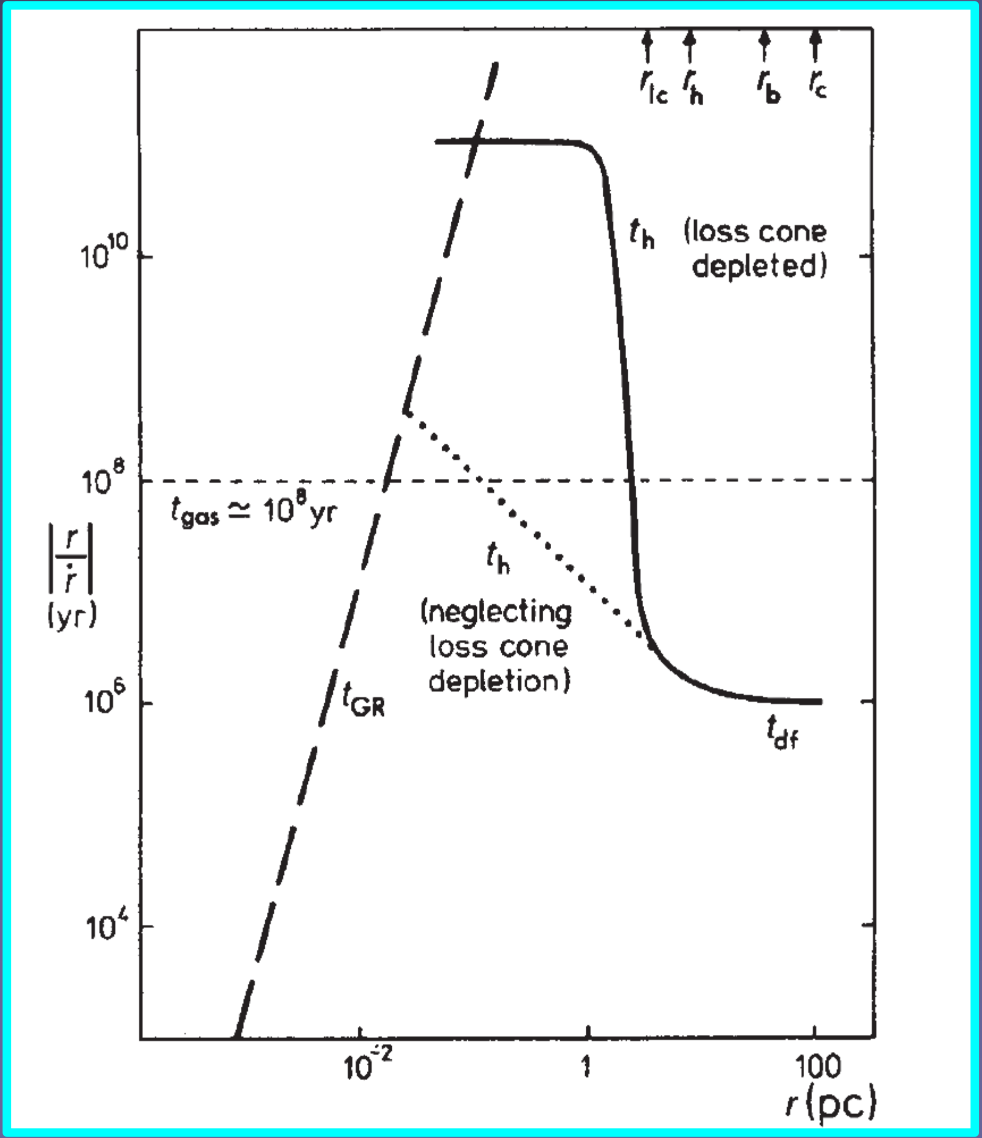


gravitational waves

Gravitational inspiral takes a Hubble time (10^{10} yr)
starting from a separation of ~10^{-3}pc ($M=10^{6}\,M_{\odot}$) or ~1 pc ($M=10^{10}\,M_{\odot}$)

The final parsec “problem”

Begelman, Blandford, Rees (1980)



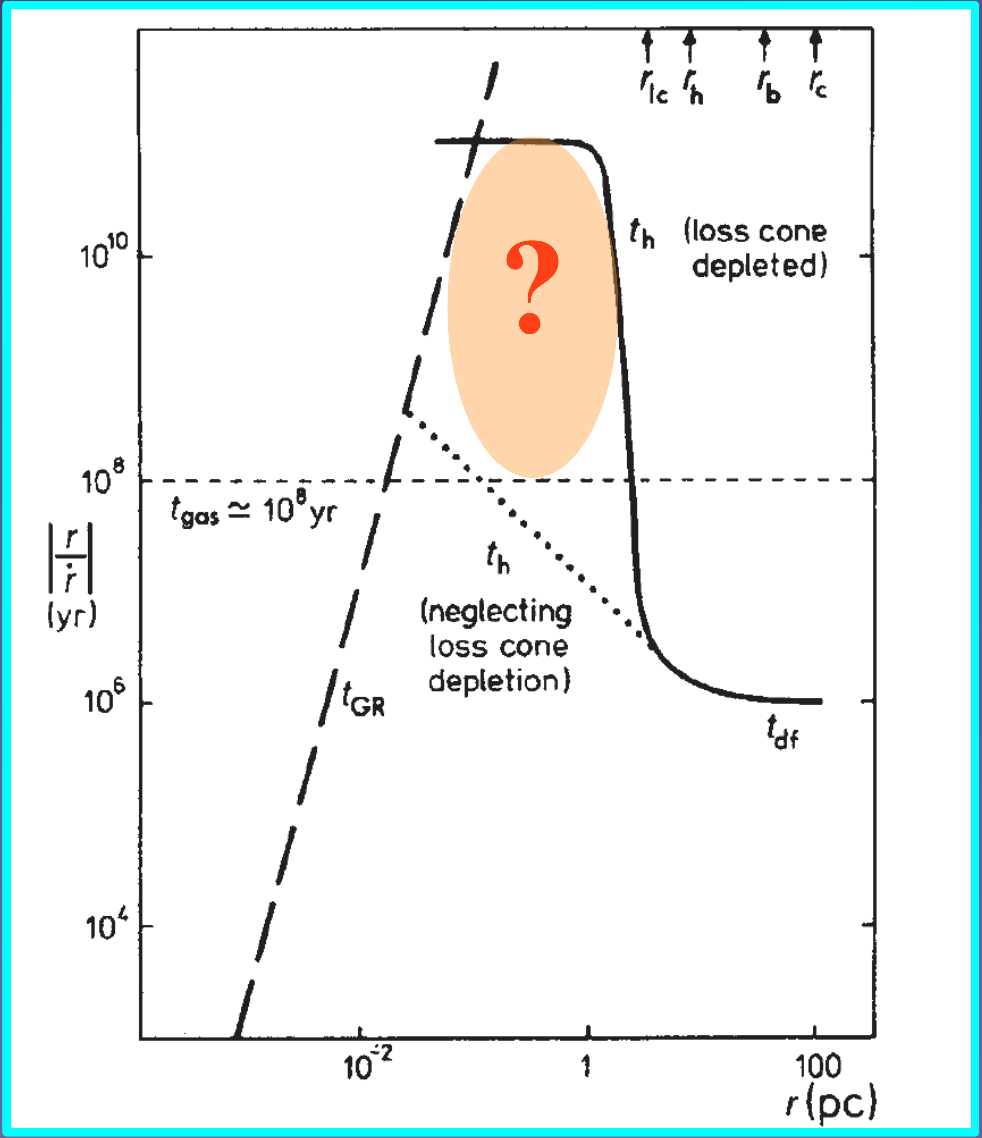
Illustrative example:

$M_1=10^8\ M_\odot$
$M_2=3\times10^7\ M_\odot$
$N_*=2\times10^9$
$m_*=1\ M_\odot$
$\sigma_*=300$ km/s
$r_c=100$ pc

→ **“Final parsec problem”**

The final parsec "problem"

Begelman, Blandford, Rees (1980)



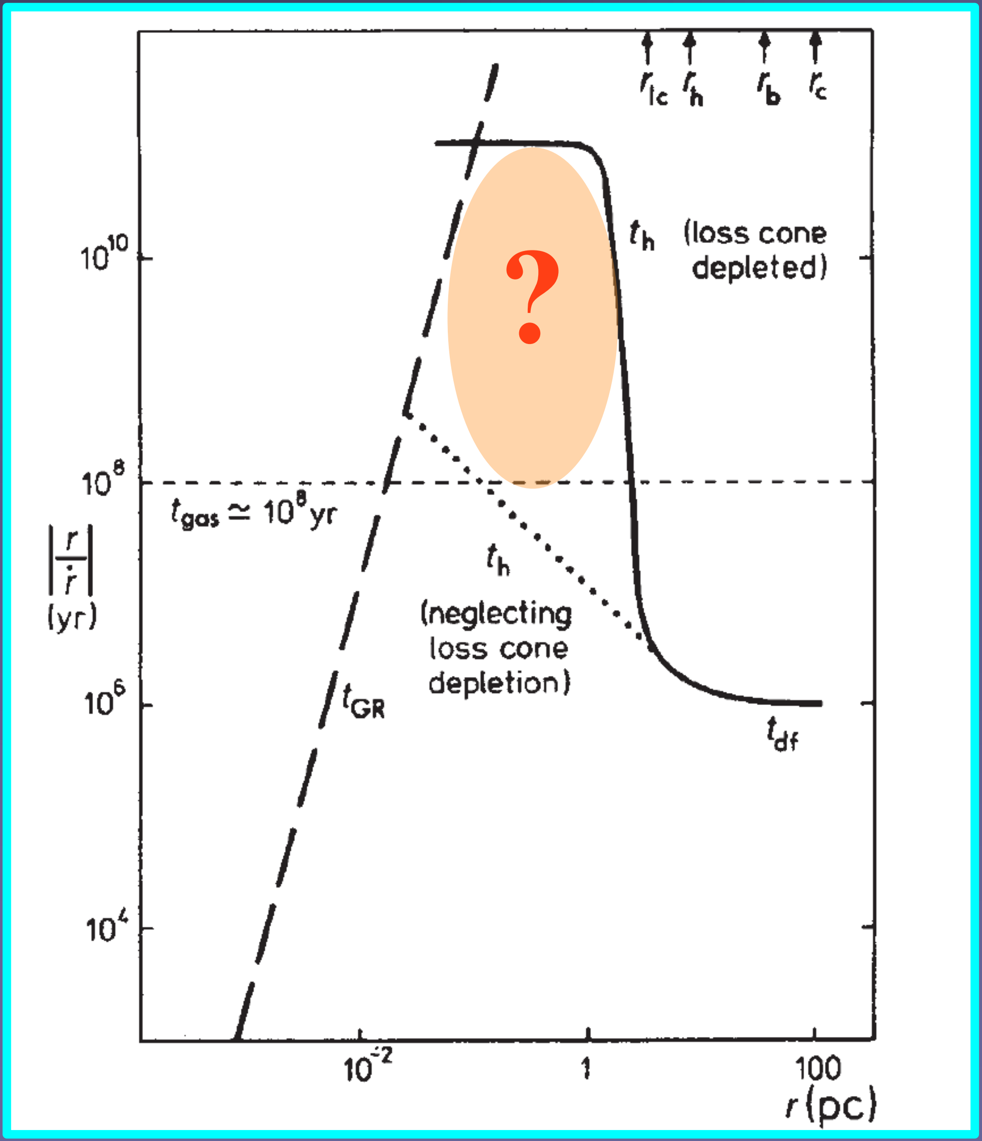
Illustrative example:

$M_1=10^8\ M_\odot$
$M_2=3\times10^7\ M_\odot$
$N_*=2\times10^9$
$m_*=1\ M_\odot$
$\sigma_*=300$ km/s
$r_c=100$ pc

→ **"Final parsec problem"**

The final parsec “problem”

Begelman, Blandford, Rees (1980)



Illustrative example:

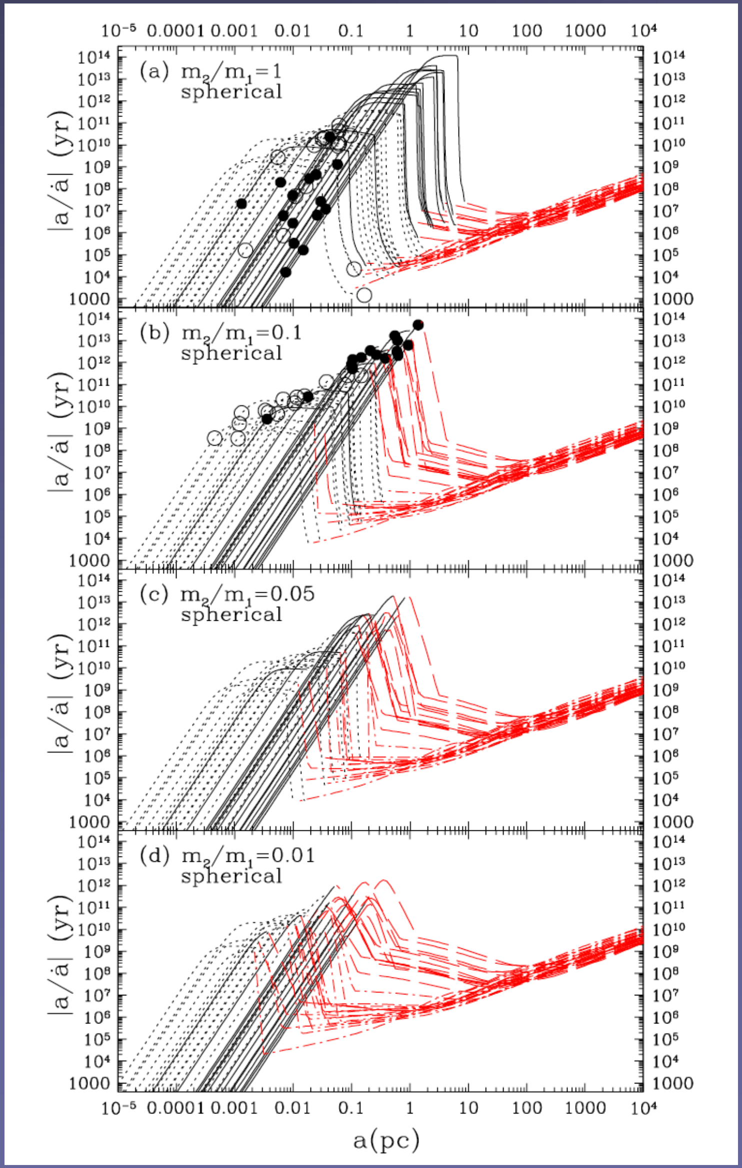
$M_1=10^8\ M_\odot$
$M_2=3\times10^7\ M_\odot$
$N_*=2\times10^9$
$m_*=1\ M_\odot$
$\sigma_*=300$ km/s
$r_c=100$ pc

→ **“Final parsec problem”**

1. **Efficiently scatter stars into loss cone (→ asymmetry)**
2. **Lose angular momentum to circumbinary gas**

Impact of stars

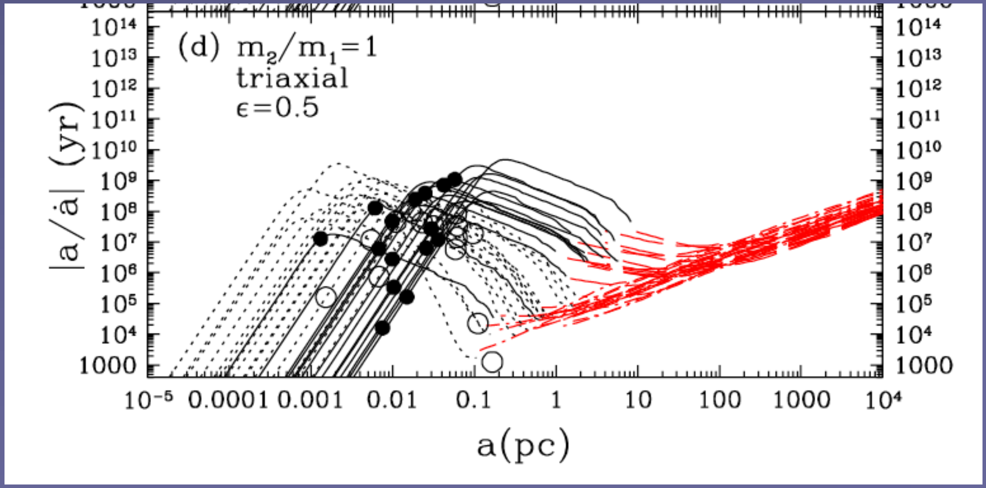
Yu (2002)



Timescales based on measured stellar profiles in (cored vs cusped) ellipticals and M_{bh}-σ_{host} relation.

