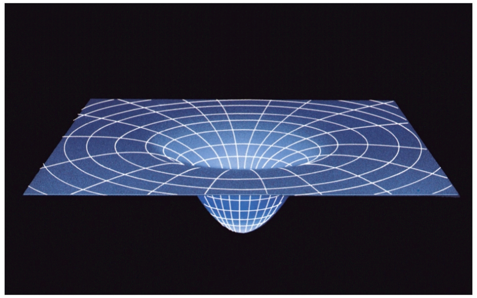
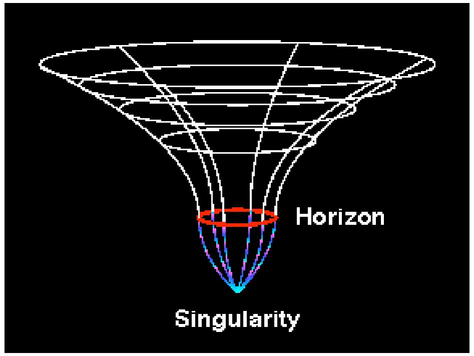
BLACK HOLES IN ASTROPHYSICS

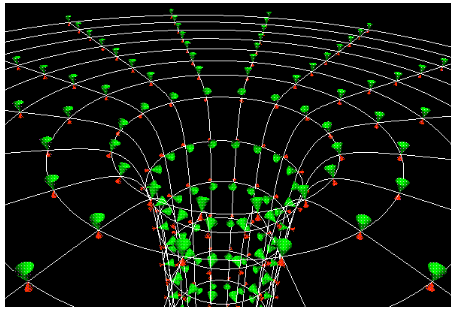
NEUTRON STARS COME MAINLY INTO 4 “FLAVOURS”
(I) RADIO PULSARS (ROTATIONAL ENERGY)
(II) ACCRETING X-RAY BINARIES (GRAVITY)
(III) MAGNETARS (MAGNETIC ENERGY)
(IV) COOLING (THERMAL ENERGY)



BLACK HOLES
(I) “ACTIVE”: ACCRETING SOURCES (GRAVITY)
XRBs, ULXs & AGNs

(II) “SILENT” : DYNAMICS OF STARS & LARGE SCALE GASEOUS DISCS
GALACTIC CENTER & NEARBY GALAXIES





BASIC CONCEPTS

NO HAIR THEOREM

BLACK HOLES ARE DESCRIBED BY THREE NUMBERS

(I) MASS M

no limits on the BH mass

From the mass Planck scale (quantum corrections) to masses of billion solar masses

(II) SPIN "a" defined such that the angular momentum J of the BH is

$$J=a\ GM^2/c$$

$$a \leq 1$$

a=0 (non-spinning BH) a=1 (maximally-spinning BH)

KERR METRIC (1963)

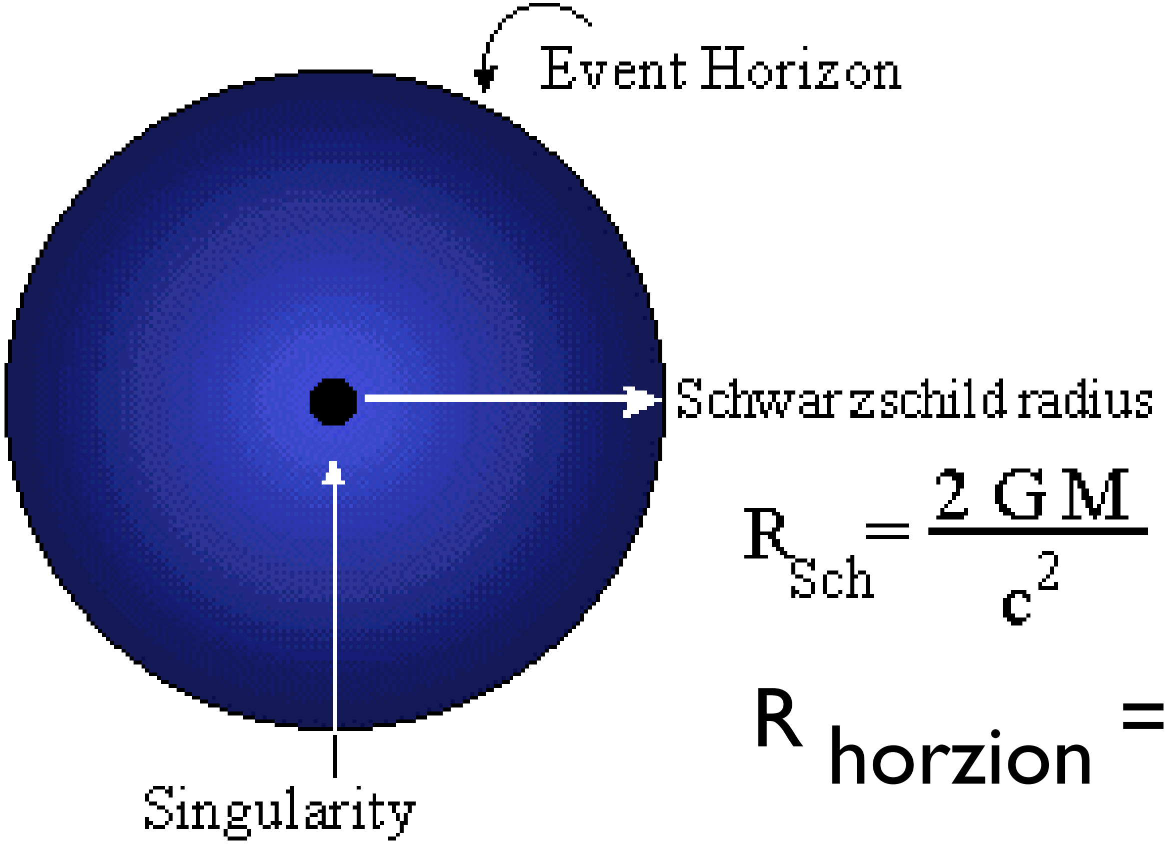
(III) ELECTRIC CHARGE

Similar to elementary particles like electrons!

Carter, Israel & Hawking 1972-1977

BLACK HOLES HAVE AN EVENT HORIZON

a one-way mambrane that causally isolates the “inside” from the rest of the Universe



$$R_{Sch} = \frac{2GM}{c^2}$$

$$R_{\text{horzion}} = M + (M^2 - a^2)^{1/2}$$

COSMIC CENSORSHIP THEOREM

GEODESICS

When considering circular orbits of
particles with finite mass “m” in the BLACK HOLE space-time
a key concept is that of the
INNERMOST STABLE CIRCULAR ORBIT
(ISCO)

R_{ISCO}

CIRCULAR ORBITS WITH RADII $R>R_{ISCO}$
ARE DYNAMICALLY STABLE

ORBITS WITH $R<R_{ISCO}$
ARE UNSTABLE to CAPTURE

For photons
UNSTABLE CIRCULAR ORBIT EXISTS

R_{ISCO}

FOR MASSIVE PARTICLES

is a FUNCTION of M & of the SPIN PARAMETER “a”

a=0 $R_{ISCO}=6M$ (Schwarzschild)

a=1 (maximally rotating Kerr)

$R_{ISCO}=M$ (for corotating orbits)

$R_{ISCO}=9M$ (for counter-rotating orbits)

PHOTONS

a=0 Rcir=3M

a=1

$R_{cir\ corotating}=M$

$R_{cir\ counter\text{-}rotating}=4M$

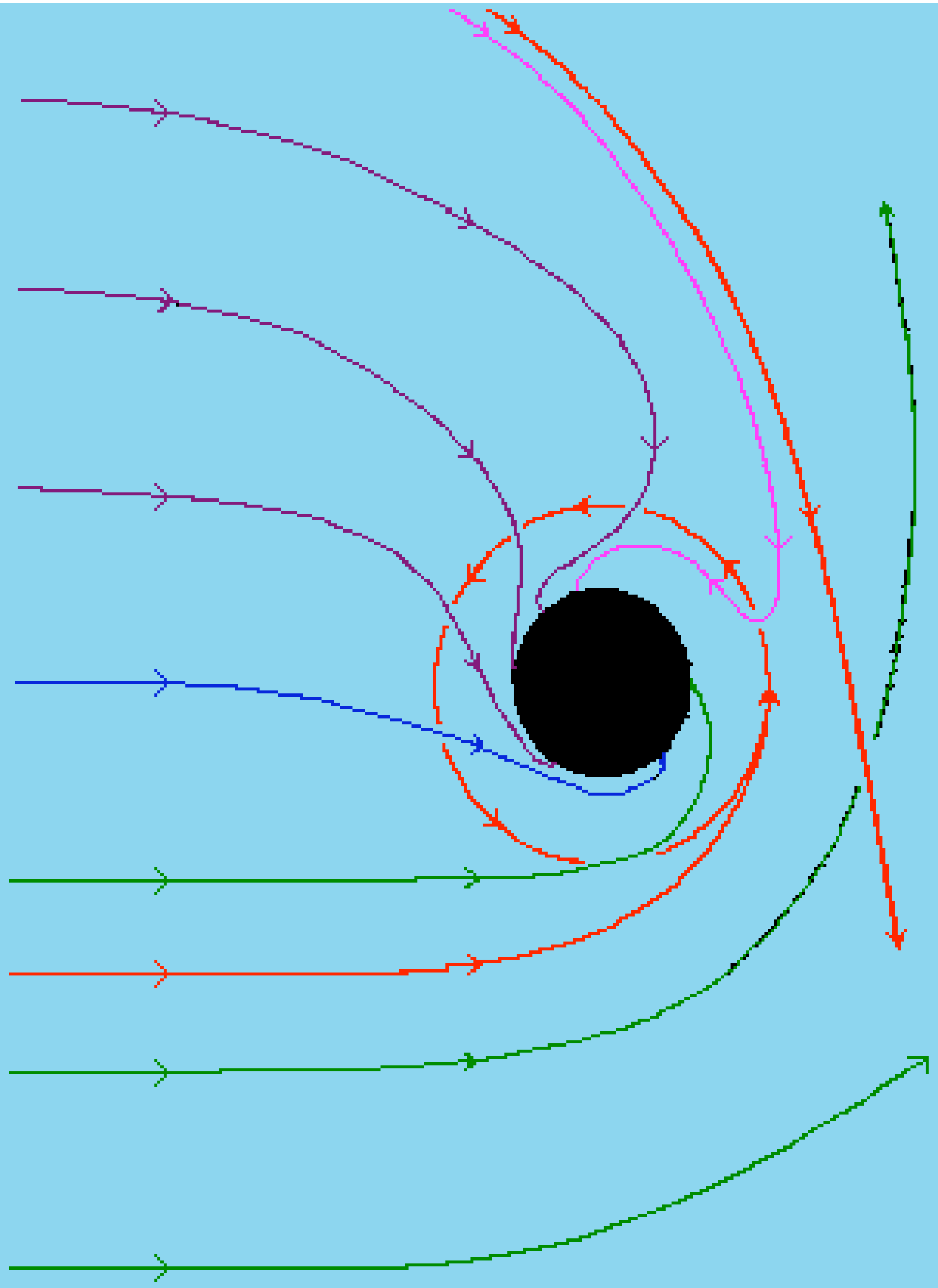
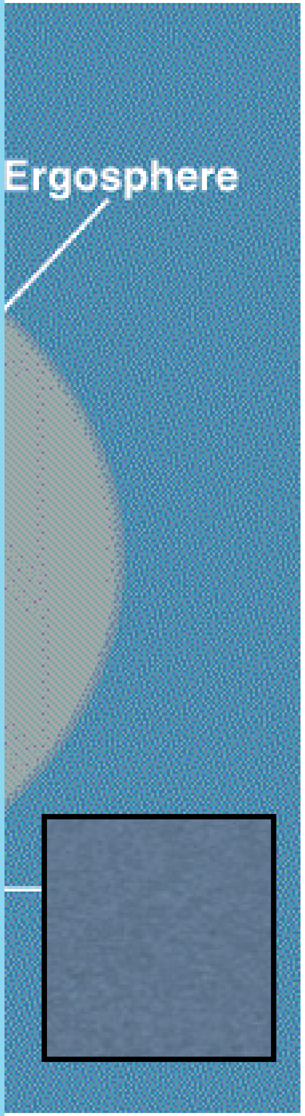


FIG. 4 — Behaviour of light near a Kerr black hole. The hole is rotating anticlockwise. The rays drawn **bright red** just barely avoid capture by the hole. Retrograde rays must be further away than direct rays in order to avoid capture.

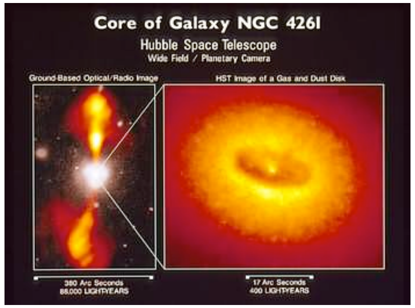
STATIC LIMIT



"ASTROPHYSICAL" BLACK HOLE
"BLACK HOLE CANDIDATES"

(I)
STELLAR MASS BLACK HOLES
BORN IN THE AFTERMATH OF SUPERNOVA EXPLOSIONS
DEATH OF THE MOST MASSIVE STARS

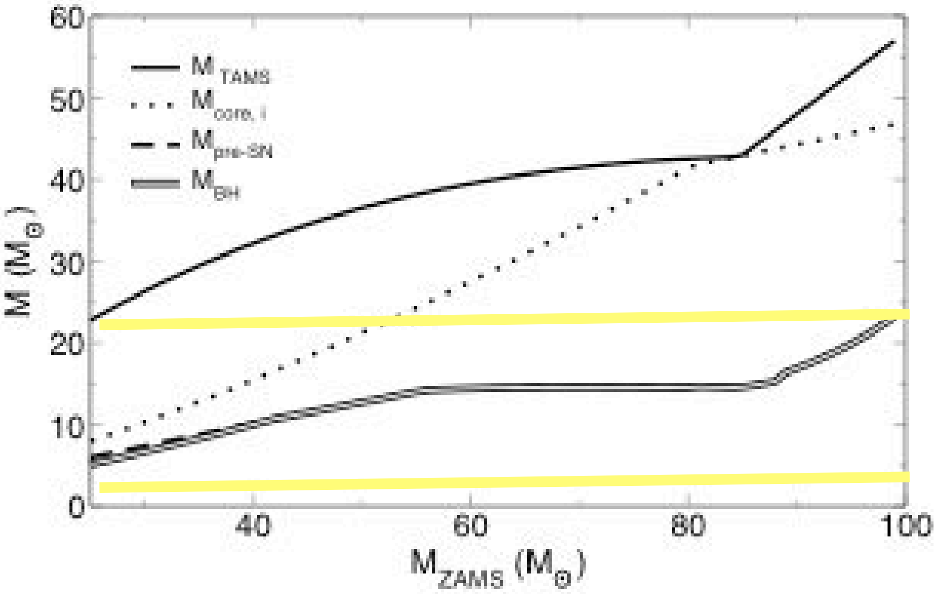
(II)
SUPERMASSIVE BLACK HOLES
GALACTIC NUCLEI



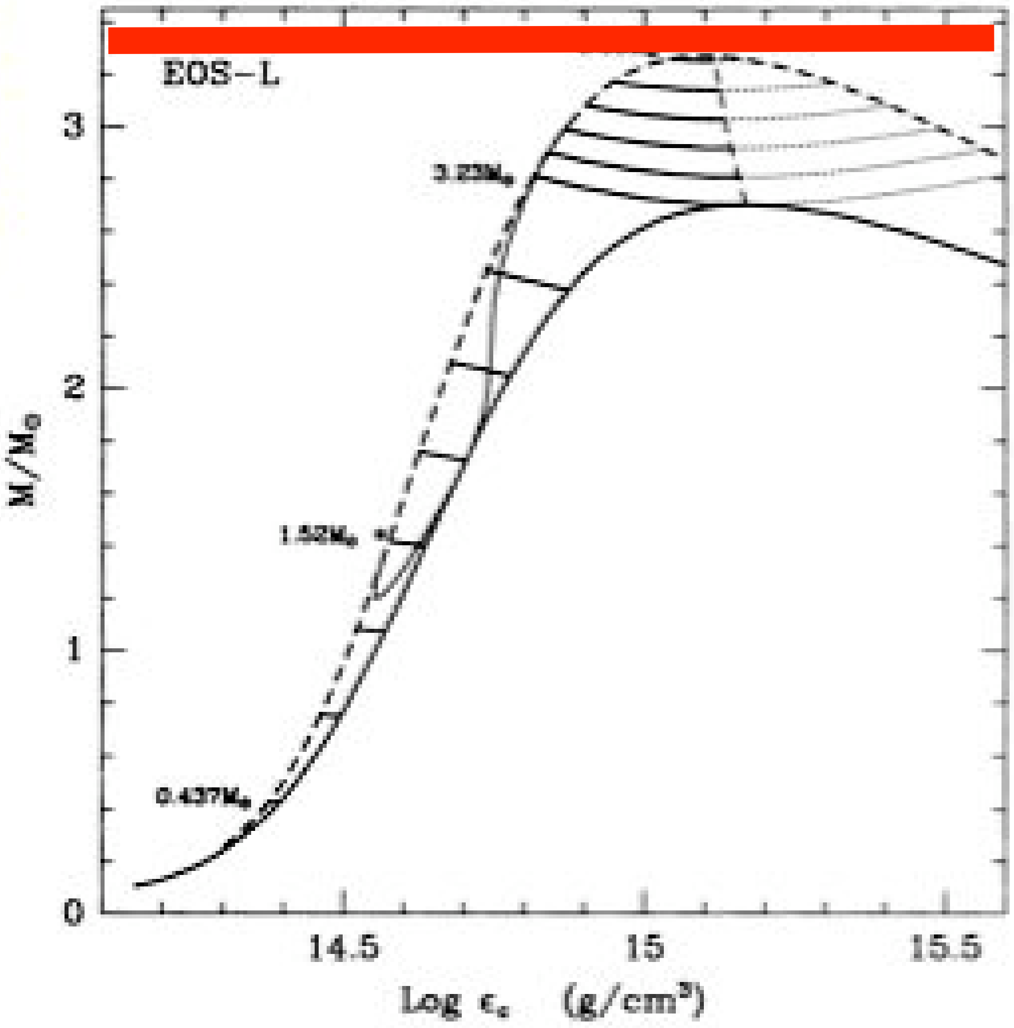
(III?)
INTERMEDIATE MASS BLACK HOLES ?
LINK WITH Pop III STARS
COSMIC GROWTH OF SUPERMASSIVE BLACK HOLES
DURING THE HIERARCHICAL ASSEMBLY OF GALAXIES

AIM OF THESE LECTURES: REVIEW THE CURRENT STATUS OF BLACK HOLE ASTROPHYSICS FOCUSSING ON BRAOD TOPICS & DISCUSSING NEW PERSPECTIVES

STELLAR-MASS BLACK HOLES



MAXIMUM
NEUTRON STAR MASS



MEASURING BLACK HOLE MASSES

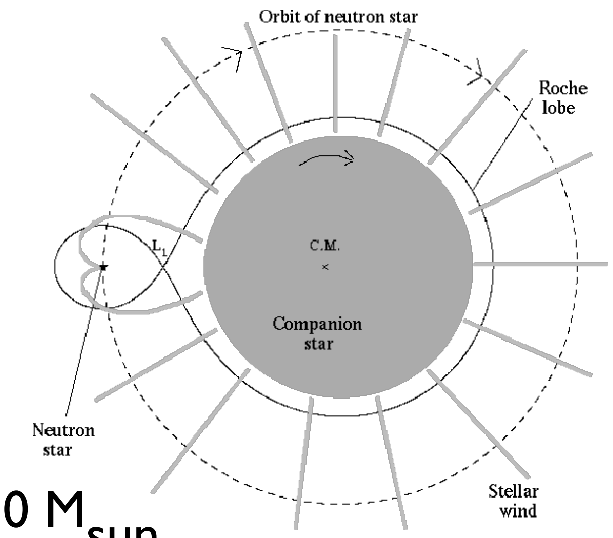
DYNAMICAL METHODS

° BLACK HOLES IN BINARIES

° PULSARS (future.....THE EXPECTED DISCOVERY OF {BH,PSR})

° GRAVITATIONAL WAVE SIGNAL FROM COALESCING BLACK HOLE BINARIES

TWO MAIN CLASSES OF XRBs



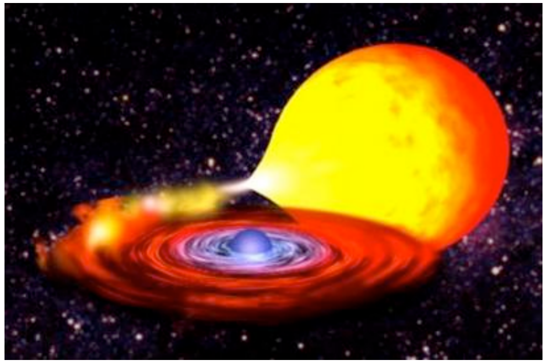
HIGH MASS X-RAY BINARIES

- ACCRETING COMPACT OBJECT: BH or a HIGH B FIELD NS
- POWERED BY THE INTENSE WIND OF THE DONOR STAR
- COMPANION STAR: LUMINOUS EARLY-TYPE O(B) STAR >10 M_{sun} (Pop I)
- LIFETIME 10^5 yr
- SPATIAL DISTRIBUTION: GALACTIC PLANE
- STELLAR POPULATION: YOUNG, AGE <10^7 yr
- TIME VARIABILITY: REGULAR X-RAY PULSATIONS FOR NEUTRON STARS

DISC FORMATION REQUIRES THE
SPECIFIC ANGULAR MOMENTUM OF THE ACCRETING MATTER BE
$J^2 > GM_{BH} R_{ISCO}$

LOW MASS X-RAY BINARIES

- ACCRETING COMPACT OBJECT: BH or a LOW B FIELD NS
- ROCHE LOBE OVERFLOW
- COMPANION STAR: FAINT LATE -TYPE STARS <1 Msun (Pop I & II)
- TIMESCALE OF ACCRETION: 10^{7-9} yr
- SPATIAL DISTRIBUTION: GALACTIC CENTER, PLANE & GLOBULAR CLUSTERS (DYNAMICAL FORMATION)
- STELLAR POPULATION:OLD
- The best "BH CANDIDATES"
- TIME VARIABILITY: X-RAY BURST (Type I) FOR NSs
- X-RAY SPECTRA: SOFT



MASS FUNCTION

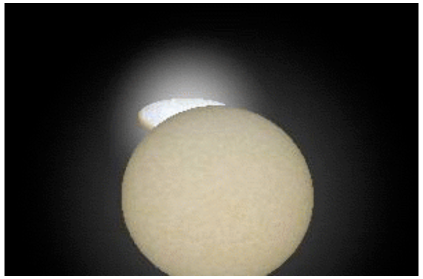
M_{BH} = BLACK HOLE MASS

M_C = MASS OF THE COMPANION STAR IN THE BINARY

° ANY SPECTRAL FEATURE EMITTED FROM Mc WILL BE DOPPLER SHIFTED

° LINE-OF-SIGHT VELOCITY

$$v_c=2\pi\, a_c \sin(i)/P_{orb}$$



° P_{orb}, v_c are measured

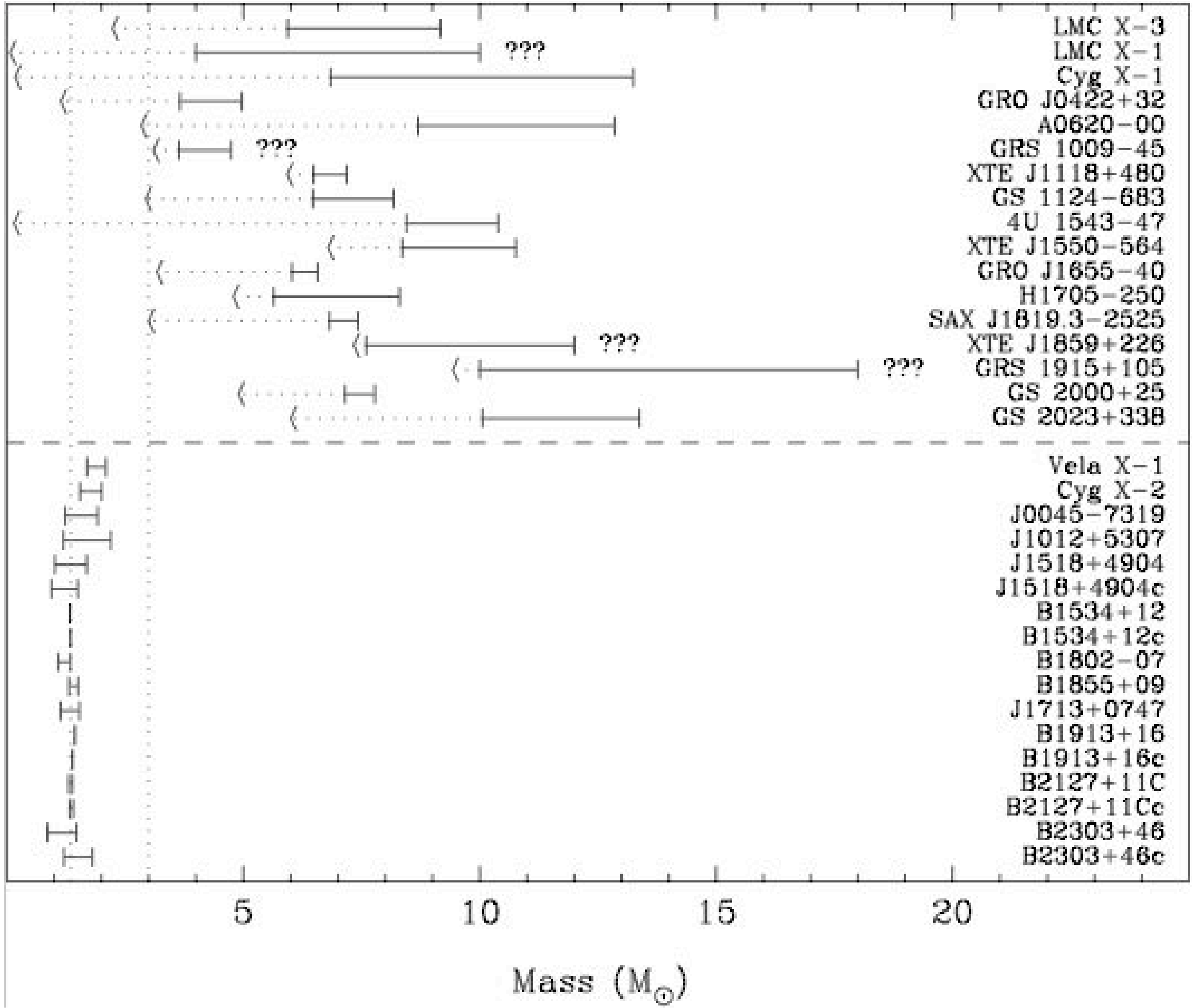
° $f_{BH}=f(M_{BH},M_c, i)=P_{orb}\, v_c^3/(2\pi G)=M_{BH}\sin^3(i)/(1+M_c/M_{BH})$

$$M_{BH}>f_{BH}$$

Table 1. Basic system parameters for the 14 transient and 3 persistent black hole binaries.

