Neutron Stars

and their importance

in the general scheme of physics

J.R. Stone

Oxford/Tennessee/Oak Ridge
I. Compact objects: white dwarfs, neutron stars and black holes
   Collapse of massive stars
   Pulsars

II. Cooling of proto-neutron stars and formation of microscopic
    make-up of the star.
    Possible exotic stars

III. Theoretical models of neutron stars and their impact in
    the general context of physics.
Type II supernovae core collapse: forms a neutron star or a black hole.
A BIT OF HISTORY:

1931:

Collapse of red giants and white dwarfs are known.
**White dwarfs** *(1910 – Henry Norris Russel, named 1922 Willem Luyten)*:

When red giants consume all their accessible fuel, the cores of the stars shrink to a very hot very dense object – not a star in technical sense: 
Mass ~ 1 solar mass, radius ~ 7000 km

Energy comes from gravitational contraction
Radiation comes from emission of stored heat (not fusion reactions)

**Example: Sirius B (Hubble image)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density in kg/m³</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (fresh)</td>
<td>1,000</td>
<td>At STP</td>
</tr>
<tr>
<td>Osmium</td>
<td>22,610</td>
<td>Near room temperature</td>
</tr>
<tr>
<td>The core of the Sun</td>
<td>~150,000</td>
<td></td>
</tr>
<tr>
<td>White dwarf star</td>
<td>$1 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>Atomic nuclei</td>
<td>$2.3 \times 10^{17}$</td>
<td></td>
</tr>
<tr>
<td>Neutron star core</td>
<td>$8.4 \times 10^{16} - 1 \times 10^{18}$</td>
<td></td>
</tr>
<tr>
<td>Black hole</td>
<td>$2 \times 10^{30}$</td>
<td>Critical density of an Earth-mass black hole</td>
</tr>
</tbody>
</table>
Final stage of stars which are not very massive (over 97% of stars of our Galaxy):

I. Hydrogen-fusing (main-sequence star of low or medium mass below 9-10 solar masses)

II. Helium fusing to carbon and oxygen in the core by the triple alpha process red giant

III. If T too low to fuse carbon, C and O accumulate in the core, outer envelope is shedded to form planetary nebula (they return light elements back to interstellar medium)

IV: White dwarf: carbon - oxygen
    oxygen-neon-magnesium
    helium

V: White dwarf is supported from gravitational collapse by electron degeneracy pressure
Electron degeneracy pressure (taken from astro.umd.edu):

I.3: Cold particle in a box

- Consider three electrons in a box. Suppose they are as cold as you can make them... they are in their quantum ground state.

\[ \lambda_1 = 2L \]
\[ \lambda_2 = 2L \]
\[ \lambda_3 = L \]

\[ mv = \frac{h}{\lambda} \]

Length L

Pauli exclusion principle
If we squeeze the box

With ever decreasing distance between electrons they have to travel with increasing speed dictated by Pauli principle, contributing to the pressure. When this pressure exceeds the pressure provided by thermal motion of the electrons, the electrons are referred to as degenerate.

\[
\Delta p \Delta x \sim \frac{1}{n_e^{1/3}} \left( \frac{3h^3n_e}{8\pi} \right)^{1/3} = (3\pi^2)^{1/3}\hbar
\]
The Sun as a main-sequence star
(diameter = $1.4 \times 10^6$ km $\approx \frac{1}{100}$ AU)

The Sun as a red giant
(diameter $\approx 1$ AU)

(a) The Sun today and as a red giant

(b) Red giant stars in the star cluster M50
Subrahmanyan Chandrasekhar –
White Dwarfs have maximum mass beyond which degeneracy pressure of electrons fails to support star against gravitational collapse
1932:
Chadwick discovers the neutron

1933:
Baade and Zwicky postulate neutron star as end result of supernova (SN) explosion.

SN releases:

$10^{53-54}$ ergs compared with the mass-energy of initial star of $\approx 10^{54-55}$ erg

Gravitational binding energy of an extremely compact object (Mass $\approx 1M_{\text{Sun}}$, R $\approx 10$km)

$\sim 0.1-0.2$ times the mass-energy of its progenitor star.

Neutrons can pack much more closely than nuclei + electrons
Fritz Zwicky
1898 – 1974
Swiss/Czech born in Bulgaria
Caltech

Walter Baade
1893 - 1960
German
Goettingen
Neutron Stars and the Extremes of Physics

“With all reserve we advance the view that super-novae represent the transition from ordinary stars into neutron stars, which in their final stages consist of closely packed neutrons.”

- W. Baade and F. Zwicky, 1933
Classical neutron star composition in 1933 – neutrons only

\[ N \sim 10^{57} \]

\[ R \sim 10 \text{ km} \]
\[ M \sim 1.5 M_{\odot} \]
Beyond White Dwarf Masses:

After Chandrasekhar’s mass is exceeded:

- Gravitational collapse continues
- Nucleon density is reached

- If mass less than 2-3 solar masses: nucleon degeneracy pressure may hold the collapse
  
  all protons are converted to neutrons via electron capture (weak interaction)
  
  and a neutron star is born with a radius about 500 times smaller than the white dwarf

- If mass bigger than 2-3 solar masses – the collapse continues to a black hole

White dwarfs and neutrons stars are the only possible stable configurations between normal stars and black holes
Gravitational collapse of a massive star:

**Progenitor: Nuclear fusion against gravity:**

Gravitational collapse which starts when the H fuel is exhausted is temporarily halted by the ignition of successive burning processes involving heavier elements and increasing T and pressure.

**Thermal runaway:**
Increase in T changes the conditions in a way that causes a further increase in temperature leading to a destructive result.

