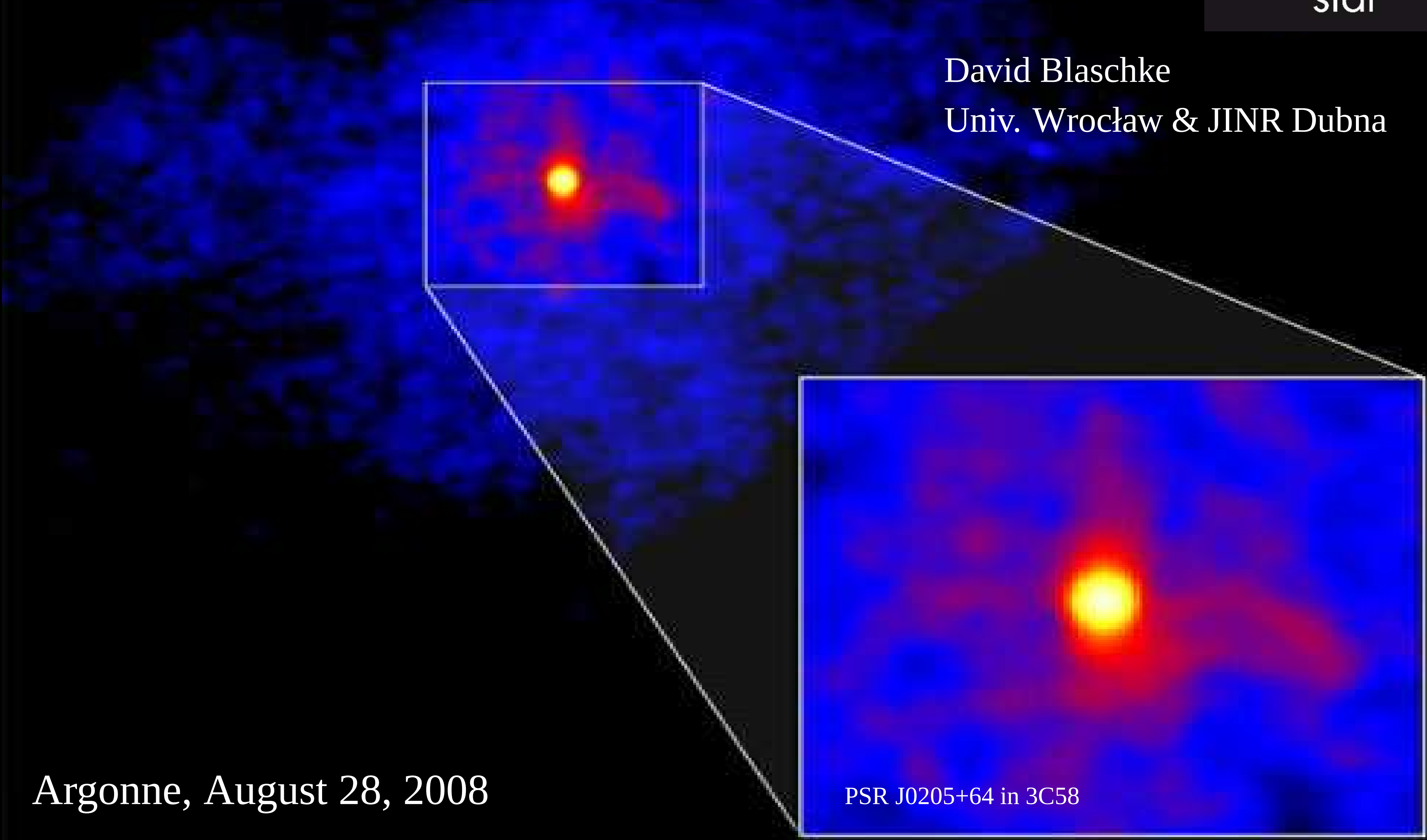
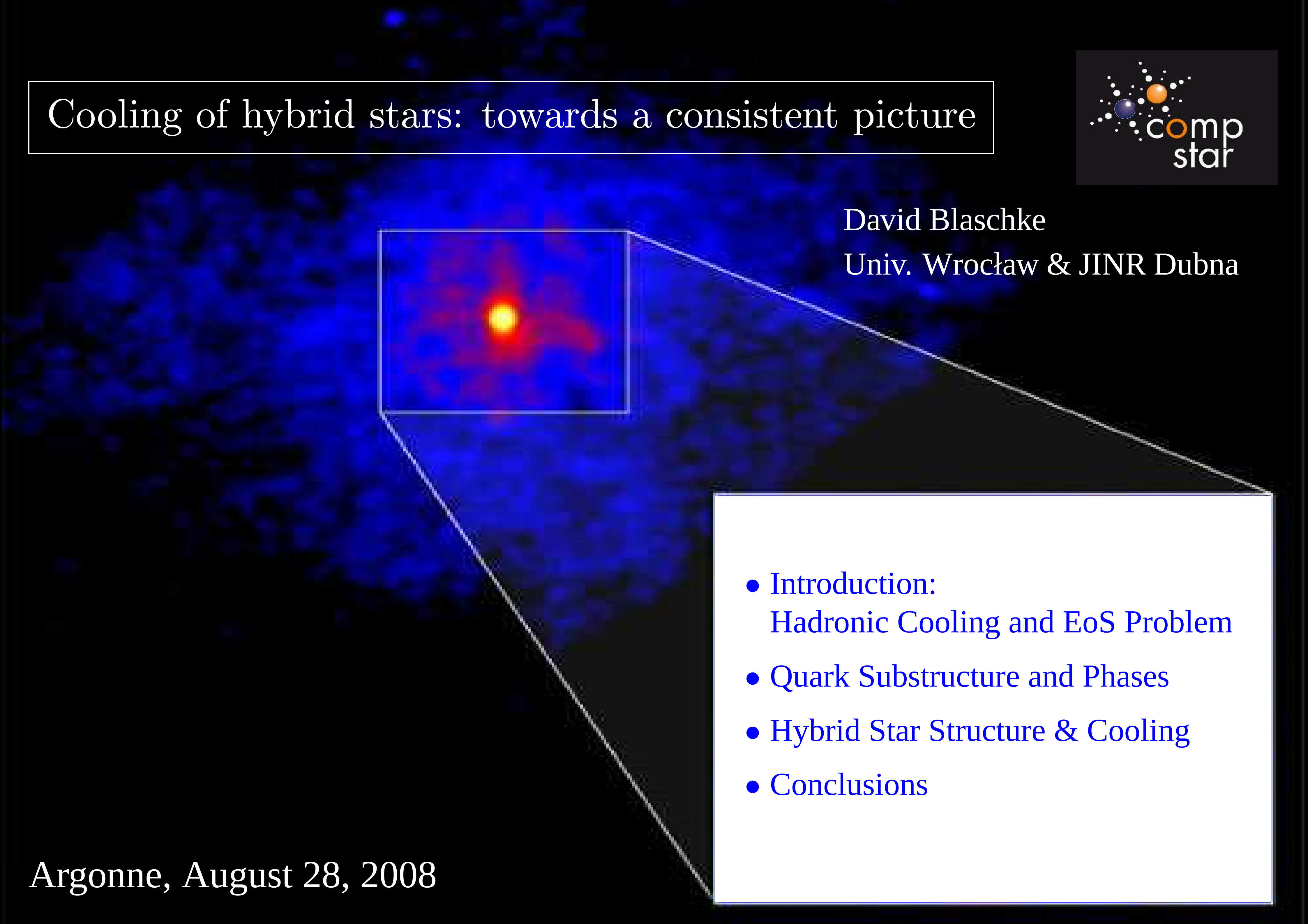
Cooling of hybrid stars: towards a consistent picture

