Astrophysical Constraints on the Nuclear Matter Equation of State

Helmholtz International Summerschool

Nuclear Theory and Astrophysical Applications

Dubna, 07. - 17.08 2007

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Part 1: Neutron Stars - Masses and Radii

Part 2: Consistence with modern Equations of State

Overview

- relativistic mean field (RMF): Walecka
- parameterisation of realistic models
- neutron star constraints (last session)
- symmetric matter: flow constraint
- cooling neutron stars: direct Urca
- quark matter phase transition

Walecka model for dense nuclear matter

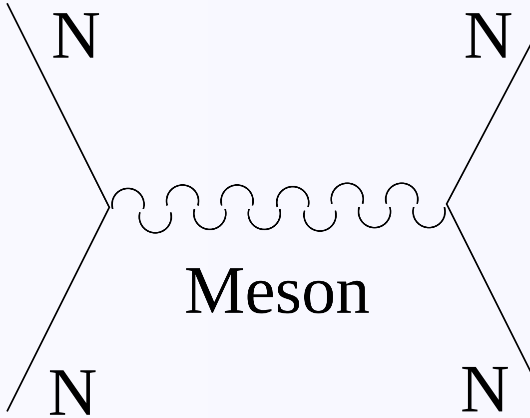
Meson exchange model

example: scalar (σ) meson

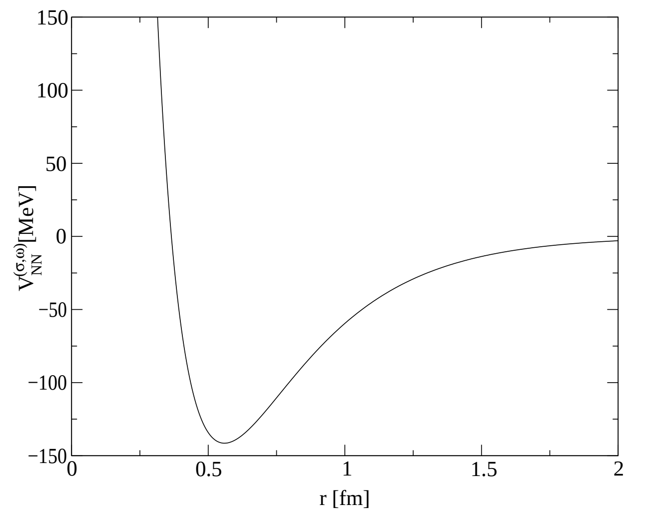
$$(-\Delta + m_\sigma^2)\sigma(\vec{r}) = -g_\sigma \delta(\vec{r})$$

$$\Rightarrow \quad \sigma(r) = -\frac{g_\sigma}{4\pi}\frac{e^{-m_\sigma r}}{r}$$

$$V_{NN}^{(\sigma)}(r) = g_\sigma \sigma(r) = -\frac{g_\sigma^2}{4\pi}\frac{e^{-m_\sigma r}}{r}$$



Meson	I^π	T	S	M[MeV]
$\pi^0, \pi^\pm$	0^-	1	0	140
σ	0^+	0	0	≈ 500
$K^0, K^\pm$	0^-	1/2	± 1	495
η	0^-	0	0	550
$\rho^0, \rho^\pm$	1^-	1	0	770
ω	1^-	0	0	780
δ	0^+	1	0	900



Walecka model for dense nuclear matter

Field theoretical formulation: Lagrangian and Path Integral for Partition Function

$$\mathcal{Z}_{gk}(T,V,\{\mu_i\}) = \int [d\overline{\Psi}][d\Psi] \exp\left\{ \int_0^{\beta=1/T} d\tau \int_V d^3\vec{x} \, \left(\mathcal{L}_0 + \mathcal{L}_I + \mu_p \Psi_p^+ \Psi_p + \mu_n \Psi_n^+ \Psi_n\right) \right\}$$

$$\begin{aligned} \mathcal{L}_0(\tau,\vec{x}) &= \overline{\Psi}(\tau,\vec{x}) \left(i\gamma_\mu \partial_\mu - m_N\right) \Psi(\tau,\vec{x}) \\ \mathcal{L}_I(\tau,\vec{x}) &= j_{\omega_\mu}(\tau,\vec{x}) \frac{G_\omega}{2} j_{\omega_\mu}(\tau,\vec{x}) - j_\sigma(\tau,\vec{x}) \frac{G_\sigma}{2} j_\sigma(\tau,\vec{x}) \end{aligned}$$

$$\begin{aligned} j_\sigma(\tau,\vec{x}) &= \overline{\Psi}(\tau,\vec{x})\Psi(\tau,\vec{x}) \\ j_{\omega_\mu}(\tau,\vec{x}) &= \overline{\Psi}(\tau,\vec{x})\gamma_\mu\Psi(\tau,\vec{x}) \end{aligned} \qquad \Psi = \begin{pmatrix} \psi_n \\ \psi_p \end{pmatrix} ; \quad \psi_n = \begin{pmatrix} u_{n,\uparrow} \\ u_{n,\downarrow} \\ v_{n,\uparrow} \\ v_{n,\downarrow} \end{pmatrix} \begin{matrix} \}\ \text{Neutron} \\ \\ \}\ \text{Antineut.} \end{matrix}$$

$\mu_n = \mu_p \quad \rightarrow$ symmetric nuclear matter

$\mu_n \neq 0;\ \mu_p = 0 \quad \rightarrow$ pure neutron matter

$\mu_n = \mu_p + \mu_{e^-} \quad \rightarrow$ neutron star matter (β-equilibrium)

Walecka model for dense nuclear matter

Evaluation of the Path Integral: Hubbard-Stratonovich trick

$$\exp\left(-\left(\overline{\Psi}\Psi\right)\frac{G_\sigma}{2}\left(\overline{\Psi}\Psi\right)\right) = \left(\det G_\sigma^{-1}\right)^{\frac{1}{2}} \int [d\sigma] \exp\left(\frac{\sigma^2}{2G_\sigma} + \sigma\overline{\Psi}\Psi\right)$$

Effective action quadratic $\Longrightarrow$ Gaussian Path Integral

$$\mathcal{S} \equiv \int_0^\beta d\tau \int d^3\vec{x} \left\{ \overline{\Psi}(\vec{x},\tau)\left(-\gamma_0\frac{\partial}{\partial\tau} + i\vec{\gamma}\vec{\nabla} - m_N + \gamma_0\mu + \sigma - \gamma_0\omega_0\right)\Psi(\vec{x},\tau) + \frac{\sigma^2}{2G_\sigma} - \frac{\omega_0^2}{2G_{\omega_0}} \right\}$$

Fourier representation: $\Psi(\vec{x},\tau) = \sqrt{\frac{T}{V}} \sum_n \sum_{\vec{p}} e^{i(\vec{p}\vec{x}+\omega_n\tau)}\Psi_n(\vec{p})$, with $\omega_n \equiv \pi T(2n+1)$

$$\int_0^\beta d\tau \int d^3\vec{x}\, \overline{\Psi}(\vec{x},\tau)\left(-\gamma_0\frac{\partial}{\partial\tau} + i\vec{\gamma}\vec{\nabla} - m_N + \gamma_0\mu + \sigma - \gamma_0\omega_0\right)\Psi(\vec{x},\tau)$$

$$= \beta\sum_n\sum_{\vec{p}} \overline{\Psi}_n(\vec{p})(-\gamma_\mu p_\mu - m_N^*)\Psi_n(\vec{p}) = \sum_n\sum_{\vec{p}} \overline{\Psi}_n(\vec{p}) G^{-1}[\sigma,\omega_0]\Psi_n(\vec{p})$$

Effective mass $m_N^* = m_N - \sigma$, chemical potential $\mu^* = \mu - \omega_0$ and quasiparticle propagator

$$G^{-1}[\sigma,\omega] = -\beta(\gamma_\mu p_\mu + m_N^*) \ , \quad p_0 = i\omega_n - \mu^*$$

Walecka model for dense nuclear matter

Evaluate fermionic Path Integral and mean field approximation:

$$\begin{aligned}
\mathcal{Z}_{gk}(T,V,\{\mu_i\}) &= \mathcal{N}\prod_{n,\vec{p}}\int[d\overline{\Psi}_n][d\Psi_n][d\sigma][d\omega_0]\exp\left\{\sum_{n,\vec{p}}\overline{\Psi}_n G^{-1}[\sigma,\omega_0]\Psi_n+\frac{\sigma^2}{2G_\sigma}-\frac{\omega_0^2}{2G_{\omega_0}}\right\}\\
&= \int[d\sigma][d\omega_0]\exp\left\{Tr\,\ln G^{-1}[\sigma,\omega_0]+\frac{\sigma^2}{2G_\sigma}-\frac{\omega_0^2}{2G_{\omega_0}}\right\}\\
&= \exp\left\{Tr\,\ln G^{-1}[\overline{\sigma},\overline{\omega}_0]+\frac{\overline{\sigma}^2}{2G_\sigma}-\frac{\overline{\omega}_0^2}{2G_{\omega_0}}\right\}
\end{aligned}$$

Stationarity condition: $\partial\ln Z_{gk}/\partial\overline{\sigma}=\partial\ln Z_{gk}/\partial\overline{\omega}_0=0$ corresponds to

$$\overline{\sigma} = -G_\sigma Tr\,G[\overline{\sigma},\overline{\omega}_0]=G_\sigma n_s\ ,\quad \overline{\omega}_0=-G_\omega Tr\,\gamma_0 G[\overline{\sigma},\overline{\omega}_0]=G_\omega n\ .$$

