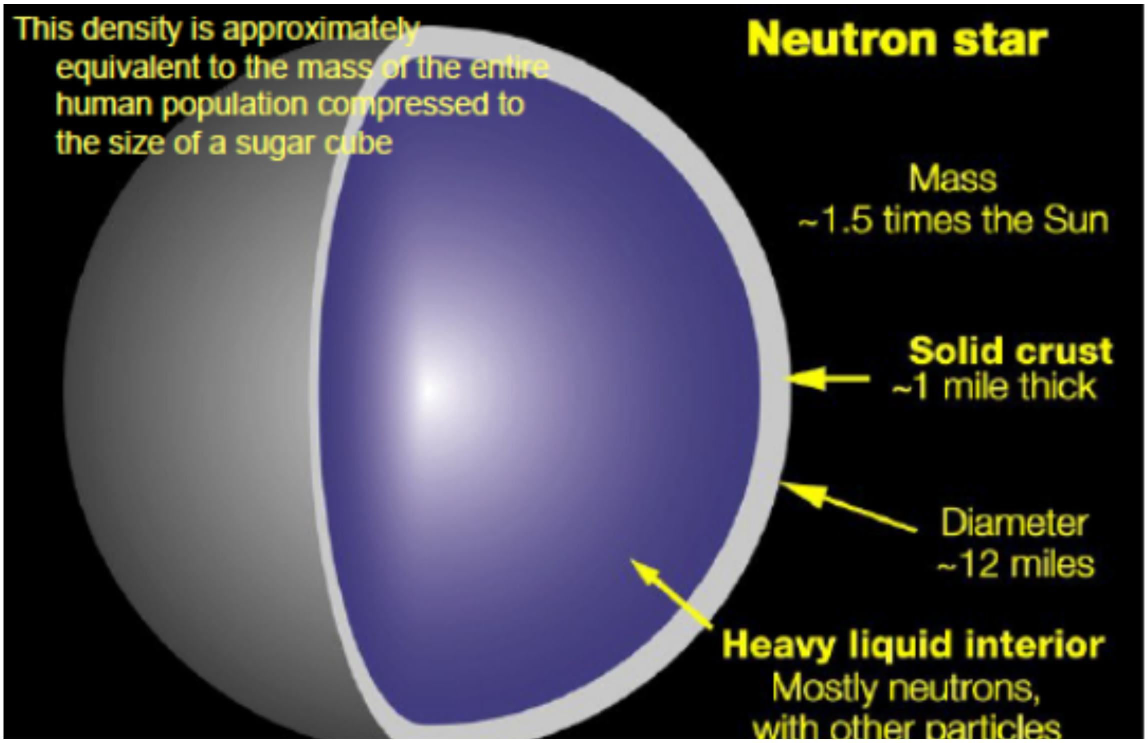
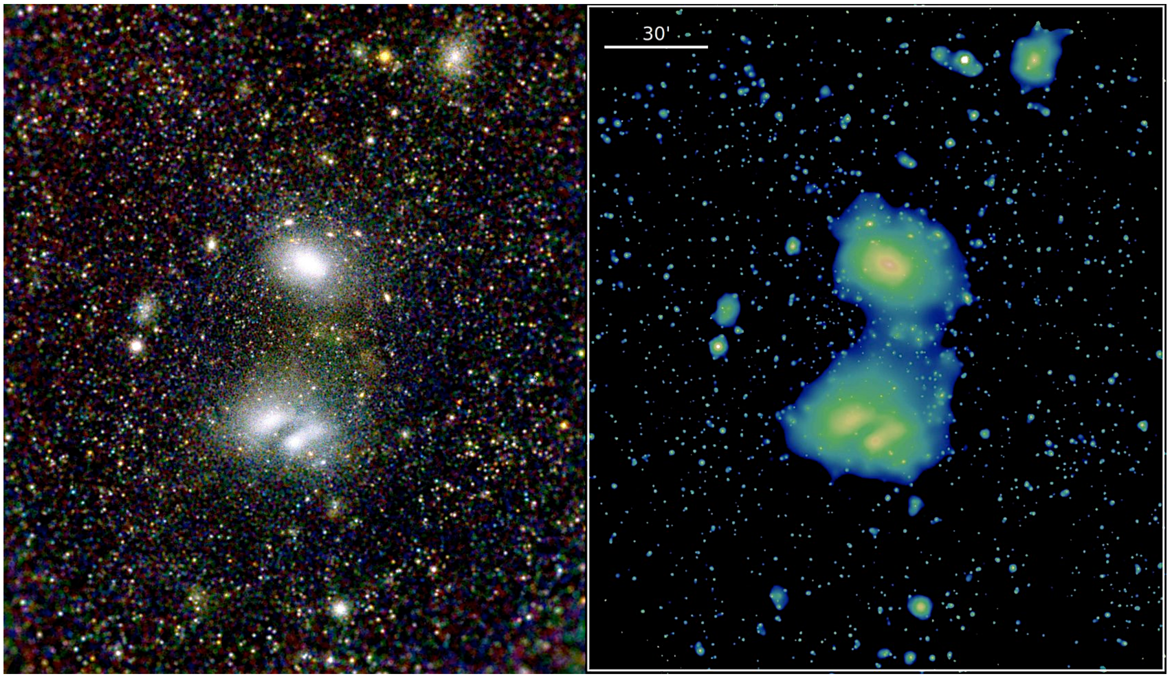
Inside Neutron Stars



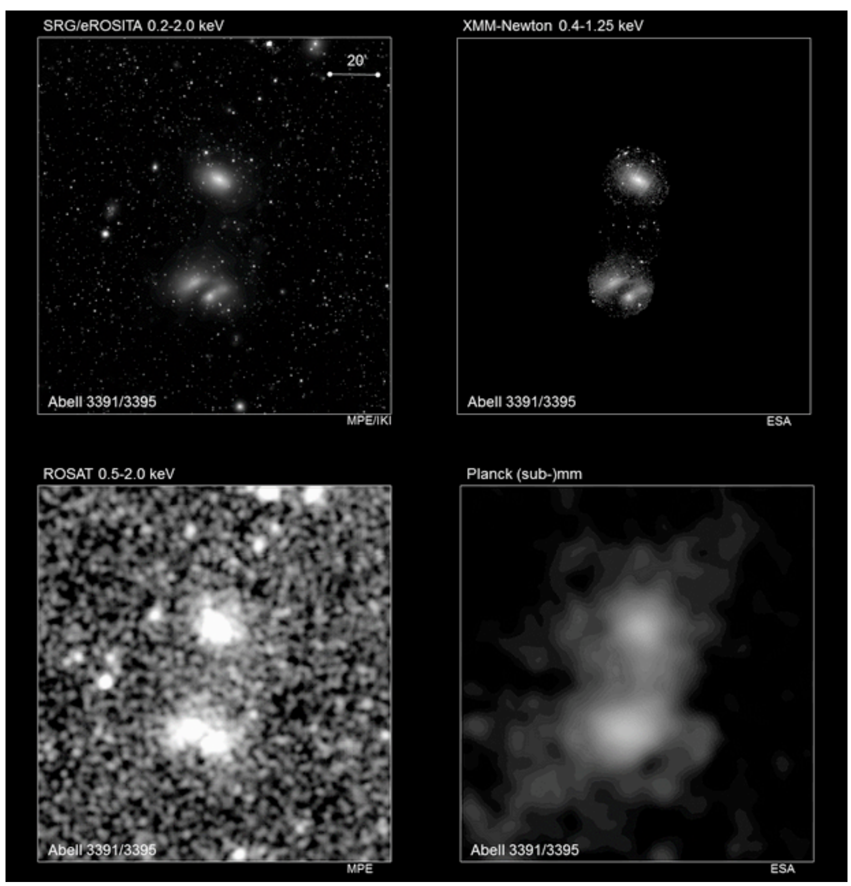
- **eRosita** first Light : Galaxy clusters A3391 and A3395

