COST Action MP1304

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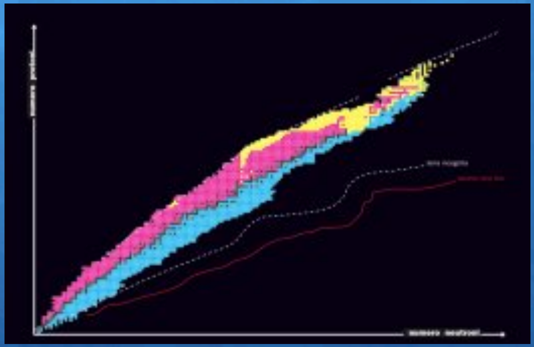
The Equation of State of Neutron Star Matter

Fiorella Burgio
INFN Sezione di Catania

The EoS : where do we stand ?

- Structure properties known for about 3339 nuclides.

- Binding energy in the Liquid Drop Model (DM).



- Extrapolating the mass formula for A-> ∞ in the symmetric case, the binding energy close to saturation $\rho_0 = 0.17\ \mathrm{fm}^{-3}$ is usually expanded as

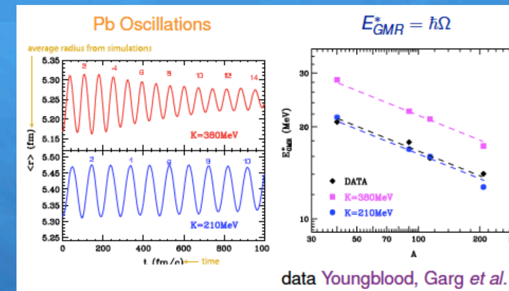
$$\frac{E}{A}(\rho,\beta) = E_0 + \frac{1}{18}K_0\varepsilon^2 + \left[S_0 - \frac{1}{3}L\varepsilon + \frac{1}{8}K_{sym}\varepsilon^2\right]\beta^2$$

$$\beta = \frac{\rho_n - \rho_p}{\rho}, \qquad \varepsilon = \frac{\rho - \rho_0}{\rho_0}$$

Close to saturation ……

★ $E_0 \approx -16 \text{ MeV}$

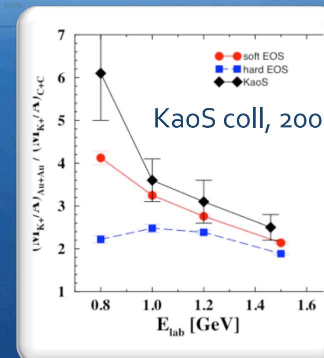
★ $K_0 = k_F^2 \left(\frac{d^2 E/A}{dk_F^2} \right)_{\rho_0} \approx 230 \pm 20 \text{ MeV}$



data Youngblood, Garg *et al.*

Results confirmed by experiments on K⁺ production in HIC

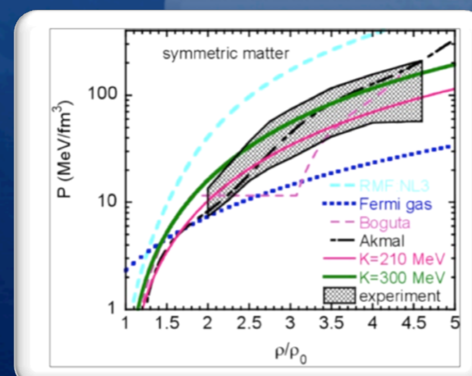
- Largest density explored : $\rho \approx 2\text{-}3\ \rho_0$
- Only calculations with a compression $180 \le K_0 \le 250$ MeV can describe the data (Fuchs, 2001)



KaoS coll, 2001

……and by collective flow data

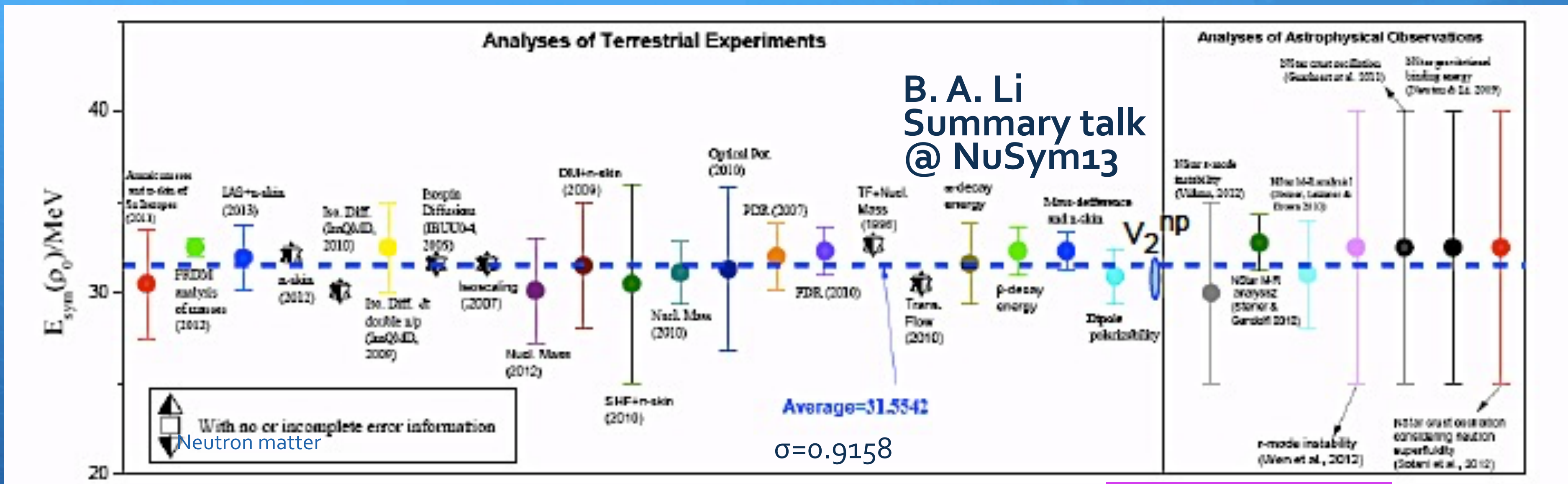
- Transverse flow measurements in Au + Au collisions at E/A=0.5 to 10 GeV
- Flow data <u>exclude</u> very repulsive equations of state



P. Danielewicz,
Science **298**, 1592 (2002)

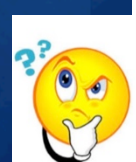
The Symmetry Energy

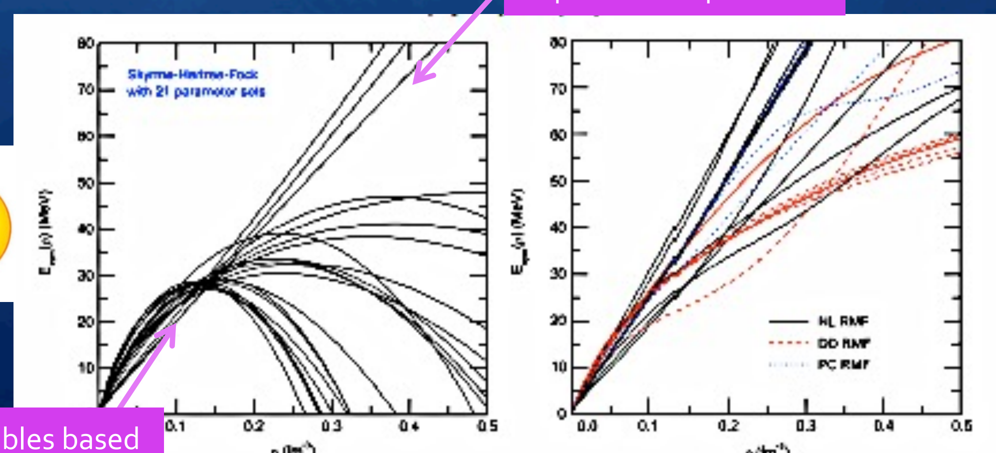
$$S_0 = \frac{1}{2}\frac{\partial^2 E/A}{\partial \beta^2}\Big|_{\beta=0}$$



The key problem is its density dependence

Ex: 21 Skyrme forces *vs.* RMF



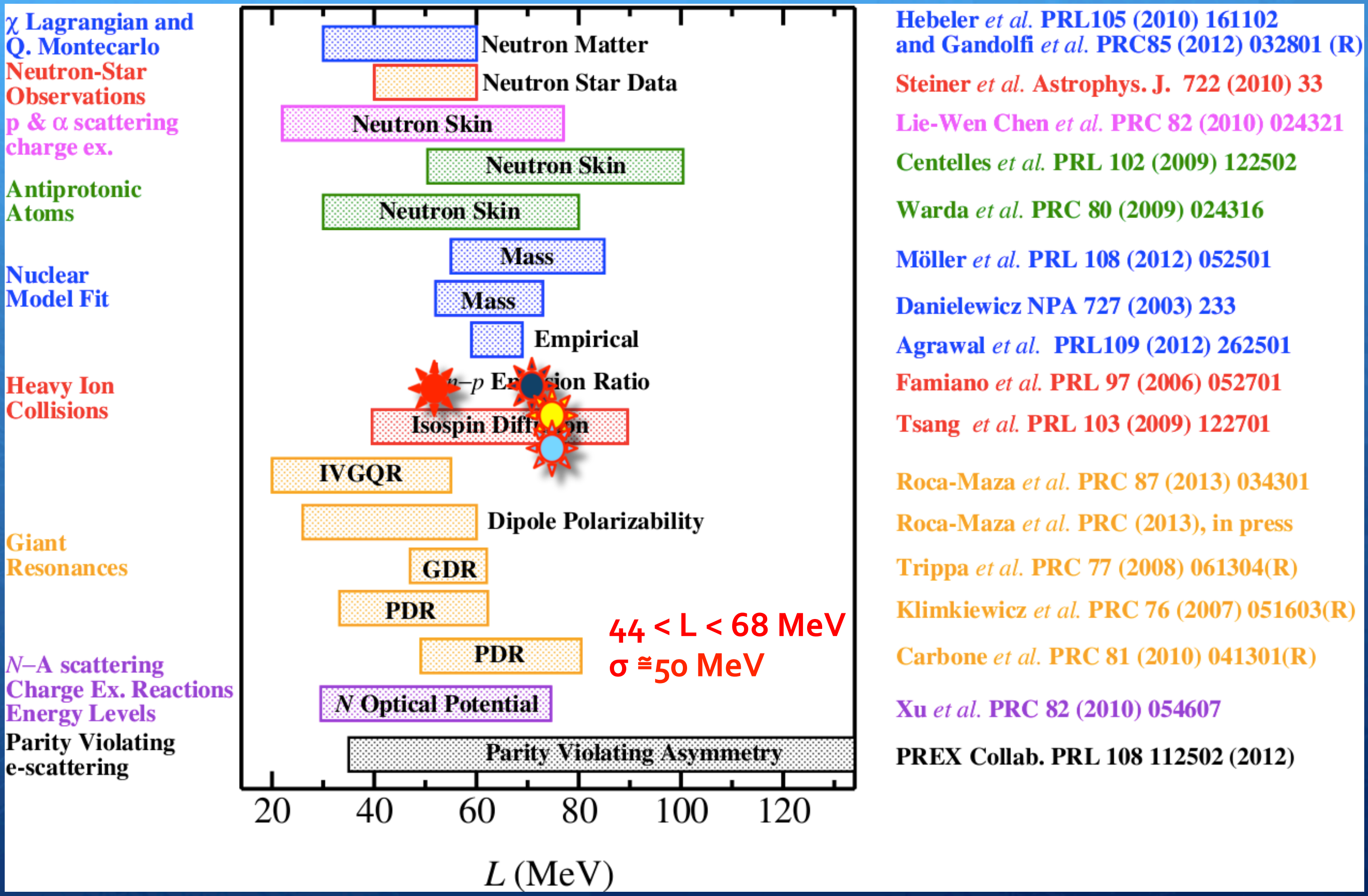


Strong differences at high densities. Lack of experimental probes.

