12th International Confernce on

Nucleus – Nucleus Collisions

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Neutron Stars

cosmic laboratories for matter under extreme conditions

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INFN Sezione di Pisa

Neutron Stars: bulk properties

Mass	$M \sim 1.5\, M_\odot$
Radius	$R \sim 10$ km
Centr. Density	$\rho_c = (4-8)\,\rho_0$
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 $\qquad B/(Mc^2) \sim 10\%$

Stellar structure:
General Relativity

Giant "atomic nucleus"
bound by gravity

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

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

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

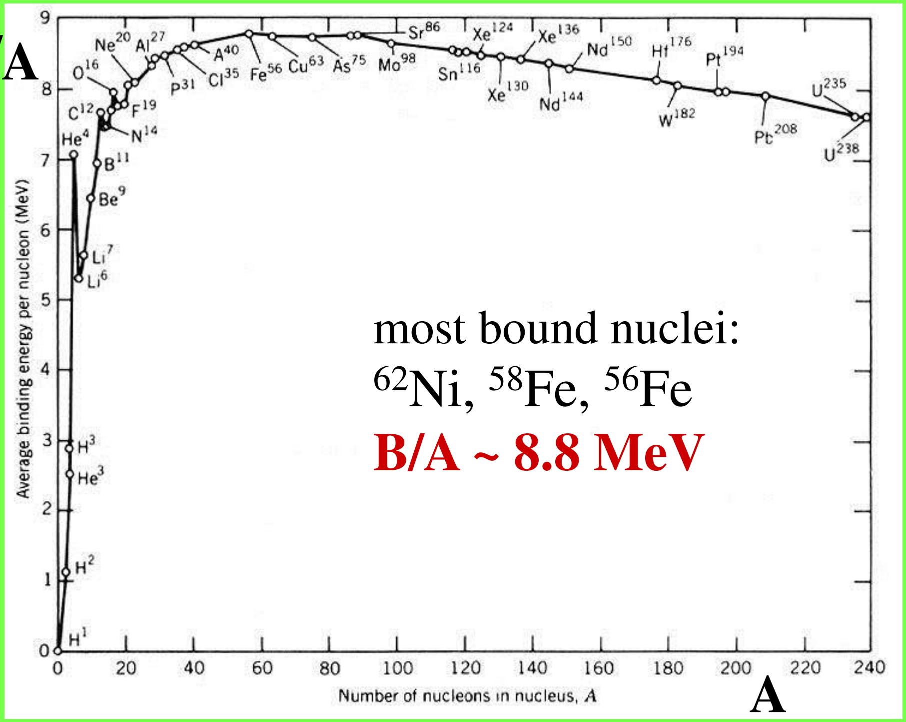
Atomic Nuclei: bulk properties

Mass number $\mathbf{A = 1 - 238}$ **(natural stable isotopes)**

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

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

B/A



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

A

$\mathbf{B/(Mc^2)}$
$\mathbf{\sim (0.1–1)\%}$

bound by
nuclear
interactions

Relativistic equations for stellar structure

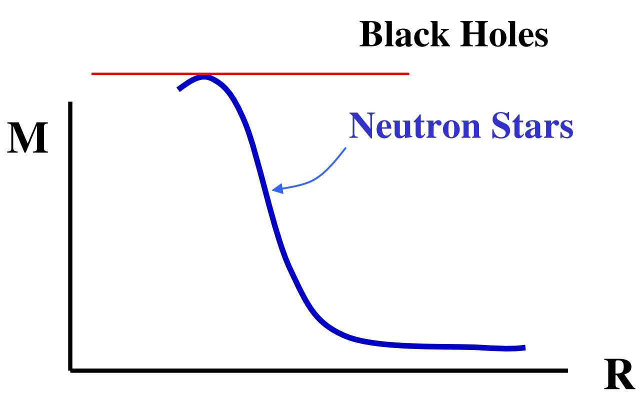
Tolman – Oppenheimer – Volkov equations (TOV)

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

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

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

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



$M_{max}(EOS) \geq$ **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 Stars

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

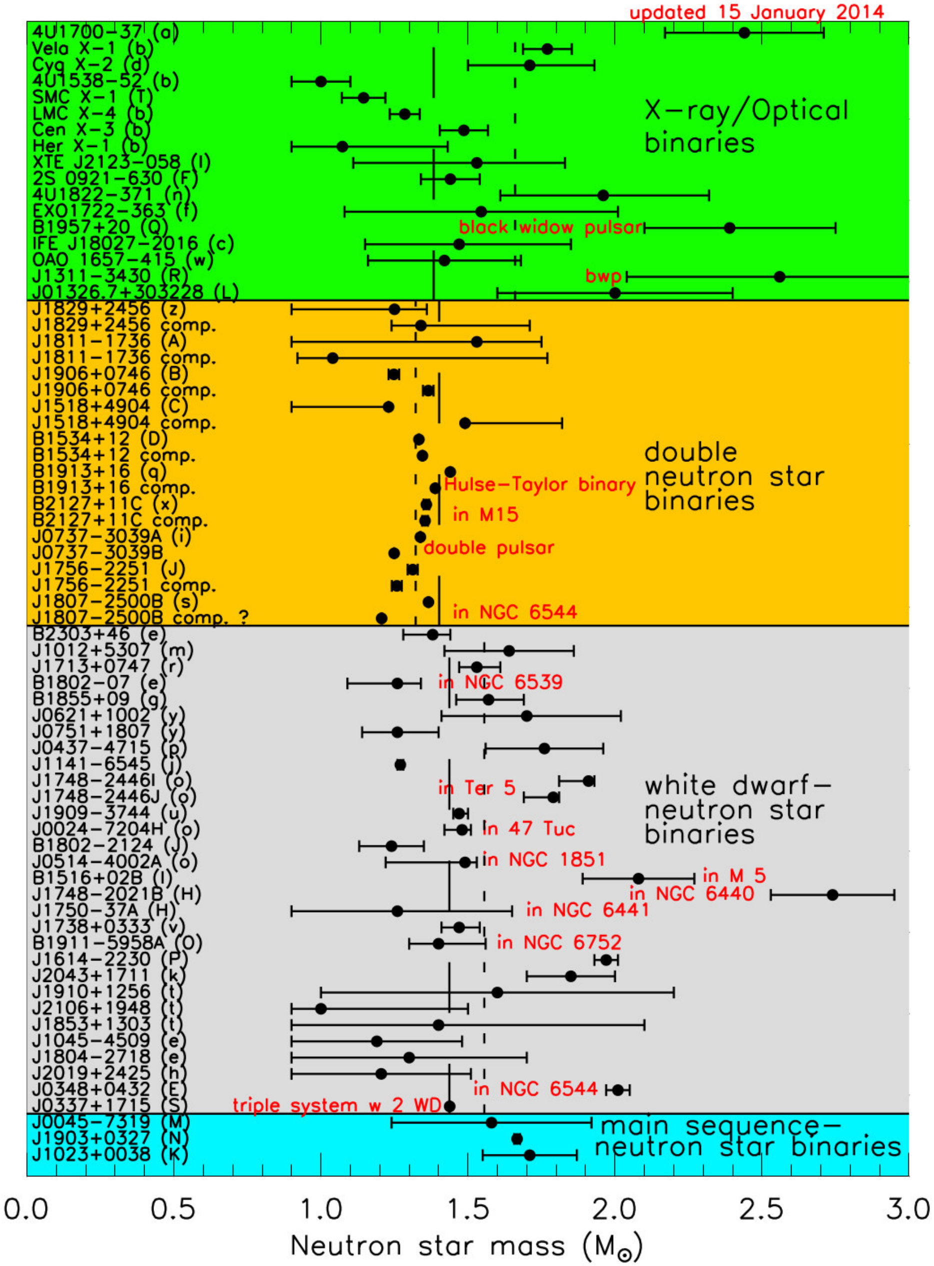
$M_{WD} = 0.172 \pm 0.003\ M_\odot$ (companion mass)

$P_b = 2.46$ 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



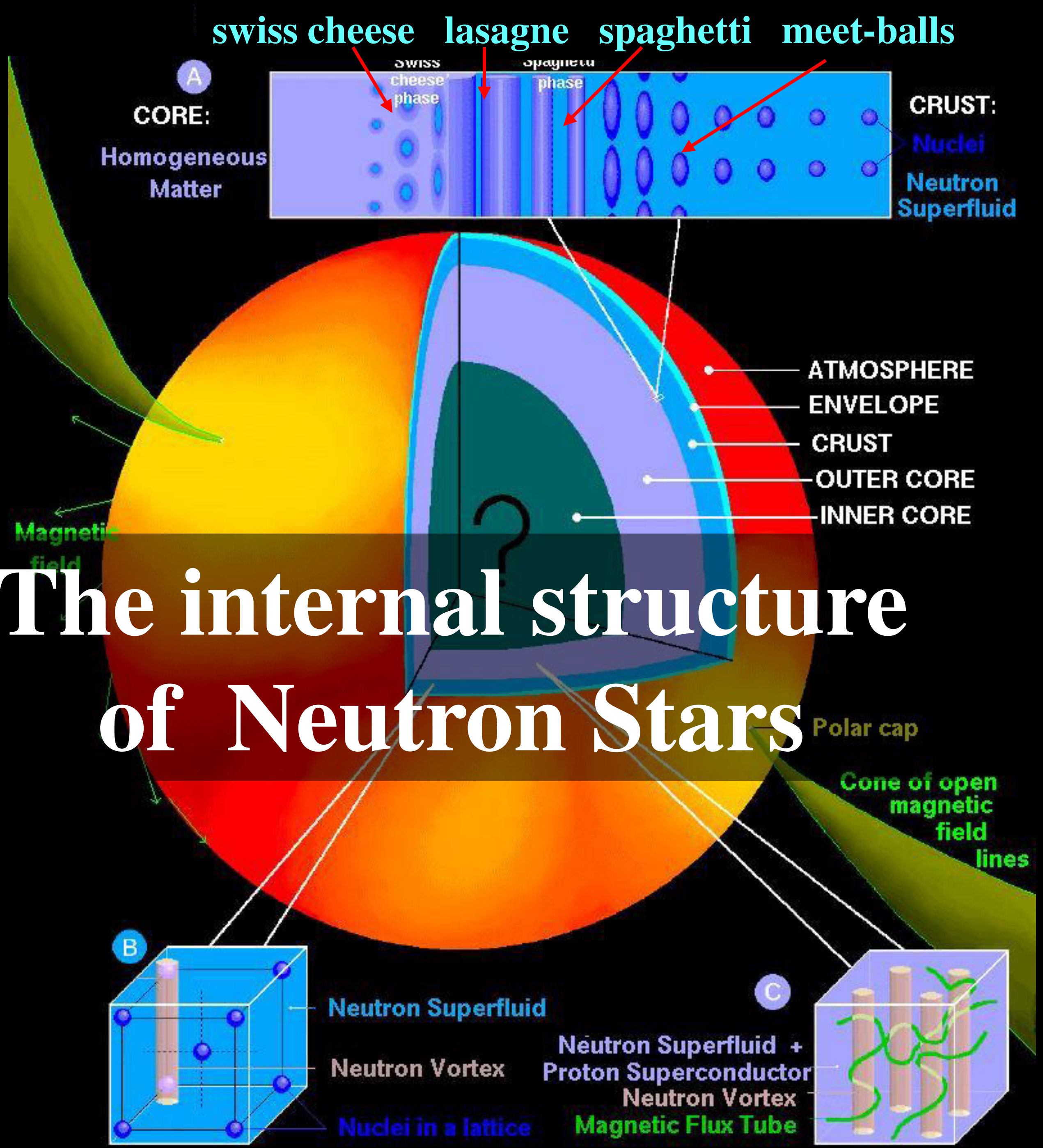
Jim Lattimer

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

Very stringent constraint on the EOS

soft EOS are ruled out

The internal structure of Neutron Stars



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^-)

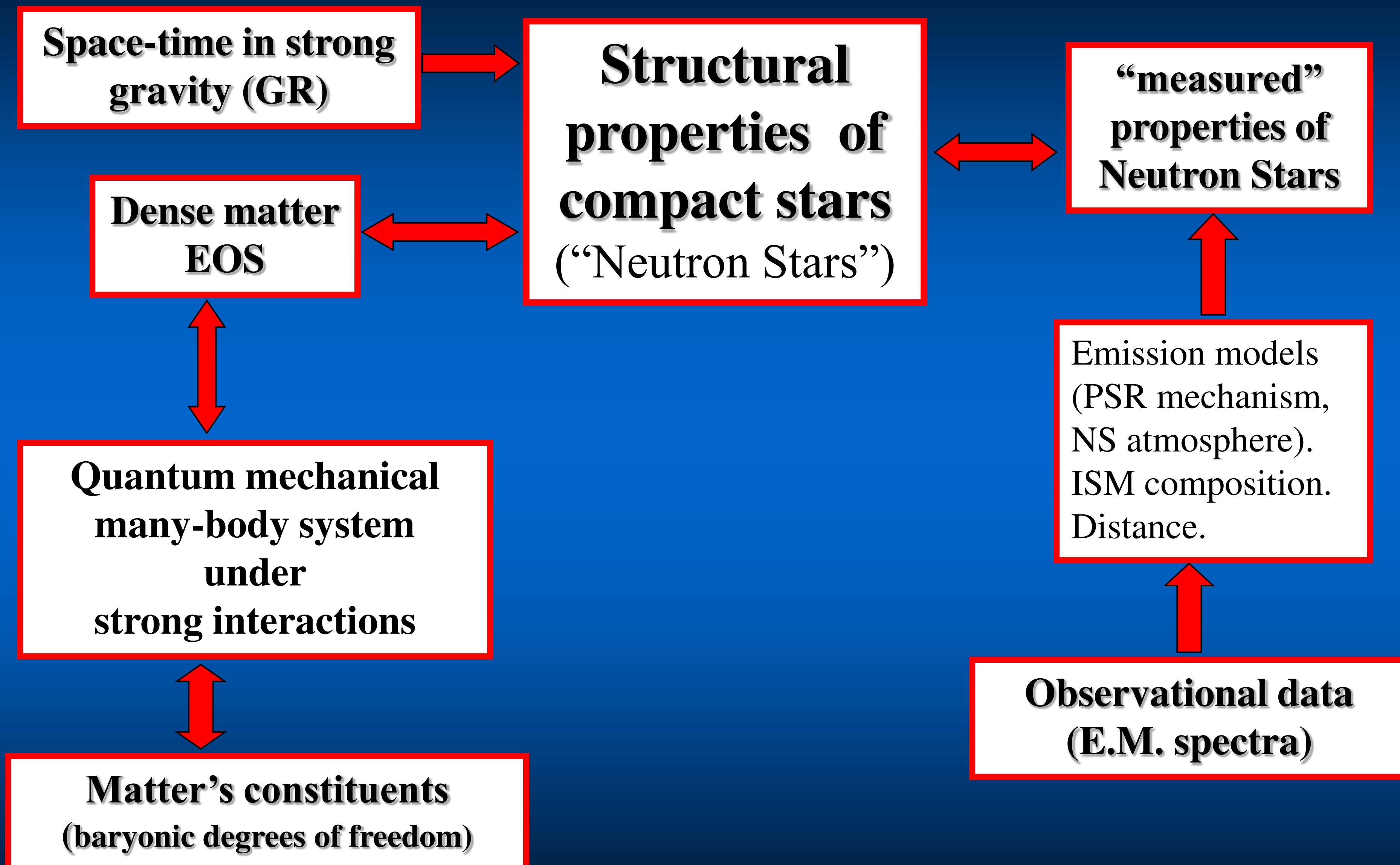
$\longrightarrow$ antisymmetric wave function for particle exchange $\rightarrow$ Pauli principle

