THE PATH TO COALESCENCE OF MASSIVE BLACK HOLE PAIRS IN MERGING GALAXIES

LISA science

Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results

MONICA COLPI
Department of Physics G. Occhialini,
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GRAMPA

PARIS: 1 September 2016

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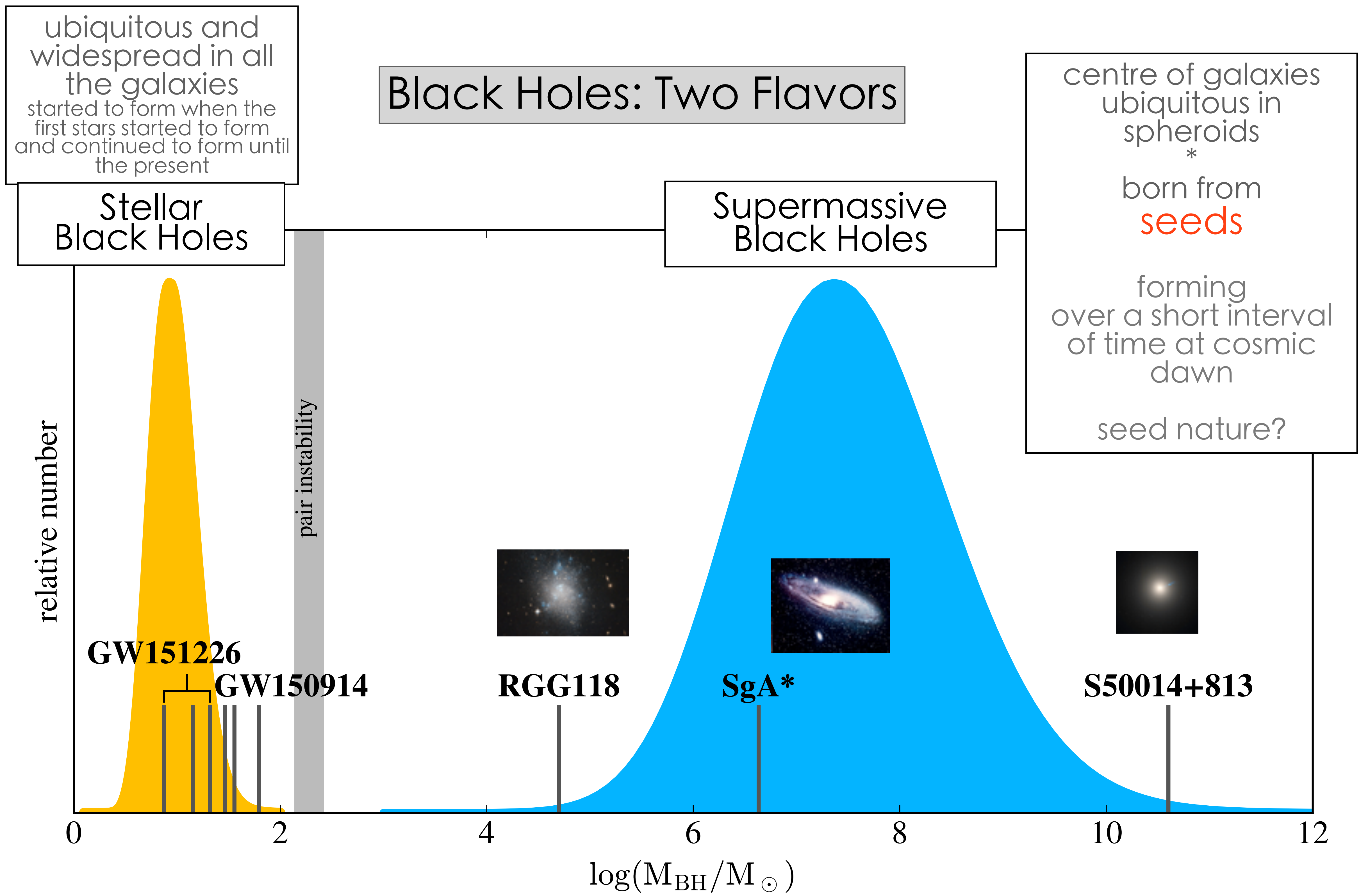
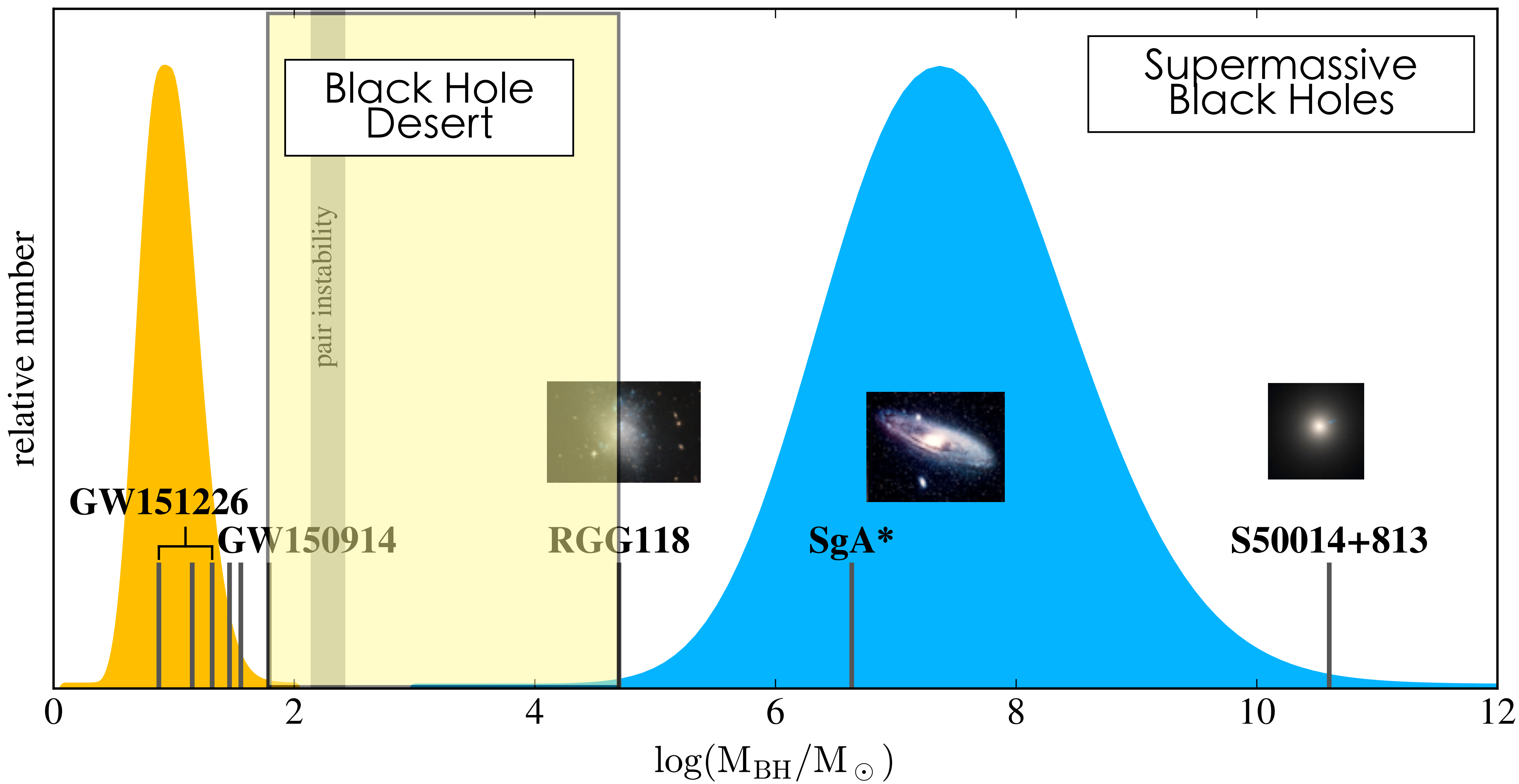


Tuesday, August 30, 16

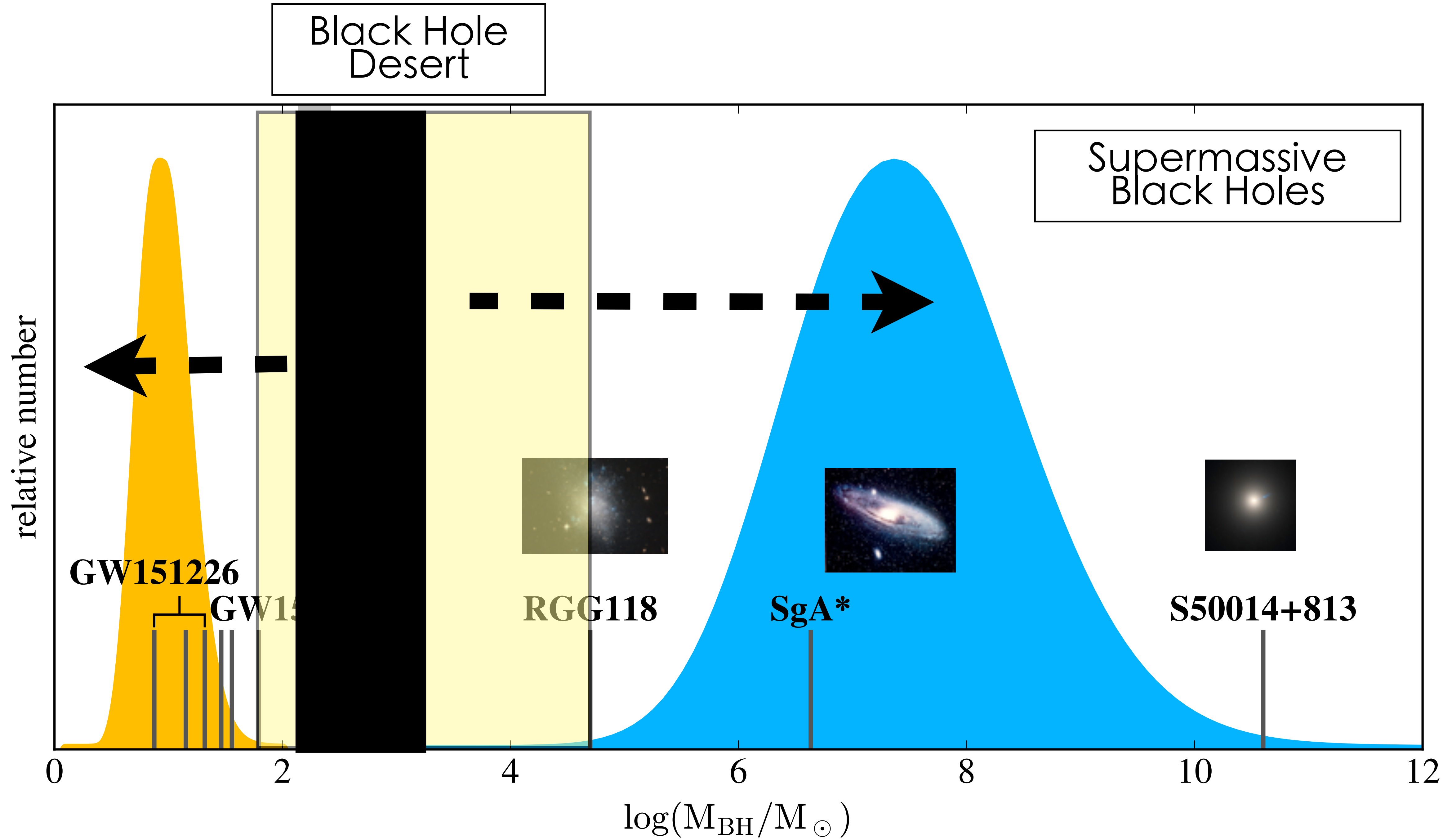
THE BLACK HOLE DESERT

- is the desert inhabited by black holes which we still do not detect?



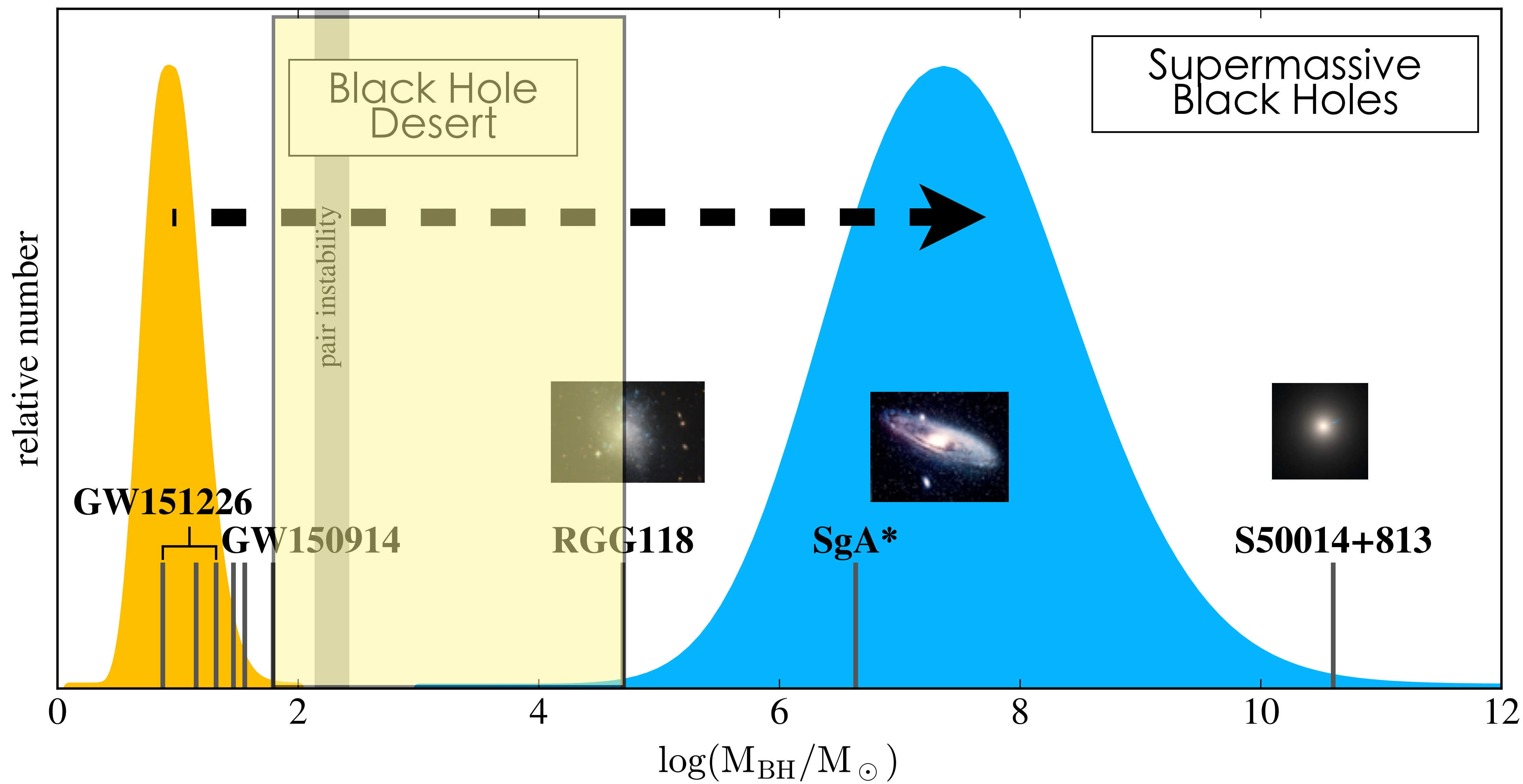
THE BLACK HOLE DESERT

- is there a genetic divide?
- is the desert consequent to the "migration" of seeds into the domain of the giants?



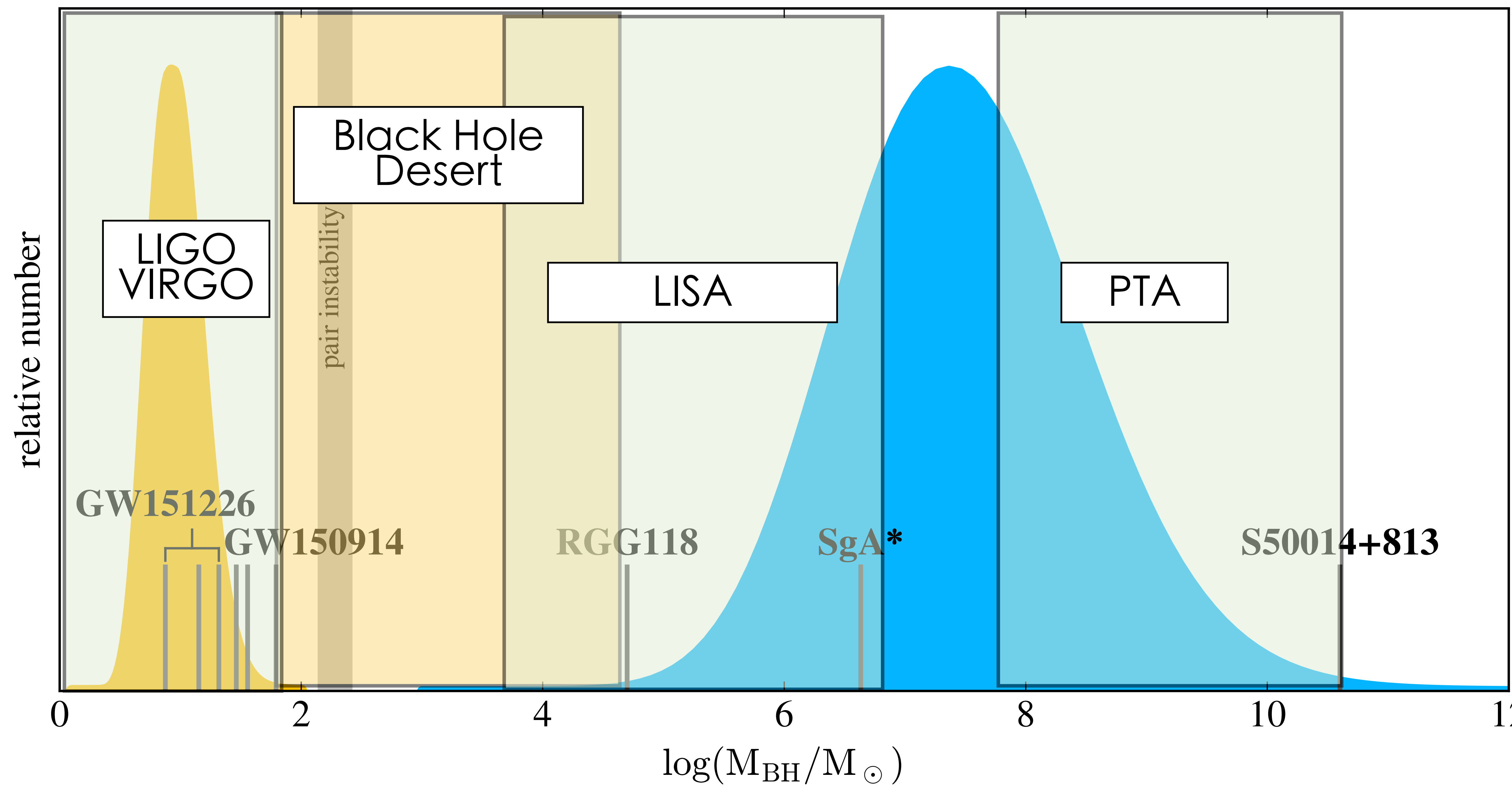
THE BLACK HOLE DESERT

- is the desert populated by transition objects, resulting from the clustering/aggregation/accretion of stellar objects viewed as single building blocks?

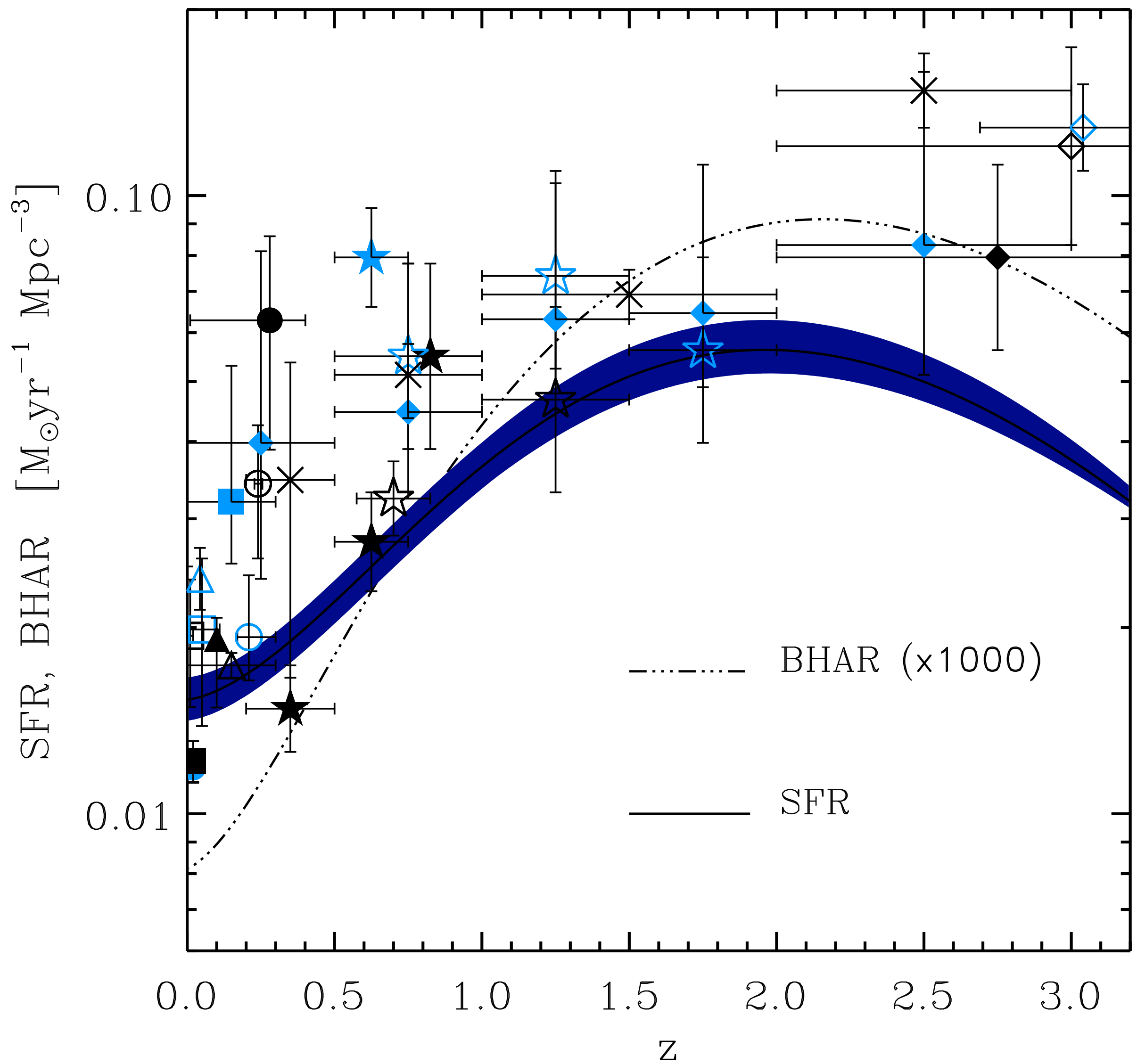


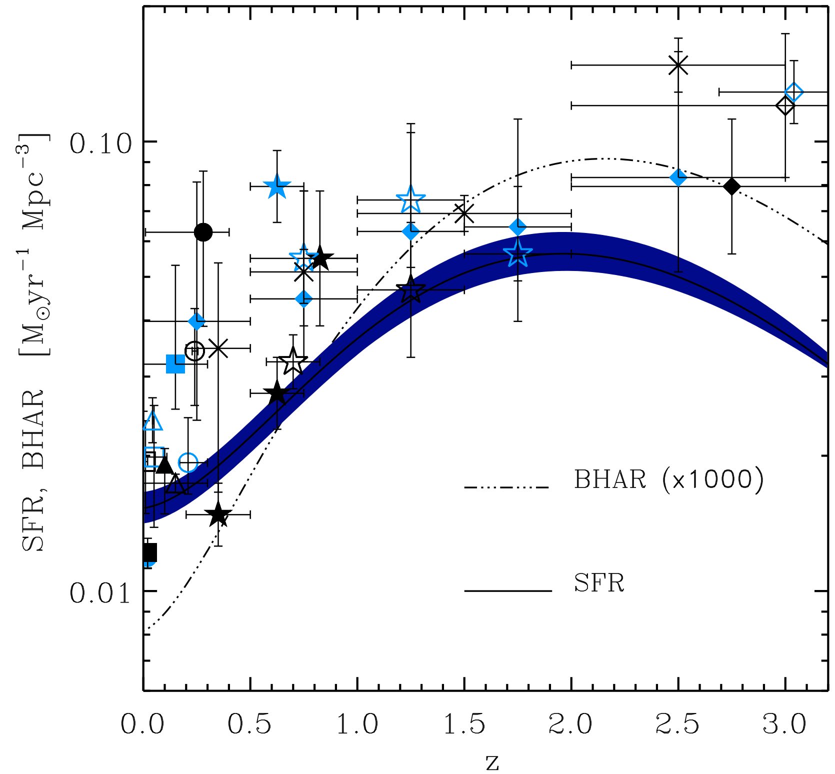
the gravitational universe

a universe of binary black holes



cosmic high noon
peak of star formation
and AGN activity





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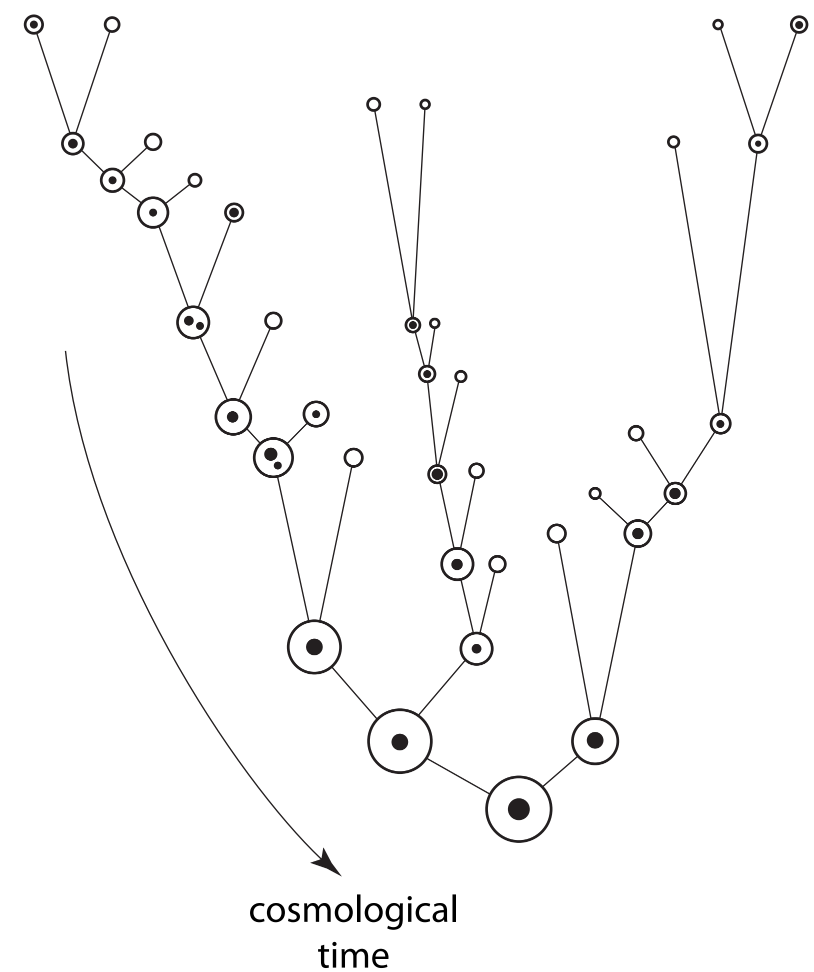
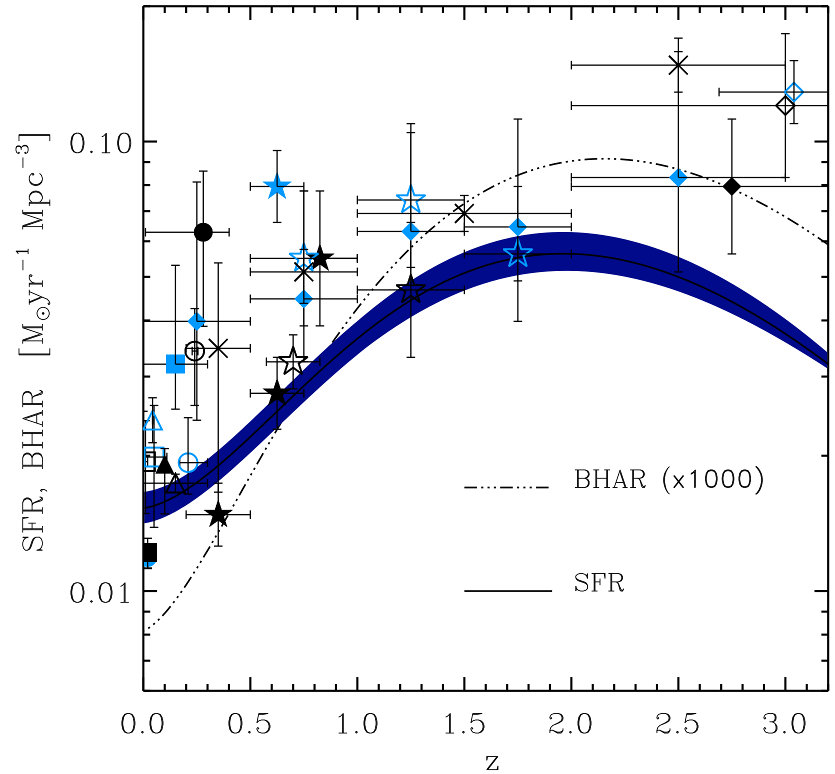


