From galaxy mergers to massive black hole binary formation and coalescence

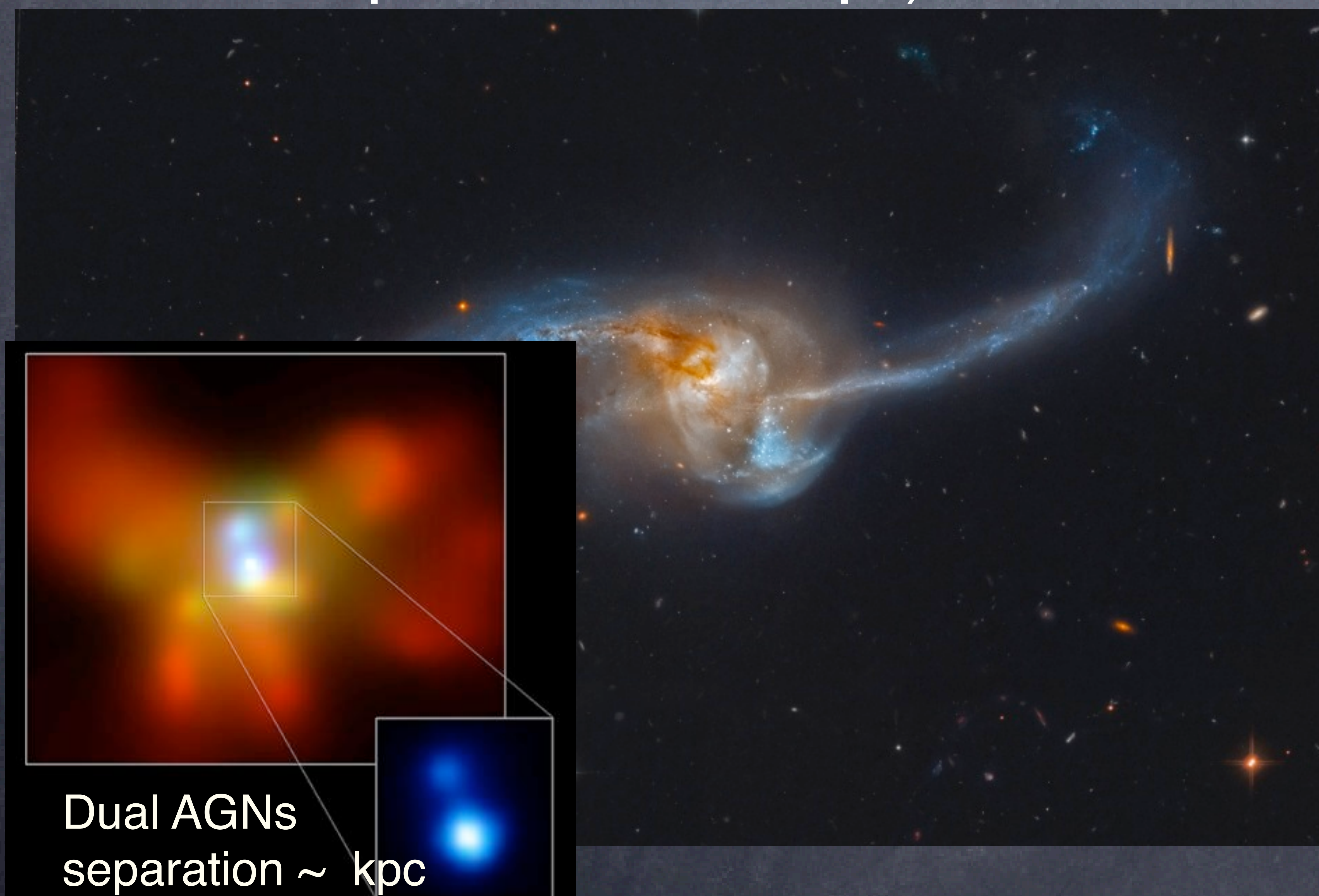
University of Zurich[UZH]

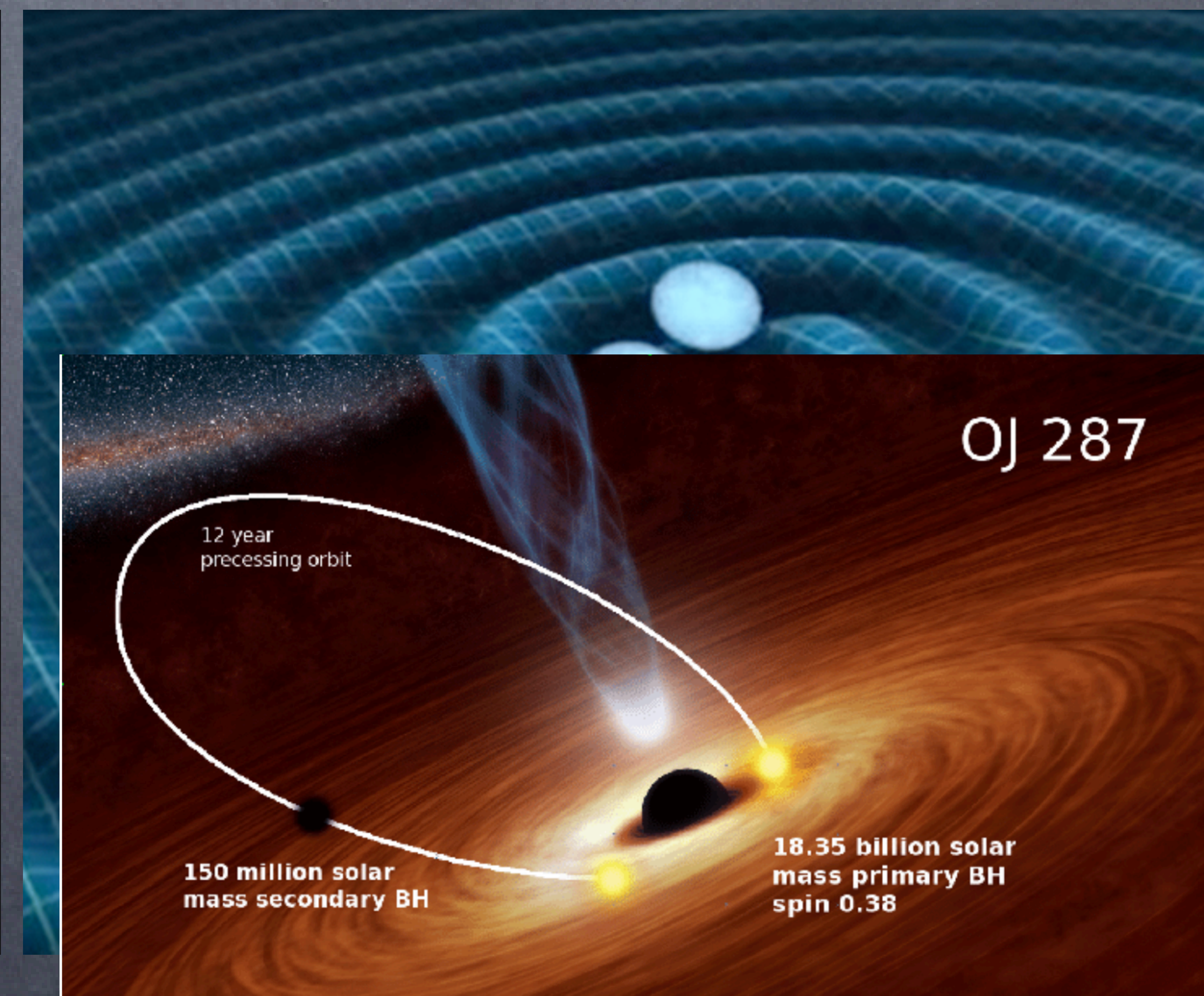
Lucio Mayer
Center for Theoretical Astrophysics and Cosmology
Institute for Computational Science
University of Zurich

with:
Pedro Capelo (UZH)
Elisa Bortolas (U.Milano-Bicocca)
Tomas Tamfal (UZH)
Valentina Tamburello (UZH)
Andrea Derdzinski (UZH)
Lorenz Zwick(UZH)
Mudit Garg (UZH)
Fazeel Khan (Islamabad Space Science Institute and Heidelberg University))
Michael Tremmel (Yale University)
Piero Madau (UC Santa Cruz)
Melvyn Davies (Lund University)
Sijing Shen (University of Oslo)
Jillian Bellovary (CUNY)
Tom Quinn (University of Washington)

(Super)massive Black Holes (M_{BH} >~ 10^5 Mo) in the landscape of hierarchical galaxy formation

Most galaxies host one (S)MBH at their center. Galaxies are observed to merge. Galaxy mergers could generate a powerful GW source if the separation between massive BHs < millipарsecs ($t_{gw} < 10^7$ yr for a binary with 10^6 Mo MBHs at separation ~ 10^{-3} pc).

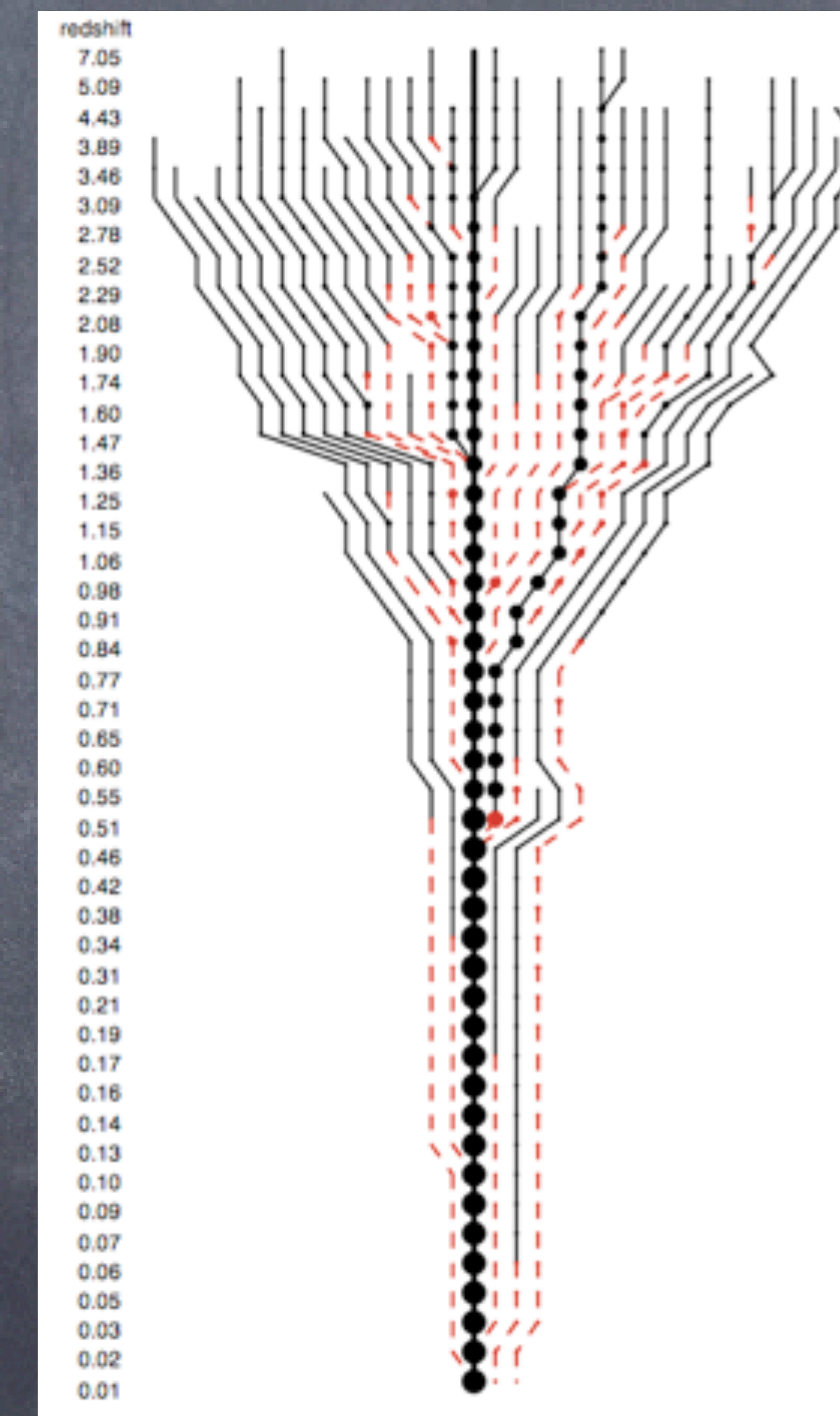




Hierarchical galaxy formation: the natural stage for recurrent galaxy mergers (and MBH mergers?)

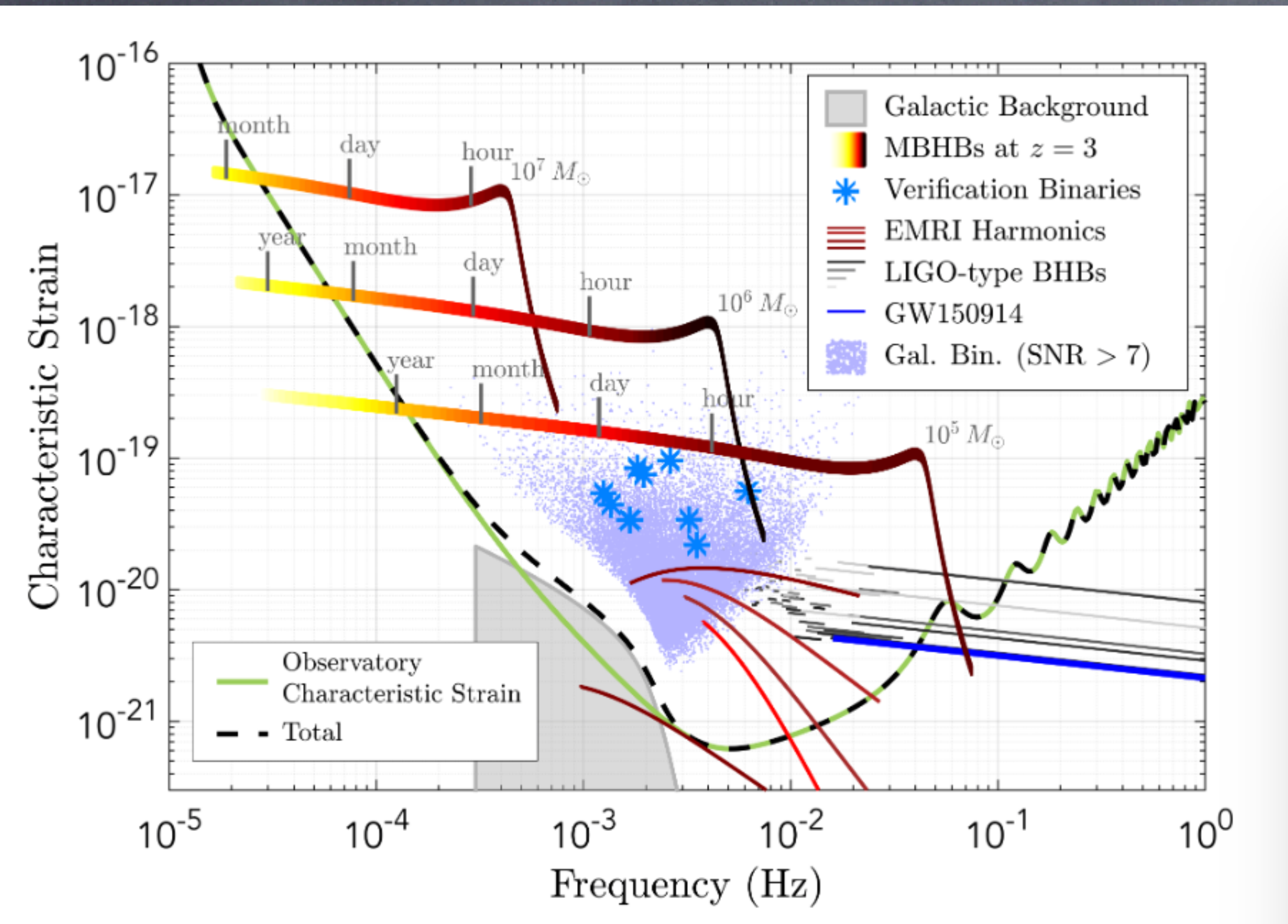
Current cosmological paradigm Lambda+Cold Dark Matter yields bottom-up "hierarchical" structure formation

Galaxies and galaxy clusters grow hierarchically from merging of smaller condensations of dark matter and baryons.
For massive galaxies about 1 merger every ~ 1-2 Gyr.



