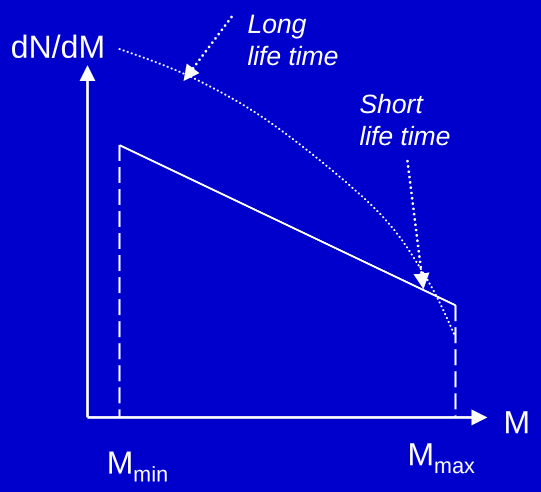
Neutron stars. Lecture 1.

Sergei Popov
(SAI MSU)

Stars in the Galaxy



Salpeter (1955) mass function:
$dN/dM \sim M^{-2.35}$

There are many modification (Miller-Scalo, Kroupa etc.).
At high masses the slope is usually steeper.
Note: it is *initial* mass function, not the present day!

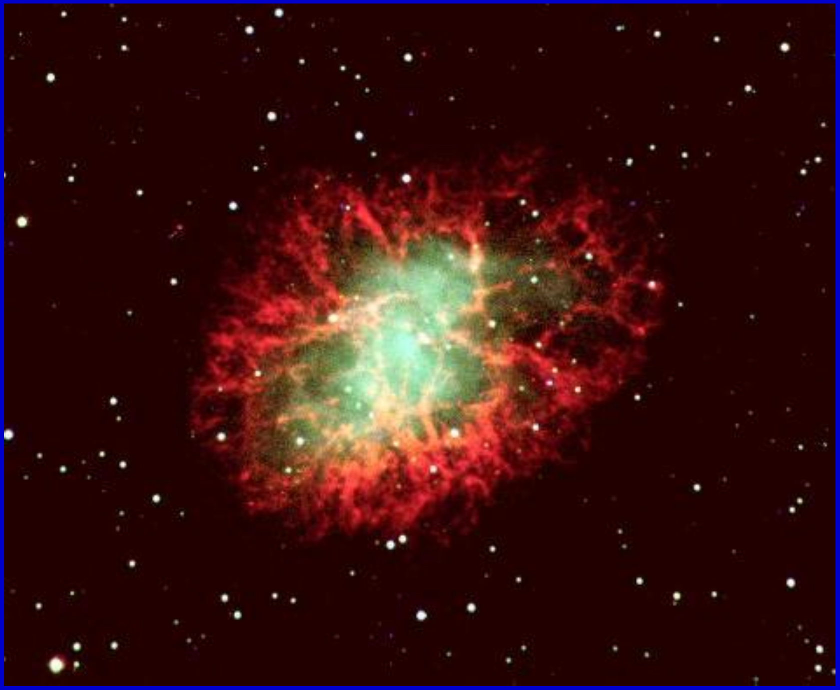
It is possible to estimate the number of NS and BH progenitors.
Then using there average lifetime we can estimate the birth rate
and total numbers (with a given age of the Galaxy and assuming constant rate)
taking the SFR~3 solar mass per year.
[see also Ch.1 in Shapiro, Teukolsky]

NS: <~10^9
BH: ~10^8

Discovery !!!!

1967: Jocelyn Bell. Radio pulsars.

Seredipitous discovery.



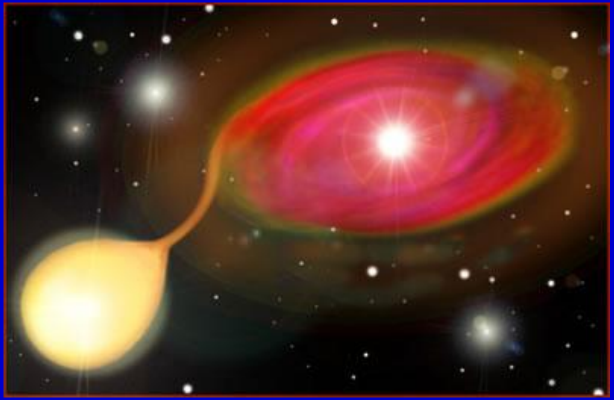
Early discovery: Sco X-1

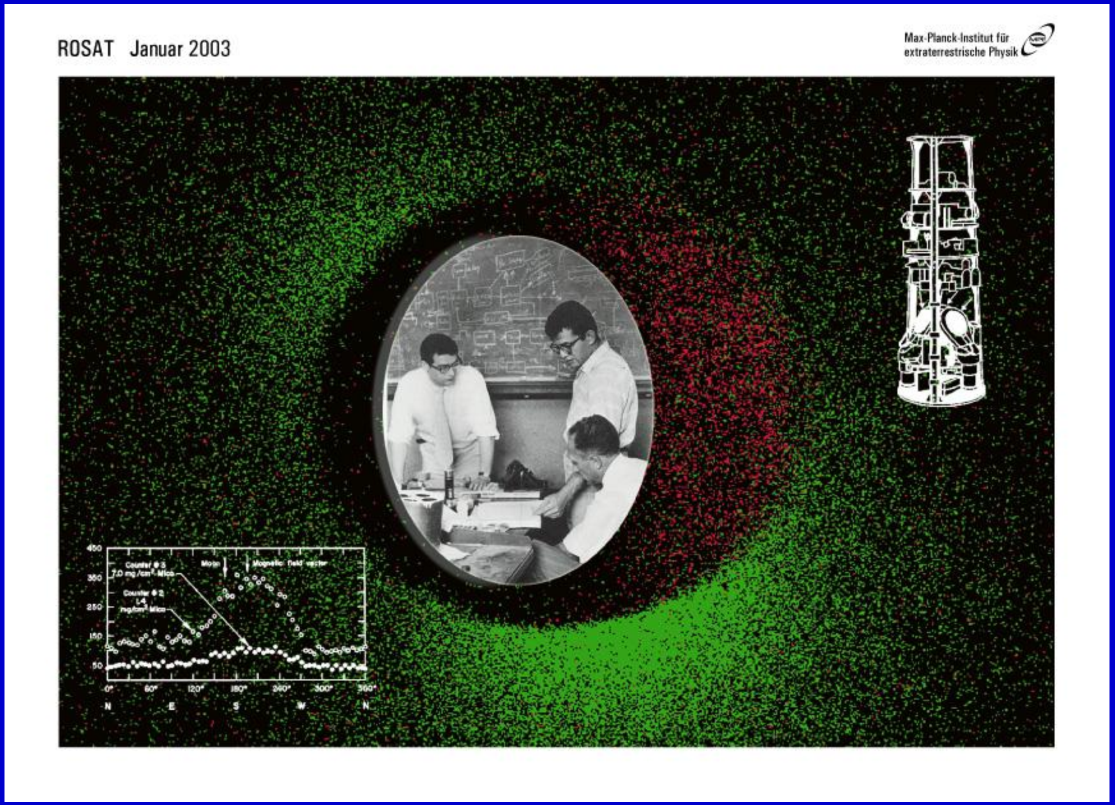
Rocket experiments

Giacconi, Gursky, Hendel

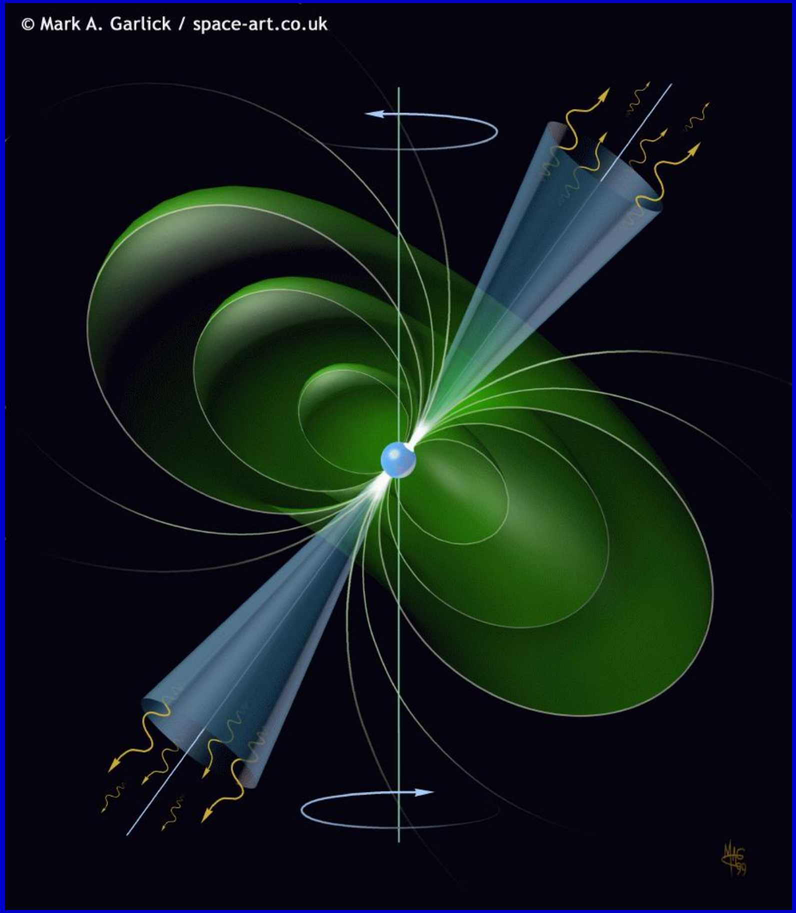
1962

In 2002 R. Giacconi was awarded with the Nobel prize.

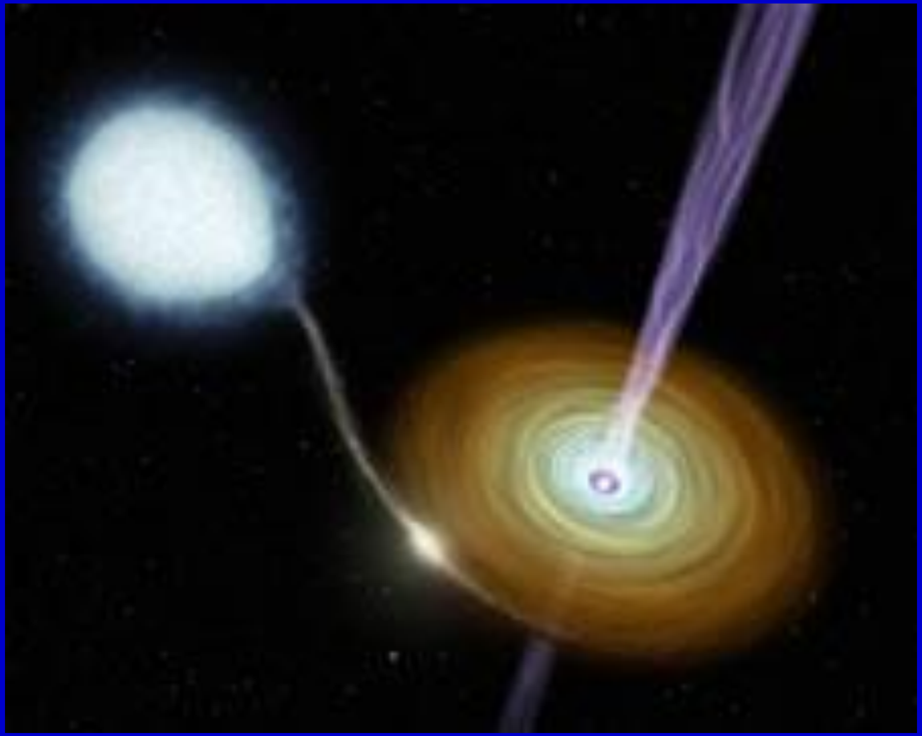




Two main types of NS sources before mid90s



Radio pulsar



A binary system

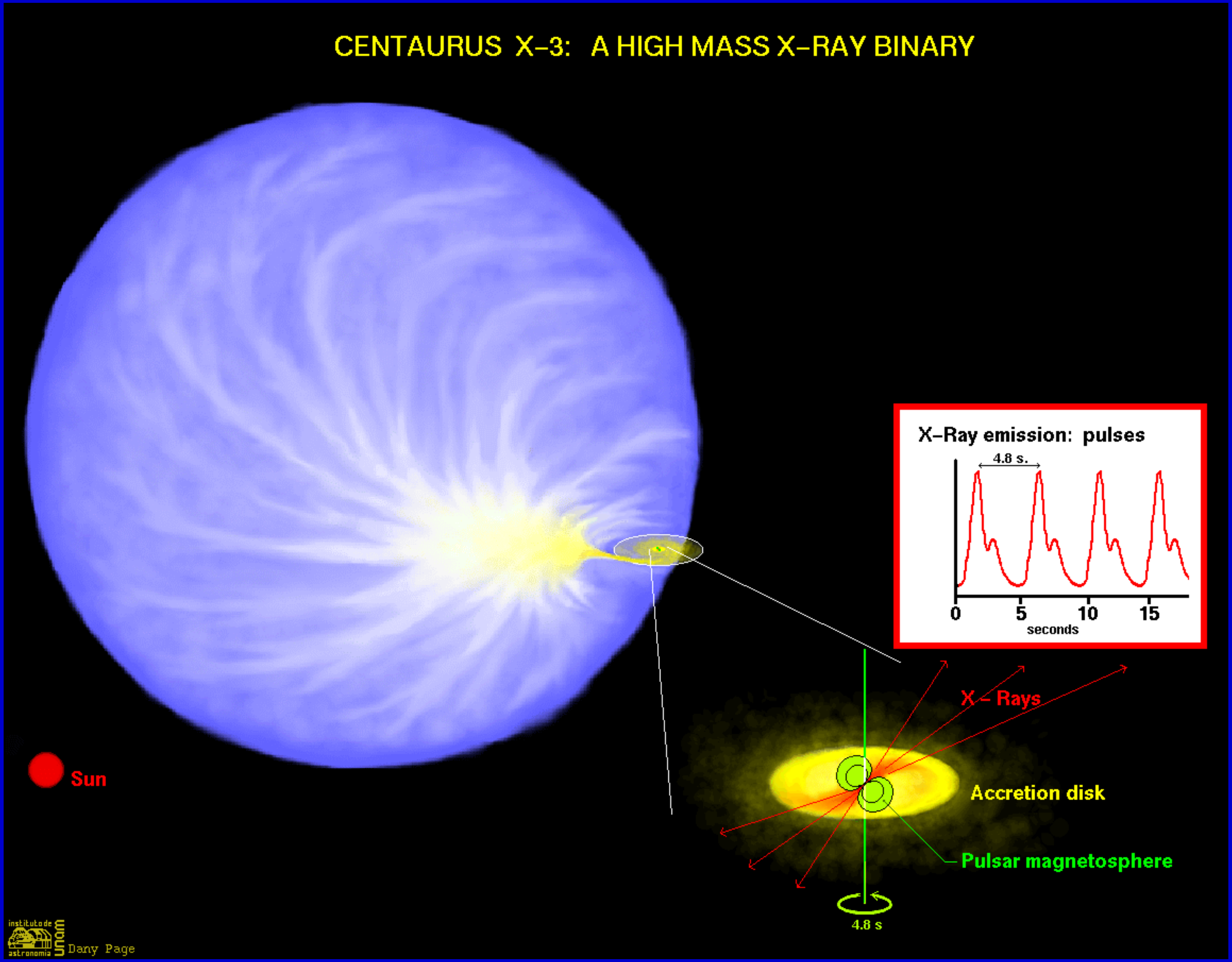
Close binaries with accreting compact objects

