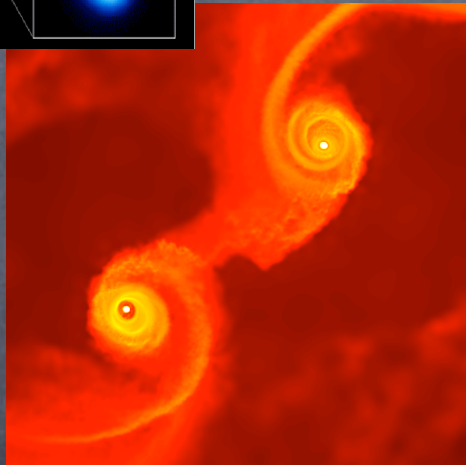
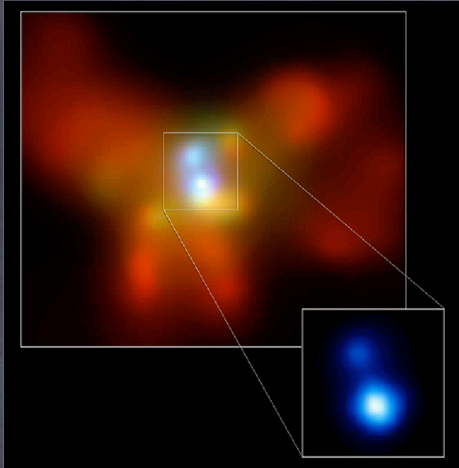


# GAS RICH GALAXY MERGERS & THE FORMATION OF MASSIVE BINARY BLACK HOLES



HIGH ENERGY ASTROPHYSICS  
&  
ASTRONOMY WITH GRAVITATIONAL WAVES

COSMIC EVOLUTION OF GALAXIES

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University of Milano Bicocca

LISA Astro-GR@AEI, 18 September 2006



# OUTLINE

° REVIEW KEY OBSERVATIONS  
OF MASSIVE BLACK HOLES IN GALAXIES

°° LINK WITH COSMOLOGY

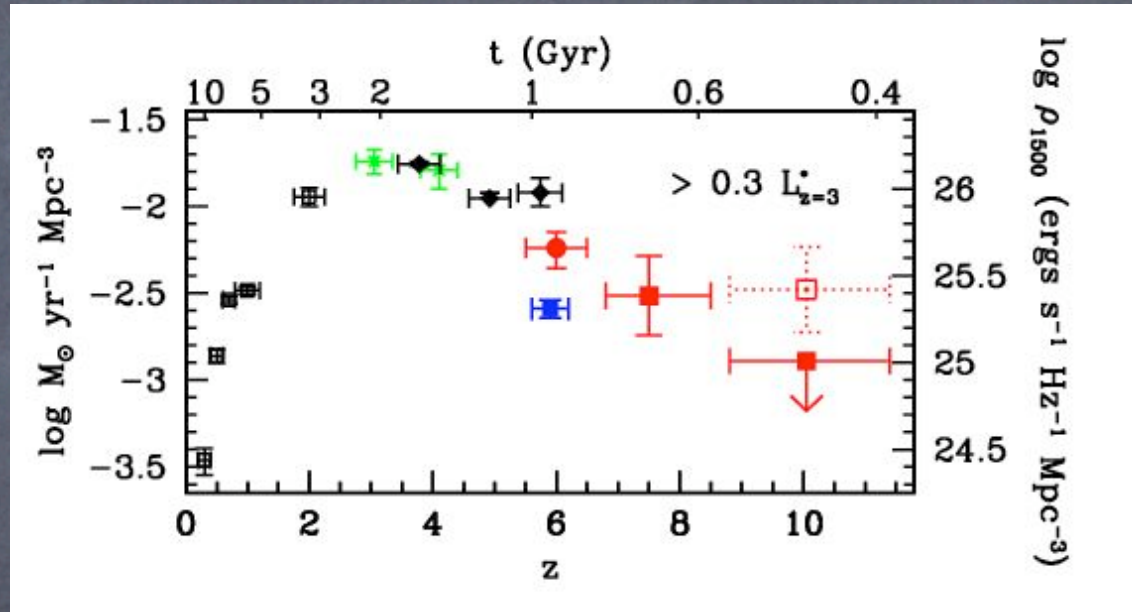
°°° THE FORMATION OF BINARY BLACK HOLES  
IN GALAXY MERGERS

°°°° SELF GRAVITATING CIRCUM-NUCLEAR DISCS  
AROUND BINARY BLACK HOLES

°°°°° ELECTROMAGNETIC SIGNAL  
DURING THE LAST YEAR OF BLACK HOLE INSPIRAL

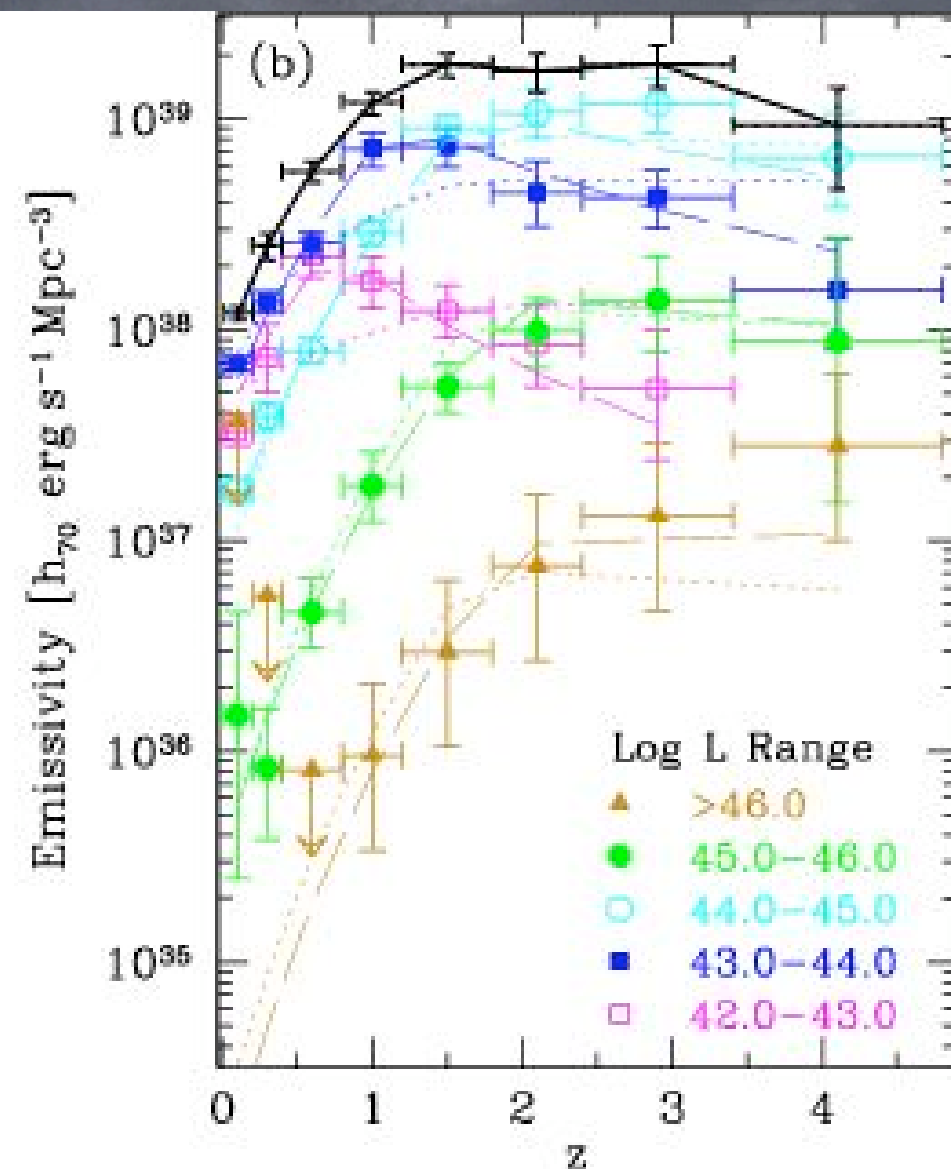
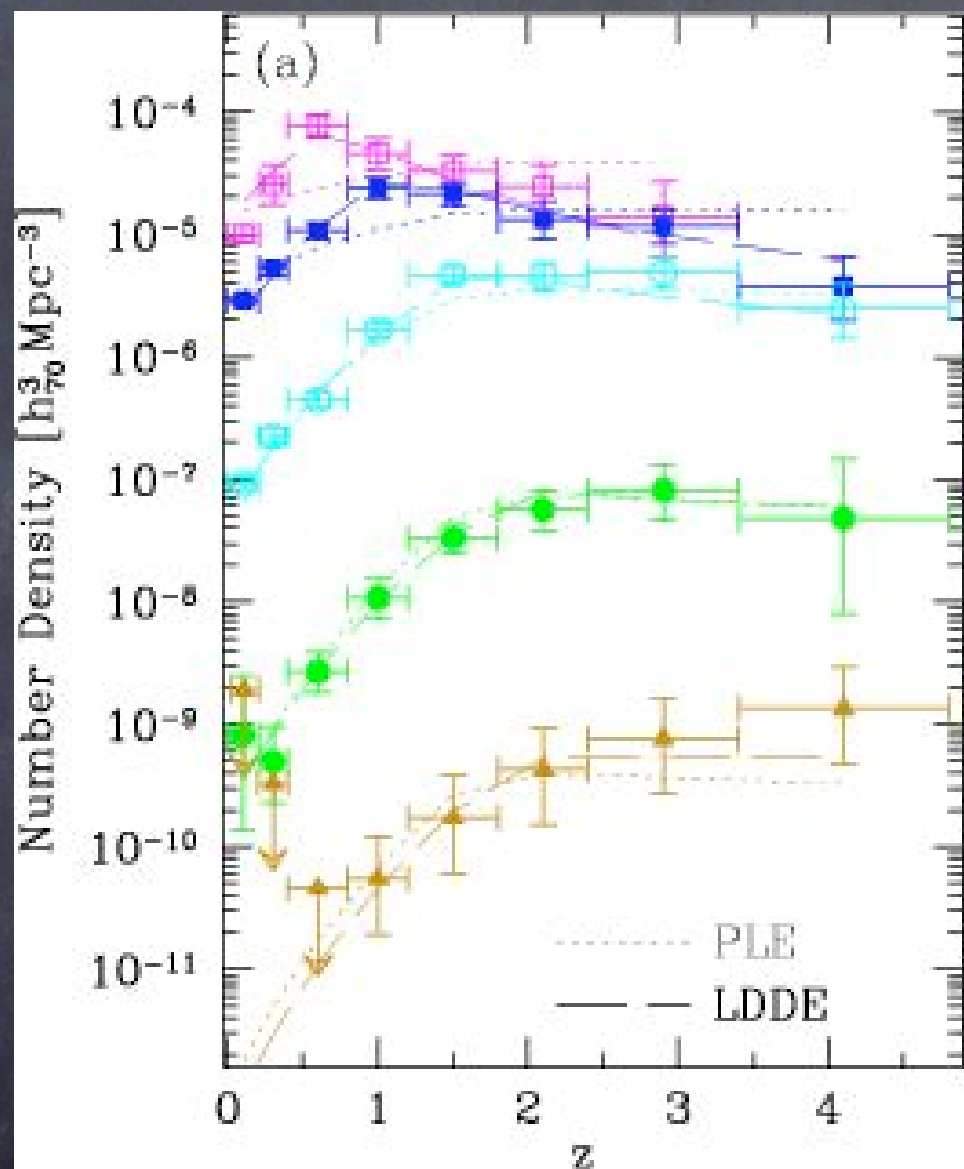
°°°°°° OPEN QUESTIONS

IN THE **HIGH REDSHIFT** UNIVERSE **BLACK HOLES** GROW IN MASS BY  
 EFFICIENT ACCRETION up  $10^6$  to  $10^9 M_{\odot}$   
 POWERING THE BRIGHT QUASARS  
 STRONG EVOLUTION WITH COSMIC TIME SYNCHRONOUS WITH  
 THAT OF GALAXIES

