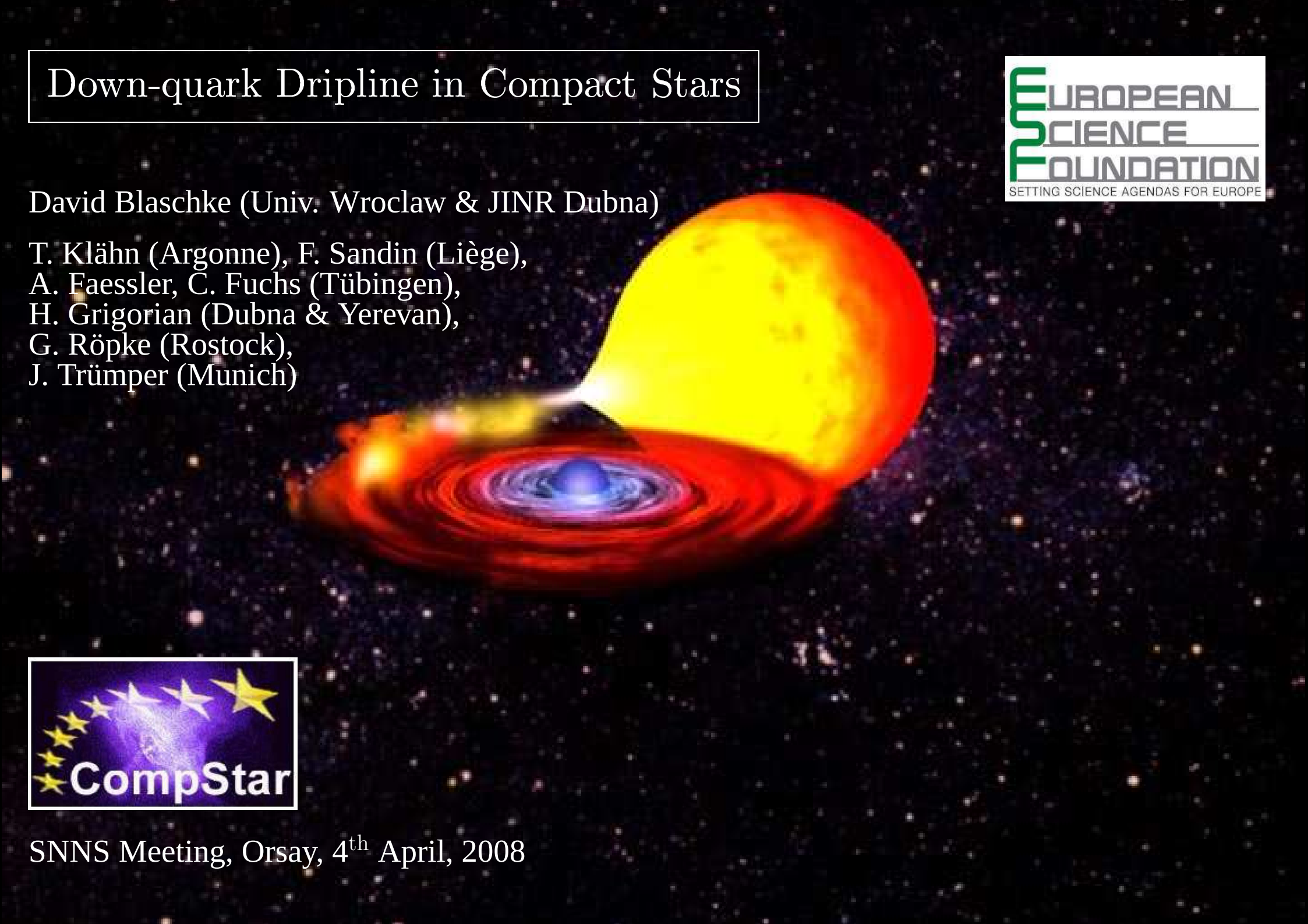
Down-quark Dripline in Compact Stars

David Blaschke (Univ. Wroclaw & JINR Dubna)

T. Klähn (Argonne), F. Sandin (Liège),
A. Faessler, C. Fuchs (Tübingen),
H. Grigorian (Dubna & Yerevan),
G. Röpke (Rostock),
J. Trümper (Munich)



SNNS Meeting, Orsay, 4th April, 2008

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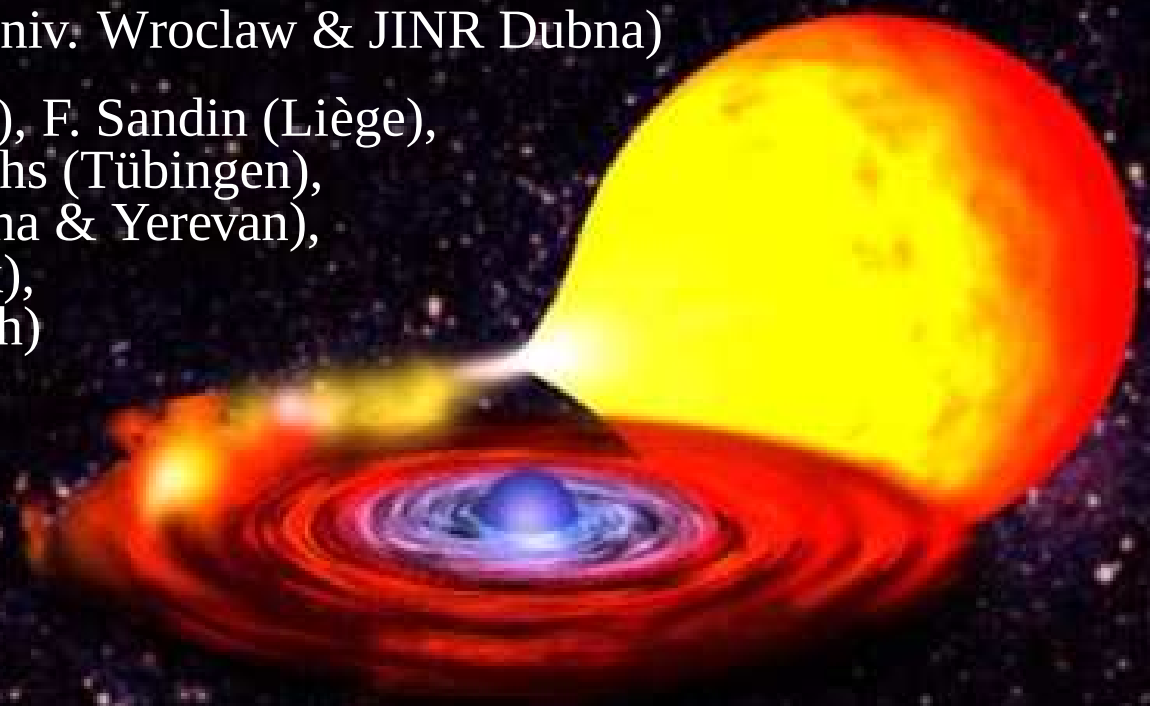

- Mass and Flow constraint on high-density EoS
- Local charge neutrality
  → 2SC + DBHF hybrid stars
- Global charge neutrality
  → d-CSL + DBHF hybrid stars

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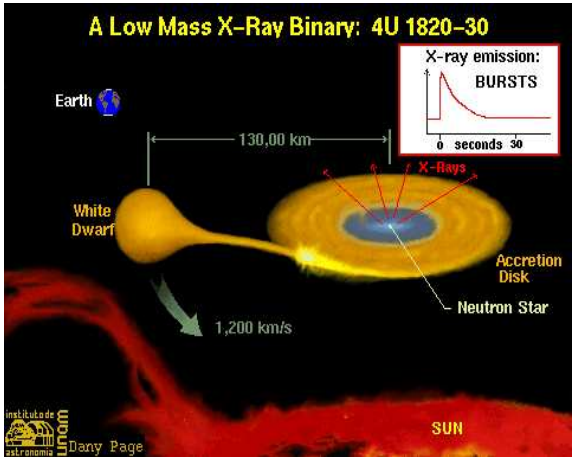
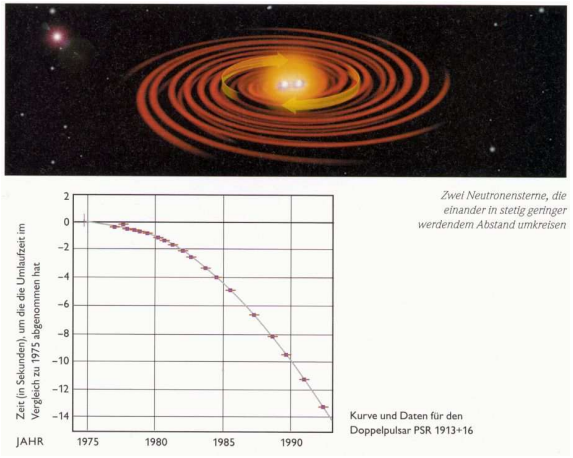
Masses of binaries

1. Mass and flow constraint
2. Chiral Quark Model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions

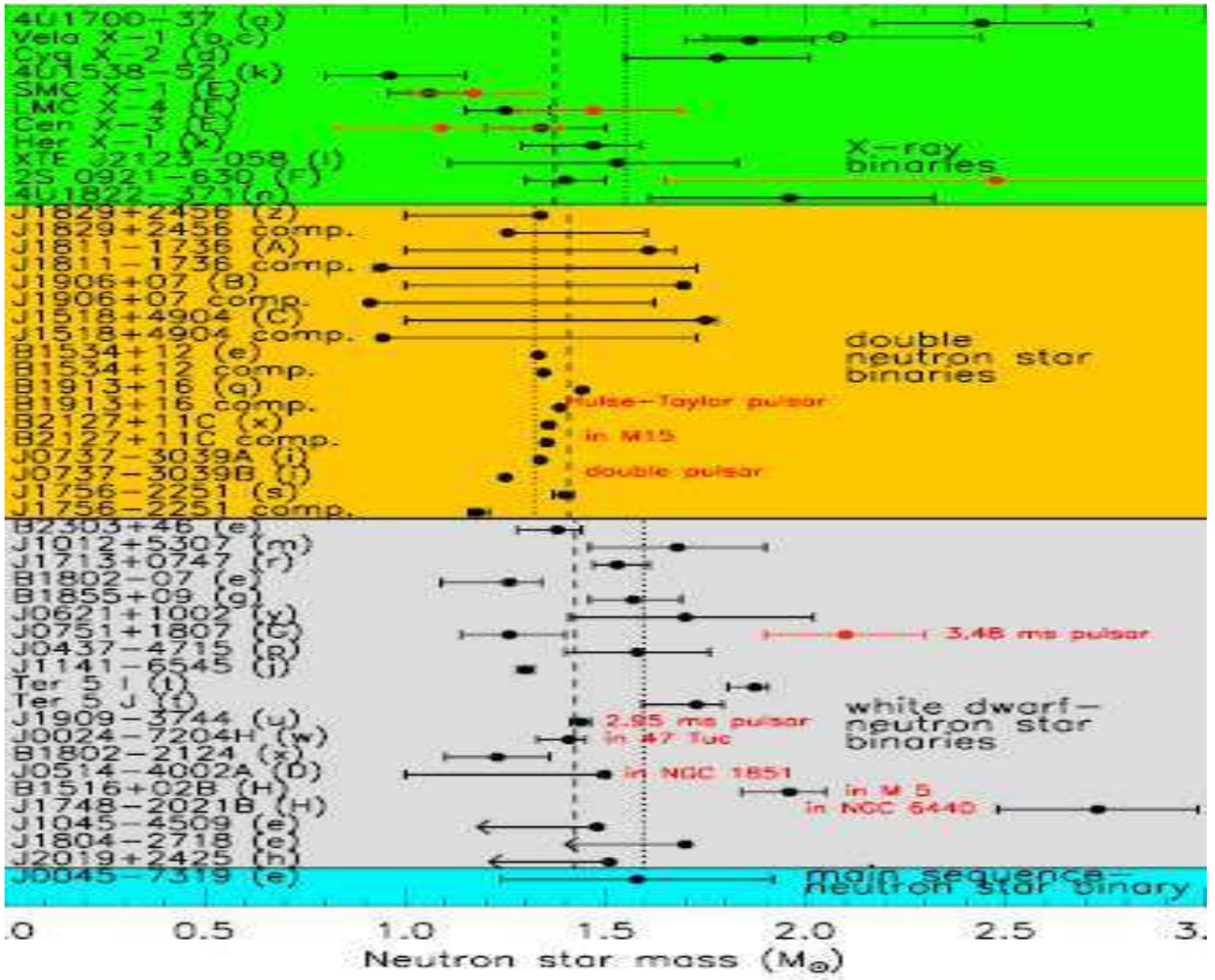
’Young’ binary system:



’Old’ binary system



Masses of Neutron Stars in binaries - clustering vs. maximum

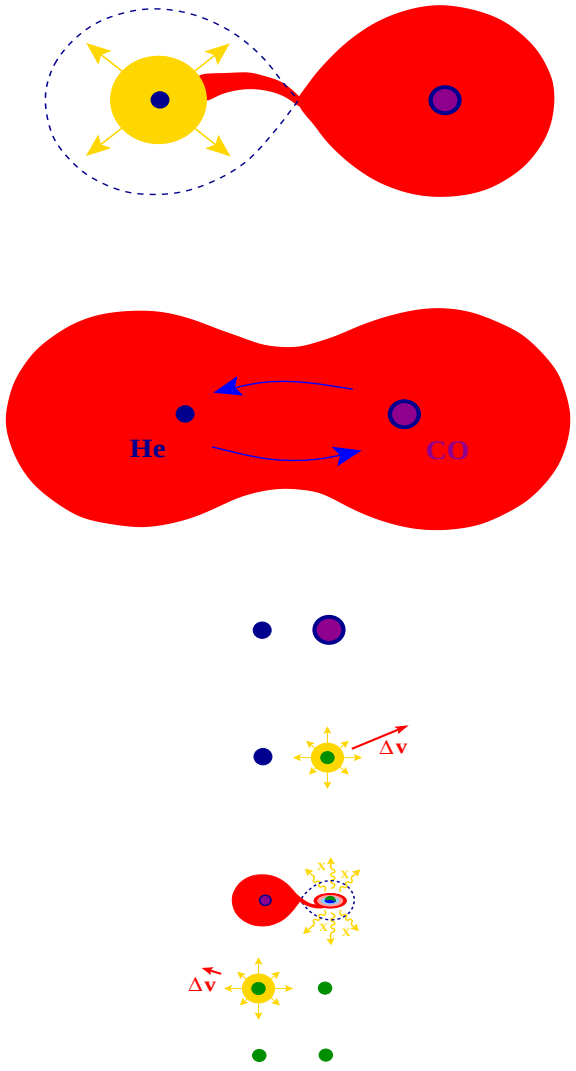


Lattimer, Prakash, PRL 94 (2005) 111101 + updates

EoS constraint from double pulsar J0737-3039?