Source	Period (days)	$f(M)$ ($M_\odot$)	$V_{\rm rot} \sin i$ (km s^{-1})	inclination (deg)	$Q \equiv M_1/M_2$ range	BH mass range ($M_\odot$)	refs.
GRO J0422+32	0.2121600(2)	1.19 ± 0.02	90^{+22}_{-27}	44 ± 2	$3.2 - 13.2$	$3.66 - 4.97$	1-3
A0620−00	0.3230160(5)	2.72 ± 0.06	83 ± 5	40.8 ± 3.0	$13.3 - 18.3$	$8.70 - 12.86$	4-6
GRS 1009−45	0.285206(2)	3.17 ± 0.12	...	67?	$6.3 - 8.0$?	$3.64 - 4.74$?	7,8
XTE J1118+480	0.169930(4)	6.1 ± 0.3	114 ± 4	81 ± 2	$22.7 - 28.8$	$6.48 - 7.19$	9-11
GS 1124−683	0.432606(3)	3.01 ± 0.15	106 ± 13	54 ± 2	$4.8 - 8.8$	$6.47 - 8.18$	12-15
4U 1543−47	1.116407(3)	0.25 ± 0.01	46 ± 2	20.7 ± 1.5	$3.2 - 4.0$	$8.45 - 10.39$	16
XTE J1550−564	1.5435(5)	6.86 ± 0.71	90 ± 10?	72 ± 5	> 12	$8.36 - 10.76$	17
GRO J1655−40	2.6219(2)	2.73 ± 0.09	93 ± 3	70.2 ± 1.2	$2.4 - 2.7$	$6.03 - 6.57$	18-20
H1705−250	0.521(1)	4.86 ± 0.13	< 79	> 60	> 18.9	$5.64 - 8.30$	21-23
SAX J1819.3−2525	2.81730(1)	3.13 ± 0.13	98.9 ± 1.5	75 ± 2	$2.22 - 2.39$	$6.82 - 7.42$	24,25
XTE J1859+226	0.382(3)	7.4 ± 1.1	...	...	...	$7.6 - 12.0$?	26
GRS 1915+105	34(2)	9.5 ± 3.0	...	70 ± 2?	...	$10.0 - 18.0$?	27-29
GS 2000+25	0.3440915(9)	5.01 ± 0.12	86 ± 8	64.0 ± 1.3	$18.9 - 28.9$	$7.15 - 7.78$	30-32
GS 2023+338	6.4714(1)	6.08 ± 0.06	38.8 ± 1.1	56 ± 4	$16.1 - 18.9$	$10.06 - 13.38$	33,34
LMC X-3	1.70479(4)	2.29 ± 0.32	130 ± 20	67 ± 3	$1.1 - 2.0$	$5.94 - 9.17$	35-37
LMC X-1	4.2288(6)	0.14 ± 0.05	...	≈ 63?	$0.3 - 0.7$?	$4.0 - 10.0$?	38
Cyg X-1	5.59983(2)	0.244 ± 0.005	94 ± 5	35 ± 5	$0.50 - 0.57$	$6.85 - 13.25$	39-42

References: **1:** Webb et al. 2000; **2:** Harlaftis et al. 1999; **3:** Gelino & Harrison 2002; **4:** Leibowitz, Hemar, & Orio 1998 **5:** Marsh, Robinson, & Wood 1994; **6:** Gelino, Harrison, & Orosz 2001; **7:** Filippenko et al. 1999; **8:** Gelino 2002; **9:** Wagne et al. 2001; **10:** Orosz 2001; **11:** McClintock et al. 2001; **12:** Orosz et al. 1996; **13:** Casares et al. 1997; **14:** Shahbaz, Naylor & Charles 1997; **15:** Gelino, Harrison, & McNamara 2001; **16:** Orosz et al. 2002b; **17:** Orosz et al. 2002a; **18:** Greene, Bailyn & Orosz 2001; **19:** Shahbaz et al. 1999a; **20:** Israelian et al. 1999; **21:** Remillard et al. 1996; **22:** Filippenko et al. 1997 **23:** Harlaftis et al. 1997; **24:** Orosz et al. 2001; **25:** Orosz et al. 2002c; **26:** Filippenko & Chornock 2001; **27:** Greiner, Cuby & McCaughrean 2001; **28:** Mirabel & Rodriguez 1994; **29:** Fender et al. 1999; **30:** Chevalier & Ilovaisky 1993; **31:** Harlaftis Horne, & Filippenko 1996; **32:** Gelino 2001; **33:** Casares & Charles 1994; **34:** Shahbaz et al. 1994; **35:** van der Klis et al. 1985 **36:** Cowley et al. 1983; **37:** Kuiper, van Paradijs, & van der Klis 1988; **38:** Hutchings et al. 1987; **39:** Brocksopp et al. 1999 **40:** Ninkov, Walker, & Yang 1987; **41:** Gies & Bolton 1986; **42:** Herraro et al. 1995.



LMC X-3
LMC X-1
???
Cyg X-1
GRO J0422+32
A0620-00
GRS 1009-45
???
XTE J1118+480
GS 1124-683
4U 1543-47
XTE J1550-564
GRO J1655-40
H1705-250
SAX J1819.3-2525
XTE J1859+226
???
GRS 1915+105
???
GS 2000+25
GS 2023+338
Vela X-1
Cyg X-2
J0045-7319
J1012+5307
J1518+4904
J1518+4904c
B1534+12
B1534+12c
B1802-07
B1855+09
J1713+0747
B1913+16
B1913+16c
B2127+11C
B2127+11Cc
B2303+46
B2303+46c
5
10
15
20
Mass (M☉)

EVIDENCE
FOR
THE EVENT HORIZON ?

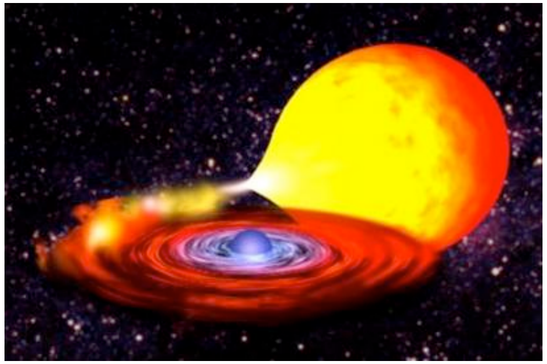
THERE IS AS YET NO EVIDENCE THAT ANY OF THE BLACK HOLE CANDIDATES DISCOVERED SO FAR IS A “TRULY” BLACK HOLE !

MASS MEASURMENTS ALONE CAN NOT PROVE THAT THE X-RAY SOURCE IS A BLACK HOLE !

TO PROVE THAT AN OBJECT IS A BLACK HOLE REQUIRES AN UNAMBIGUOUS DEMONSTRATION THAT IT POSSESES AN EVENT HORIZON

...... STUDYING “ACCRETION” IN XRBs

BASICS OF ACCRETION THEORY

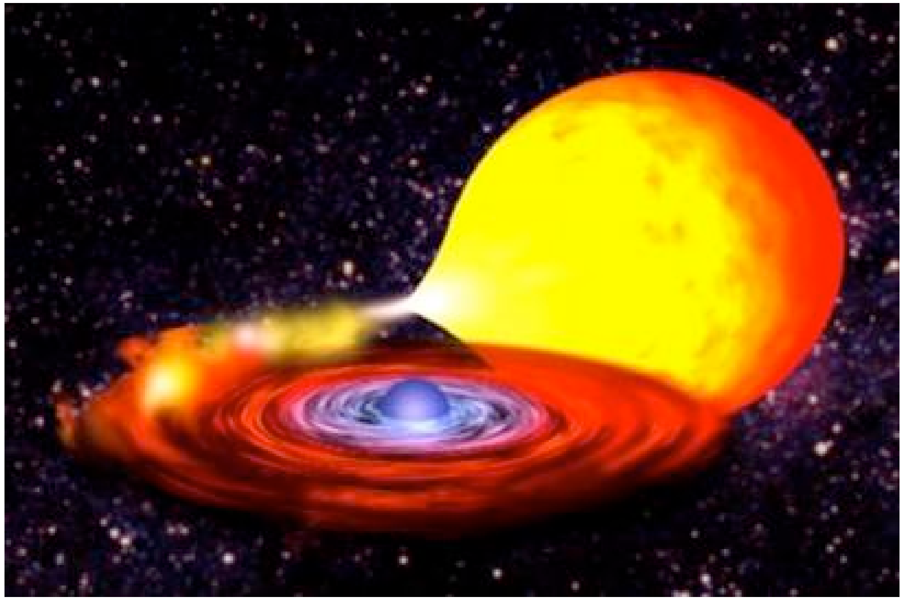


OUTER EDGE=INNER LAGRANGIAN POINT

SPIRAL IN OF GAS ALONG NEARLY KEPLERIAN ORBITS
VISCOUS EFFECTS TEND TO TRANSFER
ANGULAR MOMENTUM OUTWARD ALLOWING THE GAS
TO DRIFT INWARD DOWN TO THE

INNER EDGE = ISCO

Shakura & Sunyaev α–disc



R_{ISCO}

EFFICIENCY OF CONVERSION OF GRAVITATIONAL ENERGY
- INTERNAL ENERGY - RADIATION

THE RADIATIVE EFFICIENCY OF AN ACCRETION DISC IS DEFINED AS THE ENERGY IT RADIATES PER UNIT TIME ACCRETED MASS

$$\eta = L_{acc}/\dot{M}\, c^2$$

$$\eta = 0.057\ (a=0)$$

$$\eta = 0.42\ (a=1)$$

THE PRESENCE OF A GEOMETRICALLY THIN,
OPTICALLY THICK DISC IS CRITICAL FOR
HAVING LARGE LUMINOSITIES

$\eta=0.057\ (a=0)$
$\eta=0.42\ (a=1)$

BY CONTRAST

IN “SPHERICAL” INFLOWS
THE ACCRETION EFFICIENCY
ONTO A BLACK HOLE WOULD BE
ORDERS OF MAGNITUDE LOWER
THAN THAT OF A DISC

$\eta= 6 \times 10^{-11}\ M/M_{\odot}$

in the environment like the ISM

cause: rapid advection of the internal energy by the converging,
rapidly accreting gas

$\eta \sim 10^{-4}$

EDDINGTON LUMINOSITY

STATIONARY ACCRETION

$$- GM_{BH}m/r^2 \qquad + L\sigma_T/(4\pi c\, r^2)$$

$$L_E=4\,\pi\, c\, G\, M_{BH}\, m_p/\sigma_T = 1.3 \times 10^{38}\ \mathrm{erg\ s^{-1}}$$

for a solar mass black hole

THIN DISCS

While viscosity transports angular momentum and thus spreads the initial ring into a disc, the nature of this accretion disc is determined by the efficiency with which the disc can cool. In many cases this is high enough that the disc is *thin*: that is, its scaleheight H obeys

$$H \simeq \frac{c_{\mathrm{s}}}{v_{\mathrm{K}}} R << R \tag{1}$$

at disc radius R, where c_{s} is the local sound speed, and

$$v_{\mathrm{K}} = \left(\frac{GM}{R}\right)^{1/2} \tag{2}$$

is the Kepler velocity, with M the accretor mass. In this state the azimuthal velocity is close to v_{K}, and the radial and vertical velocities are much smaller.

If the thin disc approximation holds, the vertical structure is almost hydrostatic and decouples from the horizontal structure, which can be described in terms of its surface density Σ. If the disc is axisymmetric, mass and angular momentum conservation imply that the latter obeys a nonlinear diffusion equation

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left(R^{1/2}\frac{\partial}{\partial R}[\nu \Sigma R^{1/2}]\right). \tag{1}$$

Here ν is the kinematic viscosity, which is usually parametrized as

$$\nu = \alpha c_{\rm s} H. \tag{2}$$

where α is a dimensionless number. In a steady state this gives

$$\nu\Sigma = \frac{\dot M}{3\pi}\left[1 - \beta\left(\frac{R_{\rm in}}{R}\right)^{1/2}\right], \tag{3}$$

where $\dot M$ is the accretion rate and the dimensionless quantity β is specified by the boundary condition at the inner edge $R_{\rm in}$ of the disc. In a steady thin disc dissipation $D(R)$ per unit surface area is also proportional to $\nu\Sigma$, i.e.

$$D(R) = \frac{9}{8}\nu\Sigma\frac{GM}{R^3}\left[1 - \beta\left(\frac{R_{\rm in}}{R}\right)^{1/2}\right], \tag{4}$$

so that the surface temperature T is independent of the viscosity ν despite being entirely generated by it:

$$T = T_{\rm visc} = \left\{\frac{3GM\dot M}{8\pi R^3 \sigma}\left[1 - \beta\left(\frac{R_*}{R}\right)^{1/2}\right]\right\}^{1/4}. \tag{5}$$

$T \propto M^{-1/4}$

Disc timescales

The first is the dynamical timescale

$$t_{\mathrm{dyn}} \sim \frac{R}{v_{\mathrm{K}}} = \left(\frac{R^3}{GM}\right)^{1/2}, \tag{1}$$

characterizing states in which dynamical equilibrium is disturbed; note that vertical hydrostatic balance is resored on a timescale

$$t_z \sim \frac{H}{c_{\mathrm{s}}} = \frac{R}{v_{\mathrm{K}}} = t_{\mathrm{dyn}}. \tag{2}$$

The second is the thermal timescale

$$t_{\mathrm{th}} = \frac{\Sigma c_{\mathrm{s}}^2}{D(R)} \sim \frac{R^3 c_{\mathrm{s}}^2}{GM\nu} = \frac{c_{\mathrm{s}}^2}{v_{\mathrm{K}}^2}\frac{R^2}{\nu} = \left(\frac{H}{R}\right)^2 t_{\mathrm{visc}}. \tag{3}$$

The alpha–disc parametrization can be used to show that the viscous timescale is

$$t_{\mathrm{visc}} \sim \frac{1}{\alpha}\left(\frac{H}{R}\right)^{-2} t_{\mathrm{dyn}} \tag{4}$$

so we finally have the ordering

$$t_{\mathrm{dyn}} \sim t_z \sim \alpha t_{\mathrm{th}} \sim \alpha (H/R)^2 t_{\mathrm{visc}}, \tag{5}$$

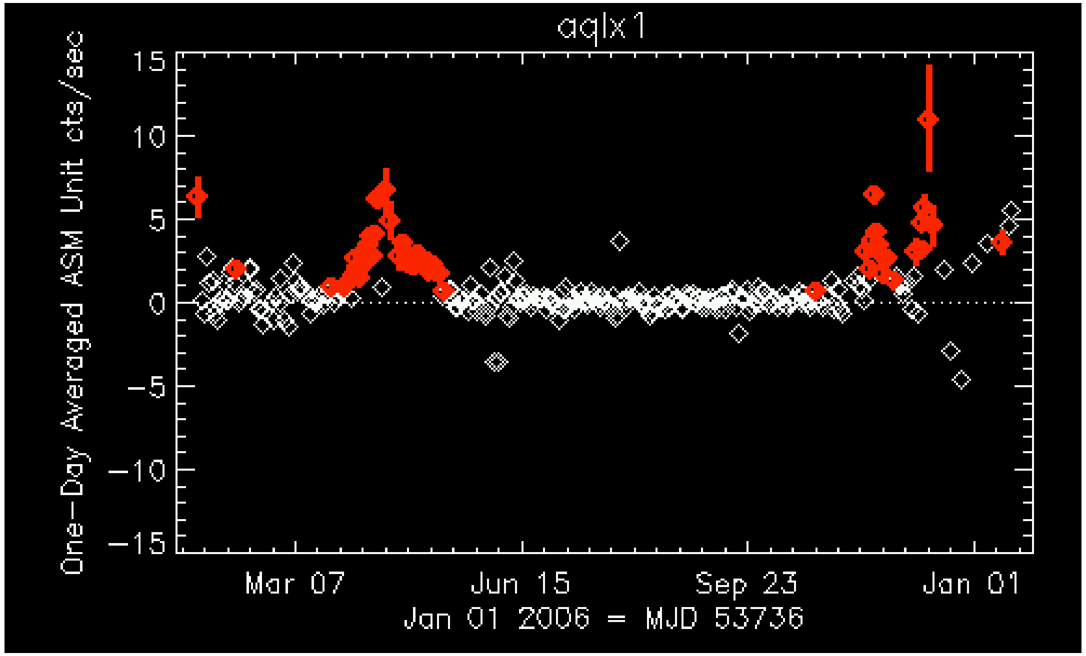
i.e. dynamical < thermal < viscous.

Breakdown of the thin disc approximation

The thin disc approximation requires the accreting matter to cool efficiently. However flows with low radiative efficiency on to a black hole can in principle occur, for at least two reasons:

- the accretion rate $\dot{M}$ may be so low that the inflowing gas has low density and thus a long cooling time,
- or conversely $\dot{M}$ may be so large that the flow is very optically thick, and radiation is trapped and dragged down the hole.

As energy is advected inwards, these flows are called ADAFs (advection–dominated accretion flows). If the accretor is not a black hole, the advected energy must be released near the surface of the accretor. This effect has been invoked to explain observations of quiescent transients.



Accretion disc stability

Many accreting sources are observed to vary strongly. The examples relevat here are soft X–ray transients (SXTs), where a black hole or neutron star accretes from a low–mass companion. In both cases the system spends most of its time in quiescence, with occasional outbursts in which it is much brighter. In SXTs, quiescence lasts $\sim 1 - 50$ yr or more, outburst $\sim$ months. The system luminosity rises from $\sim 10^{32}$ erg s^{-1} to $10^{38} - 10^{39}$ erg s^{-1}.

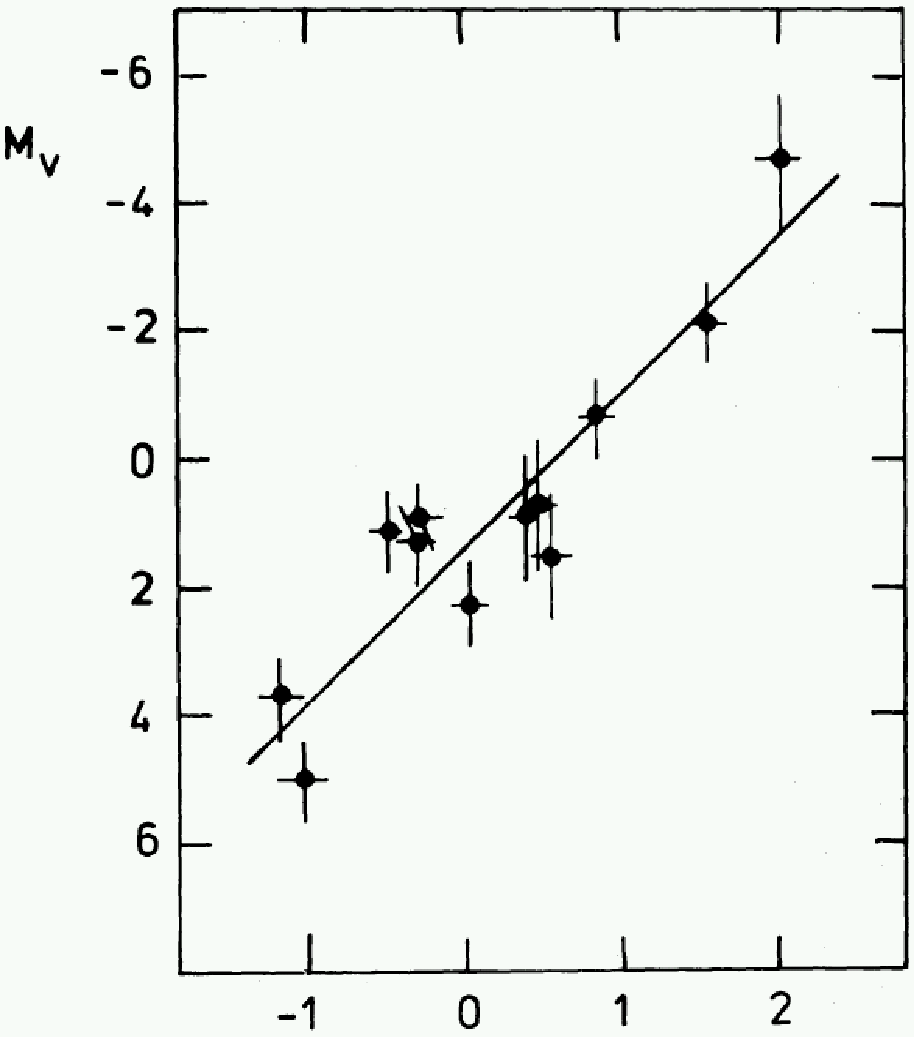
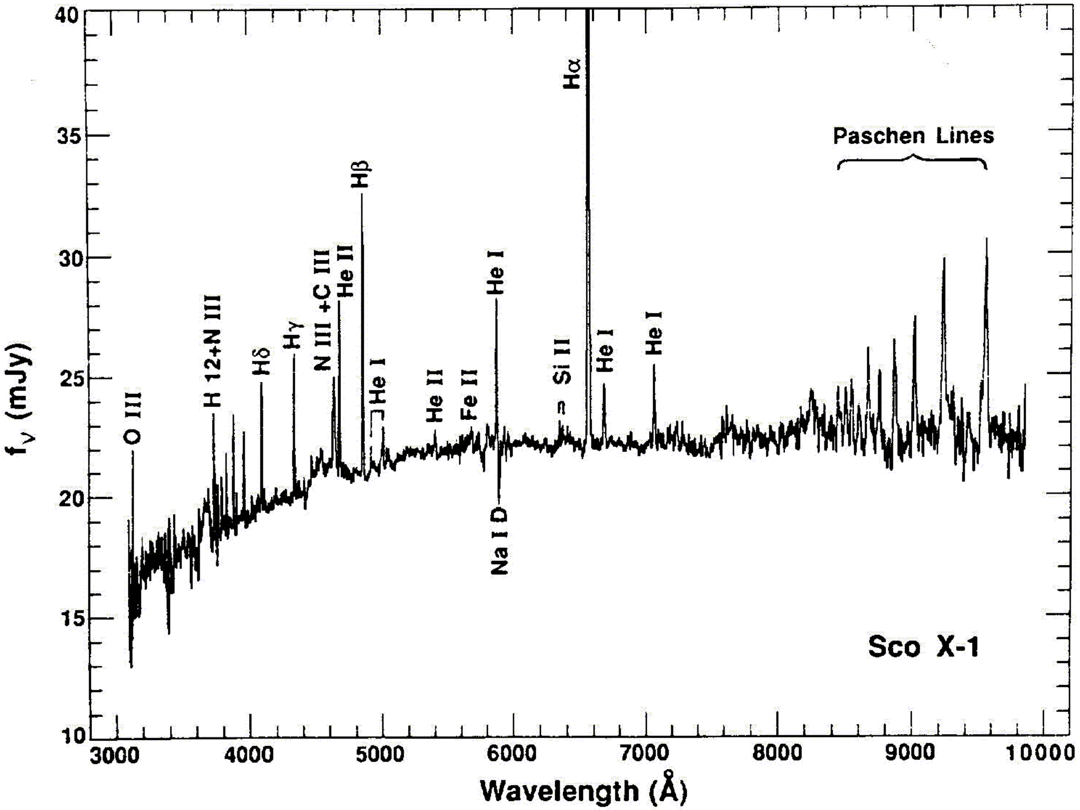


Fig. 2. Relation between the absolute visual magnitude M_V and $\Sigma = (L_X/L_{Edd})^{1/2} (P/\ 1\mathrm{hr})^{2/3}$. The straight line represents the least-squares fit (see text)



DISC INSTABILITY PICTURE

(Lasota & Frank)

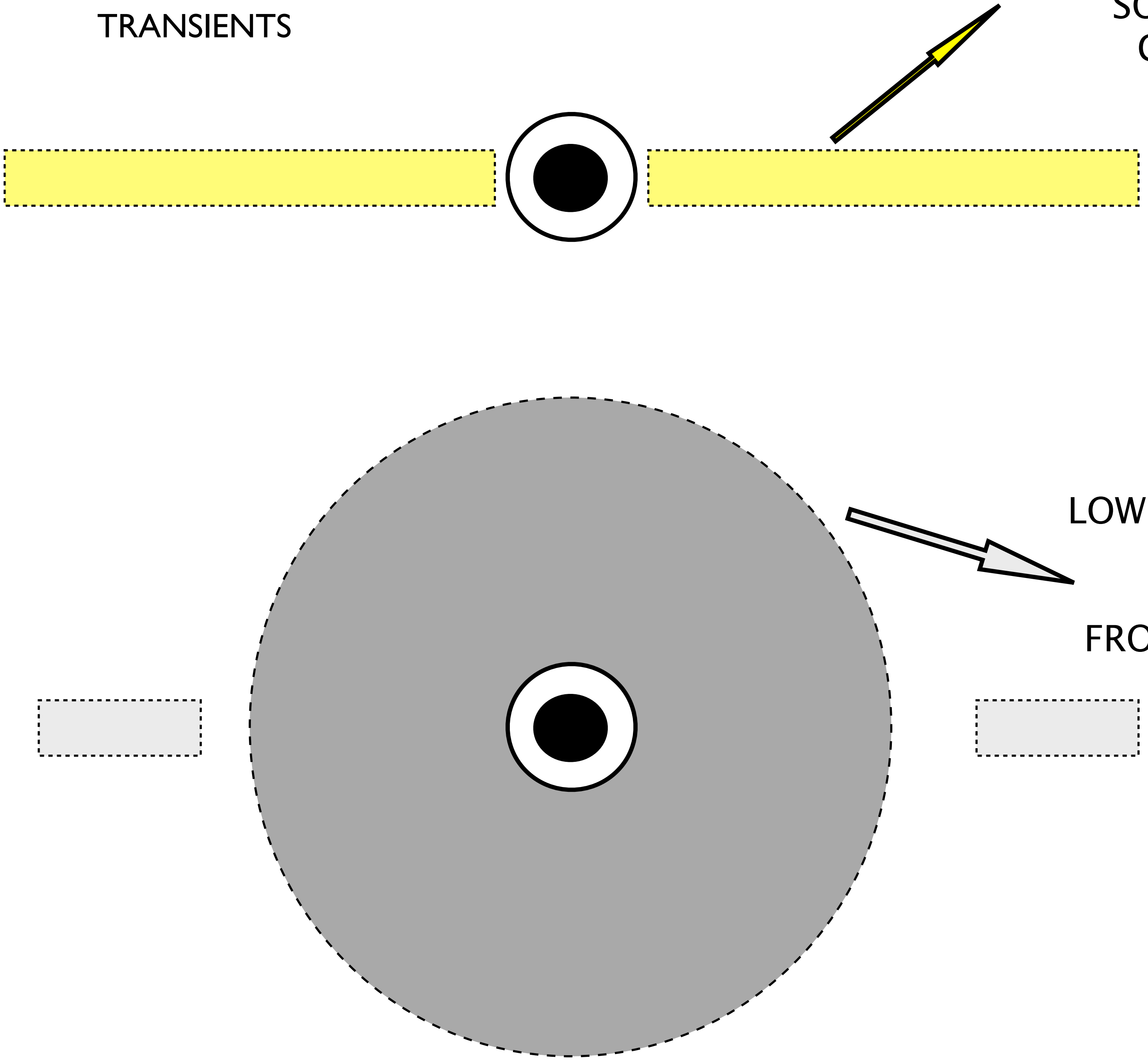
In a certain range of mass transfer rates
the disc can exist in either two states

High Viscosity State - OUTBURST

Low Viscosity State - QUIESCENCE

These two states correspond to hydrogen existing in
ionized & neutral states, respectively
The condition for a disc to be stable:
It must have NO IONIZATION zones

