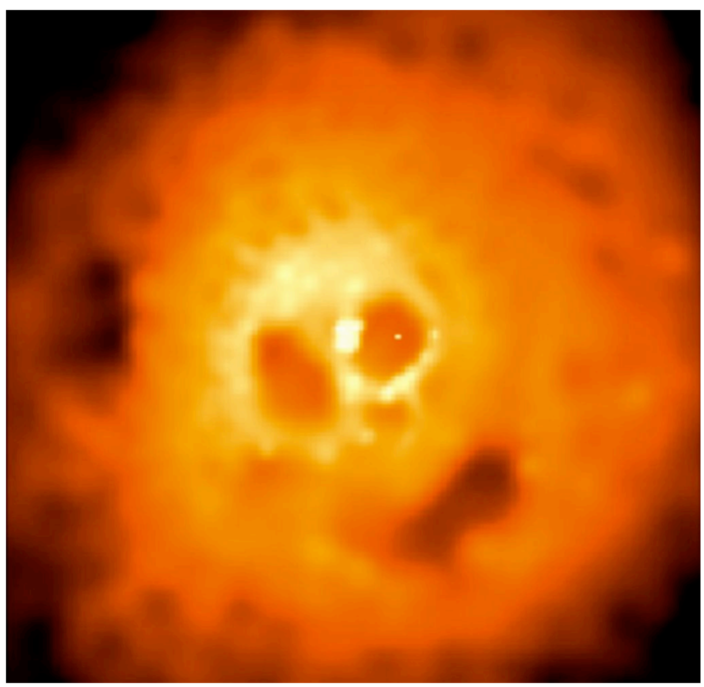
This Lecture

- How to determine the mass of the 'unseen' companion
- Downwards to black holes

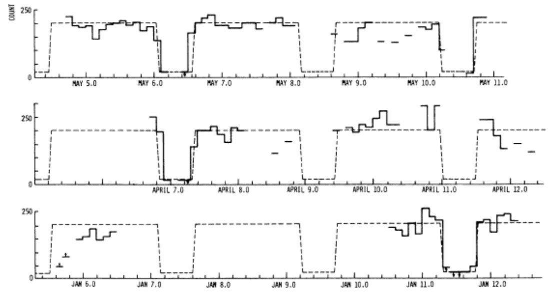
Even the Perseus Cluster

- https://apod.nasa.gov/apod/image/0010/perseushalloween_cxc_big.jpg



Eclipsing Pulsing Neutron Stars

- A breakthrough in the understanding of these objects was the discovery of eclipses and pulse timing.



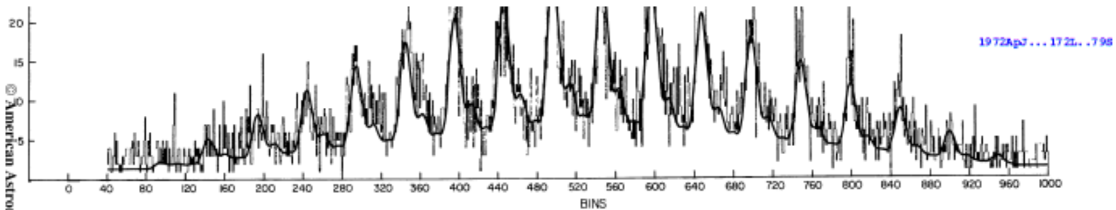


FIG. 3.—The counts accumulated in 0.096 bins from Cen X-3 during a 100-s pass on 1971 May 7 are plotted as a function of bin number. The functional fit obtained by minimizing is also shown.

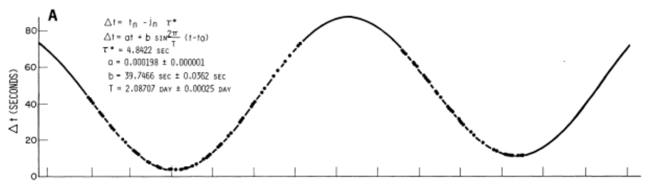


FIG. 4.—(a) The difference Δt between the time of occurrence of a pulse and the time predicted for a constant period is plotted as a function of time. A best-fit function and the values of the parameters are given. (b) The dependence of the pulsation period τ on time as derived from the best-fit phase function above is shown and the values of the parameters given. (c) The intensity observed and the light curve predictions are shown for the same set of data. Note the coincidence of the null points of the period function with the centers of the high- and low-intensity states.

Doppler curve of pulsar- difference between the predicted and observed pulse arrival time vs time

Orbit

- Sign and phase of the pulses are due to the Doppler effect
- Amplitude of the sine pulse curve gives the size of the orbit (39.75 lt sec)
- Eclipses are due to occultations of the NS by its companion
- Circular orbit from shape of time variation of pulses
- Get mass of system and orbital parameters
- Period of 4.8 sec shows that it must be a collapsed object (NS)

$$v \sin i \equiv \frac{Ac}{\tau_0} = 415.1 \pm 0.4 \text{ km s}^{-1} ,$$

$$r \sin i \equiv \frac{T}{2\pi} v \sin i = (1.191 \pm 0.001) \times 10^{12} \text{ cm} ,$$

$$\frac{M^3 \sin^3 i}{(M+m)^2} \equiv \frac{(2\pi)^2}{GT^2} (r \sin i)^3 = (3.074 \pm 0.008) \times 10^{34} \text{ g} .$$

In binary system, time between pulses affected by orbital motions–due to light travel time (distance) changing along orbit

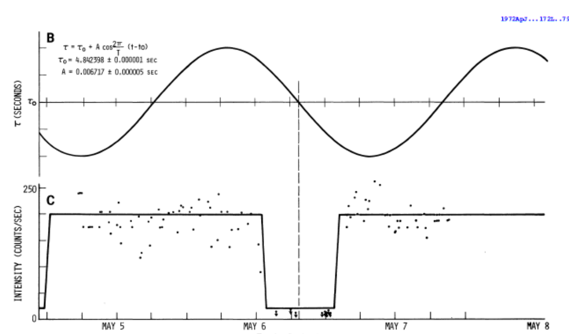
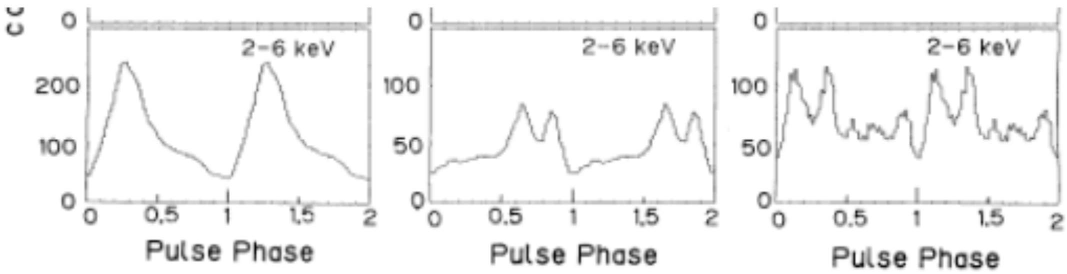


