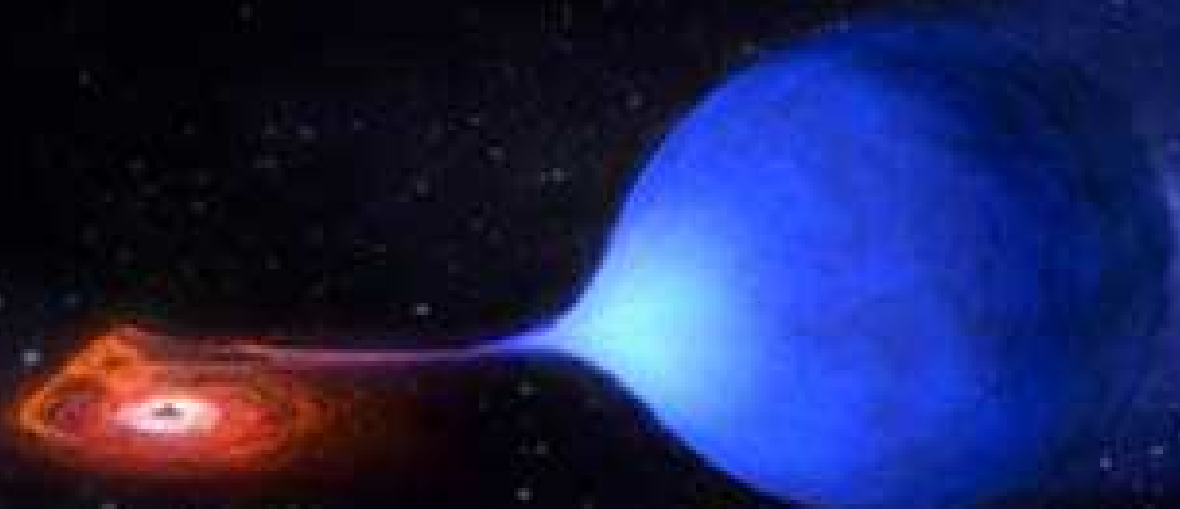


Color Spin Locking in Compact Stars



David Blaschke

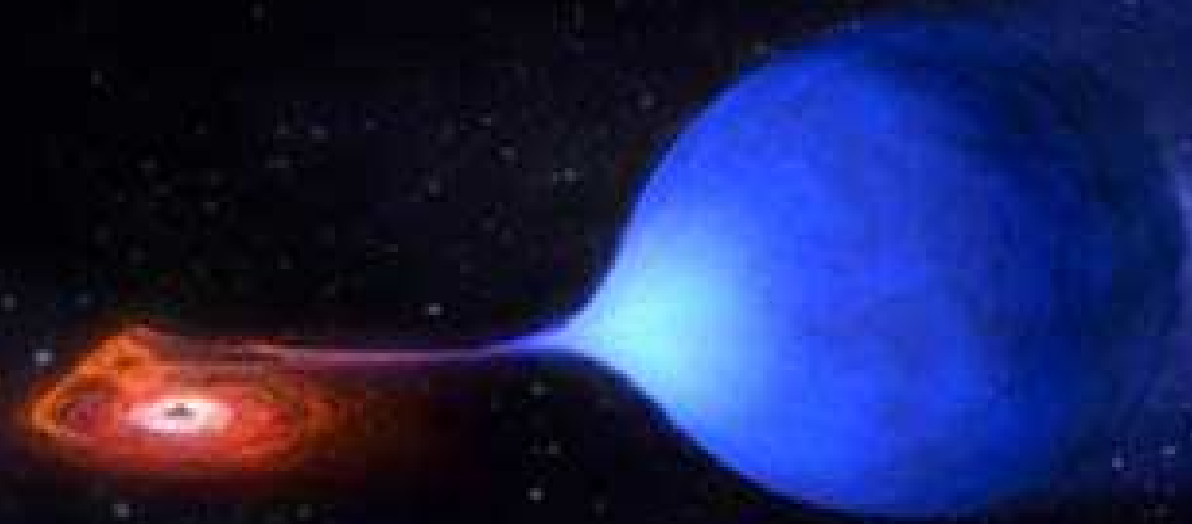
Univ. Wroclaw & JINR Dubna



Color Spin Locking in Compact Stars

David Blaschke

Univ. Wroclaw & JINR Dubna



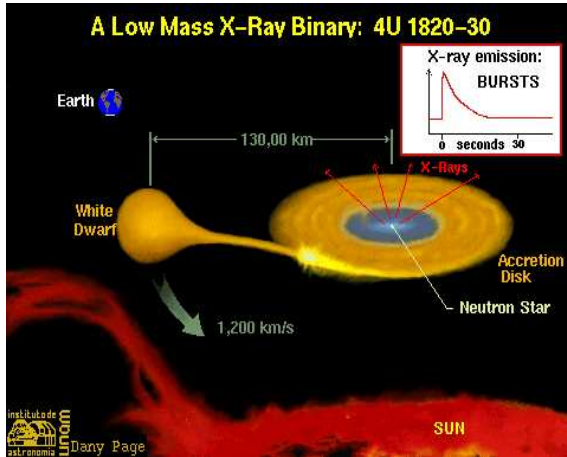
- Mass and Flow constraint on high-density EoS
- Local charge neutrality
→ 2SC + DBHF hybrid stars
- Global charge neutrality
→ d-CSL + DBHF hybrid stars



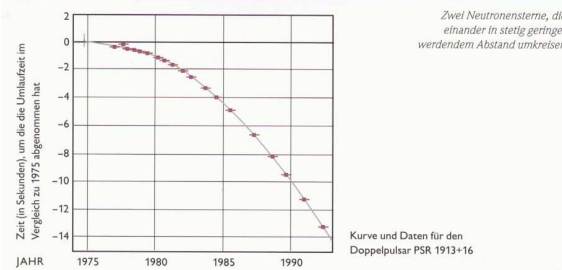
Masses of binaries

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

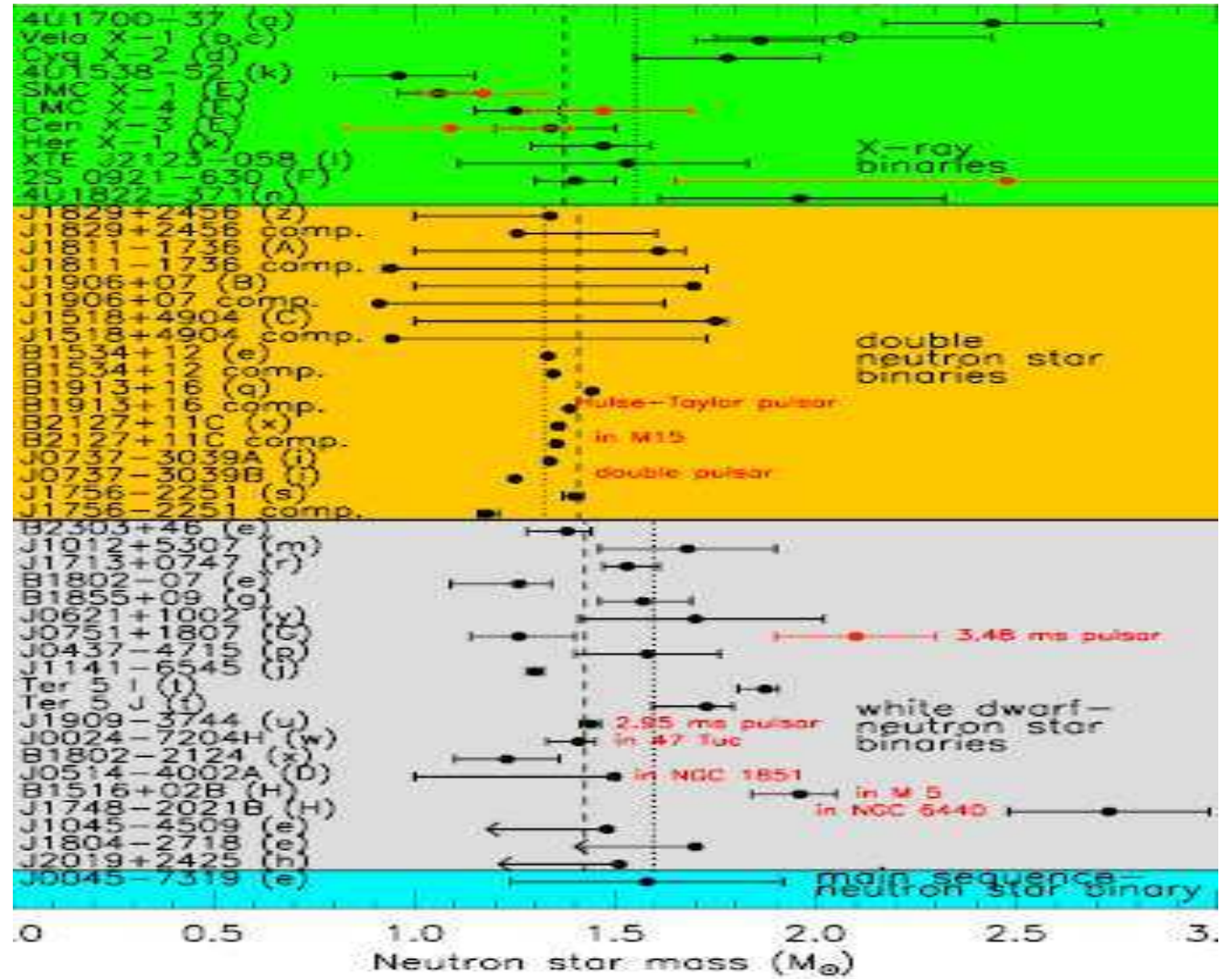
'Young' binary system:



'Old' binary system



Masses of Neutron Stars in binaries - clustering vs. maximum

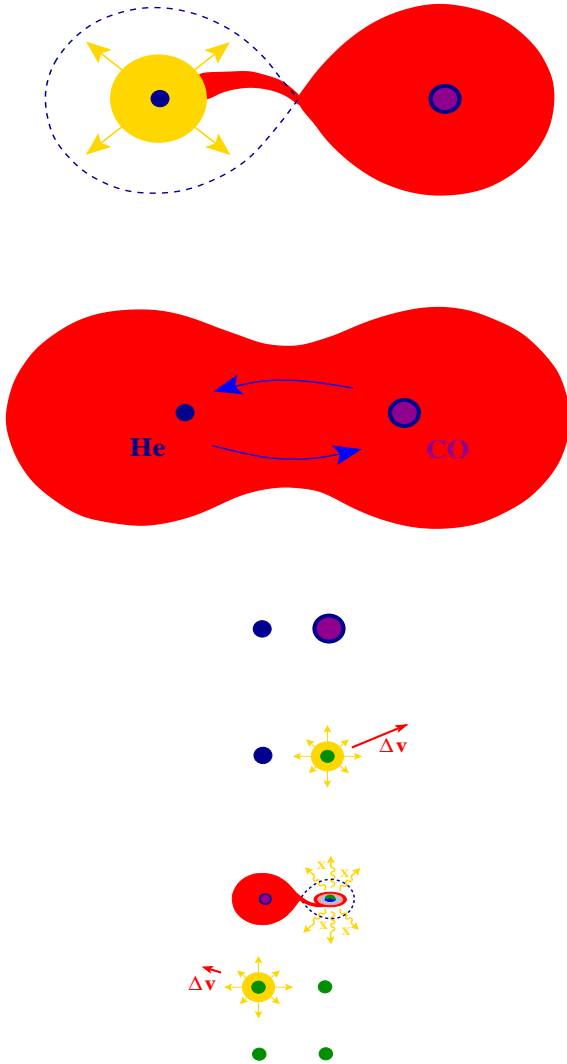


Lattimer, Prakash, PRL 94 (2005) 111101 + updates

EoS constraint from double pulsar J0737-3039?

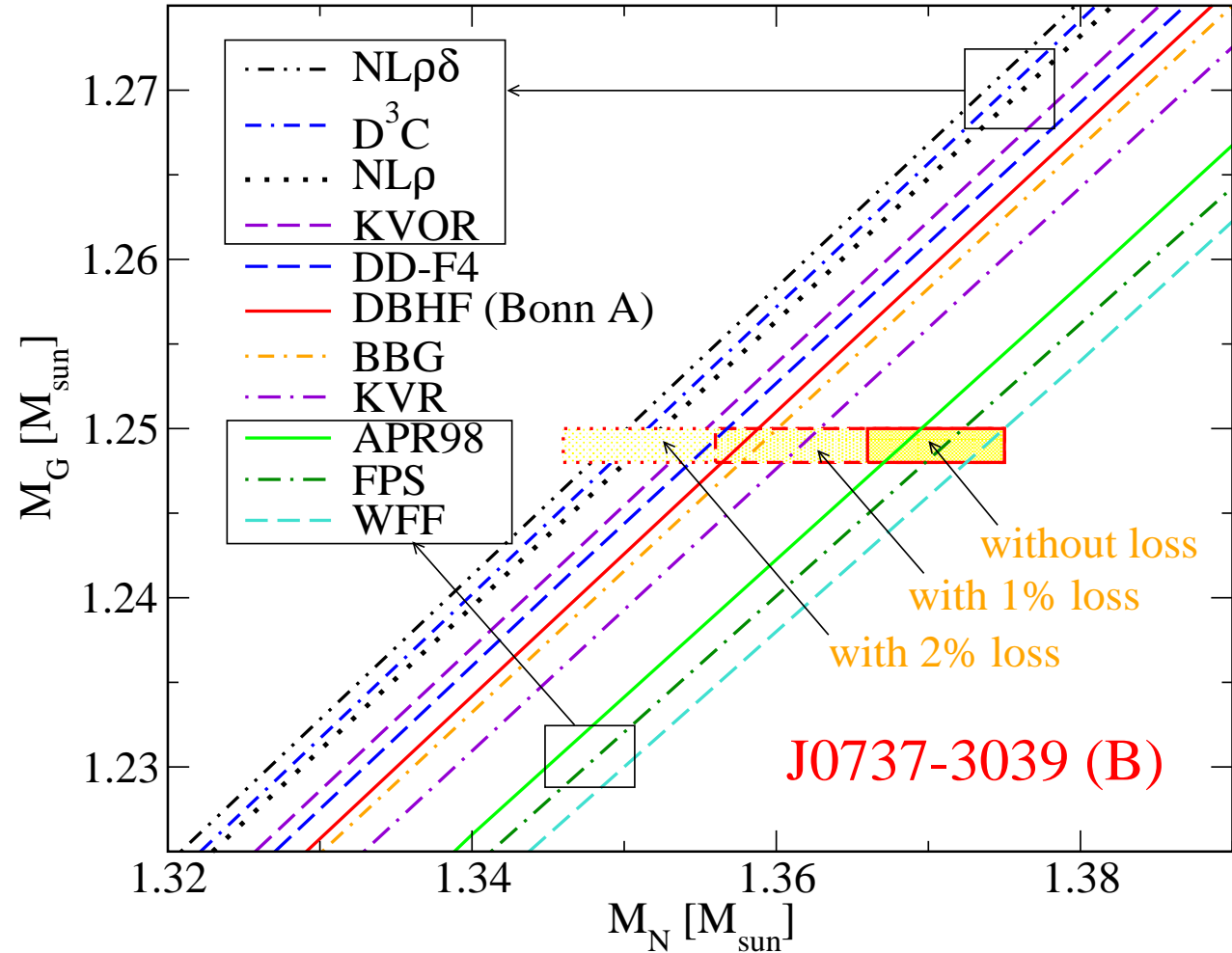
1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions

Double core scenario:



Dewi et al., MNRAS (2006)

Baryon mass vs. gravitational mass - constraint or consistency?