David Blaschke
Univ. Wrocław & JINR Dubna



Argonne, August 28, 2008

Cooling of hybrid stars: towards a consistent picture



David Blaschke
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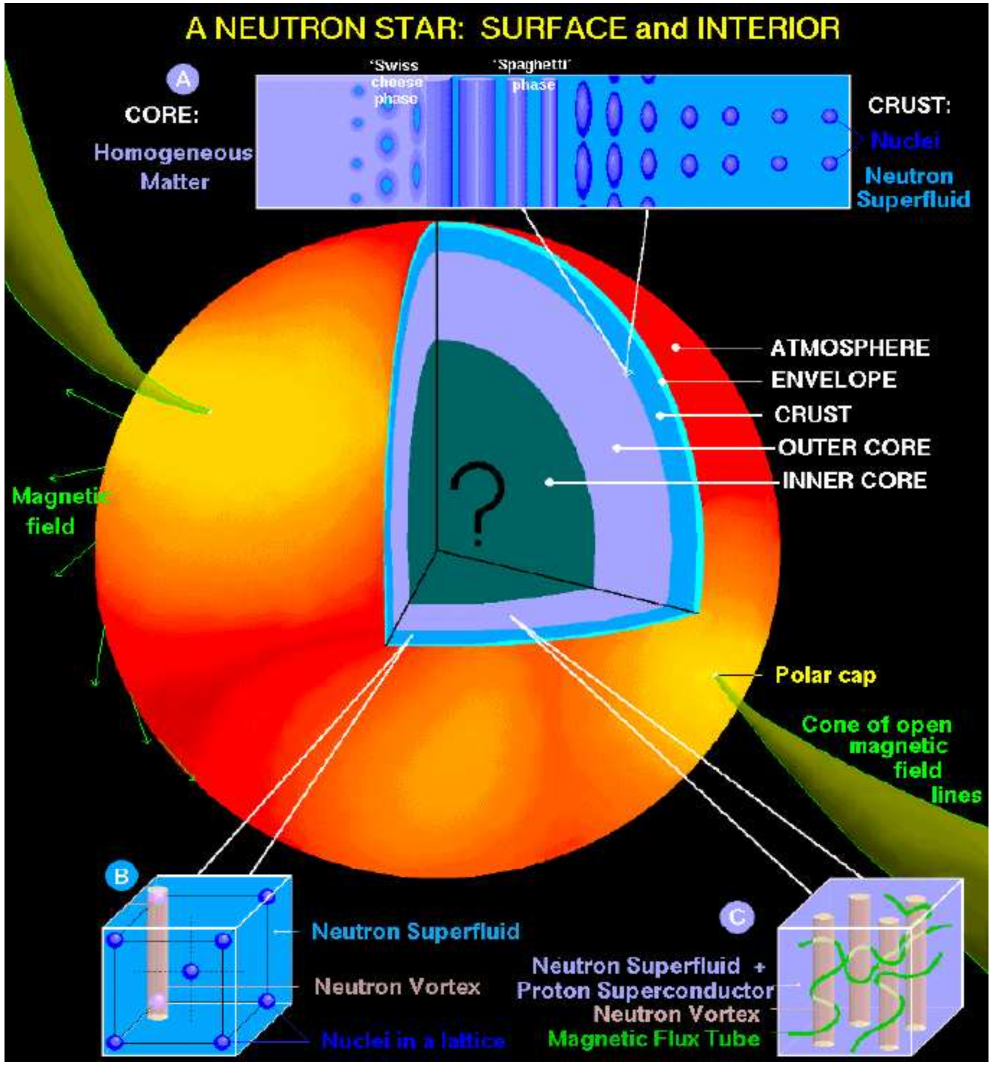
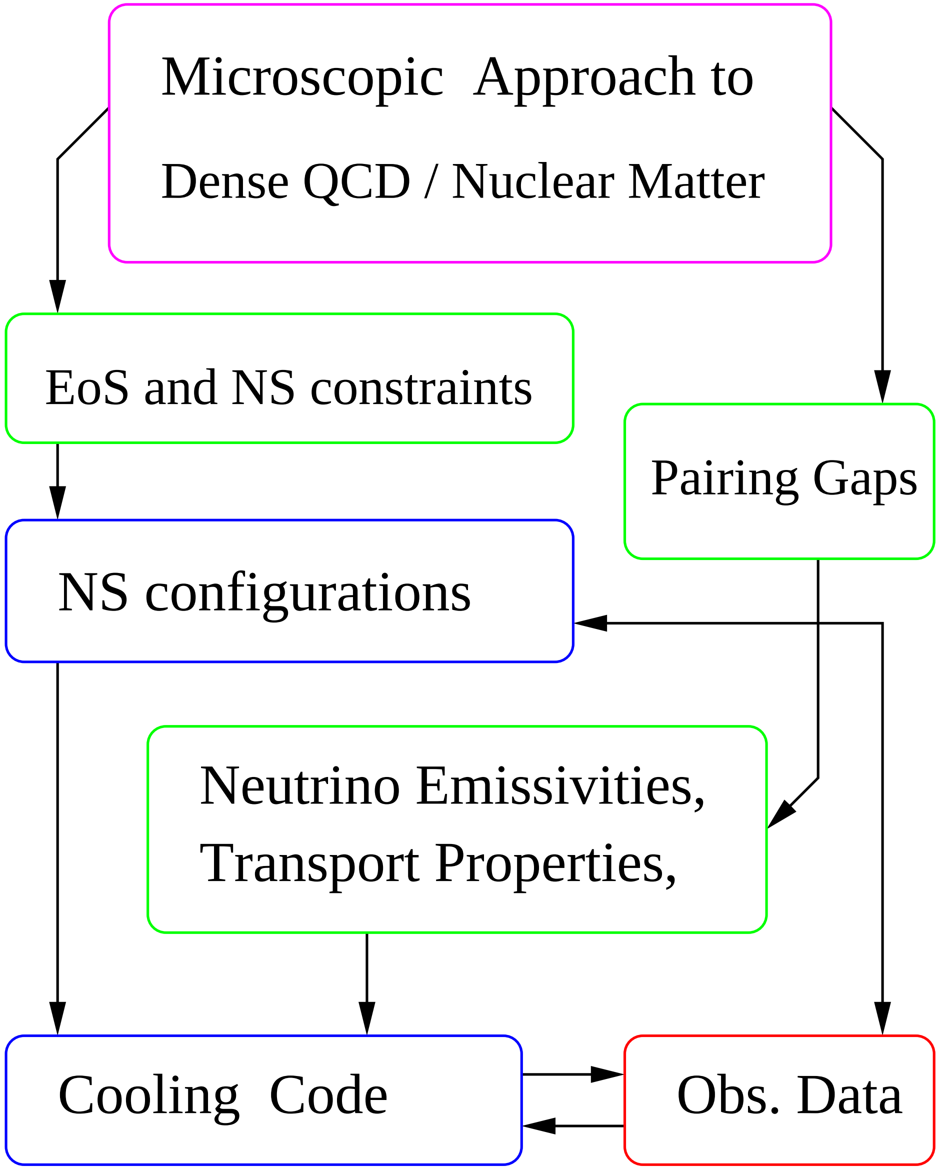
- Introduction:
  Hadronic Cooling and EoS Problem
- Quark Substructure and Phases
- Hybrid Star Structure & Cooling
- Conclusions

Argonne, August 28, 2008

Compact Star Cooling - A Complex Problem



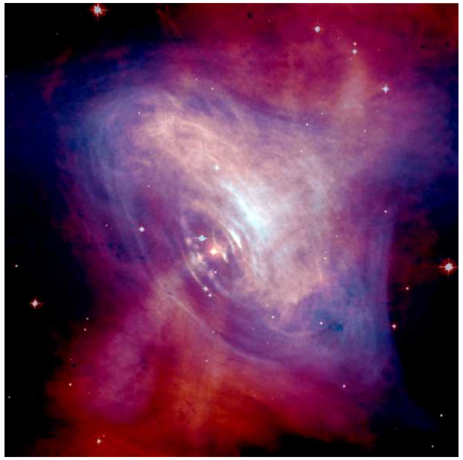
Picture taken from
http://www.astroscu.unam.mx/neutrones/NS-Picture/



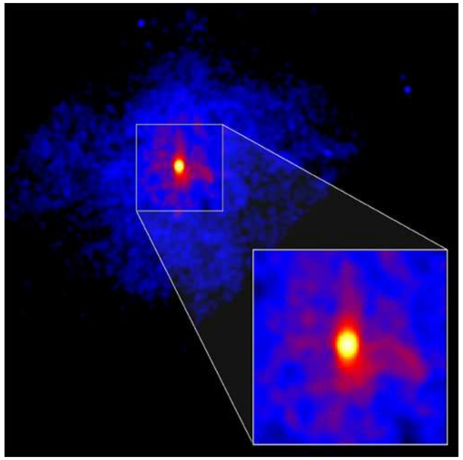
Compact Star Cooling - Introduction

Pulsars in SN remnants:

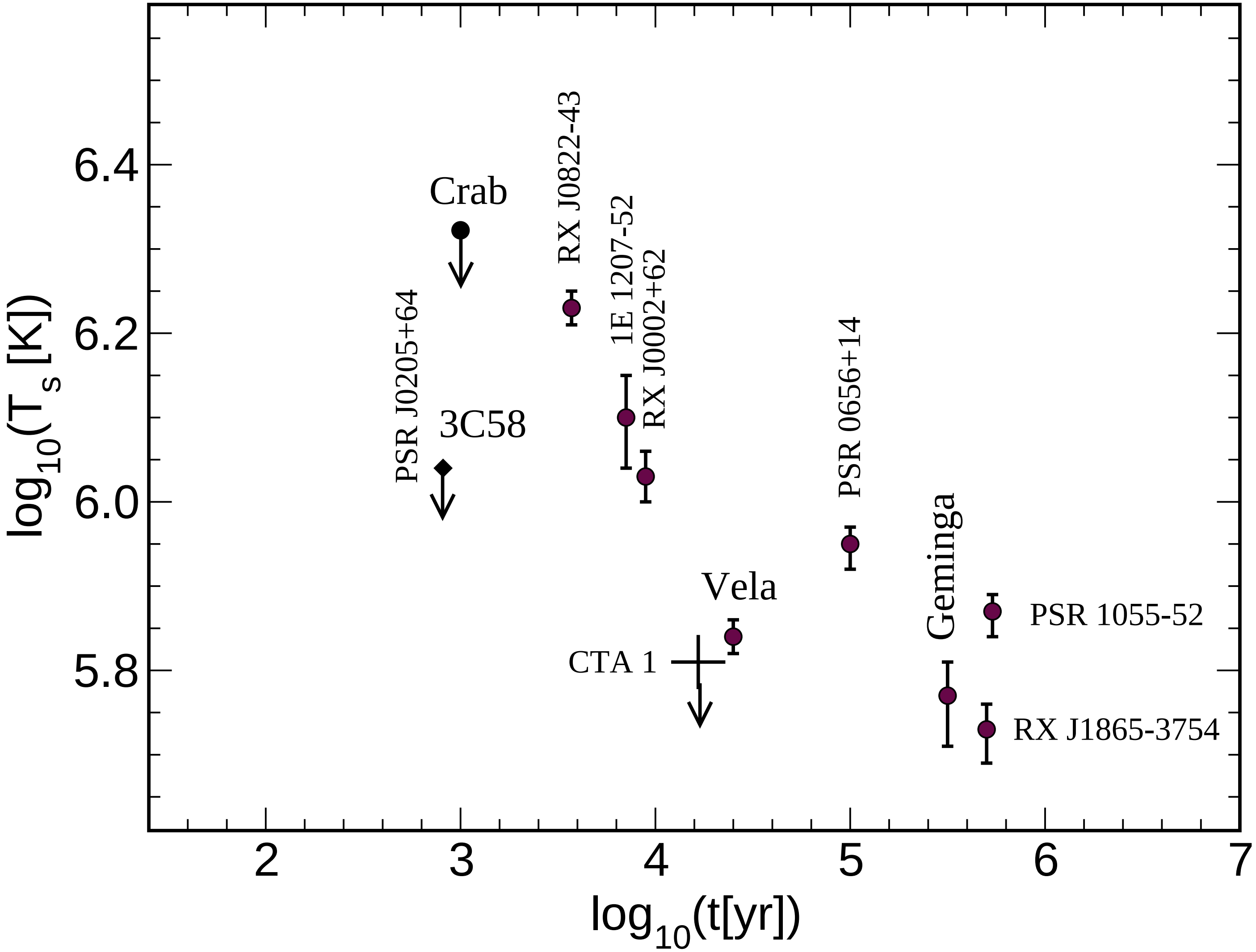
1054 - Crab



1181 - 3C58



Temperature - age plot: characterizes compact star matter properties



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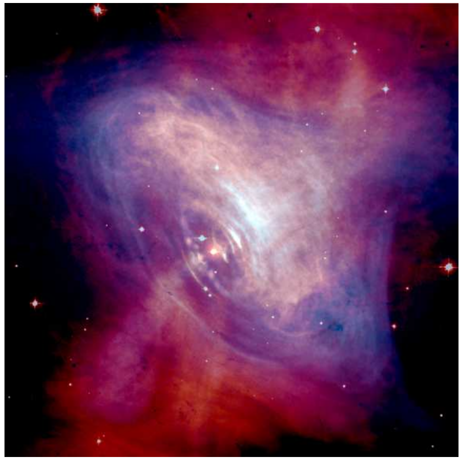

