EoS Constraints from Astrophysics of Compact Stars

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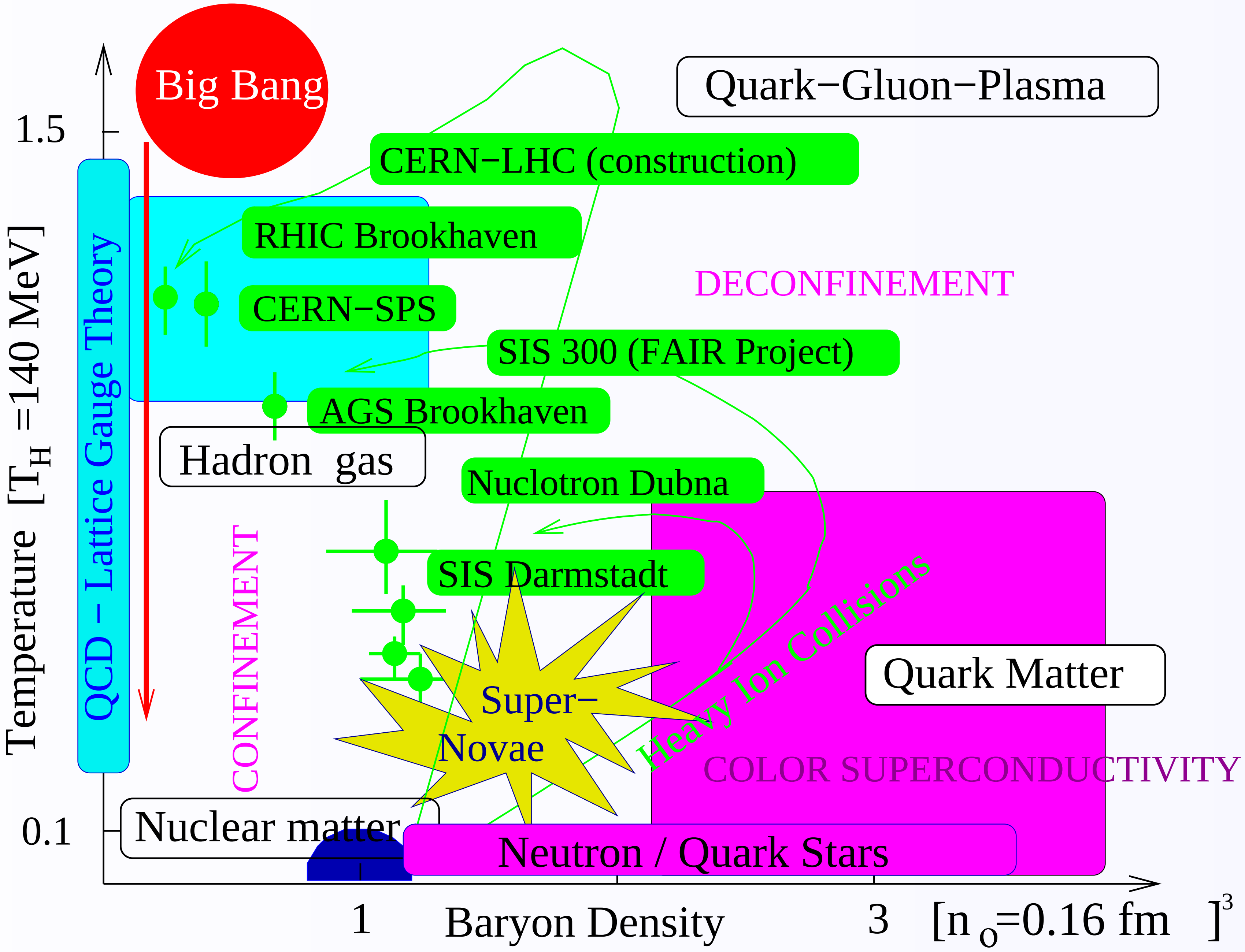
S. Typel, D.N. Voskresensky, F. Weber, H.H. Wolter

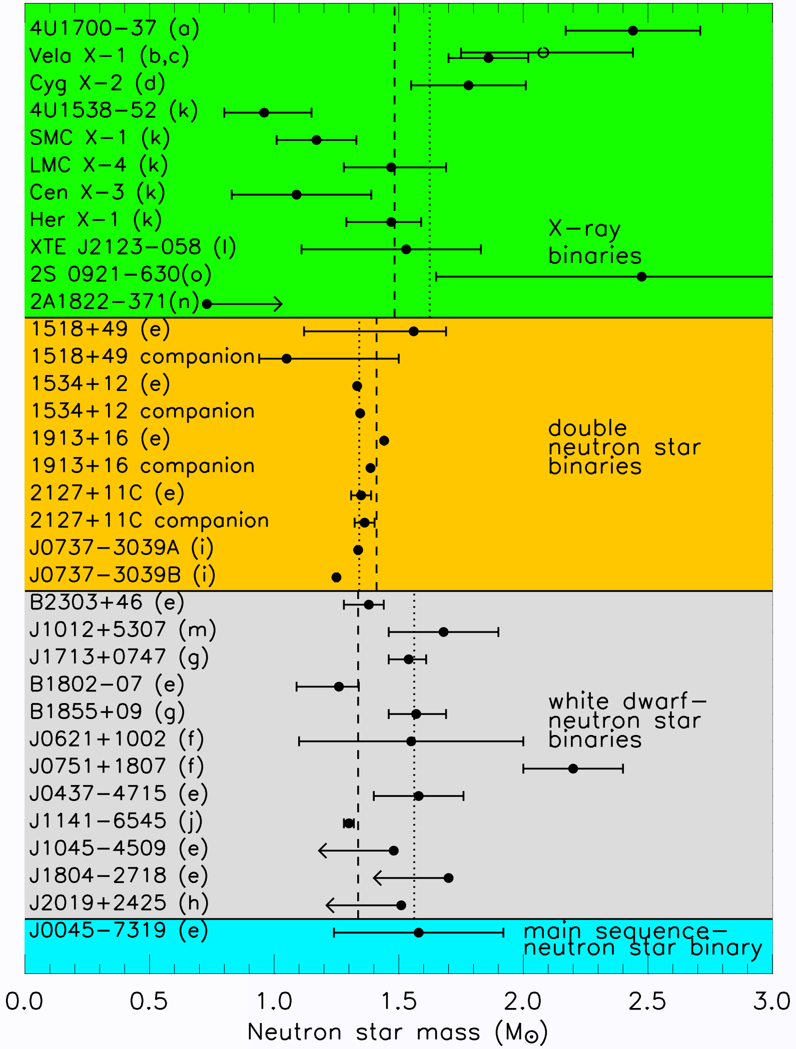
Exploring the Phase Diagram



Outline

- High Density EoS Test Scheme
  - NS Maximum Mass
  - NS Mass-Radius relation
  - NS Gravitational binding
  - Direct Urca (direct β-decay)
  - Flow in HIC
- Nuclear Matter EoS
- Test Scheme vs. Nuclear Matter
- Superconducting Quark Matter and Phase Transition
- Test scheme vs. Quark-Nuclear Matter
- Consequences for the Phase Diagram
- Conclusions

Compact Star Masses (1σ)



J. M. Lattimer and M. Prakash

Phys. Rev. Lett. 94, 111101 (2005)

binary radio pulsars:

$$M_{BRP} = 1.35 \pm 0.04 M_\odot$$

PSR J0751+1807

(D. J. Nice et al, astro-ph/0508050)

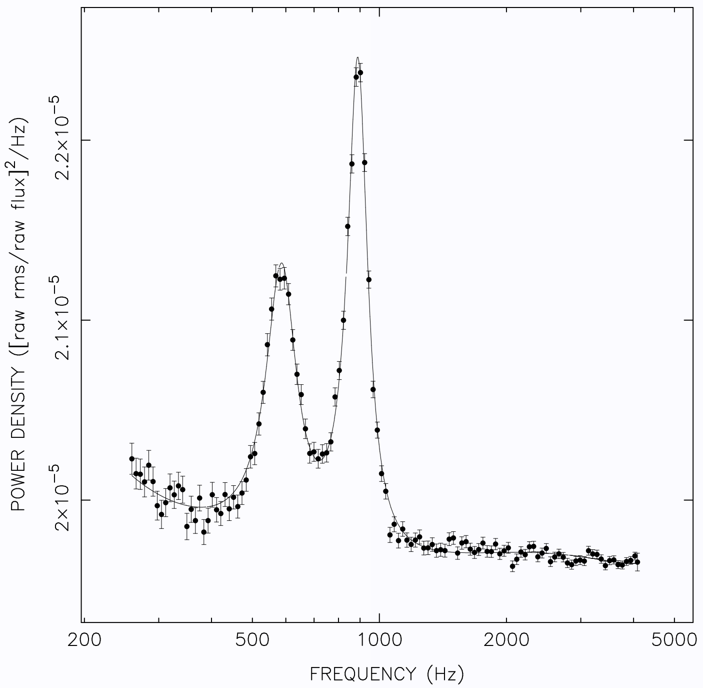
$$M = 2.1^{+0.2}_{-0.2}(^{+0.4}_{-0.5}) M_\odot$$

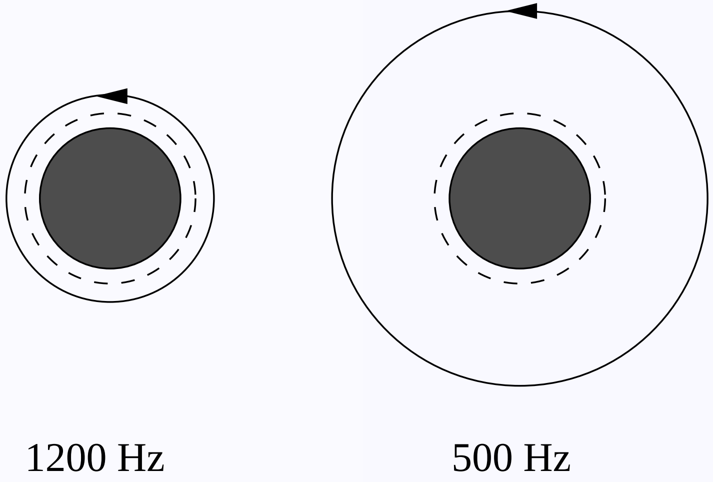
$\rightarrow$ constrains minimal **maximum mass**