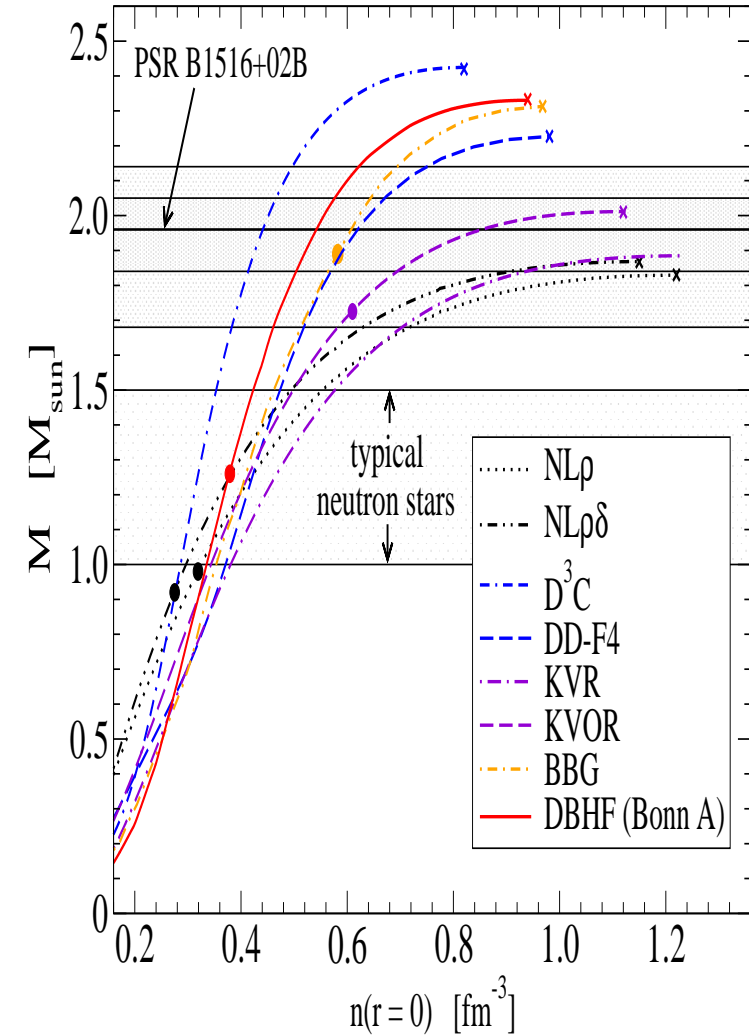
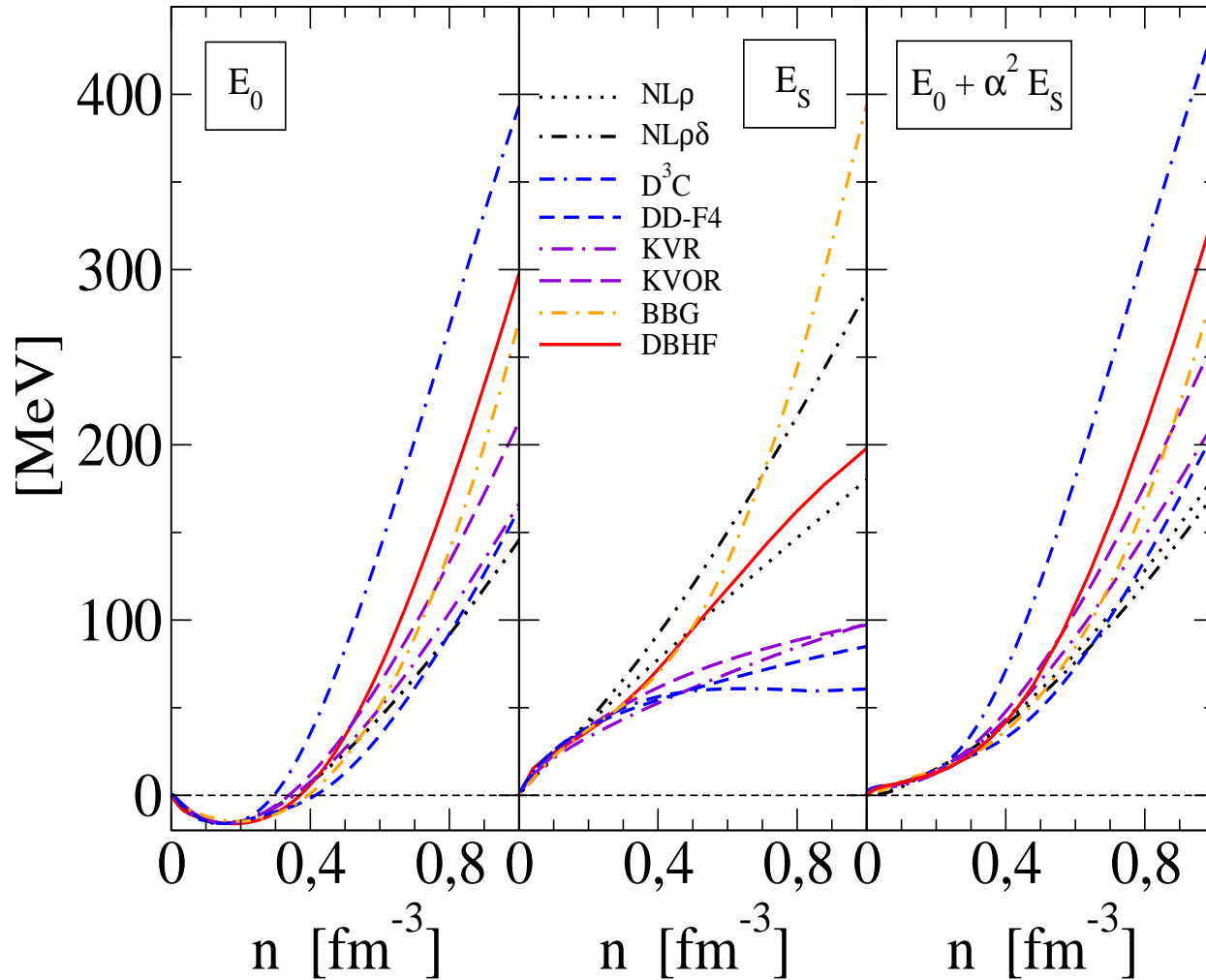


Podsiadlowski et al., MNRAS 361 (2005) 1243

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

EoS and masses - DU constraint

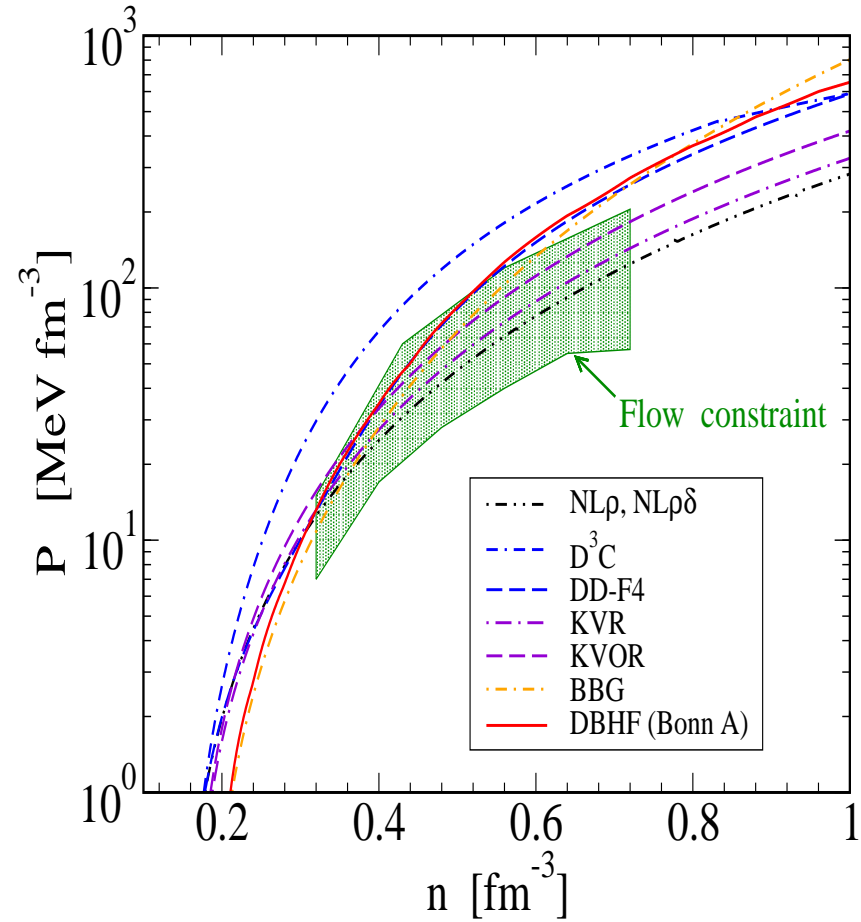
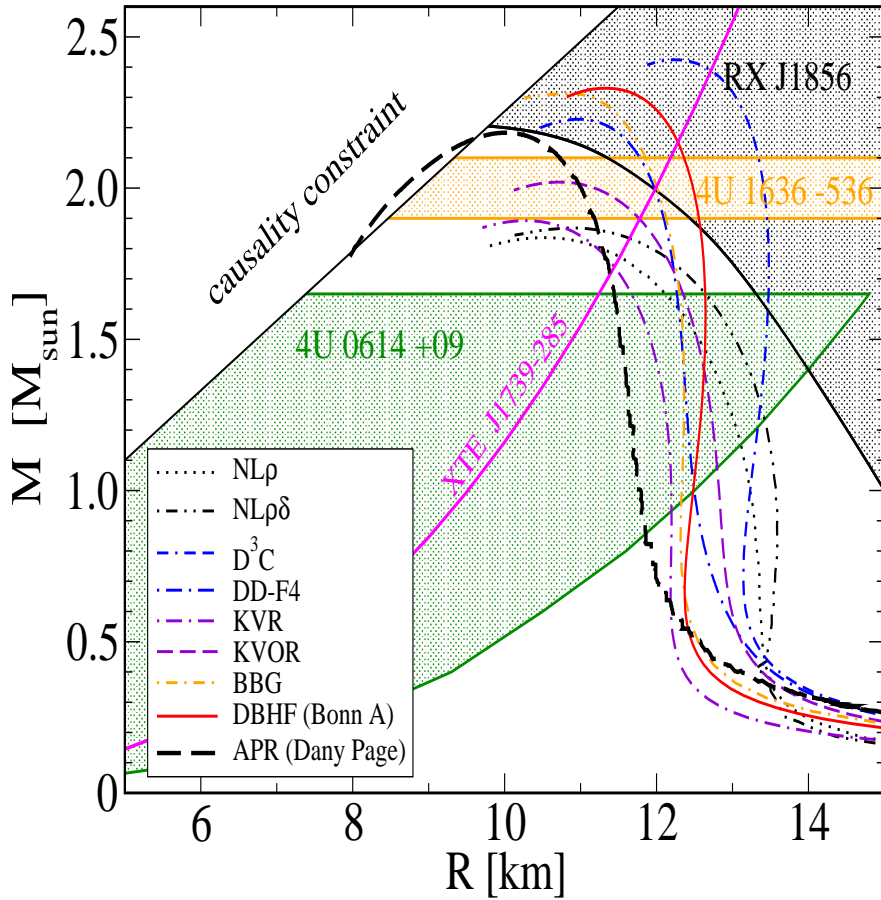
1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions



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
4. d-CSL + DBHF hybrid
5. Conclusions