Sensitivity to observables based on the N/Z asymmetry.

Collection of available estimates of the slope parameter

$$L = 3\rho_0 \frac{dS_0}{d\rho}\Big|_{\rho_0}$$



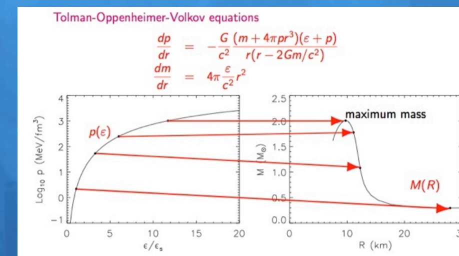
Adapted from X. Vinas et al., EPJA 50:27 (2014)

- Z.Y. Sun et al., PRC82 051603 (2010) (Chimera/MSU data)
- E. Galichet et al. PRC 79 064615 (2009) (INDRA data)
- E.d.F. et al. PRC 86 014610 (2012) (Chimera data)
- Z. Kohley et al., PRC 88 041601 (2013) (TAMU data)

EoS from astrophysical observations

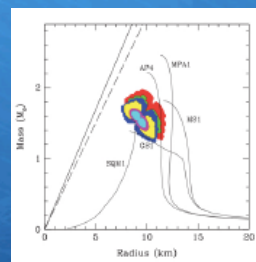
Steiner, Lattimer, Brown, ApJ 722, 33 (2010)

- TOV inversion to get model-independent EoS

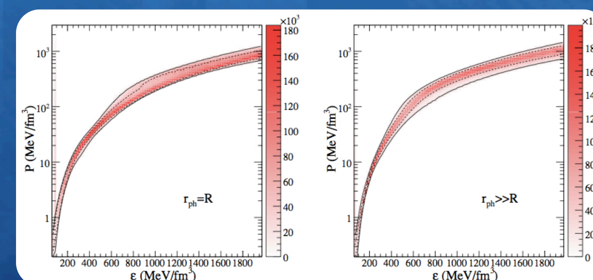


- 3 type-I X-ray bursters

  F. Ozel et al., (2009, 2010)



- 3 transient low-mass X-ray binaries
- Cooling of RX J1856-3754



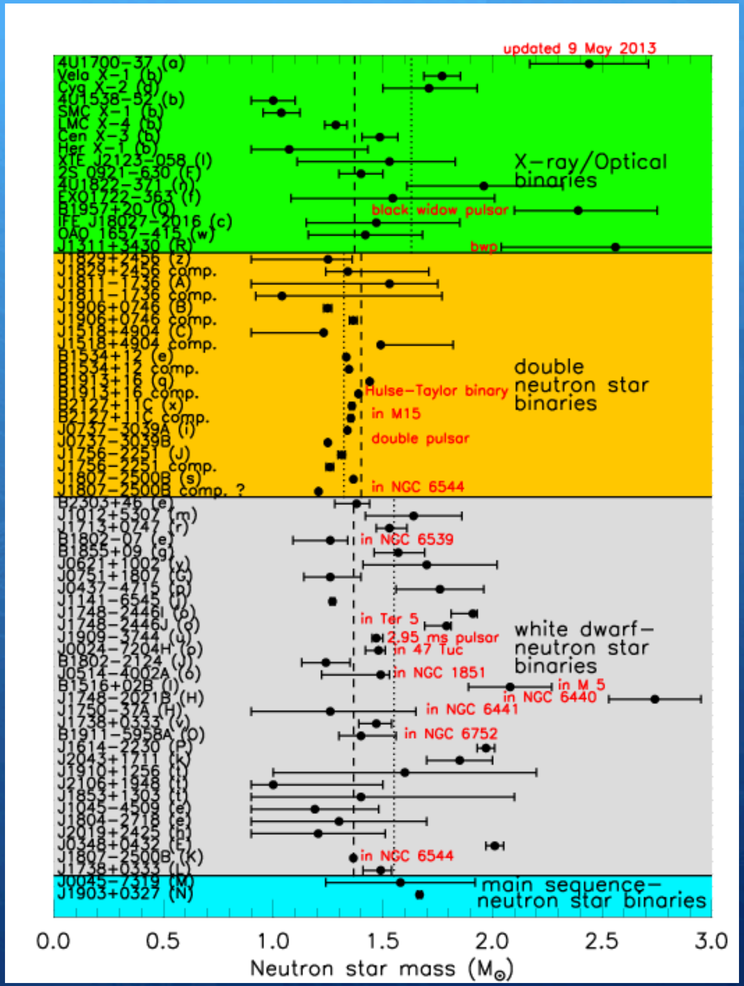
- Parameterized EoS

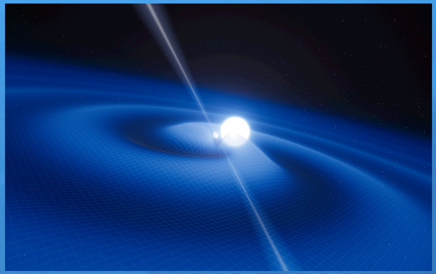
$$\epsilon = n_B\Big\{m_B + B + \frac{K}{18}(u-1)^2 + \frac{K'}{162}(u-1)^3 + (1-2x)^2\Big[S_k u^{2/3} + S_p u^\gamma\Big] + \frac{3}{4}\hbar c x(3\pi^2 n_b x)^{1/3}\Big\}$$

Table 3. Prior limits for the EOS parameters

Quantity	Lower limit	Upper limit
K (MeV)	180	280
K' (MeV)	-1000	-200
S_v (MeV)	28	38
γ	0.2	1.2
n_1 (fm^{-3})	0.2	1.5
n_2 (fm^{-3})	0.2	2.0
ε_1 (MeV fm^{-3})	150	600
ε_2 (MeV fm^{-3})	ε_1	1600

Compilation by Jim Lattimer





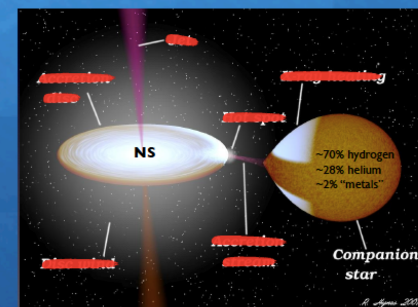
Several soft EoS are EXCLUDED !

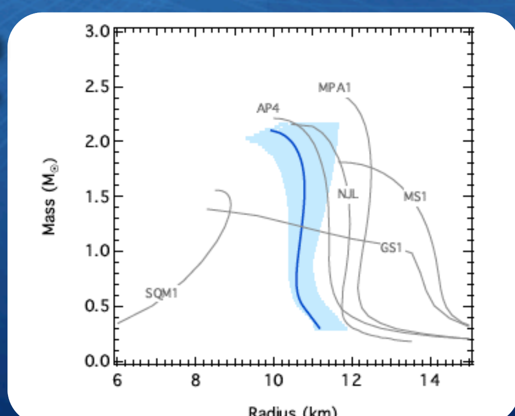
EoS from astrophysical observations

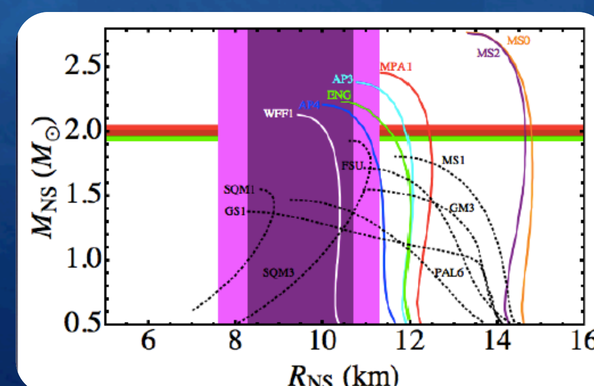
(Ozel, , Psaltis, Guver, Baym, Heinke, Guillot, arXiv:1505.05155)

Radius measurements of 12 sources

- 6 Thermonuclear bursters
- 6 Quiescent low mass X-ray binaries
- Use of Bayesian statistical framework
- Combination with $2M_o$ observation
- Strong constraints on the EoS in the density range (2-8) ρ_o







Guillot et al., 2013, ApJ 772

For a 1.5 M_o star ⟶ $10.4 < R < 11.3$ km

"Recipe" for neutron star structure calculations

- Energy density : $\epsilon\left(\rho_i\right); i = n, p, e, \mu, \Lambda, \Sigma, u, d, s.....$
- Chemical potentials : $\mu_i = \dfrac{\partial \epsilon}{\partial \rho_i}$
- Beta-equilibrium : $\mu_i = b_i \mu_n - q_i \mu_e$

$$\begin{aligned} \mu_e &= \mu_\mu = \mu_n - \mu_p \\ \mu_{\Sigma^-} &= 2\mu_n - \mu_p \\ \mu_{\Sigma^0} &= \mu_\Lambda = \mu_n \\ \mu_{\Sigma^+} &= \mu_p \end{aligned}$$

- Charge neutrality : $\sum_i x_i q_i = 0$
- Composition : $x_i(\rho)$
- Equation of state : $p(\rho) = \rho^2 \dfrac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$
- TOV equations :

$$\left\{ \begin{aligned} \frac{dP}{dr} &= -\frac{Gm}{r^2}\frac{(\epsilon + P)(1 + 4\pi r^3 P/m)}{1 - \frac{2Gm}{r}} \\ \frac{dm}{dr} &= 4\pi r^2 \epsilon(r) \end{aligned} \right.$$

- Structure of the star : $\rho(r), M(R), etc.$

Need theoretical method to calculate the energy density

The construction of the EoS : two possible philosophies

Phenomenological approaches

Based on effective density-dependent NN force with parameters fitted on nuclei properties.