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

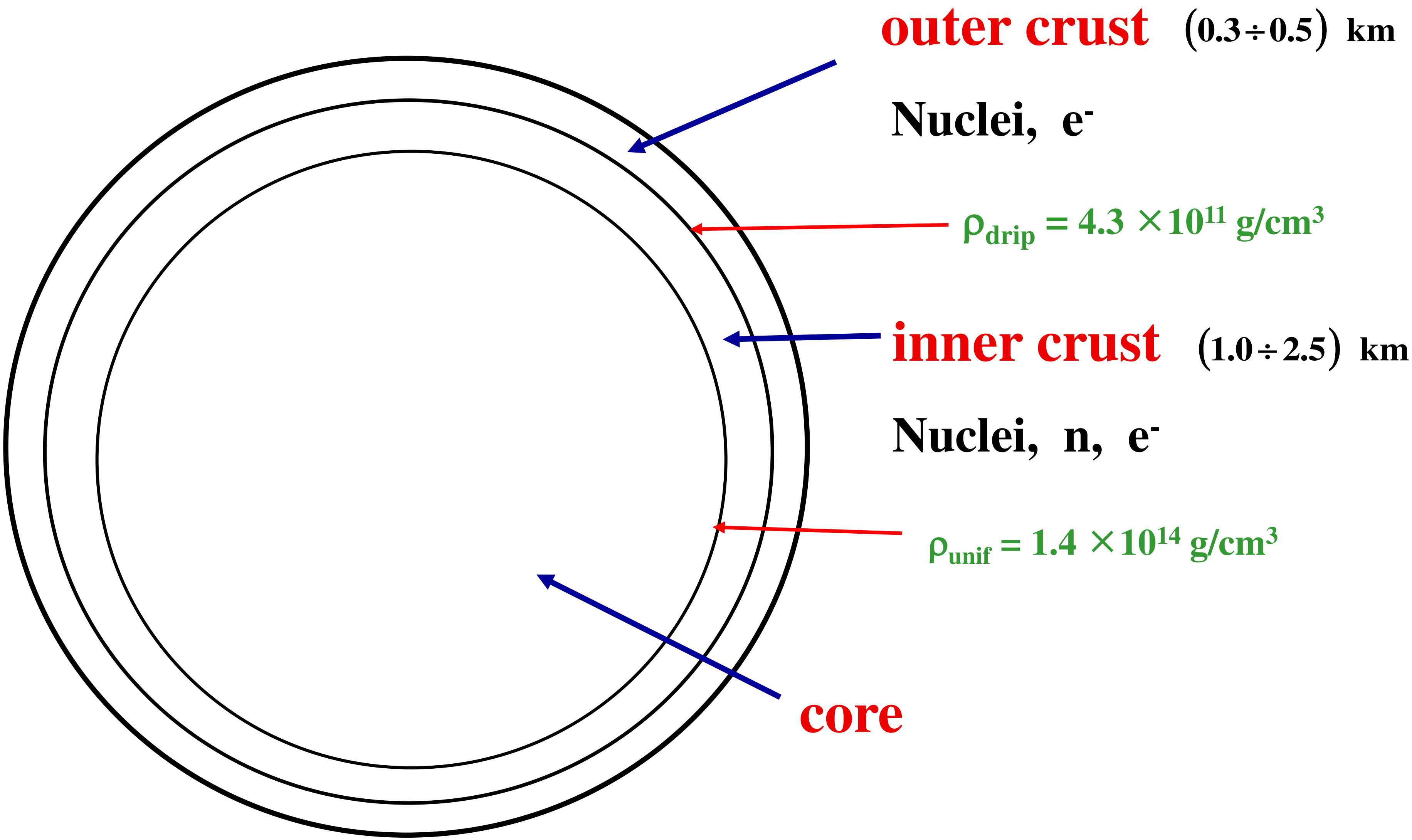
3) Weak interactions change the isospin and strangeness content of dense matter to minimize energy

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

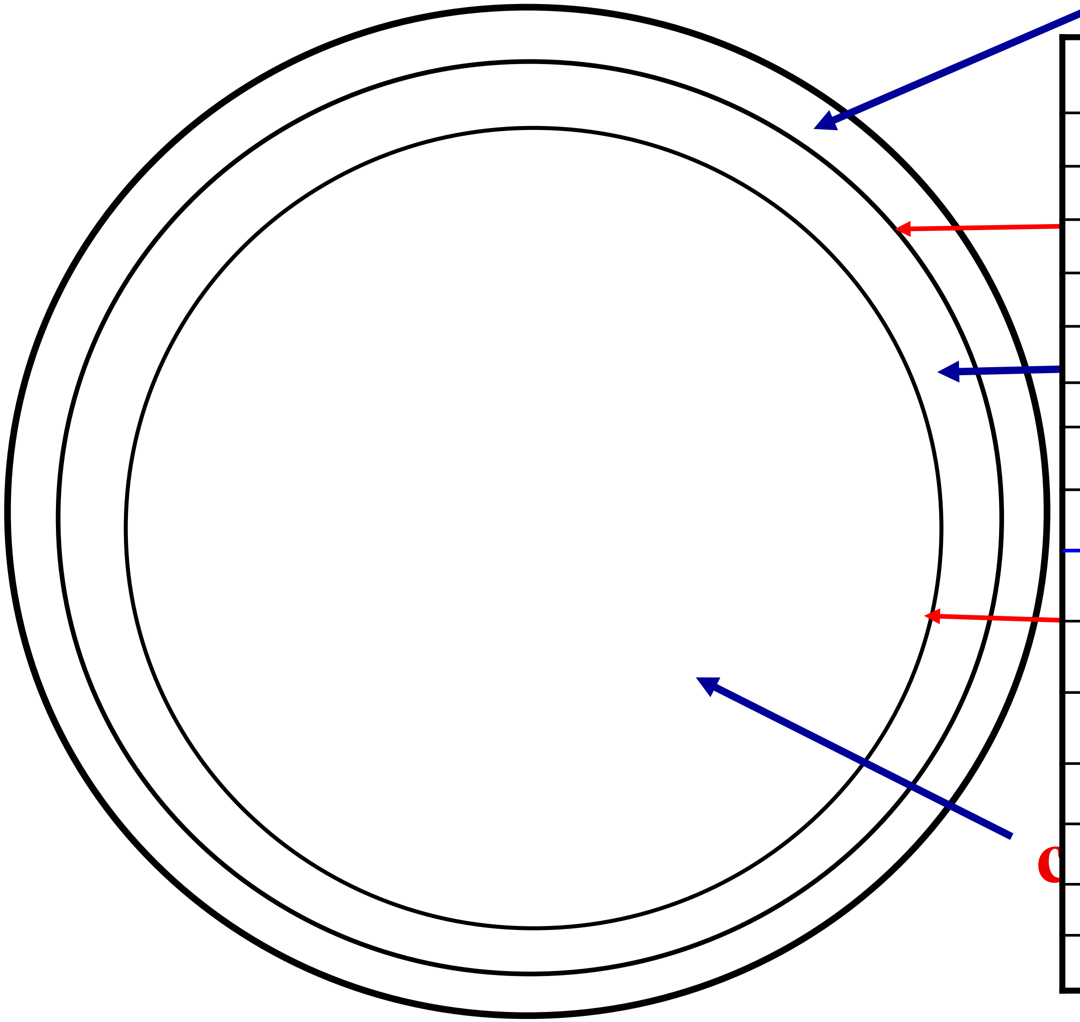
The ground state (minimum energy per baryon) of a system of **hadrons** and **leptons** with respect to their mutual **strong** and **weak interactions** at a given total baryon density n and temperature T = 0.


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)

Schematic cross section of a Neutron Star



Schematic cross section of a Neutron Star

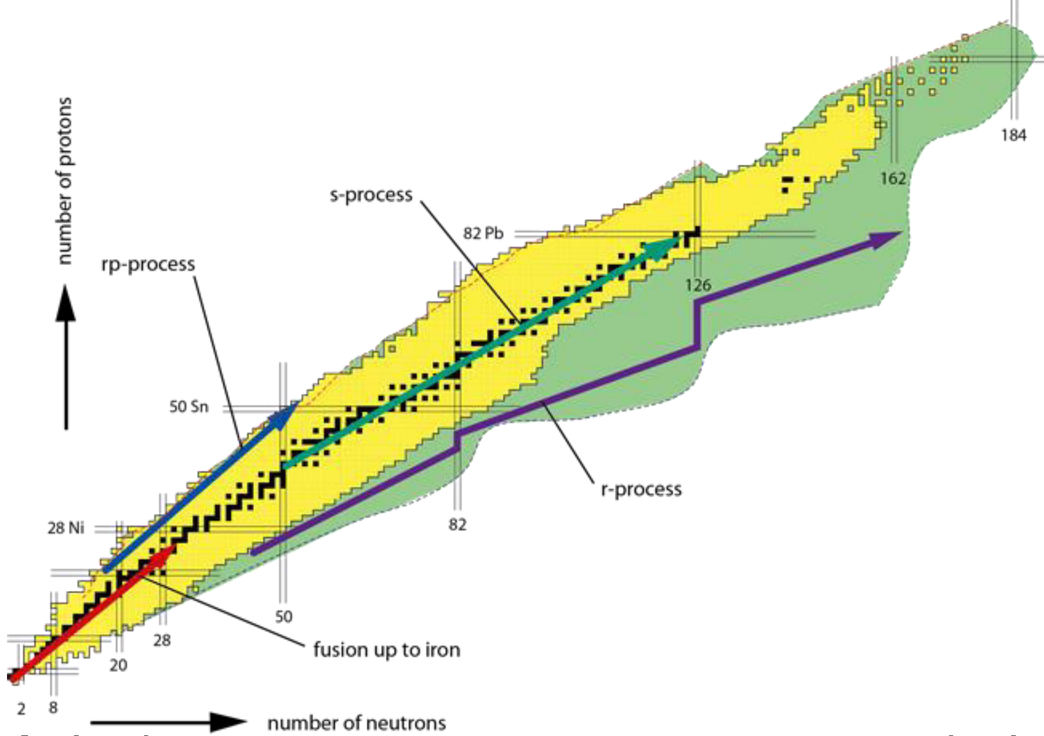


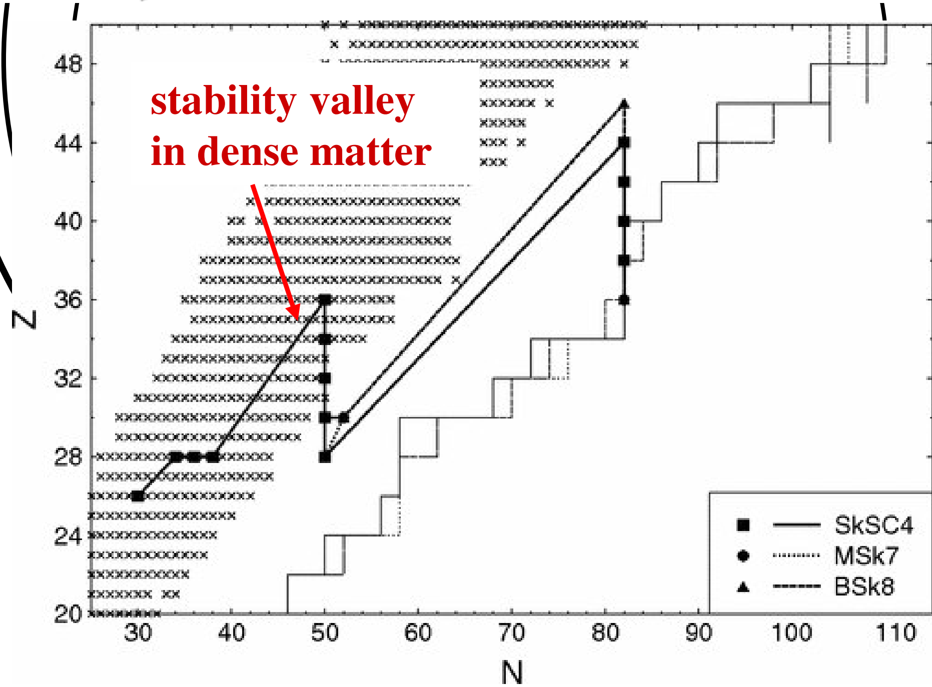
outer crust $(0.3 \div 0.5)$ km

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}

Pearson, Goriely, Chamel, Phys.Rev. C83 (2008) 065810
R. N. Wolf et al., Phys. Rev. Lett. 110 (2013) 041101

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





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^{124}Mo	42	82	2.11×10^{11}
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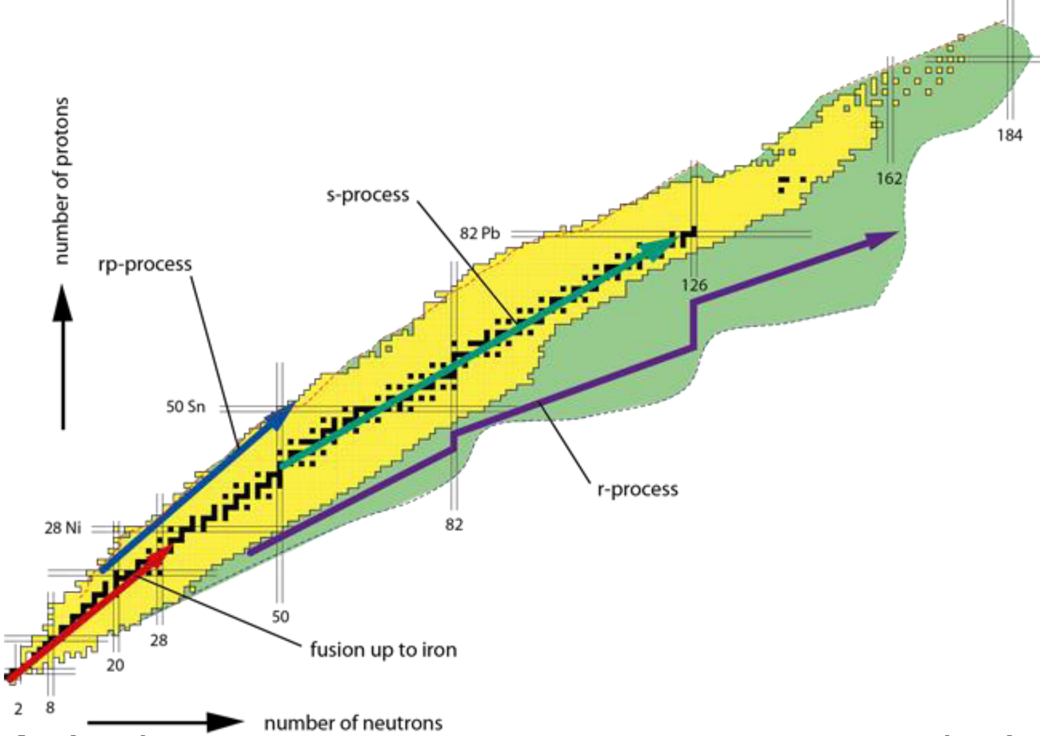
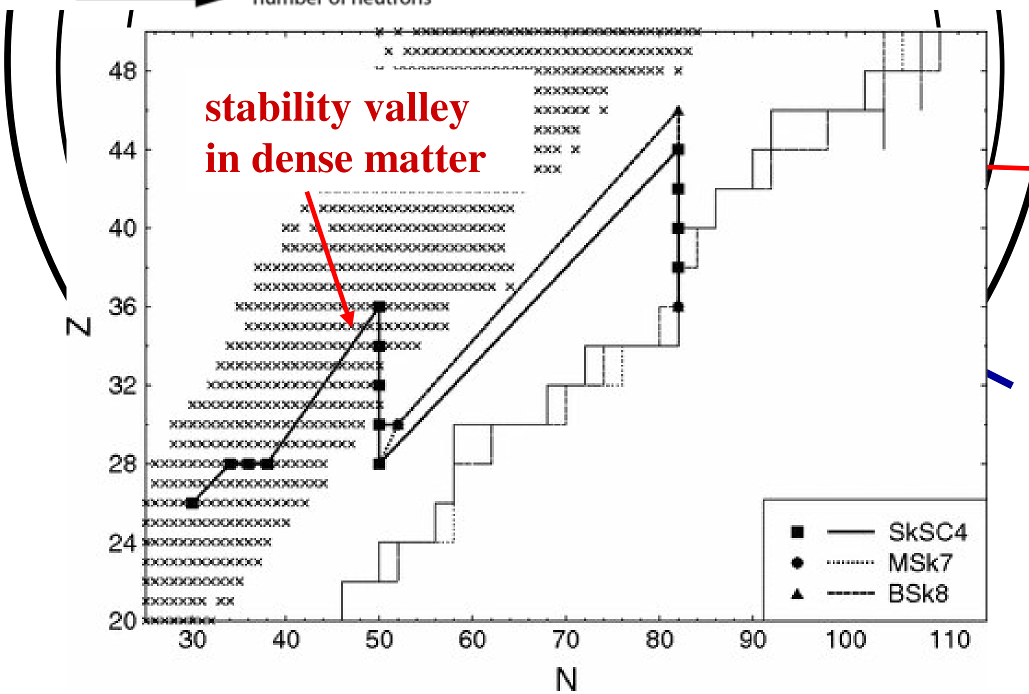
S.B. Rüster, M. Hempel, J. Schaffner-Bielich,
Phys. Rev. C73 (2006) 035804





