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THE UNIVERSITY OF WARWICK

Binary Stars

(a small selection)

STFC Summer School 2008

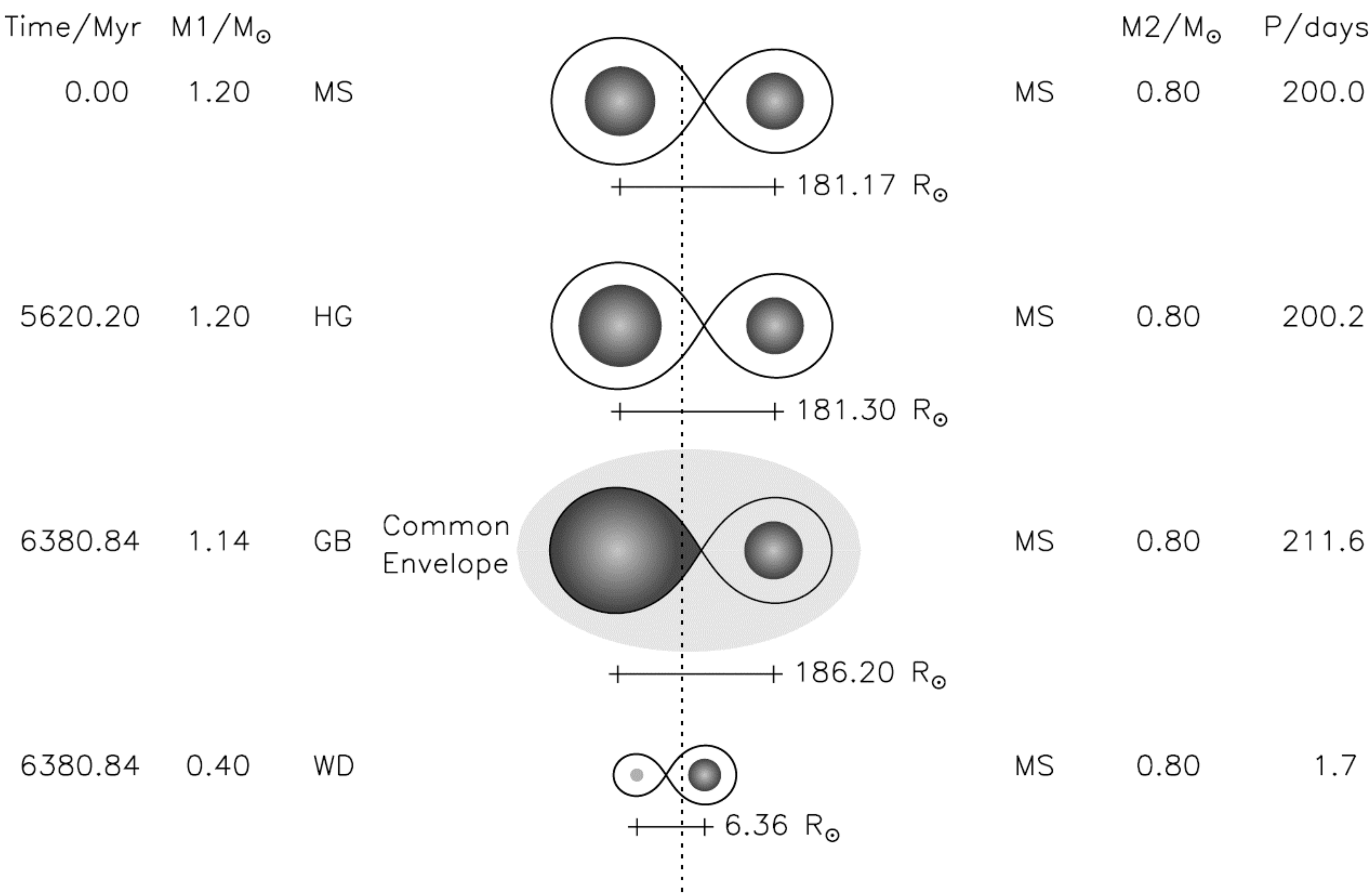
Why do we care about binary stars?

- 50% of all stars are in binaries
- (some kind of) white dwarf binaries are SNIa progenitors
- binary neutron star mergers make short γ-ray bursts
- Low-mass X-ray binaries, black hole binaries, milli-second pulsars, cataclysmic variables, symbiotic stars…

All compact binaries share some interesting physics

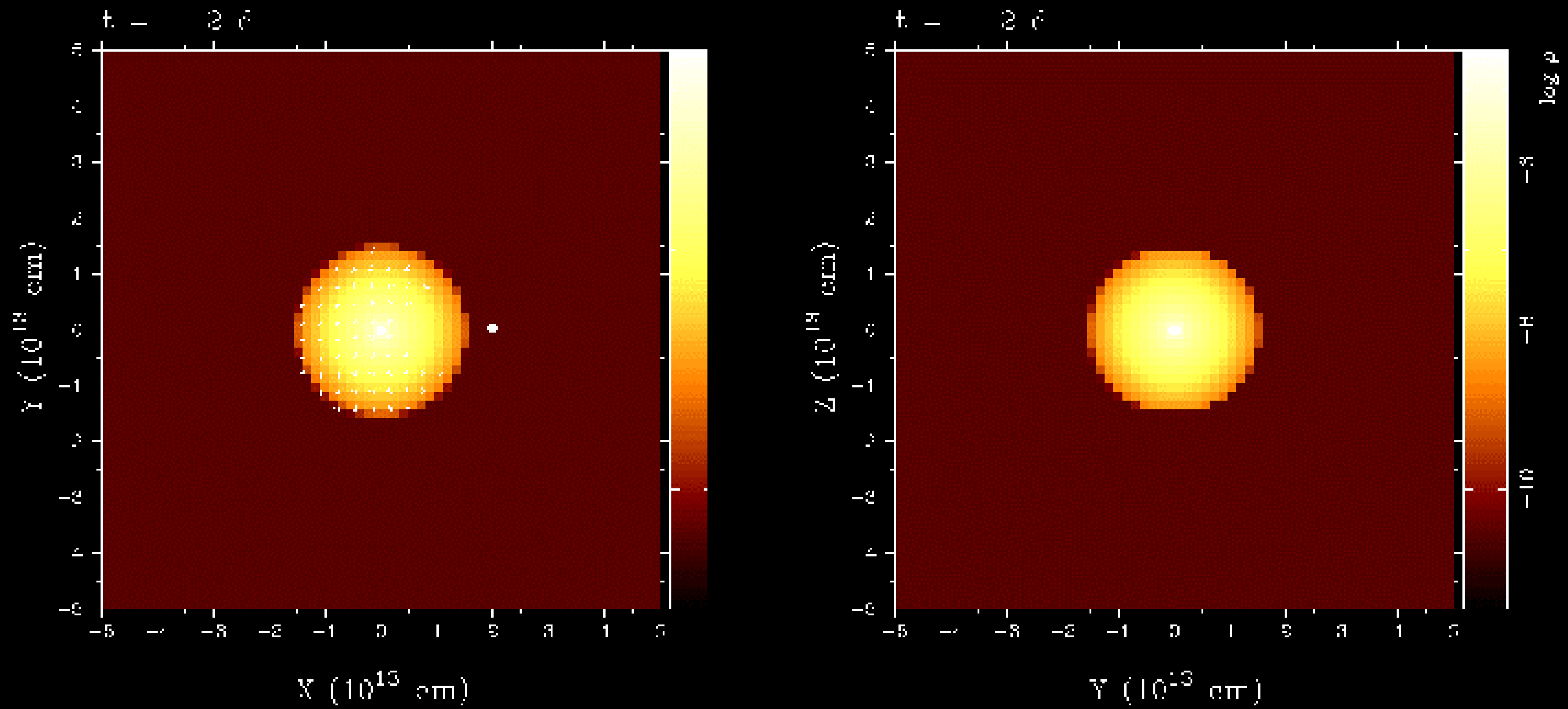
- go through at least one common envelope phase
- lose orbital angular momentum

Common envelope evolution



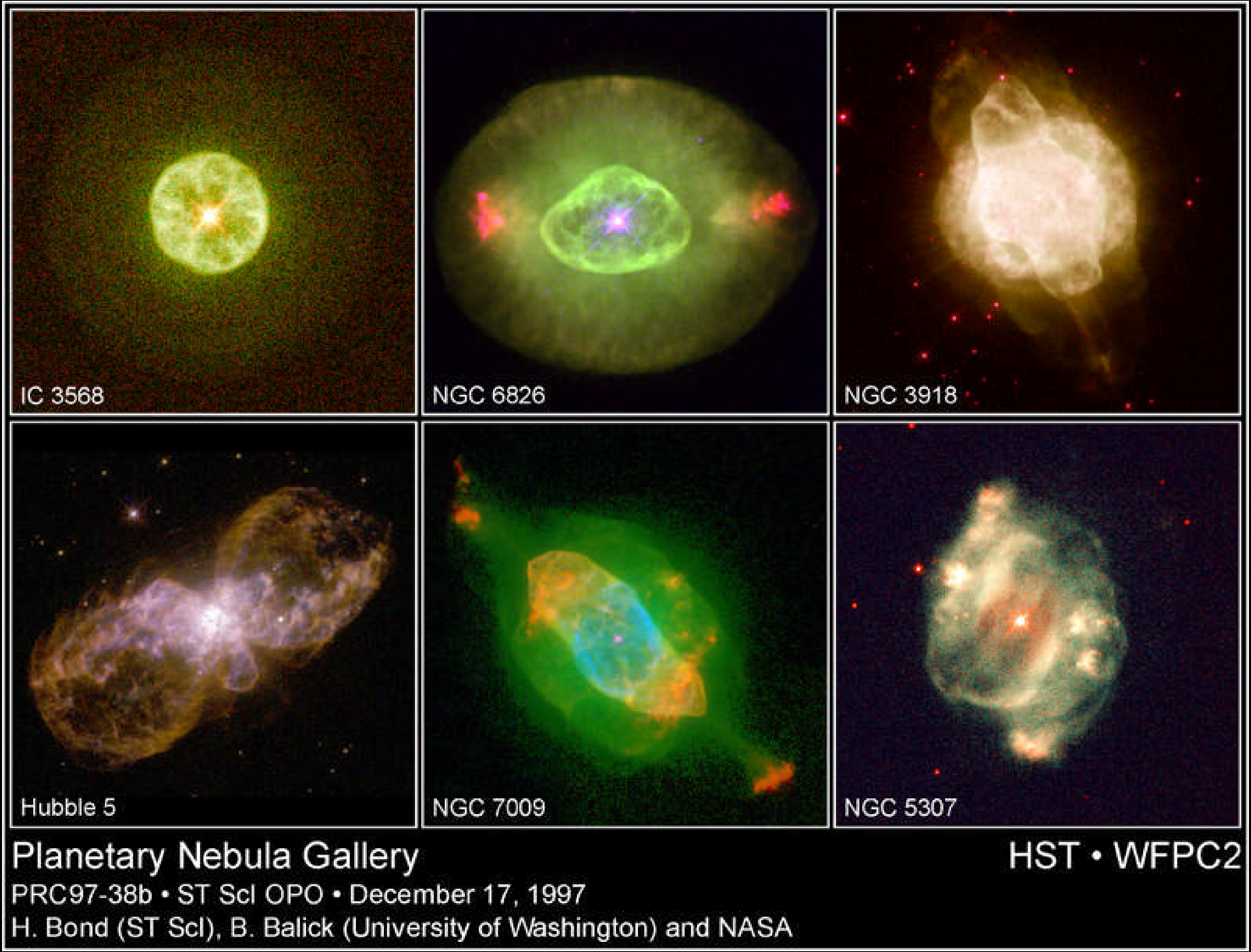
Willems & Kolb (2004)

Common envelope hydrodynamical models

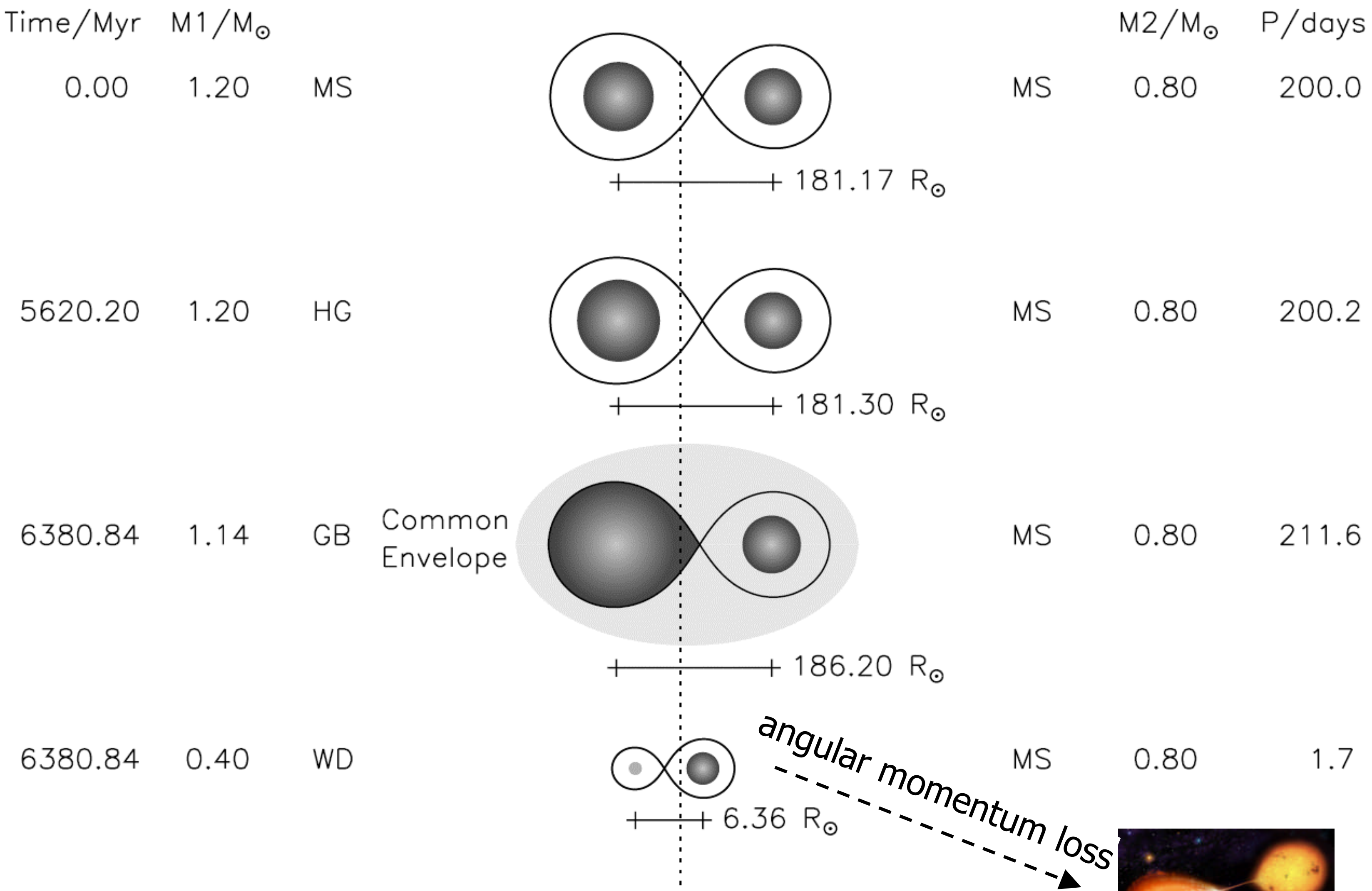


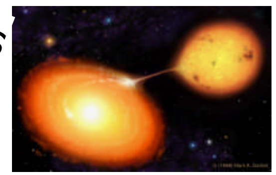
courtesy of E. Sandquist

Planetary nebula: spherical & bipolar



Common envelope evolution





Willems & Kolb (2004)

Gravitational wave radiation

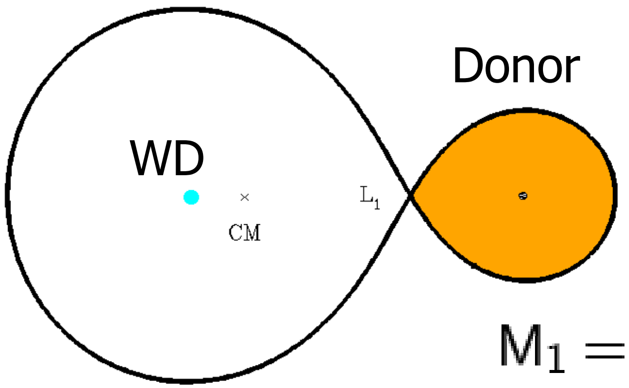
(Einsteins quadrupole eqation):

$$\dot{L}_{GR} = -\frac{32G^{7/3}}{5c^2} M_1^2 M_2^2 (M_1 + M_2)^{-2/3} \left(\frac{2\pi}{P}\right)^{7/3}$$

time scale for orbital decay: $(m_1 = M_1/M_\odot,\ m_2 = M_2/M_\odot)$

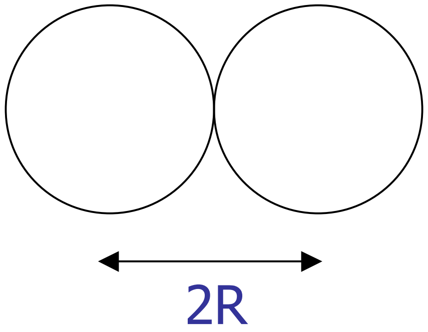
$$\tau_{GR} = -\left(\frac{L}{\dot{L}}\right) = 3.8 \times 10^{11} \frac{(m_1 + m_2)^{1/3}}{m_1 m_2} P(d)^{8/3} \mathrm{yr}$$

Examples



typical cataclysmic variable

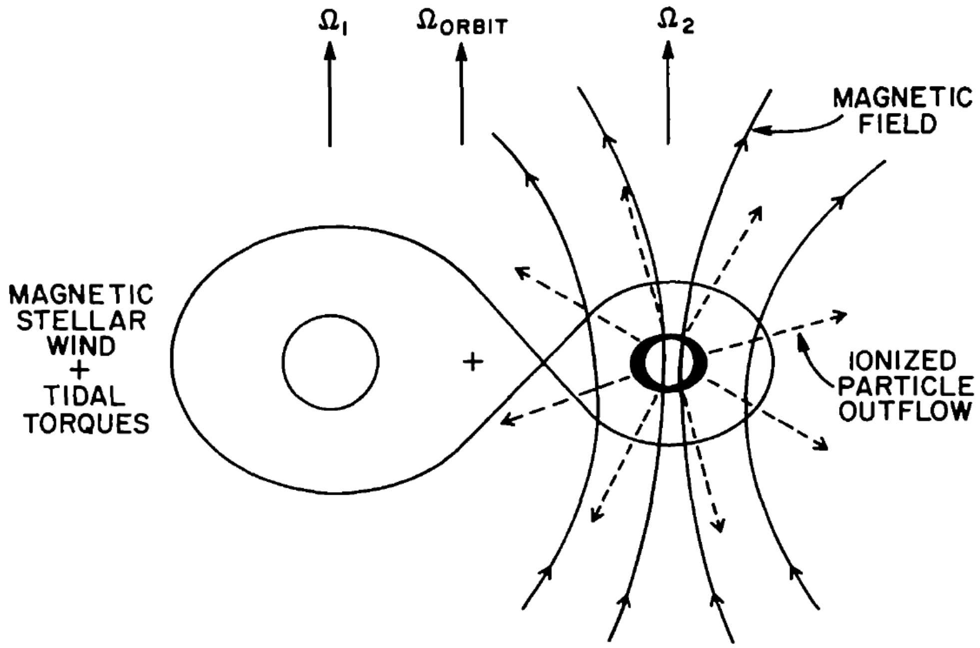
$$M_1 = 0.6\odot,\ M_2 = 0.2\odot,\ P = 2.5\mathrm{h} \Longrightarrow \tau_{GR} = 7 \times 10^9 \mathrm{yr}$$



WD-WD merger

$$M_1 = 0.6\odot,\ M_2 = 0.6\odot,\ P = 32\mathrm{sec!} \Longrightarrow \tau_{GR} \approx 790\mathrm{yr}$$

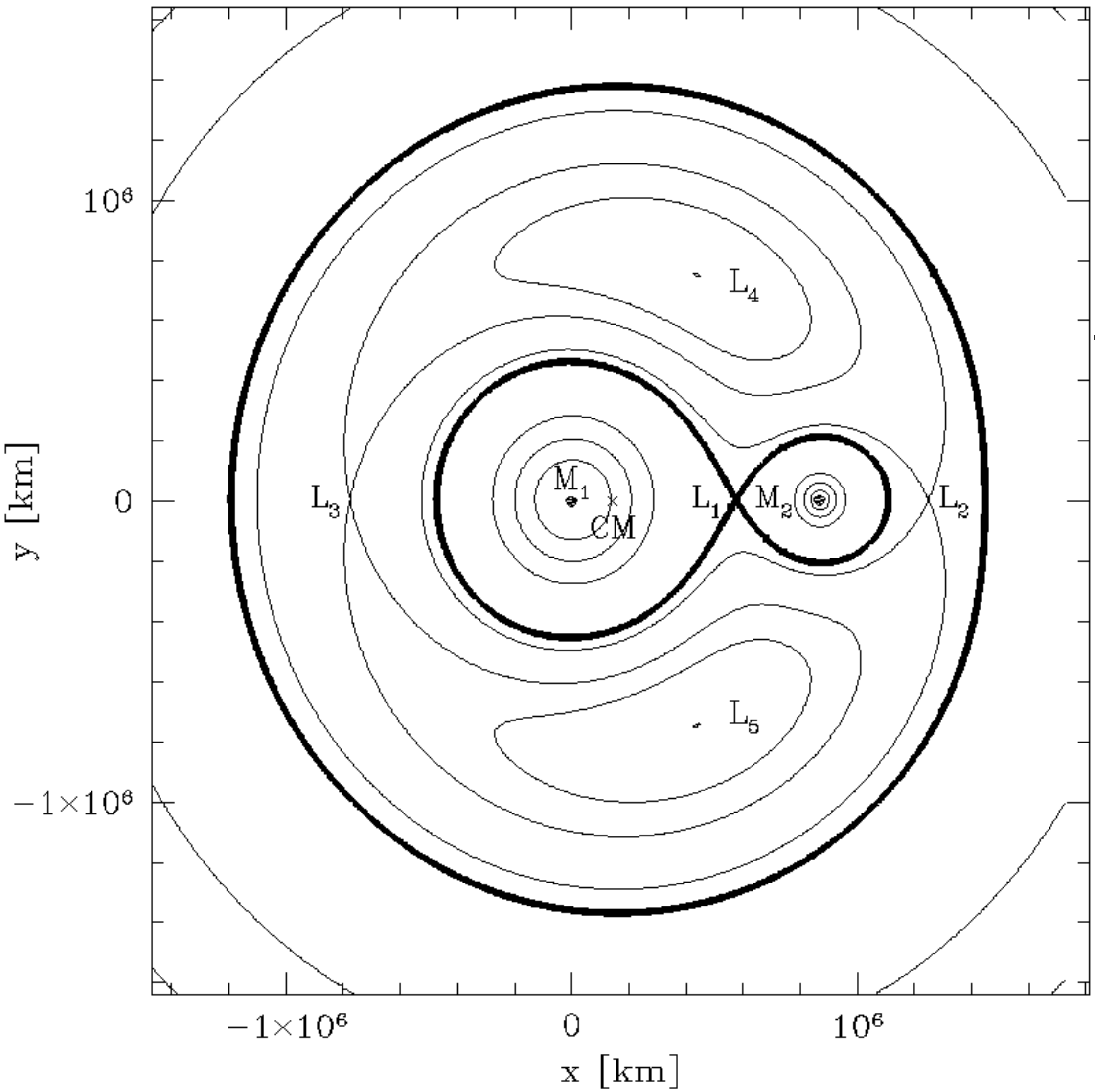
Stellar magnetic wind braking



time scale for orbital decay: $(m_1 = M_1/M_\odot,\ m_2 = M_2/M_\odot,\ r_2 = R_2/R_\odot)$

$$\tau_{MB} = -\left(\frac{L}{\dot{L}}\right) = 2.2 \times 10^9 \frac{m_1}{(m_1 + m_2)^{1/3}} r_2^{-4} P(d)^{10/3} \mathrm{yr}$$

Equipotential contours in a binary star



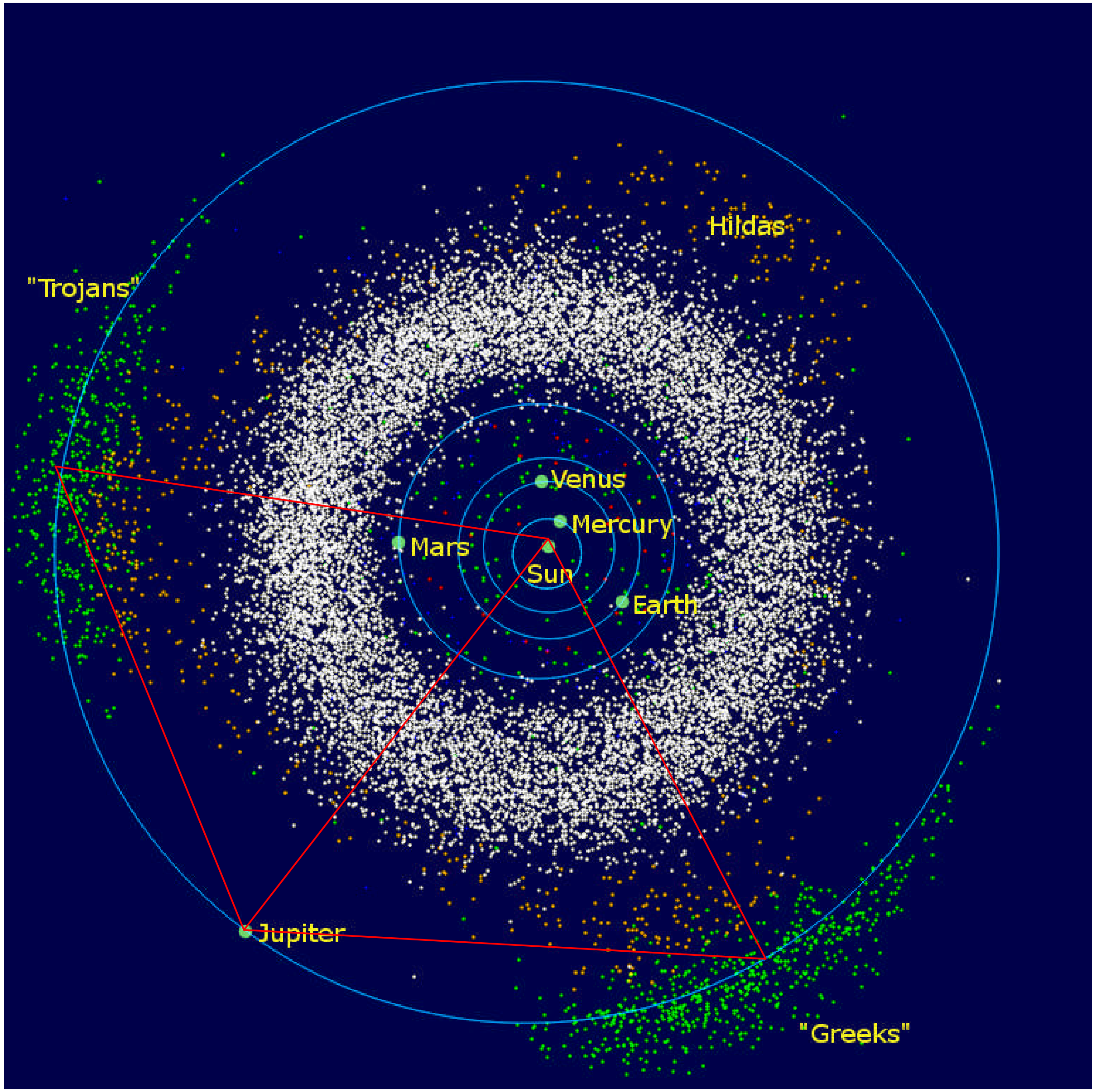
$$\phi = -G\frac{M_1}{R_1} - G\frac{M_2}{R_2} - \phi_z$$

