Neutron Stars

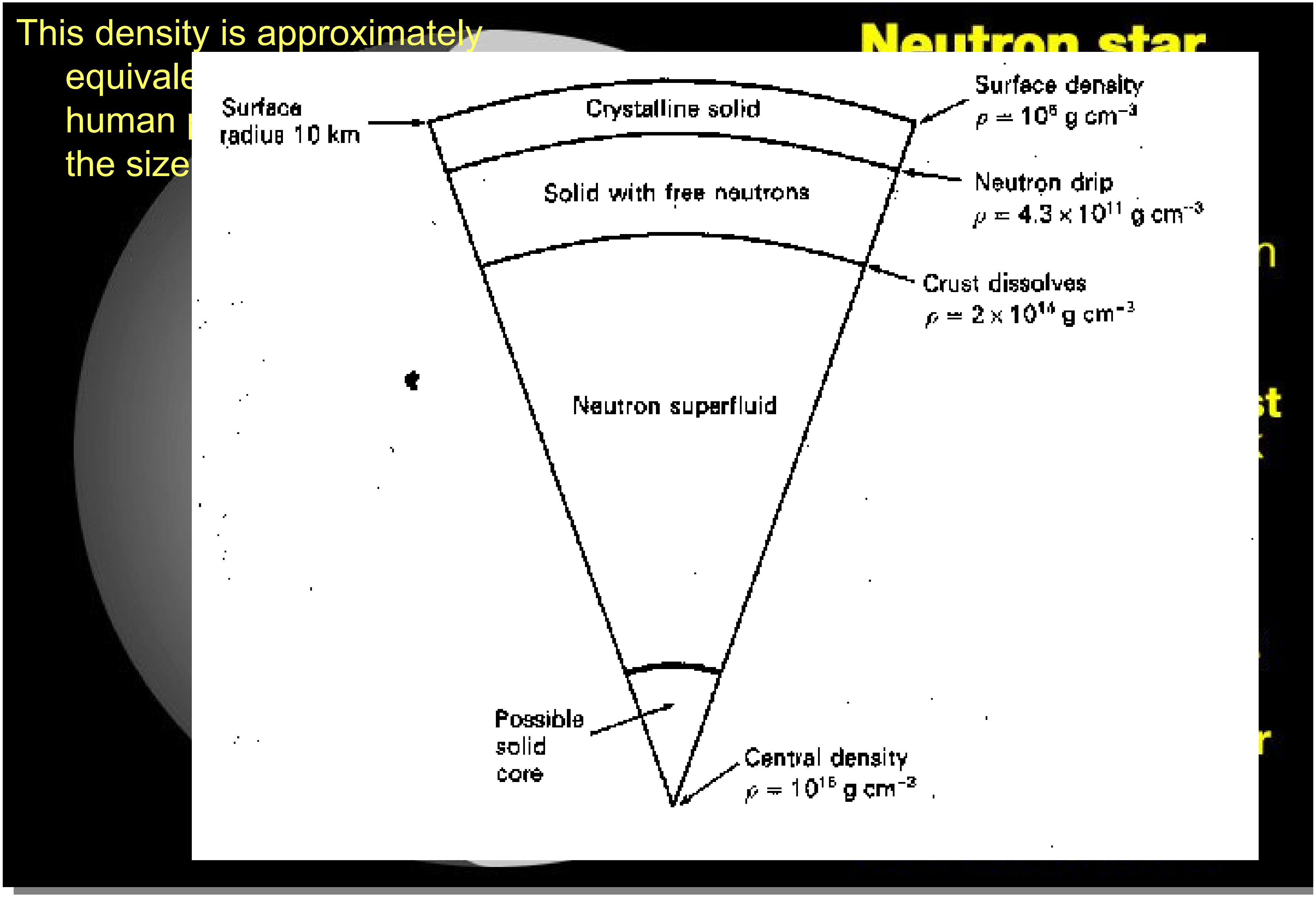
Accreting Compact Objects-

see Chapters 5 and 6 in Rosswog and Bruggen

Neutron Stars

- Predicted theoretically by Volkoff and Oppenheimer (1939)
- First 'discovered' by Hewish et al 1967 (Noble prize) as the counterparts to radio pulsars
  - short period from radio pulsars (<1s) can only be obtained from a compact object via either rotation or oscillations; also the period derivatives are small and for radio pulsar periods always increase (slow down)
    - All characteristic timescales scale as $\rho^{-1/2}$ (ρ is density)
      - ω=sqrt(GM/r^3) =sqrt(Gρ)
    - Shortest periods ~1.5ms- ight travel time arguements give a size (ct~ 500km)
- White dwarfs with $\rho \sim 10^7 – 10^8$ gmcm^{-3} maximum rotation periods $P = 2\pi/\Omega$ ~1–10 s
- To get periods of ~1ms need $\rho \sim 10^{14}$ gmcm^{-3}
- What are the sources of energy?
  - Spin down
  - accretion

Inside Neutron Stars



- Energy due to spin down
- $dE_{rot}/dt = I\ \Omega\ d\Omega/dt$ (ignoring changes in moment of intertia with time)
- $E_{rot=} = (1/2) I\ \Omega^2$
- Spin down timescale is (equating energy loss rate with total spin energy)

  $T_{slow} \sim E_{rot}/L \sim 60 I_{45}\ P^{-2} L_{37}$ yrs (I_{45} is the moment of inertia)

- Energy due to accretion - matter falling from infinity onto the surface of a neutron star (need to know mass and size)
- $E = GM/R \sim 10^{20}$ ergs per gram of

accreted matter, $\sim 0.1c^2$, makes

accretion an ideal source of power

Creation of Neutron Stars

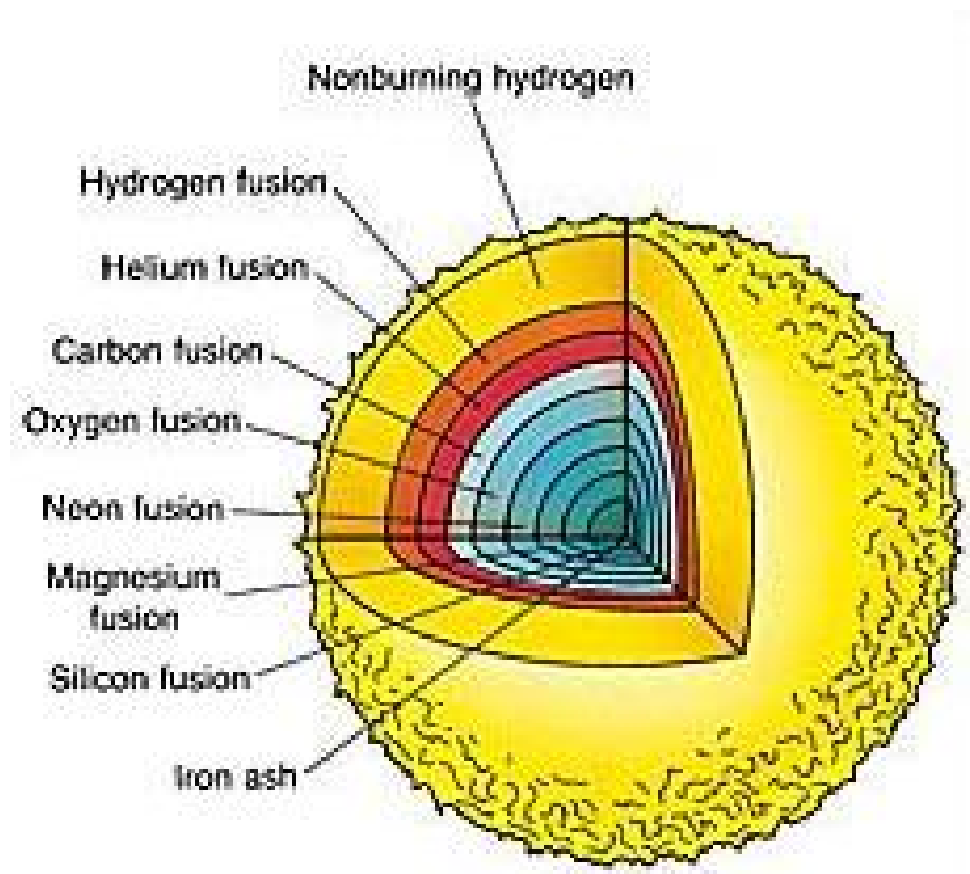
II/Ib/Ic Core-Collapse of Massive Progenitor at the end of the evolutionary history of stars.

- Massive stellar progenitor core forms neutron star or black hole
- Explosive nucleosynthesis products near core (Si and Fe) plus hydrostatically formed outer layers (O, Ne) are expelled
- Most of the explosion energy is carried away by neutrinos
- Uncertain explosion mechanism details involve neutrinos, probably large-scale shock instabilities, rotation, possibly magnetic fields
- Star must be at least $8M_{\odot}$; core at least $1.4\ M_{\odot}$.
- Stellar core collapses under the force of its own gravitation. At the very high pressures involved in this collapse, it is energetically favorable to combine protons and electrons to form neutrons plus neutrinos. The neutrinos escape after scattering a bit and helping the supernova happen, and the neutrons settle down to become a neutron star, with neutron degeneracy managing to oppose gravity.
- Energy set free by the collapse expels most of star's mass.
- Dense remnant, a neutron star, remains- due to the large reduction in radius and conservation of angular momentum the NS is born spinning very rapidly
- Observed spins ~1.4ms-30sec
- Very high surface gravity 7×10^{12}m/sec^2-10^{11}x that of the earth

(U. Hwang 2007)

I.7 : Core collapse in a massive star

- End of a massive star's life ($M>8M_{sun}$)
  - Center of star has fused all of the way to iron
  - Shells of other elements surround iron core
  - Only takes ~day to build up "dead" Chandrasekhar mass iron core
  - Core is held up by electron degeneracy pressure



From website of the Univ. of Mississippi

- Once dead core exceeds $1.4M_{sun}$, electron degeneracy pressure cannot support it.

- Core starts to collapse…
  - $\rho \approx 10^9$ kg/m^3 - Density of core when collapse begins (onset of relativistic effects in electron motions)

  - $\rho \approx 10^{10}$ kg/m^3 - Fermi energy exceeds neutron-proton mass difference…
    - Inverse beta decay becomes energetically preferable to normal beta decay

$$p + e^- \rightarrow n + \nu$$

    - Nuclei become very neutron rich… <u>neutronization</u>

– $\rho \approx 10^{14}$ kg/m^3 - Individual nuclei are so neutron rich that they start to fall apart
  - Remaining nuclei surrounded by sea of free neutrons
  - This is called the <u>neutron drip phase</u>

