Incontro Nazionale di Fisica Nucleare 2012

Padova, 24 – 26 Marzo 2014

Stelle di Neutroni

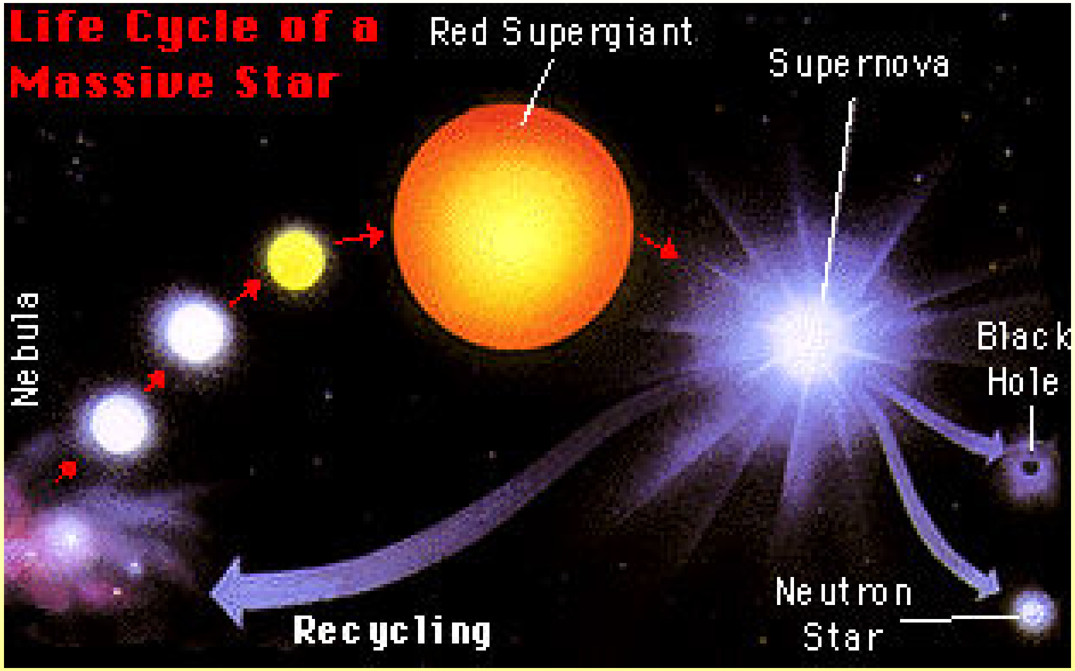
laboratori cosmici per la materia in condizioni estreme

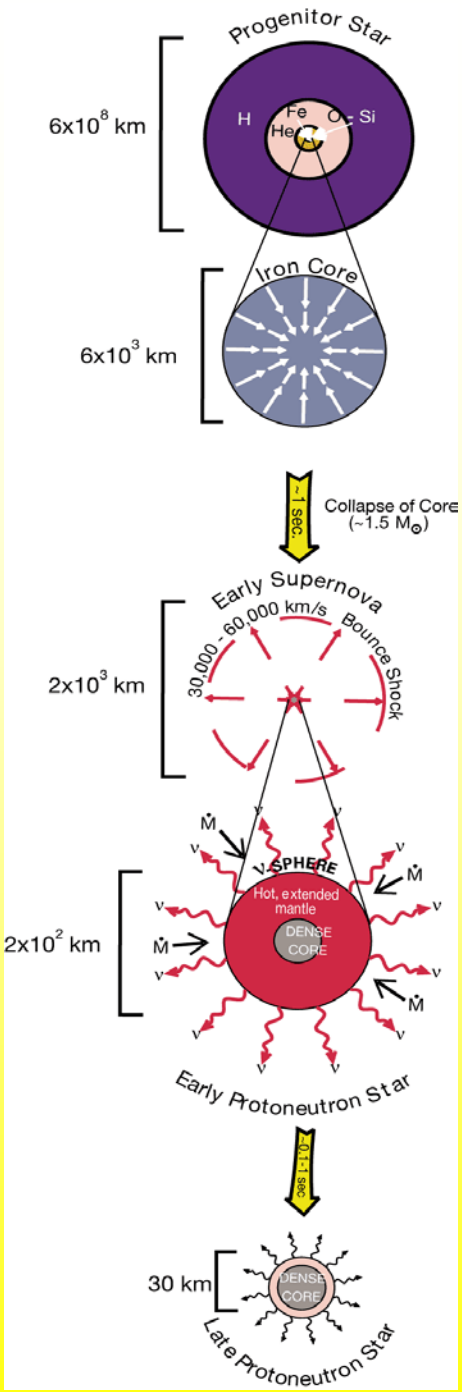
Ignazio Bombaci

Dipartimento di Fisica "E. Fermi", Università di Pisa

INFN Sezione di Pisa

The birth of a Neutron Star





Neutron stars are the compact remnants of type II Supernova explosions, which occur at the end of the evolution of massive stars ($8 < M/M_\odot < 25$).

Composition and Structure of Protoneutron Stars,
M. Prakash, I. Bombaci, M. Prakash, P.J. Ellis, J.M. Lattimer, R. Knorren
Physics Reports 280 (1997) 1.

Neutron Stars: bulk properties

Mass	$M \sim 1.5\, M_\odot$
Radius	$R \sim 10$ km
Centr. Density	$\rho_c = (4 - 10)\, \rho_0$
Compactness	$R/R_g \sim 2 - 4$
Baryon number	$A \sim 10^{57}$
Binding energy	$B \sim 10^{53}$ erg

$B/A \sim 100$ MeV **$B/(Mc^2) \sim 10\%$**

Stellar structure: General Relativity

Giant "atomic nucleus" bound by gravity

$M_\odot = 1.989 \times 10^{33}$ g $R_\odot = 6.96 \times 10^5$ km $R_{g\odot} = 2.95$ km

$\rho_0 = 2.8 \times 10^{14}$ g/cm^3 (**nuclear saturation density**)

$R_g \equiv 2GM/c^2$ (**Schwarzschild radius**)

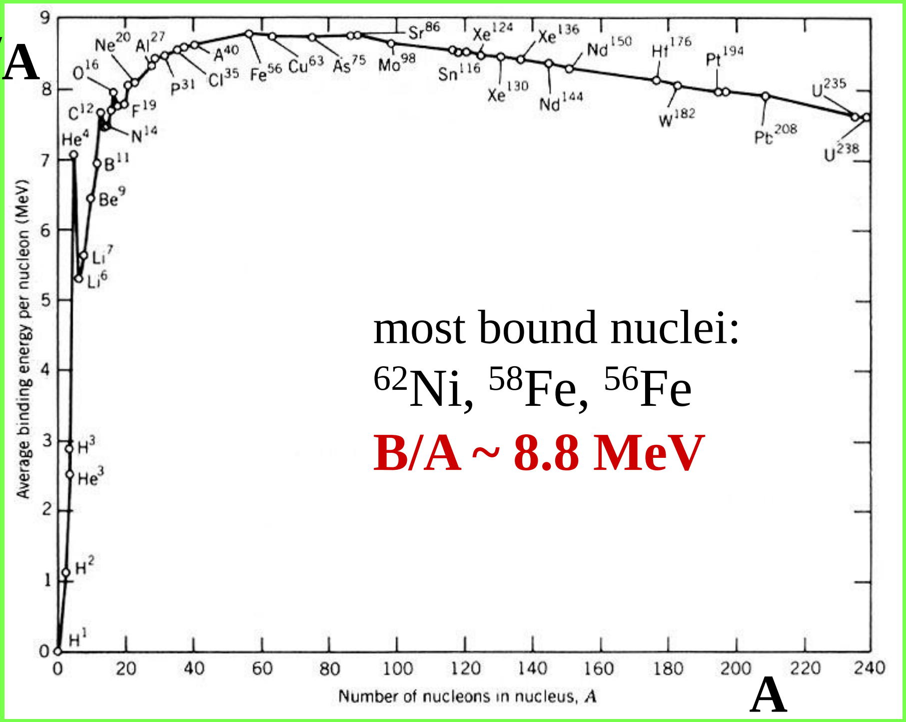
Atomic Nuclei: bulk properties

Mass number $A = 1 - 238$ **(natural stable isotopes)**

Radius $R = r_0 A^{1/3} \sim (2 - 10)$ **fm**

Density $\rho \sim \rho_0 = 2.8 \times 10^{14}$ **g/cm^3**

B/A



most bound nuclei:
^{62}Ni, ^{58}Fe, ^{56}Fe
B/A ~ 8.8 MeV

A

$B/(Mc^2) \sim (0.1–1)\%$

bound by nuclear interactions

The Neutron Star idea (Baade and Zwicky, 1934)

"With all reserve we advance the view that supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of extremely closely packed neutrons."

1st calculation of Neutron Star properties

(Oppenheimer and Volkov, 1939)

Discovery of Pulsars (J. Bell, A. Hewish et al. 1967)

Interpretation of Pulsars as rotating magnetized Neutron Strar

(Pacini, 1967, Nature 216), (Gold, 1968, Nature 218)

Pulsars (PSRs) **are astrophysical sources which emit** **periodic pulses of electromagnetic radiation.**

Number of known pulsars:

2311	**Radio PSRs**	
60	**X-ray PSRs**	(radio-quiet)
147	**γ-ray PSR**	(most recent. discov. by **LAT/Fermi)**

(March, 22nd, 2014)

Neutron Stars as sources of gravitational radiation

(1) Rotating NS (triaxial ellipsoid: $a \neq b \neq c$, $I_1 \neq I_2 \neq I_3$)

Crab Nebula: $L_{crab} = 5 \times 10^{38}$ erg/s, Crab PSR: $P = 0.033$ s, $dP/dt = 4.227 \times 10^{-13}$

$$L_{crab} = \left| \dot{E}_{grav} \right| = \frac{32}{5} (2\pi)^6 \frac{G}{c^5} \frac{I_3^2}{P^6} \varepsilon^2 \equiv A \ \varepsilon^2$$

assuming:

$I_3 = 10^{45}$ g cm^2

$A = 8.38 \times 10^{44}$ erg/s

$\varepsilon = 2 (a - b)/(a + b)$

$$\varepsilon \sim 7.7 \times 10^{-4}$$

R = 10 km

$$a - b \cong \varepsilon R \cong 7.7 \text{ m}$$

A rotating neutron star with a 8 meter high mountain at the equator could power the Crab nebula via gravitational wave emission

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A rotating neutron star with a 8 meter high mountain at the equator could powerthe Crab nebula via gravitational wave emission

braking index $n \equiv \Omega \ddot{\Omega} / \dot{\Omega}^2$ $n = 5$ **(Gravit. quadrupole radiation)**

Crab PSR (measured) $n = 2.515 \pm 0.005$ $n = 3$ (magnetic dipole radiation)

Measured upper limits (Virgo - Ligo Coll.: **J. Aasi et al., arXiv:1309.4027 (2013)**)

$\varepsilon_{crab} \leq 10^{-4}$, $R\ \varepsilon_{crab} \leq 1$ m $\left|\dot{E}_{gr}\right|_{crab} \leq 2\% \left|\dot{E}_{rot}\right|_{crab}$

The VIRGO gravitational waves antenna - Cascina (Pisa)

Relativistic equations for stellar structure

Static and sphericaly symmetric self-gravitating mass distribution

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = e^{2\Phi(r)} c^2 dt^2 - e^{2\lambda(r)} dr^2 - r^2 (d\theta^2 + \sin^2\theta \, d\varphi^2)$$

$\Phi = \Phi(r)$, $\lambda = \lambda(r)$ metric functions

$$e^{\lambda(r)} \equiv \left[1 - \frac{2G\, m(r)}{c^2 r}\right]^{-1/2}$$

for the present case the Einstein's field equations take the form called the

Tolman – Oppenheimer – Volkov equations (TOV)

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

$$\frac{dm}{dr} = 4\pi r^2 \rho(r)$$

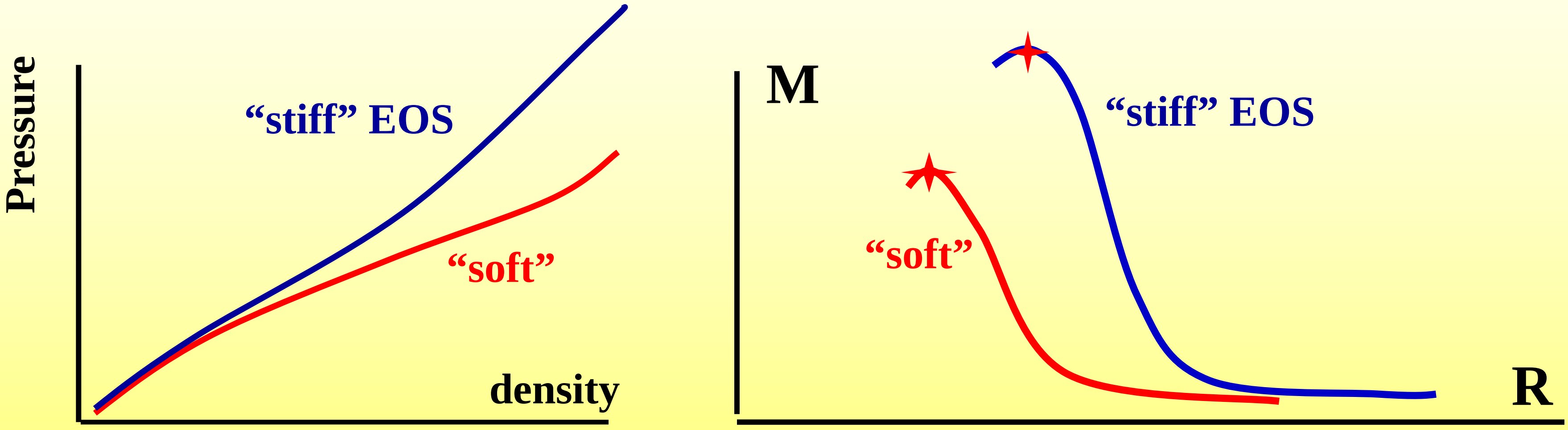
$$\frac{d\Phi}{dr} = -\frac{1}{\rho(r) c^2} \frac{dP}{dr} \left(1 + \frac{P(r)}{\rho(r) c^2}\right)^{-1}$$

One needs the **equation of state (EOS) of dense matter, P = P(ρ),** up to **very high densities**

The Oppenheimer-Volkoff maximum mass

There is a maximum value for the gravitational mass of a Neutron Star that a given EOS can support. This mass is called the Oppenheimer-Volkoff mass

$$M_{max} = (1.4 - 2.5)\, M_{\odot}$$



The OV maximum mass represent the key physical quantity to separate (and distinguish) Neutrons Stars from Black Holes.

