Neutron Stars

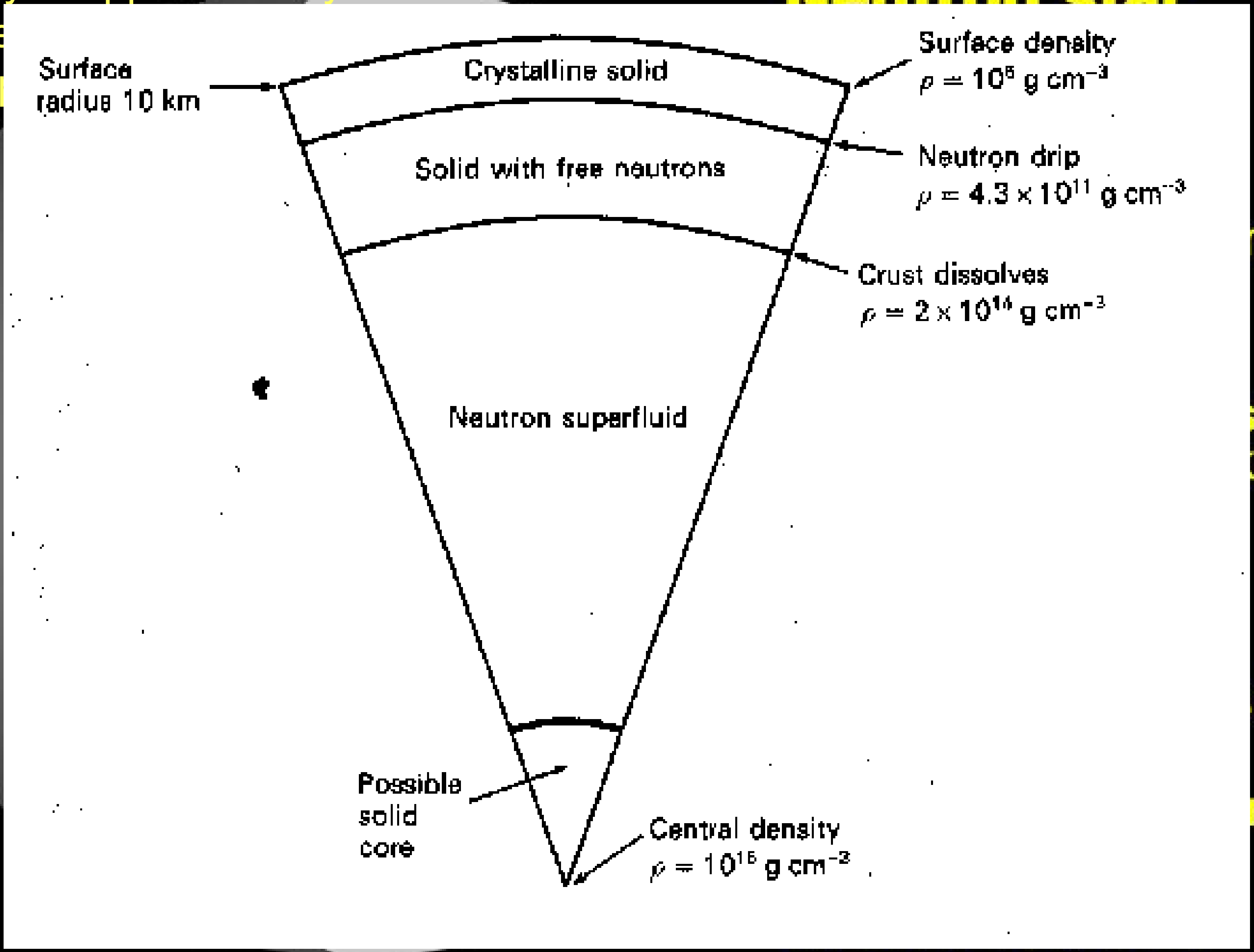
Accreting Compact Objects-

see Chapters 5 and 6 in Rosswog and Bruggen

Inside Neutron Stars

This density is approximately
equivale
human
the size

Neutron star



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 $7\text{x}10^{12}\text{m/sec}^2$-$10^{11}$x that of the earth

(U. Hwang 2007)

Courtesy of C. Reynolds

- Remember White Dwarfs…

- Where…

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

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

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)…

- Where…

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

  - 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

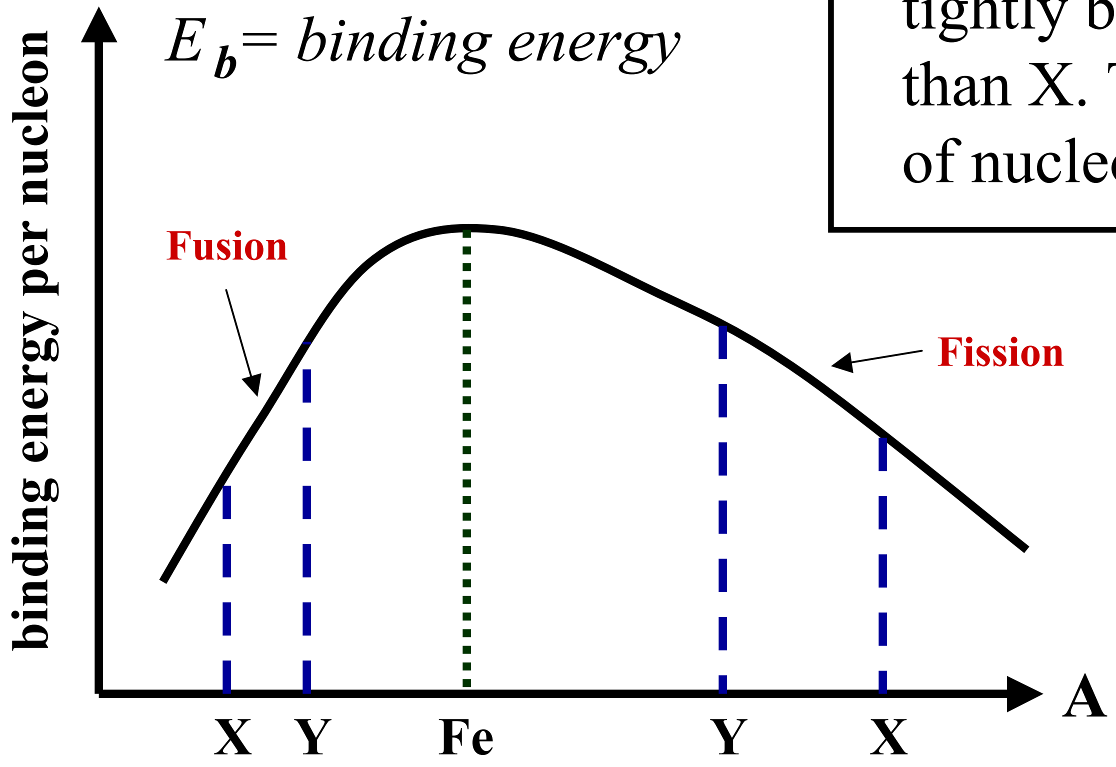
Binding energy of Nuclei - why stellar burning stops generating energy

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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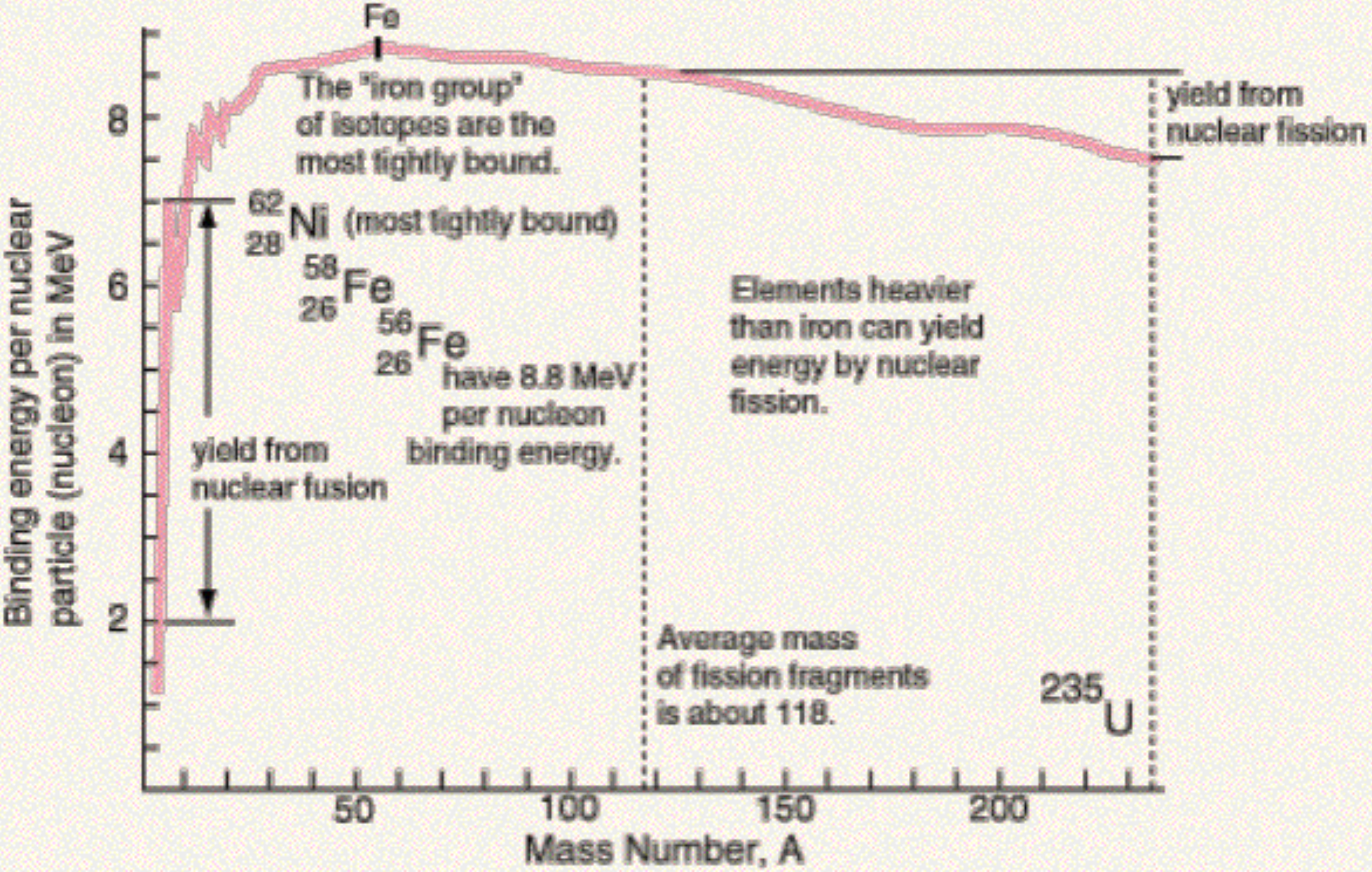
Fission and fusion can yield energy

