Neutron Star Structure with Modern Nucleonic Three-Body Forces

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PRC 77, 034316 (2008) • PRC 78, 028801 (2008)

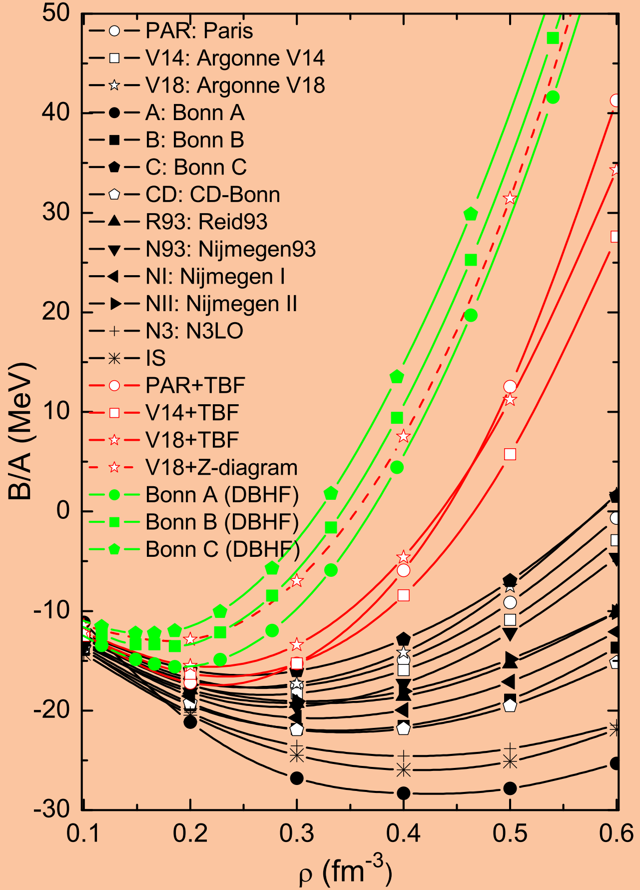
Motivation for TBF:

- Structure of (light) nuclei, nucleon-deuteron scattering
- Saturation of nuclear matter
- Nuclear EOS at high density

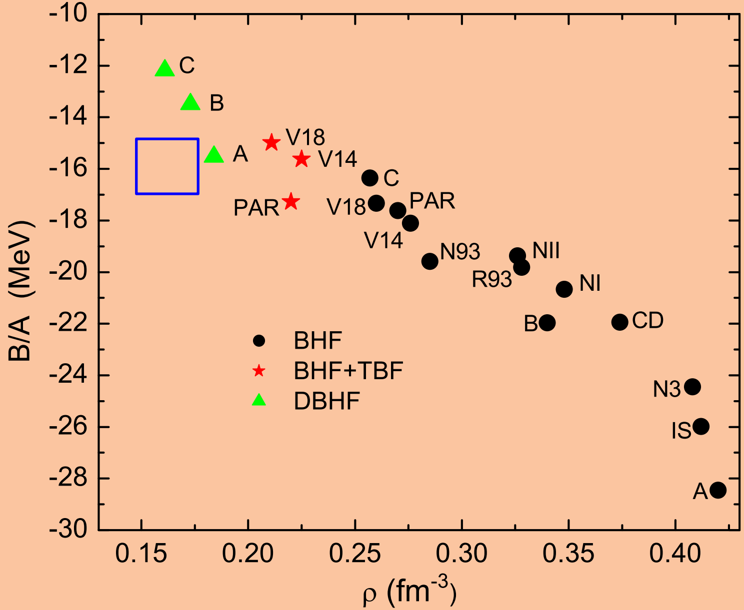
Goal:

- Construct nuclear TBF consistent with a given meson-exchange NN potential (Bonn B, Nijmegen 93)
- Use in microscopic BHF calculation of high-density nuclear matter
- Neutron star structure

● BHF Binding energy and saturation point of symmetric matter:

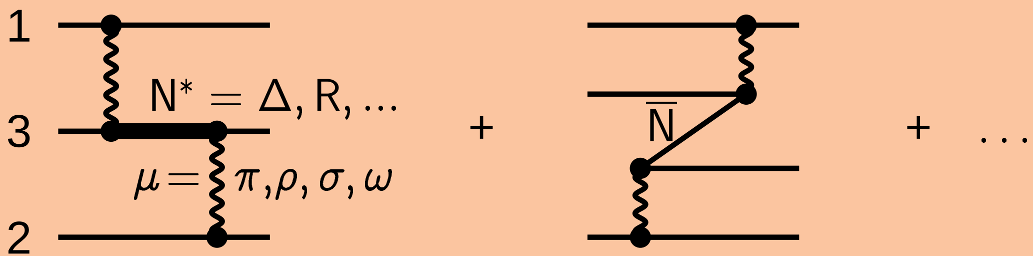


PRC 74, 047304 (2006)



➥ TBF substantially improve saturation

Three-Nucleon Forces:



- Only small effect required [$\delta(B/A) \approx 1$ MeV at ρ_0]
- Model dependent
- Use and compare microscopic and phenomenological TBF...
  - Microscopic TBF of P. Grangé et al., PRC 40, 1040 (1989):
    Exchange of $\pi, \rho, \sigma, \omega$ via $\Delta(1232)$, $R(1440)$, $N\bar{N}$
    Parameters compatible with two-nucleon potential (Paris,V_{18},...)
  - Urbana IX phenomenological TBF:
    Only 2π-TBF + phenomenological repulsion
    Fit saturation point

Microscopic Meson Exchange TBF:

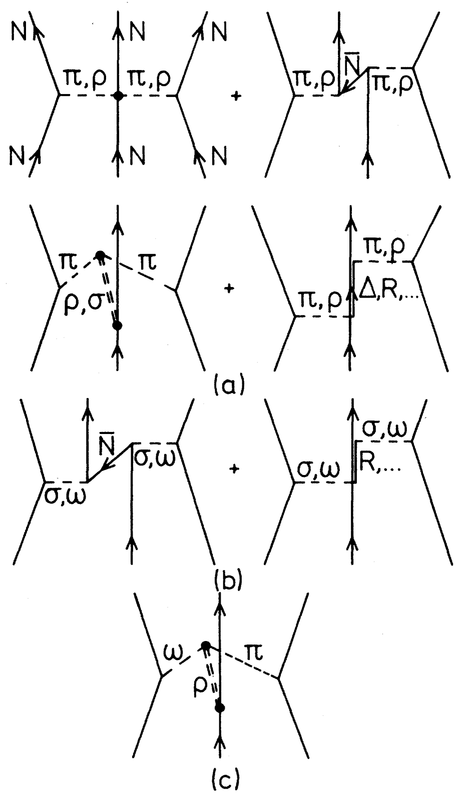


FIG. 3. Leading order contributions to the three-body force deduced from the meson-exchange current operators indicated in Fig. 2. See text for the explanation of the various groups (a)–(c).

P. Grangé, A. Lejeune, M. Martzolff, J.-F. Mathiot, PRC 40, 1040 (1989)

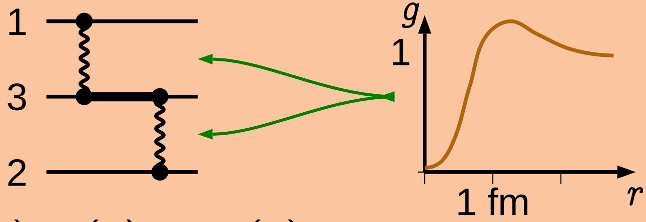
π, ρ - part based on Tuscon-Melbourne TBF:
S.A. Coon et al., NPA 317, 242 (1979);
NPA 438, 631 (1985); PRC 48, 2559 (1993); ...

- Effects of $\Delta(1232)$, $R(1440)$, $N\bar{N}$
- Parameters compatible with two-nucleon (Paris) potential

Some Details:

- Average over spectator nucleon using BHF defect function:

$$\overline{V}_{12}(\boldsymbol{r}) = \rho \int d^3 r_3 \sum_{\sigma_3,\tau_3} g(r_{13})\, g(r_{23}) V_{123}$$



$$= (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) V_C(r) + (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) V_S(r) + V_I(r)$$
$$+ S_{12}(\hat{\boldsymbol{r}}) \Big[(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) V_T(r) + V_Q(r) \Big]$$

