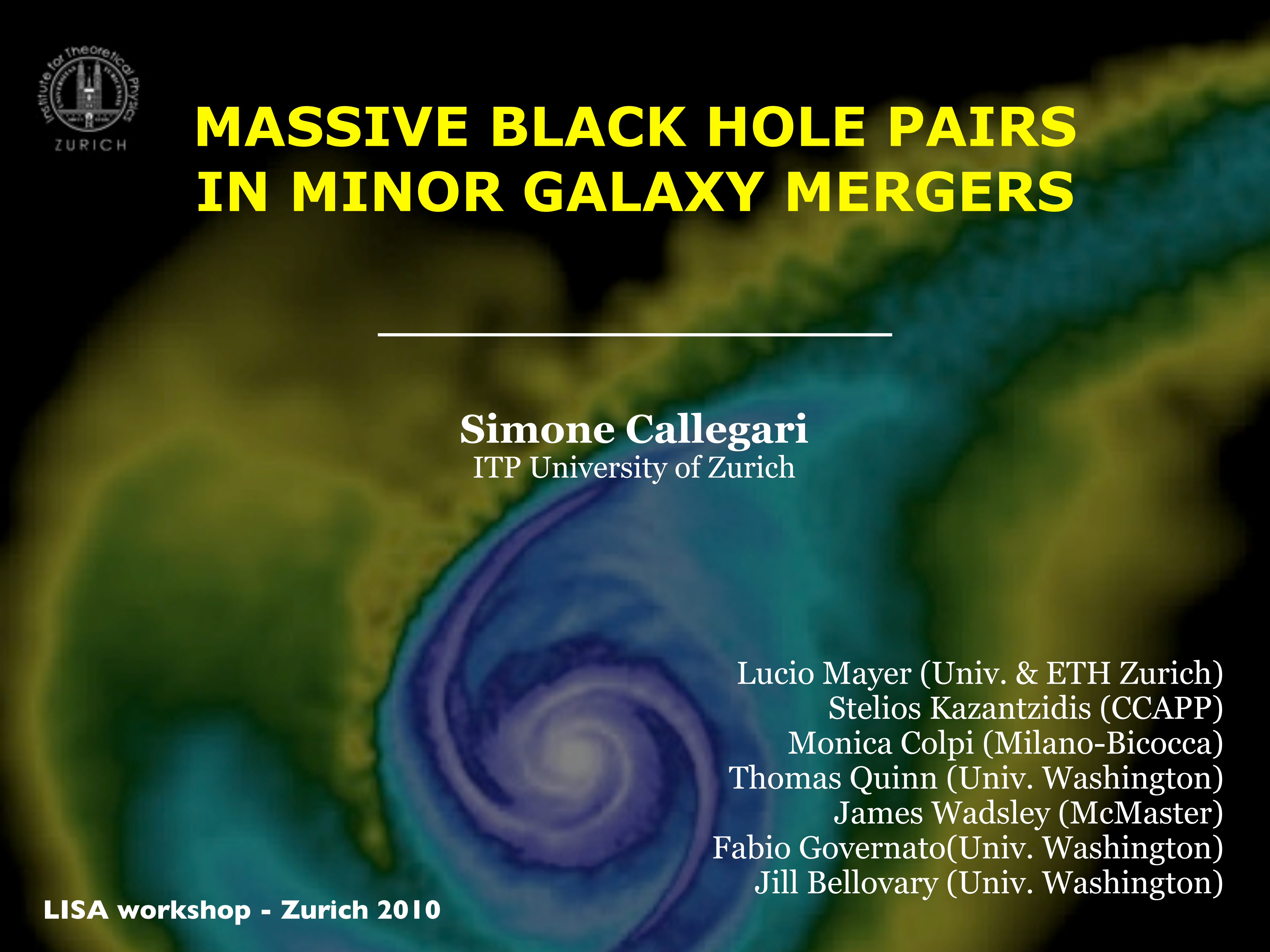

MASSIVE BLACK HOLE PAIRS IN MINOR GALAXY MERGERS

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Stelios Kazantzidis (CCAPP)
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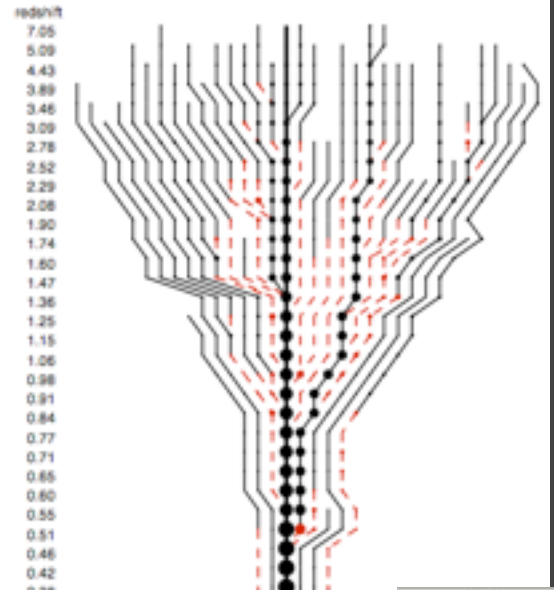
Thomas Quinn (Univ. Washington)
James Wadsley (McMaster)
Fabio Governato(Univ. Washington)
Jill Bellovary (Univ. Washington)

LISA workshop - Zurich 2010

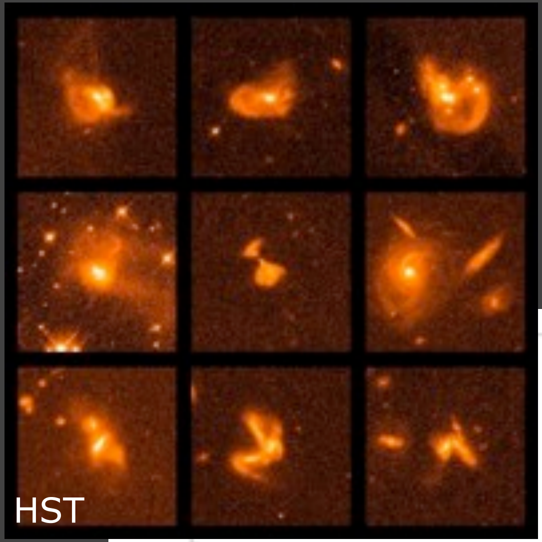
Massive Black Hole pairs?

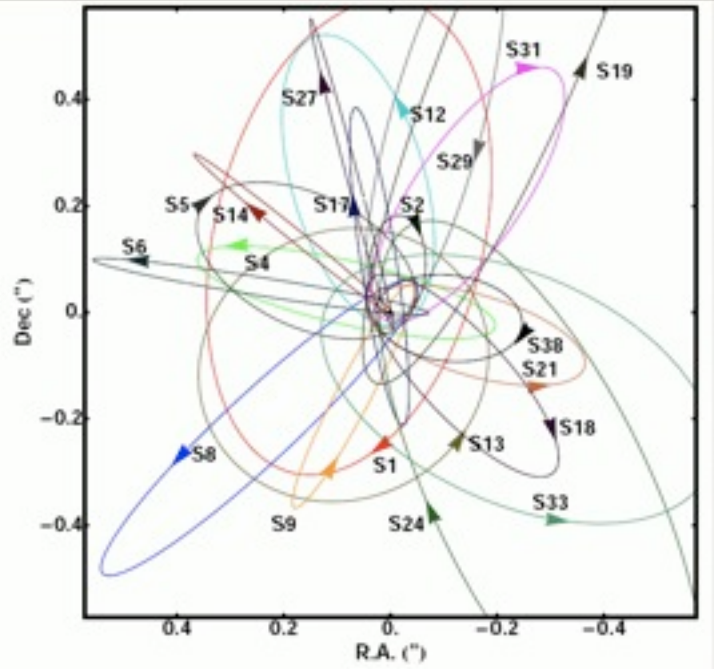
- ΛCDM hierarchical assembly of halos and galaxies

- evidence for MBH and their coevolution with galaxies

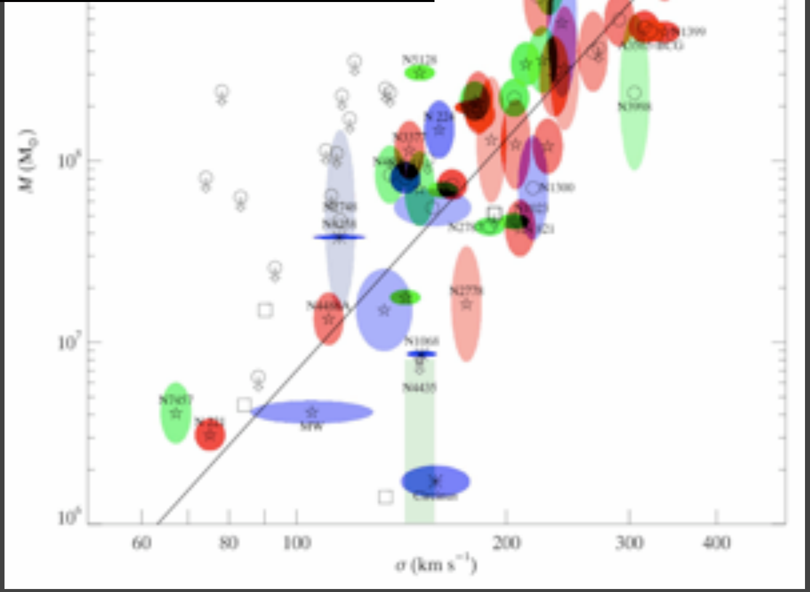


Stewart et al. 08



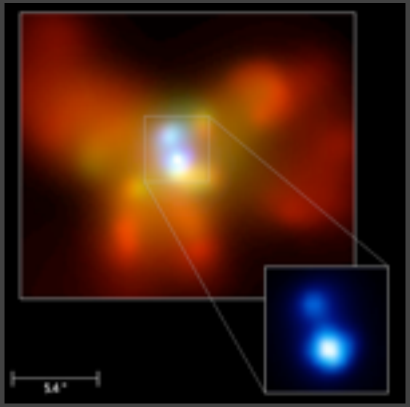


Gillessen et al. 08

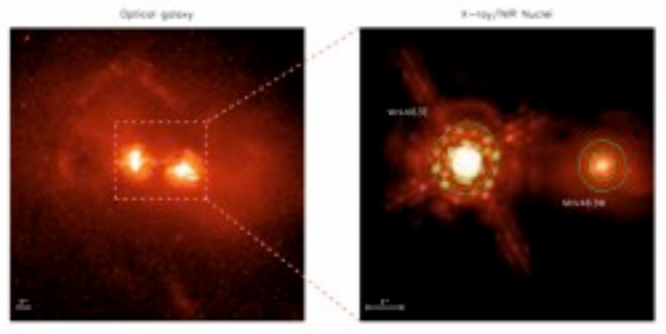


Gultekin et al. 09

Massive Black Hole pairs!