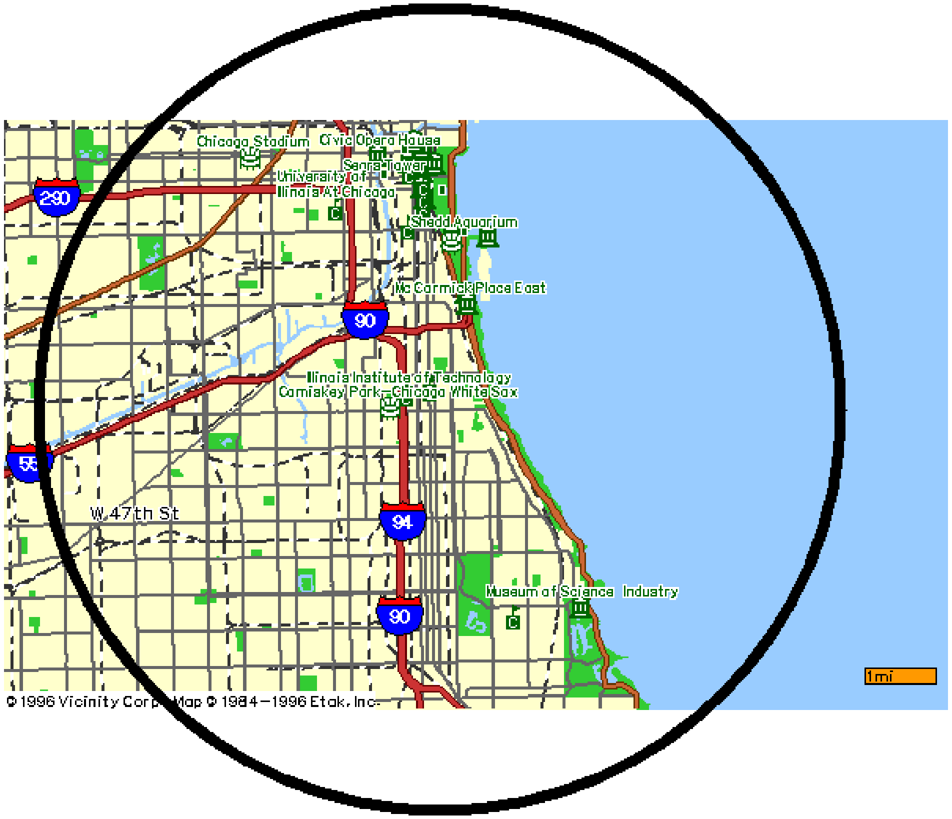
hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html



- 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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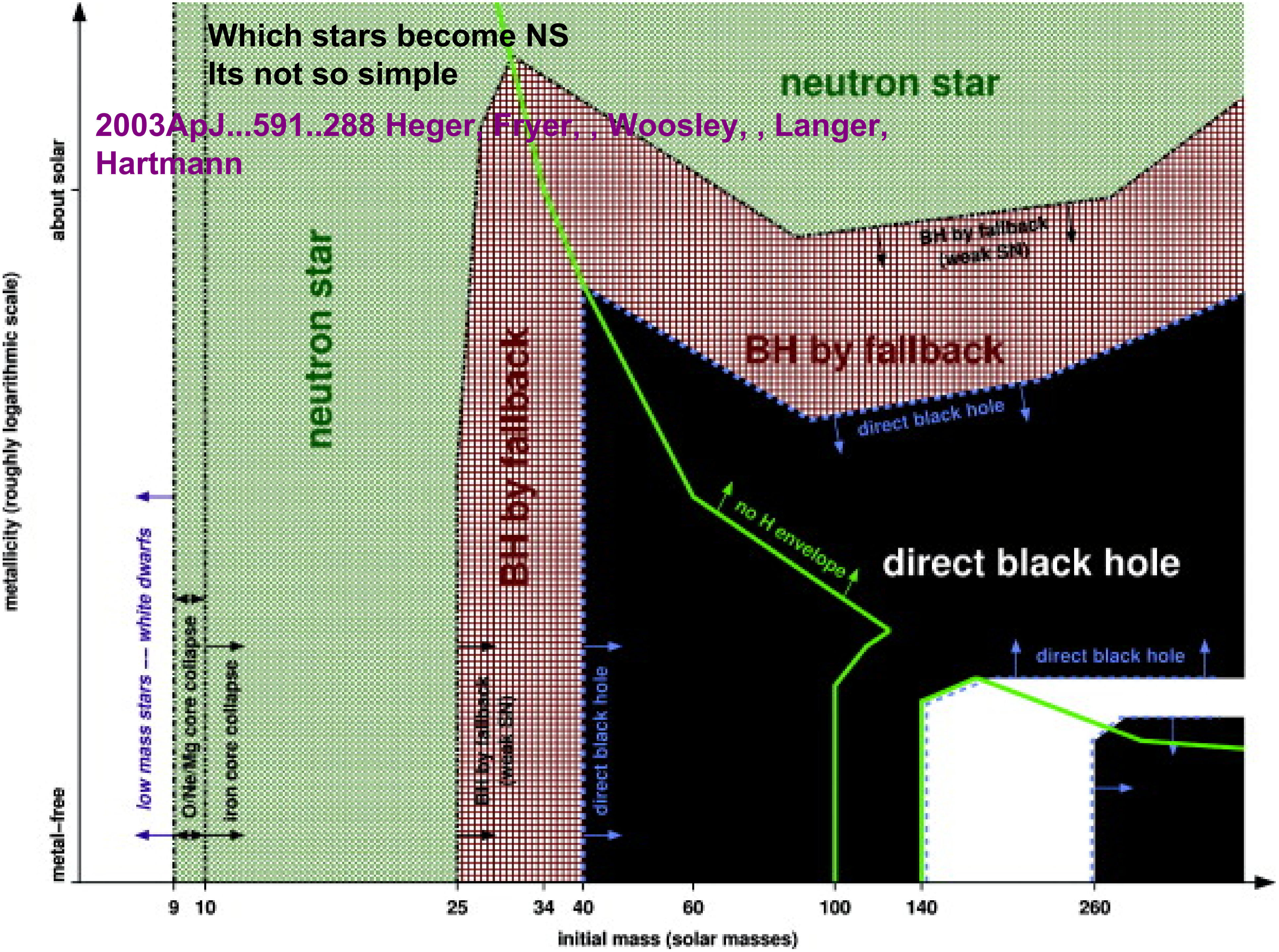
- Stars with a defined mass range evolve to produce cores that can collapse to form Neutron Stars
- Following nuclear fuel exhaustion, core collapses gravitationally; this final collapse supplies the supernova energy
- Collapse to nuclear density, in ≈ few seconds, is followed by a rebound in which the 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