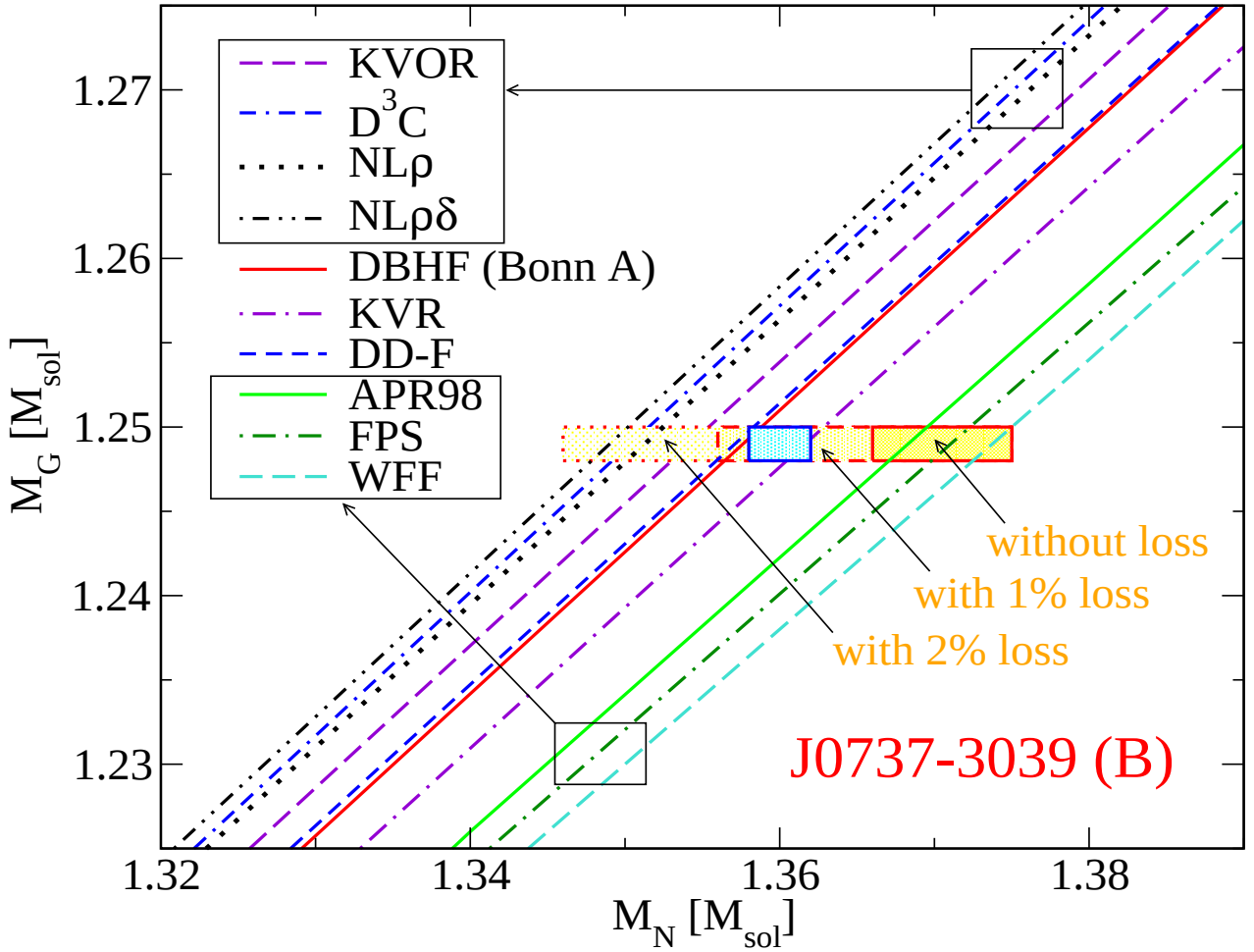
1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions

Double core scenario:



Dewi et al., MNRAS (2006)

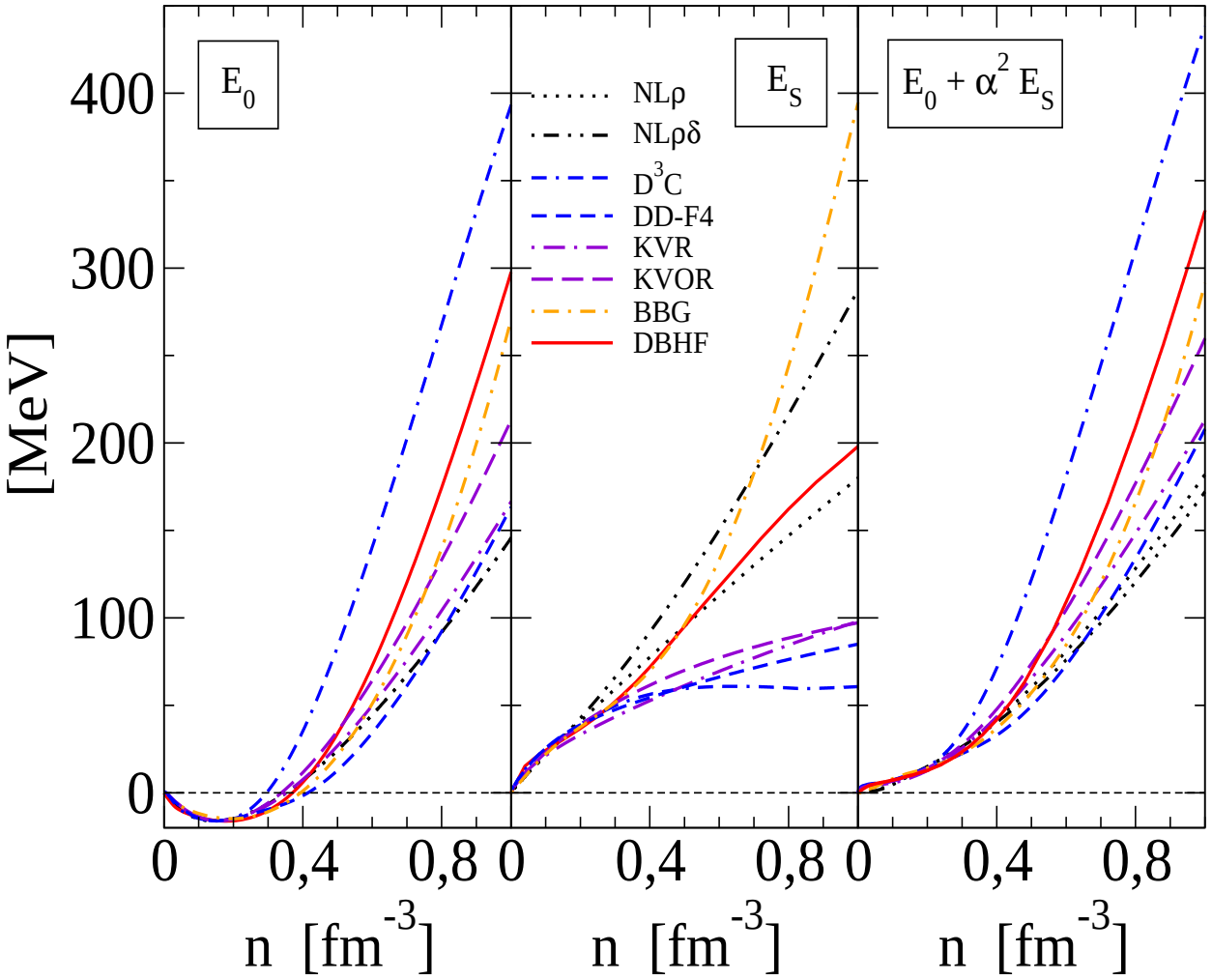
Baryon mass vs. gravitational mass - constraint or consistency check?

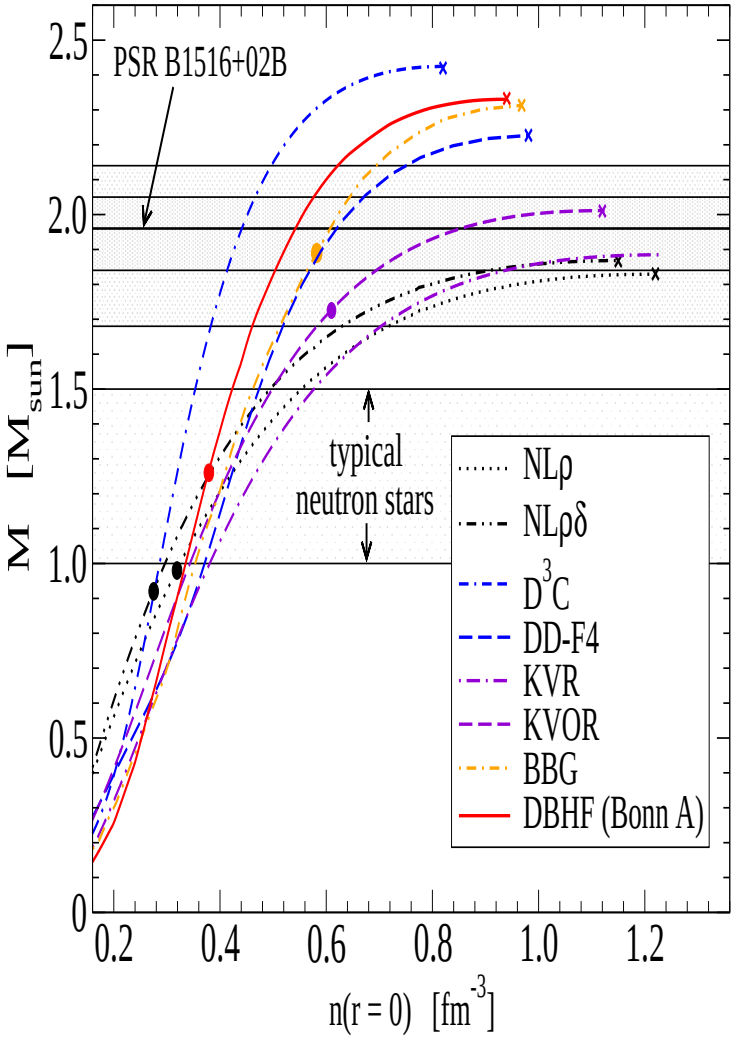


Podsiadlowski et al., MNRAS 361 (2005) 1243
Kitaura, Janka, Hillebrandt, A& A (2006); [astro-ph/0512065]
D.B., T. Klähn, F. Weber, CBM Physics Book (2008)

EoS and masses - DU constraint

1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions





DU threshold for most hadronic EoS active in neutron stars with typical masses !

Klähn, et al., PRC 74, 035802 (2006); [nucl-th/0602038]

Mass-Radius constraint and Flow constraint

1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
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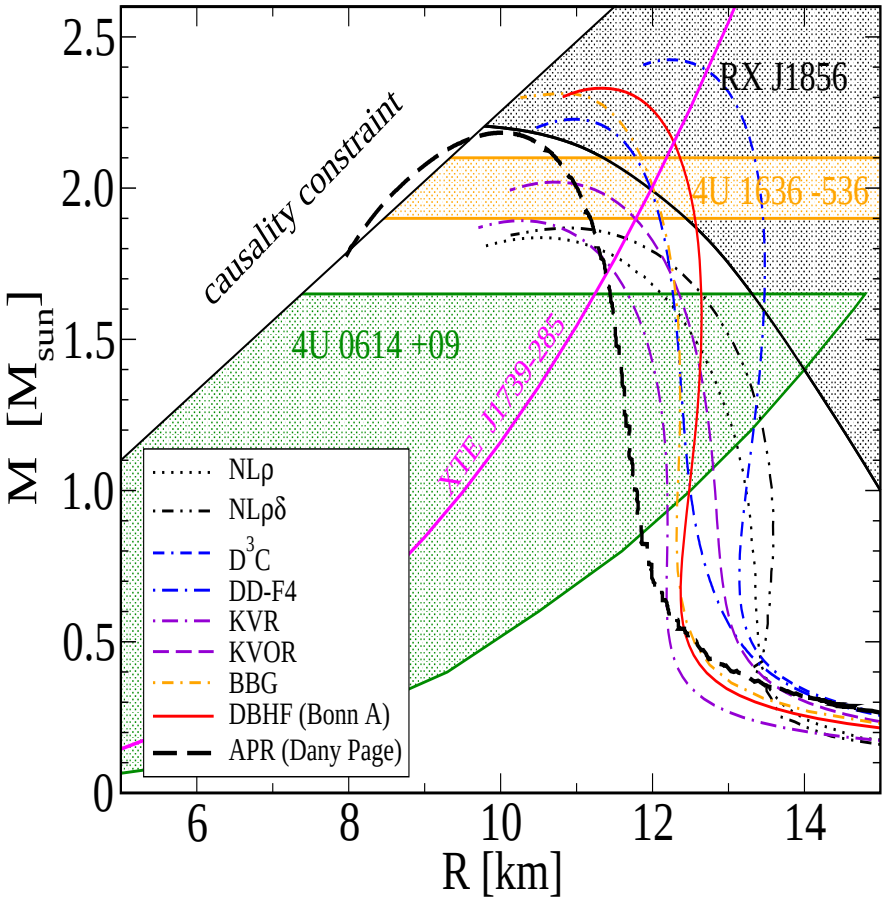
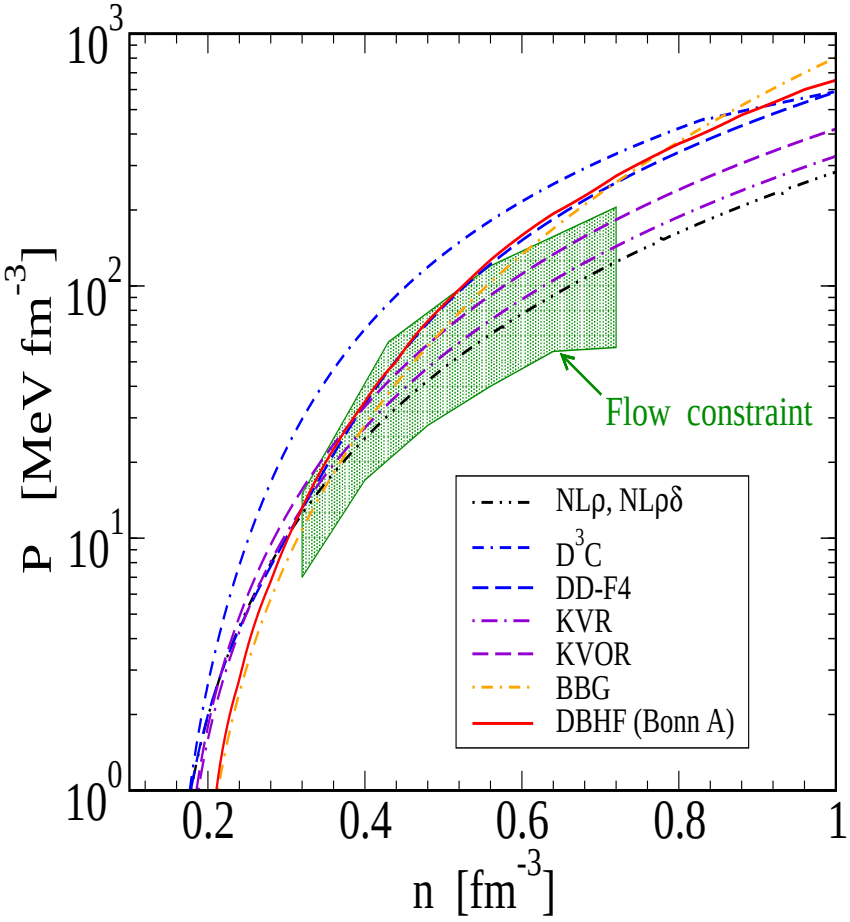
5. Conclusions