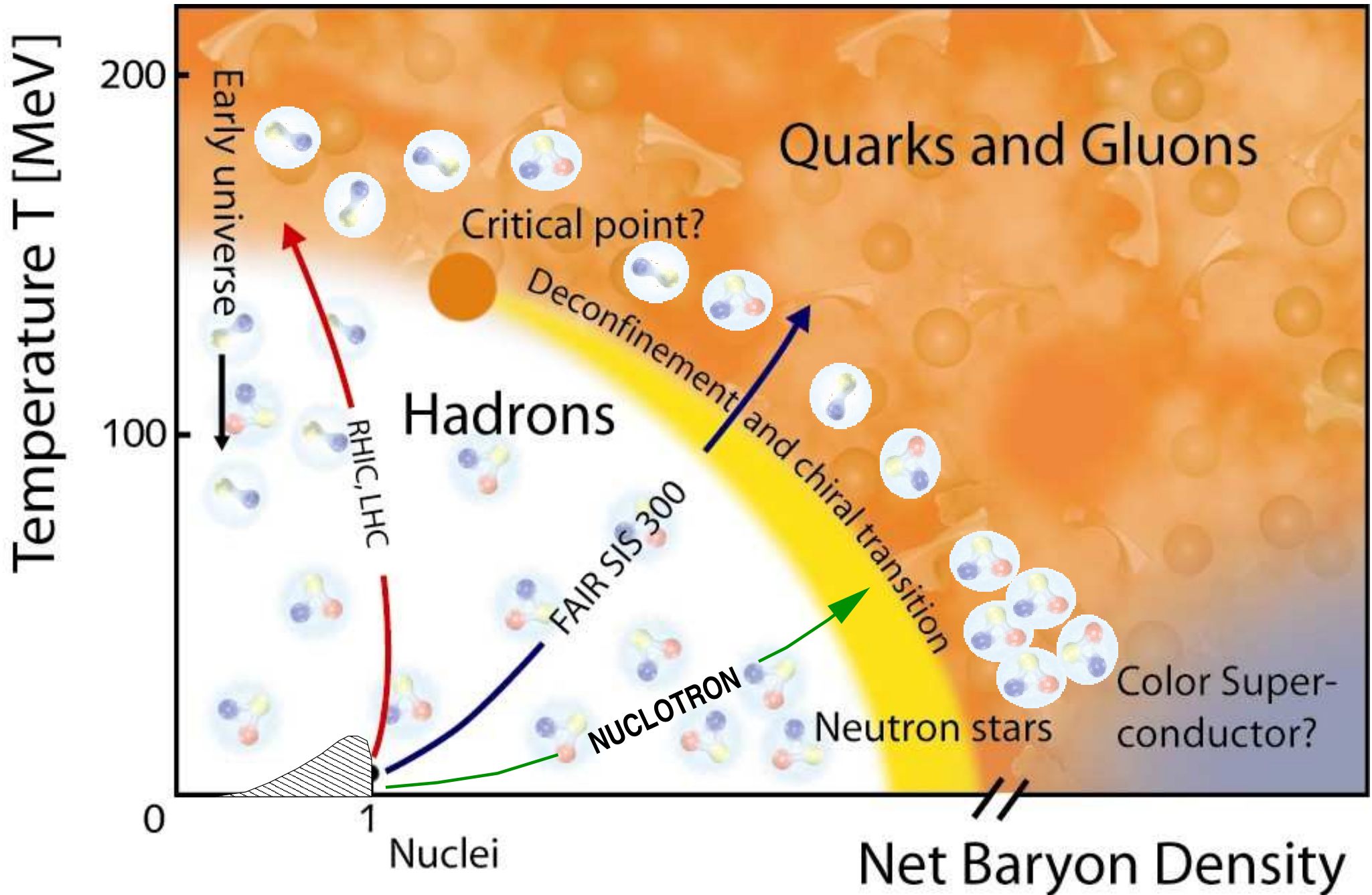


- Large Mass ($\sim 2 M_{\odot}$) and radius ($R \geq 12$ km) \Rightarrow stiff EoS;
- Flow in Heavy-Ion Collisions \Rightarrow not too stiff EoS !

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

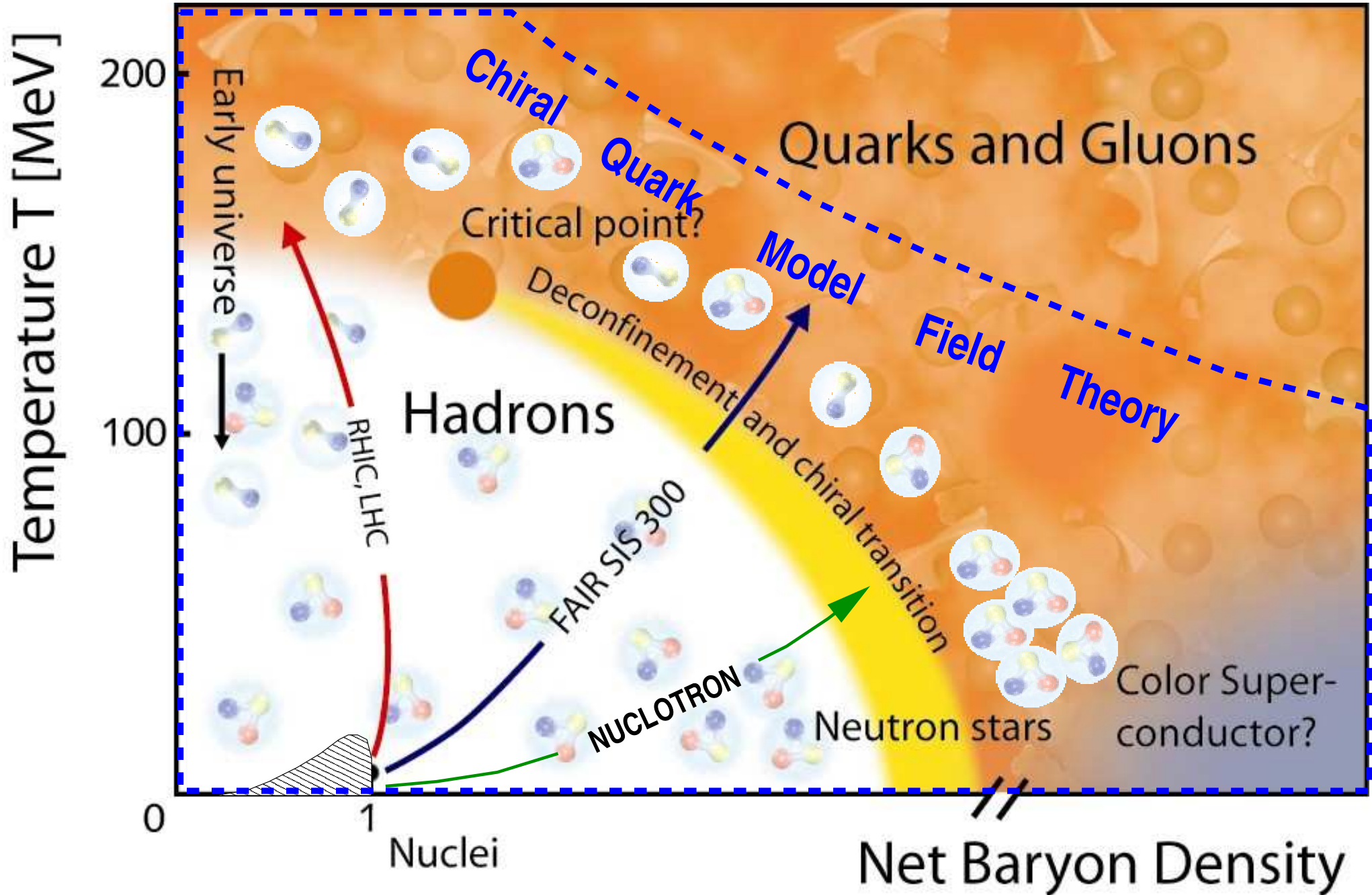
Quark Substructure and Phase Diagram

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

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

- Current-current coupling (4-fermion interaction)

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

- Bosonisation (Hubbard-Stratonovich Transformation)

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

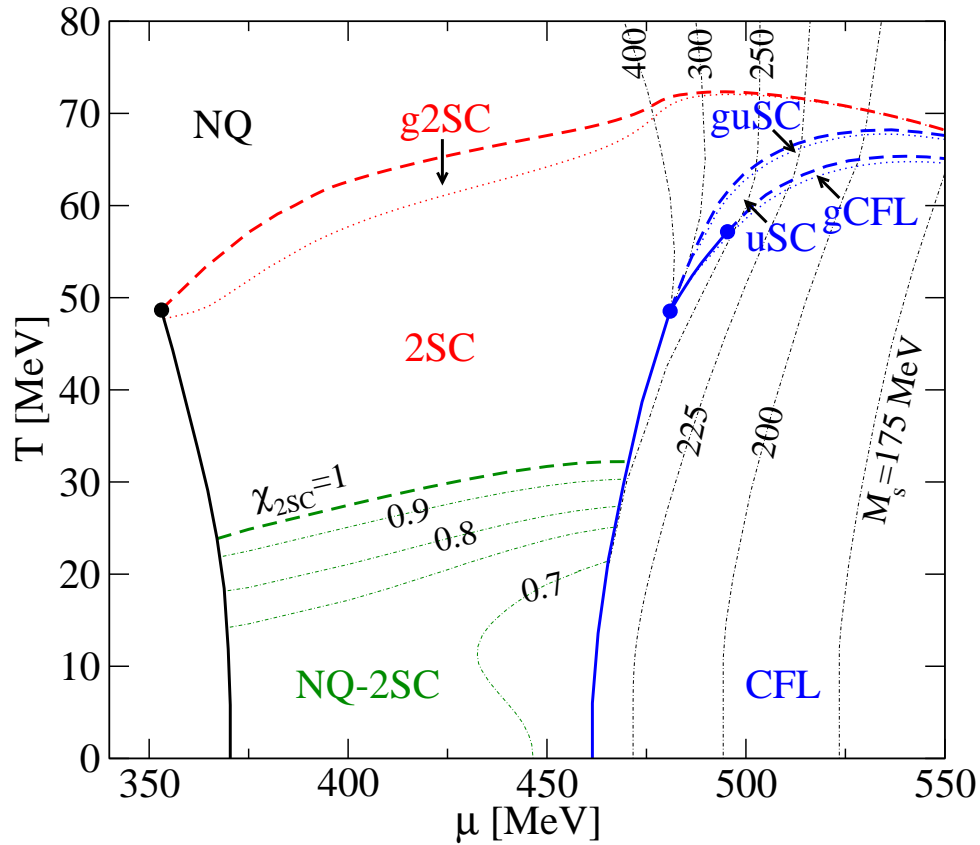
- Collective (stochastic) Fields: Mesons (ϕ_M) and Diquarks (Δ_D)

- 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:

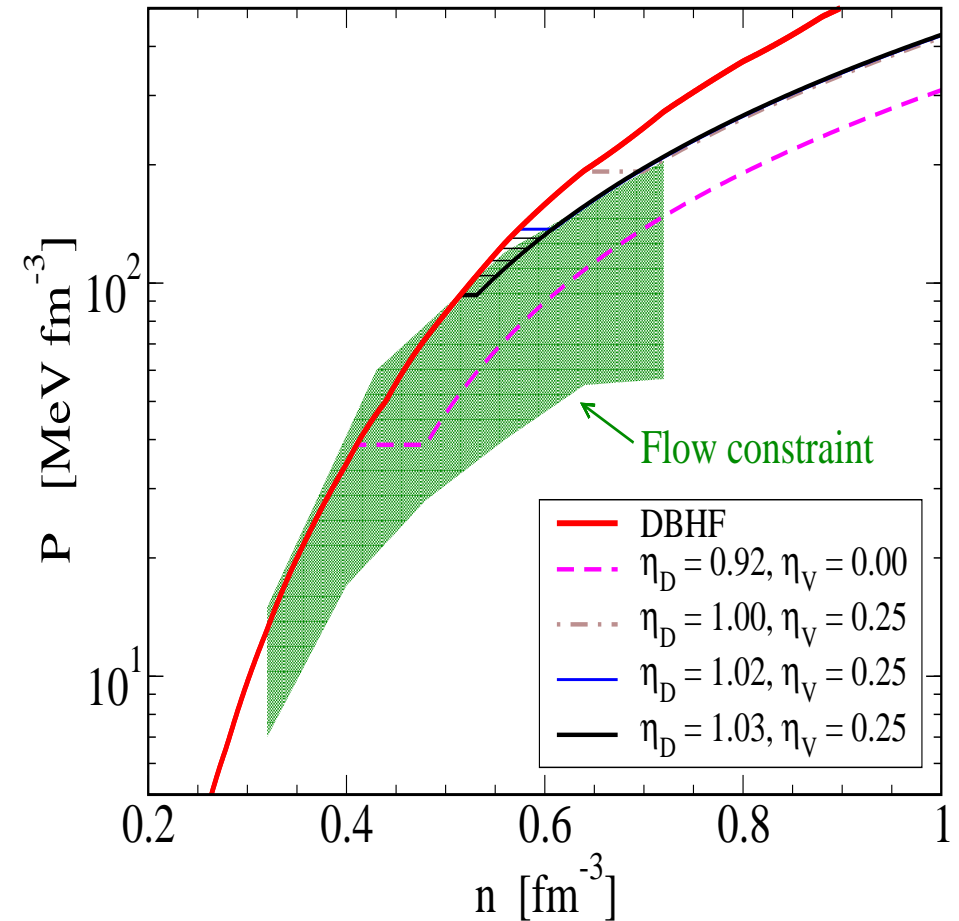
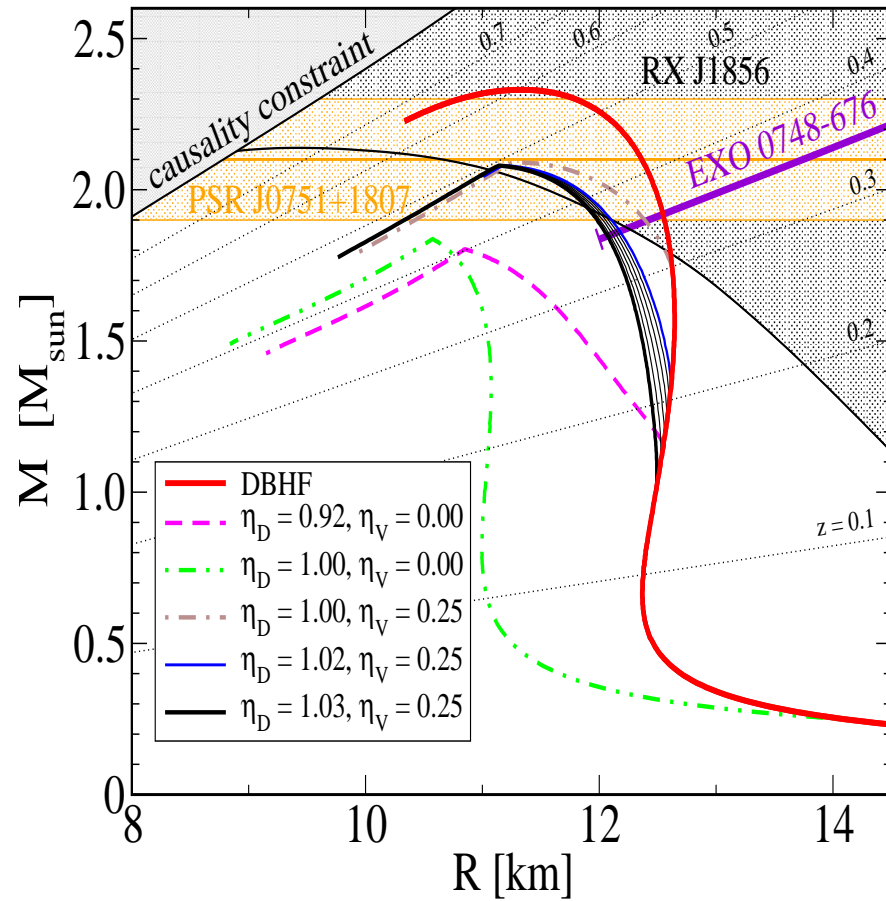
- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0, \Delta_{us} = \Delta_{ds} = 0, 0 \leq \chi_{2SC} \leq 1$;
- 2SC: $\Delta_{ud} \neq 0, \Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0, \Delta_{us} \neq 0, \Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq 0, \Delta_{ds}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

