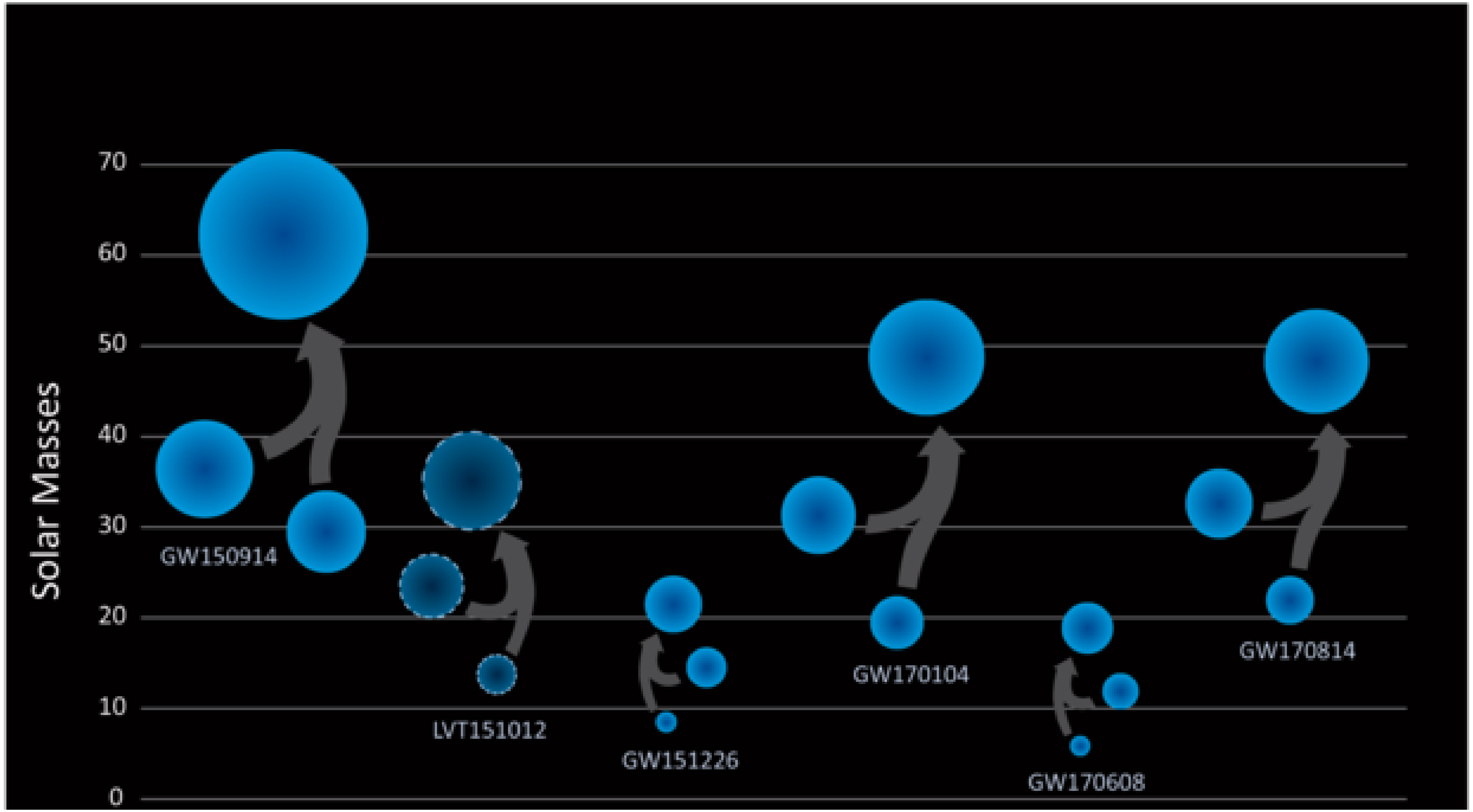
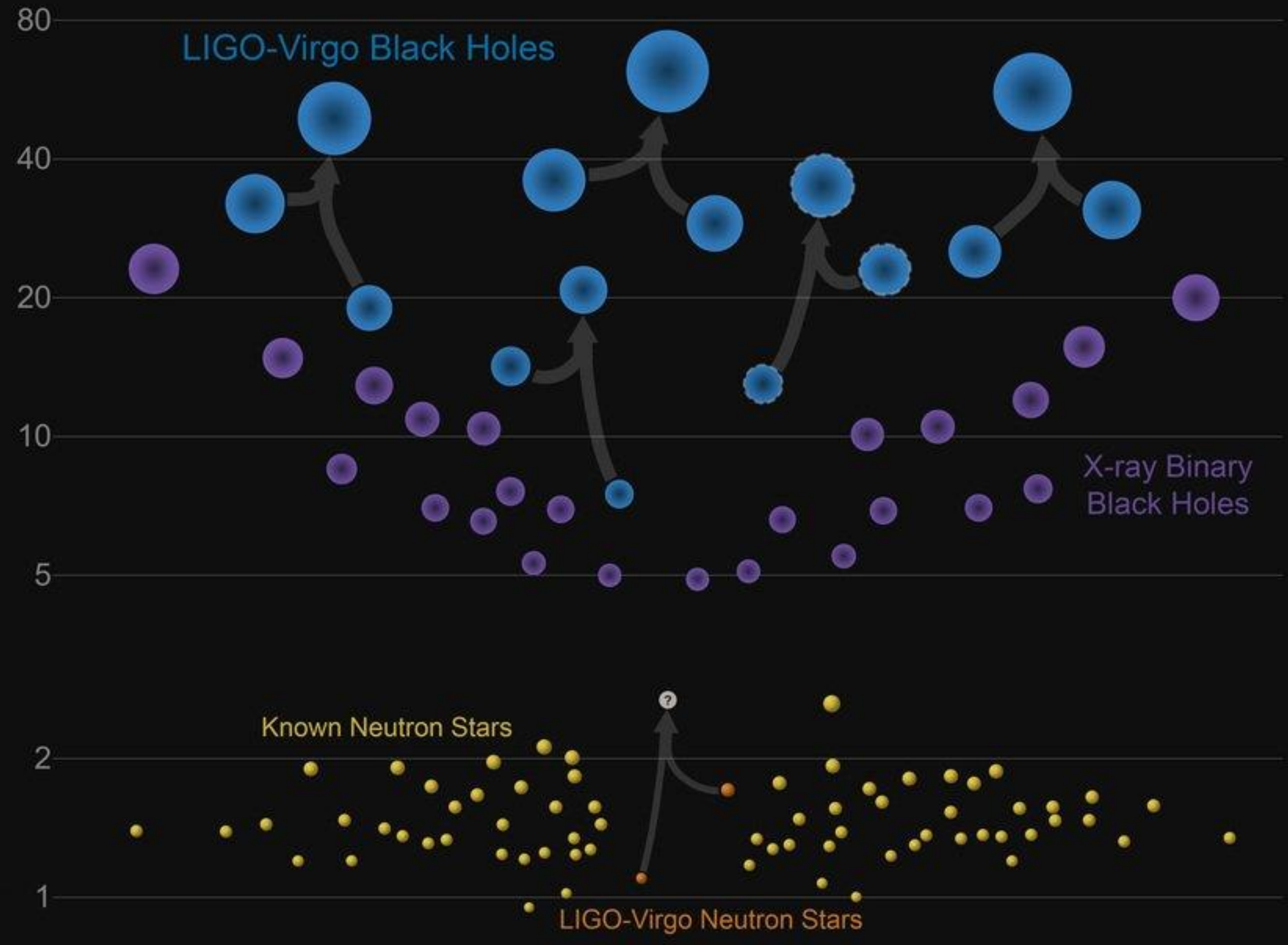
Stellar mass black holes

