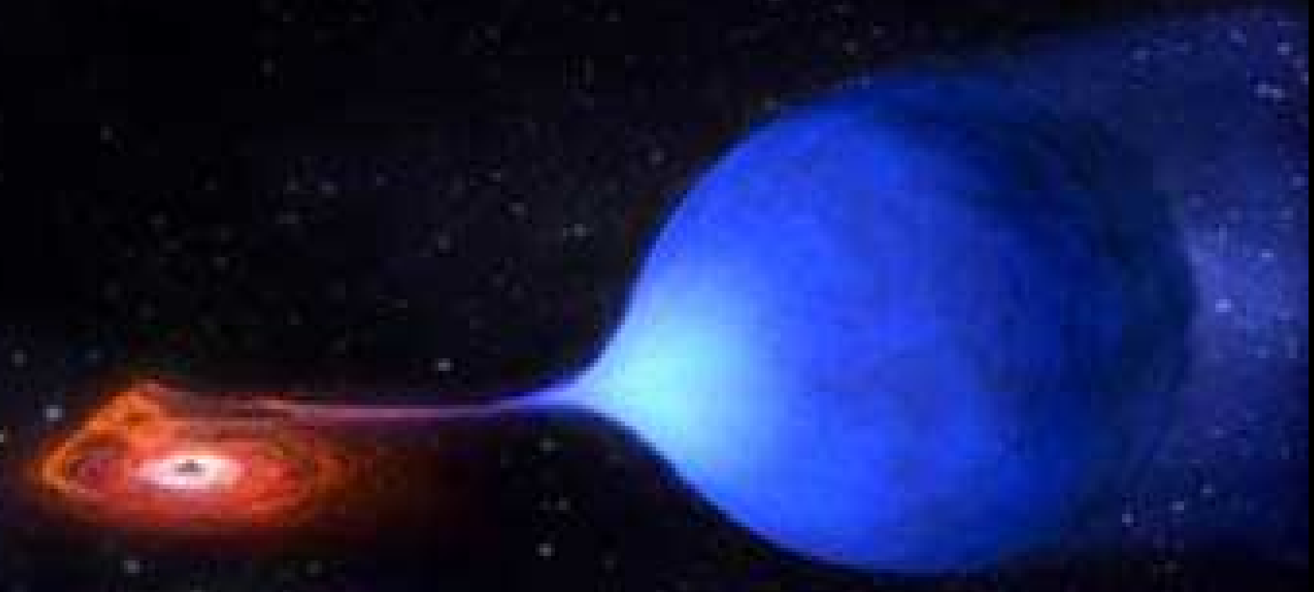
Color superconducting quark matter in compact stars

David Blaschke
Univ. Wroclaw & JINR Dubna



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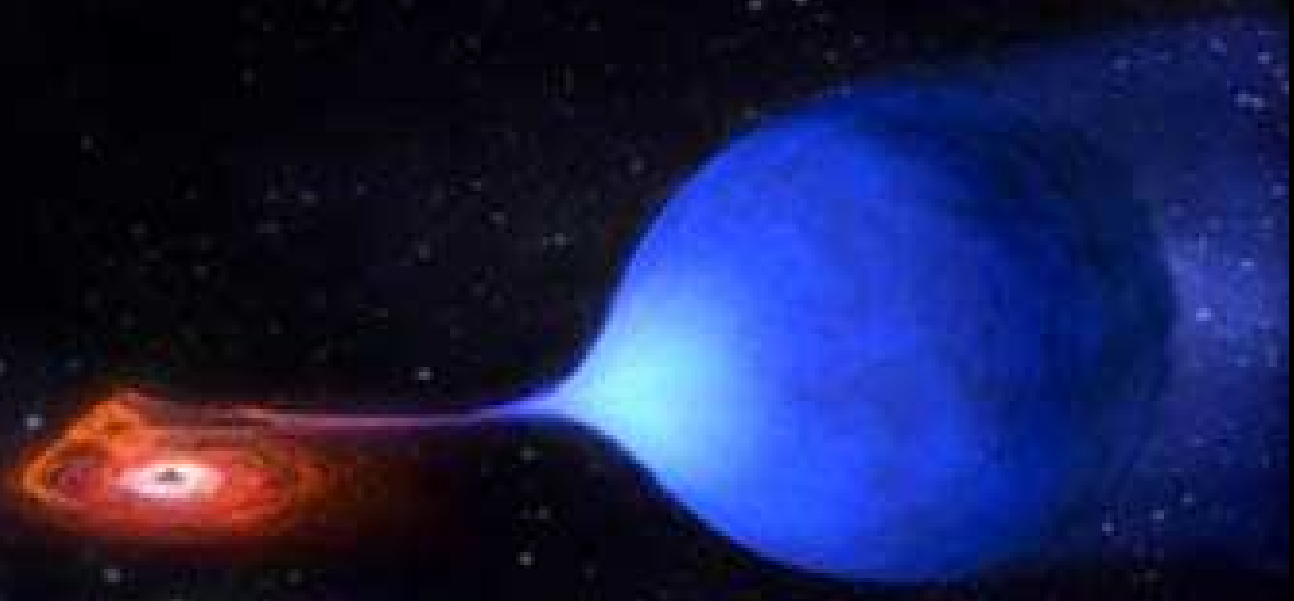
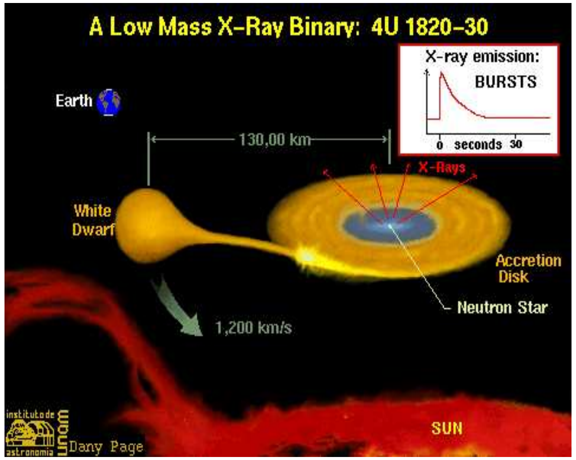


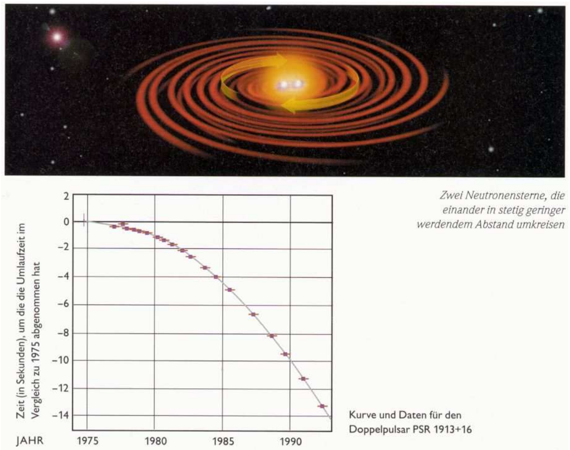
- Mass and Flow constraint on high-density EoS
- Local charge neutrality
  $\longrightarrow$ 2SC + DBHF hybrid stars
- Global charge neutrality
  $\longrightarrow$ d-CSL + DBHF hybrid stars

Masses of binaries

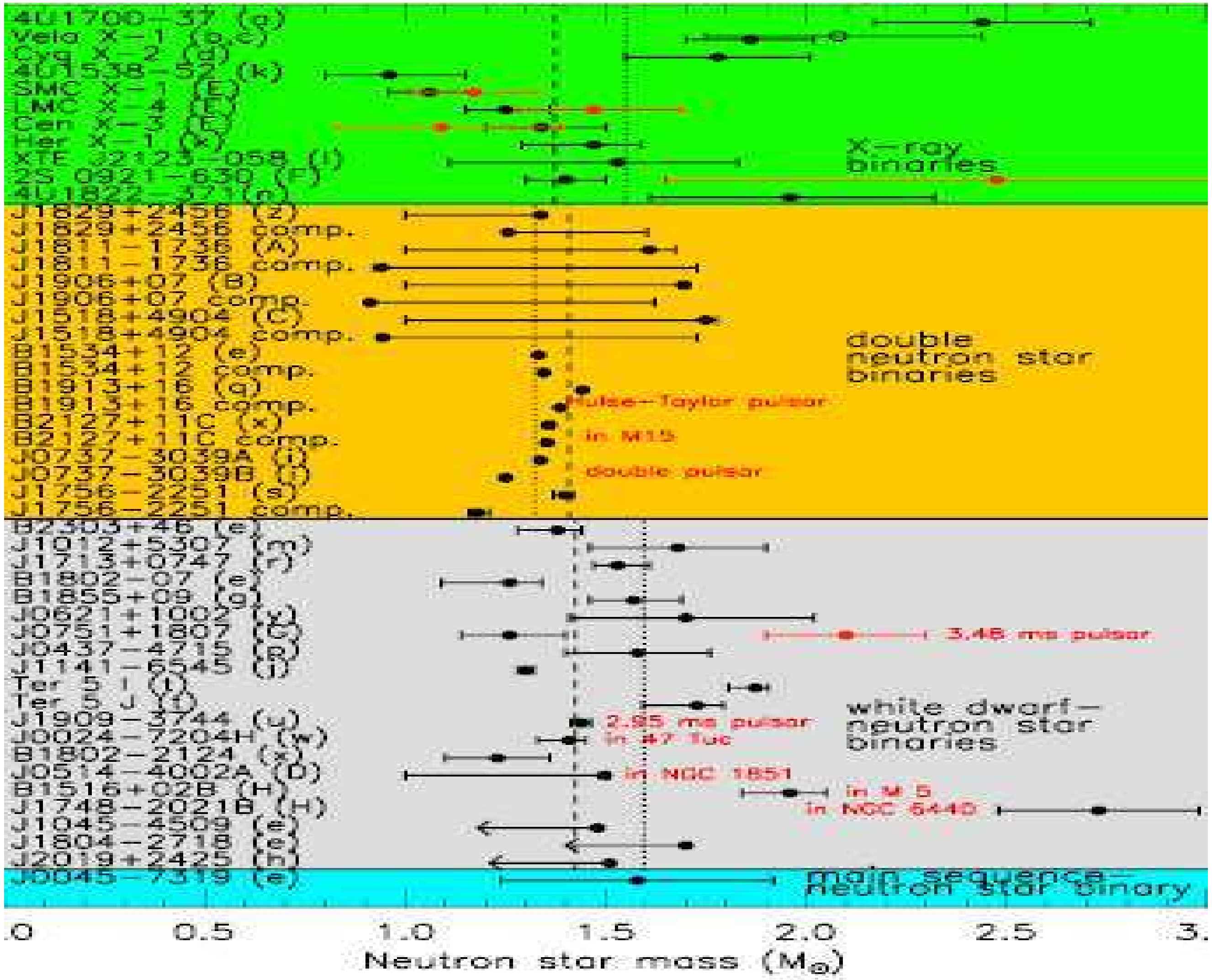
'Young' binary system:



'Old' binary system



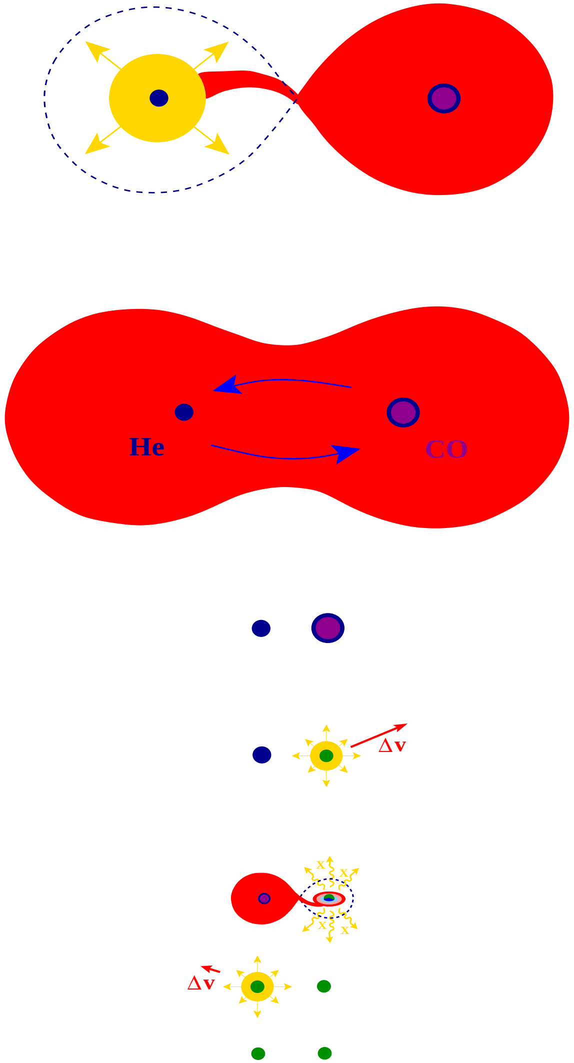
Masses of Neutron Stars in binaries - clustering vs. maximum



