EVOLUTION OF LOW-MASS CLOSE BINARIES WITH BLACK-HOLE COMPONENTS

Based on a study by
L.Yungelson, J.-P.Lasota, G.Dubus,
G. Nelemans, E. van den Heuvel,
S. Portegies Zwart, J. Dewi

Out of 20 confirmed bh-candidate binaries (Remillard & McClintock 2006) 10 have K/M secondaries and orbital periods below approx. 1 day; all of them are transient in X-ray. Belong to the class of SXT.

SXT - a class of binaries containing a K/M-type dwarf or subgiant that is transferring mass to a black hole (or neutron star) through an accretion disk.

Commonly accepted model for transience:
thermal-viscous instability of irradiated accretion disks
(Smak 1971, ..., Lasota 2001,
Dubus, Hameury, Lasota 2001,...)

Quiescence: log L=30.5 -33.5,
In outbursts – by factor 100 – 10000 brighter
Recurrence time - ten(s) of yrs
Estimated Galactic population ~ 1000 objects

OUTLINE

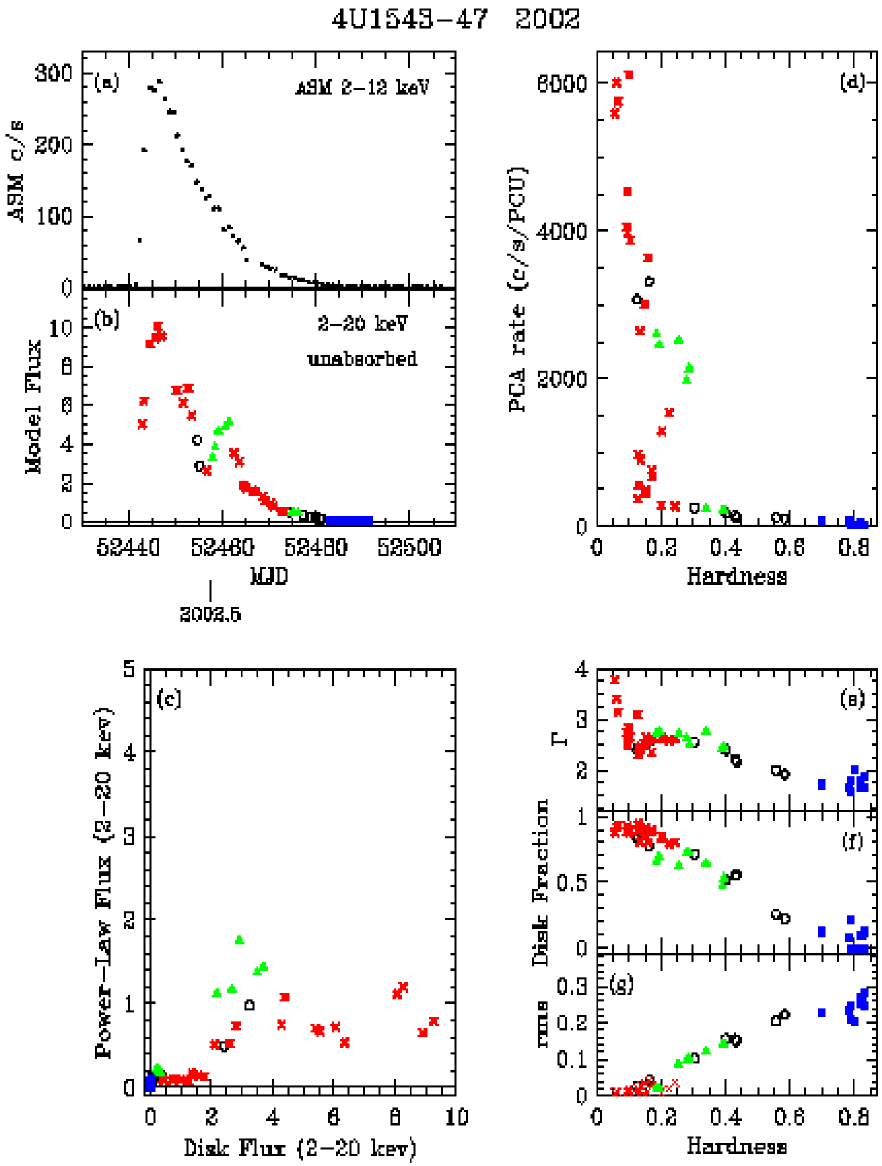
1. A model for population of low-mass short-period black-hole binaries

2. Estimate of the mass-transfer rates in soft X-ray transients

3. Possibility of existence of a population of faint stable low-mass black hole X-ray binaries

Known black-hole candidate low-mass short-period binaries

Name	P_{orb} day	Sp.	$\langle \dot{M}_{\rm recc} \rangle$ $M_\odot$ yr^{-1}	$\dot{M}_{\rm in}$ $M_\odot$ yr^{-1}
XTE J1118+480 (KV UMa)	0.171	K5/M0V	1.9×10^{-12}	1.5×10^{-10}
GRO J0422+32 (V518 Per)	0.212	M2V	1.3×10^{-11}	2.3×10^{-10}
GRS 1009-45 (MM Vel)	0.285	K7/M0V	4.4×10^{-11}	3.8×10^{-10}
XTE J1650-500	0.320	K4V	2.0×10^{-11}	4.8×10^{-10}
A0620-00 (V616 Mon)	0.323	K4V	3.3×10^{-11}	4.8×10^{-10}
GS 2000+25 (QZ Vul)	0.345	K3/K7V	2.0×10^{-10}	5.4×10^{-10}
XTE J1859+226 (V406 Vul)	0.383		4.1×10^{-10}	6.4×10^{-10}
GRS 1124-68 (GU Mus)	0.433	K3/K5V	3.4×10^{-10}	8.0×10^{-10}
H 1705-25 (V2107 Oph)	0.521	K3/7V	5.5×10^{-11}	1.1×10^{-9}
4U 1543-47 (IL Lup)	1.125	A2V	4.2×10^{-10}	4.3×10^{-9}



SXT in outburst

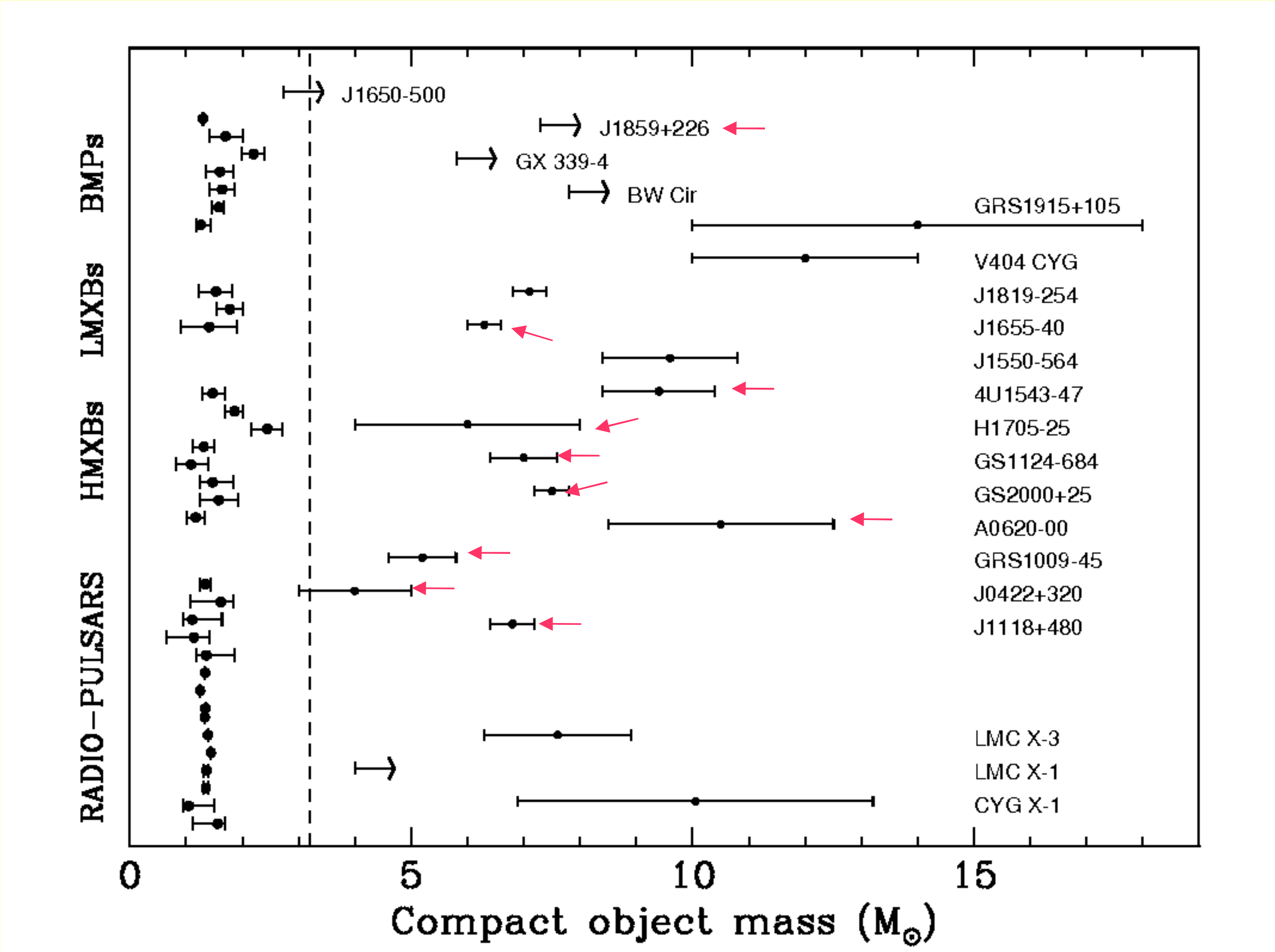
× thermal (disk)

