DYNAMICS OF MASSIVE BLACK HOLE BINARIES IN GALACTIC MERGERS

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MASSIVE BLACK HOLES: BIRTH, GROWTH AND IMPACT

KAVLI INSTITUTE, SANTA BARBARA, 6 August 2013

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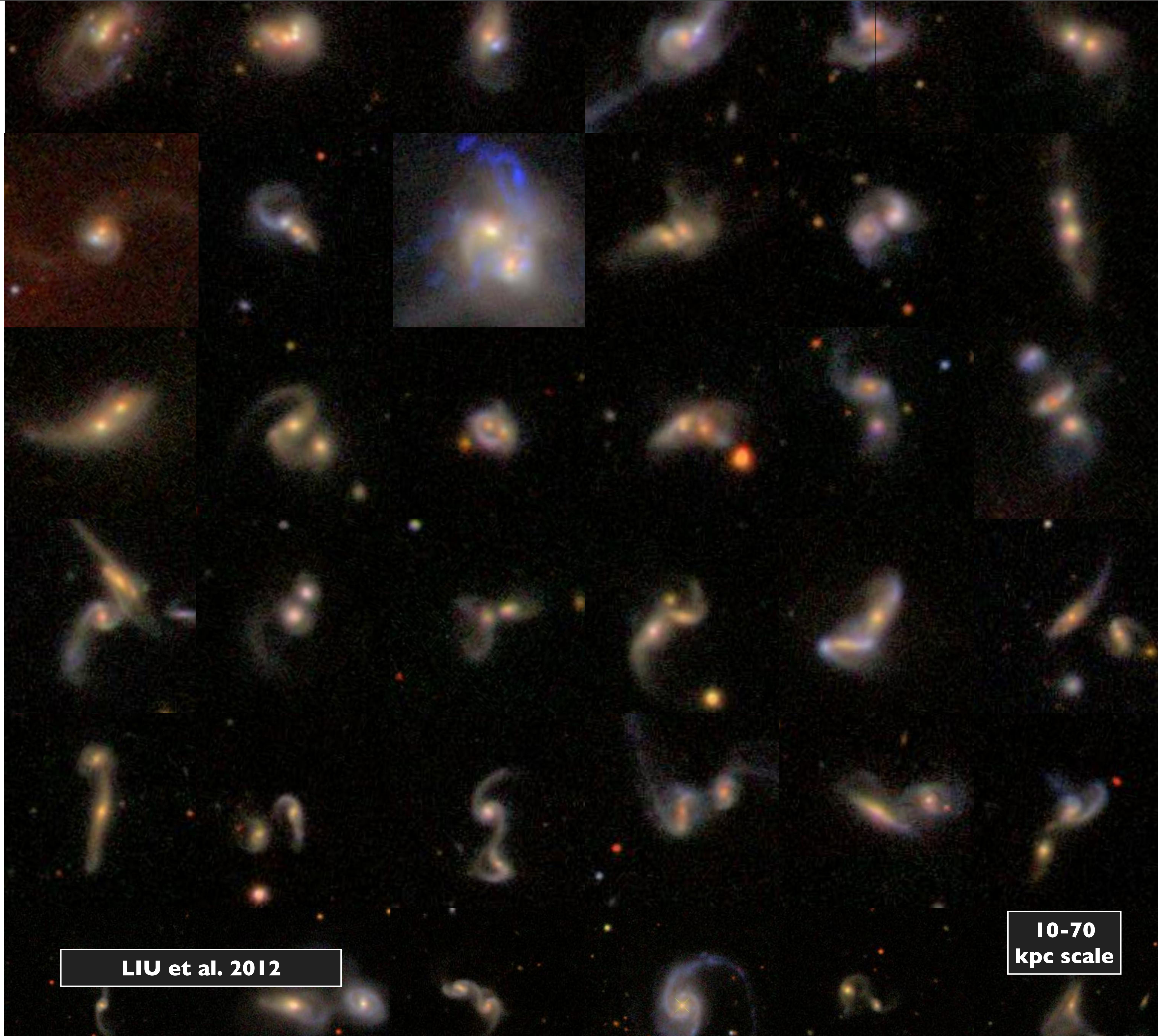
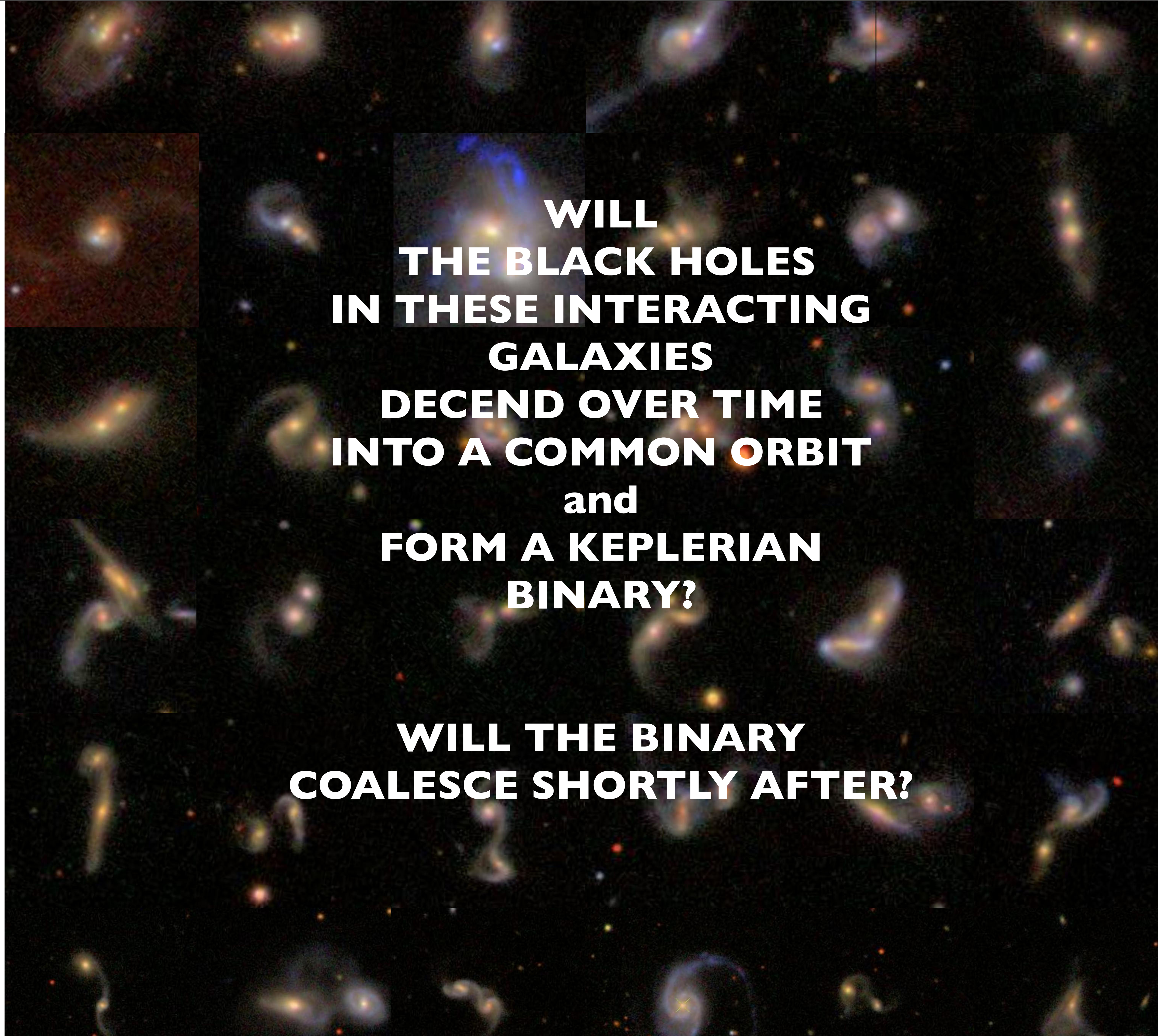
Simone Callegari (Zurich) Massimo Dotti (Milano Bicocca)
Davide Fiacconi (Zurich) Francesco Haardt (Insubria)
Lucio Majer (Zurich) Carmen Montuori (Haifa)
Marta Volonteri (Paris)

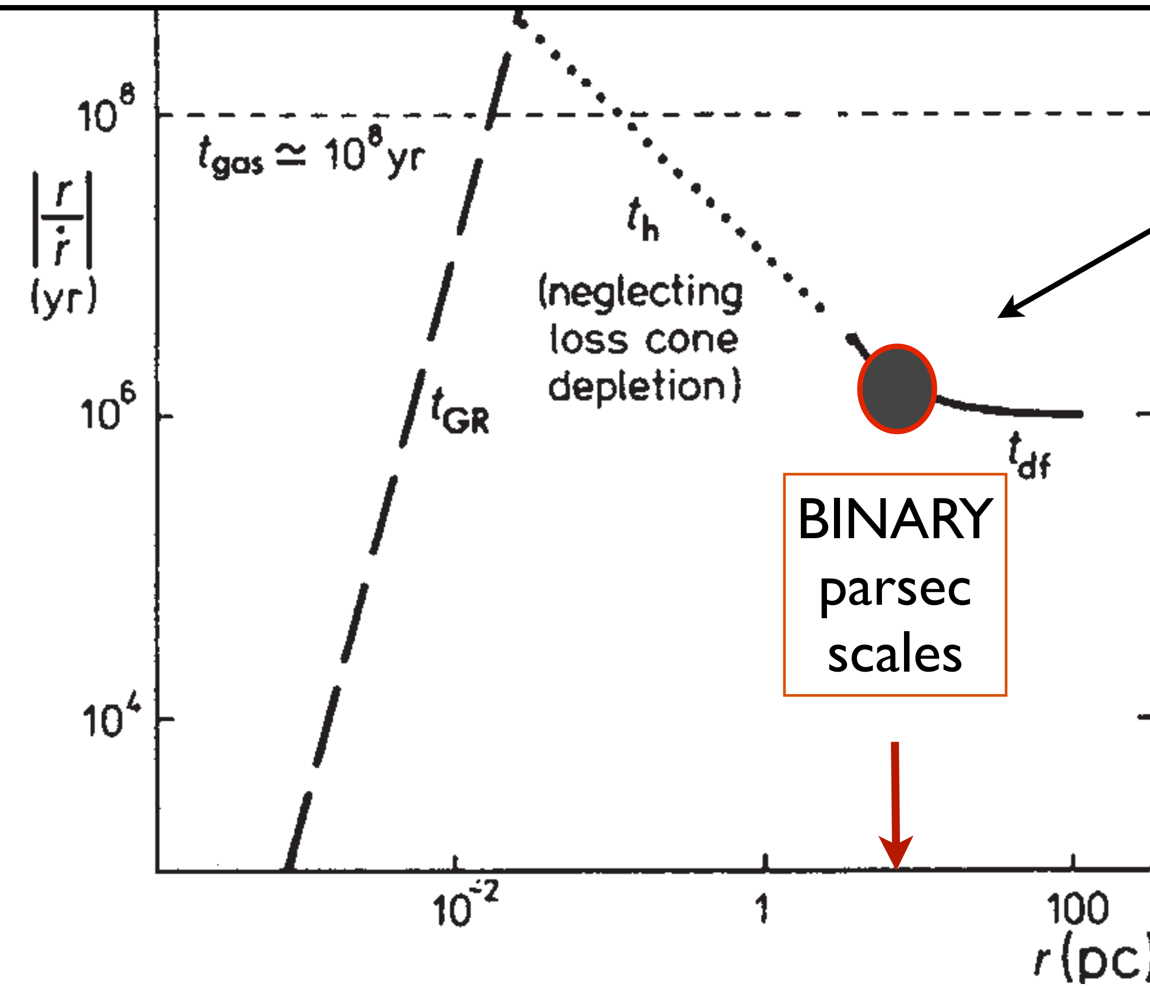

LIU et al. 2012
10-70
kpc scale


WILL
THE BLACK HOLES
IN THESE INTERACTING
GALAXIES
DECEND OVER TIME
INTO A COMMON ORBIT
and
FORM A KEPLERIAN
BINARY?
WILL THE BINARY
COALESCE SHORTLY AFTER?

Begelman, Blandford & Rees. *Nature*, 1980

PHASE I PAIRING

$$a_{\rm Binary} \sim \frac{G M_{\rm BH,T}}{\sigma^2} \sim 10 \left(\frac{M_{\rm BH,T}}{10^8\, M_\odot}\right) \left(\frac{200\,{\rm km\,s^{-1}}}{\sigma}\right)^2 \,{\rm pc}$$



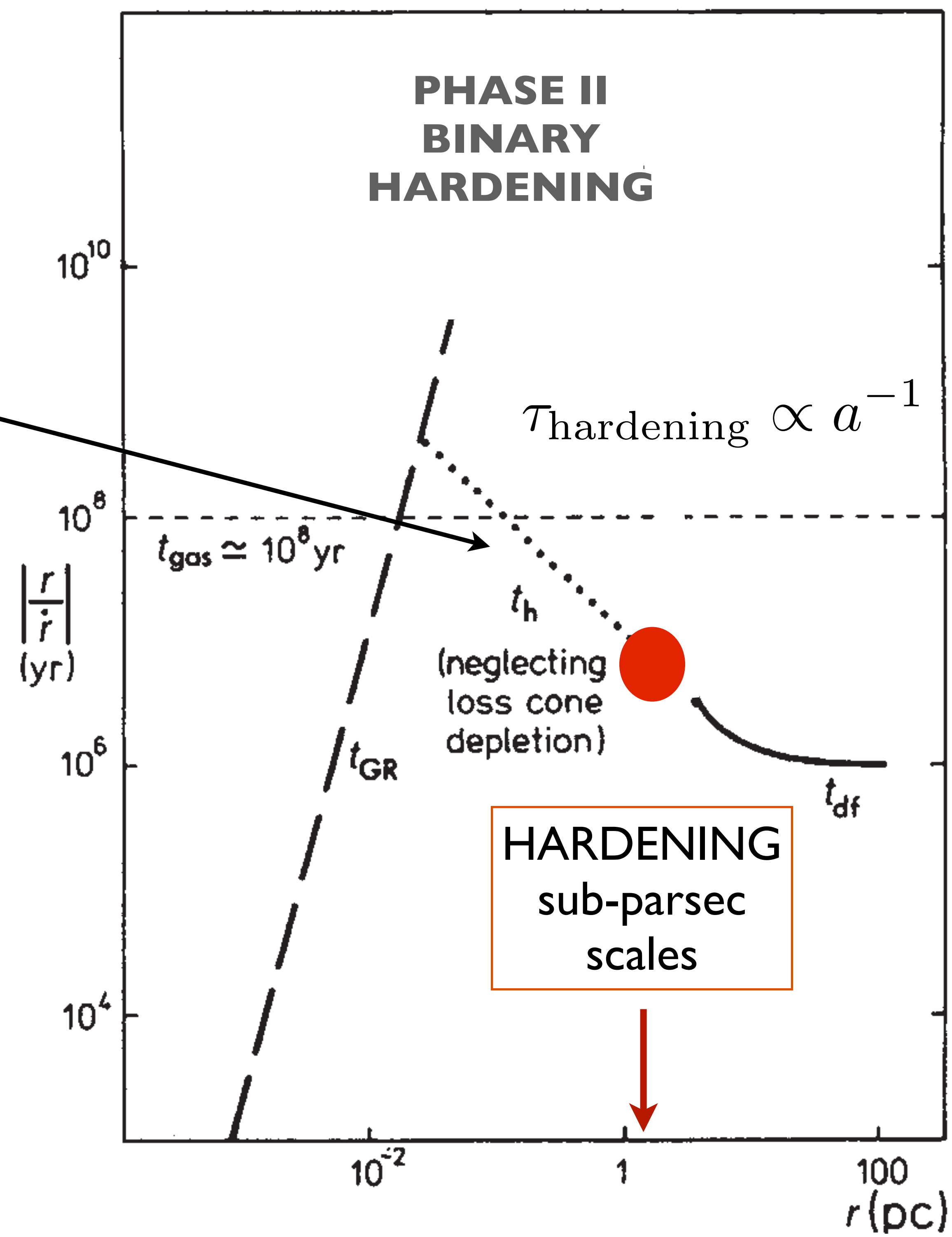
DYNAMICAL FRICTION AGAINST THE **STARS** CONTROLS THE **PAIRING** **in the "spherical" galaxy**

