GROWING BINARY BLACK HOLES THROUGH GALACTIC MERGERS

MONICA COLPI

DEPARTMENT OF PHYSICS G. OCCHIALINI, UNIVERSITY OF MILANO BICOCCA

COST Action MP0905

BLACK HOLES IN A VIOLENT UNIVERSE

3rd Working Groups Meeting, Bologna, Italy, April 12-13 2011

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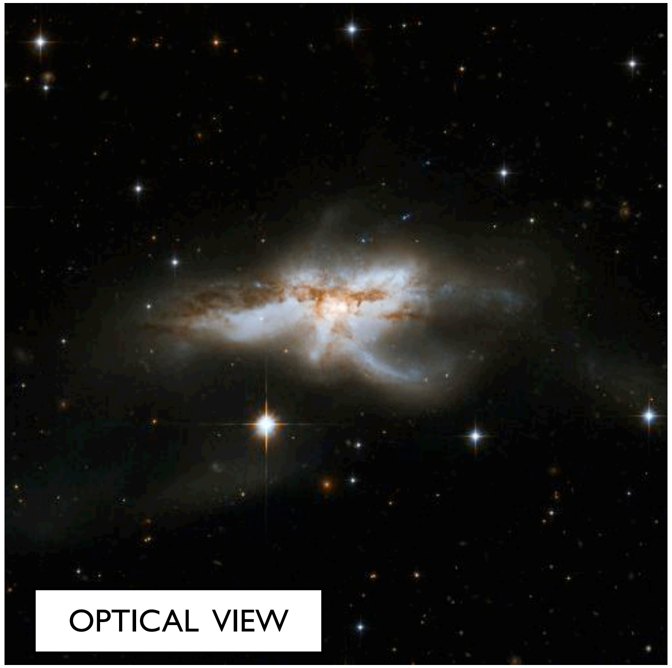
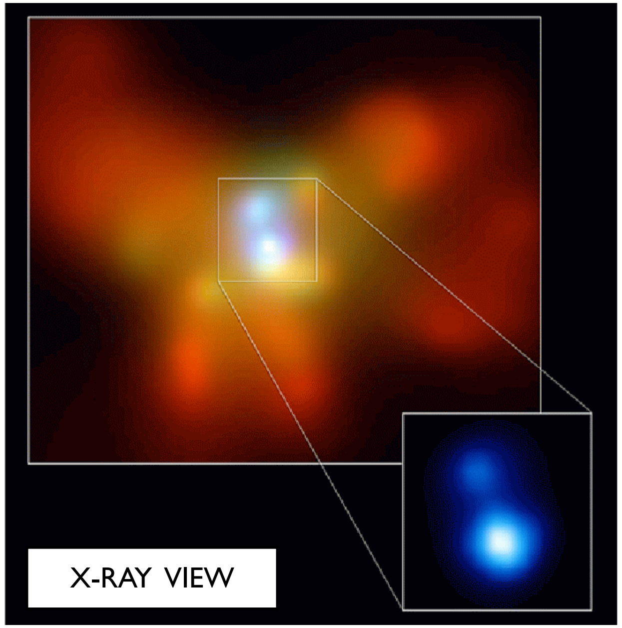
TWO SUPERMASSIVE BLACK HOLES
TWO COLLIDING GALAXIES





NGC 6240 MAJOR MERGER

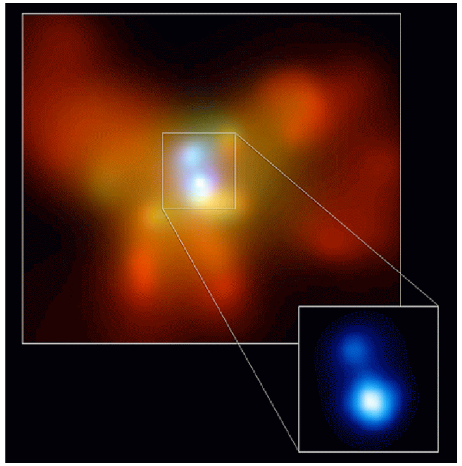
DUAL AGN

KOMOSSA et al. 1998, 2003
RISALITI et al. 2006
GREVE et al. 2006
CLARKE et al. 2007

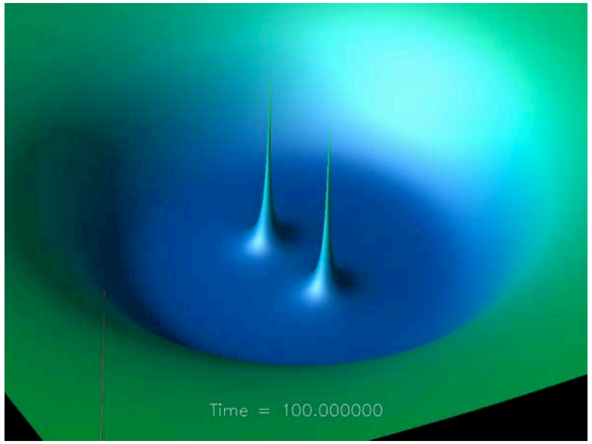
700 pc

WHAT IS THE BLACK HOLE DYNAMICAL FATE
in the time varying gravitational potential of the merger?

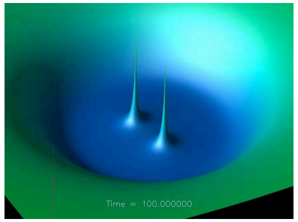
WILL THEY FORM A CLOSE PAIR?



WHEN/IF THEY FORM
A KEPLERIAN BINARY
IS NATURE
CONDUCIVE
TO BLACK HOLE
COALESCENCE
?



is coalescence important?



BINARY BLACK HOLES
POWERFUL SOURCES
OF
GRAVITATIONAL WAVES
DETECTABLE @ HIGH REDSHIFT

PRIMARY TARGETS FOR PLANNED
GRAVITATIONAL WAVE OBSERVATORIES
LASER INTERFEROMETER SPACE ANTENNA
PULSAR TIMING ARRAY EXPERIMENT

WAVEFORMS
HOLE's MASSES & SPINS
MEASURED WITH EXTREME ACCURACY

REVEALING A SEQUENCE OF EVENTS
over a wide redshift range
BLACK HOLE GENESIS

BLACK HOLES GROW IN MASS

through

“ACCRETION”

OVER COSMIC TIME

FROM

“SEEDS”

(no-coalescences)

CONTENT

in

X-RAY BACKGROUND LIGHT

(Soltan’s argument)

&

MASS

inferred from the local population of quiescent black holes in spheroids

$$\rho_{\mathrm{BH,AGN}} \sim 2.2 - 4.5 \times 10^5\, M_\odot\, \mathrm{Mpc}^{-3}$$

$$\rho_{\mathrm{BH,local}} \sim 3 - 5.5 \times 10^5\, M_\odot\, \mathrm{Mpc}^{-3}$$

YU & TREMAINE 2002, MARCONI et al. 2004, GRAHAM ET AL. 2007, SHANKAR et al. 2008

HOW LIGHT WERE THE BLACK HOLE SEEDS?