$$M_{max}(\text{EOS}) \geq \text{ all measured neutron star masses}$$

Measured Neutron Star masses in Relativistic binary systems

Measuring **post-Keplerian parameters:**

***   very accurate NS mass measurements**

***   model independent measuremets within GR**

- **PSR B1913+16** **NS (radio PSR) + NS ("silent") (Hulse and Taylor 1974)**

P_{PSR} = 59 ms, P_b = 7 h 45 min $\dot{\omega} = 4.22^0 / yr$

$M_p = 1.4408 \pm 0.0003\ M_\odot$ **$M_c = 1.3873 \pm 0.0003\ M_\odot$**

Orbital period decay in agreement with GR predictions over about 40 yr
→ indirect evidence for gravitational waves emission

- **PSR J0737-3039** **NS(PSR) + NS(PSR) (Burgay, et al 2003)**

$M_1 = 1.34\ M_\odot$ **$M_2 = 1.25\ M_\odot$**

Two "heavy" Neutron Star

PSR J1614–2230 $M_{NS} = 1.97 \pm 0.04\ M_\odot$

NS – WD binary system (He WD)

$M_{WD} = 0.5\ M_\odot$ (companion mass)

$P_b = 8.69$ hr (orbital period) $P = 3.15$ ms (PSR spin period)

$i = 89.17° \pm 0.02°$ (inclination angle)

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

PSR J0348+0432 $M_{NS} = 2.01 \pm 0.04\ M_\odot$

NS – WD binary system

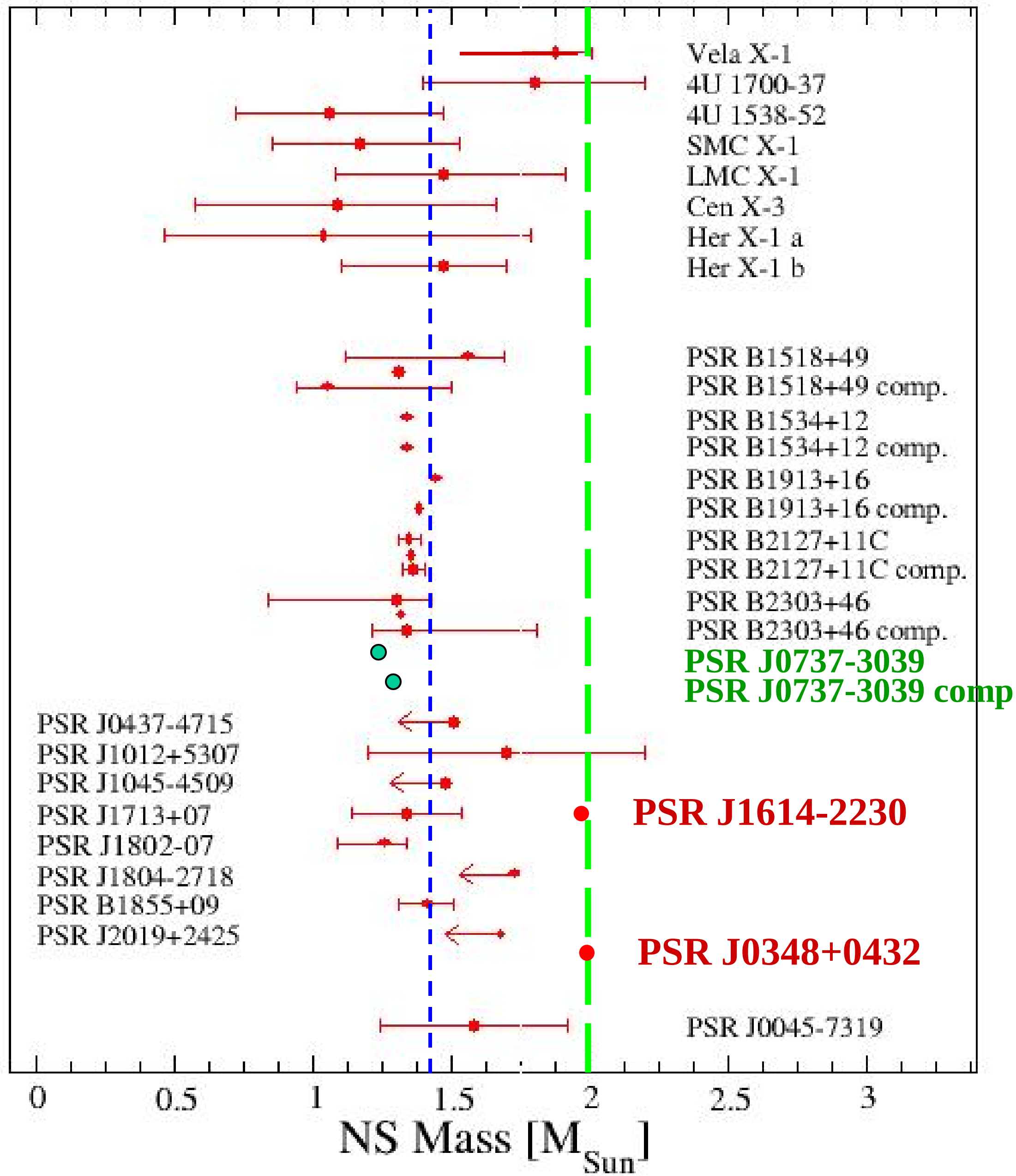
$M_{WD} = 0.172 \pm 0.003\ M_\odot$ (companion mass)

$P_b = 2.46$ hr (orbital period) $P = 39.12$ ms (PSR spin period)

$i = 40.2° \pm 0.6°$ (inclination angle)

Antoniadis et al., Science 340 (2013) 448

Measured Neutron Star Masses



$M_{max} \geq M_{measured}$

$M_{max} \geq 2\, M_{\odot}$

Very stringent constraint on the EOS

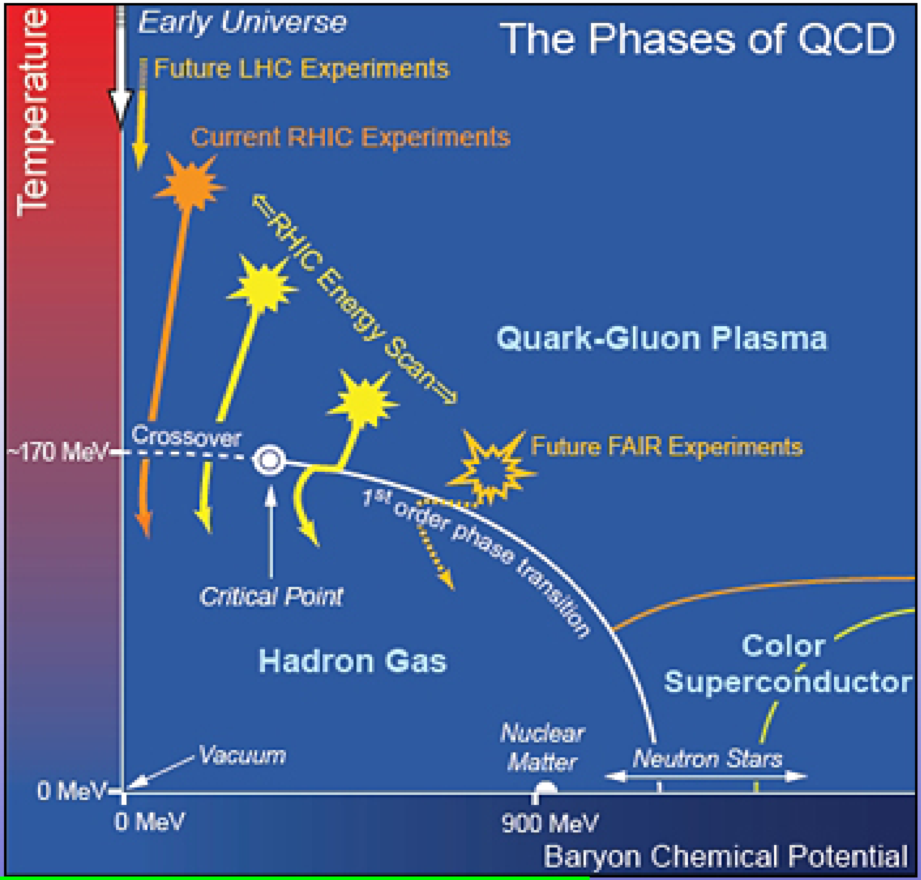
Neutron Stars in the QCD phase diagram

Lattice QCD at μ_b=0 and finite T

- **The transition to Quark Gluon Plasma is a crossover** Aoki et ,al., Nature, 443 (2006) 675
- **Deconfinement transition temperature T_c**

HotQCD Collaboration
T_c= 154 ± 9 MeV
Bazarov et al., Phys.Rev. D85 (2012) 054503

Wuppertal-Budapest Collab.
T_c= 147 ± 5 MeV
Borsanyi et al., J.H.E.P. 09 (2010) 073

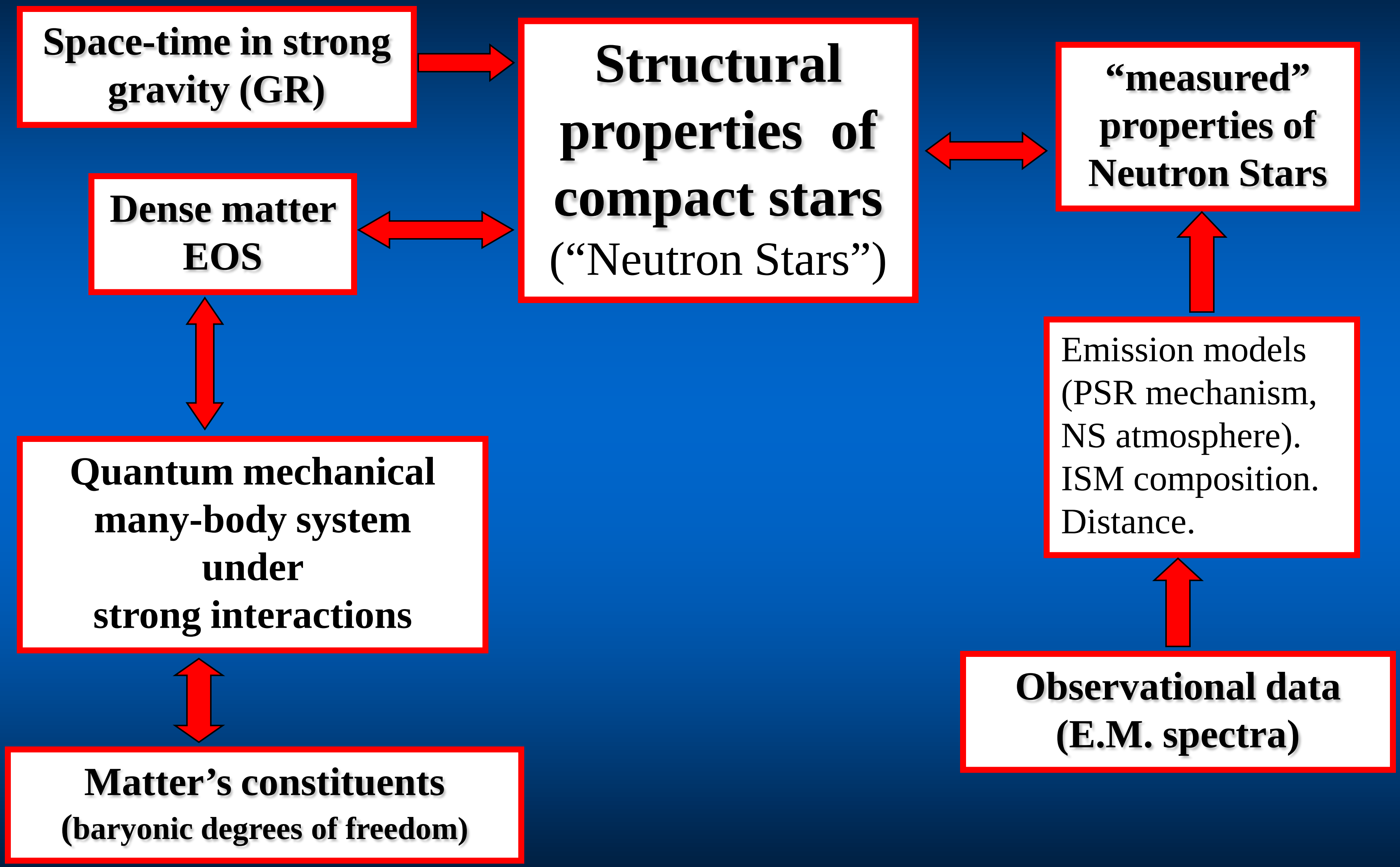


Cristalline Color superconductor

Neutron Stars: high μ_b and low T

Quark deconfinement transition expected of the first order
Z. Fodor, S.D. Katz, Prog. Theor Suppl. 153 (2004) 86

Lattice QCD calculations are presently not possible


Space-time in strong gravity (GR)
Structural properties of compact stars ("Neutron Stars")
"measured" properties of Neutron Stars
Dense matter EOS
Emission models (PSR mechanism, NS atmosphere). ISM composition. Distance.
Quantum mechanical many-body system under strong interactions
Observational data (E.M. spectra)
Matter's constituents (baryonic degrees of freedom)

Neutron star physics in a nutshell

1) Gravity compresses matter at very high density

2) Pauli priciple

Stellar constituents are different species of **identical fermions** (n, p,….,e^-, μ^-)