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

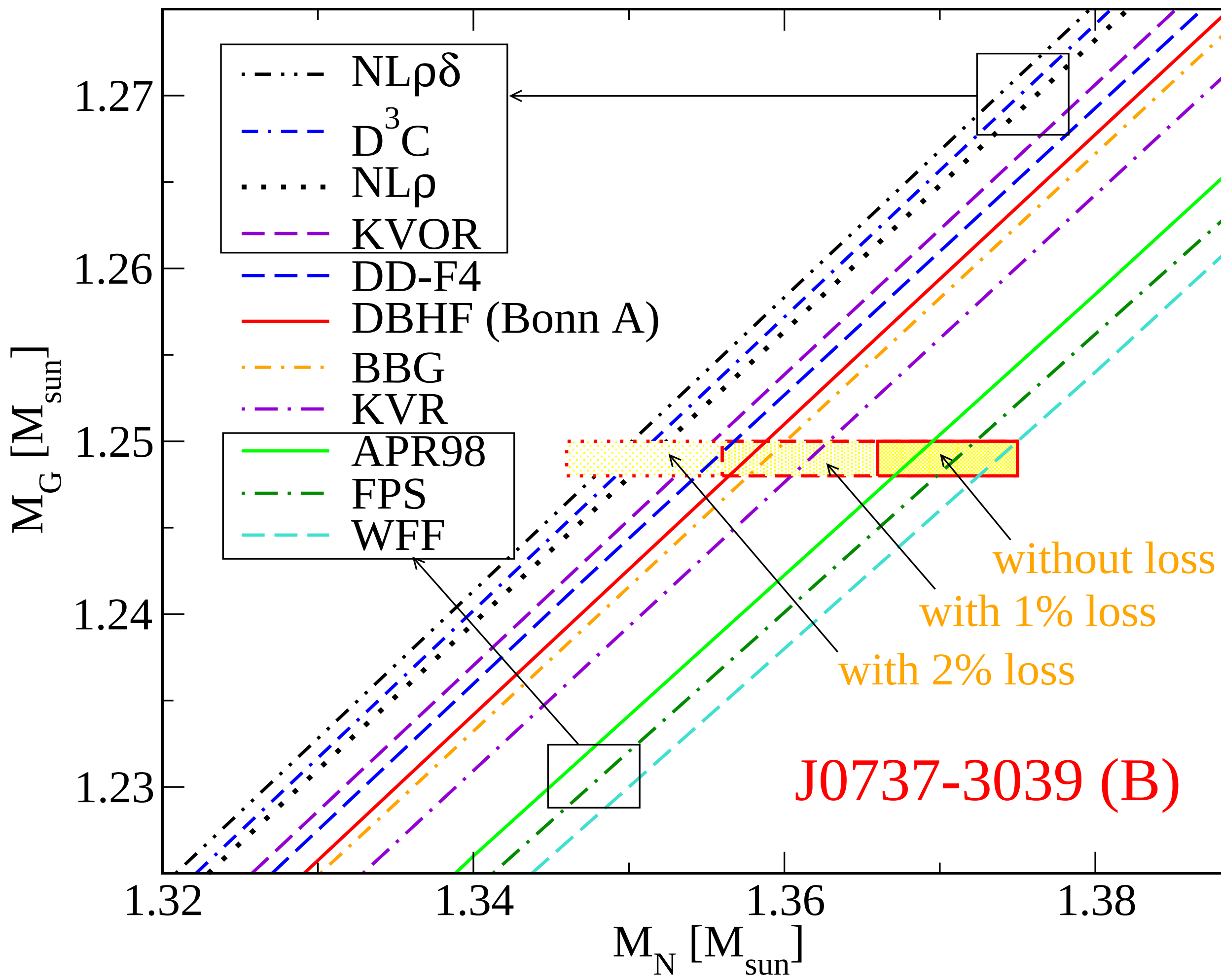
EoS constraint from double pulsar J0737-3039?

Double core scenario:



Dewi et al., MNRAS (2006)

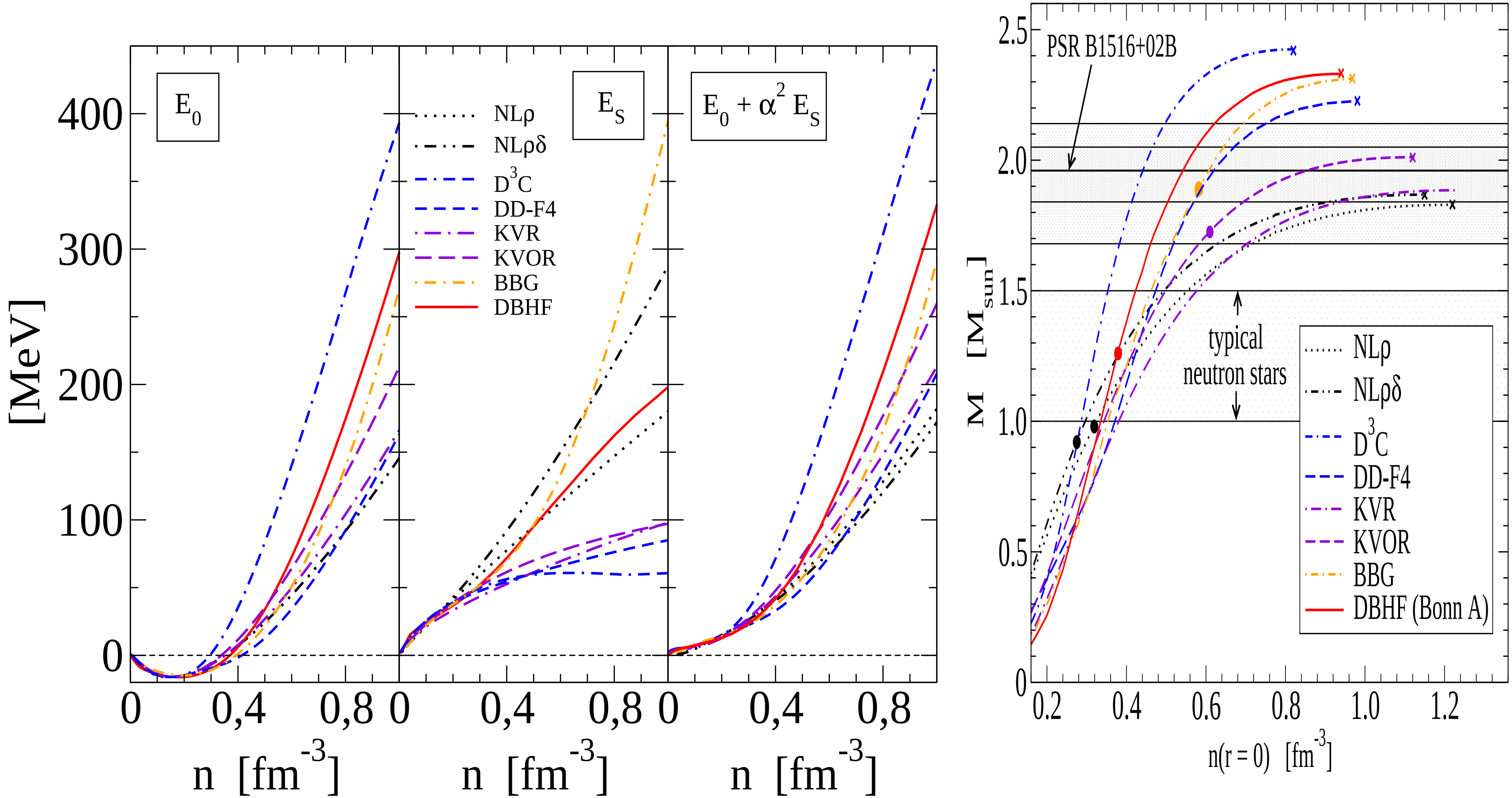
Baryon mass vs. gravitational mass - constraint or consistency?



Podsiadlowski et al., MNRAS 361 (2005) 1243

D.B., T. Klähn, F. Weber, CBM Physics Book (2008)

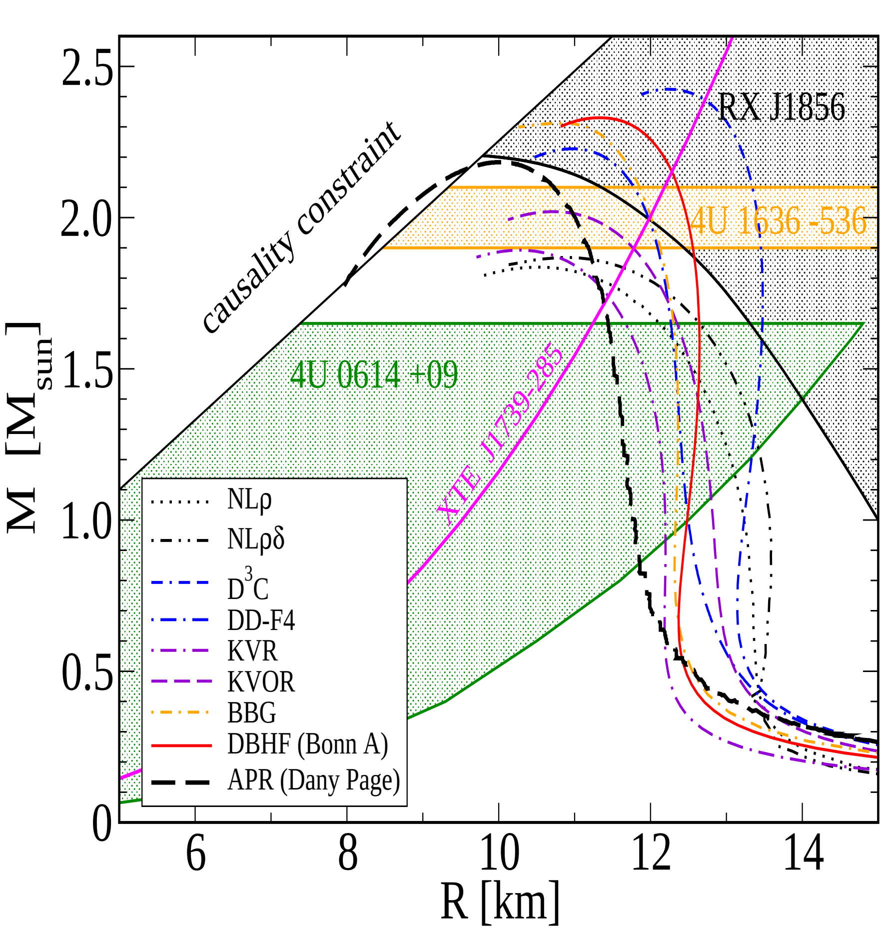
EoS and masses - DU constraint

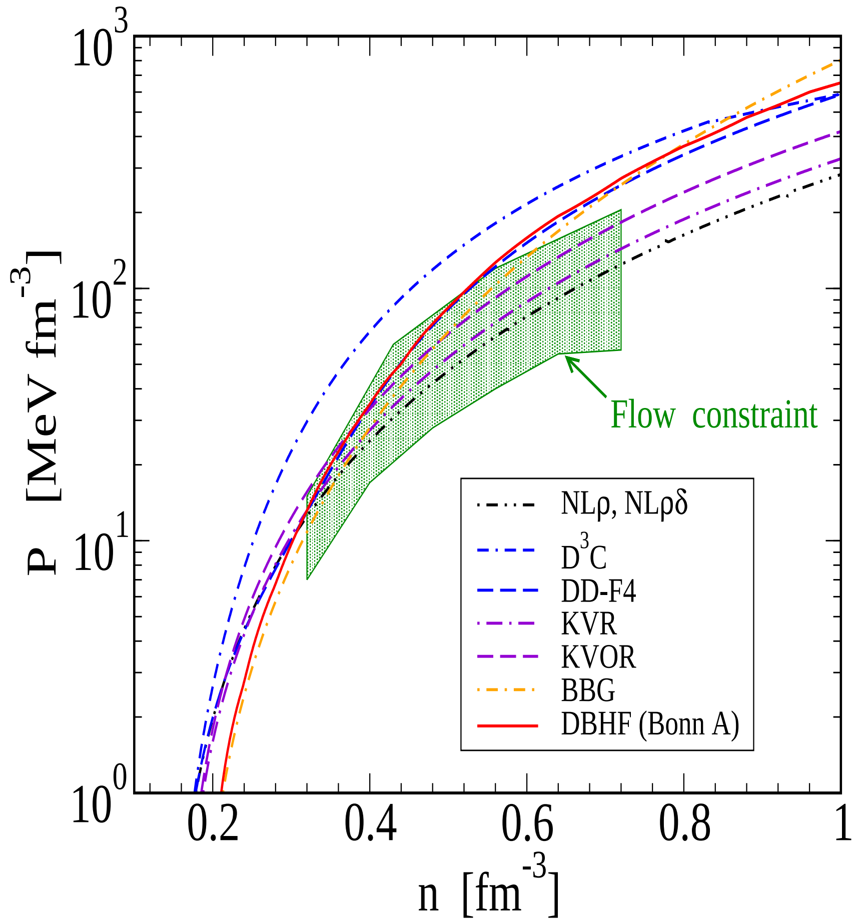


DU threshold for most hadronic EoS active in neutron stars with typical masses !

