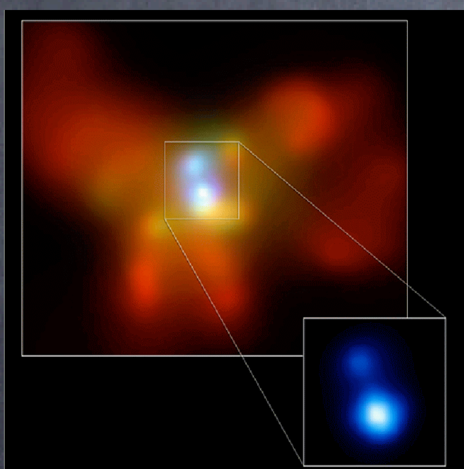
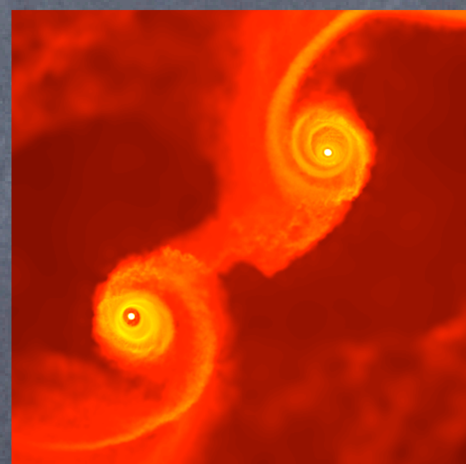
THE BIRTH OF A KEPLERIAN BLACK HOLE BINARY IN GAS RICH GALAXY MERGERS





EFFECT
GASEOUS DISSIPATION
&
ENVIRONMENT
ON THE ORBITAL
EVOLUTION
OF THE BLACK HOLES

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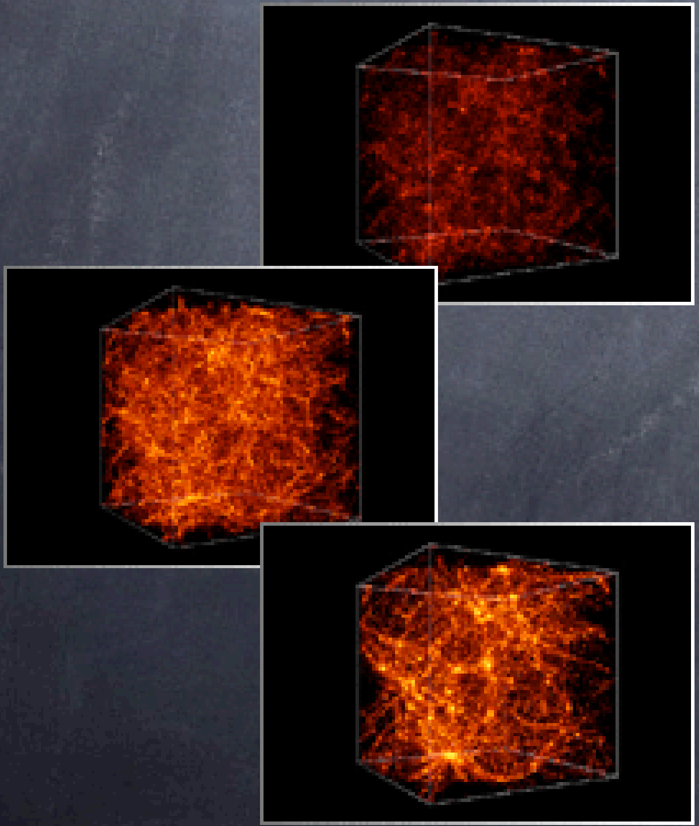
Santa Fe 11 July 2006

IN A COSMOLOGICAL CONTEXT "BINARY BLACK HOLES"
MAY PLAY A KEY ROLE:
"TRACERS"
OF THE COSMIC ASSEMBLY OF GALAXIES

IF SEED BLACK HOLES EXIST IN PRE-GALACTIC UNITS THAT
COLLIDE AND MERGE
BINARY BLACK HOLES MAY FROM 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

(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 ?

(ii) HOW RAPIDLY DO THEY COALESCE ?

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

(iii) IS DOUBLE AGN ACTIVITY EXCITED?

At which typical separations?

MERGERS OCCUR ON SCALES ~ 100 kpc

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

BLACK HOLES BIND AT A DISTANCE ≈ 10 pc

THE GAS & STELLAR MASS ENCLOSED IN THEIR ORBIT
BECOME COMPARABLE TO THE BLACK HOLE MASS

BLACK HOLES
SPHERE OF INFLUENCE (accretion)

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

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

MULTI-SCALE SIMULATIONS OF GAS-RICH GALAXY BINARY MERGERS WITH MASSIVE BLACK HOLES

*LUCIO MAYER (ETH)
*STELIOS KAZANTZIDIS (KAVLI)
*MASSIMO DOTTI (MI-BI-INSUBRIA)

MONICA COLPI (MIlano)
FRANCESCO HAARDT (Insubria)
PIERO MADAU (UC Santa Cruz)
JAMES WADSLEY (McMaster CA)
TOM QUINN (Washington)
“GASOLINE”

SUPER-COMPUTER
ZURICH & CINECA

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

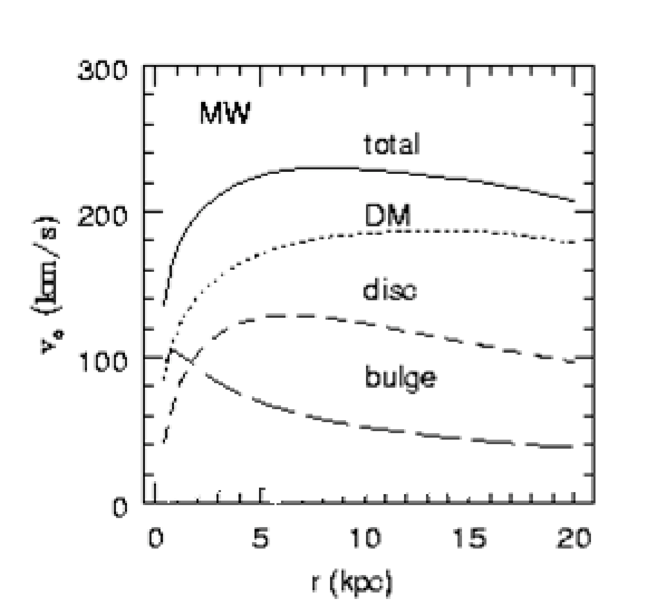
VIRIAL MASS=$10^{12}\ M_{\odot}$
BULGE MASS (STARS) = 0.008 VIRIAL MASS

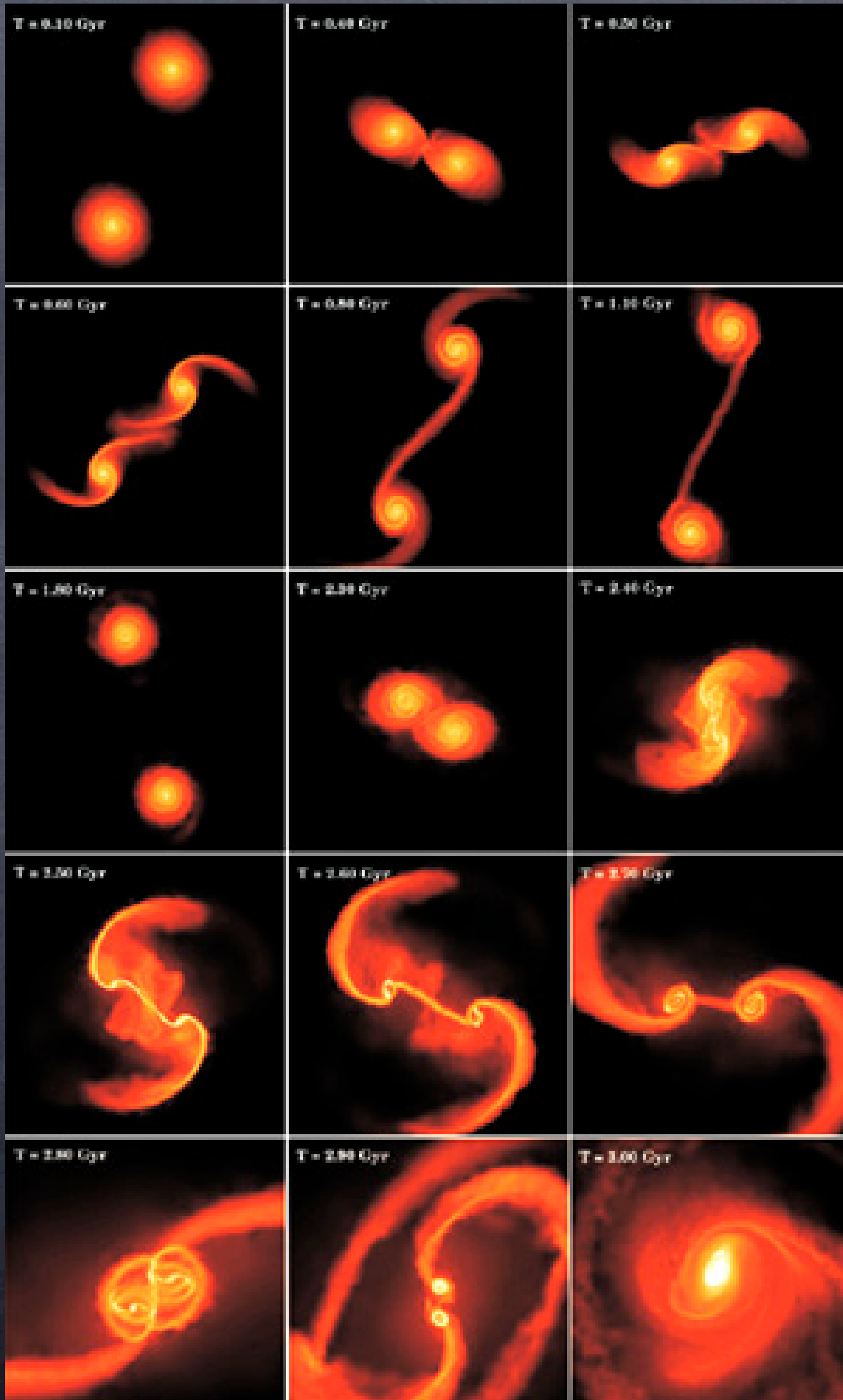
GAS PARTICLES (10%)
MASS OF GAS PARTICLES = 0.6 BULGE MASS