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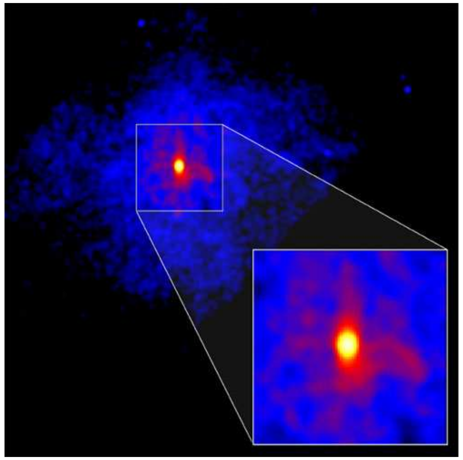
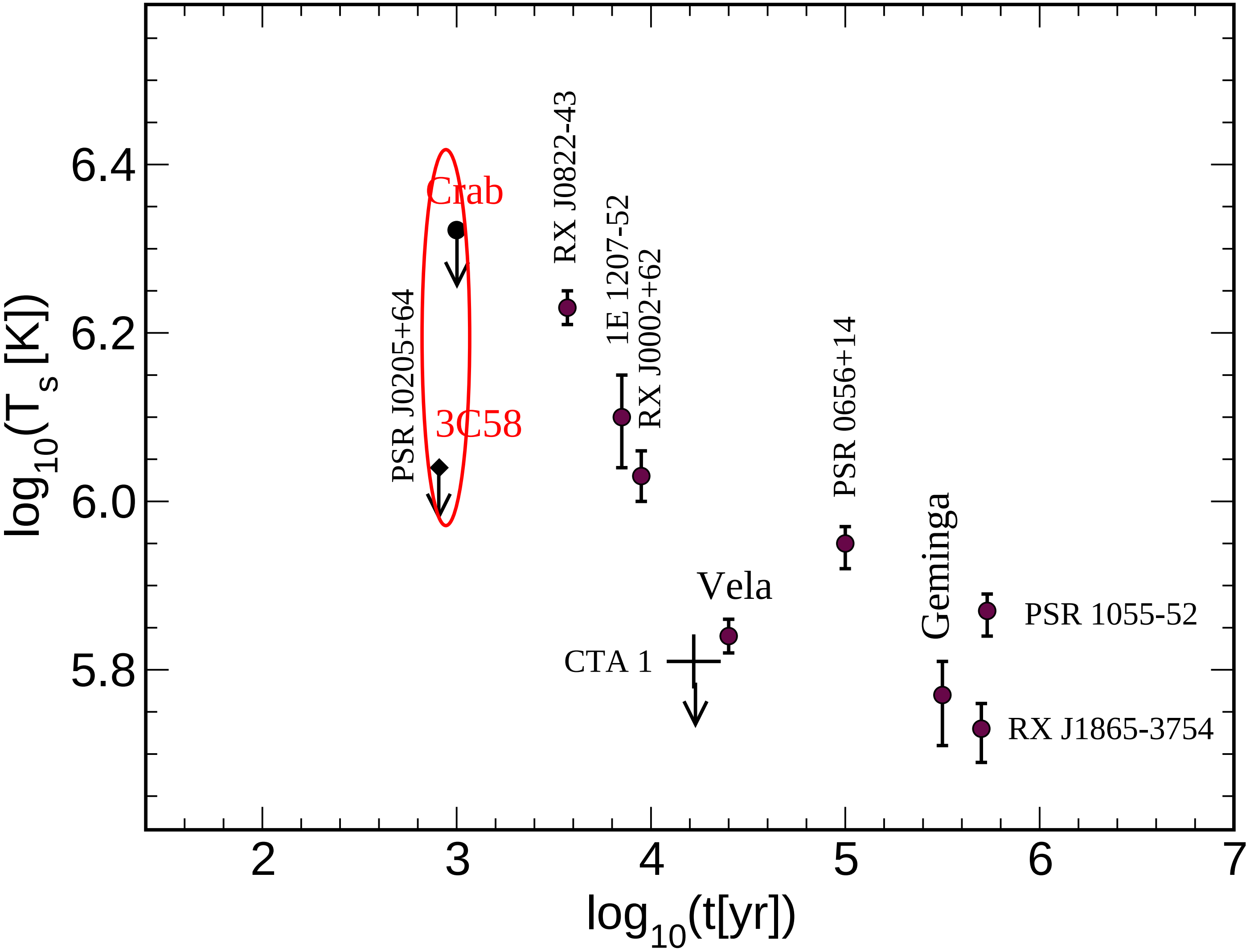
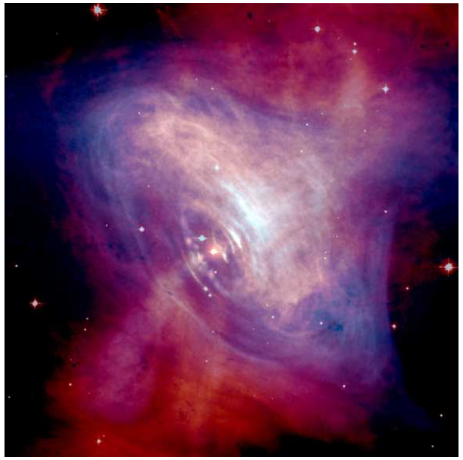


Too cool for its age: Quark matter in PSR J0205+64 ? (NASA 2002)



Compact Star Cooling - Phenomenology

Pulsars in SN remnants:
1054 - Crab



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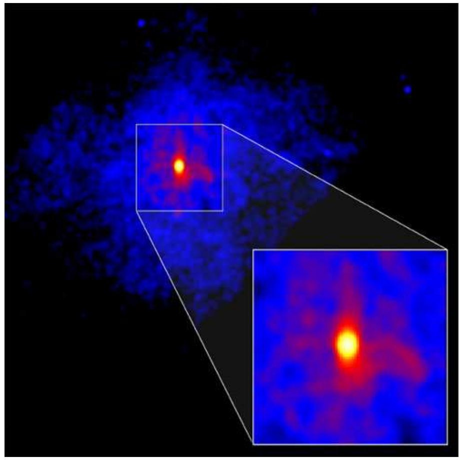

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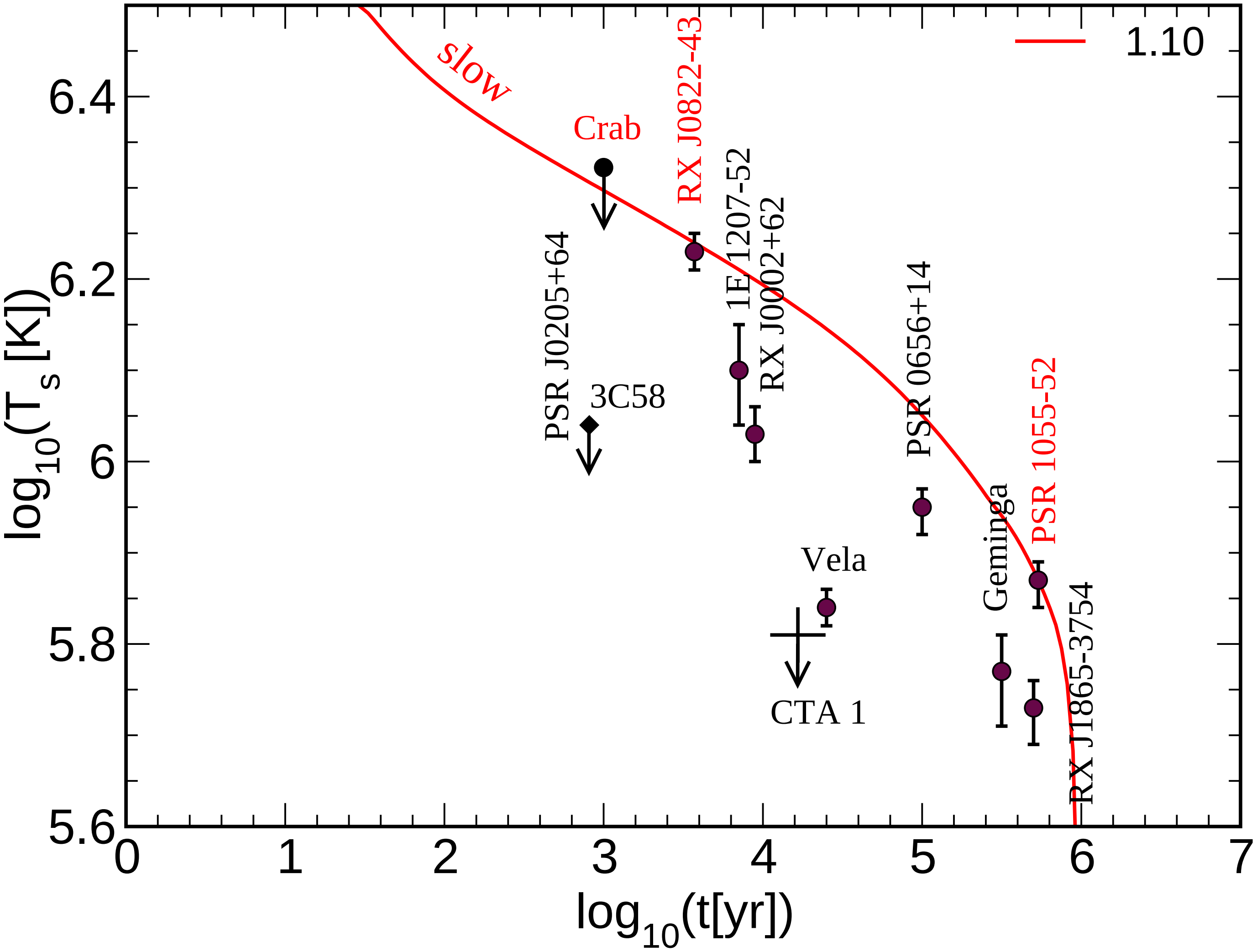

Compact Star Cooling - Introduction

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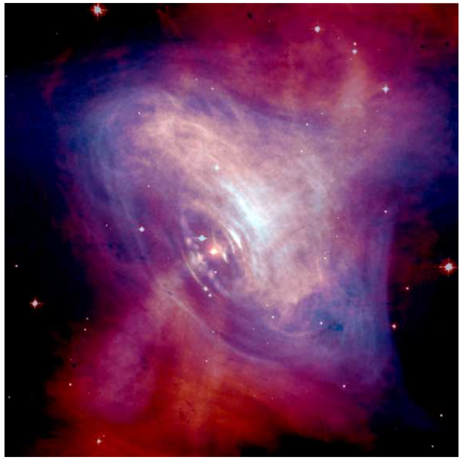

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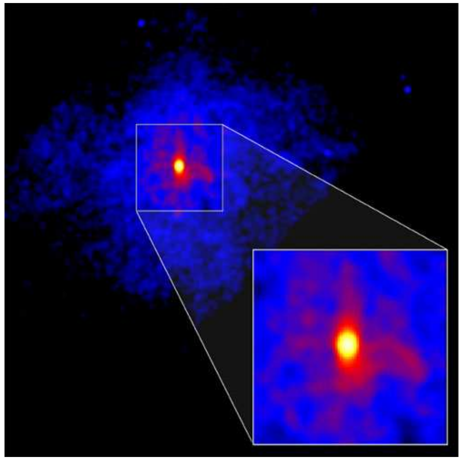