- Liquid Drop models
  - ✧ BPS Baym et al, *ApJ* ***170,*** *299 (1971)*
  - ✧ BBP Baym et al., *NPA* ***175,*** *225 (1971)*
  - ✧ LS Lattimer&Swesty, *NPA* ***535,*** *331 (1991)*
  - ✧ DH Douchin&Haensel, *A&A* ***380,*** *151 (2001)*
- TF + RMF
  - ✧ Shen et al., *NPA* ***637,*** *435 (1998)*
- ETFSI + Eff. Skyrme force
  - ✧ BSk Goriely et al.,*PRC* ***82****, 035804 (2010)*
- Hartree-Fock
  - ✧ NV Negele&Vautherin, *NPA* ***207,*** *298 (1973)*
  - ✧ RMF Serot&Walecka, *Adv. NP 16, 1 (1986)*
  - ✧ RHF Boussy et al., *PRL* ***55****, 1731 (1985)*
  - ✧ QMC Guichon et al., *NPA* ***814****, 66 (2008)*
- Statistical models
  - ✧ NSE Raduta&Gulminelli. *PRC* ***82****, 065801 (2010)*
  - ✧ HS Hempel&Schaffner-Bielich, *NPA* ***837,*** *210 (2010)*

Ab initio approaches

The nuclear problem is solved starting from the two- and three-body realistic nucleon interaction.

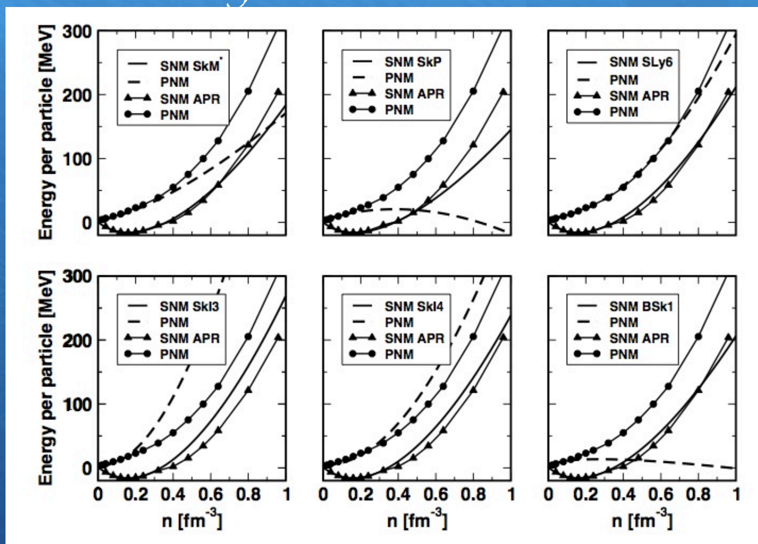
- Diagrammatic
  - ✧ BBG *Day, RMP**39**, 719 (1967)*
  - ✧ SCGF Kadanoff&Baym, Quantum Statistical Mechanics (1962)
  - ✧ DBHF Ter Haar&Malfiet, *Phys, Rep.* ***149****, 207 (1987);*
- Variational
  - ✧ APR *Akmal et al.*, *PRC* ***58****, 1804 (1998)*
  - ✧ FHNC Fantoni&Rosati, *Nuovo Cimento A**20**, 179 (1974)*
  - ✧ CBF Fabrocini&Fantoni, *PLB* ***298****, 263(1993)*
  - ✧ LOCV Owen et al., *NPA* ***277****, 45 (1978)*
- Monte Carlo
  - ✧ VMC Wiringa, *PRC**43**, 1585 (1991)*
  - ✧ GFMC Carlson, *PRC**68**, 025802 (2003)*
  - ✧ AFDMC Schmidt&Fantoni, *PLB**446**, 99 (1999)*
- Renormalization Group method
  - ✧ V_{low-k} Bogner et al., *PR 286, 1 (2003)*

Comparing phenomenological models

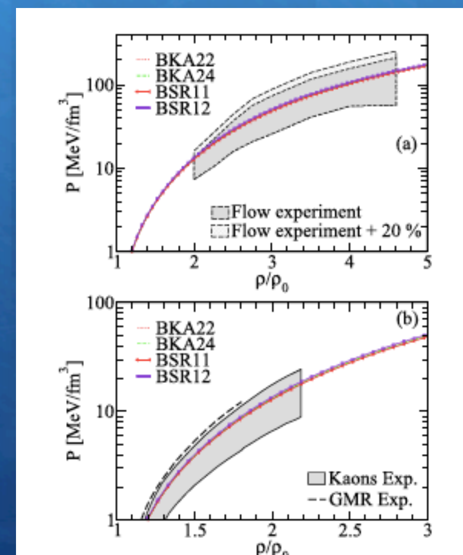
M. Doutra, et al. PRC 85, 035201 (2012)

M. Doutra, et al. PRC 90, 055203 (2014)

Skyrme forces



RMF models



- Analyzed a set of 240 Skyrme forces, checking their ability to fulfill correctly saturation of nuclear matter, compressibility, symmetry energy and its derivative, data from heavy ions and NS observations.

  Only 5 passed all tests !

- The same analysis was performed on a set of 263 parameterizations of 7 different kinds of RMF models. Only 4 (SET2a) + 3 (SET2b) passed the tests !

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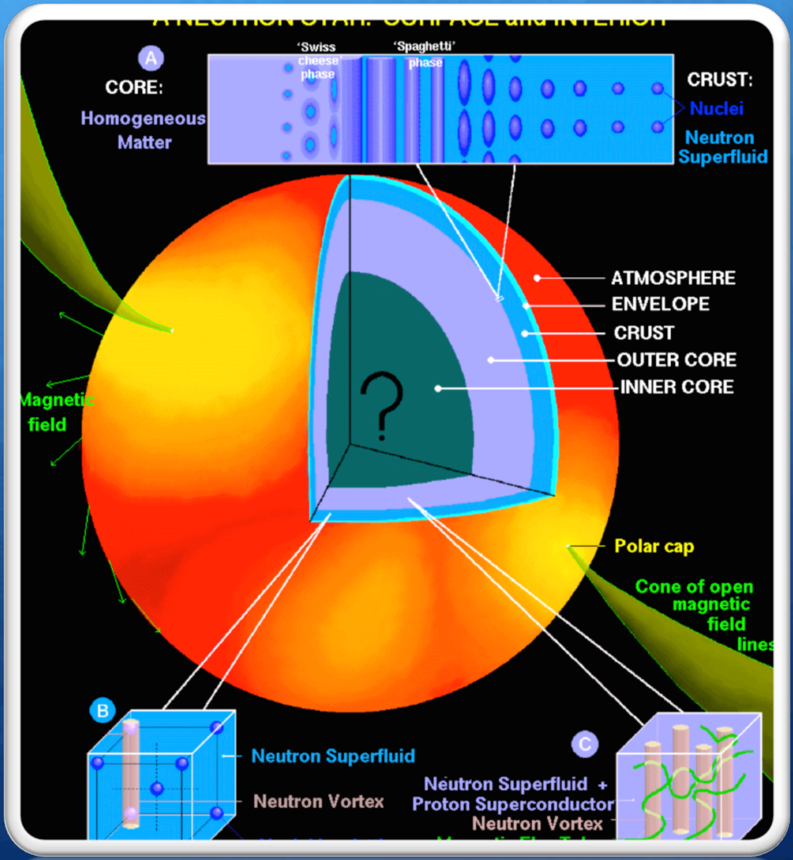
Four main layers

Outer crust ^{56}Fe ions immersed in an electron gas, as in normal metals.

Inner crust Neutron gas in chemical equilibrium with electrons and ions. Ions get very neutron rich, until the neutrons drip from nuclei. Nuclear matter from drip point (4×10^{11} g/cc) up to about half the saturation density.

Outer core Asymmetric nuclear matter above saturation. Mainly composed by neutrons, protons, electrons and muons. Its exact composition depends on the nuclear matter Equation of State (EoS).

Inner core The most unknown region. "Exotic matter" . Hyperons. Kaons? Pions? Quarks ?



by Dany Page, UNAM Mexico City

Towards a unified description from the outer crust to the core

- It is of great interest to develop a unified theory which is able to describe the overall structure of Neutron Stars, from the outer crust to the inner core. There are a few EoSes devised to describe the whole NS within a unified framework.

  - Lattimer-Swesty (CLDM, EoS from Skyrme effective force)
  - Shen (TF scheme and RMF model)
  - Douchin-Haensel (CLDM, SLy4 force fitted to microscopic neutron matter calculations)
  - BSk (ETFSI, Skyrme force fitted to known masses of nuclei and microscopic neutron matter calculations with different stiffness) (Talks by Nicolas & Anthea)
  - HSB (supernova matter)

- Recently, some of us developed a new Energy Density Functional called BCPM. It is based on the nuclear matter EOS derived in the BHF scheme plus a phenomenological part to describe the nuclear surface.

- We employ this EOS and the corresponding BCPM functional to describe the whole NS structure and compare with the results obtained with the few other methods that encompass the whole NS structure.

More in Sharma, Centelles, Vinas, Baldo, Burgio, arXiv:1506.00375

The Eos of Nuclear Matter

K. A. Brueckner, and J. L. Gammel, PR 109,1023 (1958)

The EoS is calculated with high accuracy in the Brueckner two-hole-line approximation with the continuous choice for the single-particle potential.

- Bethe-Goldstone equation for the G-matrix

$$
\left.\begin{aligned}
G[\rho;\omega] &= V + \sum_{k_a,k_b} V \frac{|k_a k_b > Q < k_a k_b|}{\omega - e(k_a) - e(k_b)} G[\rho;\omega] \\
e(k) &= e(k;\rho) = \frac{k^2}{2m} + U(k;\rho) \\
U(k;\rho) &= \sum_{k' \le k_F} < kk'|G[\rho; e(k) + e(k')]|kk' >_a
\end{aligned}\right\}
$$

- In the BHF approximation, the binding energy per nucleon is given by :

$$
\frac{E}{A} = \frac{3}{5}\frac{k_F^2}{2m} + \frac{1}{2\rho} \sum_{k,k' \le k_F} < kk'|G[(\rho; e(k) + e(k')]|kk' >_a
$$

In this calculation we used the Argonne v_{18} potential supplemented by the Urbana three-body force in order to fit correctly the saturation point of nuclear matter.

