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Compact Stars -
Introduction to Physics and Astrophysics of Neutron Stars

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NPA School Rossendorf, 11.09.2024

Physics of Compact Stars

Contents:

1. Prediction of Neutron Stars
2. Discovery of Pulsars = Rotating Neutron Stars
3. A Zoo of Pulsars: Isolated and in Binaries
4. General relativistic CS structure: Masses and Radii ↔ EOS
5. CS in the QCD Phase Diagram
6. Signals of Quark Deconfinement, Simulations of BNSM & SNe *)
7. Summary & Literature

*) Simulations can be found at: http://www.ift.uni.wroc.pl/~blaschke/Opus17_popularization.html

Literature:

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.): Exotic Matter in Neutron Stars, EPJA (2016)

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)

(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

[2]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).

[3]Giacconi, Gursky, Paolini, and Rossi (1962).

[4]Chapter 11 is devoted to this subject.

[5]The first QSO identified by Schmidt, 3C273, had a redshift $\delta\lambda/\lambda = 0.158$, which was unprecedented for a normal "star."

[6]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

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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).[1] 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.

[1] L. Landau und R. Peierls, ZS. f. Phys. 69, 56, 1931.

This is correct!

Disappered 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 supernova is about twenty days and its absolute brightness a[t] maximum may be as high as $M_{vis} = -14^M$. The visib[le] radiation L_ν of a supernova is about 10^8 times the radiatio[n] of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculation[s] indicate that the total radiation, visible and invisible, i[s] of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The super-nova 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_τ/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/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm² 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 super-novae. 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

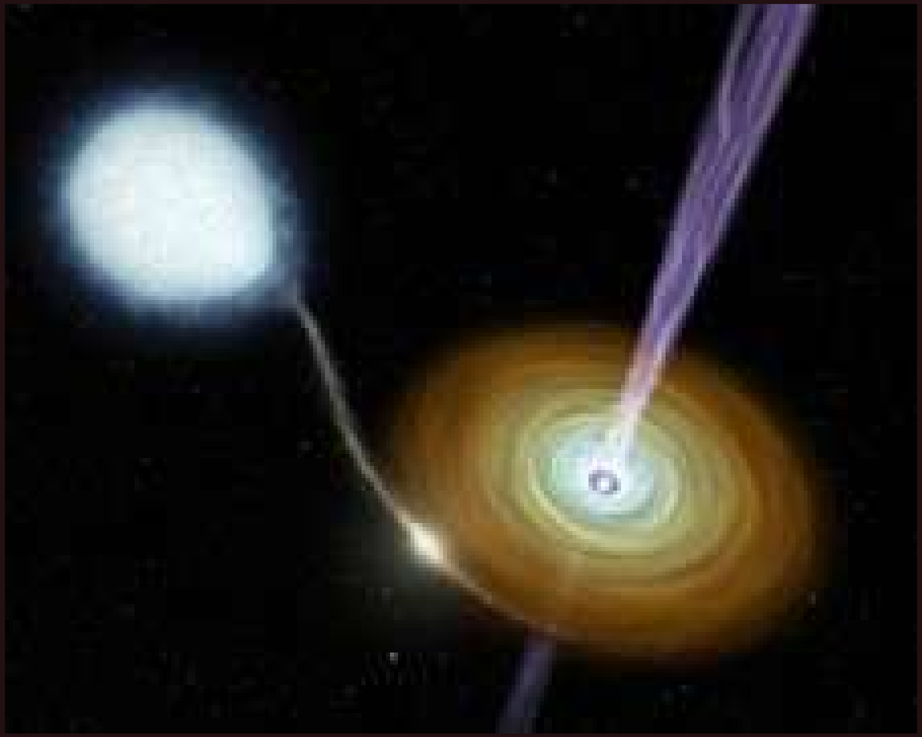
Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934

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

Good old classics

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

Crab nebula: a SN remnant



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»....

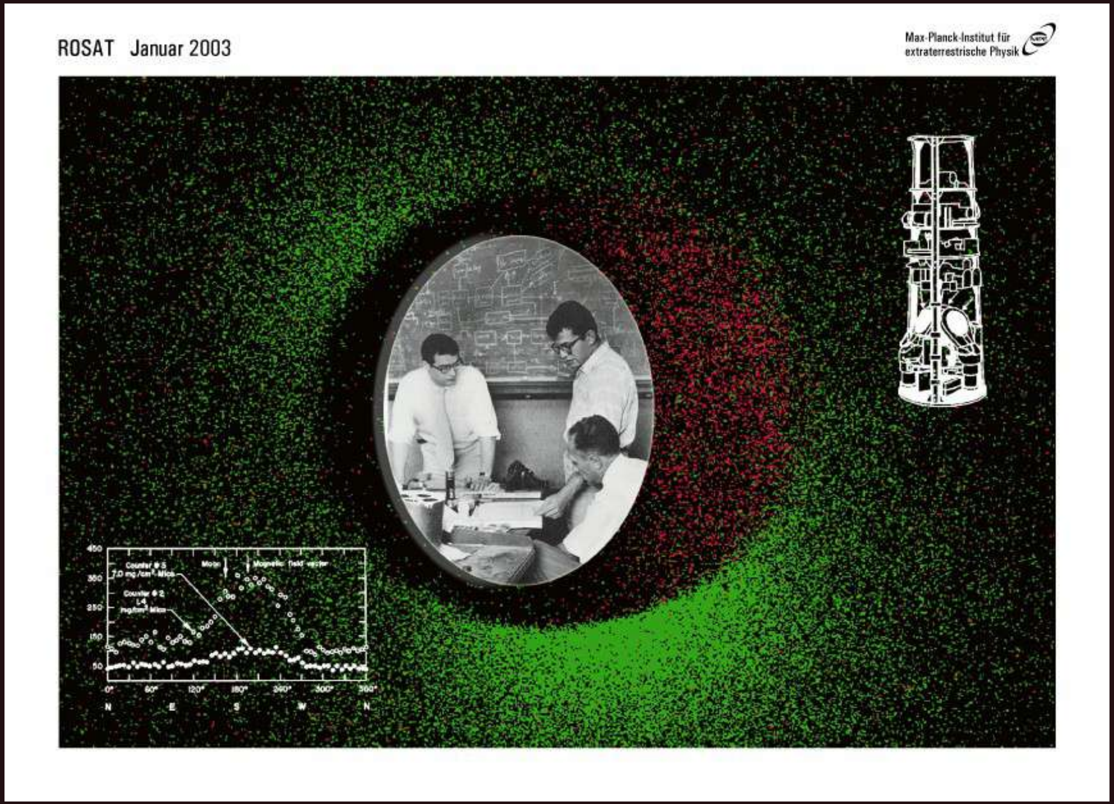
Now we know hundreds of X-ray binaries with neutron stars in the Milky Way and in other galaxies.

Rocket experiments
Sco X-1

Giacconi, Gursky, Hendel

1962

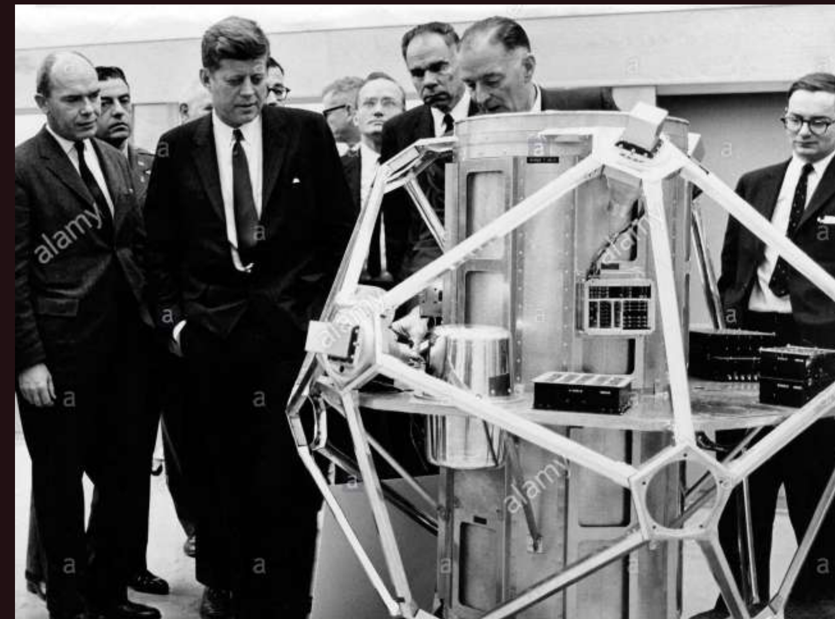
In 2002 R. Giacconi was awarded with the Nobel prize.

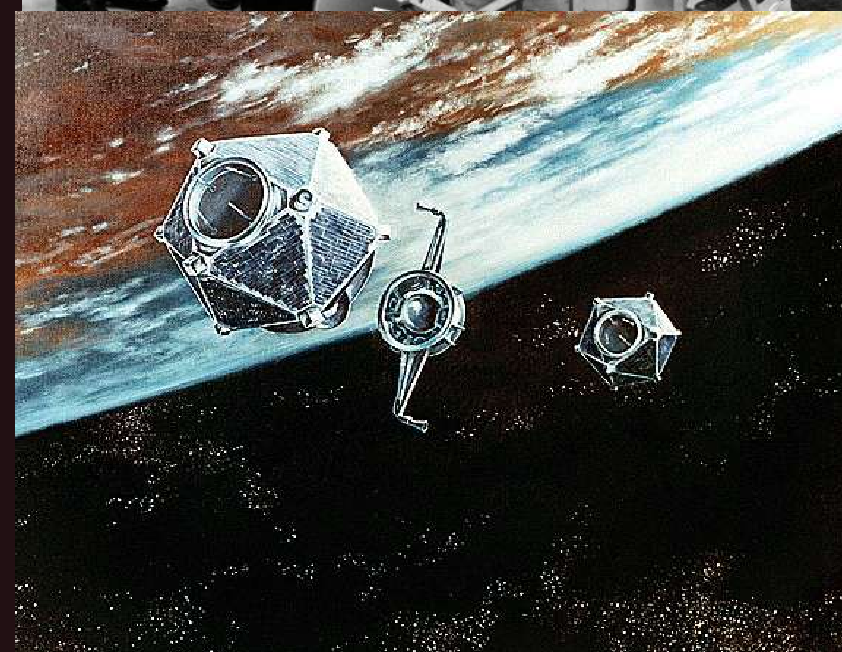


Vela satellites ...

... were launched pairwise in 1963, 1964, 1965 to monitor the Partial Test Ban Treaty (1963)

July 2, 1967: Vela 3 and 4 detect gamma flash; more flashes detected afterwards; Los Alamos team determined positions – terrestrial or solar origin excluded
(files declassified in 1973)



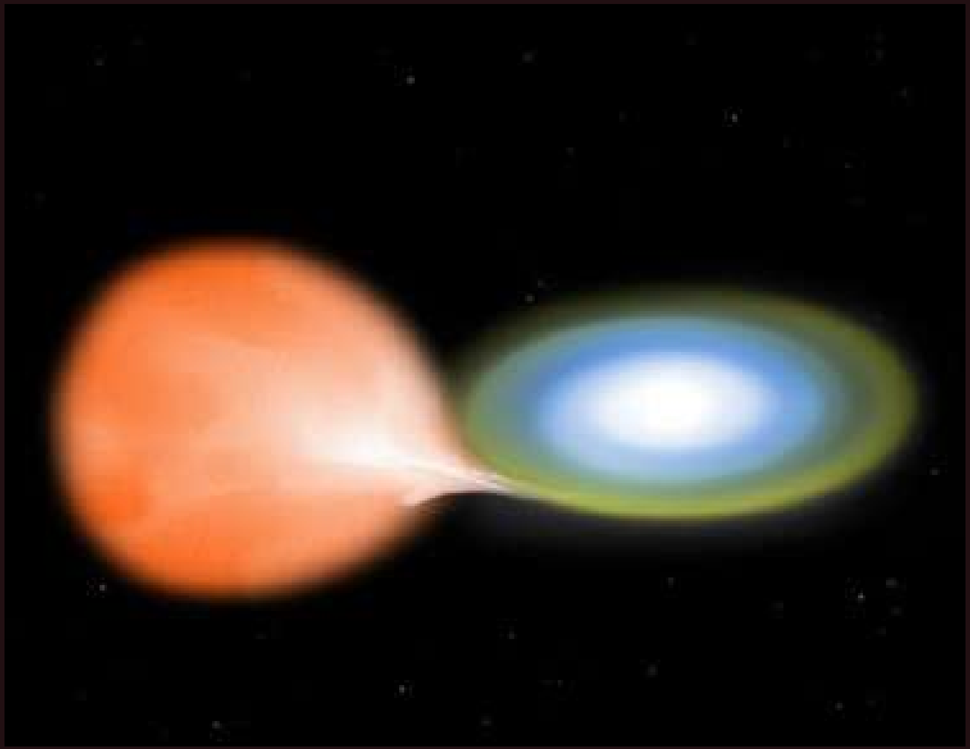


Pulsed gamma
Radiation from
Vela pulsar

Close binary systems

About ½ of massive stars
Are members of close binary
systems.

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

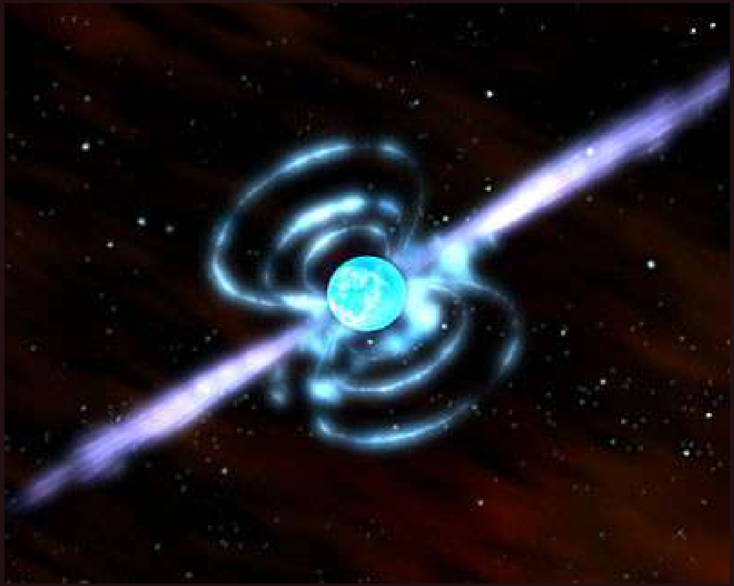


$$L = \dot{M} \eta c^2$$

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: $\Delta T/T \sim 1$ sec / 100 million million years



Discovery !!!!

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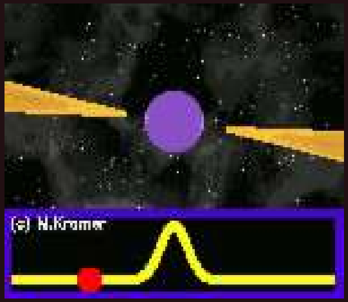
Today more than 2500 pulsars, some have extremely
Stable frequency: $\Delta T/T$ ~ 1 sec / 100 million million years

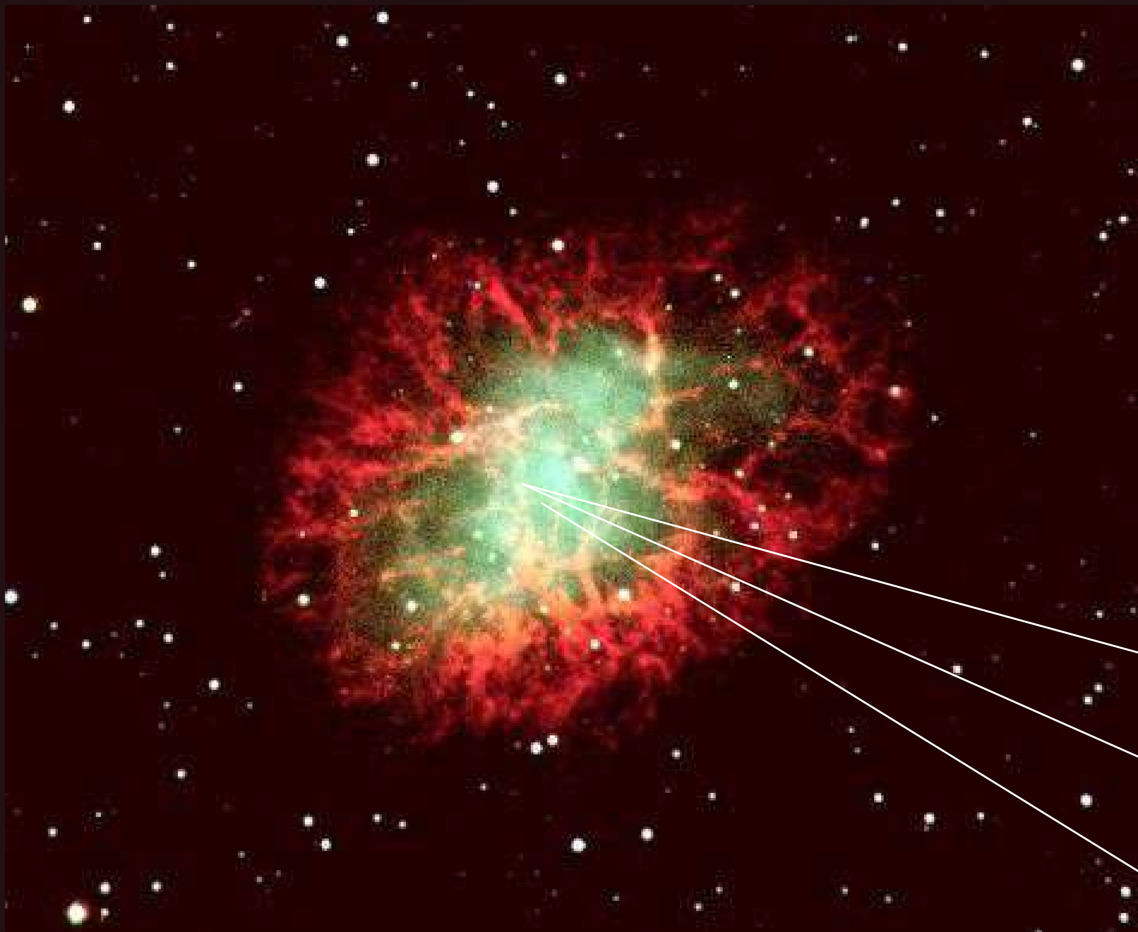
1968: Thomas Gould explains high precision by rotation
Only small objects (R~10 km) can have so short pulses



The pulsar in the Crab nebula

1969: Discovery of the pulsar
In the Crab nebula.