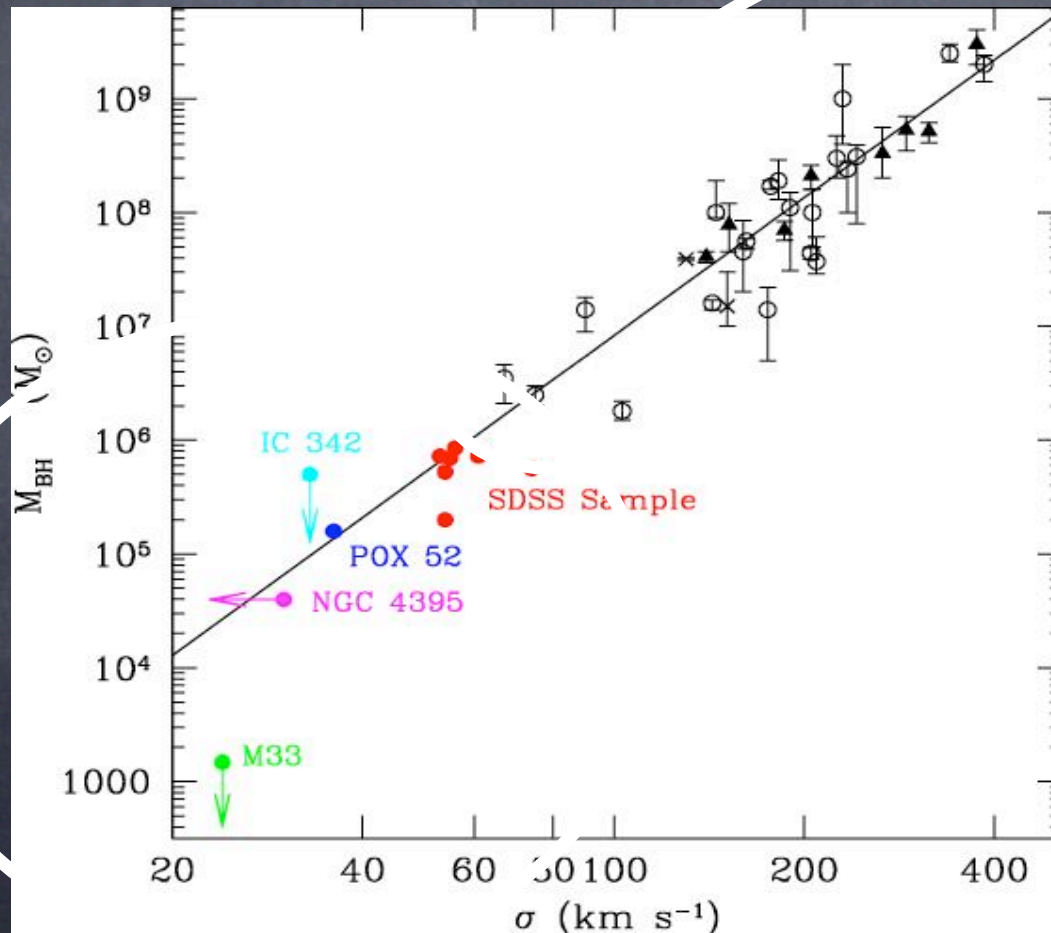


Star  
 Formation Rate  
 inside a volume  
 of 1 Mpc

IN THE **LOCAL** UNIVERSE MASSIVE QUIESCENT  
 BLACK HOLES  
 RESIDE IN BULGES & SPHEROIDS  
 MAJOR MERGERS



BLACK HOLE MASS CORRELATES TIGHTLY WITH  
THE 1D STELLAR DISPERSION VELOCITY OF THE BULGE  
SMALL MASS GALAXIES HOST LIGHT BLACK HOLES



ENERGY OR  
MOMENTUM  
RADIATION - DRIVEN  
OUTFLOWS  
ARE CAPABLE OF  
HALTING THE BLACK  
HOLE GROWTH

QUENCING STAR  
FORMATION IN THE  
HOST GALAXY

JOINT  
EVOLUTION !

BLACK HOLES GROW FROM

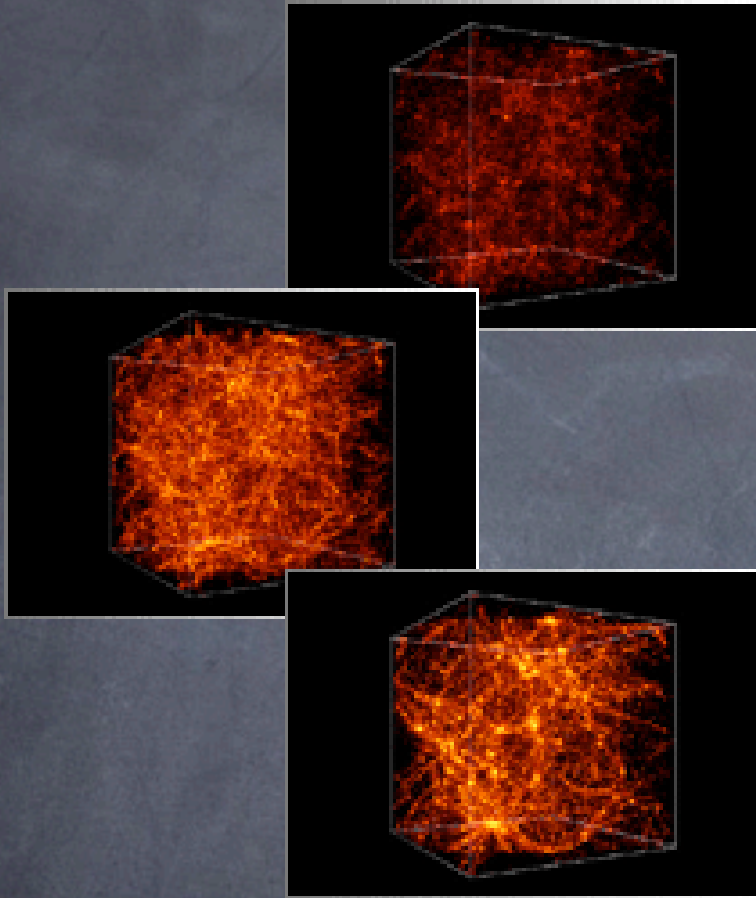
IMBH SEEDS ?

(i) RUNAWAY STELLAR COLLISIONS  
in pre-galactic structures (ULXs -Globular Clusters)

(ii) RELATIVISTIC  
INSTABILITIES FROM UNSTABLE GAS CLOUDS

(iii) RELIC OF POPULATION III STARS

Abel et al. 1999, Heger et al. 1999, Madau & Rees 2001,  
Portegies Zwart & McMillan 2004, Freitag et al. 2004,  
Begelman, Volonteri & Rees 2006



IN A COSMOLOGICAL  
CONTEXT  
KNOWLEDGE ABOUT THE  
BLACK HOLE FORMATION  
AND COSMIC GROWTH  
IN PREGALACTIC STRUCTURES

GIVES INSIGHT INTO  
THE MODE OF  
GALAXY  
ASSEMBLY

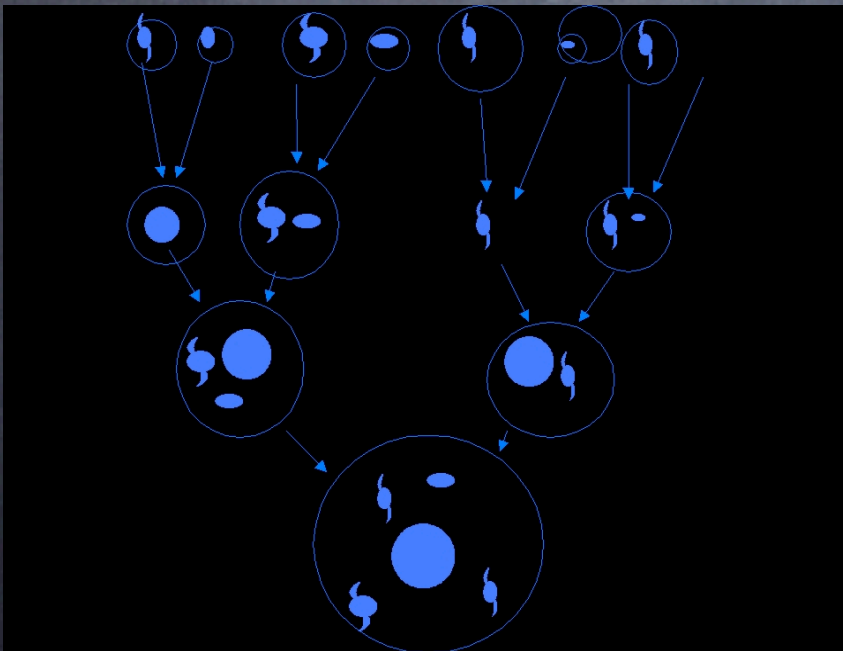
CONSIDER **BINARY BLACK HOLES** AS TRACERS  
OF THE HIERARCHICAL FORMATION OF GALAXIES

IF SEED BLACK HOLES EXIST IN PRE-GALACTIC UNITS THAT  
COLLIDE AND MERGE  
BINARY BLACK HOLES MAY FORM AND COALESCE  
SOURCES OF GRAVITATIONAL WAVES  
LASER INTERFEROMETER SPACE ANTENNA

“LISA” BLACK HOLES

$$10^4 - 10^7 M_{\odot}$$

MASS - SPIN ... learn about  
Galaxy Formation in the cleanest way  
across the entire universe



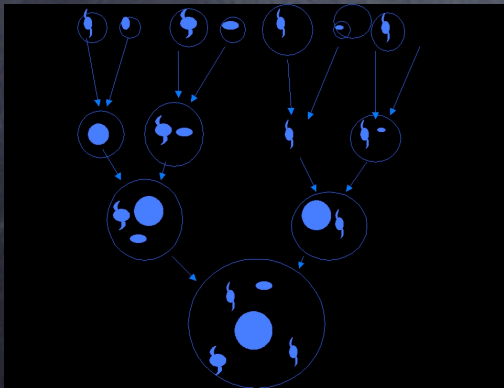
Volonteri, Haardt & Madau 2003  
Sesana, Haardt, Madau & Volonteri 2004  
Wyithe & Loeb 2004  
Haehnelt & Rees 1994  
Begelman, Blandford & Rees 1980

# ESTIMATES ON THE RATE OF BLACK HOLE BINARY COALESCENCE

64 EVENTS / year

57 EVENTS over  $0 < z < 20$   
BH MASSES  $< 10,000$  solar masses (IMBH)

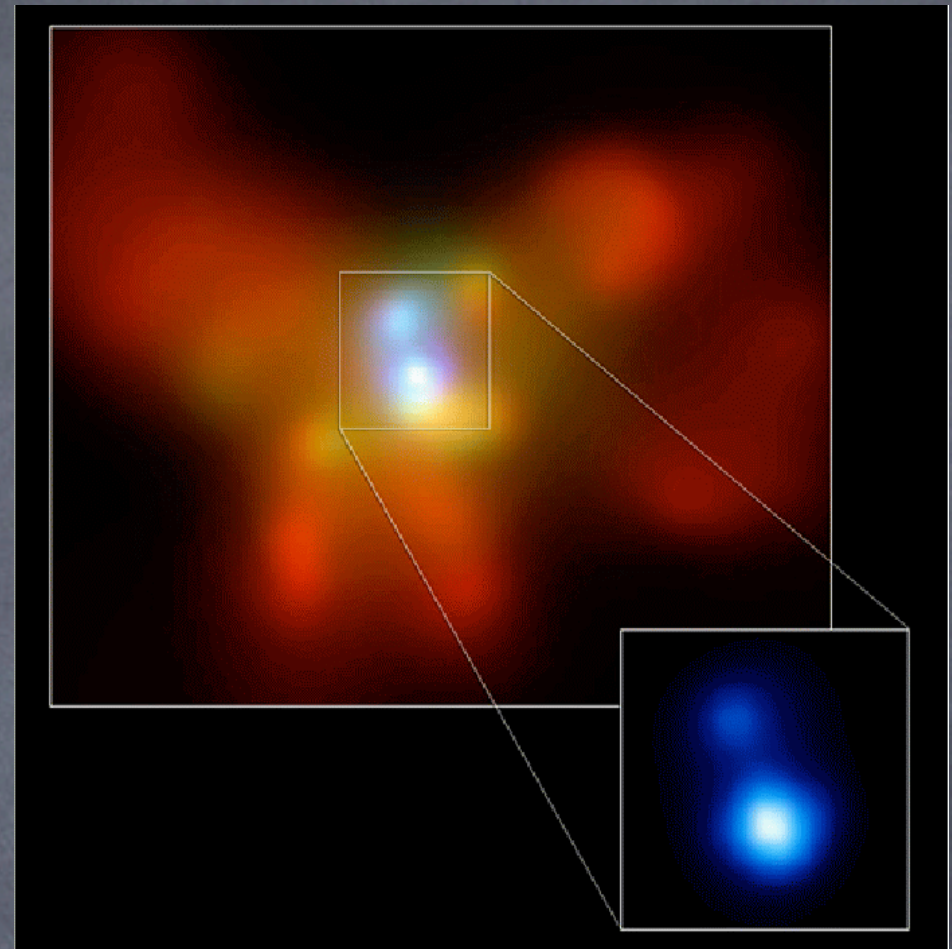
7 EVENTS over  $0 < z < 20$   
BH MASSES between 0.1 to 10 million solar masses  
peak at  $z=5$



Sesana, Haardt, Madau & Volonteri 2004  
Wyithe & Loeb 2004

DOUBLE AGN EMBEDDED  
IN A STAR BURST  
NGC 6240 ULIRG  
DOUBLE BLACK HOLES

VLBA  
RADIO GALAXY  
0402+39  
TWO COMPACT, RADIO FLAT, VARIABLE,  
DOUBLE NUCLEI  
7.3 pc  
100 million solar masses



1.4 kpc

Claims of QSOs pairs with 3-10" separations  
Komossa review 2003

HOW CAN WE STUDY  
THE MODE OF ASSEMBLY ?