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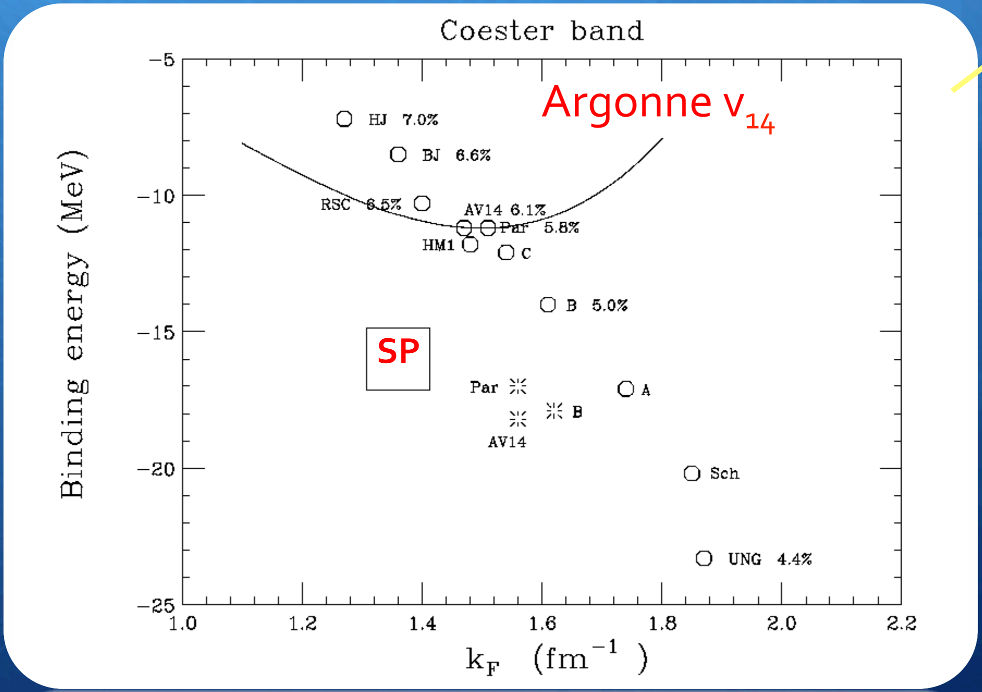
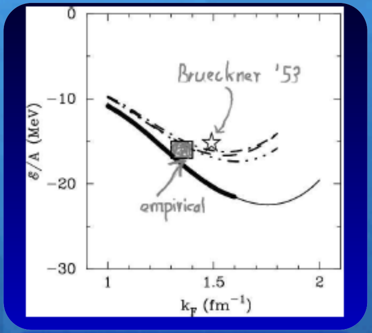
Missing the saturation point ....

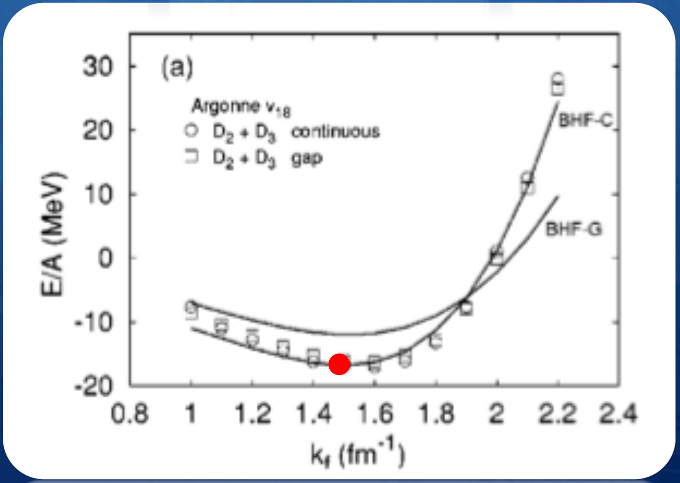
Coester et al., Phys. Rev. **C1**, 769 (1970)

Systematics by R. Machleidt, Adv. Nucl. Phys. 19, 1989.





Results up to three hole lines :



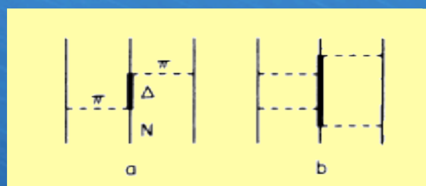
- Results depend on the adopted NN potential.
- The saturation point is missed even including the 3hl.

Role of TBF's for binding energy and saturation properties

- No complete theory available yet .
- Compare phenomenological and microscopic approaches.

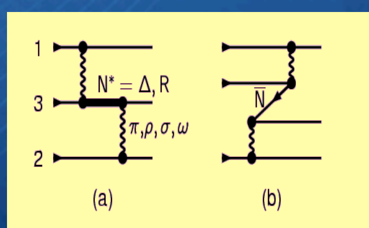
✓ Urbana IX model

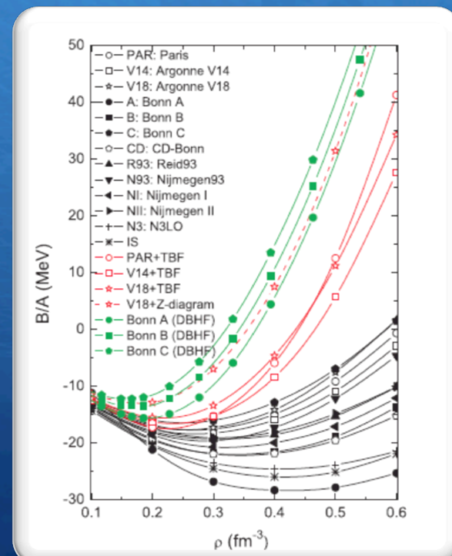
Carlson et al., NP A401,(1983) 59



✓ Microscopic model

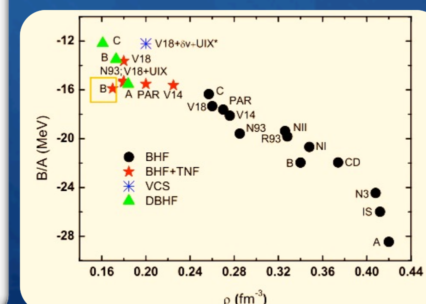
P. Grange' et al, PR C40, (1989) 1040





Z.H. Li, U. Lombardo, H.-J. Schulze, W. Zuo, PRC 74, 047304 (2006)

New Coester band



- TBF needed to improve saturation point.
- Dependence on NN potential.
- Uncertain high-density behaviour due to unknown TBF.

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Fitting the EoS

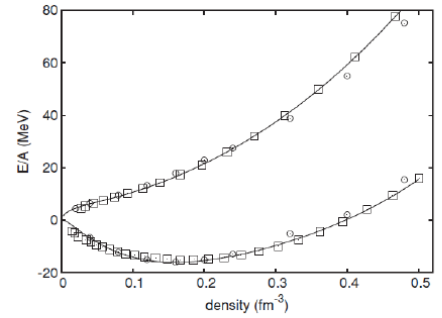
The symmetric (s) and neutron (n) matter EoS are fitted with polynomials P_s and P_n of the total density ρ

$$P_s(\rho) = \sum_{k=1}^{5} a_k^{(n)} (\rho/\rho_0)^k$$

$$P_n(\rho) = \sum_{k=1}^{5} b_k^{(n)} (\rho/\rho_{0n})^k$$

with $\rho_0 = 0.16$ fm^{-3} and $\rho_{0n} = 0.155$fm^{-3}

- Can be used up to $\rho = 0.625$ fm^{-3}



In the spirit of the Local Density Approximation it is proposed to use those fits in finite nuclei just replacing the nuclear matter density by the finite nuclei one .

M. Baldo, L. Robledo, P. Schuck and X. Vinas, PRC87, 064305 (2013)

The BCPM functional

Barcelona Catania Paris Madrid

We write our functional in the nuclear case as

$$E = T_0 + E_{int}^{\infty} + E_{int}^{FR} + E^{s.o.} + E_C$$

BHF

$$E_{int}^{\infty}[\rho_p, \rho_n] = \int d\mathbf{r}[P_s(\rho)(1-\beta^2) + P_n(\rho)\beta^2]\rho$$

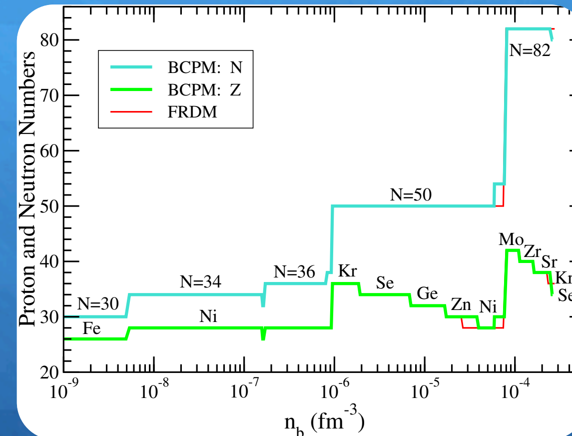
where P_s and P_n are two interpolating polynomials for symmetric and pure neutron matter, respectively, at the density $\rho = \rho_p + \rho_n$, and $\beta = (\rho_n - \rho_p)/\rho$ is the asymmetry parameter.

$$E_{int}^{FR}[\rho_n, \rho_p] = \frac{1}{2}\sum_{t,t'}\left\{\int\int d\mathbf{r}d\mathbf{r}'\rho_t(\mathbf{r})v_{t,t'}(\mathbf{r}-\mathbf{r}')\rho_{t'}(\mathbf{r}') - \gamma_{t,t'}\int d\mathbf{r}\rho_t(\mathbf{r})\rho_{t'}(\mathbf{r})\right\}$$

with $v_{t,t'}(r) = V_{t,t'}e^{-r^2/r_0^2}$ and $\gamma_{t,t'} = \int d\mathbf{r}v_{t,t'}(r)$

The strengths $V_{n,n} = V_{p,p} = V_L$, $V_{n,p} = V_{p,n} = V_U$ and the range r_0 are free parameters to be fitted using finite nuclei data

The outer crust $(10^4 \leq \epsilon \leq 4\times 10^{11} g/cm^3)$



In the outer crust the energy per baryon at given average density $\rho_B = A/V$ is given by $\varepsilon(A,Z,\rho_B) = \varepsilon_n + \varepsilon_{elec} + \varepsilon_l$, where the nuclear part reads

$$\varepsilon_n(A,Z) = \frac{M(A,Z)}{A} = \frac{(A-Z)m_n + Zm_p - B(A,Z)}{A}$$

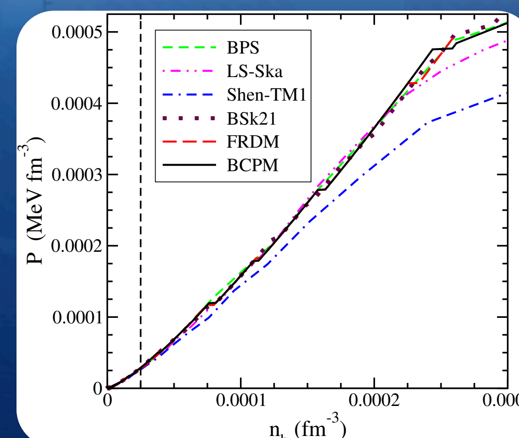
BCPM

. The electronic and lattice contributions are given by

$$\varepsilon_{elec} = \frac{m_e^4}{8\pi^2\rho_B}\left[x_e\left(2x_e^2+1\right)\sqrt{x_e^2+1} - \ln\left(x_e + \sqrt{x_e^2+1}\right)\right]$$

$$\varepsilon_l = -C_l\frac{Z^2}{A^{4/3}}m_e x_e \quad (C_l = 3.40665\times 10^{-3})$$

with $x_e = k_{F,e}/m_e$ and $k_{F,e} = (3\pi^2\rho_e)^{1/3}$.
It is assumed that thermal, hydrostatic and chemical equilibrium is reached at each layer of the outer crust. Only electronic and lattice terms contribute to the pressure: $P = P_{elec} + P_l$.
At fixed pressure the quantity to be minimized is the chemical potential $\mu(A,Z,P) = \varepsilon(A,Z,\rho_B) + \frac{P}{\rho_B}$



- ✧ Staircase structure of shells with increasing neutron-rich isotones, due to magic nucleon numbers.
- ✧ Very good agreement with FRDM calculations.
- ✧ Small jumps in the EoS due to transition from one equilibrium nucleus to another one.
- ✧ The EoS agrees well with FRDM, BPS and BSk21 approaches.
- ✧ Some differences with LS and Shen EoSes. Large discrepancy close to the transition to the inner crust.