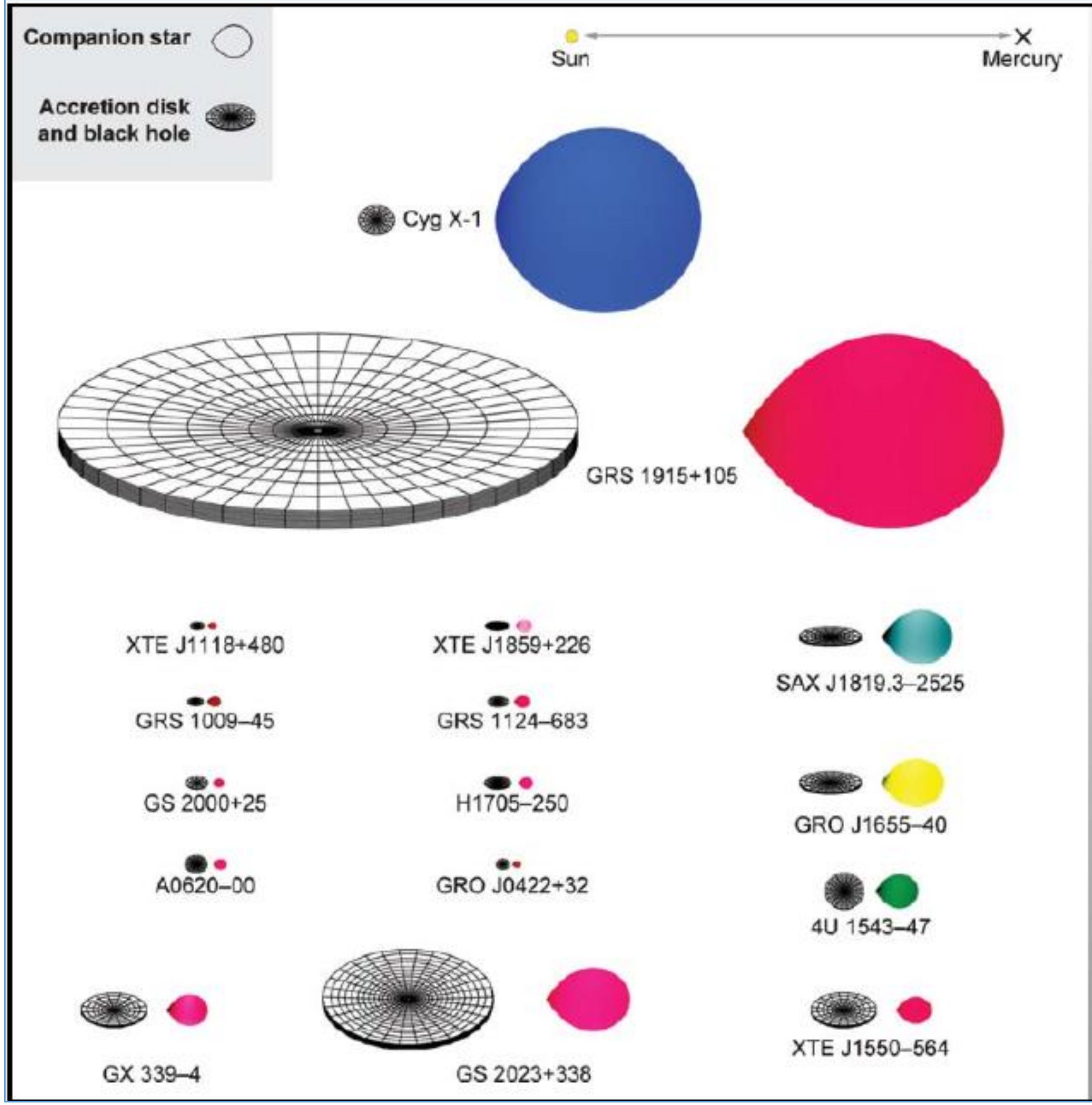
Black Hole Physics, 2018


Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814

Masses in the Stellar Graveyard

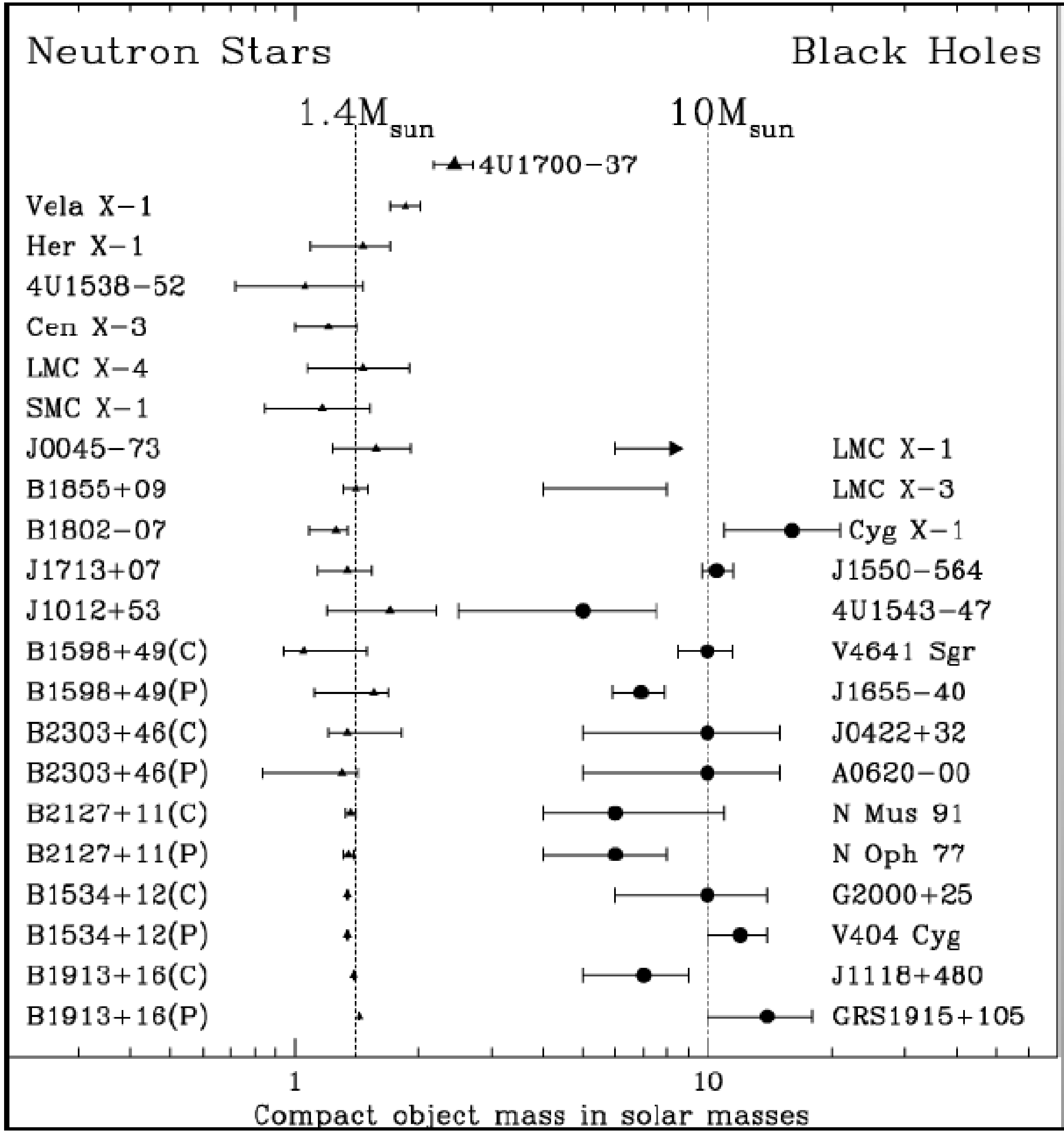
in Solar Masses



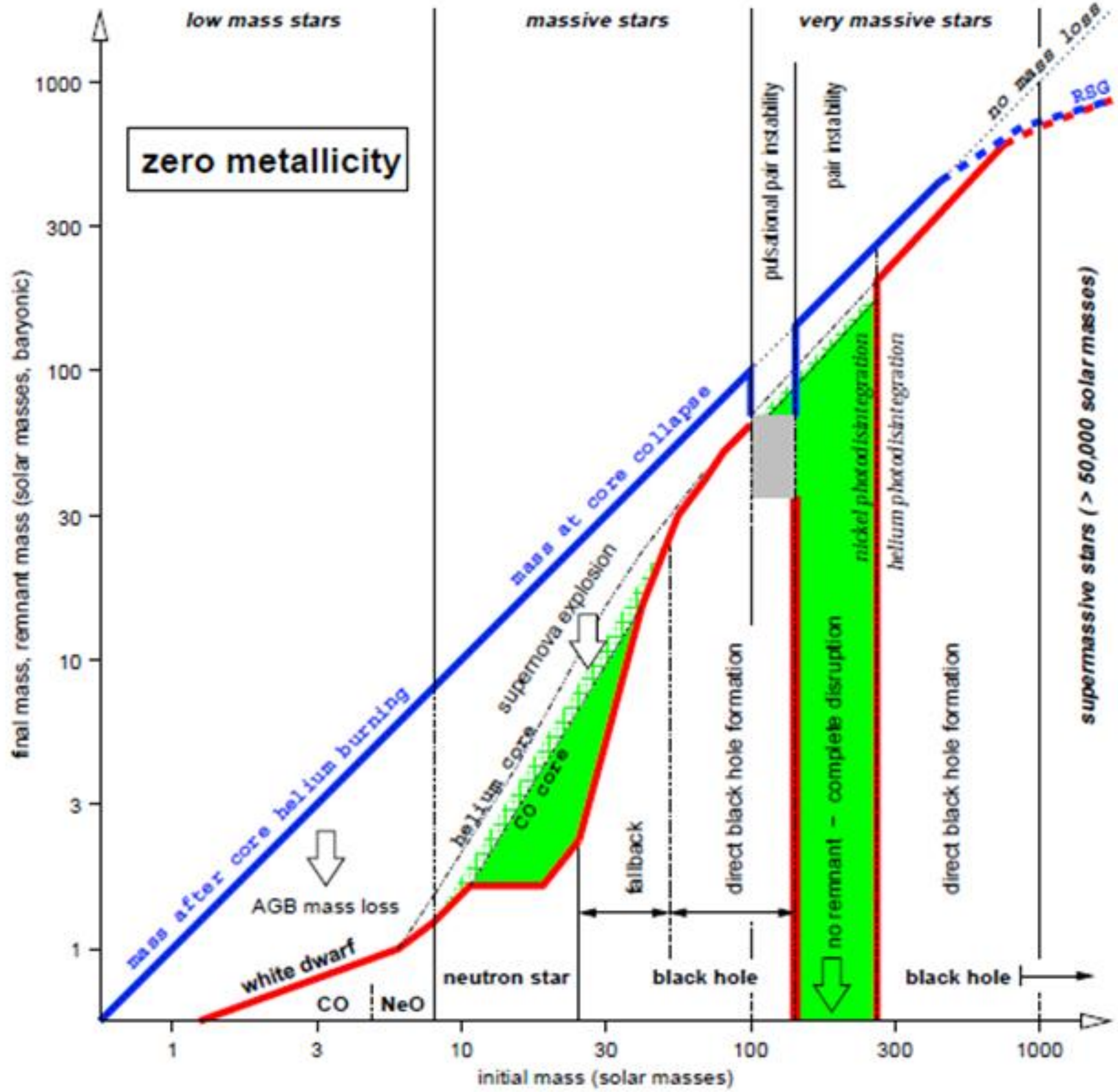


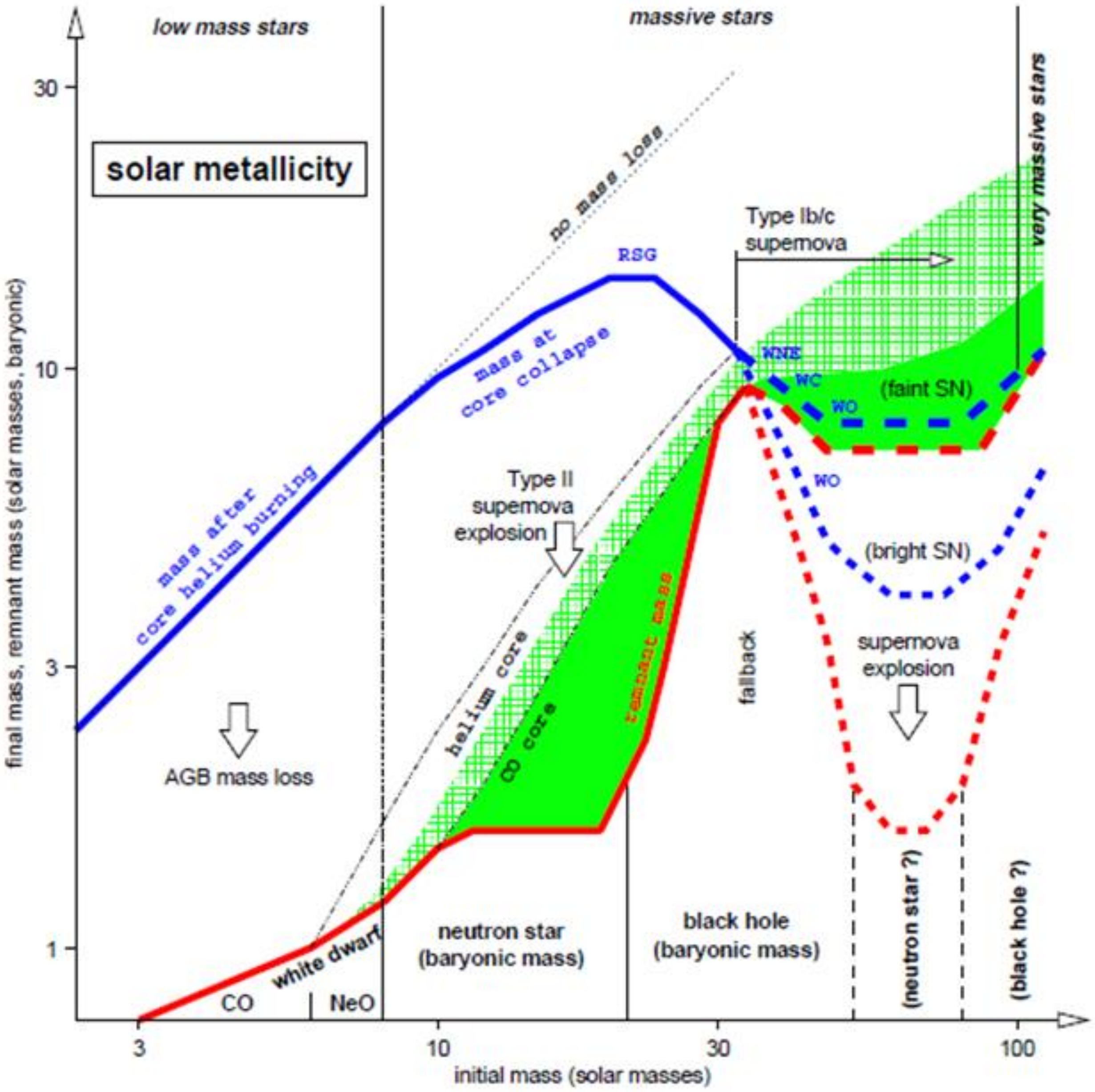
Binary systems with massive compact objects

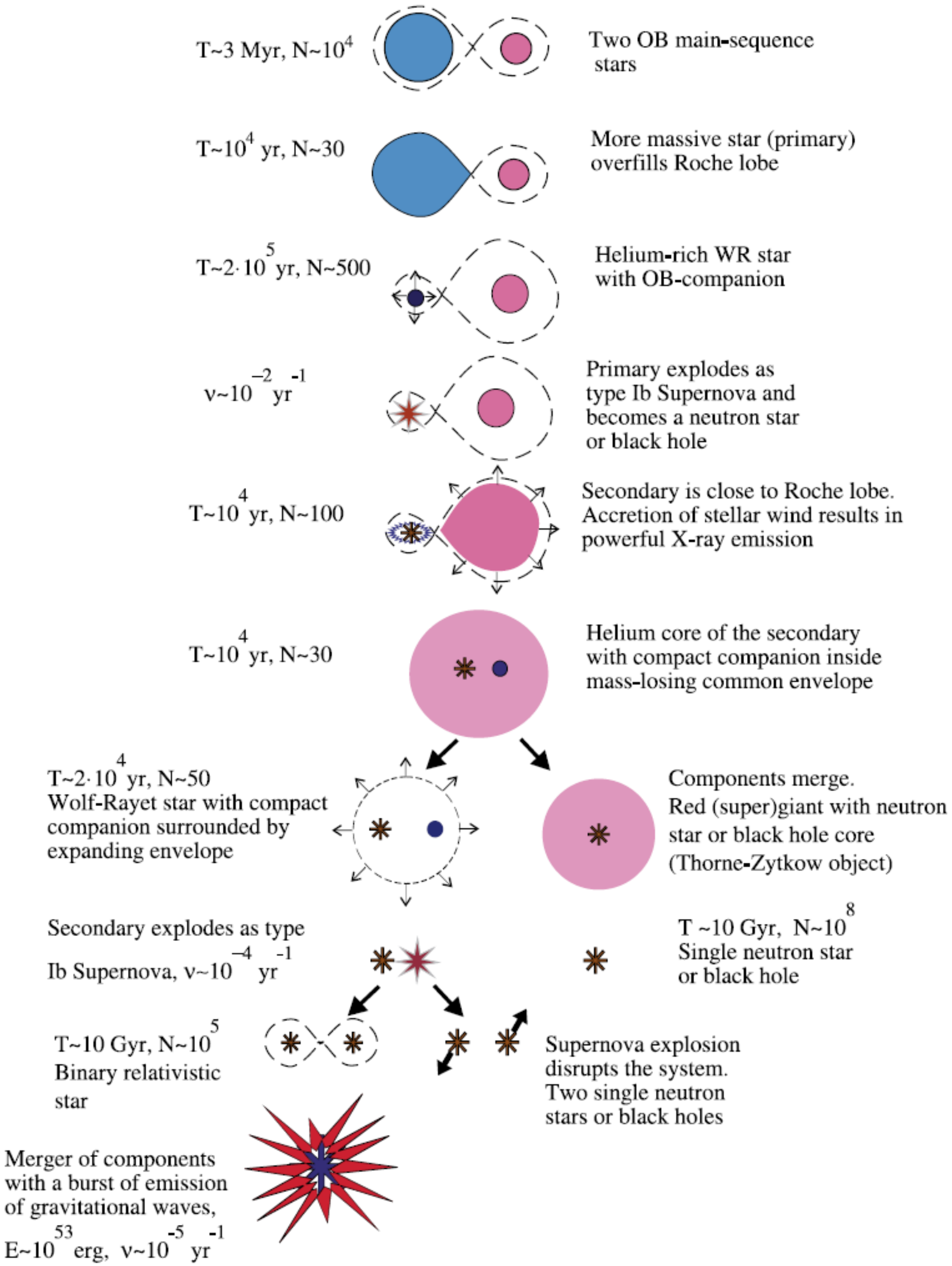
Ordinary star + "something else" – a neutron star or BH



About 20 binaries in our galaxy where the compact object seems to be too massive to be a neutron star


low mass stars
massive stars
very massive stars
no mass loss
RSG
zero metallicity
1000
300
100
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
pulsational pair instability
pair instability
mass at core collapse
mass after core helium burning
supernova explosion
helium core
CO core
nickel photodisintegration
helium photodisintegration
supermassive stars (> 50,000 solar masses)
AGB mass loss
fallback
direct black hole formation
no remnant – complete disruption
direct black hole formation
white dwarf
CO
NeO
neutron star
black hole
black hole
1
3
10
30
100
300
1000
initial mass (solar masses)


low mass stars
massive stars
very massive stars
solar metallicity
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
no mass loss
RSG
mass after core helium burning
mass at core collapse
Type Ib/c supernova
WNE
WC
WO
(faint SN)
WO
(bright SN)
Type II supernova explosion
helium core
CO core
remnant mass
fallback
supernova explosion
AGB mass loss
white dwarf
CO
NeO
neutron star (baryonic mass)
black hole (baryonic mass)
(neutron star ?)
(black hole ?)
3
10
30
100
initial mass (solar masses)


$T\sim3$ Myr, $N\sim10^4$
Two OB main-sequence stars
$T\sim10^4$ yr, $N\sim30$
More massive star (primary) overfills Roche lobe
$T\sim2\cdot10^5$ yr, $N\sim500$
Helium-rich WR star with OB-companion
$\nu\sim10^{-2}$ yr^{-1}
Primary explodes as type Ib Supernova and becomes a neutron star or black hole
$T\sim10^4$ yr, $N\sim100$
Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission
$T\sim10^4$ yr, $N\sim30$