Edouard Roche (1820-1883)

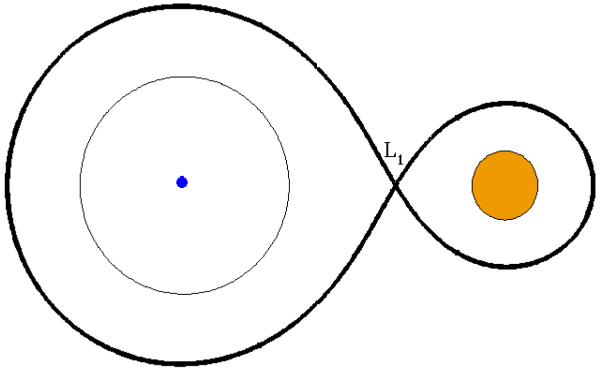
Joseph Lagrange (1736-1813)

$$M_1 = 1.0\,M_\odot$$
$$M_2 = 0.2\,M_\odot$$
$$P_{orb} = 3.5h$$

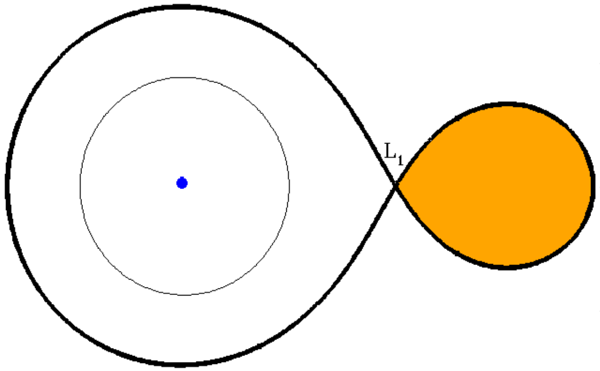
Jupiter-Sun: Trojan asteroids in $L_{4\&5}$



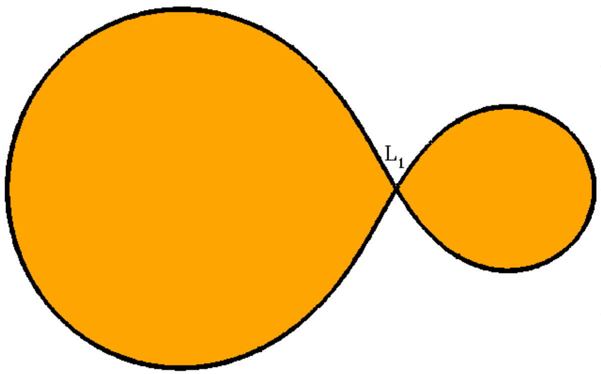
Binary star configurations and mass transfer



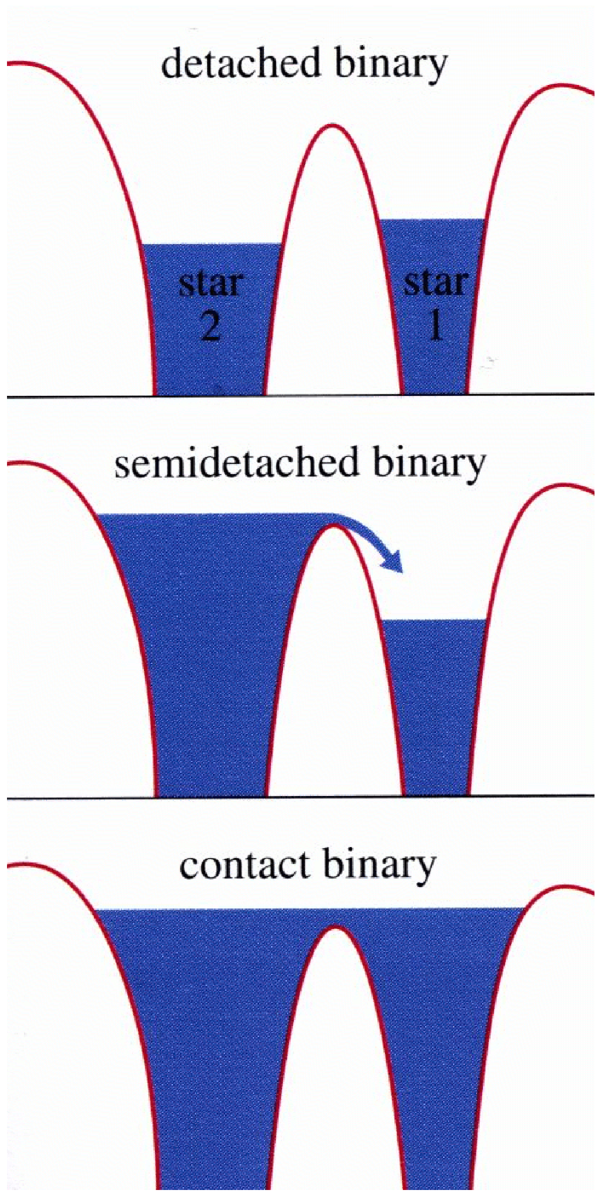
Detached



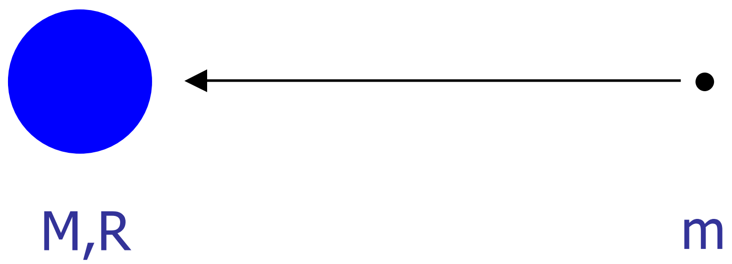
Semidetached:
mass transfer via
Roche lobe overflow



Contact



Gravitational (potential) energy



surface gravity: $g = \frac{GM}{r^2}$

grav. force: $F = mg$

work: $dE = Fdr$

total work / potential energy: $E = m \int_R^\infty g dr = m \int_R^\infty \frac{GM}{r^2} dr$

$$E = m \left[\frac{GM}{r} \right]_R^\infty$$

$$\boxed{E = \frac{GMm}{R}}$$

Accretion: a gravitational power plant

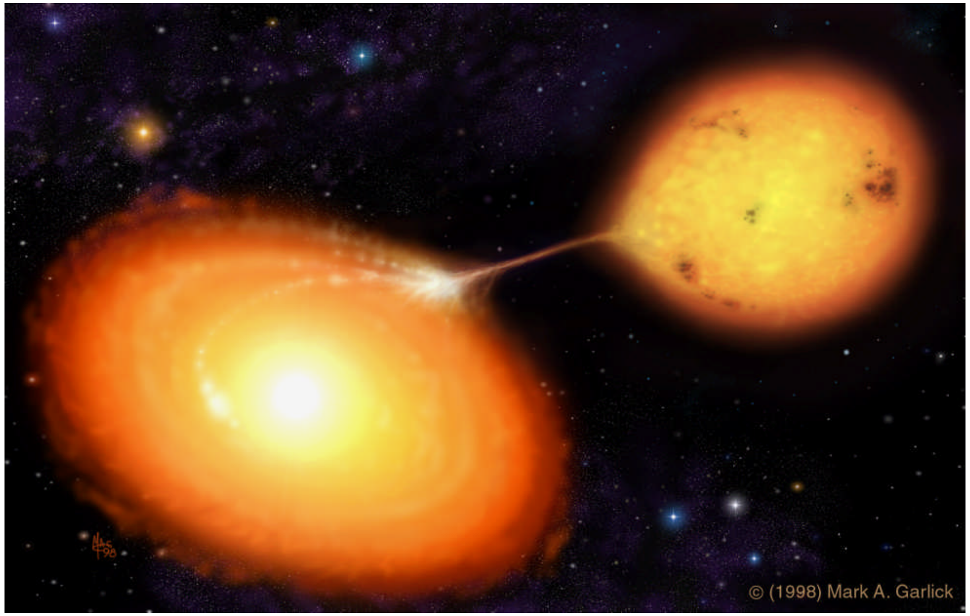
potential energy: $\frac{GM_c m}{R_c}$

$\longrightarrow$ kinetic energy: $\frac{1}{2}mv^2$

$\longrightarrow$ thermal energy: $\frac{3}{2}kT$

$\longrightarrow$ radiation: $h\nu$

Examples: White dwarf



$$M = 0.6M_{\odot} \qquad (M_{\odot} = 2 \times 10^{30}\text{kg})$$

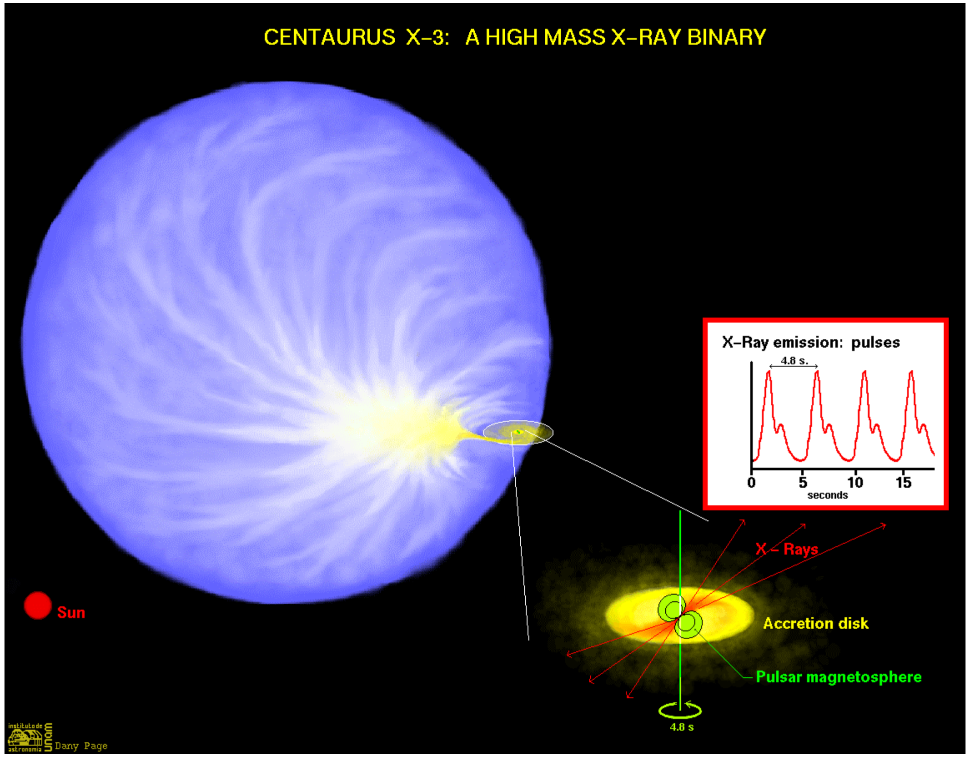
$$R = 10^7\text{m}$$

$$E = \frac{GMm}{R}$$

$$G = 6.67 \times 10^{-11}\text{Nm}^2\text{kg}^{-2}$$

$$E = 8 \times 10^{12}\text{Jkg}^{-1}$$

Example: Neutron star



$$M = 1.4 M_{\odot} \qquad (M_{\odot} = 2 \times 10^{30} \mathrm{kg})$$

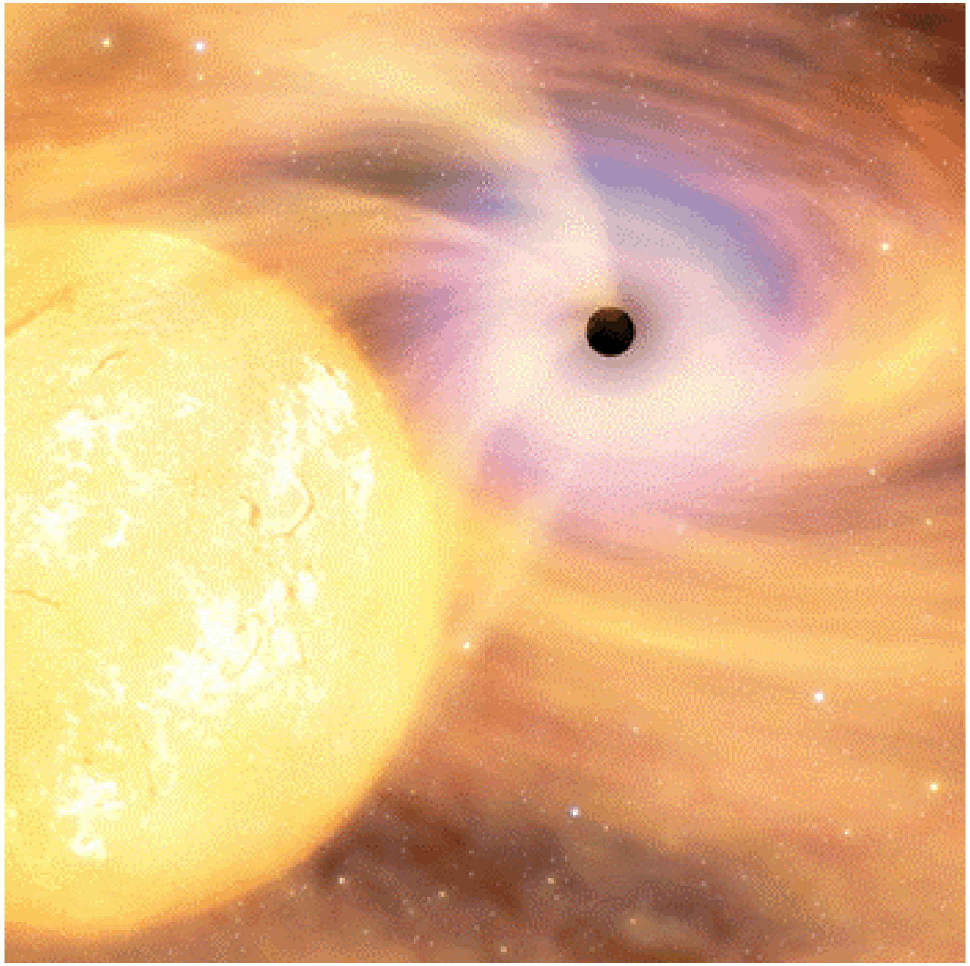
$$R = 10 \mathrm{km} = 10^4 \mathrm{m}$$

$$E = \frac{GMm}{R}$$

$$G = 6.67 \times 10^{-11} \mathrm{Nm^2 kg^{-2}}$$

$$E = 1.9 \times 10^{16} \mathrm{J kg^{-1}}$$

Example: Stellar black hole



$$M = 6M_\odot \qquad (M_\odot = 2 \times 10^{30}\text{kg})$$

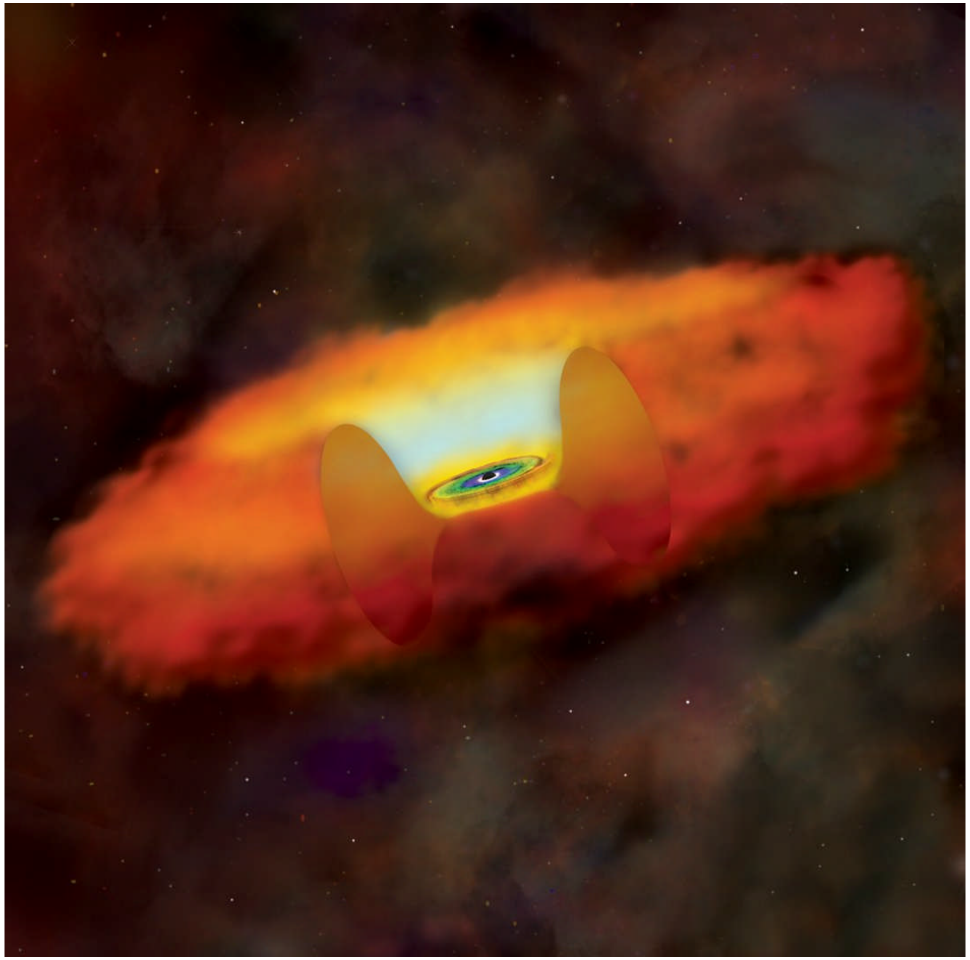
$$R = R_s = \frac{2GM}{c^2} = 17.8\text{km}$$

$$E = \frac{GMm}{R}$$

$$G = 6.67 \times 10^{-11}\text{Nm}^2\text{kg}^{-2}$$

$$E = 4.5 \times 10^{16}\,\text{Jkg}^{-1}$$

Example: Active galactic nucleus (AGN)



$$M = 10^8 M_\odot \qquad (M_\odot = 2 \times 10^{30}\text{kg})$$

$$R = R_s = \frac{2GM}{c^2} = 3 \times 10^{11}\text{km} = 2\text{AU}$$

$$E = \frac{GMm}{R}$$

$G = 6.67 \times 10^{-11}\text{Nm}^2\text{kg}^{-2}$

$$E = 4.5 \times 10^{16}\text{Jkg}^{-1}$$

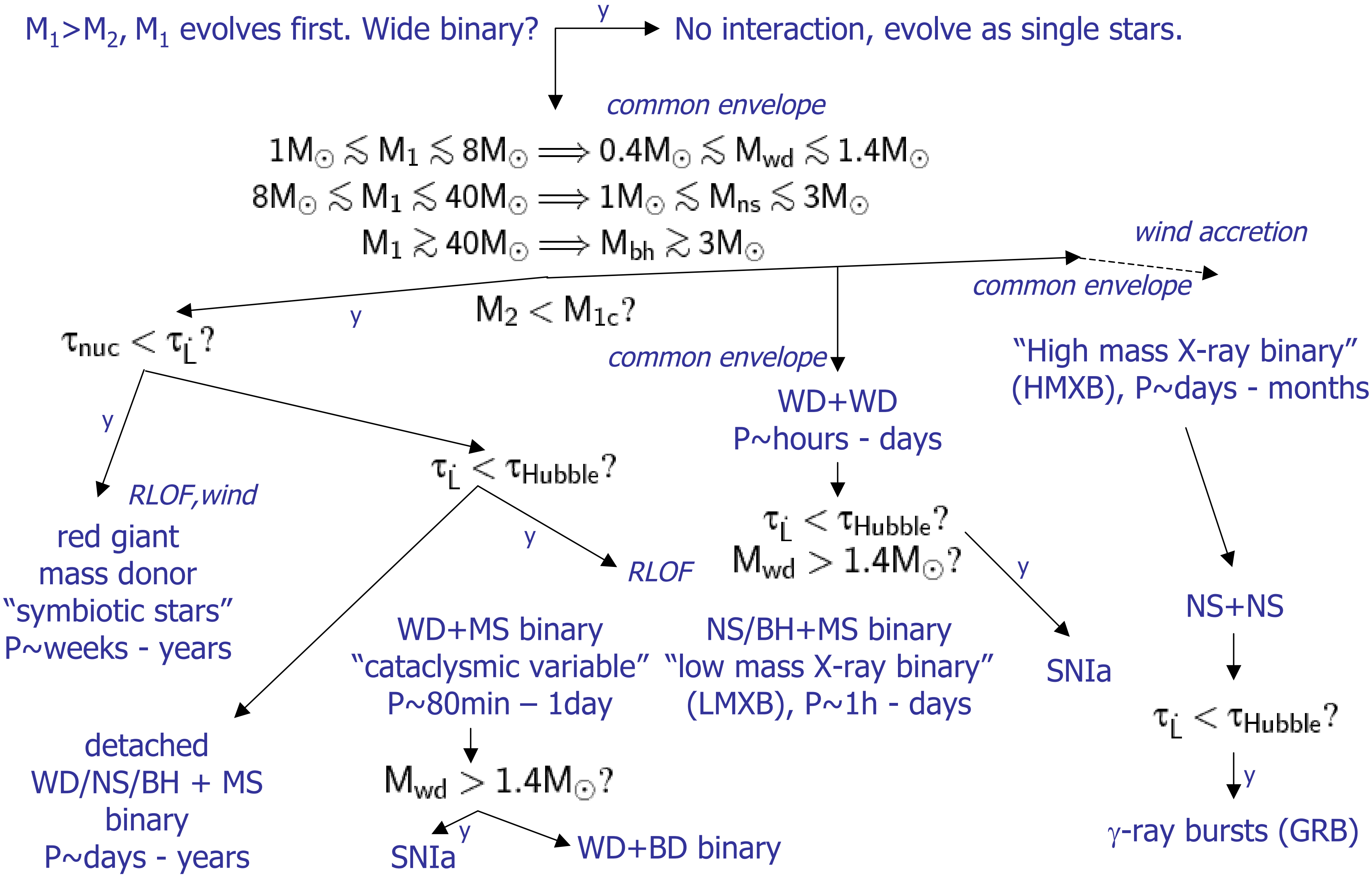
$$M = \frac{Rc^2}{2G}$$

$$E = \frac{GRc^2m}{2RG} = \frac{1}{2}mc^2$$

Accretion onto compact objects

Process	Jkg^{-1}	$f(\mathrm{H} \Longrightarrow \mathrm{He})$	$f(mc^2)$
H$\Longrightarrow$He ($E = \Delta M c^2$)	6.3×10^{14}	1.0	0.007
Accretion onto white dwarf	8.0×10^{12}	1/80	8.9×10^{-5}
Accretion onto Neutron star	1.9×10^{16}	30	0.21
Accretion onto Black hole	4.5×10^{16}	70	0.5

Binary star zoology



Binary star zoology

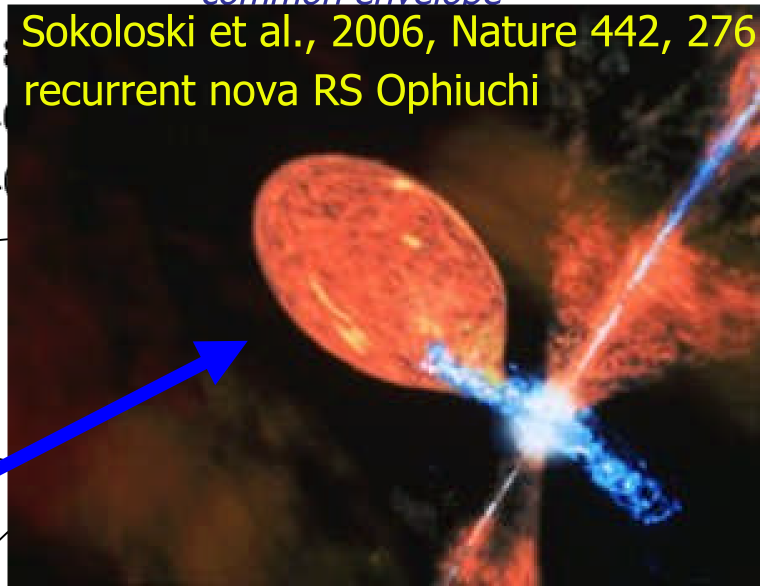
$M_1 > M_2$, M_1 evolves first. Wide binary? — y → No interaction, evolve as single stars.

common envelope

$1M_\odot \lesssim M_1 \lesssim$ 8...

$8M_\odot \lesssim M_1 \lesssim$ 4...

$M_1 \gtrsim$ 4...



wind accretion

...mmon envelope

"High mass X-ray binary" (HMXB), P~days - months

y

$\tau_{nuc} < \tau_{\dot{L}}$?

y

RLOF,wind

red giant
mass donor
"symbiotic stars"
P~weeks - years

$\tau_{\dot{L}}$

y

RLOF

$M_{wd} > 1.4M_\odot$?

y

NS+NS

WD+MS binary
"cataclysmic variable"
P~80min – 1day

NS/BH+MS binary
"low mass X-ray binary"
(LMXB), P~1h - days

SNIa

$\tau_{\dot{L}} < \tau_{Hubble}$?

y

detached
WD/NS/BH + MS
binary
P~days - years

$M_{wd} > 1.4M_\odot$?