Result:

- Gapless phases only at high T,
- CFL only at high chemical potential,
- At $T \leq 25\text{-}30$ MeV: mixed NQ-2SC phase,
- Critical point $(T_c, \mu_c) = (48 \text{ MeV}, 353 \text{ MeV})$,
- 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
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

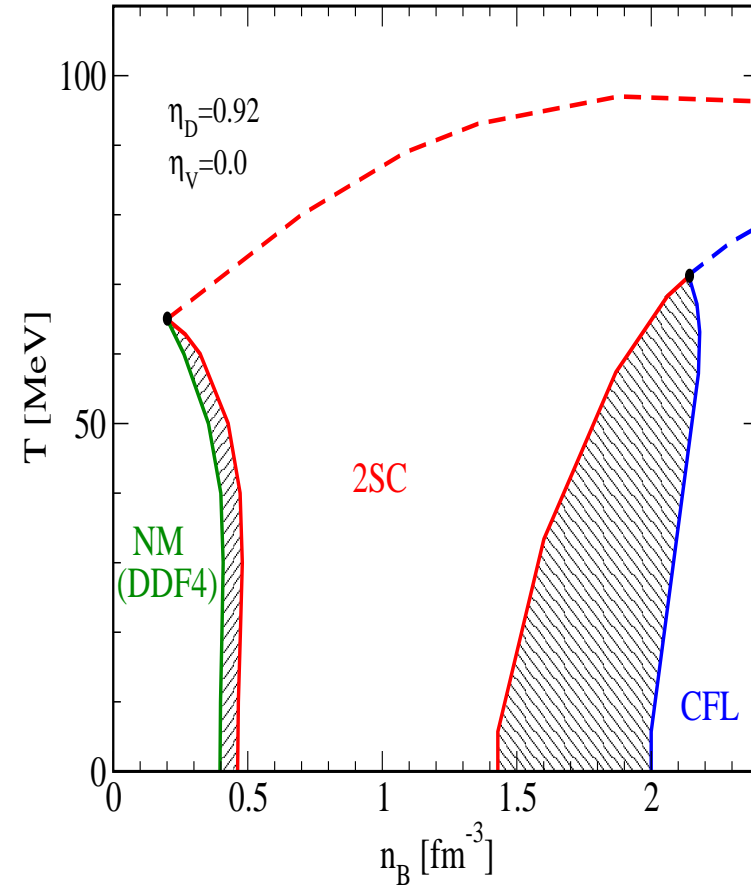
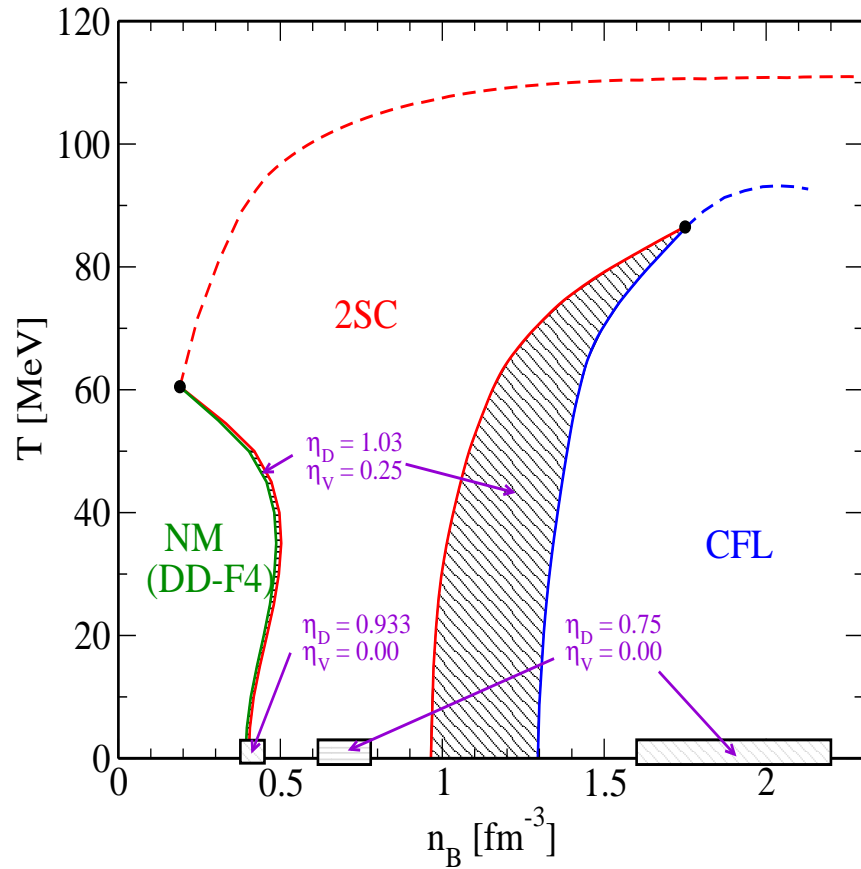


- Large Mass ($\sim 2 M_{\odot}$) and radius ($R \geq 12$ km) \Rightarrow stiff quark matter EoS;
Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!
- Flow in Heavy-Ion Collisions \Rightarrow not too stiff EoS !
Note: Quark matter removes violation by DBHF at high densities

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
4. d-CSL hybrid
5. Conclusion

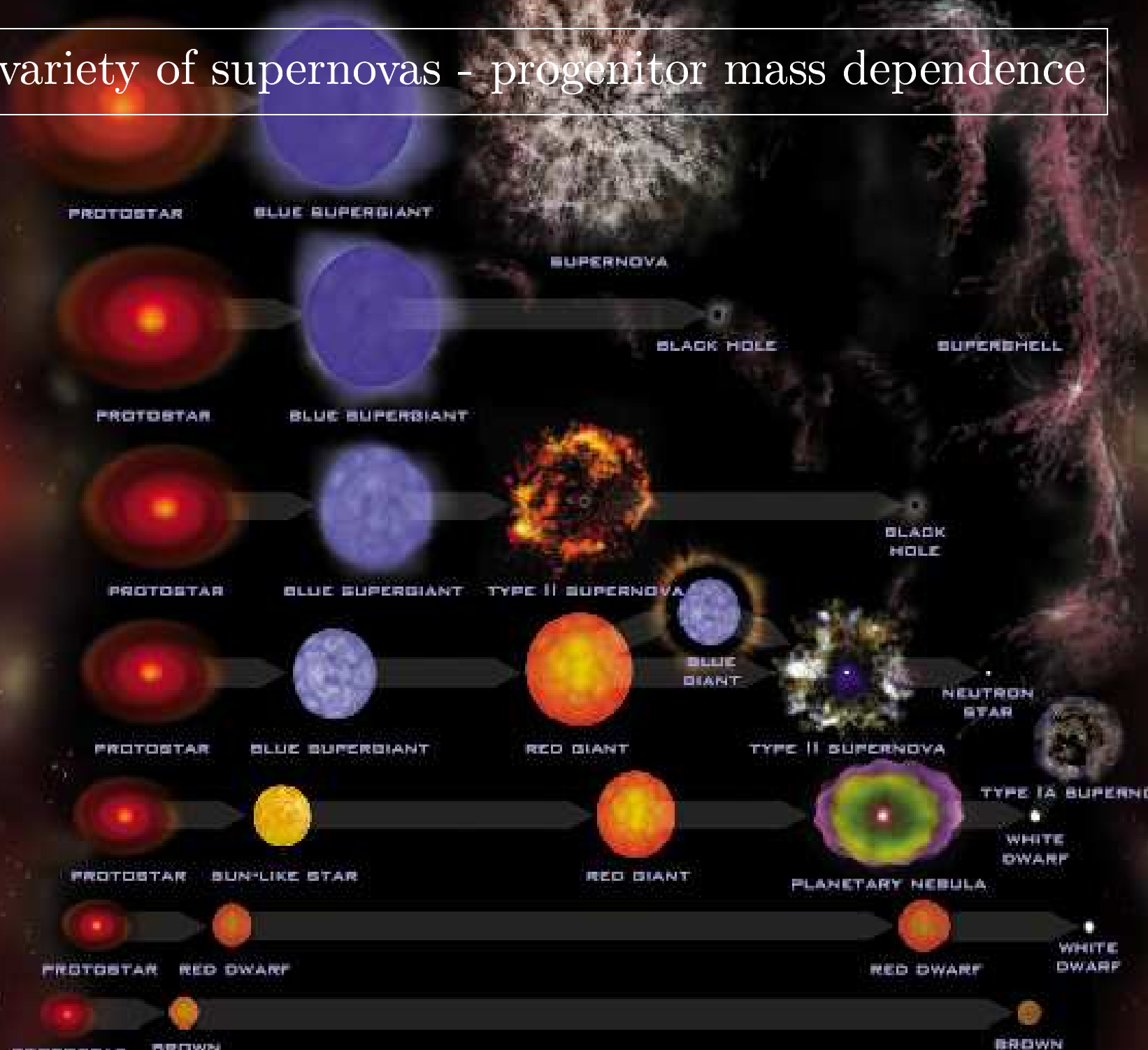


Phase diagrams for isospin-symmetric matter, for hybrid star maximum mass $M_{max} = 2.1 M_{\odot}$ (left-hand side) and $M_{max} = 1.7 M_{\odot}$ (right-hand side).