Helium core of the secondary with compact companion inside mass-losing common envelope
$T\sim2\cdot10^4$ yr, $N\sim50$
Wolf-Rayet star with compact companion surrounded by expanding envelope
Components merge.
Red (super)giant with neutron star or black hole core (Thorne-Zytkow object)
Secondary explodes as type Ib Supernova, $\nu\sim10^{-4}$ yr^{-1}
$T\sim10$ Gyr, $N\sim10^8$
Single neutron star or black hole
$T\sim10$ Gyr, $N\sim10^5$
Binary relativistic star
Supernova explosion disrupts the system. Two single neutron stars or black holes
Merger of components with a burst of emission of gravitational waves,
$E\sim10^{53}$ erg, $\nu\sim10^{-5}$ yr^{-1}

Distinctive features that can indicate the presence of a black hole

Observe **two or more** of these features to “find” a black hole:

- **Gravitational deflection of light**, by an amount requiring black hole masses and sizes.
- **X-ray and/or γ-ray emission** from ionized gas falling into the black hole.
- **Orbital motion of nearby stars or gas clouds** that can be used to infer the mass of (perhaps invisible) companions: a mass too large to be a white dwarf or a neutron star might correspond to a black hole.
- **Motion close to the speed of light**, or apparently greater than the speed of light (“superluminal motion”).
- **Extremely large luminosity** that cannot be explained easily by normal stellar energy generation.
- Direct observation of a large, massive **accretion disk**.

Stellar-mass black holes

By this we mean black holes formed by the gravitational collapse of dead stars that are too massive to become neutron stars or white dwarfs.

Best clues:

- ❑ High-energy light (X/γ rays): gives promising, but not completely unambiguous, detections of black holes.
- ❑ Orbital motion of companion stars
  - Orbit size, speed plus Newton’s laws can be used to work out the **mass** of a visibly-dim (but perhaps X-ray bright) companion. If it’s more than 2 $M_\odot$ …
  - We can’t usually resolve the details of the orbit directly in images, but we can measure orbital speeds and periods well enough to work out what the orbit is, using the Doppler effect.