The inner crust $4 \times 10^{11} \leq \epsilon \leq 1.5\ 10^{14} g/cm^3$

- ✧ Coulomb lattice of nuclear clusters permeated by a gas of free neutrons and electrons.
- ✧ Wigner-Seitz approximation.

The total energy of an esemble of neutrons, protons and electrons in a Wigner-Seitz cell of volume V_c is given by:

$$E = \int dV \left[\mathcal{H}(\rho_n, \rho_p) + \mathcal{E}_{elec} + \mathcal{E}_{coul} - \frac{3}{4}\left(\frac{3}{\pi}\right)^{1/3} e^2 \left(\rho_p^{4/3} + \rho_e^{4/3}\right) + m_n\rho_n + m_p\rho_p \right]$$

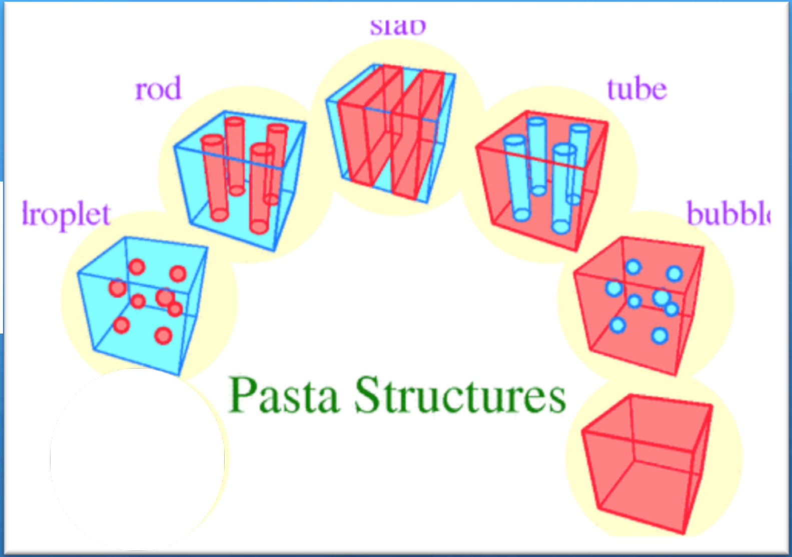
where the nuclear energy density in the TF approach reads: BCPM

$$\mathcal{H}(\rho_n, \rho_p) = \frac{\hbar^2}{2m_n}\frac{3}{5}\left(3\pi^2\right)^{2/3} \rho_n^{5/3}(\mathbf{r}) + \frac{\hbar^2}{2m_p}\frac{3}{5}\left(3\pi^2\right)^{2/3} \rho_p^{5/3}(\mathbf{r}) + \mathcal{V}(\rho_n(\mathbf{r}), \rho_p(\mathbf{r}))$$

- Perform a fully variational calculation of the energy in the WS cell under the constraints of given average density in the WS cell of size R and charge neutrality.
- Calculate the energy.
- Search for the optimal cell size for a given baryon density, just repeating the calculations for different R, and find the absolute minimum.
- Calculate the pressure.

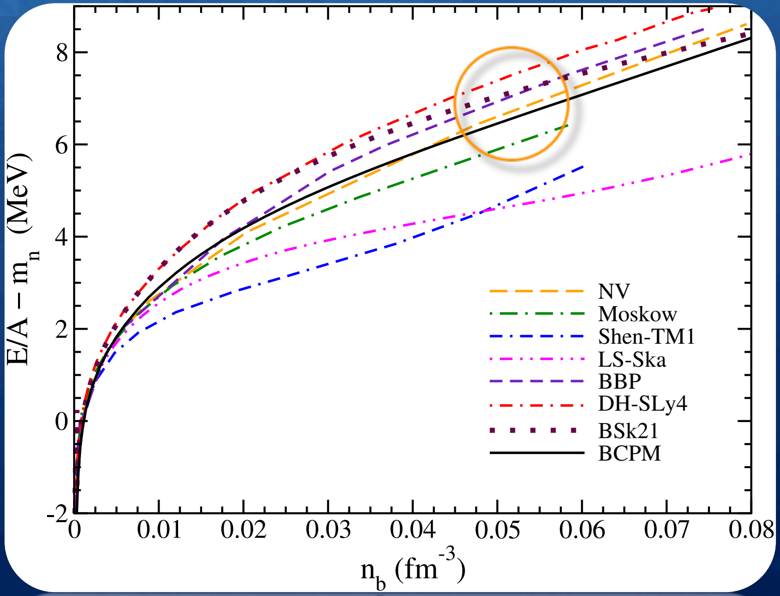
Sequence of pasta structures

drop/rod	rod/slab	slab/tube	tube/bubble	bubble/uniform
0.067	0.076	0.082	≲0.0825	≈0.0825



Energy mainly determined by the neutron gas, hence the PNM EoS plays a role.

- BCPM lies close to NV.
- Small differences among the approaches which are constrained by some information of microscopic calculations.
- Large discrepancy with LS and Shen .



The core

Equation of State

$$\varepsilon(\rho_n,\rho_p,\rho_e,\rho_\mu) = (\rho_n m_n + \rho_p m_p) + (\rho_n+\rho_p)\frac{E}{A}(\rho_n,\rho_p) + \rho_\mu m_\mu + \frac{1}{2m_\mu}\frac{(3\pi^2\rho_\mu)^{5/3}}{5\pi^2} + \frac{(3\pi^2\rho_e)^{4/3}}{4\pi^2}$$

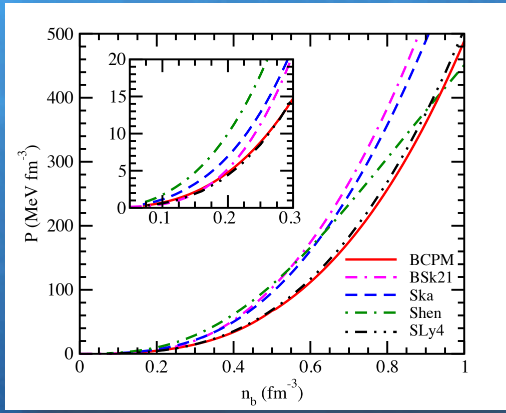
$$\mu_i = \frac{\partial\varepsilon}{\partial\rho_i}, \quad \mu_i = b_i\mu_n - q_i\mu_e, \quad \sum_i \rho_i q_i = 0$$

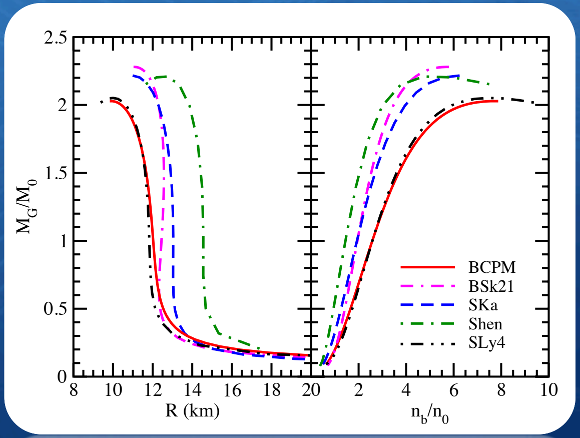
$$P(\rho) = \rho^2 \frac{d}{d\rho}\frac{\varepsilon(\rho_i(\rho))}{\rho} = \rho\frac{d\varepsilon}{d\rho} - \varepsilon = \rho\mu_n - \varepsilon$$

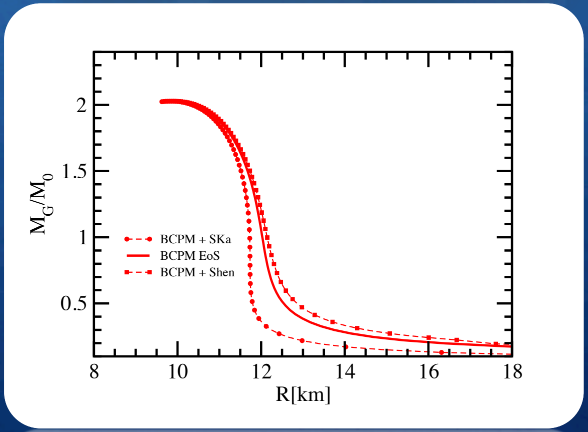
Tolman-Oppenheimer-Volkov equations

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

$$\frac{dm}{dr} = 4\pi r^2\epsilon,$$







- ✓ All EoSes are compatible with the 2.01 ± 0.04 M_0 observation
- ✓ Smaller radii for stars with BCPM and SLy4 EoSes
- ✓ Using a unified approach over the whole density range is important for the radius of NS with mass below 1 M_0

More on the TBF's .....

BBG up to three hole-lines, Quark Model Baryon-Baryon interaction

vs.

BHF, **Argonne v18 + UVIX TBF**
BHF, **Argonne v18 + micro TBF**
BHF, **Bonn B + micro TBF**
APR, **Argonne v18 + UVIX**
DBHF, **Bonn A**

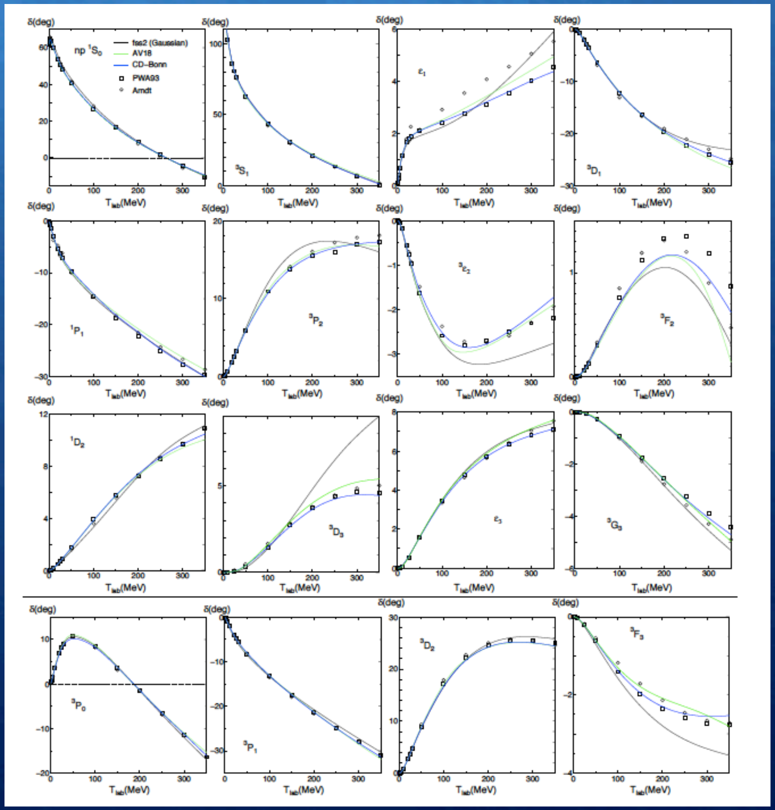
Quark model of the Baryon-Baryon interaction

Y. Fujiwara, T. Fujita, M. Kohno, C. Nakamoto, and Y. Suzuki, Phys. Rev. C 65, 014002 (2001).
Y. Fujiwara, Y. Suzuki, M. Kohno, and K. Miyagawa, Phys.Rev. C 77, 027001 (2008).
Y. Fujiwara and K. Fukukawa, Few-Body Syst. 54, 2357 (2013).