of an EoS model

Mass-Radius Constraints from QPO's

Quasi Periodic Brightness Oscillations





$\nu_{max} \approx \nu_{orbit} < \nu_{ISCO}$

Keplerian Orbit r_K

$$R < r_k = (GM/4\pi^2\nu_{max}^2)^{1/3} \rightarrow R_{max}(M)$$

$$M < 2.2 M_\odot (1000 Hz/\nu_{max})(1 + 0.75j) \rightarrow M_{max}$$

if(!) $\nu_{max} \approx \nu_{ISCO}$

$$M \approx 2.2 M_\odot (1000 Hz/\nu_{max})(1 + 0.75j)$$

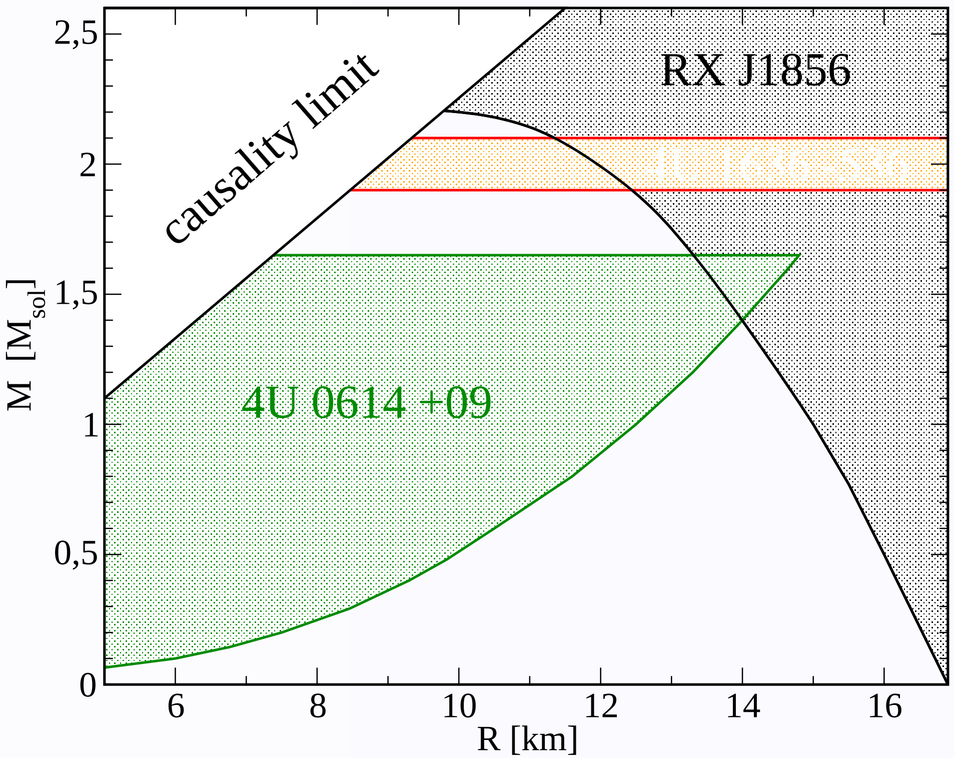
M. van der Klies, ARA&A **38**, 717 (2000)

M-R Constraint from Radio Quiet Isolated NS RXJ1856

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

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

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



<u>Mass Radius Constraints</u>

QPO : M-R upper limits

ISCO : max. mass constraint

RXJ1856: M-R lower limits

each region...

$\longrightarrow$ represents a different object

$\longrightarrow$ 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)

Gravitational Mass ↔ Baryon Number J0737-3039

Double Pulsar System J0737-3039

Pulsar A $P^{(A)}$ = 22.7 ms, $M^{(A)} \approx 1.338 M_\odot$

Pulsar B $P^{(B)}$ = 2.77 ms, $M^{(B)} = 1.249 \pm 0.001 M_\odot$ (record!)

Progenitor ONeMg white dwarf, driven hydrodyn. unstable by e^- captures on Mg & Ne; no mass-loss during collapse

Observational constraint for $M(M_N)$ from PSR J0737-3039:

- observed NSs gravitational mass (remnant star) $M^{(B)} = 1.248 - 1.250 M$
- critical baryon mass of progenitor ONeMg white dwarf $M_N^{(B)} = 1.366 - 1.375 M$

Theory: $M(M_N)$ characteristic for remnants EoS

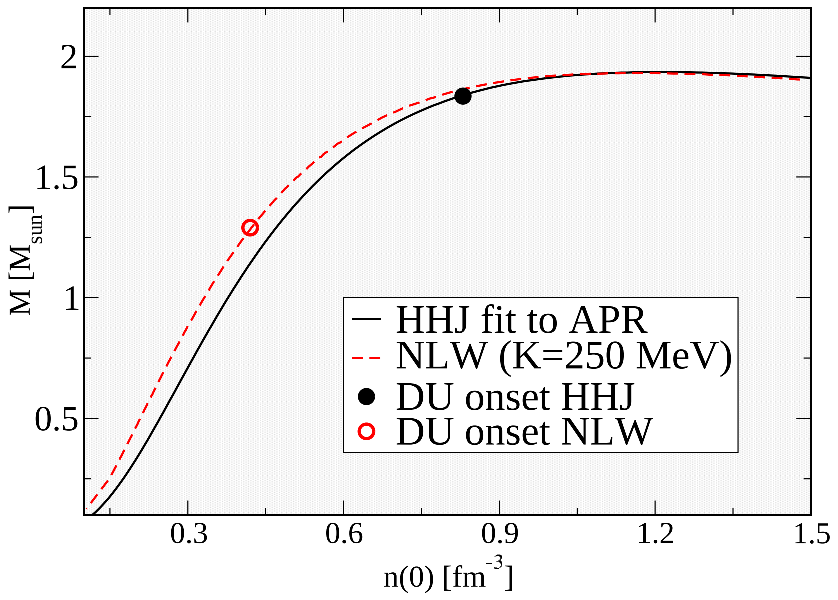
$M = 4\pi \int_0^R \mathrm{d}r r^2 \varepsilon(r)$;

$M_N = u N_B = 4\pi u \int_0^R \mathrm{d}r \frac{r^2 n(r)}{\sqrt{1 - 2GM(r)/r}}$

(conversion of baryon number to mass by $u = 931.5$ MeV)

P. Podsiadlowski et al., Mon. Not. Roy. Astron. Soc. **361**, 1243 (2005)

Direct Urca Process: $n \to p + e^- + \bar{\nu}_e$ (β - decay)

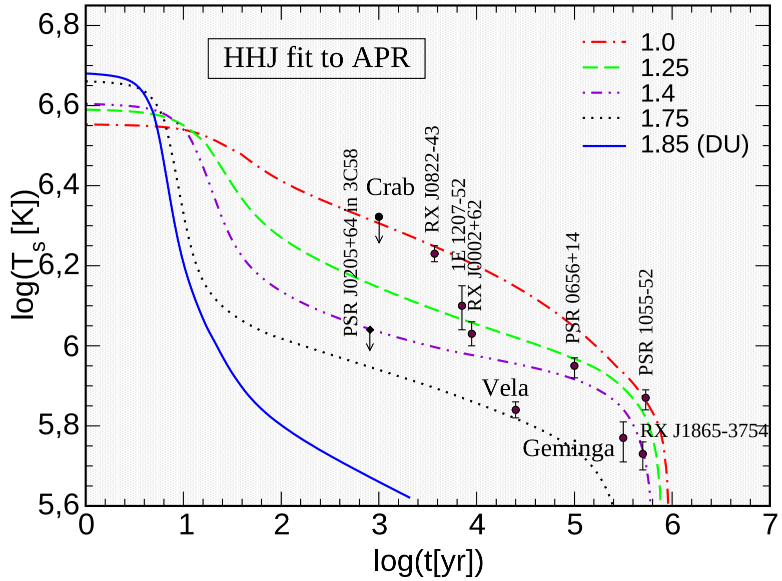


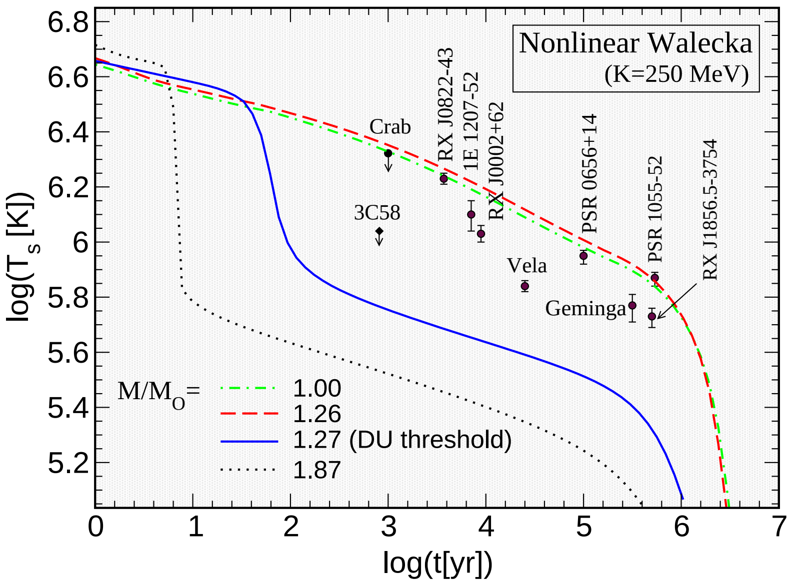
NS cooling – different masses

$\longrightarrow$ **DU cools neutron stars too rapidly**

D. Blaschke, H. Grigorian, and D. Voskresensky,

Astron. Astrophys. **424**, 979 (2004)

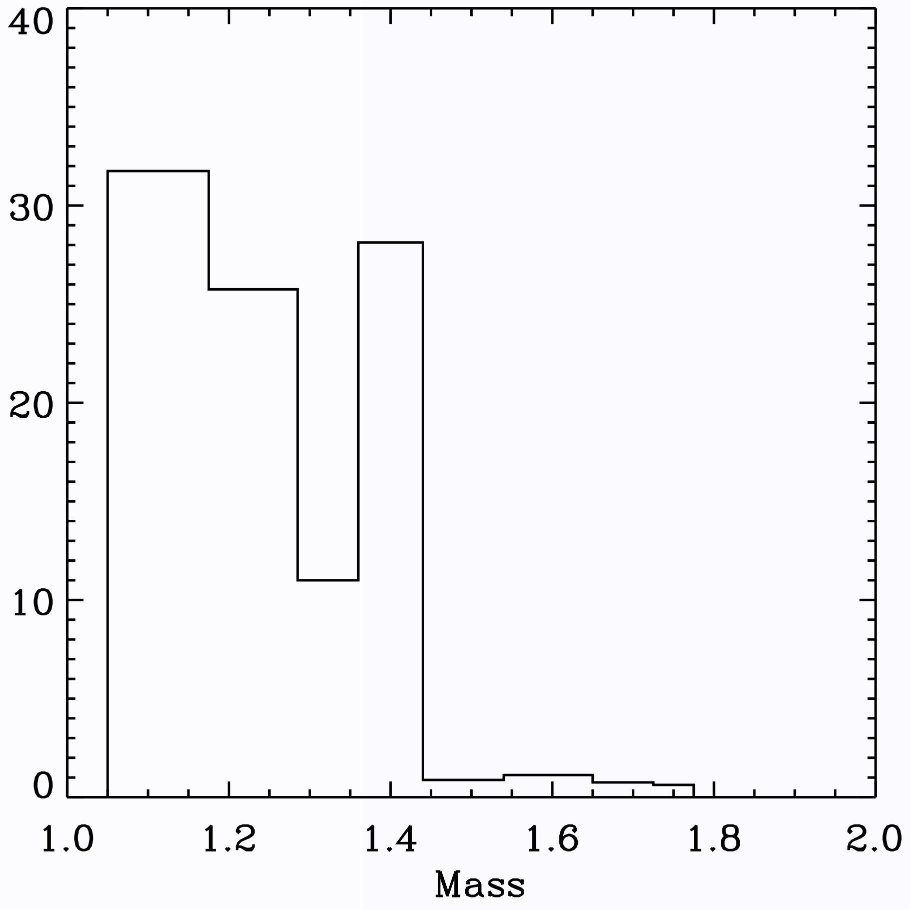




Direct Urca Process

β - decay: $n \to p + e^- + \bar{\nu}_e$, $n \to p + \mu^- + \bar{\nu}_\mu$

Mass Population Analysis of young nearby neutron NS:



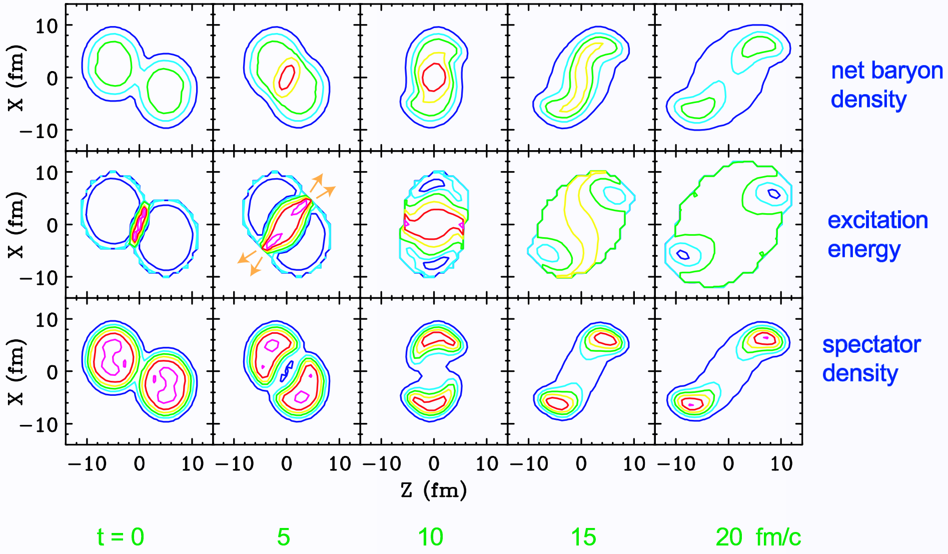
If Direct Urca process onset for $M < 1.4 M_\odot$

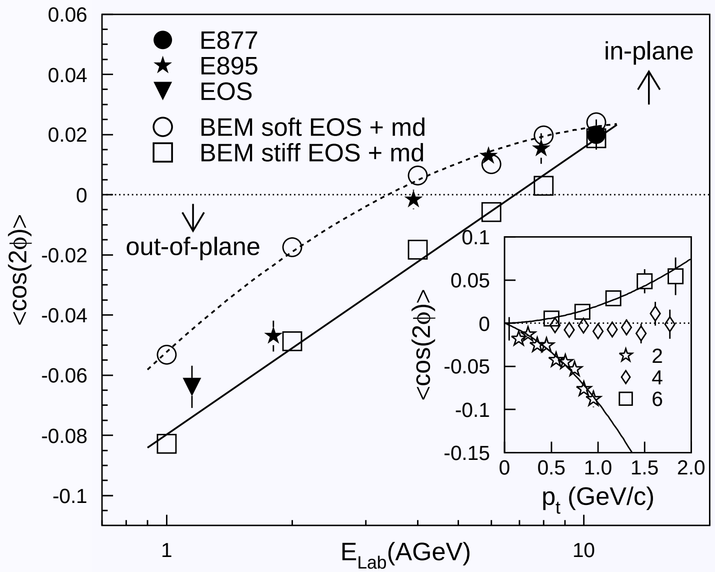
Then most of NS would cool too fast for observation

S. Popov et al., Astron. Astrophys. **448**, 327 (2006)

Elliptic Flow in HIC

Heavy Ion Collisions:

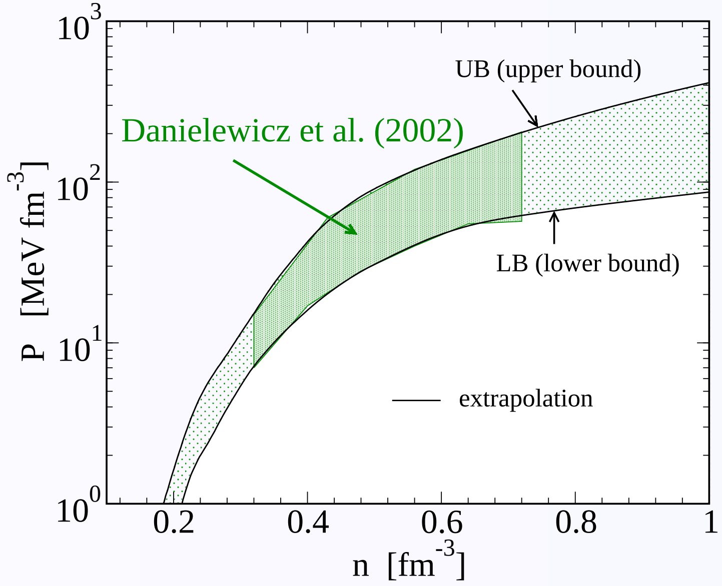




P. Danielewicz et al., Science **298**, 1592 (2002)

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

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



Nuclear Matter Equations of State (EoS)

Several approaches to describe dense nuclear matter

- Equations of State at $T = 0$

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

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

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

$$E(n, \beta) = E_0(n) + \beta^2 E_S(n)$$

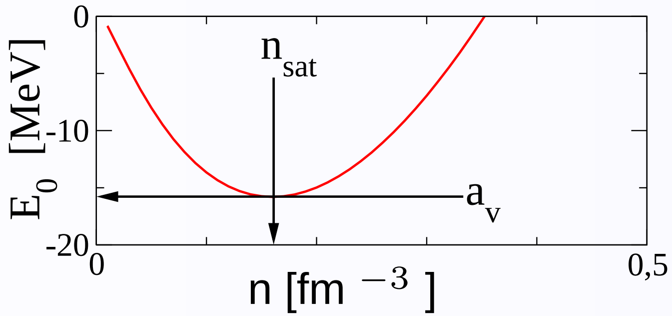
- Thermodynamical Identities hold in SNM and NSM

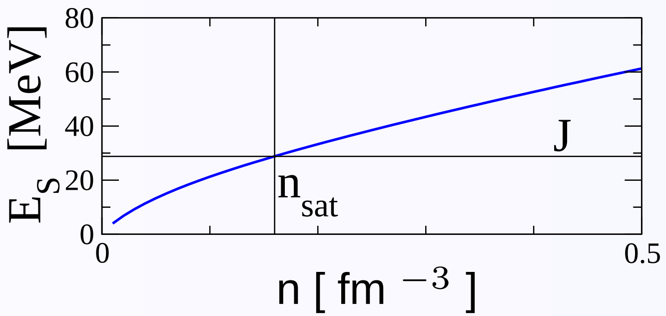
Nuclear Matter Equations of State (EoS)

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

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

Model	$n_{\rm sat}$	a_V	K	K'	J	L	m_D/m
	[fm^{-3}]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	
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



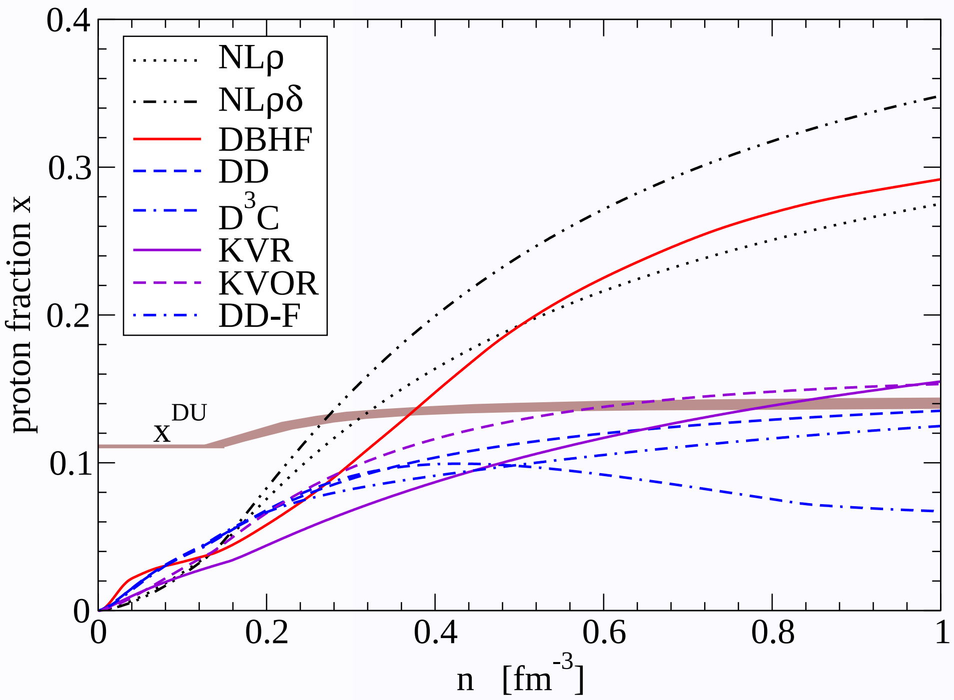


Direct Urca Process

$n \to p + e + \bar{\nu}_e$ 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 ($n_e = n_\mu$): $x_{DU} = 14.8\%$