"LIGHT SEED" BLACK HOLES of 100-1000 solar masses

POP III STARS
MULTIPLE RUNAWAY COLLISIONS OF MASSIVE STARS IN YOUNG STAR-CLUSTERS

" MASSIVE SEED" BLACK HOLES -LOW ANGULAR MOMENTUM UNSTABLE DISCS

$$M_{\rm BH,seed} \sim 5 \cdot 10^4\, M_\odot \left(\frac{M_{\rm Halo}}{10^7 M_\odot}\right) \left(\frac{1+z}{18}\right)^{3/2} \left(\frac{\lambda}{0.04}\right)^{3/2}$$

"VERY MASSIVE SEED" BLACK HOLES of 10^8 solar masses

in gas rich merger
10^8 solar masses are funneled down to sub-parsec scales in less than 10^5 years

WHICH IS THE PREFERRED SITE & PATHWAY ?
NO CLUE

coalescing binaries can provide such a clue !

MADAU & REES 2001 (POP III)
KOUSHIAPPAS et al. 2004 (UNSTABLE DISCS)
PORTEGIES ZWART & MACMILLAN 2002 (RUNAWAY STELLAR MERGERS)
DEVECCHI, VOLONTERI, MC, HAARDT 2010
BEGELMAN, VOLONTERI & REES 2006 (QUASISTARS)
MAYER et al. 2010 (MASSIVE GAS DISCS IN MERGING GALAXIES)

BLACK HOLES GROW IN SYMBIOSIS WITH GALAXIES

“bigger” black holes are hosted in “bigger” galaxies

“smaller” black holes are hosted in “smaller” galaxies

M_{BH} versus M_* relation
M_{BH} versus sigma relation

FERRARESE & MERRITT 2000, GEBHARDT et al. 2000, YU & TREMAINE 2002,
MARCONI & HUNT 2004, HARING & RIX 2004, GRAHAM et al. 2010, HOPKINS et al. 2007

Λ-CDM PARADIGM

HIERARCHICAL FORMATION OF COSMIC STRCTURES

SMALL DARK MATTER HALOS ARE BELIEVED TO
GROW THE **FIRST** BLACK HOLE **“SEEDS”**
WITH MASSES IN PROPORTION
TO THEIR BARYONIC CONTENT

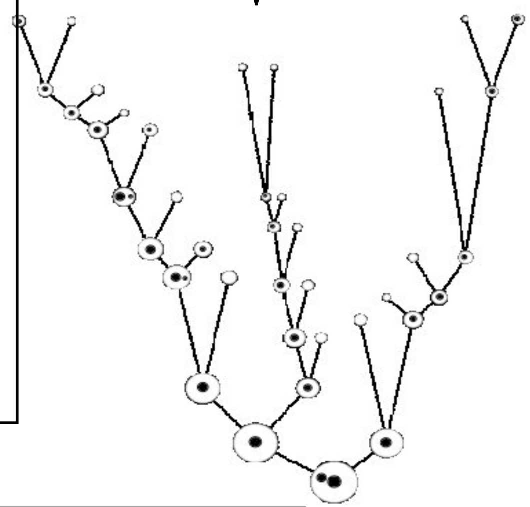
AS HALOS MERGE
SO
BLACK HOLES DO MERGE
AND INFLOWS OF GAS DRIVE THEIR GROWTH

BINARY BLACK HOLES
UNESCAPABLE OUTCOMES
OF
GALAXY FORMATION

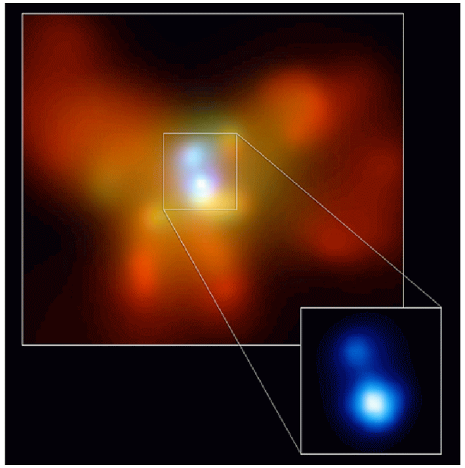
COALESCING BINARY BLACK HOLES
USED AS “PROBES”
TO TRACE IN THE CLEANEST WAY
THEIR FORMATION & GROWTH IN A COSMOLOGICAL FRAMEWORK

BLACK HOLE BINARY FORMATION & EVOLUTION
TWO COMPLEMENTARY APPROACHES

MODELING GALAXY ASSEMBLY
MONTE CARLO REALIZATIONS OF MERGER TREES
or/and
COSMOLOGICAL SIMULATIONS
supplemented by semianalytical recipes for the baryonic componet



HOW HIGH IS THE BLACK HOLE COALESCENCE RATE ?