Galaxy merger tree
VENUS simulation (Sokolowska et al. 2017)

Merging MBHs with 10^4–10^7 Mo: prime GW sources for LISA and TianQin



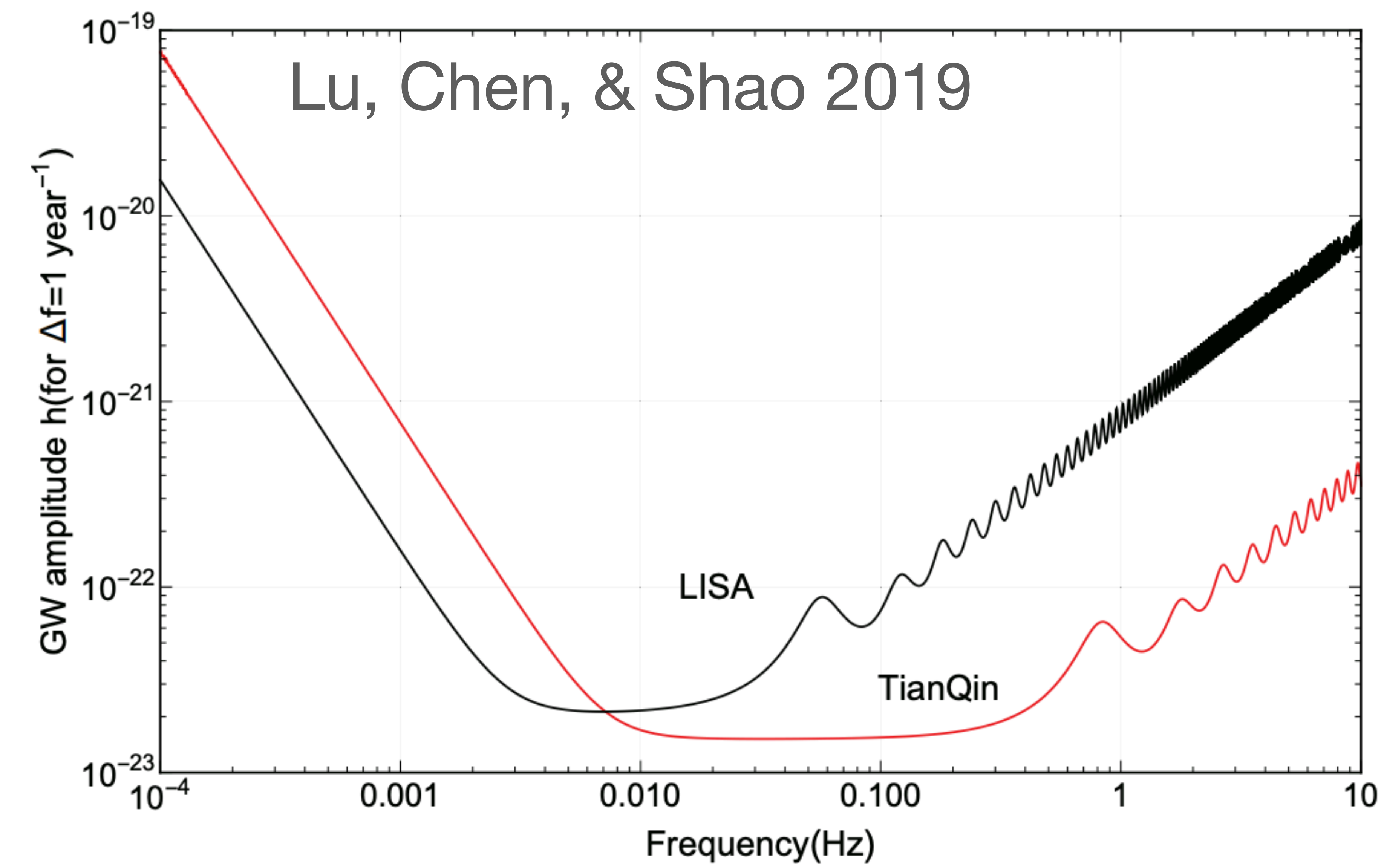


FIG. 5: Sensitivity curves for the GW detectors (LISA and TianQin) averaging all-sky sources in the four-link configurations.

$$h \sim (\mu/r)(M/R)$$

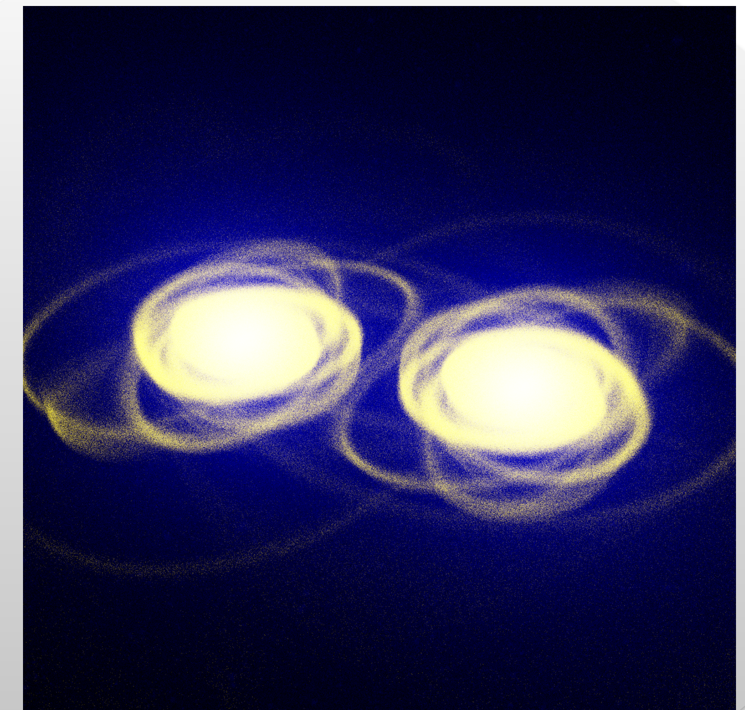
Flatter sensitivity curve at higher frequency should enable better coverage of lower mass MBH/IMBH mergers (<~10^4 Mo, likely hosted by dwarf galaxies, see later in the talk)

Detectable strain amplitude depends on:

M sum of BH masses, μ reduced mass of binary, r distance, R binary separation.

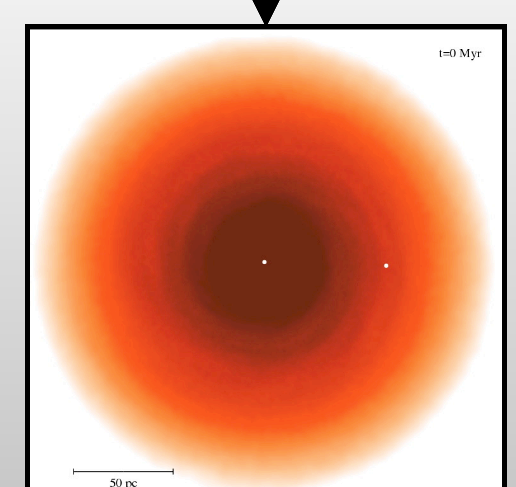
Multi-scale journey: from galaxy mergers to MBH coalescence (see also LISA Astrophysics White Paper - Amaro-Seoane et al. 2022)

Stage I:
Galaxy Merger
End State coalescence of galactic nuclei and MBH Pair inside merger remnant (drag: gas + stars+dm)



100-1 kpc scale

Stage II:
MBH pairing continues in nucleus of merger remnant (drag: gas+stars)
End State: Formation of MBH binary



100 pc to 1 pc scale

Stage III:
MBH binary hardening
(drag: gas+ stars)
End State: GW emission-dominated phase begins

1 pc to 10^{-3} pc scale

Stage IV: Coalescence via GW
(< 10^{-3} pc separation. drag: GW emission)

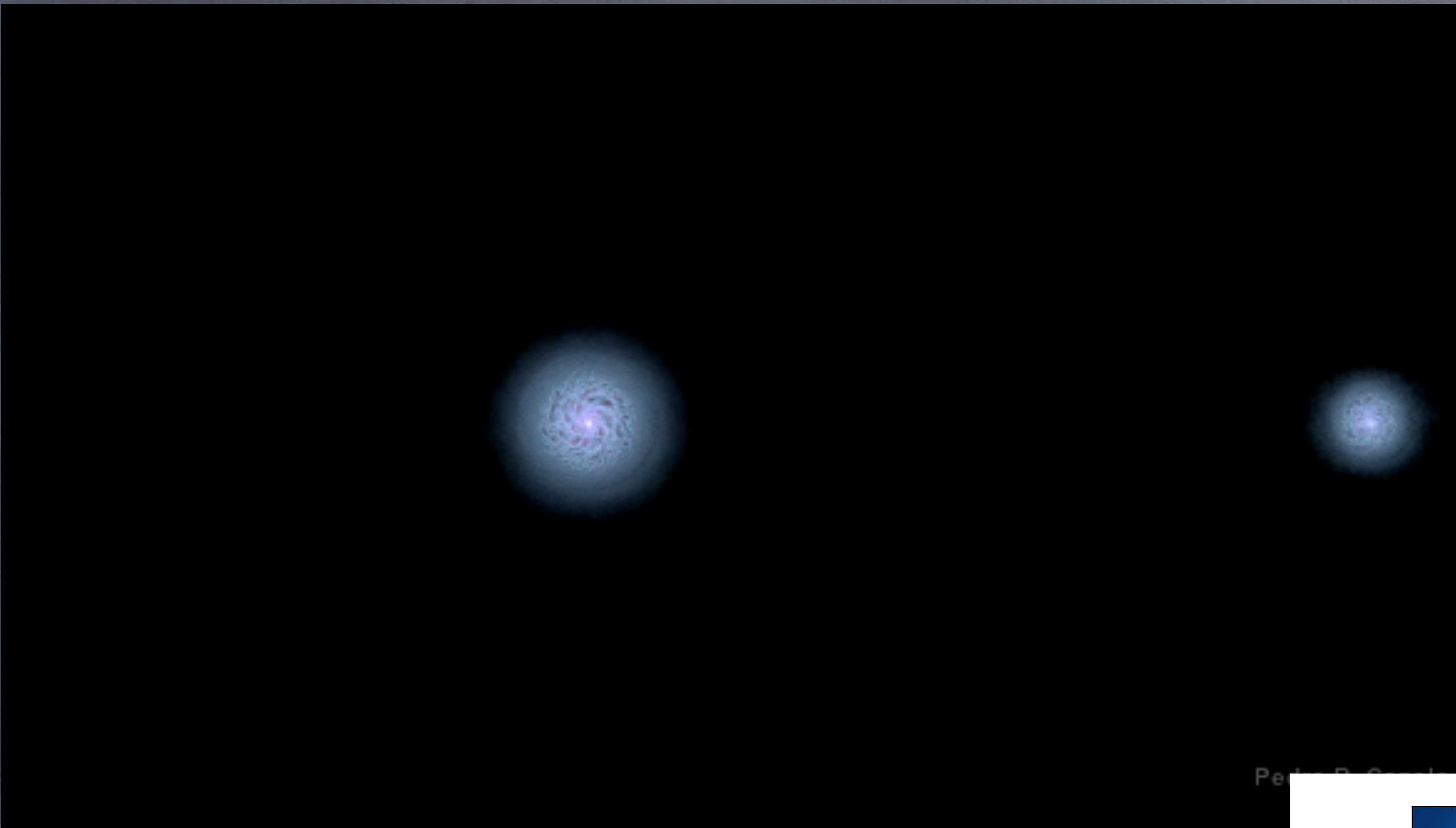
The TOTAL MBH coalescence timescale t_{coal} will be:

t_{coal} = galaxy merger timescale (1) + MBH binary formation timescale (2) + binary hardening timescale (3) + the GW-driven in-spiral timescale in the phase dominated by GW emission (4).

Timescales (2) and (3) are most challenging to determine. Tightly linked to galaxy host properties. Are needed to produce MBH merger rates forecasts (eg for LISA).
In turn, if we understand (2) and (3) in principle we can use LISA event rates to reverse-engineer and probe the galaxy assembly process.

LISA event rates forecasts are based on semi-analytical models that attempt to model phase (2) and (3) using phenomenological prescriptions (eg Sesana et al.2005; Klein et al. 2016; Salcido et al. 2016; Barausse et al. 2019;2020; de Graf & Sijacki 2020) which result in a *DELAY* of the BH binary decay relative to the galaxy merger (Volonteri et al. 2020; Barausse et al. 2020 — see E. Barausse's talk).
GALAXY AND SUB-GALACTIC SCALE SIMULATIONS SHOW A RICHER INVENTORY OF DYNAMICAL MECHANISMS AFFECTING BH PAIRING AND HARDENING
(eg LISA Astrophysics WP, https://arxiv.org/abs/2203.06016)
Predicted MBH merger rates range from a a few to 100 events/yr.

Stage I: Galaxy Merger. Separation of MBHs of order kiloparsecs.