: five components

- Example: $\rho\rho$ contribution:

$$\rho \frac{2\pi}{r} \int_0^\infty dx\, x \int_{|r-x|}^{r+x} dy\, y\, g_x g_y$$

$$V_O^{\rho\rho}(r) = -\frac{16}{81} \frac{m_\rho^2 f_{\rho NN}^2 f_{\rho N\Delta}^2}{m_\Delta - m_N} \overline{\sum_3} \Big[2 Y_x^\rho Y_y^\rho + P_r T_x^\rho T_y^\rho \Big] \quad (O = C)$$

$$\Big[\frac{P}{2} T_x^\rho T_y^\rho - P_x Y_x^\rho T_y^\rho - P_y Y_y^\rho T_x^\rho \Big] \quad (O = T)$$

ρNN, $\rho N\Delta$ form factors and kinematical factors

Meson Exchange Parameters:

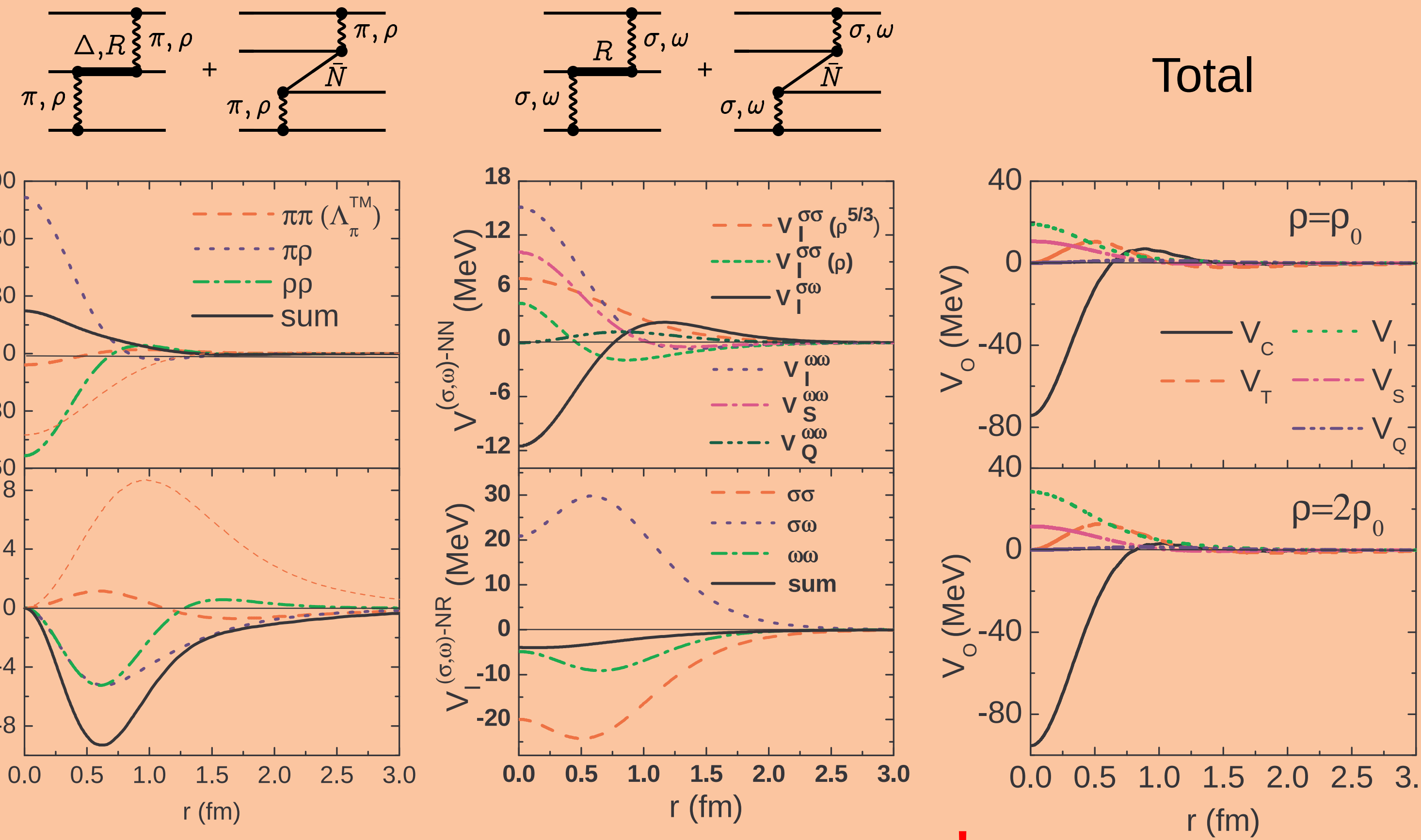
Table 1: Meson-exchange parameters of the Bonn B and Argonne V_{18} potentials.
The letter in brackets behind the form factor cutoff denotes the type of form factor: (M)onopole, (D)ipole, (R)oper.
We use the baryon masses $m_N = 938.4$ MeV, $m_\Delta = 1232$ MeV, $m_R = 1440$ MeV.