MERGERS OCCUR ON SCALES  $\sim 100$  kpc

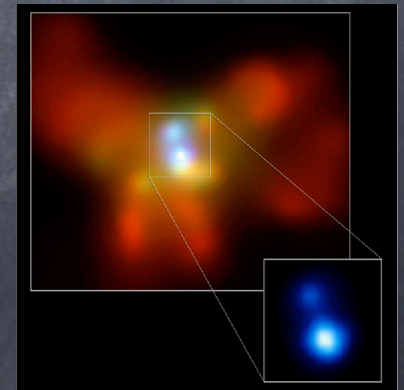
For Black Hole reference mass of  $10^6 M_{\odot}$

BLACK HOLES BIND AT A DISTANCE  
THE GAS & STELLAR MASS ENCLOSED IN THEIR ORBIT  
BECOME COMPARABLE TO THE BLACK HOLE MASS  
 $\approx 10$  pc

BLACK HOLES  
SPHERE OF INFLUENCE (accretion)

$$a \approx GM/\sigma^2 \approx M_6/\sigma_{100}^2 \approx 1 \text{ pc}$$

$$a_{\text{GW}} \approx 0.001 F(e)^{1/4} t_9^{1/4} \text{ pc}$$



# (I) CLOSE BLACK HOLE PAIRS EMBEDDED IN A GIVEN PER-DETERMINED BACKGROUND

## (1) PURE STELLAR BACKGROUNDS

Merritt 2006 for a review

## (2) PURE GASEOUS ROTATING BACKGROUNDS

Escala et al. 2004, Dotti, Colpi & Haardt 2006

# (II) MERGERS

## (1) IDEALIZED MERGERS: COLLISIONLESS SPHERICAL GALAXIES

Merritt 2006 for a review

## (2) REAL GALAXY MERGERS Dark Matter, Stars, Gas ...

Kazantzidis, Mayer, Colpi et al. 2005, Mayer et al. 2006

(i) DO BINARY BLACK HOLES FORM  
NATURALLY IN GAS-RICH MERGERS ?

Do they BIND into a Keplerian BINARY or just remain a loose PAIR ?

How does the process depend on the thermodynamics of the gas ?

Are there differences between major and minor mergers ?

Are there differences between collisionless and gas-rich mergers ?

Do they affect the shape of the remnant?

(ii) HOW RAPIDLY DO THEY COALESCE ?

In 10 Myrs during the merger or ... on much longer times when  
the merger is completed and the new galaxy found its new  
equilibrium?

(iii) CAN WE DETECT AN  
ELECTROMAGNETIC COUNTERPART TO A  
LISA EVENT ?

MULTI-SCALE SIMULATIONS OF  
GAS-RICH GALAXY BINARY MERGERS  
WITH MASSIVE BLACK HOLES  
+  
SIMULATIONS OF DOUBLE BLACK HOLES IN  
EQUILIBRIUM GASEOUS DISCS

\*LUCIO MAYER (ETH-UNIV. )

\*STELIOS KAZANTZIDIS (KAVLI)

\*MASSIMO DOTTI (MI-BI-INSUBRIA)

MONICA COLPI (Milano)

PIERO MADAU (UC Santa Cruz)

JAMES WADSLEY (McMaster CA)

TOM QUINN (Washington)

“GASOLINE”

Governato, Colpi & Maraschi 1994

Colpi, Mayer & Governato 1999

Kazantzidis, Mayer, Colpi, et al. 2005

Dotti, Colpi & Haardt 2006

Dotti, Salvaterra, Sesana, Colpi & Haardt 2006

Mayer et al. 2006 in preparation

# INITIAL EQUILIBRIUM MODEL MILKY WAY LIKE GALAXY

HALO+DISC+BULGE

+

$3 \times 10^6 M_{\odot}$  BLACK HOLE

VIRIAL MASS =  $10^{12} M_{\odot}$

BULGE MASS (STARS) = 0.008 VIRIAL MASS

GAS PARTICLES (10%)

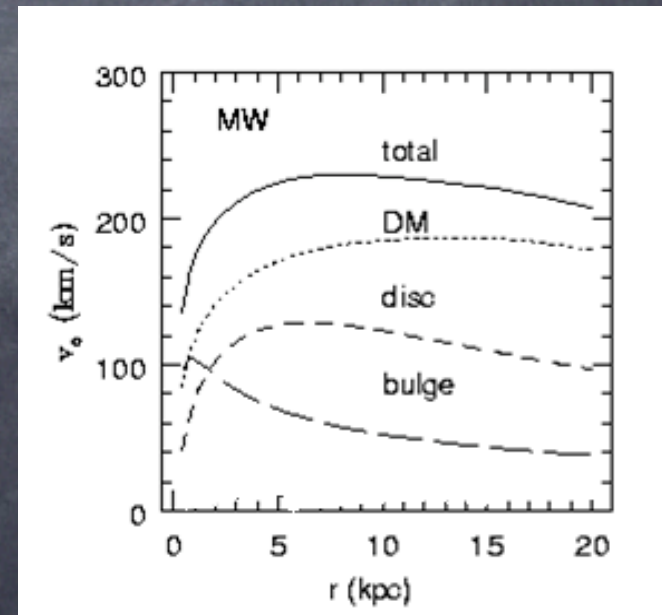
MASS OF GAS PARTICLES = 0.6 BULGE MASS

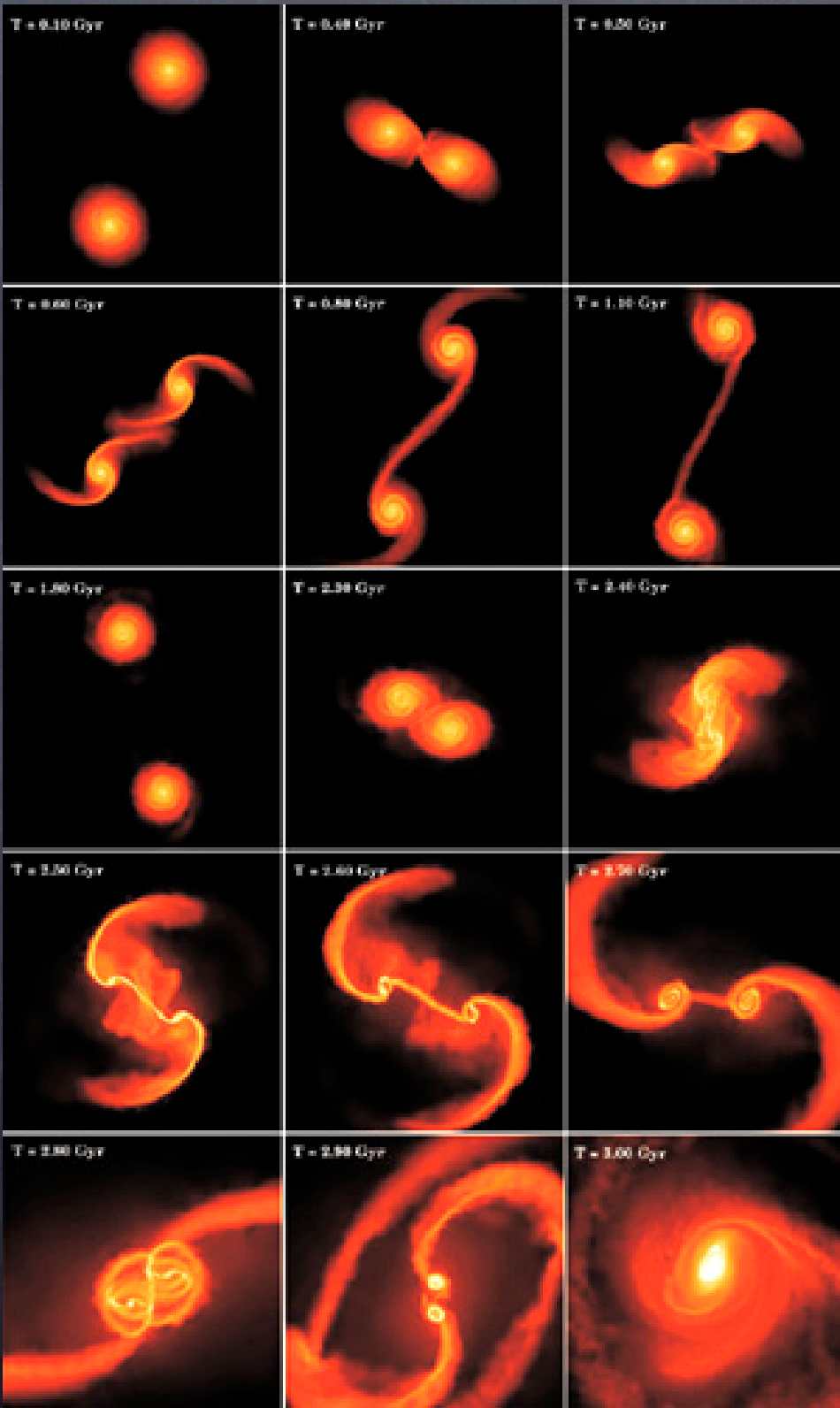
FIRST SUITE OF SIMULATIONS  
FORCE RESOLUTION 100 pc

1.2 MILLION PARTICLES in DM  
 $10^5$  SPH PARTICLES

ENERGY EQUATION

shock and compressional heating  
net radiative cooling by a cosmological  
abundance atomic H/He  
floor temperature of 20,000 K  
with star formation