-- mass ratio

-- anisotropic stellar orbits

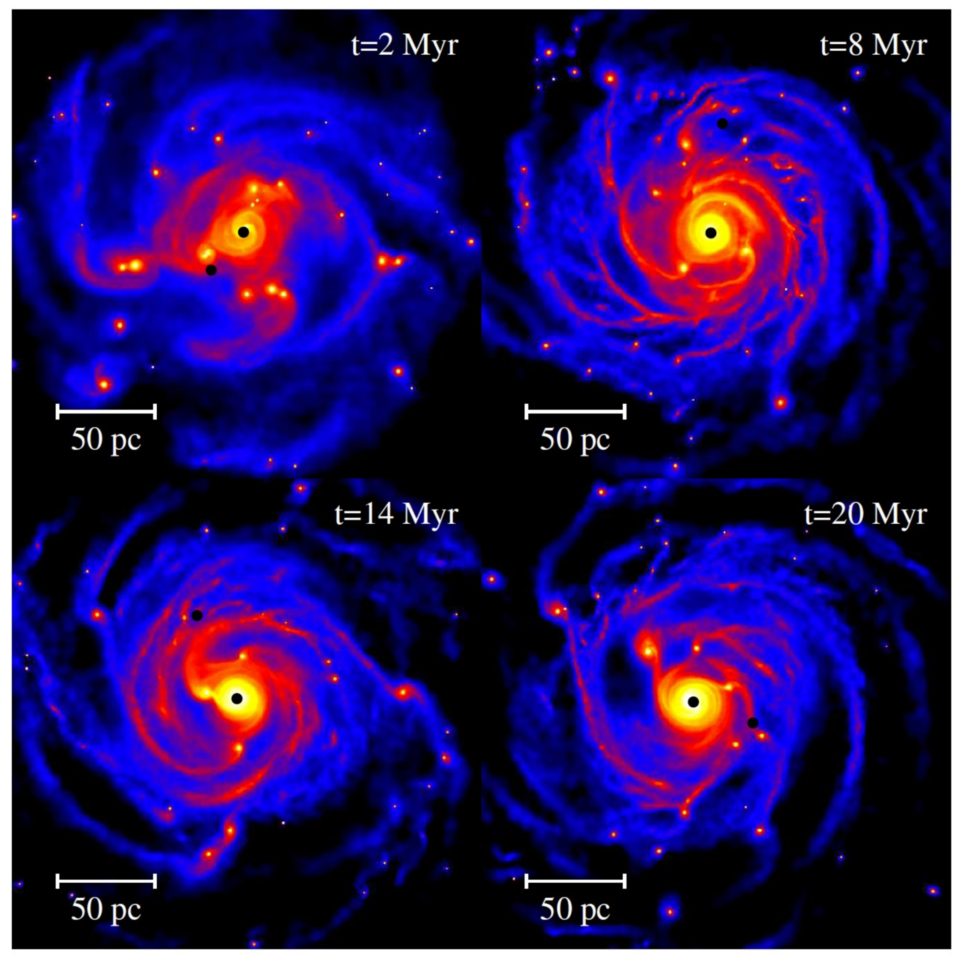


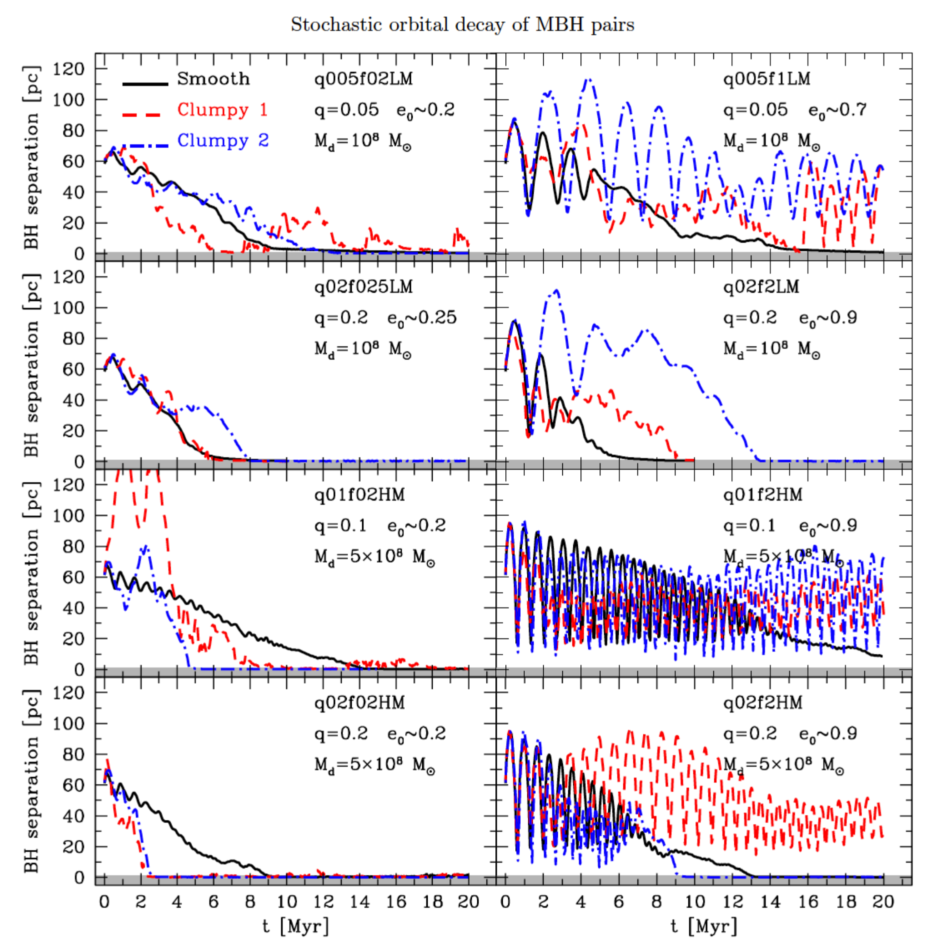
Lot of work in last few years (N-body)

Orbital evolution in clumpy disks

SPH simulations

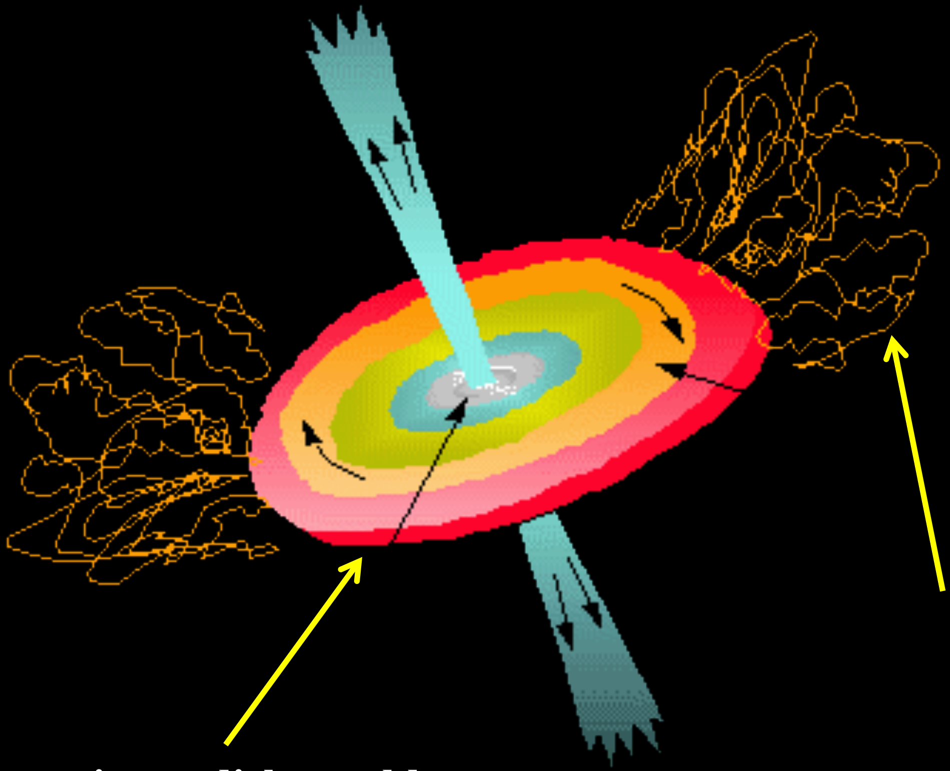
Fiacconi et al. (2013)





Impact of gas: nuclear accretion disk

Gas cools and forms a compact (~ pc) nuclear accretion disk



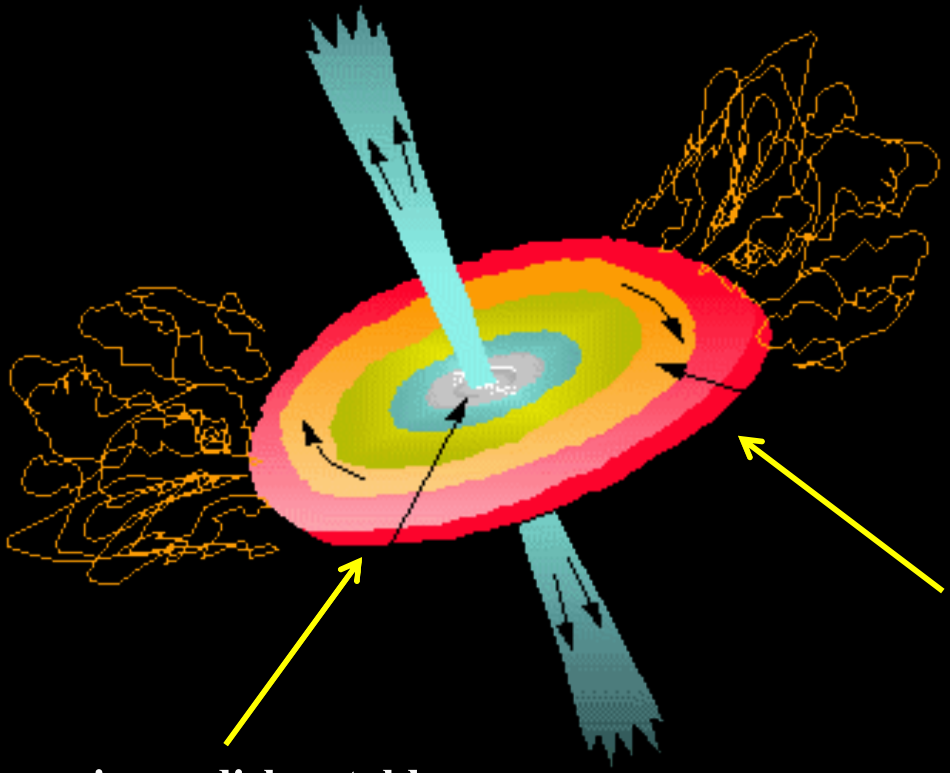
inner disk: stable,
geometrically thin,
optically thick,
$M_{disk} \ll M_{bh}$

Gravitationally
unstable region
Q(Toomre) < 1
Orbital decay of BHs
by scattering on clumps

→ What if second black hole is present ? ←

Impact of gas: nuclear accretion disk

Gas cools and forms a compact (~ pc) nuclear accretion disk



Gravitationally stable region Q(Toomre) > 1

inner disk: stable,
geometrically thin,
optically thick,
$M_{disk} \ll M_{bh}$

→ What if second black hole is present ? ←

Hydrodynamics of Binary + Disk system

1. EM signatures: - Is there gas near (~10-100 R_s) of the BHs?
- What is the mode of the accretion?

affects observability through total luminosity, spectral shape, variability

2. Orbital decay: - Do disk torques help or hinder merger ?
- Can BHs merge in a Hubble time?

affects observability through distribution of separations, periods

3. Gravitational waves: *- can we see concurrent EM emission?*
- can waveforms be modified by gas?

Modeling orbital evolution: techniques

0,   1,   2,   or   3D

Modeling orbital evolution: techniques

0D

- Use azimuthally averaged tidal torques (with local dissipation)

- Assume steady state or self-similarity.

- Useful to predict basic features and parameter-scalings

- examples -

- Milosavljevic & Phinney (2005)

central cavity, post-merger evolution

- Ivanov et al. (1999), Rafikov (2012)

self-similar solutions with "pile-up"

- Kocsis, Yunes et al. (2012), Barausse et al. (2013)

impact of gas on GW signal

- Liu & Shapiro (2010), Kocsis et al. (2012), Rafikov (2016, 2018)

migration with gaps at large radii

Equations for standard accretion disk

- Conservation of mass and angular momentum:

$$0 = 2\pi r\,\partial_t\Sigma + \partial_r(2\pi r\Sigma v_r)\,, \tag{1}$$

$$\partial_r T = 2\pi r\,\partial_t(\Sigma r^2\Omega) + \partial_r(2\pi r v_r \Sigma r^2\Omega)\,, \tag{2}$$

- Total torque T = sum of viscous and tidal torques:

$$T_\nu = -2\pi r^3(\partial_r\Omega)\,\nu\Sigma \simeq 3\pi\, r^2\Omega\,\nu\Sigma\,, \tag{3}$$

$$\partial_r T_\mathrm{d} = 2\pi r\Lambda\Sigma\,. \tag{4}$$

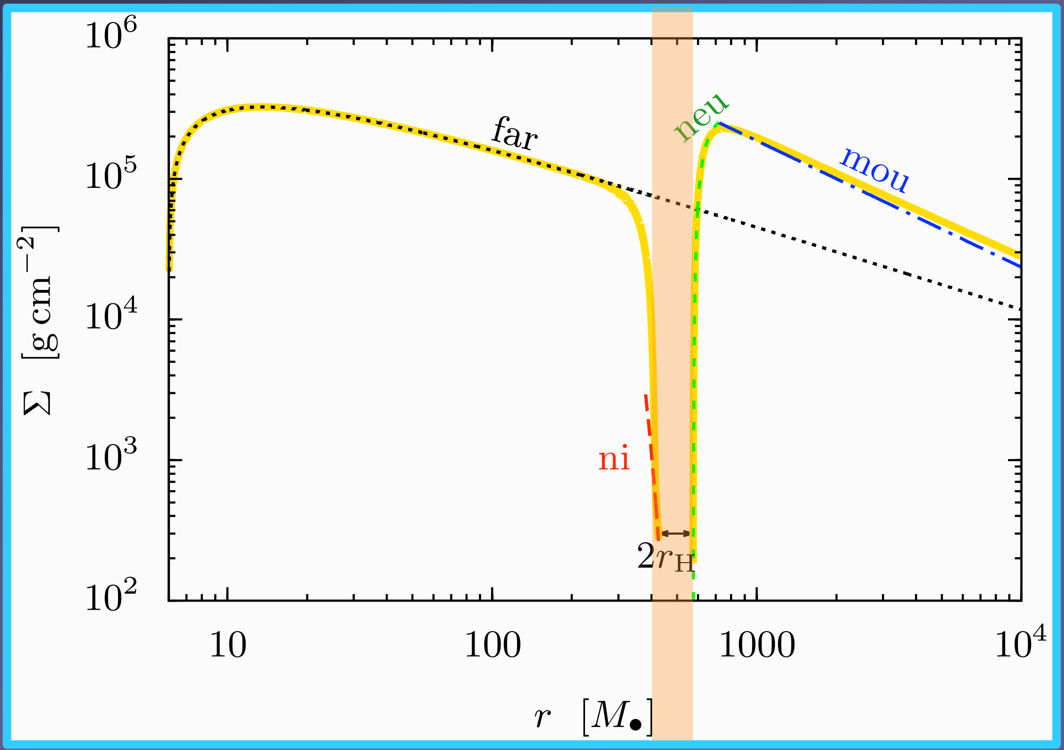
- Orbit- averaged tidal torque:

$$\Lambda \approx \begin{cases} -\frac{1}{2} f q^2 r^2 \Omega^2 r^4/\Delta^4 & \text{if } r < r_\mathrm{s}\,, \\ +\frac{1}{2} f q^2 r^2 \Omega^2 r_\mathrm{s}^4/\Delta^4 & \text{if } r > r_\mathrm{s}\,, \end{cases} \tag{5}$$

where

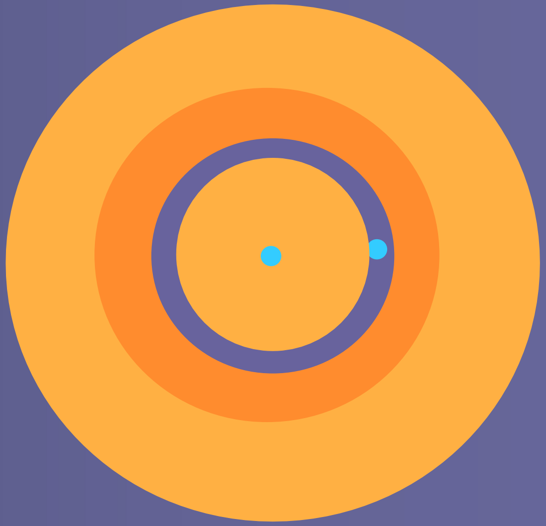
$$\Delta \equiv \max(|r - r_s|, H) \tag{6}$$

Steady-state solutions with "overflow"



Example:

$M=10^5\ M_\odot$ $r_2=500\ R_S$



- **Outer disk:** increased density, temperature, luminosity
- **Inner disk:** unmodified (Shakura-Sunyaev) profile
- **Evolution:** sequence of steady states (?)