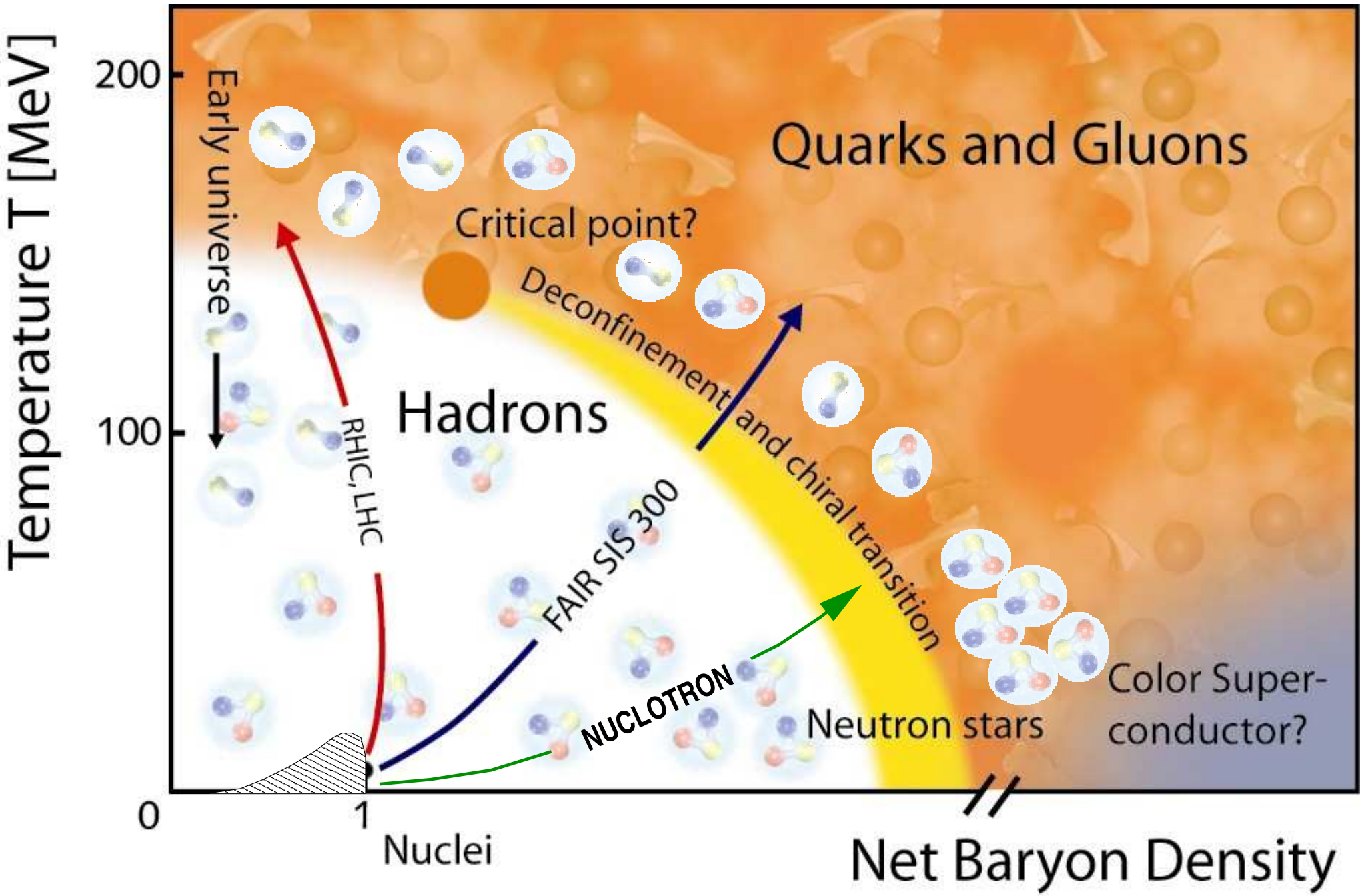
- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;

- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !

Klähn, D.B., Typel, Fuchs, Faessler, Grigorian, Miller, Roepke, Truemper, et al. PRC 74, 035802 (2006)

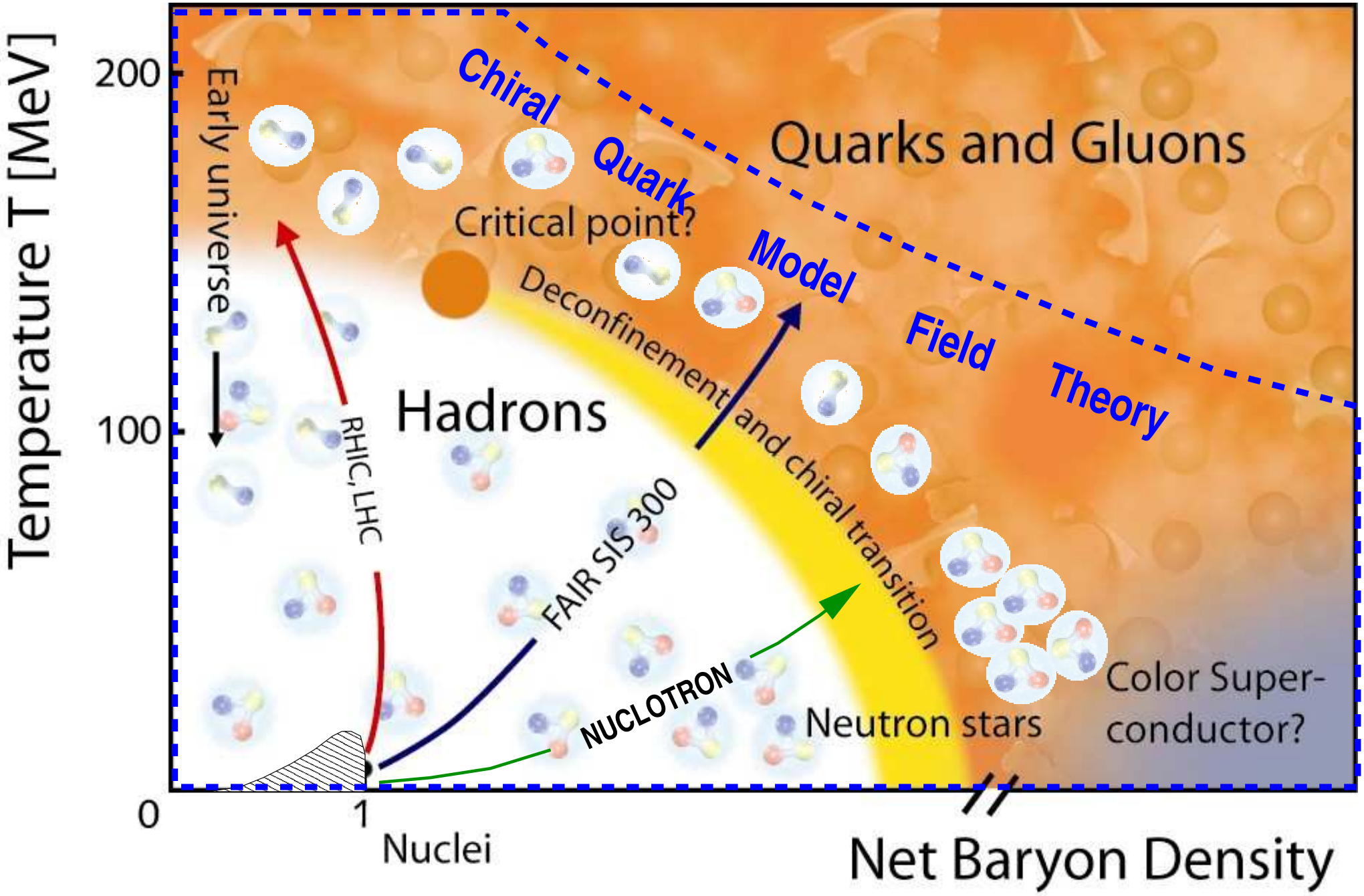
Quark Substructure and Phase Diagram

1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusion



Phase diagram of QCD: Chiral quark models

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusion



Quantum Field Theory for chiral Quark Matter

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF Hybrid
4. d-CSL + DBHF hybrid
5. Conclusion

- Partition function for chiral Quark Field theory

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp\left\{ -\int^{\beta} d\tau \int_V d^3x [\bar{\psi}(i\gamma^\mu \partial_\mu - m - \gamma^0 \mu)\psi - \mathcal{L}_{\rm int}] \right\}$$

- Current-current coupling (4-fermion interaction)

$$\mathcal{L}_{\rm int} = \sum_{M=\pi,\sigma,\ldots} G_M (\bar{\psi}\Gamma_M \psi)^2 + \sum_D G_D (\bar{\psi}^C \Gamma_D \psi)^2$$

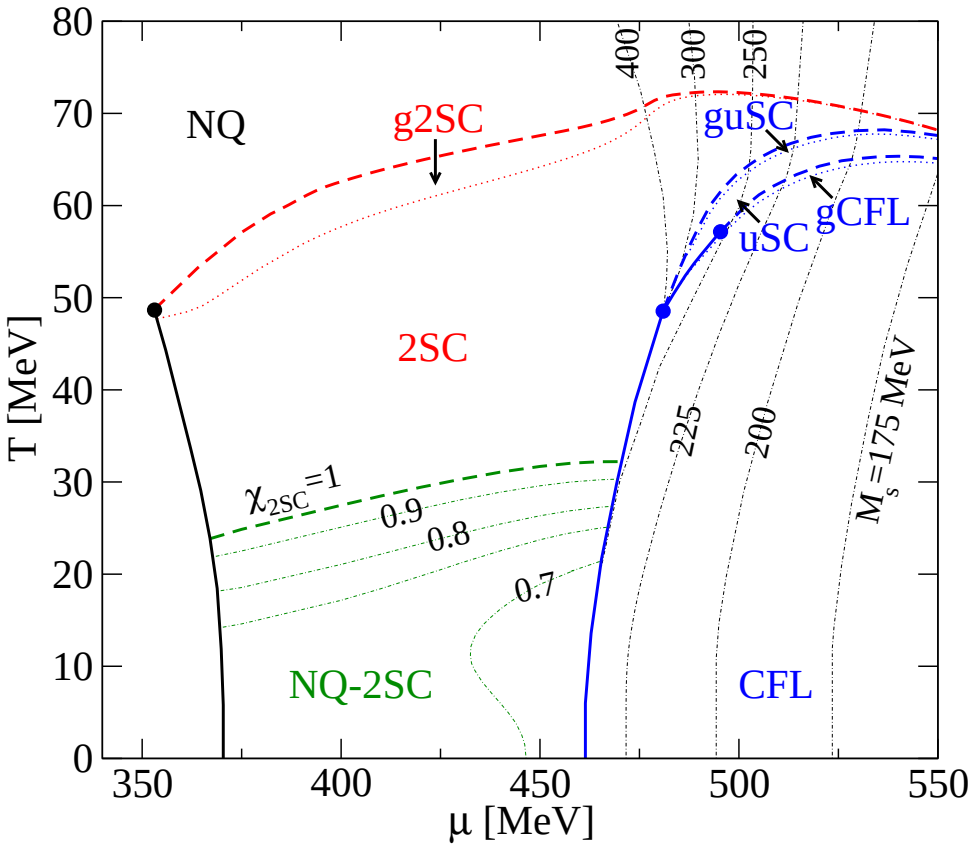
- Bosonisation (Hubbard-Stratonovich Transformation)

$$Z[T,V,\mu] = \int \mathcal{D}\phi_M \mathcal{D}\Delta_D^\dagger \mathcal{D}\Delta_D \exp\left\{ -\sum_M \frac{\phi_M^2}{4G_M} - \sum_D \frac{|\Delta_D|^2}{4G_D} + \frac{1}{2}{\rm Tr}\,\ln S^{-1}[\{M_M\},\{\Delta_D\}] \right\}$$

- Collective (stochastic) Fields: Mesons (ϕ_M) and Diquarks (Δ_D)
- Systematic Evaluation: Mean field + Fluctuations
  - Mean-field Approximation: Order parameter for Phase transitions (Gap equations)
  - Fluctuations (2. Order): Hadronic Correlations (Bound- & Scattering states)
  - Fluctuations of higher Order: Hadron-Hadron Interaction

Three-flavor Quark Matter Phase Diagram

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion



Rüster et al, PRD 72 (2005) 034004;
Blaschke et al, PRD 72 (2005) 065020;
Abuki, Kunihiro, NPA768 (2006) 118;
Warringa et al, PRD 72 (2005) 014015

The phases are:

- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$, $0 \leq \chi_{2SC} \leq 1$;
- 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq 0$, $\Delta_{ds} \neq 0$, $\Delta_{us} \neq 0$;

Result:

- Gapless phases only at high T,
- CFL only at high chemical potential,
- At T $\leq$25-30 MeV: mixed NQ-2SC phase,
- Critical point (T_c,μ_c)=(48 MeV, 353 MeV),
- Strong coupling, $G_D = G_S$, similar, no NQ-2SC mixed phase.

Mass-Radius constraint and Flow constraint (II)

1. Mass and Flow constraint
2. Chiral Quark model
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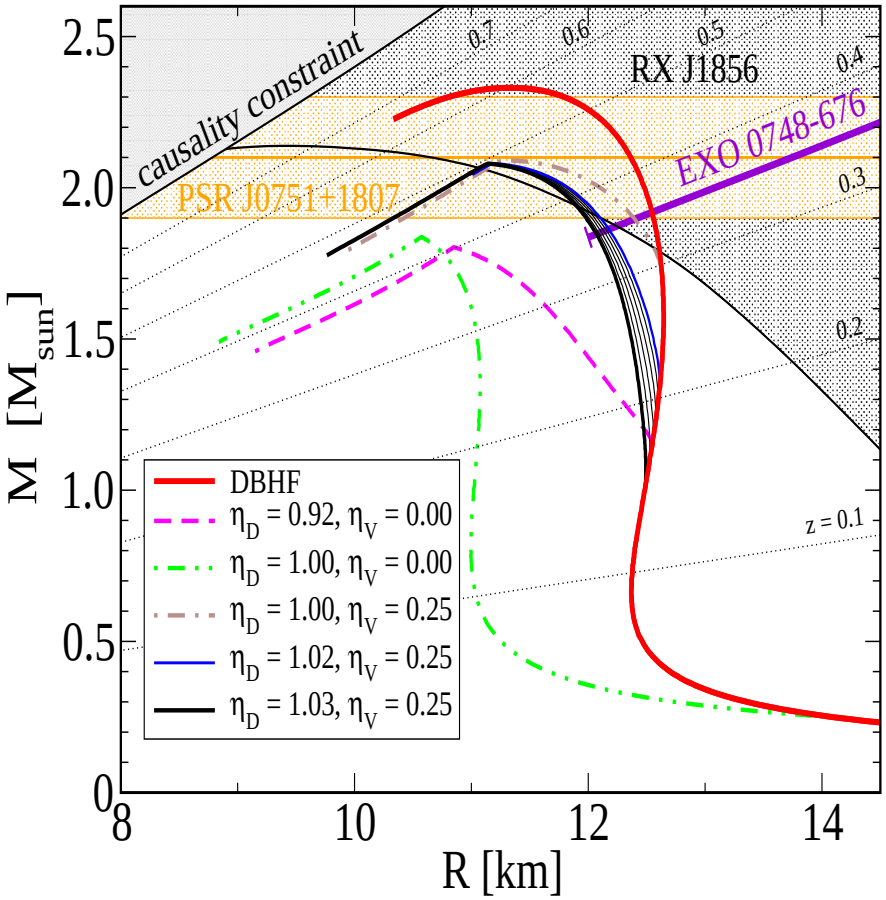
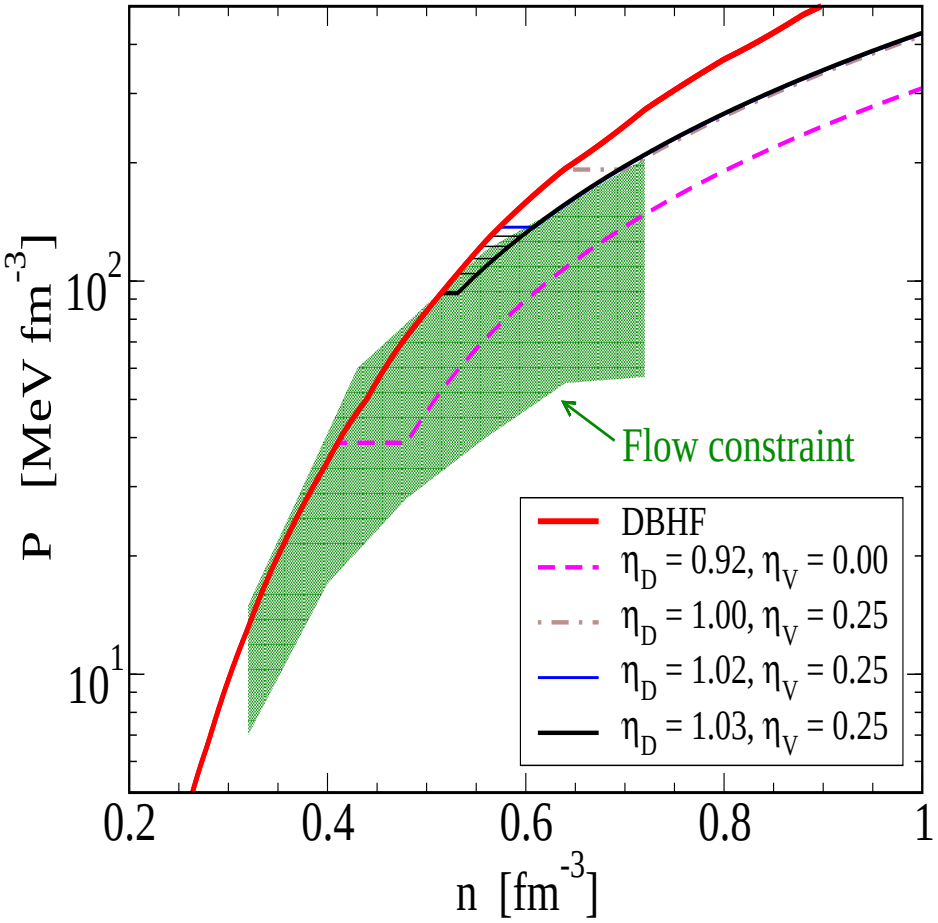
5. Conclusion





- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff quark matter EoS;
  Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !
  Note: Quark matter removes violation by DBHF at high densities

Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Roepke, Truemper, Phys. Lett. B567, 160 (2007)

Phase diagrams for the CBM experiment

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
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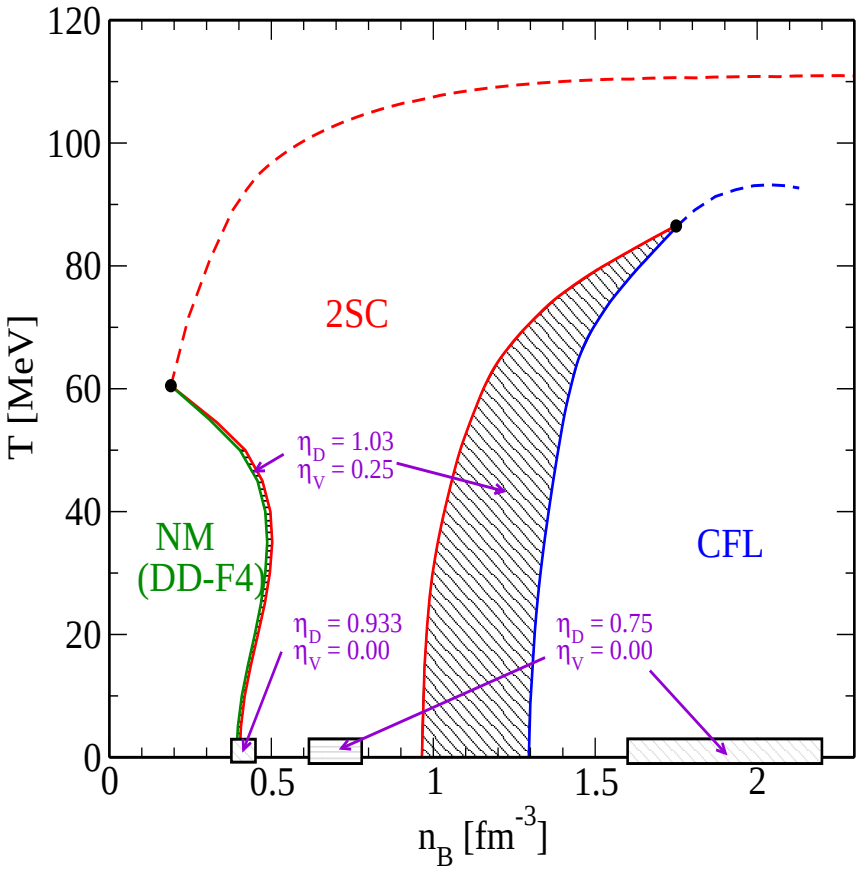
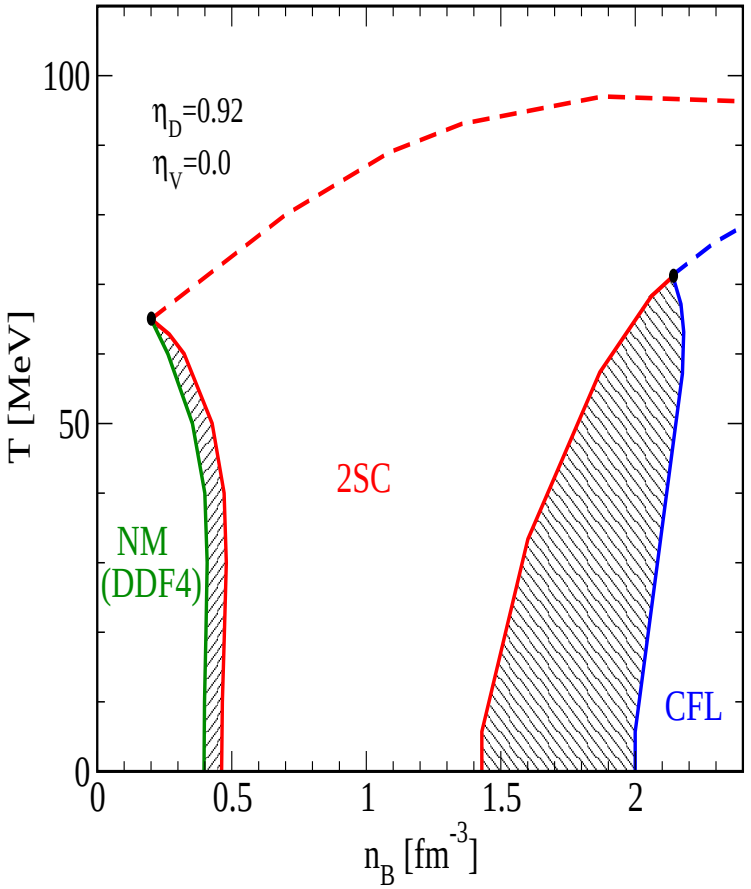
5. Conclusion

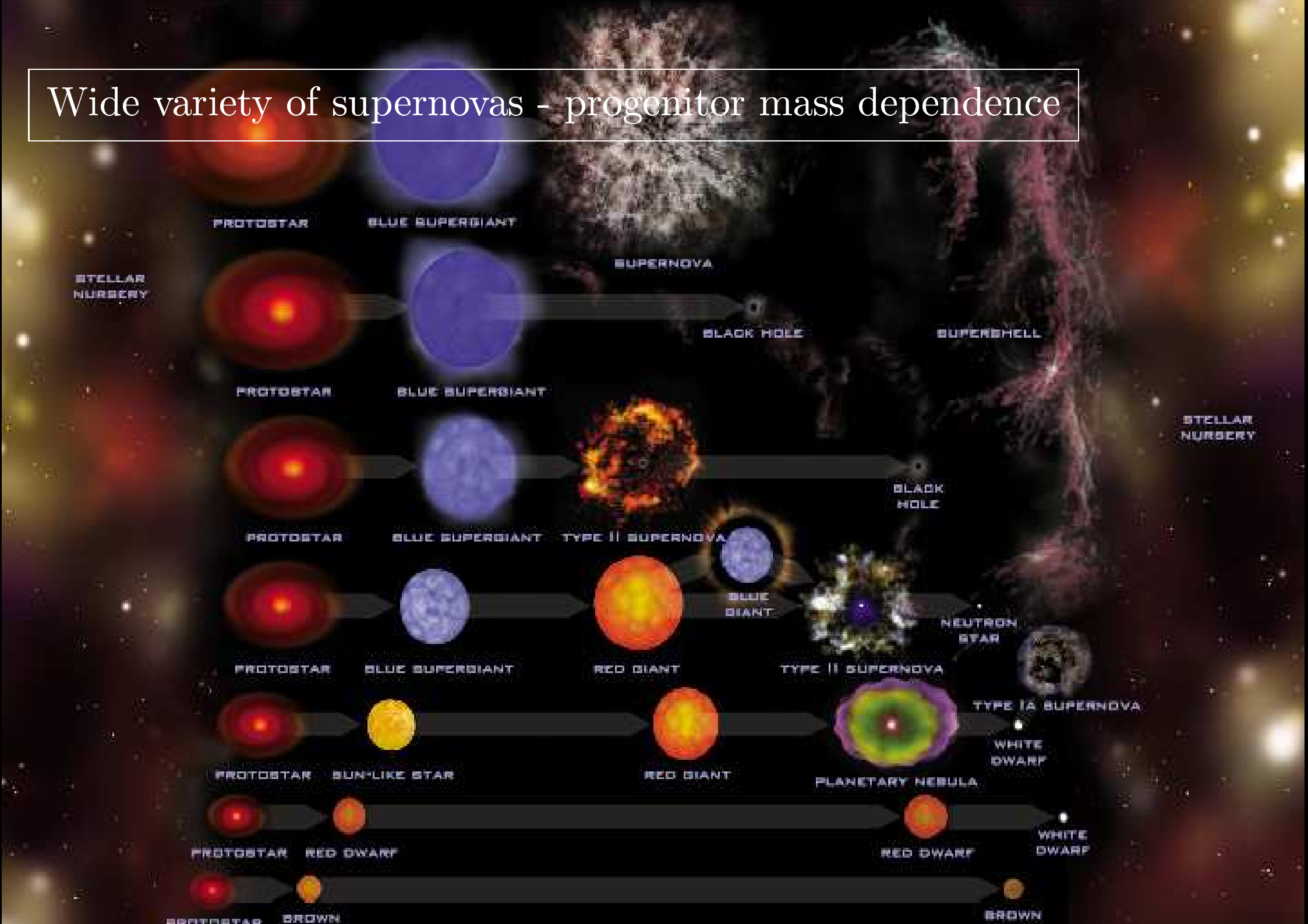




Phase diagrams for isospin-symmetric matter, for hybrid star maximum mass $M_{max} = 2.1\ M_\odot$ (left-hand side) and $M_{max} = 1.7\ M_\odot$ (right-hand side).

D.B.,F. Sandin, T. Klähn, in preparation.

Wide variety of supernovas - progenitor mass dependence



Supernova Collapse in the Phase Diagram

1. Mass and Flow constraint
2. Chiral Quark model
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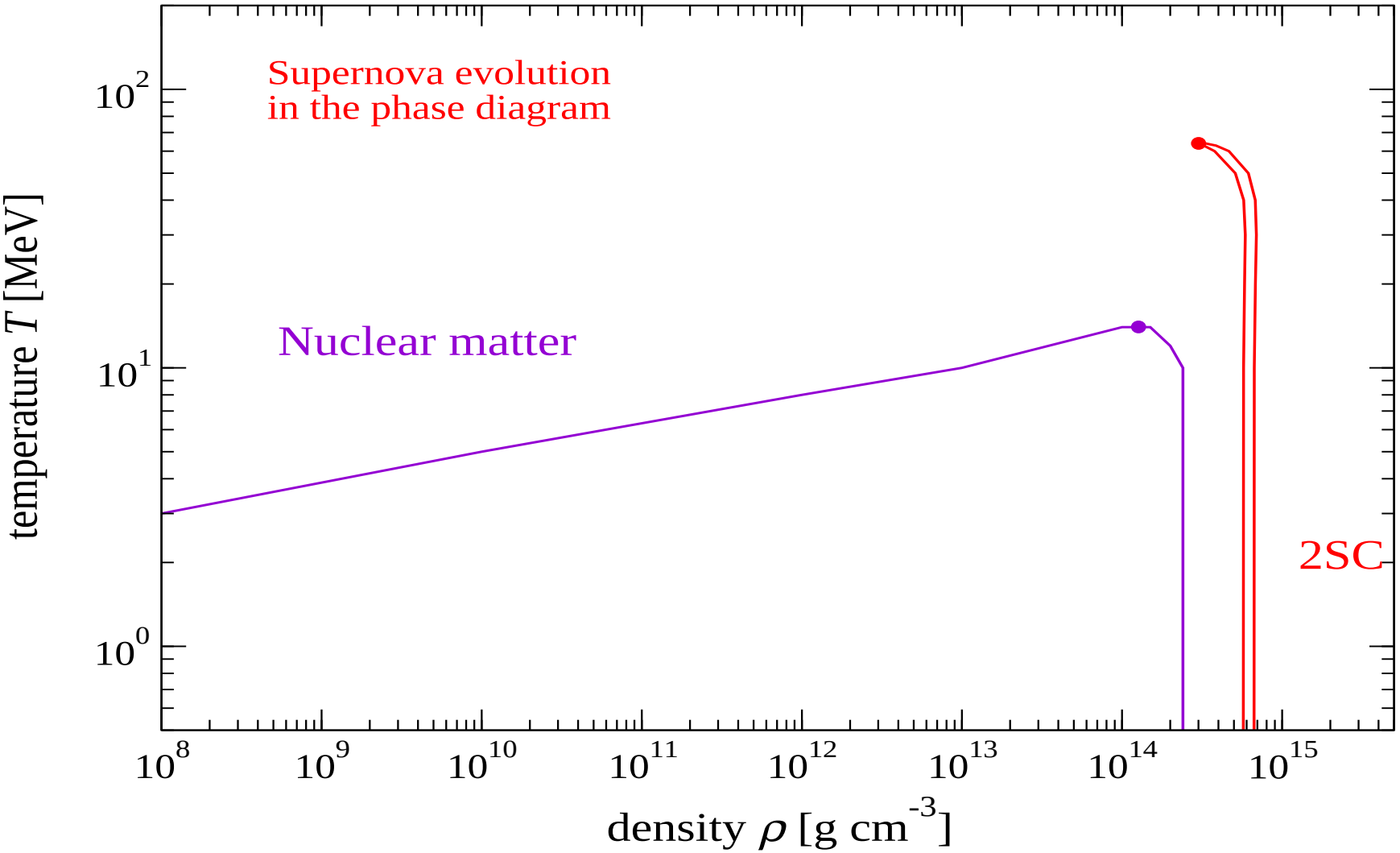
5. Conclusion



Supernova Collapse in the Phase Diagram (II)

