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50 years since the discovery of pulsars -  
precise probes of space, time and matter  
under extreme conditions

David Blaschke (Univ. Wroclaw & JINR Dubna)

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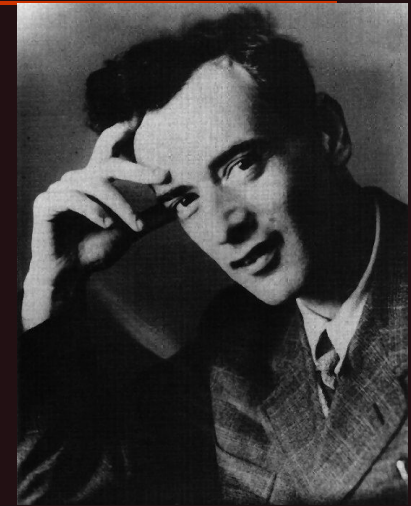
State University “Dubna”, 09.02.2017

# Prediction ...

Neutron stars have been predicted in 30s:

L.D. Landau: Star-nuclei (1932) + anecdote

Baade and Zwicky:  
neutron stars and supernovae (1934)



(Landau)



(Baade)



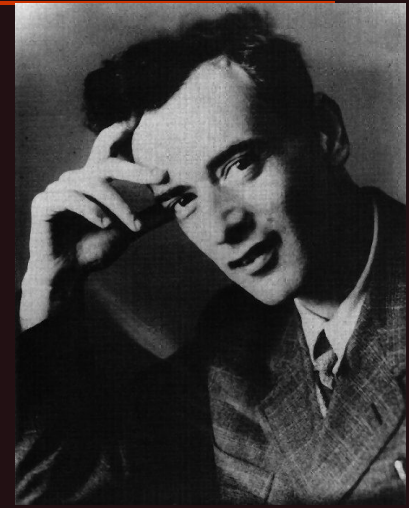
(Zwicky)

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(Landau)



(Baade)



(Zwicky)

(from lectures by D. Yakovlev)

In any case, with the discovery of X-ray sources and quasars, dozens of theoreticians focused their attention on the equilibrium properties of compact stars and on star collapse. But in spite of this mounting theoretical effort, most

<sup>2</sup>Baade and Zwicky (1934): “With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.”

— According to Rosenfeld (1974), on the day that word came to Copenhagen from Cambridge telling of Chadwick’s discovery of the neutron in 1932, he, Bohr, and Landau spent the evening discussing possible implications of the discovery. It was then that Landau suggested the possibility of cold, dense stars composed principally of neutrons. Landau’s only publication on the subject was concerned with neutron cores (Landau, 1938).

<sup>3</sup>Giacconi, Gursky, Paolini, and Rossi (1962).

<sup>4</sup>Chapter 11 is devoted to this subject.

<sup>5</sup>The first QSO identified by Schmidt, 3C273, had a redshift  $\delta\lambda/\lambda = 0.158$ , which was unprecedented for a normal “star.”

<sup>6</sup>Salpeter (1965); in addition to this argument there was strong evidence that quasar redshifts were cosmological in origin.

**Shapiro, Teukolsky (1983)**

(see detailed description in the book by Haensel, Yakovlev, Potekhin and in the e-print arXiv: 1210.0682)

# Landau paper BEFORE neutron discovery

## ON THE THEORY OF STARS.

*By L. Landau.*

(Received 7 January 1932).

From the theoretical point of view the physical nature of Stellar equilibrium is considered.

The astrophysical methods usually applied in attacking the problems of stellar structure are characterised by making physical assumptions chosen only for the sake of mathematical convenience. By this is characterised, for instance, Mr. Milne's proof of the impossibility of a star consisting throughout of classical ideal gas; this proof rests on the assertion that, for arbitrary  $L$  and  $M$ , the fundamental equations of a star consisting of classical ideal gas admit, in general, no regular solution. Mr. Milne seems to have overlooked the fact, that this assertion results only from the assumption of opacity being constant throughout the star, which assumption is made only for mathematical purposes and has nothing to do with reality. Only in the case of this assumption the radius  $R$  disappears from the relation between  $L$ ,  $M$  and  $R$  necessary for regularity of the solution. Any reasonable assumptions about the opacity would lead to a relation between  $L$ ,  $M$  and  $R$ , which relation would be quite exempt from the physical criticisms put forward against Eddington's mass-luminosity-relation.

It seems reasonable to try to attack the problem of stellar structure by methods of theoretical physics, i. e. to investigate the physical nature of stellar equilibrium. For that purpose we must at first investigate the statistical equilibrium of a given mass without generation of energy, the condition for which equilibrium being the minimum of free energy  $F$  (for given temperature). The part of free energy due to gravitation is negative and inversely proportional to some

**Physikalische  
Zeitschrift der Sowjetunion  
Vol. 1, No. 2, 285-188, 1932  
Written: Feb. 1931, Zurich  
Received: Jan. 7, 1932  
Published: Feb. 1932**

we have no need to suppose that the radiation of stars is due to some mysterious process of mutual annihilation of protons and electrons, which was never observed and has no special reason to occur in stars. Indeed we have always protons and electrons in atomic nuclei very close together, and they do not annihilate themselves; and it would be very strange if the high temperature did help, only because it does something in chemistry (chain reactions!). Following a beautiful idea of Prof. Niels Bohr's we are able to believe that the stellar radiation is due simply to a violation of the law of energy, which law, as Bohr has first pointed out, is no longer valid in the relativistic quantum theory, when the laws of ordinary quantum mechanics break down (as it is experimentally proved by continuous-rays-spectra and also made probable by theoretical considerations).<sup>1</sup> We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

On these general lines we can try to develop a theory of stellar structure. The central region of the star must consist of a core of highly condensed matter, surrounded by matter in ordinary state. If the transition between these two states were a continuous one, a mass  $M < M_0$  would never form a star, because the normal equilibrium state (i. e. without pathological regions) would be quite stable. Because, as far as we know, it is not the fact, we must conclude that the condensed and non-condensed states are separated by some unstable states in the same manner as a liquid and its vapour are, a property which could be easily explained by some kind of nuclear attraction. This would lead to the existence of a nearly discontinuous boundary between the two states.

The theory of stellar structure founded on the above considerations is yet to be constructed, and only such a theory can show how far they are true.

February 1931, Zurich.

<sup>1</sup> L. Landau und R. Peierls, ZS. f. Phys. 69, 56, 1931.

**This is correct!**

**Disappeared in reprints,  
so we have difficulties**



# Baade and Zwicky – theoretical prediction

W. Baade (Mt. Wilson Observatory)  
F. Zwicky (Caltech)

The meeting of American Physical  
Society  
(Stanford, December 15-16, 1933)  
Published in Physical Review  
(January 15, 1934)



38. Supernovae and Cosmic Rays. W. BAADE, *Mt. Wilson Observatory*, AND F. ZWICKY, *California Institute of Technology*.—Supernovae flare up in every stellar system (nebula) once in several centuries. The lifetime of a super-

nova is about twenty days and its absolute brightness a maximum may be as high as  $M_{\text{vis}} = -14^M$ . The visible radiation  $L_v$  of a supernova is about  $10^8$  times the radiation of our sun, that is,  $L_v = 3.78 \times 10^{41}$  ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order  $L_\tau = 10^7 L_v = 3.78 \times 10^{48}$  ergs/sec. The supernova therefore emits during its life a total energy  $E_\tau \geq 10^5 L_\tau = 3.78 \times 10^{53}$  ergs. If supernovae initially are quite ordinary stars of mass  $M < 10^{34}$  g,  $E_\tau/c^2$  is of the same order as  $M$  itself. In the *supernova* process *mass in bulk is annihilated*. In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae*. Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order  $\sigma = 2 \times 10^{-3}$  erg/cm<sup>2</sup> sec. The observational values are about  $\sigma = 3 \times 10^{-3}$  erg/cm<sup>2</sup> sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

$t_1 = 10^6$  years + 410 seconds for  $10^{11}$  volt electrons.

$t_2 =$  " + 47.6 days "  $10^9$  " "

$t_3 =$  " + 44 years "  $10^{11}$  " protons.

These time lags  $t_i - t$  would tend to smear out the change of intensity caused by the flare-up of individual supernovae. Dr. R. M. Langer in one of our seminars was the first to call attention to the straggling of simultaneously ejected particles.

#### 5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. BAADE

F. ZWICKY

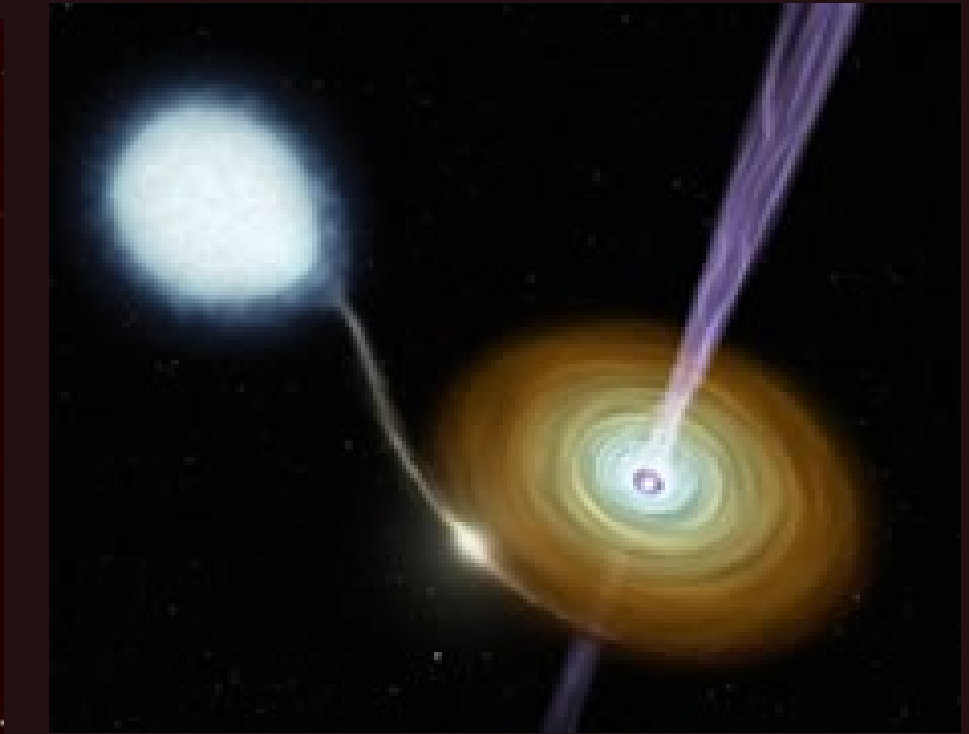
Mt. Wilson Observatory and  
California Institute of Technology, Pasadena.  
May 28, 1934.

Phys. Rev. 46, 76, 1934 (July 1)



# Good old classics

For years two main types of NSs have been discussed:  
radio pulsars and accreting NSs in close binary systems



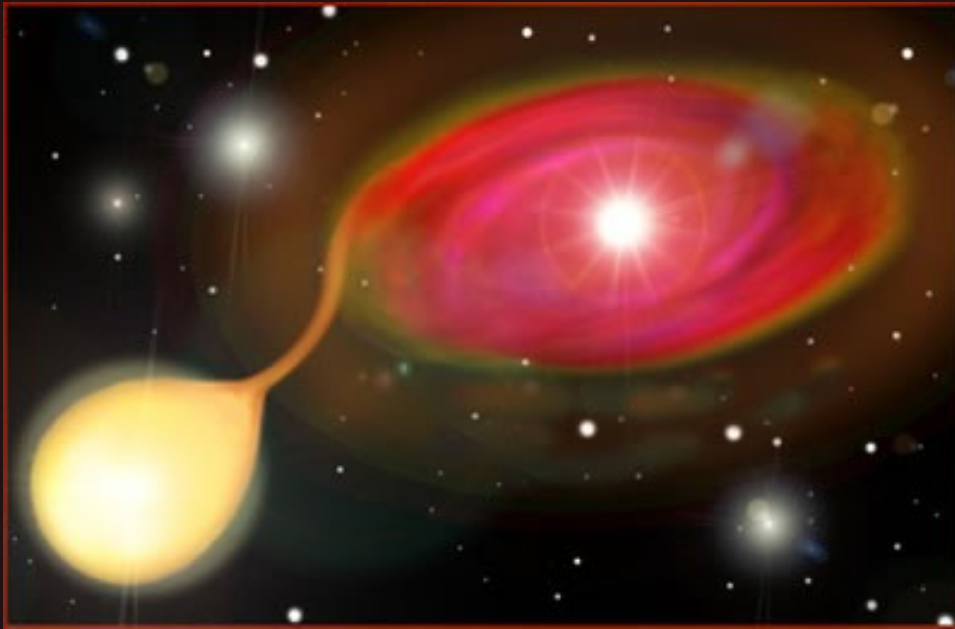
The pulsar in the Crab nebula

A binary system

# The old zoo of neutron stars

In 60s the first X-ray sources have been discovered.