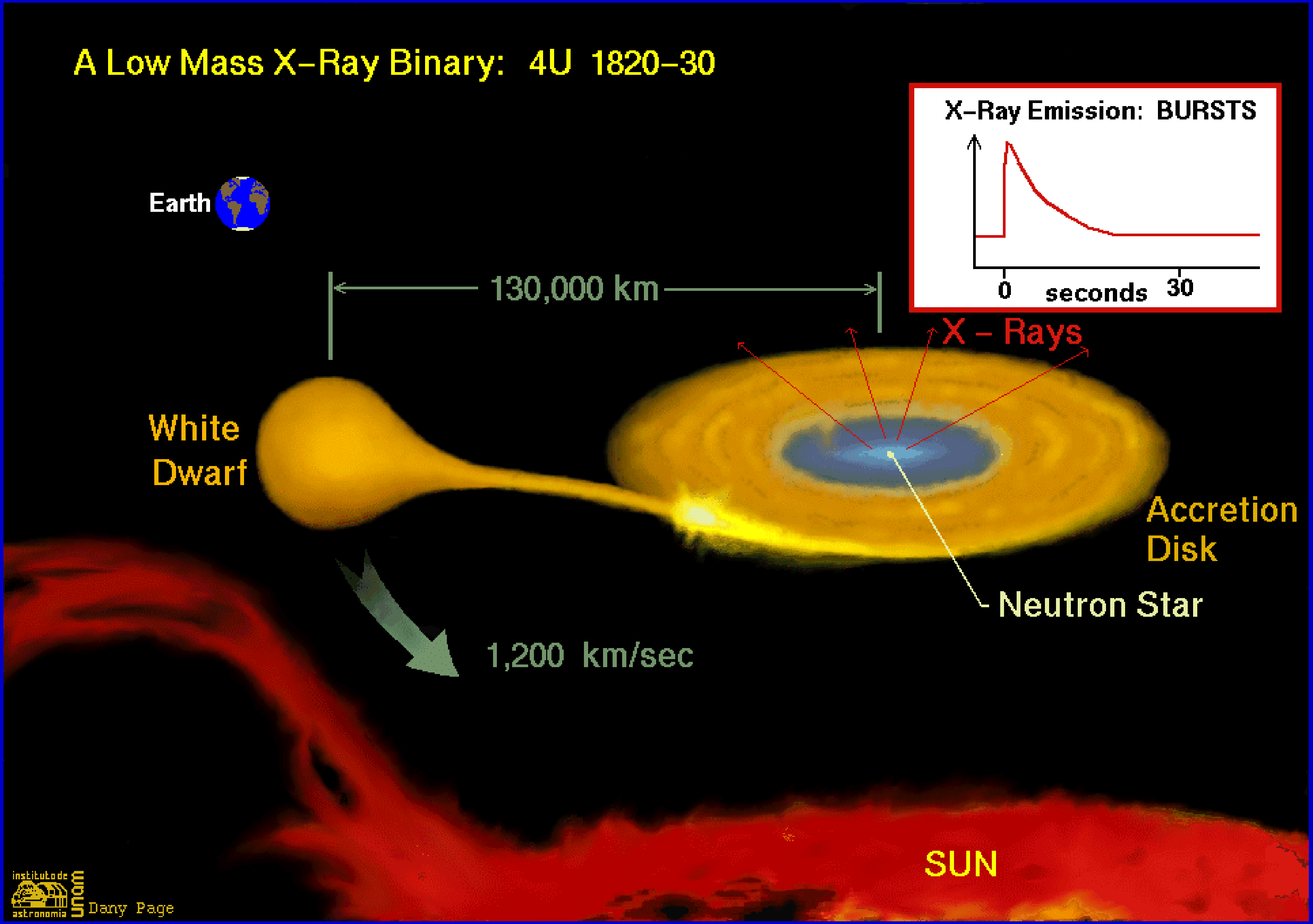
<u>LMXBs</u>
Roche lobe overflow.
Very compact systems.
Rapid NS rotation.
Produce mPSRs.

<u>IMXBs</u>
Very rare.
Roche lobe overflow.
Produce LMXBs(?)

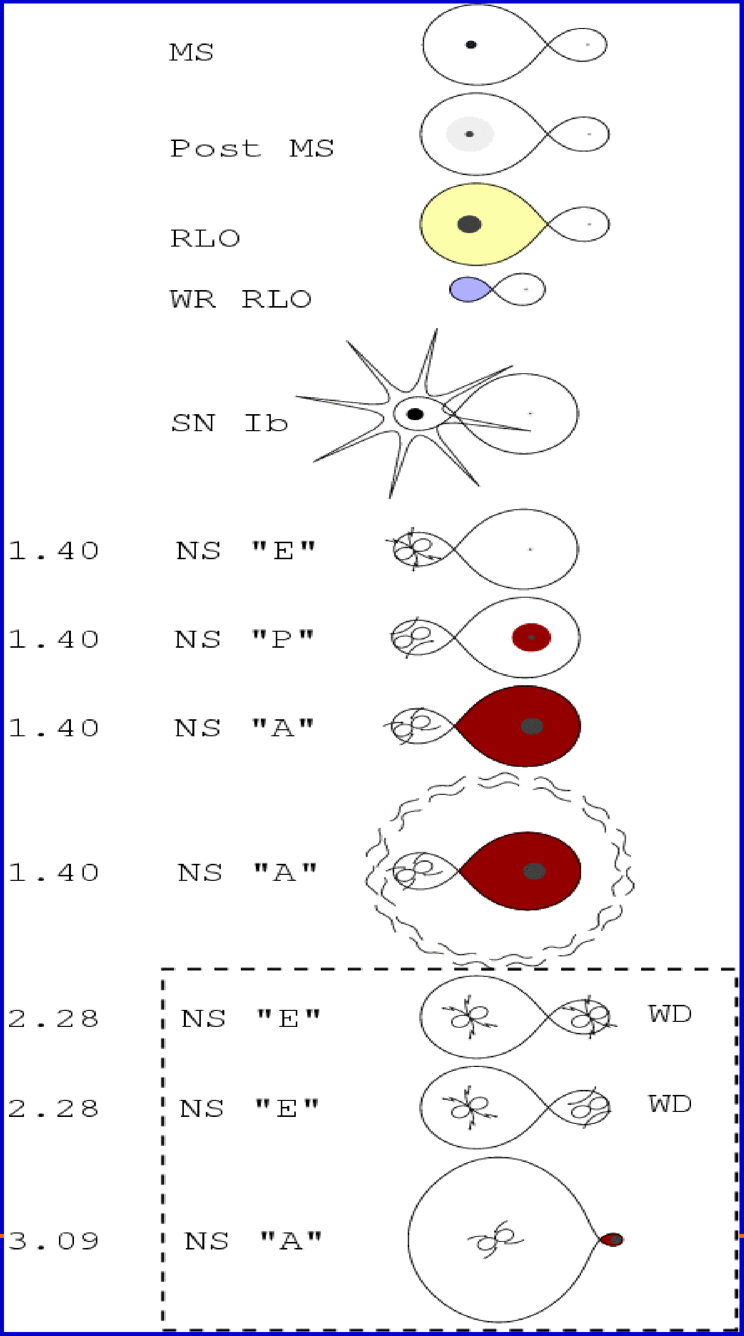
<u>HMXBs</u>
Accretion from
the stellar wind.
Mainly Be/X-ray.
Wide systems.
Long NS spin periods.
Produce DNS.

Among binaries ~ 40% are close and ~96% are low and intermediate mass ones.

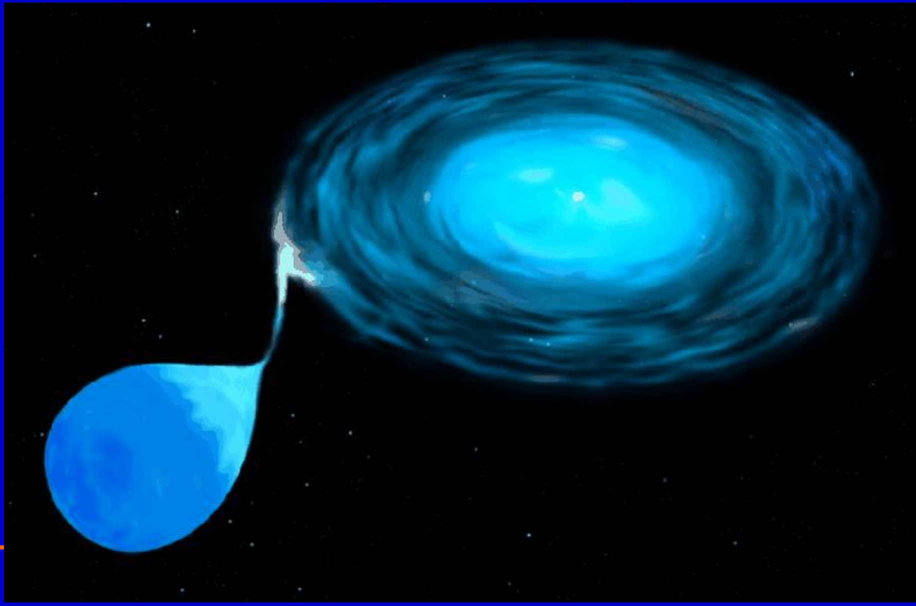

CENTAURUS X-3: A HIGH MASS X-RAY BINARY
X-Ray emission: pulses
4.8 s.
0
5
10
15
seconds
X - Rays
Accretion disk
Pulsar magnetosphere
4.8 s
Sun
Dany Page


A Low Mass X-Ray Binary: 4U 1820-30
X-Ray Emission: BURSTS
0
seconds
30
Earth
130,000 km
X - Rays
White Dwarf
Accretion Disk
Neutron Star
1,200 km/sec
SUN
instituto de astronomia unam
Dany Page

Evolution



NSs can become very massive during their evolution due to accretion.



List of reviews

- Catalogue of LMXBs. Li et al. arXiv:0707.0544
- Catalogue of HMXBs. Li et al. arXiv: 0707.0549
- Evolution of binaries. Postnov & Yungelson. astro-ph/0701059
- Extragalactic XRBs. Fabbiano. astro-ph/0511481
- General review on accreting NSs and BHs. Psaltis. astro-ph/0410536
- CVs
  - Evolution. Ritter. arXiv:0809.1800
  - General features. Smith. astro-ph/0701564
- Modeling accretion: Done et al. arXiv:0708.0148
- Population synthesis. Popov & Prokhorov. Physics Uspekhi (2007)

The new zoo of young neutron stars

During last 10-15 years
it became clear that neutron stars
can be born very different.
In particular, absolutely
non-similar to the Crab pulsar.

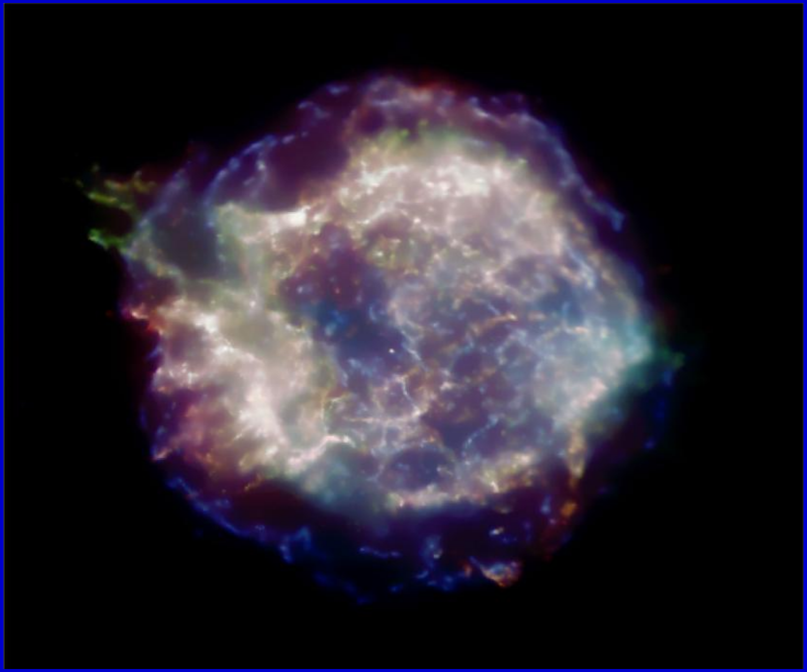
- o Compact central X-ray sources
  in supernova remnants.
- o Anomalous X-ray pulsars
- o Soft gamma repeaters
- o The Magnificent Seven
- o gamma-ray PSRs (Fermi)
- o Transient radio sources (RRATs)
- o Calvera ….