FIG. 4.—Continued

Observed Pulse Shapes

- It is fairly easy to time the pulses with an accuracy of ~0.03 sec per pulse or a light travel time distance of 10,000km –

Cen X-3 Her X-1 Vela X-1

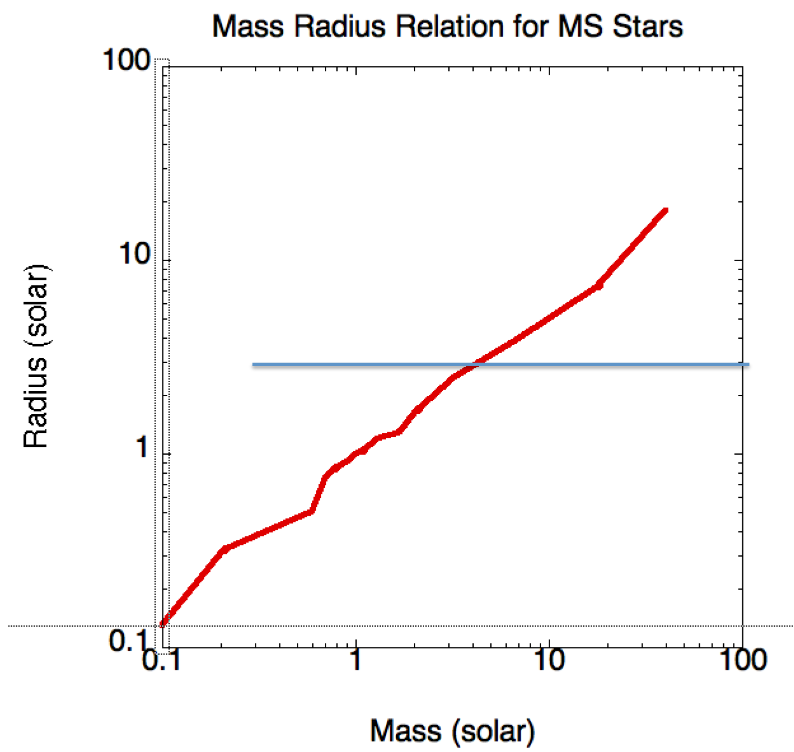


the time delay δt is then

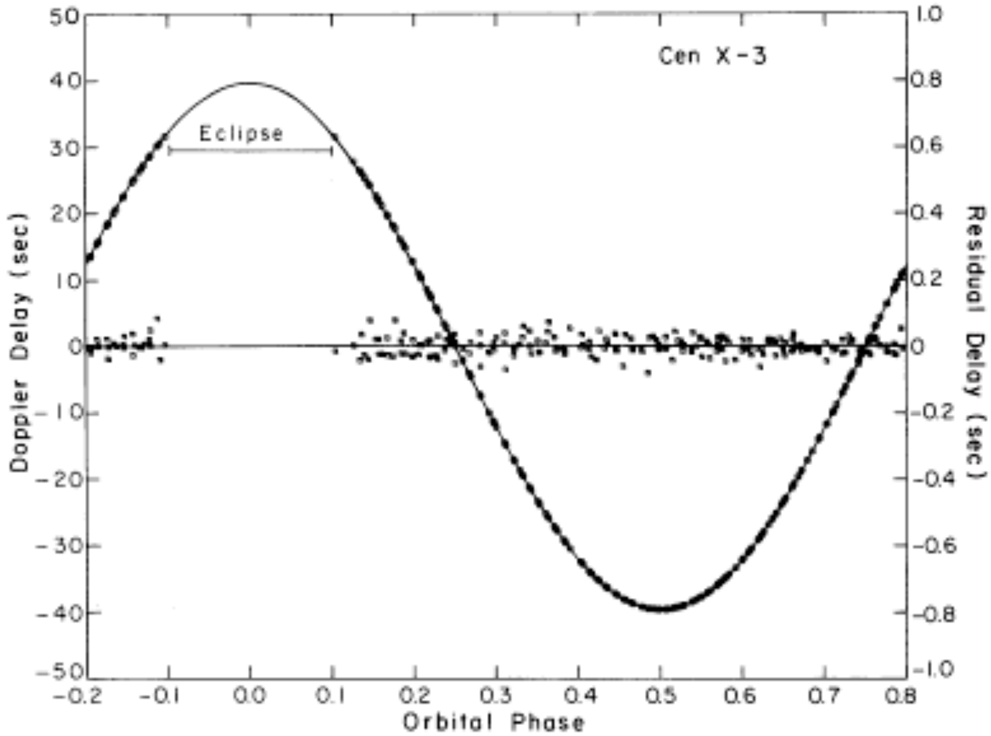
e.g. $\delta t \sim a \sin i\, [\cos(2\pi(t-t_0/P_{orb})]$;

where a is the orbital radius, i is the inclination
P_{orb} is the orbital period and t_o is a reference time

Mass Radius Relation for Main Sequence Stars



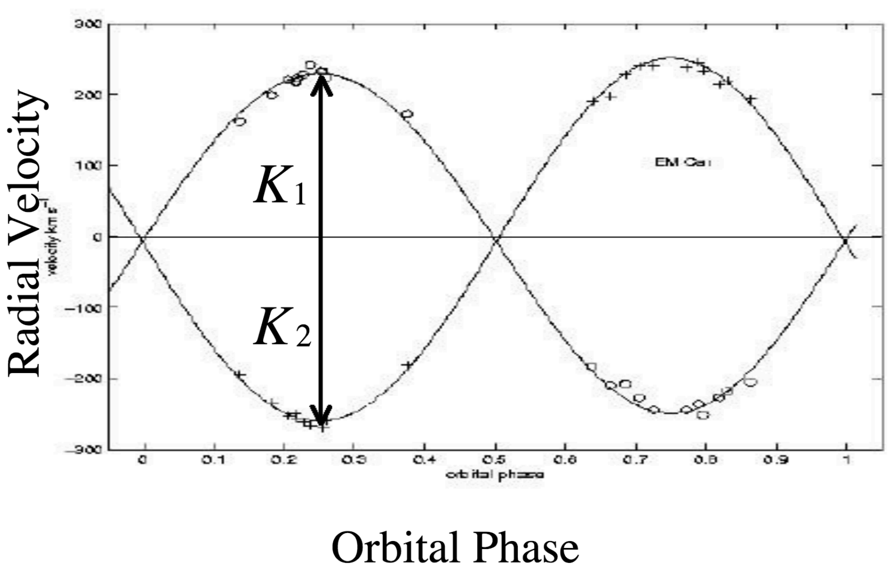
Measurement of Orbit Via Pulse Timing



Orbit with 2 Velocities

Velocity Curve

$$\text{observe}: \quad K = V \sin i$$



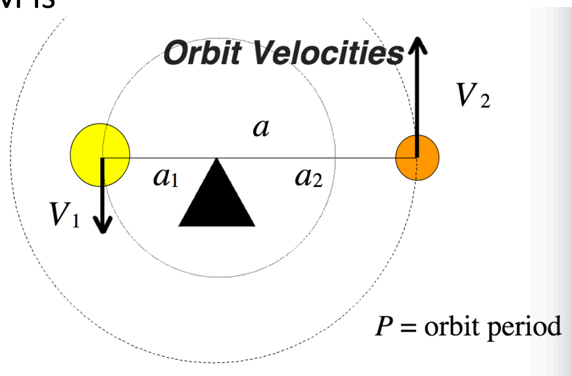
Derivation of Mass Function (K. Horne)