eRosita first Light : Galaxy clusters A3391 and A3395

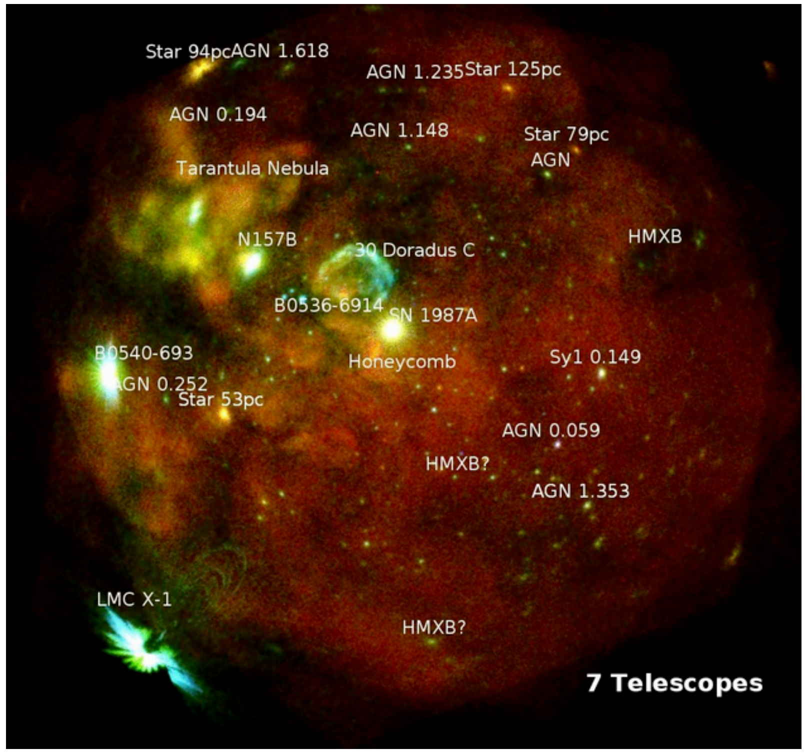


optical x-rays eRosita

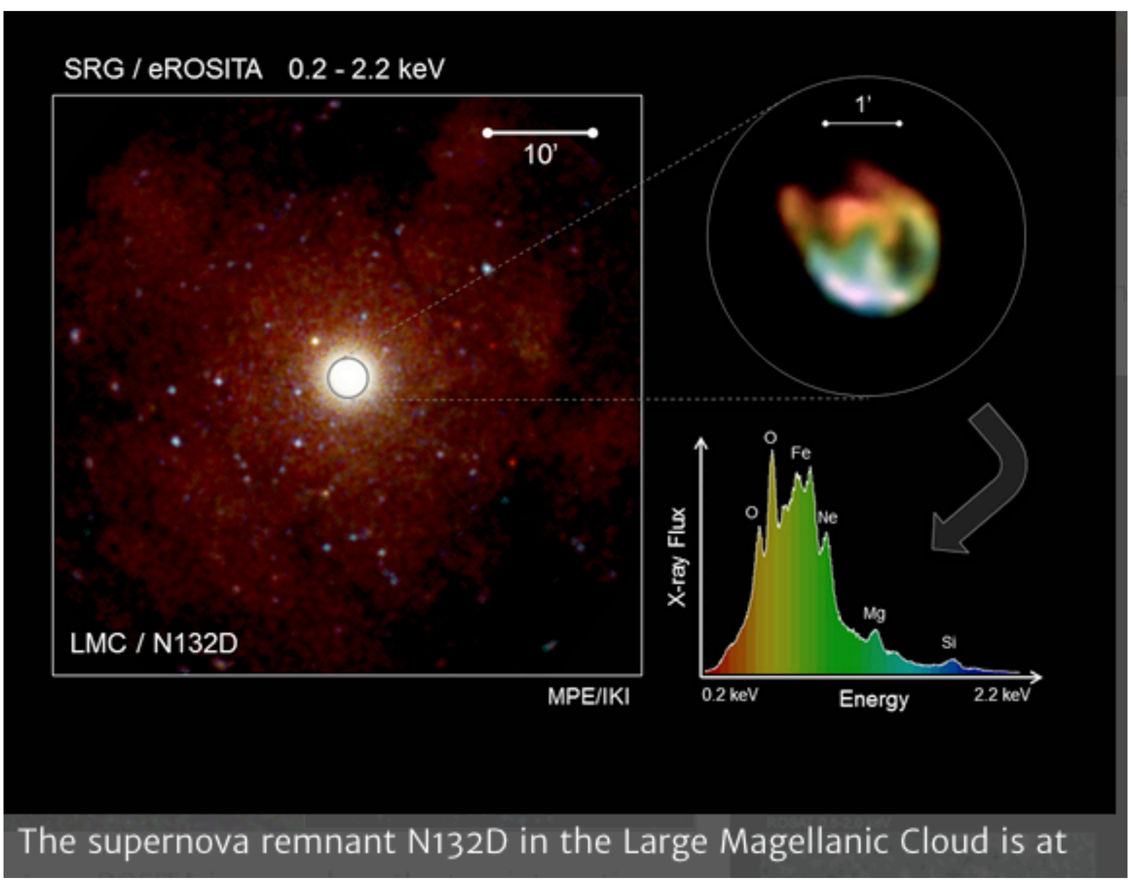
- eRosita Comparison to XMM,Rosat and Planck (S-Z)



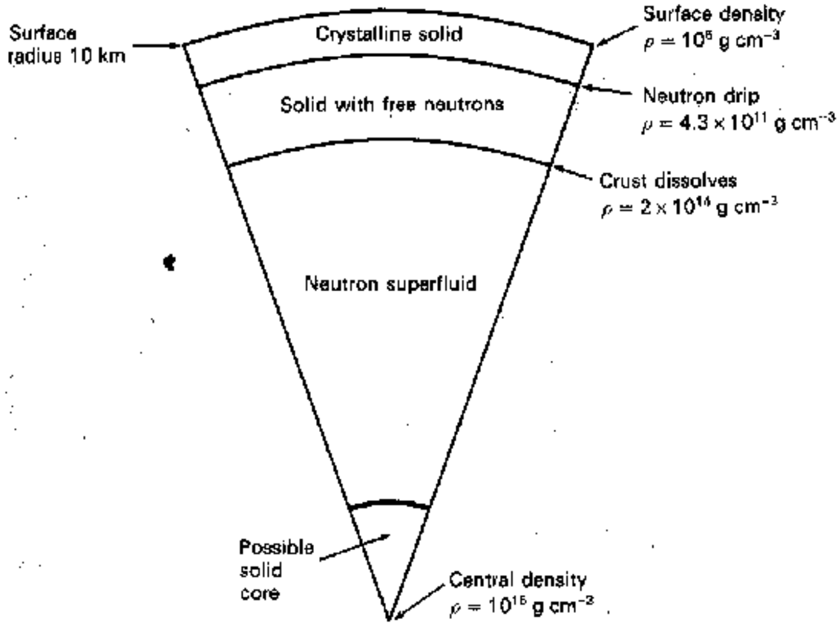
LMC from
eRosita



http://www.mpe.mpg.de/7362694/presskit-erosita-firstlight



Inside a Neutron Star



Mid-term

- Grade distribution (out of 80)