CCOs in SNRs

		Age, kyr	Distance, kpc
J232327.9+584843	Cas A	0.32	3.3–3.7
J085201.4−461753	G266.1−1.2	1–3	1–2
J082157.5−430017	Pup A	1–3	1.6–3.3
J121000.8−522628	G296.5+10.0	3–20	1.3–3.9
J185238.6+004020	Kes 79	~9	~10
J171328.4−394955	G347.3−0.5	~10	~6

[Pavlov, Sanwal, Teter: astro-ph/0311526,
de Luca: arxiv:0712.2209]

For two sources there are strong indications for large (>~100 msec) initial spin periods and low magnetic fields:
1E 1207.4-5209 in PKS 1209-51/52 and
PSR J1852+0040 in Kesteven 79
[see Halpern et al. arxiv:0705.0978]



Cas A

See a recent list in arXiv: 0911.0093

Magnetars

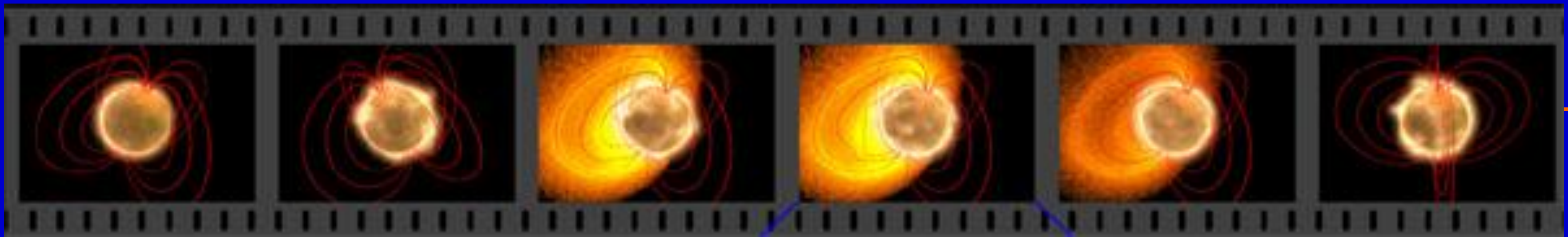
- $dE/dt > dE_{rot}/dt$
- By definition: The energy of the magnetic field is released

Magnetic fields 10^{14}–10^{15} G

- Spin down
- Long spin periods

- Energy to support bursts
- Field to confine a fireball (tails)
- Duration of spikes (alfven waves)

- Direct measurements of magnetic field (cyclotron lines)



Known magnetars

SGRs

- 0526-66
- 1627-41
- 1806-20
- 1900+14
- 0501+4516
- 1801-23 (?)
- 0418+5729 (?)
- 2013+34 (?)
- 1833-0832

AXPs

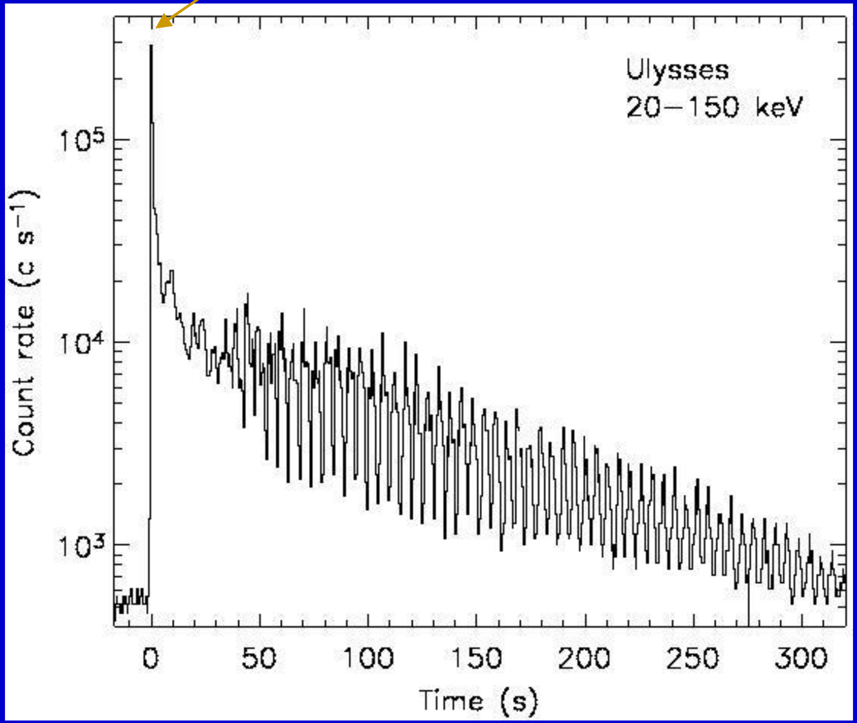
- CXO 010043.1-72
- 4U 0142+61
- 1E 1048.1-5937
- CXO J1647-45
- 1 RXS J170849-40
- XTE J1810-197
- 1E 1841-045
- AX J1845-0258
- 1E 2259+586
- 1E 1547.0-5408
- PSR J1846-0258
- CXOU J171405.7−381031

Catalogue: http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

Soft Gamma Repeaters: main properties

- Energetic “Giant Flares” (GFs, L ≈ 10^{45}-10^{47} erg/s) detected from 3 (4?) sources
- No evidence for a binary companion, association with a SNR at least in one case
- Persistent X-ray emitters, L ≈ 10^{35} - 10^{36} erg/s
- Pulsations discovered both in GFs tails and persistent emission, P ≈ 5 -10 s
- Huge spindown rates, $\dot{P}/P \approx 10^{-10}$ ss^{-1}

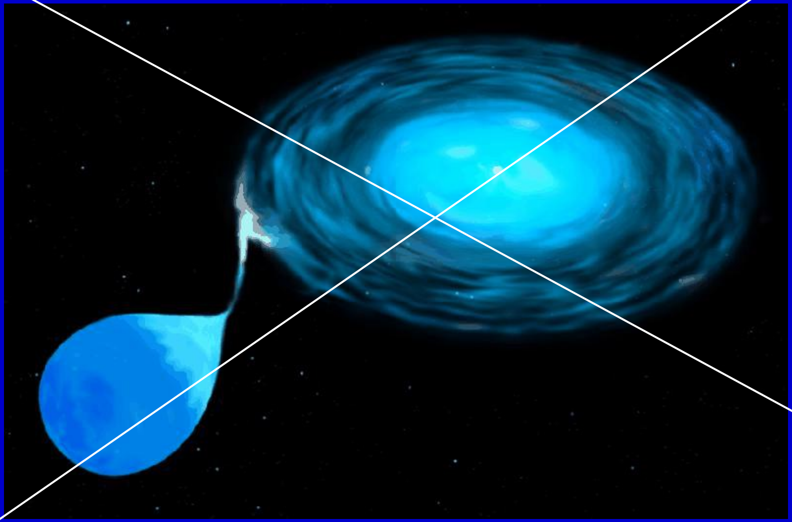
Saturation of detectors

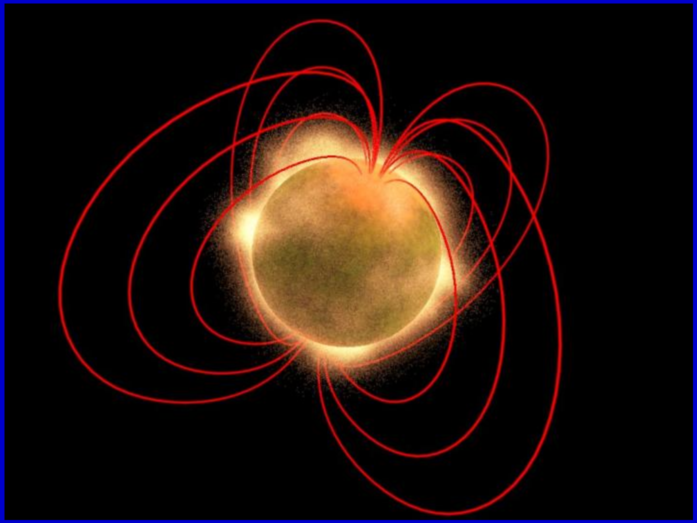


Anomalous X-ray pulsars

Identified as a separate group in 1995.
(Mereghetti, Stella 1995 Van Paradijs et al.1995)

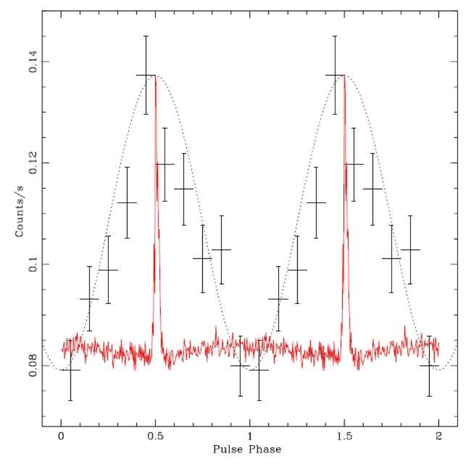
- Similar periods (5-10 sec)
- Constant spin down
- Absence of optical companions
- Relatively weak luminosity
- Constant luminosity





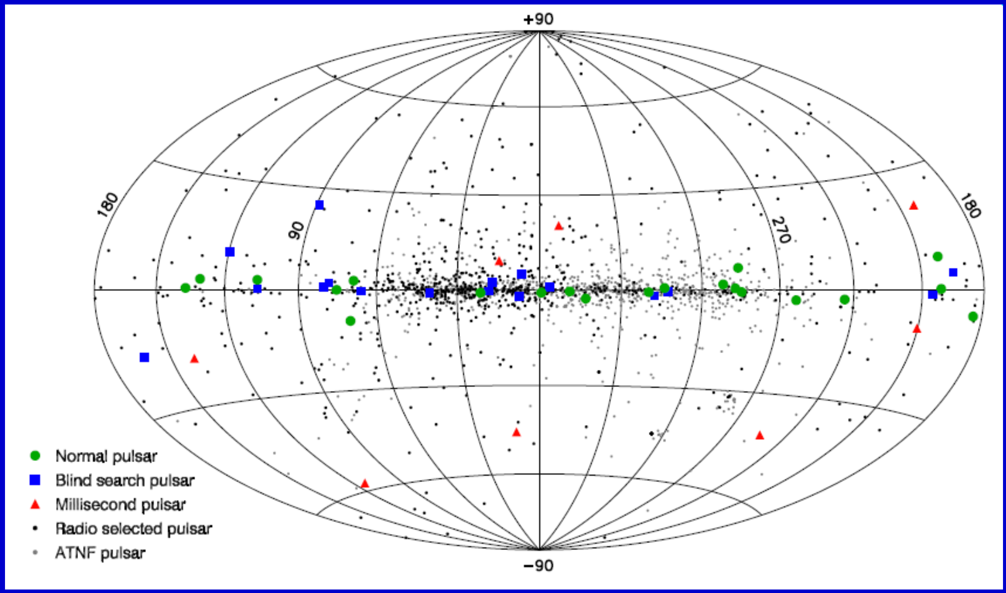
RRATs

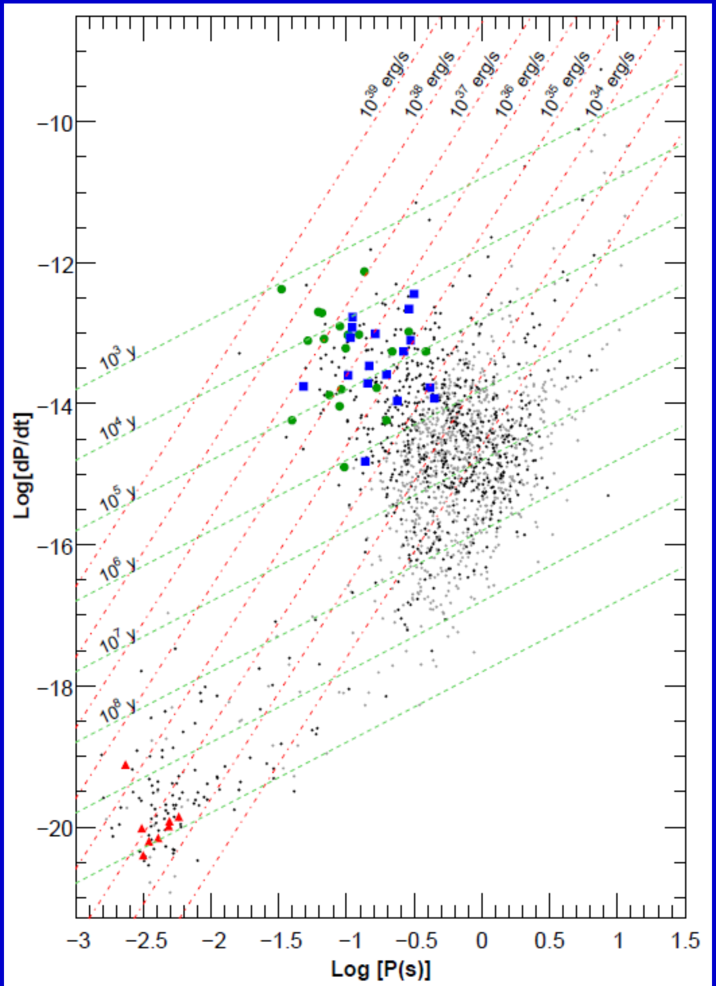
- 11 sources detected in the Parkes Multibeam Survey (McLaughlin et al 2006)
- Burst duration 2-30 ms, interval 4 min-3 hr
- Periods in the range 0.4-7 s
- Period derivative measured in 7 sources: B ~ 10^{12}-10^{14} G, age ~ 0.1-3 Myr
- New results in arXiv:0911.1790
  Now >20 sources
  Mostly related to PSRs



Fermi pulsars

46 pulsars, 16 – new (using just first 6 months).
Roughly ½ were not detected by EGRET.