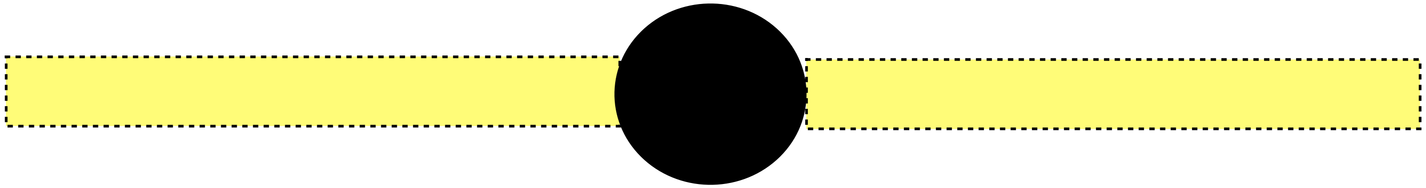
BLACK HOLE TRANSIENTS



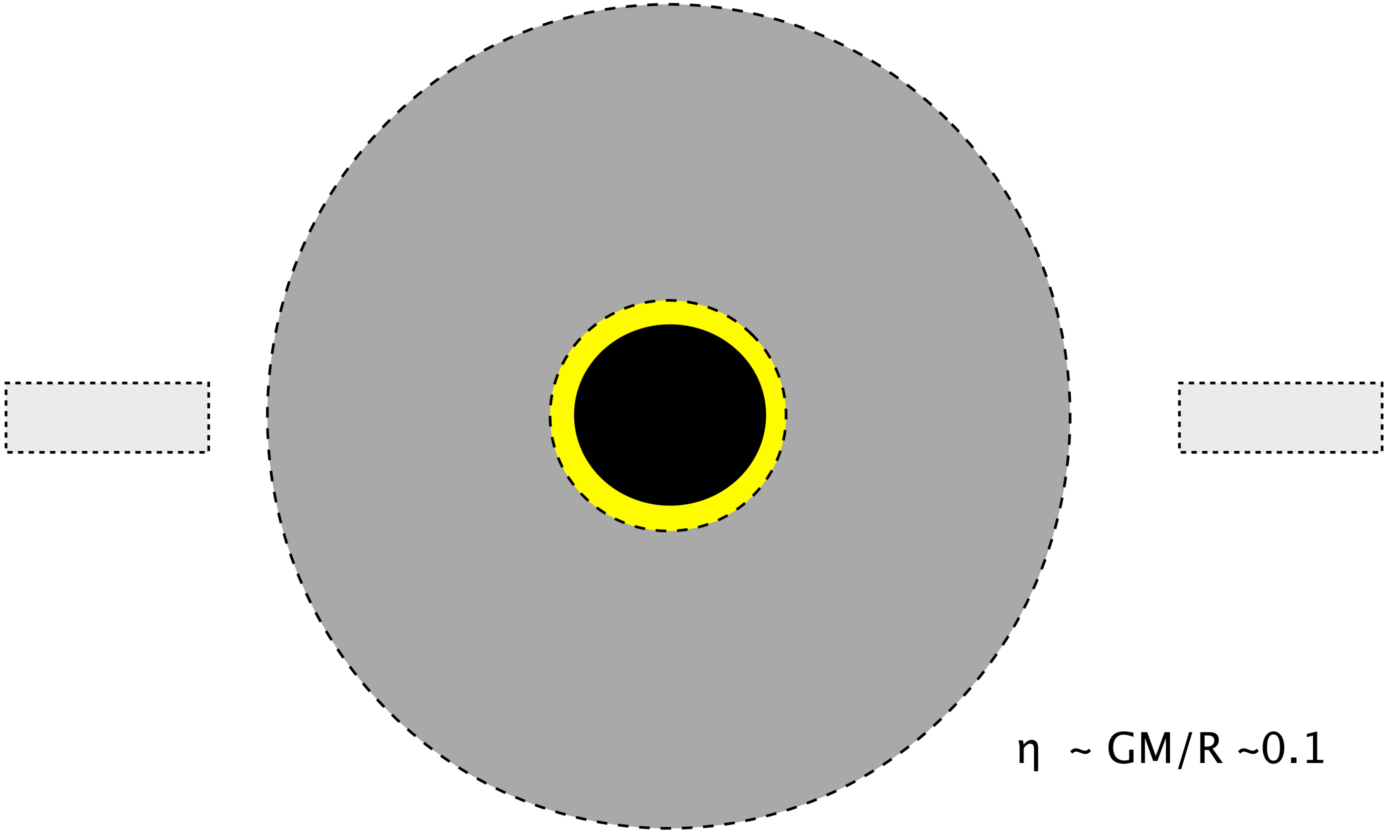
HIGH LUMINOSITY STATE
SOFT–THERMAL
COMPONENT

LOW LUMINOSITY STATE
HARD
COMPONENT
FROM A HOT CORONA

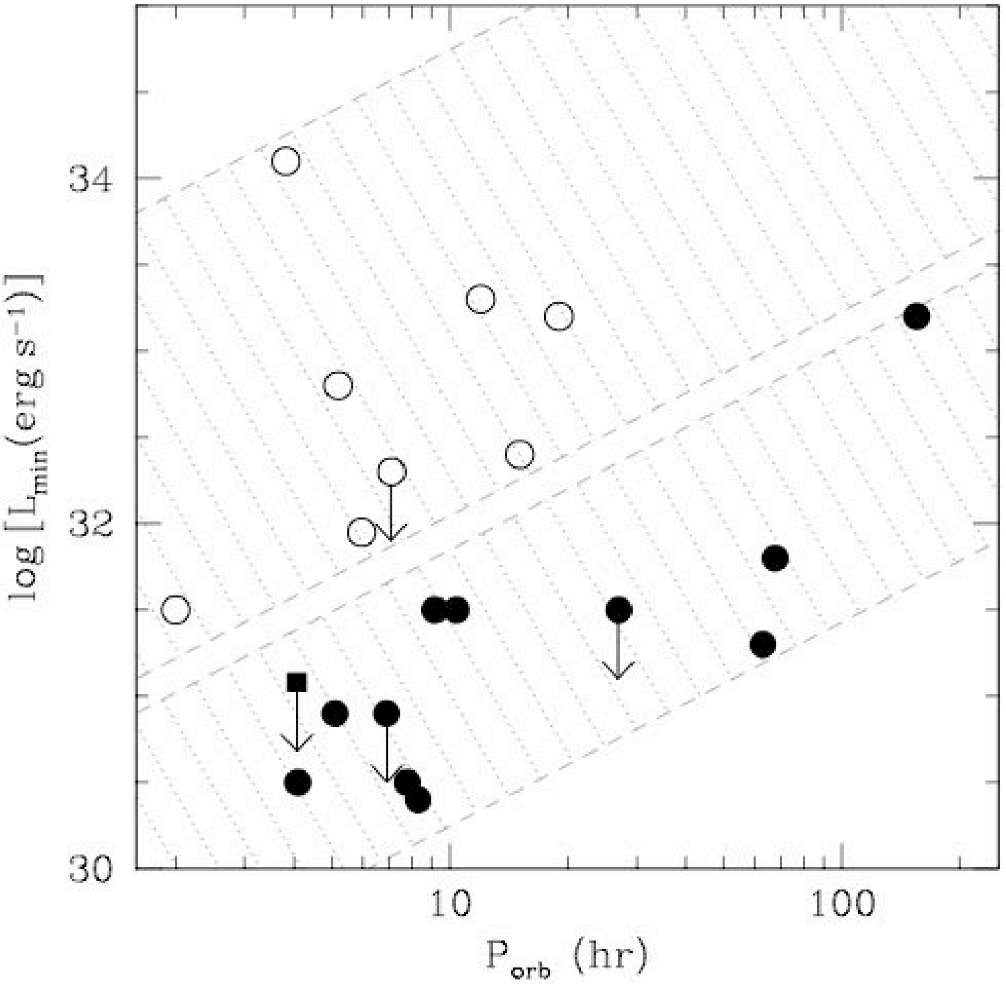
NEUTRON STAR SXR TRANSIENTS



EMISSION FROM THE
NEUTRON STAR SURFACE



$\eta \sim GM/R \sim 0.1$



QUIESCENT LUMINOSITIES OF SXRTs against ORBITAL PERIOD.
FILLED SYMBOLS CORRESPOND TO BLACK HOLE CANDIDATES,
OPEN SYMBOLS TO NEUTRON STARS
shaded bands are to guide the eye
As a group, the NSs are a factor 100 brighter than BH candidates
This difference may be interpreted as evidence that BH
candidates posses event horizons

NEUTRON STARS HAVE A SURFACE

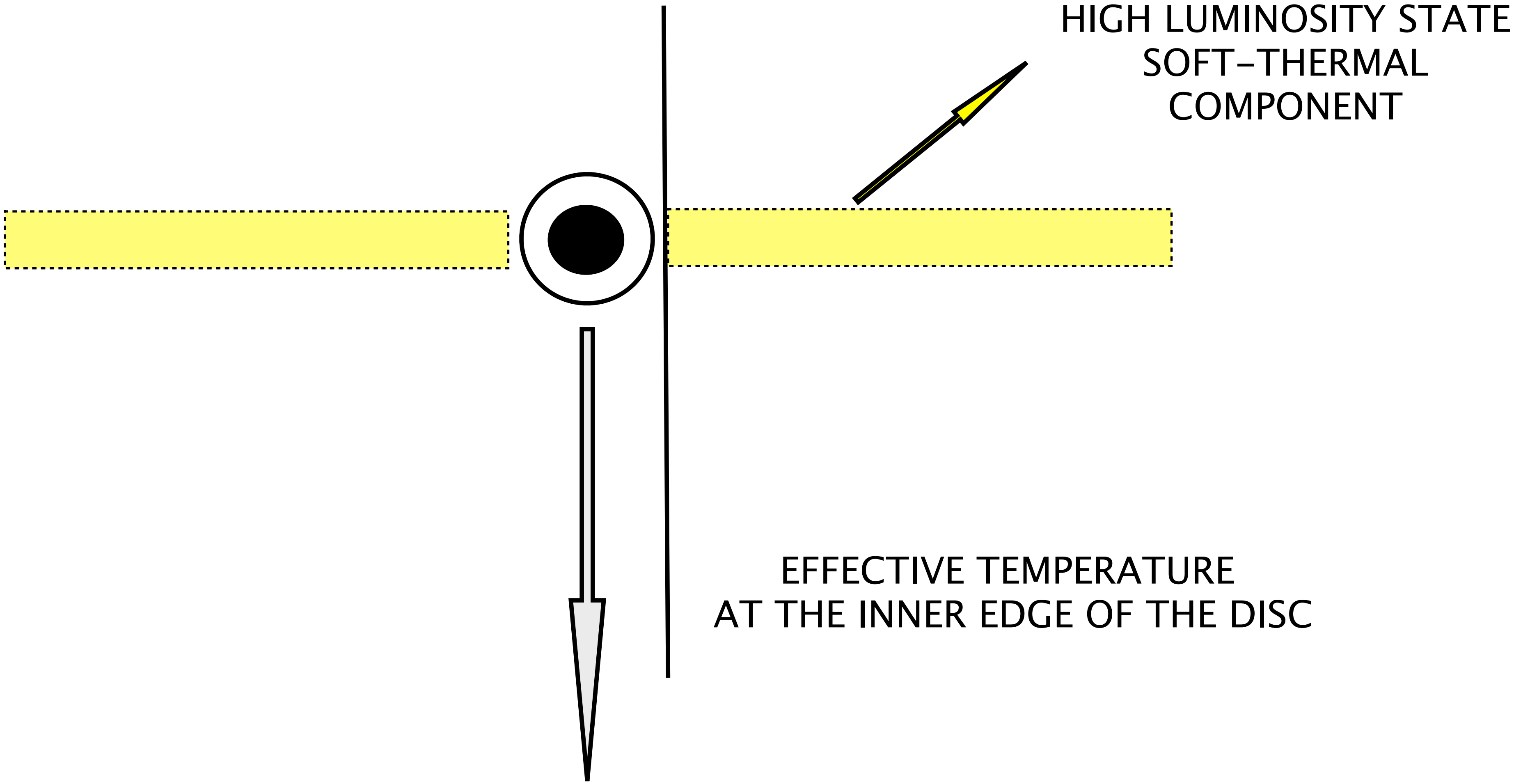
- THE RADIATIVE EFFICIENCY is always $\eta \approx GM/Rc^2 \approx 0.1$
- L=L_accretion of gas "on flight" + L_impact of gas on the surface
- L=L_radio emission DURING QUIESCENCE
- BOUNDARY LAYER ... producing power in the variability of power spectra at high frequencies (as high as 1 kHz)
- TYPE I X-RAY BURSTS - THERMONUCLEAR EXPLOSIONS OVER THE SURFACE
- QUIESCENT STATE OF SXRTs : COOLING OF THE NEUTRON STAR + SOME MAGNETOSPHERIC NON-THERMAL COMPONENT

BLACK HOLE SPIN

ESTIMATING THE MASS OF A BLACK HOLE IS RELATIVELY EASY
SINCE THE MASS HAS A MEASURABLE
EFFECT EVEN AT LARGE RADII WHERE NEWTONIAN GRAVITY APPLIES

SPIN DOES NOT HAVE ANY NEWTONIAN ANALOGUE AND ONLY FOR
RELATIVISTIC ORBITS DOES SPIN HAVE MEASURABLE EFFECTS

STUDY OF GAS NEAR THE ISCO



HIGH LUMINOSITY STATE
SOFT-THERMAL
COMPONENT

EFFECTIVE TEMPERATURE
AT THE INNER EDGE OF THE DISC

ATTEMPT TO CORRELATE THE HIGHEST BLACK BODY TEMPERATURE
FROM SPECTRAL FITTING OF A MULTI COLOR BB DISC
IN ORDER TO MEASURE
R_{ISCO} (a) KOWN THE MASS

°IRON LINE

°QPOs GAS BLOB AT ISCO

KEPLERIAN FREQUENCY IS A FUNCTION OF M and “a” (>0.5)

SUPERMASSIVE BLACK HOLES

THE GALACTIC CENTER

Genzel MPE-Cologne Group at ESO-VLT
Ghez UCLA Group at Keck

THE GALACTIC CENTER
HOSTS A VERY COMPACT RADIO SOURCE
Sagittarius A*

THE IMAGE OF Sgr A*

in millimiter radio waves indicates an angular size of about
240 micro-arcsecond corresponding to 10 light minutes

RADIO INTERFEROMETRIC DATA OVER 8 YEARS
VELOCITY PERPENDICULAR TO THE GALACTIC PLANE
-0.4 ± 0.9 km/s
THE LOW BROWNIAN MOTION
RESULTING FROM THE INTERACTION WITH STARS
IMPLIES A LARGE MASS (10^5 $M_{\odot}$)

SGR A* is also a modest X-ray source

Sagittarius A* is located at the center of a nuclear star cluster
THE STELLAR CUSP around the BLACK HOLE !

ONE OF THE RICHEST CONCENTRATIONS
OF YOUNG MASSIVE STARS IN THE MILKY WAY
....PARADOX OF YOUTH
(coud denser than 10^9 atoms/cm^3)

THE TWO GROUPS HAVE BEEN ABLE TO TRACE
THE POSITIONS IN THE SKY AS A FUNCTION OF TIME
OF A NUMBER OF CENTRAL STARS ORBITING SgrA*

°PROPER MOTION OF
STARS AS CLOSE AS 0.1 arcsec from SgrA*
1000 km/s
WITHIN THE CENTRAL LIGHT MONTH

°DOPPLER SPECTROSCOPY OF THE SAME STAR

IN THE CENTER OF OUR MILKY WAY GALAXY
THERE IS A MASSIVE DARK OBJECT

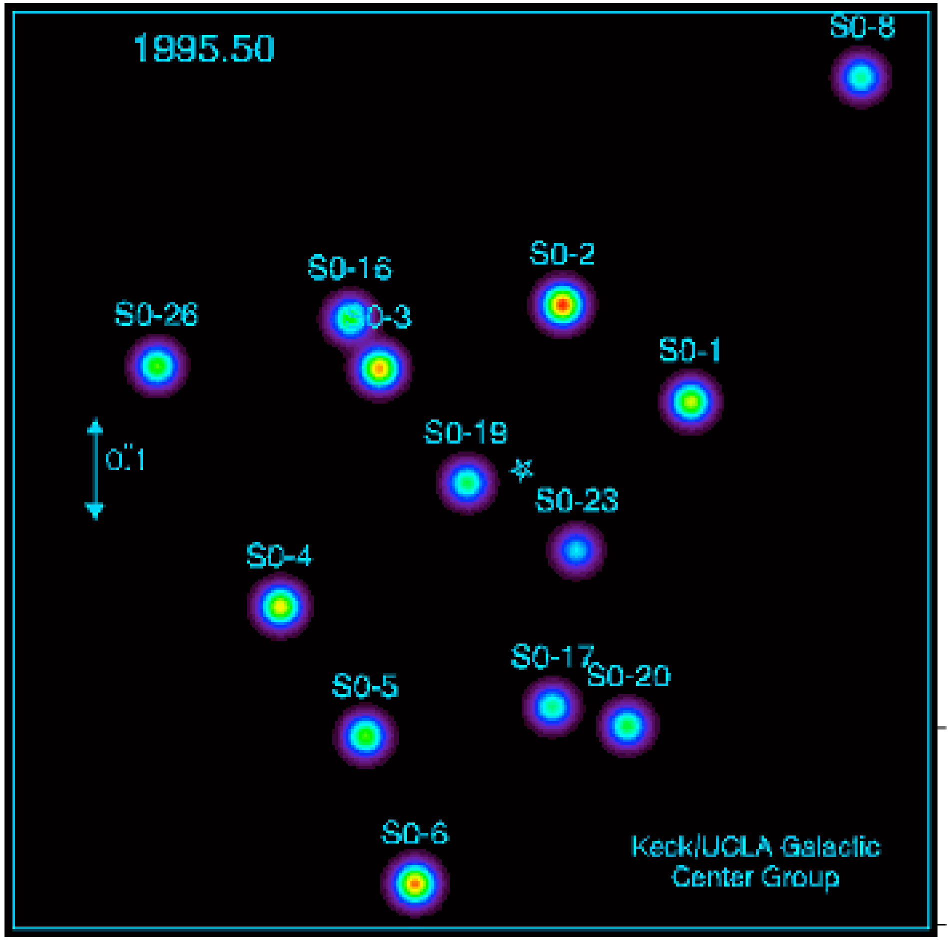
MDO

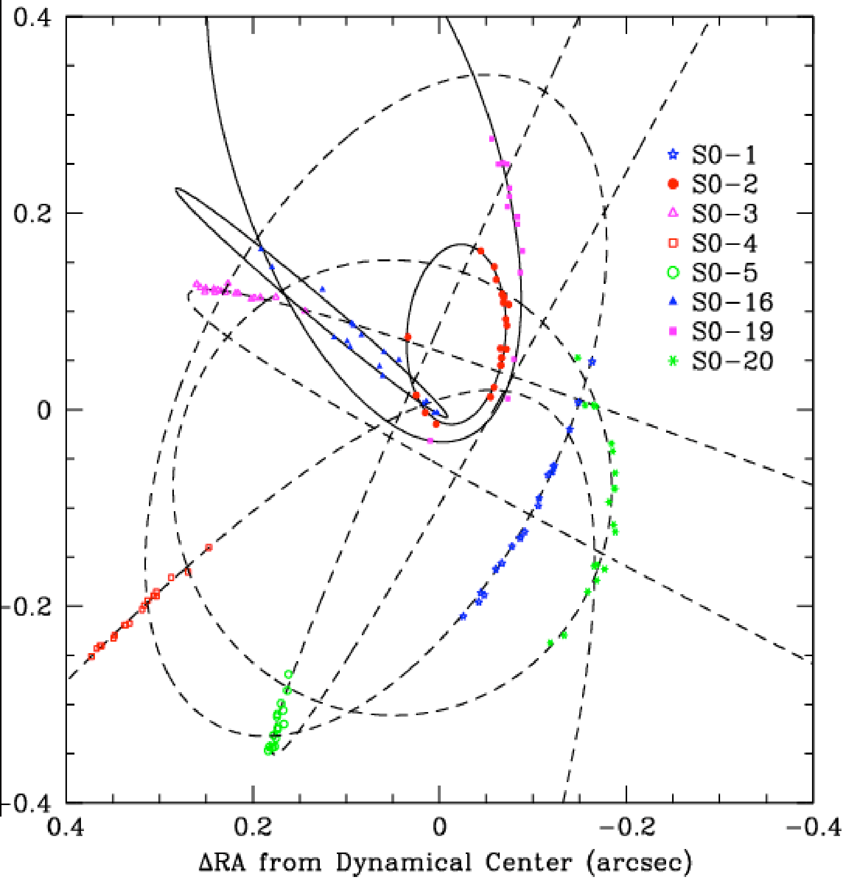
BY MODELING THE ORBITS WITH KEPLERIAN DYNAMICS

$$M_{BH} = 3.7 \pm 0.2\ M_{\odot}$$

THE SCHWARTZSCHILD RADIUS SUBTENDS A MERE 10^{-5} arcsec

GALACTIC CENTER
THREE DIMENSIONAL STRUCTURE OF SEVERAL STAR ORBITS





S14 (S0 16)

HAS PERICENTER AT 10 -20 LIGHT HOURS
70 Earth Orbit Radius
1000 GRAVITATIONAL RADII

$$\rho_{\text{orbit of S016}} \sim M_{BH}/R^3_{\text{peri}}$$

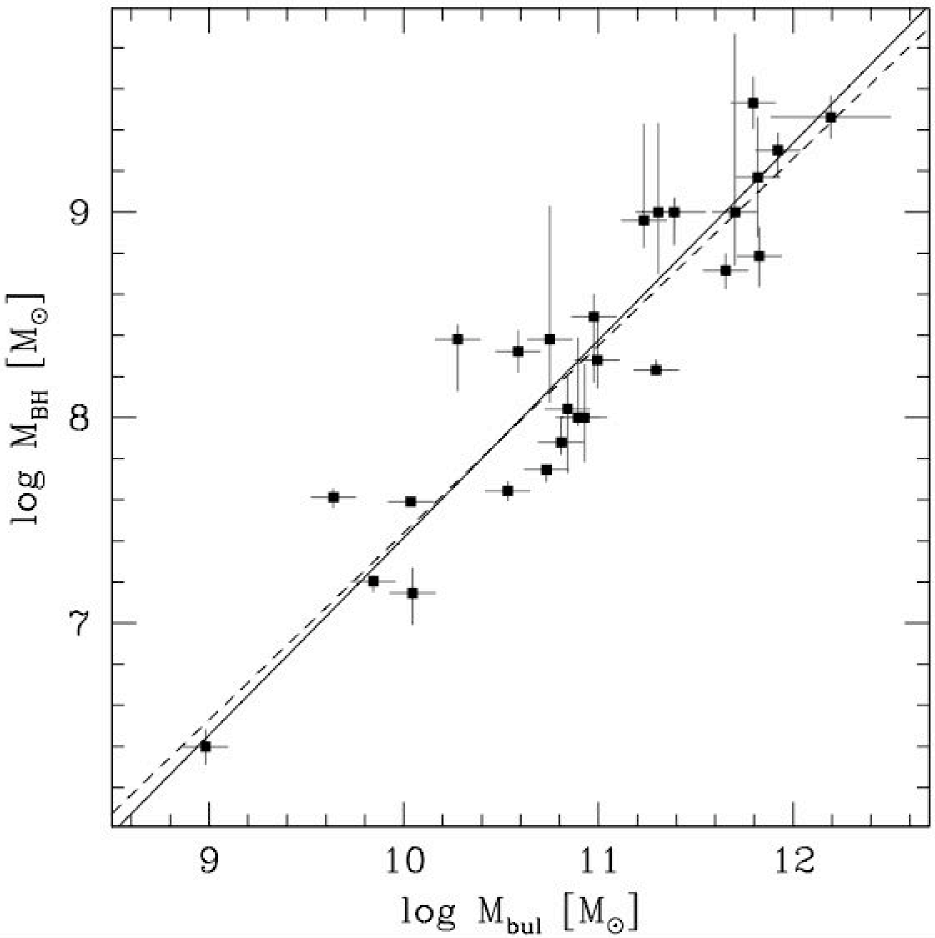
$$\rho_{MDO} > \rho_{\text{orbit of S016}}$$

$$\rho_{MDO} > 10^{19}\ M_\odot\ \text{pc}^{-3}$$

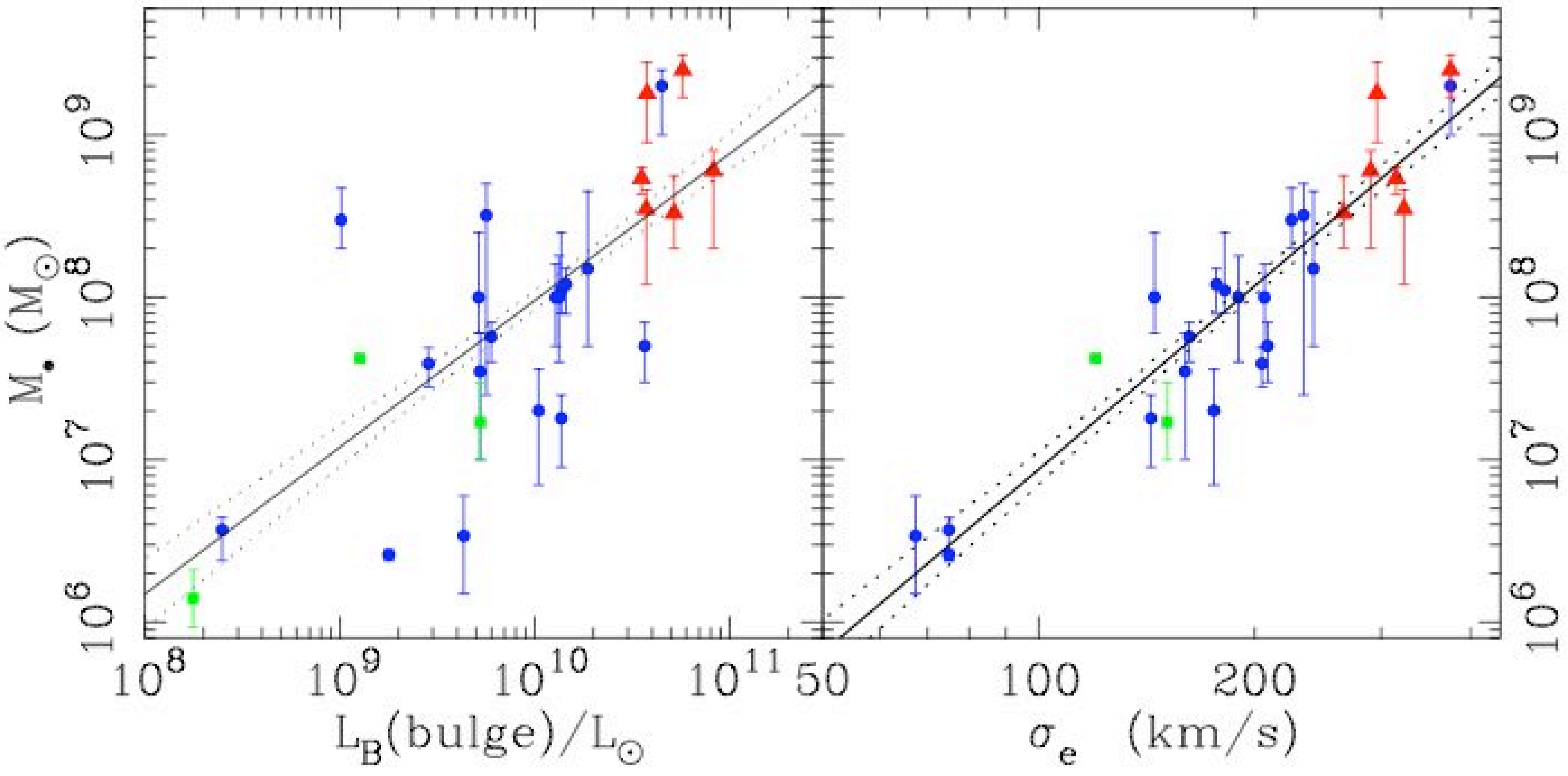
NO STAR CLUSTER OF DARK REMNANTS
(NSs or STELLAR MASS BHs)
IS DYNAMICALLY STABLE
(UNSTABLE TO EVAPORATION)