They were neutron stars in close binary systems, BUT ...  
.... they were «not recognized»....



Now we know hundreds of X-ray binaries with neutron stars in the Milky Way and in other galaxies.

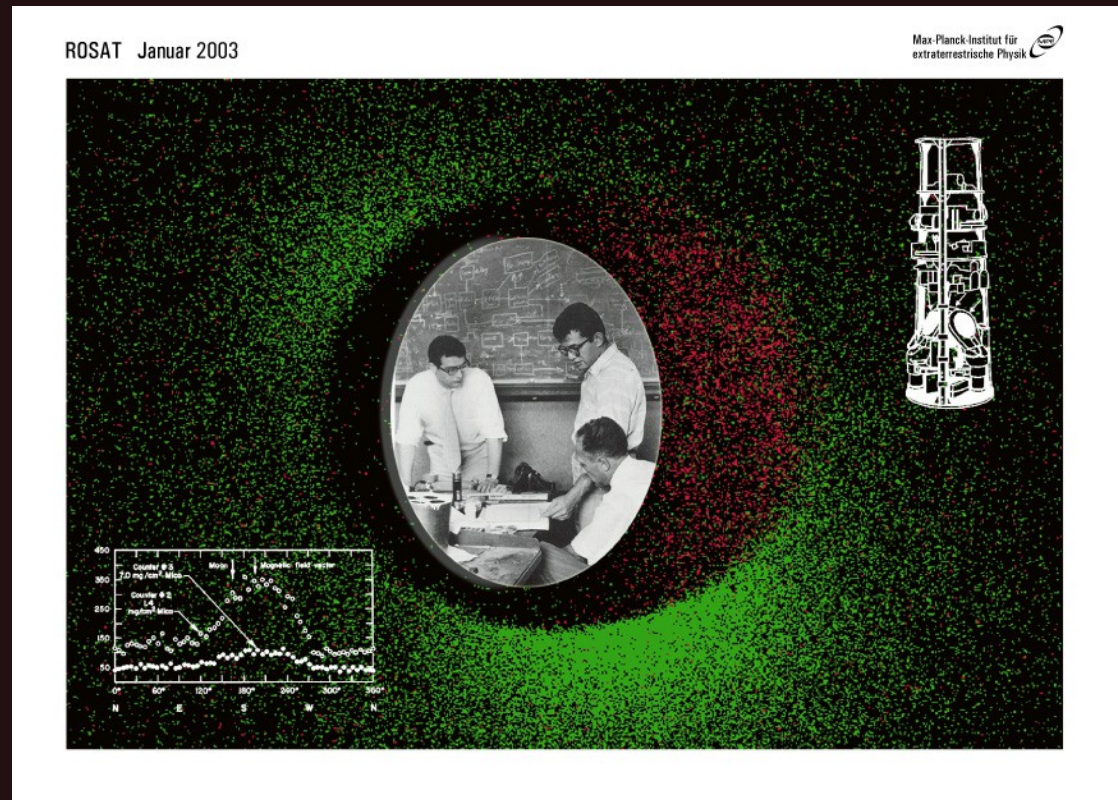
# Rocket experiments

## Sco X-1

Giacconi, Gursky, Hendel

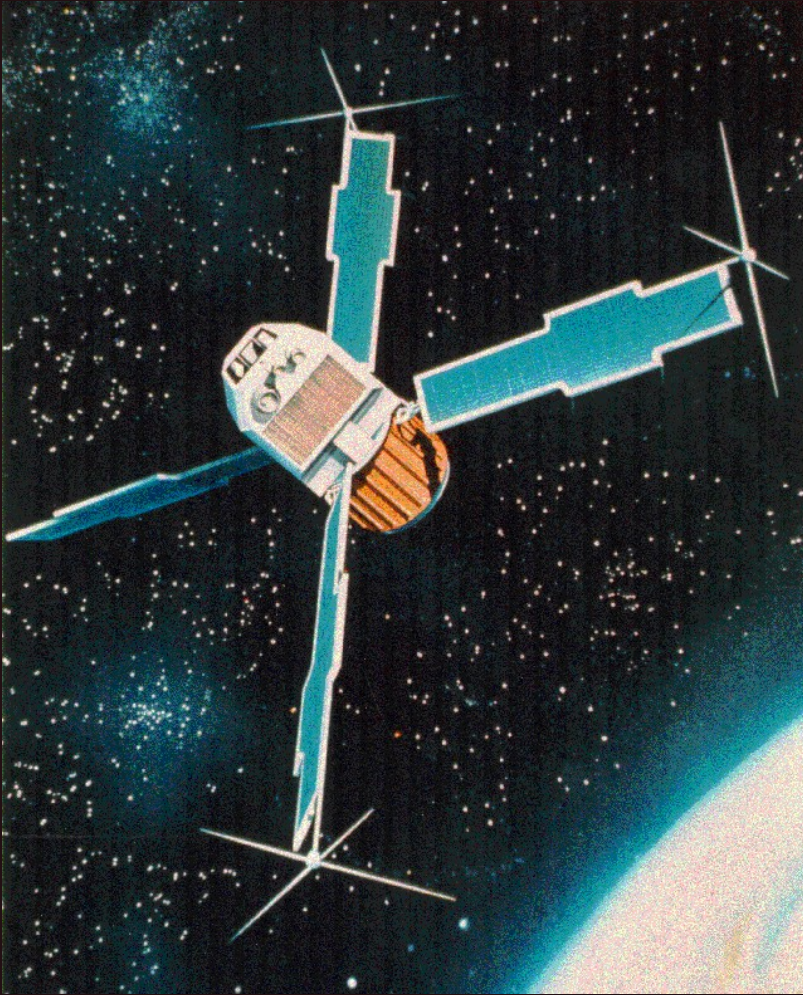
1962

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





# UHURU



The satellite was launched on December 12, 1970.

The program was ended in March 1973.

The other name SAS-1

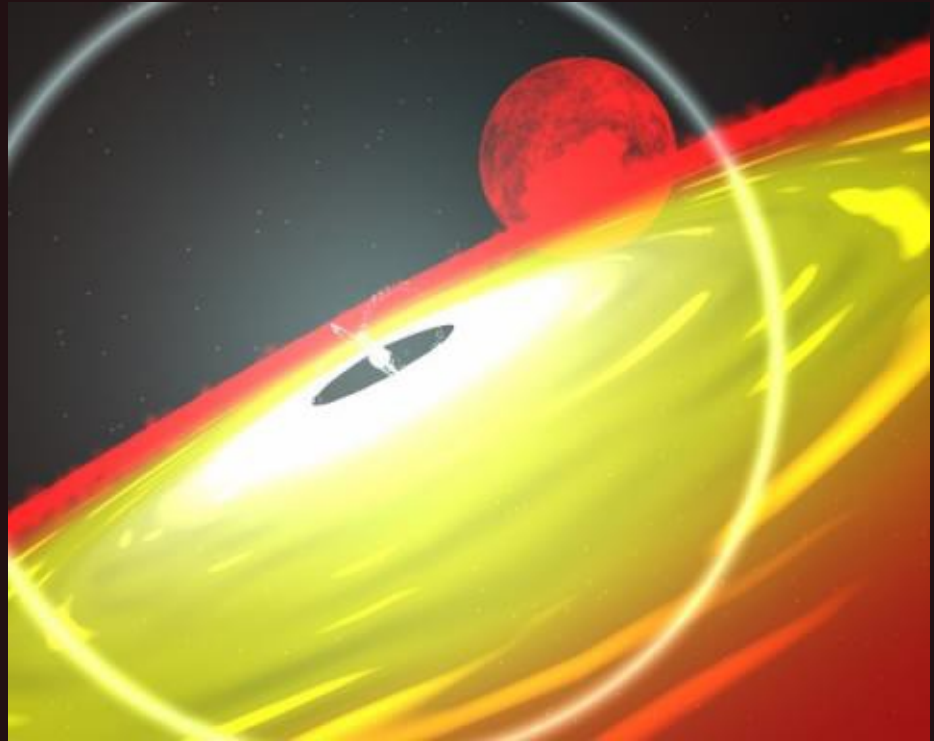
2-20 keV

The first full sky survey.  
339 sources.

# Accretion in close binaries

Accretion is the most powerful source of energy realized in Nature, which can give a huge energy output.

When matter falls down onto the surface of a neutron star up to 10% of  $mc^2$  can be released.





# Accretion disc



The theory of accretion discs was developed in 1972-73 by N.I. Shakura and R.A. Sunyaev.

Accretion is important not only in close binaries, but also in active galactic nuclei and many other types of astrophysical sources.

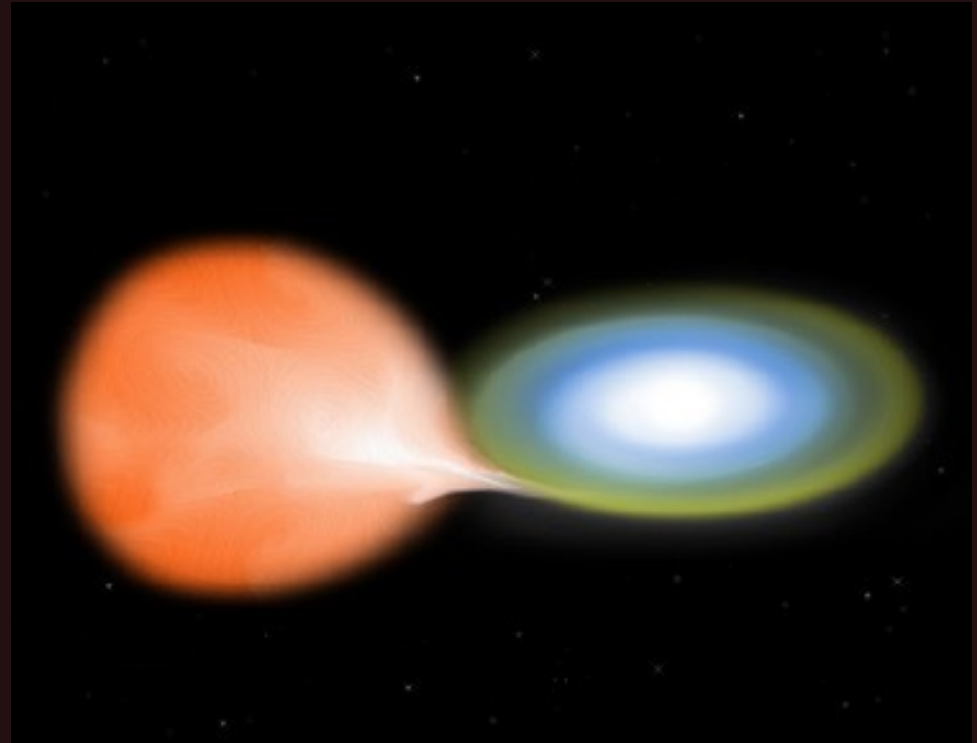
# Close binary systems

About 1/2 of massive stars  
Are members of close binary  
systems.

Now we know many dozens  
of close binary systems with  
neutron stars.

$$L = \dot{M} \eta c^2$$

The accretion rate can be up to  $10^{20}$  g/s;  
Accretion efficiency – up to 10%;  
Luminosity – thousands of hundreds of the solar.