⟶ antisymmetric wave function for particle exchange ➔ Pauli principle

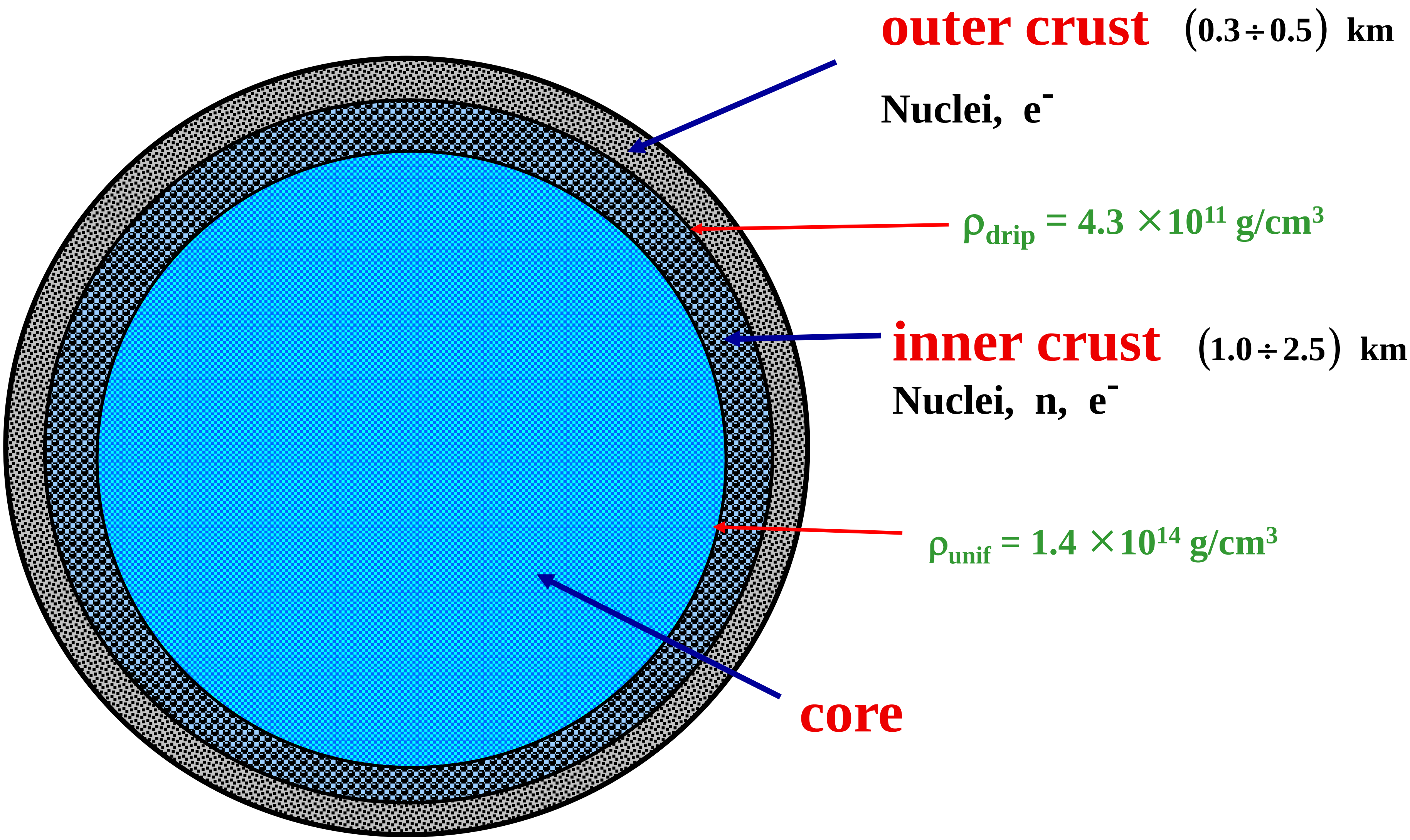
Chemical potentials $\mu_n, \mu_p, \ldots \mu_e$ rapidly increasing functions of density

3) Weak interactions changes the isospin and strangeness content of dense matter to minimize energy

Cold catalyzed matter (Harrison, Wakano, Wheeler, 1958)

The ground state (minimum energy per baryon) of a system of **hadrons** and **leptons** with respect to their mutual **strong** and **weak interactions** at a given total baryon density n and temperature T = 0.

Schematic cross section of a Neutron Star



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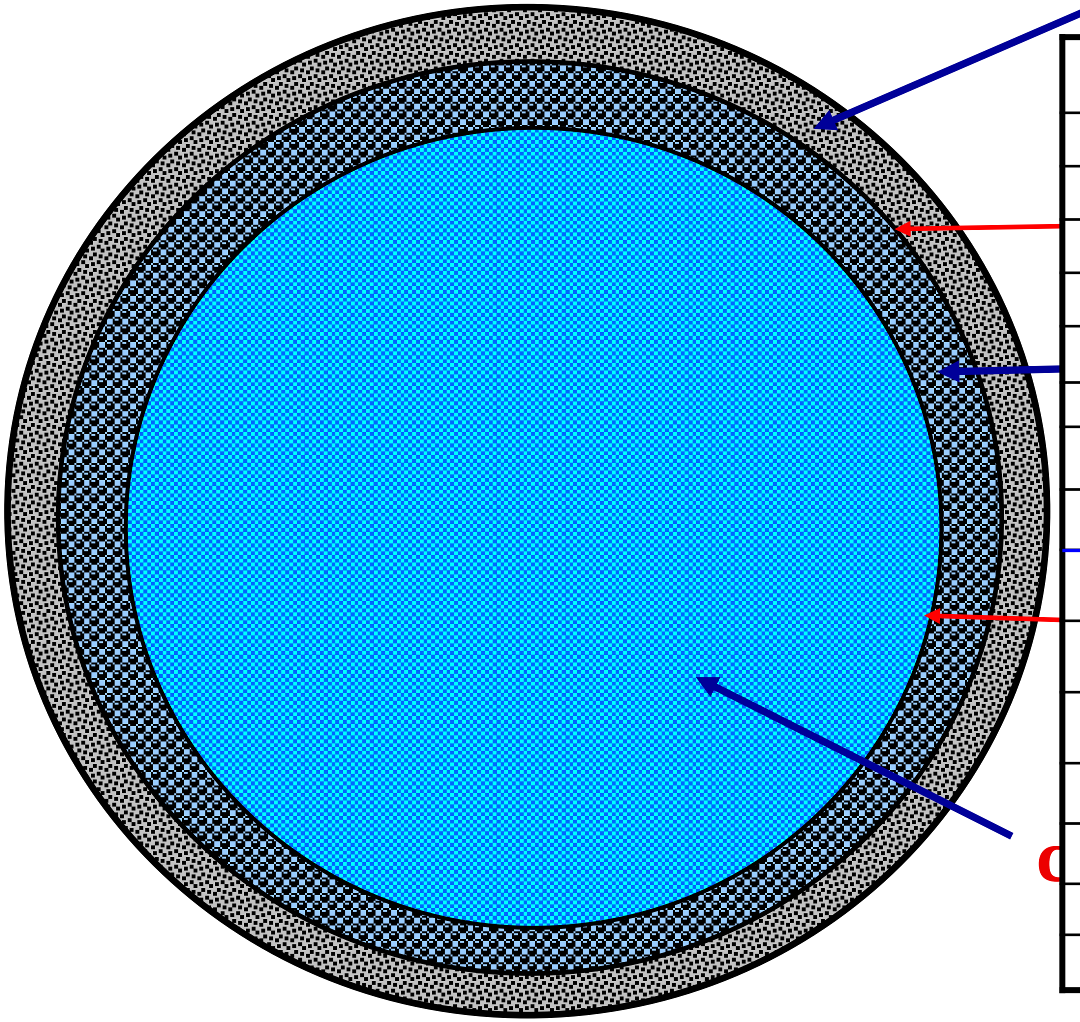

outer crust $(0.3 \div 0.5)$ km

nucleus	Z	N	$\rho_{max}(g/cm^3)$
^{56}Fe	26	30	8.02×10^{6}
^{62}Ni	28	34	2.71×10^{8}
^{64}Ni	28	36	1.33×10^{9}
^{66}Ni	28	38	1.50×10^{9}
^{86}Kr	36	50	3.09×10^{9}
^{84}Se	34	50	1.06×10^{10}
^{82}Ge	32	50	2.79×10^{10}
^{80}Zn	30	50	6.07×10^{10}
^{82}Zn	30	52	8.46×10^{10}
^{128}Pd	46	82	9.67×10^{10}
^{126}Ru	44	82	1.47×10^{11}
^{124}Mo	42	82	2.11×10^{11}
^{122}Zr	40	82	2.89×10^{11}
^{120}Sr	38	82	3.97×10^{11}
^{118}Kr	36	82	4.27×10^{11}

S.B. Rüster, M. Hempel, J. Schaffner-Bielich,
Phys. Rev. C73 (2006) 035804

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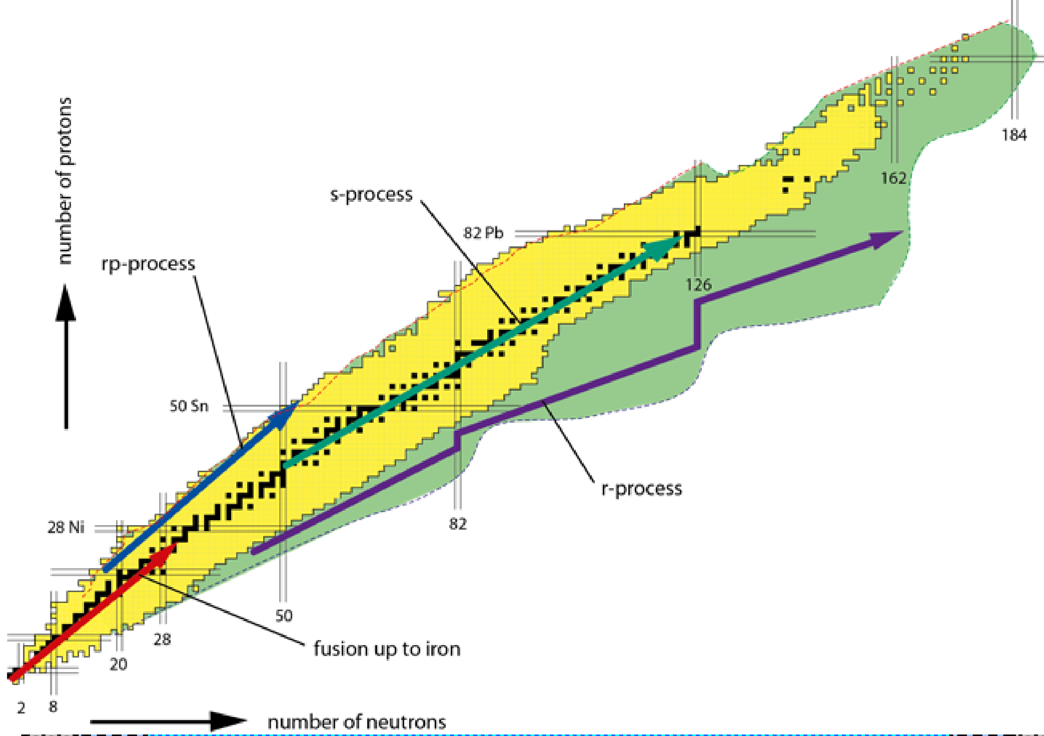