High-energy light from stellar-mass black holes

X-ray or γ-ray emission. High-energy light should be emitted by material falling into black holes; this, in fact, should be one of the principal signatures of a black hole because it is hard for ordinary astronomical objects to emit X rays.

- ☐ **Search for such objects near visible stars.** Most stars have stellar companions; if such a companion became a black hole, and the two were close enough together, material from the visible star could fall into the black hole, creating an X-ray source.
- ☐ **Difficulty**: X-rays are absorbed strongly by the Earth’s atmosphere (and by interstellar gas and dust). Observations must take place from outside the atmosphere (i.e. from satellites).

High-energy light from black holes (continued)

- X-ray detectors on rockets discovered the first stellar sources of high-energy light (Sco X-1, 1962).
- Many more were found by X-ray detectors on satellites (*Uhuru*, *Ginga*) and by X-ray and γ-ray telescopes and detectors on satellites (*Einstein*, *ROSAT, Compton GRO*).
- Some of the sources fit the description of black-hole accretion of matter.
- Most do not: some other sorts of objects also turned out unexpectedly to be bright sources of X-rays. The emission is helpful, but not sufficient, in identifying a black hole.
- Fortunately, some of the X-ray objects have visible stellar companions, from whose orbits we can estimate the mass of the corresponding X-ray objects.

Orbital motion and the detection of black holes

The stars have narrow dark lines in their spectra: specific wavelengths at which the stars are dark. (Sun’s spectrum at right.)

In moving stars these lines are shifted to different wavelengths due to the Doppler effect

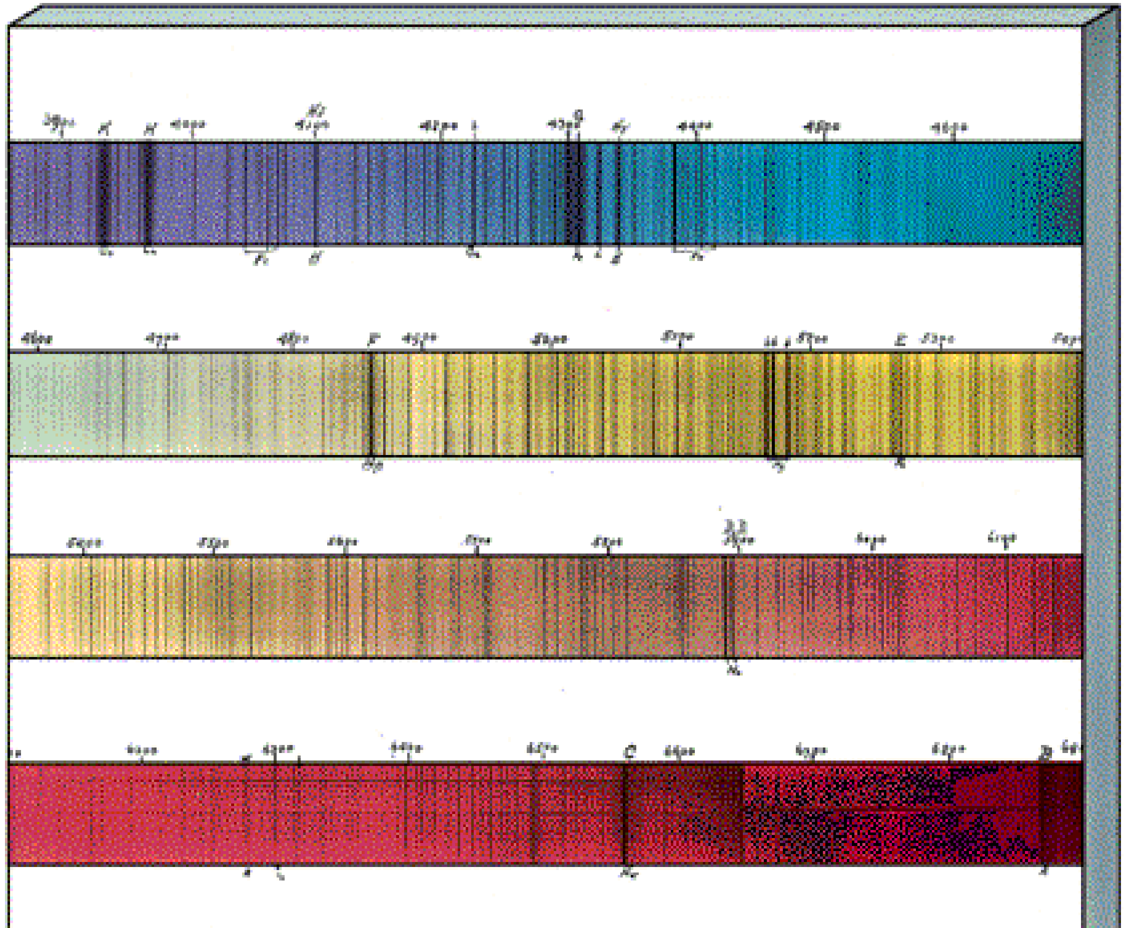


Figure: Chaisson and McMillan, *Astronomy today*

Orbital motion and the detection of black holes

Can deduce orbital speed from maximum and minimum Doppler shifts:

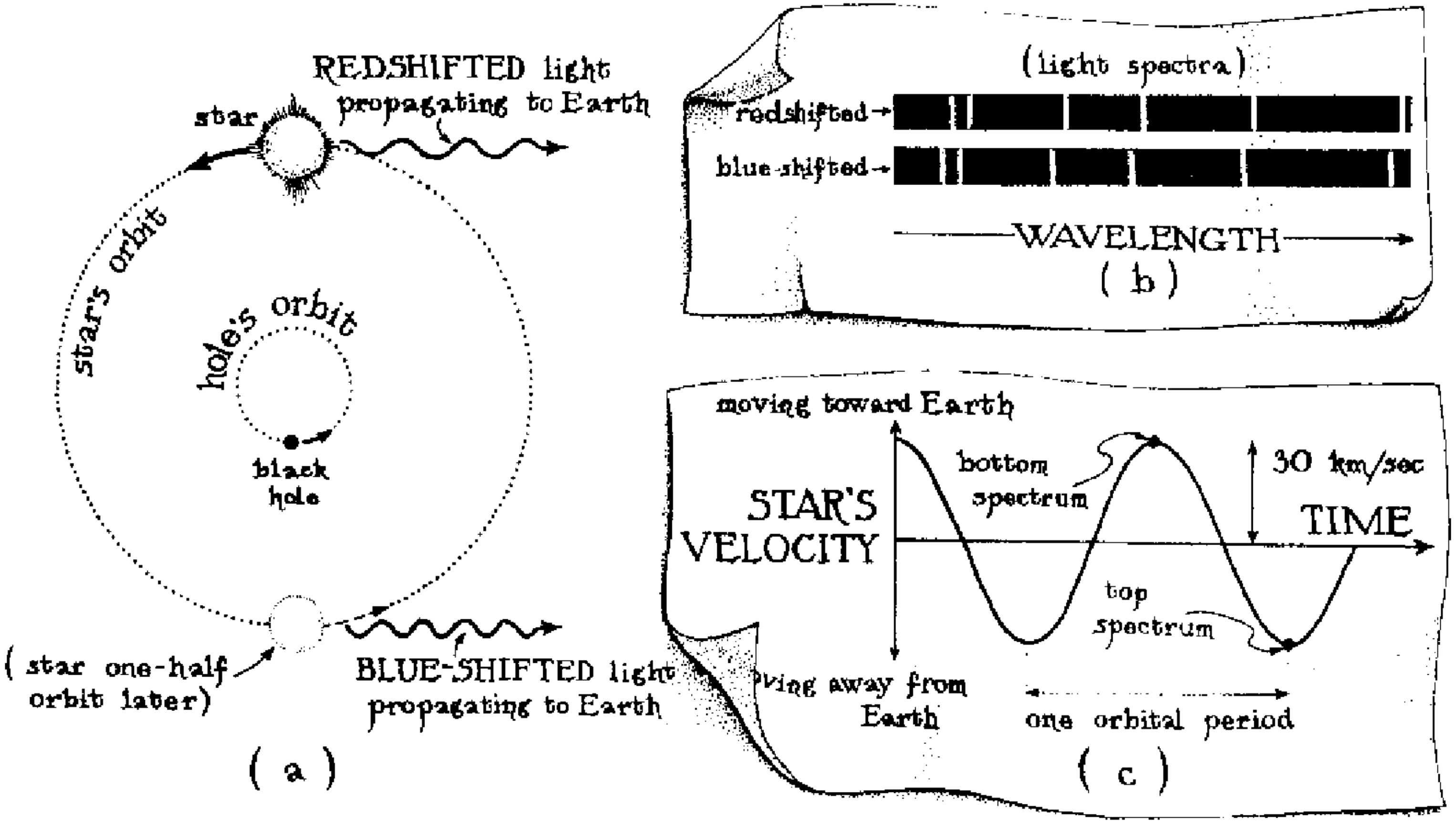
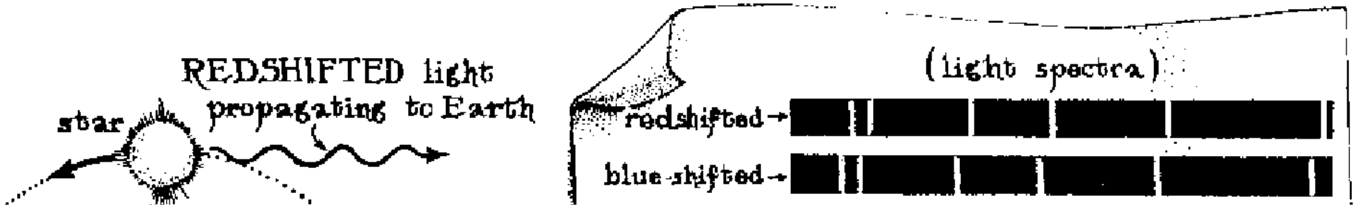


Figure: Thorne, *Black holes and time warps*

Orbital motion and the detection of black holes

Can deduce orbital speed from maximum and minimum Doppler shifts:



$$f \equiv \frac{P_{orb}\, v_{orb}^3}{(2\pi G)} = \frac{M_x^3}{(M_x + M_c)^2} \sin^3 i \; < M_x$$