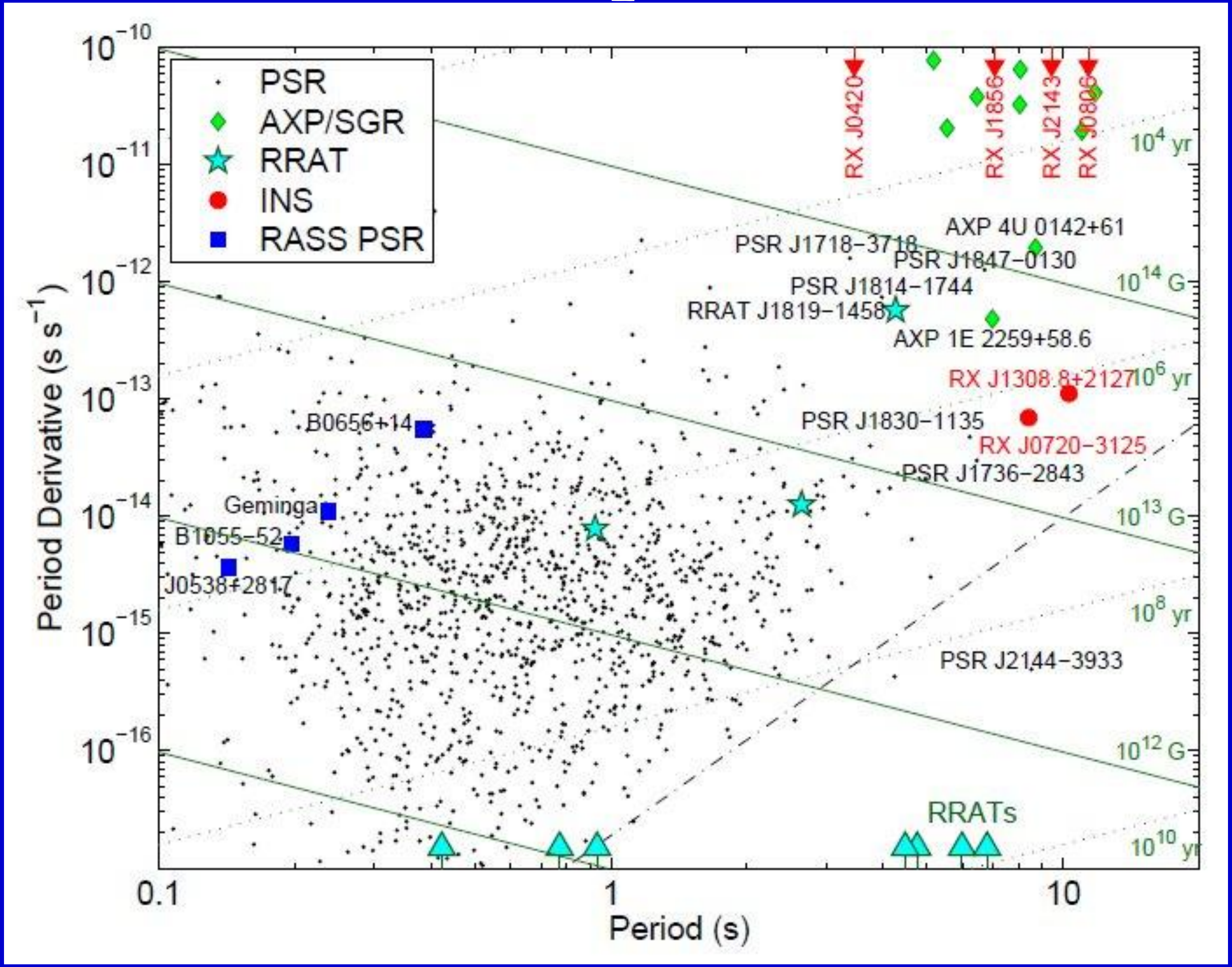




Not all of 16 new pulsars are detected in radio (see arXiv:0908.2626).

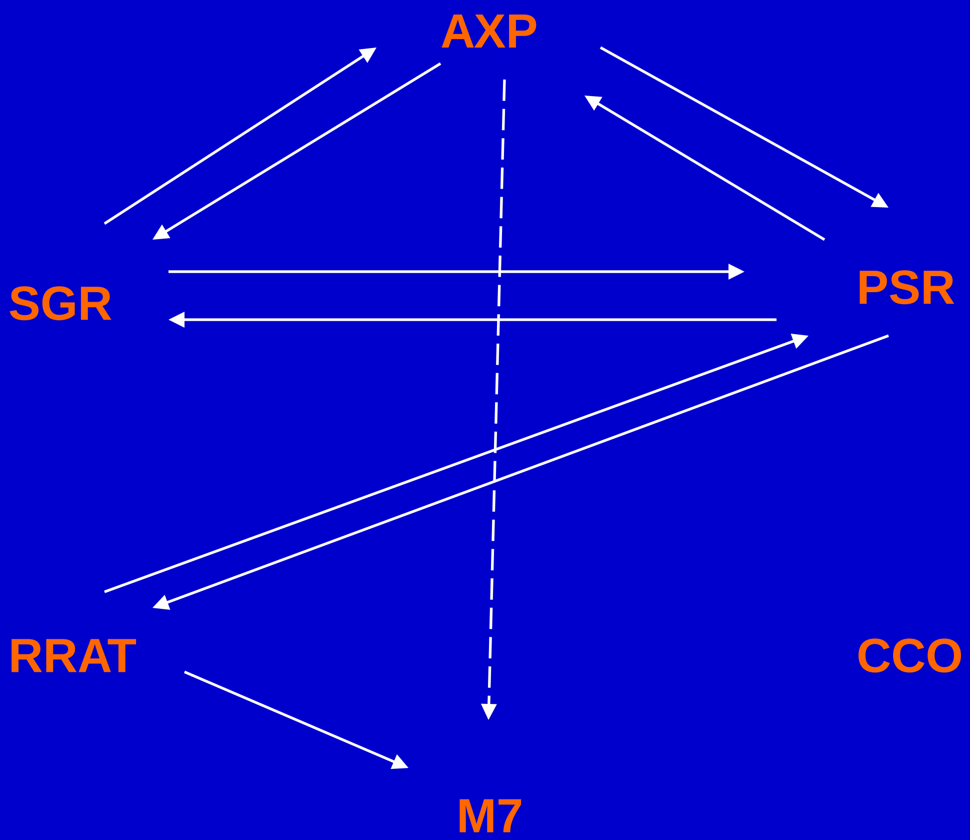
See a catalogue in 0910.1608

All NSs in one plot



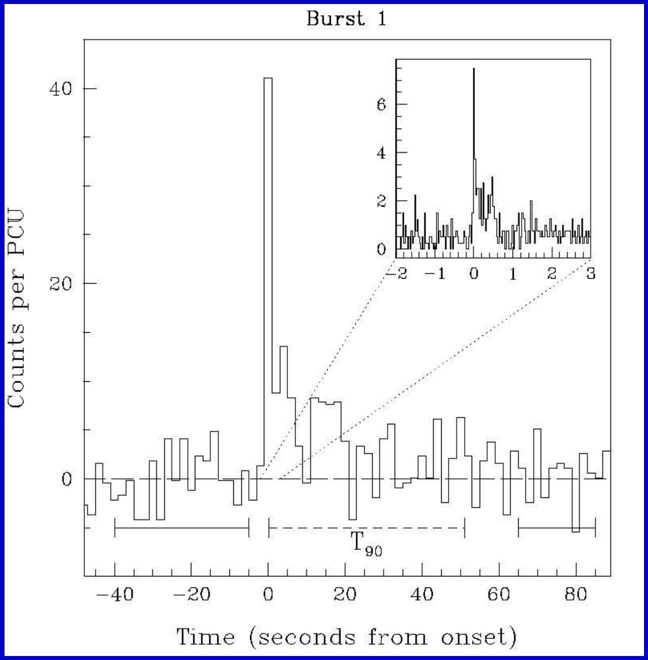
Kaplan arXiv: 0801.1143

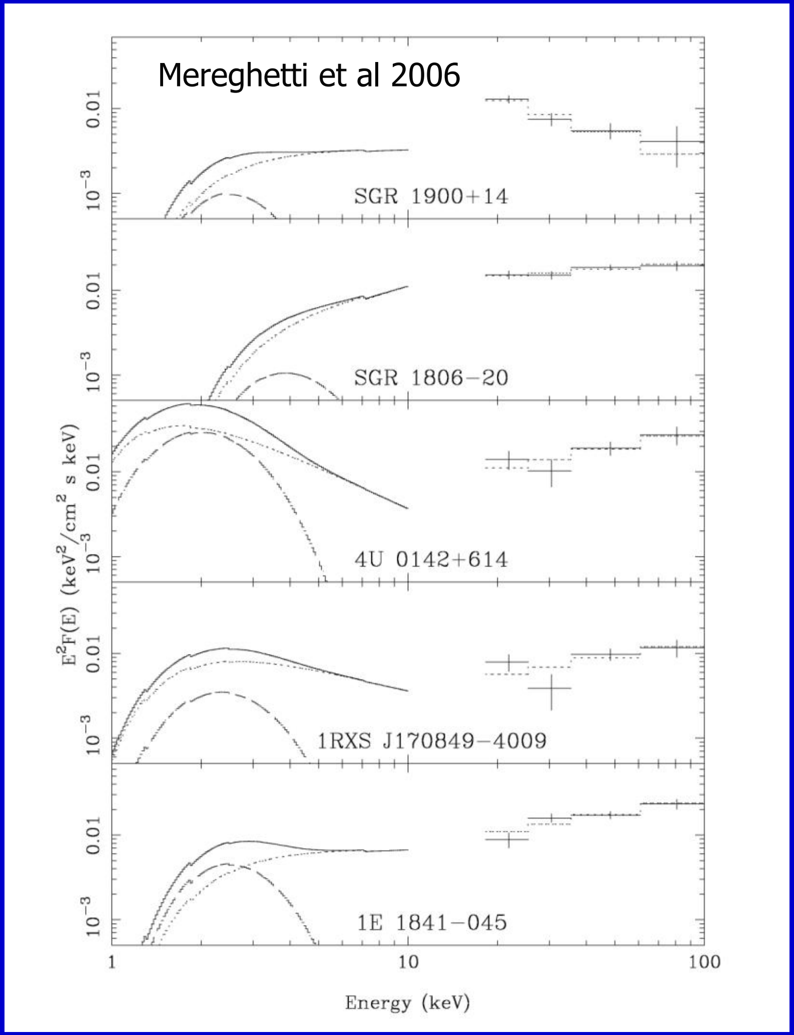
Relations, connections …



Are SGRs and AXPs brothers?

- Bursts of AXPs
  (from 6 now)
- Spectral properties
- Quiescent periods of SGRs (0525-66 since 1983)



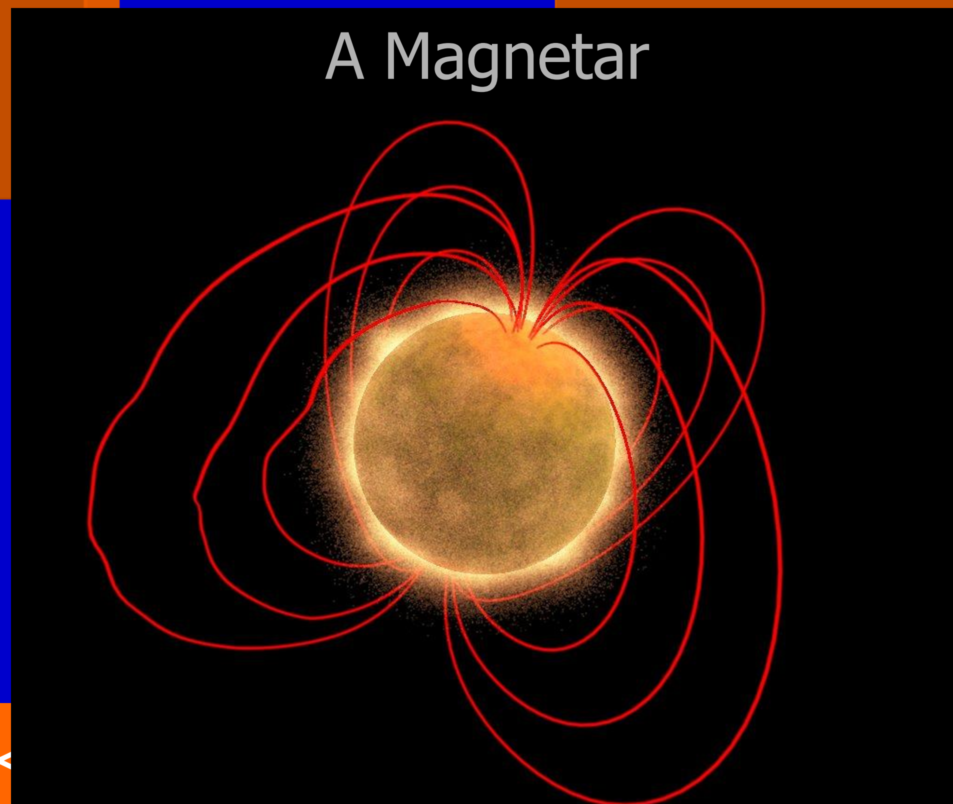


Gavriil et al. 2002

A Tale of Two Populations ?

SGRs: bursting
X/γ-ray sources

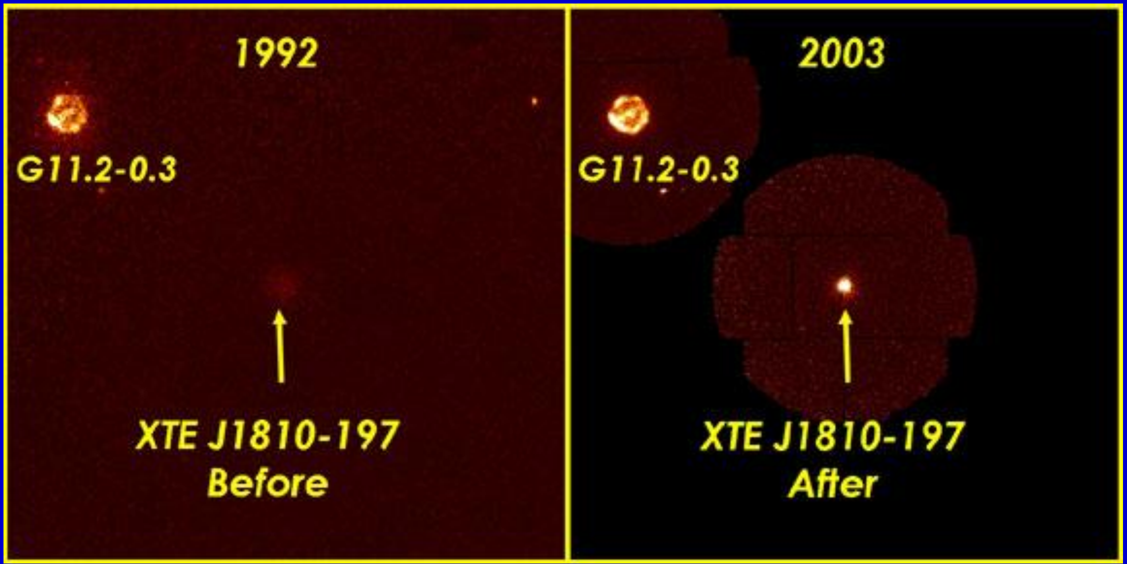
ss



R < ... ct

Pulsed X-ray emission: a neutron star

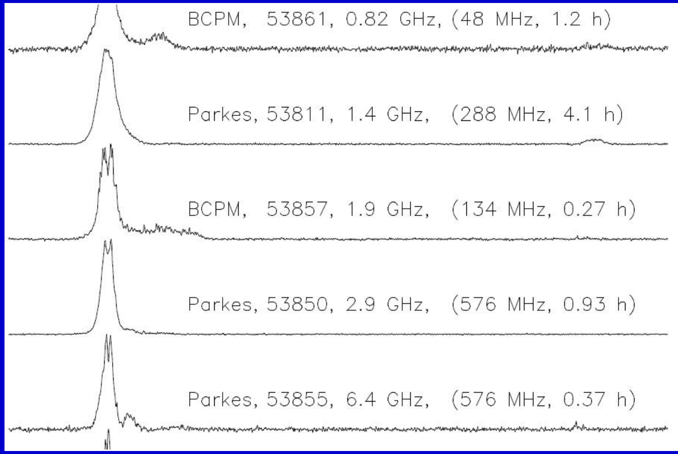
Transient radio emission from AXP



ROSAT and XMM images an X-ray outburst happened in 2003.