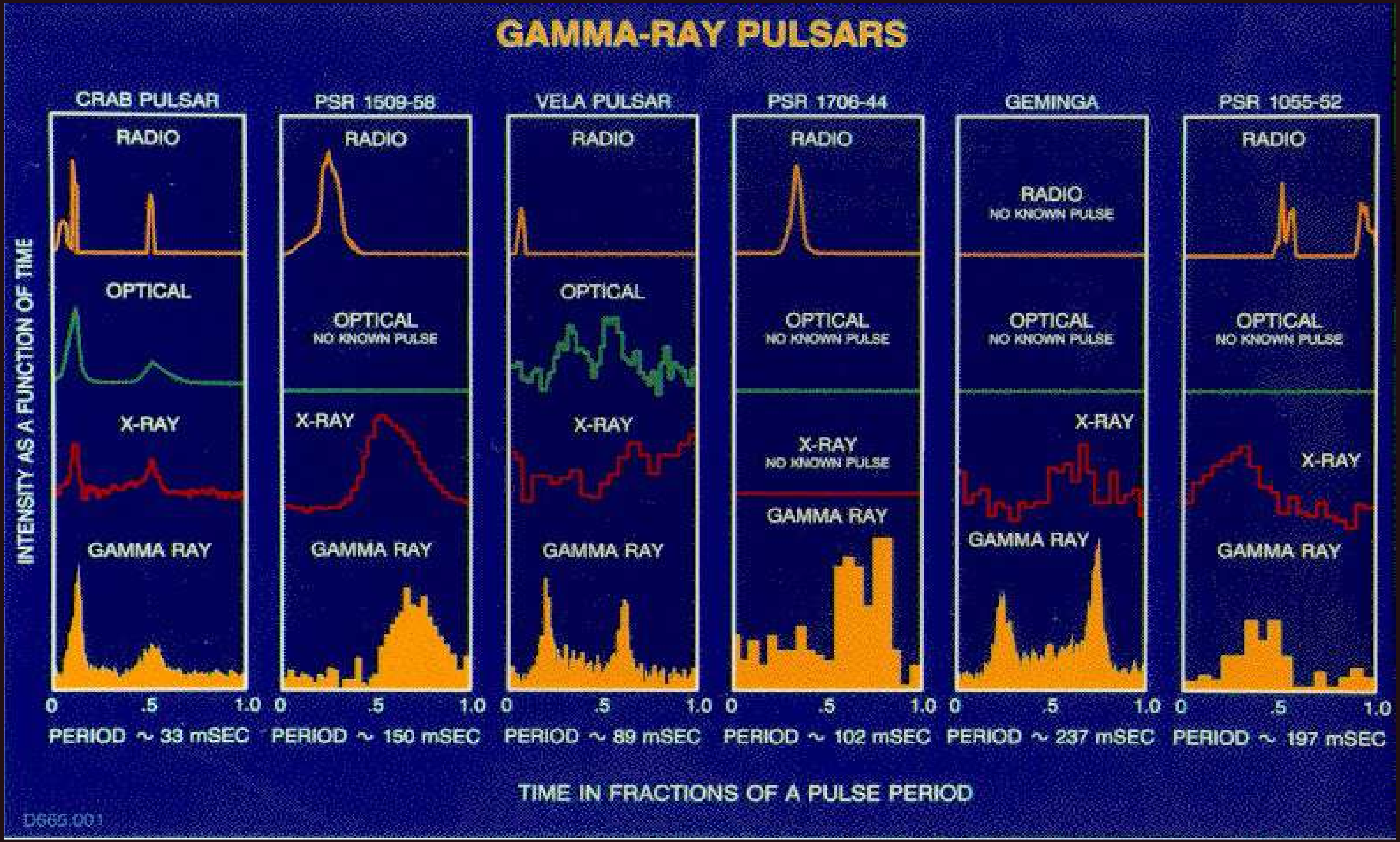
The pulsar in the Crab nebula



1969: Discovery of the pulsar
In the Crab nebula.

Connection established:
Supernova-Neutron Star-Pulsar

Pulse shapes and el.-magn. spectrum



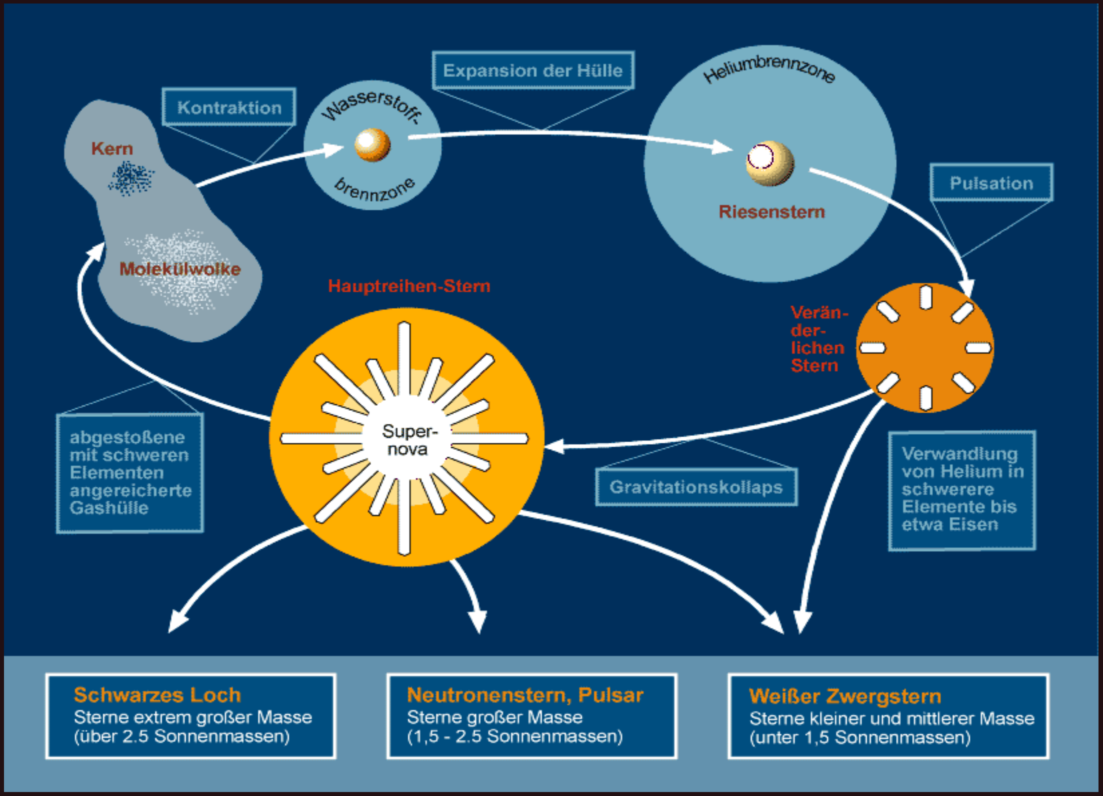
Pulsar sounds ...

Little Green Men

LGM-1 ... PSR B1919+21 ;   CETI ... SETI

The life cycle of stars

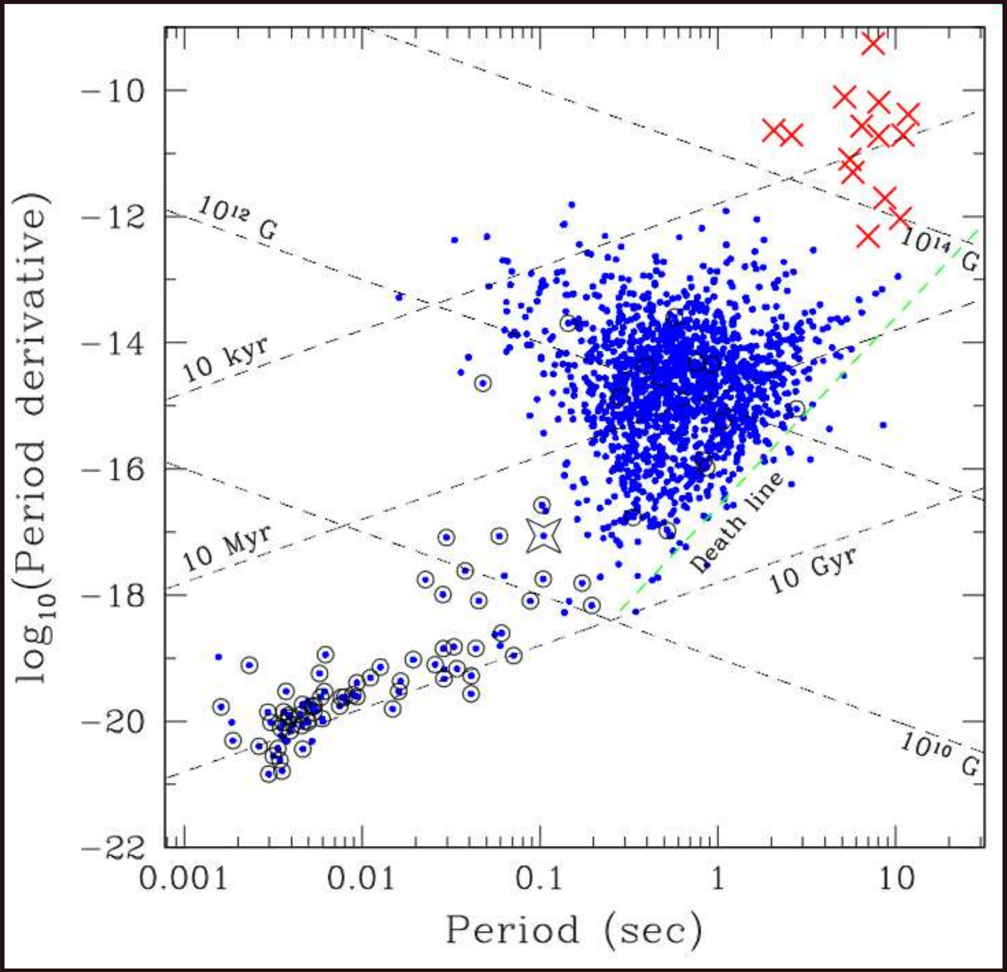
- Supernova Type I (Carbon core): Explosive 'Burning', star is completely destroyed
- Supernova Type II (Iron core): Implosion due to gravitational instability, subsequent shockwave explosion and neutrino emission $\Rightarrow$ blast of the star envelope, star interior collapses $\Rightarrow$ **NEUTRON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



Neutron star-Properties:

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

Statistics of Pulsars

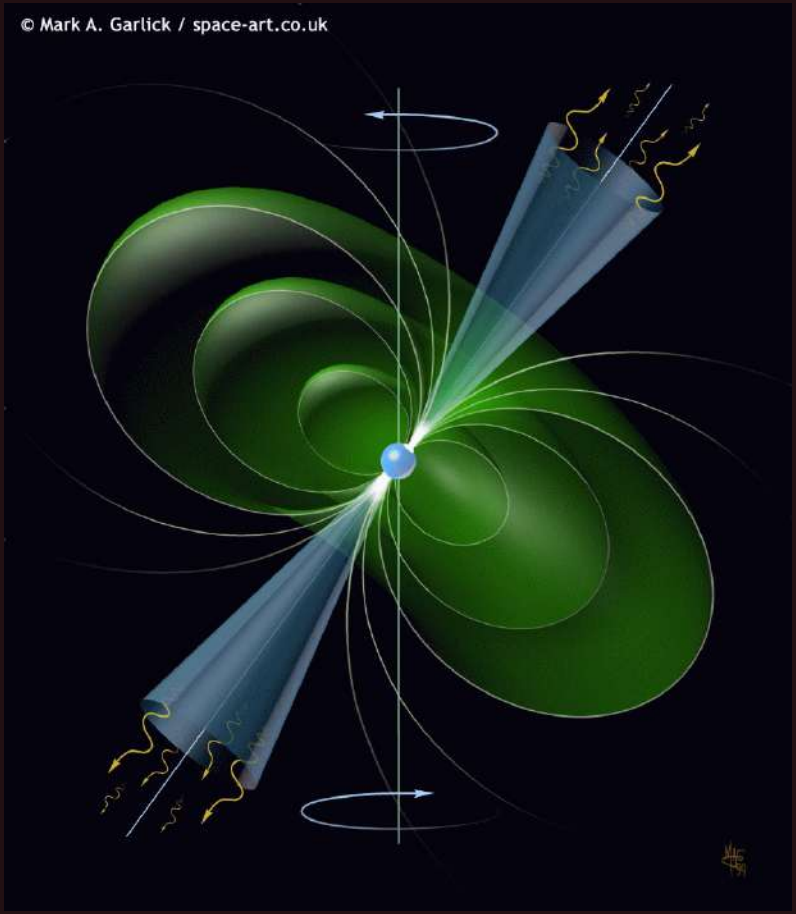


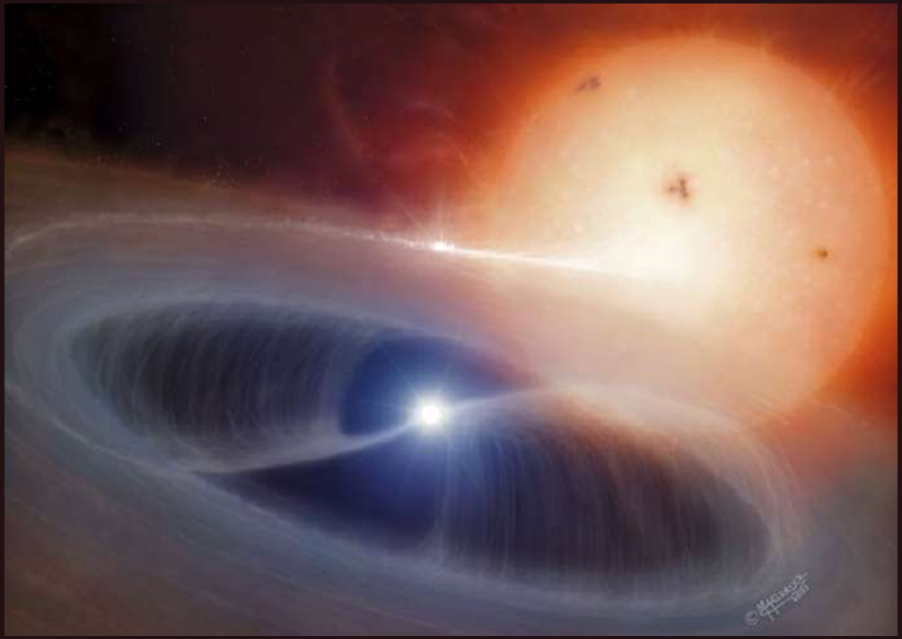
Magnetars:
B > 10^{15} Gauss

Young pulsars:
P < 1 sec
B ~ 10^{12} Gauss

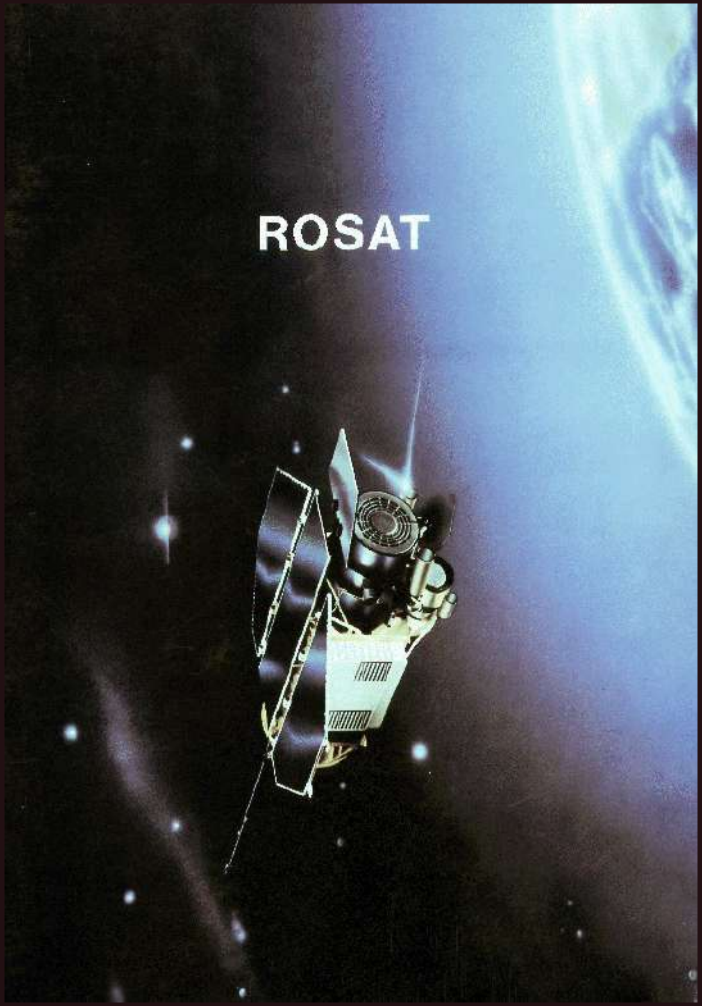
Recycled (old) Pulsars:
P ~ few milliseconds
B ~ 10^{8} Gauss

The old Zoo: young pulsars & old accretors





ROSAT

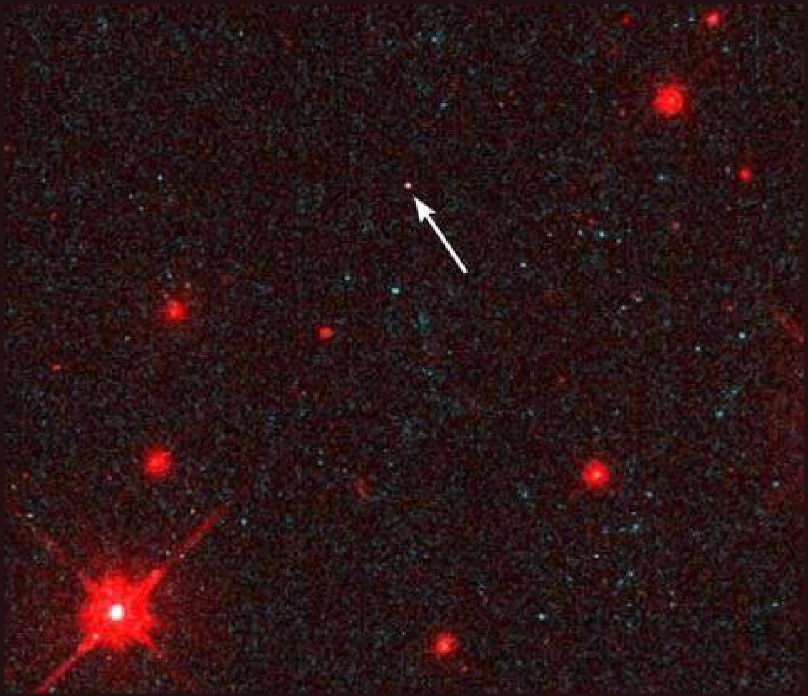


ROentgen SATellite

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)

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

Radioquiet
Close-by
Thermal emission
Absorption features
Long periods

Close-by radioquiet NSs

RX J1856.5-3754

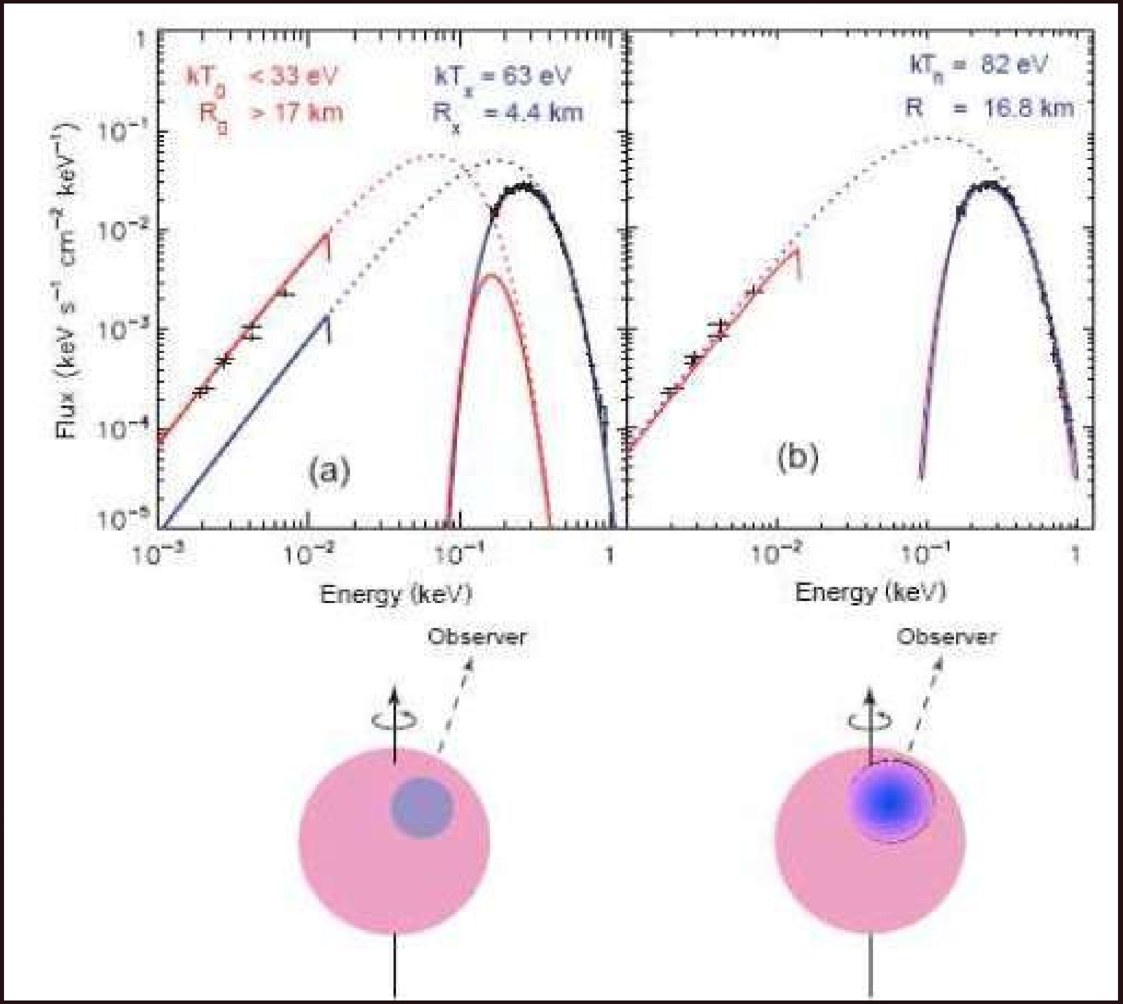
- Discovery: Walter et al. (1996)
- Proper motion and distance: Kaplan et al.
- No pulsations
- Thermal spectrum
- Later on: six brothers

Resolution of radius puzzle for RX J1856 ?