# Discovery !!!!

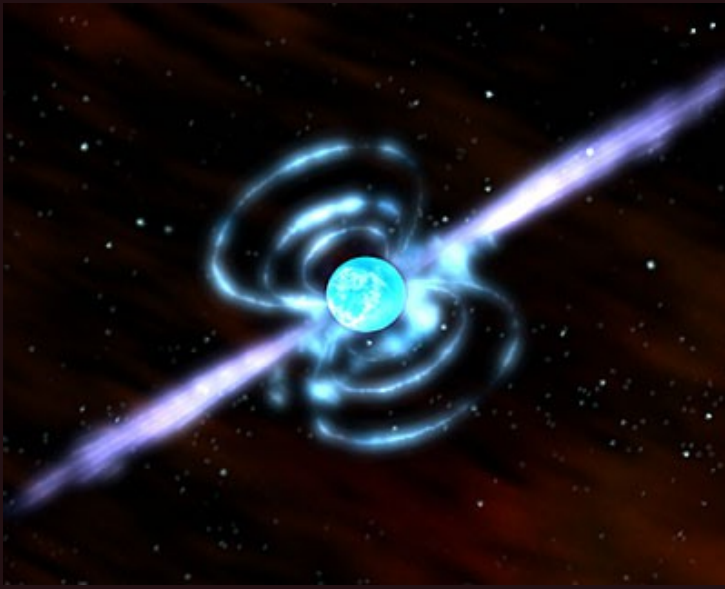
1967: Jocelyn Bell discovers pulsating radio frequency

Source, pulse interval 1.34 sec; pulse duration 0.01 sec

→ radio pulsars! (Nobel prize 1974 for Anthony Hewish)

Today more than 2500 pulsars, some have extremely

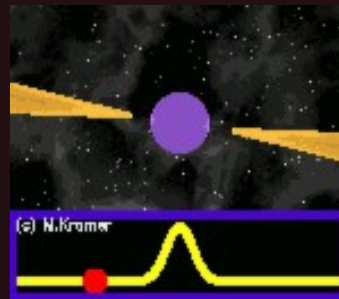
Stable frequency:  $\Delta T/T \sim 1 \text{ sec} / 100 \text{ million million years}$



# Discovery !!!!

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Today more than 2500 pulsars, some have extremely  
Stable frequency:  $\Delta T/T \sim 1 \text{ sec} / 100 \text{ million million years}$

1968: Thomas Gould explains high precision by rotation  
Only small objects ( $R \sim 10 \text{ km}$ ) can have so short pulses



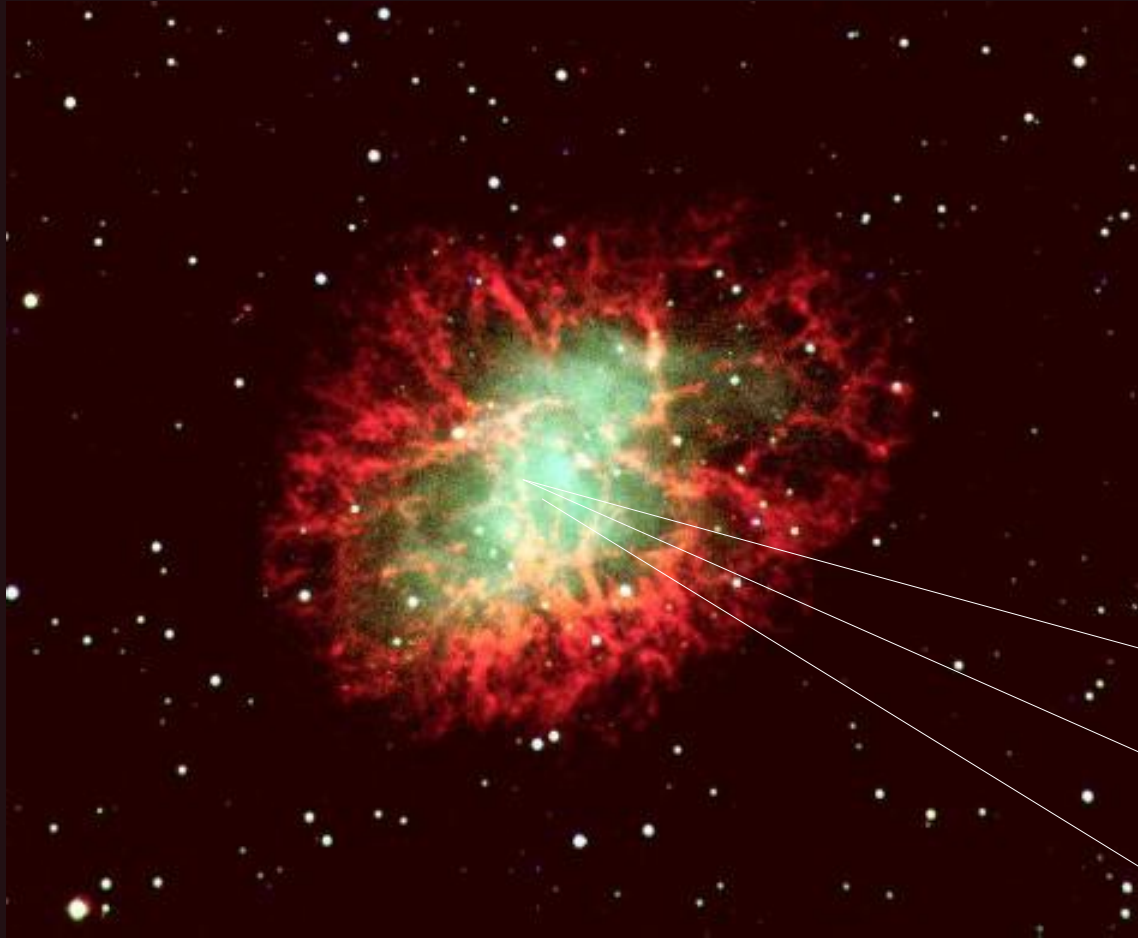
# The pulsar in the Crab nebula



1969: Discovery of the pulsar  
In the Crab nebula.



# The pulsar in the Crab nebula



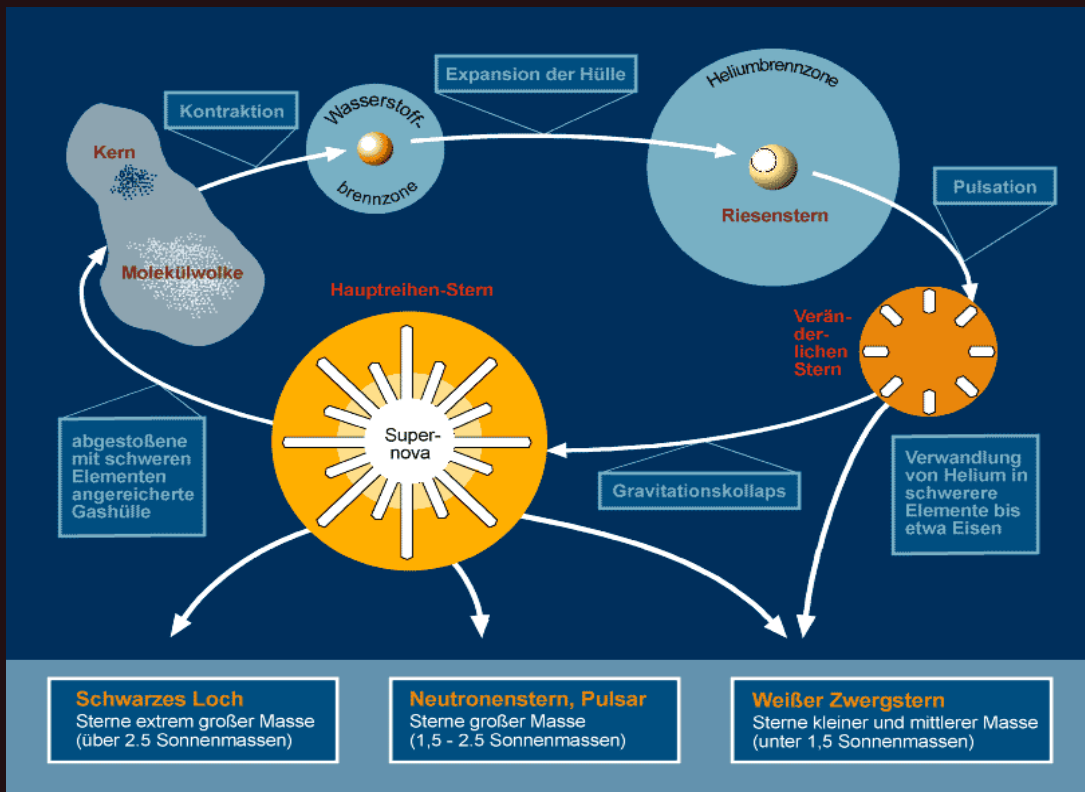
1969: Discovery of the pulsar  
In the Crab nebula.

Connection established:  
Supernova-Neutron Star-Pulsar



# The life cycle of stars

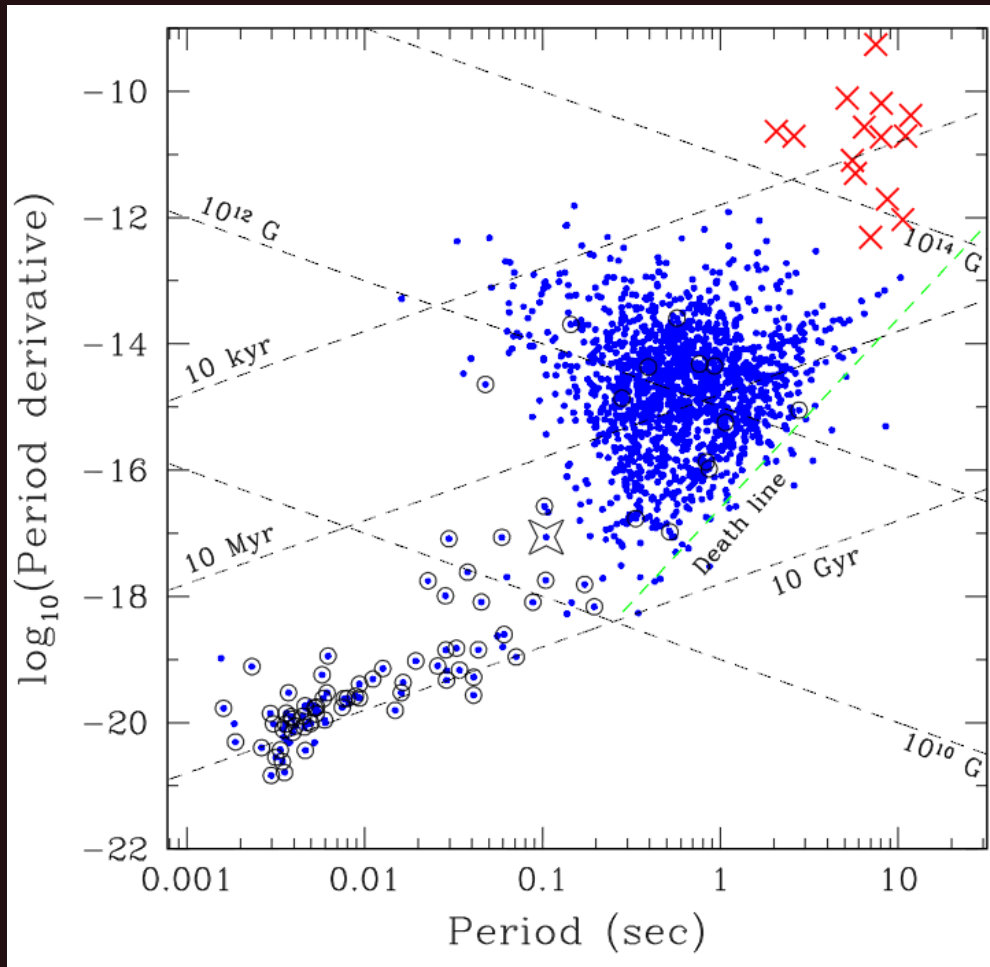
- Supernova Type I (Carbon core): Explosive 'Burning', star is completely destroyed
- Supernova Type II (Iron core): Implosion due to gravitational instability, subsequent shockwave explosion and neutrino emission ⇒ blast of the star envelope, star interior collapses ⇒ **NEUTRON STAR** or **BLACK HOLE**



## Neutron star-Properties:

- Radius:  $R \approx 10 \text{ km}$
- Density:  $\rho \approx 10^{14} \dots 10^{15} \text{ g/cm}^3$
- Mass:  $M \approx M_{\odot} = 2 \times 10^{30} \text{ kg}$
- Rotation: Period  $T < 1 \text{ sec}$ , for progenitor star  $T \approx 30 \text{ d}$  (Sun)
- Magnetic field: contraction increases the density of field lines dramatically →  $H/H_{\text{earth}} \approx 10^{12}$