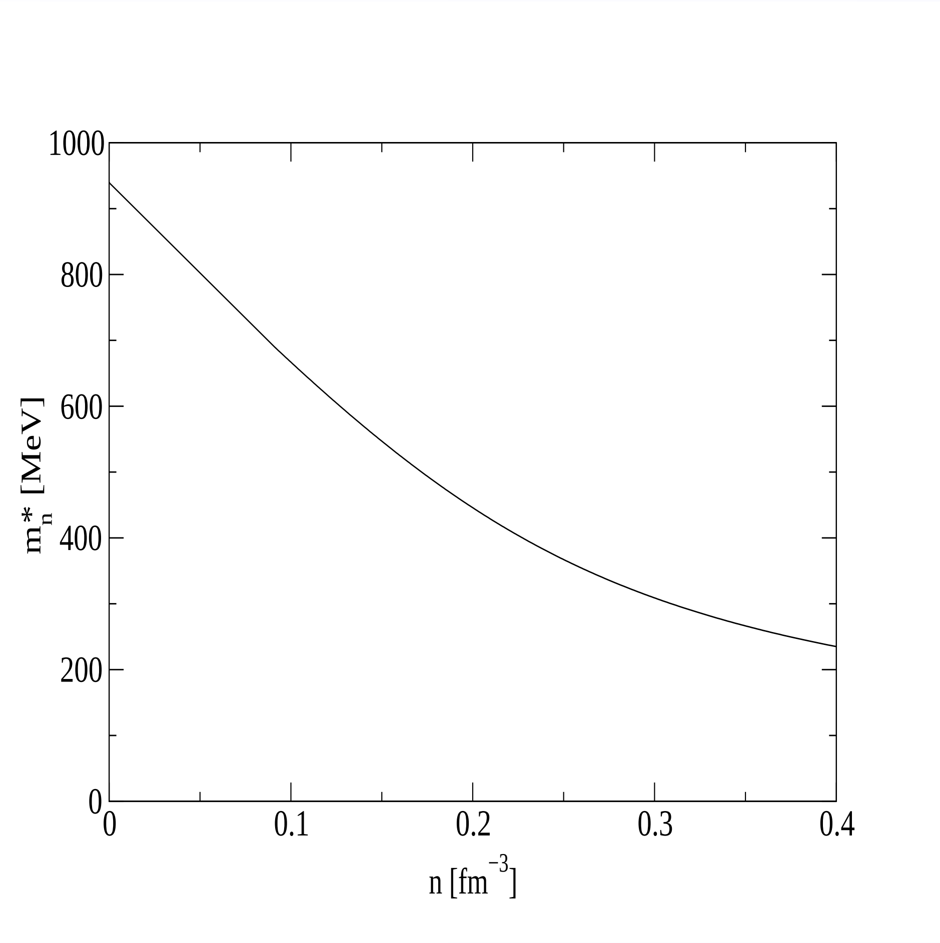
Thermodynamics: $\Omega(T,V,\mu)=-T\ln\mathcal{Z}_{gk}=-pV$

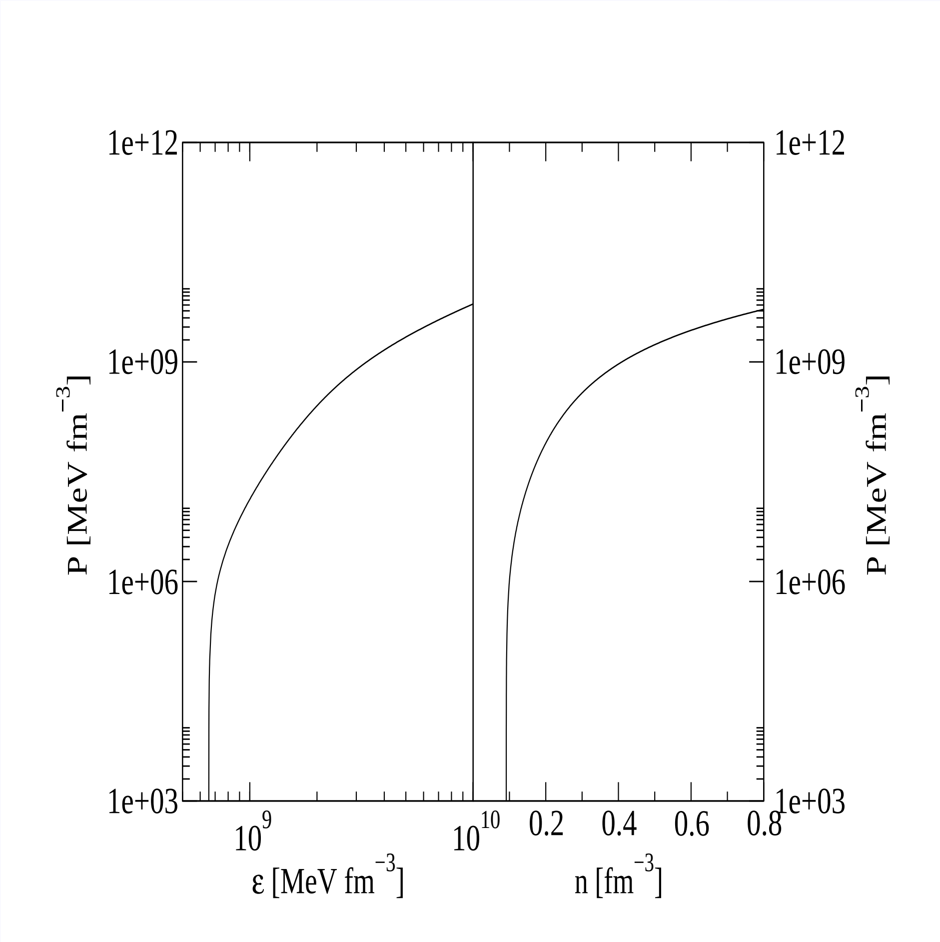
$$p(\mu,T)=\frac{1}{2}G_\omega n^2-\frac{1}{2}G_\sigma n_s^2+4T\int\frac{d^3\vec{p}}{(2\pi)^3}\left[\ln\left(1+e^{-\beta(E^*-\mu^*)}\right)+\ln\left(1+e^{-\beta(E^*+\mu^*)}\right)\right]$$

$$n=4\int\frac{d^3\vec{p}}{(2\pi)^3}\left[f_-(E^*)-f_+(E^*)\right]\ ,\ n_s=4\int\frac{d^3\vec{p}}{(2\pi)^3}\frac{m_N^*}{E^*}\left[f_-(E^*)-f_+(E^*)\right]$$

Quasiparticle properties $E^*=\sqrt{\vec{p}^2+{m_N^*}^2},\ m_N^*=m_n-G_\sigma n_s,\ \mu^*=\mu-G_\omega n\ .$

Walecka model for dense nuclear matter





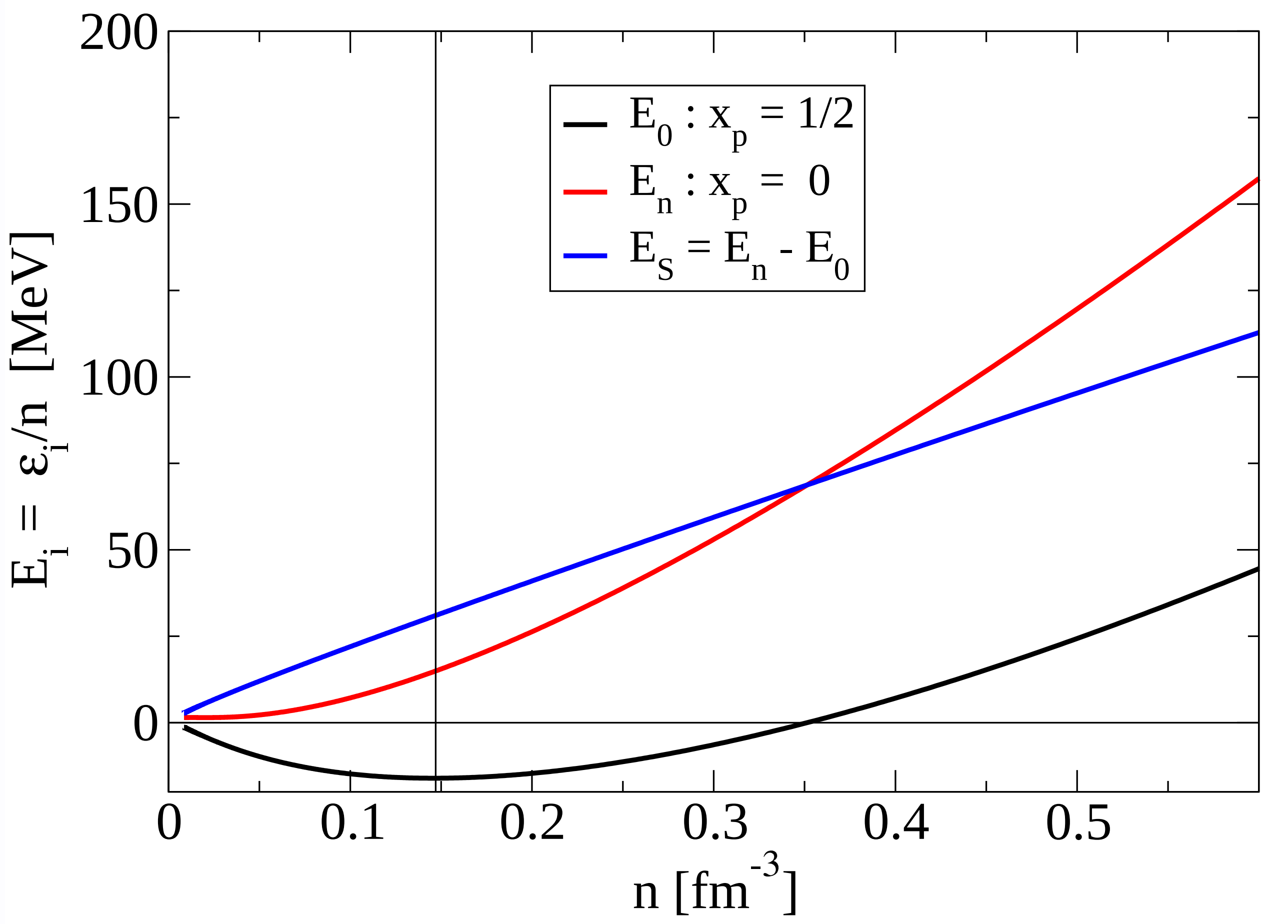
Further reading, e.g.,

Kapusta: 'Finite temperature field theory'