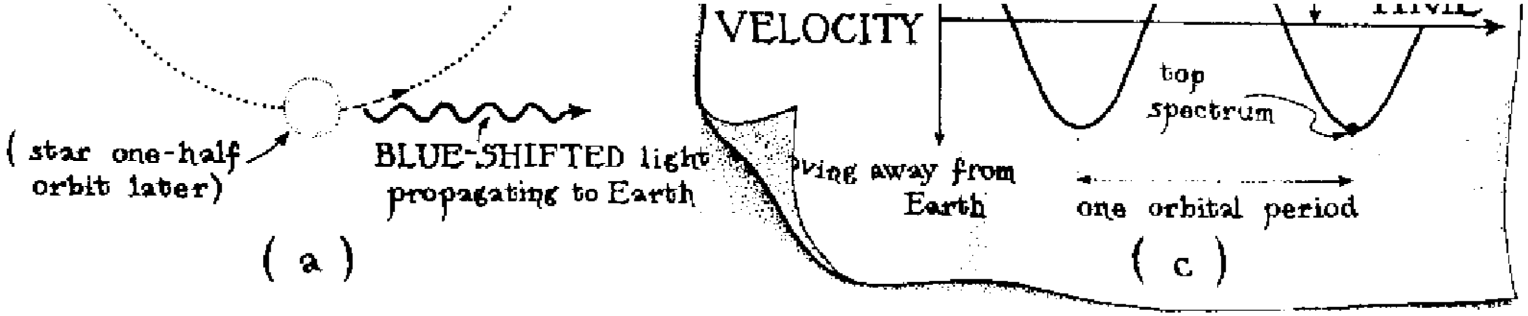


Figure: Thorne, *Black holes and time warps*

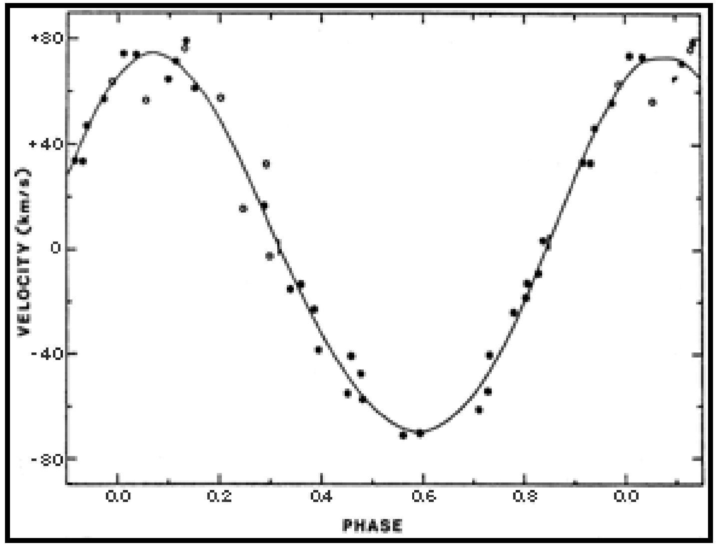
Discovery of “stellar” black holes: Cygnus X-1

Cygnus X-1 (a.k.a. Cygnus XR-1) is a bright X-ray source, the second brightest in the sky.

- ☐ Its X-ray brightness varies dramatically on time scales of 0.001 sec: the X-ray object must be about 0.003 light-seconds (940 km) in circumference.
- ☐ Essentially at the same position as the X-ray source is a bright star that appears to be in orbital motion. No other visible star nearby exhibits orbital motion; the bright star’s companion is invisible. Other stars like it are not bright in X rays. It is thus reasonable to assume that the bright star’s invisible companion is the X-ray source.
- ☐ The star and the invisible companion are too close together for telescopes to **resolve** them from our distance.

Cygnus X-1 (continued)

- Orbital parameters of the bright star (HDE 226868): distance 6000 light years, revolution period of 5.6 days, orbital circumference 6.3x10^7 km, mass of HDE 226868 about 20 $M_{\odot}$.
- The tilt of the orbit has been determined, with difficulty and not terribly accurately: the rotation axis makes an angle of about 62^{o} with respect to our line of sight (Dolan and Tapia 1989).



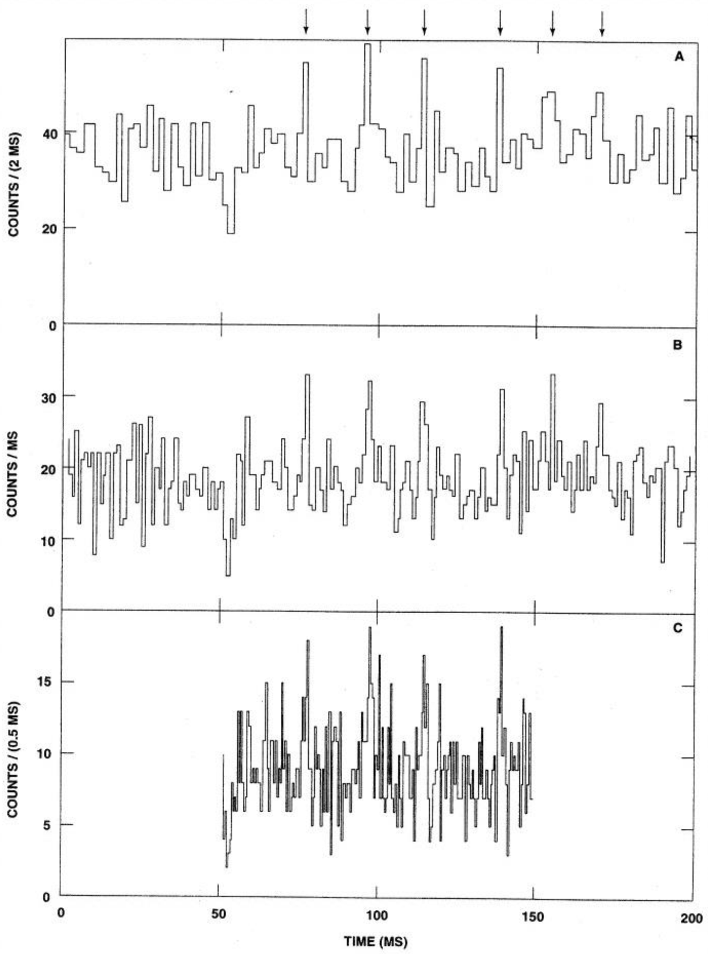
Measured orbital motion of HDE 226868.

- Applying these inputs to Newton’s laws of motion, a mass between 5 and 11 $M_{\odot}$ is derived for the invisible companion; most probable value 6 $M_{\odot}$. A black hole?

“Death spirals” in Cygnus X-1: seeing the event horizon itself?

Occasionally Cyg X-1 emits short bursts of light seen at ultraviolet wavelengths, in the form of a train of pulses that dies off toward the end. One such burst, seen with the Hubble Space Telescope by Joe Dolan (2001, *PASP* **113**, 974), is shown at right.

- ☐ Pulse period close to orbital period near innermost stable orbit
- ☐ Are we seeing material falling from an unstable orbit, and passing behind the horizon once per orbit?



Cygnus X-1: summary

- Too small, too X-ray bright, and too faint at visible wavelengths to be a 6 $M_\odot$ star.
- Far too massive to be a white dwarf or neutron star.
- Evidence of orbit instability, **and of an event horizon**, on exactly the scales expected for a 6 $M_\odot$ black hole.

The simplest, and in fact least exotic, interpretation of the observations is that Cygnus X-1 consists of a 20 $M_\odot$ star and a 6 $M_\odot$ black hole in orbit around each other.

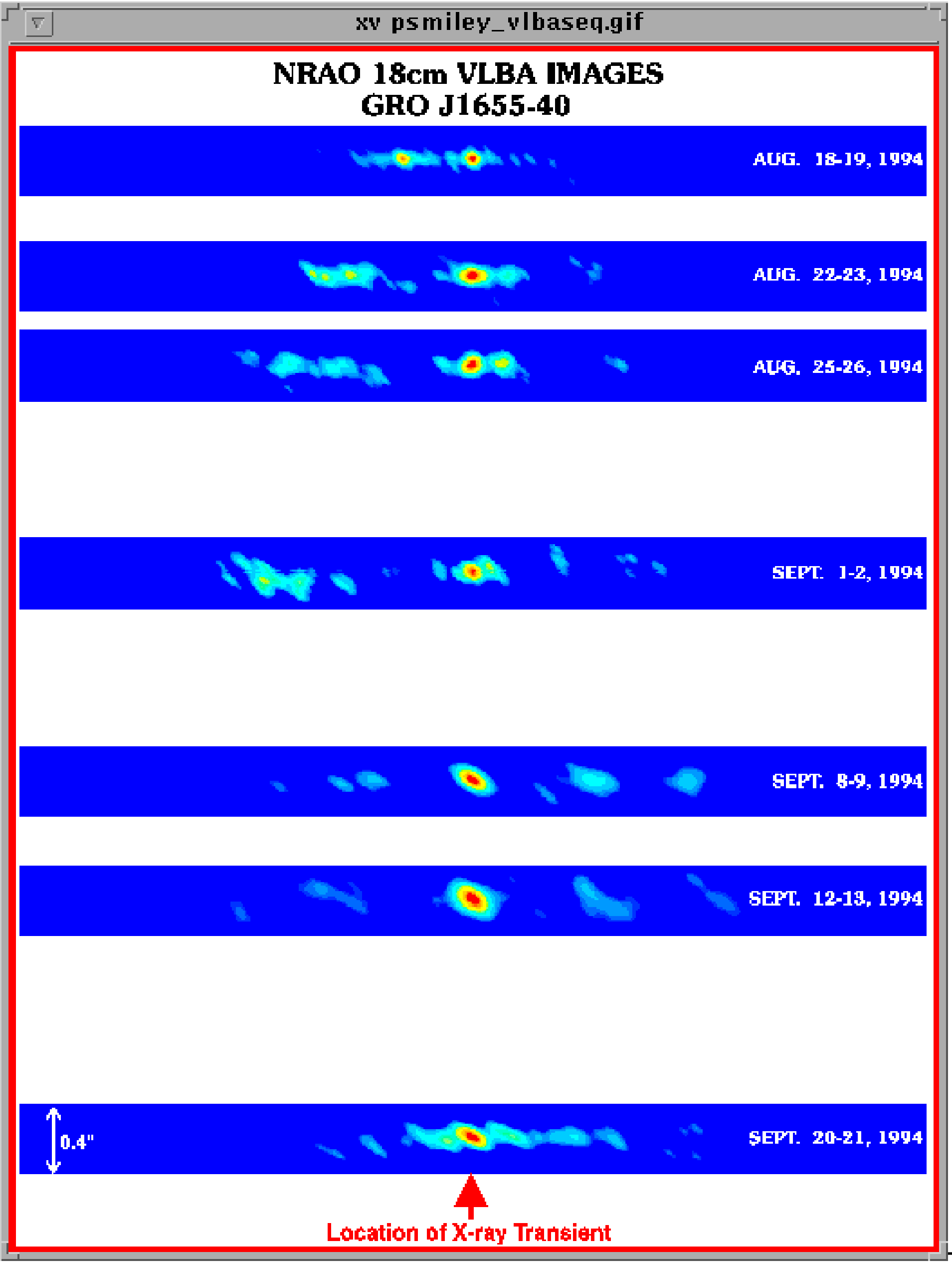
(Stephen Hawking, who used to assert that Cyg X-1 does not contain a black hole, has conceded his celebrated bet with Kip Thorne on this subject; see Thorne's book, p. 315.)