COLLISION BETWEEN "GALAXIES" WITH CENTRAL BLACK HOLES

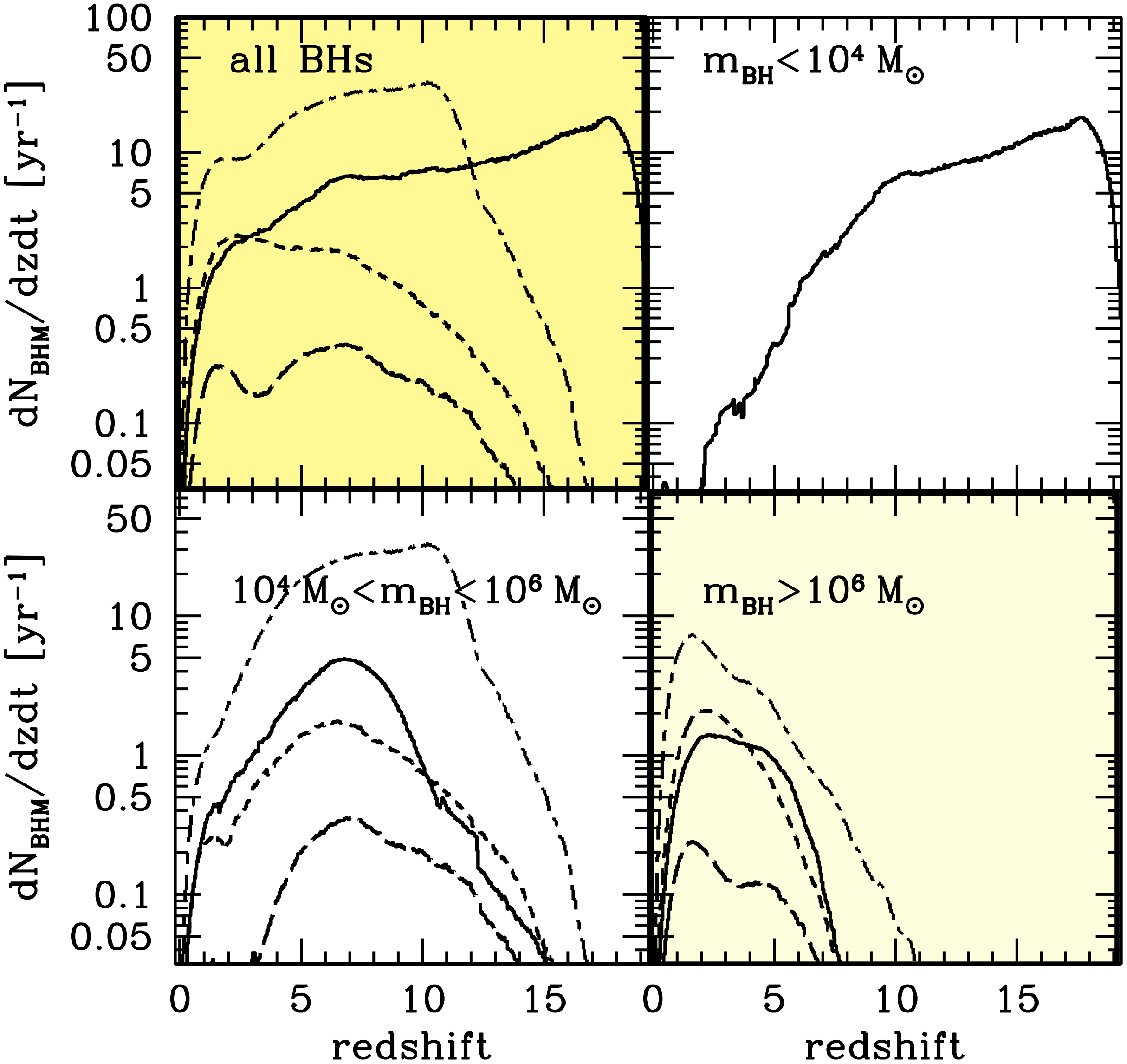
DETAILING THE **DYNAMICS**

COALESCENCE ?

Wyithe & Loeb 2003, Volonteri, Haardt & Madau 2003,
Sesana, Haardt, Madau & Volonteri 2004, Volonteri et al. 2005, Pelupessy, Di Matteo & Ciardi 2007

Escala et al. 2004, 2005, Kazantzidis, Mayer, Colpi et al. 2005, Mayer et al. 2007, Dotti et al. 2007
Springel, Di Matteo & Hernquist 2005, Di Matteo, Springel & Hernquist 2005

IMPRINT OF MASSIVE BLACK HOLE FORMATION MODELS ON THE LISA DATA STREAM
a few to 100 EVENTS over 5 years of LISA OPERATION



VHM

POP III

$M_{\rm BH,seed} \sim 100\, M_\odot$

KBD

$$M_{\rm BH,seed} \sim 5 \cdot 10^4\, M_\odot \left(\frac{M_{\rm Halo}}{10^7 M_\odot}\right) \left(\frac{1+z}{18}\right)^{3/2} \left(\frac{\lambda}{0.04}\right)^{3/2}$$

MOLECULAR COOLING

BVR

QUASISTAR

GRAVITATIONAL INSTABILITIES

SESANA, VOLONTERI & HAARDT 2007 (POP III)
KOUSHIAPPAS, BULOCK & DEKEL 2004 (HEAVY SEEDS)
BEGELMAN, VOLONTERI & REES 2006 (QUASISTARS)

ARE COALESCENCES POSSIBLE?

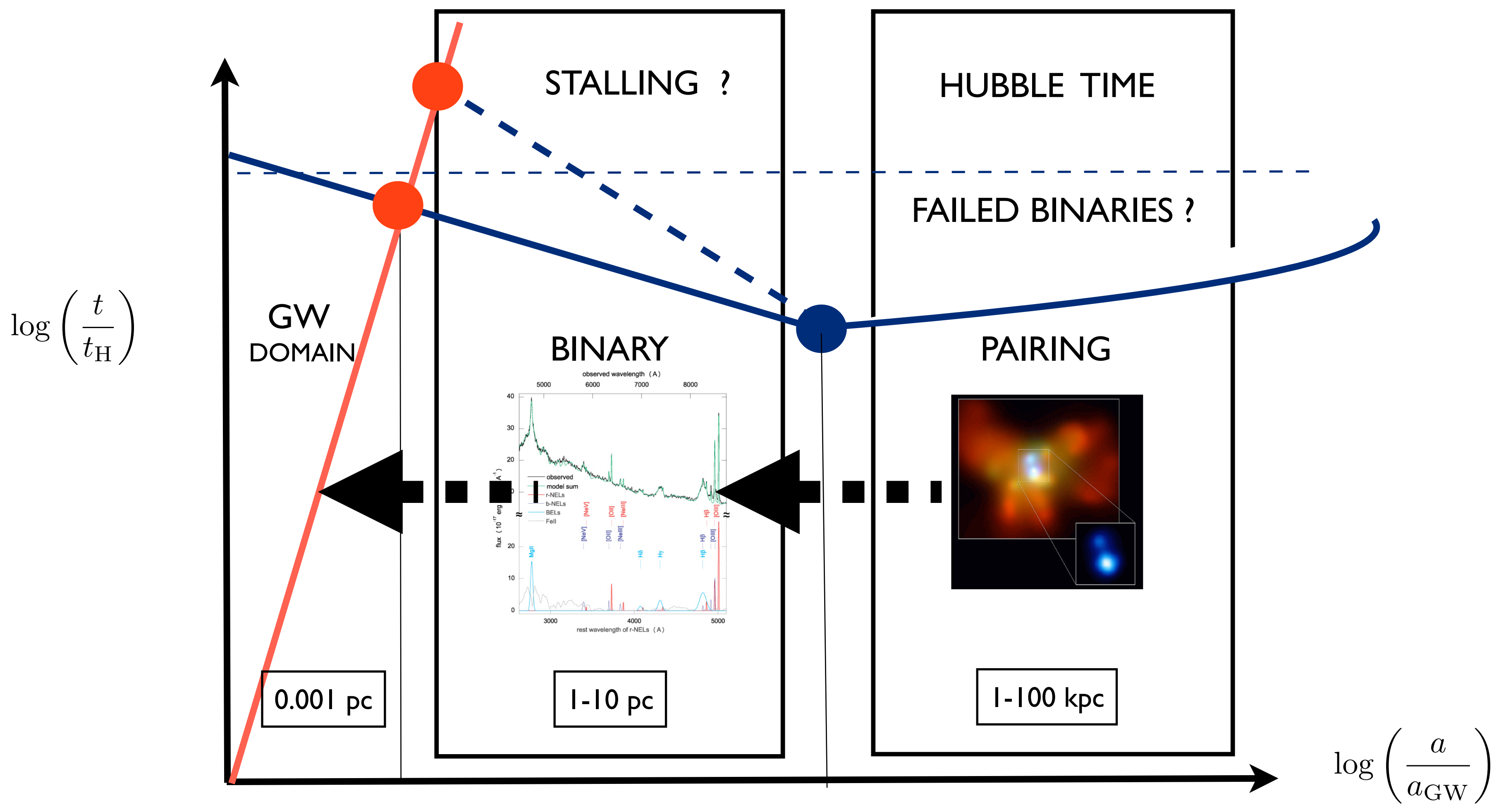
GRAVITATIONAL WAVE DOMAIN

$$a_{\rm GW} \sim 6 \cdot 10^{-3}\, f(e)^{1/4} \frac{q_{\rm BH}^{1/4}}{(1+q_{\rm BH})^{1/2}} \left(\frac{M_{\rm BH,T}}{10^7 {\rm M}_\odot}\right)^{3/4} \left(\frac{t_{\rm GW}}{10^9 {\rm yr}}\right)^{1/4} \;\; {\rm pc}$$