Glendenning: 'Compact Stars'

Symmetry Energy

Energy per particle in symmetric ($E_0(n)$) and neutron matter ($E_n(n)$) $\rightarrow$ symmetry energy



(Link to Bethe-Weizsäcker : $E_0(n_0) \approx a_{vol}$, $E_S(n_0) \approx a_{sym}$)

Exploring the Limits - The EoS

Several approaches to describe dense nuclear matter

- **relativistic** Equations of State at $T = 0$ K

$$\varepsilon(n_n, n_p, n_e, n_\mu) \rightarrow \varepsilon_h(n_n, n_p) + \sum_{e,\mu} \varepsilon_i(n_i),$$

$$\mu_i = \frac{\mathrm{d}\varepsilon}{\mathrm{d}n_i}, P = \sum_{n,p,e,\mu} \mu_i n_i - \varepsilon_h - \varepsilon_l$$

- expanding energy per particle in terms of neutron-proton asymmetry $\beta = \frac{n_n - n_p}{n_n + n_p} = 1 - 2x_p,\ n = n_n + n_p$

- $$\frac{B}{A}(n_n, n_p) \rightarrow \frac{B}{A}(n, \beta) = E_0(n) + \beta^2 E_S(n)$$

$$\begin{aligned} \varepsilon_h(n,\beta) &= n\frac{B}{A}(n,\beta), \qquad P_h(n,\beta) = n^2 \frac{\partial}{\partial n}\frac{B}{A}(n,\beta), \\ \mu_{n,p}(n,\beta) &= \left(1 + n\frac{\partial}{\partial n}\right) E_0(n) - \left(\beta^2 \mp 2\beta - \beta^2 n \frac{\partial}{\partial n}\right) E_S(n). \end{aligned}$$

Equations of State

- Phenomenological (RMF)

NLρ, NL$\rho\delta$	non linear σ terms
	(σ self interactions)
	ρ- (and δ-) Mesons
DD, D^{3}C, DD-F	density dependent couplings ($\Gamma_i \rightarrow \Gamma_i(n)$)
KVR, KVOR	density dependent mass of σ-Meson

- ab initio

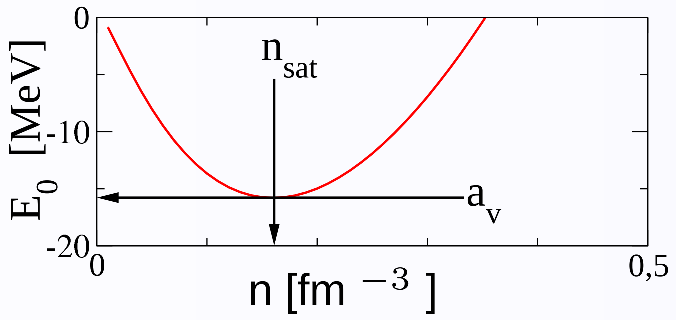
DBHF	relativistic Dirac-Brueckner-Hartree-Fock
	free N-N interaction explicitly given
	medium effects: T-Matrix (ladder approximation)

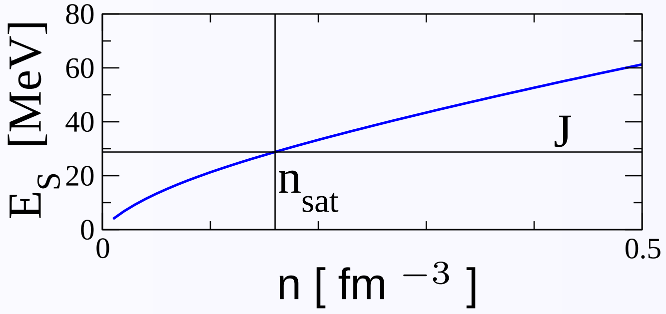
Exploring the Limits - The EoS beyond saturation

$$E(n,\beta) = E_0(n) + \beta^2 E_S(n) \approx a_V + \frac{K}{18}\epsilon^2 - \frac{K'}{162}\epsilon^3 + \ldots + \beta^2\left(J + \frac{L}{3}\epsilon + \ldots\right) + \ldots$$

$$\epsilon = (n - n_{sat})/n \qquad \beta = (n_n - n_p)/(n_n + n_p)$$

	$n_{\rm sat}$	a_V	K	K'	J	L	m_D/m
	[fm^{-3}]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	
exp.	0.16 ± 0.01	-16 ± 1	$200 - 300$		$25 - 35$		$0.6 - 1.0$
NLρ	0.1459	−16.062	203.3	576.5	30.8	83.1	0.603
NL$\rho\delta$	0.1459	−16.062	203.3	576.5	31.0	92.3	0.603
DBHF	0.1779	−16.160	201.6	507.9	33.7	69.4	0.684
DD	0.1487	−16.021	240.0	−134.6	32.0	56.0	0.565
D^{3}C	0.1510	−15.981	232.5	−716.8	31.9	59.3	0.541
KVR	0.1600	−15.800	250.0	528.8	28.8	55.8	0.800
KVOR	0.1600	−16.000	275.0	422.8	32.9	73.6	0.800
DD-F	0.1469	−16.024	223.1	757.8	31.6	56.0	0.556





T. Klähn et al., Phys.Rev.C **74**, 035802 (2006)

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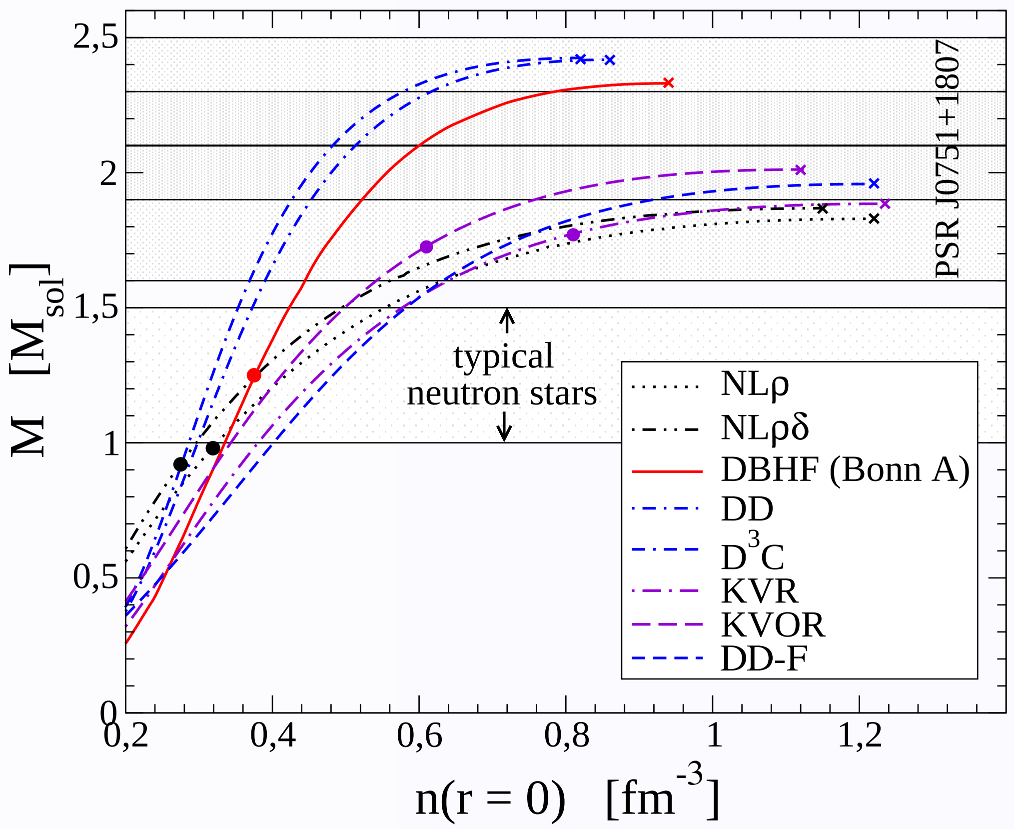
δ_{rel}	22%	2%	36%	±!	17%	65%	33%

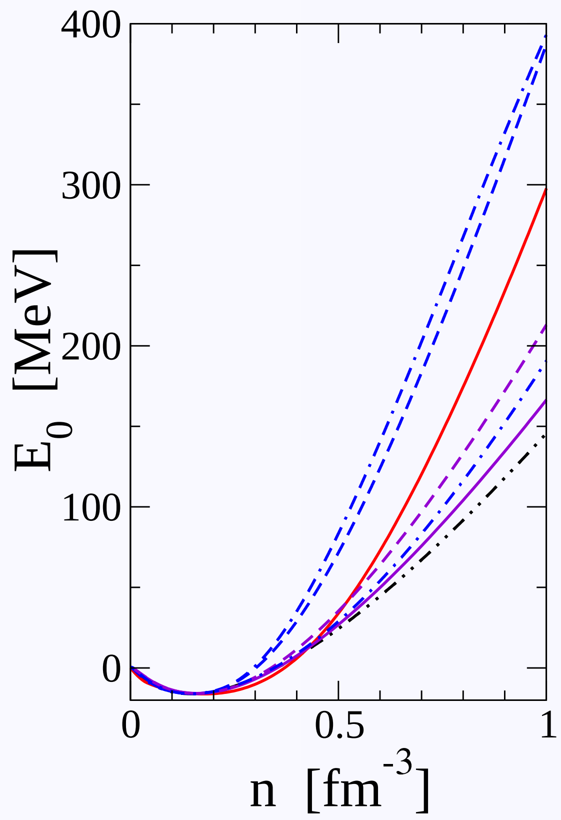
Higher order terms are barely constrained!

How to select the 'good' model?

New quality of astrophysical measurements! Constraints from NSs!