Diagram of the timescales in the approach and eventual coalescence of a supermassive binary

HARDENING THROUGH

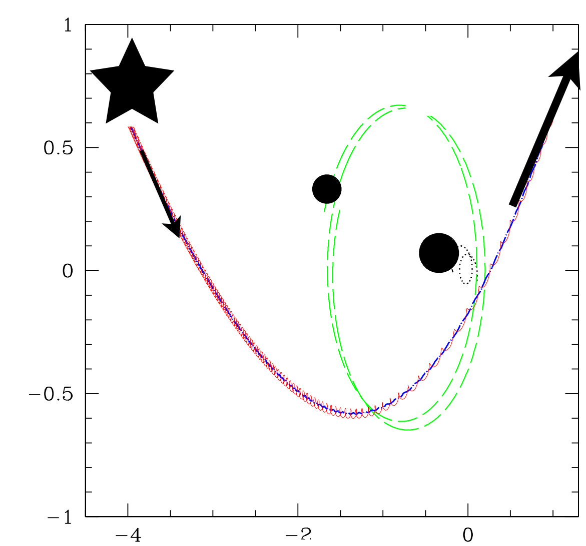
SCATTERING OFF SINGLE STARS

PLUNGING FROM NEARLY RADIAL ORBITS



$$\frac{G\mu_{\rm BH}}{2a_{\rm Hard}} > \frac{3}{2}\sigma^2$$

unbound orbit

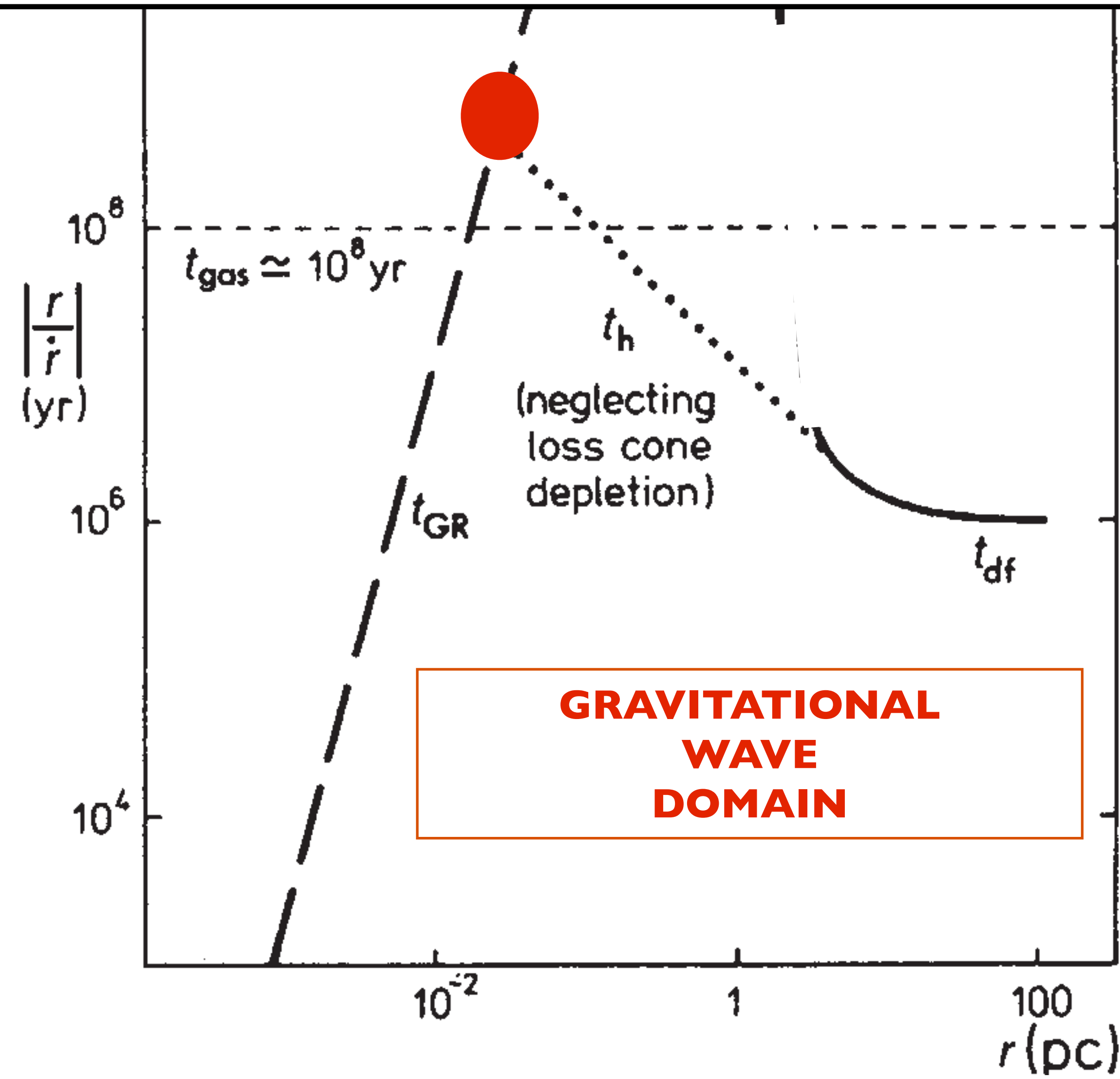


QUINLAN 1996, YU 2002

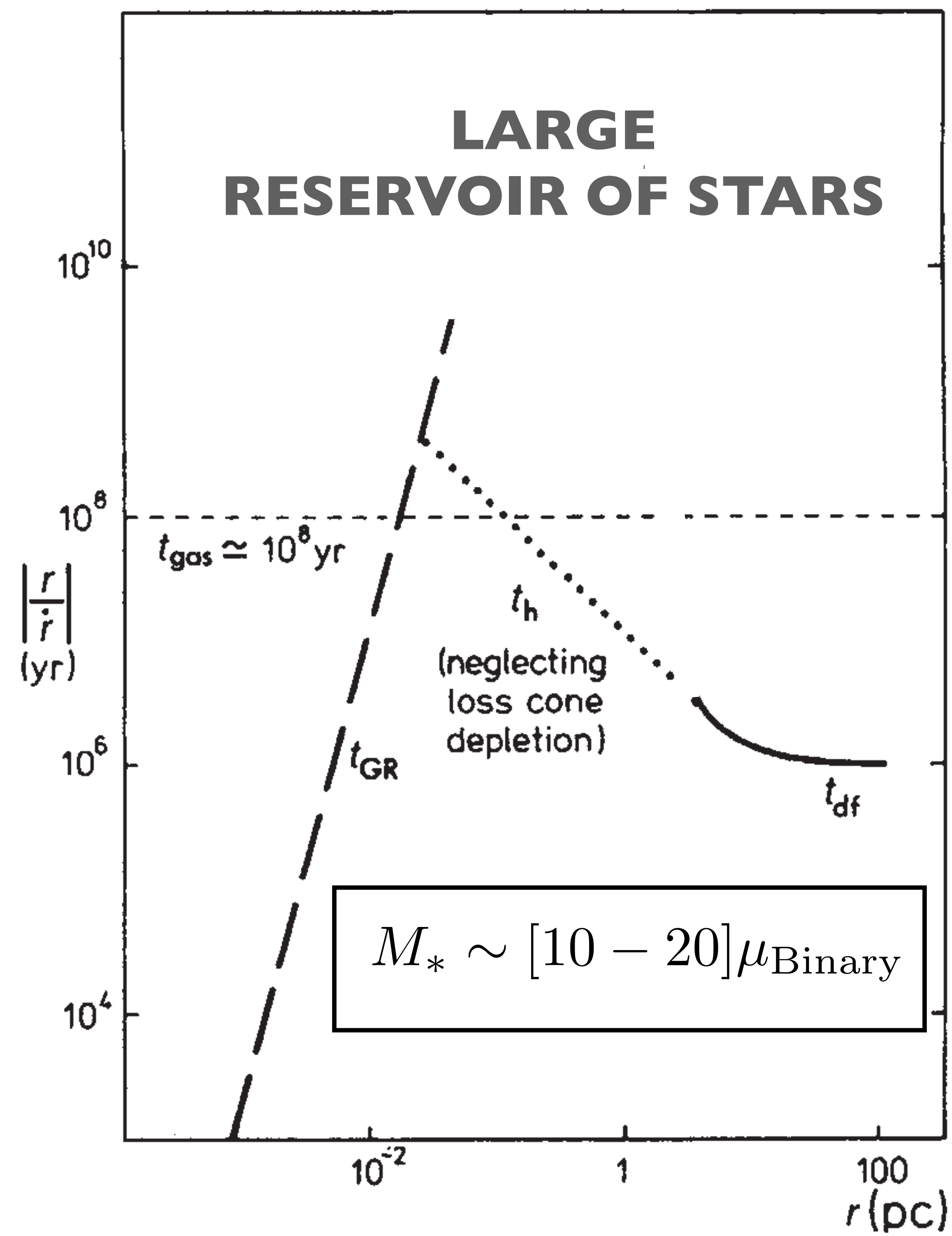
$$a_{\rm Hard} \sim \frac{G\mu_{\rm BH}}{3\sigma^2} \sim 3\frac{q_{\rm BH}}{(1+q_{\rm BH})^2}\frac{M_{\rm BH,T}}{10^8 M_\odot}\left(\frac{200\,{\rm km\,s^{-1}}}{\sigma}\right)^2 {\rm pc}$$

$$P(a_{\rm GW}) \sim 16 \left(\frac{M_{\rm BH,T}}{10^8 M_\odot}\right)^{5/8} \left(\frac{t_{\rm GW}}{10^9 {\rm yr}}\right)^{3/4} \ {\rm yr}$$

$$V_{\rm cir}(a_{\rm GW}) \sim 4130 \left(\frac{M_{\rm BH,T}}{10^8 M_\odot}\right)^{1/8} \left(\frac{t_{\rm GW}}{10^9 {\rm yr}}\right)^{-1/8} \ {\rm km\,sec^{-1}}$$



$$a_{\rm GW} \sim 25 \cdot 10^{-3} \left(\frac{M_{\rm BH,T}}{10^8 {\rm M}_\odot}\right)^{3/4} \left(\frac{t_{\rm GW}}{10^9 {\rm yr}}\right)^{1/4} \ {\rm pc}$$



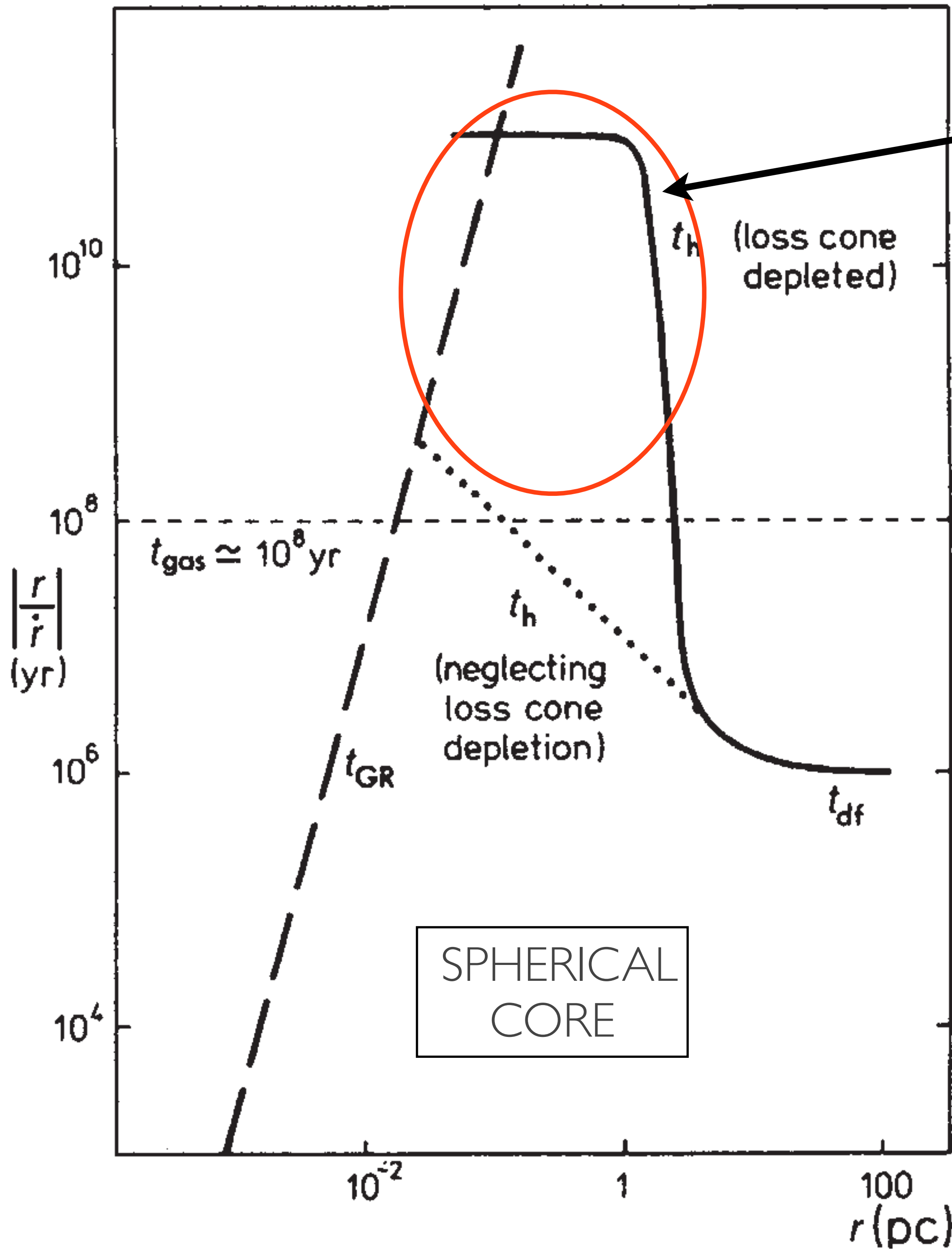
to transit
from hardening
to
GW phase

massive
ejection of stars

Diagram of the timescales in the approach and eventual coalescence of a supermassive binary
from Begelman, Blandford & Rees

THE LAST PARSEC PROBLEM

star's ejection implies DEPLETION OF THE LOSS CONE the region in the phase space of low-J orbits