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

Mass-Radius constraint and Flow constraint

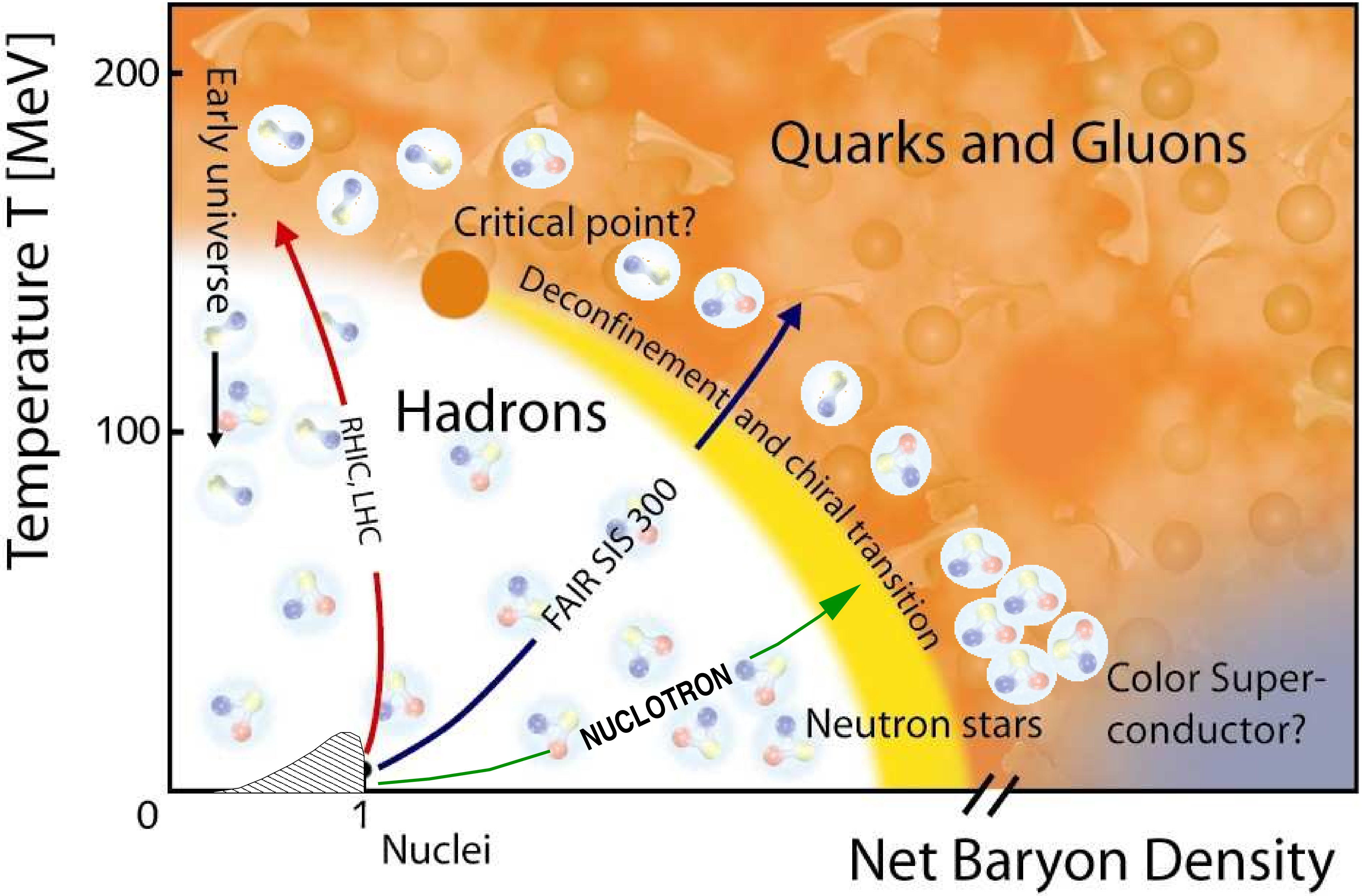




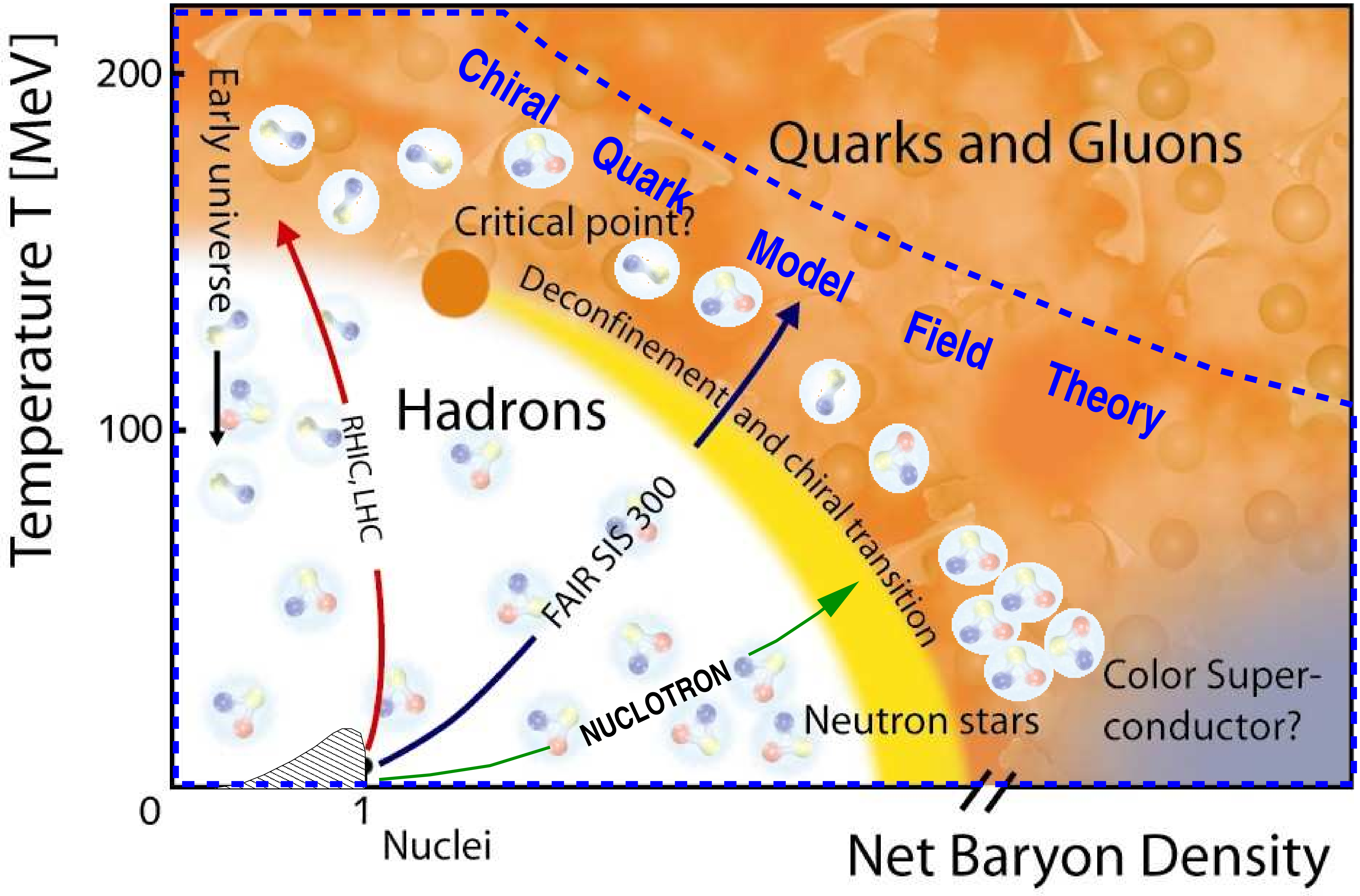
- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !

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

Quark Substructure and Phase Diagram



Phase diagram of QCD: Chiral quark models



Quantum Field Theory for chiral Quark Matter

- 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)

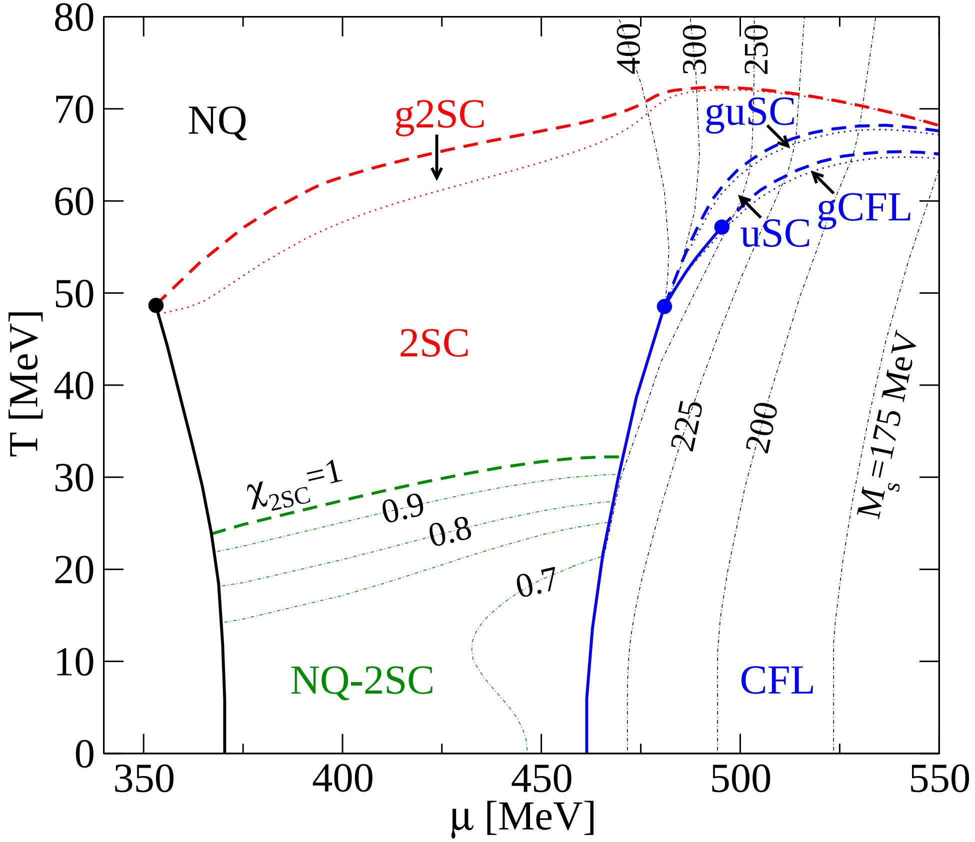
$$\mathcal{L}_{\rm int} = \sum_{M=\pi,\sigma,\dots} G_M(\bar{\psi}\Gamma_M\psi)^2 + \sum_D G_D(\bar{\psi}^C\Gamma_D\psi)^2$$

- Bosonisation (Hubbard-Stratonovich Transformation)