Maximum Neutron Star Masses





$M(n)$ correlated to $E_0(n)$

stiff: higher M_{max} at smaller densities

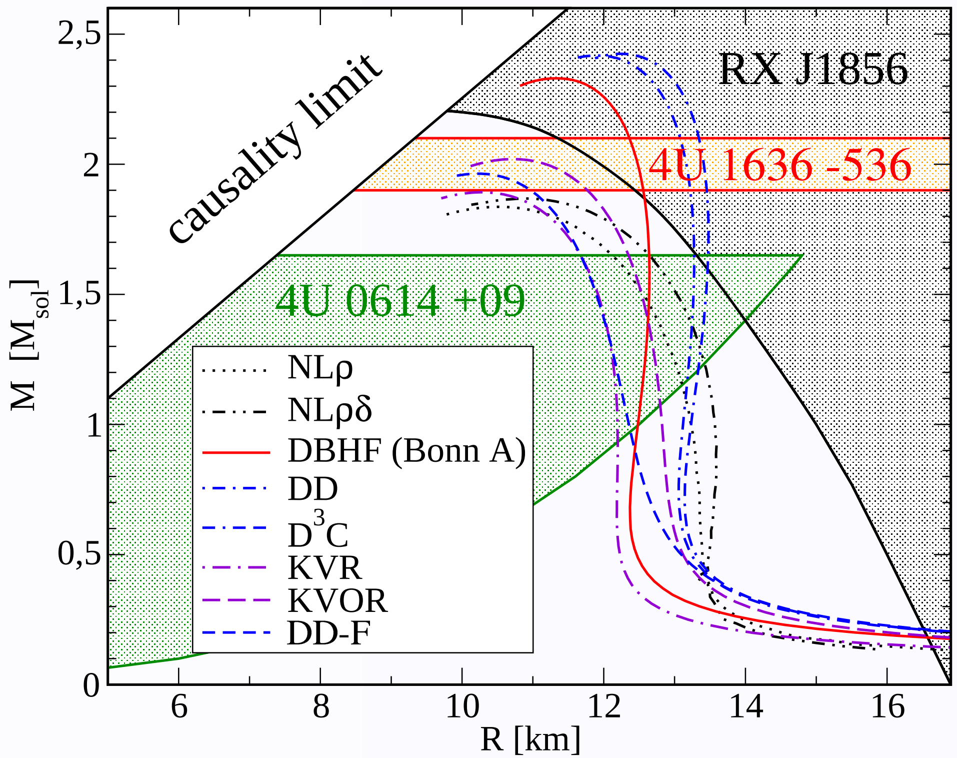
soft: smaller M_{max} at higher densities

M-R Constraints

RXJ1856 black body spectrum: $T_\infty = 57$ eV

measurement of distance: 60 pc (2002) $\rightarrow$ 117 pc (2004)

$\rightarrow$ photospheric radius: $R_\infty = R(1 - R/R_S)^{-1/2}$ $\quad R_S = 2GM$



Mass Radius Constraints

QPO : M-R upper limits

ISCO : max. mass constraint

RXJ1856: M-R lower limits

each region...

$\rightarrow$ represents a different object

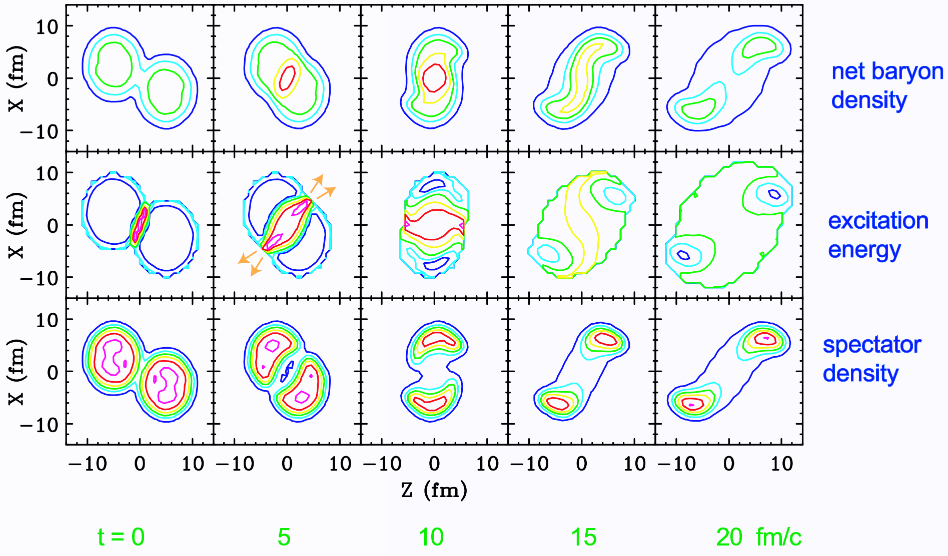
$\rightarrow$ should be touched at least once

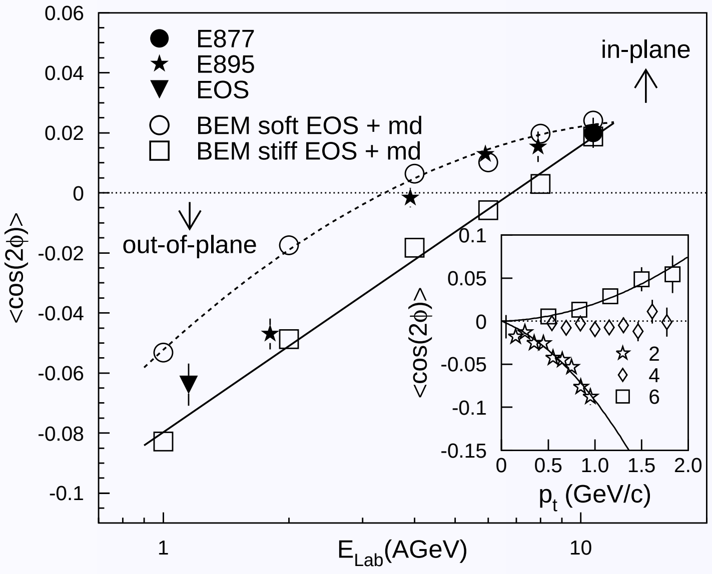
J. Trümper et al., Nucl. Phys. Proc. Suppl. 132, 560 (2004)

D. Barret, J.-F. Olive, M.C. Miller, Mon. Not. Roy. Astron. Soc. 361, 855 (2005)

Elliptic Flow in HIC

Heavy Ion Collisions:

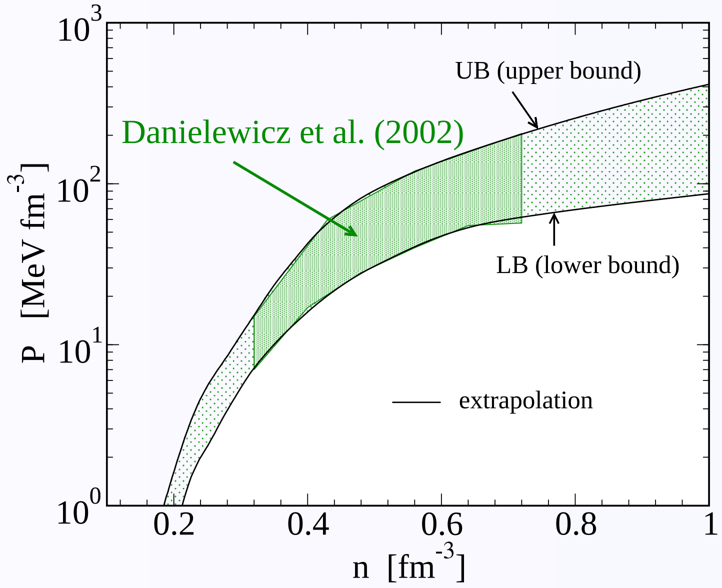




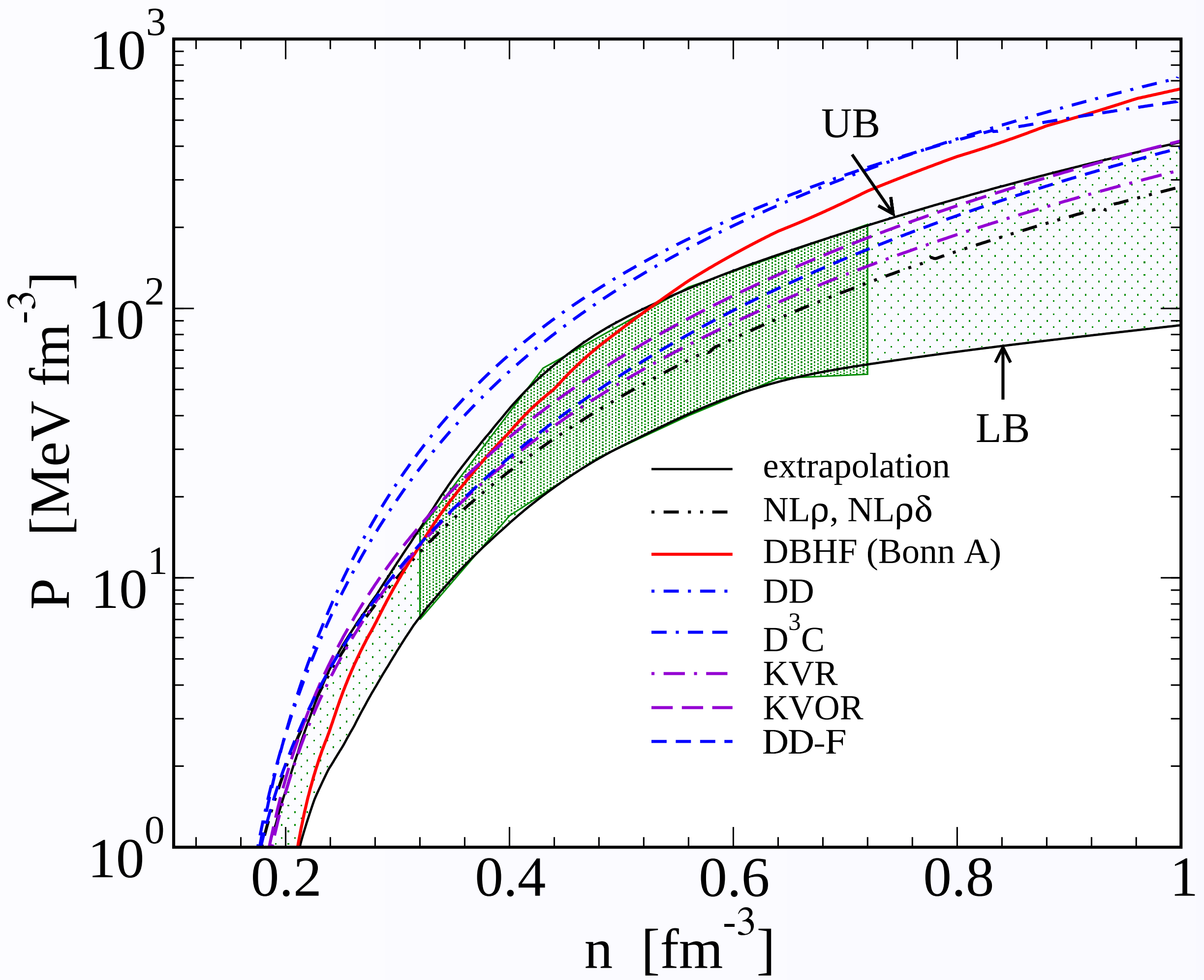
P. Danielewicz et al., Science **298**, 1592 (2002)