$$P(a_{\rm GW}) \sim 4 \left(\frac{M_{\rm BH,T}}{10^7 M_\odot}\right)^{5/8} \left(\frac{t_{\rm GW}}{10^9 {\rm yr}}\right)^{3/4} \;\; {\rm yr}$$

$$V_{\rm cir}(a_{\rm GW}) \sim 5000 \left(\frac{M_{\rm BH,T}}{10^7 M_\odot}\right)^{1/8} \left(\frac{t_{\rm GW}}{10^9 {\rm yr}}\right)^{-1/8} \;\; {\rm km\,sec^{-1}}$$

WHAT ARE THE PHYSICAL PROCESSES THAT CONTROL
THE **BLACK HOLES TRANSIT**
FROM THE **PAIRING** TO THE **BINARY STATE**
AND FINALLY TO **COALESCENCE ?**
WHAT ARE THE CHARACTERISTIC **TIMESCALES ?**



MAJOR MERGERS
OF
TWO DISC GALAXIES
MILKY WAY LIKE

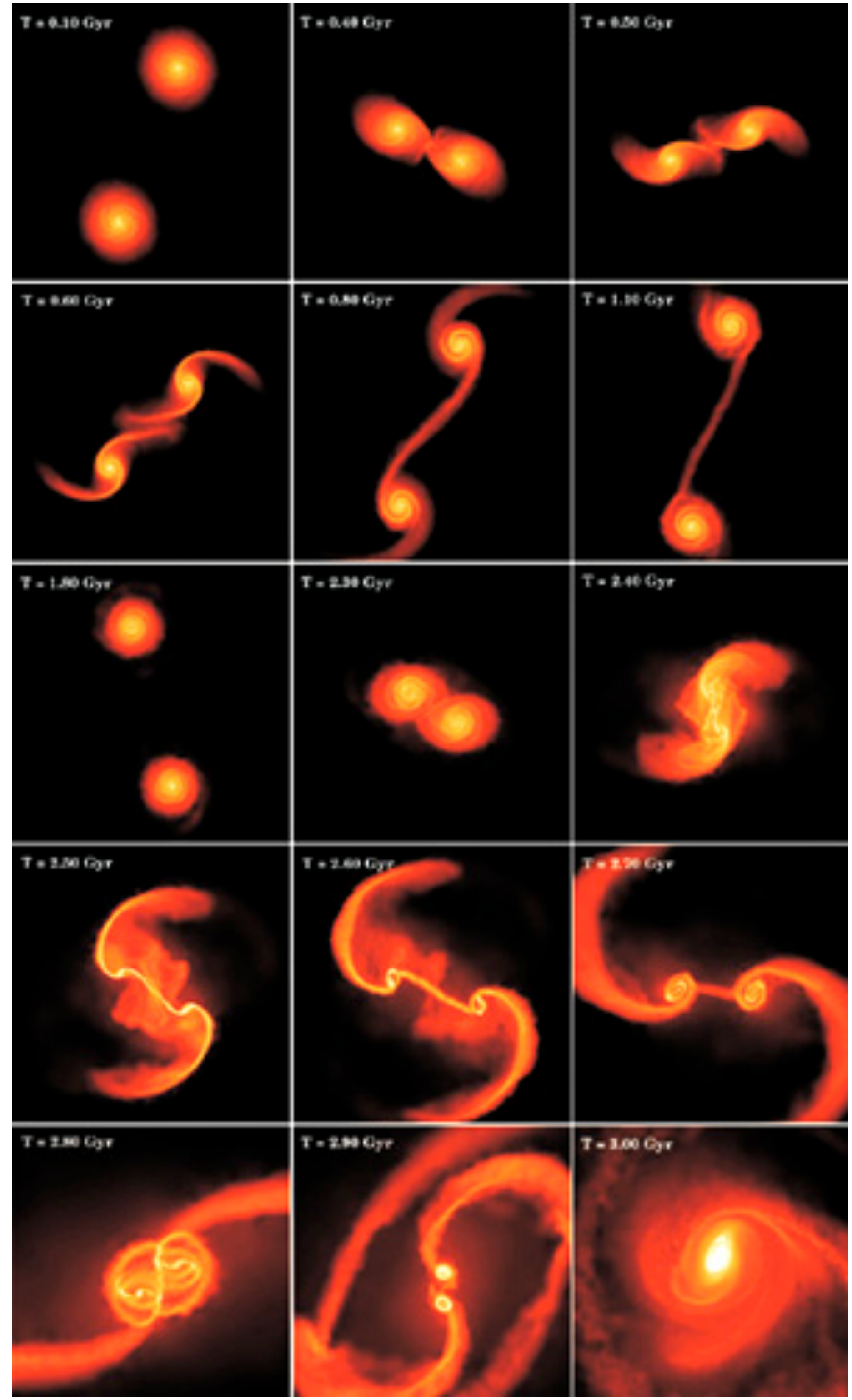
DYNAMIC RANGE
100 kpc to 2 pc

$$M_{\rm halo} \sim 10^{12}\, {\rm M}_{\odot}$$

$$M_{\rm disc} \sim 4 \times 10^{10}\, {\rm M}_{\odot}$$

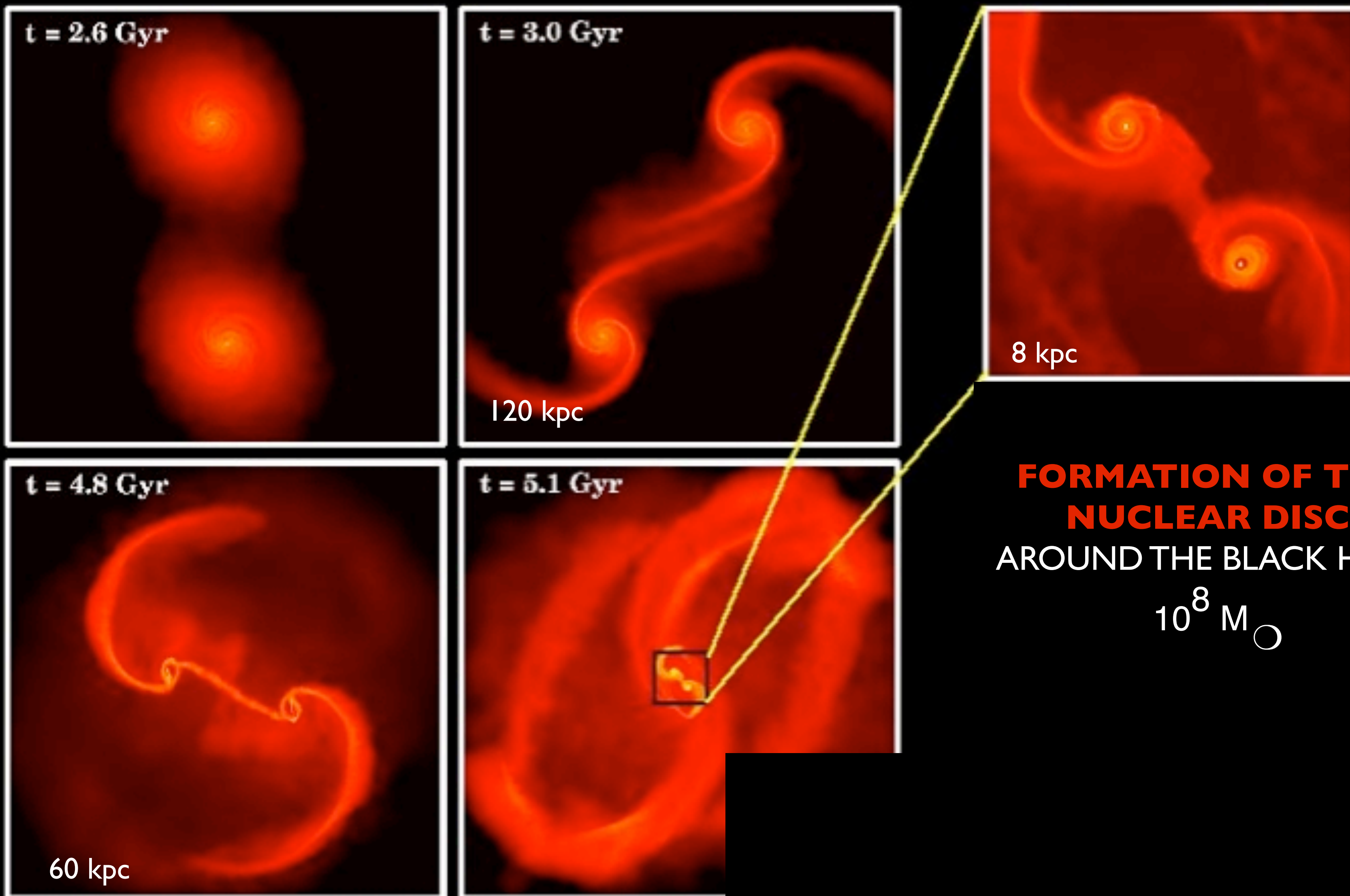
$$M_{\rm stellar\ bulge} \sim 8 \times 10^{9}\, {\rm M}_{\odot}$$

$$M_{\rm BH} \sim 3 \times 10^{6}\, {\rm M}_{\odot}$$



MAYER, MC, et al. 2007