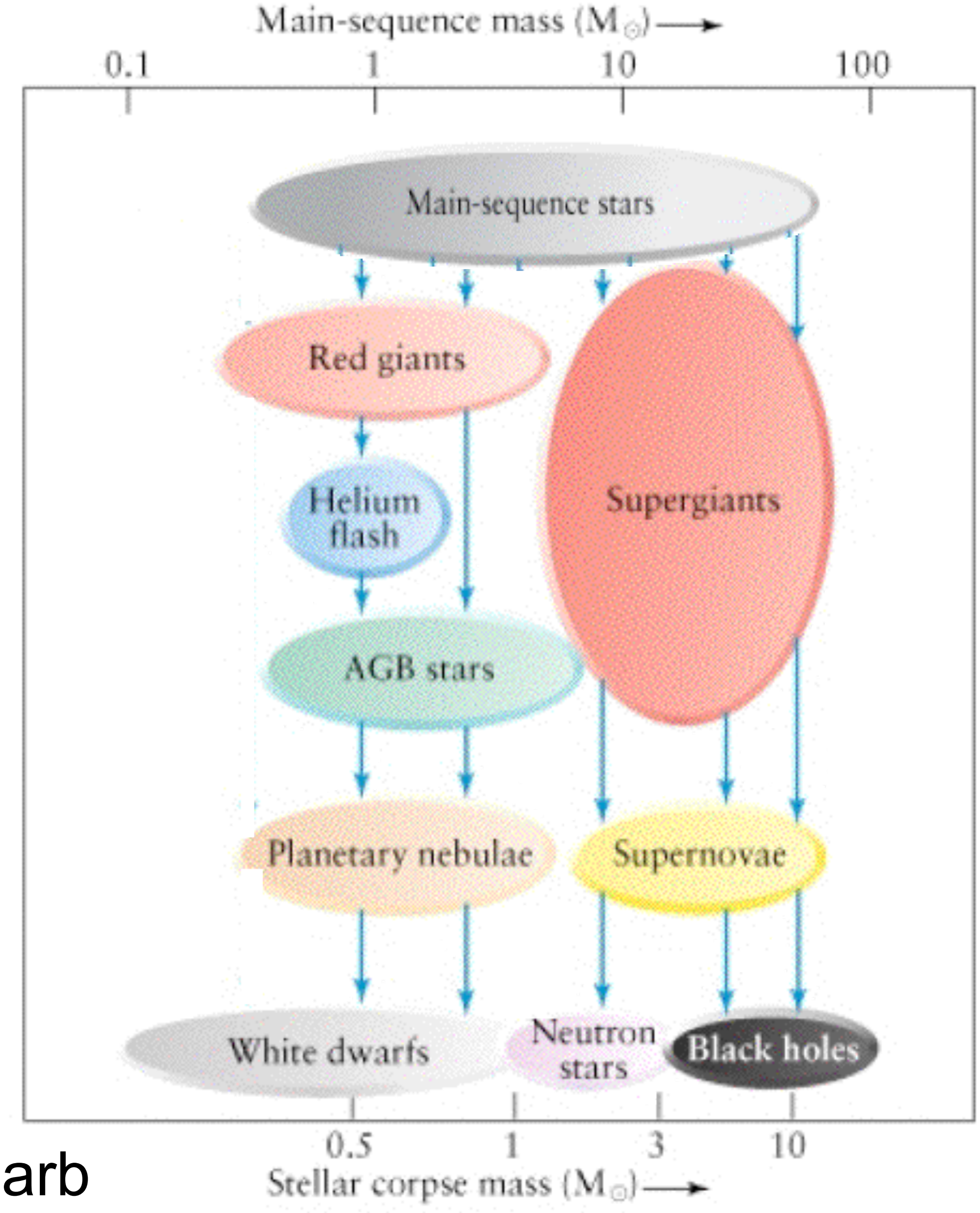
2003ApJ...591..288 Heger, Fryer, , Woosley, , Langer, Hartmann



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)

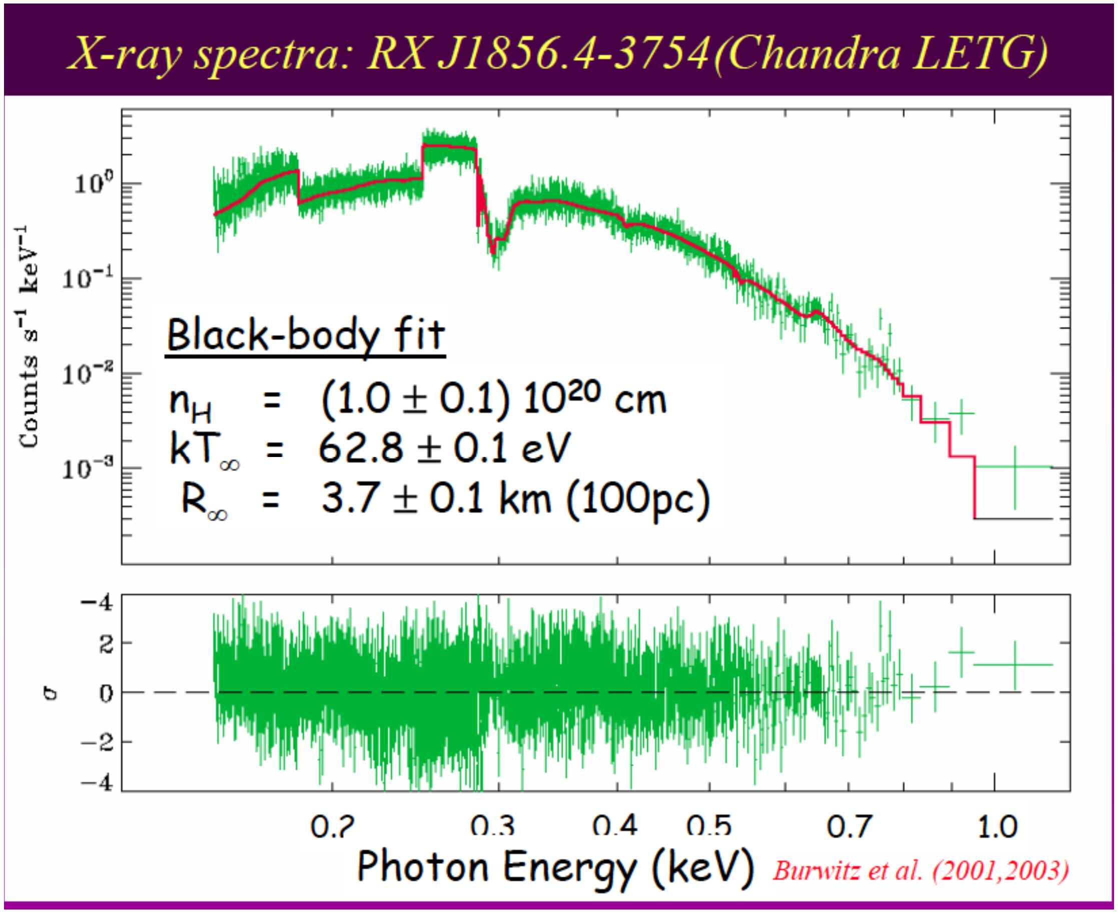


Samar Safi-Harb

Isolated Neutron Stars- Non Accreting

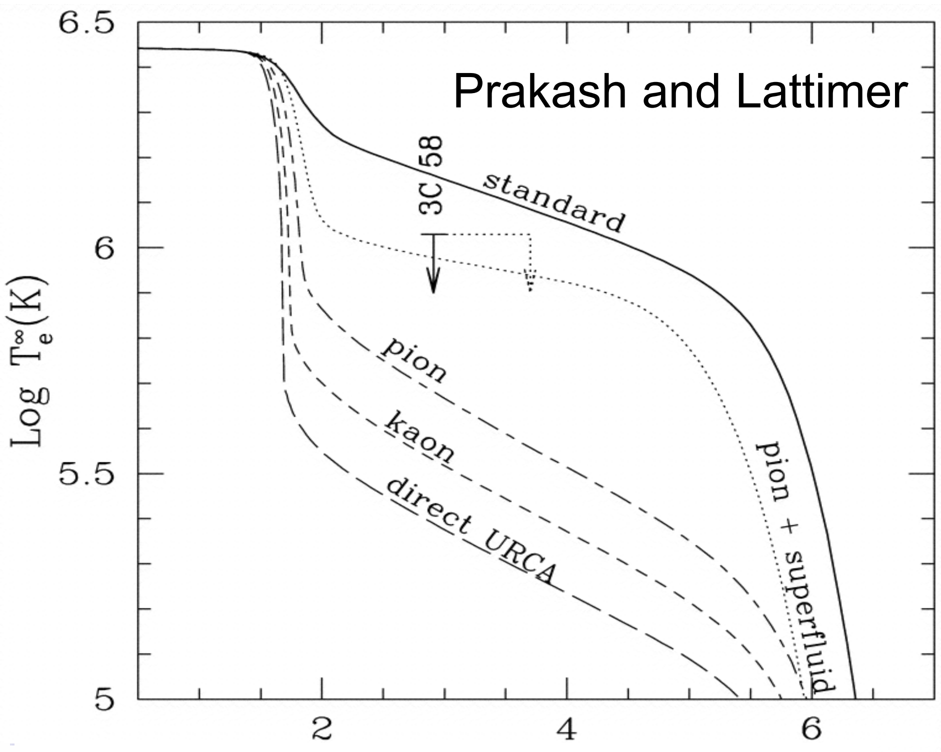
- These objects are cooling from the initial high temperature of the supernova explosion

- Recent results show that they have an almost pure black body spectrum- which is unexpected