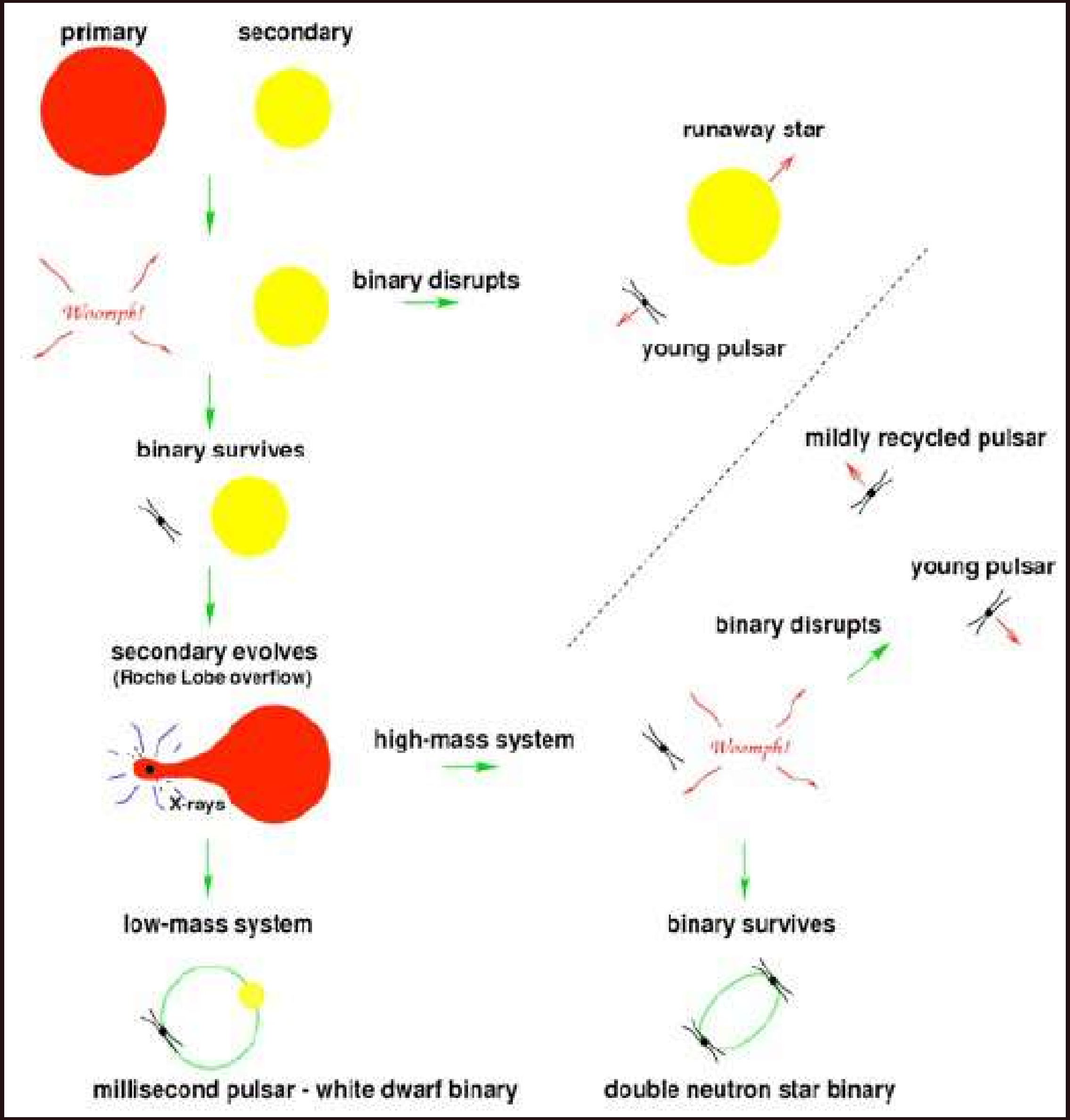
Blackbody fits to the optical
And X-ray spectra
(Truemper et al., 2004)

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

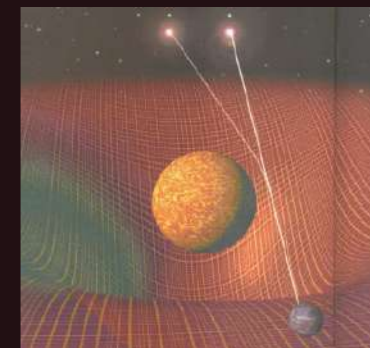
Table 1: Double neutron star systems known in the Galaxy

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
J0453+1559	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

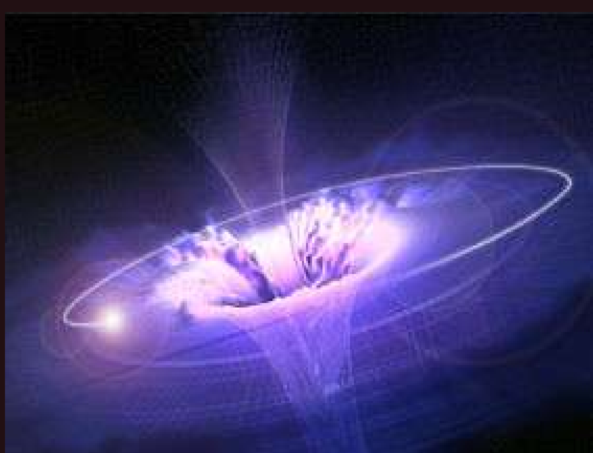
Compact stars and black holes in Einstein's General Relativity theory

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

Massive objects curve the Space-Time



Non-rotating, spherical masses → Schwarzschild Metrics



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

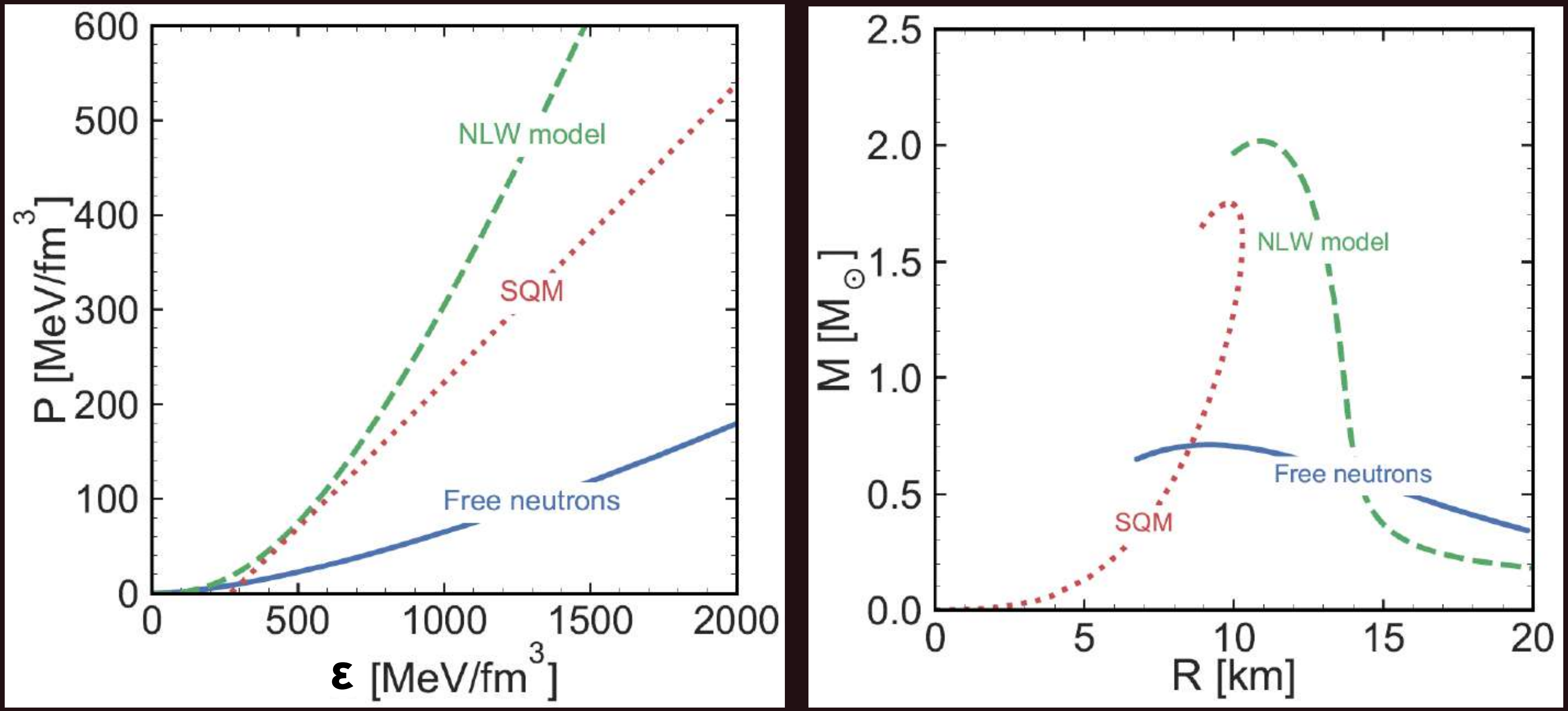
Einstein eqs. → Tolman-Oppenheimer-Volkoff eqs.
For structure and stability of compact stars

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

Newtonian case x GR corrections from EoS and metrics

The 1:1 relation P(ε) ↔ M(R) via TOV

Simple examples*)



Free neutrons: Oppenheimer & Volkoff, Phys. Rev. 55 (1939) 374
NLW (nonlinear Walecka) model: N. K. Glendenning, Compact Stars (Springer, 2000)
SQM (strange quark matter): P. Haensel, J. L. Zdunik, R. Schaeffer, A&A 160 (1986) 121

*) courtesy: Konstantin Maslov

The 1:1 relation P(ε) ↔ M(R) via TOV

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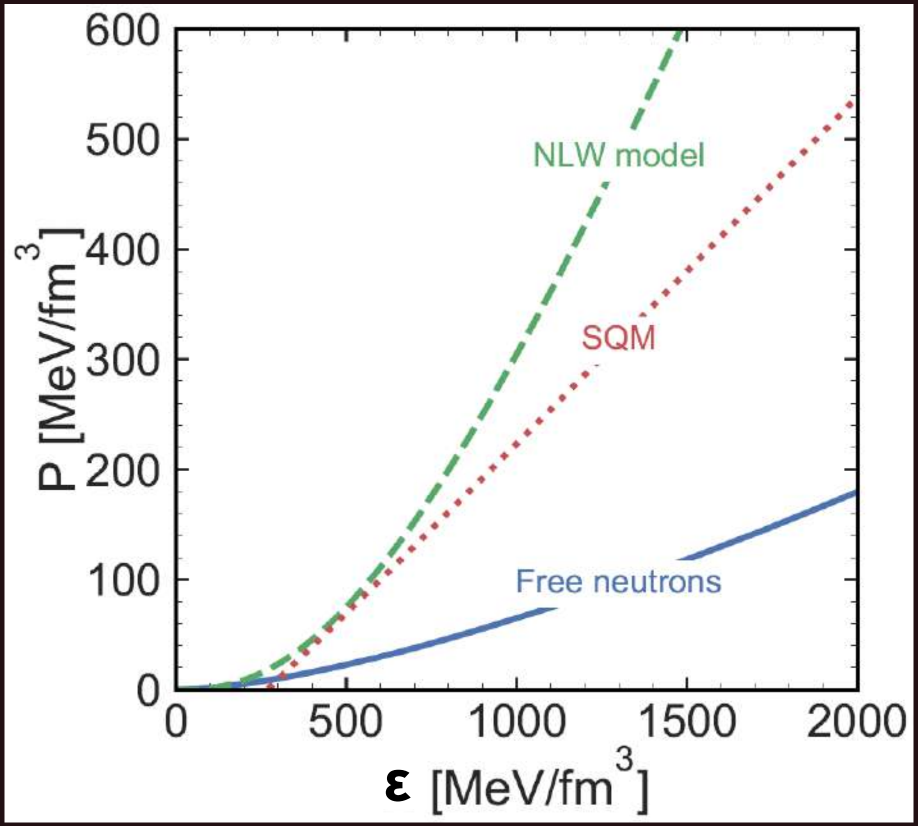

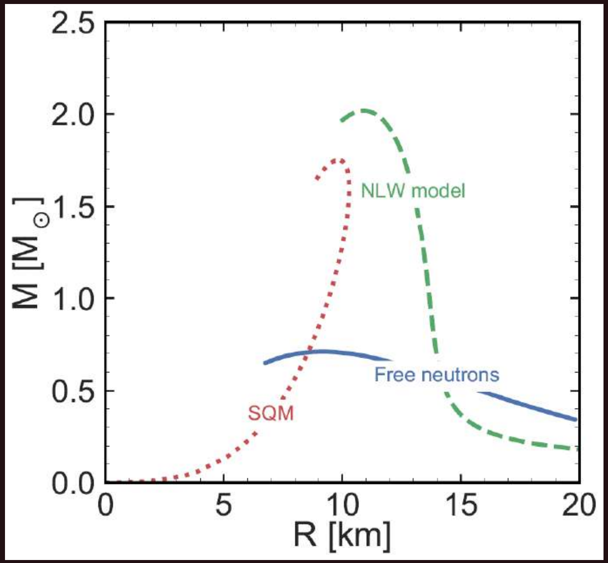

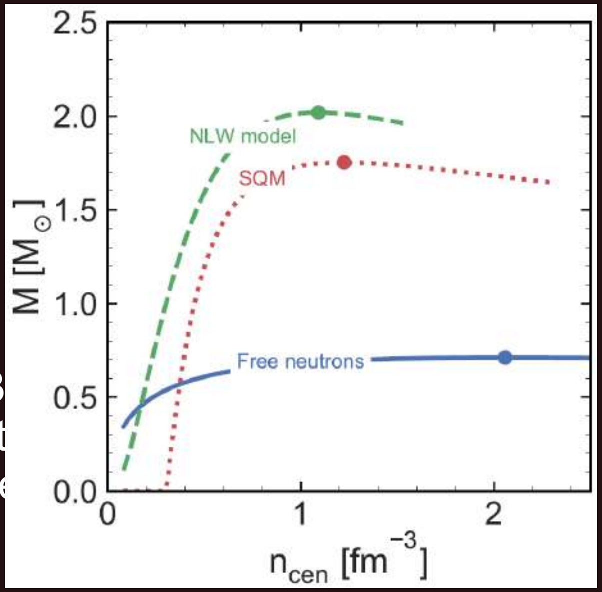

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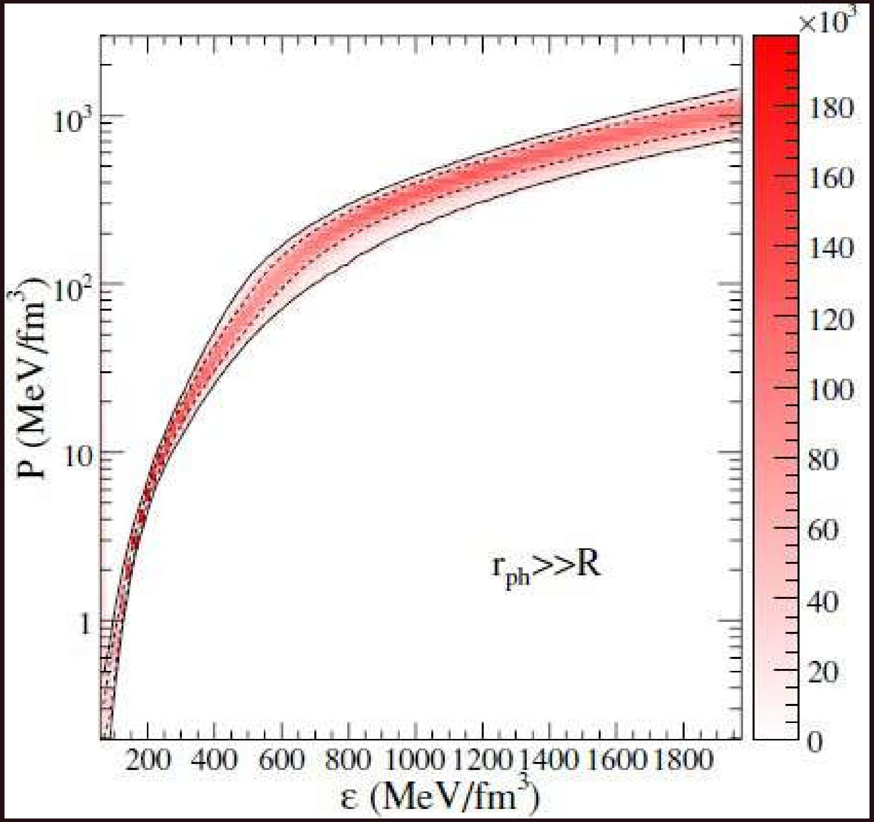
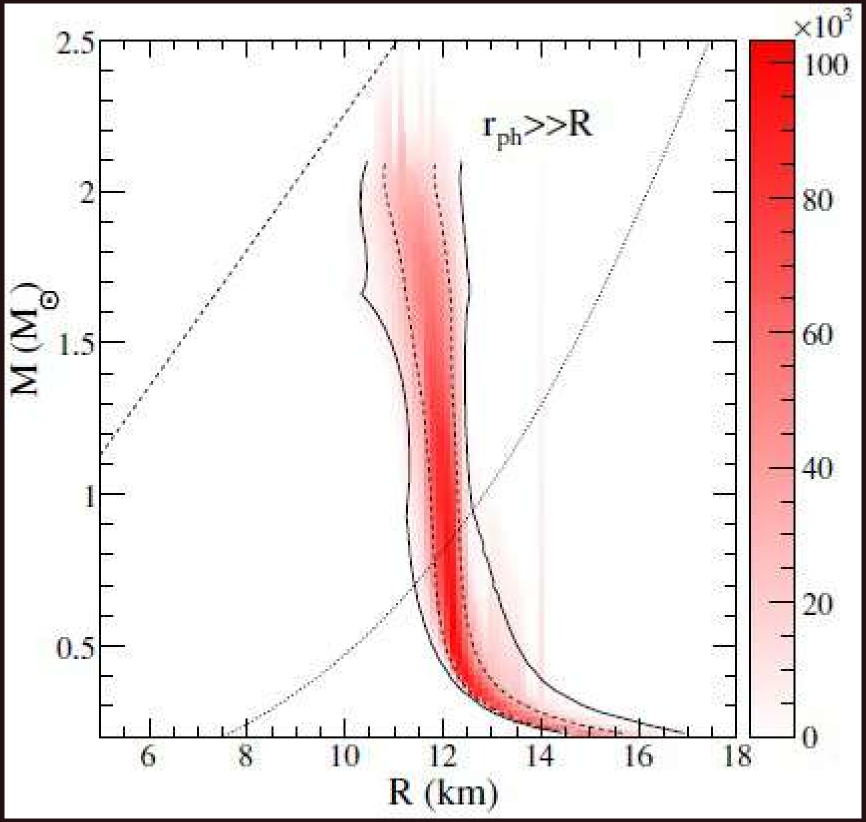
*) courtesy: Konstantin Maslov