Flow data constrain EoS up to $n \approx 4n_0$

$\longrightarrow$ finite range of possible P(n) for given n



Flow Constraint



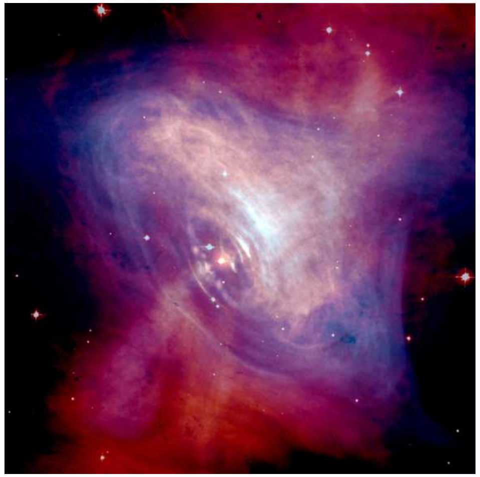
→ fulfilled for soft NLρ,NL$\rho\delta$, KVR, KVOR, DD-F;

DBHF at low densities; DD, D^{3}C fail

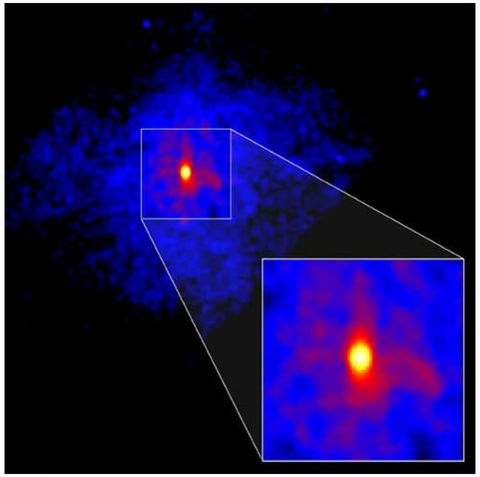
Neutron Star Cooling

Pulsars in SN remnants:

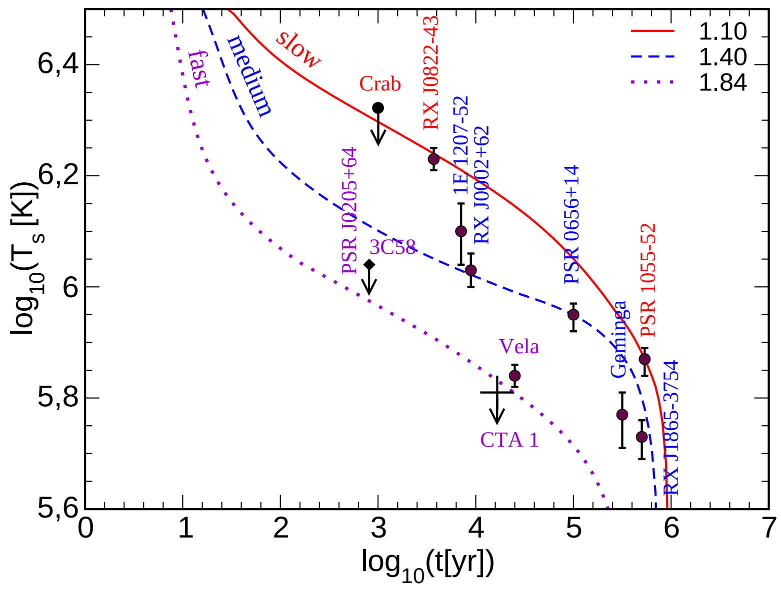
1054 - Crab



1181 - 3C58



Classification of cooling compact stars



Blaschke et al. (2004)

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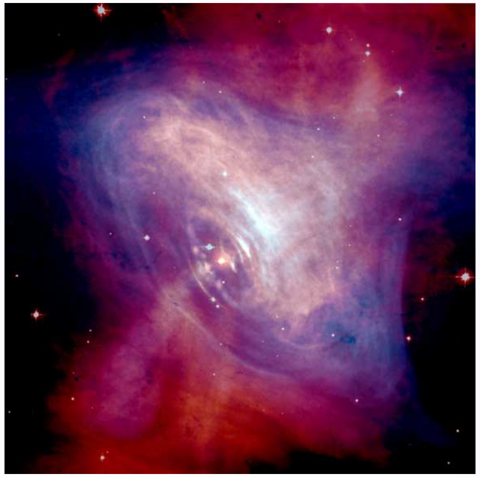

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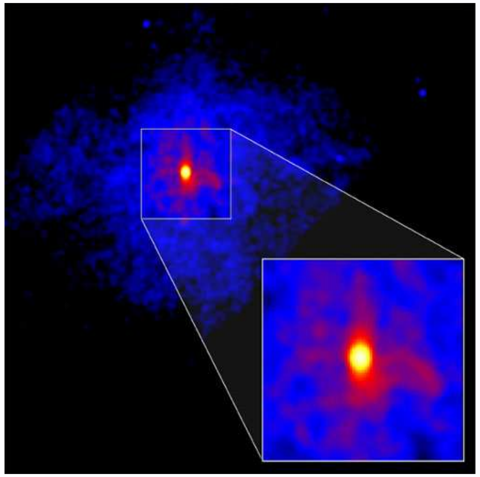

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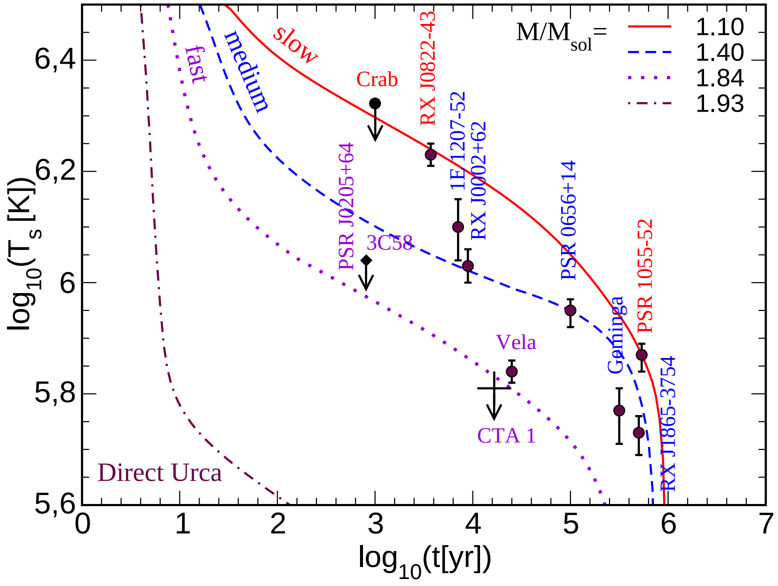


Blaschke et al. (2004)

parameter $\longrightarrow$ neutron star mass

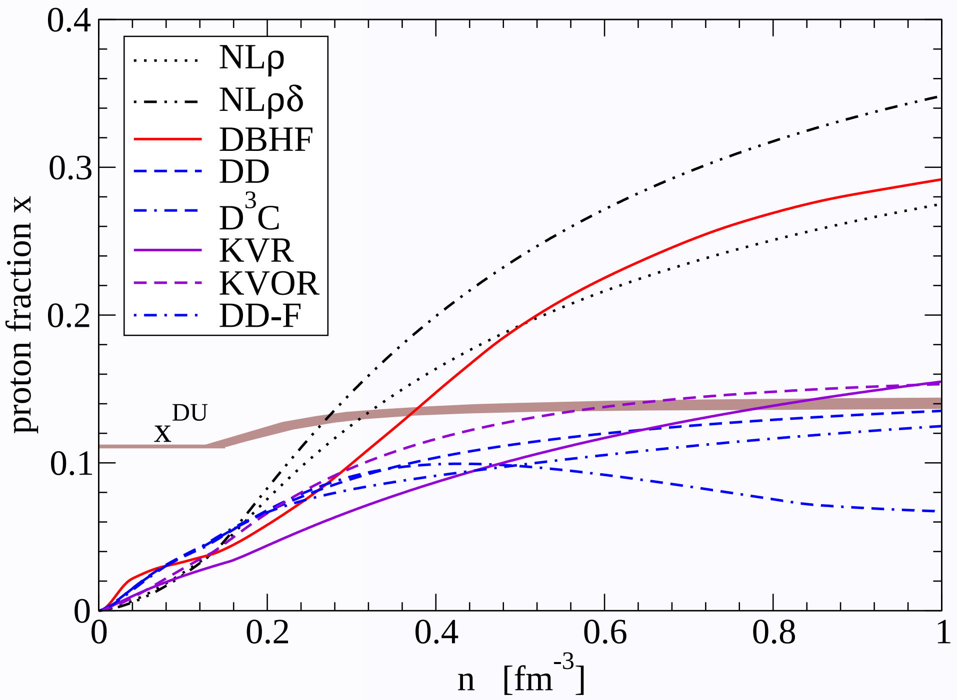
Direct Urca: $n \rightarrow p + e^- + \bar{\nu}_e$