▲ steep power law (disk corona, flares, bulk motions in the vicinity of BH?)

■ hard (jet)

○ intermediate states

Masses of known bh-candidates. Red arrows mark SXT



Original plot from Casares (2006)

Modelling of the population of LMBHB:

The method – population synthesis that combines a

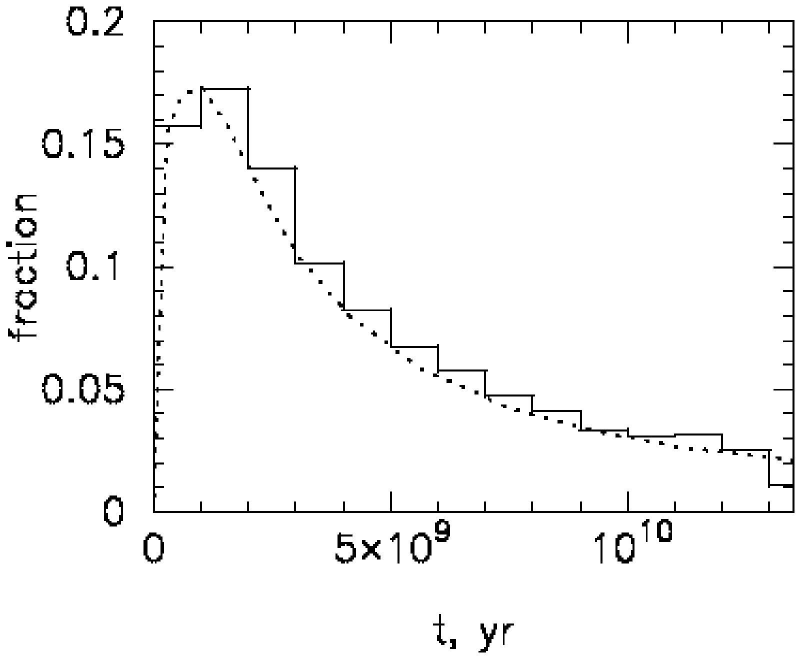
model for zero-age bh+ms binaries with a model for

their evolution

Secondaries in LMBHB are K/M stars – evolution similar to CV – governed by nuclear evolution and/or angular momentum loss via magnetic braking (MB) and/or GWR (?)

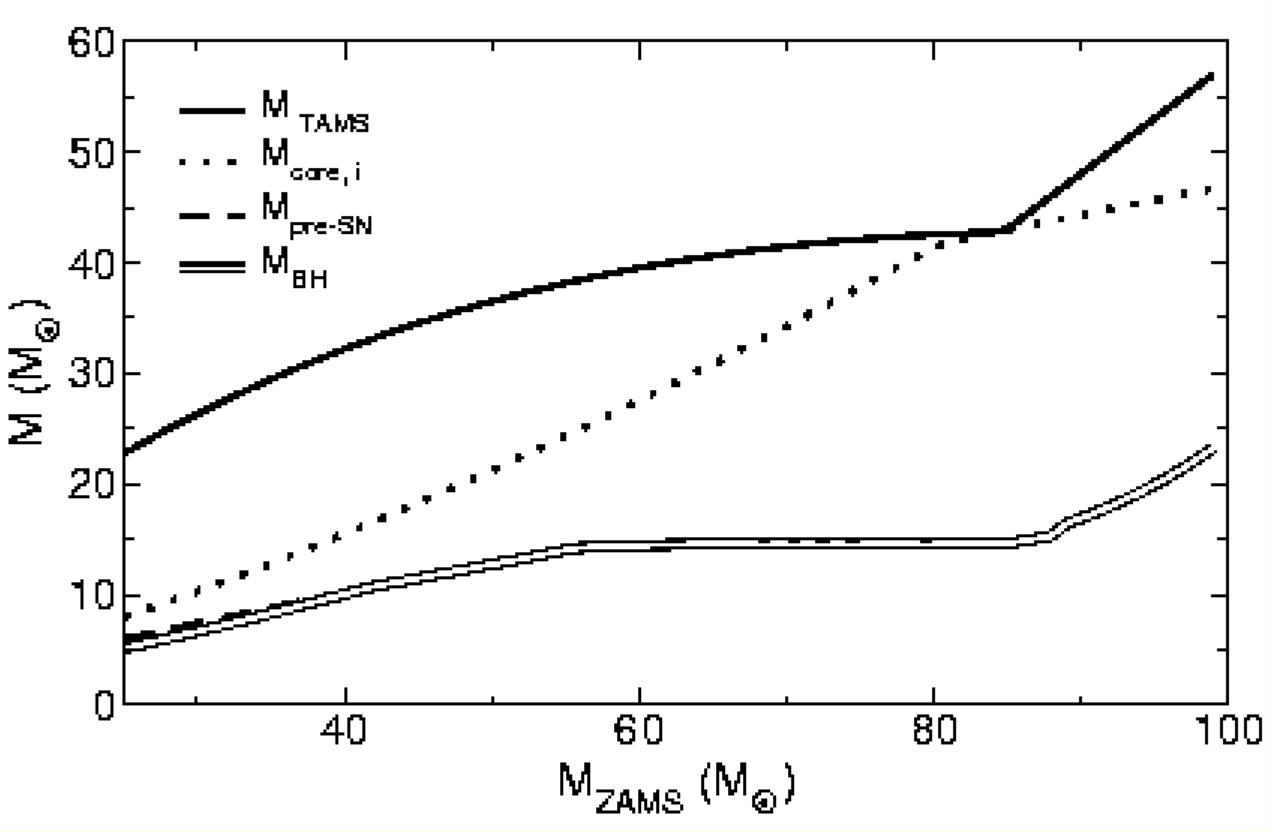
"Standard" (Verbunt & Zwaan) MB is based on extrapolation of rotation law for single stars (Skumanich law) to components of close binaries.