REFILLING OF THE LOSS-CONE ON THE RELAXATION TIMESCALE

$\tau_{\text{relaxation}} \propto N$

IN GALAXIES RELAXATION TIMESCALE LONGER HUBBLE TIMES

STALLING OF THE BINARY - NO FURTHER DYNAMICAL EVOLUTION

SLOW DIFFUSIVE REFILLING OF THE BINARY LOSS CONE WAS OBSERVED IN N-BODY STUDIES IMPLYING LOW HARDENING RATES

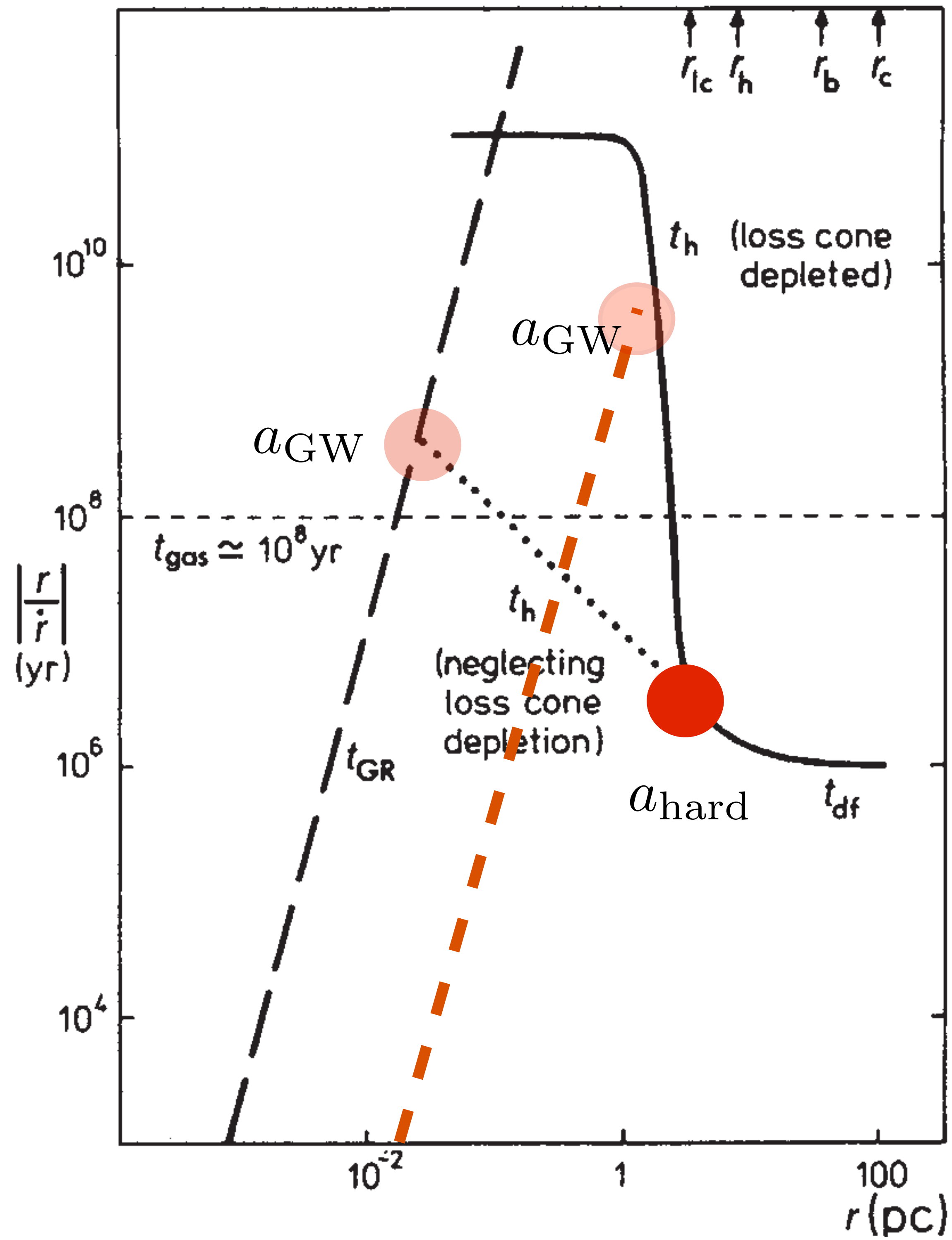
Milosavljevic & Merritt 2005

HOW CAN WE SOLVE THE LAST-PARSEC PROBLEM ?

minimal hypothesis

RUNAWAY INCREASE OF THE ECCENTRICITY with minor loss of binding energy ?

this reduces the mismatch between a_hard a_GW

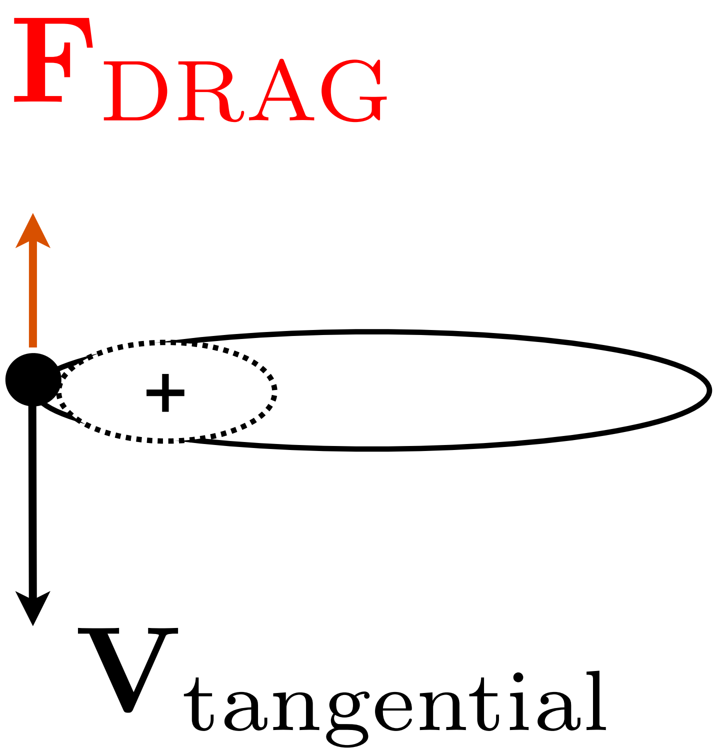


$$t_{GW} \propto (1-e^2)^{7/2} \frac{a^4}{M^3_{BH,T}}$$

$$a_{GW}(e=0.9999) \sim 2500\, a_{GW}(e=0)$$

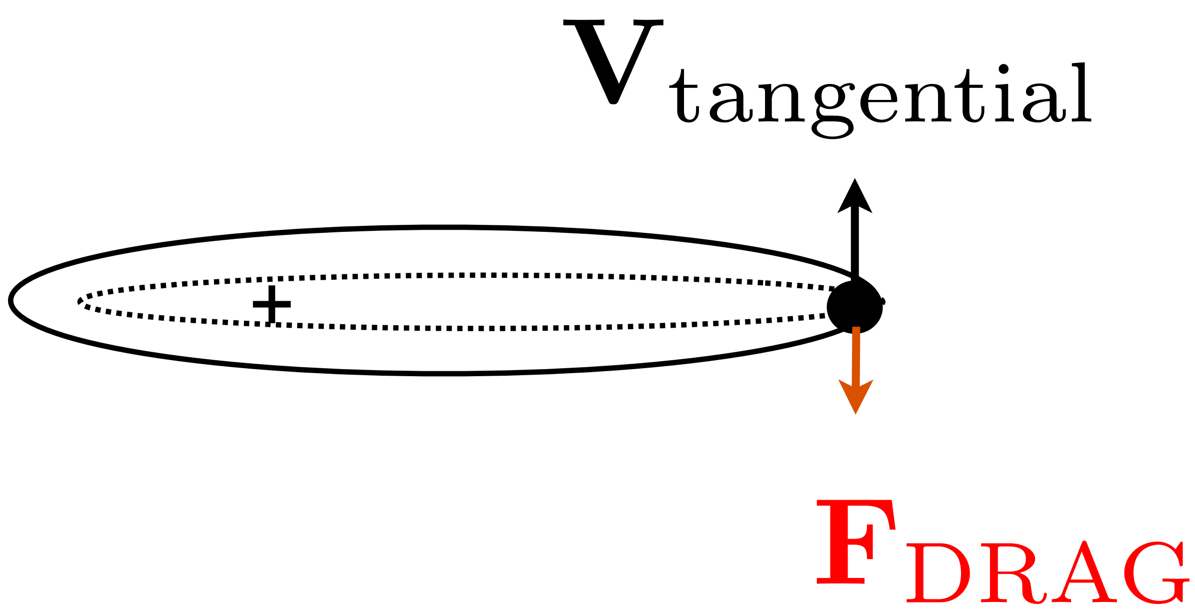
..focus on the orbit of one black hole

ECCENTRICITY DECREMENT



drag force
@
pericenter

ECCENTRICITY INCREASE



the action of the drag force
mostly confined
@
apocenter

HARDENING PHASE:
SLING-SHOT MECHANISM

the binary is a "source"
of angular momentum

the tendency is to "deposit"
angular momentum
into the stellar "bath"
... high eccentricity

QUINLAN 1996, MILOSAVLJEVIC & MERRITT 2001, HEMSENDORF ET AL. 2002, BAUMGARDT et al. 2006, AMARO SEOANE et al. 2009, MERRITT et al. 2007, SESANA et al. 2010, SESANA 2010

NEED OF A RAPID REFILLING OF THE LOSS CONE

... in reality ....

GALAXIES ARE NOT "SPHERICAL" BEING RELIC OF A MERGER

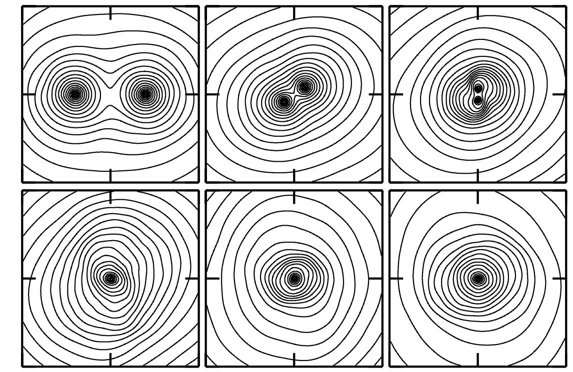
... a degree of triaxiality/axisymmetry

Khan, Just & Merritt 2011; Khan et al. 2012
Khan & Holley Bockelmann 2013
Preto et al. 2011
Berentzen et al. 2009
Preto et al. 2011,
Berczik, Merritt, Spurzem, Bischof, 2006

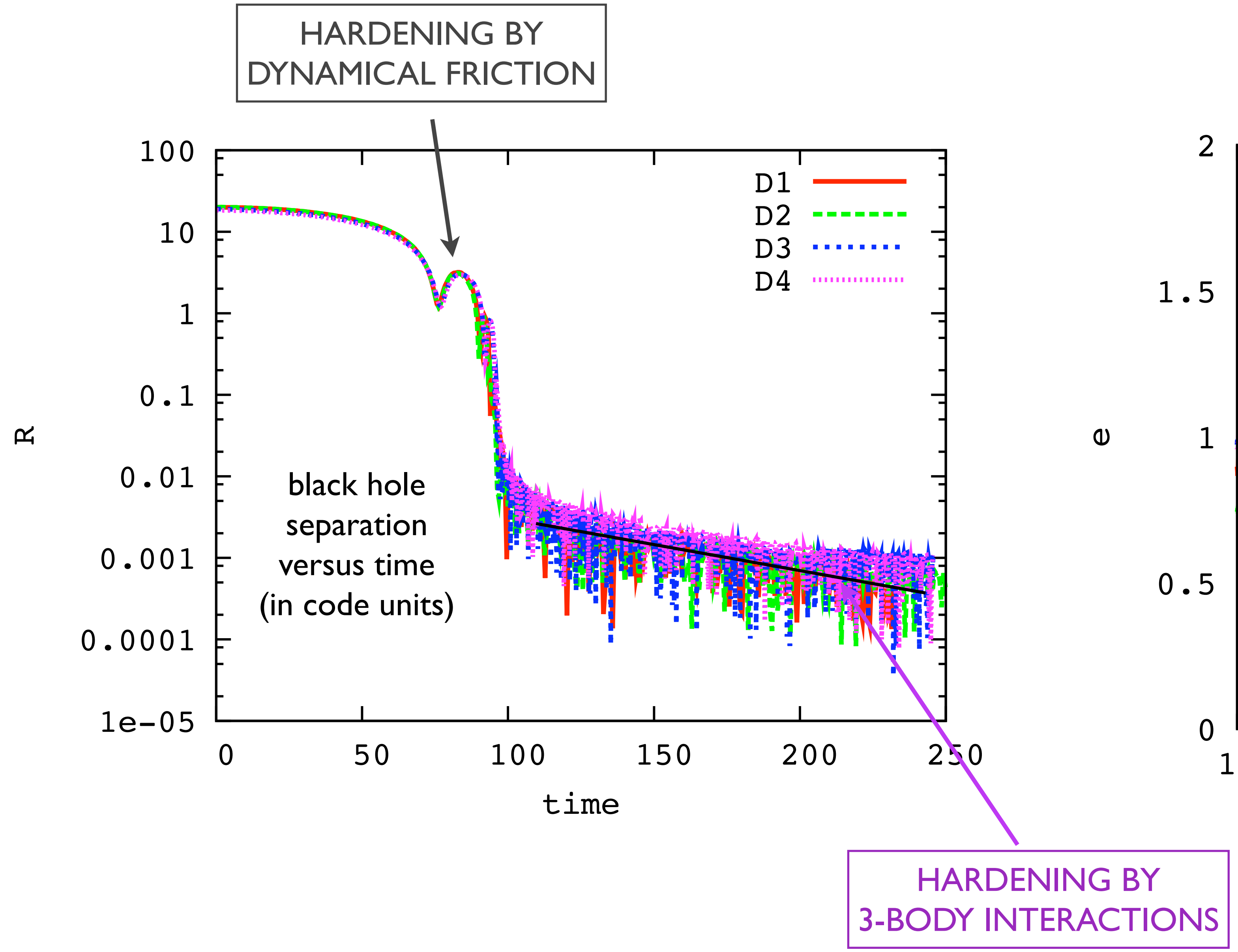
.... KHAN's TALK

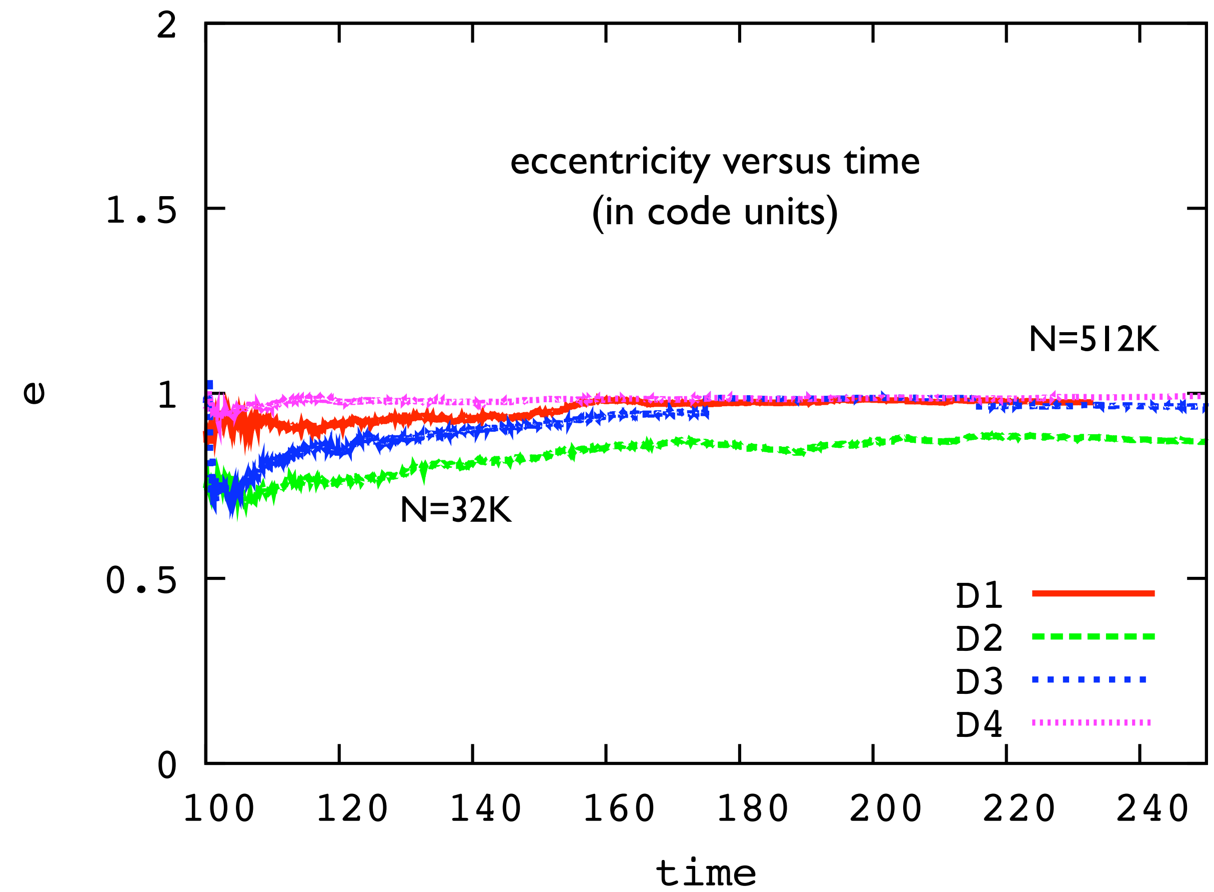
collisionless merger
between two Hernquist' s spheres
on an initially bound eccentric orbit