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

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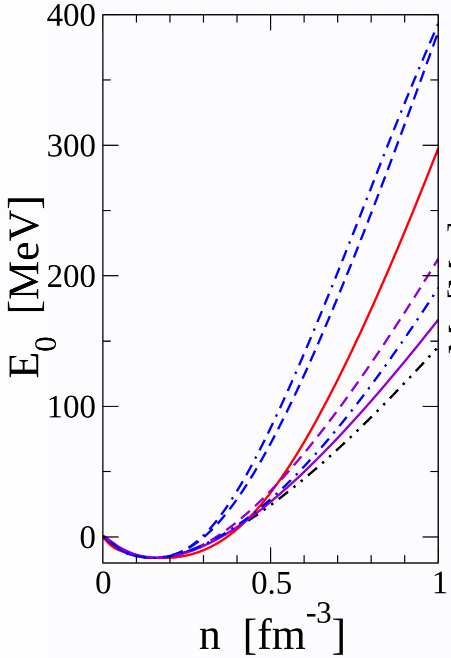
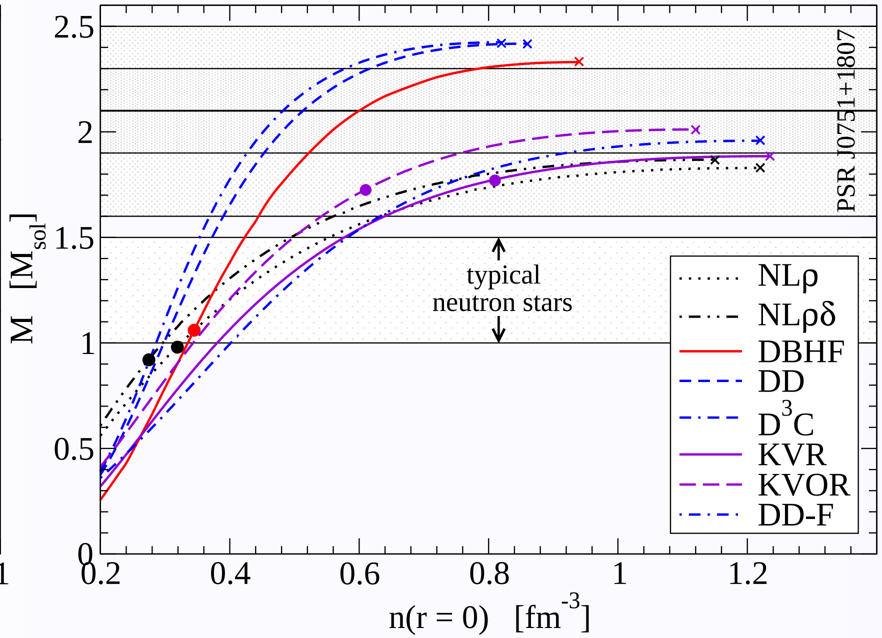




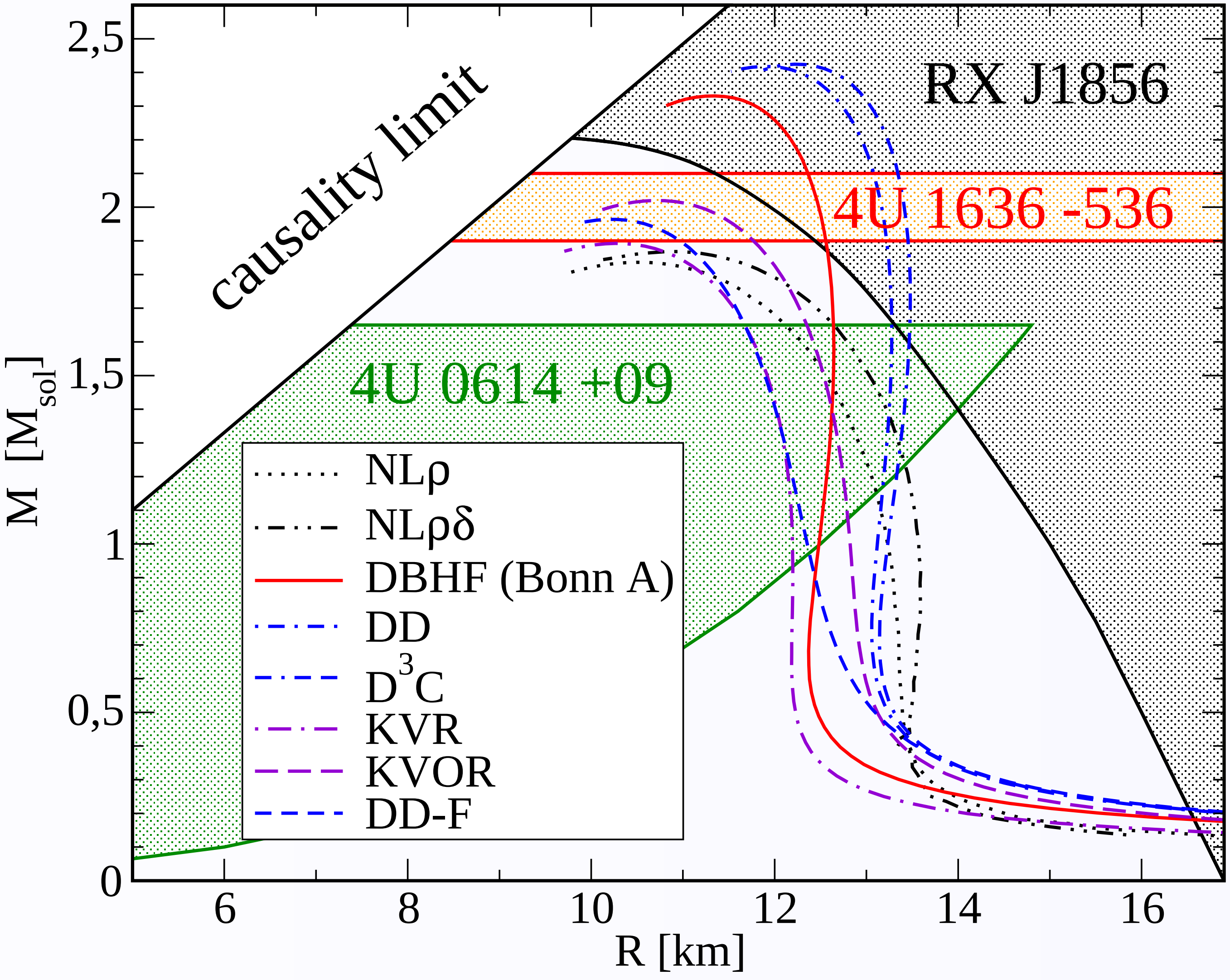
NLρ, NLρδ, DBHF :