Radioactive Ion Beam Facilities

SPES
exotic beams for science

Spiral2

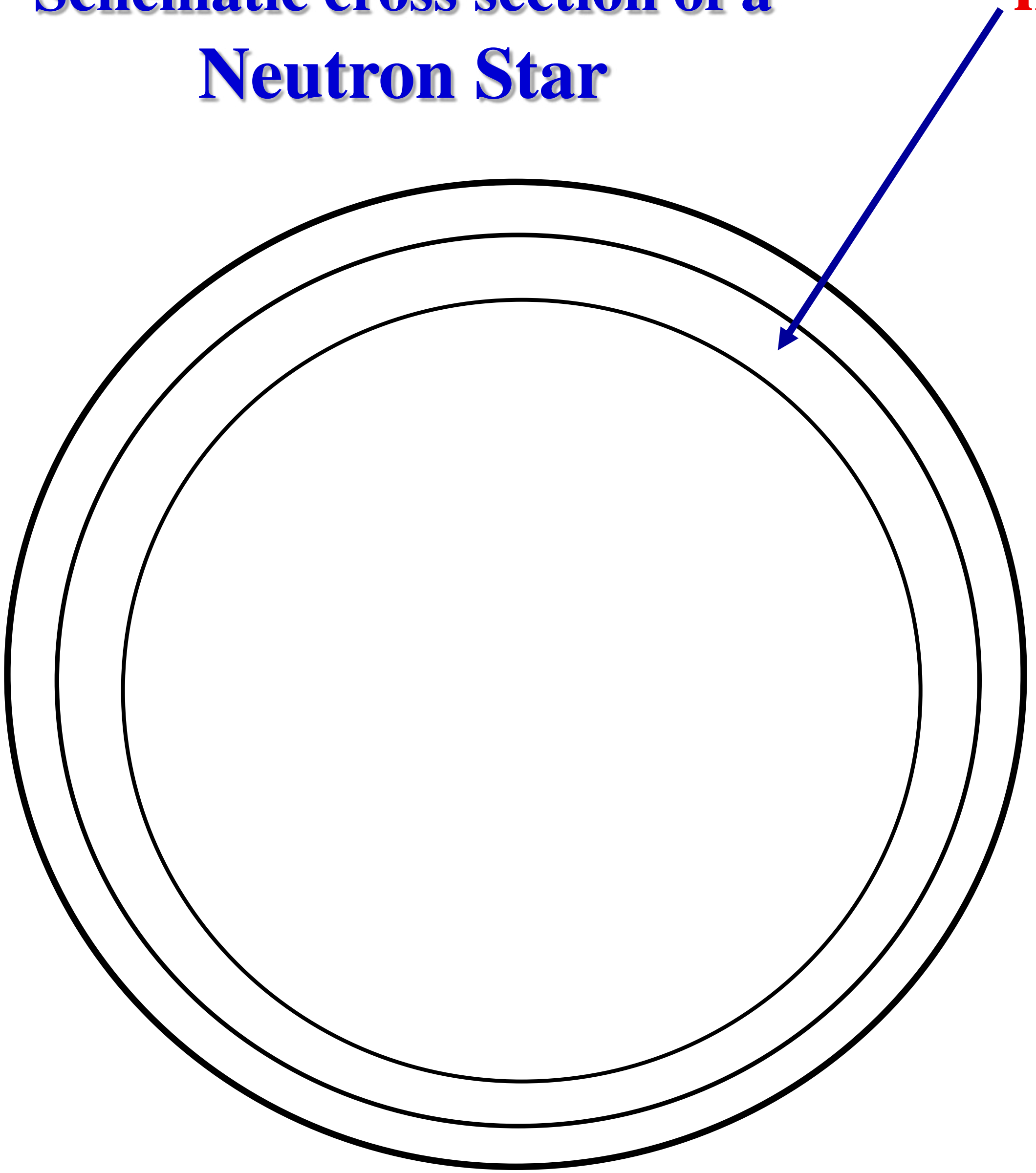
RIBF
RIKEN NISHINA CENTER
RIKEN Nishina Center for Accelerator-Based Science

FACILITY FOR
RARE ISOTOPE BEAMS

FAIR
Facility for Antiproton
and Ion Research
in Europe GmbH

EURISOL

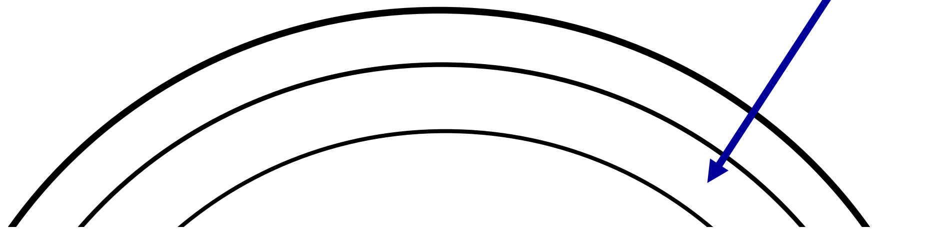
Schematic cross section of a
Neutron Star



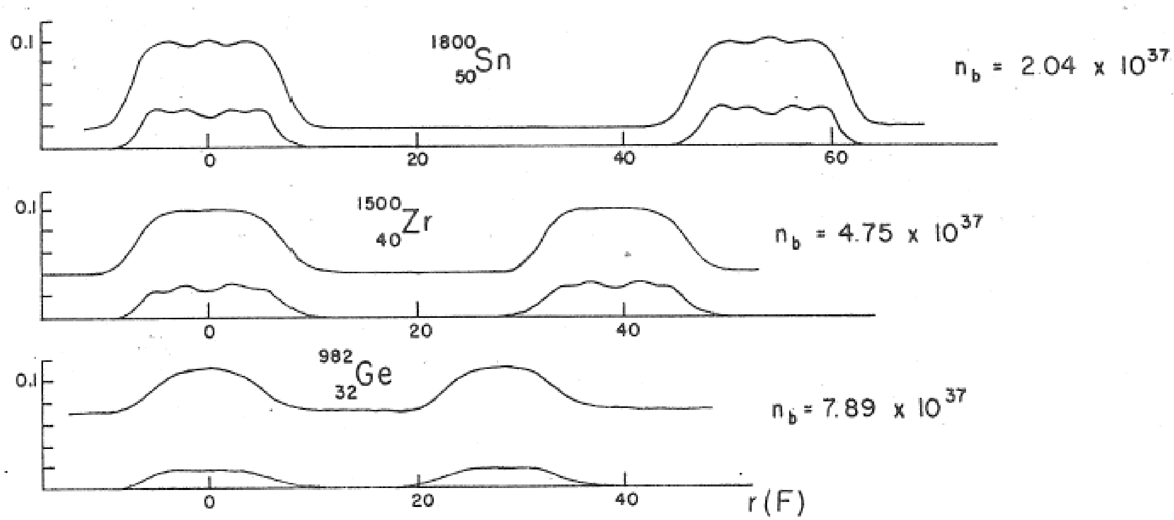
Schematic cross section of a Neutron Star

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

N. Chamel et al., Act. Phys. Pol. 46 (2015) 349

Schematic cross section of a Neutron Star

inner crust

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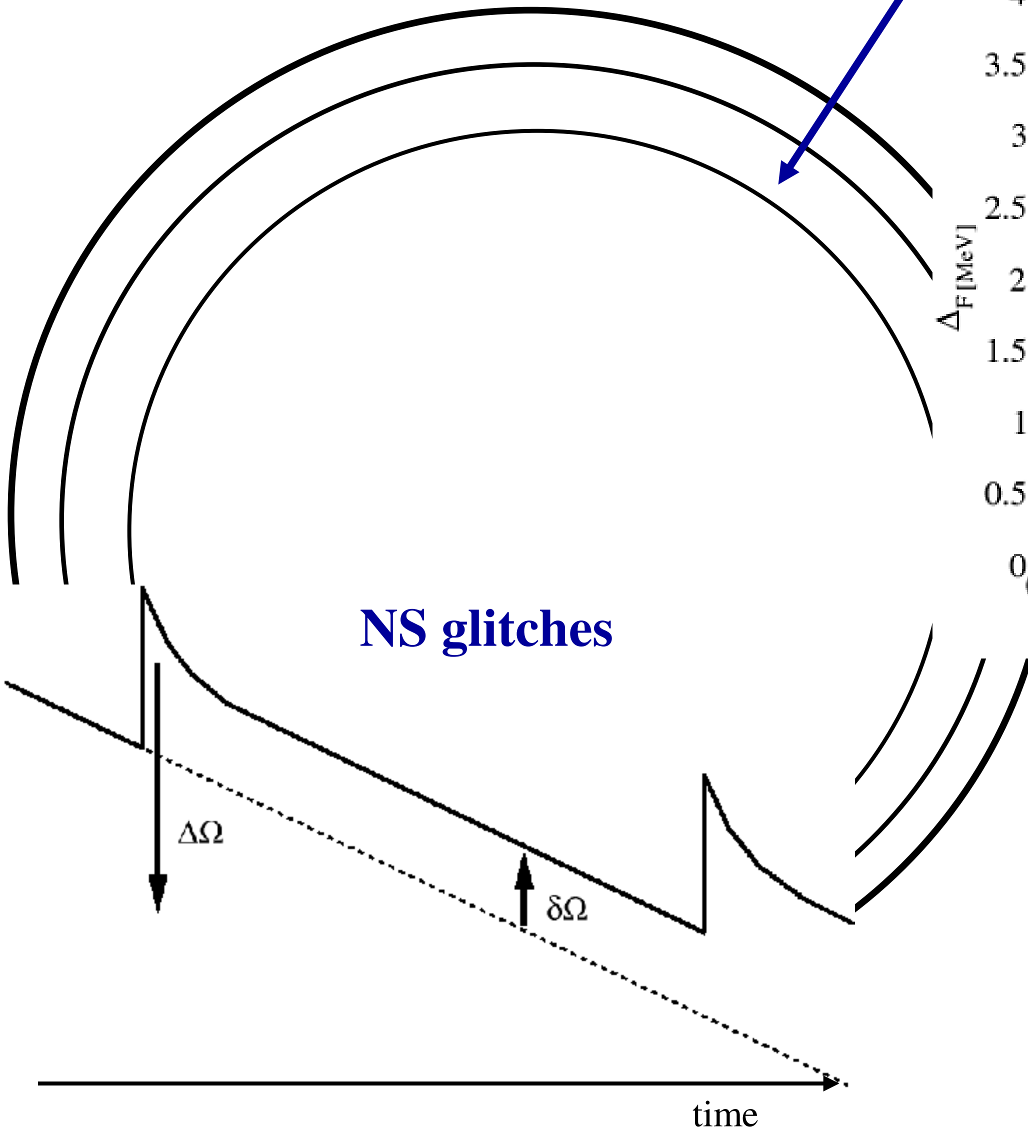
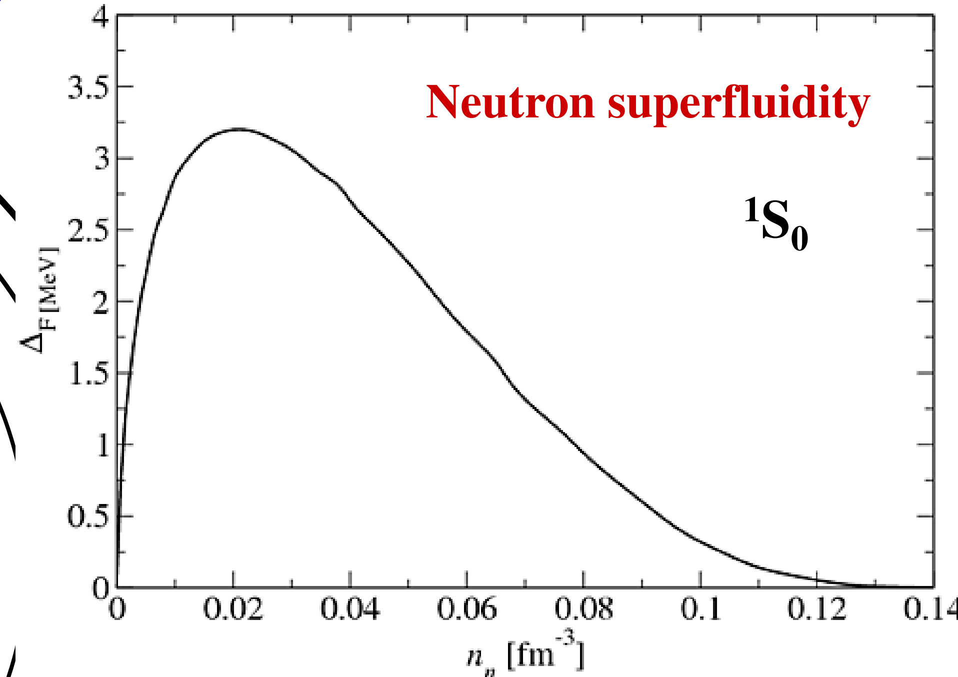




U. Lombardo, H.-J. Schulze,
Lect. Notes in Phys. vol. 578 (2001) Springer

Nucleon Stars

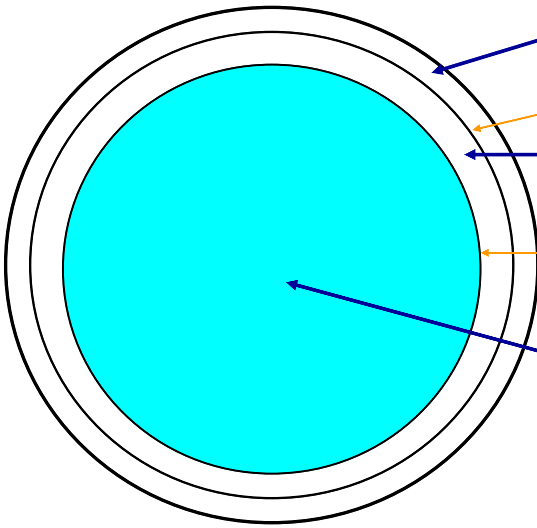
β-stable nuclear matter

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

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

$$\mu_e \geq m_\mu$$

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



- **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

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

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

$n = n_n + n_p$

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

Energy per nucleon for asymmetric nuclear matter

$$\tilde{E}(n,\beta) \equiv \frac{E(n,\beta)}{A} = \tilde{E}(n,0) + S_2(n)\beta^2 + S_4(n)\beta^4 + \ \ldots$$

$$S_k(n) = \frac{1}{k!}\left.\frac{\partial^k \tilde{E}(n,\beta)}{\partial \beta^k}\right|_{\beta=0}, \qquad k = 2,\ 4,\ \ldots..$$

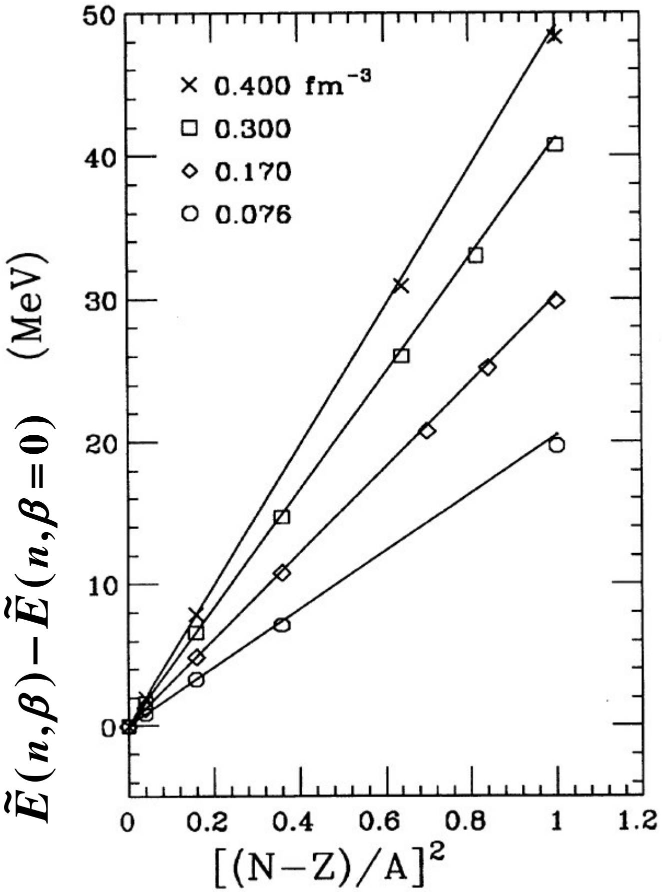
$$\boxed{E_{sym}(n) \equiv S_2(n)}$$

Nuclear symmetry energy

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

The "parabolic approximation" for the of asymmetric nuclear matter

I. Bombaci, U. Lombardo, Phys. Rev: C44 (1991)



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

up to β = 1 (i.e. $S_4(n) << E_{sym}(n)$)

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

β = 0 symmetric nucl matter

β = 1 pure neutron matter

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

In the “parabolic approximation”:

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

Chemical equil.+charge neutrality
(no muons)

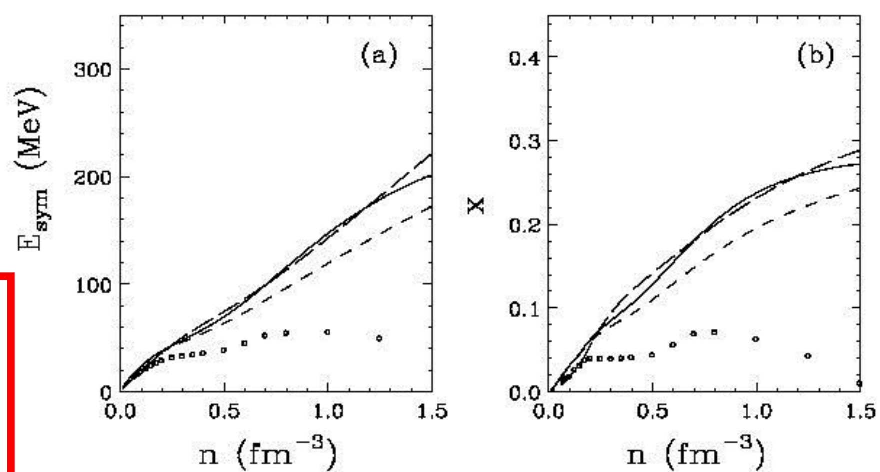
$$3\pi^2(\hbar c)^3 n\ x(n) - \left[4E_{sym}(n)(1-2x(n))\right]^3 = 0$$

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.