TRIAXIAL GALAXY REMNANT



$$\frac{M_{\rm BH}}{M_{\rm galaxy}} = 0.01$$

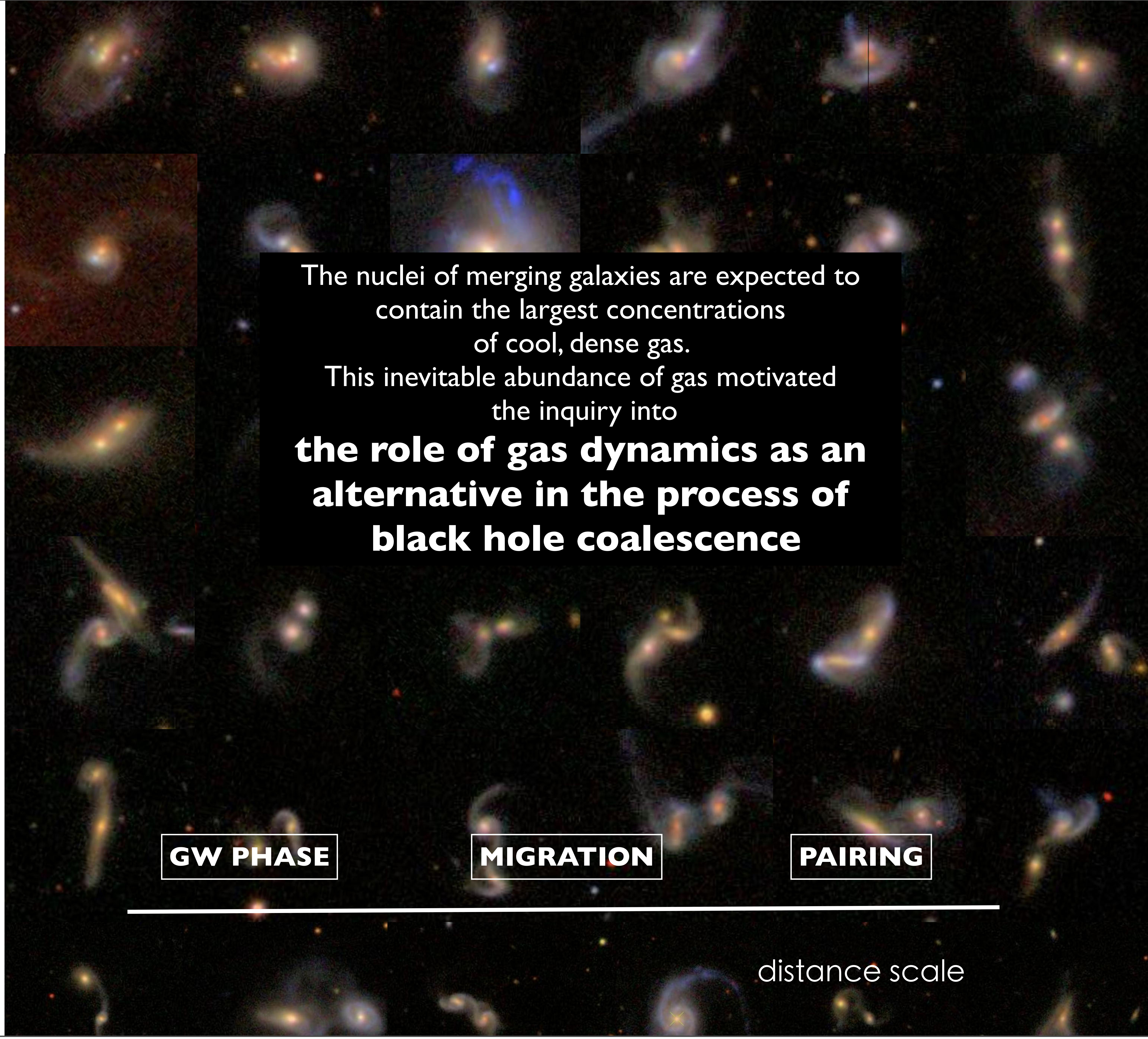




KHAN, JUST & MERRITT 2011

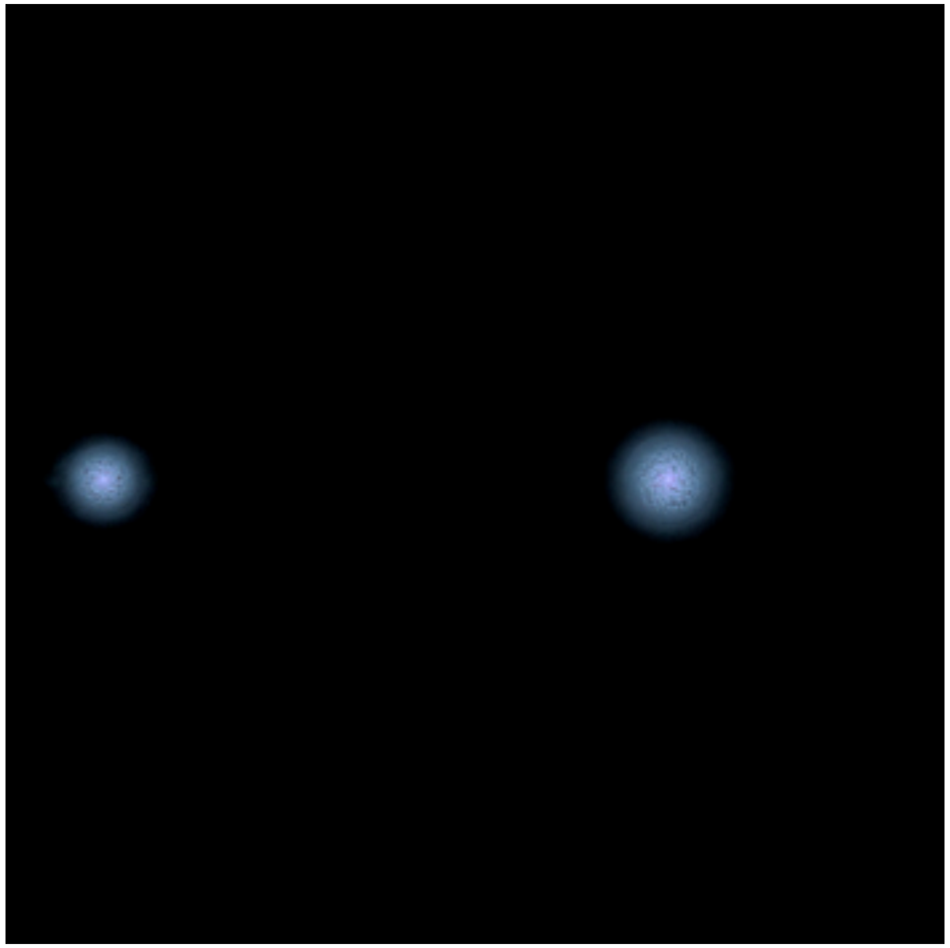
IN COLLISIONLESS MERGERS

- the "LAST PARSEC PROBLEM" as artificial product of the spherical approximation
- hardening rates in SPHERICAL MERGERS are much higher that in spherical isolated models
- coalescence times around 1 Gyr from the time of formation of the binary
- LESSON TO LEARN: attack the problem "ab initio"


The nuclei of merging galaxies are expected to contain the largest concentrations of cool, dense gas.
This inevitable abundance of gas motivated the inquiry into
the role of gas dynamics as an alternative in the process of black hole coalescence
GW PHASE
MIGRATION
PAIRING
distance scale

- major merger of gas-rich Milky Way like galaxies

COPLANAR
PROGRADE
PARABOLIC
ENCOUNTER
OF TWO
MILKY WAY
LIKE GALAXIES



SPH SIMULATION
COURTESY:
SANDOR VAN
WASSENHOVE

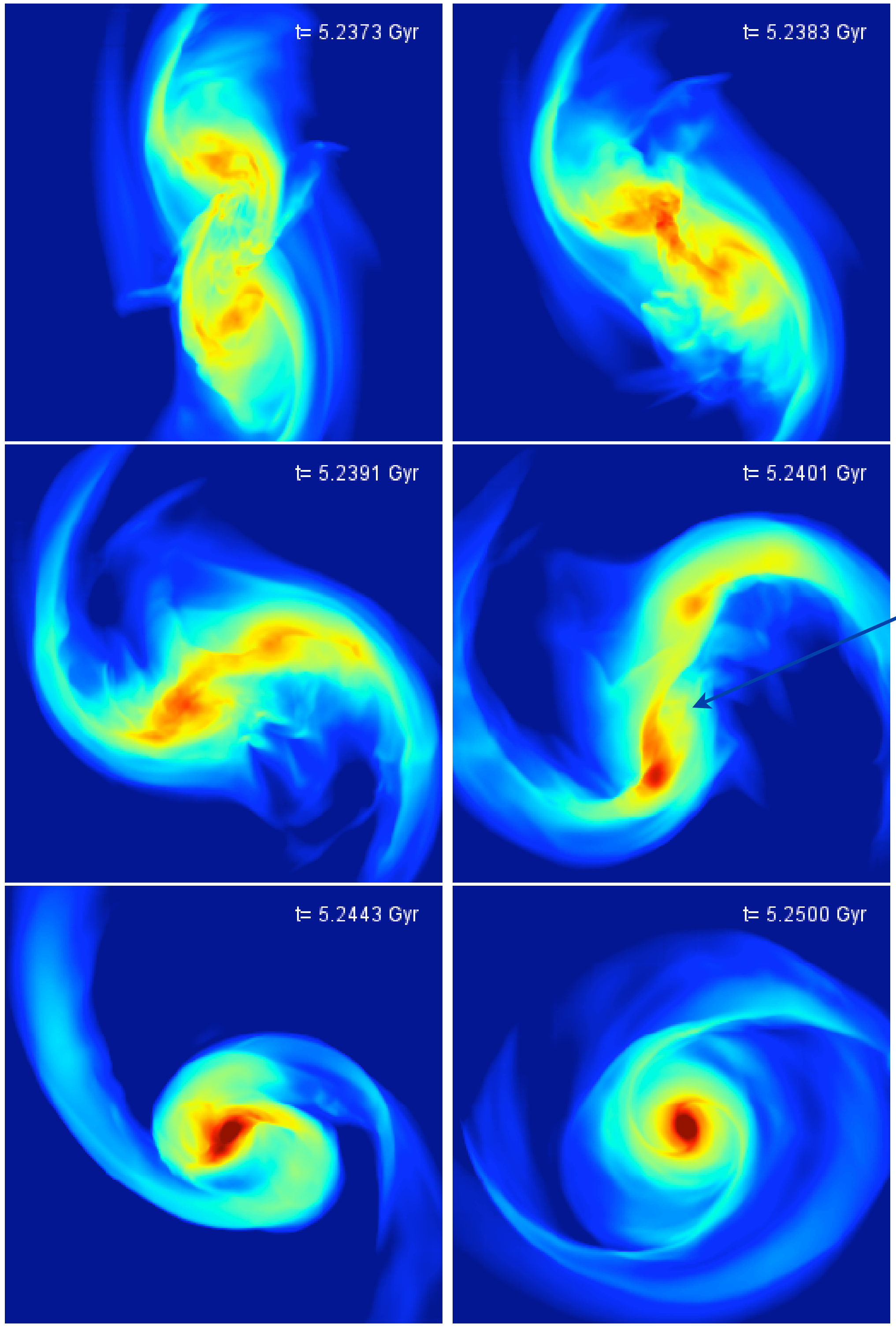
ENCOUNTER STARTS
several Gyears
BEFORE CONTACT

- trace self-consistently the sinking of the stellar and gaseous discs by dynamical friction against the dark matter background of the merging halos
- later, trace self-consistently the dynamics of the black holes in the time varying gravitational potential of the forming galaxy
- 1:1 merger has been tested against both SPH and AMR simulations

FORMATION OF A MASSIVE NUCLEAR DISC
of billion solar masses
200 pc in size 60 pc height