>72- A

69-72 B+

60-69 B

53-59 B-

45-52 C

Class average 65- B

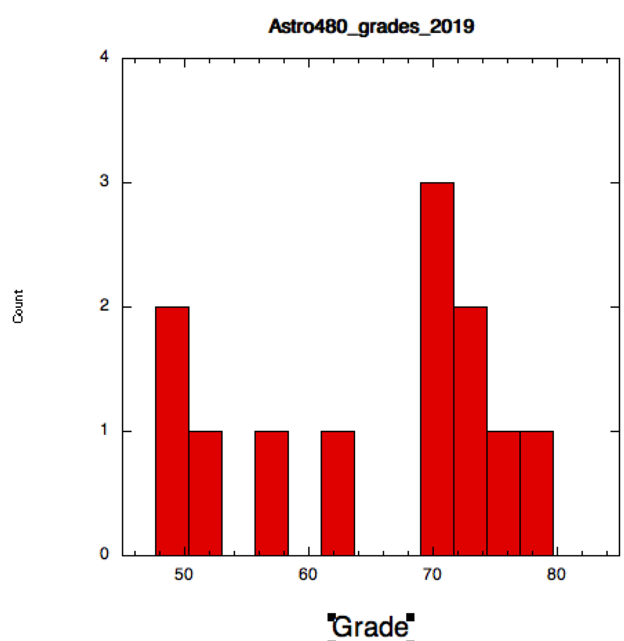
4 A's

3 B+

1 B

1 B-

3 C



Neutron Stars-Repeat from Last Time

- 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)

$\omega=1/\mathrm{sqrt}(GM/r^3) =1/\mathrm{sqrt}(G\rho)$

Shortest periods ~1.5ms- light travel time arguments give a size (ct~ 500km)

White dwarfs with $\rho \sim 10^7$–10^8 gmcm^{-3} maximum rotation periods

$P = 2\pi/\Omega \sim 1$–10 s

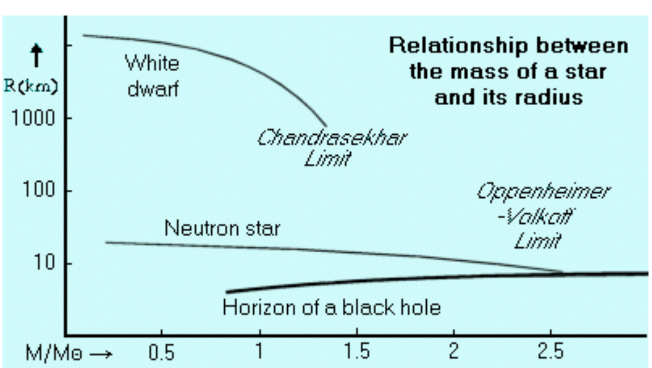
- To get periods of ~1ms (radio pulsars) need $\rho \sim 10^{14}$ gmcm^{-3}
- What are the sources of energy?
  - Spin down
  - accretion

Mass of NS

- There is an upper limit to the mass of a neutron-degenerate object, theTolman–Oppenheimer–Volkoff limit, combination of GR +QM

analogous to the Chandrasekhar limit for electron-degenerate objects. The limit for objects supported by ideal neutron degeneracy pressure is only 0.75 solar masses.

For more realistic models including baryon interactions, the precise limit is unknown, as it depends on the equations of state of nuclear matter, for which a highly accurate model is not yet available.



Assuming GR the only input required to solve the TOV equations is the equation of state of cold, neutron-rich matter in chemical equilibrium.

David Darling

Creation of Neutron Stars

- Stellar core collapses under the force of its own gravity. 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 $7\mathrm{x}10^{12}\mathrm{m/sec}^2$ -10^{11}x that of the earth

(U. Hwang 2007)

Radius of NS

- Use the 'known' density of nuclear matter

($\rho_{Neutron}$~$1.2\mathrm{x}10^{14}\mathrm{g/cm}^3$) and

the Chandrasekar mass

gives a radius

- R_{NS}~$(3M_{Chandra}/4\pi\rho_{Neutron})^{1/3}$ ~10km

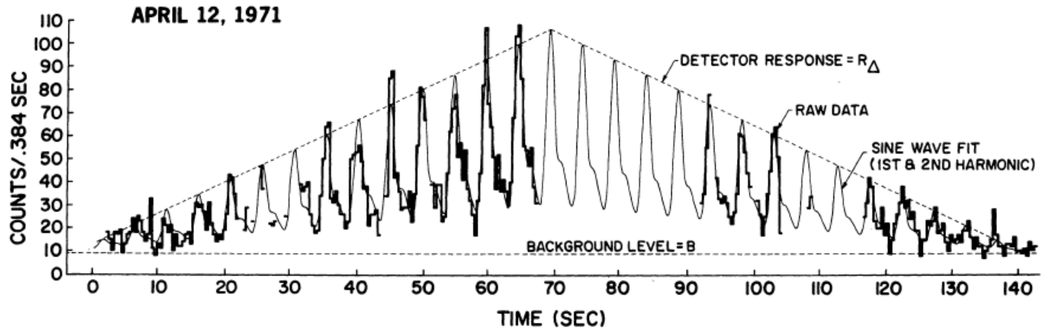
consistency between the observed spin periods,