DU occurs below $2.5\ n_0$

$M_{DU} \approx 1.0 M_\odot$

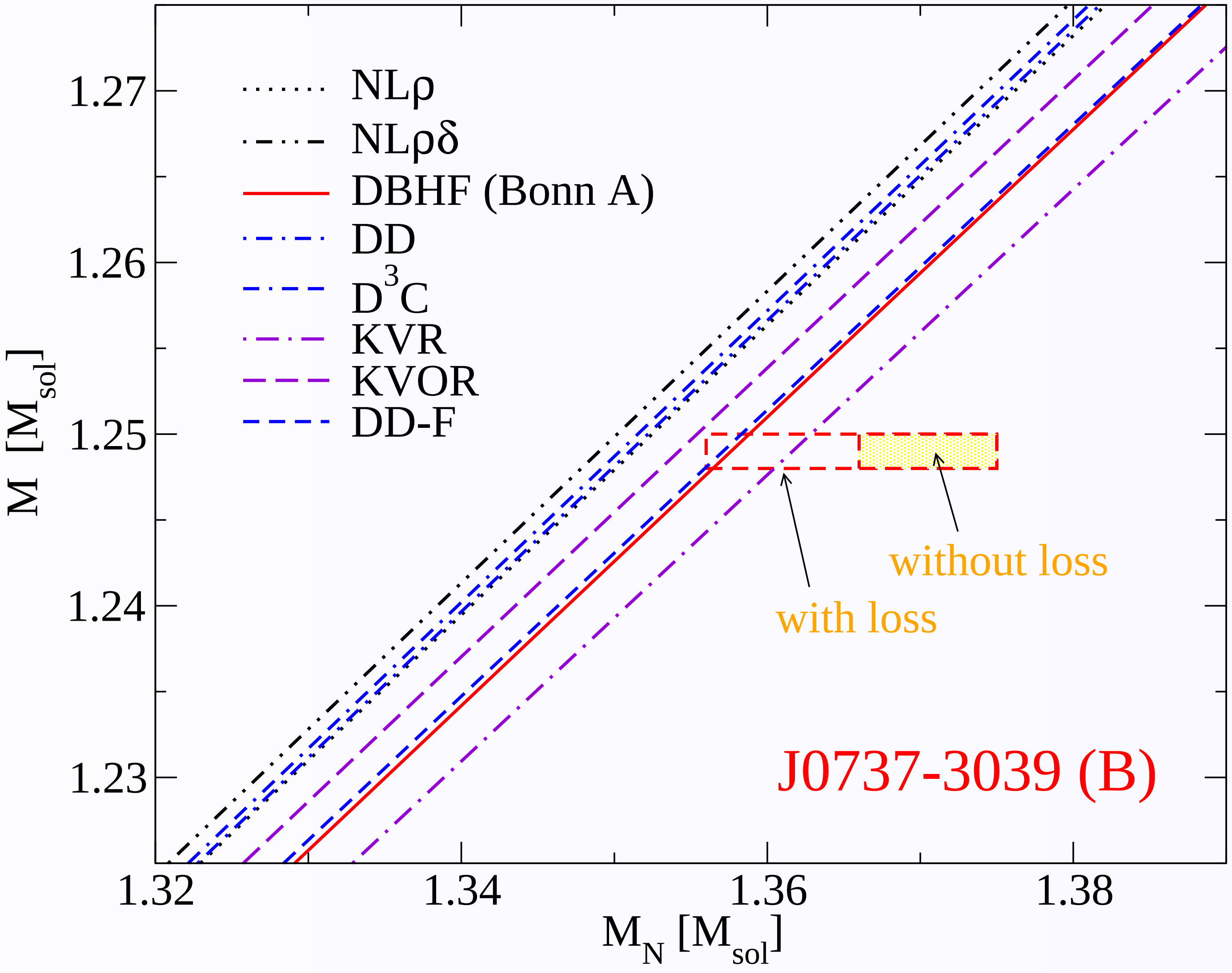
$M(n)$ correlated to $E_0(n)$

Mass Radius Relations



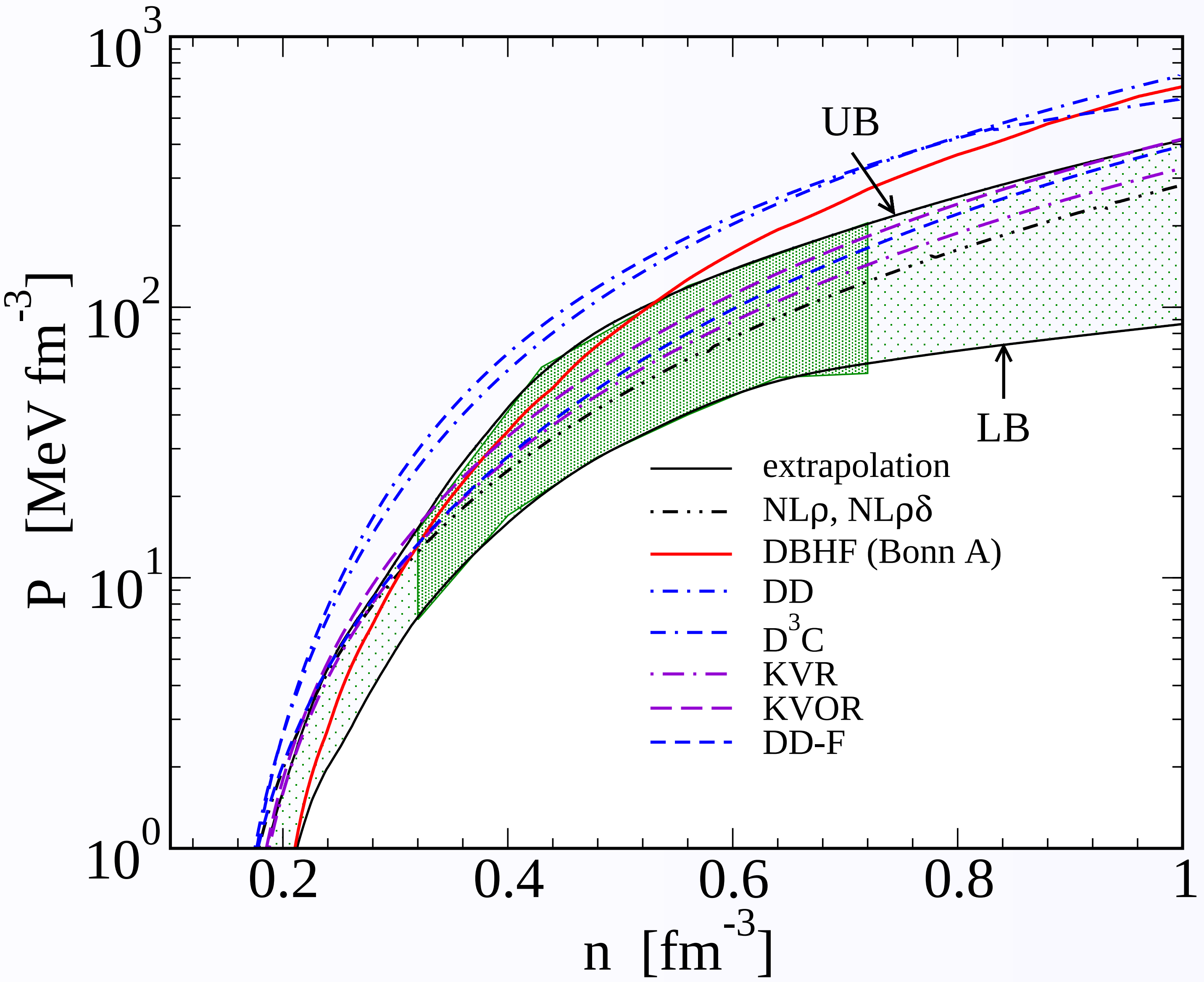
→ agreement with all mass and mass-radius constraints for DBHF, DD, D^3C

Gravitational Binding $M(M_N)$ for J0737-3039 (B)



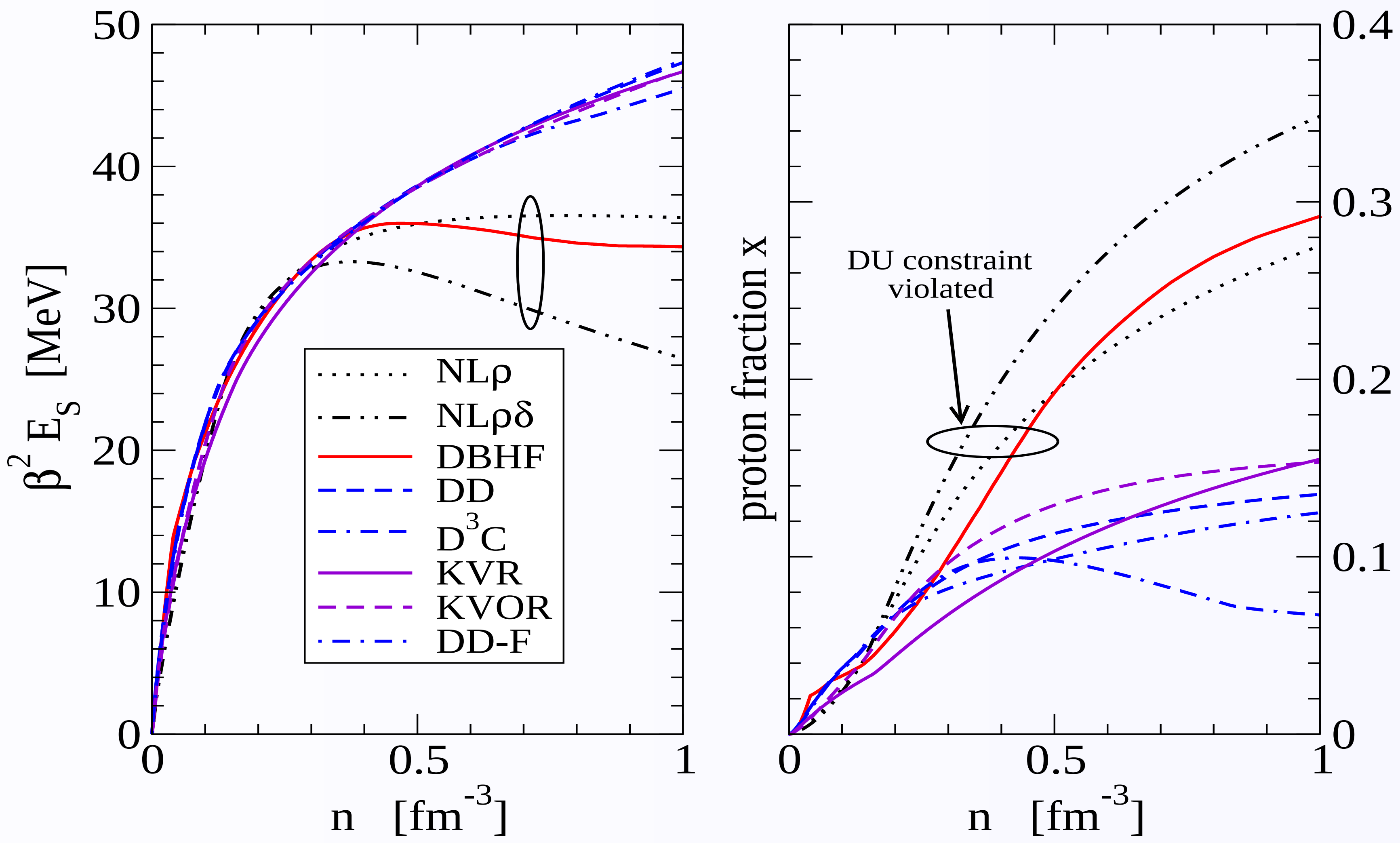
→ agreement only for 1% baryon loss during collapse (DBHF, KVOR, DD-F)

Flow Constraint



→ constraint fulfilled for NLρ,NL$\rho\delta$, KVR, KVOR, DD-F; DBHF at low densities

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

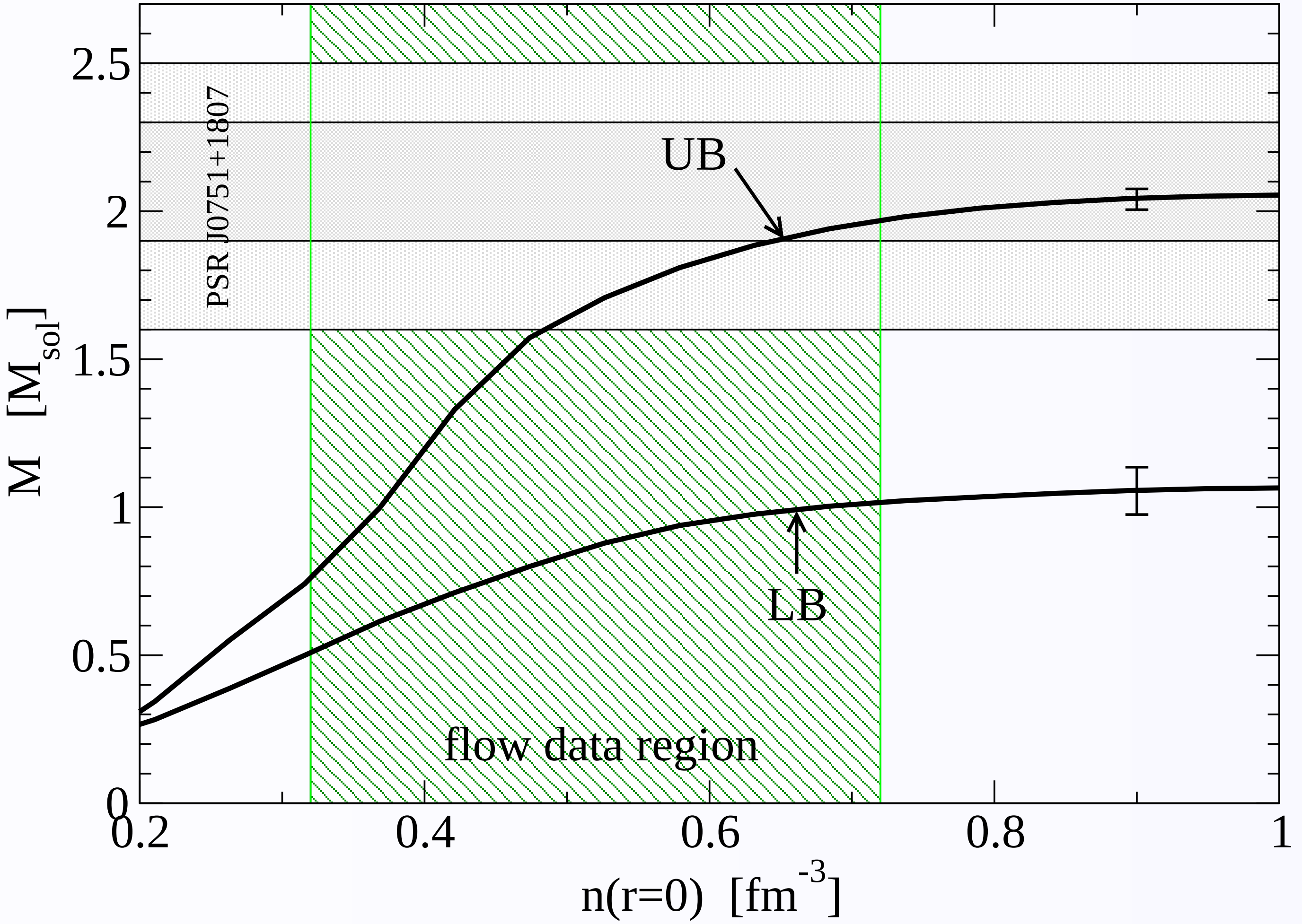


Exclude NLρ, NL$\rho\delta$, DBHF since DU constraint violated ($M_{DU} < M_{\rm typ}$)

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

Consequences: Sharpening the Flow Constraint

How strong is the flow constraint?



LB not reliable $\leftrightarrow$ Maximum mass constraint demands stiff EoS

(applied “universal” $\beta^2 E_S$ (error bars!))

Result

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% $M_\odot$)	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^{3}C	+	+	+	+	+	+	−	+	−	−	−	−	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 !