AXP has spin period 5.54 s

Radio emission was detected from XTE J1810-197 during its active state.
Clear pulsations have been detected.
Large radio luminosity.
Strong polarization.
Precise Pdot measurement.
Important to constrain models, for better distance and coordinates determinations, etc.



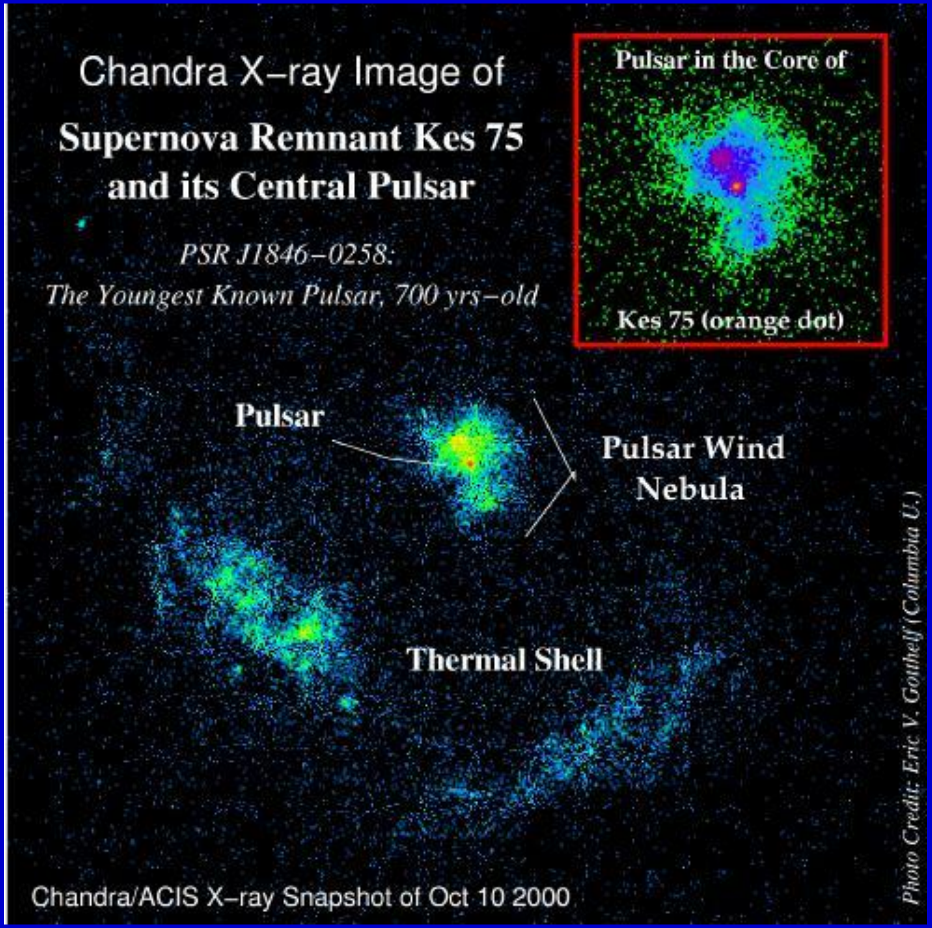
(Camilo et al. astro-ph/0605429)

Transient radiopulsar

PSR J1846-0258
P=0.326 sec
B=5 10^{13} G

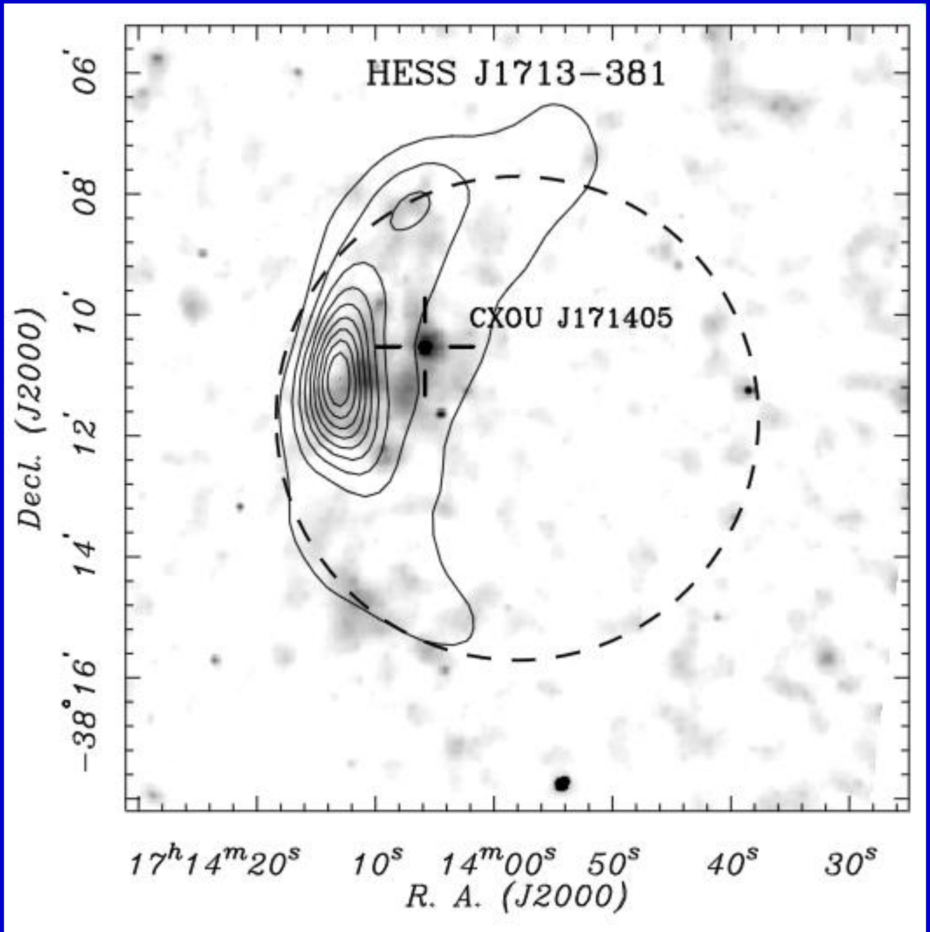
Among all rotation powered PSRs it has the largest Edot. Smallest spindown age (884 yrs).

The pulsar increased
its luminosity in X-rays.
Increase of pulsed X-ray flux.
Magnetar-like X-ray bursts (RXTE).
Timing noise.

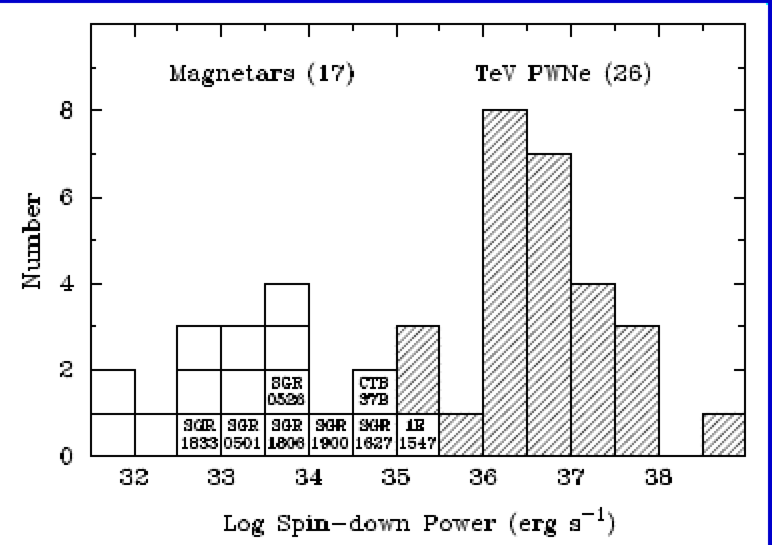


0802.1242, 0802.1704

A Magnetar in a HESS source



A magnetar with P=3.2 s is found in a SNR, which is a known TeV source.
B~ 4.8 10^{14} G
This is the only magnetar associated with a TeV source.

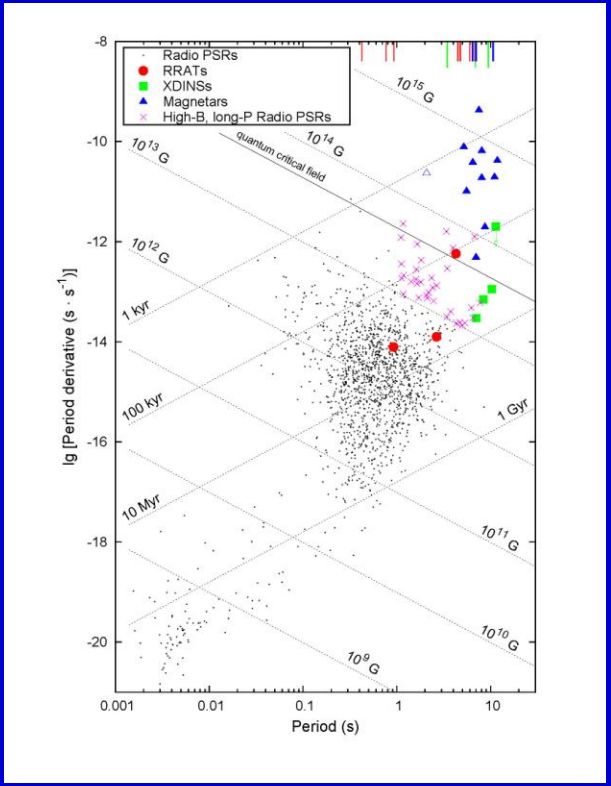


ApJ 710, 941 (2010)

1008.2558

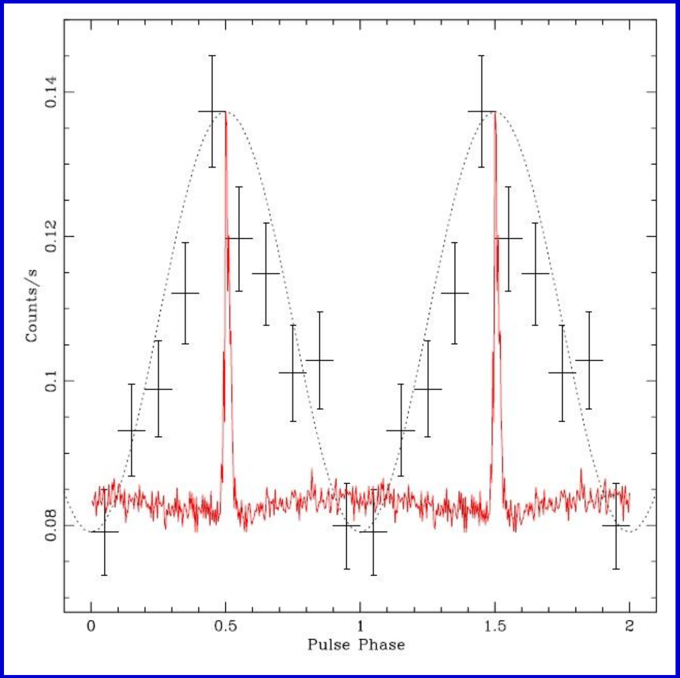
RRAT like M7

RRAT J1819-1458 detected in the X-rays, spectrum soft and thermal, kT ~ 120 eV (Reynolds et al 2006)



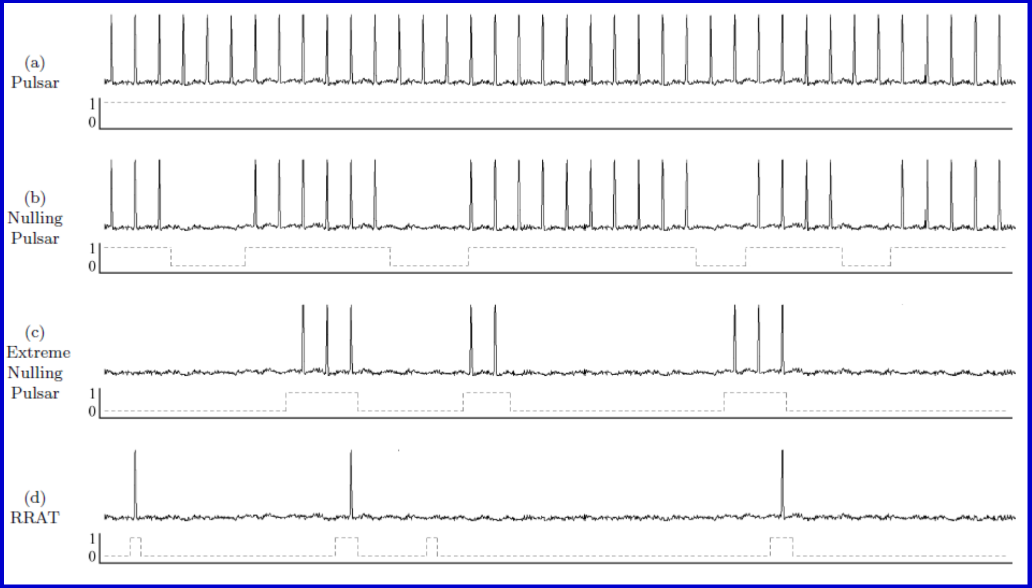
X-ray pulses overlaped on radio data of RRAT J1819-1458.

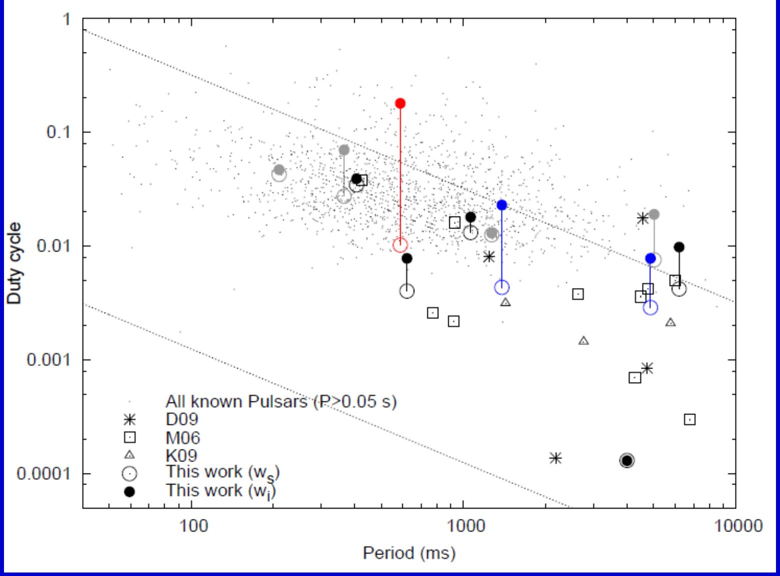
(arXiv: 0710.2056)



RRATs and PSRs

There are known PSRs which show very narrow strong bursts in radio, there are intermittent PSRs.
Now, there are RRATs, for which normal PSR emission is detected.