and neutron stars

Cen X-3

Schreier et al 1971

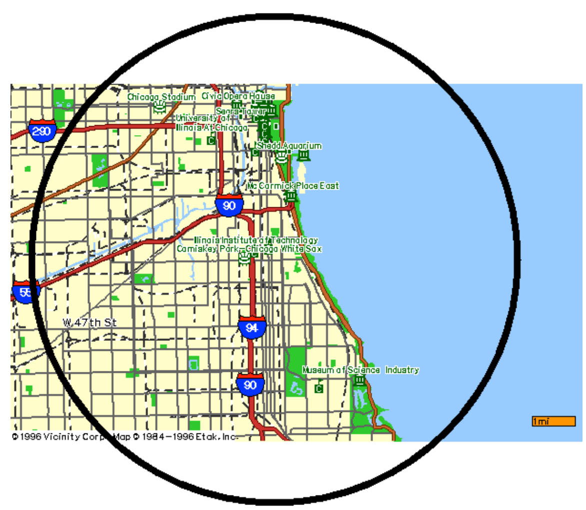
1971ApJ...167L..67G



- 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

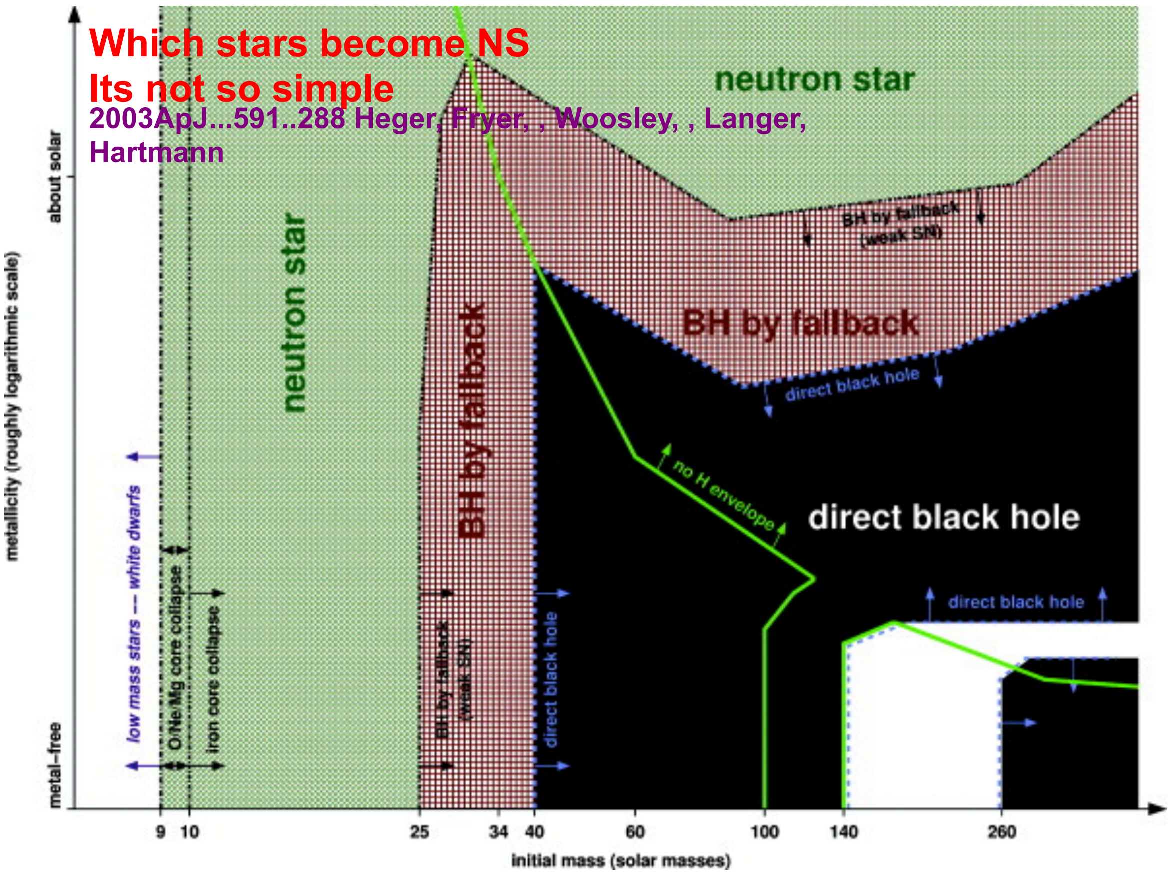
Neutron star vs. Chicago



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

Which stars become NS
Its not so simple

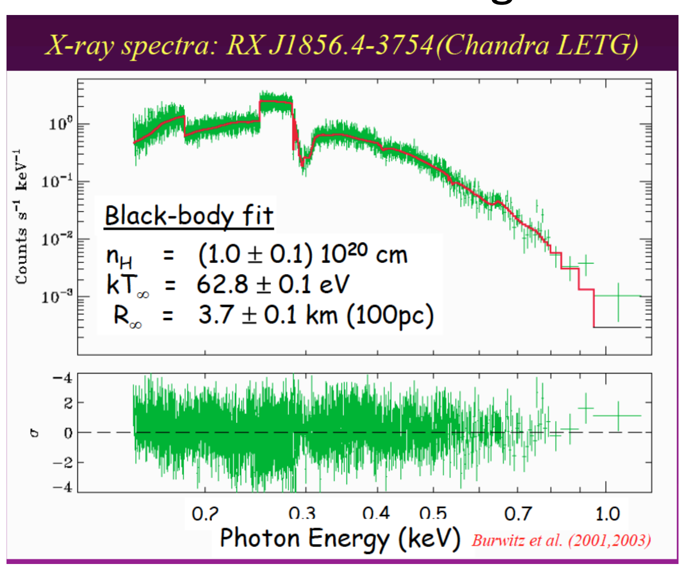
2003ApJ...591..288 Heger, Fryer, , Woosley, , Langer, Hartmann



Isolated Neutron Stars- Non Accreting

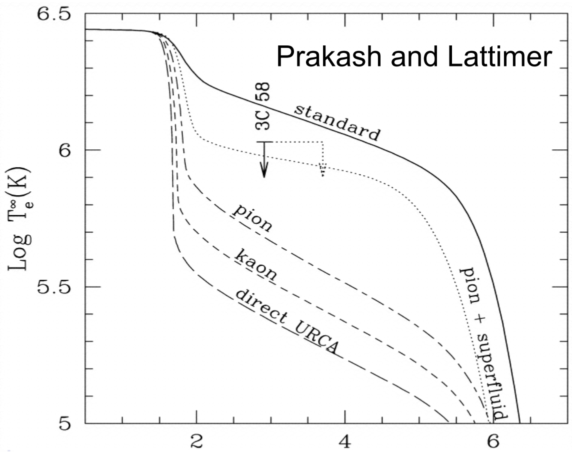
- These objects are cooling from the initial high temperature of the supernova explosion

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



Burwitz et al 2001

Neutron Star Continuum Spectroscopy and Cooling

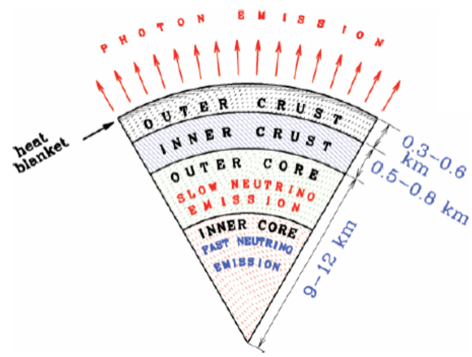


Main cooling regulators:

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

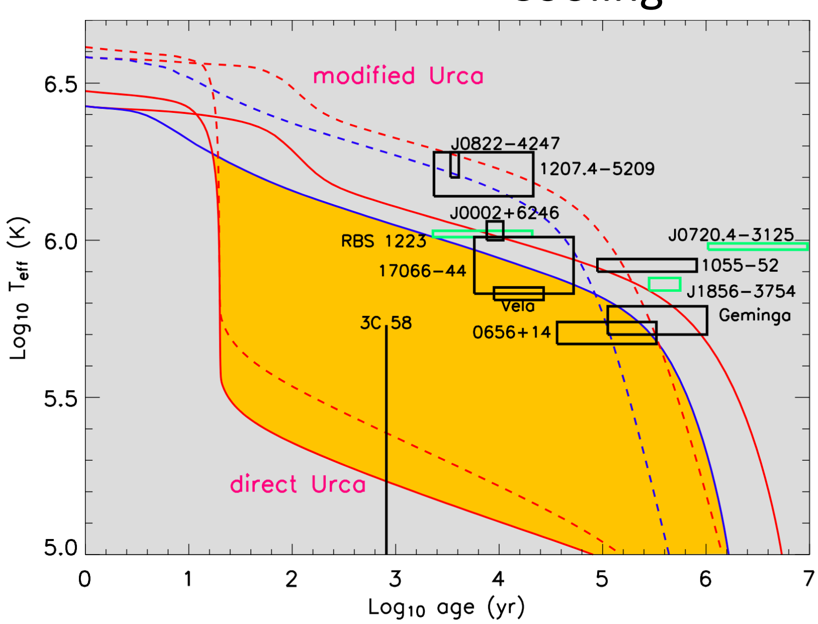
- After Neutron star is created in a supernova, if it is isolated it cools
- The rate at which it cools depends on the conductivity and heat capacity which depends on what it is made of and physics we do not truly understand.

(L. Cominsky)



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

Cooling



Observational estimates of neutron star temperatures and ages together with theoretical cooling simulations for

M= 1.4 M⊙.