DENSITY MAP OF THE GASEOUS DISCS DURING THE FINAL MERGER

TIDAL TORQUES ARE REDISTRIBUTING THE ANGULAR MOMENTUM OF THE TWO INTERACTING DISCS



ASYMMETRIC SHOCKS DUE TO TURBULENCE

AMR SIMULATION BY CHAPON, MAYER, TEYSSIER, 2011

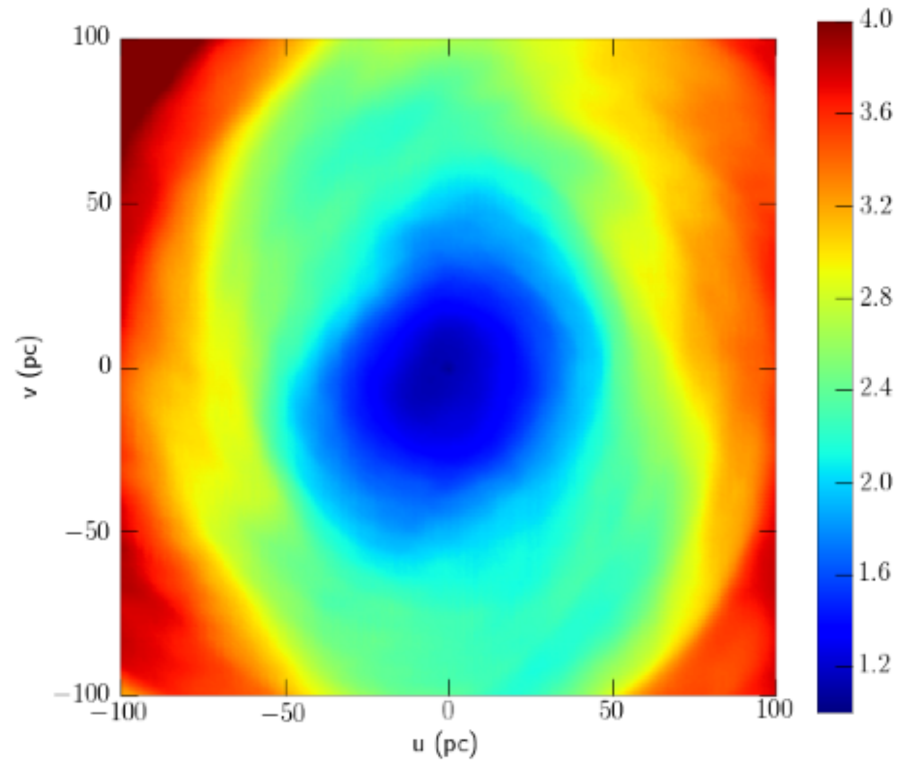
PRESSURIZED NUCLEAR DISC

ONE-PHASE GAS WITH POLYTROPIC EQUATION OF STATE INDEX

Γ=7/5

MAP OF THE LOCAL TOOMRE PARAMETER
CRITICAL FOR SMALL-SCALE FRAGMENTATION INTO STARS IF <1

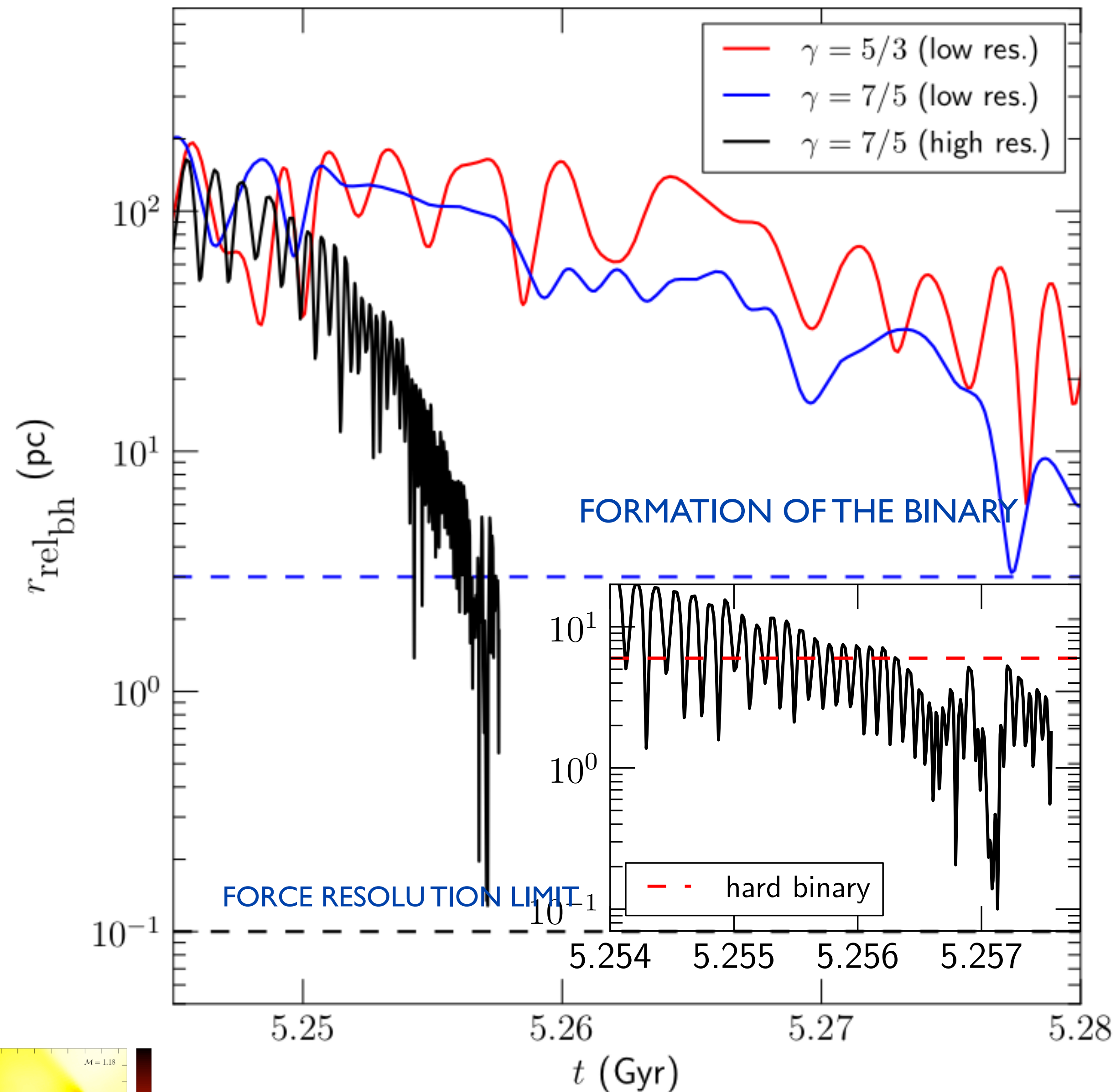
$$Q = \frac{C_{\rm sound} K_{\rm epicyclic}}{\pi G \Sigma}$$

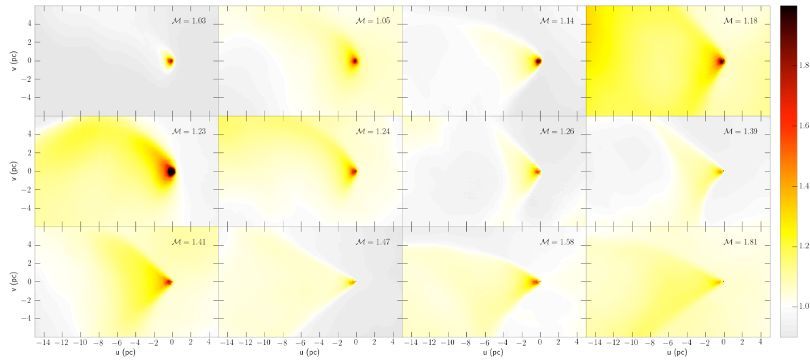


FACE ON VIEW

CHAPON, MAYER, TEYSSIER, 2011

rapid binary formation
few million years after the formation of the disc

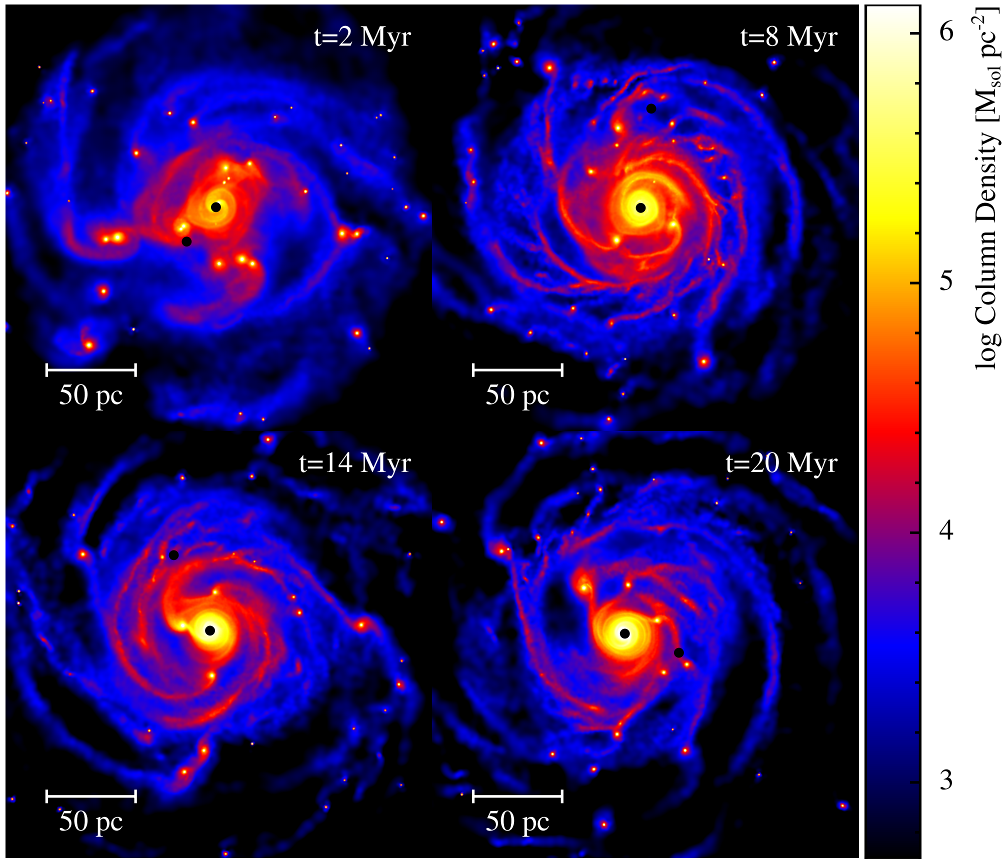




CHAPON, MAYER, TEYSSIER, 2011
MAYER et al. 2007
COLPI & DOTTI 2011 for a review

caveats

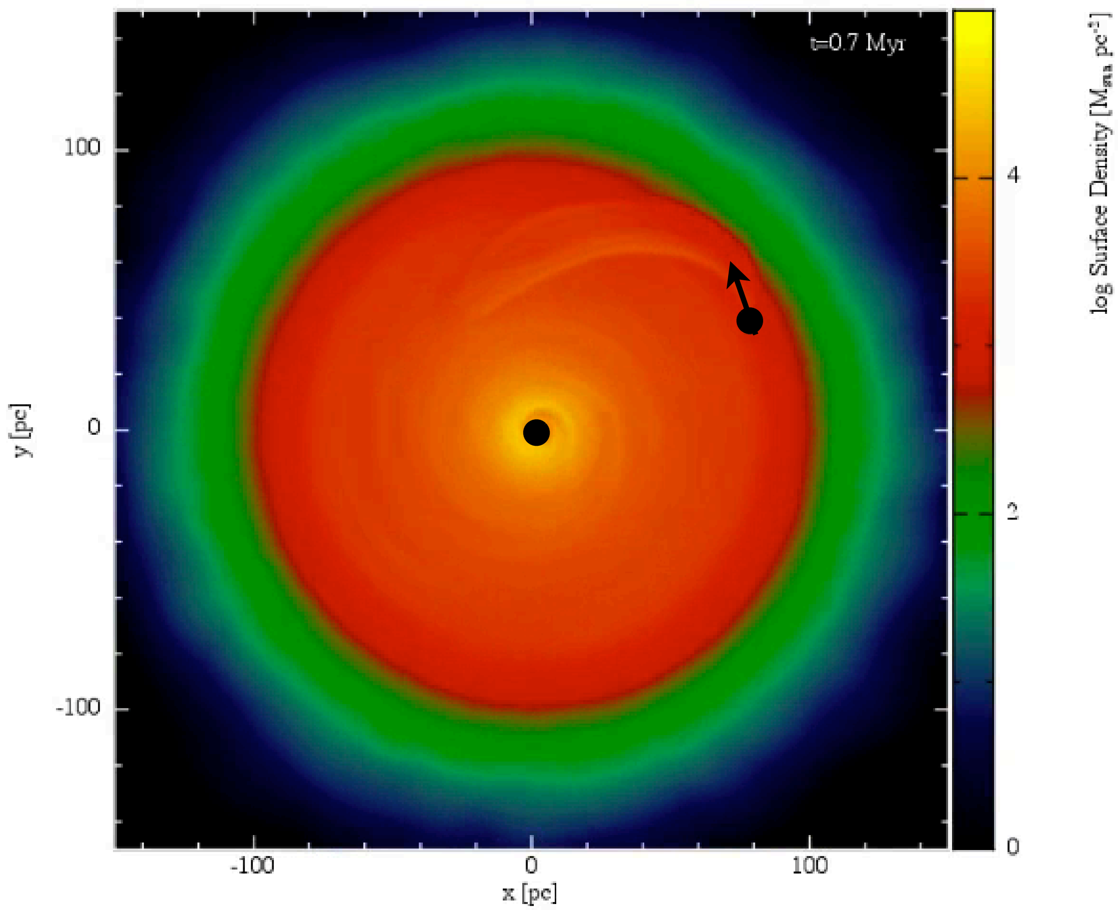
- THE ISM IS MULTI PHASE
- CIRCUM-NUCLEAR DISCS ARE UNSTABLE TO FRAGMENTATION- STAR FORMATION



.....FIACCONI's TALK

- black hole dynamics in massive circum-nuclear discs

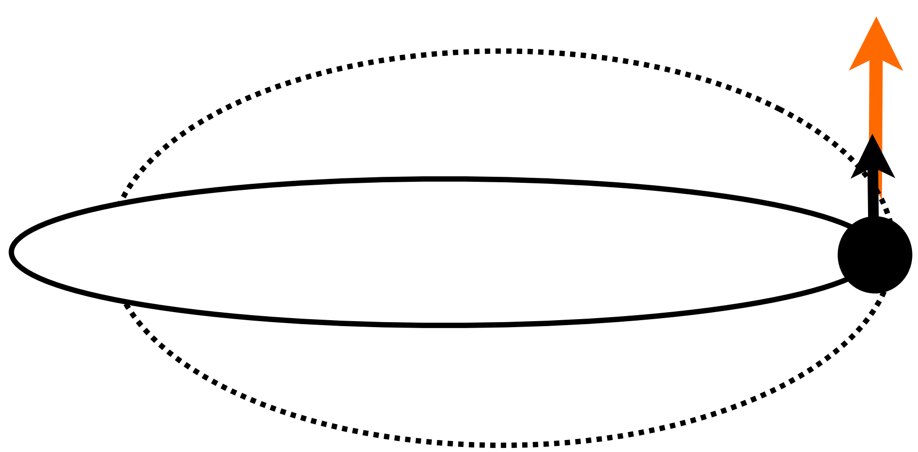
DEDICATED HIGH-RESOLUTION SIMULATIONS
OF THE BLACK HOLE EVOLUTION IN
ROTATIONALLY SUPPORTED NUCLEAR DISCS
MESTEL PROFILE