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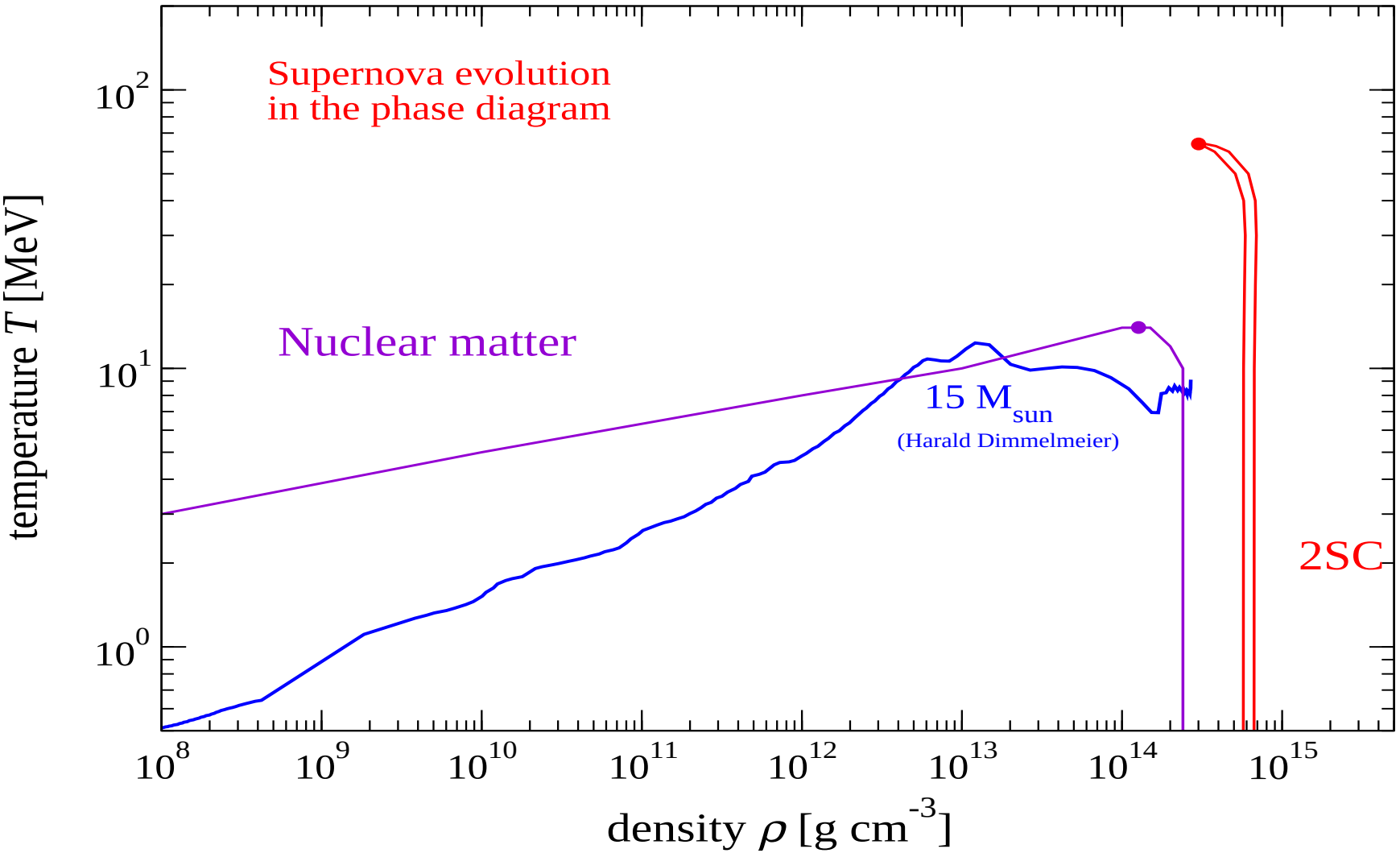

Supernova Collapse in the Phase Diagram

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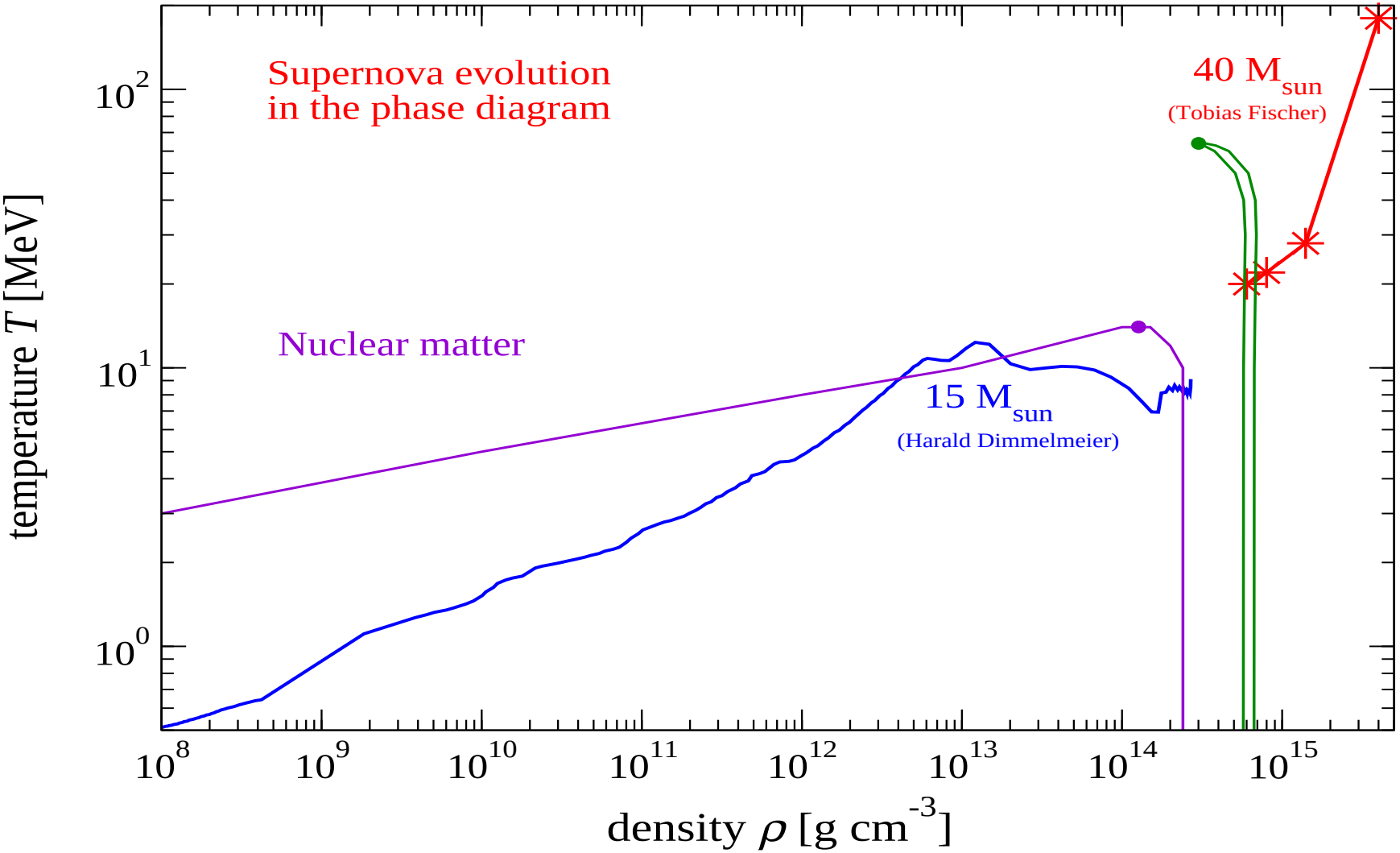
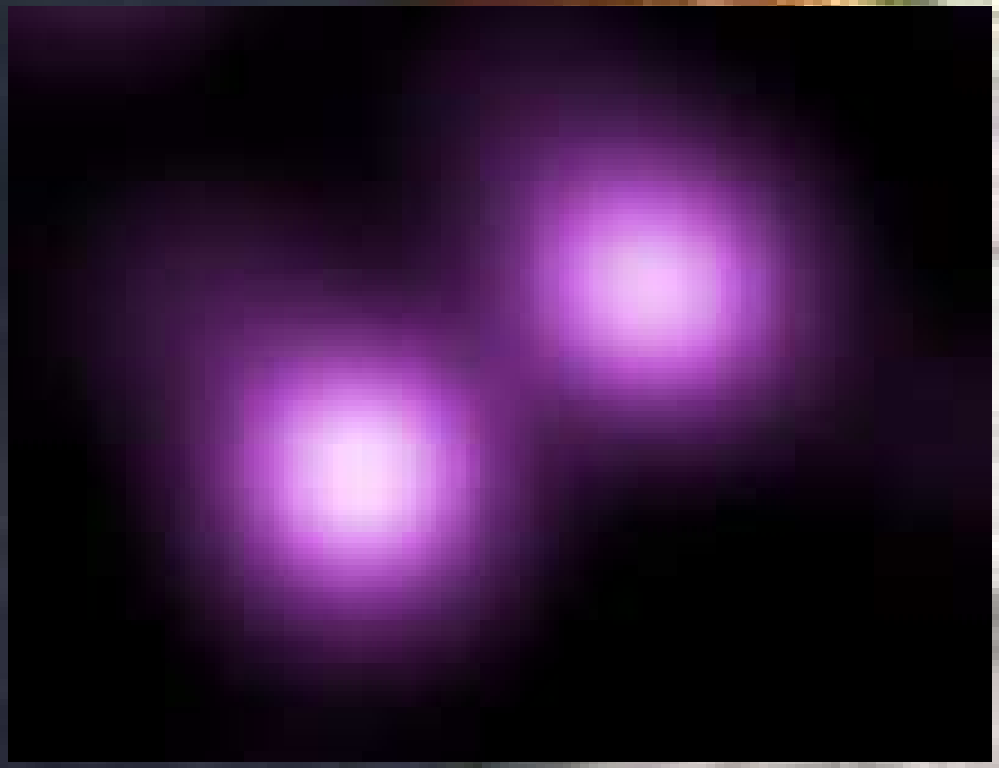
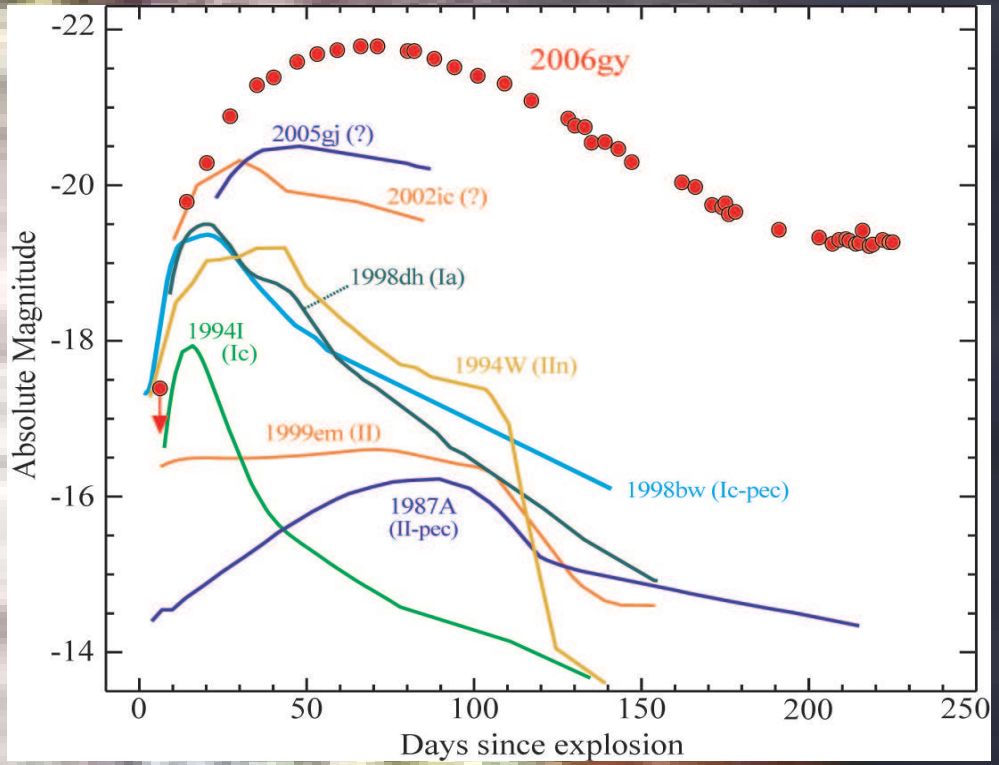


The case of SN2006gy

The case of SN2006gy - a Quarknova ?





Discovery: Sept. 18, 2006
in NGC 1260 (Perseus)
Distance: 72 Mpc=238 Mill. Ly
(Smith et al.: astro-ph/0612617)

Light curve: 70 days rise time
Energy release: 10^{52} erg= 10 bethe
Progenitor star: $\approx 150\ M_\odot$?
Engine: Quark-star formation?
(Leahy & Ouyed: 0708.1787 [astro-ph])

Quark matter analogue of 'neutron drip'

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

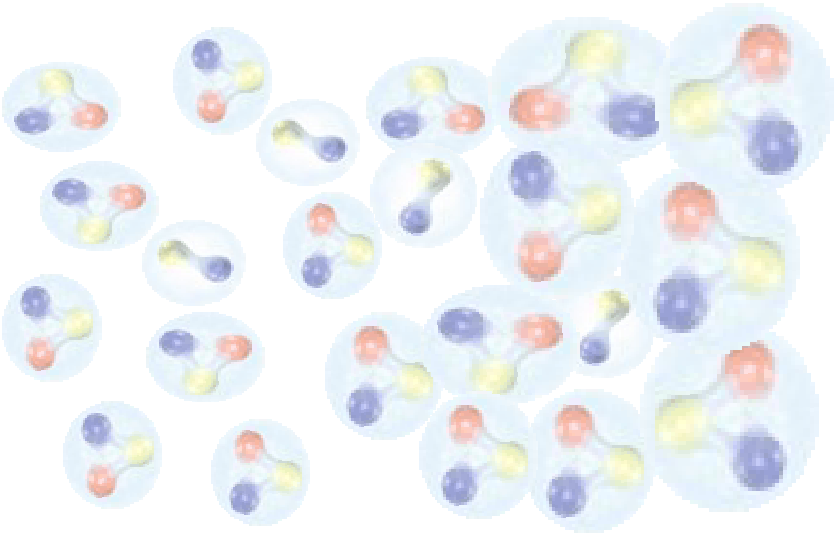
- Chemical potentials of neutrons and protons differ by $\mathcal{O}(100$ MeV)

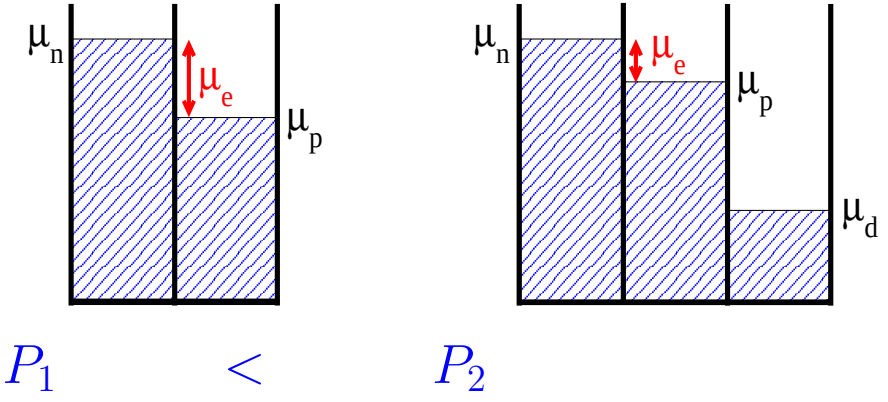
$$\mu_n = \mu_p + \mu_e = \mu_p - \mu_Q$$

- Less asymmetry if d-quark Fermi sea is populated (Mott transition for neutrons)

$$n + n \rightarrow p + 3d$$

- "Mixed phase": nonideal d-quark plasma with nucleonic bound states (clusters)
- Sequential melting of chiral condensates: d-quark dripline!