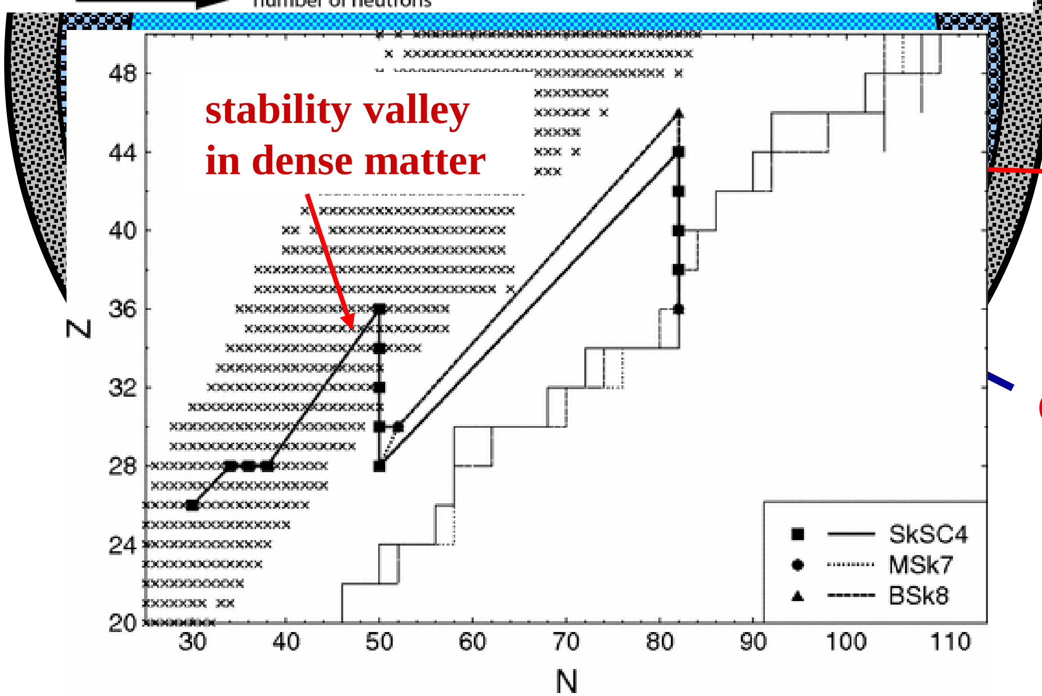

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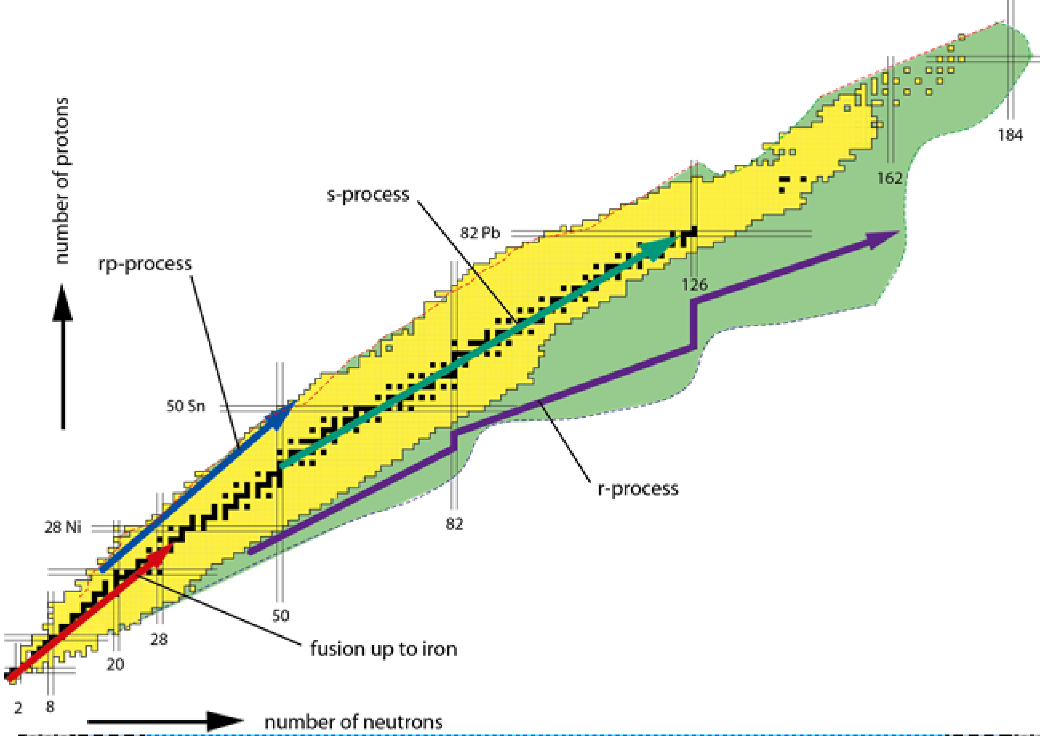
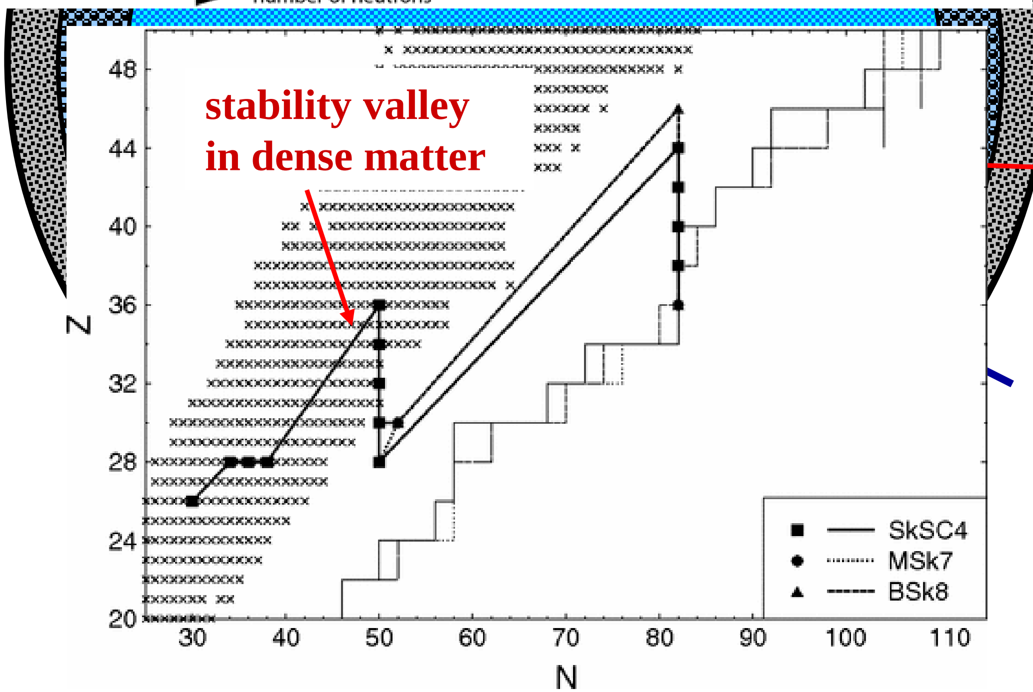




Radioactive Ion Beam Facilities

SPES exotic beams for science

Spiral2

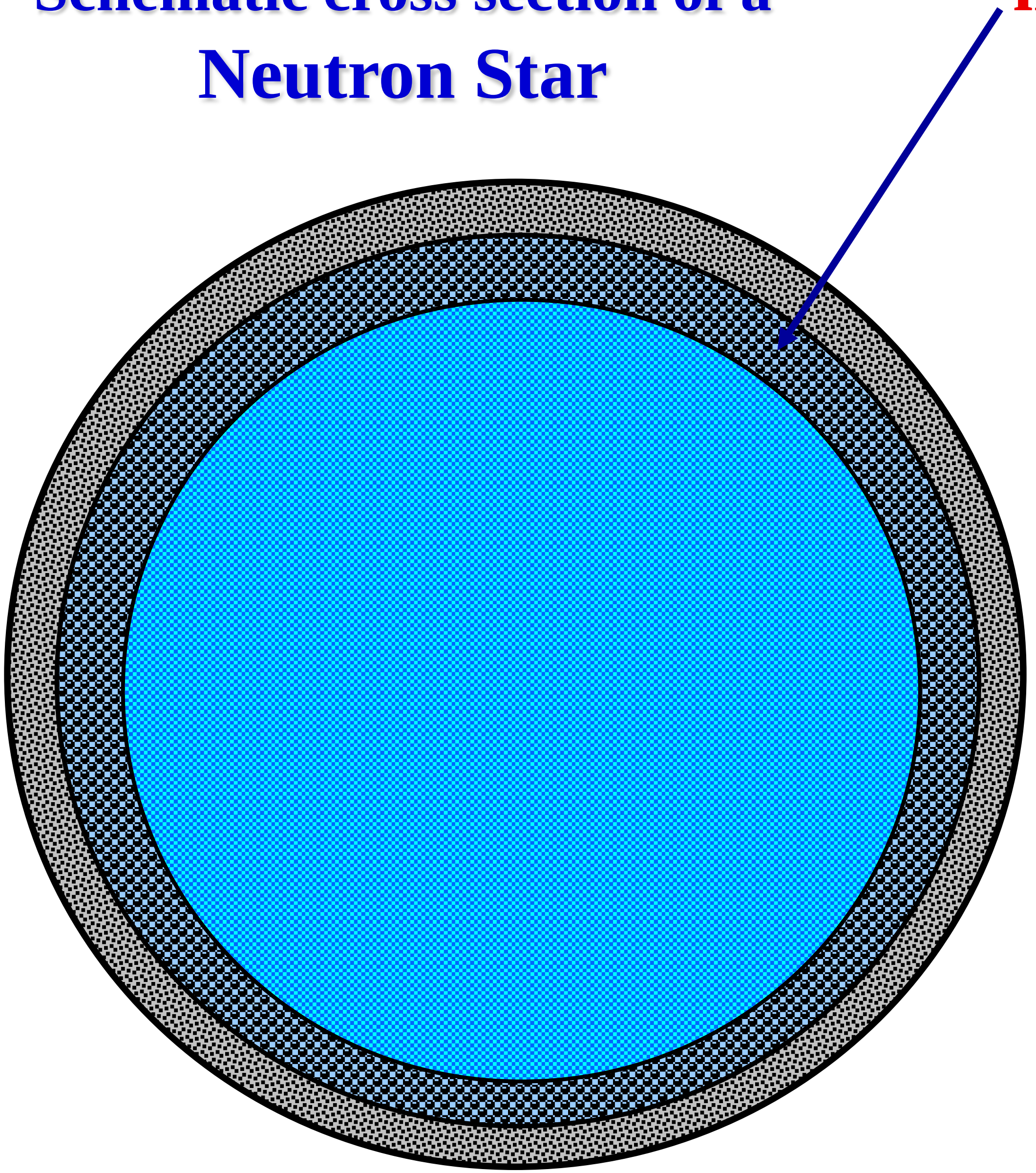
RIBF RIKEN NiSHiNA CENTER
RIKEN Nishina Center for Accelerator-Based Science

FACILITY FOR RARE ISOTOPE BEAMS

FAIR
Facility for Antiproton and Ion Research in Europe GmbH

EURISOL

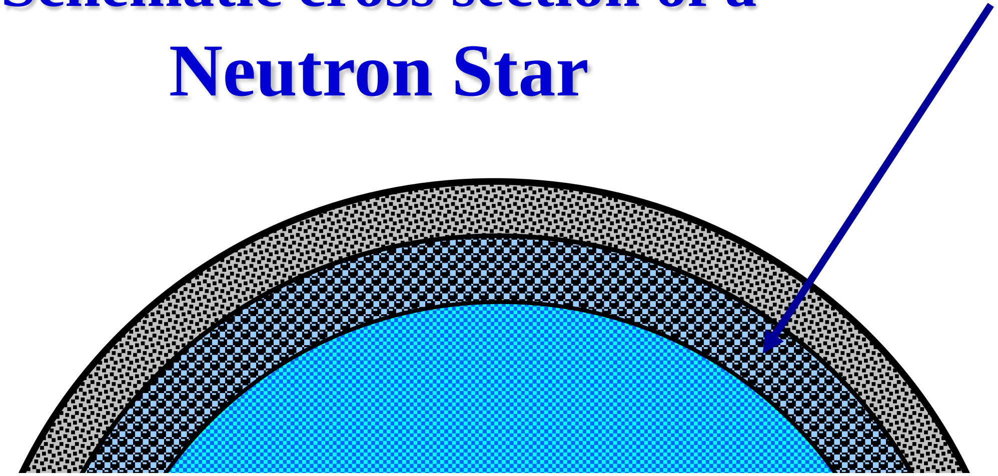
Schematic cross section of a
Neutron Star



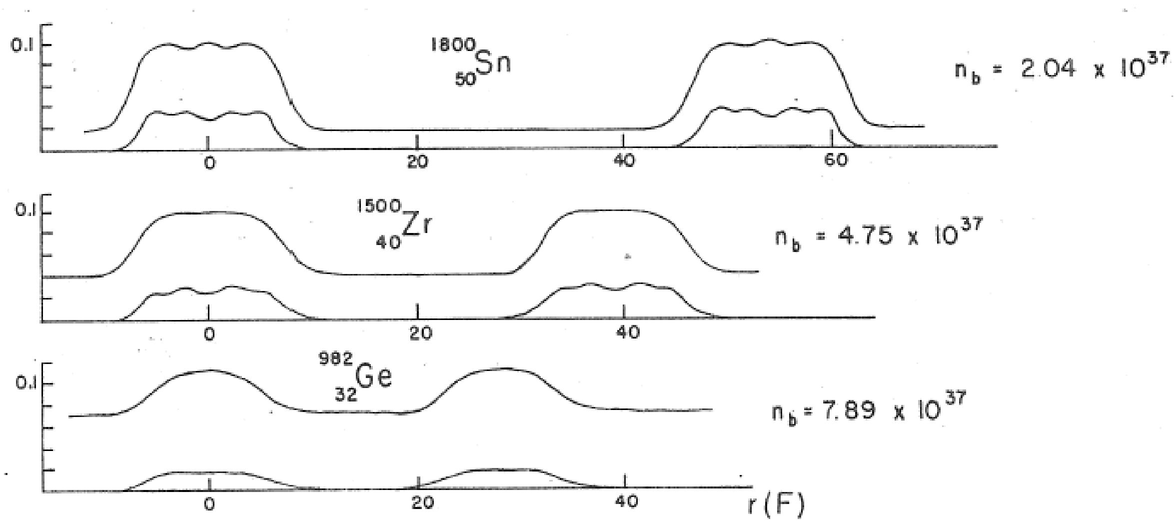
Schematic cross section of a Neutron Star

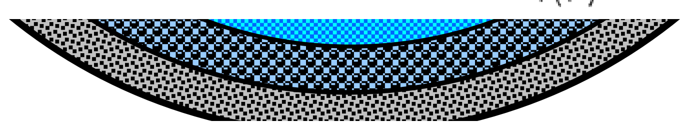
inner crust

$\rho > \rho_{drip} = 4.3 \times 10^{11}$ g/cm^3



J.W. Negele, D. Vautherin, Nucl. Phys. A 207 (1972) 298





cluster	Z	N	ρ_{max}(g/cm^3)
^{180}Zr	40	140	4.67×10^{11}
^{200}Zr	40	160	6.69×10^{11}
^{250}Zr	40	210	1.00×10^{12}
^{320}Zr	40	280	1.47×10^{12}
^{500}Zr	40	460	2.66×10^{12}
^{950}Sn	50	900	6.24×10^{12}
^{1100}Sn	50	1050	9.65×10^{12}
^{1350}Sn	50	1300	1.49×10^{13}
^{1800}Sn	50	1750	3.41×10^{13}
^{1500}Zr	40	1460	7.94×10^{13}
^{982}Ge	32	950	1.32×10^{14}

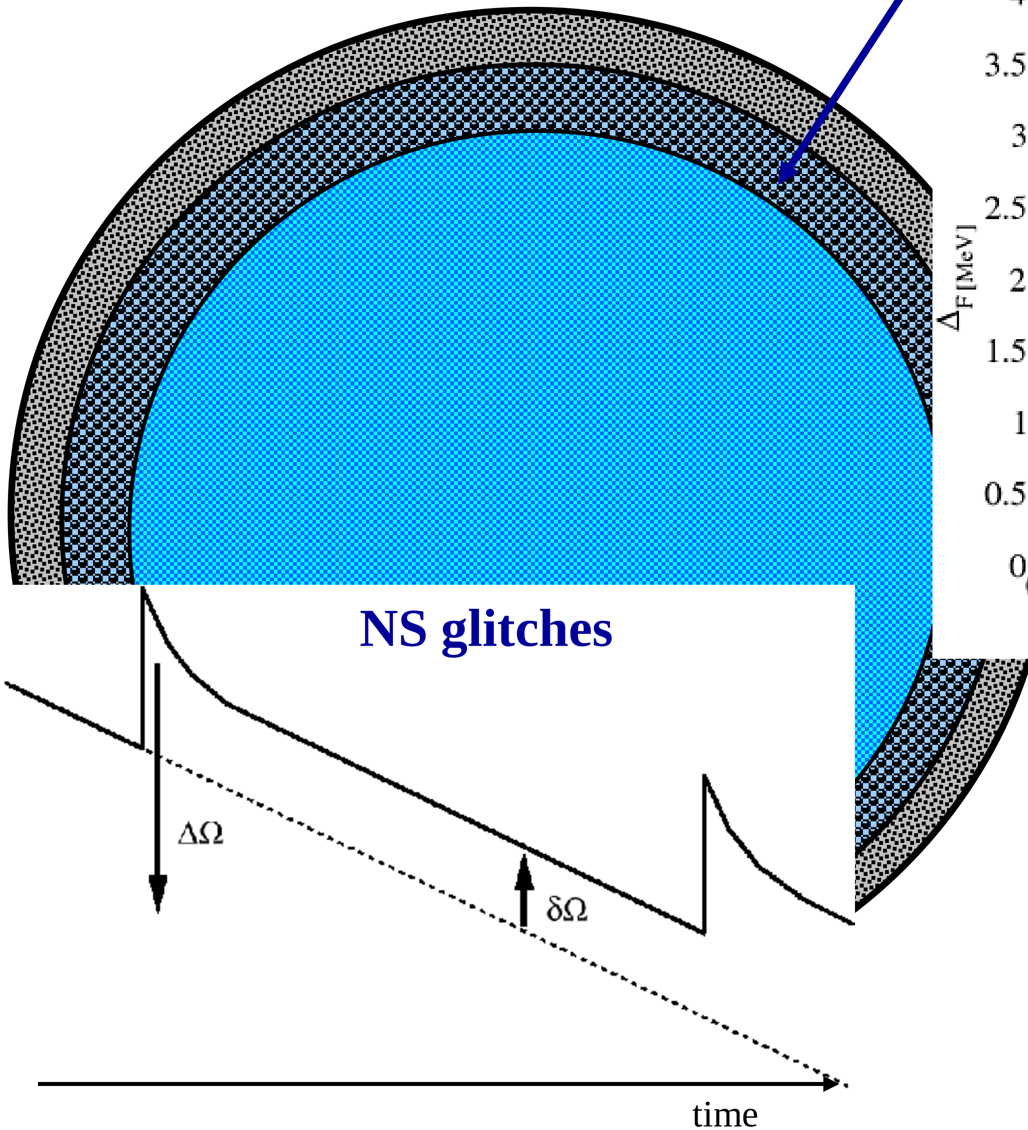
M. Baldo, U. Lombardo, E.E. Saperstein, .V. Tolokonnikov, Nucl. Phys. A 750 (2005) 409