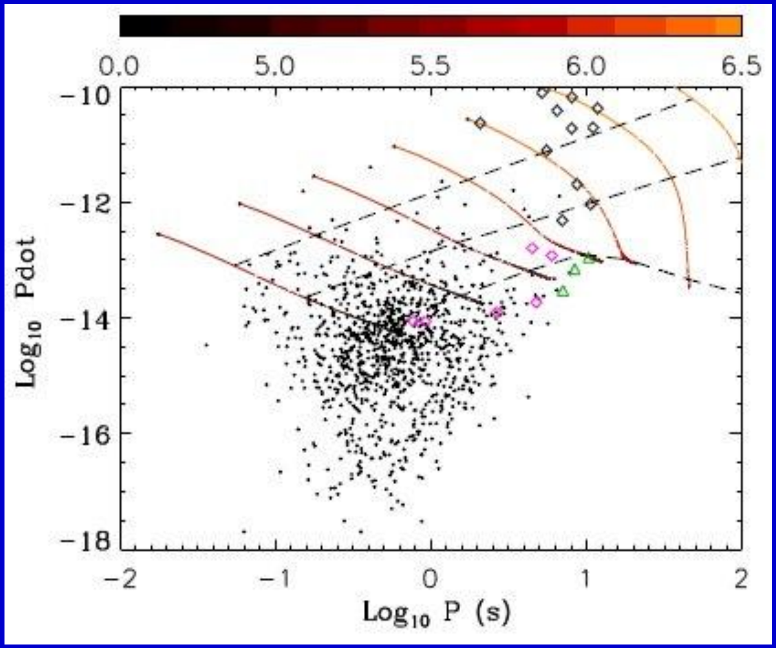


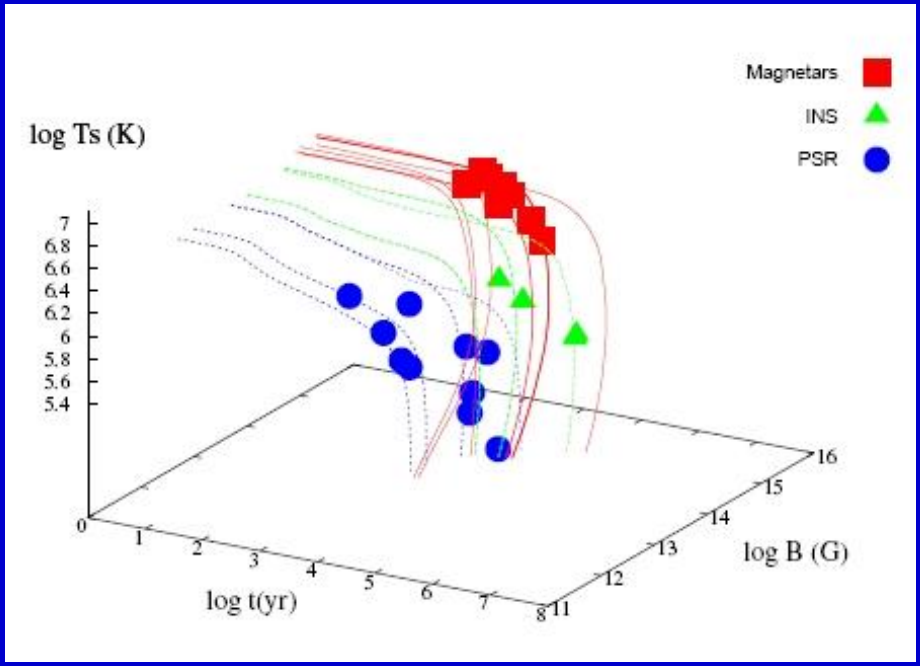
0911.1790

Grand unification

The task is to describe different observed populations of NSs in a single framework. For a recent discussion see Kaspi arXivL 1005.0876.

An attempt was made by Popov et al. (arXiv: 0910.2190) in the model of decaying magnetic field.





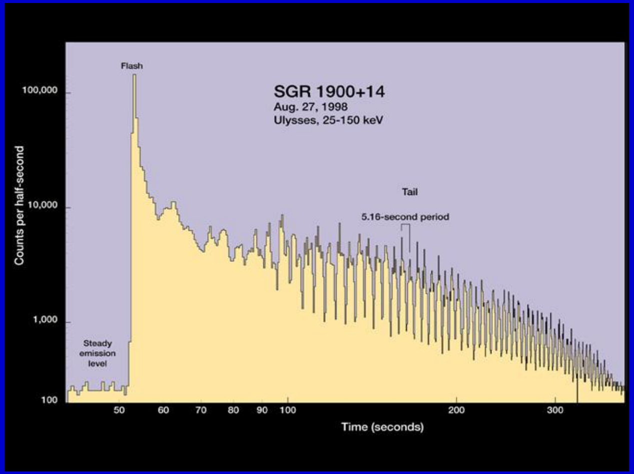
Conclusion

- There are several types of sources: CCOs, M7,

  SGRs, AXPs, RRATs ...
- Magnetars (?)
- Significant fraction of all newborn NSs
- Unsolved problems:

  1. Are there links?

  2. Reasons for diversity



Some reviews on isolated neutron stars

• NS basics:	physics/0503245
	astro-ph/0405262
• SGRs & AXPs:	astro-ph/0406133
	arXiv:0804.0250
• CCOs:	astro-ph/0311526
	arxiv:0712.2209
• Quark stars:	arxiv:0809.4228
• The Magnificent Seven:	astro-ph/0609066
	arxiv:0801.1143
• RRATs:	arXiv:0908.3813
• Cooling of NSs:	arXiv: 0906.1621
	astro-ph/0402143
• NS structure	arXiv:0705.2708
• EoS	astro-ph/0612440
	arxiv: 0808.1279
• NS atmospheres	astro-ph/0206025
• NS magnetic fields	arxiv:0711.3650
	arxiv:0802.2227
• Grand unification	arXiv:1005.0876

Read the OVERVIEW in the book by Haensel, Yakovlev, Potekhin

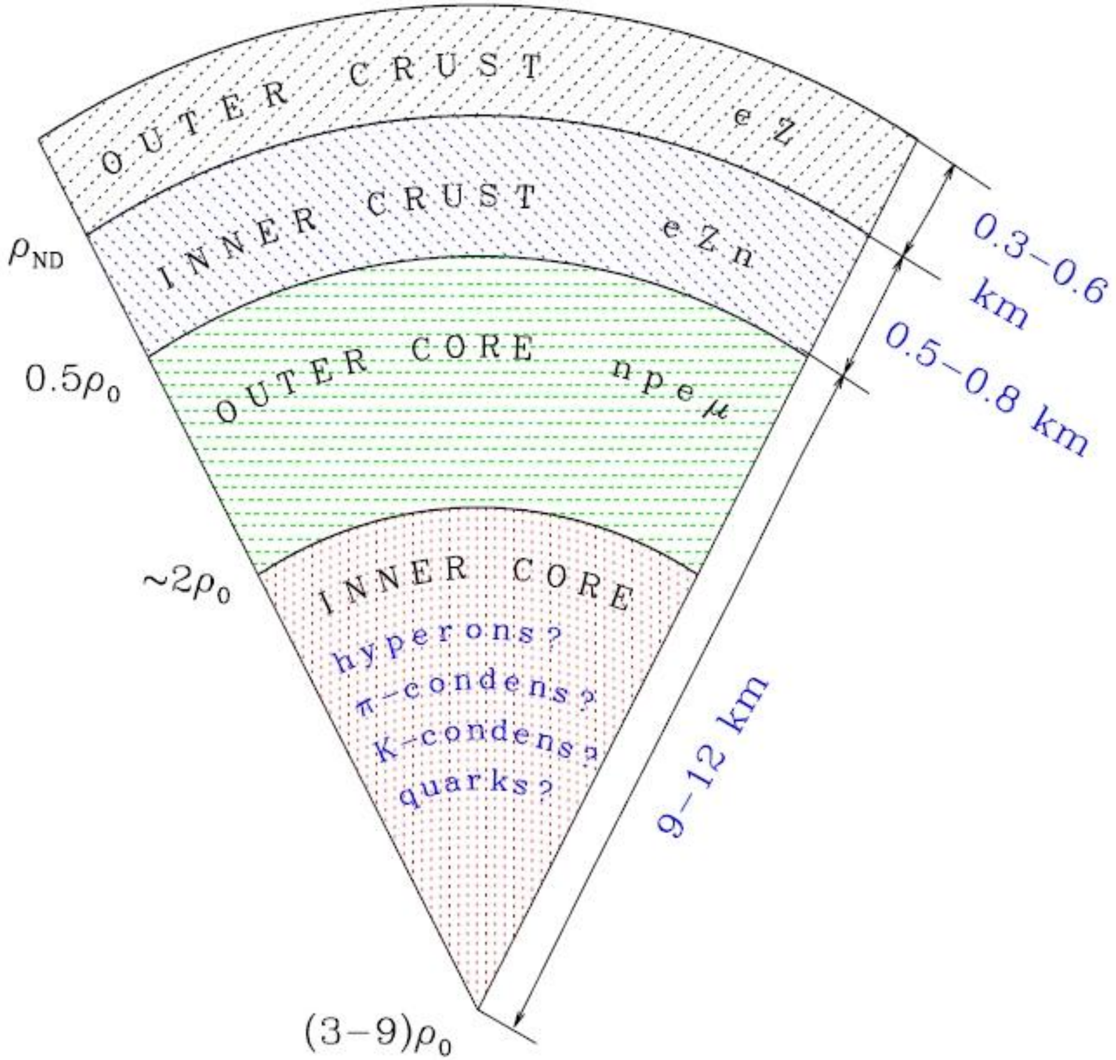
TOV equation

$$R_{ik} - \frac{1}{2} g_{ik} R = \frac{8\pi G}{c^4} T_{ik}$$

$$\begin{cases} (1) \quad \dfrac{dP}{dr} = -\dfrac{G\rho m}{r^2}\left(1 + \dfrac{P}{\rho c^2}\right)\left(1 + \dfrac{4\pi r^3 P}{m c^2}\right)\left(1 - \dfrac{2Gm}{r c^2}\right)^{-1} \\ (2) \quad \dfrac{dm}{dr} = 4\pi r^2 \rho \\ (3) \quad \dfrac{d\Phi}{dr} = -\dfrac{1}{\rho c^2}\dfrac{dP}{dr}\left(1 + \dfrac{P}{\rho c^2}\right)^{-1} \\ (4) \quad P = P(\rho) \end{cases}$$

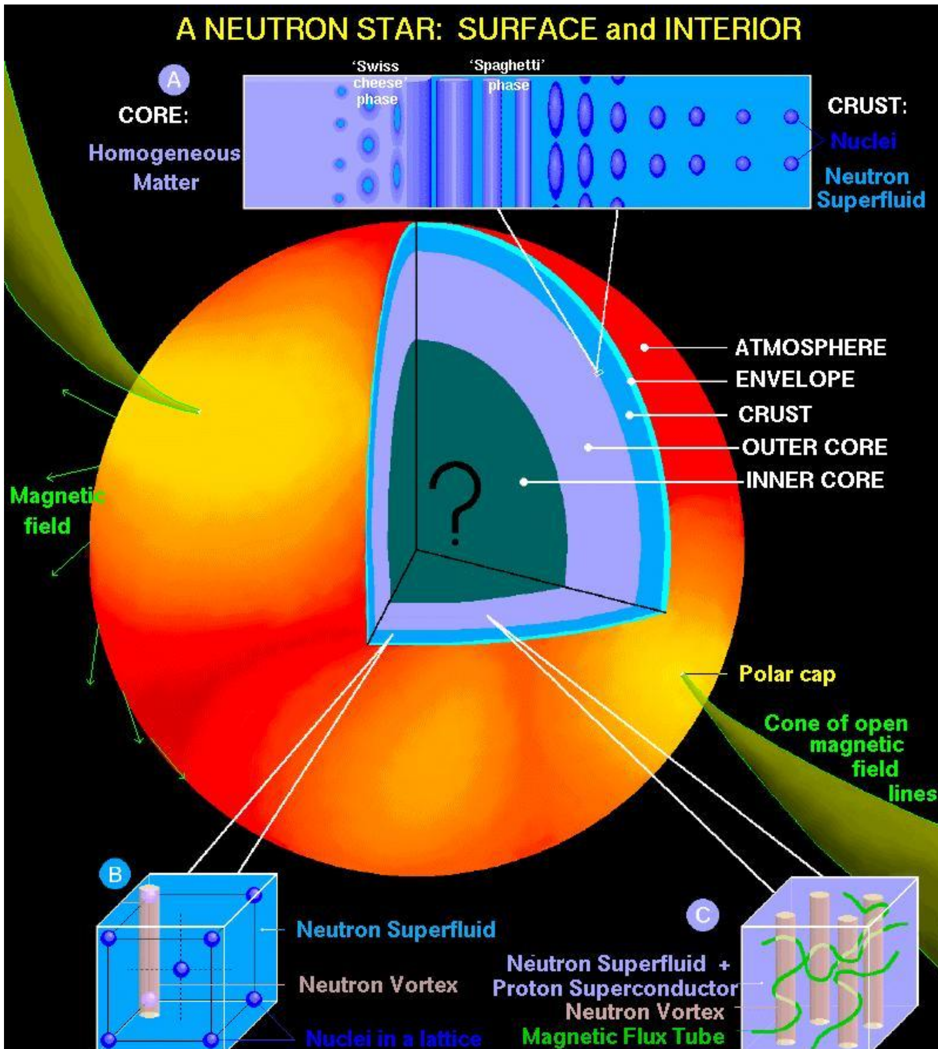
Tolman (1939)
Oppenheimer-Volkoff (1939)

Structure and layers

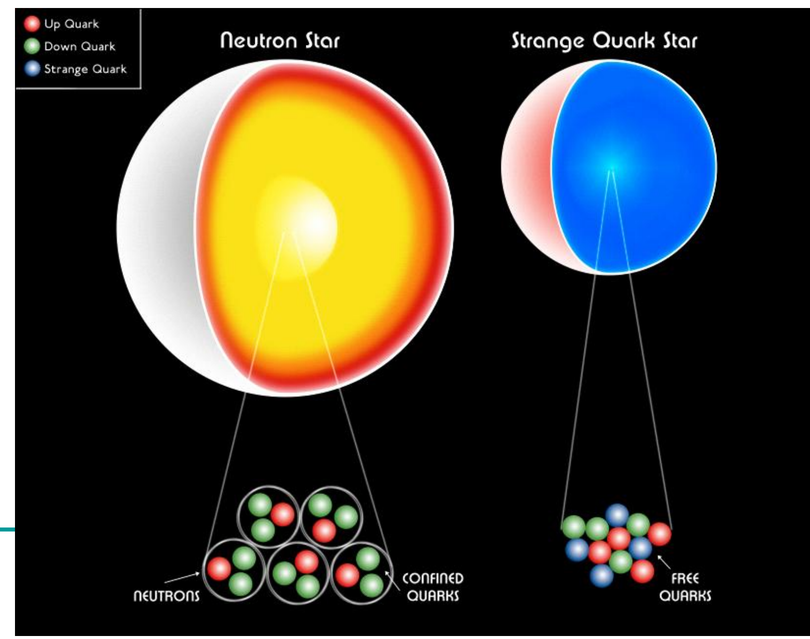


Plus an atmosphere...