GASOLINE N-BODY/SPH CODE (Wadsley et al. 2004)



FORMATION OF TWO NUCLEAR DISCS
AROUND THE BLACK HOLES
$10^8\ M_\odot$

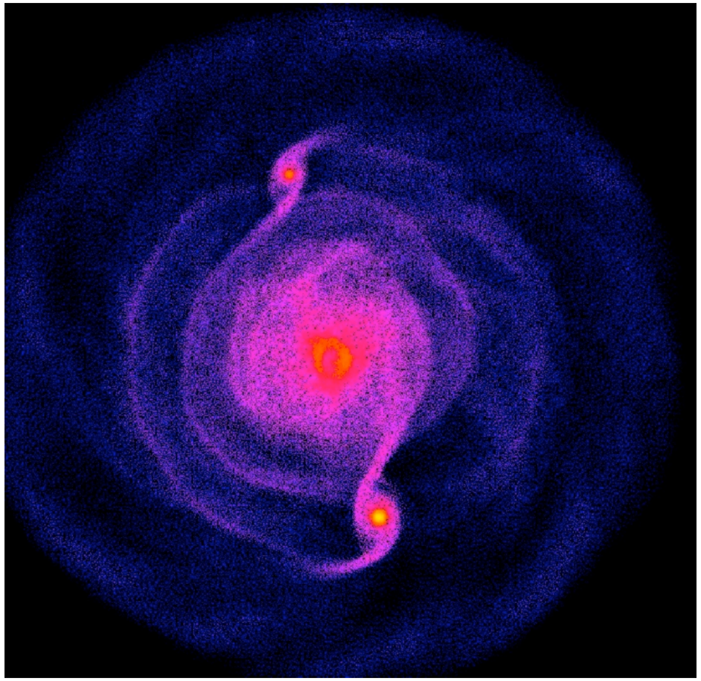
I. TIDAL FIELD EXCITES NON-AXISYMMETRIC PERTURBATIONS IN THE STELLAR DISC COMPONENT IN THE FORM OF A BAR
II. THE GAS RESPONDS TO THE PERTURBATION IN A DISSIPATIVE MANNER
III. ORBIT CROSSINGS OF FLUID ELEMENTS SHOCK THE GAS DRIVING A MAJOR INFLOW IN THE TWO DISCS WHERE THE BLACK HOLES SIT

BLACK HOLES “EMBEDDED” IN THE HEAVIER
DISCS CARRY
A MUCH LARGER MASS
AND SINK EFFECTIVELY TOWARD THE
CENTER
OF THE INTERACTING GALAXIES
BY DYNAMICAL FRICTION

FORMATION OF AN ECCENTRIC
KEPLERIAN BINARY
on parsec scales
EMBEDDED IN A MASSIVE
NUCLEAR GASEOUS DISC
OF BILLION SOLAR MASSES

MAYER, MC, et al. 2007

GAS-DYNAMICAL FRICTION GUIDES BLACK HOLE INSPIRAL IN THE MASSIVE NUCLEAR DISC DOWN TO 0.1 parsec



DOTTI et al. 2006,2007,2009a,b
COLPI & DOTTI 2009
ESCALA et al. 2005
NIXON et al. 2010

