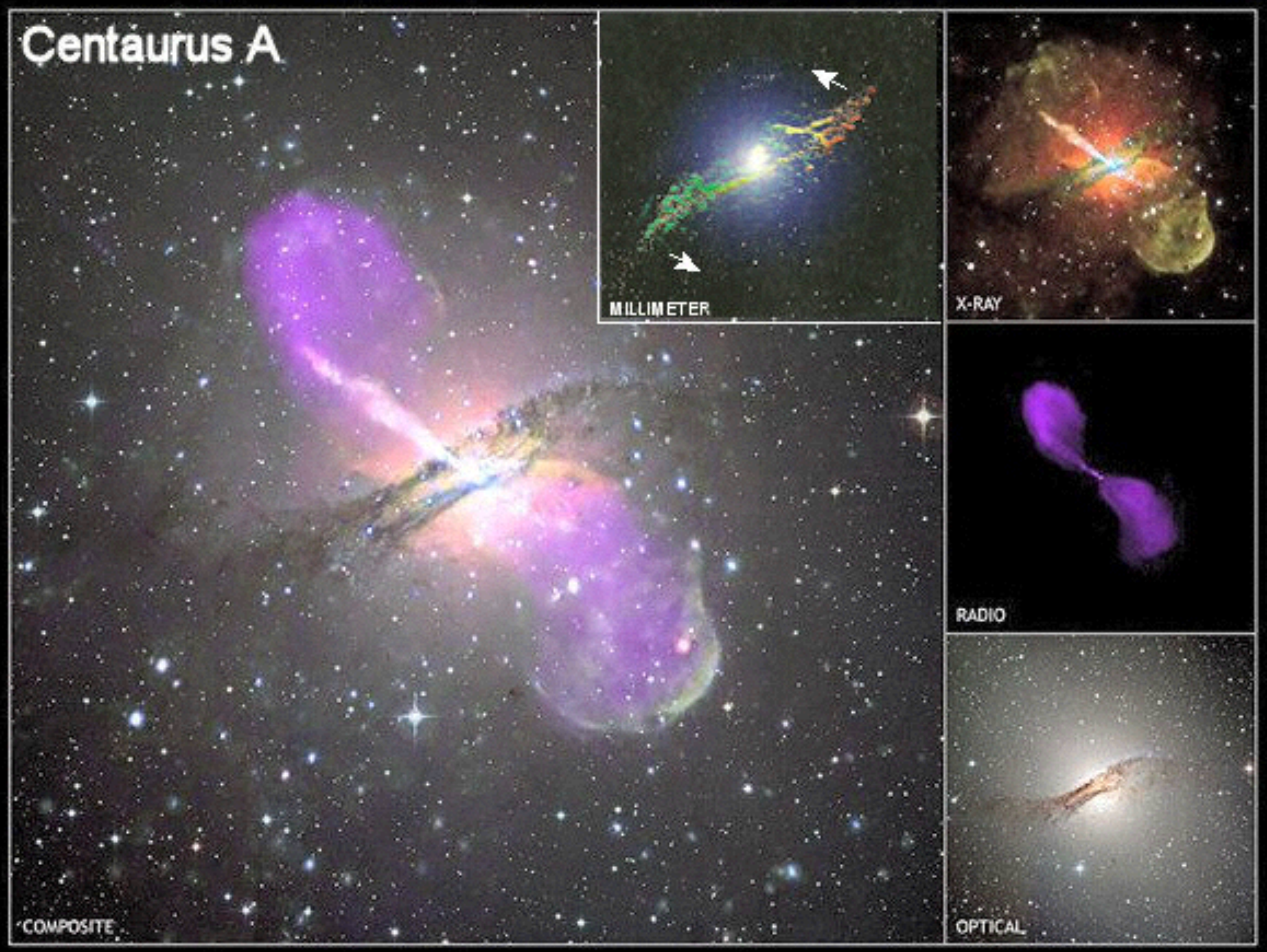
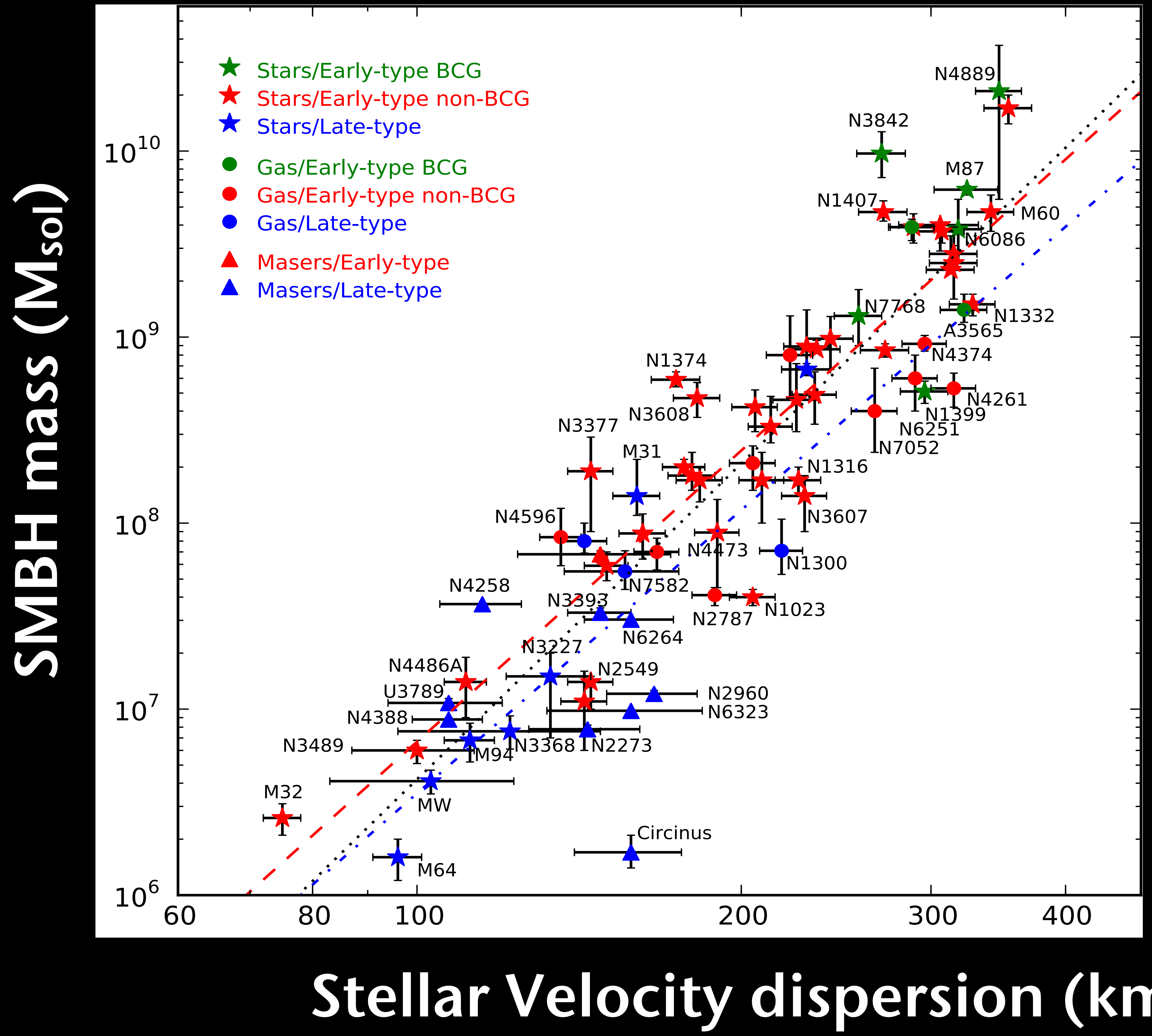
() Accreting Supermassive Black Holes (SMBHs) explain energetics of Active Galactic Nuclei (AGNs) and QSOs
() "Dormant" SMBHs from dynamical evidence: best example is Galactic Center

M_{BH}-σ; M_{BH}-Mbulge; M_{BH-} L *(Magorrian et al. 1998; Ferrarese et al. 2000;2006; Gebhardt et al. 2000 ; Lauer et al. 2006;2007;Tremaine et al. 2002; Gultekin et al. 2009)*

Black holes masses from tracers of dynamics in galactic nuclei (gas and/or stars at large radii, broad-line region for accreting BHs)



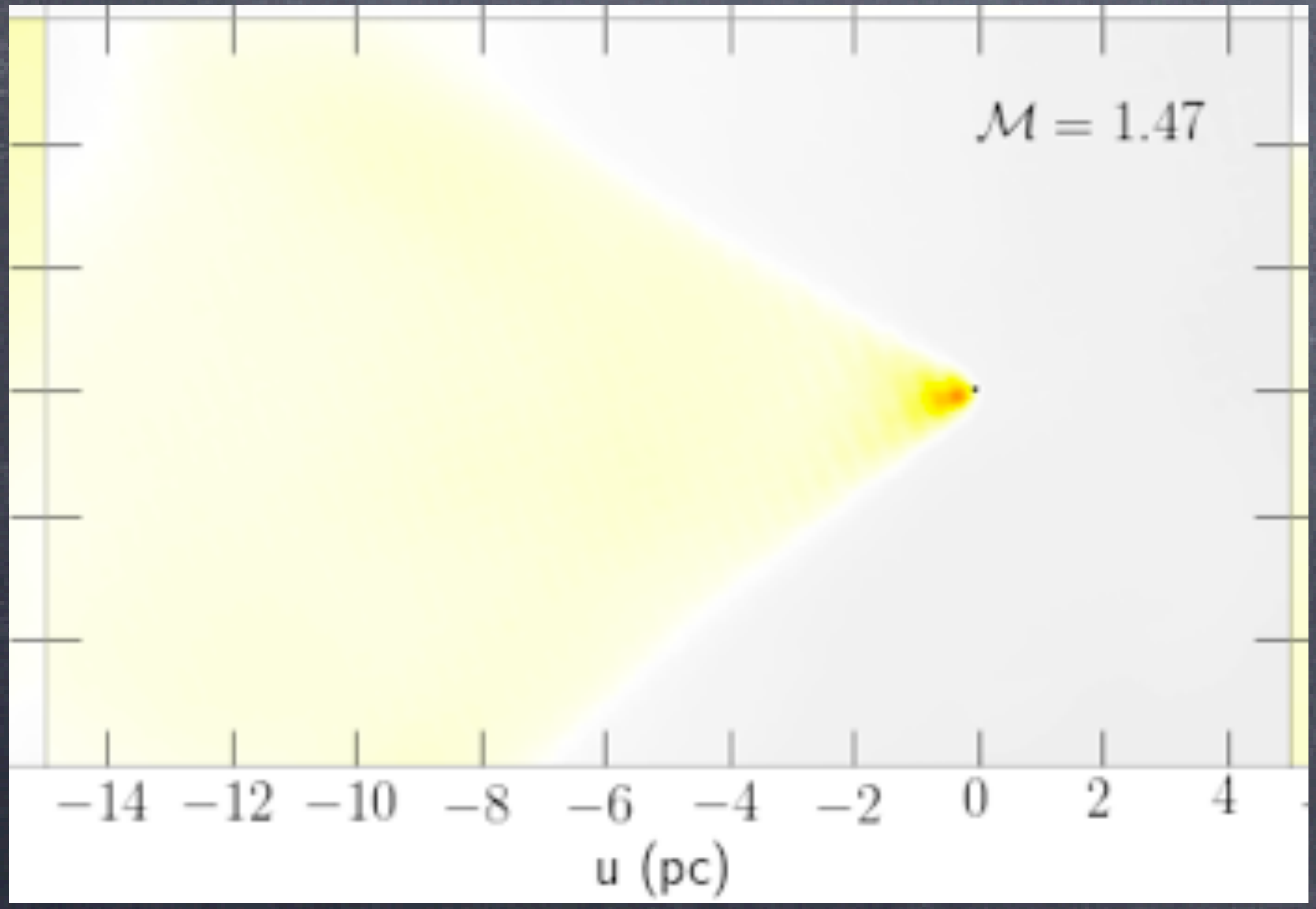


McConnell & Ma (2013)

Stage 2: The two SMBHs (SMBH pair) end up in the nucleus of the new galaxy arising from the merger and will continue to reduce their separation via dynamical friction (DF) against background (gas, stars, DM) until they form
a bound BINARY. Chandrasekhar's formula (1943) can be used for DF in
both collisionless (stars, DM) and gaseous background (has extra dependence on *Mach number* = V_{BH}*/thermal sound speed*)

$$\mathbf{F}^{\rm gas}_{\rm DF} = -4\pi \ln\left[\frac{b_{\rm max}}{b_{\rm min}}\frac{(\mathcal{M}^2-1)^{1/2}}{\mathcal{M}}\right] G^2\, M^2_{\rm BH}\rho_{\rm gas}\frac{\mathbf{V}}{V^3}, \quad \text{for} \quad \mathcal{M} > 1$$

Ostriker 1999; Colpi & Dotti 2011;
Chapon, Mayer & Teyssier 2013



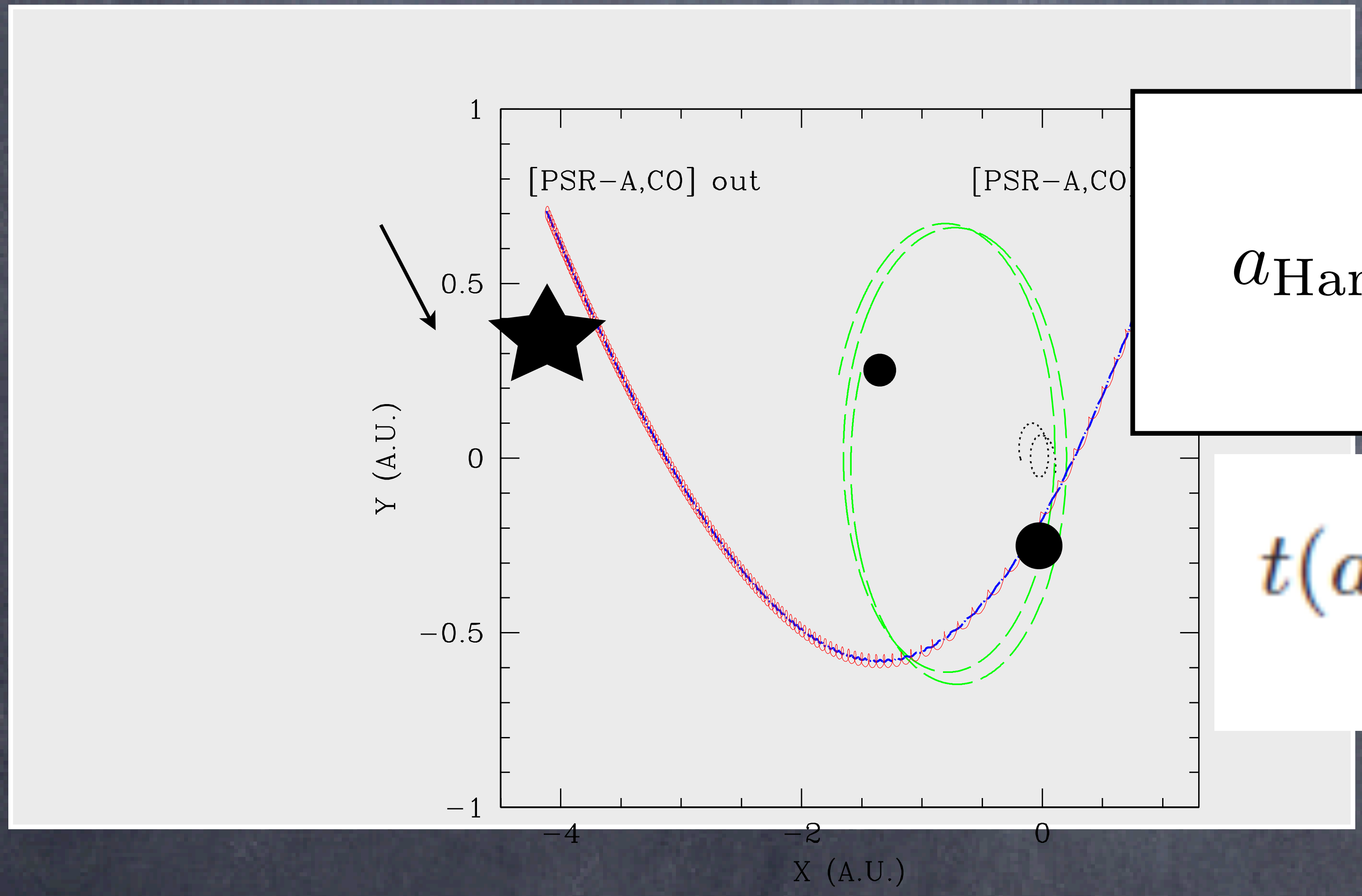
Dynamical Friction for target body (eg MBH) moving supersonically with velocity V on a straight line in infinite homogeneous gaseous medium with density ρ
(impact parameter "b_{max}" and "b_{min}" yield empirical truncation on interaction length for finite size system).

Stage 3 - Hardening Phase

At separations **a_{Hard}** such that the sum of the BH masses becomes larger than the gas/stars mass enclosed by their orbit dynamical friction is suppressed.

At this point energy loss in gravitational 3-body encounters between binary BHs and individual stars can take over the orbital decay process (Milosavljevic & Merritt 2001;2006; Berczik et al. 2006; Khan et al. 2013)

BUT THIS PROCESS EFFICIENT ONLY IF “LOSS CONE” REMAINS FILLED
IN IDEALIZED SPHERICAL ISOTROPIC GALAXIES (NO GAS) LOSS CONE EMPTIES QUICKLY ---> *LAST PARSEC PROBLEM (Milosavljevic & Merritt 2001)*



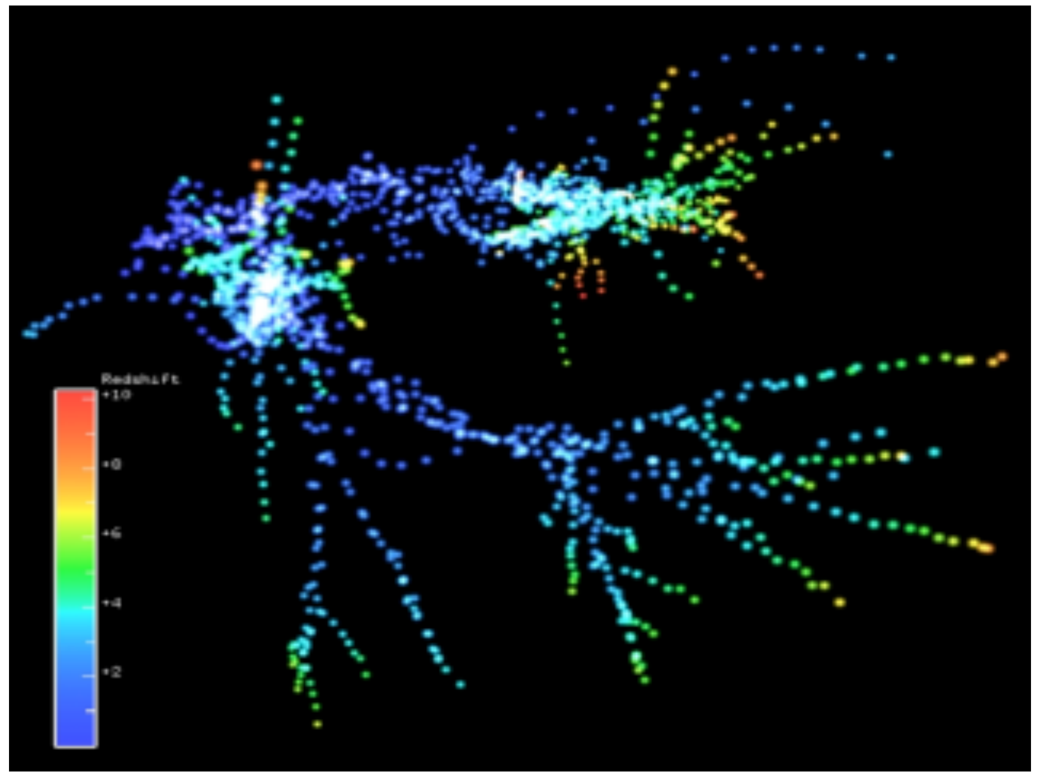
$$a_{\mathrm{Hard}} \sim \frac{G\mu_{\mathrm{BH}}}{3\sigma^2} \sim 3\,\frac{q_{\mathrm{BH}}}{(1+q_{\mathrm{BH}})^2}\,\frac{M_{\mathrm{BH,T}}}{10^8 M_\odot}\left(\frac{200\,\mathrm{km\,s^{-1}}}{\sigma}\right)^2 \mathrm{pc}$$

$$t(a_{*/\mathrm{gw}}) = \frac{\sigma_{\mathrm{inf}}}{GH\rho_{\mathrm{inf}}a_{*/\mathrm{gw}}}.$$

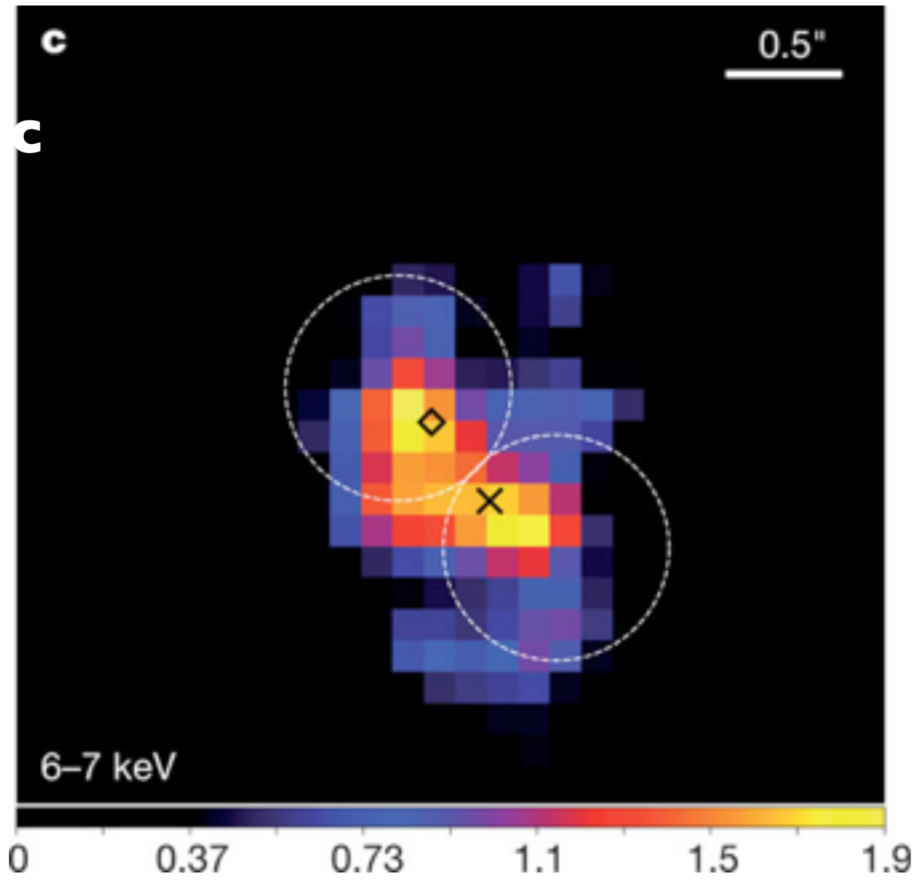
Hardening timescale for separation at which energy loss by 3-body scattering = energy loss by GW (Sesana & Khan 2015)

Proposal: in triaxial stellar systems centrophilic chaotic orbits refill loss cone and make hardening possible, GW-dominated regime reached in < a few Gyr (eg Berczik et al. 2006; Khan et al. 2012;2013), but see Vasiliev et al. (2014)

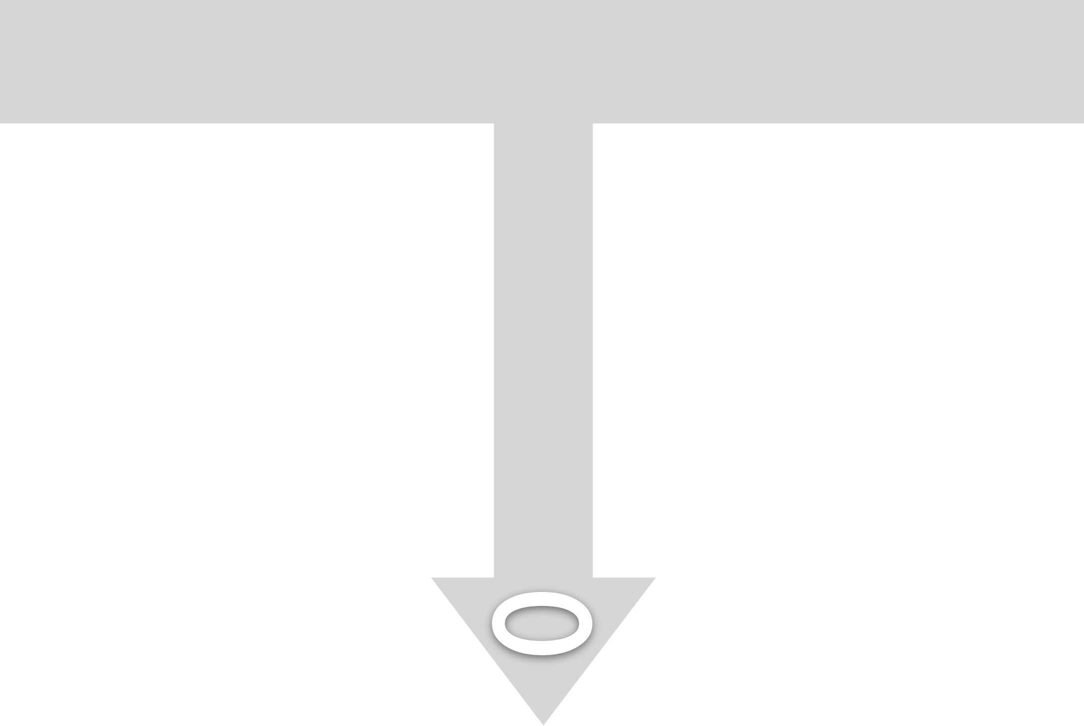
DUAL MASSIVE BLACK HOLES ($M_{BH} > 10^5$ Mo) OBSERVED IN GALAXIES AS D
AGNs



HIERARCHICAL ASSEMBLY OF
GALAXIES IN
STANDARD COSMOLOGY
(ΛCDM)



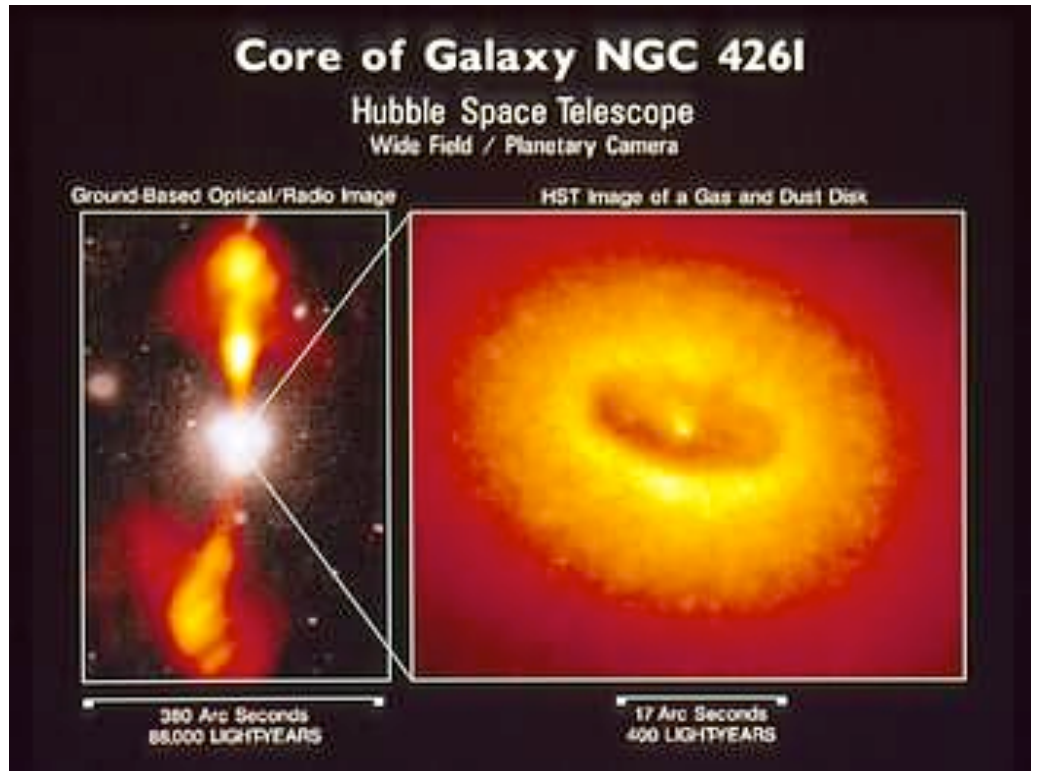
NGC 3393, Fabbiano et al. (2011)



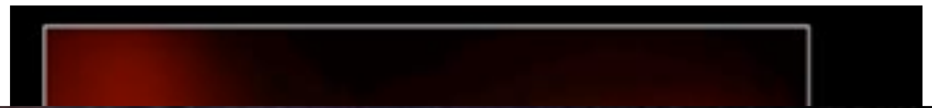
DUAL AND
BINARY MASSIVE
BLACK HOL
(MBHs)

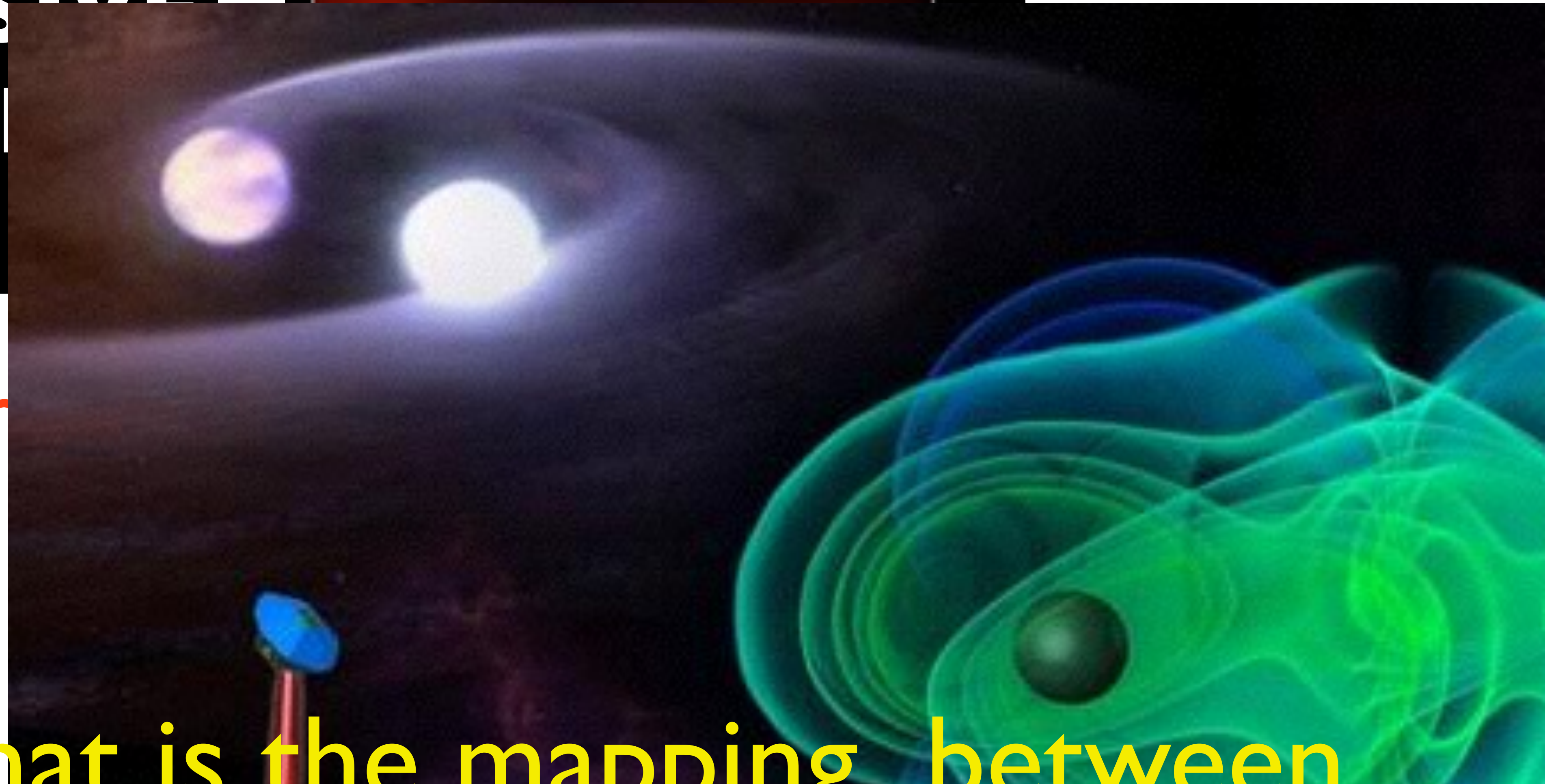
Separations between ~
and ~10 kpc

Begelman et al. (1980);
Dotti & Colpi (2009);
Mayer (2013)