NB: "Type 1.5" migration is slower than both Type II and I

Modeling orbital evolution: techniques

1D

- Use azimuthally averaged tidal torques

- Do not assume steady state or self-similarity.

- Still misses important nonaxisymmetric physics

- (surprisingly rare in literature)

- examples -

- Chen et al. (2010)

tidal "squeezing" (2D kills this!)

- Lodato et al. (2009)

evolution with finite mass supply (final pc problem remains)

- Tanaka & Menou (2010), Fontecilla et al. (2019)

cavity-filling, post-merger evolution

Modeling orbital evolution: techniques

2D

- *Resolves nonaxisymmetric physics (high-res. achievable)*
- ***Can follow binary evolution from large radius***
- *Misses vertical structure / 3d overflow, must prescribe viscosity*
- *BHs usually excised until recently, simplified thermodynamics*

- early examples -

- MacFadyen & Milosavljevic (2008); D'Orazio et al. (2013)
Farris et al (2013)

eccentricity growth, accretion rate into cavity

- Armitage & Natarajan (2002, 2005)

orbital decay, eccentricity growth

- Artymowicz & Lubow (1994, 1995)

cavity opening, mass-flow across gaps

Modeling orbital evolution: techniques

3D

- *The "ultimate", but limited # of orbits – hard to follow evolution*
- *Needed for realistic predictions of the last stages (GR)*
- *$10^{5\text{-}6}$ orbits expected (orbital decay is slow) where $M_2 \sim M_{disk}$*
- *cf: typically ~10^4 orbits (2D pure hydro)*

  ~10^2 orbits (3D PN GRMHD)

  ~10^1 orbits (full 3D GRMHD)

- some early examples -

- Hayasaki et al. (2007), Escala et al. (2005), Cuadra et al. (2009), Artymowicz & Lubow (1994, 1995), del Valle & Escala (2013, 2014), Roedig et al. (2012), Shi et al. (2012), …

Newtonian – understanding torques, migration, eccentricity, MRI

- Bode et al. (2011), Giacomazzo et al. (2012), Noble et al. (2012) Farris et al. (2012), Gold et al. (2013) … GR – late stages

2D Hydrodynamical Simulations

D’Orazio+2013, 2016, Farris+2014, 2015ab, Tang+2017, 2018,
Derdzinski+2019,2021, Duffell+2019, Tiede+2020, Zrake+2020

- **moving-mesh** grid hydro codes **DISCO, MARA**
- Solves Navier-Stokes equations of fluid dynamics
- 2D, Pseudo-Newtonian hydrodynamics
- viscosity proportional to pressure (α=0.05-0.3)
- **Cooling** (thermal) + **heating** (viscosity, shocks)
- **BHs are on the grid,** accrete via sink prescription
- Initial condition: steady single-BH disk $0 \leq r \leq 100a_{bin}$

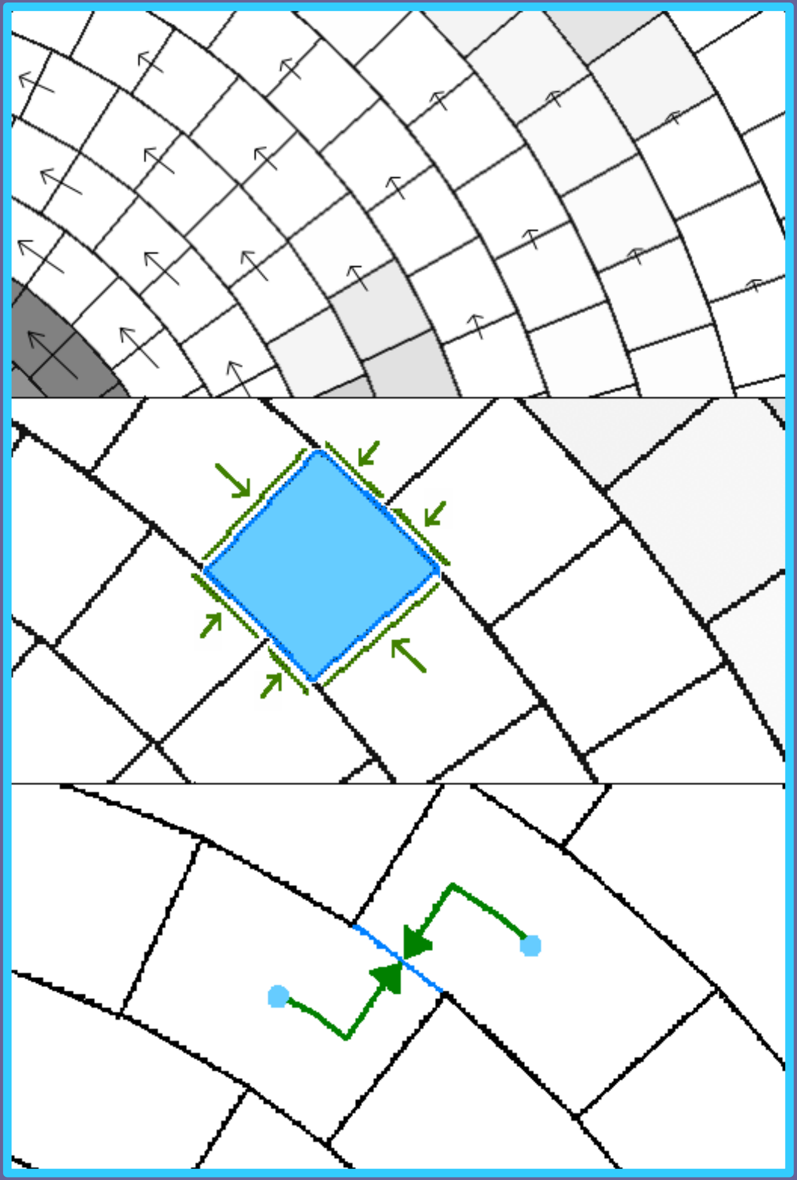
key parameters: binary mass ratio $q=M_2/M_1$, eccentricity e,
disk temperature ⟺ aspect ratio h/r

➔ *run for ~10,000 binary orbits (**>viscous time, steady-state**)*

➔ *study gas morphology, BH fueling rate, torques on binary*

similar results with **Arepo** Munoz+2019 and **Athena** Moody+2019

Moving mesh code DISCO

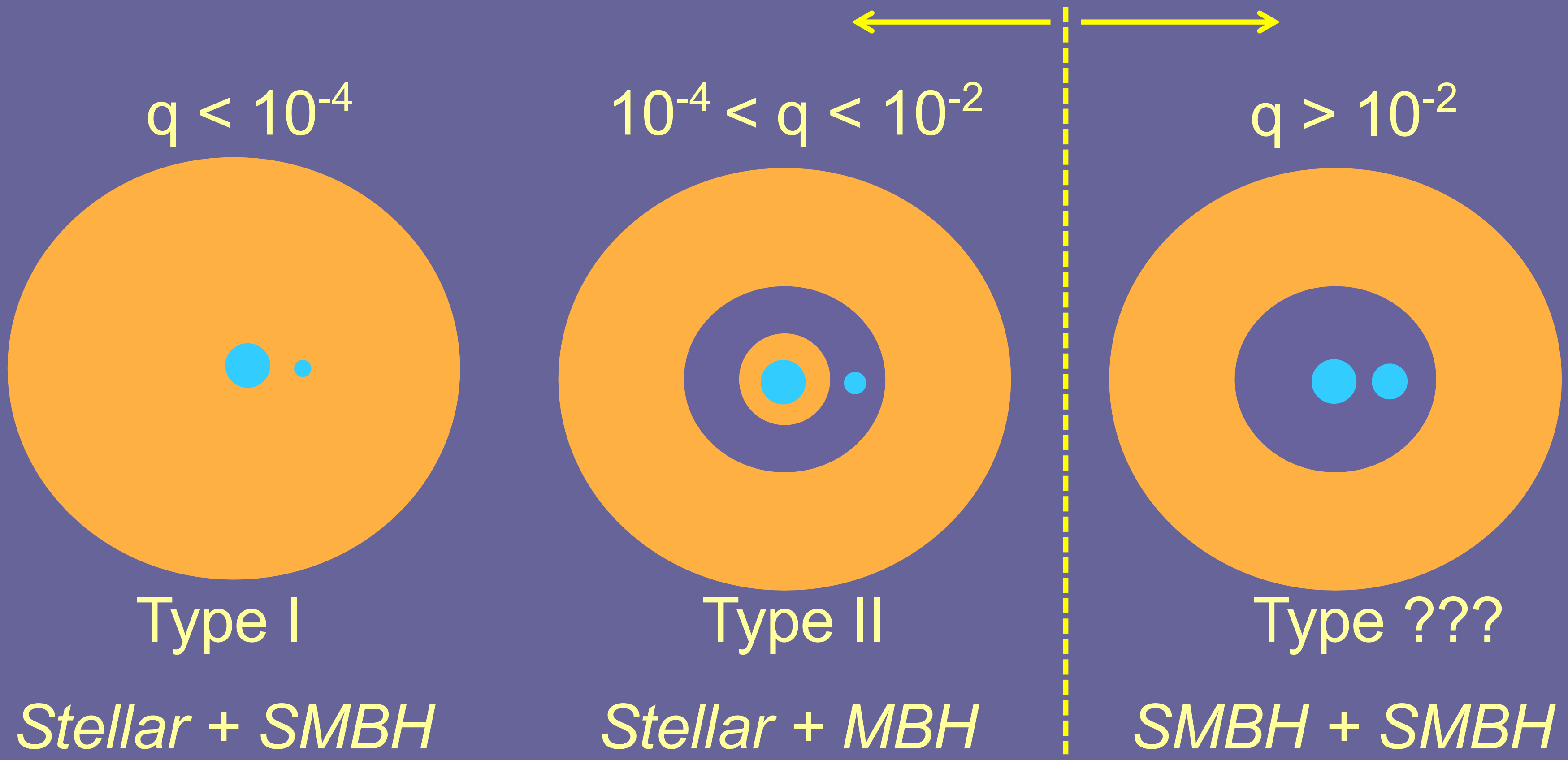


Duffell (2016) – code is public
Duffell & MacFadyen (2012, 2013)

- Solves 2D (magneto-) hydrodynamics equations
- Conservative, shock-capturing, finite volume method
- Effectively Lagrangian, cells move with the fluid
- Small advection errors permit longer time-steps
- α-viscosity assumed

Hydrodynamics of Binary + Disk system

Three regimes based on mass ratio $q=M_1/M_2$



$q < 10^{-4}$

$10^{-4} < q < 10^{-2}$

$q > 10^{-2}$

Type I

Type II

Type ???

Stellar + SMBH

Stellar + MBH
(I)MBH + SMBH

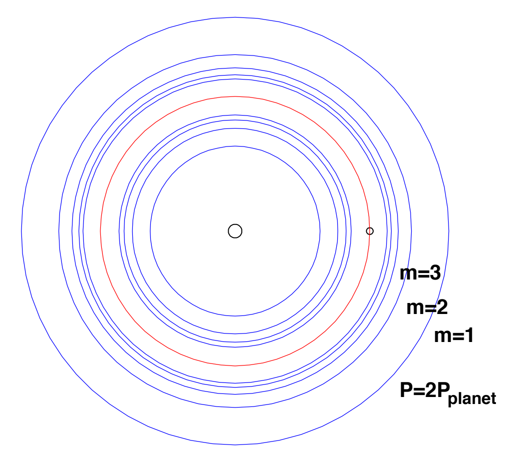
SMBH + SMBH

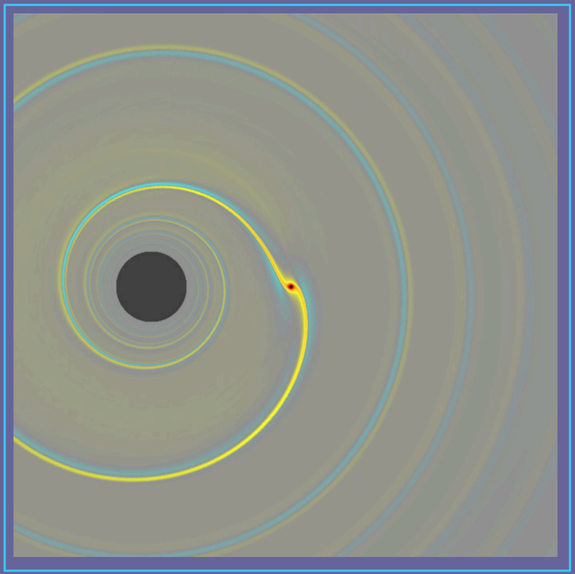
Binary-Disk Interaction (1)

through viscous-tidal ‘planetary’ torques

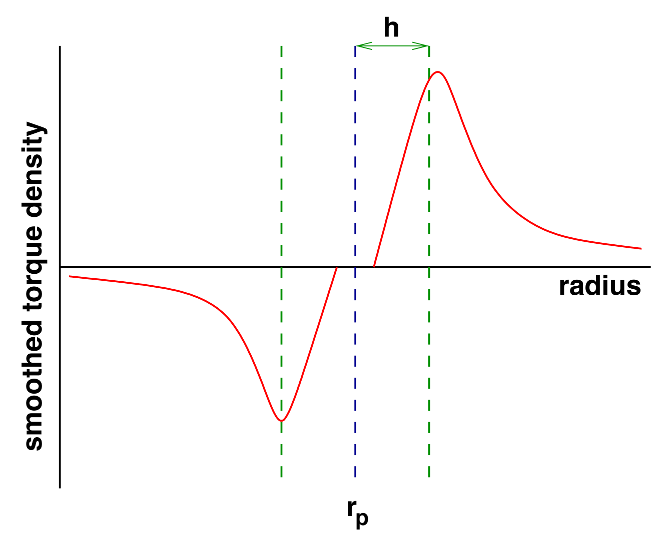
(Goldreich & Tremaine 1980; Ward 1997)

- spiral waves launched at resonances, distortions linear
- secondary migrates relative to disk (“Type I”)
- torque in isothermal disk : $T_0 = r_p^4 \Omega_p^2 \Sigma_0 (M_p/M_*)^2 \mathcal{M}^2.$
- thermodynamics can modify (even reverse) the migration