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



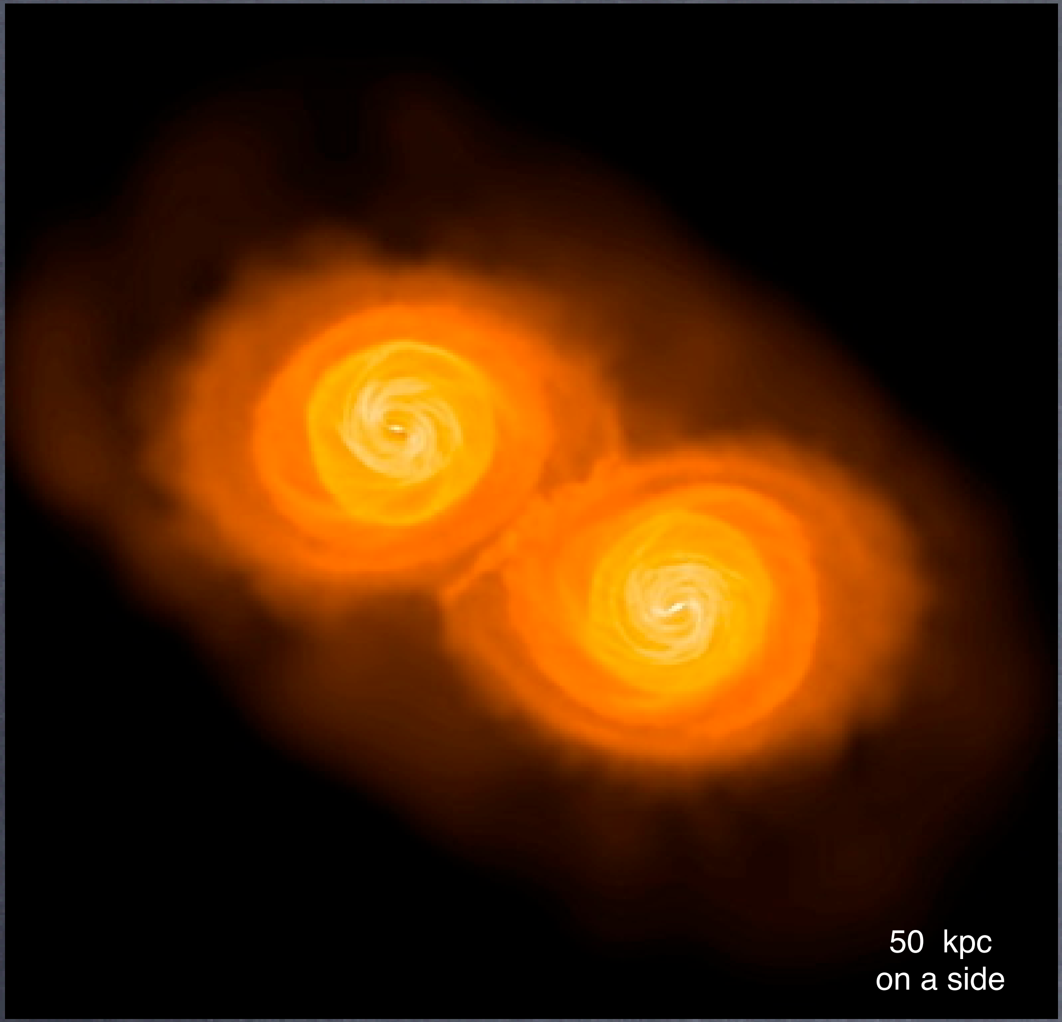


Color coded
map
of the gas
density

EQUAL MASS
MERGER

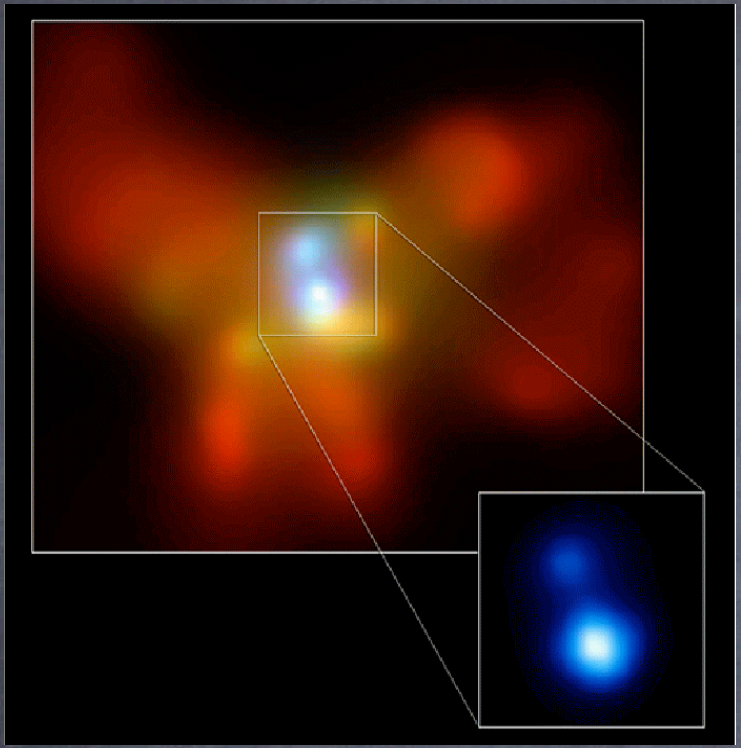
100 kpc
on a side

COPLANAR
PROGRADE
PARABOLIC
ENCOUNTER

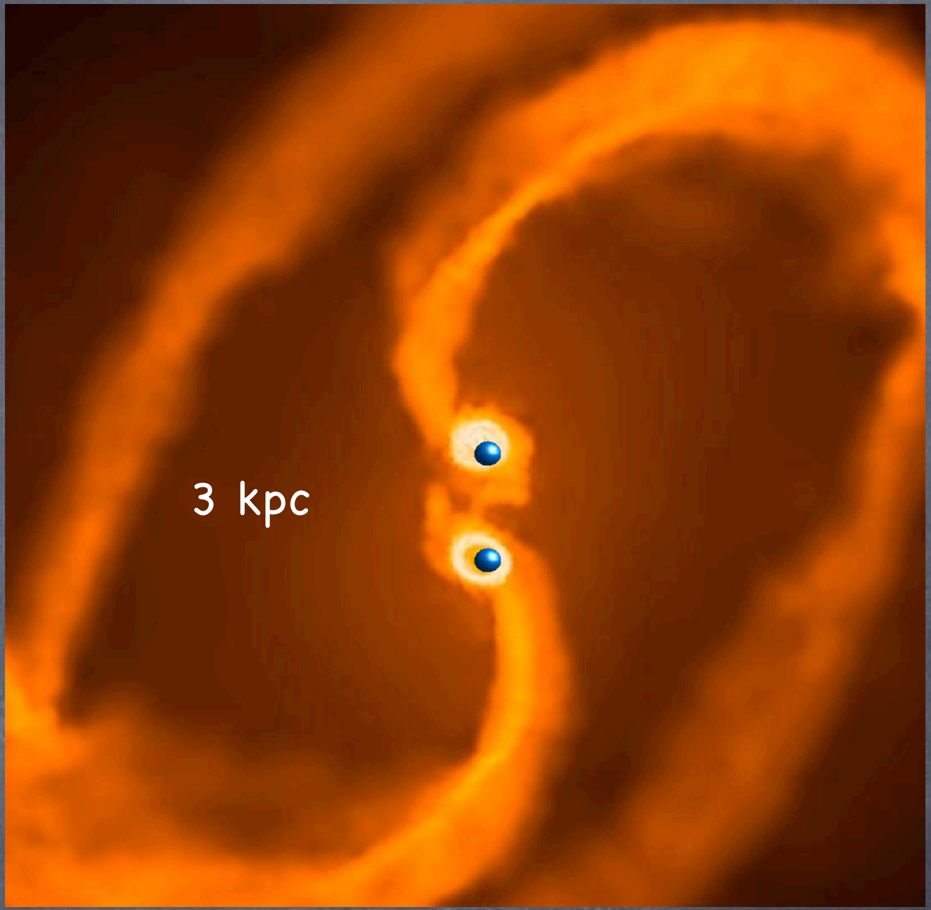


The gaseous discs touch after a few Gyrs and disrupt generating prodigious tidal torques and hydrodynamical shocks