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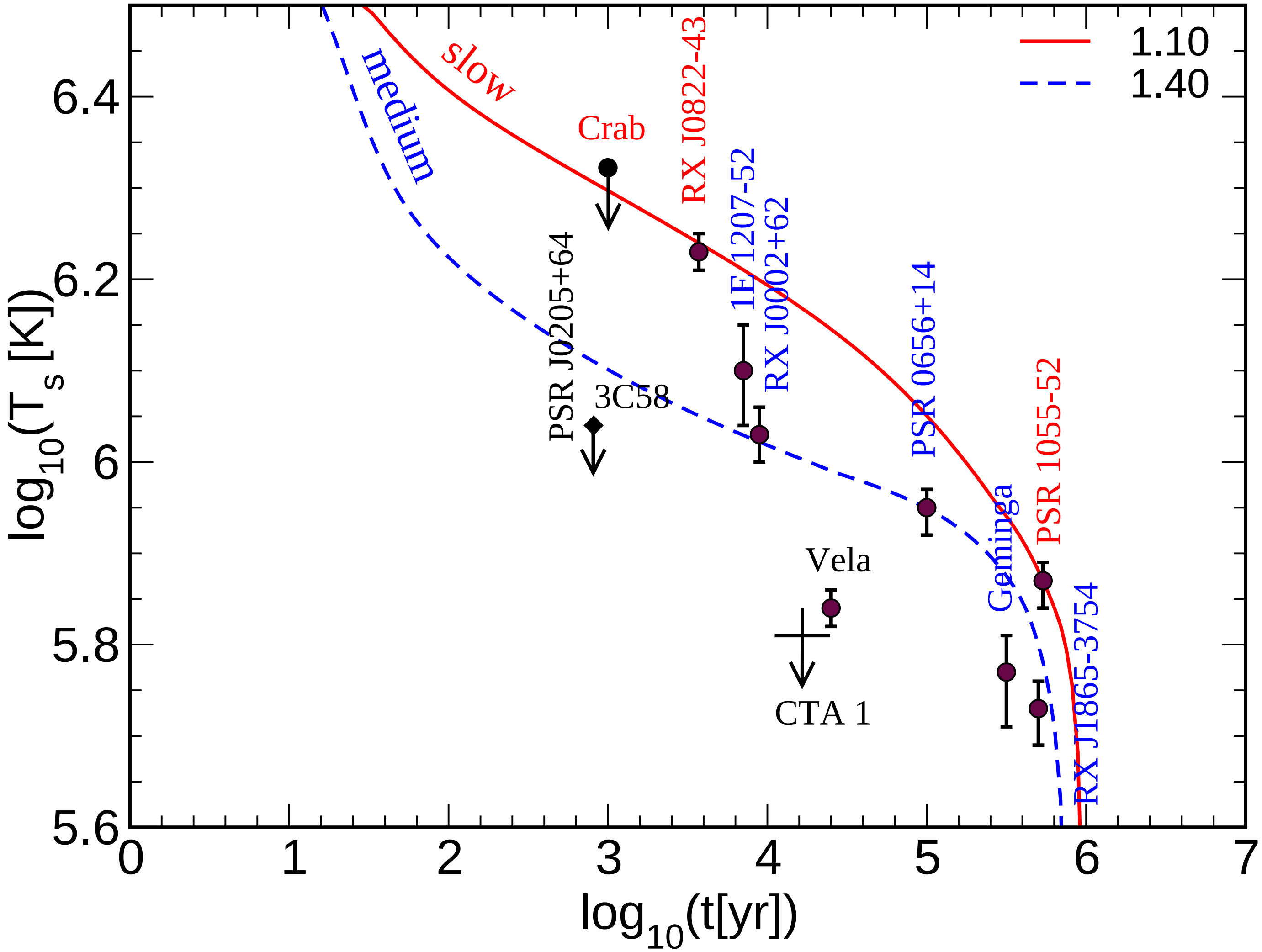

Compact Star Cooling - Introduction

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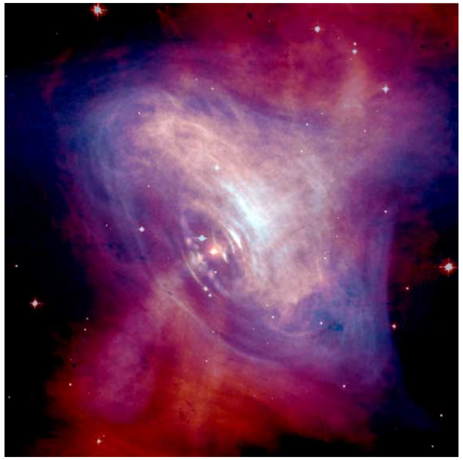

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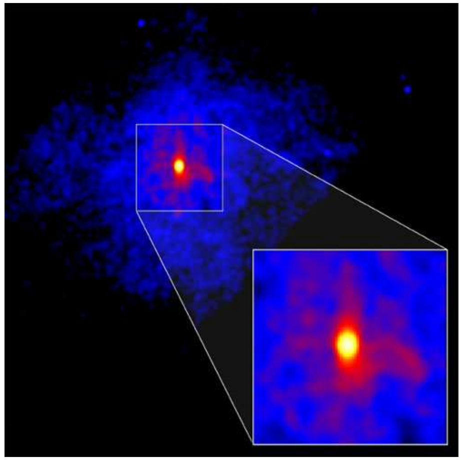
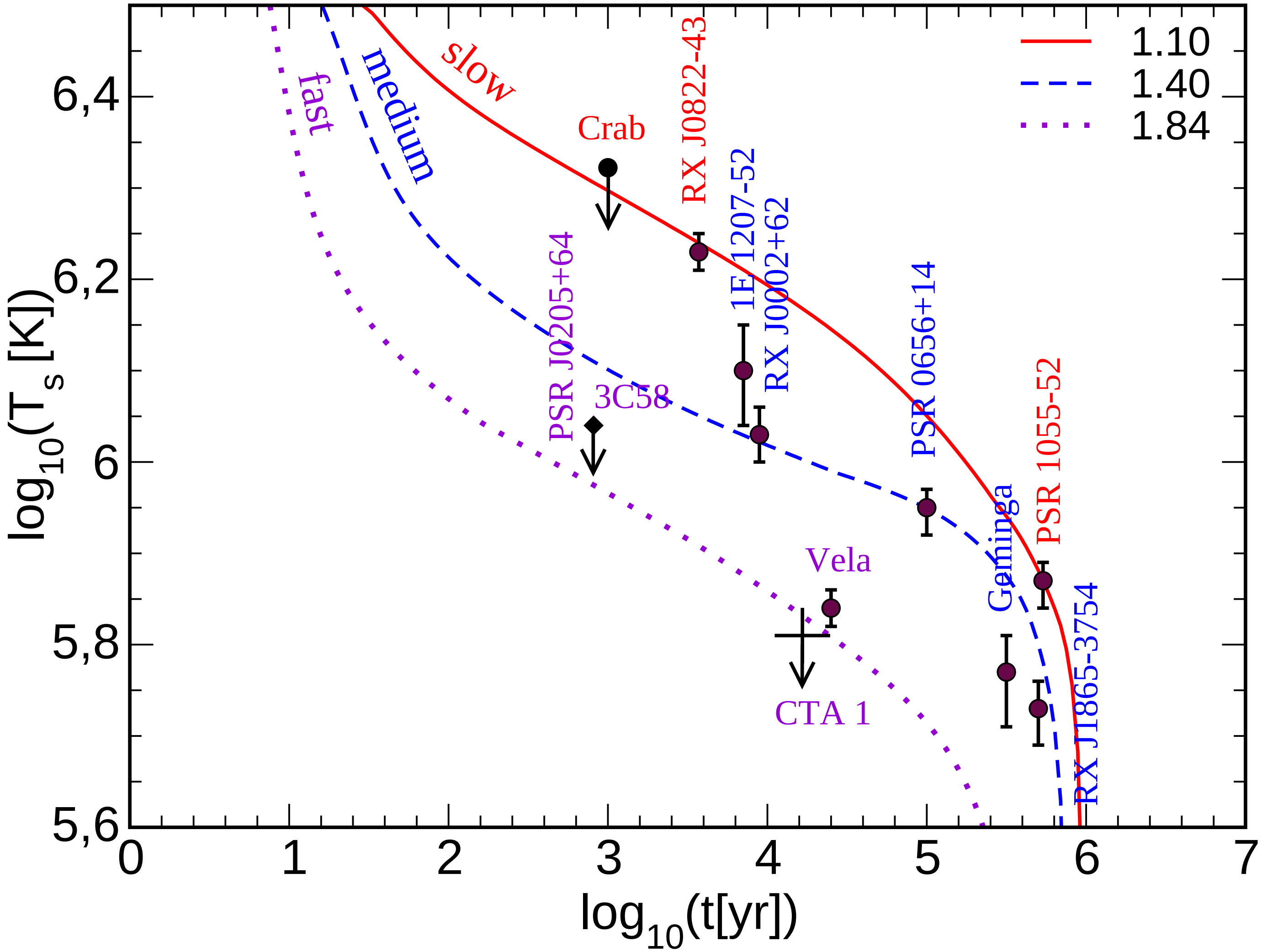


Classification of cooling compact stars



Compact Star Cooling - Hadronic Scenario

Pulsars in SN remnants:

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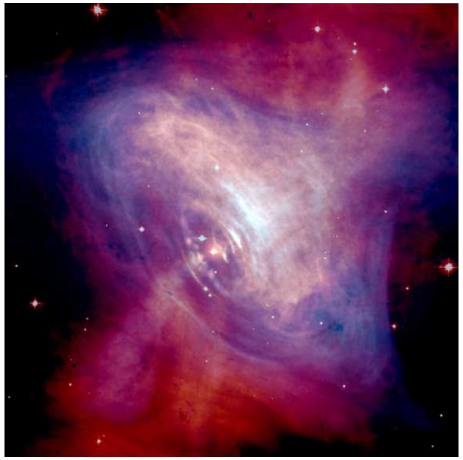