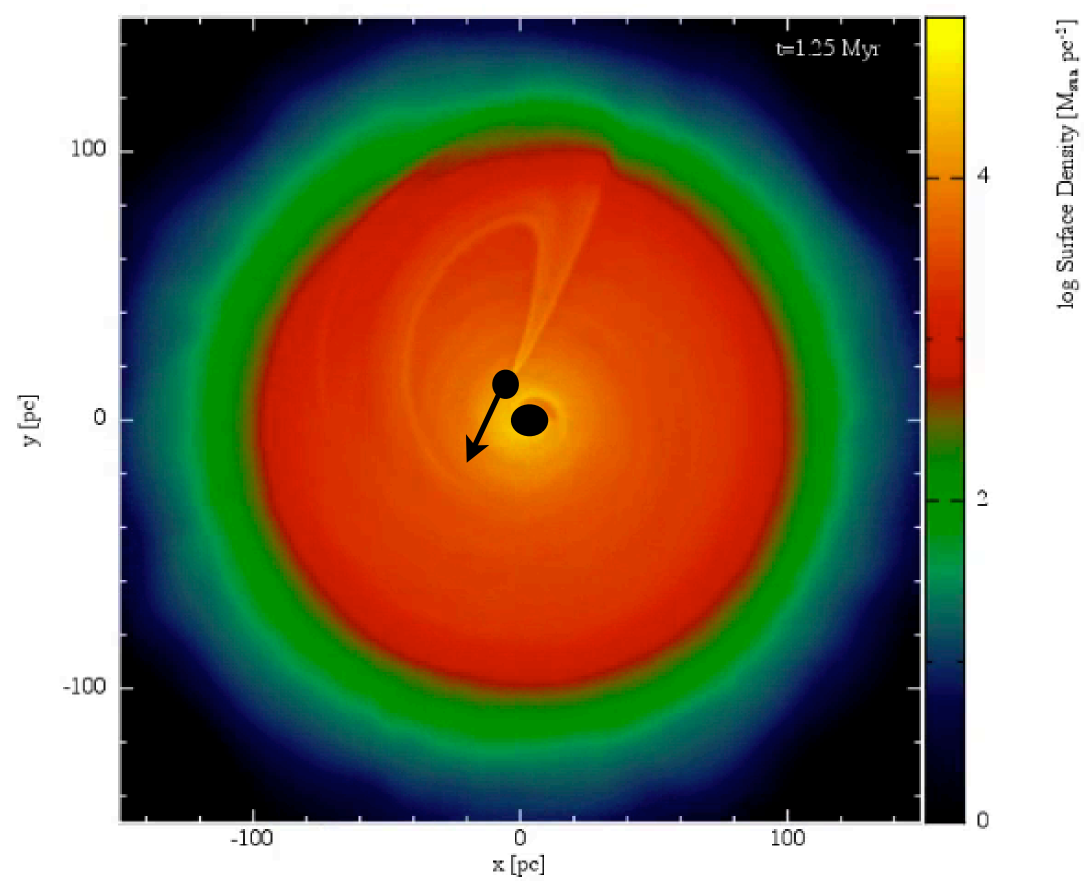


$M_{\rm disc} = 10^8\, M_\odot$ $\quad M_{\rm BH} = 10^6\, M_\odot$

THE ROTATING GASEOUS BACKGROUND FORCES THE SECONDARY BLACK HOLE TO **CO-ROTATE** WITH THE DISC
(even counter-rotating orbits get corotating)
MEMORY LOSS OF THE INITIAL ECCENTRICITY
the drag force is mostly acting at peri-center where the wake lags behinf

$$\dot{E}_{\rm bin}/E_{\rm bin} > \dot{J}_{\rm bin}/J_{\rm bin}$$

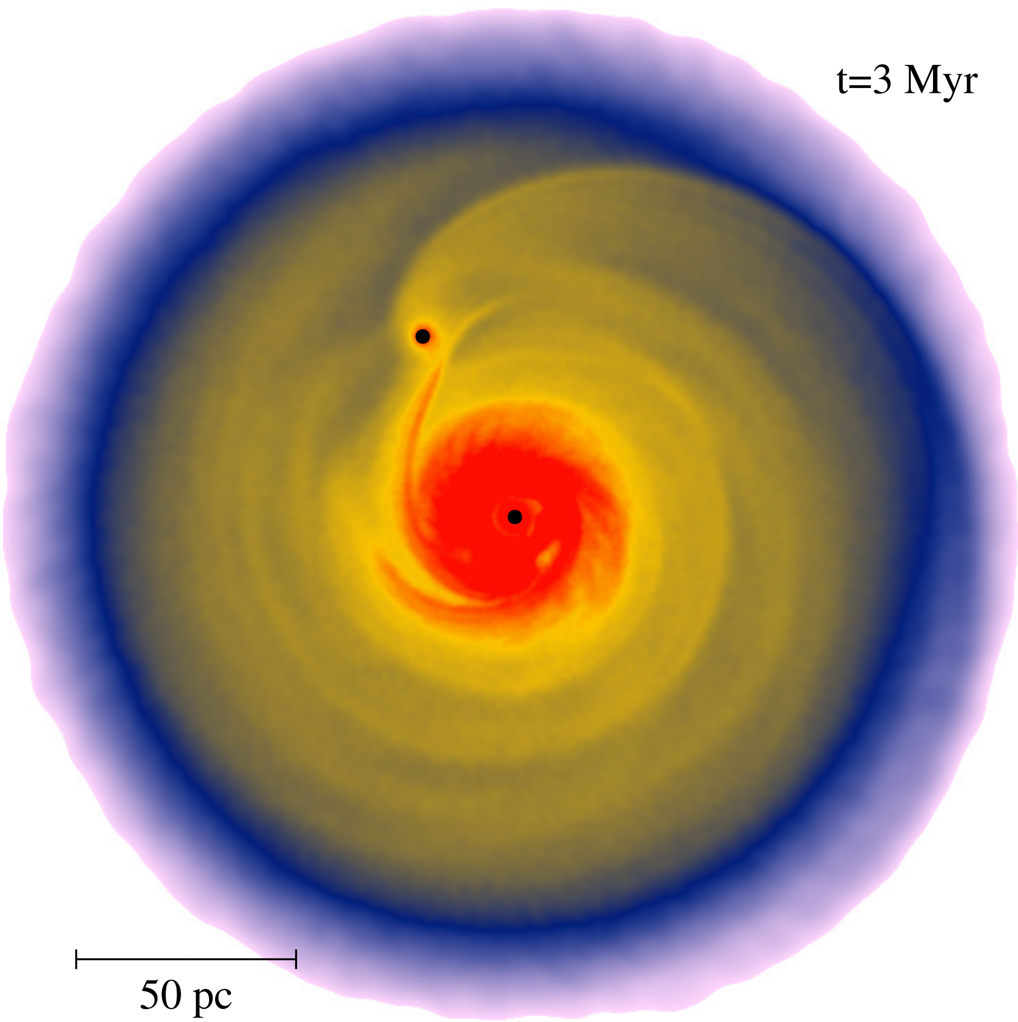




DOTTI et al. 2006,2007,2009a,b
PEREGO et al. 2009
COLPI & DOTTI, 2011
FIACCONI et a. 2013 SUBMITTED

after circularization
... torques on the secondary black hole
reminiscent Type I planet migration

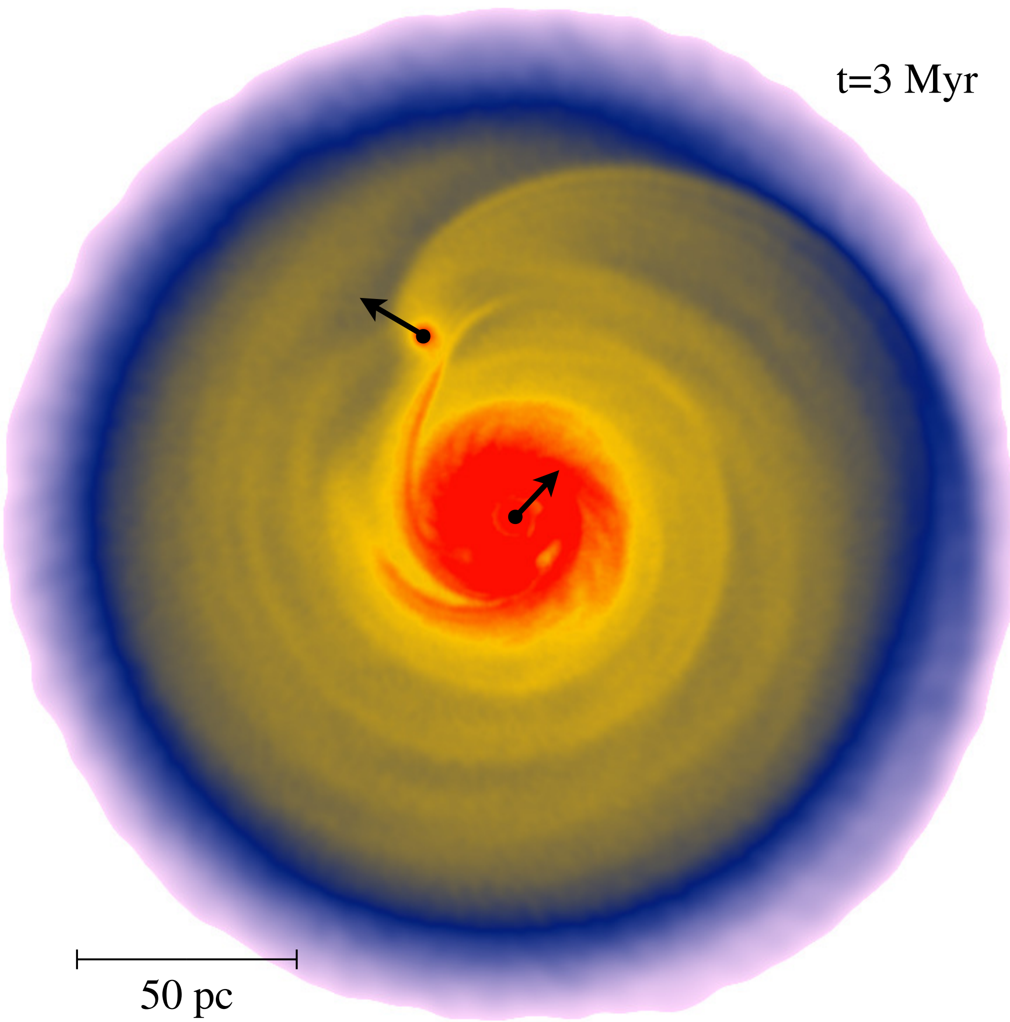
$$\frac{t_{\mathrm{migration}}}{t_{\mathrm{dyn-friction}}} \approx 2\pi \ln \Lambda \, h$$



$$M_{\mathrm{disc}} > M_{\mathrm{BH,2}}$$

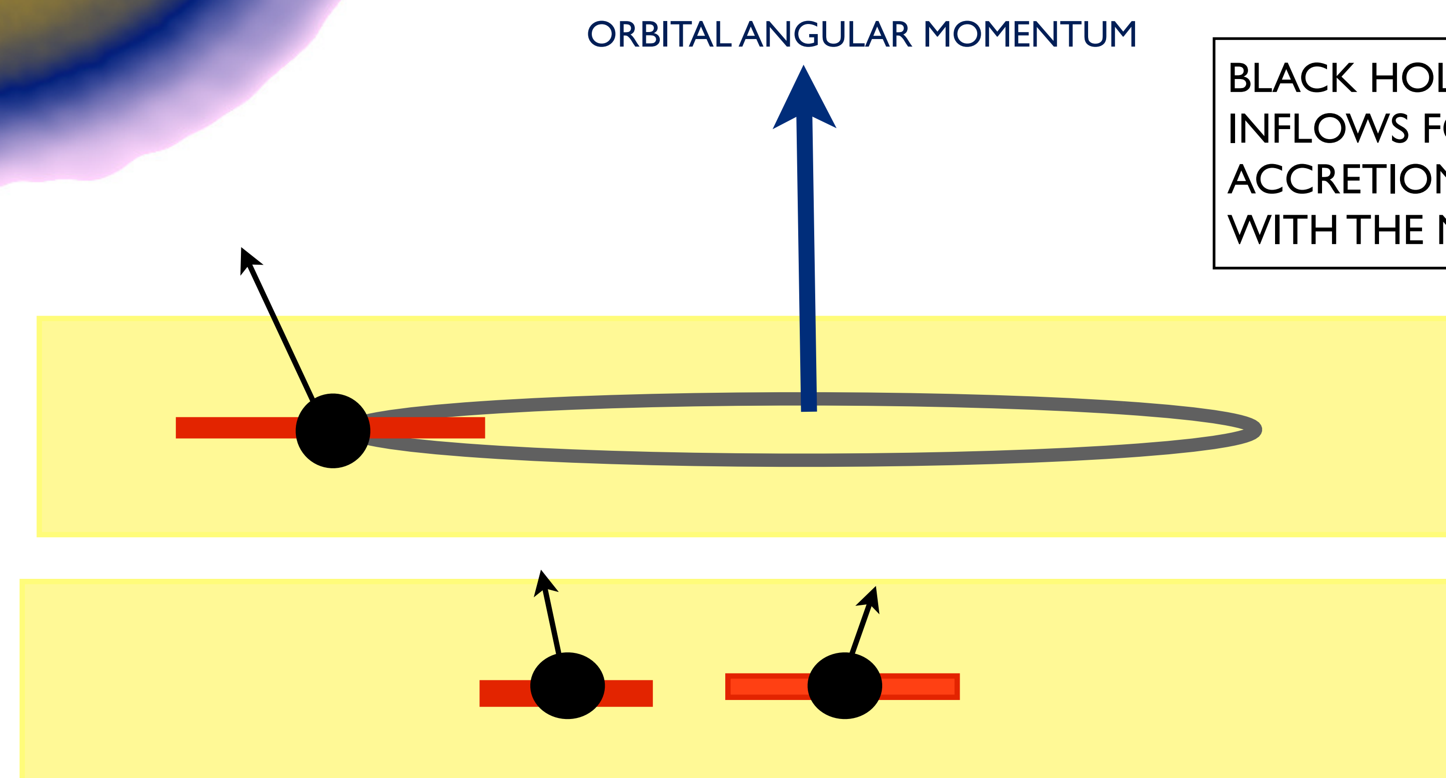
FIACCONI et al. 2013

MAYER, 2013arXiv1308.0431



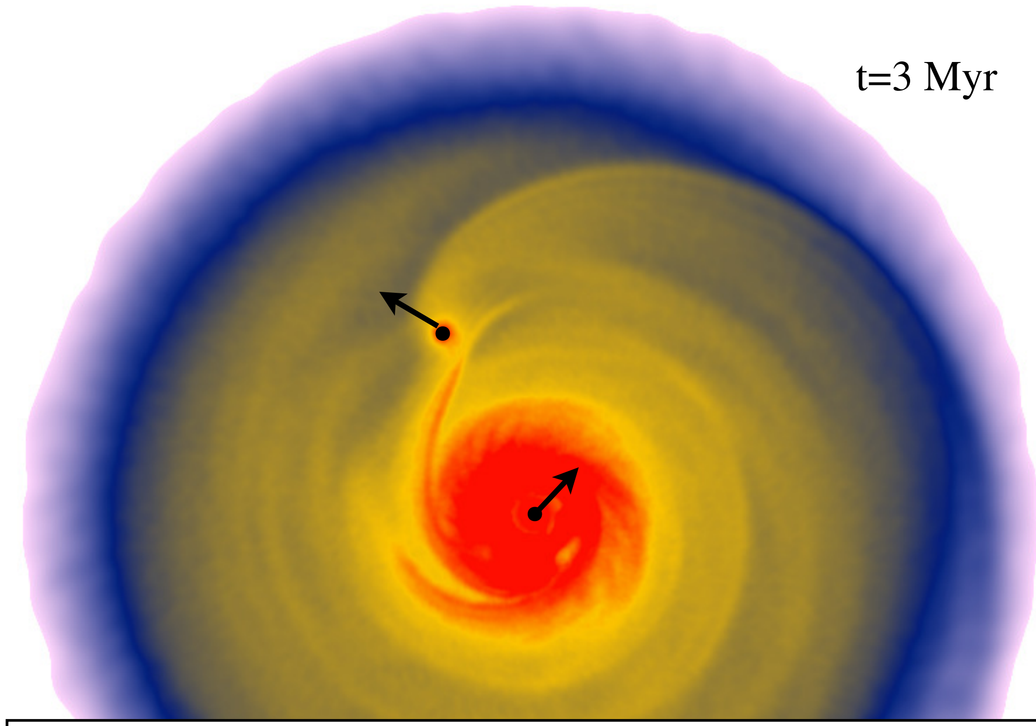
BLACK HOLE
SPIN - ORBIT ALIGNMENT
even before
BINARY FORMATION

$$\tau_{\rm al} \sim 10^5 \ a^{5/7} M_{\rm BH,6}^{-2/35} \alpha_{0.1}^{58/35} \left(\frac{f_{\rm E}}{\eta_{0.1}}\right)^{-32/35} \ \ \rm yr$$