1:4 Galaxy Merger movie (Capelo et al. 2015)

Galaxy merging time

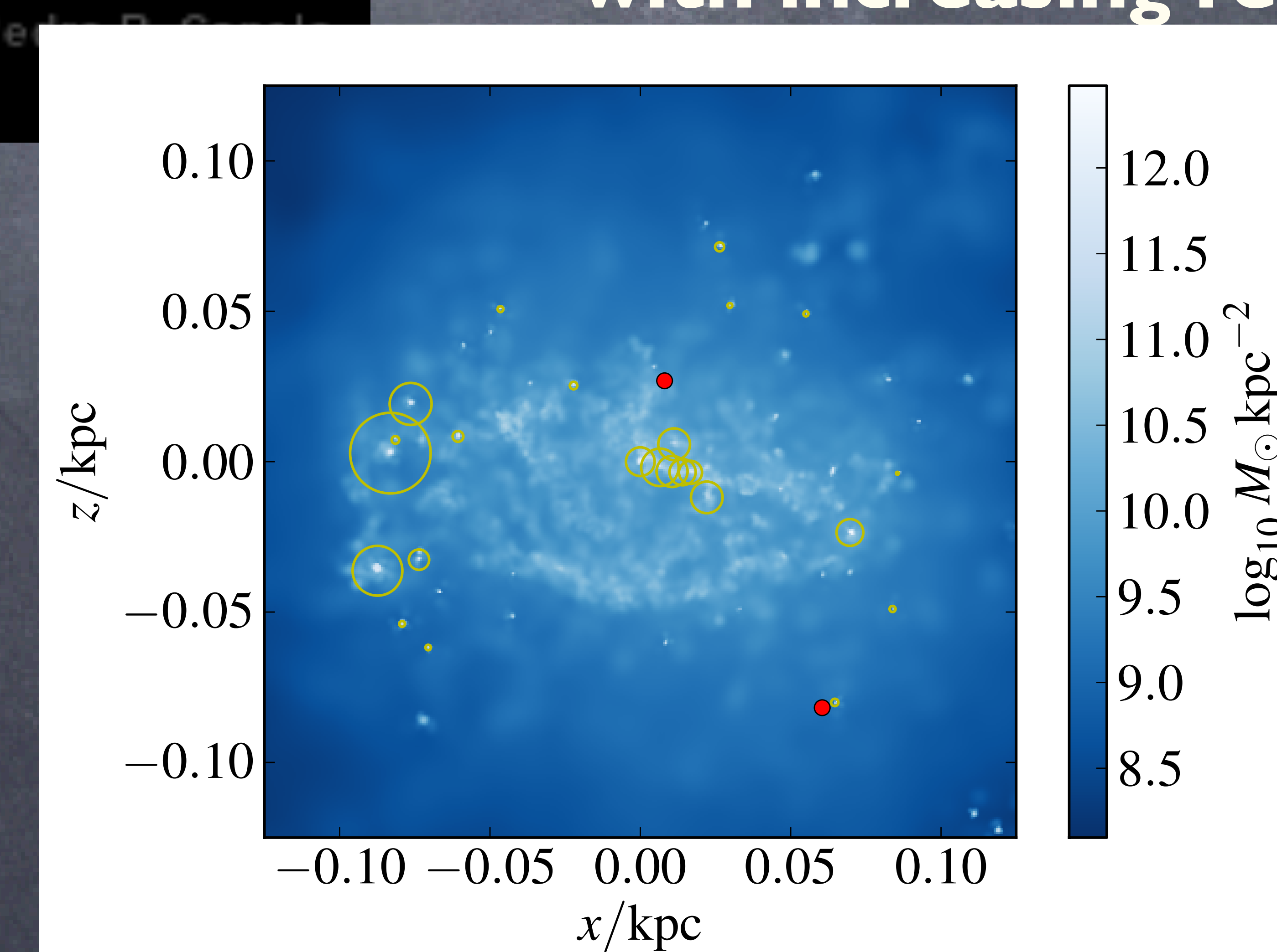
Defined as time when two separate galactic nuclei first merge (separation < 100 pc)

T_{mg} ~ 0.5-5 Gyr <~ T_{Hubble}

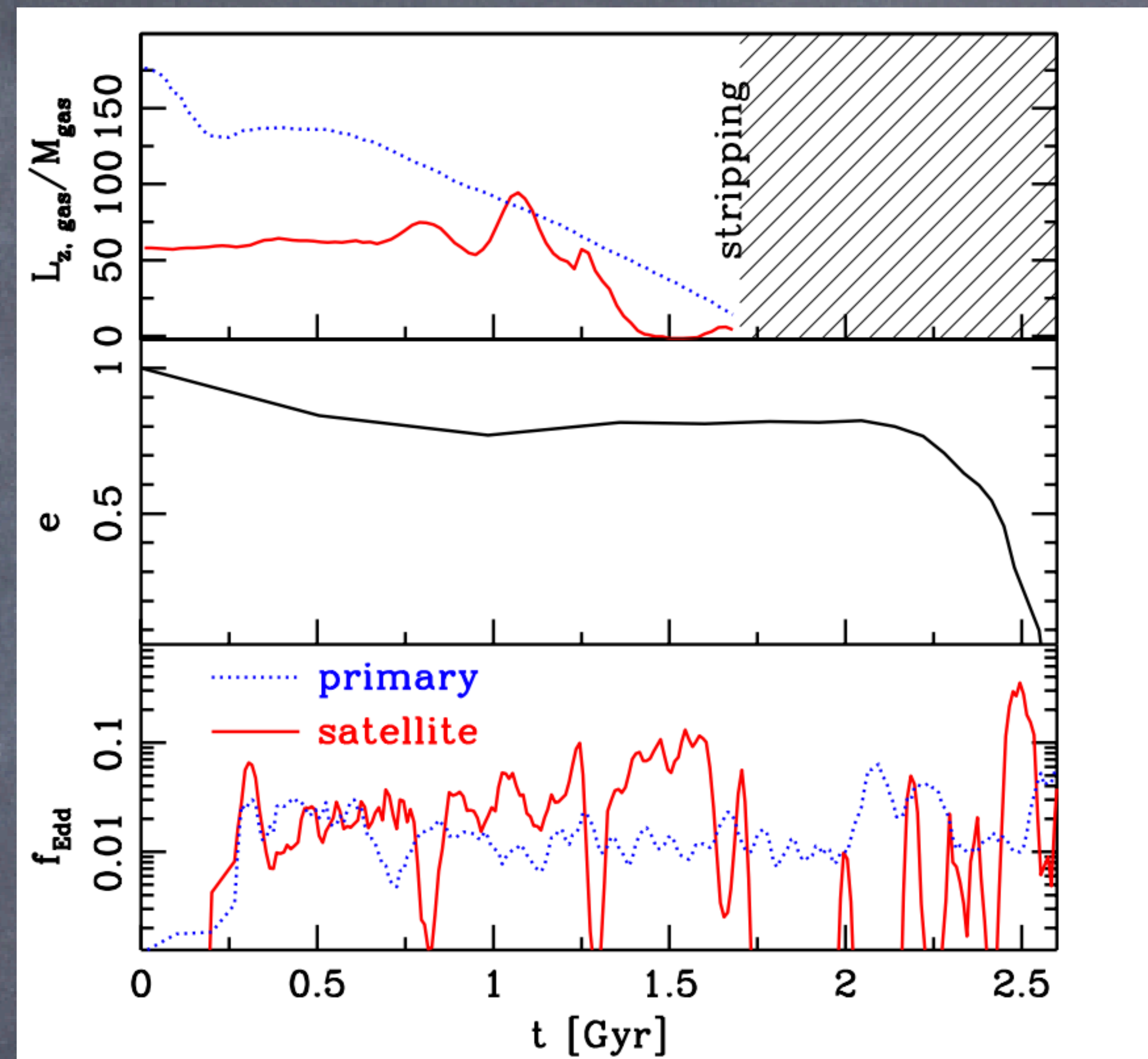
(comparable to crossing time of CDM halo, shortens with increasing redshift)

MBH merger and galaxy merger will not be coincident in time

After galaxy cores merge MBHs still displaced by a few hundred pc (eg hi-res simulations of Roskar et al. 2015, see also review de Rosa et al. 2019)



IMPORTANT POINT: Mergers of galaxies w/gas produce even more gas-rich galactic nuclei



1:10 disk galaxy mergers With embedded MBHs (10^5-10^7 Mo)
Callegari et al. 2011

Resolution 30 pc

A natural outcome of the dynamics of (gas-rich) galaxy mergers is an even more gas-rich galactic nucleus in the merger remnant due to efficient loss of angular momentum in the gas phase. The gas disk triggers orbital circularisation at ~10-100 pc separation (see above)

Caveat: *competing effects of star formation and feedback also greatly enhanced in* mergers — can consume or eject gas on a timescale ~ local dynamical time

Stage II-III. (MBHs in the merger remnant)

There are at least three classes of processes that can shr

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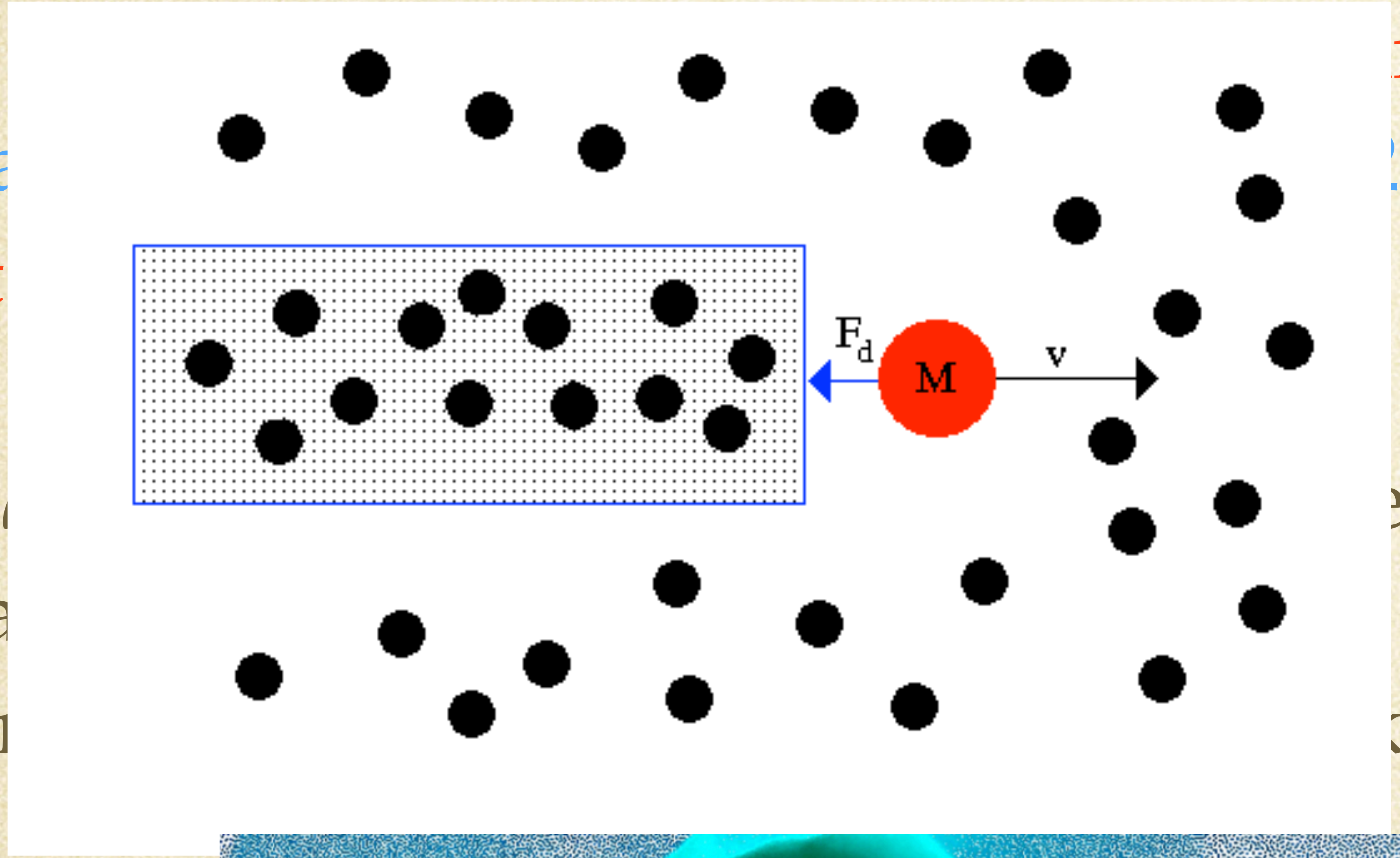

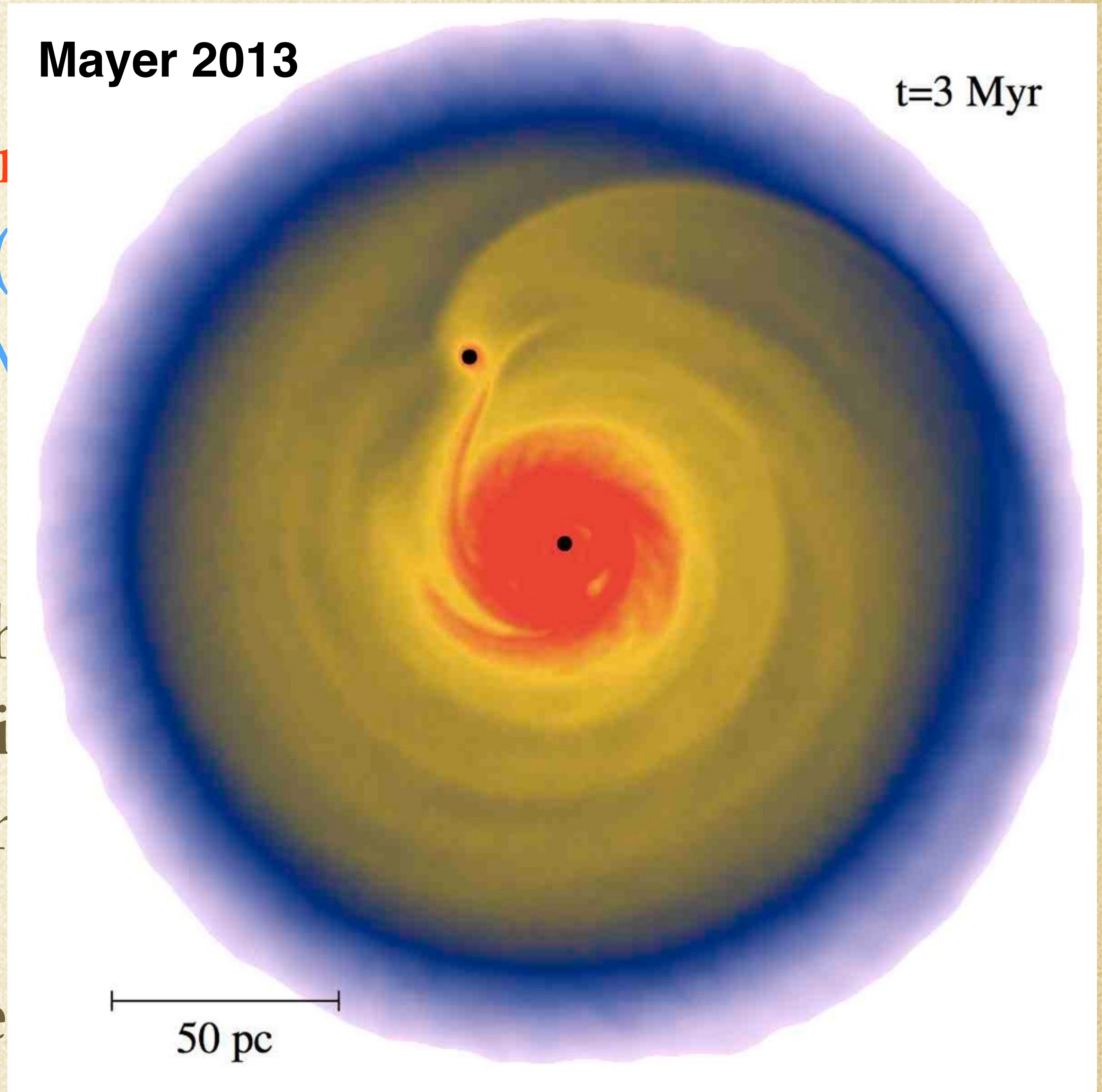

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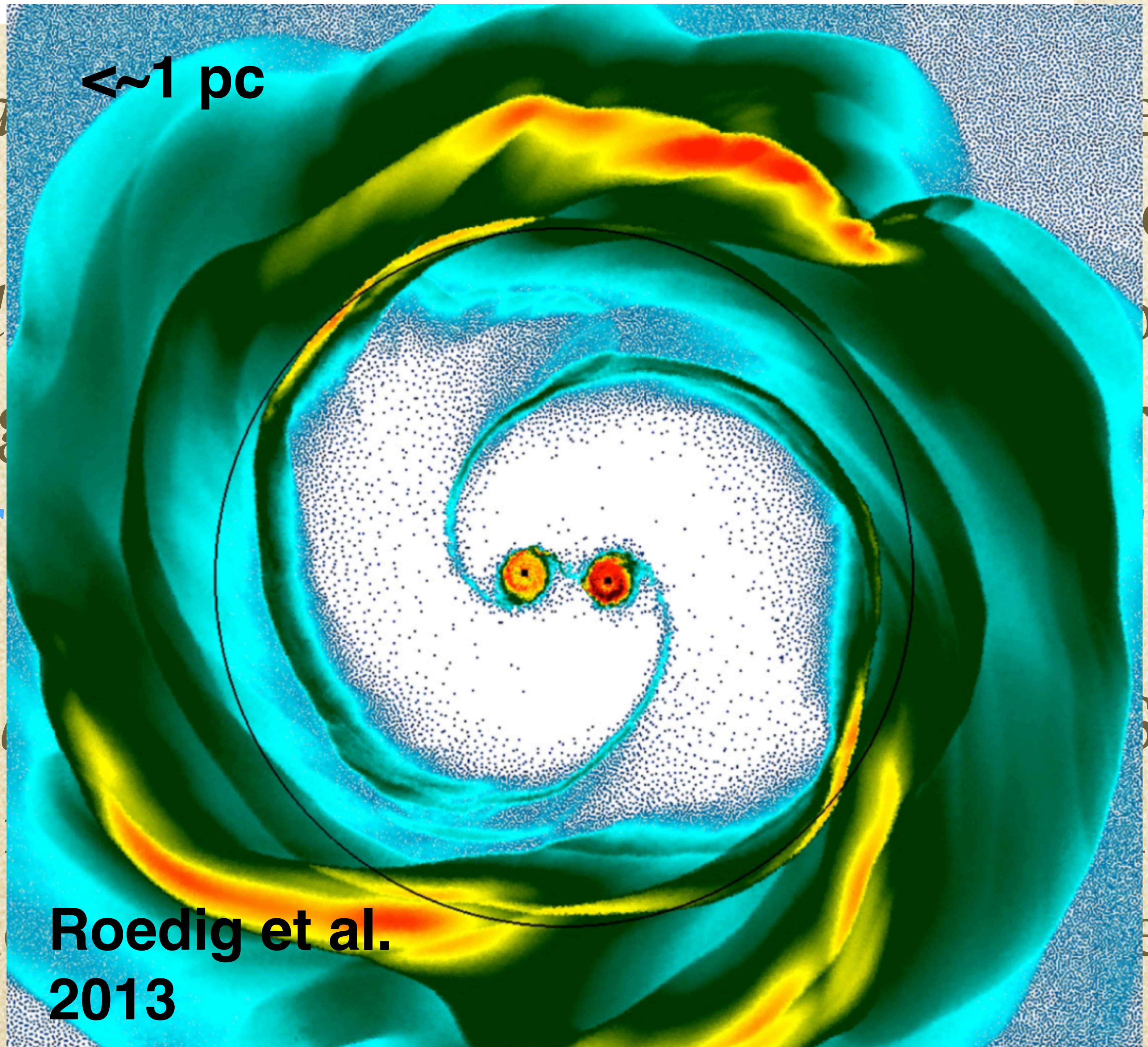