The 1:1 relation P(ε) ↔ M(R) via TOV

Equation of State from Mass and Radius observations *)





A. W. Steiner, J. M. Lattimer, E. F. Brown, Astrophys. J. 722 (2010) 33

*) caution with radius measurements from burst sources

Neutron star mass measurements with binary radio pulsars

PSR J1614-2230
Demorest et al., Nature (2010)

MSP with period P=3.15 ms

Pb = 8.68 d, e=0.00000130(4)

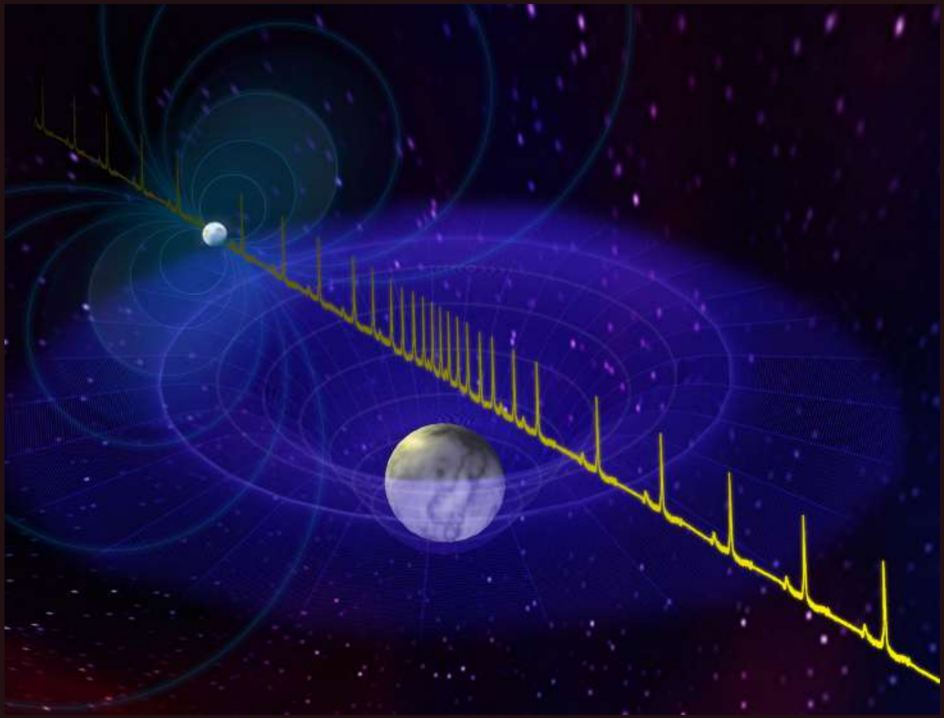
Inclination angle = 89.17(2) degrees !

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)]

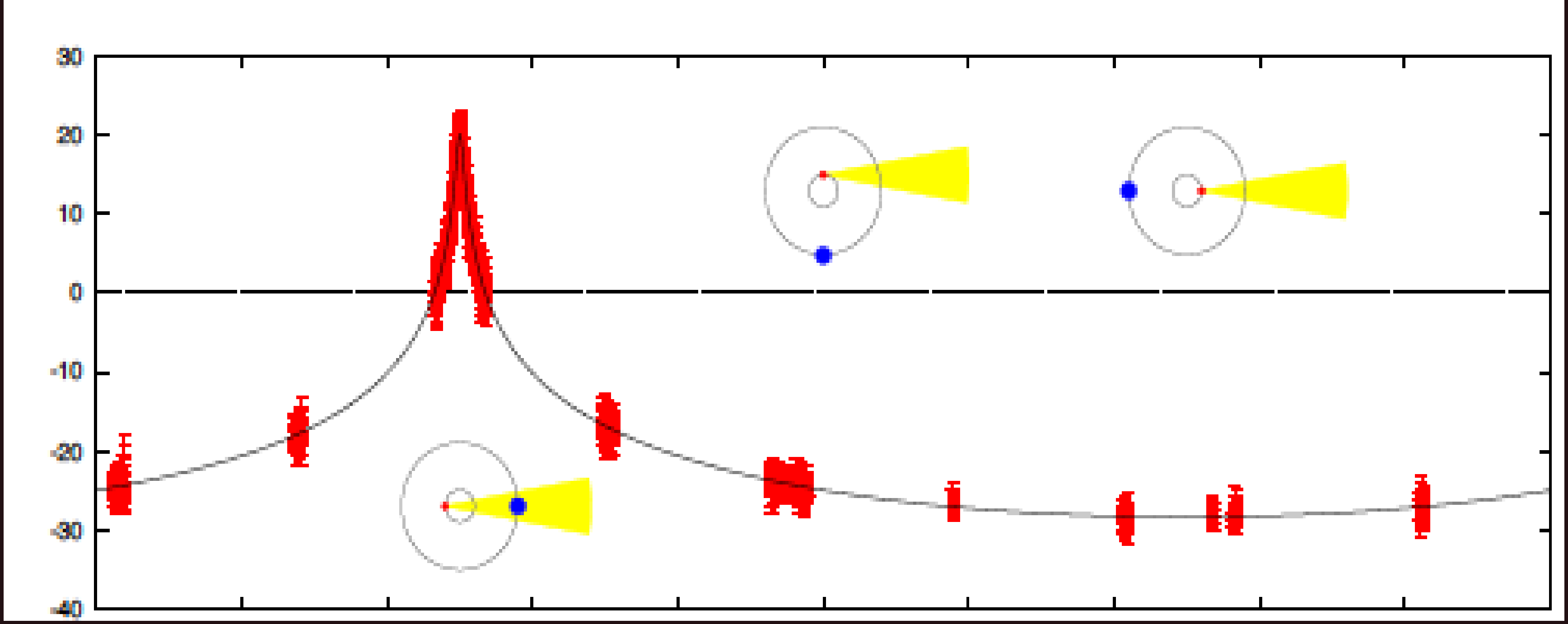
$M_p = 1.928(17)\ M_\odot$



PSR J1614-2230

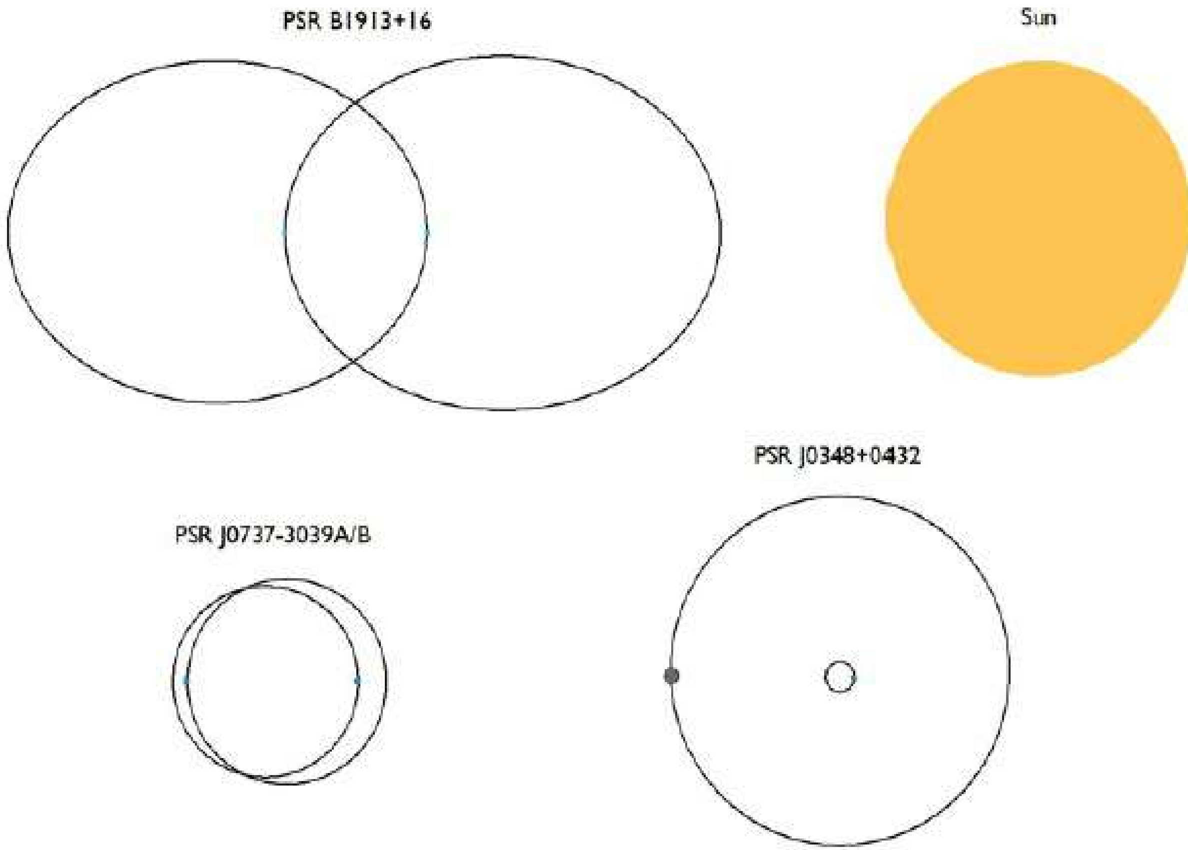
A precise AND large mass measurement

Shapiro delay:

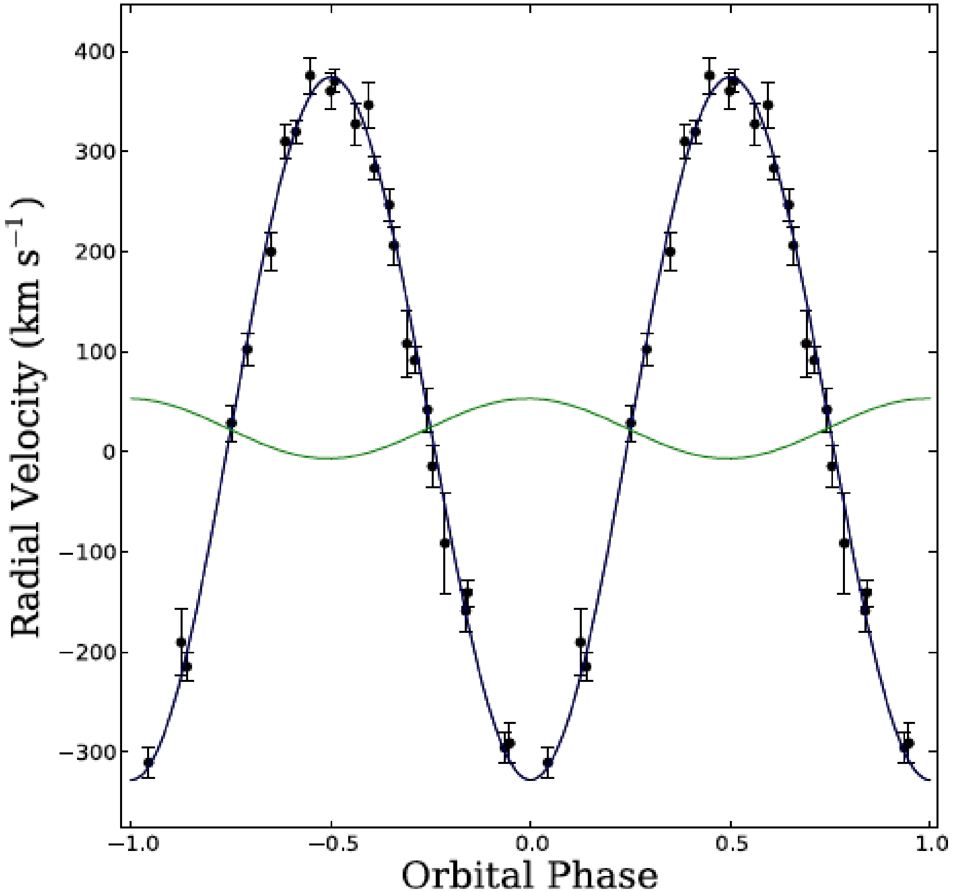


The big one: PSR J0348+0432

- 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.

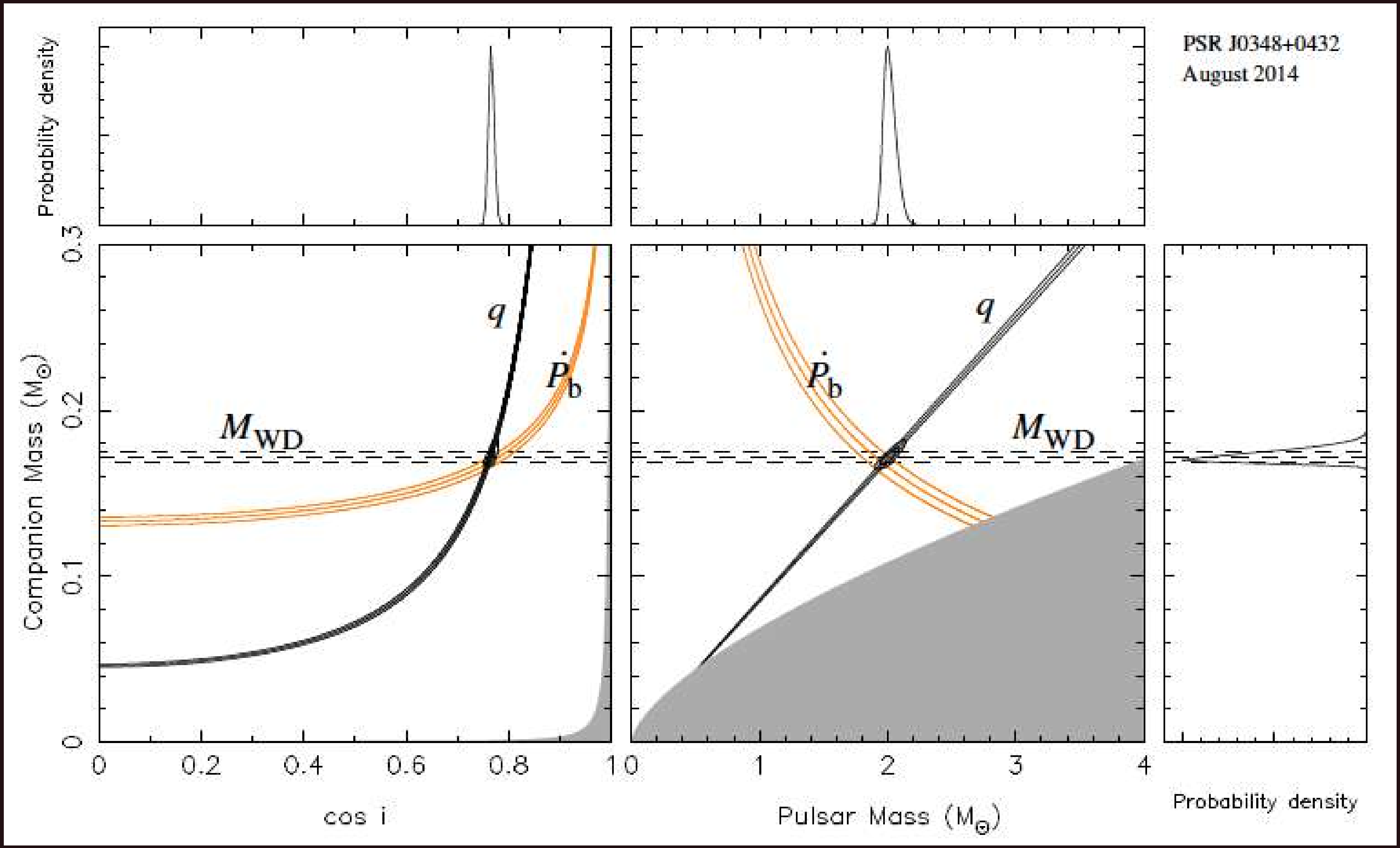


PSR J0348+0432

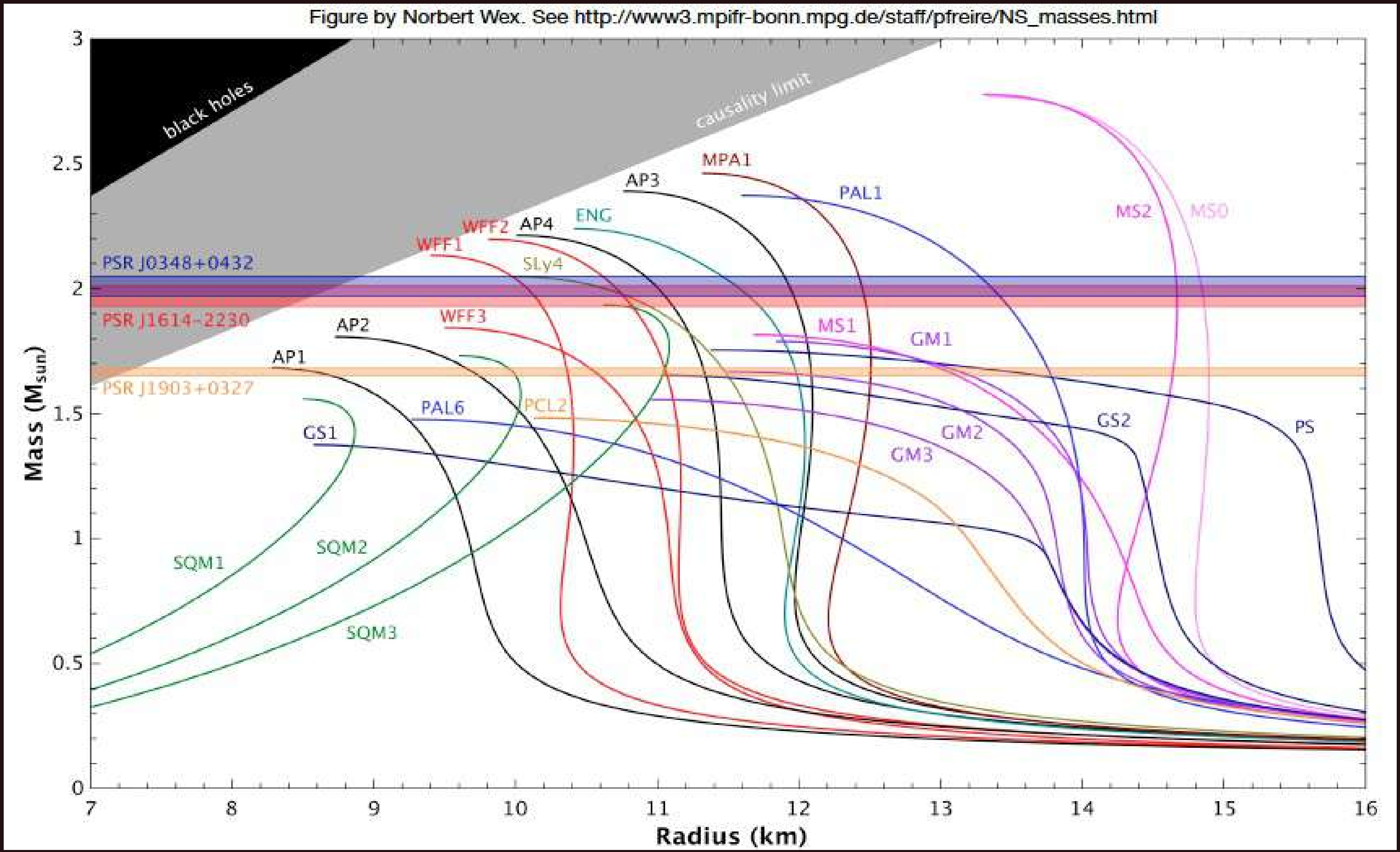


- Recent optical measurements at the VLT find a WD mass of 0.172 ± 0.003 M and **a pulsar mass of 2.01 ± 0.04 M** (Antoniadis et al. 2013, Science, 340, n. 6131).
- Most massive NS with a precise mass measurement.
- Confirms that such massive NSs exist using a different method than that used for J1614−2230. 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 μs /year!