I. THE DISTORTED WAKES ACT IN SUCH A WAY THAT THE ORBIT DECAYS AND BECOMES **CIRCULAR**

THE BINARY **COROTATES** WITH RESPECT TO THE GAS **LOSING MEMORY OF THE INITIAL ORBIT**

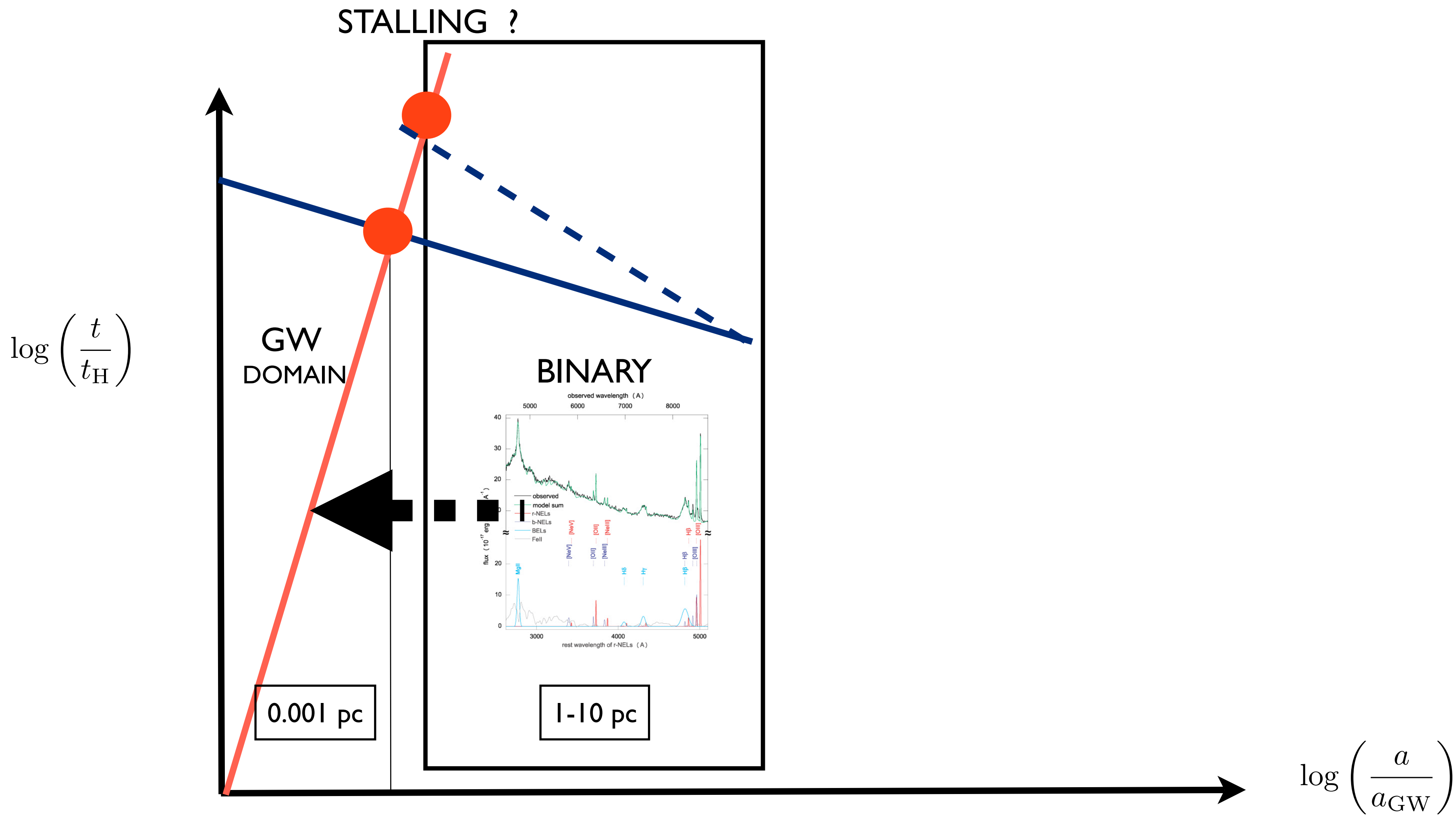
II. TENDENCY TO **COPLANARITY** OF THE ORBIT WITH THE NUCLEAR DISC

III. WHEN CIRCULAR THE TWO BLACK HOLES **START ACCRETING GAS** HAVING MINIMIZED THEIR VELOCITY RELATIVE TO THE GASEOUS BACKGROUND

IV. ORIENT THEIR SPINS PARALLEL TO THE ORBITAL ANGULAR MOMENTUM

THE LAST PARSEC PROBLEM

WILL THE BINARY CONTINUE TO HARDEN DOWN TO THE GW DOMAIN?



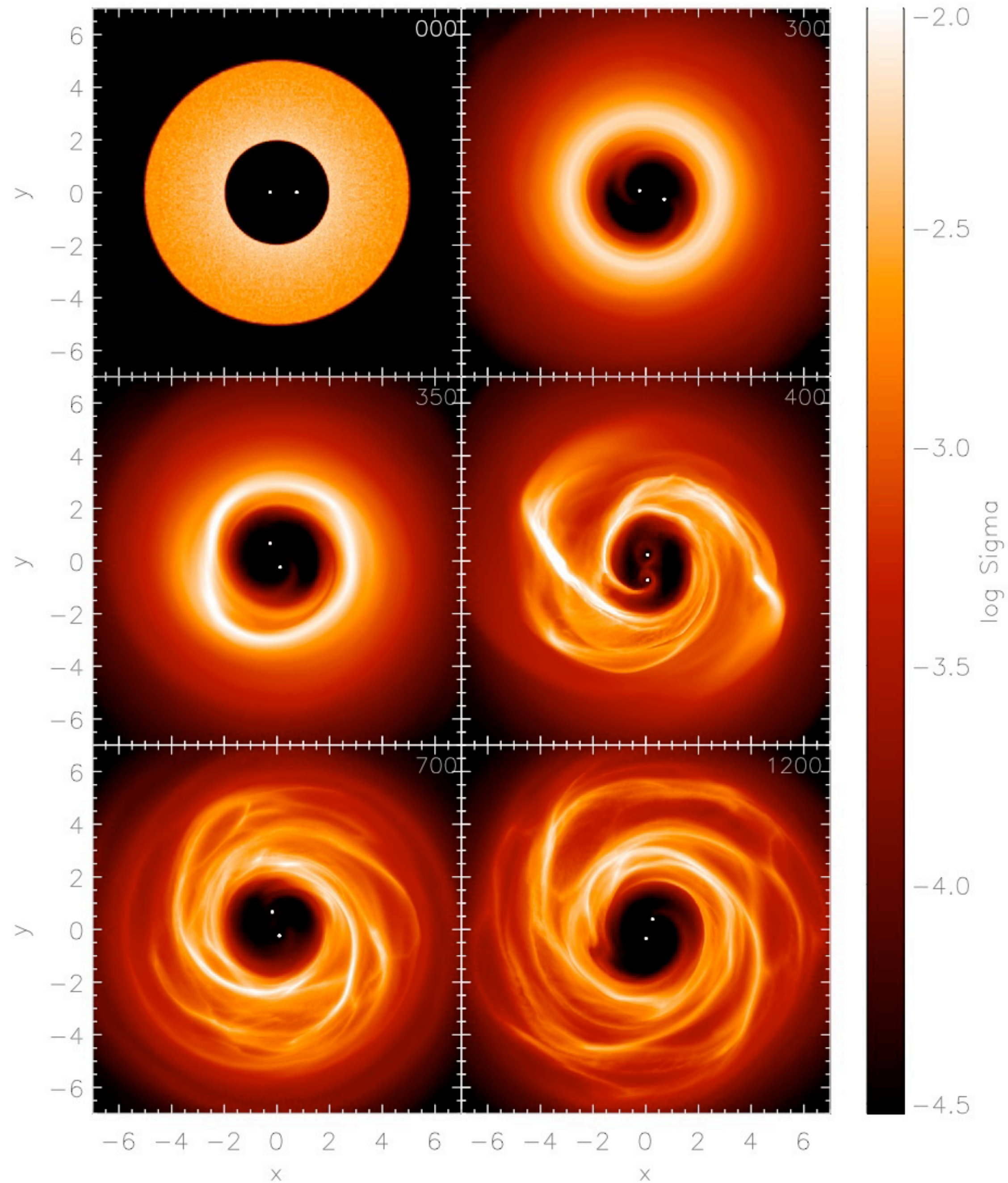
I. BINARY HARDENING IN CIRCUM-BINARY DISC