![Diagram of stellar burning shells and center of a 25 solar mass star late in its life.](image)
Table 5.7: Burning stages in massive stars (Woosley)

<table>
<thead>
<tr>
<th>Nuclear fuel</th>
<th>Nuclear products</th>
<th>Ignition temperature</th>
<th>Minimum main sequence mass</th>
<th>Period in $25M_{\odot}$ star</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>$4 \times 10^6$ K</td>
<td>$0.1M_{\odot}$</td>
<td>$7 \times 10^6$ years</td>
</tr>
<tr>
<td>He</td>
<td>C, O</td>
<td>$1.2 \times 10^8$ K</td>
<td>$0.4M_{\odot}$</td>
<td>$5 \times 10^5$ years</td>
</tr>
<tr>
<td>C</td>
<td>Ne, Na, Mg, O</td>
<td>$6 \times 10^8$ K</td>
<td>$4M_{\odot}$</td>
<td>600 years</td>
</tr>
<tr>
<td>Ne</td>
<td>O, Mg</td>
<td>$1.2 \times 10^9$ K</td>
<td>$\sim 8M_{\odot}$</td>
<td>1 years</td>
</tr>
<tr>
<td>O</td>
<td>Si, S, P</td>
<td>$1.5 \times 10^9$ K</td>
<td>$\sim 8M_{\odot}$</td>
<td>$\sim 0.5$ years</td>
</tr>
<tr>
<td>Si</td>
<td>Ni–Fe</td>
<td>$2.7 \times 10^9$ K</td>
<td>$\sim 8M_{\odot}$</td>
<td>$\sim 1$ day</td>
</tr>
</tbody>
</table>

Each of the burning stages takes shorter time and leads to higher T
Figure 1  The structure of a core collapse supernova progenitor at the onset of stellar core collapse. The size of the iron core and star are compared with the size of the earth and its orbit around the sun, respectively.
Sequence of events after the nickel/iron core is reached (no more fusion possible)

When the mass of the iron core exceeds Chandrasekhar limit:

1. Core starts to collapse under gravity – T and density increases

**Photo-disintegration**

\[ \gamma + ^{56}\text{Fe} \rightarrow 13\alpha + 4n \quad Q = -124\text{ MeV} \]

**Neutronization**

\[ p^+ + e^- \rightarrow n + \nu \]

- Kinetic energy of electrons
- Pressure
- Electron fraction $Y_e$
- Neutrinos escape
- Pressure
- Collapse
2. Core collapse proceeds on the time scale of milliseconds

inner core (homologous and subsonic)
outer core (free-fall – supersonic)

3. Collapse slow compared to reaction rates

approximate equilibrium and constant entropy $S \approx 1$ and the Fe core remains ordered during the collapse

4. As $T$ and density keep rising:

neutrino interaction are stronger and free mean path shorter - *origin of neutrino trapping*

5. Low entropy – little nuclear excitations

increased density results in nuclei touching each other macro-single-nucleus is formed

Pressure increases dramatically by the repulsive NN interaction at short distances
6. As the transition to nuclear matter (with stiff equation of state) progresses nucleon pressure starts to dominate lepton pressure.

7. **Rebound:** dramatic change in pressure makes the core incompressible; the in-falling layers crash into the core and rebound sending a reflected pressure wave outwards.

Pressure wave propagates outwards with the speed of sound – creates a shock wave.

**BUT – THE SHOCK WAVE STALLS!!!**
Proto-neutron star – hot, fast rotating and magnetized

Simulation

Crab Nebula (constellation Taurus) remnant of 1054 core-collapse SN

Composition of the star is created at this stage.
Models of Neutron Star composition in 2004

F. Weber

Prog. Part. Nucl. Phys. 54, 193 (2005)
Neutron Stars are Exotic!

- Of order 1 solar mass
- 10km radius
- Average density $10^{14-15}$ g/cm$^3$
- $10^{10}$ humans on Earth @ 50,000g each = $5 \times 10^{14}$g
- Compress them all into a sugar cube and we reach neutron star density!
- $g \approx 10^{12}$ ms$^{-2}$!
- Neutron Stars are test bed for exotic physics under extreme conditions
• A Brief Story of Observation of Neutron Stars

• Problem:
  - No energy generation after formation
  - Small surface > rapid initial cooling
    and low optical luminosity

Can the theoretical concept of neutron star to be identified with the observational phenomena of pulsars?
1967:
Hewish and Bell:

Pulsed radio emission from object way outside solar system
- P = 1.337s: Must be compact object (WD or NS)
- Period gradually increasing: rotational period rather than oscillation period

1968:
Crab and Vela pulsars - SN remnant association
- Crab period 33ms: must be NS
- From spin down rate, Crab pulsar energy loss ≈ 10^{38} erg/s
Antony Hewish

1924 (age 87)
British

Cambridge

Nobel price 1974
with Martin Ryle

Susan Jocelyn Bell Burnell, DBE, FRS, FRAS
(born 15 July 1943)

Dame Commander of the Most Excellent Order of the British Empire (DBE)
- **Crab nebula**: remnant of 1054 SN
  - Radiating in optical, radio, X-ray
  - Energy input to nebula \( \approx 10^{38} \text{erg/s} \)
  - The center of the Crab Nebula shows ragged shreds of gas that are expanding away from the explosion site at over three million miles per hour

The radiation emission is observed in pulses

The Crab is arguably the single most interesting object, as well as one of the most studied, in all of astronomy. The image is the largest image ever taken with Hubble's WFPC2 workhorse camera.
At the center of the Crab Nebula is a city-sized, magnetized neutron star that spins 30 times a second, where ring-like structures emit x-rays as high-energy particles slam into the nebular material.

Being relatively young, the Crab Pulsar was the first known example of a neutron star which was located at the site of an optically visible object.

The inner part of the ring surrounding the Crab Pulsar spans a light-year, hiding the neutron star.
- **Approx. dipolar B field, axis offset from spin axis**

- **Rotation** induces strong E quadrupole field, accelerates charged particles off surface into magneto-sphere $F_{el}/F_{gr} \sim 10^{12}$

- **Conduction** of material is strong along B lines, low perpendicular to them: particles forced into co-rotation

- **Light cylinder**: $v = R_L \omega = c$ – particles forced to cones above magnetic poles

- **Emission mechanism**: probably curvature radiation (radiation of a charged particle accelerated along a curved field line)

- **Coherent emission** to explain high brightness of small emitting region: bunches of particles moving in the same direction and radiating in phase
If the magnetic and rotational axes of the star are not aligned the bi-polar beam sweeps out two opposite areas of the skies observer at one of these areas – always sees pulses when the beam sweeps his line of sight

Emits radiation with almost every wavelength

2007 – new observation of secondary pulses, possibly connected to FOUR magnetic poles as the secondary pulses are radically different from the primary ones
Lovell telescope at Jordell bank in Cheshire, England

At 76 meters in diameter this is the world's 3rd-largest fully-steerable telescope.

