Compact Stars I: Phenomenology & Basics

David Blaschke (Univ. Wroclaw & JINR Dubna)

Supernova 1987A HUBBLESITE.org

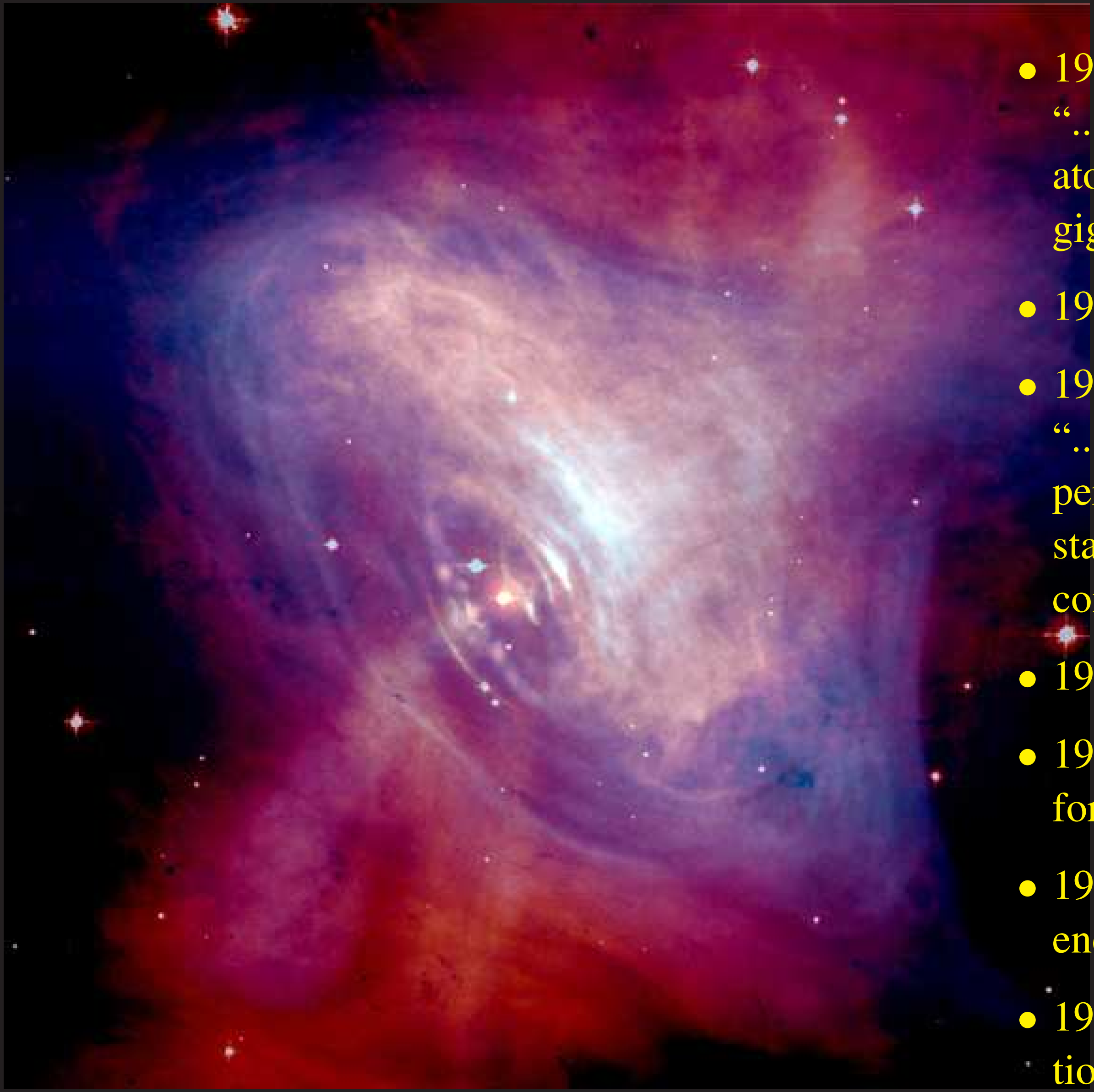
- Historical Remarks
- Compact Star Population
- Compactness: Masses and Radii
- Cooling: Temperatures and Ages
- Summary: Compact Star Properties
- Outlook: Compact Stars & QCD Phase Diagram

EUROPEAN SCIENCE FOUNDATION

comp star

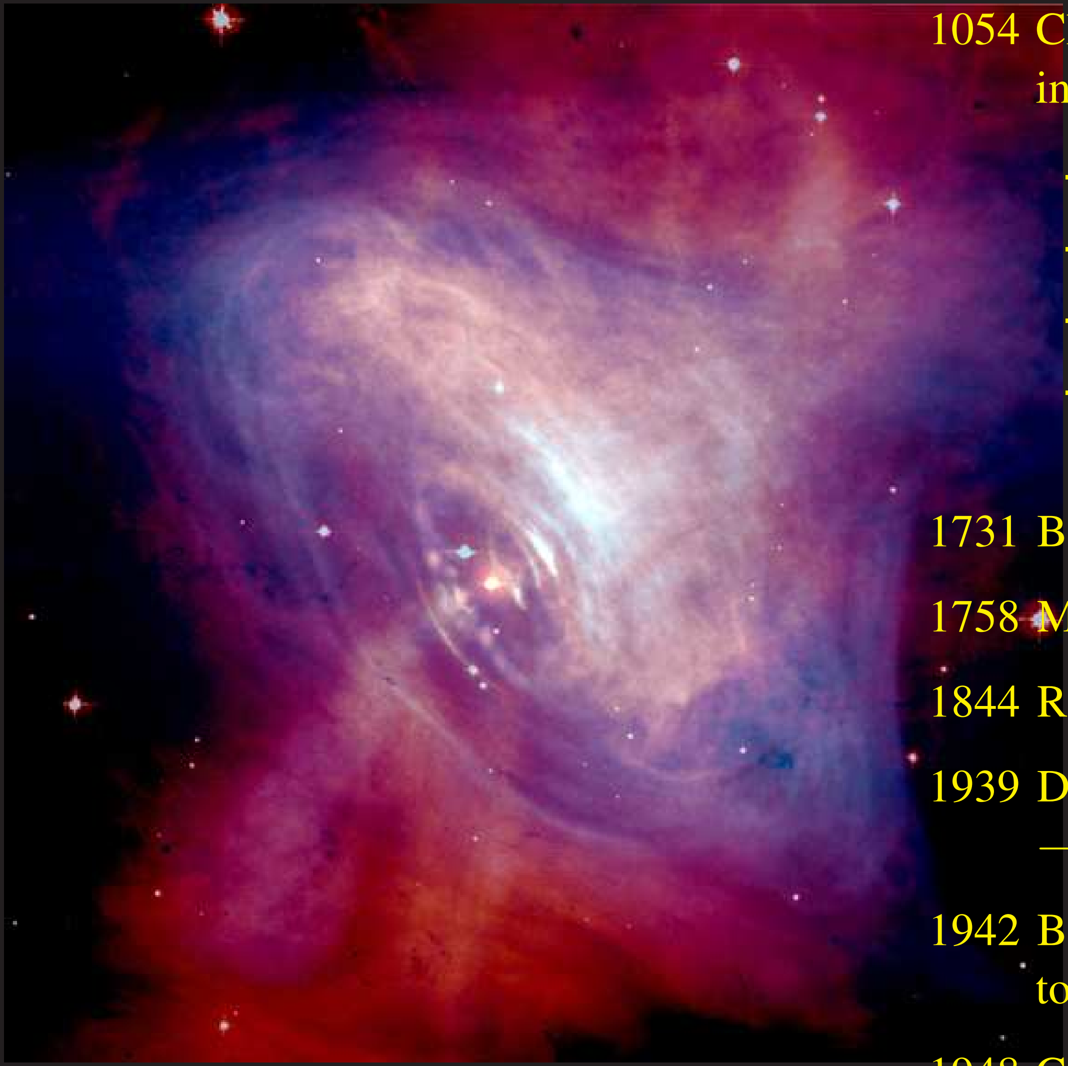
Zakopane, May 24th, 2012

Short History of Compact Stars before Discovery



- 1931/32 Landau, Anticipation:
  "… the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus."
- 1932 Chadwick, Discovery of the neutron
- 1934 Baade & Zwicky, Prediction:
  "… With all reserve we advance the view that supernovae represent the transitions from ordinary stars to neutron stars, which in their final stages consist of extremely closely packed neutrons."
- 1933 Sterne, EoS with β- capture and β- decay
- 1934 von Neumann & Chandrasekhar, GR eqs. for hydrostatic equilibrium (unpublished)
- 1937 Gamov and Landau suggest source of stellar energy (indep.)
- 1938 Bethe & Critchfield, Thermonuclear reactions as energy source
- 1939 Tolman, Oppenheimer& Volkoff: GR eqs. for stability, $M_{\max} = 0.71\ M_\odot$ for neutron gas

Example: Crab nebula and Supernova 1054



CHANDRA (BLUE) + HUBBLE (RED)

1054 Chinese Astronomers observe 'Guest-Star'
in the vicinity of constellation Taurus

- 6times brighter than Venus, red-white light
- 1 Month visible during the day, 1 Jahr at evenings
- Luminosity ≈ 400 Million Suns
- Distance d $\sim$ 7.000 Lightyears (ly)
  (when d $\leq$ 50 ly Life on earth would be extingished)

1731 BEVIS: Telescope observation of the SN remnants

1758 MESSIER: Catalogue of nebulae and star clusters

1844 ROSSE: Name 'Crab nebula' because of tentacle structure

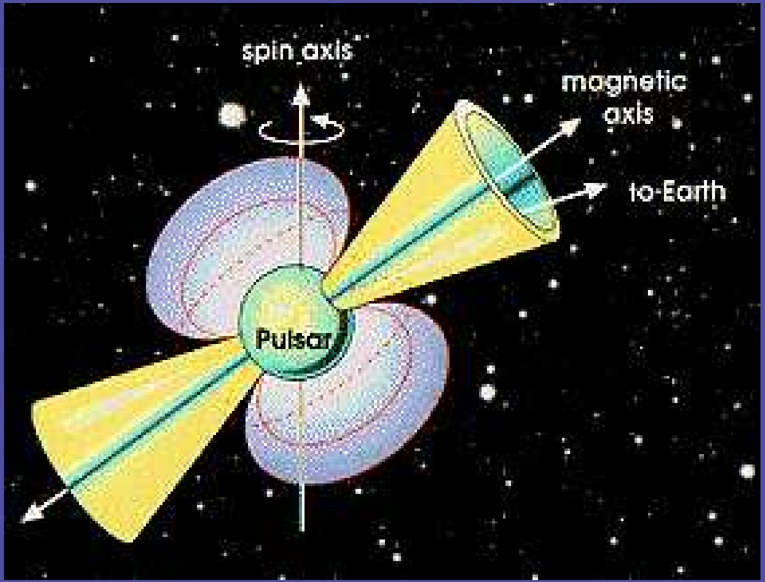
1939 DUNCAN: extrapolates back the nebula expansion
$\longrightarrow$ Explosion of a point source 766 years ago

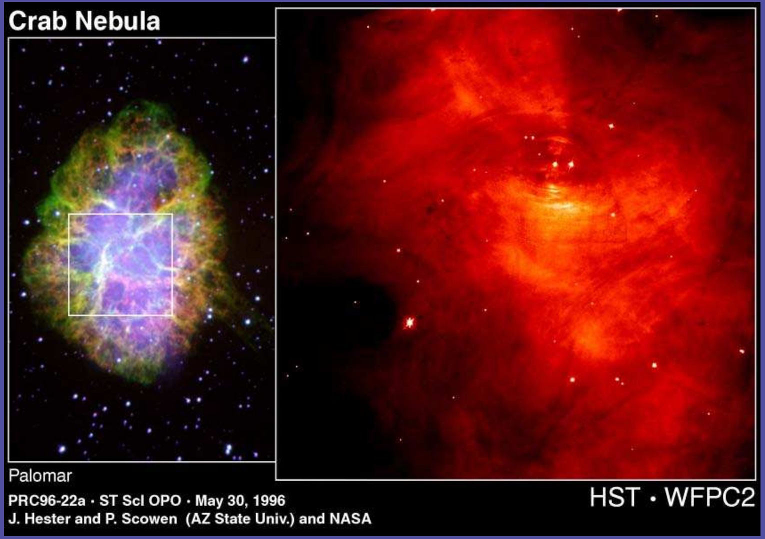
1942 BAADE: Star in the nebula center could be related
to its origin

1948 Crab nebula one of the brightest radio sources in the sky

1968 BAADE's star identified as pulsar

Pulsars: Rotating Neutron stars





1967 Jocelyne BELL discovers (Nobel prize 1974 for HEWISH) pulsating radio frequency source (pulse interval: 1.34 sec; pulse duration: 0.01 sec)

Today more than 1700 of such sources are known in the milky way ⇒ **PULSARS**
Pulse frequency extremely stable: $\Delta T/T \approx 1$ sec/100 million million years

1968 Explanation of the phenomenon GOLD as
⇒ **ROTATING NEUTRON STARS**, since:

- only Rotation explains high precision of pulses
- only small objects ($R \approx 10$ km) can have so small pulse duations

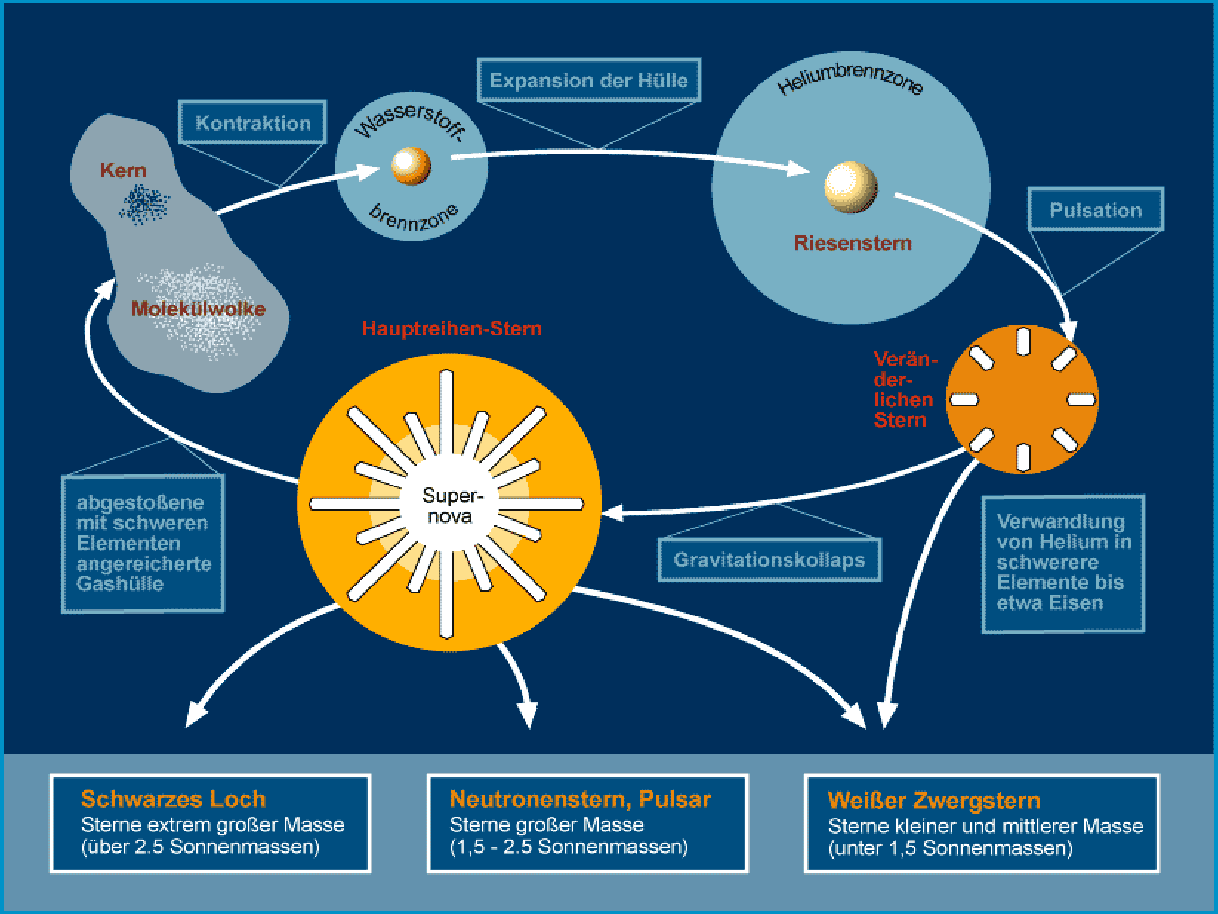
1969 Discovery of the pulsar in the Crab nebula
Connection established:
SUPERNOVA - NEUTRON STAR - PULSAR

1968 Discovery of the binary Pulsar **PSR 1913+16** by HULSE and TAYLOR (Nobel prize 1993)

How is a neutron star formed ?

Two Scenarios after ceasing of nuclear fusion reactions in the star interior

- Supernova Type I (O-Ne-Mg core): e^- capture instability of white dwarf in a binary
- 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**



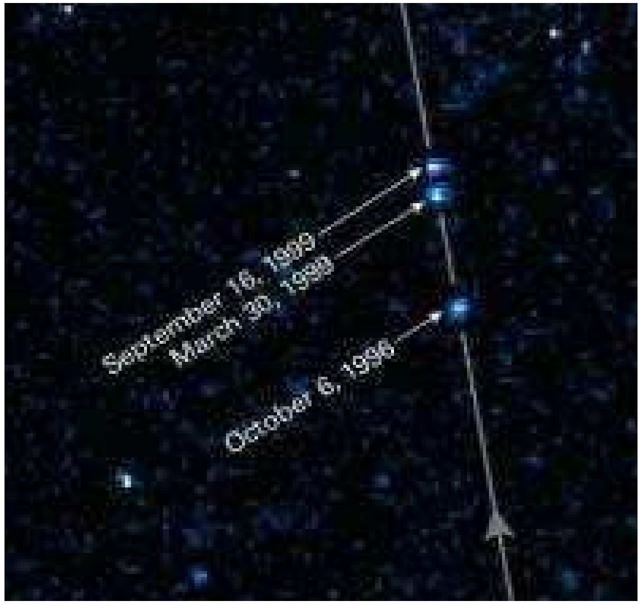
Neutron star-Properties:

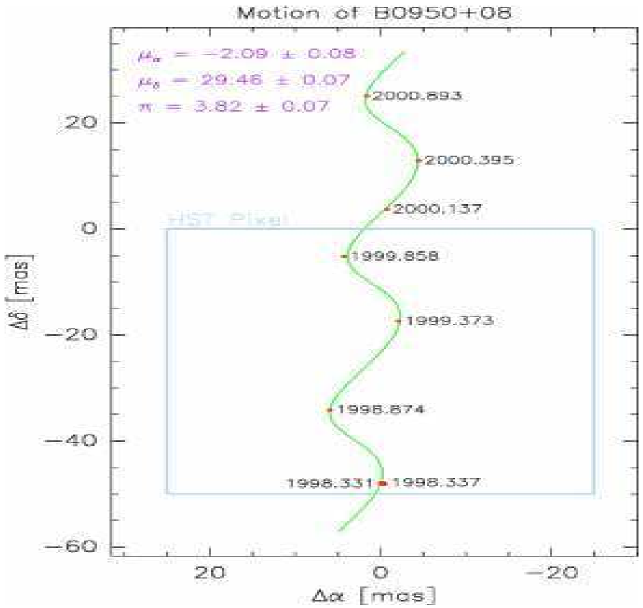
- Radius: $R \approx 10$ km
- Density: $\rho \approx 10^{14} \ldots 10^{15}$ g/cm^3
- Mass: $M \approx M_\odot = 2 \times 10^{30}$ kg
- Rotation: Period $T < 1$ sec, for progenitor star $T \approx 30$ d (Sun)
- Magnetic field: contraction increases the density of field lines dramatically $\rightarrow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

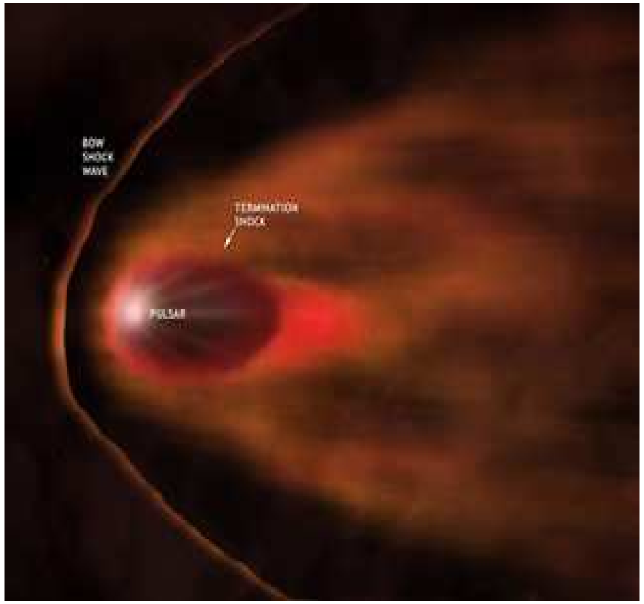
Observations of pulsar kicks

Optical: Hubble Space Telescope

- Lonely neutron star RX J1856.5-3754
- Motion of binary system B 0950+08
- Bow shock