SMBH IN GALAXIES TO
POWER X-RAY/UV EMISSION
FROM GALACTIC NUCLEI





What is the mapping between

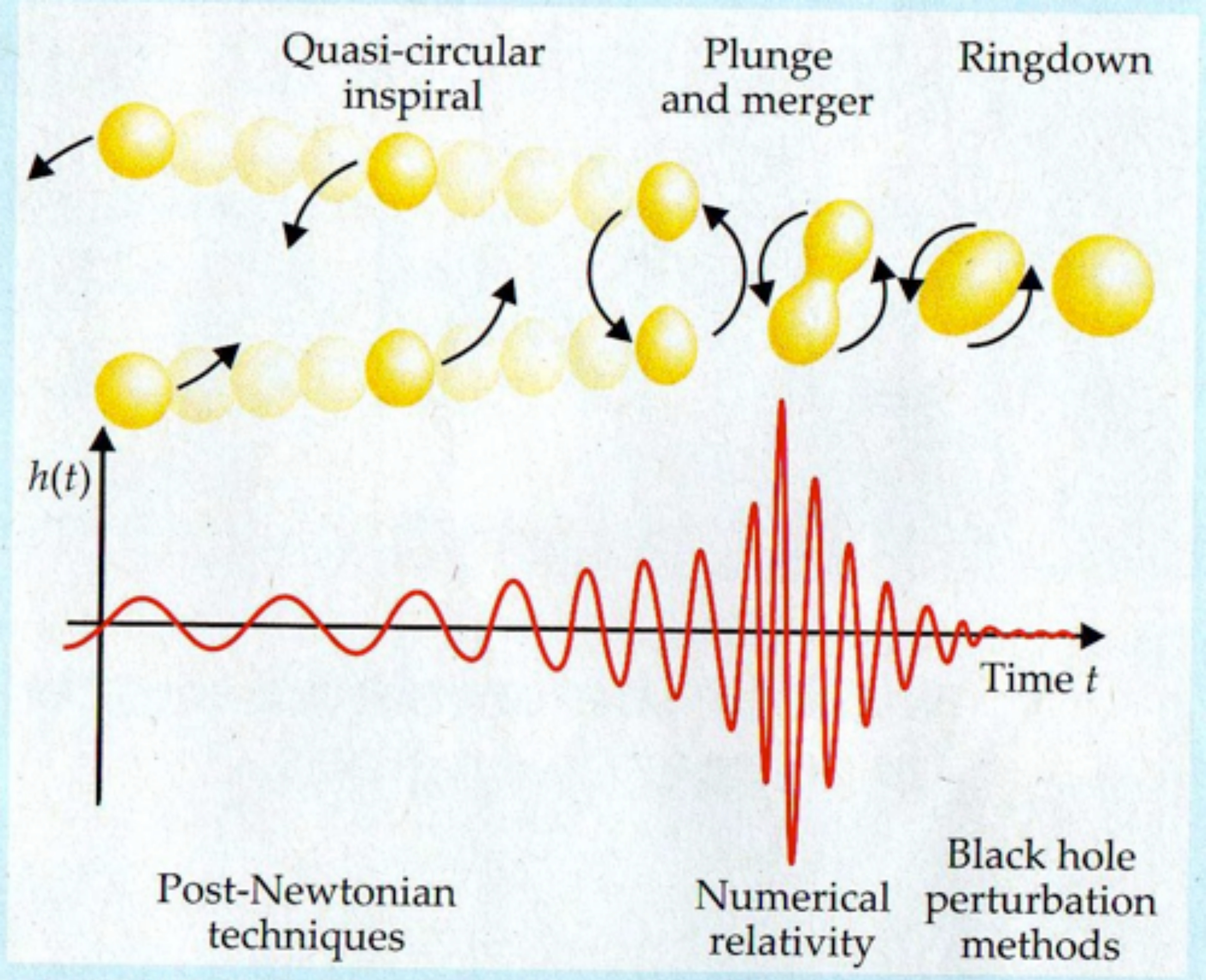
Stage 4 - when separation decreases further eventually the energy loss of the binary by gravitational wave radiation becomes stronger than the energy loss via 3-body scattering

BHs will coalesce on a timescale
set by rate of energy loss via GWs

$$t_{\rm GW} \propto (1 - e^2)^{7/2} \frac{a^4}{M^3_{\rm BH,T}}$$

t_{GW} <~ 10^8 yr << T_{hubble}
for SMBHs with separation
a ~ 10^{-2} pc and M_{BH} ~ 10^7 Mo,
zero eccentricity
--> t_{gw} comfortably smaller
than lookback time at z ~ 2-6,
where eLISA has high sensitivity
(high eccentricity would reduce
timescale significantly)

Can we shrink a SMBHs binary to separation ~10^{-2} pc in <~ 10^8 yr after the galaxies have merged?



We will now explore critically and at great depth the conditions and physical processes relevant to the various stages.

From now on this talk will:

(a) provide evidence that SMBH should merge
in realistic environments (i.e. no last parsec problem!)

(b) provide evidence that in certain conditions orbital decay can be fast , namely SMBHs reach GW emission stage in <~ 10^8 yr after galaxies have merged

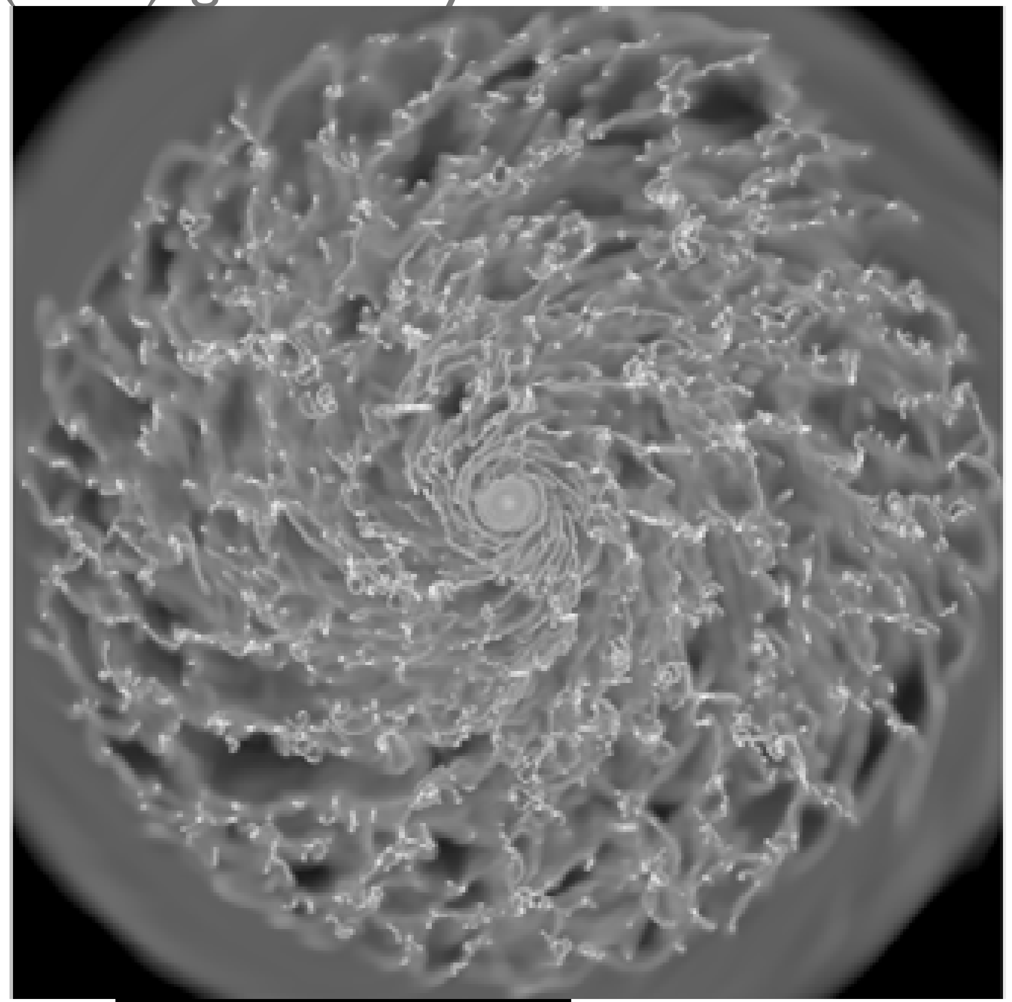
(c) show that coalescence not necessarily faster in gaseous environments as opposed to stellar environments

DYNAMICS OF SMBH PAIRS IN A CLUMPY INTERSTELLAR MEDIUM

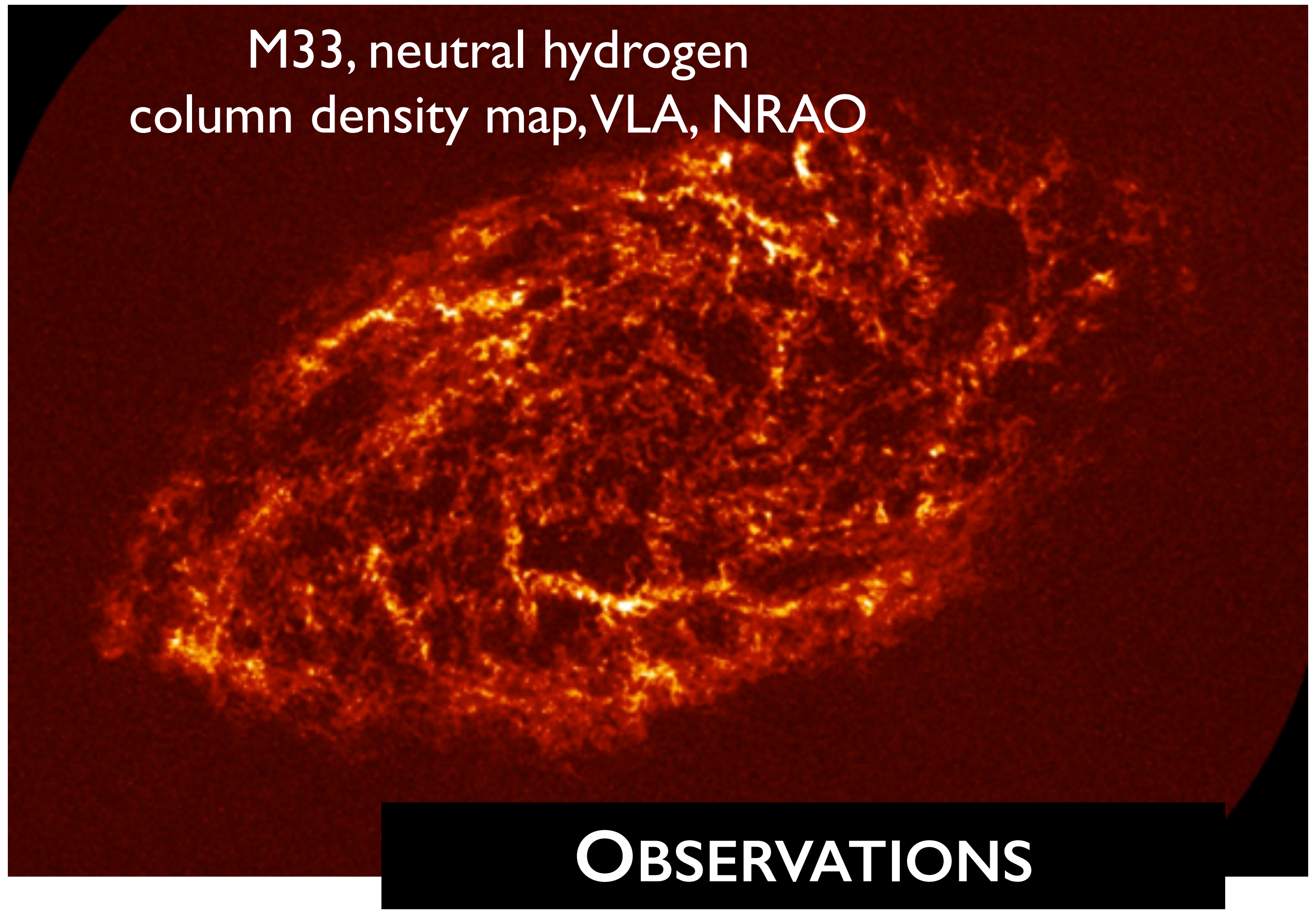
INTERSTELLAR GAS IN GALAXIES IS CLUMPY AND MULTI-PHASE

----> NOTION OF DYNAMICAL FRICTION/TORQUES IN SMOOTH BACKGROUND INADEQUATE!

Tasker & Tan (2009): gas density in disk simulation



THEORY



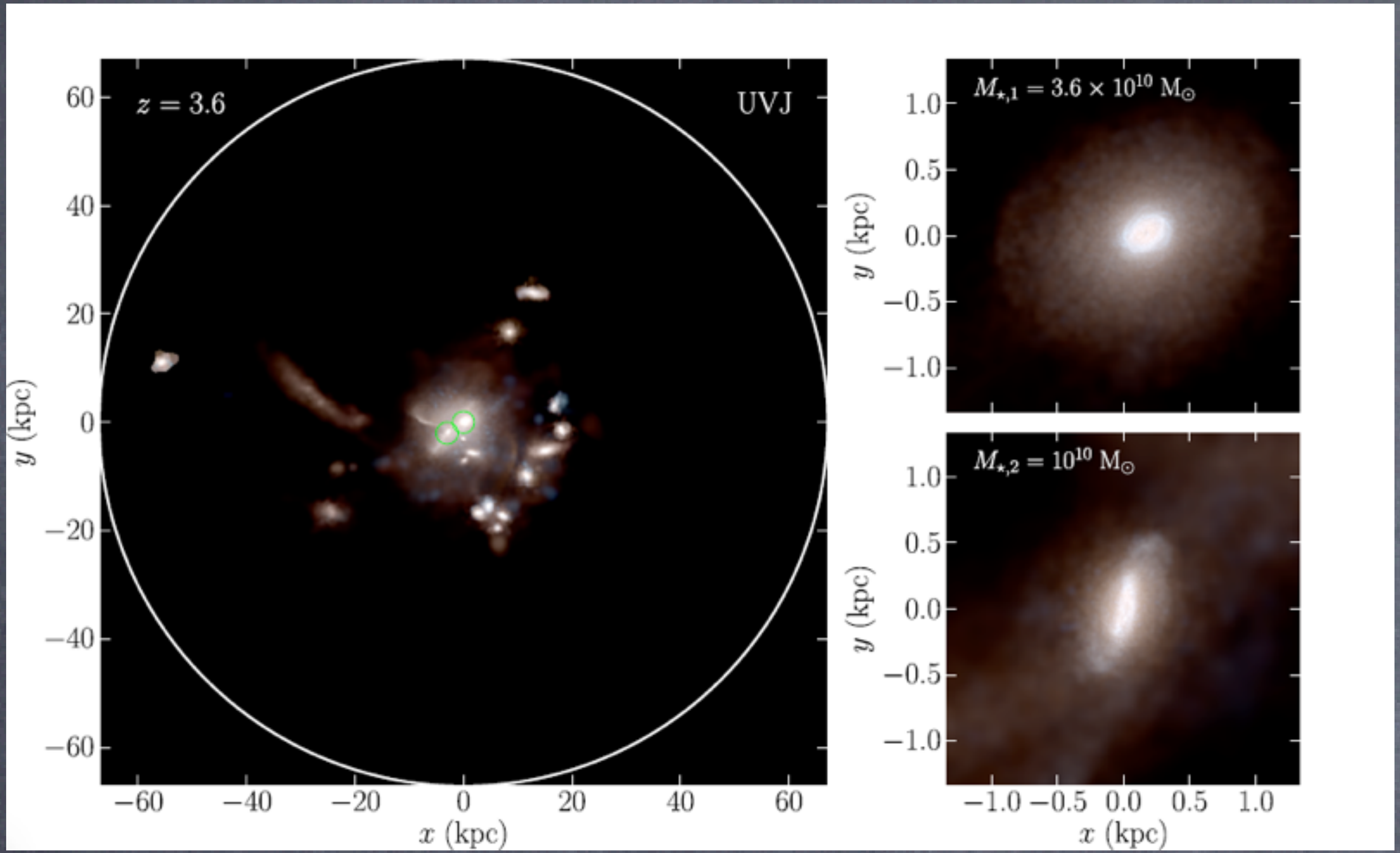
M33, neutral hydrogen column density map, VLA, NRAO

OBSERVATIONS

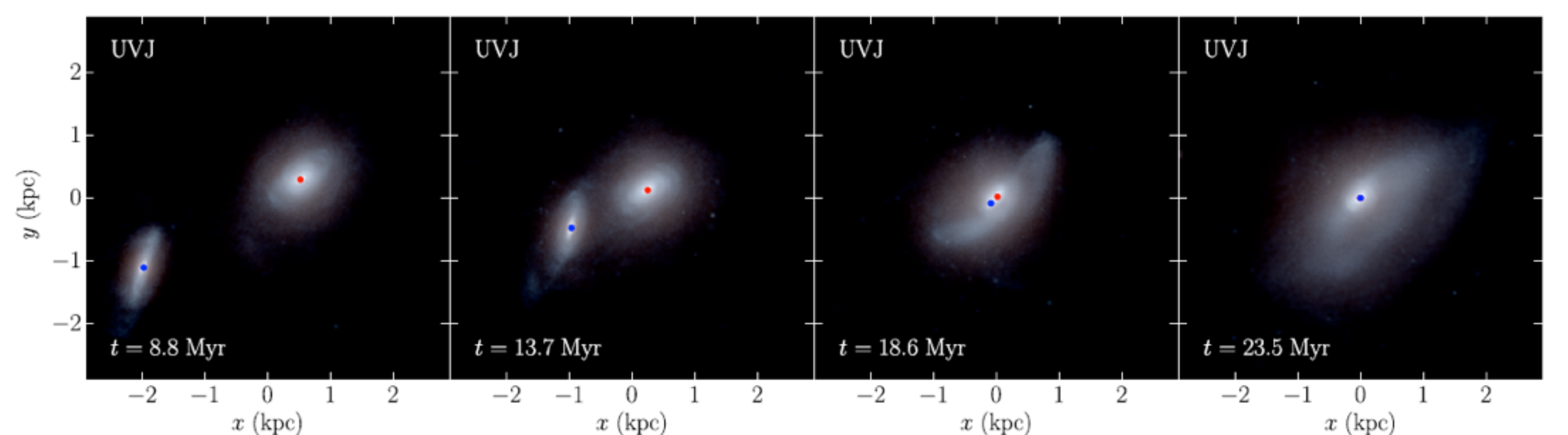
(GIANT) MOLECULAR CLOUDS (~10^4-10^6 $M_\odot$, ~5-100 PC) SEEDED Y GRAVITATIONAL INSTABILITY + "GIANT CLUMPS" IN HI REDSHIFT GALAXIES (~ 10^8 MO, 500 PC - 1 KPC, EG GENZEL ET AL. 2006; TACCONI ET AL. 2012)

INFLUENCE ON CLUMPINESS ON DUAL MBH DYNAMICS?

1. Start from a merger of two "typical" massive star forming galaxies in the fully hydrodynamical hi-res cosmological simulations ARGO (Feldmann & Mayer 2015) at z ~ 3.5.



Initial Resolution = 150 pc.
Before galaxies merge SPH particle splitting applied to reach 5 pc resolution (see also Roskar et al. 2015)
Two SMBHs are "implanted" at the center with mass ~ 10^8 Mo consistent with M_{BH}-σ,

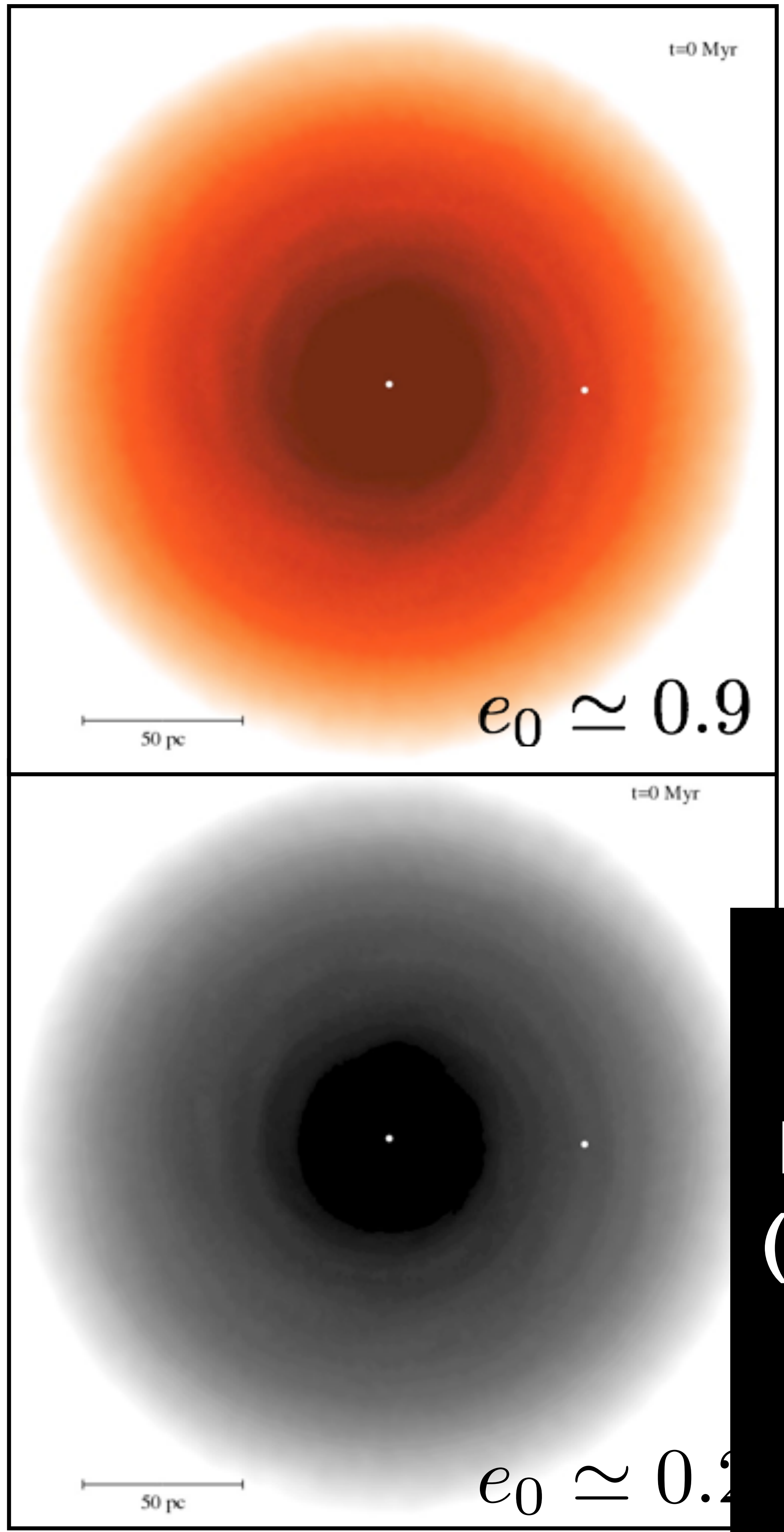


HARDENING OF BH PAIRS IN CNDS

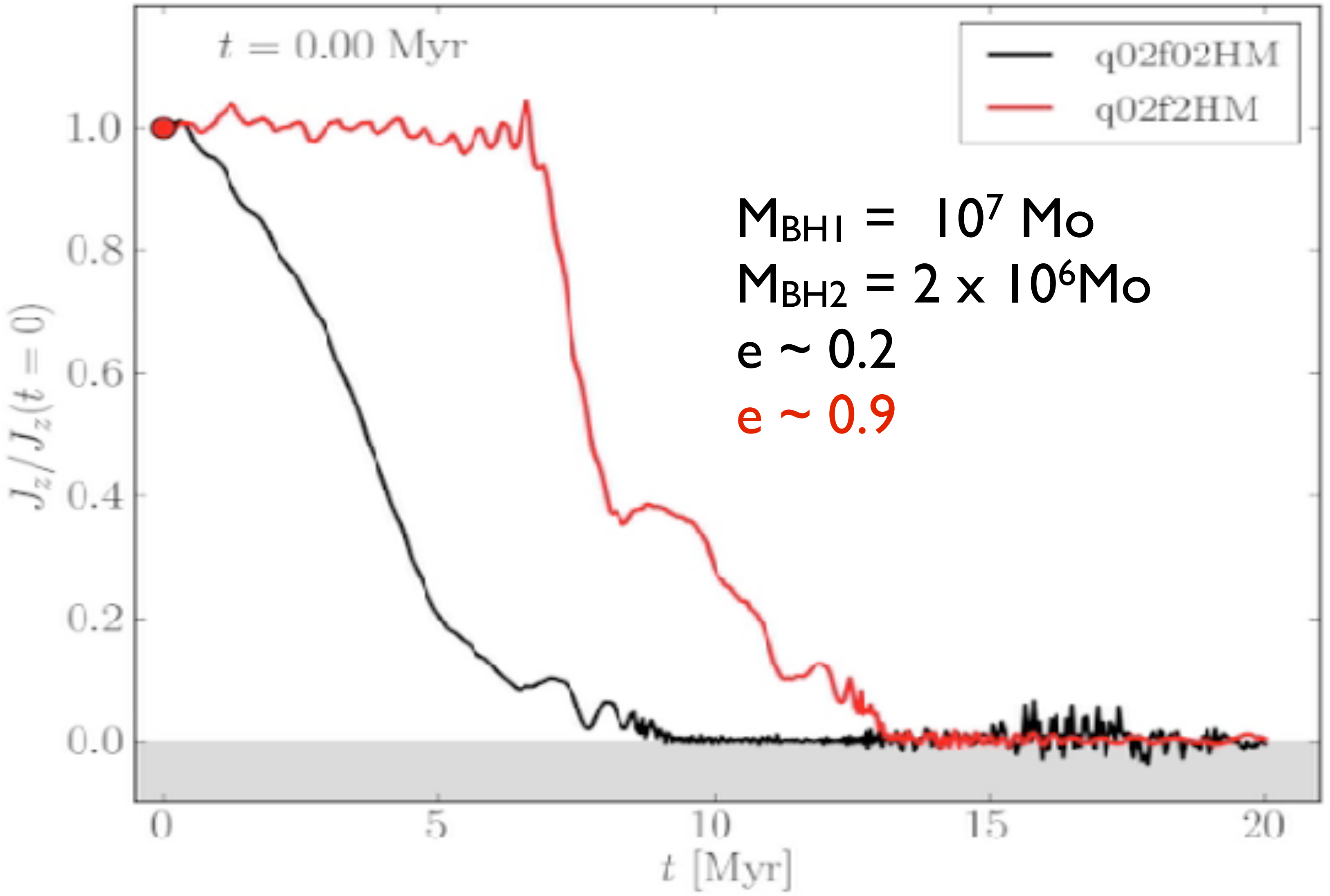
SMOOTH DISK CASE ($T_{COOL} > T_{ORB}$): OVERVIEW

q02f2HM

q02f02HM



Fiacconi, Mayer et al. (2013)



M_{BH1} = 10^7 Mo
M_{BH2} = 2 x 10^6Mo
e ~ 0.2
e ~ 0.9

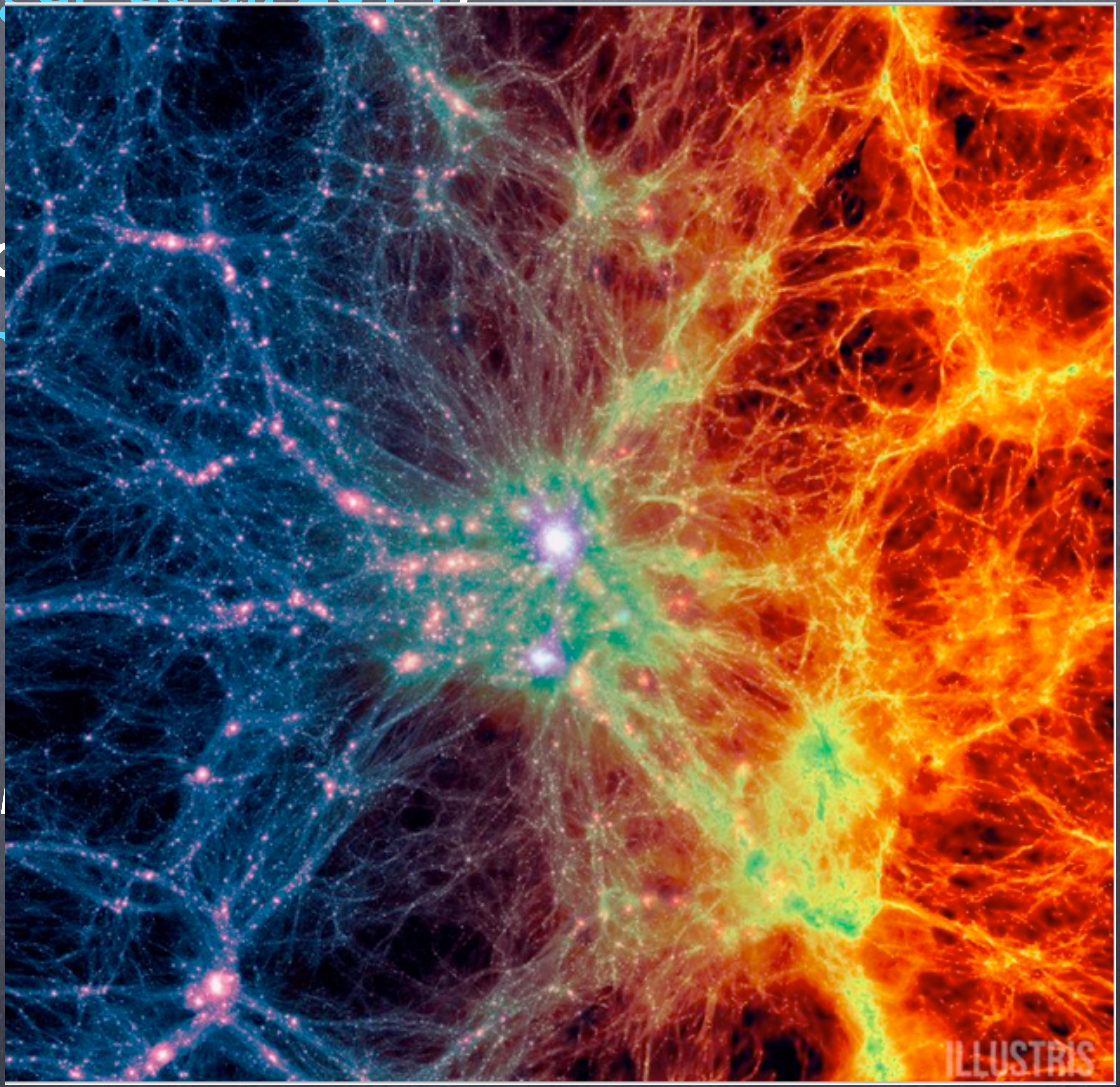
PHASE 1 - SLOW DECAY BY DYNAMICAL FRICTION + ORBIT CIRCULARIZATION

PHASE 2- FAST HARDENING DUE TO SPIRAL WAVE-INDUCED TORQUES (ANALOGOUS TO TYPE-III PLANET MIGRATION) ~5-15 MYR TO ~0.1 PC SEPARATION

IF NO SUBSEQUENT GAP OPENING <~ 10^8 YR TO GW EMISSION PHASE

Dotti et al. (2006,2007); Mayer 2013 (CQG)

Cosmological simulations simply assume that pairs of SMBHs in merging galaxies merge *instantaneously* when their separation reaches the resolution limit, which is 100 pc -1 kpc pc (recent example is ILLUSTRIS simulation, Vogelsberger et al. 2014)



This implies automatically mergi
merger rate of dark matter halc
Semi-analytical models (eg Sesar
small-scale astrophysics but still

Are current models sensible at all?