Direct Urca Process → Rapid Cooling

$n \rightarrow p + e + \bar{\nu}_e$ implies $p_n \leq p_p + p_e$, same for muons: $e \leftrightarrow \mu$
charge neutrality: $n_p = n_e + n_\mu$, i.e. $p_p^3 = p_e^3 + p_\mu^3$ results in

$$x_p \geq x_{DU}(x_e) = [1 + (1 + x_e^{1/3})^3]^{-1} \qquad x_e = n_e/(n_e + n_\mu)$$

- no muons: $x_{DU} = 11.1\%$
- relativistic limit ($n_e = n_\mu$): $x_{DU} = 14.8\%$



$E_S(n)$:
soft for DU onset at high n

NLρ, NL$\rho\delta$, DBHF :
DU occurs below $2.5\ n_0$

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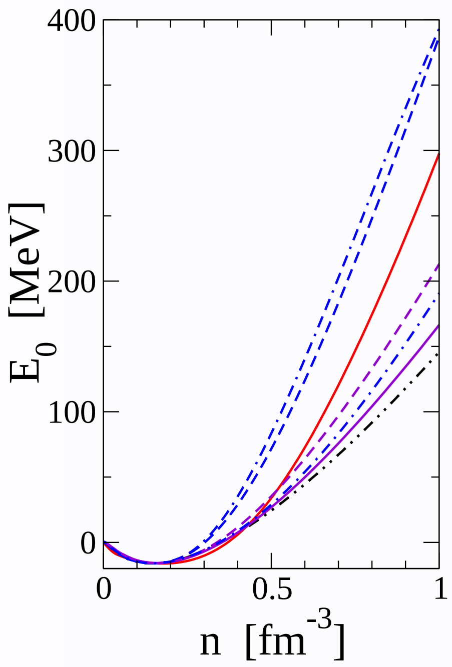
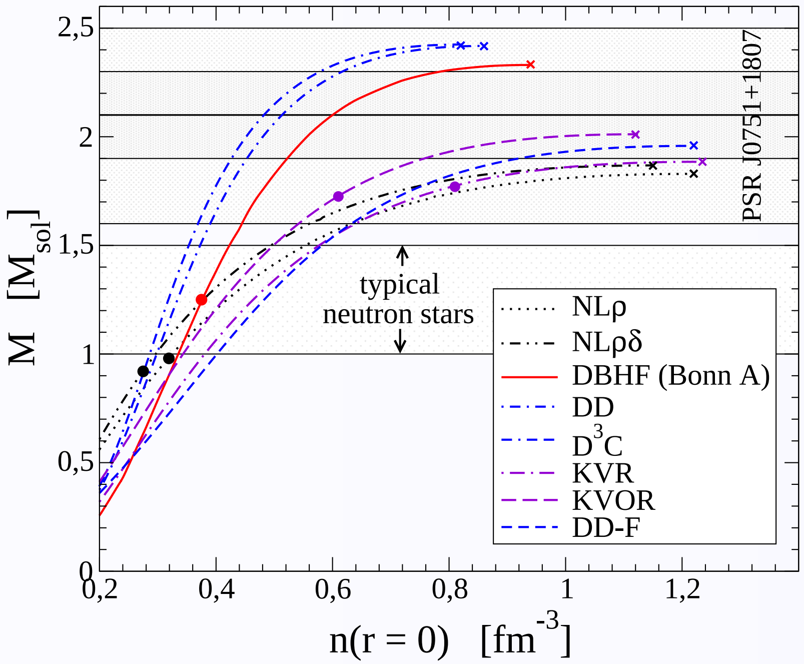




$E_S(n)$:

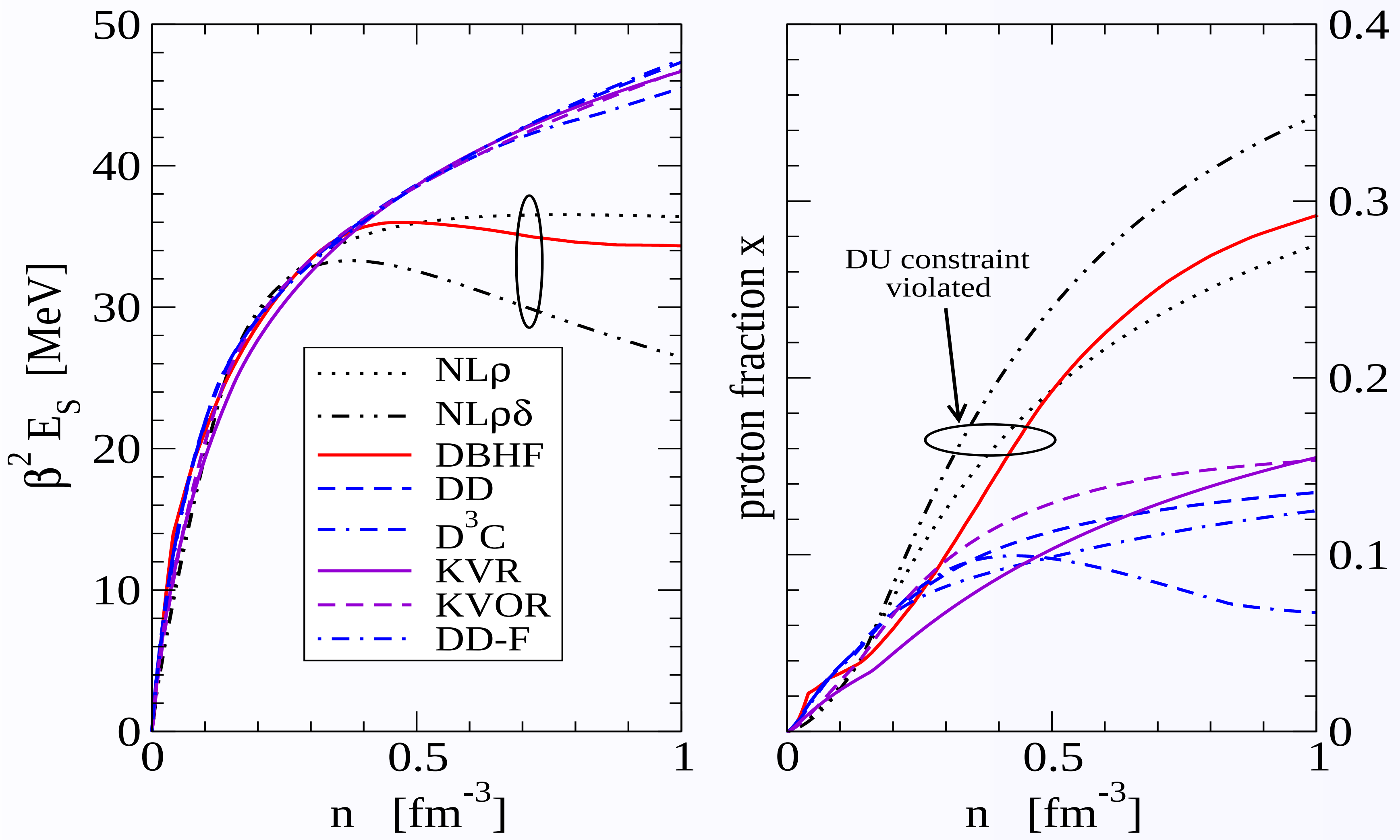
soft for DU onset at high n

NLρ, NL$\rho\delta$, DBHF :

DU occurs below $2.5\ n_0$

$M_{DU} < 1.3 M_\odot$

Consequences: Universality conjecture for $\beta^2 E_S(n)$



Exclude NLρ, NL$\rho\delta$, DBHF since DU constraint violated ($M_{DU} < M_{\rm typ}$)

$\rightarrow$ universal $\beta^2 E_S$

Exploring the Limits: Nuclear Matter beyond Saturation

Model	$M_{max} \geq 1.9\ M_\odot$	$M_{max} \geq 1.6\ M_\odot$	$M_{DU} \geq 1.5\ M_\odot$	$M_{DU} \geq 1.35\ M_\odot$	4U 1636-536 (u)	4U 1636-536 (l)	RX J1856 (A)	RX J1856 (B)	J0737 (no loss)	J0737 (loss 1%)	SIS+AGS flow constr.	SIS flow+ K^+ constr.	No. of passed strong tests	No. of passed weak tests
NLρ	−	+	−	−	−	−	−	−	−	−	+	+	1	2
NL$\rho\delta$	−	+	−	−	−	−	−	−	−	−	+	+	1	2
DBHF	+	+	−	−	+	+	−	+	−	+	−	+	2	5
DD	+	+	+	+	+	+	−	+	−	−	−	−	3	4
D^3C	+	+	+	+	+	+	−	+	−	−	−	−	3	4
KVR	∘	+	+	+	−	∘	−	−	−	+	+	+	3	5
KVOR	+	+	+	+	−	+	−	−	−	∘	+	+	3	5
DD-F	+	+	+	+	−	+	−	−	−	+	+	+	3	5

Complementary scheme with strong (left columns) and weak (right columns) constraints

Favourite EsoS: DBHF, KVR, KVOR, DD-F; None passes all constraints !