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



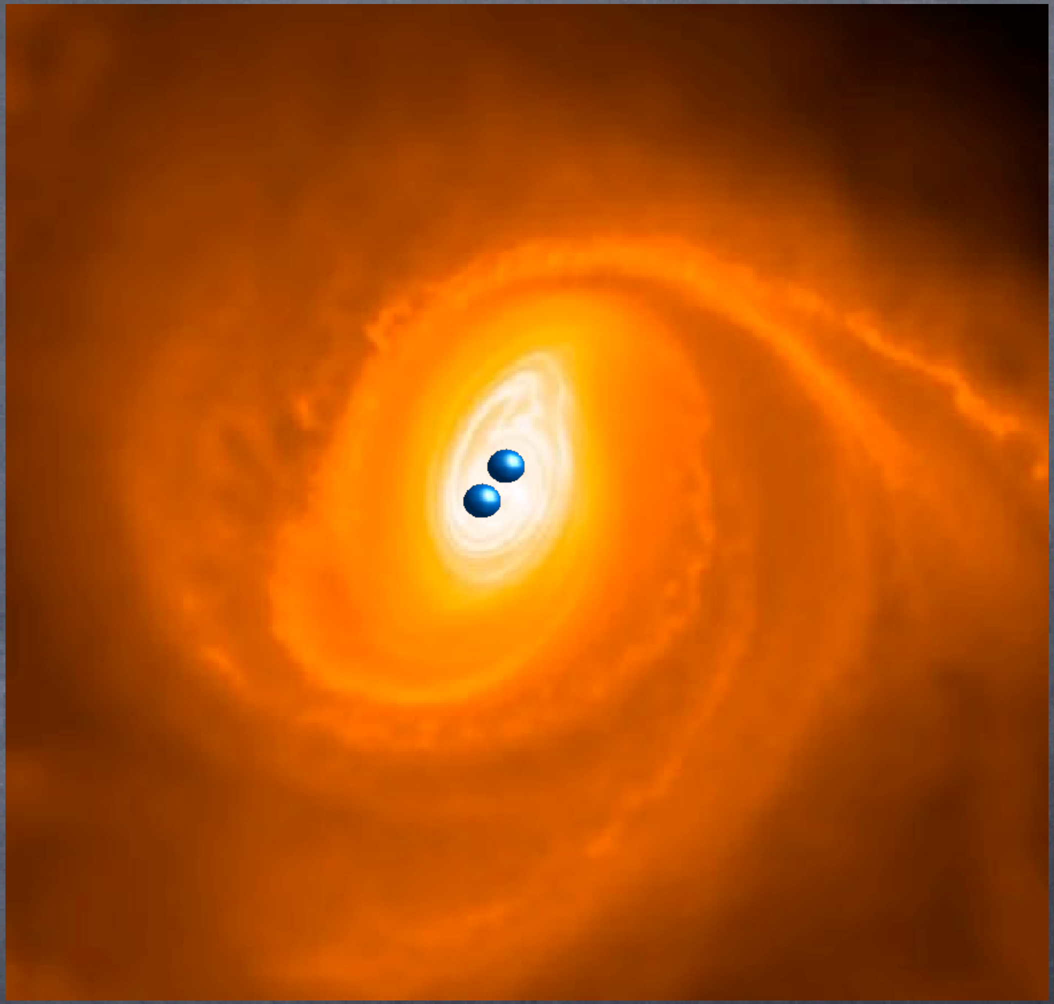
50 Myrs before final merger



STARBURST IS TRIGGERED
AT THIS TIME

POSSIBILITY OF EXCITING DOUBLE AGN ACTIVITY

END OF THE MERGER
CIRCUMNUCLEAR DISC
1-2 kpc
SECOND STAR BURST
IS TRIGGERED 30 M/yr



THE TWO BLACK HOLES
FORM A PAIR
100 pc ASIDE
at the resolution limit

Springel, Di Matteo & Hernquist 2005

A BLACK HOLE PAIR
IN THE ENVIRONMENT OF A STARBURST

WE CONTINUED THE SIMULATION INCREASING THE FORCE RESOLUTION VIA PARTICLE SPLITTING TECHNIQUE APPLIED OVER A REGION OF 6 kpc IN SIZE IN ORDER TO EXPLORE FURTHER THE BLACK HOLE EVOLUTION

Resolution 3 pc scale

P=P(rho, Tg,Td,V,Irad,C)
Local physics of the multiphase ISM

Due to the huge computational effort we decided to model the thermodynamics of a starburst introducing a polytropic index according to Spaans & Silk 2000