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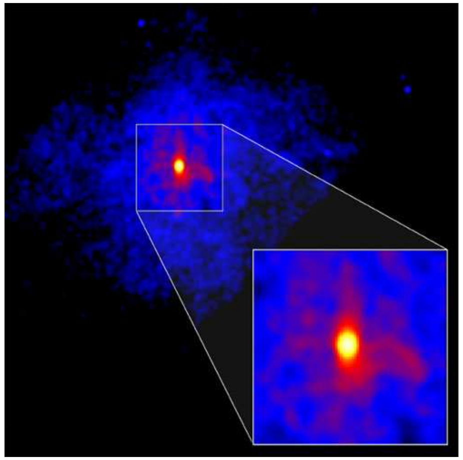
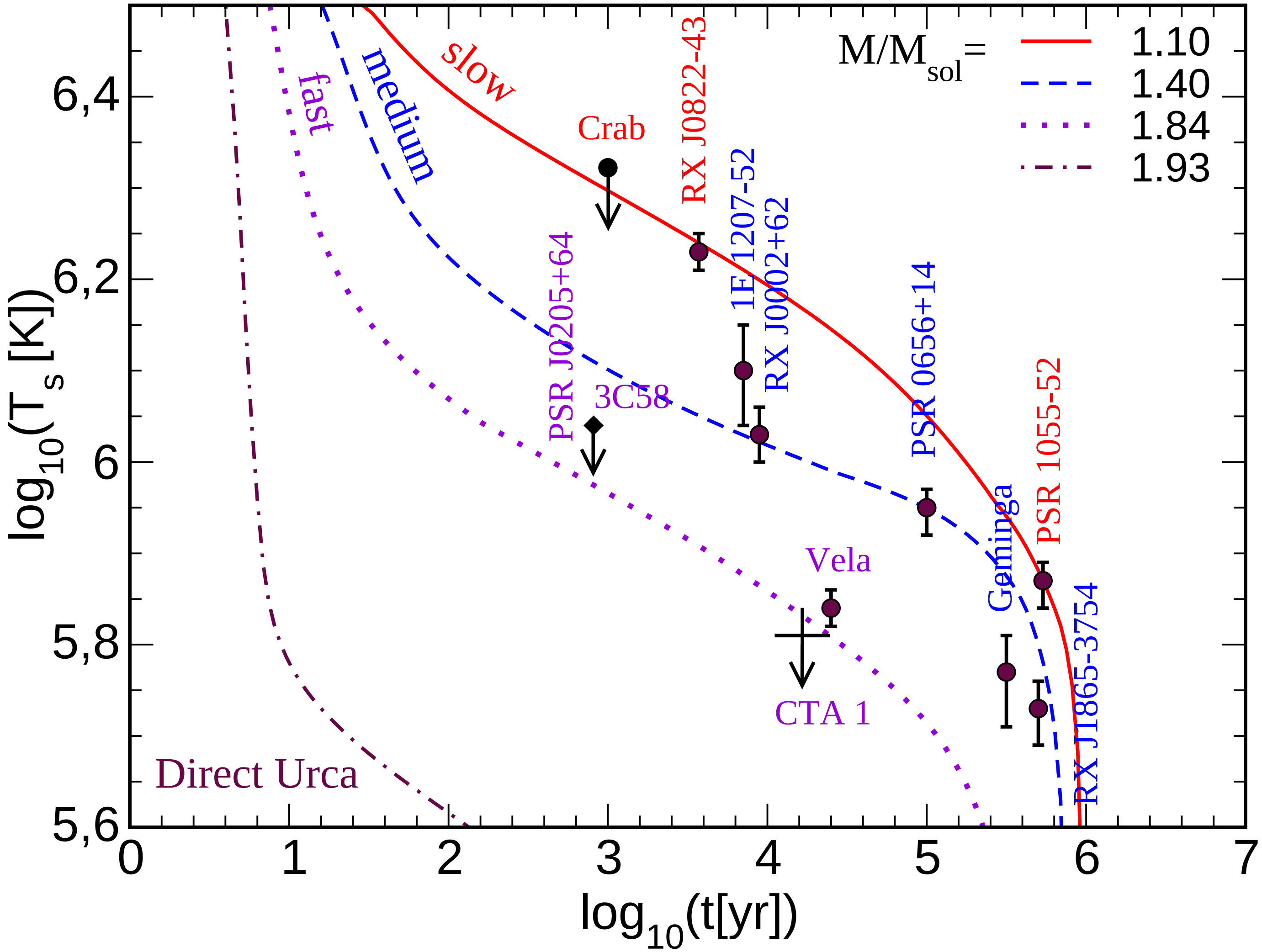


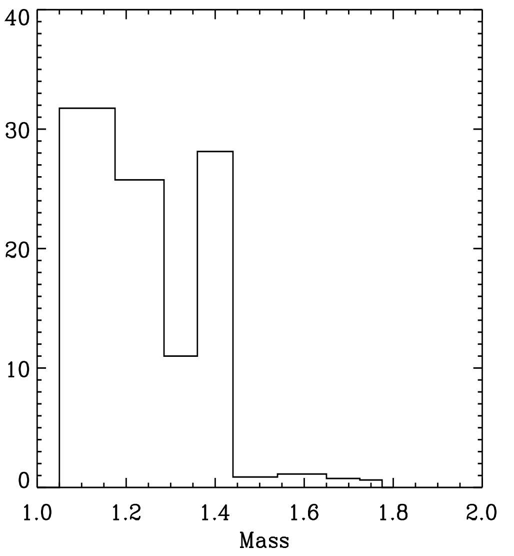
Classification of cooling compact stars: parameter - mass

D.B., Grigorian, Voskresensky, A& A 424, 979 (2004)



Compact Star Cooling - Hadronic Scenario

Mass distribution from population synthesis models for the solar vicinity

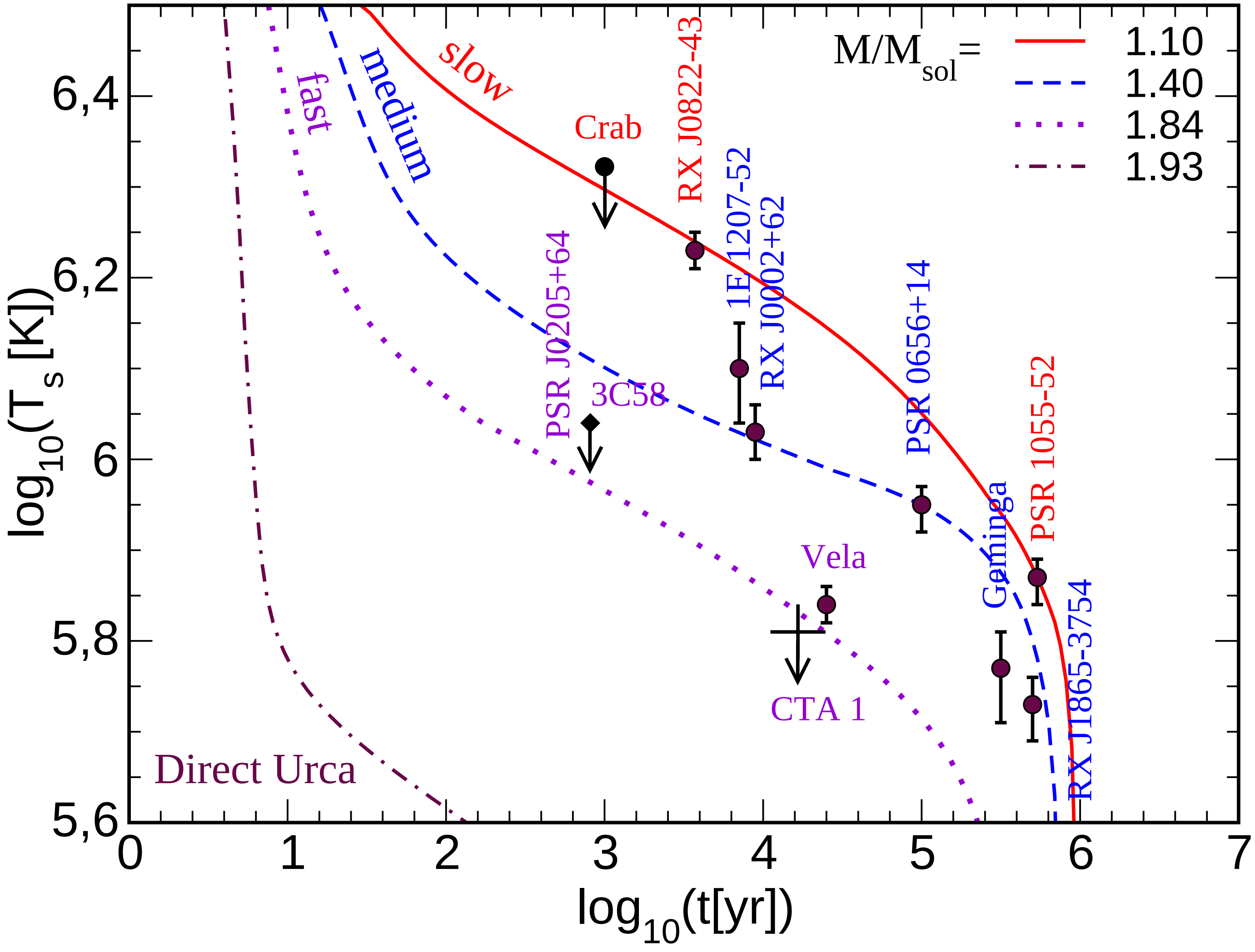


Popov et al: A&A 448 (2006)

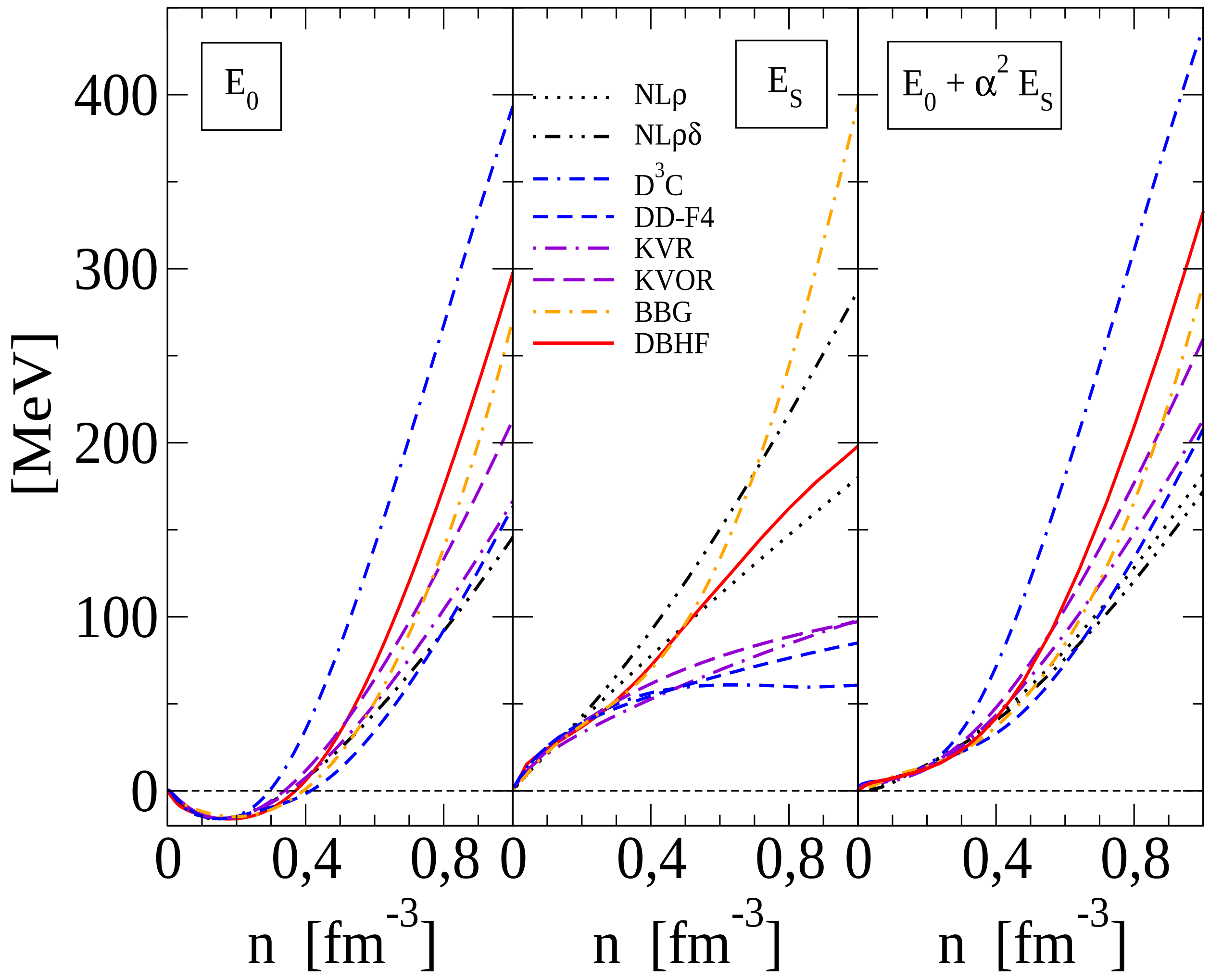
Typical radiopulsar masses ($1.4\ M_\odot$) not sufficient to explain, e.g., Vela cooling