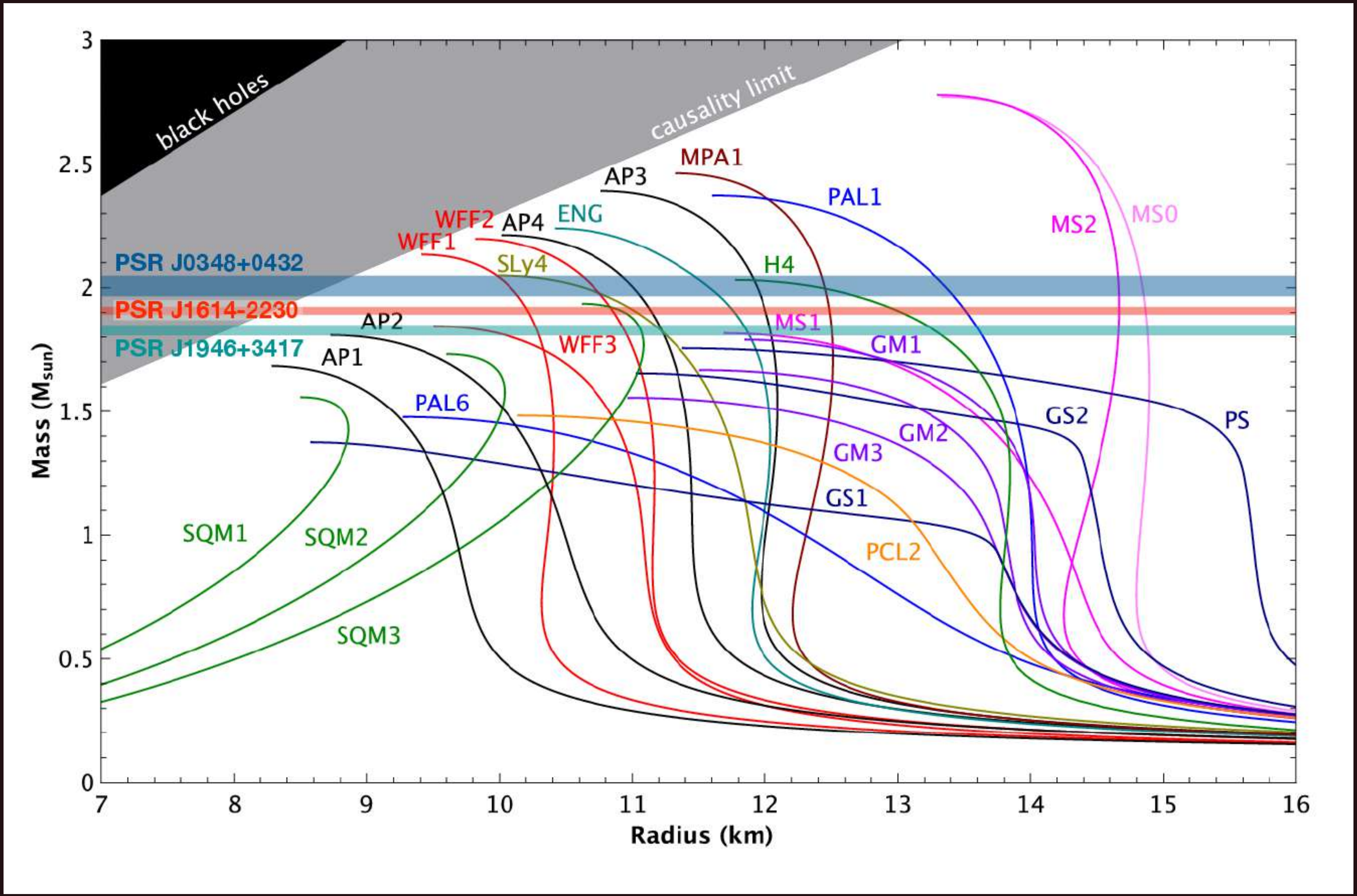
GR test / better mass measurement



NS Masses and Radii ↔ EoS



NS Masses and Radii ↔ EoS

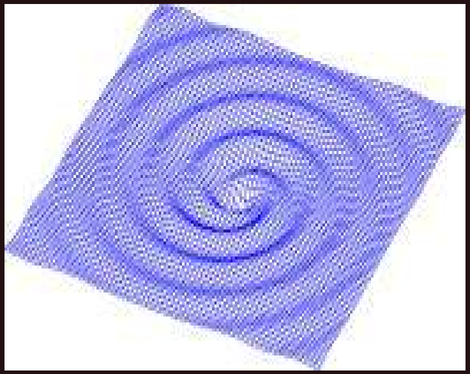


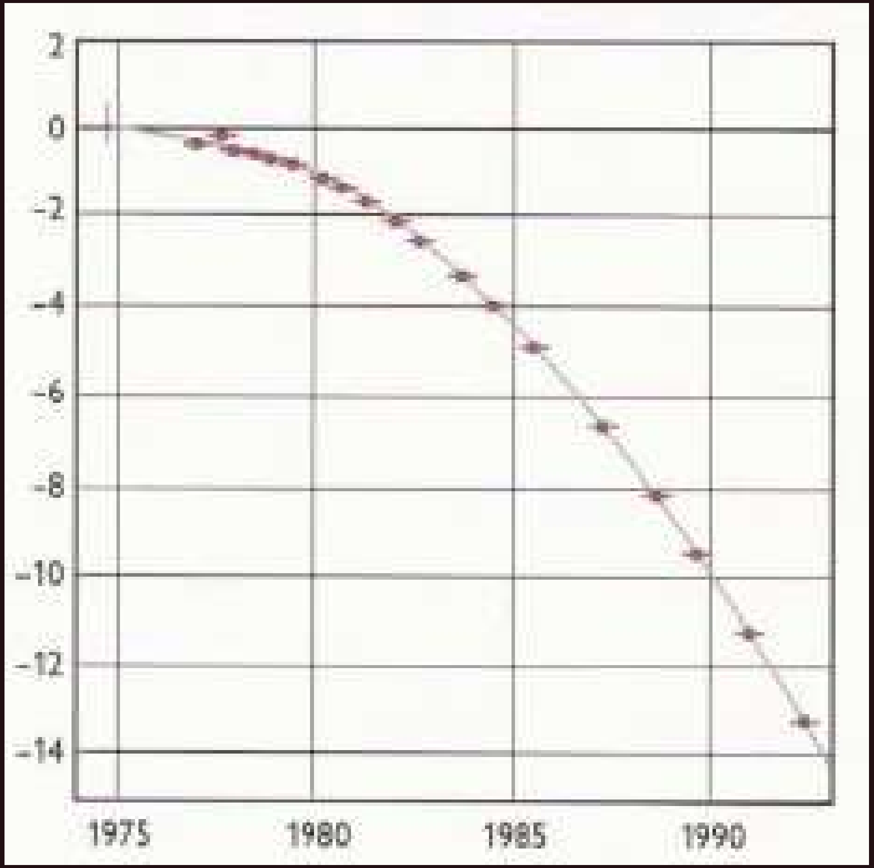
www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Hulse-Taylor pulsar – binary system

PSR B1913+16 (now J1915+1606)

Nobel Prize for Hulse and Taylor (1993)





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

Direct measurement of gravitational waves – merging of two massive black holes (2015)

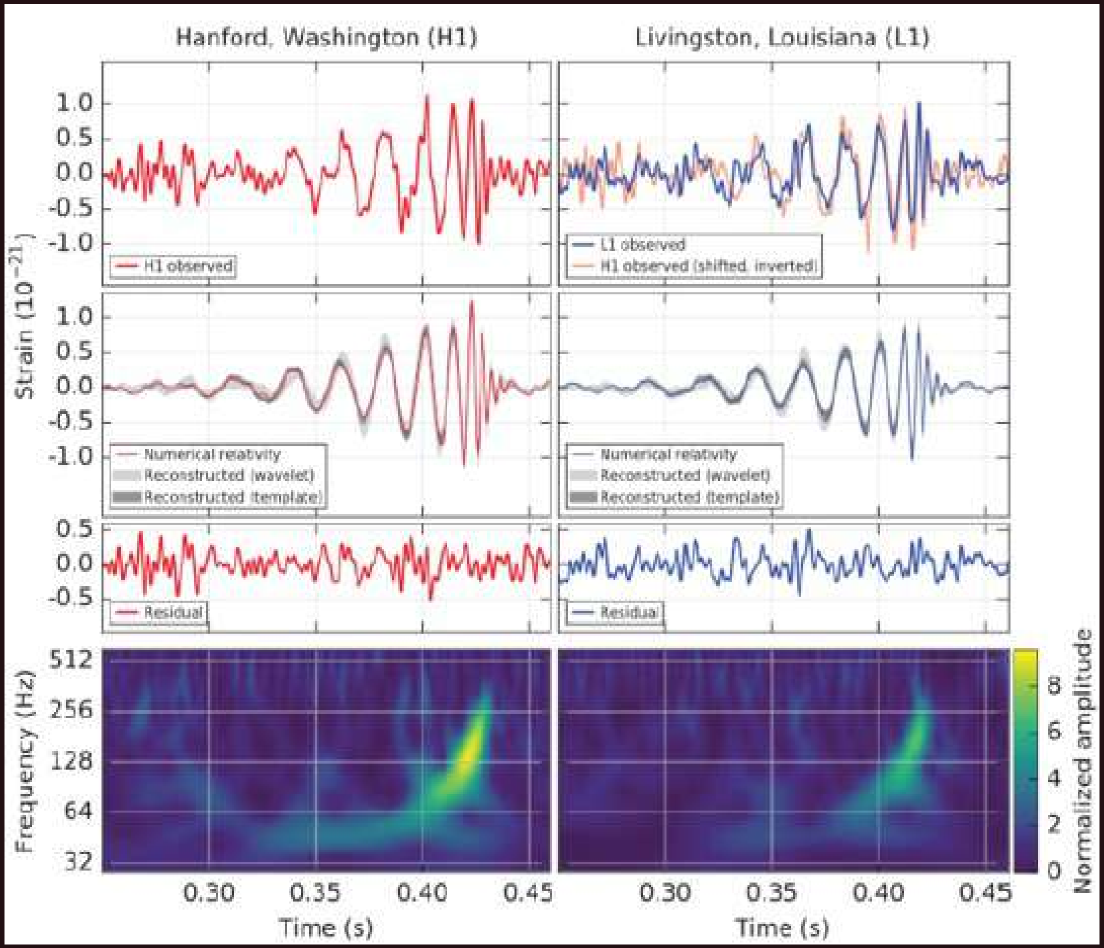
First detection of gravitational waves
September 14, 2015 at 5:51 a.m. EDT
(LIGO Collaboration)

Source at 410(18) Mpc [z=0.09(4)]

Initial black hole masses:
36(5) Mo and 29(4) Mo
Final black hole mass:
62(4) Mo

Energy release in gravitational waves
3.0(5) Mo c^2

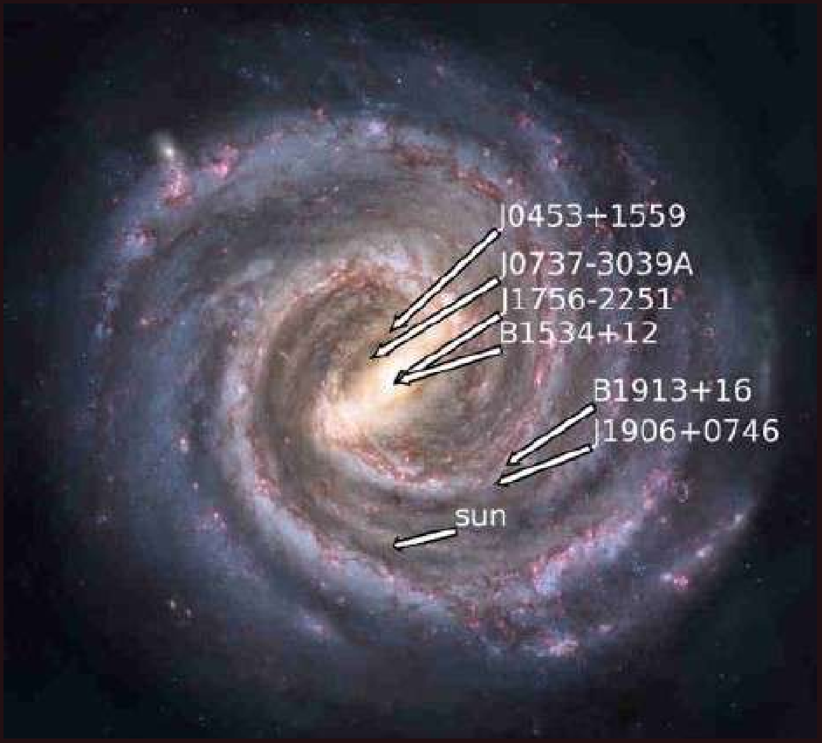
Phys. Rev. Lett. 116, 061102 (2016)

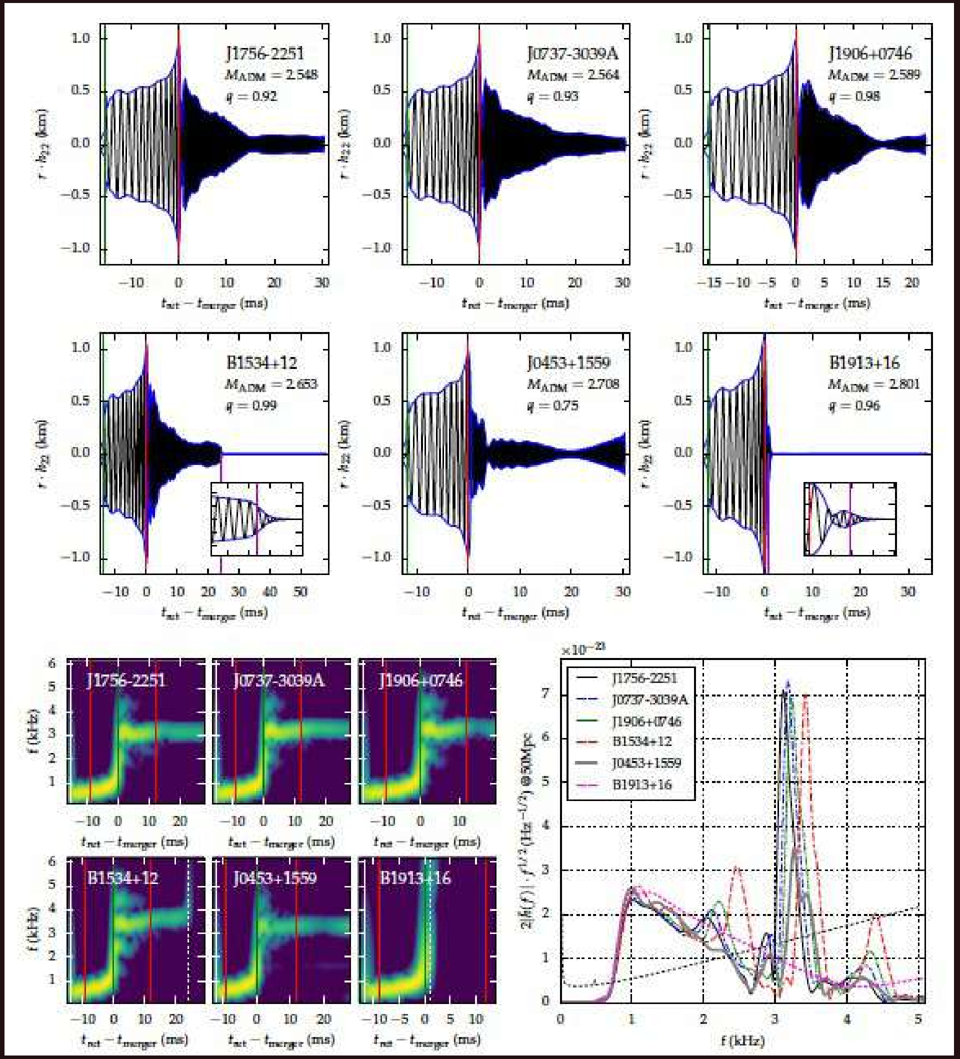


Nobel Prize Physics 2017 !! Rainer Weiss, Barry C. Barish, Kip Thorne

Ultimate goal: neutron star merger !

Simulated NS-NS merger events *)
--> Sensitivity to the NS equation of state!

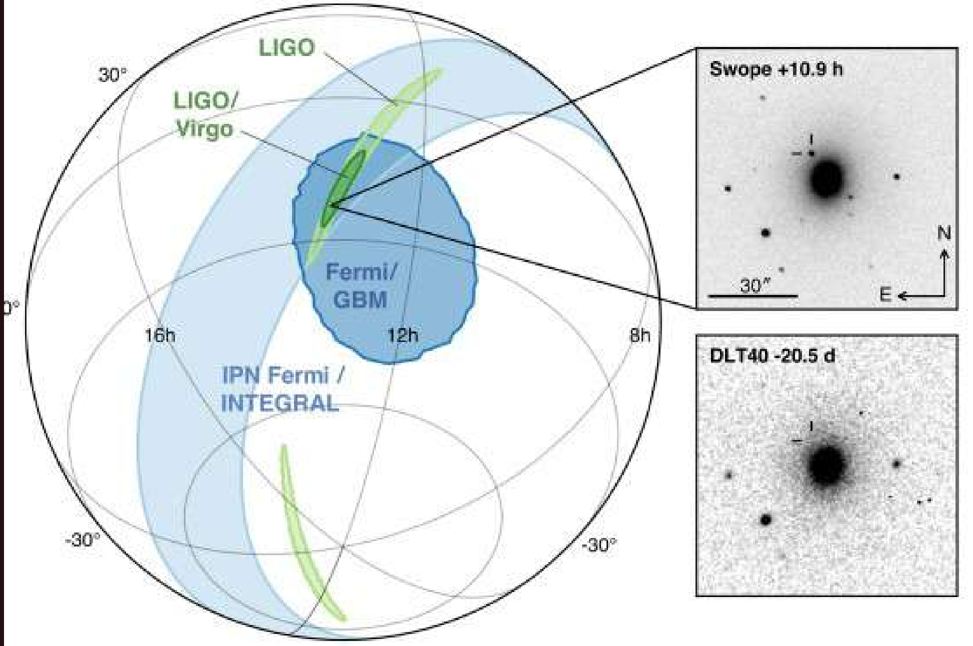


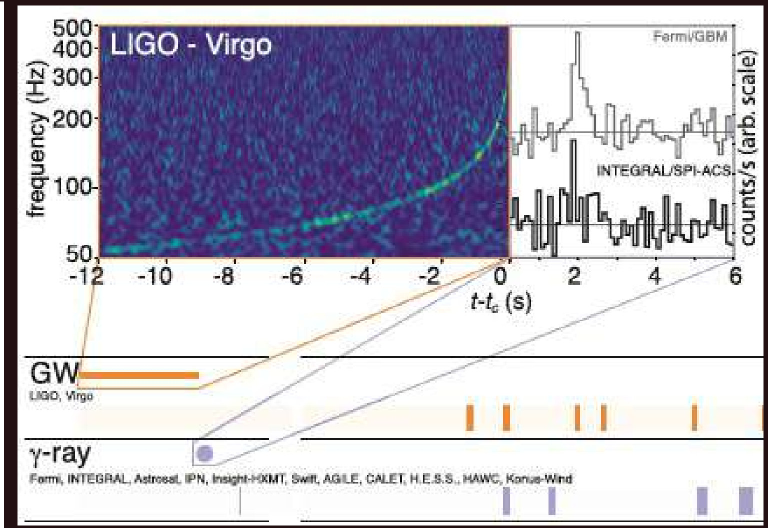


Expected rate ~ 0.2 – 200 events/year for
LIGO/Virgo Collaboration in 2016 - 2019

*) A. Feo, R. DePietri & F. Maione, Class. Quant. Grav. 34 (2017) 034001

Discovery: neutron star merger !