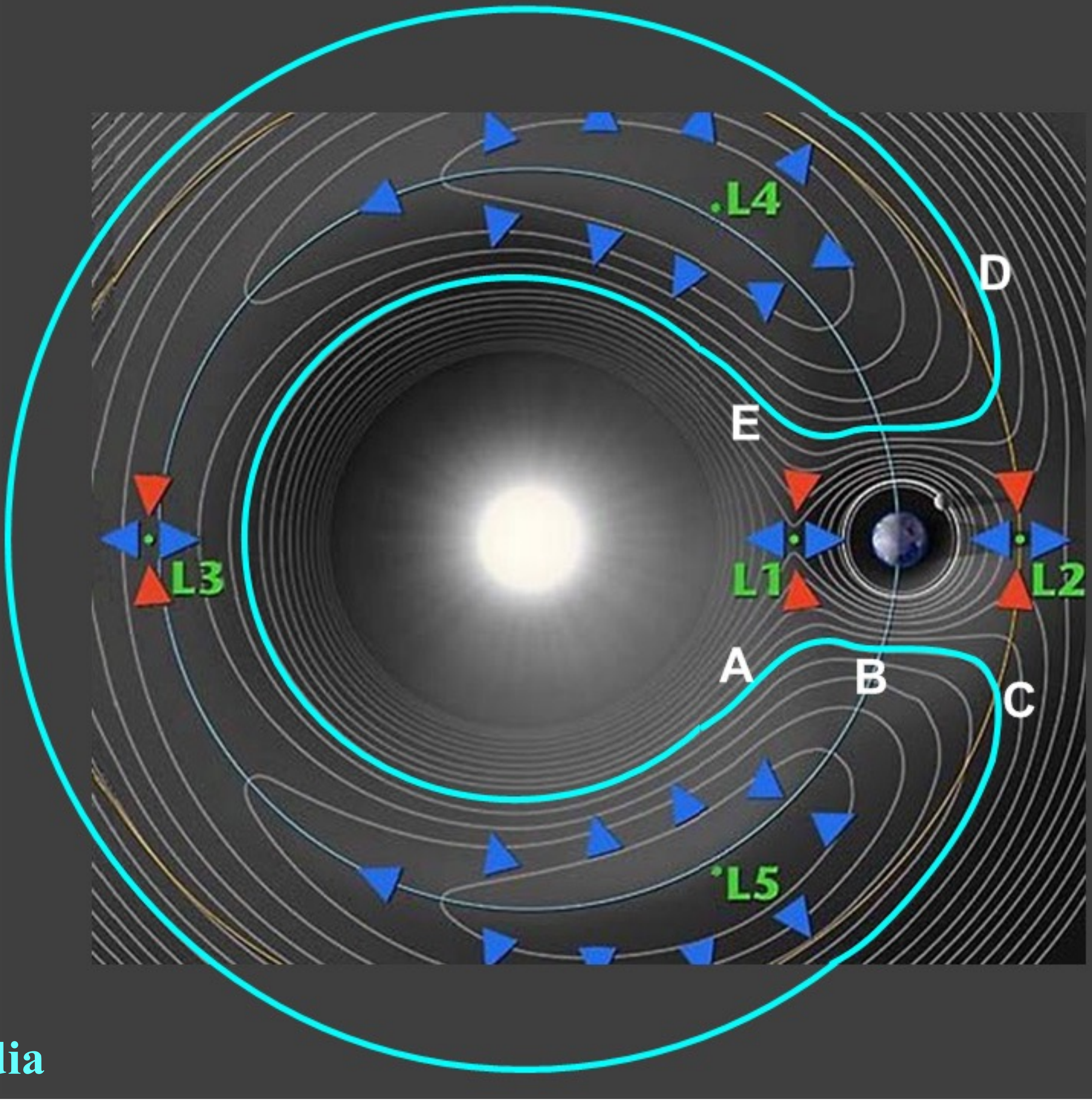


Duffell et al. (2012)



Armitage (2007)

Orbits in Hill annulus



Credit: wikipedia

Binary-disk interaction (2)

- disk strongly distorted, annular gap divides inner/outer disk
- migration on viscous timescale (“Type II”) for q > ~ 10^{-4}

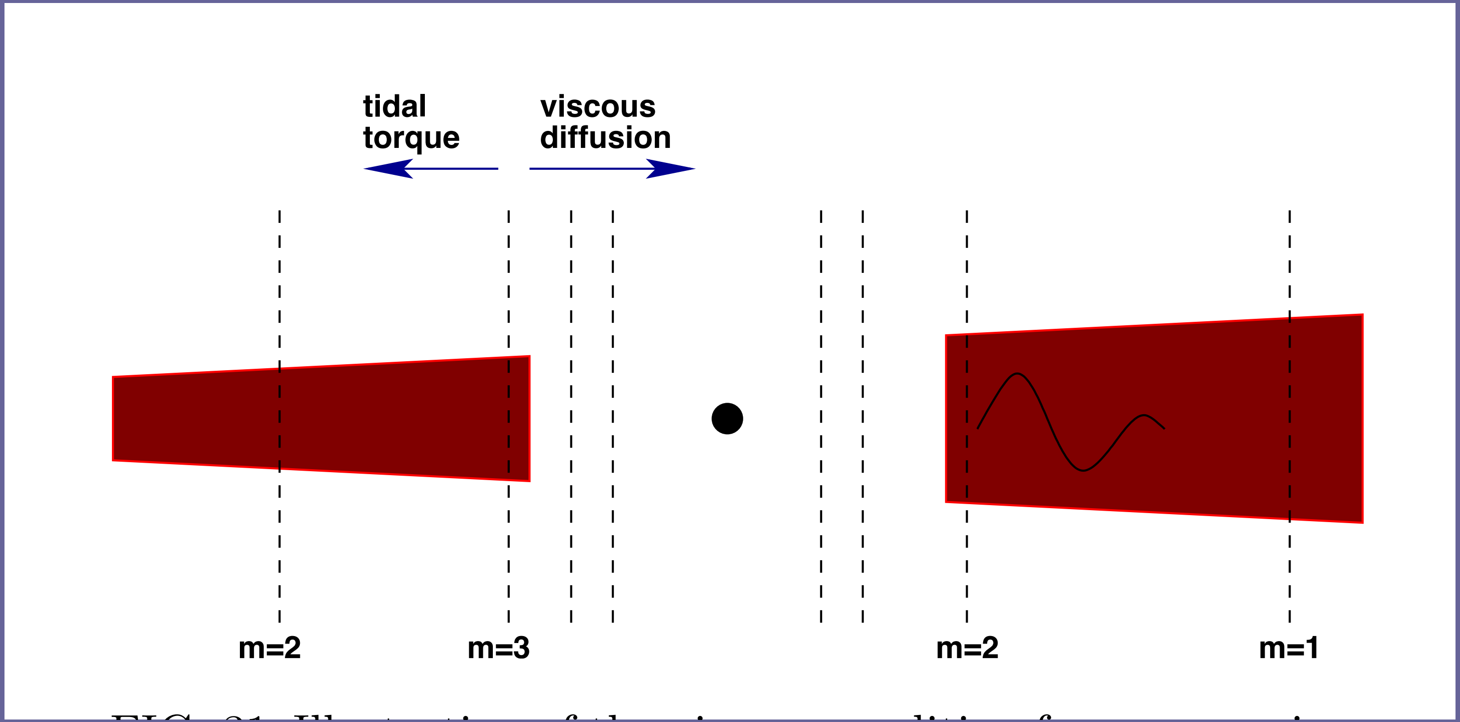
(Ward 1997; Armitage 2007; Crida 2011)

criterion I (thermal)

$$r_H \equiv \left(\frac{M_p}{3M_*}\right)^{1/3} r \gtrsim h$$

criterion II (viscosity)

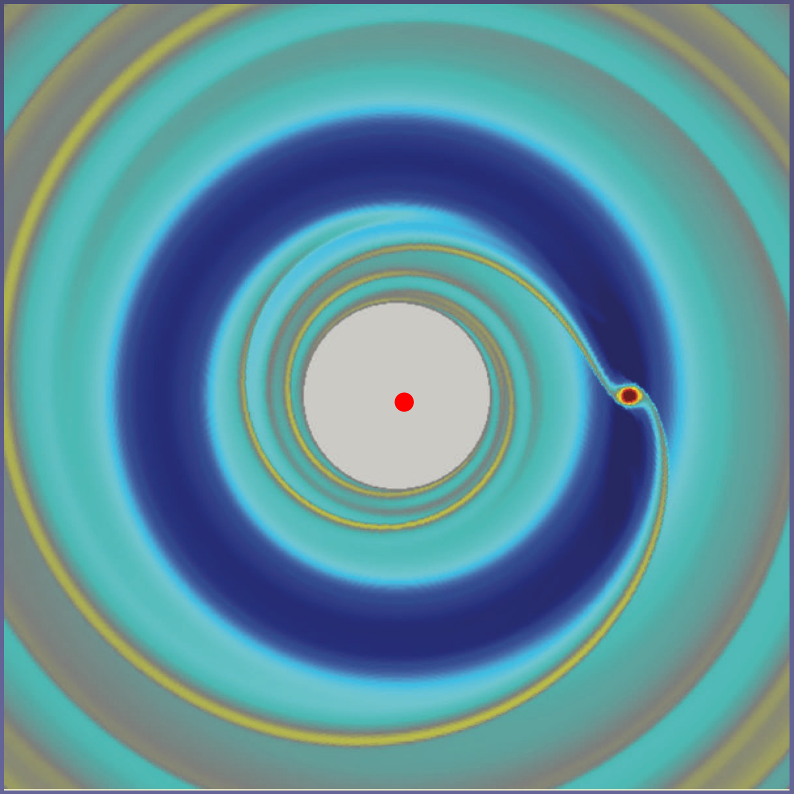
$$q \gtrsim \left(\frac{c_s}{r_p\Omega_p}\right)^2 \alpha^{1/2}.$$



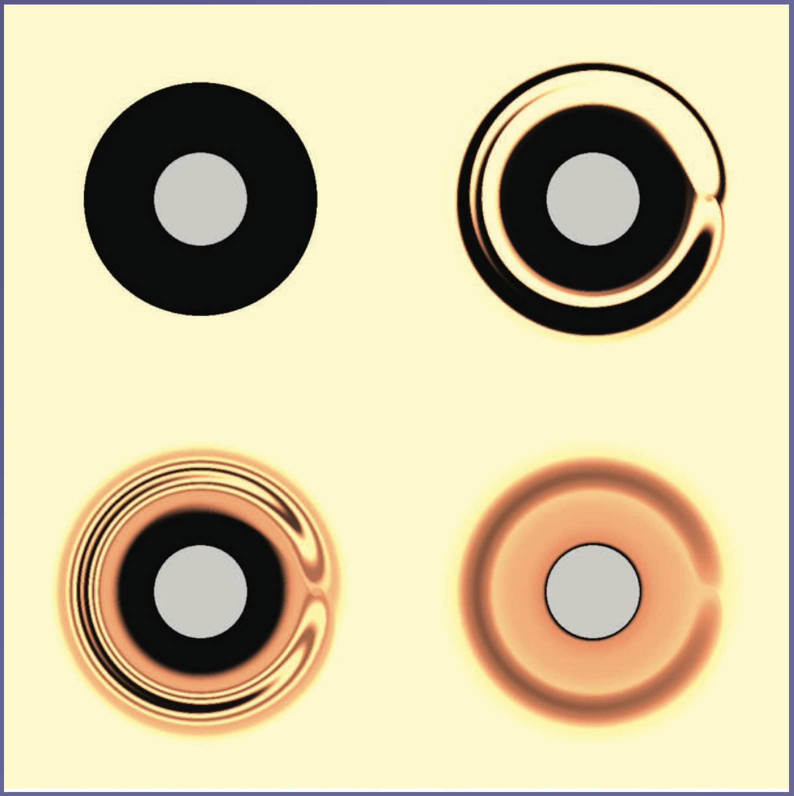
Mass flow across gap unimpeded

Duffell, ZH, MacFadyen, D'Orazio, Farris (2014)

- Solve 2D viscous Navier-Stokes equations w/moving mesh code DISCO
- constant Σ, v, c_s disk (α=0.01) $q = M_2/M_1 = 10^{-3}$



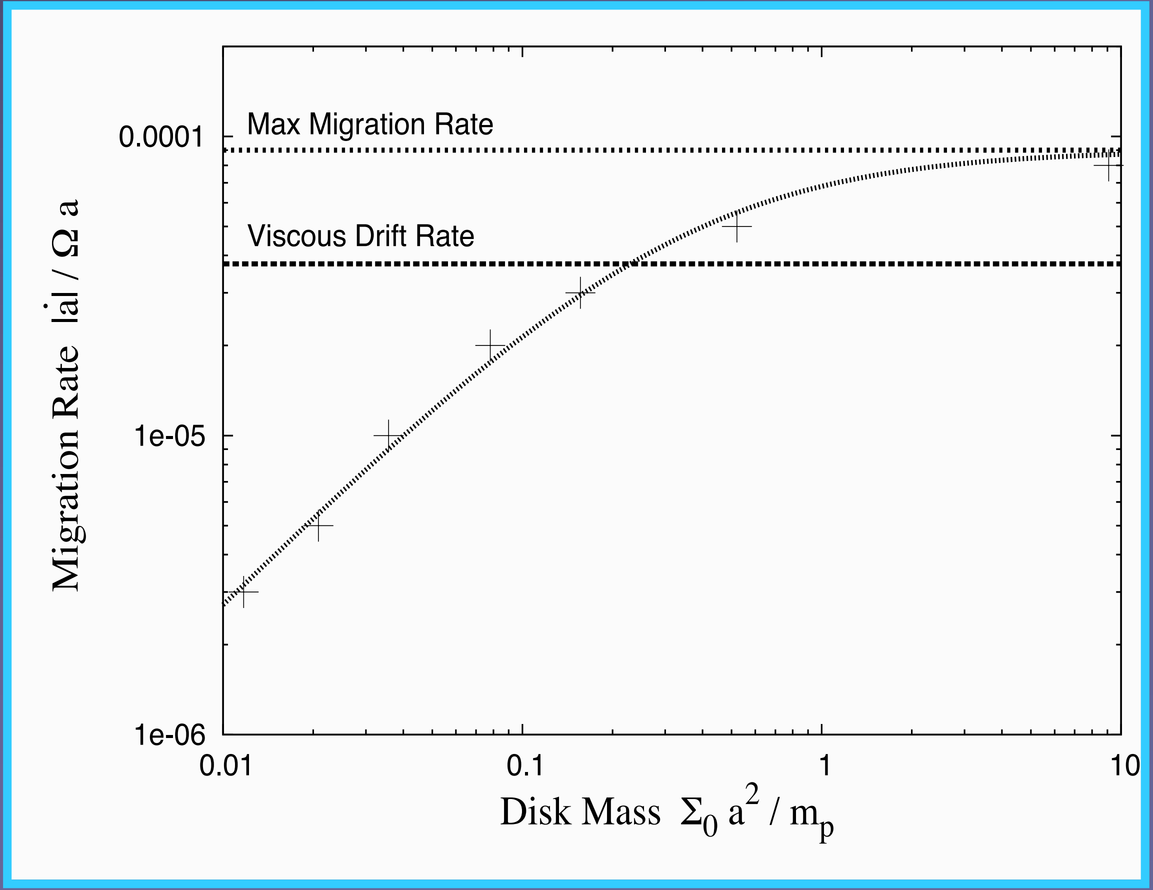
Steady-state with gap in 300 orbits



Inner disk replenished
(0, 6, 40, and 400 orbits shown)

Steady-state migration rate

- up to five times the viscous drift rate
- slows down when M(disk) < m(secondary)
- gas can stream across gap in either direction



Binary-disk interaction (3)

periodic non-intersecting adjacent orbits → cavity ?