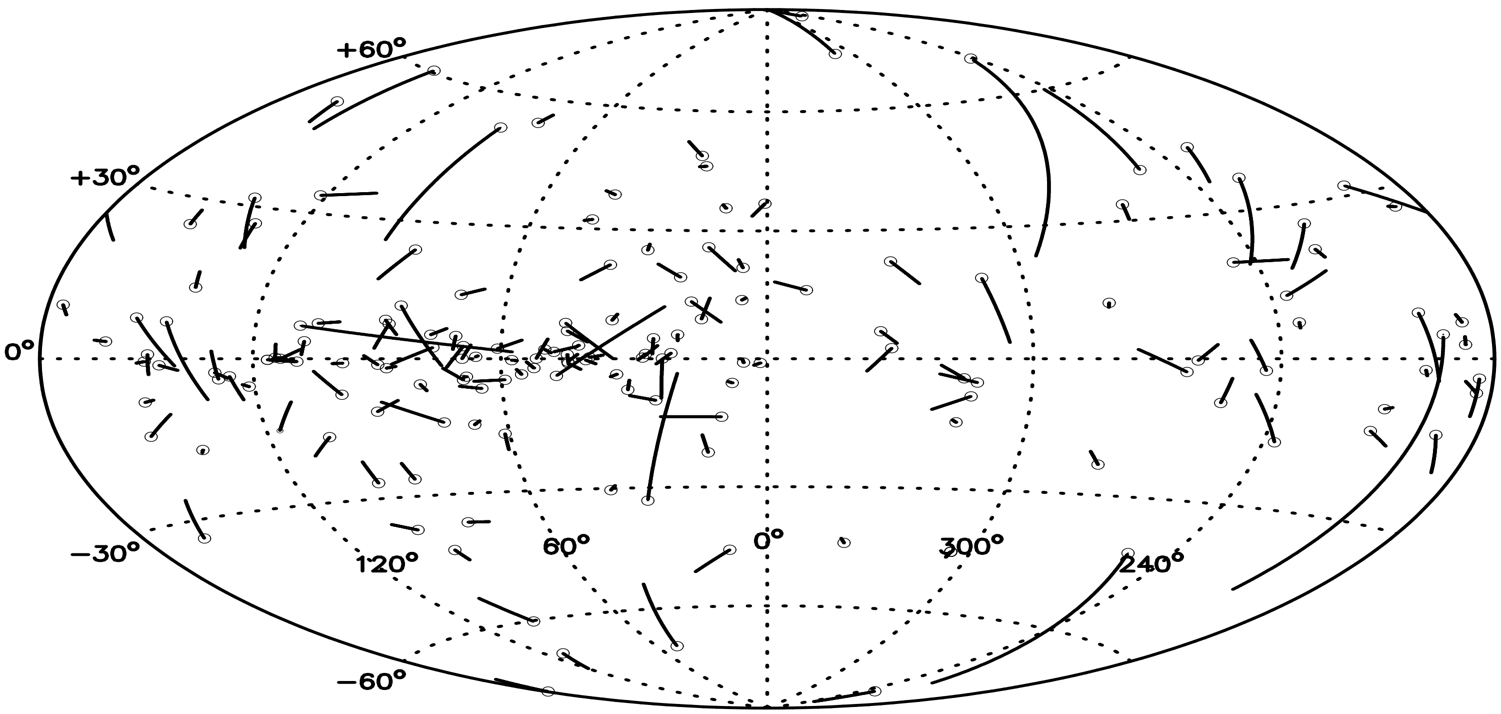




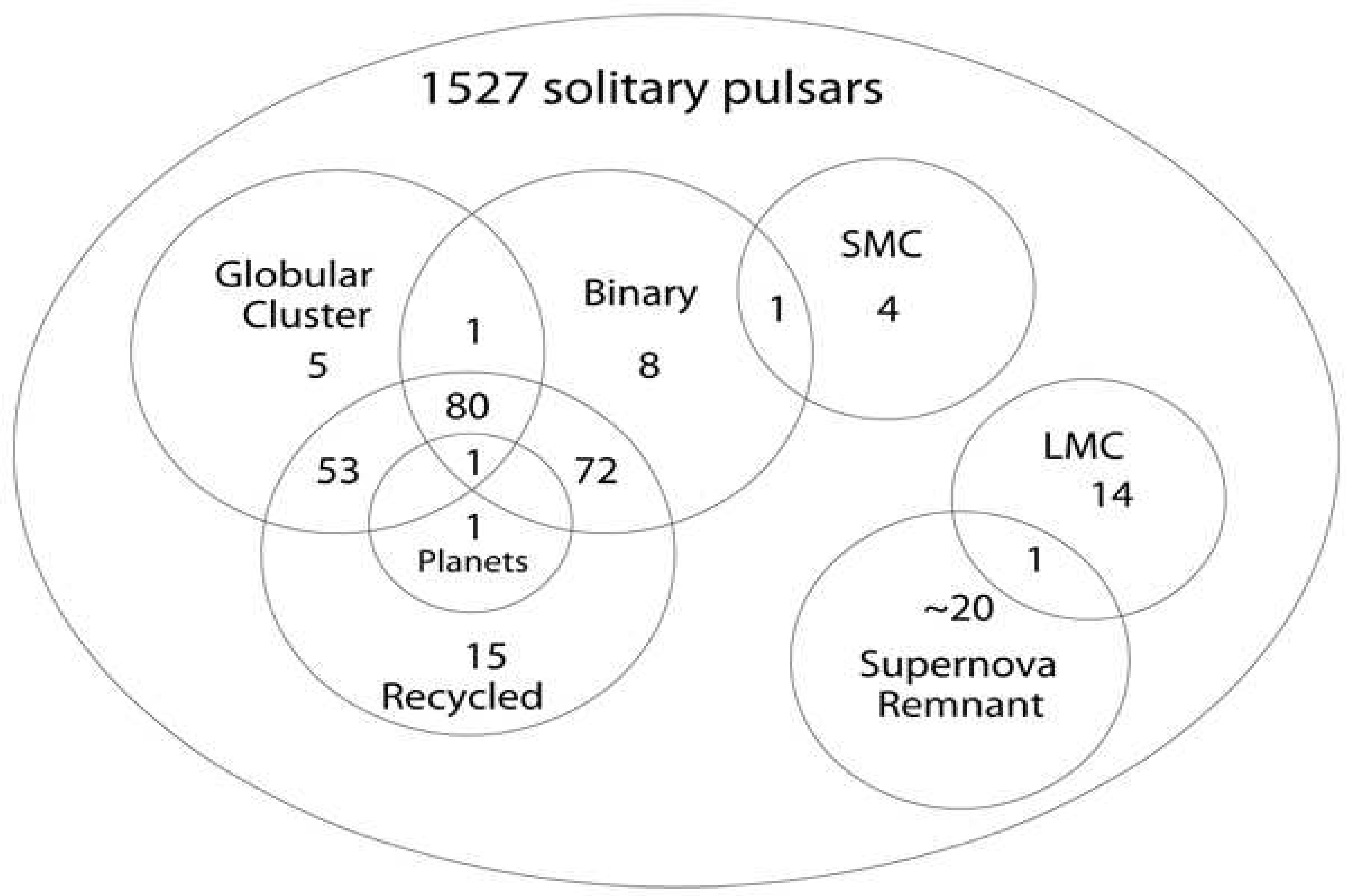


Observations - Map

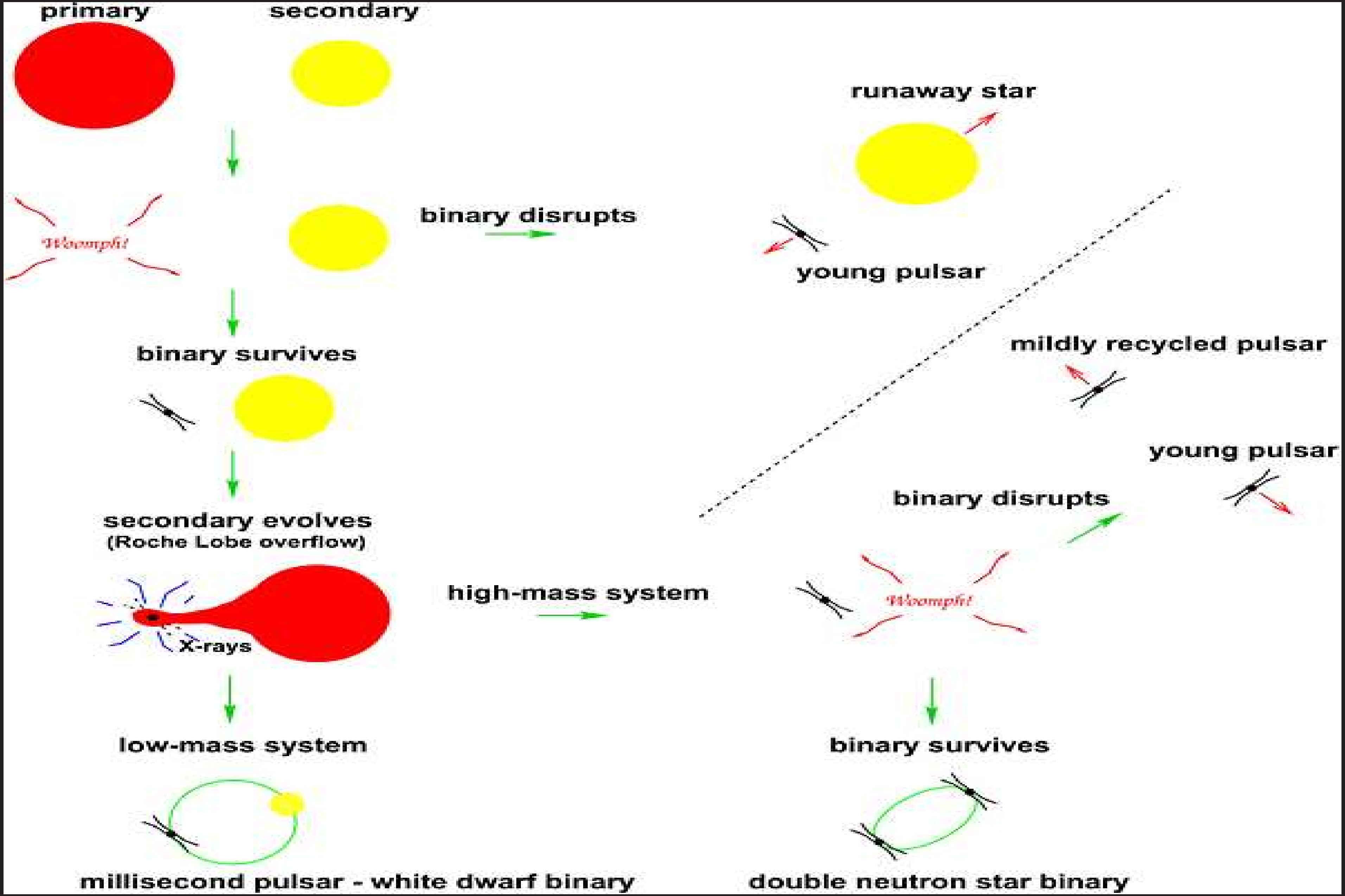
- small fraction of 10^9 NS/galaxy visible
- proper motion (pulsar timing 58%,interferometer 41%,optical 1%)
- 50% of pulsars in solar neighborhood will escape the galaxy
- 10% of pulsars ¡ 20 kyr outside their host remnants



Population of Pulsars (Venn Diagram), 2008



Evolution of Neutron Stars in Binary Systems



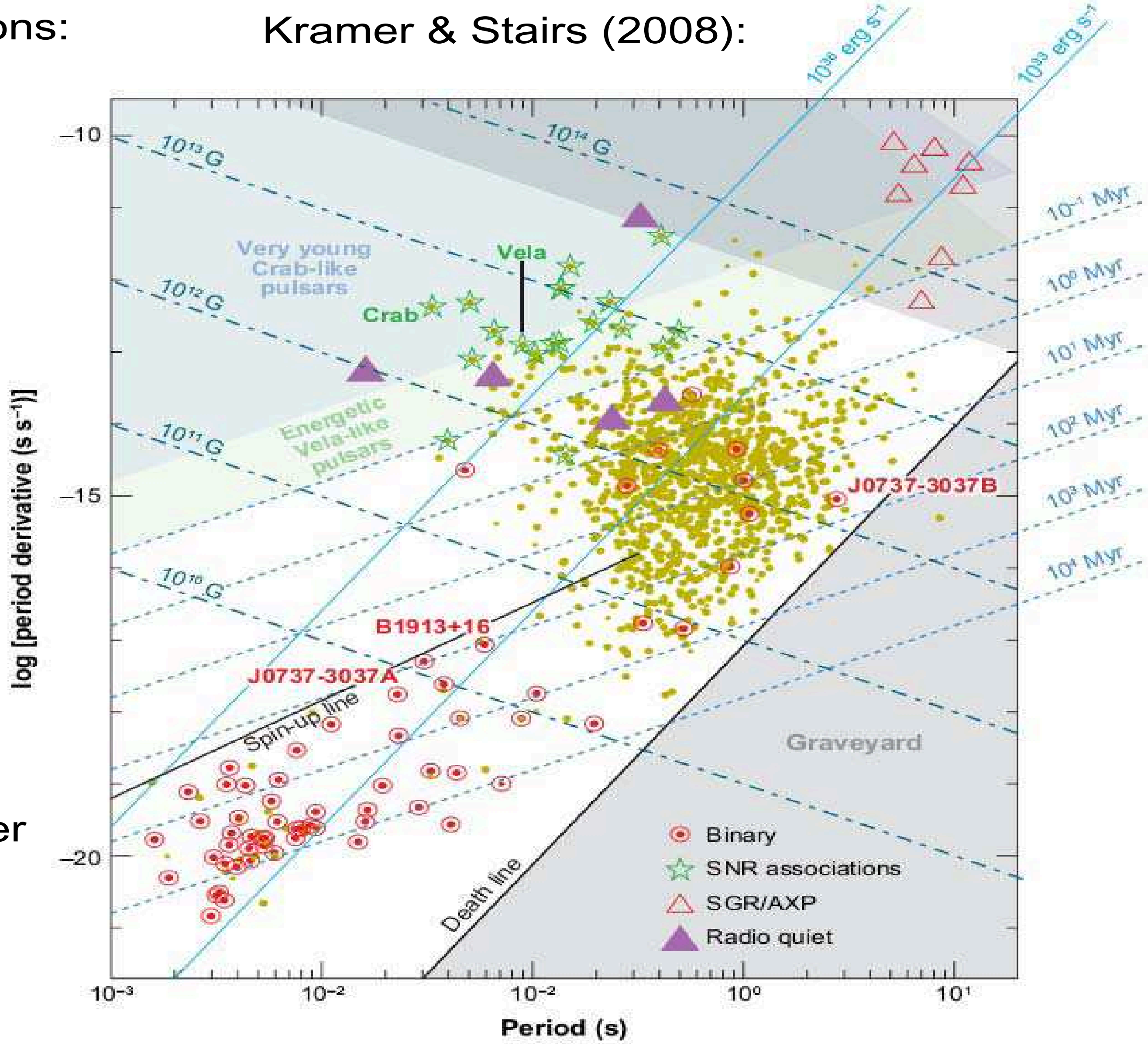
Pulsars in the $\dot{P} - P$ Diagram

Some model based assumptions:

$$\tau_a = \frac{P}{2\dot{P}} [\mathrm{s}]$$

$$B = 3.2 \times 10^{19} \sqrt{P\dot{P}} [\mathrm{G}]$$

Kramer & Stairs (2008):



- -majority of PSRs:
  P~0.5s, dP/dt~10-15
- -young NSs have strong B
- -NSs in binaries rotate faster
- -correlation SNR-NS
- -low B NSs in binaries and
  weak braking

Courtesy: Paolo Freire, Hirschegg 2009

How to Measure Pulsar Masses

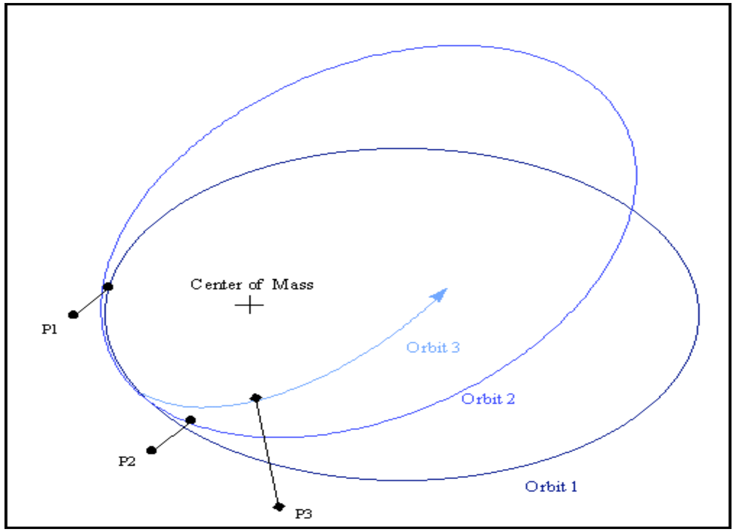
- Five Keplerian parameters can normally be measured from fitting the velocity (or, preferably, the delay) curves: orbital period (P_b), projected size of the orbit, in light seconds (x), eccentricity (e), longitude of periastron (ω) and time of passage through periastron (T_0). A non-changing Keplerian orbit is exactly what is predicted by Newtonian gravity.
- Without access to information on transverse velocities, the individual masses of the components (m_1 and m_2) and the inclination of the system (i) cannot be measured, but...
- The mass function, a relation between these three quantities, can be measured to excellent precision, as it depends on two observable parameters:

$$
\begin{aligned}
f(m_1, m_2, i)/\mathrm{M}_\odot &\equiv \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} \\
&= x^3 \left(\frac{2\pi}{P_b}\right)^2 \left(\frac{1}{T_\odot}\right)
\end{aligned}
$$

$$
T_\odot \equiv \frac{\mathrm{GM}_\odot}{c^3} = 4.925490947\,\mu s
$$

Courtesy: Paolo Freire, Hirschegg 2009

How to Measure Pulsar Masses



$$\begin{aligned} M &= m_1 + m_2\,,\ n_b = \frac{2\pi}{P_b} \\ \dot{\omega} &= 3 n_b^{5/3} (M T_\odot)^{2/3} (1 - e^2)^{-1} \\ \gamma &= n_b^{-1/3} e m_2 (2 m_2 + m_1) M^{-4/3} T_\odot^{2/3} \end{aligned}$$

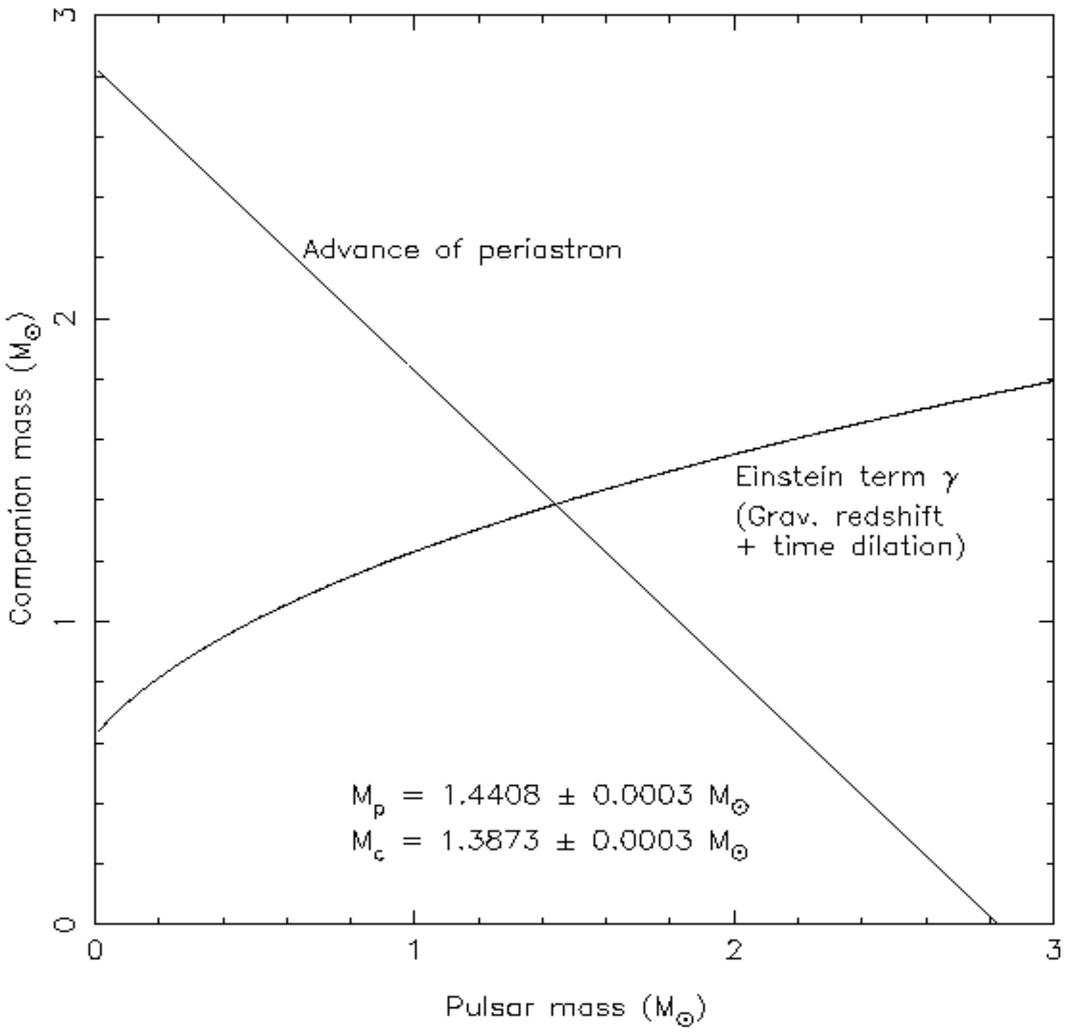
- *According to general relativity*, these quantities depend on the known Keplerian parameters and the masses of the two components of the binary.

- We now have **three equation for three unknowns**! We can determine the masses of the components and the inclination.

Courtesy: Paolo Freire, Hirschegg 2009

How to Measure Pulsar Masses

- An excellent example is “the” (first) binary pulsar, PSR B1913+16, discovered at the Arecibo Observatory by Russell Hulse and Joe Taylor.
- Mass determination lead to prediction of the orbital decay due to emission of gravitational waves: the orbital period should getting 75.8 microseconds shorter every year.