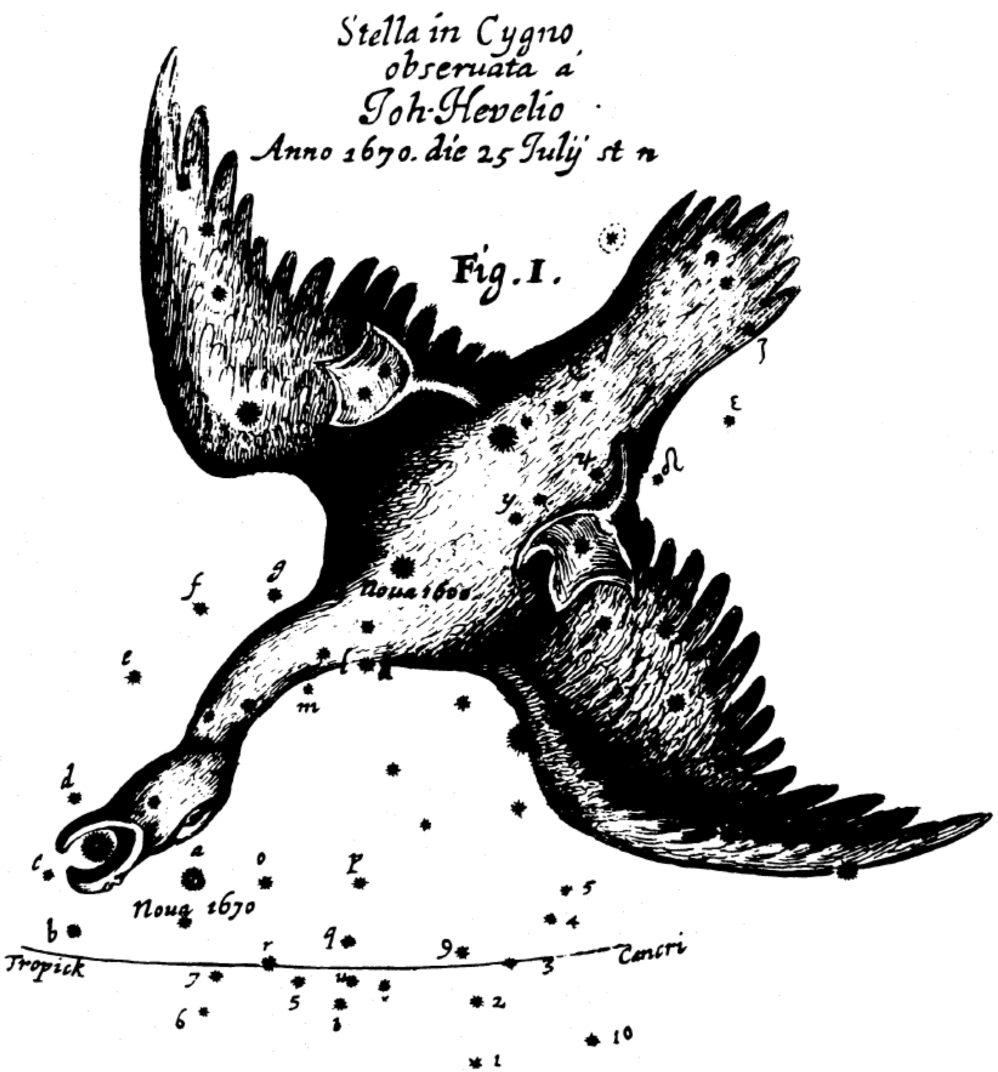
y

SNIa

WD+BD binary

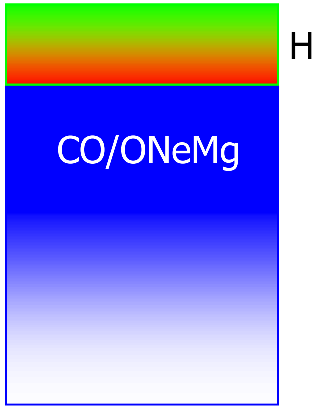
γ-ray bursts (GRB)

CK Vul = Nova Vulpeculae 1670



Hevelius (1670, Phil. Trans. Roy. Soc. 5, No. 65, 2087)

Classical novae: explosive hydrogen shell burning



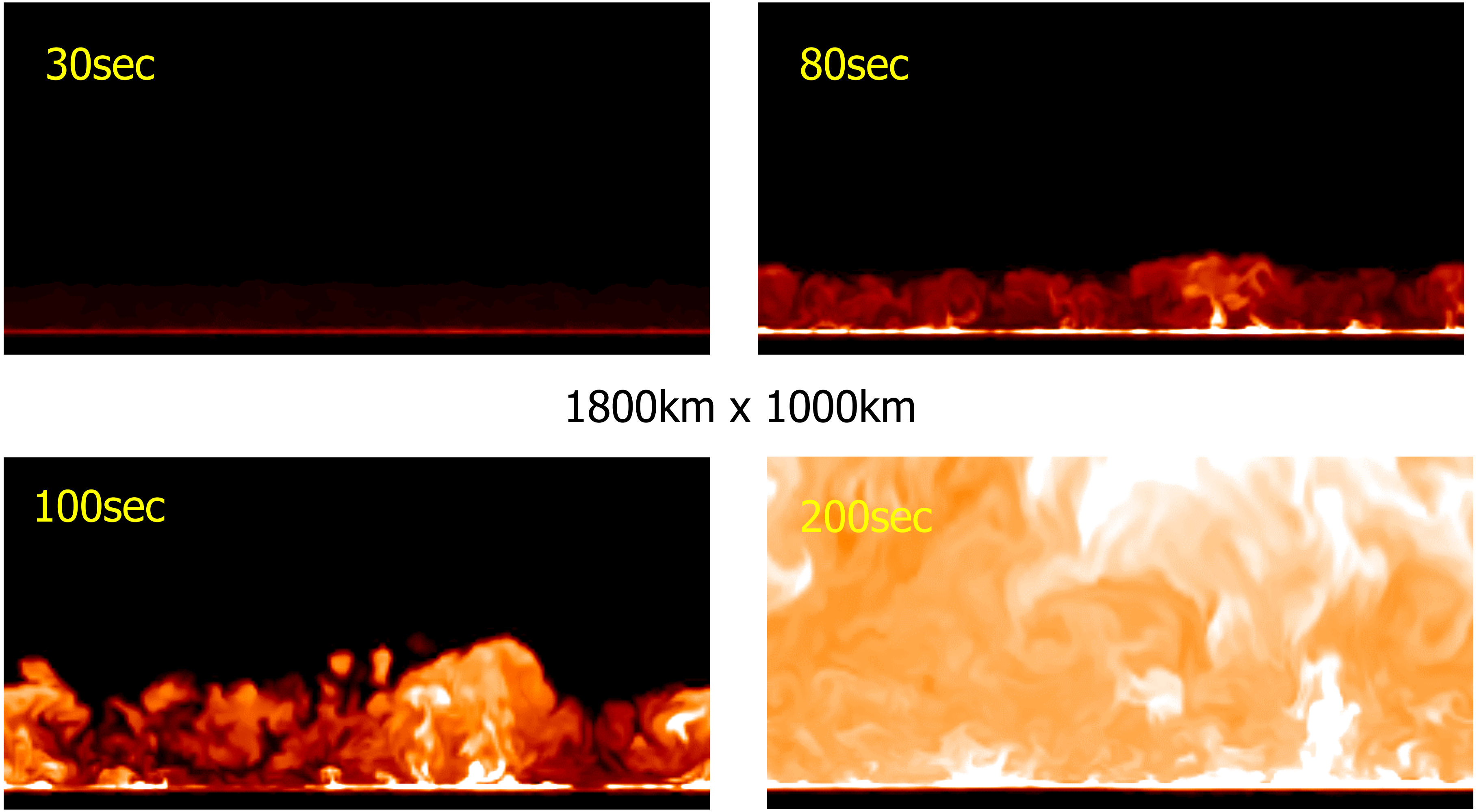
- accretion builds up an envelope of hydrogen
- T & P at the base of the envelope increase
- Eventually, conditions for p-p fusion are met
- If the base of the envelope is degenerate,

$$\rho \neq f(T) \Longrightarrow T \uparrow$$

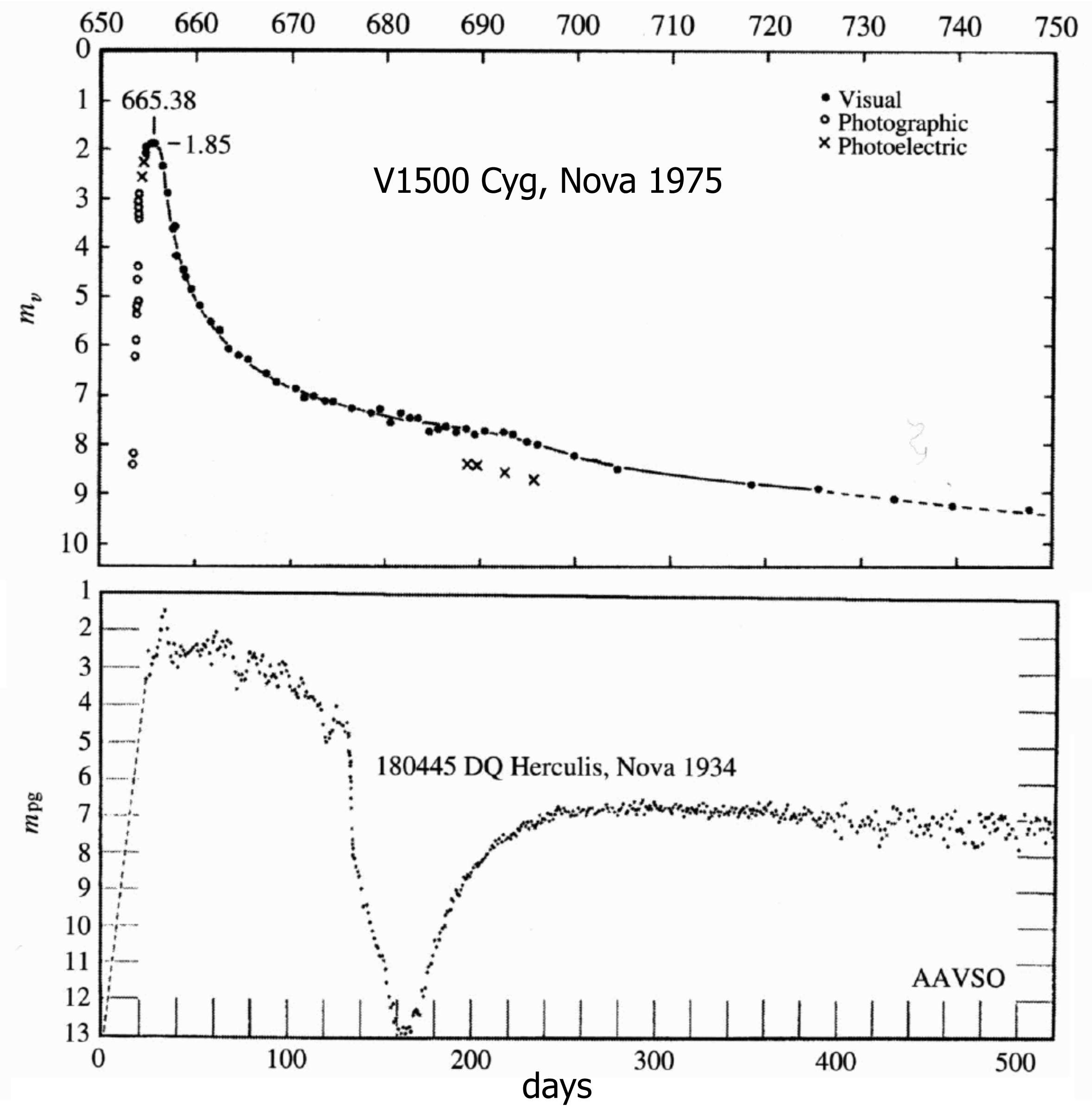
- At $T \simeq 2 \times 10^7 K$, CNO burning takes over, $E_{CNO} \propto T^{16}$

- $^{13}N, ^{14}O, ^{15}O, ^{17}F$ are radioactive (β^-) with h.l. times of ~100-1000s deposit large amounts of energy in the envelope
- Eventually, $E_{th} > E_F$ degeneracy is lifted, and the nova shell expands
- Enrichment in Ne is observed in some nova, suggests dredge-up from the white dwarf core

Hydrodynamical simulations: ^{14}O concentration



Typical classical novae



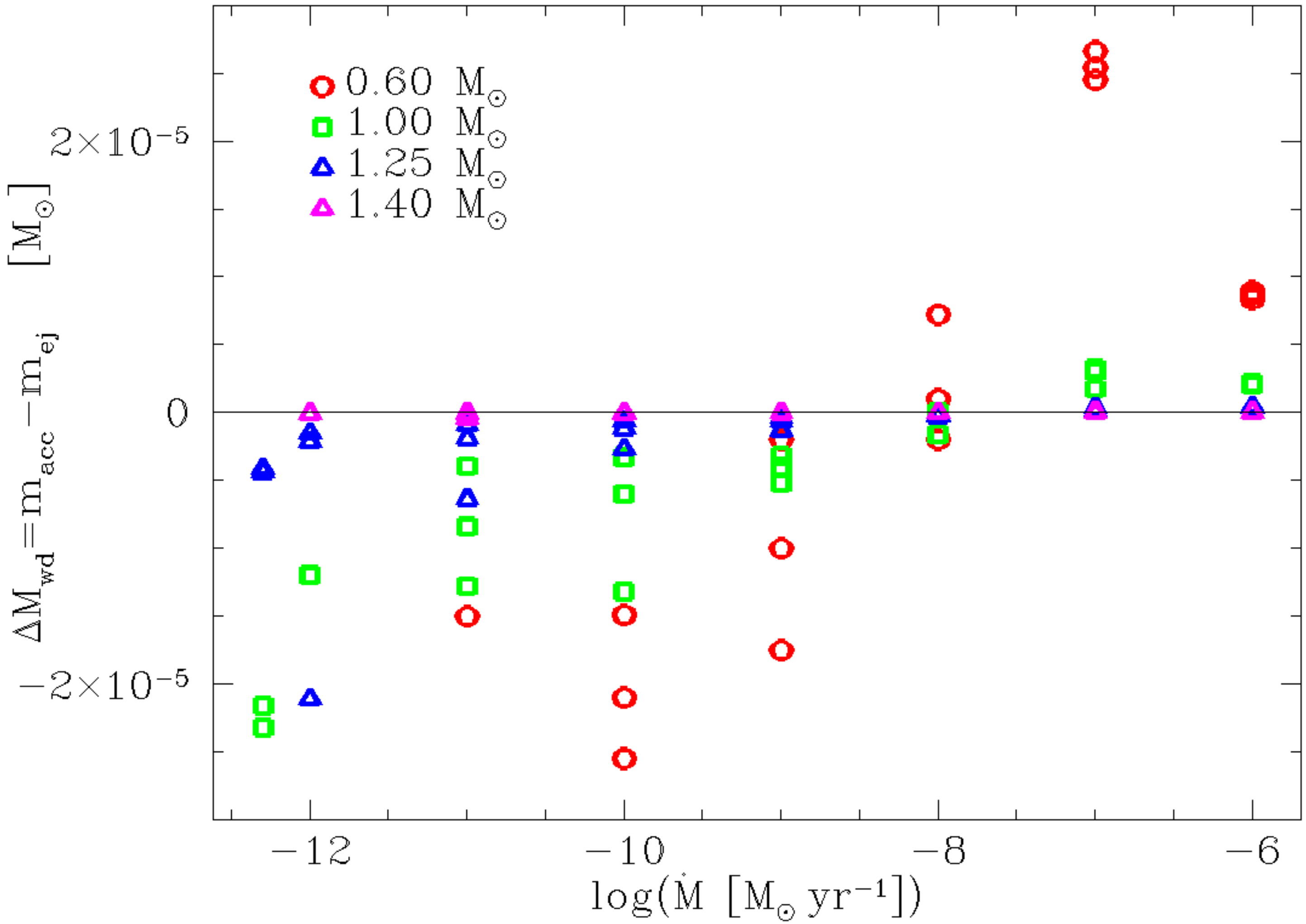
$V_{min} \simeq 18.6 \Longrightarrow \Delta m \simeq 16.7$

$\Longrightarrow \Delta L \simeq 4.4 \times 10^6$

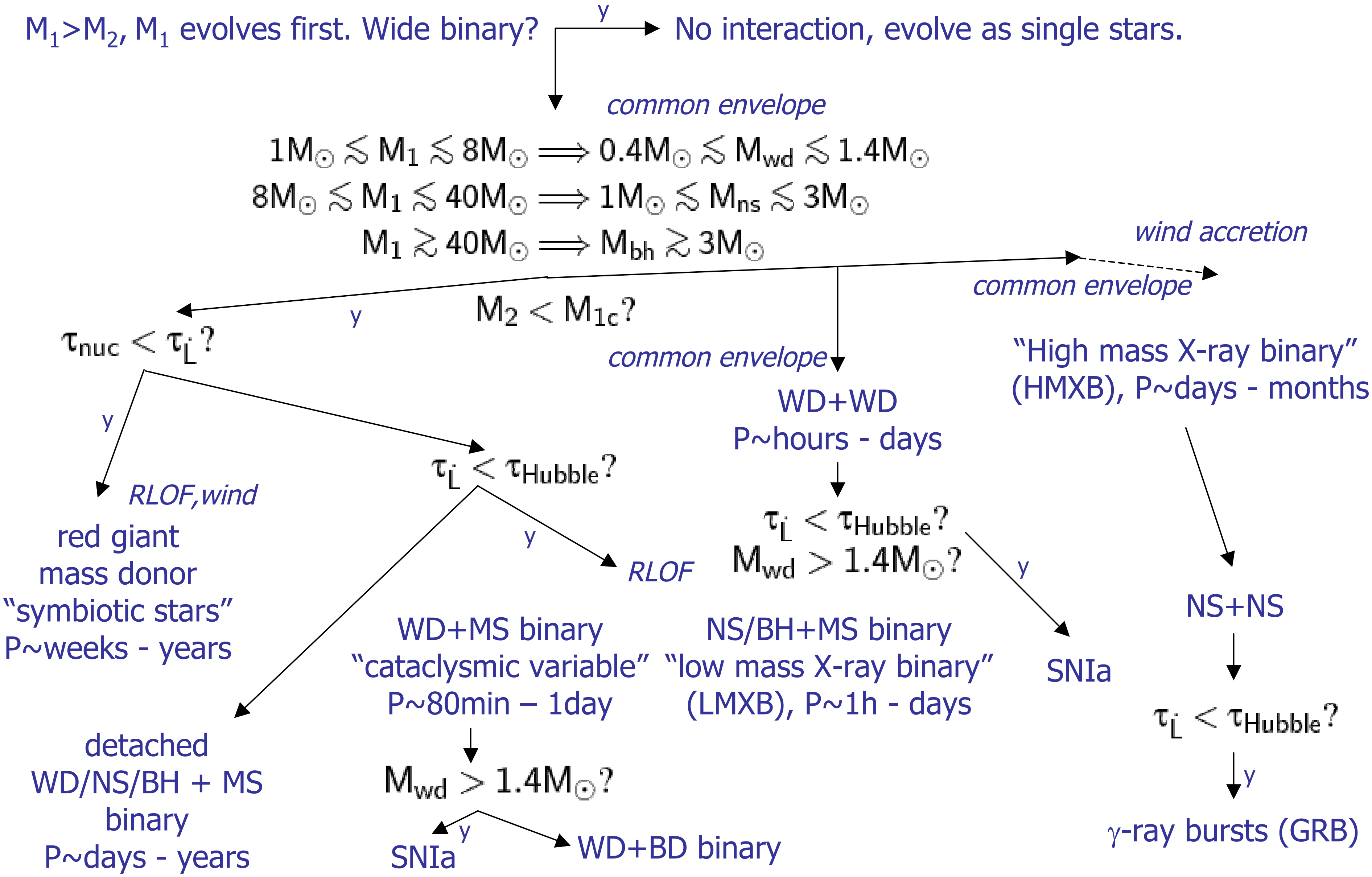
$V_{min} \simeq 17.7 \Longrightarrow \Delta m \simeq 15.7$

$\Longrightarrow \Delta L \simeq 1.9 \times 10^6$

Does the white dwarf grow in mass ...?



Binary star zoology



Binary star zoology

$M_1 > M_2$, M_1 evolves first. Wide binary? —y→ No interaction, evolve as single stars.

common envelope

$$1M_\odot \lesssim M_1 \lesssim 8M_\odot \Longrightarrow 0.4M_\odot \lesssim M_{wd} \lesssim 1.4M_\odot$$
$$8M_\odot \lesssim M_1 \lesssim 40M_\odot \Longrightarrow 1M_\odot \lesssim M_{ns} \lesssim 3M_\odot$$
$$M_1 \gtrsim 40M_\odot \Longrightarrow M_{bh} \gtrsim 3M_\odot$$

wind accretion

y

$\tau_{nuc} < \tau_L$?

y

RLOF,wind

red giant
mass donor
"symbiotic stars"
P~weeks - years


Maxted et al., 2006, Nature 442, 543

ary"
onths

WI
"catac
P~

$\tau_L < \tau_{Hubble}$?

detached
WD/NS/BH + MS
binary
P~days - years

$M_{wd} > 1.4M_\odot$?

y

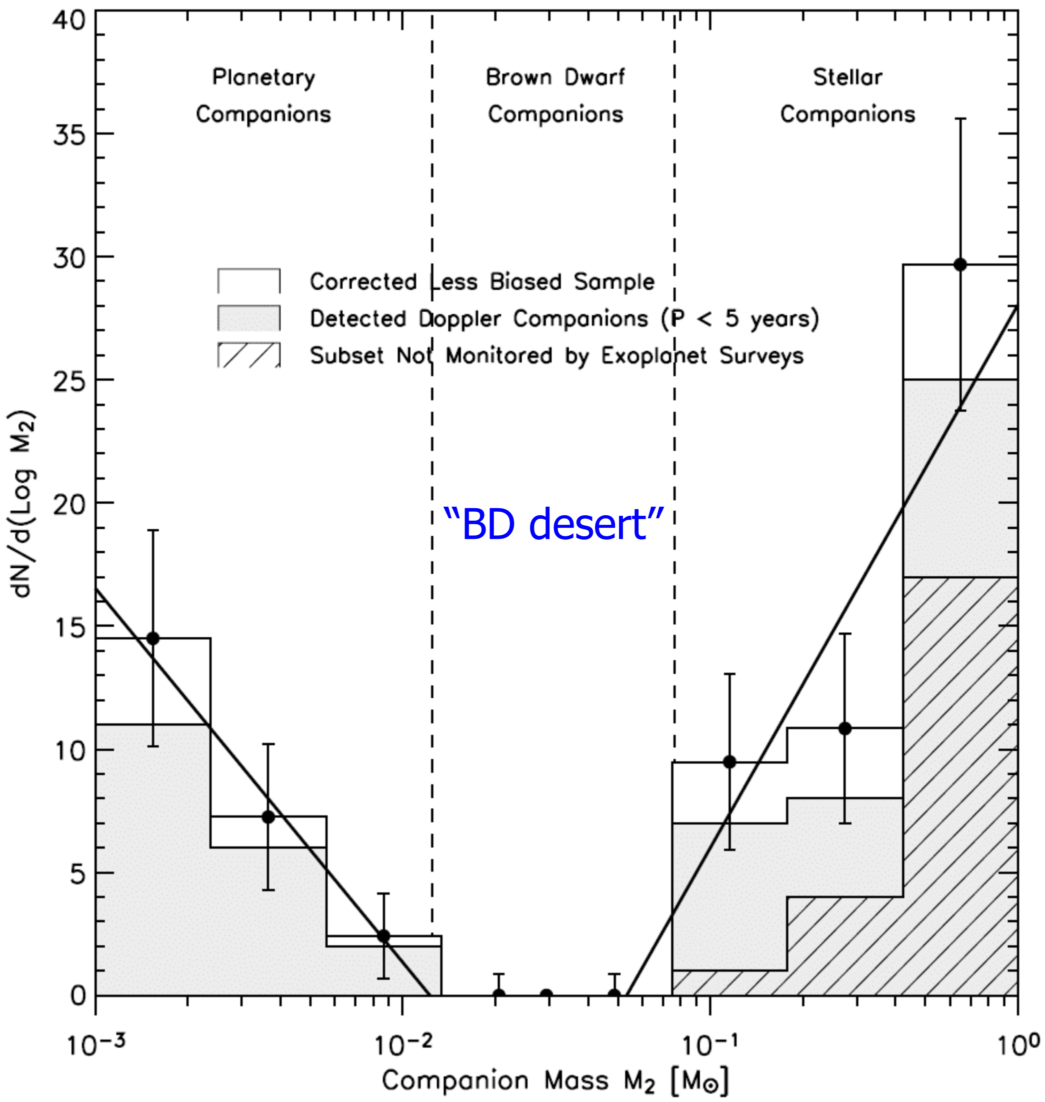
SNIa

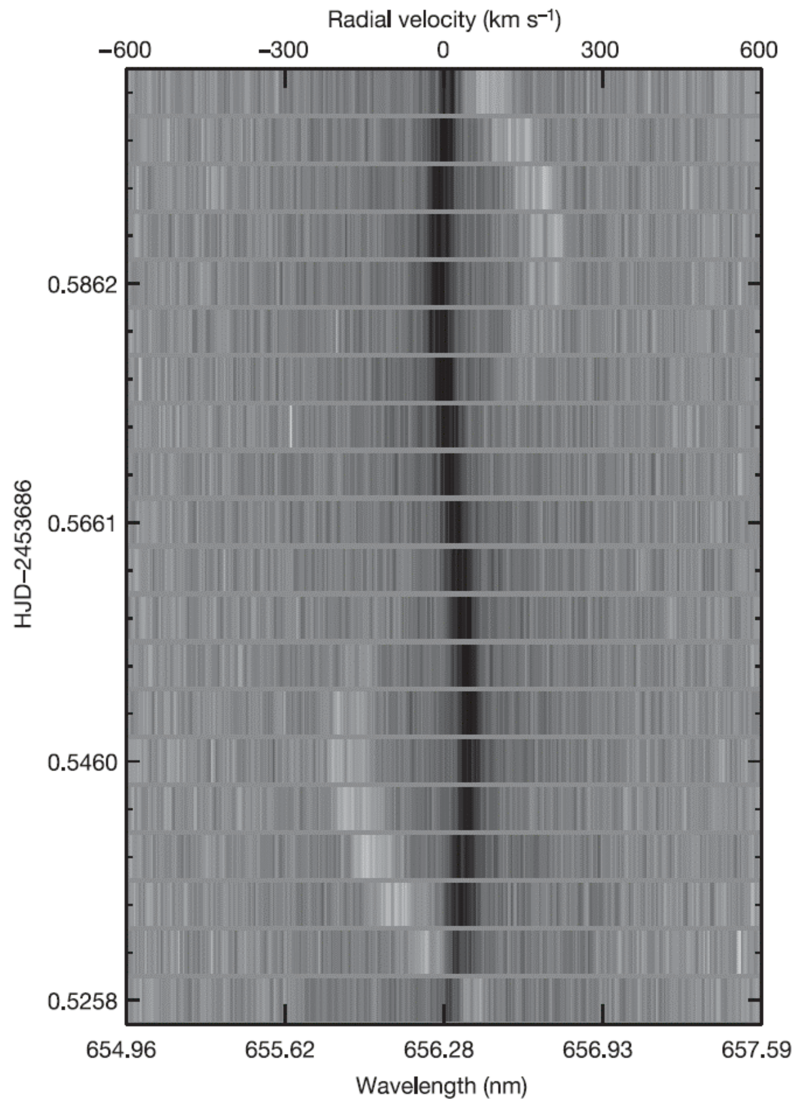
WD+BD binary

y

γ-ray bursts (GRB)

Mass distribution of MS-MS binaries

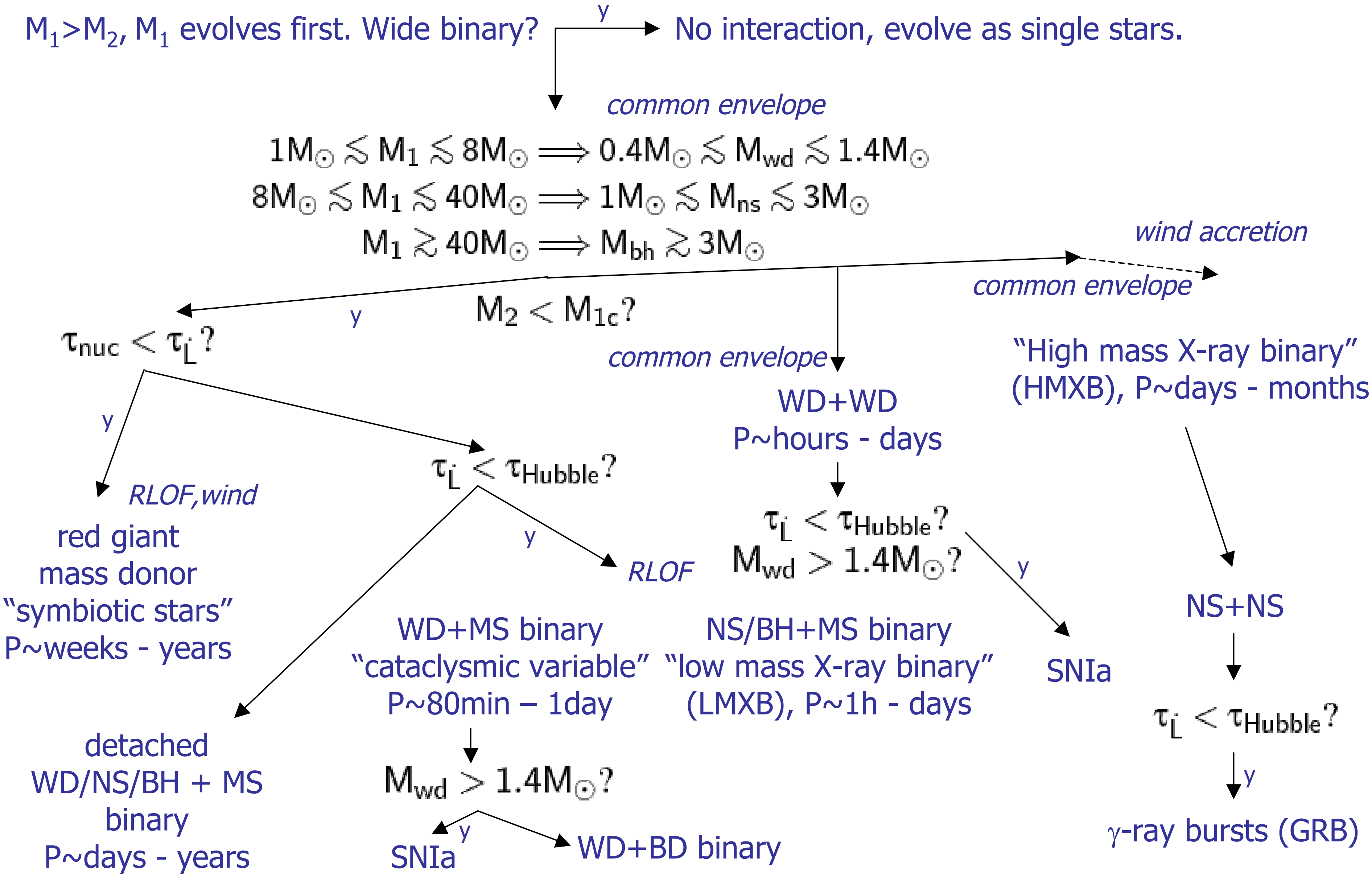




Grether & Lineweaver (2006, ApJ 640 1051)

Maxted et al. (2006, Nature 442, 543)

Binary star zoology



$M_1 > M_2$, M_1 evolves first. Wide

$1M_\odot \lesssim M_1$

$8M_\odot \lesssim M_1$

M_1

y

$\tau_{nuc} < \tau_L$?

y

RLOF,wind

red giant
mass donor
"symbiotic stars"
P~weeks - years

detached
WD/NS/BH + MS
binary
P~days - years

y

RLOF

WD+MS binary
"cataclysmic variable"
P~80min – 1day

$M_{wd} > 1.4M_\odot$?

