UNVELING BINARY BLACK HOLES IN GLOBULAR CLUSTERS WITH PULSAR DYNAMICS

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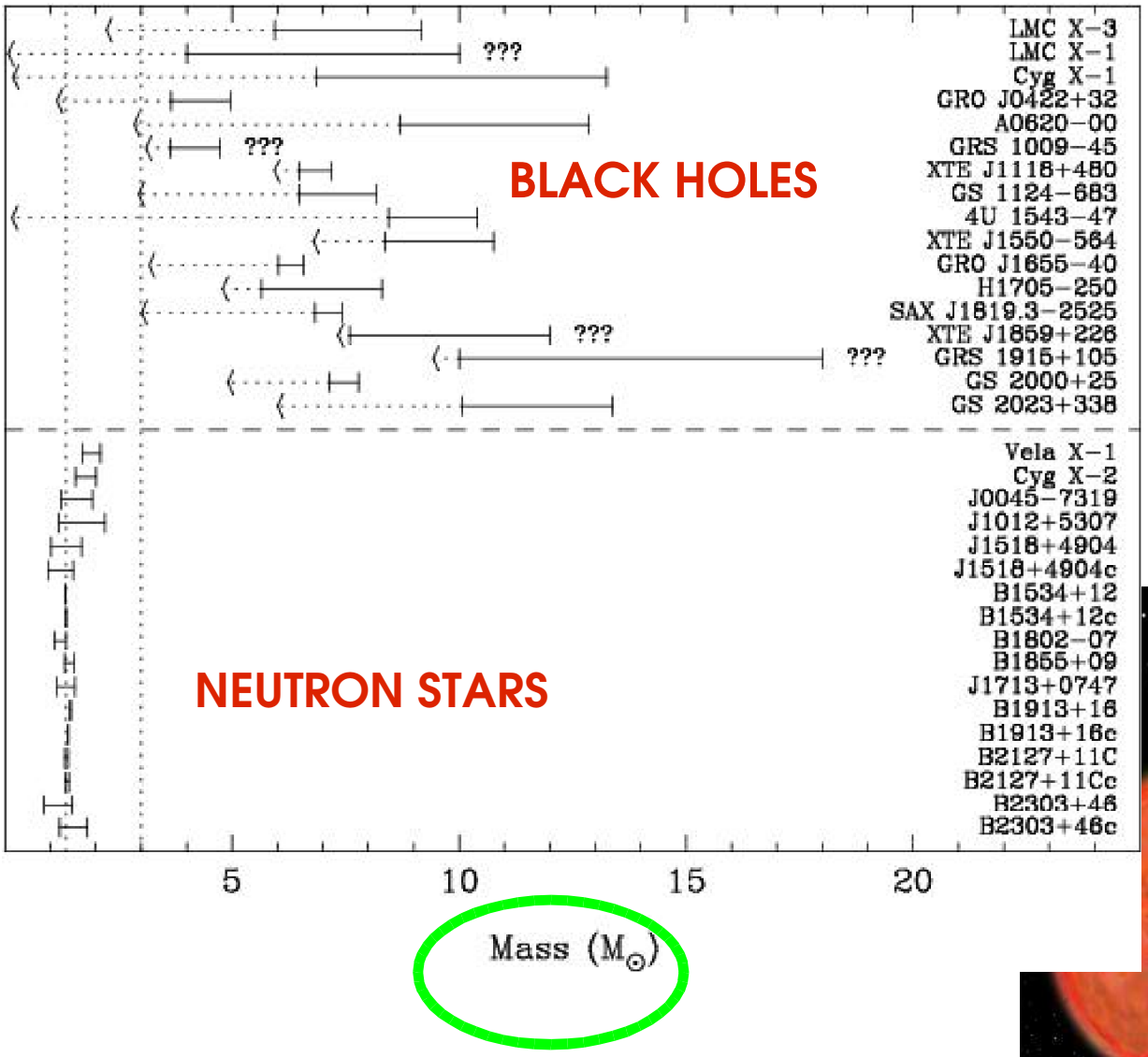
ADVANCED SCHOOL AND CONFERENCE ON SOURCES OF GRAVITATIONAL WAVES, ICTP, TRIESTE 15–26 SEPTEMBER 2003

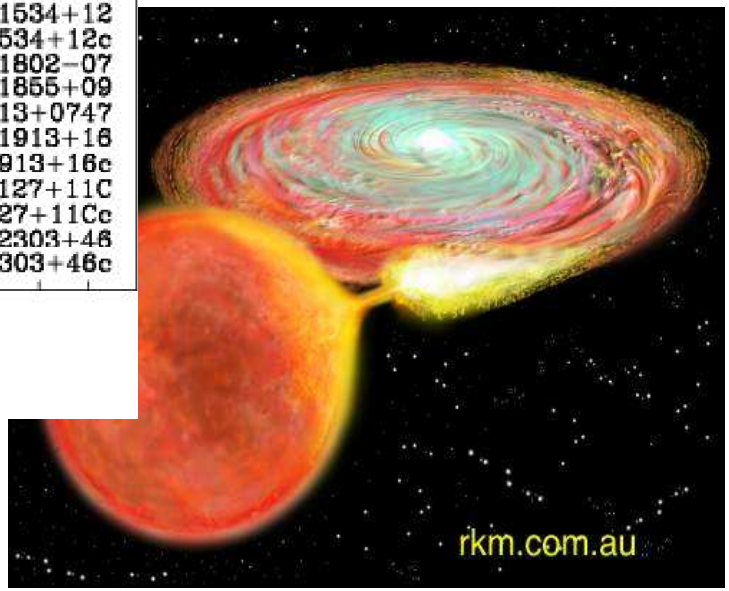
GLOBULAR CLUSTERS
FERTILE GROUNDS
FOR THE FORMATION OF BLACK HOLES

BINARY BLACK HOLE
INTERMEDIATE MASS BLACK HOLE
$M>100\ M_O$

SEVERAL HUNDRED
BLACK HOLES FORM
IN A CLUSTER
FOLLOWING ORDINARY
STELLAR EVOLUTION
SCALO IMF

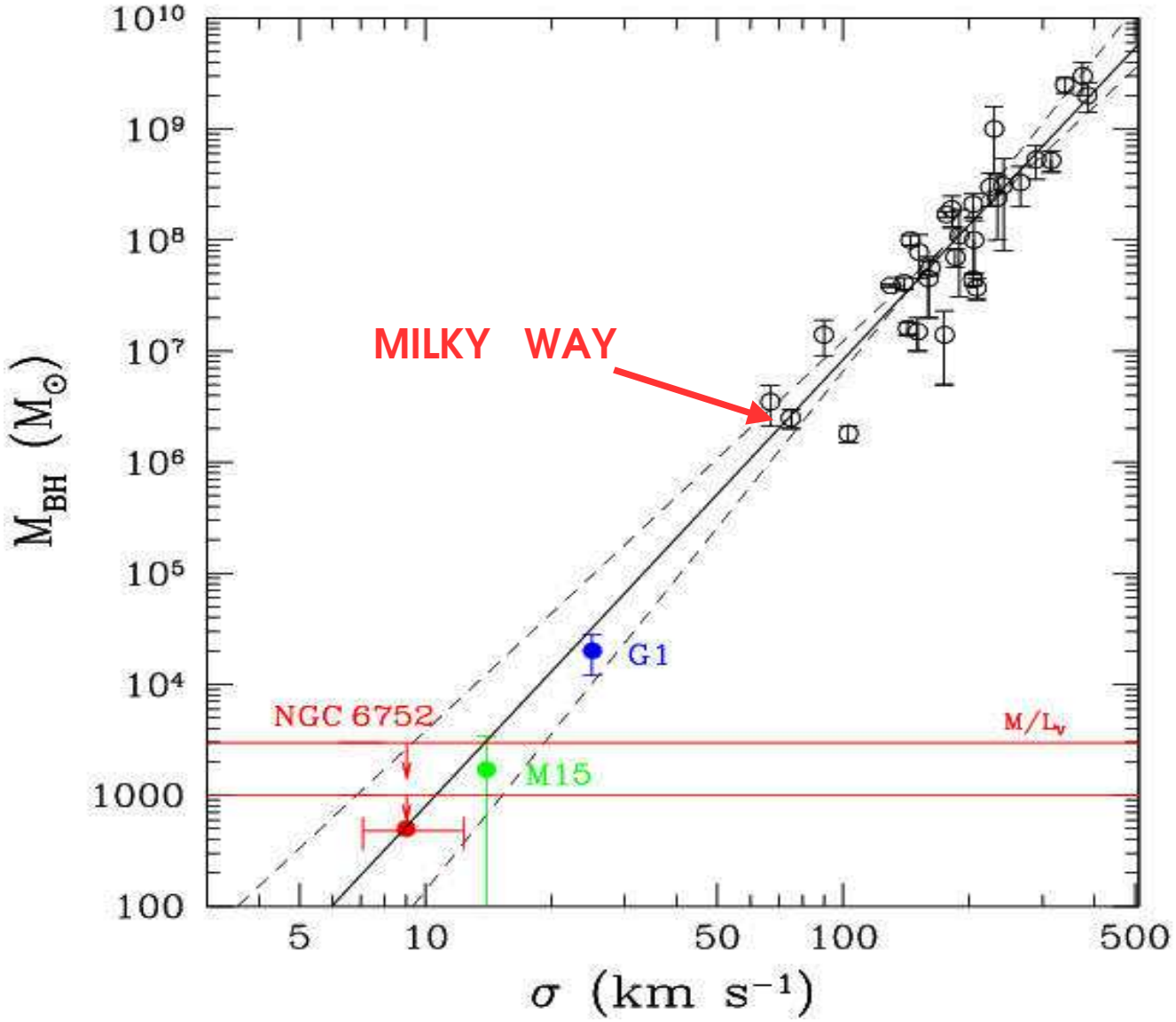
STELLAR–MASS BLACK HOLES IN THE MILKY WAY