Courtesy of Marta



cosmic high noon
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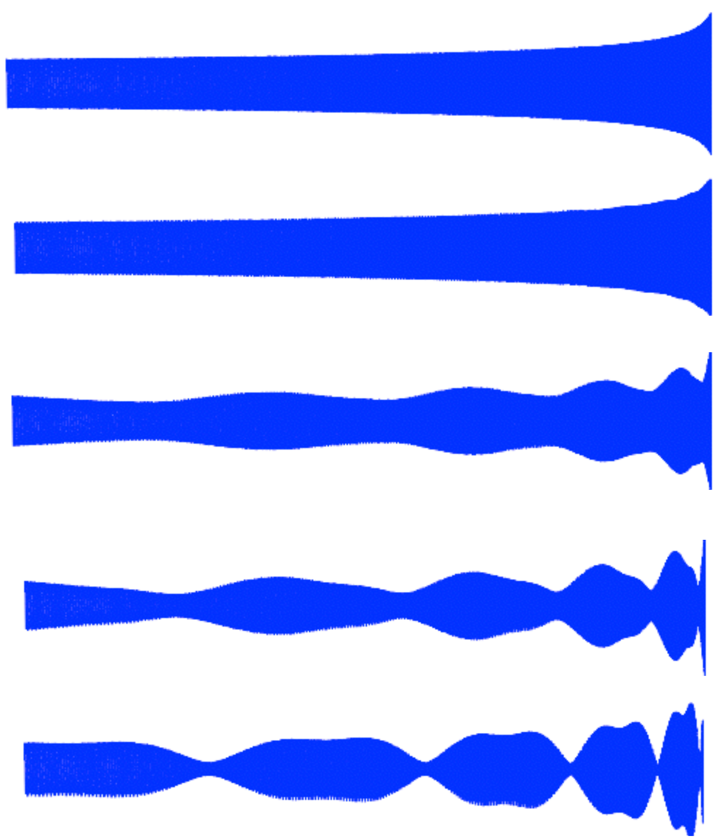
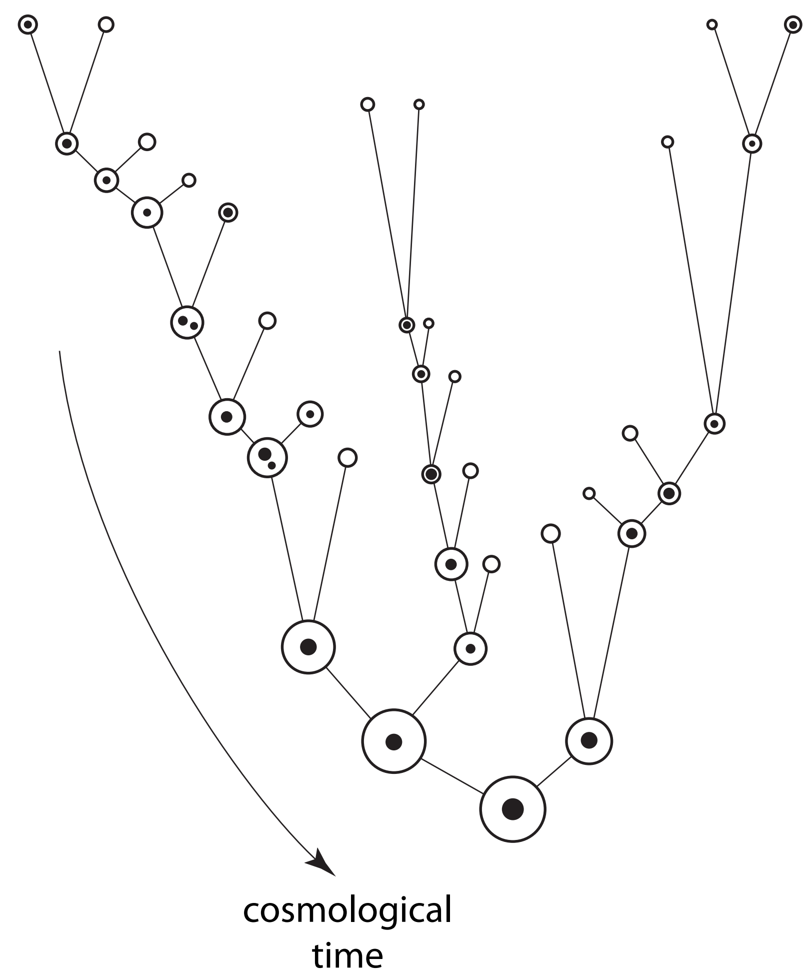
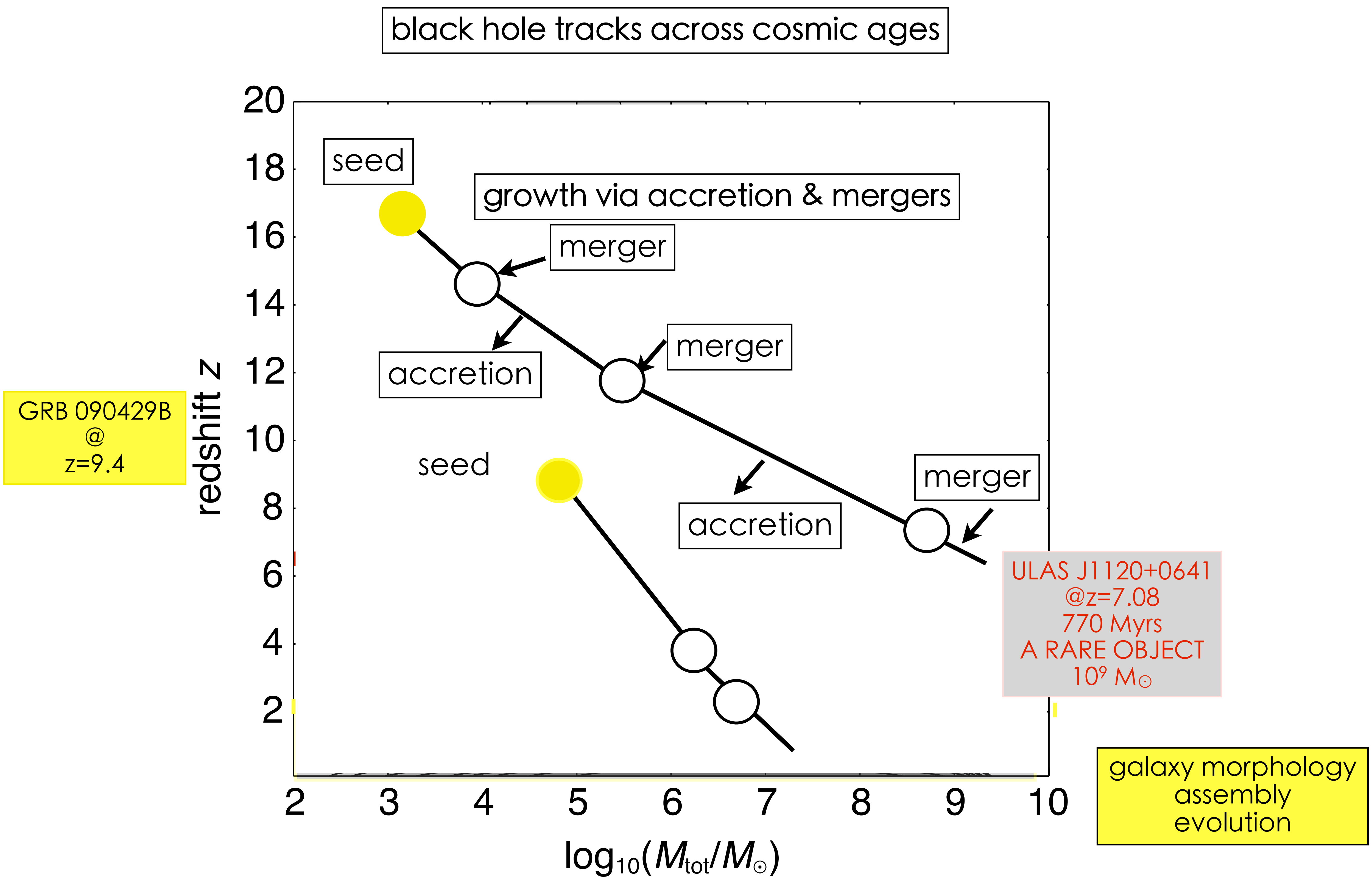
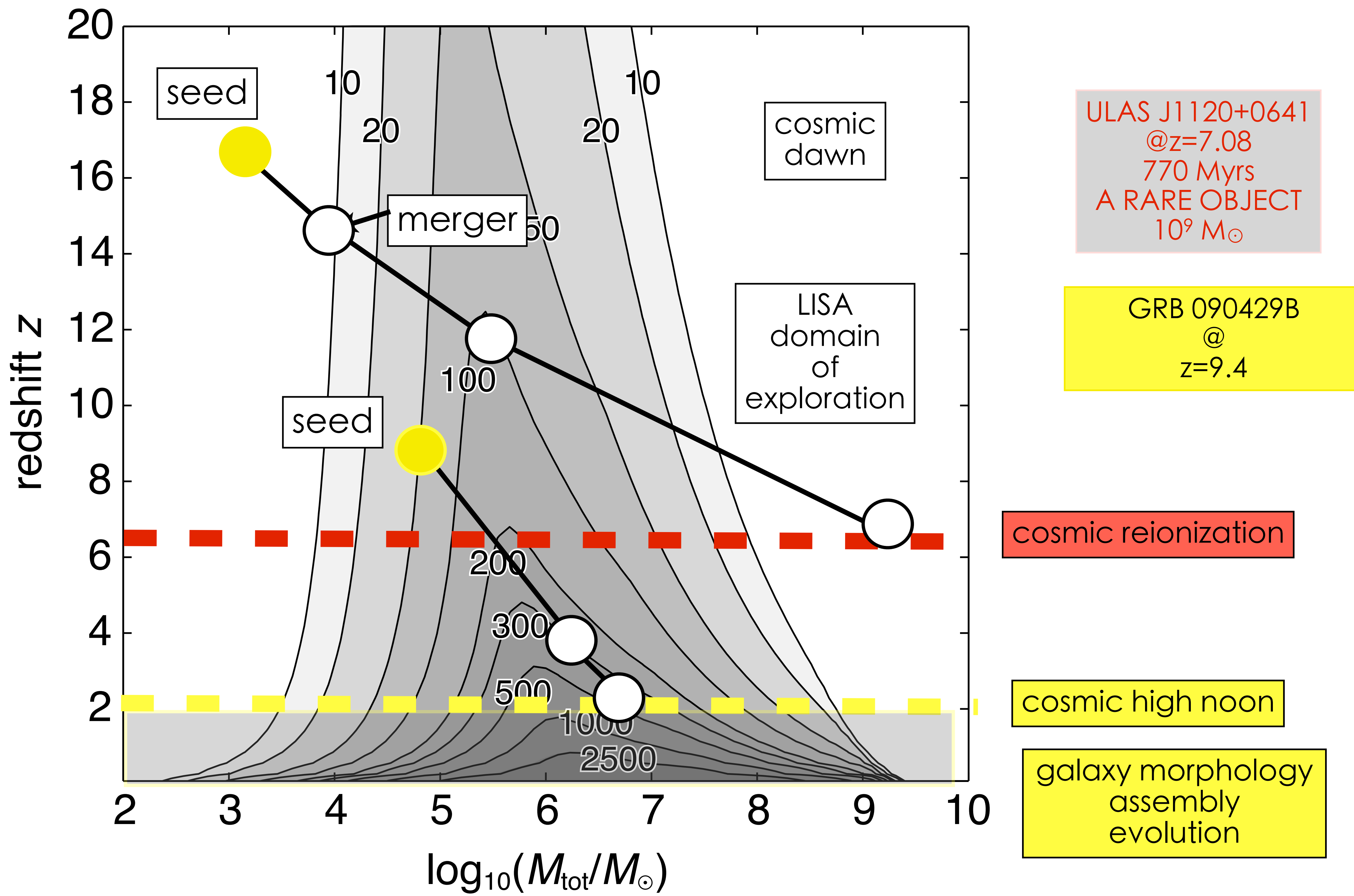


deep
connection
black holes
&
galaxies
racked over
a wide range
of redshift

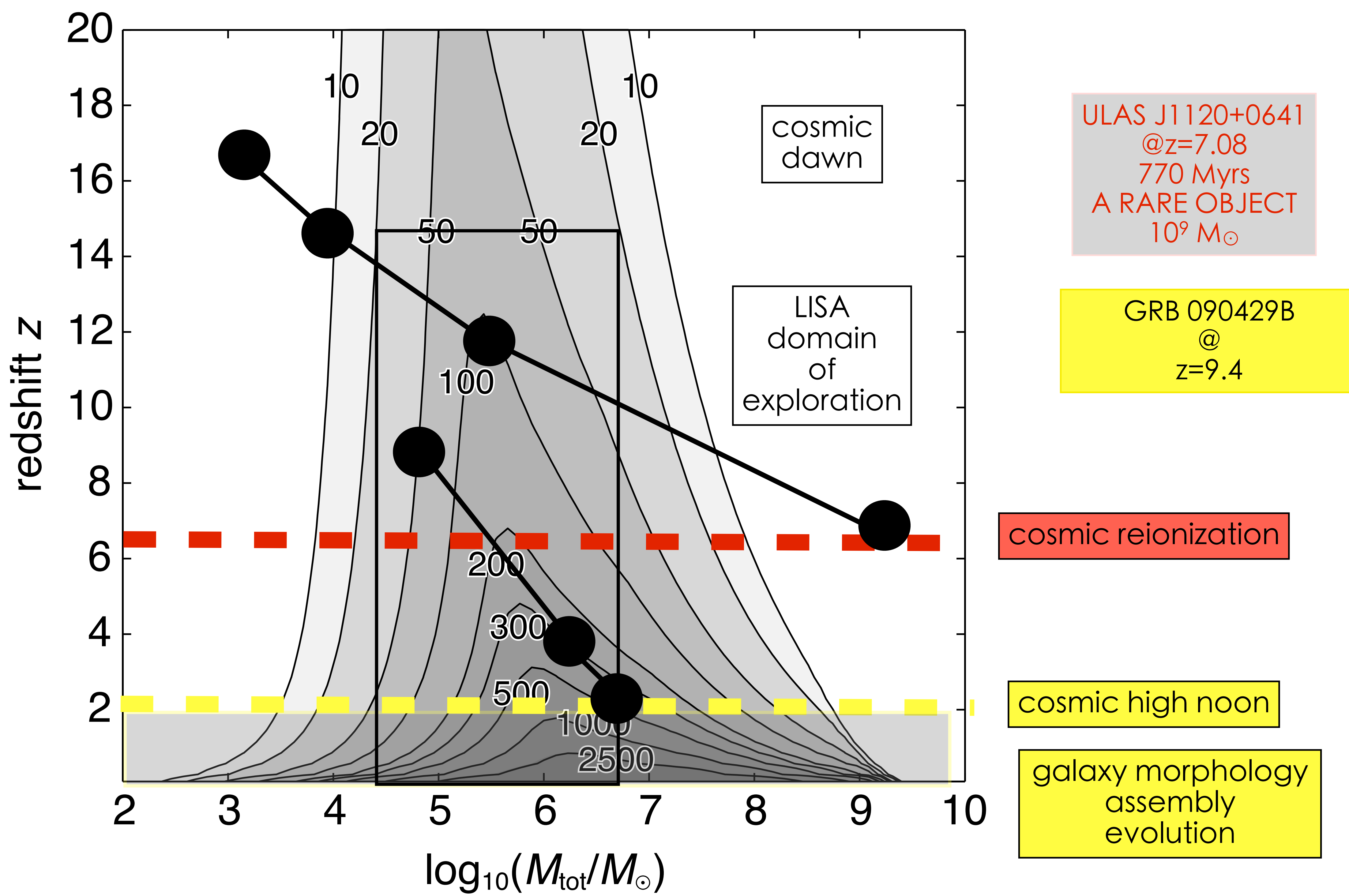



black hole tracks across cosmic ages
seed
growth via accretion & mergers
merger
accretion
merger
merger
accretion
seed
GRB 090429B
@
z=9.4
ULAS J1120+0641
@z=7.08
770 Myrs
A RARE OBJECT
10⁹ M☉
galaxy morphology
assembly
evolution
redshift z
log10(Mtot/M☉)
20
18
16
14
12
10
8
6
4
2
2
3
4
5
6
7
8
9
10

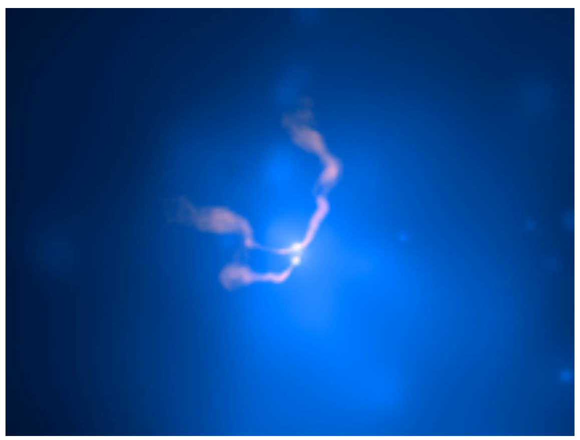
LISA BLACK HOLES
THE ONLY PROBES OF SEEDS IN THE HIGH REDSHIFT UNIVERSE



peering deep into the epoch of cosmic dawn & high noon

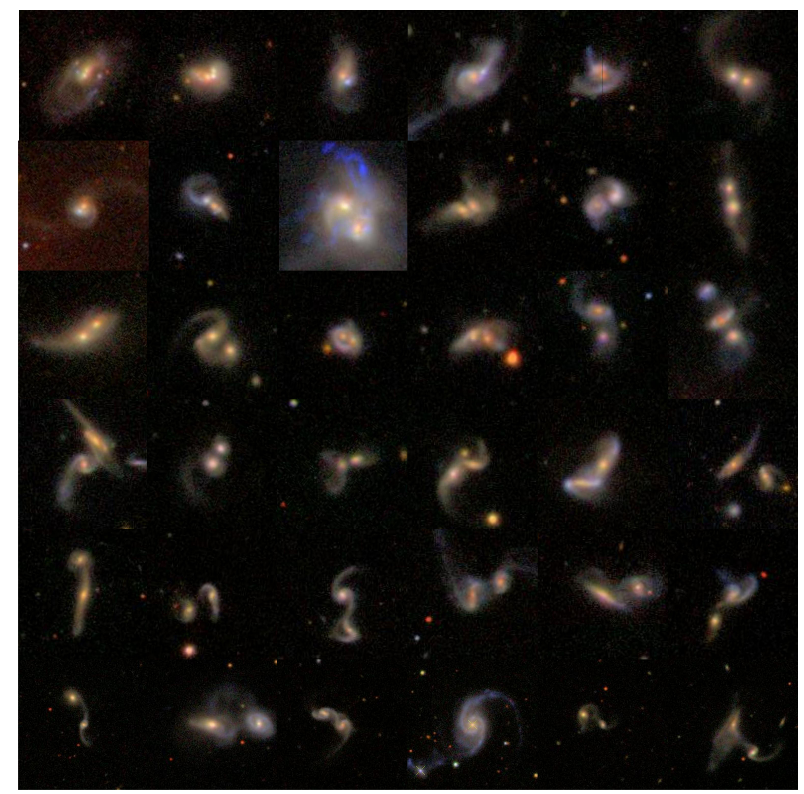


- do we have EM evidence of binary black holes to anchor our modeling of GW sources?