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SNIa

WD+BD binary

$M_{wd} > 1.4M_\odot$?

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NS/BH+MS binary
"low mass X-ray binary"
(LMXB), P~1h - days

SNIa

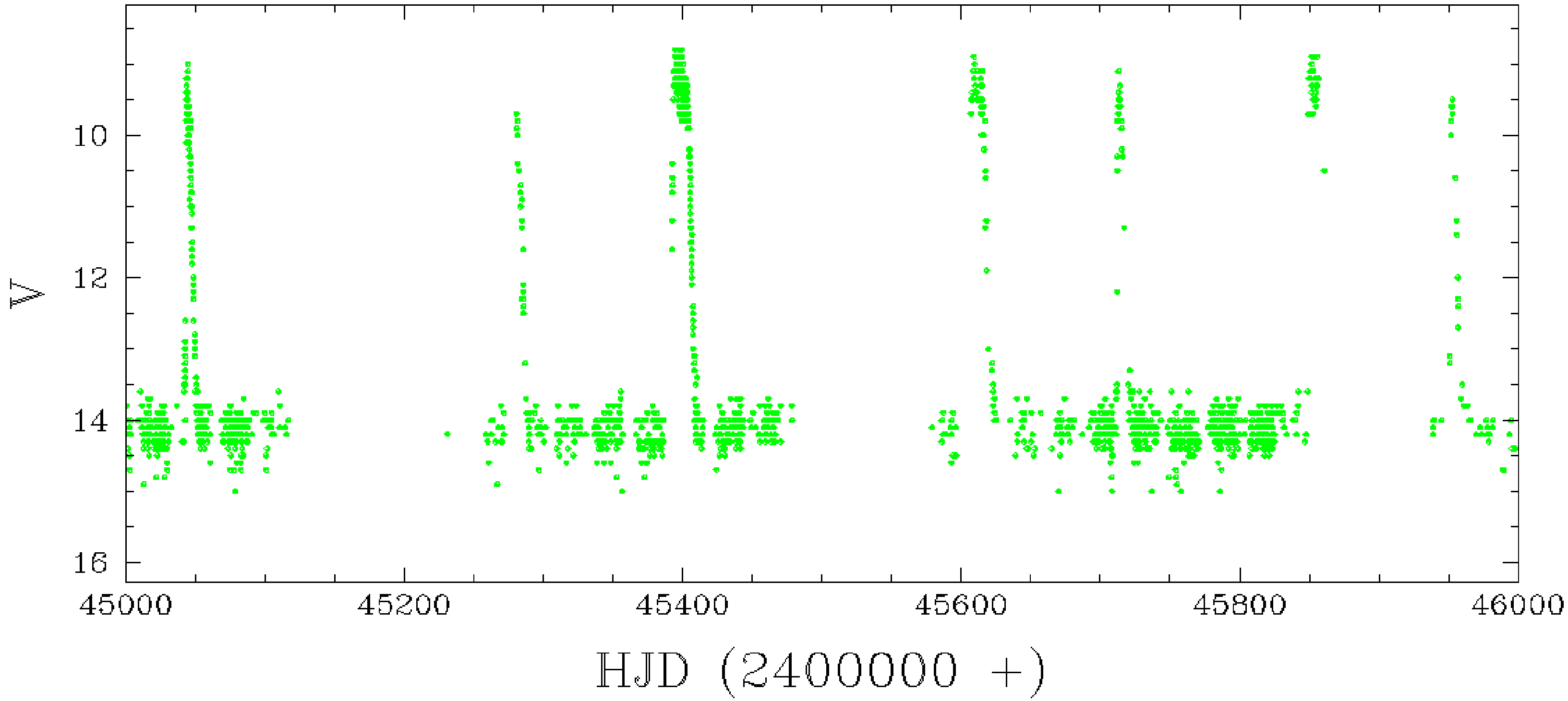
NS+NS

$\tau_L < \tau_{Hubble}$?

y

γ-ray bursts (GRB)

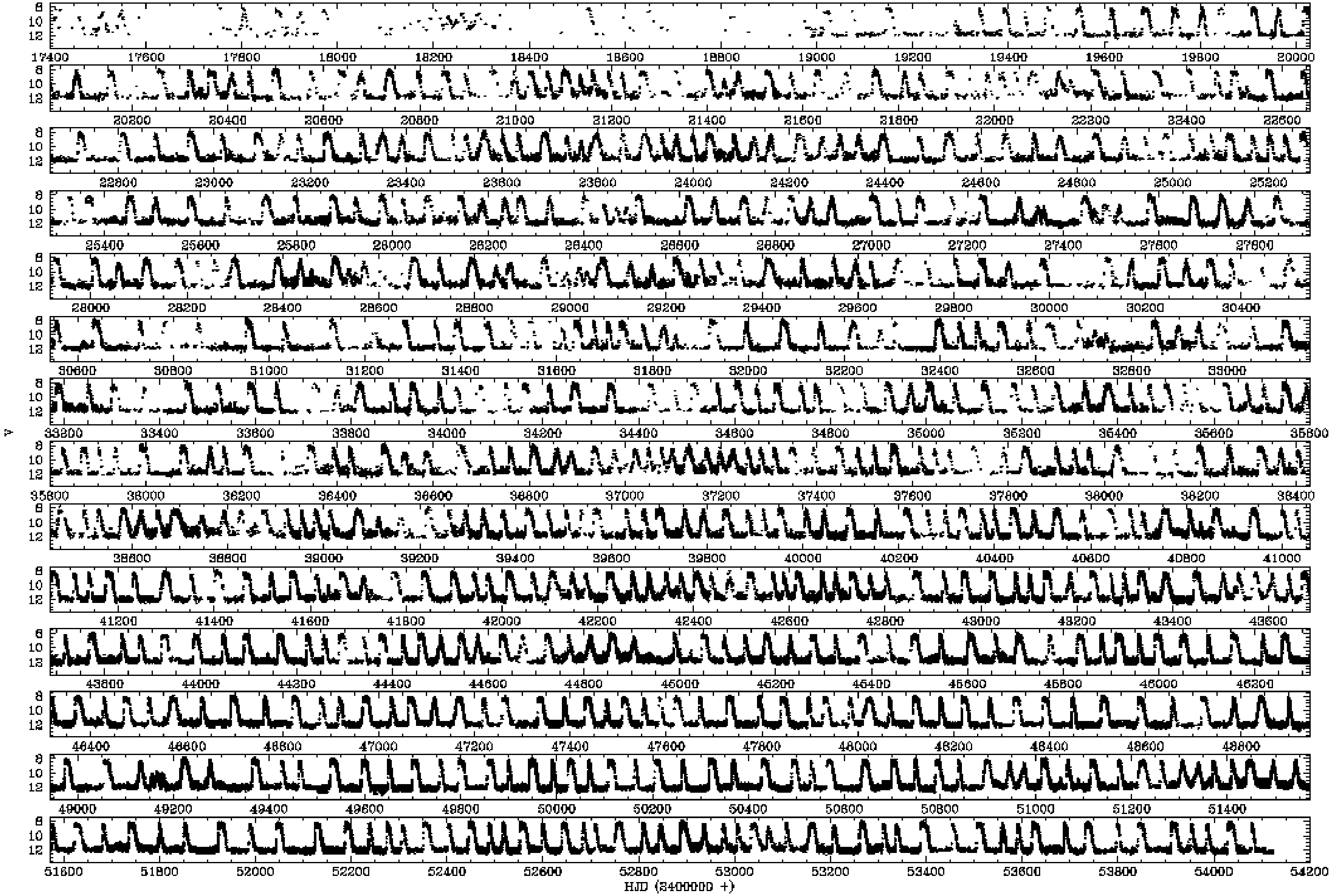
Cataclysmic *Variables*



AAVSO data of the dwarf nova U Geminorum

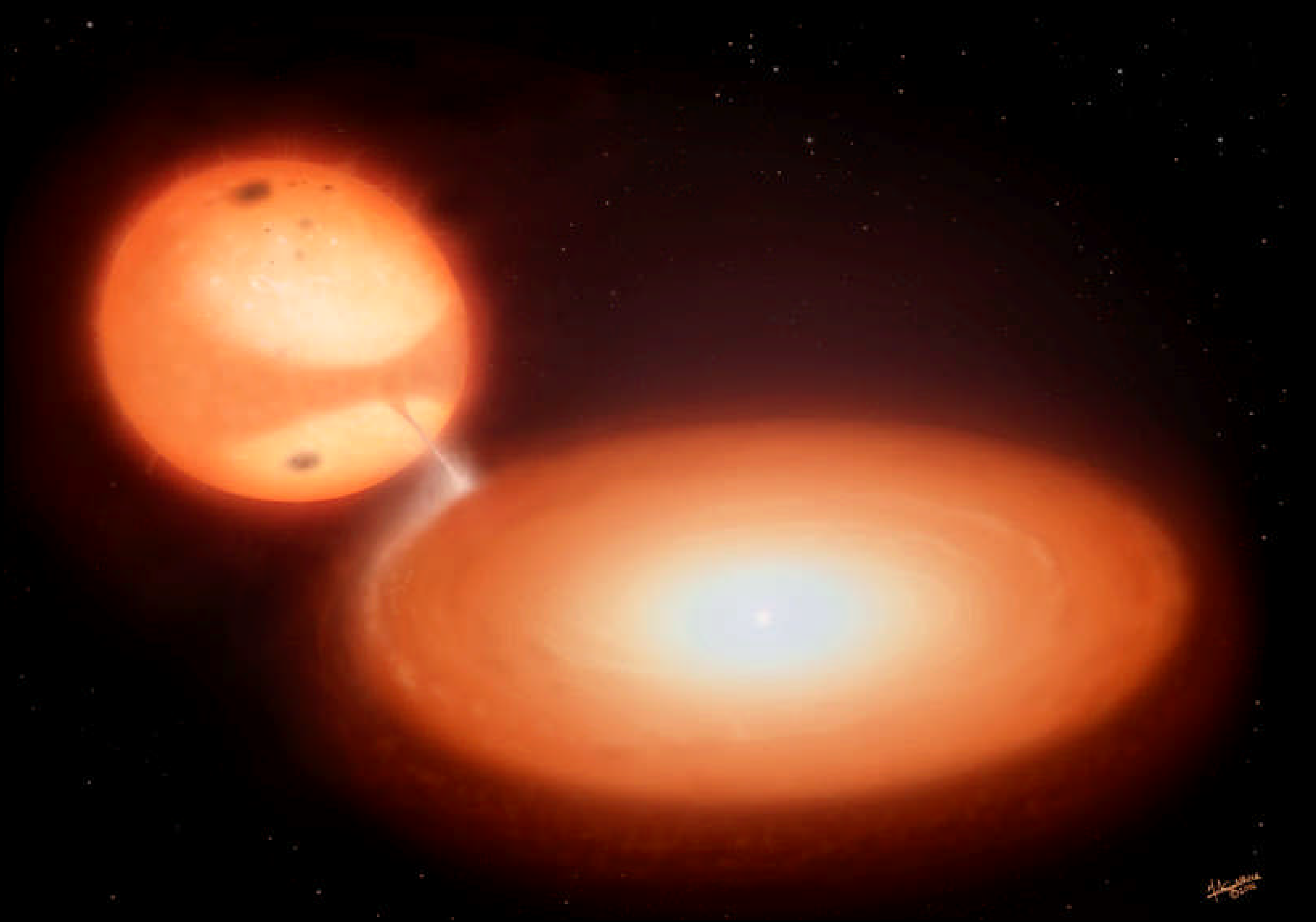
SS Cygni: 400000 observations in 103 years

17-05-1904



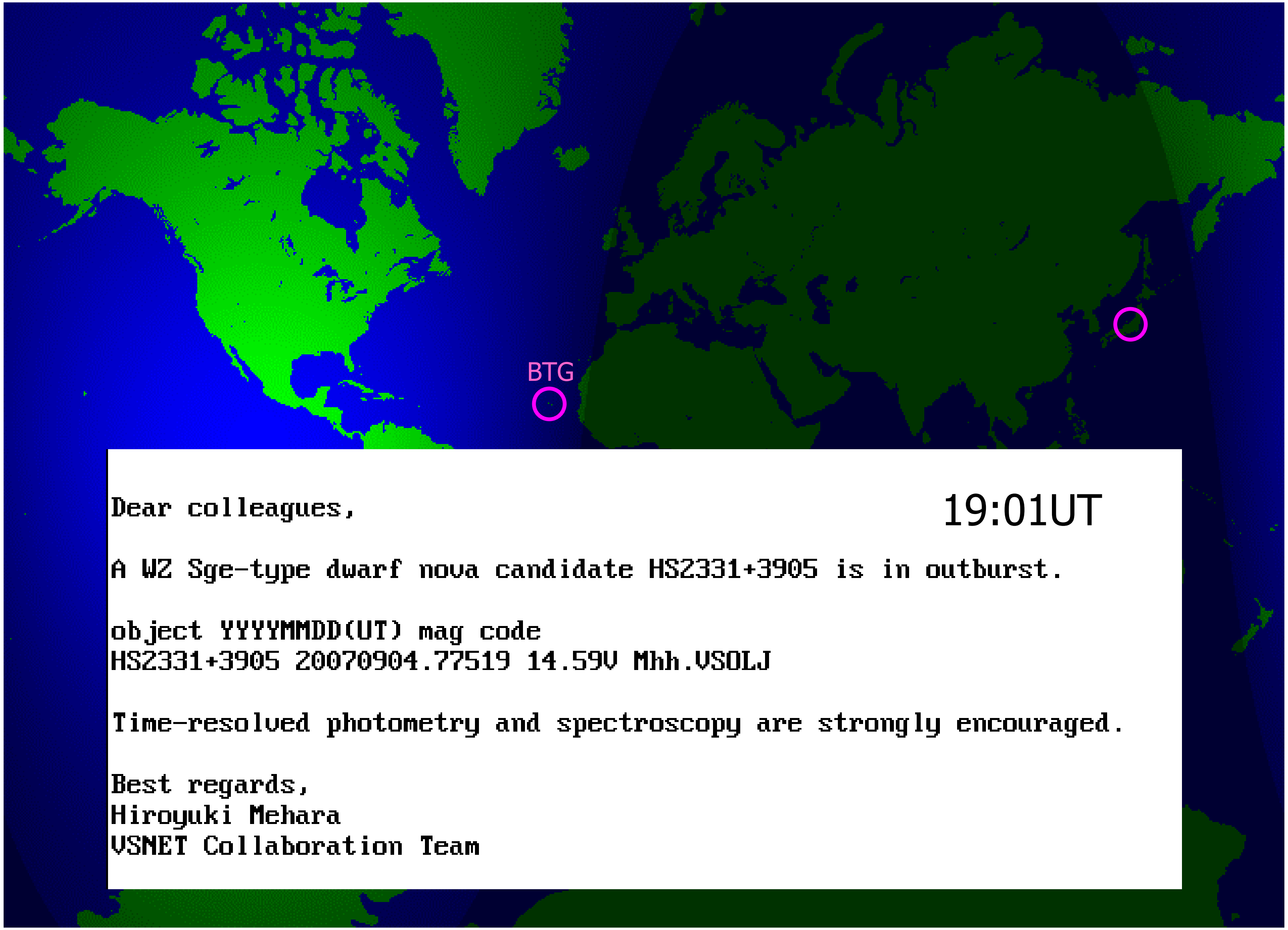
21-01-2007

Accretion disc instability



courtesy of M. Garlick

September 5, 2007 – what a day!



Dear colleagues,

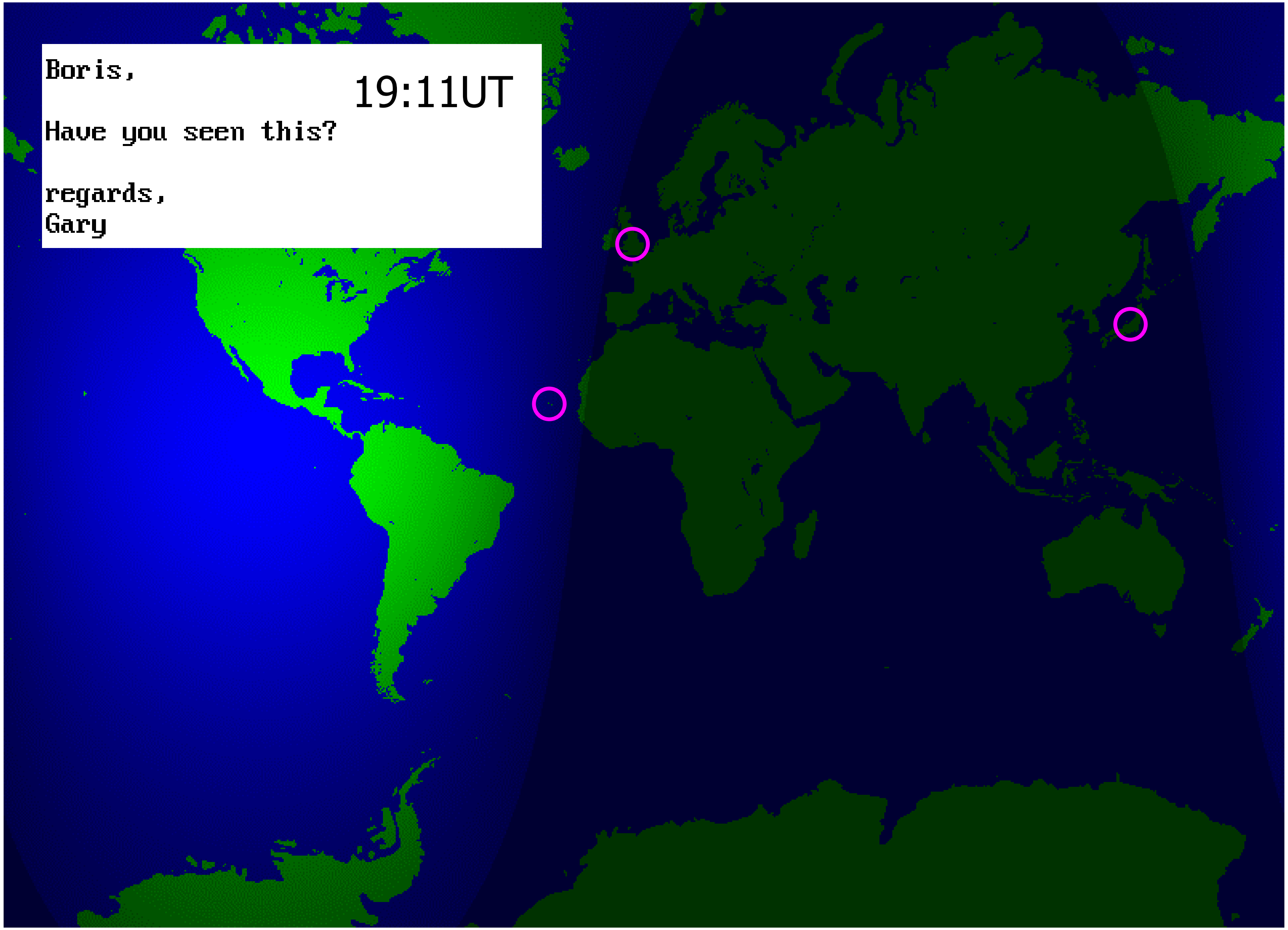
A WZ Sge-type dwarf nova candidate HS2331+3905 is in outburst.

object YYYYMMDD(UT) mag code
HS2331+3905 20070904.77519 14.59V Mhh.VSOLJ

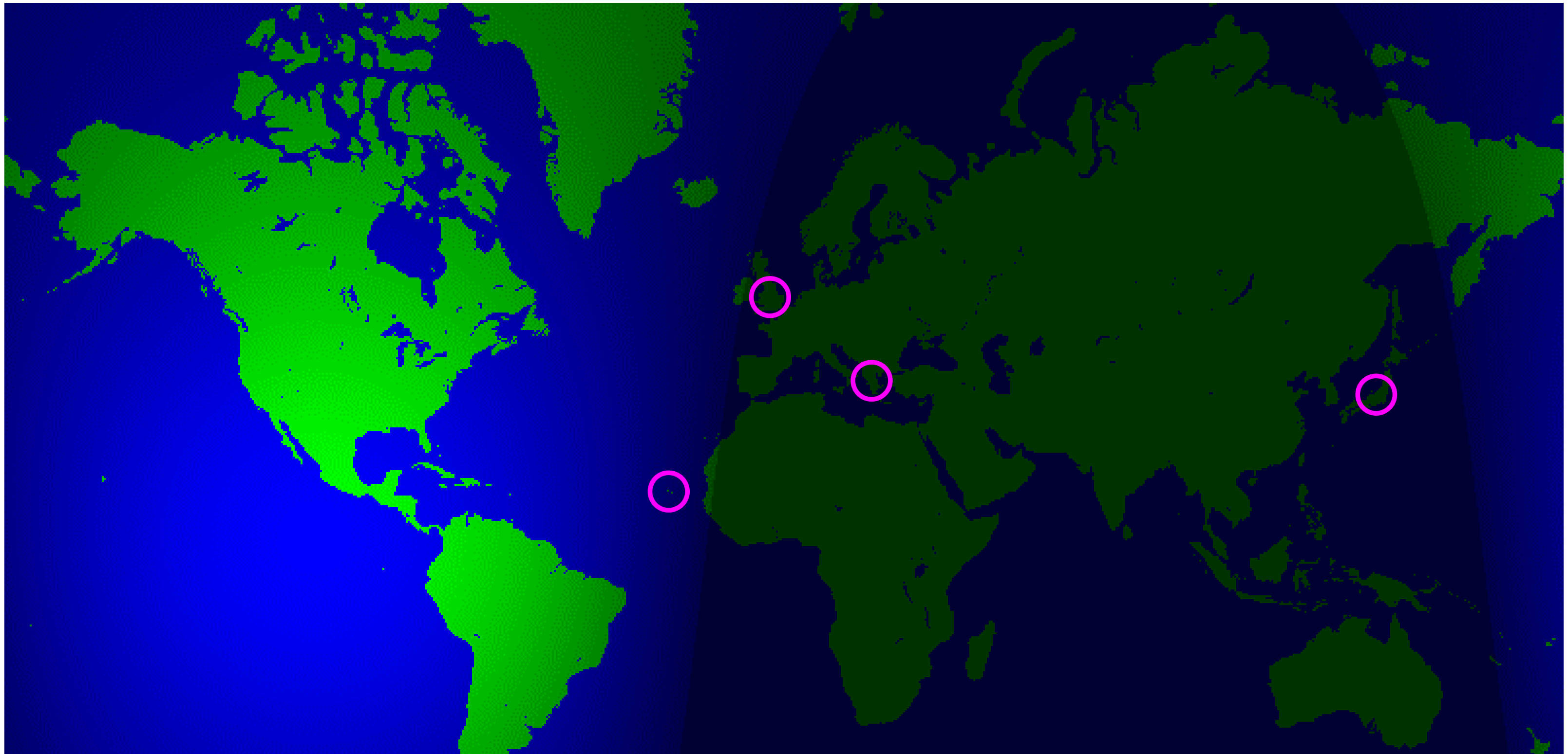
Time-resolved photometry and spectroscopy are strongly encouraged.

Best regards,
Hiroyuki Mehara
VSNET Collaboration Team

September 5, 2007 – what a day!



September 5, 2007 – what a day!