Addressing timescales is crucial to *al*
wave experiments,e.g. for eLISA as
as for Pulsar Timing Arrays (PTAs)

Take-home message delivered by this talk:

SMBH mergers and their relevant timescales *before gravitational waves (GWs) take over* are a highly complex problem which cannot be addressed without a deep understanding of the galactic and sub-galactic environments in which they take place, and without differentiating low redshift and high redshift environments.

But Direct Multi-Scale Simulations are now computationally feasible on Supercomputers ($> 10^5$ cores) and can address the problem...

But impact parameter of galaxy merger is orders of magnitude larger , > 1 kpc (10^3 pc)!

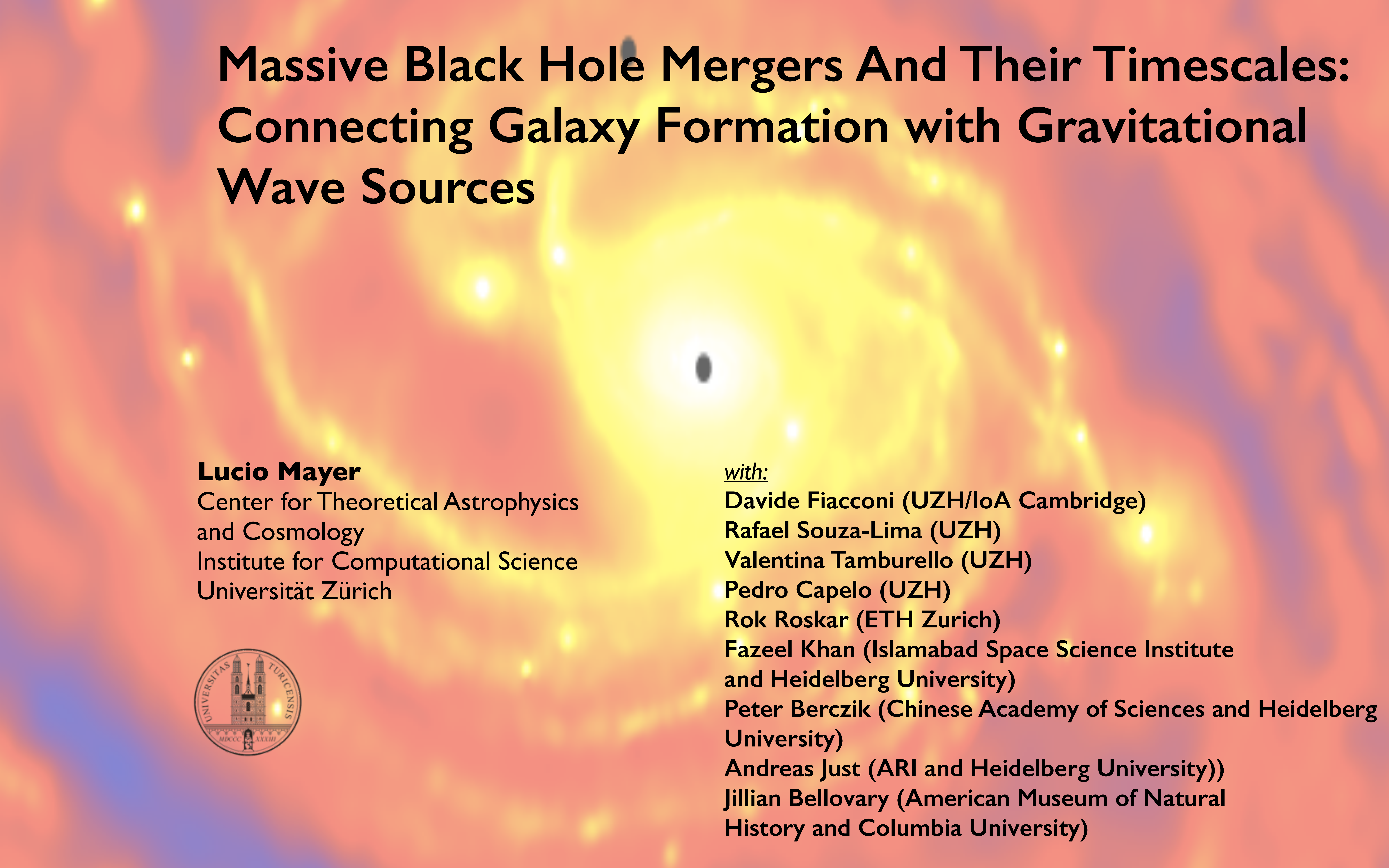
So how can the orbit shrink from kpc to milliparsec SMBH separation?

Typical Galaxy Merger
Timescale 1-2 Gyr

Merger movie: Rok Roskar (w/ GASOLINE and PINBODY codes)

From Roskar, Fiacconi, Mayer et al. 2015

Astrophysics of SMBHs orbital decay *before* gravitational wave emission phase: a complex, multi-stage process (Begelman, Blandford & Rees 1980; Mayer 2013)



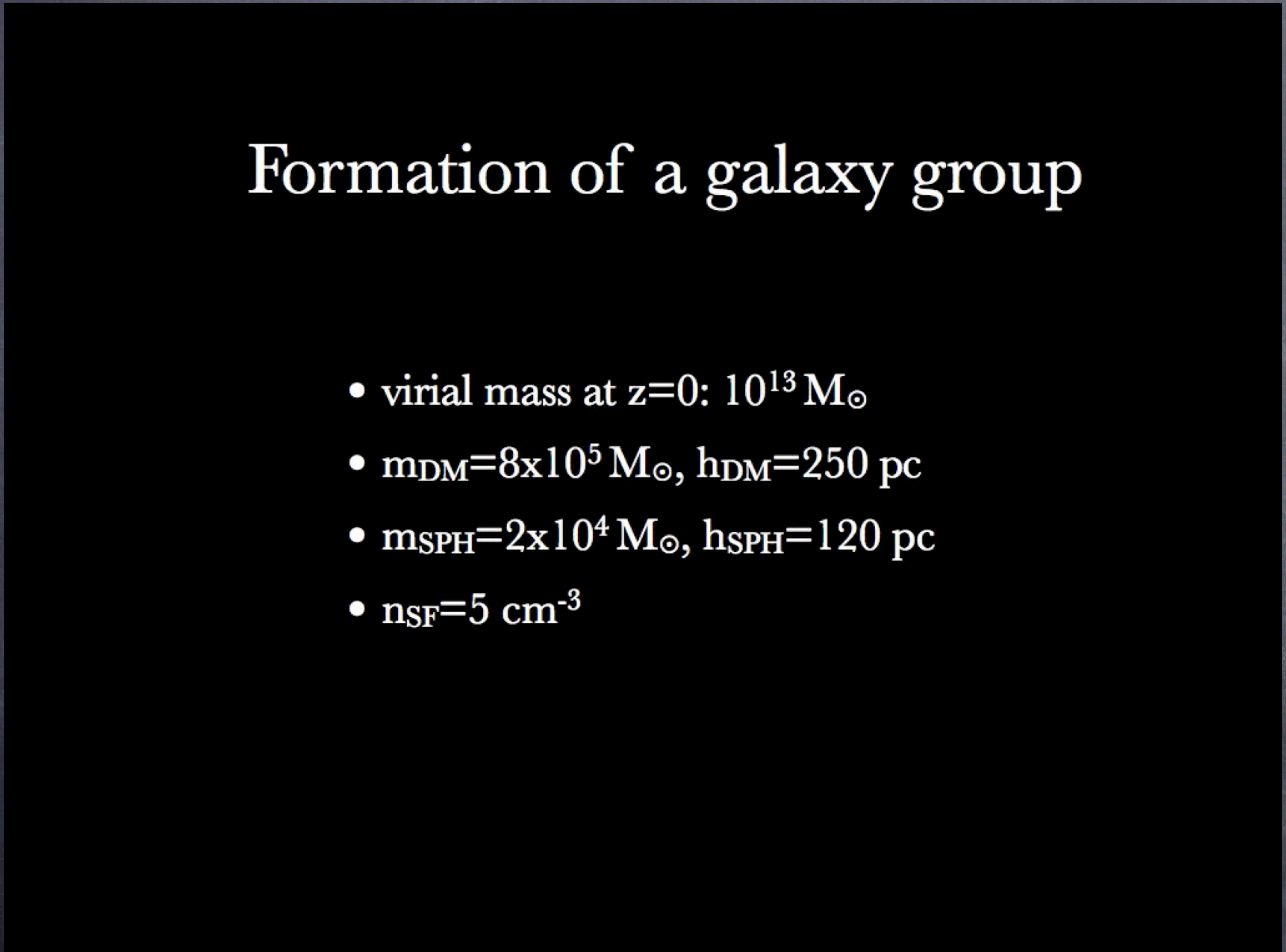
Massive Black Hole Mergers And Their Timescales: Connecting Galaxy Formation with Gravitational Wave Sources

Lucio Mayer
Center for Theoretical Astrophysics
and Cosmology
Institute for Computational Science
Universität Zürich

with:
Davide Fiacconi (UZH/IoA Cambridge)
Rafael Souza-Lima (UZH)
Valentina Tamburello (UZH)
Pedro Capelo (UZH)
Rok Roskar (ETH Zurich)
Fazeel Khan (Islamabad Space Science Institute
and Heidelberg University)
Peter Berczik (Chinese Academy of Sciences and Heidelberg
University)
Andreas Just (ARI and Heidelberg University))
Jillian Bellovary (American Museum of Natural
History and Columbia University)

Structure Formation: the LambdaColdDarkMatter Model

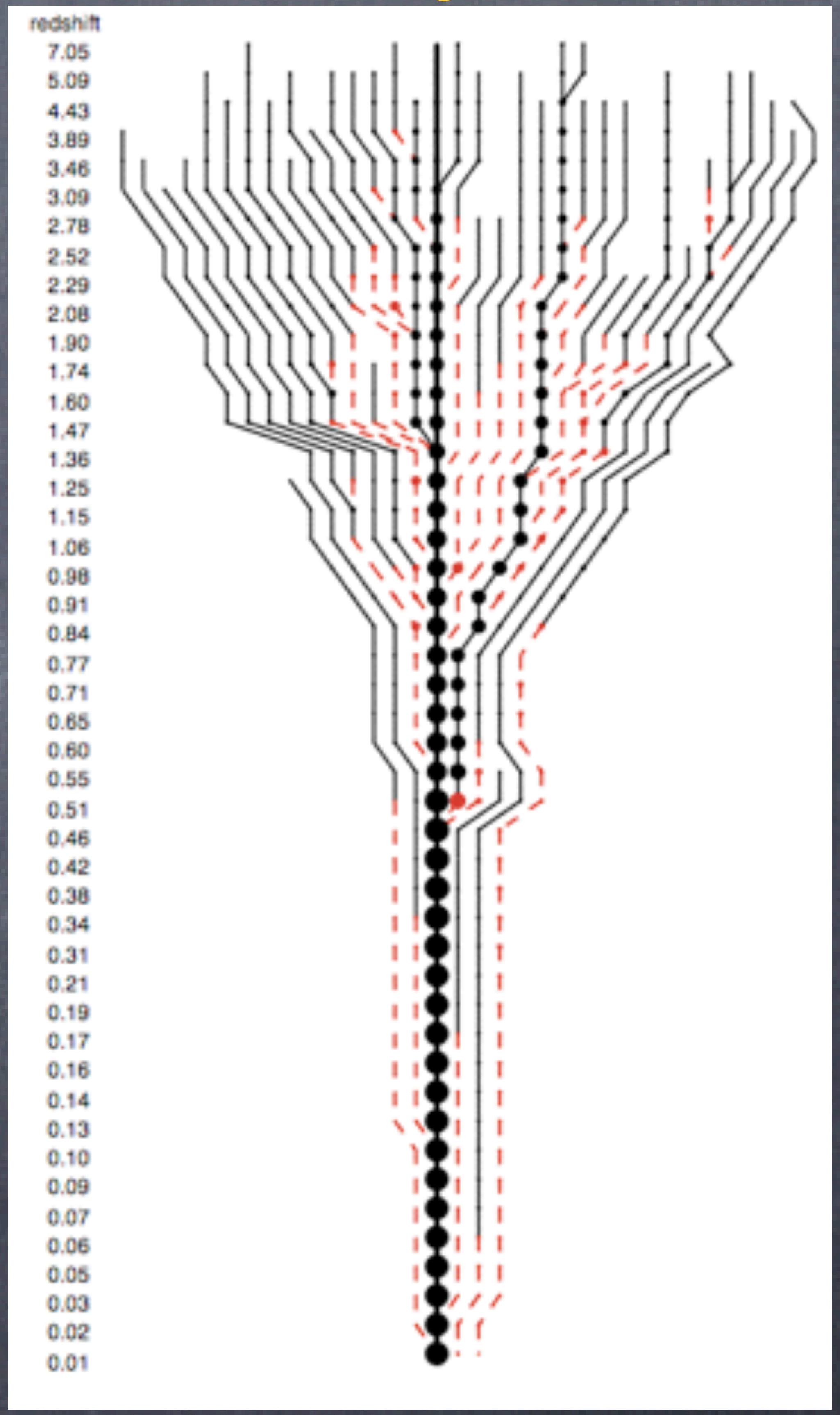
Cosmic structures, such as galaxies and galaxy clusters, form via hierarchical merging of smaller condensations of dark matter and baryons



Formation of a galaxy group

- virial mass at z=0: $10^{13}\,M_\odot$
- $m_{DM}=8\times10^5\,M_\odot$, $h_{DM}=250$ pc
- $m_{SPH}=2\times10^4\,M_\odot$, $h_{SPH}=120$ pc
- $n_{SF}=5\ \mathrm{cm}^{-3}$

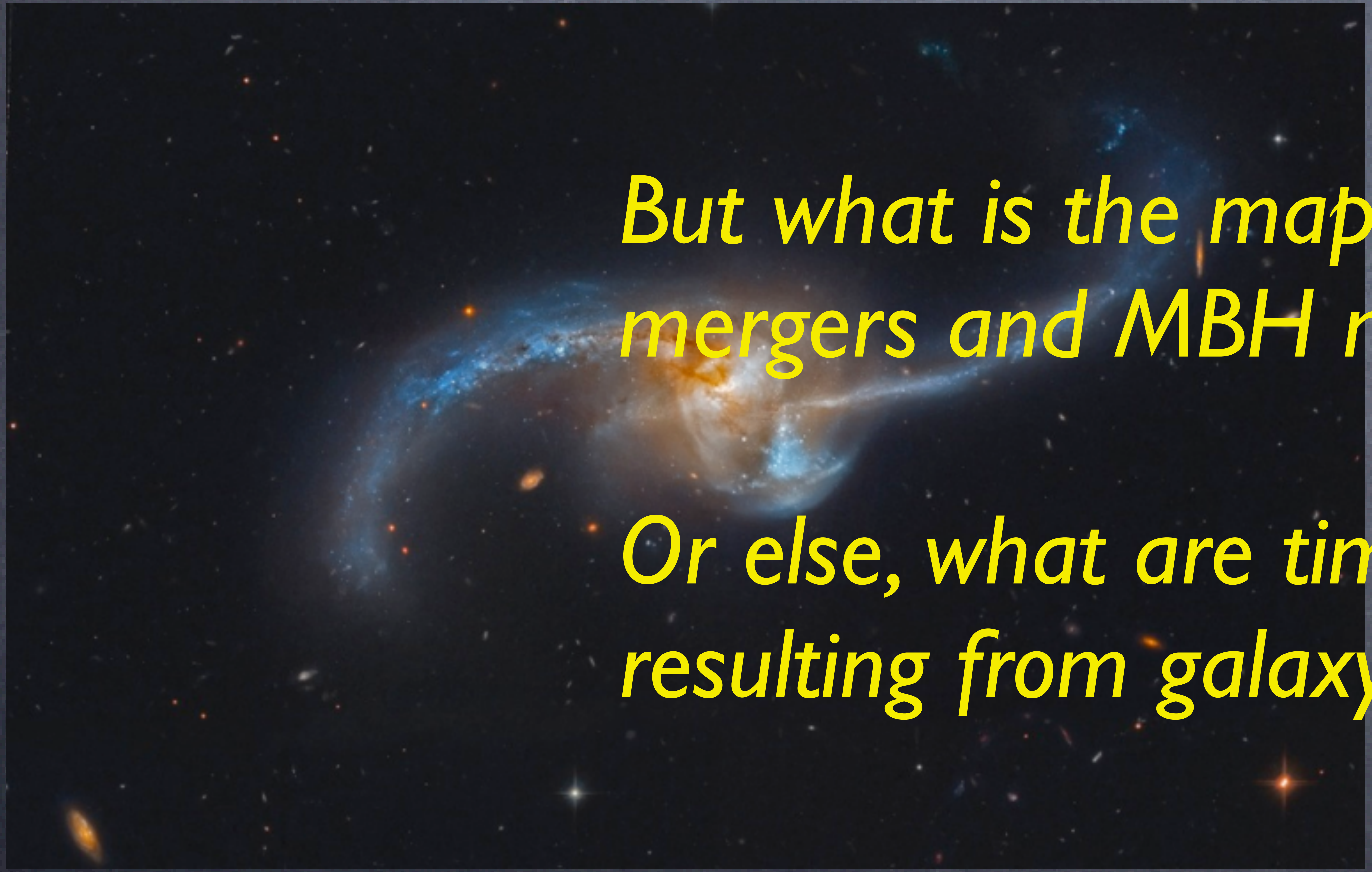
Galaxy merger tree

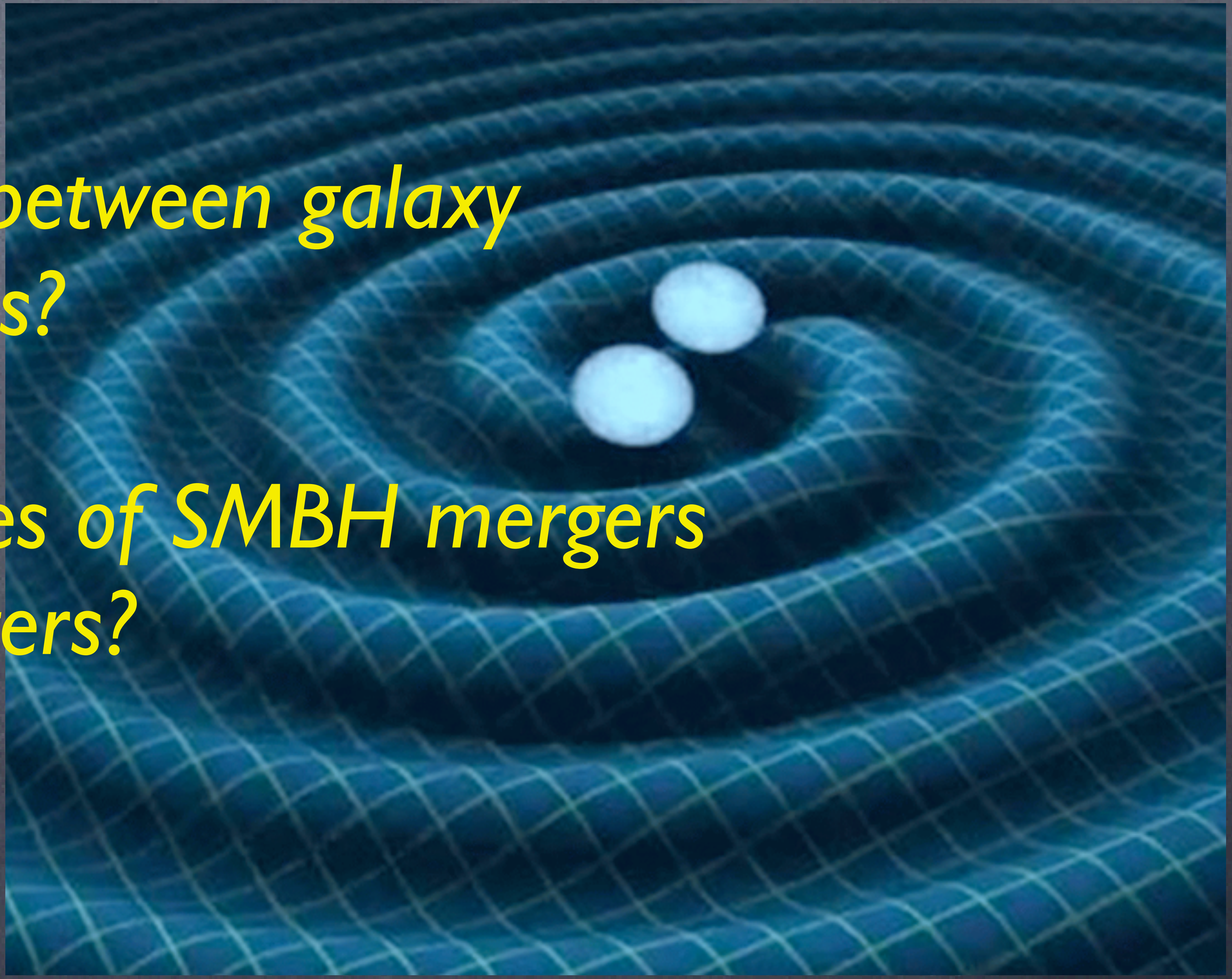


Feldmann & Mayer (2015)

Supermassive Black Holes (SMBHs - $M_{BH} > 10^5$ Mo) in the landscape of the LambdaColdDarkMatter Cosmology:

If, as it seems, most galaxies host a SMBH at their center then each galaxy merger could produce a powerful GW source





But what is the mapping between galaxy mergers and MBH mergers?

Or else, what are timescales of SMBH mergers resulting from galaxy mergers?

Astrophysics of SMBHs orbital decay *before* gravitational wave emission phase: multi-stage process (Begelman, Blandford & Rees 1980; Colpi & Dotti 2009; Mayer 2013)

Galaxy merging time (major merger)

$\tau_{mg} \sim 1$ Gyr $<\sim T_{Hubble}$

Several Gyr for minor mergers

(for mass ratio of galaxies > 5:1)

Depends on redshift (see Bertschinger 1985;Mo, Mao & White 1998)

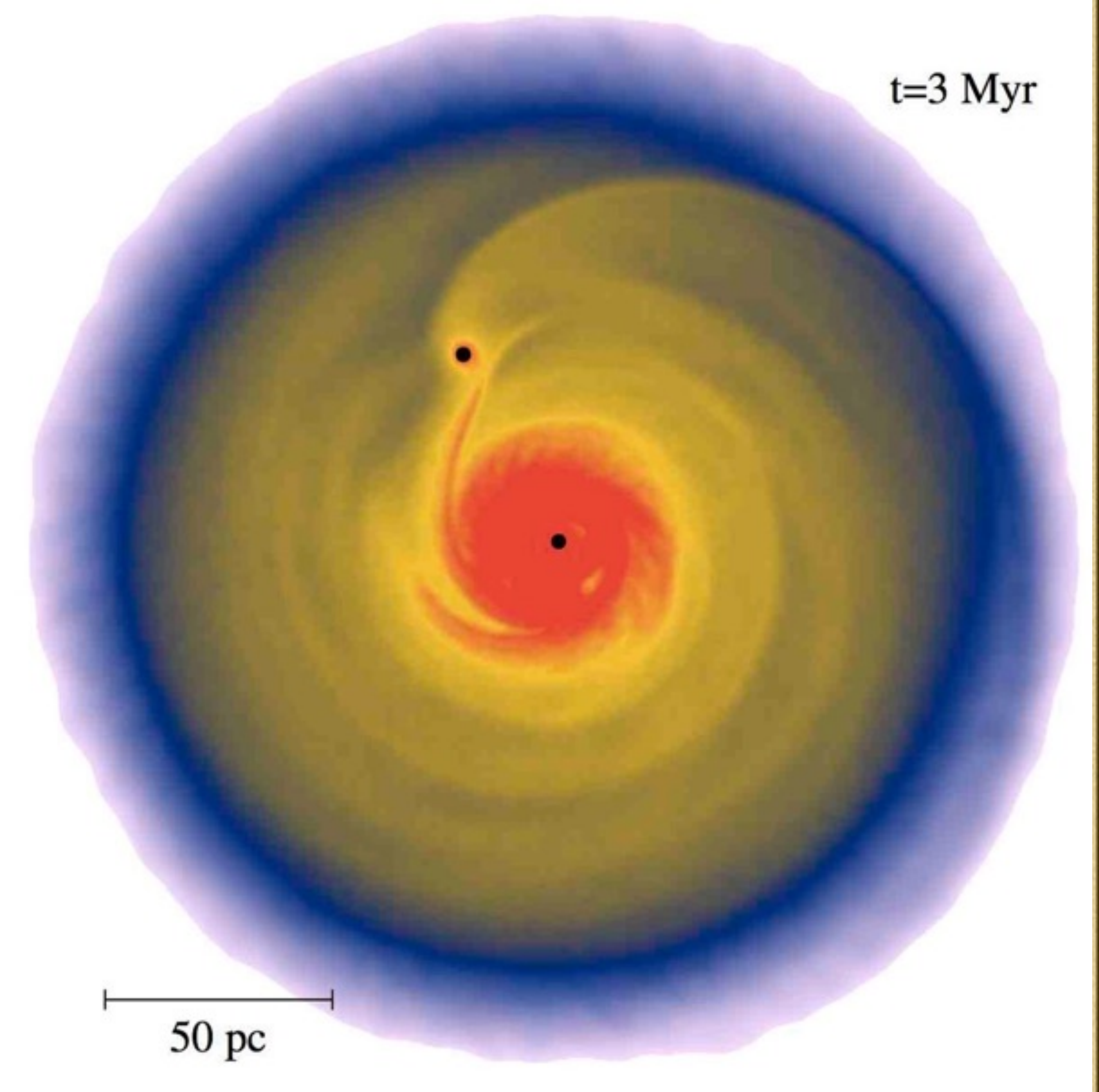
τ_{mg} of order orbital time of halos:

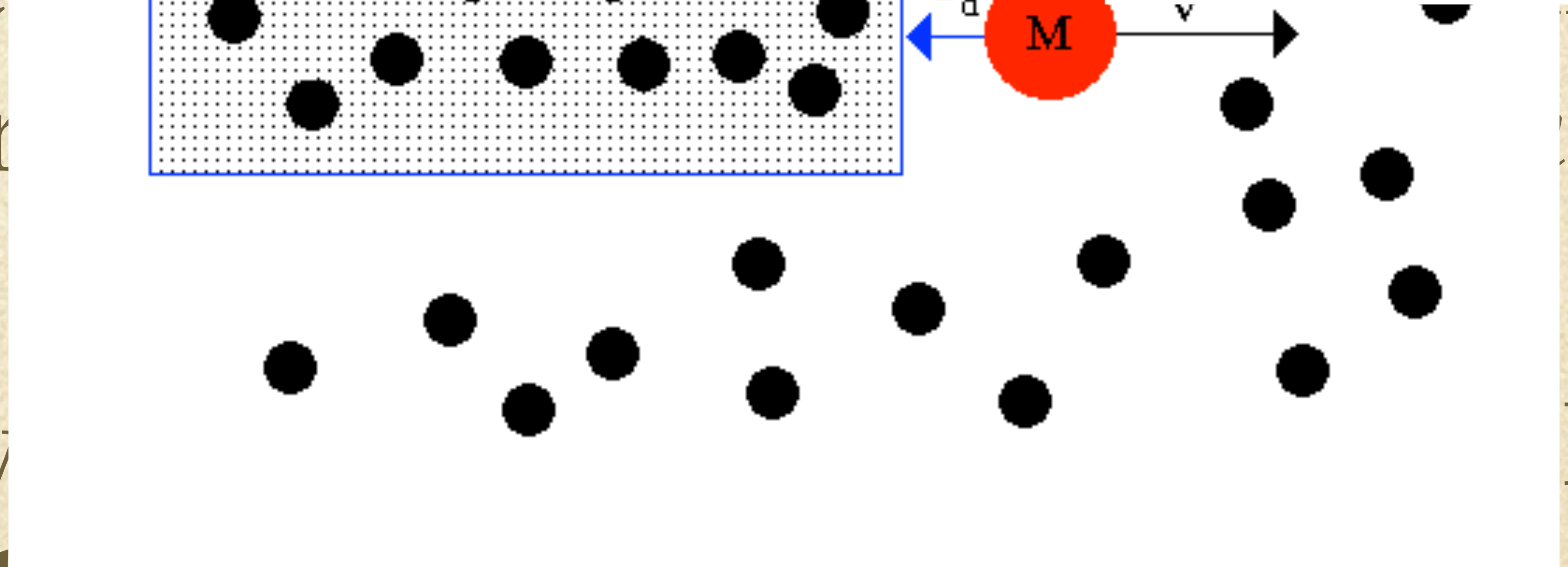
Torb ~ Rvir/Vcirc ~ 1/H(z) ~ 1/(1+z)$^{3/2}$
(Ω_0=1, Ω_Λ=0)
Vcirc virial velocity (eg 200 Km/s Milky Way)

Galaxies smaller and denser as redshift increases in Cold Dark Matter Universe

There are at least three processes that can sh
when once it is in the merger remnant but it
They all are means to extract orbital energy a

- *dynamical friction* from the background ma
merger remnant (from stars, gas and dark m
the binary)





- if the merger remnant
can arise from spiral str *et migration*)

- *3-body encounters* betw H.
Can dominate orbital shrinking when SMBHs have separations of
<~ pc (*hard binary*), provided that there is a high density of stars
always available (*full loss cone*)

N-body models of idealized, gas-free galaxy mergers: dynamical friction by stars only, hardening via 3-body encounters

(e.g. Berczik et al. 2006; Khan et al. 2011; Khan et al. 2012; 2013)

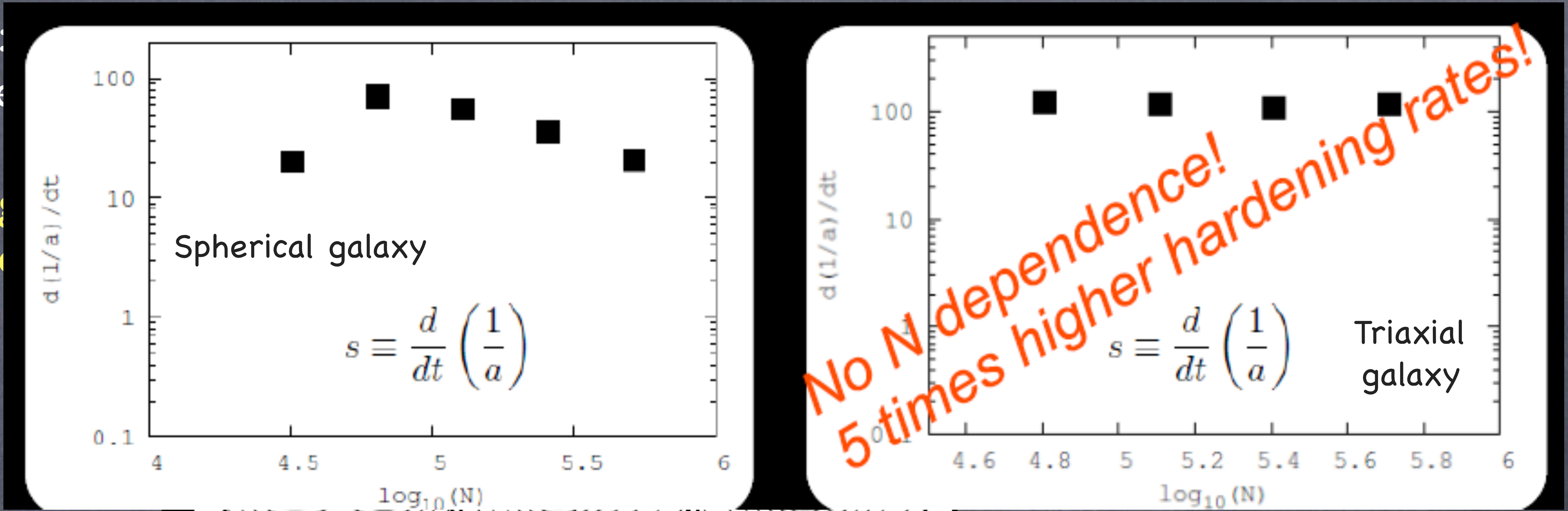
Typical setup:

(e.g. stellar de

-> Results in

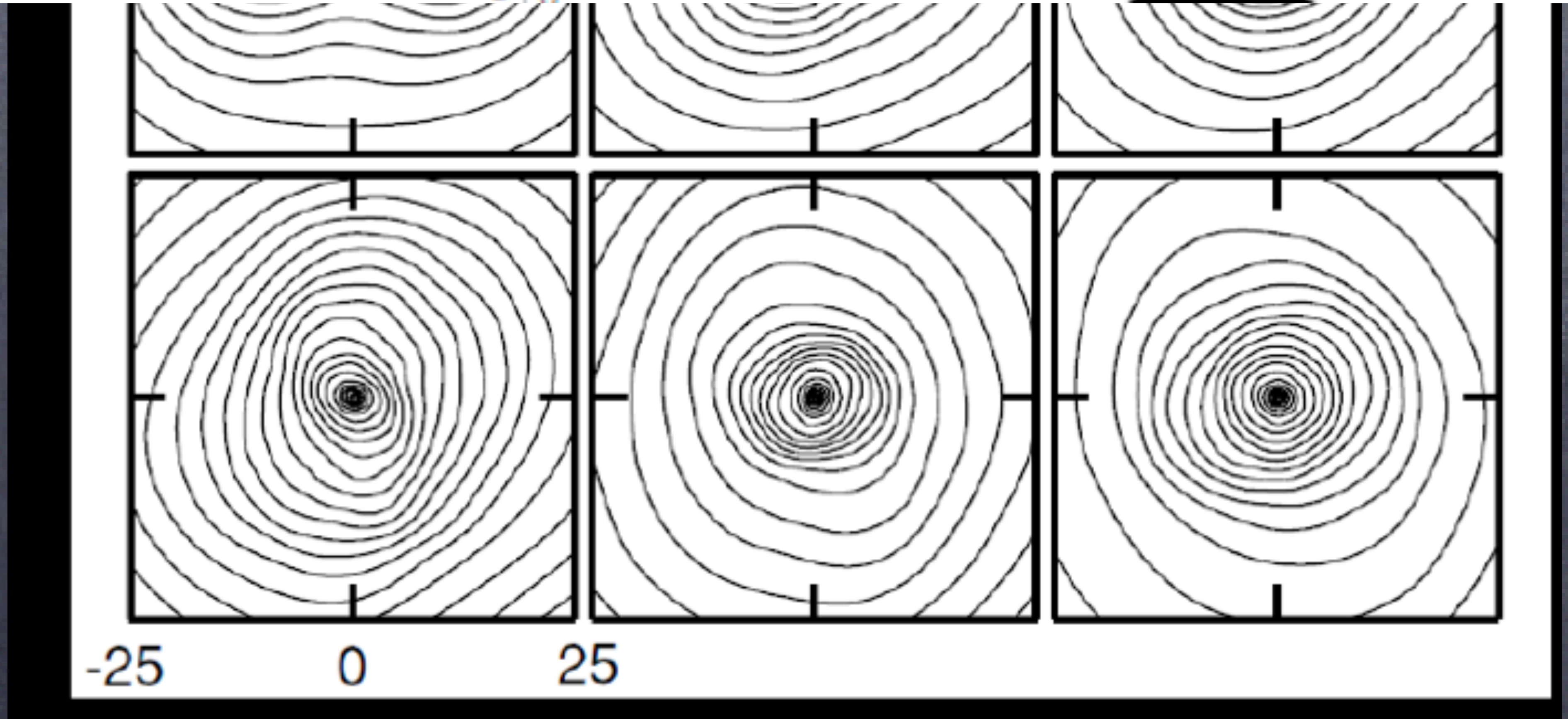
- > Hardenin

(no N depen



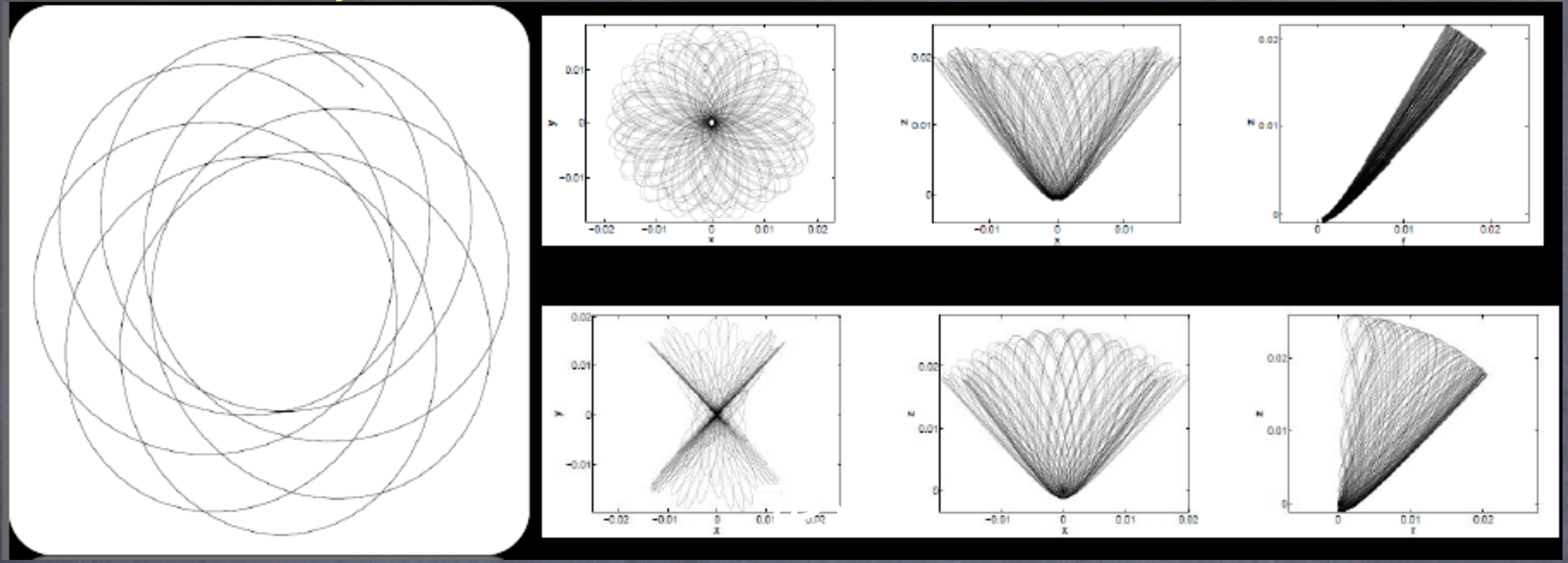
No N dependence!

5 times higher hardening rates!



Khan, Just & Merritt 2011, ApJ .

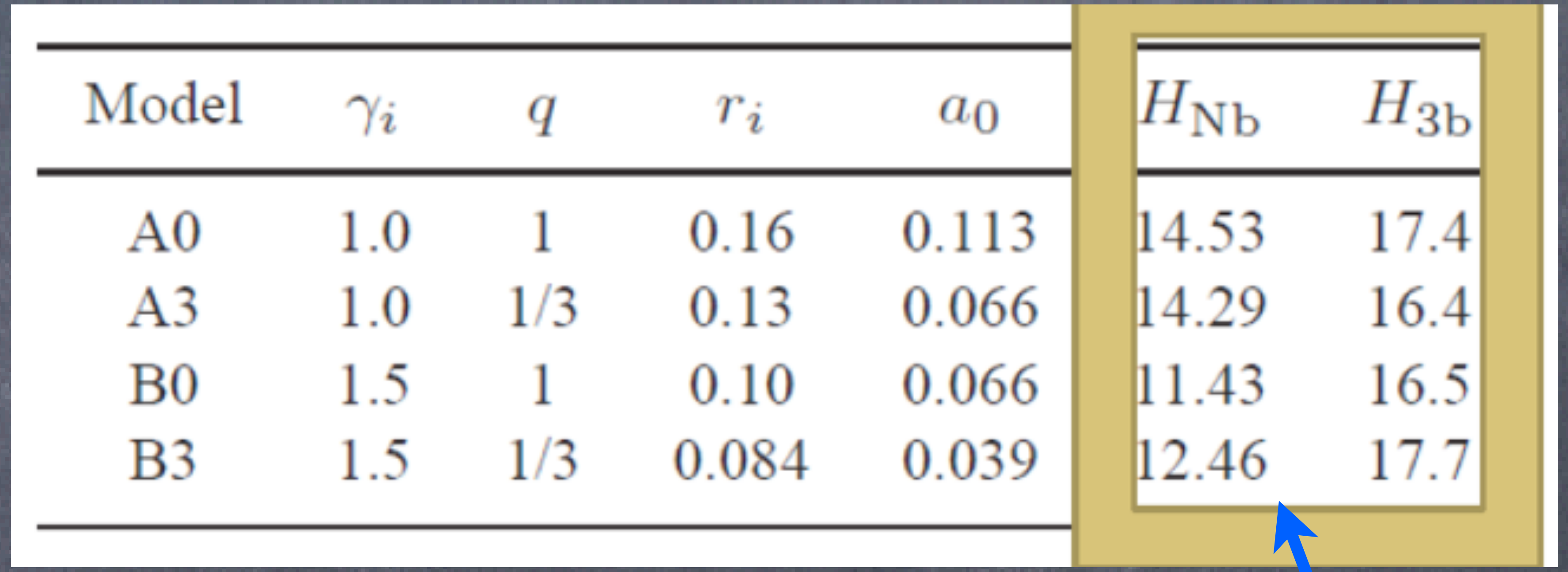
In triaxial systems loss cone kept almost full owing to various families of centrophilic orbits (Berczik et al. 2006; Khan et al. 2013)



H = d/dt(1/a) * σ/Gρ

dimensionsless hardening rate

(a=semi-major axis σ, ρ stellar velocity dispersion and density)

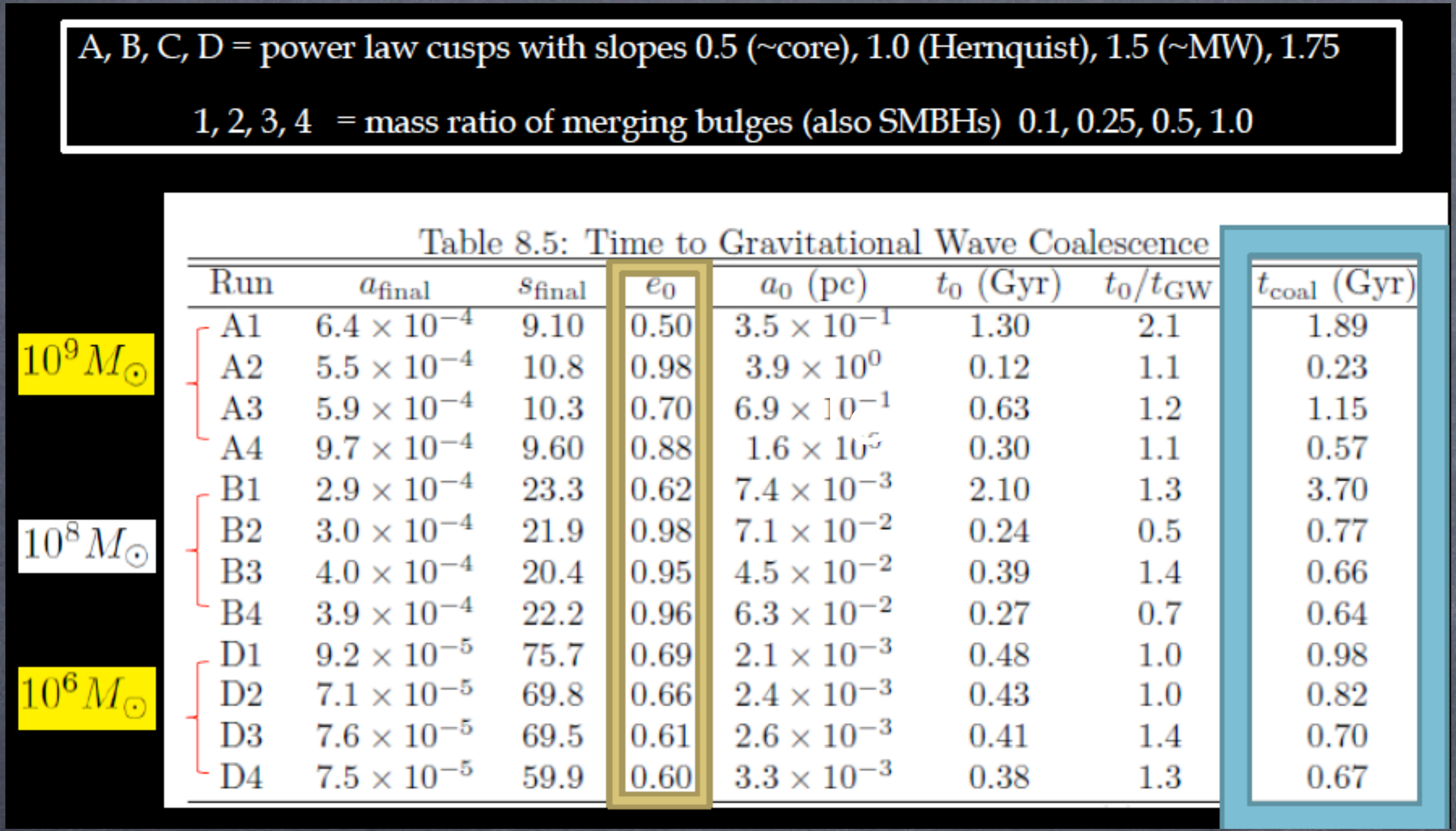


Model	γ_i	q	r_i	a_0	$H_{\rm Nb}$	$H_{\rm 3b}$
A0	1.0	1	0.16	0.113	14.53	17.4
A3	1.0	1/3	0.13	0.066	14.29	16.4
B0	1.5	1	0.10	0.066	11.43	16.5
B3	1.5	1/3	0.084	0.039	12.46	17.7

Sesana & Khan 2015: comparison of N-body simulations and scattering experiments with full loss cone case shows differences is only ~ 30%

But predicted SMBH merging timescales very long, as shown by eg Khan et al. 2012 (see table below)

(timescales extrapolated to GW emission phase using Peters 1964, not directly calculated in simulations)



A, B, C, D = power law cusps with slopes 0.5 (~core), 1.0 (Hernquist), 1.5 (~MW), 1.75

1, 2, 3, 4 = mass ratio of merging bulges (also SMBHs) 0.1, 0.25, 0.5, 1.0

Table 8.5: Time to Gravitational Wave Coalescence

	Run	$a_{\rm final}$	$s_{\rm final}$	e_0	a_0 (pc)	t_0 (Gyr)	$t_0/t_{\rm GW}$	$t_{\rm coal}$ (Gyr)
$10^9 M_\odot$	A1	6.4×10^{-4}	9.10	0.50	3.5×10^{-1}	1.30	2.1	1.89
	A2	5.5×10^{-4}	10.8	0.98	3.9×10^{0}	0.12	1.1	0.23
	A3	5.9×10^{-4}	10.3	0.70	6.9×10^{-1}	0.63	1.2	1.15
	A4	9.7×10^{-4}	9.60	0.88	1.6×10^{0}	0.30	1.1	0.57
$10^8 M_\odot$	B1	2.9×10^{-4}	23.3	0.62	7.4×10^{-3}	2.10	1.3	3.70
	B2	3.0×10^{-4}	21.9	0.98	7.1×10^{-2}	0.24	0.5	0.77
	B3	4.0×10^{-4}	20.4	0.95	4.5×10^{-2}	0.39	1.4	0.66
	B4	3.9×10^{-4}	22.2	0.96	6.3×10^{-2}	0.27	0.7	0.64
$10^6 M_\odot$	D1	9.2×10^{-5}	75.7	0.69	2.1×10^{-3}	0.48	1.0	0.98
	D2	7.1×10^{-5}	69.8	0.66	2.4×10^{-3}	0.43	1.0	0.82
	D3	7.6×10^{-5}	69.5	0.61	2.6×10^{-3}	0.41	1.4	0.70
	D4	7.5×10^{-5}	59.9	0.60	3.3×10^{-3}	0.38	1.3	0.67

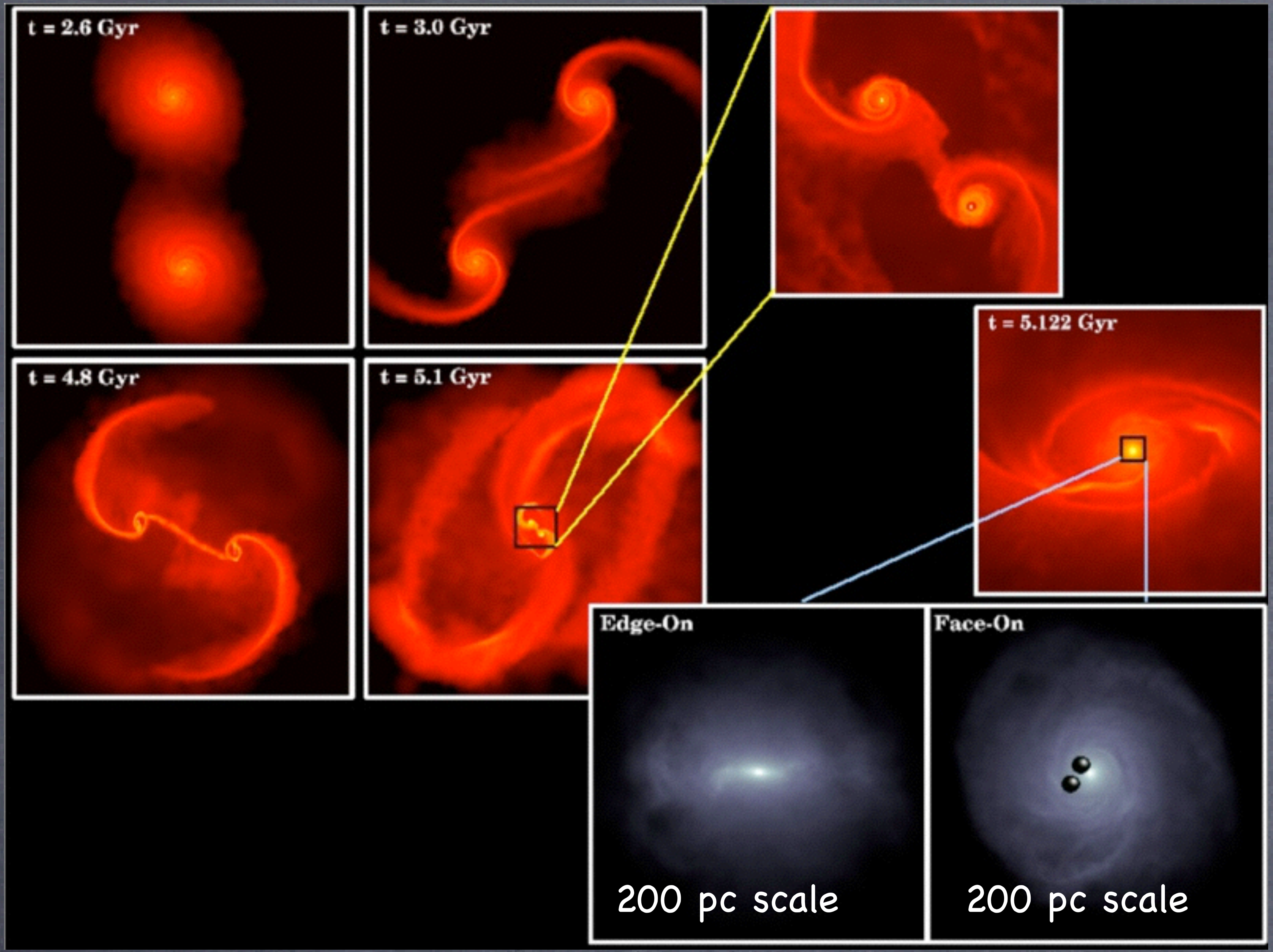
Coalescence Timescale in Table defined as hardening + GW phase (i.e. starting from binary formation)

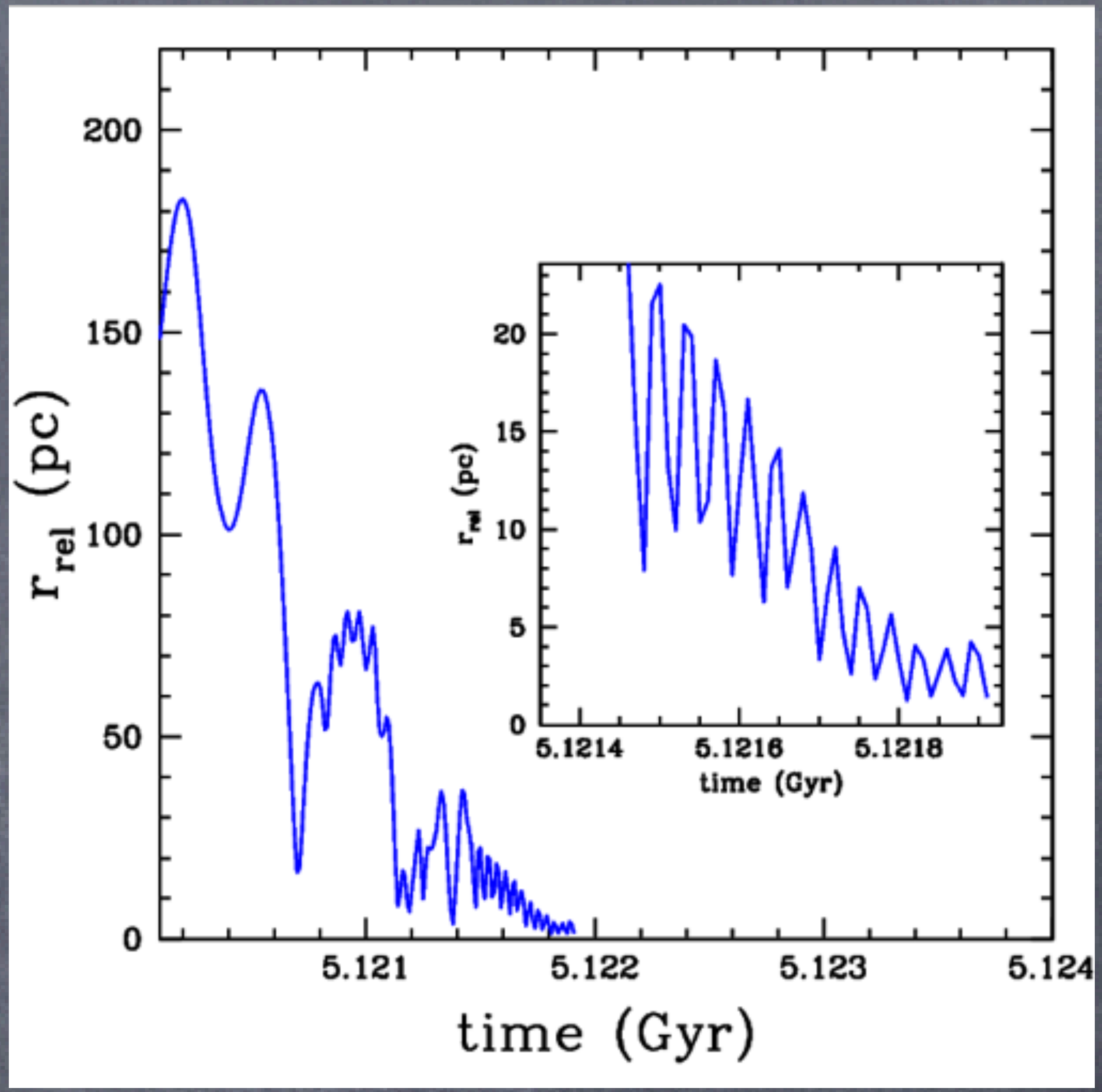
TOTAL Merging timescales of ~ 2 Gyr (includes ~ 1 Gyr merging timescale of galaxies).
Potentially problematic for LISA since lookback time just 3 Gyr at z ~ 2!

Only exception Ultramassive SMBHs (masso of SMBH >~ 10% mass of host galaxy) which nearly skip 3-body encunter phase due to their overly short dynamical friction times (Khan et al. 2015)

THE ROLE OF GAS IN SMBH DECAY: MAJOR GALAXY MERGERS

Rapid SMBH binary formation (parsec separations)





Mayer et al. 2007, Science

() SMBH binary binds in a few Myr in DENSE CIRCUMNUCLEAR GAS DISK (CND) forming after merger, friction by gas x10 stronger than by stars and dark matter

() Simulations adding star formation confirm result even when a substantial fraction of the CND mass is converted into stars (Dotti et al. 2007) --> key point is high density in CND gives strong drag

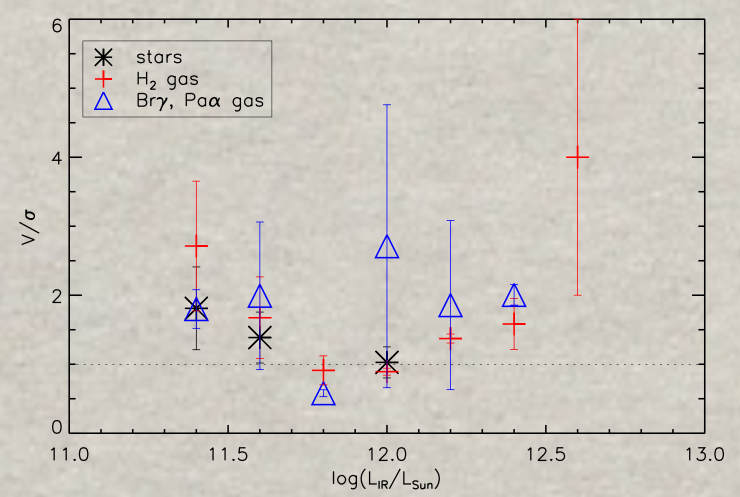
() Gas thermodynamics plays crucial role in drag (idealized, with effective equation of state)

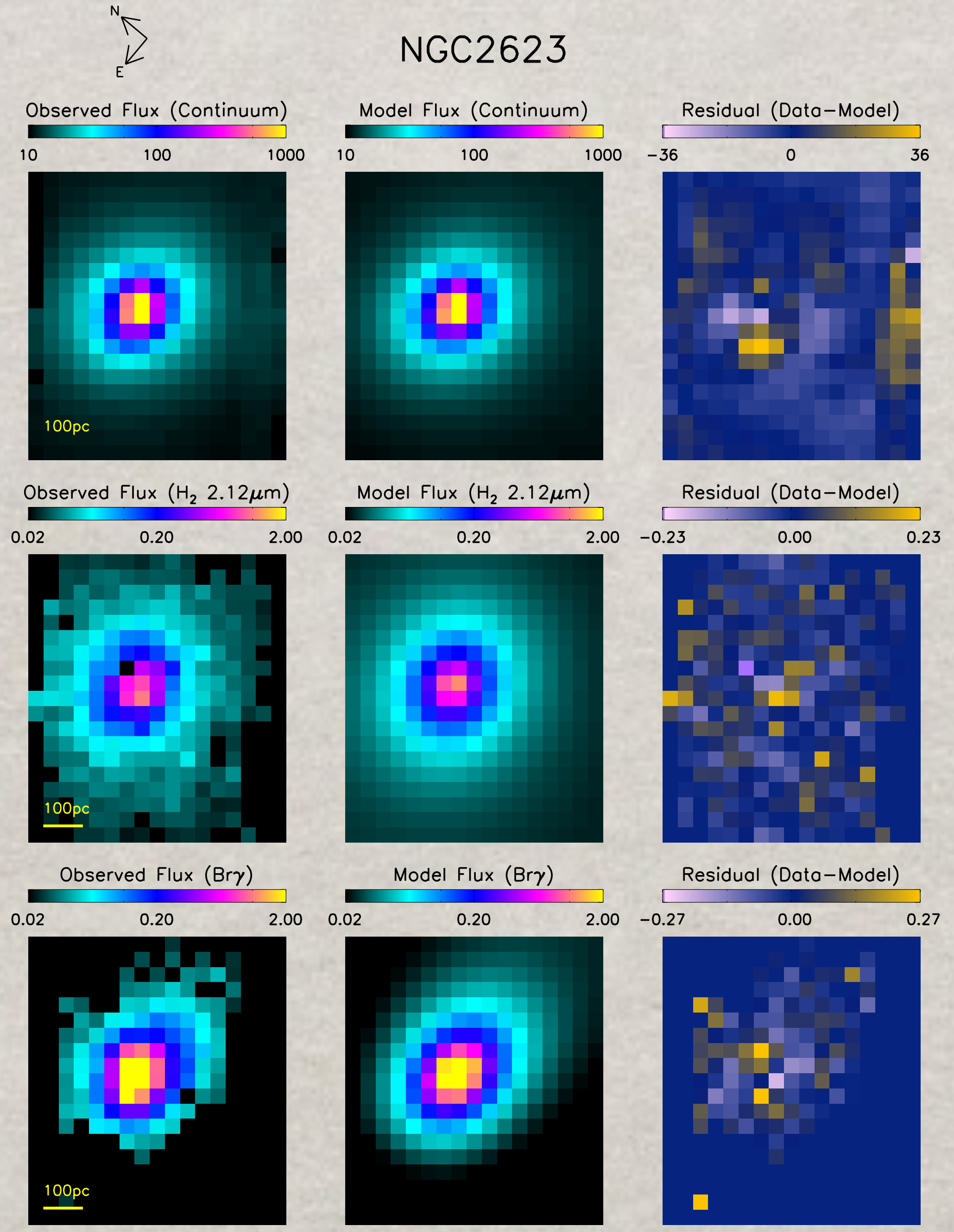
Observational Evidence for CNDs

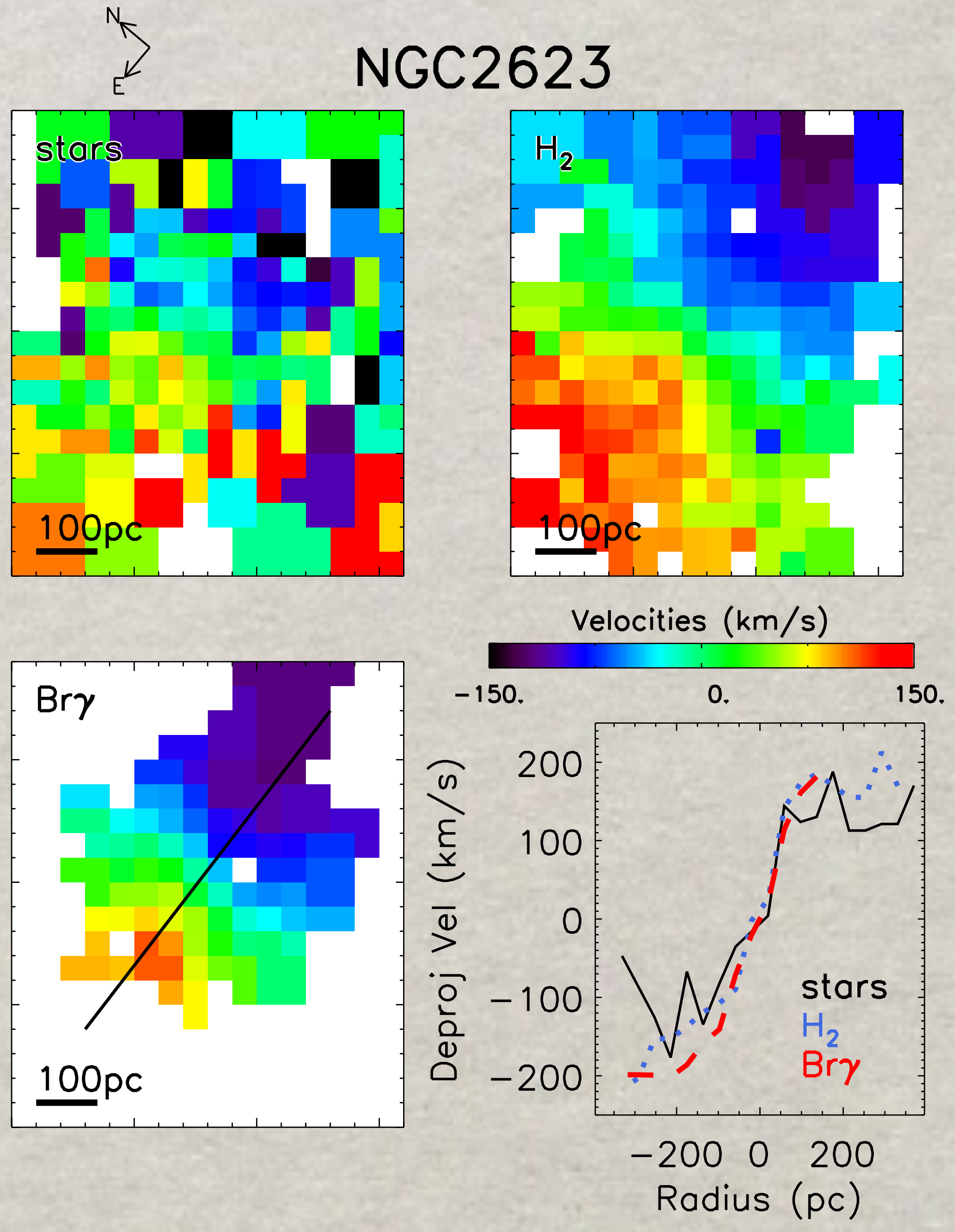
- Circumnuclear disks of gas and stars (100-500 pc in size) ubiquitous in photometric + spectroscopic observations of interacting galaxies/mergers (Downes & Solomon 1998)