NGC6240



MRK463

At large sub-galactic separations (1-10 kpc): **some accreting doubles**

- double AGN embedded in starburst **NGC6240** at ~7 kpc (Komossa et al. 03)
- Mrk 463: double-nucleus ULIRG at ~4 kpc (Bianchi et al. 08)

At small separations (<<1 kpc): **a few candidates**

- **VLBA RADIO GALAXY 0402+39**: two compact, radio flat, variable nuclei – two SMBHs at 7.3 pc separation (Rodriguez et al. 06)
- **Blazar OJ287** with periodic outbursts could be explained by secondary black hole crossing accretion disk of primary (inferred binary separation ~ 0.07 pc, Valtonen et al. 07)
- **SDSS J092712.65+294344.0** spectroscopic candidate (Dotti et al. 09, Bogdanovic et al. 09)
- **SDSS J105041.35+345631.3** spectroscopic candidate (Shields et al. 09)
- **SDSS J1130+0057** X-shaped radio + double peak lines (Zhang et al. 07)
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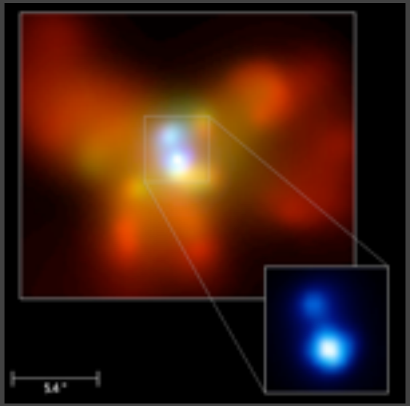
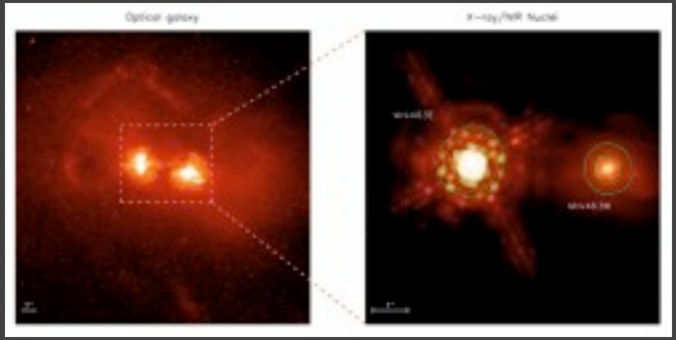
Massive Black Hole pairs!


NGC6240

MRK463



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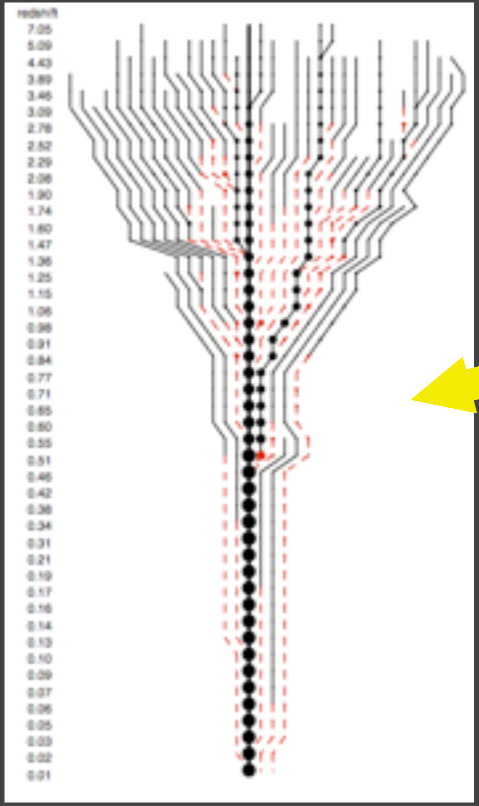
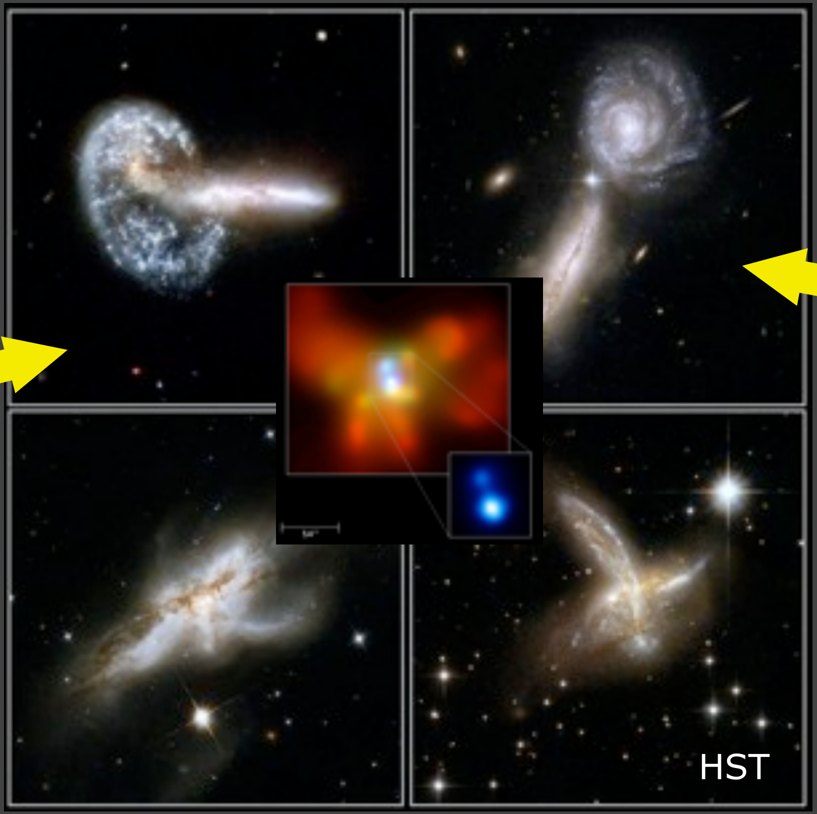
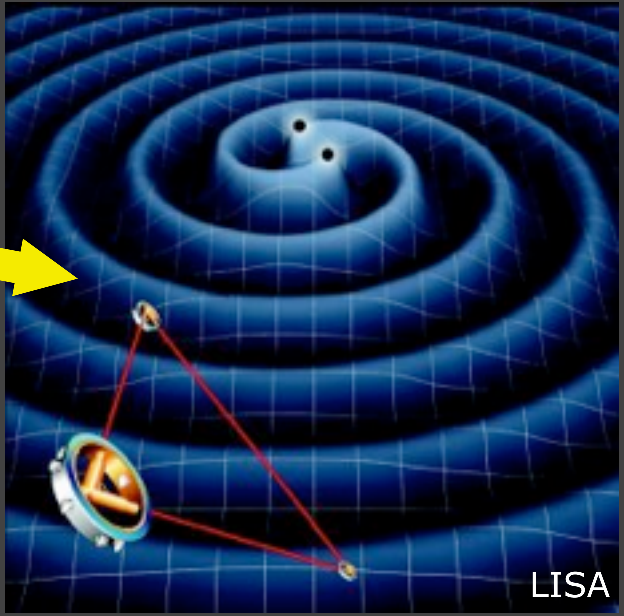
when and how do galaxy mergers lead to MBH pairs and binaries?