Detects radio-signals from pulsars
PSR B0329+54

- 1.4 rotations / sec

PSR B0531+21 (CRAB)

- 30 rotations / s

PSR B1937+21

- 642 rotations / s
Pulsars irregularities:
Detection of timing irregularities in pulsed emission requires dedicated observation of many pulsars to increase the possibility that irregular rotational behavior is found.

Two types of timing irregularities in pulsar timing:
"timing-noise" which is random phase wandering in pulses relative to the general slow-down model,
"glitches" which are discontinuous changes in the rotation period, accompanied by quasi-exponential recoveries with timescales of hours up to years.

Such variation in can be interpreted as changes in the pulsar environment and/or neutron star interior. This irregular behavior is not isolated to changes in rotational frequency and pulse phase, but also extends to the intensity and timescale of observed emission, as well as variation in the shapes of pulse profiles.
Pulse Profiles: Integrated pulse profiles for a sample of nine pulsars showing the variability of pulsar emission. Copyright: Handbook of Pulsar Astronomy
Neutron stars (we know about)

Radio-quiet neutron stars

Radio loud neutron star

Single pulsars

- General term for neutron stars that emit directed pulses of radiation towards us at regular intervals (due to their strong magnetic fields).

Rotation-powered pulsar ("radio pulsar")

Magnetar—a neutron star with an extremely strong magnetic field (1000 times more than a regular neutron star), and long rotation periods (5 to 12 sec)

Soft gamma repeater (SGR)

Anomalous X-ray pulsar (AXP)
Binary pulsars

Low-mass X-ray binaries (LMXB)

Intermediate-mass X-ray binaries (IMXB)

High-mass X-ray binaries (HMXB)

Accretion-powered pulsar ("X-ray pulsar")

X-ray burster—a neutron star with a low mass binary companion from which matter is accreted resulting in irregular bursts of energy from the surface of the neutron star.

Millisecond pulsar (MSP) ("recycled pulsar")

Sub-millisecond pulsar
Examples of tests of general relativity with pulsars:

Decrease of orbital period due to gravitational wave emission

Gravitational red-shift

Precession of periastron

Gravitational waves
The Hulse-Taylor Pulsar (the first binary pulsar)

Using the Arecibo 305m antenna, Hulse and Taylor detected pulsed radio emissions and thus identified the source as a pulsar, a rapidly rotating, highly magnetized neutron star. The neutron star rotates on its axis 17 times per second; thus the pulse period is 59 milliseconds.

After timing the radio pulses for some time, Hulse and Taylor noticed that there was a systematic variation in the arrival time of the pulses. Sometimes, the pulses were received a little sooner than expected; sometimes, later than expected. These variations changed in a smooth and repetitive manner, with a period of 7.75 hours. They realized that such behavior is predicted if the pulsar were in a binary orbit with another star.
Example #1: PSR B1913+16

PSR B1913+16

1.9 Mill: km

unseen

$M_c = 1.39 \, M_\odot$

$P_b = 7.8 \, h$

$P = 59 \, ms$

$M_p = 1.44 \, M_\odot$

e = 0.617

Discovered by Hulse & Taylor in 1974
1950 (age 61)  
American  
Institutions  
UT Dallas  
Princeton Plasma Physics Laboratory  
NRAO

1941 (age 70)  
American  
Institutions  
Princeton University  
University of Massachusetts  
Five College Radio Astronomy Observatory

Nobel Prize  1993  

Nobel Prize  1993
• General relativity predicts system will lose energy through gravitational radiation, steadily decreasing the orbital period
• Pulses provide extremely accurate clock: their timing allows, for example, monitoring of the arrival of the pulsar at periastron every orbital period
The pulse repetition frequency, that is, the number of pulses received each second, can be used to infer the radial velocity of the pulsar as it moves through its orbit.

When the pulsar is moving towards us and is close to its periastron, the pulses should come closer together; therefore, more will be received per second and the pulse repetition rate will be highest. When it is moving away from us near its apastron, the pulses should be more spread out and fewer should be detected per second.

At periastron – gravitational field is strongest: time dilatation

precession of periastron
The Hulse-Taylor Pulsar (Weisberg and Taylor 2003)

- GR and observation in extremely close agreement!
- Orbital period decreasing by about $7.6 \times 10^{-6}$ s/y
- Merger in $\approx 300$ million years
- Emission of grav. waves $7.35 \times 10^{24}$ watts

<table>
<thead>
<tr>
<th>Fitted Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_p \sin i$ (s)</td>
<td>2.341774</td>
<td>0.000001</td>
</tr>
<tr>
<td>$e$</td>
<td>0.6171338</td>
<td>0.0000004</td>
</tr>
<tr>
<td>$T_0$ (MJD)</td>
<td>46443.99588317</td>
<td>0.00000003</td>
</tr>
<tr>
<td>$P_b$ (d)</td>
<td>0.322997462727</td>
<td>0.000000000005</td>
</tr>
<tr>
<td>$\omega_0$ (deg)</td>
<td>226.57518</td>
<td>0.00004</td>
</tr>
<tr>
<td>$\langle \dot{\omega} \rangle$ (deg/yr)</td>
<td>4.226607</td>
<td>0.000007</td>
</tr>
<tr>
<td>$\gamma$ (s)</td>
<td>0.004294</td>
<td>0.000001</td>
</tr>
<tr>
<td>$P_b$ ($10^{-12}$ s/s)</td>
<td>-2.4211</td>
<td>0.0014</td>
</tr>
</tbody>
</table>
Possible sources of Gravitational Waves:

Examples

Compact binary inspiral: “chirps”

Orbital decay of the Hulse-Taylor binary neutron star system (Nobel prize in 1993) is the best evidence so far.