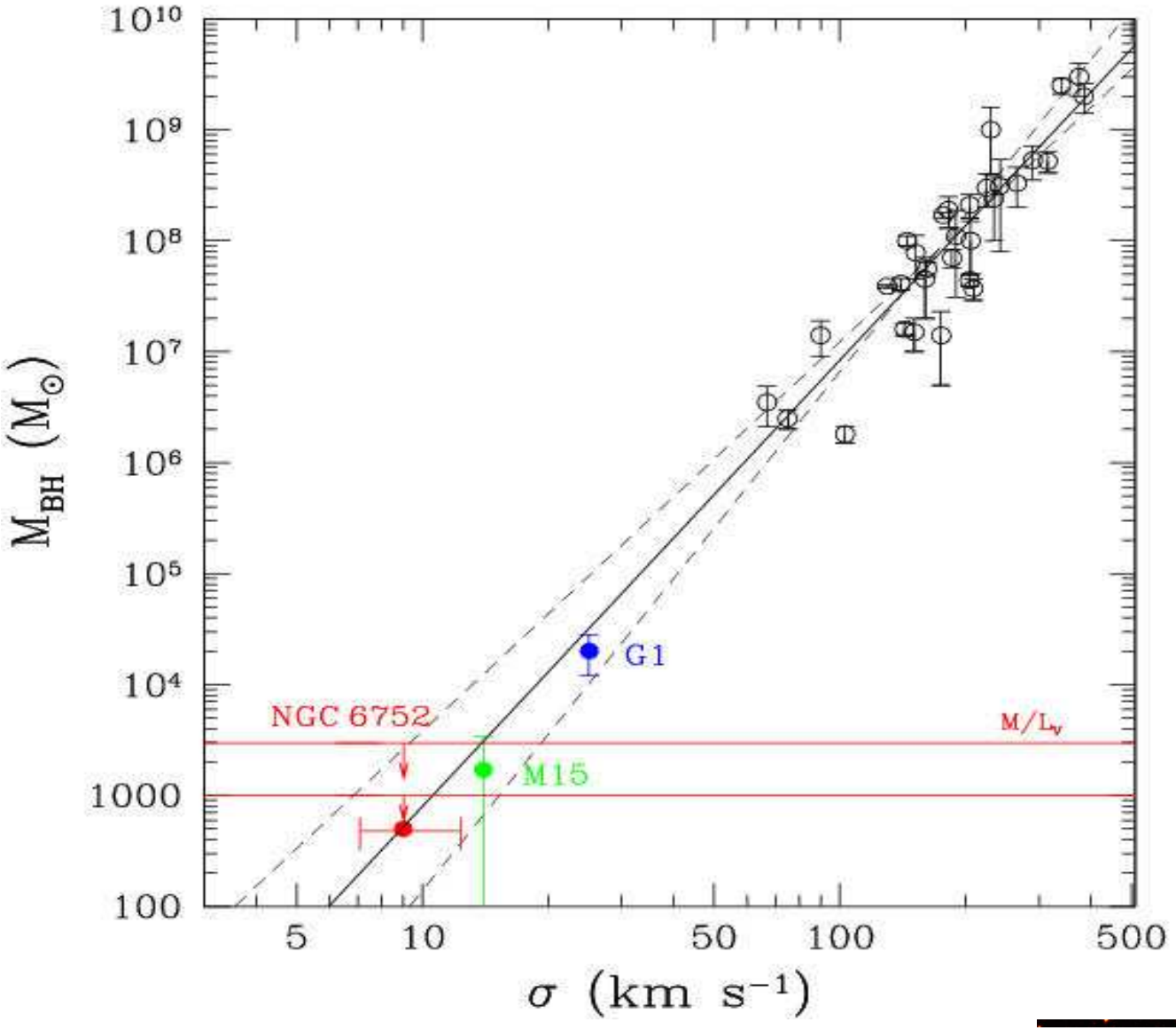


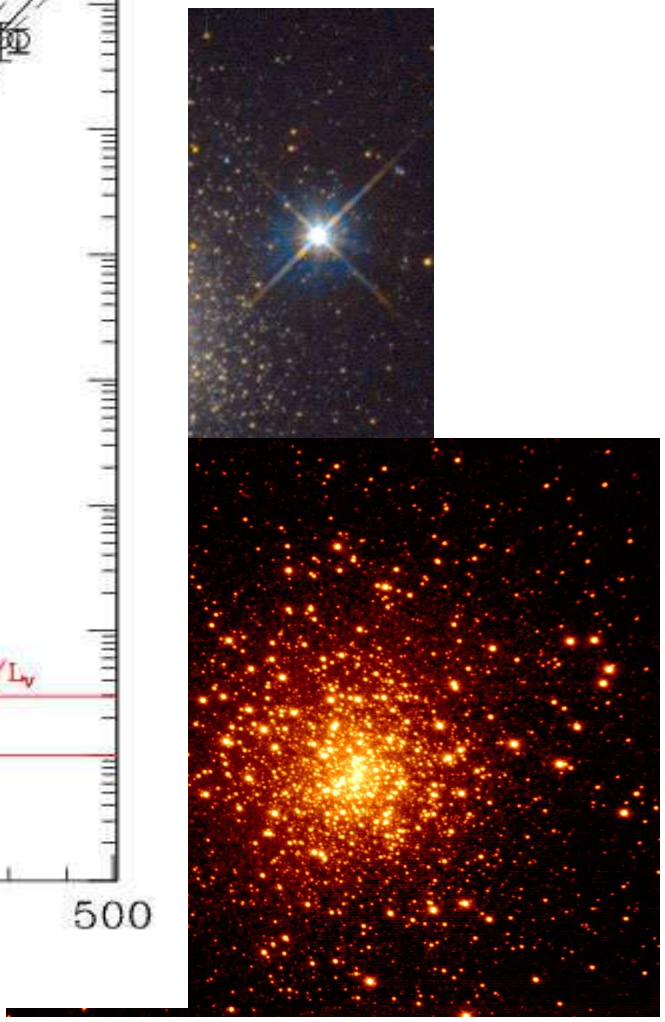
SUPER–MASSIVE QUIESCENT BLACK HOLES IN SPHEROIDS

FERRARESE & MERRIT 2000; GEBHARDT et al. 2000

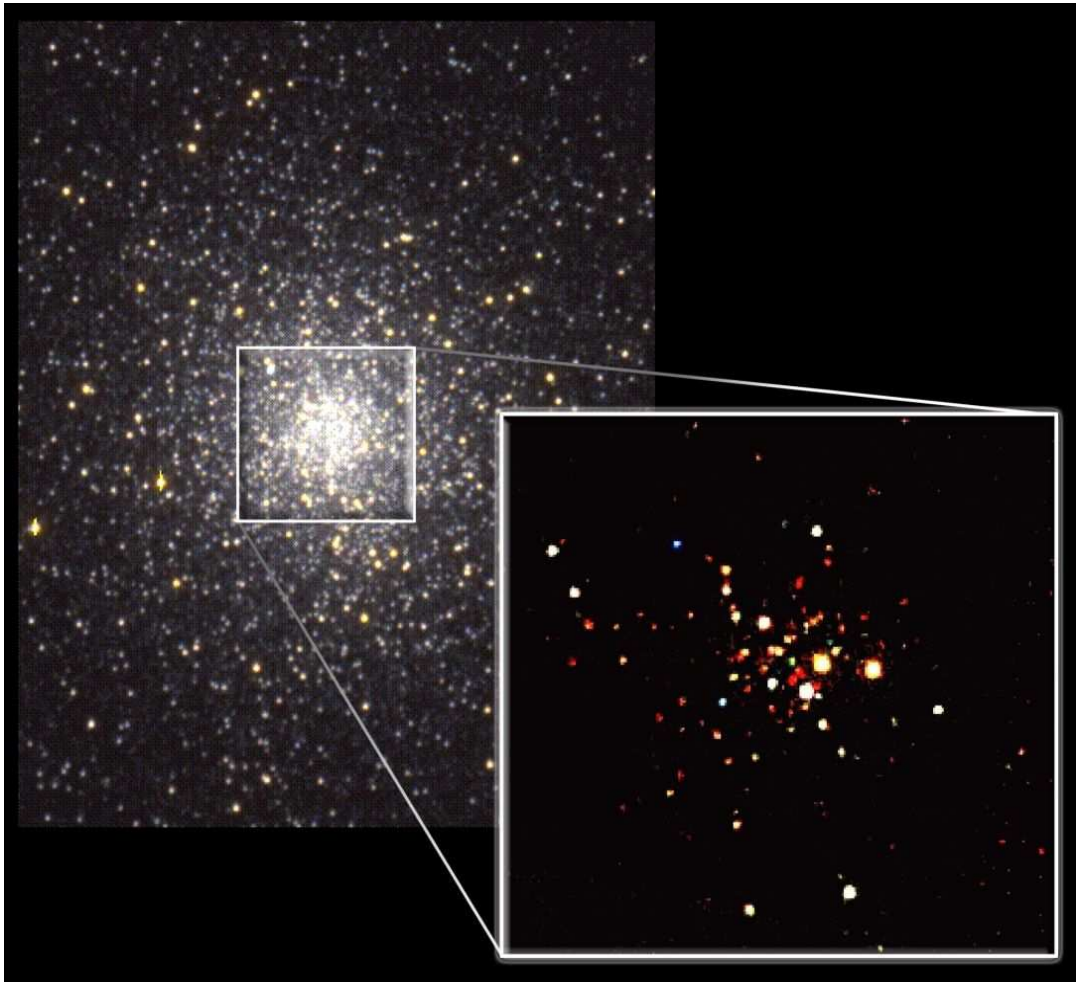


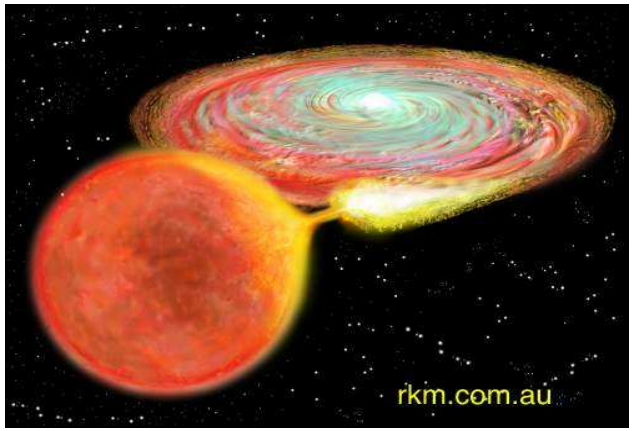
DYNAMICAL EVIDENCE OF INTERMEDIATE MASS BLACK HOLES (IMBHs) – BUILDING BLOCKS OF SUPERMASSIVE BLACK HOLES



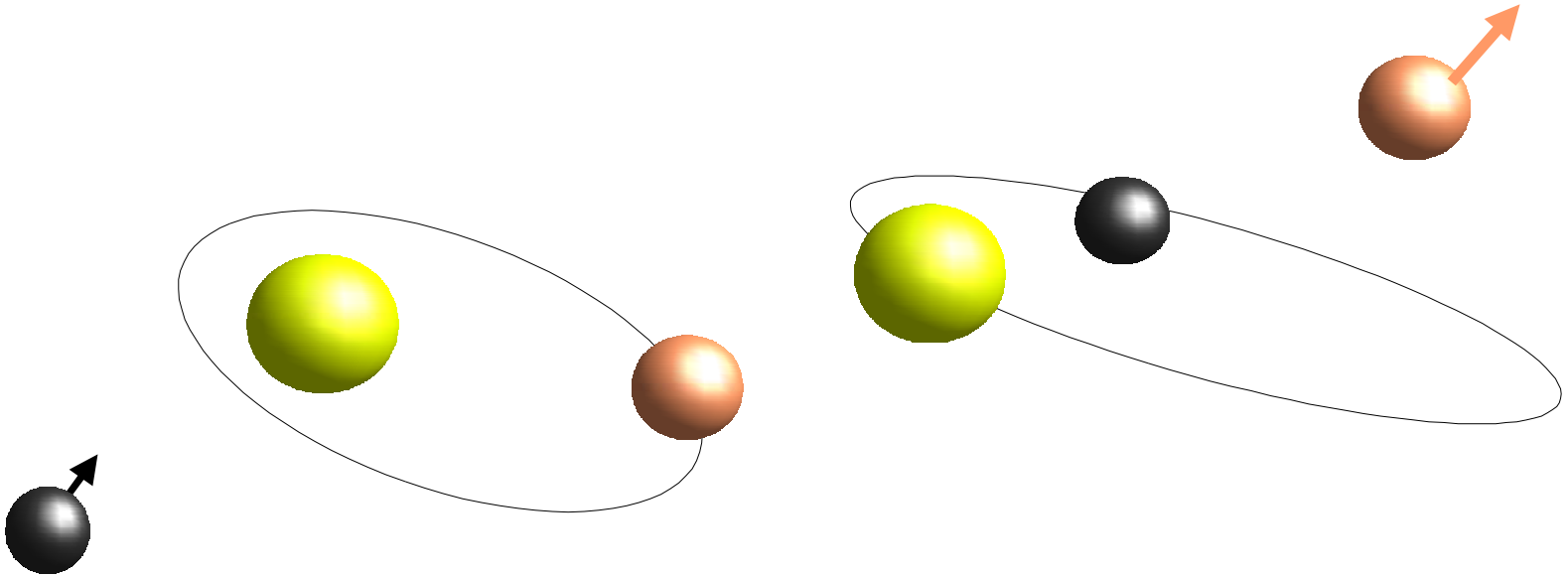


X-RAY OBSERVATIONS MAP THE STELLAR REMNANTS





OVER ABUNDANCE OF MSPs and LOW MASS X-RAY BINARIES HOSTING A NEUTRON RELATIVE TO THE FIELD attributed to stellar encounters BUT NO BLACK HOLE CANDIDATE HAS BEEN OBSERVED YET IN GALACTIC GLOBULAR CLUSTERS !



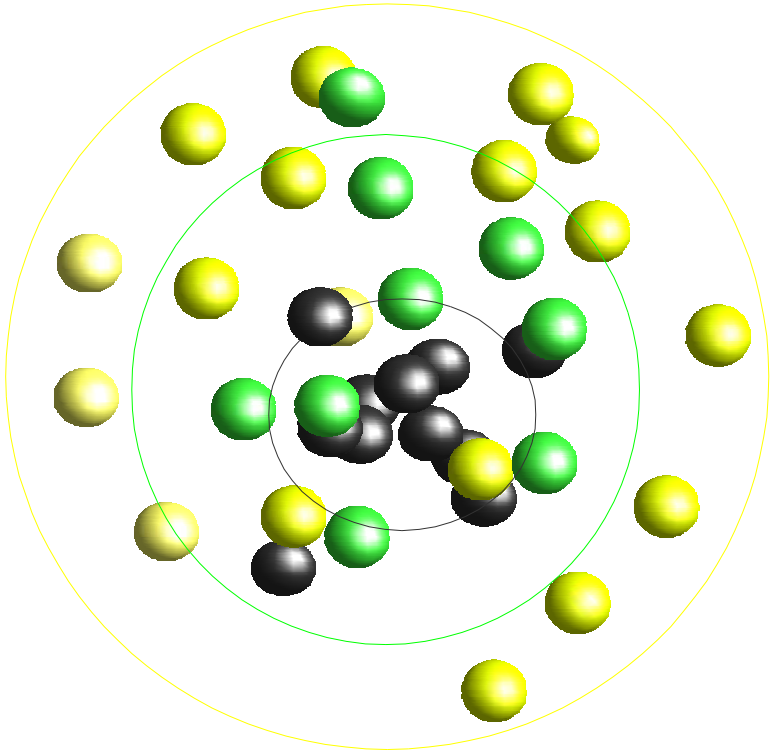
INCOMING BLACK HOLE

FORMATION OF A LOW MASS
BINARY BLACK HOLE CANDIDATE
THROUGH EXCHANGE INTERACTIONS

SMALL NUMBER STATISTICS + TRANSIENT NATURE

BLACK HOLES EVOLVE DIFFERENTLY THAN NEUTRON STARS IN GLOBULAR CLUSTERS

DYNAMICAL FRICTION LEAD TO
MASS SEGREGATION
THEIR CONFINEMNET IN THE CORE
ON A TIME COMPARABLE 1/10 HALF MASS
RELAXATION TIME
3-BODY EXCHANGES
INVOLVING STARS & BLACK HOLES
BUILD UP OF A POPULATION OF BLACK HOLES
IN BINARIES !!