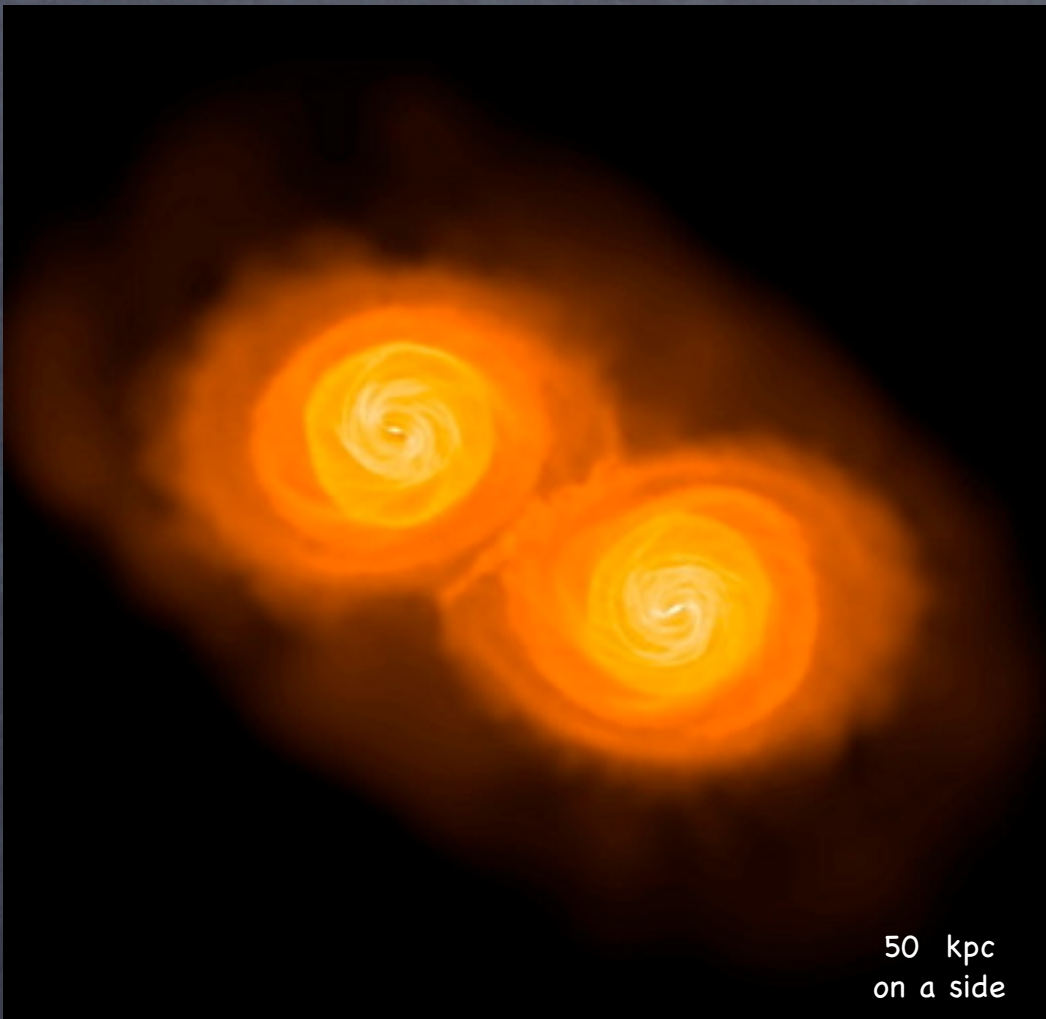


Color coded  
map  
of the gas  
density

# EQUAL MASS MERGER

100 kpc  
on a side

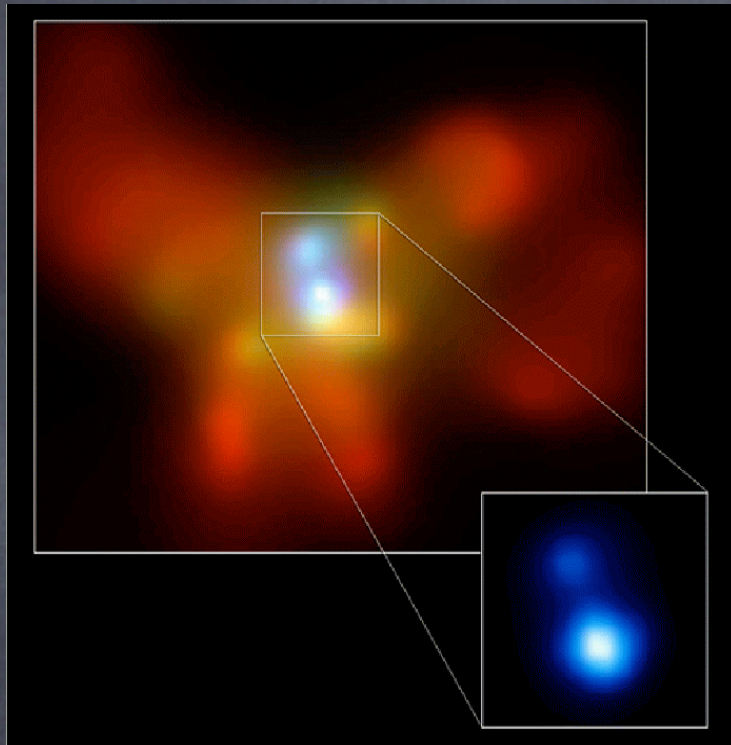
COPLANAR  
PROGRADE  
PARABOLIC  
ENCOUNTER



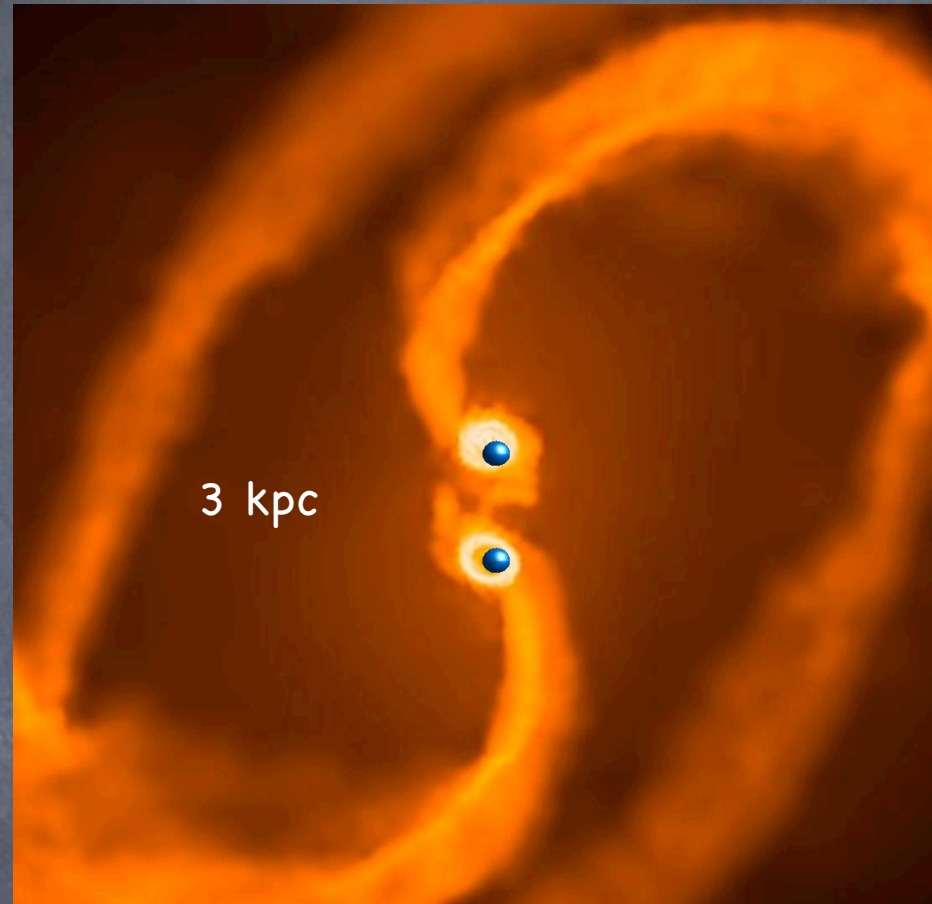
The gaseous discs touch after a few Gyrs and disrupt generating prodigious tidal torques and hydrodynamical shocks



100 million solar mass of gas is funneled inside a few hundred pc  
FORMATION OF TWO GASEOUS NUCLEAR DISCS