Some ingredients of population synthesis

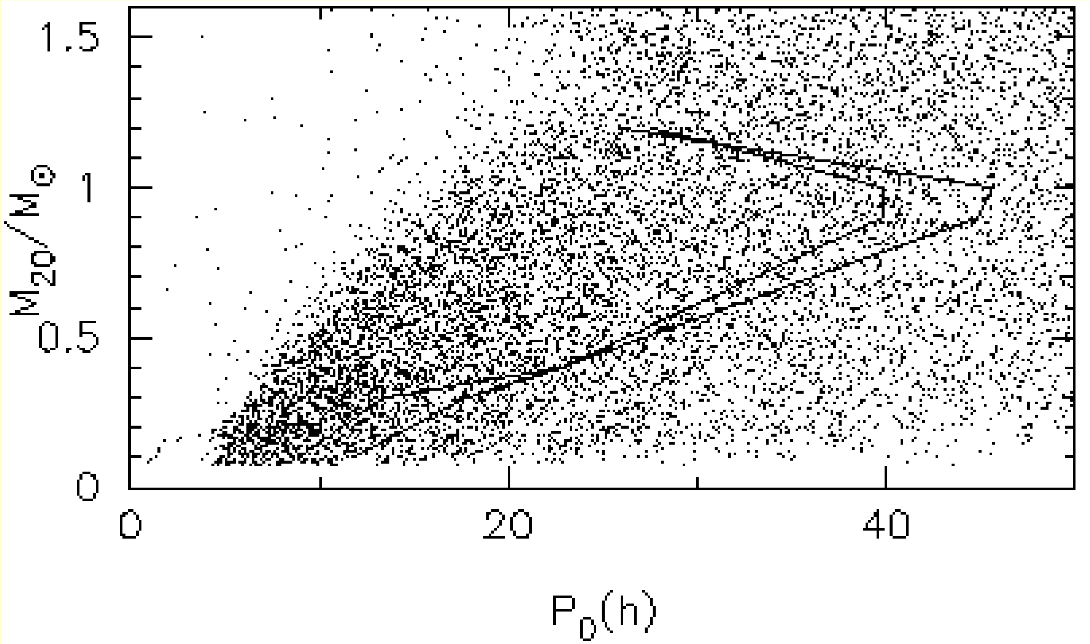


Star formation history (after Boissier & Prantzos with a bulge added, doted line) and history of LMBHB formation (in terms of fractions of currently existing population, solid line)

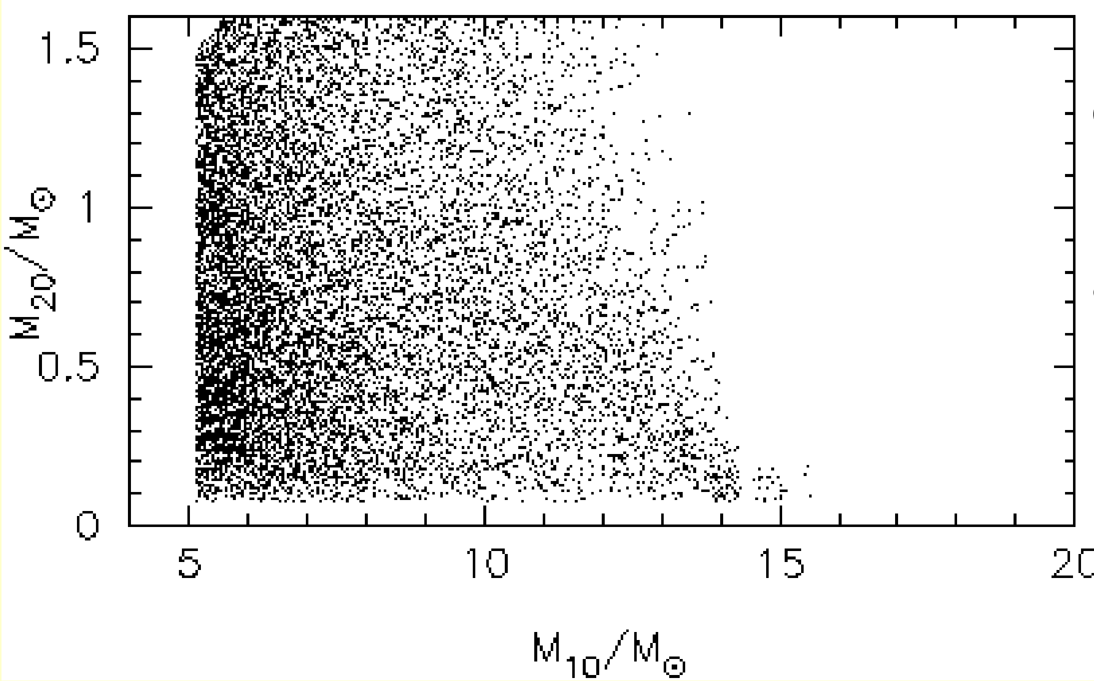
Summary of evolution of massive stars



Adopted initial-final mass relations
BH are formed by stars with M0 >25 Msun
Pre-SN are virtually naked He-stars



~49000 binaries with
black hole mass ≥5Msun,
companion mass ≤1.6Msun
and initial orbital period ≤ 2 day
formed in the Galaxy in Hubble
time (~0.01% of all bh binaries)



Up to ~14000 evolve into
contact and then to shorter
periods under
“standard” (Verbunt & Zwaan)
assumptions on magnetic
braking.

Equations governing the evolution and DIM-instability criterion

Magnetic braking (Verbunt & Zwaan 1981)

$$\frac{\mathbf{d}\ln\mathbf{J}}{\mathbf{dt}} = -\frac{\mathbf{1}}{\mathbf{2}} \times \mathbf{10^{-28}k^2}\left(\frac{\mathbf{2}\pi}{\mathbf{P}}\right)^{\mathbf{10/3}} \frac{\mathbf{1}}{\mathbf{G^{2/3}}} \frac{(\mathbf{M_1}+\mathbf{M_2})^{\mathbf{1/3}}\mathbf{R_2^4}}{\mathbf{M_1}\lambda^2}$$

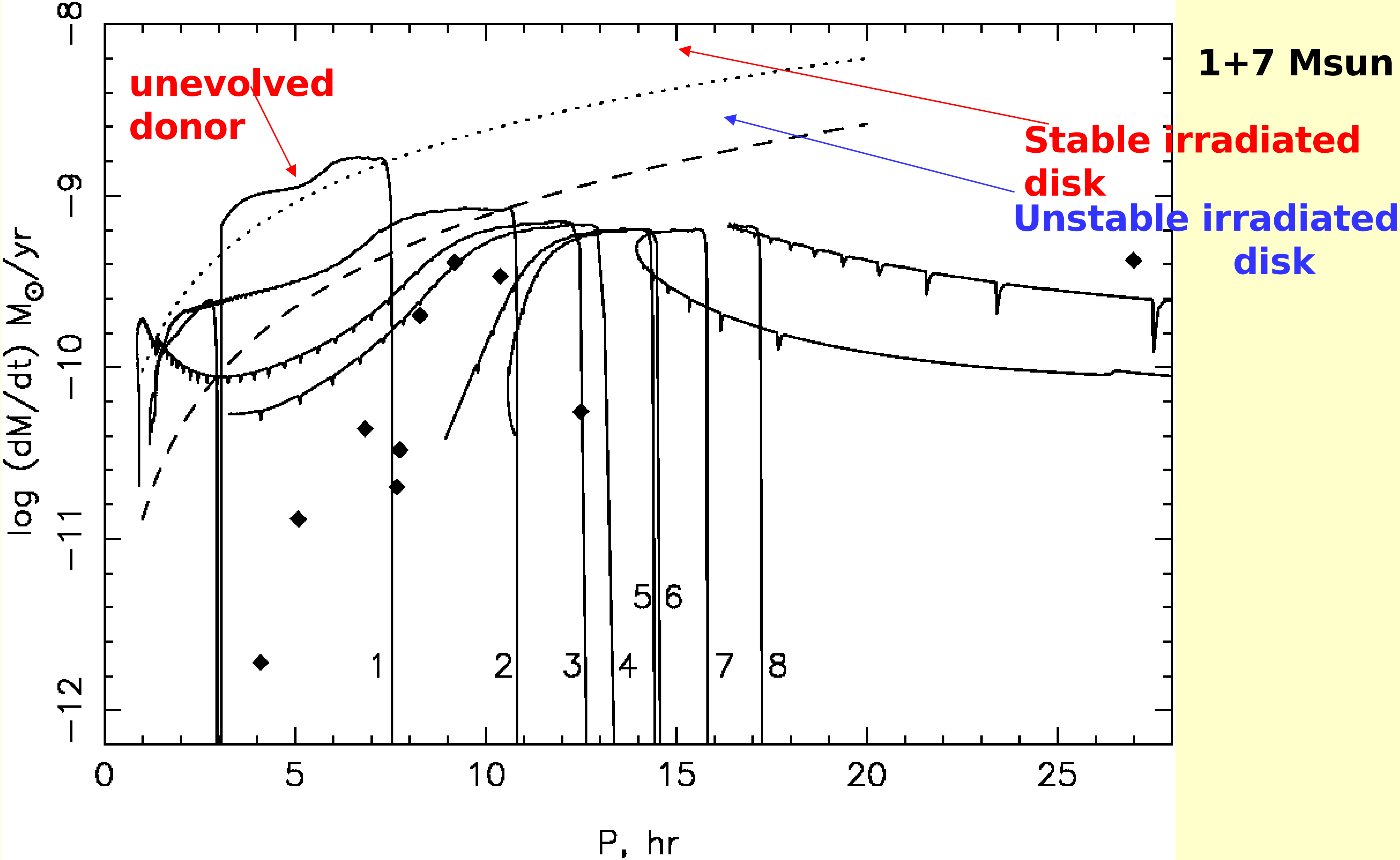
Gravitational waves radiation (Landau & Lifshitz 1971)