BLACK HOLES ARE FED BY GAS INFLOWS FORMING ACCRETION DISCS COPLANAR WITH THE NUCLEAR DISC

BARDEEN 1970; BARDEEN & PETTERSON 1975; BOGDANOVIC et al. 2007; PEREGO et al. 2009; DOTTI et al. 2009, MILLER & KROLIK 2013

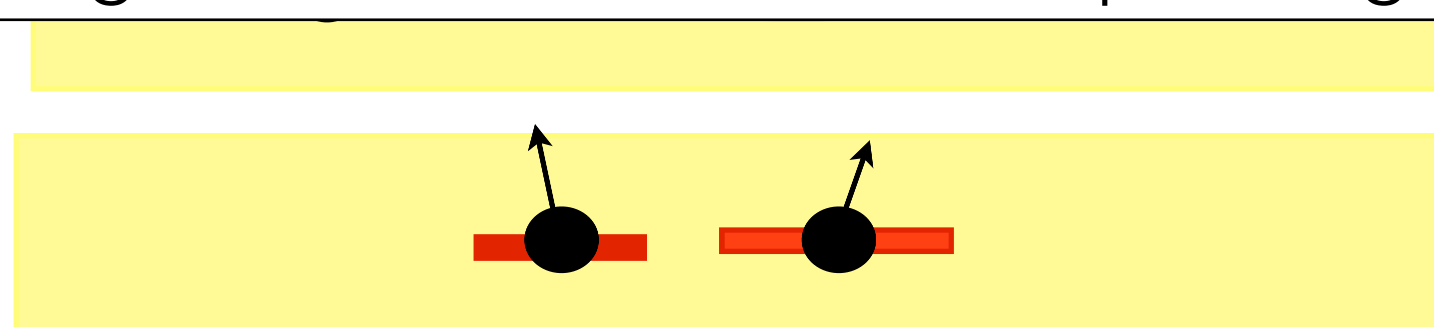


BLACK HOLE
SPIN - ORBIT ALIGNMENT
BEFORE BINARY FORMATION

if the spin configuration is maintained down to coalescence

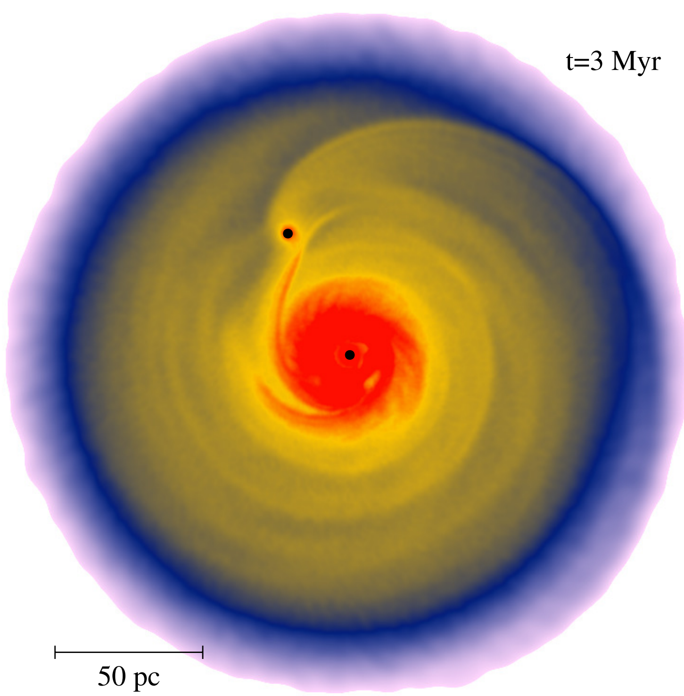
recoil velocities < 100 km/s

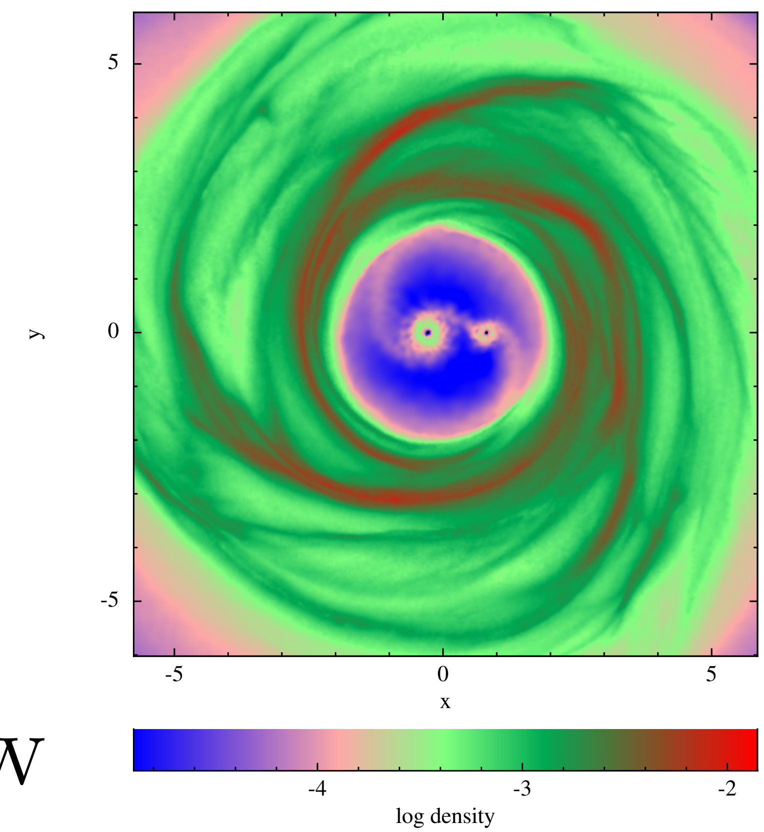
anchoring the new black hole to the parent galaxy



BARDEEN 1970; BARDEEN & PETTERSON 1975; BOGDANOVIC et al. 2007; PEREGO et al. 2009; DOTTI et al. 2009,2010, MILLER & KROLIK 2013
COLPI & DOTTI 2011 for a review

GAP FORMATION ?





$$a_{\rm gap} > a_{\rm GW}$$

$$t_{\rm migration}?$$

del VALLE & ESCALA 2013

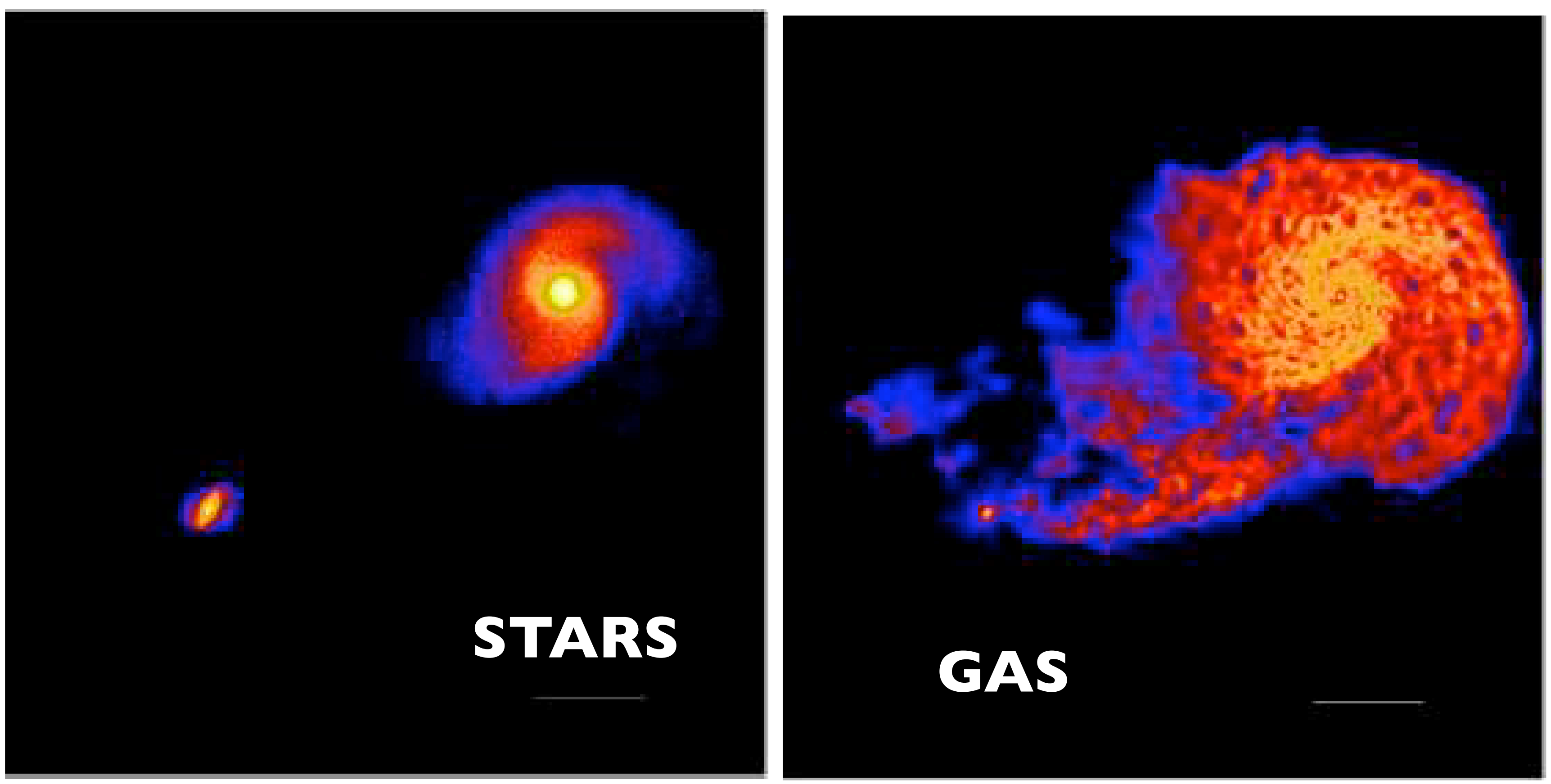
.... CUADRA's TALK

when and where the gap forms ?..... here are the most interesting observational signatures

IN DISSIPATIVE MERGERS

- rapid sinking of the black hole pair by dynamical friction and type I migration against the gas
- multi phase medium ...
- circularization of the orbit
- accretion - spin orbit alignment
- migration in circumbinary disc
- competitive shrinking from stellar interactions

- black hole dynamics in unequal mass merger (1:4, 1:10)



SINKING OF DARK MATTER SATELLITES IN LARGER DRAK MATTER HALOS
NFW

$$\frac{t_{\rm merging}}{t_{\rm dyn}}\Big|_{\rm vir} \approx \frac{\Theta({\rm orbit})}{\ln(1+M_{\rm host}/M_{\rm sat})}\,\frac{M_{\rm host}}{M_{\rm sat}}$$

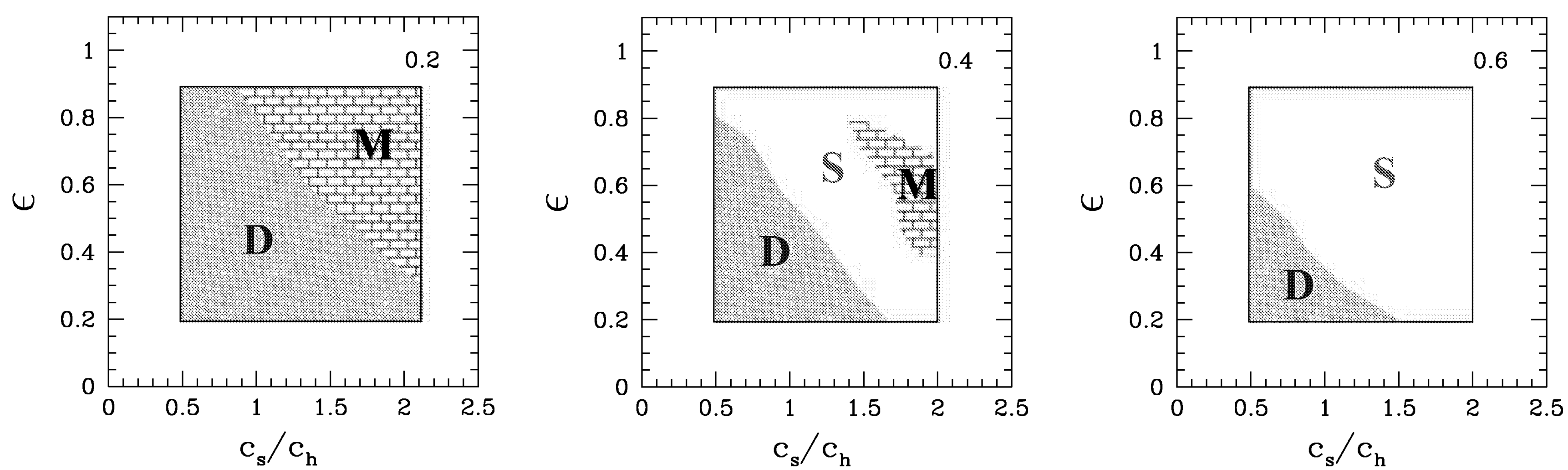
live satellites

$$\Theta({\rm orbit}) = \Theta(E, \varepsilon, c)$$

orbital energy

circularity

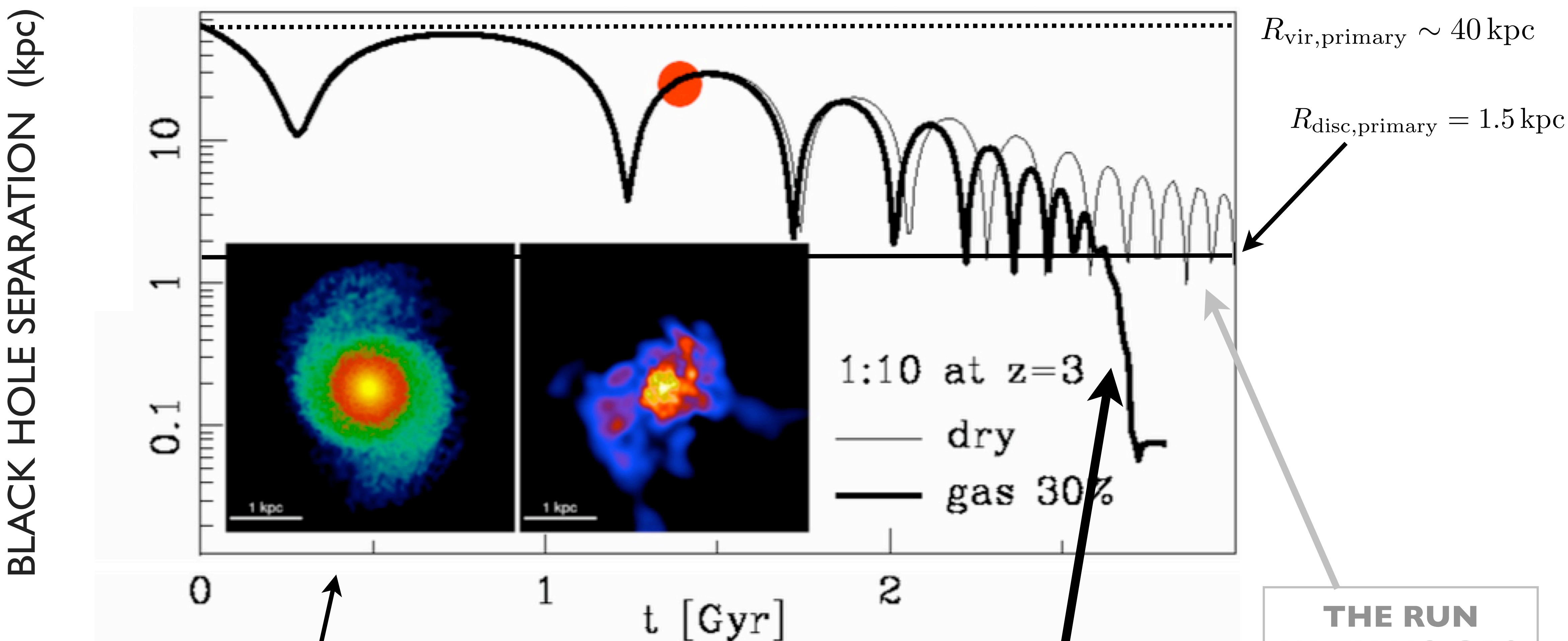
relative concentration (s/h)



GOVERNATO, COLPI MARASCHI 1994, COLPI, MAYER GOVERANTO 2000, TAFFONI et al. 2002, BOYLAN-KOLCHIN 2008

BLACK HOLE PAIRING ?