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

Wide variety of supernovas - progenitor mass dependence

STELLAR NURSERY



STELLAR NURSERY

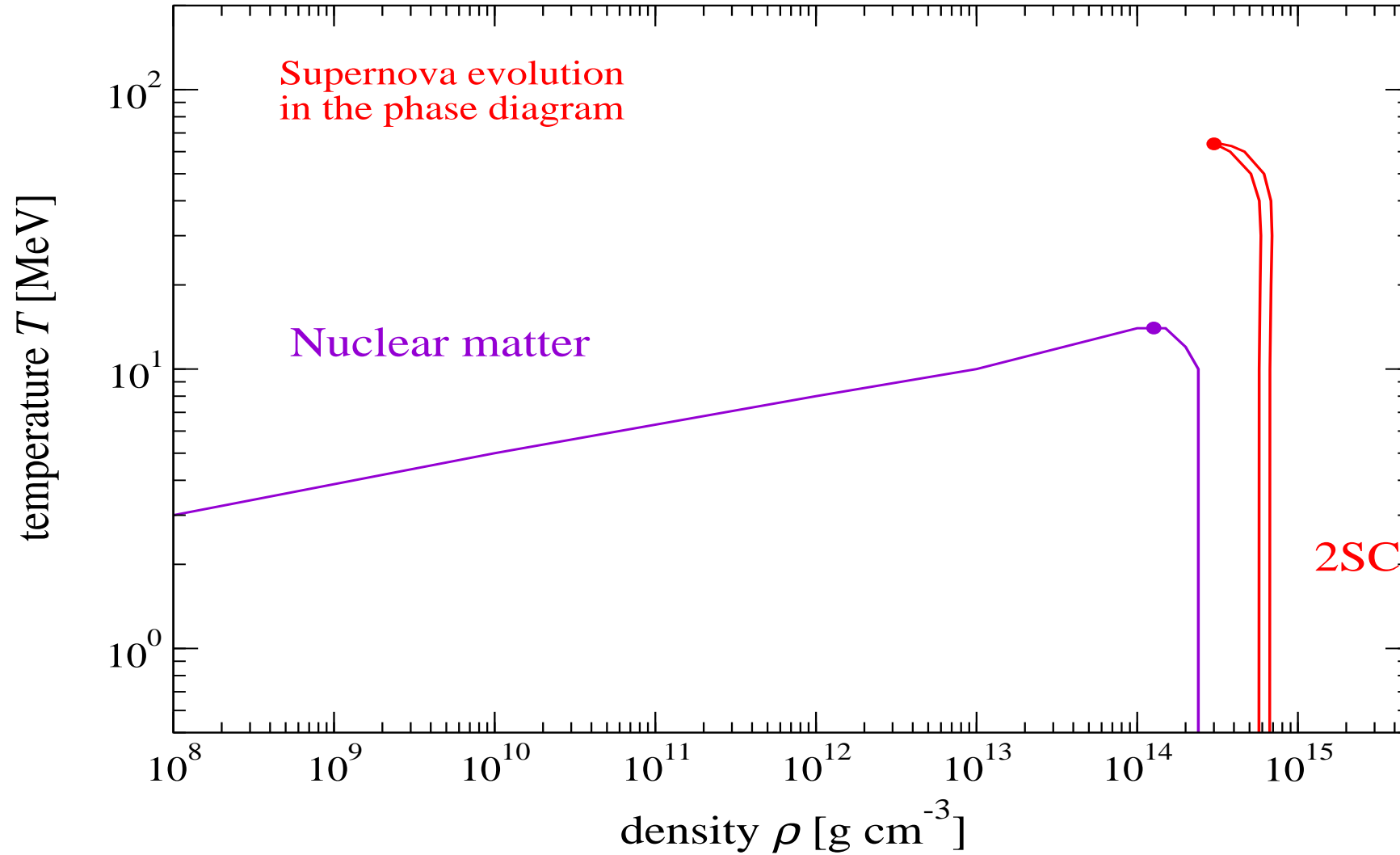
PROTOSTAR

BROWN

BROWN

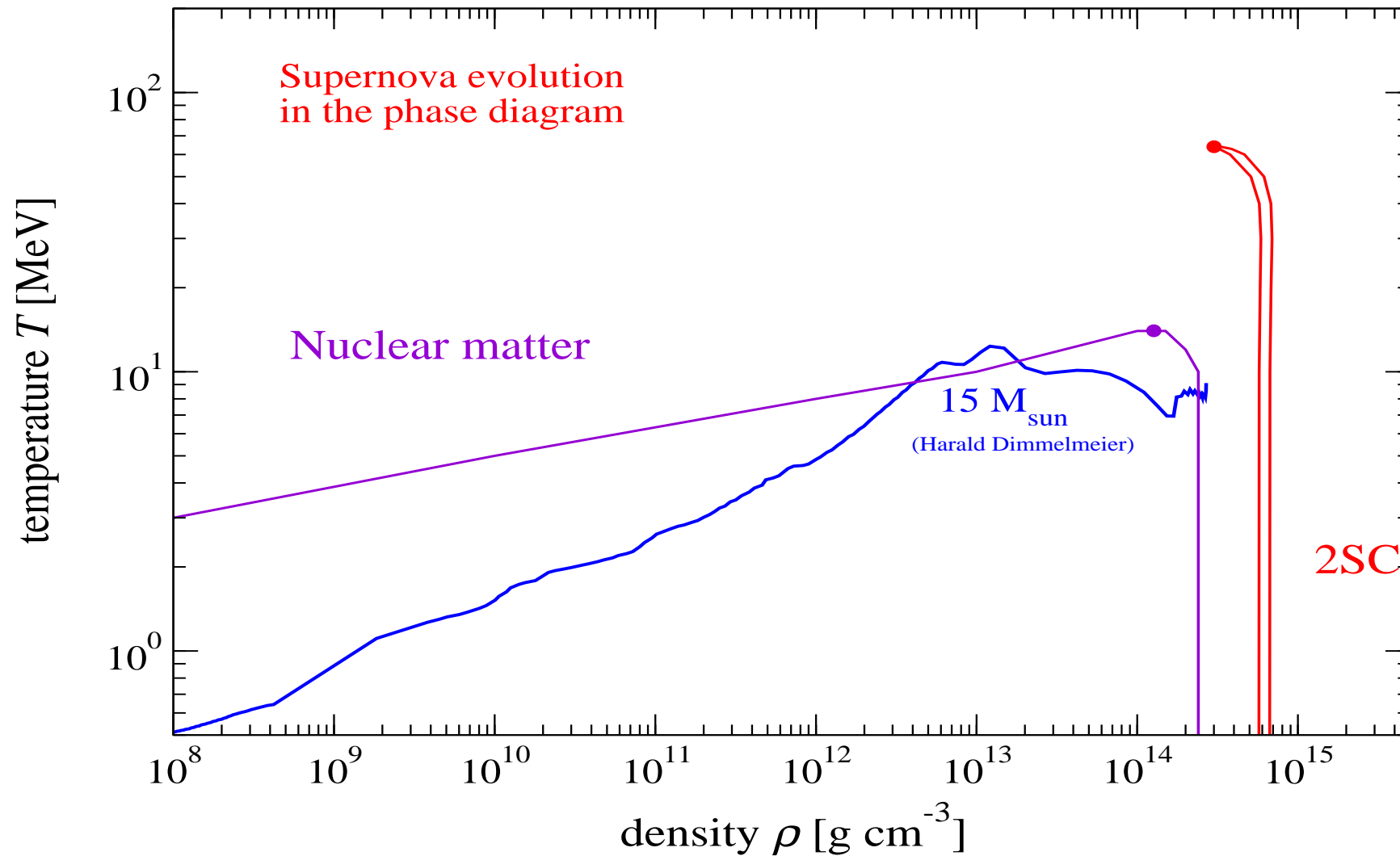
Supernova Collapse in the Phase Diagram

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



Supernova Collapse in the Phase Diagram (II)

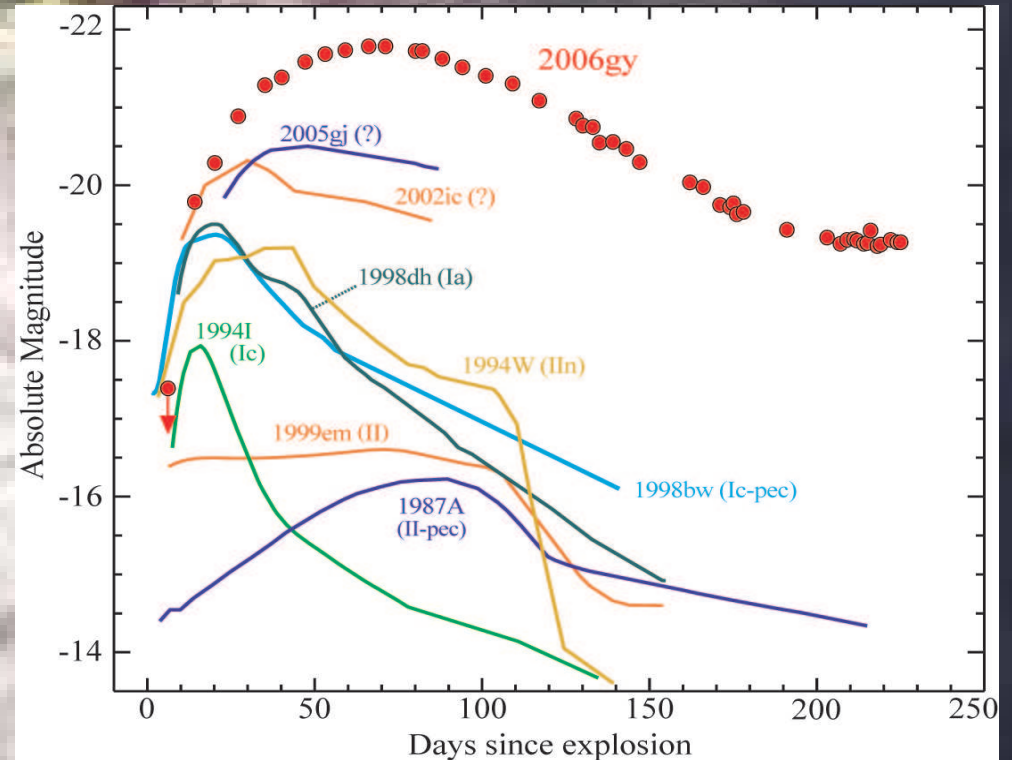
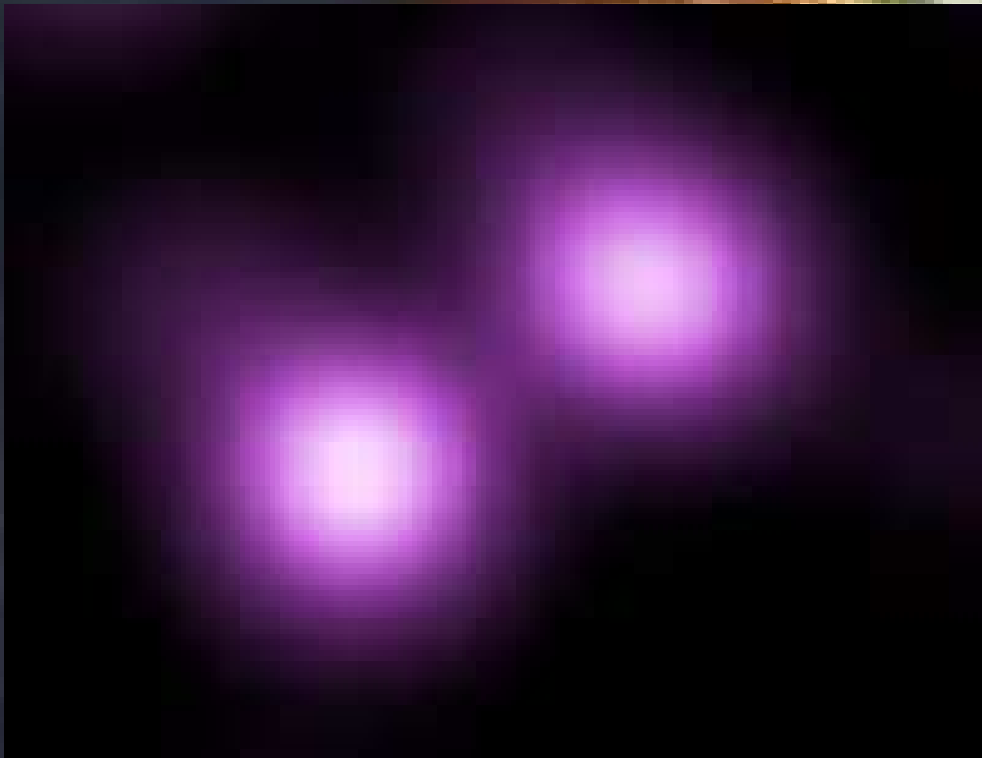
1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion



The case of SN2006gy



The case of SN2006gy - a Quarknova ?

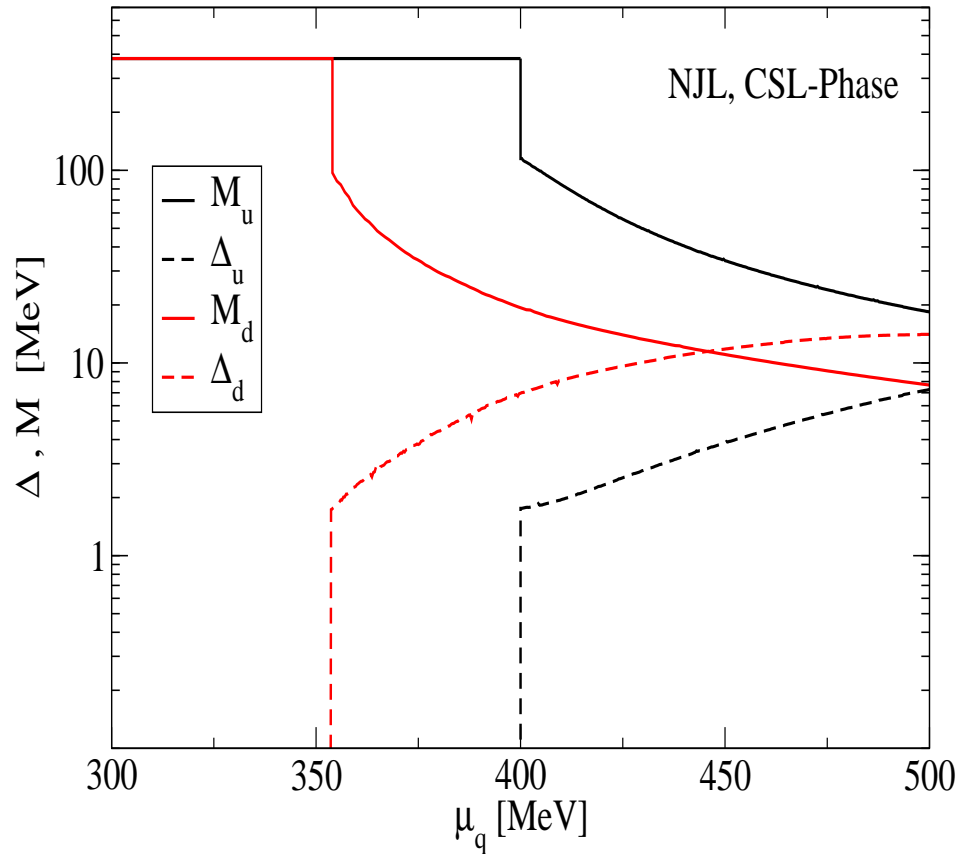


Discovery: Sept. 18, 2006
in NGC 1260 (Perseus)
Distance: 72 Mpc=238 Mill. Ly
(Smith et al.: astro-ph/0612617)