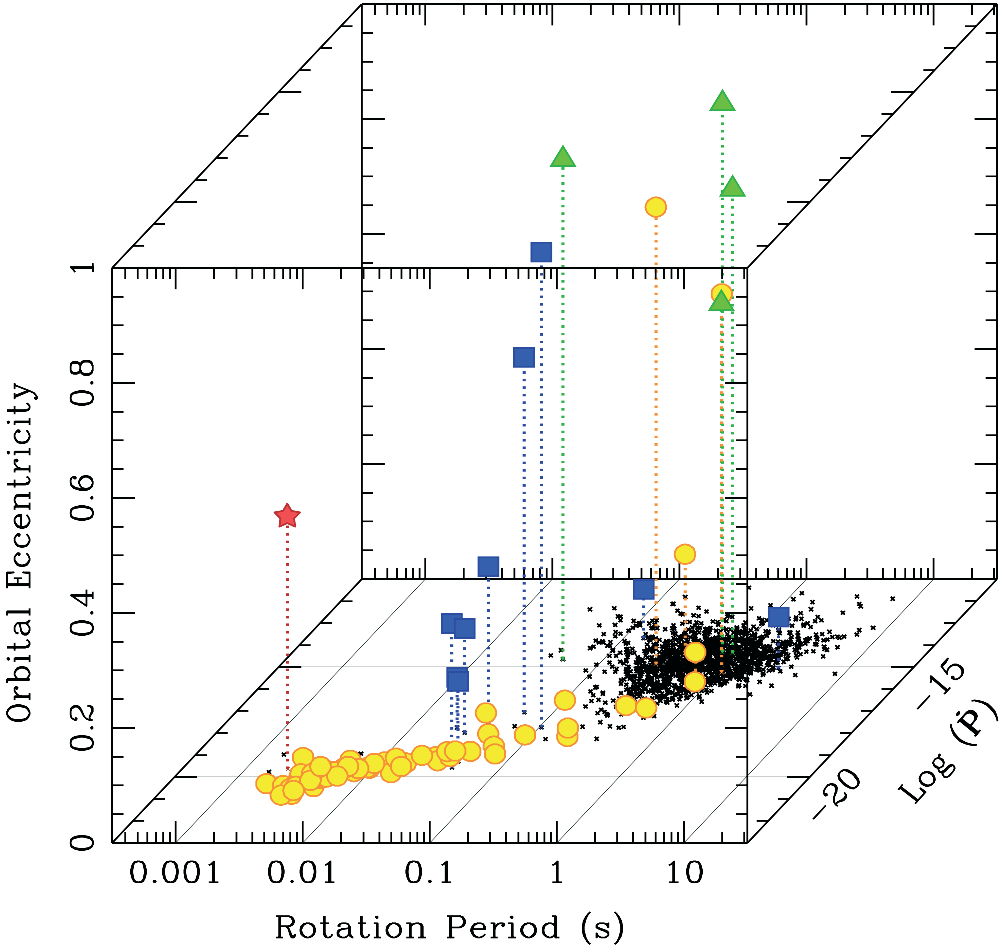


From: Weisberg and Taylor, ASP Conf. Series vol. 302, p. 93, 2003

Courtesy: Paolo Freire, Hirschegg 2009

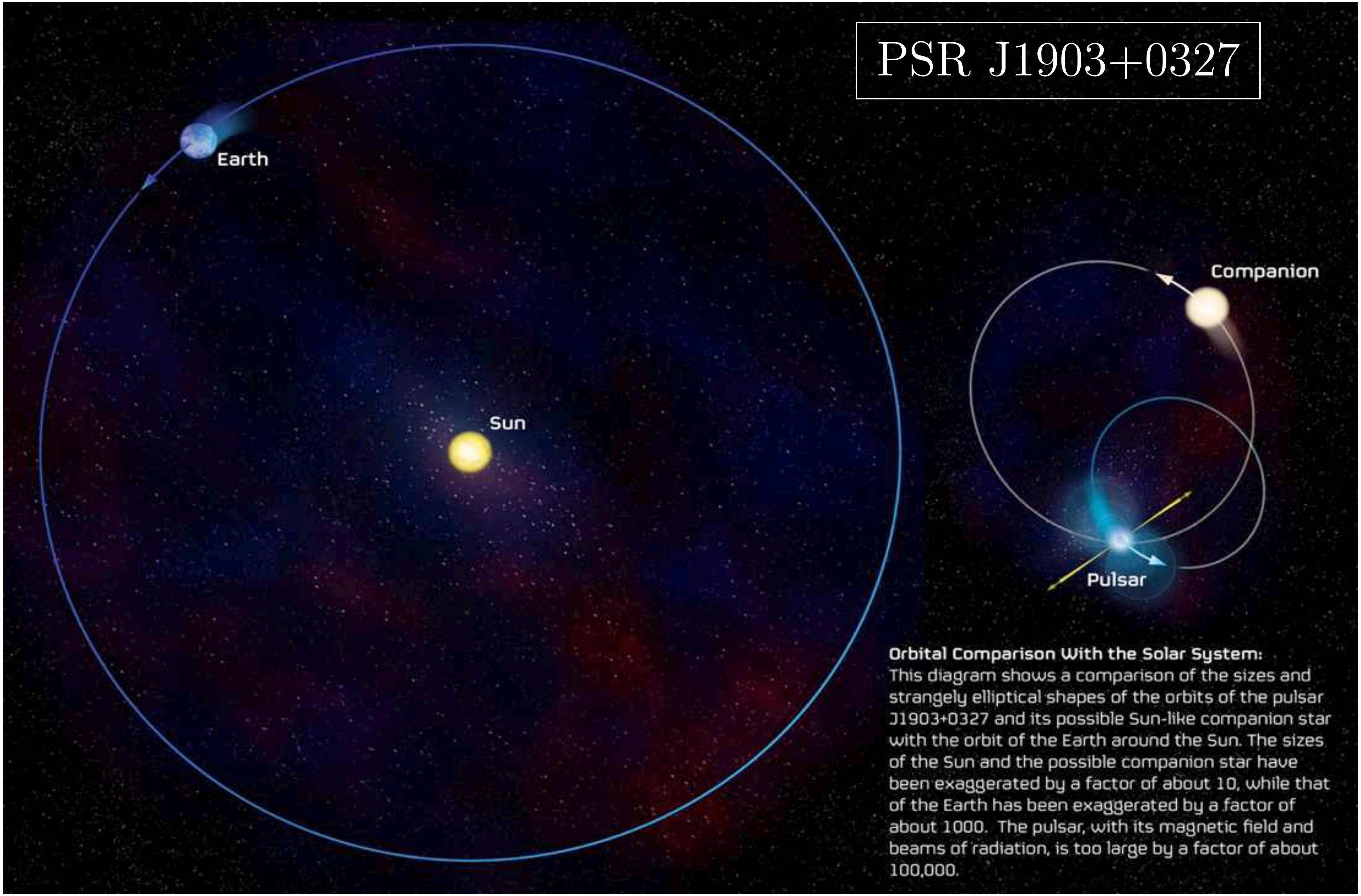
The PSR J1903+0327 Binary System

- With a spin period of 2.15 ms, PSR J1903+0327 was the first millisecond pulsar (MSP) discovered in Arecibo's ALFA pulsar survey.
- It is in a 95-day binary system. Its $m_c \sim 1.0$ M_{sun} companion is by far the most massive of any MSP with a similar spin period.
- *It is the first millisecond pulsar in the disk of the Galaxy to have an eccentric orbit*: $e = 0.44$. All other MSPs in binary systems have $e < 0.002$ (Champion et al., Science, 320, 1309).
- It is very difficult to explain the formation of such a binary system with previous stellar evolution theory.



From: Champion et al., Science, 320, 1309 (2008)

PSR J1903+0327



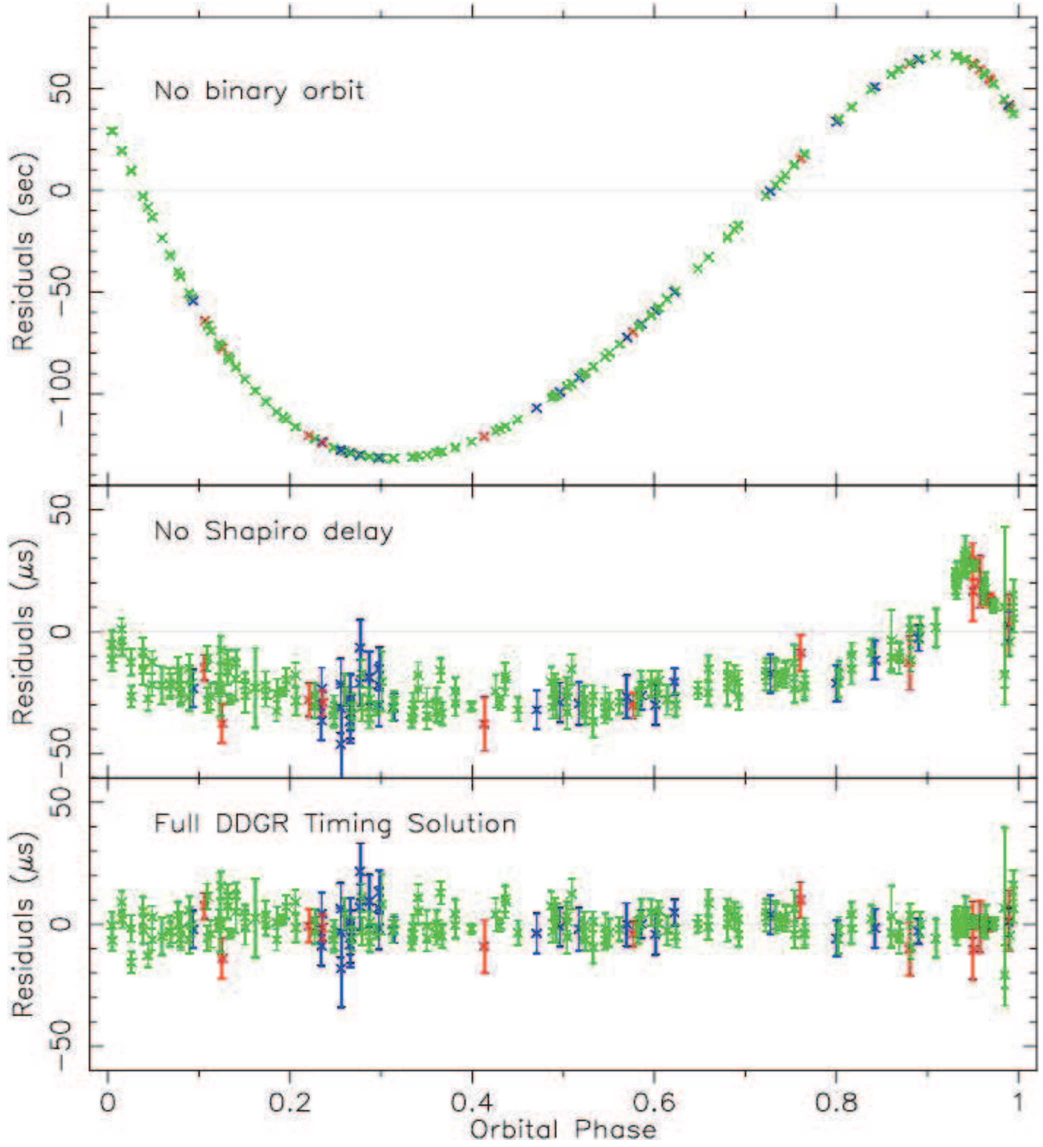
Orbital Comparison With the Solar System:
This diagram shows a comparison of the sizes and strangely elliptical shapes of the orbits of the pulsar J1903+0327 and its possible Sun-like companion star with the orbit of the Earth around the Sun. The sizes of the Sun and the possible companion star have been exaggerated by a factor of about 10, while that of the Earth has been exaggerated by a factor of about 1000. The pulsar, with its magnetic field and beams of radiation, is too large by a factor of about 100,000.

From: NRAO / Cornell University Press Release

Courtesy: Paolo Freire, Hirschegg 2009

Measuring the Mass of PSR J1903+0327: Part I

- Apart from presenting an evolutionary puzzle, the unusual characteristics of this binary system are interesting because they allow the measurement of post-Keplerian orbital parameters that lead to a precise determination of the masses of the components of the system.
- The eccentricity of this binary system allowed a measurement of the apsidal motion even in the early GBT timing. Assuming GR is correct, *this gives us the total mass of the system*.
- The large companion mass, coupled with the good timing precision, allow a measurement of the *Shapiro delay*.
- This is a truly unusual set of circumstances for a MSP binary system!

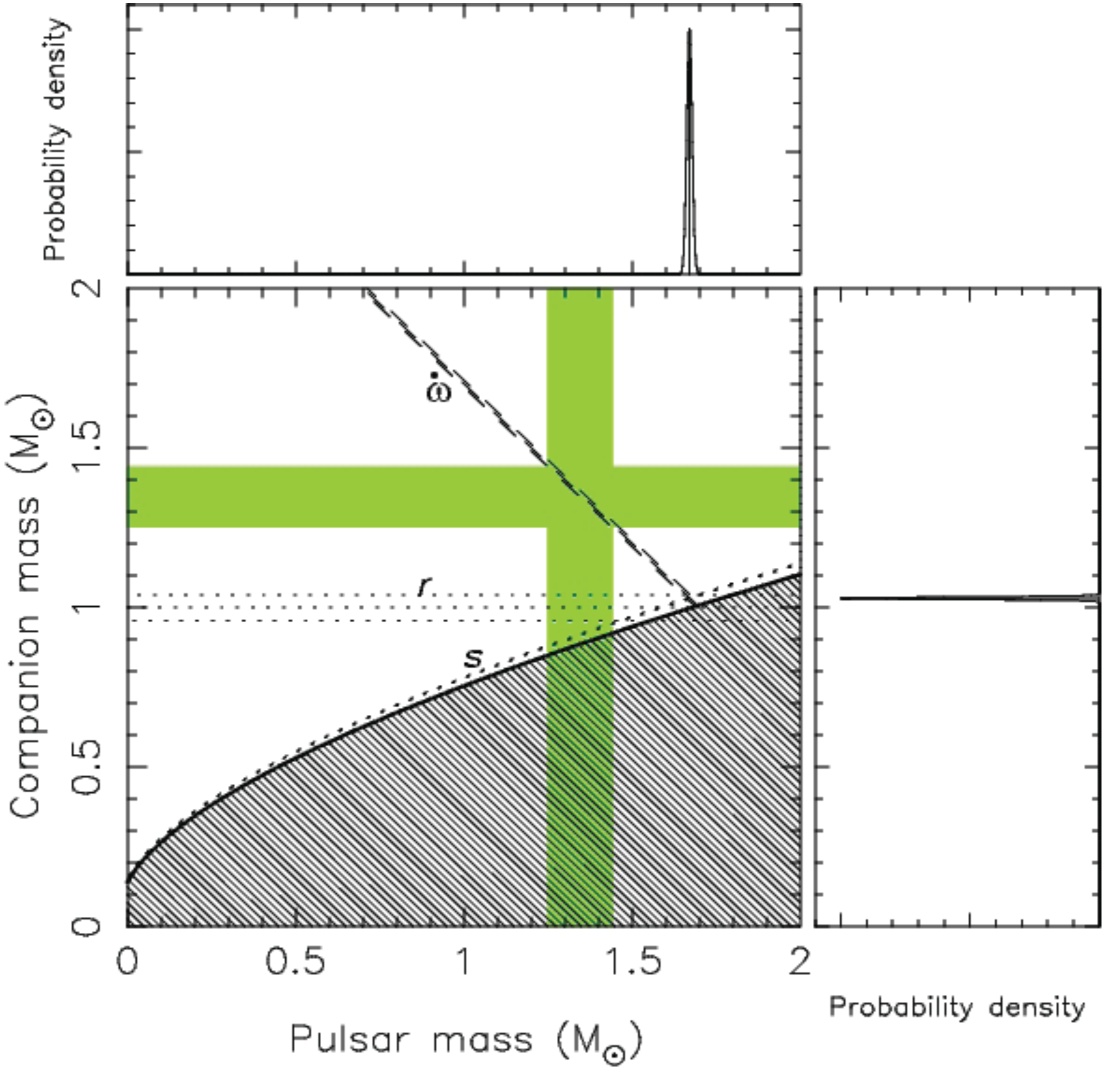


From: Champion et al., Science, 320, 1309 (2008)

Courtesy: Paolo Freire, Hirschegg 2009

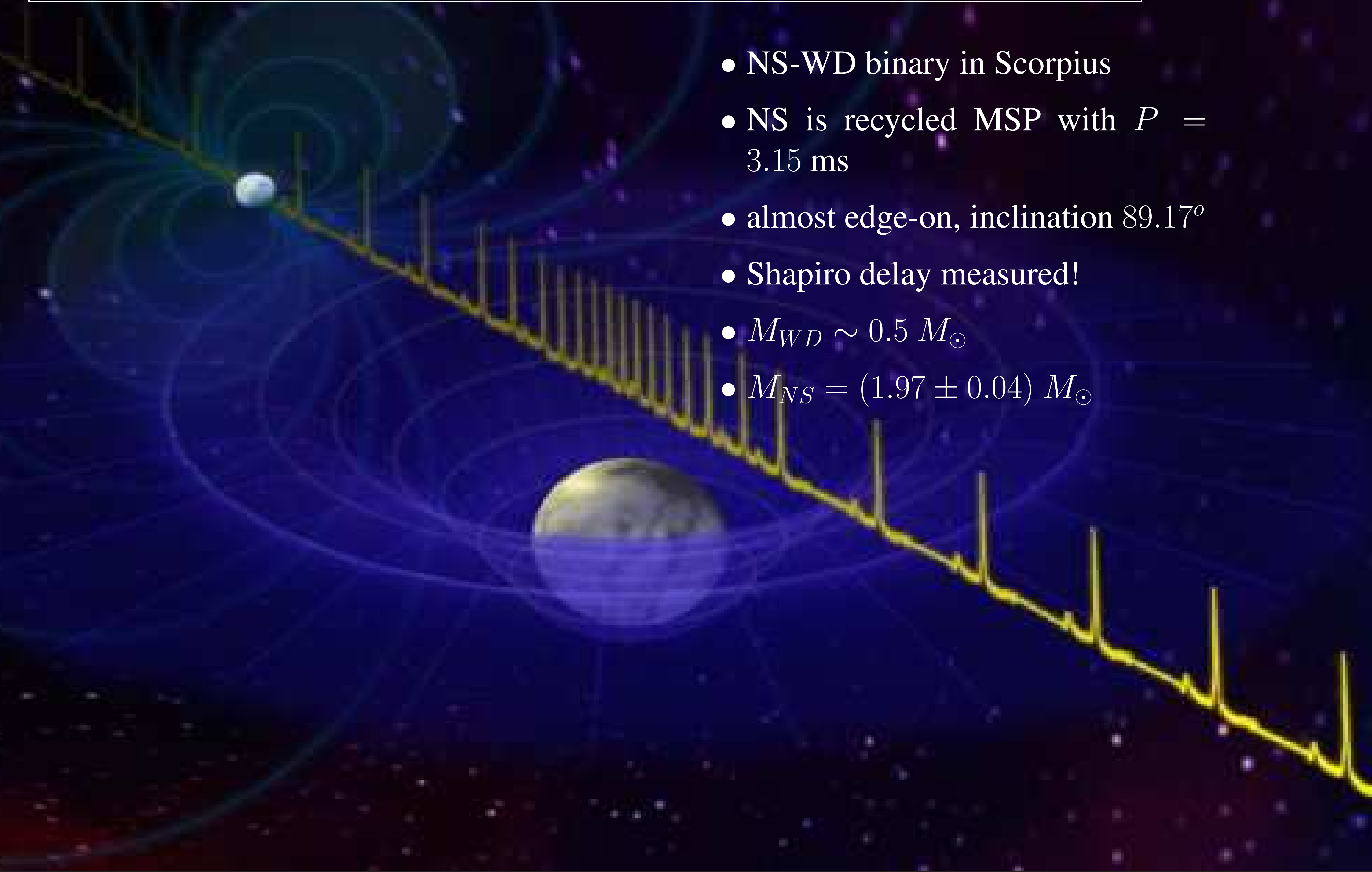
Results

- The improvement in the apsidal motion and the Shapiro *s* now leads to a pulsar mass of 1.67 +/- 0.01 solar masses. This is 1.75-sigma lower that the measurement in Champion et al. (2008), the variation is probably caused by correlations with other parameters.
- The mass measurement has became very stable after 1 year of S-band Arecibo data.
- These parameters predict a companion mass of 1.028 +/- 0.004 solar masses.
- The companion mass derived from Shapiro *r* is 1.00 +/- 0.04 solar masses. The predicted value is 0.7 sigma above this - not statistically different.