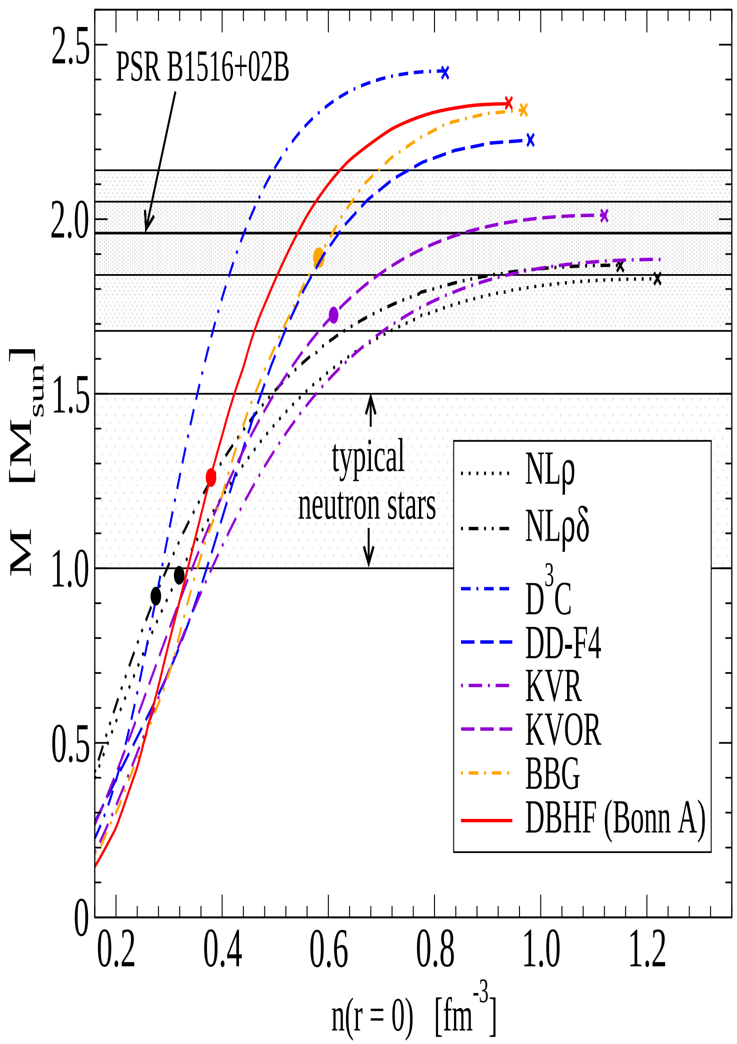
Classification of cooling compact stars: parameter - mass

D.B., Voskresensky, Grigorian, A& A 424, 979 (2004)



EoS and masses - DU constraint

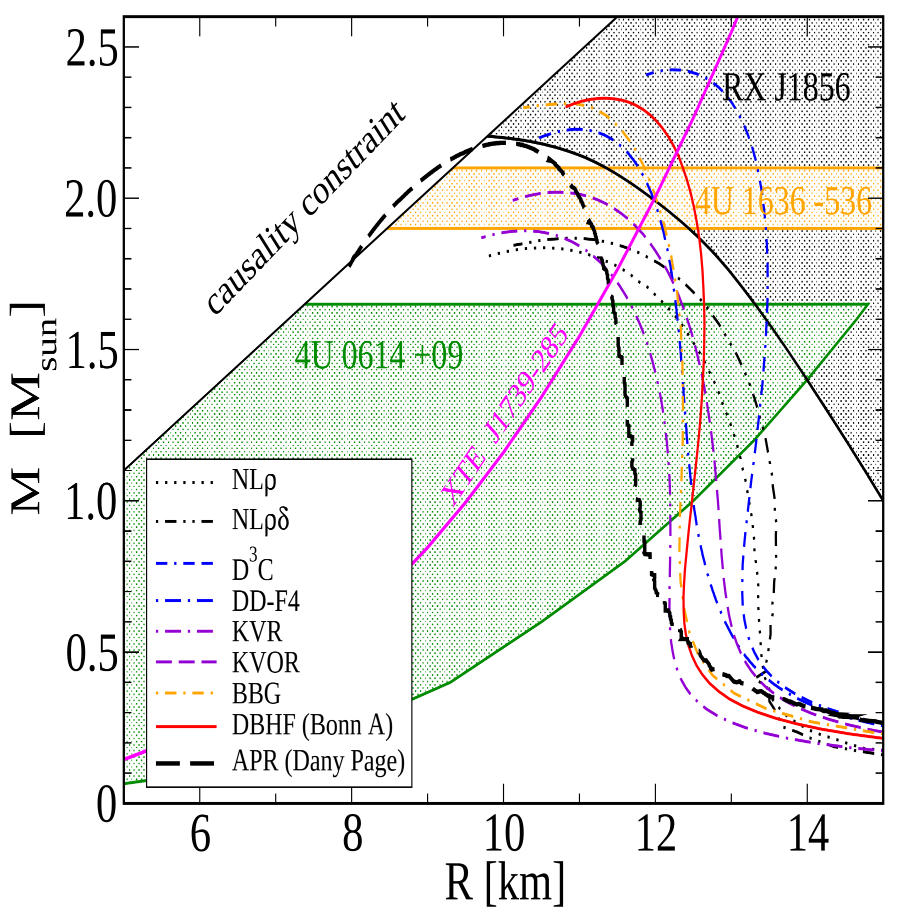


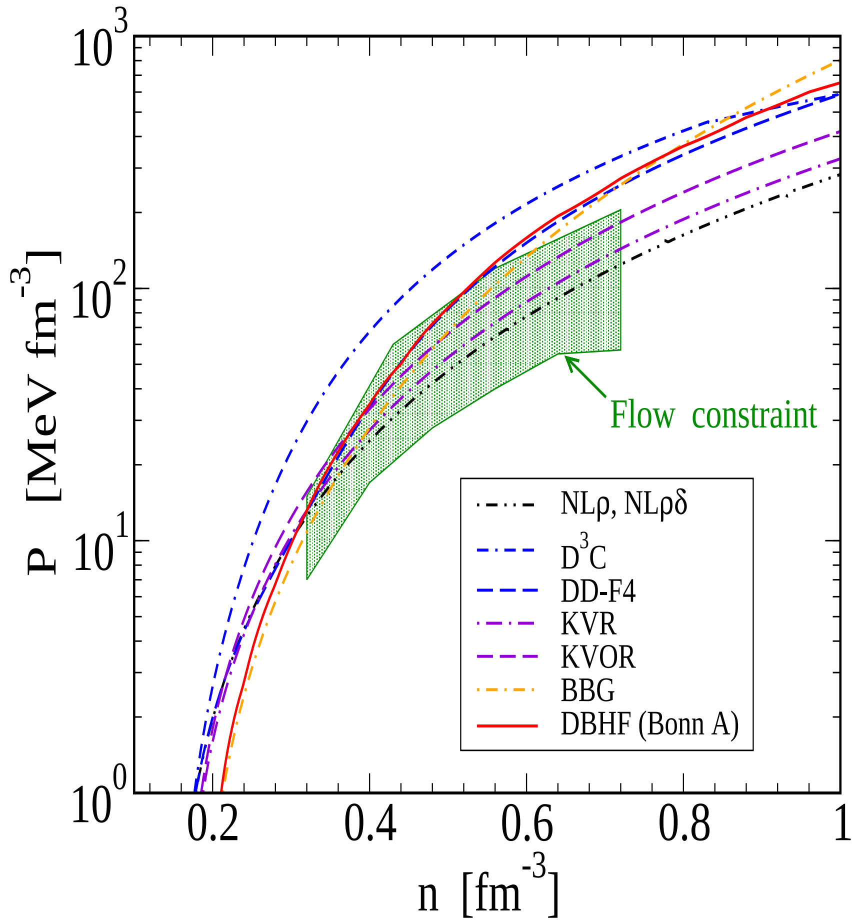


DU threshold for most hadronic EoS active in neutron stars with typical masses !