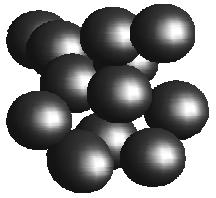
SEPARATED POPULATION FORMING
A HIGH DENSITY
CLUSTER OF BLACK HOLES
SINGLE OR IN BINARIES

Kulkarni, Hut, & McMillan 1993
Sigurdsson & Phinney 1993

BLACK HOLE CORE CONFINEMENT
DRIVES FURTHER EVOLUTION

CLOSE GRAVITATIONAL ENCOUNTERS AMONG BLACK HOLES

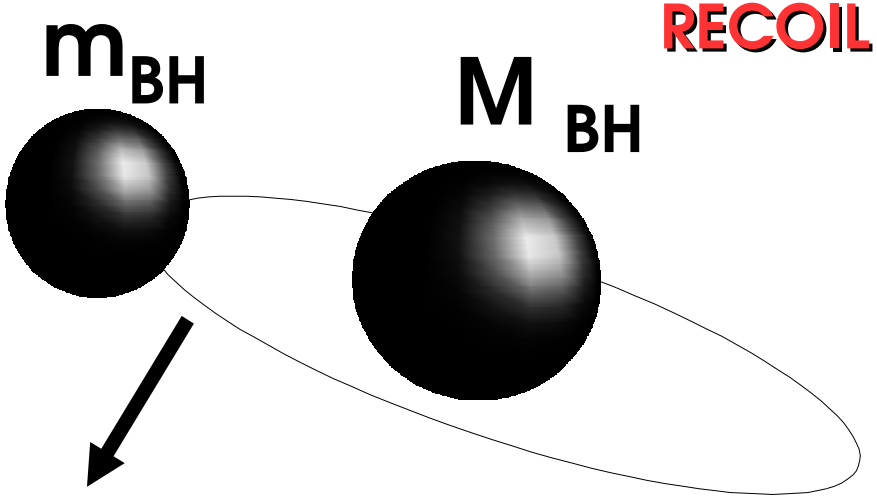
TWO POSSIBLE OUTCOMES



COMPLETE EVAPORATION
OR
ABORTED EVAPORATION
SOME BLACK HOLE LEFT IN THE CORE

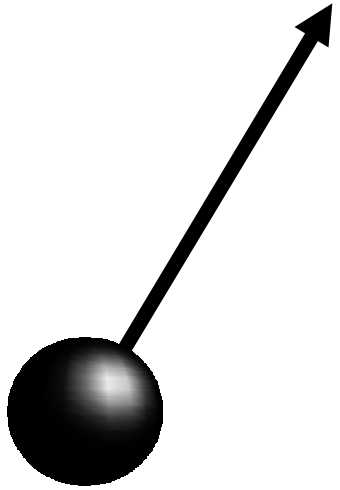
(Sigurdsson & Hernquist 1993; kulkarni, Hut & McMillan 1993; P. Zwart & McMillan 2001)

RECOIL INDUCED EVAPORATION



BLACK HOLE BINARY HARDENING

OUTGOING SINGLE BLACK HOLE ACQUIERS KINETIC ENERGY EXTRACTED FROM THE BINDING ENERGY OF THE BINARY



$M_{BH,field}$

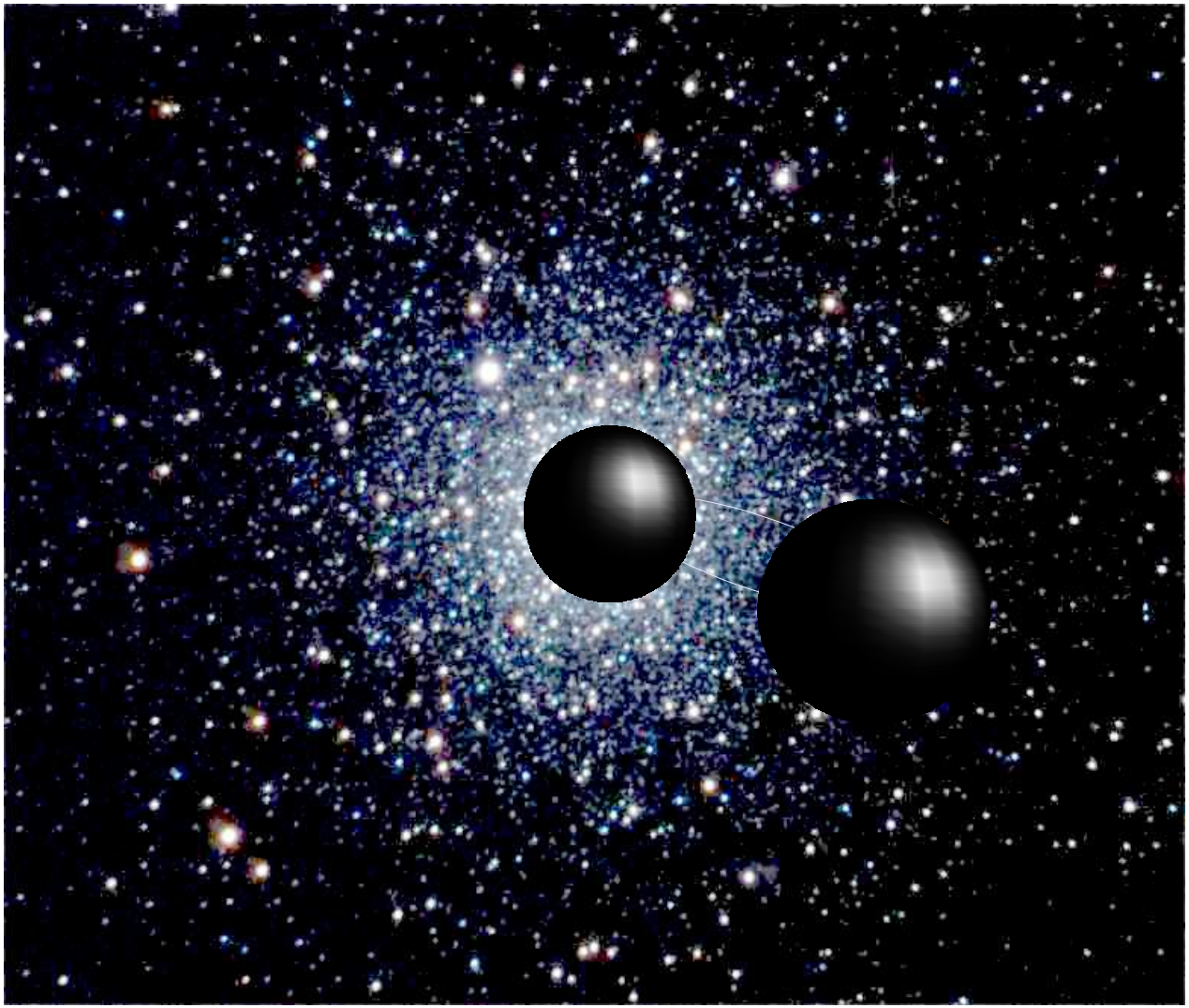
$$(M_{BH} + m_{BH}) = M$$

$$\Delta E/E = \Xi \, (M_{BH,filed}/M)$$

$$V^2_{BH,field} = \Xi \, G M_{BH} m_{BH}/(M\, a)$$

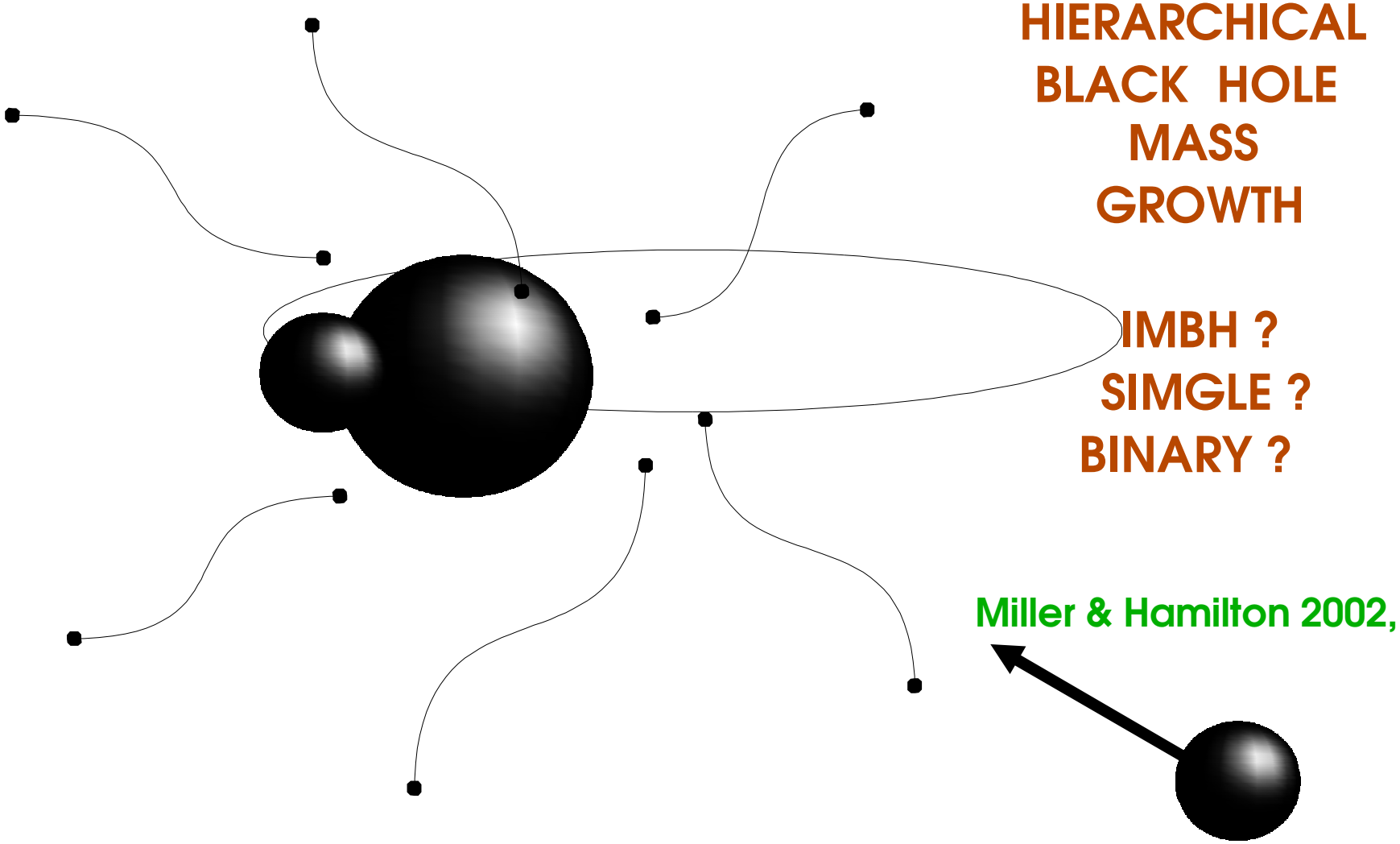
$$V_{BINARY} = V_{BH,field} M_{BH,field}/M$$

THE BLACK HOLES THAT REMAIN TEND TO BE THE MOST MASSIVE AND IN THE FORM OF A BINARY



(Portegies Zwart & McMillan 2000)

DURING THE EVAPORATION some BINARY BALCK HOLE EXPERIENCES COALESCENCE BY EMISSION OF GRAVITATIONAL WAVES before EXPERIENCING THE FATAL KICK