Burwitz et al 2001

Neutron Star Continuum Spectroscopy and Cooling

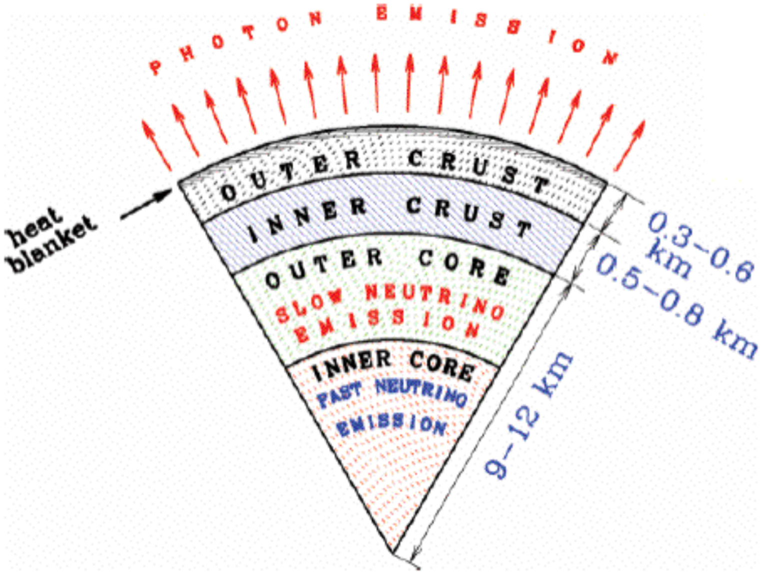


Main cooling regulators:

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

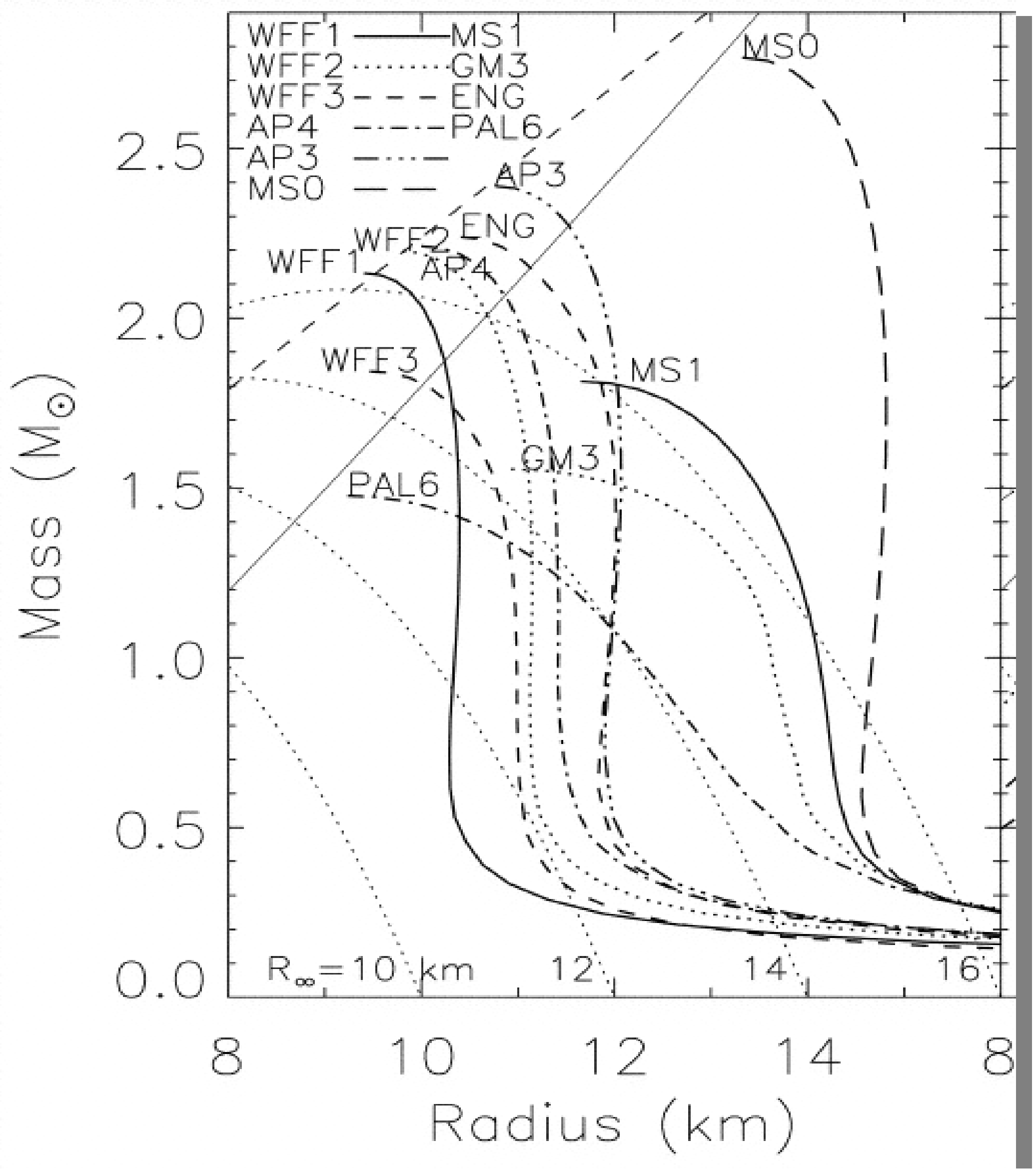
- After Neutron star is created in a supernova, if it is isolated it cools
- The rate at which it cools depends on the conductivity and heat capacity which depends on what it is made of and physics we do not truly understand.

(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)

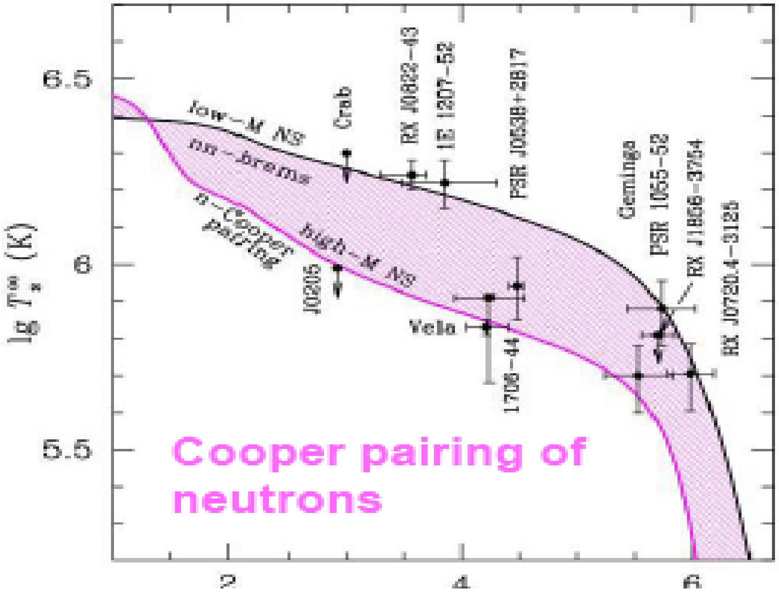


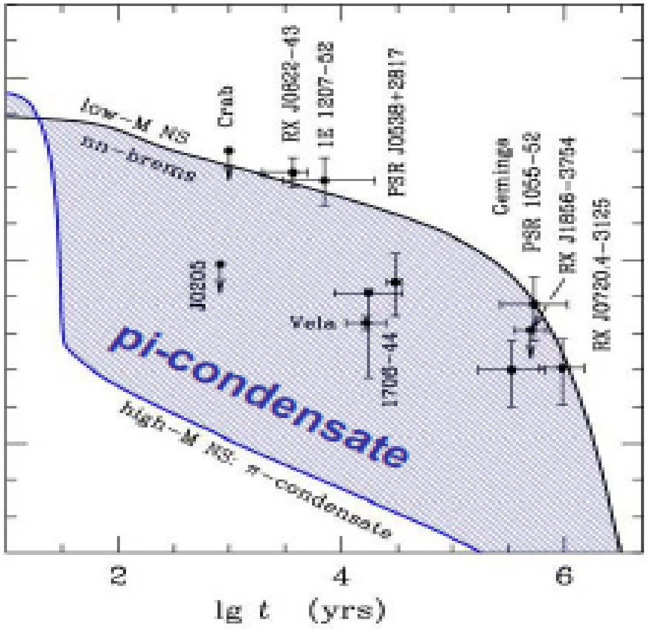
$$dP/dr = -\rho\, G\, M(r) / r^2$$

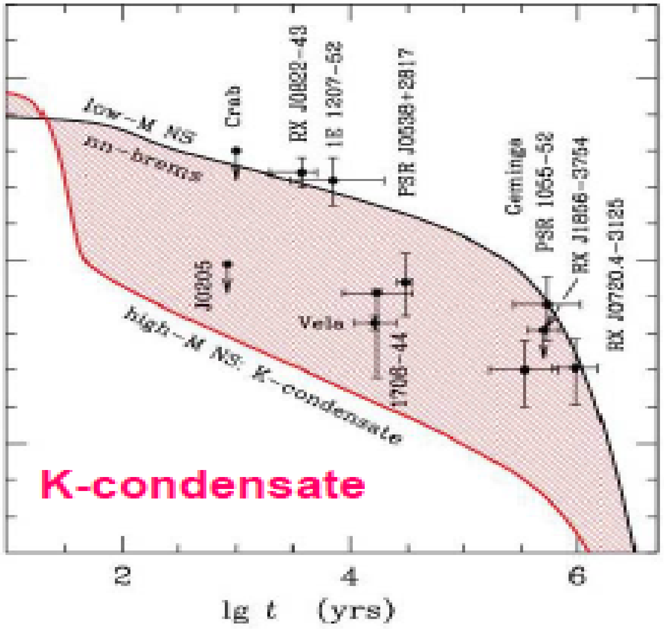
- High mass limit sets highest possible density achievable in neutron stars (thus, in nature, “the MOST dense”).
- Radius is prop. to $P^{1/4}$ at nuclear saturation density. Directly related to symmetry energy of nuclear interaction
- Other issues: have to use general relativistic eq for hydrostatic 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