$P_1 \quad < \quad P_2$

Quark matter analogue of 'neutron drip'

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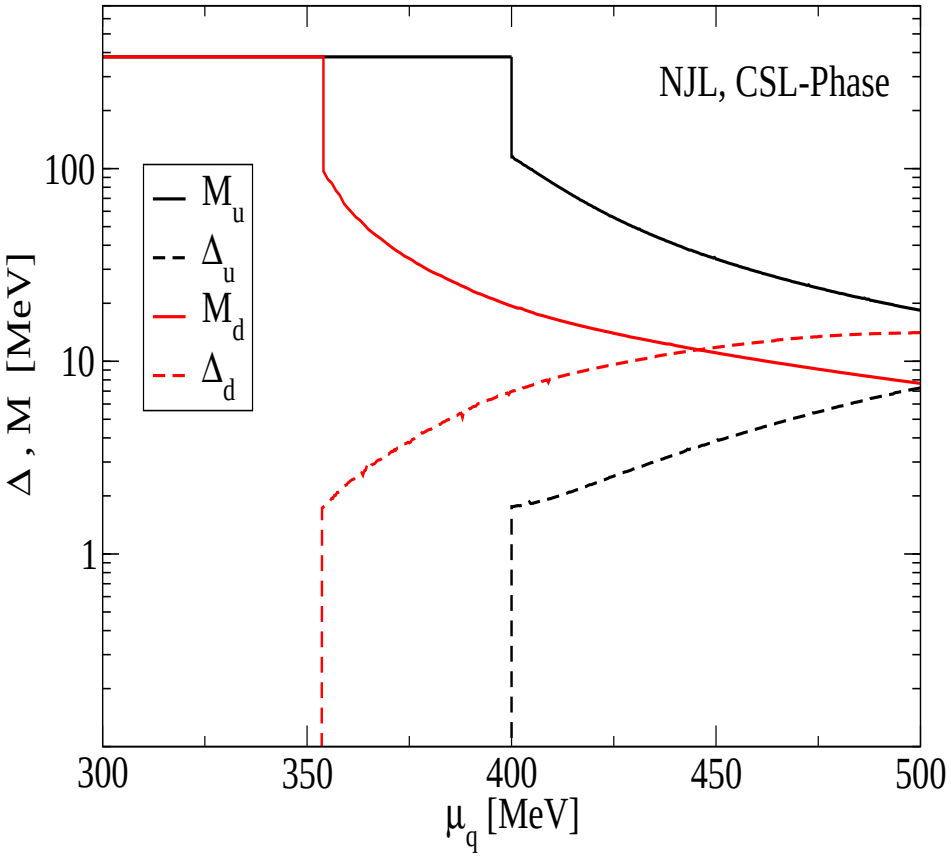

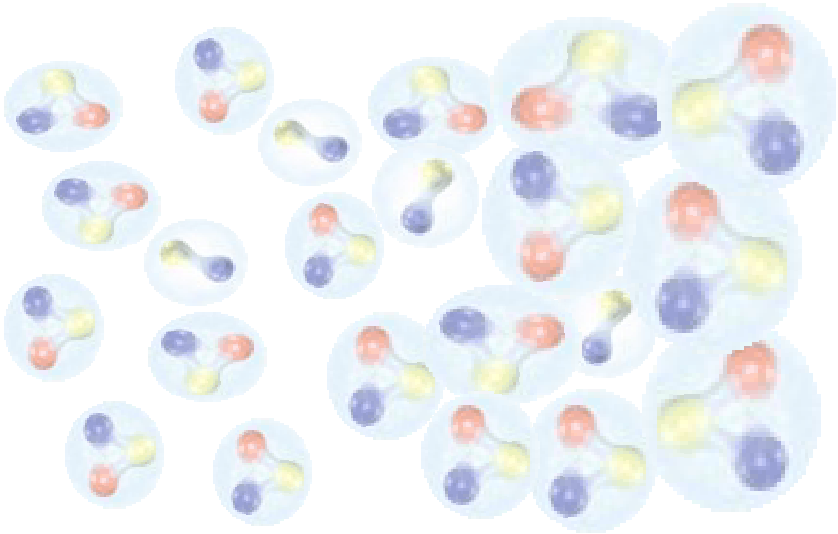

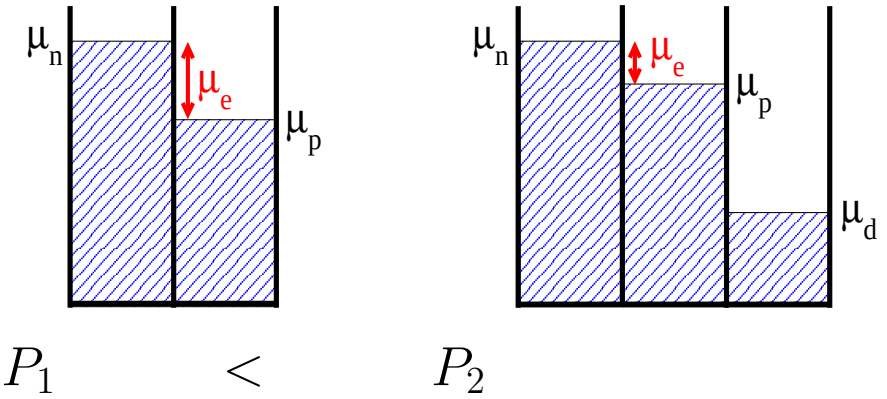

$P_1 \quad < \quad P_2$

Sequential melting of chiral condensates:
d-quark dripline!

D.B., T. Klähn, F. Sandin, in preparation

Single flavor (d-CSL) Phase in Compact Stars

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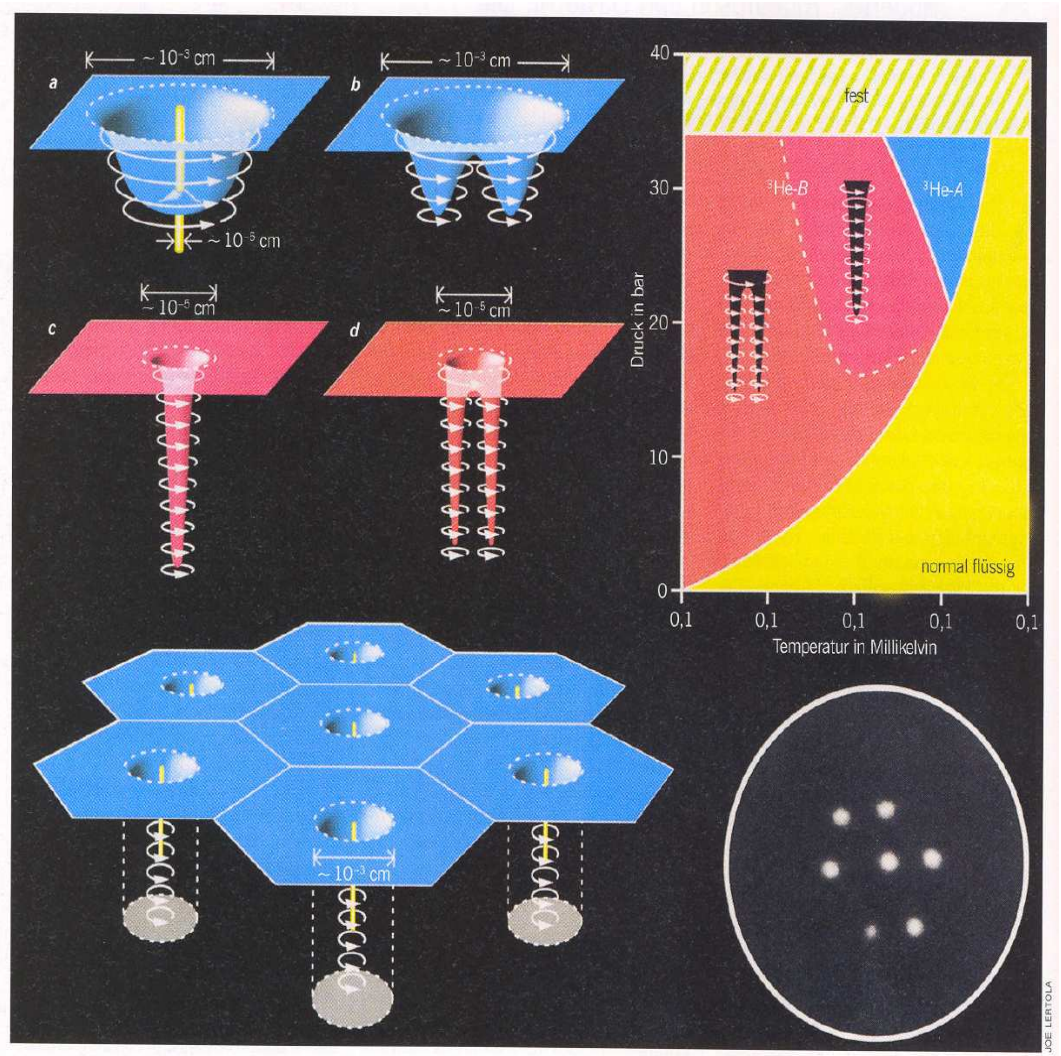
5. Conclusion

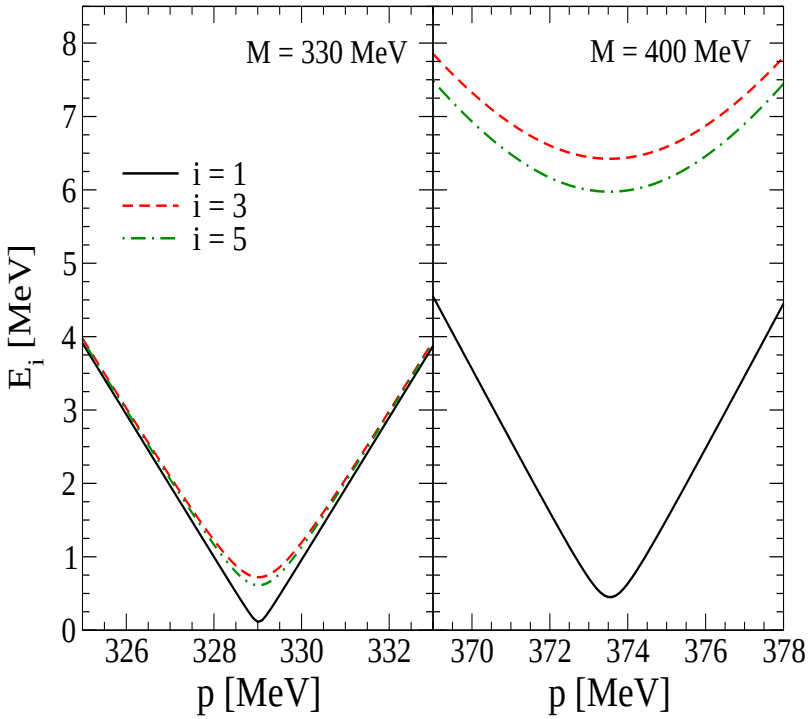


Phases of superfluid ^{3}He

Ansatz Color-spin-locking (CSL) gap:

$$\hat{\Delta} = \Delta(\gamma^3\lambda_2 + \gamma^1\lambda_7 + \gamma^2\lambda_5)$$

Aguilera et al., PRD 72 (2005) 034008; PRD 74 (2006) 114005



Global charge neutrality: quark-nuclear hybrid

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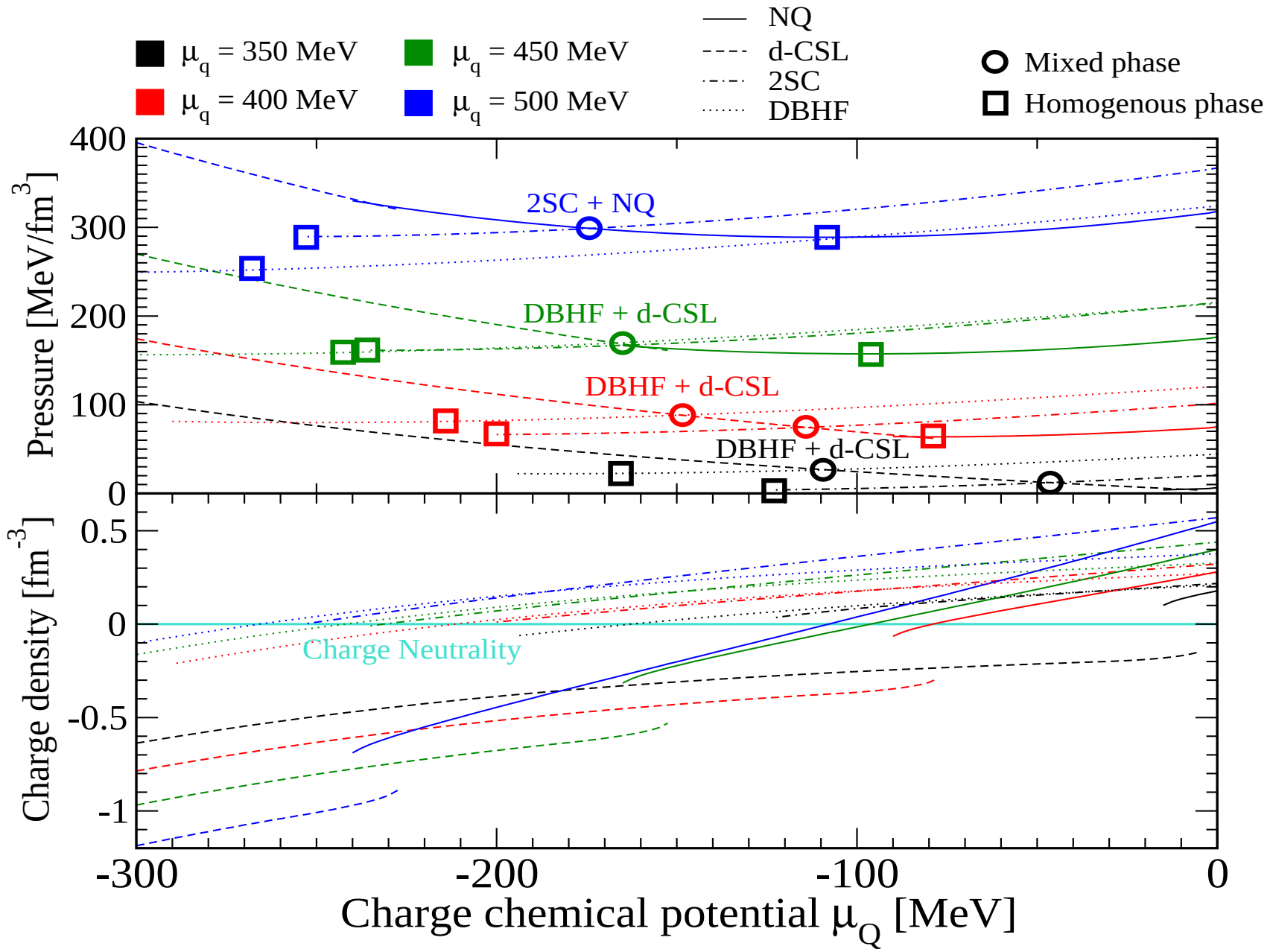
5. Conclusion