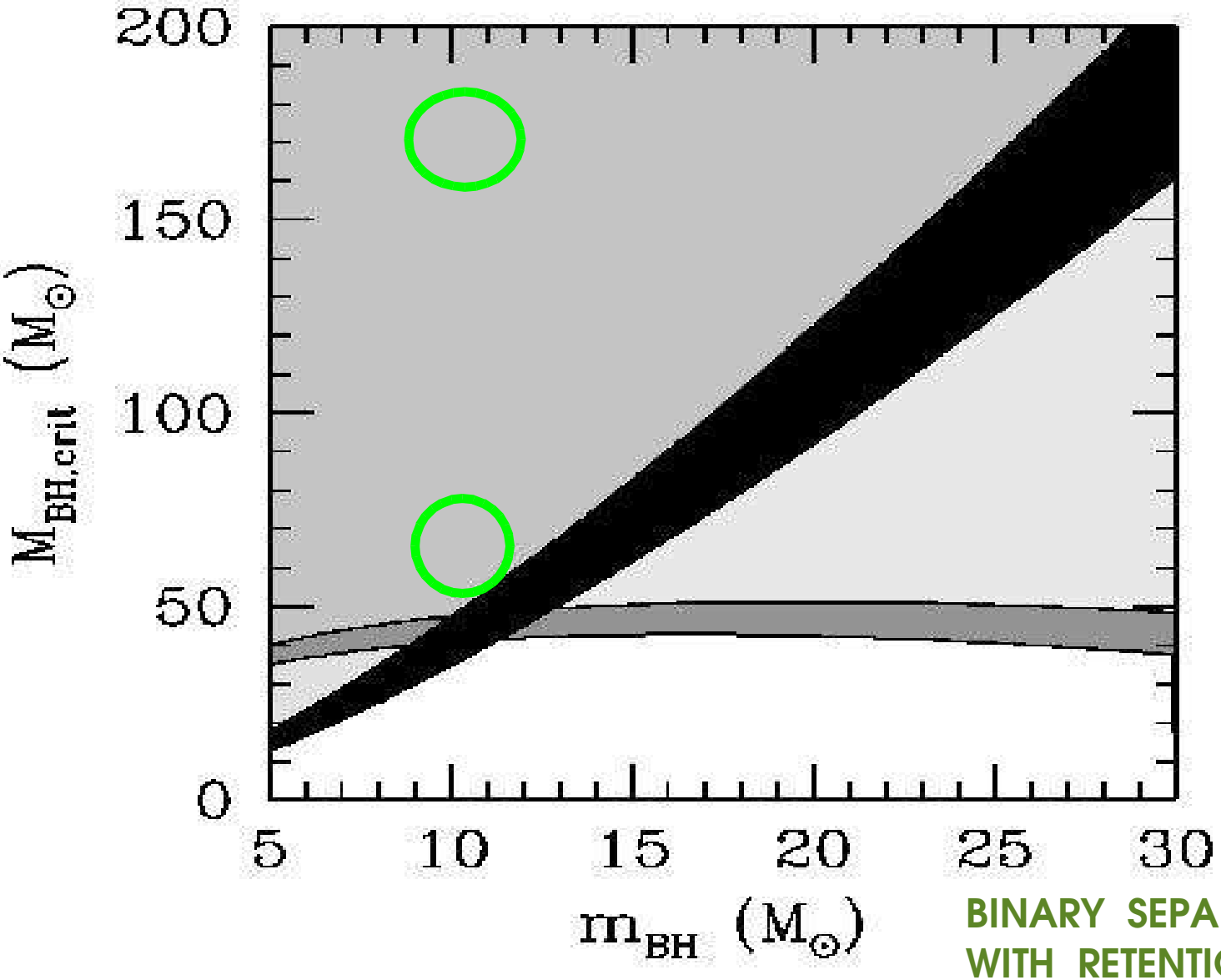


HIERARCHICAL BLACK HOLE MASS GROWTH

IMBH ?
SIMGLE ?
BINARY ?

Miller & Hamilton 2002,

HOW TO CHOOSE THEIR MASSES AND SEPARATIONS ?



BINARY SEPARATION CONSISTENT WITH RETENTION CONDITION IN THE CLUSTER CORE

Miller & Hamilton 2002; Colpi, Mapelli & Possenti 2003

CAN WE INFER THE PRESENCE OF A SINGLE OR BINARY BLACK HOLE IN THE CORE OF A GLOBULAR CLUSTER ? CAN WE ESTABLISH ITS MASS ?

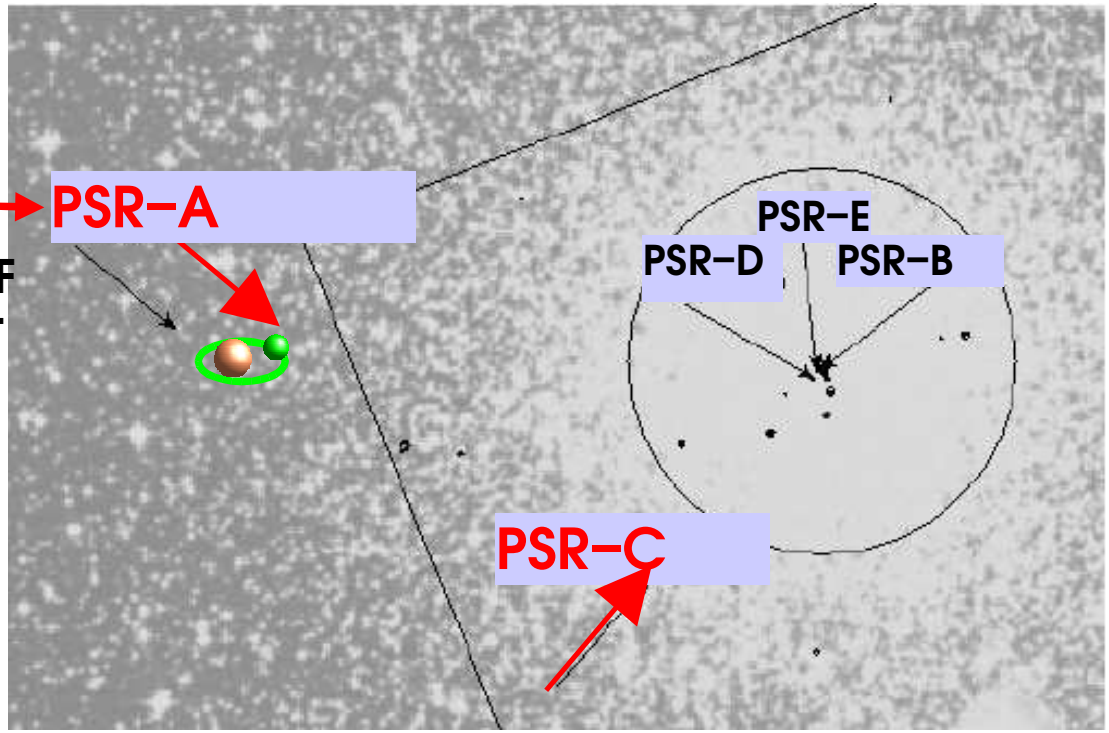
SEARCH FOR A DYNAMICAL FEATURE USING MSPs AS PROBES

MICHELA MAPELLI, ANDREA POSSENTI, & ALESSIA GUALANDRIS

NGC 6752 HOSTS TWO HALO PULSARS

D'Amico , Possenti et al.(2002)

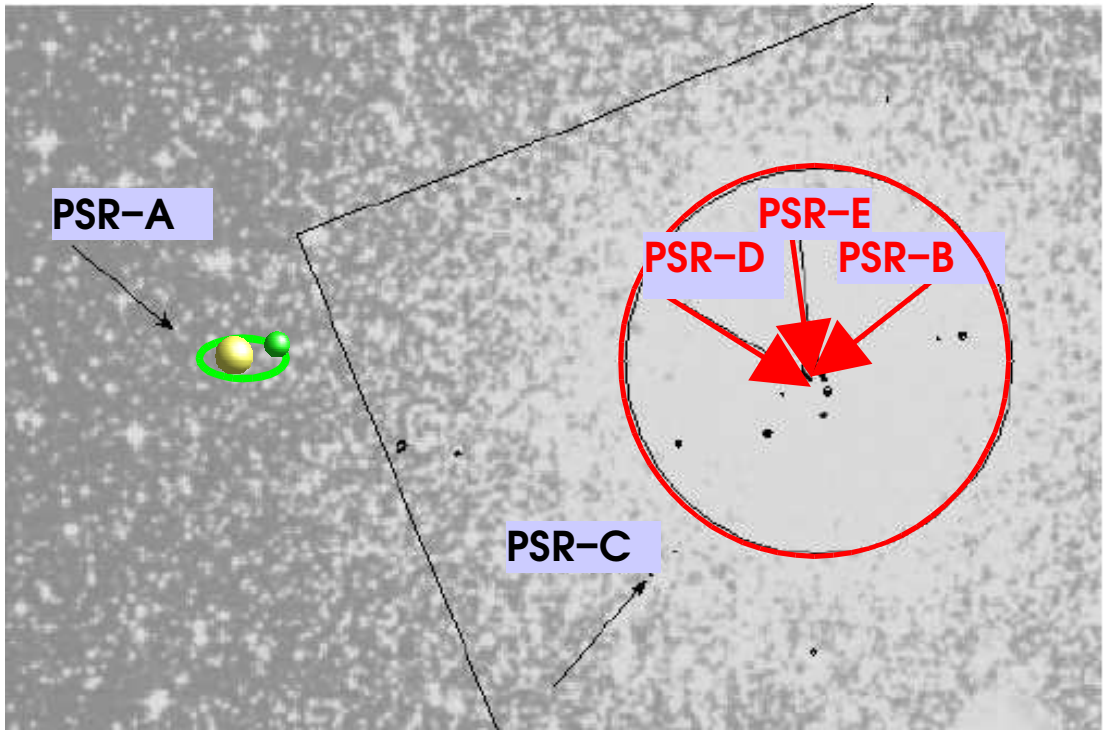
BINARY
He WHITE DWARF
CIRCULAR ORBIT
0.86 days



- PSRA–A IS THE OUTERMOST MSP EVER OBSERVED AMONG OF 41 GLOBULAR CLUSTER MSP .. AT 3.3 HALF MASS RADII
- PSR–C RANKS SECOND IN THIS LIST AND IT IS SINGLE
- Remember .... that MSPs should live preferentially in the core !

NGC 6752 HOSTS THREE CORE PULSARS

D'Amico et al.(2002)



PSR–D SHOWS THE THIRD LARGEST POSITIVE PERIOD DERVIATIVE

PSR–B and PSR–E SHOW LARGE NEGATIVE PERIOD DERIVATIVES

→ LINE OF SIGHT ACCELERATION BY A " DYNMICAL PERTURBER " (Phinney 1992) ? Pdot/P of the order of a/c

IS THIS PERTURBER LOCAL OR GLOBAL ?

THE CORE PULSARS IMPLY CONCENTRATION of UNDER–LUMINOUS MATTER IN THE CORE OF NGC 6752

Pdot/P GIVES A LOWER LIMIT TO M / L_V

↓

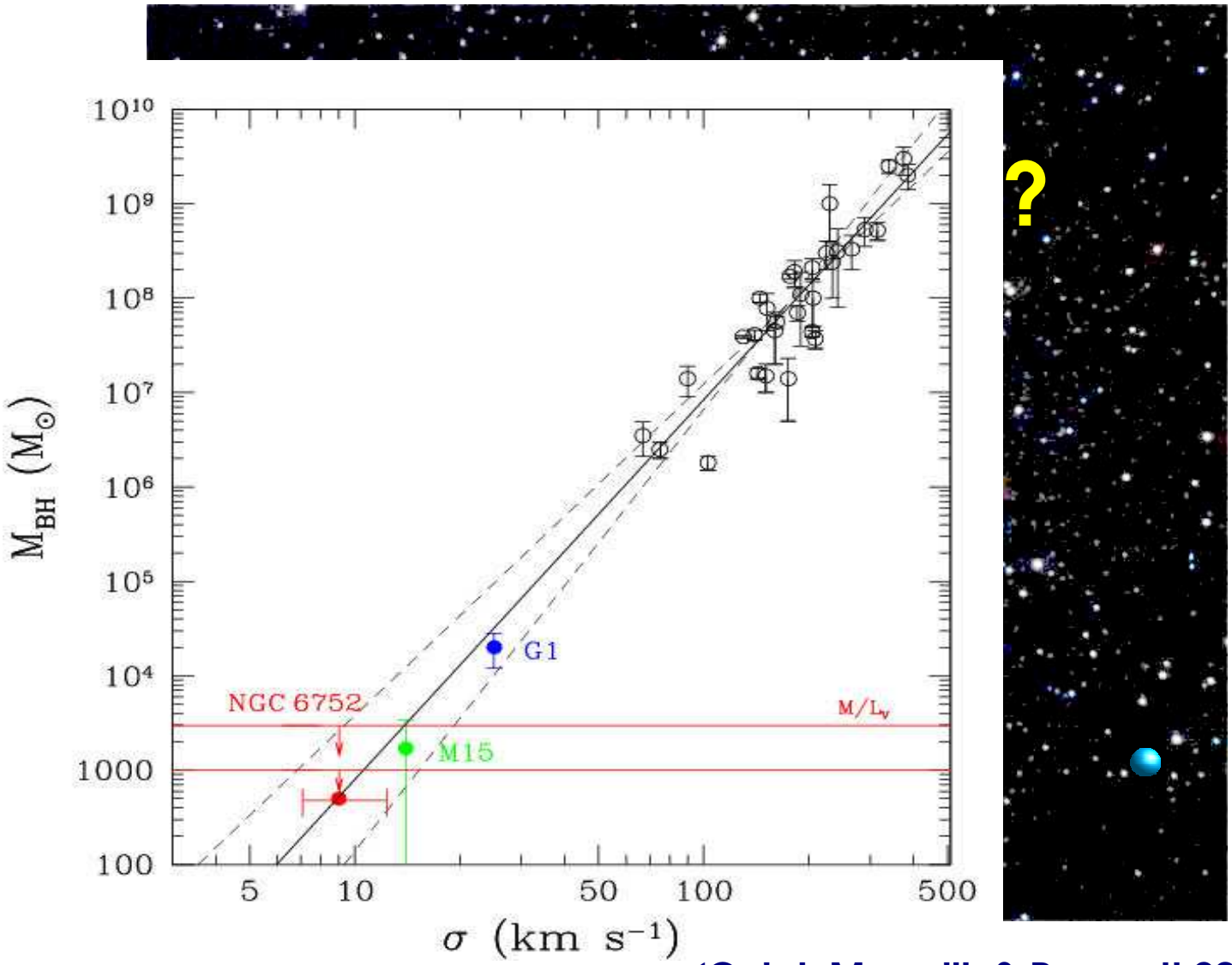
2,000 SOLAR MASSES

COMPACT REMANTS
NEUTRON STARS & WHITE DWARFS

SINGLE INTERMEDIATE MASS BLACK HOLE
?