ENERGY EQUATION
with shock capturing artificial viscosity

EFFECTIVE POLYTROPIC INDEX

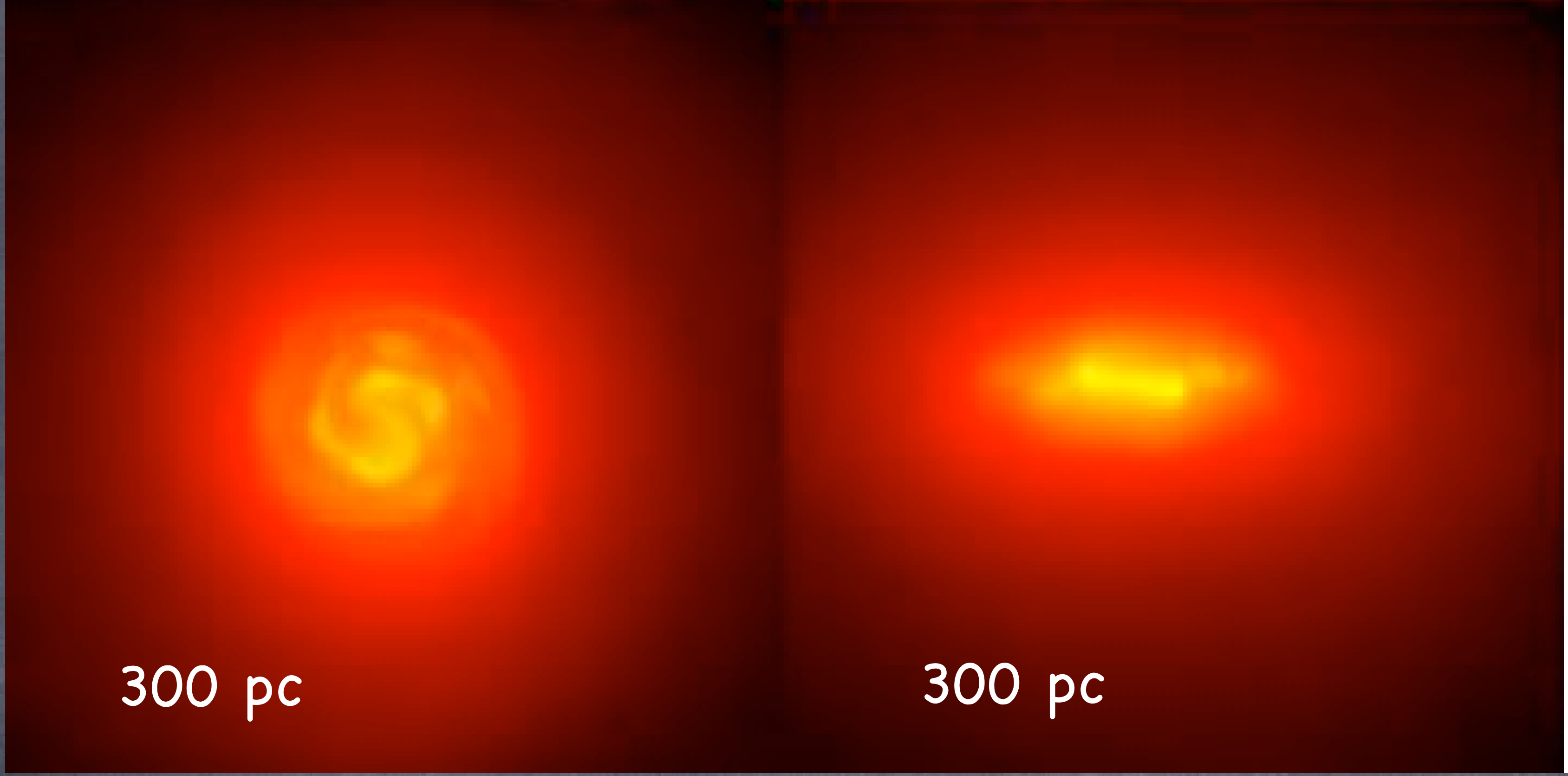
$\Upsilon=7/5$

TYPICAL OF A STARBURST

$\Upsilon=5/3$

to explore the sensitivity
of the black hole dynamics

MIMIC A WARMER MEDIUM
HEATED BY AGN FEEDBACK



WHEN $\Upsilon=7/5$

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

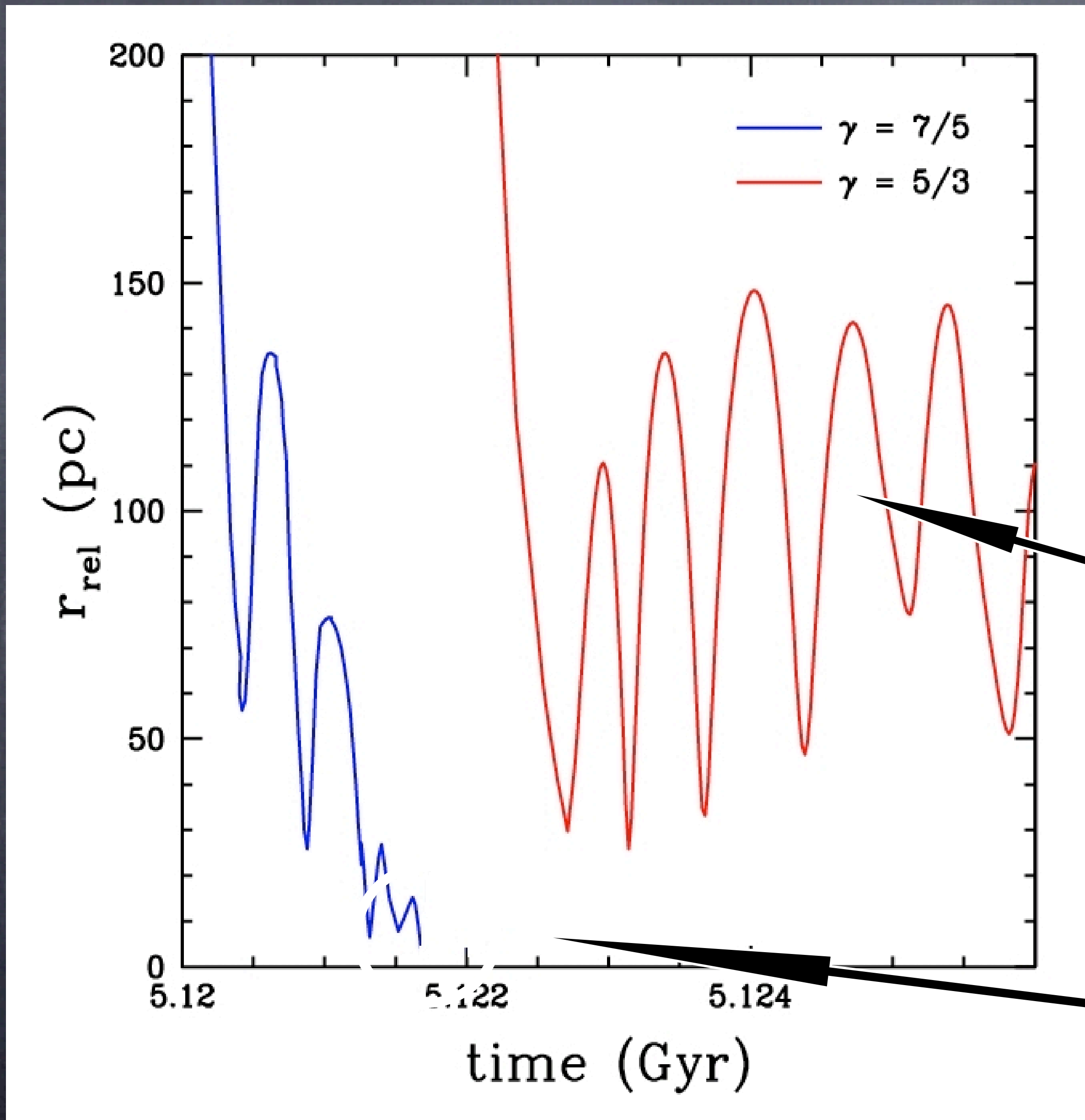
RADIAL INFLOWS OF 30-100 km/s lasting 100,000 years

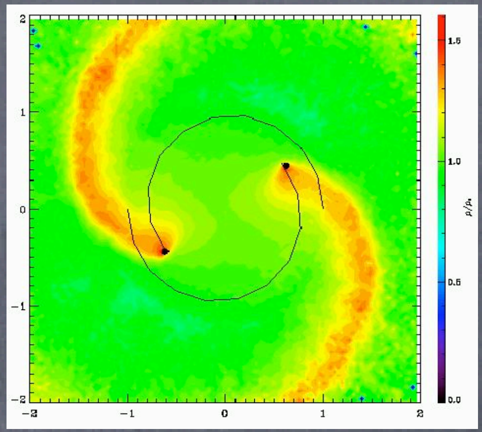
$V_{sound} < V_{turb} < V_{rot}$

(Wada & Norman 2002) 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 will cause
its shrinking on a much
longer time scale)

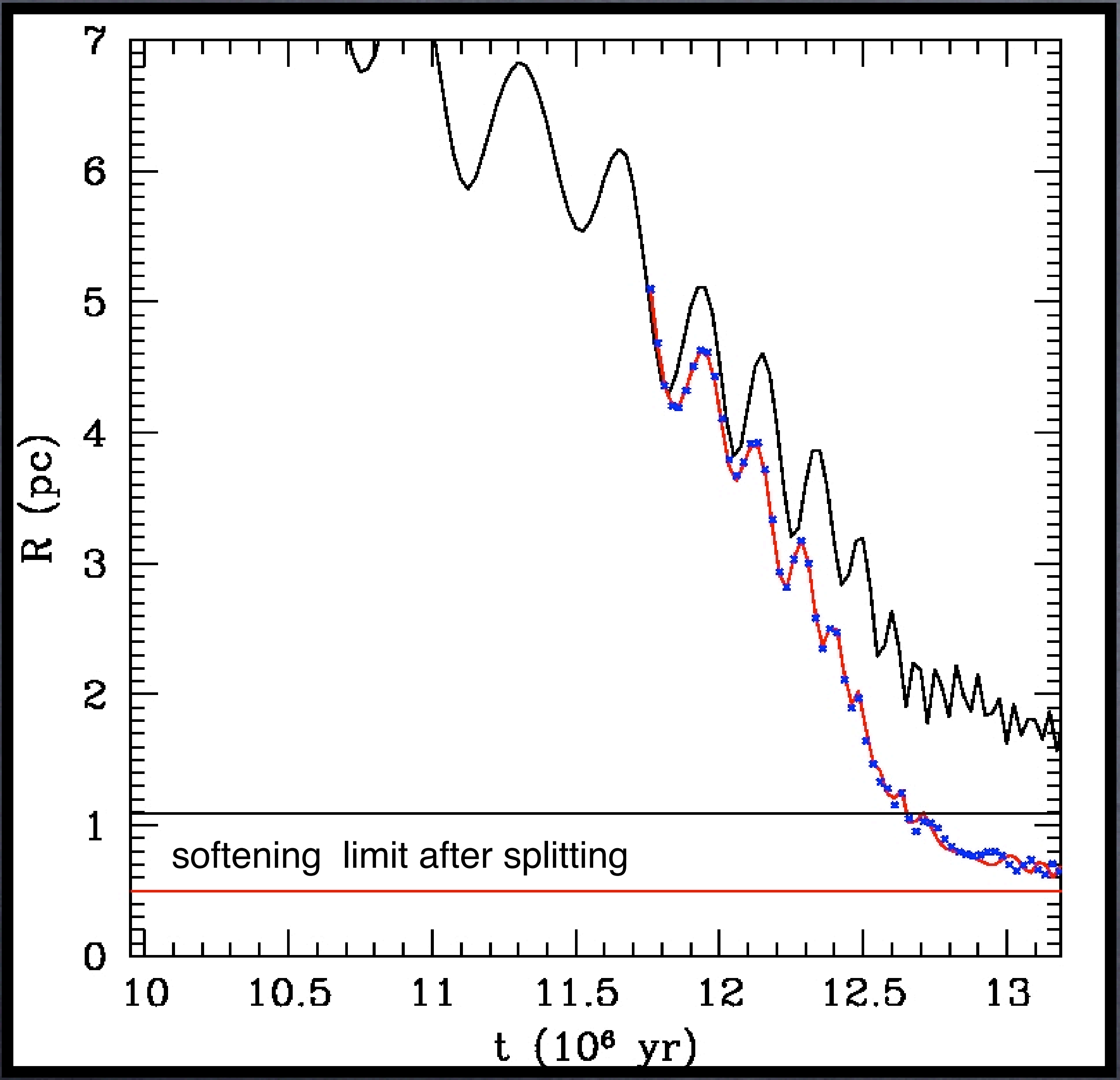
Keplerian mildly
eccentric Binary formed
in a Myr after merger
is completed
(supersonic motion)

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

....
the ability to BIND depends on Υ

✓ STAR BURST ENVIRONMENT
✓ COOLER AMBIENT MEDIUM
✗ HOT VIRIALIZED MEDIUM
AGN FEEDBACK DURING MERGER WOULD ABORT / DELAY
THE FORMATION OF A KEPLERIAN BINARY

WHAT HAPPEN THEN?
BELOW ... 10 pc .... down to 0.001 pc?