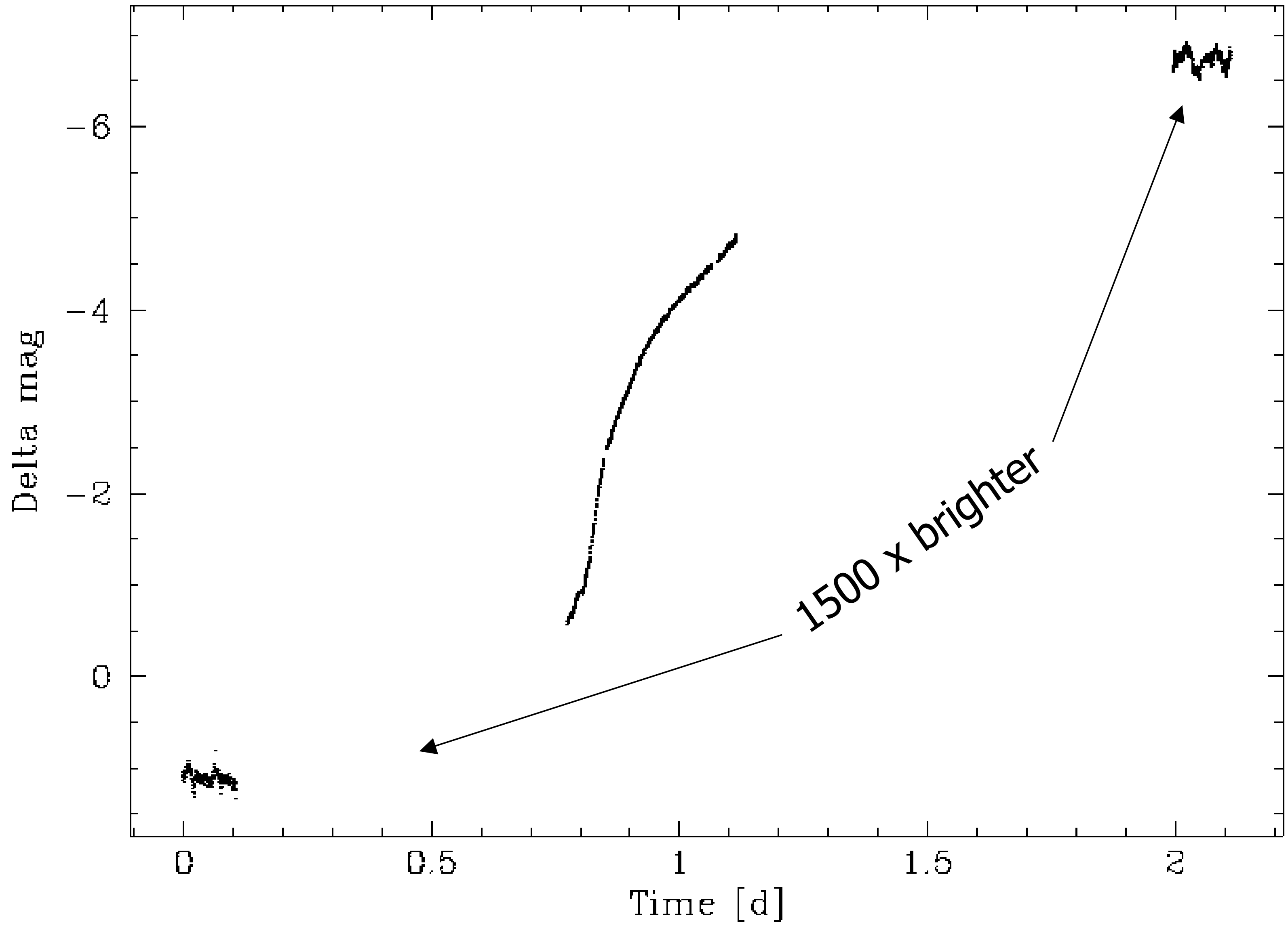
Hi Boris,

20:07UT

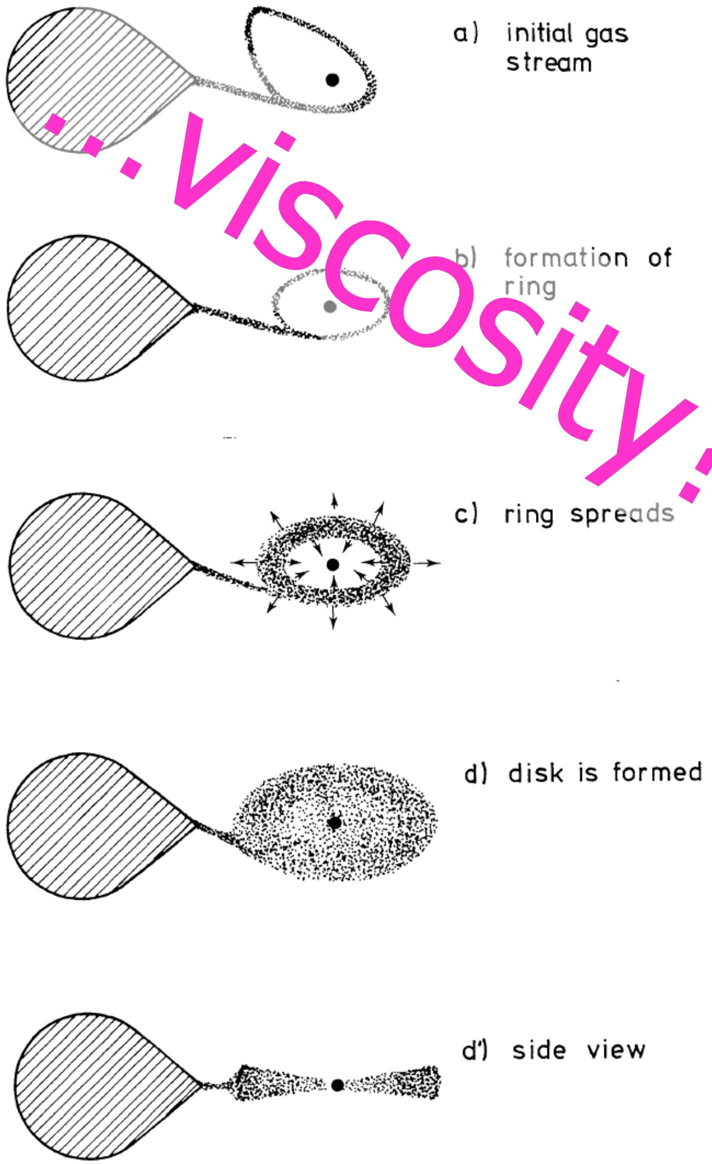
I have actually noticed that on the frames and I was about to email you asking for the possibility of an outburst 8) Since I am at Kryoneri, 3sec. is pretty much out of the question (sorry, it just won't work) but I have pushed it down to 8sec. I started observing at about 19:00 UT and will carry on throughout the night (I'm not changing to SDSS0110, I could probably get the eclipse tomorrow...). I will try to send you the lightcurve and the "org" file tomorrow...

Stelios

Rise to the outburst @ Kryoneri observatory



Formation of an accretion disc



...viscosity? What viscosity?

transport of
- M inwards
- L outwards

$$E_{tot} = -\frac{GMm}{r} + \frac{1}{2}mv^2$$

$$= -\frac{GMm}{r} + \frac{1}{2}\frac{GMm}{r}$$

$$= -\frac{1}{2}\frac{GMm}{r}$$

$$L_{disc} = \frac{1}{2}\frac{GMm}{R} = \frac{1}{2}L_{acc}$$

(the other half: boundary layer disc and star between)

The α Ansatz for the viscosity

$$\nu = \alpha c_s H$$

$$\nu \lesssim H$$

$$v_d \lesssim c_s$$

$$\alpha \lesssim 1$$

Astron. & Astrophys. 24, 337 – 355 (1973)

Black Holes in Binary Systems. Observational Appearance

N. I. Shakura
Sternberg Astronomical Institute, Moscow, U.S.S.R.

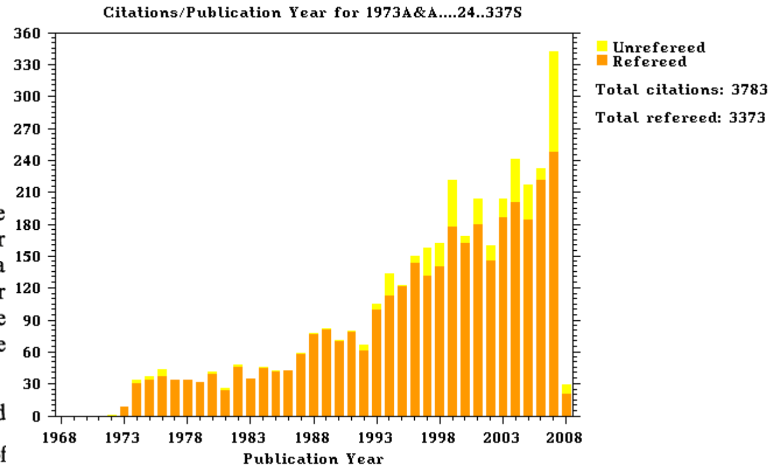
R. A. Sunyaev
Institute of Applied Mathematics, Academy of Sciences, Moscow, U.S.S.R.

Received June 6, 1972

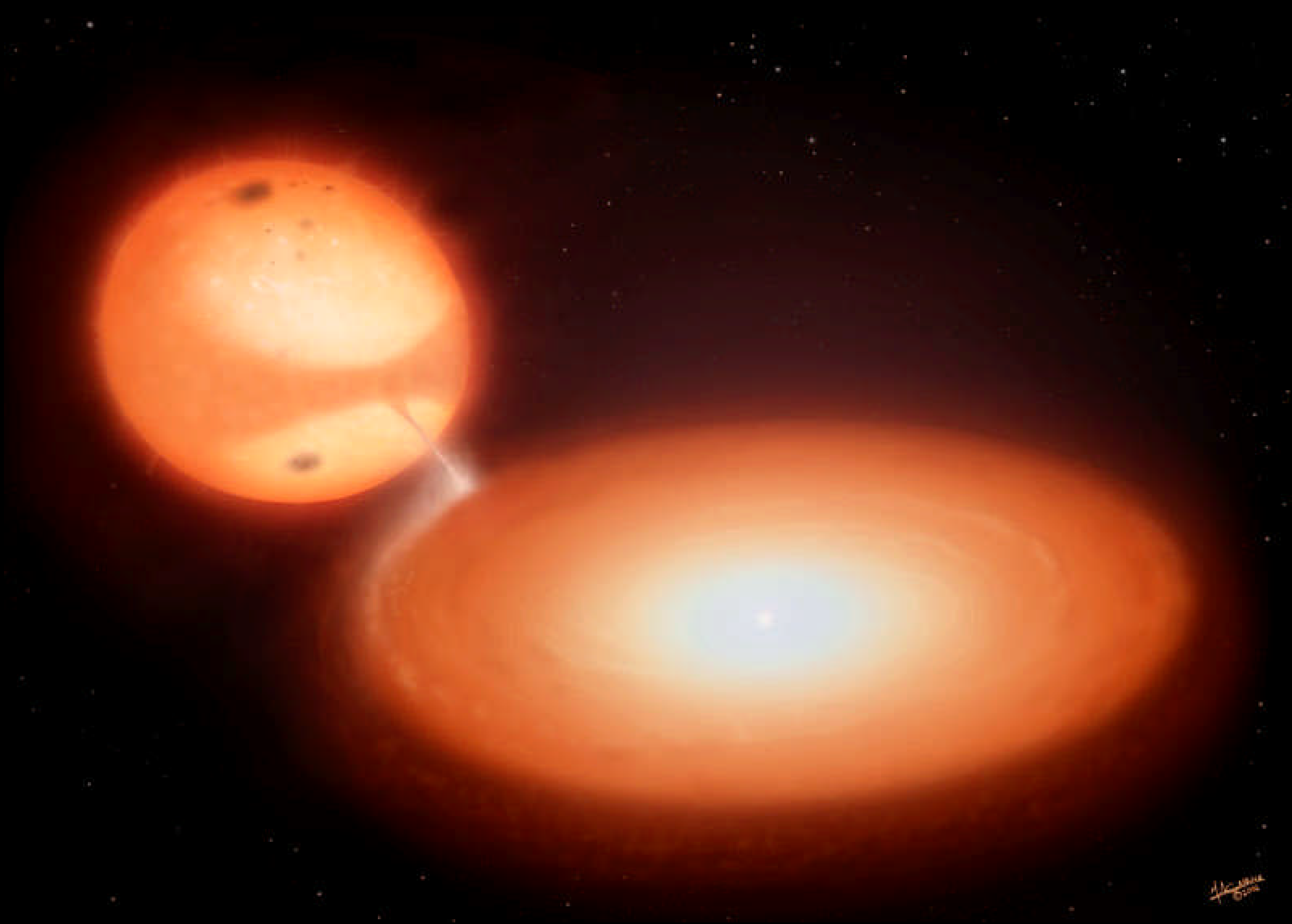
Summary. The outward transfer of the angular momentum of the accreting matter leads to the formation of a disk around the black hole. The structure and radiation spectrum of the disk depend, mainly on the rate of matter inflow $\dot{M}$ into the disk at its external boundary. The dependence on the efficiency of mechanisms of angular momentum transport (connected with the magnetic field and turbulence) is weaker. If $\dot{M} = 10^{-9} - 3 \cdot 10^{-8} \frac{M_\odot}{\text{year}}$ the disk around the black hole is a powerful source of X-ray radiation with $h\nu \sim 1 - 10$ keV and luminosity $L \approx 10^{37} - 10^{38}$ erg/s. If the flux of the accreting matter decreases, the effective temperature of the radiation and the luminosity will drop. On the other hand, when $\dot{M} > 10^{-9} \frac{M_\odot}{\text{year}}$ the optical luminosity of the disk exceeds the solar value. The main contribution to the optical luminosity of the black hole arises from reradiation of that part of the X-ray and ultra-violet energy which is initially produced in the central high temperature regions of the disk and which is then absorbed by the low temperature outer regions. The optical radiation spectrum of such objects must be saturated by broad recombination and resonance emission lines. Variability, connected with the character of the motion of the black hole, with gas flows in a binary system and with eclipses, is possible. Under certain conditions, the hard radiation can evaporate the gas. This can counteract the matter inflow into the disk and lead to autoregulation of the accretion. If $\dot{M} \gg 3 \cdot 10^{-8} \frac{M_\odot}{\text{year}}$ the luminosity of the disk around the black hole is stabilized at the critical level of $L \approx 10^{38} \frac{M}{M_\odot} \frac{\text{erg}}{\text{s}}$. A small fraction of the accreting matter falls under the gravitational radius whereas the major part of it flows out with high velocity from the central regions of the disk. The outflowing matter is opaque to the disk radiation and completely transforms its spectrum. In consequence, at the supercritical regime of accretion the black hole may appear as a bright, hot, optical star with a strong outflow of matter.

Key words: black holes – binary systems – X-ray sources – accretion

4th most-cited astrophysics paper



Accretion discs can not be spatially resolved

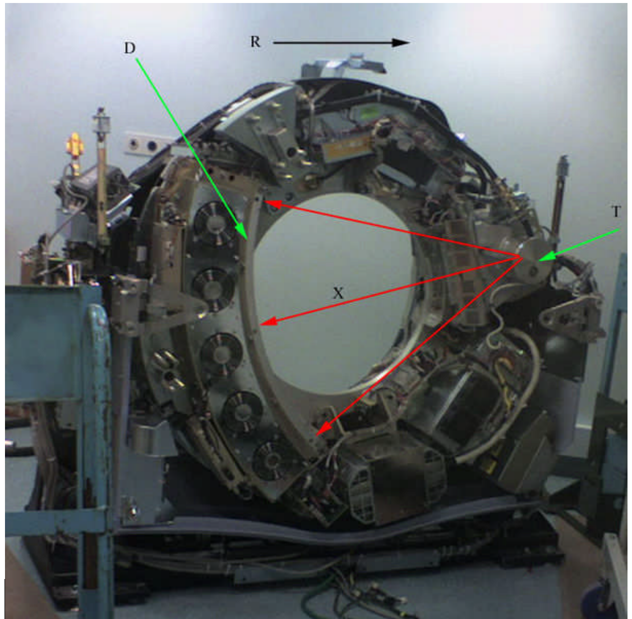


courtesy of M. Garlick

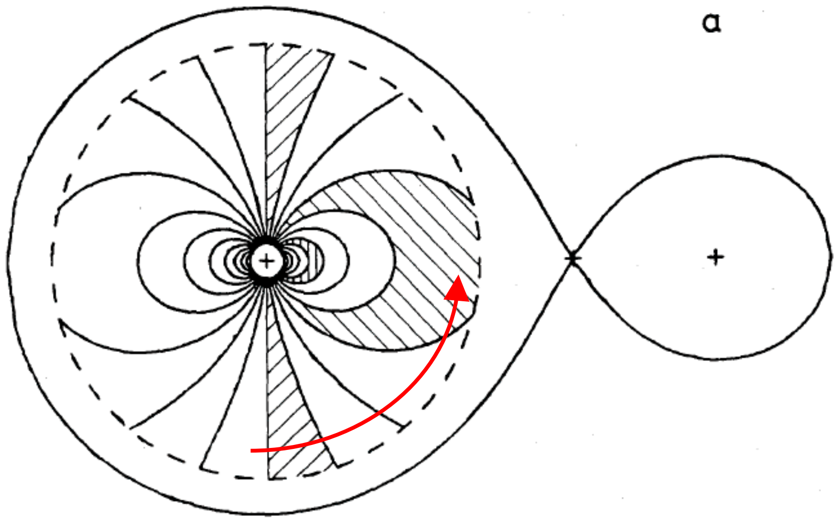
Accretion discs can not be spatially resolved

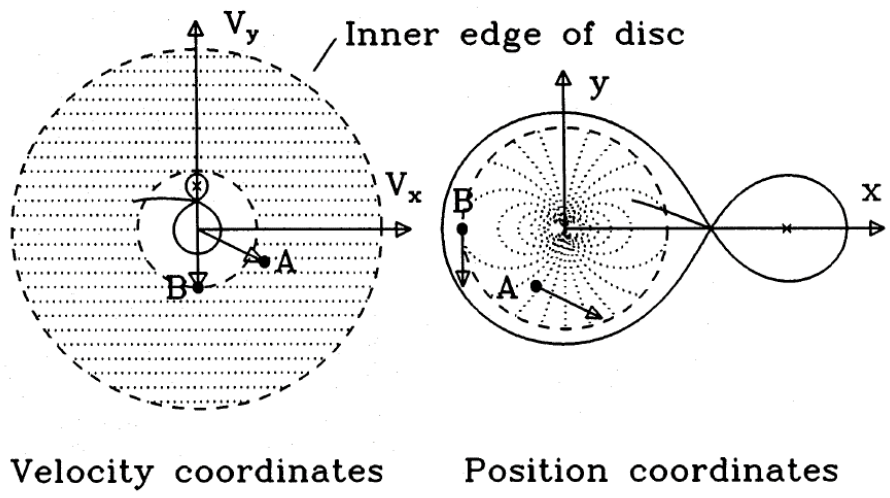
courtesy of M. Garlick

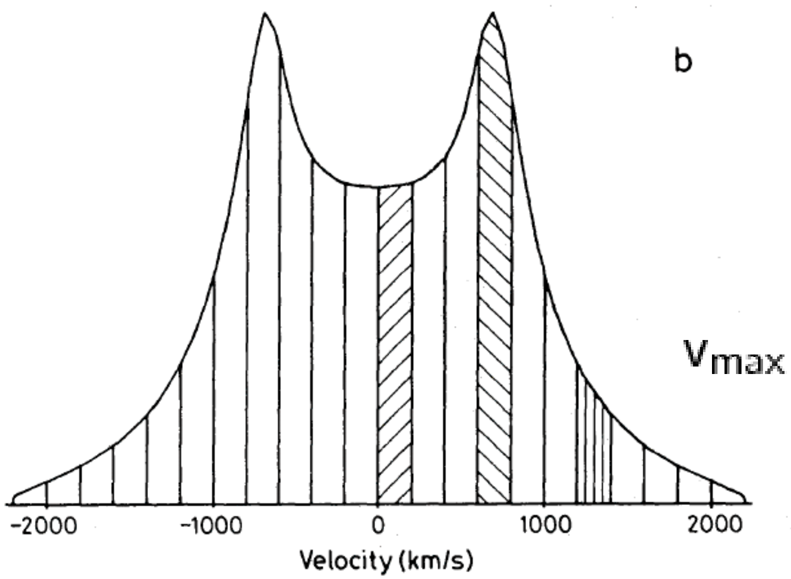
Making the invisible visible I: NMR & CT imaging



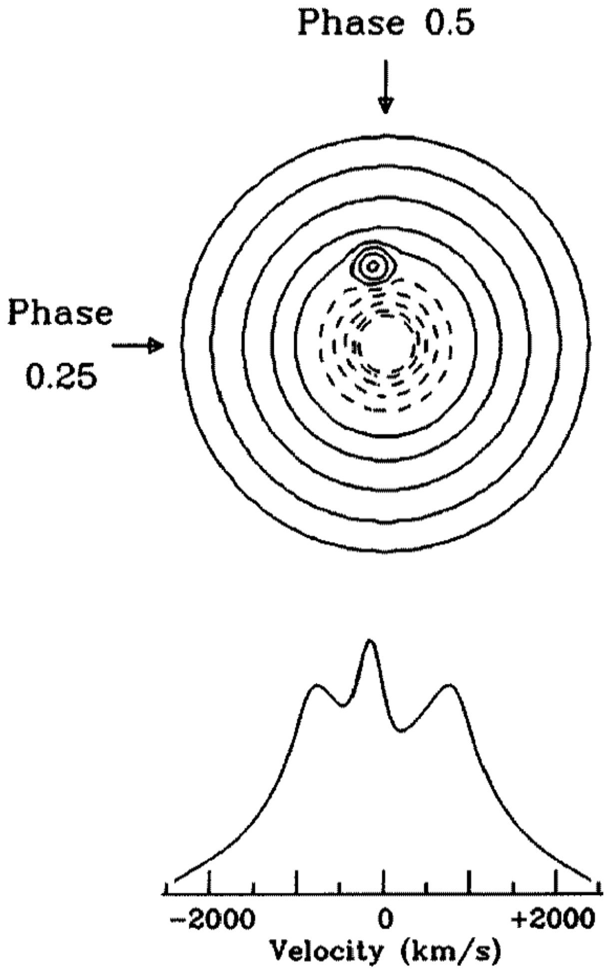
Making the invisible visible II: Doppler tomography