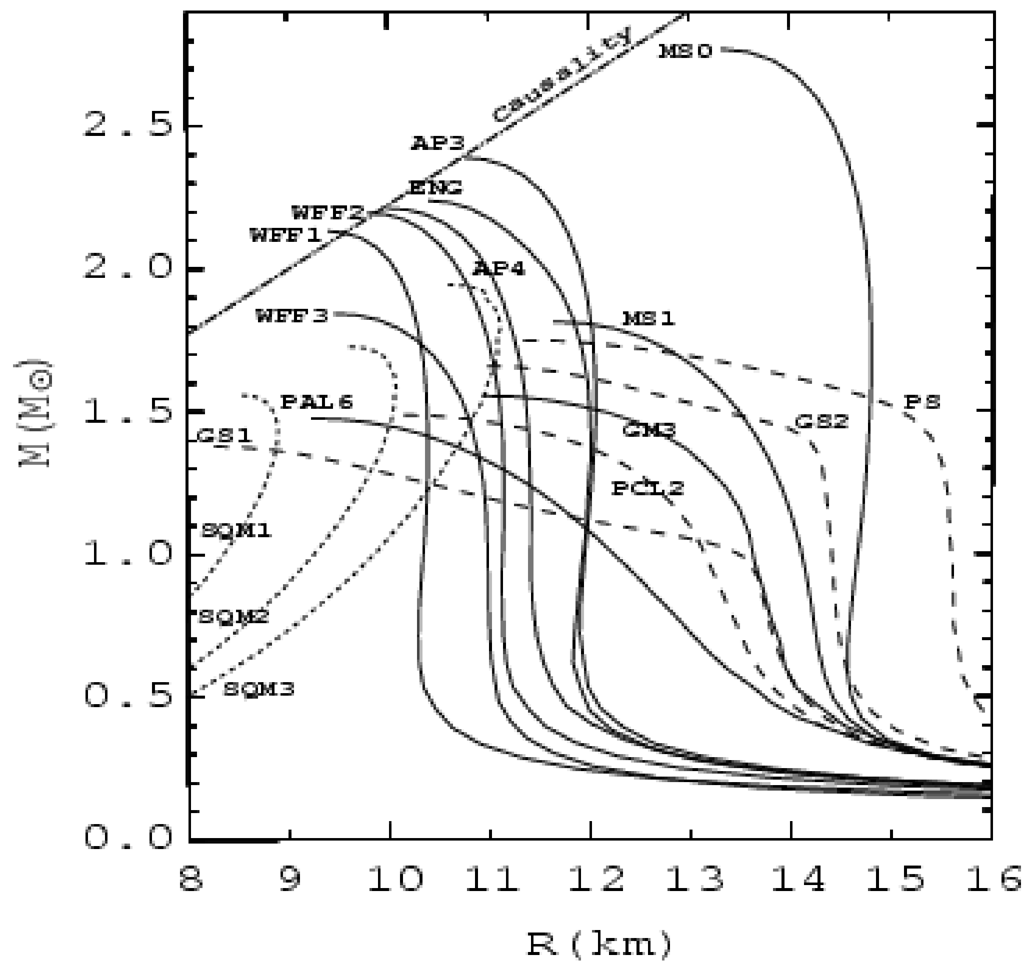
– $\rho \approx 10^{16}$ kg/m^3 - Neutron degeneracy pressure starts to become important

– $\rho \approx 10^{18}$ kg/m^3 - Neutron degeneracy finally halts the collapse provided that $M<3M_{sun}$

– End up with a neutron star… typical mass of $1.4M_{sun}$ with a radius of 10km

EOS of Neutron Star- Size/Mass Relation

- Rather Complex
  - Have to use General Relativistic form of hydrostatic equilibrium equation
  - Neutrons don't behave like an ideal degenerate gas… strong force interactions are crucial
  - There remain uncertainties about the "equation of state" of neutron stars



From website of Kaya Mori (CITA)

Courtesy of C. Reynolds

- For All objects the size is related to the density …

$$R \sim \frac{K}{GM^{1/3}}$$

For objects supported by degeneracy pressure the constant K can be calculated from first Principles related to the Fermi energy

$$P_c = K\rho_c^{5/3} \qquad\qquad P = \frac{3^{2/3}\pi^{4/3}\hbar^2}{5m_e\mu^{5/3}m_p^{5/3}}\rho^{5/3}$$

Mass of particle producing degeneracy pressure

Number of nucleons per degenerate particle

Courtesy of C. Reynolds

- By analogy, neutron stars have (to a crude approximation)…

$$R_n \sim \frac{K_n}{GM^{1/3}}$$

  - I.e., degenerate particles have mass m_n, and μ=1

$$P_n = K_n \rho^{5/3} \qquad P_n = \frac{3^{2/3}\pi^{4/3}\hbar^2}{5m_n^{8/3}}\rho^{5/3}$$

Courtesy of C. Reynolds

- So, we can try to estimate radius of neutron star given what we know about white dwarfs
  - We know that
  - So we expect

$$\boxed{\frac{R_n}{R_{wd}} \sim \frac{m_e}{m_n} 2^{5/3}}$$

$$R_{wd} \sim 10^4\,\mathrm{km}$$

$$R_n \sim 16\,\mathrm{km}$$


Neutron
Star

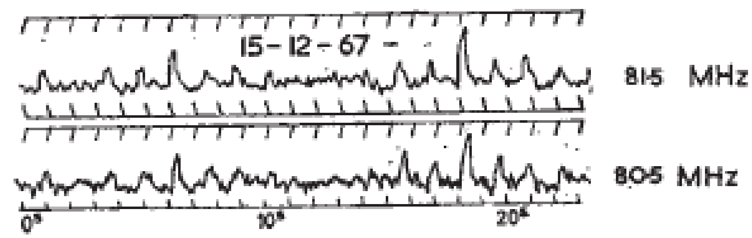
Maximum Mass of a Compact Object

- The Chandrasekar limit (maximum mass of a white dwarf) corresponds to the situation in which it costs less energy for a electron to fuse with a proton to form a neutron then to climb higher in the Fermi sea.
  - Above this limit the compact object becomes all neutrons (a neutron star)
- An alternative way of looking at this is to calculate the equation of state (EOS) of degenerate matter and use hydrostatic equilibrium.
- Pressure $P \sim M/R^3$ (Bradt sect 3.6, Rossweg and Bruiggen pg 124-125+sec 5.6.1))
  - $P_e=(1/20)(3/\pi)^{2/3}(h^2/m_e)\,(\rho/\mu_e m_p)^{5/3}$ Bradt eq 3.64 ρ is the total mass density and $\mu_e m_p$ is the mass per electron (composition of the material) - or more simply
  - $P_e \sim \rho^{5/3}$ - non relativistic
  - for relativistic matter $P_e=(1/8)(3/\pi)^{1/3}ch(\rho/\mu_e m_p)^{4/3}$ Bradt eq 3.69- notice the appearance of the speed of light
  - $P_e \sim \rho^{4/3}$
  - in hydrostatic equilibrium (remember $dP(r)/dr=GM(r)\rho(r)/r^2$

  $P \sim GM^2/R^4$
- Setting the 2 pressures equal produces the Chandrasekhar limit at which a white dwarf collapses to a neutron star $M \sim 1.46 M_\odot$ (but depends on its composition μ_e, eg an iron core??))

Radius of NS- Following Bradt sec 4.4

- Use the 'known' density of nuclear matter ($\rho_{Neutron}$~1.2x10^{14}g/cm^3) and use the Chandrasekar mass
- the radius R_{NS}~$(3M_{Chandra}/4\pi\rho_{Neutron})^{1/3}$ ~ 10km
- consistency between the observed spin periods, and neutron stars



Rotating Neutron Stars as the Origin of the Pulsating Radio Sources

by

T. GOLD

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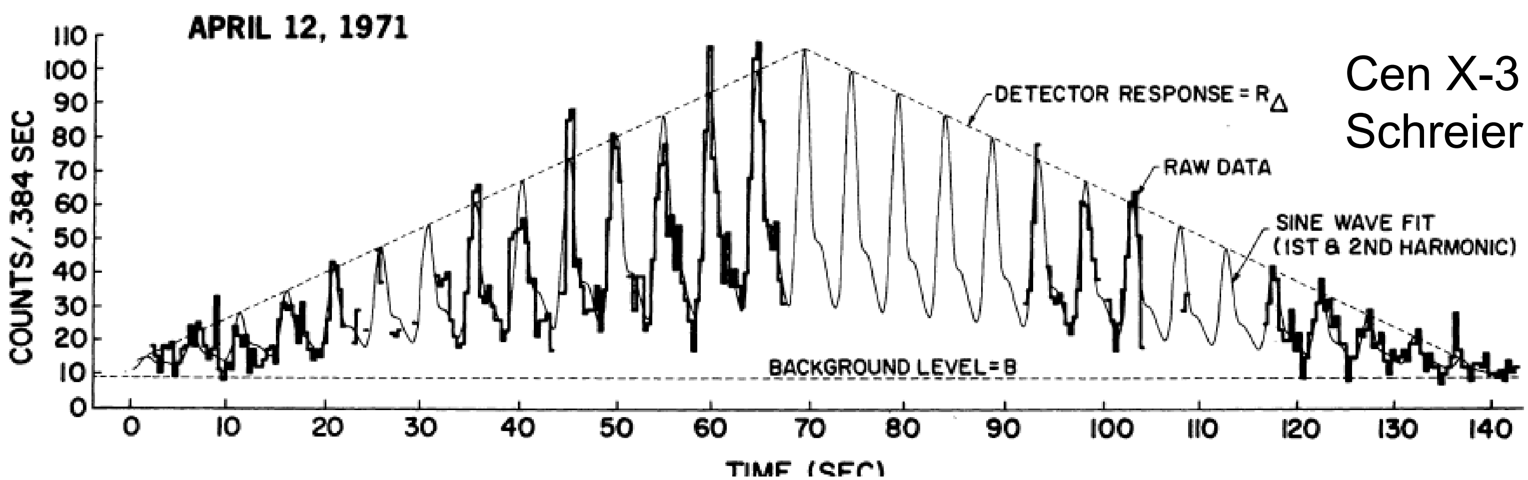
Ithaca, New York

The constancy of frequency in the recently discovered pulsed radio sources can be accounted for by the rotation of a neutron star. Because of the strong magnetic fields and high rotation speeds, relativistic velocities will be set up in any plasma in the surrounding magnetosphere, leading to radiation in the pattern of a rotating beacon.

1971ApJ...167L..67G



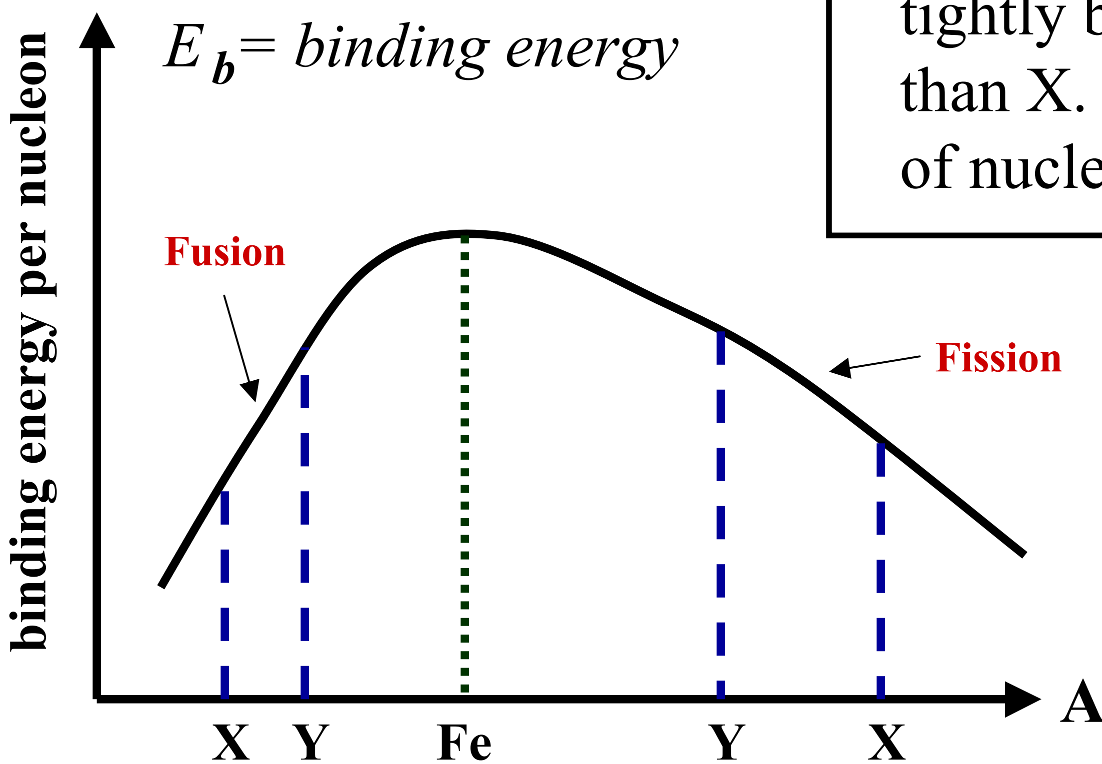
Cen X-3
Schreier et al 1971

Binding energy of Nuclei - why stellar burning stops generating energy

A=total no. nucleons

Z=total no. protons

E_b*= binding energy*



Change from X to Y emits energy since Y is more tightly bound per nucleon than X. This is a function of nucleon mass