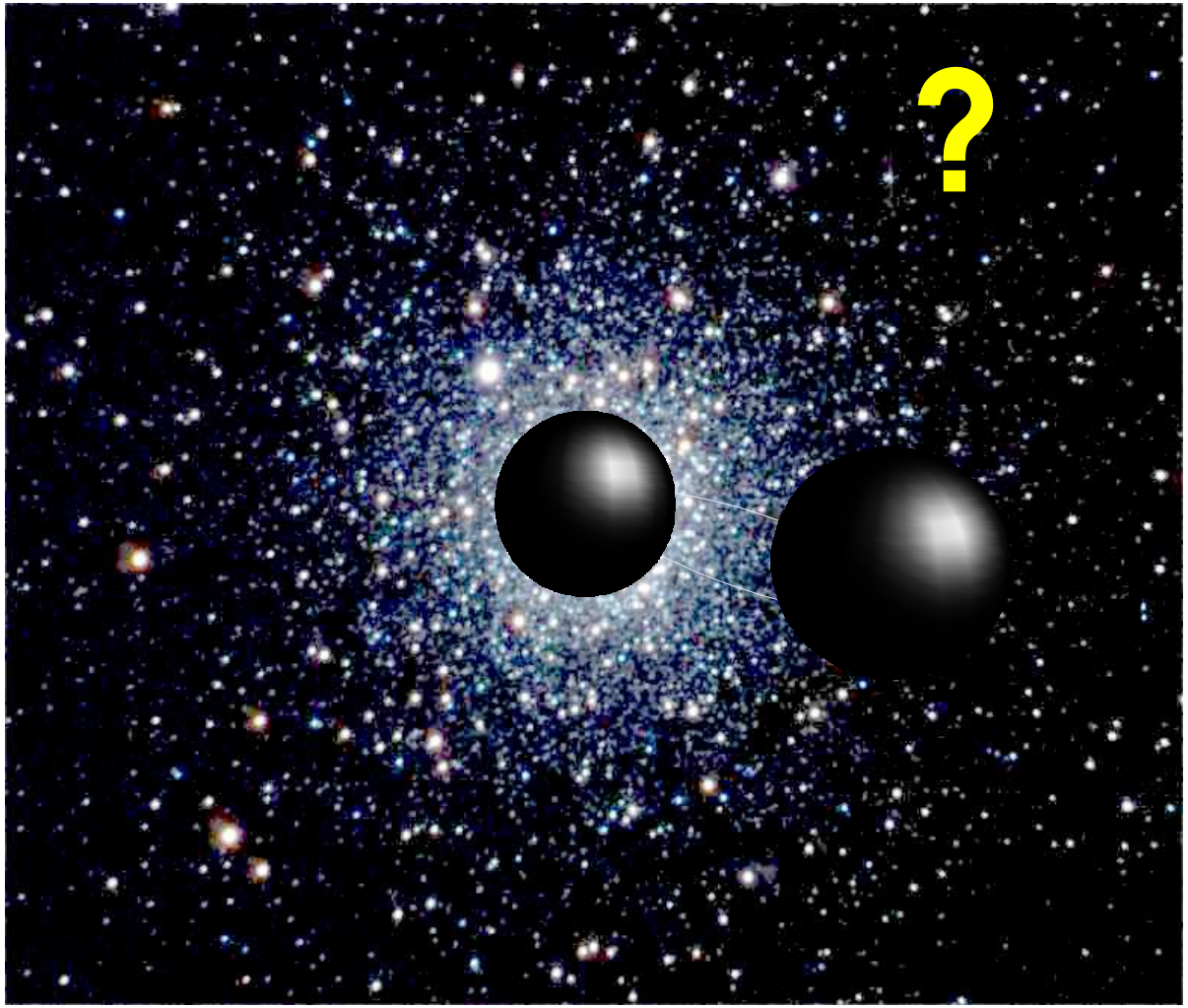
FERRARO et al. 2003 COLPI, MAPELLI, & POSSENTI 2003

SINGLE INTERMEDIATE MASS BLACK HOLE



(Colpi, Mapelli, & Possenti 2003)

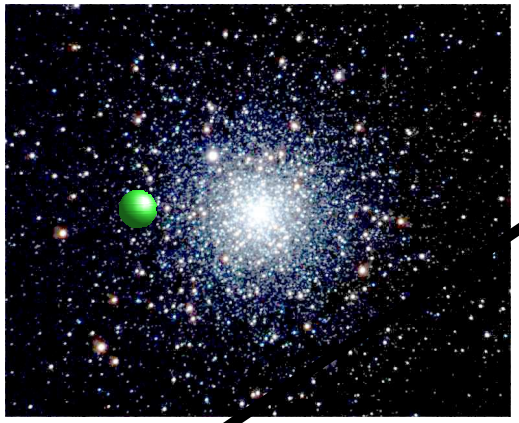
ALTERNATIVELY THE CORE PULSARS MAY BE ACCELERATED BY A BINARY BLACK HOLE SUITABLY DISPLACED



PSR–A IN THE HALO

IS THERE A LINK BETWEEN ITS PECULIAR POSITION AND BINARY OR SINGLE BLACK HOLE ?

MORE CONVENTIONAL EXPLANATION



PSR–A AS THE EVOLVED REMNANT OF A PRIMORDIAL BINARY ?

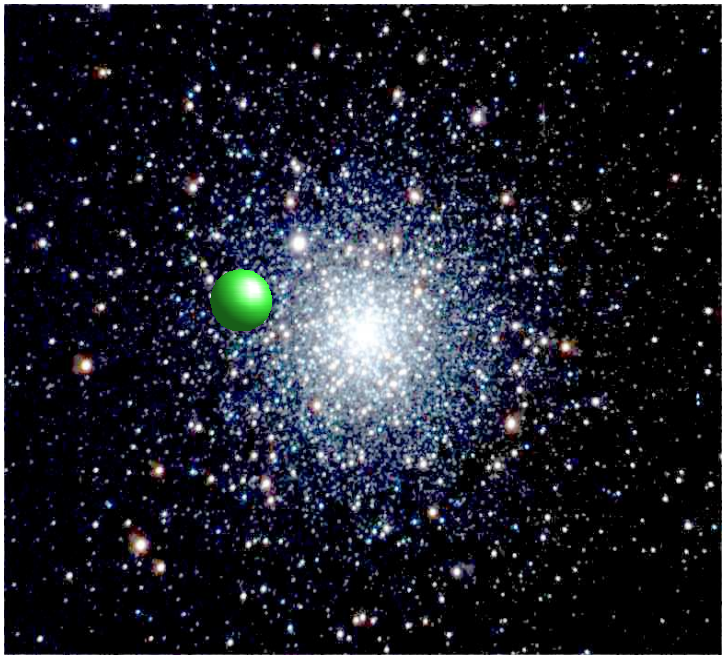
UNUSUALLY LOW NATAL KICK IF BORN ON A CENTROPHOBIC ORBIT

EJECTED DURING SUPERNOVA EXPLOSION FORM THE CORE ?

DYNAMICAL FRICTION TIME OF ABOUT 1 Gyear ...
NOT SURVIVED UNTIL PRESENT TIME !

WAS PSR–A BORN IN THE CORE AND EJECTED AS A RESULT OF GRAVITATIONAL ENCOUNTER ?

PSR–A HAS 1 Gyr LIFETIME IN THE HALO

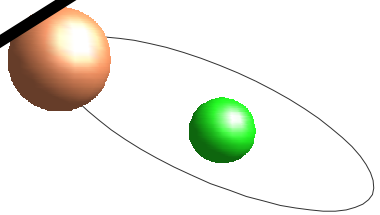


EJECTION VELOCITY 40 km/s

WHAT TYPE OF TARGET ?

STARS AS TARGETS

GIVEN THE 20 HOUR BINARY
PERIOD OF
PSR–A
AND THE HIGH DEGREE
OF CIRCULARITY OF THE PULSAR

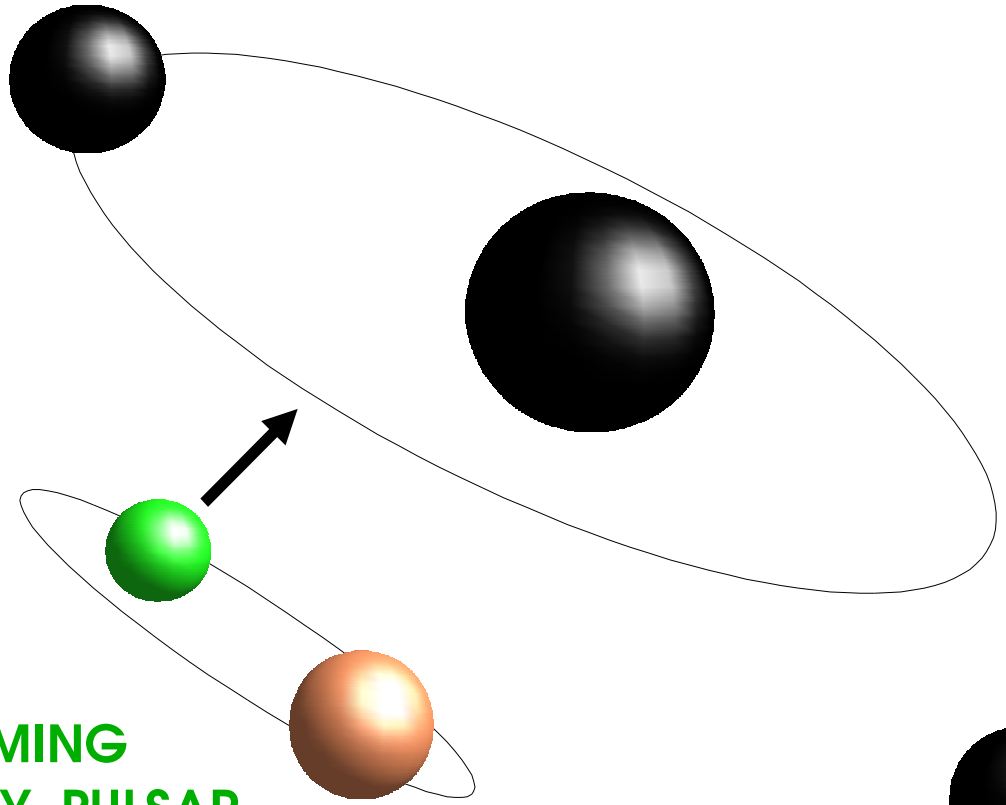


FLY BY EVENT:
NOT ENOUGH BINDING ENERGY
AVAILABLE FOR EJECTION

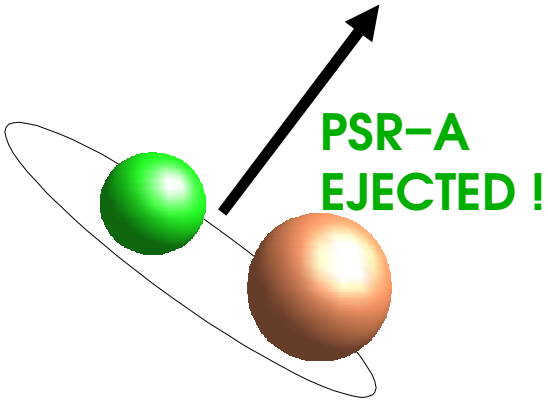
EXCHANGE EVENT :
TARGET SHOULD HAVE
BEEN SO HARD
THAT THE EXCHANGE EVENT
TIMESCALE WOULD EXCCEED
THE CLUSTER LIFE TIME

(Colpi, Possenti & Gualandris 2002)

PSR–A SCATTERING OFF A BLACK HOLE BINARY AS TARGET !