d-CSL: single-flavor phase in competition

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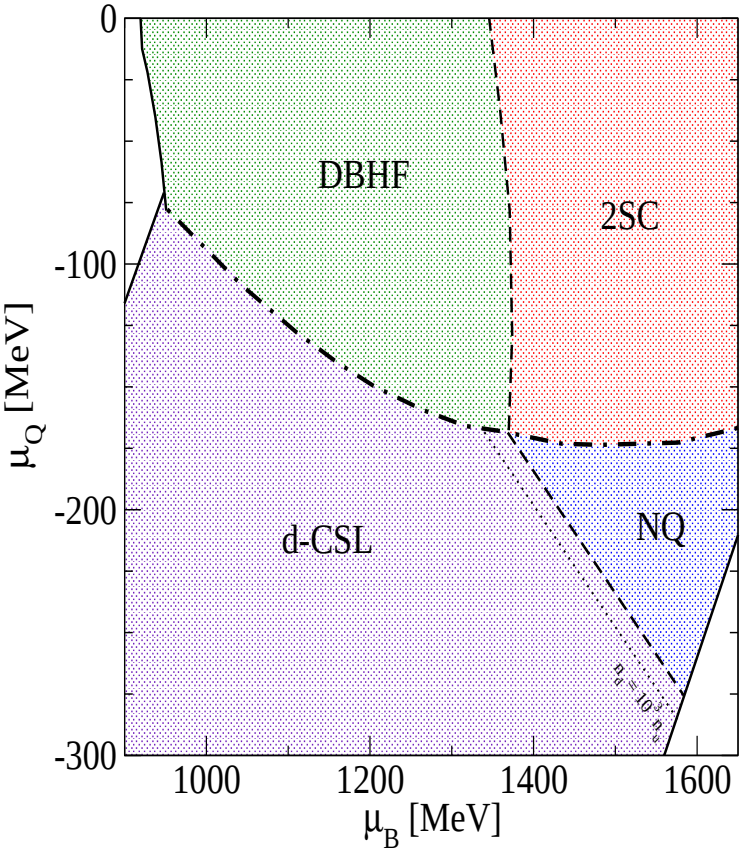
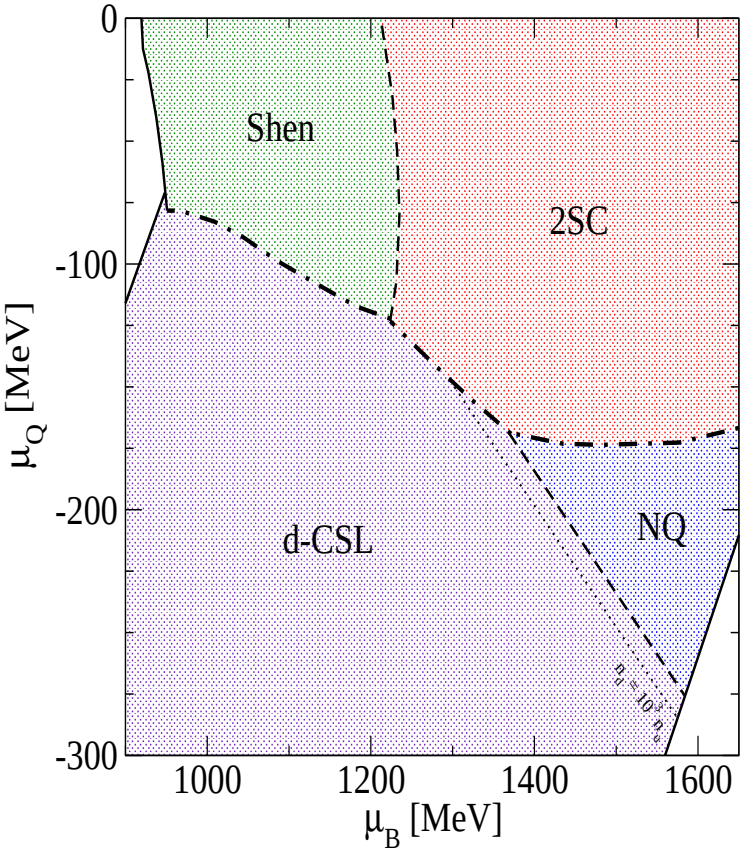
5. Conclusion





Dash-dotted lines: border between oppositely charged phases

D.B.,F. Sandin, T. Klähn, in preparation.

d-CSL: single-flavor phase in neutron stars

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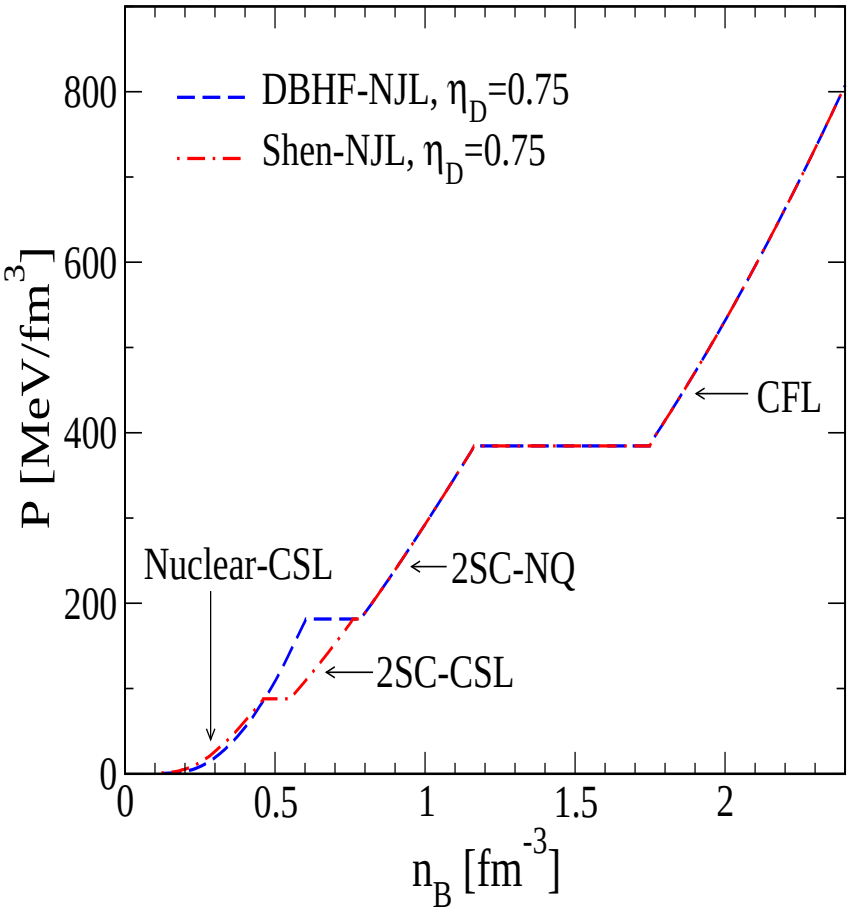
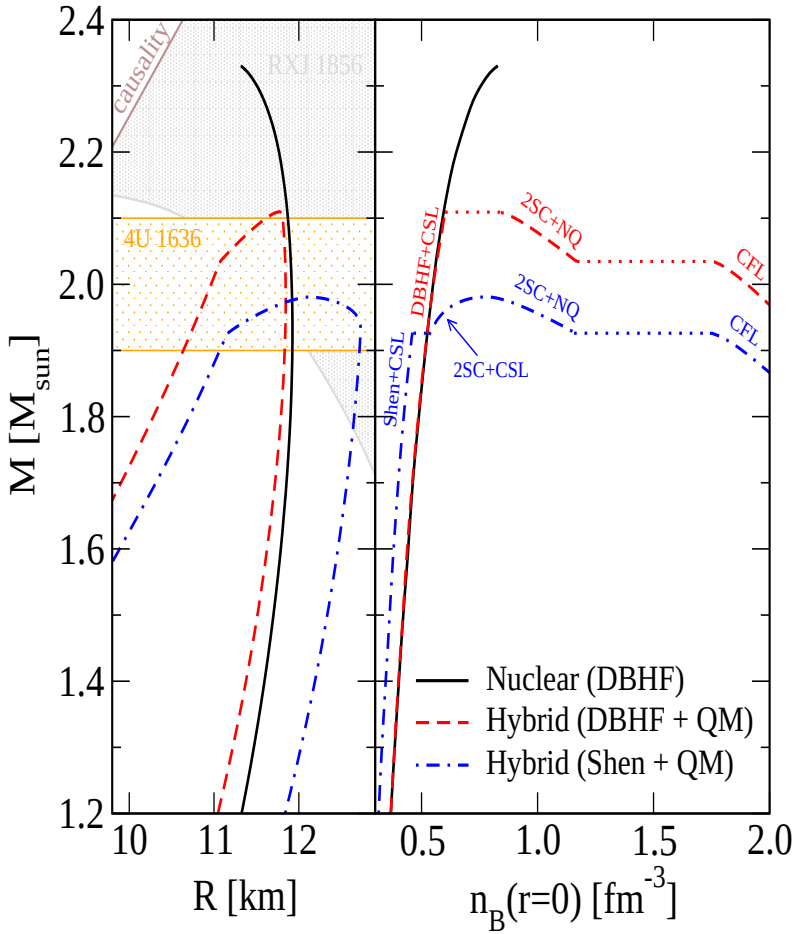
5. Conclusion





D.B.,F. Sandin, T. Klähn, in preparation.

d-CSL: single-flavor phase in neutron stars (II)

1. Mass and Flow constraint
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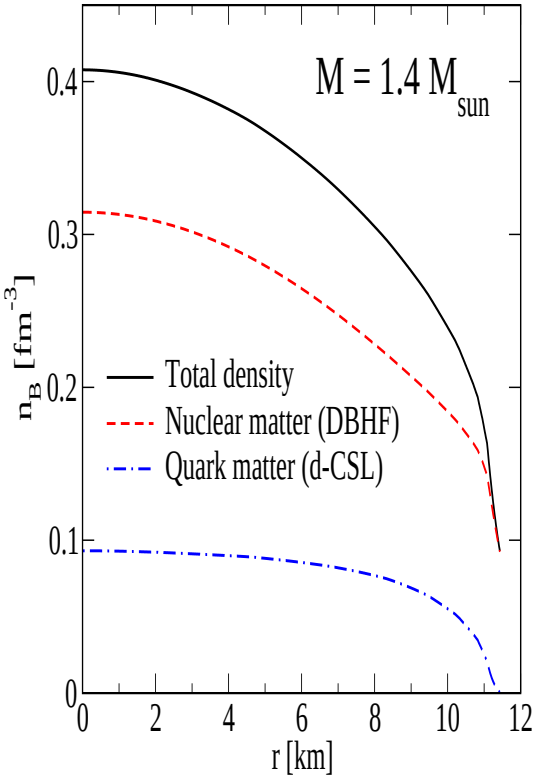
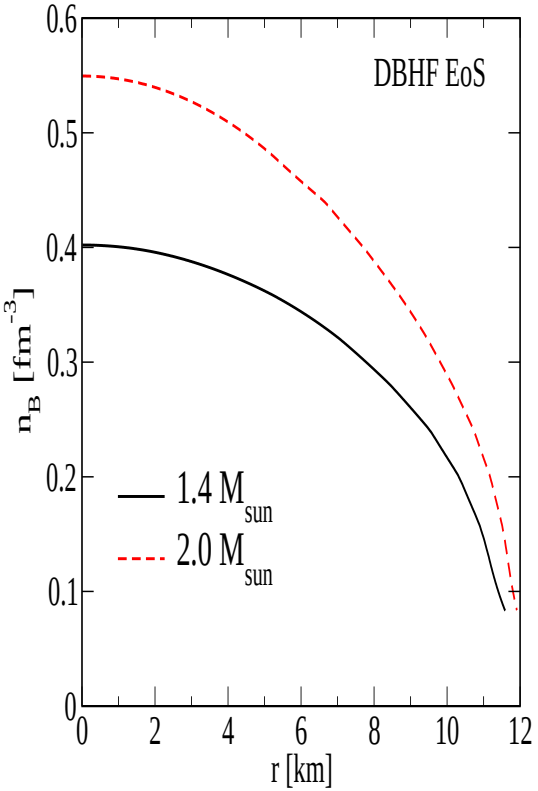
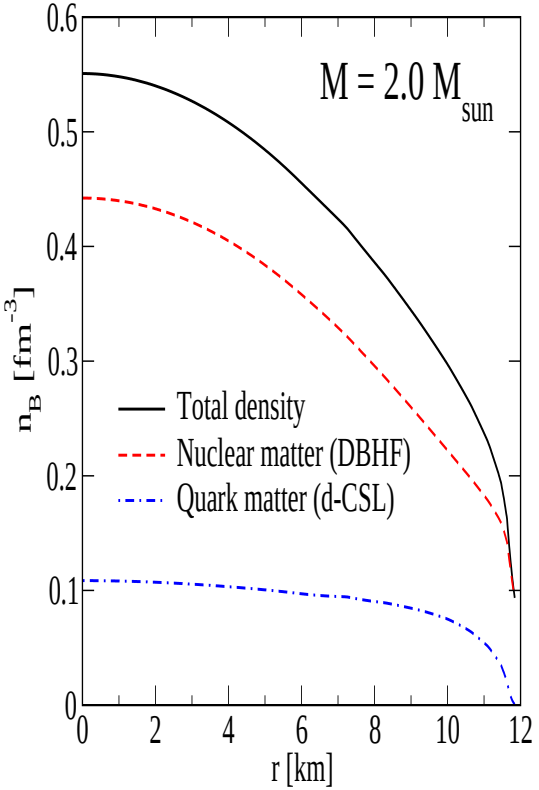
4. d-CSL hybrid
5. Conclusion







D.B.,F. Sandin, T. Klähn, in preparation.