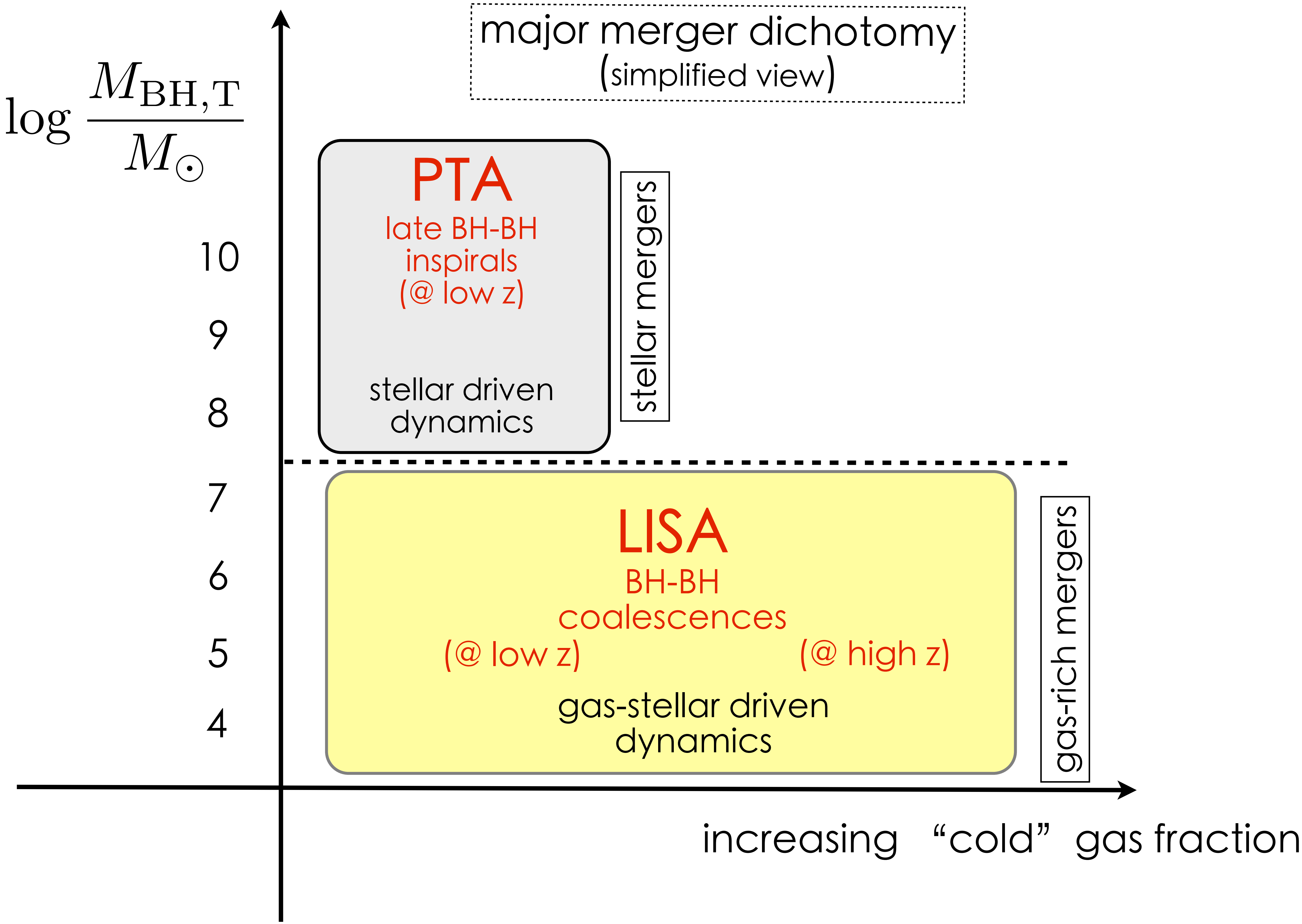


3C75

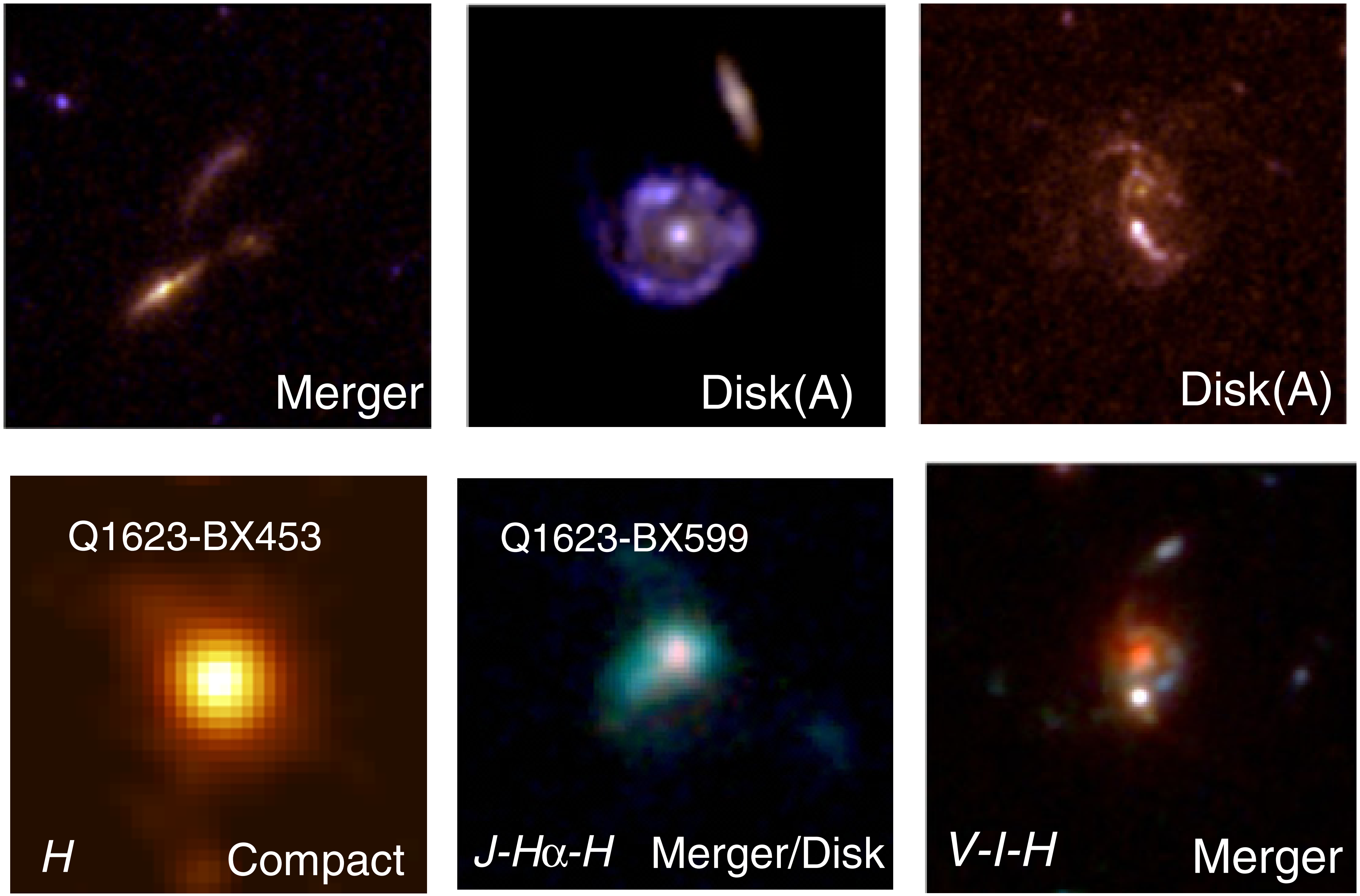
NGC6240



inventory of nearby interacting galaxies

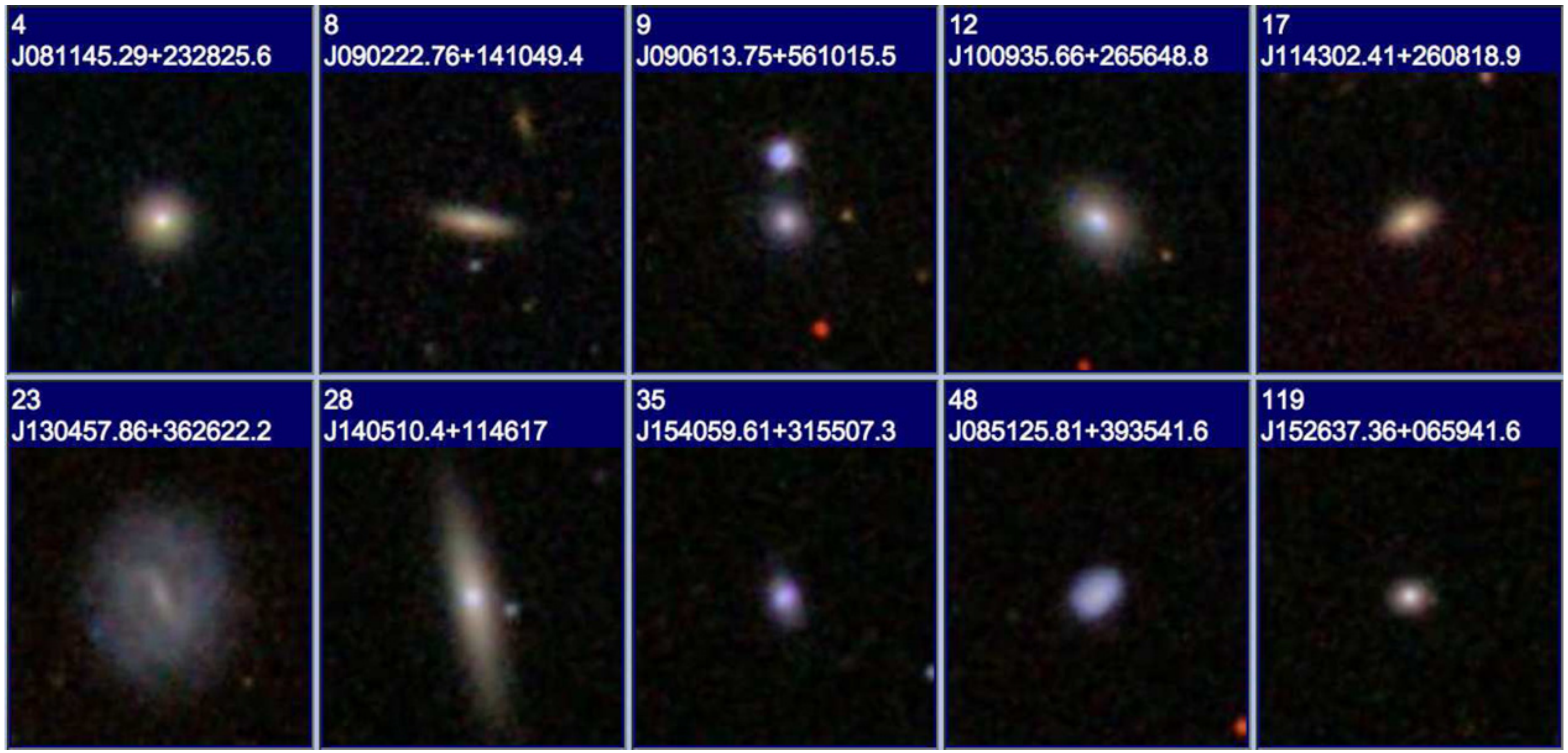

major merger dichotomy
(simplified view)
$\log \frac{M_{\rm BH,T}}{M_\odot}$
10
9
8
7
6
5
4
PTA
late BH-BH
inspirals
(@ low z)
stellar driven
dynamics
stellar mergers
LISA
BH-BH
coalescences
(@ low z)
(@ high z)
gas-stellar driven
dynamics
gas-rich mergers
increasing "cold" gas fraction

TACCONI+ 2013



- HST images of main sequence star forming galaxies @ z=1-2 - CO3 -2 survey - with high fraction of molecular gas 0.3-0.5 (0.08 for SFG @ z=0)
- (70%) rotationally supported massive discs + (20%)mergers

DWARF GALAXIES with OPTICAL SIGNATURES OF
ACTIVE "LISA" BLACK HOLES

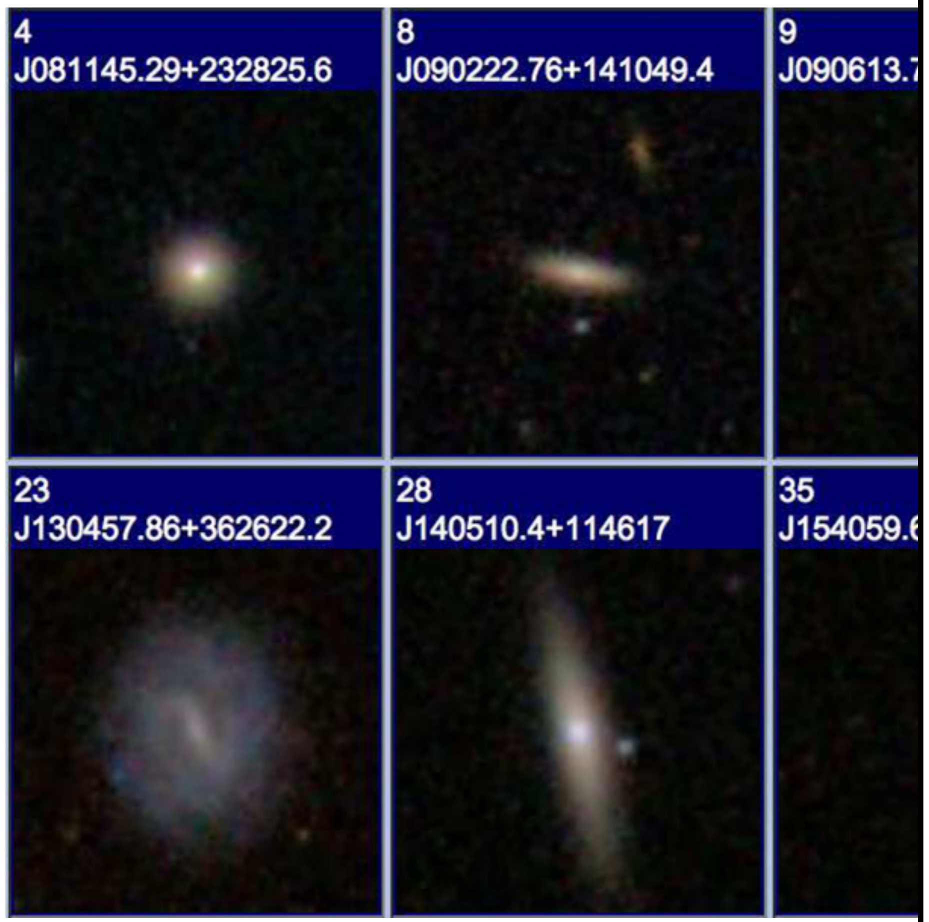


8.5<log M*<9.5 @ z<0.055 with a variety of Sersic indexes

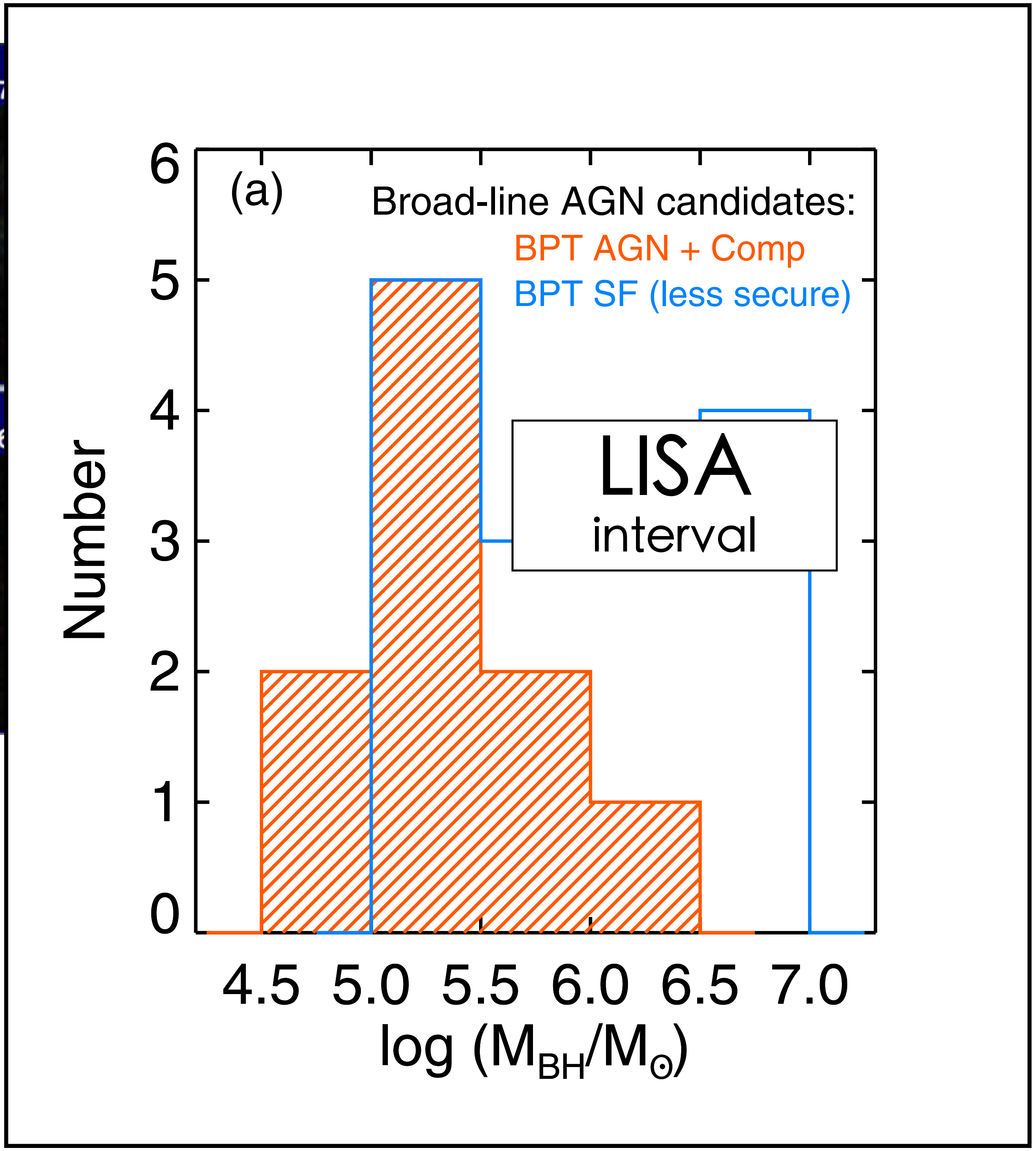
dwarf as light as the Magellanic clouds host "nuclear black holes"
are they representing the z=0 replica of
the mini-halos forming at cosmic dawn?

REINES, GREENE, GEHA 2013

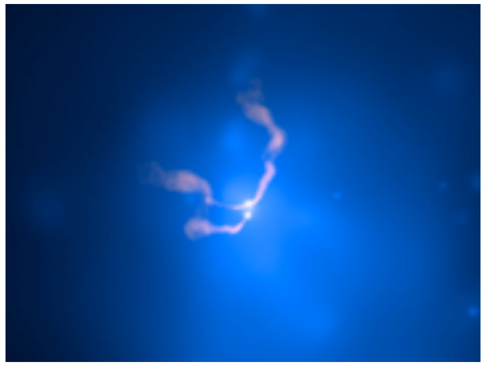
DWARF GALAXIES with OPTICAL SIGNATURES OF ACTIVE MASSIVE BLACK HOLES



REINES, GREENE, GEHA 2013



5<log M(BH)<6



- will the black holes in these interacting galaxies (of many diverse morphologies) descend over time into a common orbit and coalesce shortly after or is there a delay?
- are there preferred site for rapid coalescence?

MC 2014, review

THE GRAVITATIONAL WAVE DOMAIN

$$t_{\rm GW} = \frac{5}{256 f(e)} \frac{c^5}{G^3} \frac{a_{\rm GW}^4}{\nu M_{\rm BH,T}^3}$$

$$\nu = \mu / M_{\rm BH,T}$$

$$a_{\rm GW} \sim 10^{-3} f(e)^{1/4} \nu^{1/4} \left(\frac{M_{\rm BH,T}}{10^6 {\rm M}_\odot} \right)^{3/4} \left(\frac{t_{\rm GW}}{1\,{\rm Gyr}} \right)^{1/4} \ {\rm pc}$$

$$\frac{a_{\rm GW}}{(G M_{\rm BH,T}/c^2)} \sim 4000 f(e)^{1/4} \nu^{1/4} \left(\frac{t_{\rm GW}}{1\,{\rm Gyr}} \frac{10^6\,M_\odot}{M_{\rm BH,T}} \right)^{1/4}$$

$$\frac{a_{\rm GW}}{(G M_{\rm BH,T}/c^2)} = \left(\frac{256}{5} f(e) \right)^{1/4} \nu^{1/4} \left(\frac{c^3 t_{\rm GW}}{G M_{\rm BH,T}} \right)^{1/4}$$

$$f(e) = \frac{1}{(1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right)$$

$$P(a_{\rm GW}) \sim 1 \left(\frac{M_{\rm BH,T}}{10^6\,M_\odot}\right)^{5/8} \left(\frac{t_{\rm GW}}{1\,{\rm Gyr}}\right)^{3/4} \ {\rm yr}$$

$$V_{\rm cir}(a_{\rm GW}) \sim 2700 \left(\frac{M_{\rm BH,T}}{10^6\,M_\odot}\right)^{1/8} \left(\frac{t_{\rm GW}}{10^{10}{\rm yr}}\right)^{-1/8} \ {\rm km\,sec^{-1}}$$

$$V_{\rm circ}(a_{\rm GW}) \gg \sigma_*$$

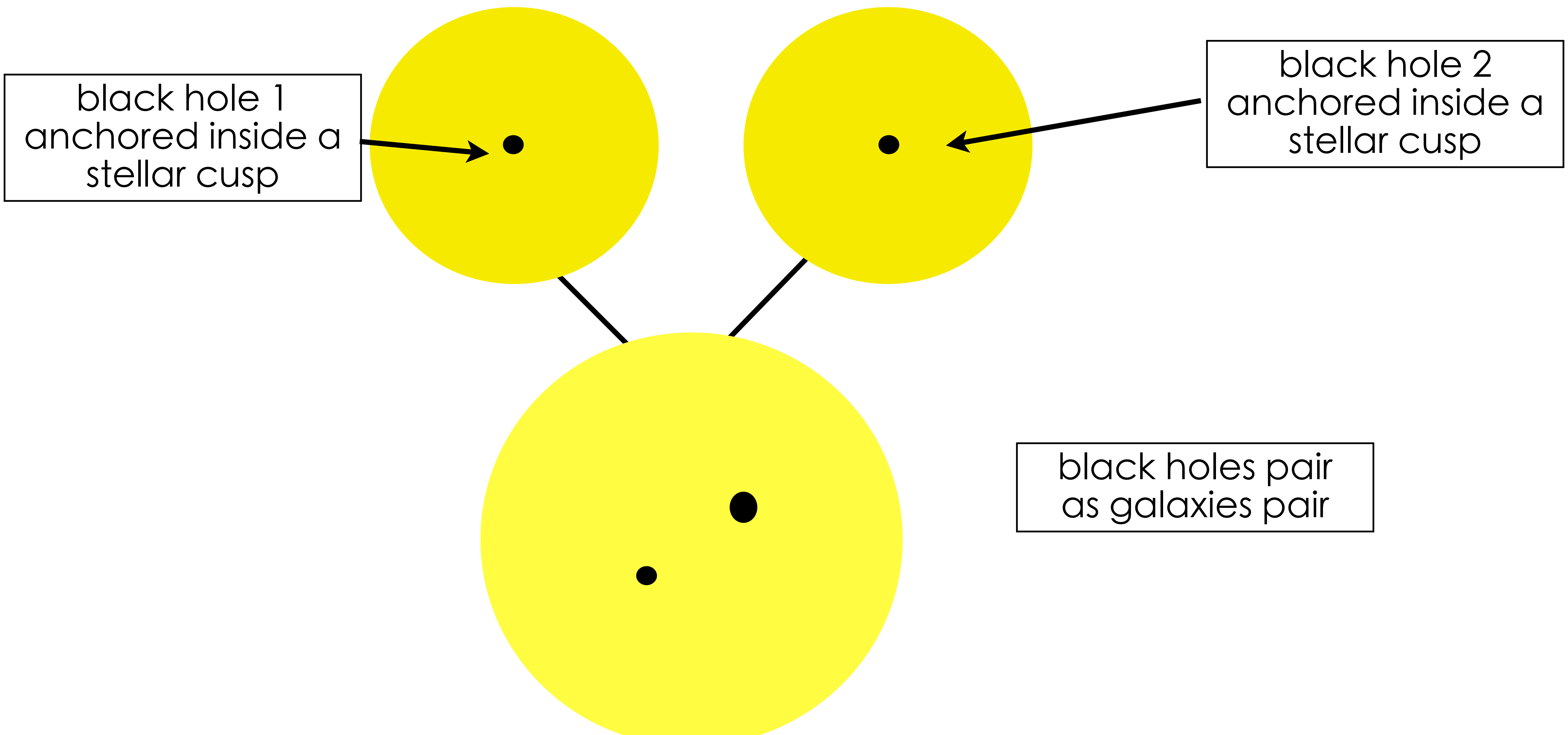
- black hole dynamics in merging galaxies

PTA
late BH-BH
inspirals
(@ low z)

stellar driven
dynamics

Begelman, Blandford & Rees. Nature, 1980

- major mergers of gas-free spherical galaxies

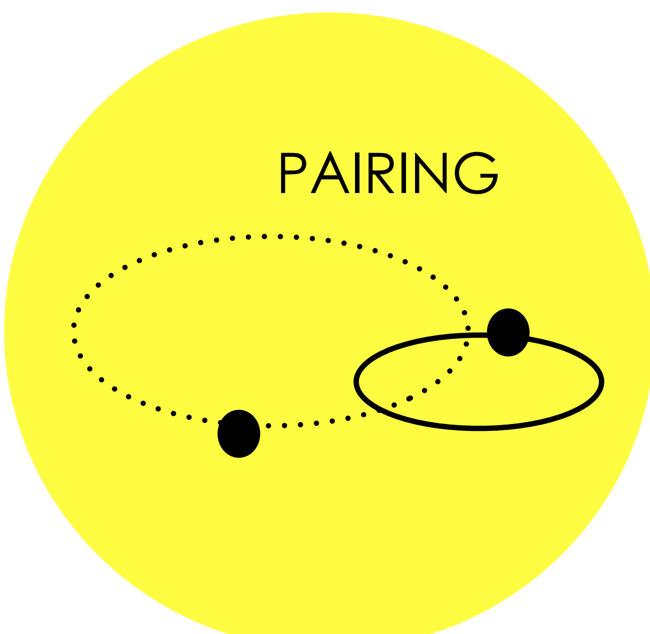


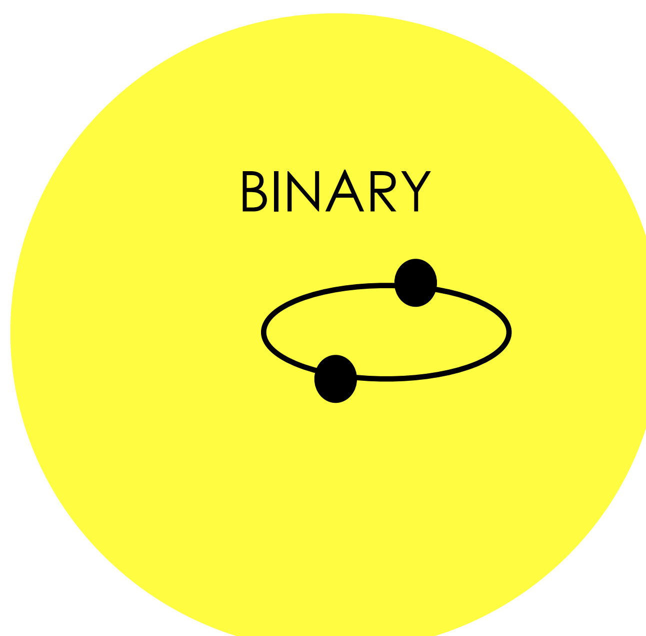
I. PAIRING PHASE
DYNAMICAL FRICTION AGAINST STARS

$$\mathbf{F}_{\rm DF}^{\rm stars} = -4\pi \ln \Lambda G^2 M_{\rm BH}^2 \boxed{\rho_*(r)\mathcal{F}\left(\frac{V_{\rm BH}(r)}{\sigma_*(r)}\right)} \frac{\mathbf{V}_{\rm BH}}{V_{\rm BH}^3}$$

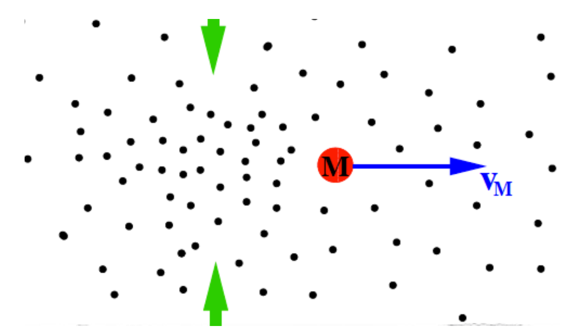
after a violent relaxation phase
the galaxies relax to an equilibrium state

drag from stars moving slowlier
that the BH





stellar over-density

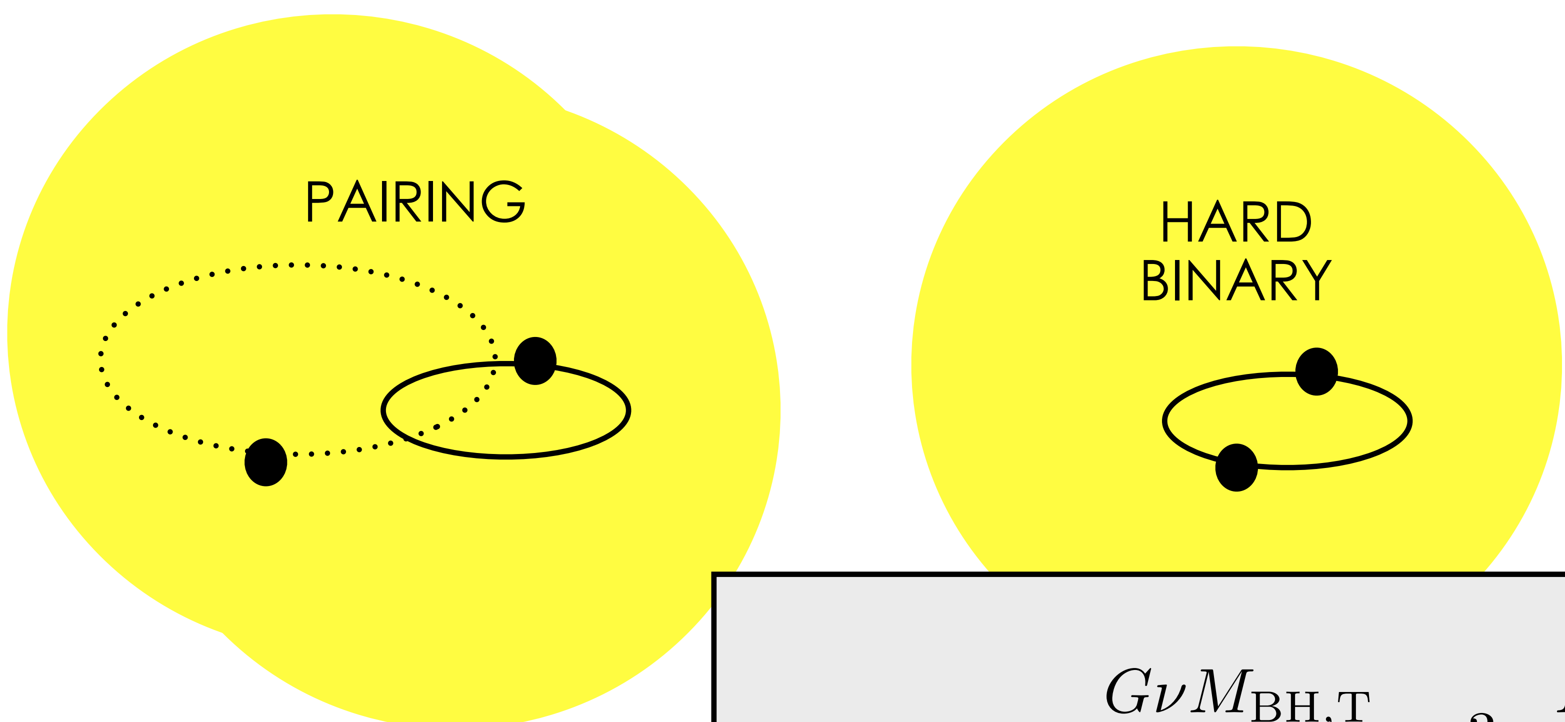


MC 1999

I. END OF THE PAIRING PHASE

$$\frac{G\nu M_{\rm BH,T}}{2a_{\rm Hard}} > \frac{3}{2}\sigma_*^2$$

$$\mathbf{F}_{\rm DF}^{\rm stars} = -4\pi \ln\Lambda G^2 M_{\rm BH}^2 \rho_*(r) \mathcal{F}\left(\frac{V_{\rm BH}(r)}{\sigma_*(r)}\right) \boxed{\frac{\mathbf{V}_{\rm BH}}{V_{\rm BH}^3}}$$