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

- 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



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

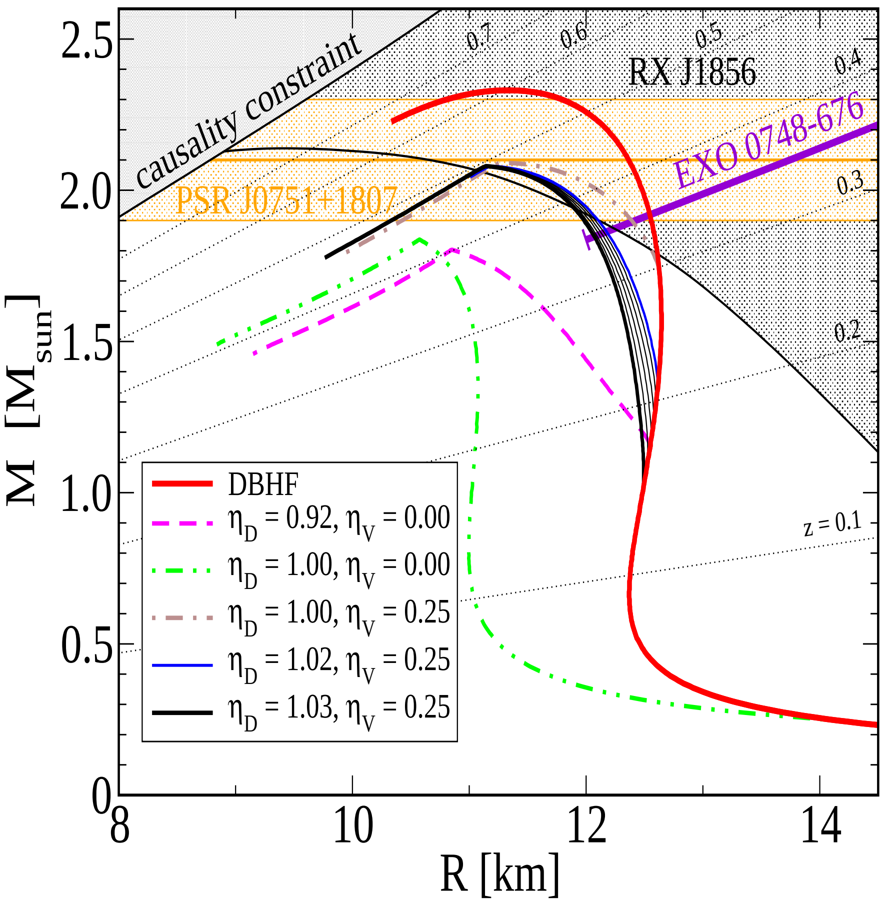
The phases are:

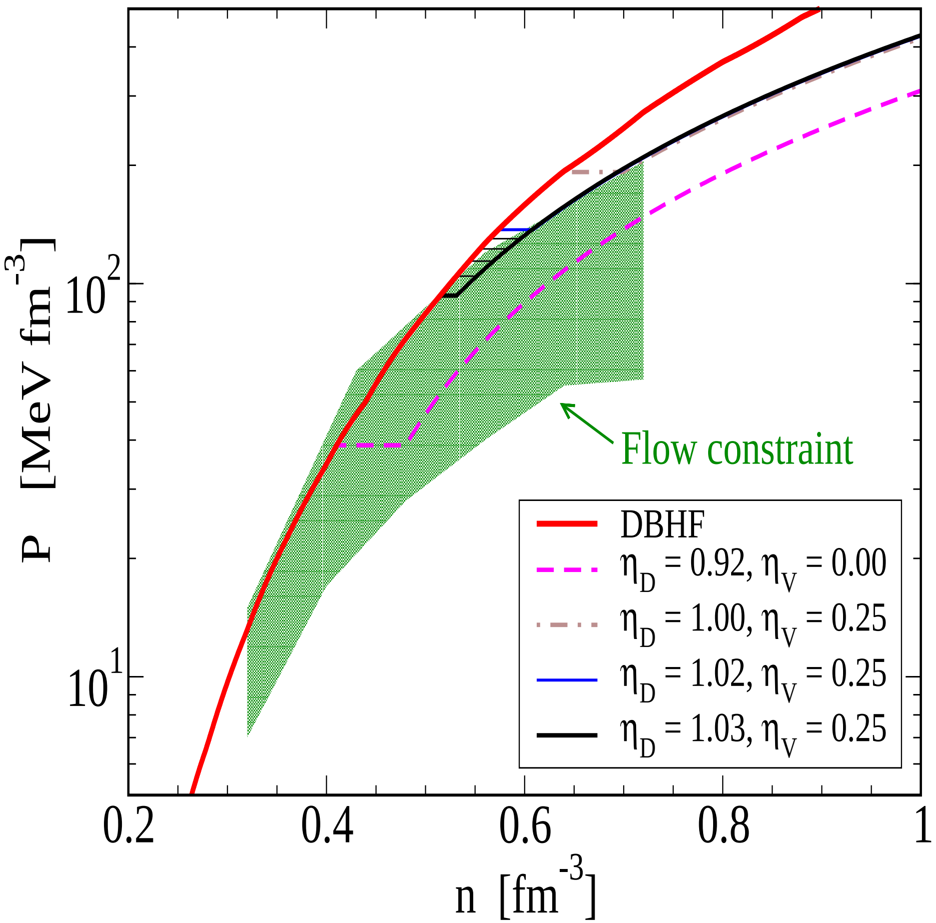
- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$, $0 \leq \chi_{2SC} \leq 1$;
- 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq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

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)

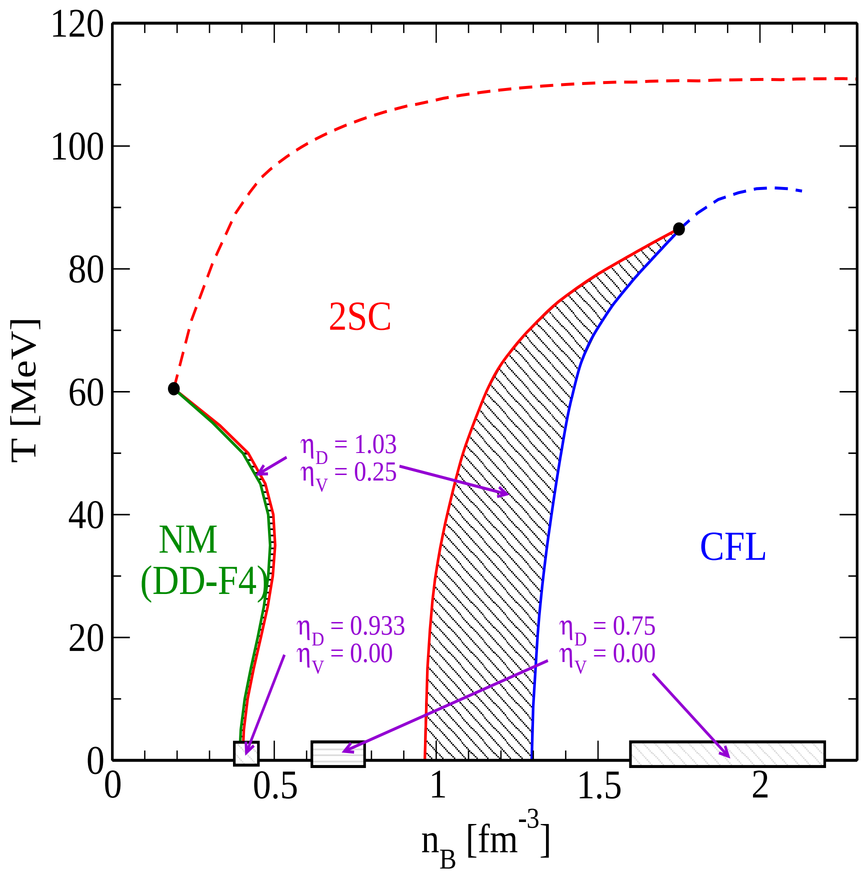


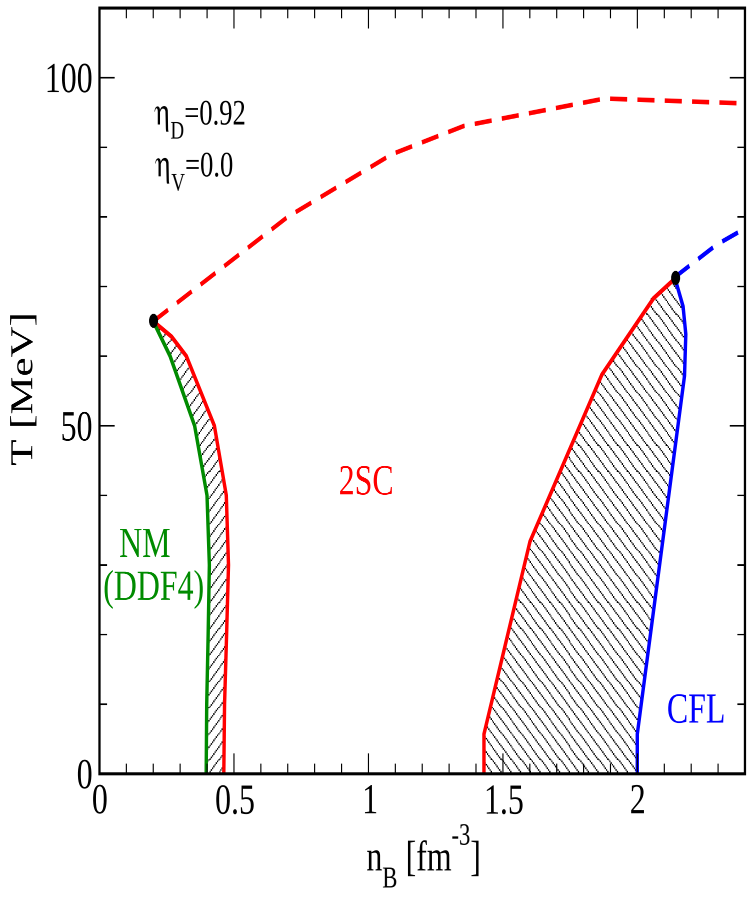


- Large Mass ($\sim 2\,M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff quark matter EoS;
  Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !
  Note: Quark matter removes violation by DBHF at high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