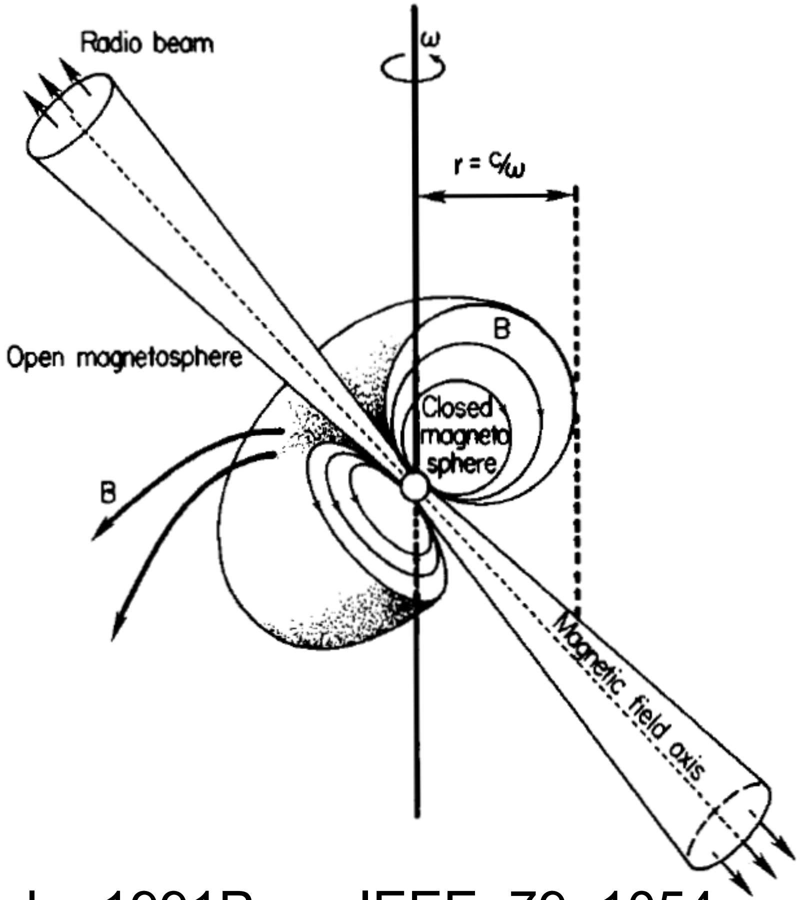






Isolated Neutron Stars

- Most isolated neutron stars that are known are radio and γ-ray pulsars -
- These are rapidly spinning neutron stars that emit relativisitic particles that radiate in a strong magnetic field
- Energy loss goes as $\Omega^4 B^2$
- As they radiate the star spins down- they live for ~10^7 yrs



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

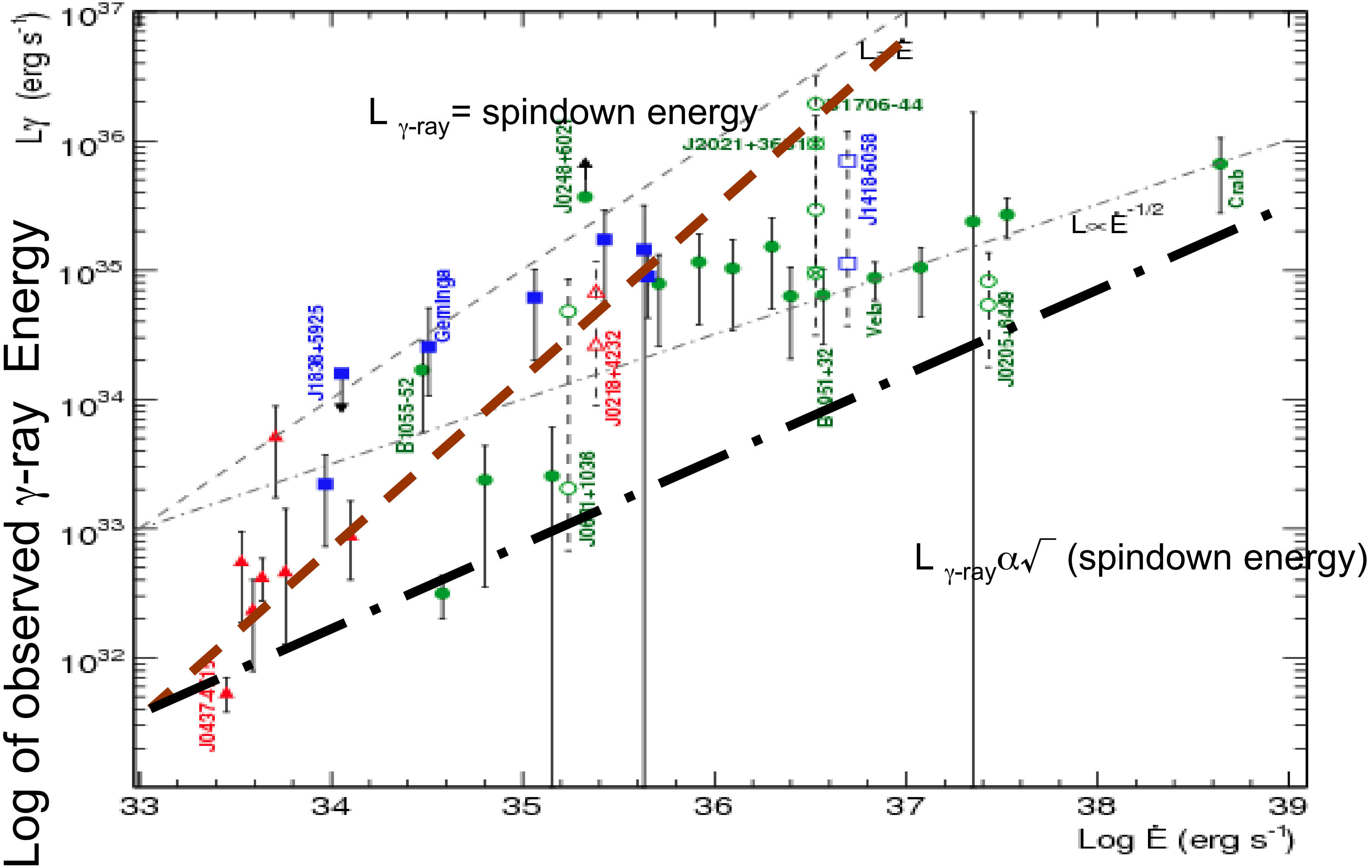
- The shortest period (or angular velocity Ω) which a star of mass M and radius R can have without being torn apart by centrifugal forces is (approximately)
- $\Omega^2 R \sim GM/R^2$
- Putting in the average density of the star ρ,
- $\Omega \sim (G\rho)^{1/2}$

- 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 $E_{rot} = 1/2\ I\Omega^2 \sim 2x10^{46} I_{45} P^{-2}$ 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 $E_{rot} \sim I\Omega(d\Omega/dt) + 1/2(dI/dt)\Omega^2 \sim 4x10^{32} I_{45} P^{-3} dP/dt$ 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



$L_{\gamma\text{-ray}}$= spindown energy

$L_{\gamma\text{-ray}} \alpha \sqrt{\ }$ (spindown energy)