- Lattimer and Prakash 2004

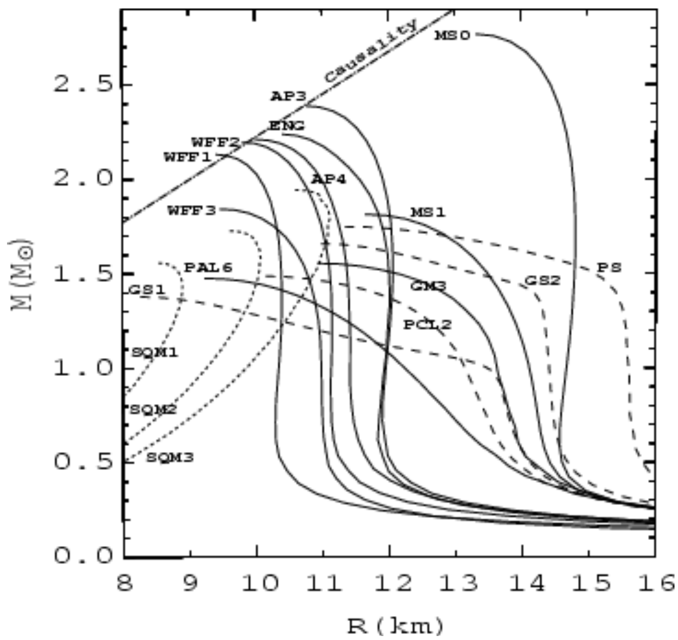
EOS of Neutron Star- Size/Mass Relation

- 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



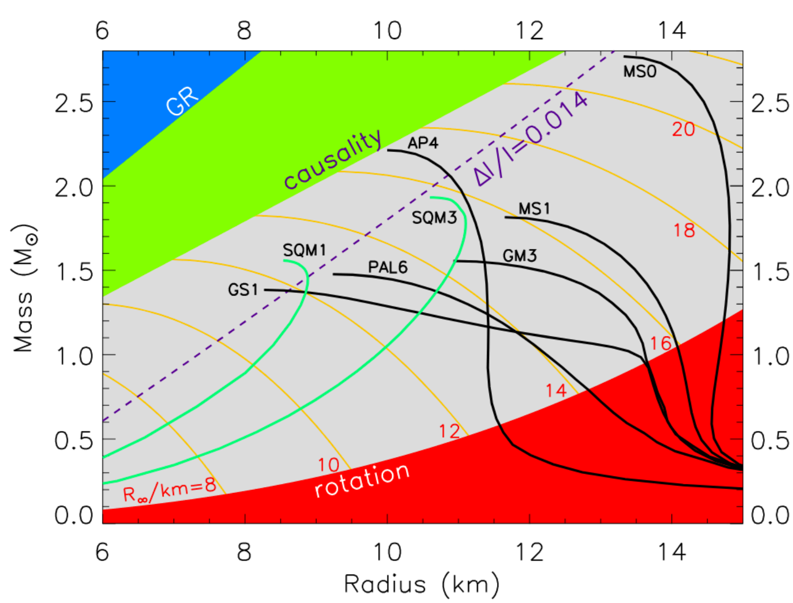
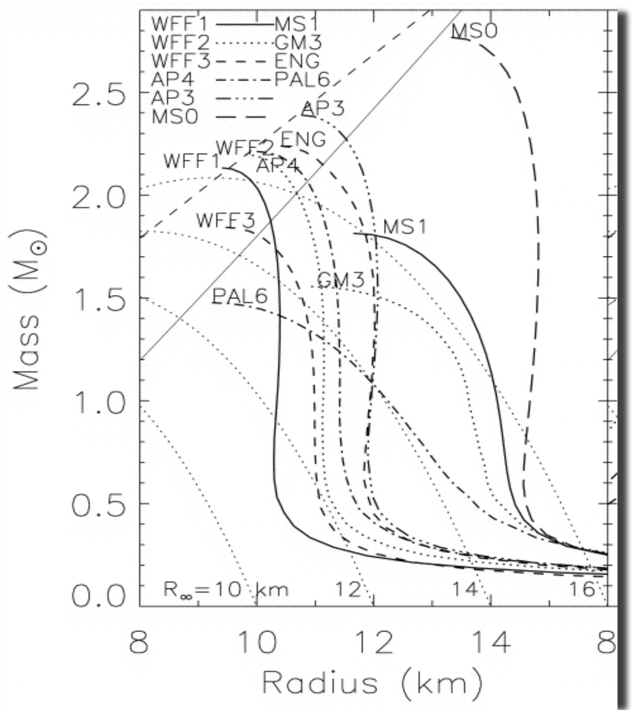


FIG. 2: Mass-radius diagram for neutron stars. Black (green) curves are for normal matter (SQM) equations of state [for definitions of the labels, see [27]]. Regions excluded by general relativity (GR), causality and rotation constraints are indicated. Contours of radiation radii R_∞ are given by the orange curves. The dashed line labeled $\Delta I/I = 0.014$ is a radius limit estimated from Vela pulsar glitches [27].

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

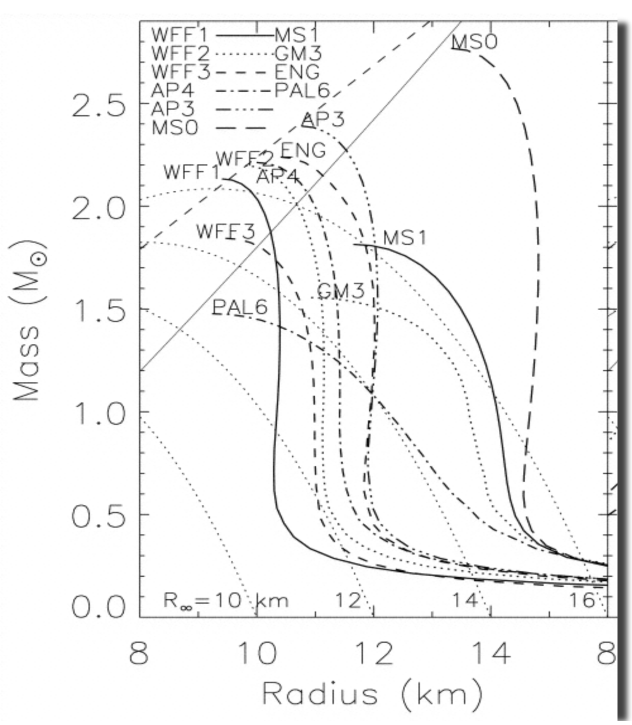
$$dP/dr = -\rho\, G\, M(r) / r^2$$



- High mass limit sets highest possible density achievable in neutron stars (thus, in nature, "the MOST dense").
- Radius ~$P^{1/4}$ at nuclear n density. Directly related to symmetry energy of nuclear interaction
- Other issues: have to use general relativistic eq for hydrostatic equil
- Maximum mass measurements, limits softening of EOS from hyperons, quarks, other "exotica".

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".

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) $dP/d\rho \geq 0$, -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., $dP/d\rho \leq c^2$, hence signals cannot be superluminal and causality is satisfied.

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

Under these conditions mass of NS is maximum for 'stiffest' equation of state

-the sound speed is the speed of light

$$c^2_s = dP/d\rho = c^2.$$

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

Most massive neutron star ever detected, almost too massive to exist

September 16, 2019

Source: Green Bank Observatory

Summary:

Astronomers have discovered the most massive neutron star to date, a rapidly spinning pulsar approximately 4,600 light-years from Earth. This record-breaking object is teetering on the edge of existence, approaching the theoretical maximum mass possible for a neutron star.