Quark Matter EoS: NJL-type Model

$$S[\bar\psi,\psi] = \sum_p \bar\psi(\not p - \hat m)\psi$$
$$+\sum_{p,p'}\left[(\bar\psi g(p)\psi)G_S(\bar\psi g(p')\psi) + (\bar\psi i\gamma_0 g(p)\psi)G_V(\bar\psi i\gamma_0 g(p')\psi)\right.$$
$$\left.+(\bar\psi i\gamma_5\tau_2\lambda_2 C g(p)\bar\psi^T)G_D(\psi^T C i\gamma_5\tau_2\lambda_2 g(p')\psi)\right],$$

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

$$\Omega_q(\phi,\omega_0,\Delta;\mu_u,\mu_d,T) = \frac{\phi^2}{4G_S} + \frac{|\Delta|^2}{4G_D} + \frac{\omega_0^2}{4G_V} - T\sum_n\int\frac{d^3p}{(2\pi)^3}\,\frac{1}{2}\mathrm{Tr}\ln\left(\frac{1}{T}\tilde S^{-1}(i\omega_n,\vec p)\right)$$

Nambu-Gorkov Propagator

$$\tilde S^{-1}(p_0,\vec p) = \begin{pmatrix} \not p - \hat M(p) - \hat\mu\gamma_0 & \Delta\gamma_5\tau_2\lambda_2 g(p) \\ -\Delta^*\gamma_5\tau_2\lambda_2 g(p) & \not p - \hat M(p) + \hat\mu\gamma_0 \end{pmatrix}.$$

Dynamical quark mass matrix (NJL: $g(p) = \Theta(\Lambda - |p|)$

$$\hat M(p) = \mathrm{diag}(m_u + \phi g(p), m_d + \phi g(p))$$

Renormalized chemical potential matrix

$$\hat\mu = \mathrm{diag}(\mu_u - \omega_0, \mu_d - \omega_0)$$

Nonlocal, Chiral Quark Model (MF)

- chiral gaps (constituent quark mass $m_i = m_i^0 + \phi_i$)

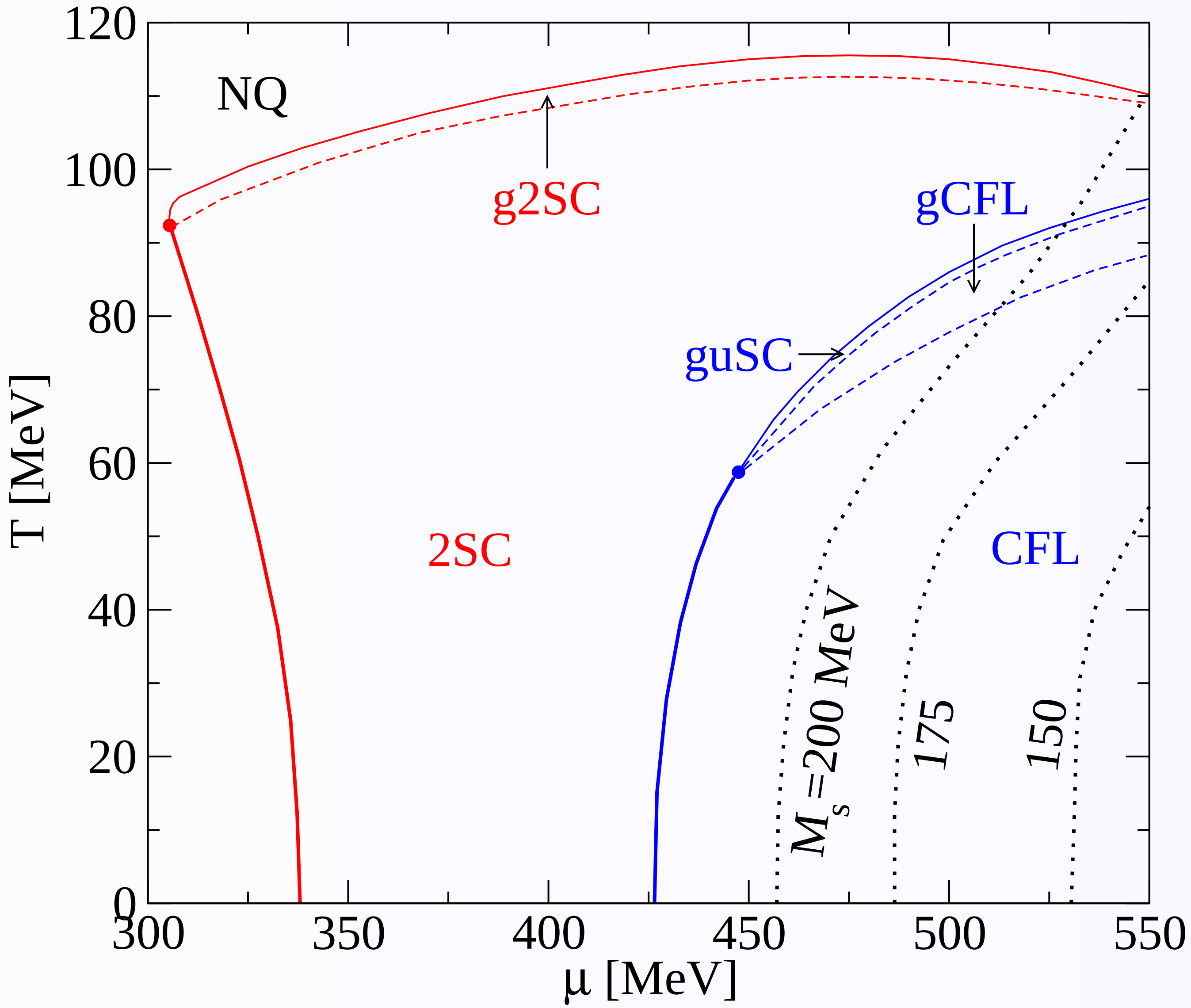
$$\phi_i = -4G_S \langle\langle \bar{q}_i q_i \rangle\rangle$$

- diquark gaps

$$\Delta_{k\gamma} = 2G_D \langle\langle \bar{q}_{i\alpha} i\gamma_5 \epsilon_{\alpha\beta\gamma}\epsilon_{ijk} q^C_{j\beta} \rangle\rangle$$

1. NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
2. NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$ (0<$\chi_{2\mathrm{SC}}$<1);
3. 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
4. uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
5. CFL: $\Delta_{ud} \neq 0$, $\Delta_{ds} \neq 0$, $\Delta_{us} \neq 0$;

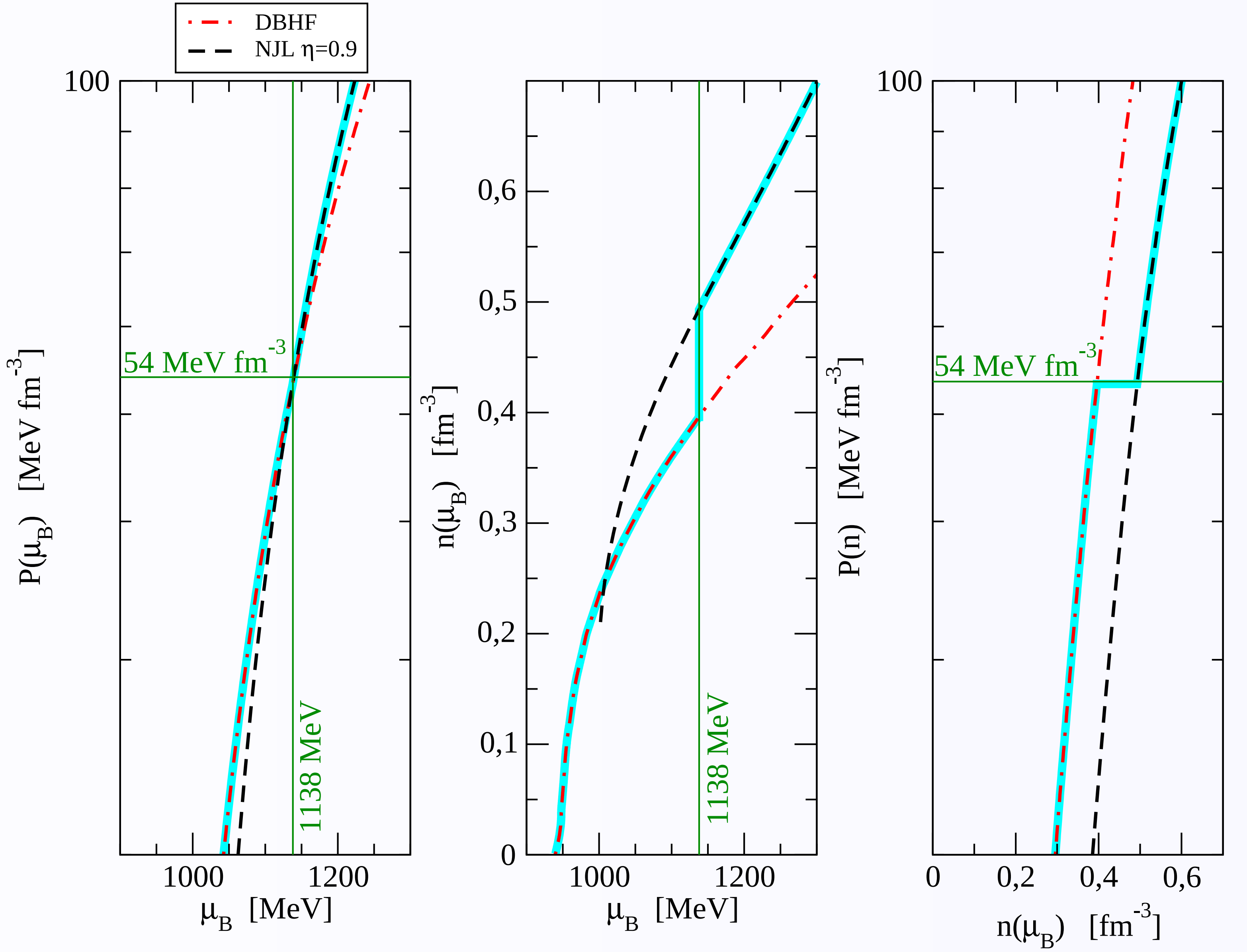
Quark Matter Phase Diagram (NJL case)