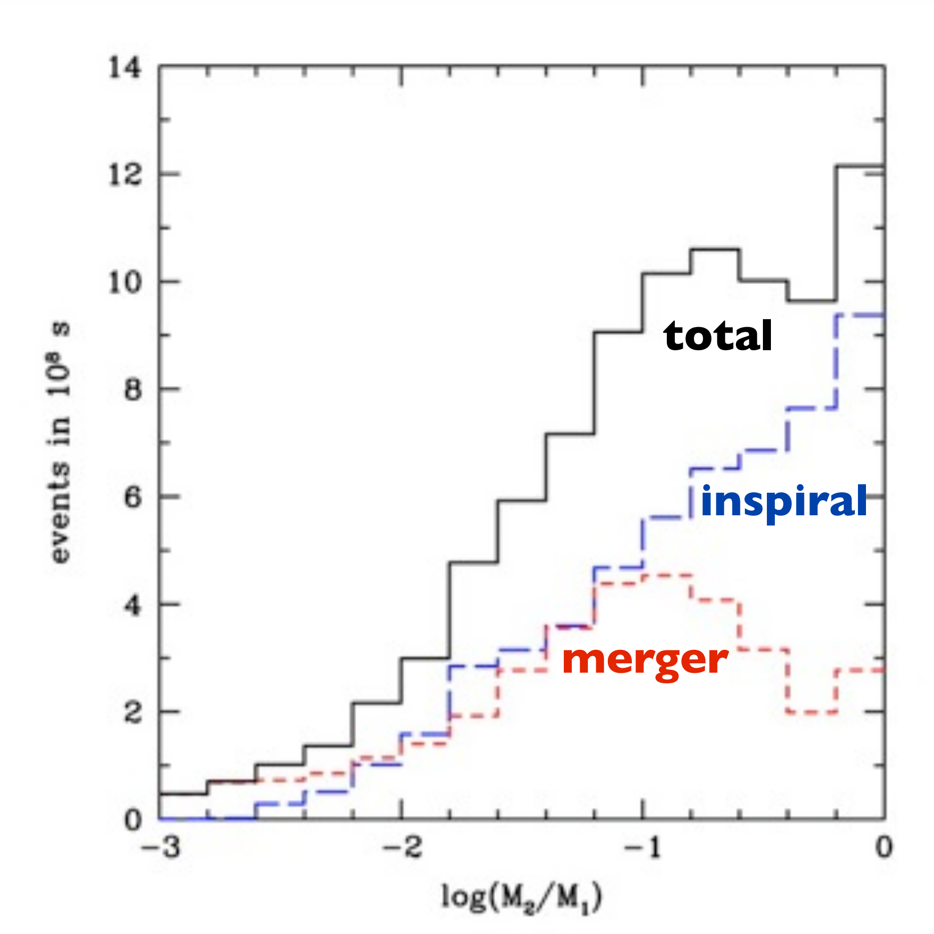




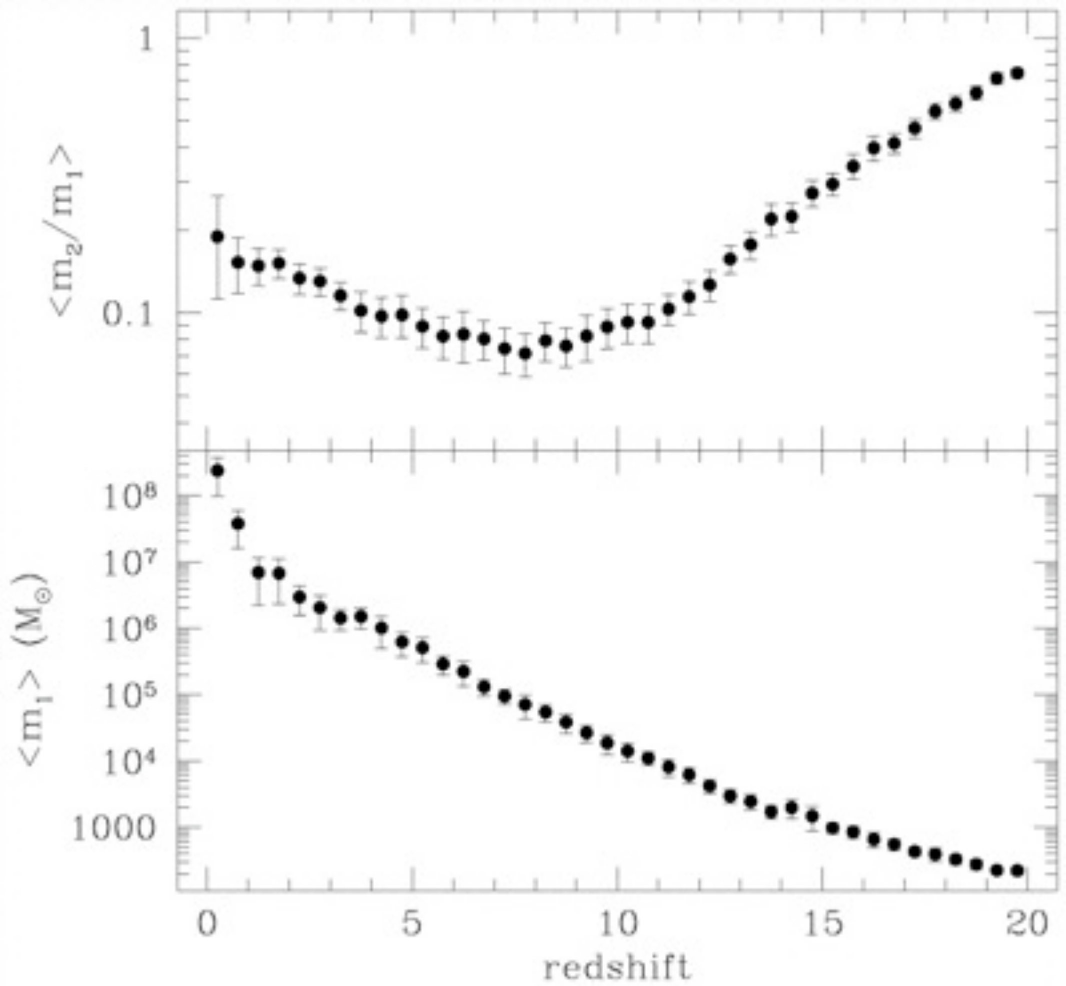
- fundamental physics: emission of gravitational waves (**LISA**), SMBH merger and gravitational recoil (electromagnetic precursors?)
- ejection of stars and compact objects
- scaling relations of MBHs and galaxies
- phenomenology of jets, shifted/double AGN lines...

when and how do galaxy mergers lead to MBH pairs and binaries?

Unequal-mass (minor) mergers

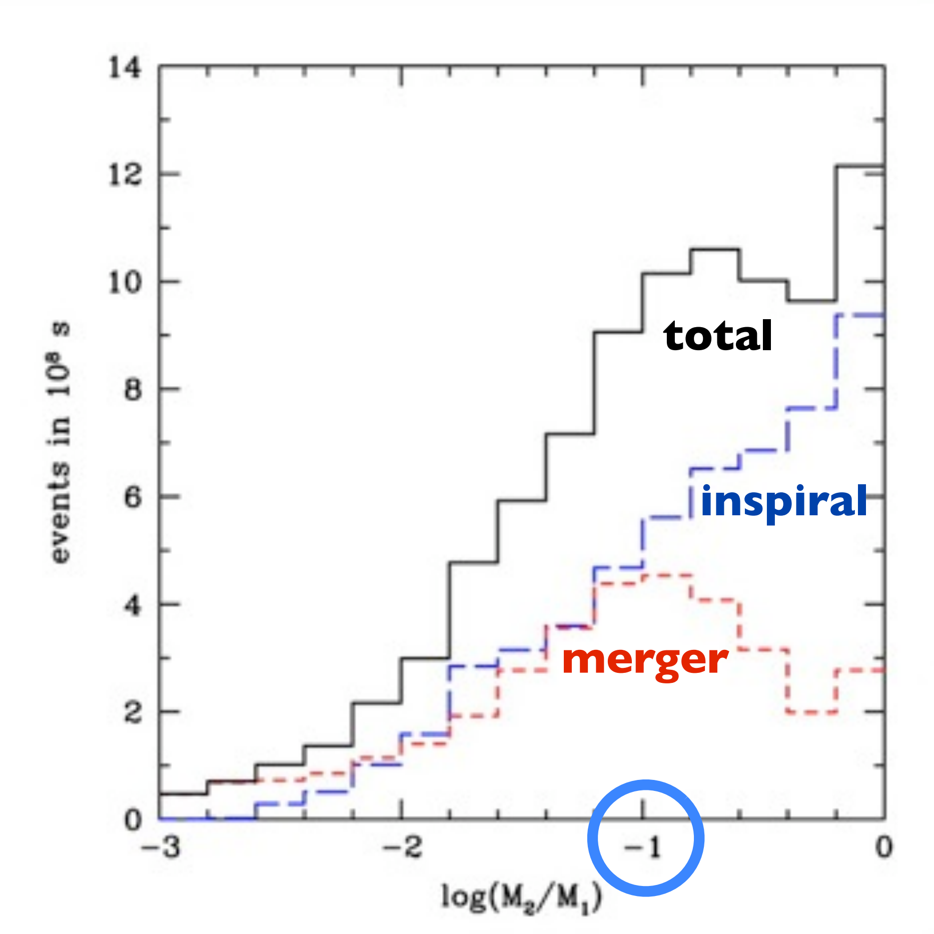


Sesana et al. 05

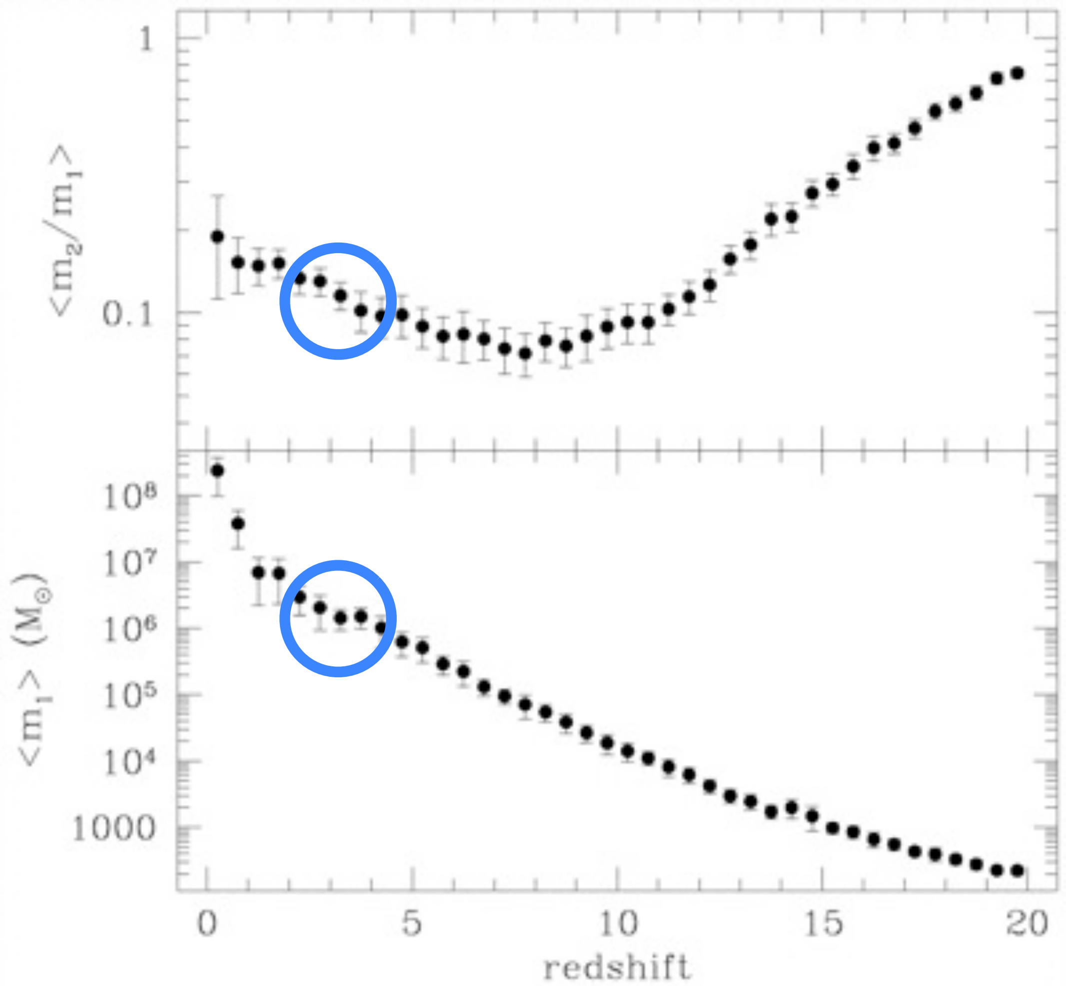


Volonteri et al. 03

Unequal-mass (minor) mergers



Sesana et al. 05



Volonteri et al. 03

1:10 mergers at z=3
1:4 mergers at z=0
with MBH mass 5 x 10^4 $M_o < M_{BH} <$ 3 x 10^6 M_o
in the LISA WINDOW

- Early-type galaxies (bulge + disk + halo + MBH) with varying gas fractions (0, 10%, 30% of disk) run with **GASOLINE**