- Observable velocities $K_1 = V_1 \sin i$ and $K_2 = V_2 \sin i$
- mass ratio $q = m_2/m_1 = a_1/a_2 = V_1/V_2 = K_1/K_2$
- $V_1 + V_2 = 2\pi a/P$
- Which gives the orbit size a
  - $2\pi a \sin i = (K_1 + K_2)P$

Using Keplers Law $M = m_2 + m_1 = 4\pi^2 a^3/GP^2$

$P^2 \sim R^3$ and the minimum mass M is

$M\sin^3 i = P(K_1 + K_2)^3/2G\pi$



Mass Function,F,- Longair 13.33

If we only have velocity information for the star (and not the compact object)

$F(m_1, m_2, i) = m^3_x \sin^3 i/(m_x + m_2)^2$

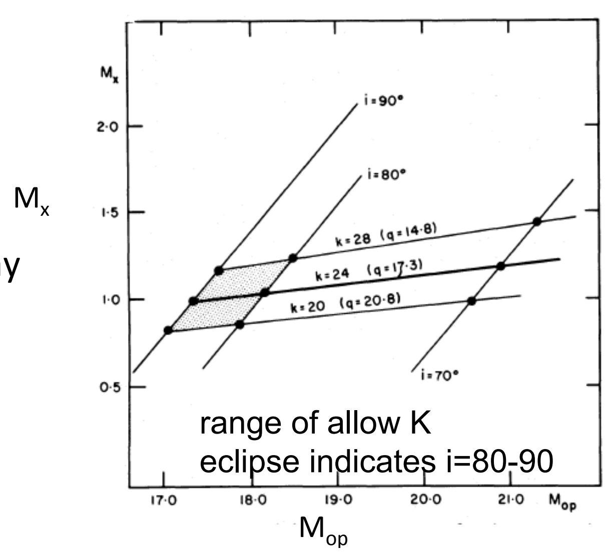
- Re-writing this as

  $M_p = Fq(1+q)^2/\sin i^3$

- q=ratio of the mass of the x-ray star to its companion
- $M = (m_x + m_2)$

The delays in the observed arrival time of the pulses gives $a_2 \sin i/c$ and the period thus $F(m_1, m_2, i)$

The duration of the eclipse tells us about the star size and thus mass



Mass Function,F,- Longair 13.33

equivalently

$F=P_{orb}K^3/2\pi G$ where for circular orbits, $K=v_2 \sin i$

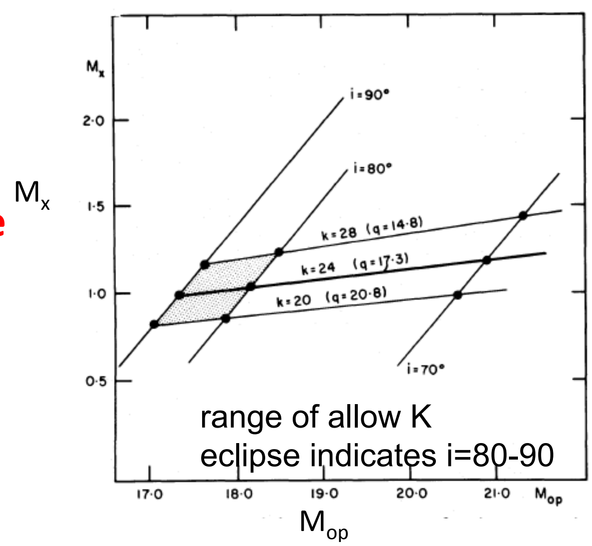
or alternatively

$F=m_2 \sin i^3/(1+q)^2$

- A minimum mass is obtained if $i=90^0$
- **The mass function for the observed star gives a minimum mass for the *unseen* companion $F<m_x$**

The delays in the observed arrival time of the pulses gives $a_2 \sin i/c$ and the period thus $F(m_1,m_2,i)$

The duration of the eclipse tells us about the star size and thus mass



Mass Function,F,- see Rosswog and Bruggen ch 6

If we have the velocity of both components F_1 and F_2

$F_1(m_1,m_2,i)=[m_2 \sin i]^3/M^2$

and

$F_2(m_1,m_2,i)=[m_1 \sin i]^3/M^2$

- mass ratio, q,

  $q=(F_2/F_1)^{1/3}$

Alternative Formulation when have pulse information

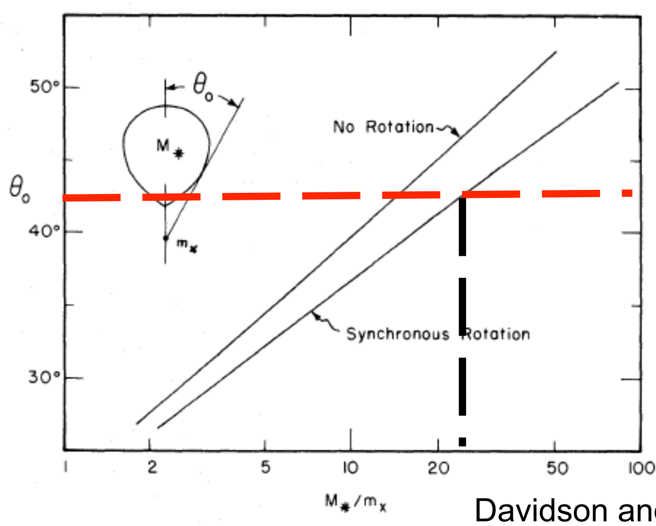
- In order to measure the mass of the neutron star and its optical companion we need to measure the mass function. For a circular orbit it can be shown that this is defined

$$M_X = K^3_O P_{orb} / 2\pi G \sin^3 i \; (1 + K_X/K_O)^2$$

- M_O and M_X are the mass of the optical component and the X-ray source, respectively,
- K_X , K_O are the semi-amplitude of the radial velocity curve for the x-ray and optical companion,
- P is the period of the orbit and i is the inclination of the orbital plane to the line of sight.

•K_X and P can be obtained very accurately from X-ray pulse timing delay measurements

• K_o is measured from optical spectra for the companion



Davidson and Ostriker 1973

FIG. 1.—Eclipse half-angles in the equatorial plane, for cases in which the eclipsing star is nonrotating and fills its tidal lobe, and in which it rotates synchronously with the binary orbital period and fills its Roche lobe.