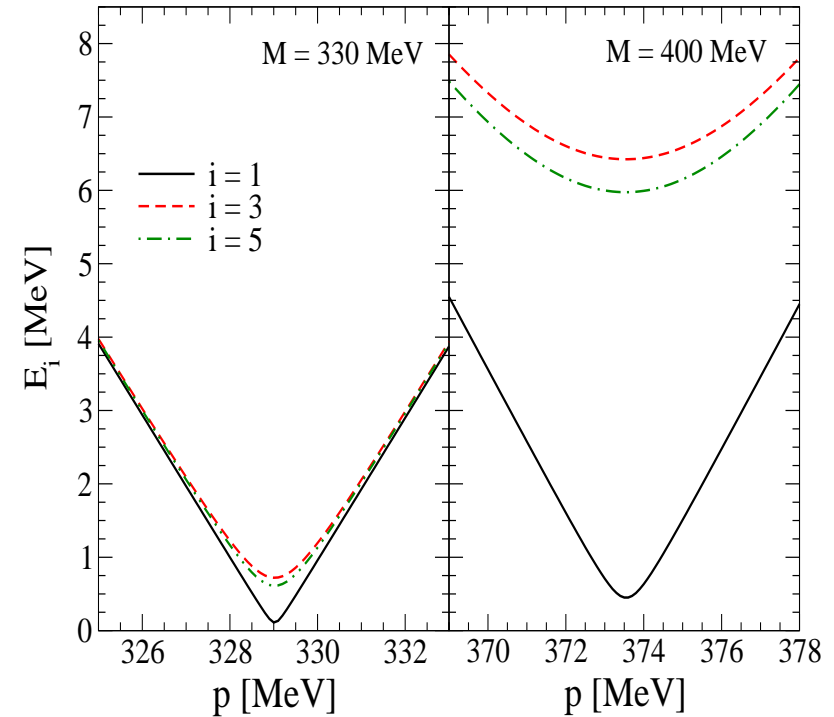
Light curve: 70 days rise time
Energy release: 10^{52} erg= 10 bethe
Progenitor star: $\approx 150 M_{\odot}$?
Engine: Quark-star formation?
(Leahy & Ouyed: 0708.1787 [astro-ph])

Single flavor (d-CSL) Phase in Compact Stars

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



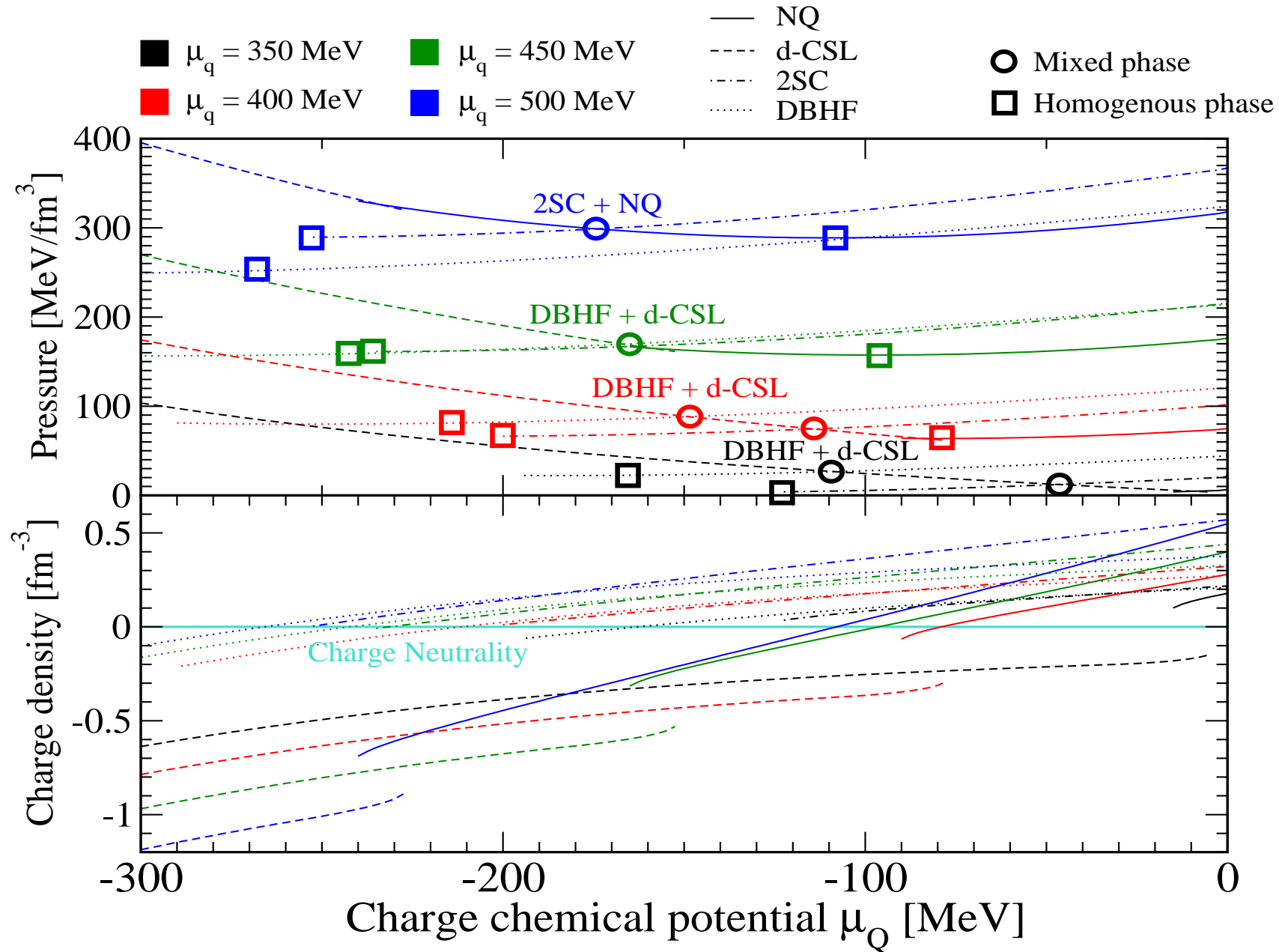
Ansatz **Color-spin-locking (CSL)** gap:
 $\hat{\Delta} = \Delta(\gamma^3 \lambda_2 + \gamma^1 \lambda_7 + \gamma^2 \lambda_5)$
 Aguilera et al., PRD 72 (2005) 034008;
 PRD 74 (2006) 114005



Flavor-asymmetry $-\mu_Q = \mu_e = \mu_d - \mu_u > 0$
 \rightarrow **Sequential melting of chiral condensates:**
d-quark dripline!

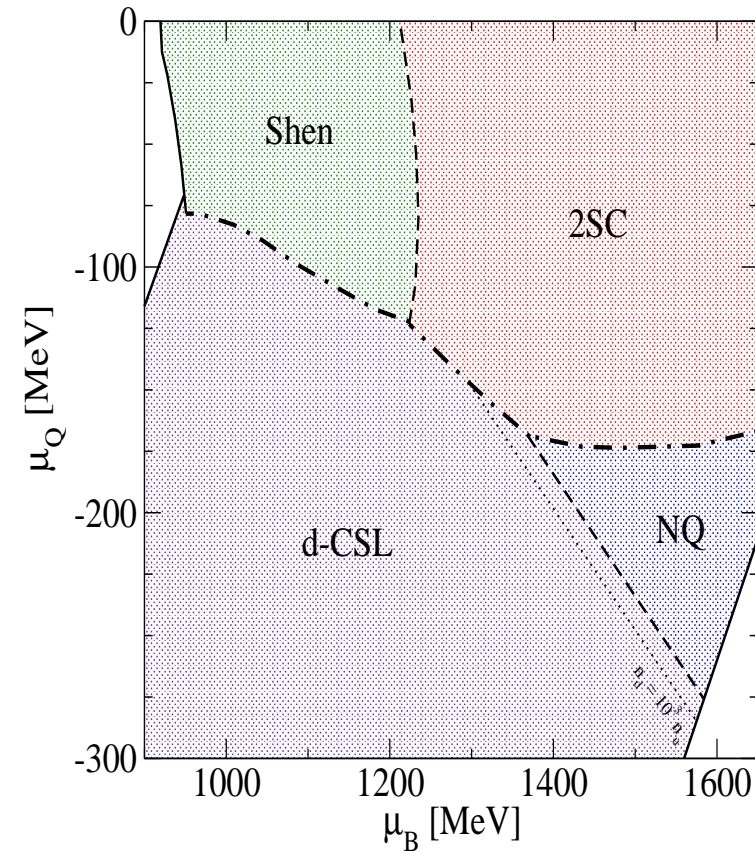
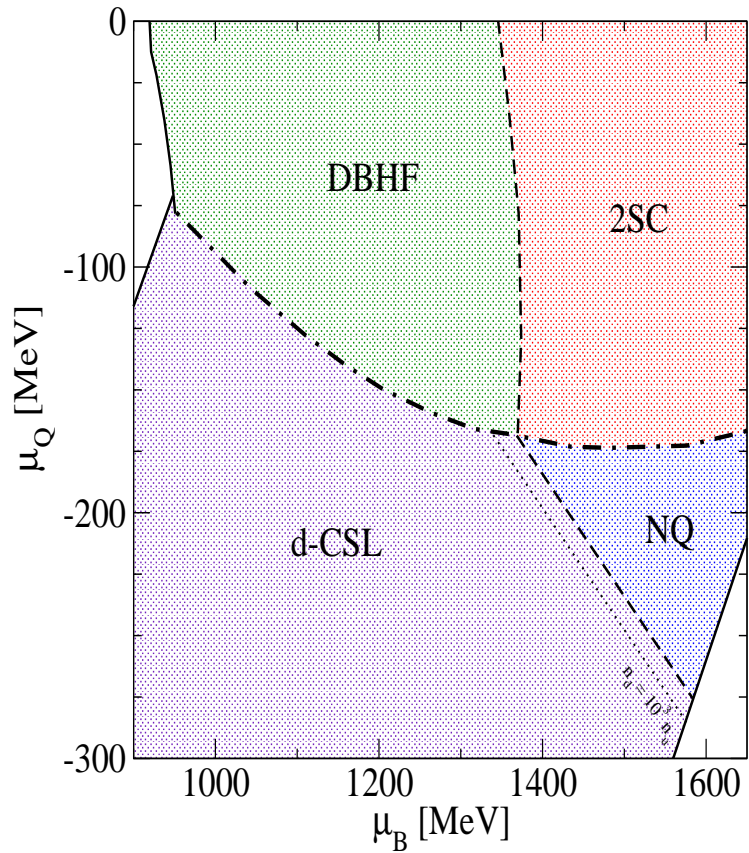
Global charge neutrality: quark-nuclear hybrid

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



d-CSL: single-flavor phase in competition

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

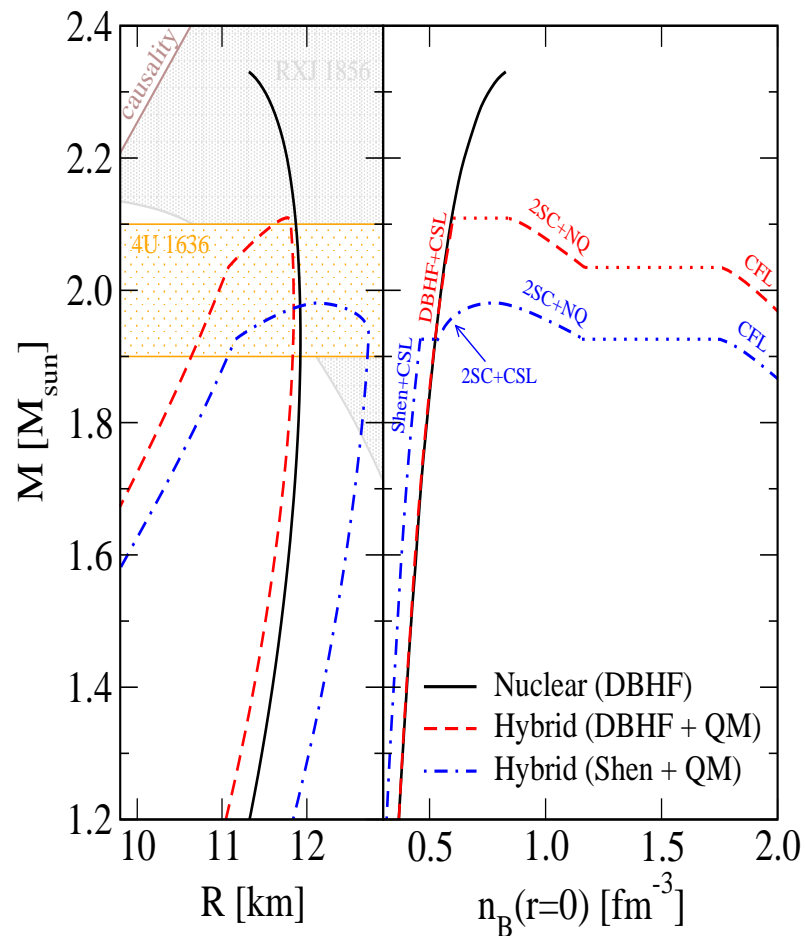
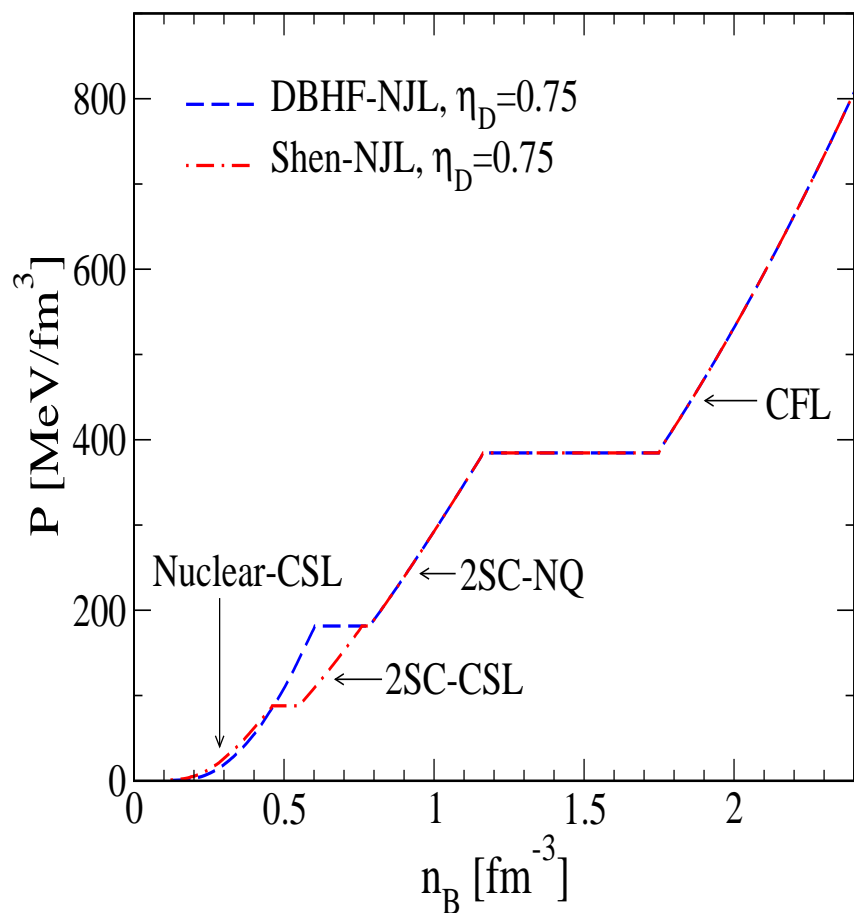