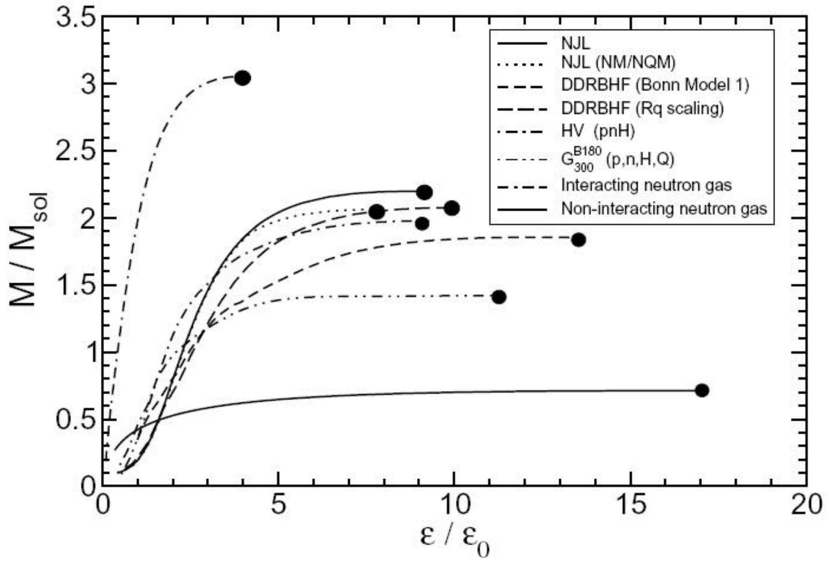
Neutron star interiors



Radius: 10 km
Mass: 1-2 solar
Density: above the nuclear
Strong magnetic fields

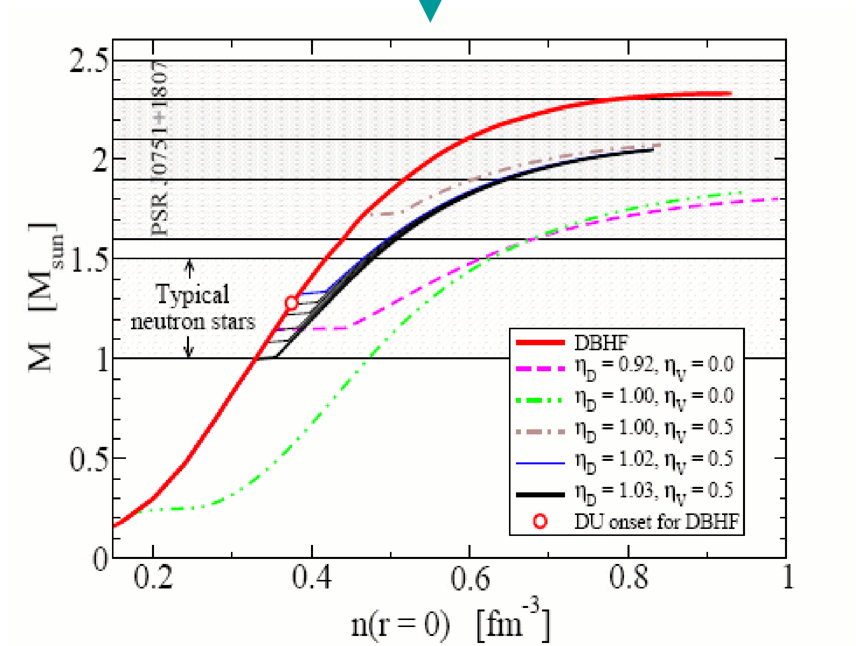


Configurations



NS mass vs. central density (Weber et al. arXiv: 0705.2708)

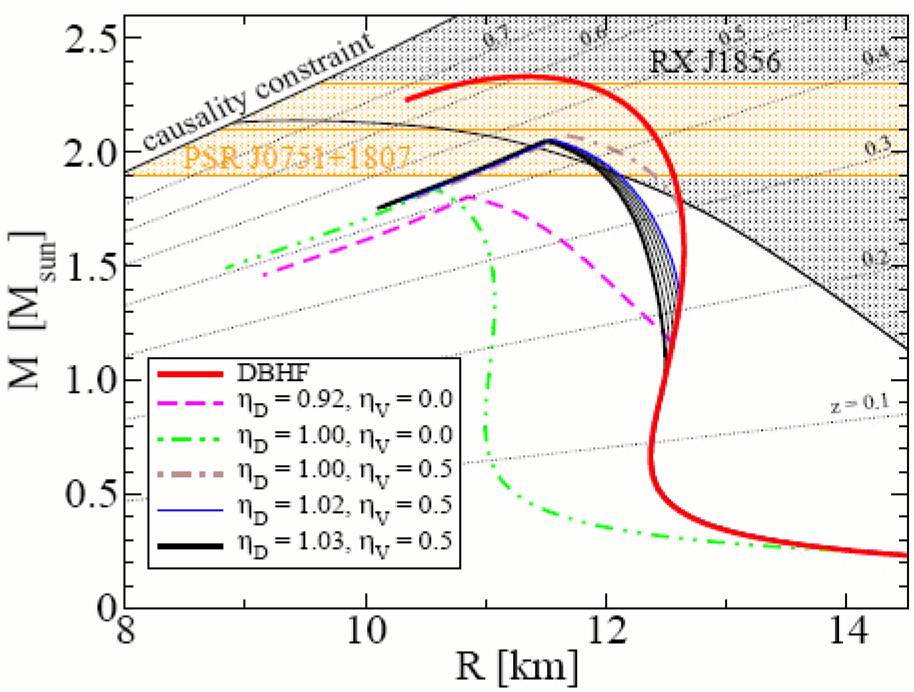
Stable configurations for neutron stars and hybrid stars (astro-ph/0611595).



A RNS code is developed
and made available to the public
by Sterligioulas and Friedman
ApJ 444, 306 (1995)
http://www.gravity.phys.uwm.edu/rns/

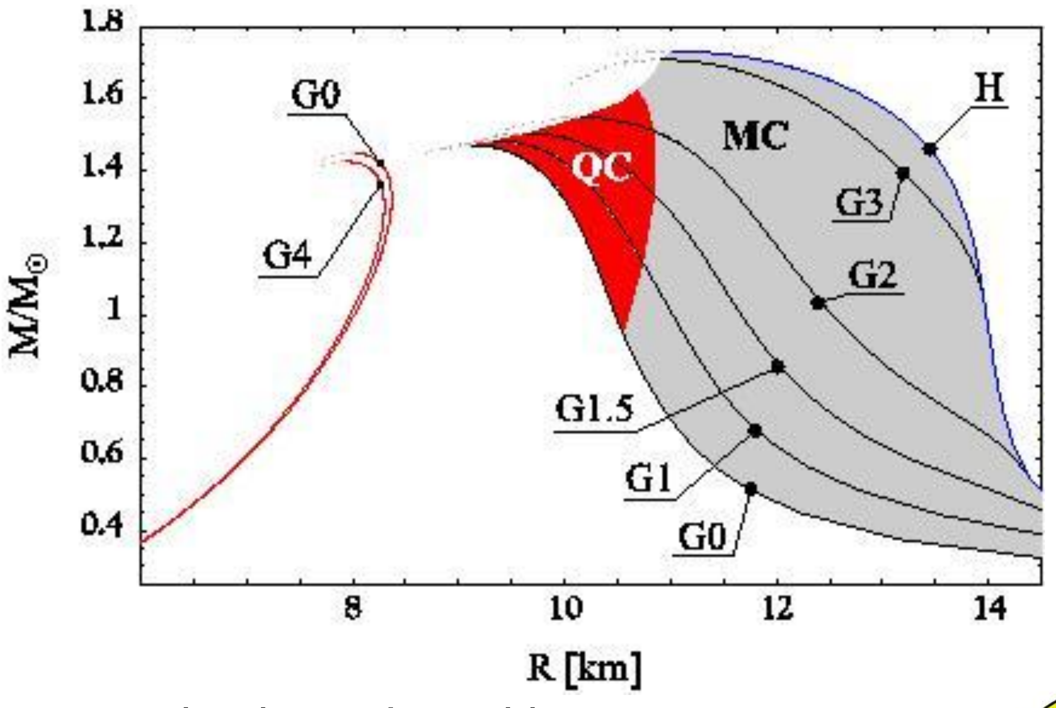
Mass-radius

Mass-radius relations for CSs with possible phase transition to deconfined quark matter.



(astro-ph/0611595)

Mass-radius relation

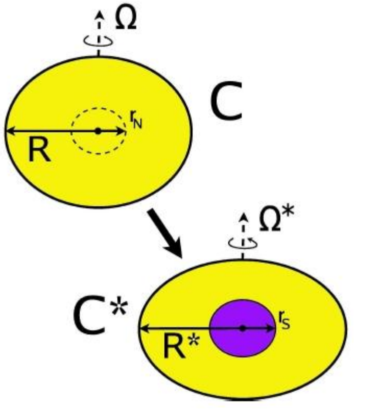


Main features

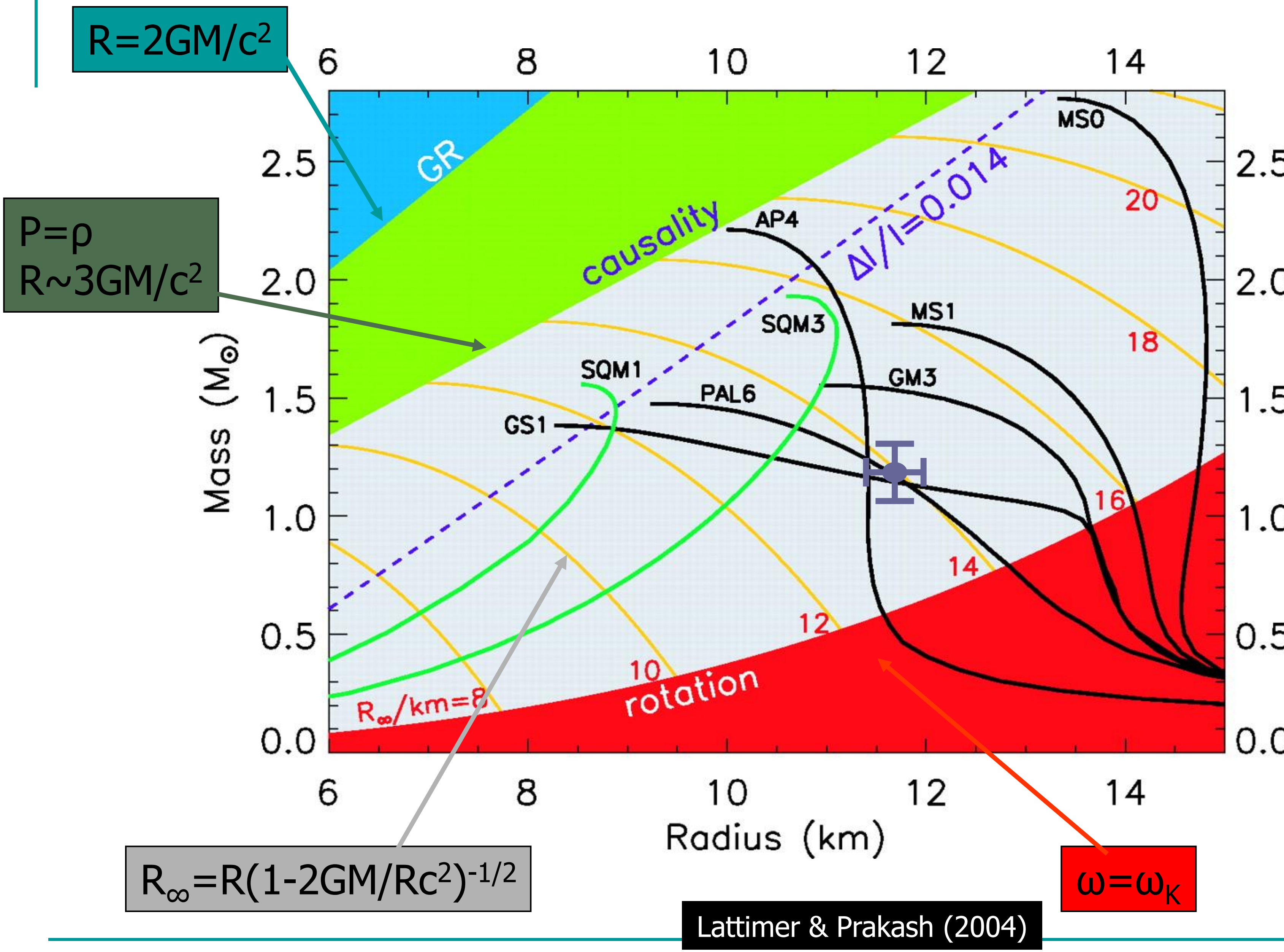
- Max. mass
- Diff. branches (quark and normal)
- Stiff and soft EoS
- Small differences for realistic parameters
- Softening of an EoS with growing mass

Rotation is neglected here.
Obviously, rotation results in:
- larger max. mass
- larger equatorial radius

Spin-down can result in phase transition.