GAP OPENING

I. THE BLACK HOLES DEPOSIT ORBITAL ANGULAR MOMENTUM IN THE DISC AFTER EXCITING A TRAILING **SPIRAL WAVE OPENING A GAP**

II. TURBULENCE & VISCOSITY REDISTRIBUTE THE DISC ANGULAR MOMENTUM CAUSING INFLOWS THAT MAINTAIN THE CONTACT OF THE BINARY WITH THE DISC

EQUILIBRIUM BETWEEN **GRAVITATIONAL** TORQUE FROM THE BINARY AND **VISCOUS** TORQUE IN THE DISC
LEADS TO BLACK HOLE **MIGRATION**



CUADRA et al. ,2009, ROEDIG, MC et al. 2011
ARMITAGE & NATARAJAN 2002
GOULD 1990

II. BINARY BLACK HOLE HARDENING IN a STELLAR BACKGROUND

KEY PHYSICAL MECHANISM
single 3-BODY INTERACTION of
a STAR PLUNGING ONTO THE BINARY FROM
LOW ANGULAR MOMENTUM ORBIT

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

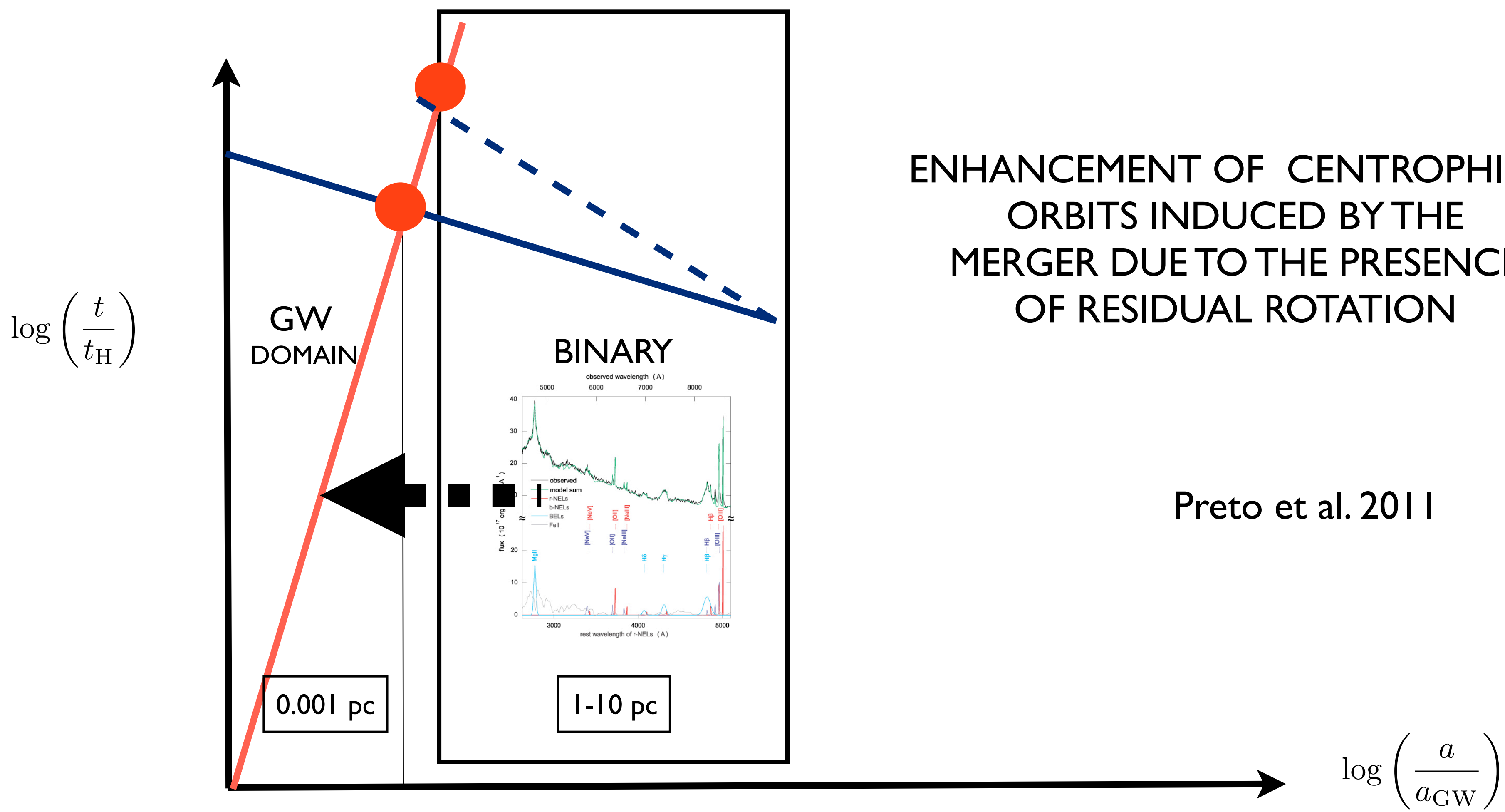
EJECTION sling-shot

LARGE RESERVOIR OF LOW J STARS
REFILLING OF THE LOSS CONE
ON RELAXATION TIMESCALE

MERRITT & MILOSAVLJEVIC
for a review 2005-08

THE LAST PARSEC PROBLEM REVISITED

COALESCENCE WITHIN A HUBBLE TIME



ENHANCEMENT OF CENTROPHILIC ORBITS INDUCED BY THE MERGER DUE TO THE PRESENCE OF RESIDUAL ROTATION

Preto et al. 2011

LISA (mHz)
EVENTS IN PRE-GALACTIC STRUCTURES
@
HIGH REDSHIFT

$$10^3 < M_{\rm BH}/M_\odot < 10^7$$

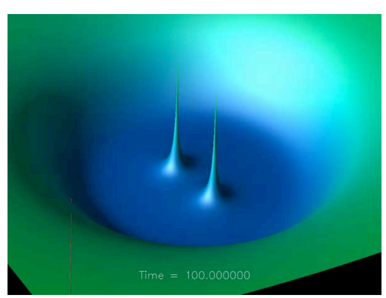
LISA
WILL UNVEIL THE UNKOWN
"LIGHT" SEED BLACK HOLES