		m (MeV)	$g^2/4\pi$	Λ (MeV)	
Bonn B	π	138	14.4	1700 (M)	$a = 1.38,\ b = -2.80,\ c = 1.25$ [TM(99)]
	ρ	769	0.90	1850 (D)	$\kappa = 6.1,\ g_{\pi N\Delta}/g_{\pi NN} = g_{\rho N\Delta}/g_{\rho NN} = 1.8$
	σNN	550	8.94	1900 (M)	
	ωNN	783	24.5	1850 (D)	
	σNR	550	0.8	2000 (R)	$\alpha = 1$
	ωNR	783	1.0	1850 (R)	$\alpha = 1$
V_{18}	π	138	14.43	1580 (M)	$a = 1.12,\ b = -2.49,\ c = 0.98$ [TM(81)]
	ρ	776	0.55	1400 (M)	$\kappa = 6.6,\ g_{\pi N\Delta}/g_{\pi NN} = g_{\rho N\Delta}/g_{\rho NN} = 1.8$
	σNN	540	11.9	1100 (M)	
	ωNN	780	33.0	1300 (M)	
	σNR	540	2.58	1450 (R)	$\alpha = -2.35$
	ωNR	780	4.23	1550 (R)	$\alpha = -2.33$

Nij93 has many more parameters: 2 scalar mesons, wide σ and ρ mesons, “pomeron”

- Results with Bonn B potential ...

Individual Meson Exchange Contributions:



↪ Strong compensation !

Phenomenological TBF (Urbana Model):

- Two pion exchange + phenomenological repulsion:

$$V_{ijk} = \sum_{\text{cyc.}} \Big[\quad A \{X_{ij}, X_{jk}\} \{\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j, \boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k\} + \frac{A}{4} [X_{ij}, X_{jk}] [\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j, \boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k] + U\, T^2_{ij} T^2_{jk} \Big]$$

$$X_{ij} = Y(m_\pi r_{ij}) \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j + T(m_\pi r_{ij}) S_{ij}$$

$$Y(x) = \frac{e^{-x}}{x} \left(1 - e^{-cr^2}\right) , \quad T(x) = \left(1 + \frac{3}{x} + \frac{3}{x^2}\right) \frac{e^{-x}}{x} \left(1 - e^{-cr^2}\right)^2$$

- Corresponds to micro TBF with only $\pi\pi$ contribution and

$$A = -\frac{2}{81} \frac{(m_\pi f_{\pi NN} f_{\pi N\Delta})^2}{m_\Delta - m_N}$$

- Optimal parameters for BHF+TBF (with V_{18} 2BF):