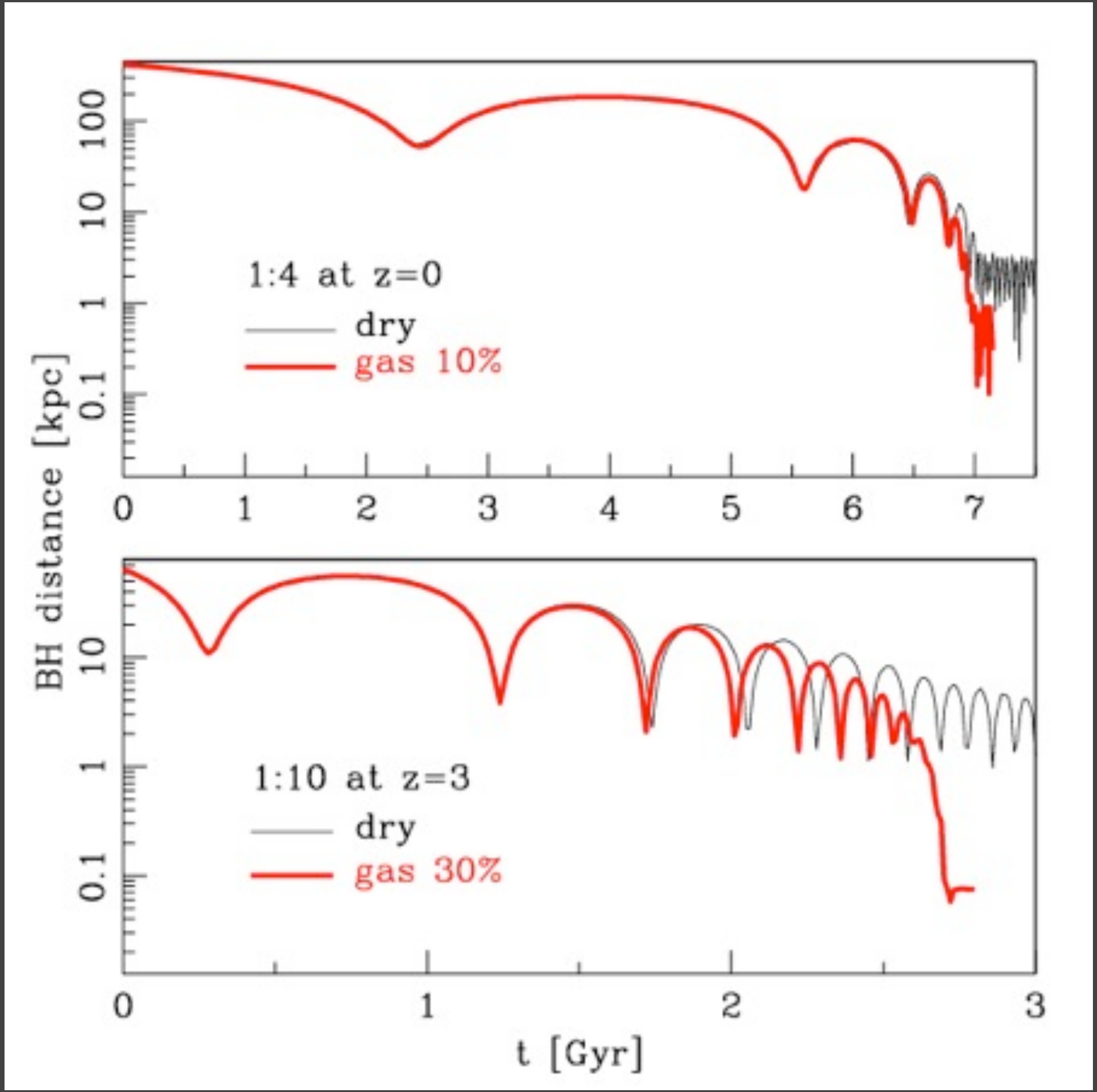
- Characteristic densities and parabolic orbits mimic mergers happening at 0 < z < 3 based on ΛCDM (e.g. Li et al. 07; Mo, Mao & White 98)

- About 1.5 million particles per galaxy model, best spatial resolution ~30 pc, gas mass resolution in satellite: 2500 M_o

- **Star formation** and blast-wave **supernova feedback** model (based on McKee & Ostriker 79 – see Stinson et al. 06) which produces realisitic disk galaxies in cosmological simulations (Governato et al. 07; Mayer, Governato & Kaufmann 08)

- Standard **BH accretion** (Bondi-Hoyle-Lyttleton) and thermal **AGN feedback**

$$\dot{M}_{\rm BH} = \frac{4\pi G^2 M_{\rm BH}^2 \rho_{\rm gas}}{(c_s^2 + v_{\rm rel}^2)^{3/2}} \qquad \frac{dE}{dt} = \epsilon\, \epsilon_{\rm rad}\, \dot{M}_{\rm BH}\, c^2$$



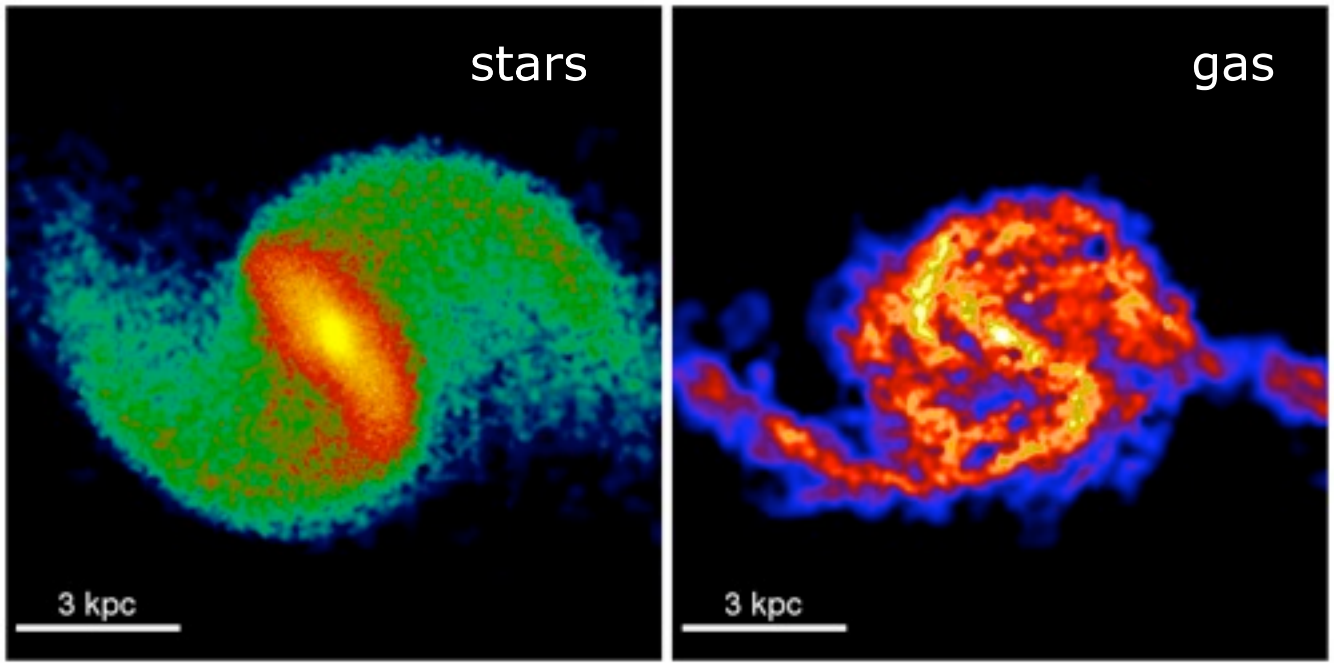
orbits of prograde mergers

The impact of gas physics/SF on the survivability of the satellite’s core translates into SMBH pairing efficiency

A dry satellite cannot dissipate energy gained via tidal shocks and is disrupted at large distances (~ a few kpc) where a “wandering” BH is left

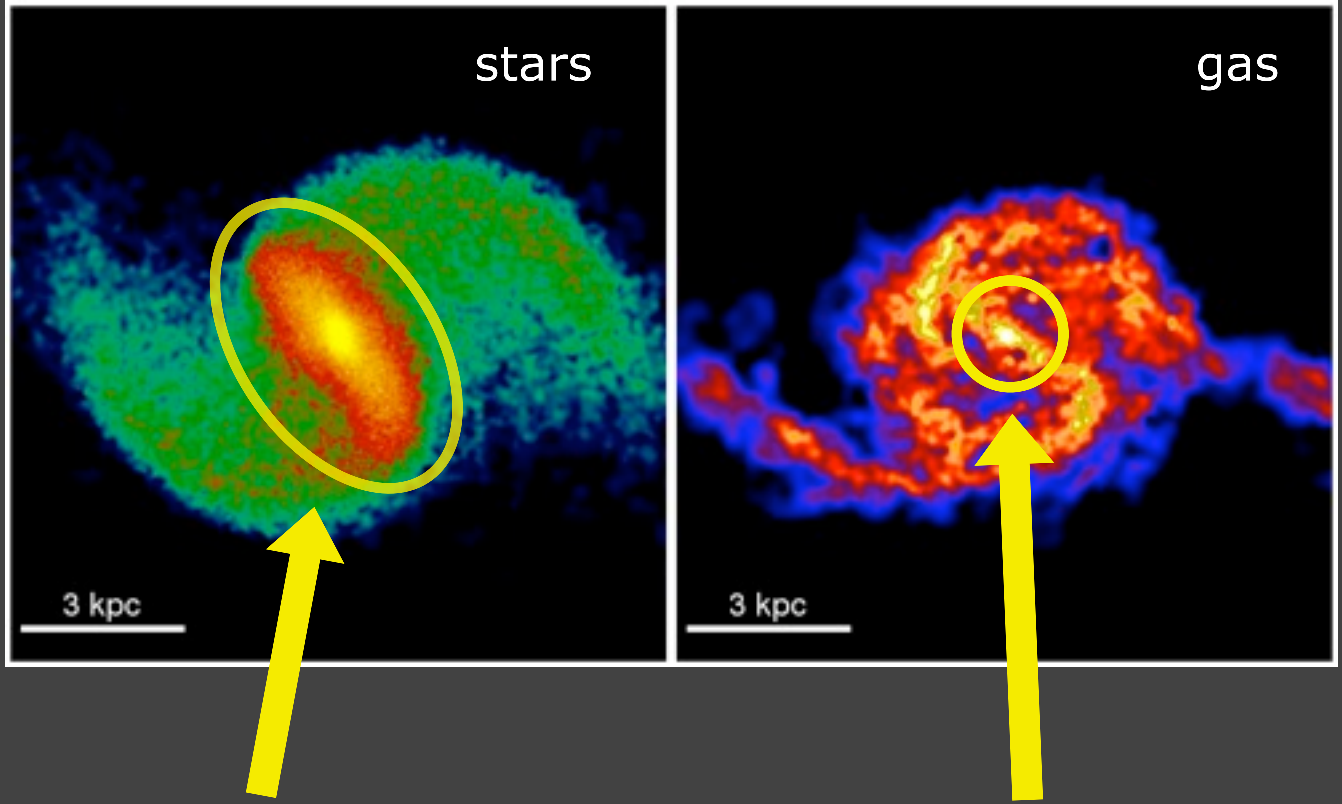
In all these unequal-mass cases, the presence of gas efficiently drives MBH pairing down to our force softening scale