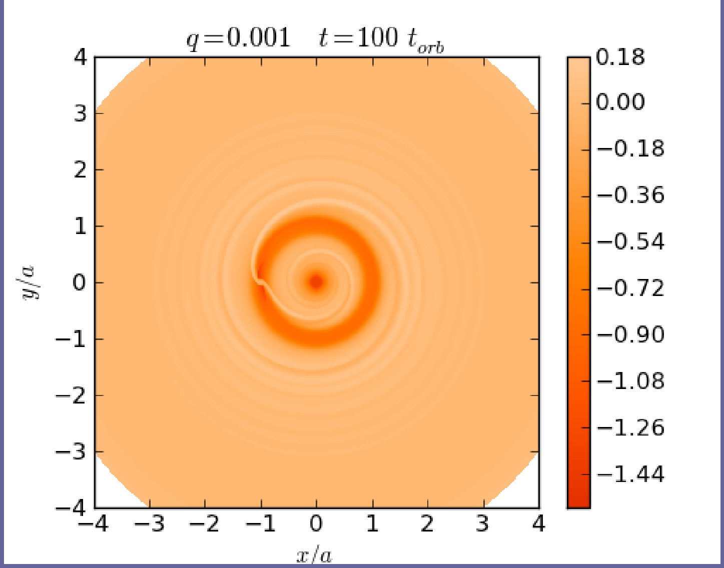
Paczynski (1977), Rudak & Paczynski (1981), Milosavljevic & Phinney (2005)

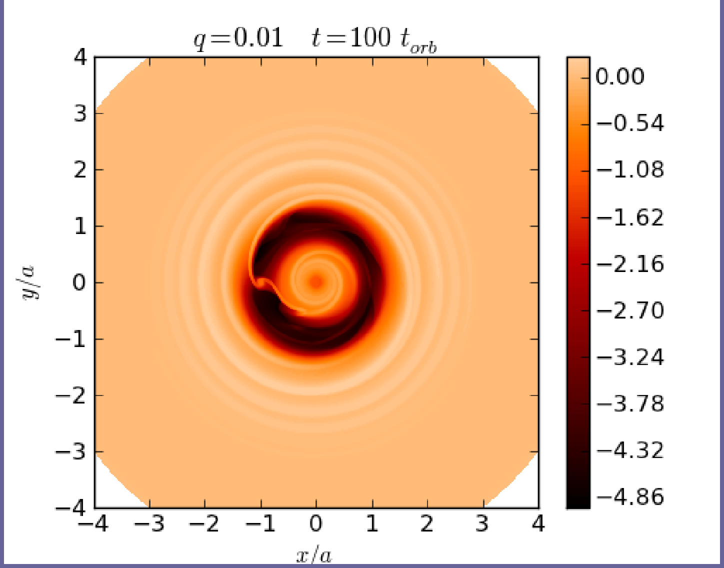
???

Binary-disk interaction (3)

2^{nd} transition at q~0.03-0.05 -- caused by orbital instability(?)

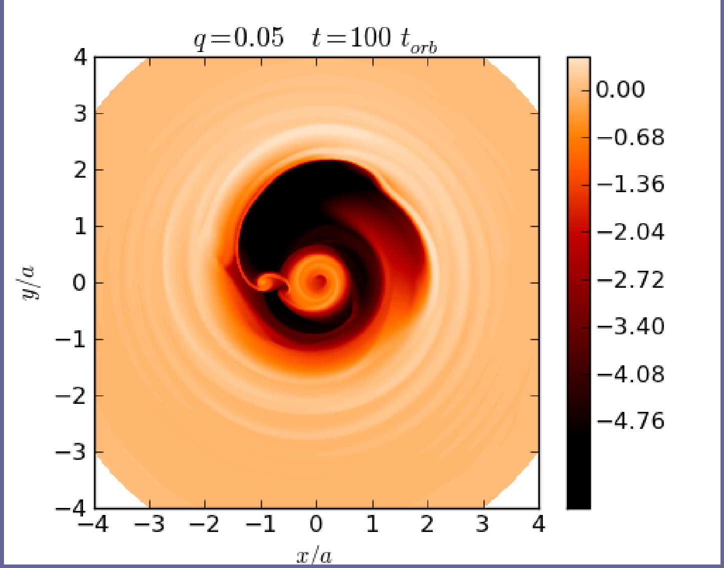
$q=10^{-3}$

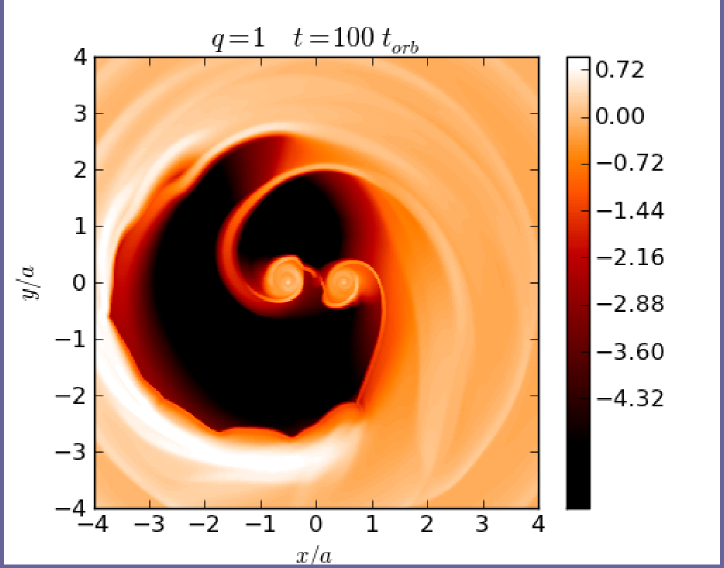




$q=10^{-2}$

q=0.05



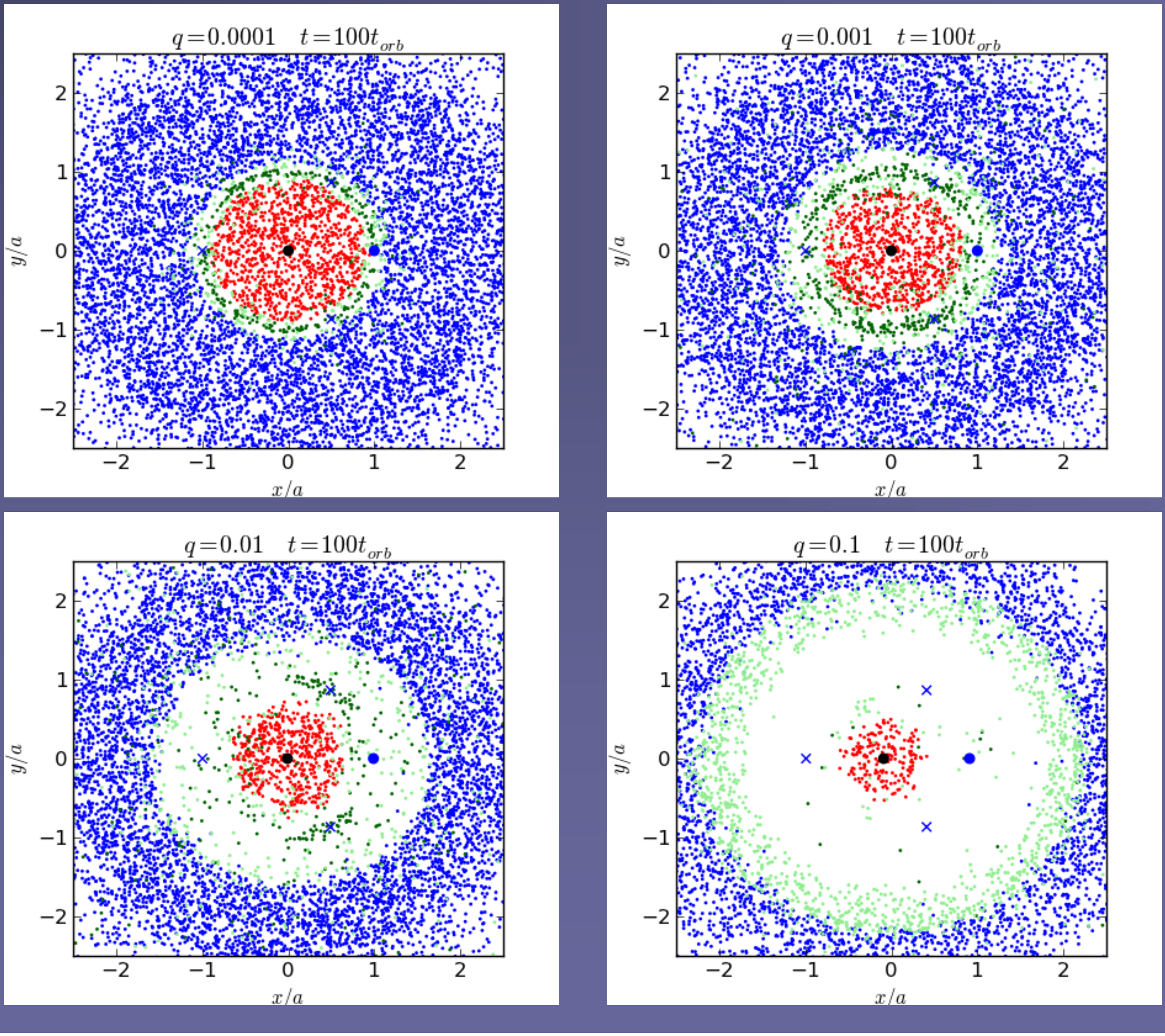


q=1

Binary-Disk Interaction: Restricted 3-Body

qualitative changes at q~10^{-3}, ~0.04 and ~0.3

D'Orazio et al. (2016)



$q=10^{-4}$

$q=10^{-3}$

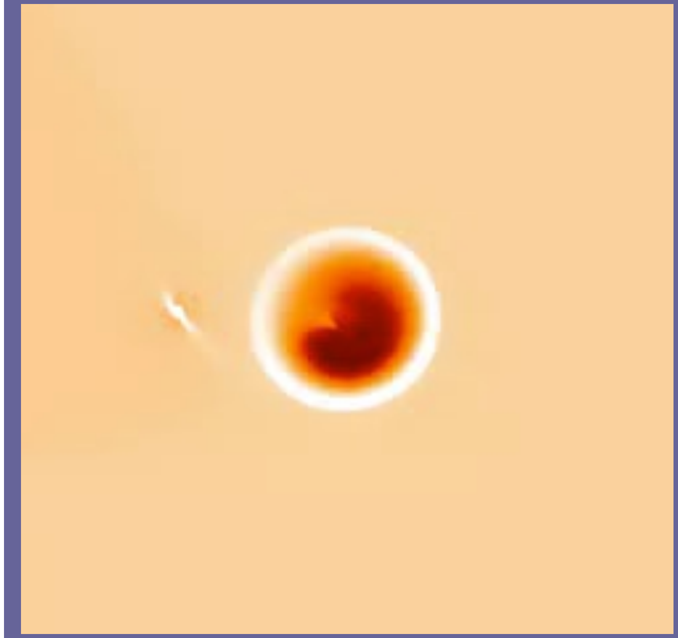
$q=10^{-2}$

$q=10^{-1}$

$\boxed{q_{crit}=0.04}$

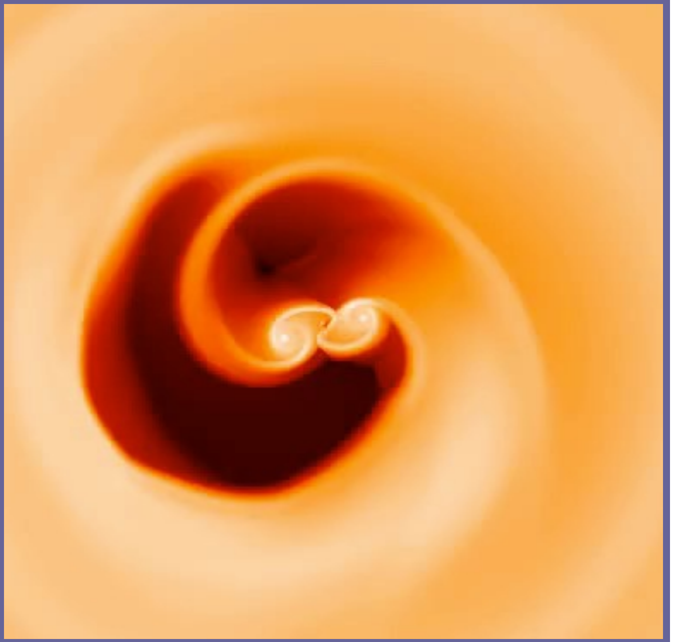
Accretion and Variability

Three regimes based on mass ratio $q=M_2/M_1$



q=0.01

q=0.05



q=1

steady accretion

q≈0.04

loss of stable orbits

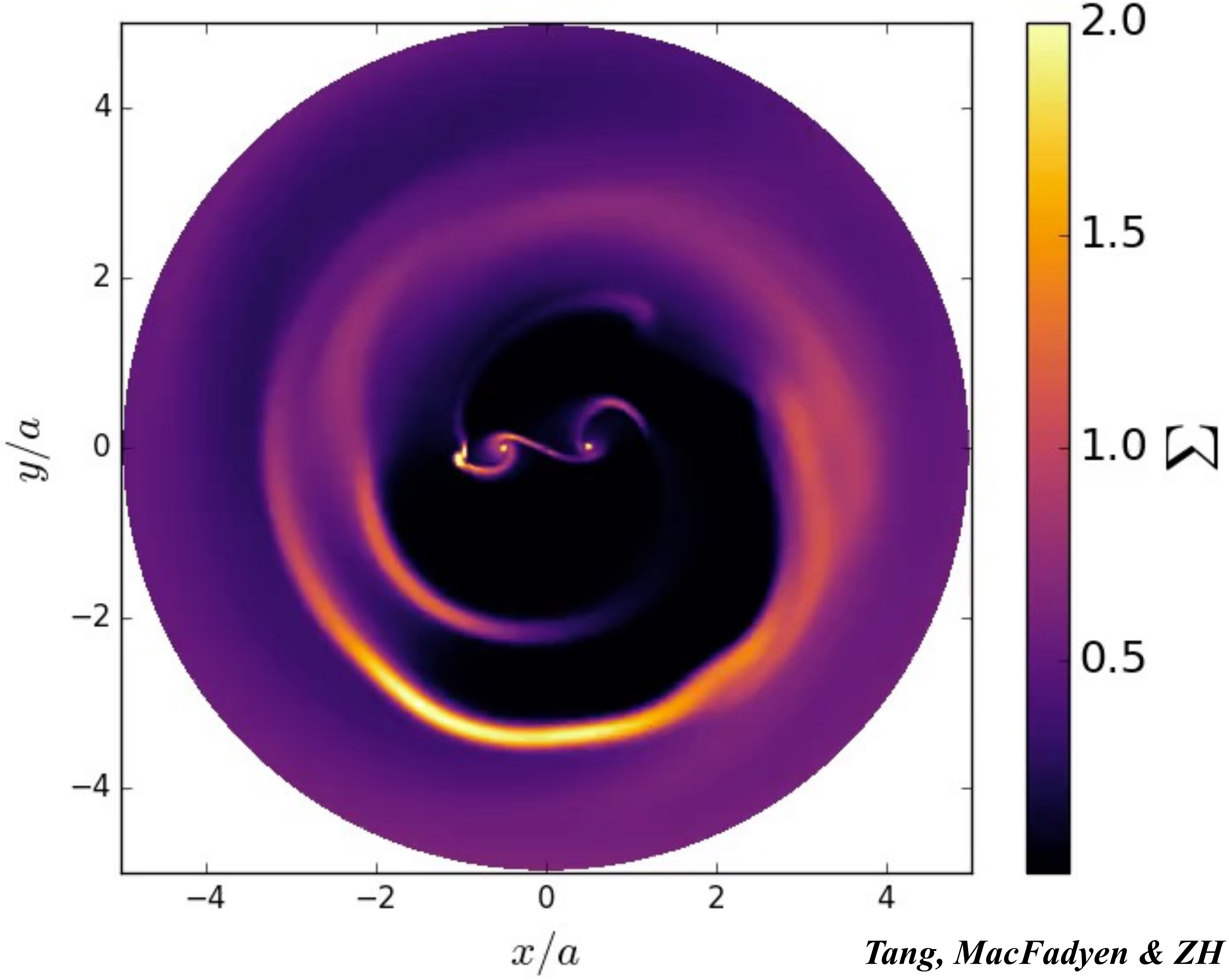
orbital time scale regime

q≈0.3

lump at cavity

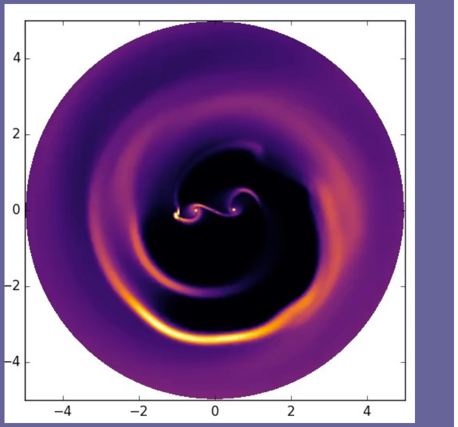
cavity wall regime

Equal-Mass Binary



Tang, MacFadyen & ZH (2018)