Discovery of “stellar” black holes: GRO J1655-40

GRO J1655-40 is an X-ray transient source discovered by NASA’s *Compton Gamma-Ray Observatory* (GRO) in 1994.

- Rapidly-variable emission in its X-ray bursts: the X-ray object is a few hundred km around.
- The X-ray source has a stellar companion, a star rather similar to the Sun (about 1.1 $M_\odot$); the X-ray source and the visible star revolve around each other with a period of 2.92 days. Their distance from us is measured to be 6500 light years.
- A stroke of luck: it is an **eclipsing** system, so the orbit is known to be tilted edge on to our line of sight.
- Thus we know the mass of the X-ray bright companion rather accurately: it must be between 5.5 and 7.9 $M_\odot$, with a most probable value of 7.0 $M_\odot$. (Shahbaz *et al.* 1999)
- Also has radio jets with motions close to the speed of light!

GRO J1655-40 (continued)



- Two jets, perpendicular to the plane of the orbit, with ejection speed 0.92c.
- Too small and massive to be a white dwarf or a neutron star, X-ray bright, and associated with relativistic ejection speeds: GRO J1655-40 is more likely to harbor a black hole than any other object of which we know.

Radio images: R. Hjellming and R. Rupen, NRAO.

GRO J1655-40 spins, too.

We expect it to spin, but now we can demonstrate this:

A 7 $M_{\odot}$ black hole has a horizon circumference 130 km, and if it doesn’t spin its innermost stable orbit circumference is 390 km. Material in this orbit will circle the black hole **314 times per second.**

- However, one often sees the X-ray brightness of GRO J1655-40 modulate at **450 times per second** for long stretches of time (Tod Strohmayer 2001, *ApJL* 552, L49).
- Nothing besides very hot material in a stable orbit can do this so reproducibly at this frequency.
- Thus there are stable orbits closer to the black hole than they can be if it doesn’t spin.

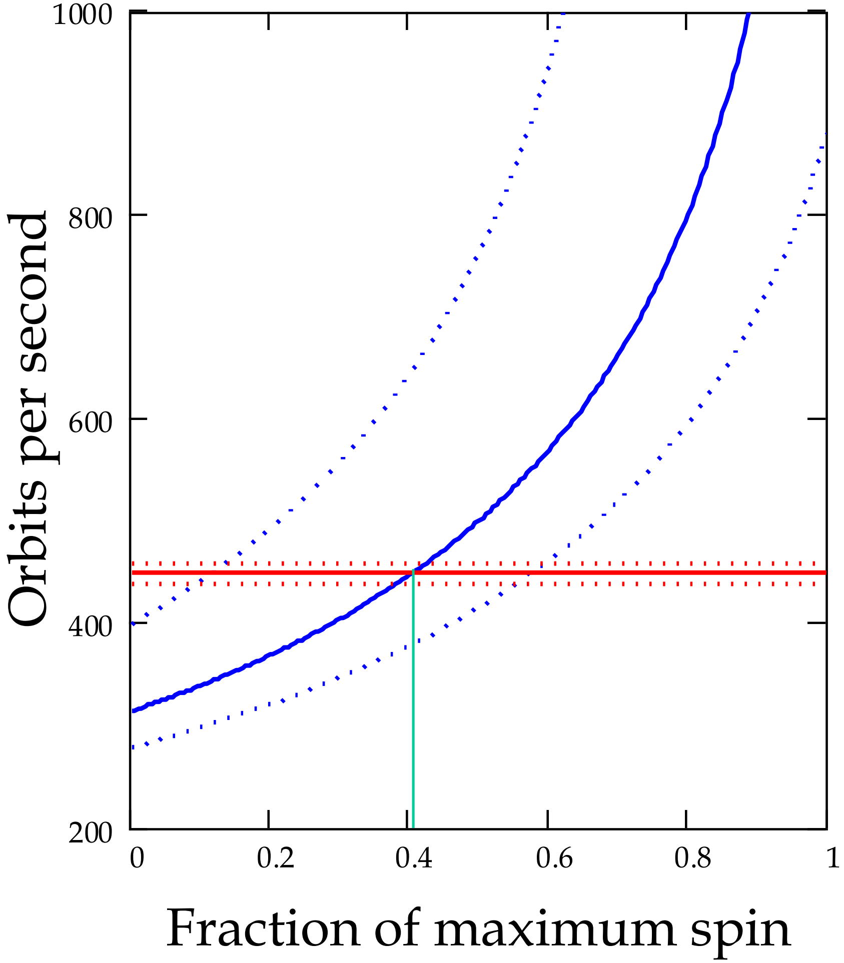
GRO J1655-40 spins, too (continued).

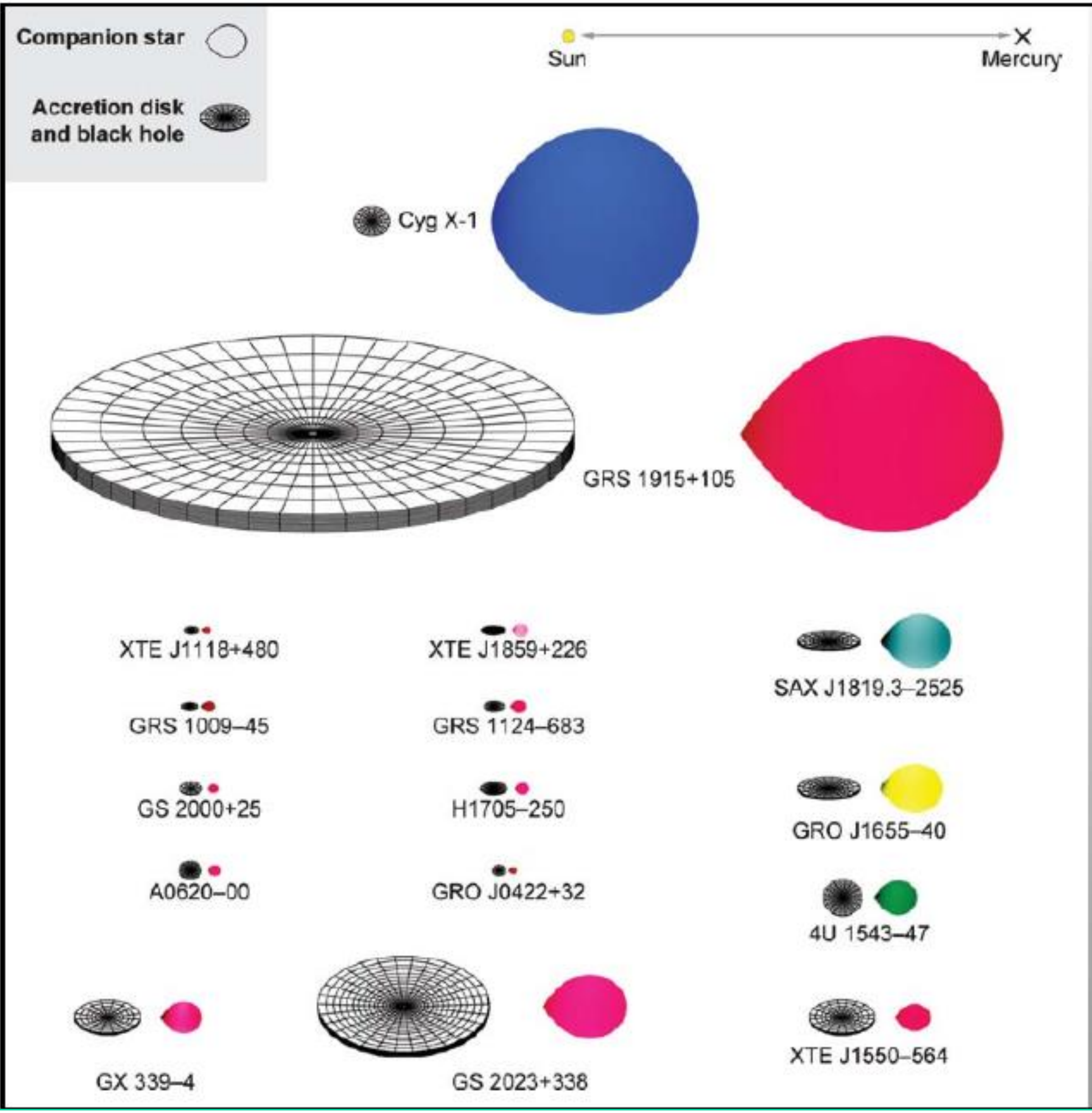
Most probably, the black hole in GRO J1655-40 is spinning at about 40% of its maximum rate. Within the uncertainties the spin rate lies in the range 12%-58% of maximum; zero spin is quite improbable.

In blue: innermost stable orbits per second for 7.0 $M_{\odot}$ black holes, with uncertainties.