- ✧ Nucleons described as three-quarks clusters with confinement.
- ✧ Quark exchange and effective meson exchange interaction.

Features :

- ✧ NN potential turns out to be highly non-local with momentum cut-off.
- ✧ Phase shifts well reproduced.
- ✧ Triton underbound by 200 keV.
- ✧ Data on pd scattering well reproduced.



- ✧ What about nuclear matter ?

M. Baldo and K. Fukukawa, Phys. Rev. Lett. 113, 242501 (2014).

- The Bethe-Bruckner-Goldstone many-body theory is used to describe the correlations up to the three hole-line approximation with no extra parameters.

- At variance with other nonrelativistic realistic interactions, *the three hole-line contribution turns out to be non-negligible and to have a substantial saturation effect.*

- The saturation point of nuclear matter, the compressibility, the symmetry energy, and its slope are within the phenomenological constraints.

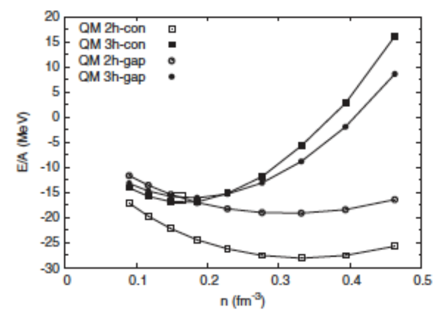


FIG. 2. EOS of symmetric nuclear matter at the two-hole level of approximation (open symbols) and at the three hole-line level (full symbols) for the continuous (squares) and the gap (circles) choices, respectively.

	ρ_0	E/A	K	So	L
CC	0.148	-16.19	228	34	54
GC	0.185	-15.58	192	33.7	53

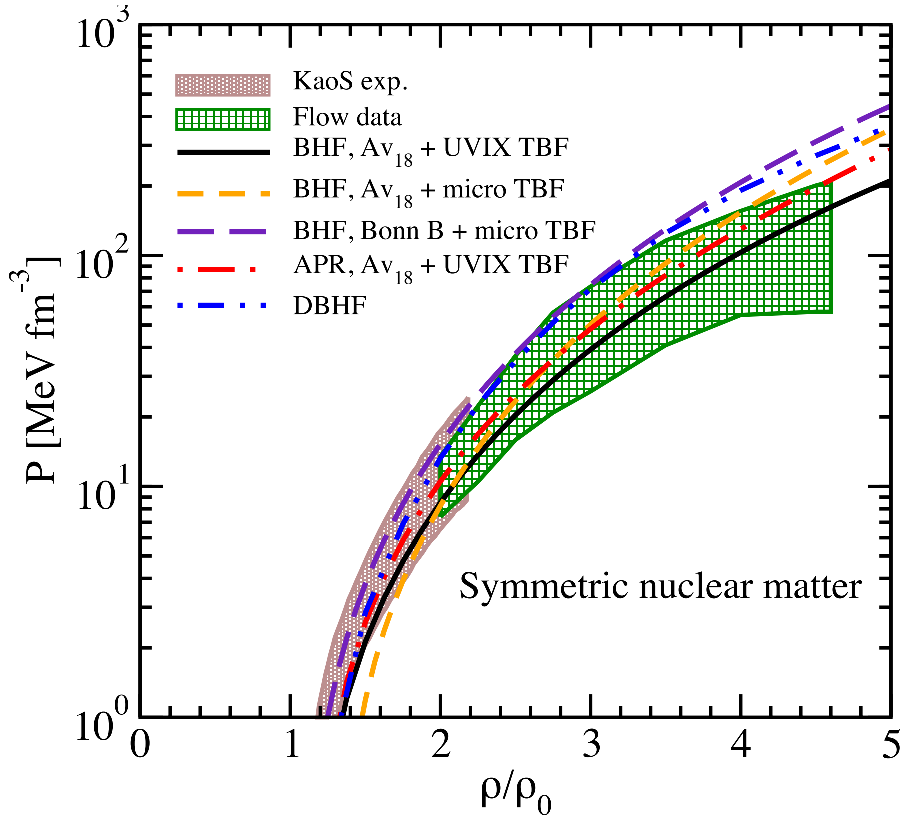
The explicit introduction of the quark degrees of freedom within the considered constituent quark model is expected to reduce the role of three-body forces.

More results at high density coming soon ….

Microscopic EoS's reproduce well the data from phenomenology

TABLE I. Calculated properties of symmetric nuclear matter.

EoS	ρ_0 (fm^{-3})	$\frac{E}{A}$ (MeV)	K_0 (MeV)	S_0 (MeV)	L (MeV)
BHF, Av_{18} + UVIX TBF	0.16	−15.98	212.4	31.9	52.9
BHF, Av_{18} + micro TBF	0.2	−15.5	236	31.3	82.7
BHF, Bonn B + micro TBF	0.17	−16.	254	30.3	59.2
APR, Av_{18} + UVIX TBF	0.16	−16.	247.3	33.9	53.8
DBHF, Bonn A	0.18	−16.15	230	34.4	69.4



G. Taranto et al., Phys. Rev. C87, 045803 (2013)

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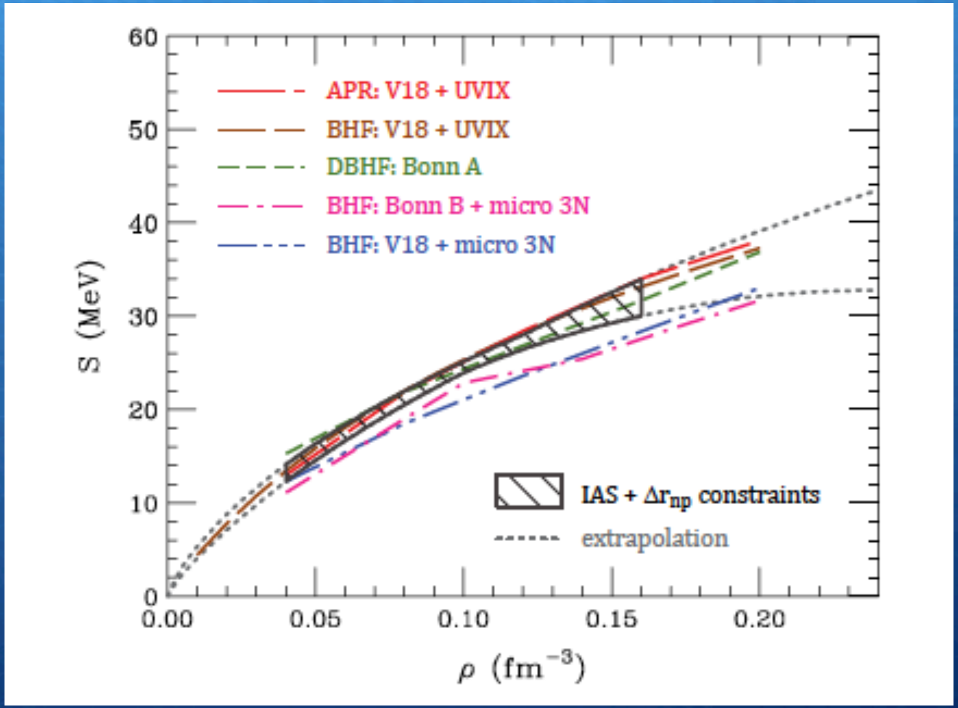
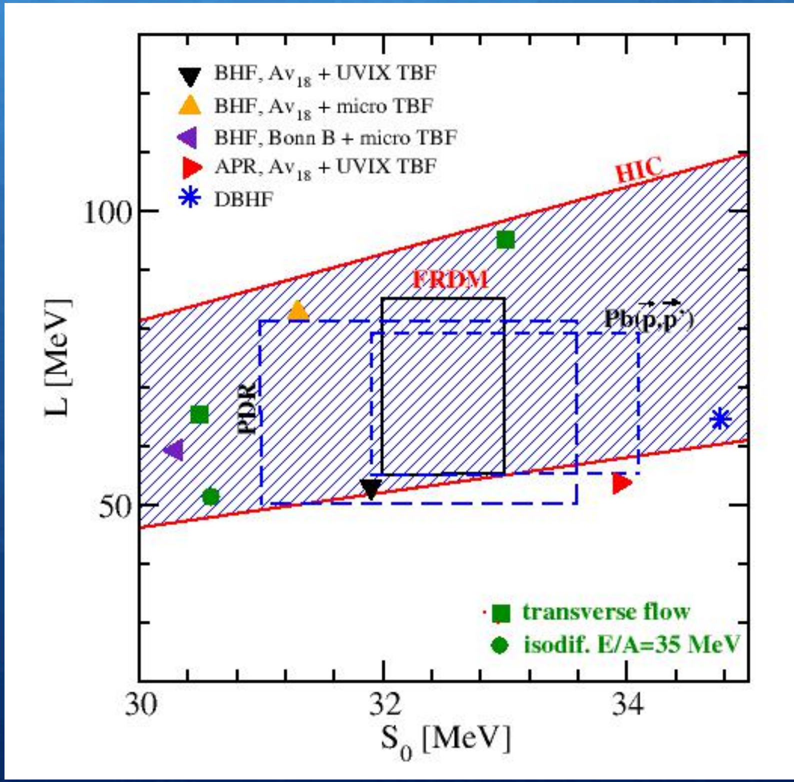
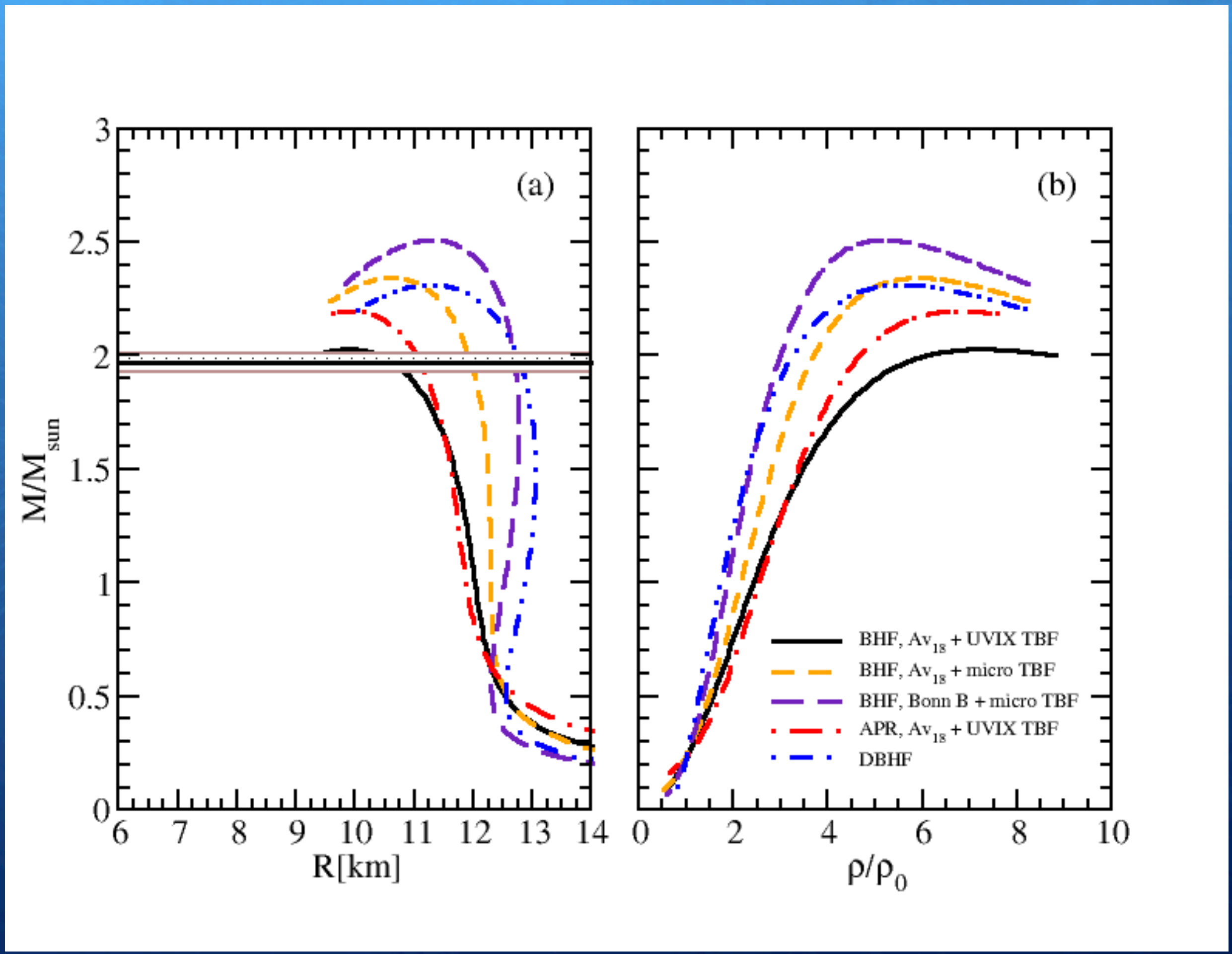