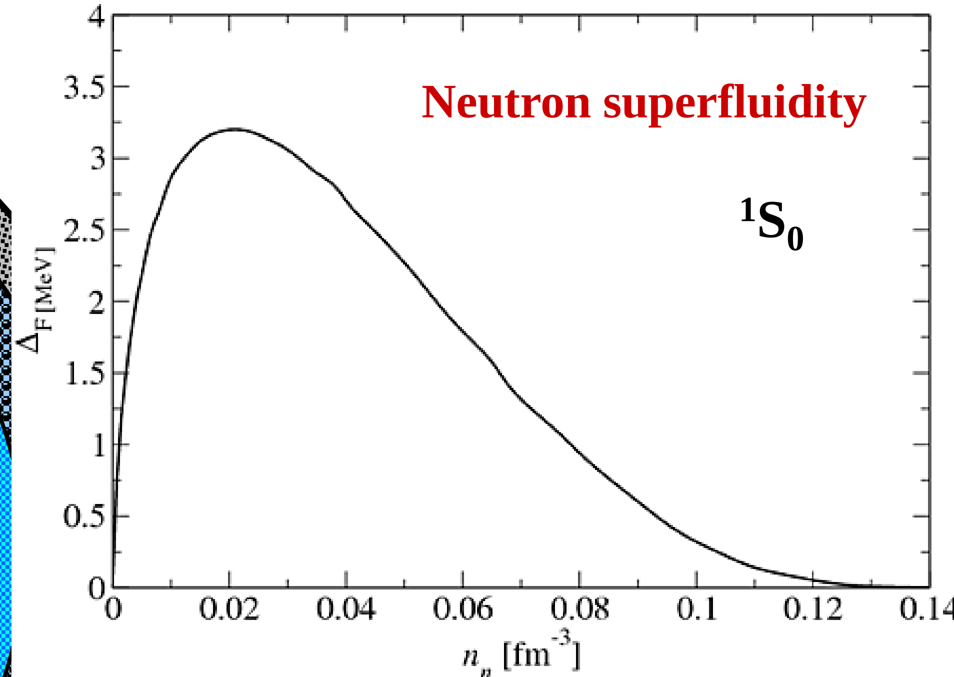
M. Baldo, E.E. Saperstein, .V. Tolokonnikov, Phys. Rev. C 76 (2007) 025803

Schematic cross section of a Neutron Star

inner crust

$\rho > \rho_{drip} = 4.3 \times 10^{11}$ g/cm^3





U. Lombardo, H.-J. Schulze,
Lect. Notes in Phys. vol. 578 (2001) Springer

Nucleon Stars

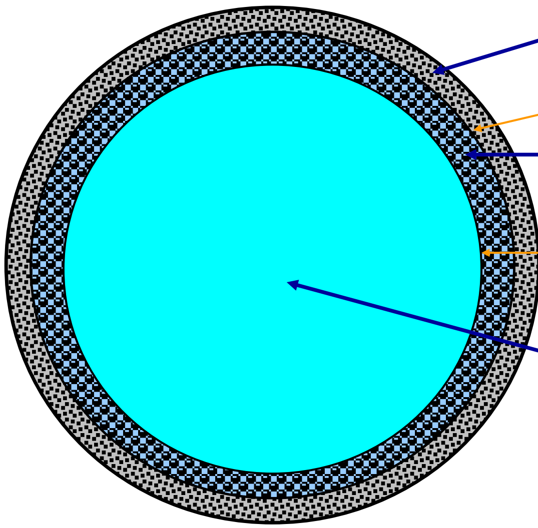
β-stable nuclear matter

$$p + e^- \leftrightarrow n + \nu_e$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

$$\mu_e \geq m_\mu$$

$$e^- \rightarrow \mu^- + \nu_e + \bar{\nu}_\mu$$



Equilibrium with respect to the weak interaction processes

$$\mu_n - \mu_p = \mu_e$$

$$\mu_\mu = \mu_e$$

neutrino-free matter

$$\mu_\nu = \mu_{\bar{\nu}} = 0$$

Charge neutrality

$$n_p = n_e + n_\mu$$

To be solved for any given value of the total baryon number density n_B

Proton fraction in β-stable nuclear matter and role of the nuclear symmetry energy

$$\hat{\mu} \equiv \mu_n - \mu_p = -\left.\frac{\partial(E/A)}{\partial x}\right|_n = 2\left.\frac{\partial(E/A)}{\partial \beta}\right|_n$$

$\beta = (n_n - n_p)/n = 1 - 2x$

$n = n_n + n_p$

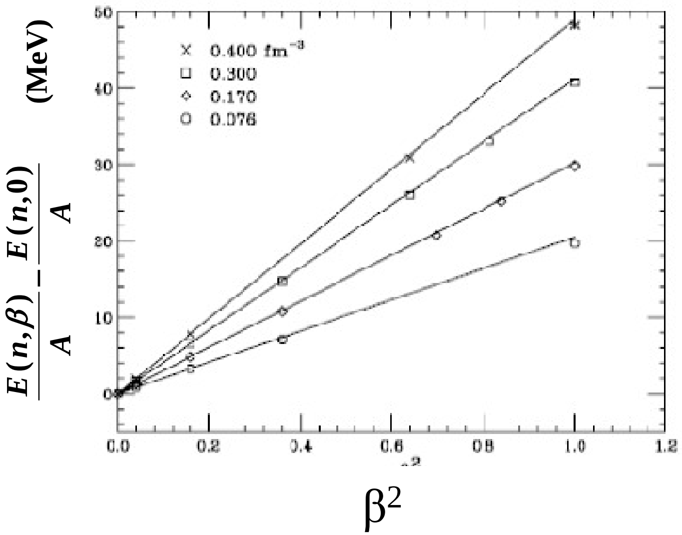
$x = n_p/n$ **proton fraction**

Energy per nucleon for asymmetric nuclear matter

$$\frac{E(n,\beta)}{A} = \frac{E(n,0)}{A} + E_{sym}(n)\beta^2 + S_4(n)\beta^4 + ...$$

Symmetry energy

$$E_{sym}(n) \equiv \frac{1}{2}\left.\frac{\partial^2(E/A)}{\partial \beta^2}\right|_{\beta=0}$$



The "parabolic approximation" (*)

$$\frac{E(n,\beta)}{A} = \frac{E(n,0)}{A} + E_{sym}(n)\beta^2$$

(*) Bombaci, Lombardo, Phys. Rev: C44 (1991)

Proton fraction in β-stable nuclear matter and role of the nuclear symmetry energy

In the "parabolic approximation":

$$E_{sym}(n) = \frac{E(n,\beta=1)}{A} - \frac{E(n,\beta=0)}{A}$$

$\beta = 0$ **symm nucl matter**
$\beta = 1$ **pure neutron matter**

$$\hat{\mu} = 4\; E_{sym}(n)\; [1-2x]$$

Chemical equil.+charge neutrality
(no muons)

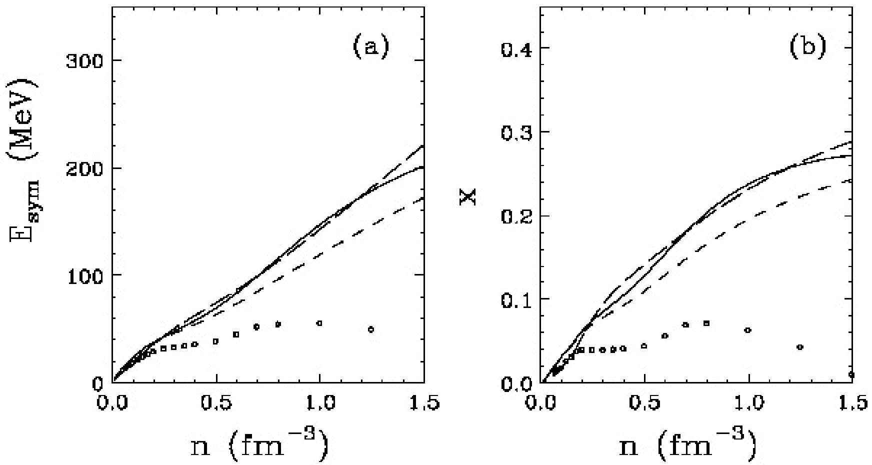
$$3\pi^2(\hbar c)^3 n\;\; x(n) - [4E_{sym}(n)(1-2x(n))]^3 = 0$$

if **x<<1/2**

$$x_{eq}(n) \approx \frac{1}{3\pi^2}\frac{1}{n}\left(\frac{4E_{sym}(n)}{\hbar c}\right)^3$$

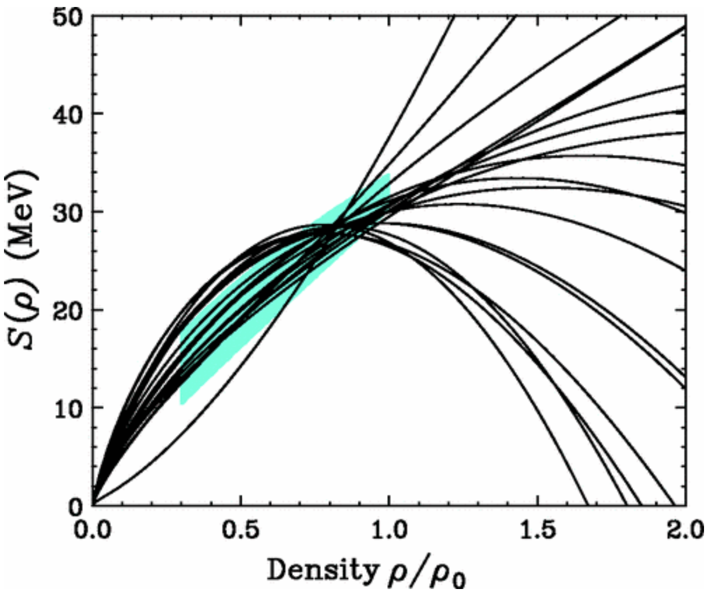
The composition of β-stable nuclear matter is strongly dependent on the nuclear symmetry energy.

Symmetry en. **proton fraction**



M. Baldo, I. Bombaci, G. Burgio, Astr. & Astrophys. 328 (1997)

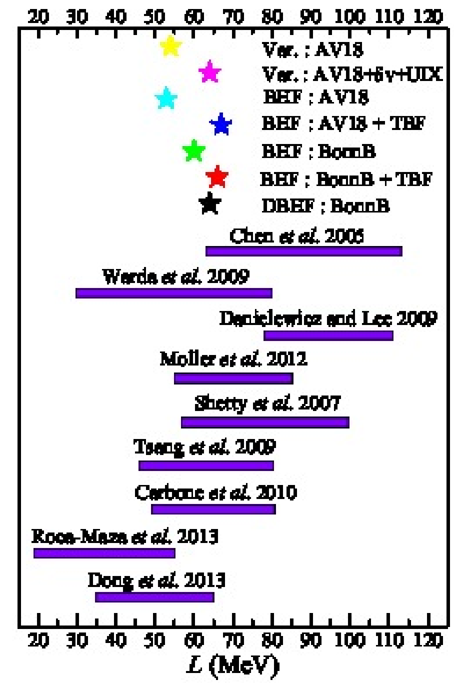
Density dependence of the nuclear symmetry energy



B.A. Brown, Phys. Rev. Lett. 85 (2000) 5296

slope

$$L = 3\rho_0 \left. \frac{\partial E_{sym}(\rho)}{\partial \rho} \right|_{\rho_o}$$



W. Zuo, I. Bombaci, U. Lombardo, Eur. Phys. J A 50 (2014) 12

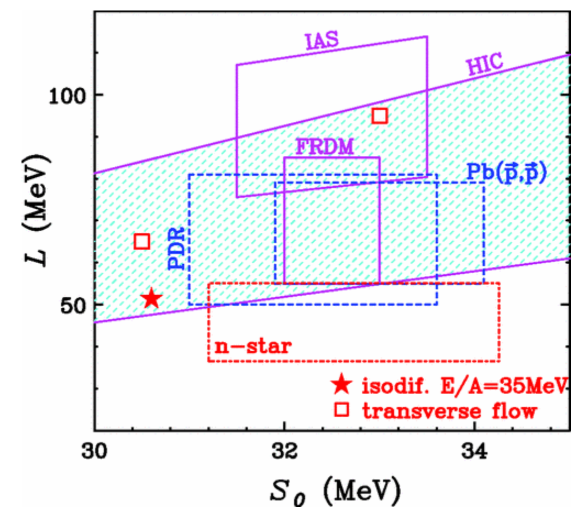
Probing the nuclear symmetry energy with heavy-ion collisions

Experiments: CHIMERA @ LNS

E. De Filippo, A. Pagano, Eur. Phys. J. A 50 (2014)32

Theory:

M. Di Toro, V. Baran, M. Colonna, V. Greco, J. Phys. G: Nucl. Part. Phys. 37 (2010) 083101



M.B. Tsang et al., Phys. Rev. C 86 (2012) 015803

Microscopic approach to nuclear matter EOS

input

Two-body nuclear interactions: V_{NN}

"realistic" interactions: e.g. Argonne, Bonn, Nijmegen interactions.
Parameters **fitted to NN scatering data** with χ^2**/datum ~1**

Three-body nuclear interactions: V_{NNN}

semi-phenomenological. Parameters fitted to

- binding energy of **A = 3, 4** nuclei or
- empirical saturation point of symmetric nuclear matter: $n_0 = 0.16\ fm^{-3}$, **E/A = -16 MeV**