BOSON STARS ?
(fine tuned conditions)

BLACK HOLES ARE UBIQUITOUS IN SPHEROIDS
“in low angular momentum environments ”



Magorian et al. 1999, Ferrarese & Merritt 2000, Gebhardt et al. 2000, Tremaine et al. 2002



LOGARITHMIC SLOPE OF THE M_{BH} - σ RELATION
BETWEEN 4 and 5

BLACK HOLE SPHERE OF INFLUENCE $2GM_{BH}/\sigma^2$

THE BLACK HOLE

$L = L_E \propto M_{BH}$

THE BULGE of mass M σ

E (Binding Energy) ~ $GM^2/R \propto M\sigma^2$

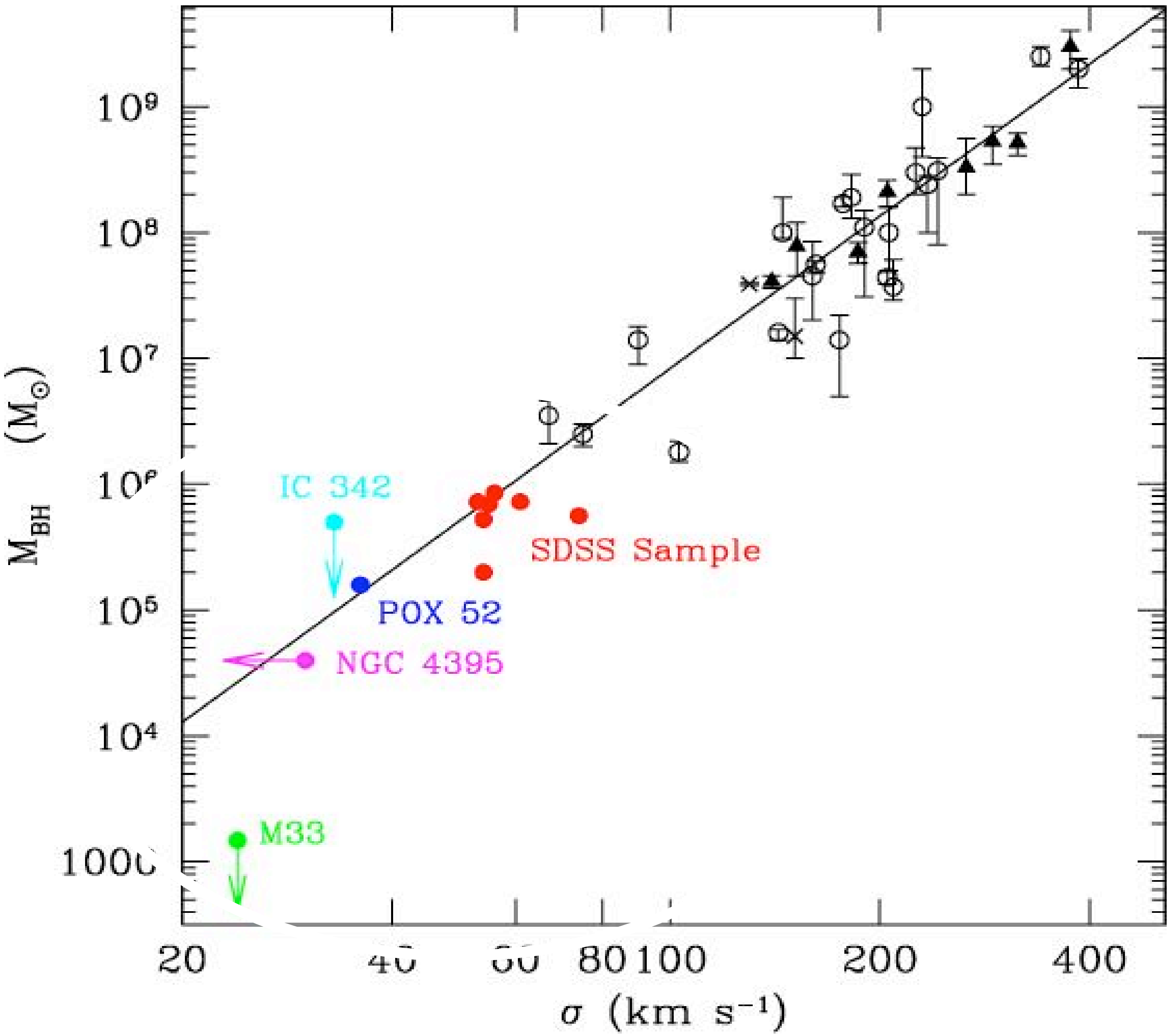
DYNAMICAL TIMESCALE

$\tau \sim R/\sigma \sim GM/\sigma^3$

$L\tau = E$

$M_{BH} \propto E/\tau \propto \sigma^5$

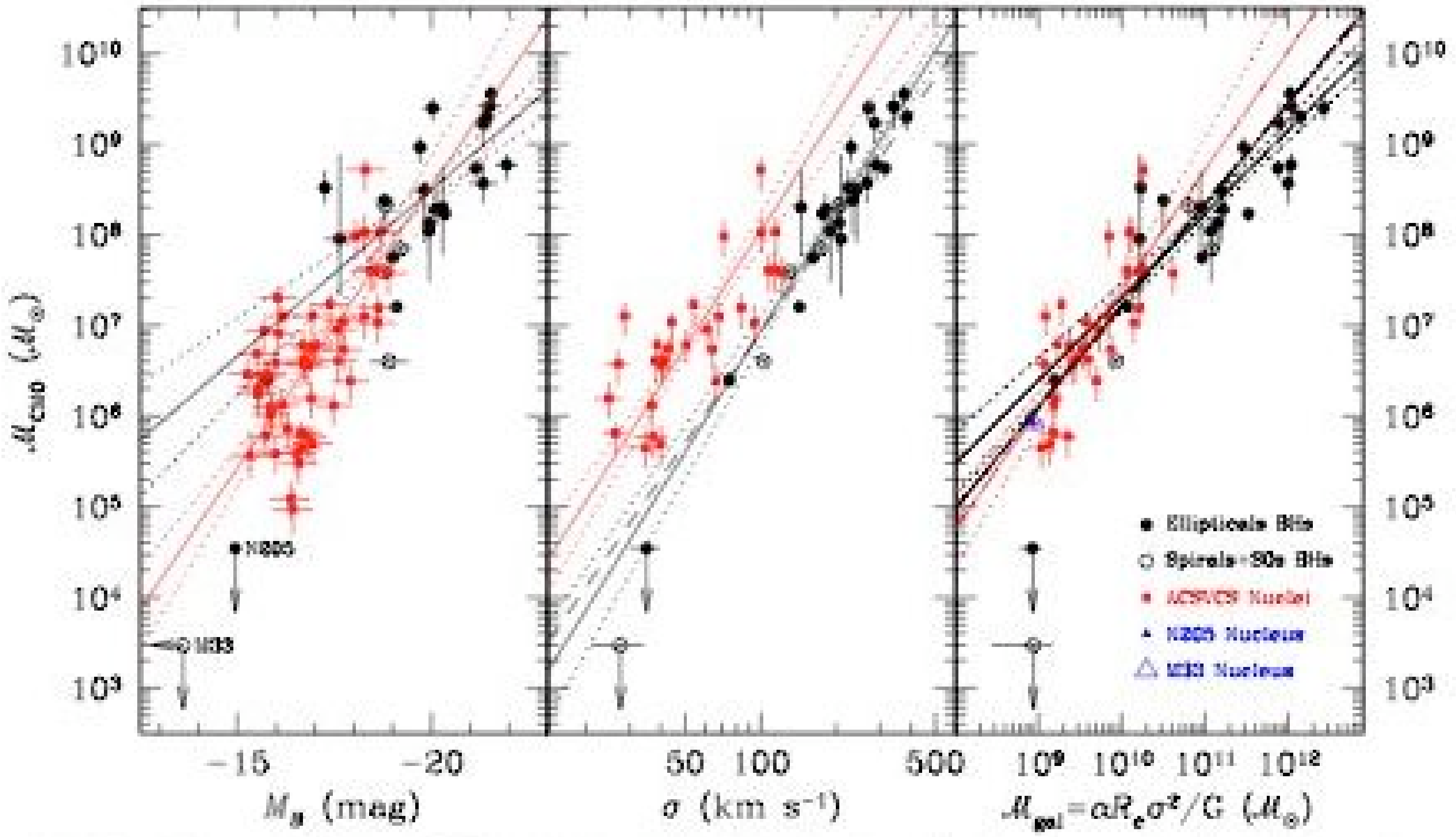
BLACK HOLE SEEDS ?



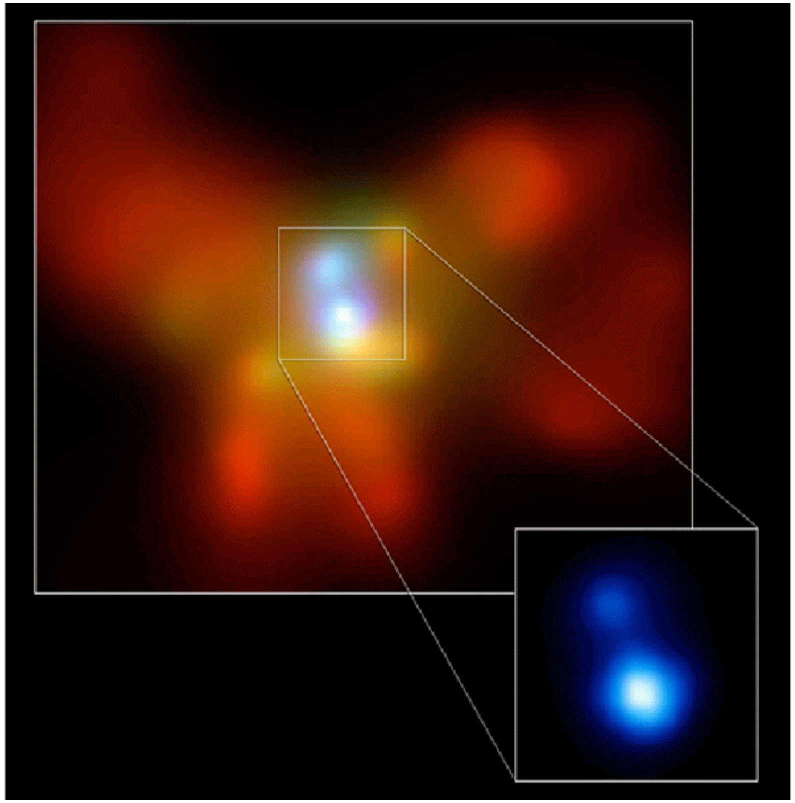
Barth, Green & Ho 2004


Galaxy M33
Yuuji Kitahara
Kitahara Astronomical Observatory No.951017

A Relation Between Stellar Nuclei and SBHs

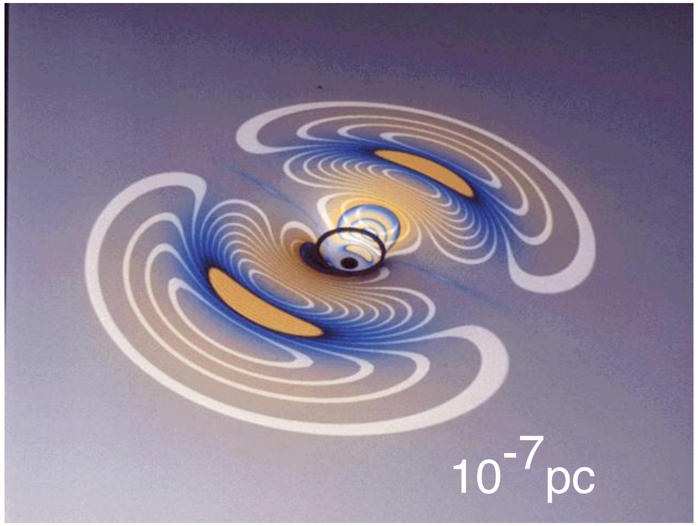


GALAXY COLLISIONS DRIVE THE FORMATION OF CLOSE BLACK HOLE PAIRS



1.4 kpc

NGC 6240 - AN ONGOING MERGER
ACCRETING BLACK HOLES



LASER INTERFEROMETER
SPACE ANTENNA

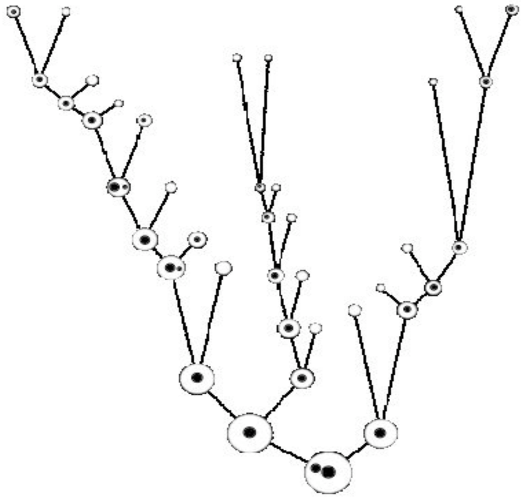
AT LARGE REDSHIFTS

Komossa et al. 1998,2003, Risaliti et al 2006, Greve et al. 2006

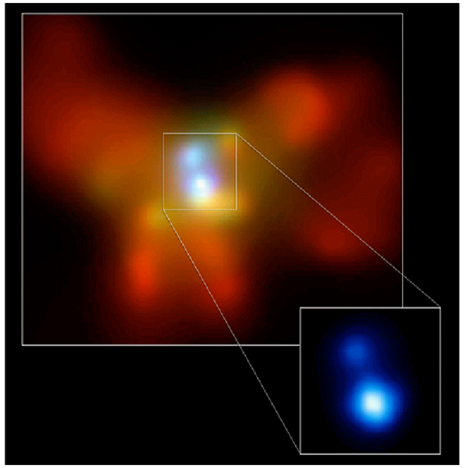
BLACK HOLE FORMATION & EVOLUTION

TWO COMPLEMENTARY APPROACHES

MODELING GALAXY ASSEMBLY
MONTE CARLO REALIZATIONS OF MERGER TREES
or/and
COSMOLOGICAL SIMULATIONS
TO ESTIMATE
THEIR MASS GROWTH
&
THE RATE OF COALESCENCE



Volonteri, Haardt & Madau 2003



COLLISION BETWEEN "GALAXIES"
WITH CENTRAL BLACK HOLES

DETAILING THE DYNAMICS

CRITICAL FOR ESTABLISHING THEIR COALESCENCE

Wythe & 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

“LISA” BLACK HOLES

$10^6\ M_\odot$

(1)

DOES A KEPLERIAN BINARY FORM
IN A COLLISION BETWEEN GAS-RICH GALAXIES ?

100 kpc to 1 pc

(2)

DOES THE BINARY CONTINUE TO DECAY
DOWN TO THE DOMAIN WHERE GRAVITATIONAL WAVE LOSSES
CONTROL THE RATE OF INSPIRAL?
WHAT IS THE ECCENTRICITY EVOLUTION?

1 pc to 0.001 pc

(+)

ELECTROMAGNETIC COUNTERPARTS ?

ALONG THE COURSE OF THE ENTIRE MERGER

1 pc to 0.001pc

MERGERS BETWEEN EQUAL MASS GALAXIES

INITIAL EQUILIBRIUM MODEL
REPRODUCES
A MILKY WAY LIKE GALAXY

HALO - DISC - BULGE - BLACK HOLE

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

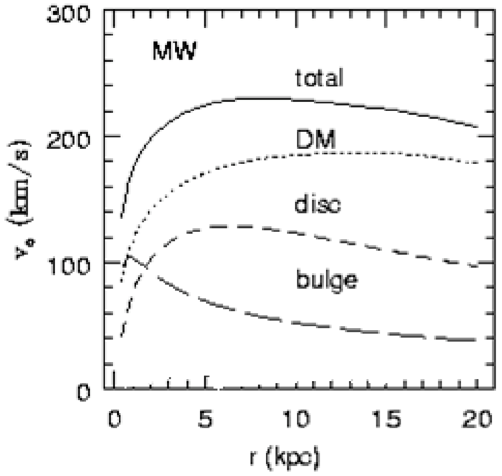
DISC MASS = 0.04 VIRIAL MASS (gas: 0%, 10%, or 50% of the disc mass)

BULGE MASS (STARS) = 0.008 VIRIAL MASS

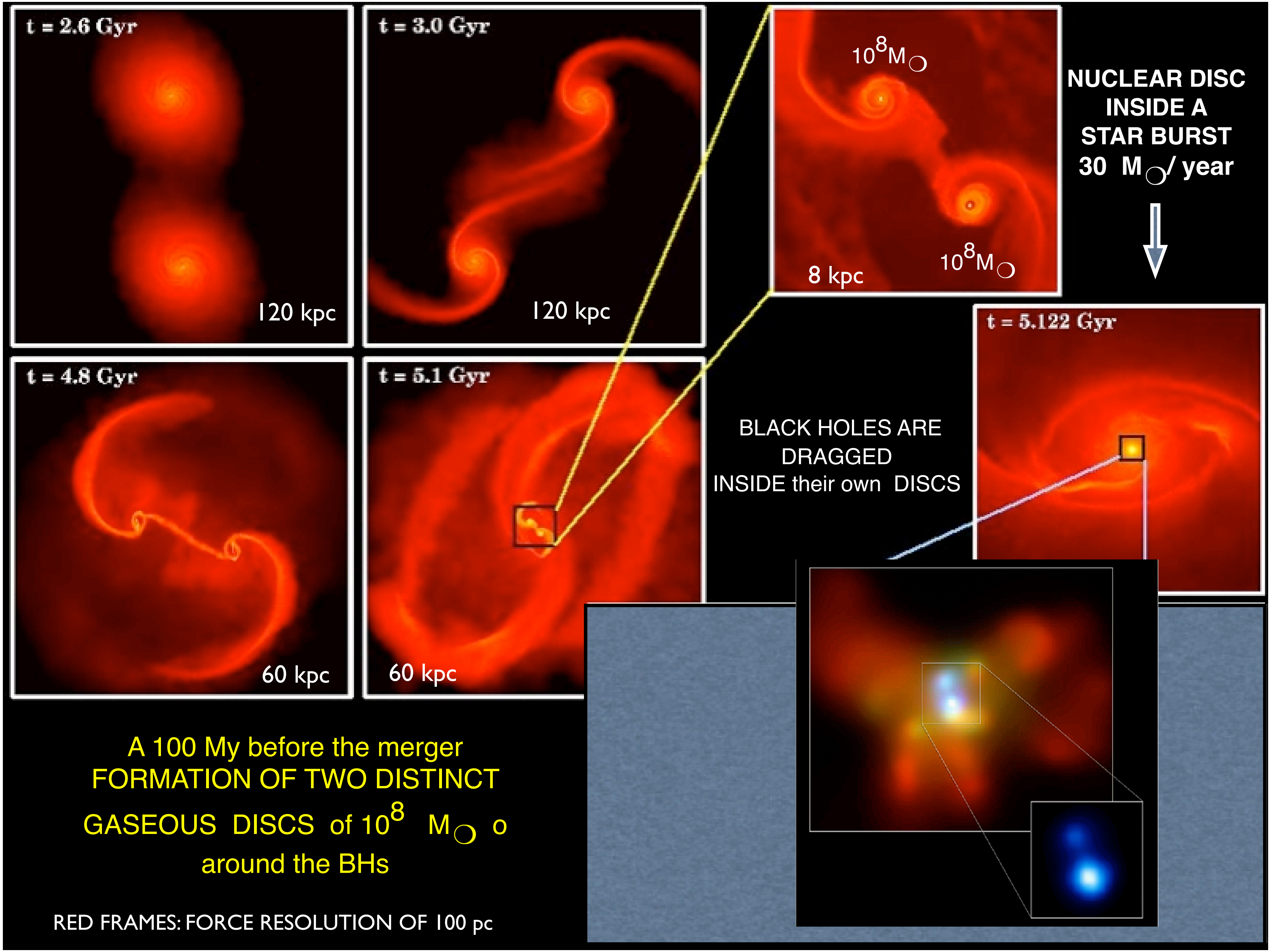
BLACK HOLE MASS = 3×10^{6} $M_\odot$

ENERGY EQUATION

SHOCKS & COMPRESSIONAL HEATING
H/ He ATOMIC COOLING
STAR FORMATION



1:1 COPLANAR PROGRADE PARABOLIC ENCOUNTER

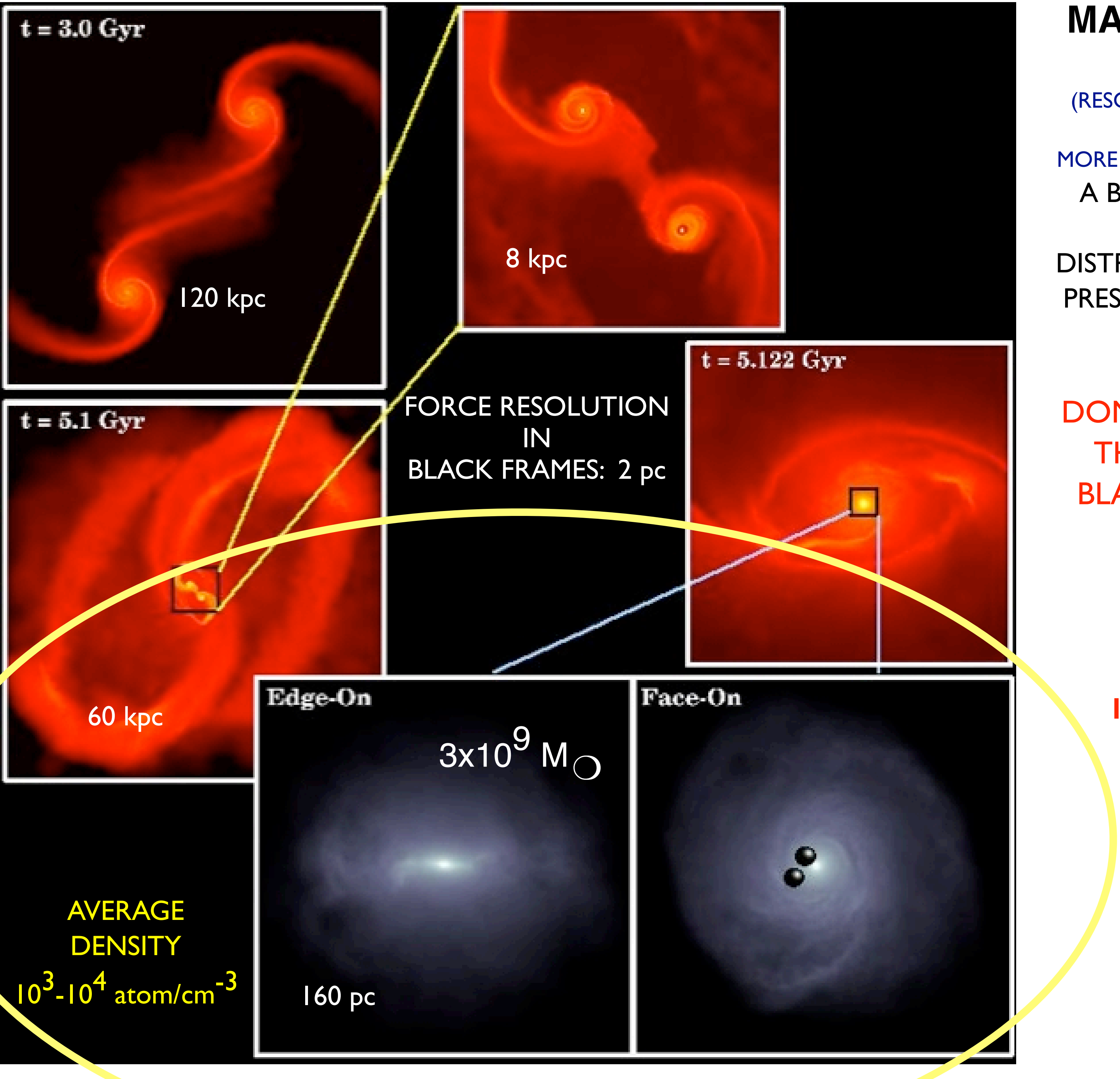


**NUCLEAR DISC
INSIDE A
STAR BURST
$30\ M_\odot$/ year**

BLACK HOLES ARE
DRAGGED
INSIDE their own DISCS

A 100 My before the merger
FORMATION OF TWO DISTINCT
GASEOUS DISCS of 10^8 $M_\odot$ o
around the BHs

RED FRAMES: FORCE RESOLUTION OF 100 pc



FORCE RESOLUTION
IN
BLACK FRAMES: 2 pc

$3\times10^{9}\ M_{\odot}$

AVERAGE
DENSITY
10^3-10^4 atom/cm^{-3}

MASSIVE NUCLEAR DISC

(RESOLVED WITH UNPRECEDENTED
ACCURACY
MORE MASSIVE THAN THE TWO DISCS)

A BACKGROUND OF DARK
MATTER & STARS
DISTRIBUTED IN A SPHEROID IS
PRESENT AROUND THE DISCK
BUT
THE GAS IS THE
DOMINANT COMPONENT
THAT CONTROLS THE
BLACK HOLE DYNAMICS