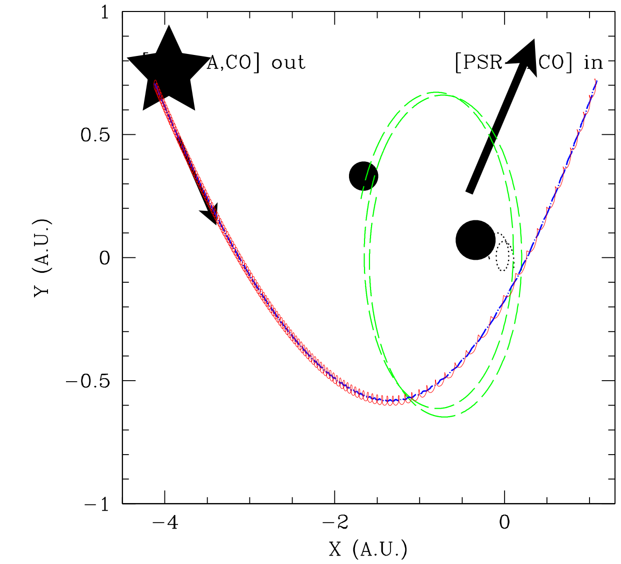
$$a_{\rm Hard} \sim \frac{G\nu M_{\rm BH,T}}{3\sigma_*^2} \sim 3\nu \frac{M_{\rm BH,T}}{10^8 M_\odot} \left(\frac{200\,{\rm km\,s^{-1}}}{\sigma_*}\right)^2 {\rm pc}$$

HARDENING
THROUGH

SCATTERING
OFF
SINGLE
unbound
STARS

PLUNGING
FROM
NEARLY
RADIAL ORBITS

star



$$\frac{\Delta E_{\rm BHB}}{E_{\rm BHB}} \approx \frac{m_*}{M_{\rm BHB}}$$

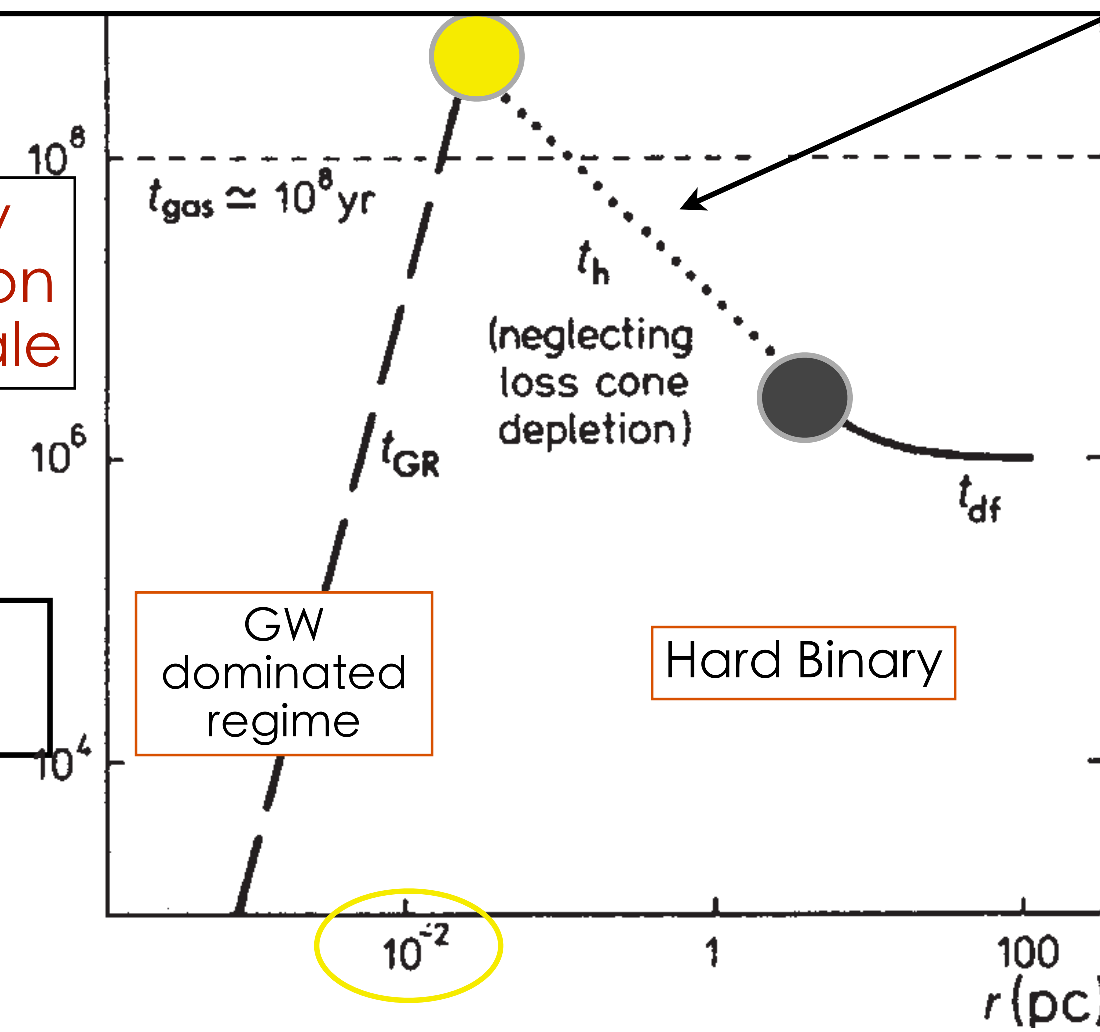
Begelman, Blandford & Rees. *Nature*, 1980

II.HARDENING PHASE
SLINGSHOT

$$\tau_{\rm hardening} \sim \frac{\sigma_*(r_{\rm BHB,inf})}{\rho_*(r_{\rm BHB,inf})}\frac{1}{HGa}$$

binary evolution timescale

$$\tau_{\rm GW} \propto a^4$$

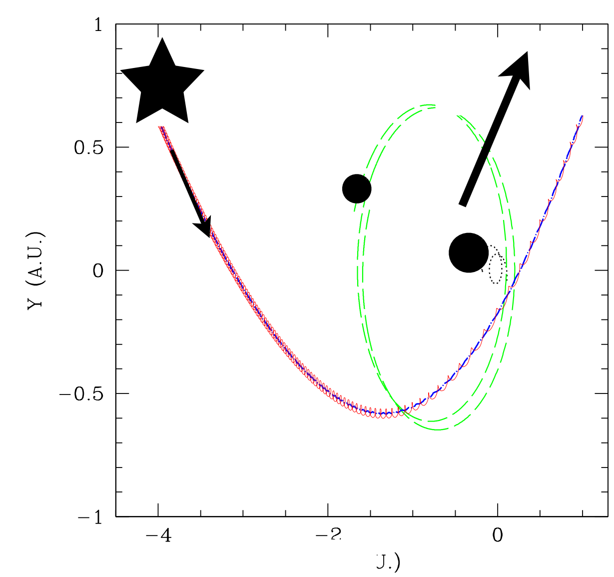


HARDENING THROUGH

SCATTERING OFF SINGLE unbound STARS

PLUNGING FROM NEARLY RADIAL ORBITS

star

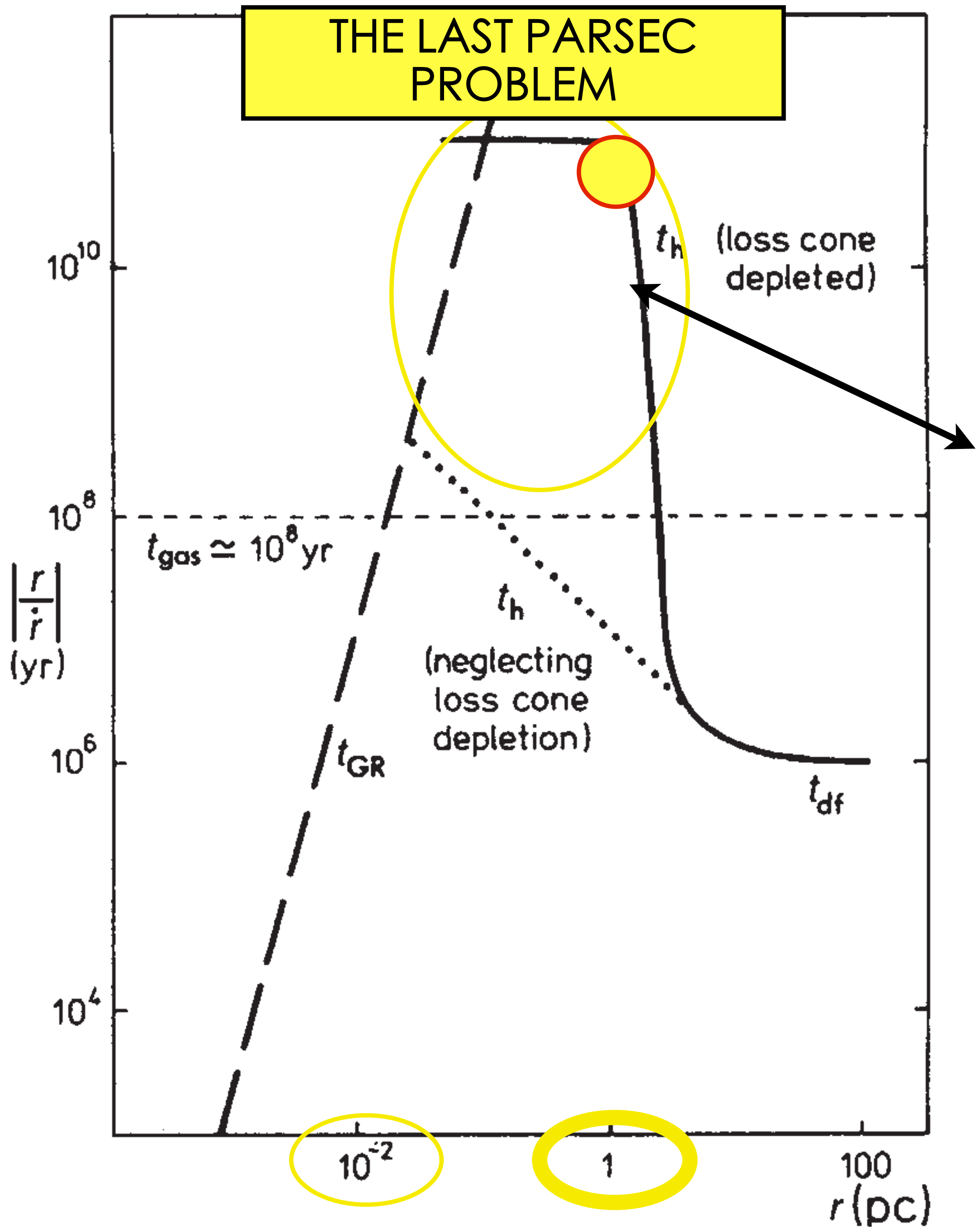


QUINLAN 1996, YU 2002, SESANA & KHAN, 2015

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

THE LAST PARSEC PROBLEM

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

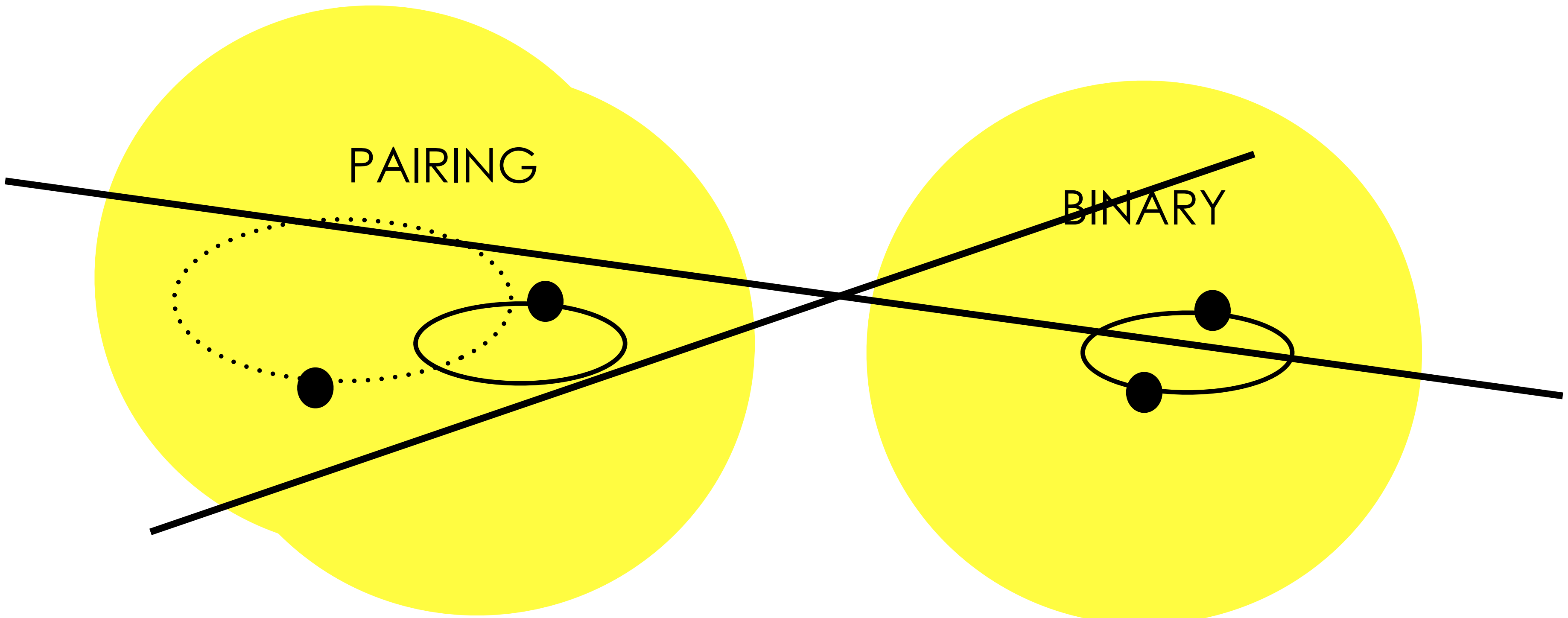


REFILLING OF THE LOSS-CONE
occurs
ON THE TWO-BODY
RELAXATION TIMESCALE

$$\tau_{\rm relaxation} \propto N/\ln N$$

IN GALAXIES
two-body RELAXATION
TIMESCALE
LONGER
HUBBLE TIME

MILOSAVLJEVIC & MERRITT 2005



GALAXIES ARE NOT "SPHERICAL"
BEING RELIC OF (major) MERGERS

... a degree of triaxiality/rotation/counterotation
"solve the last parsec problem"
even in absence of two-body relaxation

VASILIEV+2015
Sesana & Khan 2015
Holley Bockelmann & Khan 2015

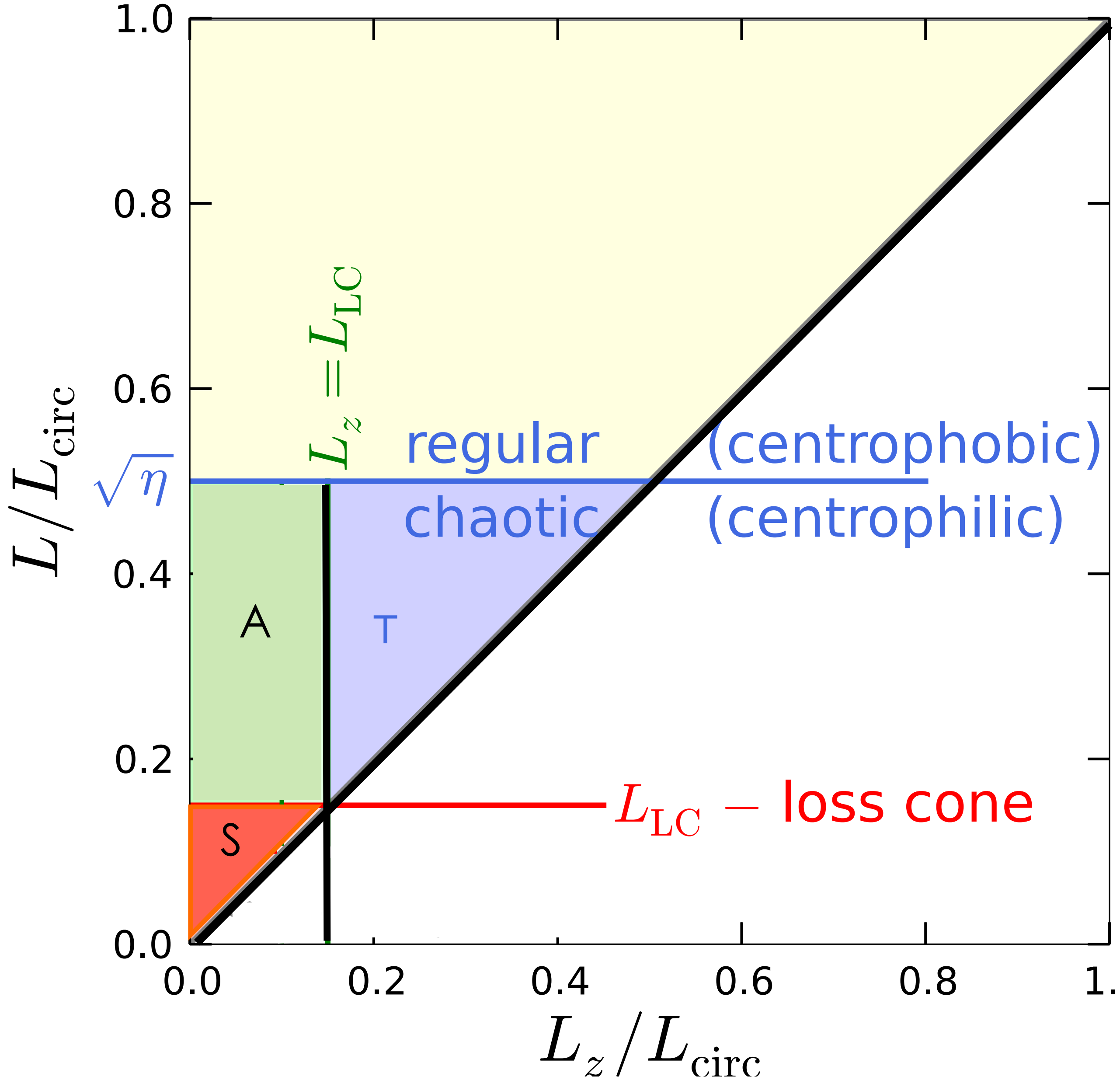
Vassiliev+2013, Khan & Holley Bockelmann 2013, Khan, Just & Merritt 2011
Khan+ 2012, Preto+ 2011,Berentzen+ 2009, Preto+ 2011, Berczik+ 2006

collisionless
galaxy merger remnants

- loss cone in collisionless triaxial galaxies is far richer of low L stars than in spherical galaxies
- collisionless=stars change L due to large scale torques in the overall non spherical gravitational potential
- presence of chaotic orbits that arise in non-spherical geometries
- the axisymmetric case is halfway

$$L_{\rm LC} = \sqrt{GM_{\rm BH,T}a}$$

VASILIEV+2015

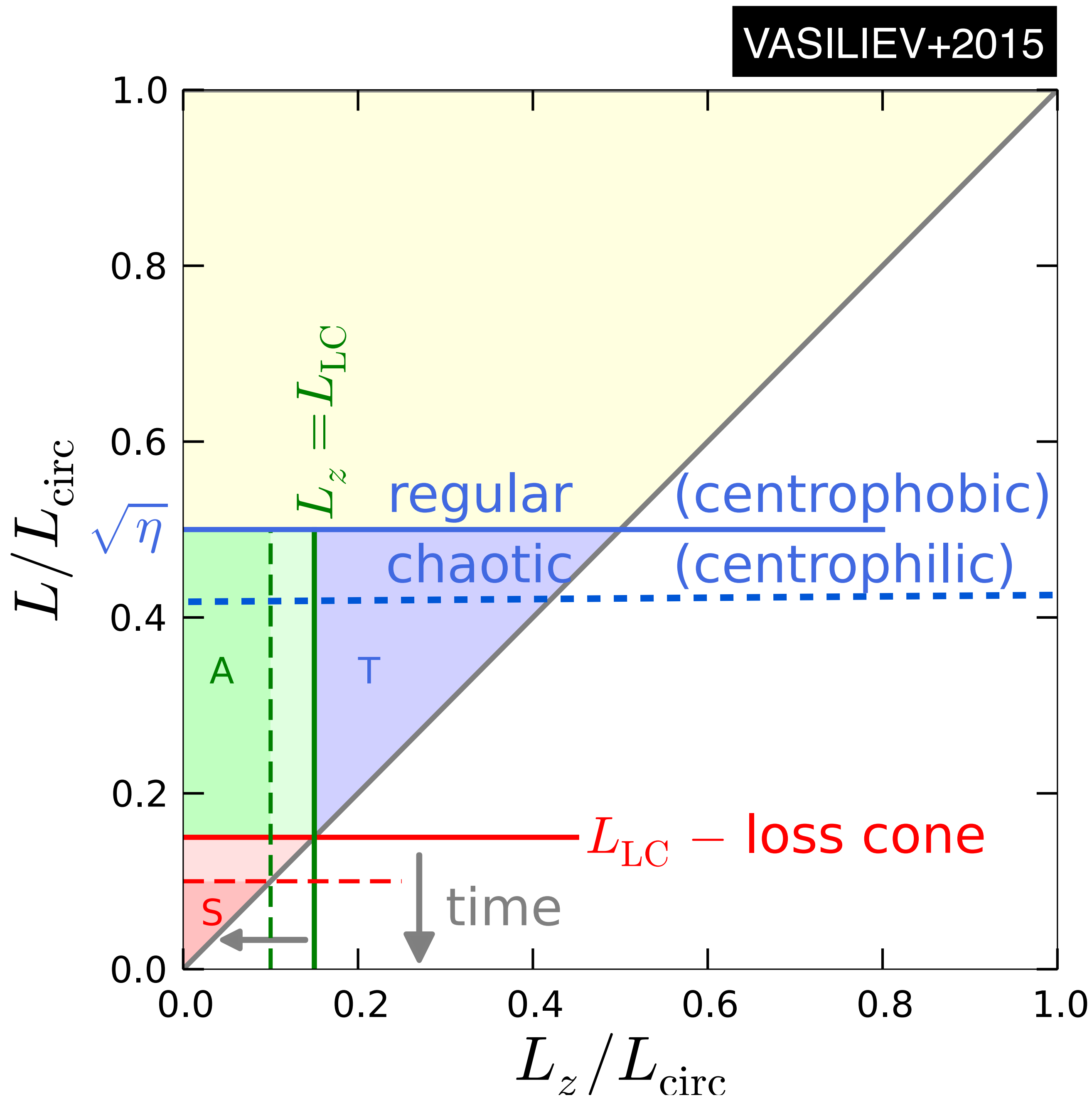


- slice in phase space at fixed energy
- η = fraction of chaotic orbits
- orbits determined by L, $L_{\rm circ}$

- mass in stars on chaotic orbits is in general larger than the mass of the black hole binary

I

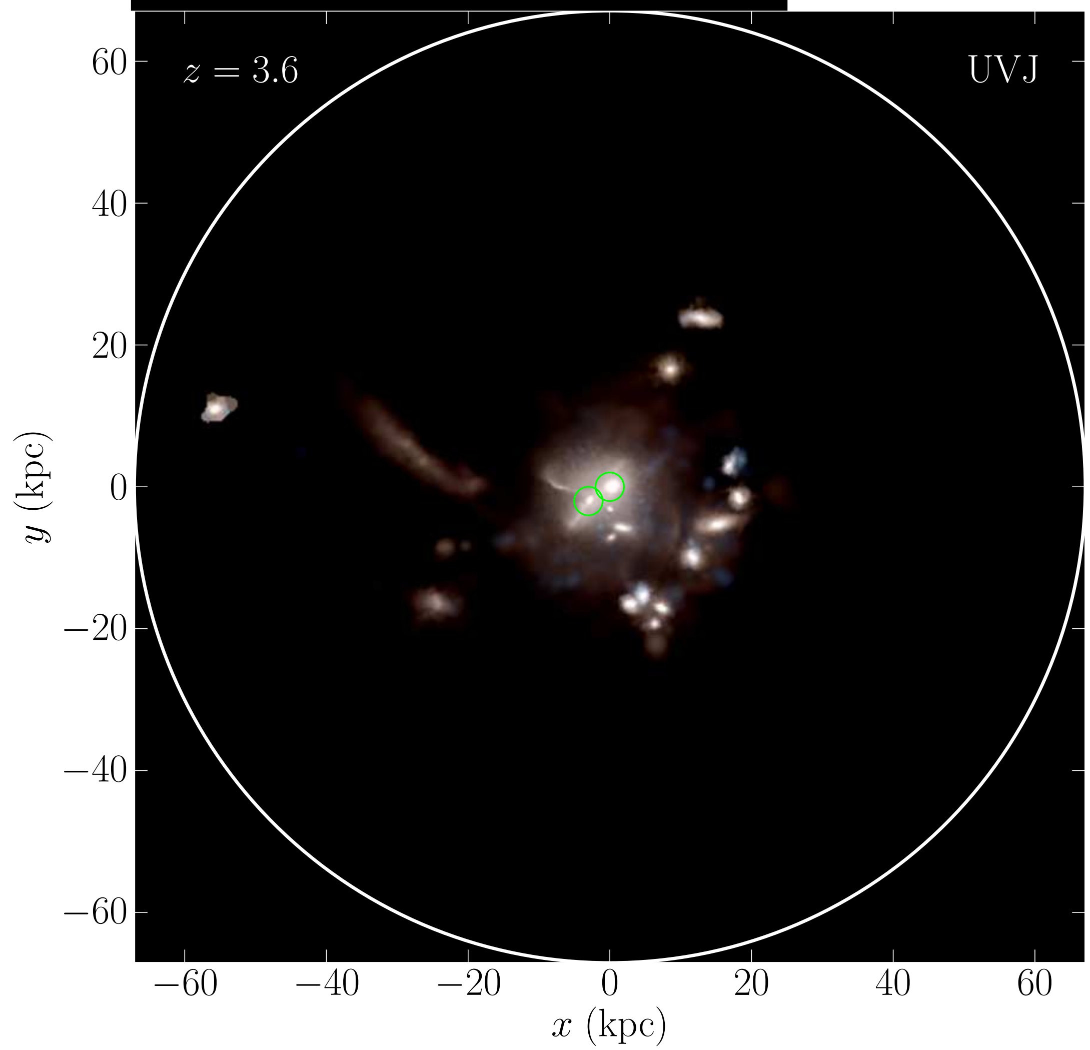
- to the extent that mergers result in galaxy shapes that are slightly non axisymmetric --> the final problem is not a problem in most galaxies
- hardening rates never rich the "full loss cone" regime
- coalescence times fall in the range of 100 Myr (for very eccentric orbits) -1 Gyr (for circular orbits) typically