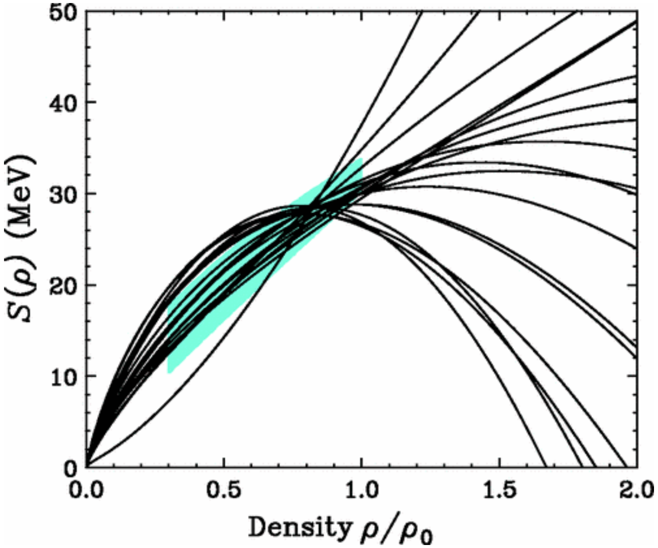
Symmetry en. **proton fraction**



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

Density dependence of the nuclear symmetry energy

$$S_2(n) = S_2(n_0) + L\left(\frac{n-n_0}{3n_0}\right) + \frac{1}{2!}K_{sym}\left(\frac{n-n_0}{3n_0}\right)^2 + \frac{1}{3!}Q_{sym}\left(\frac{n-n_0}{3n_0}\right)^3 + \ldots\ldots$$



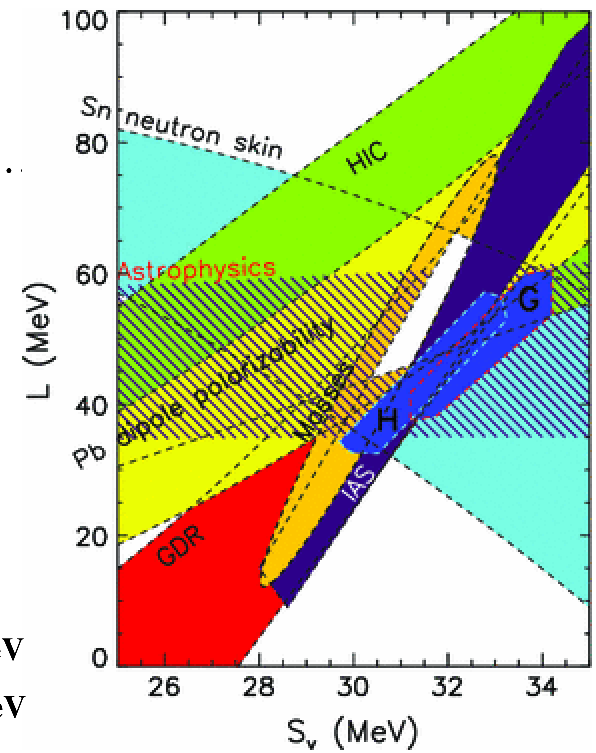
B.A. Brown, Phys. Rev. Lett. 85 (2000) 5296

$$L = 3n_0 \left.\frac{\partial S_2(n)}{\partial n}\right|_{n_0},$$

$$K_{sym} = (3n_0)^2 \left.\frac{\partial^2 S_2(n)}{\partial n^2}\right|_{n_0},$$

$$Q_{sym} = (3n_0)^3 \left.\frac{\partial^3 S_2(n)}{\partial n^3}\right|_{n_0}, \ldots$$

$E_{sym}(n_0)$ — L correlation



J. M. Lattimer, Gen. Rel. Grav. 46 (2014) 1713
J. M. Lattimer, Y. Lim, Astrophys. J. 771 (2013) 51

free Fermi gases

$$L = 2E_{sym}(n_0)$$

29.0 MeV $< S_v <$ 32.7 MeV

40.5 MeV $< L <$ 61.9 MeV

Probing the nuclear symmetry energy with heavy-ion collisions

Experiments: CHIMERA @ LNS

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

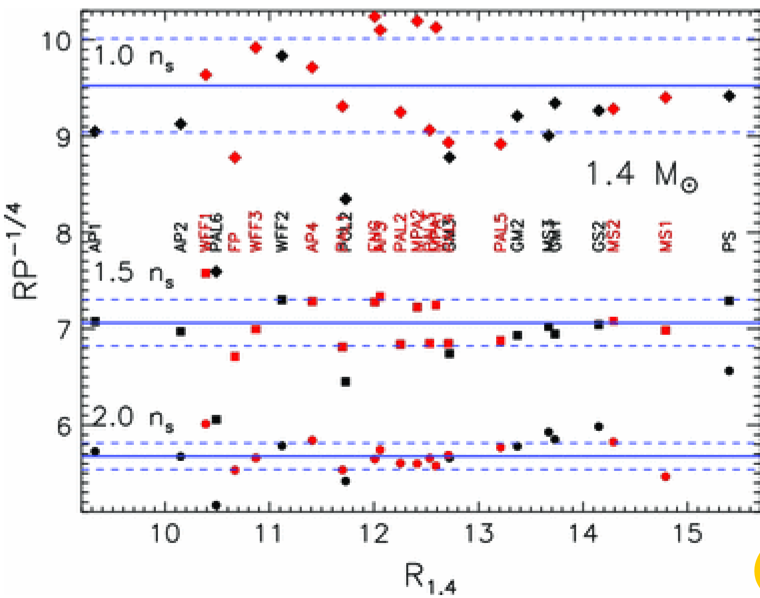
Theory:

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

Symmetry energy and Neutron Star Radius

Pressure in β-stable nuclear matter at the saturation density n_0

$$P(n_0) \approx \frac{1}{3} n_0 L \left[1 - \left(\frac{4E_{sym}(n_0)}{\hbar c} \right)^3 \frac{4 - \frac{3}{L} E_{sym}(n_0)}{3\pi^2 n_0} \right]$$



$$R_M = C(n, M) [P(n)]^{1/4}$$

J. M. Lattimer, M. Prakash, Astrophys. J. 550 (2001) 426

$M_{max} > 2.0\ M_\odot$

$$R_{1.4} = C(n_0, 1.4) [P(n_0)]^{1/4}$$

$$C(n_0, 1.4) = 9.52 \pm 0.49 \ \frac{\mathrm{km}}{(\mathrm{MeV/fm}^3)^{1/4}}$$

measured **L, $E_{sym}(n_0)$**

$$R_{1.4} = 11.9 \pm 1.2\ \ \mathrm{km}$$

J. M. Lattimer, Y. Lim, Astrophys. J. 771 (2013) 51

Microscopic approach to asymmetric nuclear matter EOS

Two-nucleon forces: V_{NN}

Parameters **fitted to NN scatering data** with **χ^2/datum ~1**

Three-nucleon forces: V_{NNN}

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

New generation of TNF models **(A. Kievsky et al., Phys. Rev. C 81 (2010) 044003)**

Parameters fitted to

- **binding energy of A = 3, 4 nuclei** **and**
- **neuron-deuteron doublet scattering length:** $^2a_{nd} = (0.645 \pm 0.003 \pm 0.007)\,\mathrm{fm}$

$^2a_{nd}$ is **not** reproduced by many of the present TNF model

	AV18	AV18/UIX	
$^2a_{nd}$	1.258	0.578	fm

	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

Microscopic EOS for nuclear matter:
Brueckner-Bethe-Goldstone theory

$$G_{\tau\tau'}(\omega) = V + V \sum_{k_a k_b} \frac{|k_a k_b\rangle Q_{\tau\tau'} \langle k_a k_b|}{\omega - e_\tau(k_a) - e_{\tau'}(k_b) + i\varepsilon} G_{\tau\tau'}(\omega)$$

$$e_\tau(k) = \frac{\hbar^2 k^2}{2m} + U_\tau(k)$$

$$U_\tau(k) = \Re\left\{ \sum_{\tau'} \sum_{k'} \langle kk' | G_{\tau\tau'}(e_\tau(k) + e_{\tau'}(k')) | kk' \rangle_A \right\}$$

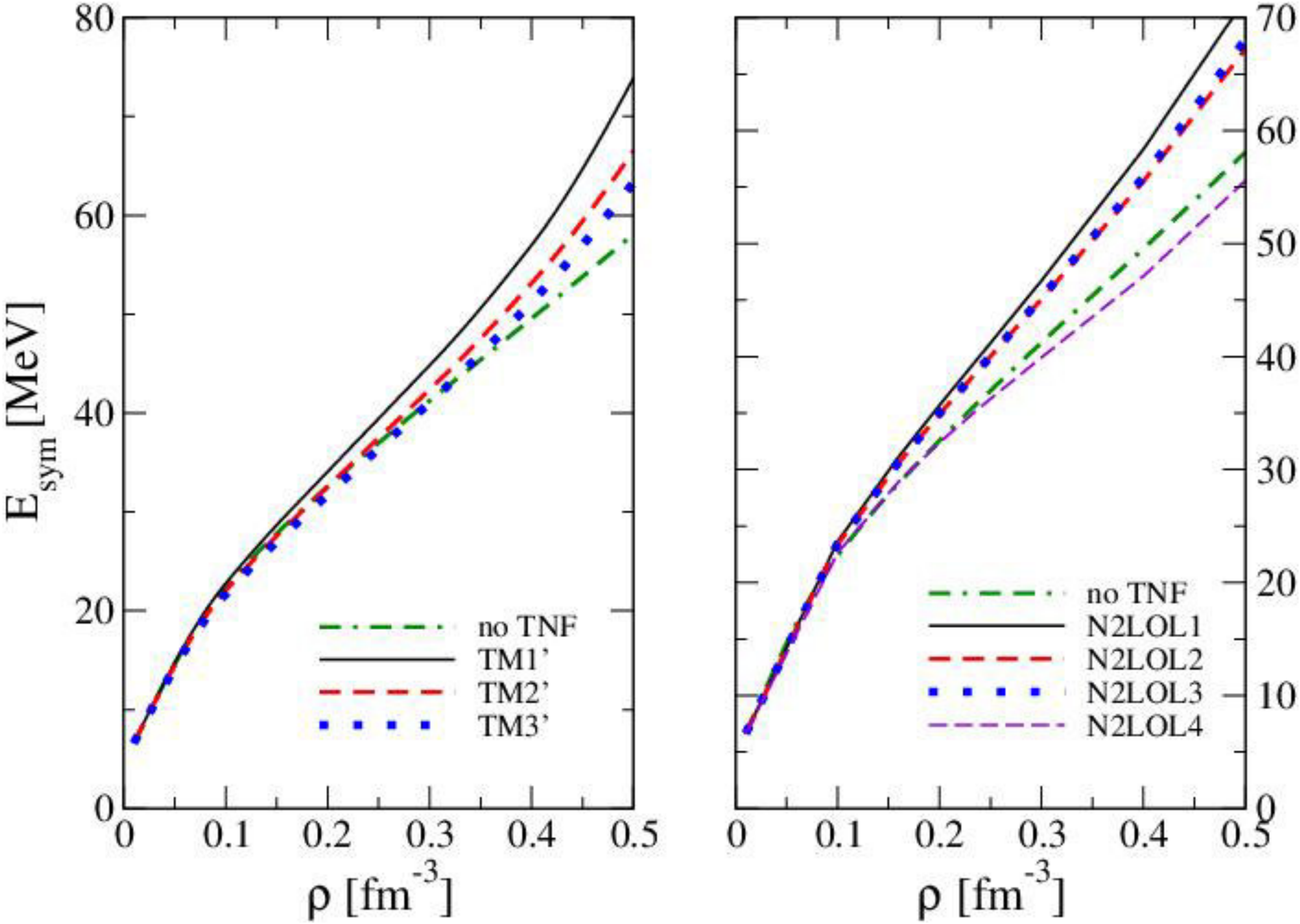
Energy per baryon in the Brueckner-Hartree-Fock (BHF) approximation

$$\tilde{E}(n_n, n_p) \equiv \frac{E}{A} = \frac{1}{A}\left\{ \sum_\tau \sum_k \frac{\hbar^2 k^2}{2M} + \frac{1}{2} \sum_\tau \sum_k U_\tau(k) \right\}$$

$$n_n = \frac{1}{2}(1+\beta)n$$

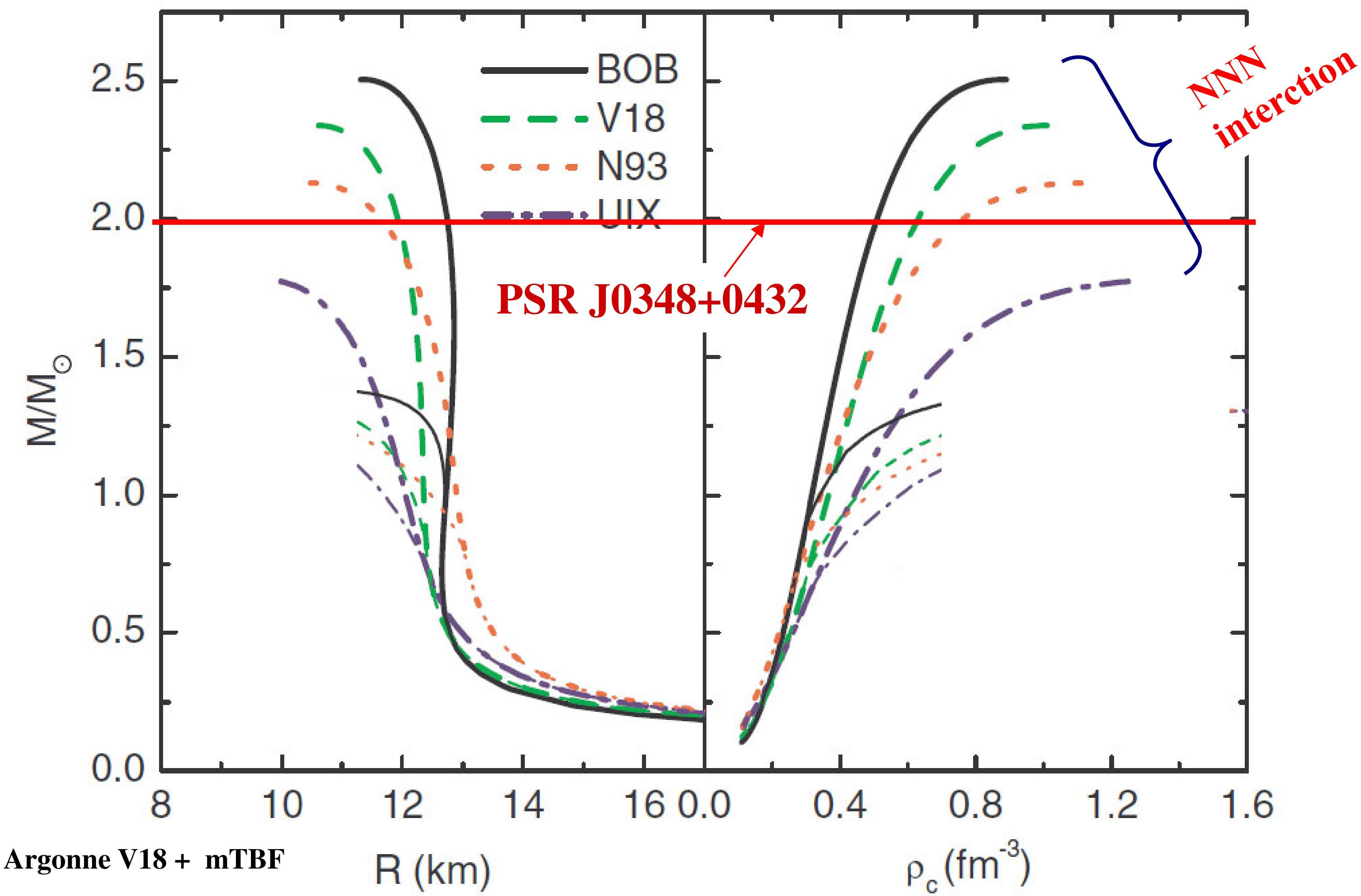
$$n_p = \frac{1}{2}(1-\beta)n$$

Symmetry energy (BHF: Av18+TNF)