RADIAL INFLOWS

30-100 km s^{-1}

SHORT-LIVED
lasting 100,000 years

VELOCITY

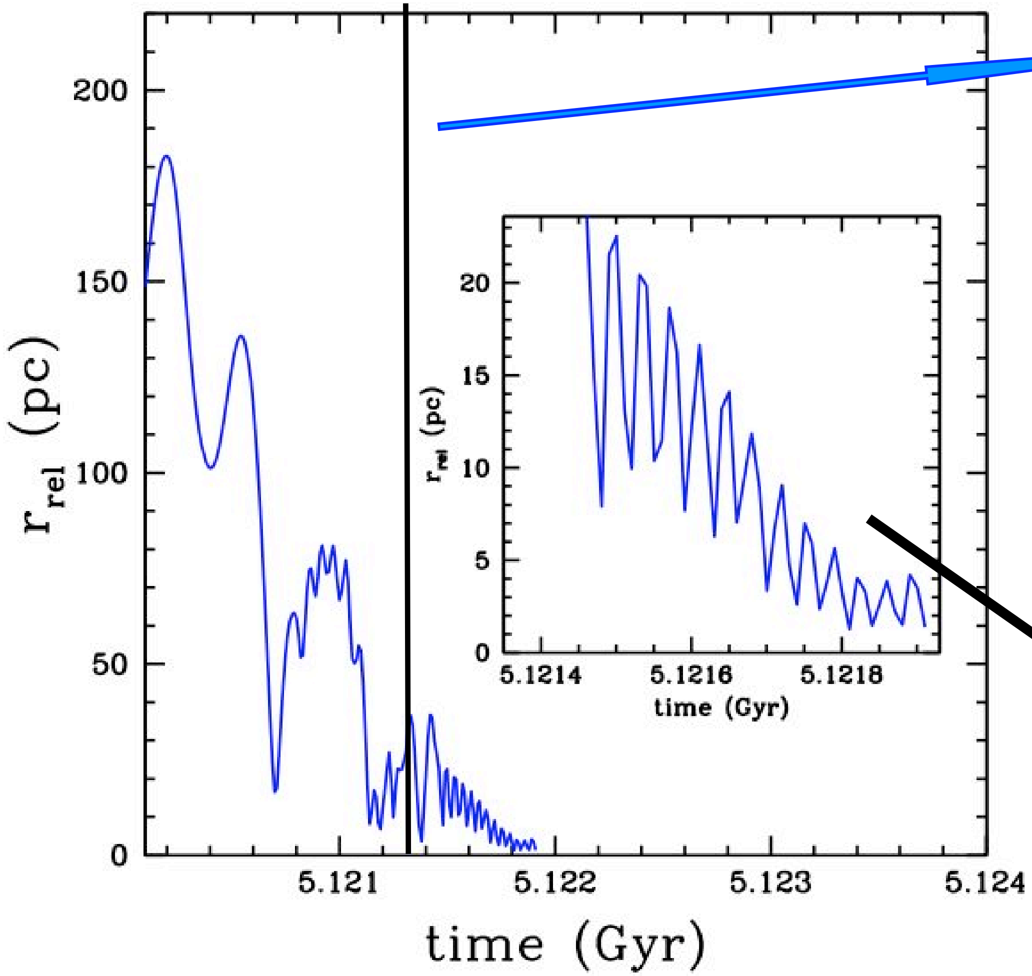
V_{rot} = 300 km s^{-1}

V_{turb} = 100 km s^{-1}

V_{s} = 45 km s^{-1}

ORBITAL SEPARATION OF THE TWO BLACK HOLES IN THE LATEST STAGE OF THE GALAXY MERGER

ORBITAL DECAY IS CONTROLED BY GRAVITATIONAL DRAG AGAINST THE GASEOUS DISC



UNTIL t=5.1215 Gyr THE BLACK HOLES ARE INSIDE THEIR OWN GASEOUS CORE

&

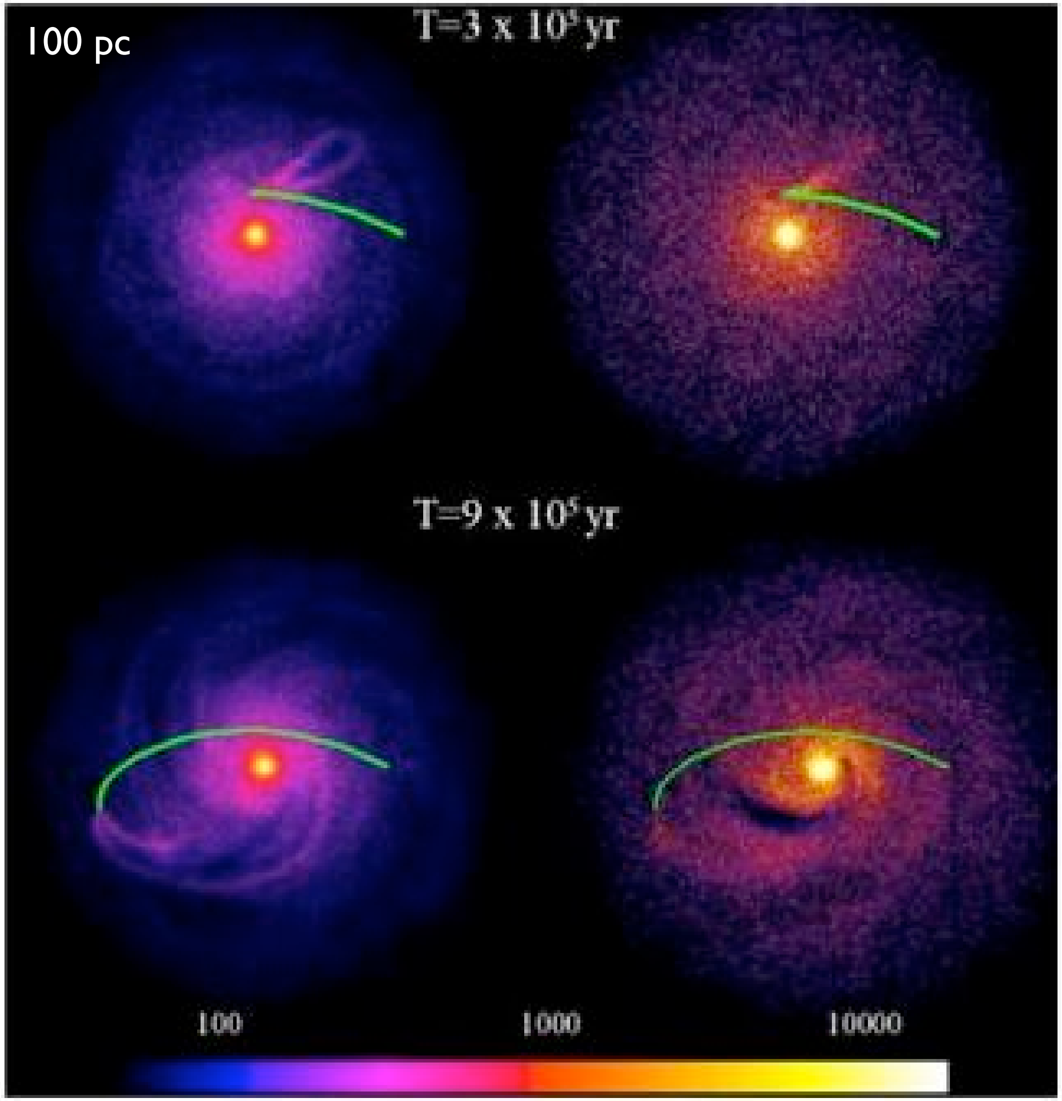
THE ORBIT IS THE RESULT OF THE RELATIVE MOTION OF THE CORES COMBINED WITH THE RELATIVE MOTION OF EACH BLACK HOLE RELATIVE TO CORE, EXPLAINING THE PRESENCE OF MORE ORBITAL FREQUENCIES

AN ECCENTRIC BINARY FORMS

($P_{orb}=10^5$ years)

CONTROLING AGAIN THE PAIRING ... AND THE CIRCULARIZATION

FACE ON z-AVERAGED DENSITY MAP



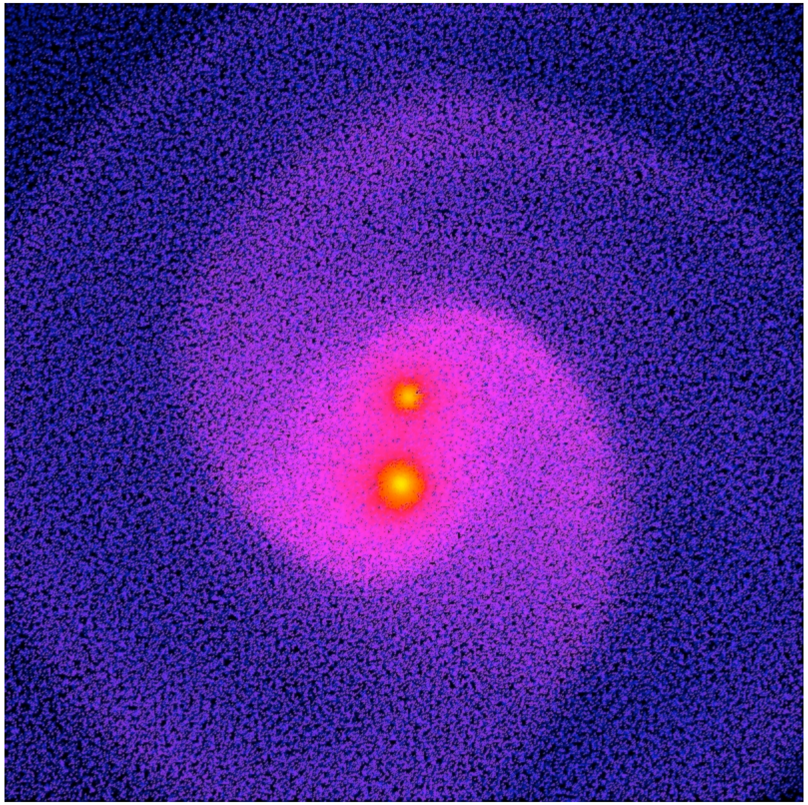
GAS STARS (f*=66%)

PERICENTER: WAKE
DEVELOPS BEHIND
THE BLACK HOLE
IN THE COOLER, SLOWLIER
ROTATING SIDE

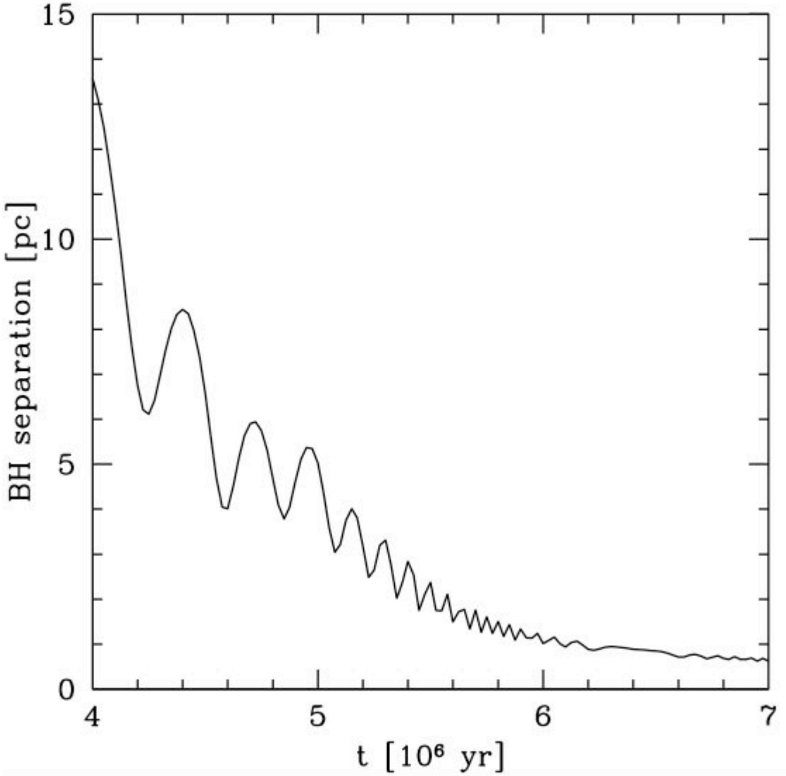
APOCENTER: WAKE
SHIFTS IN FRONT
OF THE BLACK HOLE
ACCELERATED TANGENTIALLY

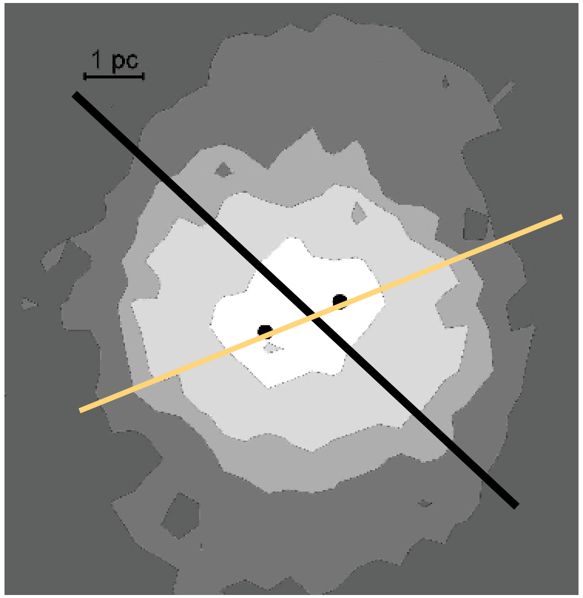
COROTATING ECCENTRIC
ORBITS BECOME CIRCULAR

AGN ACTIVITY
MAY DEPEND ON
THE ORBITAL ECCENTRICITY



(I)
DYNAMICAL FRICTION AGAINST GAS
BRINGS THE BINARY DOWN 0.1 pc



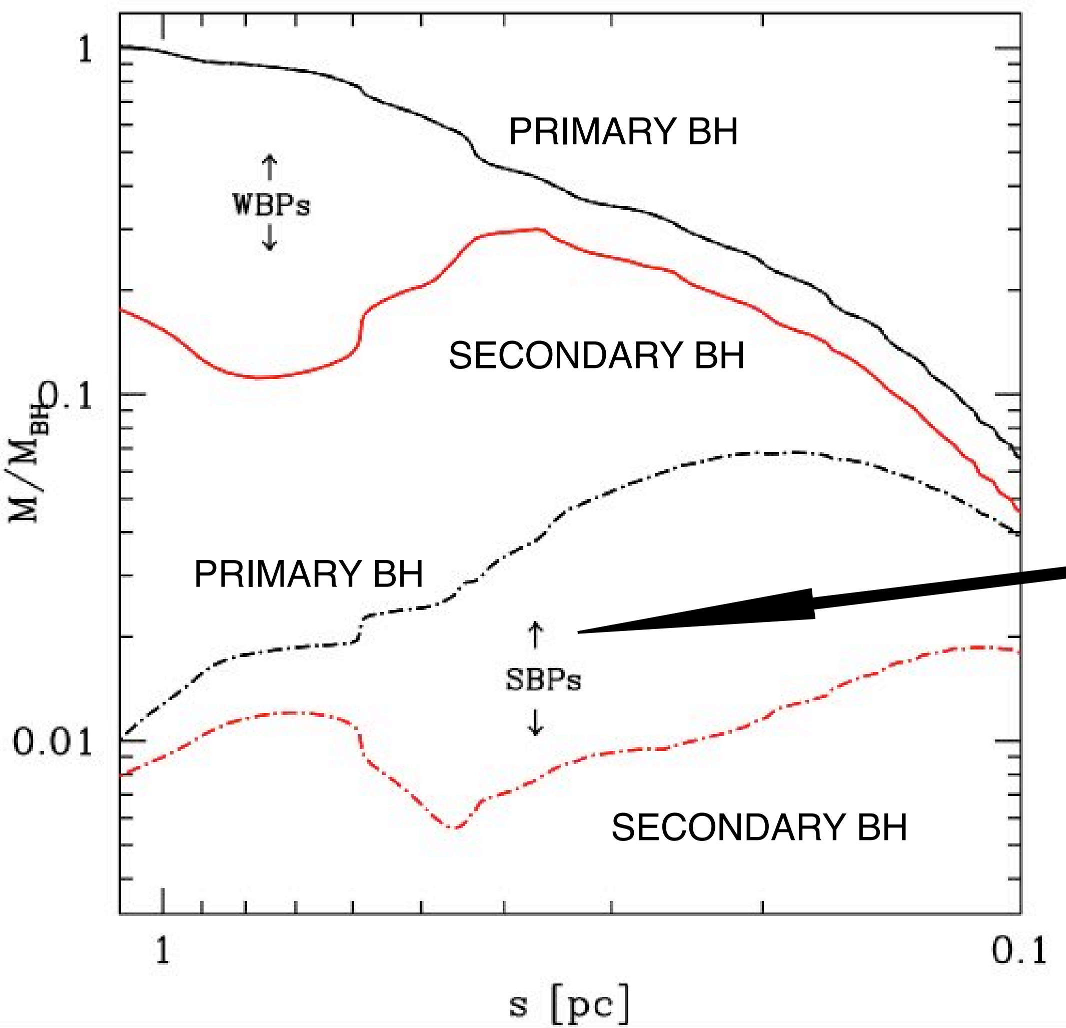


(II)
ASYMMETRIC FLOW PATTERN IN
THE FORM OF AN
ELLIPSOIDAL DEFORMATION IN A
COOLER ENVIRONMENT (q_{BH}=1)

PROMOTES DECAY
see also Escala et al. 2005

SOLVING FOR THE GRAVITATIONAL SPHERE OF INFLUENCE OF EACH BLACK HOLE

y-axis
BOUND MASS
AROUND EACH
BLACK HOLE



x-axis BLACK HOLE BINARY SEPARATION

MASS
OF STRONGLY
BOUND
GAS PARTICLES

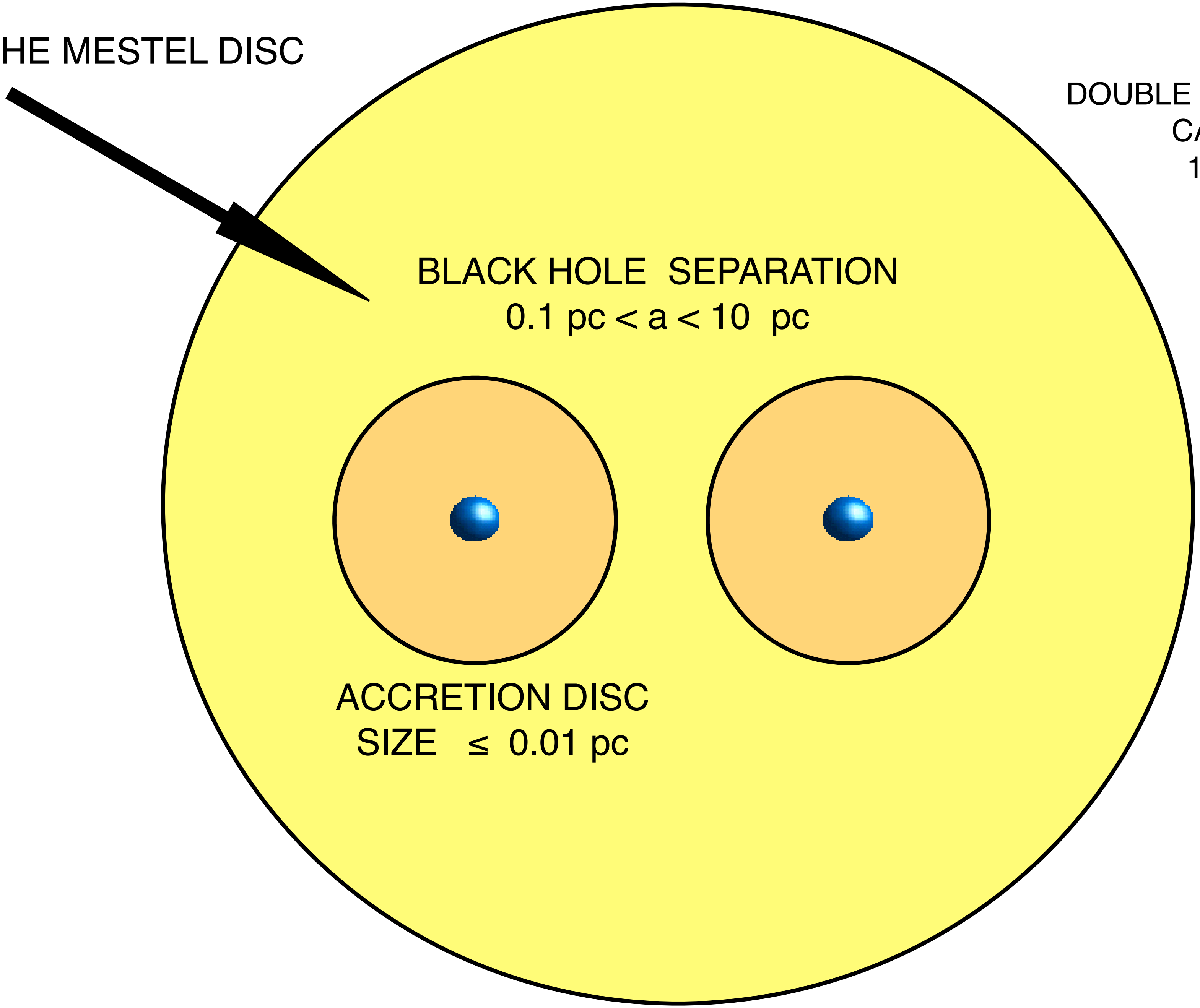
10^7 atoms cm $^{-3}$

THEY HAVE NET
ANGULAR MOMENTUM
⬇
FORMATION OF COOL
SMALL
ACCRETION DISC

$$t_{acc} \sim \epsilon/(1-\epsilon)\, \tau_s \ln \sim (1+ M_{accSB}/M_{BH,0})$$

OF THE MESTEL DISC

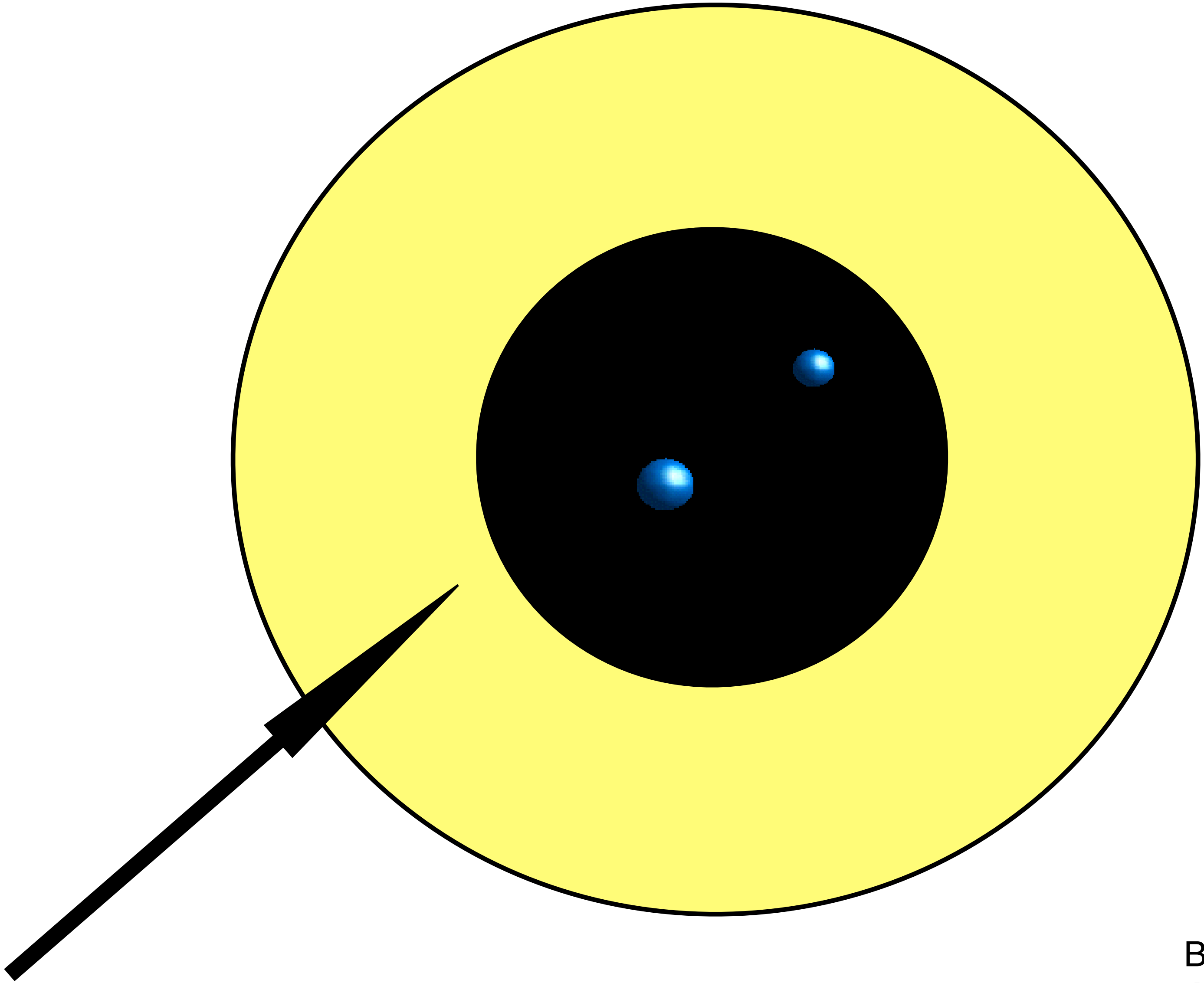
DOUBLE AGN ACTIVITY
CAN LAST
1-10 Myrs



BLACK HOLE SEPARATION
0.1 pc < a < 10 pc

ACCRETION DISC
SIZE ≤ 0.01 pc

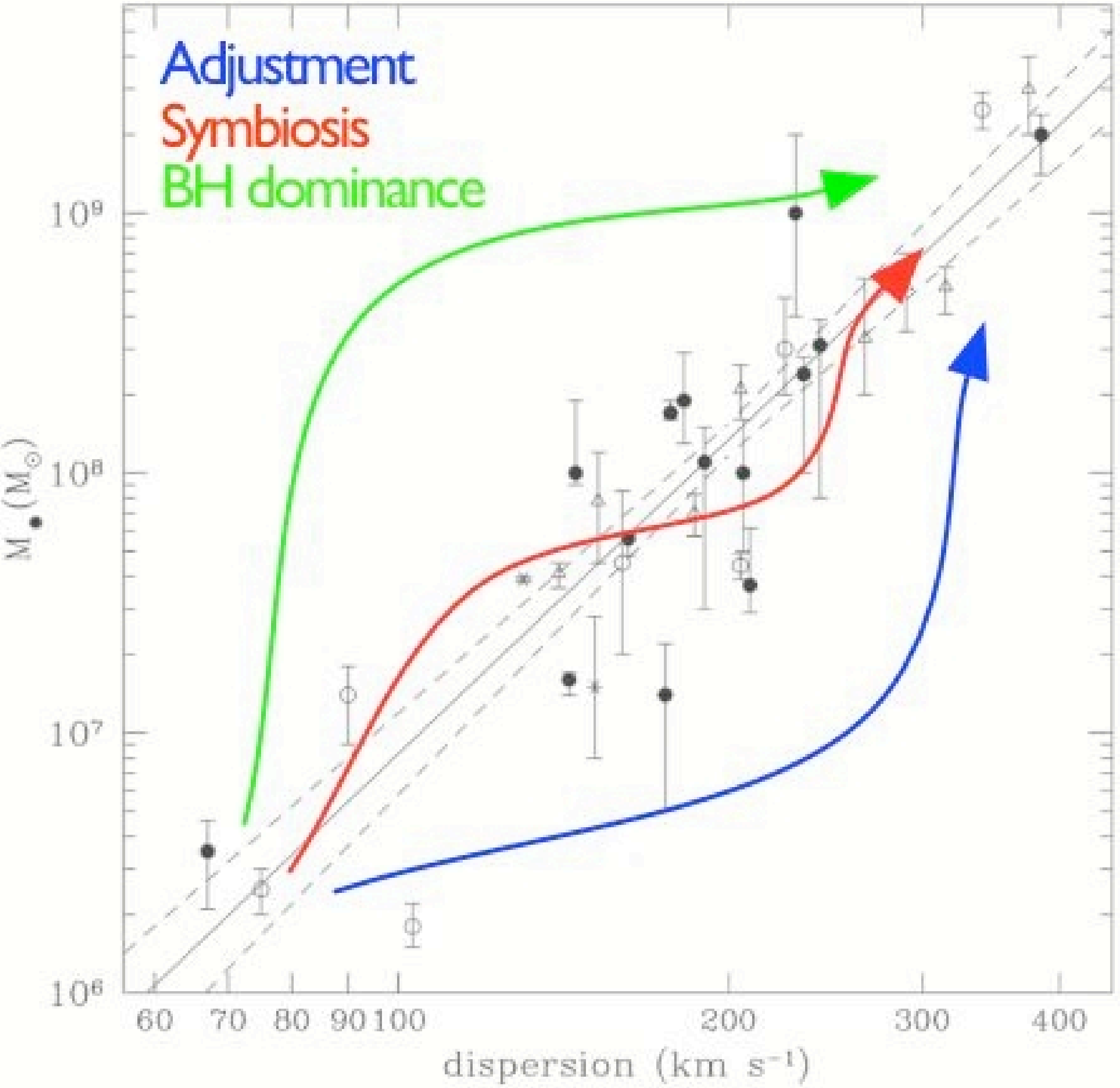
DISC DRIVEN BLACK HOLE TYPE II MIGRATION ON THE VISCOUS TIME



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

OUTER CIRCUMBINARY α−DISC

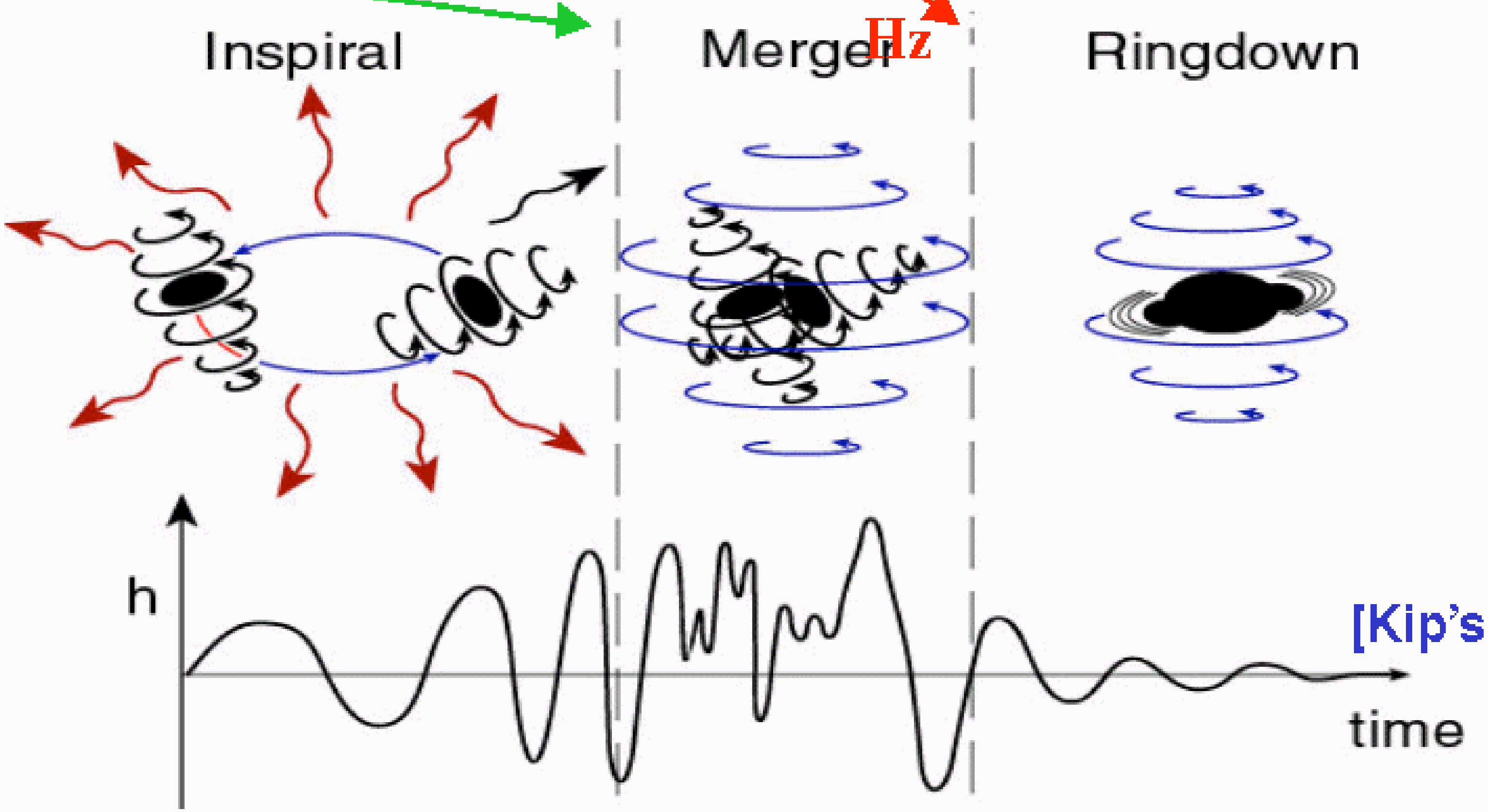
BLACK HOLE
MASS RATIO
$q_{BH} < 1$


Adjustment
Symbiosis
BH dominance
$M_\bullet (M_\odot)$
10^6
10^7
10^8
10^9
60
70
80
90
100
200
300
400
dispersion (km s^{-1})