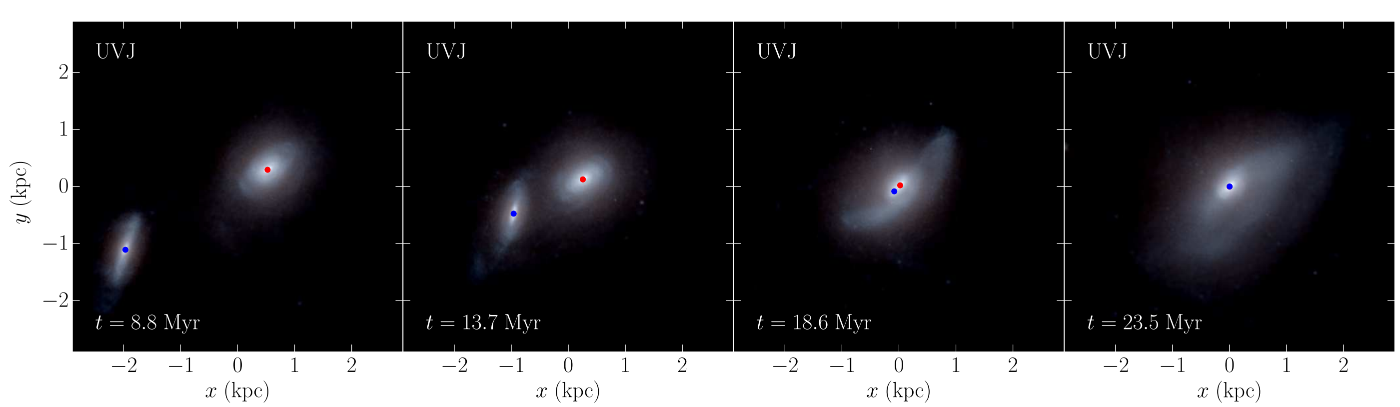
$$L_{\rm LC} = \sqrt{G M_{\rm BH,T} a}$$

SWIFT COALESCENCE OF TWO SUPERMASSIVE BLACK HOLES IN A COSMOLOGICAL MERGER (gas poor)

Khan, Mayer, Ficconi+ 2016

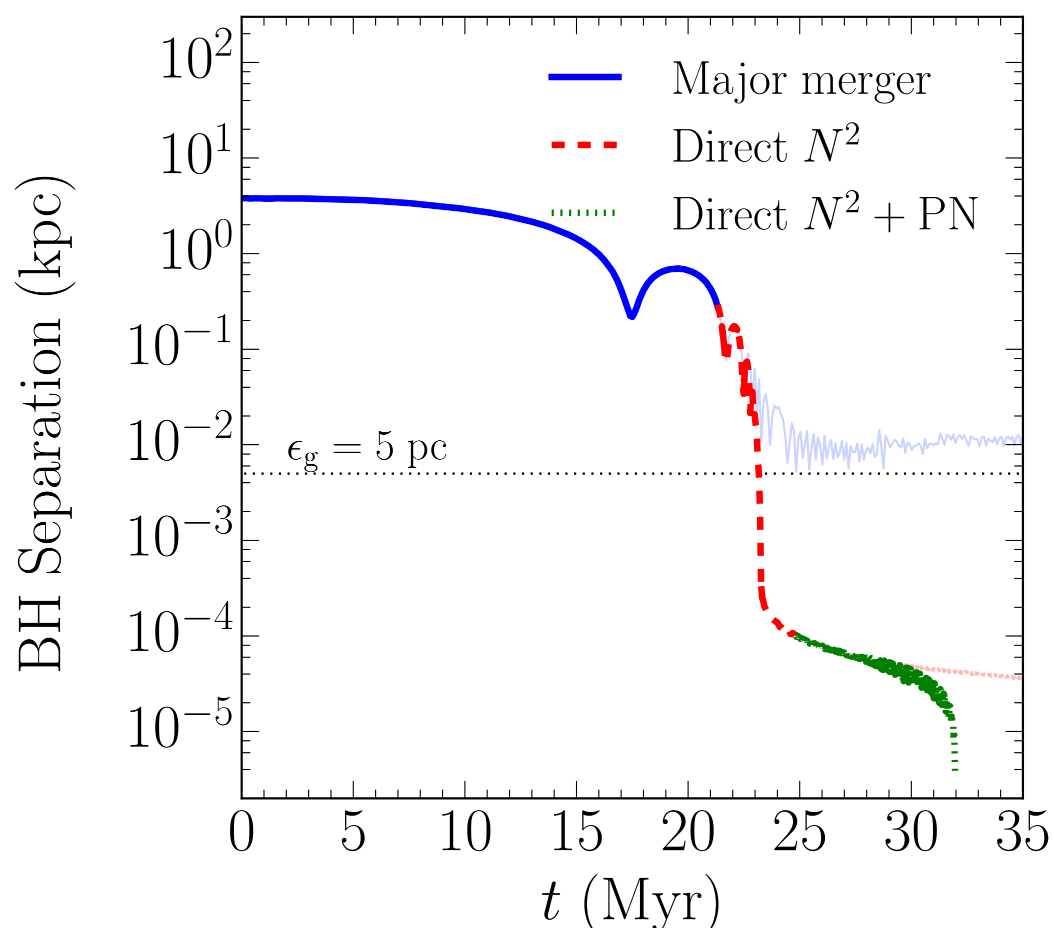


- Argo cosmological simulation
- galaxy group @ z=3.5
- identification of the two main spirals undergoing a major merger
- gas fractions of 10% or less
- first "ab initio" simulation of two galaxies ending with the coalescence of the 100 million-sun black holes

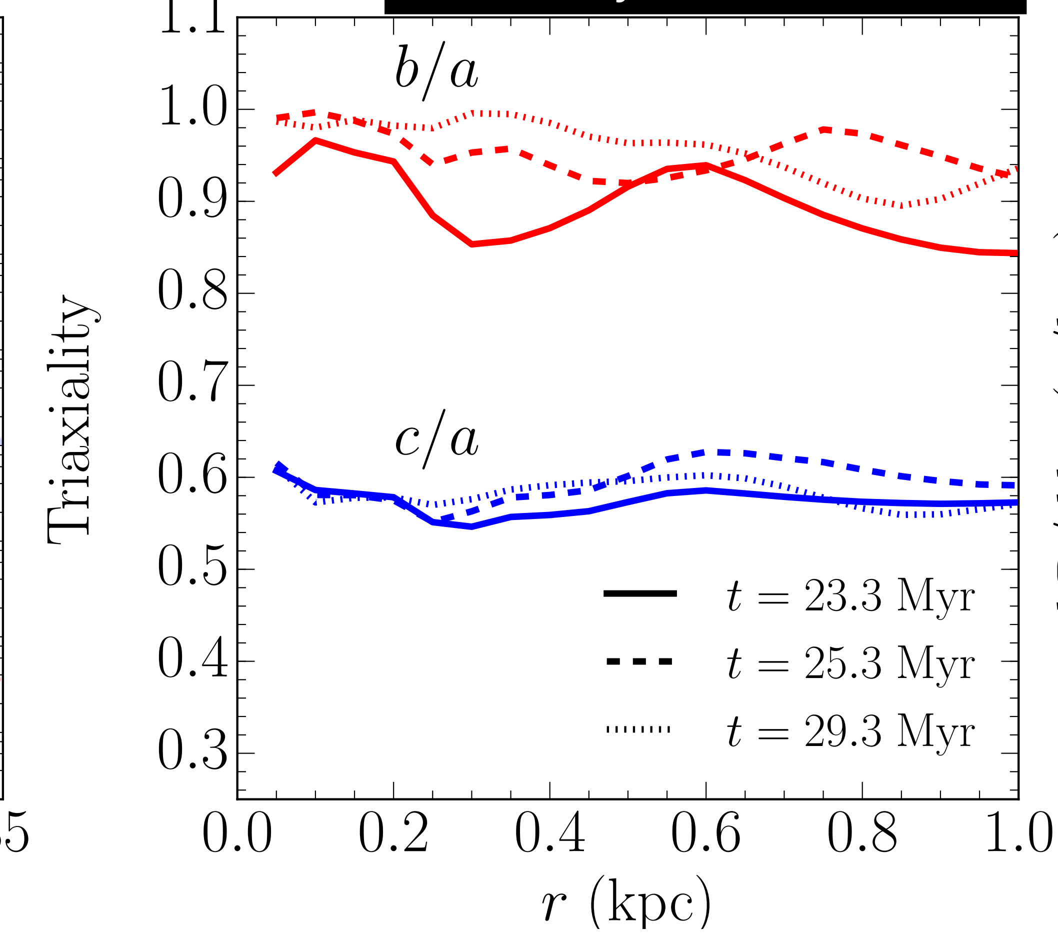


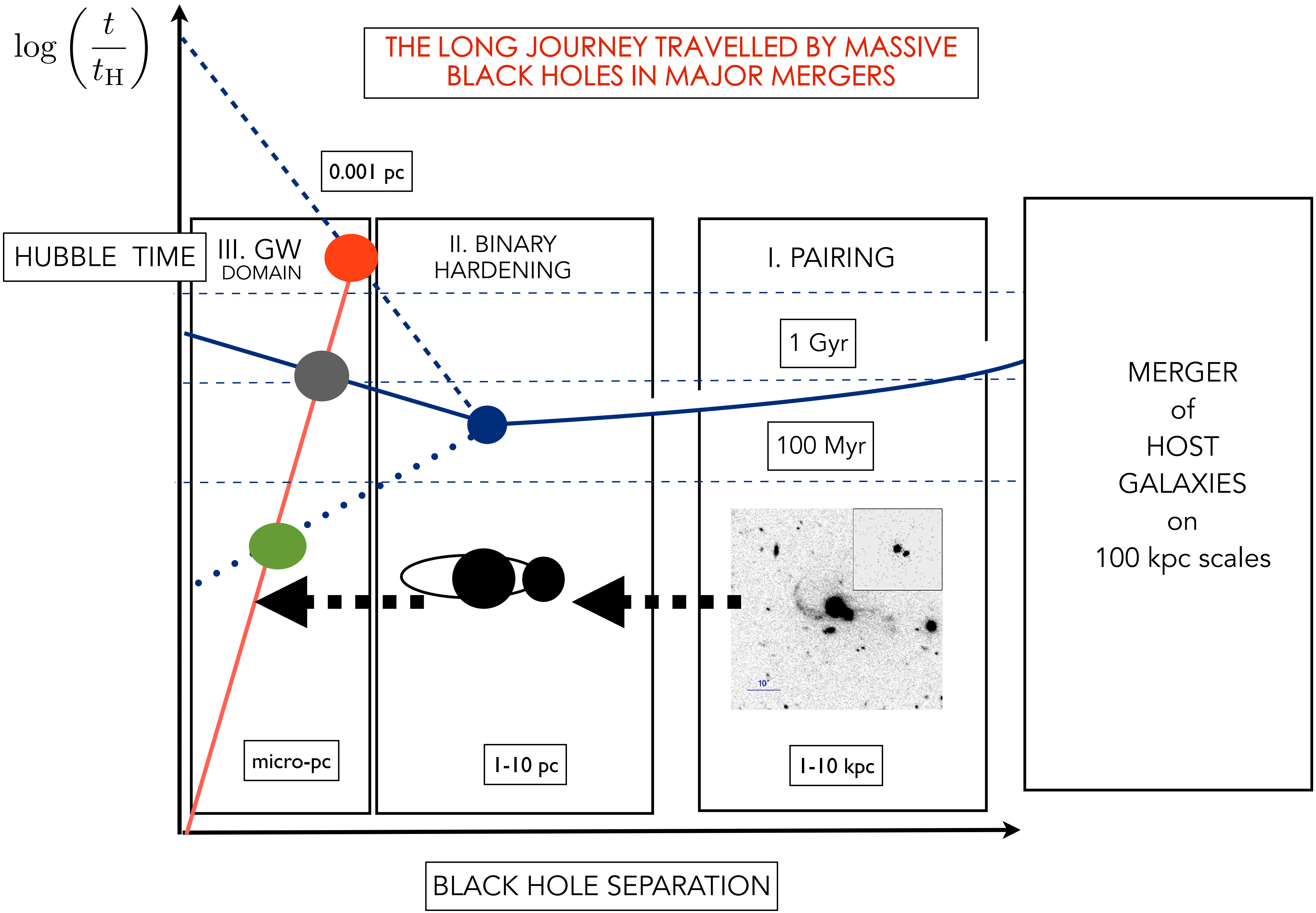
- gas dissipation is instrumental before the merger in creating a high central stellar density, result of gas inflows in the inner 500 pc due to cosmological gas inflows and accretion prior to mergers
- @ t=20 Myrs the merger remnant is gas poor owing to gas consumption. The black holes are surrounded by dense stellar cusps (central regions are devoid of DM)
- dynamical friction by stars (and gas in the early stages) controls the dynamics of the two black holes all the way down to the hardening phase
- the hard binary hardens by slingshot

- the remnant is triaxial
- black holes coalesce swiftly
- inclusion of PN terms is important

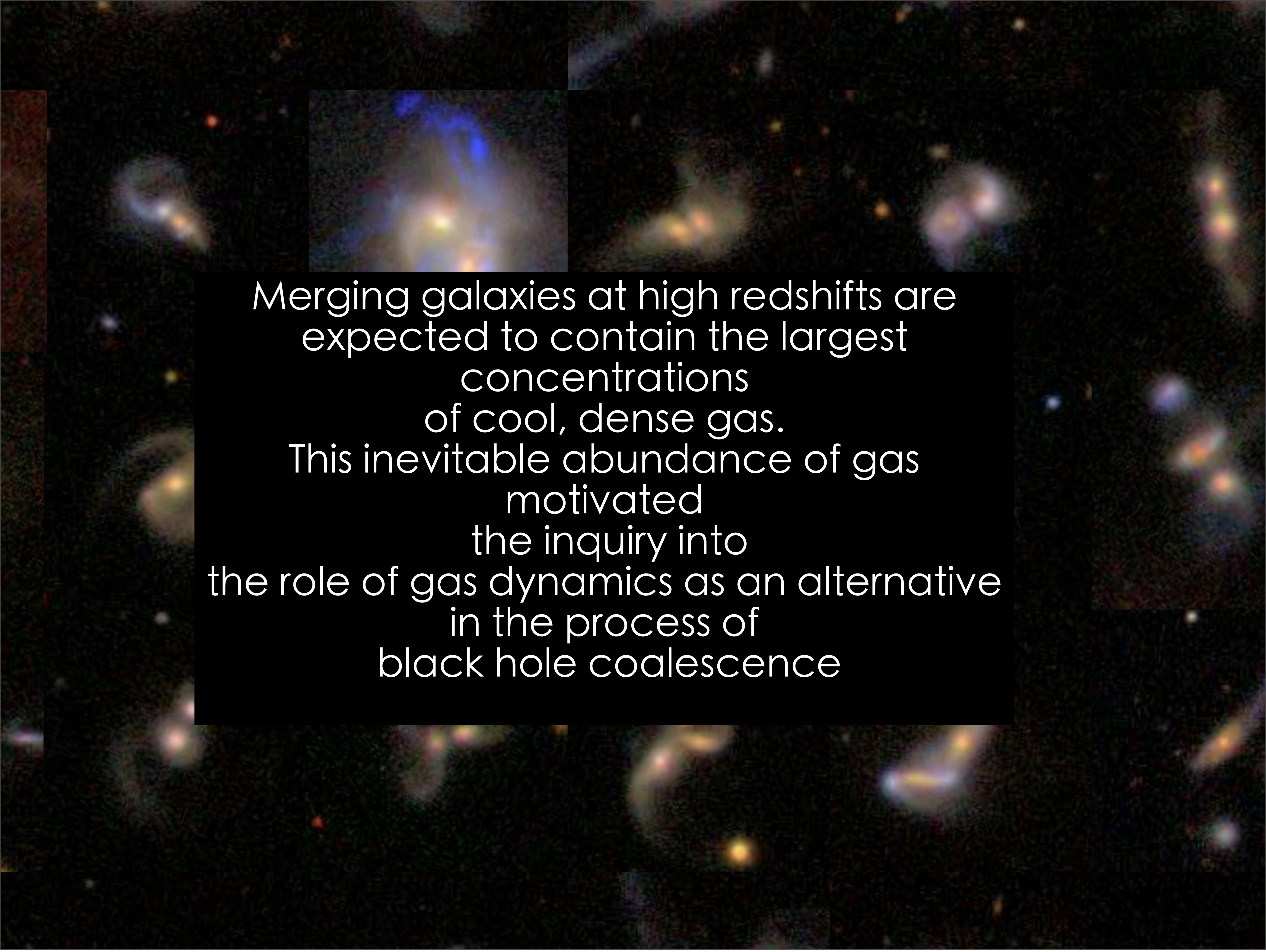


Khan, Mayer, Ficconi+2016





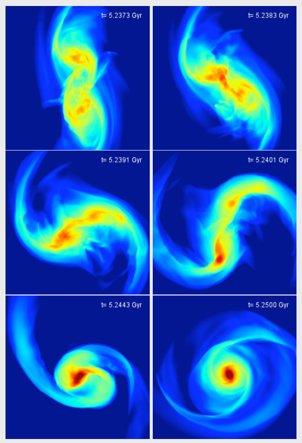
$\log\left(\frac{t}{t_H}\right)$
THE LONG JOURNEY TRAVELLED BY MASSIVE BLACK HOLES IN MAJOR MERGERS
0.001 pc
HUBBLE TIME
III. GW DOMAIN
II. BINARY HARDENING
I. PAIRING
1 Gyr
100 Myr
MERGER of HOST GALAXIES on 100 kpc scales
micro-pc
1-10 pc
1-10 kpc
BLACK HOLE SEPARATION

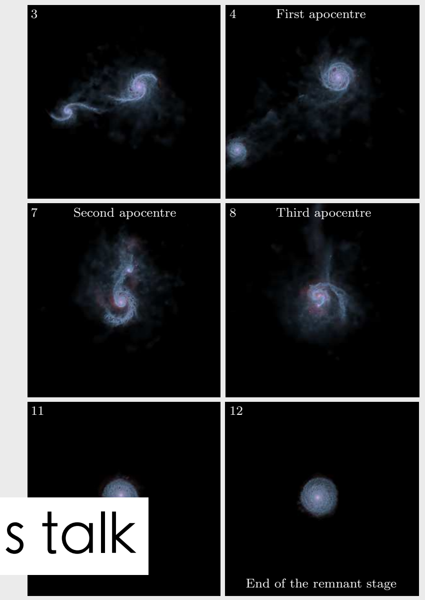


Merging galaxies at high redshifts are expected to contain the largest concentrations of cool, dense gas.
This inevitable abundance of gas motivated the inquiry into the role of gas dynamics as an alternative in the process of black hole coalescence

major mergers of gas rich galaxies

ab initio simulations of major mergers of disc galaxies on 100 kpc scales

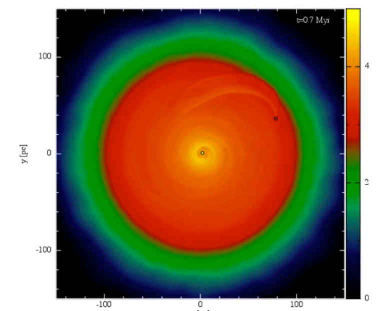


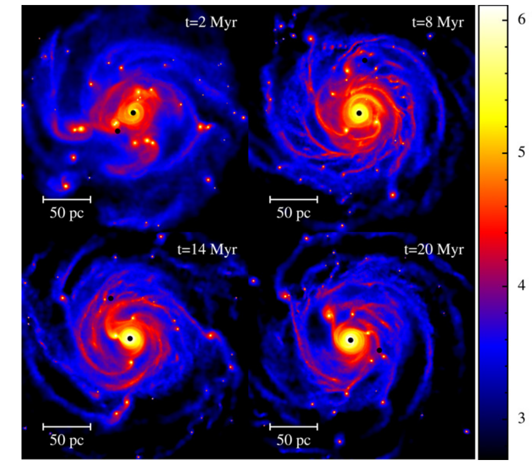


Marta's talk

simulations of nuclear gas discs on 500 pc scales

50% gas fraction



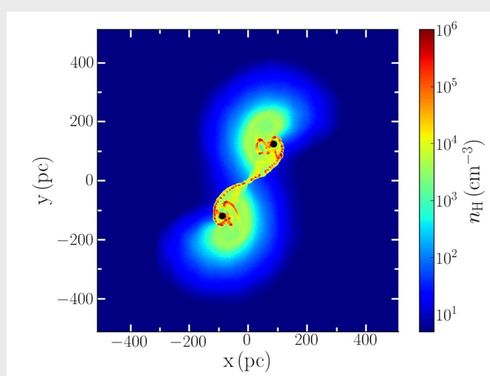


single/ two-phase medium

BINARY FORMATION

simulations of colliding gaseous galactic discs on 500 pc scales

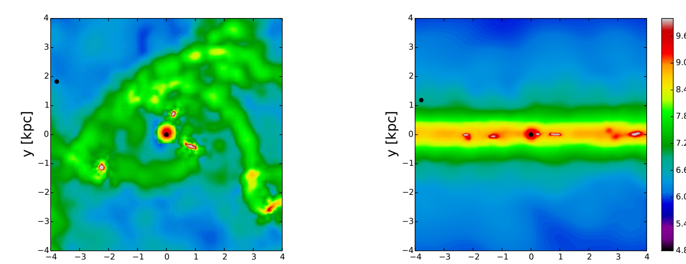
50% gas fraction



multi-phase medium

star formation
stellar feedback

simulations of massive isolated disc galaxies (no bulge)



multi-phase medium
high gas fraction >50%

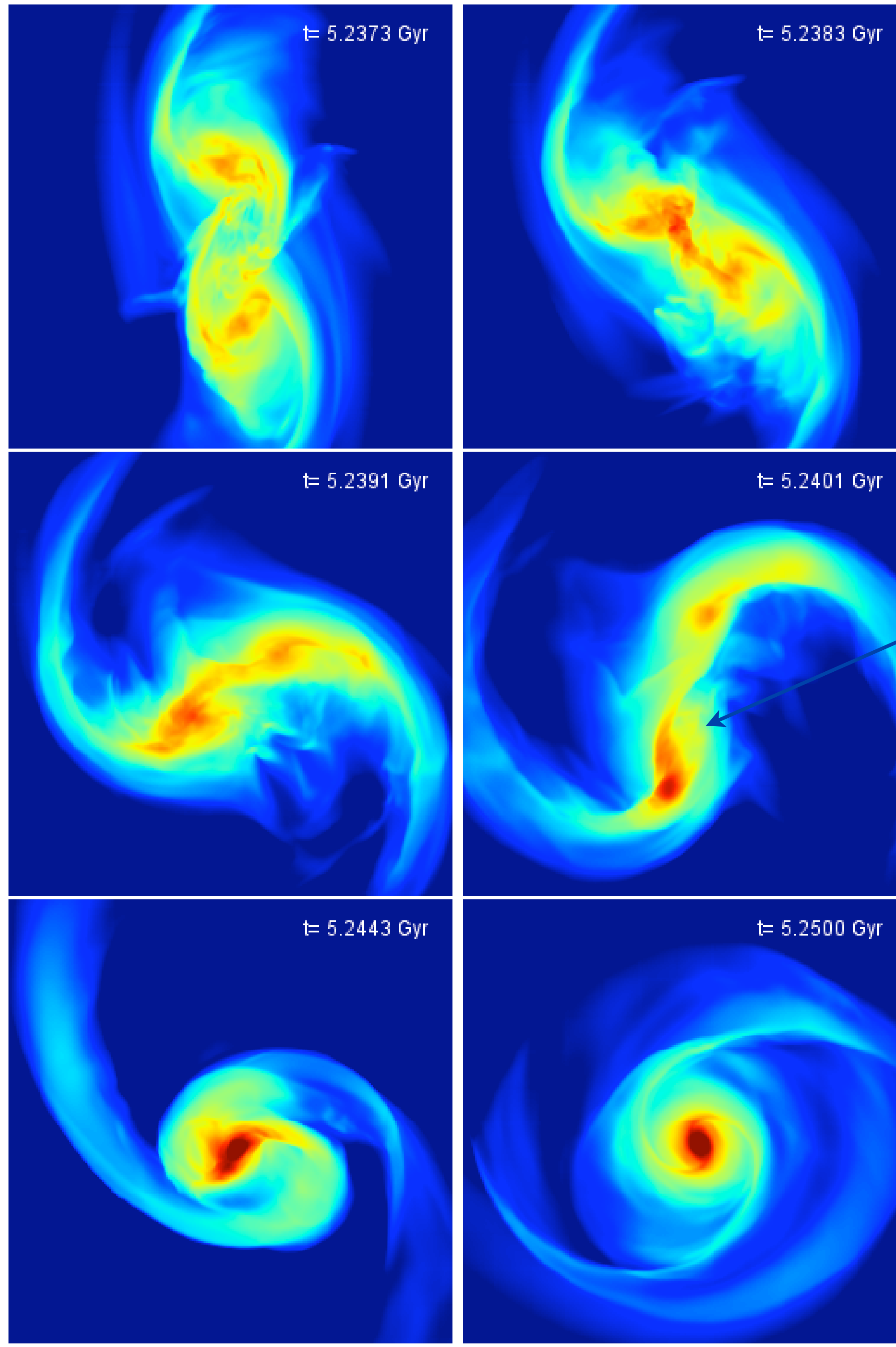
star formation
AGN feedback

MC 2014, review

FORMATION OF A MASSIVE NUCLEAR DISC @ last pericentre
of billion solar masses
200-300 pc in size 60 pc height

DENSITY MAP
OF THE GASEOUS
DISCS DURING THE
FINAL
prograde,
coplanar
MERGER

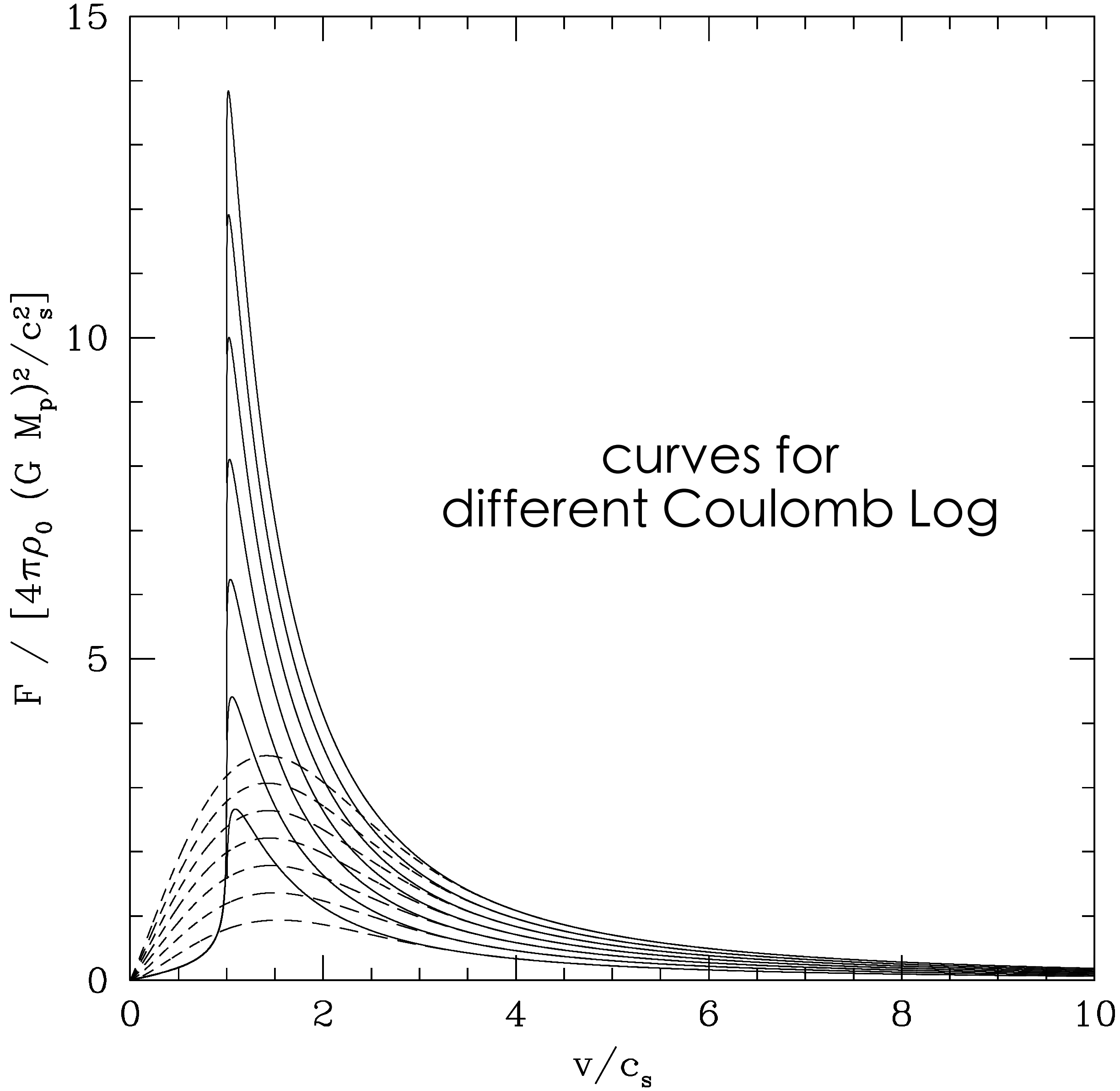
TIDAL TORQUES ARE
REDISTRIBUTING THE
ANGULAR
MOMENTUM OF THE
TWO INTERACTING
DISCS