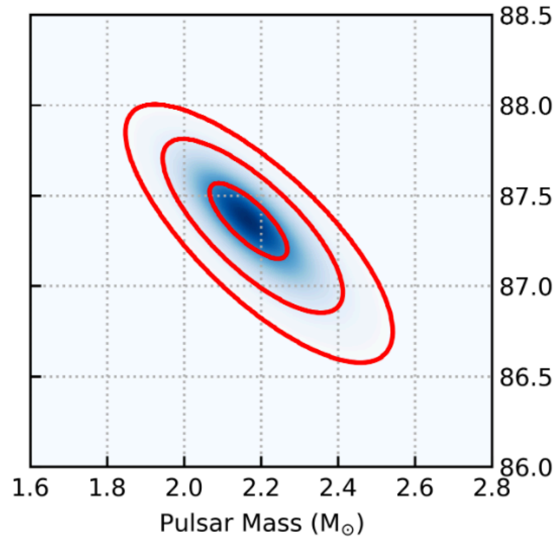
$$M_{max} = 6.7\, M_{\odot} \left(\frac{\rho_0}{10^{14} \mathrm{g\, cm^3}} \right)^{-1/2}.$$

New Max Mass

- Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar - only easily observed in a small subset of high-precision, highly inclined (nearly edge-on) binary pulsar systems

  Cromartie et al 1904.06759.pdf

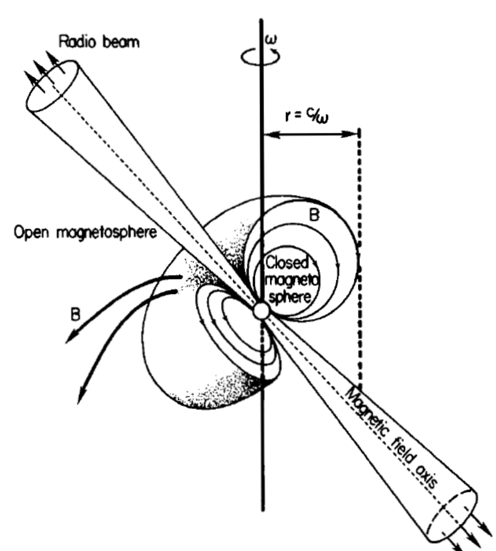
2.3 Solar-mass neutron star would rule out most currently proposed equations of state



1,2,3 σ probability of mass vs system inclination

Isolated Neutron Stars Longair 13.5.1

- 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
- The pulses originate from beams of radio emission emitted along the magnetic axis-the pulsar loses energy by electromagnetic radiation which is extracted from the rotational energy of the neutron star.

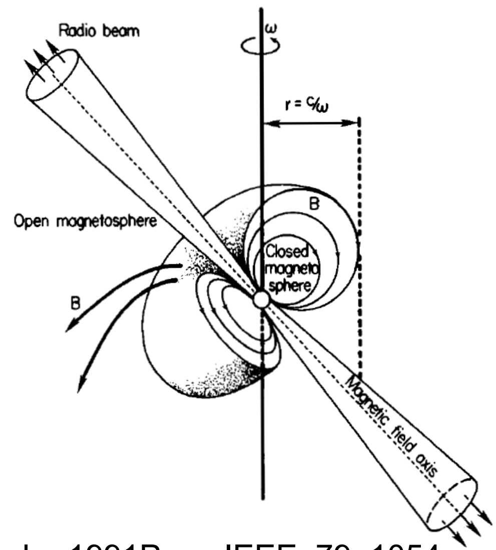


Taylor 1991Proc. IEEE, 79, 1054

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

Isolated Neutron Stars Longair 13.5.1

- In order to produce pulsed radiation from the magnetic poles, the magnetic dipole must be oriented at an angle with respect to the rotation axis and then the magnetic dipole displays a varying dipole moment
- **Energy loss goes as $\Omega^4 B^2$**
- As they radiate the star spins down- **visible for ~10^7 yrs**



Taylor 1991Proc. IEEE, 79, 1054

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

- 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 $P=2\pi/\Omega$ <1 sec requires density of $>10^8$gm/cm^3
- .

Radiation Mechanism

$-dE/dt \sim \Omega^4 p^2_{m0}/6\pi c^3$ .eq 13.33

Where p is the magnetic moment

- This magnetic dipole radiation extracts rotational energy from the neutron star.

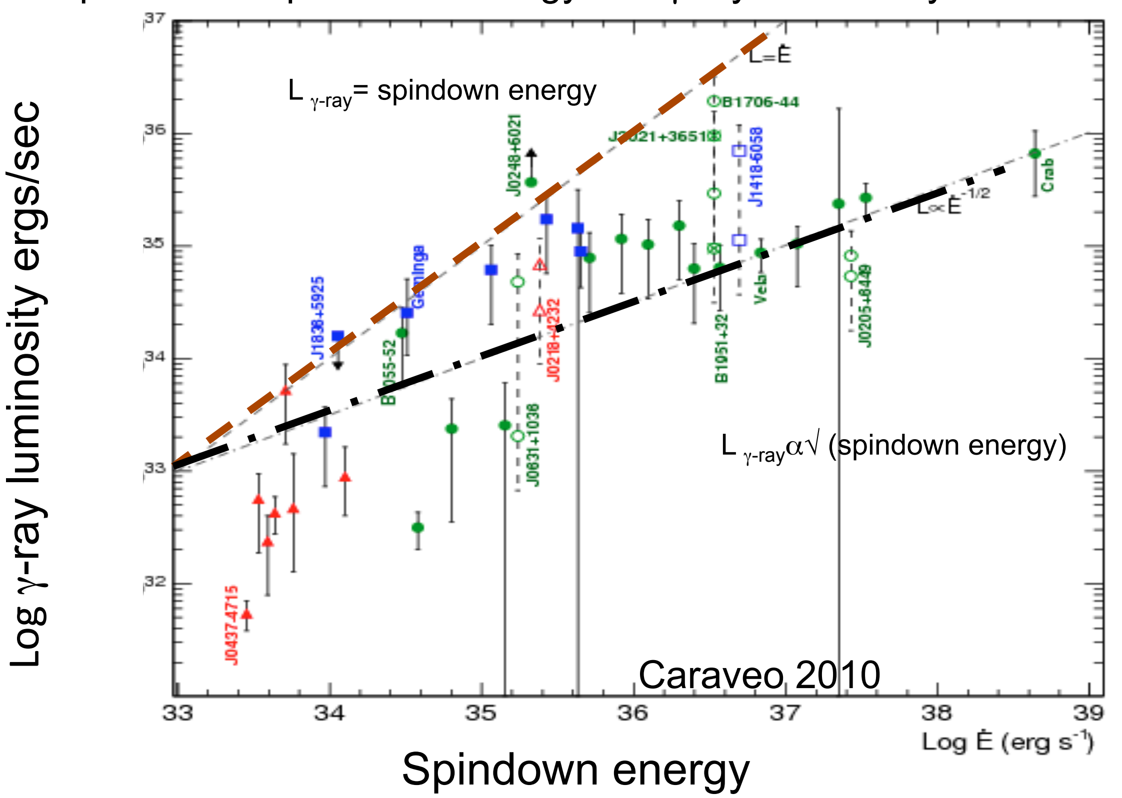
.