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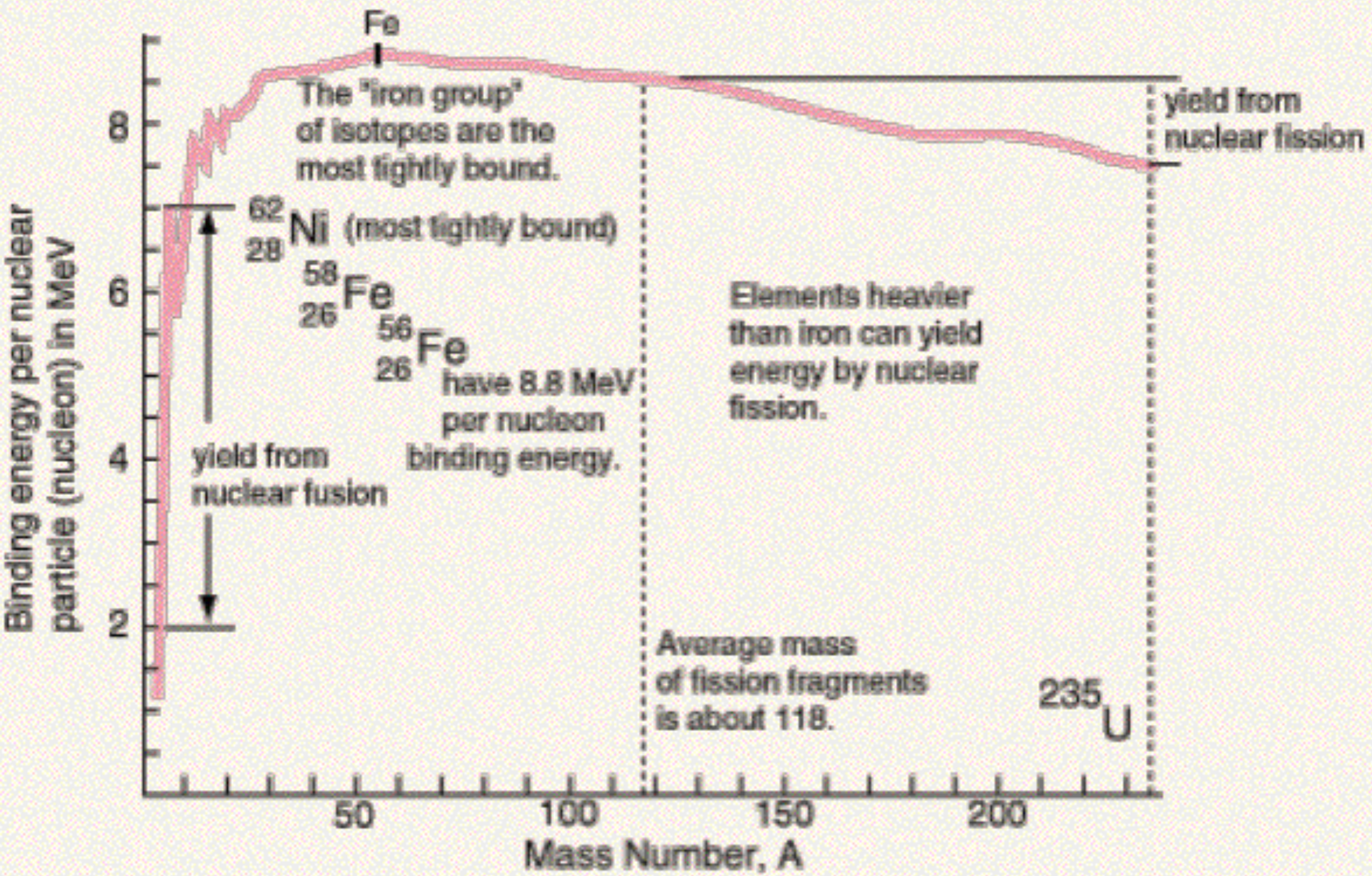
Fission and fusion can yield energy

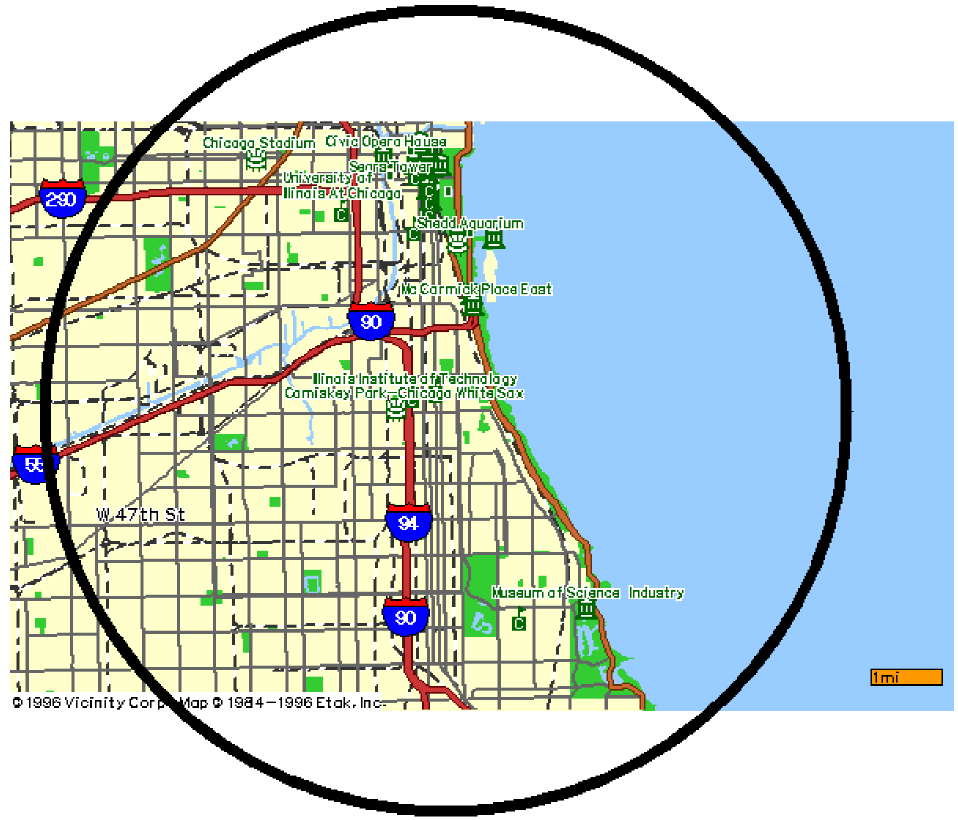
hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html



- one teaspoon of a neutron star has a mass of ~5 x 10^{12} kilograms.
- http://videos.howstuffworks.com/nasa/13498-chandra-neutron-stars-video.htm

C. Miller

Neutron star vs. Chicago



Mass=1.4 M_{sun}, Radius=10 km
Spin rate up to 38,000 rpm
Density~10^{14} g/cc, Magnetic field~10^{12} Gauss

Stellar Evolution and Supernovae

- Stellar evolution – a series of collapses and fusions

H => He => C => Ne => O => Si

- Outer parts of star expand to form opaque and relatively cool envelope (red giant phase).
- Eventually, Si => Fe: most strongly bound of all nuclei
- Further fusion would *absorb energy* so an inert Fe core formed
- Fuel in core exhausted hence star collapses

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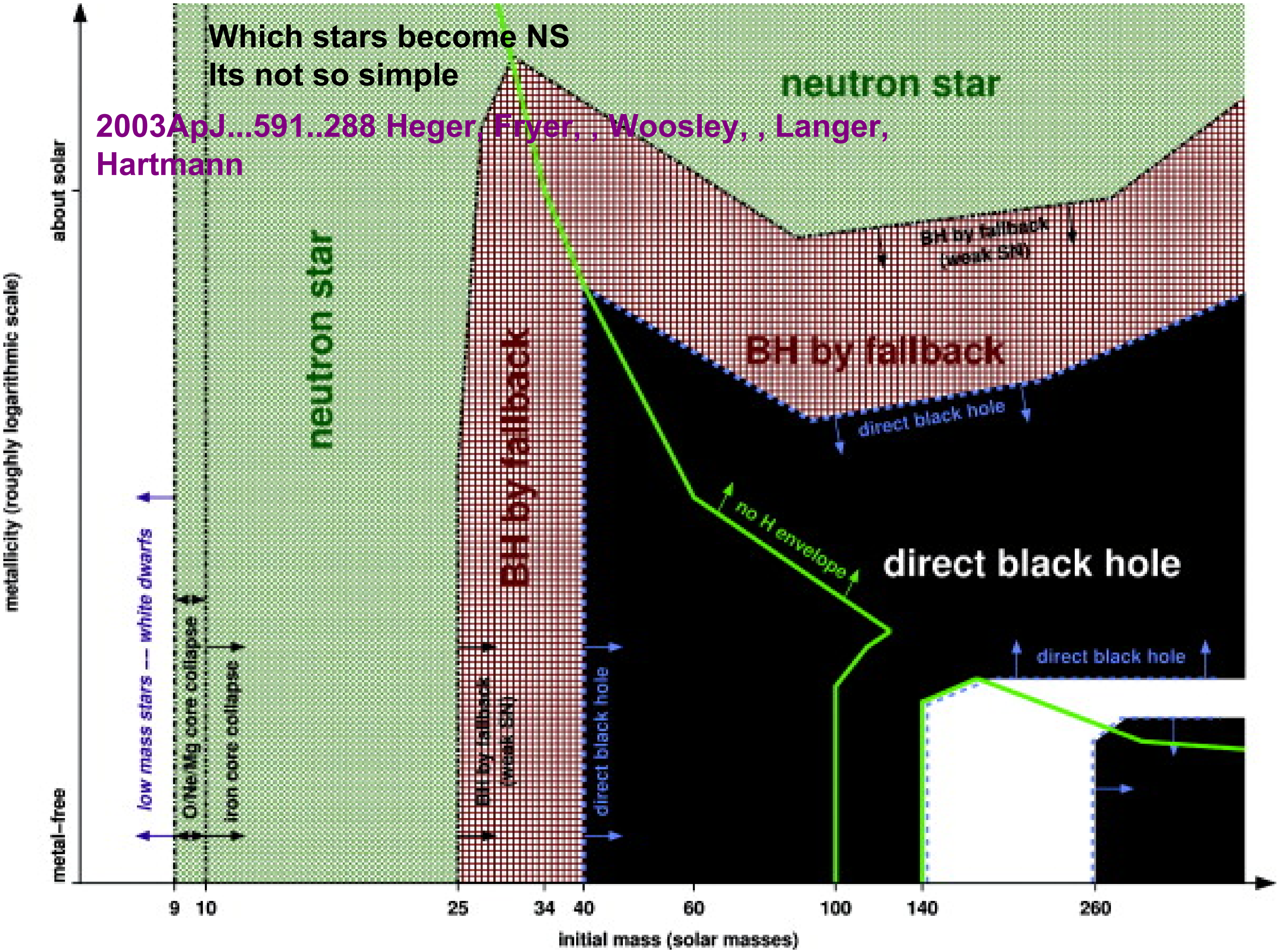
- Stars with a defined mass range evolve to produce cores that can collapse to form Neutron Stars
- Following nuclear fuel exhaustion, core collapses gravitationally; this final collapse supplies the supernova energy
- Collapse to nuclear density, in $\approx$ few seconds, is followed by a rebound in which the outer parts of the star are blown away
- The visible/X-ray supernova results due to radiation
    - i. From this exploded material
    - ii. Later from shock-heated interstellar material
- Core may
    - i. Disintegrate
    - ii. Collapse to a Neutron star
    - iii. Collapse to a Black Hole

according to its mass which in turn depends on the mass of the original evolved star