From multi-scale 1:1 results (Mayer et al. 07) we can argue that
the MBHs will form a bound binary at ~ 1 pc scale
if they “pair” below ~100 pc and nucleus of remnant is not gas-poor



1:4 merger at z=0
gas 10%

t = 5.75 Gyr
(second apocenter)



1:4 merger at z=0
gas 10%

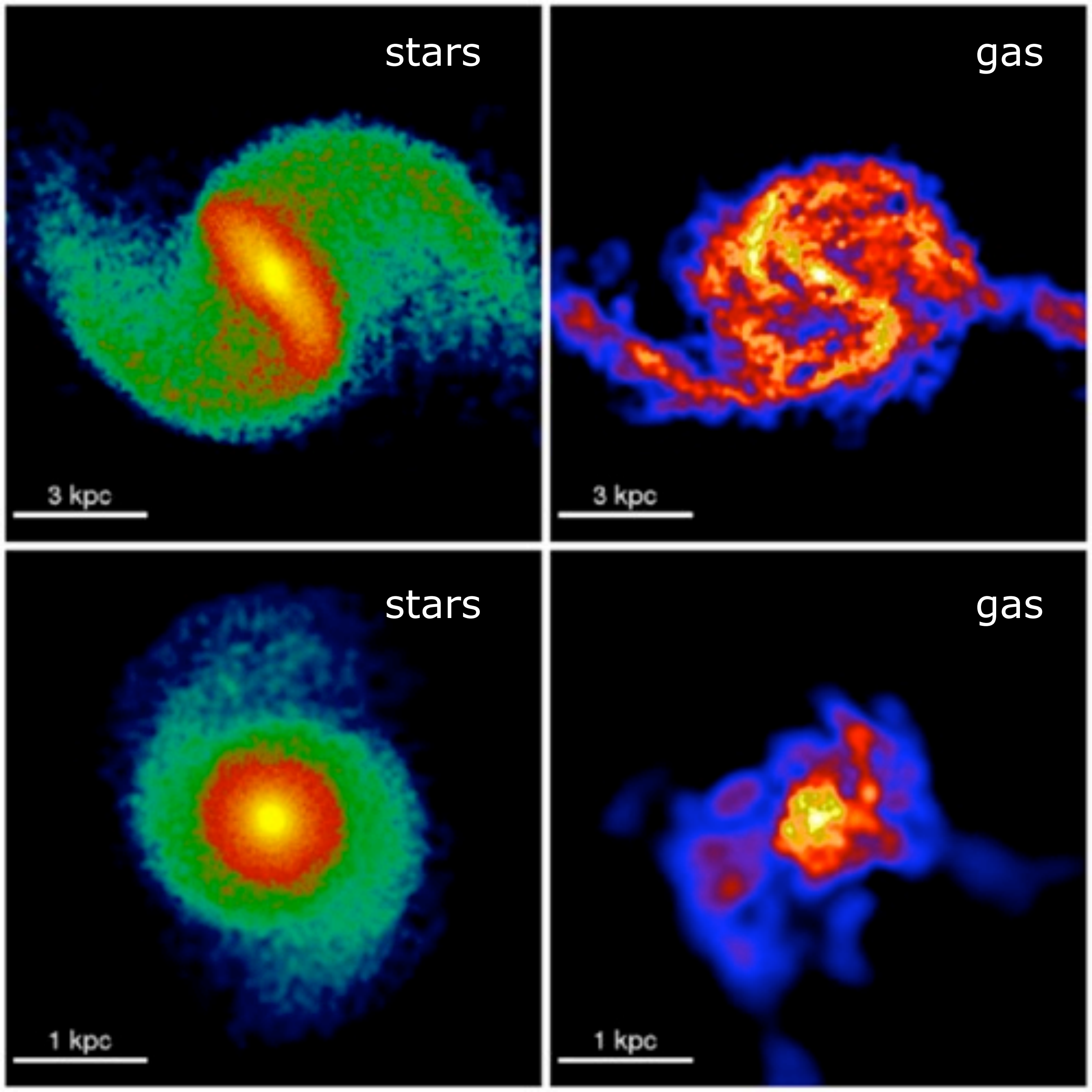
t = 5.75 Gyr
(second apocenter)

strong bar instability

gaseous inflow driven
by torques exerted by
the stellar bar

A *gas-rich* dense core survives tidal stripping/shocks,
dragging the SMBH within it

The SMBH sinks in ~100 Myr from ~10 kpc down to ~300 pc



1:4 merger at z=0
gas 10%

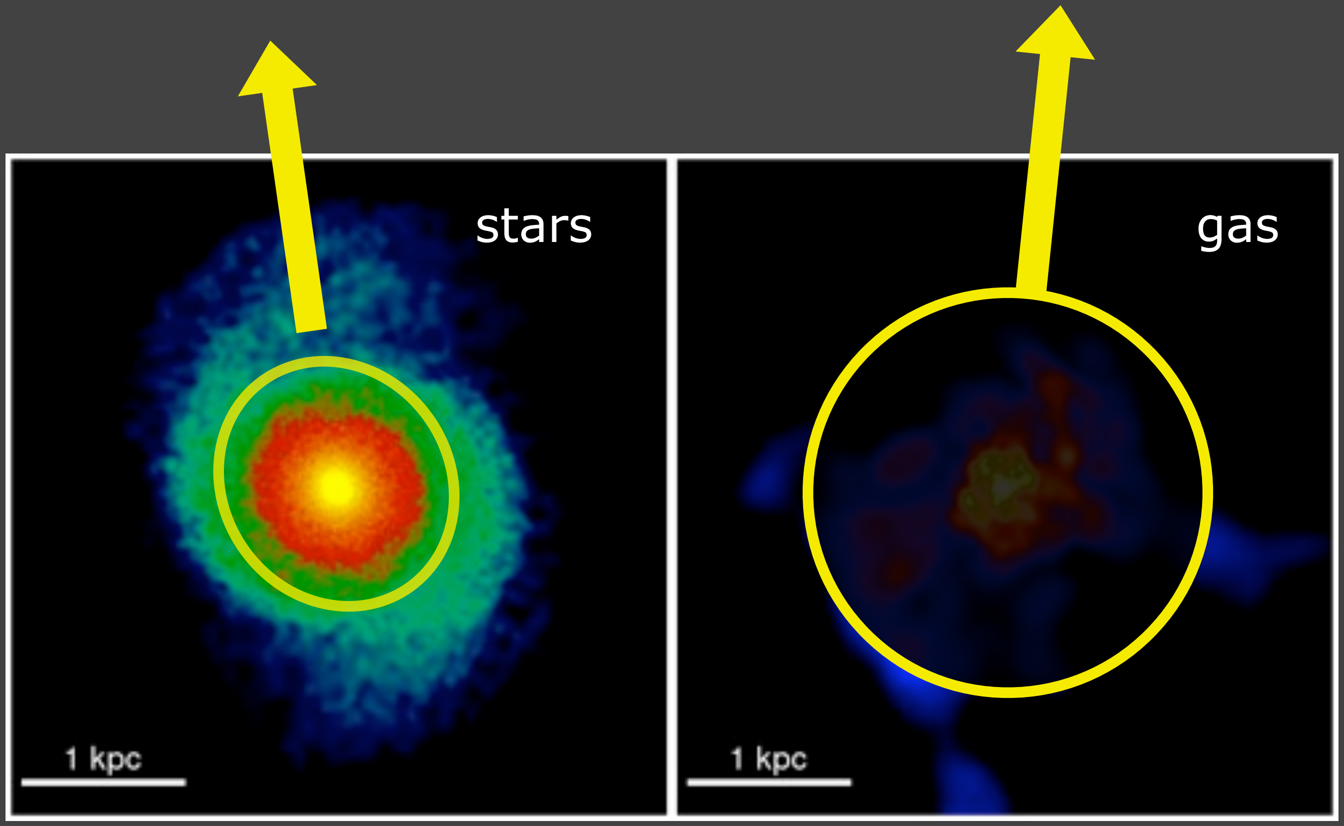
t = 5.75 Gyr
(second apocenter)

1:10 merger at z=3
gas 30%

t = 1.35 Gyr
(second apocenter)