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

Phase diagrams for the CBM experiment

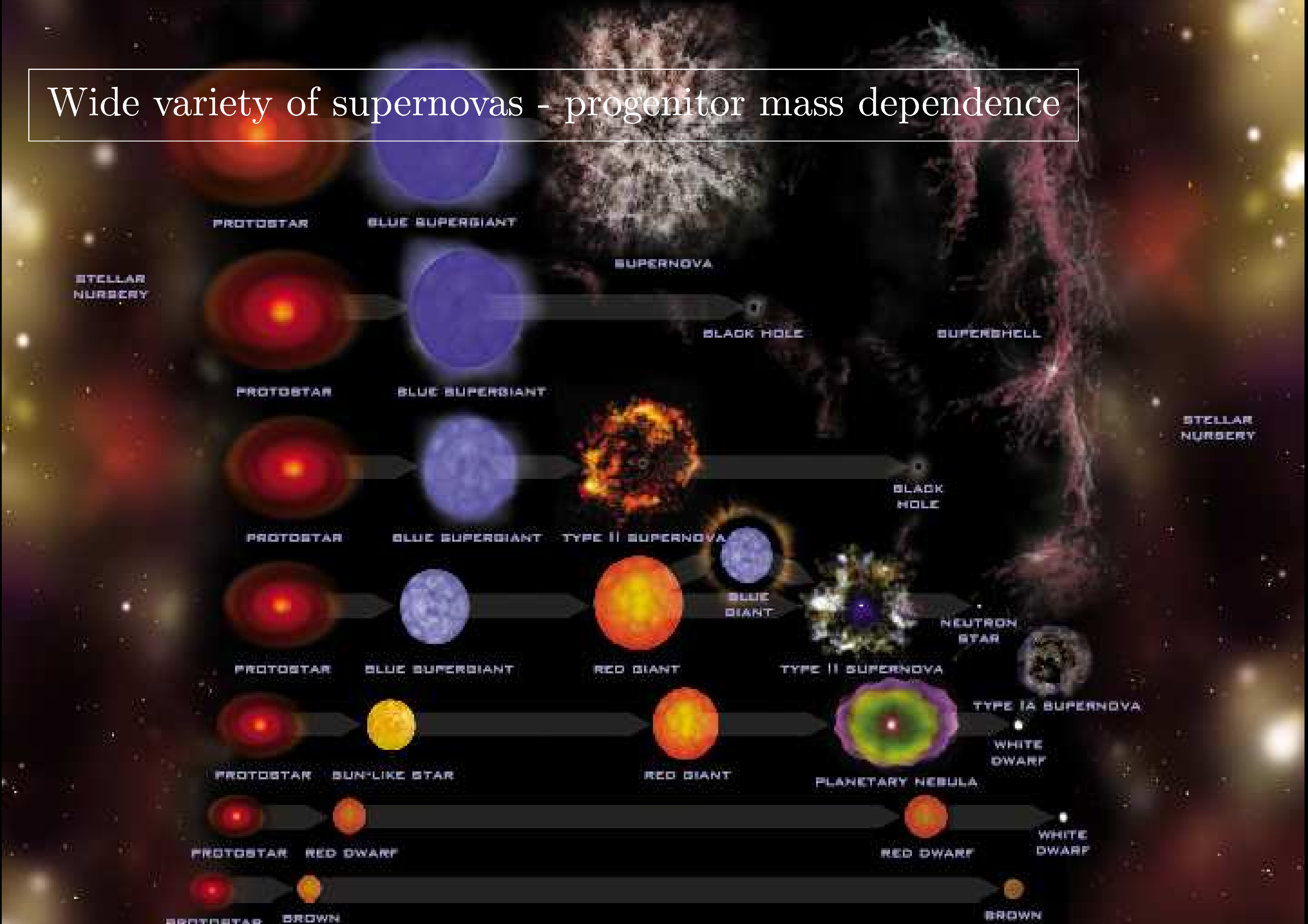




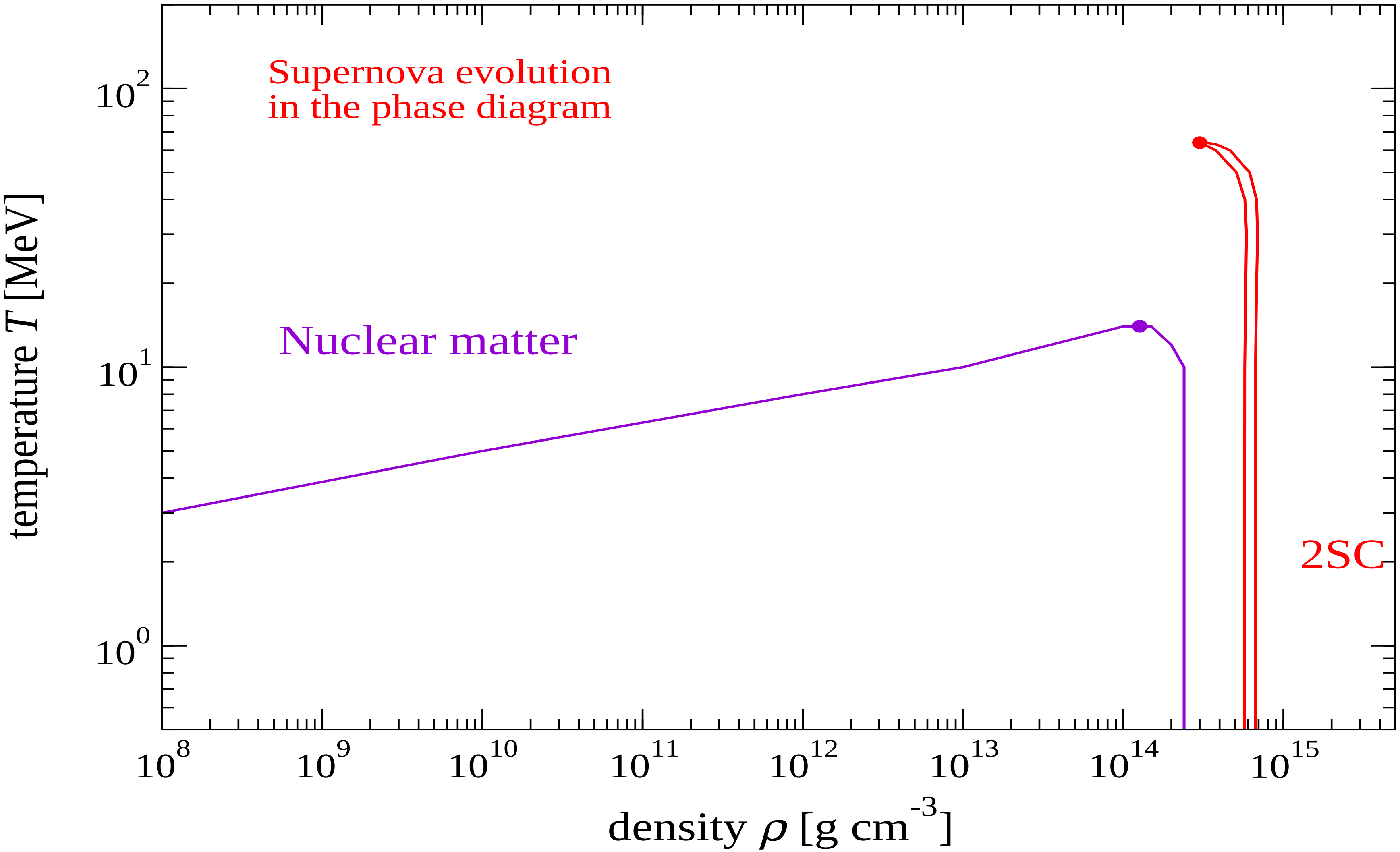
Phase diagrams for isospin-symmetric matter, for hybrid star maximum mass $M_{max} = 2.1\ M_\odot$ (left-hand side) and $M_{max} = 1.7\ M_\odot$ (right-hand side).

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

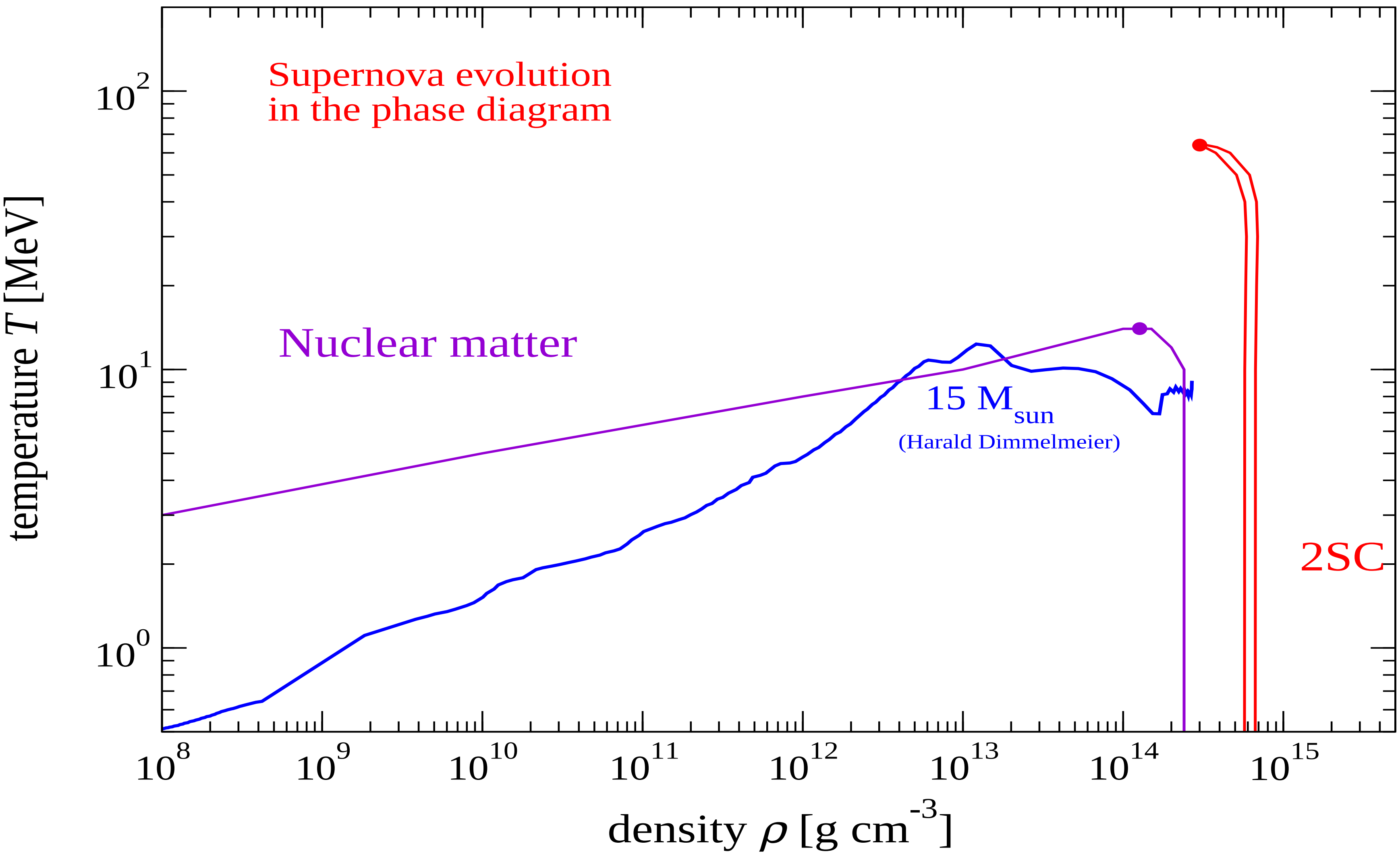
Wide variety of supernovas - progenitor mass dependence



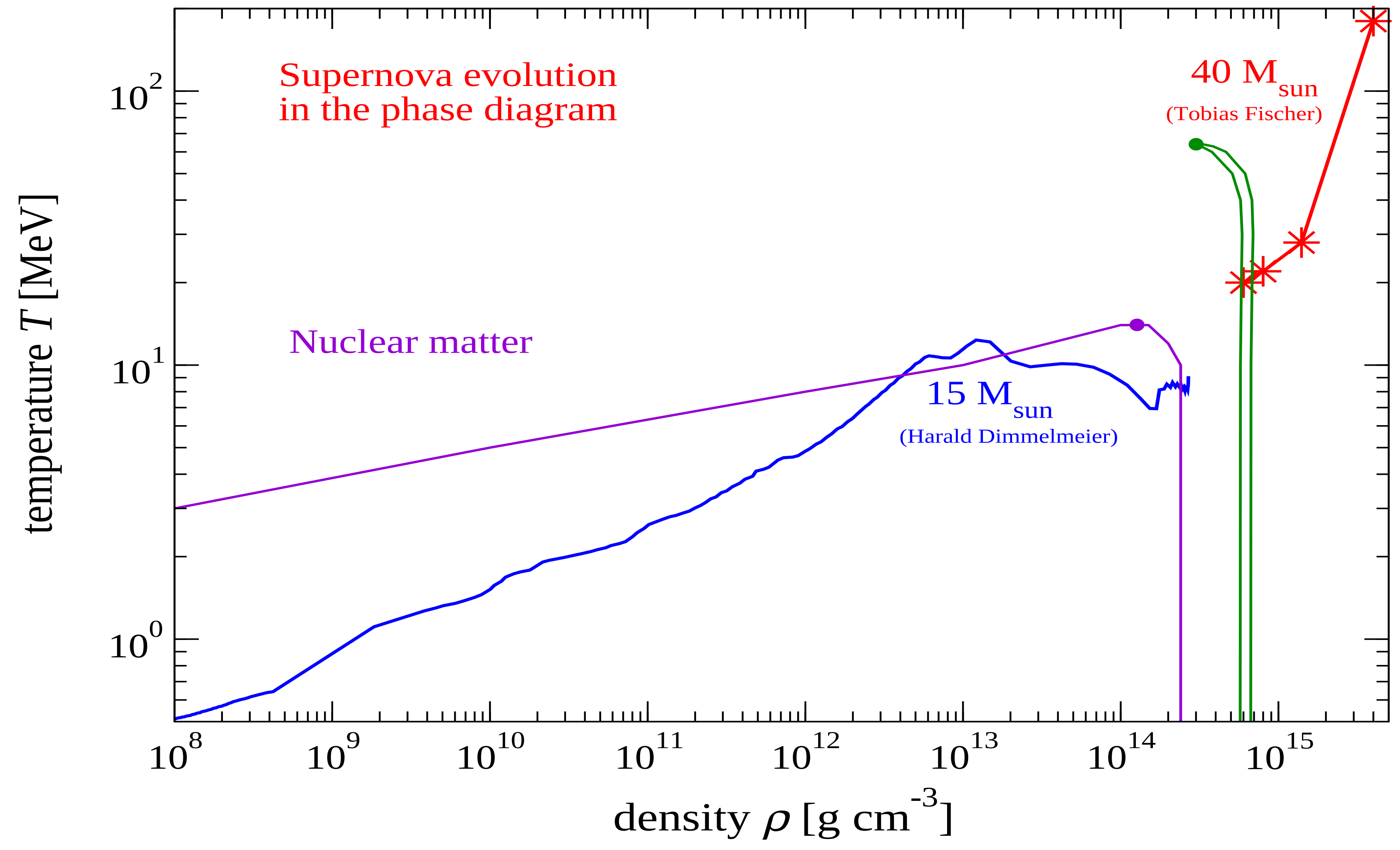
Supernova Collapse in the Phase Diagram



Supernova Collapse in the Phase Diagram (II)