$$\frac{\mathbf{d}\ln\mathbf{J}}{\mathbf{dt}} = -\frac{\mathbf{32}}{\mathbf{5}}(\mathbf{2}\pi)^{\mathbf{8/3}}\frac{\mathbf{G^{5/3}}}{\mathbf{c^5}}\frac{\mathbf{1}}{\mathbf{P^{8/3}}}\frac{\mathbf{M_1 M_2}}{(\mathbf{M_1}+\mathbf{M_2})^{\mathbf{1/3}}}$$

Irradiated disk stability criterion (Dubus, Lasota, Hameury, Charles 1999)

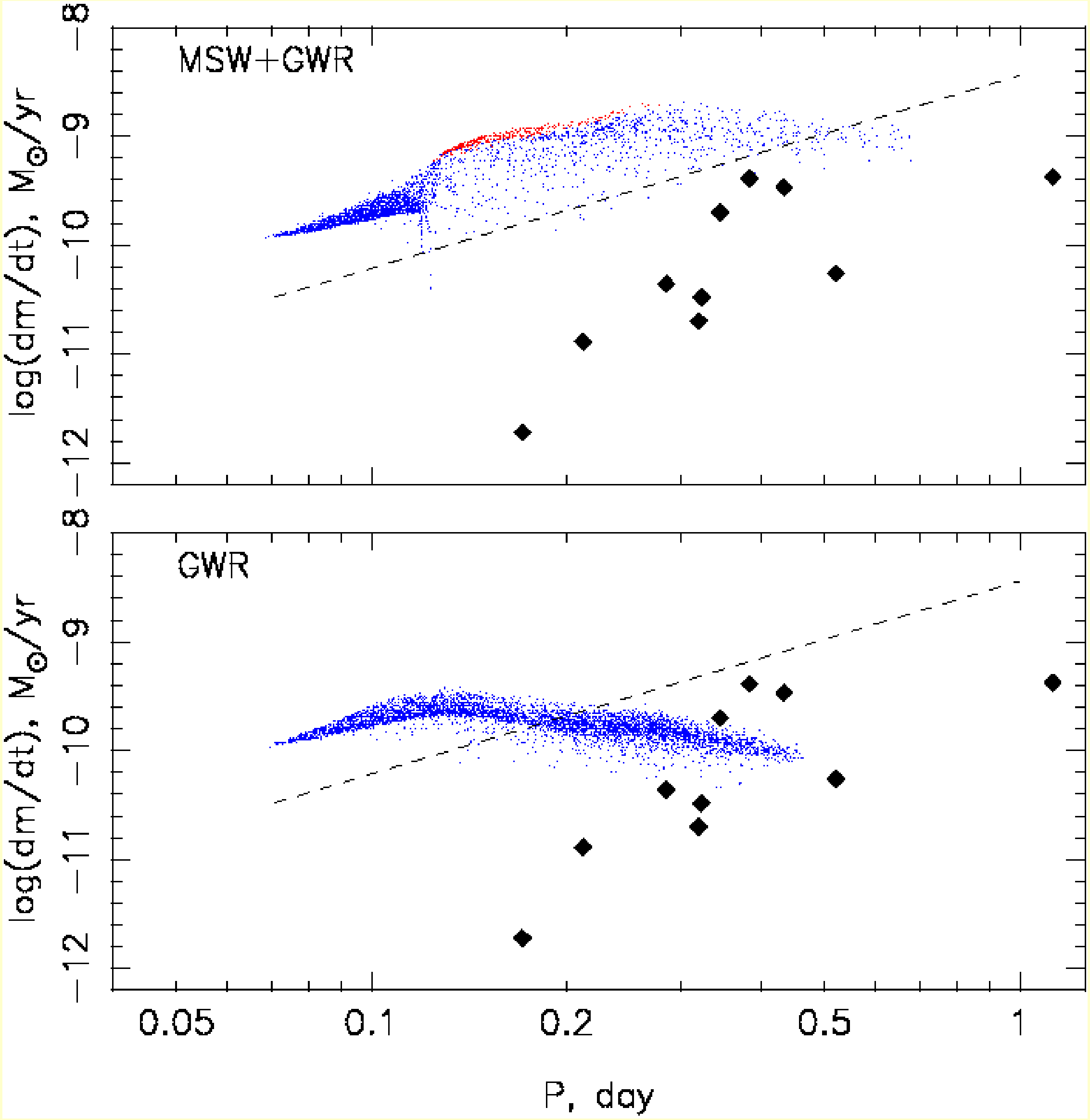
$$\dot{M}^{+}_{\rm crit} \approx \mathbf{2.4 10^{-11}}\mathbf{M}_{\rm BH}^{\mathbf{-0.4}}\left(\frac{\mathbf{R_d}}{\mathbf{10^{10}}\ \rm cm}\right)^{\mathbf{2.1}}\left(\frac{\mathcal{C}}{\mathbf{5}\times\mathbf{10^{-4}}}\right)^{\mathbf{-0.5}}\mathbf{M}_\odot/\mathbf{yr}$$

C is the measure of heating of the disk by X-rays



Bifurcation of tracks: depending on central H-abundance at RLOF stars may evolve to longer or shorter periods. Systems may secularly change from stable to unstable state.

Strongly evolved donors do not explain periods and dm/dt in SXT blue - transient, red – stable



“Standard” MSW +GWR predict several 100 bright (~1e36erg/s) persistent sources in the Galaxy

Several 10 “observable” (above RXTE ASM completeness limit)

Observations – **0 !!!**

Upper panel – results of computations under 'standard' assumptions

The models suggest 3000 – 5000 LMBHB in the Galaxy.

With recurrence time ~100 yr and Lx ~0.1Ledd

this yields way too high outbursts rate. Are then

transients sub-Eddington or most of them

have recurrence times >> 100 yr?