A *gas-poor but dense* core survives tidal stripping/shocks

The SMBH sinks in ~100 Myr from ~3 kpc down to ~30 pc

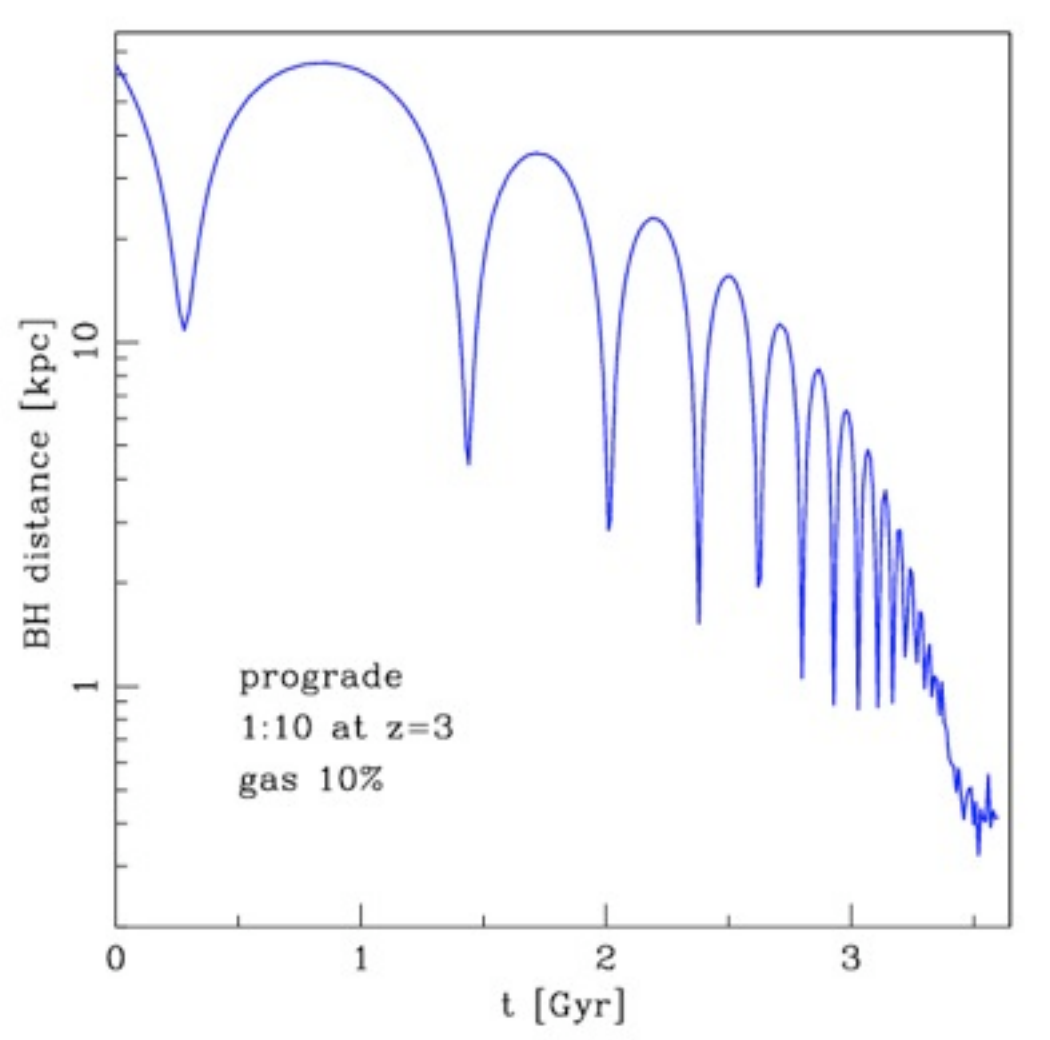


concentrated star formation due to inflow and compressive tides

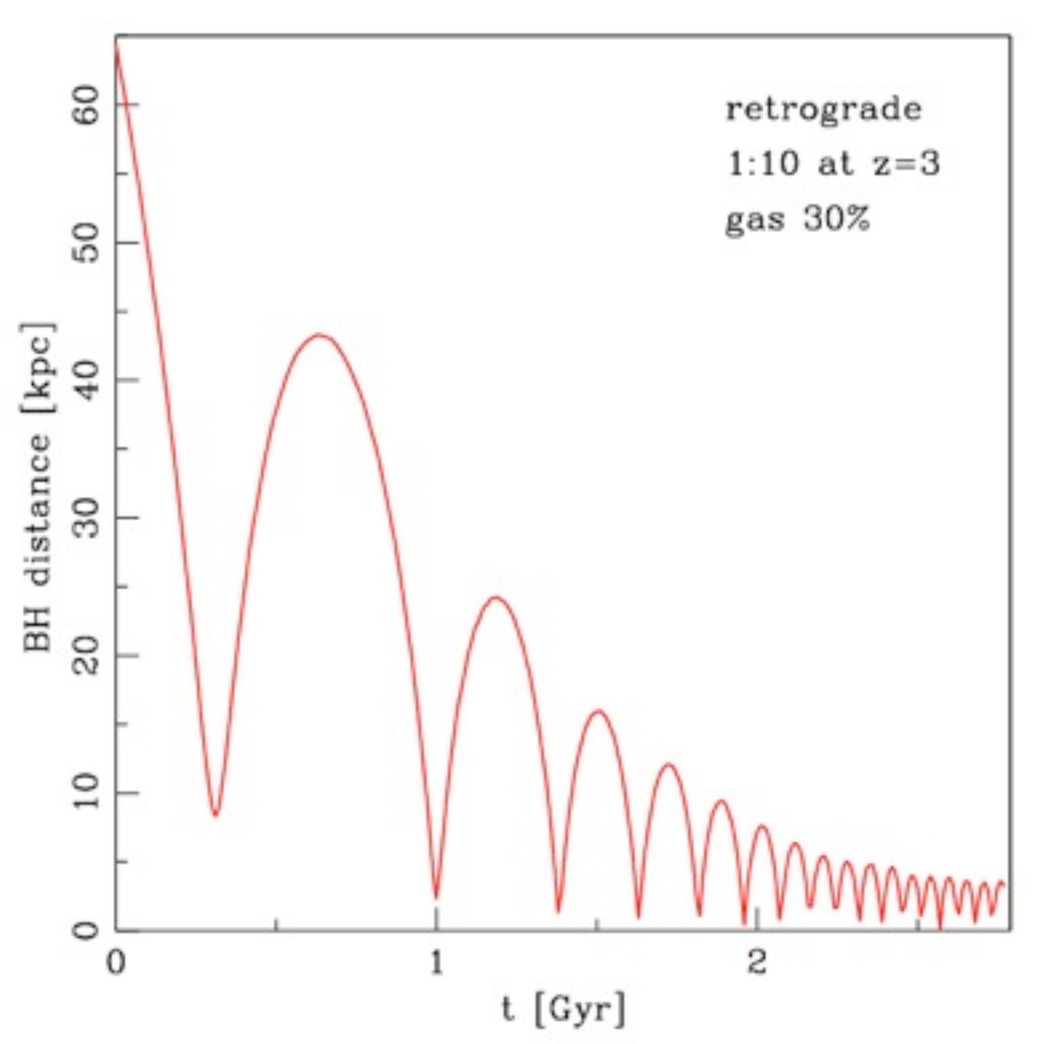
ram pressure stripping of the gas in the satellite after first two orbits

1:10 merger at z=3
gas 30%

t = 1.35 Gyr
(second apocenter)



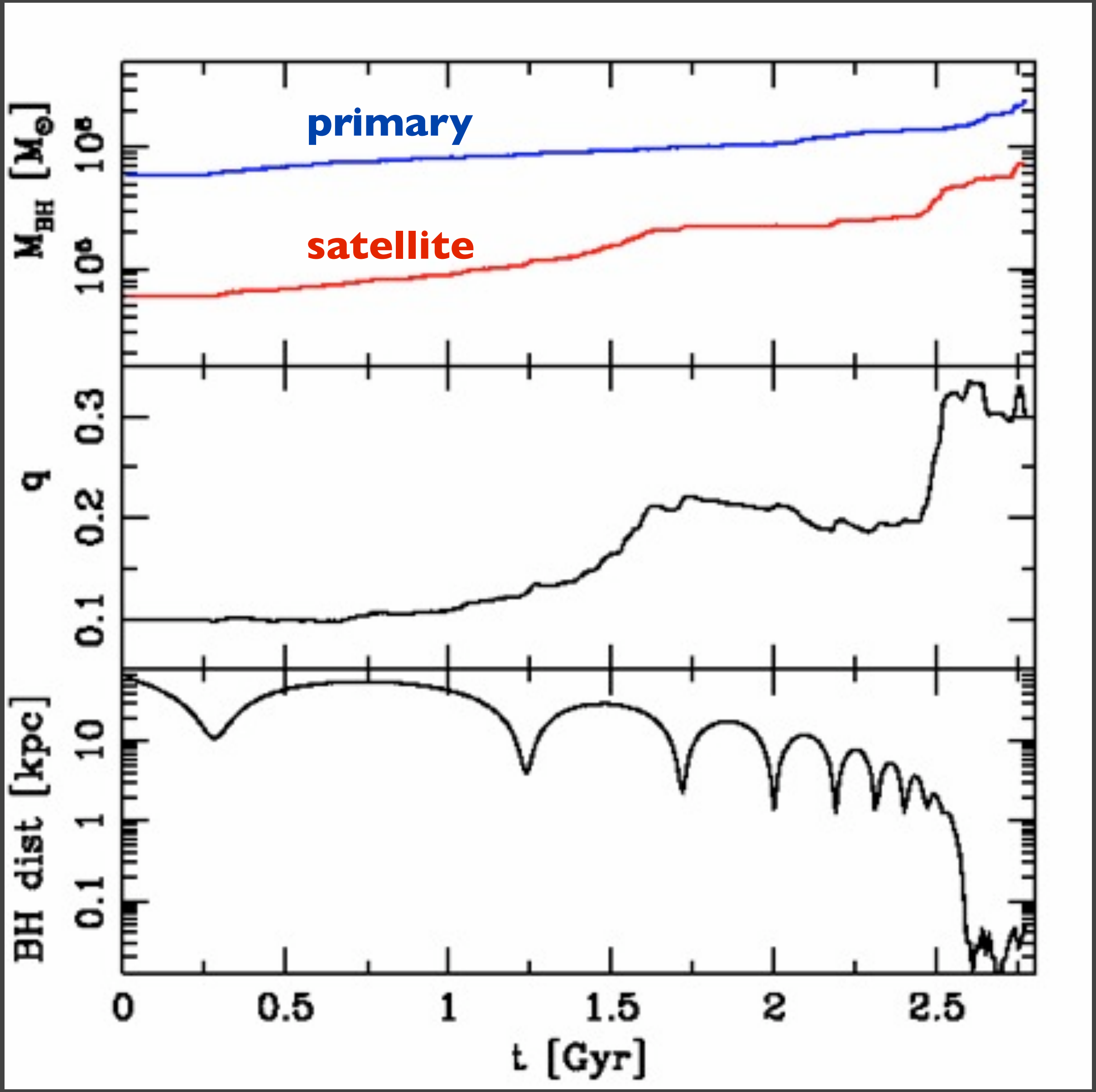
- with lower gas fractions, the SMBH is left at larger distances in the bulge, with dynamical friction timescales < t_{Hubble} :
delay of pair formation



- with lower gas fractions, the SMBH is left at larger distances in the bulge, with dynamical friction timescales < t_{Hubble} : **delay of pair formation**