# Statistics of Pulsars



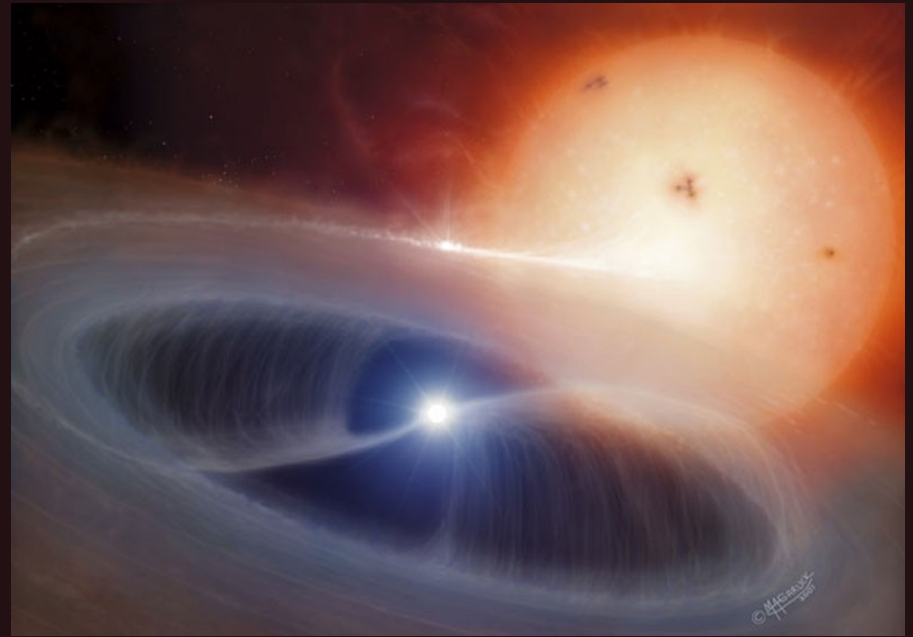
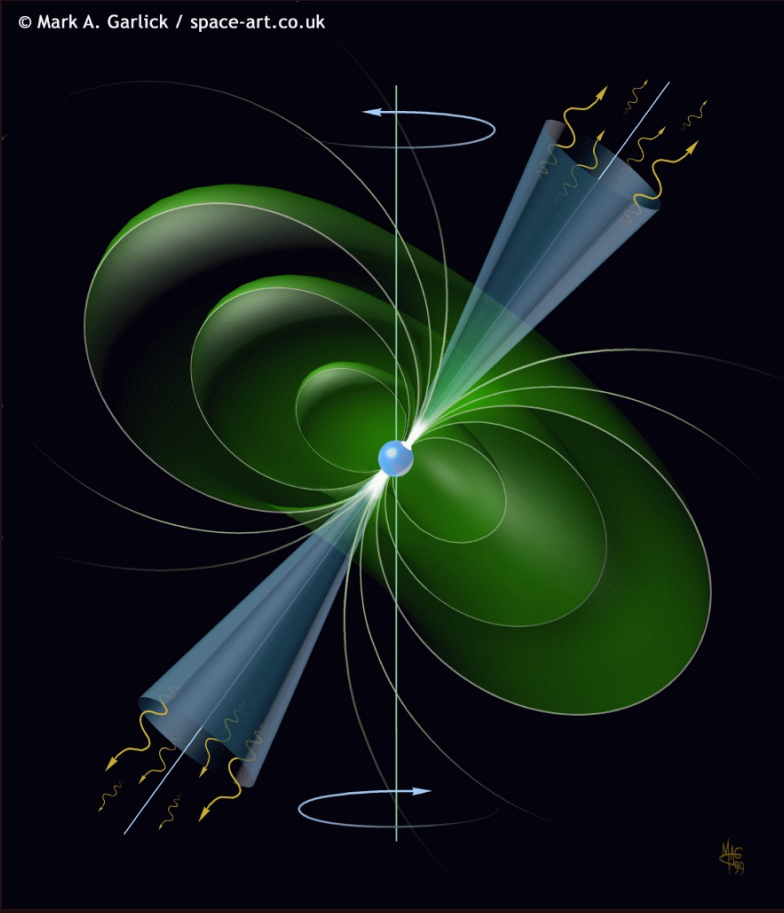
Magnetars:  
 $B > 10^{15}$  Gauss

Young pulsars:  
 $P < 1$  sec  
 $B \sim 10^{12}$  Gauss

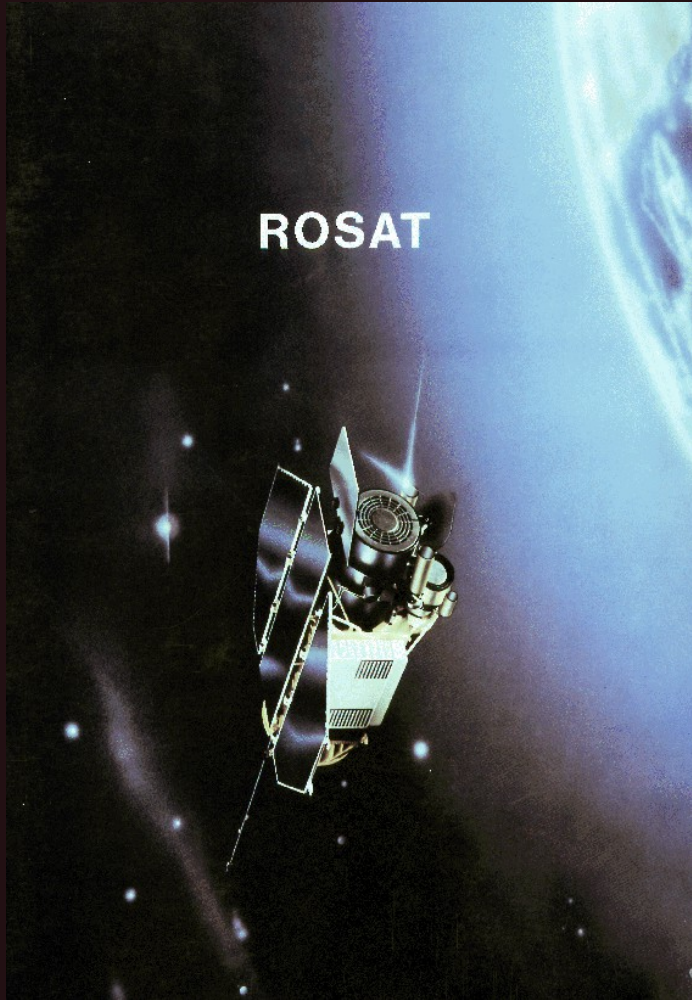
Recycled (old) Pulsars:  
 $P \sim$  few milliseconds  
 $B \sim 10^8$  Gauss

# The old Zoo: young pulsars & old accretors

© Mark A. Gartick / space-art.co.uk



# ROSAT



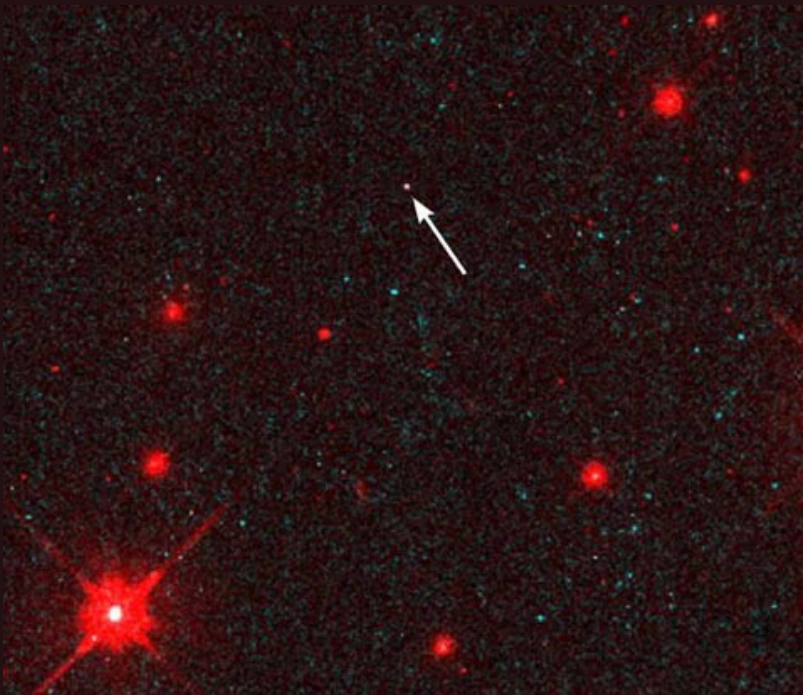
## ROentgen SATellite

German satellite  
(with participation of US and UK).

Launched 01 June 1990.  
The program was successfully ended  
on 12 Feb 1999.



# Close-by radioquiet NSs



RX J1856.5-3754

- Discovery: Walter et al. (1996)
- Proper motion and distance: Kaplan et al.
- No pulsations
- Thermal spectrum
- Later on: six brothers

# Magnificent Seven (M7)



**Radioquiet**  
**Close-by**  
**Thermal emission**  
**Absorption features**  
**Long periods**

Name	Period, s
RXJ 1856	7.05
RXJ 0720	8.39
RBS 1223	10.31
RBS 1556	6.88?
RXJ 0806	11.37
RXJ 0420	3.45
RBS 1774	9.44

# Resolution of radius puzzle for RX J1856 ?

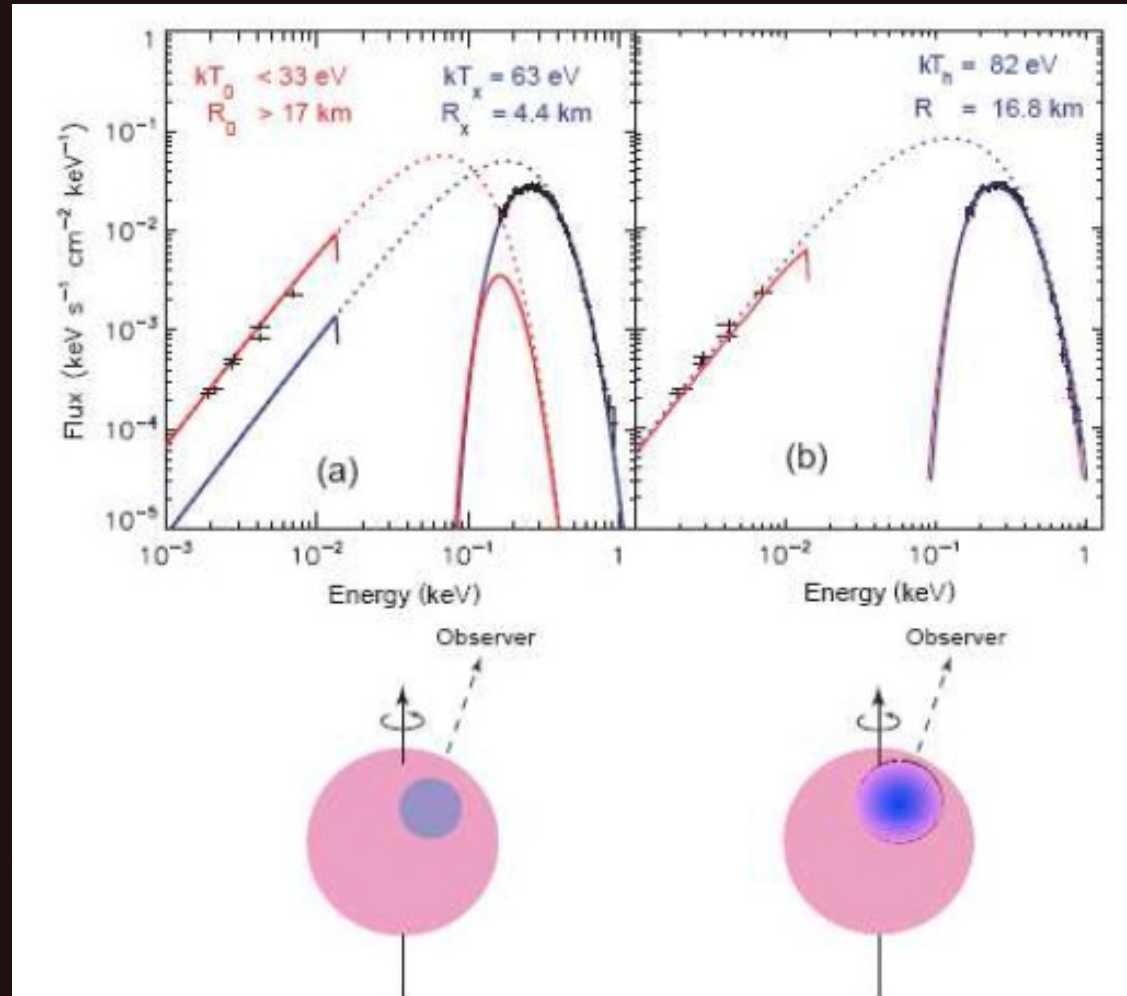
Blackbody fits to the optical  
And X-ray spectra  
(Truemper et al., 2004)

Two-component model or  
Model with continuous  
T-distribution (hot spots)