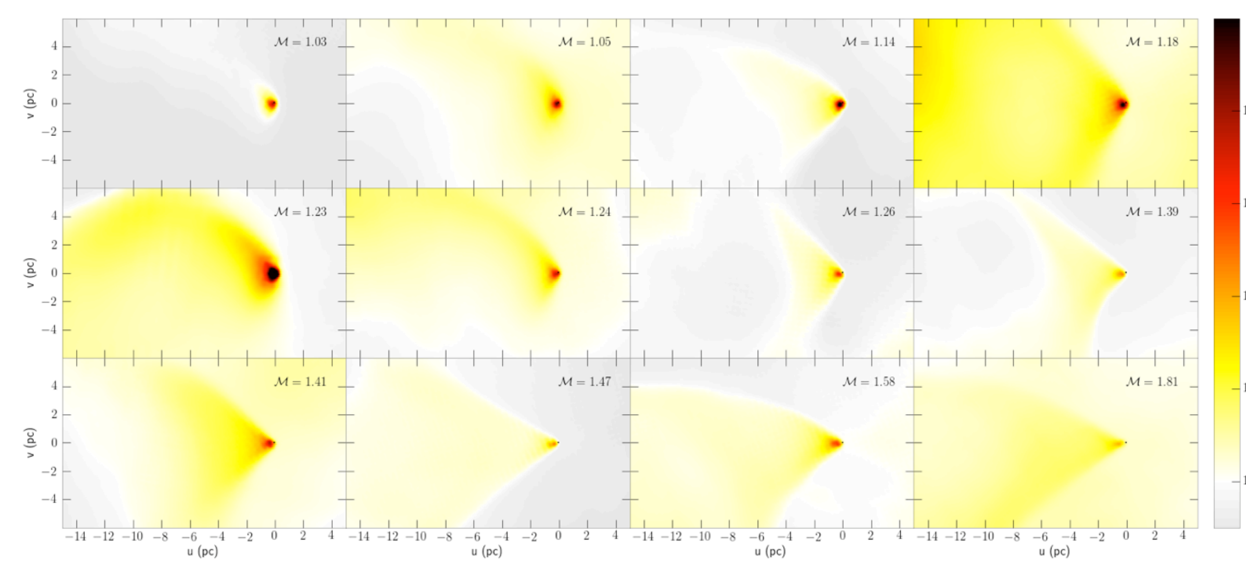
ASYMMETRIC
SHOKS DUE TO
TURBULENCE

MAYER, MC+ 2007, AMR SIMULATION BY CHAPON+ 2011

- gas dynamical friction

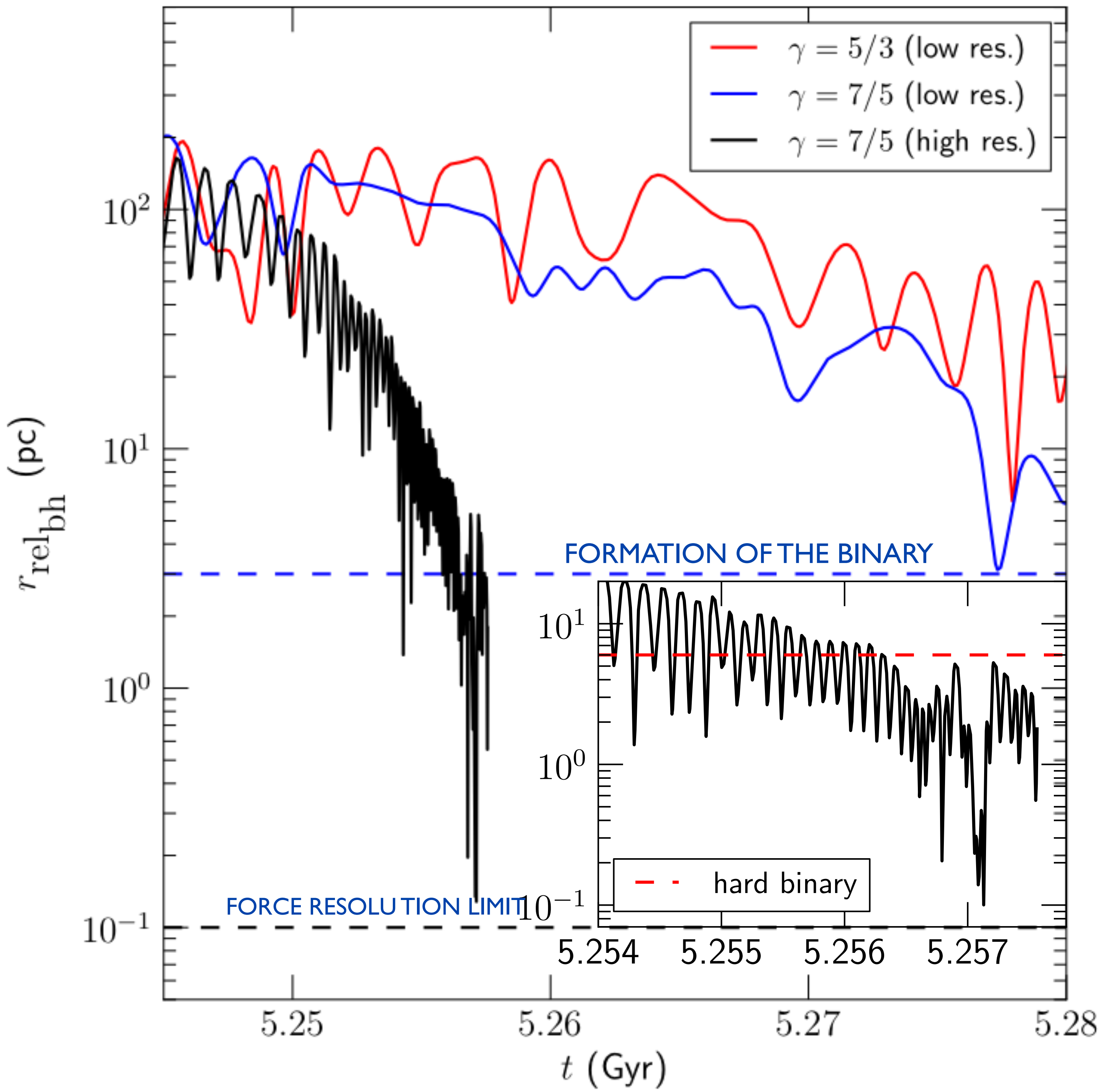


gas over-density



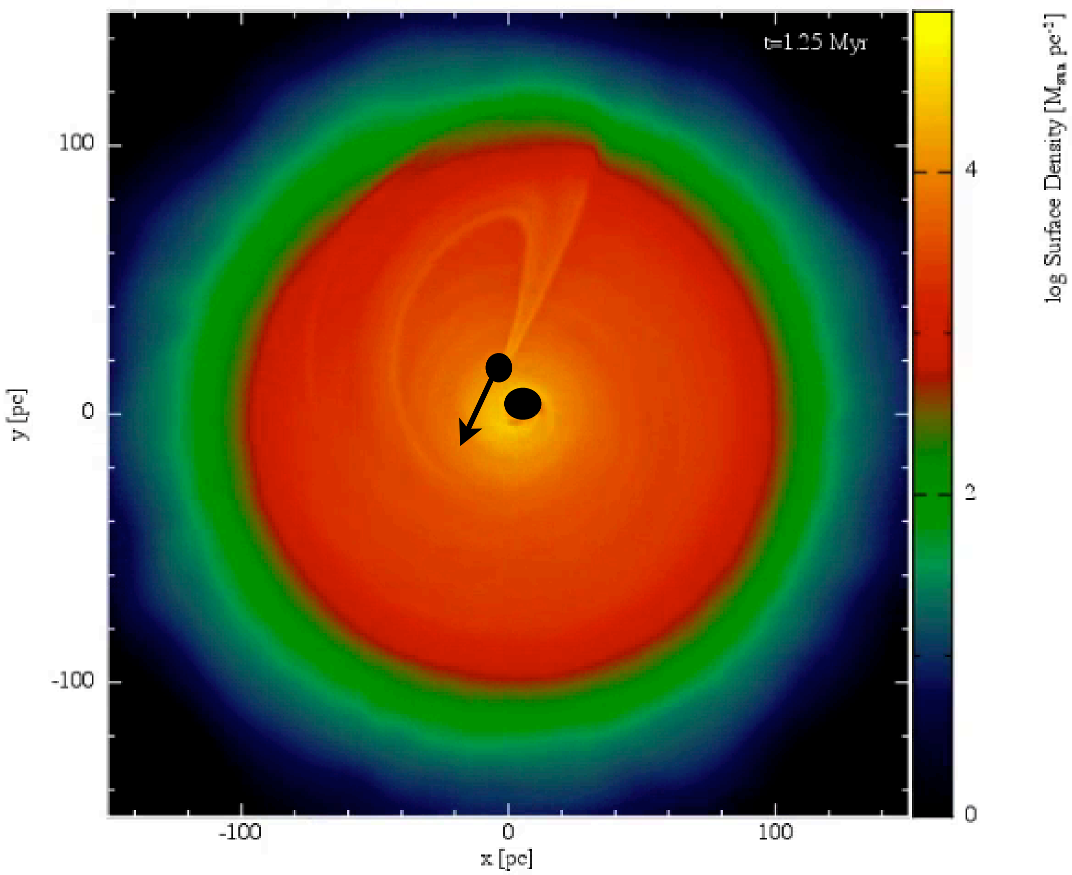
OSTRIKER 1999, CHAPON+ 2011

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



MAYER, MC + 2007
CHAPON, MAYER, TEYSSIER, 2011

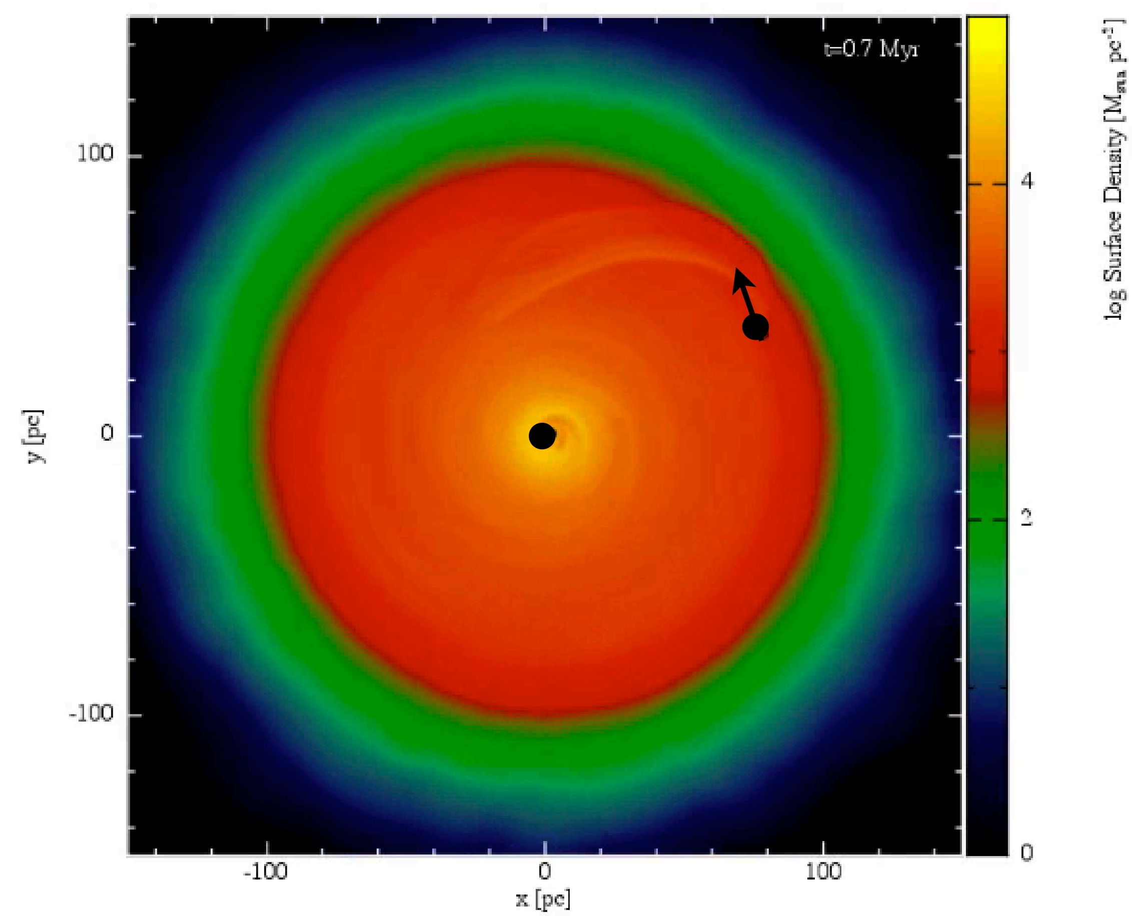
DEDICATED HIGH-RESOLUTION SIMULATIONS OF THE BLACK HOLE EVOLUTION IN ROTATIONALLY SUPPORTED NUCLEAR DISCS MESTEL PROFILE

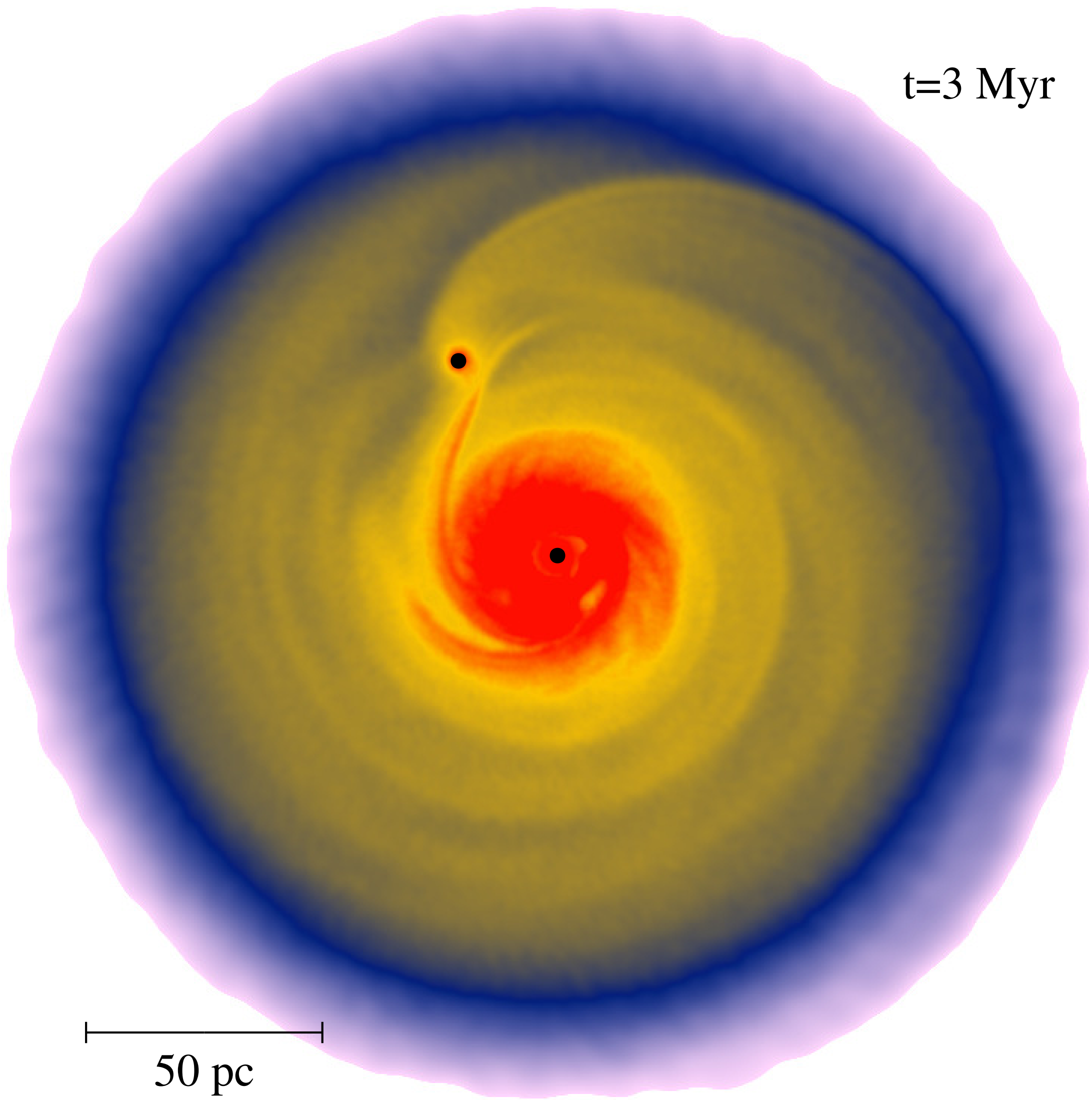


the disc and BH corotate counterclockwise
the drag force is mostly acting at peri-center
where the wake lags behind

THE UNDERLYING ROTATING GASEOUS BACKGROUND FORCES THE SECONDARY BLACK HOLE TO CO-ROTATE WITH THE DISC
MEMORY LOSS OF THE INITIAL ECCENTRICITY

DOTTI, MC+2006,2007,2009a,b
PEREGO+ 2009
MC & DOTTI, 2011





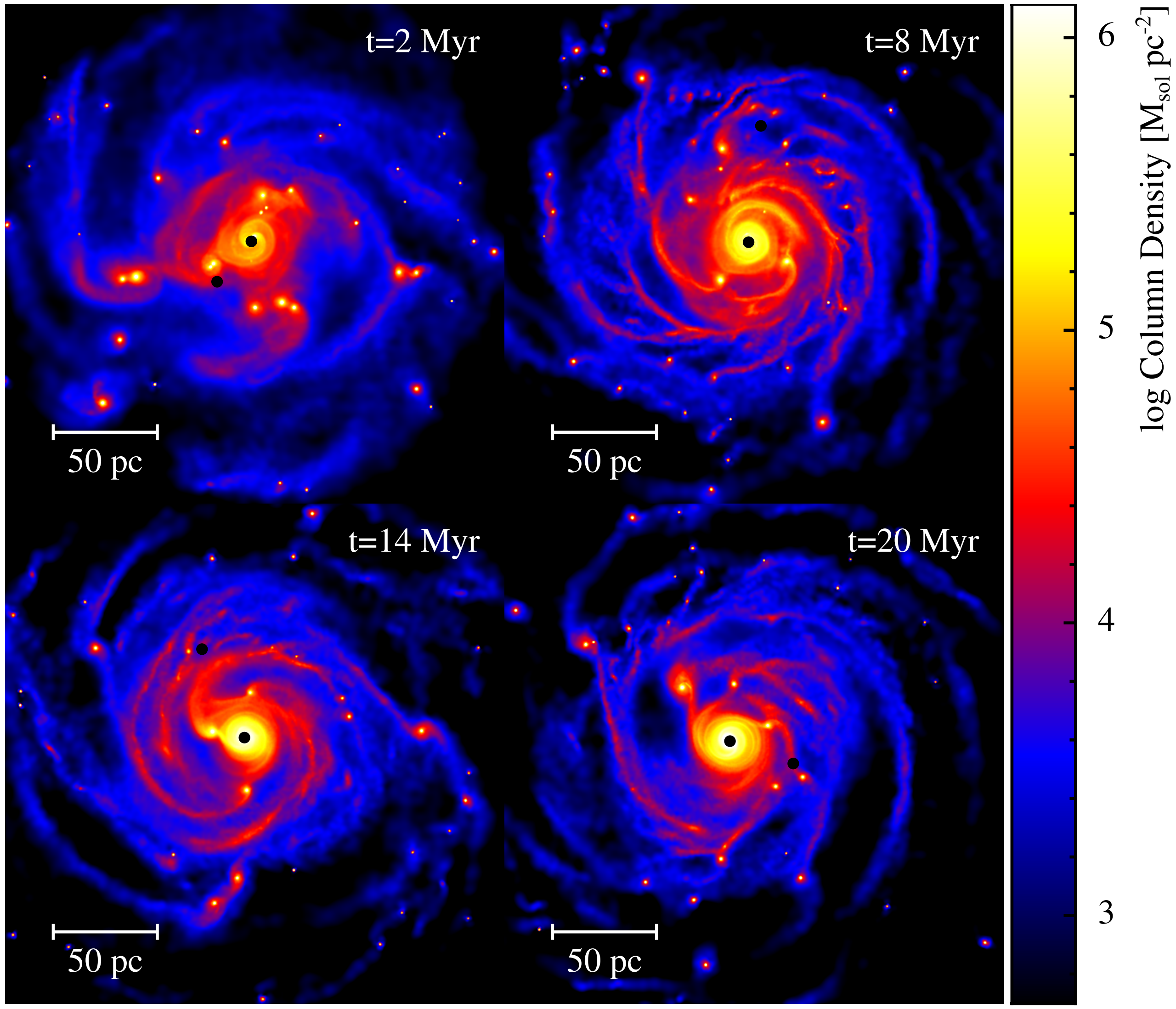
- after circularization the black hole has reduced its velocity relative to the underling medium
- the black hole dynamics is reminiscent of the type I planet migration
- disc mass dominate over the mass of the secondary black hole

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

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

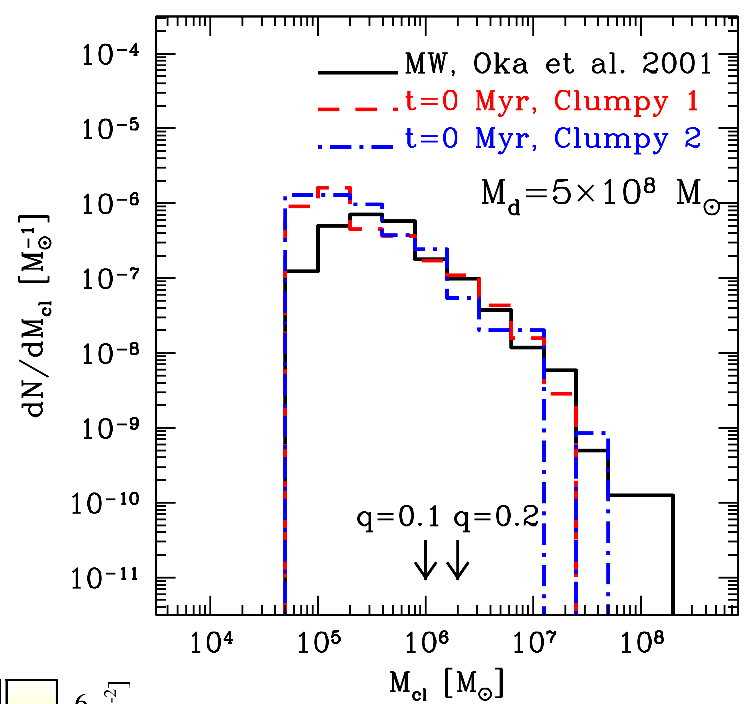
FIACCONI, MC+ 2013

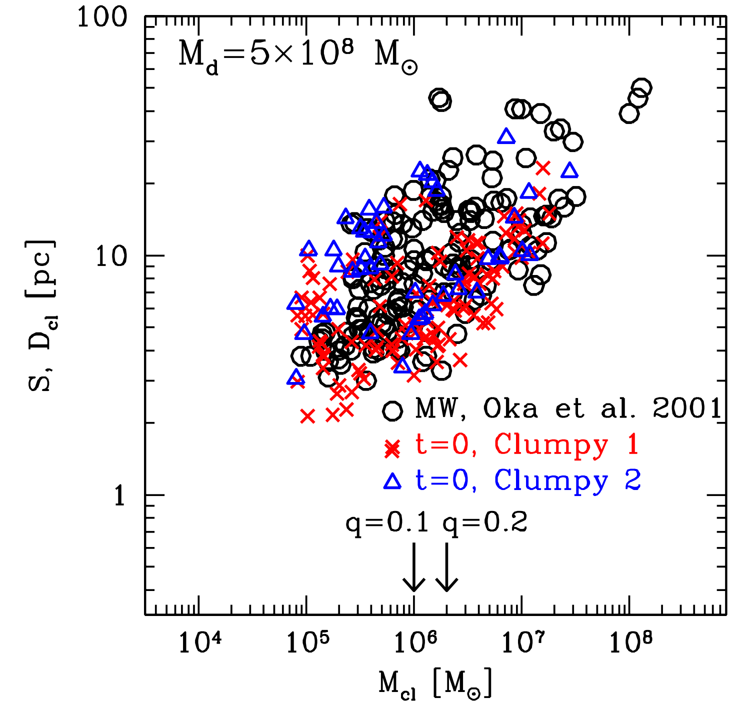
- black hole dynamics in massive circum-nuclear discs
- switch forcefully cooling (only) in an unstable Mestel disc
(M(disc)=100 million suns; M(BH, primary)=10 million suns, q(mass ratio)=0.1)
- formation of massive clumps