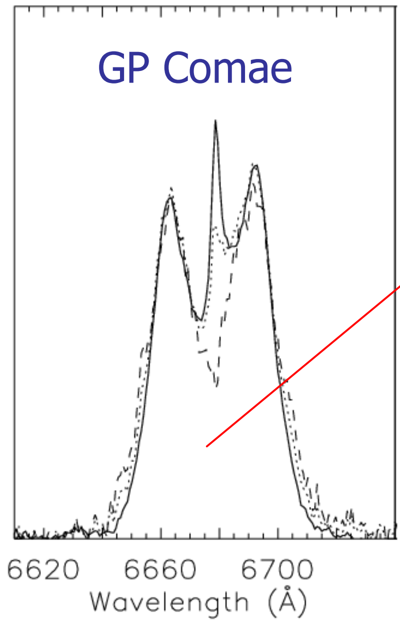


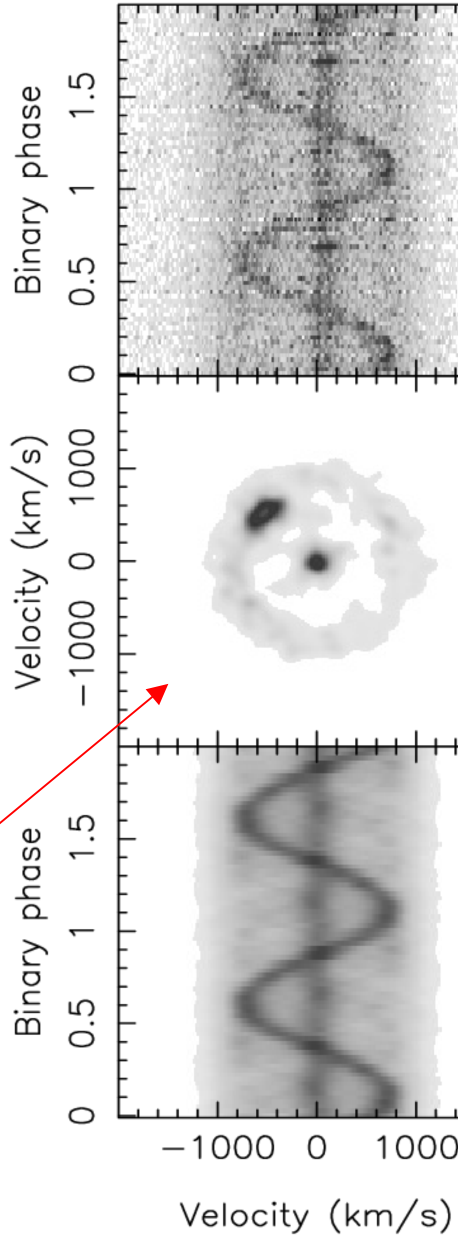




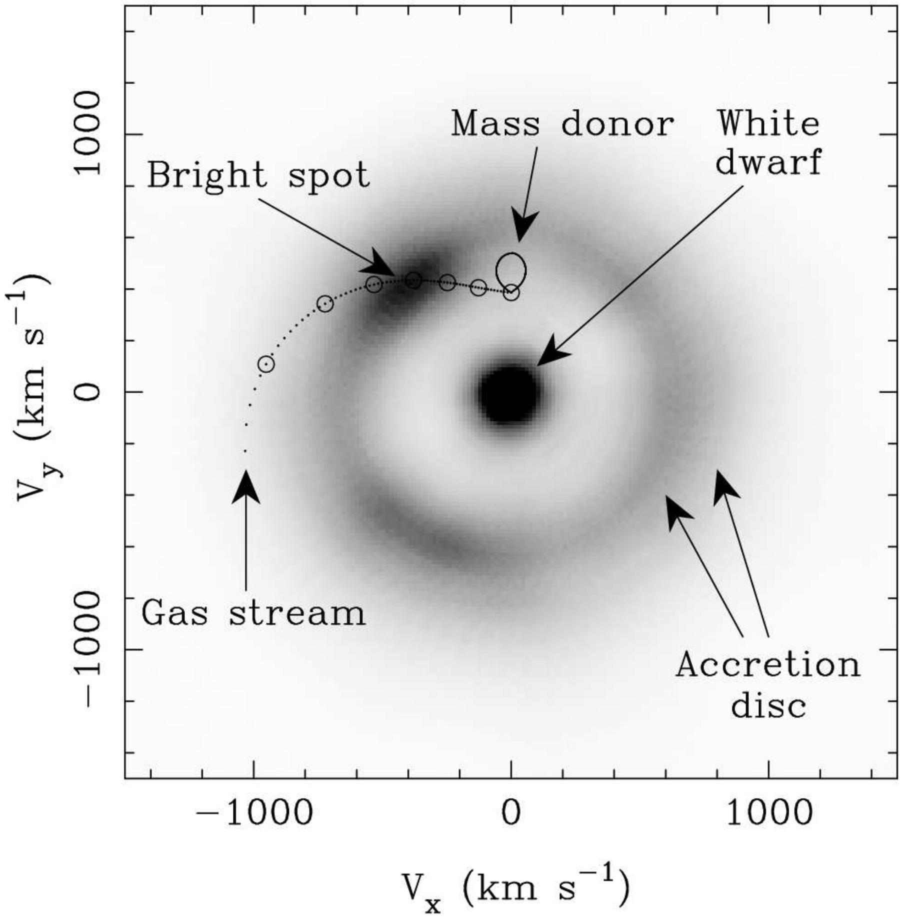
"bright spots" in Doppler maps

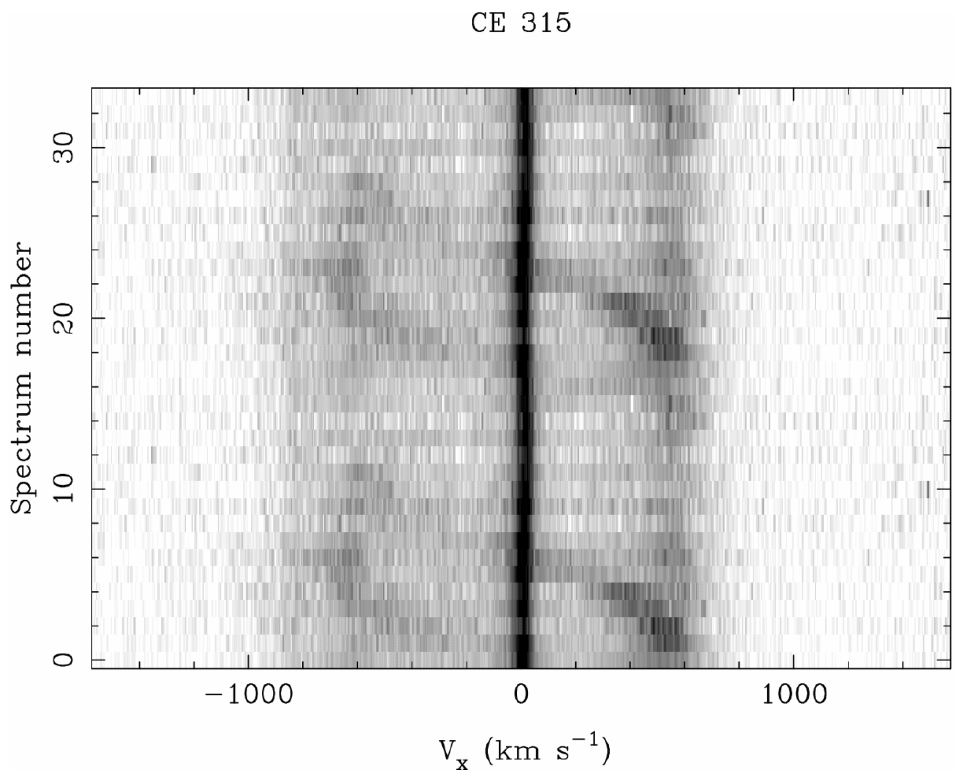




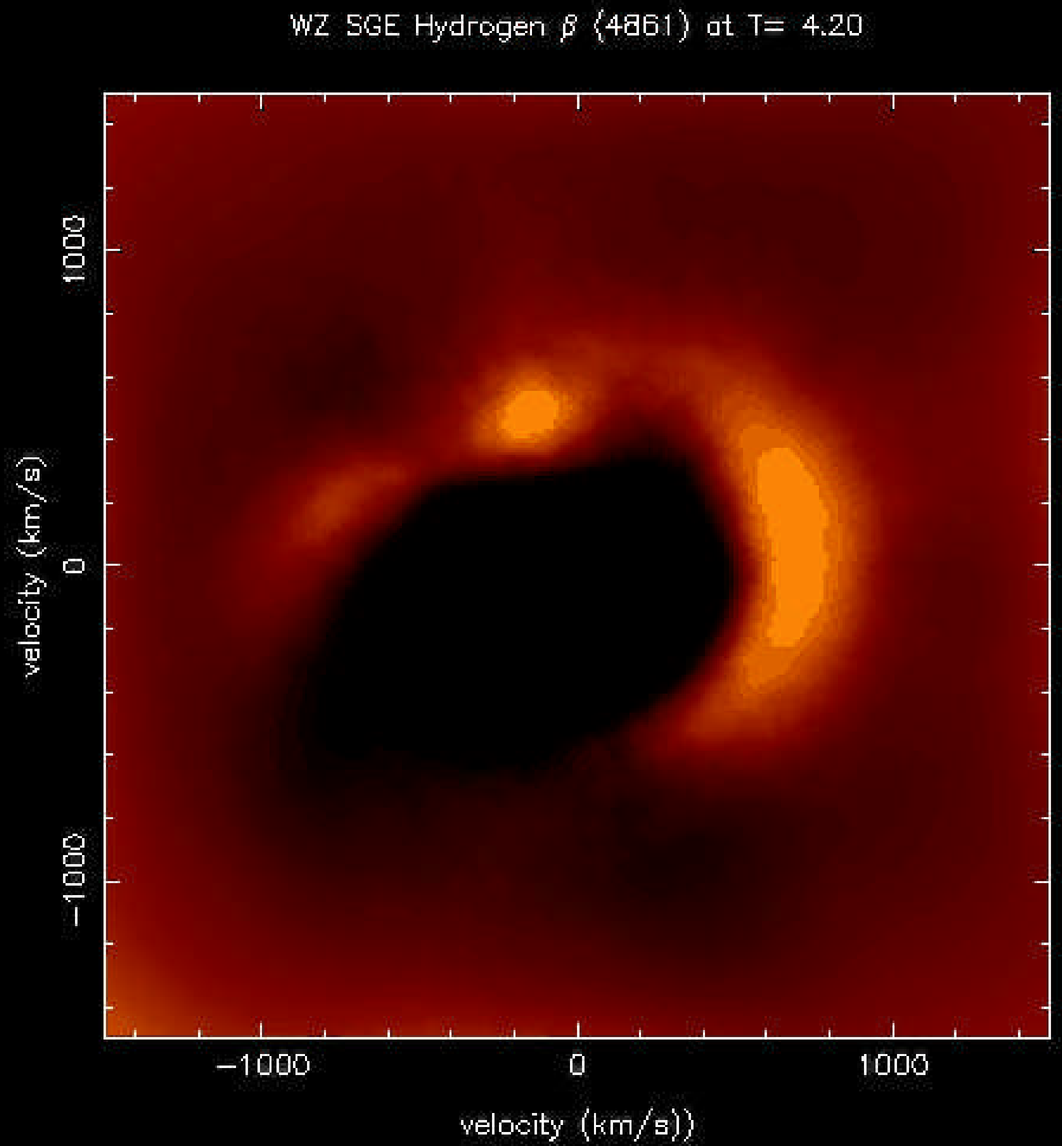


The components of a binary star in a Doppler map



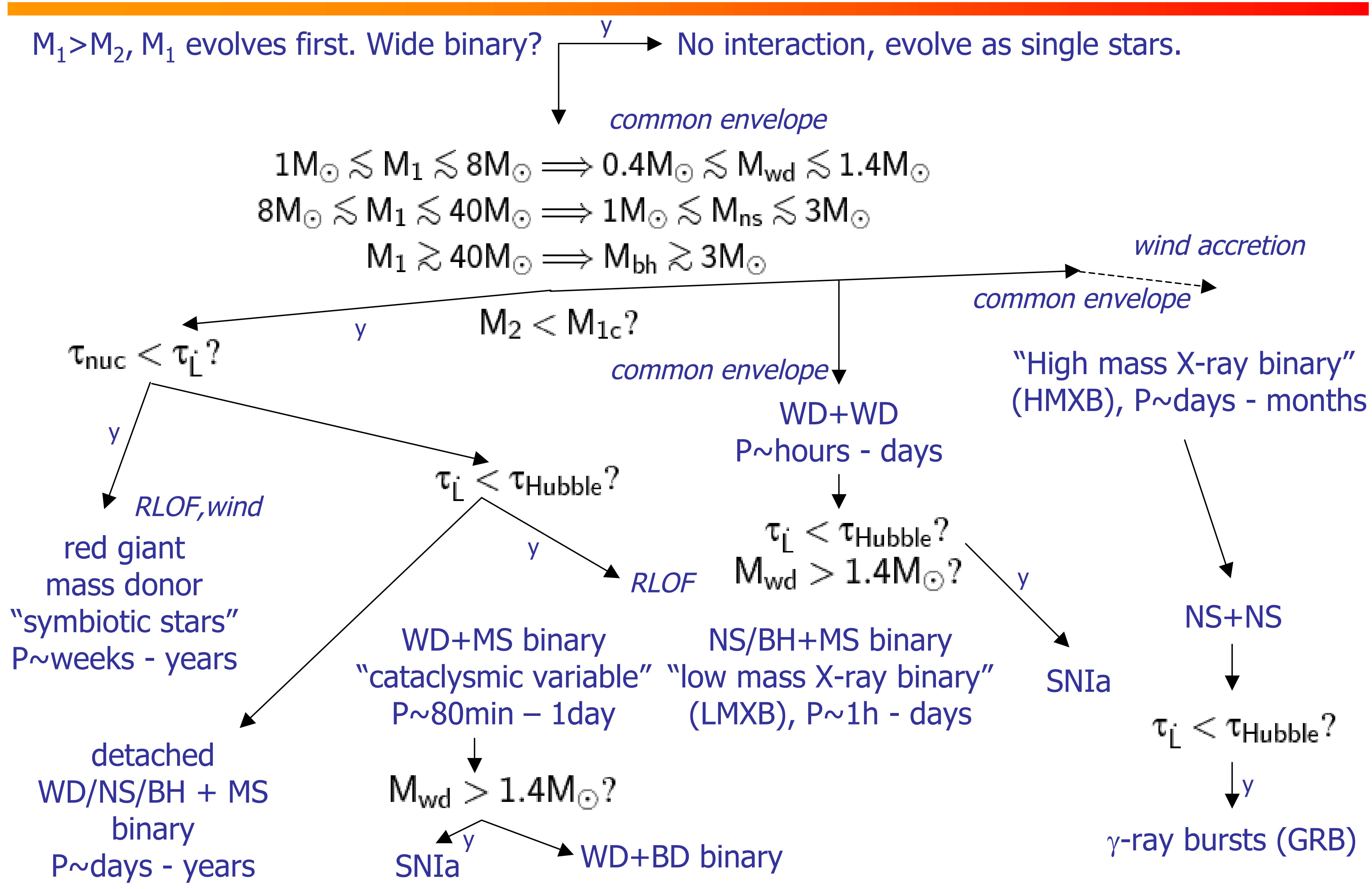


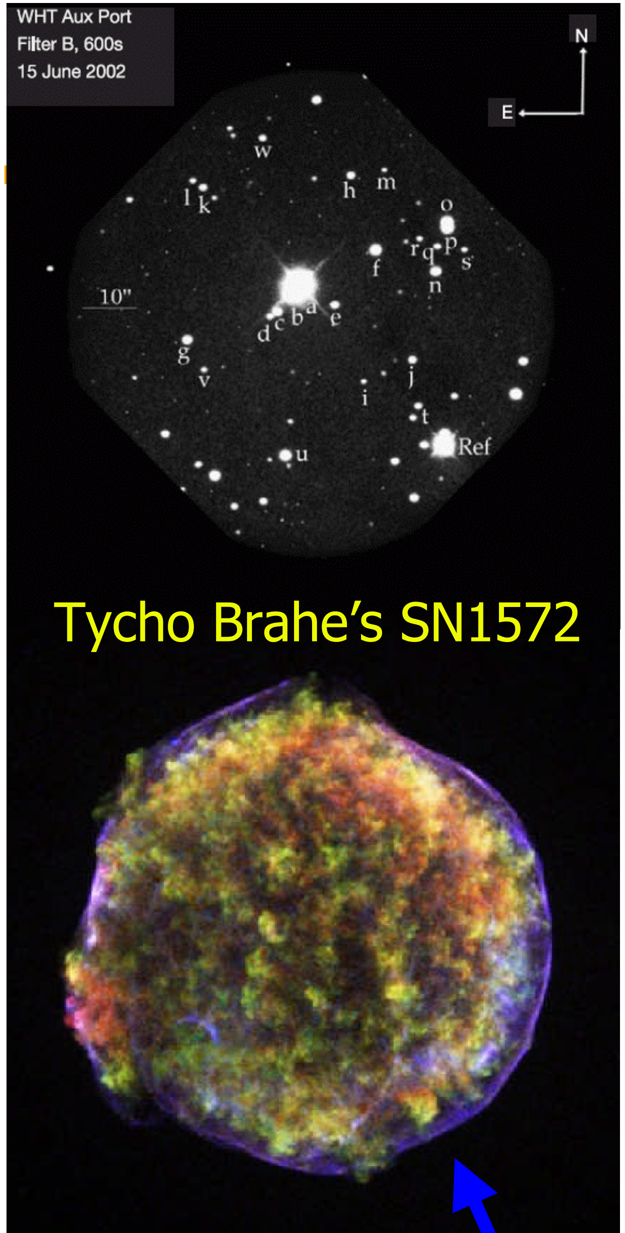
Time-resolved Doppler maps

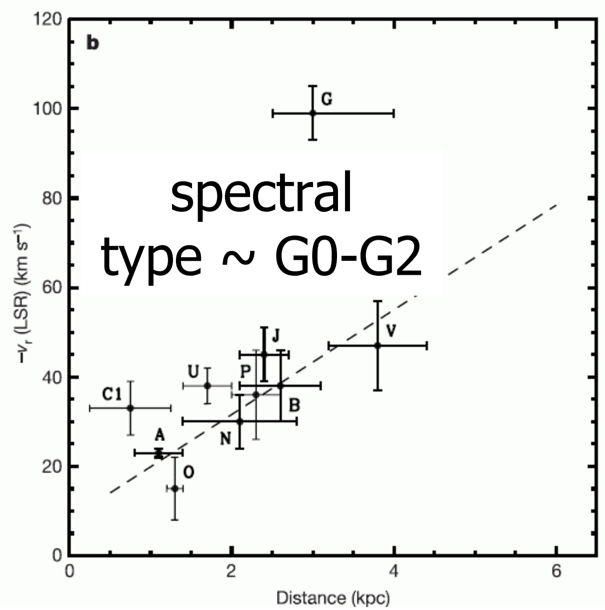


(D. Steeghs)

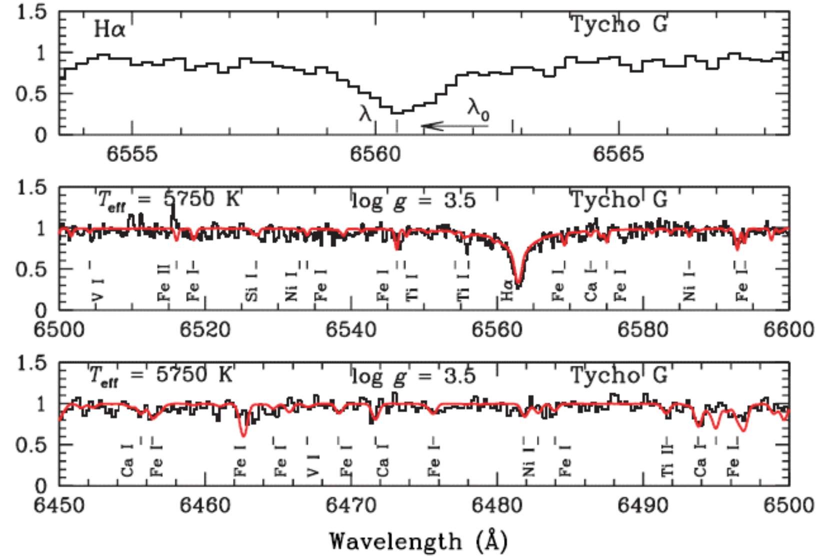
Binary star zoology







Ruiz-Lapuente et al. 2004, Nature 431, 1069



volve as single stars.

l$_\odot$

wind accretion

common envelope

igh mass X-ray binary"
MXB), P~days - months

NS+NS

SNIa

$\tau_L < \tau_{Hubble}$?

y

γ-ray bursts (GRB)

WD/NS/BH + MS
binary
P~days - years

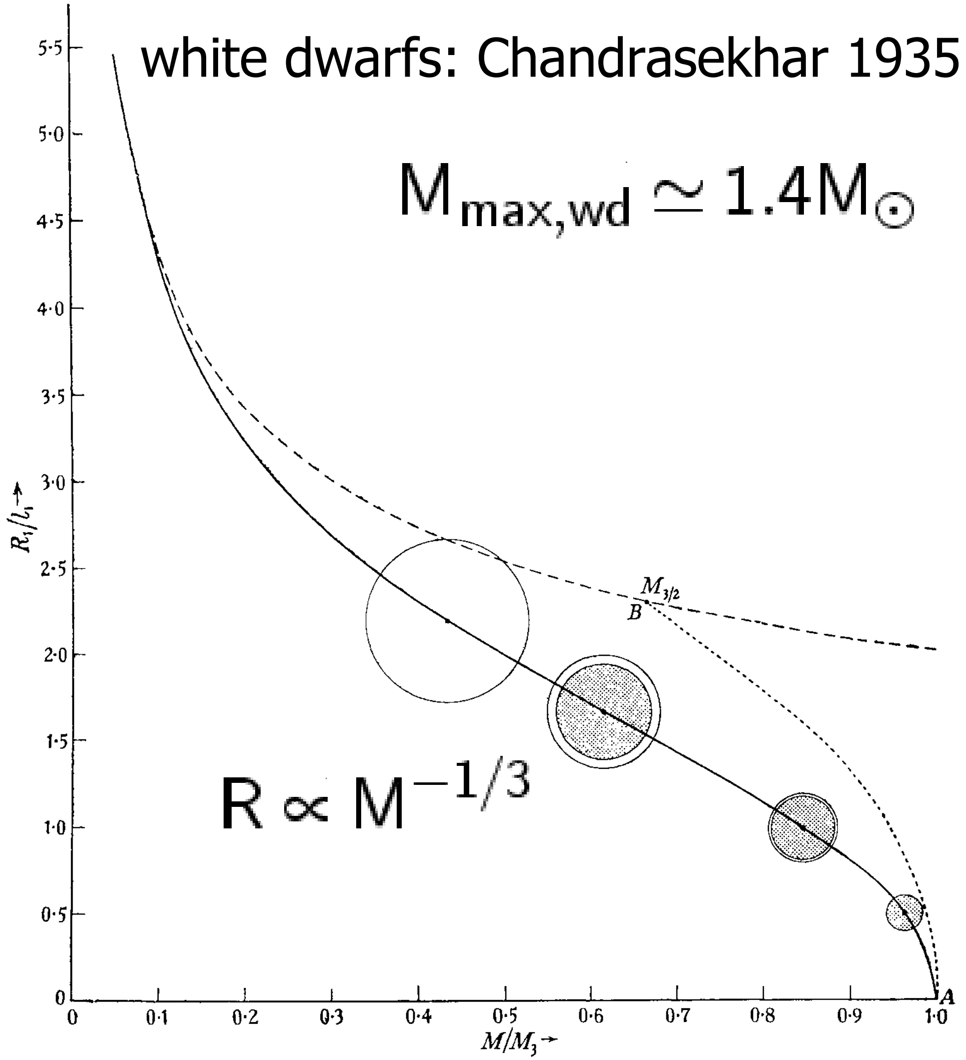
$M_{wd} > 1.4M_\odot$?

SNIa

y

WD+BD binary

Mass-radius relation of compact stars

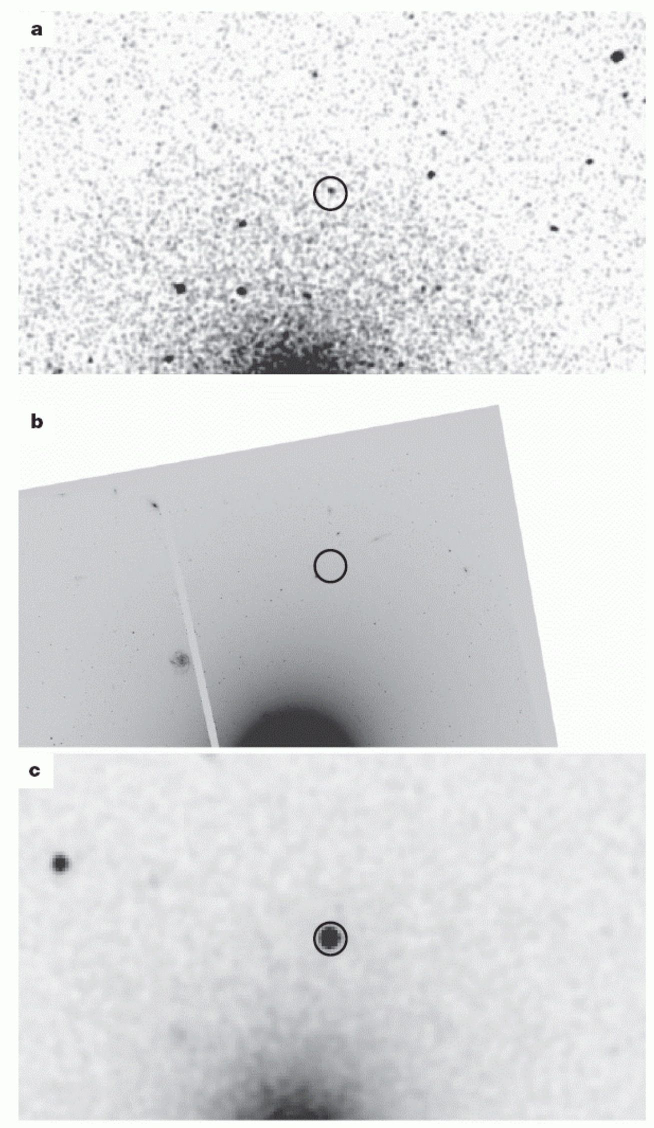


SNIa: the last seconds of an accreting white dwarf

- approaching the Chandrasehkar limit, WD rapidly shrinks
- ion gas (C/O) is not degenerate, hence heats up (P=NkT)
- C/O burning starts in the core, producing heavier elements up to iron
- nuclear flame propagates outwards:
  subsonic (deflagration) or supersonic (detonation)? Not well known

...movie time...

The first progenitor detection of a SNIa?



SN2007on in NGC1404

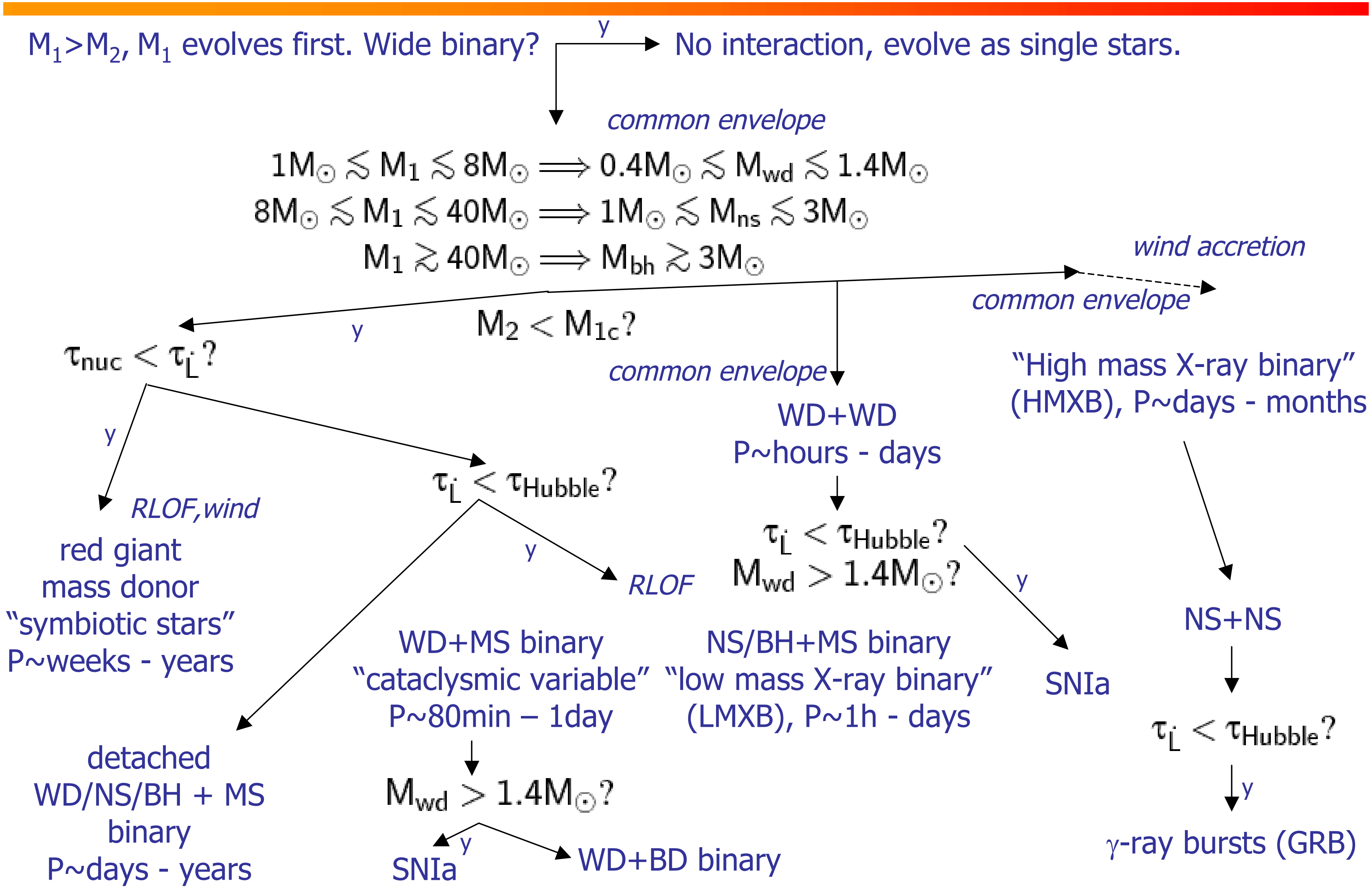
pre-explosion Chandra X-ray image

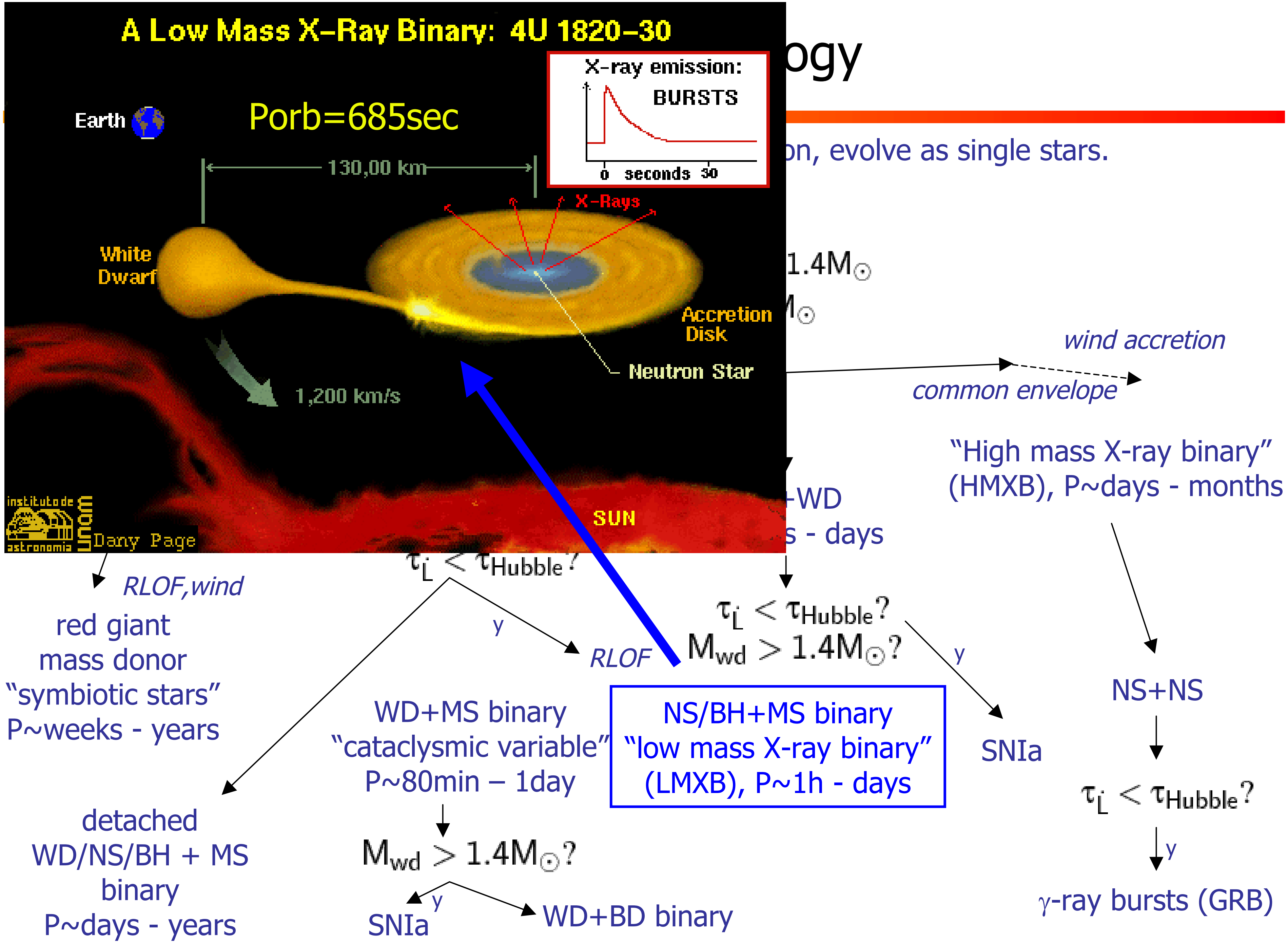
pre-explosion HST optical image

post-explosion Swift optical image

Voss & Nelemans (2008, Nature 451, 802)