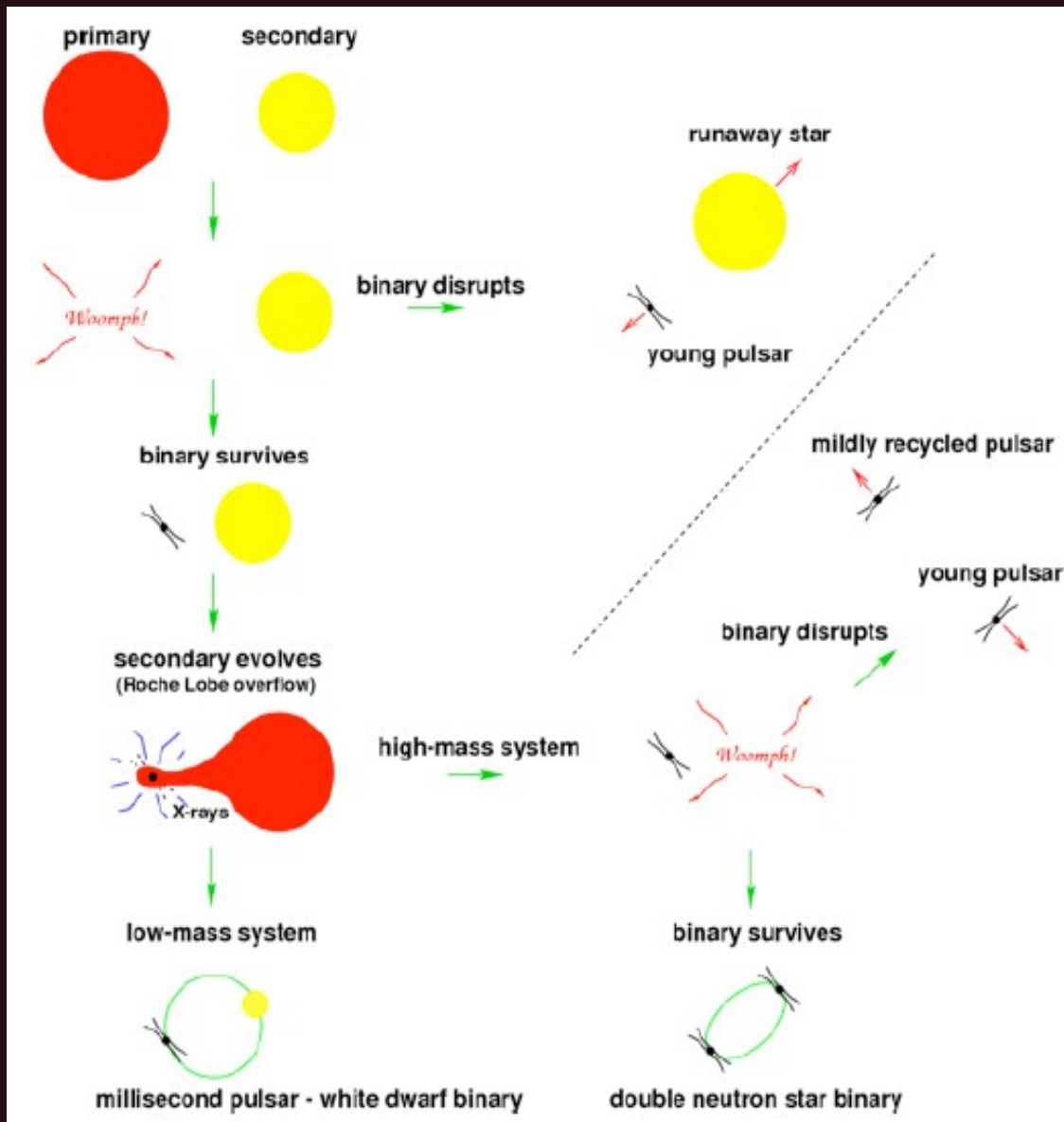
Radius determination

--> EoS

--> matter at high densities



# Double Neutron Stars and Millisecond Pulsars



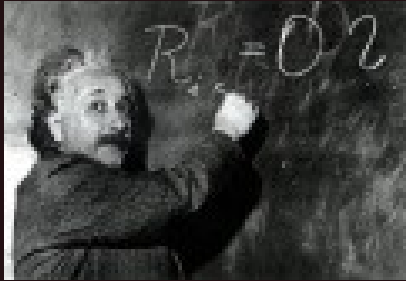
# Double Neutron Stars and Millisecond Pulsars

Table 1: Double neutron star systems known in the Galaxy

Pulsar	Period (ms)	$P_b$ (days)	$x$ (lt-sec)	$e$	$M$ ( $M_\odot$ )	$M_p$ ( $M_\odot$ )	$M_c$ ( $M_\odot$ )	References
J0737–3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	1
J0737–3039B	2773.461		1.516					
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	-	-	2
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	3
J1753–2240	95.138	13.638	18.115	0.303582(10)	-	-	-	4
J1756–2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	5
J1811–1736	104.1	18.779	34.783	0.82802(2)	2.57(10)	-	-	6
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)	-	-	7
J1906+0746*	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	8
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	9
J1930–1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)	-	-	10
<b>J0453+1559</b>	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This Letter
Globular cluster systems								
J1807–2500B*	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	12
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	13

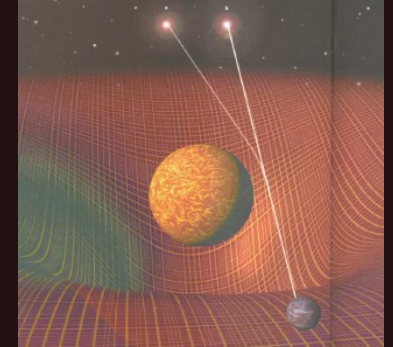


# Compact stars and black holes in Einstein's General Relativity theory



Space-Time  $G_{\mu\nu} = 8\pi G T_{\mu\nu}$  Matter

Massive objects curve the Space-Time



Non-rotating, spherical masses  $\rightarrow$  Schwarzschild Metrics

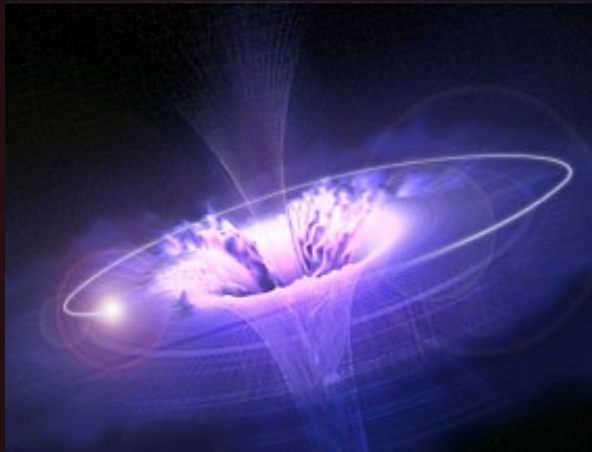
$$ds^2 = -\left(1 - \frac{2M}{r}\right)dt^2 + \left(1 - \frac{2M}{r}\right)^{-1}dr^2 + r^2d\Omega^2$$

Einstein eqs.  $\rightarrow$  Tolman-Oppenheimer-Volkoff eqs.

For structure and stability of compact stars

$$\frac{dP(r)}{dr} = -G \frac{m(r)\epsilon(r)}{r^2} \left(1 + \frac{P(r)}{\epsilon(r)}\right) \left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right) \left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

Newtonian case x GR corrections from EoS and metrics

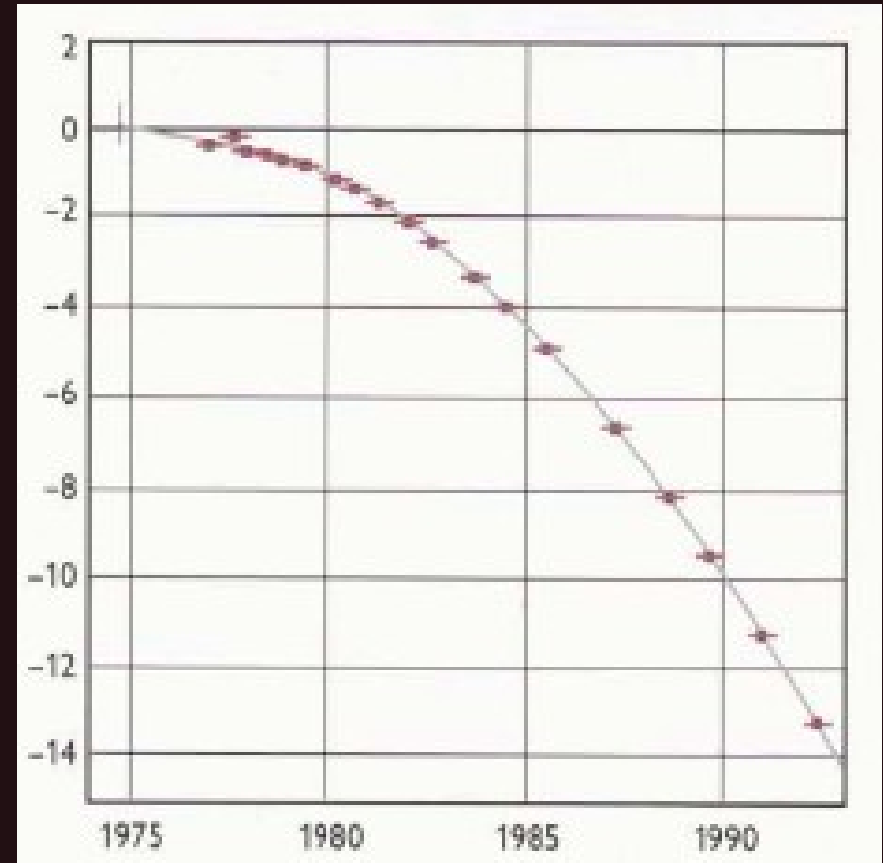
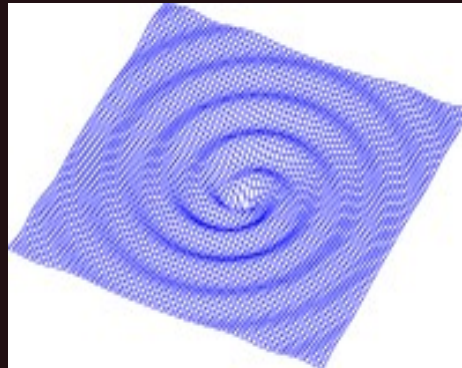


# Hulse-Taylor pulsar – binary system

PSR 1913+16



Nobel Prize for  
Hulse and Taylor



Excellent confirmation of Einstein theory of GW emission by observation of period decay

# Neutron star mass measurements with binary radio pulsars

MSP with period  $P=3.15$  ms

$P_b = 8.68$  d,  $e=0.00000130(4)$

Inclination angle =  $89.17(2)$  degrees !

Precise masses derived from  
Shapiro delay only:

$$M_p = 1.97(4) M_\odot$$

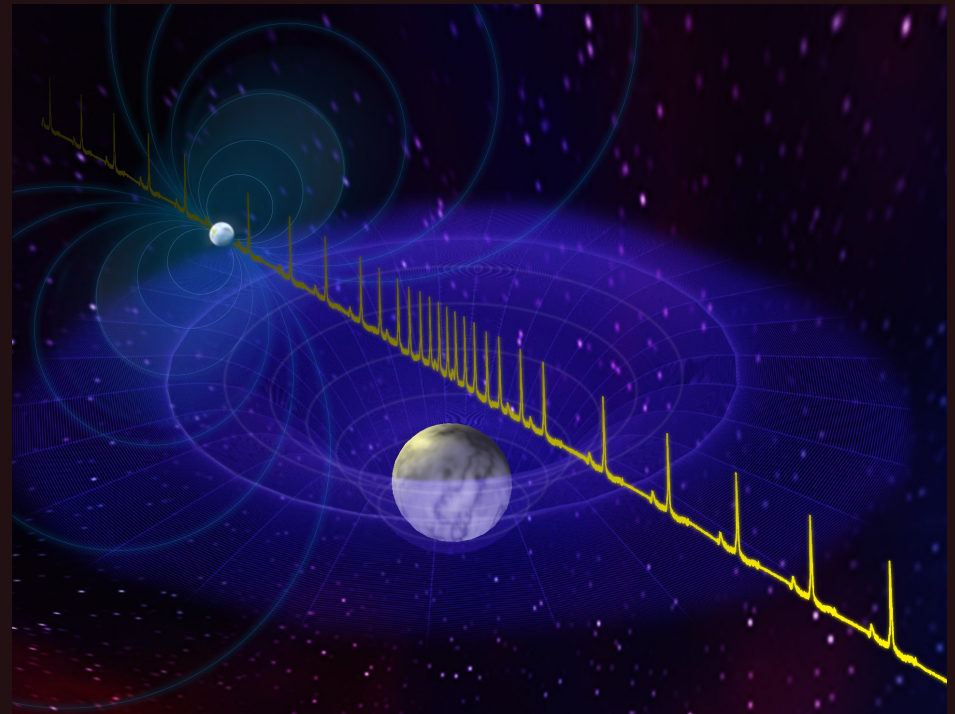
$$M_c = 0.500(6) M_\odot$$

Update [Fonseca et al. (2016)]