Exploring the Limits - Summary

- High density EoS testing scheme
  - set of constraints from HIC flow and new astrophysical observations
  - complementary tests for $E_0(n)$ and $E_S(n)$
- Present-day conclusions
  - “soft” $E_S(n)$ (NS cooling, direct Urca)
  - $\beta^2 E_S(n)$ shows universal behaviour
  - “stiff” $E_0(n)$ at intermadiate densities (maximum masses)
  - “soft” $E_0(n)$ at high densities (flow data)
- Open: transition to quark matter?
  - does quark matter in compact stars contradict observations?
  - might a phase transition to quark matter
    solve problems of hadronic EoS (DBHF→DU, flow)?
  - how to prove a possible quark core in NSs?

Quark Matter - NJL-type Model EoS

$$\mathcal{L}[\bar{q}, q] = \quad \bar{q}\left(i\partial\!\!\!/ - \hat{m} + \hat{\mu}\gamma^0\right) q + G_S \Big[\sum_{a=0,3,8} (\bar{q}\tau_a q)^2 - \eta_V (\bar{q}\gamma^0 q)^2$$

$$+\eta_D \sum_{A=2,5,7} (\bar{q} i\gamma_5 \tau_A \lambda_A C \bar{q}^T)(q^T i C \gamma_5 \tau_A \lambda_A q) \Big]$$

Bosonization (Hubbard-Stratonovich trick) $\rightarrow$ Mean-field approximation

$$\Omega_{MF}(T, \mu) = \quad \frac{1}{8G_S} \Big[\sum_{i=u,d,s} (m_i^* - m_i)^2 - \frac{2}{\eta_V}(2\omega_0^2 + \phi_0^2) + \frac{2}{\eta_D} \sum_{A=2,5,7} |\Delta_{AA}|^2$$

$$- \int \frac{d^3p}{(2\pi)^3} \sum_{a=1}^{18} \left[E_a + 2T \ln\left(1 + e^{-E_a/T}\right)\right] + \Omega_l - \Omega_0$$

Dispersion E_a : Eigenvalues of Nambu-Gorkov Propagator

$$\tilde{S}^{-1}(p_0, \vec{p}) = \begin{pmatrix} p\!\!\!/ - \hat{M}(p) - \hat{\mu}^*\gamma_0 & \Delta \gamma_5 \tau_2 \lambda_2 \\ -\Delta^* \gamma_5 \tau_2 \lambda_2 & p\!\!\!/ - \hat{M}(p) + \hat{\mu}^*\gamma_0 \end{pmatrix} .$$

Vector coupling : renormalizes chemical potentials

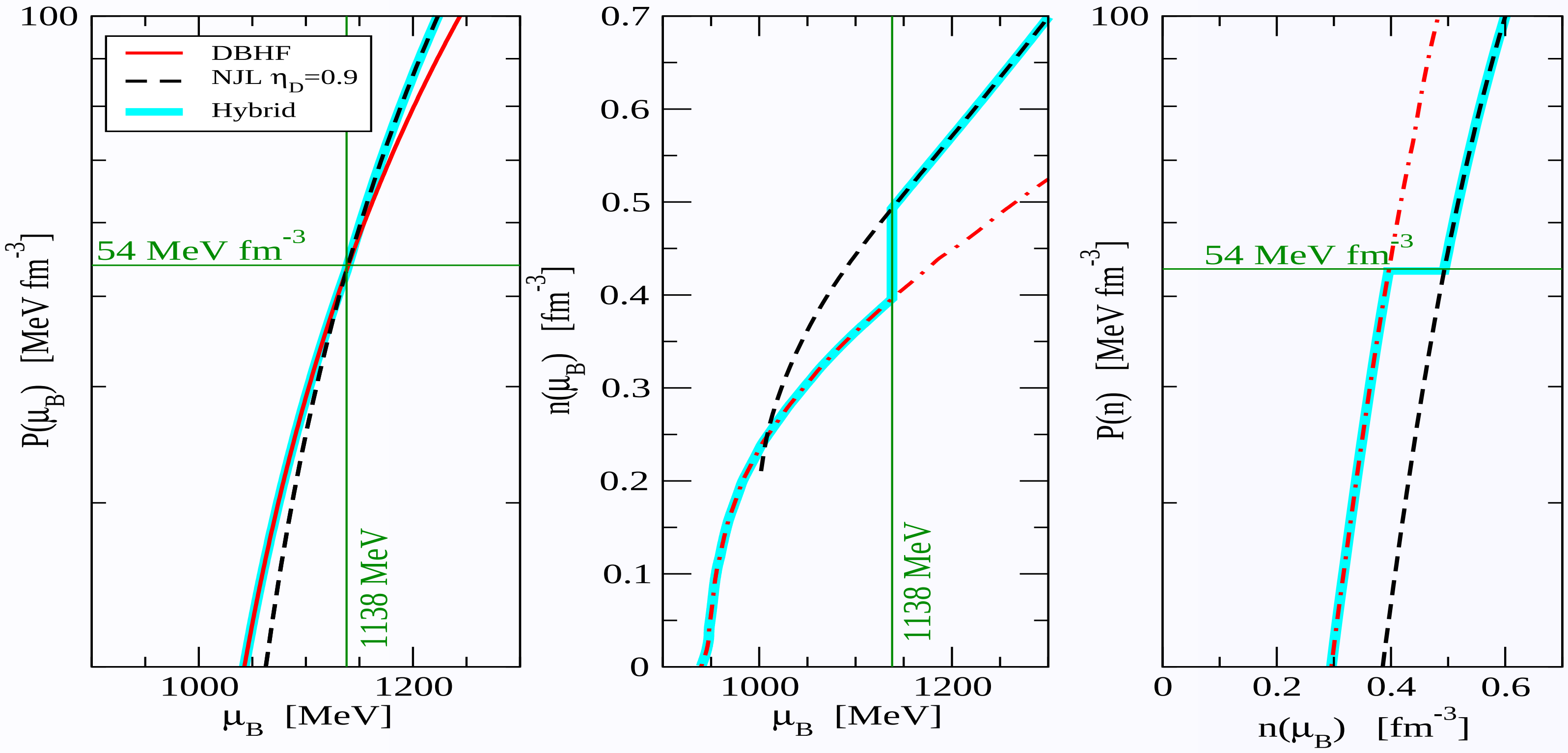
$$\hat{\mu}^* = \mathrm{diag}_f(\mu_u - G_S\eta_V\omega_0, \mu_d - G_S\eta_V\omega_0, \mu_s - G_S\eta_V\phi_0)$$

$$\eta_V = G_V/G_S, \;\; \eta_D = G_D/G_S$$

TK et al., nucl-th/0609067

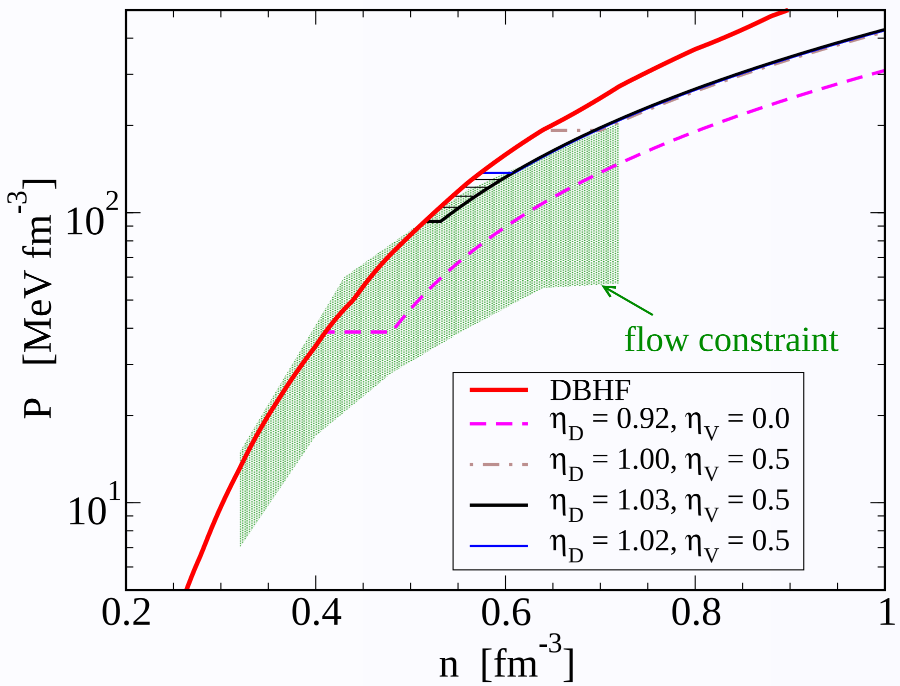
Phase Transition to Quark Matter

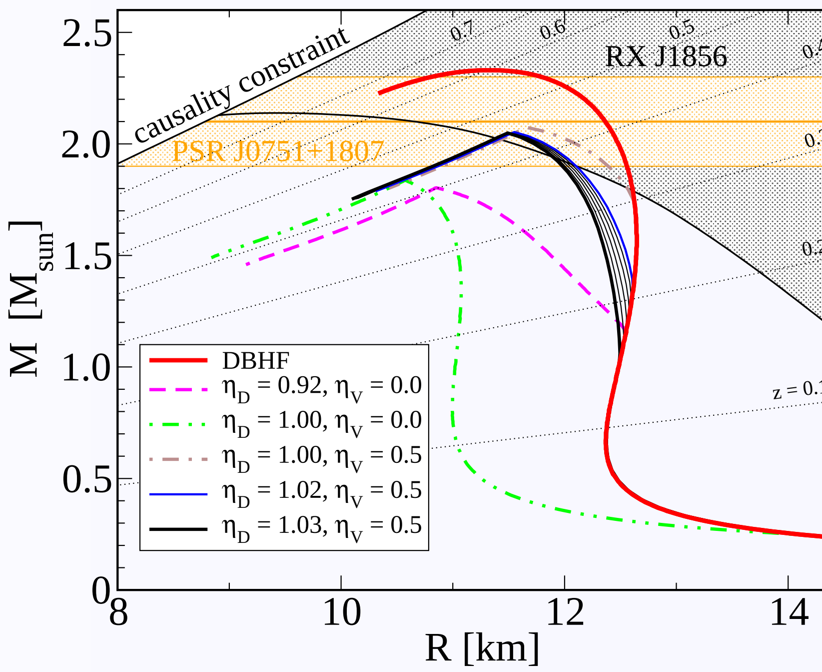
- traditional: two-phase construction



- "masquerade" problem: quark and hadron eos almost identical!
- challenge: hadrons as quark bound states