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

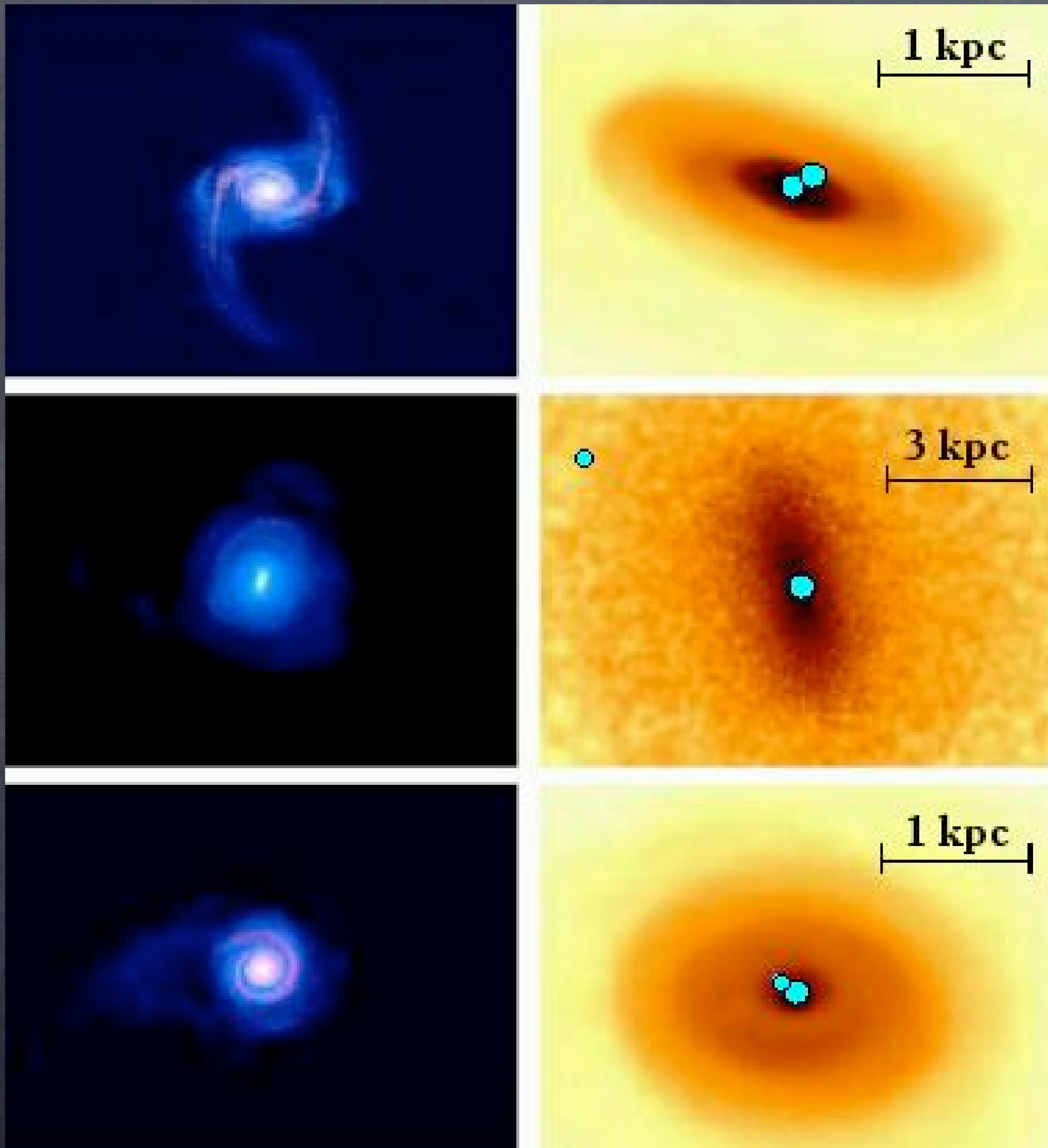
COALESCENCE IN
10 Myrs

Escala et al. 2005
Dotti et al. 2006

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

(i)

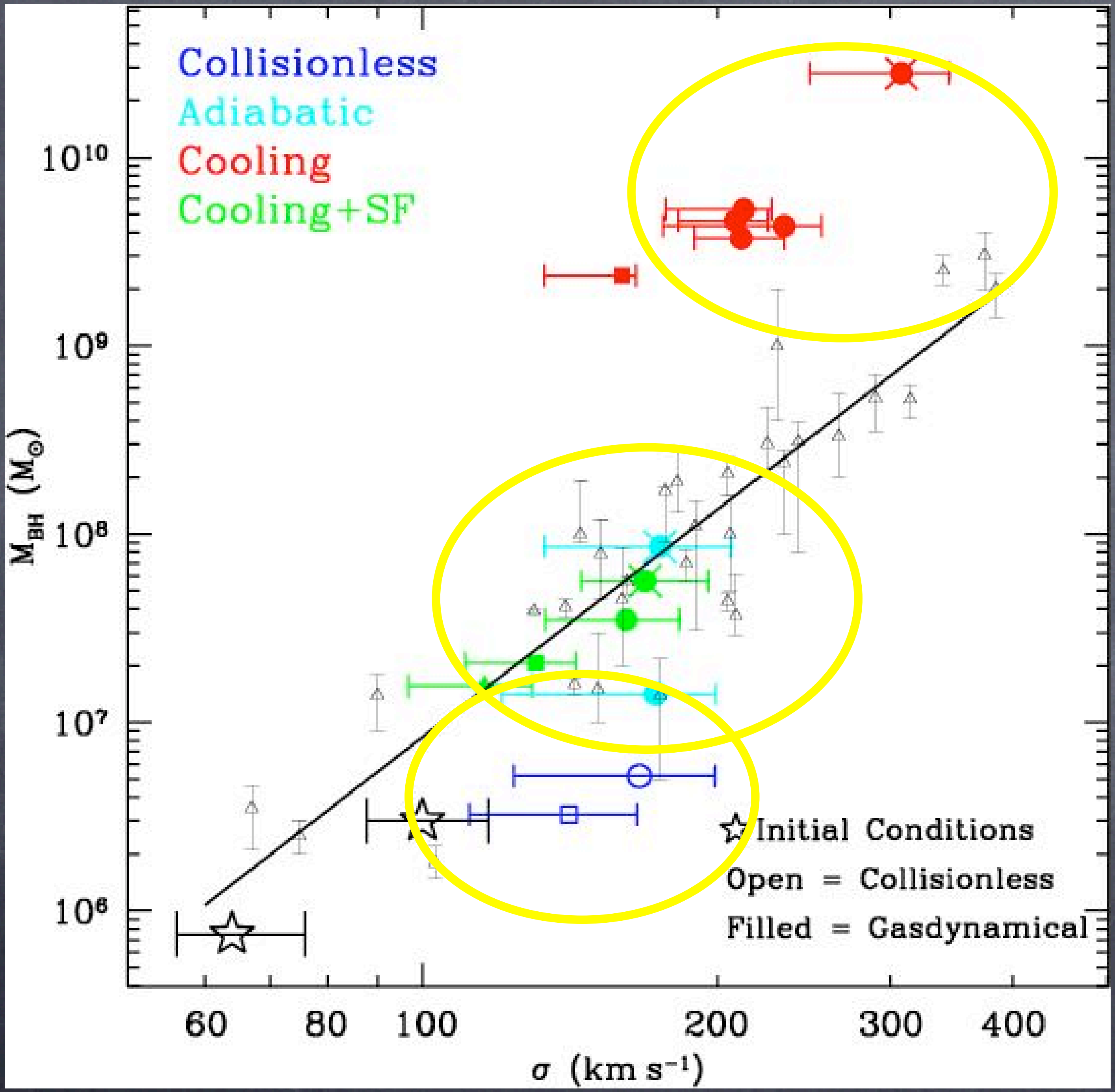
Are there differences between major and minor mergers ?