$$M_p = 1.928(17) M_\odot$$

PSR J1614-2230

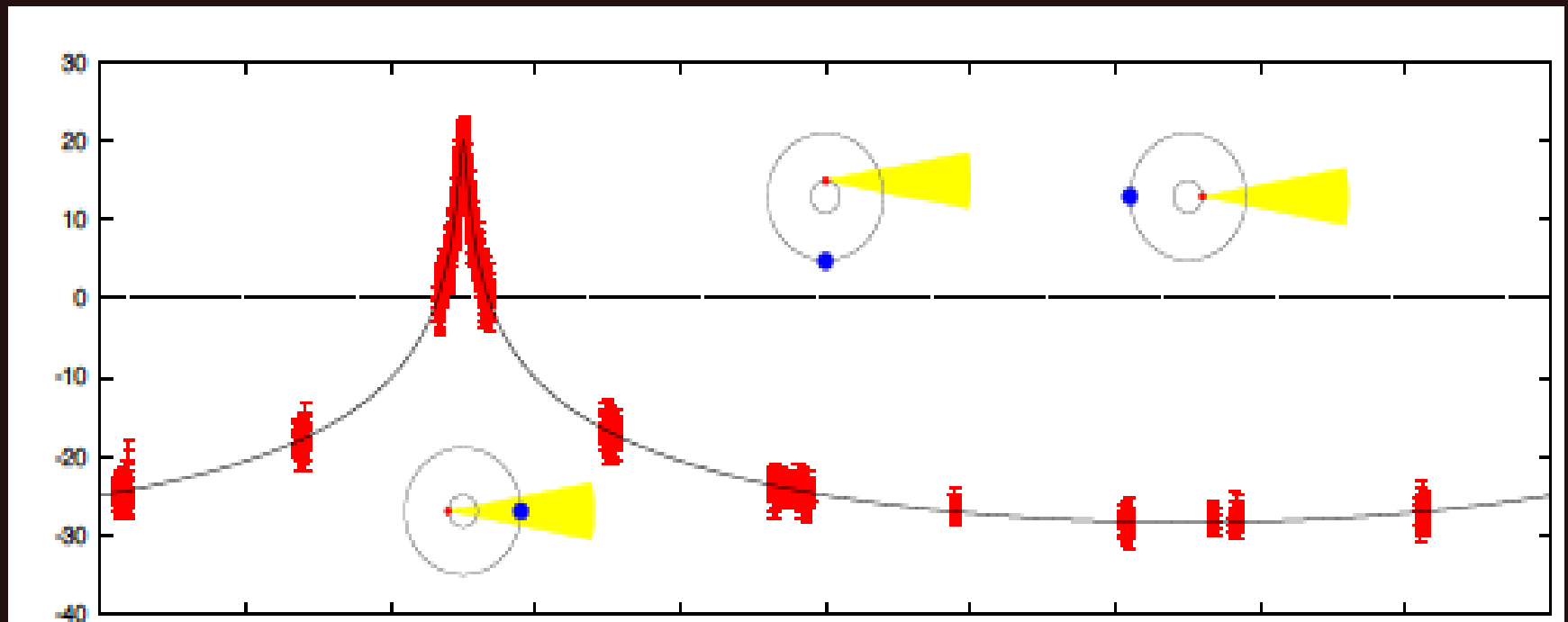
Demorest et al., Nature (2010)



# PSR J1614-2230

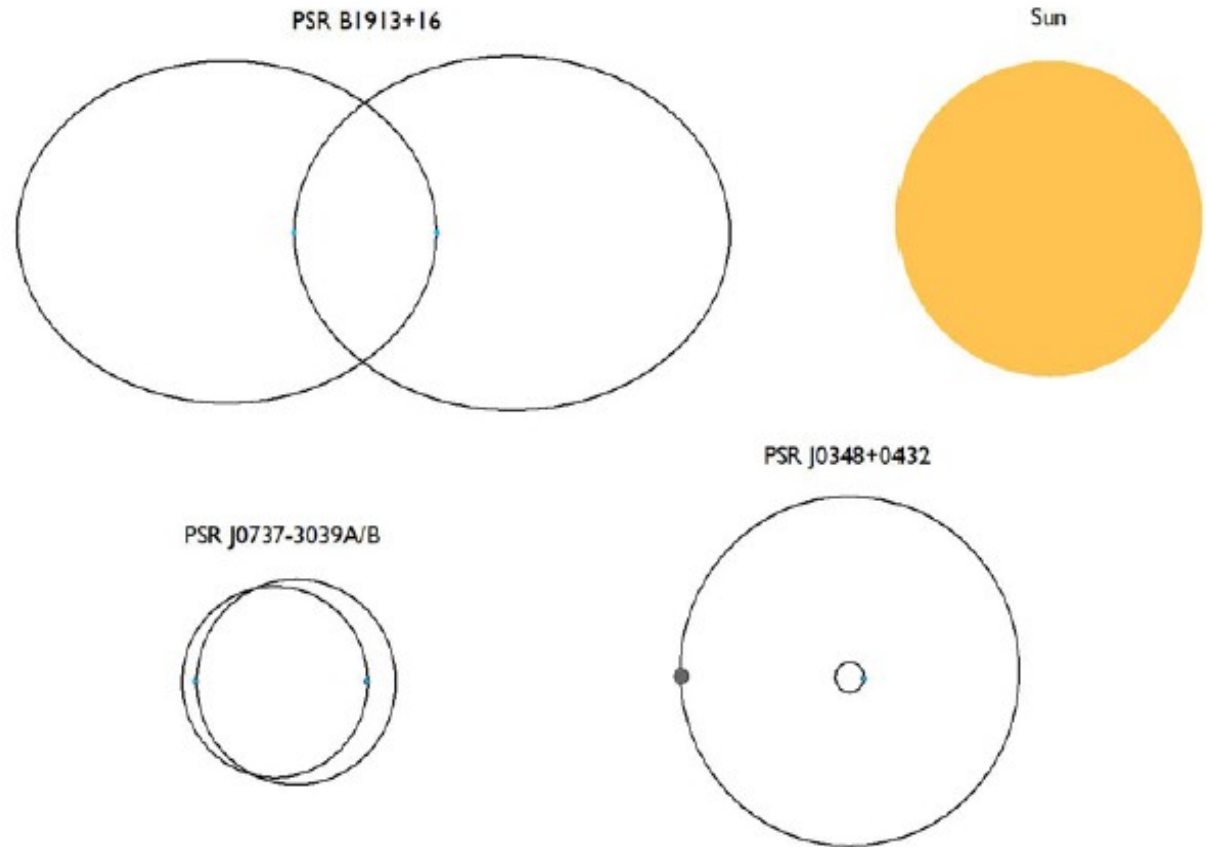
A precise AND large mass measurement

Shapiro delay:



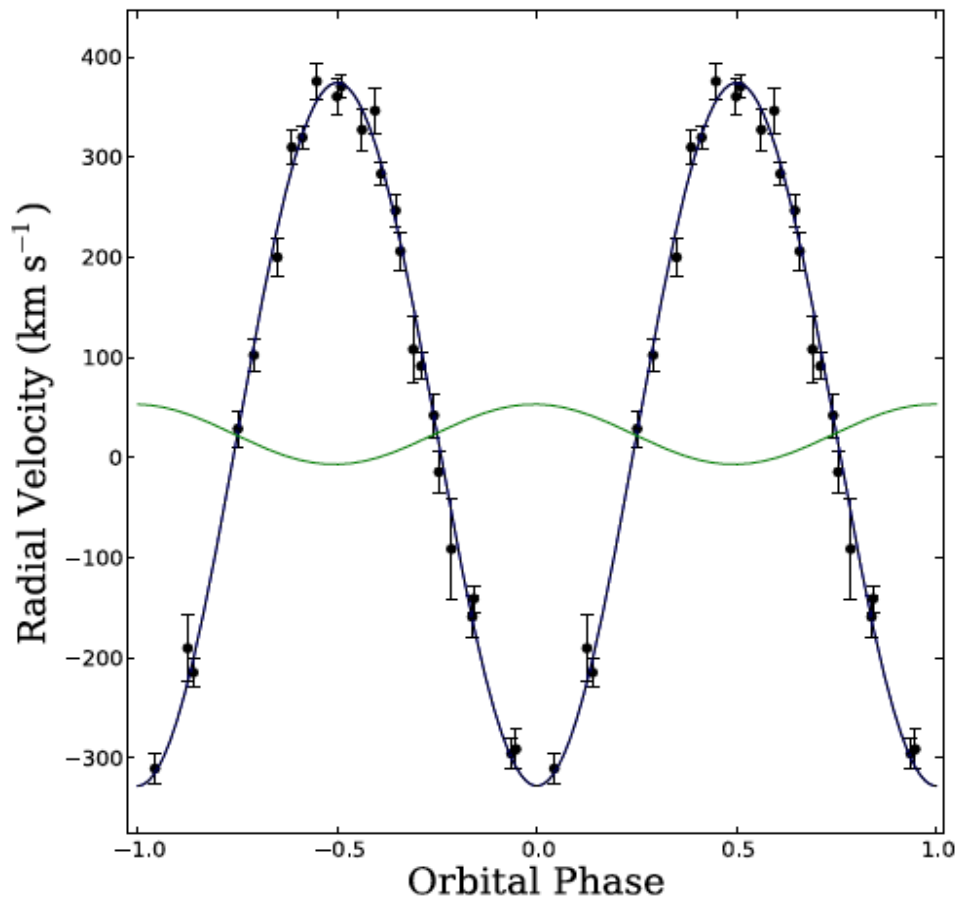
# The big one: PSR J0348+0432

- This is a pulsar with a spin period of 39 ms discovered in a GBT 350-MHz drift-scan survey (Lynch et al. 2013, ApJ. 763, 81).
- It has a WD companion and (by far) the shortest orbital period for a pulsar-WD system: 2h 27 min.