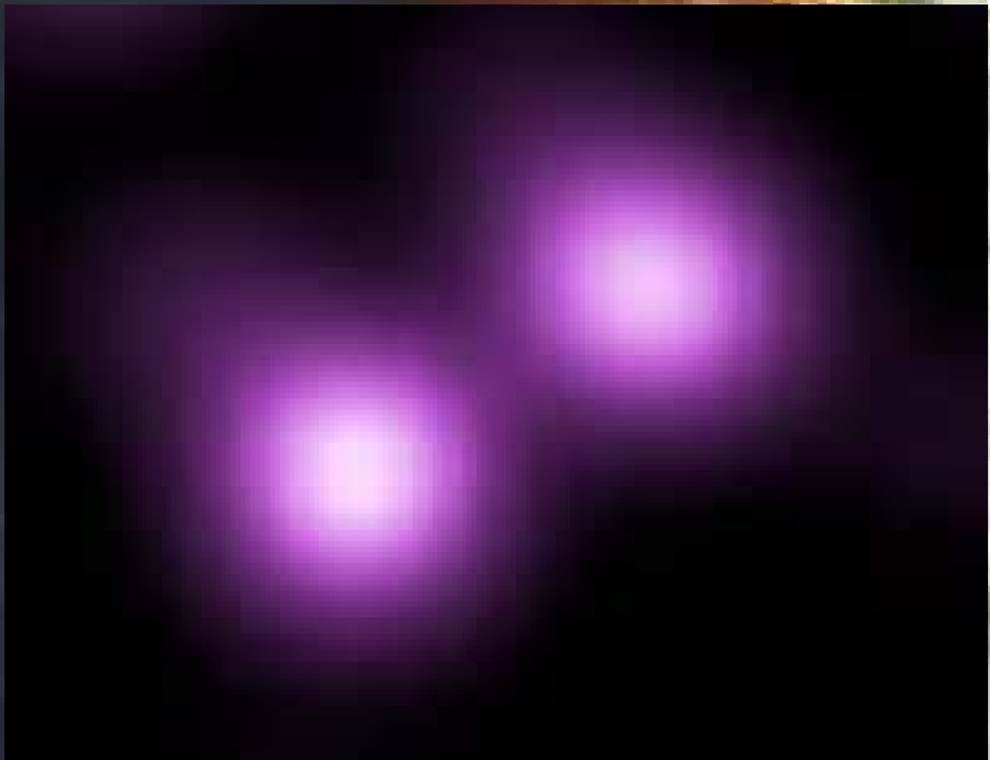


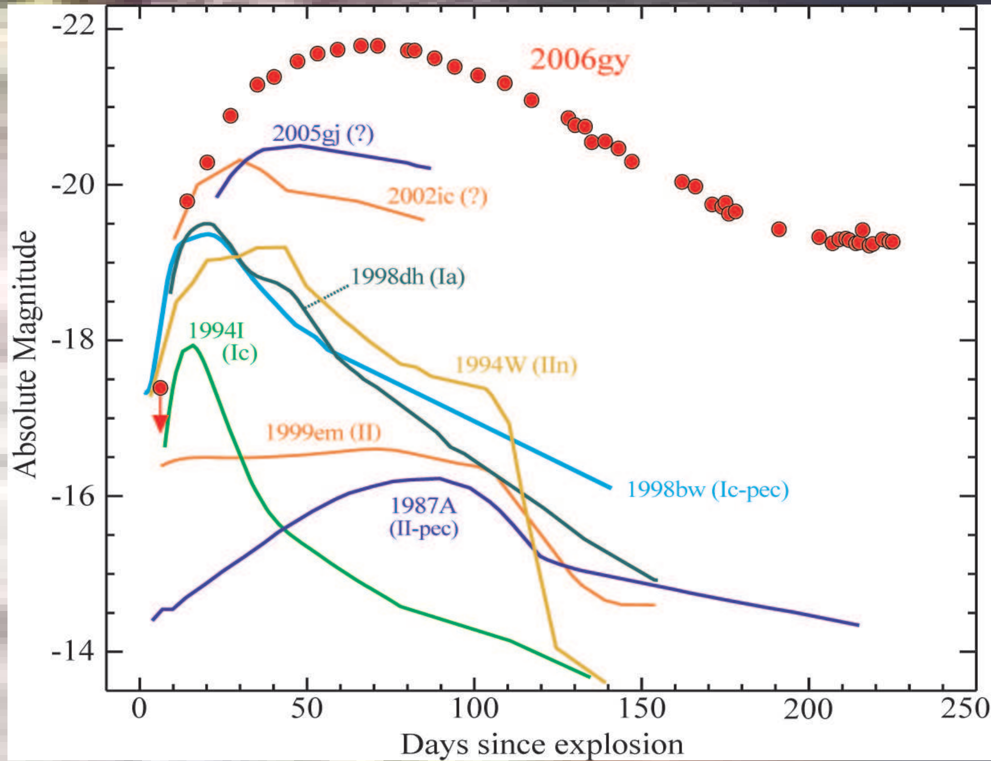
Supernova Collapse in the Phase Diagram



The case of SN2006gy

The case of SN2006gy - a Quarknova ?

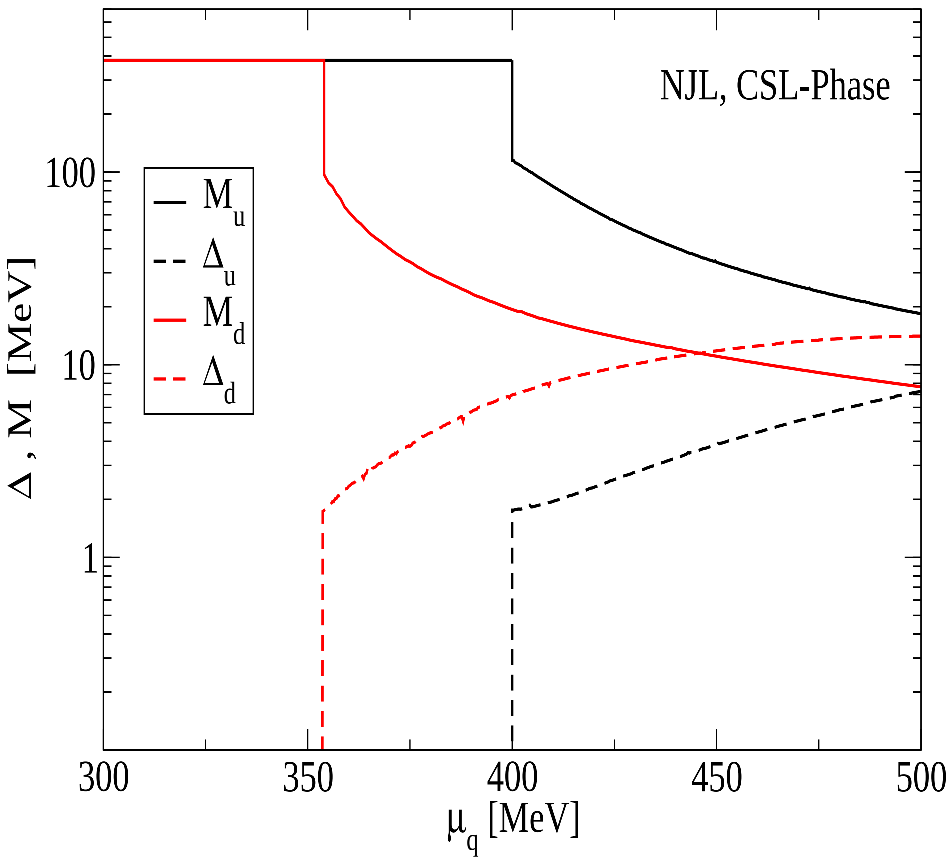




Discovery: Sept. 18, 2006
in NGC 1260 (Perseus)
Distance: 72 Mpc=238 Mill. Ly
(Smith et al.: astro-ph/0612617)

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])

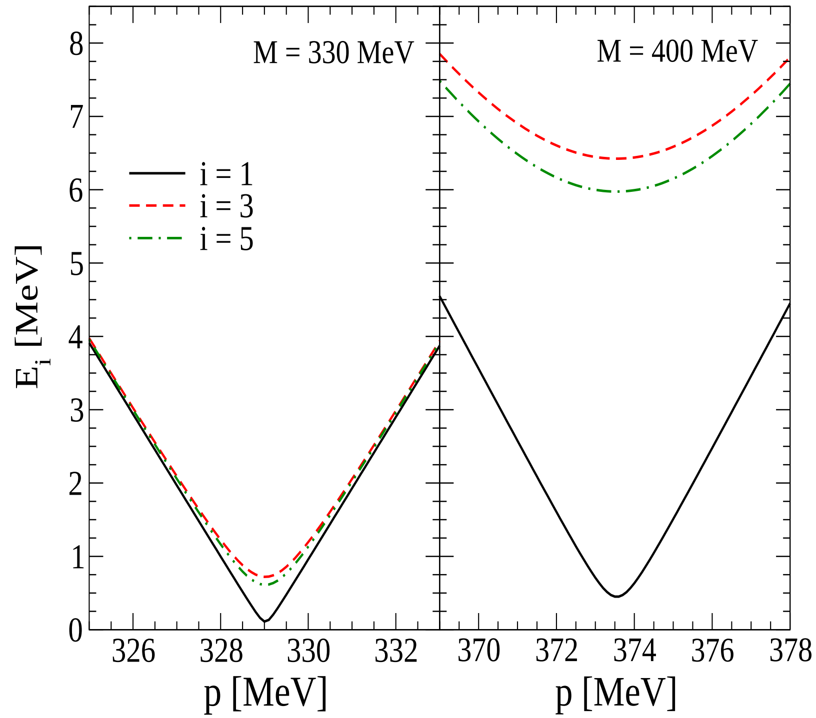
Single flavor (d-CSL) Phase in Compact Stars



Ansatz Color-spin-locking (CSL) gap:

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

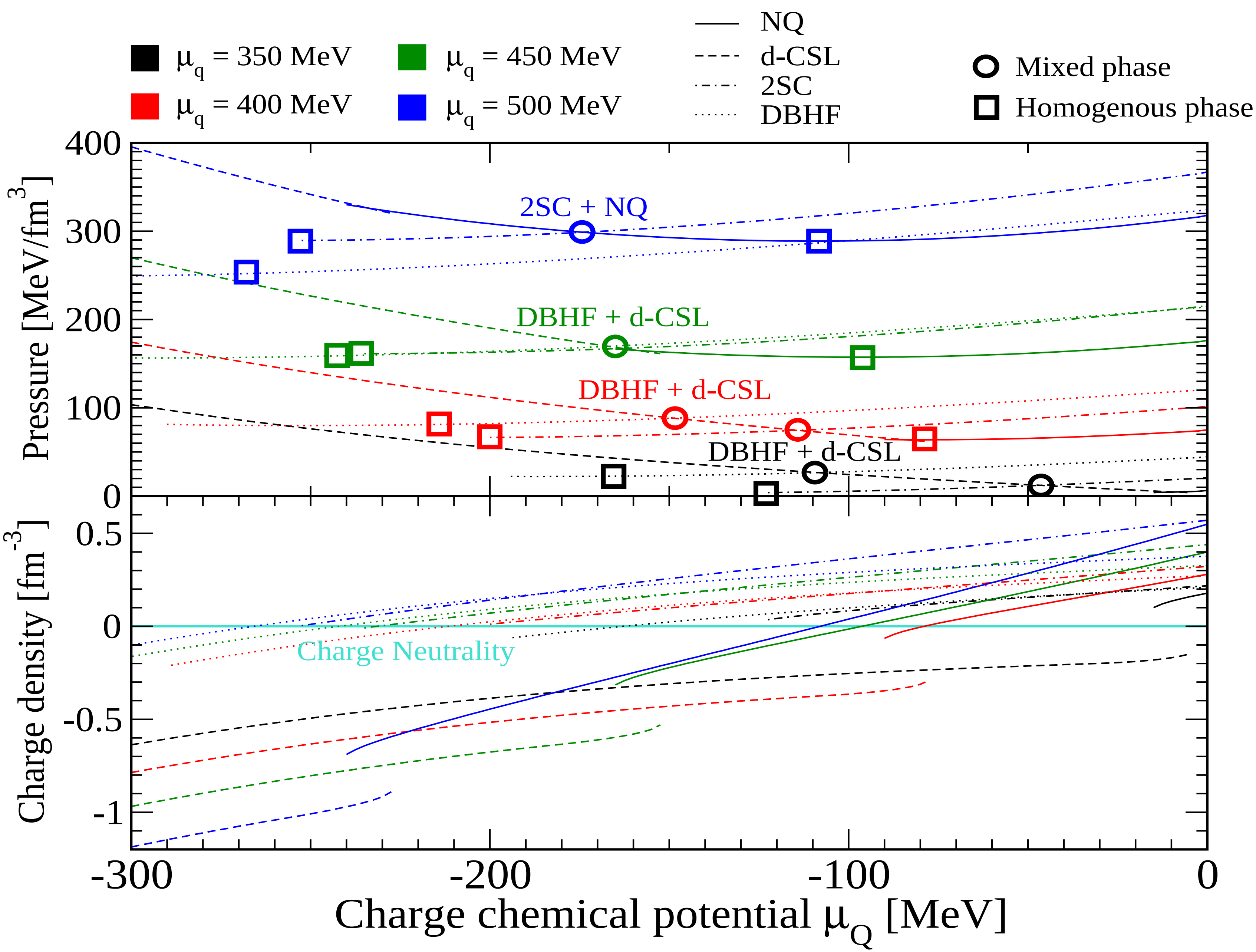
Aguilera et al., PRD 72 (2005) 034008; PRD 74 (2006) 114005