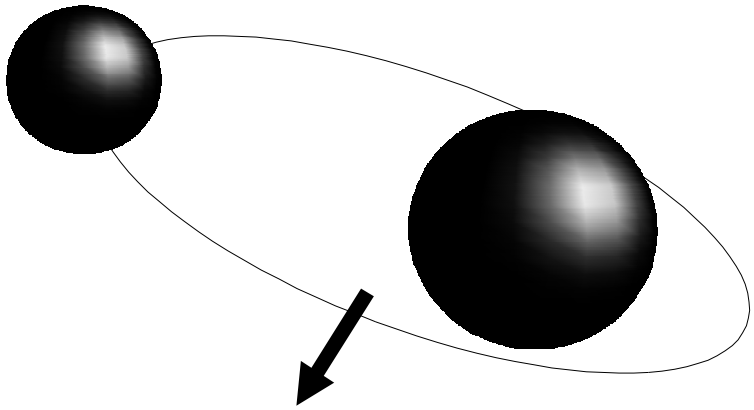


INCOMING
BINARY PULSAR

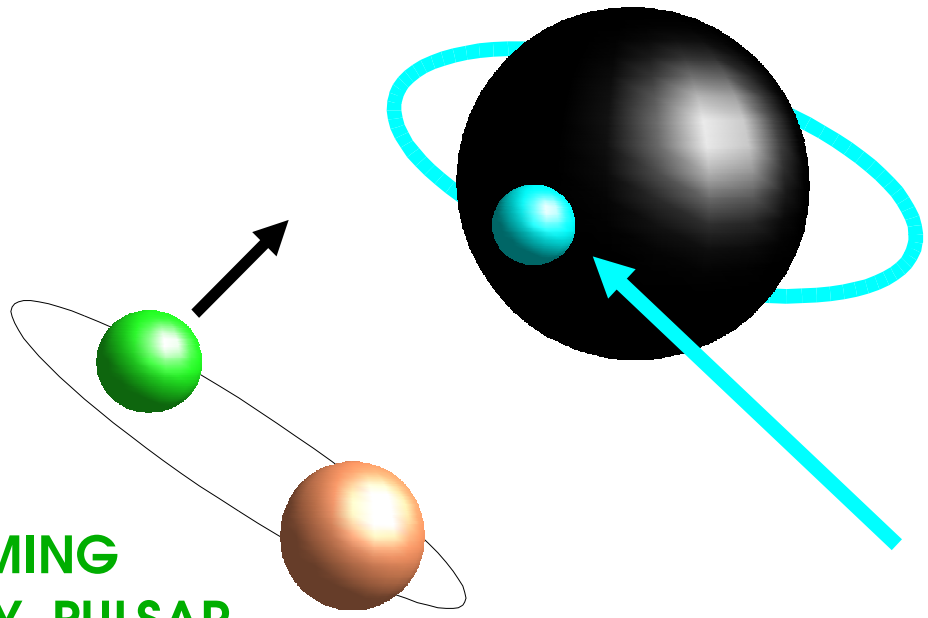


PSR–A
EJECTED !

THE BINARY
BLACK HOLE
RECOIL



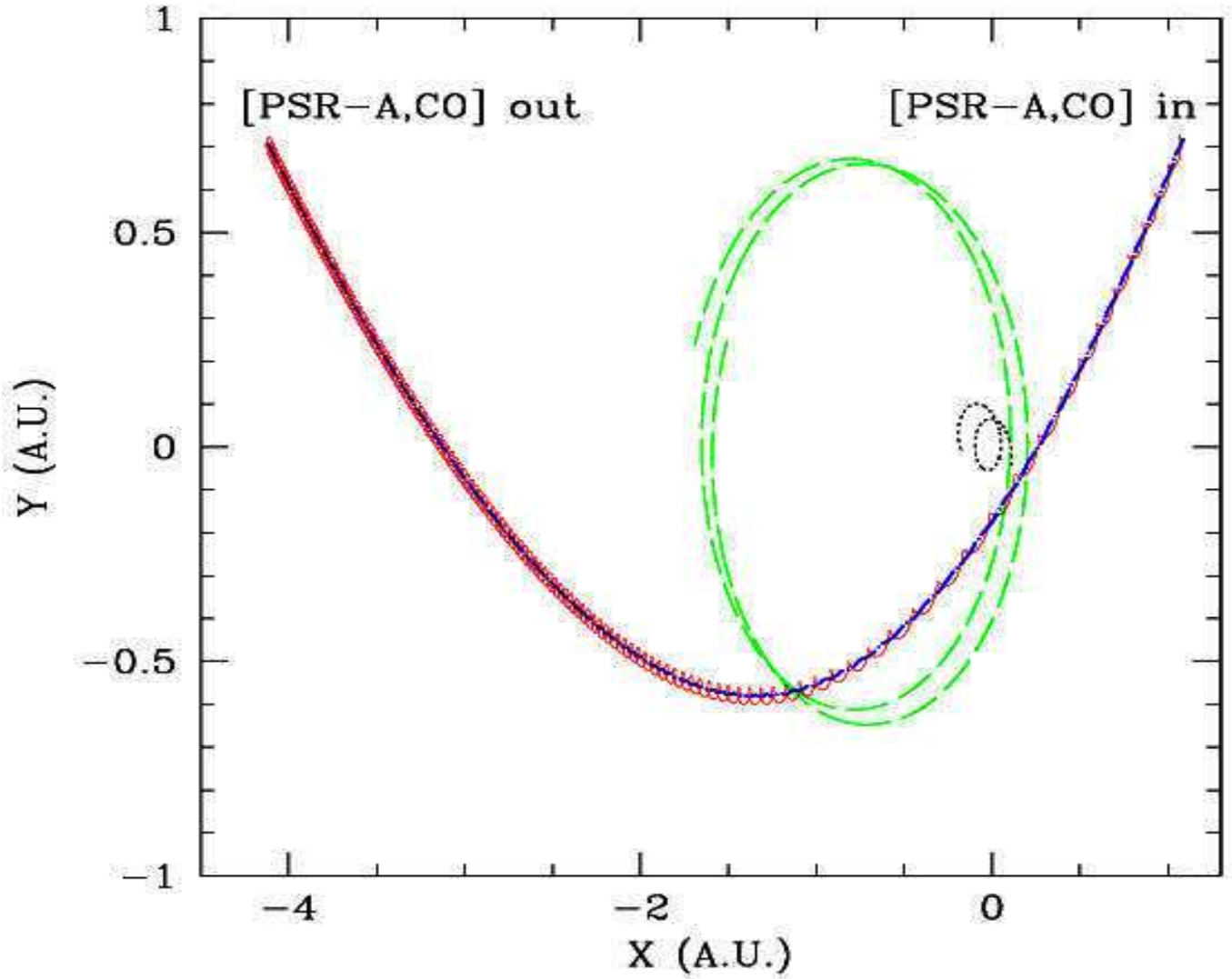
PSR–A SCATTERING OFF A SINGLE INTERMEDIATE – MASS BLACK HOLE (500 Solar Masses) !



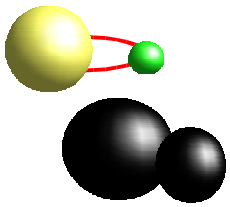
INCOMING
BINARY PULSAR

THE STAR OF THE CUSP
(1 solar masses)