Elliptically deformed pulsars: “periodic”

Supernovae / GRBs: “bursts”

Non-radial oscillations of neutron stars

Latest relativistic core-collapse simulations show a complicated signal with a large number of frequency peaks. Typical strength is $10^{-22}$ at 10 kpc.
PROTO-NEUTRON STARS:

Hot, fast rotating, highly magnetized

Initial conditions:

Gravitational energy: $3 \times 10^{53}$ ergs of gravitational energy

Density $2 \times 6 \times 10^{14}$ g/cm$^3$

Temperature $5 - 40$ MeV

emits neutrinos of all flavors: $t < 1$ s after bounce - supernova explosion mechanism and in-falling material

$t > 1$ s PNS EoS, neutrino opacities etc $10^5 - 10^6$ years

At later stages photon emission takes over – from the surface
Before collapse: Fraction of protons $\sim y_p \sim 0.4$

\[ p + e^- \rightarrow n + \nu_e. \]

Electron capture inhibited – core becomes opaque to neutrinos

After collapse: Neutrinos free to escape – neutronisation first $y_p \sim 0.1$
Later development of beta-equilibrium

\[ p + e^- \rightarrow n + \nu_e. \]

\[ n \rightarrow p + e^- + \bar{\nu}_e. \]

Both processes lead to generation of neutrinos which escape from the star continues energy loss.
George Gamov
1904 – 1968
Russian/American

Mario Schönberg
1914 – 1990
Brazilien
Gamow and Schoenberg, Phys. Rev. 59, 539, 1941

Cooling on new-born proto-neutron stars by neutrino emission

As Gamow (1970) recounted, “We called it the Urca Process, partially to commemorate the casino in which we first met, and partially because the Urca Process results in a rapid disappearance of thermal energy from the interior of a star, similar to the rapid disappearance of money from the pockets of the gamblers on [sic] the Casino da Urca.” In case Physical Review asked for an explanation of the origin of the name, the authors had an alternative version of its derivation available—an abbreviation of “unrecordable cooling agent”—but they were never asked. This may, however, account for the word being spelled “URCA” in some places, presumably because it is thought to be an acronym.
Urca

casino

~1940

Rio de Janeiro
Urca process – (originally though to take place in red giants to decrease pressure and contribute to their collapse).

**Direct Urca process** in n.p.e matter

\[ n \rightarrow p + e^- + \bar{\nu}_e, \]

\[ p + e^- \rightarrow n + \nu_e. \]

Conservation of energy and angular momentum in degenerate matter requires (momenta are close those on Fermi surface)

\[ \mathbf{p}_n = \mathbf{p}_p + \mathbf{p}_e + \mathbf{p}_\nu. \]

\[ |p_{FP} - p_{Fe}| \leq p_{Fn} \leq p_{FP} + p_{Fe}. \]

\[ n_i = p_{Fi}^3 / 3\pi^2\hbar^3, \]

\[ n_p/n_b \geq x_{crit} = 1/9 = 11.1\%. \]
Modified Urca process:

Chiu and Salpeter, PRL 12, 413 (1964)

\[ n + n \rightarrow n + p + e^- + \bar{\nu}_e , \]

\[ n + p + e^- \rightarrow n + n + \nu_e . \]

Significant difference in neutrino emissivity – cooling efficiency characteristic time

\[ \tau = -T/\dot{T} = c_v T/\dot{E}. \]

\[ \tau_{\text{Urca}} \sim \frac{1 \text{ min}}{T_9^4}, \]

\[ \tau_{\text{mod Urca}} \sim \frac{1 \text{ yr}}{T_9^6}. \]

Pethick, RMF 64, 133 (1992)

\[ T_9 = 10^9 \text{ K} \]
Exotic Urca cooling:

I. **Pion condensate** - isospin dependent potential - nucleon excitations f - superposition of protons and neutrons

\[ f \rightarrow f + e^- + \bar{\nu}_e \]

\[ f + e^- \rightarrow f + \nu_e \]

~10 x less efficient than direct Urca

II. **Kaon condensate**: f = coherent superposition of neutron + Σ⁻ and proton + Σ₀+Λ

~1000 x less efficient than direct Urca

III. Free quarks: (e.g.)

\[ d \rightarrow u + e^- + \bar{\nu}_e \]

\[ u + e^- \rightarrow d + \nu_e \]

rate uncertain – but smaller than direct Urca
Rapid cooling by hyperons and Δ isobars

$$\Lambda \rightarrow p + e^- + \bar{\nu}_e ,$$
$$\Sigma^- \rightarrow n + e^- + \bar{\nu}_e ,$$
$$\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu}_e ,$$
$$\Delta^- \rightarrow n + e^- + \bar{\nu}_e .$$

$$p_{F\Lambda} \geq |p_{Fp} - p_{Fe}|$$

charge neutrality

and

$$p_{F\Sigma^-} \geq |p_{Fn} - p_{Fe}| .$$

No change of strangeness

These processes can produce fast cooling in cases when nucleon direct Urca is not allowed, in particular, trace amount of Λ would be very efficient.
Overview of neutrino emitting processes relevant for neutron star cooling [1]