- To 'radiate' away the rotational energy $E_{rot} = 1/2\ I\Omega^2 \sim 2\times10^{46} I_{45} P^{-2}$ ergs
- Takes $\tau_{loss} \sim E_{rot}/L \sim 60 I_{45} P^{-2} L_{37}^{-1}$ 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

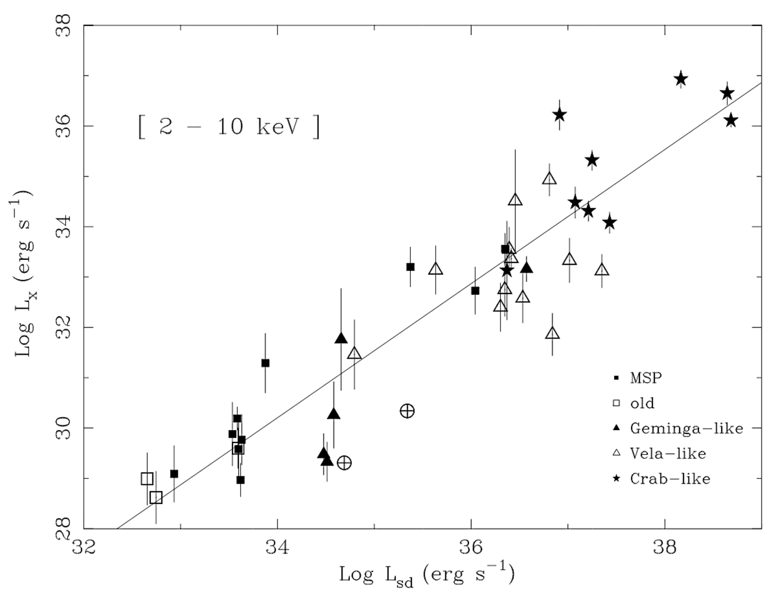
- However only a tiny fraction of the spindown energy goes into radio pulses- a major recent discovery is that most of it goes into particles and γ-rays.

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



What Fraction Appears in the X-ray

- $L(x) \sim 10^{-4} L_{spindown}^{4/3}$



Radiation Mechanism

If I is the moment of inertia of the neutron star,

- $I\Omega d\Omega/dt = \Omega^4 p^2_{m0}/6\pi c^3$ and so $d\Omega/dt \propto \Omega^3$

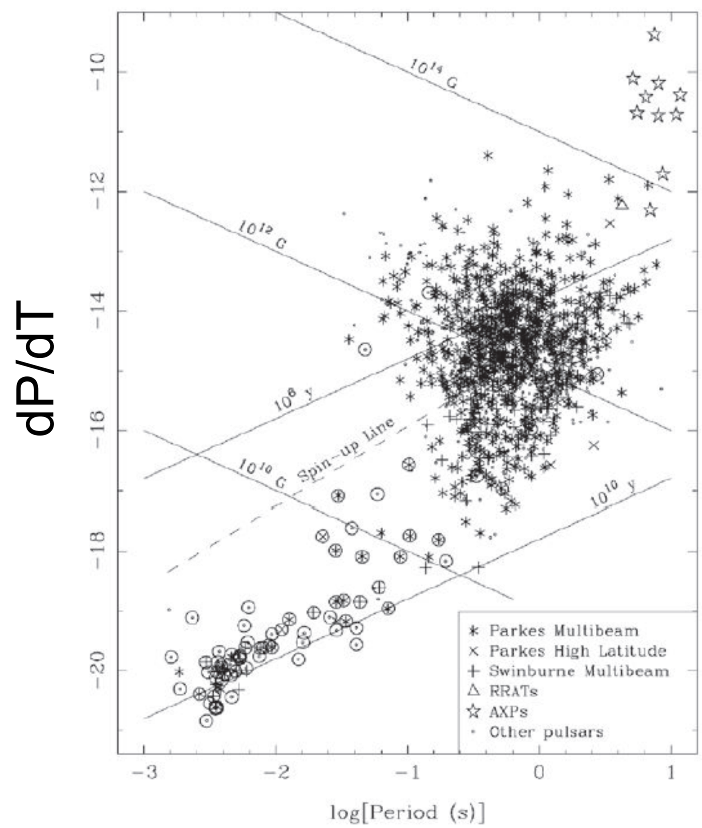
- The age of the pulsar can be estimated if it is assumed that its deceleration can be described by $d\Omega/dt \propto \Omega^n$ if n throughout its lifetime is constant

- It is conventional to set n = 3 to derive the age of pulsars , τ,

  and so $\tau = P/(2\, dP/dt)$.

- Using this relation the typical lifetime for normal pulsars is about 10^5–10^8 years.

- Where radio pulsars lie in the P,dP/dt plot.
  - the lines correspond to constant magnetic field and constant age.
- If magnetic braking mechanism slows-down of the neutron star then (see eqs 13.40-13.42)
- $B_s \approx 3\text{x}\ 10^{19}((P\ (dP/dt\ ))^{1/2}$ G *(lines of constant B in plot)*



Magnetars

Their defining properties occasional huge outbursts of X-rays and soft-gamma rays, as well as luminosities in quiescence that are generally orders of magnitude greater than their spin-down luminosities.

- Their are two classes: the 'anomalous X-ray pulsars' (AXPs) and the 'soft gamma repeaters' (SGRs)

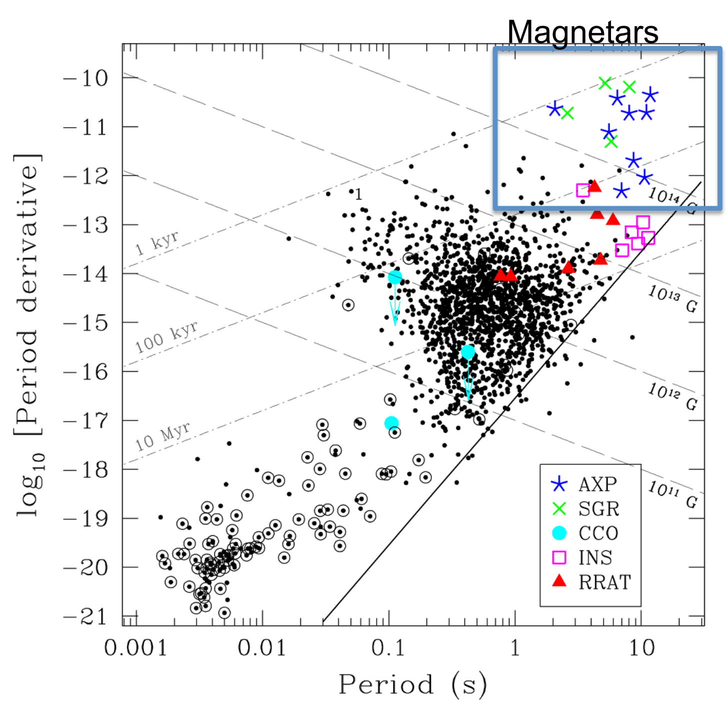
Magnetars are thought to be young, isolated neutron stars powered ultimately by the decay of a very large magnetic field.

Their intense magnetic field [25, 26], inferred via spin-down to be in the range 10^{14}-10^{15}G 'quantum critical field' $B_{QED} \equiv m^2_e c^3/he$= 4.4×10^{13}G.