D. Logoteta, I. Vidaña, I. Bombaci, A. Kievsky, Phys. Rev. C 91 (2015) 064001

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

Message taken from **Nucleon Stars**

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

NN interactions essential to have "large" stellar mass

For a free neutron gas $M_{max} = 0.71\ \mathbf{M_{\odot}}$

(Oppenheimer and Volkoff, 1939)

NNN interactions essential

(i) to reproduce the correct empirical saturation point of nuclear matter

(ii) to reproduce measured neutron star masses, i.e. to have $\mathbf{M_{max} > 2\ M_{\odot}}$

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": $n_c \approx (4 - 10)\, n_0$

  ($n_0 = 0.17$ 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)

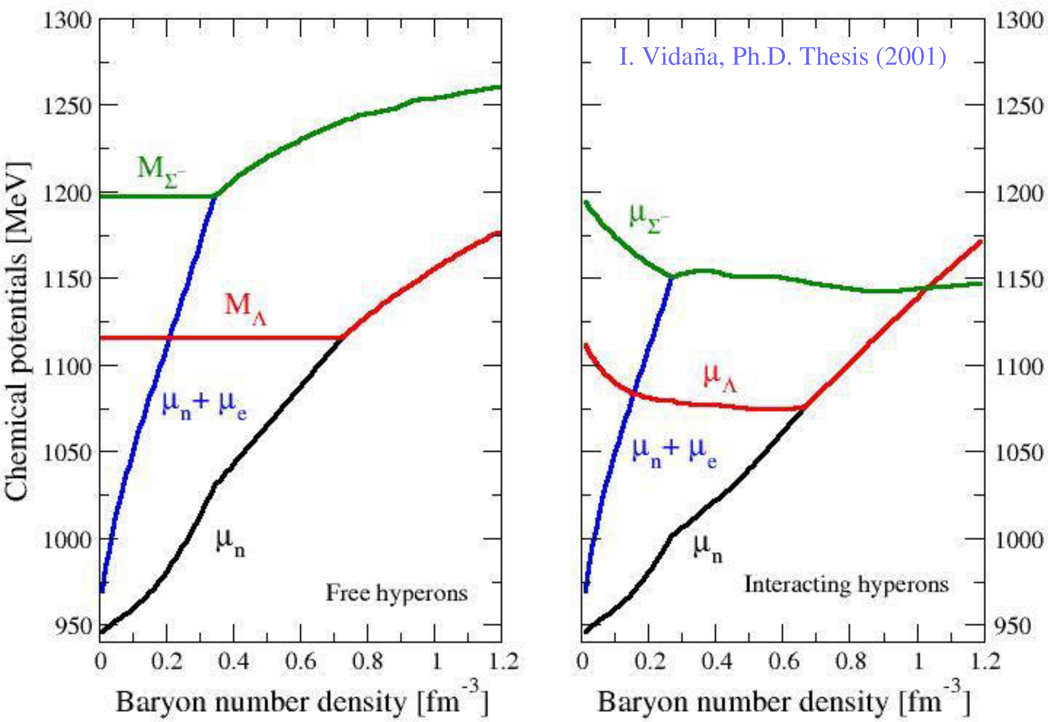
In Greek mythology Hyperion (Ὑπερίων) was one of the twelve Titan son of Gaia and Uranus

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.

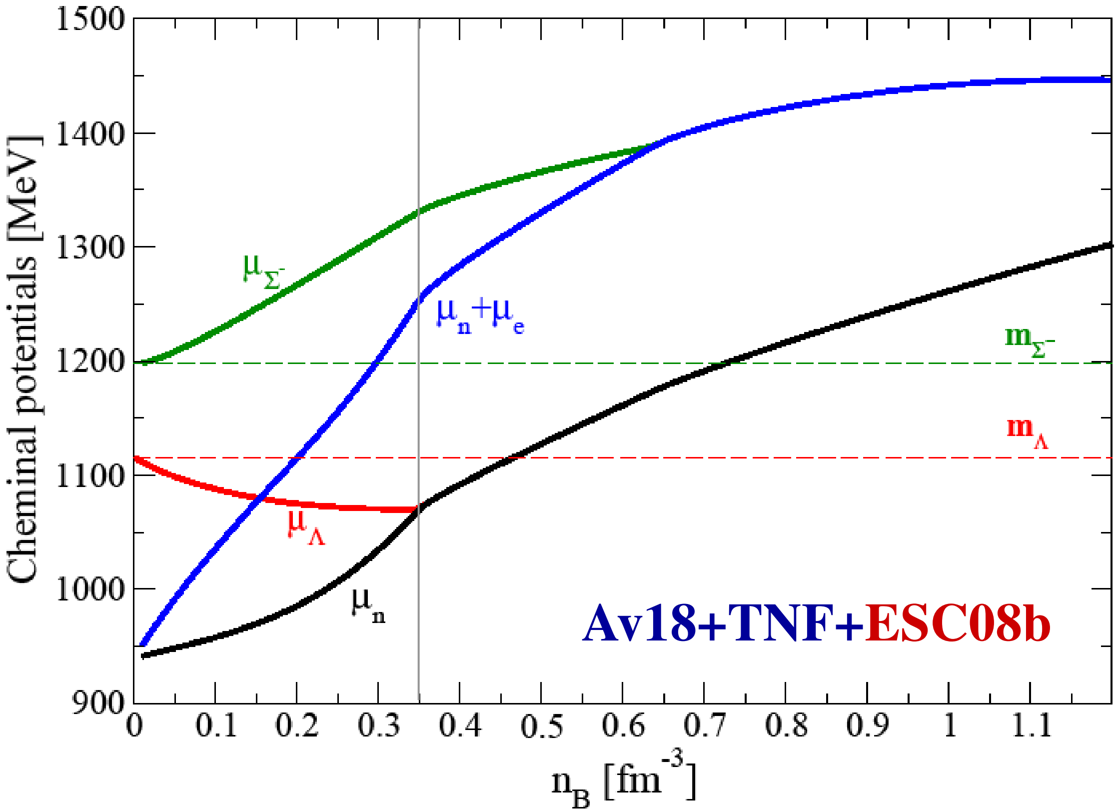


$$\mu_p = \mu_n - \mu_e = \mu_{\Sigma^+}$$
$$\mu_n = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_\Lambda$$
$$\mu_n + \mu_e = \mu_{\Sigma^-} = \mu_{\Xi^-}$$
$$\mu_\mu = \mu_e$$
$$n_p + n_{\Sigma^+} = n_e + n_\mu + n_{\Sigma^-} + n_{\Xi^-}$$

Av18+TNF+NSC97e

$U_{\Sigma^-}(k=0, n_0) = -25$ MeV

$$m_\Lambda = 1115.7 \text{ MeV} \qquad \mu_n = \mu_\Lambda$$
$$m_{\Sigma^-} = 1197.5 \text{ MeV} \qquad \mu_n + \mu_e = \mu_{\Sigma^-}$$



D. Logoteta, I. Bombaci (2014)

TNF: Z H.. Li, U. Lombardo, H.-J. Schulze. W. Zuo, Phys. Rev. C 77 (2008)

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**

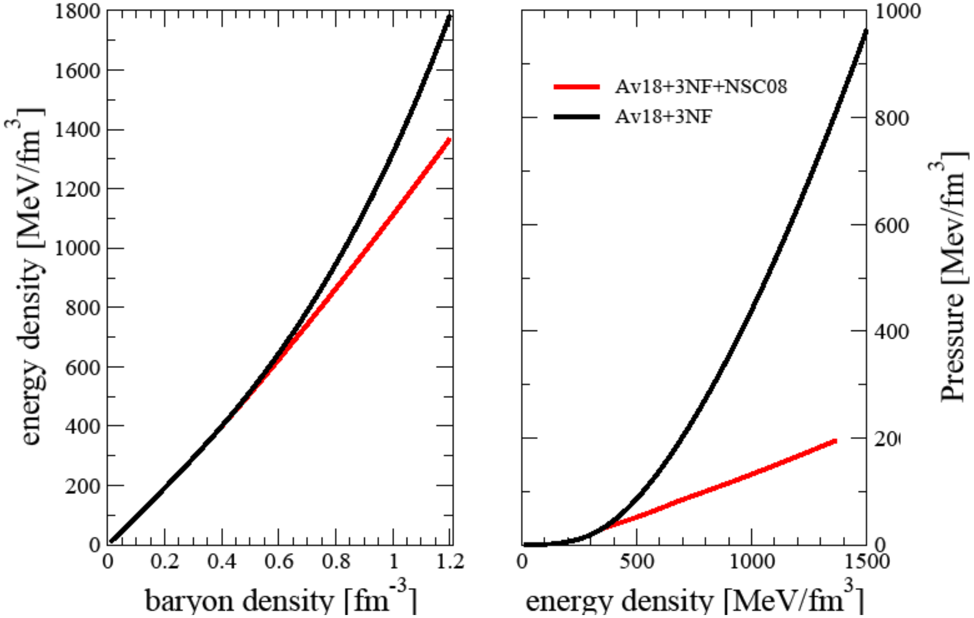
Hypernuclear experiments

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

other approaches to hyperonic matter EOS

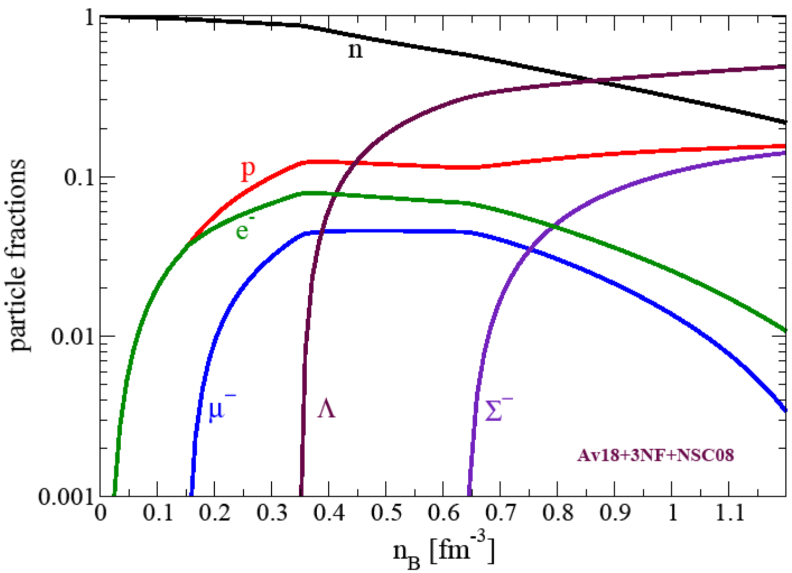
Relativistic Mean Fiels Models (Glendenning 1995, Knorren et al 1995, Schaffner-Bielich Mishustin 1996)
Skyrme-like potential models (Balberg and Gal 1997)
Chiral Effective Lagrangians (Hanauske et al 2000)
Quark-meson coupling model (Pal, Hanuske, Zakout, Stoker, Greiner, 1999)

Equation of State of Hyperonic Matter

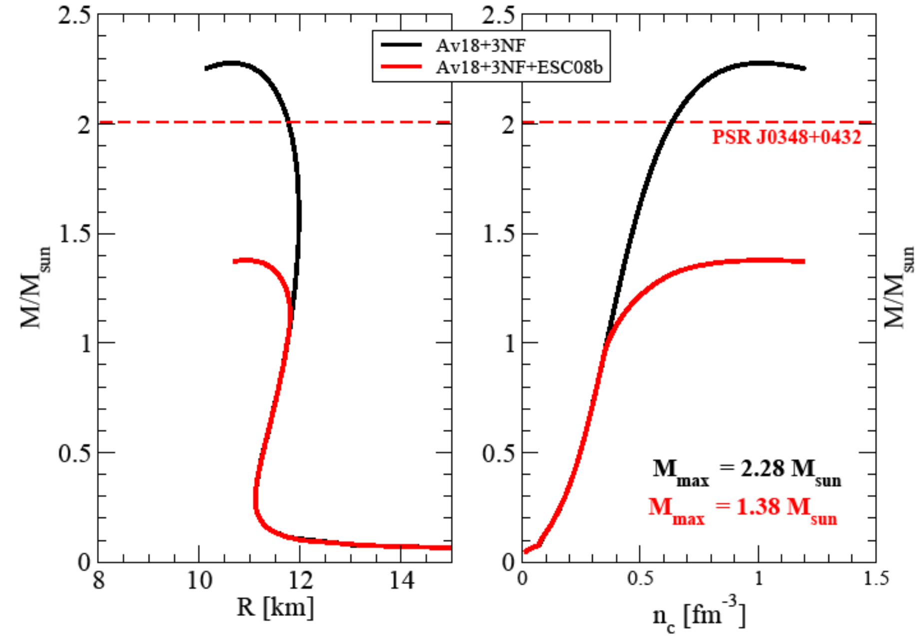


hyperons produce a strong softening of the EOS

Particle fractions



Stellar mass

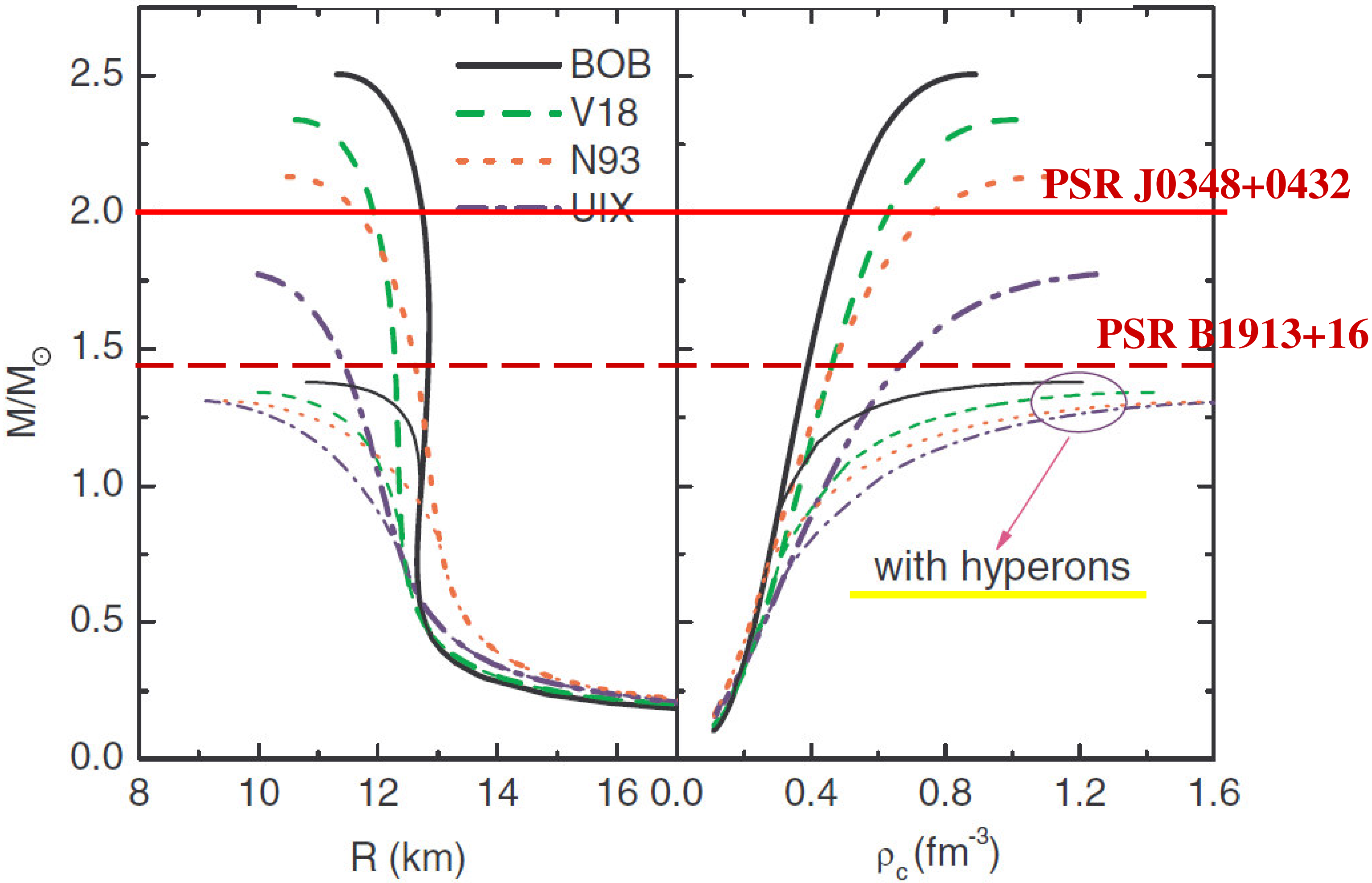


D. Logoteta, I. Bombaci (2014)

The stellar mass-radius relation

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

interaction: NN + NY + YY + NNN



NY,YY: Nijmegen NSC89 potential (Maessen et al, Phys. Rev. C 40 (1989)