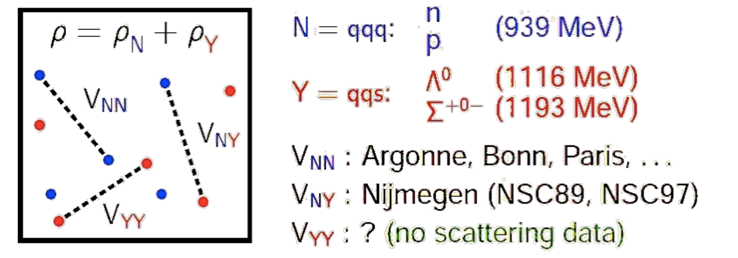
G. Taranto et al., Phys. Rev. C87, 045803 (2013)

Neutron star Mass M and Radius R



Different many-body techniques and matter compositions predict different results for the M-R relation.

INCLUDING HYPERONS



- Extension of the BBG theory.

  Several reaction channels involved, more time consuming calculations.

- Few experimental data of hypernuclei on nucleon-hyperon interaction.

  Nijmegen parametrization, Phys. Rev. C40, 2226 (1989) (NSC89)

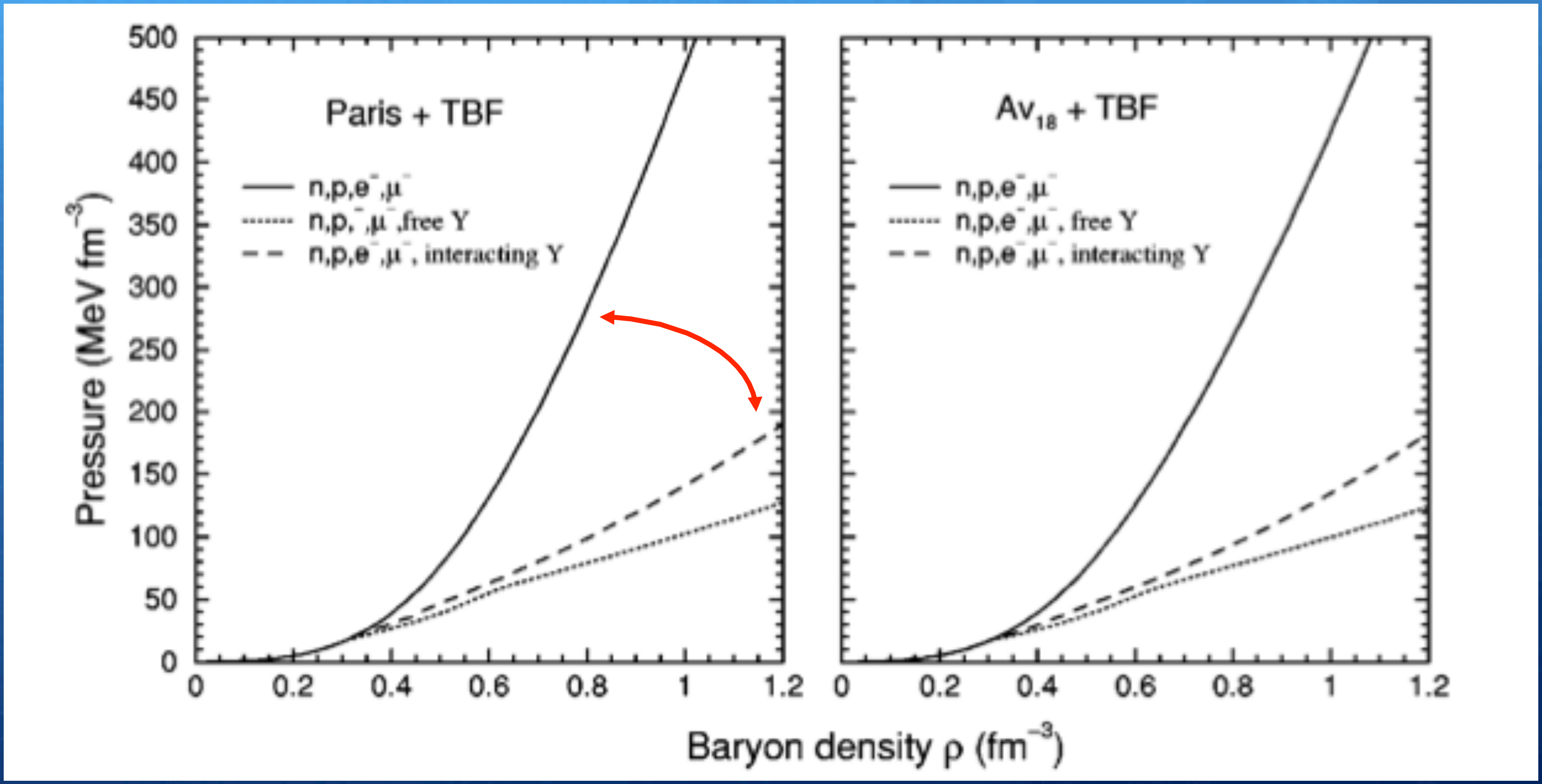
- Unknown HH interaction.

  Use of NSC97 and ESC08

- Strong consequences for NS structure.

  Softening of the EoS

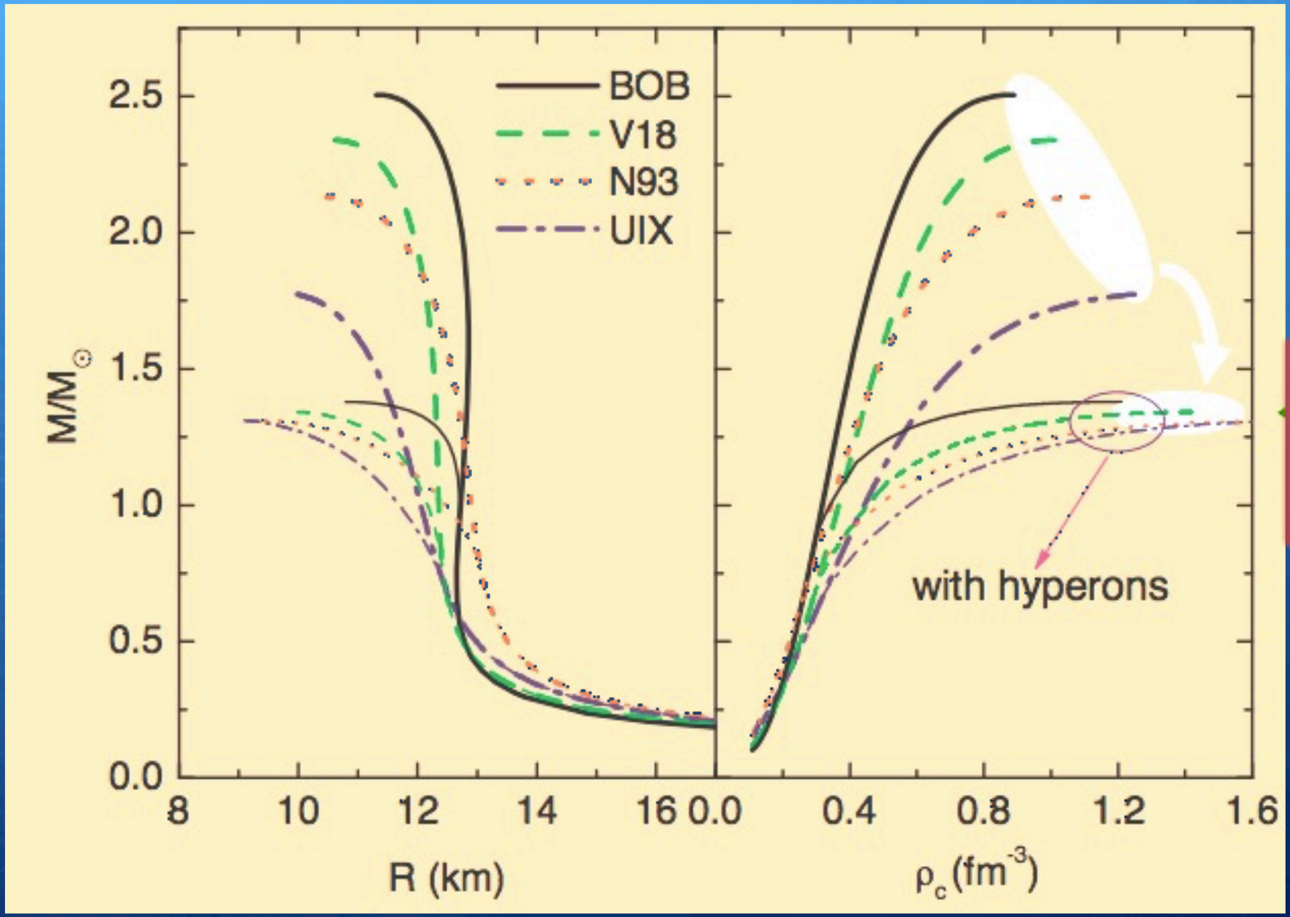
- Eos of neutron star matter



Strong softening due to hyperons !