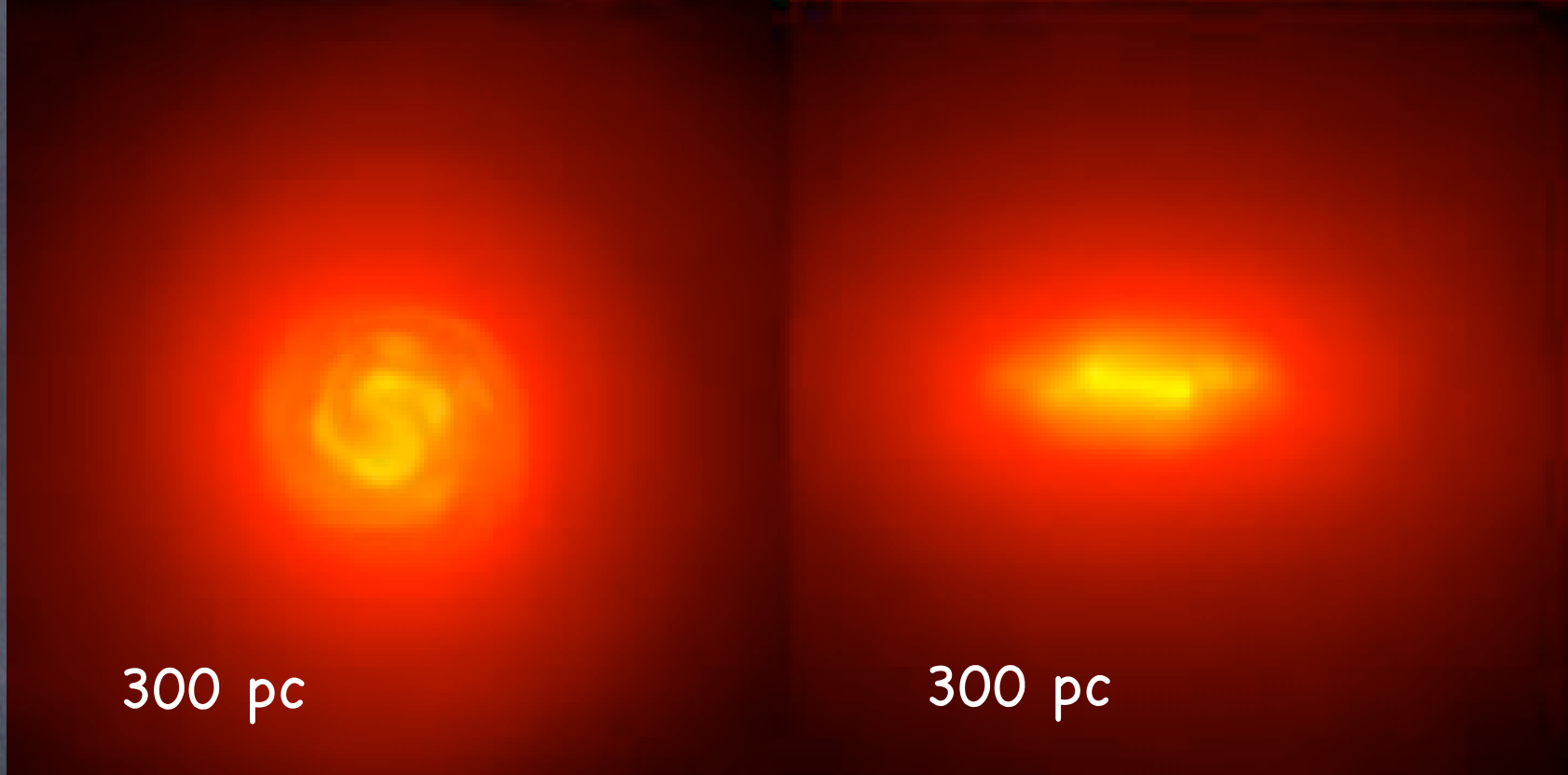


50 Myrs before final merger



STARBURST IS TRIGGERED  
AT THIS TIME

POSSIBILITY OF EXCITING DOUBLE AGN ACTIVITY



FORMATION OF A NON AXISYMMETRIC GASEOUS TURBULENT  
ROTATIONALLY SUPPORTED DISC OF  
A BILLION SOLAR MASSES

of 80 pc in size vertical scale of 20 pc

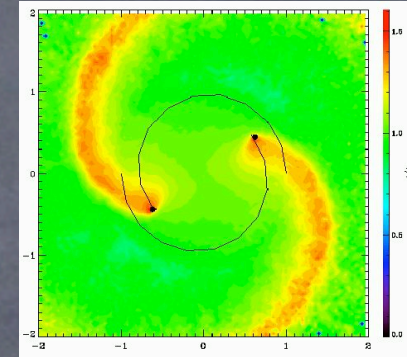
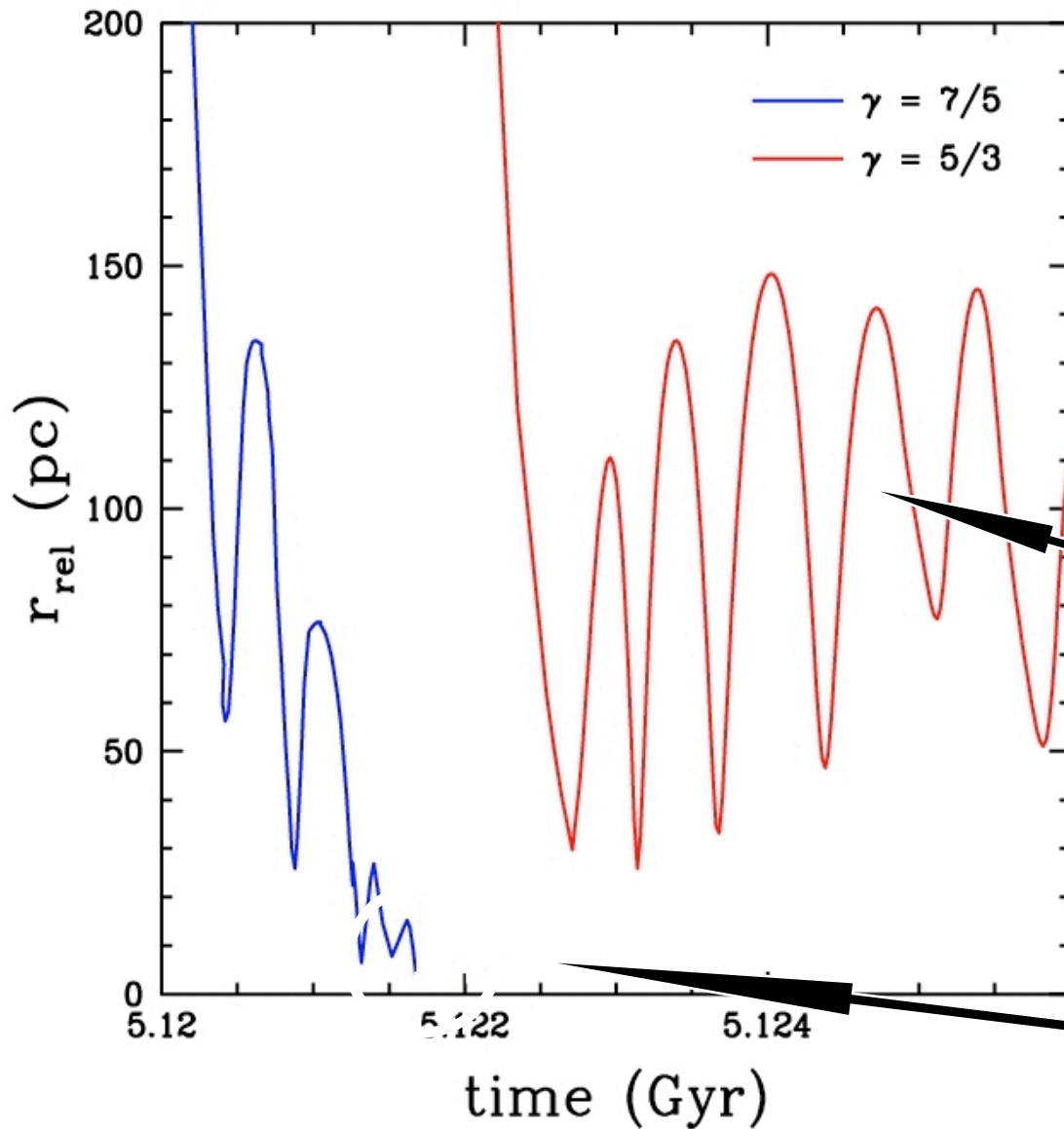
RADIAL INFLOWS OF 30-100 km/s lasting 100,000 years

$$V_{\text{sound}} < V_{\text{turb}} < V_{\text{rot}}$$

THE NUCLEAR DISC IS SURROUNDED BY A NEARLY  
SPHEROIDAL DISTRIBUTION OF STARS

gravitational torques are well resolved only when the force resolution is below 10 pc

# BLACK HOLE RELATIVE DISTANCE



Black hole separation stalls  
subsonic motion  
stars + gas will cause its shrinking

Mildly Eccentric Binary formed a Myr after the merger is completed (supersonic motion)

A KEPLERIAN BINARY HAS FORMED  
SURROUNDED BY A MASSIVE  
TURBULENT  
ROTATIONALLY SUPPORTED DISC

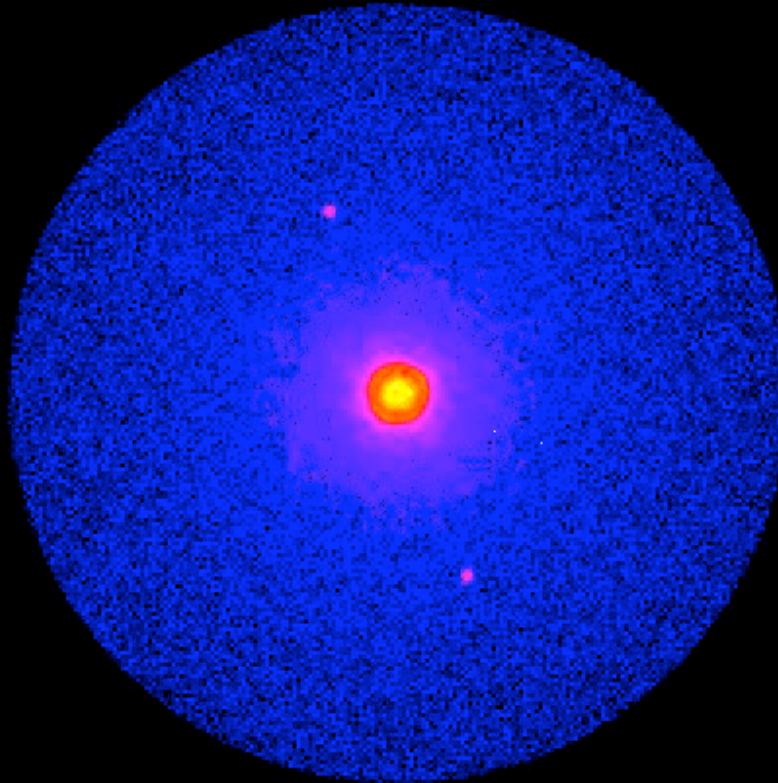
....  
the ability to BIND during the merger depends  
on the  
thermodynamical state of the gas

CAN WE REACH THE GW DOMAIN?  
BELOW ... 10 pc .... down to 0.001 pc?

# MESTEL DISK EMBEDDED IN A PLUMMER SPHERE OF STARS

$$\rho(r) =$$

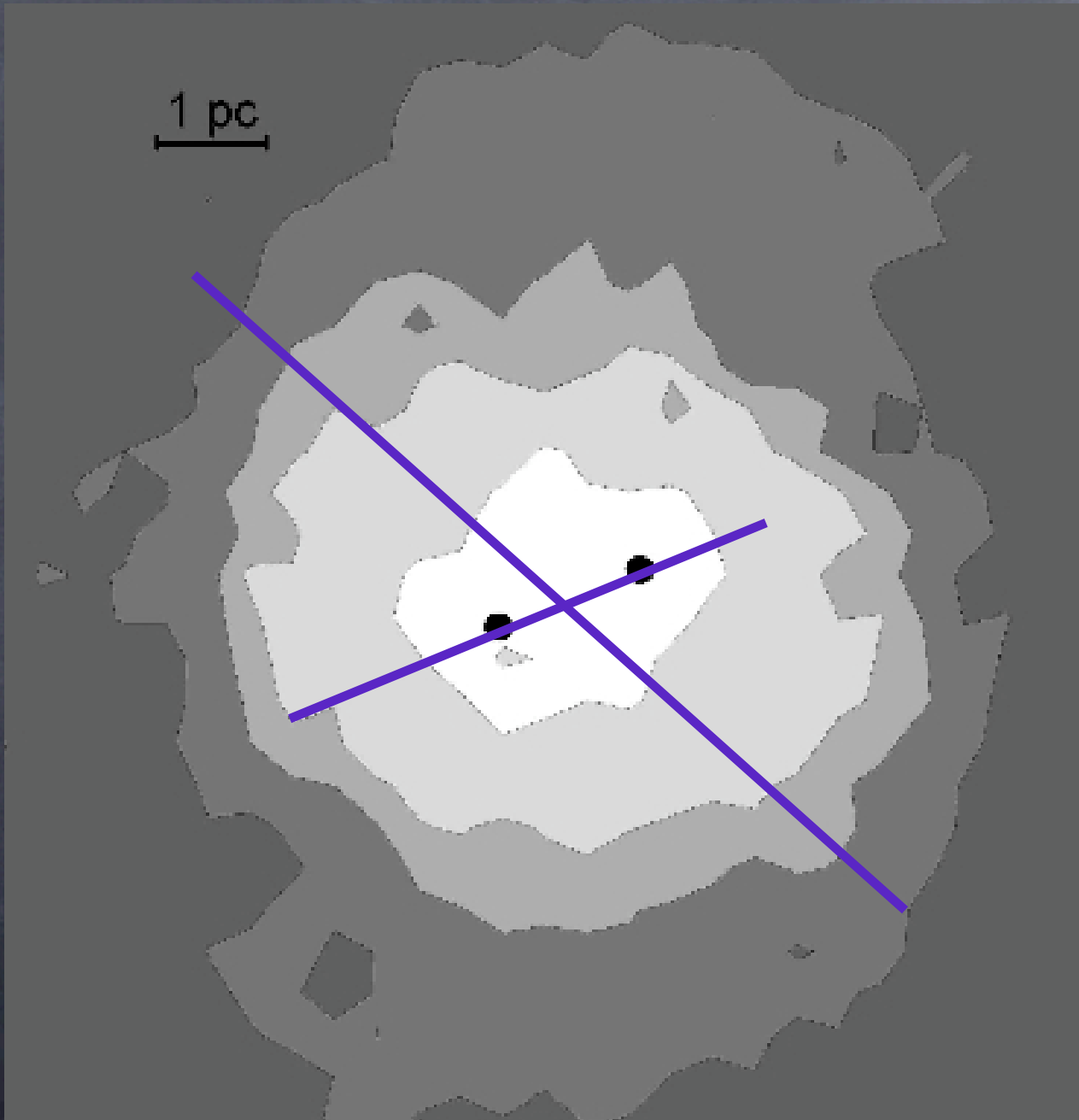
$$\Sigma_{\text{Disk}}(R)$$



Down



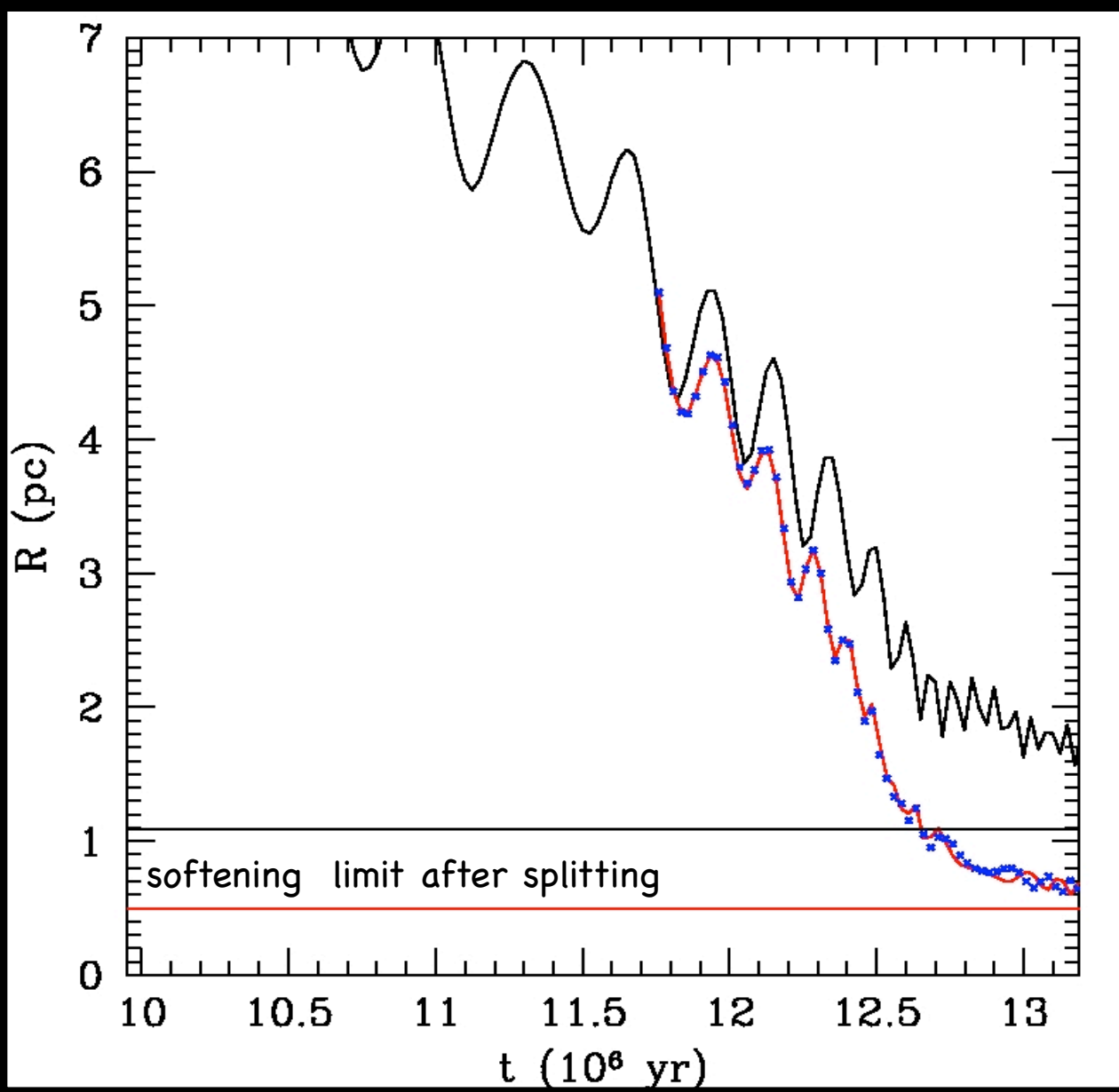
Up



ELLIPSOIDAL DEFORMATION  
RESULTING  
FROM THE SUPERPOSITION  
OF THE WAKES  
PROVIDES THE TORQUE TO  
PROMOTE ORBITAL DECAY  
DOWN TO  
THE DOMAIN  
WHERE  
GRAVITATIONAL WAVES  
DRIVE  
EVOLUTION

...keep evolving  
and zooming in.....