MAJOR
MERGER

4:1 MINOR
MERGER
NO COOLING
WANDERING
BLACK HOLES

4:1 MINOR
MERGER
WITH COOLING



Collisionless
Adiabatic
Cooling
Cooling+SF
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
M_{BH} ($M_{\odot}$)
☆ Initial Conditions
Open = Collisionless
Filled = Gasdynamical
60
80
100
200
300
400
σ (km s^{-1})

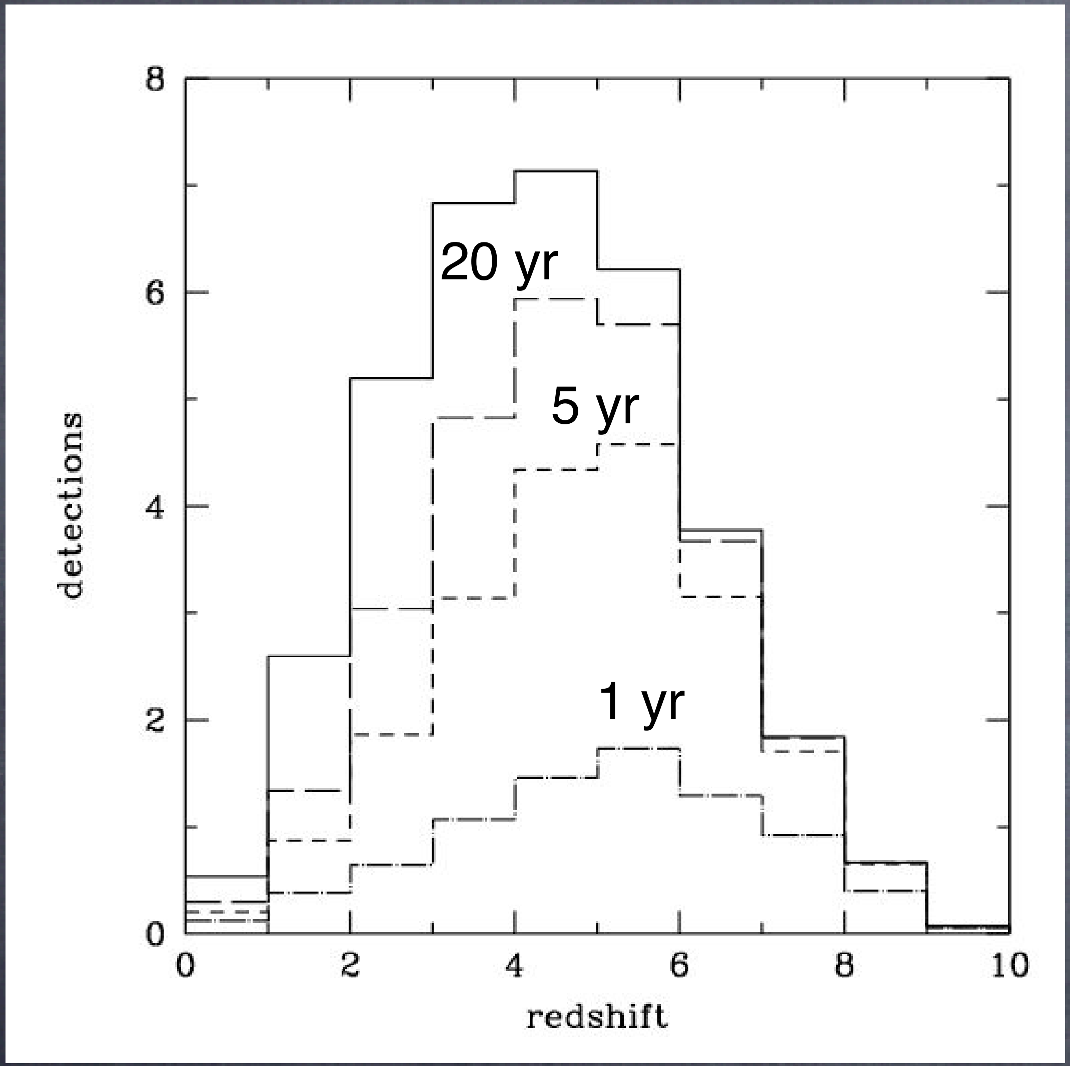
MERGER EVOLUTIONARY SCHEME

IN MAJOR GAS RICH MERGERS A
KEPLERIAN BINARY FORMS
BLACK HOLE COALESCENCE LIKELY OCCURS
ASSISTED ONLY BY GAS DYNAMICAL PROCESSES
τ_{coal} ~ 10 Myrs
QSO & FEEDBACK

IN MAJOR MERGERS & "HOT" NUCLEAR ENVIRONMENT
LOOSE BINARY is LEFT IN THE CORE
(τ_{coal} ~ billion years or ...... more due to the drag from stars)

MINOR MERGERS
WANDERING BLACK HOLES
we need to investigate q=0.01 0.1 more

AGN ACTIVITY
SINGLE OR DOUBLE

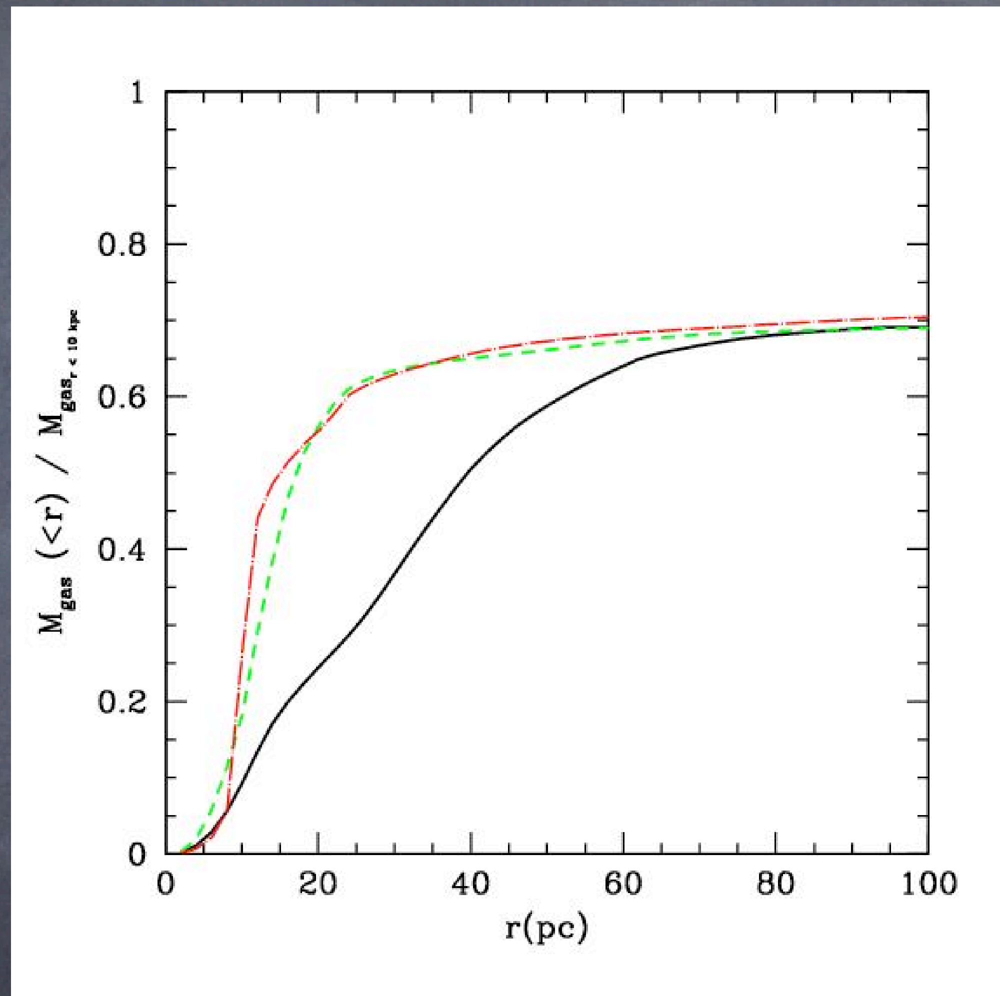


XEUS or
CONSTELLATION X
FLUX LIMIT

0.5 5 keV
neglecting photoelectric
absorption at the source

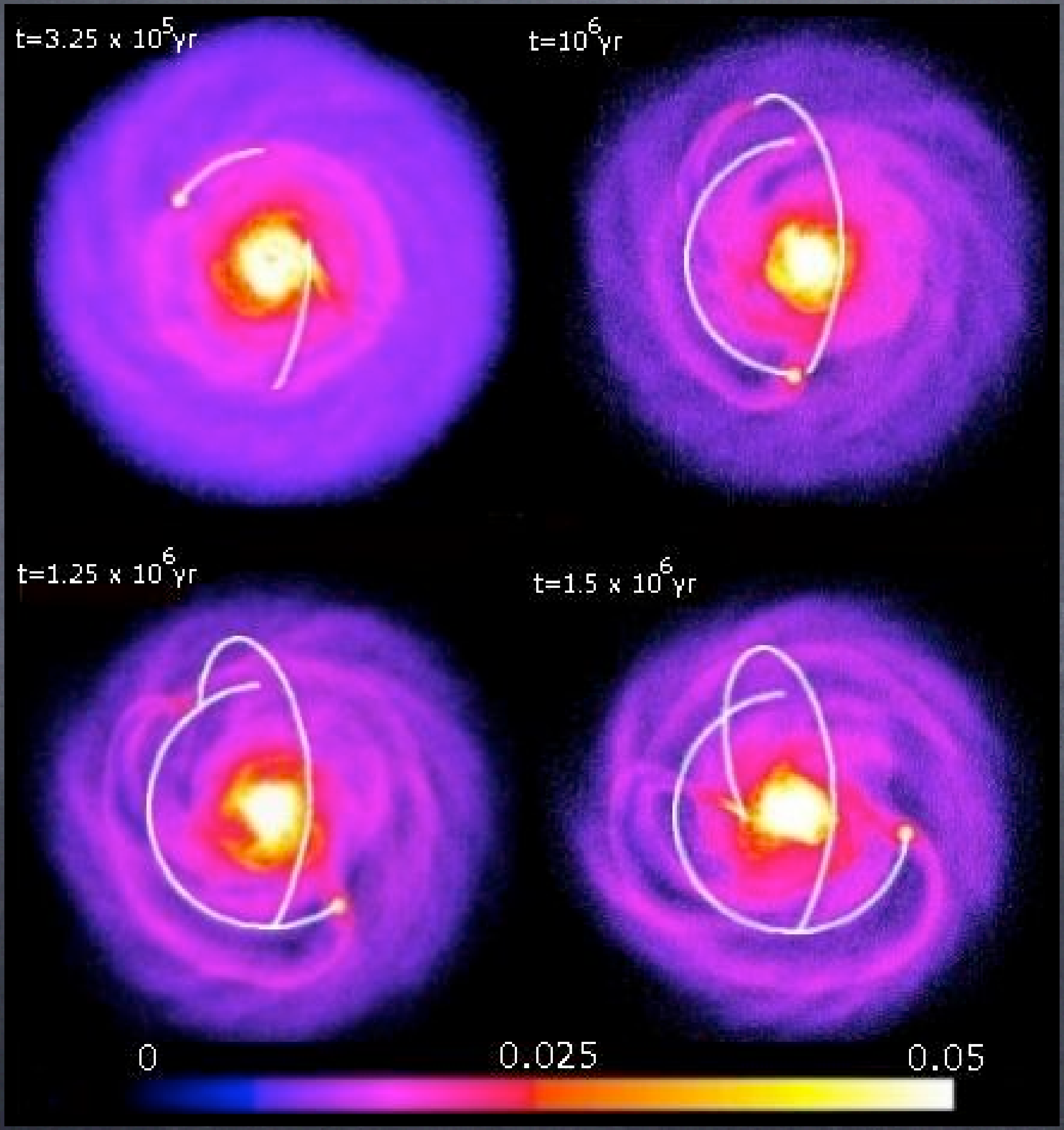
Dotti, Salvaterra, Sesana, Colpi, Haardt 2006