Coalescence of binary systems

$f = 4\,[\,M\,(1+z)\,/10^3\,M_{\bullet}\,]^{-1}$ Hz

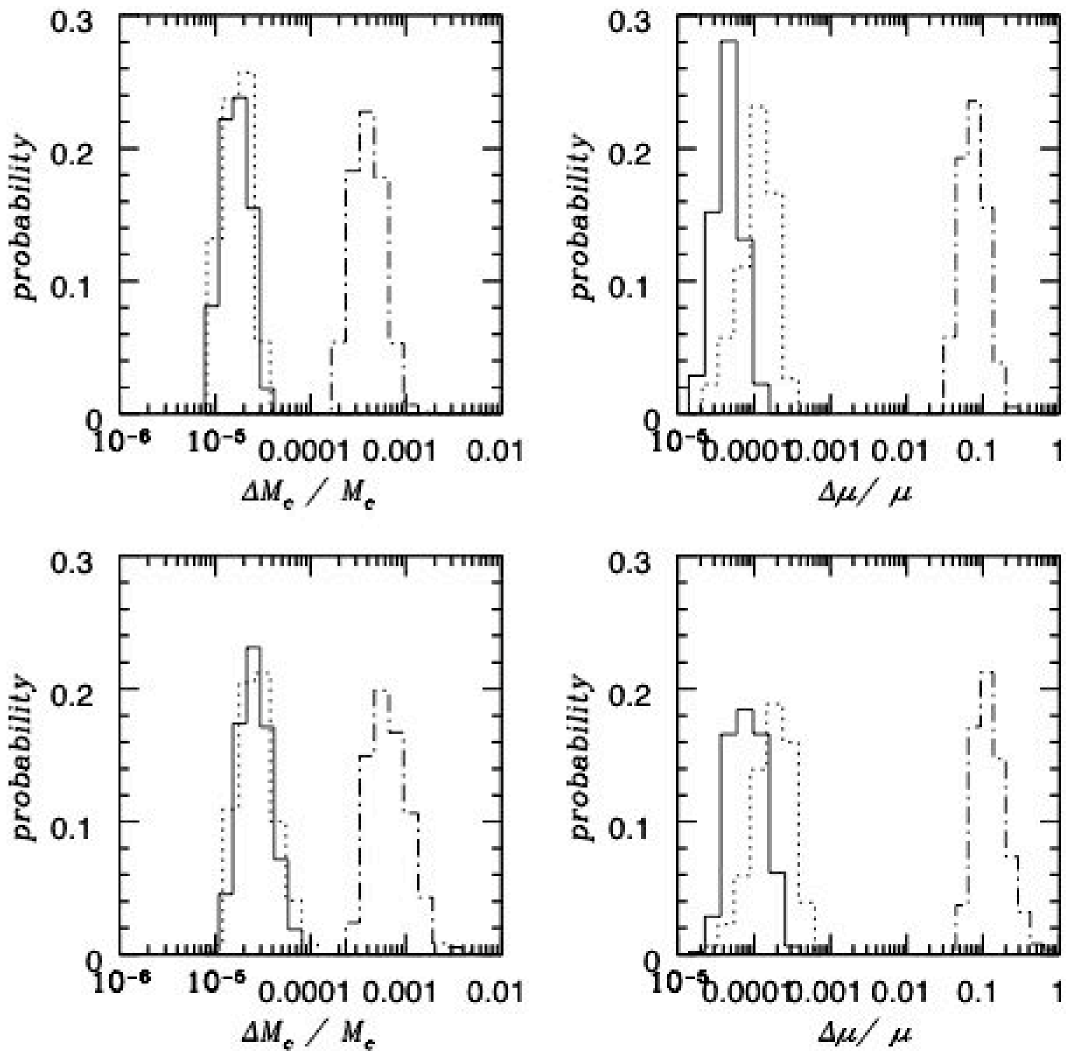
$f = 32\,[\,M\,(1+z)\,/10^3\,M_{\bullet}\,]^{-1}$ Hz



[Kip's cartoon]

Long lived

Short lived



PROBABILITY
DISTRIBUTION
OF THE ERRORS
IN THE CHIRP MASS
AND REDUCED MASS
DETERMINATION

dashed line zero SPIN

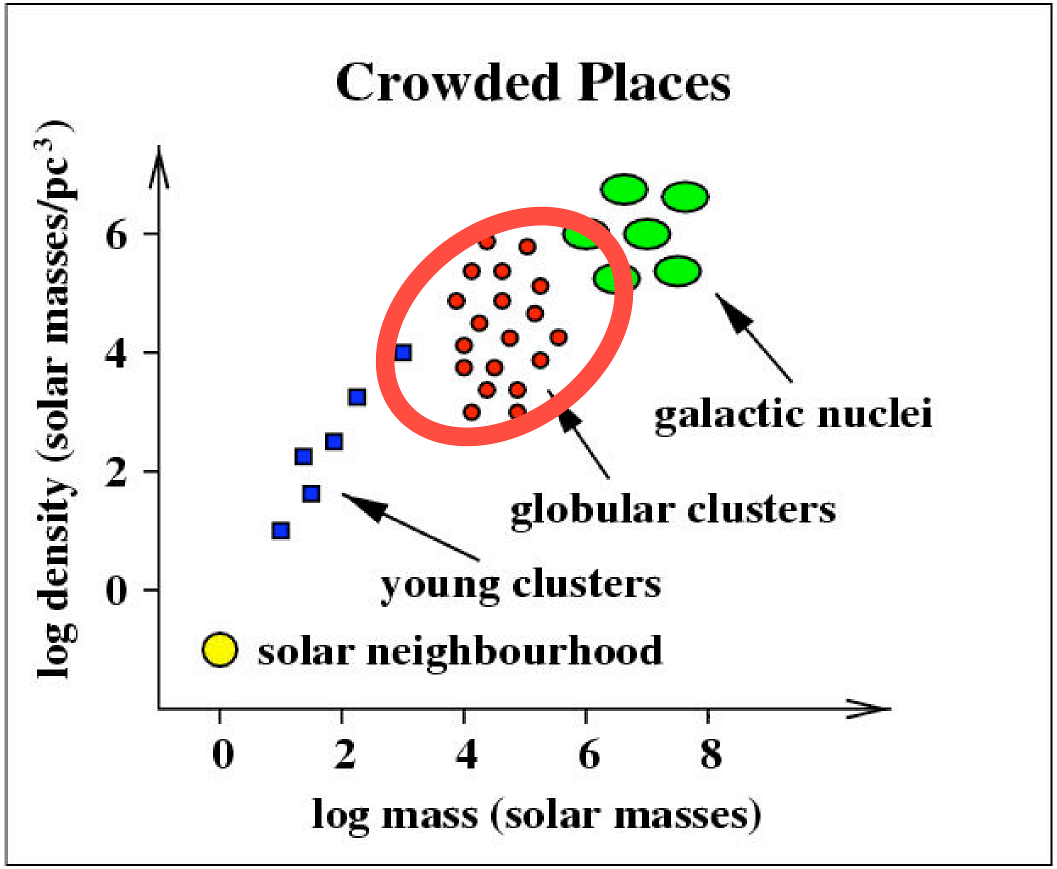
PRECESSING
BINARIES
SHOW A MUCH
GREATER RICHNESS
OF FEATURES THAN
NON SPINNING
BINARIES

Vecchio 2004

SEARCH
OF
INTERMEDIATE MASS BLACK HOLES
IN THE LOCAL LUNIVERSE

IMBHs
100 - 10,000 solar masses

IN LOW VELOCITY DISPERSION SPHEROIDS ?



RELAXATION TIMES
& DYNAMICAL
FRICTION TIMES
ARE
SHORTER
THAN COSMIC TIME

$$\tau_{rel} \propto \sigma^3/n$$

$$\tau_{dyn} \propto \tau_{rel}/m$$

GLOBULAR CLUSTER

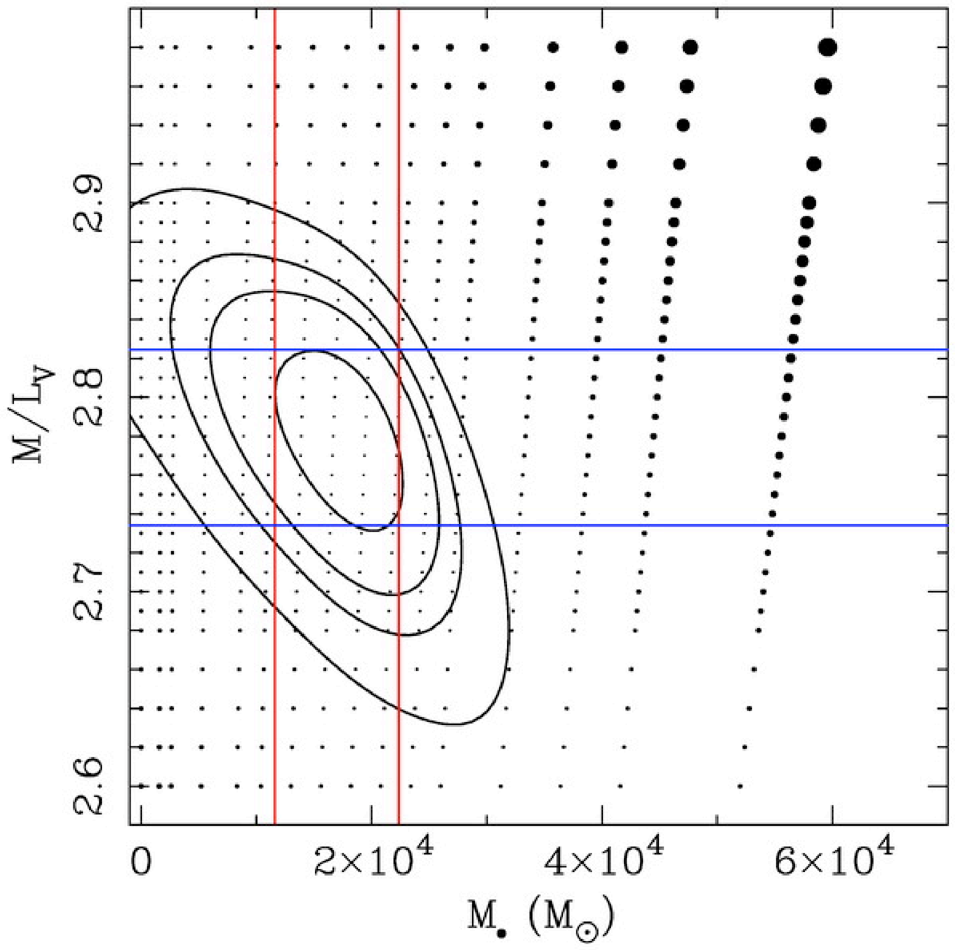
G1:

the interpretation of the surface brightness profile (HST) and of the velocity profile (Keck spectra) suggests the presence of a

$1.8\ (\pm 0.5)\ \mathrm{x}\ 10^4\ M_{\odot}$

IMBH

on the basis of axisymmetric models



SPHERE OF INFLUENCE

GM/σ^2 IS ONLY 0.035”

stellar light 0.1” (HST)

Gebhardt, Rich, Ho 2005

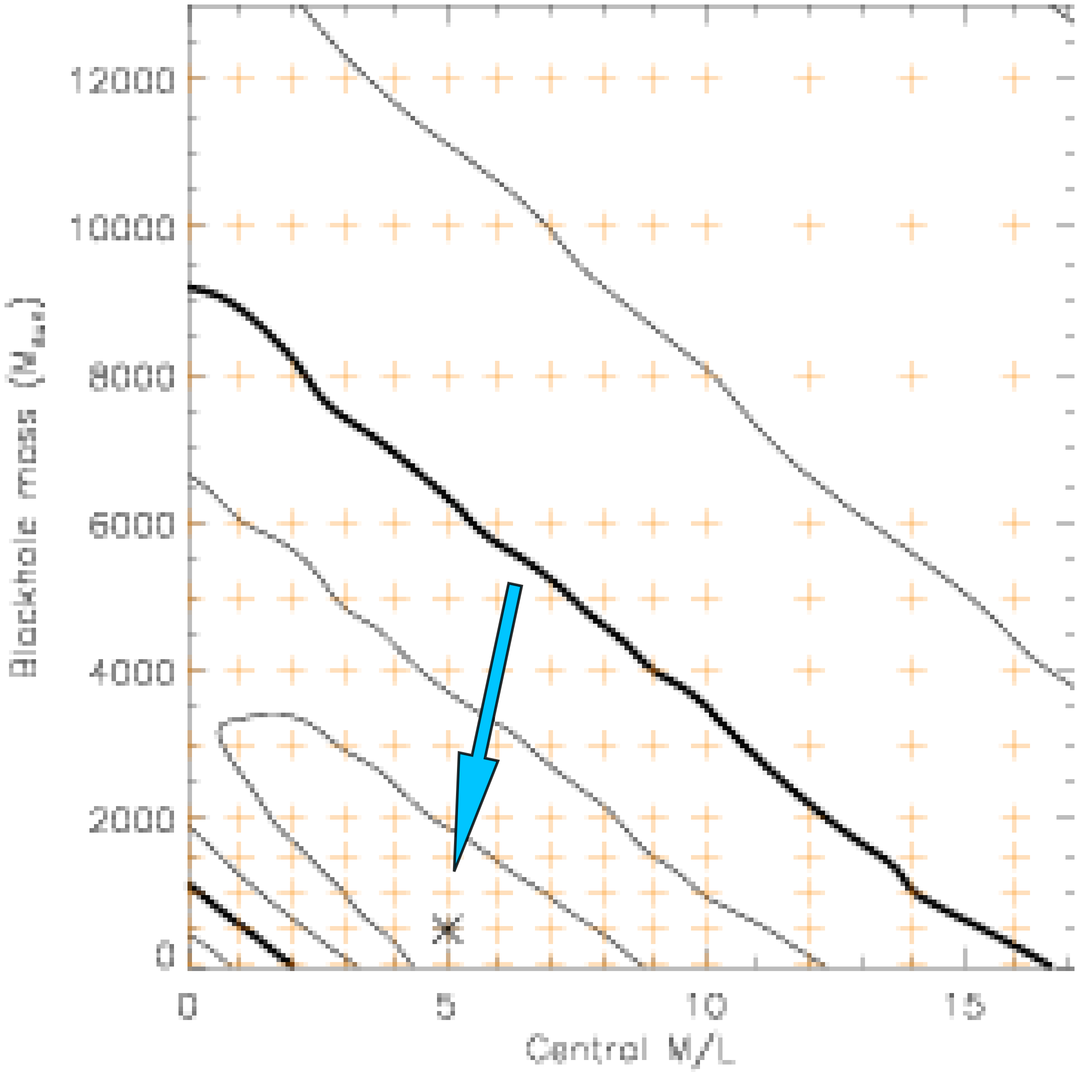
M15:

Orbit-based axisymmetric dynamical models
fit ground and HST
line of sight velocities and
proper motions

(a) to constrain the M/L ratio as a function of radius
(b) to infer a limit on the mass of 3400 M○
in the central 0.05 pc
--> a density of
$7\times10^6 M_\odot/\mathrm{pc}^3$.

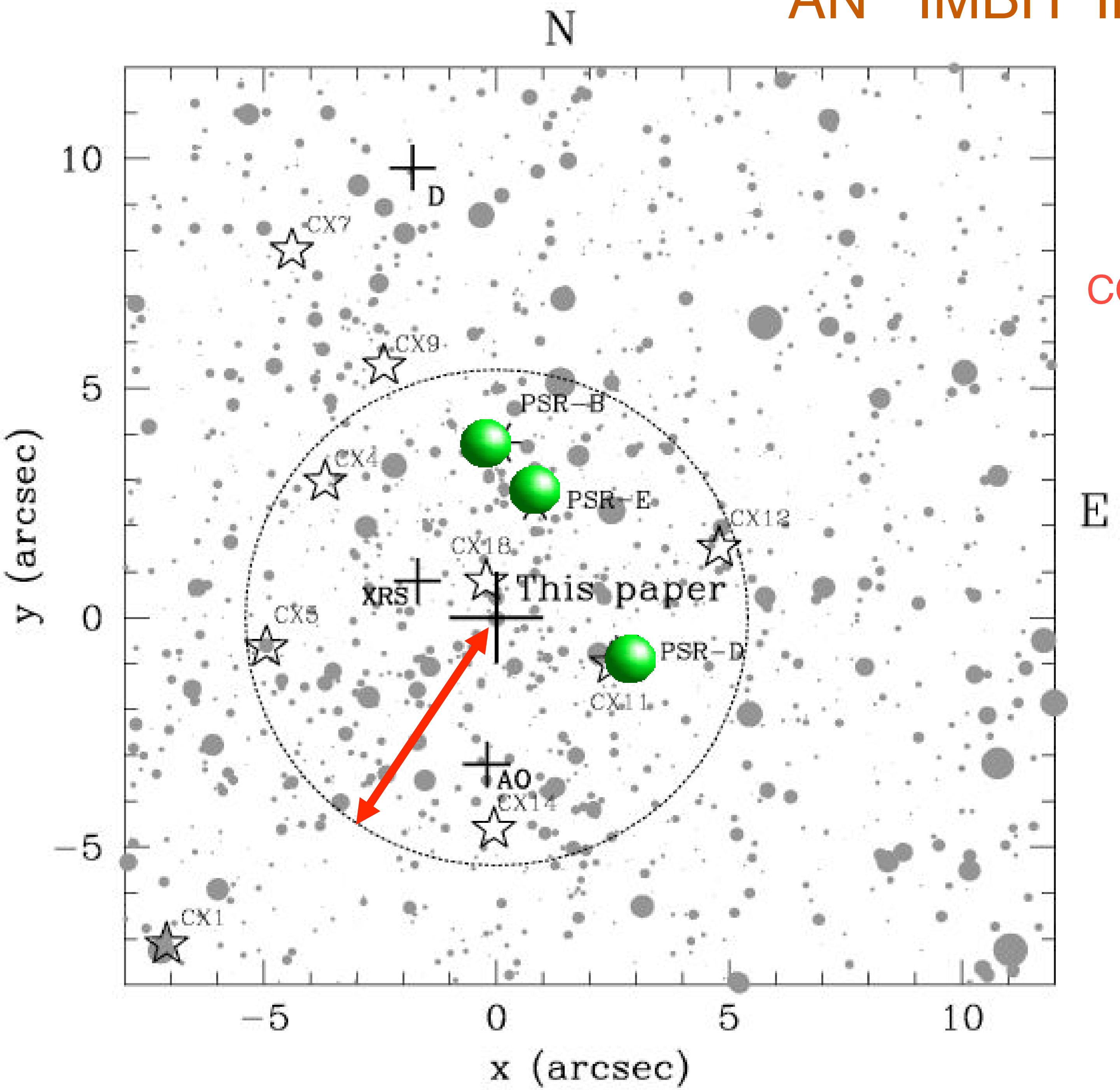
The central 4” appears to rotate.

Van den Bosch et al. 2005



The inner three marginalized χ^2 contours are drawn at formal 68.3%, 95.4%, and 99.7%

AN IMBH IN NGC 6752 ?



3 PULSARS

CORE RADIUS 0.11 pc

PULSAR PROJECTED
DISTANCE FROM
THE CENTER
0.08 pc
WITH LARGE
AND NEGATIVE
PERIOD DERIVATIVES
IMPLYING MORE
THAN
2000 M$_\odot$
of UNDERLUMINOUS
MATTER

Ferraro et al. 2003
D'Amico et al. 2002
Colpi et al. 2003

SCENARIOS FOR THE FORMATION OF IMBH

(I) MASS SEGREGATION OF COMPACT REMNANTS IN GLOBULAR CLUSTERS

(II) RUNAWAY COLLISIONS OF MASSIVE STARS IN YOUNG DENSE STAR CLUSTERS

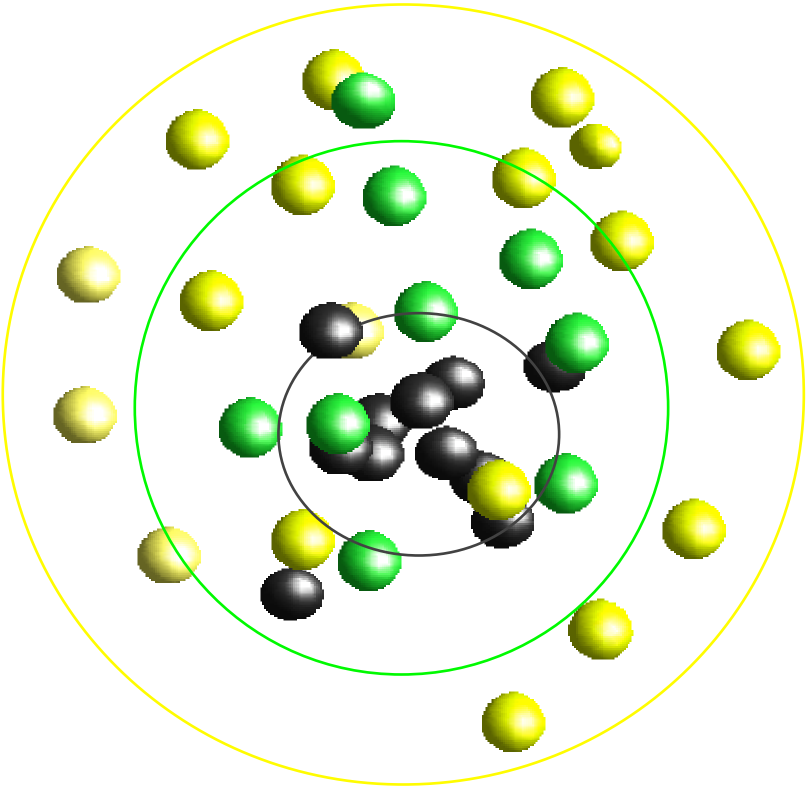
Sigurdsson & Hernquist 1993
Kulkarni et al. 1993
Miller et al. 2004
Portegies Zwart et al. 2004
Colpi et al., 2002, 2004,2005

(I) MASS SEGREGATION OF COMPACT REMNANTS IN GLOBULAR CLUSTERS

DYNAMICAL FRICTION LEADS TO
MASS SEGREGATION
BH CONFINEMENT IN THE CORE

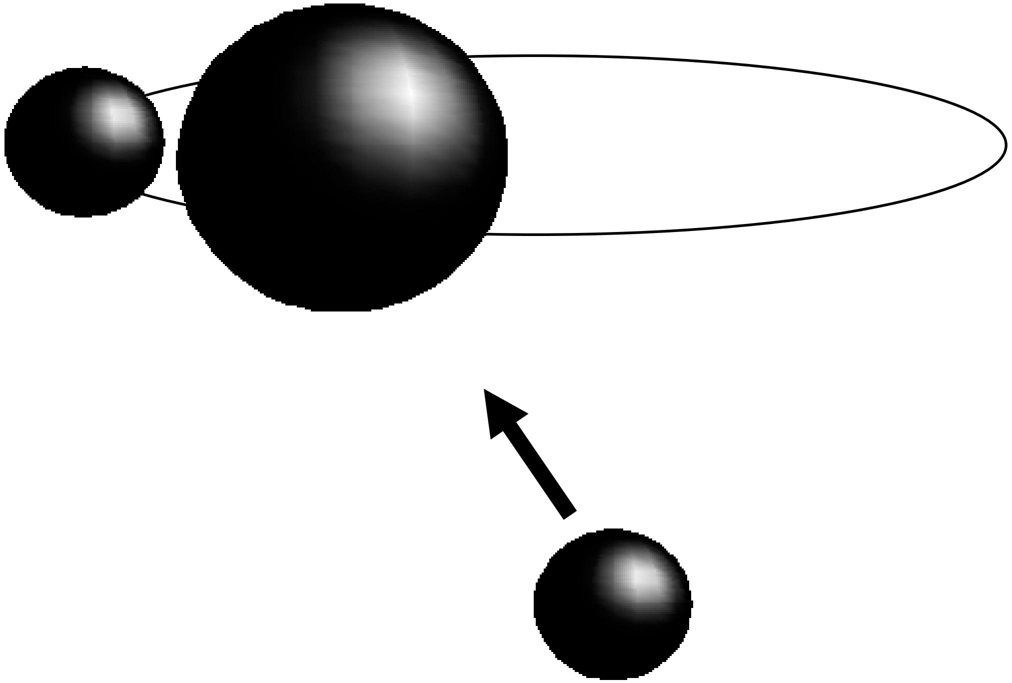
3-BODY EXCHANGES
INVOLVING STARS & BLACK HOLES
BUILD UP OF A POPULATION OF
BLACK HOLES IN BINARIES
EVOLVING ALMOST IN ISOLATION