From L. Cominsky

Which stars become NS
Its not so simple

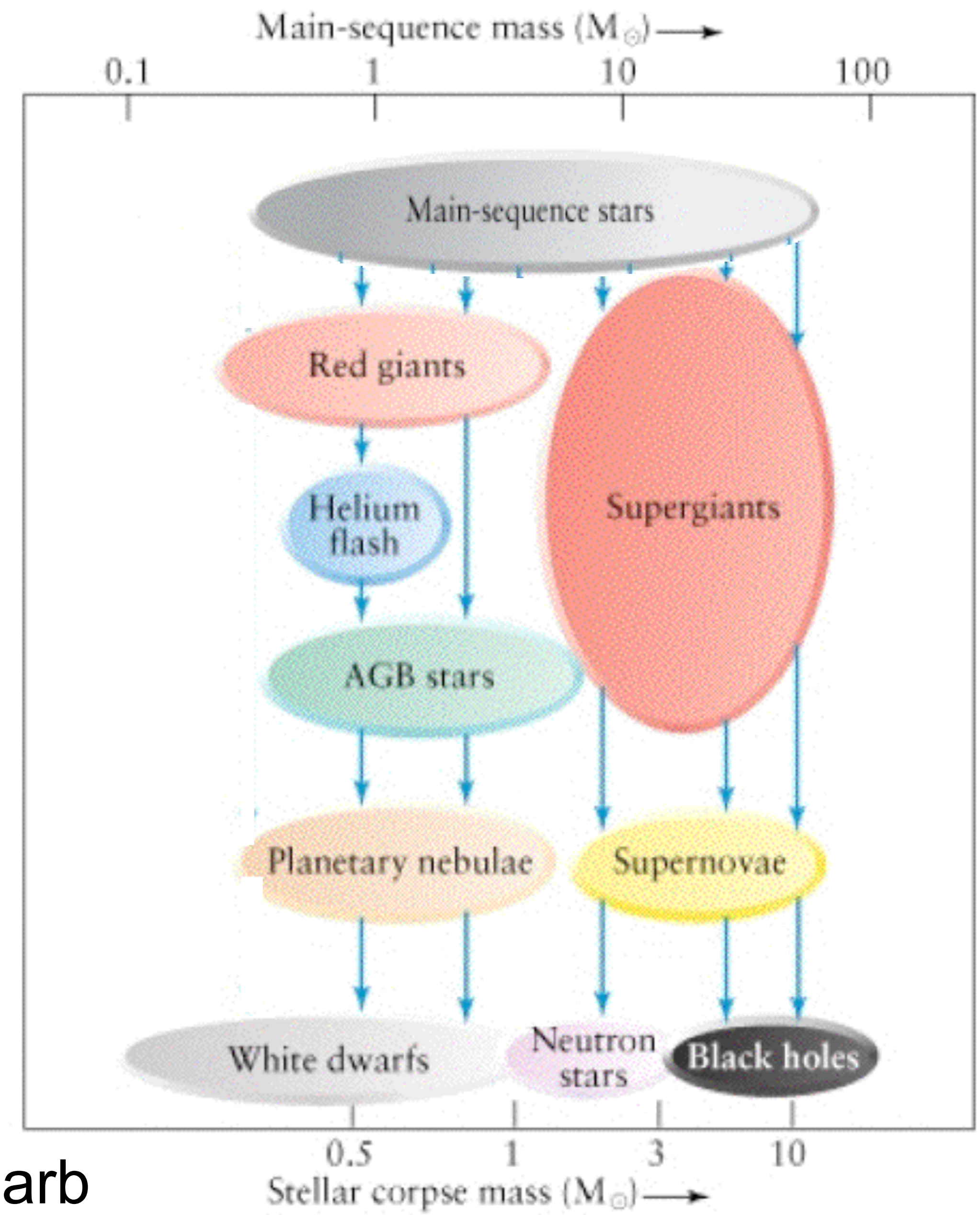
2003ApJ...591..288 Heger, Fryer, , Woosley, , Langer, Hartmann



Progenitors of Compact Objects

- Main sequence stars evolve and at the end of their 'life' (period of nuclear burning) end up as compact objects
- $t_{MS}/t_{sun} \sim (M/M_{sun})^{-2.5}$

- The most massive end up as black holes
- The least massive as white dwarfs (the main sequence lifetime of stars less than 1/2 M_{sun} is greater than the Hubble time so they have never got to white dwarfs)

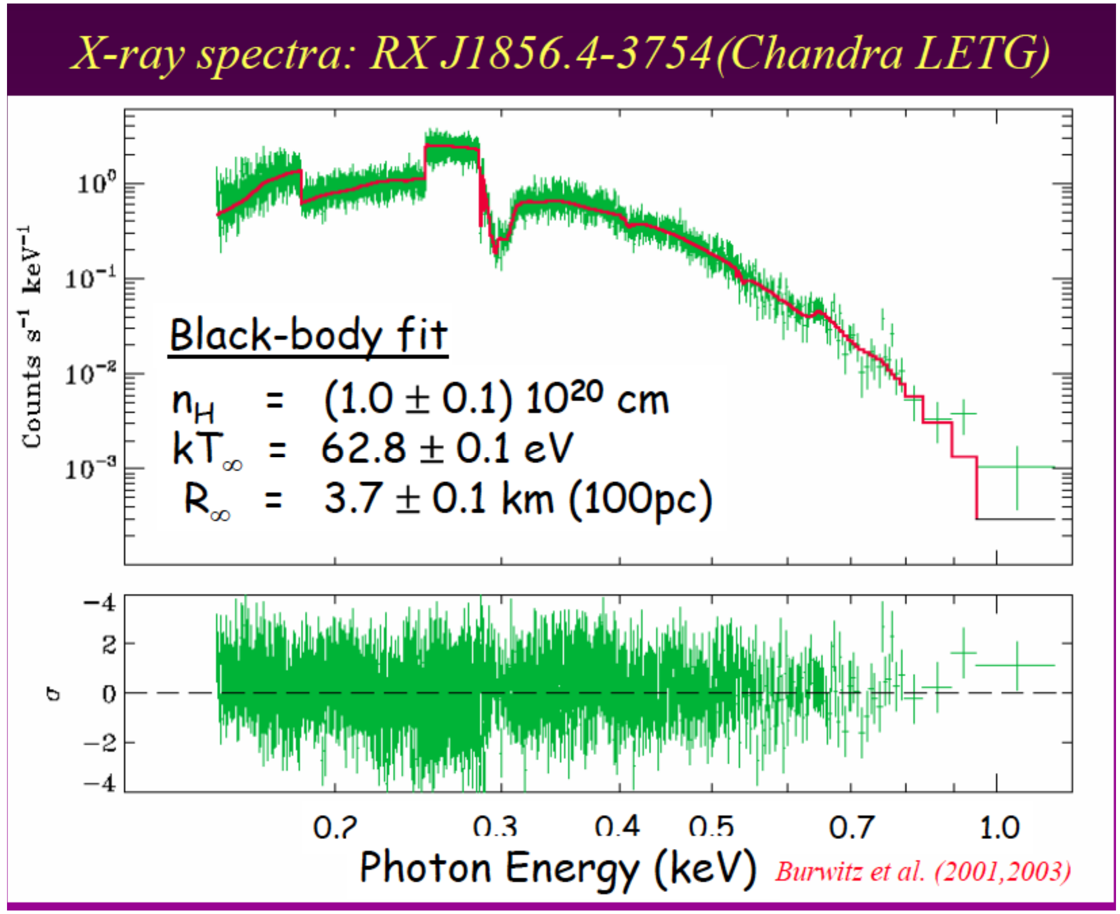


Samar Safi-Harb

Isolated Neutron Stars- Non Accreting

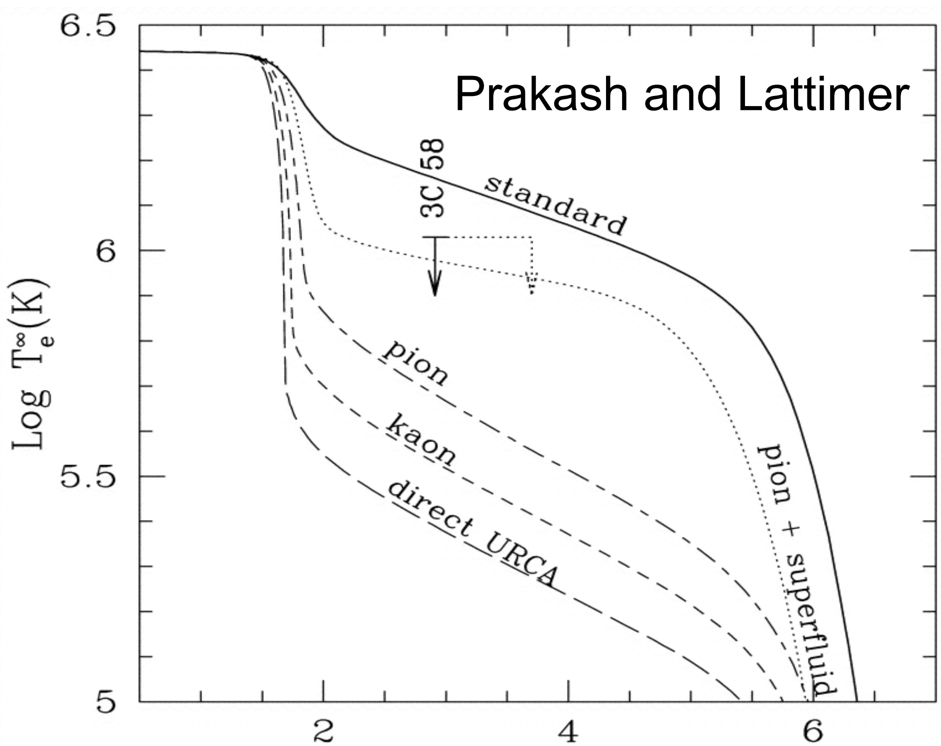
- These objects are cooling from the initial high temperature of the supernova explosion

- Recent results show that they have an <u>almost pure black body spectrum</u>- which is unexpected since they have an 'atmosphere'



Burwitz et al 2001

Neutron Star Continuum Spectroscopy and Cooling

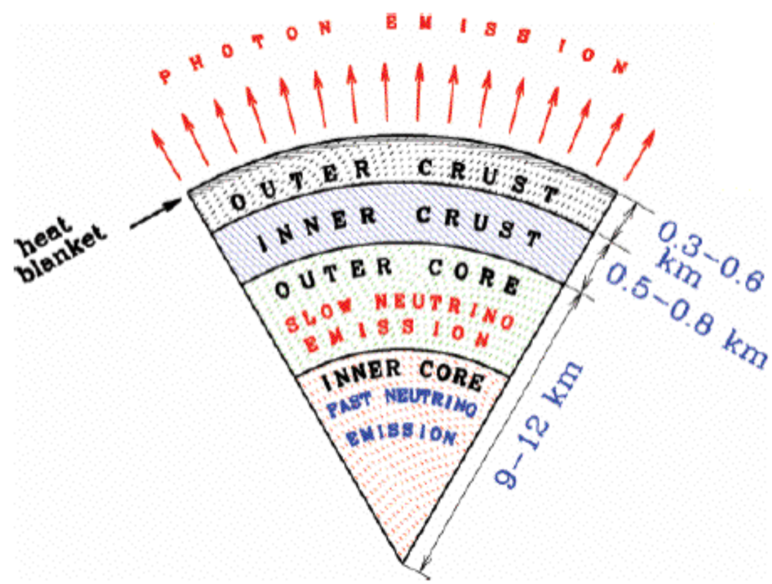


Main cooling regulators:

1. EOS
2. Neutrino emission
3. Superfluidity
4. Magnetic fields
5. Light elements on the surface

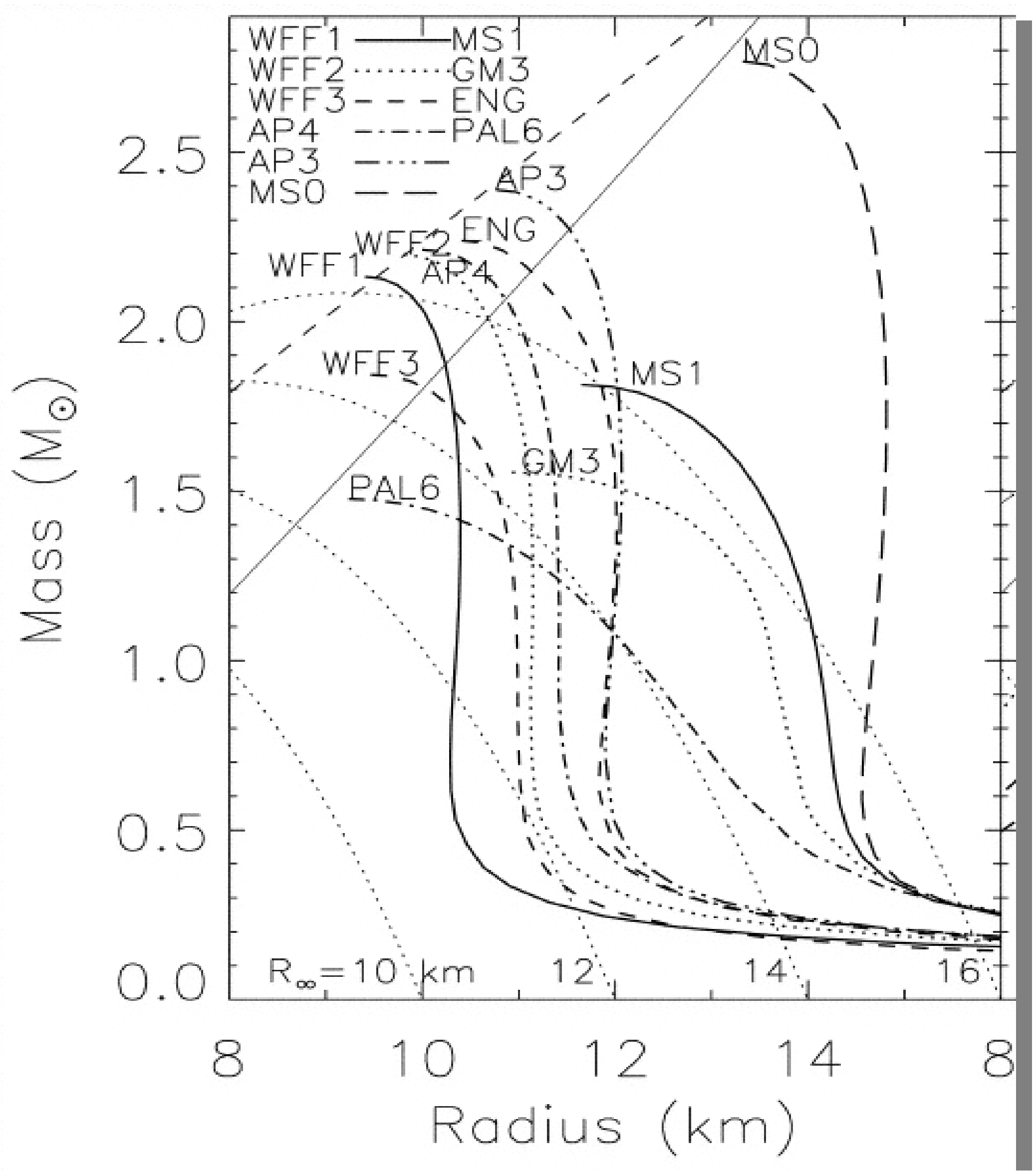
- After Neutron star is created in a supernova, if it is isolated it cools
- The rate at which it cools depends on the conductivity and heat capacity which depends on what it is made of and physics we do not truly understand.

(L. Cominsky)



D.G. Yakovlev, O.Y. Gnedin*, M.E. Gusakov, A.D. Kaminker
K.P. Levenfish, A.Y. Potekhin

Fundamental Physics: The Neutron Star Equation of State (EOS)

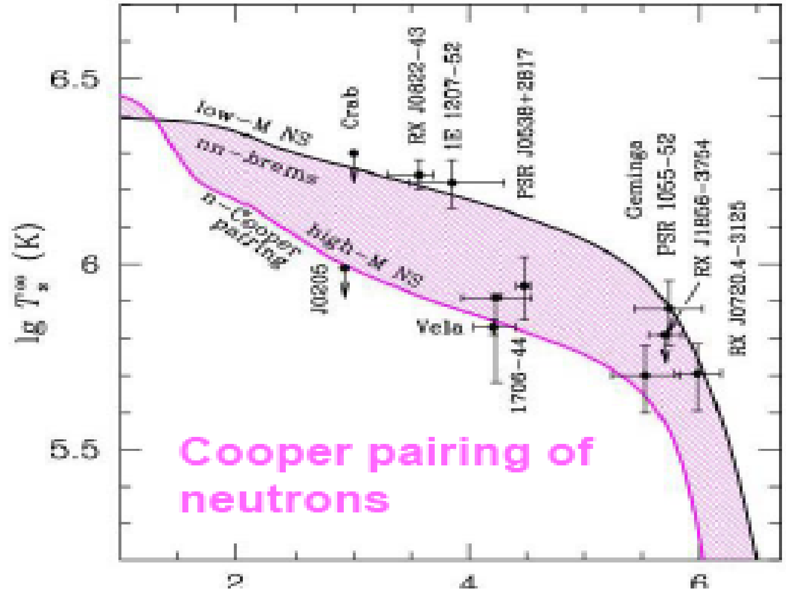


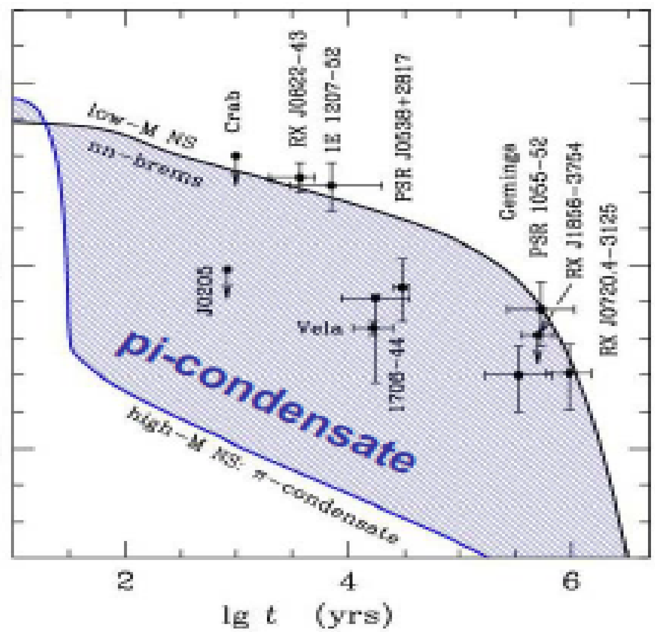
$$dP/dr = -\rho \; G \; M(r) \; / \; r^2$$

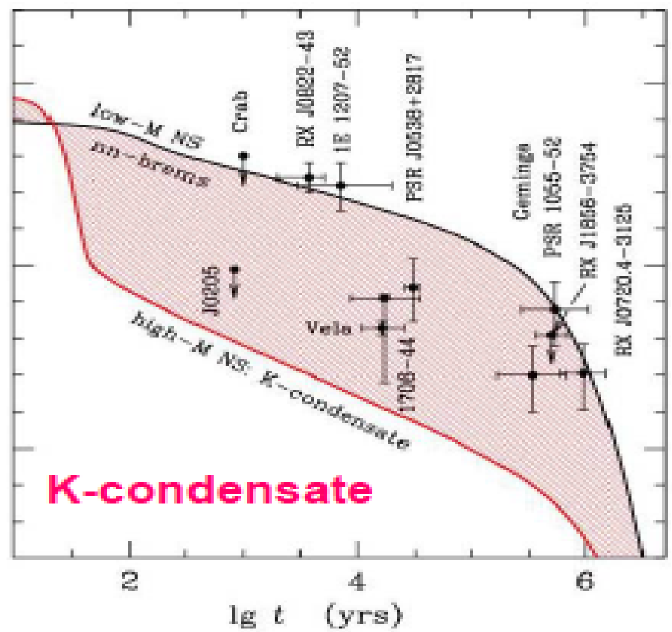
- High mass limit sets highest possible density achievable in neutron stars (thus, in nature, “the MOST dense”).
- Radius ~ $P^{1/4}$ at nuclear saturation density. Directly related to symmetry energy of nuclear interaction
- Other issues: have to use general relativistic eq for hydrostatic equil
- Effect of strong interaction makes neutrons not an ideal gas
- Do not understand the eq of state (relation between pressure and density)
- Maximum mass measurements, limits softening of EOS from hyperons, quarks, other “exotica”.

Interesting Physics- Will Not Discuss Further

THEORY versus OSERVA-TIONS

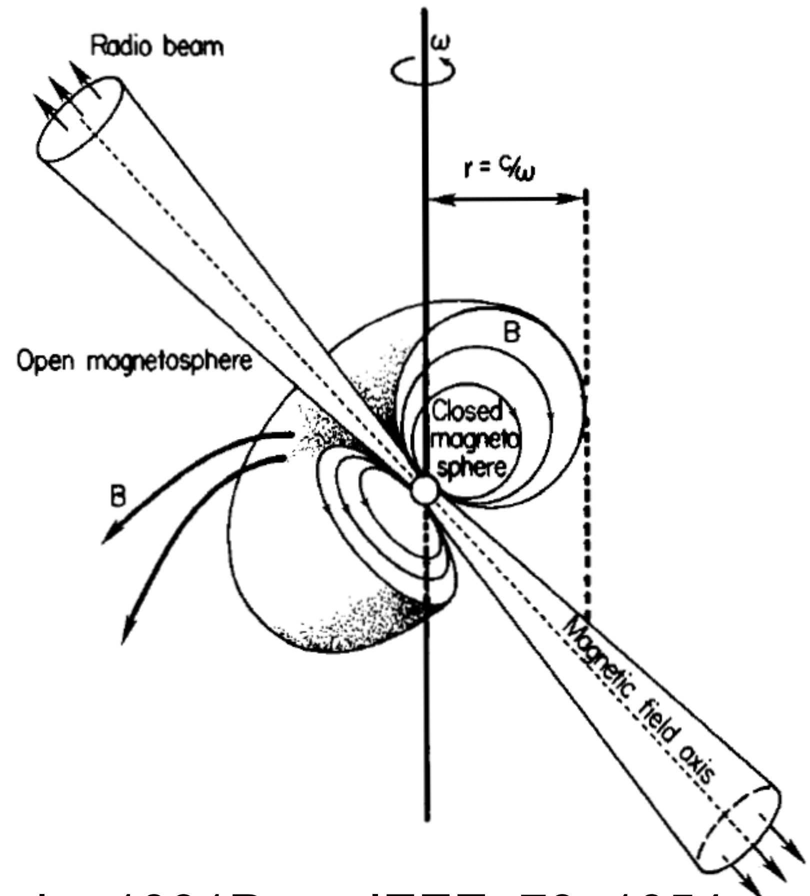






Isolated Neutron Stars

- Most isolated neutron stars that are known are radio and γ-ray pulsars -
- These are rapidly spinning neutron stars that emit relativistic particles that radiate in a strong magnetic field
- Energy loss goes as Ω^4B^2
- As they radiate the star spins down- they live for $\sim 10^7$ yrs
- Discovery of many isolated spinning NS is a recent major Fermi discovery