- *Disk-driven gra*

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nuclear gas or

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waves (*as in pl*

ons (< pc) a cavity and

circumbinary

rther sinking to GW-dominated

phase (eg Farr

azio and Duffell 2021)

- *3-body encount*

SMBH. When gas sub-dominant

determine orb

tions of <~ pc (*hard binary*),

provided the l

enough (*full loss cone*)

Should the timescales of binary BH formation and binary hardening depend on host galaxy properties?

Yes they do because:

All processes causing orbital d
stars, gas or dark matter), on t
perturber (MBH) and the back
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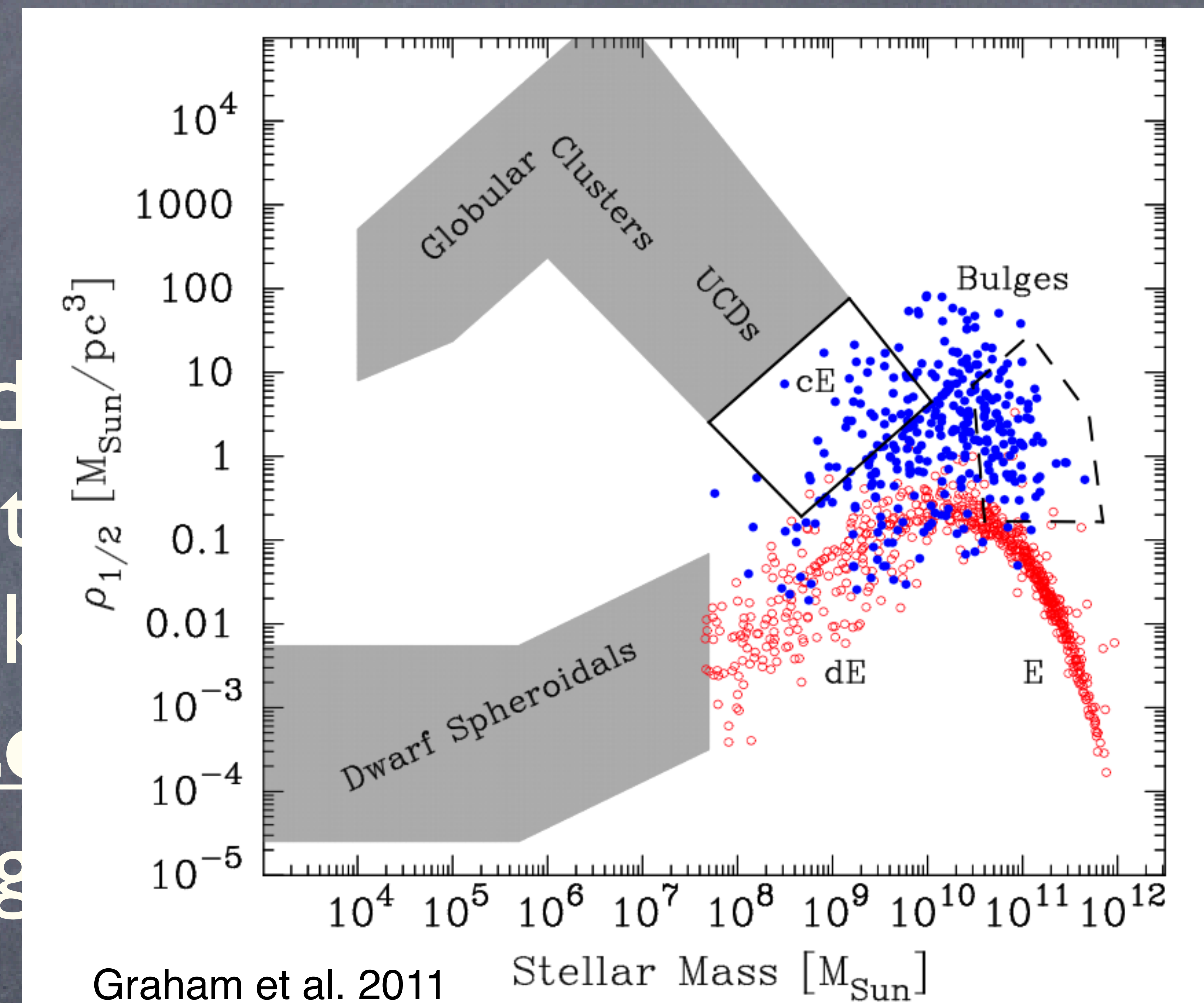

Graham et al. 2011

Eg for dynamical friction in high velocity limit (by combined of stars, dark matter, gas)

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

MBHs in LISA/TianQin band have masses <~ 10^7 Mo

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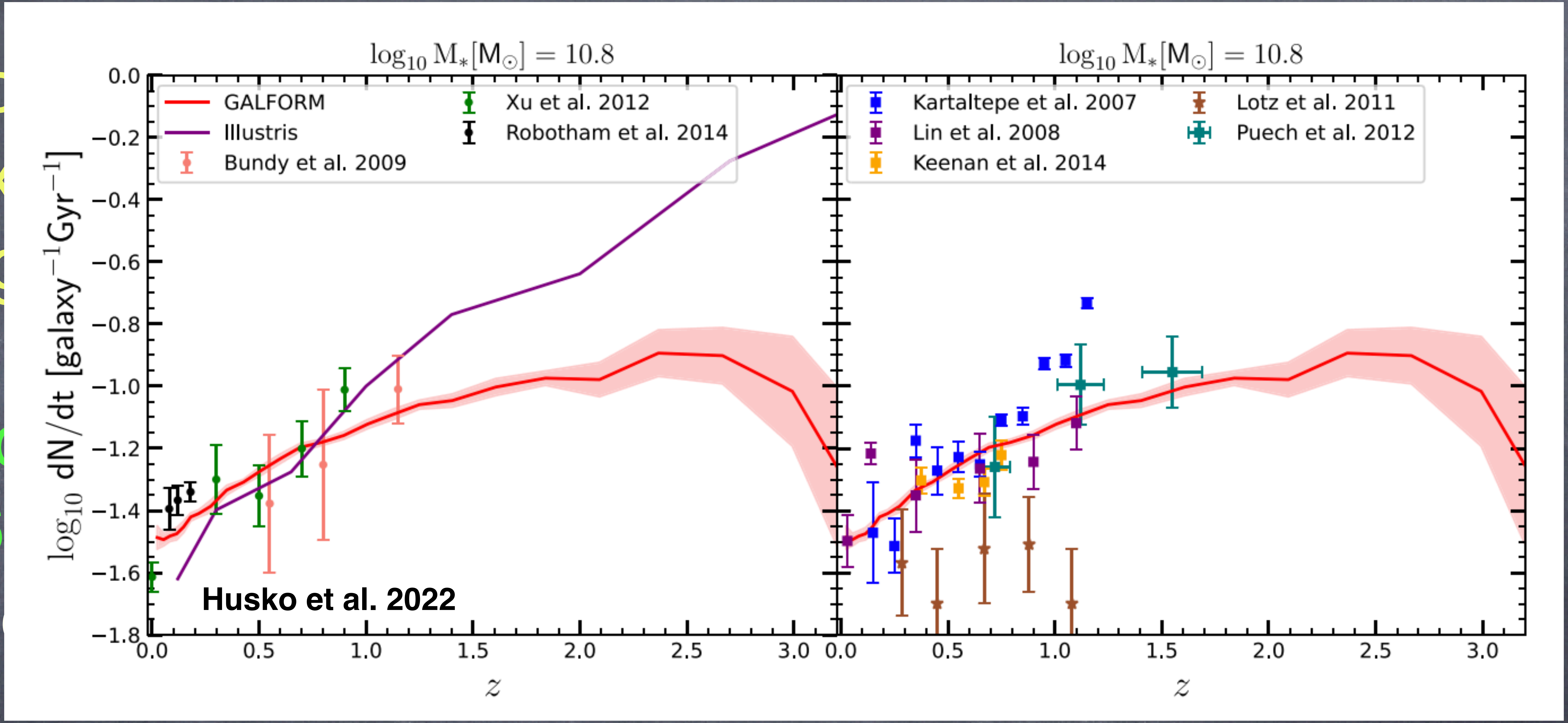
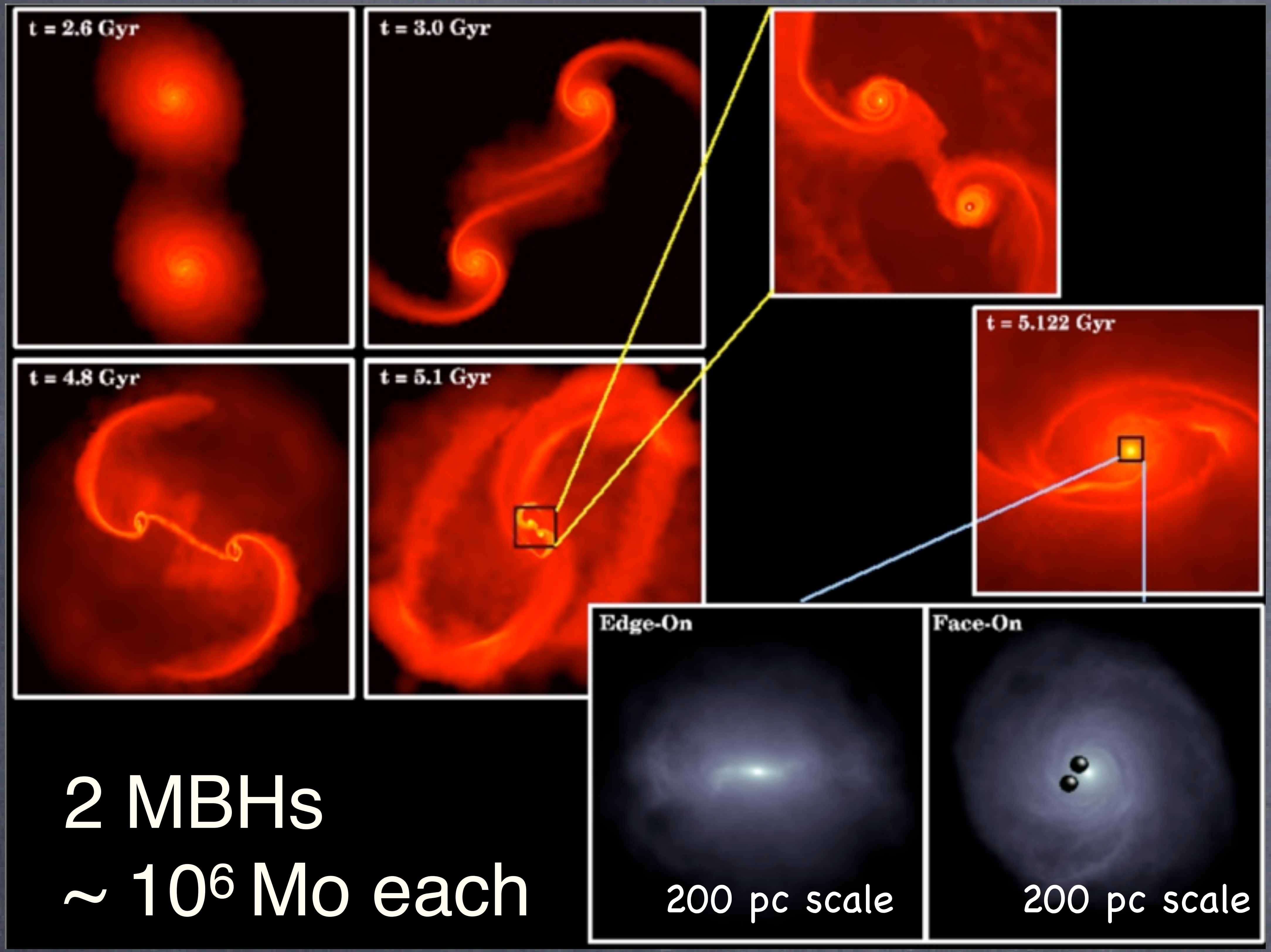