SPITZER INSTABILITY



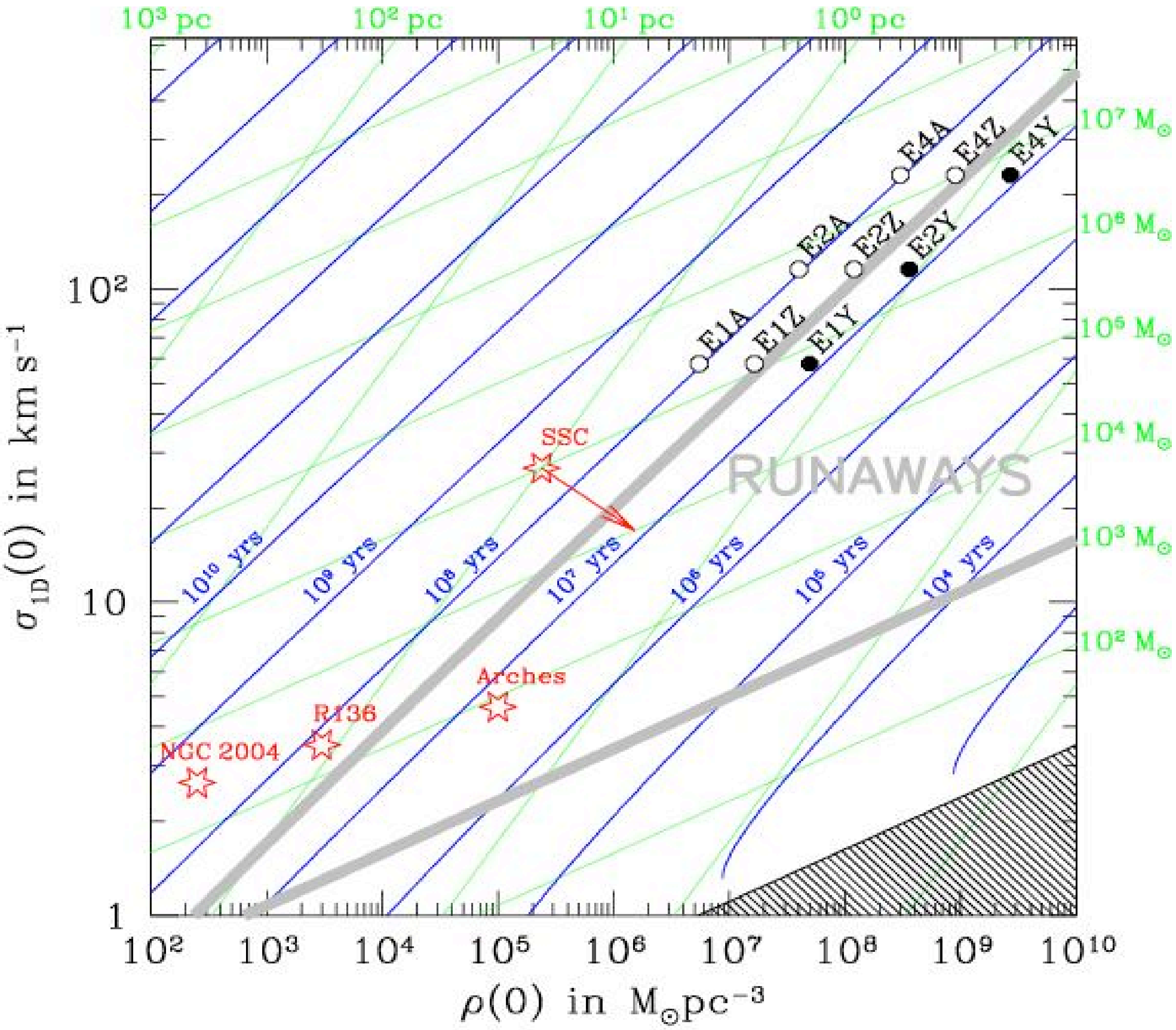
Kulkarni, Hut, & McMillan 1993
Sigurdsson & Phinney 1993

SOME BINARY BLACK HOLE EXPERIENCES COALESCENCE BY EMISSION OF GRAVITATIONAL WAVES before EXPERIENCING A LARGE RECOIL FOR FINAL ESCAPE



HIERARCHICAL BLACK HOLE MASS GROWTH THROUGH A CHAIN OF EXCHANGES AND MERGERS

IMBH ?
SINGLE ?
BINARY ?



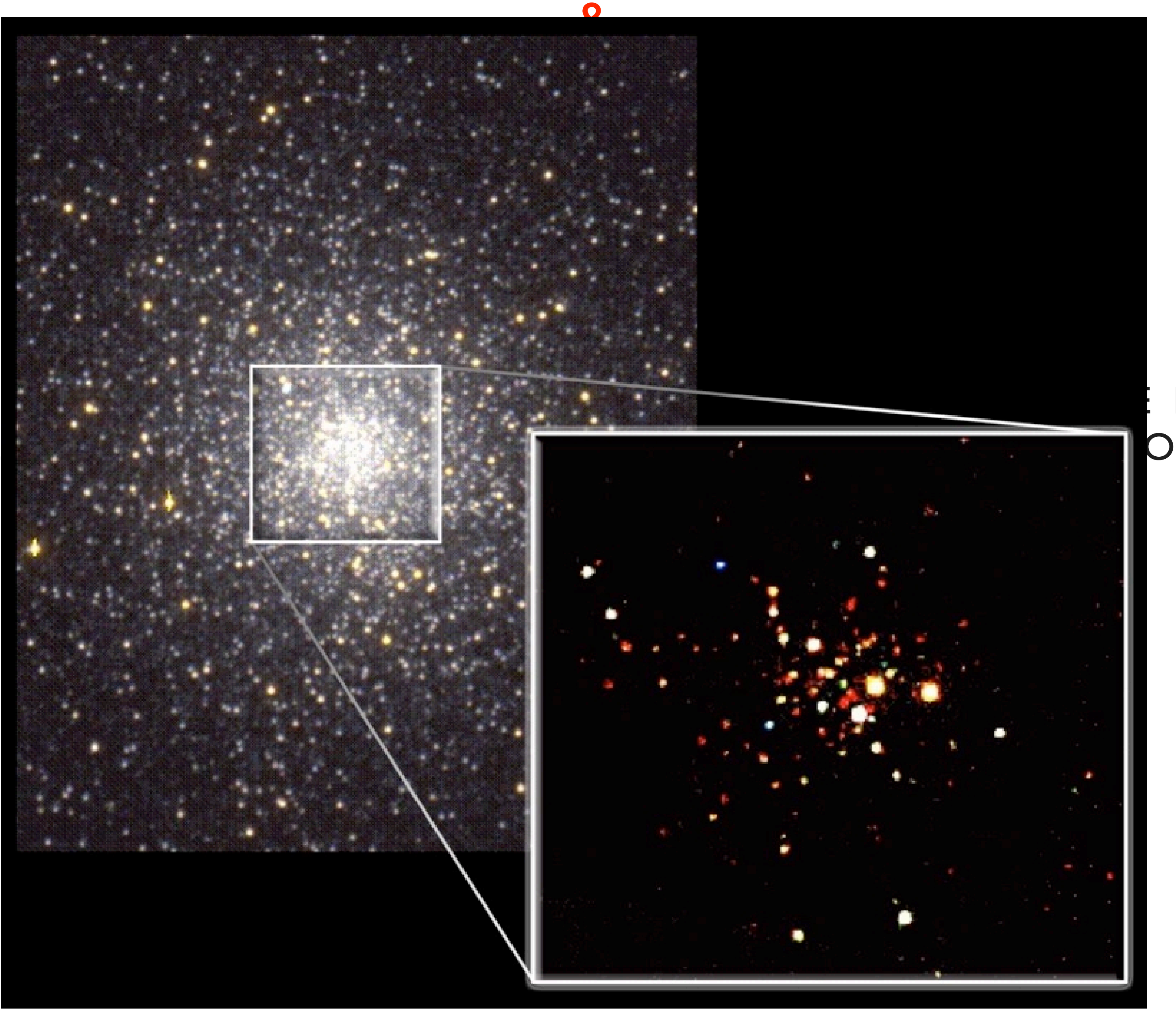
RELAXATION TIMES
& DYNAMICAL
FRICTION TIMES
SHORTER
THAN 1 Myears

$\tau_{rel} \propto \sigma^3/n$

$\tau_{dyn} \propto \tau_{rel}/m$

SPECIAL CONDITIONS TO GROW AN IMBH IN A YOUNG STAR CLUSTER !

STELLAR MASS BLACK HOLE CANDIDATES



FIELD

° ACCRE

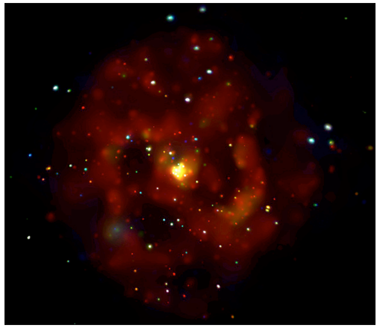
OBULAR

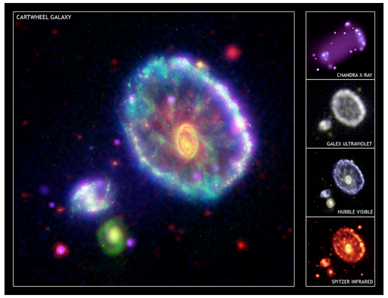
STELLAR MASS BLACK HOLE CANDIDATES
&
XRBs
IN EXTERNAL GALAXIES

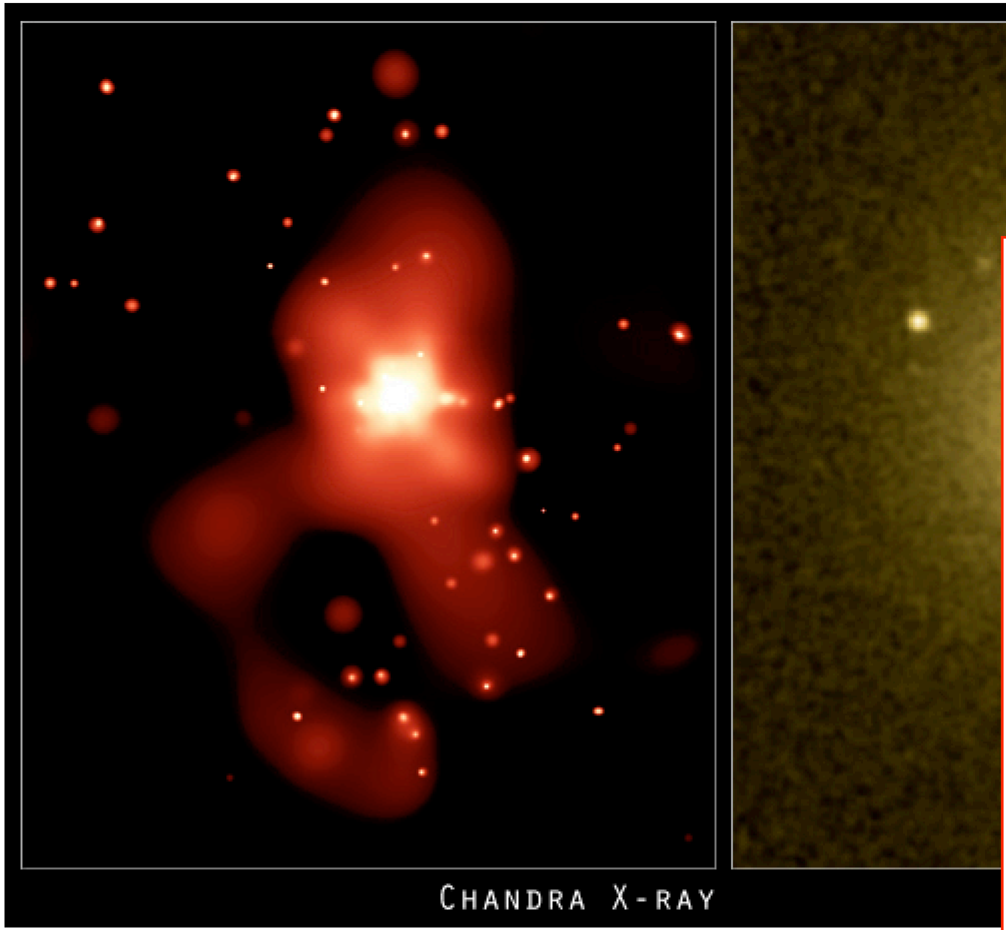
XRBs HAVE BEEN DISCOVERED WITH EINSTEIN BUT MAJOR ADVANCES
OCCURRED MAINLY WITH THE ADVENT OF
CHANDRA & XMM NEWTON

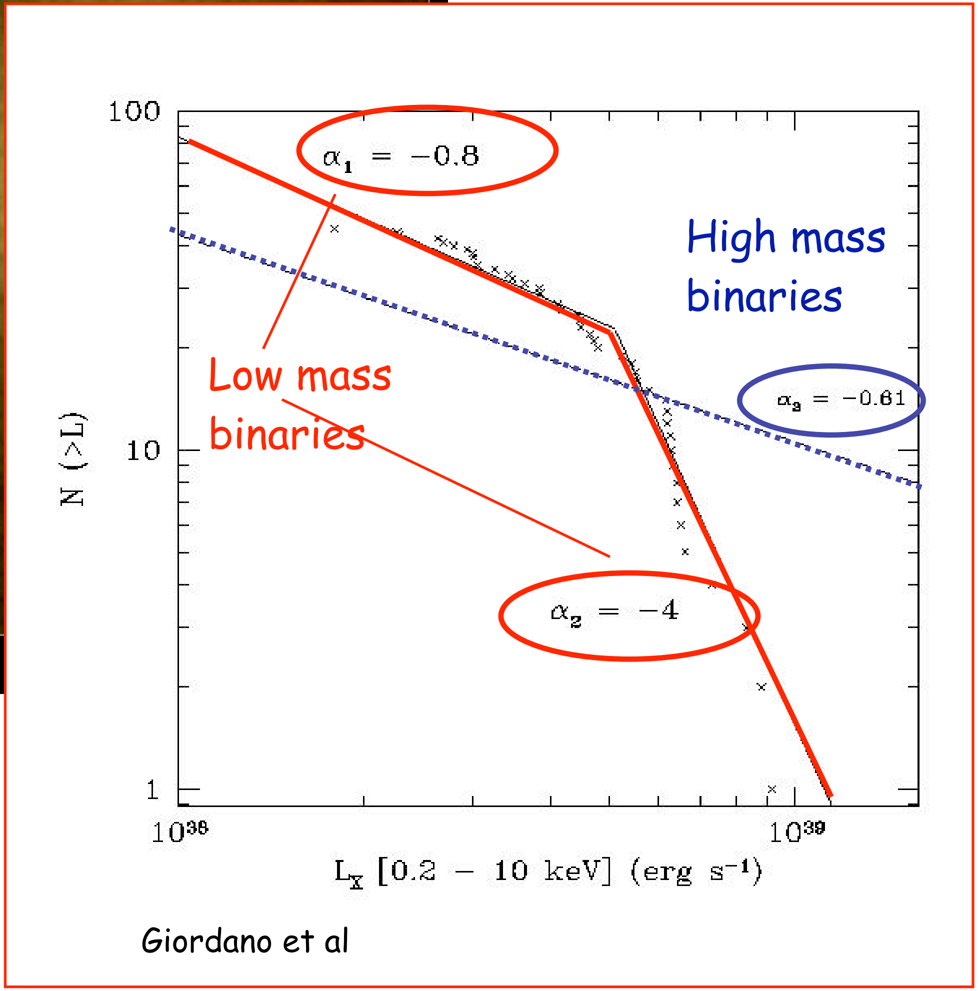
ONLY THE VERY BRIGHT XRBs ARE DETECTED

+"EASY TO SEE" SPATIAL DISTRIBUTION
LARGE SAMPLE
- DIFFICULT TO STUDY INDIVIDUALLY









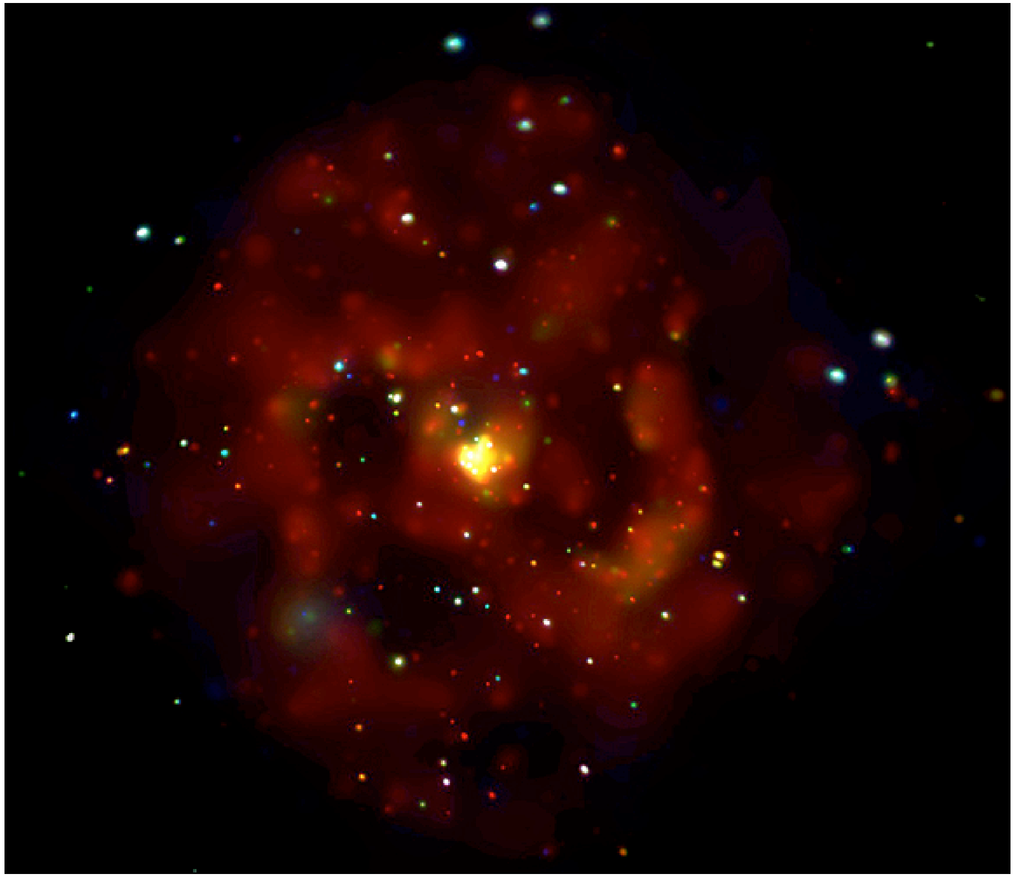
High mass binaries

Low mass binaries

Giordano et al

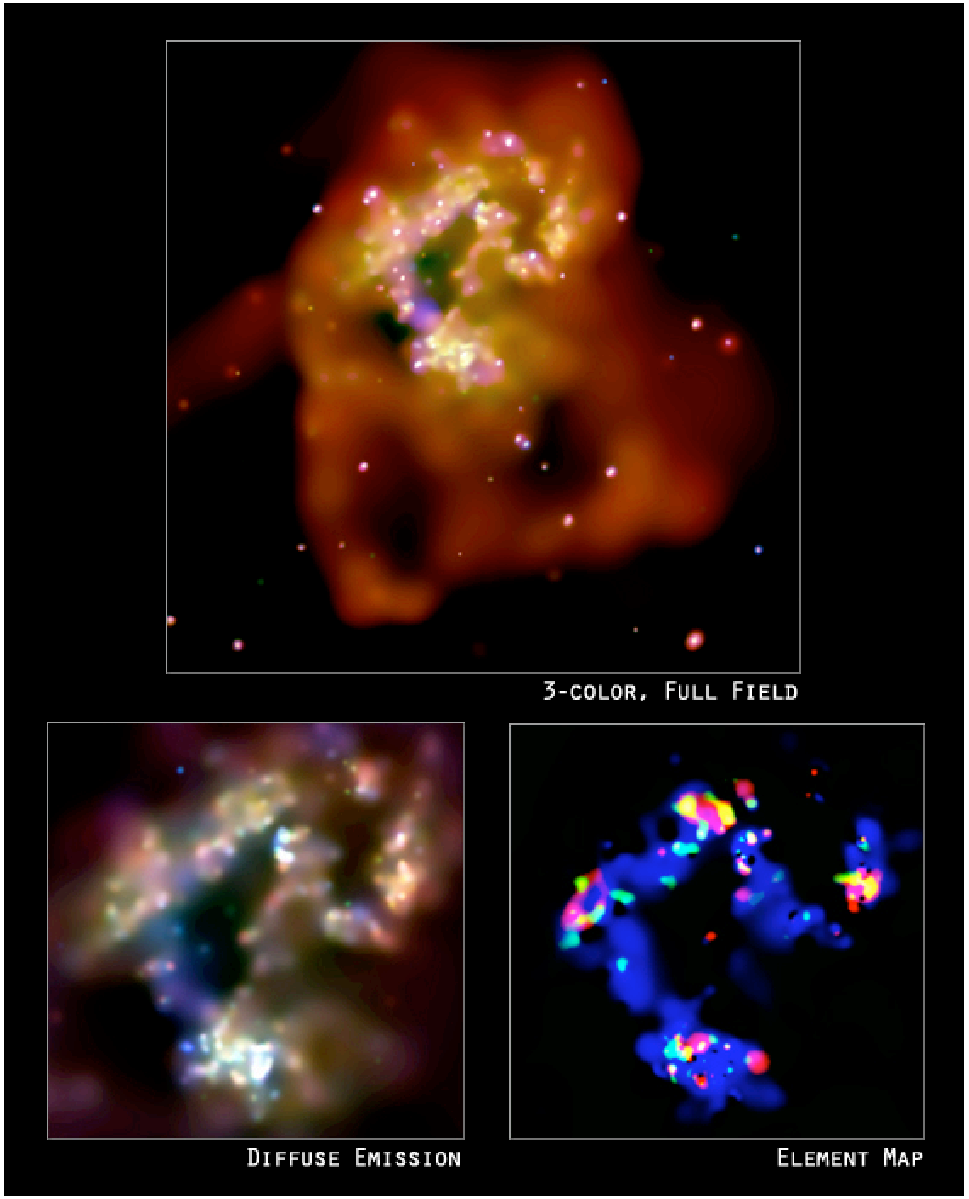
ELLIPTICAL GALAXY
NGC 4261
1/2 ASSOCIATED TO GLOBULAR CLUSTERS

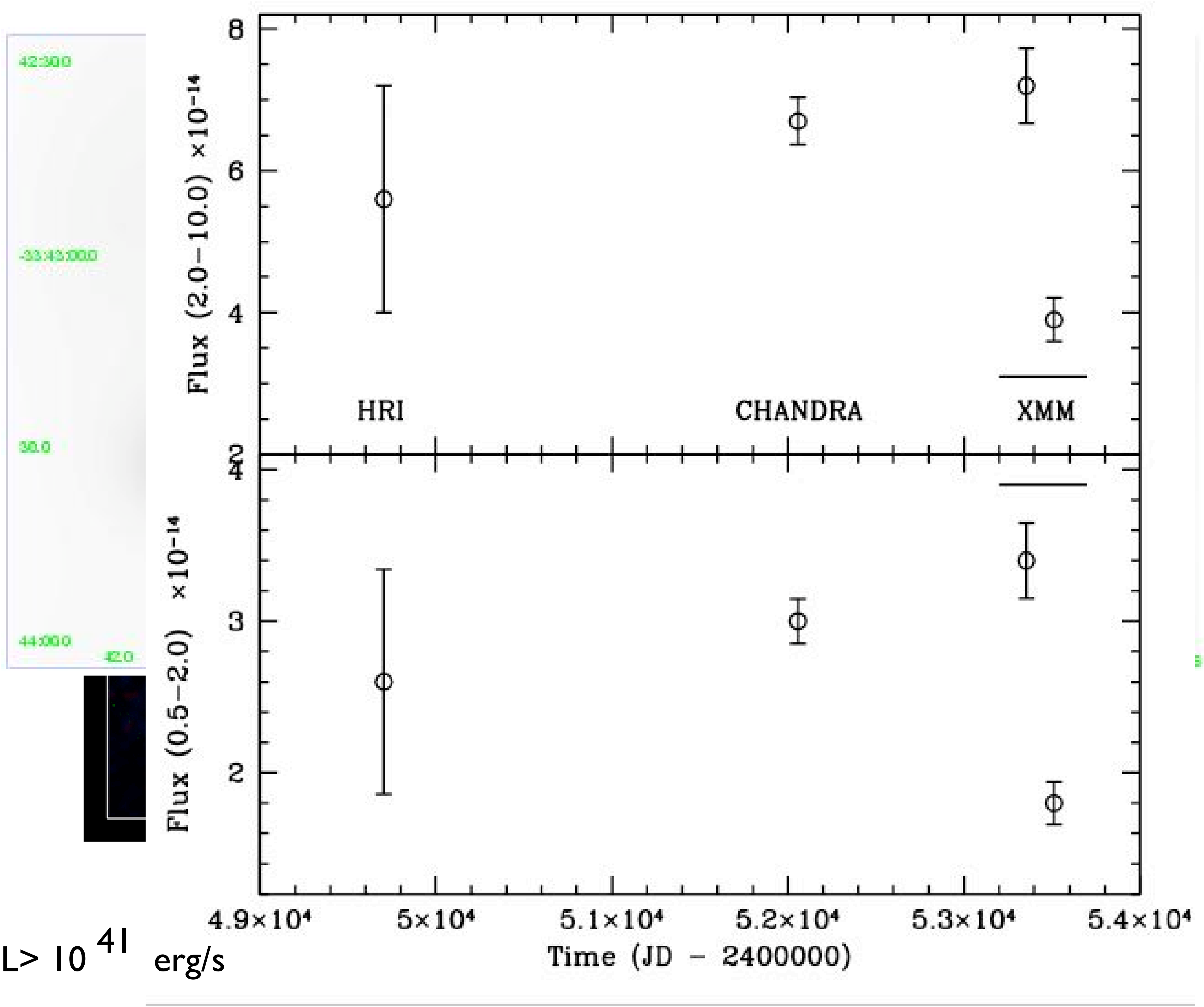
- DISCOVERY OF A BLACK HOLE (IMBH?) IN A GLOBULAR CLUSTER OF NGC 4472 (Maccarone et al. 2007)