Taylor 1991Proc. IEEE, 79, 1054

http://www.jb.man.ac.uk/~pulsar/Education/Tutorial/tut/tut.html

For More Details see "Rotation and Accretion Powered Pulsars" by Pranab Ghosh

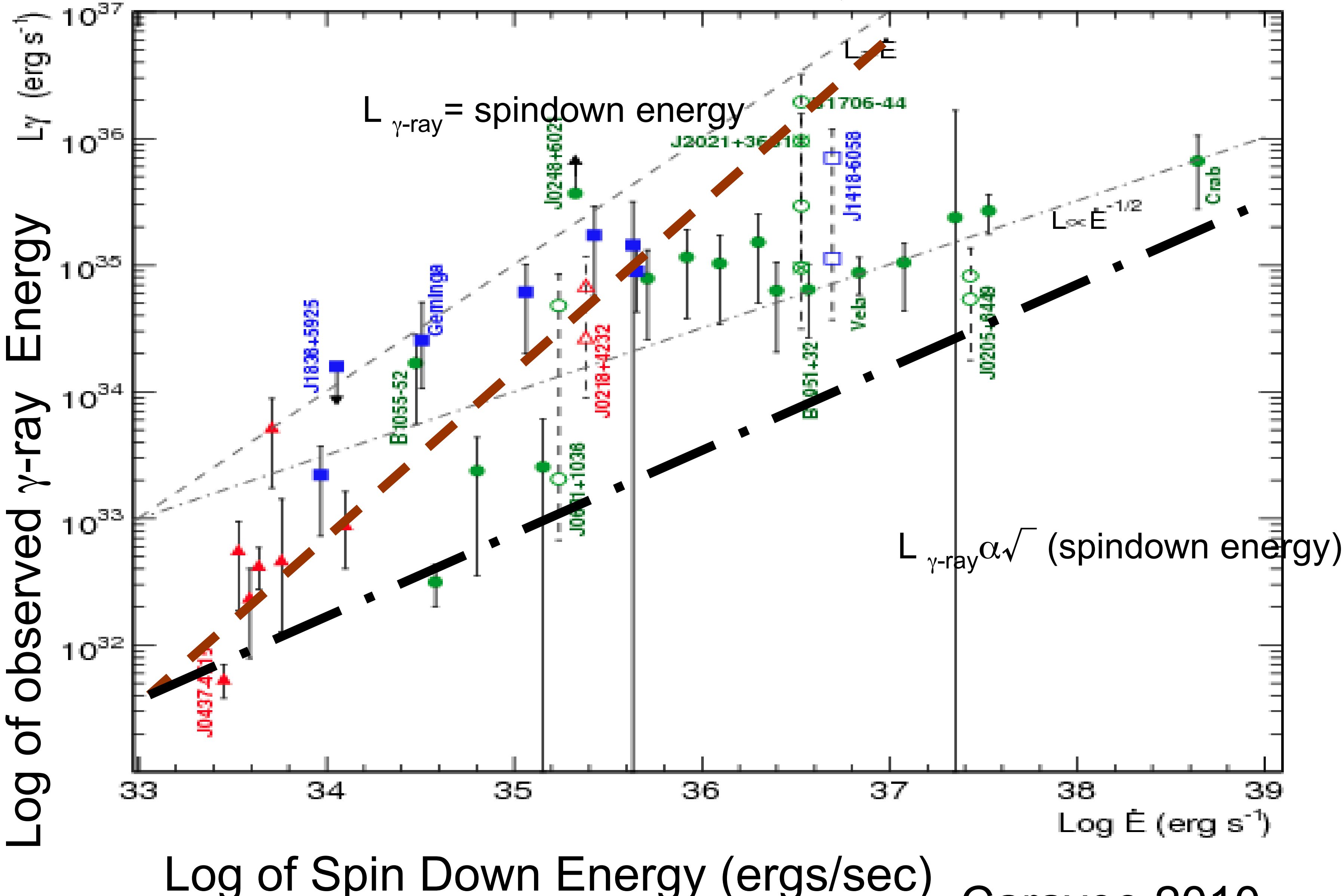
- The shortest period (or angular velocity Ω) which a star of mass M and radius R can have without being torn apart by centrifugal forces is (approximately)
- $\Omega^2 R \sim GM/R^2$
- Putting in the average density of the star ρ,
- $\Omega \sim (G\rho)^{1/2}$

- Putting in some numbers rotation periods of $P=2\pi/\Omega \sim 1$ sec requires density of 10^8gm/cm^3

- To 'radiate' away the rotational energy $E_{rot} = 1/2\ I\Omega^2 \sim 2\times10^{46} I_{45} P^{-2}$ ergs
- Takes $T_{loss} \sim E_{rot}/L \sim 60 I_{45} P^{-2} L_{37}^{-1}$ yr ($I=2/5MR^2$)
- *Where the moment of inertia I is in units of 10^{45} gmcm^2*

- If the star is spinning down at a rate $d\Omega/dt$ its rotational energy is changing at a rate $E_{rot} \sim I\Omega(d\Omega/dt) + 1/2(dI/dt)\Omega^2 \sim 4\times10^{32} I_{45} P^{-3} dP/dt$ ergs/sec (second term handles any possible change in the moment of Inertia)
- However only a tiny fraction of the spindown energy goes into radio pulses- a major recent discovery is that most of it goes into particles and γ-rays.

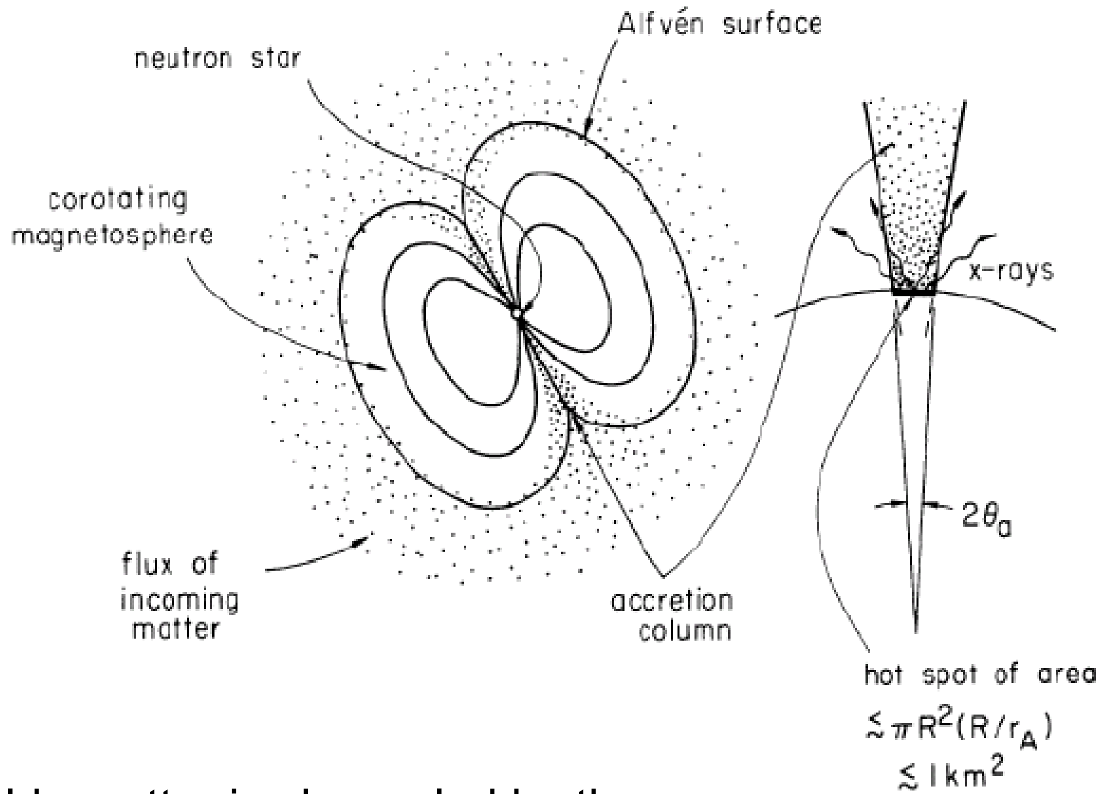
Comparison of Spin Down Energy and γ-ray Luminosity of Pulsars



Caraveo 2010

Accreting Neutron Stars

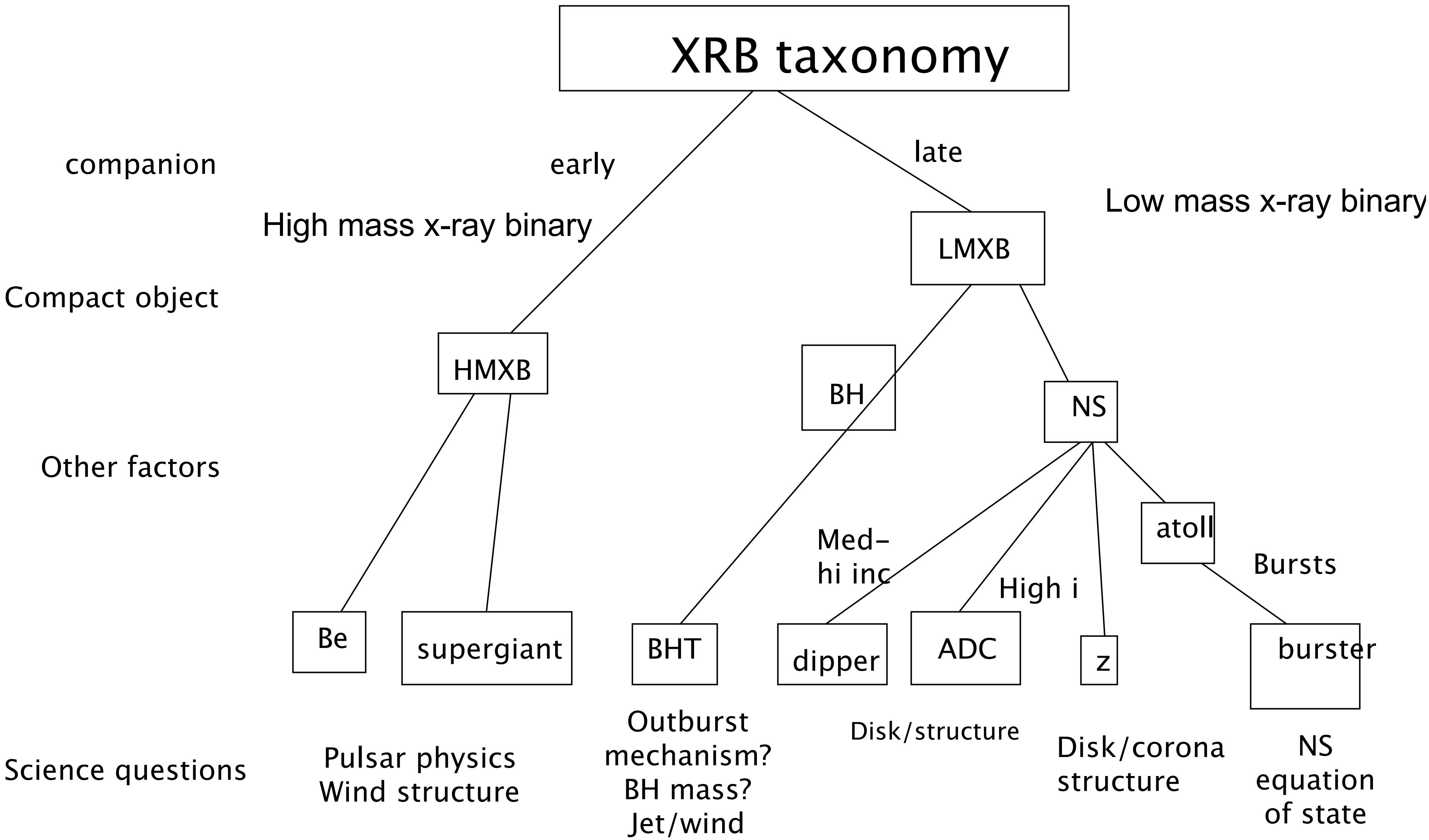
- These are the brightest x-ray sources in the sky and were the first x-ray sources discovered
- They have a wide range of properties (spectral and temporal) and show an almost bewildering array of behaviors
- Their luminosities range over 6 orders of magnitude