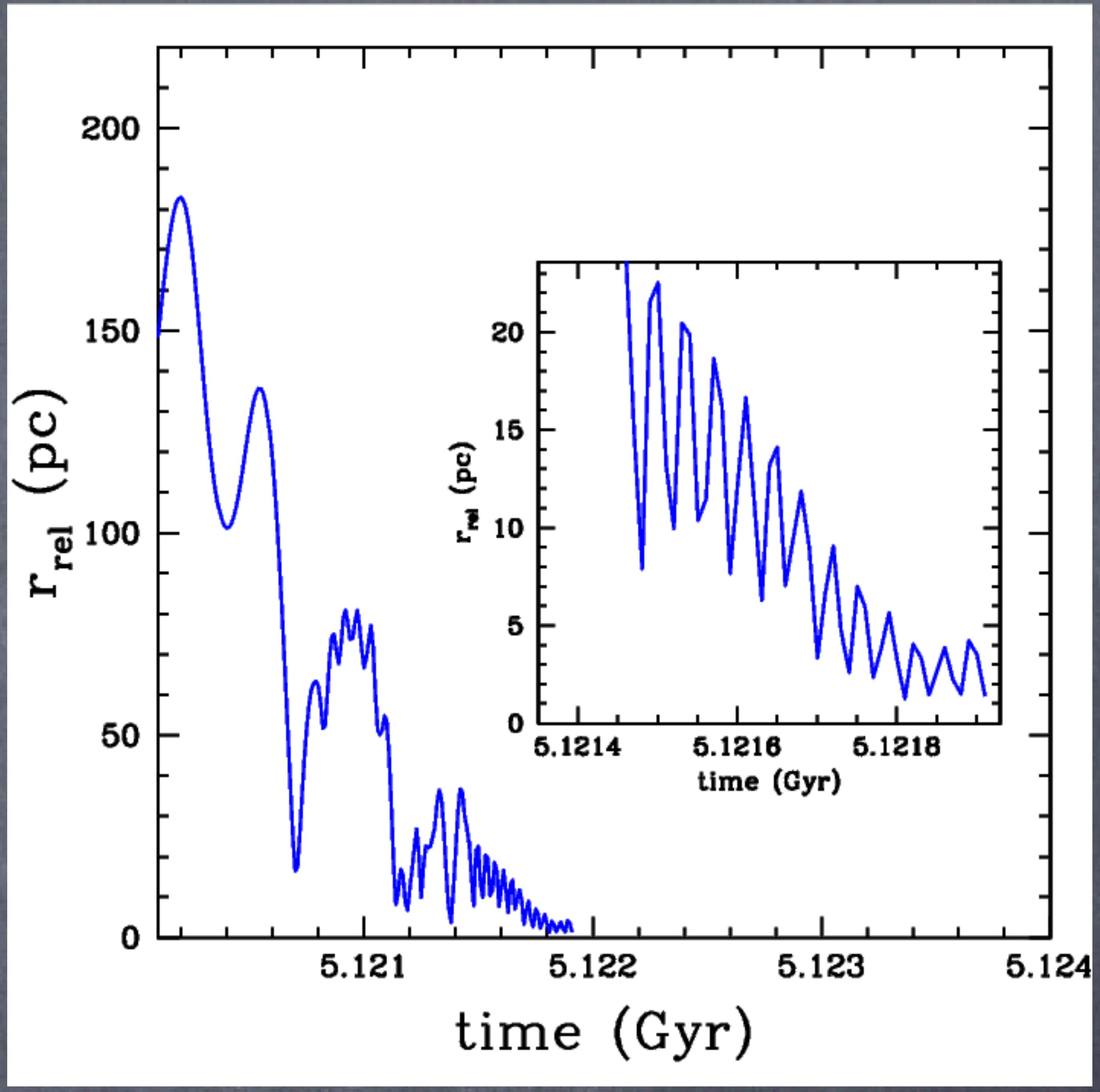
To battle computational complexity one is forced to model the effects of interstellar gas in Stage I-II and III-IV separately

Stage I-II: *MBH pairing and binary formation in spiral galaxies*

SMBH binary formation at pc scales just few Myr after galaxies merge

Equal mass coplanar galaxy mergers considered





Mayer et al. 2007, Science

Binary SMBH forms in gaseous circumnuclear disk (CND) generated by gas inflow

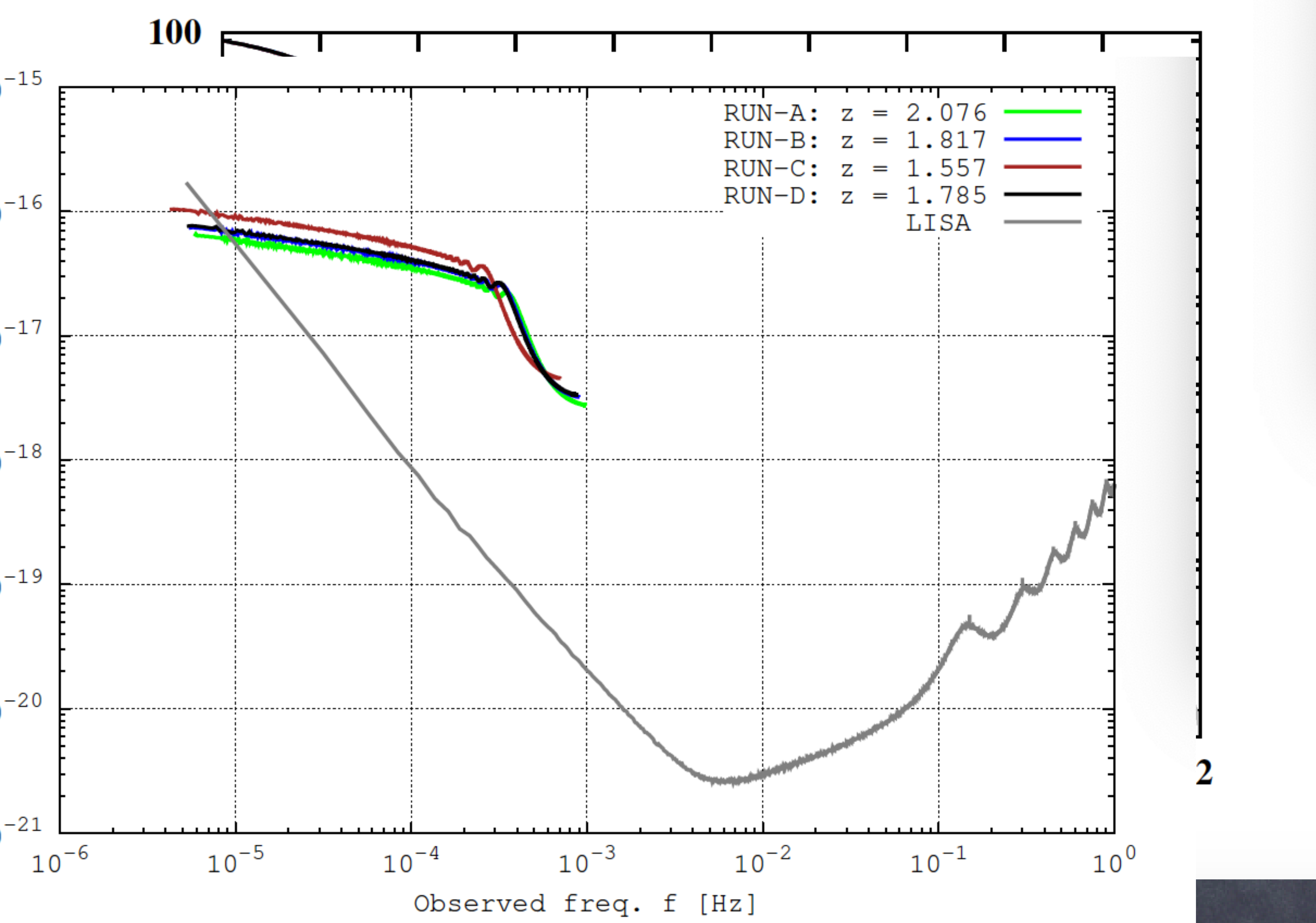
() High density in CND gives strong drag, x10 stronger than by stars and dark matter

() Gas thermodynamics plays also play some role in drag (here was idealized, with effective equation of state, see also Chapon, Mayer & Teyssier 2013)

() Short binary formation timescale (a few Myr) also in unequal mass mergers (Pfister et al. 2017)

Stage I-III: multi-scale simulations of unequal mass galaxy mergers

(Khan, Capelo, Mayer & Berczik 2018, 1:2 mergers of gas-rich disk galaxies with ~10^7 Mo BHs, each one has different orbital configuration)



Wide range of BH coalescence timescales (10 Myr to 2 Gyr)
Hardening timescales a few hundred Myr calculated neglecting effect of residual gas (only 3-body stellar encounters)

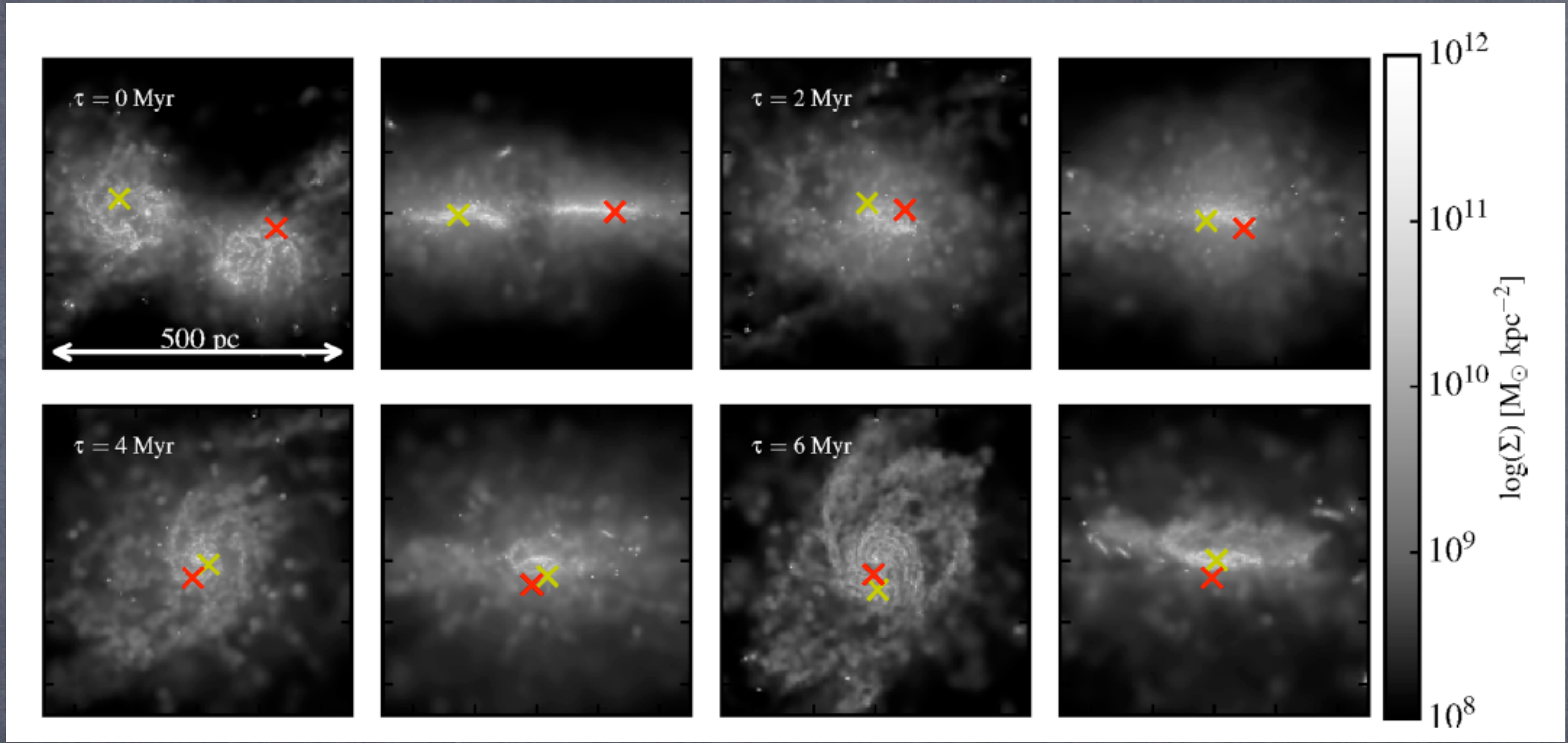
Variations due mainly to different density of merger remants

Note these are unequal mass mergers hence the galaxy/halo merger timescale is > 1 Gyr (but only barely dominates total MBH merger time)

Stage I-II: Galaxy Mergers with improved ISM model

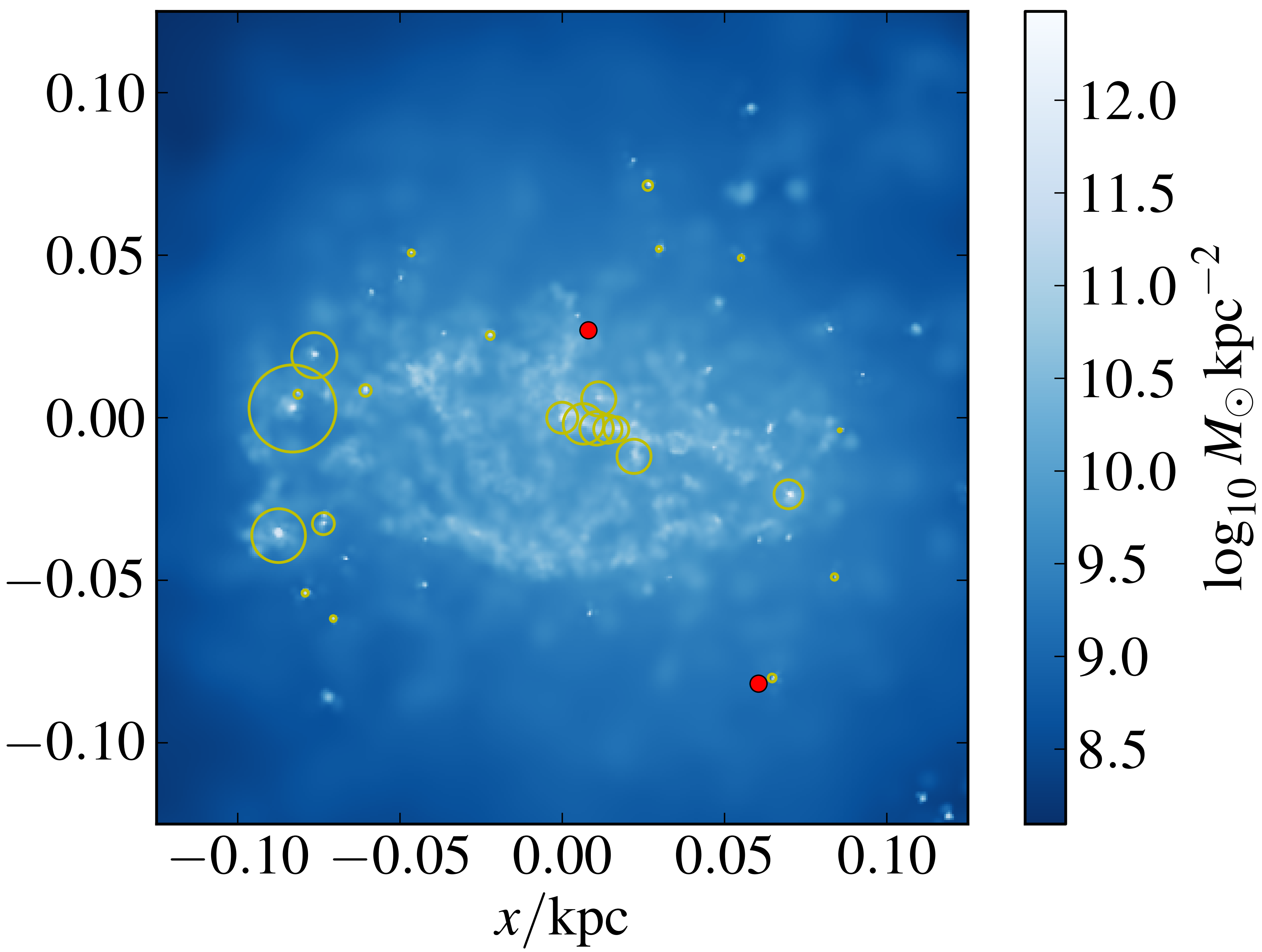
Rich inventory of physics processes: radiative cooling with self-shielding and line trapping at high optical depth, star formation, stellar UV and IR radiation and SN feedback.