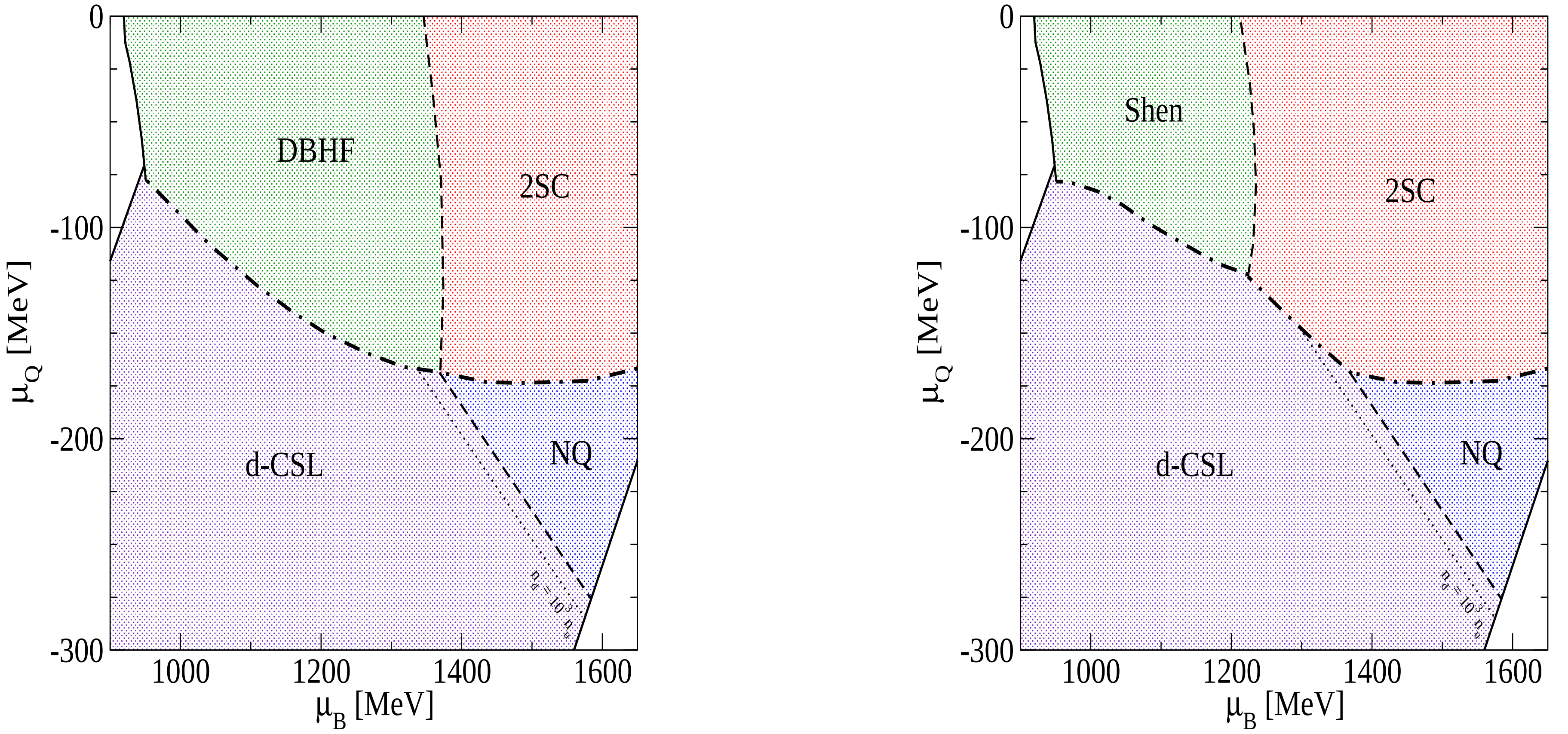
Flavor-asymmetry $-\mu_Q = \mu_e = \mu_d - \mu_u > 0$

$\rightarrow$ **Sequential melting of chiral condensates: d-quark dripline!**

Global charge neutrality: quark-nuclear hybrid



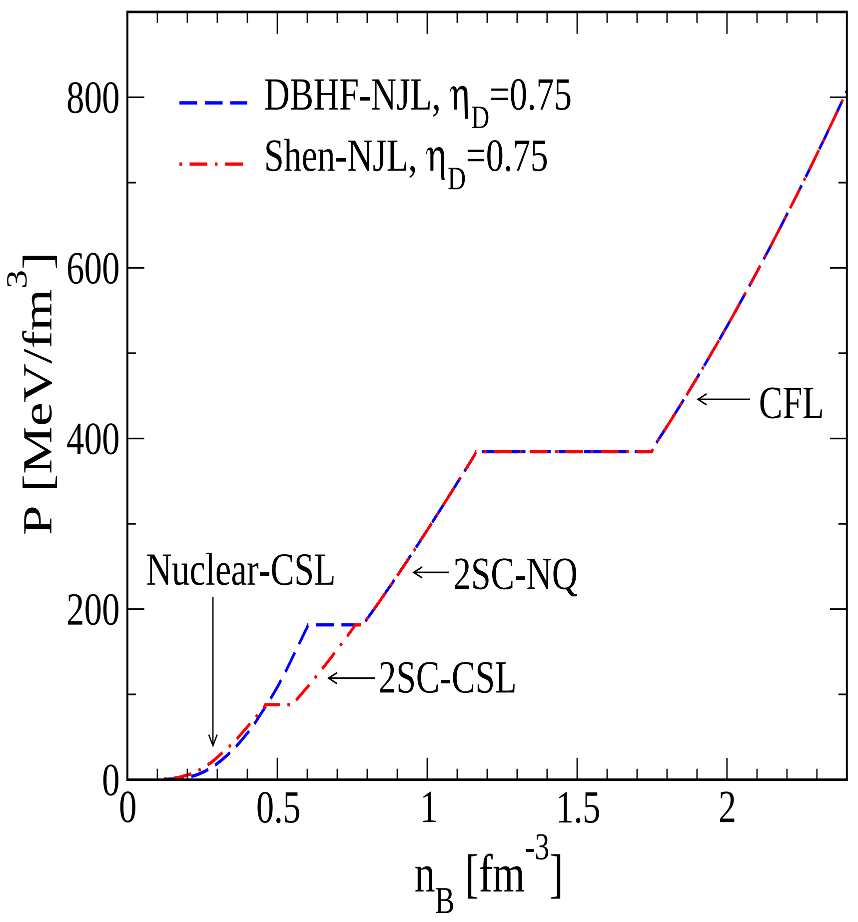
d-CSL: single-flavor phase in competition

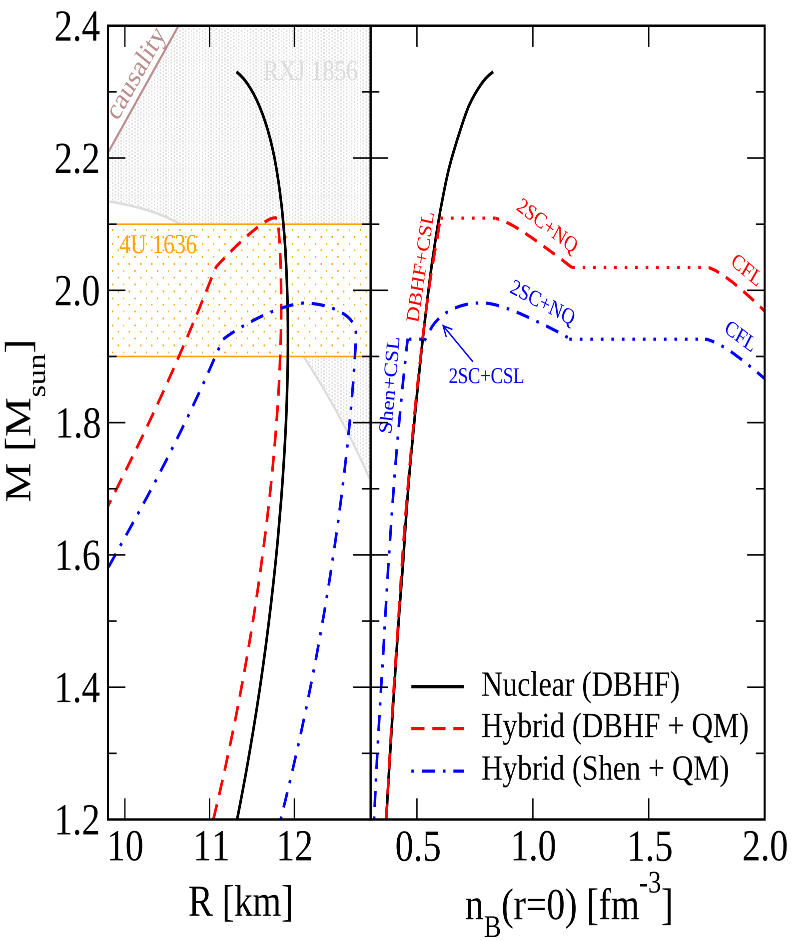


Dash-dotted lines: border between oppositely charged phases

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

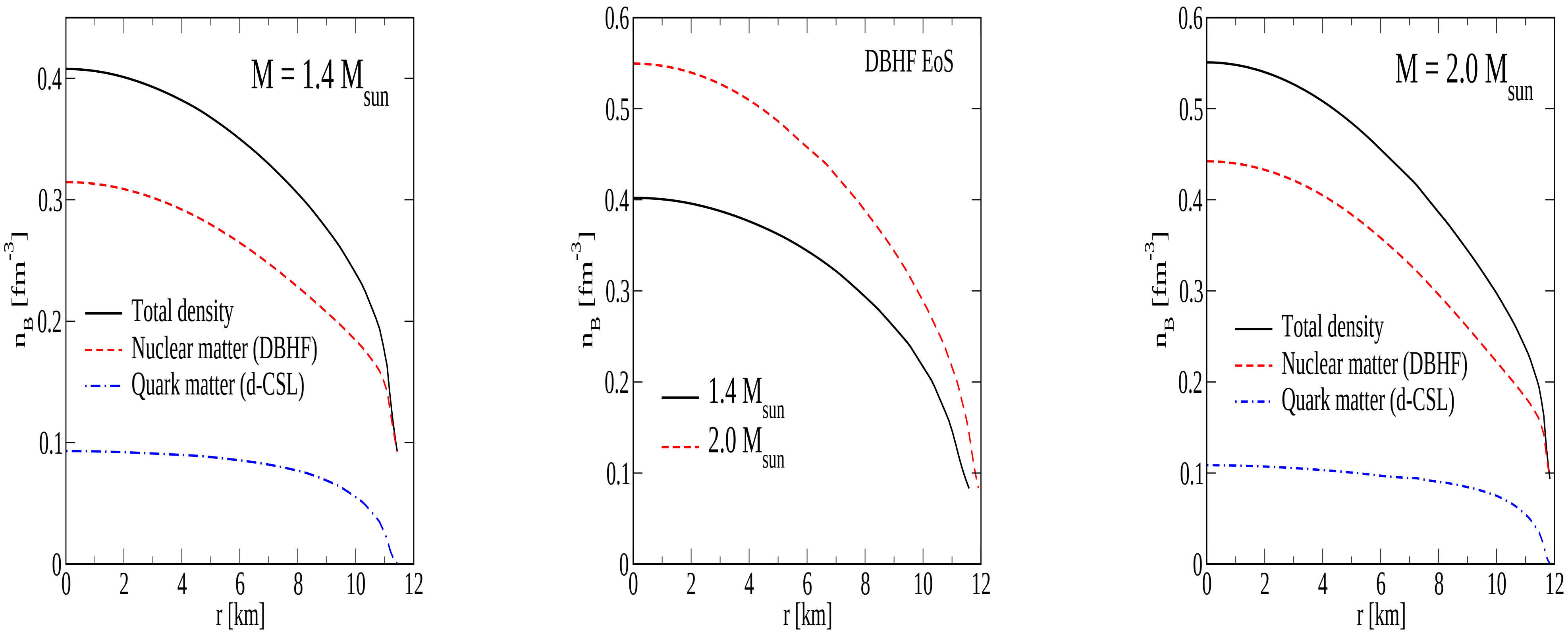
d-CSL: single-flavor phase in neutron stars