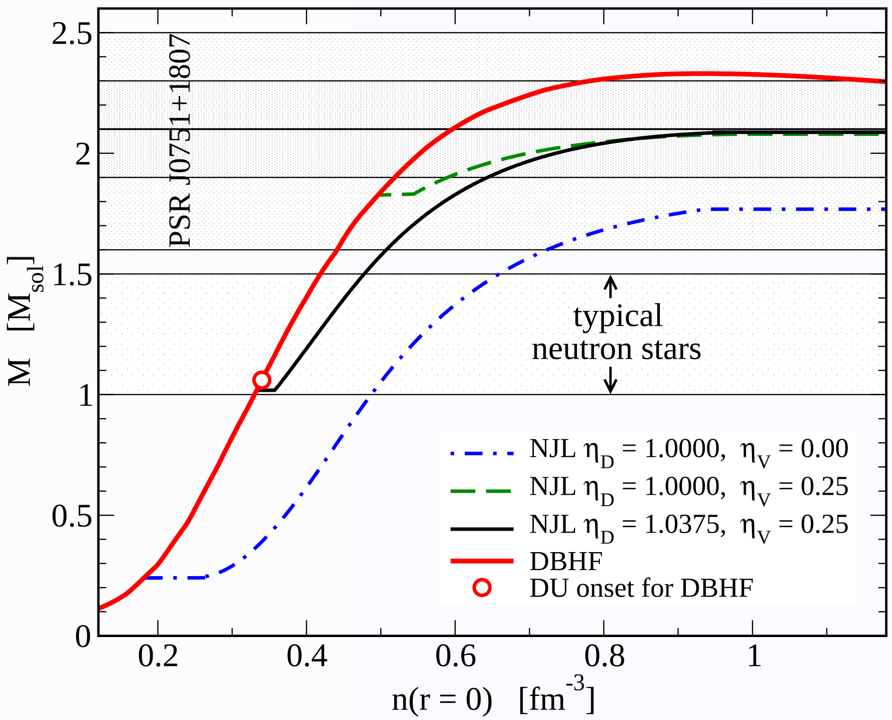
D.Blaschke et al, Phys.Rev. D **72** (2005) 065020

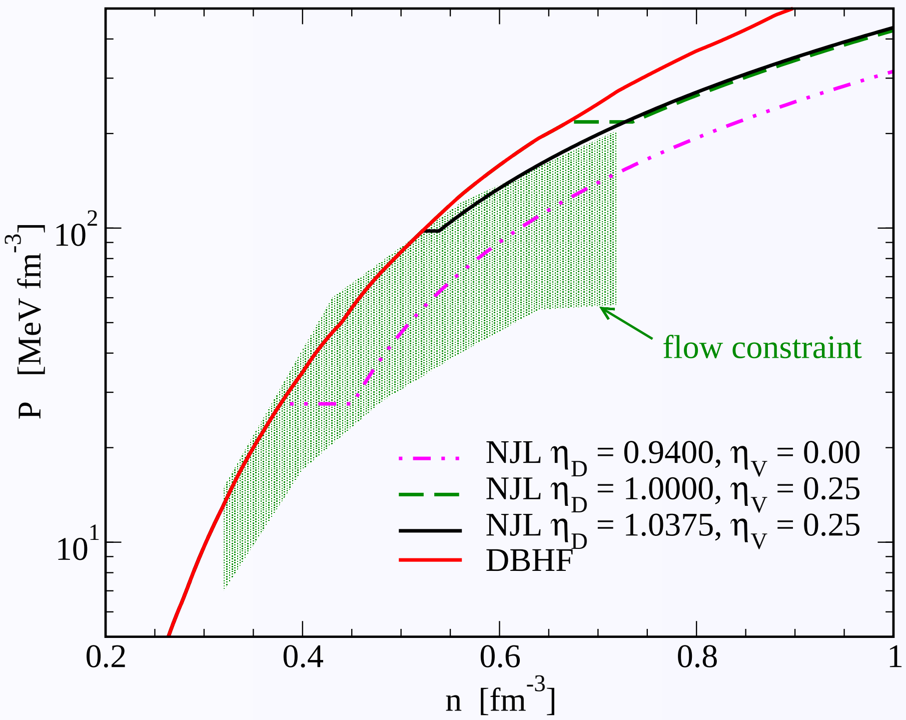
self-consistent strange quark masses !

Phase Transition to Quark Matter



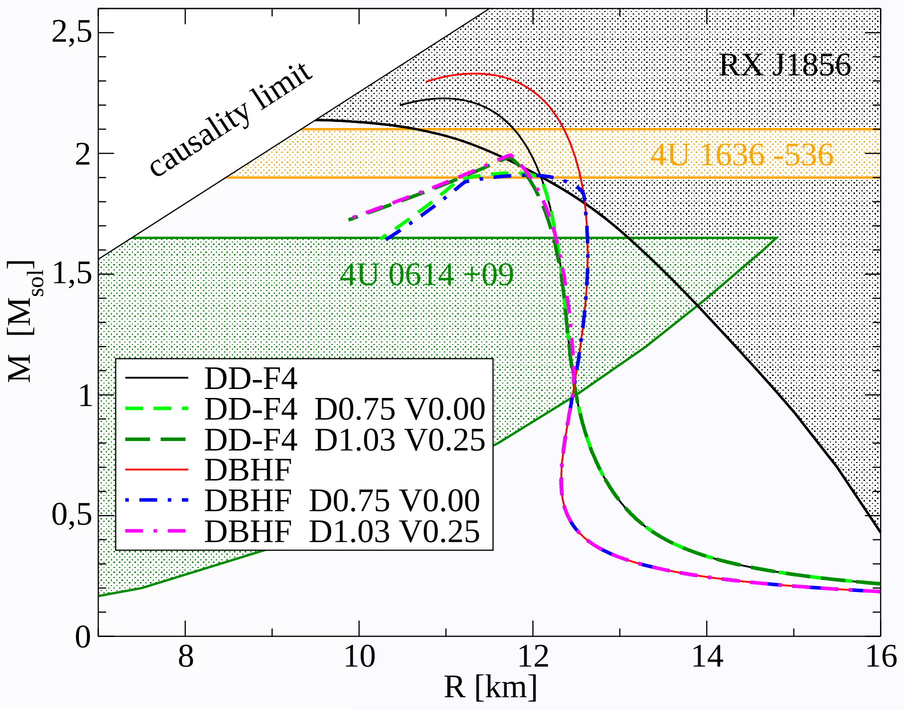
Phase Transition to Quark Matter

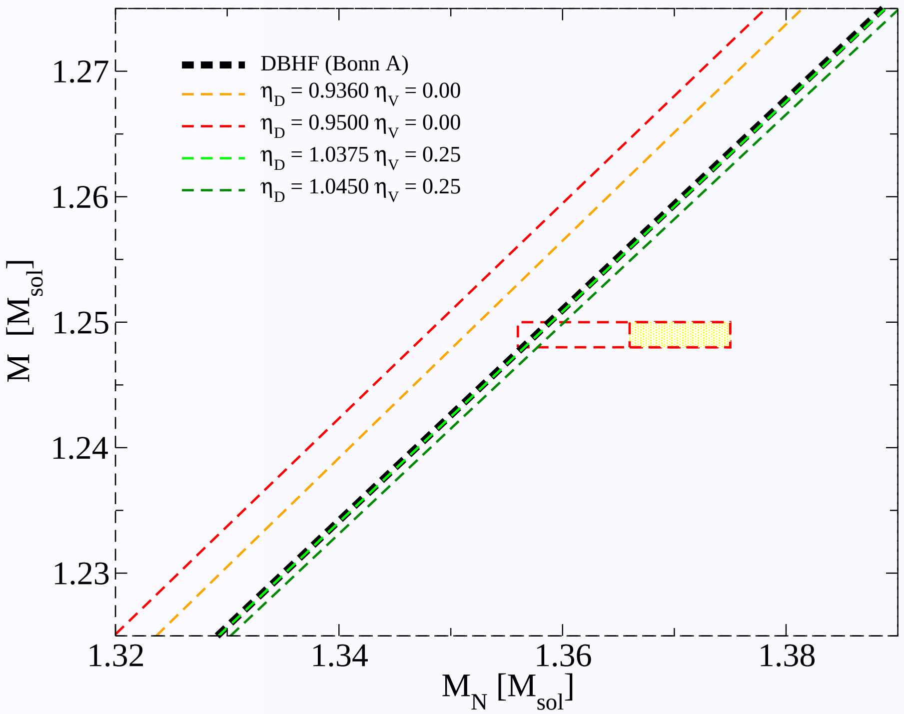




- NJL model for Quark Matter: in 2SC phase with scalar diquark (coupling $\eta_D = G_D/G_S$) and isoscalar vector (coupling $\eta_V = G_V/G_S$) mean fields
- Phase transition removes simultaneously the problems with DU constraint (left) and Flow constraint (right) for the hadronic DBHF EoS.

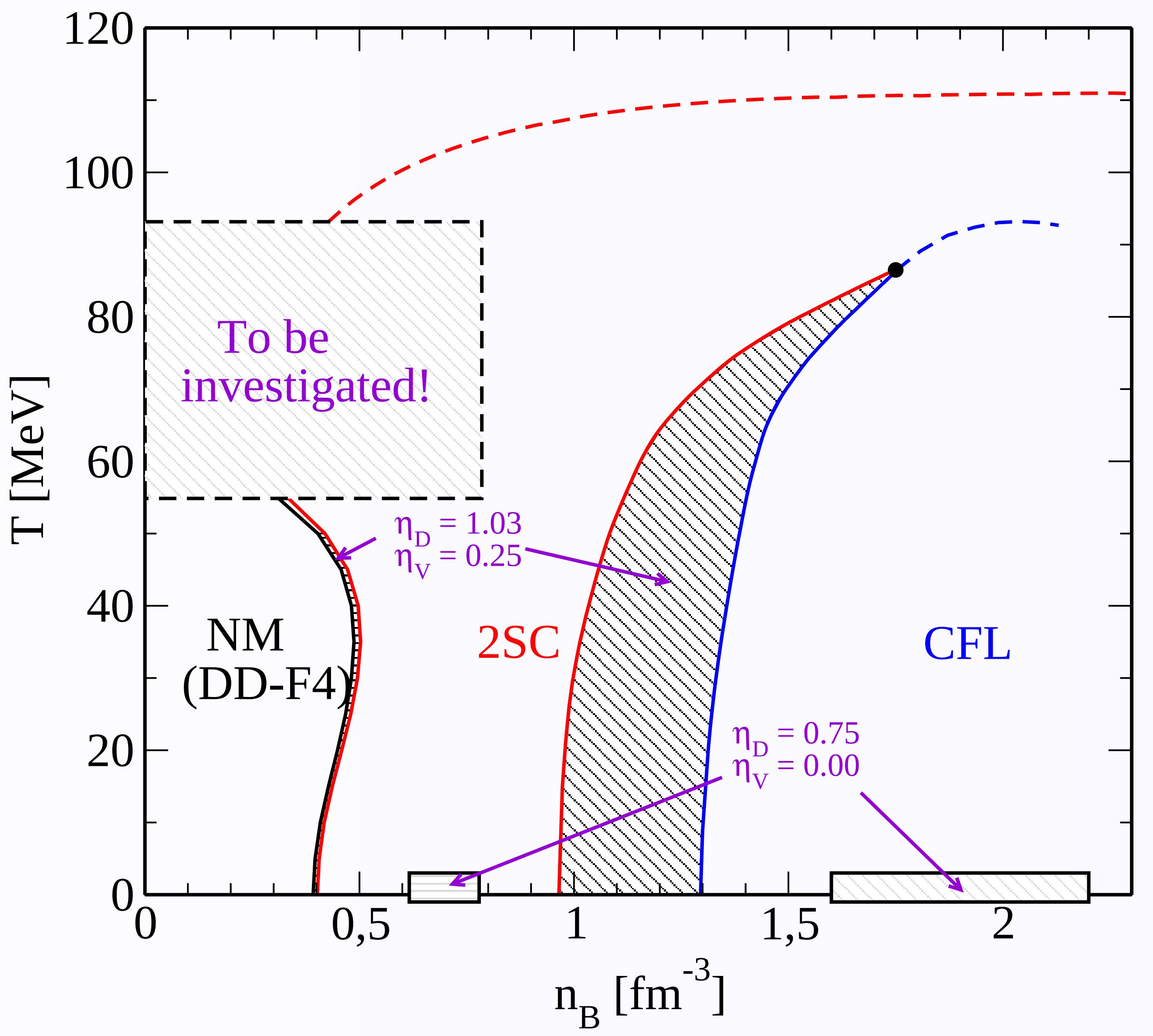
Phase Transition to Quark Matter





- NJL model for Quark Matter: in 2SC phase with scalar diquark (coupling $\eta_D = G_D/G_S$) and isoscalar vector (coupling $\eta_V = G_V/G_S$) mean fields
- More massive hybrid star configurations with increasing η_V (left) and fullfillment of the gravitational binding constraint (right)
- DBHF-NJL hybrid EoS fulfills all constraints