Roskar, Fiacconi, Mayer et al. 2015

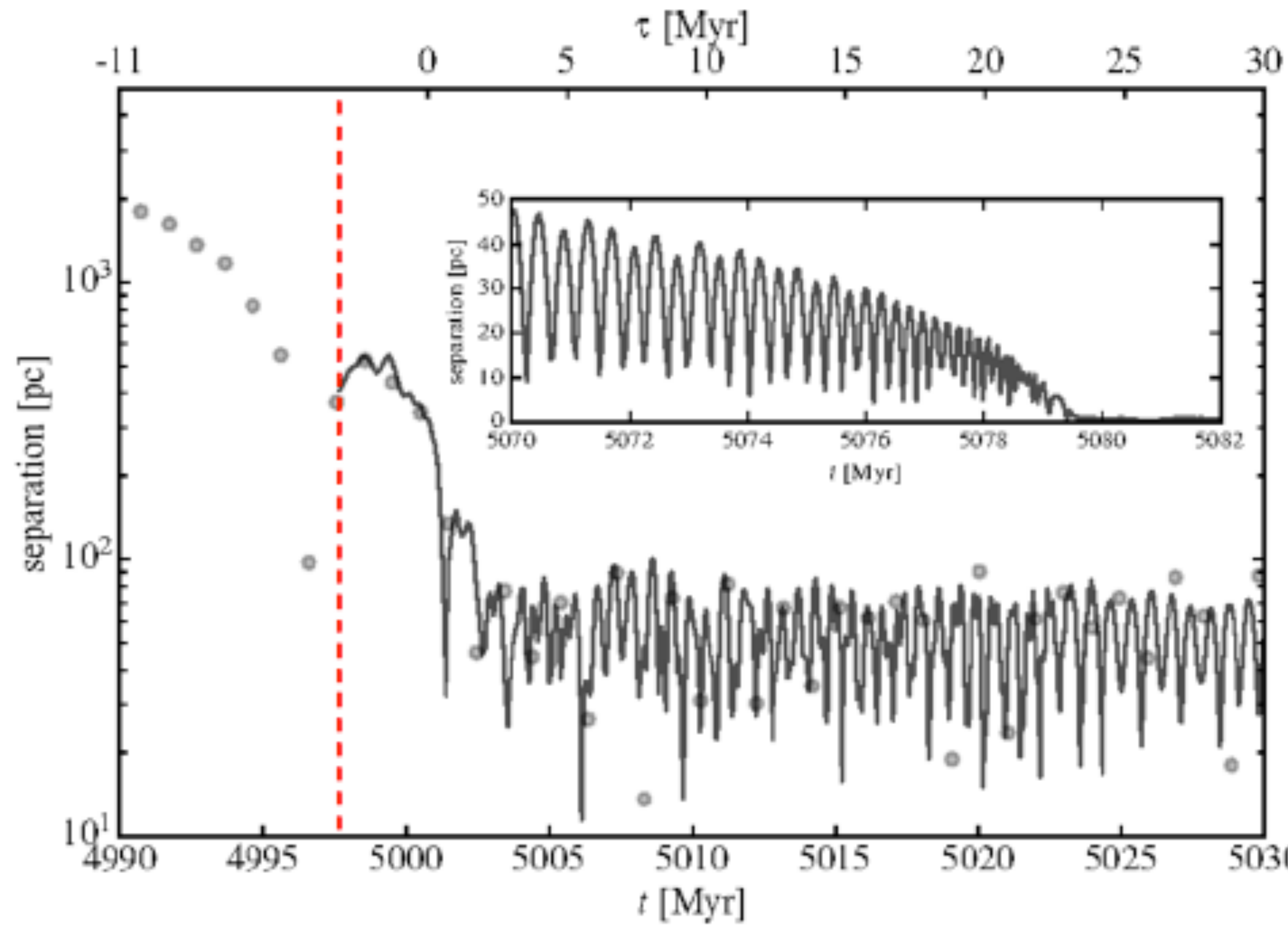


Complex dynamics of last phase of galaxy merger -- Supernovae-driven kpc-wide outflows when the galaxy cores collide and undergo starburst, Dense CND forms, but after galaxy merger (~ a few 10^7 yr later).

Delayed Formation of SMBH Binary



SMBH Ejection out of nuclear disk plane due to gravitational scattering by gas clouds and spiral structure & Temporary Stall



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

to reach pc-scale separation after galaxy merger, so only up to Stage II!