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

Mass-Radius constraint and Flow constraint



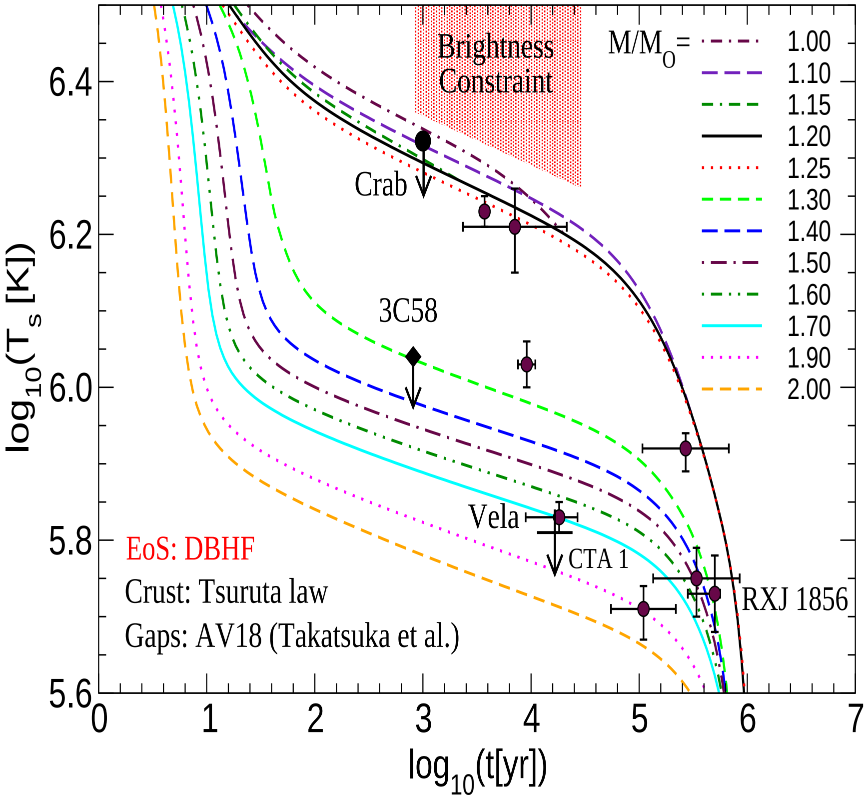


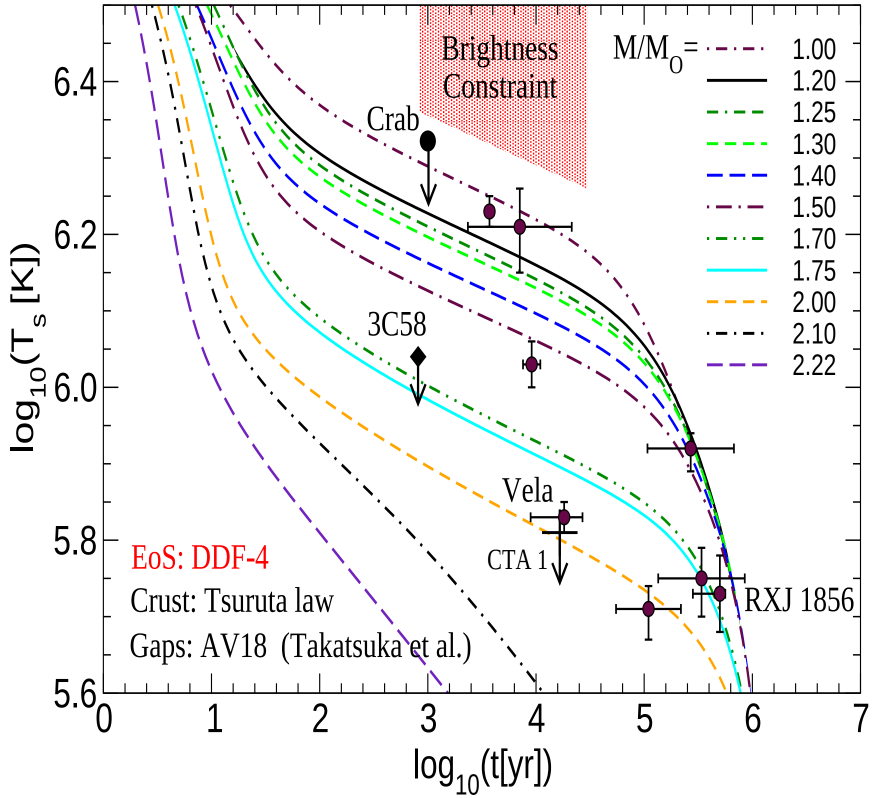
- Large Mass ($\sim 2\, M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;

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

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

DU threshold and 'hadronic' neutron stars (II)

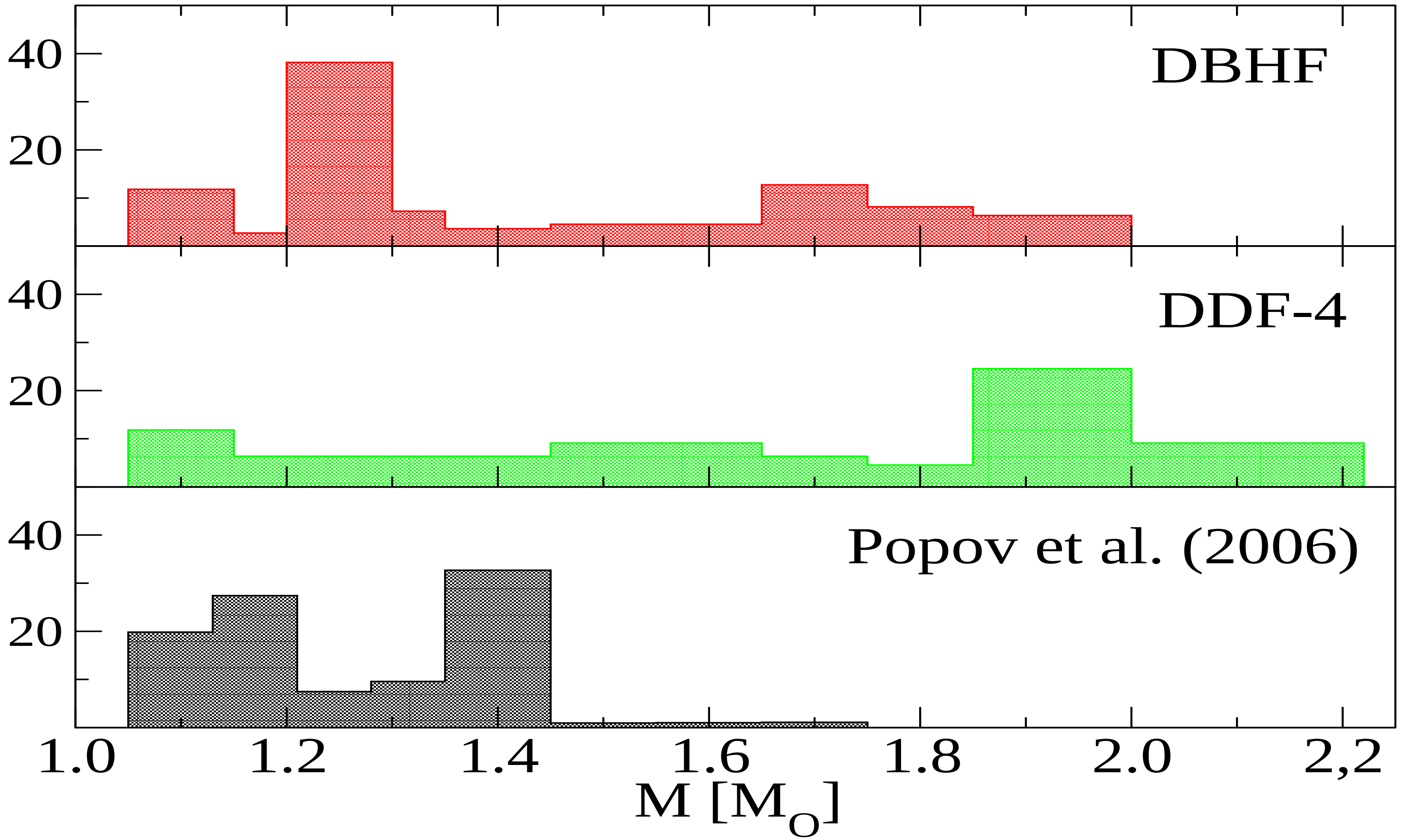




- DU threshold ⇒ sensitivity to tiny mass variations;
- Description of Vela not possible with typical masses !

S. Popov et al., PRC 74 (2006); D.B. and H. Grigorian, Prog. Part. Nucl. Phys. 59 (2007) 139

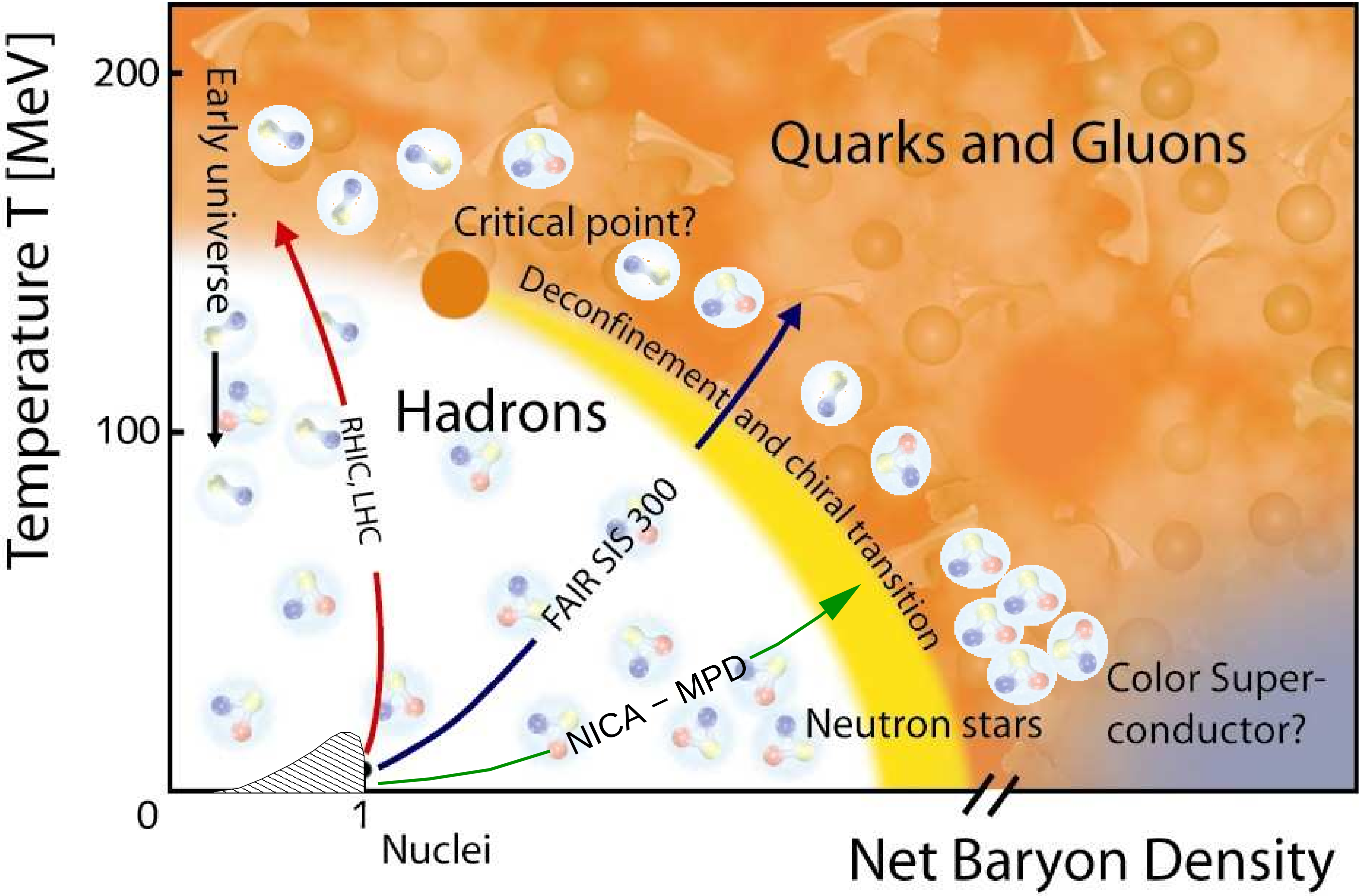
DU threshold and 'hadronic' neutron stars (III)