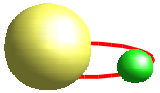
FLY BY OF THE BINARY PULSAR



BH,BH (10,50) – 1 AU AS BINARY SEPARATION

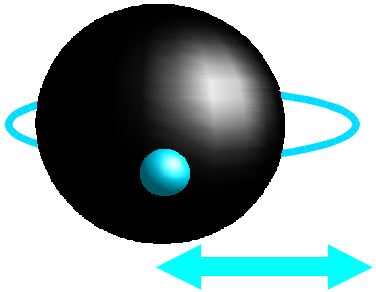


PSR–A EJECTION VELOCITY

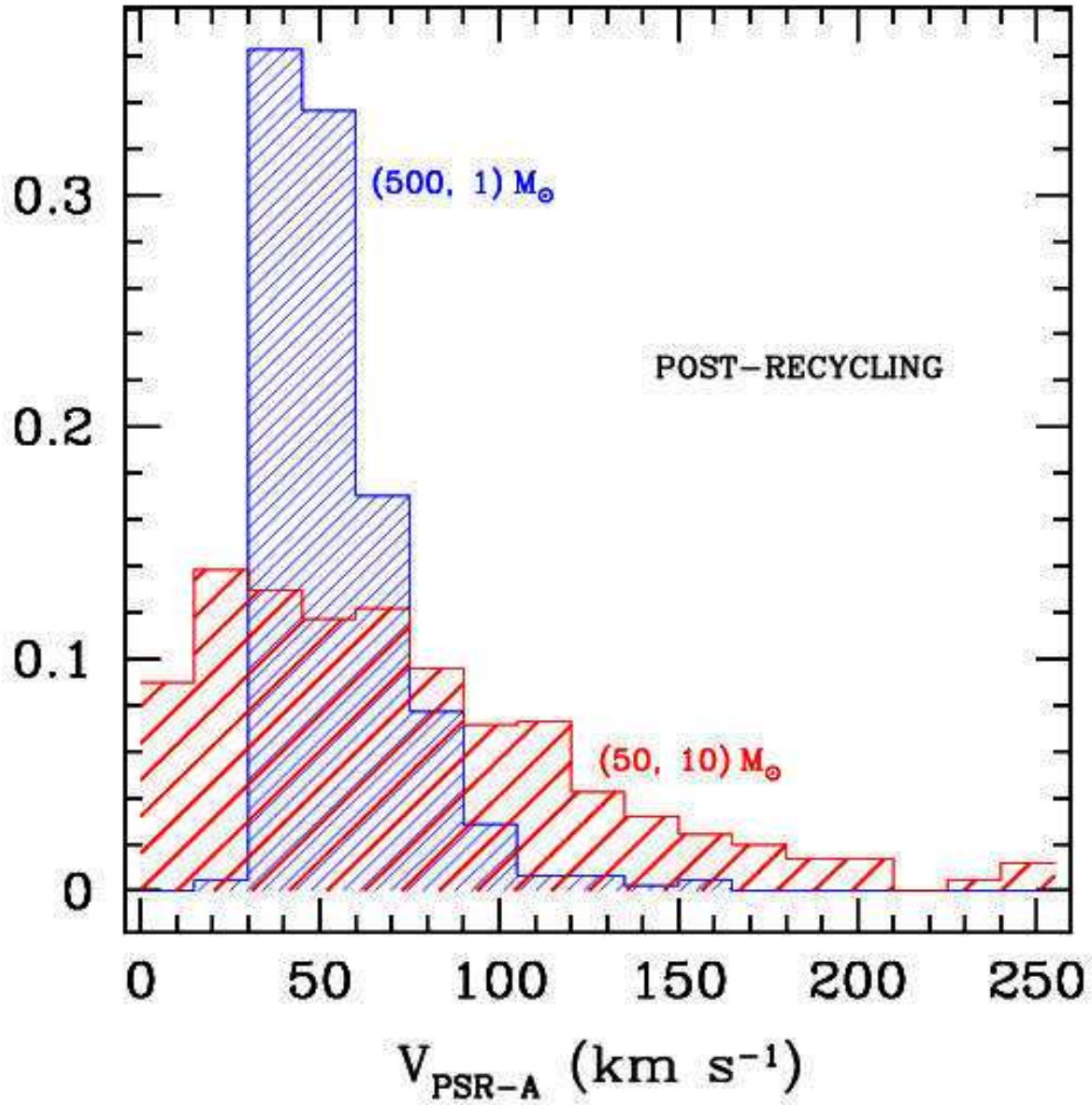


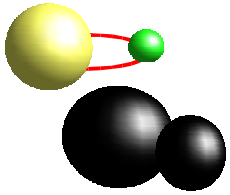
BH–BH BINARY
SEPARATION OF = 1 AU

POST–RECYCLING

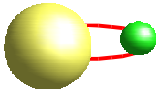


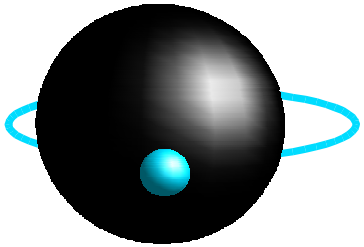
STAR–BH BINARY
SEPARATION OF = 1 AU

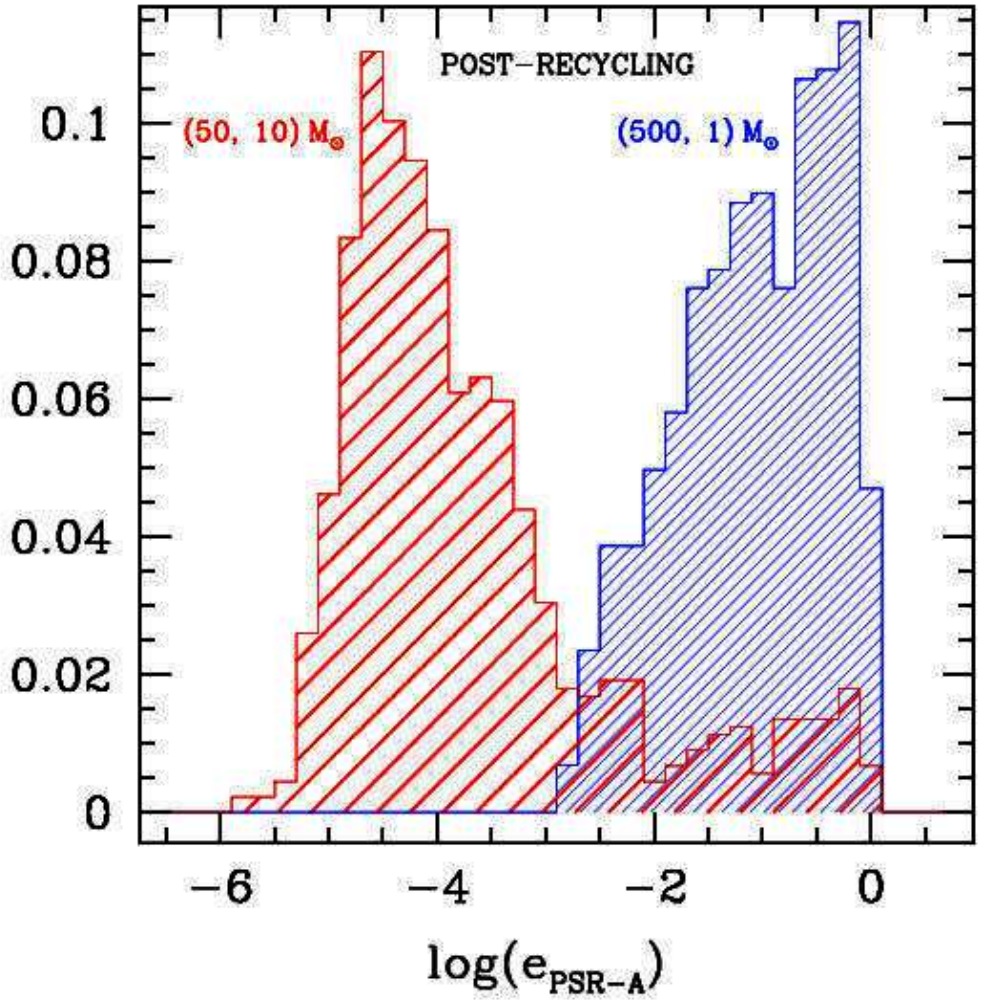




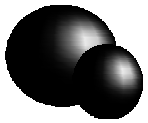
PSR–A POST ENCOUNETR ECCENTRICITY



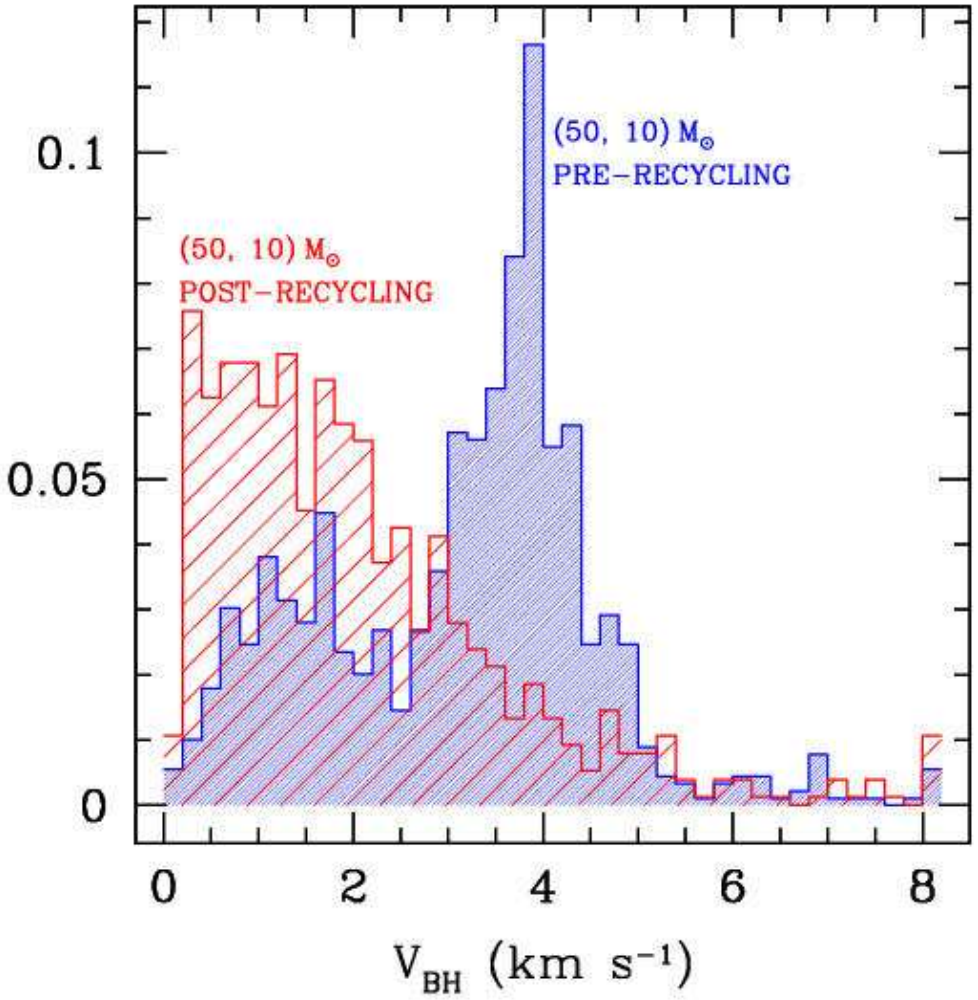


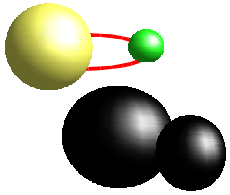


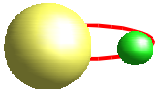
THE CENTRAL IMBH DAMAGES SIGNIFICANTLY THE ECCENTRICITY OF THE BINARY PULSAR ------> EJECTION IS POSSIBLE ONLY IF THE BINARY WAS EJECTED BEFORE THE RECYCLING PHASE.

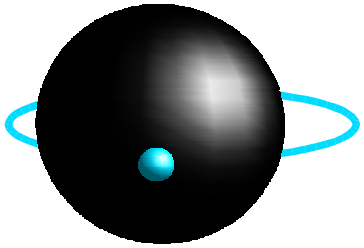


BLACK HOLE BINARY RECOIL VELOCITY – BROWNIAN MOTION DUE TO SUPER–ELASTIC ENCOUNTERS







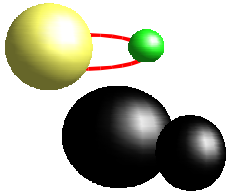


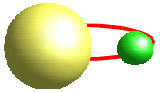
END–STATE PROPERTIES OF OUR MORE THAN 10,000 SIMULATES BINARY–BINARY ENCOUNTERS

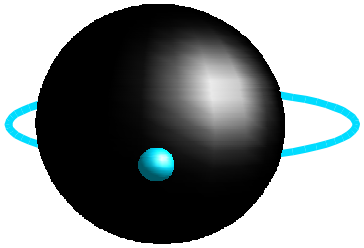
Table 1. End-states in the post-recycling scenario.

	(500 $M_\odot$, 1.0 $M_\odot$)	(50 $M_\odot$, 1.4 $M_\odot$)	(30 $M_\odot$, 3 $M_\odot$)	(10 $M_\odot$, 10 $M_\odot$)	(50 $M_\odot$, 10 $M_\odot$)	(200 $M_\odot$, 10 $M_\odot$
[a] $V_{p,\,PSR\text{-}A}$ (km s^{-1})	45^{+30}_{-20}	15^{+30}_{-10}	15^{+40}_{-10}	18^{+25}_{-10}	30^{+10}_{-20}	90^{+60}_{-60}
[b] $\langle V_{PSR\text{-}A}\rangle$ (km s^{-1})	55^{+29}_{-13}	27^{+44}_{-15}	35^{+62}_{-21}	32^{+112}_{-16}	73^{+78}_{-42}	101^{+116}_{-40}
[c] $V_{p,\,BH}$ (km s^{-1})	$0.2^{}_{-0.1}$	$0.5^{+1.2}_{-0.3}$	$0.8^{+2.5}_{-0.5}$	$2.0^{+2.0}_{-1.5}$	$0.8^{+3.}_{-0.5}$	$0.7^{+0.}_{-0.5}$
[d] $\langle V_{BH}\rangle$ (km s^{-1})	$0.3^{+0.8}_{-0.2}$	$1.0^{+3.8}_{-0.6}$	$1.9^{+3.5}_{-1.1}$	$4.9^{+10.9}_{-2.6}$	$2.1^{+2.8}_{-1.1}$	$0.8^{+1.4}_{-0.3}$
[e] $V_{rms,\,BH}$ (km s^{-1})	0.465	1.51	2.45	6.83	2.62	1.01
[f] $e_{p,\,PSR\text{-}A}$ ($\times 10^{-5}$)	$5^{+3}_{-5}\cdot 10^4$	2^{+77}_{-2}	1^{+70}_{-1}	1^{+7}_{-1}	3^{+76}_{-2}	5^{+744}_{-45}
[g] $\langle\frac{\Delta E}{E_0}\rangle_{PSR\text{-}A}$ ($\times 10^{-3}$)	40^{+858}_{-40}	4^{+712}_{-4}	9^{+175}_{-9}	5^{+4082}_{-5}	2^{+577}_{-2}	-1^{+6}_{-716}
[h] $\langle\frac{\Delta E}{E_0}\rangle_{BH}$ ($\times 10^{-2}$)	$0.1^{+1.0}_{-0.9}$	$0.4^{+8.9}_{-0.8}$	$1.0^{+18.4}_{-1.1}$	$3.3^{+119.0}_{-3.3}$	$1.8^{+47.8}_{-1.8}$	$0.7^{+12.5}_{-0.7}$
[i] $\langle\frac{\Delta J}{J_0}\rangle_{BH}$ ($\times 10^{-2}$)	$-0.01^{+1.43}_{-1.53}$	6^{+63}_{-27}	-2^{+25}_{-15}	-2^{+16}_{-12}	-2^{+9}_{-8}	$-0.3^{+2.2}_{-2.2}$
[l] ξ_{BH} ($\xi_{BH,\,FBs}$)	0.3 (2.4)	0.1 (0.9)	0.2 (0.8)	0.4 (0.5)	0.7 (1.1)	0.9 (1.6)

[a]Peak value of the end-state recoil velocity distribution of [PSR-A,CO] considering only FBs. [b]Average recoil velocity of [PSR-A,CO] consideri only FBs. [c]Peak value of the end-state recoil velocity distribution of [BH,BH] binary considering FBs and IONs. [d]Average recoil velocity [BH,BH] binary considering FBs and IONs. [e]Root mean square recoil velocity of [BH,BH] binary considering FBs and IONs. [f]Peak value of t final eccentricity distribution of [PSR-A,CO], considering only FBs. [g]Relative average change of the [PSR-A,CO] binding energy normalized to initial value (E_0), considering only the FBs. [h]Relative average change of the [BH,BH] binary binding energy normalized to its initial value (I







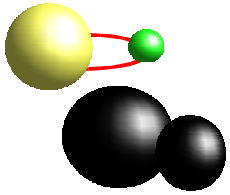
THE STATISTICS OF THE EVENTS

FLY BY

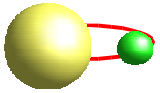
Table 2. Statistics of the outgoing states in the post-recycling scenario.