MBH pairs in the clumpy disks of star forming galaxies at z >~1: not just delay

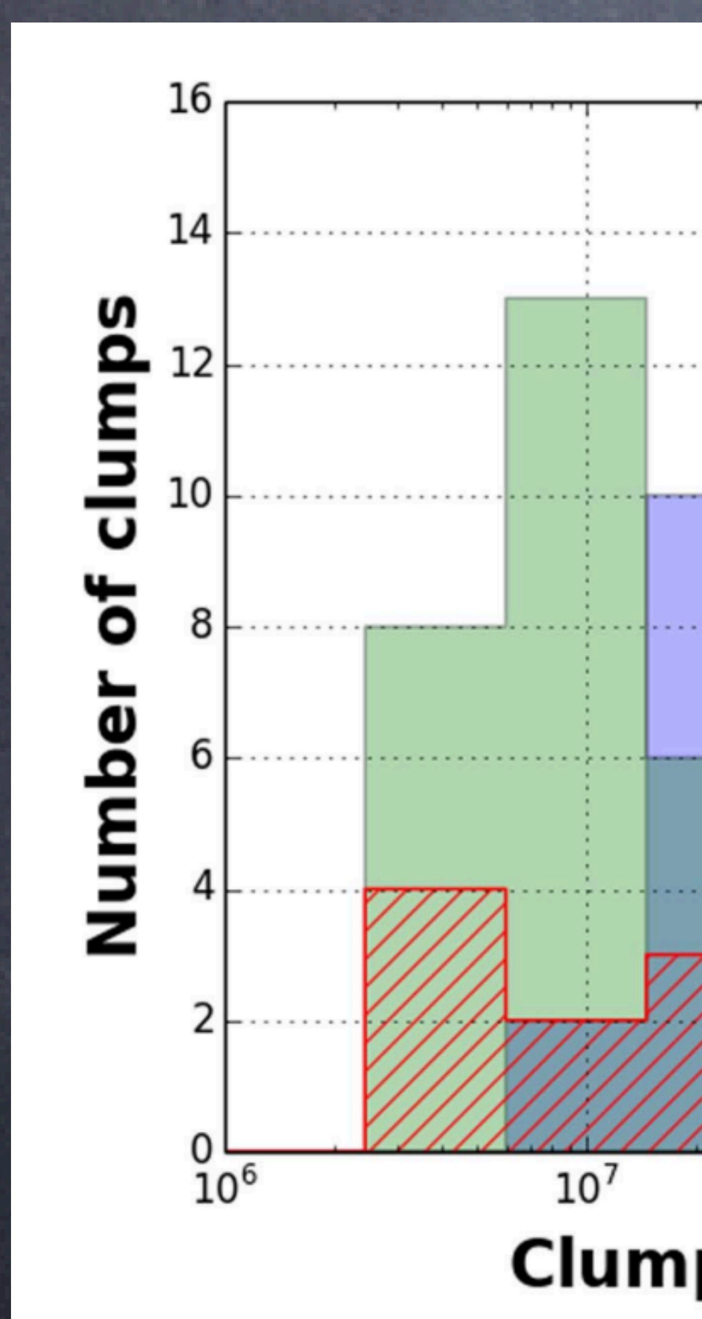
(Fiacconi et al. 20

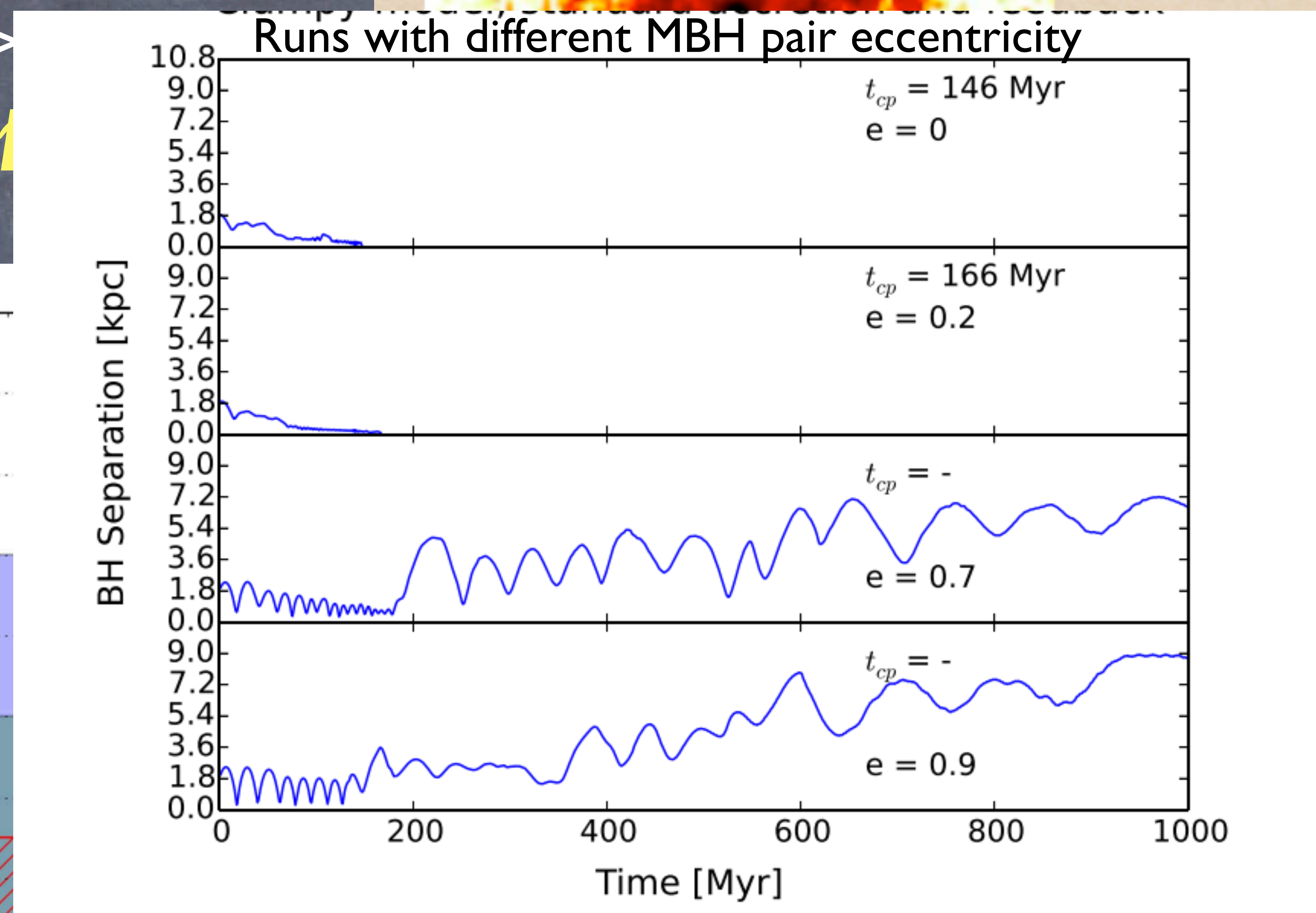
(M_{BH} ~ 5 x 10⁷

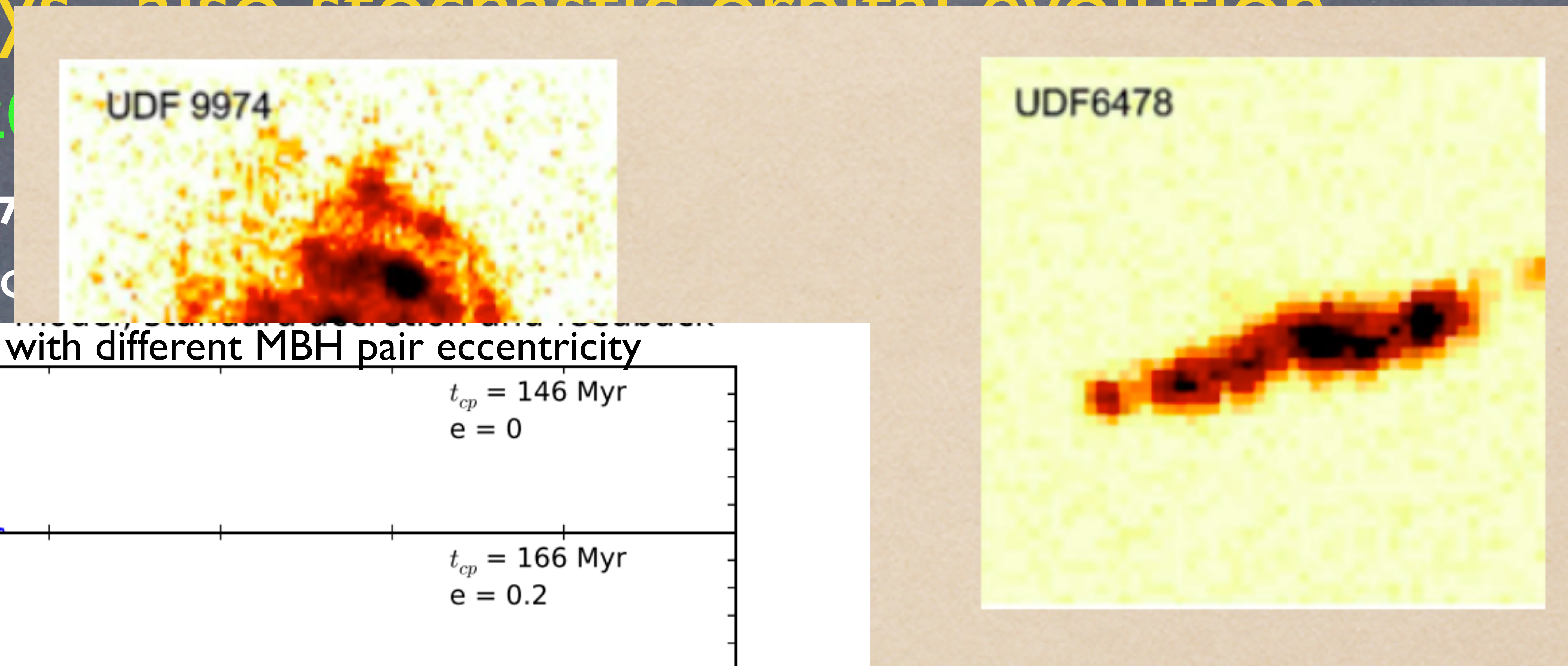
BH scattering/ejection by due to

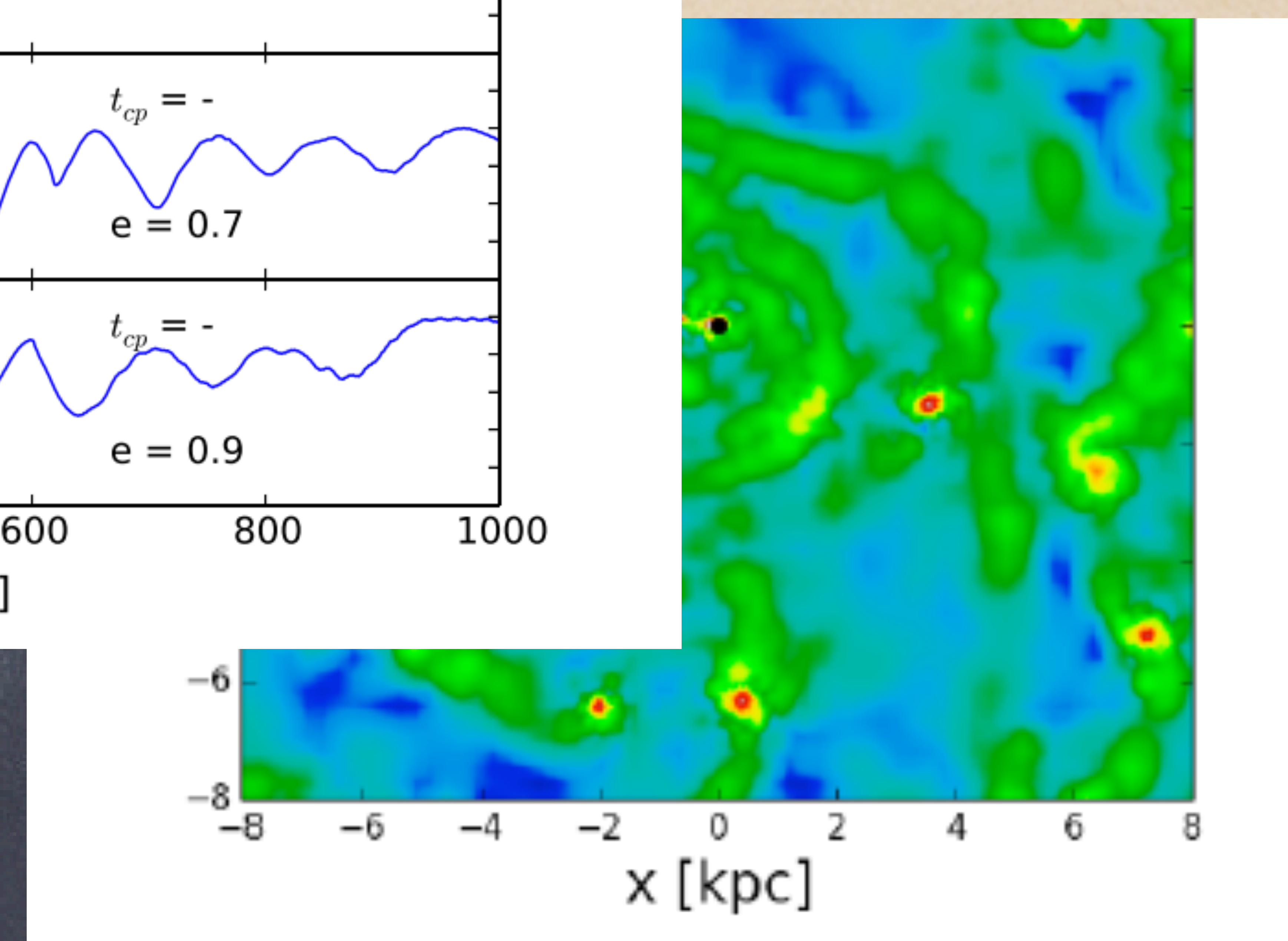
spiral structure--->

after clumpy









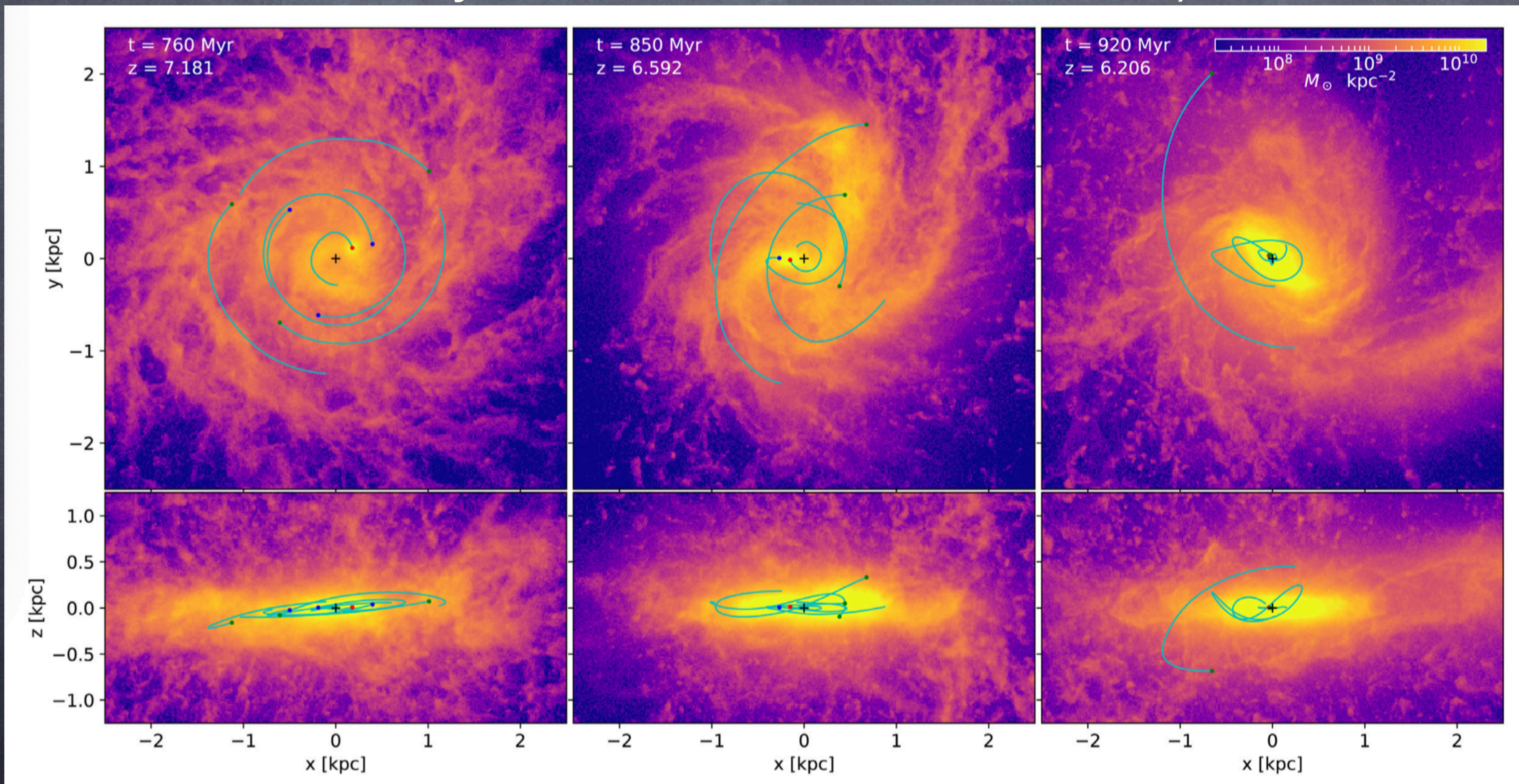
What about galaxies at even higher redshift, z >~3?

Simulations that match observed star forming galaxies show that **disks at very high-z are extremely gas-rich, self-gravitating and highly turbulent due to strong effects of SN feedback** caused by high specific SF rates (eg Fiacconi et al. 2017; Tamfal et al. 2022)

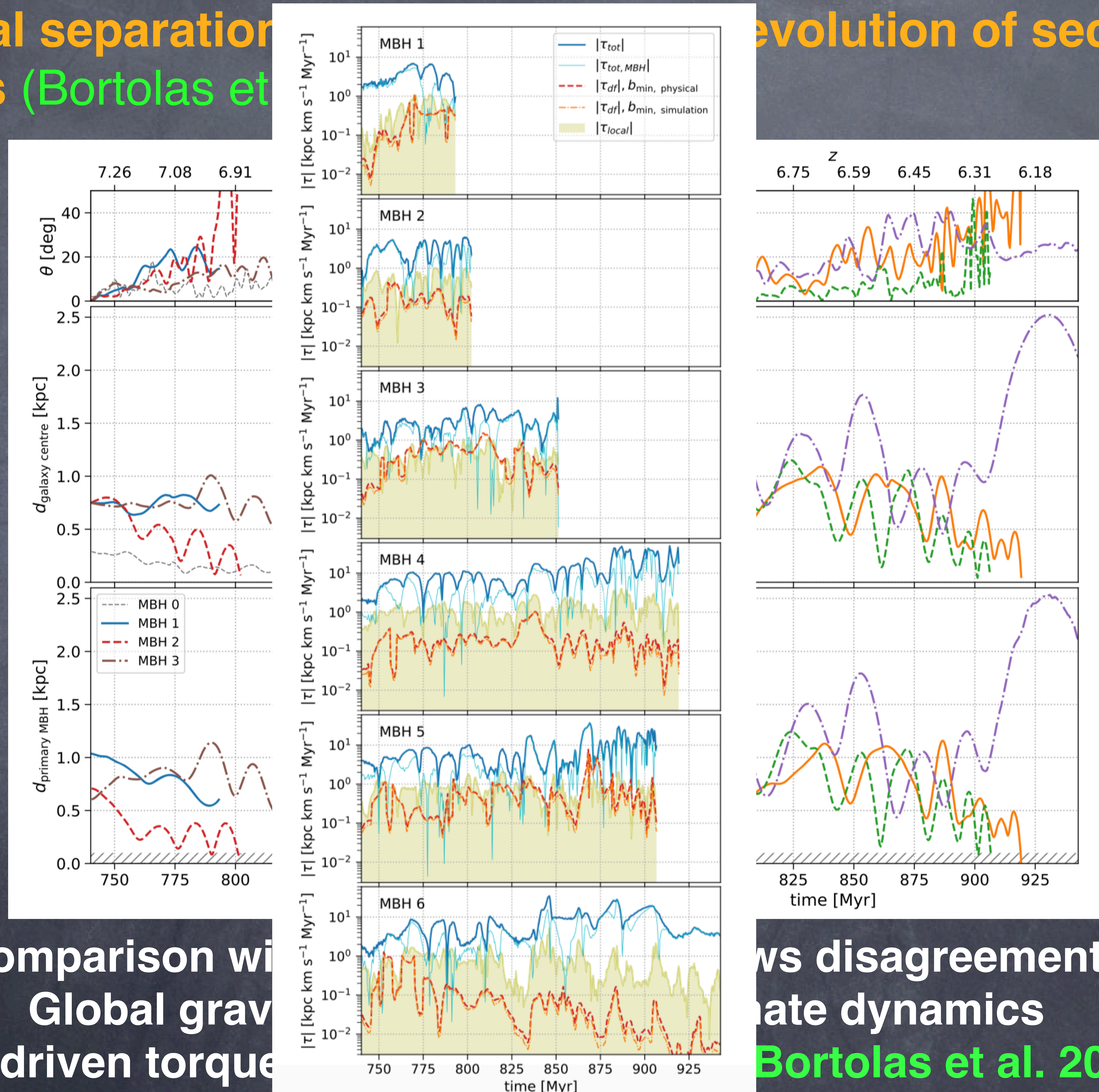
Strong asymmetries, bars and spiral structure in the gas and stellar disks —-> **global disk torques dominate over dynamical friction**

Global torques—>stochasticity in MBH binary formation (Stage I-II)
(Bortolas et al. 2020, using the PONOS cosmological "zoom-in" simulations))

10^6 Mo black holes released at different at angles and distances from primary (4×10^6 Mo) into typical disk galaxy at z ~ 7 (such an SMBH binary would be in the LISA band)



Orbital separation … evolution of secondary MBHs (Bortolas et …



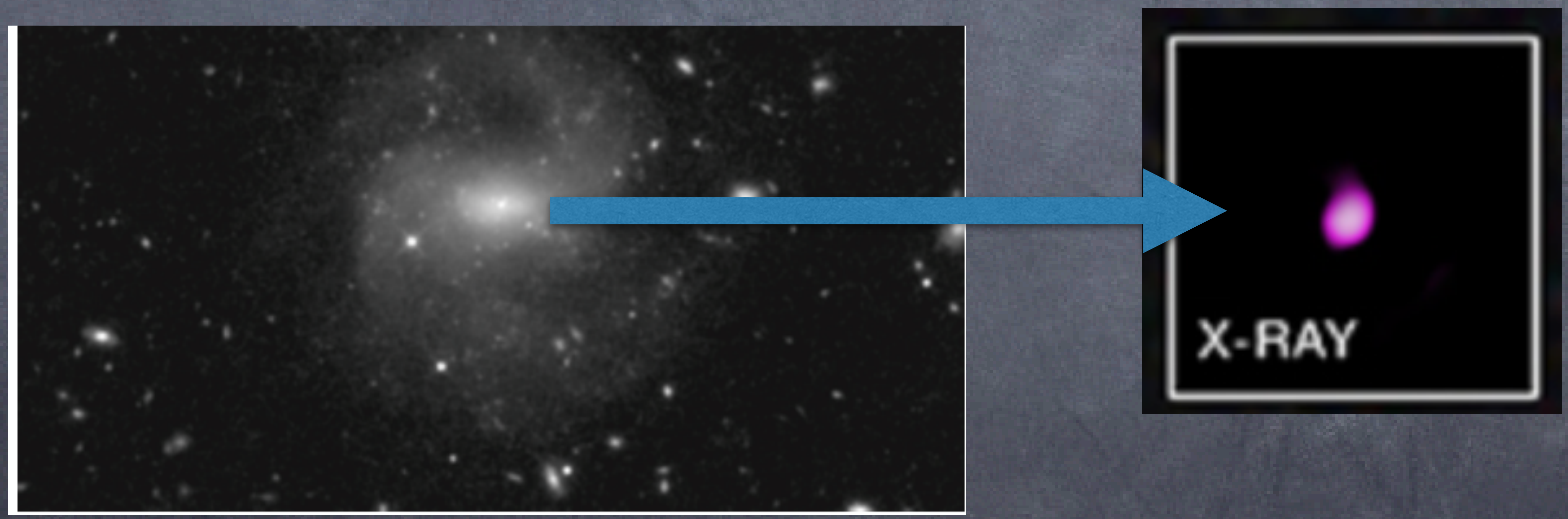
Comparison wi… …ws disagreement.
Global grav… …nate dynamics
(bar-driven torque… Bortolas et al. 2021)

Stage I-III in the dark matter dominated regime: Intermediate Mass BH Binaries in merging dwarf galaxies

Merging MBHs in the 10^4-10^5 Mo range should be ideal target for TianQin (adavantage over LISA given flatter shape of sensitivity curve at high frequency).

These are naturally hosted in low-mass/dwarf galaxies.

Only recently X-ray detections of sources compatible with such low mass MBHs (IMBHs) have been collected in dwarf galaxies (eg Reines et a 2013; Baldassare et al. 2015;2017; Chandra COSMOS Legacy survey, Mezcua et al. 2018; Baldassare, Geha & Greene 2018)



—-> Potentially different regime for BH orbital dynamics since dwarf galaxies are dark matter dominated even at scales ~<1 kpc.

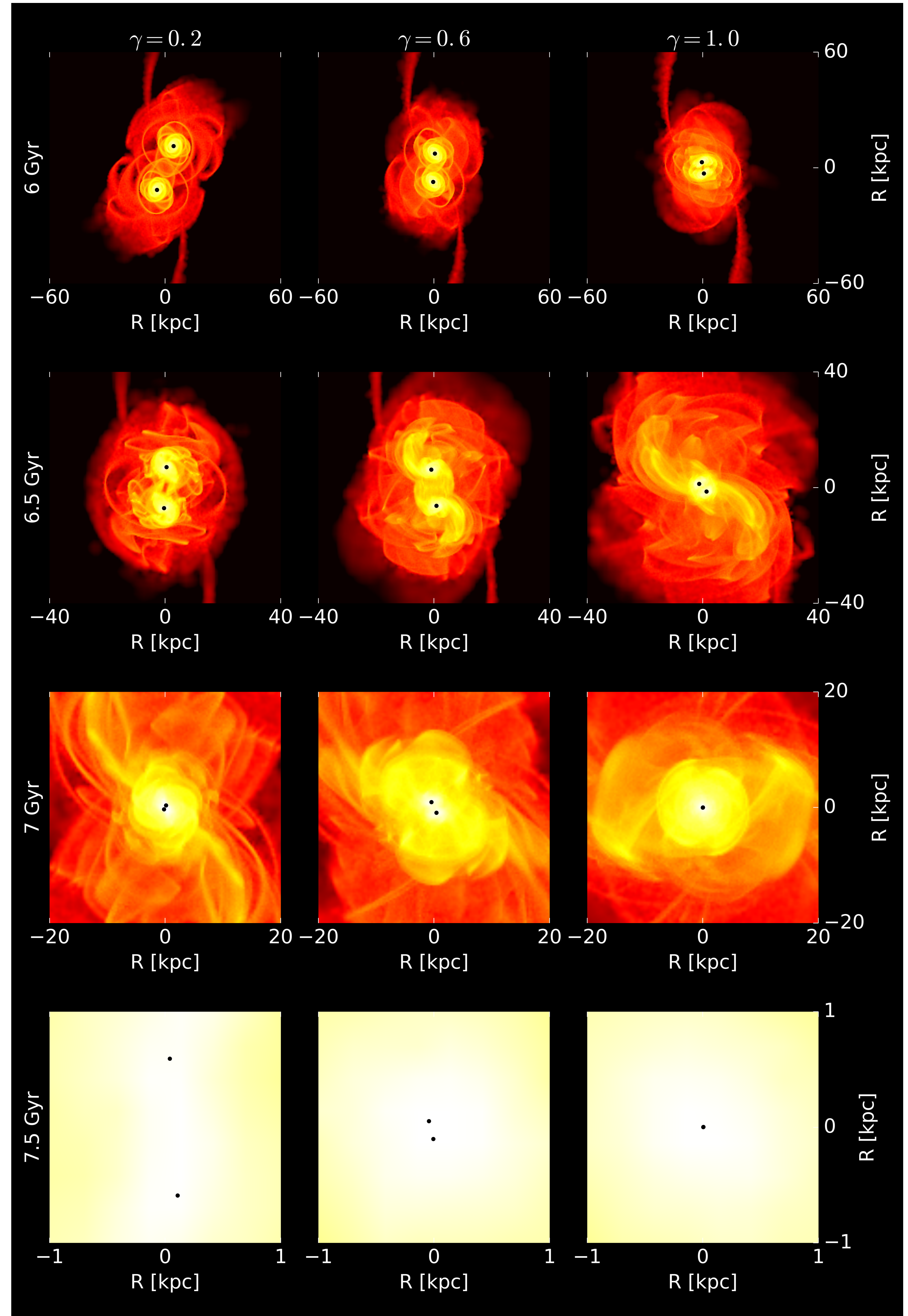
Hi-res dwarf galaxy merger simulations with varying dark matter density profile

$$\rho = \frac{\rho_s}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Our default resolution:
1.2 x 10^8 particles
4 pc spatial res.