- For Cen X-3 he eclipse lasts .488 days out of the 2.1 day period or an opening angle of 43 degrees (.488/2.1/2). We know the mass function

$M_*^3 \sin i^3/(Mx+M_*)^2=15$ in this case) M_x ~1

Importance of Eclipses

- If the pulsar is eclipsed by the donor (≈40% chance in Roche-lobe overflowing systems) then the inclination angle ***i*** is given by

$\sin \boldsymbol{i}=\mathrm{sqrt}\ [1-(R_{opt}/a)^2]/\cos\theta$

- where θ is the eclipse half-angle,a the binary separation and R_{opt} the stellar radius.
- R_{Lopt}/a is a function of the binary mass ratio $\mathbf{q}=M_X/M_{opt}=K_{opt}/K_X$

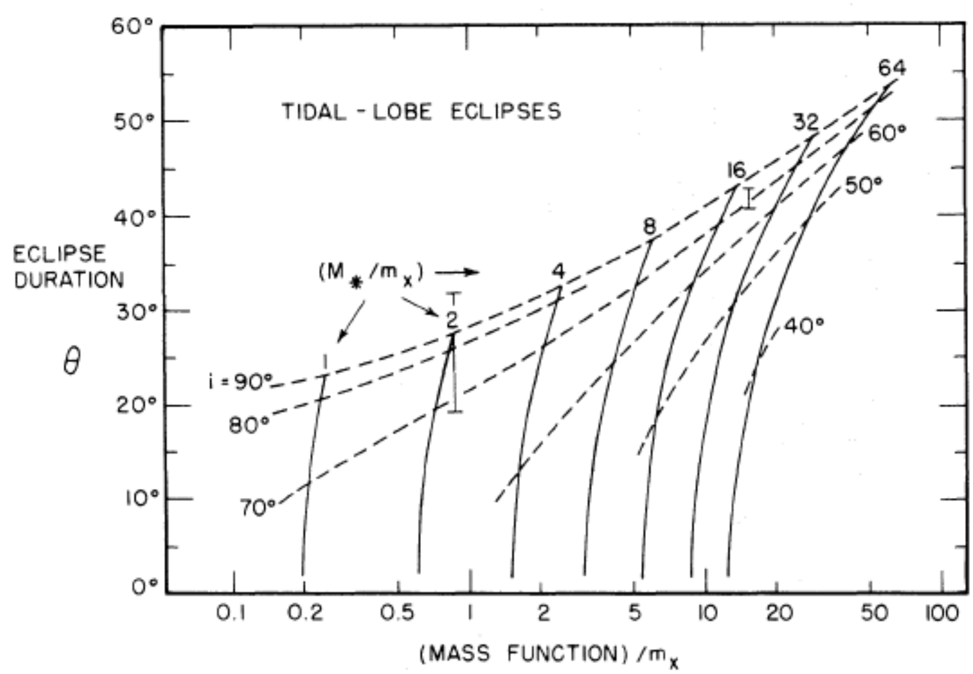
(K=vsin *i*)

Then we can solve for the mass (assuming circular orbits)

$M_{opt}=[K_X{}^3P/2\pi G\sin^3\ i](1+q)^2$

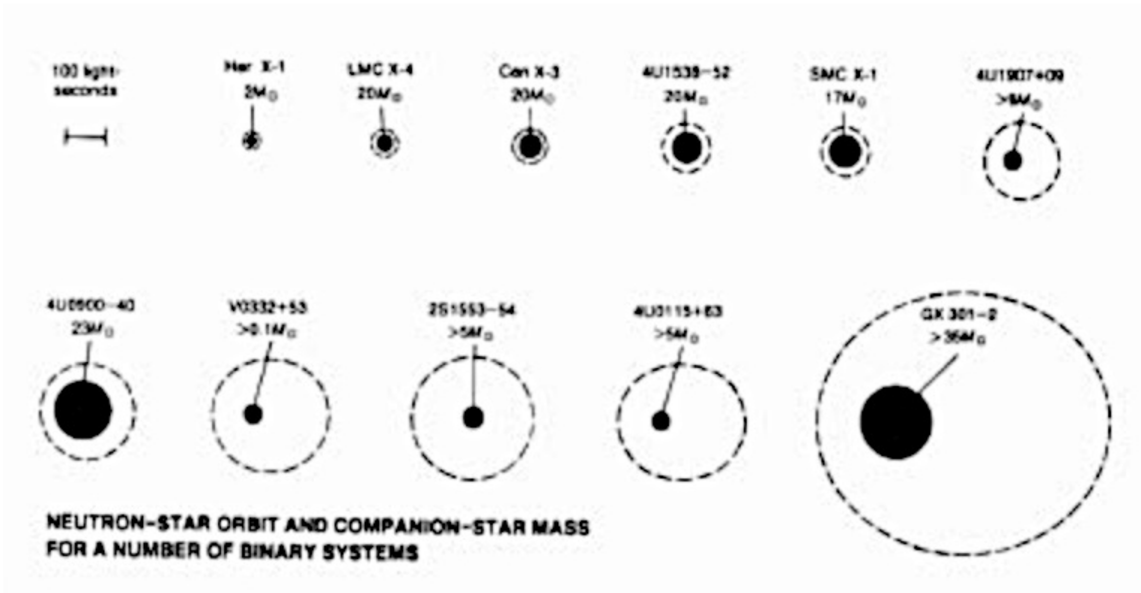
$M_x=[K_{opt}{}^3P/2\pi G\sin^3\ i](1+q)^2$

precise masses for ~9 objects



Values of mass vs eclipse duration and inclination angle for a given mass function

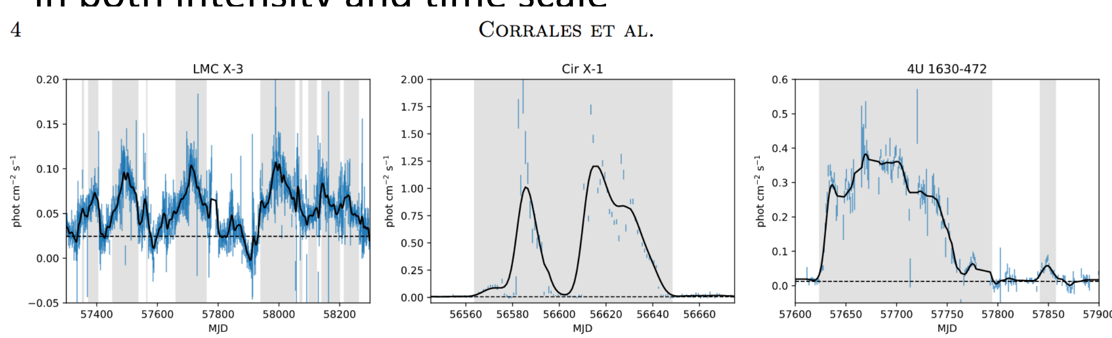
Neutron Star Orbits

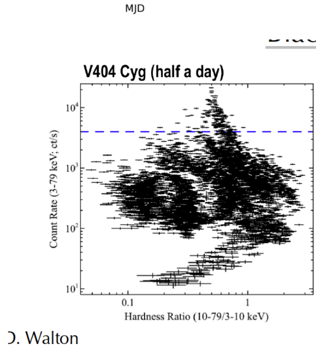


Charles and Seward

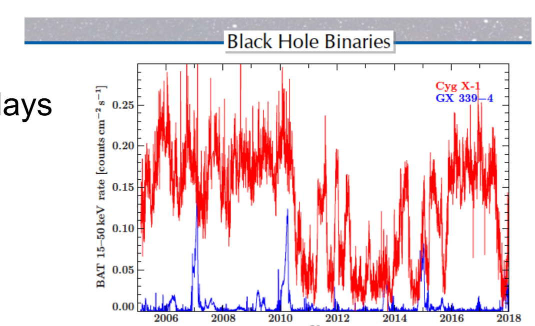
Time Variability

- Virtually all x-ray binaries show a wide range of variability in both intensity and time scale