30% GAS-RICH COPLANAR PROGRADE PARABOLIC ENCOUNTER

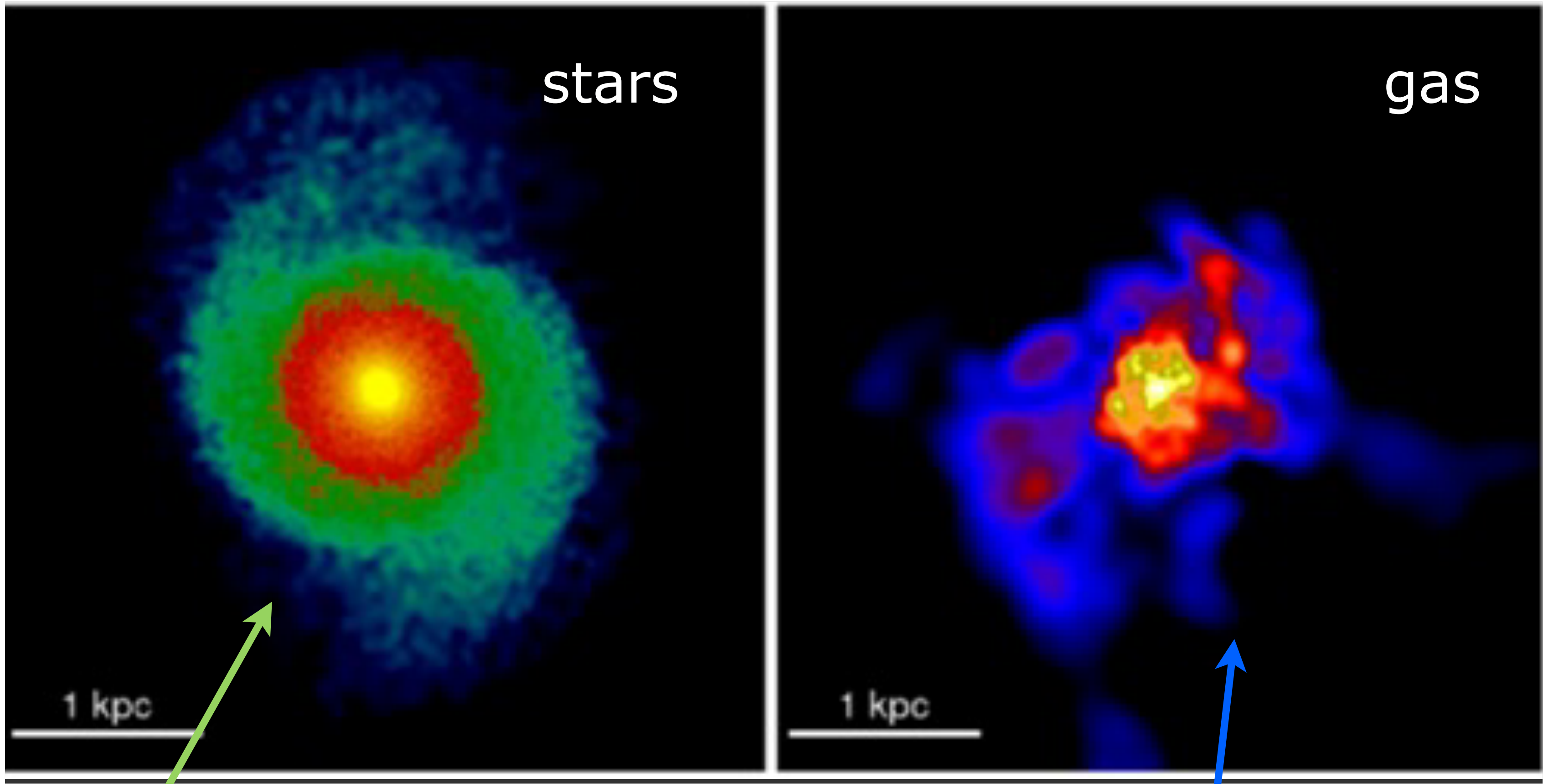


THE BLACK HOLE IS AT TH CENTER OF THE COMPACT CORE

THE RUN WITH NO GAS WANDERING BLACK HOLE

IN GAS-RICH ENVIRONMENT **THE SECONDARY BLACK HOLE REACHES A SEPARATION OF 100 pc**

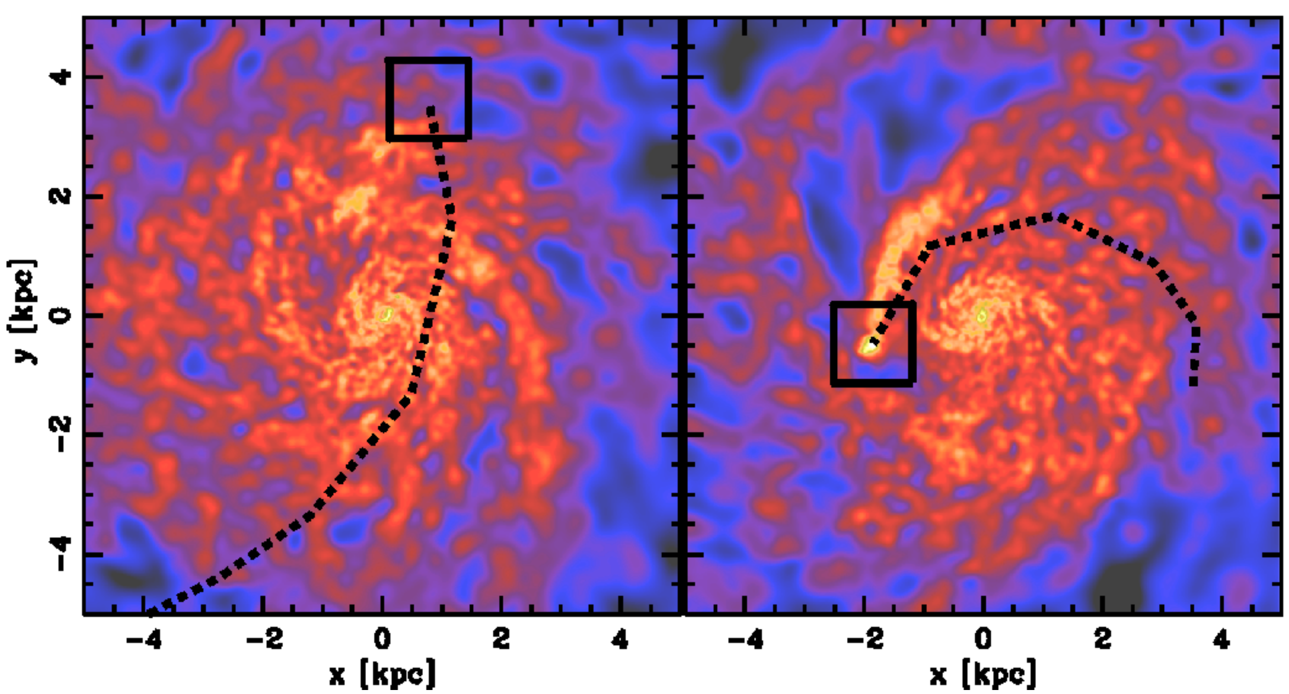
IMAGE @ II PERI-GALACTIC APPROACH



CONCENTRATED STAR FORMATION EPISODE DUE TO INFLOWS BY COMPRESSIVE TIDES

THE **GALACTIC DISC** DEVELOPS A CLUMPY IRREGULAR STRUCTURE
MOST OF THIS GAS WILL BE RAM-PRESSURE STRIPPED WHEN PLUNGING INTO THE DISC OF THE PRIMARY GALAXY

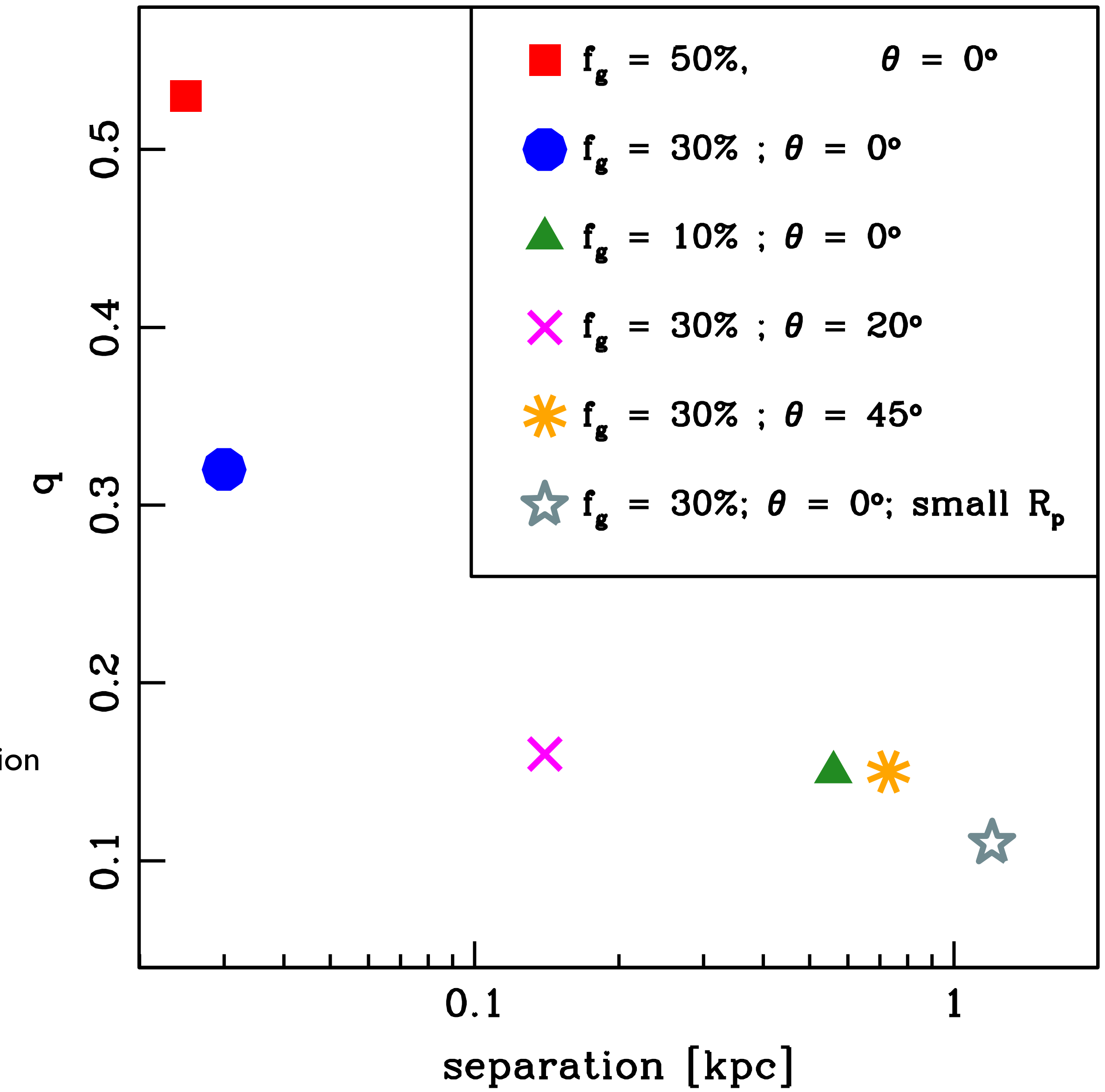
ACCRETION FOLLOWING THE
CIRCULARIZATION
OF THE BLACK HOLE ORBIT



$$\dot{M}_{\rm BHL} \sim 4\pi \frac{G^2 M_{\rm BH}^2(t)\rho_{\rm gas}(t)}{[c_{\rm sound}^2(t) + V_{\rm rel}^2(t)]^{3/2}}$$

correlating
PAIRING versus BLACK HOLE MASS RATIO

$$\left.\frac{M_{\rm BH,2}}{M_{\rm BH,1}}\right|_{\text{end of the simulation}}$$



@ end of the simulation

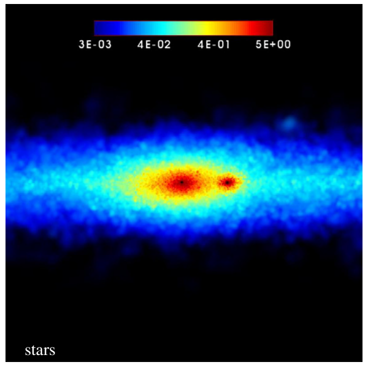
the ability of pairing depends on the strength of torques in creating a dense cuspy stellar core around the secondary black hole
+
accretion

BARYONIC PHYSICS + COSMOLOGICAL ORBITAL PARAMETERS
DETERMINE THE OUTCOME OF A MERGER

BOTTLENECK
minor mergers

- the bottleneck is in the pairing phase
- baryonic physics + cosmological parameters determine the outcome of the merger
- existence of a limiting q (0.1) below which coalescence is aborted or delayed

KHAN et al. 2012a,b



after 30 years...

there has been a number of advances

all studies have enriched the question
on whether stars or/and gas disc
in more realistic environments alleviate the last parsec problem
still knowledge is fragmented and incomplete
having explored a relatively small
parameter space

WISHFUL LIST FOR FURTHER PROGRESS

(I) GALAXIES WITH IMPROVED PHYSICS AND IMPROVED MODELING OF THE GAS THERMODYNAMICS

(II) STUDY THE DYNAMICS DURING STRUCTURE FORMATION AT LARGE REDSHIFT

(III) CLOSER INSPECTION OF THE GAP OPENING CONDITIONS