- Circumnuclear disks found in Seyfert galaxies (gas-rich spirals as typical hosts), with much higher incidence relative to non-active gas-rich spirals (Hicks et al. 2013)

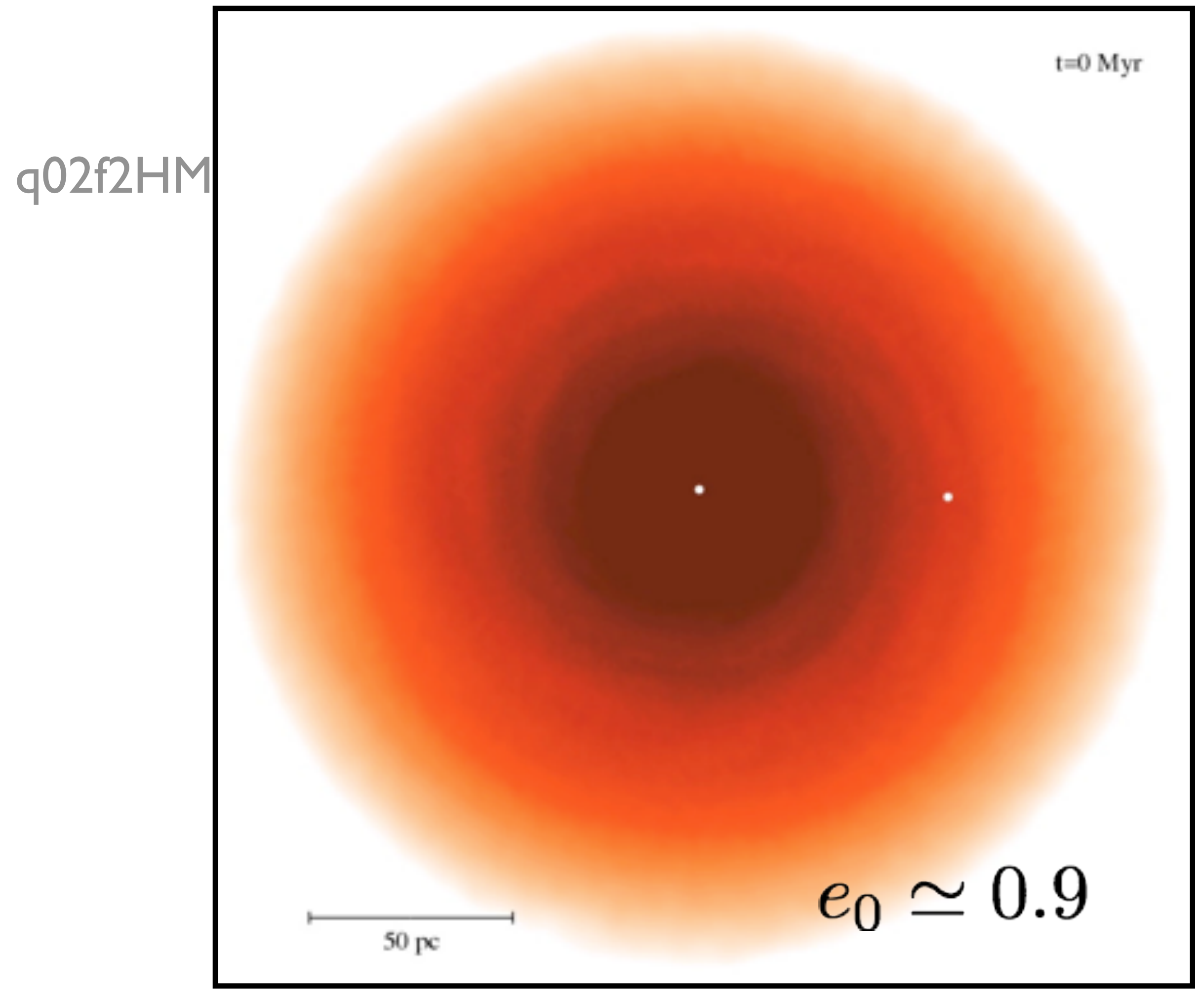
- Recent observations (photometry and spectroscopy) have high enough resolution (~tens of pc) to characterize a circumnuclear disks at least in the low z Universe (Medling et al. 2014 - **OSIRIS IFU spectroscopy at Keck II aided by Laser Guide Stars, LIRGs and ULIRGs from GOALS sample)**

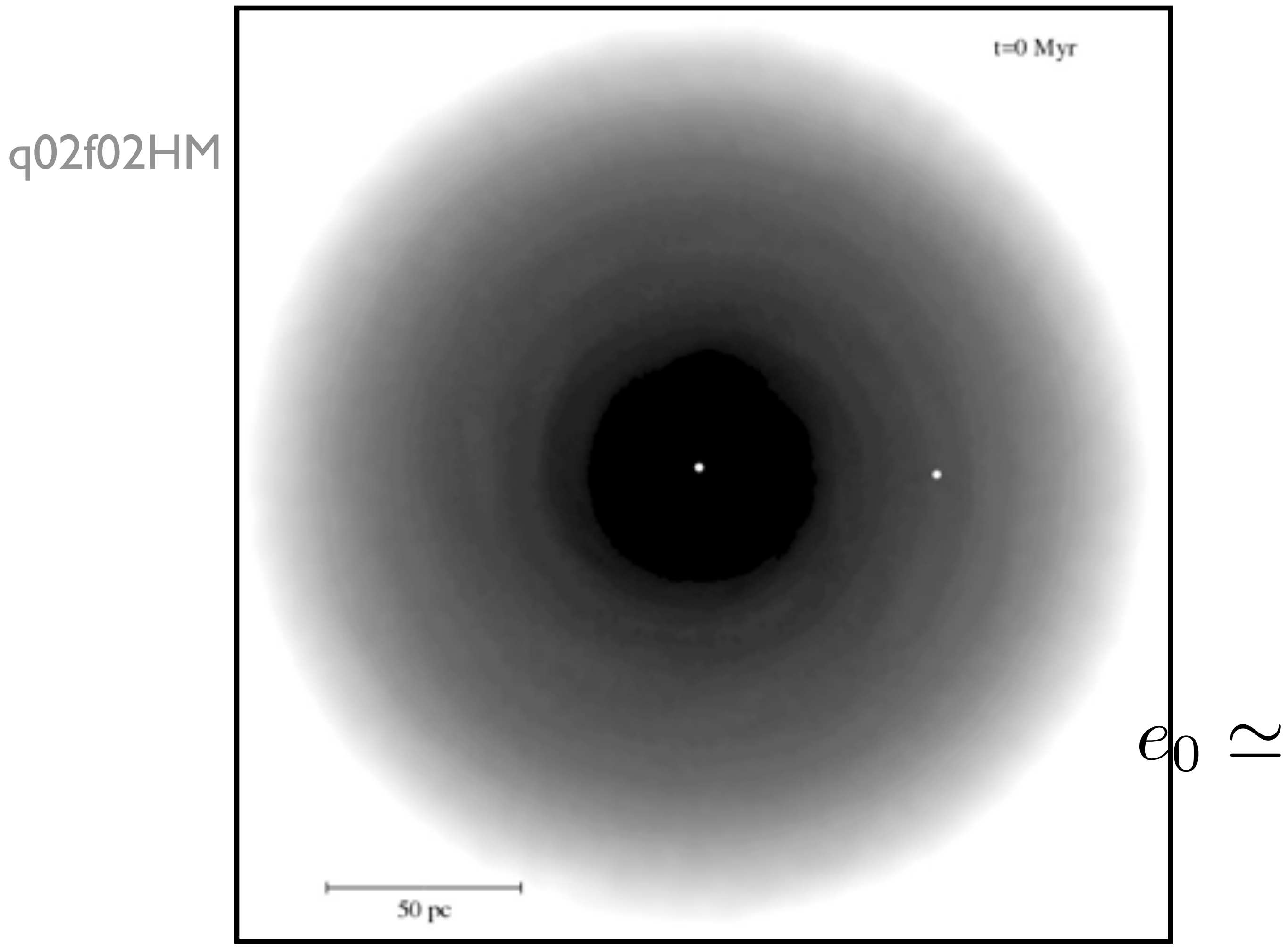


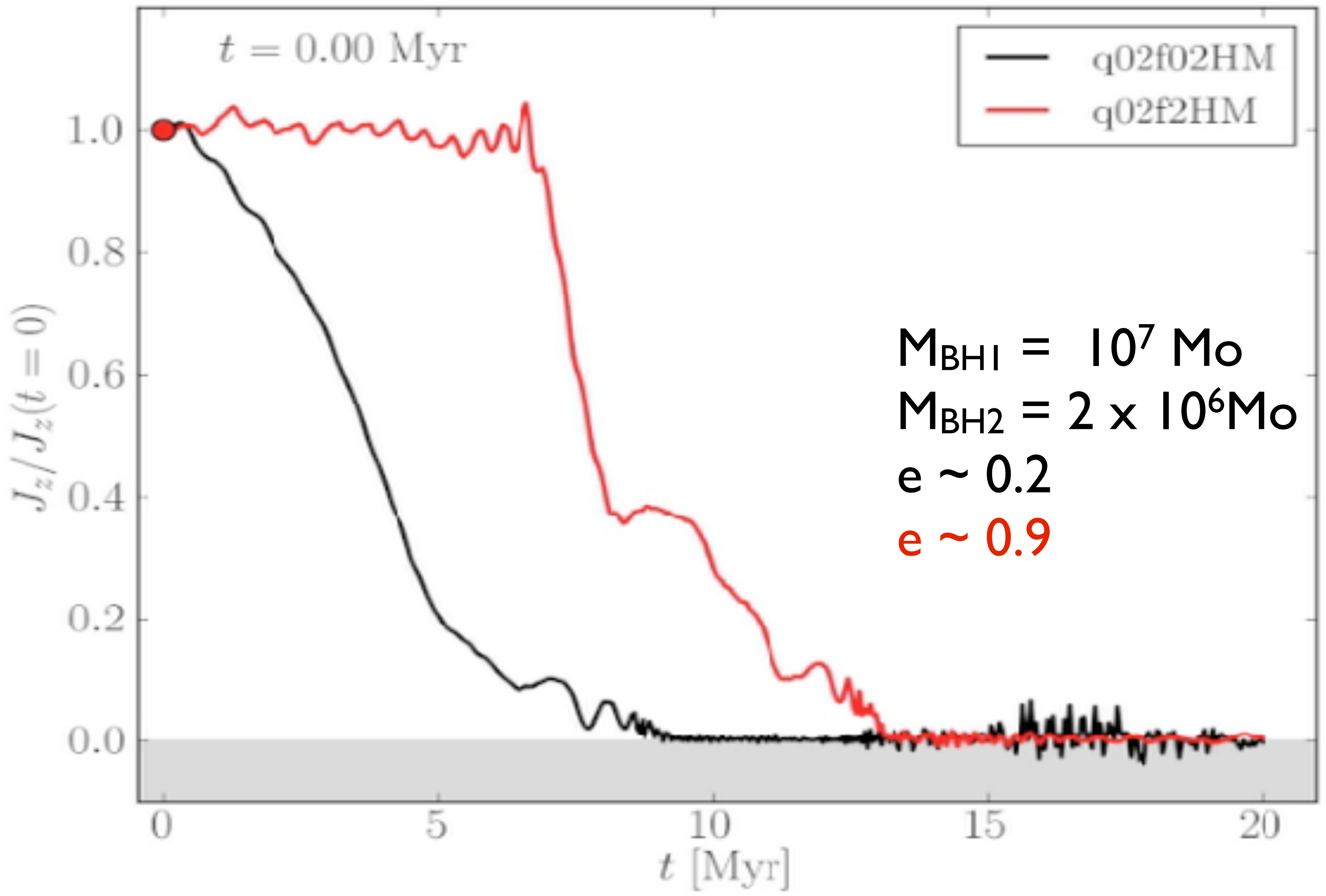




(Further) Orbital decay of BH Pairs in galactic nuclear disks with radiative cooling (~ 0.1 pc resolution)







M_{BH1} = 10^7 Mo
M_{BH2} = 2 x 10^6Mo
e ~ 0.2
e ~ 0.9

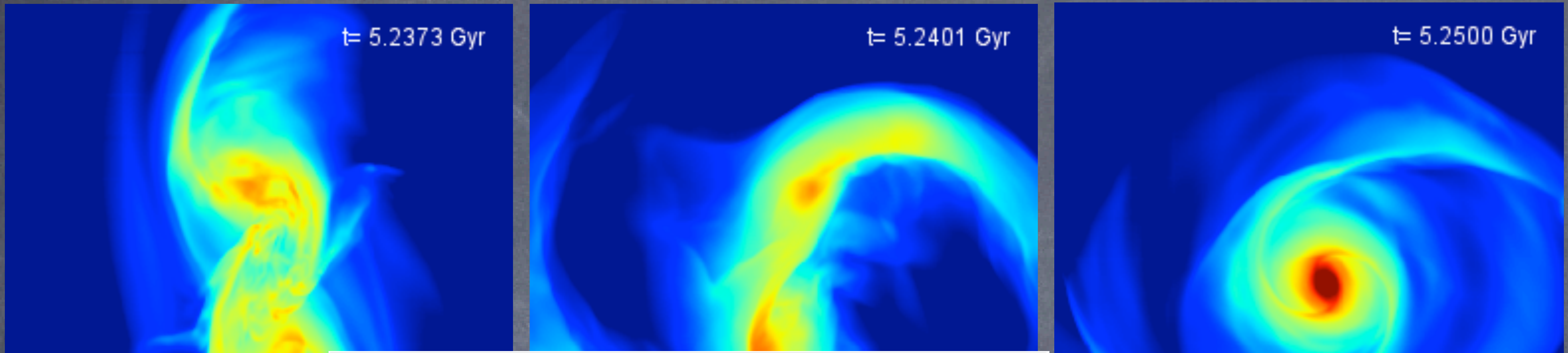
Phase 1 - Slow Decay by Dynamical Friction + Orbit Circularizatio
Phase 2- Fast Hardening due to spiral wave-induced torques

Decay timescales to 0.1 pc separation <~ 10^7 yr,
below this scale unclear, depends on gap opening, viscous
and tidal torques if circumbinary disk arises

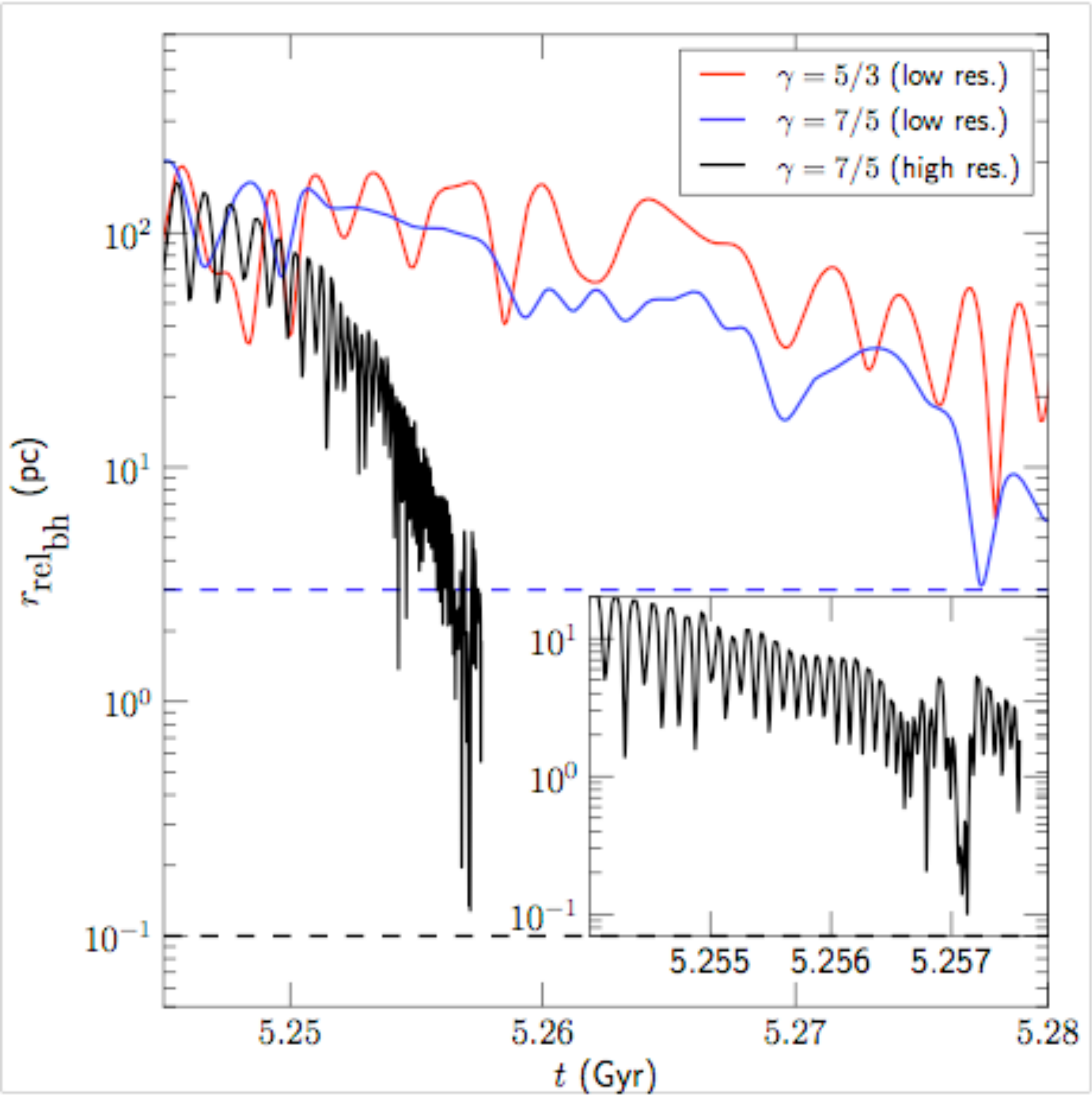
Mayer 2013 (Classical and Quantum Gravity Review)

Fiacconi, Mayer et al. (2013)

One more step: gas-rich mergers at 0.1 pc resolution (w/effective EOS as in Mayer et al. 2007 Chapon, Mayer & Teyssier (2013) confirm binary formation/decay to ~ pc scale in < 10^7 yr, but then binary stalls, no evidence of effective disk torques...



200 pc
scale
frames



Note sinking stalls at resolution well above resolution limit of 0.1 pc.

Two options: (a)resolution effect or (b)limitations of equation of state which gives hot uniform density core for CND, a condition in which dynamical friction shuts off and no disk torques arise

In real galaxies drag at < pc scales should come from both gas dynamical friction/torques and 3-body encounters with stars.

How do we put all physical processes together in a single calculation, and down to the beginning of the inspiral phase at milliparsec scales?

Khan, Fiacconi, Mayer, Berczik & Just et al. 2016
(predecessor with idealized binary galaxy merger in Khan et al. 2013).

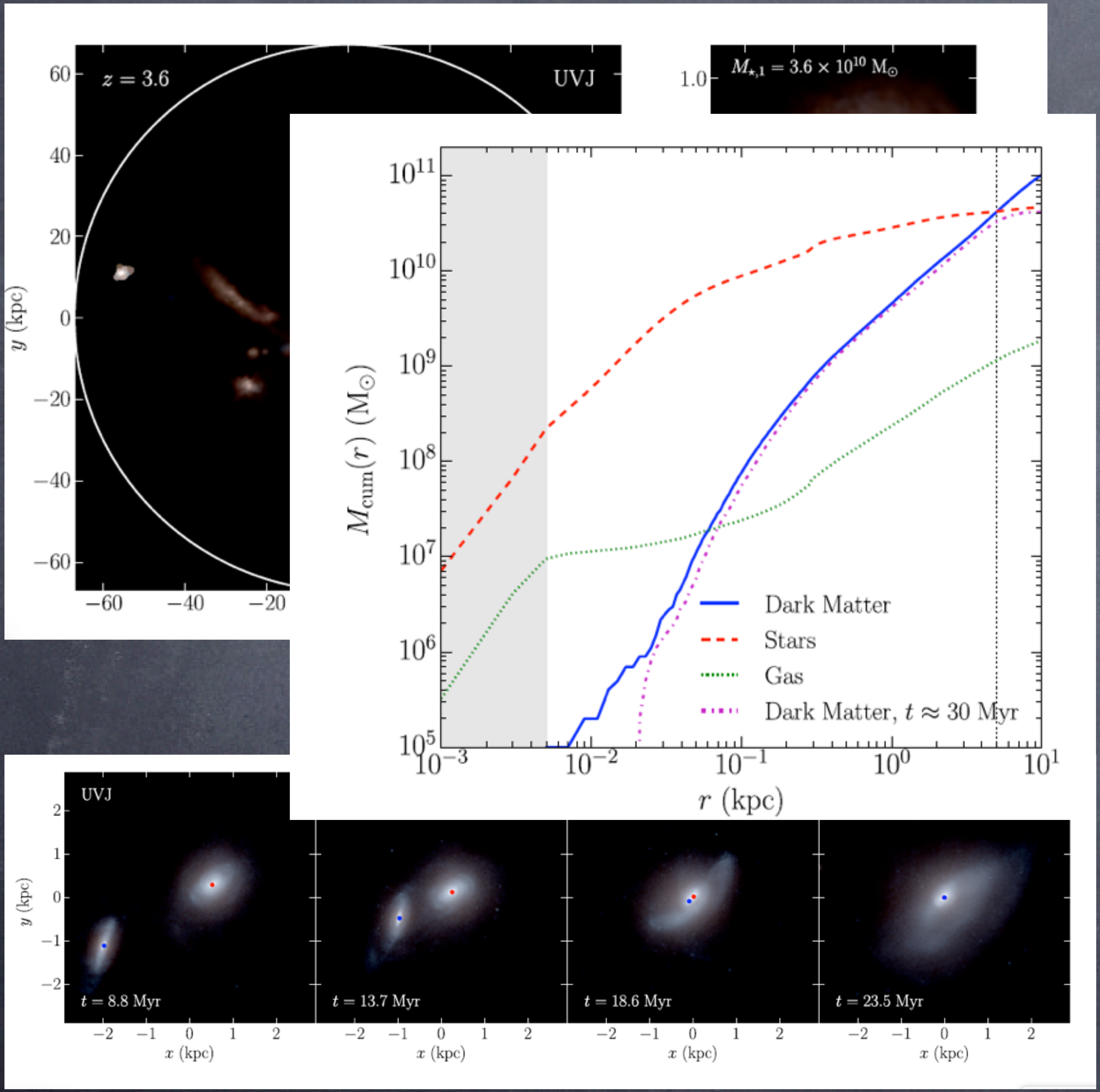
A challenging calculation: ab-initio cosmological hydro simulation with galaxy mergers attached to direct N-Body calculation of nuclear dynamics with post-newtonian corrections (from Mpc scales to milliparsec scales, > 1 yr supercomputing time)

The ARGO Cosmological Galaxy Formation Simulation
(Feldmann & Mayer 2015; Fiacconi, Feldmann & Mayer 2015)

Highest resolution simulation to date that models the formation of a GALAXY GROUP

Run on PizDaint Supercomputer at the Swiss National Supercomputing Center

I. Start from a merger of two "typical" massive star forming galaxies in the ARGO cosmological simulation (Khan, Fiacconi, Mayer et al. 2016)



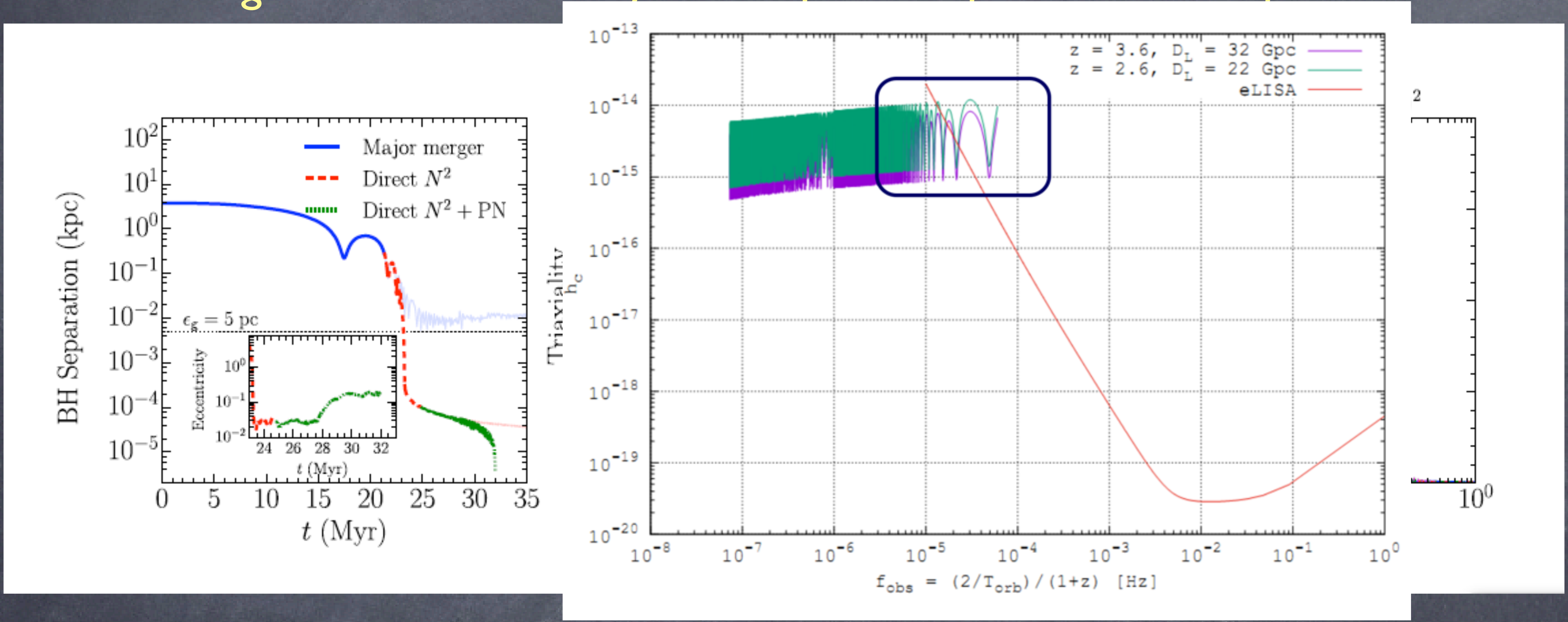
II. Before galaxies merge increase resolution to 5 pc (particle splitting) *Two SMBHs are "implanted" at the center with mass ~ 10^8 Mo*

III. After merger most of the gas consumed into stars inside 1 kpc. Simulation continued with purely gravitational code (direct N-Body on Graphic Processing Units (GPUs) with 0.001 pc force resolution

IV. Include post-newtonian corrections (up to 3.5 order) to capture relativistic effects up to beginning of inspiral

Fast coalescence **in <~ 10 Myr** after the two galaxy cores merge owing to repeated encounters with stars (loss cone almost full all the time)

Stars interacting with SMBH binary come from as far as 10-100 pc



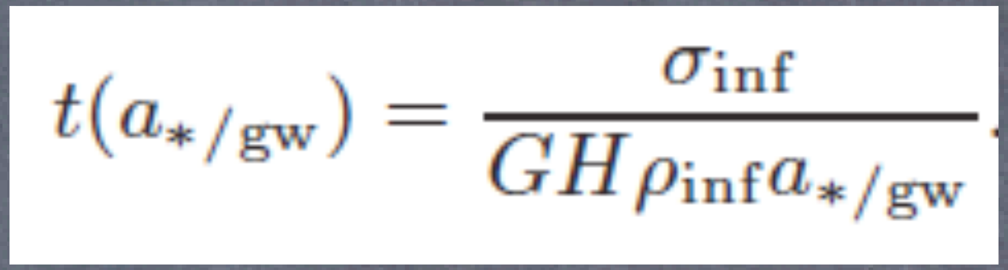
Short timescales due to high background density, *natural for galaxy formation in CDM model at early epochs (matter density higher + gas cools faster) and confirmed by observations of galaxies at z ~ 2-3 (eg Szomoru et al. 2012; Papovich et al. 2015)*

Important implications for LISA event rates from SMBH mergers (work in progress with Khan, Baraussse and Sesana)

The importance of galaxy host structure as a function of redshift for SMBH merger timescales

Matching old and new timescales: rescale N-Body models of Khan et al. (2012) to the density of our cosmological merger remnant and recompute hardening phase (assuming same SMBH mass and same central velocity dispersion)

Following Sesana & Khan (2015) and using



$$t(a_{*/\mathrm{gw}}) = \frac{\sigma_{\mathrm{inf}}}{G H \rho_{\mathrm{inf}} a_{*/\mathrm{gw}}}.$$

hardening timescale becomes ~ 10-30 Myr (instead of 1 Gyr!), consistent with results in Khan et al. (2015)

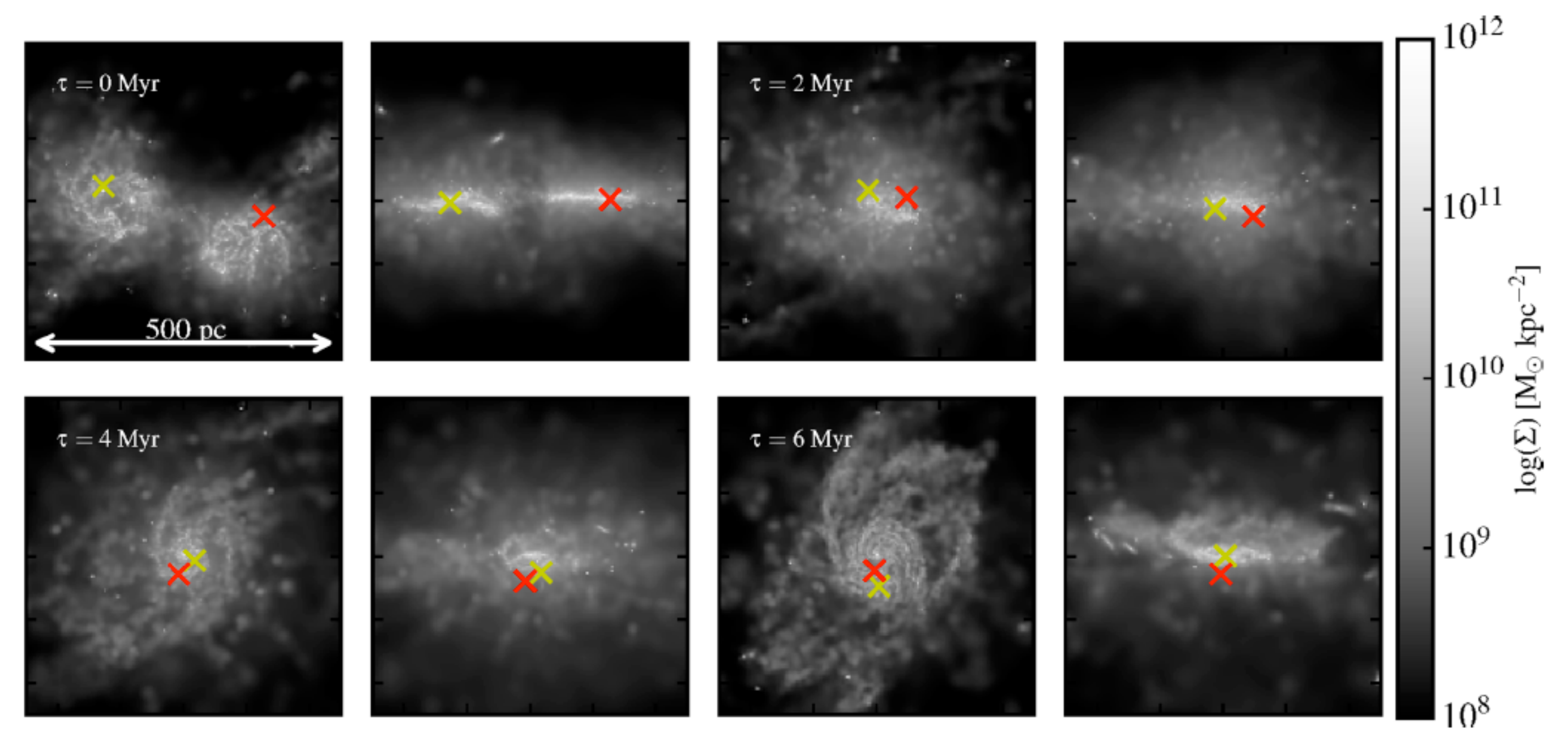
Characteristic density is thus key parameter despite more complex structure of galaxies in cosmological simulations vs. idealized N-Body models!