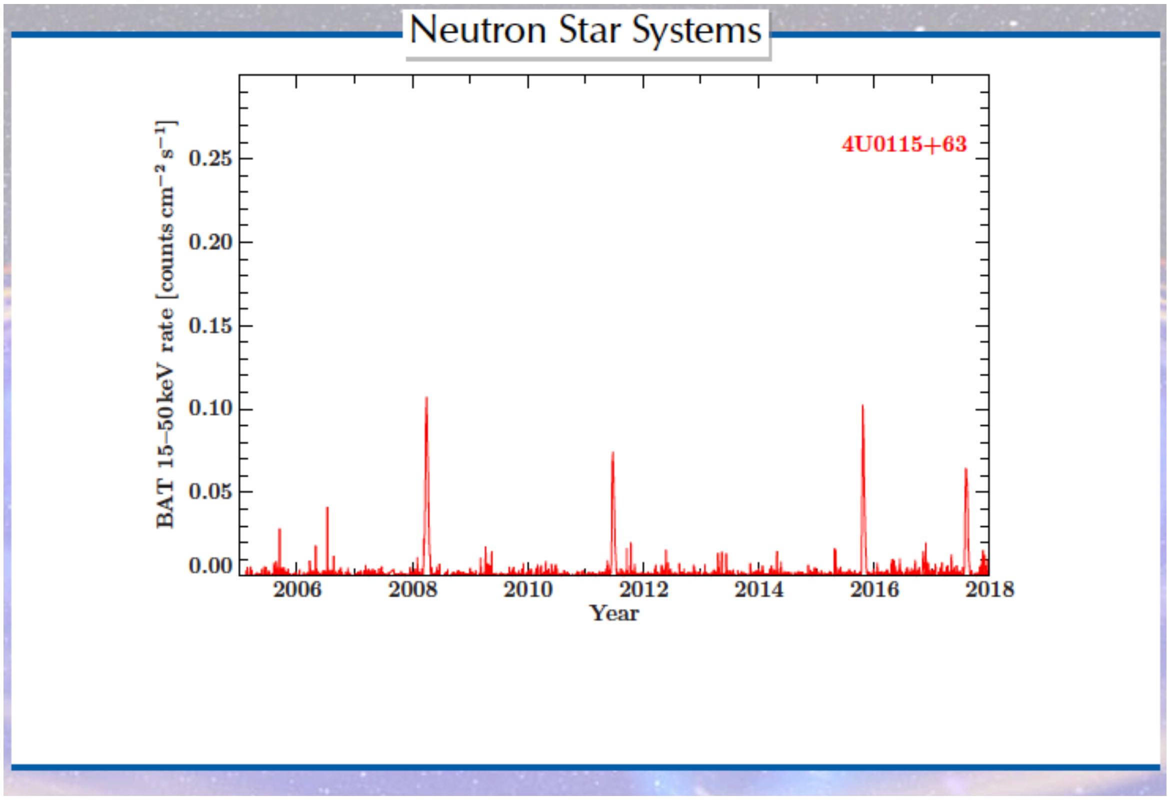




Seconds,days
years



On vs Off



summary

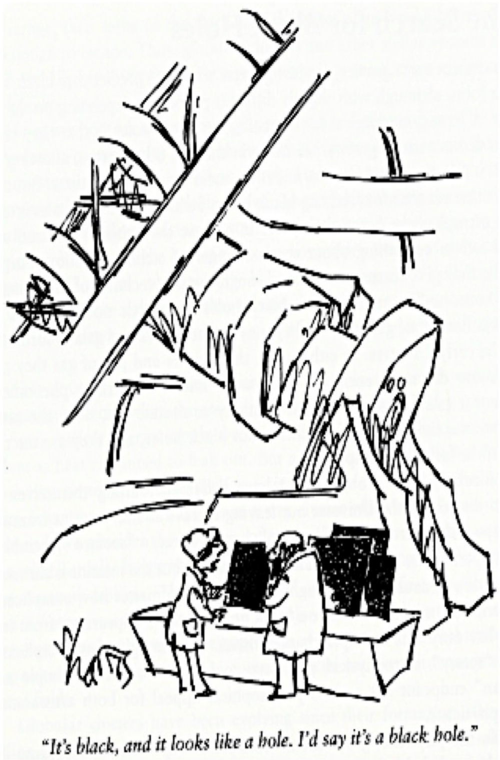
- X-ray binaries exhibit a wide range of behaviors, but much of the interesting physics/astrophysics is common to all
- Understanding of accretion disks, accretion flows, X-ray induced winds, compact object evolution are all in an active state of research.

This is a vast field - here are some references for further reading

- Dippers: Smale et al. 1988 MNRAS 232 647
- Black hole transient lmxbs: Remillard and McClintock, 2006 ARAA 44, 49
- Color-color diagrams for atoll/Z sources : Hasinger and VanderKlis 1989
- Microquasar GRS 1915+105: Mirabel and Rodriguez 1995 PNAS 92 11390
- ADC sources: White and Holt 1982 Ap. J. 257 318
- Iron line from Cyg X-1: Miller et al. 2003 Ap. J. 578, 348
- Cyg X-3 Chandra HETG: Paerels et al. 2000 Ap. J. 533, 135
- Accretion disk corona modeling: Jimenez-Garate et al. 2002 Ap. J. 558, 458
- 4U1822-37 spectrum :Cottam et al., 2001 Ap. J. 557, 101
- 'Accretion power in Astrophysics' Frank, King and Raine
- Catalog of X-ray Binaries, Liu Van Paradijs and Lewin 2007 A&A 469, 807
- GRO J1655 chandra spectrum: Miller et al., 2006 Nature 441, 953
- Hydrodynamics of HMXB winds: Blonding 1994 Ap. J.

Downwards to Black Holes!

- The maximum mass of a neutron star
- Complete gravitational collapse to a black hole
- Basic anatomy of a black hole
- Observational discovery of black holes



- **Are there black holes?**
  Are BH binaries typical? What about the GW BH-BH binaries?
- **What is the physics of accretion?**
  Accretion: one of most fundamental physical processes in the Universe ⟹ BH-XRB/AGN best way to study them due to different timescales!
- **How do black holes interact with their environment?**
  e.g., XRB: energetic input into ISM, AGN: galaxy evolution ("feedback"), heating IGM,...
- **What is the behavior of matter under extreme conditions?**
  neutron stars: strong B-fields ($10^{12} \ldots 10^{14}$ G), high ρ, bursts,...
- **How do stars evolve?**
  CV, NS-XRB, BH-XRB populations

J. Wilms

Maximum Mass of a Compact object (Kalogera and Baym 1996)

- The set of fundamental constraints, independent of the detailed physical properties of neutron matter, imposed on the equation of state of the inner core are
- (i) the mass density, ρ, is non-negative, i.e., gravity is attractive;
- (ii) the pressure,P, at zero temperature is a function of ρ only, i.e., neutron matter is a fluid
- (iii) dP/dρ ≥ 0, -sound speed of neutron matter $(dP/d\rho)^{1/2}$ is real and matter is stable against collapse;
- (iv) the sound speed does not exceed the speed of light, i.e., dP/dρ≤ c^2, hence signals cannot be superluminal and causality is satisfied.