Focus on binary formation and initial hardening phase for equal mass black holes (~10^5 Mo) in major mergers.
Slopes shallower than NFW can be produced by SN-driven outflows (Governato et al. 2010) or in alternative dark matter scenarios (see Mayer 2022 for a review)

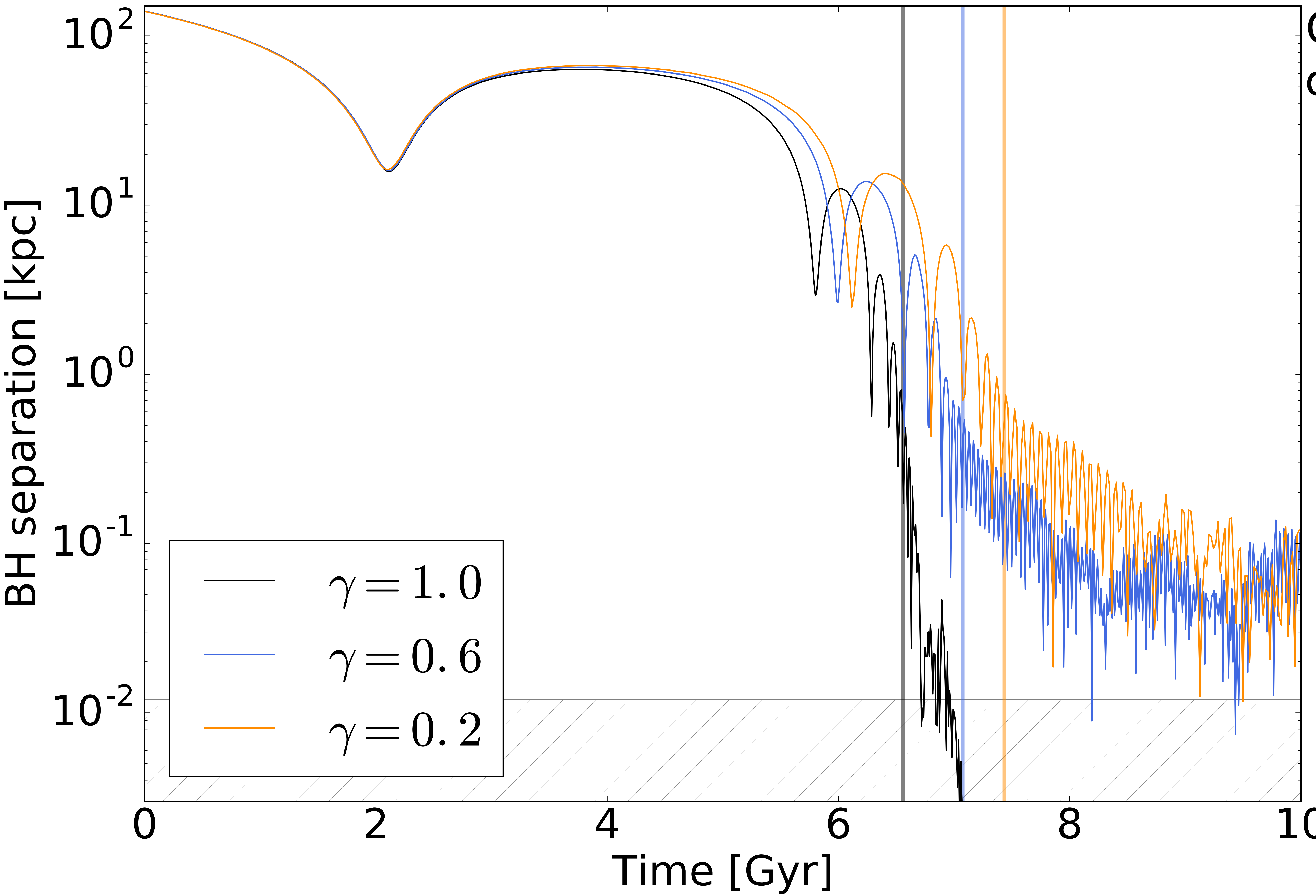
First study considered gas-free galaxy mergers (Tamfal et al. 2018, with N-Body code PKDGRAV3)



γ = 1 (NFW) default in Cold Dark Matter cosmology

Suppression of dynamical friction (expected) in shallow/cored density distribution (Goerdt et al. 2007,2010; Petts et al. 2015; 2017).

(a) Lower central density + (b) Non-maxwellian velocity distribution with “N-horn” DM particles moving faster than the BHs and accelerating them (Cole et al. 2012; Petts et al. 2017).

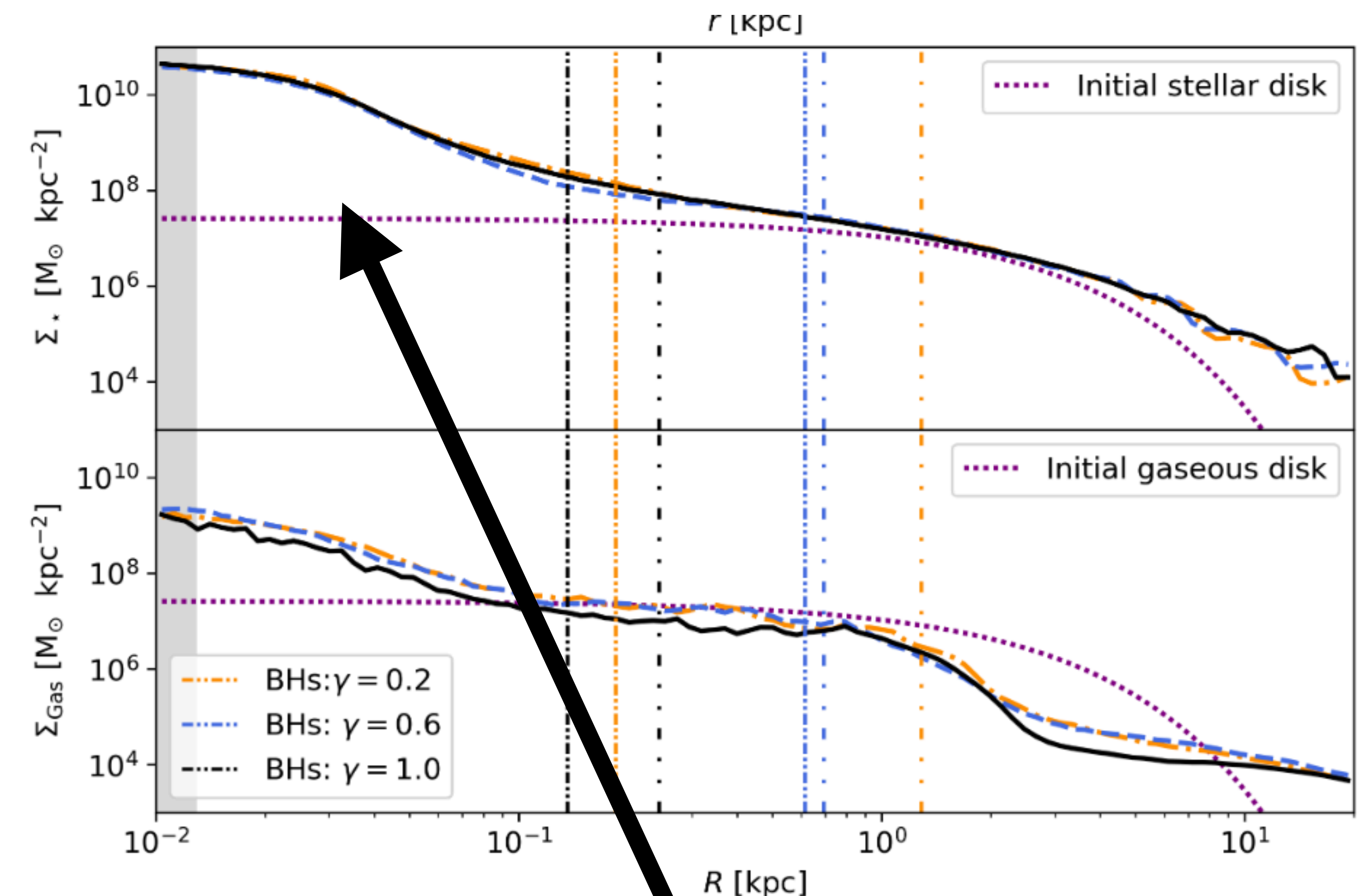


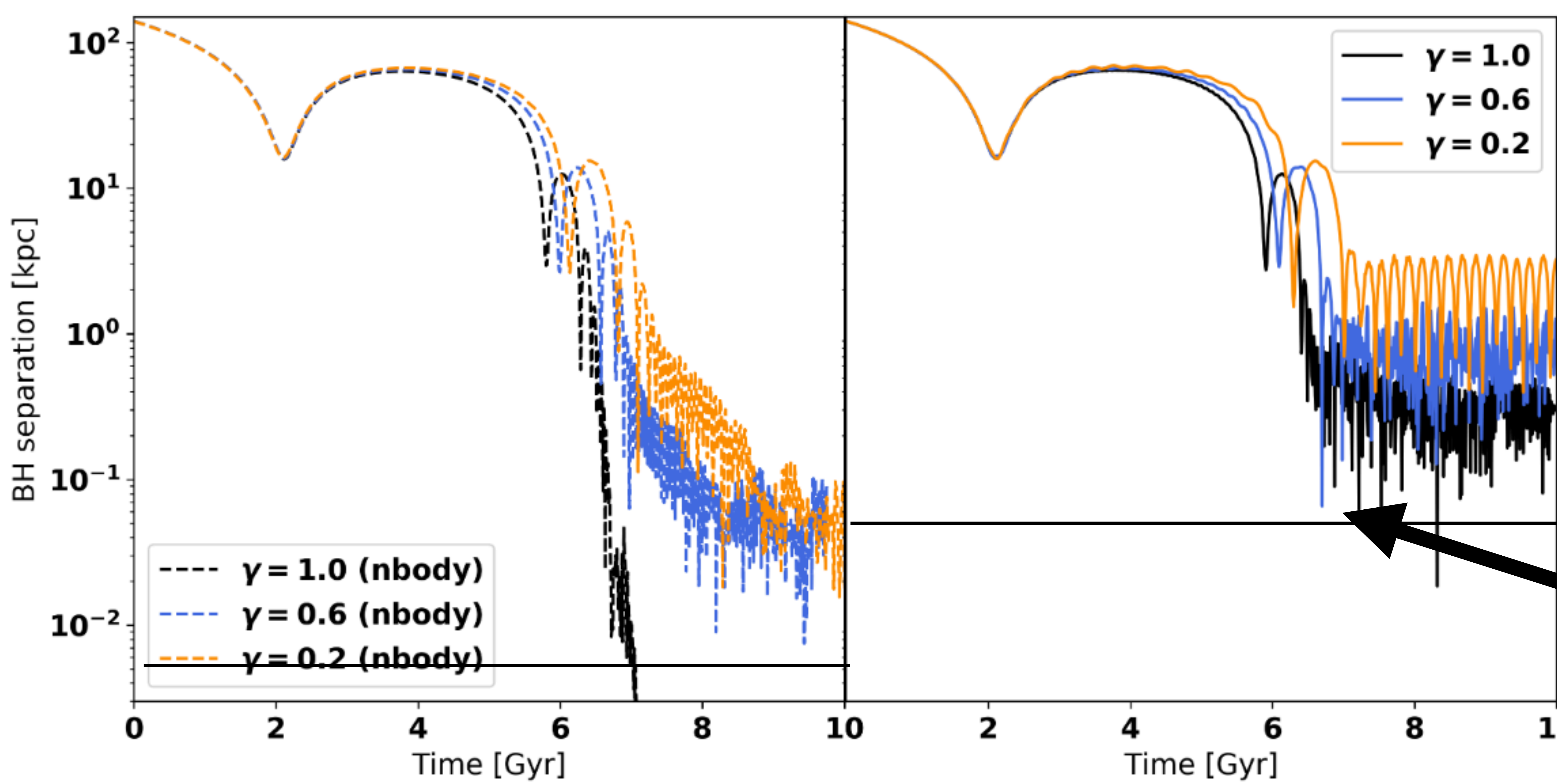
Gas-free equal mass dwarf galaxy mergers

WARNING; analytical Extrapolation shows even in NFW case sub-pc hardening timescale > t_{Hubble}

—> **need central stellar density enhancement, eg nuclearstar cluster (NC)**

Dwarf galaxy mergers with gas (Tamfal et al. 2022), same Galaxy models and IMBH masses but baryonic disk has 50% of its mass in cold gas phase





Gas inflow triggered by merger increases the central density a ot (formation of Nuclear Star Cluster (NSC)?) but the IMBHs Lag behind in low density outer region "evacuated" by inflow

—-> **$t_{dynfriction} > t_{inflow}$**

slowdown of orbital decay relative to gas-free mergers

Conclusions

I. For LISA and TianQin the MBH mergers in the relevant mass range must happen in gas-rich nuclei —-> at all scales gaseous phase plays key role in MBH binary evolution

II. MBH/IMBH binary formation + hardening is tightly linked with host galaxy properties, in particular depends on complex ISM physics, feedback processes, and DM distribution, hence depend on galaxy type and redshift (eg clumpy galaxies at z >~ 1)

→ predicting (S)MBH merger rates is thus **computationally challenging** because it requires modelling both the cosmological context and the sub-pc scale physical processes in galactic nuclei. **An EM census of MBH binaries at sub-pc to 100 pc scales would help a lot!**

III. HIGH-RESOLUTION GALAXY-SCALE SIMULATIONS OF GAS-RICH NUCLEI SHOW THAT GLOBAL DISK TORQUES DOMINATE OVER DYNAMICAL FRICTION, RESULTING IN STOCHASTIC ORBITAL EVOLUTION

Such Sensitivity means we can learn a lot on galaxy formation and on the co-evolution of galaxies and (S)MBHs from the LISA datastream