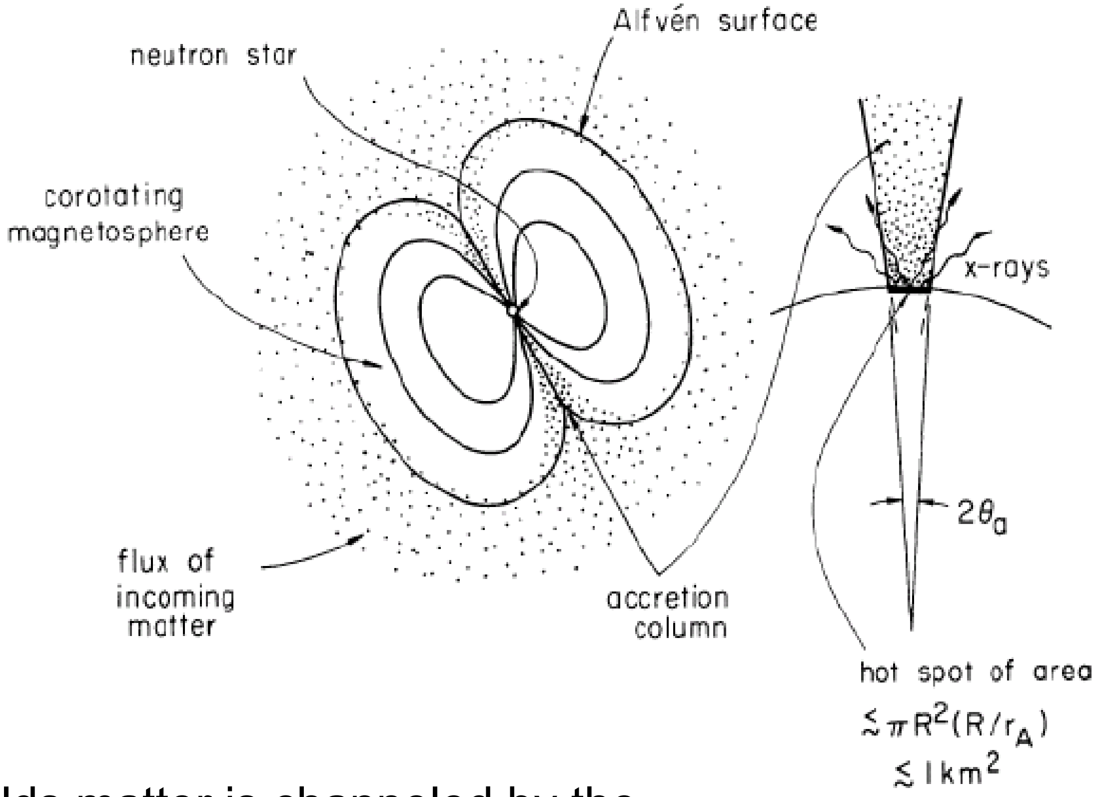
Log of observed γ-ray Energy

Log of Spin Down Energy (ergs/sec)

Caraveo 2010

Accreting Neutron Stars

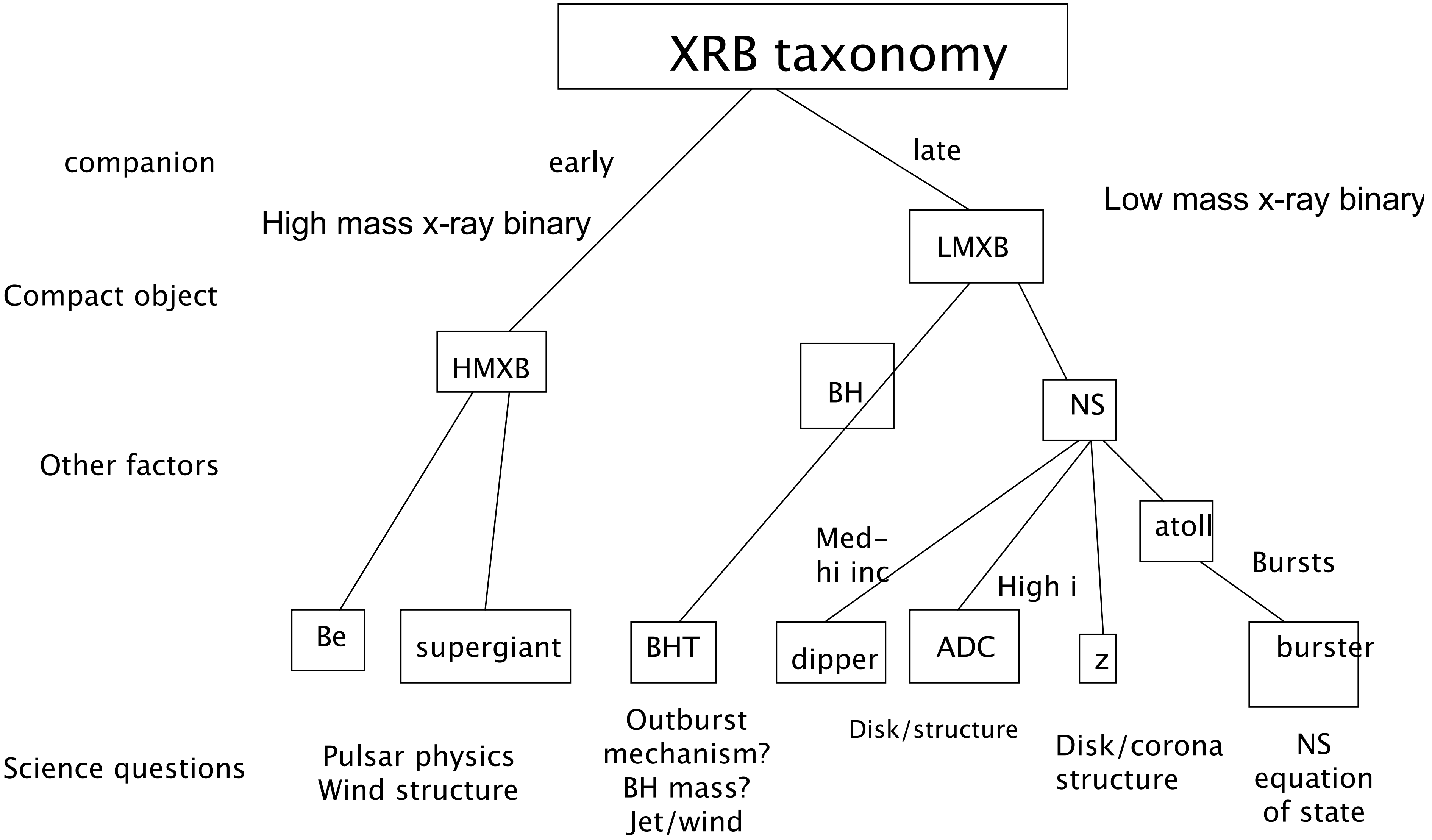
- These are the brightest x-ray sources in the sky and were the first x-ray sources discovered
- They have a wide range of properties (spectral and temporal) and show an almost bewildering array of behaviors
- Their luminosities range over 6 orders of magnitude