From: Freire et al., 2009 (in preparation)

PSR J1614-2230 - A new constraint for the Compact Star EoS



- NS-WD binary in Scorpius
- NS is recycled MSP with $P = 3.15$ ms
- almost edge-on, inclination 89.17^o
- Shapiro delay measured!
- $M_{WD} \sim 0.5\ M_\odot$
- $M_{NS} = (1.97 \pm 0.04)\ M_\odot$

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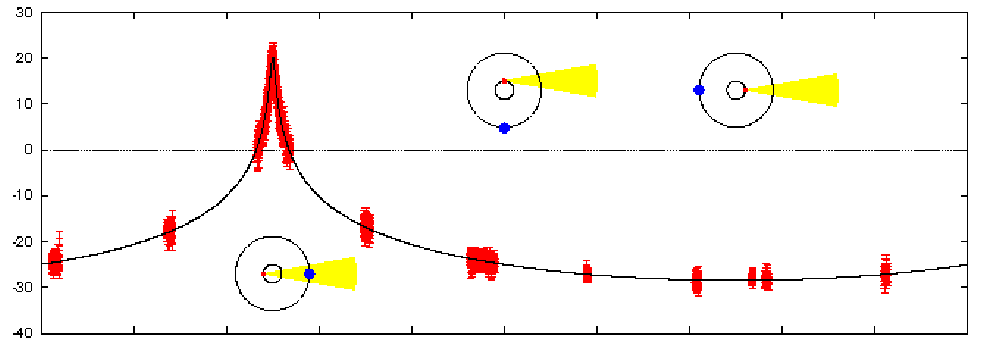

Demorest et al., Nature 467, 1081 (2010)

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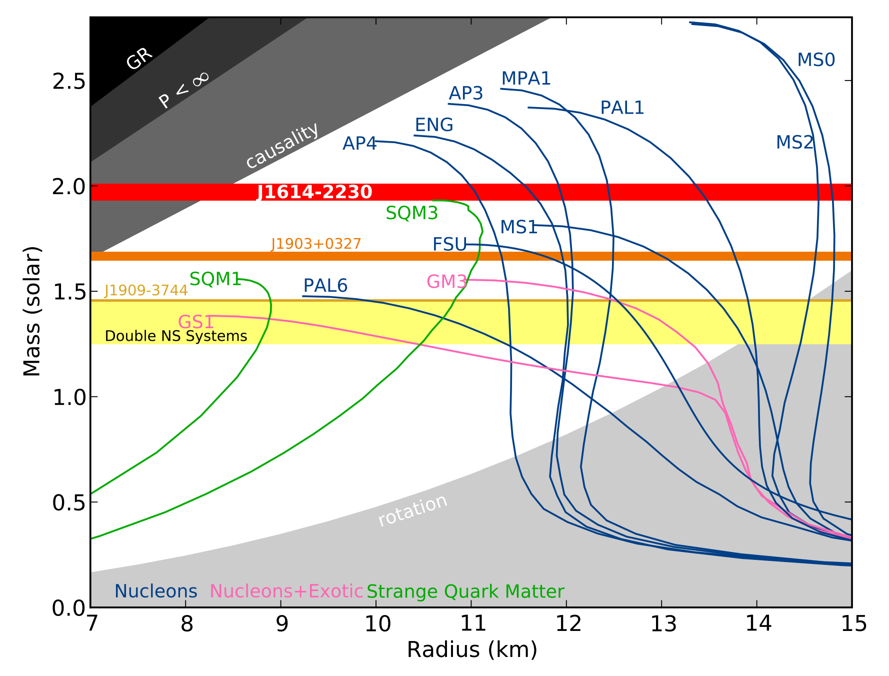

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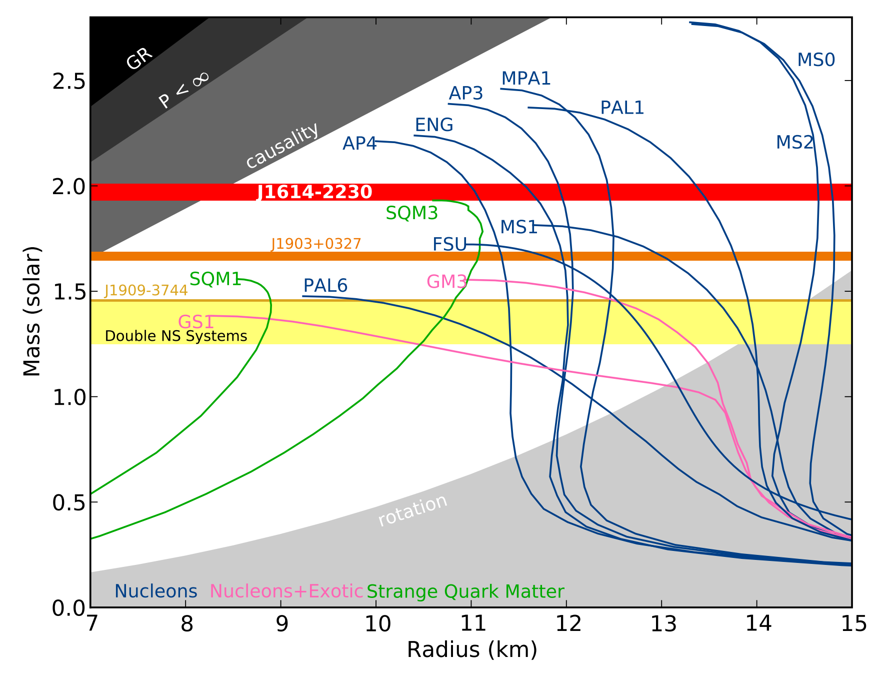
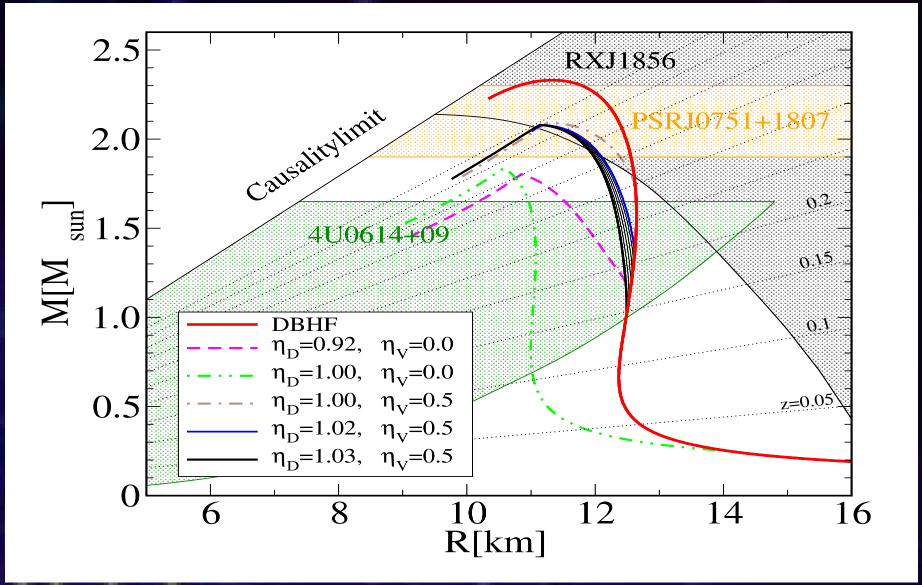


Demorest et al., Nature 467, 1081 (2010)

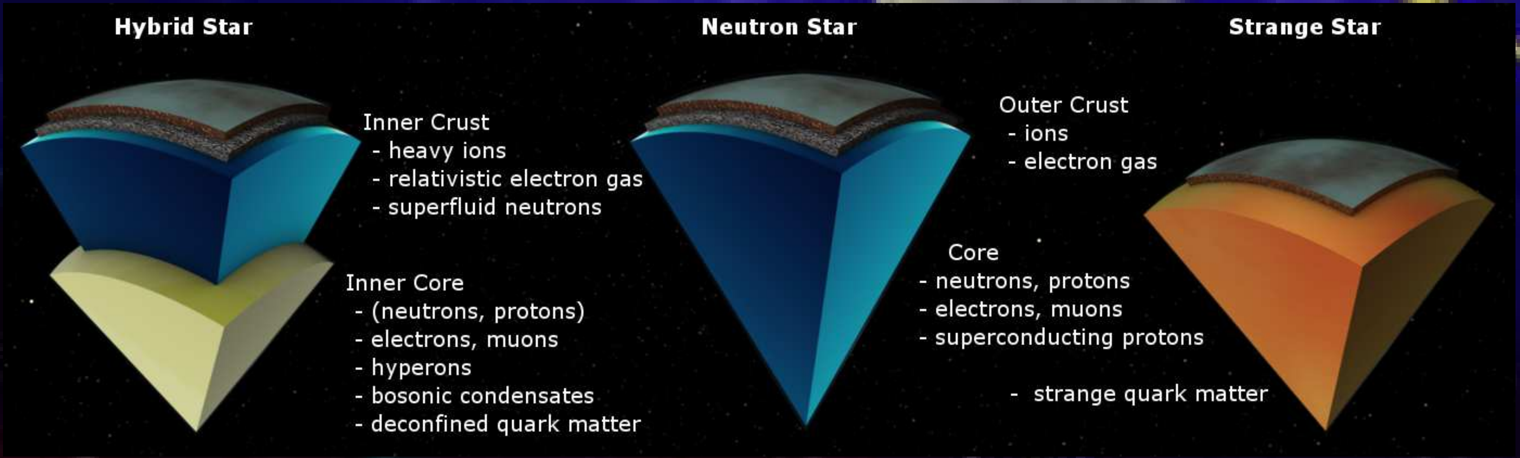
Some “soft” EoS are now ruled out !

What about hybrid stars? Strong constraints for quark matter!

PSR J1614-2230 - A new constraint for the Compact Star EoS



Klähn et al., PLB 654, 170 (2007)



Hybrid Star

Neutron Star

Strange Star

Inner Crust
- heavy ions
- relativistic electron gas
- superfluid neutrons

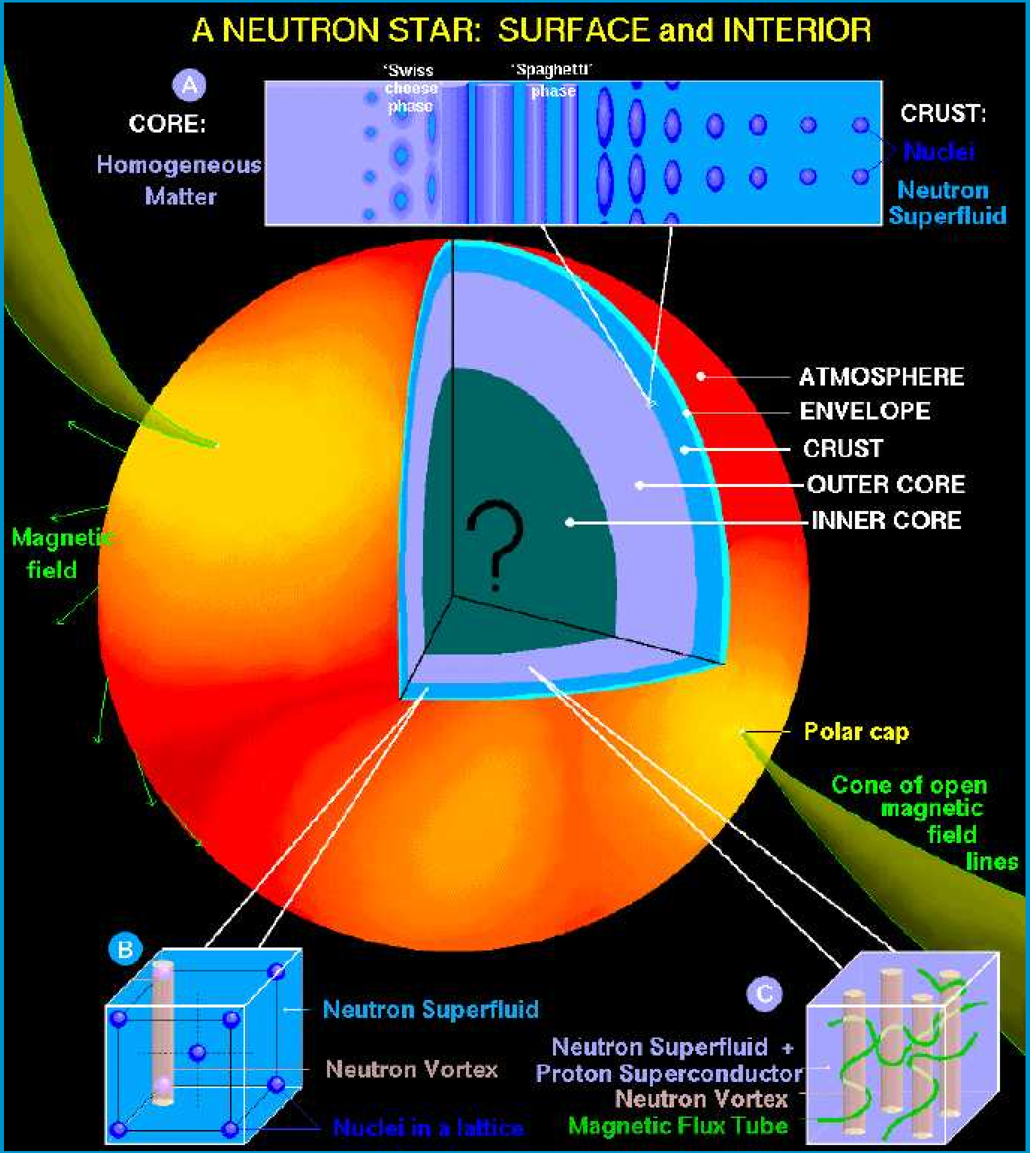
Inner Core
- (neutrons, protons)
- electrons, muons
- hyperons
- bosonic condensates
- deconfined quark matter

Outer Crust
- ions
- electron gas

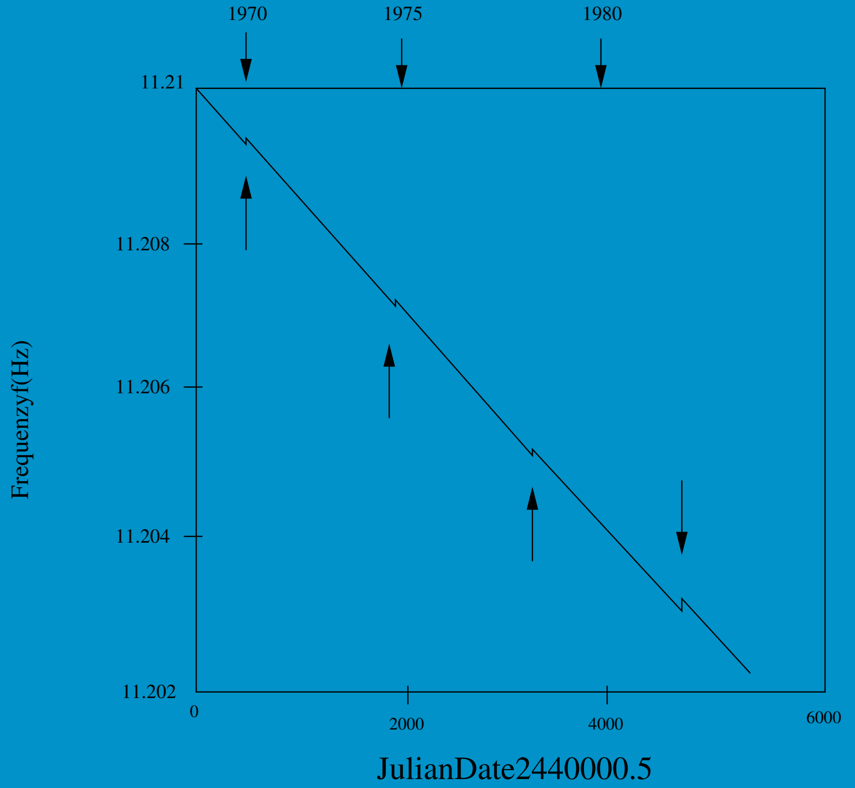
Core
- neutrons, protons
- electrons, muons
- superconducting protons

- strange quark matter

Pulsars: Laboratories for Many-particle Physics



Glitches: Superfluid Nuclear Matter



Nature of Glitches: Vortex-Crust Unpinning → suddenly smaller momet of inertia → jump in $\Omega = d\phi/dt$ (angular momentum conservation)

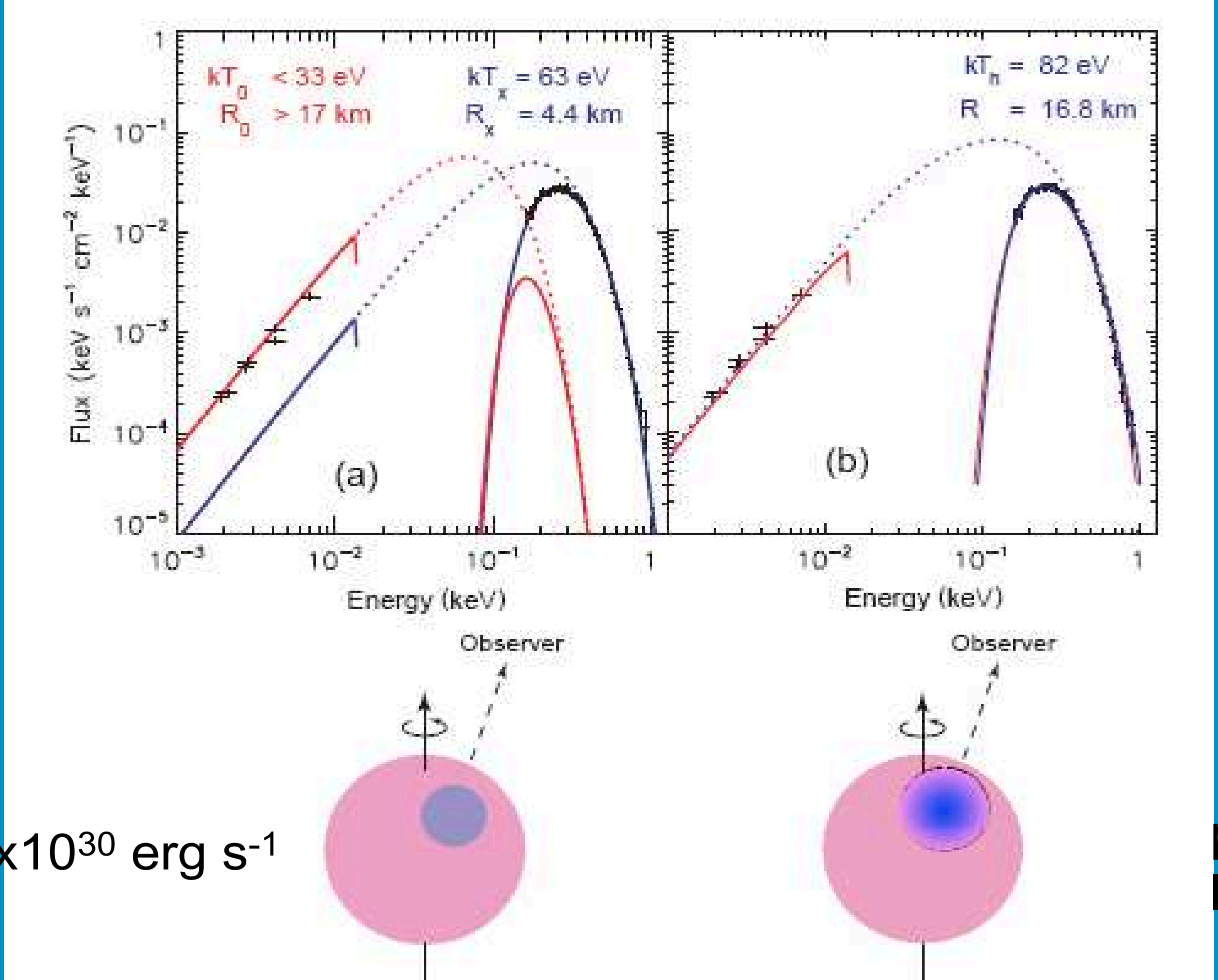
RX J1856-375 - one of the “Magnificent Seven”

blackbody fits to the optical and X-ray spectra of RX J1856.5-3754 (Trümper,2004)

radius determination ⇒ EoS ⇒ state of matter at high densities

two-component model

model with continuous T-distribution



completely featureless X-ray spectrum:
condensed surface?
⇒ strong B?

$L_x = 5.4 \times 10^{30}$ erg s^{-1}

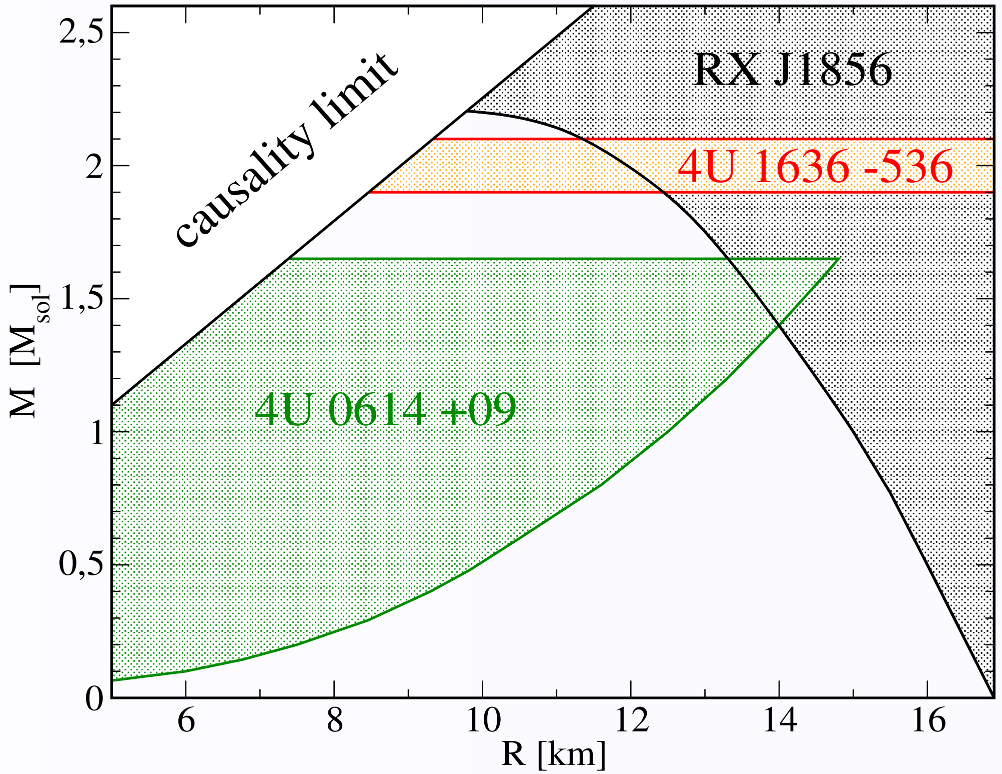
pulsed fraction < 1% ⇒
line of sight || rotation axis?

M-R Constraint from Radio uiet Isolated NS R J1856

RXJ1856 black body spectrum: $T_\infty = 57$ eV

measurement of distance: 60 pc (2002) $\rightarrow$ 117 pc (2004)

$\rightarrow$ photospheric radius: $R_\infty = R(1 - R/R_S)^{-1/2}$ $R_S = 2GM/R$



<u>Mass Radius Constraints</u>

QPO : M-R upper limits

ISCO : max. mass constraint

RXJ1856: M-R lower limits

each region...