Furthermore, *to first order scaling of density with redshift is consistent with the natural* $(1+z)^3$ *scaling of cosmological density with redshift*

Back to gas-rich Major Mergers:

with more realistic radiative physics, star formation and stellar/SN feedback

gas in circumnuclear disks multi-phase amd clumpy rather than smooth!



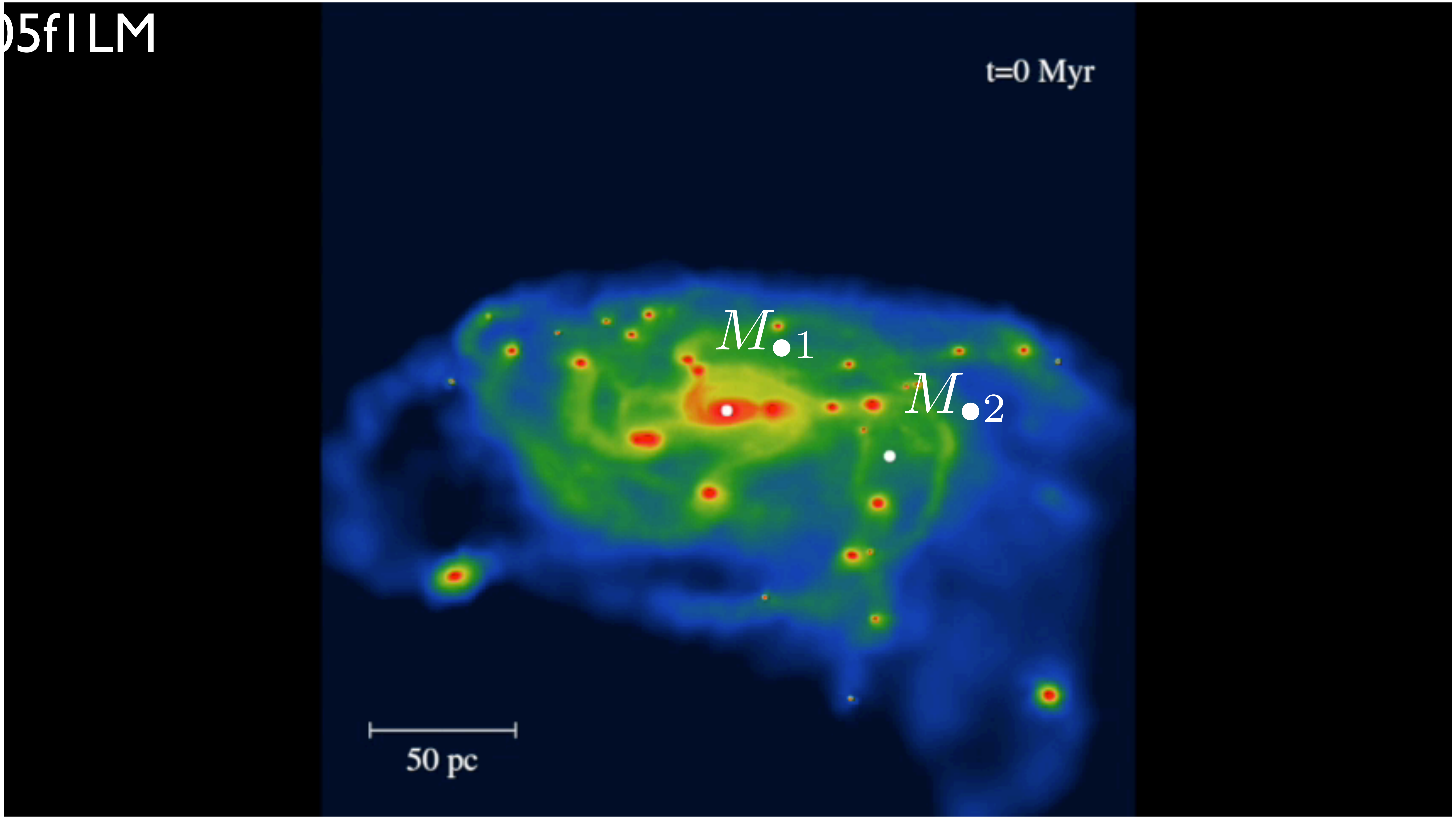
Roskar, Fiacconi, Mayer et al. 2015

() Complex dynamics of last phase of galaxy merger -- Supernovae-driven kpc-wide outflows when the galaxy cores collide and undergo starburst, dense CND forms afterwards

() SMBHs fluctuate around midplane of remnant, the enter in CND gradually assembled by fall-back of gas outflows. *But CND has a highly clumpy ISM*

SMBH Pairs in Clumpy CNDs

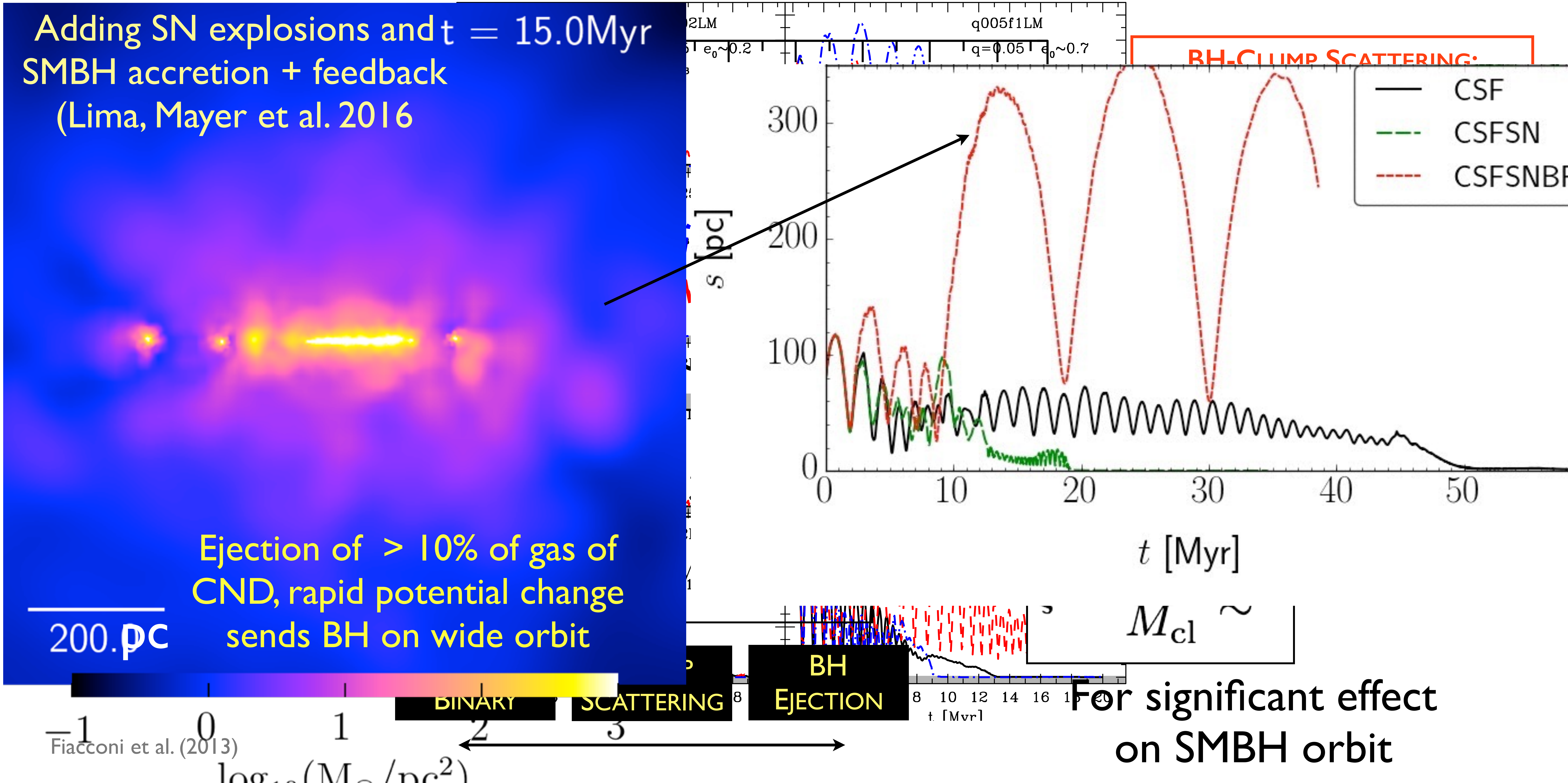
Clumpiness Arises naturally when gas cools rapidly via radiative emission ($T_{cool} \ll T_{orb}$),satisfied in nuclear gas disks due to atomic and molecular line Cooling



Fiacconi, Mayer et al. (2013)

SMBH PAIRS IN CLUMPY CNDS

NEW REGIME: STOCHASTIC ORBITAL DECAY



Adding SN explosions and SMBH accretion + feedback (Lima, Mayer et al. 2016

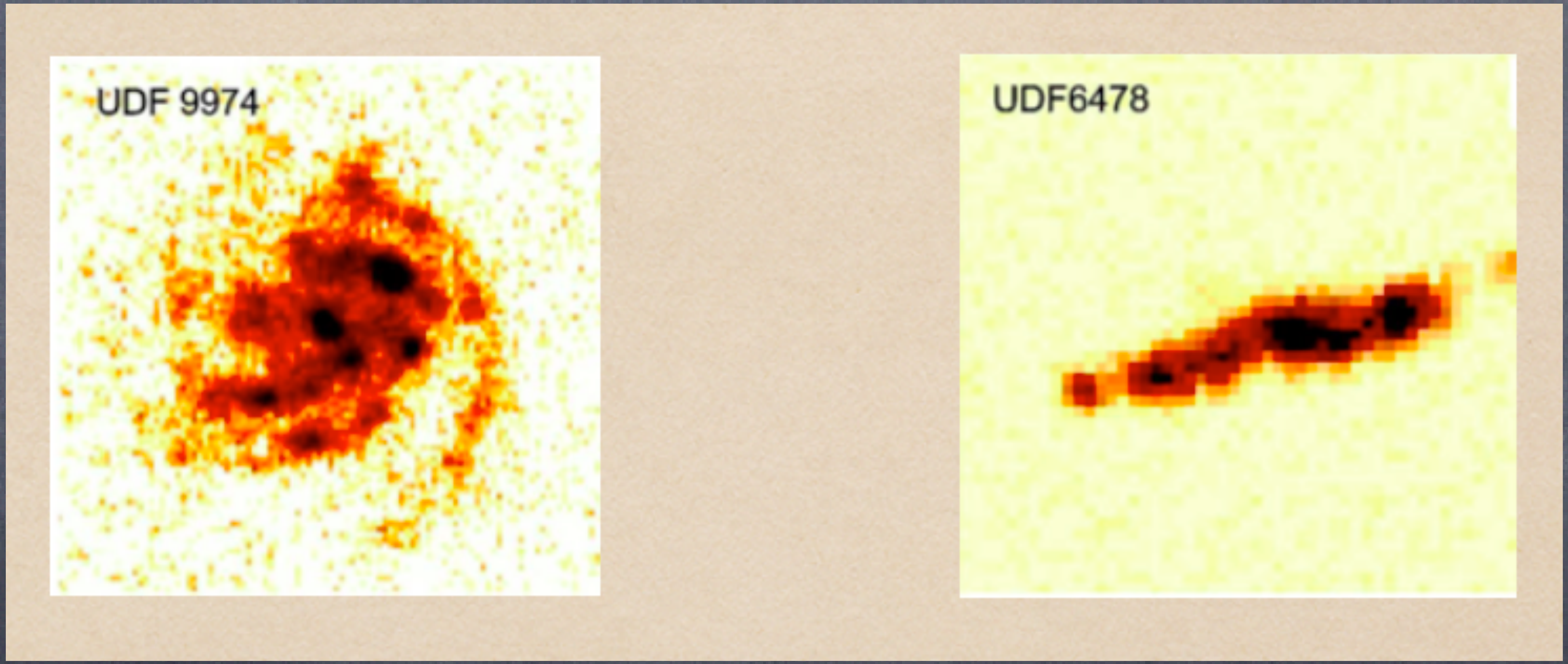
Ejection of > 10% of gas of CND, rapid potential change sends BH on wide orbit

Fiacconi et al. (2013)

For significant effect on SMBH orbit

Effect of clumpy ISM in high-redshift massive gas-rich *galactic* disks (>~ kpc scales)

At z > 1 most bright, star forming galaxies have gas-rich disks that are clumpy on scales >~ 10 larger than a low z , as if star forming clouds are >~ 10 larger and more massive than Giant Molecular Clouds (>~ 100 pc, 10^7-10^8 Mo) (100 pc-1 kpc rather than 10-10 pc). Observations mostly optical/UV, now new ALMA observations.

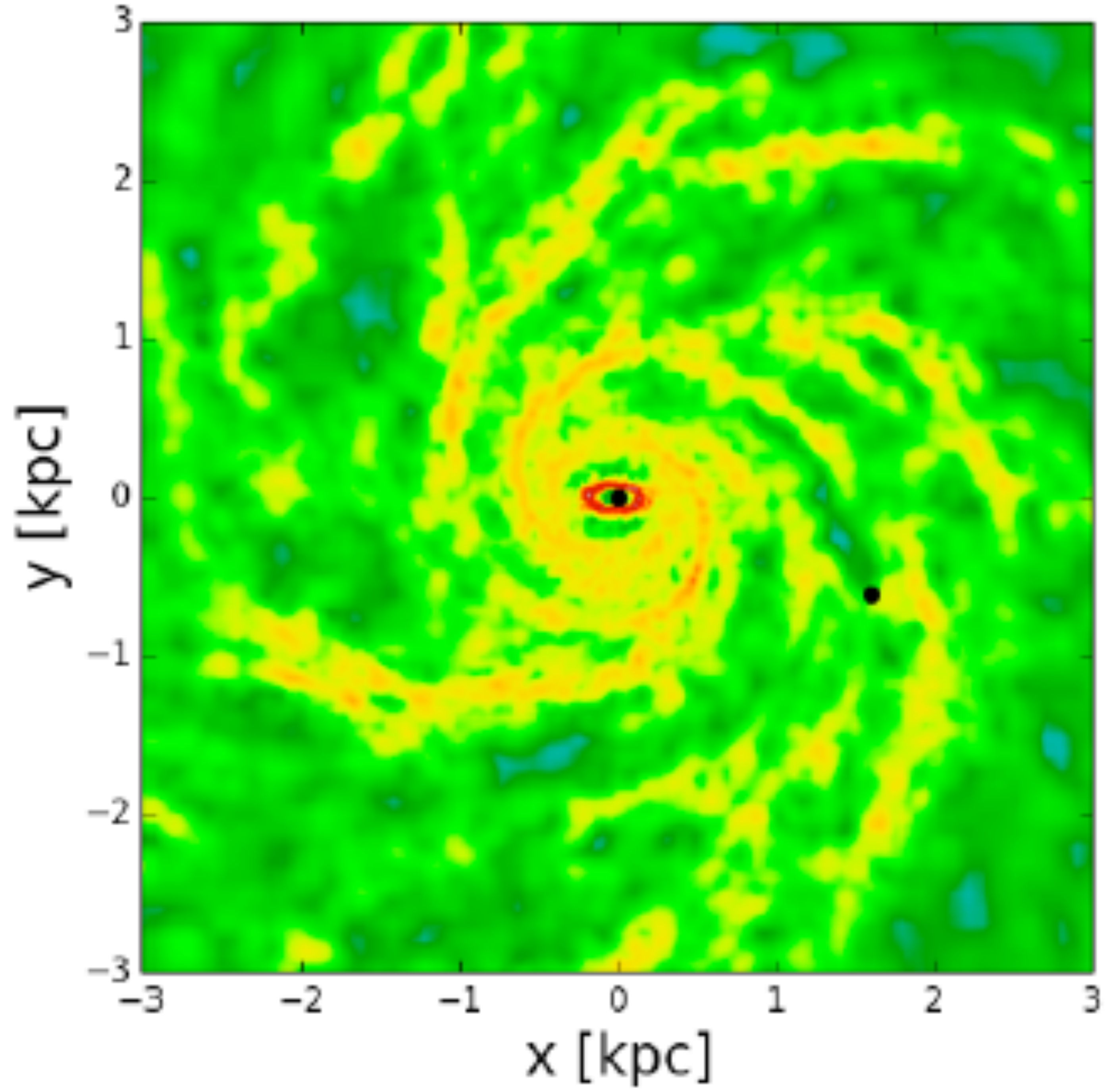


Cores of smaller companion galaxies (=minor mergers) and/or produced by fragmentation of massive gas disk due to gravitational instability (eg Ceverino & Dekel 2010; Bournaud et al. 2013; Mandelker et al. 2015; Mayer et al. 2015).

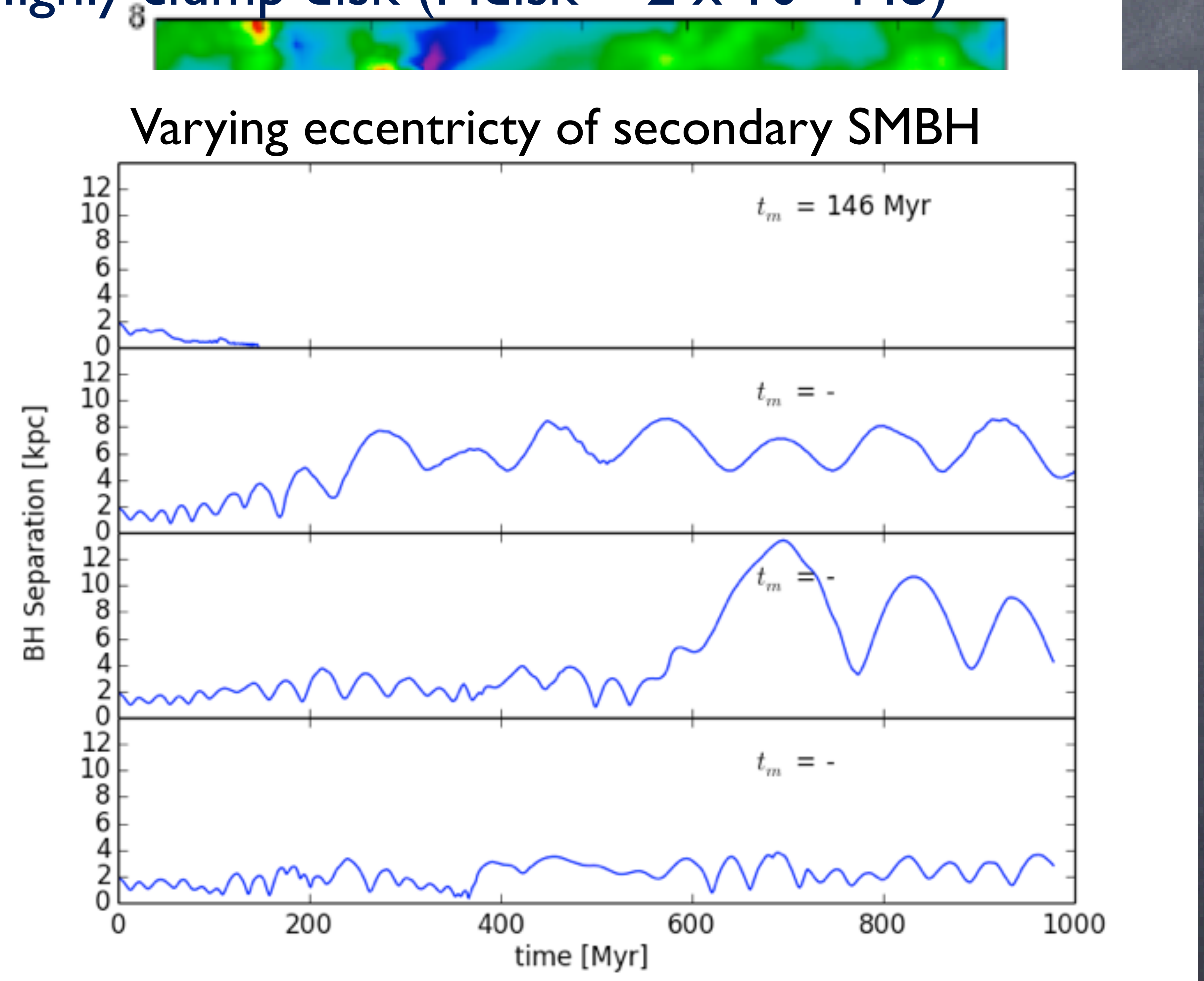
Tamburello, Capelo, Mayer & Bellovary (2016): suite of hydro simulations with pair of SMBHs embedded in clumpy galactic disks, start at kpc separation.
(M_{BH} ~ 5 x 10^7-5 x 10^8 Mo, 1:5 mass ratio).

Same effect as in clumpy CND simulations of Fiacconi et al. (2013) but with longer timescales because SMBHs still at kpc separations
---> *stochastic orbital decay, SMBH mergers delays up to >~ 1 Gyr*

Mildly clump disk (Mdisk ~ 2 x 10^{10} Mo)



Highly clump disk (Mdisk ~ 2 x 10^{10} Mo)



Varying eccentricty of secondary SMBH

Conclusions

() The Process of MBH binary formation and hardening is tightly connected with the properties of the host galaxy at all scales

Must be studied in the full galaxy formation context and it is highly dependent on redshift because galaxy properties are. This is the only way to make LISA capable of probing structure formation with SMBH mergers (and viceversa to predict event rates as a function of redshift)

() Gas-rich and Gas-poor mergers behave very differently ("two modes" of SMBH mergers)

In gas-rich mergers a variety of processes can delay or speed-up the orbital decay of SMBHs (decay time to 0.1 pc separations from a few Myr to > 1 Gyr)

ISM clumpiness crucial at all scales, ***regime of stochastic decay****, to be modeled statistically.*

() HARDENING OF SMBHs IN STELLAR DOMINATED NUCLEI EMERGING FROM GAS DISSIPATON VERY FAST AT HIGH Z ($<\sim 10^7$ yr) DUE TO HIGH ENVIRONMENTAL DENSITY AND TRIAXIALITY

AT LOW REDSHIFT TIMESCALES OF > ~ Gyr BECAUSE NUCLEAR DENSITY LOWER

- High baryonic density crucial for *short SMBH decay timescales* in both dynamical friction-dominated phase and hardening phase dominated by 3-body collisions
- Neglecting possible residual gas-driven torques at in hardening phase implies our timescales ~ upper limit

Overall short coalescence time natural product of compact nature of galaxies at high-z plus effect of gas dissipation and star formation, also boosted at high-z

What about galaxy+SMBH mergers at lower-z?

But recall : for massive z > 2 galaxies in which gas is dominating the dynamics of an SMBH binary different scenario as disky merger remnant should be clumpy at both galactic and sub-galactic scales (Tamburello et al. 2015 + Roskar et al. 2015)
-----> *binary formation alone will take ~ 10^9 yr (hardening unexplored in these conditions, but likely < 10^9 yr from CND simulations)*

Emerging (Qualitative) Scenario

1 - Massive Gas Poor Galaxies (hosts of large SMBHs, $M_{BH} > 10^7$ Mo)

(a) High-z (z > 2) SMBH mergers FAST:
Galaxy Merger ~ a few 10^8 yr
SMBH binary formation + hardening ~ 10^7 yr

(b) Low-z (z < 1) SMBH mergers SLOW:
Galaxy Merger ~ a few 10^9 yr
SMBH binary formation + hardening ~ 10^9 yr

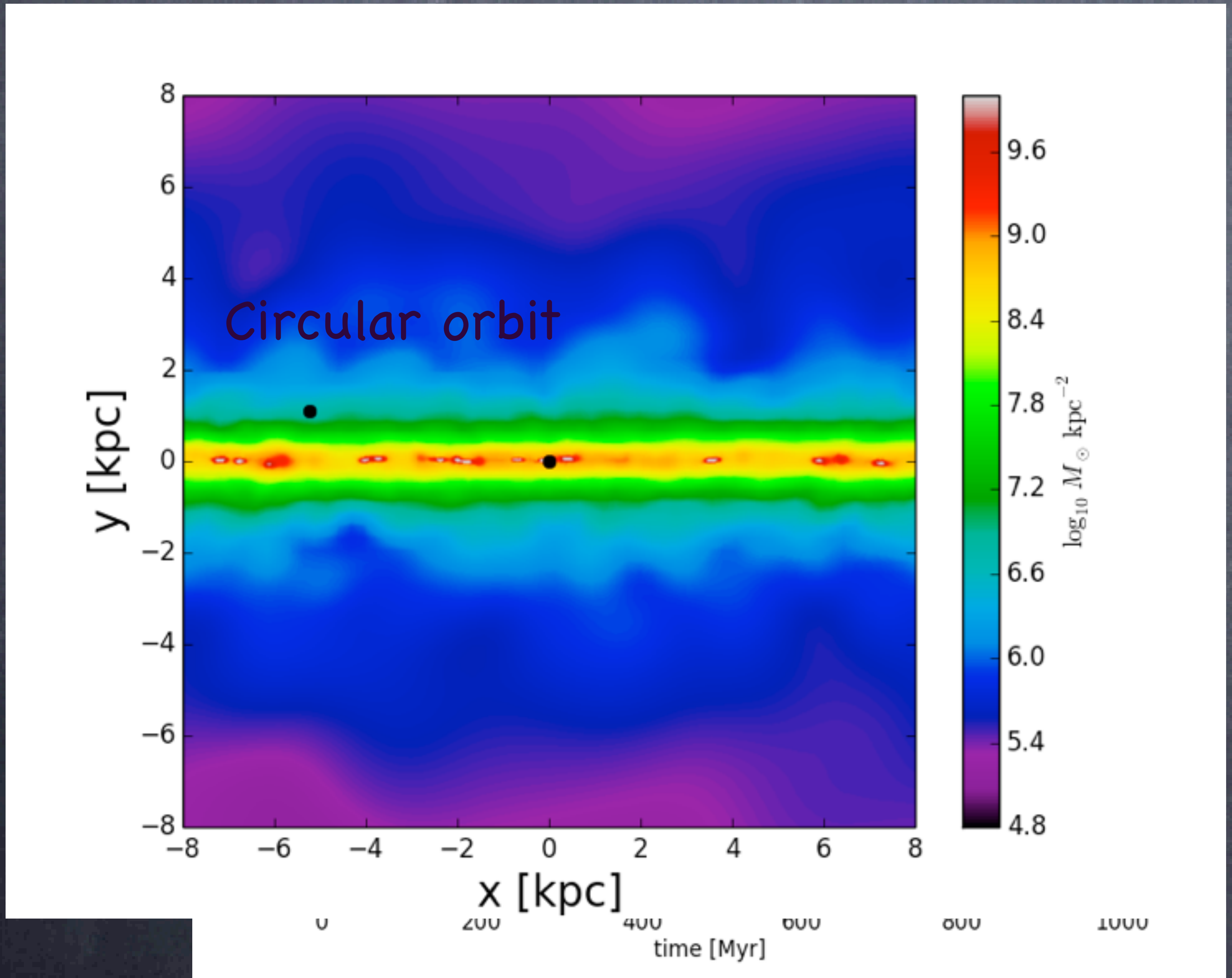
()Highly stochastic SMBH decay from kpc to <~ 100 pc (loose SMBH binary) due to perturbations by massive clumps and non-axisymmetric structures (eg spirals), plus heating by AGN feedback reducing density of gaseous and stellar background (lower drag).

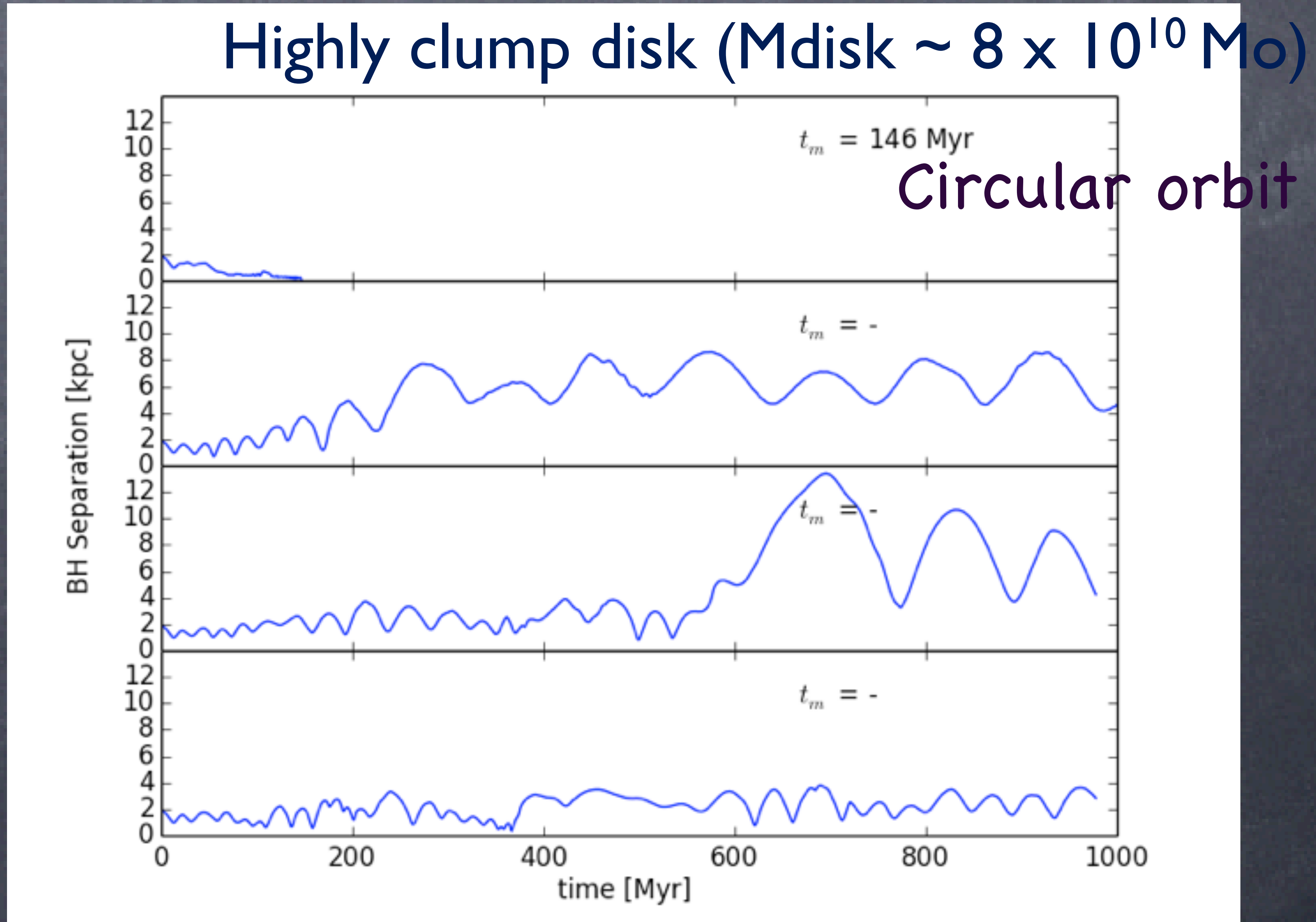
Effects stronger with higher eccentricity orbits for SMBHs

()SMBH binary formation timescale from ~ 10^8 to ~ 10^9 yr

At z ~ 2-3 lookback time ~ a few Gyr so "SMBH binary stalling" possible in some cases.