GW170817A , announced 16.10.2017 *)

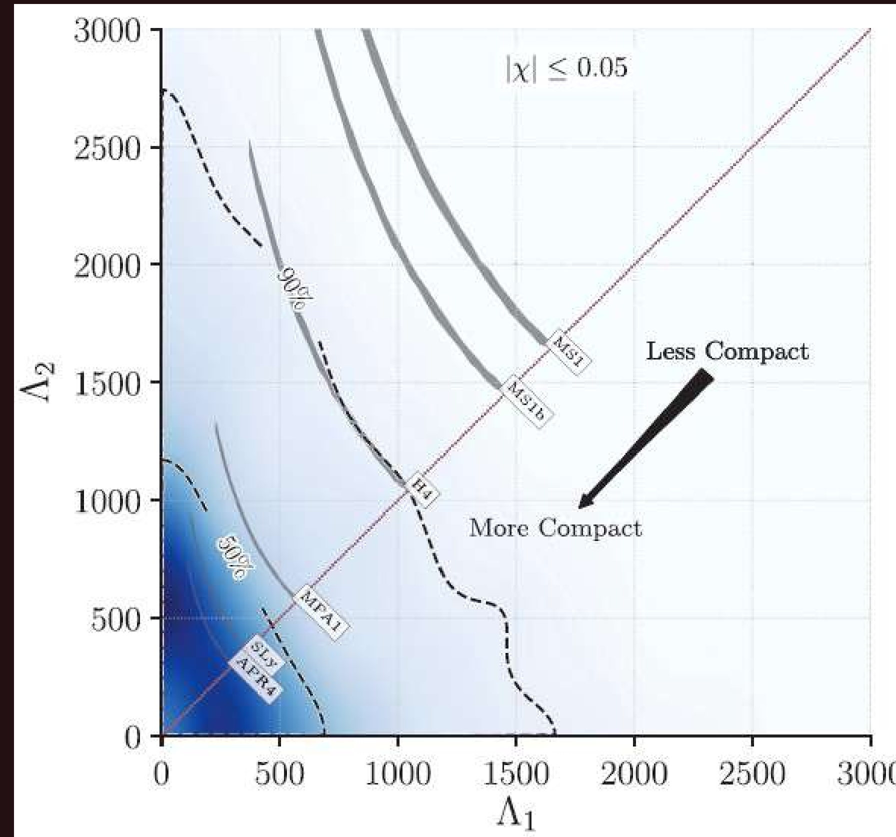
*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

NS-NS merger !

GW170817A , announced 16.10.2017 *)

Multi-Messenger Astrophysics !!

	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	$1.36–1.60\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7–1.0$
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc



Constraint on parameter (Λ<800)

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$

Constraint on neutron star maximum mass

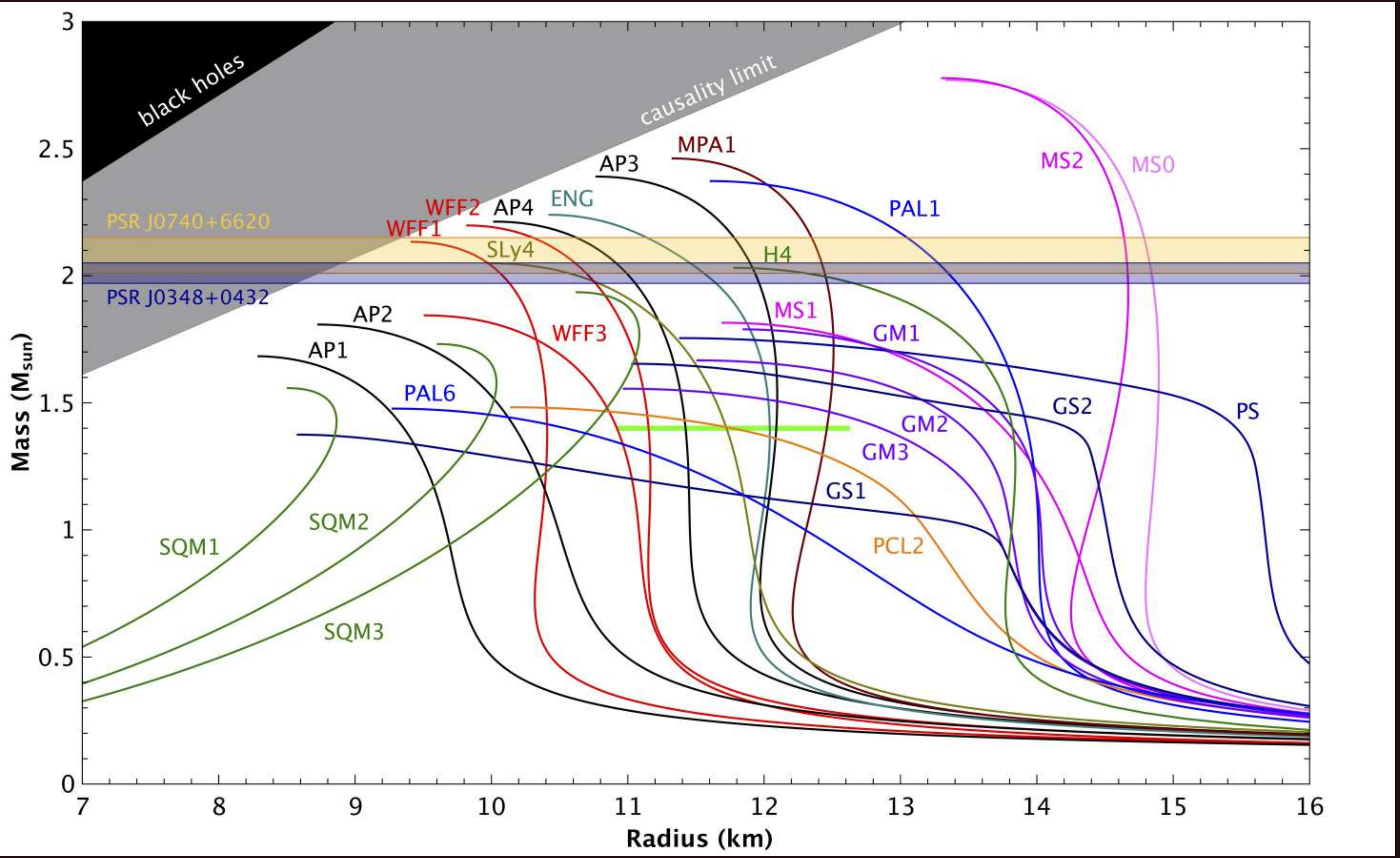
M<2.17 M_sun (arxiv:1710.05938)

Dimensionless tidal deformability

$$\Lambda = (2/3) k_2 [(c^2/G)(R/m)]^5$$

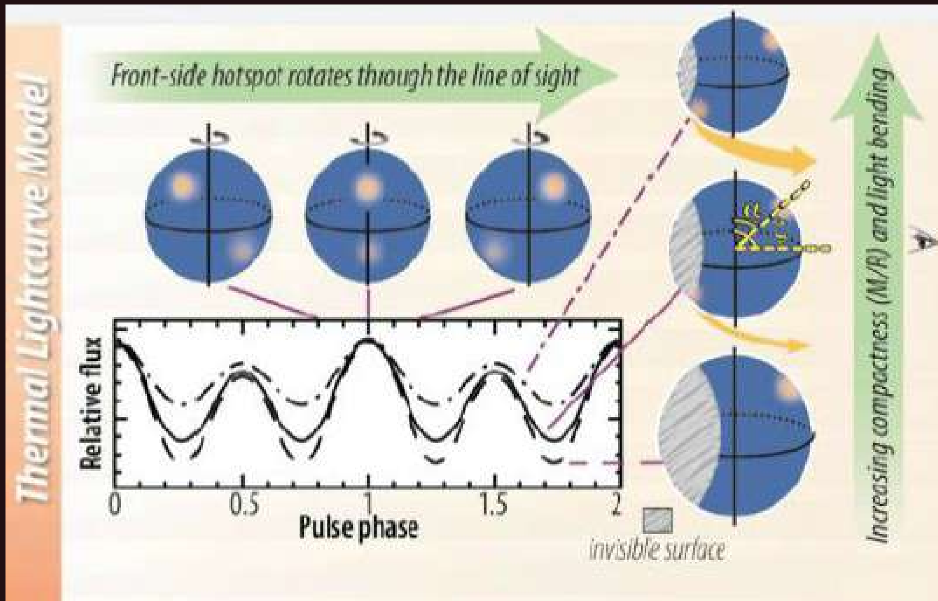
*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

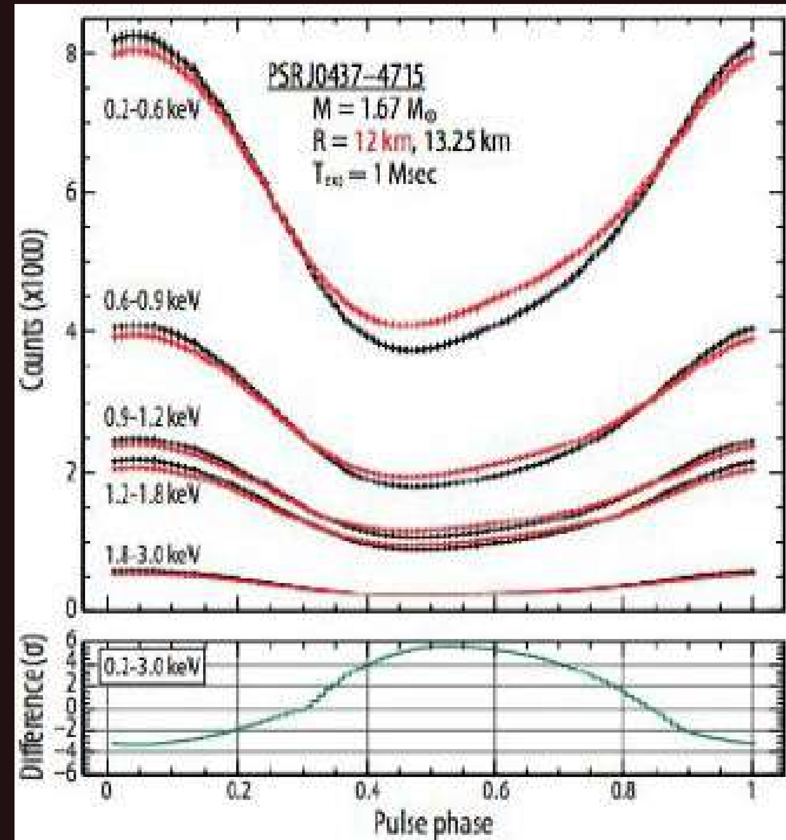
NS Masses and Radii ↔ EoS



www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Measure NS Radii ...

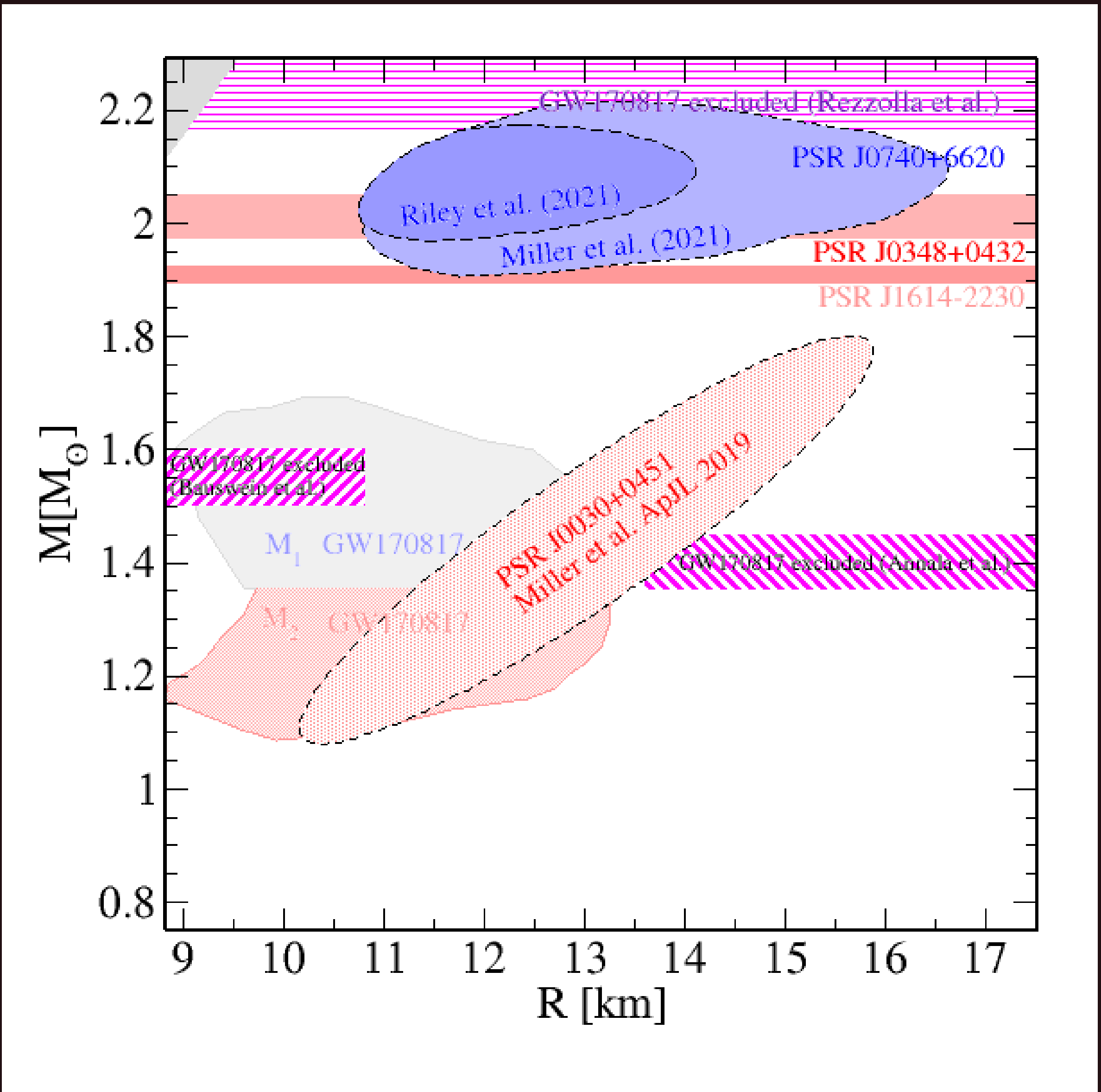




Thermal lightcurves: NS with “hot spots”

K.C. Gendreau et al., Proc. SPIE 8443 (2012) 844313 – launch: 2017; results: 2019, 2021

New constraints on NS mass and radii !



New NICER mass-radius data

PSR J0740+6620

(Riley et al., arxiv:2105.06980
Miller et al., arxiv:2105.06979)

Hypernuclear EoS out ?!

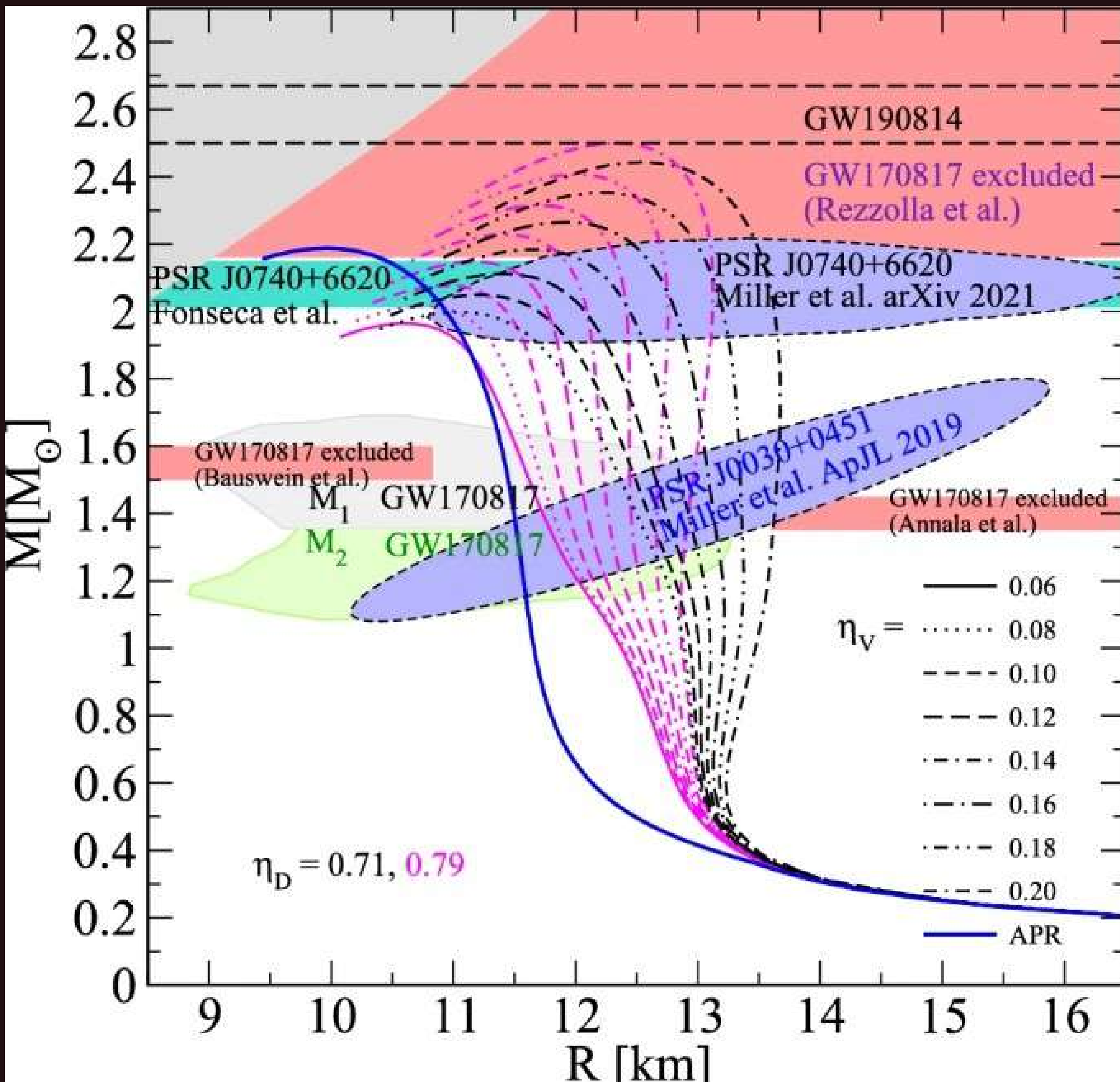
→ stiff hypernuclear matter
→ early onset of deconfinement
(M_onset < 1.5 M_sun)

New quark matter paradigm:

→ deconfinement to stiff QM EoS
→ hybrid stars larger, higher M_{max}

LVC radius constraint
GW170817
(Abbott et al., PRL (2018))
NICER mass -radius constraint
PSR J0030+0451
(Miller et al., ApJLett. (2019))
PSR J0740+6620
(Miller et al., arxiv:2105.06979)

New constraints on NS mass and radii !