Key Features of Binary Accretion



Central cavity:

- Lack of stable orbits within ~twice the binary separation
- Density suppressed by factor of ~100

Lopsided cavity wall with lump:

- circumbinary disk strongly lopsided (nonlinear instability)
- dense lump appears at cavity wall, modulating accretion

Streamers:

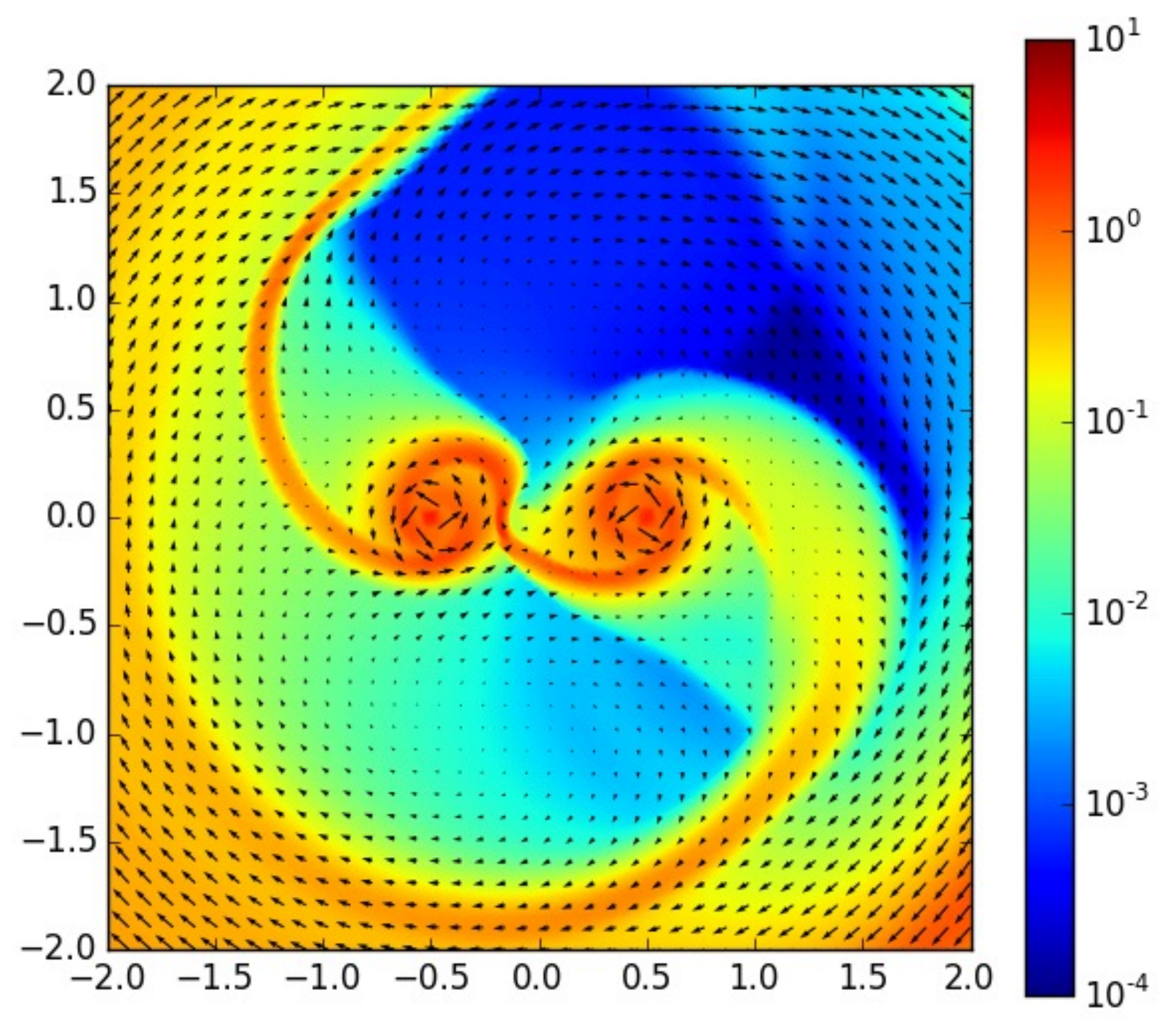
- enter cavity wall via strong shocks, extend into tidal region of BHs
- fuel accretion is via gravity and shocks --- not viscosity!

Minidisks:

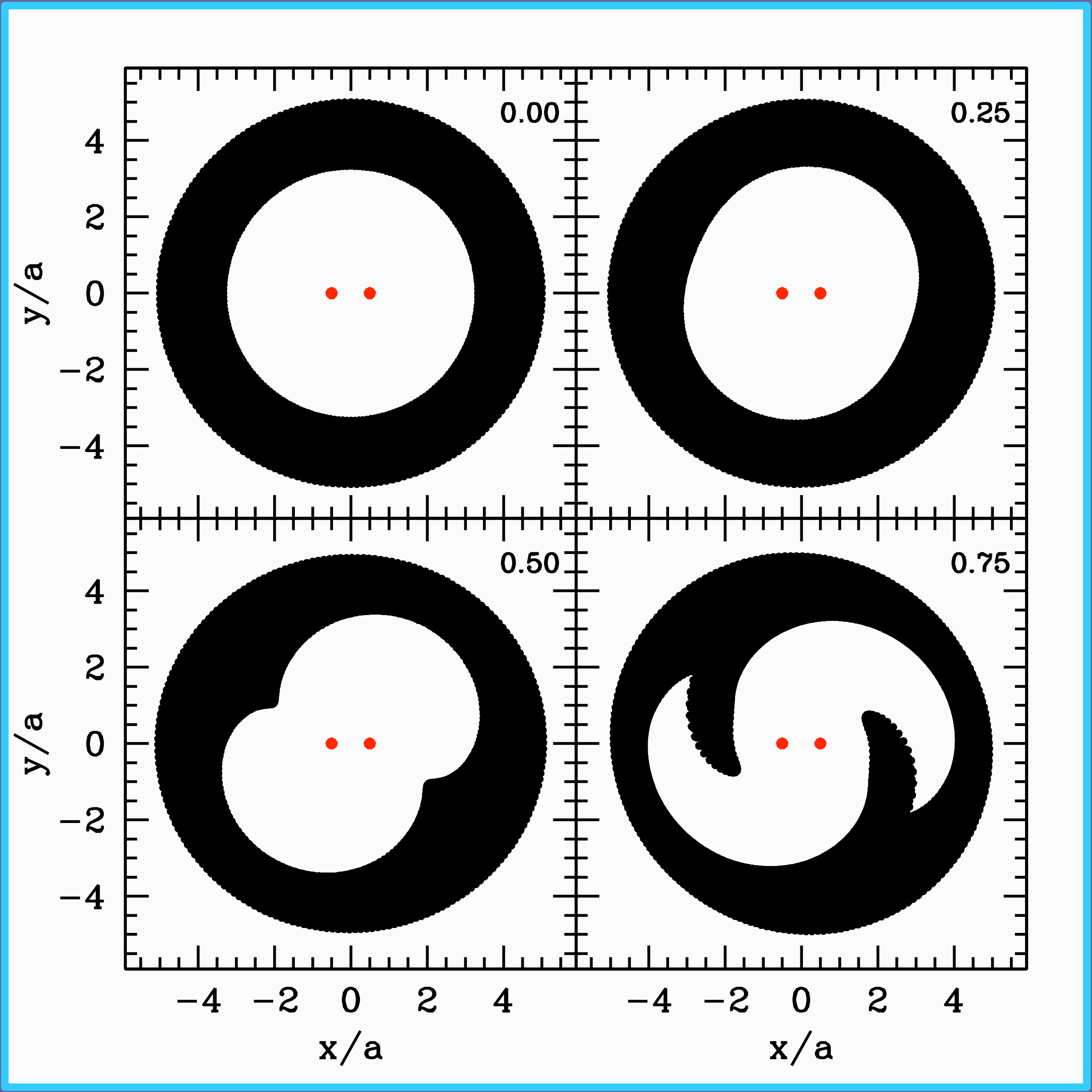
- fueled by streamers -- net accretion rate matches that of single BH
- strong shocks, periodically appear and disappear

Why does binary accrete at all?
shocks inside the cavity

Tang, MacFadyen, ZH (2017), Tiede et al. (2020)

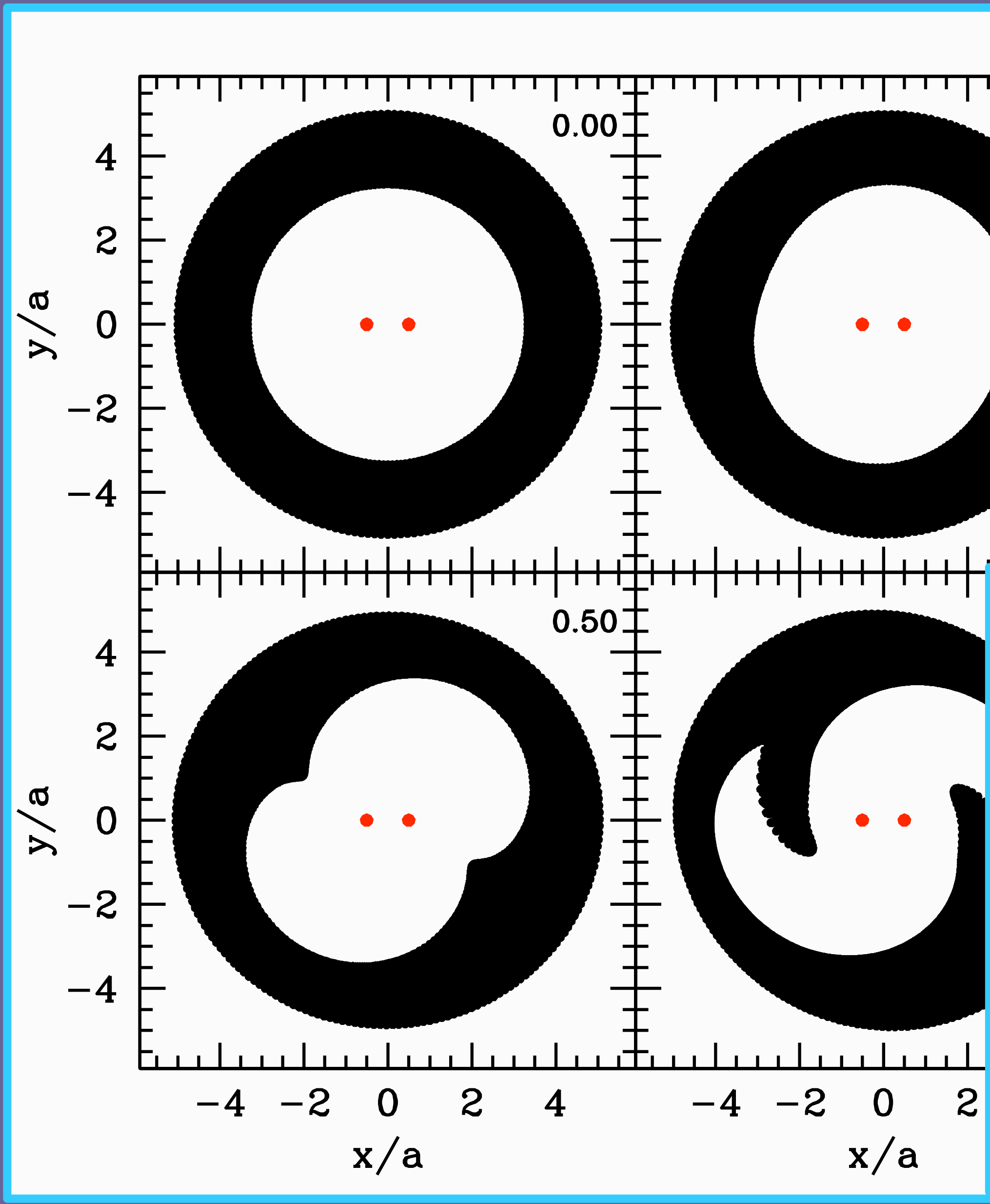


Gas flow into the Cavity - kinematics

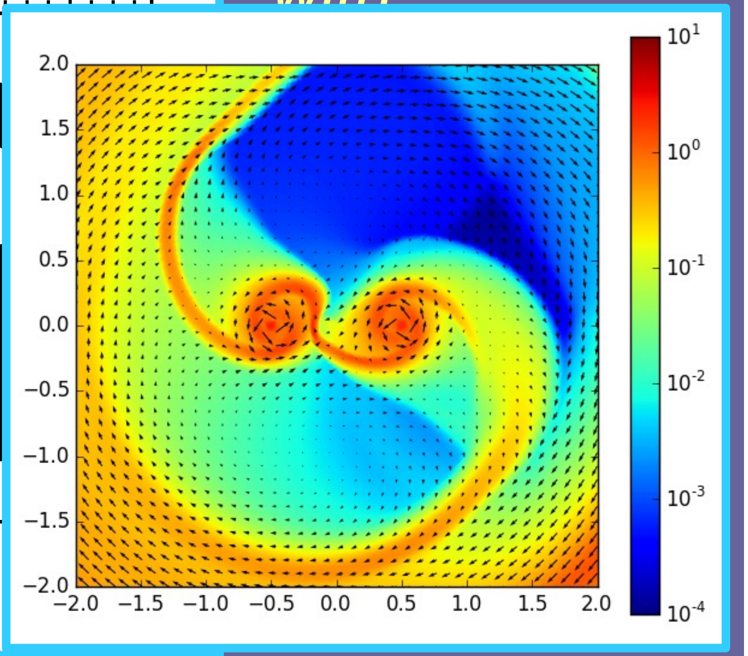


particle distribution evolved with restricted three-body approximation

Gas flow into the Cavity - kinematics



particle distribution evolved with



Sharp changes in behavior

At $q=0.05$ – caused by linear instability at L4/L5:

- Accretion rate becomes strongly variable
- Annular gap → central cavity
- Secondary out-accretes primary (by factor of 20 for $q\sim0.05$)

At $q=0.3$ – caused by nonlinear runaway:

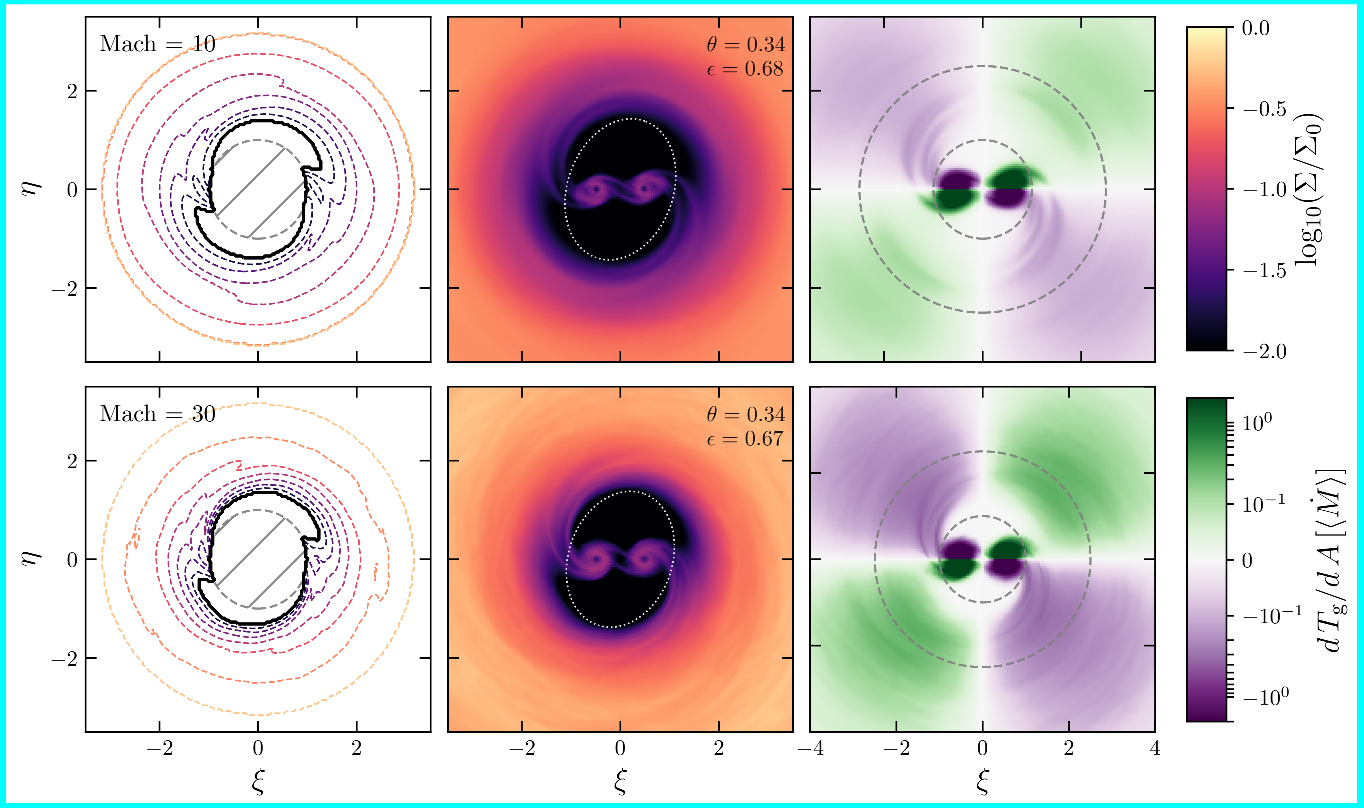
- circumbinary disk strongly lopsided (runaway/instability)
- dense lump appears at cavity wall, modulating accretion

Accretion rate is never suppressed :

- remain ~ same (or enhanced) compared to single BH
- Note: accretion is via gravity and shocks --- not viscosity!

Disk torques and orbital evolution

Tiede, Zrake, MacFadyen, ZH (2020)



warm disk
(h/r=0.1)

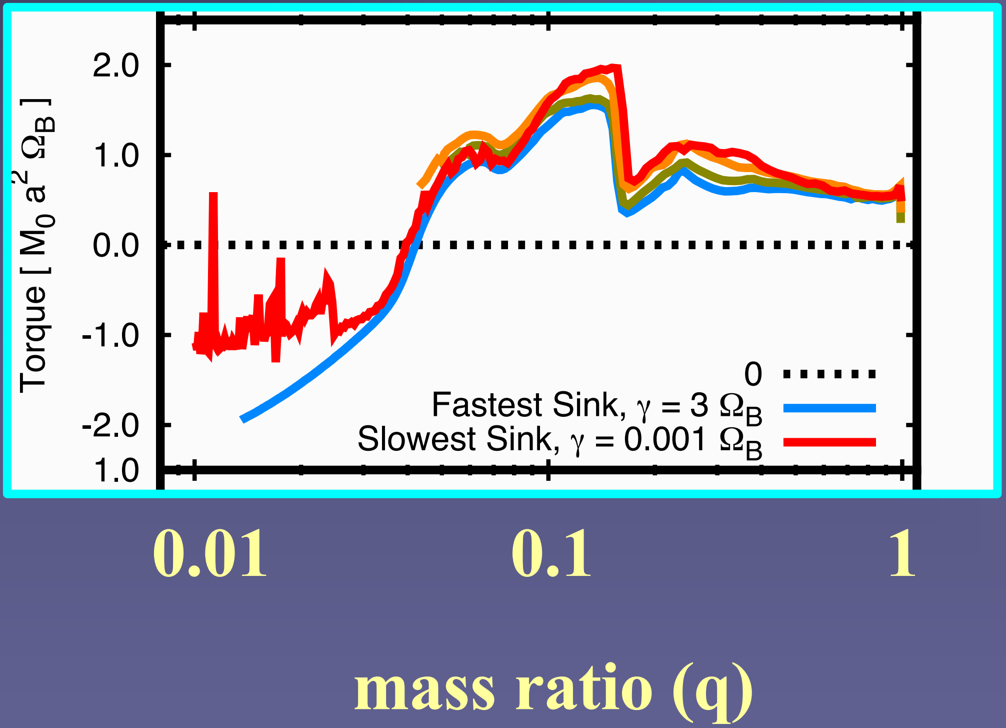
cooler disk
(h/r=0.03)

- **Gravitational torques dominate over accretion (of mass and momentum)**
- **Torque dominated by minidisk/cavity wall**
- **Switches to inspiral for h/r < 0.04**

“realistic” disk promotes merger in few × 10 Myr

Inspiral or outspiral? Impact of mass ratio

Duffell et al. (2020)

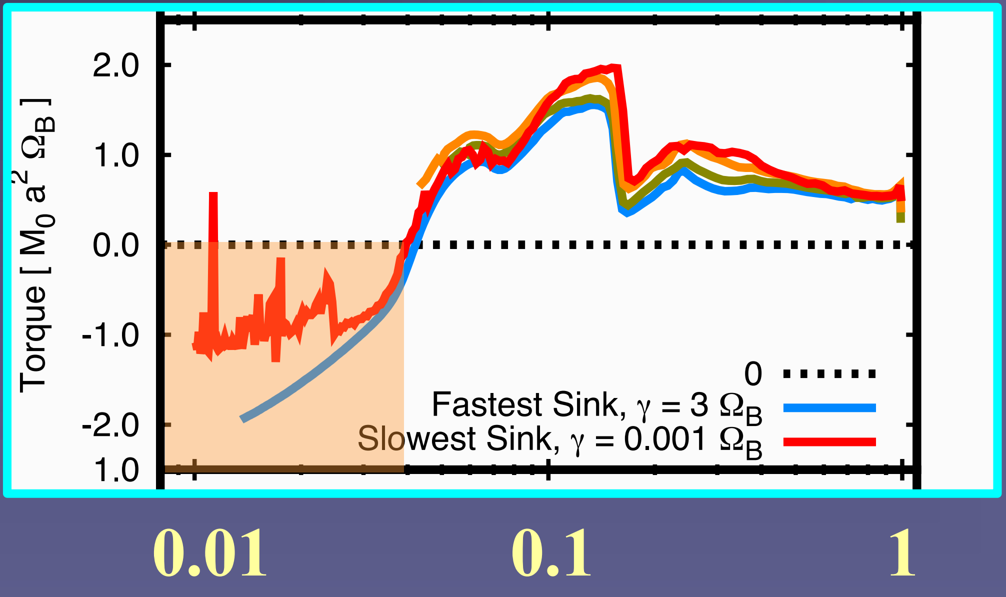


outspiral

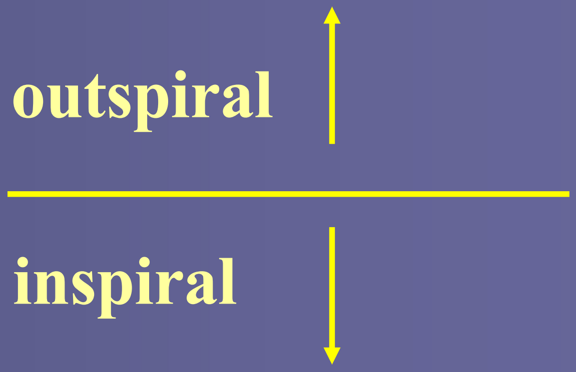
inspiral

Inspiral or outspiral? Impact of mass ratio

Duffell et al. (2020)



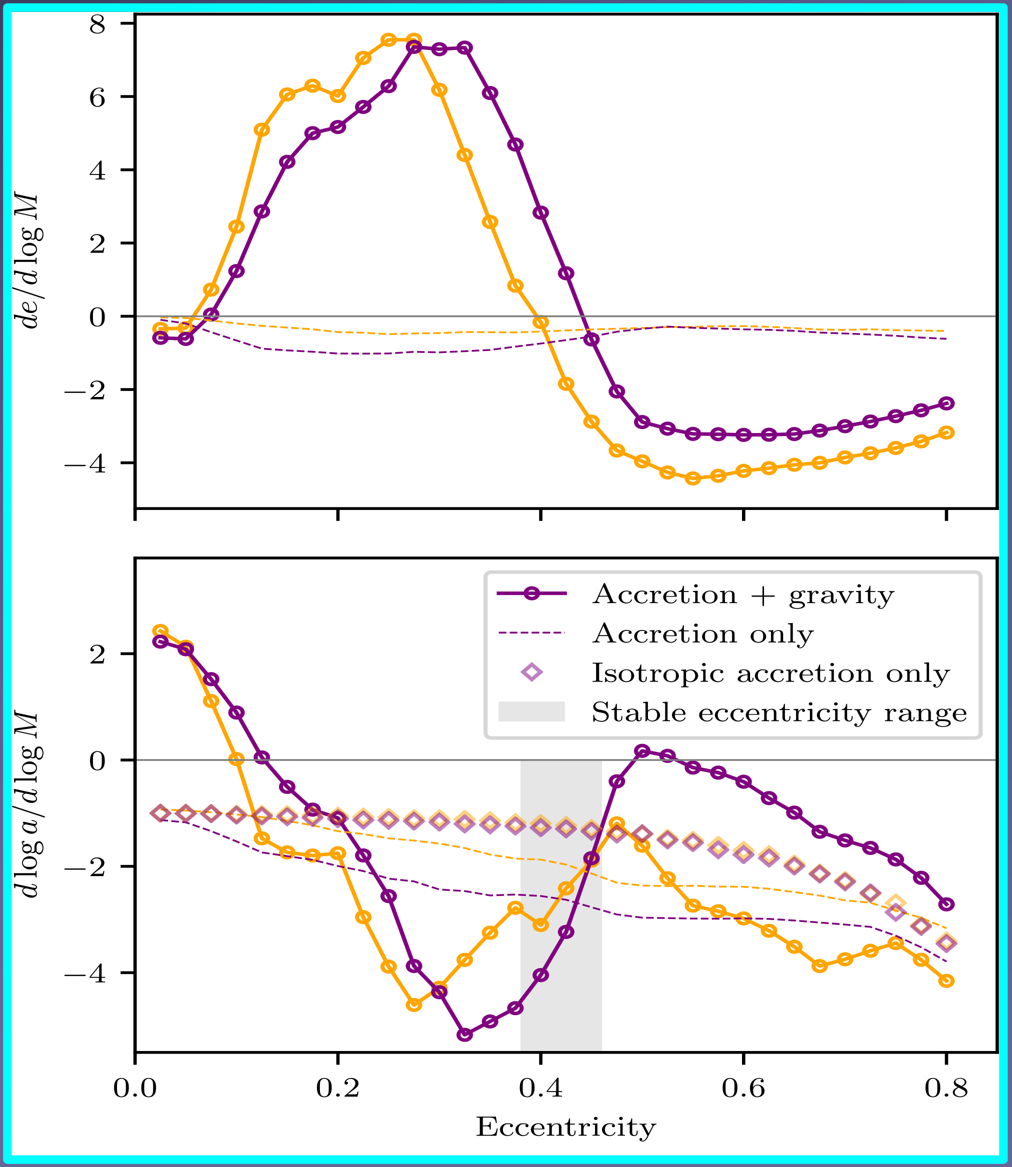
mass ratio (q)