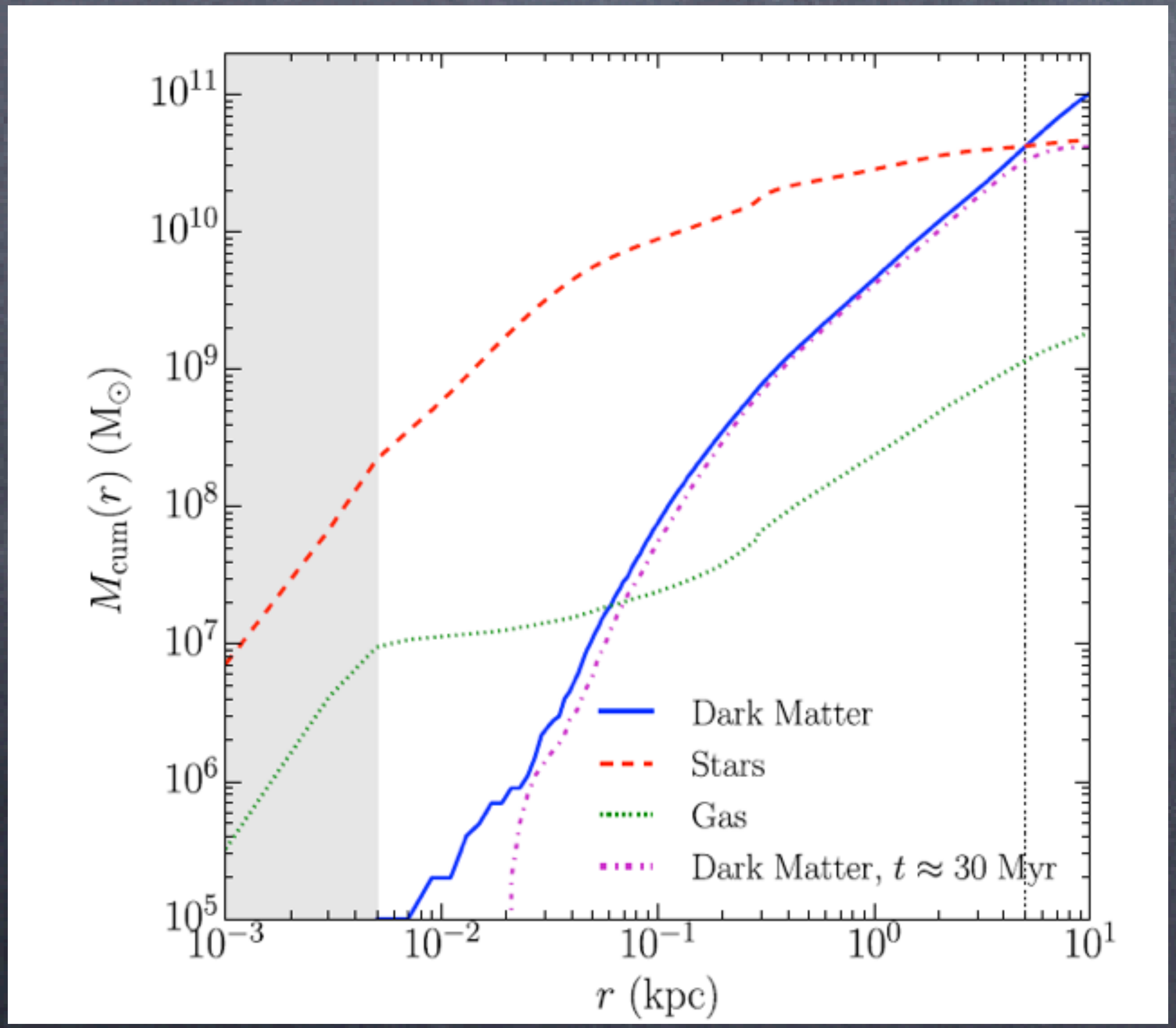
Longest timescales for higher eccentricity SMBHs

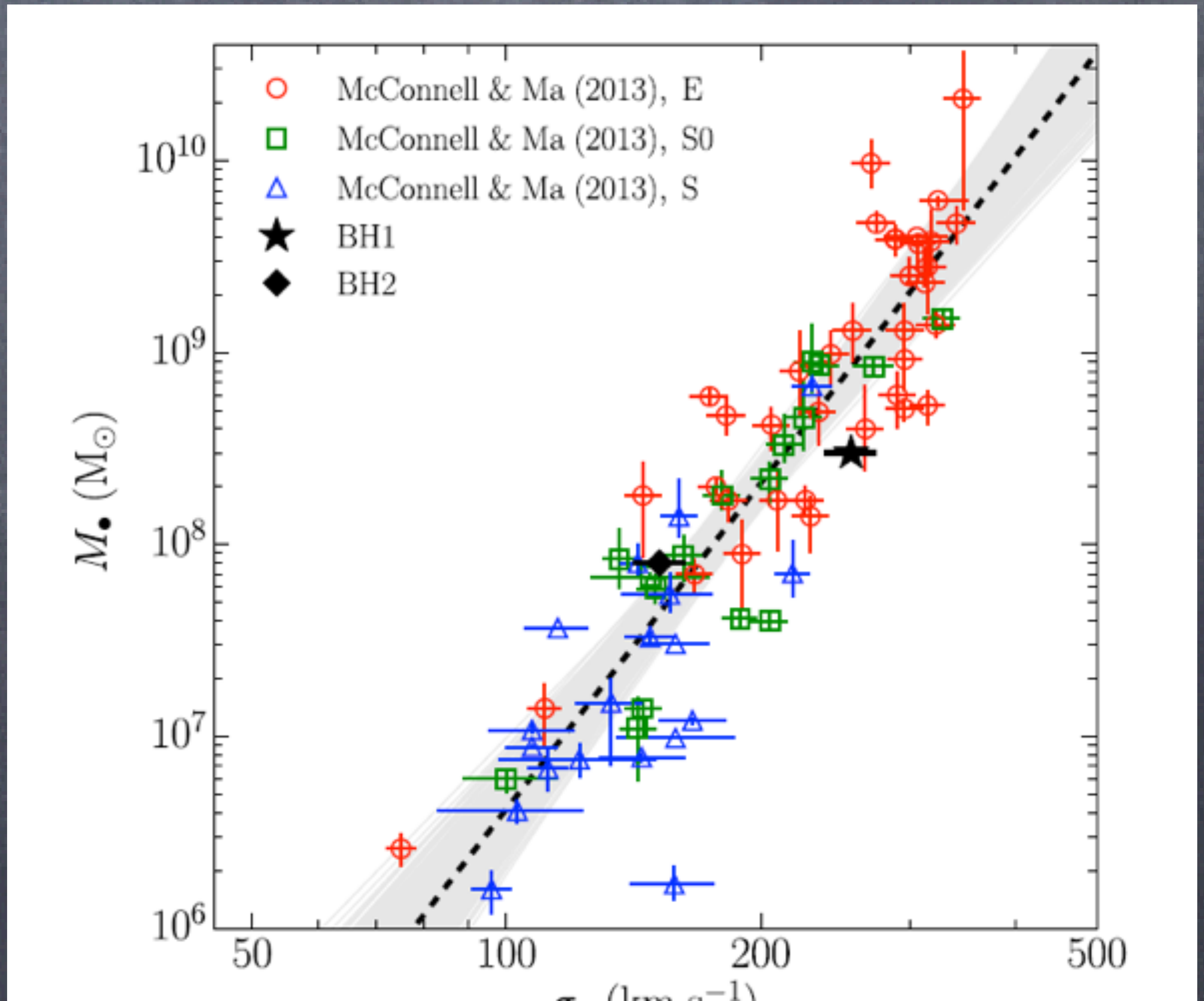



Highly clump disk (Mdisk ~ 8 x 10^{10} Mo)

Merger remnant is (1) gas poor as a result of gas consumption by star formation and truncation of cosmological gas accretion (Feldmann & Mayer 2015; Feldmann, Hopkins et al. 2016) and (2) has central velocity dispersion and effective radius (projected half-mass radius of stellar light) consistent with massive early-type galaxy at z ~ 2-3 (Szomoru et al. 2012) ---> *realistic characteristic density*

After SMBHs form a binary at >~5 pc separation resolution is gradually increased by factor of > 100 (to ~0.01 pc) and new stage run with phiGPU fast parallel direct N-Body code with post-newtonian terms up to 3.5
(small gas residual converted into stars)





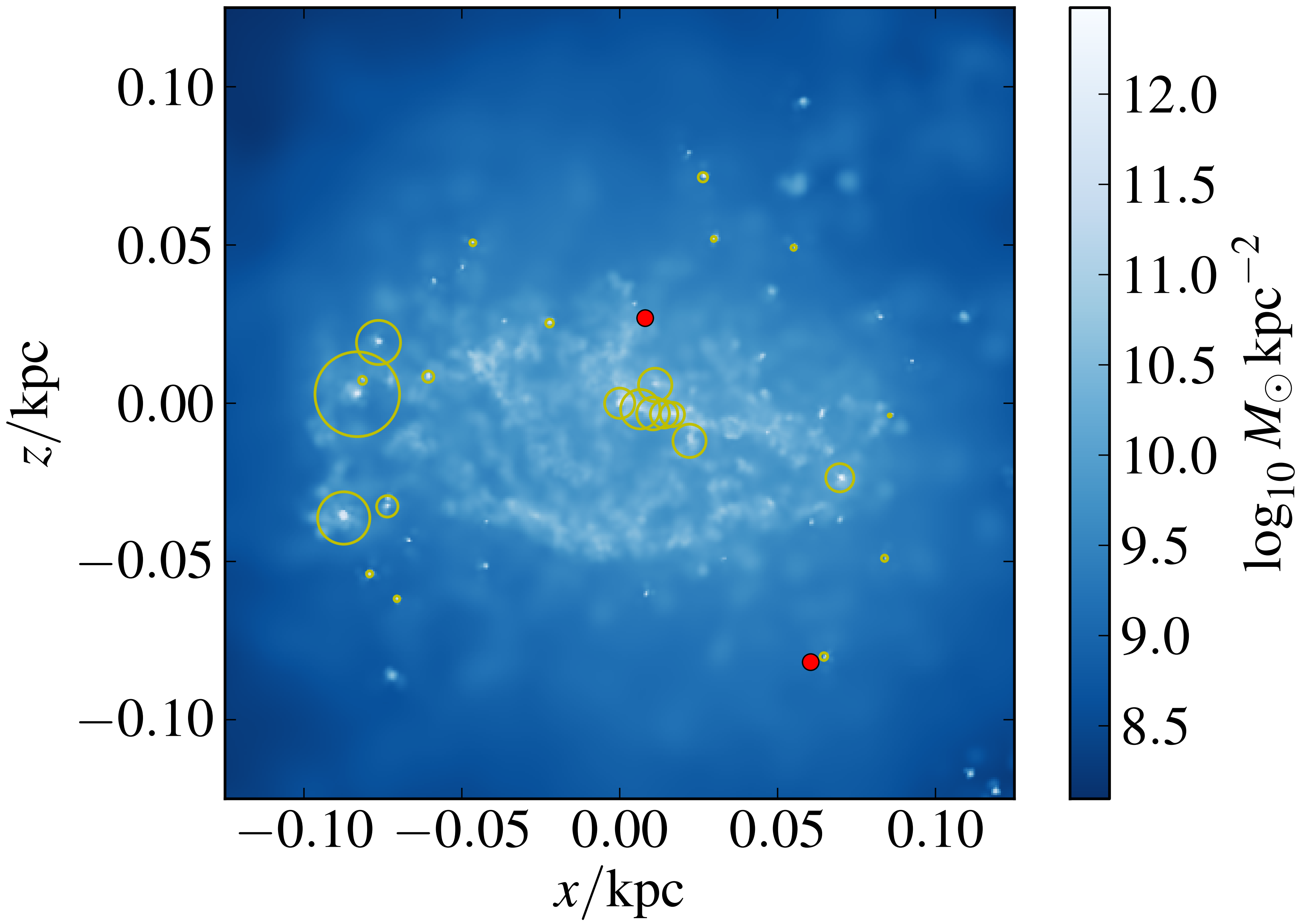
II - Massive Gas-Rich (Clumpy) Galaxies (hosts of large SMBHs, $M_{BH} > 10^7$ Mo) -- only present at z > 1!

SMBH mergers SLOW:
Galaxy Merger ~ a few 10^8 yr
SMBH binary formation + hardening >~ 10^9 yr

I - Low-Mass Gas-Rich (Smooth) Galaxies (hosts of "small" SMBHs, $M_{BH} < 10^7$ Mo -- relevant for eLISA!):

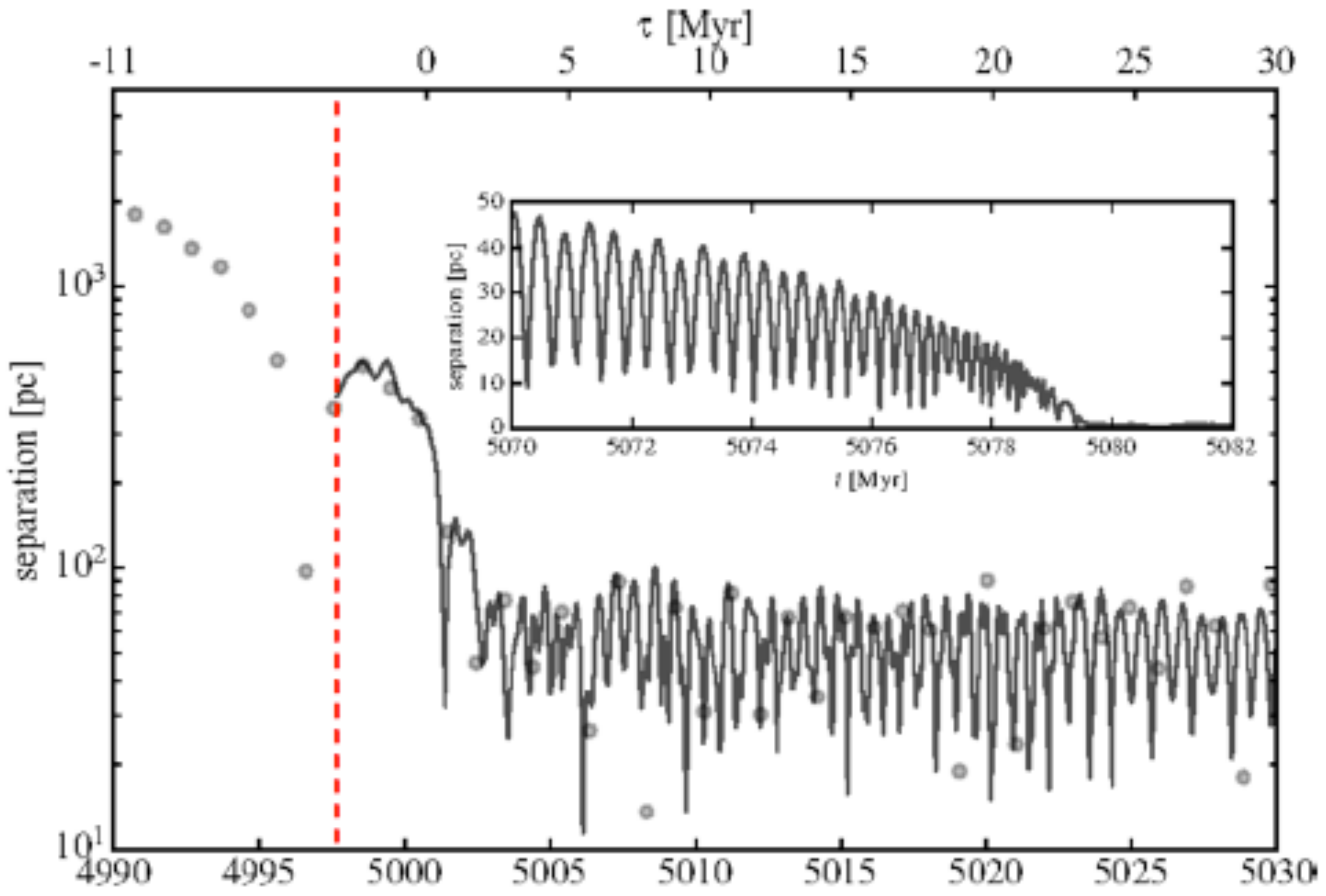
SMBH mergers MODERATELY FAST:
Galaxy Merger ~ a few 10^8 yr (high-z) to a few Gyr (low z)
SMBH binary formation + hardening <~ 10^8 yr (but
late hardening phase in circumbinary disk not explored enough)

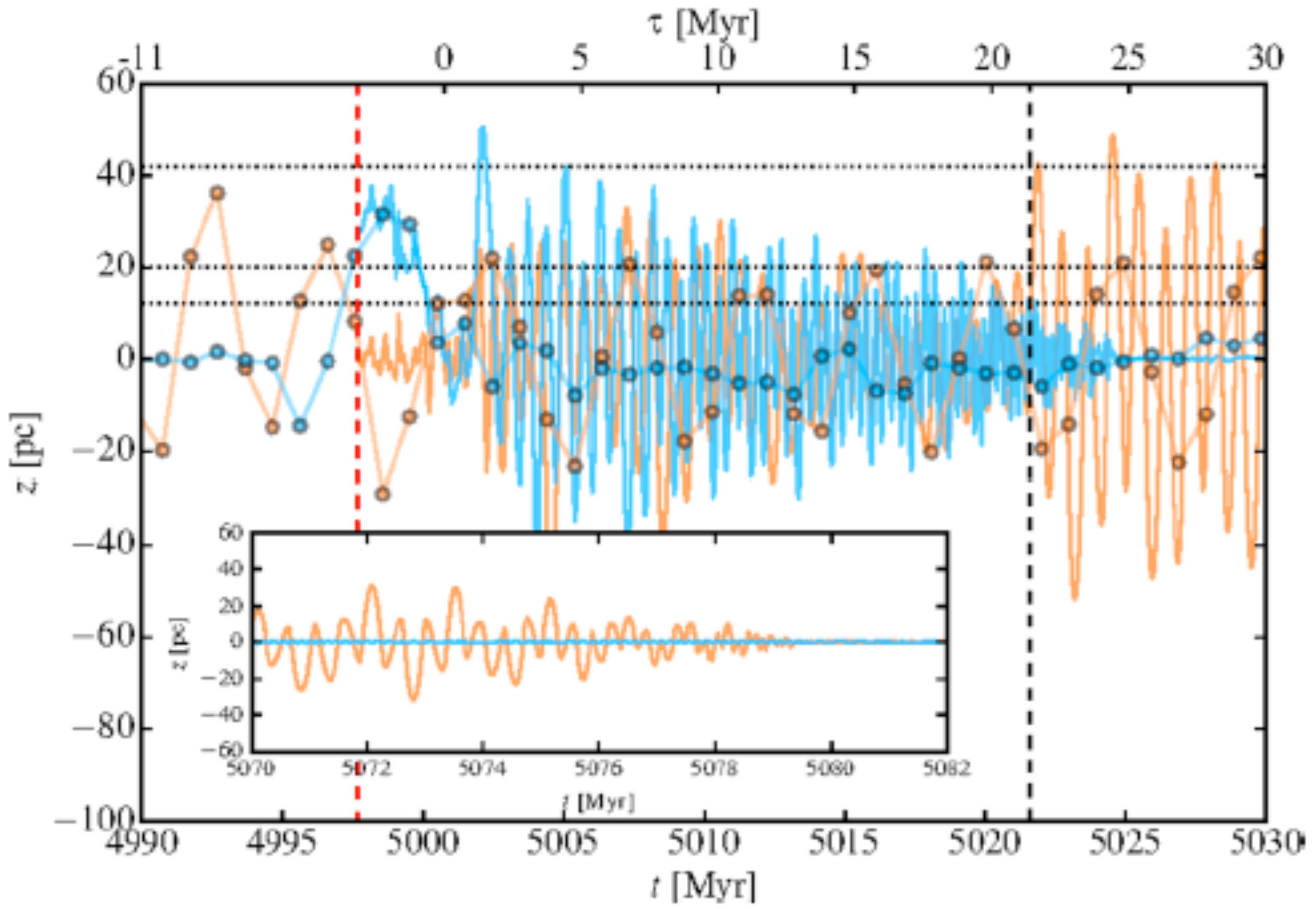
DELAYED FORMATION OF HARD BINARY COMFIRMED



SMBH Ejection out of disk plane & Temporary Stall

Roškar, Mayer, Fiacconi et al. 2014



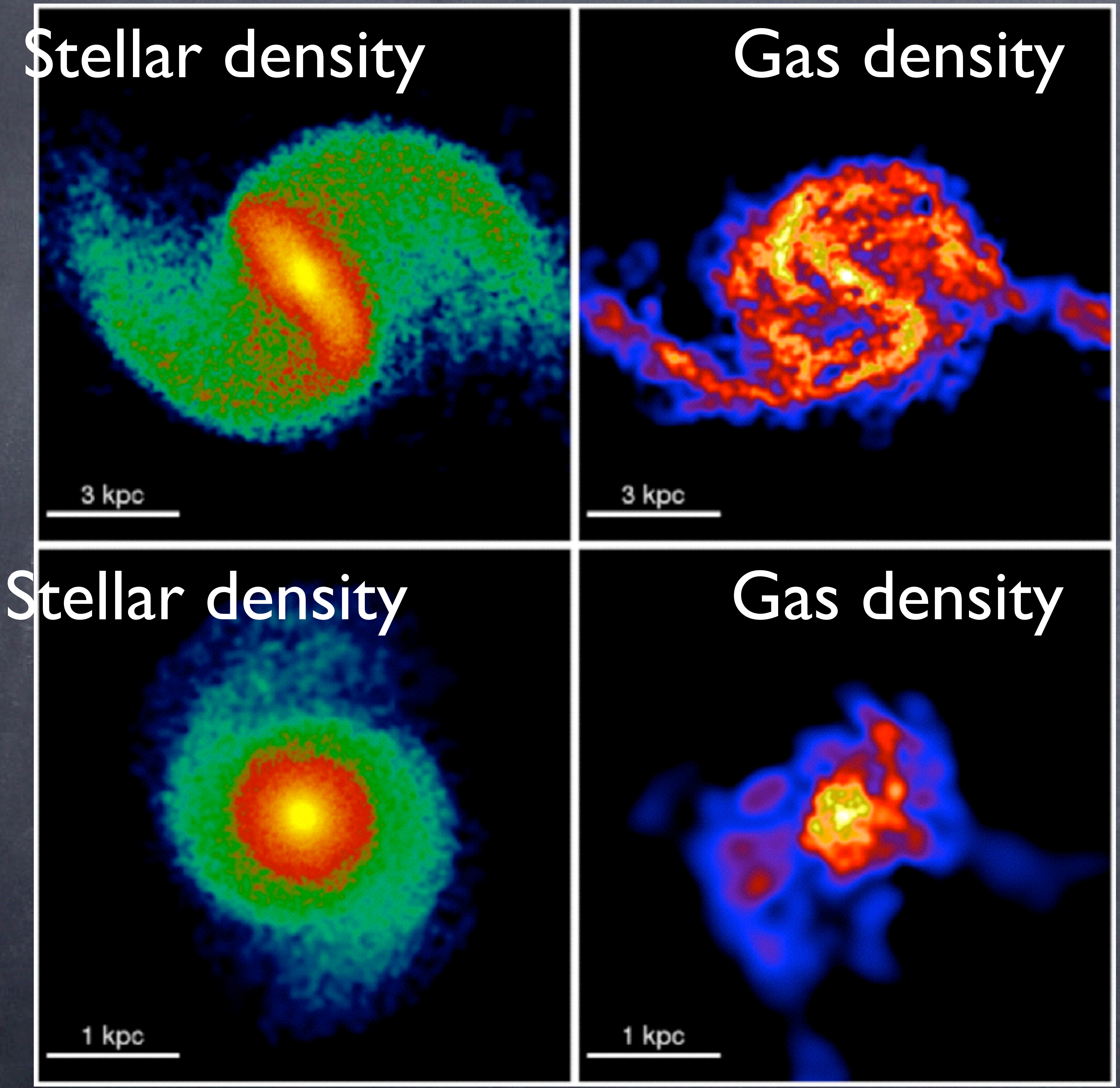


$$\tau_{\rm decay} \sim 100\ \mathrm{Myr}$$

to reach pc-scale separation

--> SLOW MBH binary formation

A higher complexity is minor mergers: competition between gas inflows and stripping



The secondary galaxy in a 1:4 merger at last pericenter (primary is a Milky-Way sized galaxy at z ~ 3)

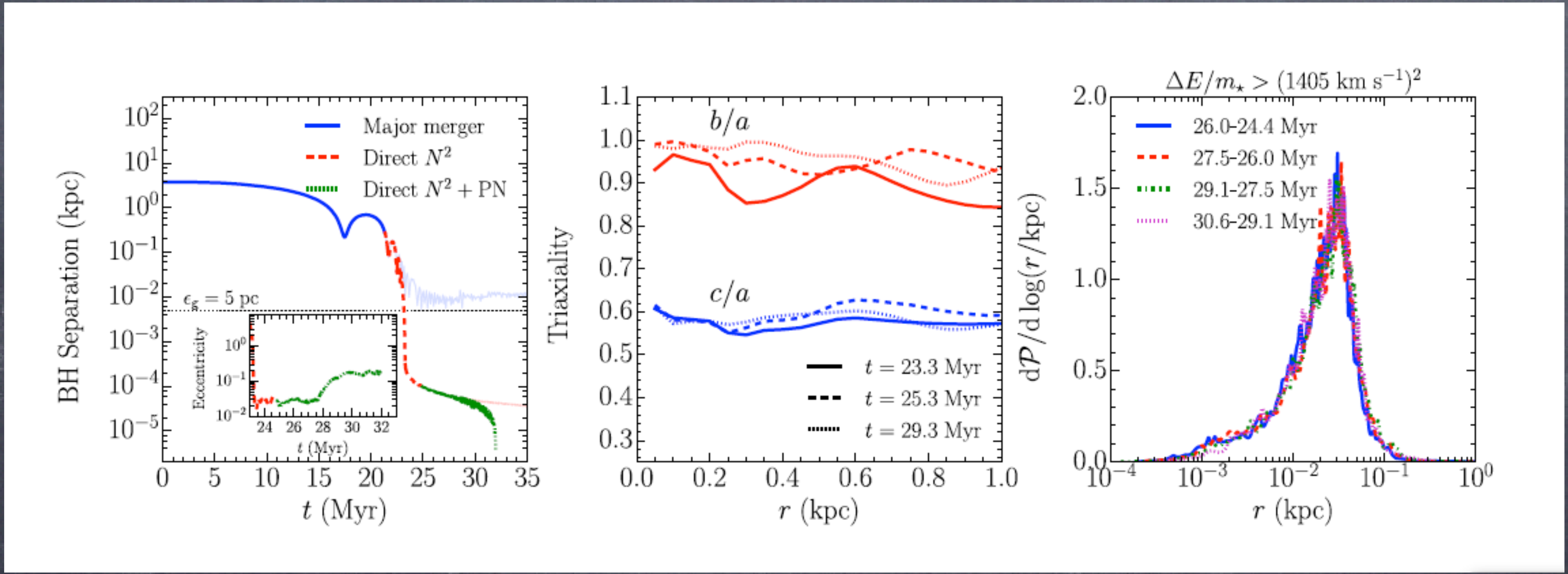
Tides of the primary trigger a bar-like mode that drives gas to the center forming a compact CND

The secondary galaxy in a 1:10 merger at last pericenter:

gas is stripped more efficiently by ram pressure through disk of primary, no dense compact CND

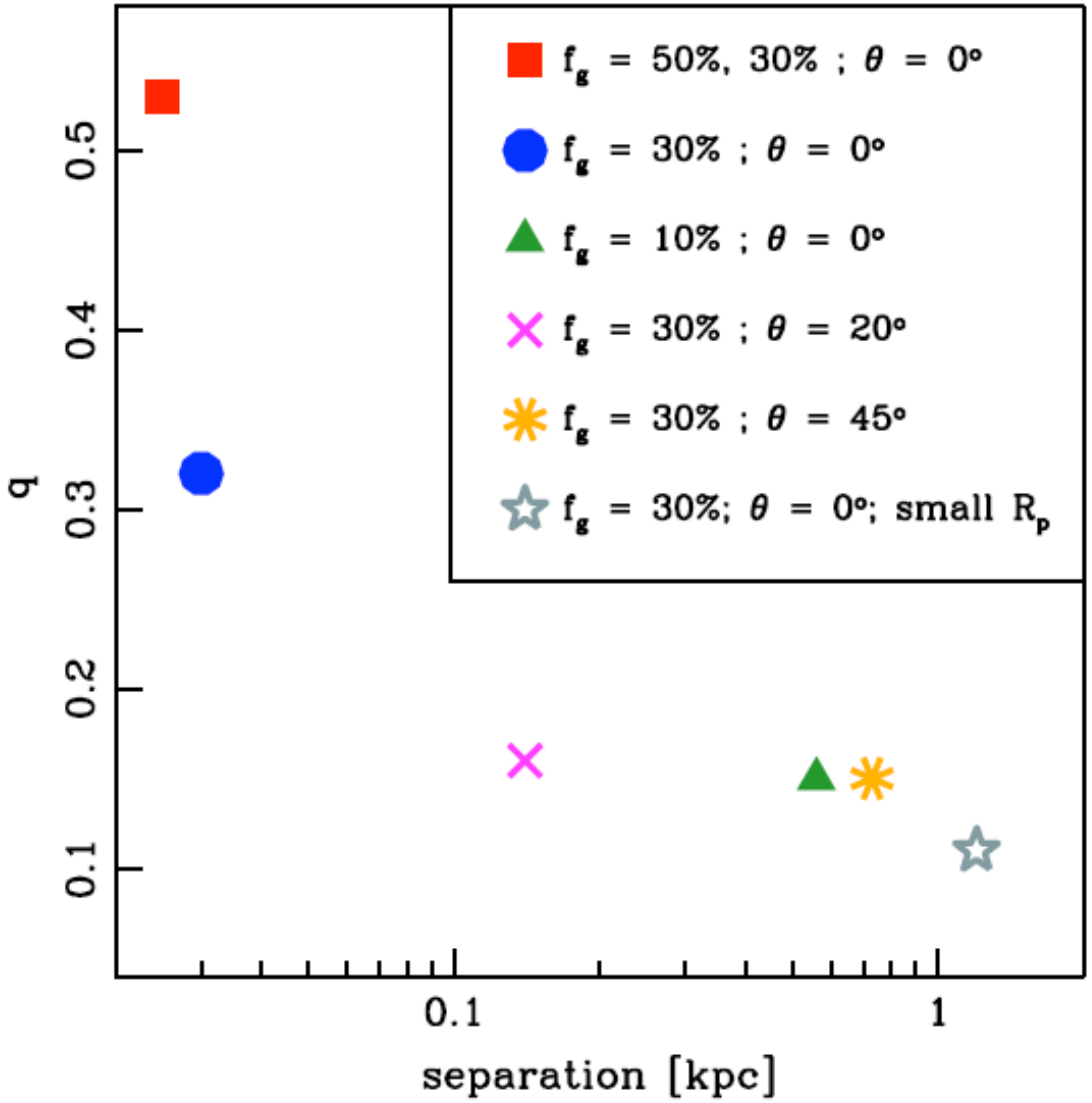
Fast coalescence in ~ 10 Myr after the two galaxy cores merge (only a few Myr after SMBH binary formation at few pc separation) owing to refilling of loss cone in triaxial potential.