d-CSL: single-flavor phase in neutron stars

1. Mass and Flow constraint
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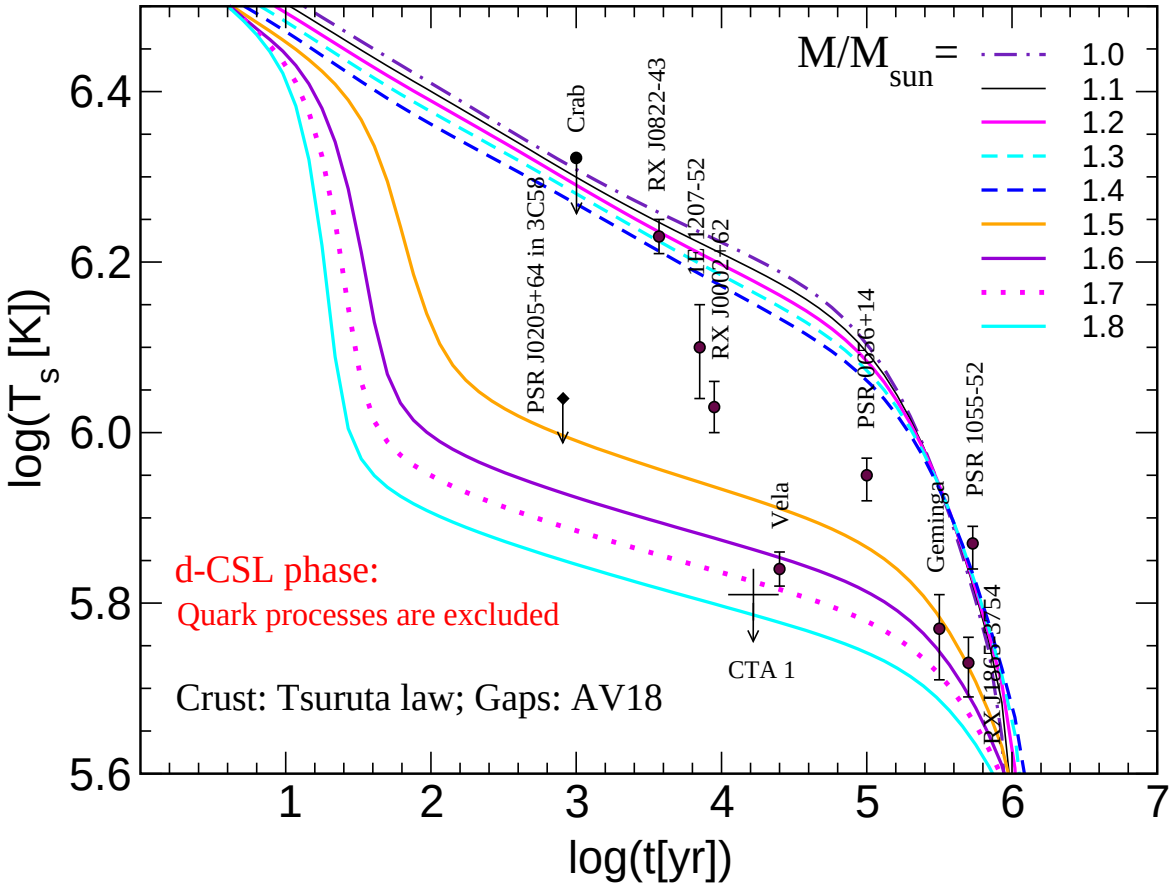
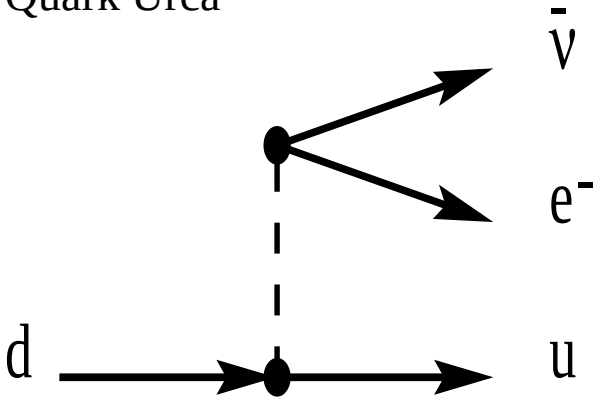
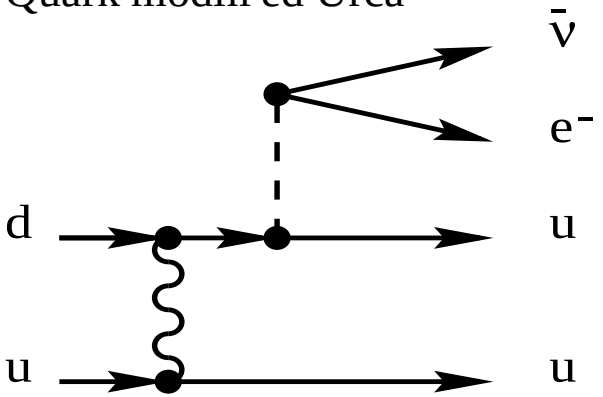
Cooling: processes in single-flavor quark matter are blocked!



Quark Urca



Quark modifi ed Urca



not operative since u-quark Fermi sea not populated ($p_{F,u} = 0$)

D.B.,F. Sandin, H. Grigorian, in preparation.

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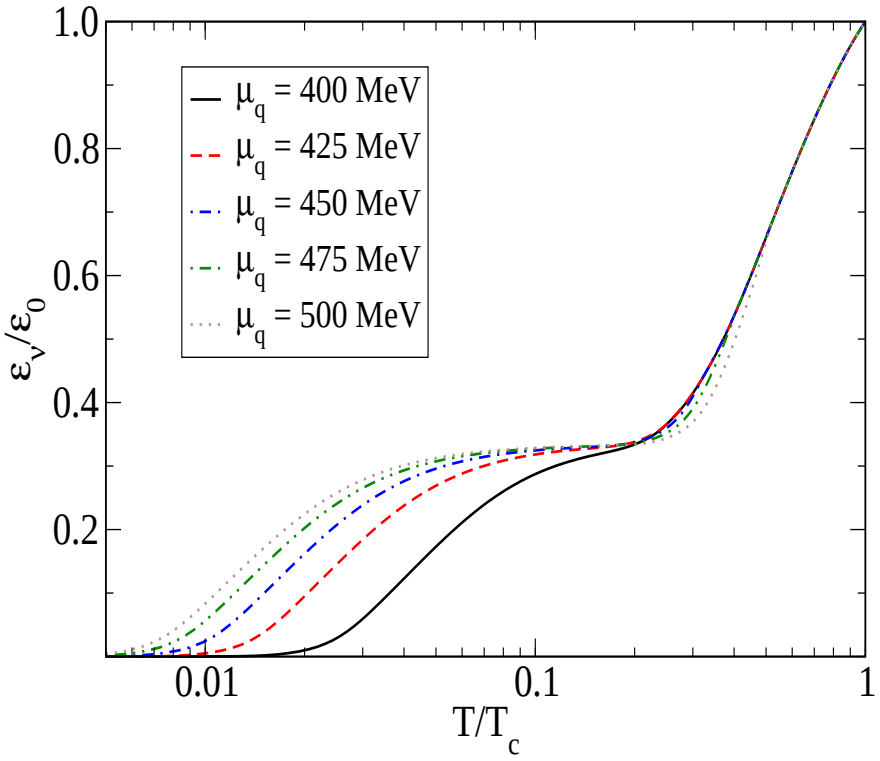
DUrca emissivity:



D.B., J. Berdermann, arXiv:0710.5243 [hep-ph].

$$\epsilon_{\rm Urca} \;=\; \epsilon_0\, G_3(\Delta_u, \Delta_d),$$

Normal quark Urca emissivity

$$\epsilon_0 = \frac{457}{630}\alpha_s G_F^2\, \mu_e\mu_u\mu_d\, T^6\ ,$$

Suppression function

$$G_n(\Delta_u, \Delta_d) \;=\; \frac{5040}{1371\pi^6}\int_0^\infty dz\; z^n\,[\mathcal{F}_1(z) + \mathcal{F}_3(z) + \mathcal{F}_5(z)]$$

with

$$\mathcal{F}_r(z) \;=\; \sum_{e_1,e_2=\pm}\int_0^\infty\int_0^\infty dxdy$$
$$(e^{-e_1\sqrt{y^2+a_{u,r}\Delta_u^2}}+1)^{-1}(e^{e_2\sqrt{x^2+a_{d,r}\Delta_d^2}}+1)^{-1}$$
$$\times(e^{z+e_1\sqrt{y^2+a_{u,r}\Delta_u^2}-e_2\sqrt{x^2+a_{d,r}\Delta_d^2}}+1)^{-1},$$

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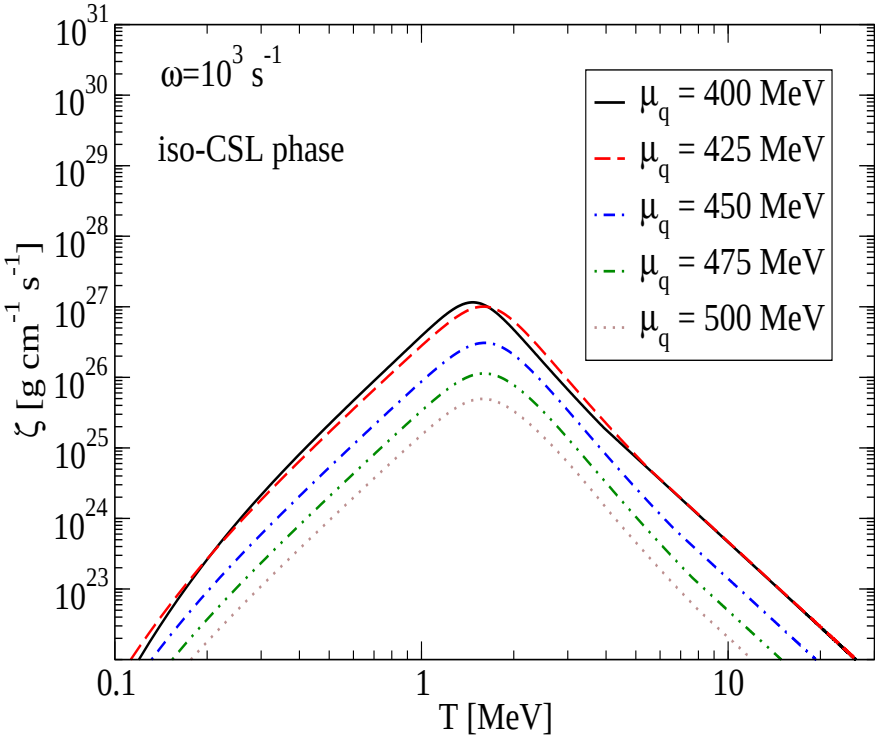
Bulk viscosity:



D.B., J. Berdermann, arXiv:0710.5243 [hep-ph].

$$\zeta = \frac{\lambda C_t^2}{\omega^2 + (\lambda B/n)^2} \tag{1}$$

with $C_t = C + C'$ and the coeffi cients functions

$$\begin{aligned} C &= \frac{M_u^2}{3\mu_u} - \frac{M_d^2}{3\mu_d}, \\ C' &= \frac{4\alpha_s}{3\pi}\left[\frac{M_d^2}{\mu_d}\left(\ln\frac{2\mu_d}{M_d} - \frac{2}{3}\right) - \frac{M_u^2}{\mu_u}\left(\ln\frac{2\mu_u}{M_u} - \frac{2}{3}\right)\right] \\ B &\simeq \frac{\pi^2}{3} n \left(\frac{1}{\mu_u^2} + \frac{1}{\mu_d^2} + \frac{1}{\mu_e^2}\right). \end{aligned} \tag{2}$$

$$\lambda = \frac{3}{2}\frac{\epsilon_0}{T^2} G_1(\Delta_u, \Delta_d) ,$$

Bulk viscosity must be large enough to avoid r-mode instabilities in the protoneutron star evolution!

N. Andersson, ApJ.502, 708 (1998)
A. Drago et al., arXiv:0704.1510 [astro-ph]

Conclusions

Constraints on the high-density EoS

- Compact star masses $\sim 2\ M_\odot$ require stiff EoS
- Flow data provide upper limits on the stiffness

Local charge neutrality: 2SC + DBHF hybrid

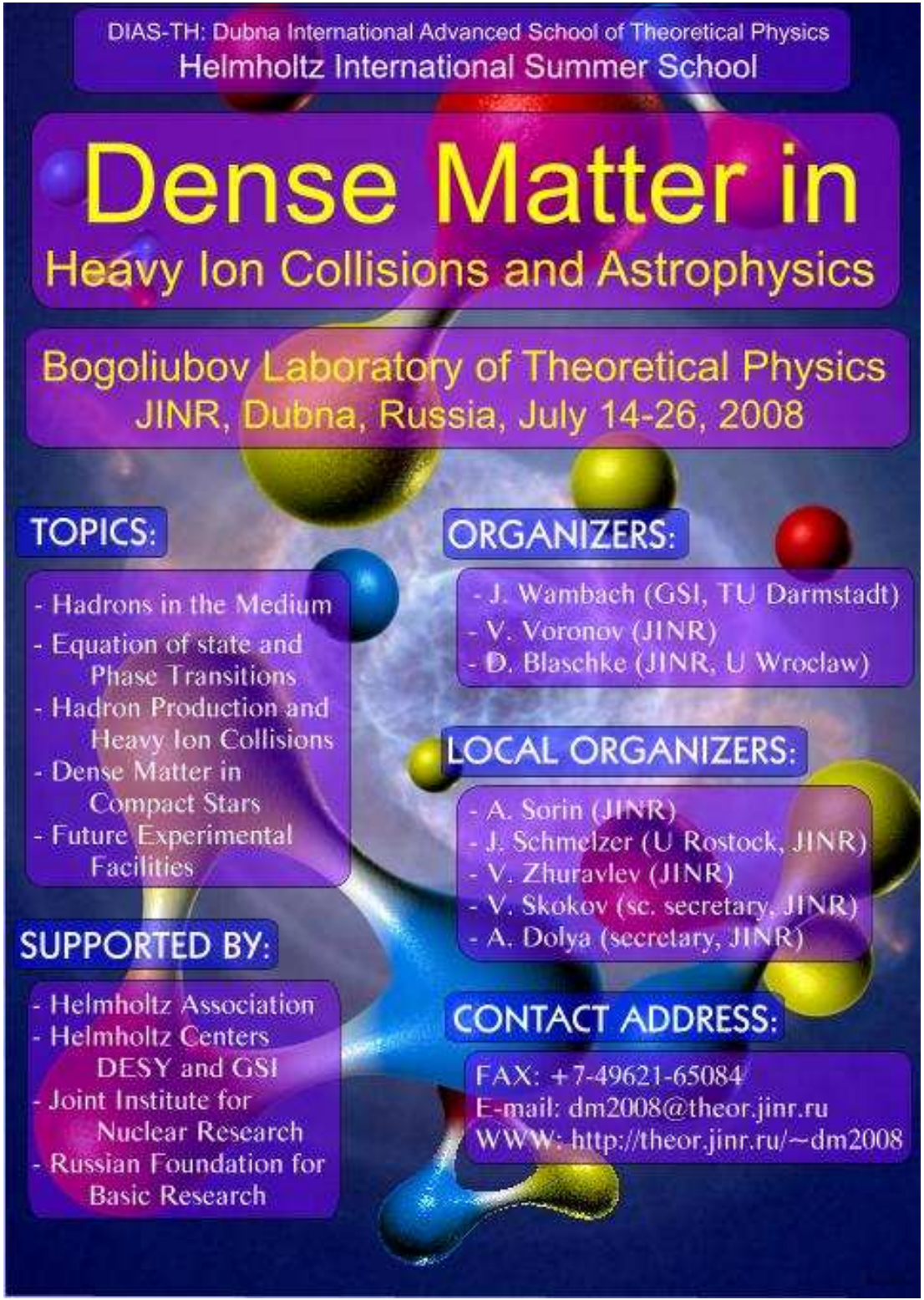
- diquark couling lowers phase transition density
- vector meanfi eld stiffens quark matter EoS

Global charge neutrality: d-CSL + DBHF hybrid

- single flavor phase (d-CSL) as consequence of dynamical χSR
- no d-CSL in symmetric matter: $x_{p,crit} < 0.2$
- no Urca cooling processes $\rightarrow$ no neutrino trapping?

Next steps

- Inhomogeneous phases: surface tension and Coulomb effects
- Study effects on high-mass supernova simulations!



Invitations

Helmholtz International Summer School
"Dense Matter in Heavy-Ion Collisions and Astrophysics",
Dubna, Russia, July 14-26, 2008
http://theor.jinr.ru/∼dm2008

ESF Research Networking Programme
"CompStar" (2008-2013)
http://www.esf.org/compstar