Standard MB does not work (?):

VZ AML is based on extrapolation of rotational velocities of single stars of 1-30 km/s, while in CV rotational velocities are > 100km/s and on assumption of efficient spin-orbital coupling

Andronov et al. 2003: VZ is inconsistent with data on rotation of stars in open clusters, AML rate is 2 orders of mag. lower; no evidence on abrupt AML behaviour change for completely convective stars

Hameury, King, Lasota, Ritter 1988: Mestel-Spruit law better fits observations

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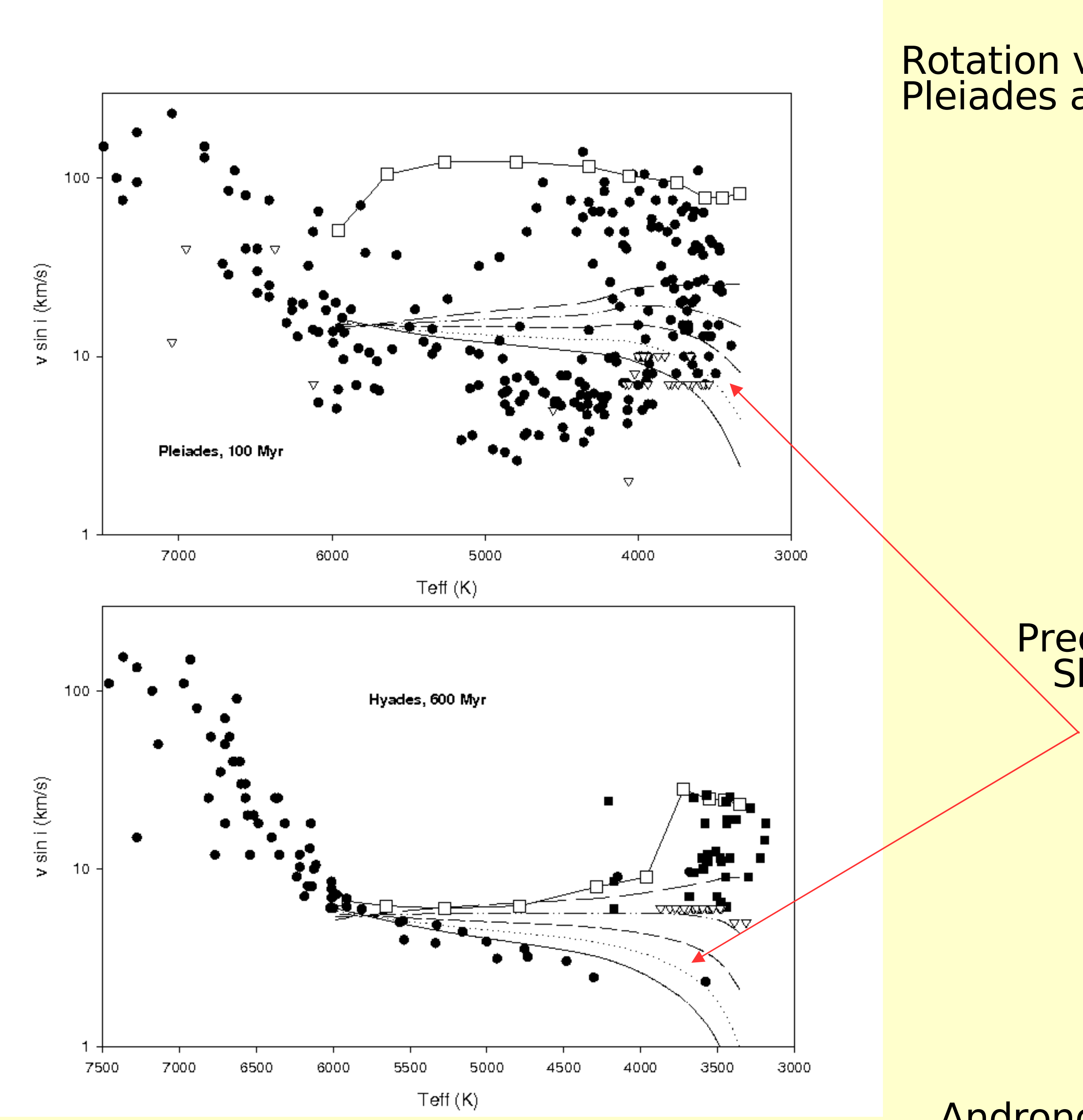
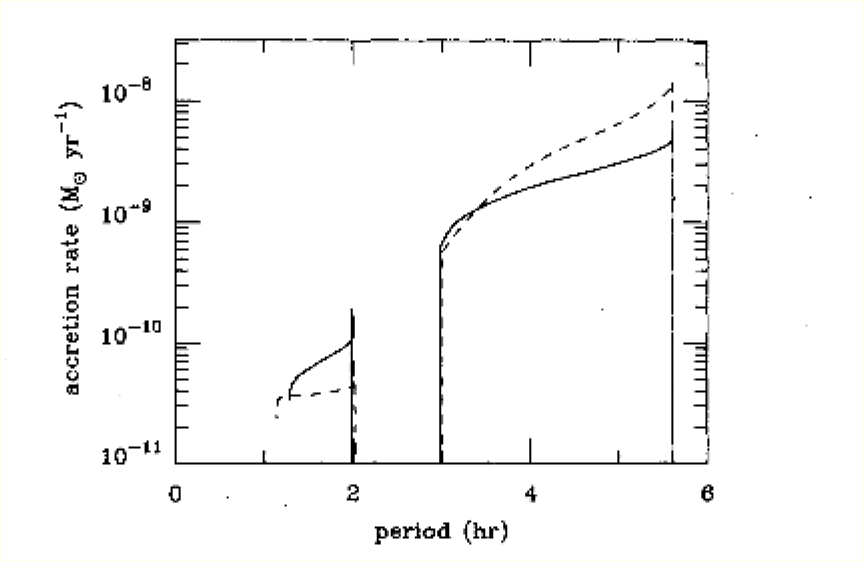
Ivanova & Taam 2003: VZ-type law does not allow to reproduce observed mass-transfer rates in CV