Dash-dotted lines: border between oppositely charged phases

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

d-CSL: single-flavor phase in neutron stars

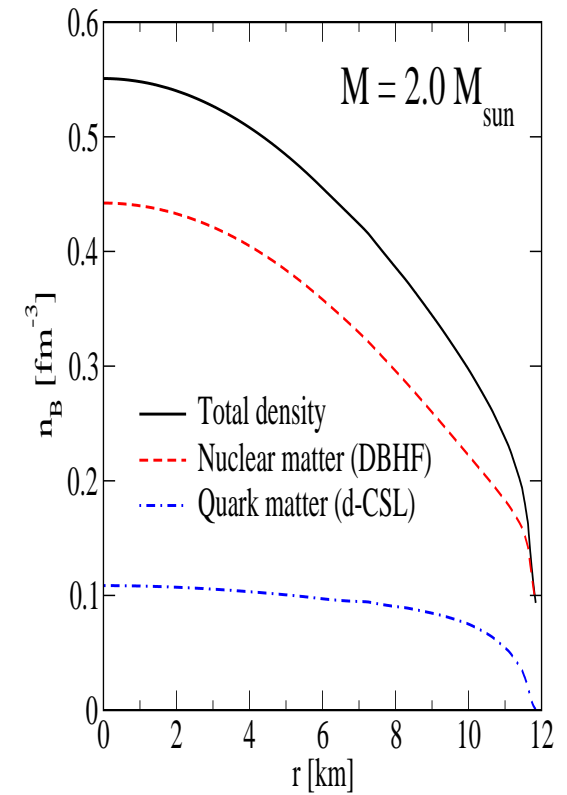
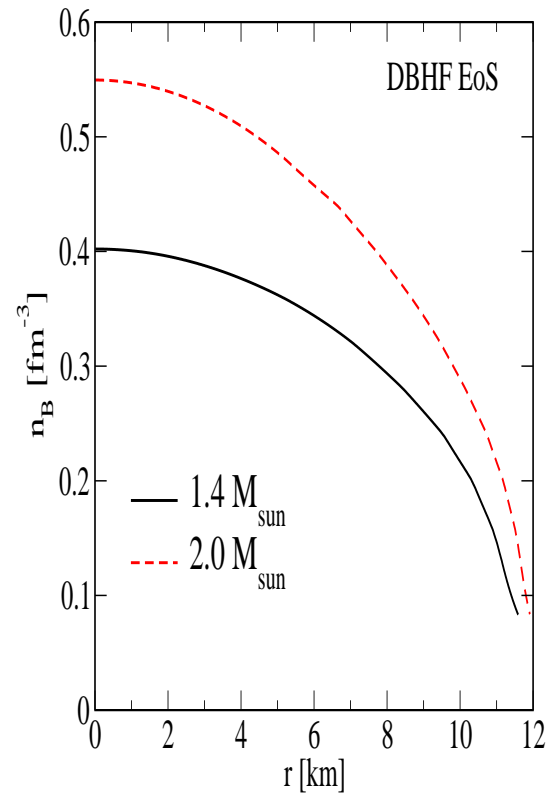
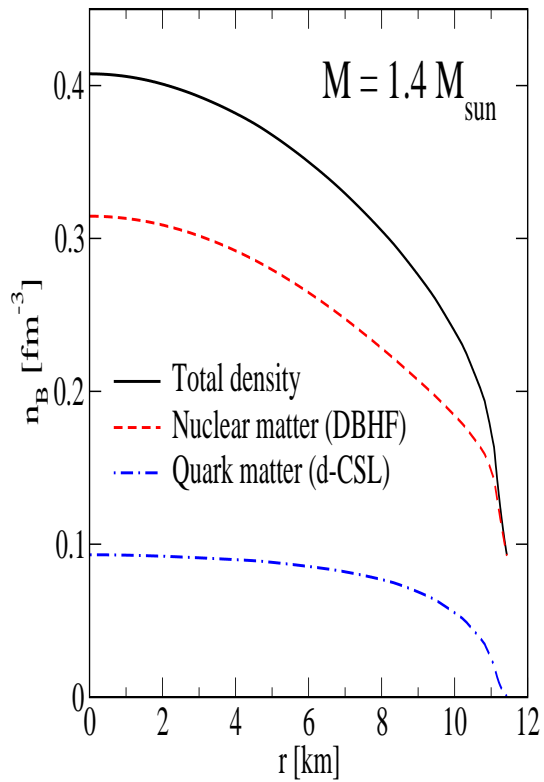
1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion



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

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

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

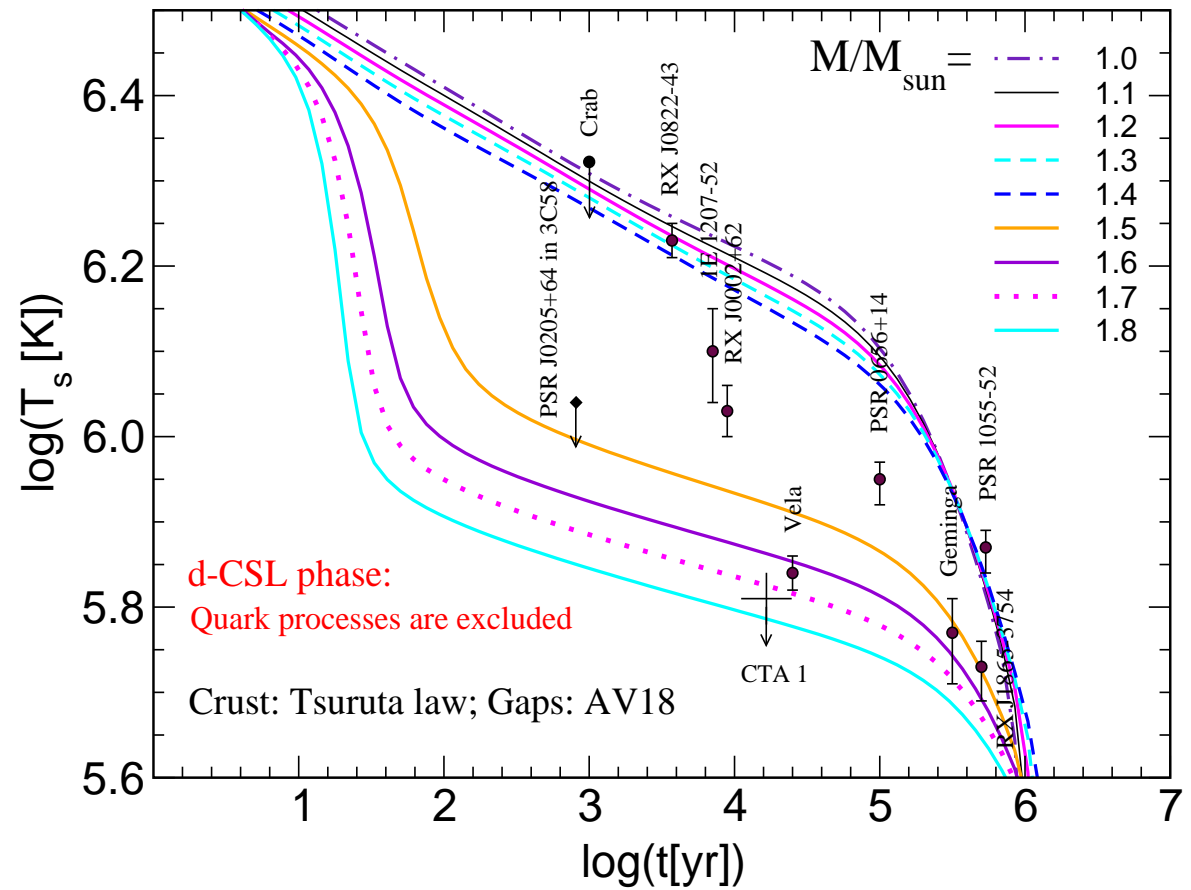


D.B.,F. Sandin, T. Klähn, in preparation.

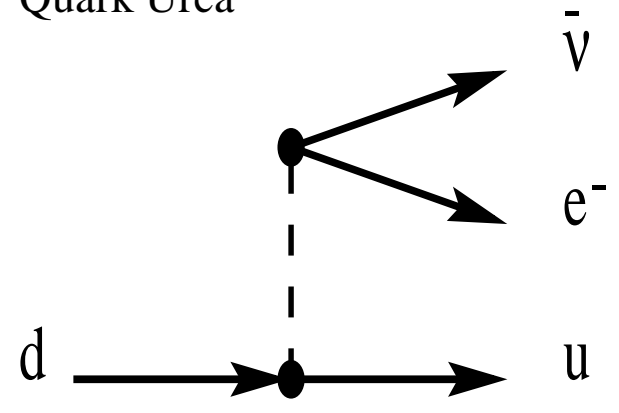
d-CSL: single-flavor phase in neutron stars

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

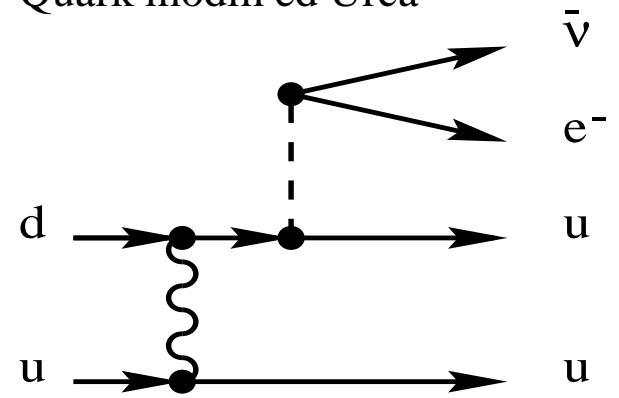
Cooling: processes in single-flavor quark matter are blocked!



Quark Urca



Quark modified Urca



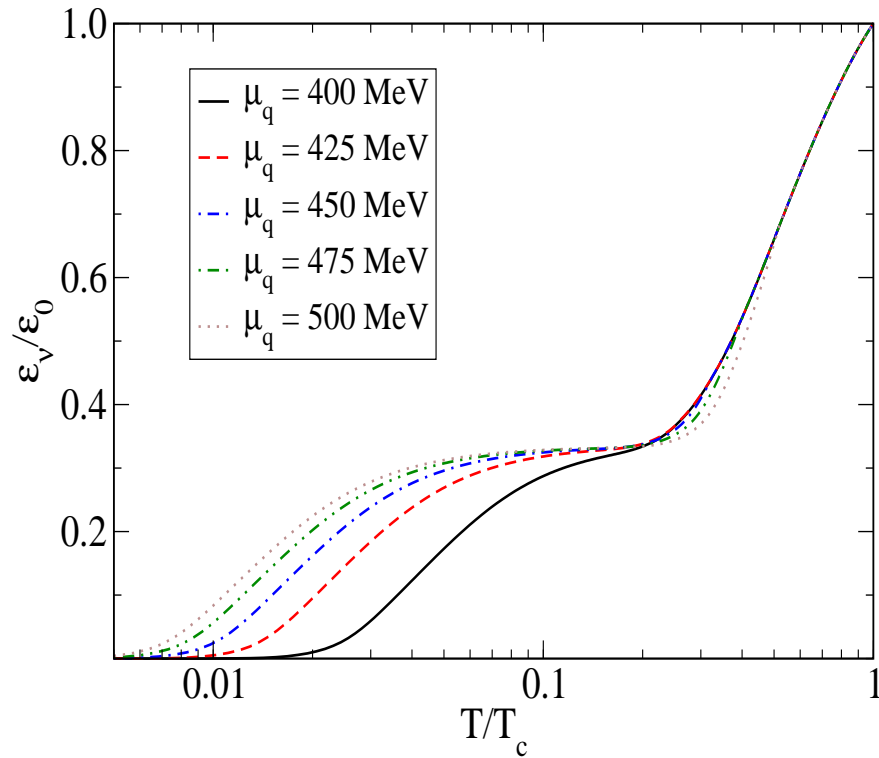
not operative since u-quark Fermi sea not populated ($p_{F,u} = 0$)