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**

Neutron Stars in the QCD phase diagram

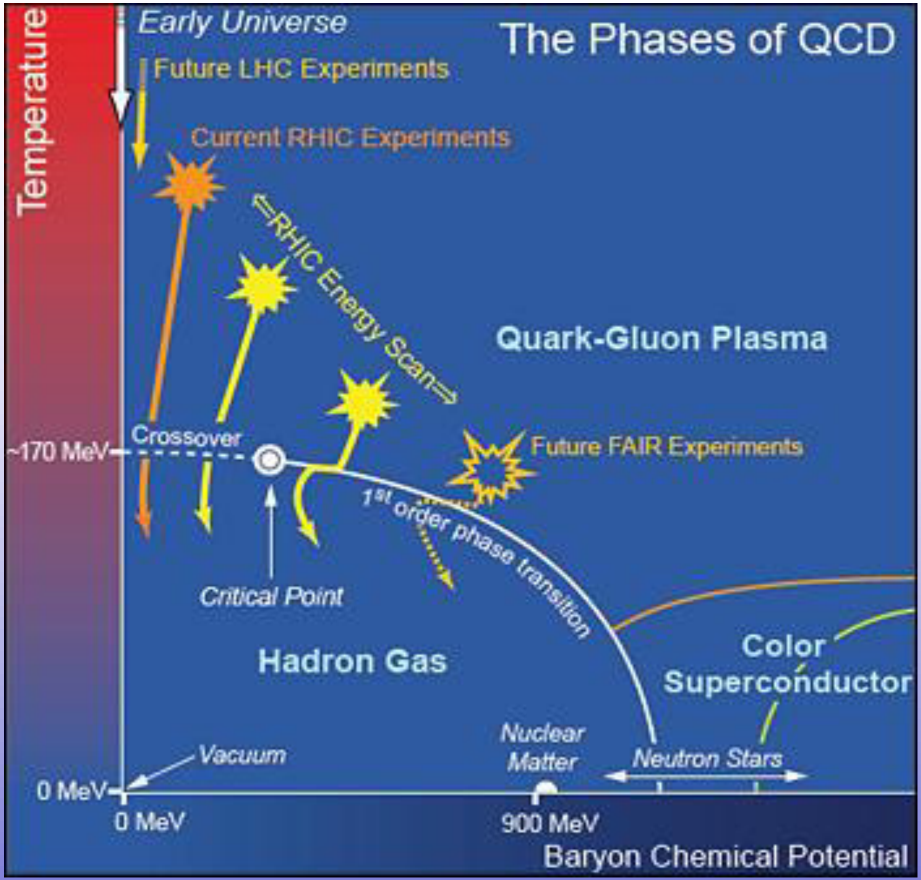
Lattice QCD
at μ_b=0 and finite T

► 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

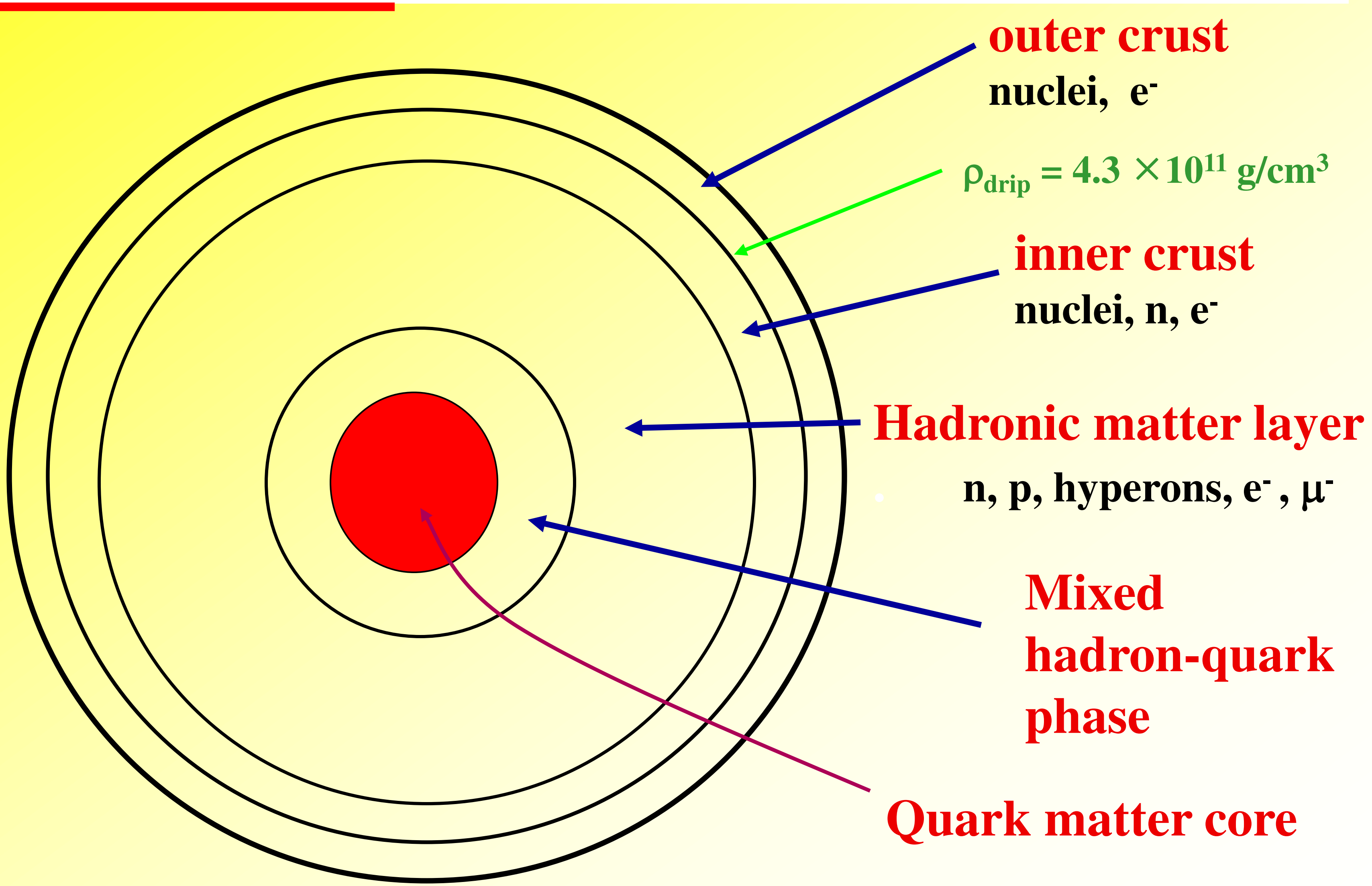


Neutron Stars: high μ_b and low T

Lattice QCD calculations are presently not possible
Quark deconfinement transition expected of the first order
Z. Fodor, S.D. Katz, Prog. Theor Suppl. 153 (2004) 86

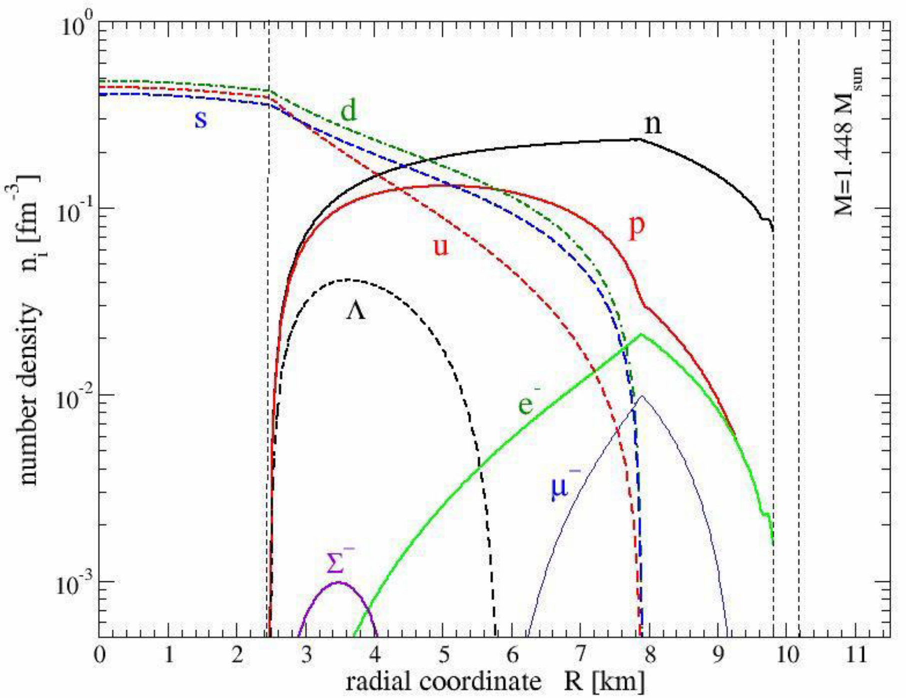
"A link between lattice QCD and measured neutron star masses"
I. Bombaci, D. Logoteta, Mont. Not. Royal Astron. Soc. 433 (2013) L79

Hybrid Stars (neutron stars with a quark matter core)

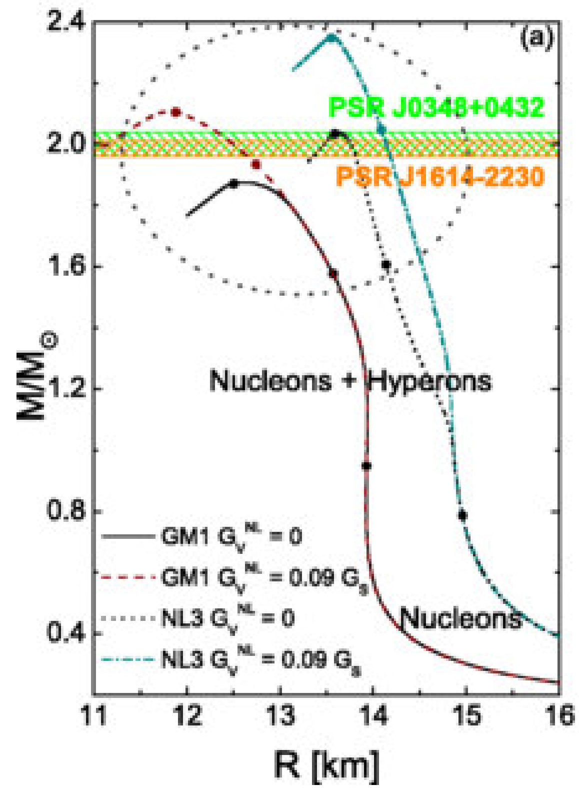


Hybrid Stars (neutron stars with a quark matter core)

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



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



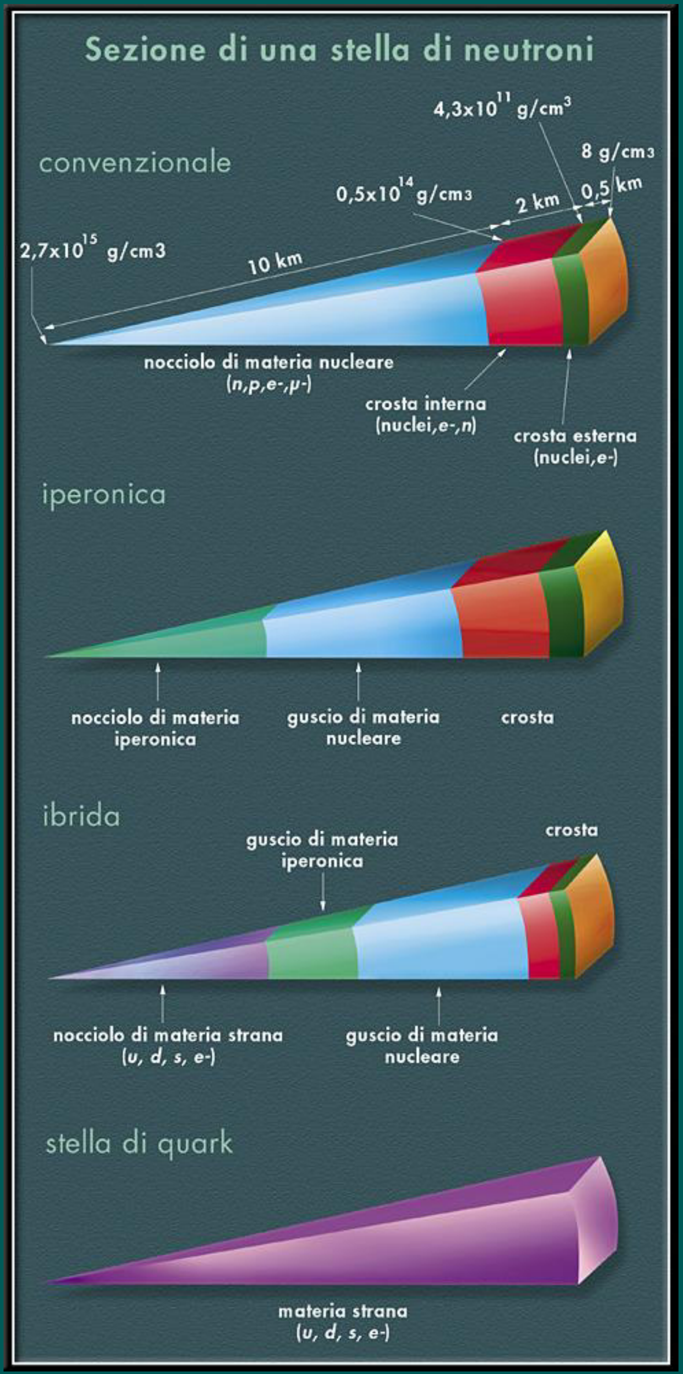
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, Phys. Rev. C 89 (2014) 015806

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



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

“Neutron Stars”

Nucleon Stars

Hyperon Stars

Hybrid Stars

Strange Stars

Quark matter nucleation inNeutron Stars

1st order phase transitions are triggered by the **nucleation** of a **critical size drop** of the **new (stable) phase** in a **metastable mother phase**

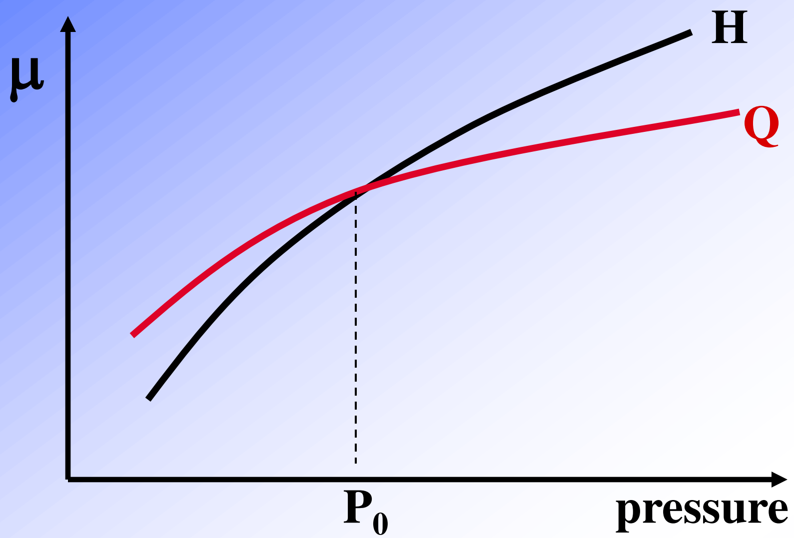
Virtual drops of the stable phase are created by small localized **fluctuations** in the state variables of the **metastable phase**

<u>A common event in nature</u>, e.g.:

- **fog or dew formation in supersaturated vapor**
- **ice formation in supercooled water**

Pure and distilled water at standard pressure (100 kPa) can be supercooled down to a temperature of -48.3 C. In the tempearture range (-48.3 □ 0) C, water is in a metastable phase and ice cristals will form via a nucleation process.