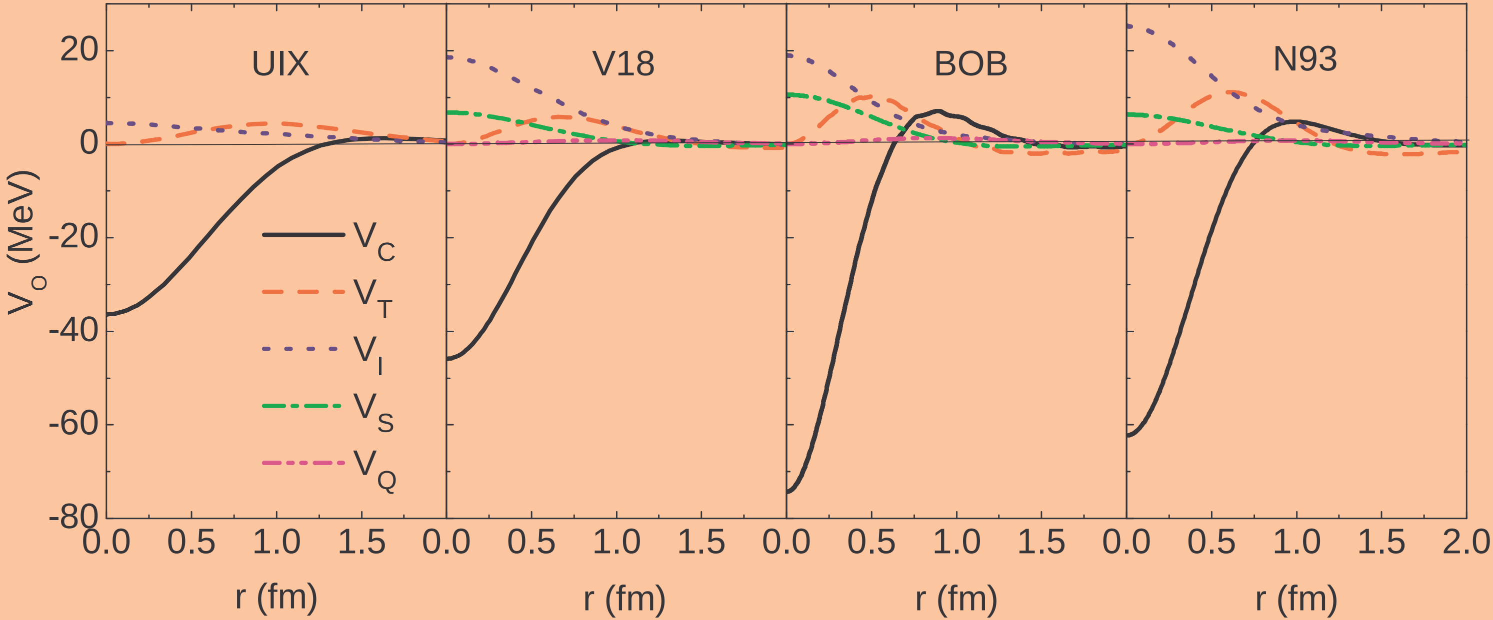
$$A \approx -0.0500 \text{ MeV} , \quad U \approx 0.00042 \text{ MeV}$$

Phenomenological vs. Microscopic TBF:

- Compare micro TBF with V_{18}, Bonn B, or Nijmegen 93 potential and UIX TBF (with V_{18}):

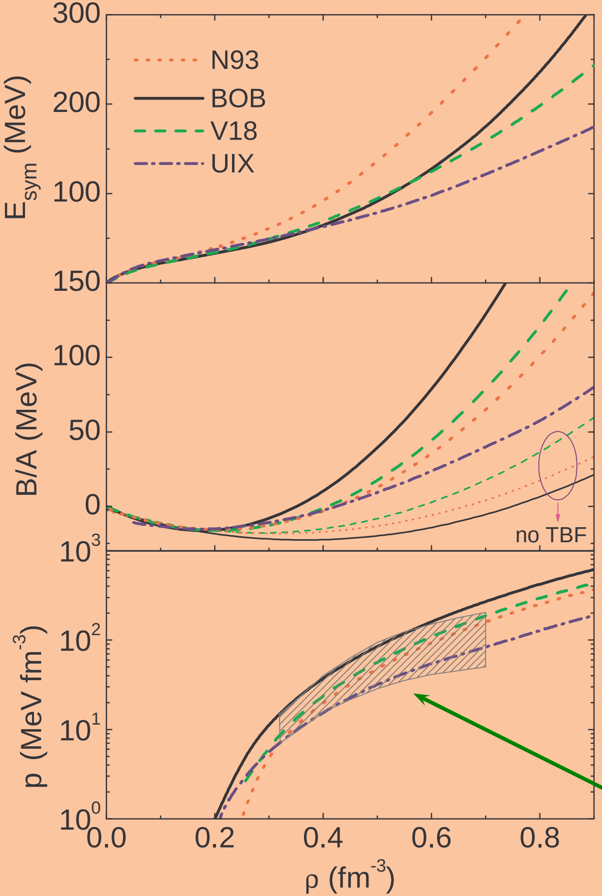
$$\overline{V_{ij}}(\boldsymbol{r}) = (\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)V_C(r) + (\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)V_S(r) + V_I(r) + S_{ij}(\hat{\boldsymbol{r}})\left[(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)V_T(r) + V_Q(r)\right]$$

at $\rho = \rho_0$:



Results of BHF Approach:

- Symmetry energy, EOS, Saturation properties:

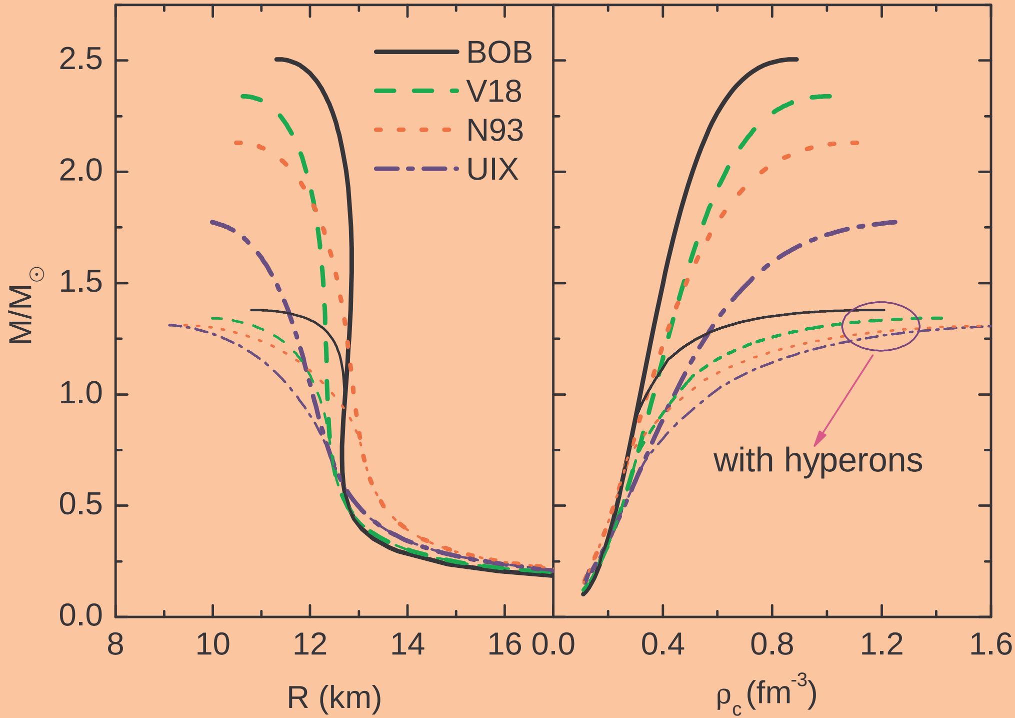


	$[\rho, B/A]_0$ [fm^{-3},MeV]	K MeV	$E_{\rm sym}$ MeV	$E'_{\rm sym}$ MeV
N93	[0.18,-15.4]	216	34.0	35.5
BOB	[0.17,-15.9]	244	29.4	24.8
V18	[0.20,-14.7]	226	30.6	33.8
UIX	[0.18,-15.3]	192	33.5	24.5

Nuclear flow analysis of Science 298, 1592 (2002)

Neutron star structure:

- Solve TOV equations:



NSC89 NY potential
No YY
No hyperon TBF

➥ Large variation with nucleonic TBF
Self-regulating softening due to hyperon appearance

Summary:

- Consistent microscopic TBF + BHF provide reasonable saturation
- Uncertain high-density behaviour: $M_{\text{max}} \approx \mathbf{1.8, ..., 2.5}\, M_\odot$
- BHF EOS including hyperons predicts $M_{\text{max}} \approx \mathbf{1.3, ..., 1.5}\, M_\odot$
- Inclusion of quark matter phase raises M_{max} to less than $\mathbf{1.7}\, M_\odot$
- Masses above $\mathbf{2}\, M_\odot$ not explainable in our theoretical frame !

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Future:

- Technical improvements: 3rd nucleon average, static approx., ...
- BHF with TBF + 3 hole line corrections
- Micro TBF in light nuclei ?