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

d-CSL: single-flavor phase in neutron stars

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

DUrca emissivity:



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

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

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

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

d-CSL: single-flavor phase in neutron stars

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

Bulk viscosity:

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

with $C_t = C + C'$ and the coefficients functions

$$C = \frac{M_u^2}{3\mu_u} - \frac{M_d^2}{3\mu_d},$$

$$C' = \frac{4\alpha_s}{3\pi} \left[\frac{M_d^2}{\mu_d} \left(\ln \frac{2\mu_d}{M_d} - \frac{2}{3} \right) - \frac{M_u^2}{\mu_u} \left(\ln \frac{2\mu_u}{M_u} - \frac{2}{3} \right) \right]$$

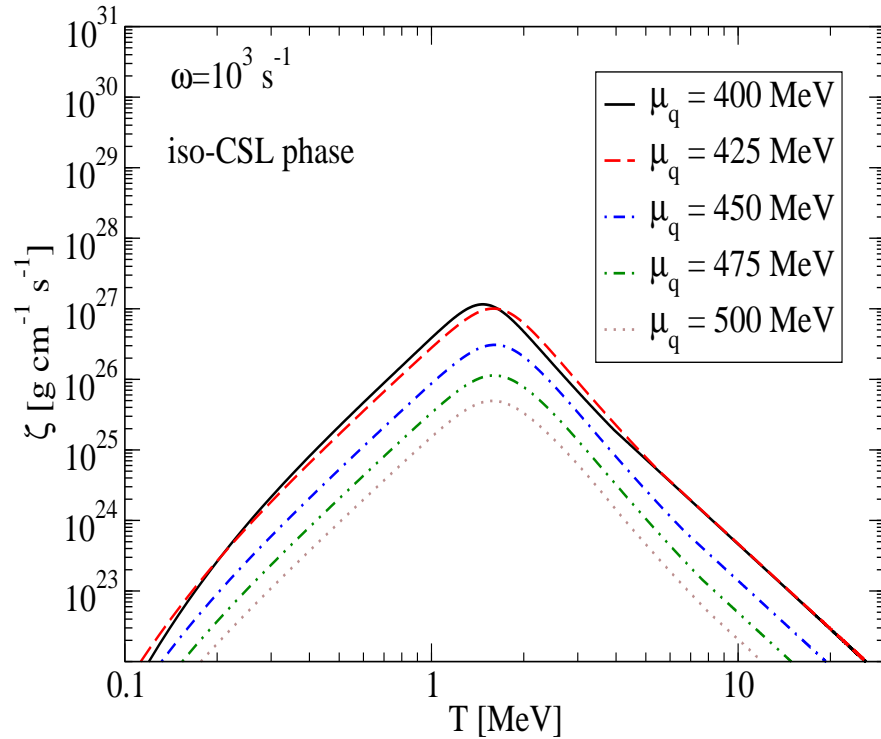
$$B \simeq \frac{\pi^2}{3} n \left(\frac{1}{\mu_u^2} + \frac{1}{\mu_d^2} + \frac{1}{\mu_e^2} \right). \quad (2)$$

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

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]



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

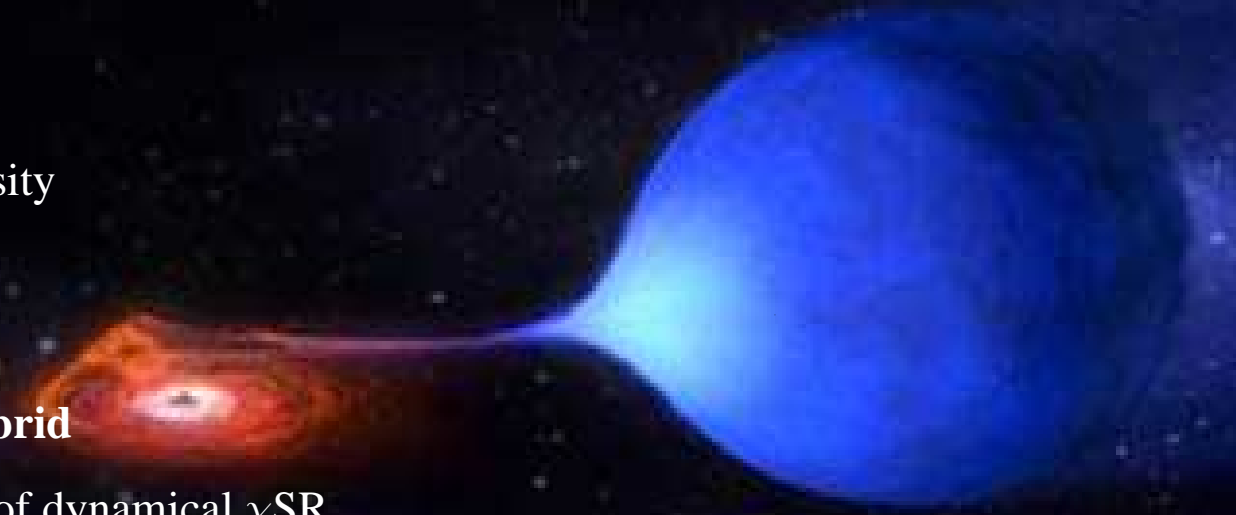


Local charge neutrality: 2SC + DBHF hybrid

- diquark coupling 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 χ SR
- no d-CSL in symmetric matter: $x_{p,crit} < 0.2$
- no Urca cooling processes \rightarrow no neutrino trapping?

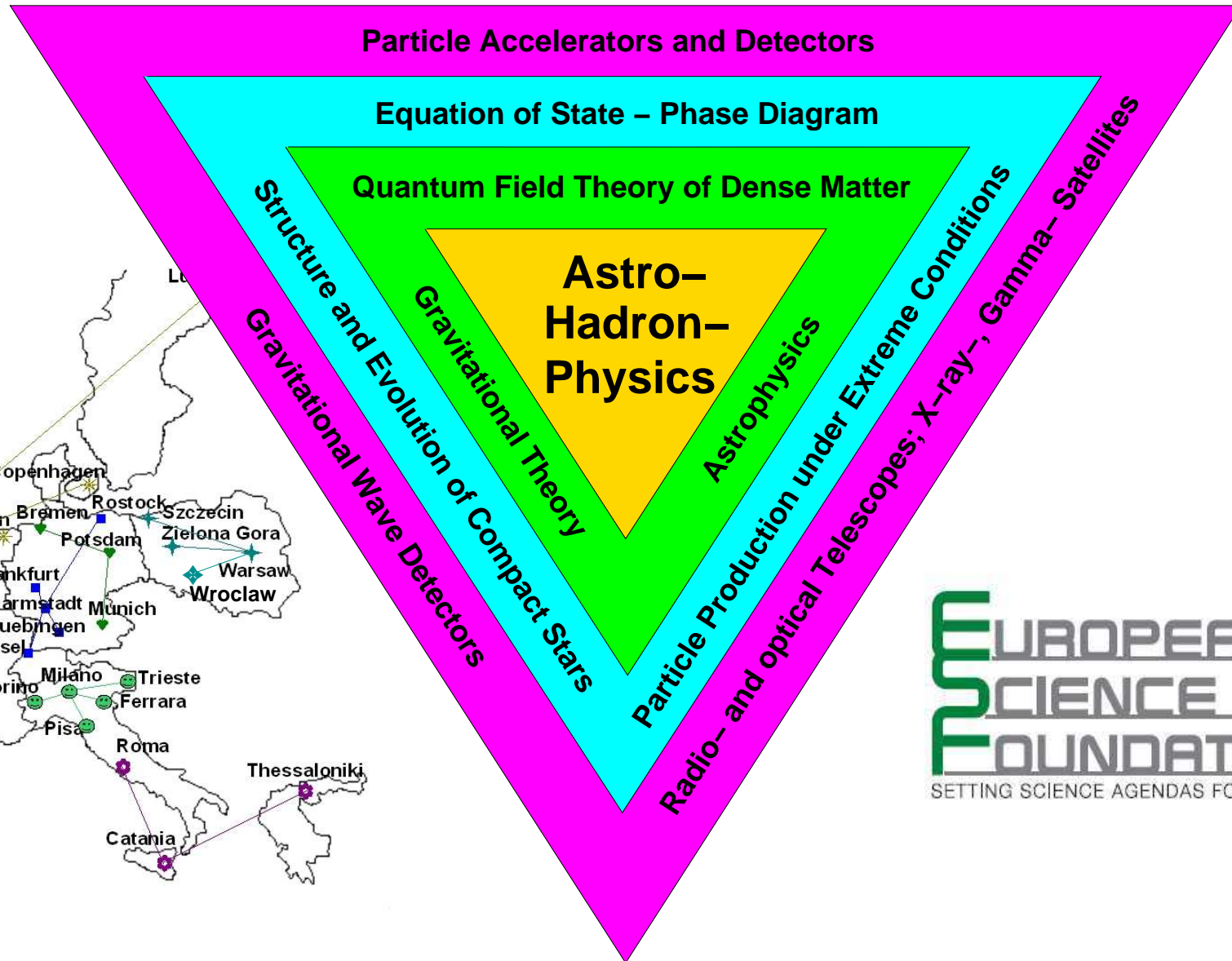
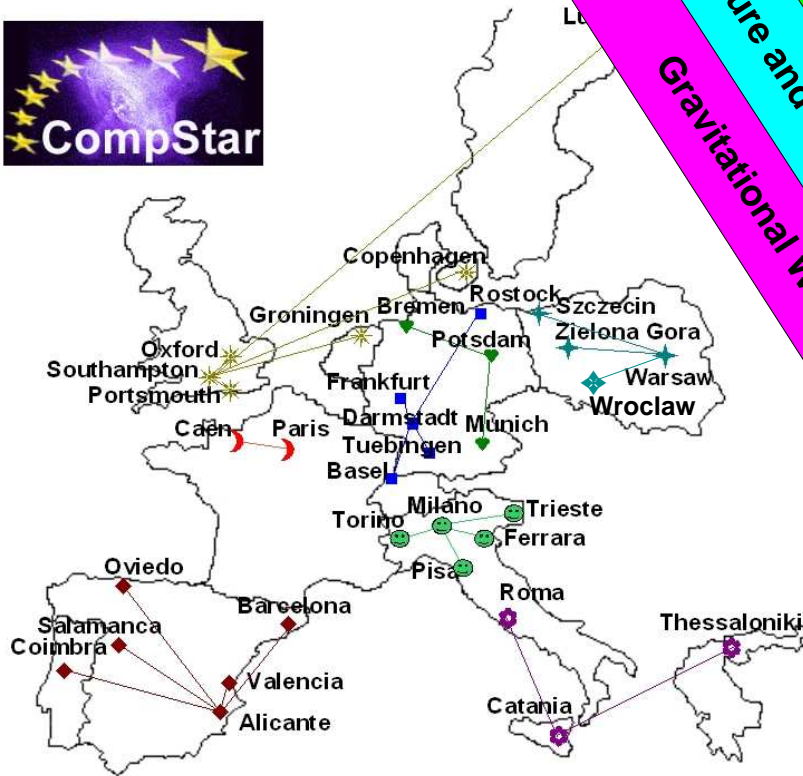


Next steps

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

New ways to understand dense Matter

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



DIAS-TH: Dubna International Advanced School of Theoretical Physics
Helmholtz International Summer School

Dense Matter in Heavy Ion Collisions and Astrophysics

Bogoliubov Laboratory of Theoretical Physics
JINR, Dubna, Russia, July 14-26, 2008

TOPICS:

- Hadrons in the Medium
- Equation of state and Phase Transitions
- Hadron Production and Heavy Ion Collisions
- Dense Matter in Compact Stars
- Future Experimental Facilities

ORGANIZERS:

- J. Wambach (GSI, TU Darmstadt)
- V. Voronov (JINR)
- D. Blaschke (JINR, U Wroclaw)

LOCAL ORGANIZERS:

- A. Sorin (JINR)
- J. Schmelzer (U Rostock, JINR)
- V. Zhuravlev (JINR)
- V. Skokov (sc. secretary, JINR)
- A. Dolya (secretary, JINR)

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- Joint Institute for Nuclear Research
- Russian Foundation for Basic Research

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Invitations

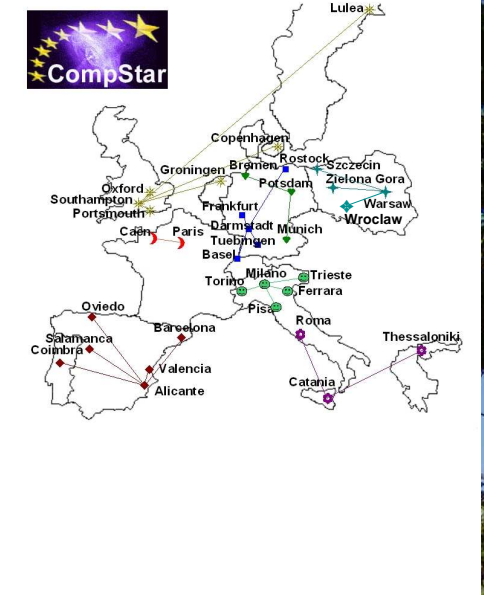
Helmholtz International Summer School
“Dense Matter in Heavy-Ion Collisions
and Astrophysics”,
Dubna, Russia, July 14-26, 2008
<http://theor.jinr.ru/~dm2008>

ECT* Workshop
“Heavy Quarkonia Production in Heavy-Ion
Collisions”
Trento, Italy, October 2008
<http://www.ect.it>

ESF Research Networking Programme
“CompStar” (2008-2013)
<http://www.esf.org/compstar>

PERSPECTIVES

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



Thanks to the Organizers!



... and the patient audience !