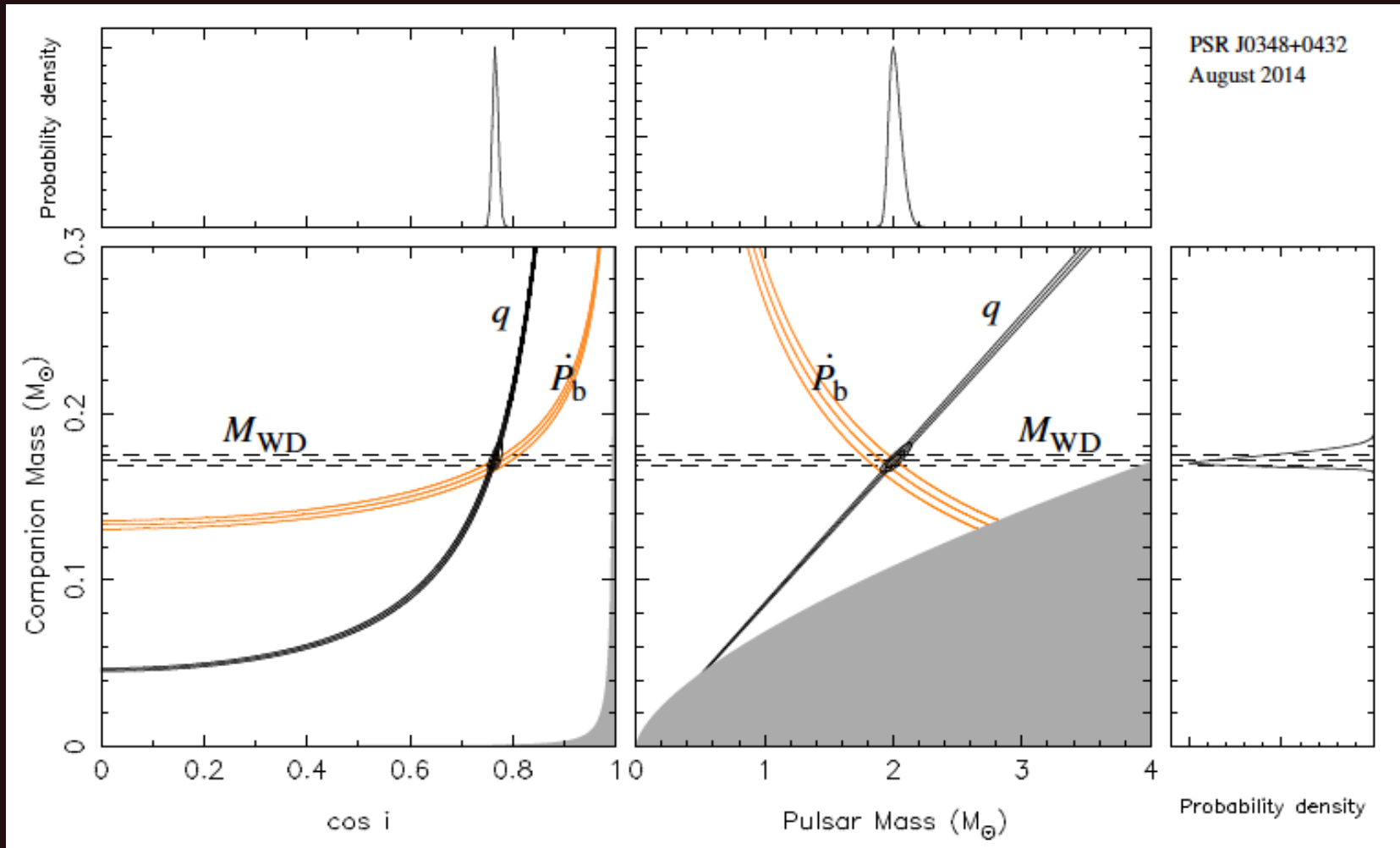


# PSR J0348+0432



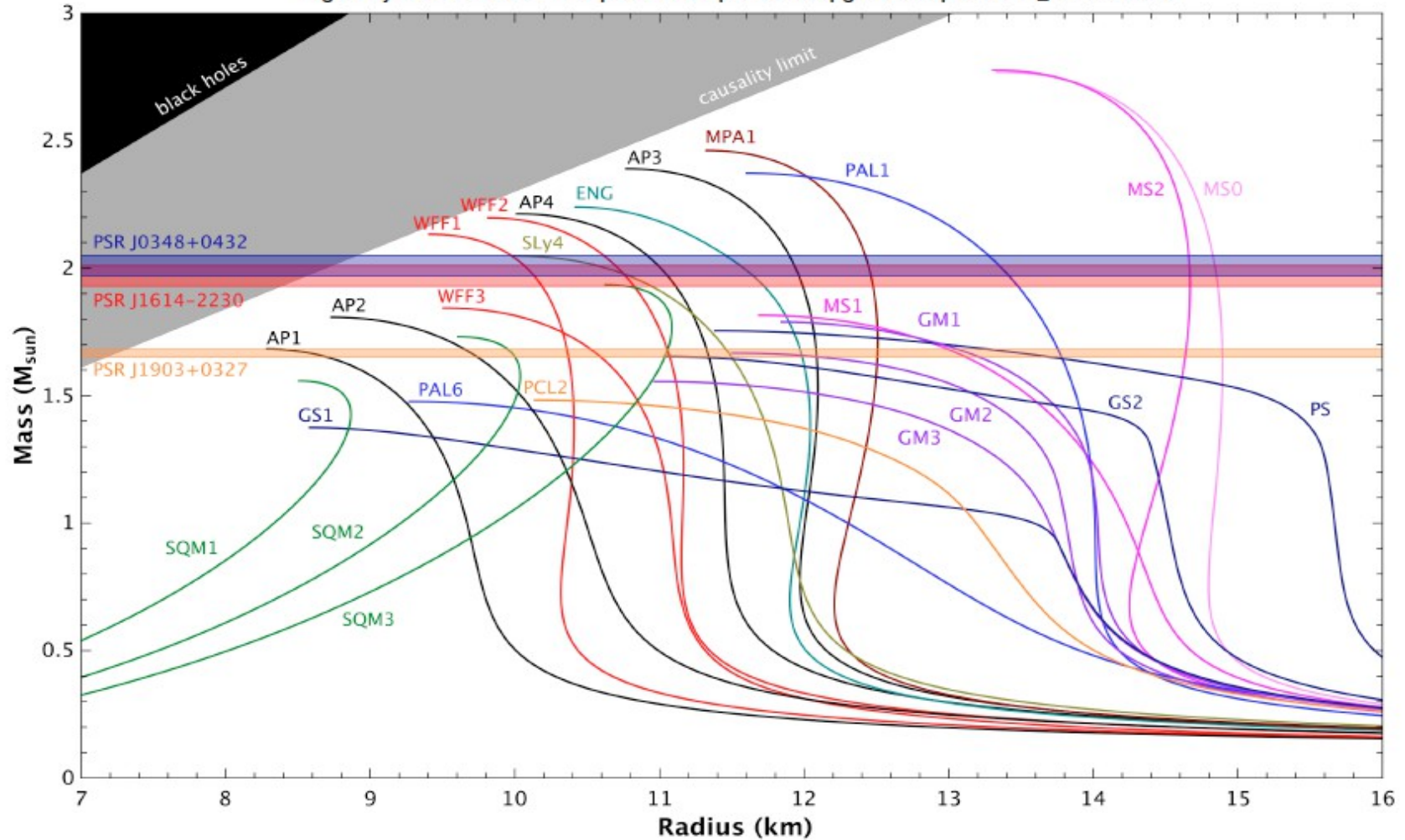
- Recent optical measurements at the VLT find a WD mass of  $0.172 \pm 0.003 M$  and a **pulsar mass of  $2.01 \pm 0.04 M$**  (Antoniadis et al. 2013, Science, 340, n. 6131).
- Most massive NS with a precise mass measurement.
- Confirms that such massive NSs exist using a different method than that used for J1614–2230. It also shows that these massive NSs are not rare.
- Allows, for the first time, tests of general relativity with such massive NSs! Prediction for orbital decay:  $-8.1 \mu\text{s}/\text{year}$ !

# GR test / better mass measurement

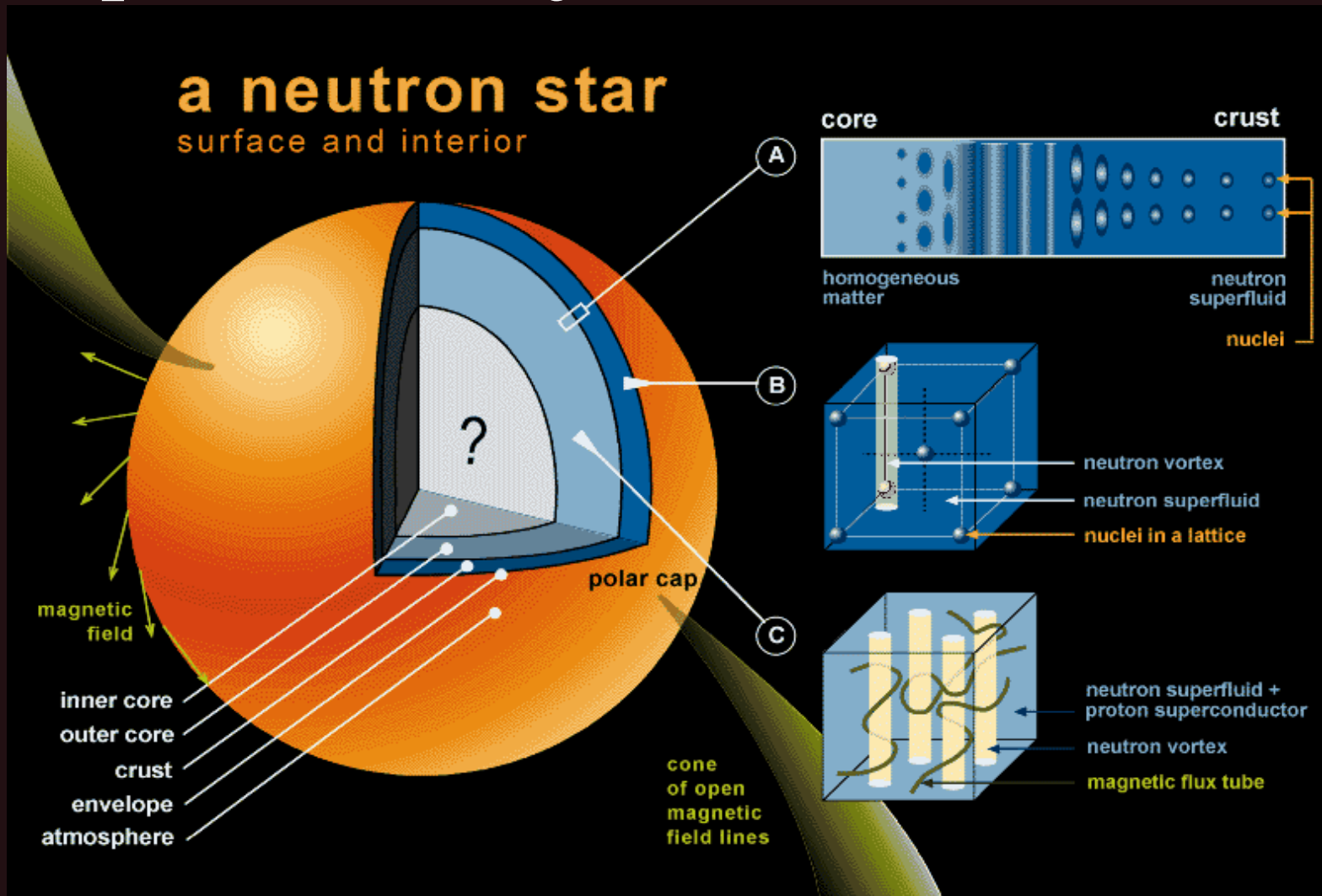


# NS Masses and Radii $\leftrightarrow$ EoS

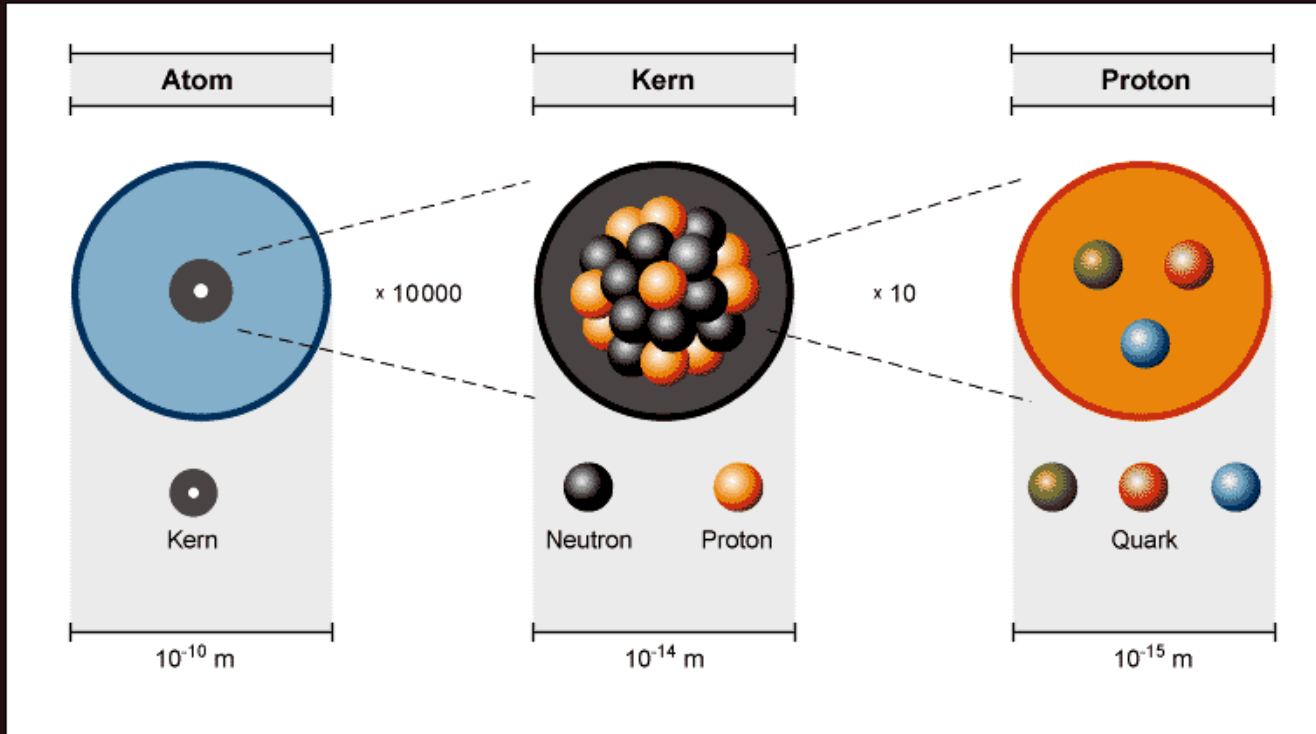
Figure by Norbert Wex. See [http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS\\_masses.html](http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html)