Rotation velocities in Pleiades and Hyades



Predictions based on Skumanich law

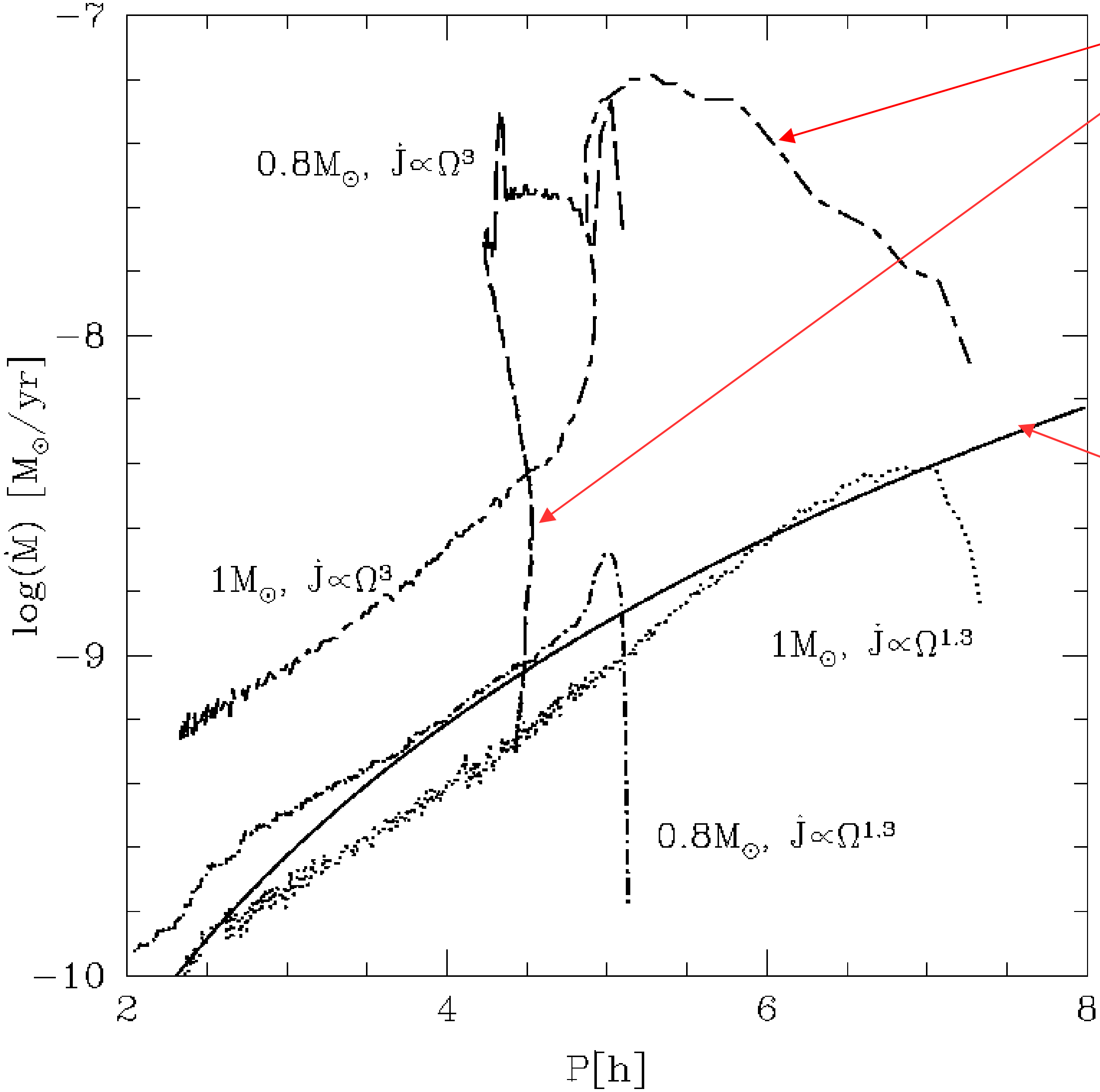
Andronov et al. 2003



Hameury, King, Lasota, Ritter 1988

Computation with Mestel-Spruit braking law
for (1+1)Msun system.

Flatter P-dm/dt -> better fit to observations



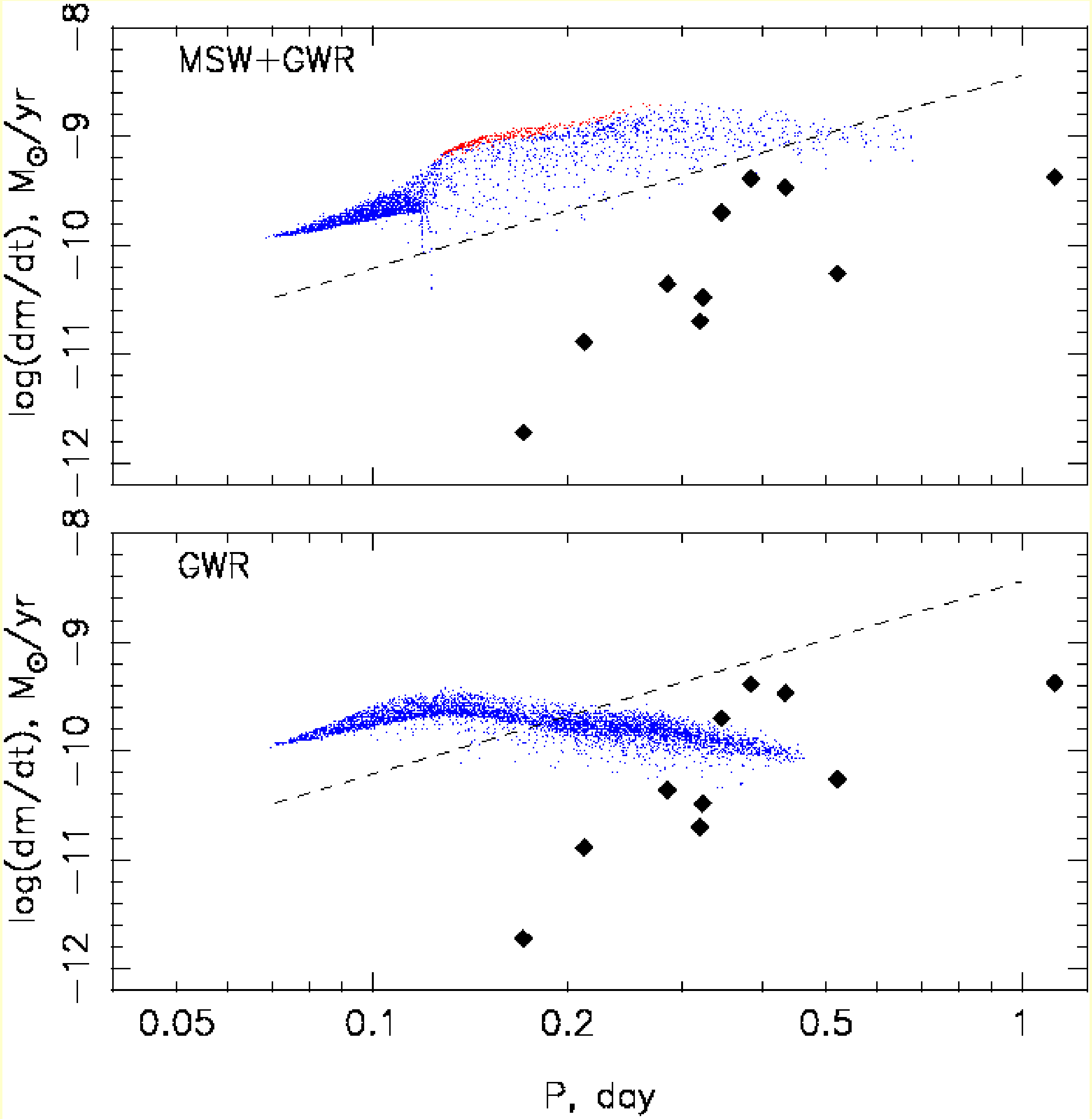
Skumanich law

0.8Msun unevolved
1Msun evolved
0.6Msun wd

Fit to observations
(Patterson 1984)

Evolutionary timescales
differ by factor ~5

Ivanova & Taam 2003



“Standard” MSW +GWR predict several 100 bright (~1e36erg/s) persistent sources
Several 10 “observable” (above RXTE ASM completeness limit)

Observations – 0

Model with only GWR after contact – no persistent sources. Provides lower bound to dm/dt.

dm/dt should be ~ 10 times lower than in the “standard” model

Lower panel – results of modeling under assumption that magnetic braking does no operate after Roche lobe overflow

It is clear that a mechanism of angular momentum loss additional to gravitational waves radiation must exist, but its nature is still enigmatic.

Mass-transfer rates: usually estimated from energetics of the outbursts:

disk is non-leaky reservoir filled until instability is triggered.

Lasota 1996; Lasota, Narayan, Yi 1996 -- explanation of quiescent luminosities requires inner truncation of the disks --> they are leaky

Mass transfer rate:

$$\dot{\mathbf{M}}_{\rm tr} \approx \frac{\epsilon \mathbf{M}_{\rm D,max}}{\mathbf{t}_{\rm recc}} + \dot{\mathbf{M}}_{\rm in}$$

$\dot{\mathbf{M}}_{\rm in}$ – accretion rate at the disc's inner edge

Maximum quiescent disk mass

$$\mathbf{M}_{\rm D,max} = \mathbf{2.7 \times 10^{21}} \alpha^{\mathbf{-0.83}} \left(\frac{\mathbf{M_1}}{\rm M_\odot}\right)^{\mathbf{-0.38}} \left(\frac{\mathbf{R_d}}{\mathbf{10^{10}}\ \rm cm}\right)^{\mathbf{3.14}}$$