In their most luminous outburst magnetars can briefly out-shine all other cosmic soft-gamma-ray sources combined

[Kaspi 2010]

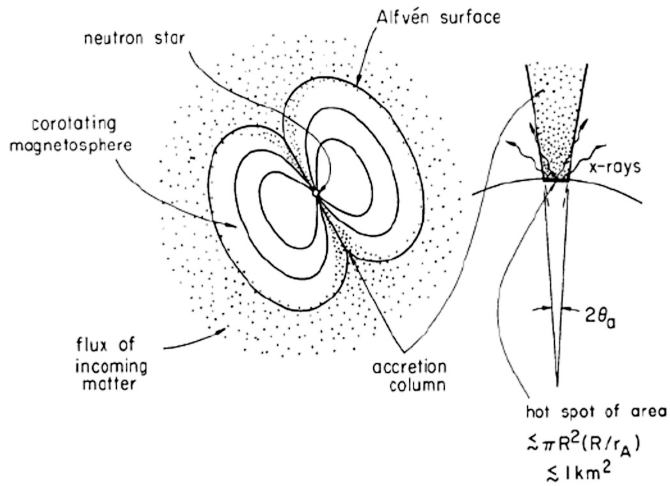
- AXPS and Magnetars **Longair 13.5.3-13.5.5**



Open circles are in binaries

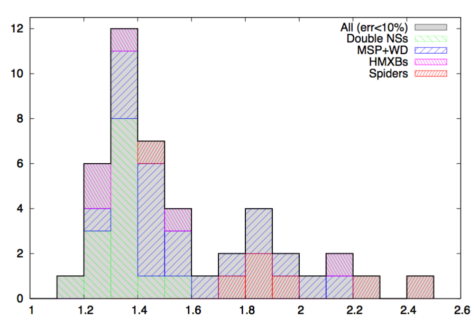
Accreting Neutron Stars: Longair 13.5.2- Also Ch 14

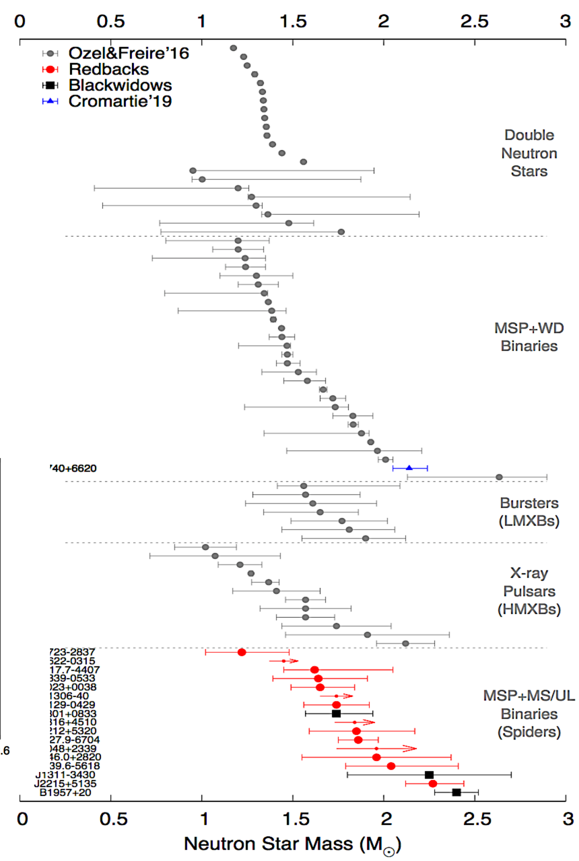
- These are the brightest x-ray sources in the sky and were the first x-ray sources discovered
- They have a wide range of properties (spectral and temporal) and show an almost bewildering array of behaviors
- Their luminosities range over 6 orders of magnitude



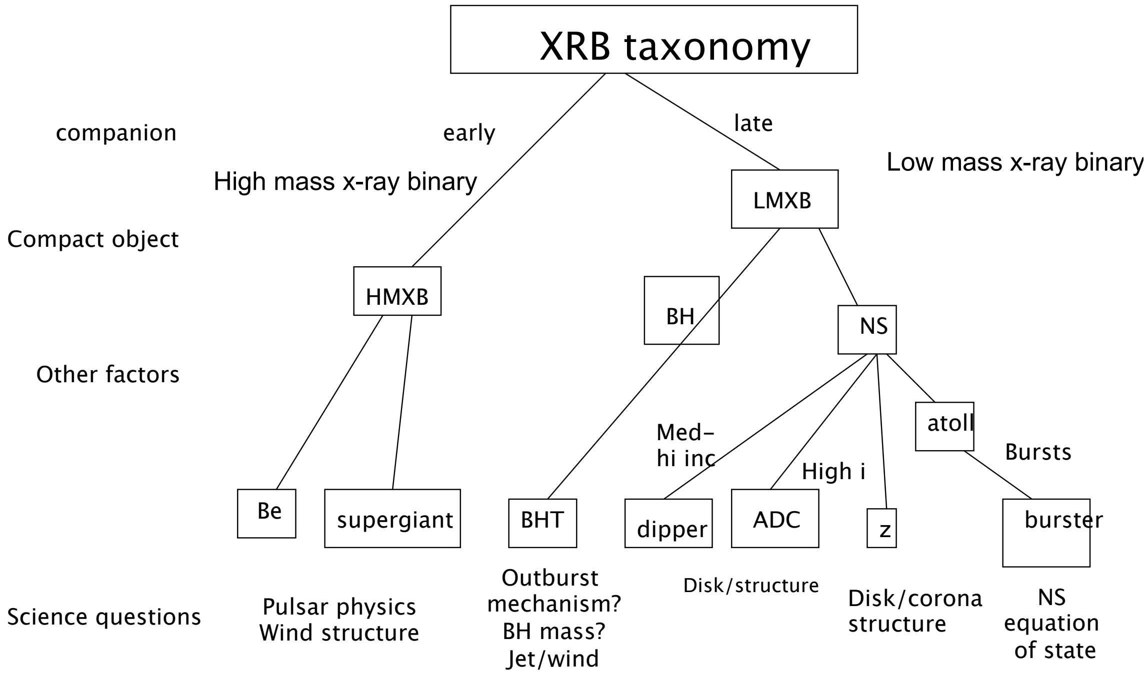
Masses of NS with small errors

- Linares /1910.09572.pdf





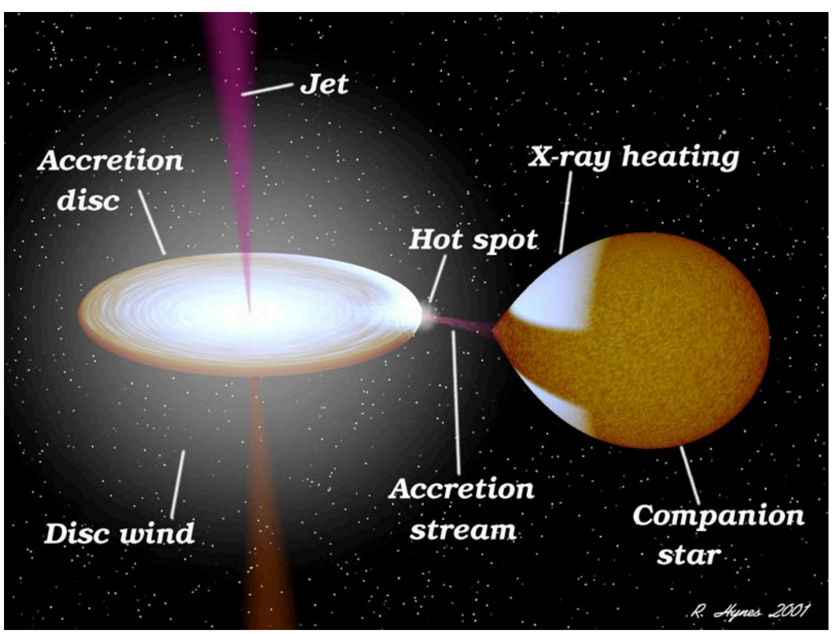
A Short Introduction to terminology



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,b remms-like
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

(from M. Porzio)