MASSIVE CIRCUM-NUCLEAR GASEOUS THICK DISK



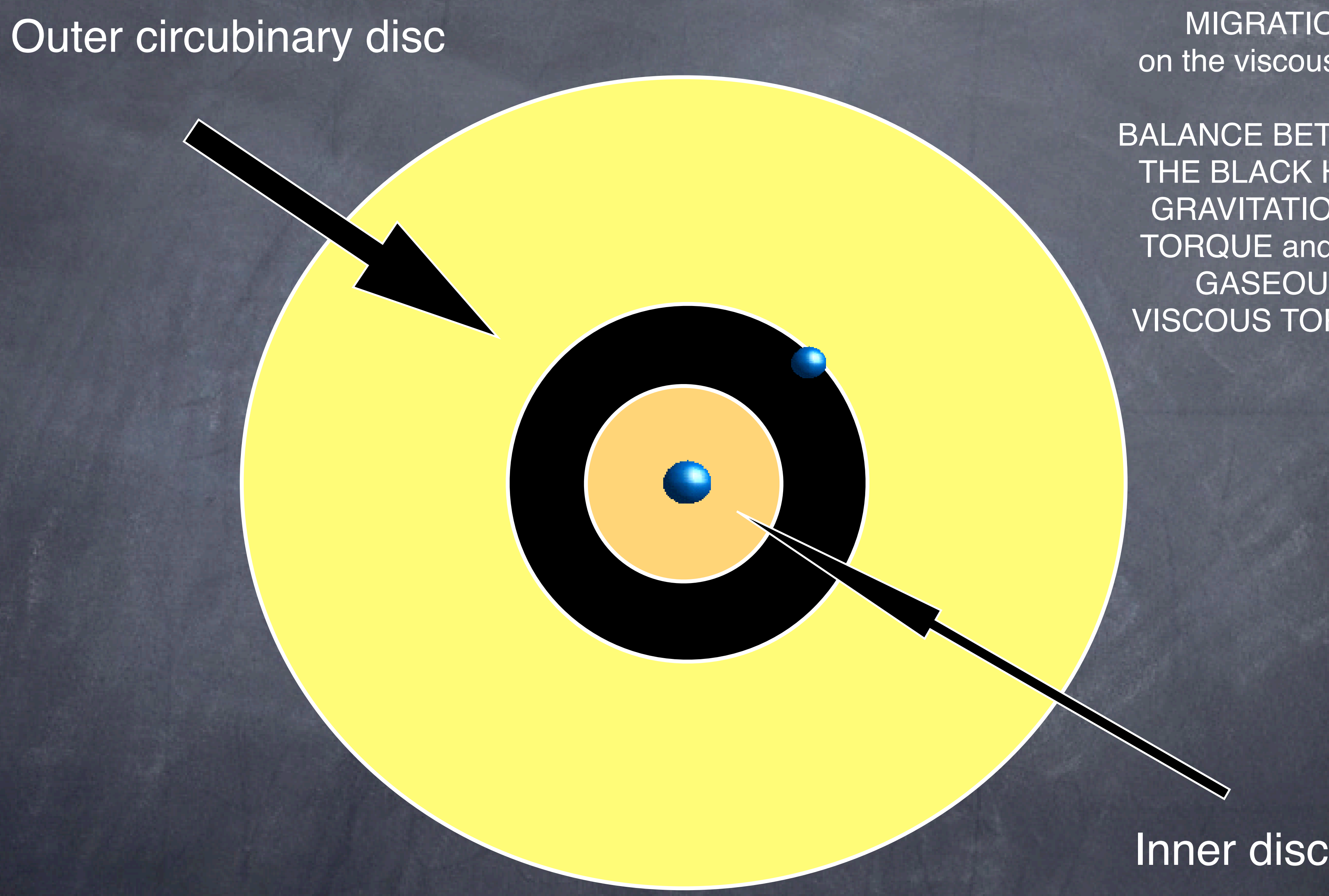
Gas inflow stronger with increasing force resolution because gravitational torques better resolved. Convergence approached at ~ 10 pc resolution.

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



FORMATION OF A GAP
BLACK HOLE
MIGRATION
on the viscous time

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



Armitage & Natarajan 2004

Milosavljevic & Phinney 2005

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

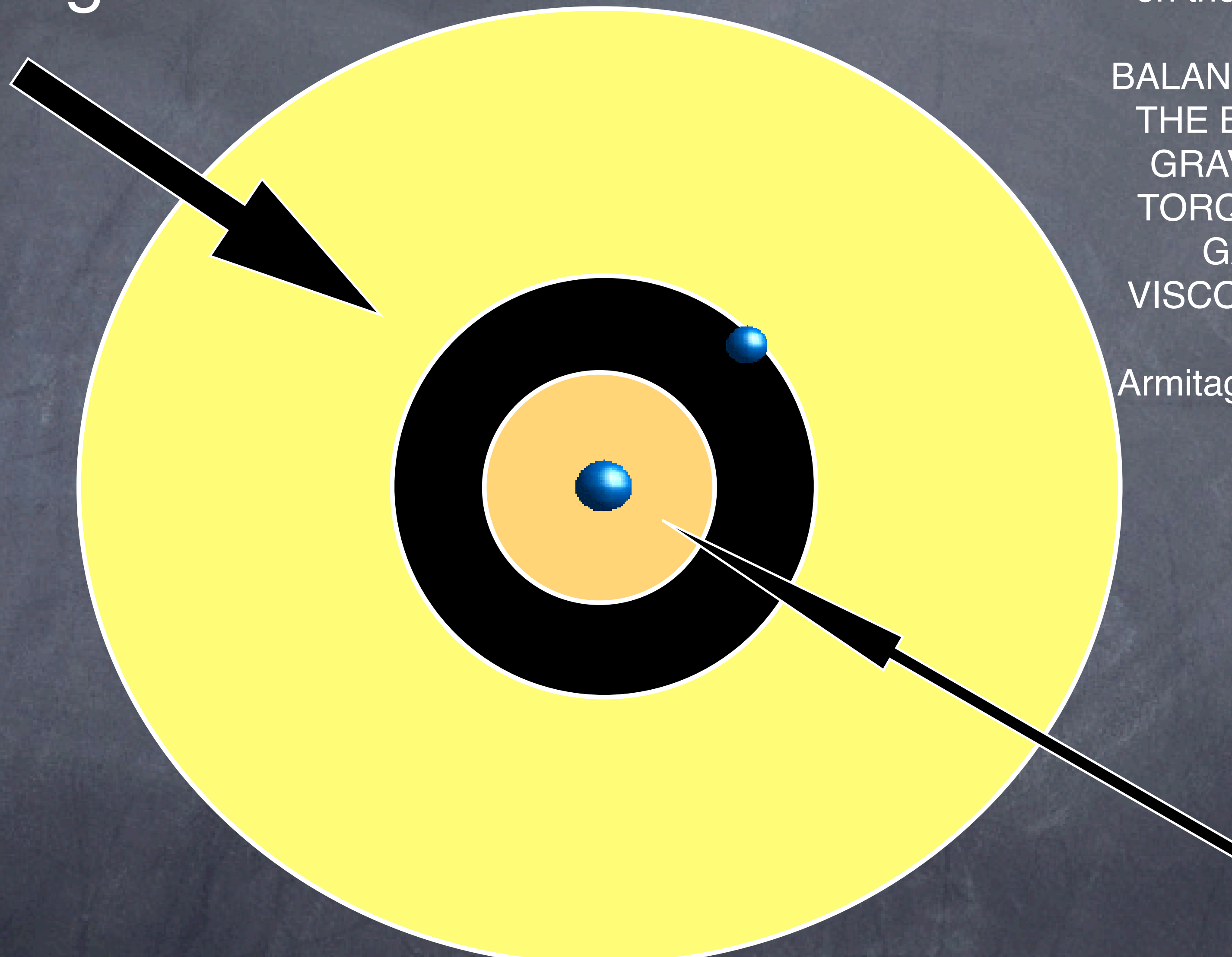
$$t \approx 7(1+z)(M/M_{\odot})^{1.32} \text{ years}$$