Phase diagram, symmetric matter



(T. Klähn et al., in preparation)

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 (June 1, 2006 - ’Kindertag’)
  - ⋆ “soft” $E_S(n)$ (NS cooling, direct Urca)
  - ⋆ $\beta^2 E_S(n)$ shows universal behaviour
  - ⋆ “soft” $E_0(n)$ at intermediate densities (flow data)
  - ⋆ “stiff” $E_0(n)$ at high densities (maximum masses)
  - ⋆ phase transition to quark matter can solve problems with hadronic EoS
  - ⋆ phase diagram for CBM: very weak 1st order transition, early onset!
- Outlook
  - ⋆ implementation of new astrophysical data (e.g. NS moment of inertia)
  - ⋆ discussion of hyperons and hadronic resonances
  - ⋆ correlations beyond mean-field: effects on phase transition

Collaborators

- *Scheme Development:* D. Blaschke, H. Grigorian, T. Klähn, 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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  - ⋆ DFG, BMBF, Helmholtz Gemeinschaft VH-VI-041 (Germany)
  - ⋆ US DoE, NSF, Research Corporation, Goddard Space Flight Center (USA)

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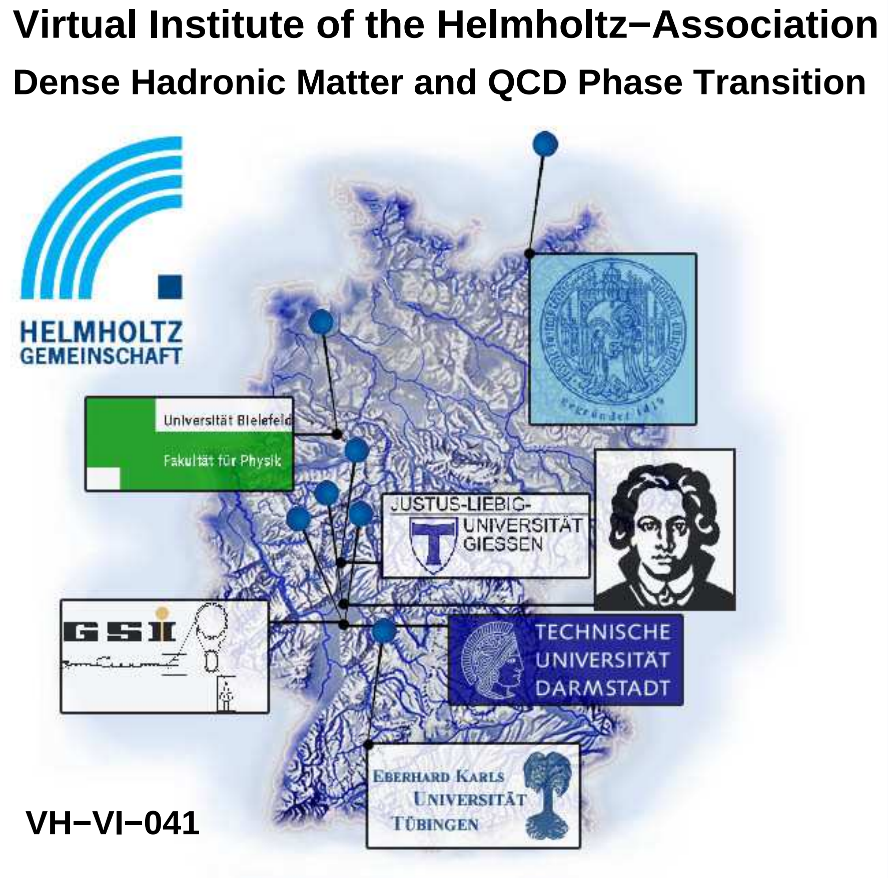

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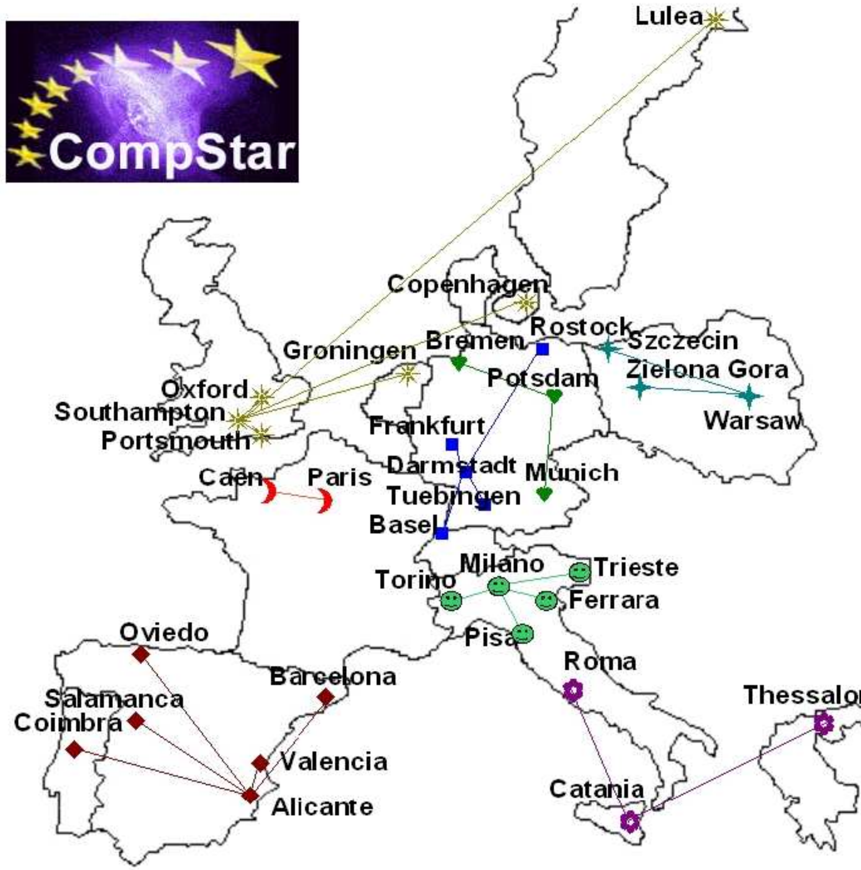

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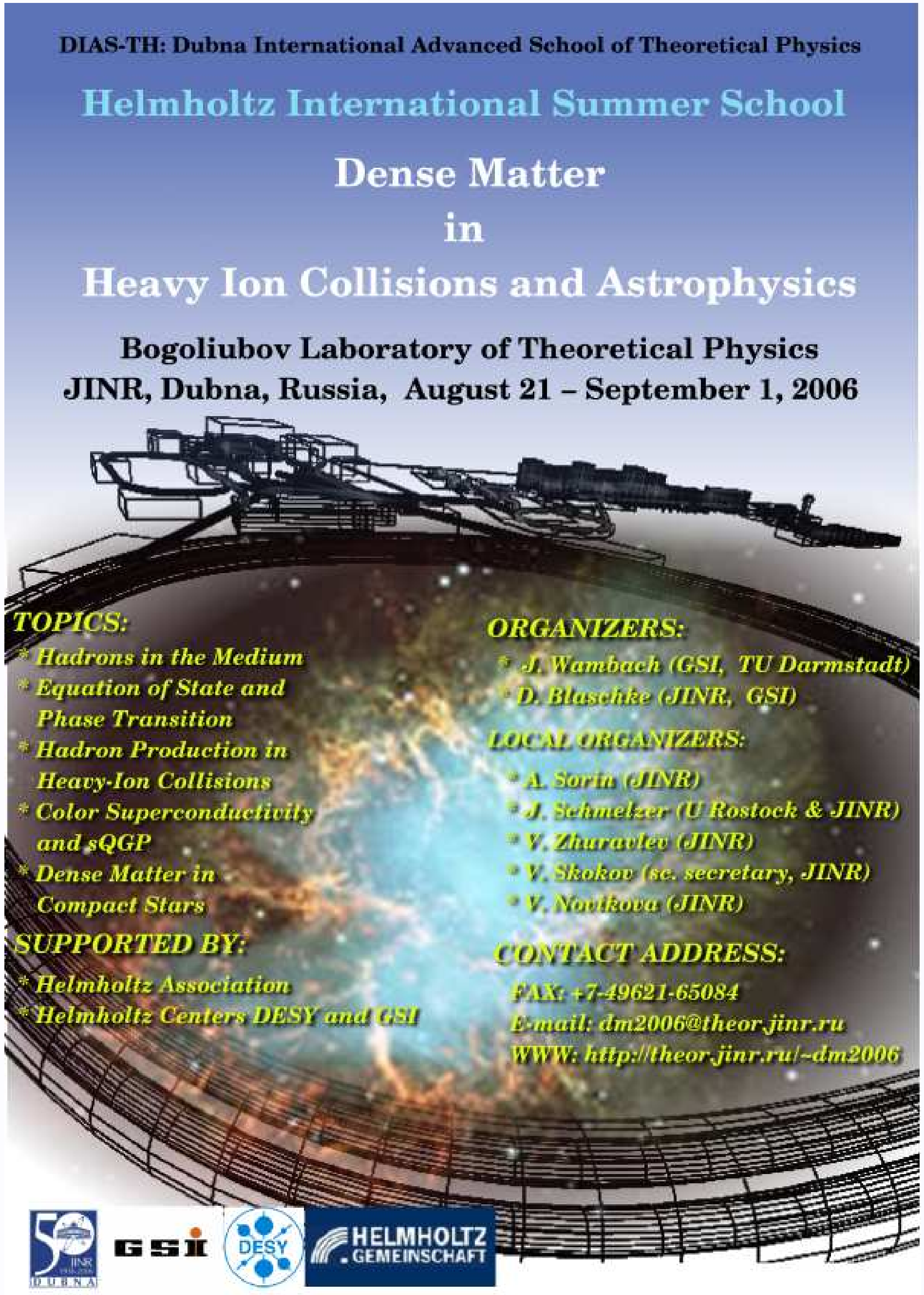

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