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

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

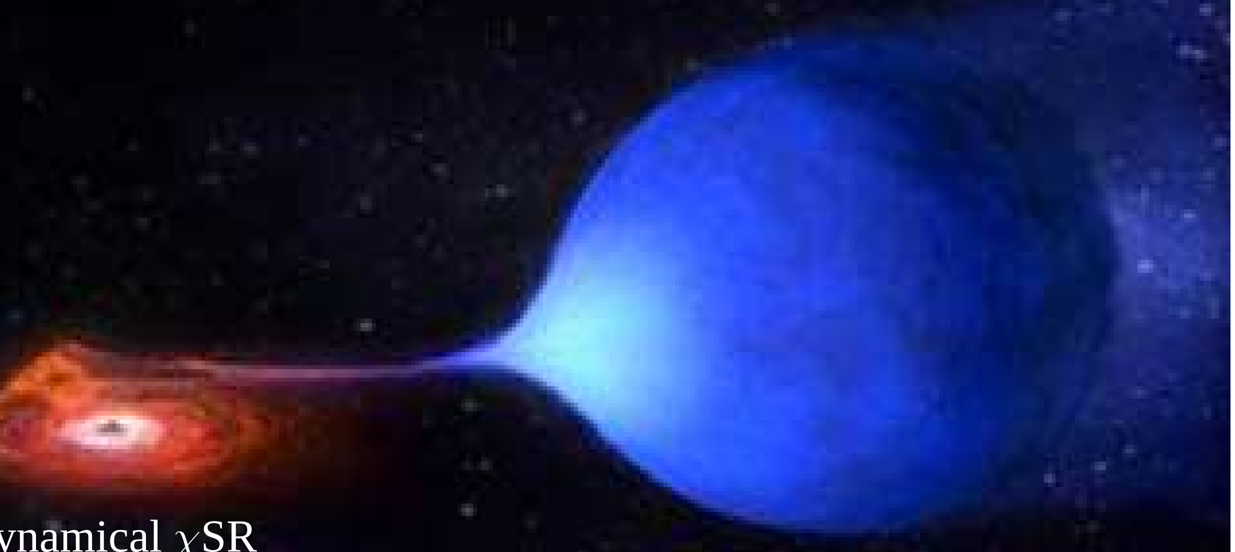


D.B.,F. Sandin, T. Klähn, in preparation.

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

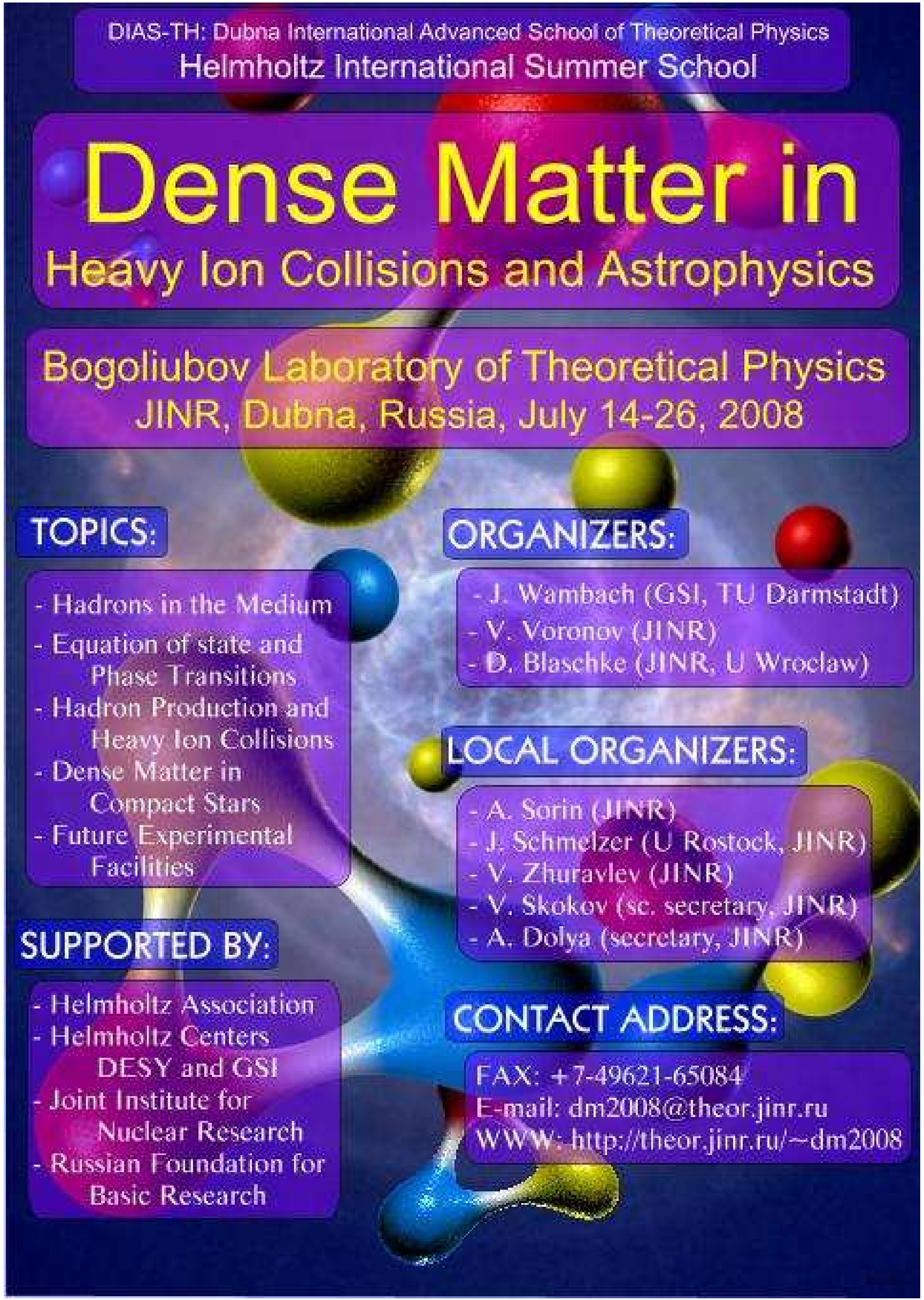
- diquark couling lowers phase transition density
- vector meanfield stiffens quark matter EoS

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 $\longrightarrow$ no neutrino trapping?

Next steps

- Inhomogeneous phases: surface tension and Coulomb effects
- Study effects on high-mass supernova simulations!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Heavy Ion Collisions and Astrophysics
Bogoliubov Laboratory of Theoretical Physics
JINR, Dubna, Russia, July 14-26, 2008
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- Equation of state and Phase Transitions
- Hadron Production and Heavy Ion Collisions
- Dense Matter in Compact Stars
- Future Experimental Facilities
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- V. Voronov (JINR)
- D. Blaschke (JINR, U Wroclaw)
LOCAL ORGANIZERS:
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- J. Schmelzer (U Rostock, JINR)
- V. Zhuravlev (JINR)
- V. Skokov (sc. secretary, JINR)
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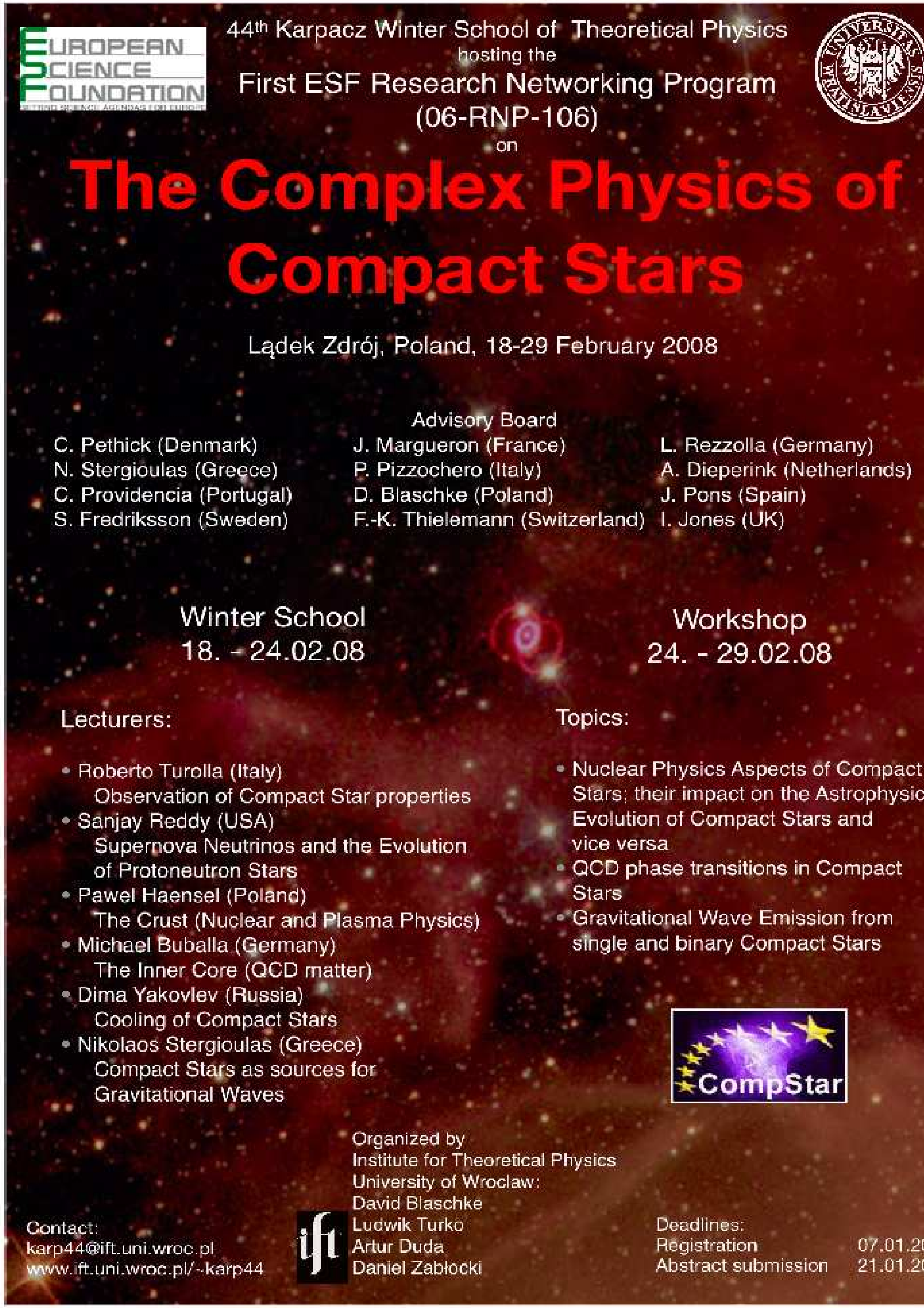
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(06-RNP-106)
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• Pawel Haensel (Poland)
The Crust (Nuclear and Plasma Physics)
• Michael Buballa (Germany)
The Inner Core (QCD matter)
• Dima Yakovlev (Russia)
Cooling of Compact Stars
• Nikolaos Stergioulas (Greece)
Compact Stars as sources for Gravitational Waves
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• QCD phase transitions in Compact Stars
• Gravitational Wave Emission from single and binary Compact Stars
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