Under these conditions mass of NS
Is maximum for 'stiffest' equation of state
-the sound speed is the speed of light
$c_s^2 = dP/d\rho = c^2$.

A huge amount of messy nuclear physics define the equation of state and it is not well understood.

Using the equation of hydrostatic equilibrium in general relativity

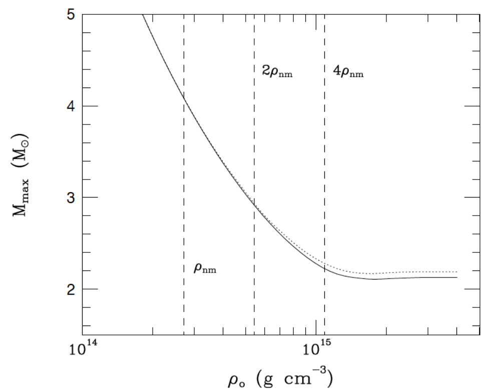
$$\frac{dP}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[m(r) + 4\pi r^3\frac{P(r)}{c^2}\right]\left[1 - 2G\frac{m(r)}{rc^2}\right]^{-1},$$

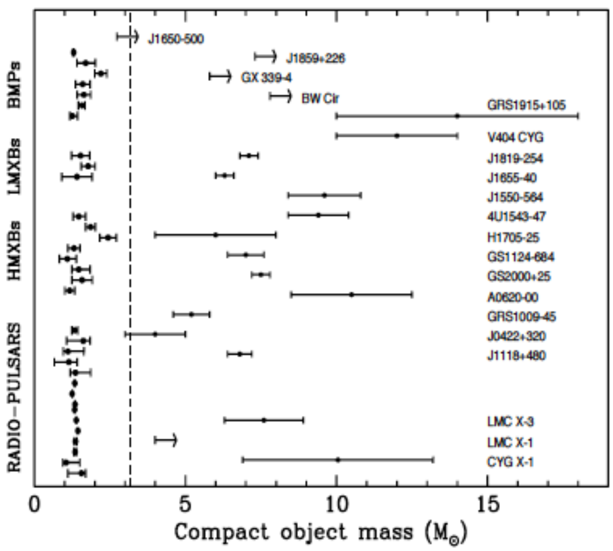
$$M_{max} = 6.7\, M_\odot \left(\frac{\rho_0}{10^{14}\mathrm{g\,cm^3}}\right)^{-1/2}.$$

Maximum Mass (Cont)

nuclear matter density $\rho_{nm} = 2.7 \times 10^{14}\,\mathrm{g\,cm^{-3}}$.

- None of the objects thought to be NS have a mass $>2.4M_{sun}$ but objects exist in the Milky Way way with a mass up to $19M_{sun}$

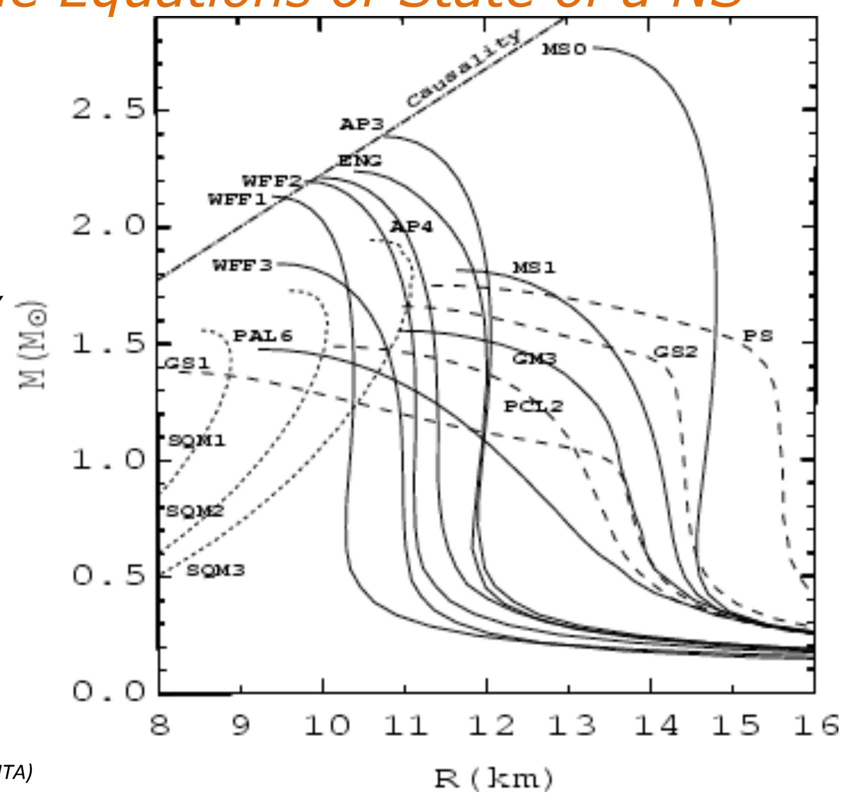




Possible Equations of State of a NS

Each line represents a different possible equation of state- the relationship between Pressure and density

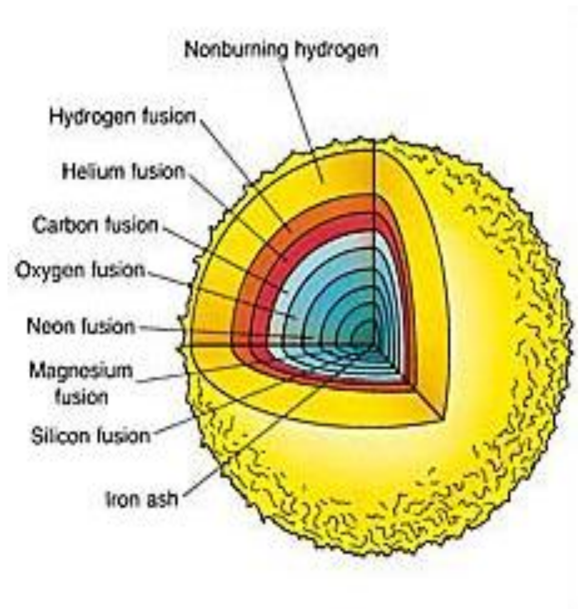
Maximum mass is ~3M☉



From website of Kaya Mori (CITA)

Beyond neutron stars…

- Suppose collapsing core has mass that exceeds maximum mass for a neutron star…this can happen in several ways
  - Maybe a more massive iron core forms before it cools to the point that degeneracy pressure kicks in…
  - … or initial core collapse of 1.4M core is followed by more infall from stellar envelope?
- What then when the gravitational attraction exceeds the degeneracy pressure?
- We know of no physics that can prevent a <u>total</u> gravitational collapse of the core



Downwards to Black Holes!- Longair 13.11

- a neutron star has a maximum mass
- If this mass is exceeded on has a complete gravitational collapse to a black hole
- Basic anatomy of a black hole
- Observational discovery of black holes
- see 1810.07041.pdf Accreting Black Holes S. Nampalliwar and C. Bambi

The color of the companion star roughly indicates its surface temperature (from brown to white as the temperature increases).