Quark Matter - NJL-type Model EoS





Vector coupling (η_V):

quark matter stiffness $\rightarrow$ high density limit

Diquark coupling (η_D):

shifts transition density $\rightarrow$ fine tuning

Flow constraint fulfilled!

mass and radius constraints:

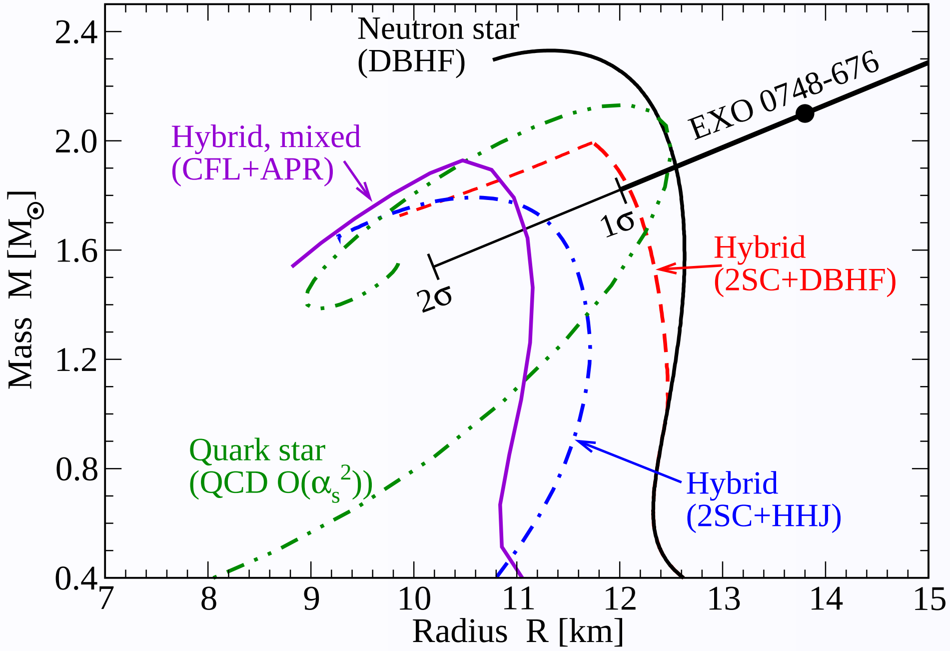
fulfilled for both pure and hybrid NSs

possible: QM cores in typical NSs

$(1.0 \ldots 1.5 M_\odot)$

How to distinguish?

Quark Matter - EXO 0748



The EXO constraint[1]

3 Observables, 3 Unknowns

$$F_{edd} = \frac{GM}{D^2 \kappa_{es}} \left(1 - \frac{2GM}{R}\right)^{1/2}$$

$$F_{cool}/\sigma T_c^4 = f_\infty^2 \frac{R^2}{D^2} \left(1 - \frac{2GM}{R}\right)^{-1}$$

$$z = \left(1 - \frac{2GM}{R}\right)^{-1/2} - 1$$

Conclusion 1: Stiff EoS for NS matter

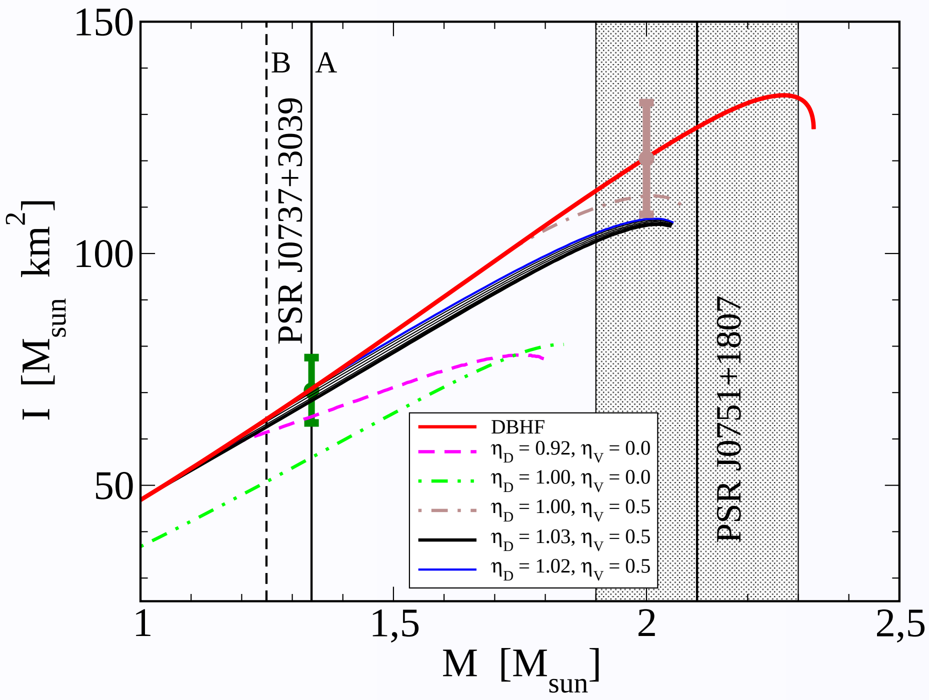
Conclusion 2: No quark matter in NS

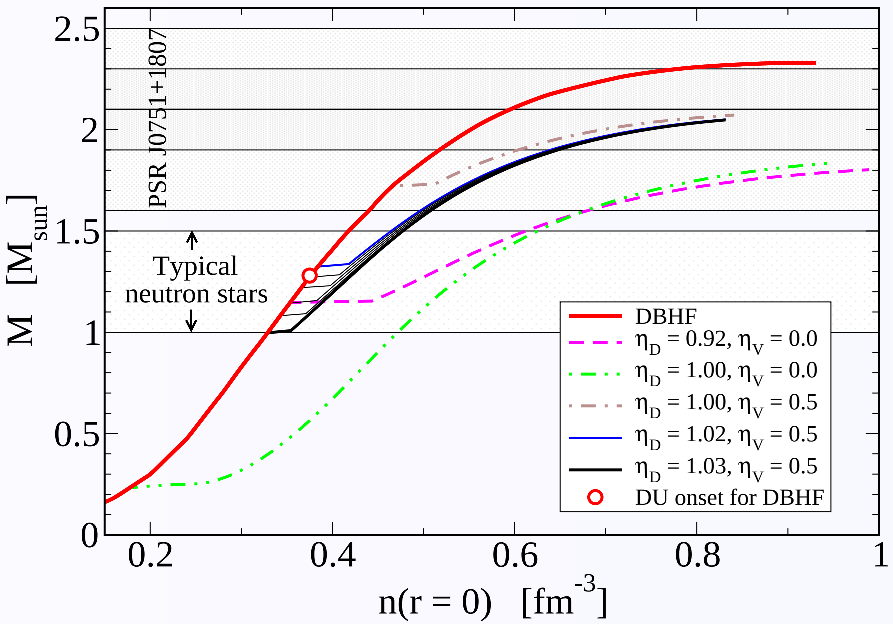
BUT:

- Conclusion 2: several examples for QM EoS in accordance with EXO[2]
- redshift measurement ($z = 0.35$) has not been confirmed[3] : $2 \leftrightarrow 3$
- **However**: a measured point in $M - R$ plane would be a serious constraint!

[1] F.Özel (2006), [2] M. Alford et al.(2007), [3] M. Mendez, priv. comm.

Quark Matter - NJL-type Model EoS





<u>Moment of inertia:</u>

expected to be measured for PSR J0737

(within 10% accuracy)

→ sorts out NM EoS, but not QM

Based on macroscopic properties!

<u>Thermal evolution:</u>

DU suppressed in QM

→ different cooling behavior

Blaschke et al., ApJ **533**, 406 (2000)

Jaikumar et al., PRC **73**, 042801 (2006)

Account for microscopic processes!

Quark Matter - Summary

- Constraints as a tool to adjust free parameters of effective NJL model
  - vector coupling $\rightarrow$ sufficient stiffness
  - diquark coupling $\rightarrow$ fine tuning of critical density
  - G_V, G_D **are model dependent**
- Quark matter can not be excluded by high density EoS constraints!
  - if QM exists in NS its **EoS is stiff**
- How to distinguish between pure and hybrid NS configurations?
  - macroscopic quantities (M, R, I) $\rightarrow$ masquerade
  - **microscopic information needed** $\rightarrow$ cooling

Collaborators

- *Rostock Group:* D. Blaschke, H. Grigorian, G. Röpke
- *Equations of State*

NLρ, NL$\rho\delta$	T. Gaitanos, M. Di Toro, S. Typel, V. Baran, C. Fuchs, V. Greco, H.H. Wolter
	Nucl. Phys. A**732**, 24-48 (2004)
DBHF	E.N.E. van Dalen, C. Fuchs, A. Faessler
	Nucl. Phys. A**744**, 227-248 (2004)
DD, D^{3}C(, DD-F)	S. Typel
	Phys. Rev. C**71**, 064301 (2005)
KVR, KVOR	E.E Kolomeitsev, D.N.Voskresensky
	Nucl. Phys. A**759**, 373 (2005)
NJL	F. Sandin
	Phys. Rev. D**72**, 065020 (2005)

- *Astrophysical Expertise:* M.C. Miller, J. Trümper, A. Ho, F. Weber

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- *Further thanks to:* M. Alford, J. S. Bielich, A. Drago, K. H. Langanke, N. Scoccola
- *Supported by*
  - ⋆ DFG, BMBF, Helmholtz Gemeinschaft VH-VI-041 (Germany), GSI
  - ⋆ US DoE, NSF, Research Corporation, Goddard Space Flight Center (USA)