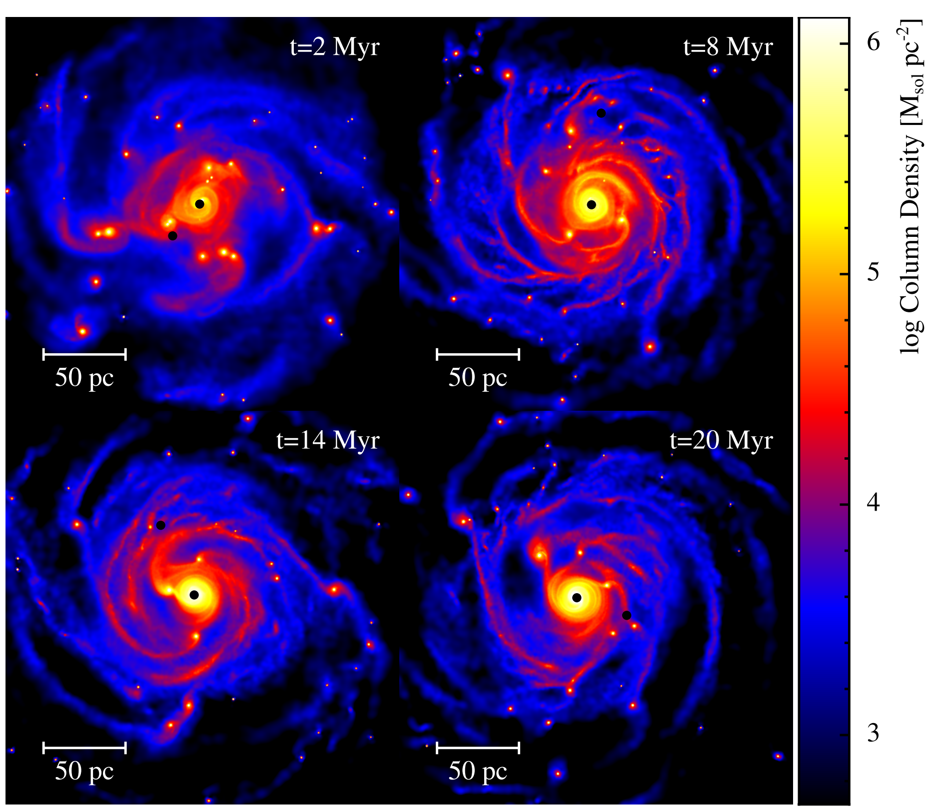


FIACCONI,MC+ 2015

- clump distribution and size ("clumpy 1" - cooling time 0.2 Myr, "clumpy 2" 2 Myr)







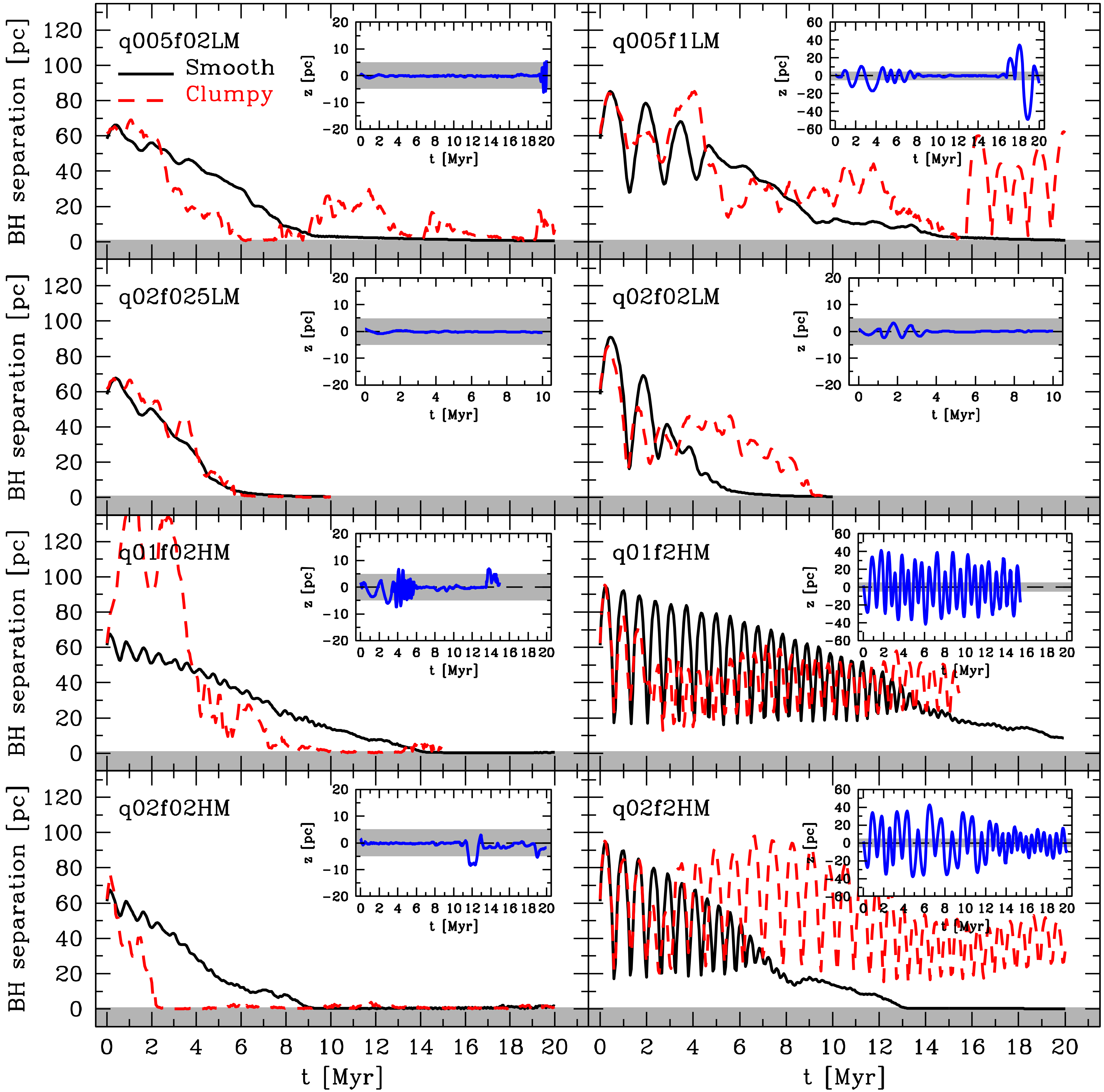
- clumps migrate to the centre
- the black hole can tidally disrupt a clump
- the black hole can be "captured" by the clump

- close encounters between the secondary black hole and massive clumps act as "gravitational slingshots"

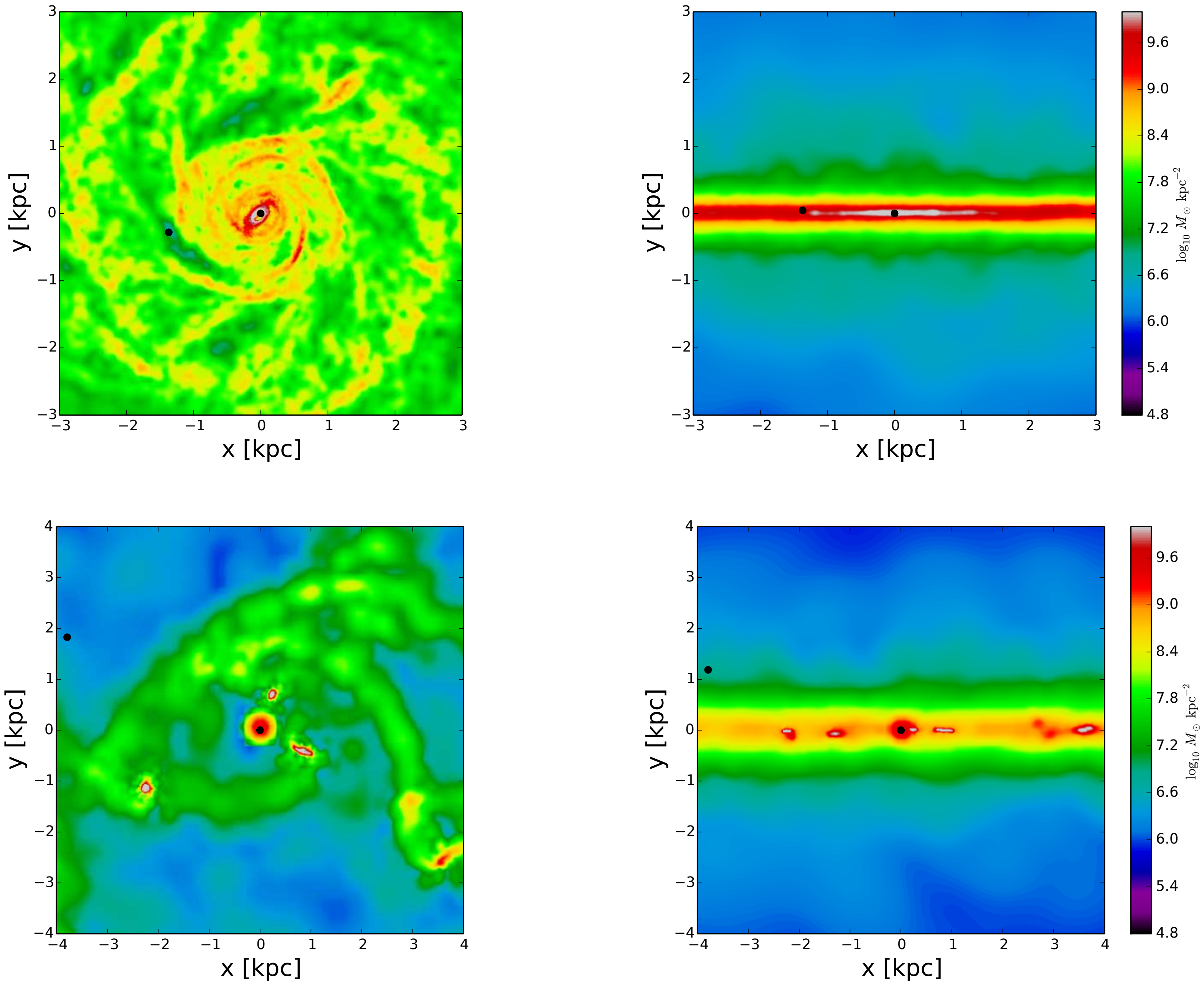
- impulsive perturbations cause the black hole to deviate from its original orbit: tilt of the plane and increase of the eccentricity

- stochastic behavior when M(BH)<M(clump)

- broadening of the inspiral time scale to form a Keplerian binary -10-50 Myrs

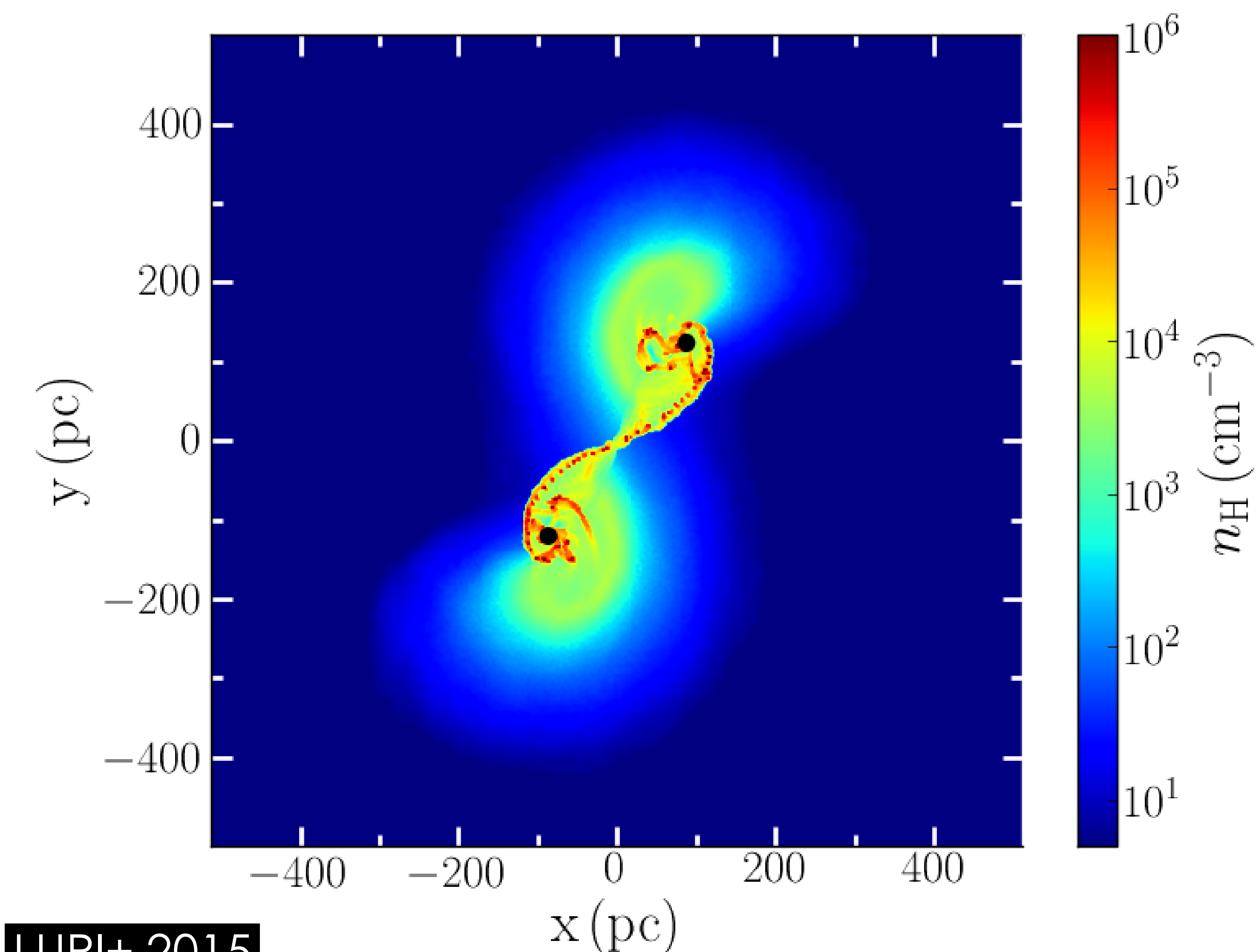


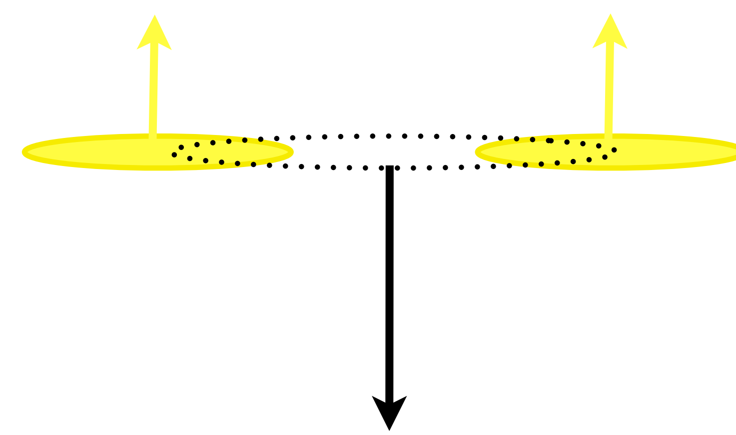
- very massive large scale gas disc simulating disc galaxies @ high z with M(disc)=10 billion suns and gas fraction of 0.5: phase of violent disc instability
- including black hole accretion and AGN feedback the delay and off-plane scattering can be even more significant

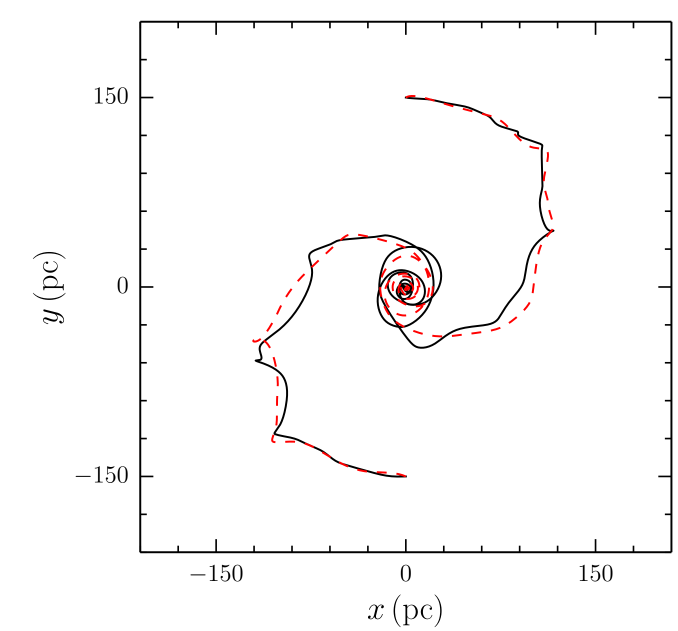


TAMBURELLO+ 2016

- extreme show case: disc angular momenta anti-parallel to the orbital angular momentum
- shocks become sites of intense star formation and stellar feedback alters the thermal and dynamical state of the gas
- only few clumps form with mass comparable to the black hole mass, so the orbit is perturbed but not as stochastic as in the previous models (due to the geometry of the collision that confines star formation along the oblique shock)
- black hole dynamics not strongly affected by the recipe of feedback

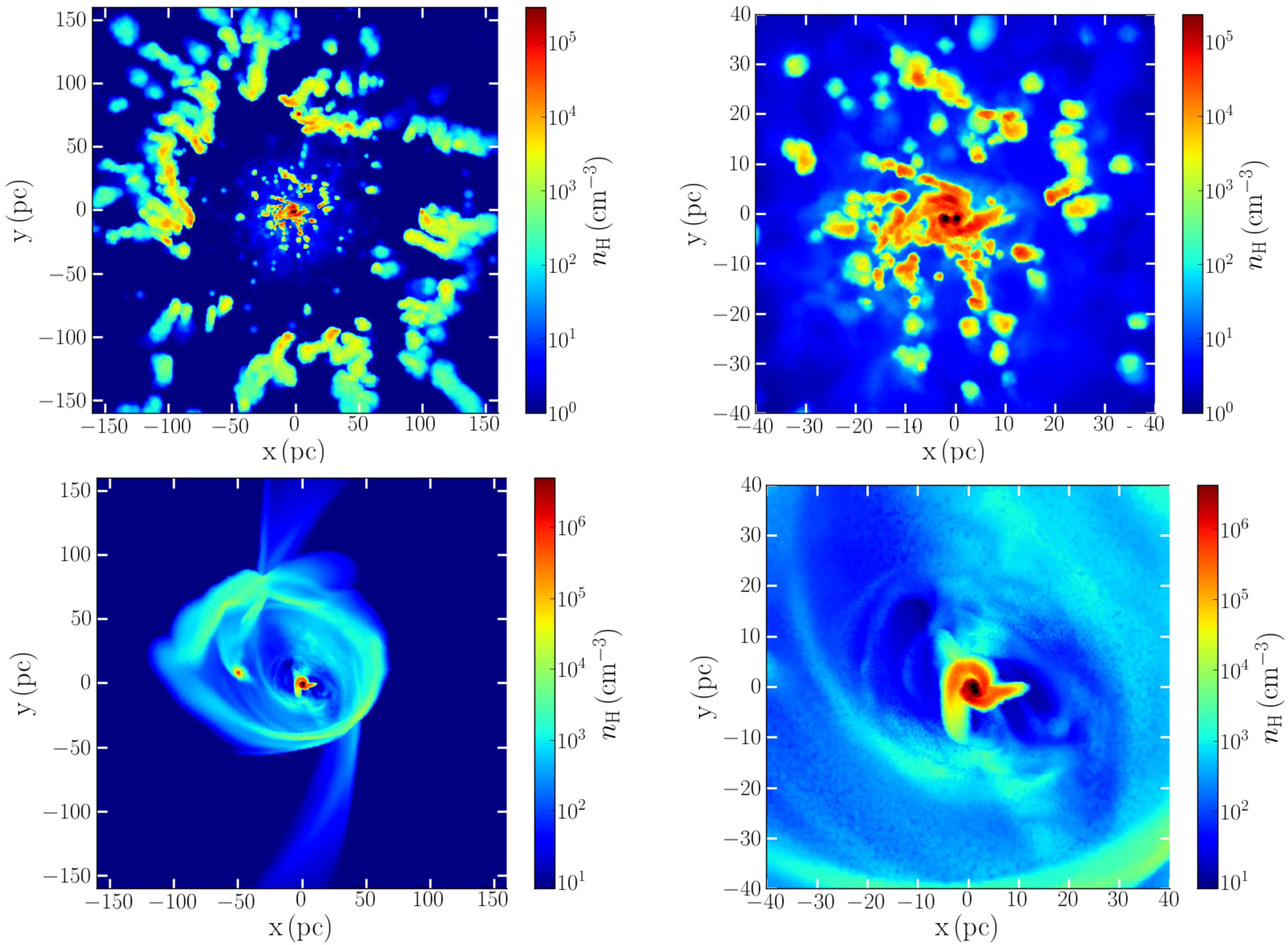




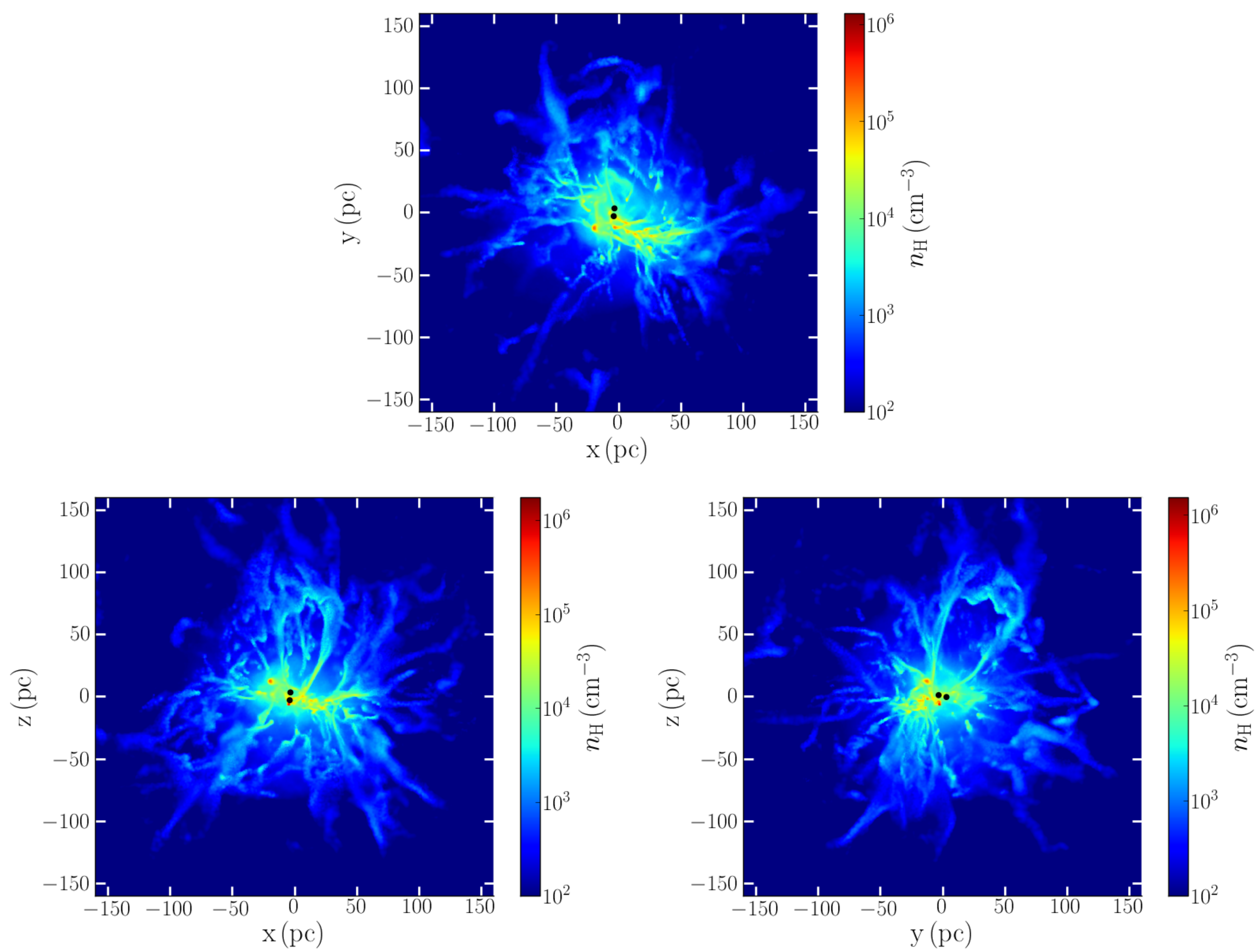


LUPI+ 2015

- thermal feed back with delayed SN explosions leaves a inner disc and no main disc structures around
- thermal feedback with prompt SN explosions leaves an outer counter-rotating ring + an inner co-rotating ring



- blast wave feed back, modeling the expansion of supernova driven bubbles, leave the black holes in the midst of a triaxial gas distribution with a denser central core
- need of recipes "calibrated" - matching observations with simulations
- caution - not faithful modeling of the feedback implies unphysical results