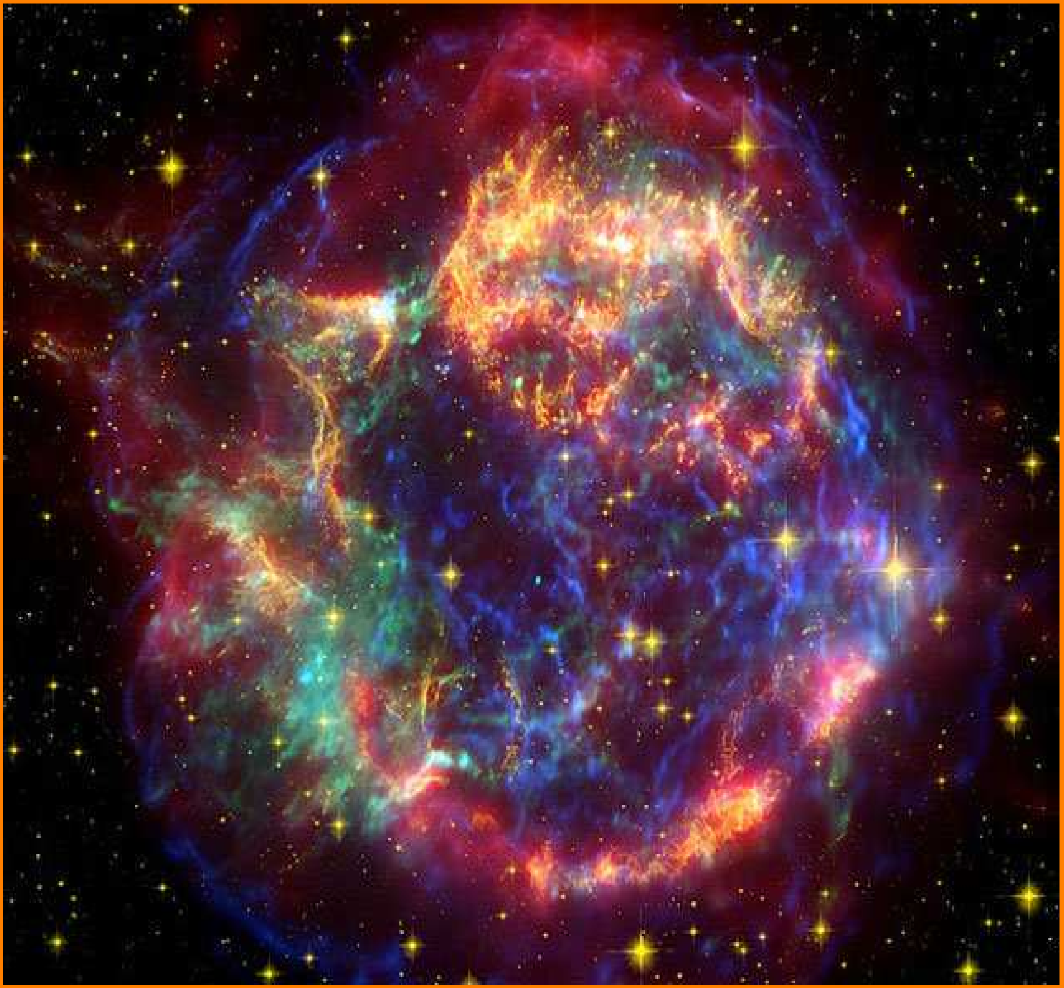
$\rightarrow$ represents a different object

$\rightarrow$ should be touched at least once

J. Trümper et al., Nucl. Phys. Proc. Suppl. 132, 560 (2004)

D. Barret, J.-F. Olive, M.C. Miller, Mon. Not. Roy. Astron. Soc. 361, 855 (2005)

Cas A - the youngest neutron star in our galaxy

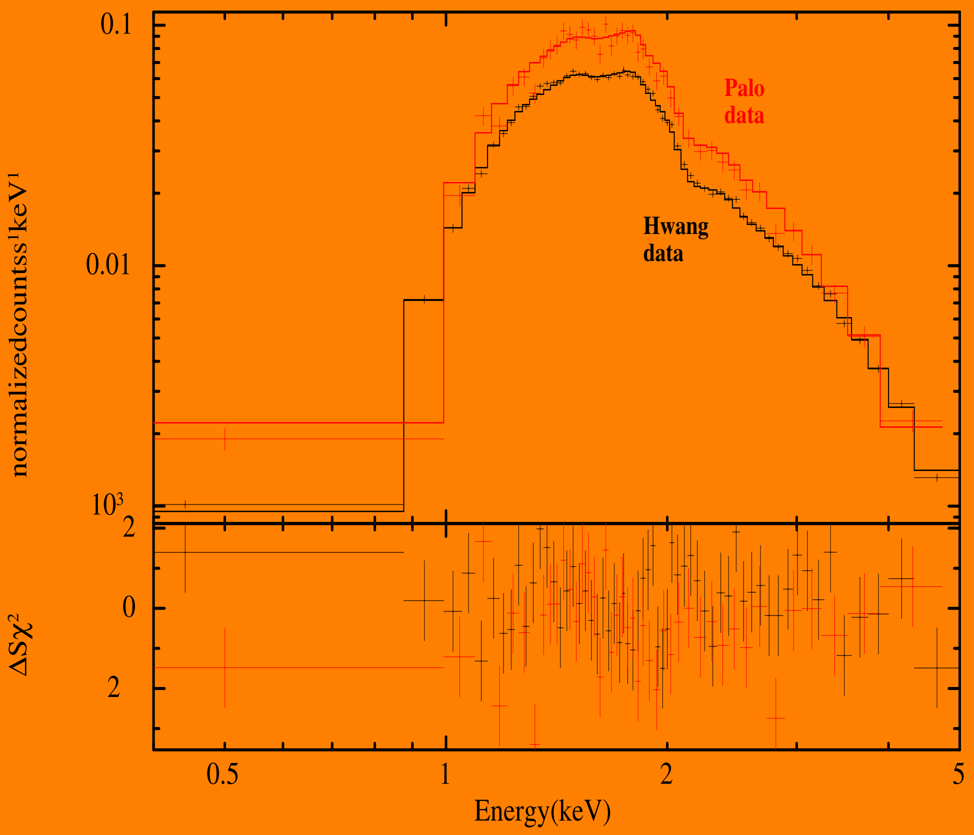


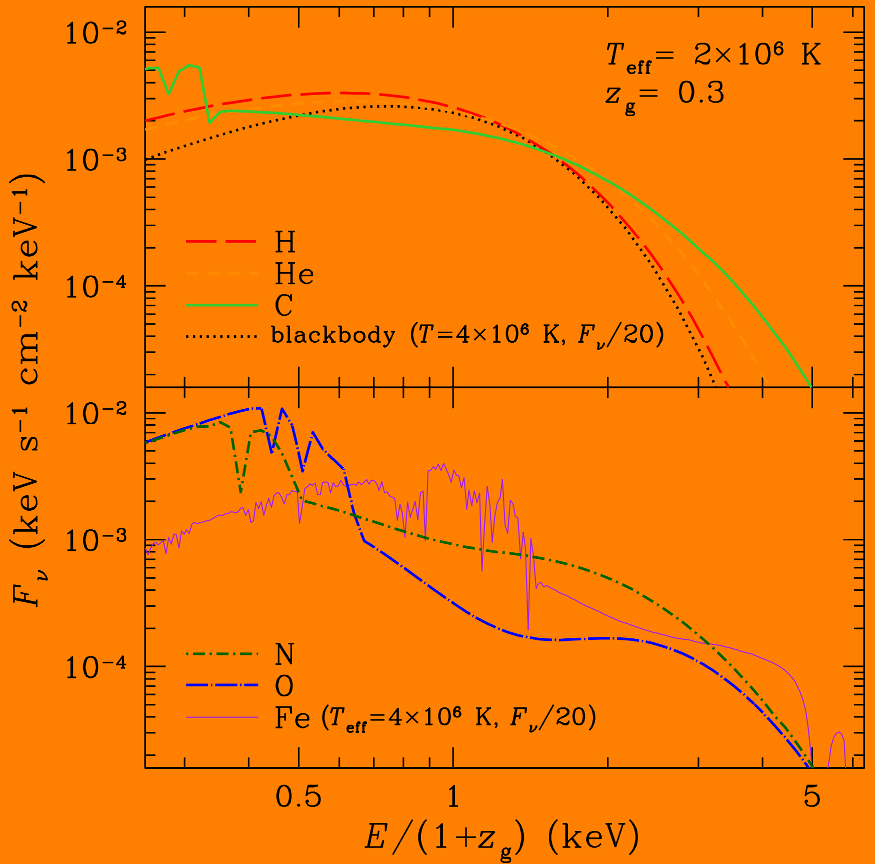
- 16.08.1680 John Flamsteed, 6m star 3 Cas
- 1947 re-discovery in radio
- 1950 optical counterpart
- $T \sim 30$ MK
- $v_{\rm exp} \sim 4000 - 6000$ km/s
- distance 11.000 ly = 3.4 kpc

Picture: Spitzer Space Telescope

D.B., H. Grigorian, D. Voskresensky, F. Weber, PRC 85 (2012) 022802

Cas A - cooling neutron star seen by Chandra





W.C.G. Ho, C.O. Heinke, Nature 462, 71 (2009)

Cas A - cooling neutron star seen by Chandra

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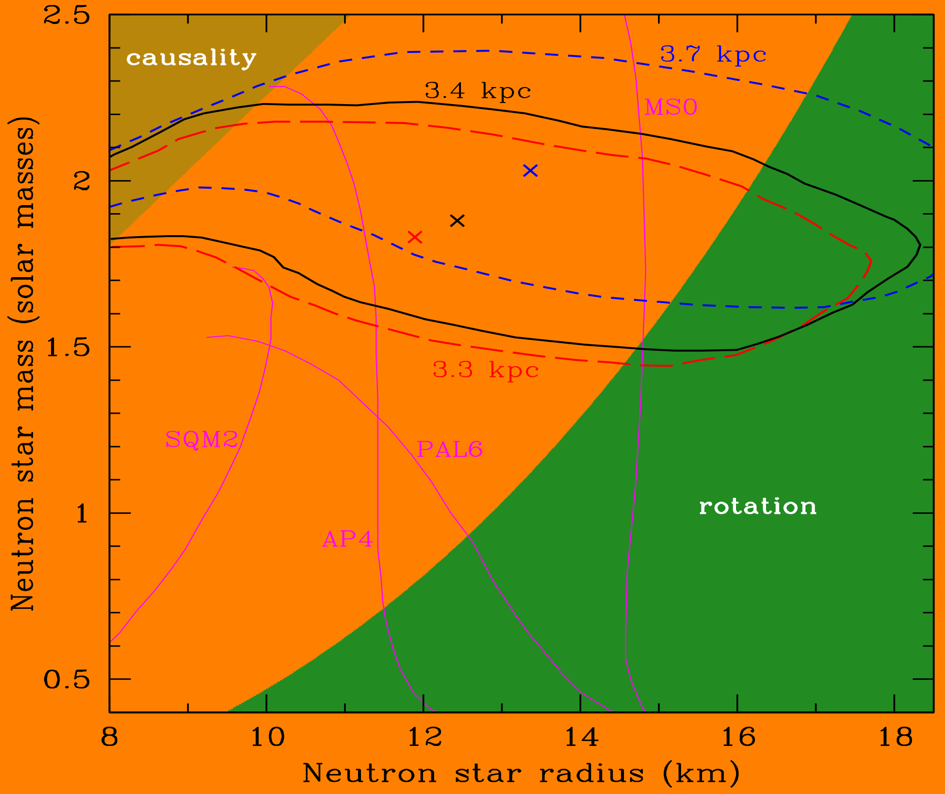
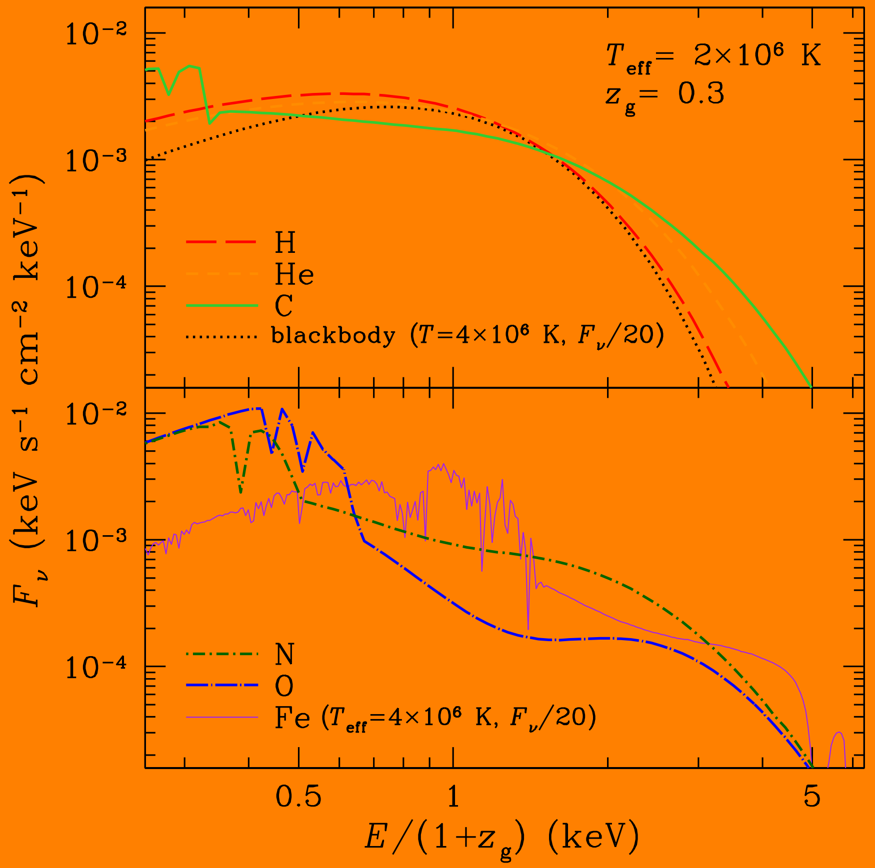


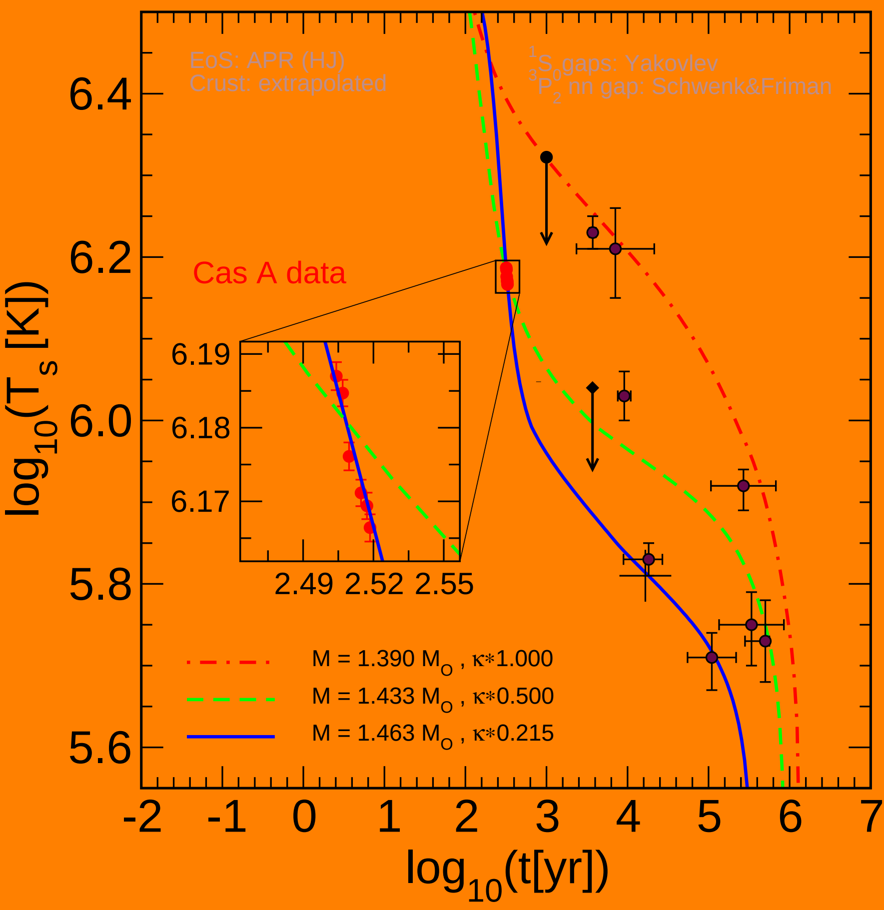


W.C.G. Ho, C.O. Heinke, Nature 462, 71 (2009)

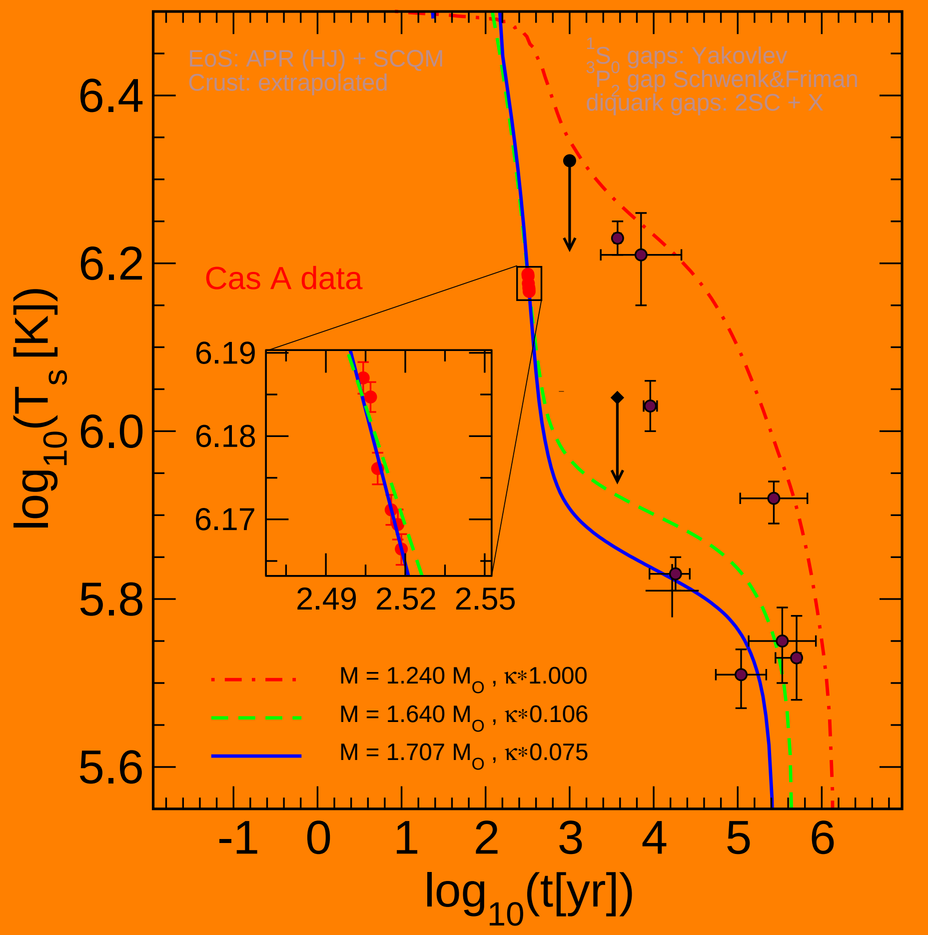
Cas A - cooling neutron star with superfluid interior!

m

D. Blaschke, H. Grigorian, D.N. Voskresensky, Astron. & Astrophys. 424, 979 (2004)



H. Grigorian, D. Blaschke, D.N. Voskresensky, Phys. Rev. C 71, 045801 (2005)



D.B., H. Grigorian, D. Voskresensky, F. Weber, PRC 85 (2012) 022802

Gravitational Mass ↔ Baryon Number J0737-3039

Double Pulsar System J0737-3039

Pulsar A $P^{(A)}$ = 22.7 ms, $M^{(A)} \approx 1.338 M_\odot$

Pulsar B $P^{(B)}$ = 2.77 s, $M^{(B)} = 1.249 \pm 0.001 M_\odot$ (record!)