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

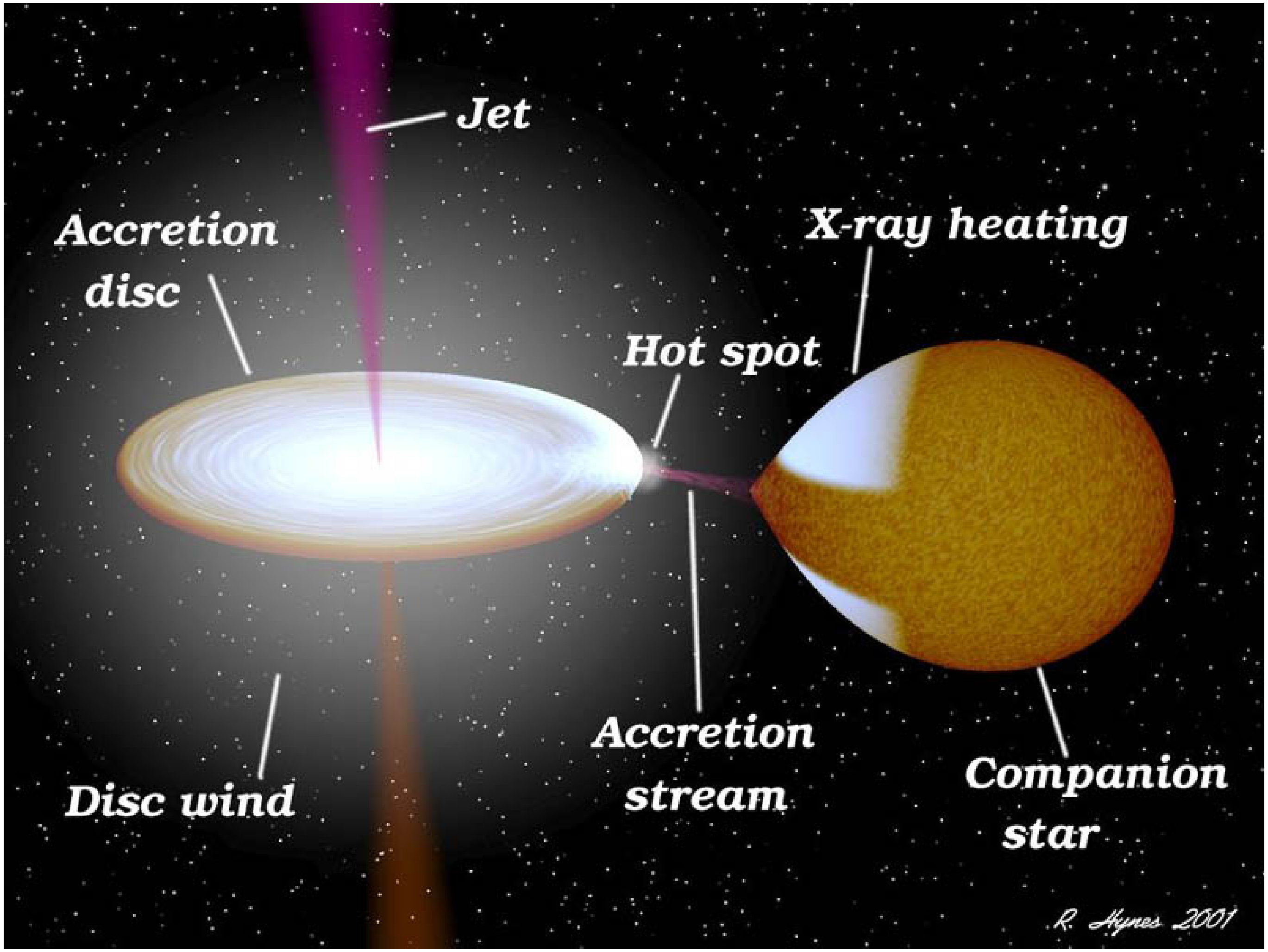
A Short Introduction to terminology



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

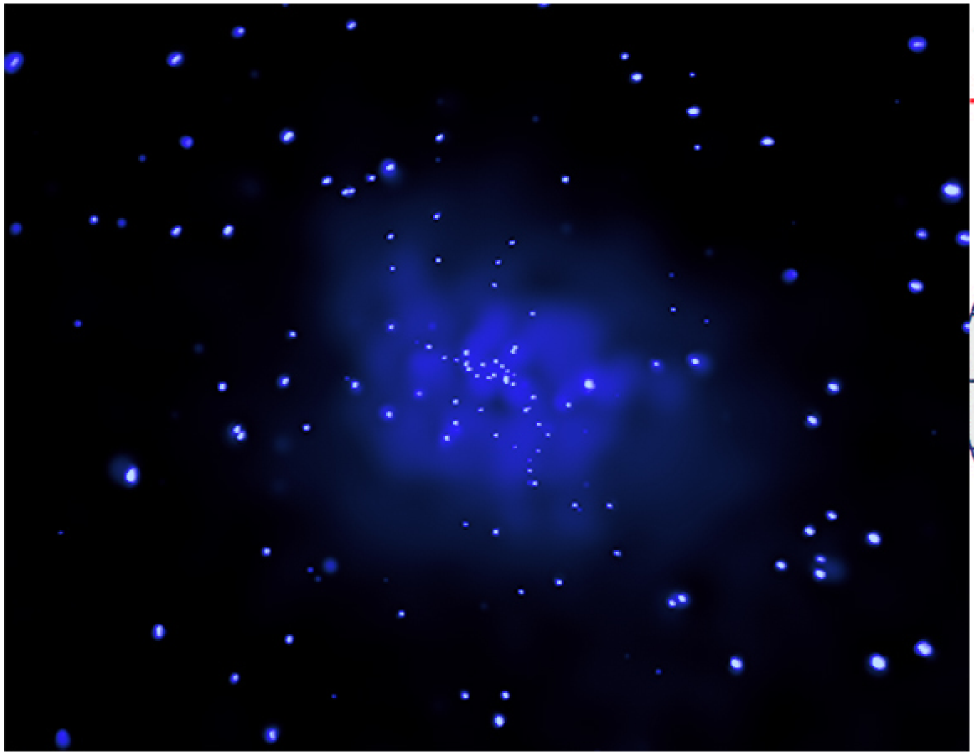
- Two types- based on mass of companions
  - Low mass x-ray binaries-NS star tends to have low magnetic field- - are 'old' (~10^{9-10} yrs) -BHs are transient
  - High mass-NS tends to have high magnetic field- - are are 'young' (~10^{7-8} yrs)-BHs on all the time

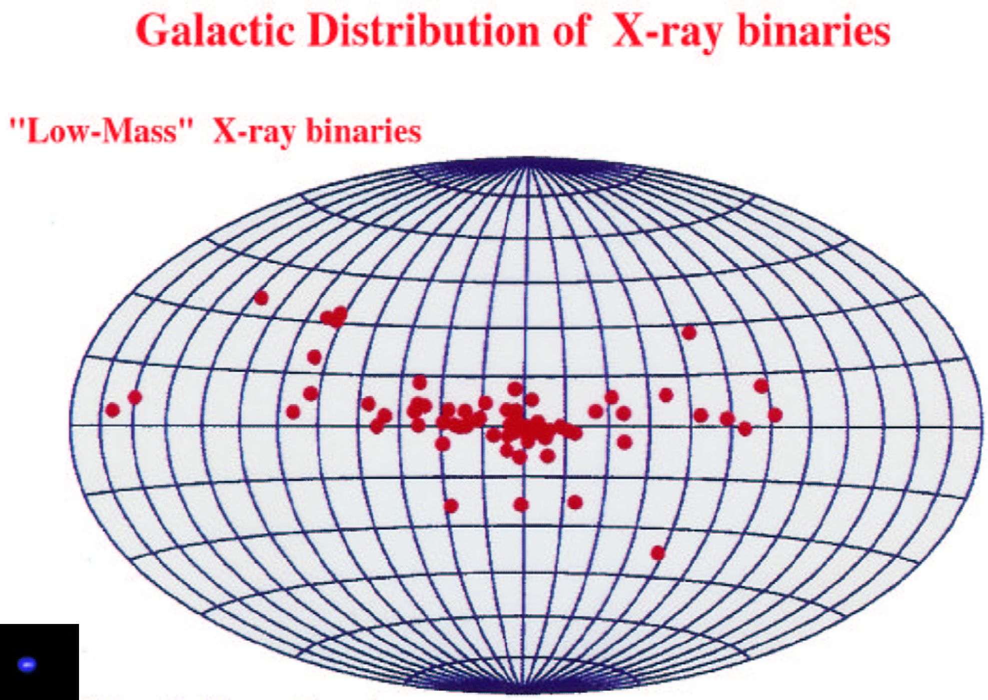
	HMXB	LMXB
Donor star	O-B ($M>5M_{sun}$)	K-M ($M<1M_{sun}$)
Age/Population	10^7 yrs I	5-15x10^9 II
L_x/L_{opt}	0.001-10	10-1000
X-ray Spectrum	flat power law	kT<10keV
Orbital period	1-100d	10min-10d
X-ray eclipses	common	rare
Magnetic field	strong (~10^{12}G)	weaker (10^7-10^8 G)
X-ray pulsations	common (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

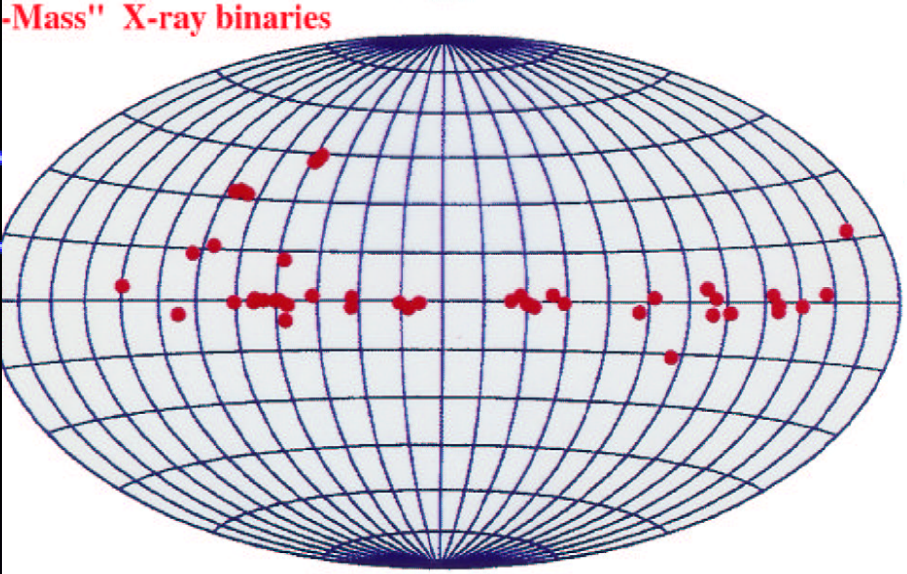
(drawn from M. Porzio)