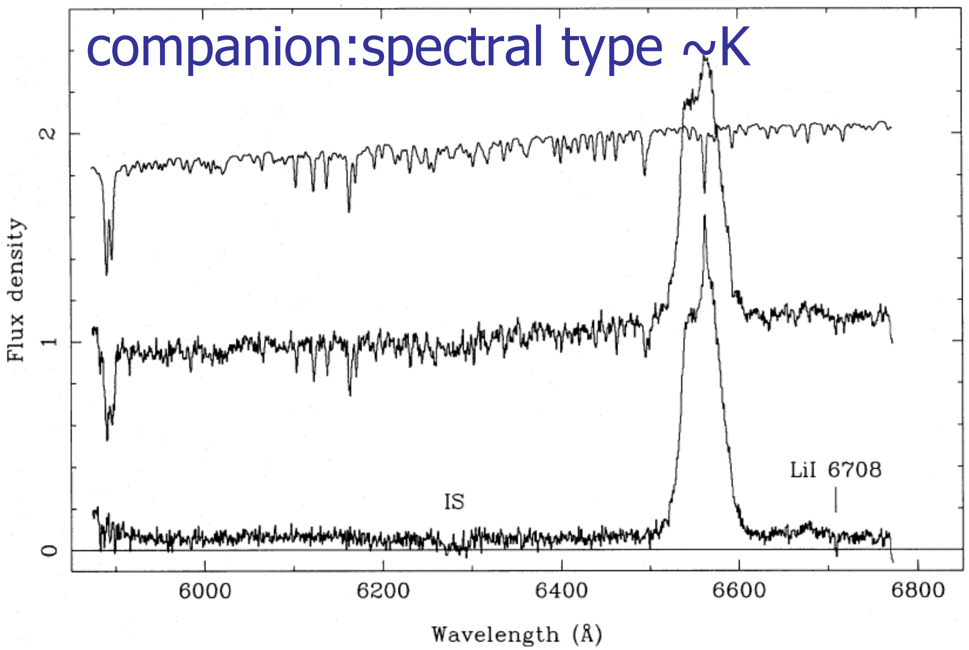
Binary star zoology

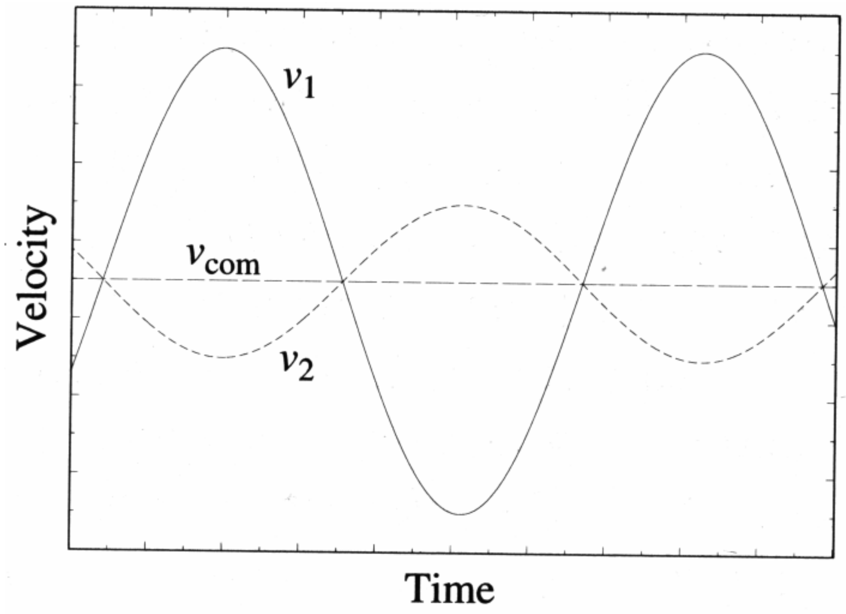




A Low Mass X-Ray Binary: 4U 1820-30
X-ray emission:
BURSTS
0 seconds 30
Earth
Porb=685sec
130,00 km
X-Rays
White Dwarf
Accretion Disk
Neutron Star
1,200 km/s
SUN
instituto de astronomia unam
Dany Page
ogy
on, evolve as single stars.
1.4M⊙
wind accretion
common envelope
"High mass X-ray binary" (HMXB), P~days - months
-WD
s - days
$\tau_{\dot{L}} < \tau_{Hubble}$?
RLOF,wind
red giant
mass donor
"symbiotic stars"
P~weeks - years
y
RLOF
$\tau_{\dot{L}} < \tau_{Hubble}$?
$M_{wd} > 1.4M_\odot$?
y
NS+NS
NS/BH+MS binary
"low mass X-ray binary"
(LMXB), P~1h - days
SNIa
WD+MS binary
"cataclysmic variable"
P~80min – 1day
detached
WD/NS/BH + MS
binary
P~days - years
$\tau_{\dot{L}} < \tau_{Hubble}$?
y
$M_{wd} > 1.4M_\odot$?
y
SNIa
WD+BD binary
γ-ray bursts (GRB)

The mass function





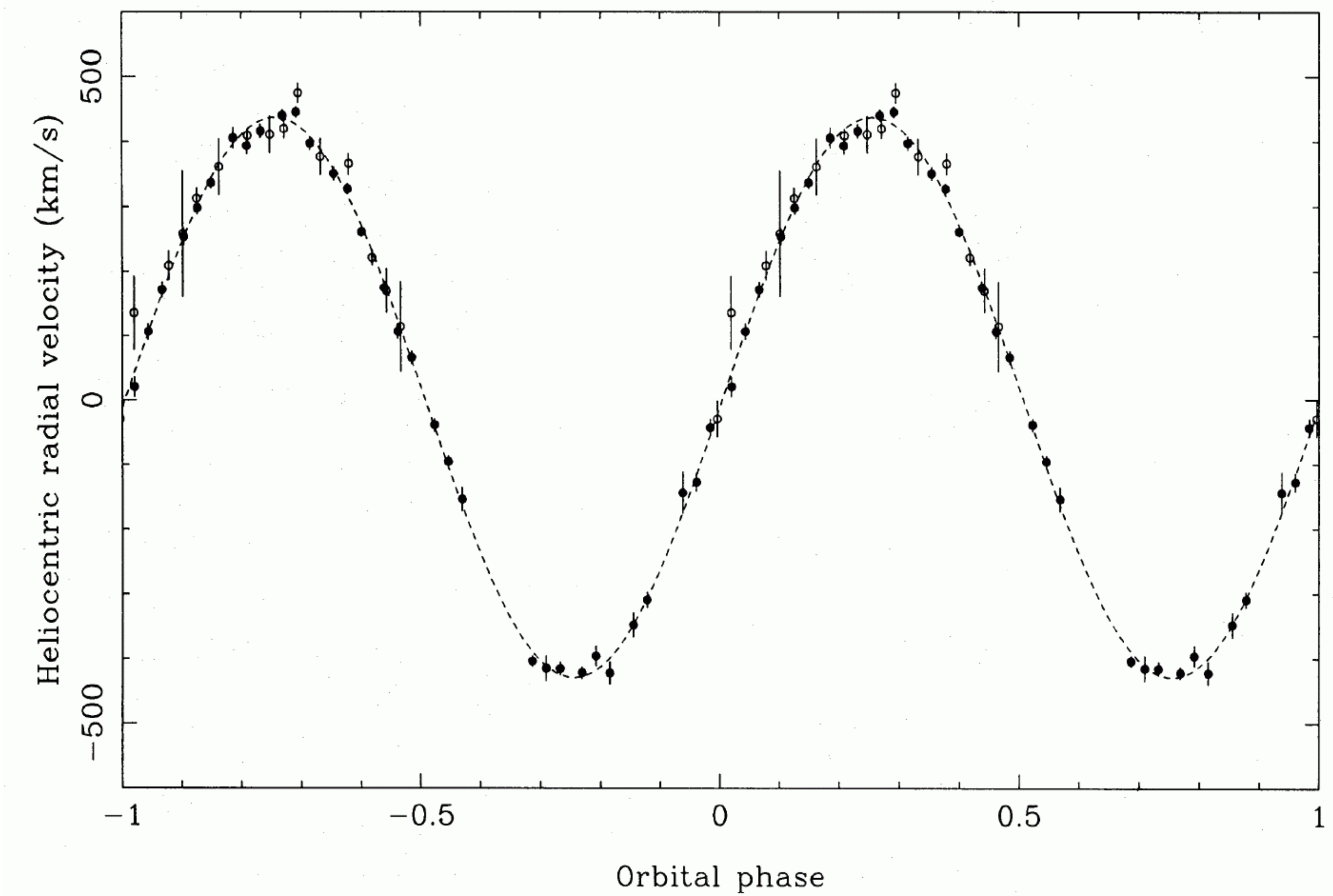
$$f(M_1) = \frac{(M_1 \sin i)^3}{(M_1 + M_2)^2} = \frac{P_{orb} v_{2r}^3}{2\pi G}$$ "mass function"

Kepler III

$$P_{orb}^2 = \frac{4\pi^2 r^3}{G(M_1 + M_2)}$$

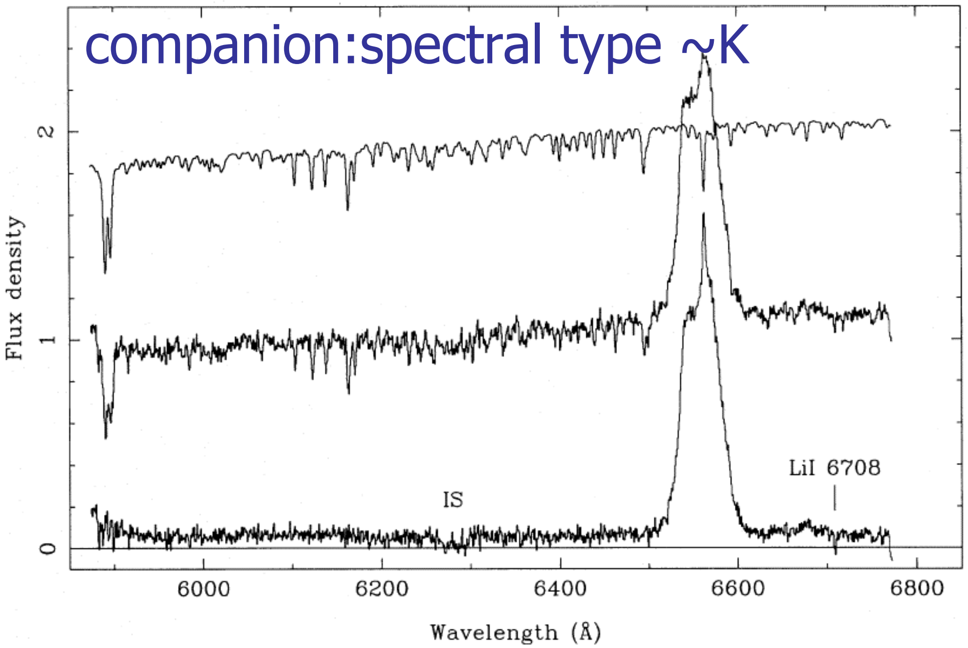
$$M_1 > f(M_1)$$

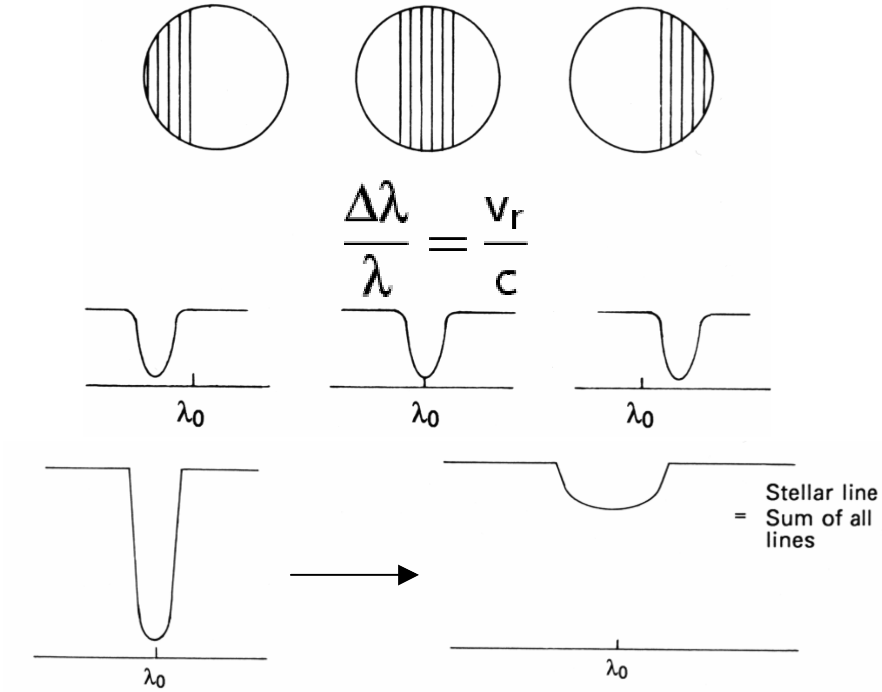
Weighing the X-ray nova A0620-00 = V616 Mon



$$P_{orb} = 7.75\text{h}$$
$$K_2 = 433 \pm 3\,\text{km}\,\text{s}^{-1}$$
$$\Longrightarrow M_1 > f(M_1) = 2.6 M_\odot$$

Weighing the X-ray nova A0620-00 = V616 Mon





Rotational velocity of a Roche-lobe filling star: $\frac{v \sin i}{K_2} = 0.46[(1+q)^2]^{1/3}$ $\quad q = \frac{M_2}{M_1}$

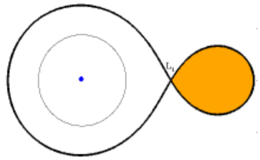
$$v \sin i = 83 \pm 5 \mathrm{km\,s}^{-1} \Longrightarrow q = 0.067 \pm 0.01$$

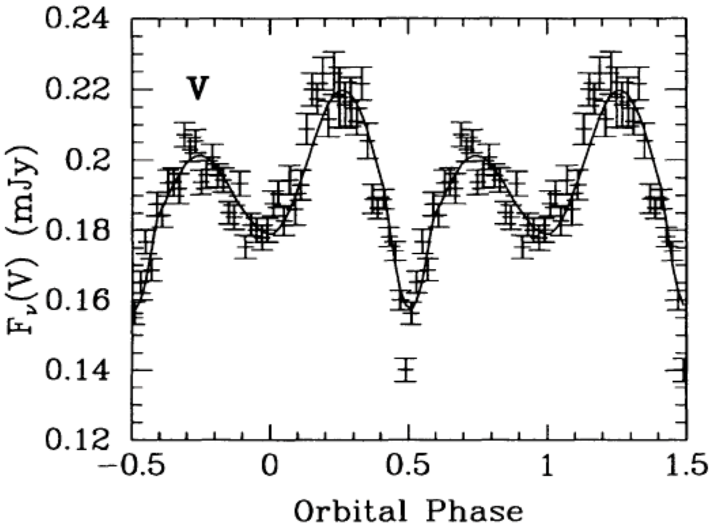
$$M_1 = \frac{3.09 \pm 0.09}{\sin^3 i} M_\odot$$

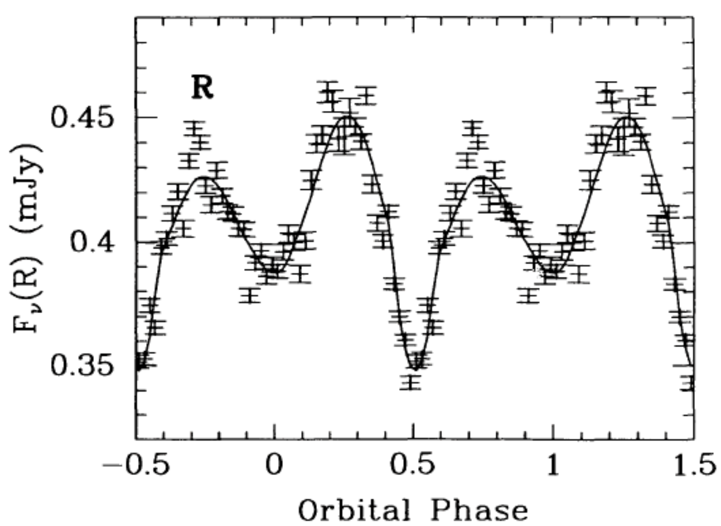
$$M_2 = \frac{0.21 \pm 0.04}{\sin^3 i} M_\odot$$

Weighing the X-ray nova A0620-00 = V616 Mon

ellipsoidal modulation



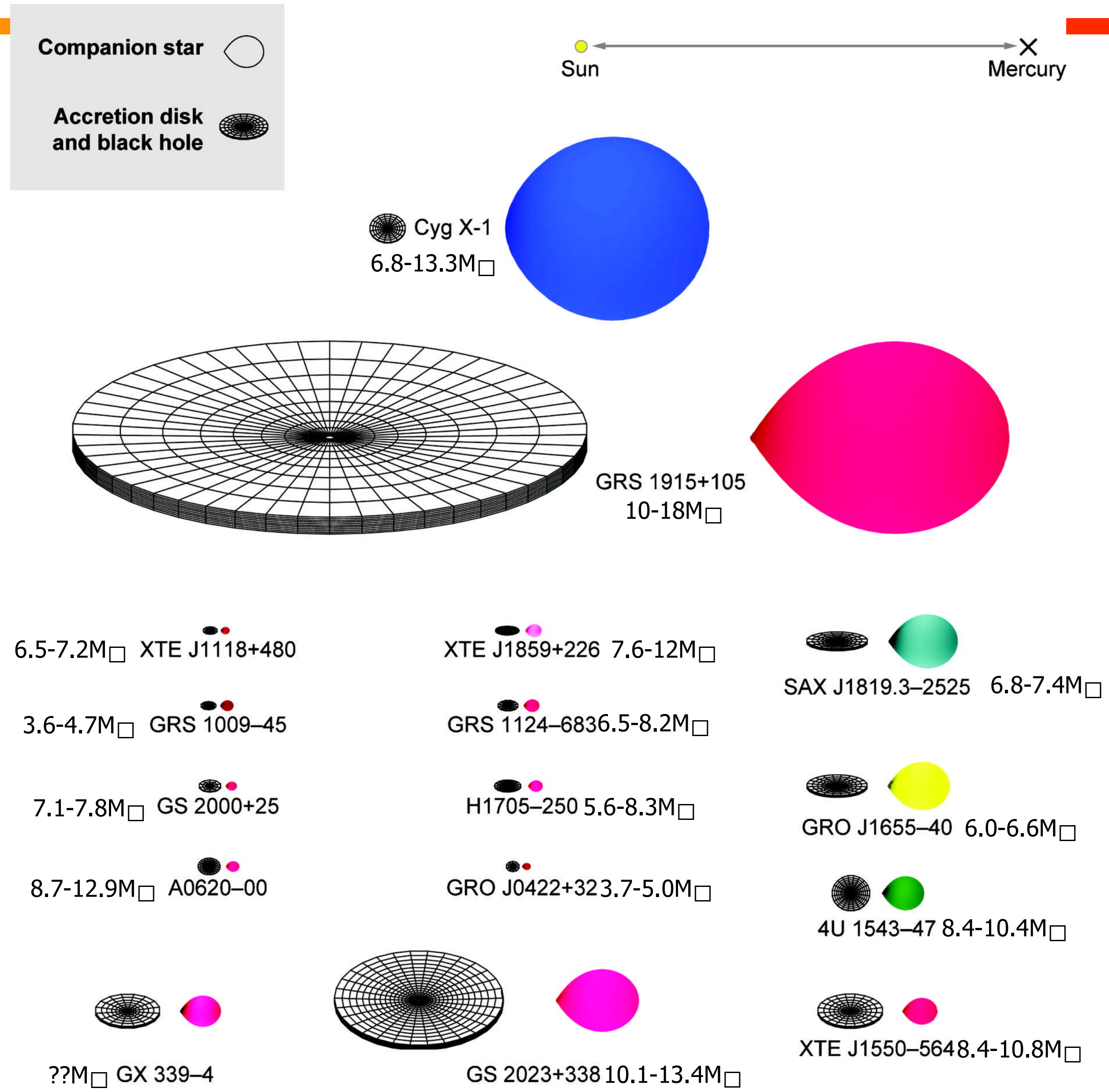




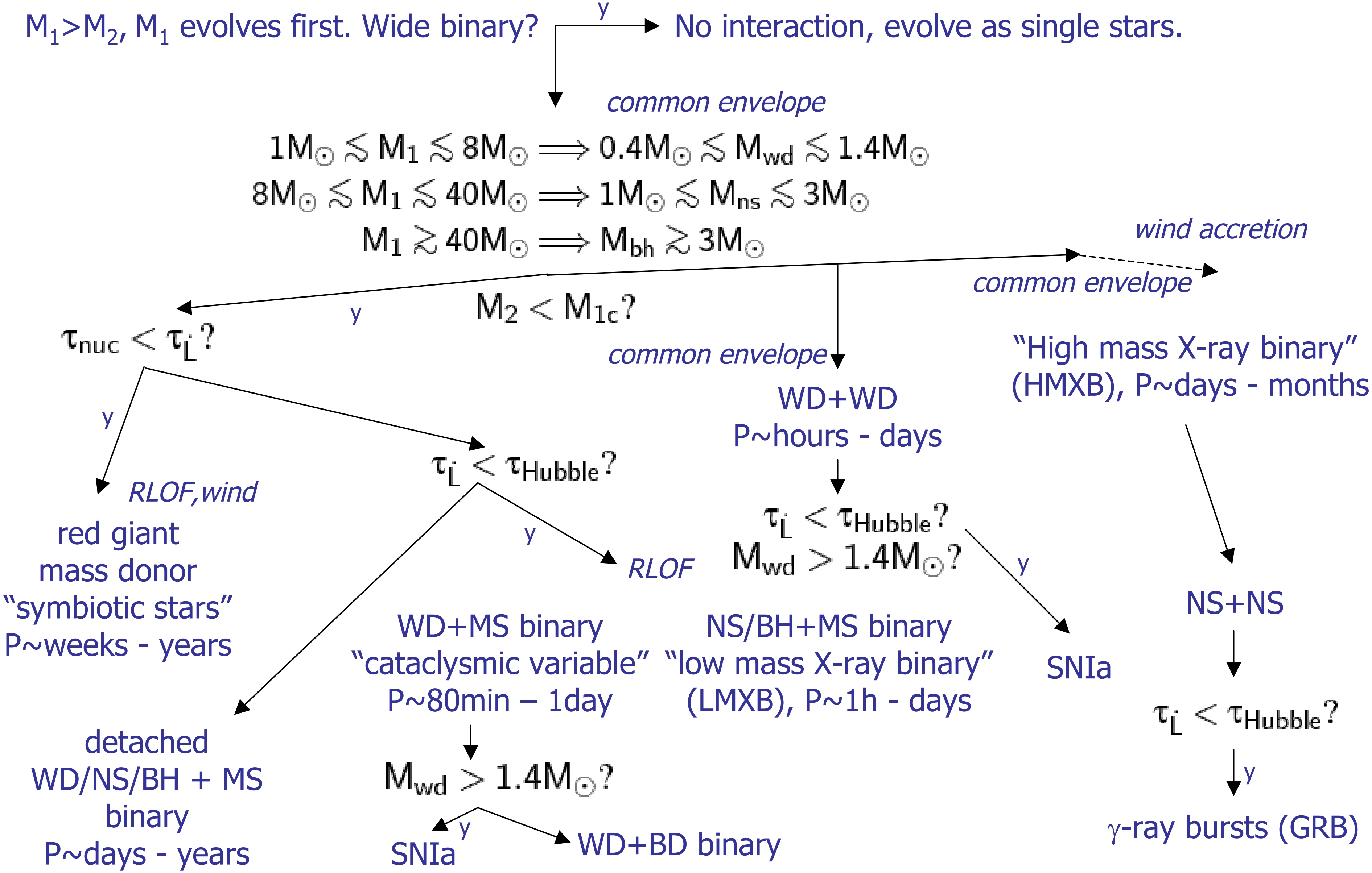
$$66.5^\circ < i < 73.5^\circ$$

$$3.89M_\odot < M_1 < 4.12M_\odot \quad 0.19M_\odot < M_2 < 0.32M_\odot$$

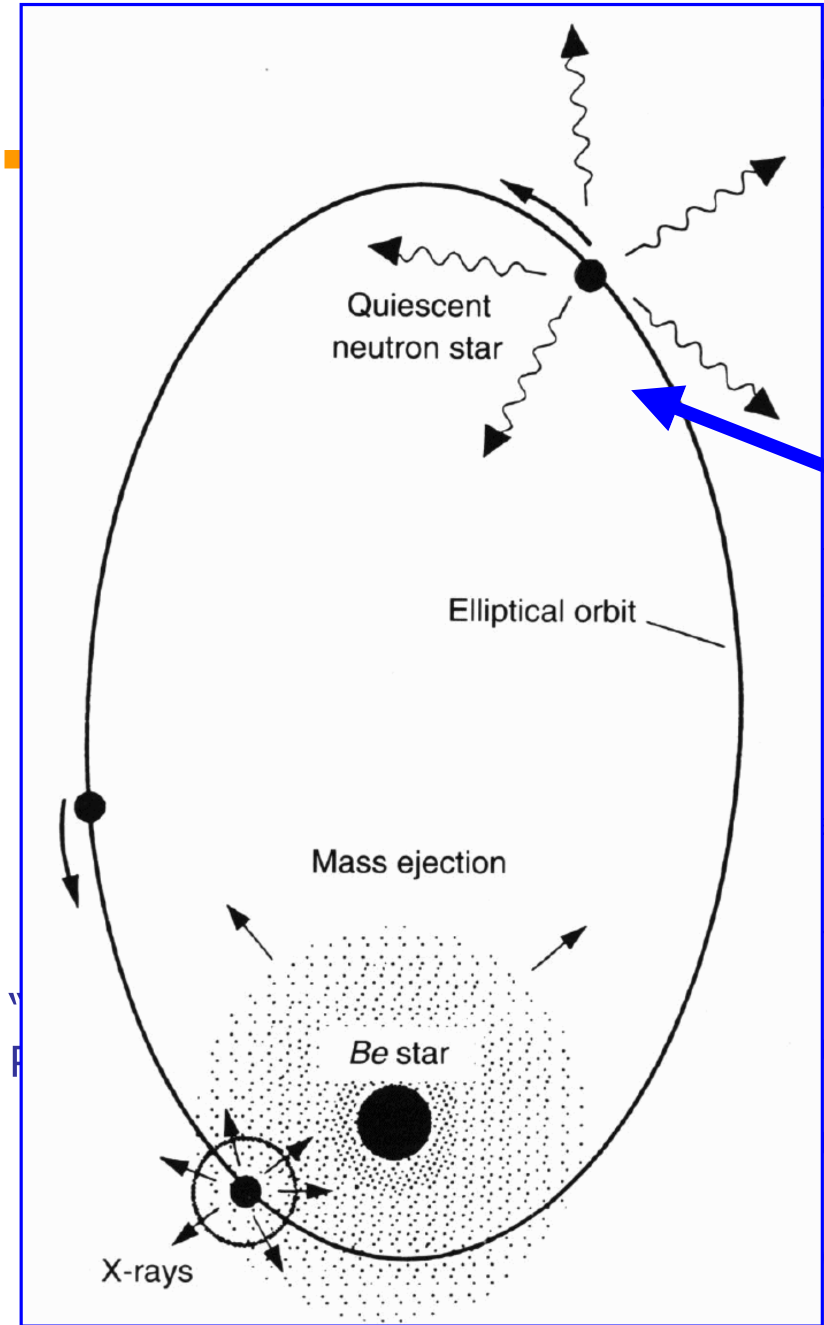
Black hole binaries



Binary star zoology



…y star zoology



y → No interaction, evolve as single stars.

common envelope

$0.4M_\odot \lesssim M_{wd} \lesssim 1.4M_\odot$

$1M_\odot \lesssim M_{ns} \lesssim 3M_\odot$

$M_{bh} \gtrsim 3M_\odot$

wind accretion

common envelope

1c?

common envelope

"High mass X-ray binary"
(HMXB), P~days - months

WD+WD
P~hours - days

$\tau_{\dot{L}} < \tau_{Hubble}$?
$M_{wd} > 1.4M_\odot$?

y

SNIa

NS+NS

$\tau_{\dot{L}} < \tau_{Hubble}$?

y

γ-ray bursts (GRB)

RLOF

NS/BH+MS binary
"low mass X-ray binary"
(LMXB), P~1h - days

…ble"
…y

?