In the case of strong magnetic fields matter is channeled by the magnetic field and accretions at/near the magnetic poles

When magnetic pressure is less than the thermal pressure the accreting material usually accretes in a disk all the way down to the NS surface

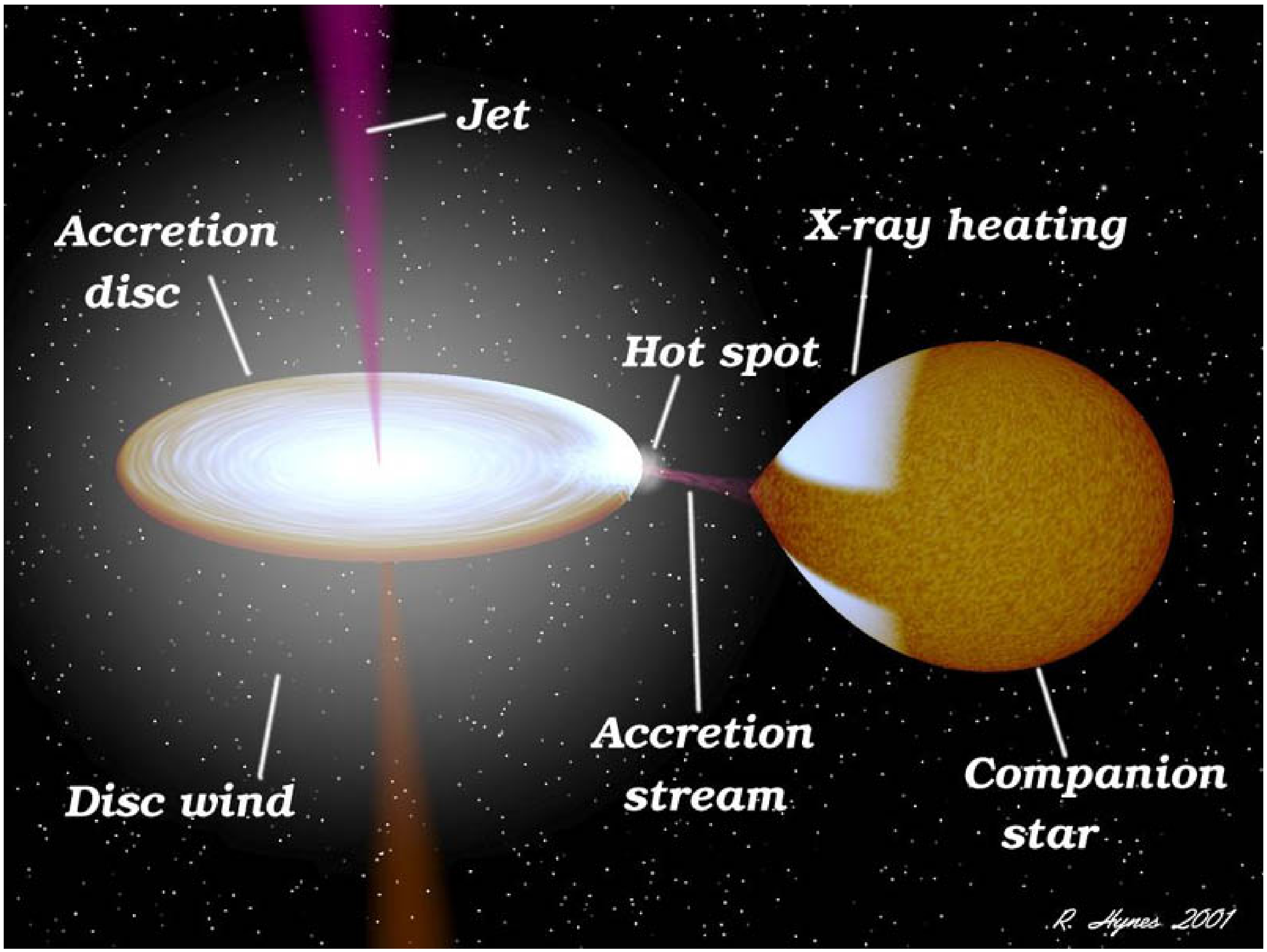
A Short Introduction to terminology



Kallman 2009

Accreting Neutron Stars

- Two types- based on mass of companions
  - Low mass x-ray binaries-NS star tends to have low magnetic field- BHs are transient
  - High mass-NS tends to have high magnetic field- BHs on all the time



Accreting Neutron Stars

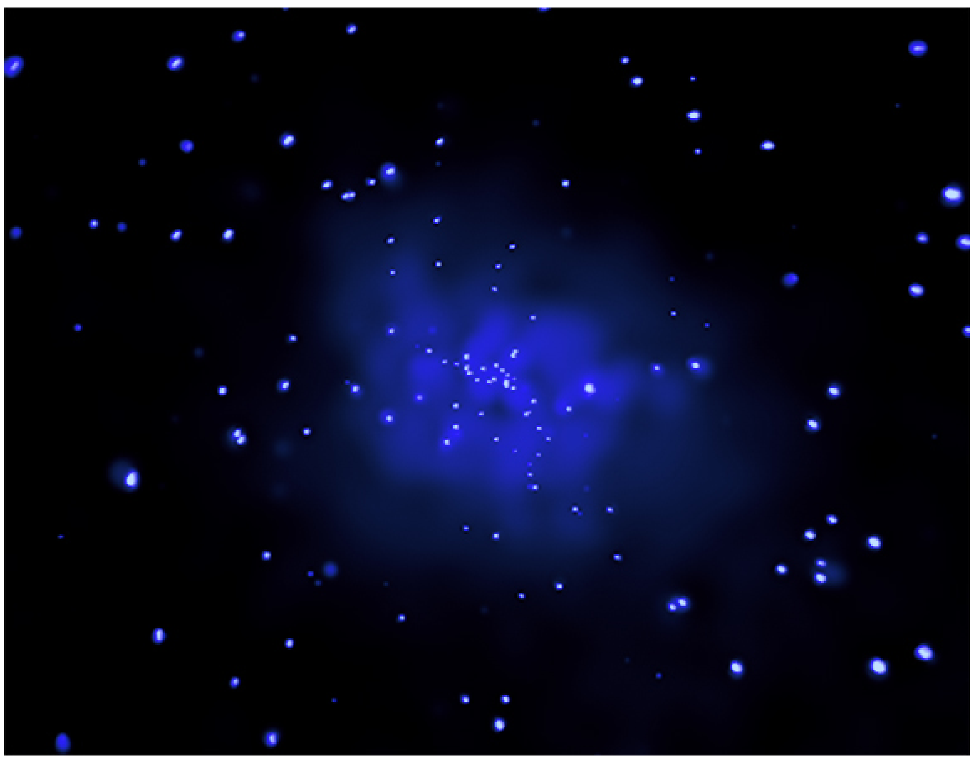
- Two types- based on mass of companions
  - Low mass x-ray binaries-NS star tends to have low magnetic field- - are 'old' (~10^{9-10} yrs) -BHs are transient
  - High mass-NS tends to have high magnetic field- - are are 'young' (~10^{7-8} yrs)-BHs on all the time

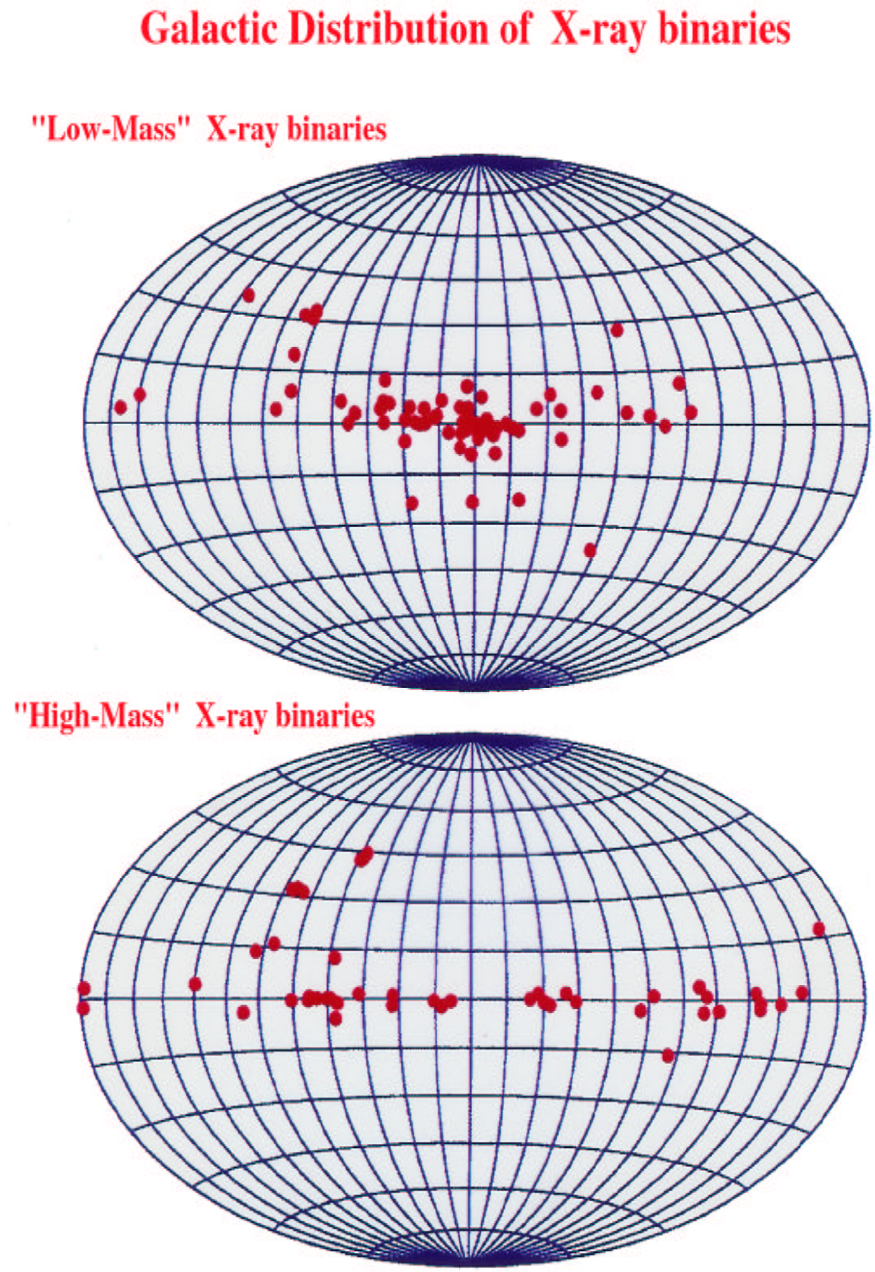
	HMXB	LMXB
Donor star	O-B ($M>5M_{sun}$)	K-M ($M<1M_{sun}$)
Age/Population	10^7 yrs I	5-15x10^9 II
L_x/L_{opt}	0.001-10	10-1000
X-ray Spectrum	flat power law	kT<10keV
Orbital period	1-100d	10min-10d
X-ray eclipses	common	rare
Magnetic field	strong (~10^{12}G)	weaker (10^7-10^8 G)
X-ray pulsations	common (0.1-1000s)	rare (and often transient)
X-ray bursts	never	often
X-ray luminosity	~10^{35-37}	10^{33-38}
# in MW	~35	~100
Accretion mode	stellar wind	Roche Lobe overflow
In glob clusters	never	frequently