SPIRAL M83

INTERACTING GALAXIES
THE ANTENNAE

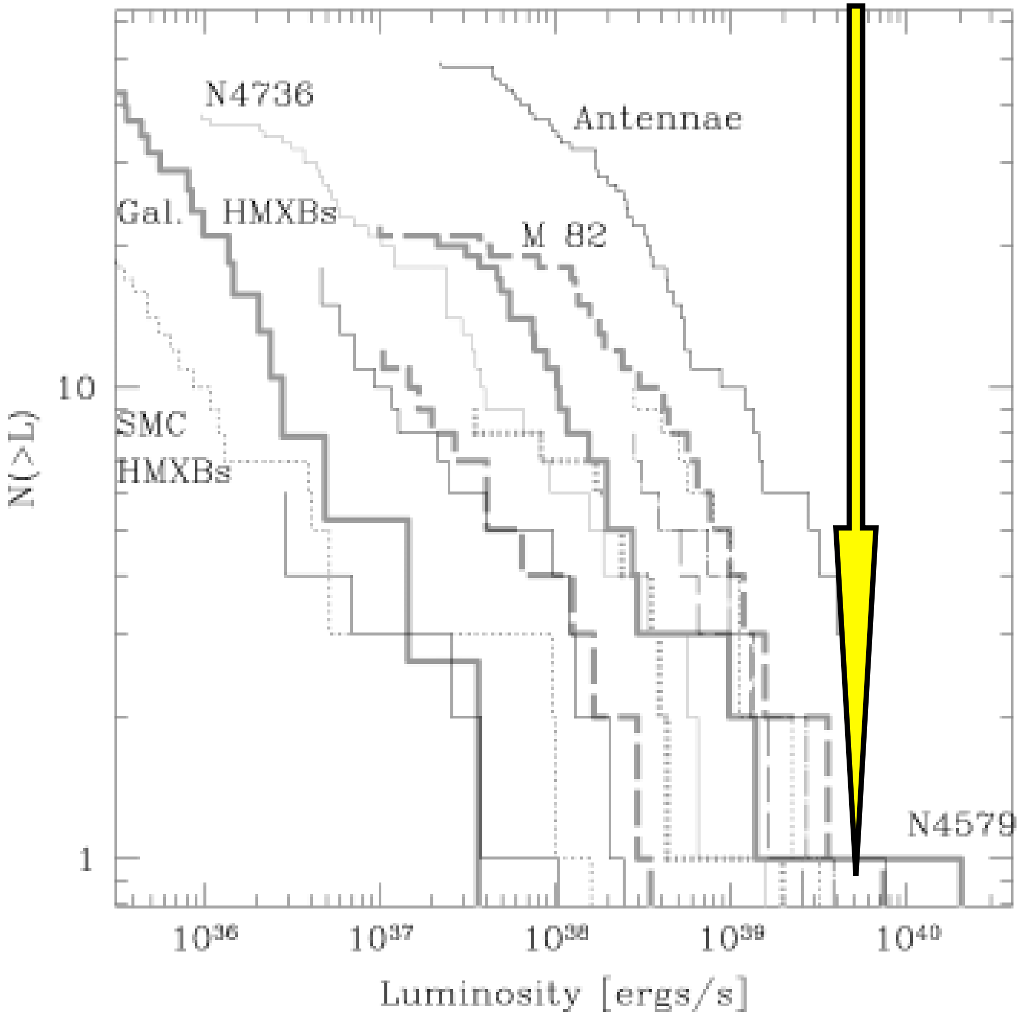


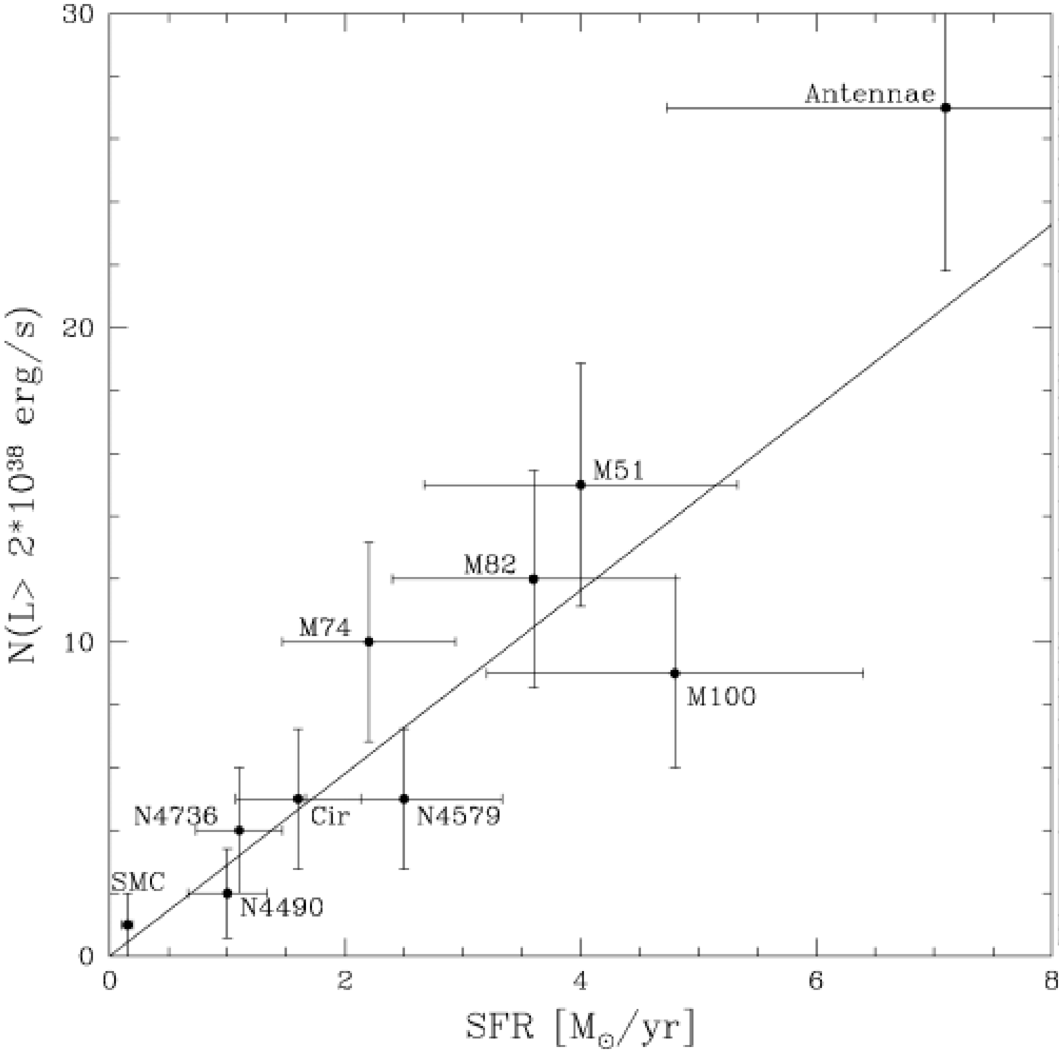

42:30.0
-33:43:00.0
30.0
44:00.0
42.0
Flux (2.0–10.0) ×10⁻¹⁴
8
6
4
2
HRI
CHANDRA
XMM
Flux (0.5–2.0) ×10⁻¹⁴
4
3
2
4.9×10⁴
5×10⁴
5.1×10⁴
5.2×10⁴
5.3×10⁴
5.4×10⁴
Time (JD − 2400000)

L> 10^{41} erg/s

LUMINOSITY FUNCTION of HMXB IN EXTERNAL GALAXIES

Universal? Dependent on SFR? Grimm & Gilfanov important contributions

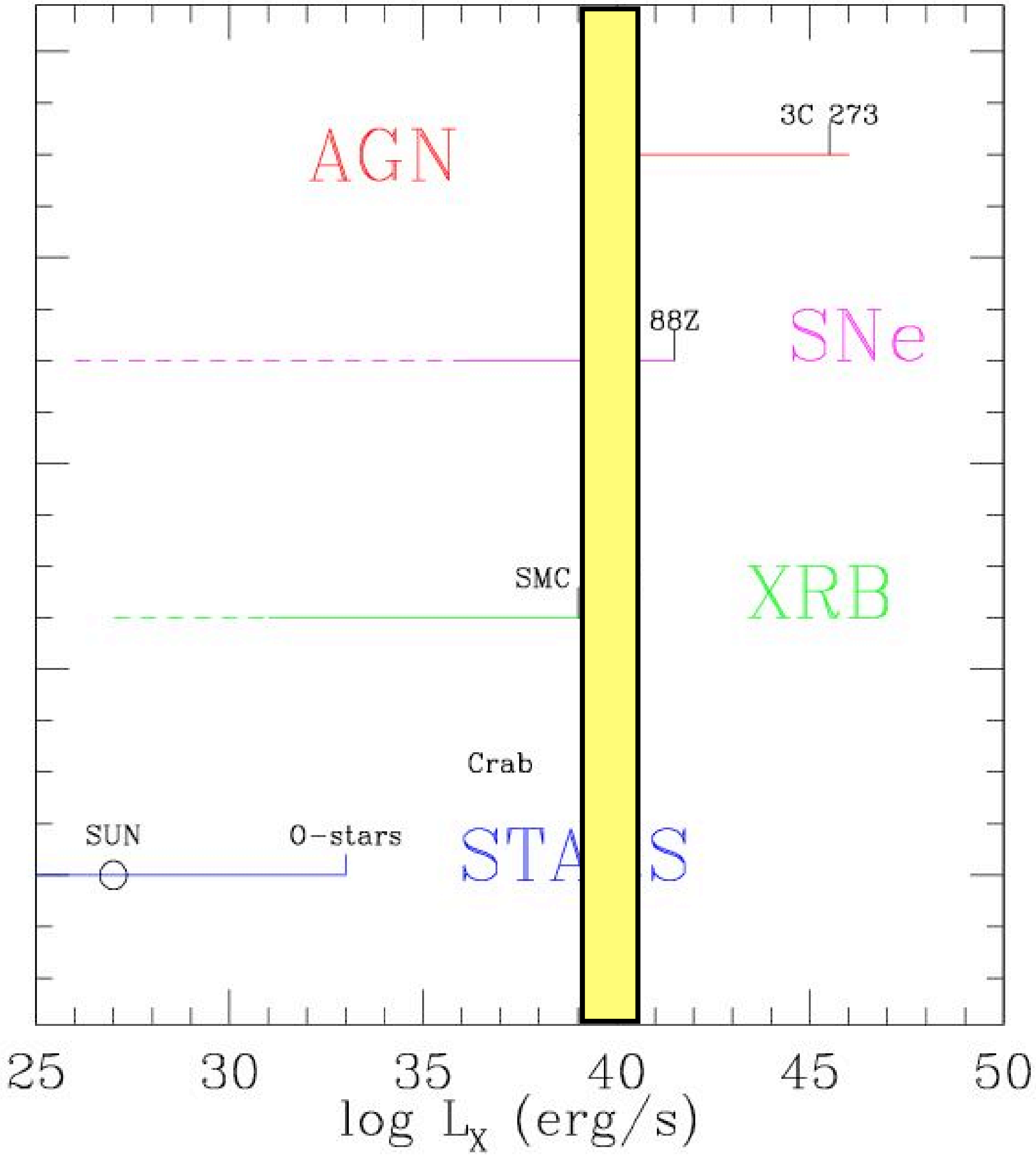




Power law with high luminosity cut-off @ L_X~2x10^{40} erg/s

Normalization proportional to SFR

ULTRA LUMINOUS SOURCES (ULXs)



INTERMEDIATE MASS BLACK HOLES ?

AFTER THE DISCOVERY OF ULXs MANY MODELS HAVE BEEN SUGGESTED

(I) SUPERNOVAE IN DENSE ENVIRONMENTS

$L_x \sim 10^{38} - 2 \times 10^{40}$ erg/sec

(lifetime - years or more)

(II) SPIN-DOWN LUMINOSITY OF A YOUNG PULSAR

(III) ACCRETORS

INTERMEDIATE MASS BLACK HOLES

(ISOTROPIC EMISSION)

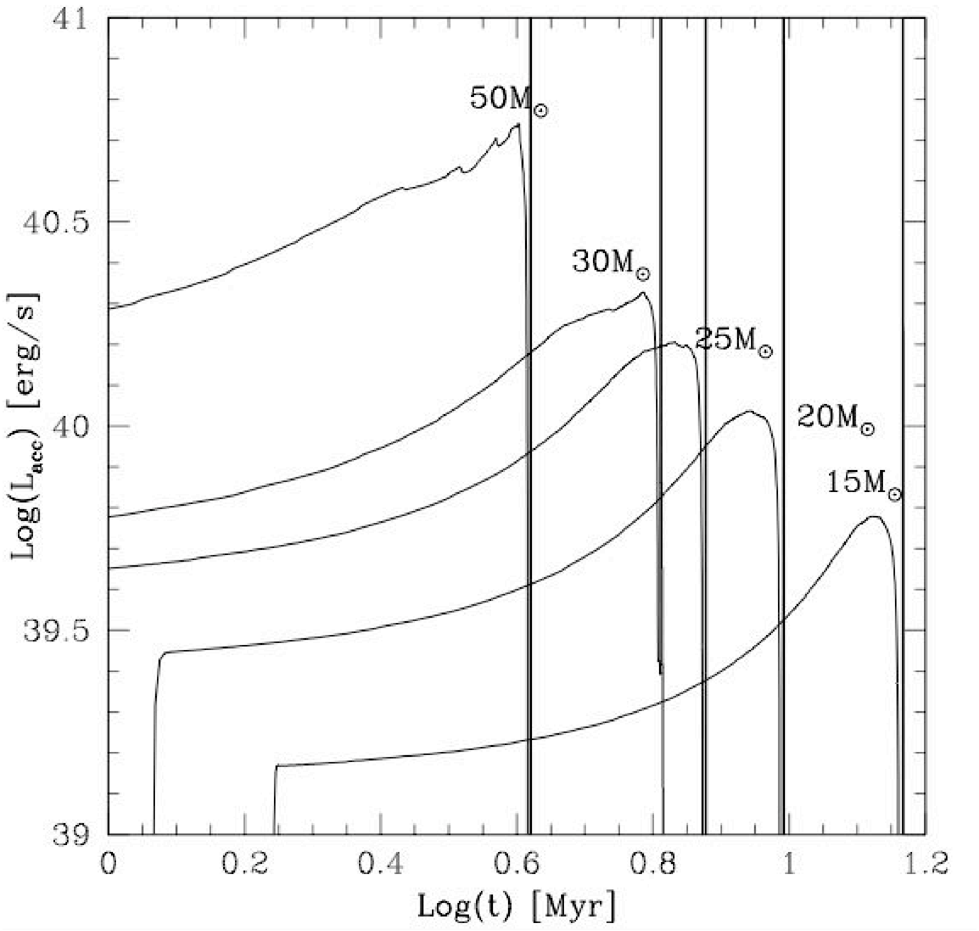
$10^2 - 10^4$

SOLAR MASSES

NOT RESULTING FROM CURRENT

STELLAR EVOLUTION

ASSOCIATION OF ULXs to STAR FORMING REGIONS



MASSIVE OPTICAL
COMPANION
ROCHE LOBE
OVERFLOW ONTO
IMBH

PERSISTENT LONG
LIVED SOURCE ON
ZAMS

ON THE RED GIANT
THE SOURCE
CAN BE TRANSIENT

HMRXs --- PROGENITORS OF IMBH-PSR SYSTEM

(IV) ULXs AS EXTREME ENDS of an HMXB POPULATION FORMED IN STAR FORMING REGIONS

EXCEEDING THE EDDINGTON LUMINOSITY OF
A SOLAR MASS BLACK HOLE

ANISOTROPIC EMISSION
CONFINED TO A SOLID ANGLE 4πb
"b" the beaming factor

BEAMED EMISSION FROM A RELATIVISTIC JET
(GRS 1915+105-MICROBLAZAR)

STABLE SUPER-EDDINGTON LUMINOSITY DUE TO A SUITABLE GEOMETRICAL ARRANGEMENT OF EMISSION ALLOWING PREFERENTIAL PHOTON ESCAPE
(geometrically thick accretion disc producing pair of scattering funnels through which the accretion radiation emerges)

How can we constrain their nature?

If ULXs are IMBHs they should have properties intermediate to the Stellar BHs and AGNs

OPTICAL

°Optical nebulae with large kinetic energies and size 200-600 pc
(ULX in Holmberg II....in favor of isotropic emission)
° Optical Stars
2 sources with probable O-star counterpart
very high X-ray/Optical ratios
puzzling...LMXBs versus HMXBs
(not expected in AGNs)
no contribution from an accretion disc

RADIO

AGN, SNR, beaming, HII regions

°ULXs have a lower radio/X-ray ratio than BL Lacs
and also optical/X-ray ratios inconsistent
This lessens the likelihood that the ULX are beamed objects
° Many ULXs host resolved radio emission by VLA
(against relativistic beaming)

°More luminous SN remnant than CAS-A

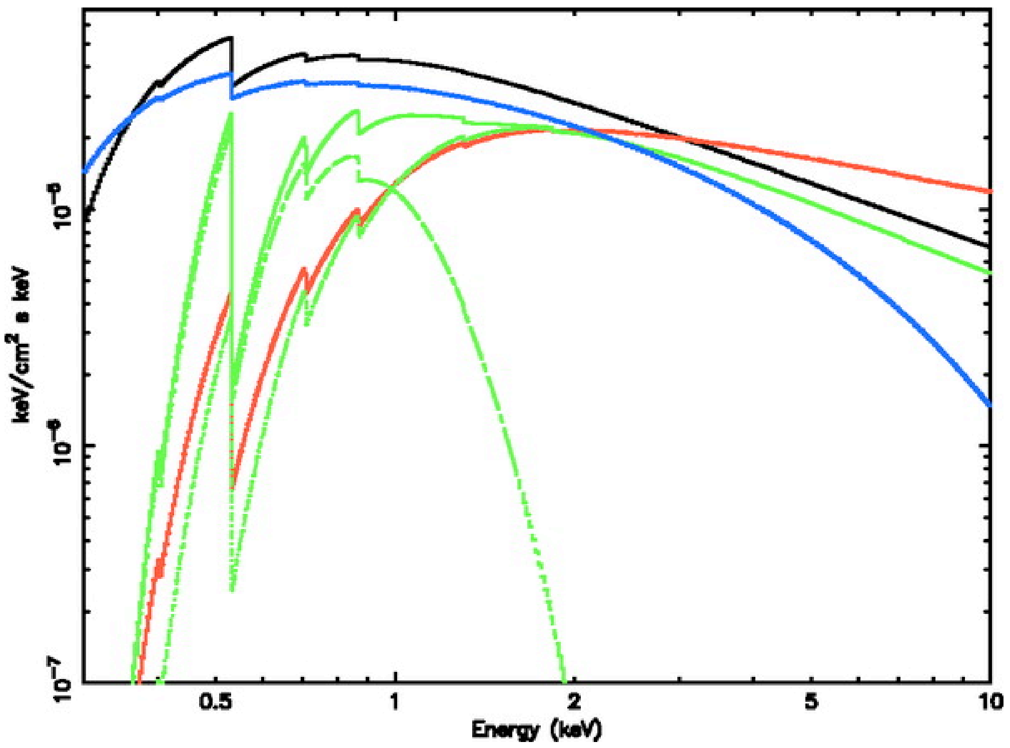
X-RAYS

°soft spectral component
°variability

TIME VARIABILITY

° X-ray Periods.... Binary Periods (eclipses) ?
°both low and large amplitude variability
(transients?)
°QPOs Keplerian frequence at ISCO?
-some have (X-7 in NGC 4559) and
power density spectra similar to BH Candidates
-some do not have any QPOs

Spectral properties: 4 examples @ ≥10^{40} erg/s, constant flux



$T \propto M^{-1/4}$

Black: $\Gamma=1.48$ for X-11.

Red: $\Gamma=1.9$ for X-16.

Green: MCD ($kT=0.13$ keV) plus $\Gamma=2$ for X-37 (with disk and power-law components also shown).

Blue: Bremsstrahlung ($kT=3.7$ keV) for X-44.

> “Clearly, the best-fit models for the ULX spectra that we consider are significantly different; this may indicate different source types.”

Miller et al. 2004

HETEROGENEOUS CLASS?

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in “Compact Stellar X-ray Sources” Es. Lewin et al.
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King: Accretion in Compact Binaries
in “Compact Stellar X-ray Sources” Es. Lewin et al.
Cambridge University Press

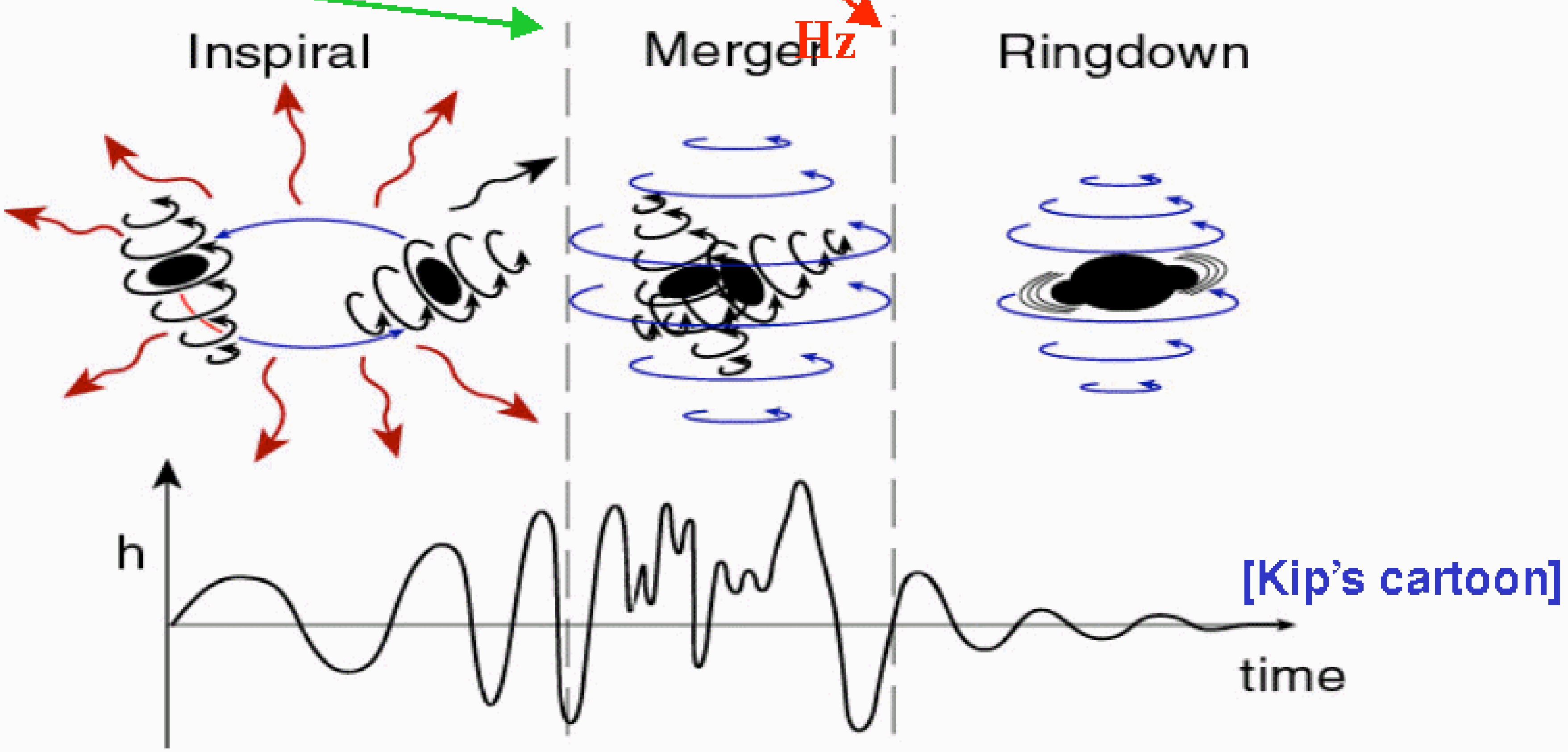
Genzel et al. arXiv:07041281 & References therein

Mushotzky: ULXs in Nearby Galaxies
arXiv: astro-ph/0411040

Coalescence of binary systems

$f = 4\,[\,M\,(1+z)\,/10^3\,M_{\odot}\,]^{-1}$ Hz

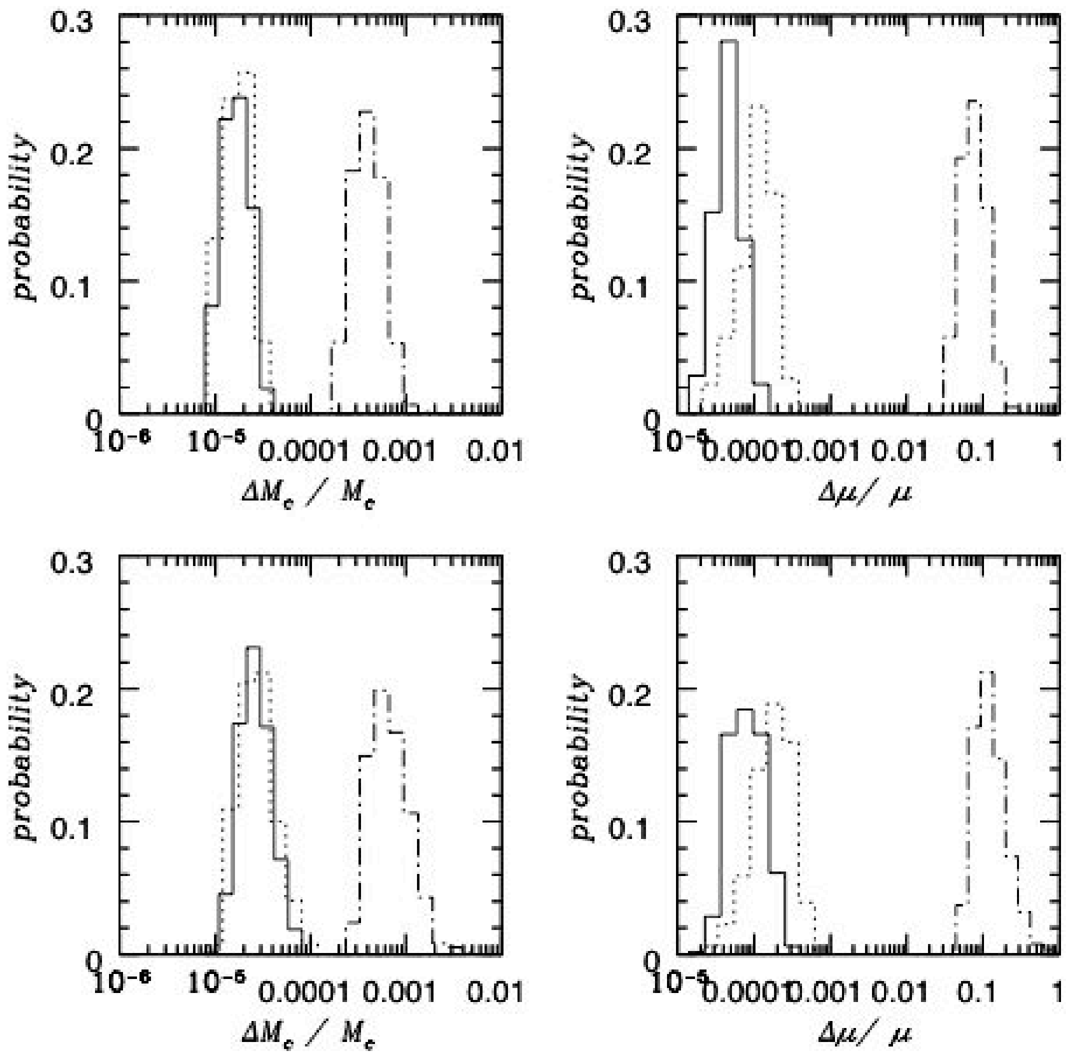
$f = 32\,[\,M\,(1+z)\,/10^3\,M_{\odot}\,]^{-1}$ Hz



[Kip's cartoon]

Long lived

Short lived



PROBABILITY DISTRIBUTION OF THE ERRORS IN THE CHIRP MASS AND REDUCED MASS DETERMINATION

dashed line zero SPIN

PRECESSING BINARIES SHOW A MUCH GREATER RICHNESS OF FEATURES THAN NON SPINNING BINARIES

Vecchio 2004