Escala et al 2005  
Dotti et l. 2006



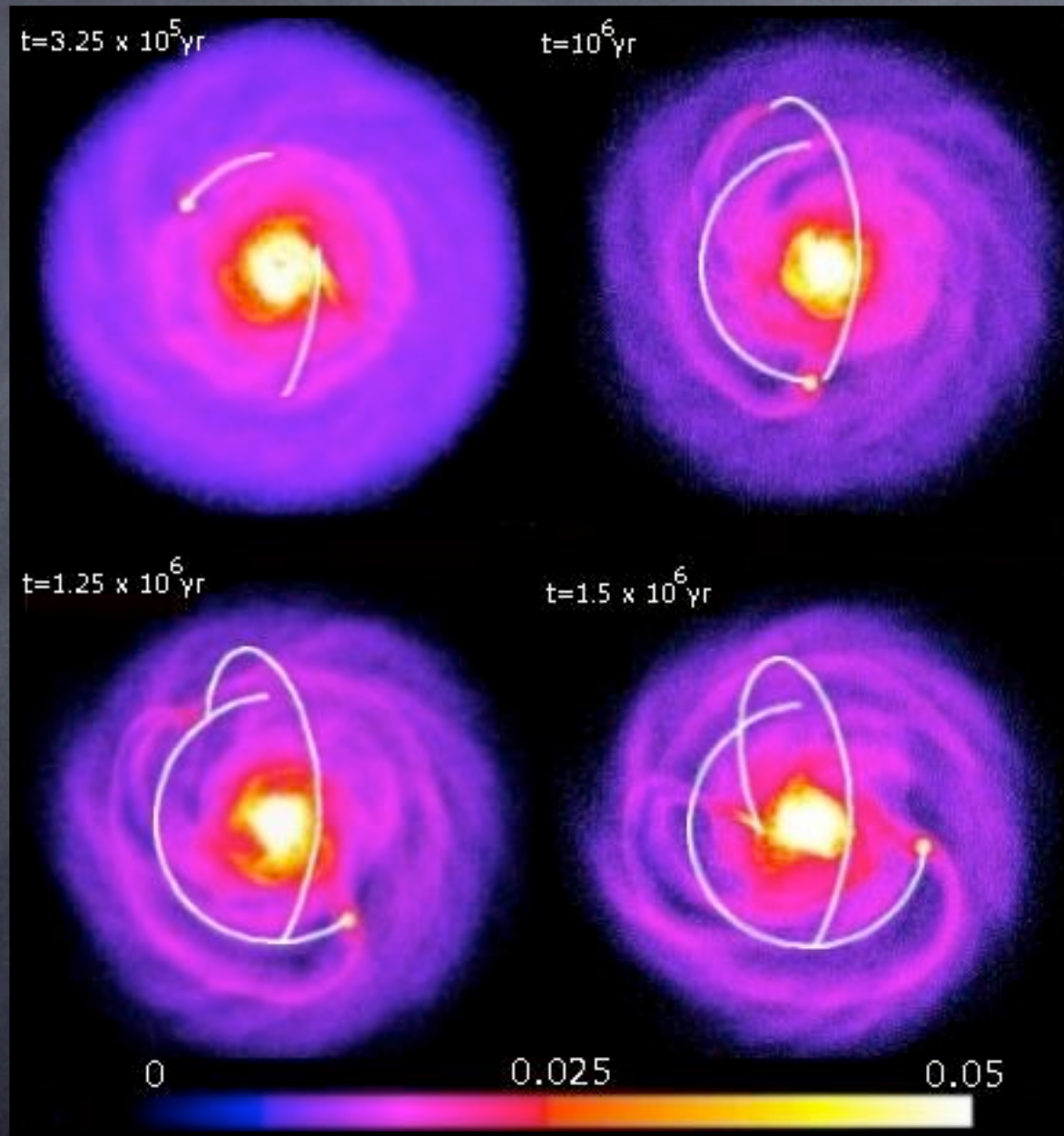
DYNAMICAL FRICTION  
ELLIPSOIDAL TORQUES  
THAT FORM DUE TO THE  
OVERLAPPING OF THE  
WAKES  
CAUSE THE INSPIRAL  
CLEAR EFFECT  
OF CIRCULARIZATION

COALESCENCE IN  
10 Myrs

Escala et al. 2005  
Dotti et al. 2006

Dotti et al. 2006, Mayer et al. 2006 in preparation

Circularization in rotationally supported Mestel disk (Dotti et al. 2006)