<table>
<thead>
<tr>
<th>Name</th>
<th>Processes</th>
<th>Emissivity</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified Urca</td>
<td>$n + n \rightarrow n + p + e^- + \bar{\nu}_e$</td>
<td>$\sim 10^{20} T_9^8$</td>
<td>slow</td>
</tr>
<tr>
<td></td>
<td>$n + p + e^- \rightarrow n + n + \nu_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Urca</td>
<td>$n \rightarrow p + e^- + \bar{\nu}_e$</td>
<td>$\sim 10^{27} T_9^6$</td>
<td>fast</td>
</tr>
<tr>
<td></td>
<td>$p + e^- \rightarrow n + \nu_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quark modified Urca</td>
<td>$d + u + e^- \rightarrow d + d + \nu_e$</td>
<td>$\sim 10^{20} T_9^8$</td>
<td>slow</td>
</tr>
<tr>
<td></td>
<td>$u + u + e^- \rightarrow u + d + \nu_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$d + u + e^- \rightarrow d + s + \nu_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$u + u + e^- \rightarrow u + s + \nu_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quark direct Urca</td>
<td>$d \rightarrow u + e^- + \bar{\nu}_e$</td>
<td>$\sim 10^{26} T_9^6$</td>
<td>fast</td>
</tr>
<tr>
<td></td>
<td>$u + e^- \rightarrow d + \nu_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$s \rightarrow u + e^- + \bar{\nu}_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$u + e^- \rightarrow s + \nu_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^-$ condensate</td>
<td>$n + &lt;\pi^-&gt; \rightarrow n + e^- + \bar{\nu}_e$</td>
<td>$\sim 10^{26} T_9^6$</td>
<td>fast</td>
</tr>
<tr>
<td>$K^-$ condensate</td>
<td>$n + &lt;K^-&gt; \rightarrow n + e^- + \bar{\nu}_e$</td>
<td>$\sim 10^{26} T_9^6$</td>
<td>fast</td>
</tr>
<tr>
<td>Quark bremsstrahlung</td>
<td>$Q_1 + Q_2 \rightarrow Q_1 + Q_2 + \nu + \bar{\nu}$</td>
<td>$\sim 10^{20} T_9^8$</td>
<td>slow</td>
</tr>
<tr>
<td>Core bremsstrahlung</td>
<td>$n + n \rightarrow n + n + \nu_e + \bar{\nu}_e$</td>
<td>$\sim 10^{19} T_9^8$</td>
<td>slow</td>
</tr>
<tr>
<td></td>
<td>$n + p \rightarrow n + p + \nu_e + \bar{\nu}_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$e^- + p \rightarrow e^- + p + \nu_e + \bar{\nu}_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crust bremsstrahlung</td>
<td>$e^- + (A, Z) \rightarrow e^- + (A, Z)$</td>
<td></td>
<td>slow</td>
</tr>
<tr>
<td></td>
<td>$+ \nu_e + \bar{\nu}_e$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EVIDENCE FOR URCA PROCESS

A Type II supernova in the Large Magellanic Cloud (LMC) discovered on February 24, 1987. Supernova 1987A was the first naked-eye supernova since 1604 and reached a peak brilliance, on May 20, 1987, of magnitude 2.9.

11 neutrino pulses detected!

Super-Kamiokande
The world's largest underground neutrino observatory; a joint Japanese-American facility, it is located in the Kamioka Mine, about 200 km north of Tokyo. It consists of a tank of ultra-pure water, 40 meters in diameter by 40 meters tall, that is monitored by thousands of sensitive phototubes.

The water-based Kamiokande and IMB instruments detected antineutrinos of thermal origin, while the gallium-71-based Baksan instrument detected neutrinos (lepton number = 1) of either thermal or electron-capture origin.
“Neutron” Star Cooling

Courtesy of F. Weber
Models of Neutron Star composition in 2004

Possible building blocks

**Hadrons**

**Baryons**
- $p, n, \Sigma, \Lambda, \Xi, \Delta$

**Leptons**
- $e^-, \mu^-$

**Boson condensates**
- $\pi^-, K^-, H$

**Quarks**

- Spin $= 1/2$

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c$^2$</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.006</td>
<td>$-1/3$</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>$-1/3$</td>
</tr>
<tr>
<td>$t$ top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.3</td>
<td>$-1/3$</td>
</tr>
</tbody>
</table>

Courtesy F. Weber
nucleons + leptons + hyperons
nucleons + leptons + quarks
nucleons + leptons + hyperons + quarks

+ Kaons
+ H-dibaryons (ududs)
+ quark condensates

Finite temperatures (excited state):
Supernova
Proto-neutron star
non-equilibrium state

“Zero” temperatures ground state
Cold old neutron stars
grand beta-equilibrium
charge and baryon number conservation
chemical equilibrium
Development of strangeness in neutron stars

Strangeness is not conserved in neutron stars!

Strong interaction time scale: $\tau \approx 10^{-22} \text{ s}$

Weak interaction time scale: $\tau \approx 10^{-10} \text{ s}$

Proton-neutron star cooling: $\tau \approx 10^{-3} \text{ s} - 10\text{s}$

Examples of chemical equilibrium:

$$N + N \rightarrow N + \Lambda + K$$
$$K^0 \rightarrow 2\gamma,$$
$$K^- \rightarrow \mu^- + \nu,$$
$$\mu^- + K^+ \rightarrow \mu^- + \mu^+ + \nu \rightarrow 2\gamma + \nu.$$

$\mu_{K^0} = 0$, $\mu_{K^-} = \mu_e$, $\mu_{K^+} = -\mu_e$, $\mu_\Lambda = \mu_n$. 

Interaction between hyperons and hyperons and nucleons is the main uncertainty in calculation of hyperon related properties of high density matter.

Experimental data on hypernuclei used for this purpose.

Hypernuclear physics $\rightarrow$ recent NH and HH different from those used in 1980-1990s

$m_{\Lambda}c^2 + U_{\Lambda} = \mu_n$ - strong binding in nuclear matter, lowest threshold density

$m_{\Sigma^-}c^2 + U_{\Sigma^-} = \mu_n - \mu_e$ - unlikely, no binding but repulsion in nuclear matter

$m_{\Xi^-}c^2 + U_{\Xi^-} = \mu_n - \mu_e$ - less binding and higher threshold than for $\Lambda$

$m_{\Xi^0}c^2 + U_{\Xi^0} = \mu_n$ - higher density threshold than for $\Xi^-$

Current status? Old claim Nuclear Physics A639 (1998) 103c-110c of observation of a bound state of $^4\Sigma$He – confirmed?
True ground state of matter?


Courtesy F. Weber
Color superconductivity (boson condensates)

If quark matter exists, it should be color superconducting

strong interaction amongst quarks – very attractive in some channels

Cooper pairs created – the condensate is breaking color symmetry

BUT:

Matter must be: 
(i) neutral with respect to electric and color charge
(ii) in chemical equilibrium with respect to weak interactions changing one flavor to another

IF the mass of strange quark is heavy enough – 2SC two flavor u and d pairs

Other possible condensation patterns are CFL-K0, CFL-K+, and CFL-π0, gCFL (a gapless CFL phase)1SC (single-flavor pairing) CSL (a color–spin locked phase) and the LOFF (crystalline pairing) phase, depending on: 
$m_s$, chemical potential $\mu$, and the electric charge density
Color-flavor locking (CFL): the quarks form Cooper pairs whose color properties are correlated with their flavor properties in a symmetric pattern.