(drawn from M. Porzio)

Space Distribution of X-ray Binaries

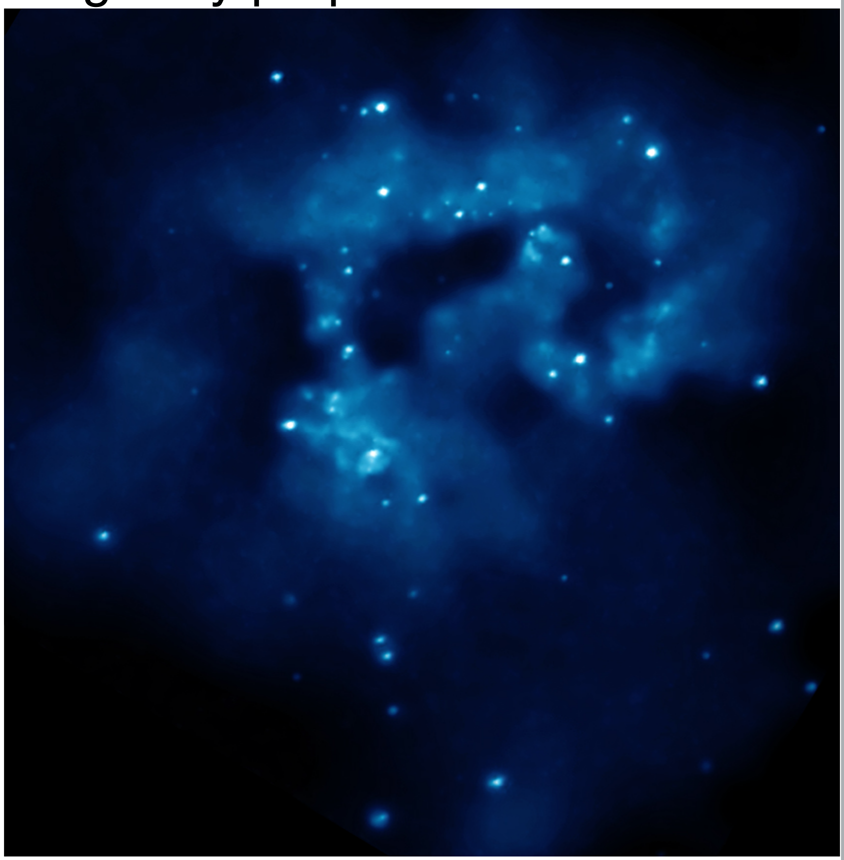
- X-ray binaries are concentrated in the galactic plane and in the two nearby satellite galaxies of the Milky Way (the Magellanic clouds)
- Chandra images of XRB in nearby galaxies (core of M31 below)





M31 and the Antenna

- Chandra can see x-ray binaries to d~100 Mpc
- allows population studies relation of x-ray binaries to galaxy properties



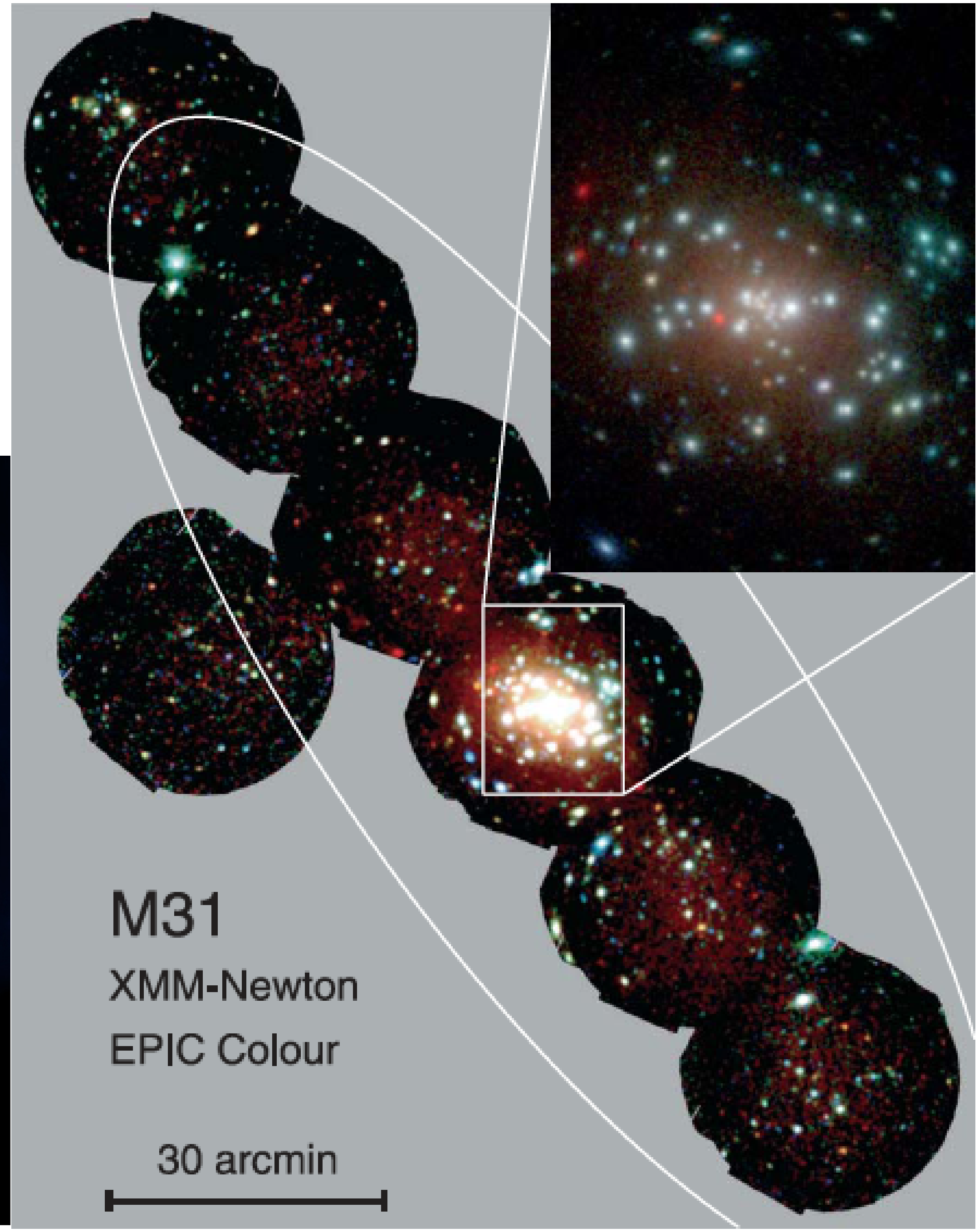
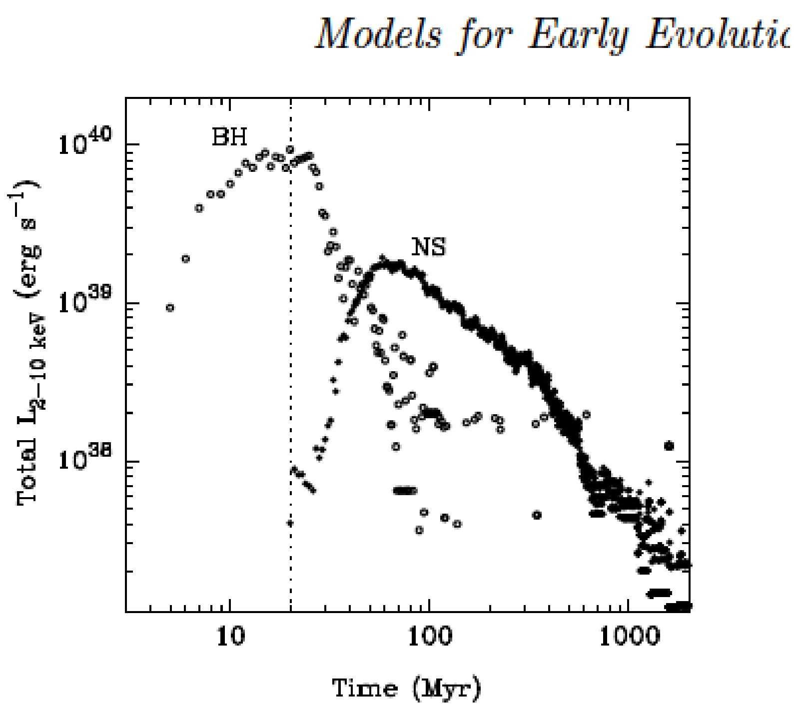


Fig. 1 (online colour at: www.an-journal.org) Logarithmically-scaled, three-color XMM-

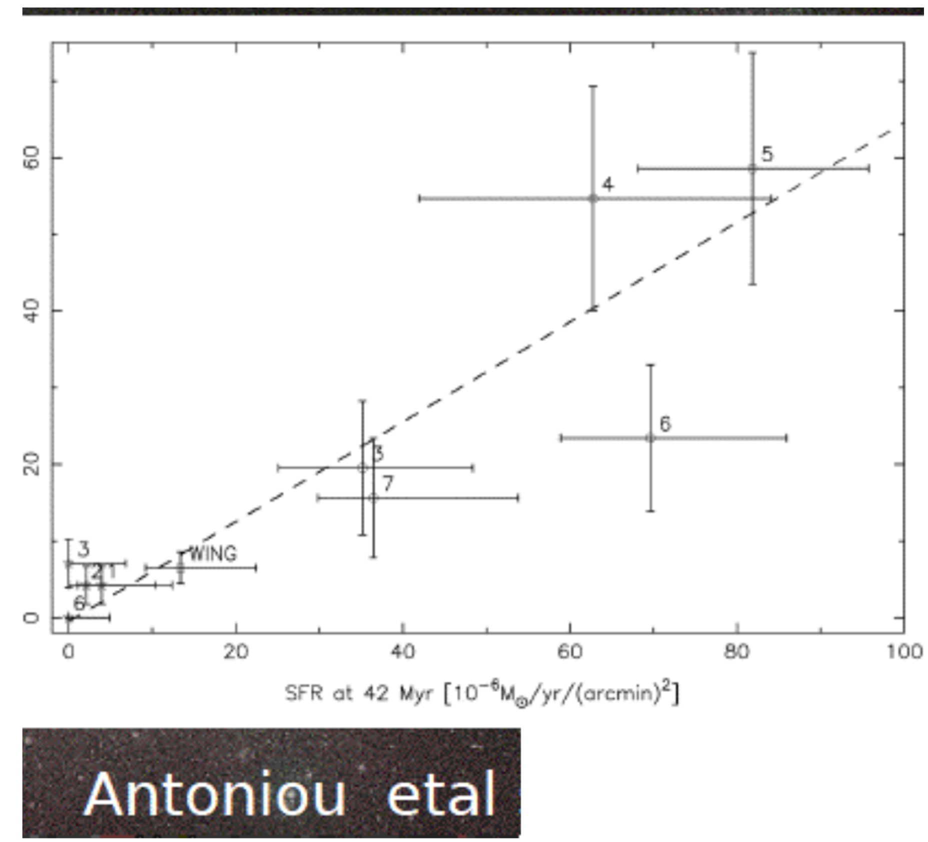
Relation to Star Formation

- Since HMXB are young stars the relative number of them should be related to amount of star formation in the galaxy!
- Another way of measuring star formation rate



Star formation rate

HMXB rate



Example of a theoretical model of the luminosity in x-ray binaries in a star forming galaxy Eracleous et al 2009