1st order phase transitions are triggered by the **nucleation** of a **critical size drop** of the **new (stable) phase** in a **metastable mother phase**



In **NS cores** when **$P(r=0) > P_0$**

Hadronic matter phase is metastable

stable Quark matter phase
formed by a **nucleation process**

μ_j = Gibbs' energy per baryon
(j-phase average chemical pot.) j = H, Q

Gibbs' criterion for phase equilibrium

$$\mu_H = \mu_Q \equiv \mu_0$$

$$T_H = T_Q \equiv T$$

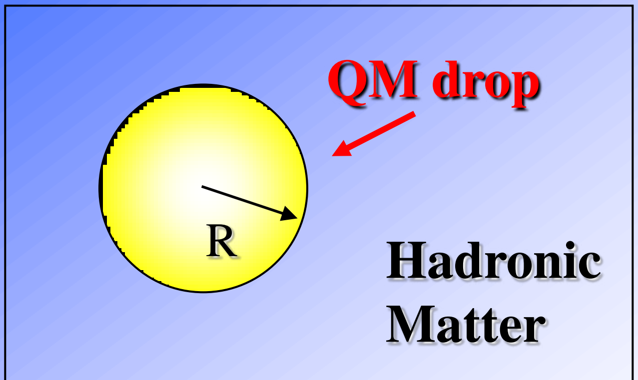
$$P(\mu_H) = P(\mu_Q) \equiv P(\mu_0) \equiv P_0$$

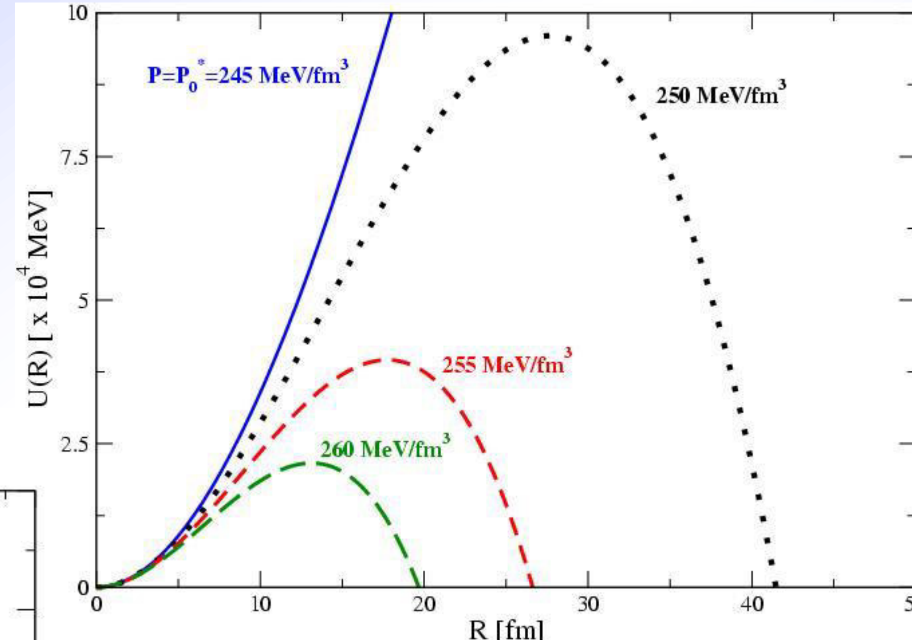
$$\mu_H = \frac{\varepsilon_H + P_H - s_H T}{n_{b,H}}$$

$$\mu_Q = \frac{\varepsilon_Q + P_Q - s_Q T}{n_{b,Q}}$$

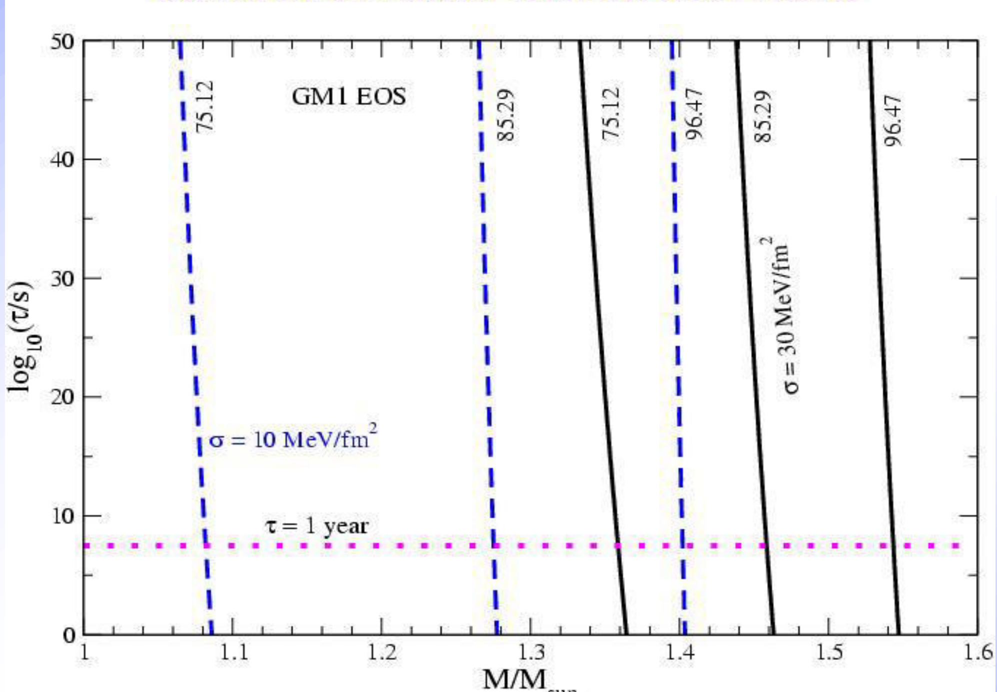
Quantum nucleation theory

I.M. Lifshitz and Y. Kagan, 1972; K. Iida and K. Sato, 1998





Hadronic Star mean-life time



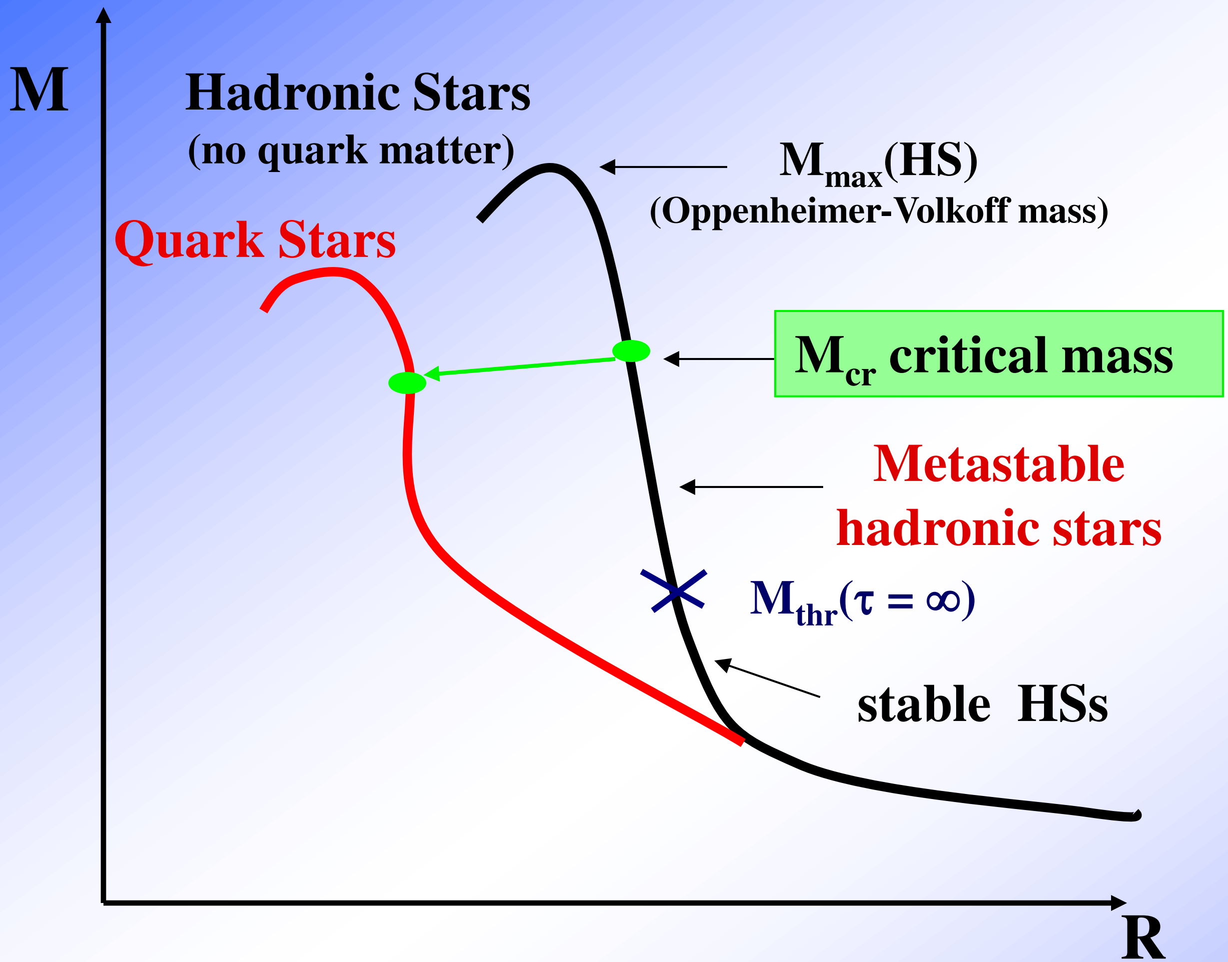
$$U(R) = (4/3)\pi\, R^3\, n_{Q*}\, (\mu_{Q*} - \mu_H) + 4\pi\sigma\, R^2$$

I. Bombaci, I. Parenti, I. Vidaña,
Astrophys. Jour. 614 (2004) 314

Astrophysical consequences of the **nucleation process of quark matter (QM)** in the **core of massive pure hadronic compact stars** (“Hadronic Stars”, HS)

Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, G. Lugones, I. Vidaña, Astron. &Astrophys. 462 (2007) 1017
I. Bombaci, P.K. Panda, C. Providencia, I. Vidaña, Phys. Rev. D 77 (2008) 083002
I. Bombaci, D. Logoteta, P.K. Panda, C. Providencia, I. Vidaña, Phys. Lett. B 680 (2009) 448
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, Astr. and Astrophys. 528 (2011) A71

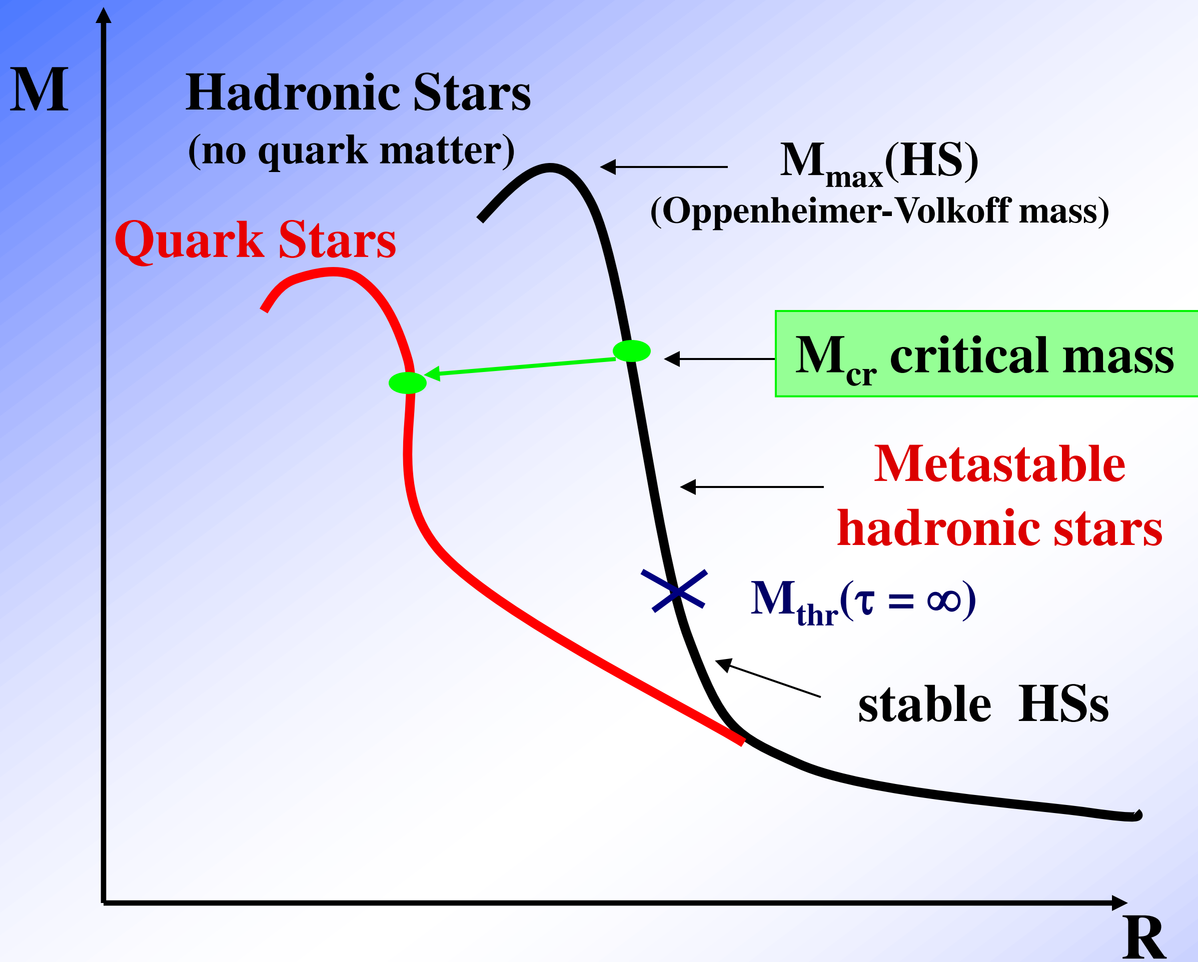
Metastability of Hadronic Stars



Hadronic Stars above a threshold value of their gravitational mass are **metastable** to the **conversion** to **Quark Stars (QS)** (hybrid stars or strange stars)

Berezhiani, Bombaci, Drago, Frontera, Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, G. Lugones, I. Vidaña, Astron. &Astrophys. 462 (2007) 1017