According to the standard model, the color-flavor locked phase is **THE HIGHEST DENSITY PHASE OF THREE COLOR MATTER**

For e.g. up and down quark must have colors red and green and so on.

The CFL phase has several remarkable properties.

- It breaks chiral symmetry
- It is a superfluid.
- It is an electromagnetic insulator, in which there is a "rotated" photon, containing a small admixture of one of the gluons.
- It has the same symmetries as sufficiently dense hyperonic matter.

There are several variants of the CFL phase, representing distortions of the pairing structure in response to external stresses such as a difference between the mass of the strange quark and the mass of the up and down quarks.
Fig. 7. The conjectured phase diagram for QCD [33]. For small $m_s^2/\Delta$ there is a direct transition from nuclear matter to CFL color superconducting quark matter. For large $m_s^2/\Delta$ there is an intermediate phase where condensation patterns such as the CFL-$K^0$, CFL-$K^+$, CFL-$\pi^0$, gCFL, 2SC, 1SC, CSL, and LOFF phases (see the text) may exist. Figure reprinted with permission from M. Alford, J. Phys. G 30 (2004) S441.

M. Alford et al., Rev. Mod. Phys. 80, 1455
Phases in Quark Matter (Rüster et al. (2005))

- first order phase transition based on symmetry arguments!
- phases of color superconducting quark matter in $\beta$ equilibrium:
  - normal (unpaired) quark matter (NQ)
  - two-flavor color superconducting phase (2SC), gapless 2SC phase
  - color-flavor locked phase (CFL), gapless CFL phase, metallic CFL phase
  - (Alford, Rajagopal, Wilczek, Reddy, Buballa, Blaschke, Shovkovy, Drago, Rüster, Rischke, Aguilera, Banik, Bandyopadhyay, Pagliara, ...)

Courtesy of J. Shaeffner-Bielich
H-dibaryon, a doubly strange six-quark composite with spin and isospin zero, baryon number two and strangeness -2 may appear in the centre of a neutron star.

Λ’s could combine to form H-dibaryons, which could lead to the formation of H-dibaryon matter at densities somewhere above \( \sim 3 \) nuclear saturation density.

H-dibaryon matter could thus exist in the cores of either moderately dense neutron stars (1.4 solar mass) or in stars heavier than 1.6 solar masses in dependence on the medium optical potential (positive or negative).

They may trigger the conversion of neutron stars into hypothetical strange stars.

P. E. Shanahan, A.W. Thomas, and R. D. Young, PRL 107, 092004 (2011)

H dibaryon is likely to be unbound by 13 ±14 MeV at the physical point.
Superfluidity

Since mature neutron stars are cold ($10^8 \text{K} \ll T_{\text{Fermi}}=10^{12} \text{K}$) they should be either solid or superfluid!

Theory:

Since late 1950’s, nuclear physics calculations indicate neutron and proton “BCS-like” pairing gap energies.

Exotica:

Deep core may contain superfluid hyperons and/or colour superconducting deconfined quarks.

Nils Andersson
Nordita March 2008
Neutron star matter under certain conditions may become a mix between superconductive (charged) superfluid (neutral) condensates, interacting via density and gradient interactions. These interaction may lead to instabilities in neutron stars leading to phase transitions and possible emission of gravitational waves. Complicated theoretical problem.
• All pulsars slow down electromagnetically \((10^{-20} < dP/dt < 10^{-13})\), but some spin up discontinuously sometimes: glitches

• High-density, degenerate neutrons in the inner and outer cores, superfluidity hypothesized
The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature.

**THIS IS THE FIRST DIRECT EVIDENCE THAT SUPERFLUIDITY AND SUPERCONDUCTIVITY OCCUR AT SUPRANUCLEAR DENSITIES WITHIN NEUTRON STARS.**

Our prediction that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star.

This mechanism would only work if the neutron star has a low mass with low central density and thus it is likely that nucleons keep their identity in the centre of the star.

Current estimates of the mass – $1.25 \, M_{\odot}$ (3 σ)
Wide range of theories –

BUT

what we really know about neutron stars from observation?

ARE OUR DATA SENSITIVE ENOUGH TO DISTINGUISH BETWEEN THEORIES?
Lattimer and Prakash, 2010
# Observational Data: Radii

## The Best Measured Neutron Star Radii

<table>
<thead>
<tr>
<th>Name</th>
<th>$R_{\infty}$</th>
<th>$D$</th>
<th>$kT_{\text{eff,}\infty}$</th>
<th>$N_{\text{H}}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(km/D)</td>
<td>(kpc)</td>
<td>(eV)</td>
<td>($10^{20}$ cm$^{-2}$)</td>
<td></td>
</tr>
<tr>
<td>omega Cen</td>
<td>13.5 ± 2.1</td>
<td>5.36</td>
<td>66.2 ± 0.5</td>
<td>(9)</td>
<td>Rutledge et al (2002)</td>
</tr>
<tr>
<td>(Chandra)</td>
<td></td>
<td>±6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>omega Cen**</td>
<td>13.6 ± 0.3</td>
<td>5.36</td>
<td>67 ± 2</td>
<td>9 ± 2.5</td>
<td>Gendre et al (2002)</td>
</tr>
<tr>
<td>**(XMM)</td>
<td></td>
<td>±6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M13**</td>
<td>12.6 ± 0.4</td>
<td>7.80</td>
<td>76 ± 3</td>
<td>(1.1)</td>
<td>Gendre et al (2002)</td>
</tr>
<tr>
<td>**(XMM)</td>
<td></td>
<td>±2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47 Tuc X7</td>
<td>34.13 ± 22</td>
<td>5.13</td>
<td>84.13 ± 12</td>
<td>0.13 ± 0.06</td>
<td>Heinke et al (2006)</td>
</tr>
<tr>
<td>(Chandra)</td>
<td></td>
<td>±4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M28**</td>
<td>14.5 ± 3.8</td>
<td>5.5</td>
<td>90.10 ± 30</td>
<td>26 ± 4</td>
<td>Becker et al (2003)</td>
</tr>
<tr>
<td>**(Chandra)</td>
<td></td>
<td>±10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M30</td>
<td>16.9 ± 4.3</td>
<td>--</td>
<td>94.12 ± 17</td>
<td>2.9 ± 1.2</td>
<td>Lugger et al (2006)</td>
</tr>
<tr>
<td>(Chandra)</td>
<td></td>
<td>±5.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 2808</td>
<td>??</td>
<td>9.6</td>
<td>103.33 ± 18</td>
<td>18.11 ± 7</td>
<td>Webb et al (2007)</td>
</tr>
<tr>
<td>(XMM)</td>
<td></td>
<td>(?)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$R_{\infty} < 5\%$