Progenitor ONeMg white dwarf, driven hydrodyn. unstable by

e^- captures on Mg & Ne; no mass-loss during collapse

Observational constraint for $M(M_N)$ from PSR J0737-3039:

- observed NSs gravitational mass (remnant star) $M^{(B)} = 1.248 - 1.250 M_\odot$
- critical baryon mass for ONeMg white dwarf $M_N^{(B)} = 1.366 - 1.375 M_\odot$

Theory: $M(M_N)$ characteristic for remnants EoS

$M = 4\pi \int_0^R \mathrm{d}r r^2 \varepsilon(r)$;

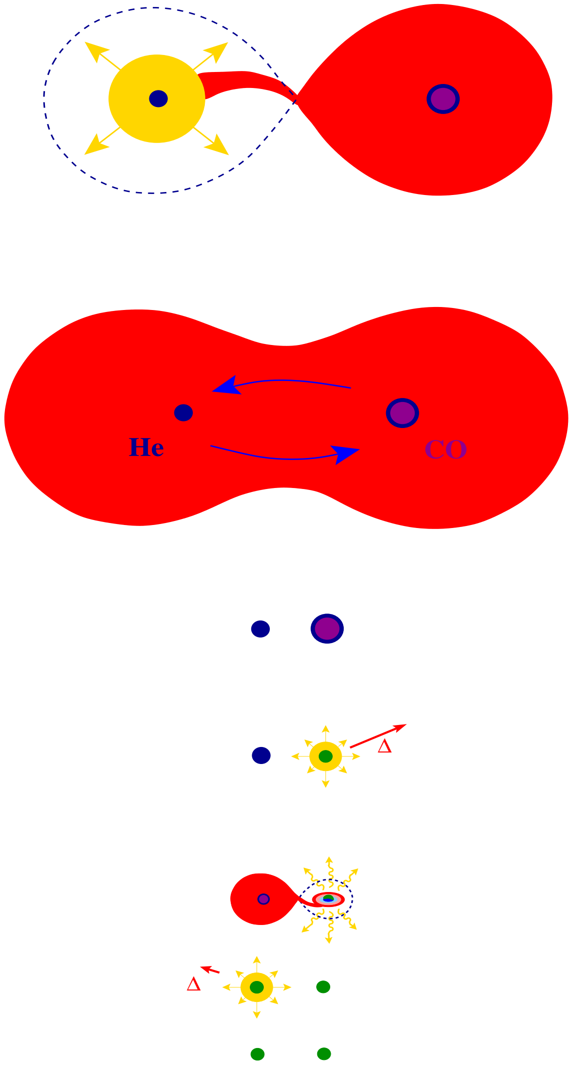
$M_N = u N_B = 4\pi u \int_0^R \mathrm{d}r \frac{r^2 n(r)}{\sqrt{1-2GM(r)/r}}$

(conversion of baryon number to mass by $u = 931.5$ MeV)

P. Podsiadlowski et al., Mon. Not. Roy. Astron. Soc. **361**, 1243 (2005)

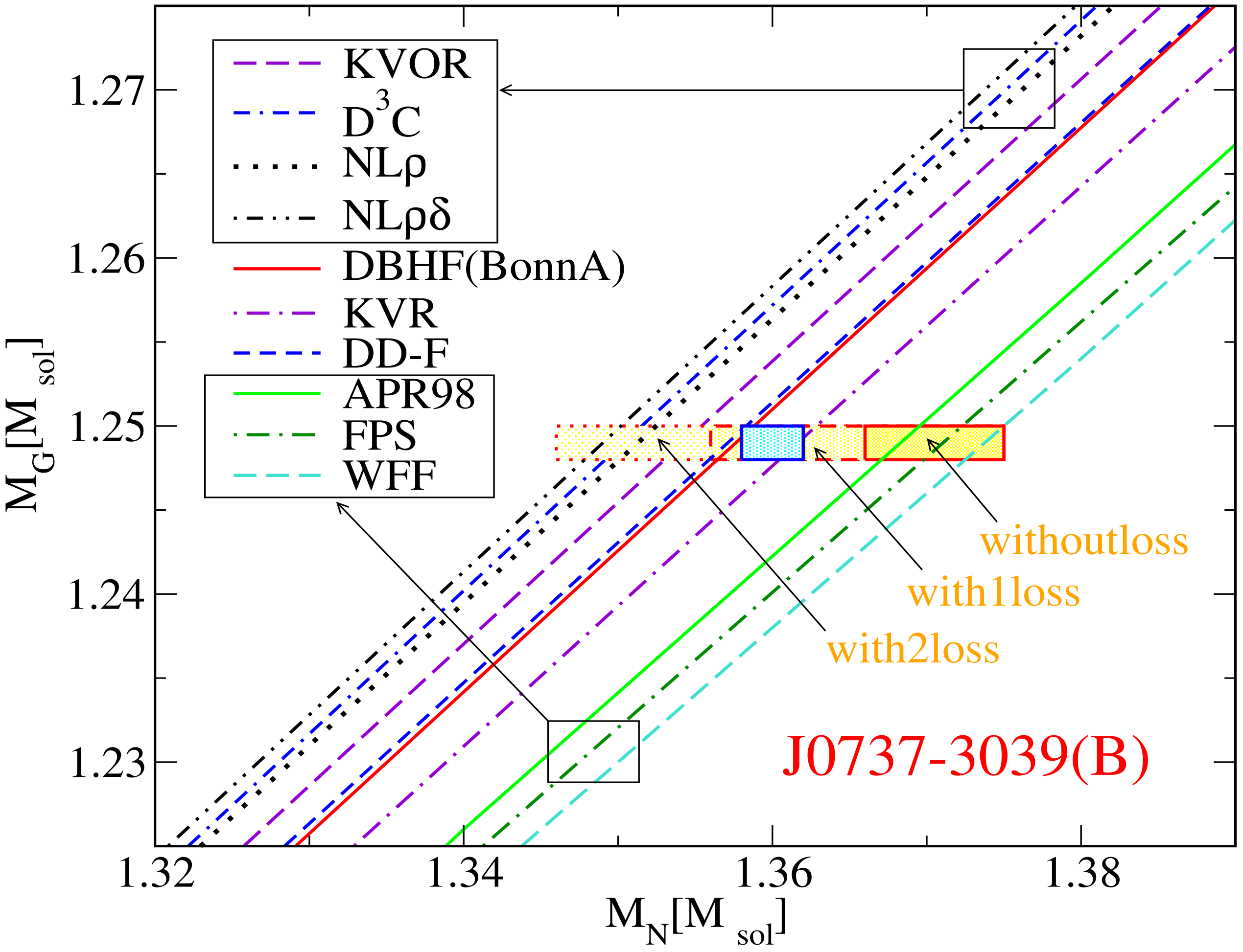
EoS constraint from double pulsar J0737-3039?

Double core scenario:



Dewi et al., MNRAS (2006)

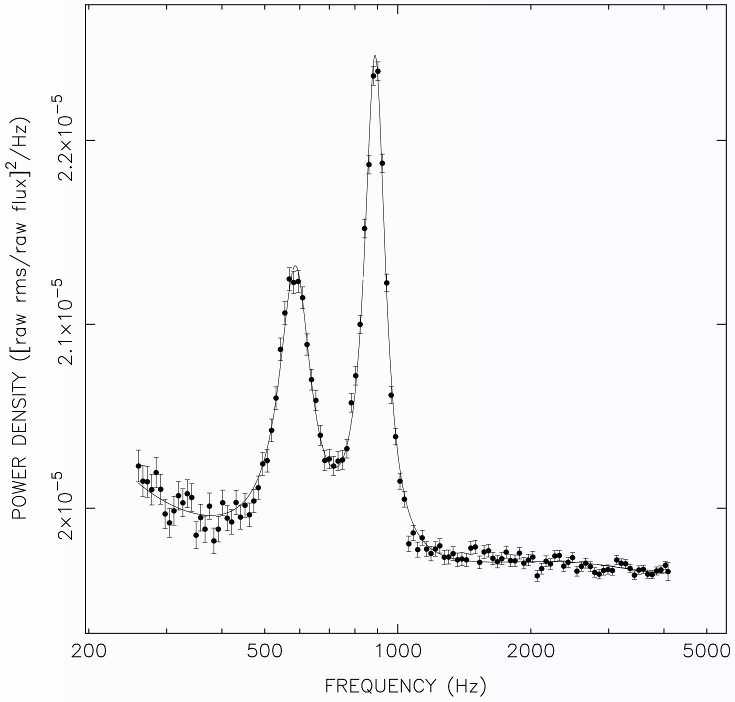
Baryon mass vs. gravitational mass - constraint or consistency check?

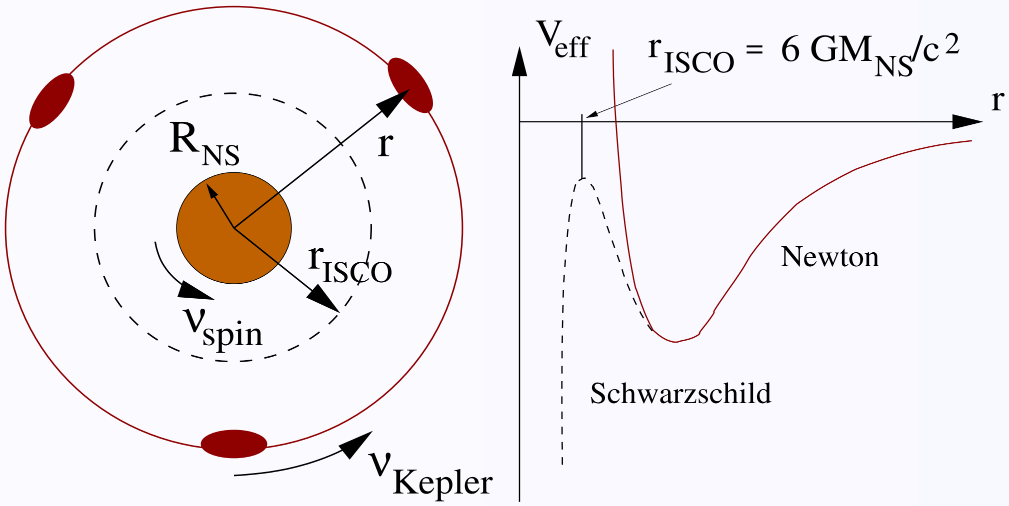


Podsiadlowski et al., MNRAS 361 (2005) 1243
Kitaura, Janka, Hillebrandt, A& A (2006); [astro-ph/0512065]
D.B., T. Klähn, F. Weber, CBM Physics Book (2008)

Mass-Radius Constraints from PO s

Quasi Periodic Brightness Oscillations





$$\nu_{max} \approx \nu_{orbit} < \nu_{ISCO}$$

Keplerian Orbit r_K

$$R < r_k = (GM/4\pi^2\nu^2_{max})^{1/3} \longrightarrow R_{max}(M)$$

$$M < 2.2 M_\odot (1000Hz/\nu_{max})(1 + 0.75j) \longrightarrow M_{max}$$

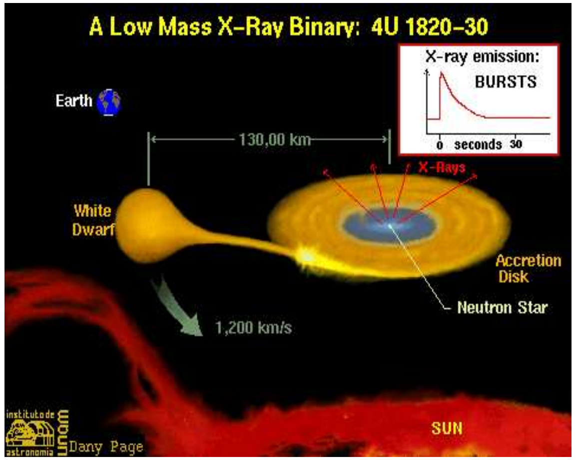
if(!) $\nu_{max} \approx \nu_{ISCO}$

$$M \approx 2.2 M_\odot (1000Hz/\nu_{max})(1 + 0.75j)$$

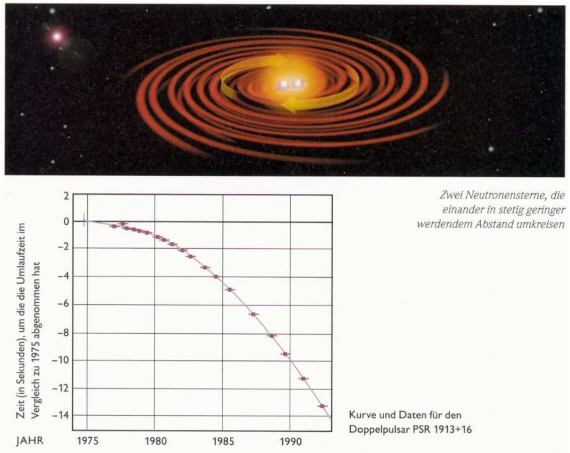
M. van der Klies, ARA&A **38**, 717 (2000)

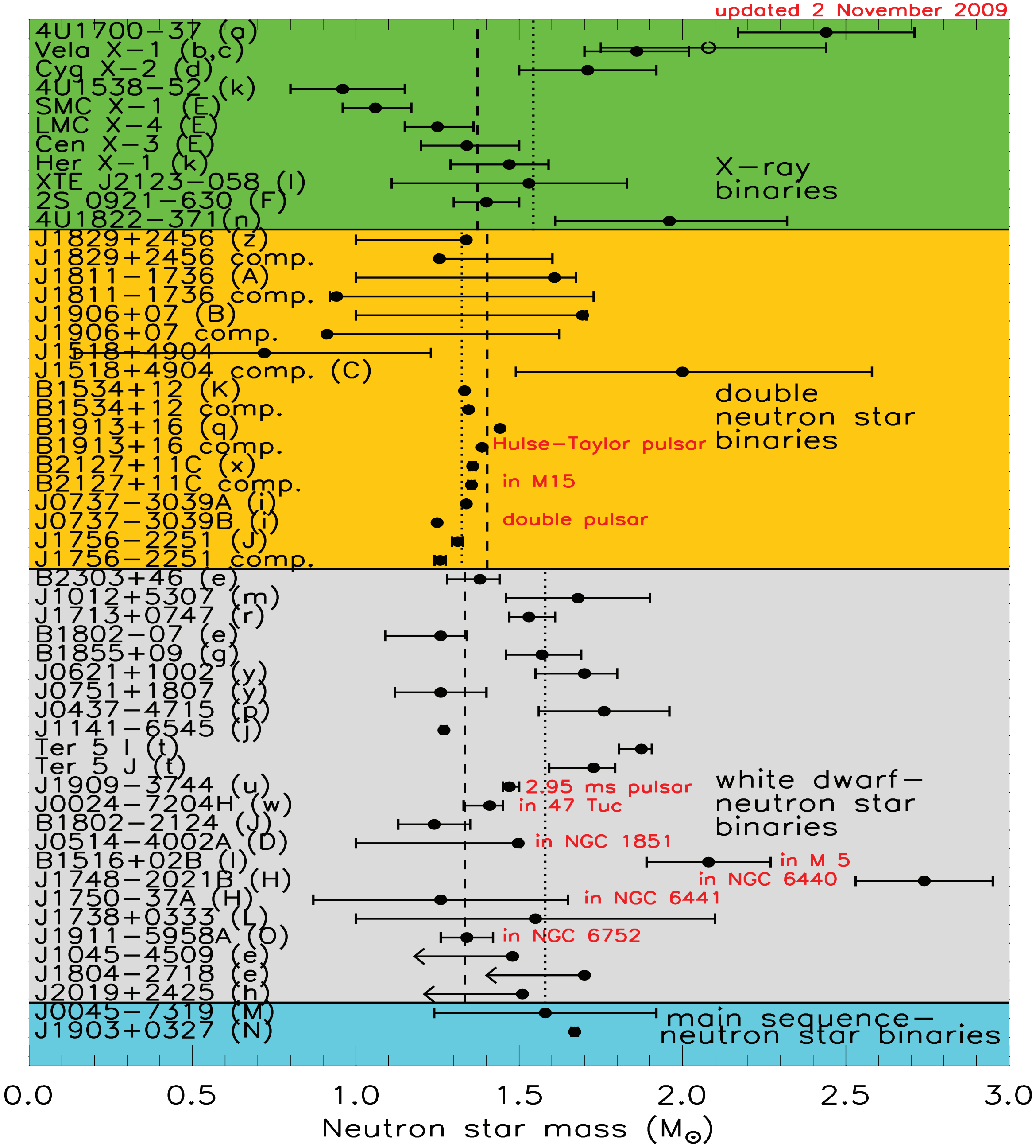
Masses of binaries

LMXB, might evolve to ...



double neutron star





Lattimer, Prakash, PRL 94 (2005) 111101 + updates

Equation of State and Stability of Compact Stars

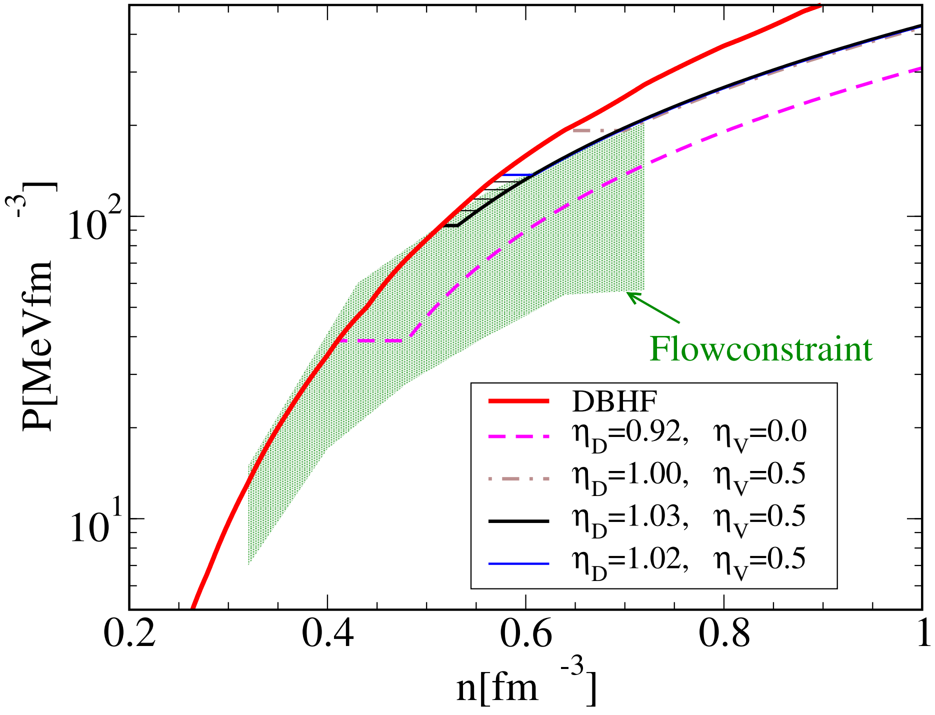
Tolman-Oppenheimer-Volkoff Equations

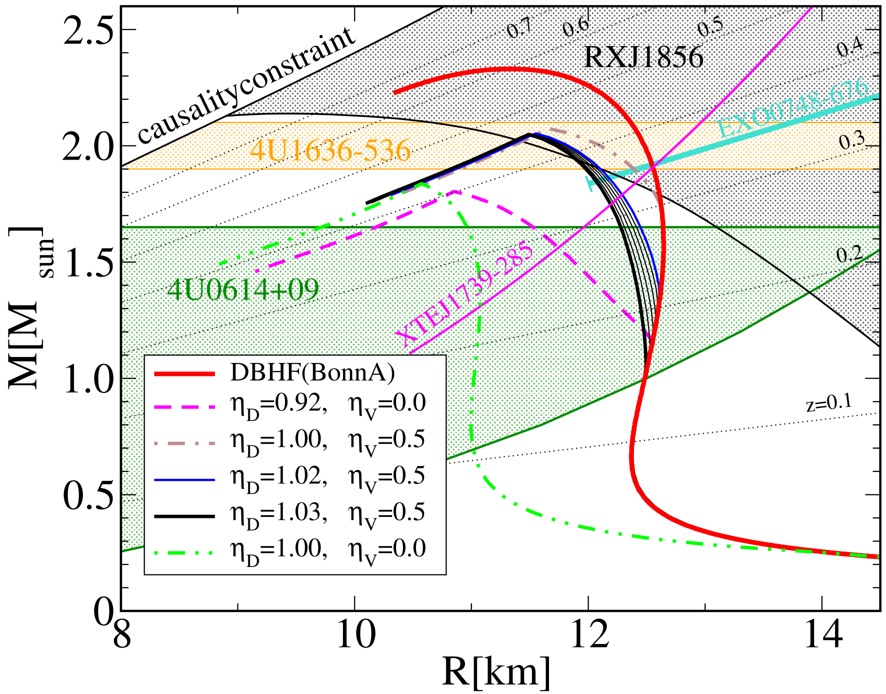
1. Stability: General Relativistic Hydrostatic Equilibrium

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

NEWTON EINSTEIN CORRECTIONS GENERAL REL. THEORY

2. Mass Distribution: $m(R) = \int_0^R \varepsilon(r)\, 4\pi\, r^2\, dr$



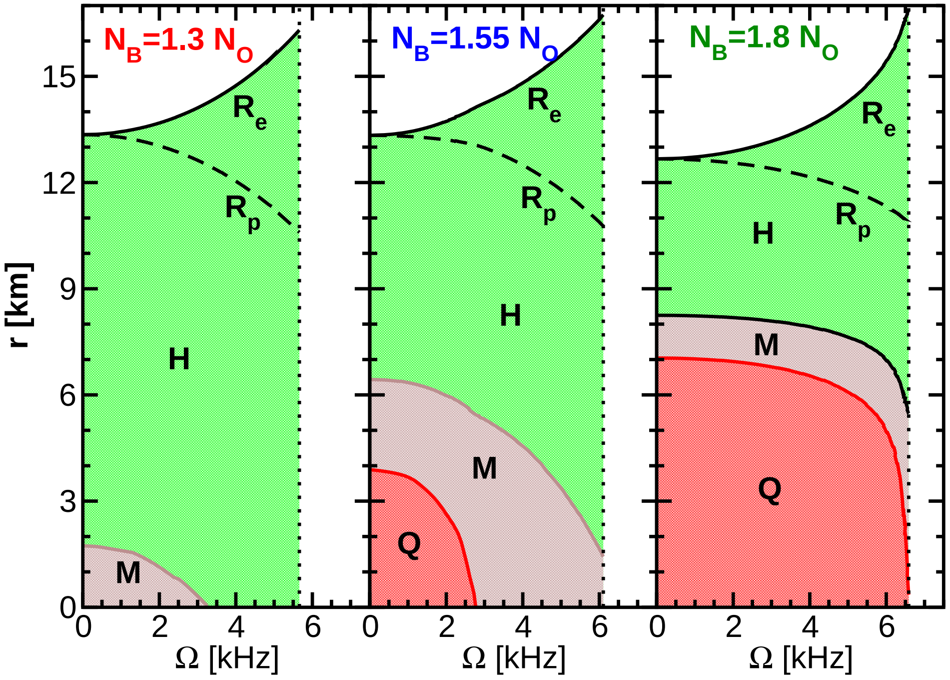


T. Klähn et al., Phys. Lett. B 654, 170 (2007)

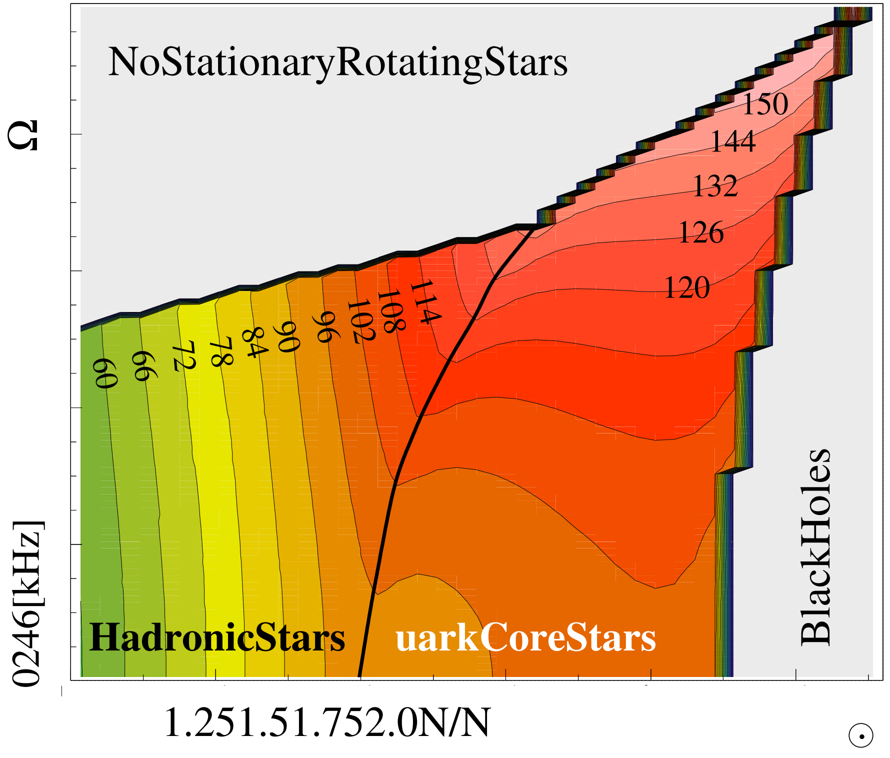
Rotation and Star Structure

Axially symmetric solutions of the EINSTEIN-equations for compact stars show::

- Deformation (Excentricity)
- new density distribution (centrifugal forces)
- further general relativity effects



Phase transition to Quark matter depends on Mass (Baryon number N) and Angular velocity ($\Omega = d\phi/dt$) of the Star!