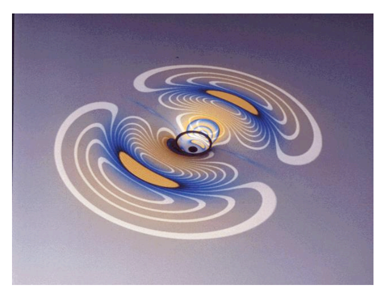
PULSAR TIMING ARRAYS (nHz)
INSPIRAL
@
LOW REDSHIFTS

$$10^8 < M_{\rm BH}/M_\odot < 10^9$$

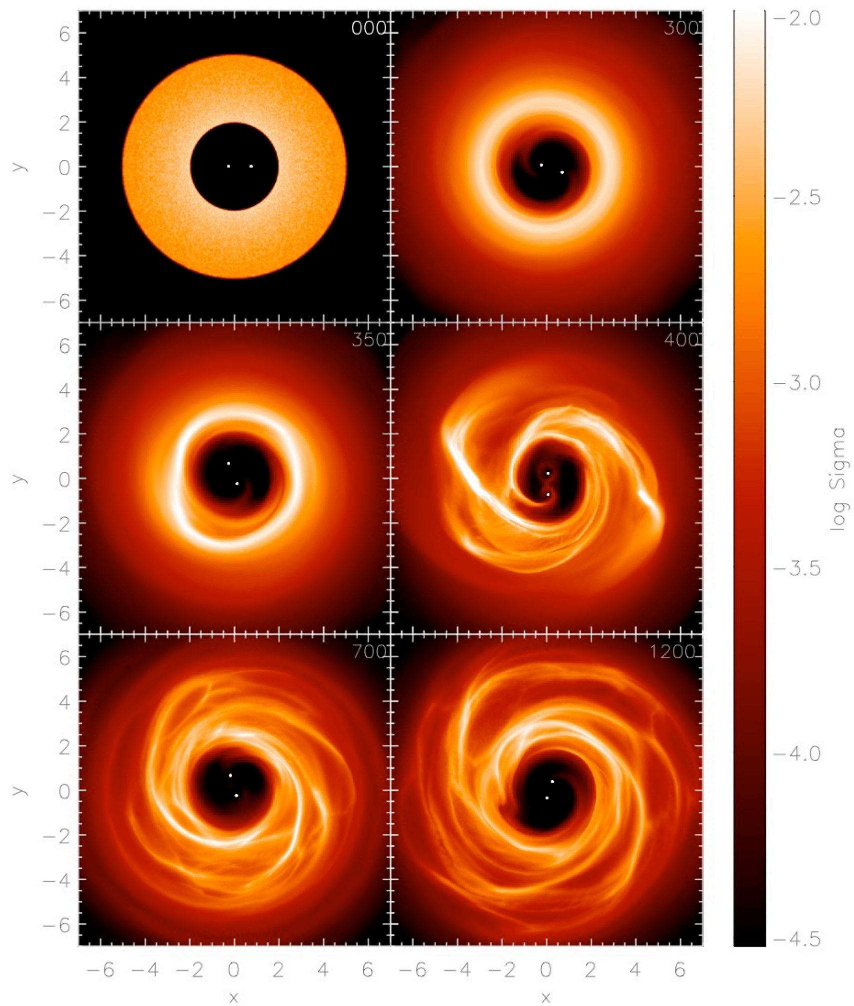
CONCLUSIONS & OUTLOOK

- **BINARY BLACK HOLES OCCUPY A SPECIAL PLACE IN THE VIOLENT UNIVERSE**
- **RICH PHYSICS**
- DISCOVERY PHASE: ONGOING INTENSIVE SEARCH OF **DUAL - BINARY - RECOILING AGN**
- **GRAVITATIONAL WAVE** "ASTRONOMY"
- **BLACK HOLE GENESIS**





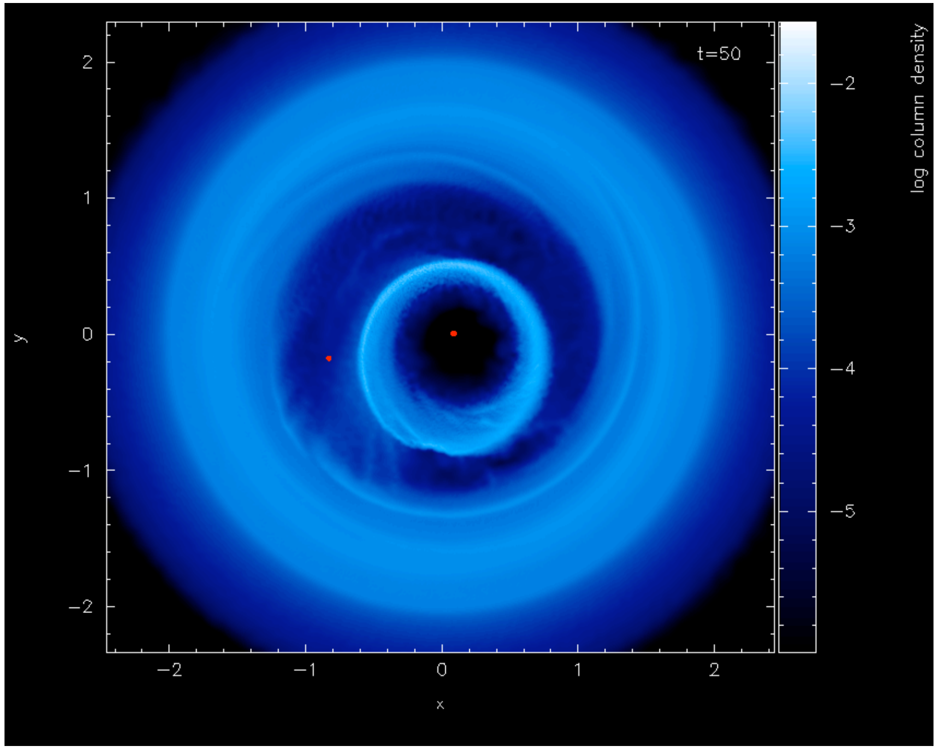
EXCRETION
DISC
PROGRADE ACCRETION



Pringle 1980

CUADRA et al. ,2009, ROEDIG, MC et al. 2011

RETROGRADE ACCRETION
NO GAP



NIXON et al. 2011