	AV18	AV18/UIX	Exp.
B(3H)	7.624	8.479	8.482
B(3He)	6.925	7.750	7.718
B(4He)	24.21	28.46	28.30

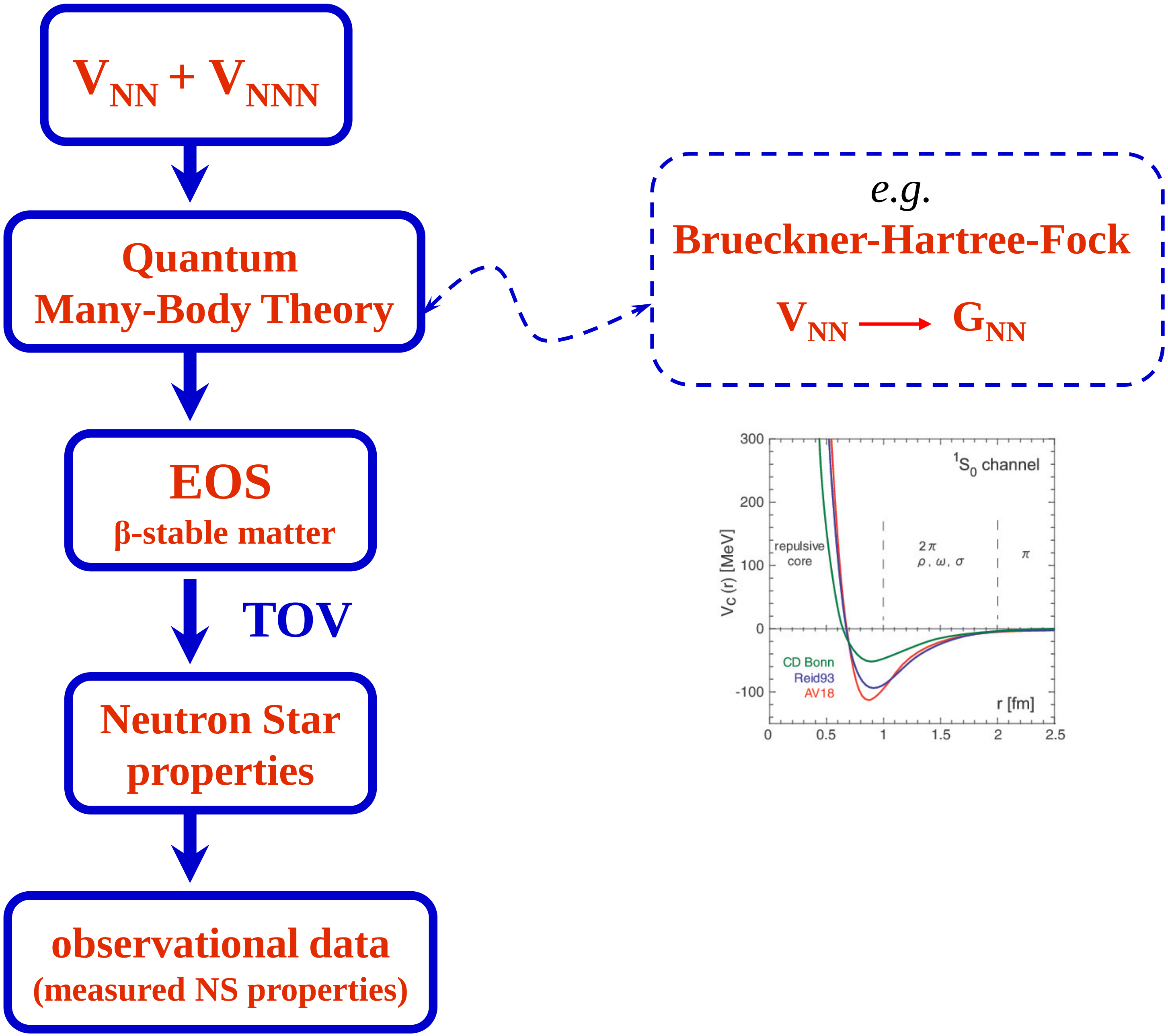
Values in MeV

Nuclear Matter at **$n = 0.16\ fm^{-3}$**

$E^{pot}(2BF)/A \sim -40$ MeV

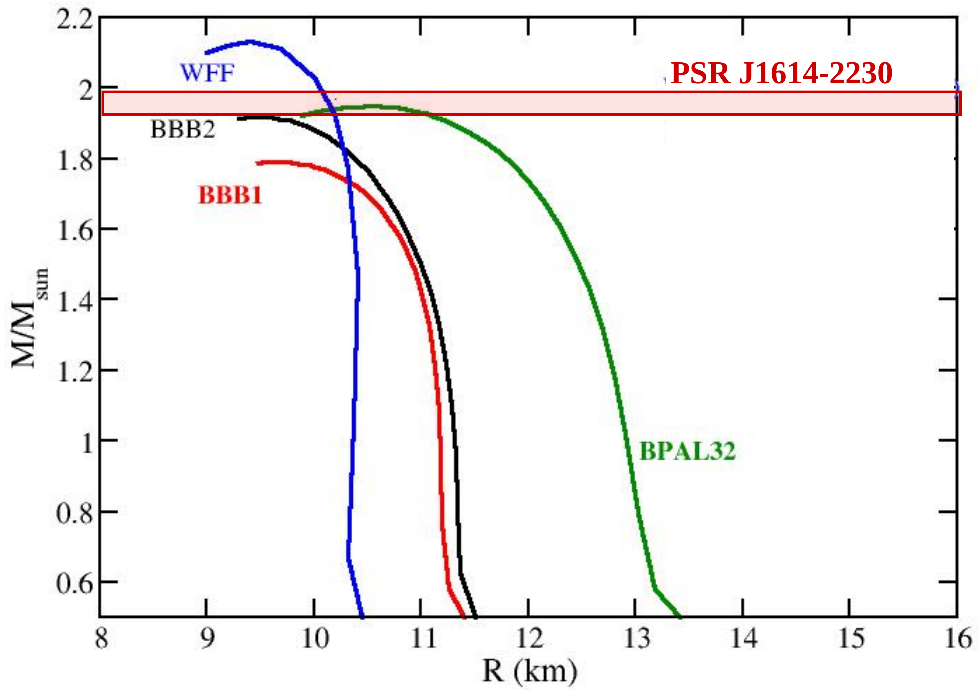
$E^{pot}(3BF)/A \sim -1$ MeV

A. Kievsky, S. Rosati, M.Viviani, L.E. Marcucci, L. Girlanda, Jour. Phys.G 35 (2008) 063101
A. Kievsky, M.Viviani, L. Girlanda, L.E. Marcucci, Phys. Rev. C 81 (2010) 044003
Z.H. Li, U. Lombardo, H.-J. Schulze, W. Zuo, Phys. Rev. C 77 (2008) 034316



V_NN + V_NNN
Quantum Many-Body Theory
EOS
β-stable matter
TOV
Neutron Star properties
observational data
(measured NS properties)
e.g.
Brueckner-Hartree-Fock
V_NN → G_NN
¹S₀ channel
Vc (r) [MeV]
300
200
100
0
-100
repulsive core
2π
ρ, ω, σ
π
CD Bonn
Reid93
AV18
r [fm]
0
0.5
1
1.5
2
2.5

Mass-Radius relation for Nucleon Stars



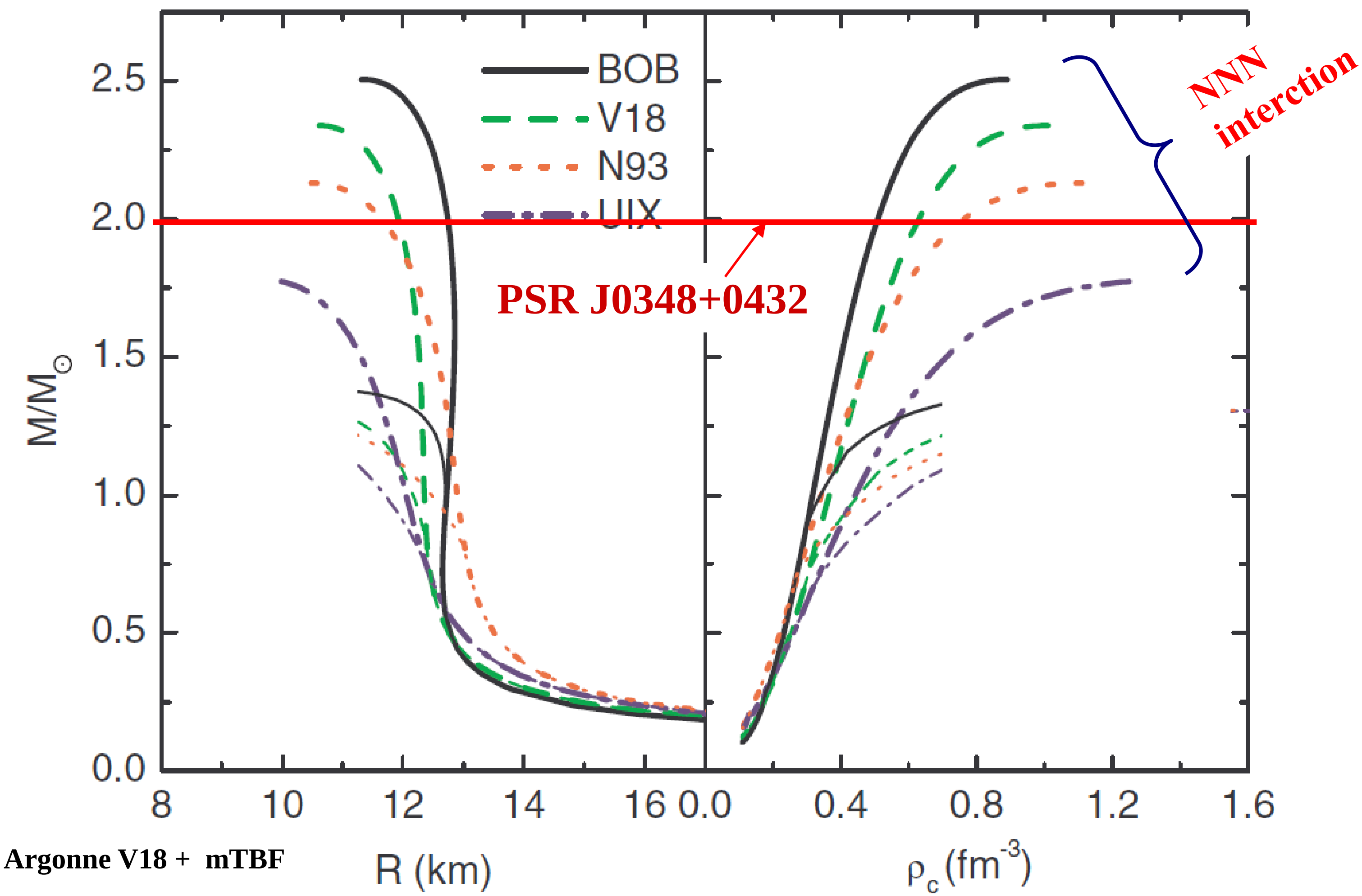
Maximum mass configuration for Nucleon Stars

EOS	$M_G/M_\odot$	R(km)	n_c / n_0
BBB1	1.79	9.66	8.53
BBB2	1.92	9.49	8.45
WFF	2.13	9.40	7.81
APR	2.20	10.0	7.25
BPAL32	1.95	10.54	7.58
KS	2.24	10.79	6.30

WFF: Wiringa-Ficks-Fabrocini, 1988.
BPAL: Bombaci, 1995.
BBB: Baldo-Bombaci-Burgio, 1997.
APR: Akmal-Pandharipande-Ravenhall, 1988.
KS: Krastev-Sammarruca, 2006

$$M_{max} = (1.8 \text{ 羊 } 2.3)\ M_\odot$$

Z.H. Li, H.-J. Schulze, PHYSICAL REVIEW C **78**, 028801 (2008)



V18: Argonne V18 + mTBF

BOB: Bonn B + mTBF

N93: Nijmegen 93 + mTBF

UIX: Argonne V18 + Urbana IX

models of Nucleon Stars

(i.e. Neutron Stars with a pure nuclear matter core)

are able to explain

measured Neutron Star masses

as those of

PSR J1614-2230 and PSR J0348+0432

$$M_{NS} \approx 2\ M_{\odot}$$

Happy?

Not the end of the story!

Hyperon Stars

Why is it very likely to have hyperons in the core of a Neutron Star?

- **Pauli principle.** **Neutrons (protons) are identical Fermions, thus their chemical potentials (Fermi energies) increase very rapidly as a function of density.**

  The central density of a Neutron Star is "high": $n_c \approx (4 - 10)\, n_0$
  ($n_0 = 0.17\ \mathrm{fm}^{-3}$)

- **above a threshold density, $n_{cr} \approx (2 - 3)\, n_0$, weak interactions in dense matter can produce strange baryons (hyperons)**

$$n + e^- \rightarrow \Sigma^- + \nu_e$$
$$p + e^- \rightarrow \Lambda + \nu_e$$

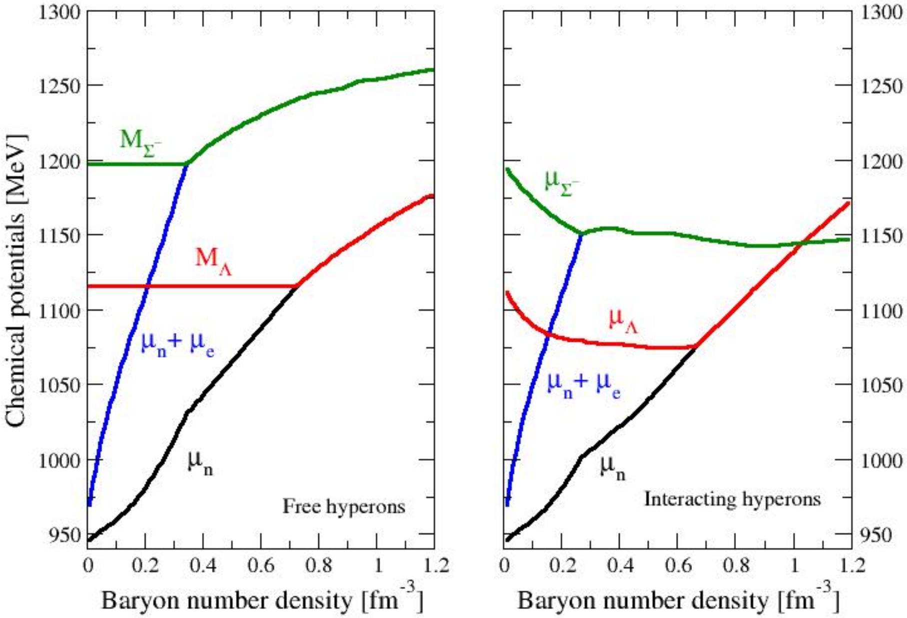
etc.