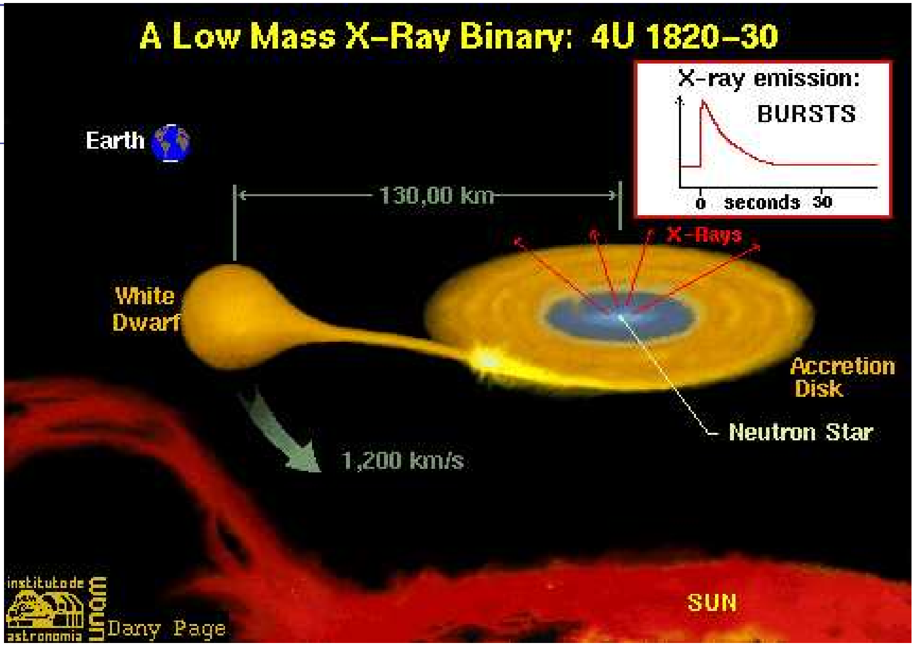


Phase diagram ($\Omega - N$ plane) $\Longrightarrow$ visualizes observable Signals:

- Braking index (spin-down)
- Population-clustering (accretion)

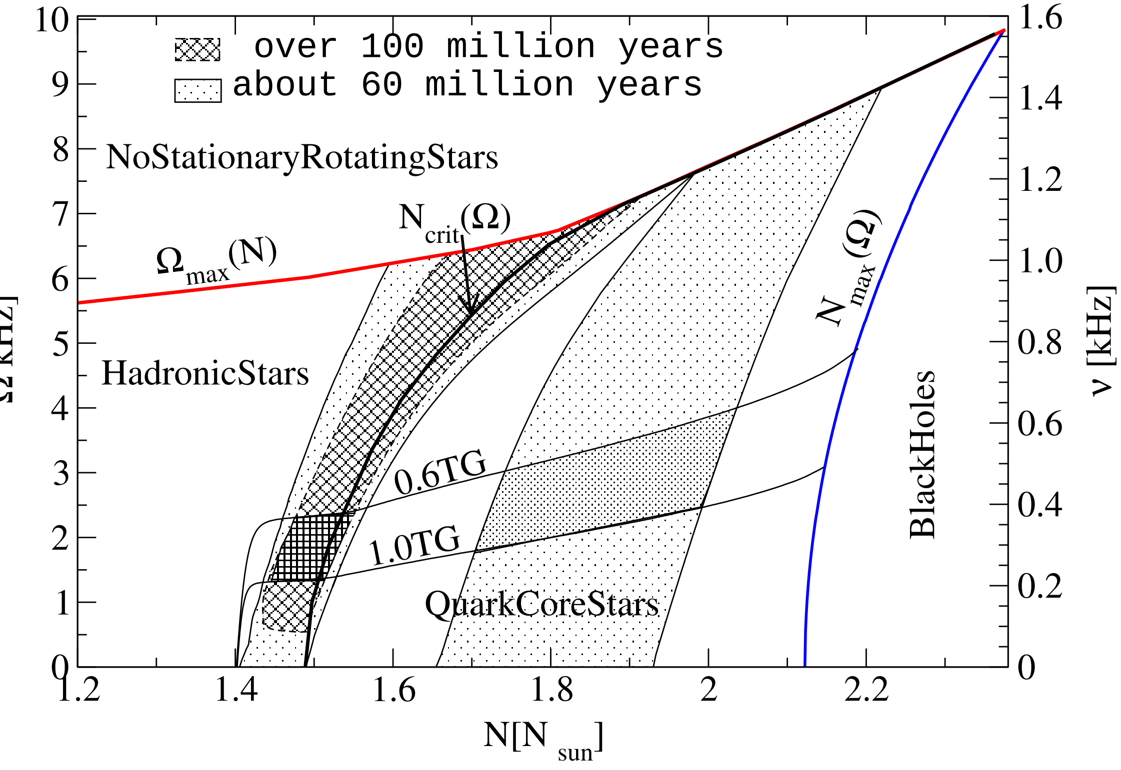
Moment of inertia $\Longleftrightarrow$ Phase transition!

Low-mass X-ray Binary (LMXB)



LMXB's show:

- Accretion (N - Evolution)
- X-ray bursts with quasiperiodic Brightness Oscillations (QPO's)
- further general rel. effects (ISCO)



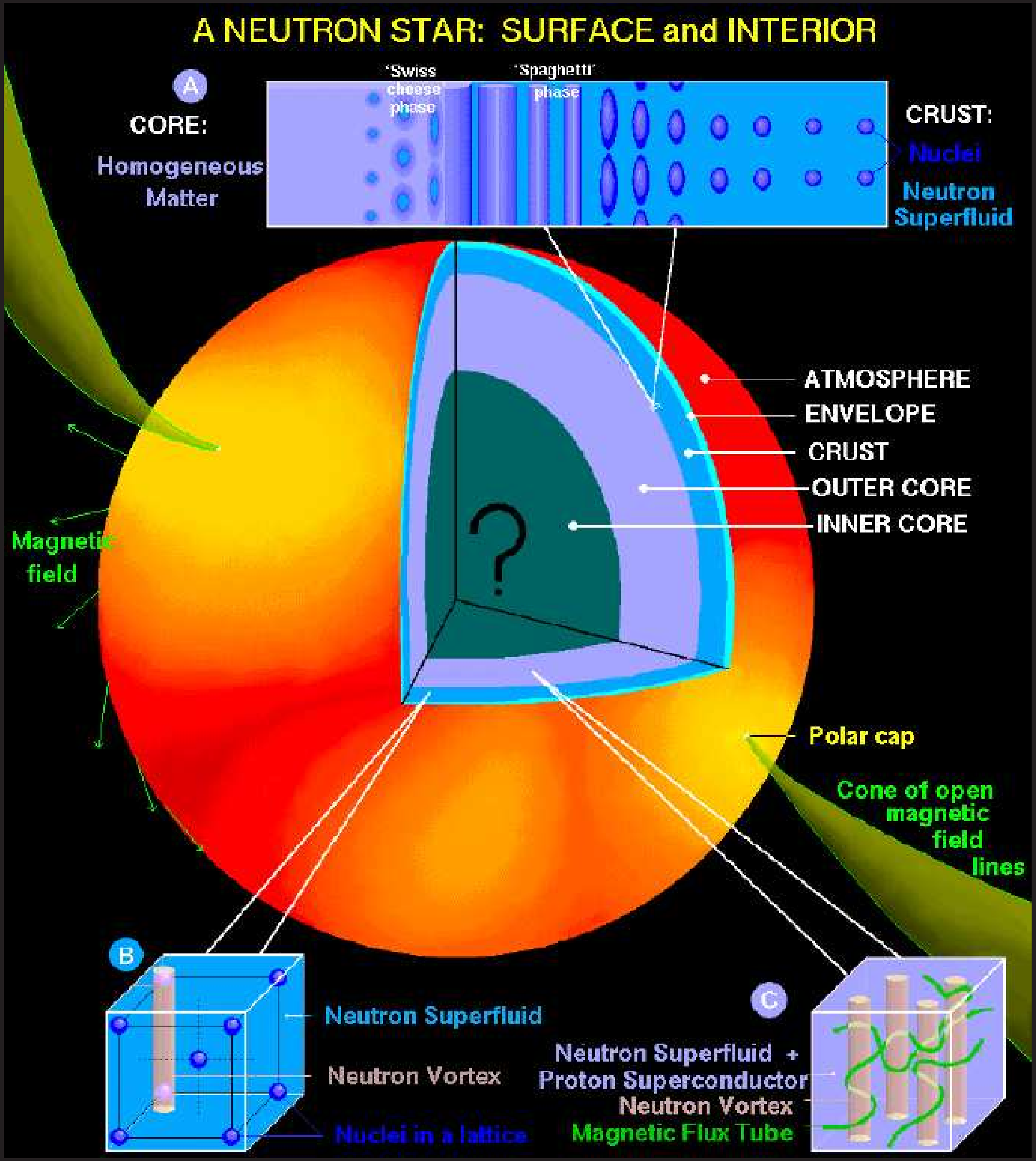
Phase transition Signal:
Population clustering at $N_{\rm crit}(\Omega)$

QPO-Phenomenon gives informations about:

- Mass-radius relation
- Rotation frequency

Ω–N plane $\Longleftrightarrow$ Hertzsprung-Russell-Diagram for QPO's!

Pines theorem (1990): “Compact Stars are Superstars”



PROOF:

- *Super*dense objects
- *Super*fast rotators
- *Super*fluid interior
- *Super*conducting interior
- *Super*strong magnetic fields
- *Super*precise timers
- *Super*rich physics involved

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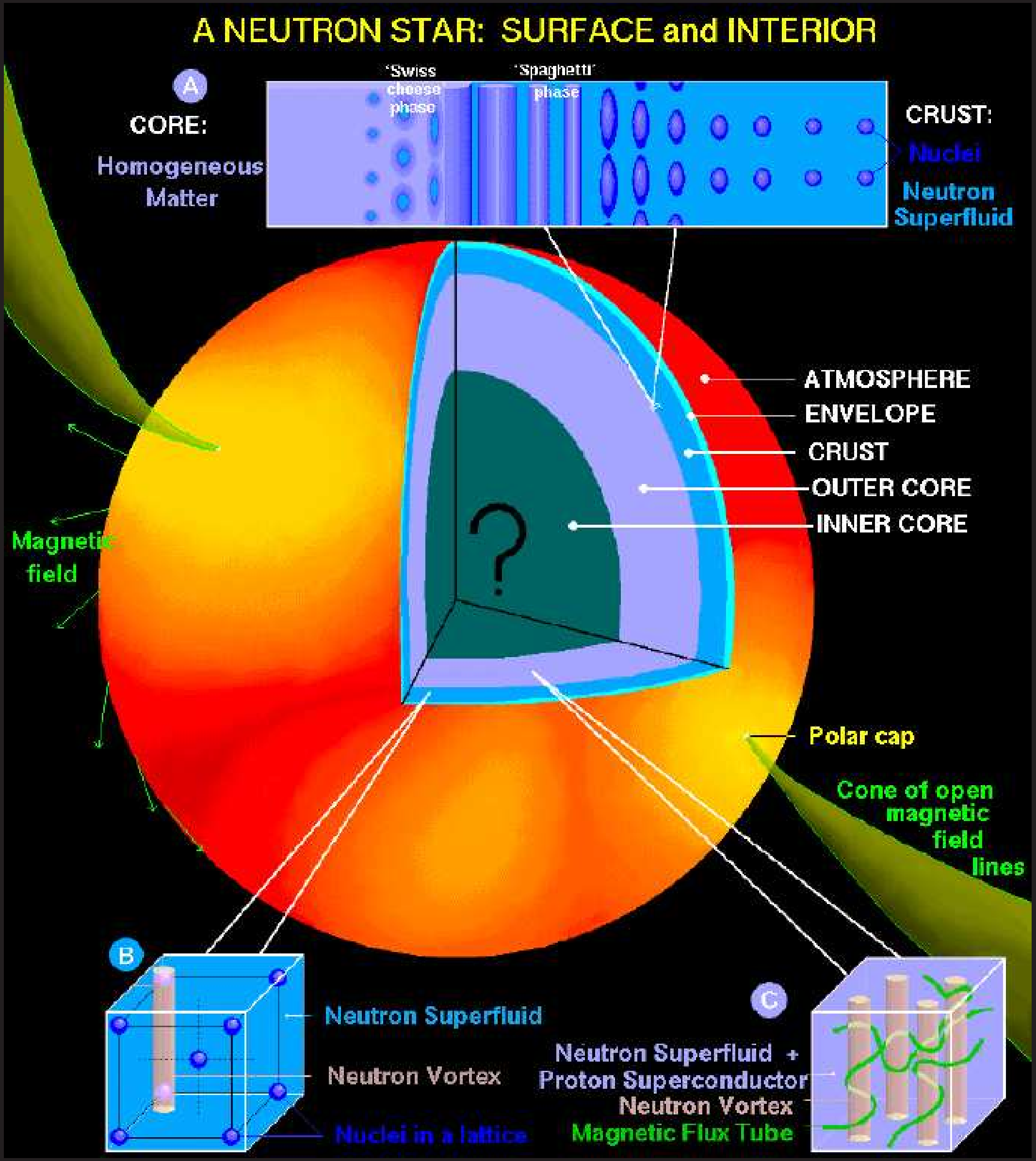

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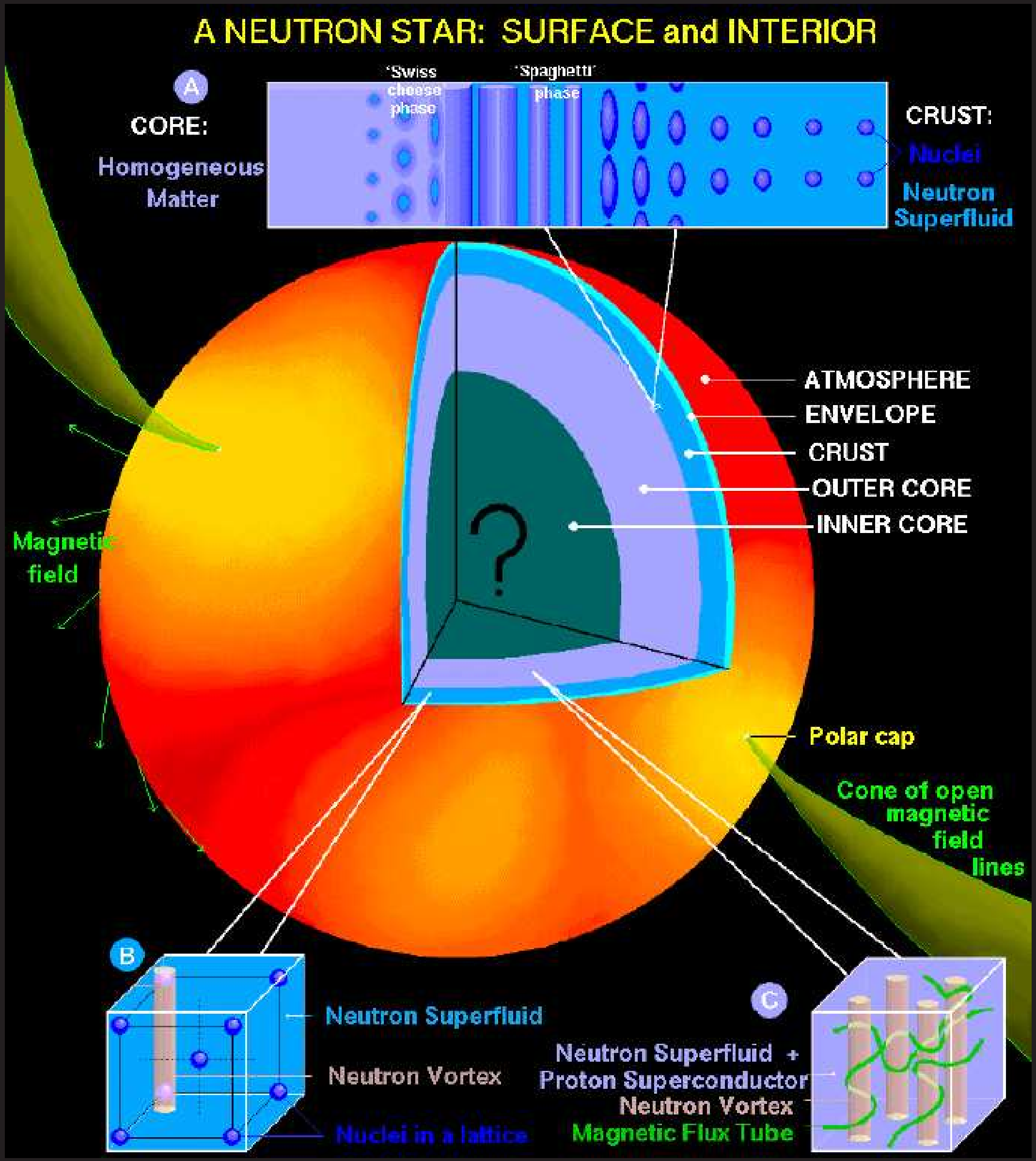

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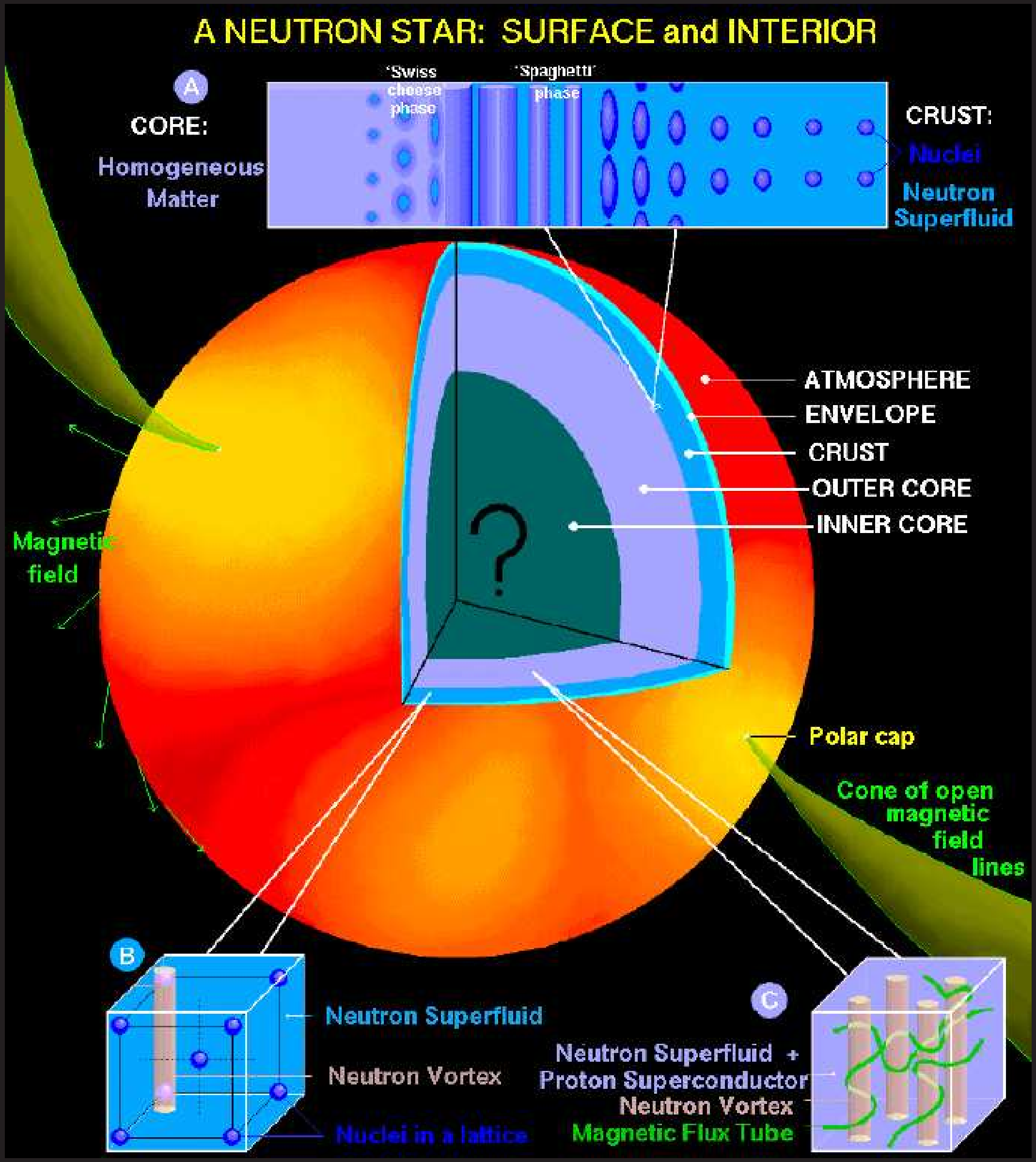