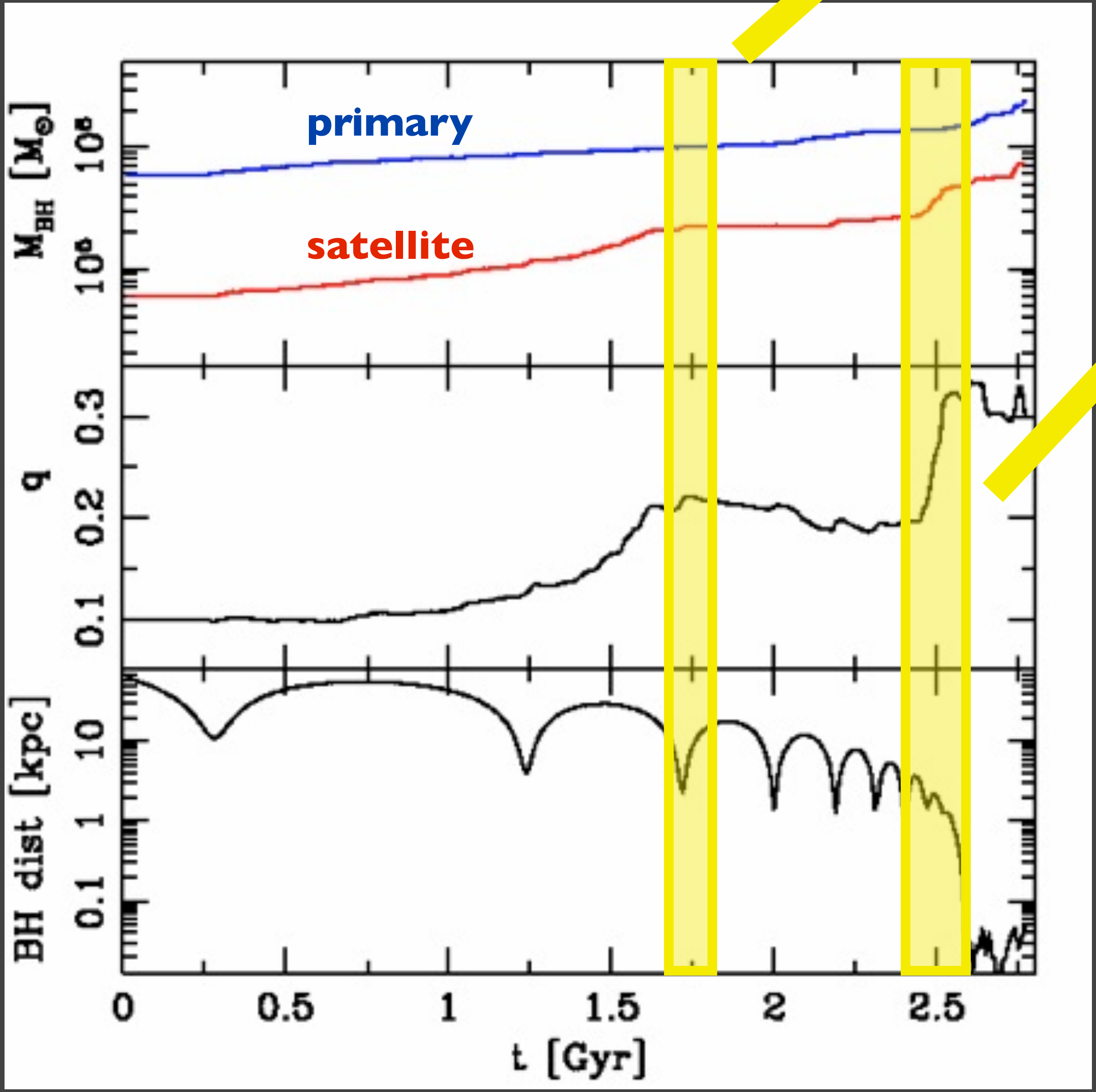
- in retrograde mergers, the satellite undergoes more tidal shocks: **a "wandering" BH is left** at a few kiloparsecs from the center, where dynamical friction timescales are > t_{Hubble}

MBH evolution
1:10 merger
z=3
gas 30%



the MBH mass ratio increases in the first two orbits because tides act more strongly on the satellite, relative to the primary galaxy

MBH evolution
1:10 merger
z=3
gas 30%



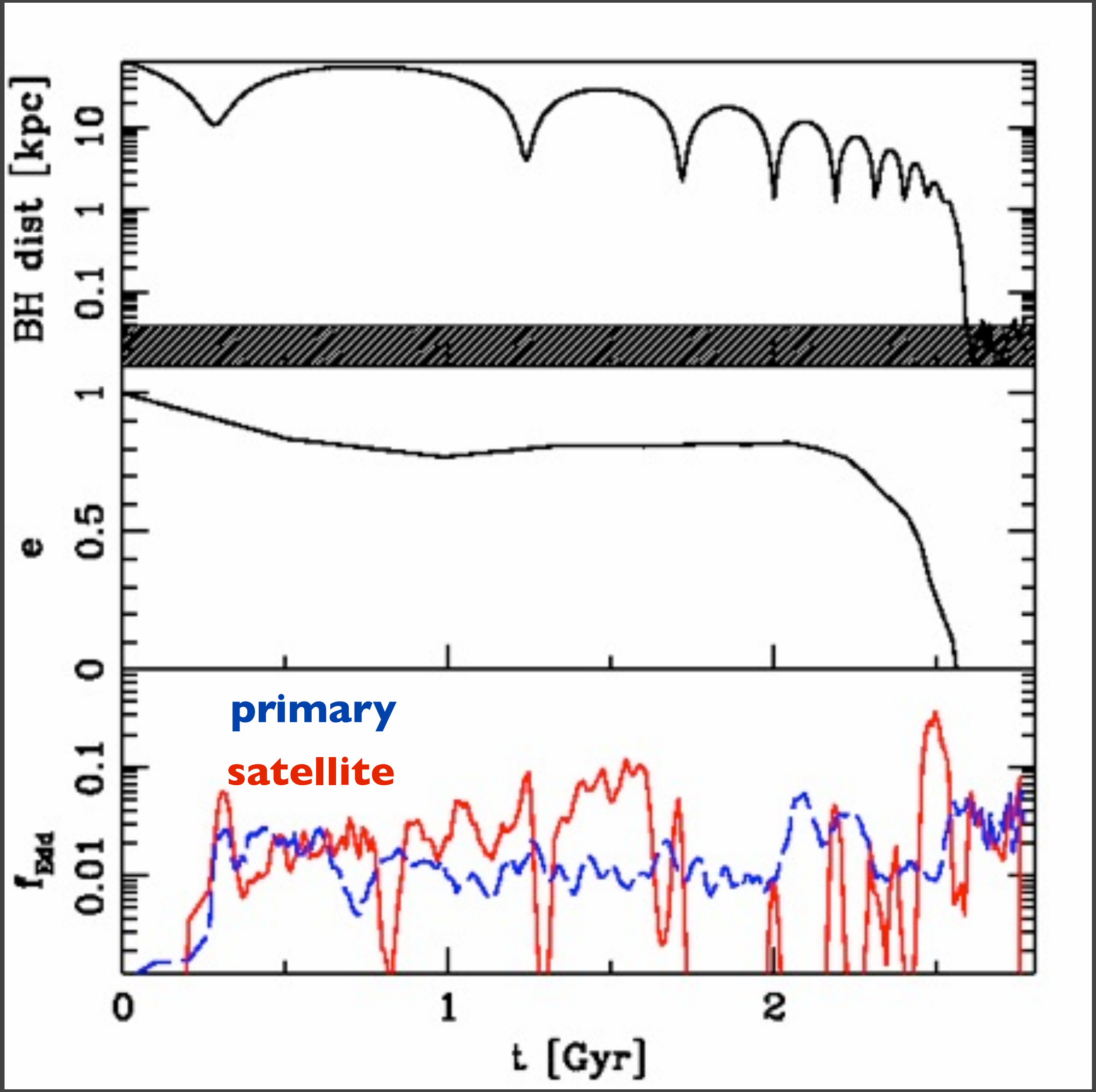
ram pressure stripping
halts MBH growth
in the satellite
at third pericenter

a second increase in mass ratio happens at the last stage of inspiral (~ 1 kpc)

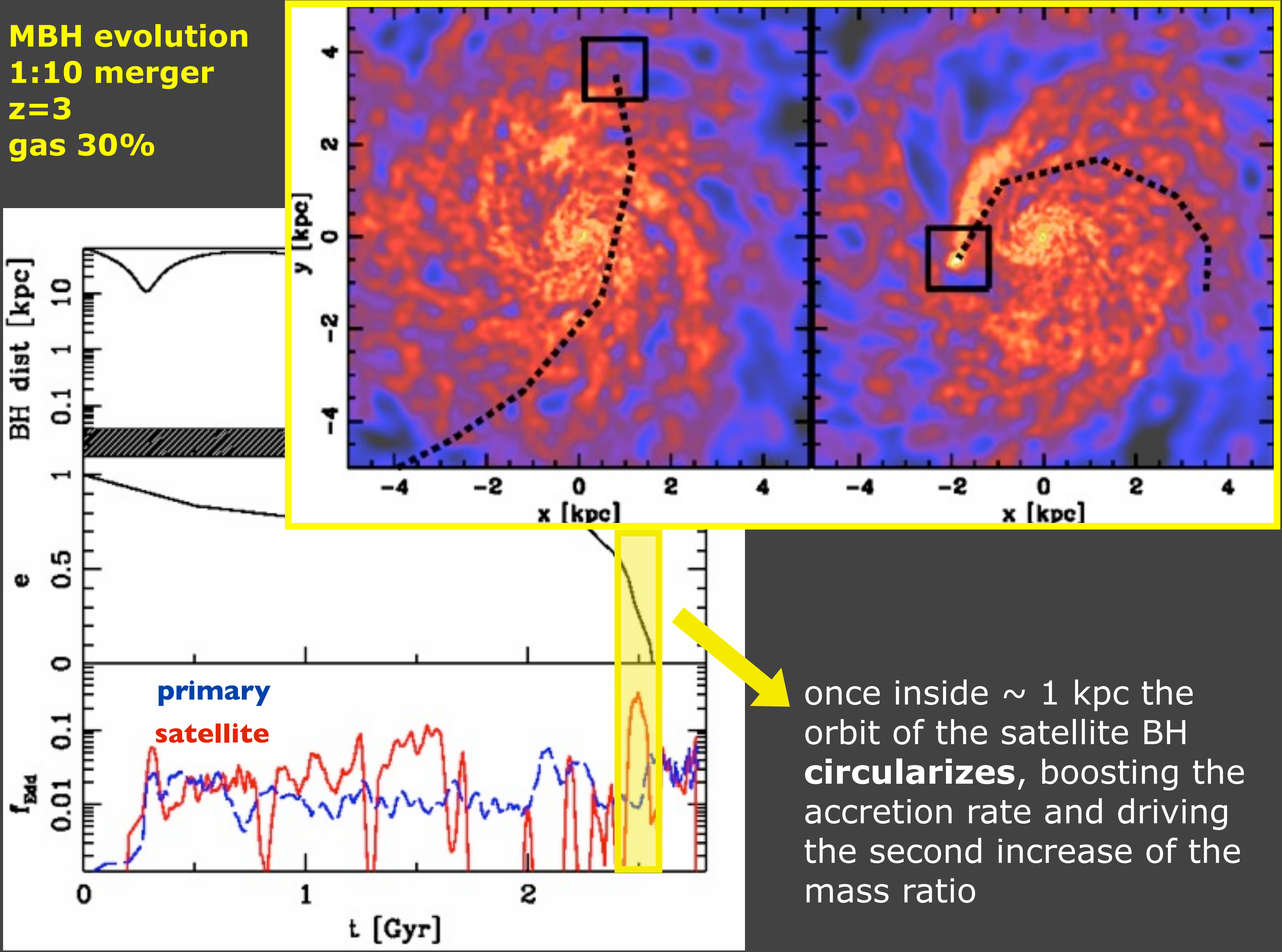
the MBH mass ratio increases in the first two orbits because tides act more strongly on the satellite, relative to the primary galaxy