Ayriyan, Blaschke, Alvarez-Castillo et al., EPJA 57 (2021) 318

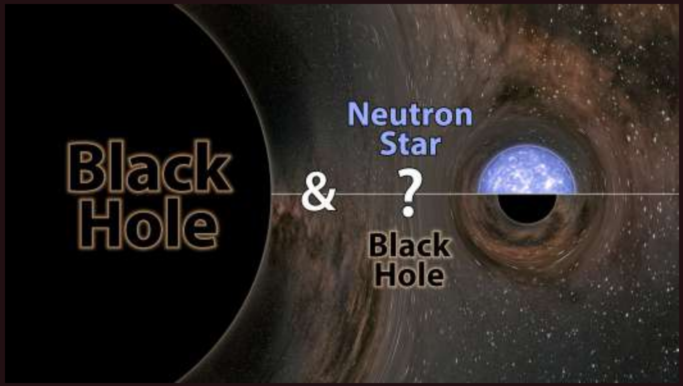
GW190814 - Enigma

Heaviest NS or Lightest BH ??

M_1 = 22.2 – 24.3 M_o

M_2 = 2.50 – 2.67 M_o

(Abbott et al., ApJL 896 (2020) L44)



LVC radius constraint

GW170817

(Abbott et al., PRL 121 (2018) 161101)

NICER mass -radius constraint

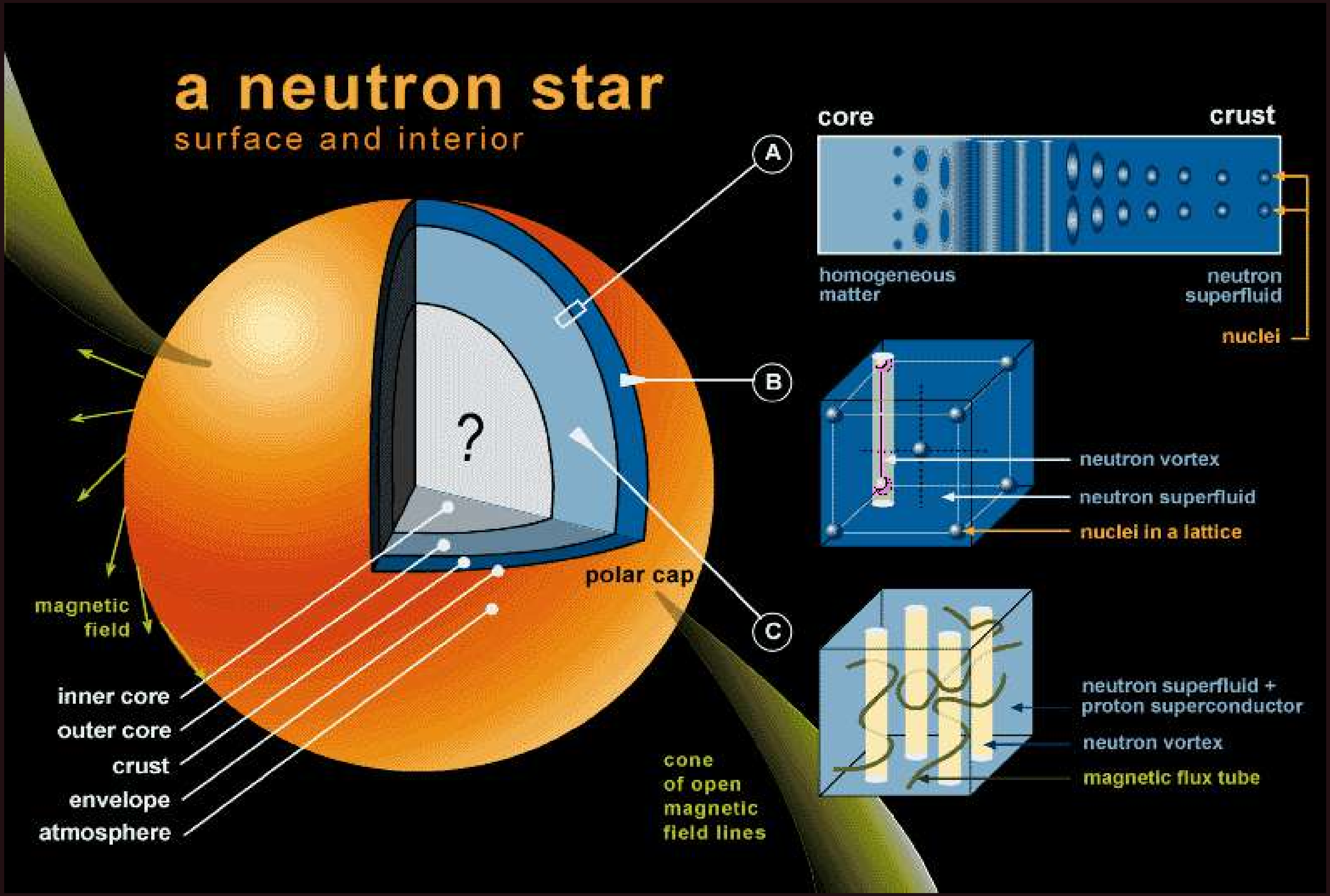
PSR J0030+0451

(Miller et al., ApJLett. 887 (2019) L24)

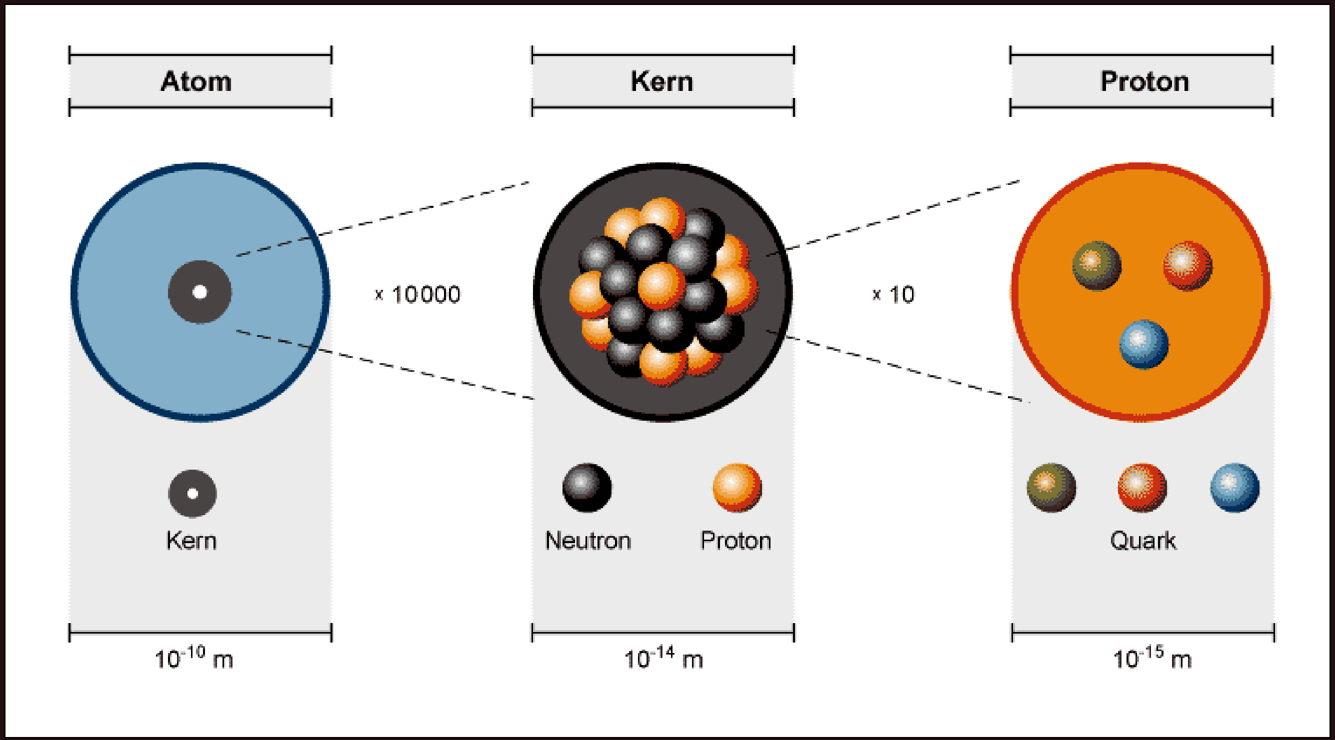
PSR J0740+6620

(Miller et al., ApJLett. 918 (2021) L28)

Superdense objects – what is inside?



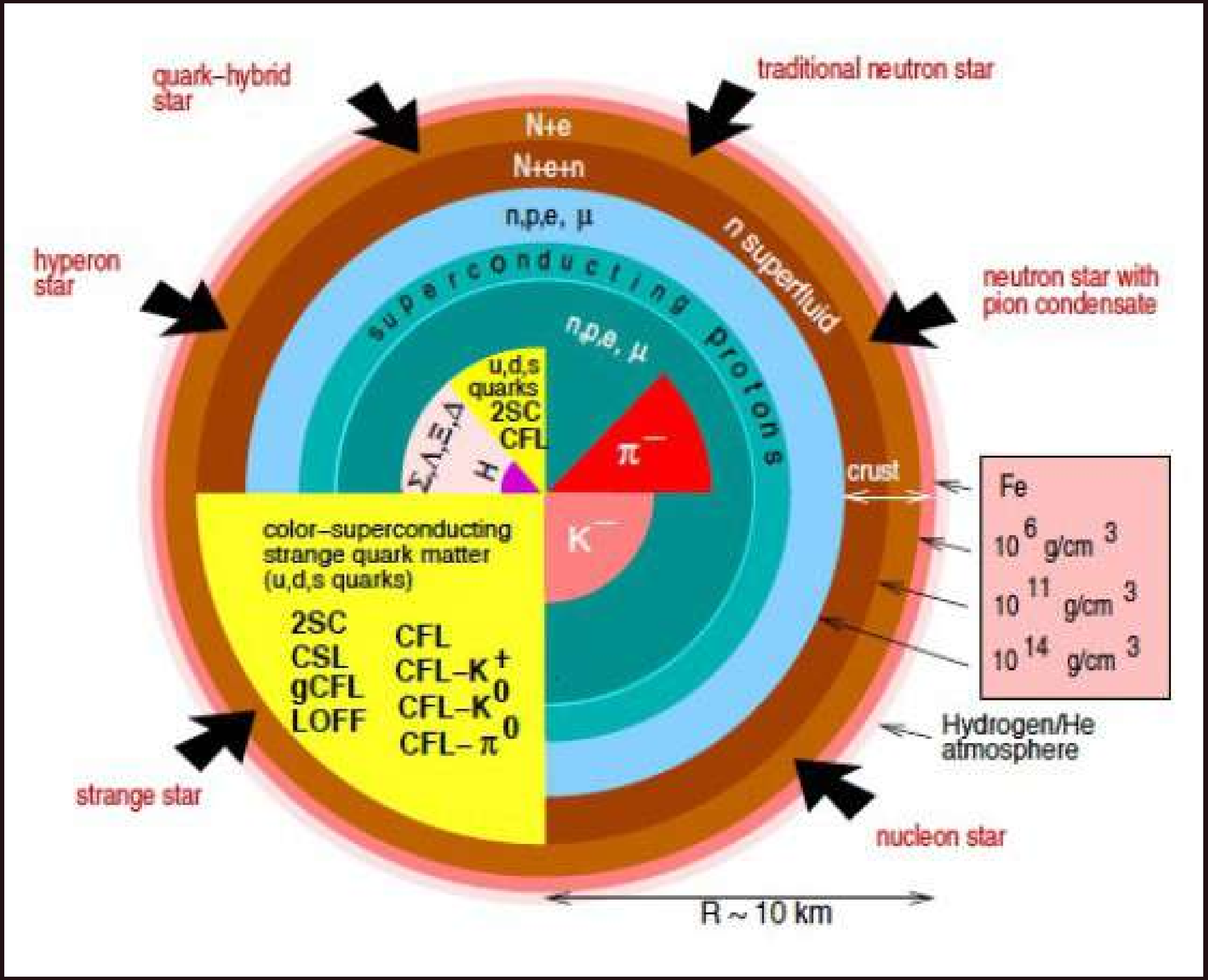
Superdense objects – what is inside?



Nucleus, A nucleons: R_A=1.2 10^{-13} cm $A^{1/3}$; ρ_0=A1.67 10^{-24} g/(4π/3 $R_A^{\ 3}$)= 2.3 10^{14} g/cm^3

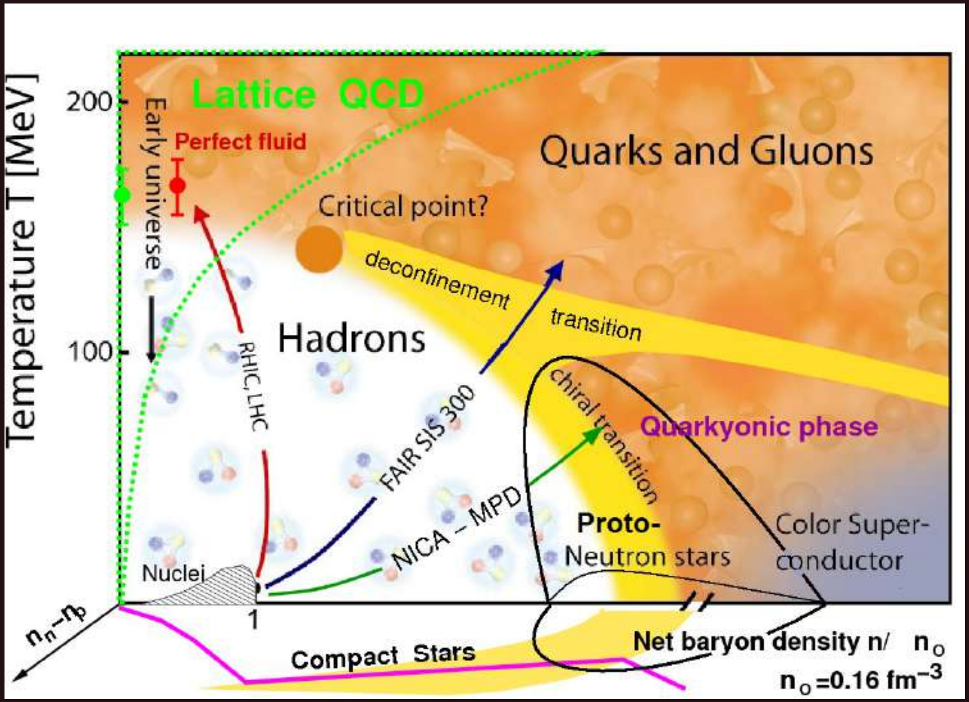
Neutron star: R= 10 km; ρ= 2 Mo/(4π/3 R^3) = 4 10^{33} g/(4 10^{18} cm^3)= 10^{15} g/cm^3 = 4 ρ_0

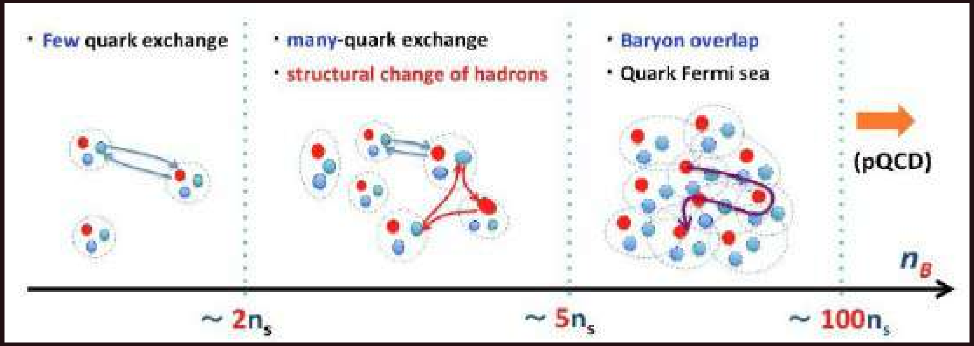
Superdense objects – what is inside?



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

Quark Matter in Neutron Stars ?





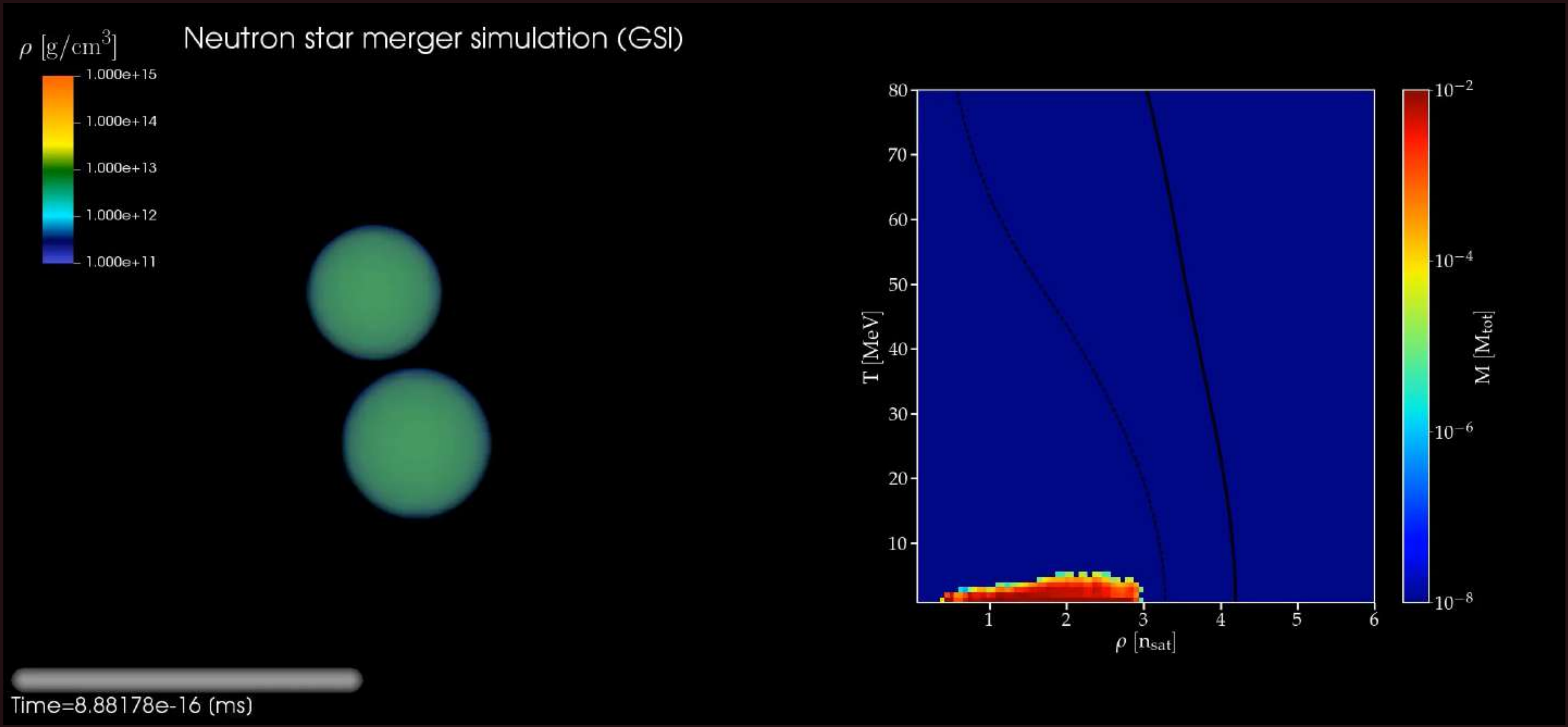
If the two high-mass pulsars (2 Mo), PSR J1614-2230 & PSR J0348+0432, would have significantly different radii, Say 11 km and 13 km, then they could be considered as "high-mass twin stars", i.e. Objects that would provide evidence For a strong first-order phase transition (to quark matter) in compact stars.

This would be evidence for the existence Of a critical endpoint in the QCD phase Diagram that is searched for in heavy-ion Collision experiments, also at NICA.

D. Blaschke et al., arxiv:1310.3803
S. Benic et al., A&A 577 (2015) A40
D. Alvarez-Castillo et al., EPJA 52 (2016) 232

Quark Matter in a Binary NS merger ?

Population of the QCD Phase Diagram – Quark Matter and Mixed Phase
Simulation of a BNS merger 1.35+1.35 solar masses, time = 6 … 25 ms
S. Blacker, A. Bauswein et al., Phys. Rev. D 102 (2020) 123023



Hybrid Compact Stars birth in Supernova?