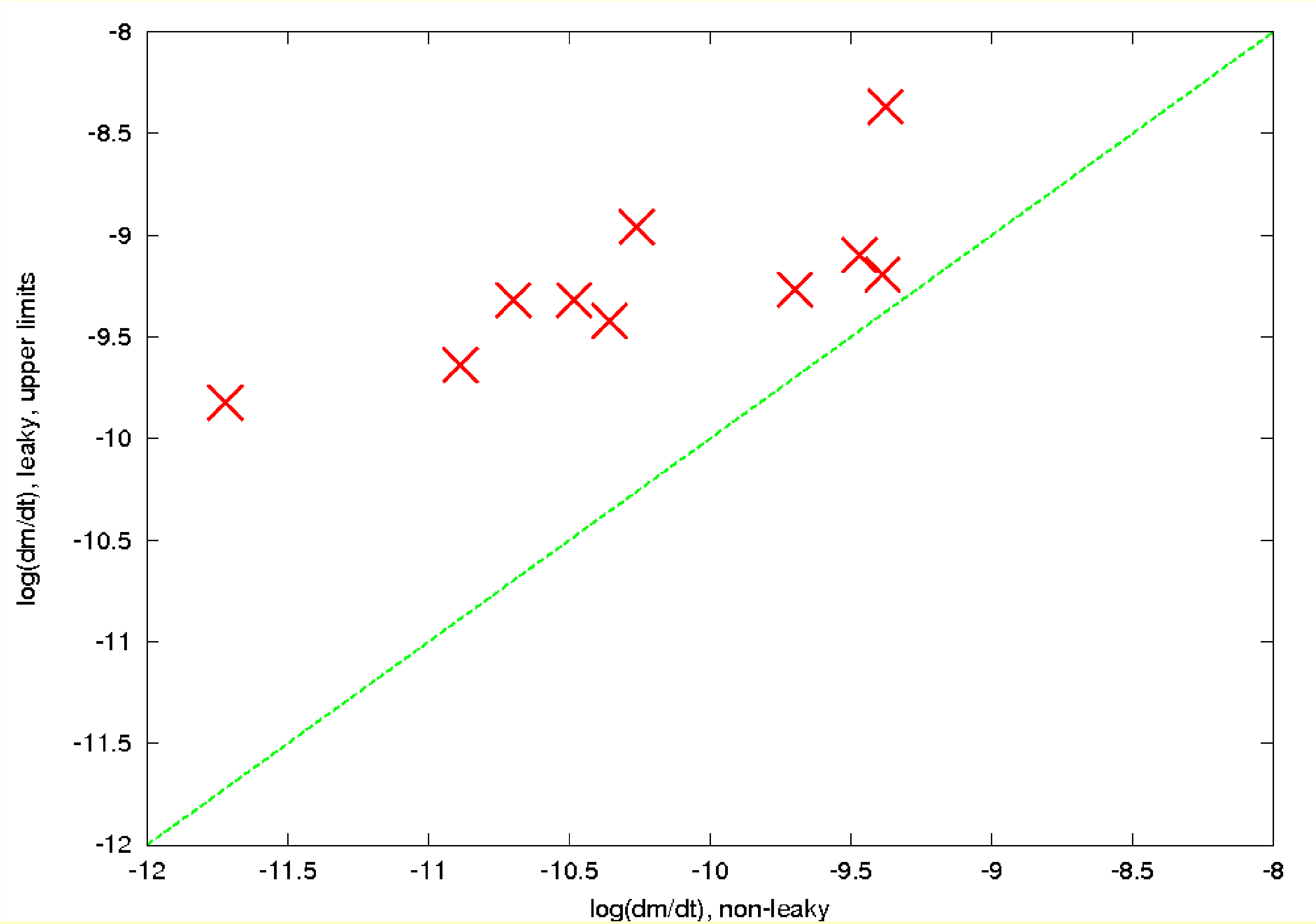
$\epsilon = \mathbf{\Delta M}_{\rm D}/\mathbf{M}_{\rm D,max}$ – fraction of the disk mass lost in outburst

$\mathbf{R_d}$ – disk outer radius

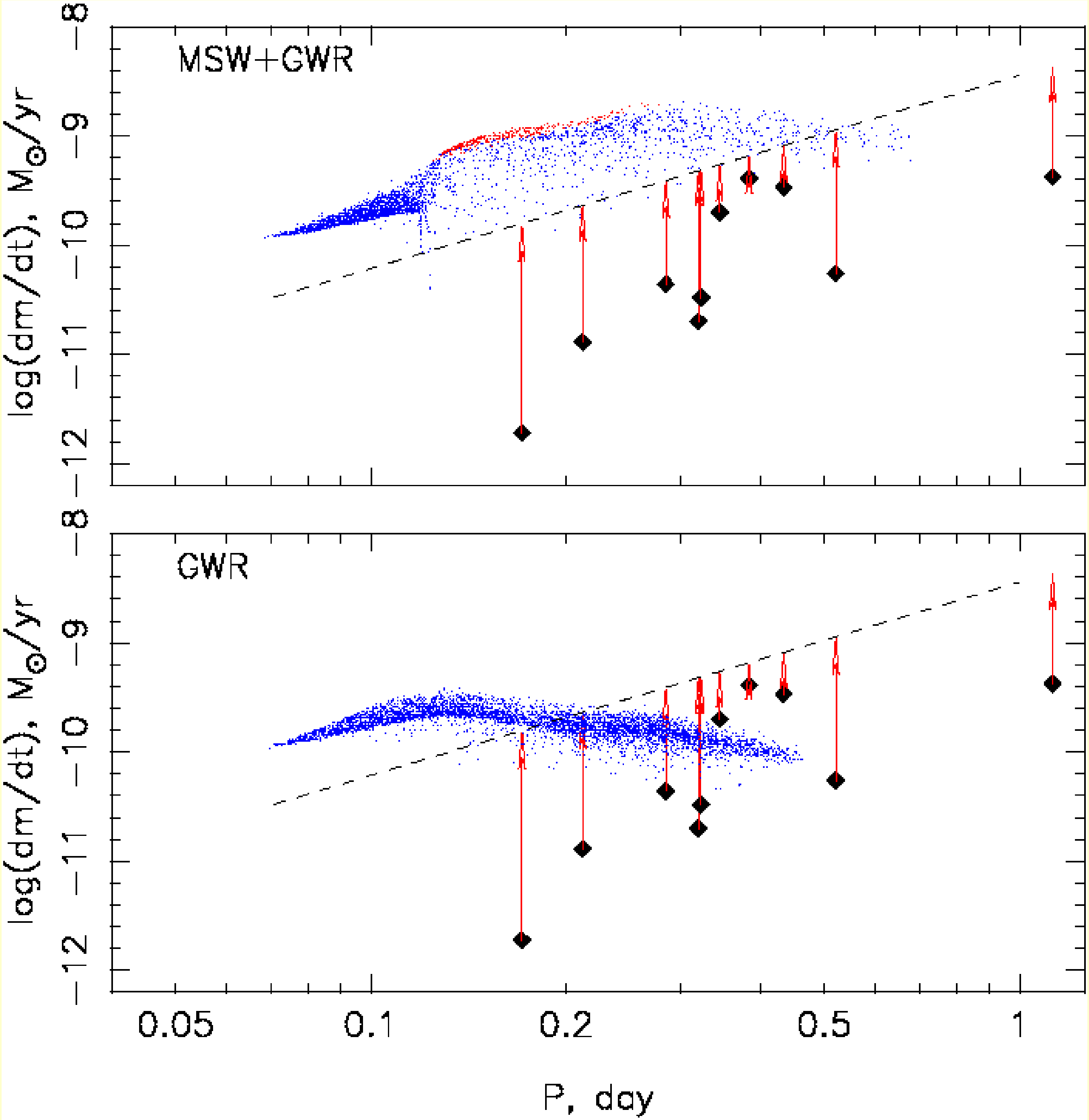
$$\dot{\mathbf{M}}_{\rm in} \lesssim \mathbf{3.6 \times 10^{-9} P}_{\rm day}^{\mathbf{1.77}} M_\odot\ \rm y^{-1}.$$

Mass-transfer rate has two terms on r.h.s.: average mass-loss in outbursts and ´leaking´ term