	(300 $M_\odot$, 1.0 $M_\odot$)	(50 $M_\odot$, 1.4 $M_\odot$)	(30 $M_\odot$, 3 $M_\odot$)	(10 $M_\odot$, 10 $M_\odot$)	(50 $M_\odot$, 10 $M_\odot$)	(200 $M_\odot$, 10 $M_\odot$)
FBs	0.452	0.623	0.645	0.867	0.657	0.594
EXs	0.0	0.001	0.0	[illegible]	0.0	0.0
IONs (Triplets)	0.273 (0.267)	0.052 (0.043)	0.083 (0.072)	0.059 (0.048)	0.107 (0.092)	0.121 (0.103)
Qs s	0.272	0.313	0.247	0.072	0.233	0.277
UEs	0.003	0.011	0.025	0.002	0.003	0.008

BLACK HOLE(S) DOMINATE THE STATISTICS OF THE EVENT
ONE EVENT PER GYEAR IS A CONCRETE POSSIBILITY
Sigurdsson (2003)



OCCURRENCE RATE OF ONE EVERY GIGAYEAR IMPLIES A MINIMUM NEUTRON STAR DENSITY



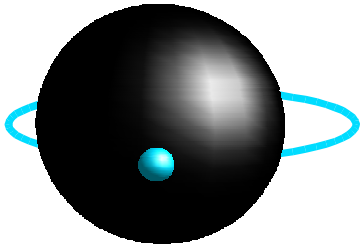
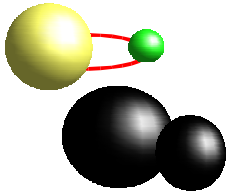


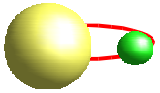
Table 1. Minimum neutron star density

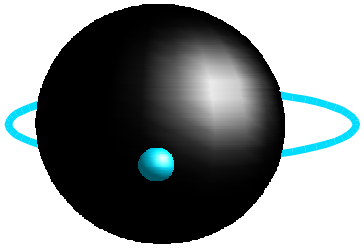
M, m ($M_\odot$)	$a_{max,BH}$ (A.U.)	$f n_{NS}$ (#/pc^3)
500, 1.0	1	$2.9 \cdot 10^2$
50, 1.4	1	$1.5 \cdot 10^3$
30, 3	2	$1.1 \cdot 10^3$
10, 10	3.6	$7.6 \cdot 10^2$
50, 10	6	$2.0 \cdot 10^2$
200, 10	7	$5.5 \cdot 10^1$

IF A BLACK HOLE BINARY OR THE CENTRAL IMBH IS PRESENT BOTH THEY WOULD DOMINATE THE EVENT RATE

(Sigurdsoon)



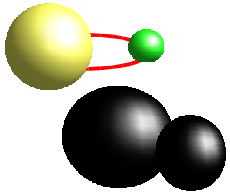


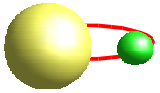


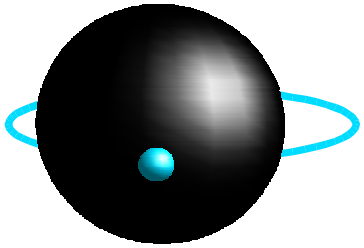
THE STATISTICS OF THE EVENTS PRE–RECYCLING BINARY BLACK HOLE VERUS SINGLE IMBH + CUSP STAR

Table 1. Statistics of the outgoing states in the pre-recycling scenario.

	$(500\,M_\odot, 1.0\,M_\odot)$	$(50\,M_\odot, 10\,M_\odot)$
FBs	0.068	0.232
EXs	0.0	0.0
IONs (Triplets)	0.844 (0.669)	0.686 (0.341)
Qs	0.087	0.079
UEs	0.0003	0.003







THE STATISTICS OF THE EVENTS

HIERARCHICAL TRIPLETS

Table 2. Statistics of the outgoing states in the post-recycling scenario.

	(500 $M_\odot$, 1.0 $M_\odot$)	(50 $M_\odot$, 1.4 $M_\odot$)	(30 $M_\odot$, 3 $M_\odot$)	(10 $M_\odot$, 10 $M_\odot$)	(50 $M_\odot$, 10 $M_\odot$)	(200 $M_\odot$, 10 $M_\odot$)
FBs	0.452	0.623	0.645	0.867	0.657	0.594
EXs	0.0	0.001	0.0	0.0	0.0	0.0
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Qs s	[illegible]	0.313	0.247	0.072	[illegible]	0.277
UEs	0.003	0.011	0.025	0.002	0.003	0.008

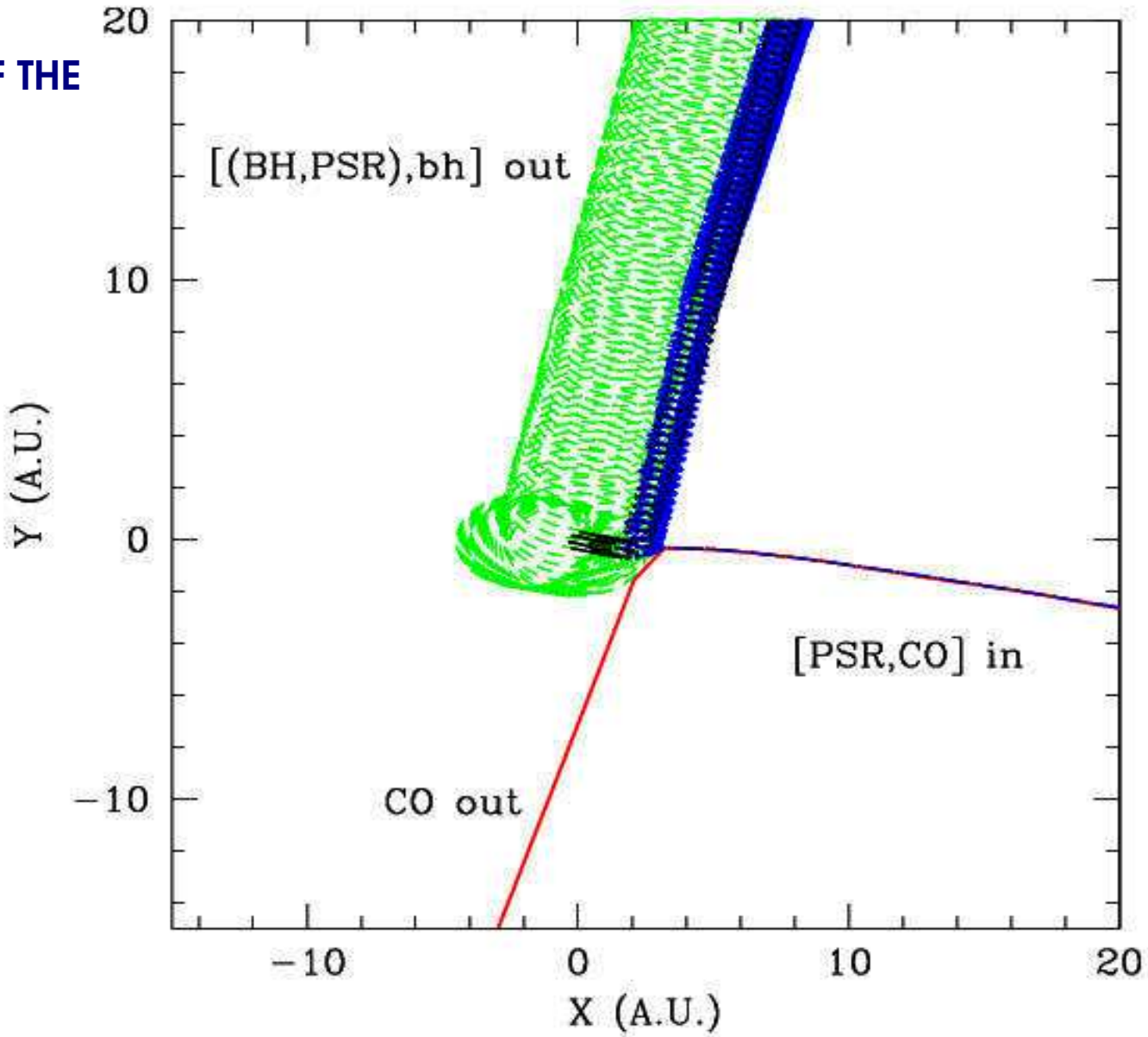
5% OF ALL EVENTS ENDS IN STABLE TRIPLETS IF THE BINARY IS SUFFICIENTLY WIDE

RATE OF FORMATION OF 1 EVERY 20 Myears off STARS

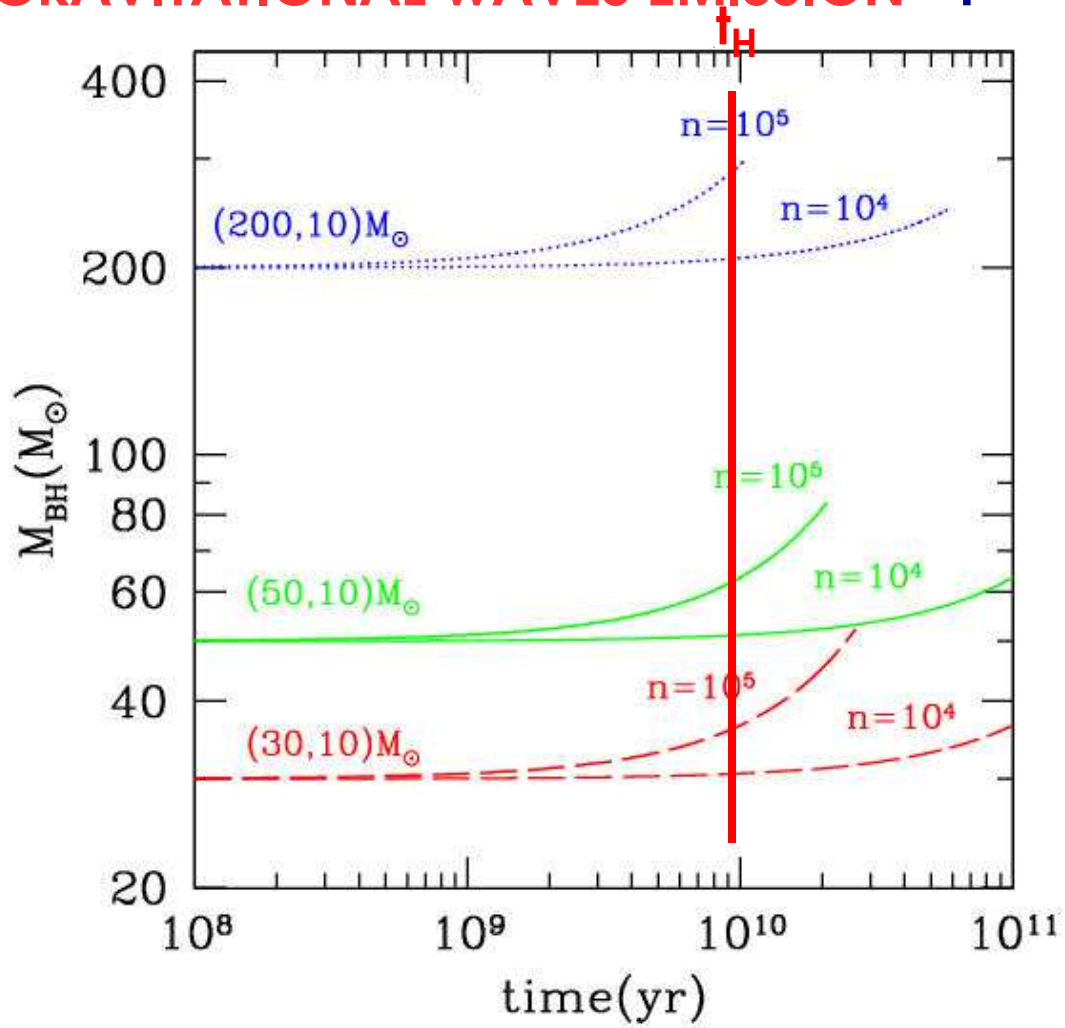
A HIERARCHICAL TRIPLET : A BINARY BALCK HOLE + MSP !

LONG−TERM STABLE AGAINST EJECTION OF THE MSP, ACCORDING TO MARDLING & AARSETH CRITERIUM

THE MSP ORBITS AROUND THE HEAVIER HOLE ON A VERY ECCENTRIC ORBIT (0.28AU, e=0.97). THE OTHER HOLE ORBIT HAS A SEMI−MAJOR AXIS OF 5AU
1 every 10 Gyears with active pulsars



HOW LONG CAN A BINARY BLACK HOLE SURVIVE IN A CLUSTER AGAINST HARDENING BY COLLISIONS OFF BACKGROUND STARS AND GRAVITATIONAL WAVES EMISSION ?



⇒ ''light'' binaries (20–60 $m_\odot$) MORE EASILY SURVIVE

EVIDENCE THAT SOME UNCOMMON DYNAMICS

IS RESPOSIBLE FOR THE UNUSUAL POSITION OR

ACCELERATION OF THE FIVE MILLISECOND

PULSARS IN NGC6752

WE WOULD LIKE TO ATTRIBUTE THIS TO A NOT TOO MASSIVE BINARY BLACK HOLE OR TO AN INTERMEDIATE MASS BLACK HOLE

EXOTIC TRIPLETS AS NEW SOURCES FOR GWS