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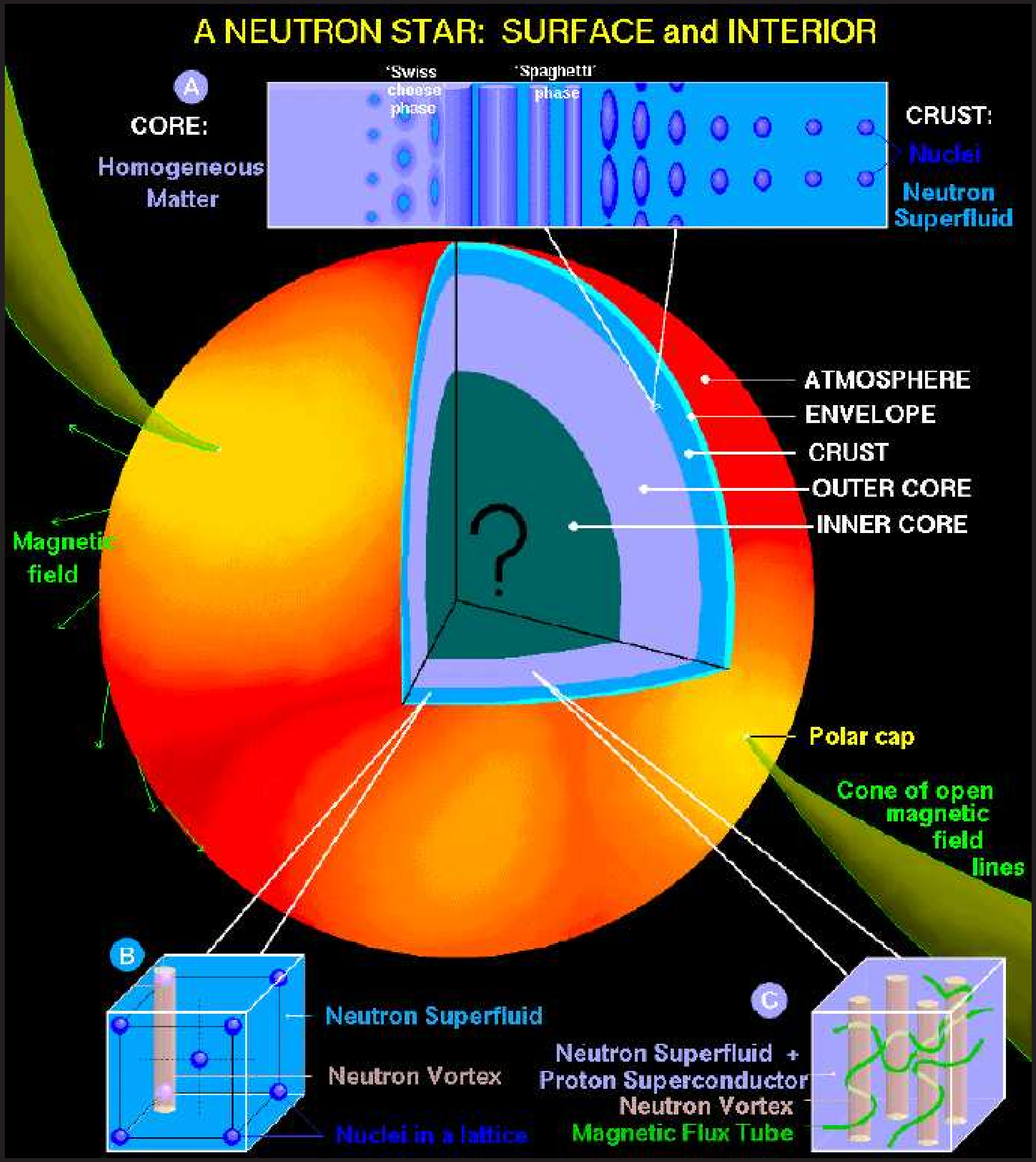

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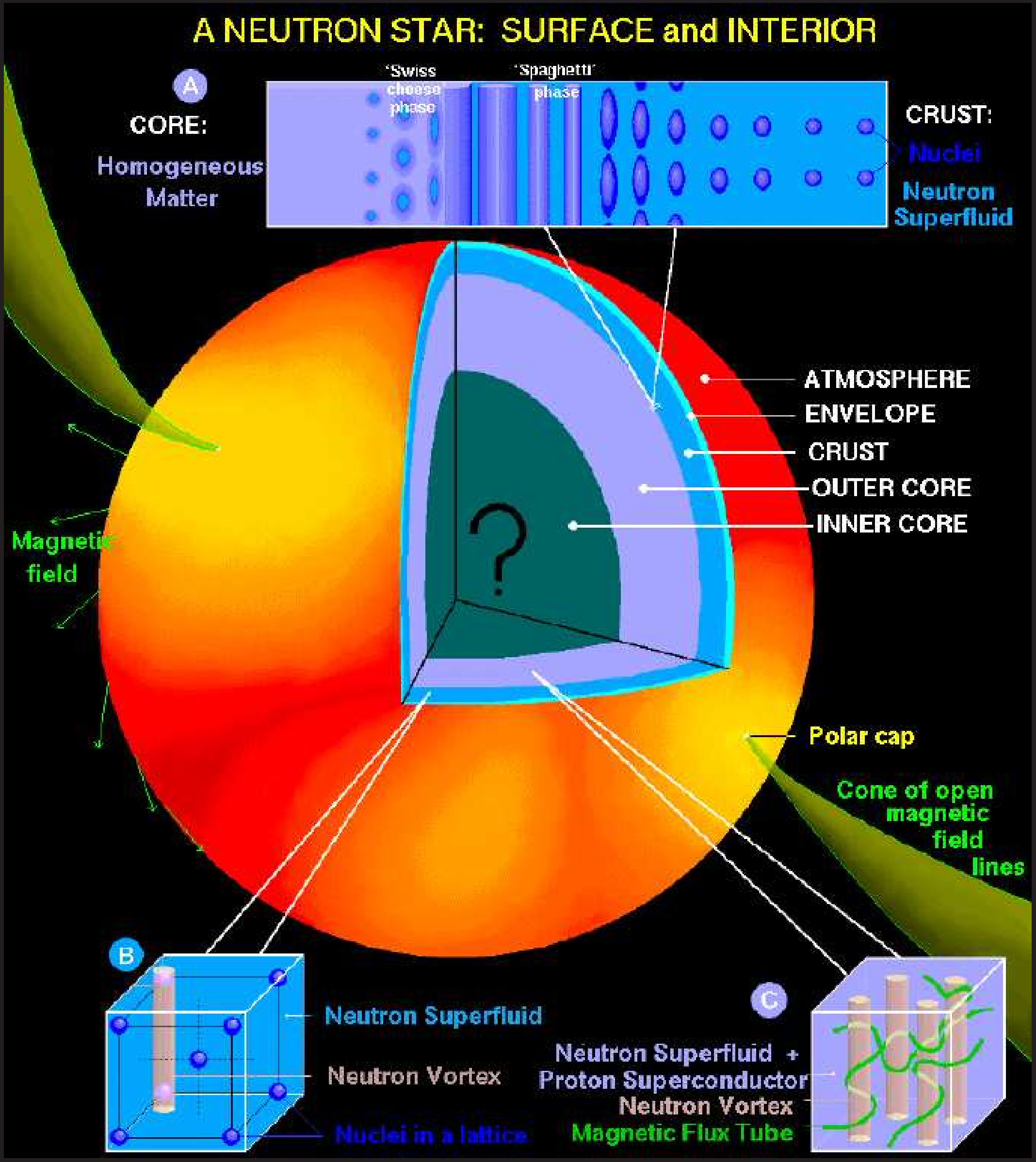

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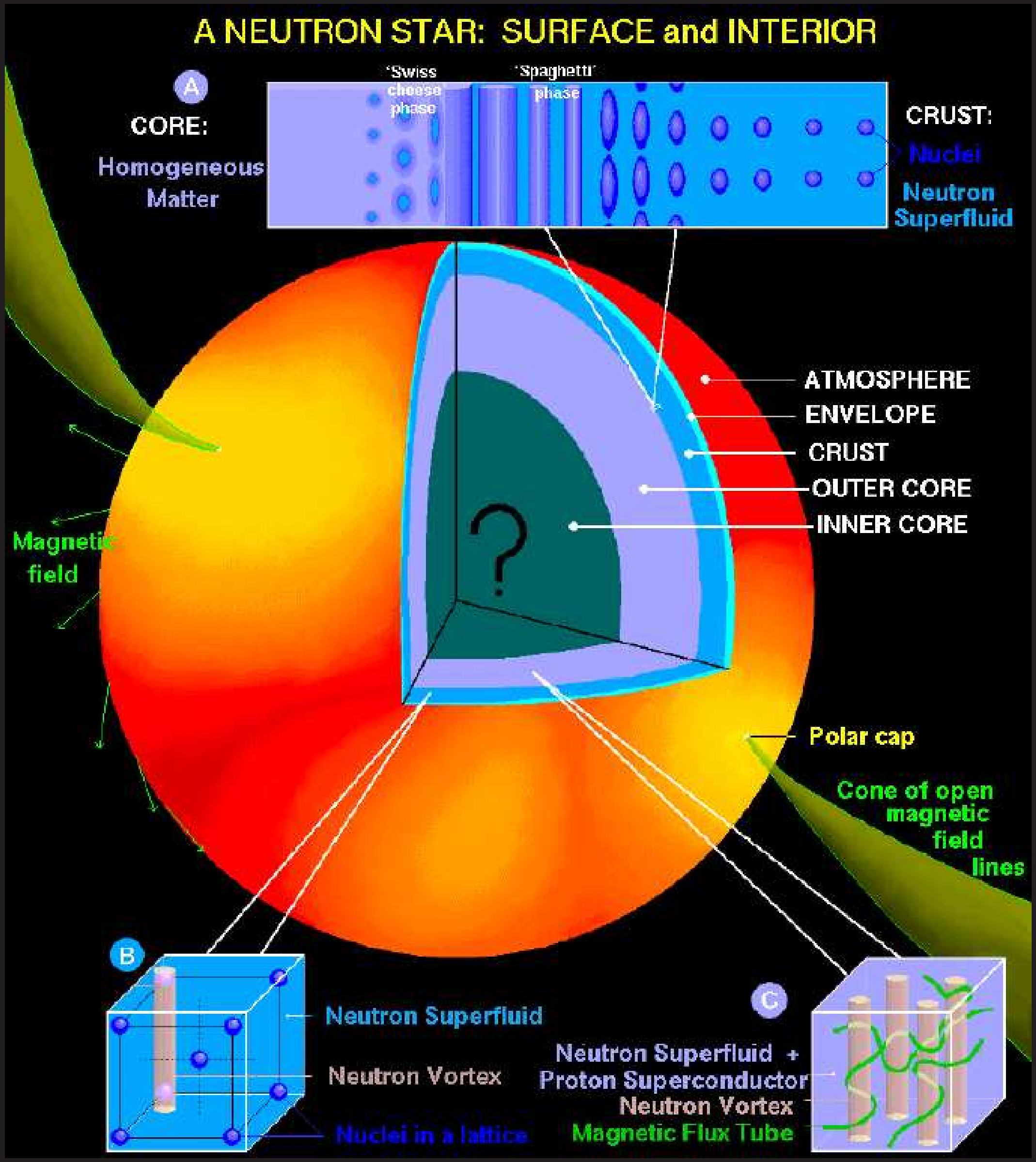

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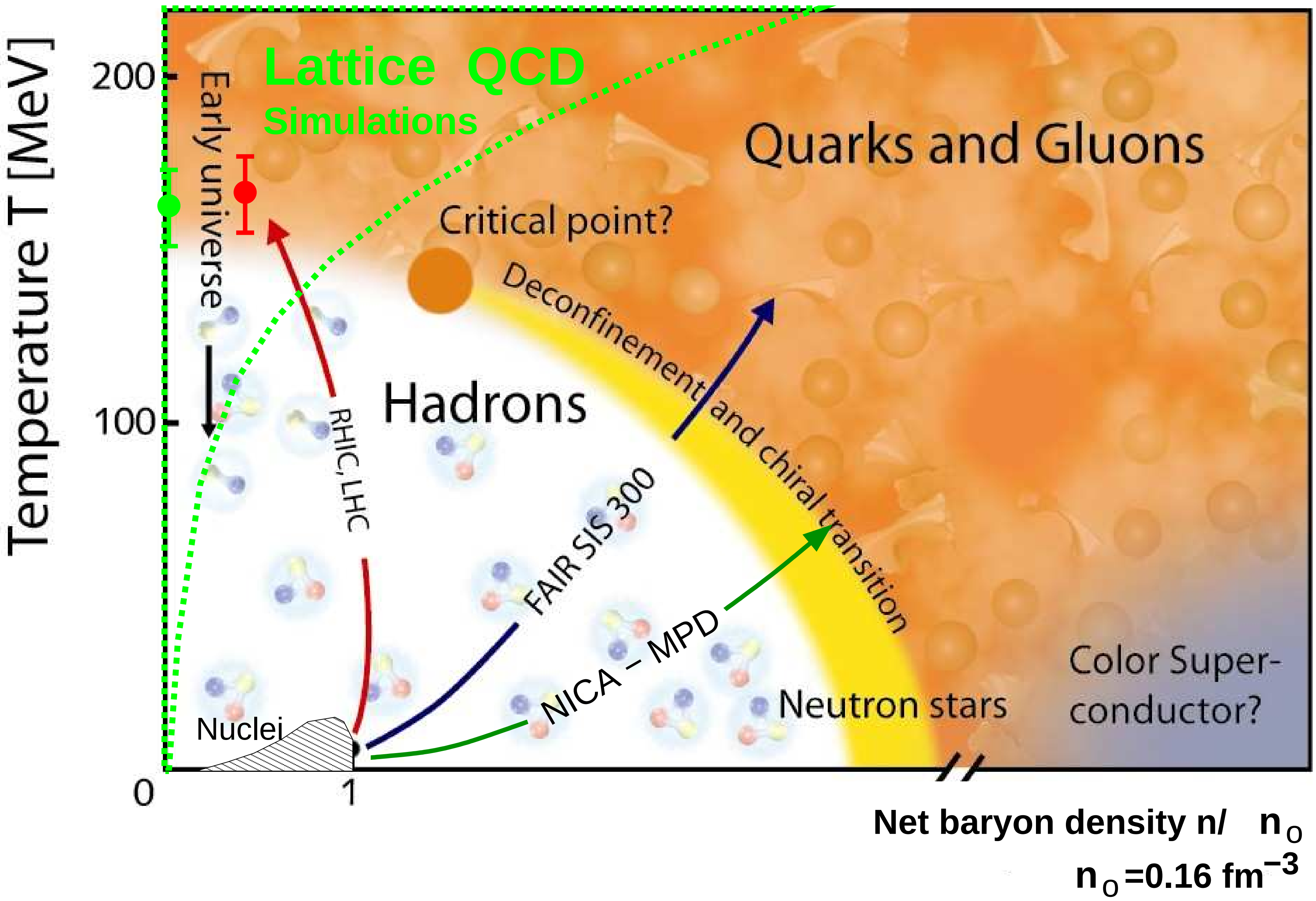
Extreme States of Matter - The Phase Diagram



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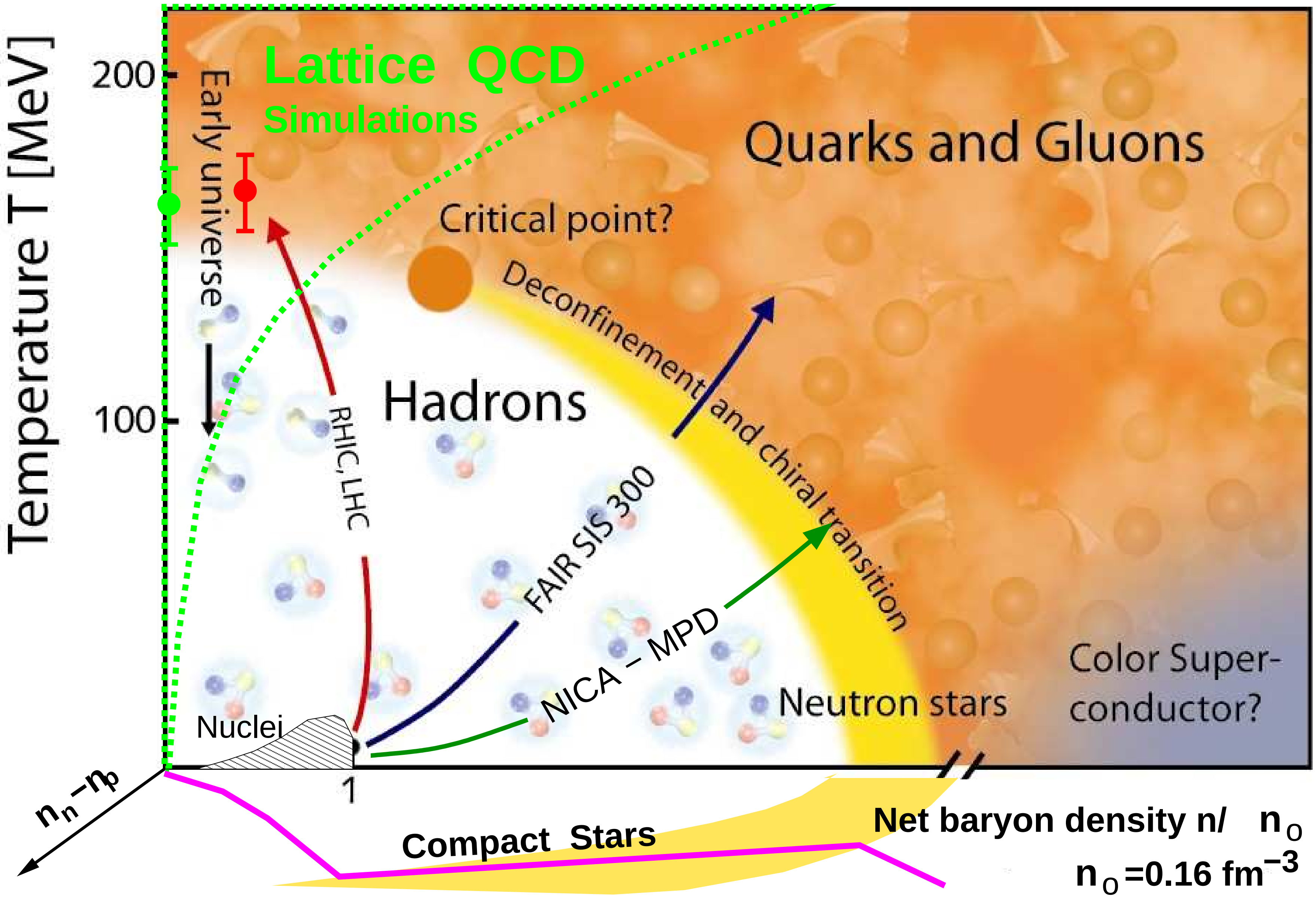

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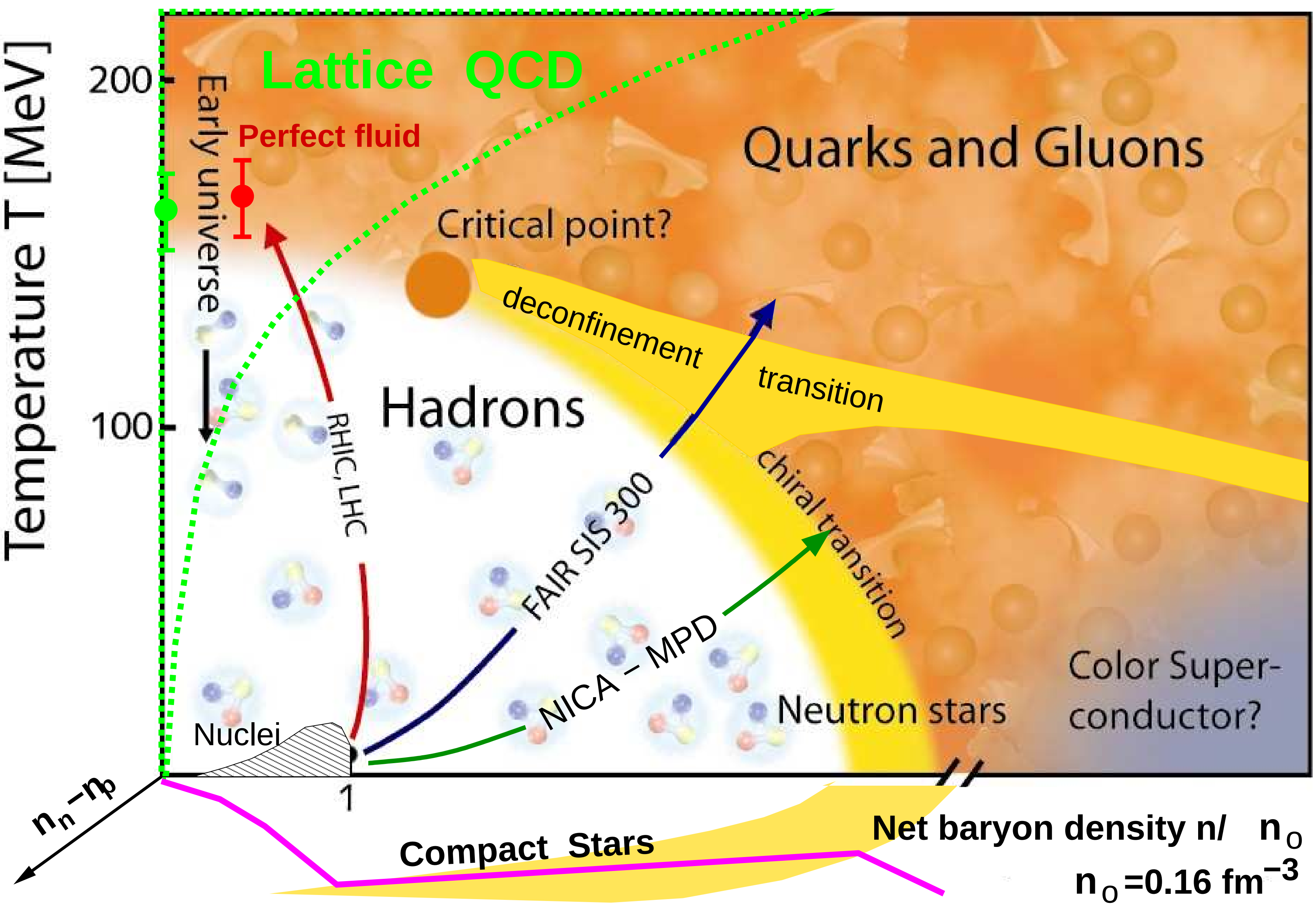

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