In red: measured orbits per second, with uncertainties

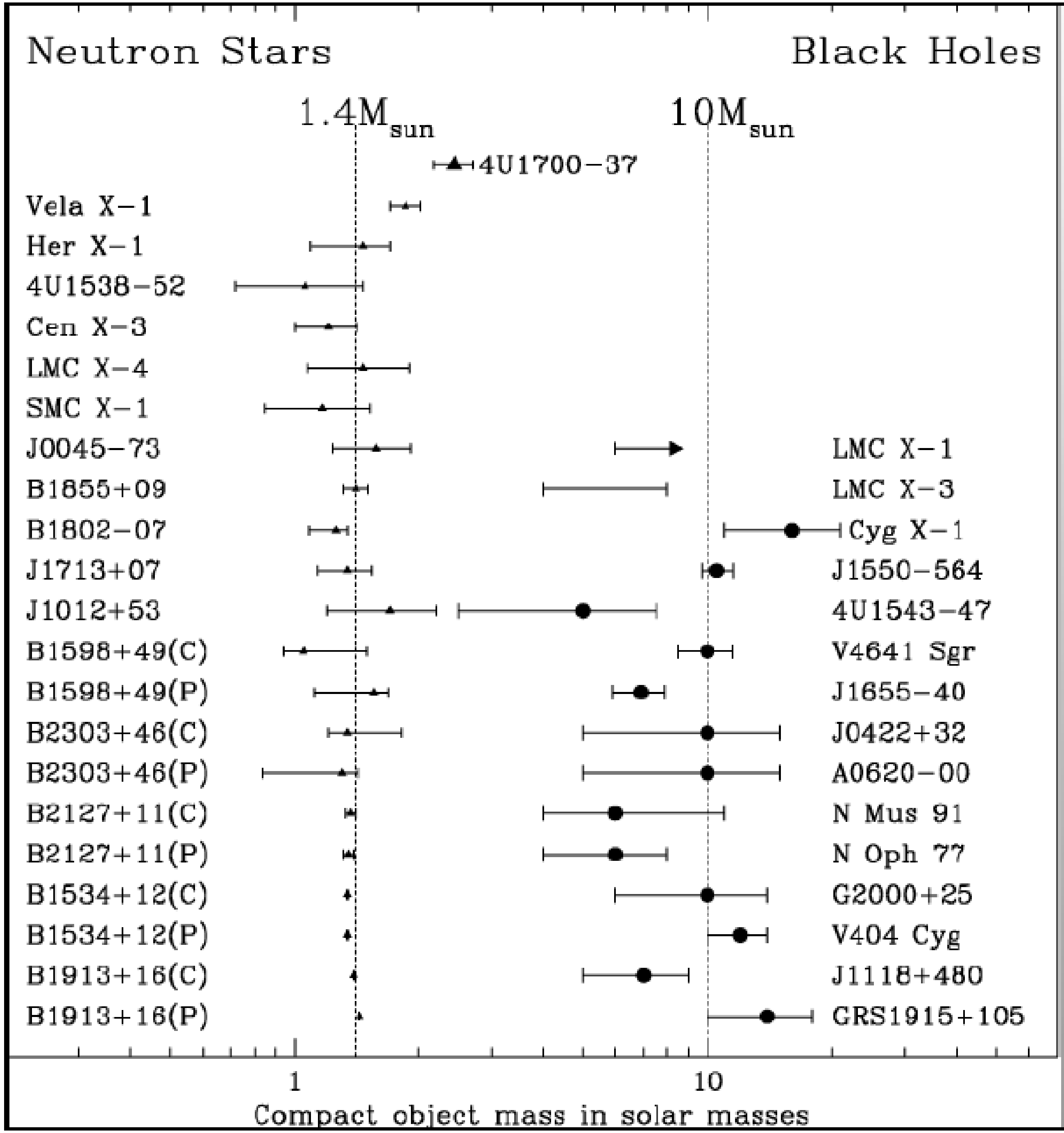
(by Tod Strohmayer, with the *Rossi* X-ray Timing Explorer).



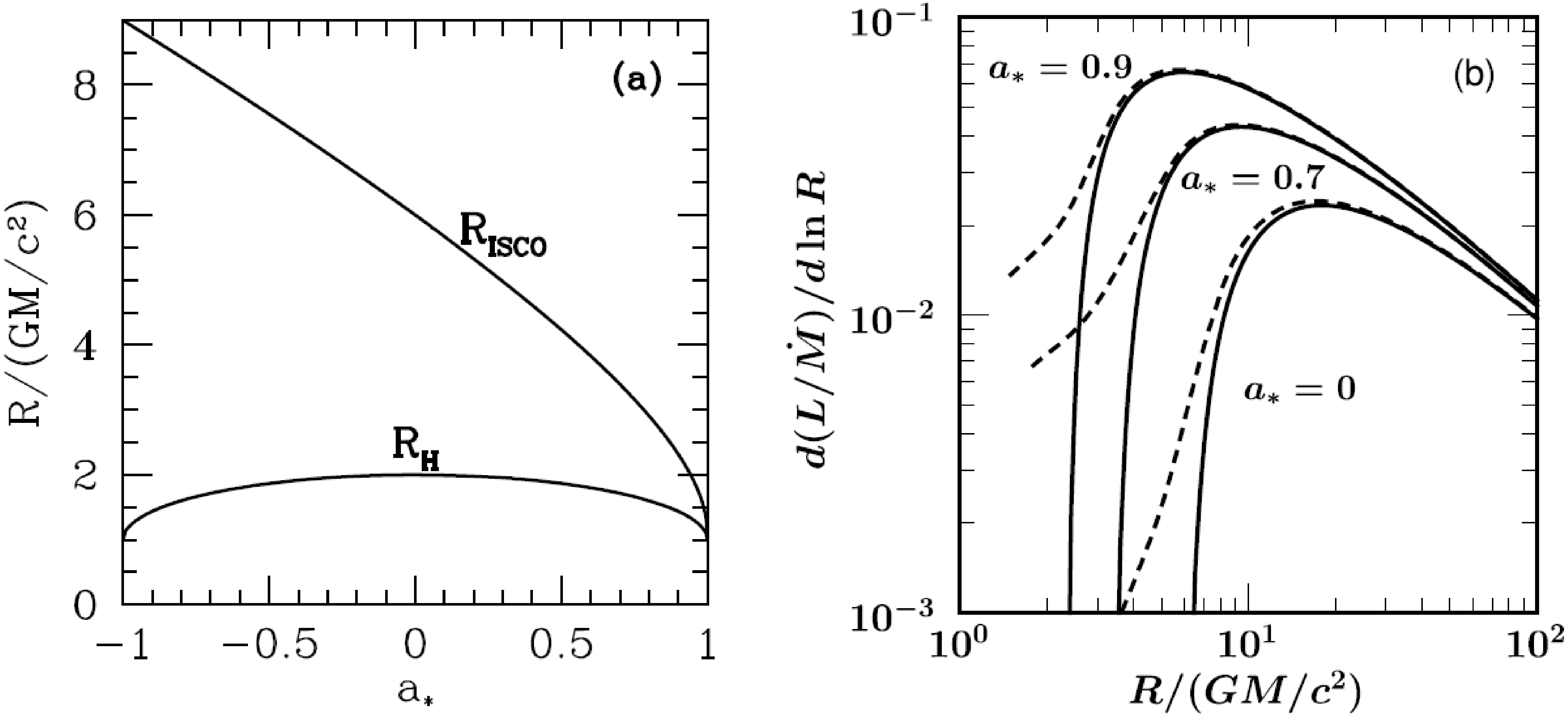


Binary systems with massive compact objects

Ordinary star + “something else” – a neutron star or BH



About 20 binaries in our galaxy where the compact object seems to be too massive to be a neutron star


(a)
$R_{\rm ISCO}$
$R_{\rm H}$
$R/(GM/c^2)$
a_*
0
2
4
6
8
−1
−0.5
0
0.5
1
(b)
$a_* = 0.9$
$a_* = 0.7$
$a_* = 0$
$d(L/\dot{M})/d\ln R$
$R/(GM/c^2)$
10^{-1}
10^{-2}
10^{-3}
10^0
10^1
10^2

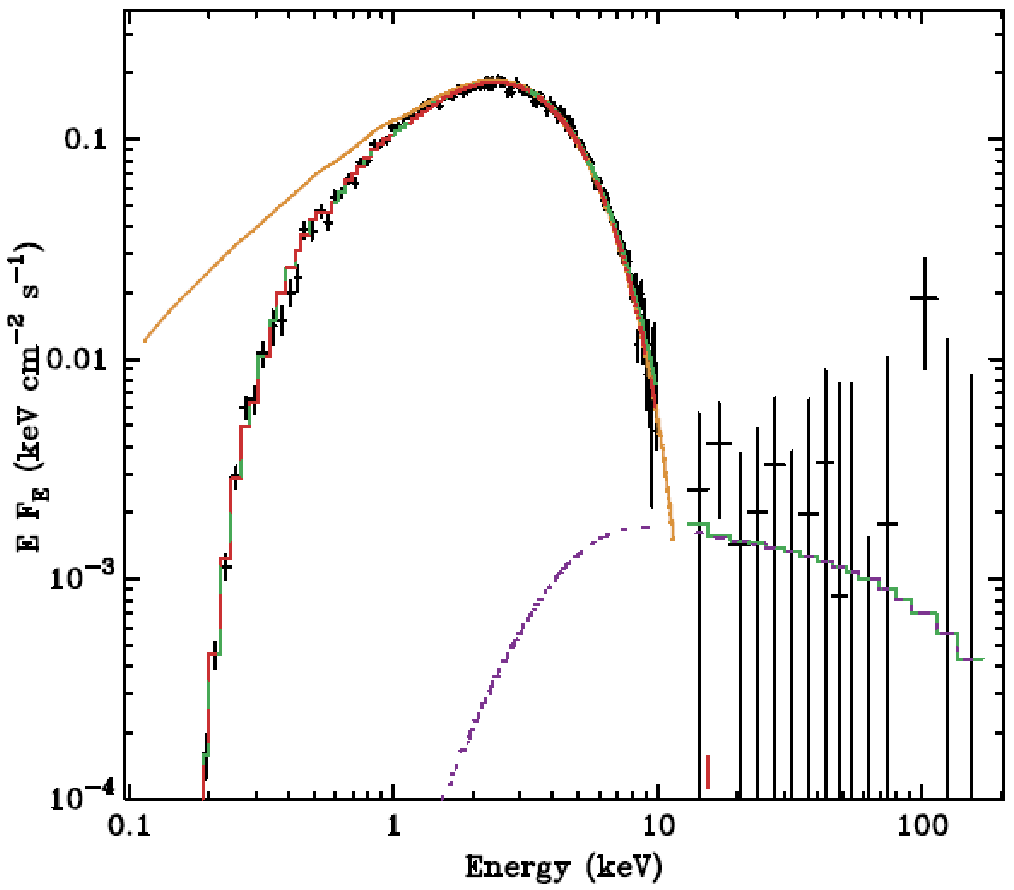


Fig. 4 Model fit to a disk-dominated spectrum of LMC X-3 obtained using detectors aboard the *BeppoSAX* satellite for $D = 52$ kpc, $i = 67°$ and $M = 10\ M_\odot$ (Davis et al. 2006). A *green solid curve*, which is difficult to discern because it hugs the data, is the total model. Also shown is the thermal component (*red long-dashed curve*) and the Compton component (*violet short-dashed curve*). The reflected component is negligible and was not included. The *orange solid curve* shows the total model with the effects of interstellar absorption removed. Note that the peak Compton flux is only 1 % of the peak thermal flux