# Superdense objects – what is inside?



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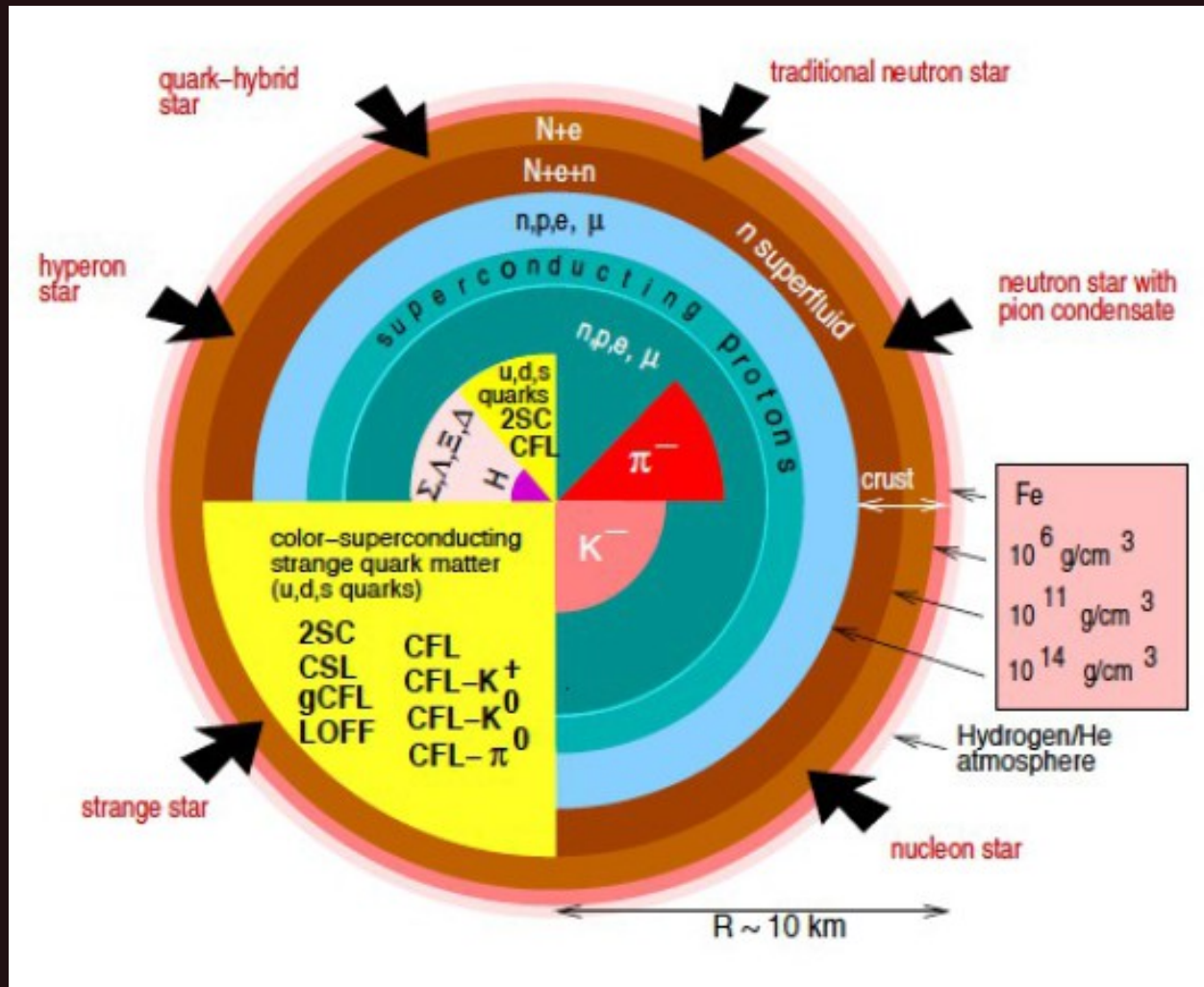


Nucleus, A nucleons:  $R_A = 1.2 \cdot 10^{-13} \text{ cm } A^{1/3}$ ;  $\rho_0 = A \cdot 1.67 \cdot 10^{-24} \text{ g} / (4\pi/3 R_A^3) = 2.3 \cdot 10^{14} \text{ g/cm}^3$

Neutron star:  $R = 10 \text{ km}$ ;  $\rho = 2 \text{ Mo} / (4\pi/3 R^3) = 4 \cdot 10^{33} \text{ g} / (4 \cdot 10^{18} \text{ cm}^3) = 10^{15} \text{ g/cm}^3 = 4 \rho_0$

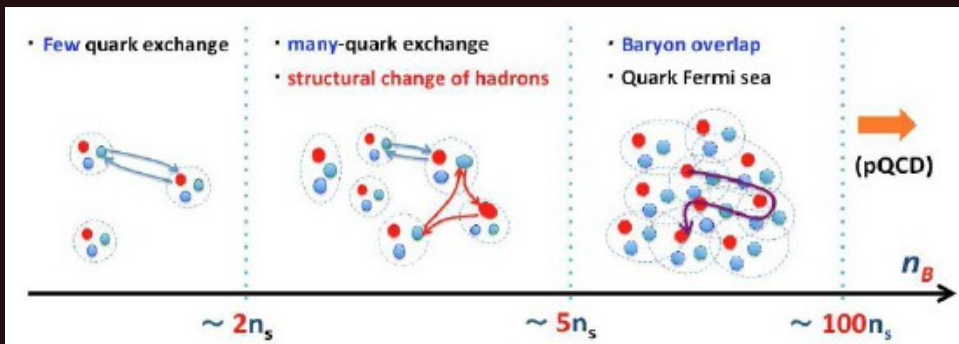
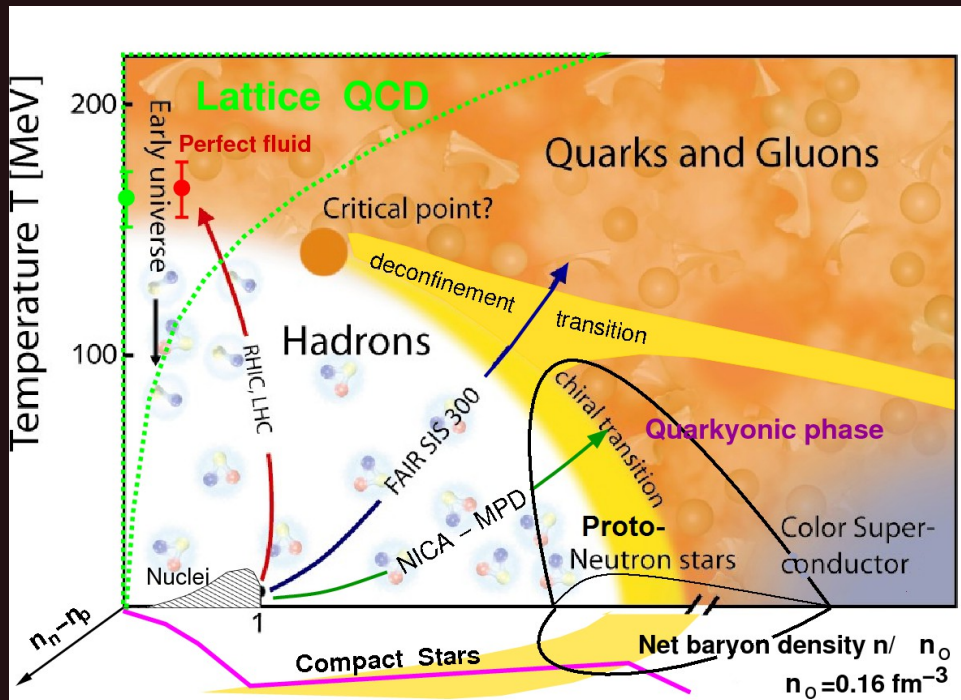


# Superdense objects – what is inside?



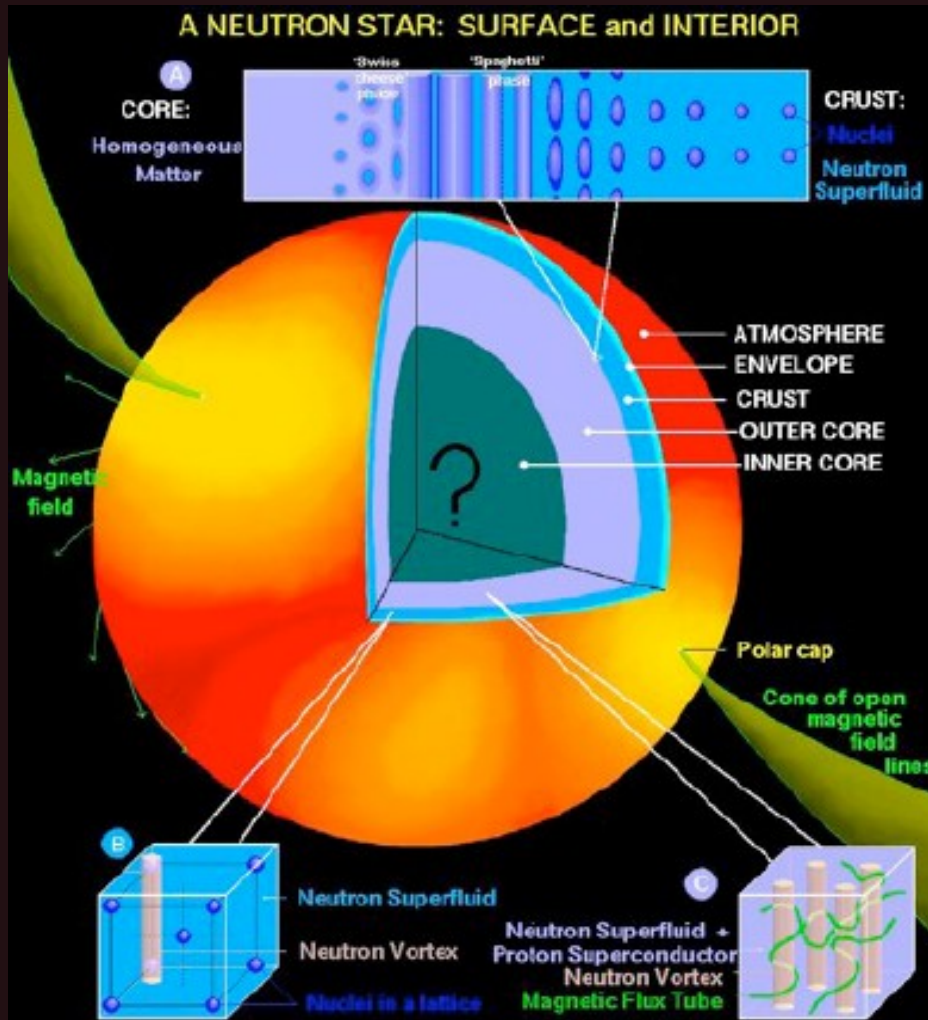
F. Weber:  
 “Neutron stars -  
 Cosmic Laboratories ...”  
 IoP Bristol, 1999

# Quark Matter in Neutron Stars ?



# Neutron stars are Super-Stars!

Pines theorem (1990)



## PROOF:

- *Superdense objects*  
 $\rho \sim 2\rho_0 = 5 \cdot 10^{14} \text{g/cm}^3, 2GM/R \rightarrow 0.5$
- *Superfast rotators*  
 $P_{\min} = 1.6 \text{ ms}, \Omega \sim \Omega_{\text{Kepler}}/2$
- *Superfluid interior*  
 $\Delta_{\text{nn}} \sim 0.1 - 1 \text{ MeV}$
- *Superconducting interior*  
 $\Delta_{\text{pp}} \sim \Delta_{\text{nn}}$
- *Superstrong magnetic fields*  
 $B \rightarrow 10^{15} \text{ G}$
- *Superprecise timers*  
 $\Delta P/P \rightarrow 10^{-14} \text{ s/y}$
- *Super-rich physics involved*

# Further reading ...

- Norman Glendenning:**  
**Compact Stars (Springer, 2000)**
- Pawel Haensel et al.:**  
**Neutron Stars (Springer, 2007)**
- Fridolin Weber:**  
**Pulsars as astrophysical laboratories ...**  
**(IoP Publ., 1999)**
- Stuart Shapiro & Saul Teukolsky:**  
**Black Holes, White Dwarfs & Neutron Stars**  
**(Wiley, 1983)**
- David Blaschke et al. (Eds.):**  
**Physics of Neutron Star Interiors (Springer, 2001)**
- D. Blaschke, J. Schaffner-Bielich, H.-J. Schulze (Eds.):**  
**Topical Issue on Exotic Matter in Neutron Stars,**  
**EPJA 52 (2016)**

<https://www.litres.ru/sergey-popov-3/superobekty-zvezdy-razmerom-s-gorod/>