Space Distribution of X-ray Binaries

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

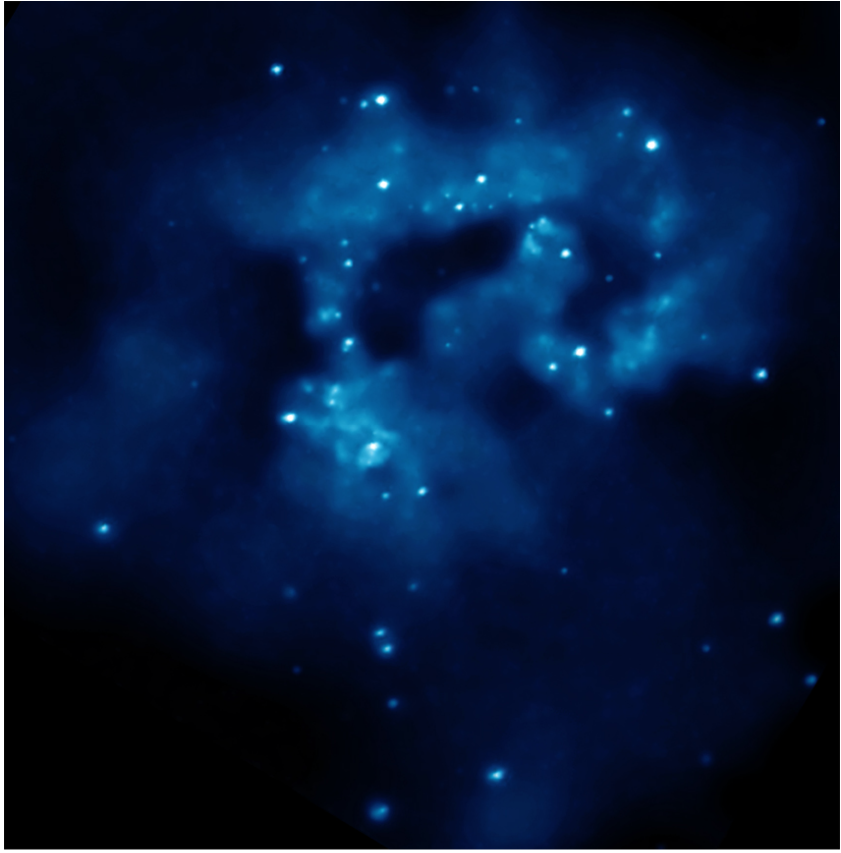






M31 and the Antenna

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



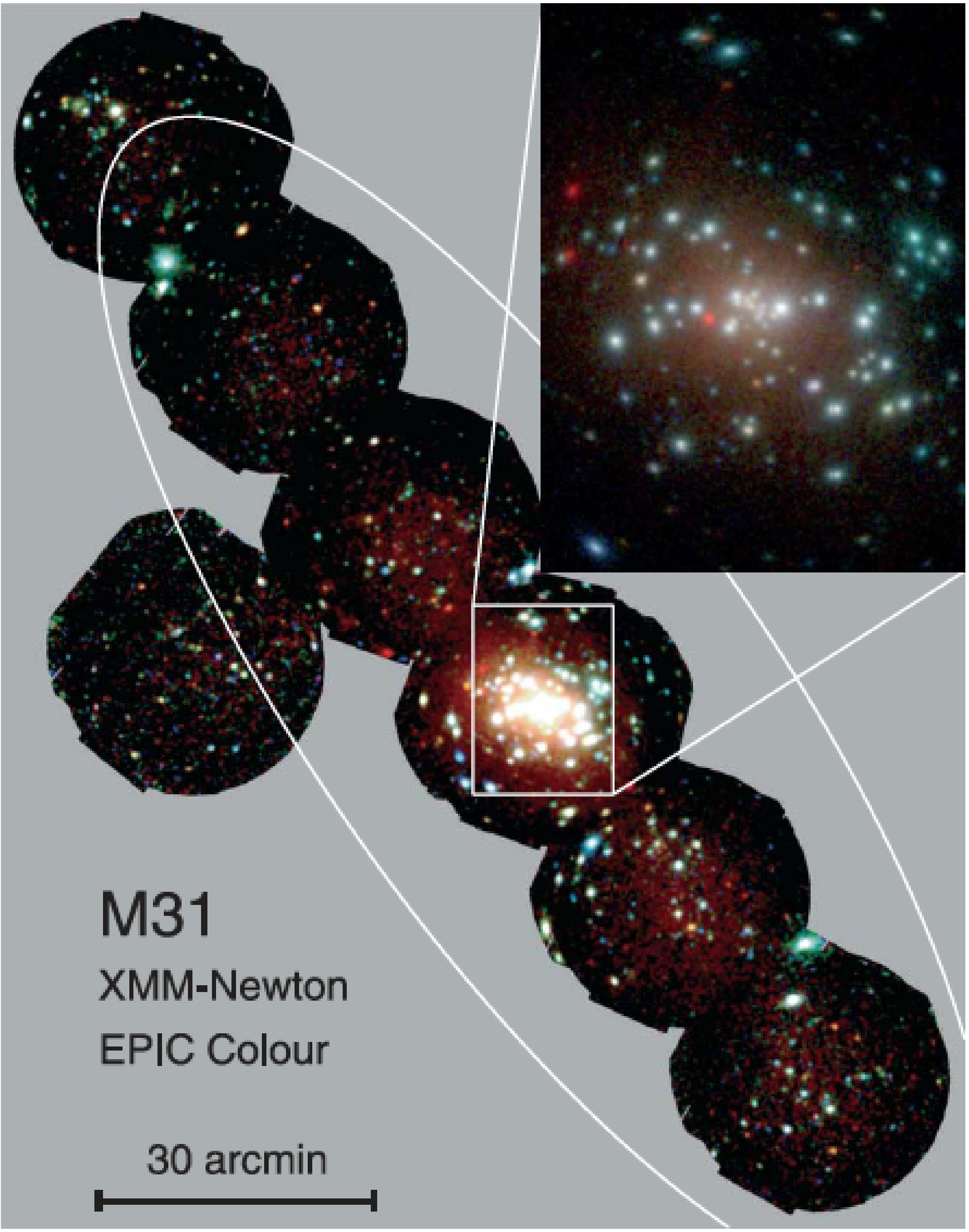
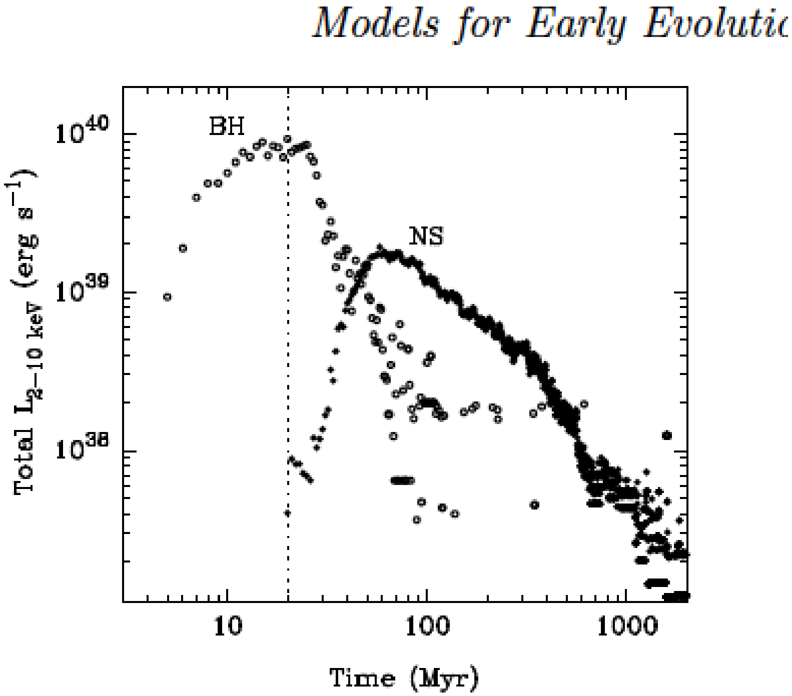
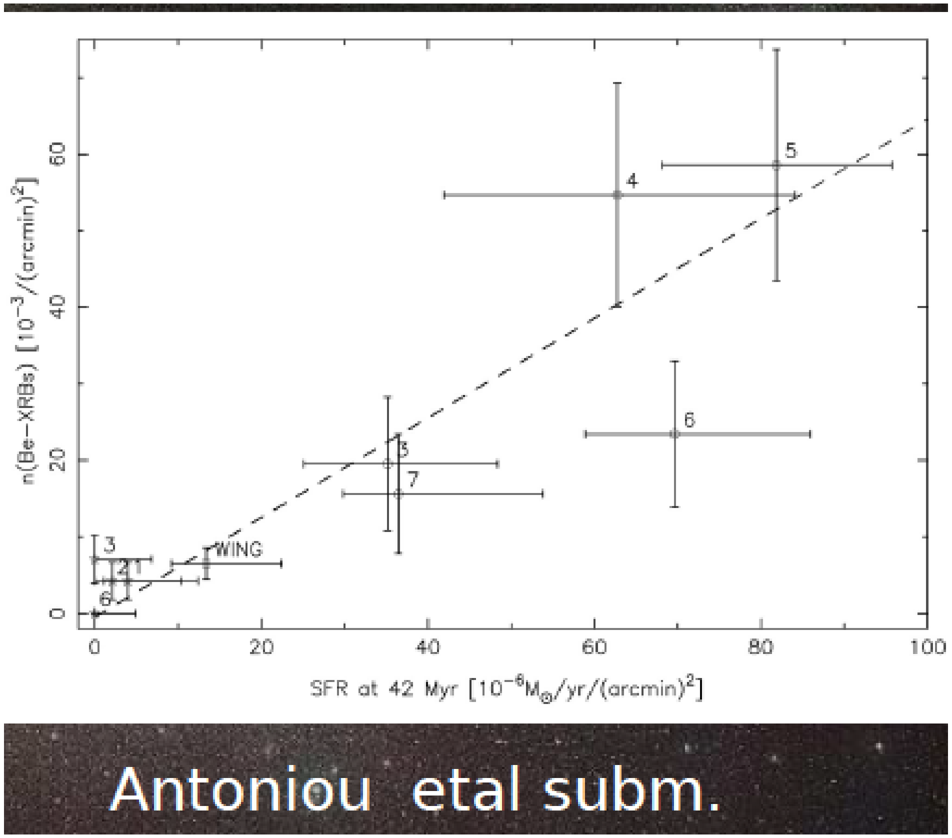


Fig. 1 (online colour at: www.an-journal.org) Logarithmically-scaled, three-color XMM-

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





Antoniou etal subm.

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