### Caveats:
- All IIdd by X-ray spectrum (47 Tuc, Omega Cen now have optical counterparts)
- Calibration uncertainties

**Distances:**

---

Courtesy of B. Rutledge, NFQCD 2010 meeting
Simultaneous determination of mass and radius low-mass X-ray binary KS 1731−260

Ozel, Gould, and Guver,

**X-ray burst spectroscopy:**
well-constrained values for the apparent angular area and the Eddington flux of the source

distance estimate based on the density of stars in the line of sight.

$R < 12.5 \text{ km}$, while confining its mass to $M < 2M$. 

---

![Graph showing mass-radius relationship for various models.](image-url)
High resolution X-ray spectroscopy of the photospheric emission of a hot neutron star is sensitive to the fundamental stellar parameters, through the effects of pressure broadening, relativistic kinematics (rotation, Doppler shift, time dilation, beaming), and general relativity (light bending around the star, gravitational redshift, frame dragging) on atomic absorption lines (Özel and Psaltis 2003; Bhattacharyya, Miller, and Lamb 2006).
Radar signals passing near a massive object take slightly longer to travel to a target and longer to return than it would if the mass of the object were not present.
Observational Constraints for Neutron Stars

- Maximum and Minimum Masses (binary pulsars)
- Minimum Rotational Period*
- Radiation Radius or Redshift*
- Neutron Star Thermal Evolution (URCA or not)*
- Crustal Cooling Timescale from X-ray Transients*
- X-ray Bursts from Accreting Neutron Stars*
- Seismology from Giant Flares in SGR’s*
- Moment of Inertia*
- Proto-Neutron Star Neutrinos (Binding Energy, Opacities, Radii)*
- Pulse Shape Modulation*
- Gravitational Radiation* (Masses, Radii from tidal Love numbers)

* Significant dependence on symmetry energy
Current observations are not sufficient – and is unlikely to be soon.

Would a closer look at existing theories help to get stronger constraints?
**Ideal gas law:**

**Variables: pressure, density and temperature**

\[ pV = NkT \]

- \( p \) number of molecules, \( k \) Boltzmann constant
- from kinetic theory
- average pressure for an ideal gas

\[ p = \frac{1}{3} \frac{N}{V} m\bar{v}^2 \]

- average translational kinetic energy

\[ \frac{1}{2} m\bar{v}^2 = \frac{3}{2} kT \]

\[ p = \frac{NkT}{V} = \varepsilon \quad \text{total energy density of the gas} \]

at temperature \( T \) and density \( \rho = \frac{N}{V} \)

\[ p = \varepsilon(\rho, T) \quad \text{EQUATION OF STATE} \]

Ludwig Boltzmann
total energy density

\[ \varepsilon = \varepsilon_B(\rho_p, \rho_n, ...) + \varepsilon_\ell(\rho_e, \rho_\mu) \]

\[ \varepsilon_B = \sum_f (E_f + M_f)\rho_f \]

\( \varepsilon_f \) - energy per baryon, \( \rho_f \) - number density of f-baryon species

\[ P_B = \rho_B^2 \frac{\partial}{\partial \rho_B} \left( \frac{\varepsilon_B}{\rho_B} \right) \]

Baryonic pressure as a function of energy density and number density

Key point:

\( \varepsilon_f \) must be calculated using nuclear and/or particle models
Relativistic

Non-relativistic

Realistic

Phenomenological

Theories

Potentials

Reid 93
Paris
Bonn A, B, C
CD Bonn
Nijmegen
v14 (+ UVII)
v18 (+UIX)

NR Mean field:
Skyrme, Gogny, SMO

R mean field:
NL1, NL-SH, NL3,..
TM1, GM, GL
KVR, KVOR

QMC model

Other techniques: Quantum Monte Carlo, Chiral effective Field Theory

Potentials

QMC model

Quark matter:
MIT Bag, NJL

Other techniques: Quantum Monte Carlo, Chiral effective Field Theory
Testing of models of EOS:

1. Real systems

2. Hypothetical simplified system – nuclear matter

Infinite medium made of nucleons and leptons with uniform density and no boundary conditions:

Symmetric: \( n_p = n_n = \frac{1}{2} n \) \((\text{SNM})\)

Pure neutron: \( n_p = 0, n_n = n \) \((\text{PNM})\)

Beta-equilibrium: \((\text{BEM})\)

\[ n \leftrightarrow p + e^- \leftrightarrow p + \mu^- \]

Close to star matter and interior of heavy nuclei
Ground state:

Symmetric (SNM) - saturation density $\rho_0$ 0.16 fm$^{-3}$

$n_p = n_n = 1/2$ energy per particle $E/A(\rho_0)$ - 16 MeV

symmetry energy $a_s$

$E/A_{(SNM)} - E/A_{(PNM)}$ 28-32 MeV

Incompressibility $K(\rho_0)$ MeV

Pressure $P(\rho_0)$ 0

Excited states:

Asymmetric matter – n+p+e+\mu (in $\beta$-equilibrium)
density dependence of:

- proton fraction $y_p = \rho_p / \rho$

- symmetry energy $S$ (coefficient $a_s$)