FORMATION OF A GAP
BLACK HOLE
MIGRATION
on the viscous time

BALANCE BETWEEN
THE BLACK HOLE
GRAVITATIONAL
TORQUE OF THE
GASEOUS
VISCOUS TORQUE

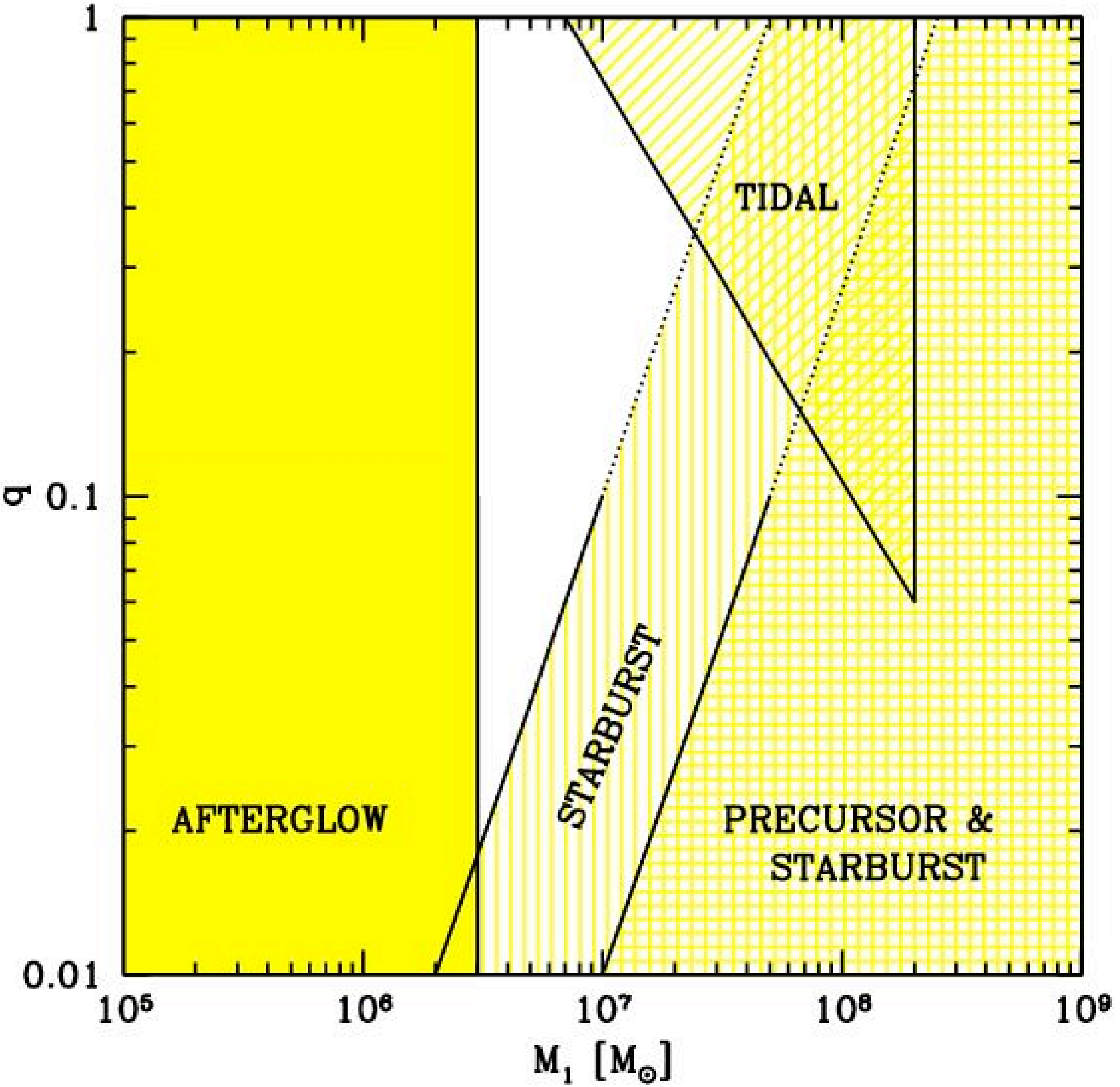
Armitage & Natarajan
2004

Afterglow



Preglow - last year of inspiral

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



1
0.1
0.01
q
10^5
10^6
10^7
10^8
10^9
M_1 [$M_\odot$]
AFTERGLOW
STARBURST
TIDAL
PRECURSOR &
STARBURST

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

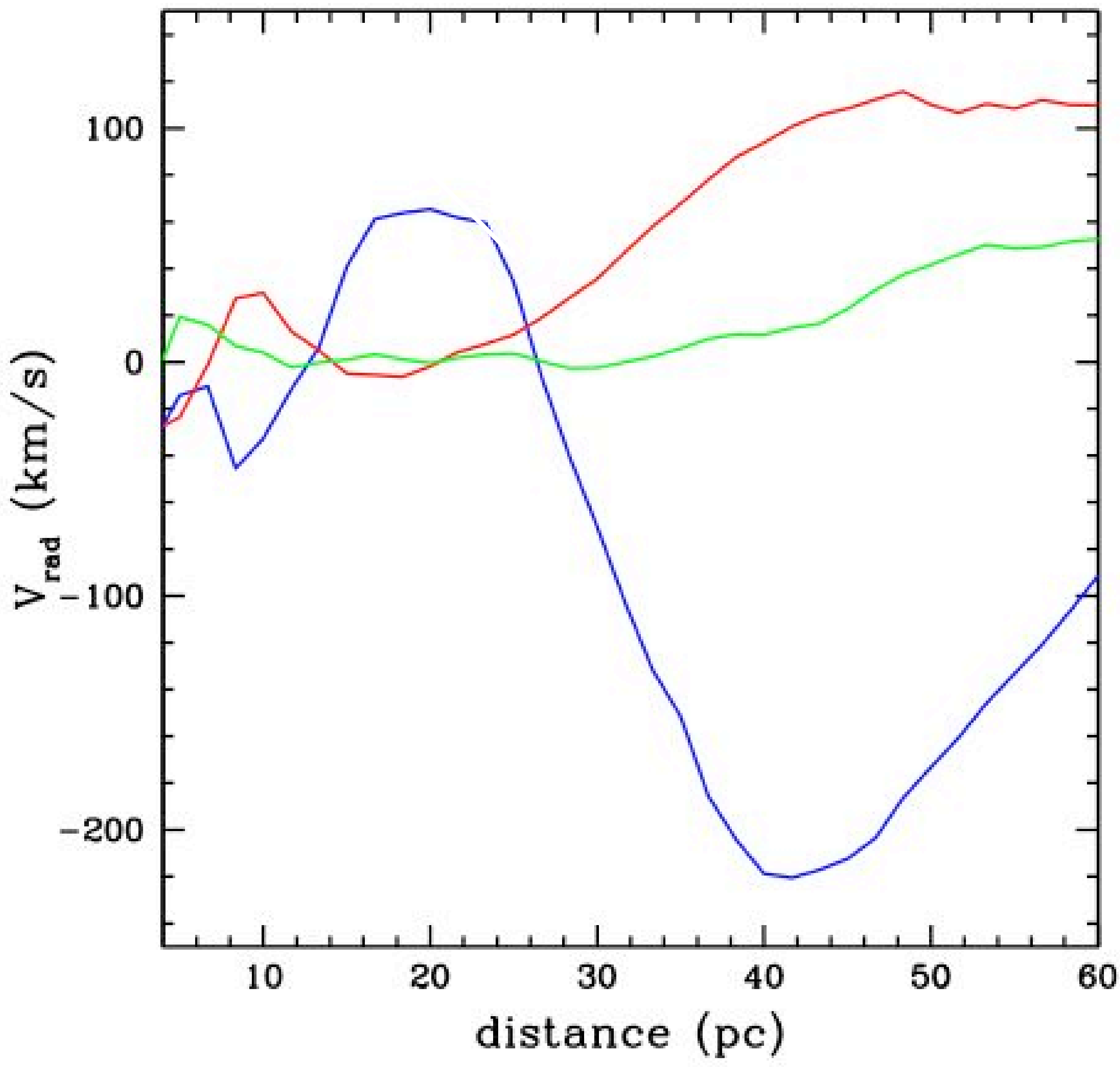
$\delta\Omega \sim 0.01\text{-}3$ deg ^{2}

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

Holz & Hughes 2005



100
0
−100
−200
V_{rad} (km/s)
10
20
30
40
50
60
distance (pc)