inspiral for q $\lesssim$ 0.05

Inspiral or outspiral? Impact of eccentricity

Zrake et al. 2021



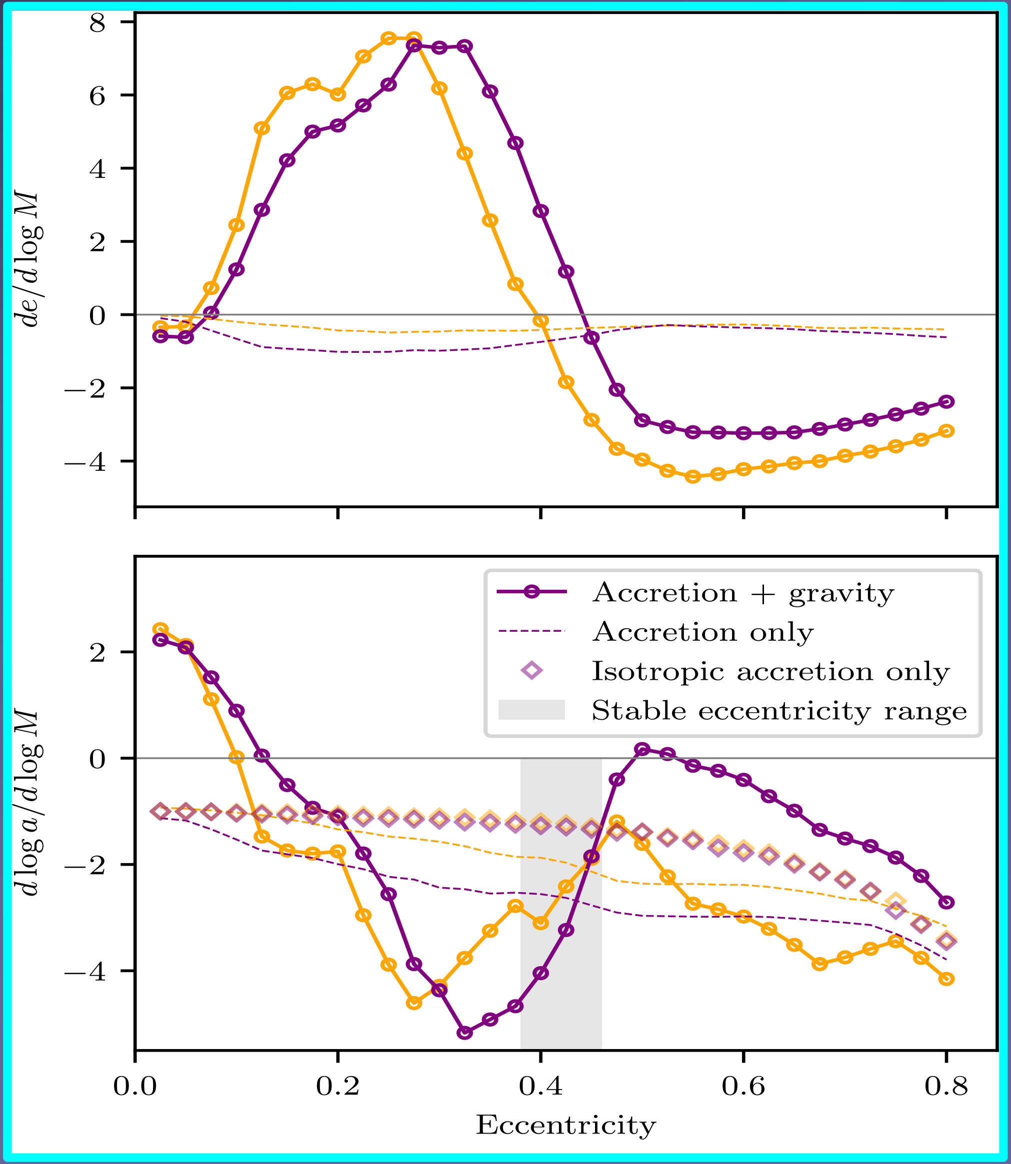
e → 0.45

outspiral ↑

inspiral ↓

Inspiral or outspiral? Impact of eccentricity

Zrake et al. 2021



e → 0.45

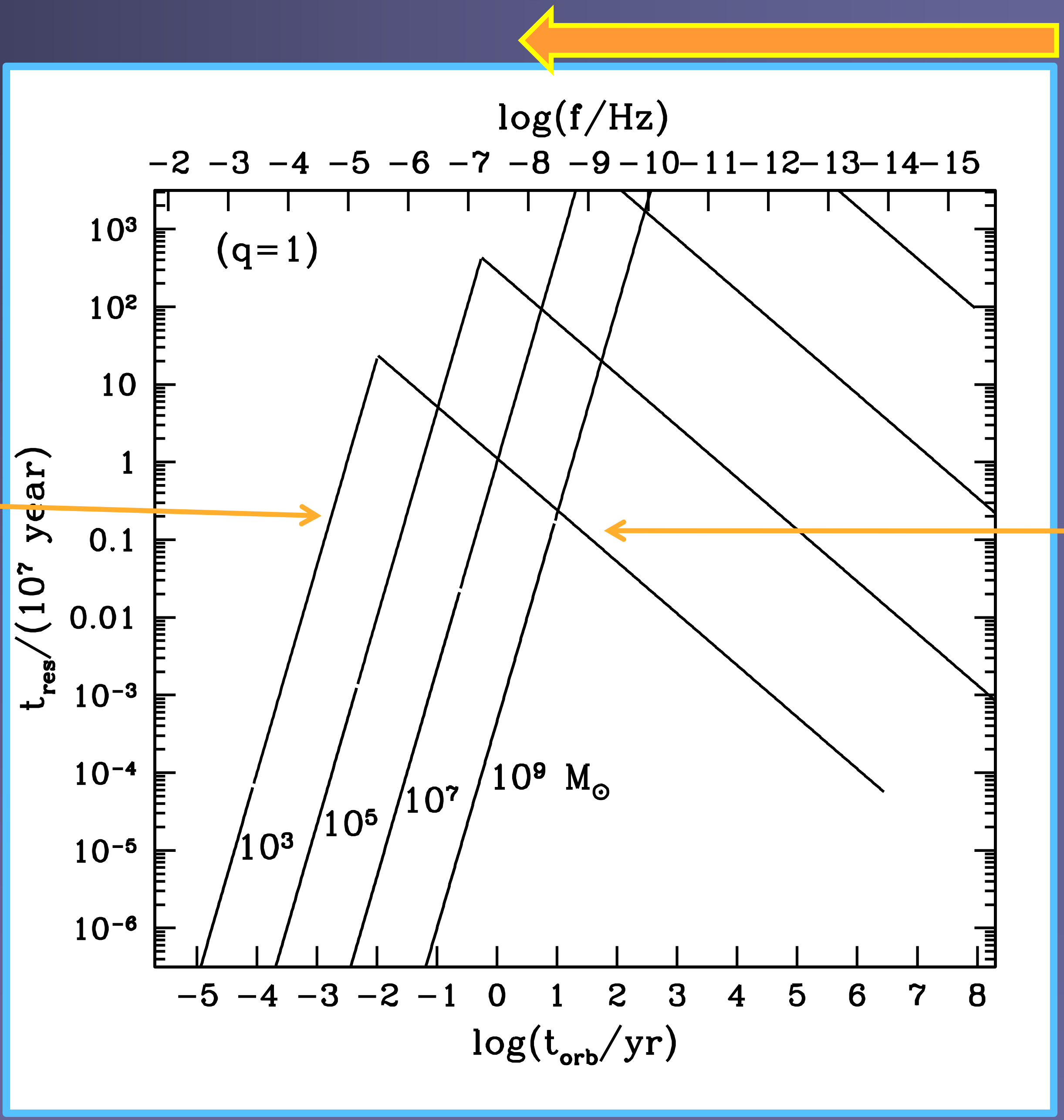
outspiral

inspiral

inspiral for e ≳ 0.15

Orbital decay of binaries

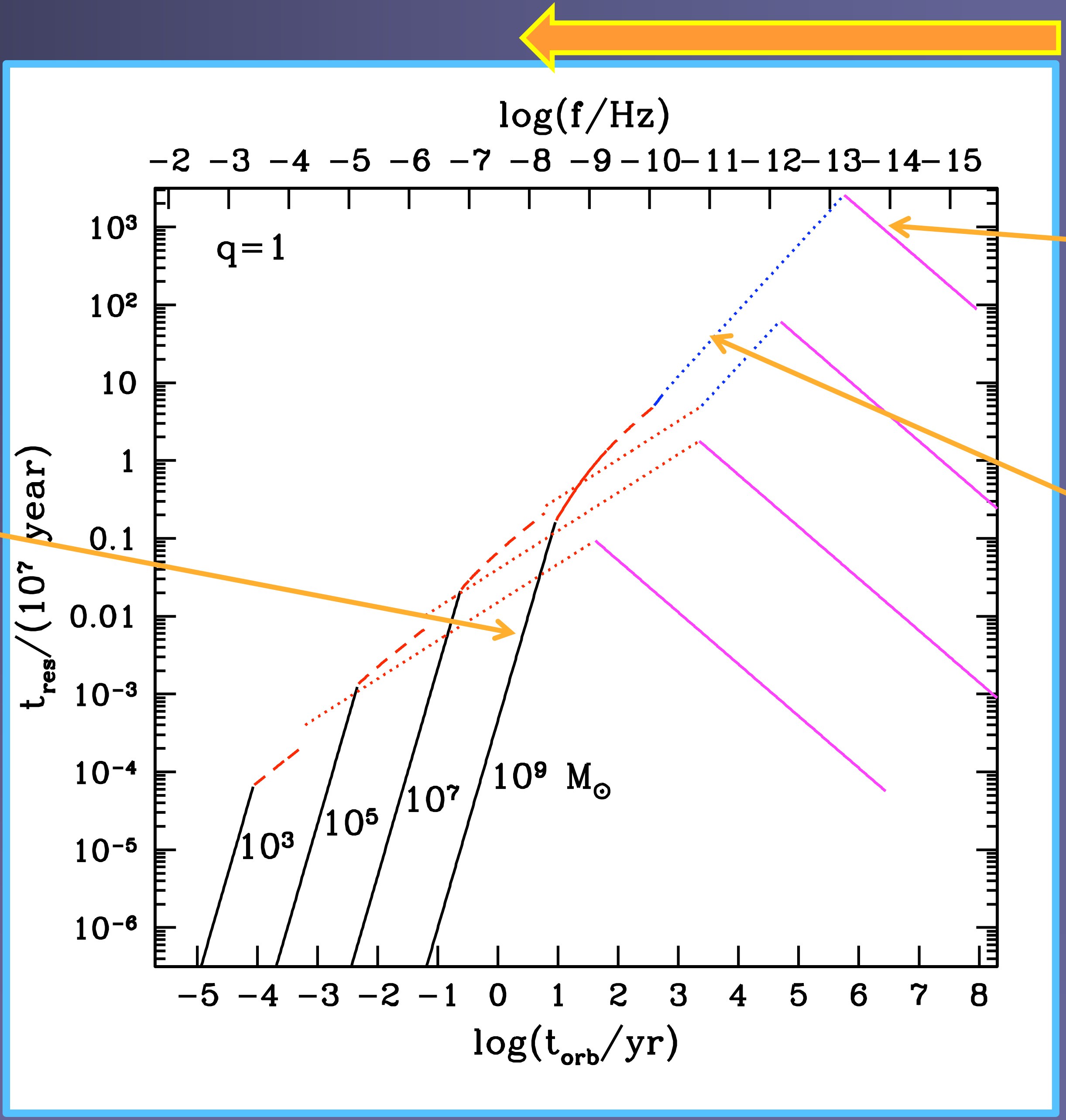
GW-driven decay



Stellar Scattering driven decay

ZH, Kocsis, Menou (2009)

Orbital decay of binaries



Stellar Scattering driven decay

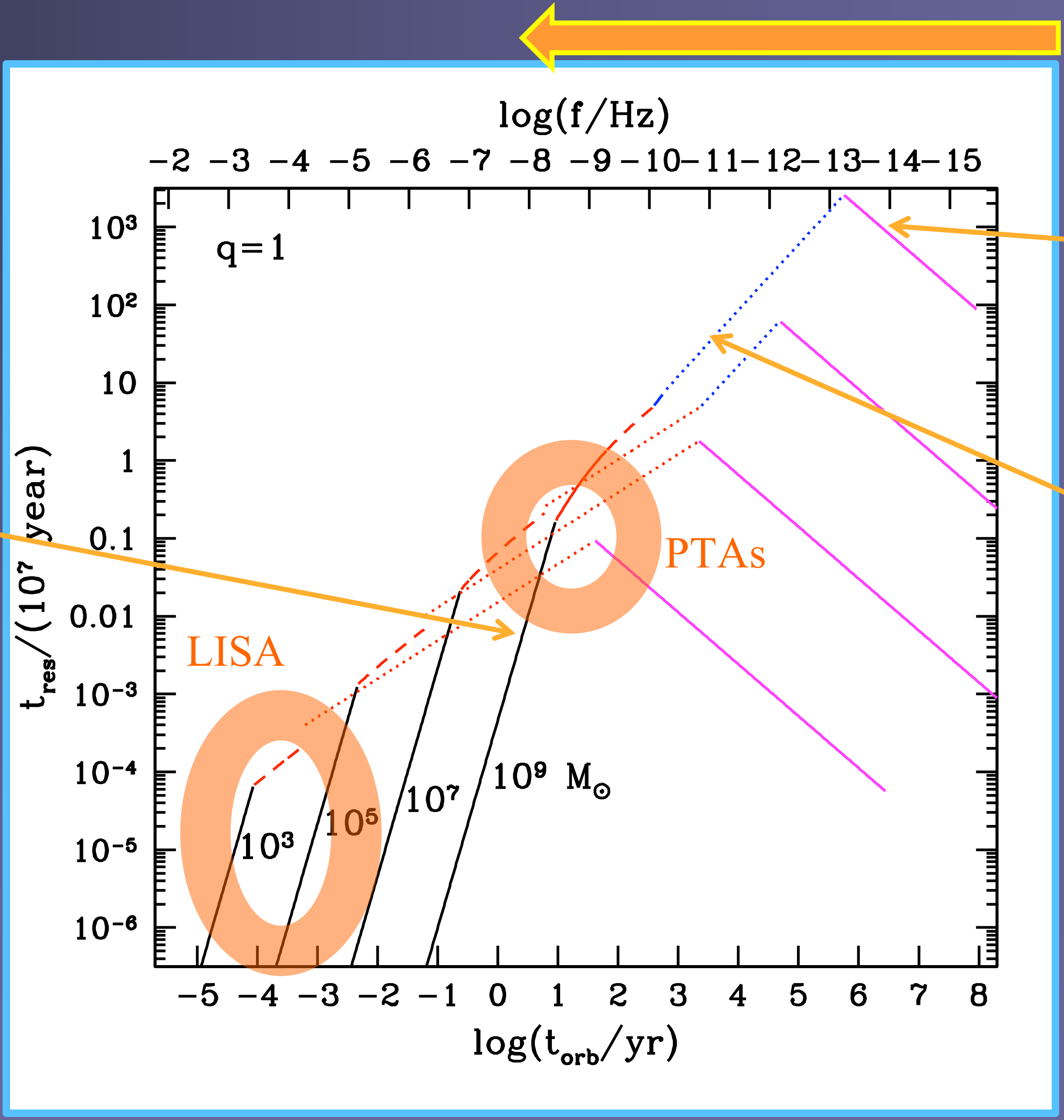
GW-driven decay

Gas disk Driven decay

[sensitive to accretion disk model]

ZH, Kocsis, Menou (2009)

Orbital decay of binaries



Stellar Scattering driven decay

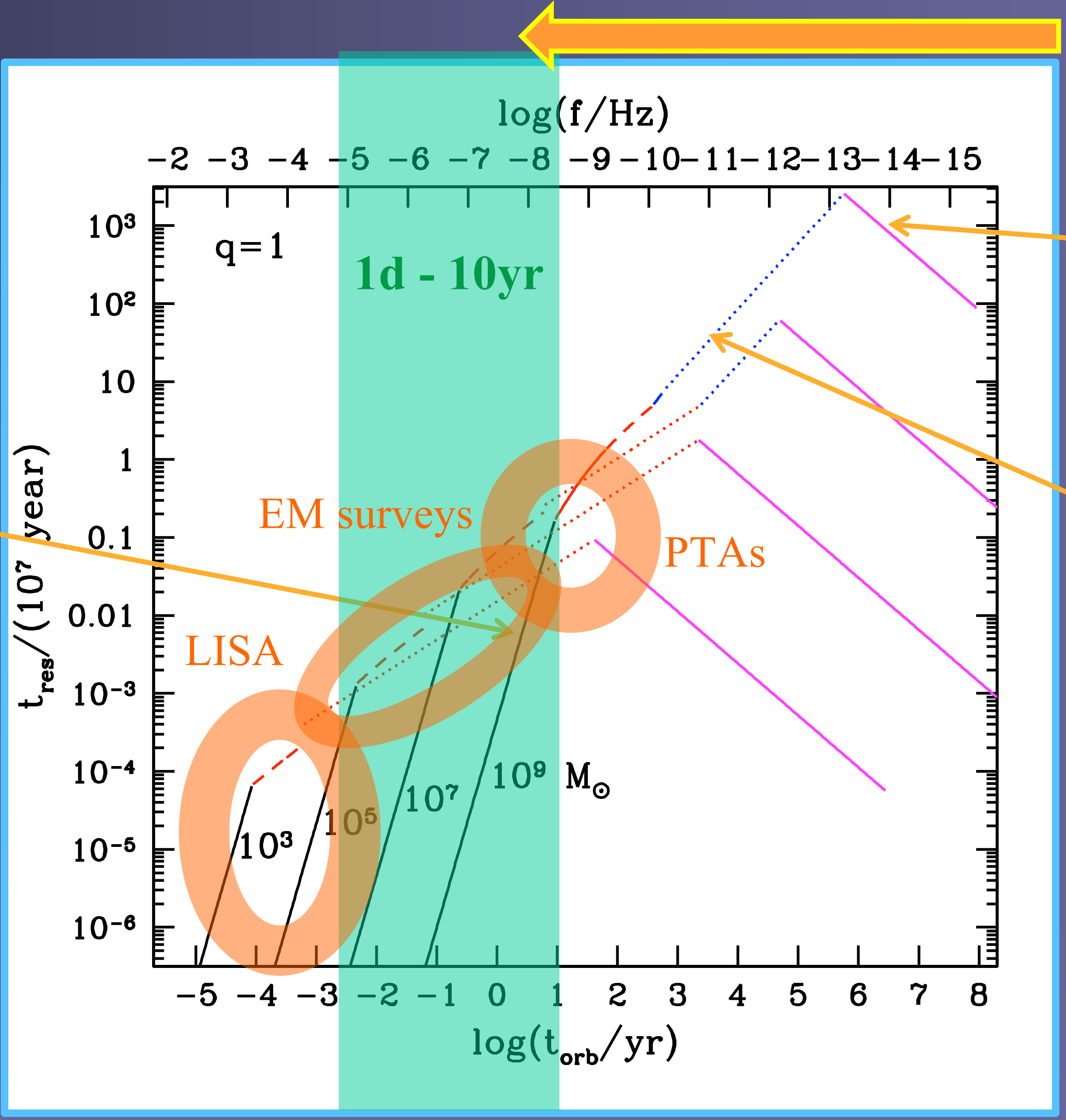
GW-driven decay

Gas disk Driven decay

[sensitive to accretion disk model]

ZH, Kocsis, Menou (2009)

Orbital decay of binaries



Stellar Scattering driven decay

GW-driven decay

Gas disk Driven decay

[sensitive to accretion disk model]

ZH, Kocsis, Menou (2009)