Quark Deconfinement as a supernova explosion mechanism for massive blue supergiant stars (M = 50 M_sun); T. Fischer et al., Nature Astron. 2 (2018) 980

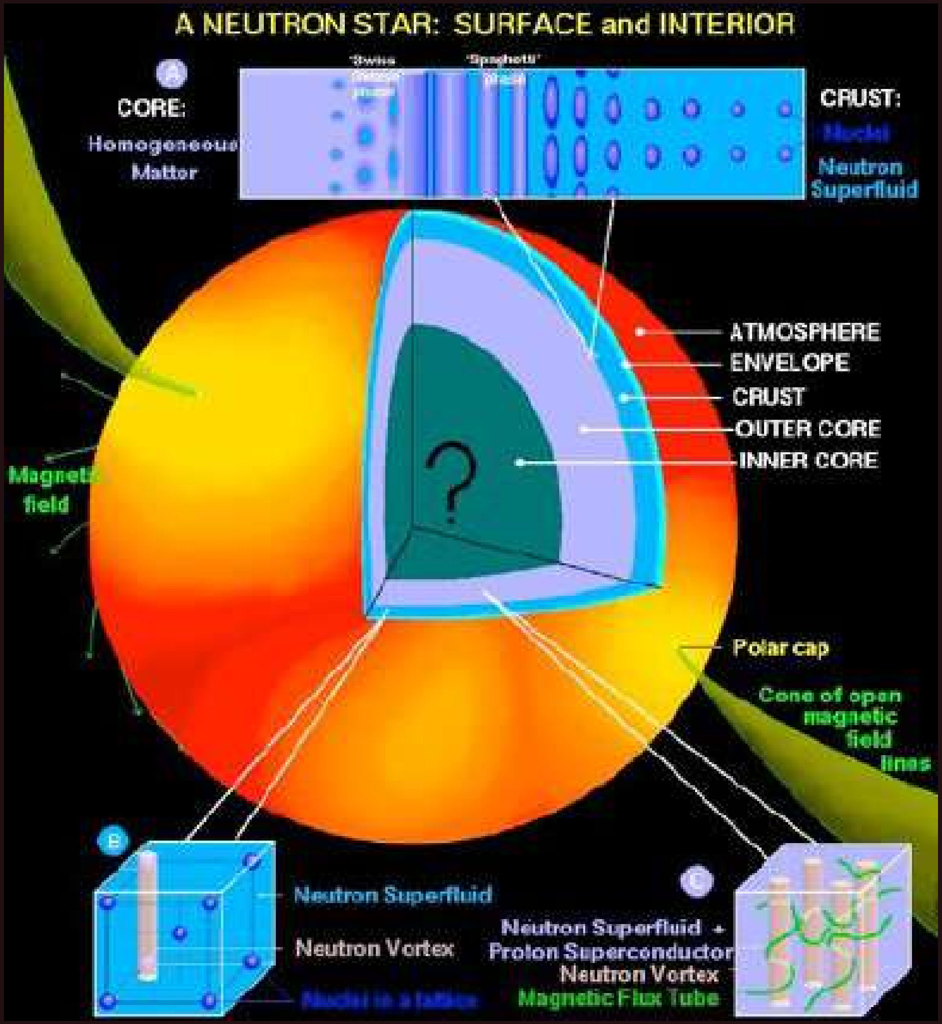
SCI ANI

Science Animated

SUB

FOL

Neutron stars are Super-Stars! Pines theorem (1990)



PROOF:

- *Super*dense objects
  $\rho \sim 2\rho_0 = 5 \cdot 10^{14}\mathrm{g/cm^3}, 2GM/R \to 0.5$
- *Super*fast rotators
  $P_{\min} = 1.6\ \mathrm{ms}, \Omega \sim \Omega_{\mathrm{Kepler}}/2$
- *Super*fluid interior
  $\Delta_{\mathrm{nn}} \sim 0.1 - 1\ \mathrm{MeV}$
- *Super*conducting interior
  $\Delta_{\mathrm{pp}} \sim \Delta_{\mathrm{nn}}$
- *Super*strong magnetic fields
  $B \to 10^{15}\ \mathrm{G}$
- *Super*precise timers
  $\Delta P/P \to 10^{-14}\ \mathrm{s/yr}$
- *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.):
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EPJA 52 (2016)

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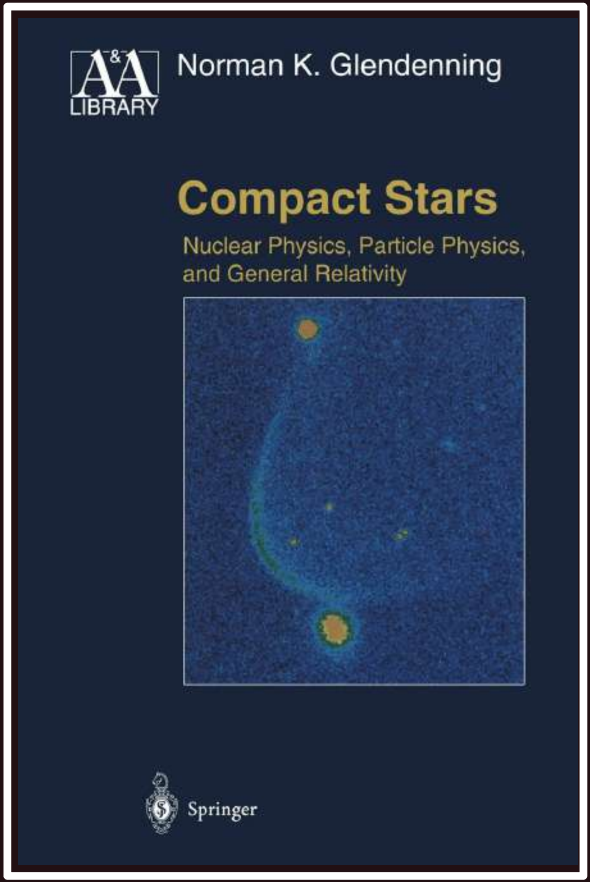

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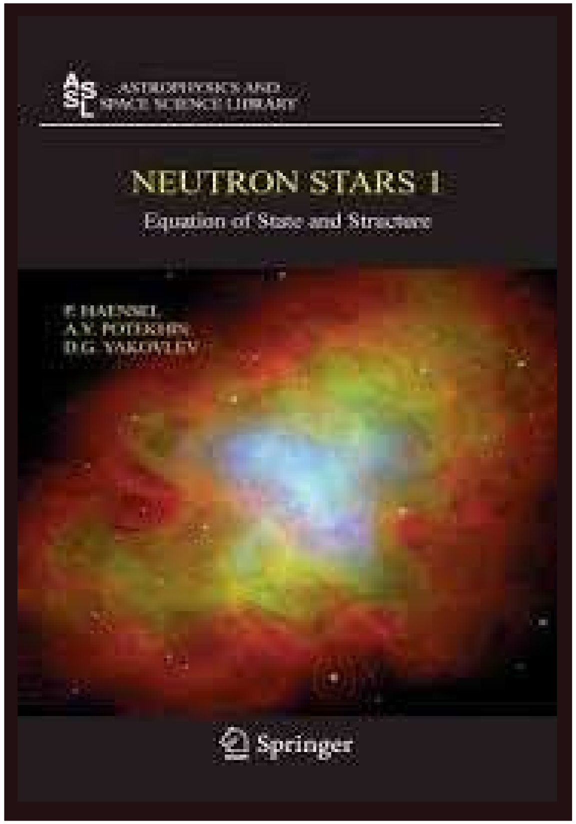

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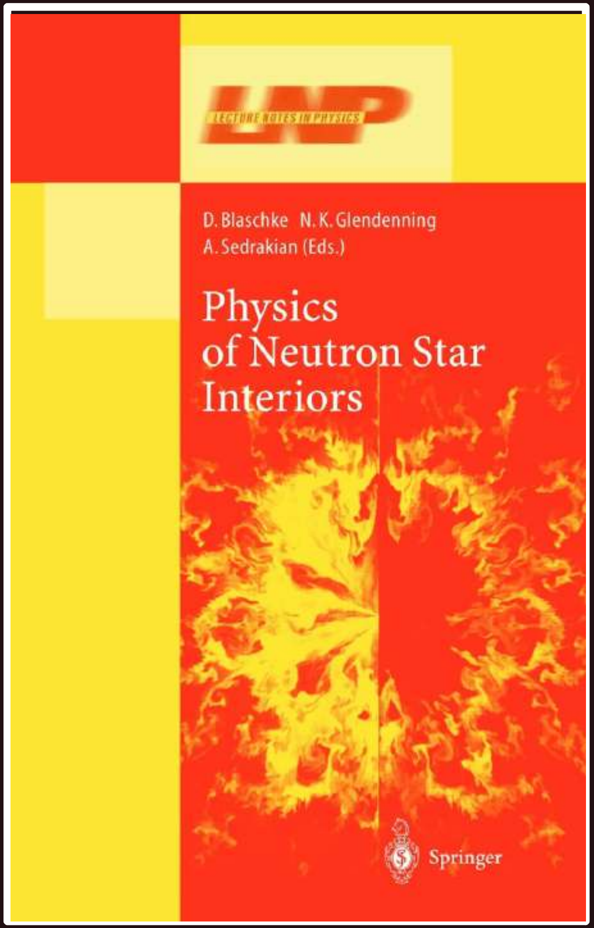
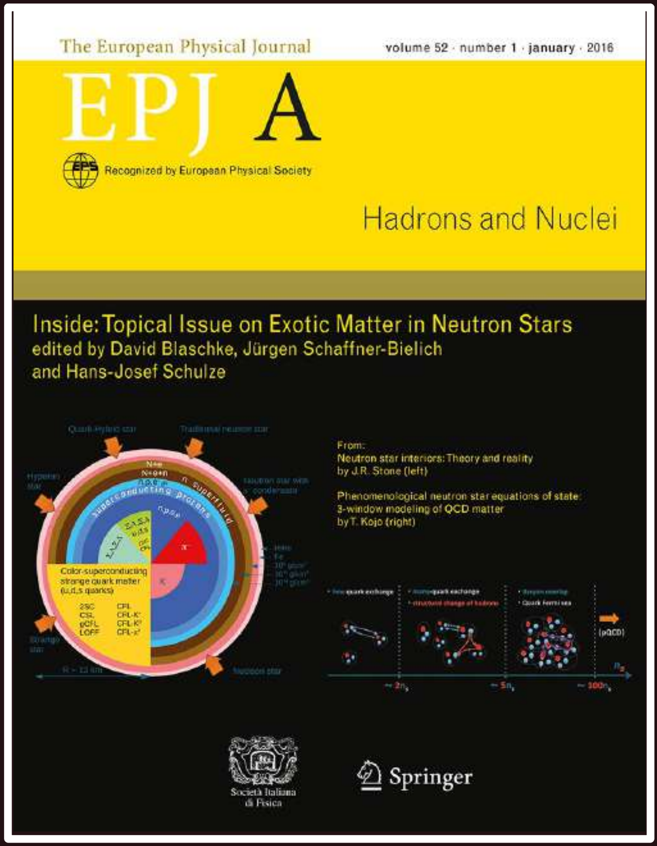


Further reading ...



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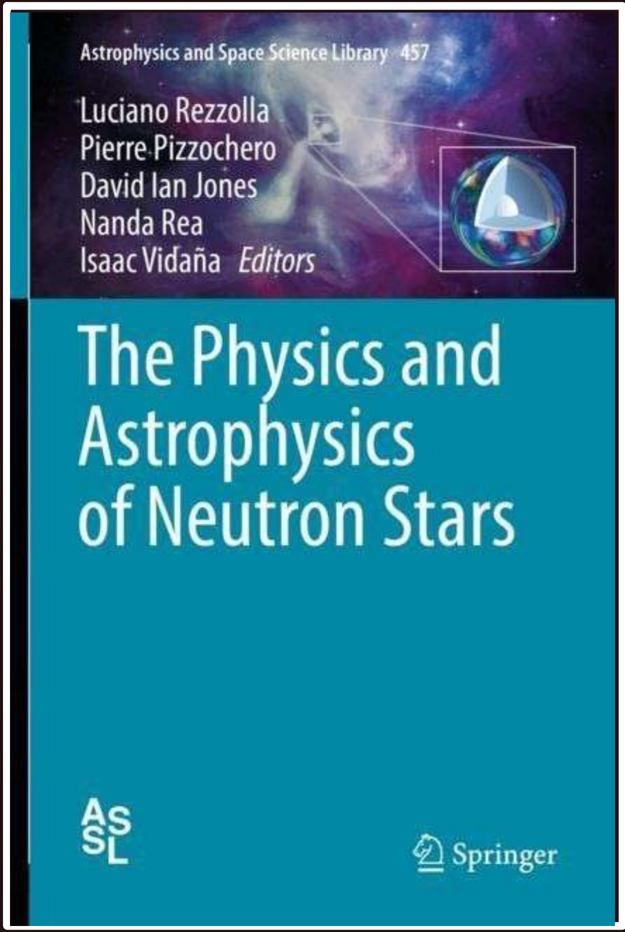

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EPJA 52 (2016)

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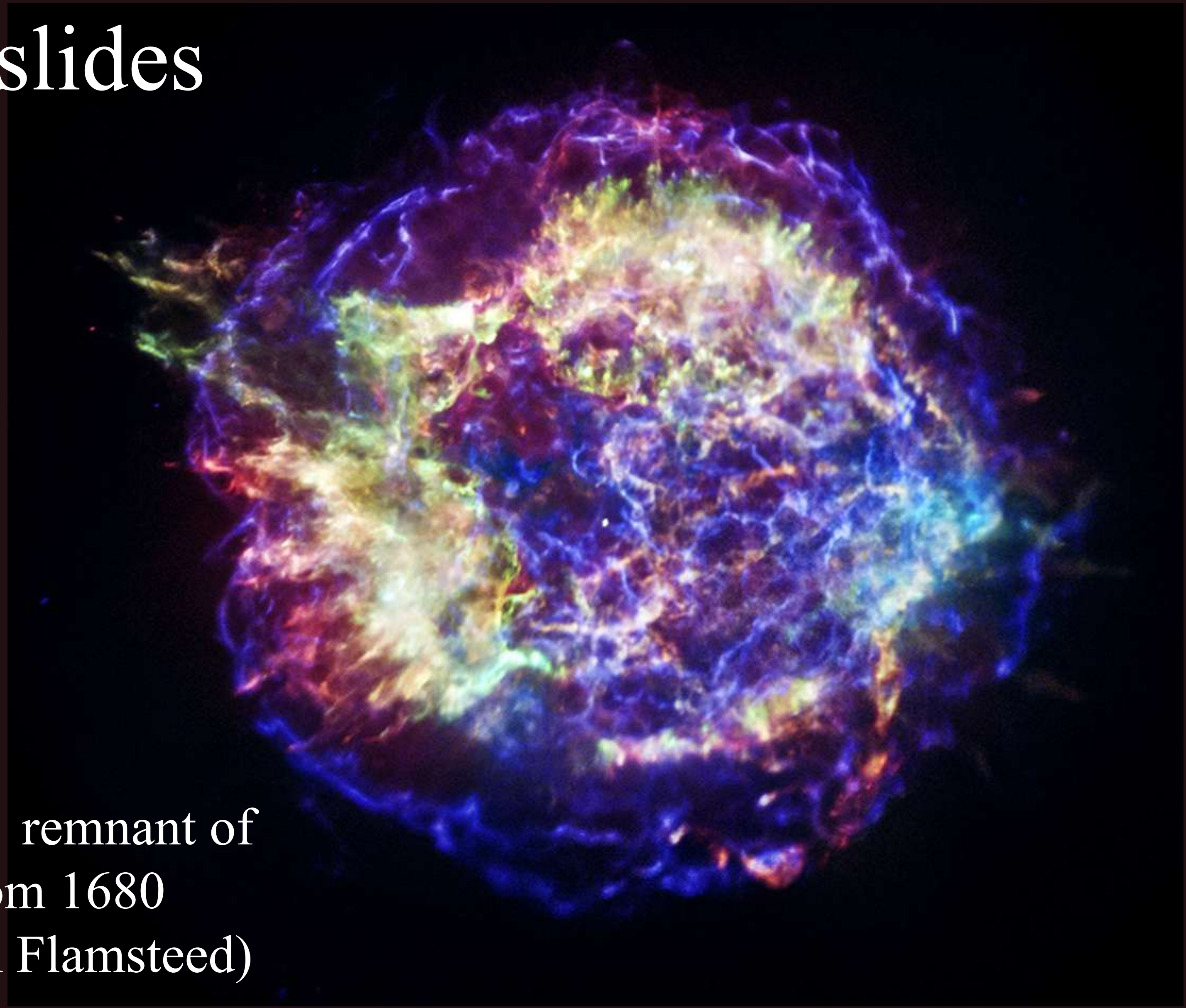
The Physics and Astrophysics of Neutron Stars
(Springer, 2018)

Backup slides



Cassiopeia A – remnant of
a supernova from 1680
(observer: John Flamsteed)

A recent, nearby supernova ...

23.02.1987
Supernova 1987A
in the Large
Magellanic Cloud is
observed on Earth ...
... first time also a
neutrino signal of a
SN is detected

How do SN explode?
Ask Tobias Fischer at
Wroclaw University!

Accretion in close binaries

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

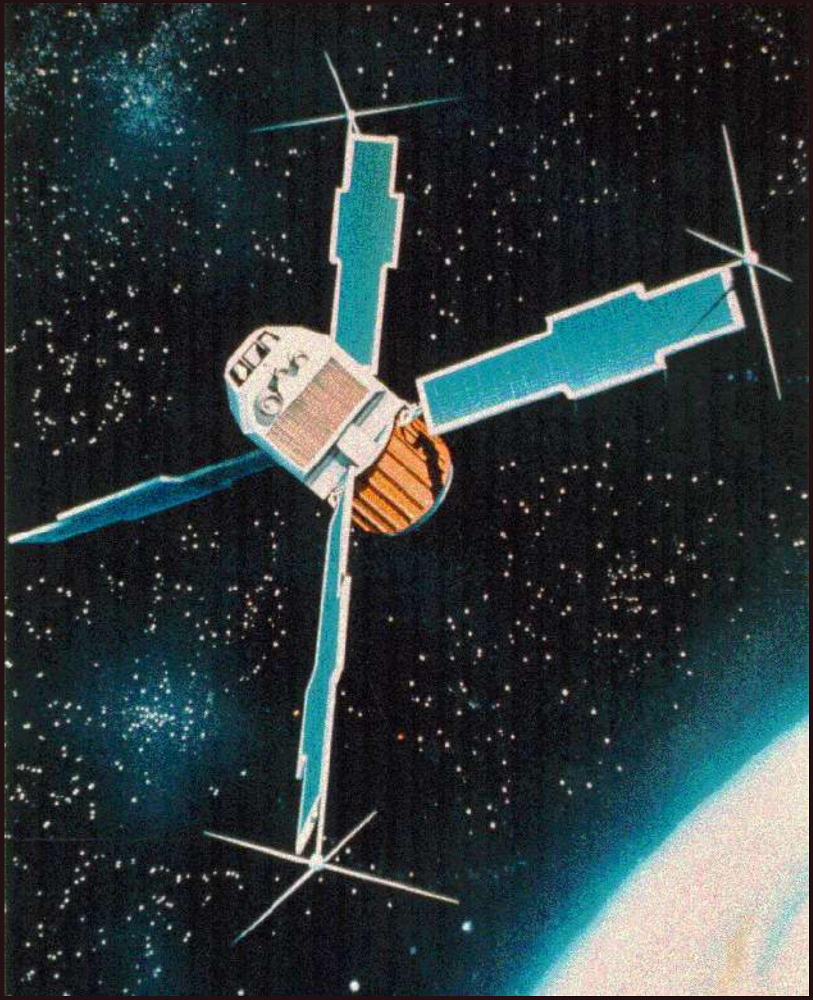
When matter falls down onto the surface of a neutron star up to 10% of mc^2 can be released.

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.

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.