The orientation of the disks indicates the inclination angles of the binaries

Jerome Orosz (from Nampalliwar and Bambi)

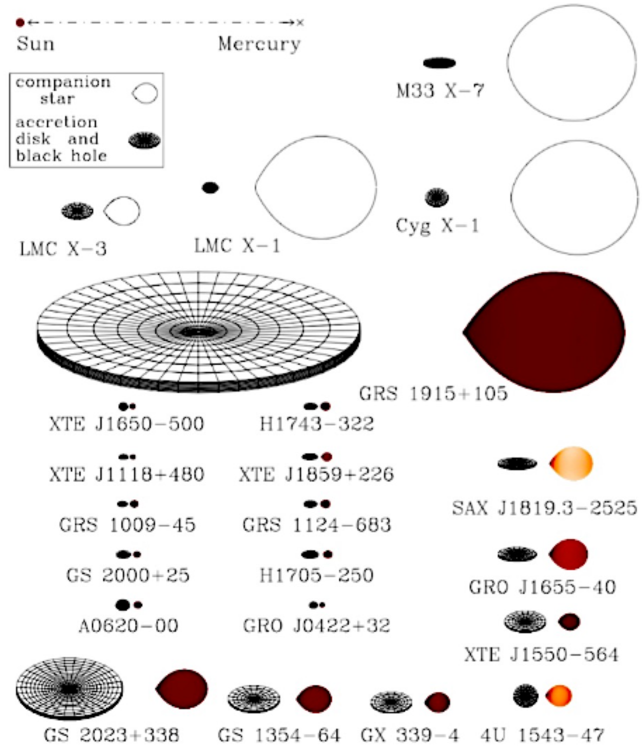


Fig. 1: Sketch of 22 X-ray binaries with a stellar-mass black hole confirmed by dy-

Black Holes

- What do you mean 'black holes' ?
- We know of objects whose mass (derived from observations of the lines from the companion objects and Newton's (Einstein) laws) which are larger than possible for a NS or white dwarf.
- *They have other unusual properties (related to their x-ray spectrum and timing behavior)*
- **Big differences- no surface, no (?) magnetic field, higher mass strong GR effects**.

Table 4.3. *Candidate black hole binaries*[a]

Source	RA(2000)	DEC(2000)	r_x[b]	BH trait[c]	Grade[d]	Referen
1354–645 (BW Cir)	13 58 09.74	-64 44 05.2		LH,HS	A	1,2,
1524–617 (KY TrA)	15 28 16.7	-61 52 58		LH,HS	A	5,
4U 1630–47	16 34 01.61	-47 23 34.8		LH,HS	A	8,9,10,11
XTE J1650–500	16 50 01.0	-49 57 45		LH,HS,VH	A	12,13,14,15
SAX J1711.6–3808	17 11 37.1	-38 07 06		LH,HS	B	17
GRS 1716–249[e]	17 19 36.93	-25 01 03.4		LH	B	19,20
XTE J1720–318	17 19 59.06	-31 44 59.7		LH:,HS	C	22,23
KS 1730–312	17 33 37.6	-31 13 12	30″	LH,HS	C	25
GRS 1737–31	17 40 09	-31 02.4	30″	LH	B	27,28
GRS 1739–278	17 42 40.03	-27 44 52.7		LH,HS,VH	A	30,31,32,33
1E 1740.7–2942	17 43 54.88	-29 44 42.5		LH,HS,J	A	35,36,37,38
H 1743–322	17 46 15.61	-32 14 00.6		HS,VH	A	40,41,42,80,81
A 1742–289	17 45 37.3	-29 01 05		HS:	C	43,44,45
SLX 1746–331	17 49 50.6	-33 11 55	35″	HS:	C	47,48
XTE J1748–288	17 48 05.06	-28 28 25.8		LH,HS,VH,J	A	50,51,52,53
XTE J1755–324	17 55 28.6	-32 28 39	1′	LH,HS	B	55,56,57
1755–338 (V4134 Sgr)	17 58 40.0	-33 48 27		HS	B	59,42,60,61
GRS 1758–258	18 01 12.67	-25 44 26.7		LH,HS,J	A	63,38,64,65
EXO 1846–031	18 49 16.9	-03 03 53	11″[f]	HS	C	
XTE J1908+094	19 08 53.08	+09 23 04.9		LH,HS	B	68,69,70
1957+115 (V1408 Aql)	19 59 24.0	+11 42 30		HS	C	72,42,73,74
XTE J2012+381	20 12 37.70	+38 11 01.2		LH,HS	B	76,77,78

~20 black holes with a dynamical measurement of the mass

Compact Object Masses Determined via Dynamics

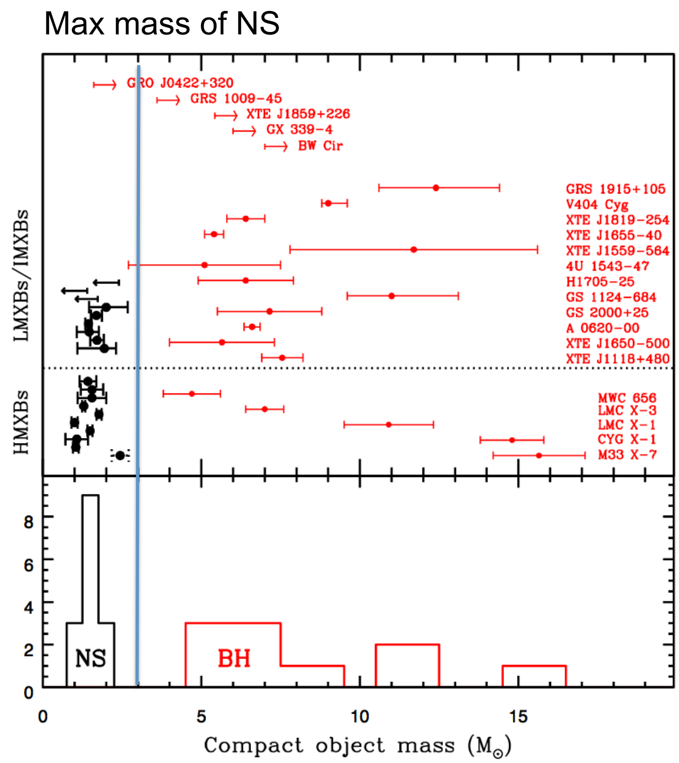
NS in black

BHs in red

is there a gap between~2-5 $M_\odot$

the most massive black holes (~15 $M_\odot$) are found in HMXBs.