(more Fermi seas available)

- Mass-Radius relations with different nucleonic TBF's

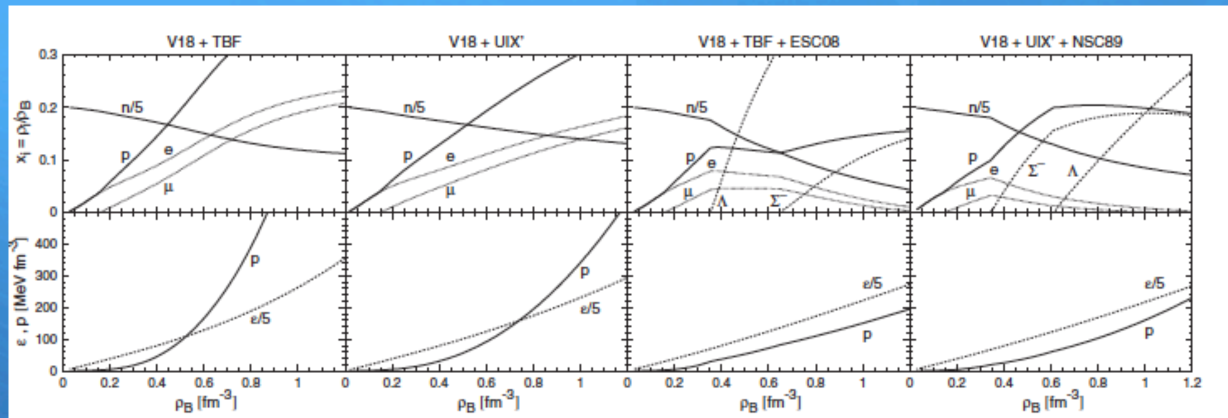


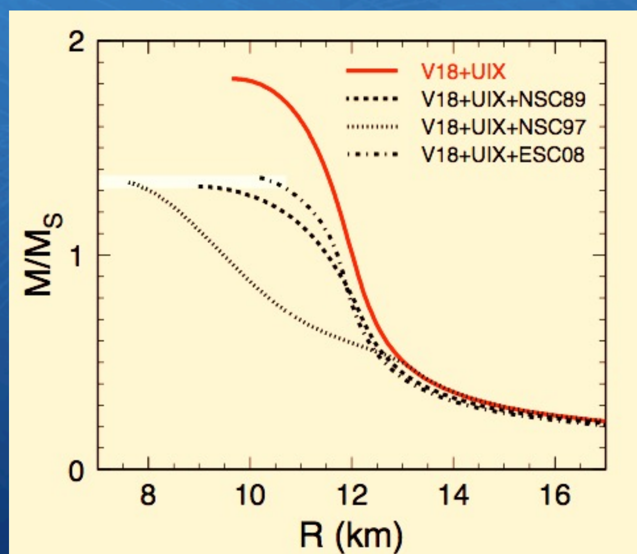
NSC89 NY potential
No YY
No hyperon TBF

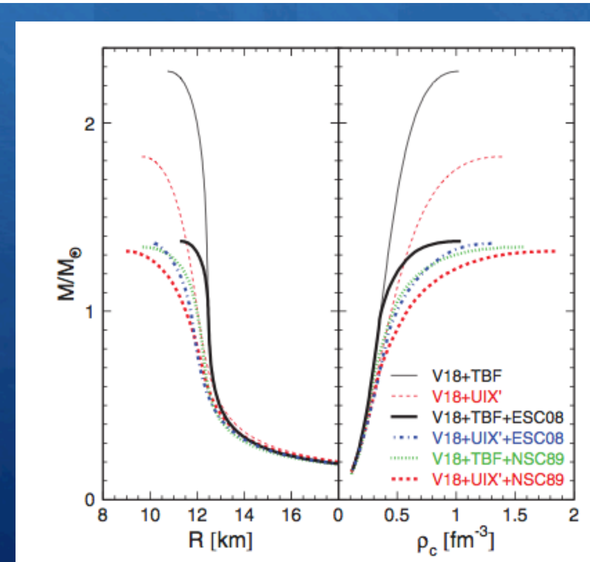
- Large variation of M_{max} with nucleonic TBF's
- Self-regulating softening due to hyperon appearance

(stiffer nucleonic EOS -----> earlier hyperon onset)

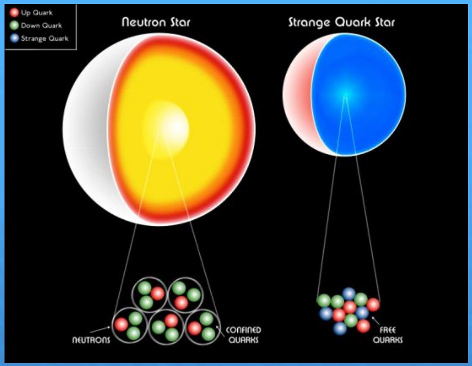
- Using different NYpotentials







- Maximum mass independent of NY potentials.
- Maximum mass too low (< 1.4 M_o !)
- Hyperonic TBF's do not help (Isaac talk)



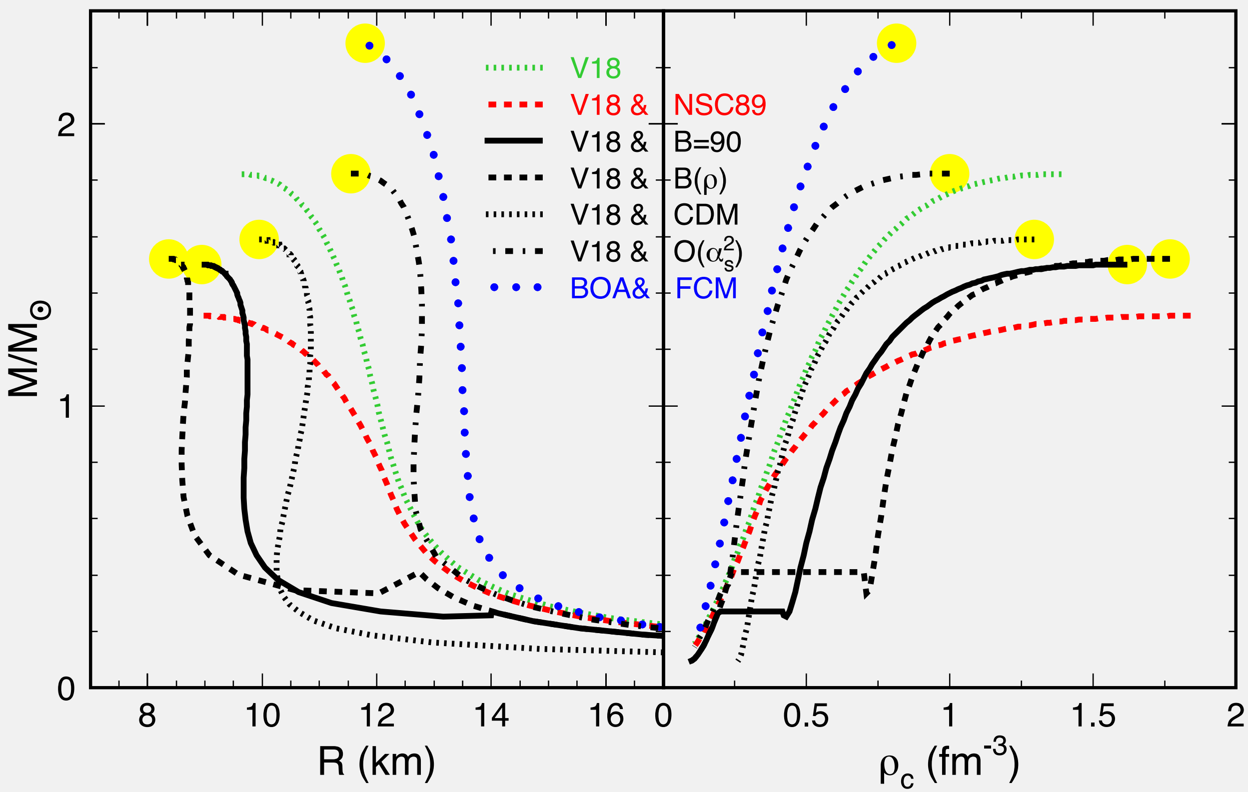
Quark matter in NS (hybrid stars)

- Since we have no theory which describes both confined and deconfined phases, we use two separate EOS for baryon and quark matter and look at the crossing in the P-μ plane .
- Constraints from nuclear phenomenology on the general quark EOS : In symmetric nuclear matter one can expect a transition to quark matter at some density, but it must be larger than at least normal nuclear matter density.
- Maximum NS mass at least equal to 2. solar mass $M_\odot$

<u>Several models of quark matter</u>

- MIT bag model
- Nambu-Jona—Lasinio model
- Color Dielectric model
- Dyson-Schwinger model
- FCM
- pQCD *(Vuorinen talk)*

<u>They all give different hybrid star structure and mass limits.</u>



- When hyperons are present in the hadron phase, the maximum mass stays below 2.
- With NJL, Dyson-Schwinger, FCM hyperons prevent the phase transition and the maximum mass can be larger than 2 solar masses.

Lot of homework to do !!!!

- The EoS of nucleonic matter is much under control up to 4-5 times normal density.
- Excellent agreement with experimental data on nuclei from HIC.
- Large uncertainty at high density both for the TBF's and three-body correlations.

- Hyperons appearance : open question
  Need of experimental data from hypernuclei (J-PARC, PANDA@FAIR)
- Phase transition to quark matter : open question

- More observational data. LOFT and NICER.

Thank you !