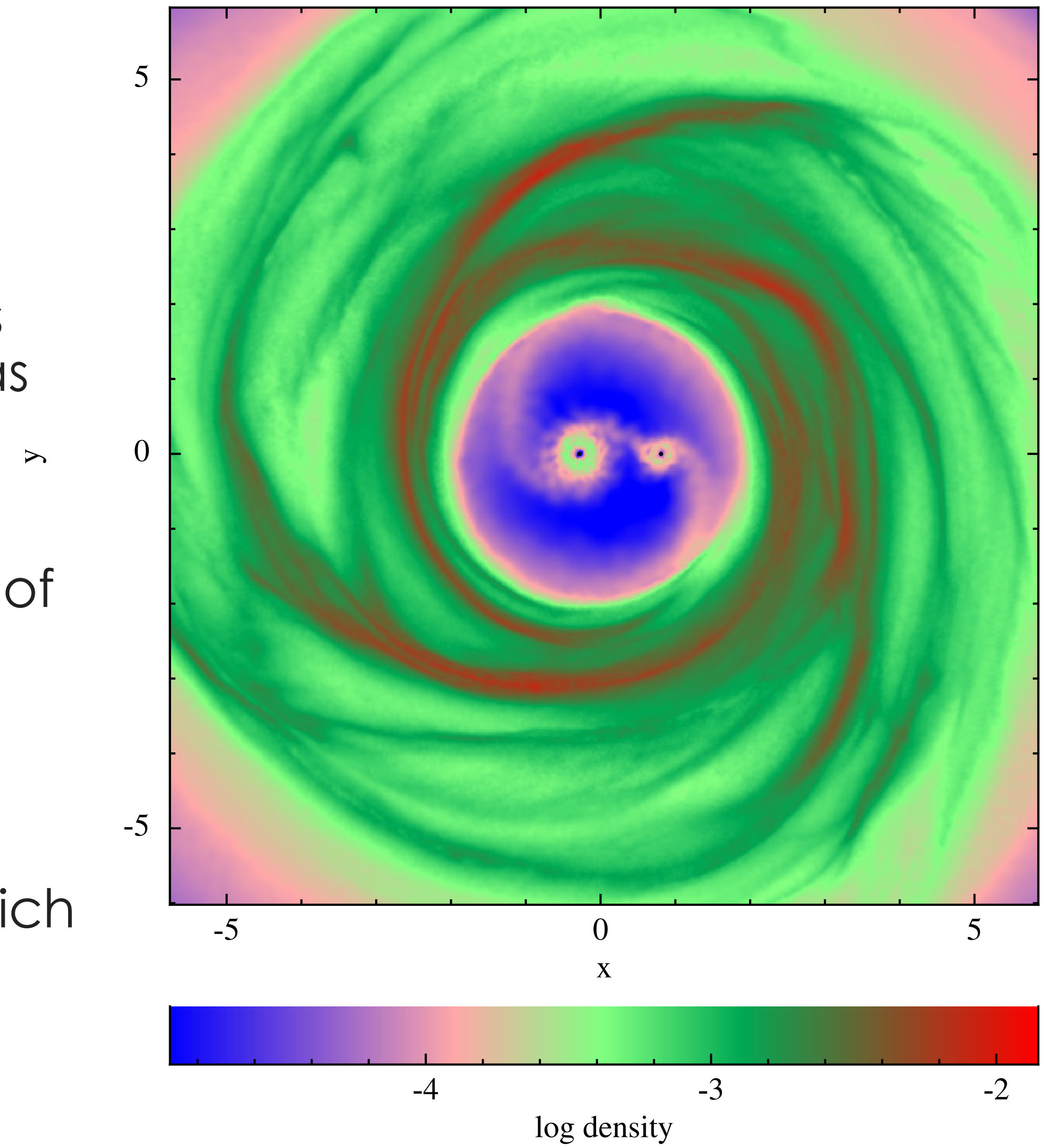


- focus now on a binary surrounded by a circum-binary disc

GAP OPENING
TYPE II MIGRATION

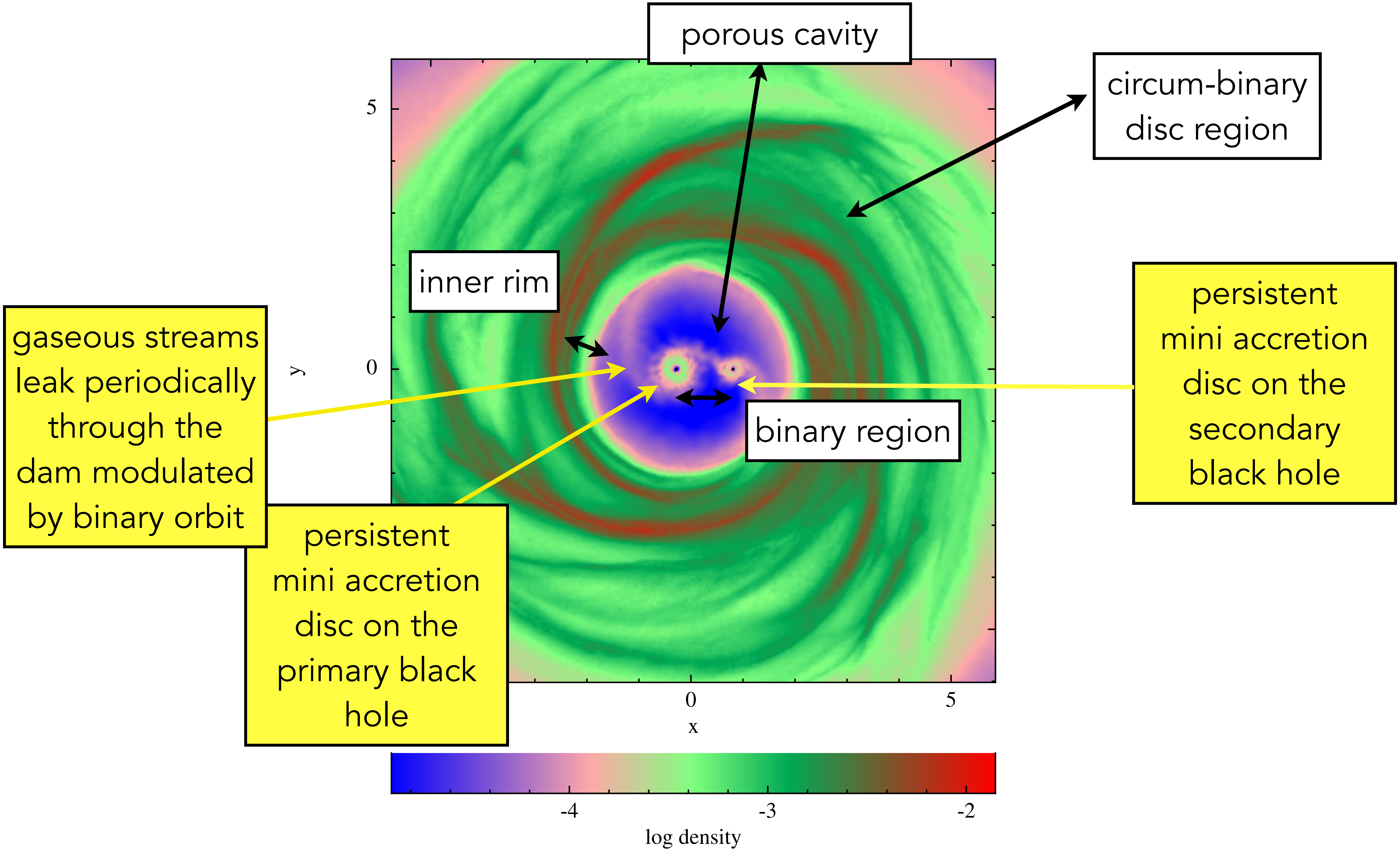
- Tidal torques from the binary drive gas outward clearing a hollow cavity. Viscous torques in the circum-binary disc allow gas to flow inward and refill the cavity
- Balance of tidal and viscous torques determine the location of the inner edge of the circum-binary disc $\tau_{viscous} < \tau_{GW}$
- Cavity has a size “twice the orbital separation”
- Gas enters the cavity through streams which feeds persistent mini-discs

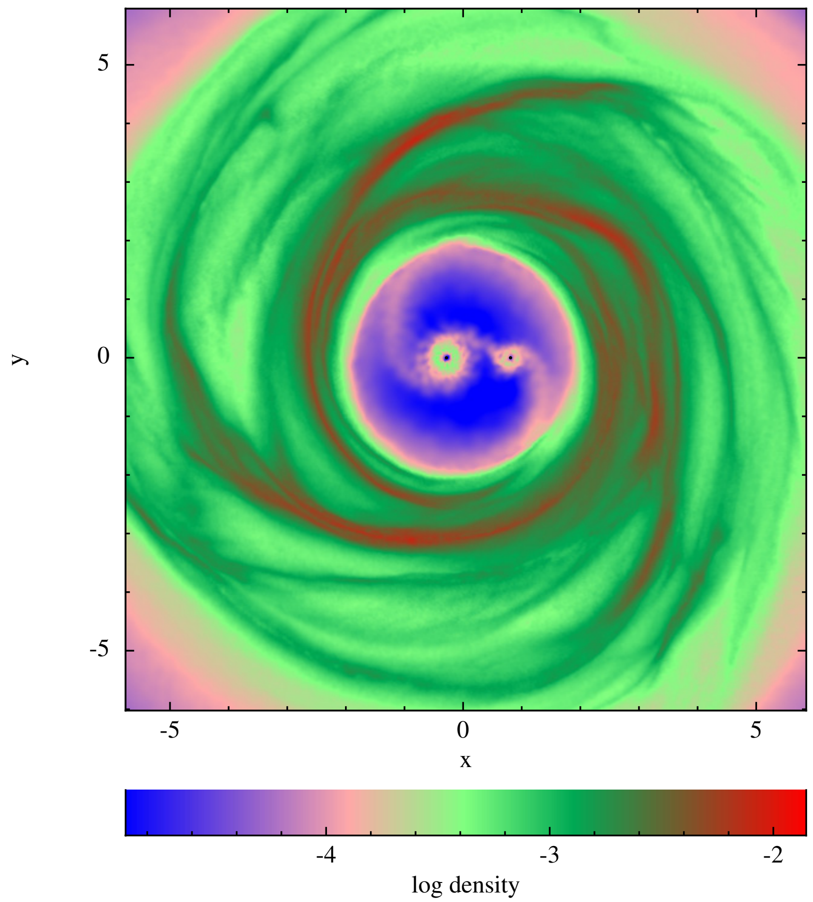
Color Coded Surface Density
face-on view of a geometrically
thin self-gravitating gas disc



SPH 3D simulations
Roedig, Sesana, MC +. 2011
Roedig, Sesana + 2012
Farris+ 2014

Pre-decoupling phase

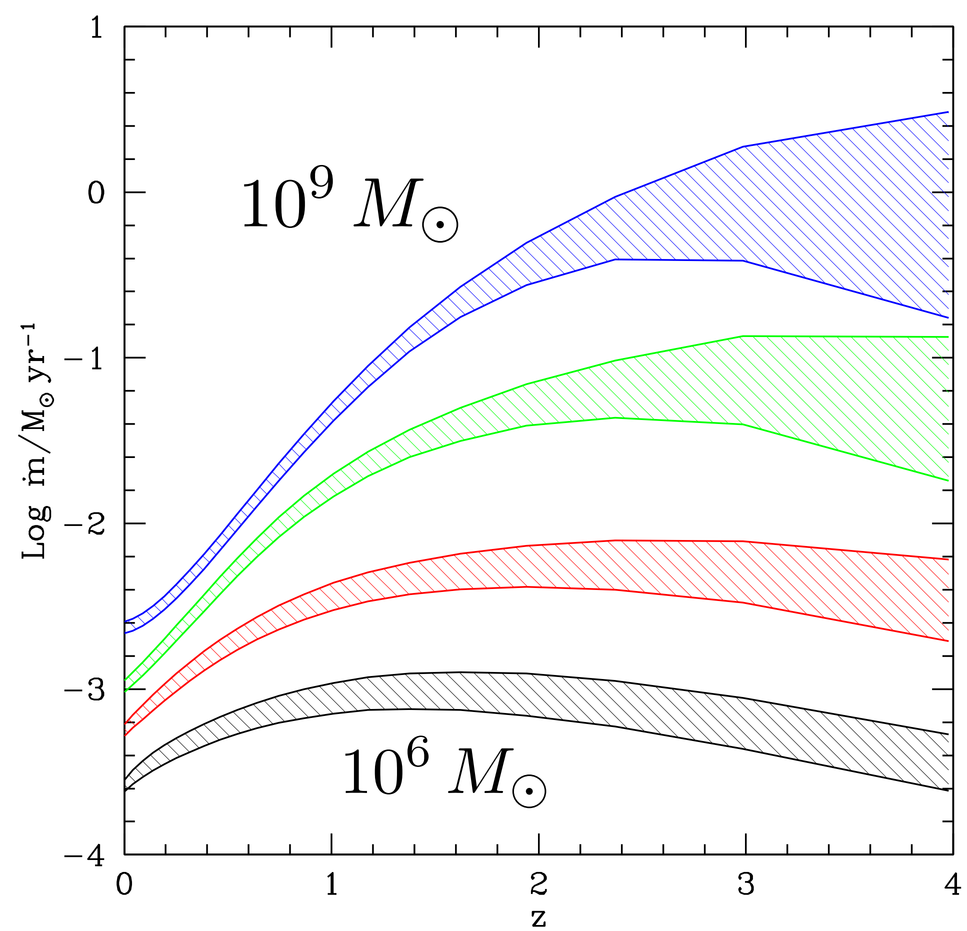




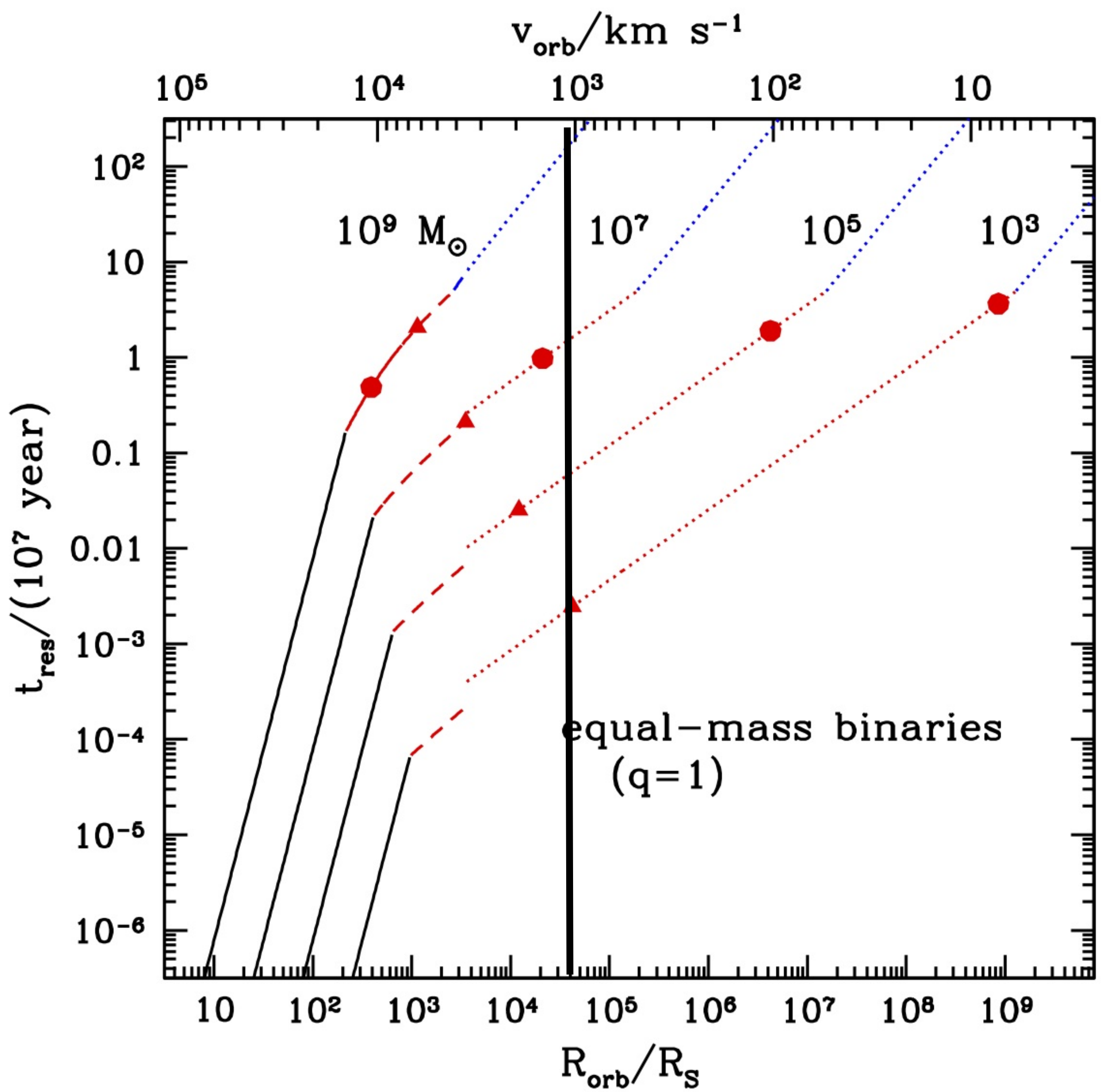
$$\frac{dL_{\rm BHB}}{dt} = \dot{m}\sqrt{GM_{\rm BHB}r_{\rm GAP}}$$

$$\frac{\mu}{2\sqrt{2}}\,\frac{\mathrm{d}a}{a} \approx -\dot{m}\,\mathrm{d}t,$$

$$\Delta t_{\rm BHB} \sim \ln\left(\frac{a_i}{a_c}\right)\frac{\mu\,\epsilon\,c^2}{2\sqrt{2}\,L_{\rm Edd}} \sim 10^7\,\frac{q}{(1+q)^2}\ln\left(\frac{a_i}{a_c}\right)\,\mathrm{yr}$$

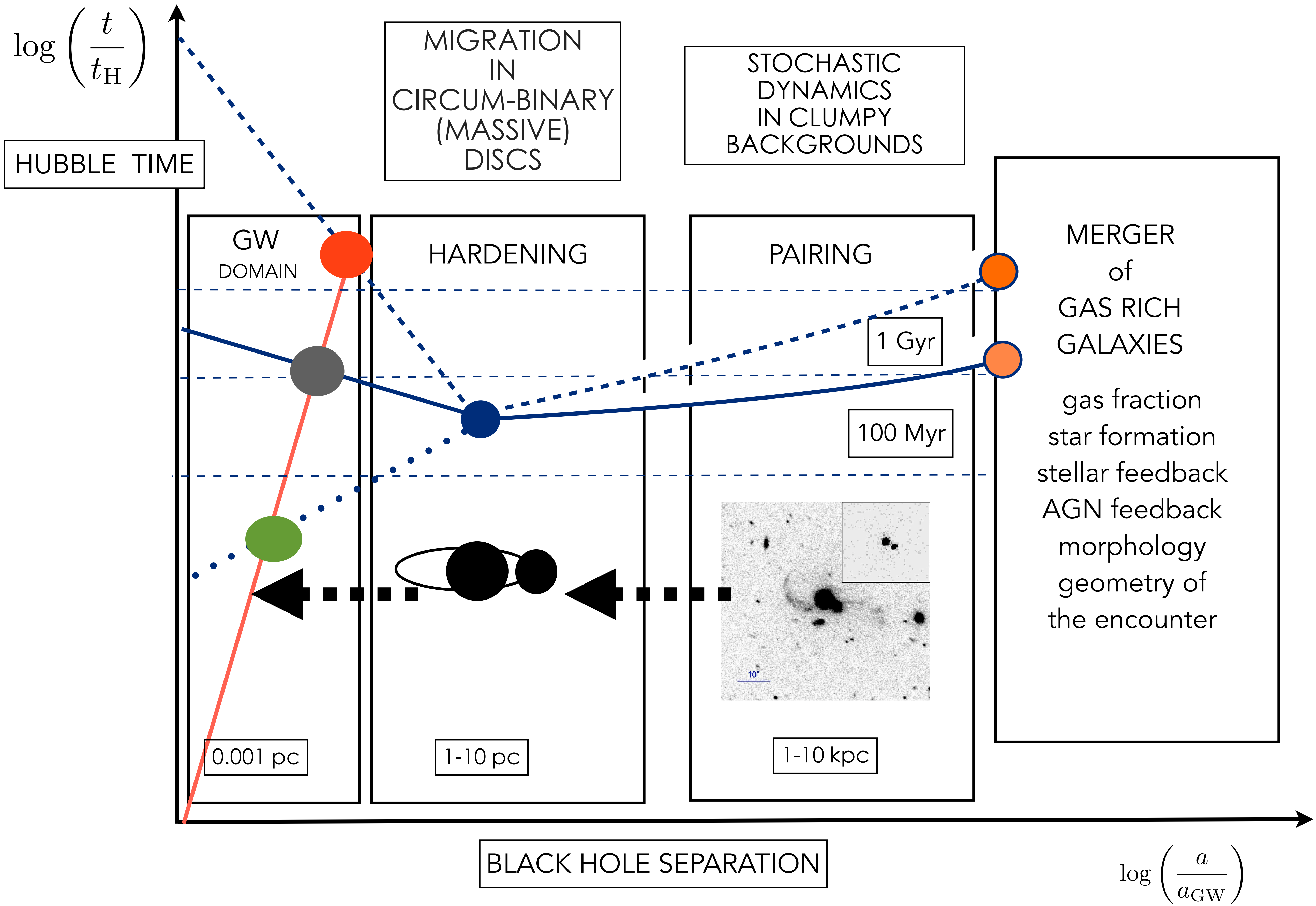


- constraining the accretion rate for AGN samples
- Dotti+2015 find that any binary formed at z~2 can coalesce within current timee

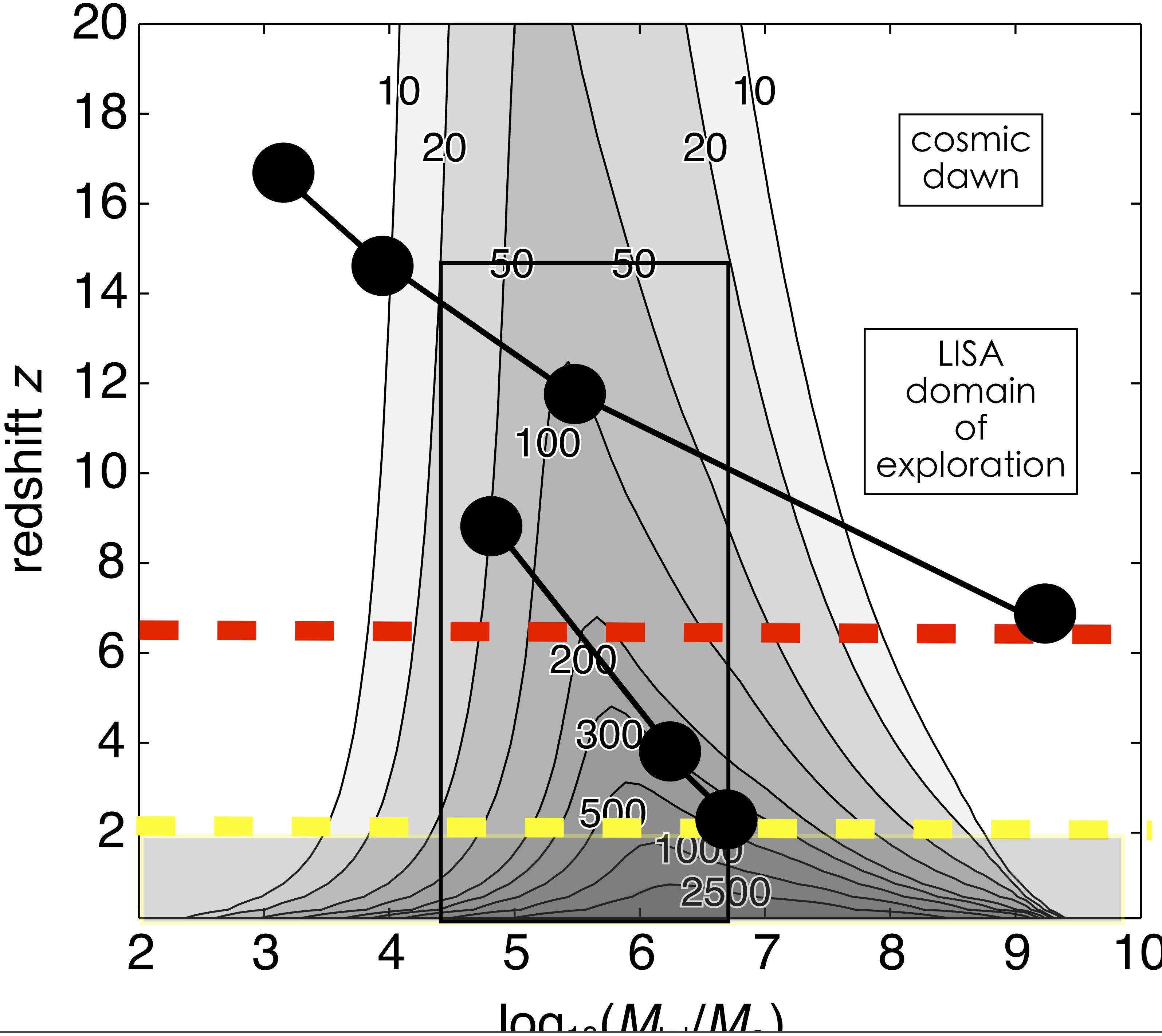


v_{orb}/km s^{-1}
10^5
10^4
10^3
10^2
10
$10^9\ M_\odot$
10^7
10^5
10^3
10^2
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$t_{res}/(10^7$ year)
equal−mass binaries
(q=1)
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
R_{orb}/R_S

HAIMAN+ 09

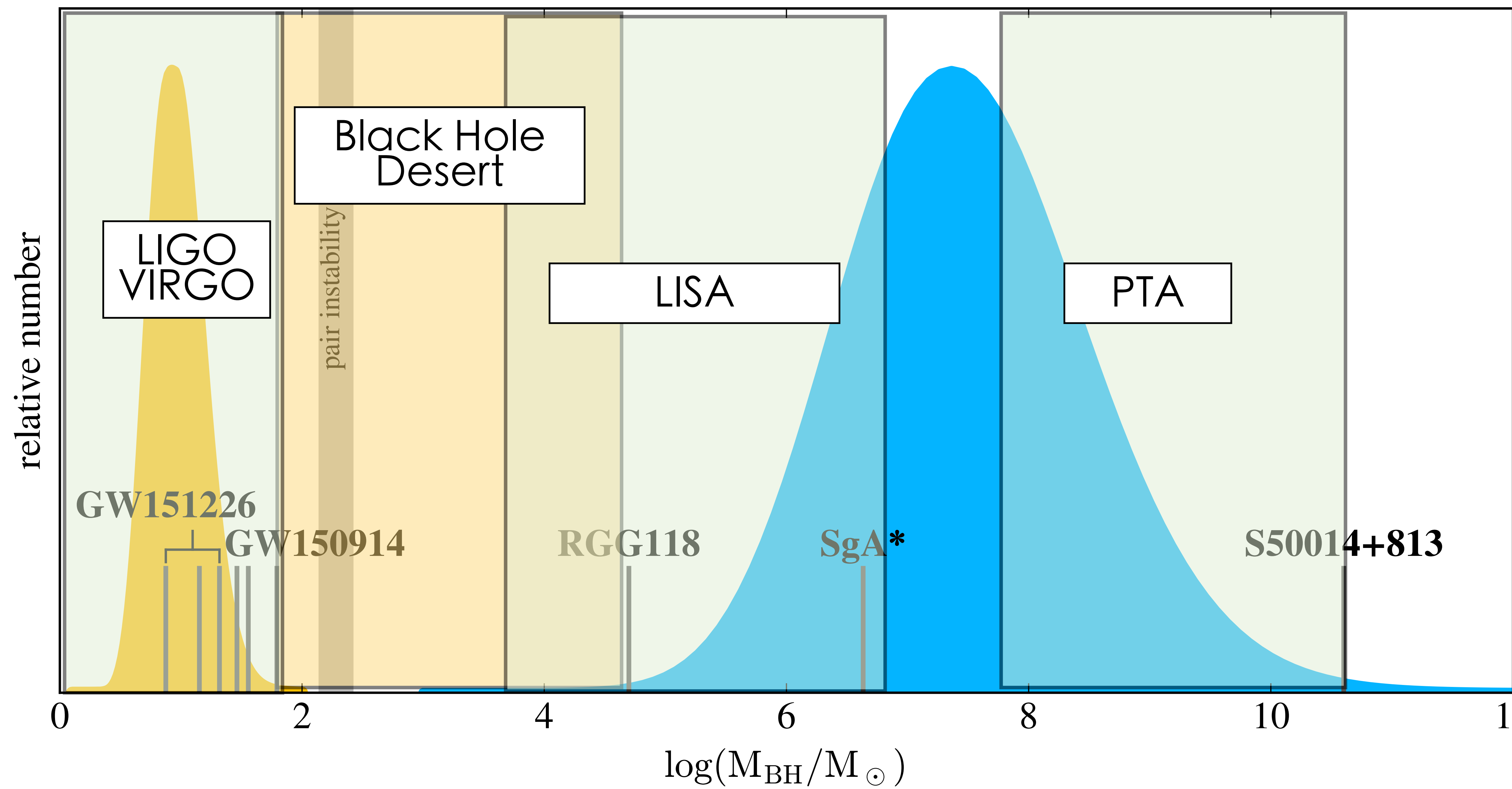

$\log\left(\frac{t}{t_H}\right)$
HUBBLE TIME
MIGRATION IN CIRCUM-BINARY (MASSIVE) DISCS
STOCHASTIC DYNAMICS IN CLUMPY BACKGROUNDS
GW DOMAIN
HARDENING
PAIRING
MERGER of GAS RICH GALAXIES
gas fraction
star formation
stellar feedback
AGN feedback
morphology
geometry of the encounter
1 Gyr
100 Myr
0.001 pc
1-10 pc
1-10 kpc
BLACK HOLE SEPARATION
$\log\left(\frac{a}{a_{GW}}\right)$

the beauty & strength of LISA science



the gravitational universe

a universe of binary black holes



CONCLUSIONS

- the last parsec problem resolved (1 Gyr)
- gas-rich mergers are far more complex to model
- gas-fraction/amount of molecular gas/star formation/ stellar feedback/AGN feedback make black hole dynamics far more complex to model
- state of the art numerical simulations are just in their infancy - need to explore a wide parameter space
- EM observations of DUAL- sub-pc binary AGN are in their infancy
- EM observations of galaxies at high redshift will better anchor our modeling of galaxy mergers