A. Ambarsumyan, G.S. Saakyan, (1960)
V.R. Pandharipande (1971)

In Greek mythology Hyperion (Ὑπερίων) was one of the twelve Titan son of Gaia and Uranus

Threshold density for hyperons in neutron matter:
a simple estimate (ideal non-rel. Fermi gas of neutrons)

$$n_{cr} = \frac{1}{3\pi^2 (\hbar c)^3} \left[2 m_n c^2 (m_\Lambda - m_n) c^2 \right]^{3/2}$$



I. Vidaña, Ph.D. thesis (2001)

Hyperons appear in the stellar core above a threshold density $\rho_{cr} \approx (2-3)\,\rho_0$

$n + e^- \rightarrow \Sigma^- + \nu_e$
$p + e^- \rightarrow \Lambda + \nu_e$
etc.

$$\mu_p = \mu_n - \mu_e = \mu_{\Sigma^+}$$
$$\mu_n = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_\Lambda$$
$$\mu_n + \mu_e = \mu_{\Sigma^-} = \mu_{\Xi^-}$$
$$\mu_\mu = \mu_e$$
$$n_p + n_{\Sigma^+} = n_e + n_\mu + n_{\Sigma^-} + n_{\Xi^-}$$

$m_\Lambda = 1115.7$ MeV $\qquad \mu_n = \mu_\Lambda$

$m_{\Sigma^-} = 1197.5$ MeV $\qquad \mu_n + \mu_e = \mu_{\Sigma^-}$

Microscopic approach to hyperonic matter EOS

input

2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)

e.g. Nijmegen, Julich models

3BF: NNN, NNY, NYY, YYY

Hyperonic sector: experimental data

1. **YN scattering (very few data)**
2. **Hypernuclei**

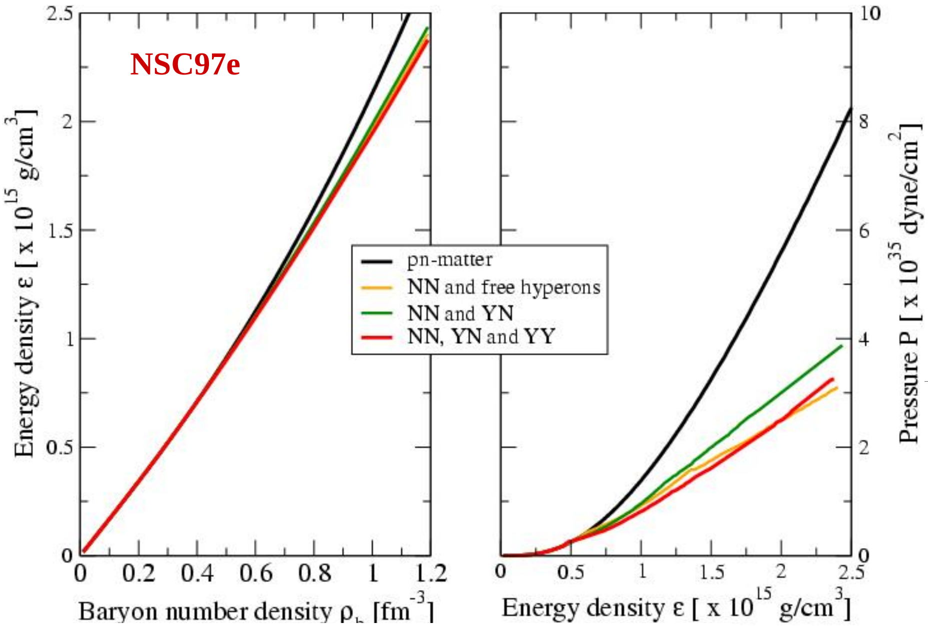
Hypernuclear experiments

FINUDA (LNF-INFN),
PANDA and HypHI (FAIR/GSI),
Jeff. Lab, J-PARC

Phenomenological approaches to hyperonic matter EOS

Relativistic Mean Fiels Models (Glendenning 1995, Knorren et al 1995, Schaffner-Bielich Mishustin 1996)
Skyrme-like potential models (Balberg and Gal 1997)
Chiral Effective Lagrangians (Hanauske et al 2000)
Quark-meson coupling model (Pal, Hanuske, Zakout, Stoker, Greiner, 1999)

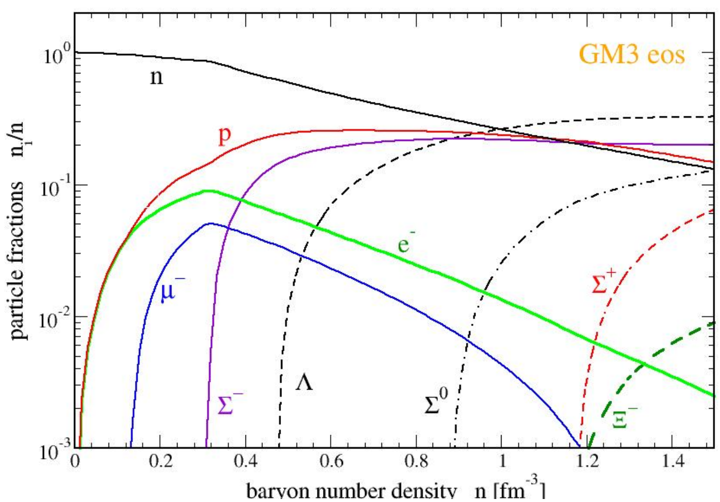
Equation of State of Hyperonic Matter



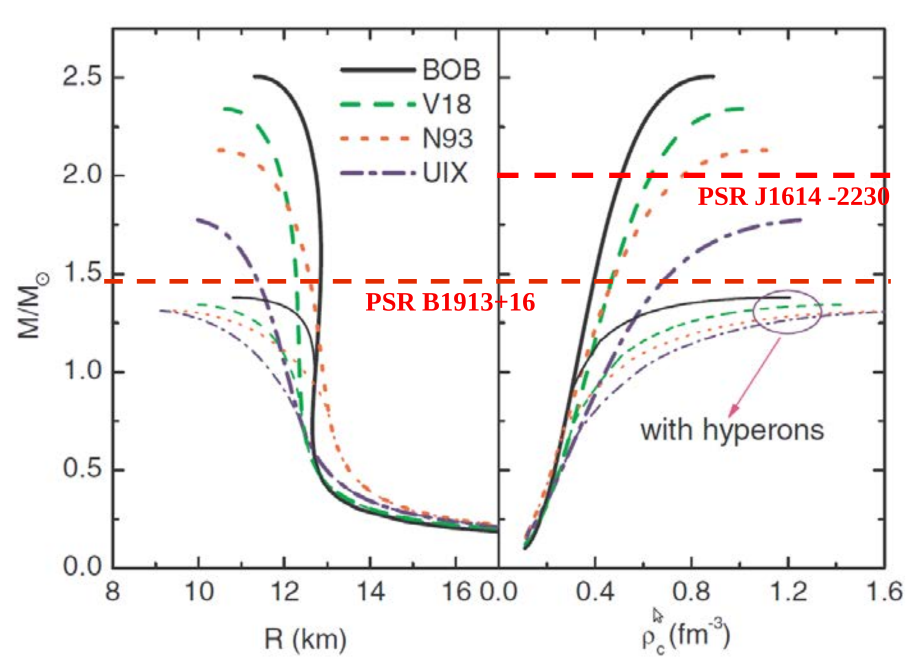
I. Vidaña et al., Phys. Rev: C62 (2000) 035801

hyperons produce a strong softening of the EOS

Particle fractions



Stellar mass



NN + NY + YY + NNN interactions

Z. H. Li and H.-J. Schulze Phys. Rev: C78 (2008) 028801

Hyperons in Neutron Stars: implications for the stellar structure

The presence of hyperons reduces the maximum mass of neutron stars:

$$\Delta M_{max} \approx (0.5 - 1.2)\, M_{\odot}$$

Therefore, **to neglect hyperons always leads to an overestimate of the maximum mass of neutron stars**

Microscopic EOS for hyperonic matter: "very soft" non compatible with measured NS masses

→

Need for extra pressure at high density

↔

Improved NY, YY two-body interaction

Three-body forces*: NNY, NYY, YYY

↑

More experimental data from hypernuclear physics

(*) A preliminary study: **I. Vidana, D. Logoteta, C. Providencia, A. Polls, I. Bombaci, EPL 94 (2011) 11002**

Quark Matter in Neutron Stars

only *u, d, s* quark flavors are expected in Neutron Stars (SQM)

$$m_c = 1275 \pm 25 \ \ \text{MeV}$$

$$q_c = \frac{2}{3}|e|$$

- **Threshold density for the *c* quark**

$$s \rightarrow c + e^- + \bar{\nu}_e$$

perfect Fermi gas
massless **u,d,s** quarks
in beta-equil.
$Q_{tot} = 0$

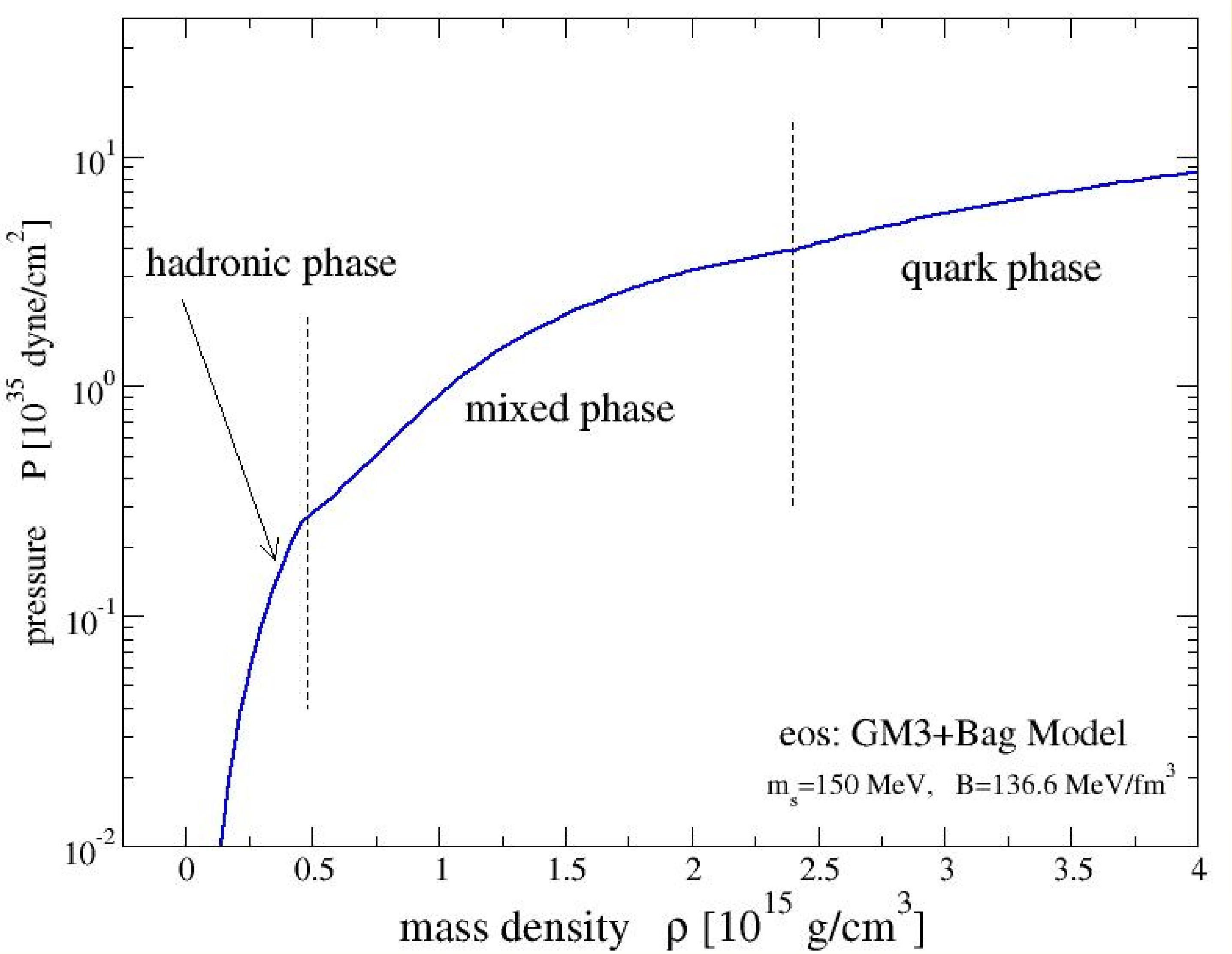
→ $\mathbf{n_B = n_u = n_d = n_s}$

$$E_{Fq} = \hbar c\, k_{Fq} = \hbar c\, (\pi^2 n_q)^{1/3} =$$
$$= \hbar c\, (\pi^2 n_B)^{1/3} \geq m_c$$