Metastability of Hadronic Stars



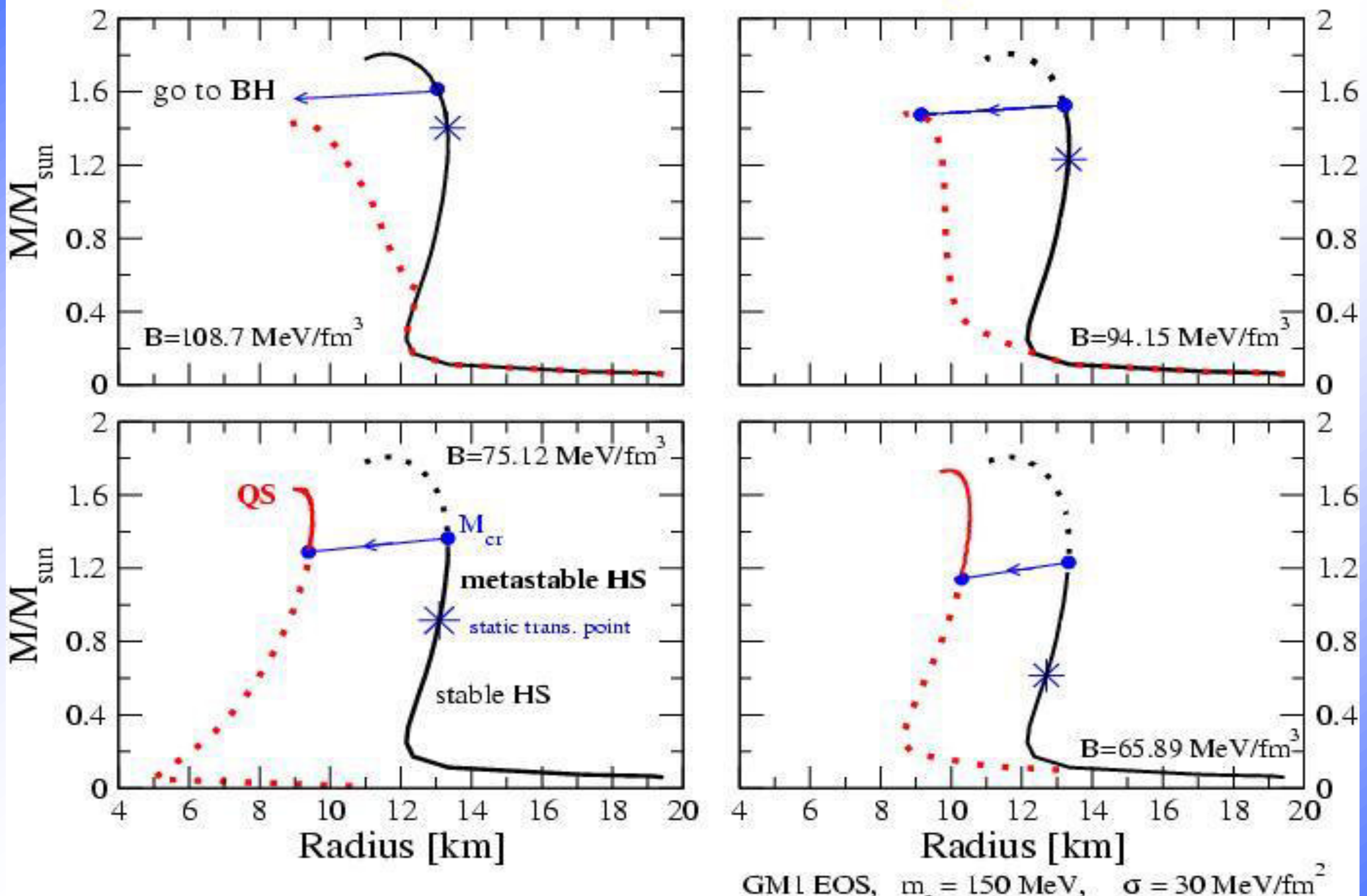
- **M_{cr} , critical mass of hadronic stars.**
- **Two branches of compact stars**
- **stellar conversion HS→QS**

$E_{conv} \sim 10^{53}$ erg (possible energy source for some GRBs)

extension of the concept of limiting mass of compact stars with respect to the *classical* one given by Oppenheimer and Volkoff

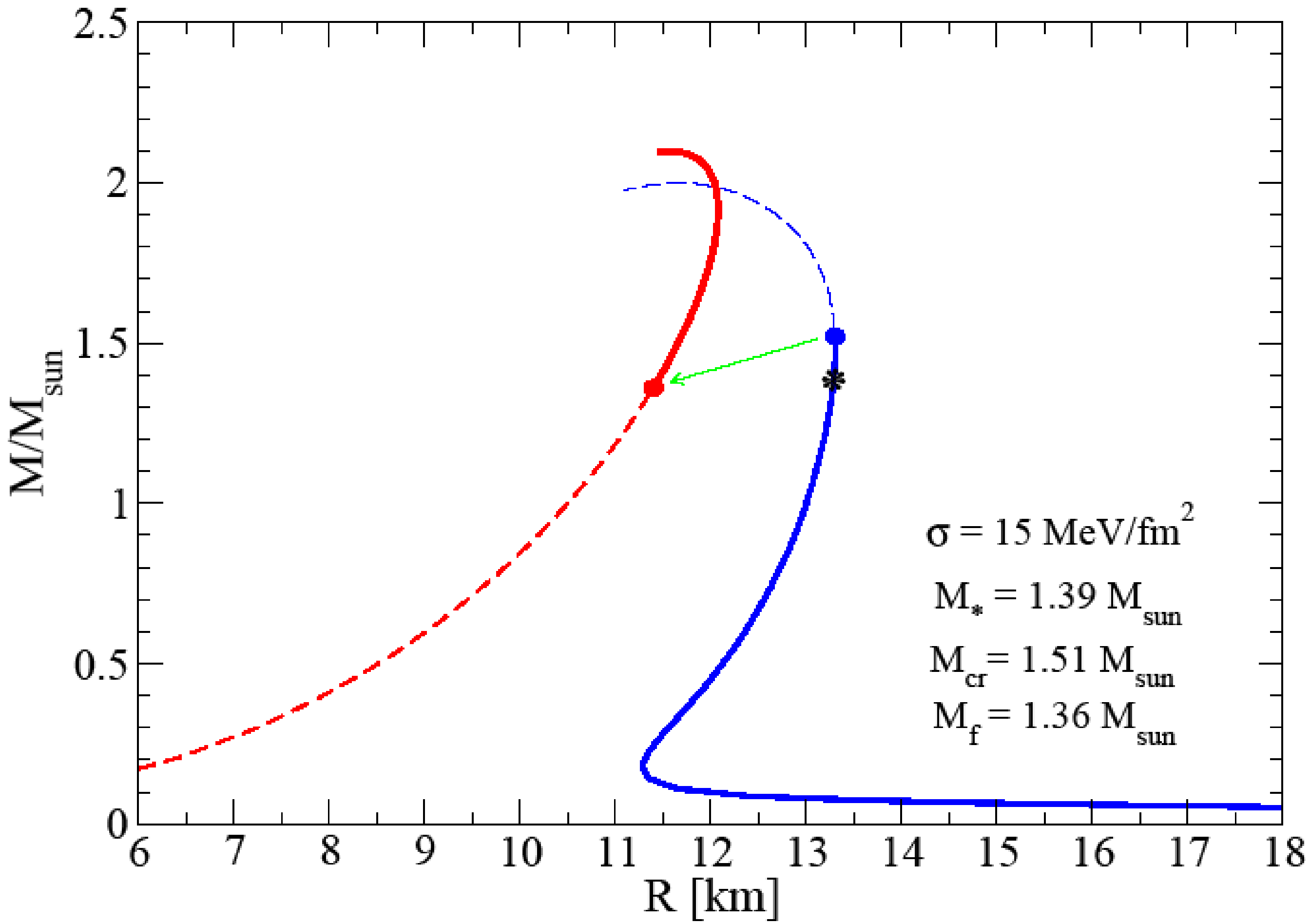
Berezhiani, Bombaci, Drago, Frontera, Lavagno, Astr
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 61
I. Bombaci, G. Lugones, I. Vidaña, Astron. &Astroph

The two families of Compact Stars



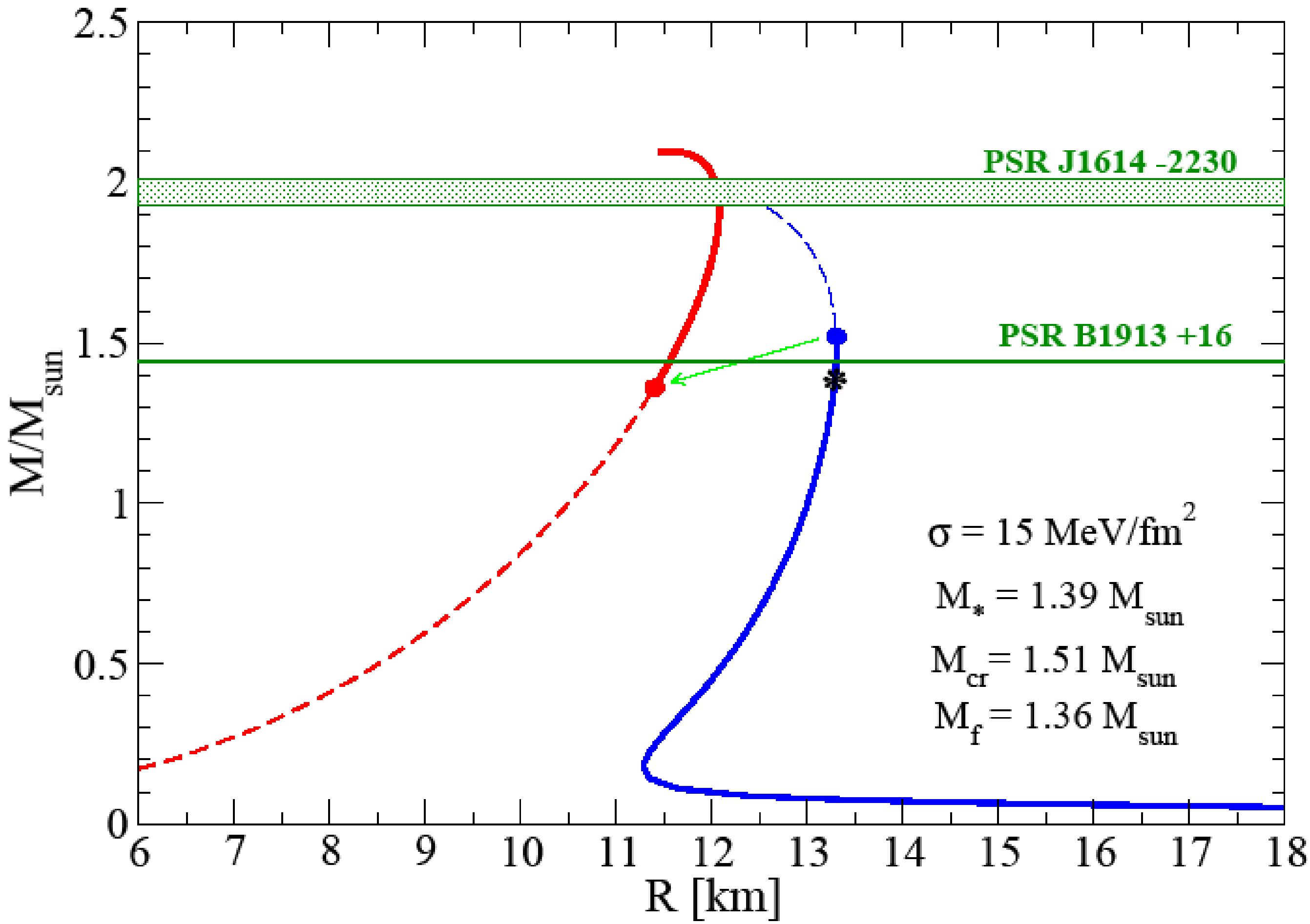
Hadronic Stars: nucleons + hyperons

I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314



I. Bombaci, D. Logoteta (2014)

SQM EOS: Alford et al. Astrophys. J. 629 (2005); Fraga et al., Phys. Rev. D 63 (2001)

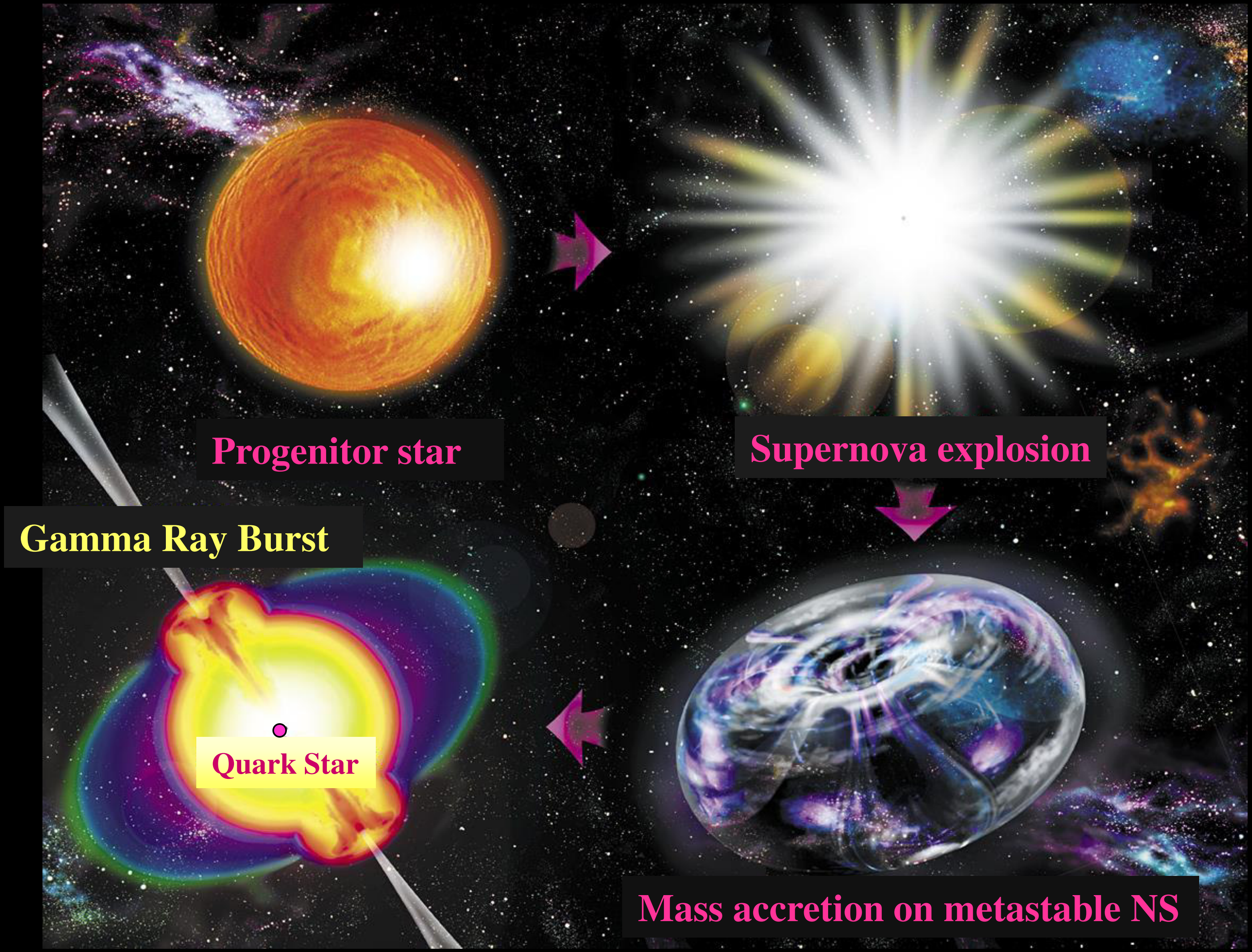


I. Bombaci, D. Logoteta (2014)

SQM EOS: Alford et al. Astrophys. J. 629 (2005); Fraga et al., Phys. Rev. D 63 (2001)

Hadronic Star → Quark Star conversion model

Berezhiani, Bombaci, Drago, Frontera, Lavagno, Astrophys. Jour. 586 (2003) 1250



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**

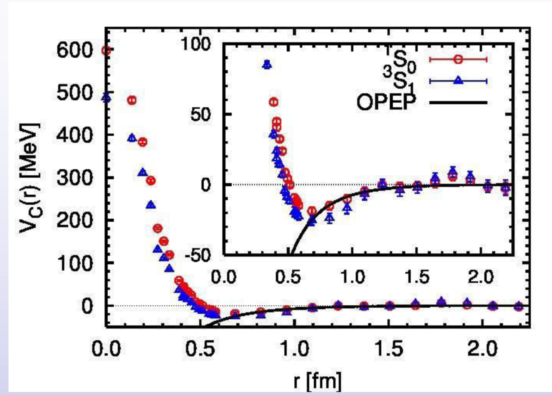
(2a) (1a) + (1b) $\longrightarrow$ crucial to determine ρ_{crit}

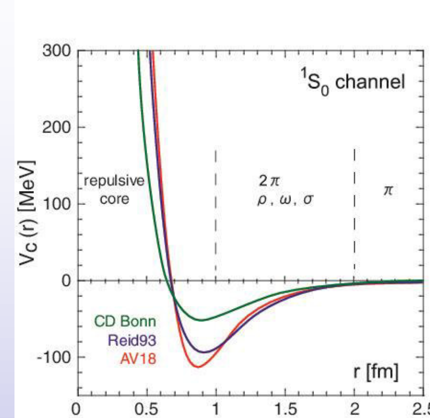
(2b) inclusion of non-perturbative QCD effects which are crucial to determine the nature of the deconfinement transition and the stiffness of the quark matter phase EOS

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

P. Cea, et al., Phys. Rev. D 85, 094512 (2012)