MBH evolution

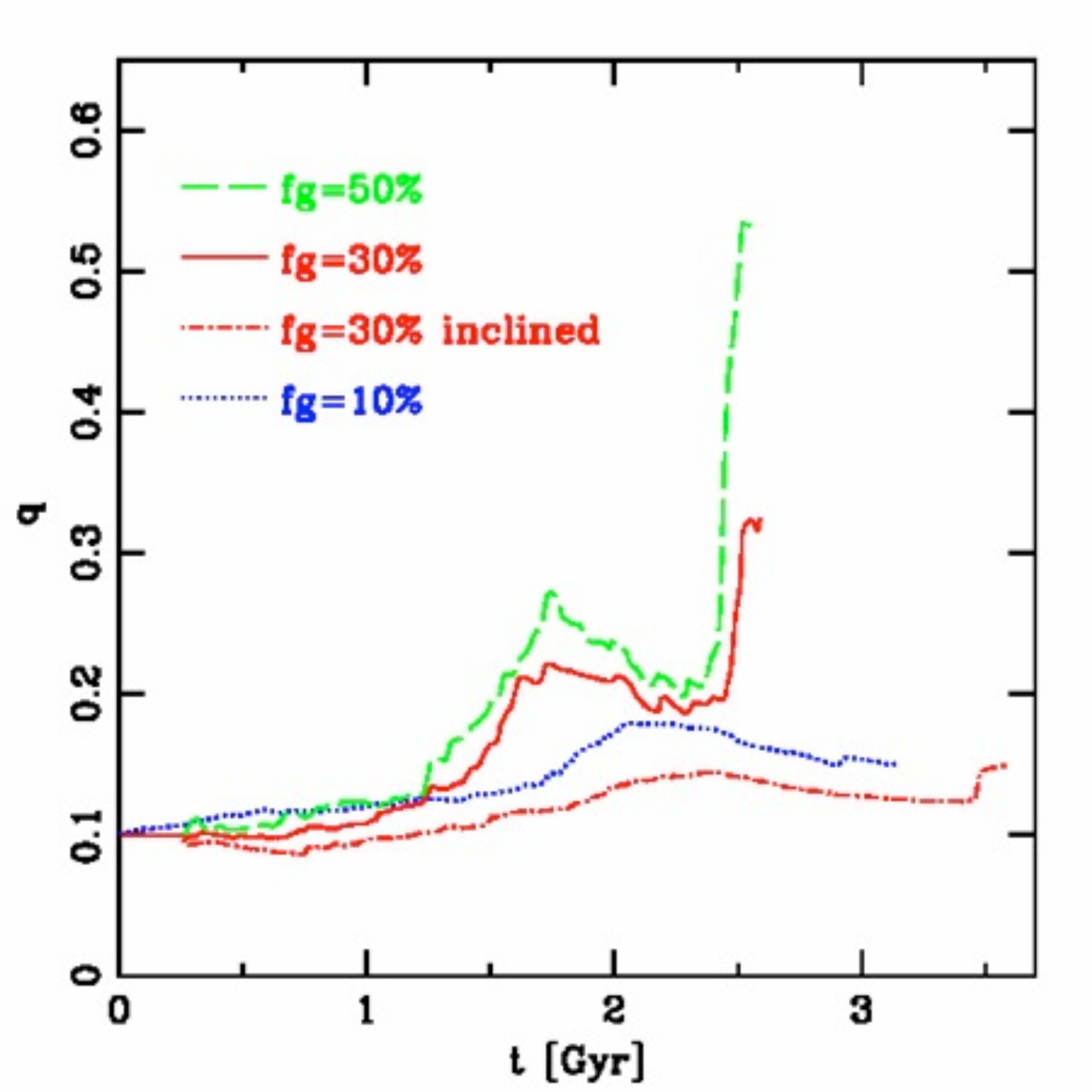
1:10 merger
z=3
gas 30%



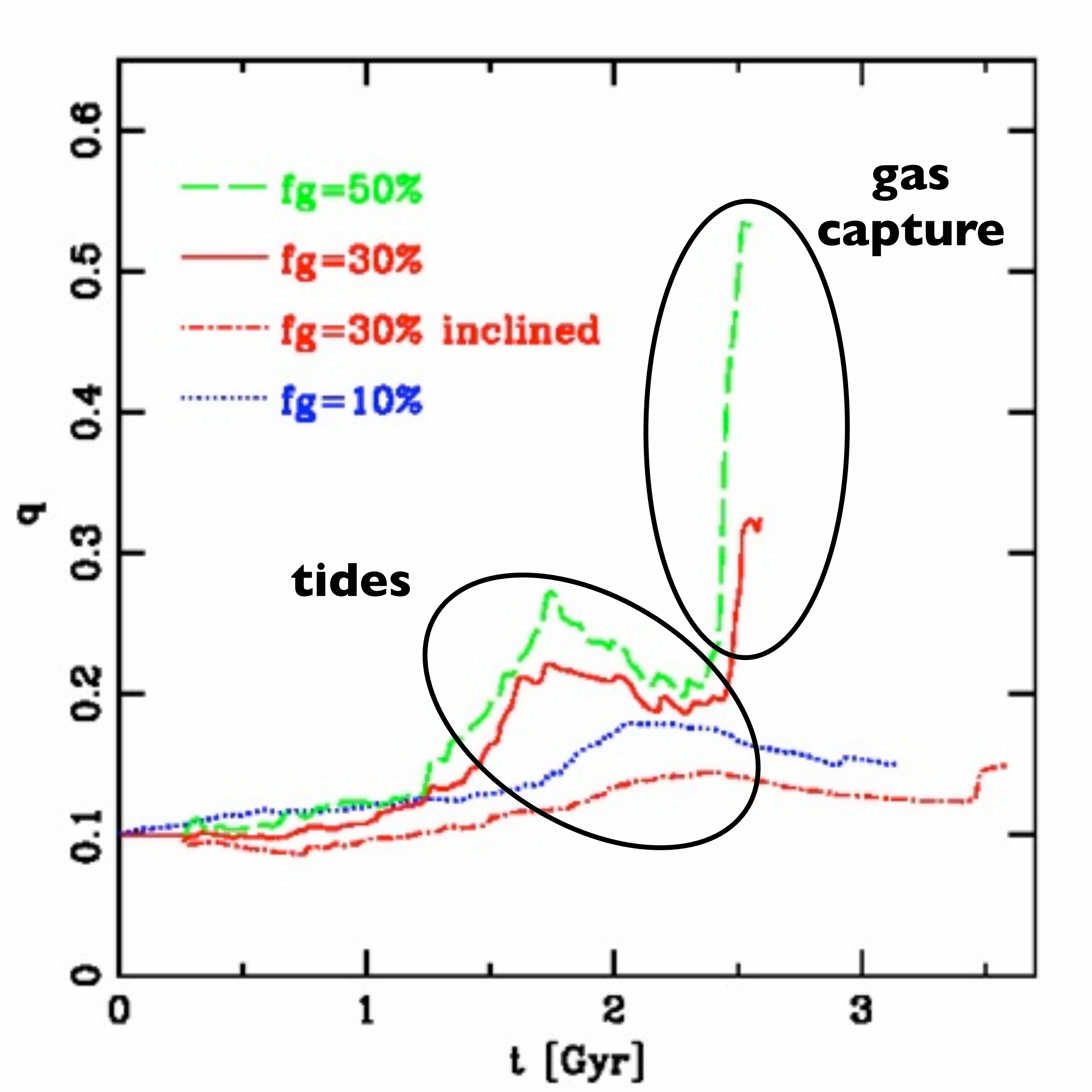
MBH evolution
1:10 merger
z=3
gas 30%



once inside ~ 1 kpc the orbit of the satellite BH **circularizes**, boosting the accretion rate and driving the second increase of the mass ratio



mass ratios of 1:10 mergers



mass ratios of 1:10 mergers

Depending on the gas fraction of the galaxy disks and orbital evolution, there can be two main accretion modes for the MBH in the satellite:

- initial accretion due to **tidal perturbation** of the satellite

- second phase due to **gas capture** when the orbit circularizes in the central region of the primary galaxy (see Dotti et al. 2009 for the analogue in circumnuclear gaseous disks)

In these cases, **the merger dynamics drives an increase in the mass ratio of the final MBH pair** compared to the expected value from scaling relations in the merging galaxies

Summary

The gas component in galaxies can drive the formation of MBH binaries, from large to small scales

- at > 1 kpc scales, it can determine whether or not the cores of two galaxies will merge and MBH pair can form (unequal-mass case)

The properties of MBH pairs are sensitive to details of merger physics

- occurrence and promptness of MBH pairing in unequal-mass mergers is sensitive to orbital/structural parameters

- the mechanisms that drive MBH pairing also increase the MBH mass ratio

- final mass ratio can be very different compared to what inferred from initial conditions and MBH scaling relations

Forthcoming work

- Use remnants for MBH recoil studies
(with Javiera Guedes and Piero Madau at UCSC)

- Map N-body/SPH results into semianalytics of galaxy/MBH coevolution
(with Marta Volonteri at Univ. Michigan)

- Quantify the relative importance of MBH feeding via secular instability, minor interactions or major mergers during the history of a galaxy

- Use fully cosmological simulations
(Callegari, Mayer et al. in prep.)

- Improved ISM physics in nuclear disks via a multiphase model of the gas
(with Rok Roskar at Univ. Washington)