Stars interacting with SMBH binary mostly from 10-100 pc distances from the center (distributio of orbital radii, right panel) --> centrophilic orbits



(a) Triaxiality natural from dissipative cosmological merger, and (b) short timescales due to high background density, alsonatural result of structure formation at high-z plus high dissipation

Stochasticity in SMBH binary formation minor galaxy mergers (1:4 - 1:10)



Callegari, Mayer et al. (2009)
Callegari et al. (2011),
van Wassenhoeve et al. (2014)

M_{BH} ~ 10^5-10^7 Mo (relevant to eLISA band)

$t_{\text{decay (to pc separations)}}$ ~ 10^8-10^9 yr, depends on multiple parameters (orbits, gas fraction, central density)

In some cases MBH pairs stall at 100 pc -1 kpc scales Lose gaseous envelope by **ram pressure stripping,** then "naked" MBH yields T_{df} >~ T_{Hubble} (see also Van Wassenhoeve et al. 2014). *Should be modeled using a probabiliy distribution in semi-analytical models to get GW event rates*

So far:

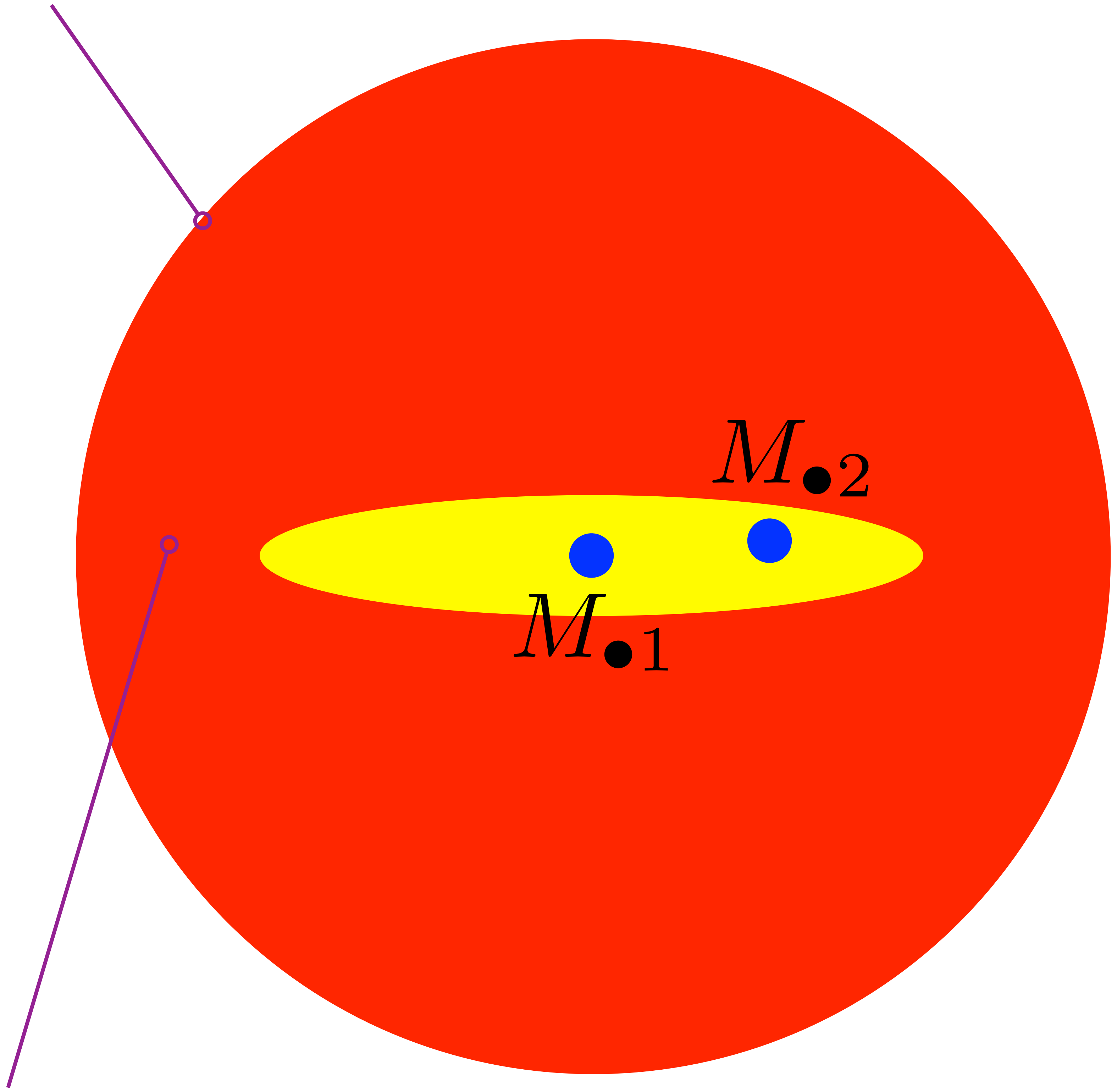
SMBH binary formation timescales ~ 10^6-10^7 yr in MAJOR mergers, 10^8-10^9 yr in MINOR mergers (final separations >~ 10 pc)

...Let's now look at Stage (3), namely the hardening phase, in stellar environments first and gaseous environments second

HARDENING OF MBH PAIRS IN CNDs

SIMULATION SET-UP

STELLAR BULGE ($\lesssim$500 PC)



GASEOUS CIRCUMNUCLEAR DISK (CND, ~100 PC SIZE)

RESOLUTION 0.1 PC

Fiacconi et al. (2013), ApJL

- SPH SIMULATION WITH GADGET2
- PLUMMER STELLAR SPHEROID
- SELF-GRAVITATING MESTEL CIRCUMNUCLEAR GASEOUS DISK

$$M_\star/M_{\rm d} = 5$$

LIST OF PERFORMED SIMULATIONS AND OF THEIR PARAMETERS.

Label	$M_{\rm d}$ [$M_\odot$]	q[a]	f	e_0[b]	$t_{\rm cool}$ [Myr]
q005f02LM	10^8	0.05	0.2	0.2	1.0
q005f1LM	10^8	0.05	1.0	0.7	1.0
q02f025LM	10^8	0.2	0.25	0.25	1.0
q02f2LM	10^8	0.2	2.0	0.9	1.0
q01f02HM	5×10^8	0.1	0.2	0.2	0.5
q01f2HM	5×10^8	0.1	2.0	0.9	0.5
q02f02HM	5×10^8	0.2	0.2	0.2	0.5
q02f2HM	5×10^8	0.2	2.0	0.9	0.5

[a] $q = M_{\bullet 2}/M_{\bullet 1}$, $M_{\bullet 1} = 10^7\ {\rm M}_\odot$.

[b] $e_0 \sim \sqrt{1 - 1/(1+f^2)}$.

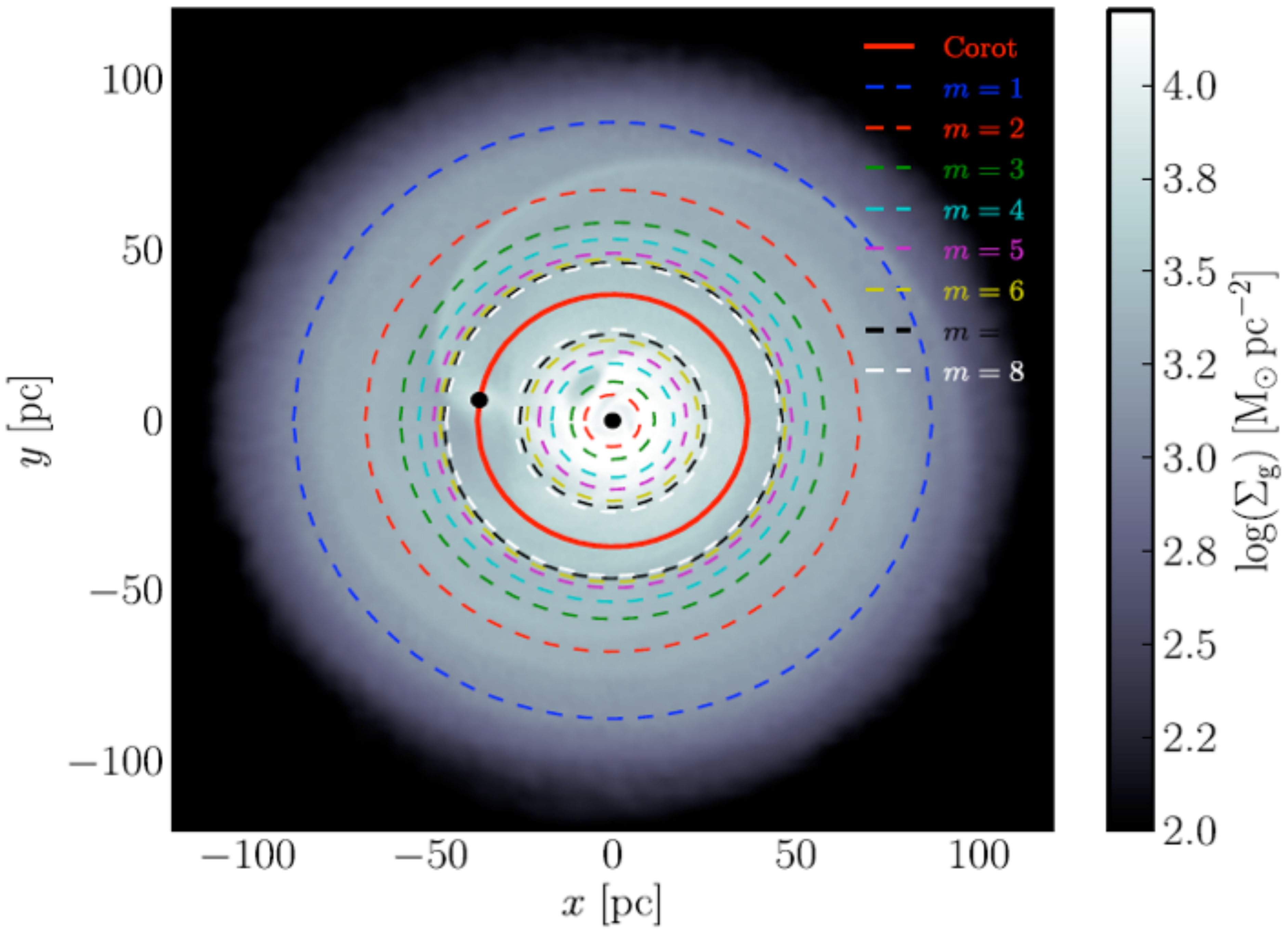
SIMPLE RADIATIVE COOLING PRESCRIPTION

$$\Lambda_{\rm cool} = -\frac{u}{t_{\rm cool}}$$

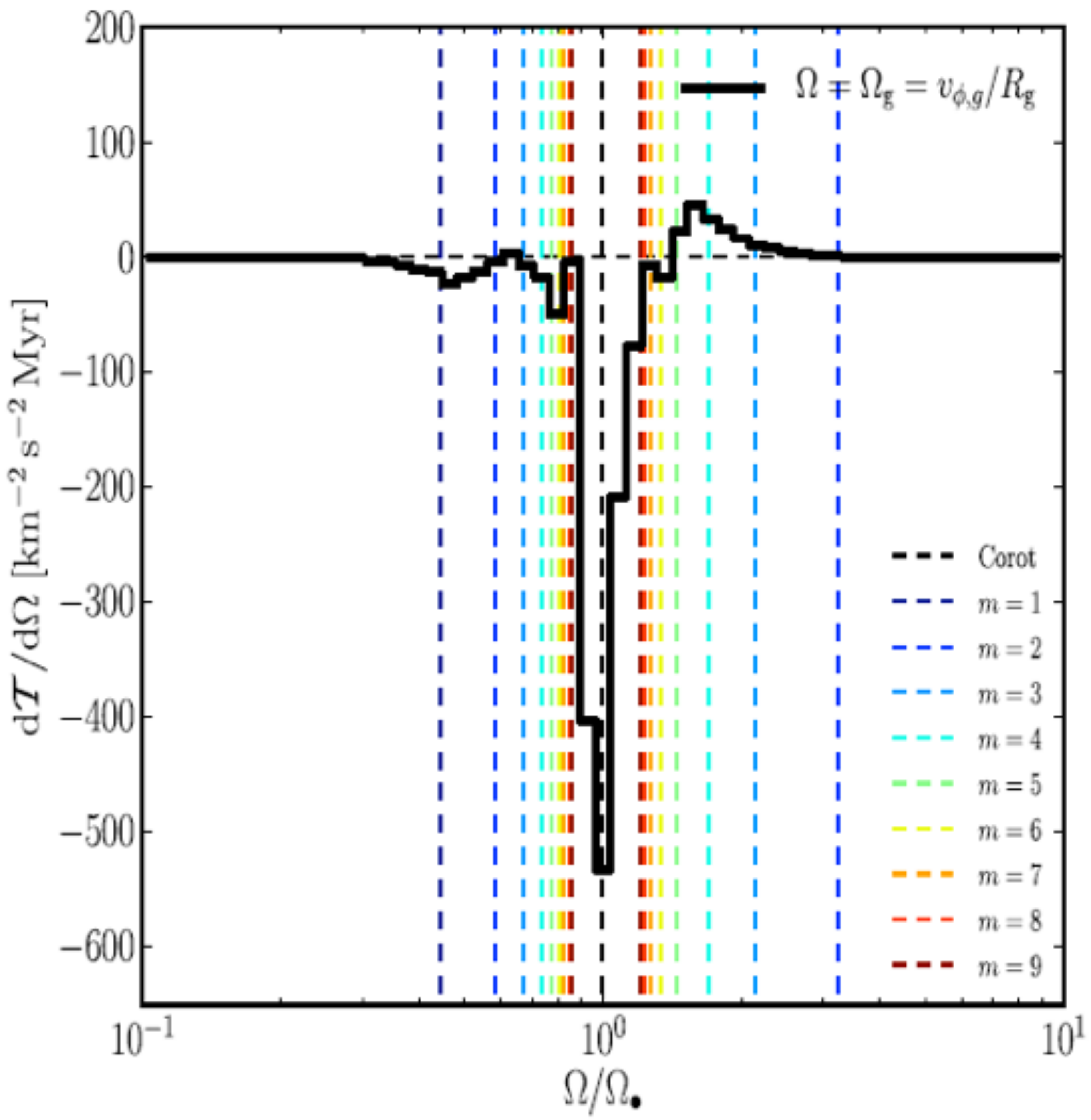
$$n_{\rm th} = 5 \times 10^5\ {\rm H\,cm^{-3}}$$

Short hardening timescale (< 10^7 yr) well explained by linear torque theory which assumes main negative torque at outer Lindblad resonance
(Type I migration - e.g. Nelson et al. 2007)

However torque behaviour shows peak at corotation, more like Type-III planer migration, which is fastest migration mode studied also
in nonlinear conditions (Masset et al. 2003; Malik et al. 2015)



Mayer (CQG, 2013)



$M_{BH1} = 10^7$ Mo $M_{BH2} = 5 \times 10^5$ Mo

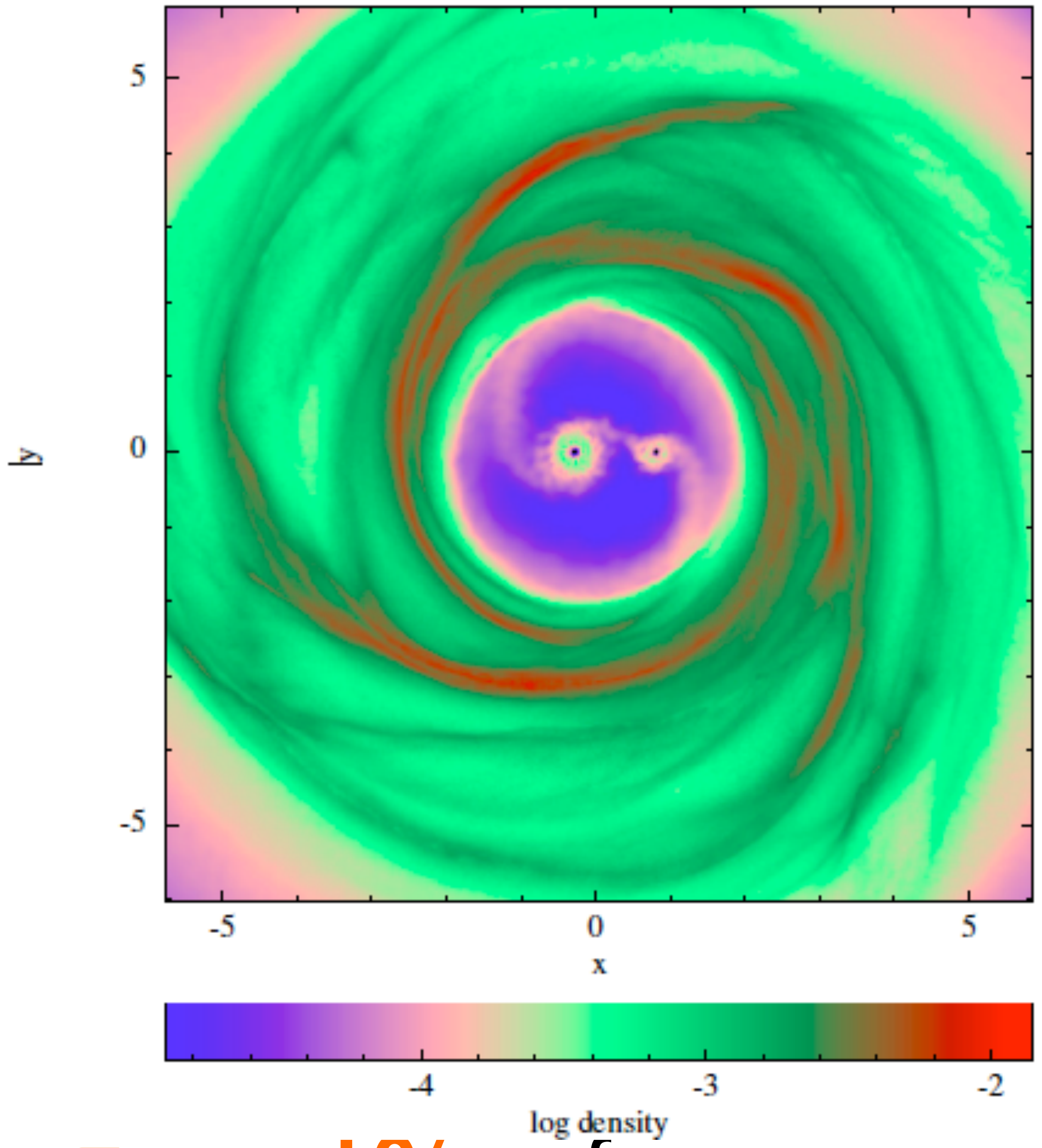
Below 0.1 pc the binary could be hard enough to open a gap if the following condition is satisfied (but see Malik et al. 2015 on the difficulty of gap opening in non-laminar, self-gravitating disk flows), valid for
highly viscous disks:

$$M_{\rm BH} \geqslant (h/pc)^2 \times 7.2 \times 10^5 M_{\odot}.$$

Typical h ~ 10-30 pc
for observed CNDs

↓

Formation of circumbinary disk



In non self-gravitating circumbinary disk viscous accretion disk then orbital decay to GW emission phase would occur on the diffusion timescale $\tau_{visc} \sim 10'$ yr for standard viscosity by MHD phenomena (Armitage & Natarajan 2005).
In self-gravitating disks gap is partially filled by gas flow due to gravitoturbulence and the torque is tidal due to the asymmetries in the sourrounding gas distribution (Roedig et al. 2012) Hardening timescales not well determined as simulations have limited coverage τ_{hard} >~ 10^8 yr →

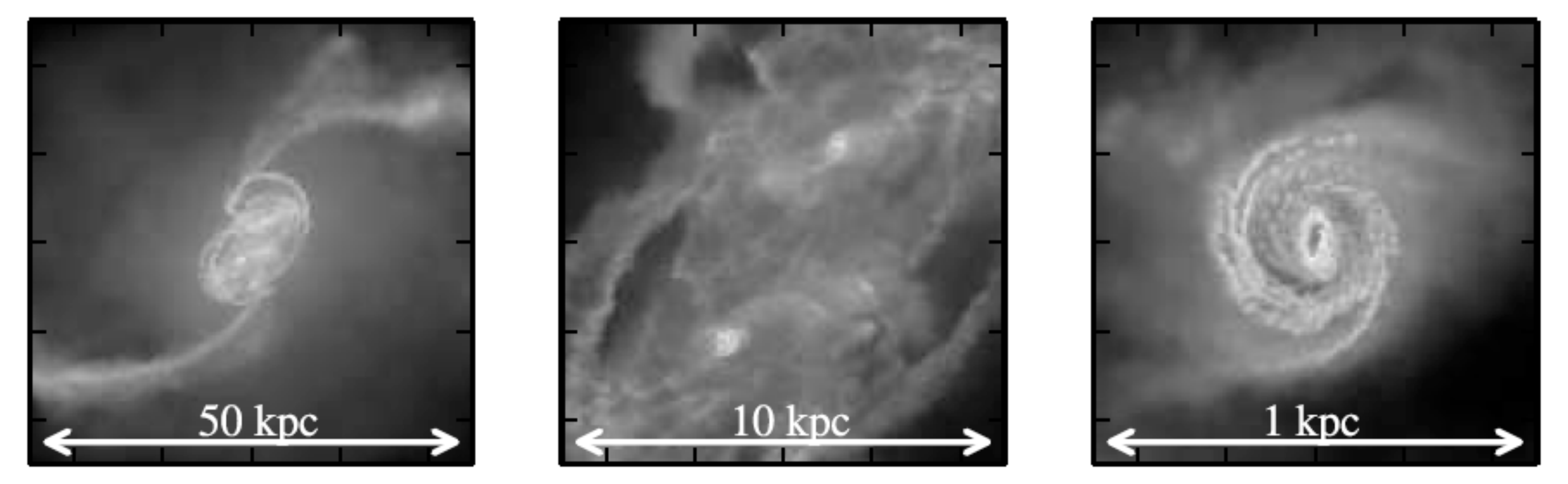
Major Mergers with Clumpy ISM

1:1 Major Merger of gas-Rich Galaxies with Multi-Phase ISM and 0.1 pc resolution

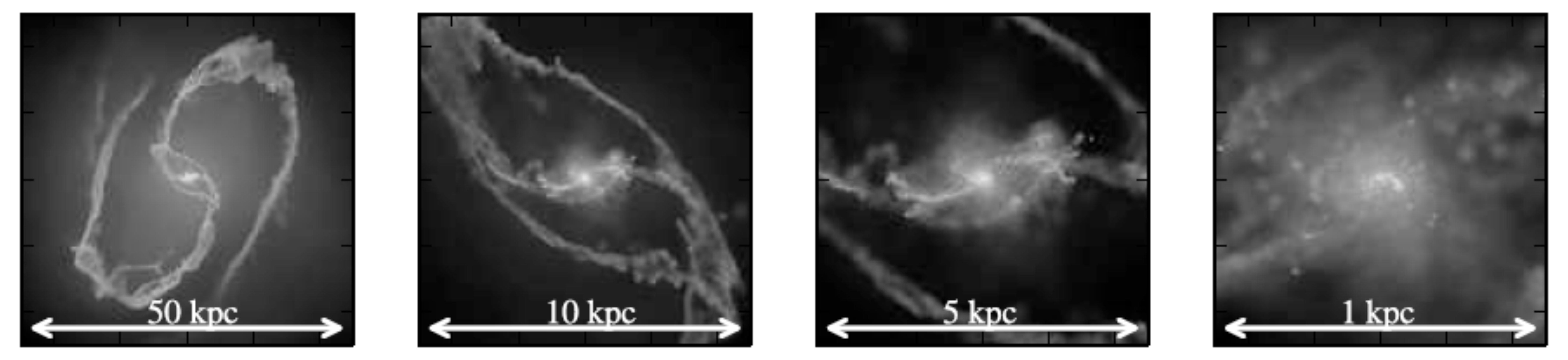
(optically-thin radiative cooling with metal lines + thermal balance model for optically thick gas calibrated with radiative transfer code, star formation + SN feedback)

Roškar, Fiacconi, Mayer et al. 2015

before galaxy merger

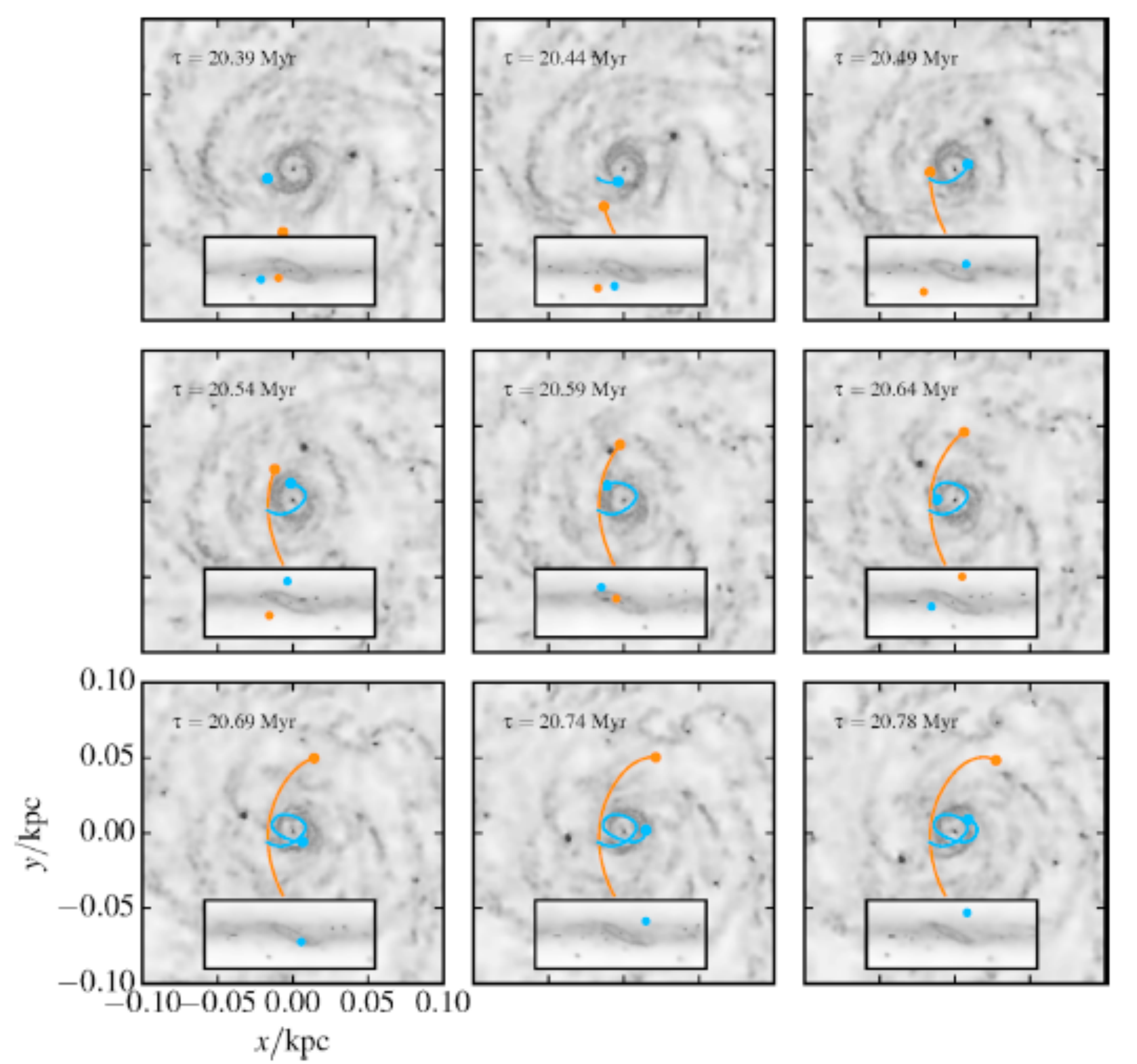


fter galaxy merger



SMBH orbits are perturbed by both close and distant encounters with GMC-scale clumps as well as torques by spiral arms and warps (sign of torque stochastic, one SMBH even becomes retrograde from prograde).

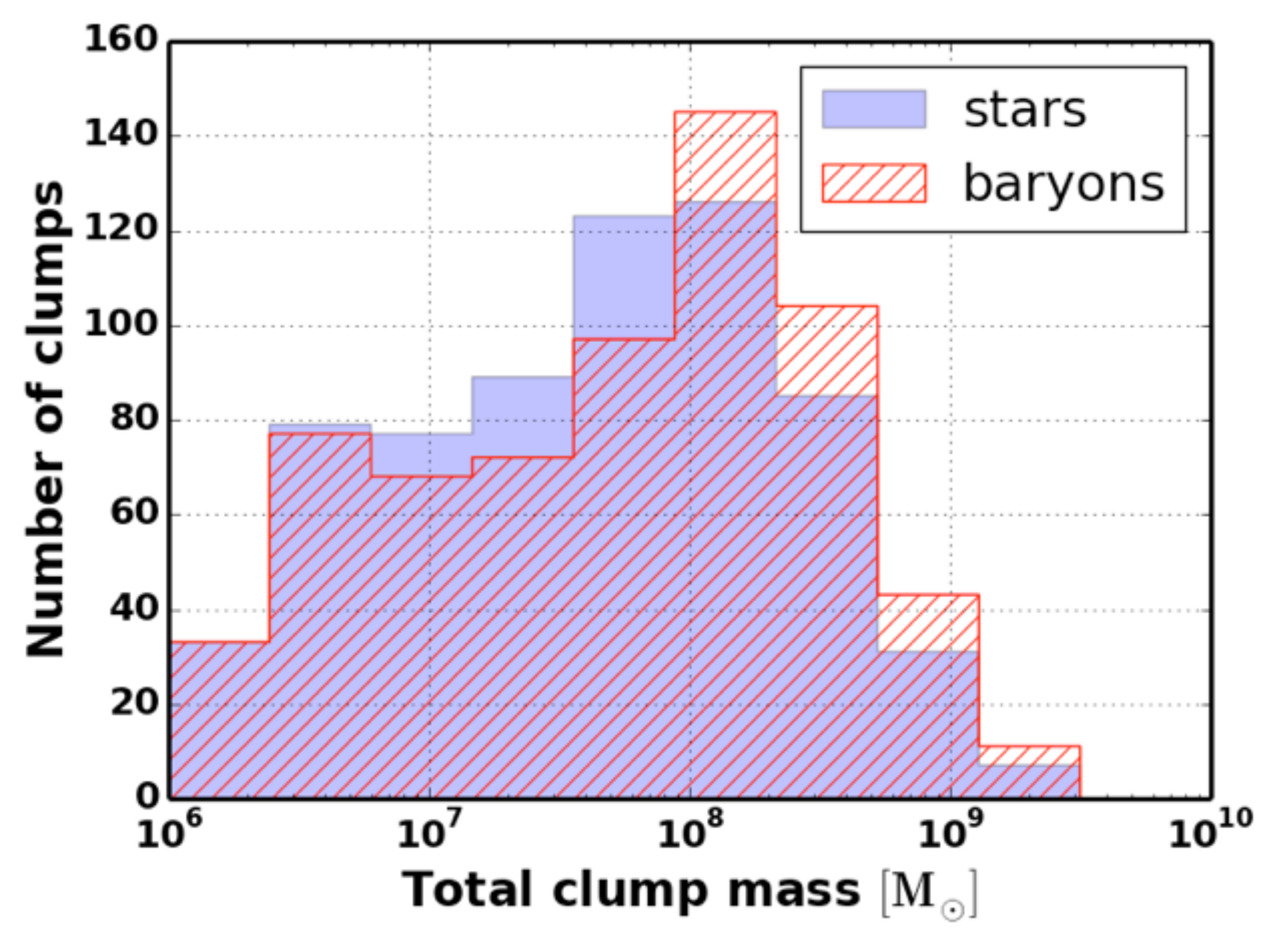
Stronger deviation from orbital plane of one SMBH caused by single close encounter with very massive GMC (~ 10^7 Mo)



On the left the two SMBHs and their trajectories in orange and blue

In Tamburello, Mayer et al. (2015) we have reassessed fragmentation of high-z disks using more realistic heating by stellar and SN feedback which matches stellar mass - halo mass relation of deduced from
various observational constraints (eg abundance matching).

We have revised down the mass of clumps, in the range 10^7-10^8 Mo for galaxies with stellar masses 10^{10}-10^{11} Mo at z ~ 2 (see also Mandelker et al. 2015) which should host SMBHs with $M_{BH} > 10^7$ Mo (likely progenitors of present-day ellipticals). Still clumps much larger than present-day GMCs, and of order mass of sizable SMBHs



Result from large suite of simulations with varying
galaxy masses, gas fraction, feedback strength, gas cooling
physics etc.