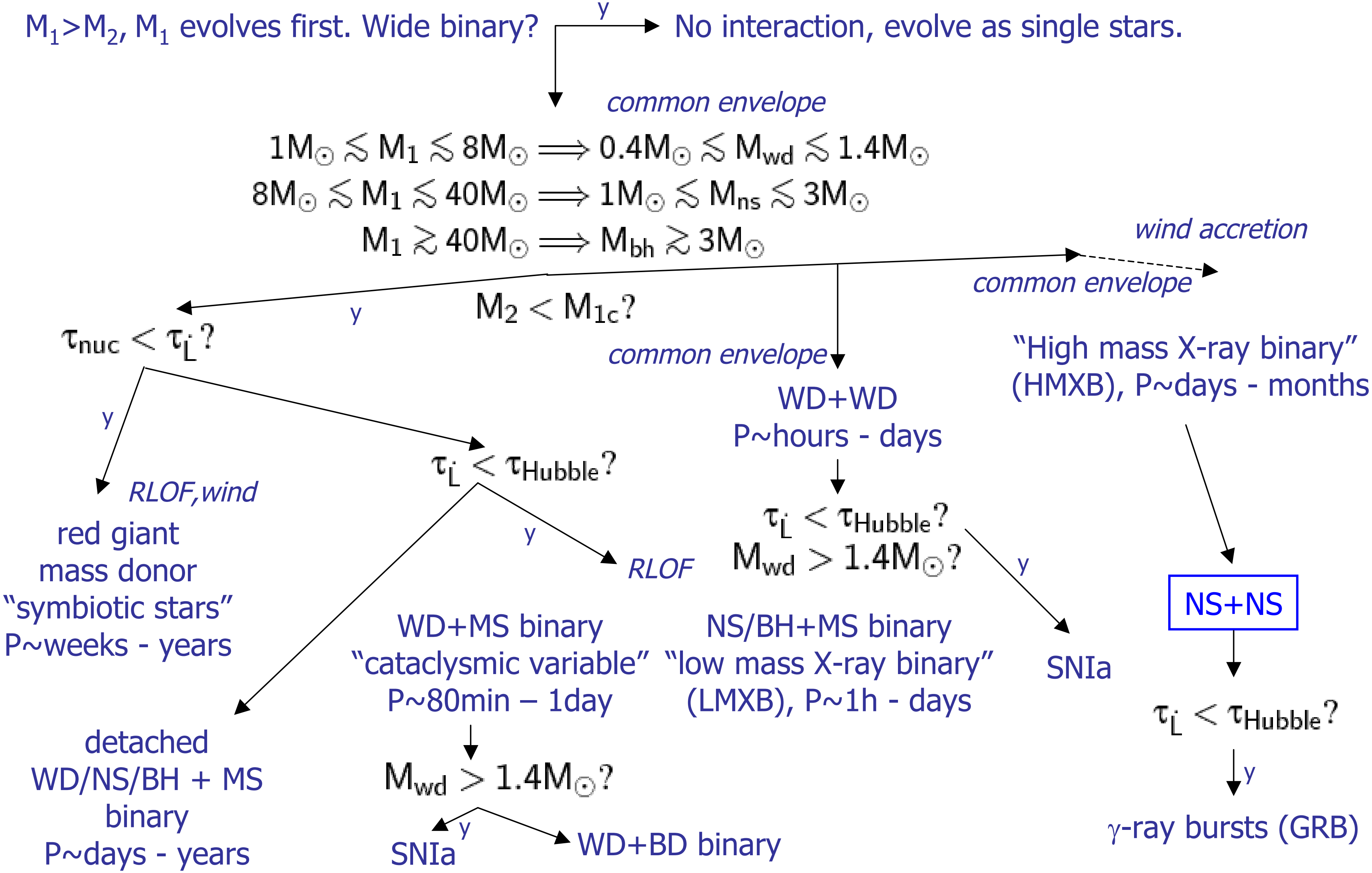
?

P~days - years

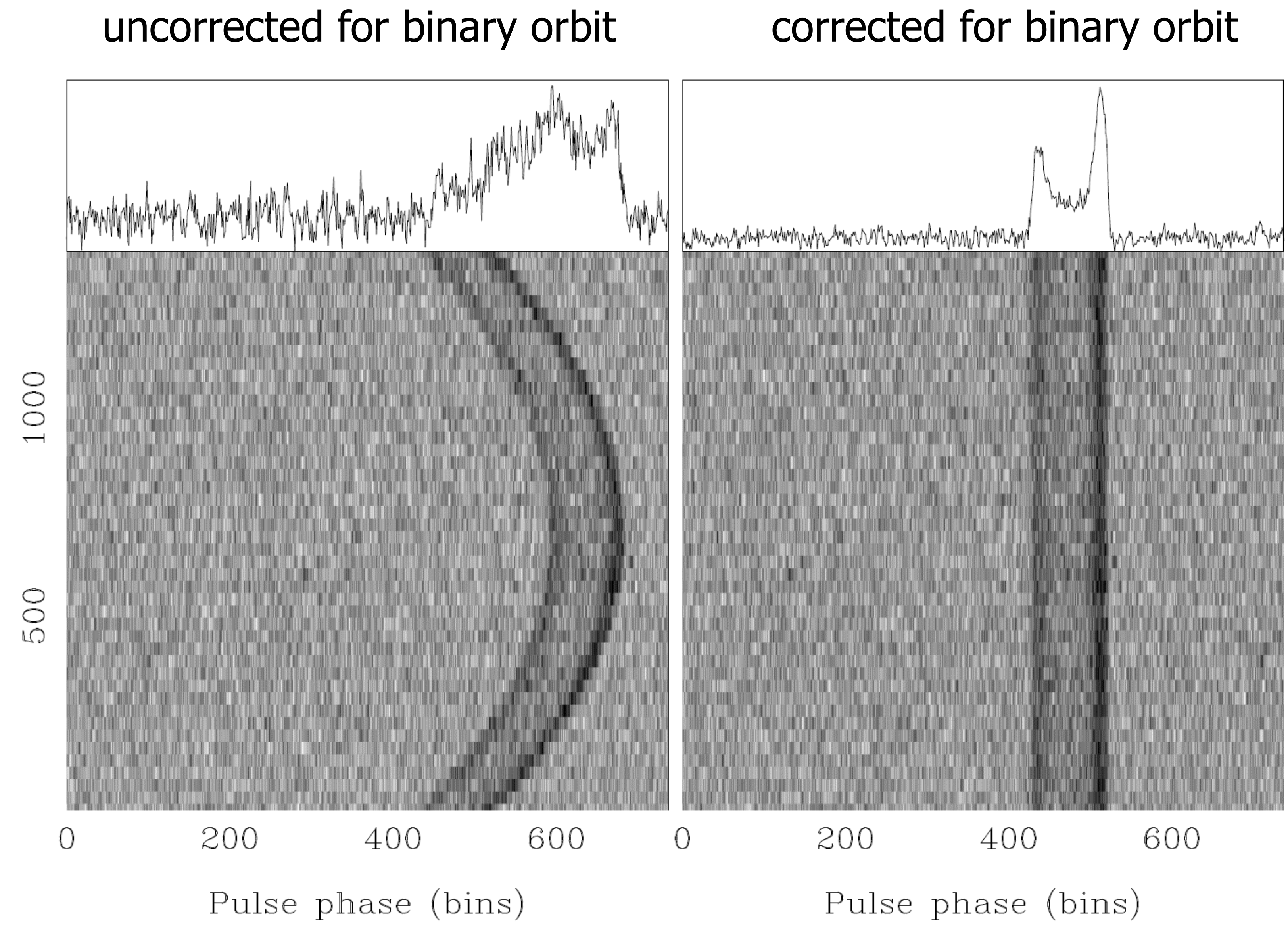
SNIa

WD+BD binary

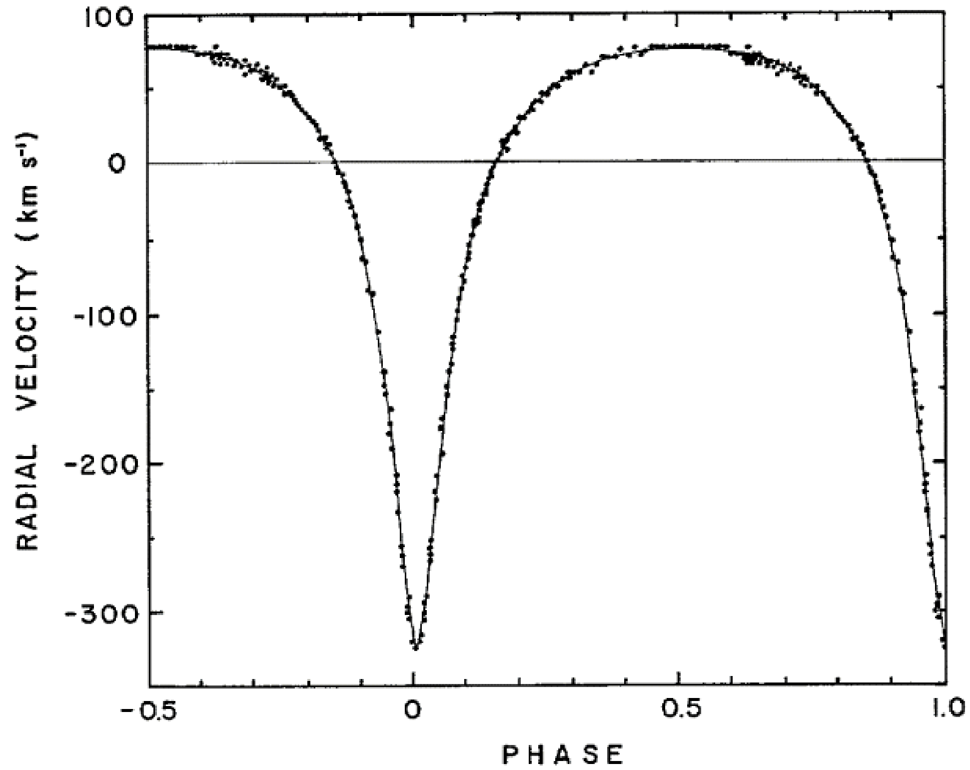
Binary star zoology



22.5min in the life of PSR 1913+16



The binary pulsar PSR 1913+16

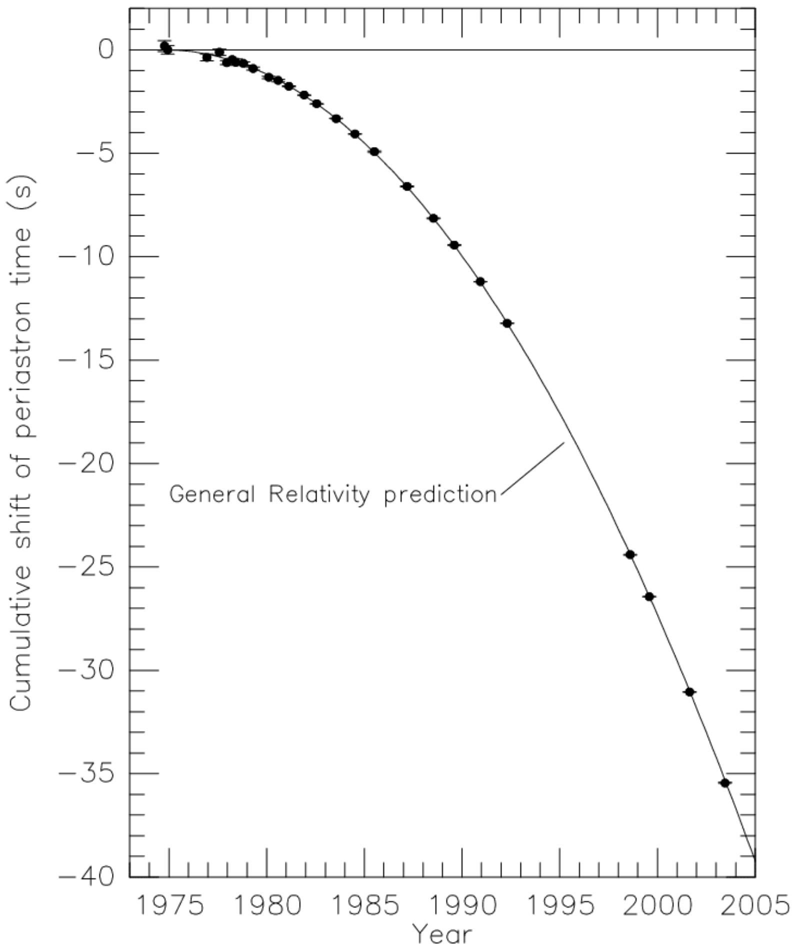


ELEMENTS OF THE ORBIT

$$K_1 = 199 \pm 5 \text{ km s}^{-1}$$
$$P_b = 27908 \pm 7 \text{ s}$$
$$e = 0.615 \pm 0.010$$
$$\omega = 179° \pm 1°$$
$$T = \text{JD } 2{,}442{,}321.433 \pm 0.002$$
$$a_1 \sin i = 1.00 \pm 0.02\ R_\odot$$
$$f(m) = 0.13 \pm 0.01\ M_\odot$$

pulse period varies over the binary orbit due to the Doppler effect

The binary pulsar PSR 1913+16



gravitational wave radiation

$$\dot{P}_o = -\frac{192\pi}{5c^5} \frac{M_1 M_2}{(M_1 + M_2)^{1/3}} \left(\frac{G2\pi}{P_o}\right)^{5/3} \times f(e)$$

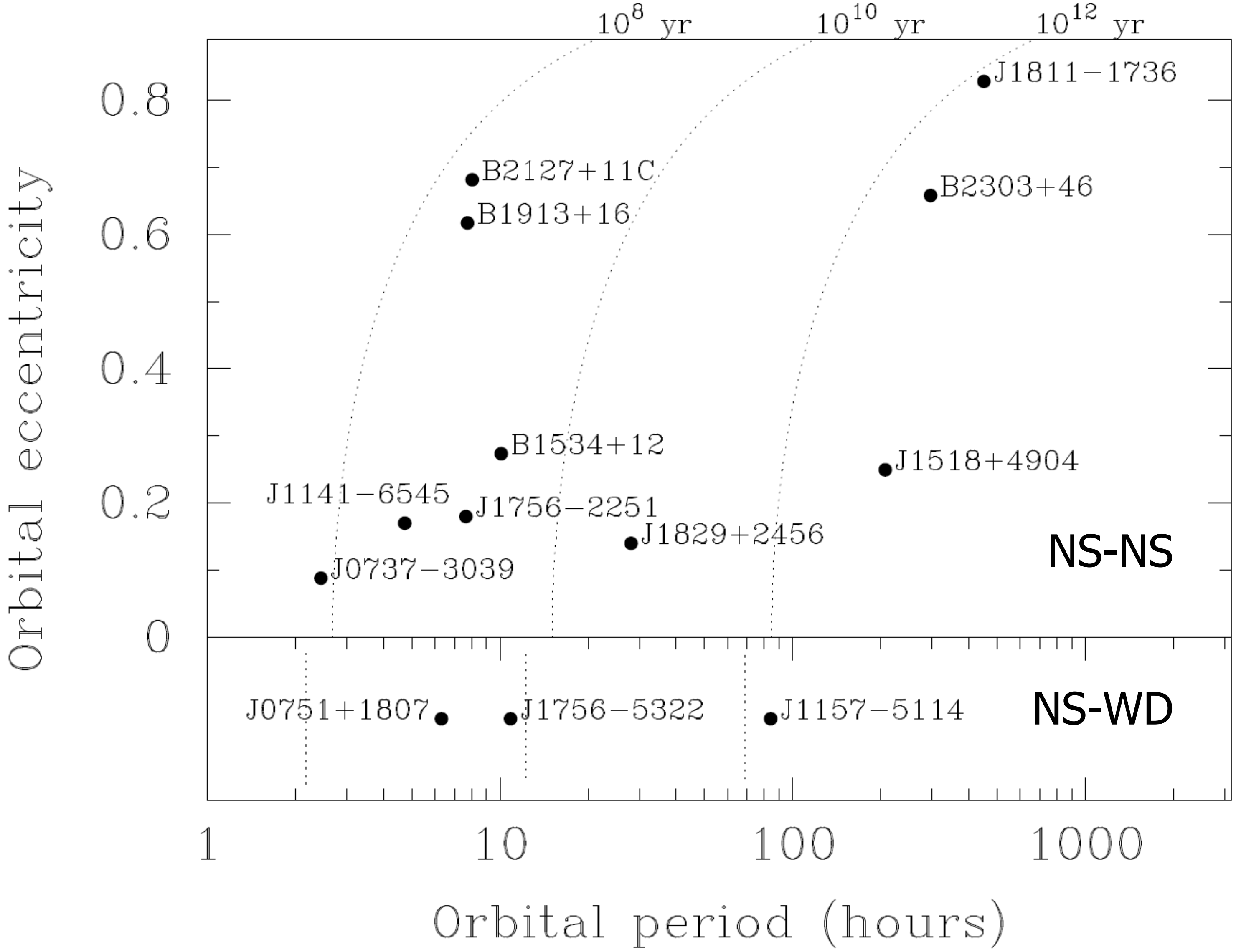
$$f(e) = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1 - e^2)^{-7/2}$$

$$M_1 = M_2 = 1.4 M_\odot, \;\; P = 7.75\text{h}, \;\; e = 0.617 \;\; \Longrightarrow \dot{P}_o = 2.4 \times 10^{-12} \text{ss}^{-1}$$

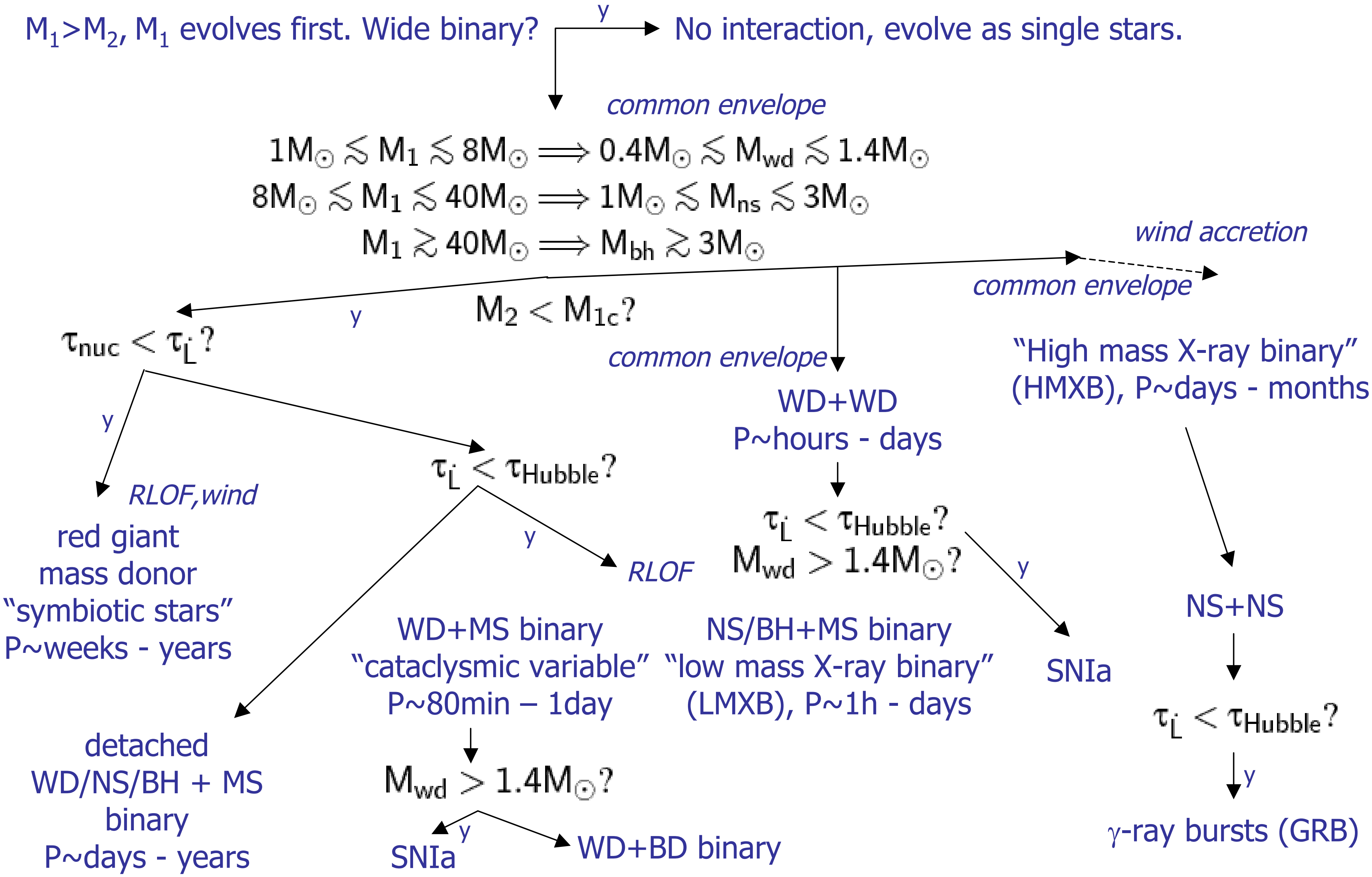
GR confirmed to better than 1%

1993: Nobel prize for Hulse & Taylor

Relativistic neutron star binaries



Binary star zoology



Binary star zoology

$M_1>M_2$, M_1 evolves first. Wide bina[redacted]s single stars.

$1M_\odot \lesssim M_1 \lesssim 8$M[redacted]

$8M_\odot \lesssim M_1 \lesssim 40$M[redacted]

$M_1 \gtrsim 40$M[redacted]

wind accretion

mmon envelope

y

$\tau_{nuc} < \tau_{\dot{L}}$?

N[redacted]

"High mass X-ray binary" (HMXB), P~days - months

WD+WD
P~hours - days

$\tau_{\dot{L}} < \tau_{Hubble}$?
$M_{wd} > 1.4M_\odot$?

y

SNIa

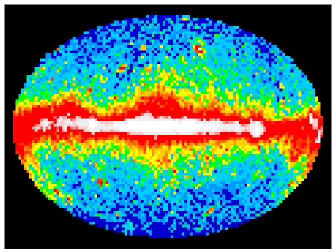
NS+NS

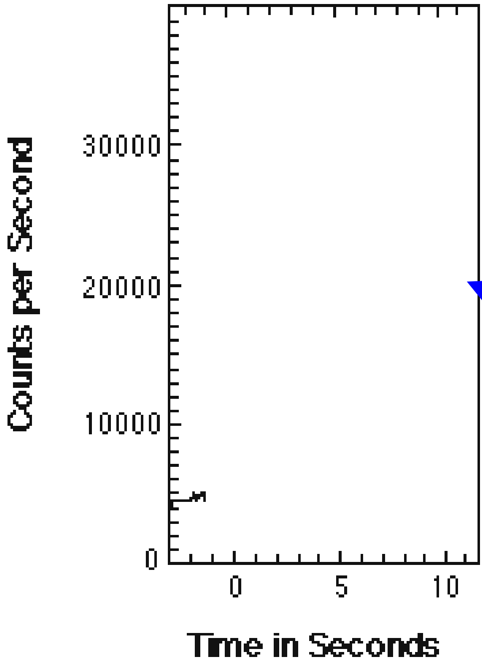
$\tau_{\dot{L}} < \tau_{Hubble}$?

y

γ-ray bursts (GRB)

"
F





.OF

NS/BH+MS binary
"low mass X-ray binary"
(LMXB), P~1h - days

BD binary