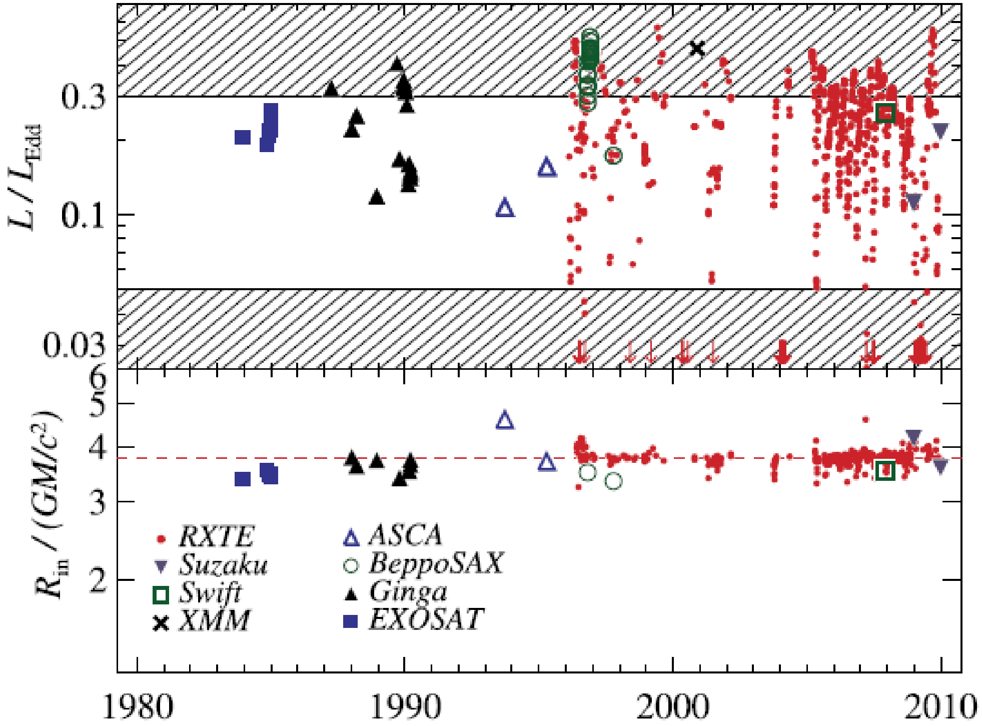


Fig. 5 (*top*) Accretion disk luminosity in Eddington-scaled units (for $M = 10\ M_\odot$) versus time for all the 766 spectra considered in a study of LMC X-3 by Steiner et al. (2010). (*Downward arrows* indicate data that are off scale.) Selected data in the unshaded region satisfy the thin-disk selection criterion $L/L_{\rm Edd} < 0.3$ and avoid confusion with strongly-Comptonized hard-state data with $f_{\rm SC} \gtrsim 25\ \%$ (Sect. 3.2; Remillard and McClintock 2006). (*bottom*) Fitted values of the inner-disk radius are shown for *thin-disk* data in the *top panel* that meet the selection criteria of the study (a total of 411 spectra). Despite large variations in luminosity, the inner-disk radius remains constant to within a few percent over time. The median value for just the 391 selected *RXTE* spectra is shown as a *red dashed line*

Table 1 The masses and spins, measured via continuum-fitting, of ten stellar black holes[a]

System	a_*	$M/M_\odot$	References
Persistent			
Cyg X-1	>0.95	14.8 ± 1.0	Gou et al. 2011; Orosz et al. 2011a
LMC X-1	$0.92^{+0.05}_{-0.07}$	10.9 ± 1.4	Gou et al. 2009; Orosz et al. 2009
M33 X-7	0.84 ± 0.05	15.65 ± 1.45	Liu et al. 2008; Orosz et al. 2007
Transient			
GRS 1915+105	>0.95[b]	10.1 ± 0.6	McClintock et al. 2006; Steeghs et al. 2013
4U 1543–47	0.80 ± 0.10[b]	9.4 ± 1.0	Shafee et al. 2006; Orosz 2003
GRO J1655–40	0.70 ± 0.10[b]	6.3 ± 0.5	Shafee et al. 2006; Greene et al. 2001
XTE J1550–564	$0.34^{+0.20}_{-0.28}$	9.1 ± 0.6	Steiner et al. 2011; Orosz et al. 2011b
H1743–322	0.2 ± 0.3	~ 8[c]	Steiner et al. 2012a
LMC X-3	<0.3[d]	7.6 ± 1.6	Davis et al. 2006; Orosz 2003
A0620–00	0.12 ± 0.19	6.6 ± 0.25	Gou et al. 2010; Cantrell et al. 2010

[a] Errors are quoted at the 68 % level of confidence, except for the three spin limits, which are estimated to be at the 99.7 % level of confidence.

[b] Uncertainties greater than those in papers cited because early error estimates were crude.

[c] Mass estimated using an empirical mass distribution (Özel et al. 2010).

[d] Preliminary result pending improved measurements of M and i.

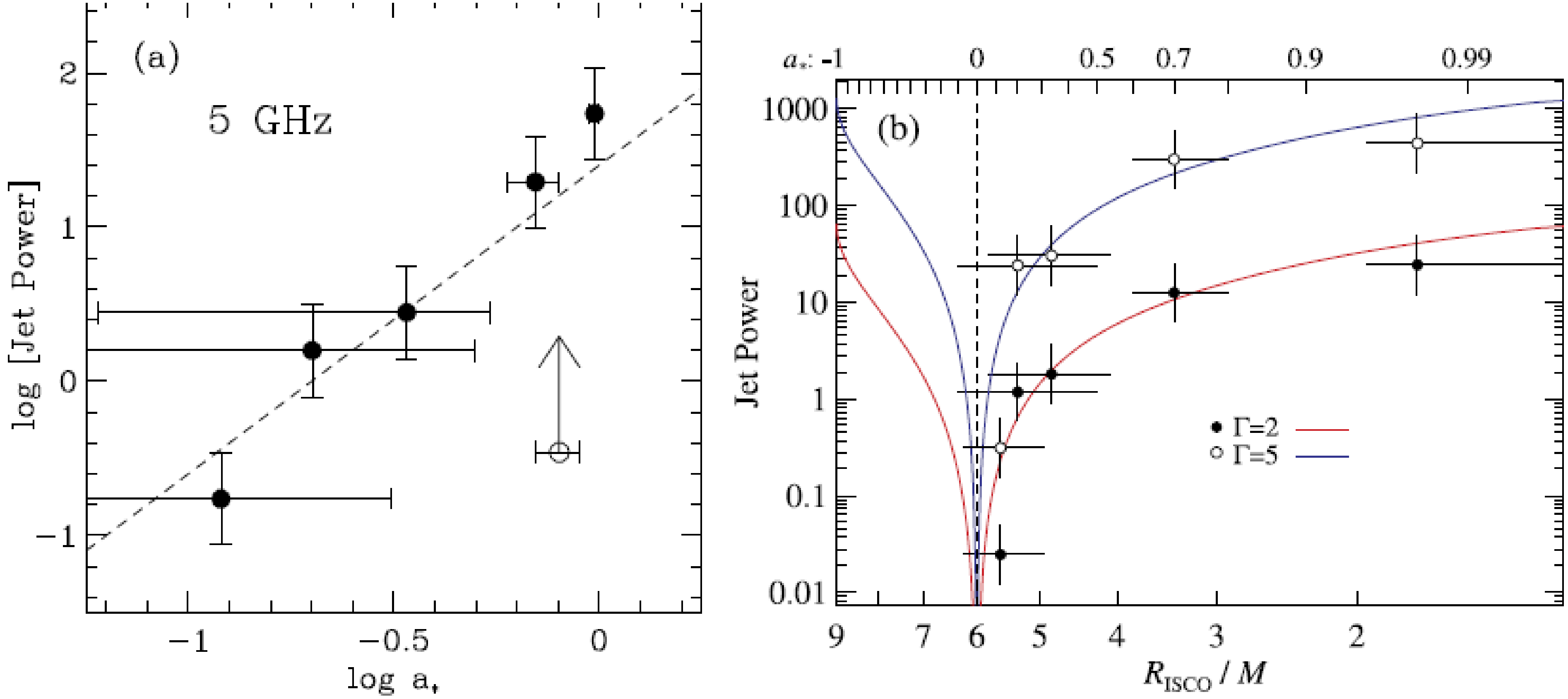


Fig. 6 (**a**) Plot of the quantity Jet Power, which measures the 5 GHz radio luminosity at light curve maximum, versus black hole spin, measured via the continuum-fitting method for five transients (Narayan and McClintock 2012; Steiner et al. 2013). The *dashed line* has slope equal to 2. (**b**) Plot of Jet Power versus $R_{\mathrm{ISCO}}/(\mathrm{GM}/\mathrm{c}^2)$. Here the radio luminosity has been corrected for beaming assuming a bulk Lorentz factor $\Gamma = 2$ (*filled circles*) or $\Gamma = 5$ (*open circles*). The *solid lines* correspond to Jet Power $\propto \Omega_{\mathrm{H}}^2$, where Ω_{H} is the angular frequency of the horizon (Steiner et al. 2013)