- chemical potentials $\mu_n$, $\mu_p$, $\mu_e$, $\mu_\mu$

Pure neutron (PNM) - does not saturate ($E/A > 0$)
Hydrostatic equilibrium of a spherical object with isotropic mass distribution in general relativity: Tolman-Oppenheimer-Volkoff equations:

\[
\frac{dP}{dr} = - \frac{GM(r)\varepsilon (1 + P / \varepsilon c^2)(1 + 4\pi r^3 P / M(r)c^2)}{r^2 1 - 2GM(r) / rc^2}
\]

\[
M(r) = \int_0^r 4\pi r'^2 \varepsilon(r') dr'
\]

G - gravitational constant
M - gravitational mass,
P - pressure
\varepsilon - total energy density

Input: \( P(\varepsilon) \)
Pressure as a function of total energy density - EQUATION OF STATE
Output: \( M(r) \)
Gravitational mass as a function of the corresponding radius
$P(\varepsilon)$ \quad $M(R)$

**EoS**

- $P$ [dyn/cm$^2$]
- $\varepsilon$ [g/cm$^3$]

- Maximum mass
- Unstable models
- Stable models
Non-relativistic ‘realistic’ potential
Av18+ δ ν+UIX*
# parameters: 18+

Density dependent effective Skyrme interaction
#parameters: 13+
over 240 parameter sets

Akmal et al. PRC58,1804 (1998)

Relativistic mean field  
#parameters ~10  
over 30 parameter sets

Relativistic Quark-Meson Coupling model  
# parameters 8

Fatfoyev and Piekarewicz  

Guichon, Stone, Thomas, Matevosyan and Sandulescu  
(NPA 601,349 and  NPA772,1)
Non-relativistic ‘realistic’ potential
Av18+ δν+UIX*
# parameters: 18+

Density dependent effective Skyrme interaction
#parameters: 13+
over 240 parameter sets

Akmal et al. PRC58,1804 (1998)
General beta-equilibrium condition
onset of free quarks?

- Composition of neutron star matter:

  - No hyperons
  - Free hyperons
  - Interacting hyperons ($\Sigma^-$ repulsive, $\Lambda$ attractive)
    YN interaction determines $Y$ onset

Courtesy H.-J. Schultze
Typical results:

- Hyperon onset occurs at $\rho \sim 2 \ldots 3 \rho_0$
- NS structure including hyperons and including quark matter

Courtesy H.-J. Schultze
Latest version of QMC:

FIG. 2. Species fractions \( Y_i = \rho_i / \rho \) for NY\( \kappa_I \). NY\( \kappa_{II} \) differs only in the presence of the \( \Lambda \) which is absent in that case, yet this leads to widely diverging EoS as demonstrated in Figure 1.
Latest version of QMC 2012

Red – nucleons only
Blue Nucleons + hyperons

D. L. Whittenbury, J. D. Carroll,
A. W. Thomas, K. Tsushima, J. R. Stone
third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!

- generates stars more compact than neutron stars!
- possible for any first order phase transition!
The Third Family: Quark Stars, Hyperon Stars ...

- MIT bag model (Glendenning and Kettner, 2000)
- massive quasi-particles of quarks (Schertler, C. Greiner, JSB, Thoma, 2000)
- interacting quarks in pQCD (Fraga, JSB, Pisarski, 2001)
- Kaon condensate (Banik and Bandyopadhyay, 2001)
- Hyperon Matter (JSB, Hanauske, Stöcker, W. Greiner, 2002)
- MIT bag model (Mishustin, Hanauske, Bhattacharyya, Satarov, Stöcker, W. Greiner, 2003)
- color-superconducting quarks (Banik and Bandyopadhyay, 2003)
- MIT bag and rotation (Bhattacharyya, Ghosh, Hanauske, Raha, 2004)
- Kaon condensate, quarks and rotation (Banik, Hanauske, Bandyopadhyay, W. Greiner, 2004)
Quarks Stars vs Neutron stars

Quark stars
$R \leq 10\ km$

"Neutron" stars
$R \geq 10\ km$

Cyg X-2
Vela X-1

PSR $^{1913+16}_{18}$

Strange stars
$B^{1/4} = 160$

with nuclear crust

Neutron gas

Courtesy F. Weber
Mass-radius and maximum density of pure quark stars

- green curves: MIT bag model
- blue curves: perturbative QCD calculations
  (Fraga, JSB, Pisarski 2001)

- case 2: $M_{\text{max}} = 1.05 M_\odot$, $R_{\text{max}} = 5.8 \text{ km}$, $n_{\text{max}} = 15 n_0$
- case 3: $M_{\text{max}} = 2.14 M_\odot$, $R_{\text{max}} = 12 \text{ km}$, $n_{\text{max}} = 5.1 n_0$

- other nonperturbative approaches: Schwinger–Dyson model (Blaschke et al.), massive quasiparticles (Peshier, Kämpfer, Soff), NJL model (Hanauske et al.), HDL (Andersen and Strickland)
Ultracompact Neutron Stars with Hyperons — Hyperon Stars

(Heintzmann, Hillebrandt, El Eid, Hilf 1974(!): Hyperon Stars within Pandharipande’s EoS with hyperons)

- new stable solution in the mass–radius diagram!
- neutron star twins:
  \[ M_{\text{hyp}} \sim M_n \text{ but } R_{\text{hyp}} < R_n \]
- selfbound compact stars for strong attraction with \( R = 7 - 8 \text{ km} \)

(JSB, Hanauske, Stöcker, Greiner, PRL 89, 171101 (2002))

Courtesy J.Schaeffner-Bielich
Rotating neutron stars could give a clue?

Frequency Dependence of Particle Thresholds in Rotating Neutron Stars

\[ \varepsilon_0 = 140 \text{ MeV/fm}^3 \]
(nuclear matter density)


Courtesy F. Weber
The big picture

- **Temperature T [MeV]**
  - Early universe
  - RHIC, LHC
  - FAIR SIS 300
  - Nuclei

- **Net Baryon Density**
- **Quarks and Gluons**
- **Critical point?**
- **Deconfinement and chiral transition**
- **Neutron stars**
- **Color Superconductor?**
Conclusions

• Neutron star theory draws on every area of fundamental physics, often in their extreme

• Observations of neutron stars provide a way to test our physical theories in exotic circumstances not replicable in the laboratory

• As we develop more numerous and sophisticated models, so we need more accurate and innovative observations to test them
Examples of possible EoS of neutron stars