Circularization  
of corotating  
eccentric orbits

Counterrotating  
orbits remain  
eccentric

Memory  
of the  
merger/dynamics

Dotti et al. 2006

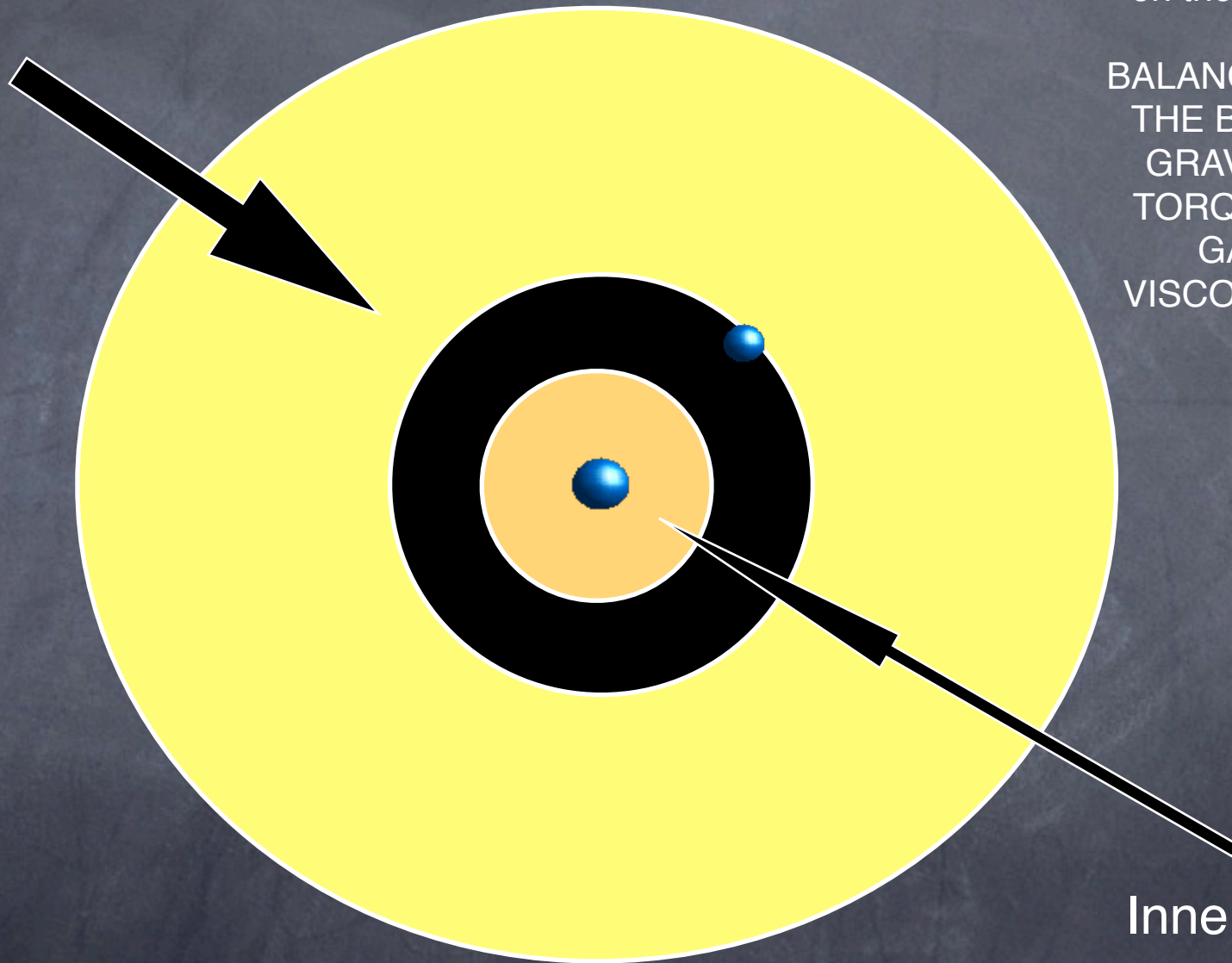
TRANSITION

SELF-GRAVITATING  
ROTATIONALLY  
SUPPORTED DISC



ACCRETION DISC  
DOMINATED BY  
THE GRAVITY OF THE  
TWO BLACK HOLES

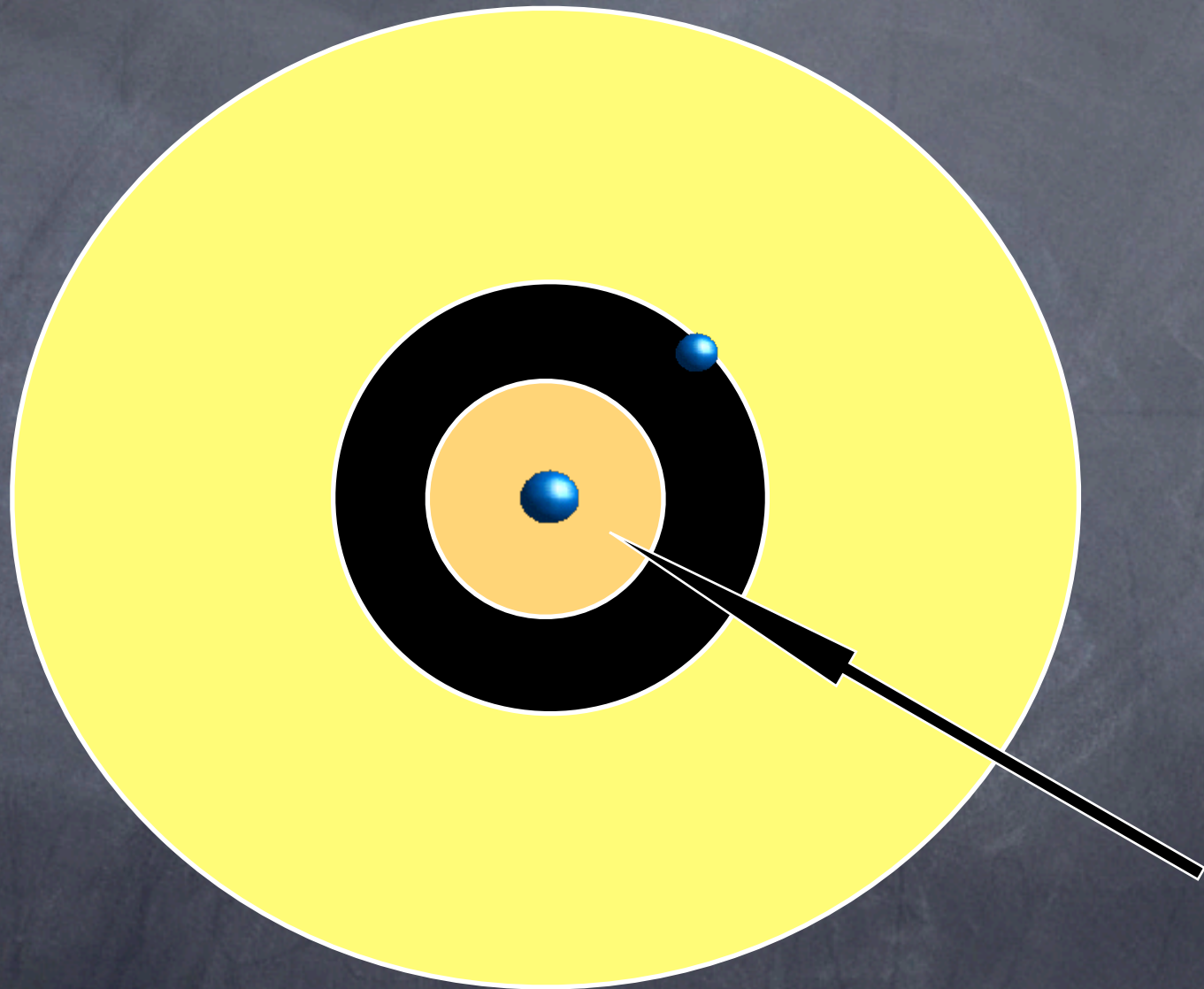
Outer circubinary disc



FORMATION OF A GAP  
BLACK HOLE  
MIGRATION  
on the viscous time

BALANCE BETWEEN  
THE BLACK HOLE  
GRAVITATIONAL  
TORQUE and THE  
GASEOUS  
VISCIOUS TORQUE

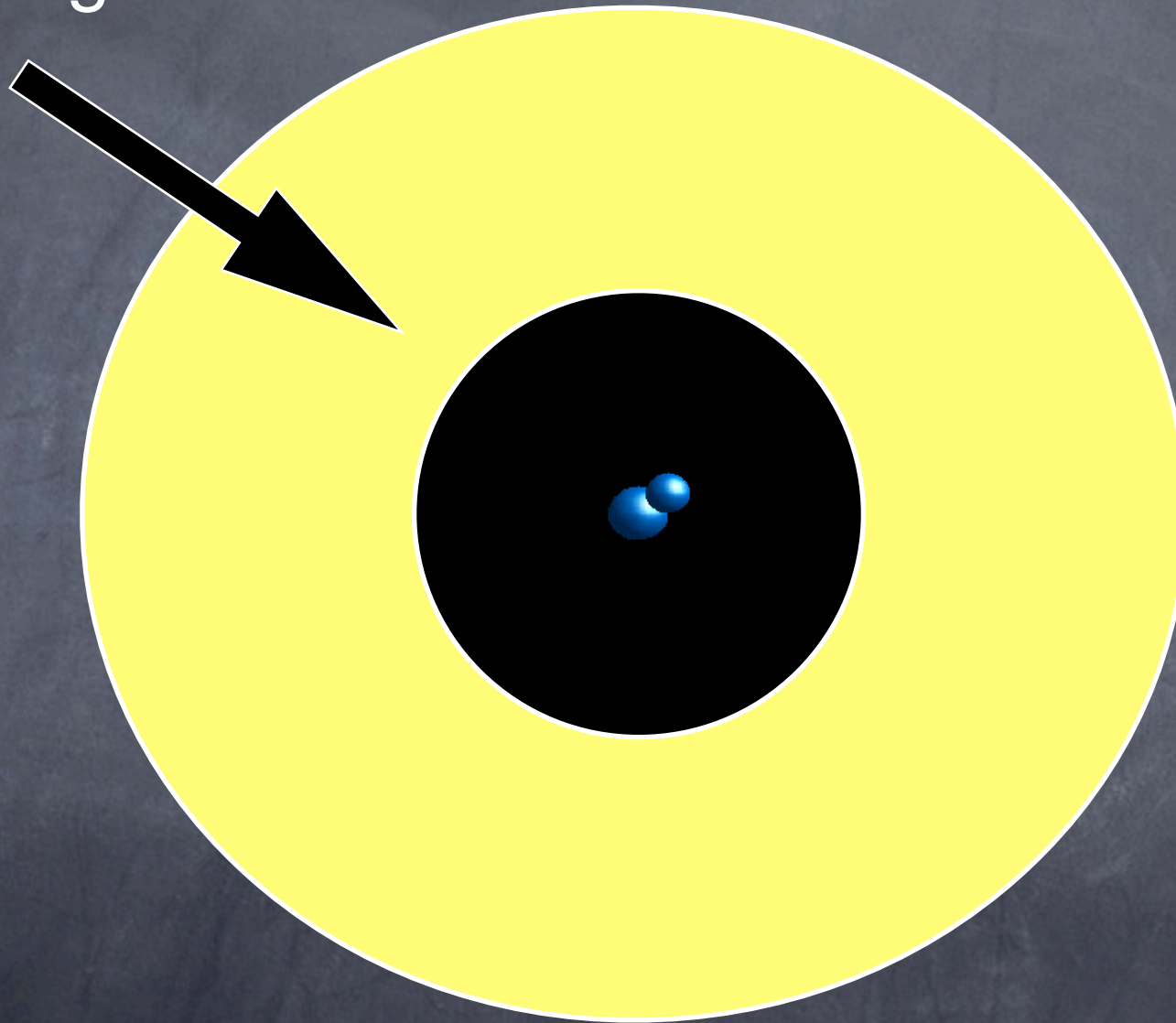
Inner disc



Preglow - last year of inspiral

$$\tau_{\text{coal}} < \tau_{\text{accr inner disc}}$$

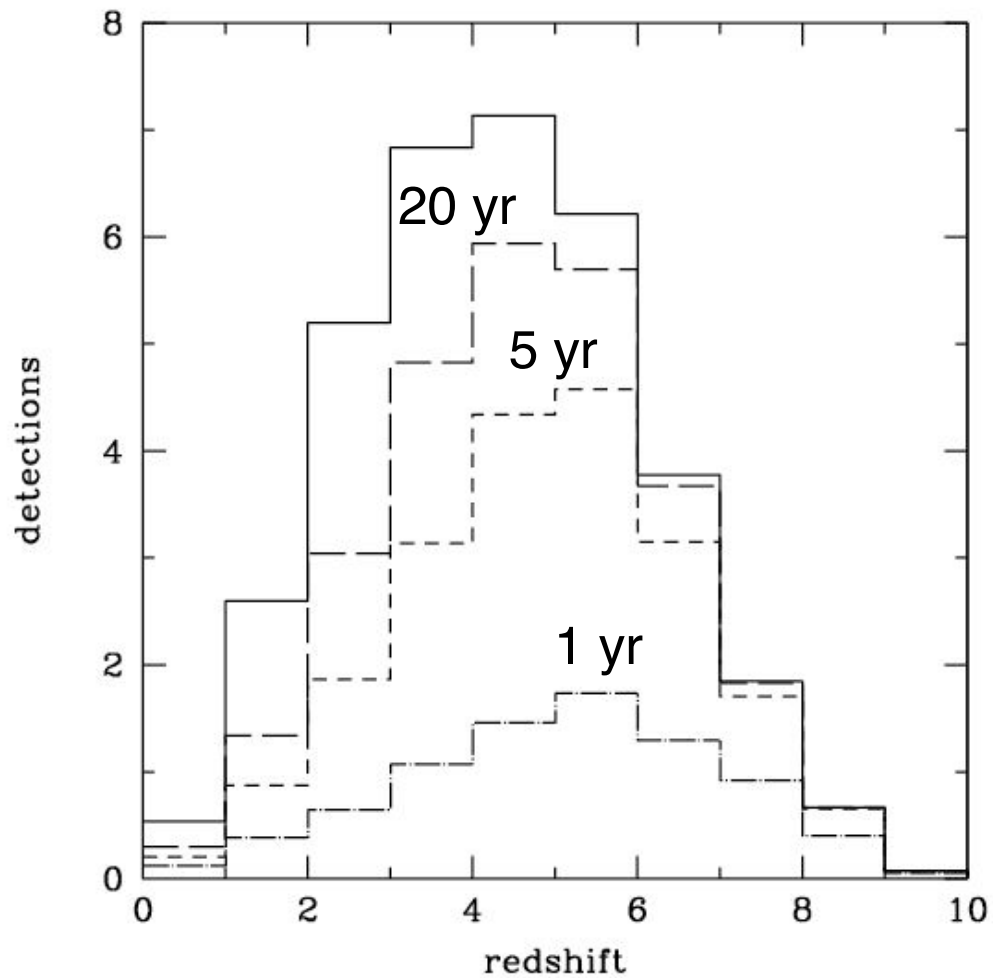
Afterglow



Migration of the inner edge of the outer circumbinary disc after coalescence causes accretion and activation of a X-ray source EM afterglow of a LISA event

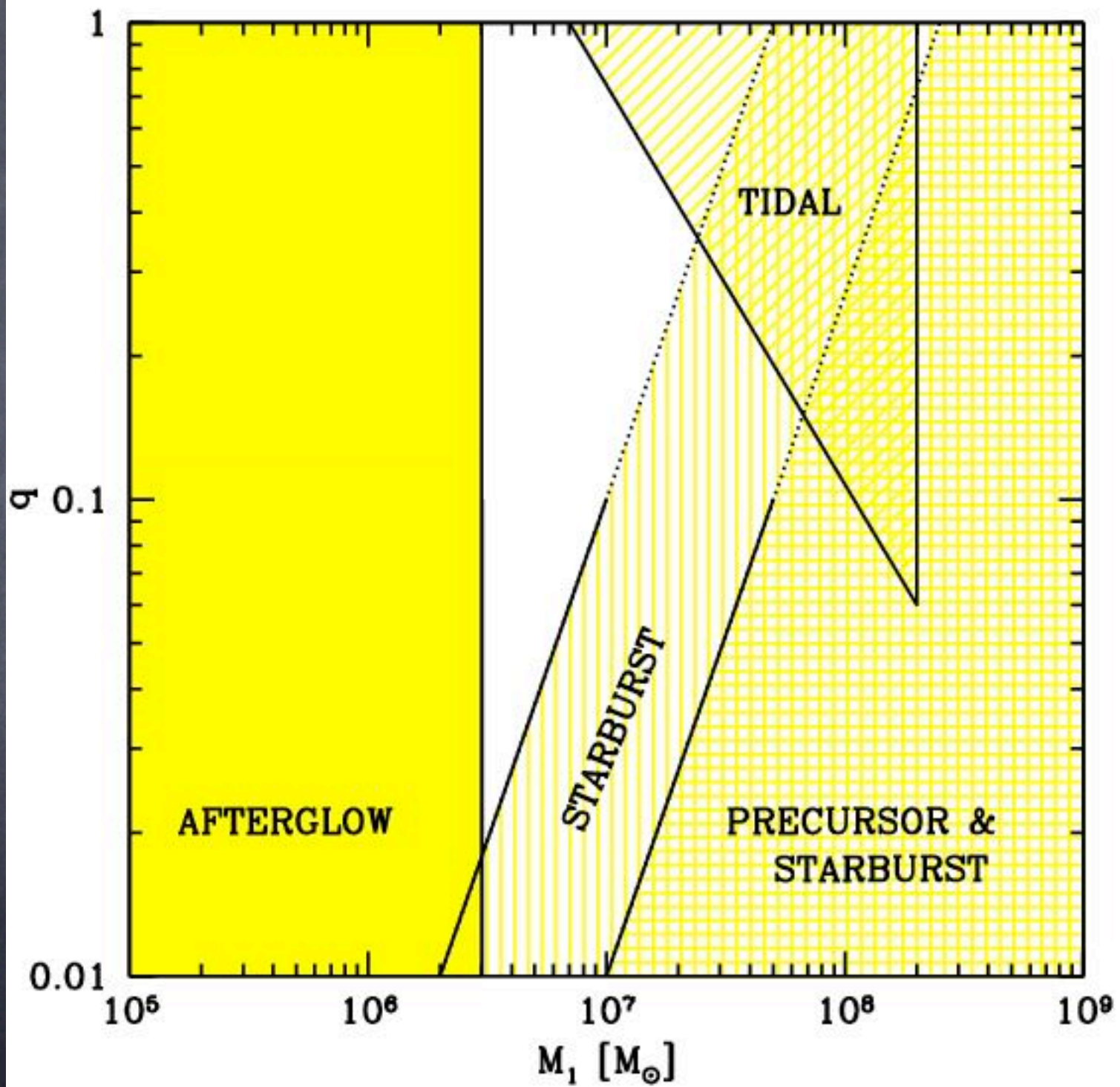
Milosavljevic & Phinney 2005  
Mac Fyden & Milosavljevic 2006