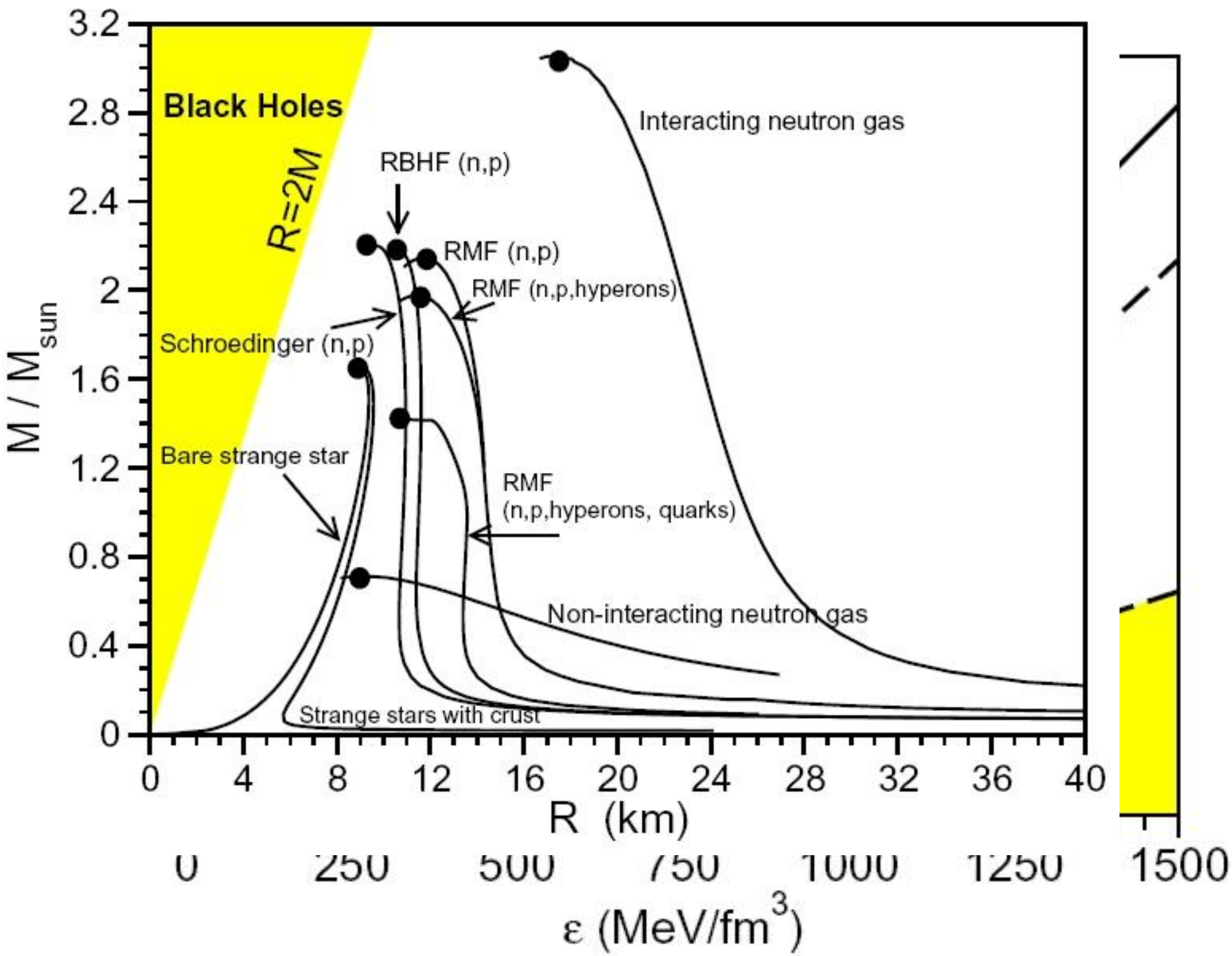


Haensel, Zdunik
astro-ph/0610549



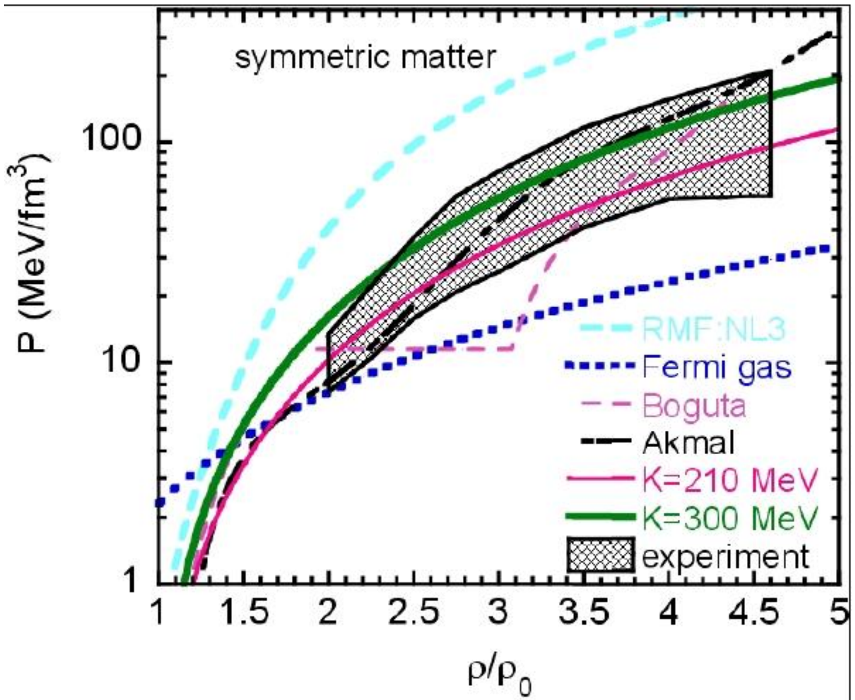
R=2GM/c²
P=ρ
R~3GM/c²
GR
causality
ΔI/I=0.014
MS0
AP4
MS1
SQM3
SQM1
GM3
PAL6
GS1
20
18
16
14
12
10
R∞/km=8
rotation
Mass (M☉)
Radius (km)
R∞=R(1-2GM/Rc²)^-1/2
ω=ωK
Lattimer & Prakash (2004)

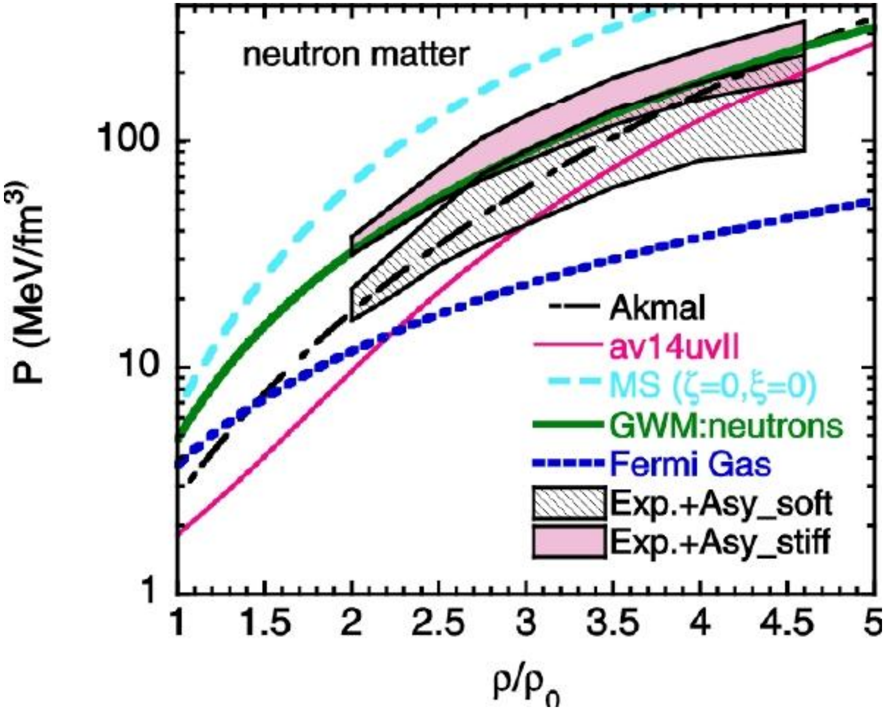
EoS



(Weber et al. ArXiv: 0705.2708)

Experimental results and comparison





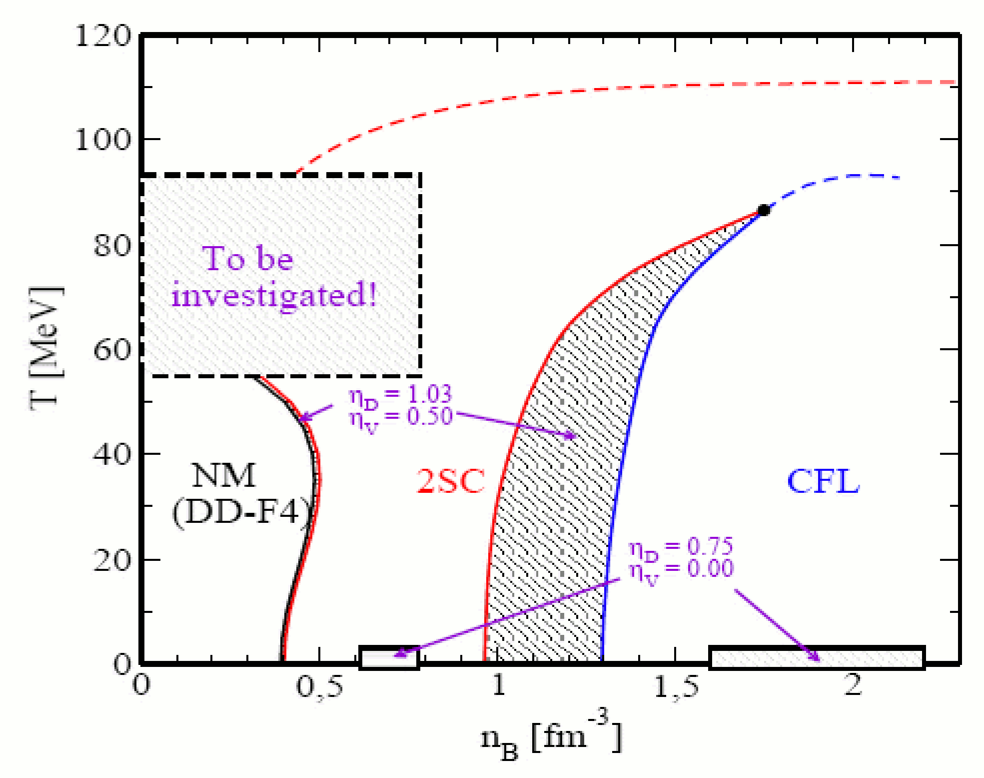
1 Mev/fm^3 = 1.6 10^{32} Pa

GSI-SIS and AGS data

(Danielewicz et al. nucl-th/0208016)

Phase diagram

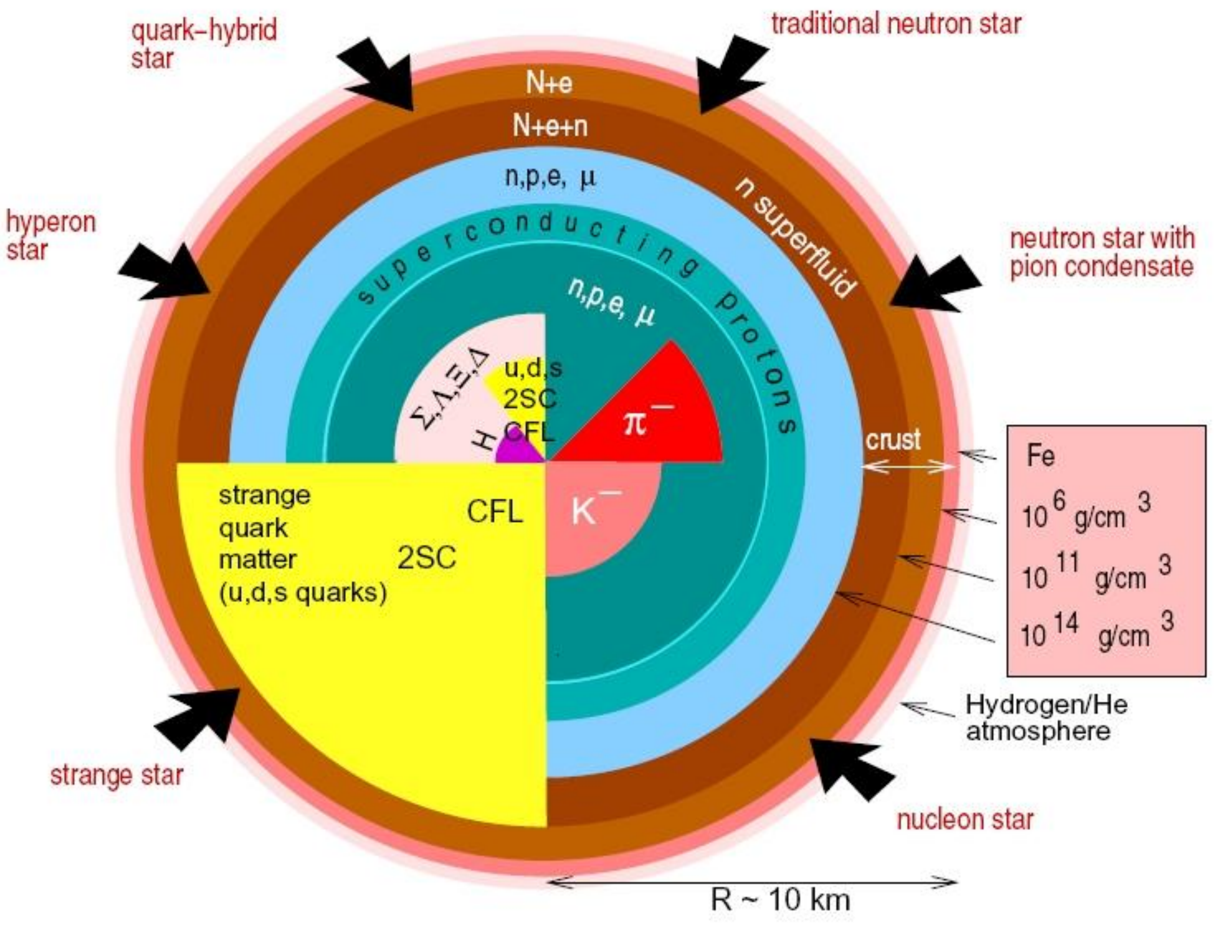
Neutron stars are cold!
That makes them a unique tool.



Phase diagram for isospin symmetry using the most favorable hybrid EoS studied in astro-ph/0611595.

(astro-ph/0611595)

NS interiors: resume



(Weber et al. ArXiv: 0705.2708)

Papers to read

1. astro-ph/0405262 Lattimer, Prakash "Physics of neutron stars"

2. 0705.2708 Weber et al. "Neutron stars interiors and equation of state of superdense matter"

3. physics/0503245 Baym, Lamb "Neutron stars"

4. 0901.4475 Piekarewicz “Nuclear physics of neutron stars” (first part)

5. 0904.0435 Paerels et al. “The Behavior of Matter Under Extreme Conditions”

6. The book by Haensel, Yakovlev, Potekhin