Upper limit

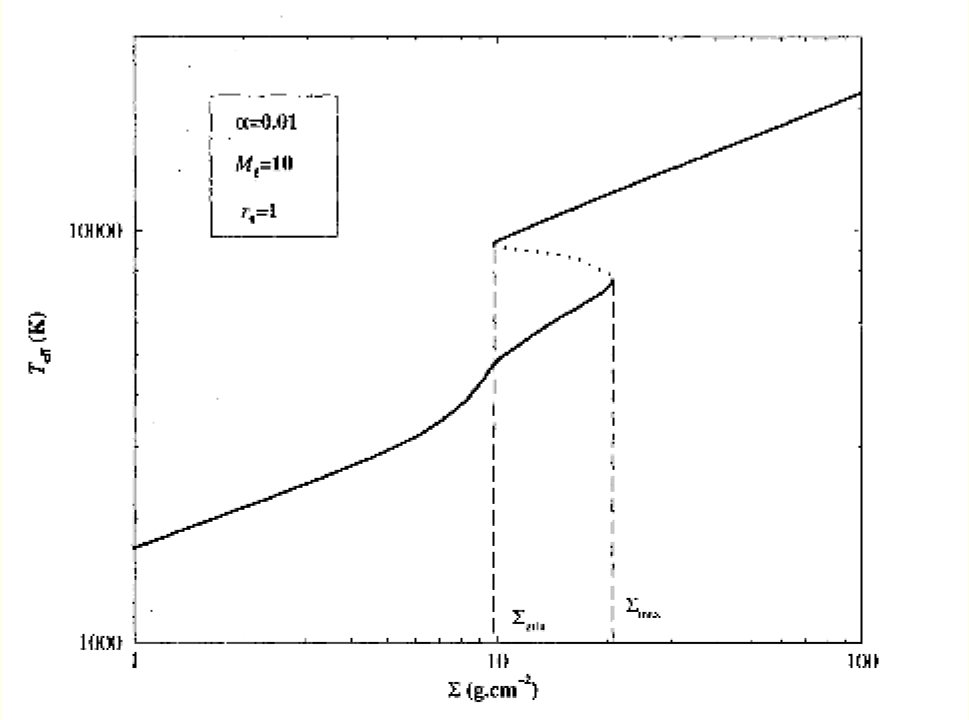


Leaky disks have mass-transfer rates consistent with GWR AML + small amount of additional (via currently not recognized mechanism) AML



MSW+GWR
GWR
log(dm/dt), M⊙/yr
−8
−9
−10
−11
−12
0.05
0.1
0.2
0.5
1
P, day

Thermal-viscous instability



If anywhere in the disk Teff corresponds to the middle branch, disk cannot be in stable equilibrium (no irradiation, no tidal heating or stream impact)

ANOTHER SOLUTION (Menou, Narayan, Lasota 1999):

whole quiescent disk is in cold termal equilibrium if at every *r* ***accretion rate***

dm/dt(r) < than certain *dm/dt(r, M1)crit.*

Hence, at the truncation radius (*dm/dt)in* < *dm/dt (rin, M1)*

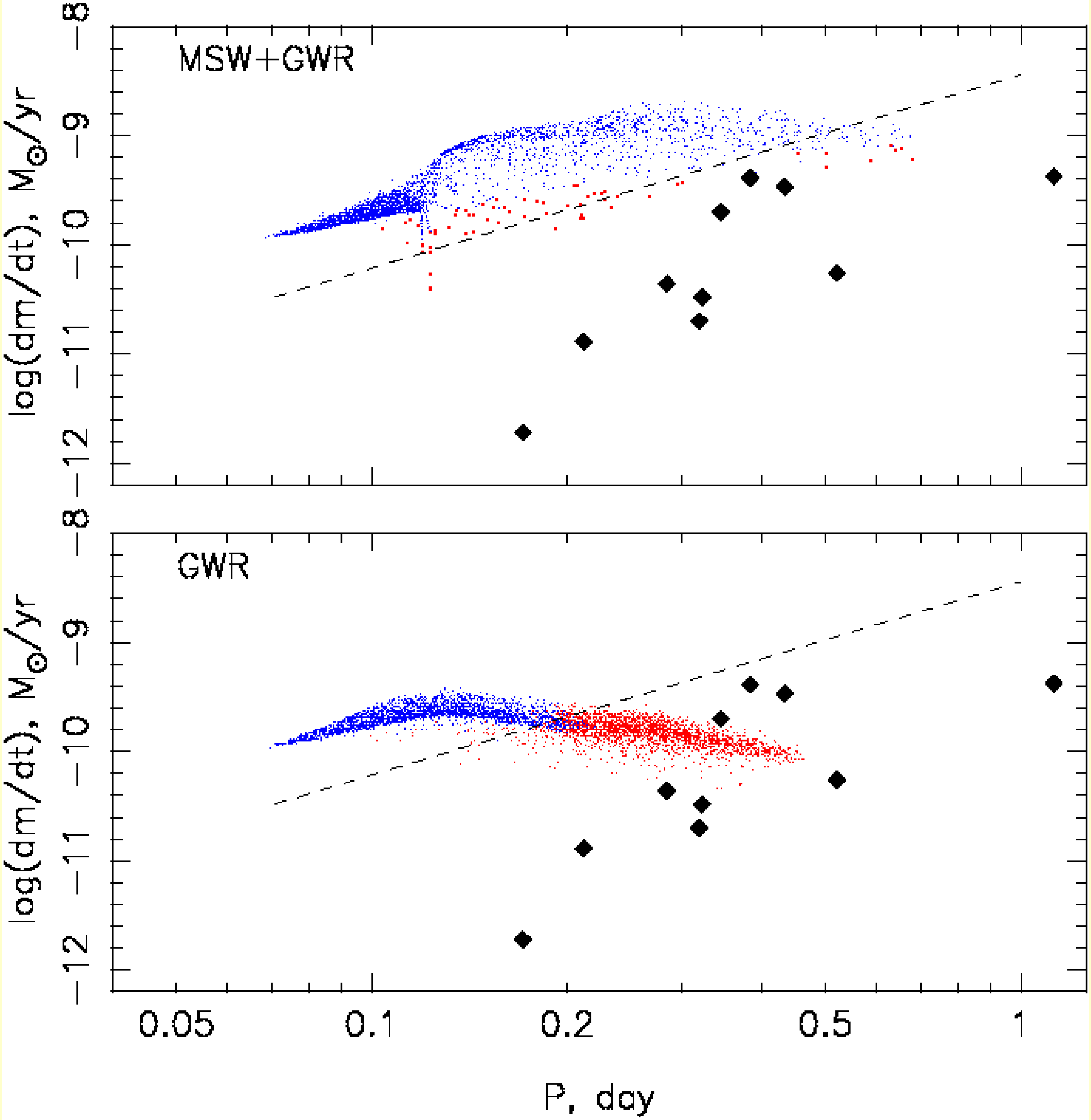
If truncation radius exceeds certain critical limit, disks are cold and globally stable, since then their accretion rates are sufficiently low.

Disks are cold and stable if

$$\dot{M} \lesssim 1.75 \cdot 10^{-9} \alpha^{-0.04} \left[(1+q)^{1.33} (0.5 - 0.227 \log q)^4 P_d^{0.67} f_t \right]^{2.67} M_\odot/yr$$

$$q = M_2/M_{bh}$$

$f_t < 0.48$ - truncation radius



truncation at 0.48Rcirc

blue – transient

red – cold and stable

About 50% are stable because of lower dm/dt

If truncation radius is ~Rcirc, it is possible that all systems are stable

Then SXT are a result of variability in dm/dt and/or truncation radius and not triggered by irradiated disk instability

Results of computations for two models

CONCLUSION

1. "Standard" (based on Skumanich rotation braking law) prescription for AML via magnetic braking produces unobserved persistent LMBHB, while pure GWR AML produces only transient systems. The strength of MSW AML should be significantly reduced.

2. A model with initially strongly evolved (X_c < several $0.01 M_{sun}$) cannot explain observed orbital periods of SXT.

3. Estimates of mass transfer rates in SXT based on energetics of the outbursts and recurrence times may be strongly underestimated since accretion disks are truncated and, hence, leaky.

4. An ALTERNATIVE model suggests that if accretion disks are truncated in quiescence they could be cold and stable. Then reduced (GWR+?) AML and truncation up to ~R_{circ} may make virtually all LMBHB cold and stable. SXT outbursts are not related to DIM and are random events that result from "external factors", like enhanced mass transfer?