$$t \approx 7(1+z)(M/10^6 M_{\odot})^{1.32} \text{ years}$$



XEUS or  
CONSTELLATION X  
FLUX LIMIT

0.5 - 5 keV  
neglecting photoelectric  
absorption at the source



# LISA

WILL BE ABLE TO MEASURE THE LUMINOSITY DISTANCE OF  
A COALESCING BLACK HOLE BINARY

WITH 1% TO 10% ACCURACY BUT NOT THE REDSHIFT

GW SOURCES ARE GENERALLY POORLY LOCALIZED  
IN THE BEST CASE THE POINTING ACCURACY IS  $\delta\theta \sim 1$  arcmin

$$\delta\Omega \sim 0.01-3 \text{ deg}^2$$

## EM COUNTERPART

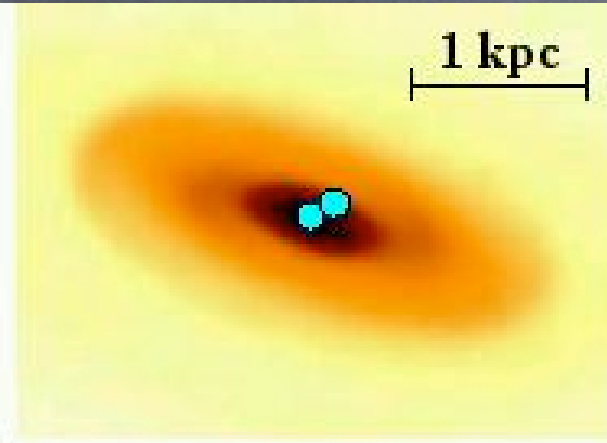
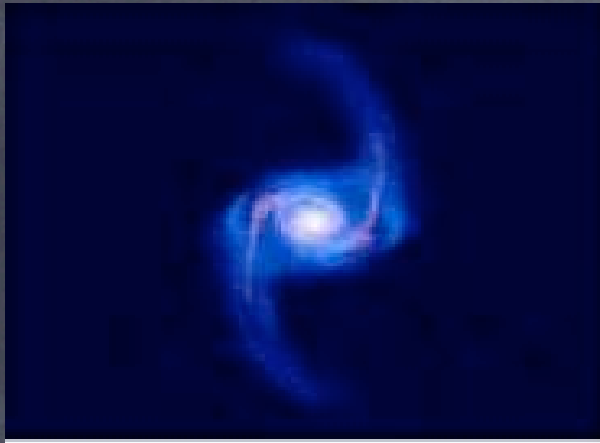
WOULD DETERMINE THE SOURCE REDSHIFT

BBHS STANDARD SIRENS VISIBLE AT HIGH REDSHIFTS  
DISTANCE - REDSHIFT RELATION  
WHICH MAPS THE EXPANSION HISTORY OF THE  
UNIVERSE

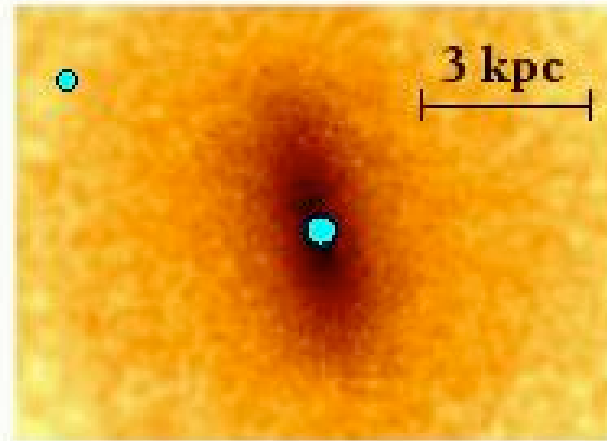
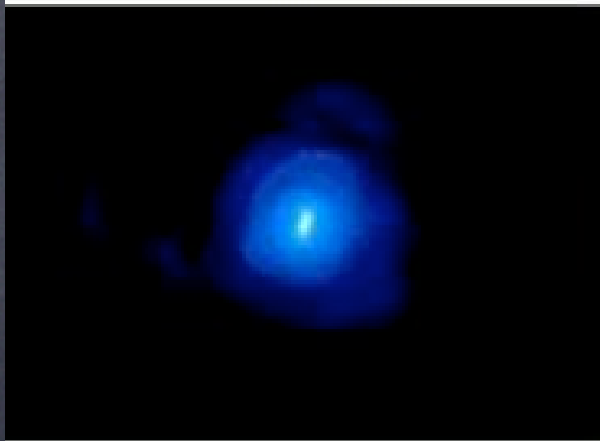
WHAT ABOUT  
MINOR MERGERS?

WHAT ABOUT  
COLLISIONLESS  
“DRY”  
MERGERS?

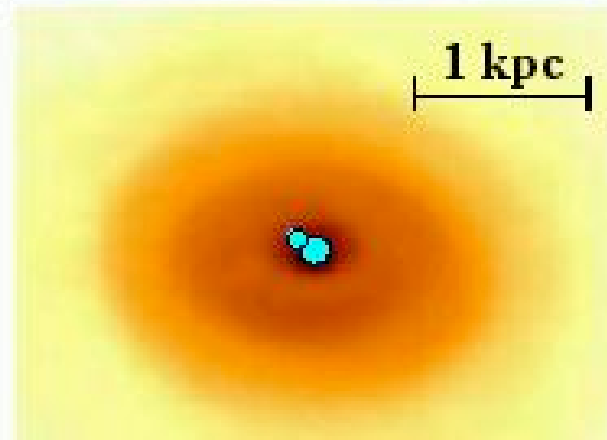
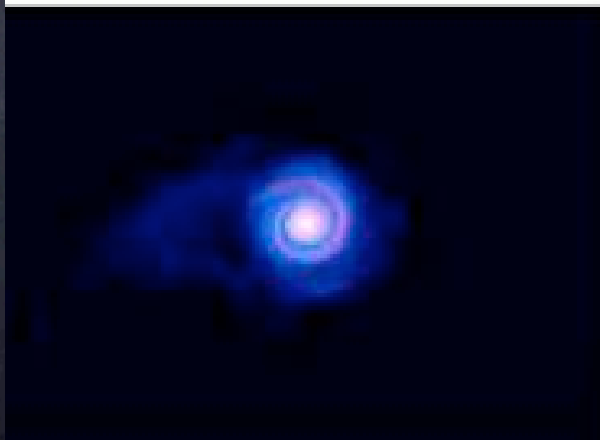
# Are there differences between major and minor mergers ?



MAJOR  
MERGER



4:1 MINOR  
MERGER  
NO COOLING  
WANDERING  
BLACK HOLES



4:1 MINOR  
MERGER  
WITH COOLING

THE ROLE OF GASEOUS DISSIPATION IS CRUTIAL

IN MAJOR GAS RICH MERGERS A  
KEPLERIAN BINARY FORMS

BLACK HOLE COALESCENCE LIKELY OCCURS  
ASSISTED ONLY BY GAS DYNAMICAL PROCESSES

$\tau_{\text{coal}} \sim 10 \text{ Myrs}$

QSO & FEEDBACK

IN MAJOR MERGERS & “HOT” NUCLEAR ENVIRONMENT  
A PAIR is LEFT IN THE CORE

( $\tau_{\text{coal}} \sim \text{billion years}$  assisted by stars)

MINOR MERGERS

WANDERING BLACK HOLES

we need to investigate  $q=0.01$  0.1 more

## OPEN ISSUES

MINIMUM MASS RATIO “ $q$ ” FOR BH COALESCENCE  
in gas-rich/ gas poor environments

ECCENTRICITY ISSUES  
stellar versus gaseous backgrounds

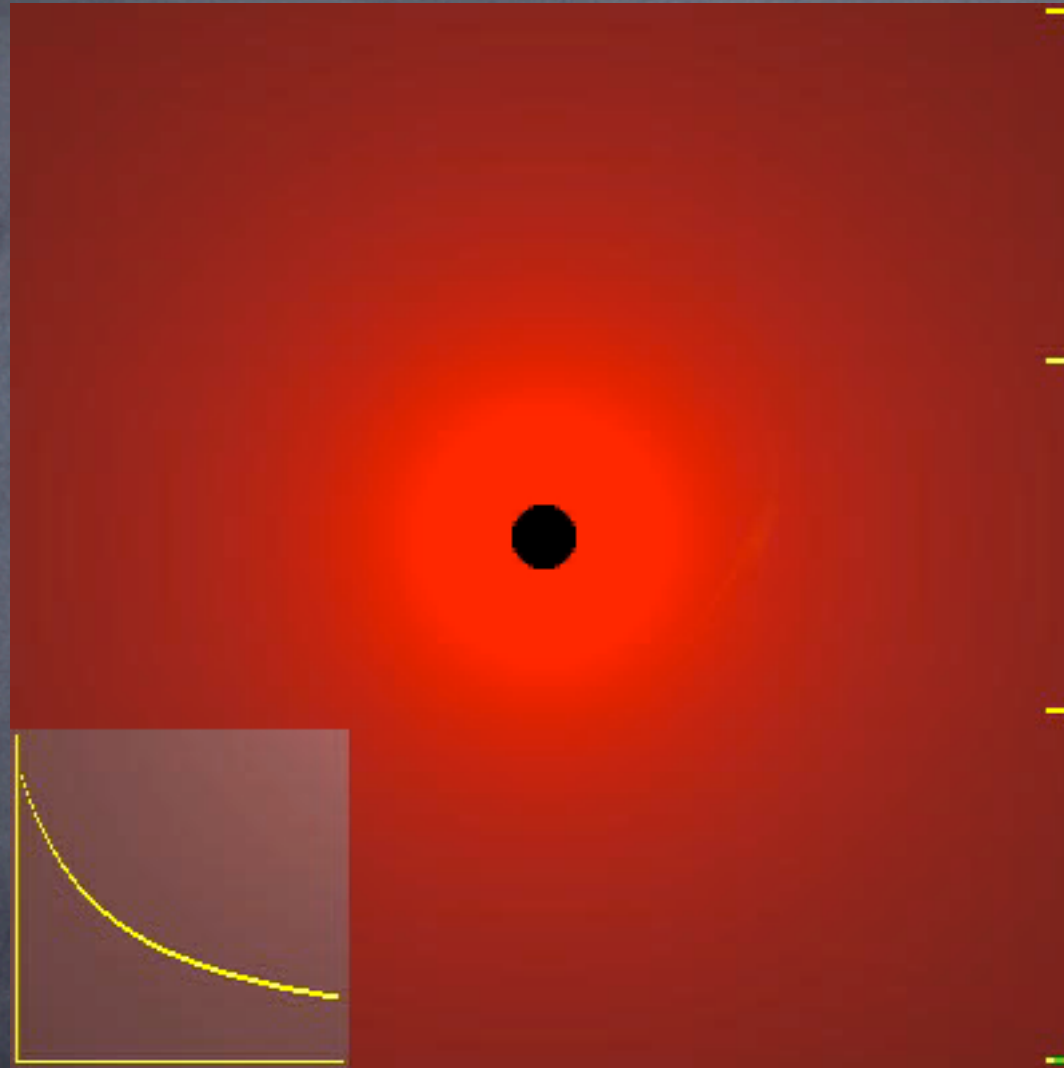
LATEST PHASES OF ORBITAL DECAY  
IN THE REAL ENVIRONMENT OF A REMNANT  
GAS & STARS

STUDY OF THE STELLAR PROFILES (CUSPY/CORE) OF GALACTIC  
NUCLEI

STELLAR DISRUPTION AROUND  
BINARY BLACK HOLES NEAR COALESCENCE

ELECTROMAGNETIC COUNTERPARTS AT HIGH  $Z$

IMPROVE THE STATISTICAL APPROACH IN  
DESCRIBING COSMIC ASSEMBLY & THE DOWNSIZING PROBLEM



Armitage