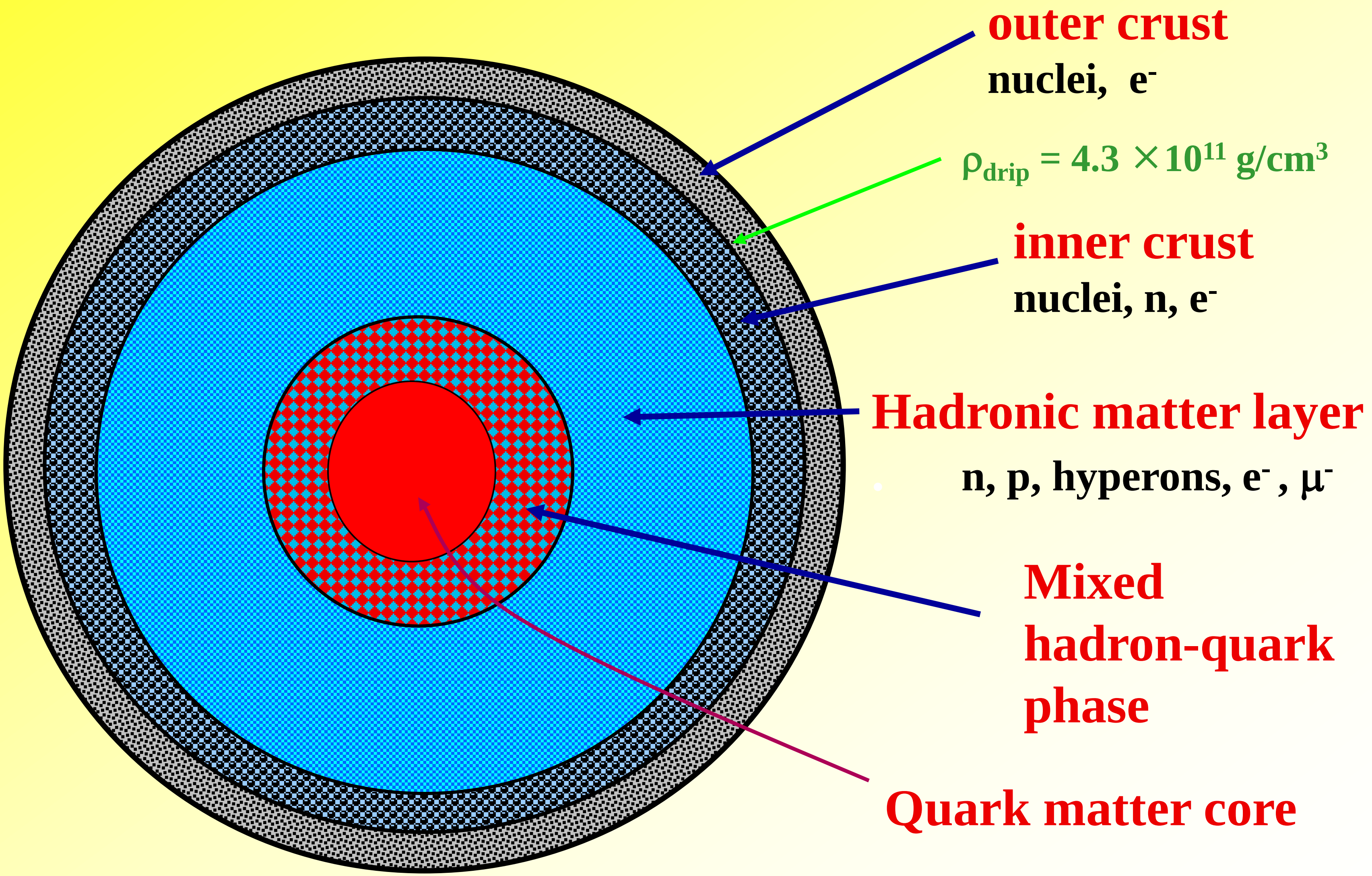
$\Rightarrow$

$$n_B \geq 27.3 \ \ \text{fm}^{-3} \approx 171 \ \ n_0$$

The EOS for Hybrid Stars

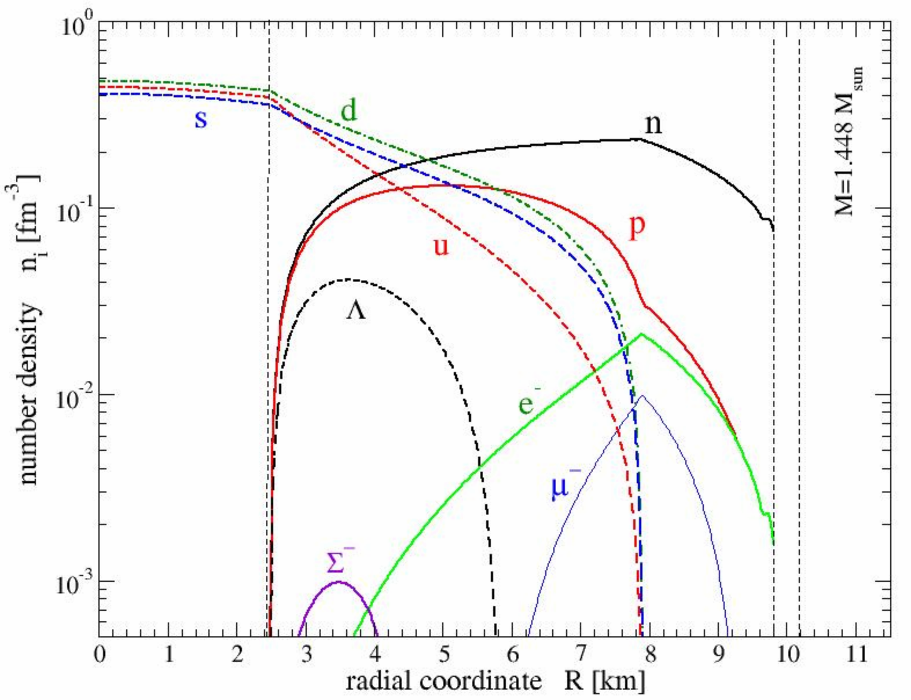


Hybrid Stars (neutron stars with a quark matter core)

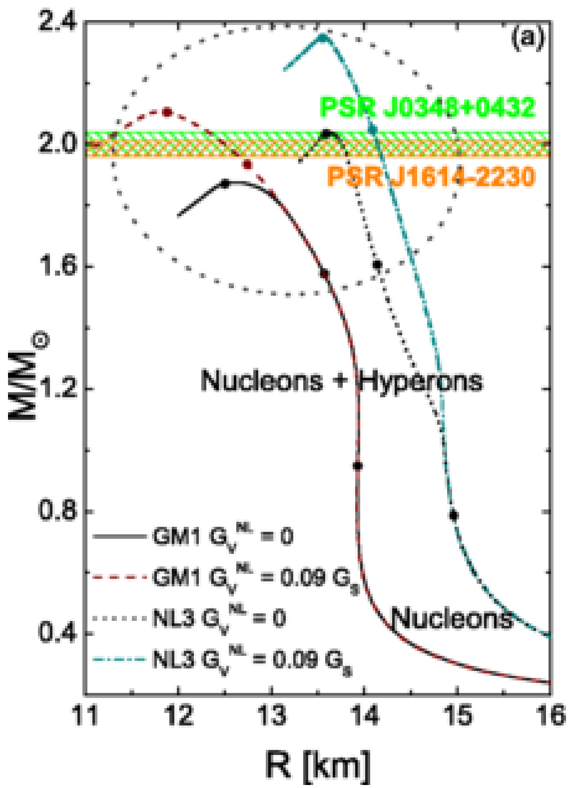


Hybrid Stars (neutron stars with a quark matter core)

GM3+Bag model m_s=150 MeV, B=13.6.6Mev/fm^3



I. Bombaci, I. Parenti, I. Vidaña (2004)



M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, Phys. Rev. C 89 (2014) 015806

perturbative QCD calculations up to α_s^2

A. Kurkela et al., Phys. Rev. D 81, (2010) 105021

M_{max} up to ~ 2 $M_\odot$

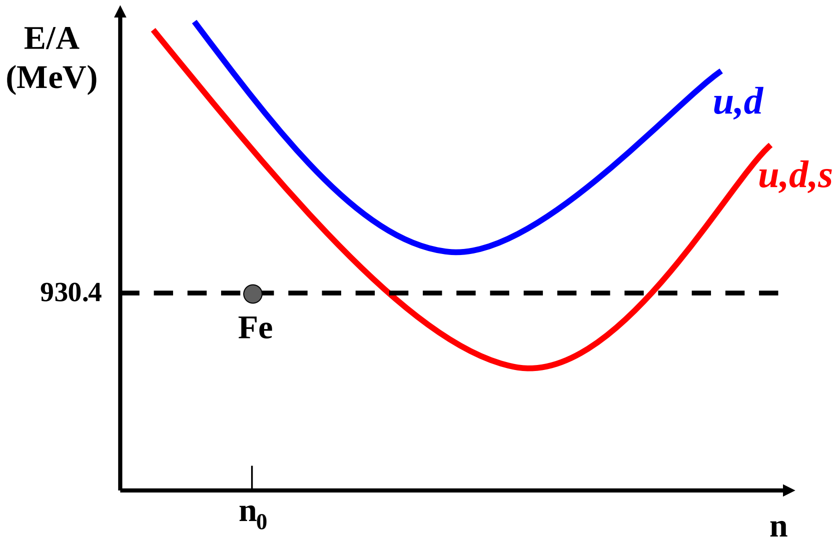
Present measurd NS masses do not exclude the possibility of having QM in the stellar core

Strange Stars (compact stars made of strange quark matter)

The Strange Matter hypothesis (Bodmer (1971), Terazawa (1979), Witten (1984))

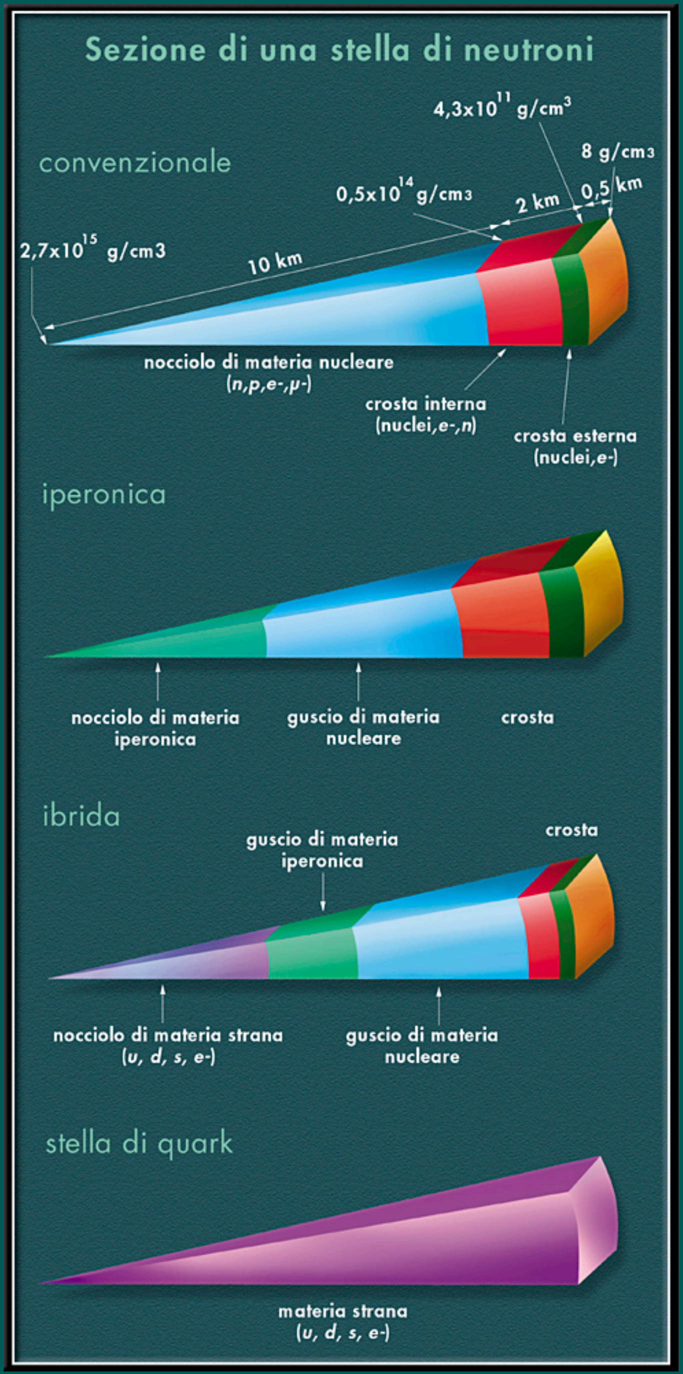
Three-flavor *u,d,s* quark matter, in equilibrium with respect to the weak interactions, could be the true ground state of strongly interacting matter, rather than ^{56}Fe

$$E/A|_{SQM} \leq E(^{56}Fe)/56 \sim 930.4 \text{ MeV}$$



Stability of atomic nuclei with respect to *u,d* QM decay

$$E/A|_{ud} \geq E(^{56}Fe)/56$$



I. Bombaci, A. Drago, INFN Notizie, n. 13, 15 (2003)

"Neutron Stars"

Nucleon Stars

Hyperon Stars

Hybrid Stars

Strange Stars

Dense matter EOS: open problems

(1) The Hadronic matter phase

(1a) uncertainties in the strenght of the NNN interactions at high densities

(1b) Poor knowledge of the NY, YY and NNY, NYY, YYY interactions

(2) The Quark matter phase

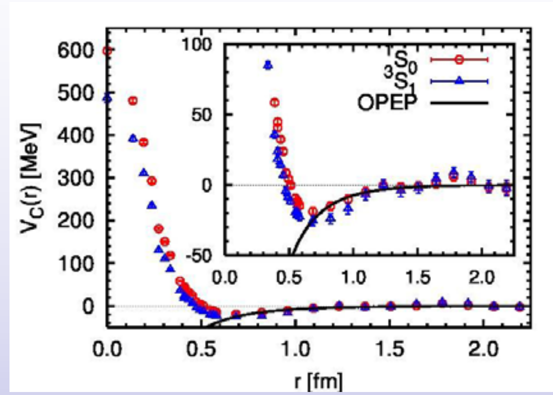
(2a) (1a) + (1b) $\longrightarrow$ crucial to determine ρ_{crit}

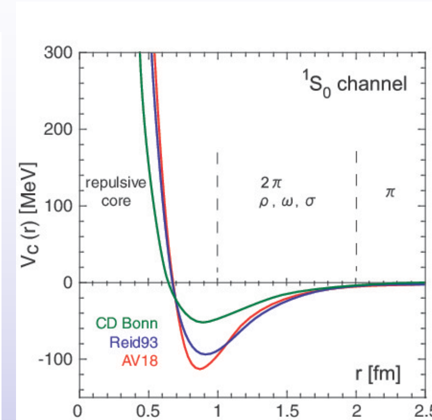
(2b) inclusion of non-perturbative QCD effects which are crucial to determine the nature of the deconfinement transition and the stiffness of the quark matter phase EOS

Dense matter EOS: a true microscopic approach

Lattice QCD

NN inter.





N. Ishii, S. Aoki, T. Hatsuda, Phys. Rev. Lett. 99, 022001 (2007)
S. Aoki, T. Hatsuda, N. Ishii, Prog.Theor. Phys. 123, 89 (2010)

NY inter.

H. Nemura, N. Ishii, S. Aoki, T. Hatsuda, arXiv:0806:1096 nucl-th

NNN inter.

T. Doi et al. (HAL QCD collaboration), arXiv:1106.2276 hep-lat

EOS from Lattice QCD at finite density

M. D'Elia, M. P. Lombardo, Phys. Rev. D 67, 014505 (2003)
M. D'Elia, M. P. Lombardo, Phys. Rev. D 70, 074509 (2004)
P. Cea, L. Cosmai, M. D'Elia, A. Papa, F. Sanfilippo, Phys. Rev. D 85, 094512 (2012)