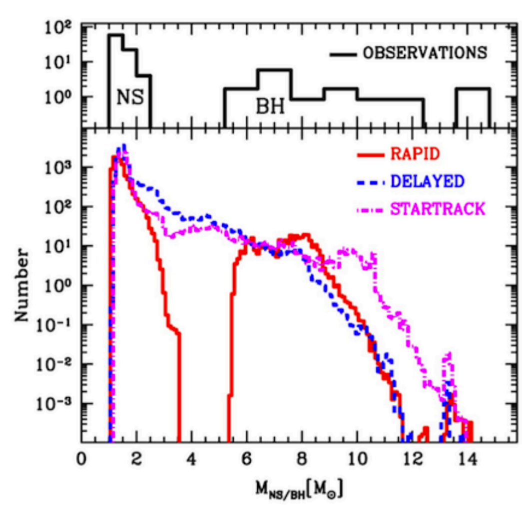
J. Casares, P.G. Jonker, and G. Israelian 1701.07450.pdf



Is this Distribution Telling us something about Supernova??

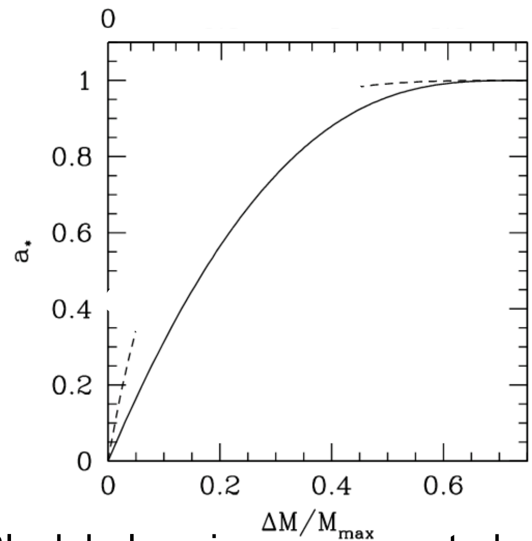
Mass distribution of compact SN remnants from theory

J. Casares, P.G. Jonker, and G. Israelian 1701.07450.pdf



Black Holes Growth in Binaries

- Since HMXBs only 'live' for ~10^7 years and at the Eddington limit for a 10M BH accrete at
- dM/dt~1.4×10^{19} gm/sec=$2\times10^{-7} M_\odot$/yr
  - if the efficiency of converting mass to luminosity is 10%
- they can increase their mass by only 20%
- Therefore HMXB BHBs are born massive AND their spin is also 'natal' (how much angular momentum can be accumulated, King and Kolb 1999)- to get high spin need to accrete at least ~1/2 of the final mass



Black hole spin a_* vs. accreted rest–mass ΔM,
in units of the final mass M_{max} at maximum spin (solid line,bottom axis),

How Can We Observe Black Holes

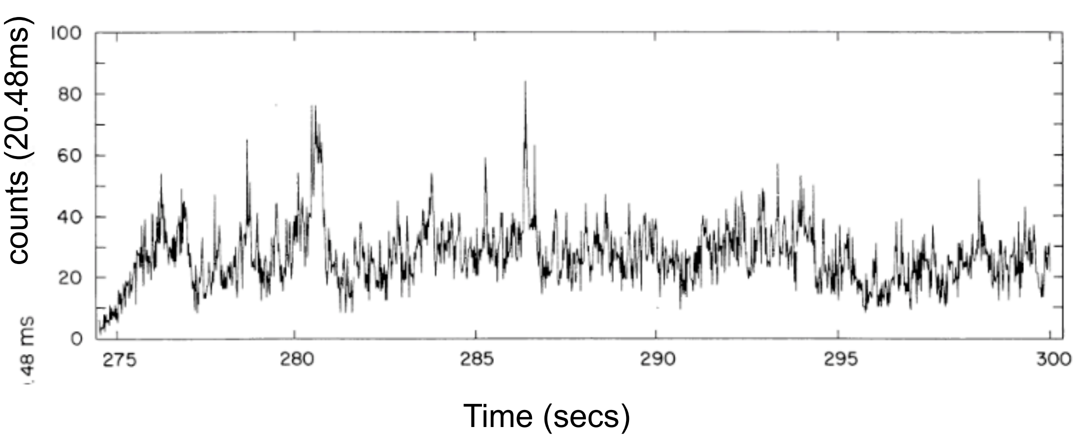
- If a black hole is a 'place' where radiation cannot escape to infinity how can they be observed ?
- Dynamical effects on 'nearby' material
- "Shining" black holes- a black hole can be a place where accretion occurs and as we have seen the process of accretion around a compact object can produce huge amounts of energy and radiation- making the black hole 'visible'

General properties of emission from black hole systems

- Emission usually variable on wide variety of timescales
  - Galactic black hole binaries : millisecond and up
  - AGN : minutes and up
  - Most rapid variability approaches light-crossing timescale limit of physical size of object (τ~R/c)

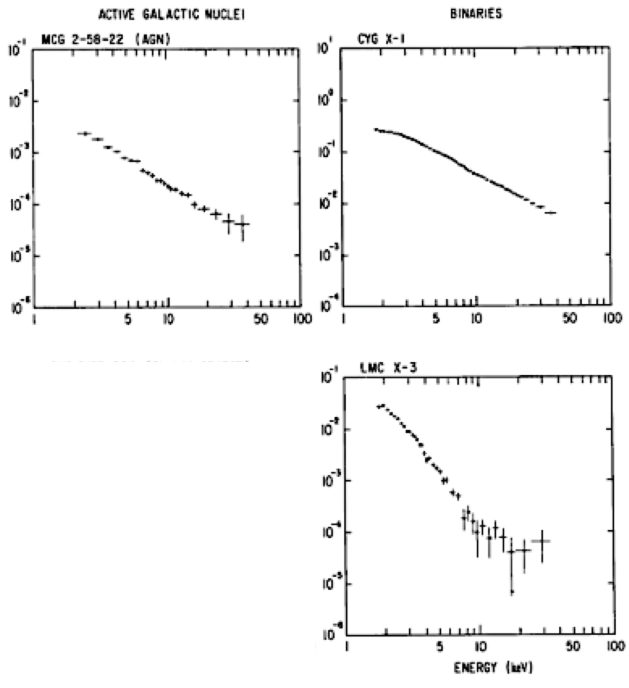
General properties of emission from black hole systems

- Emission usually variable on wide variety of timescales
  - Galactic black hole binaries : millisecond and up
  - AGN : minutes and up
  - Most rapid variability approaches light-crossing timescale limit of physical size of object (τ~R/c)



General properties of emission from black hole systems

- Significant emission over **very** broad spectral range (radio to hard X-ray or gamma-rays)-NS and WDs tend to have 'thermal' like spectra (relatively narrow in wavelength)
- Lack of a signature of a surface - not a pulsar, no boundary layer emission (no x-ray bursts), no 'after glow' from cooling
- unique x-ray spectrum



X-ray Spectra of Stellar Mass Black Holes

Power law and thermal states
in thermal state the E<10 keV data are well fit by the disk model