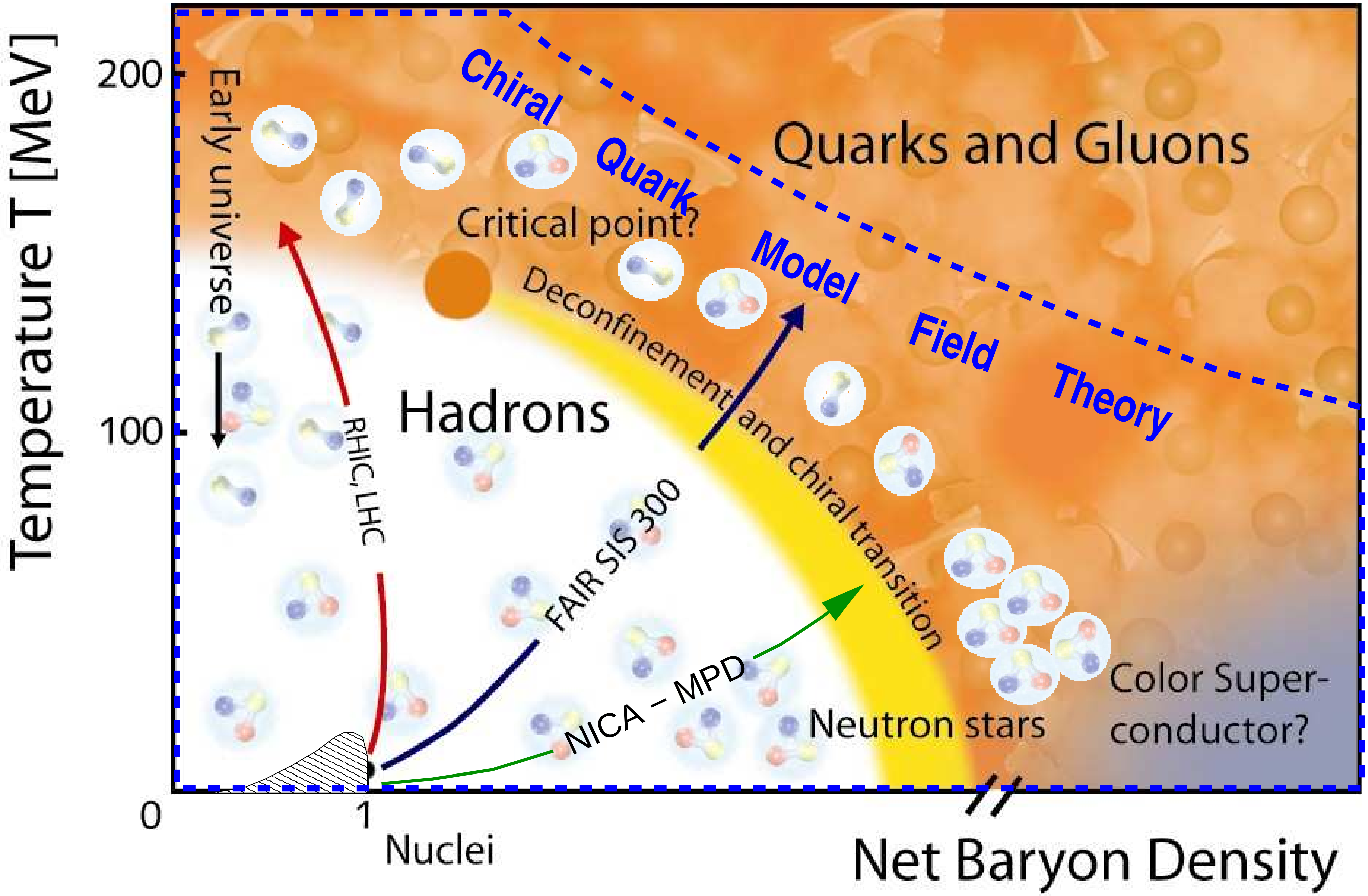
- DU threshold: overpopulation of a small mass window;
- Hadronic cooling not fast enough to describe Vela with $M < 1.5\ M_\odot$!

D.B. and H. Grigorian, Prog. Part. Nucl. Phys. 59 (2007) 139; [astro-ph/0612092]

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)

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

- Bosonisation (Hubbard-Stratonovich Transformation)

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

- 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

Phase diagram for 3-Flavor Quark Matter

Thermodynamic Potential $\Omega(T,\mu) = -T \ln Z[T,\mu]$

$$\Omega(T,\mu) \;=\; \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} - T\sum_n \int \frac{d^3p}{(2\pi)^3}\frac{1}{2}\mathrm{Tr}\ln\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right) + \Omega_e - \Omega_0 .$$

$$\mathrm{InverseNambu-GorkovPropagator} \quad S^{-1}(i\omega_n,\vec{p}) = \begin{bmatrix} \gamma_\mu p^\mu - M(\vec{p}) + \mu\gamma^0 & \widehat{\Delta}(\vec{p}) \\ \widehat{\Delta}^\dagger(\vec{p}) & \gamma_\mu p^\mu - M(\vec{p}) - \mu\gamma^0 \end{bmatrix},$$

$$\Delta_{k\gamma} = 2G_D\langle \bar{q}_{i\alpha} i\gamma_5 \epsilon_{\alpha\beta\gamma}\epsilon_{ijk} g(\vec{q}) q^C_{j\beta}\rangle . \quad \widehat{\Delta}(\vec{p}) = i\gamma_5\epsilon_{\alpha\beta\gamma}\epsilon_{ijk}\Delta_{k\gamma} g(\vec{p}).$$

Fermion Determinant (Tr ln D = ln det D)

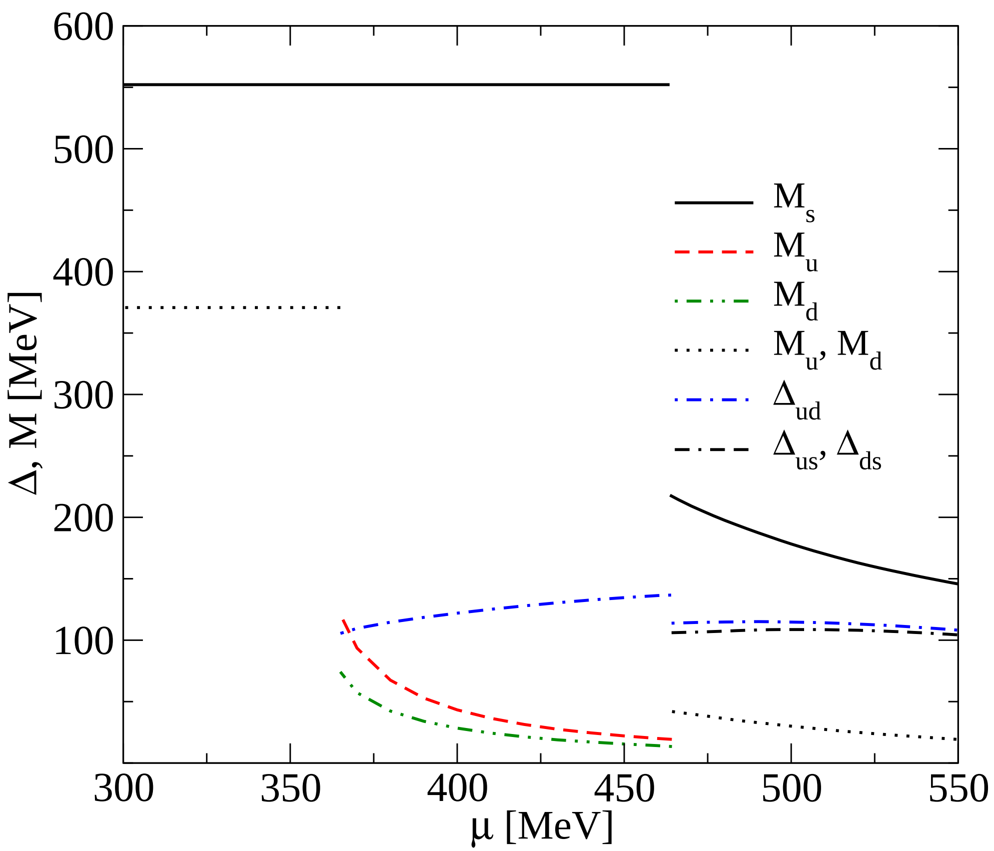
$$\mathrm{lndet}\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right) = 2\sum_{a=1}^{18}\ln\left(\frac{\omega_n^2+\lambda_a(\vec{p})^2}{T^2}\right).$$

Result for the thermodynamic Potential (Meanfield approximation)

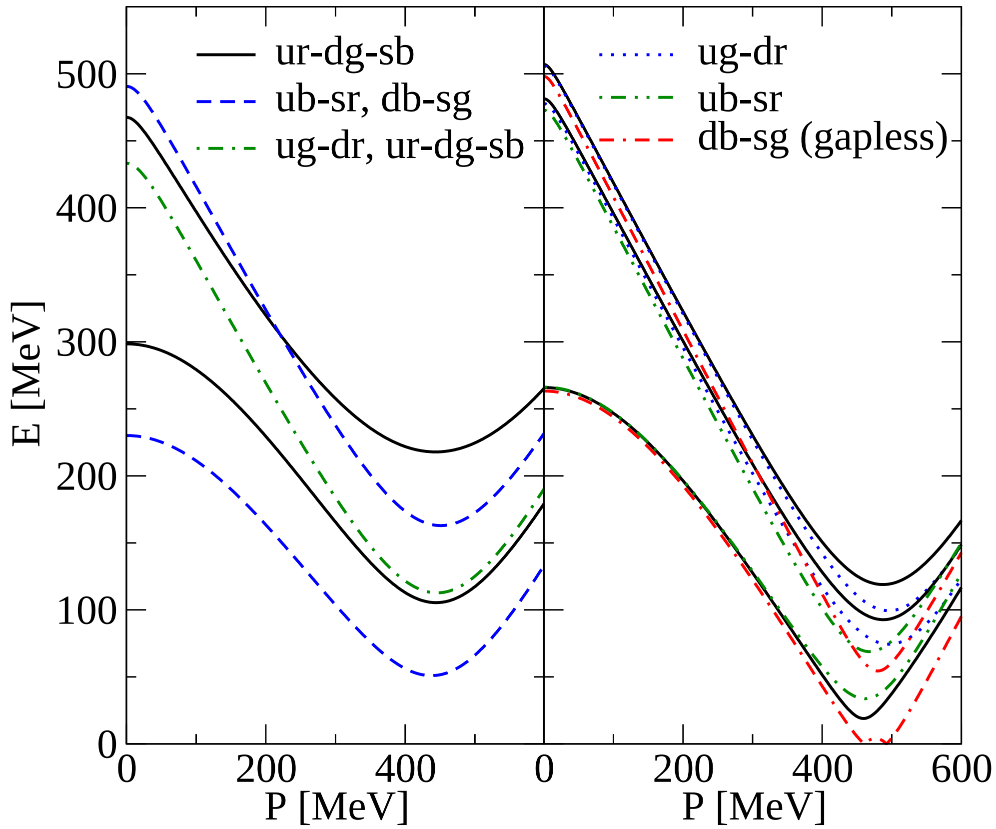
$$\Omega(T,\mu) \;=\; \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} - \int \frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left[\lambda_a + 2T\ln\left(1+e^{-\lambda_a/T}\right)\right] + \Omega_e - \Omega_0 .$$

Neutrality constraints: $n_Q = n_8 = n_3 = 0$, $n_i = -\partial\Omega/\partial\mu_i = 0$,
Equations of state: $P = -\Omega$, etc.

Quark Masses, Diquark Gaps, Gapless Modes



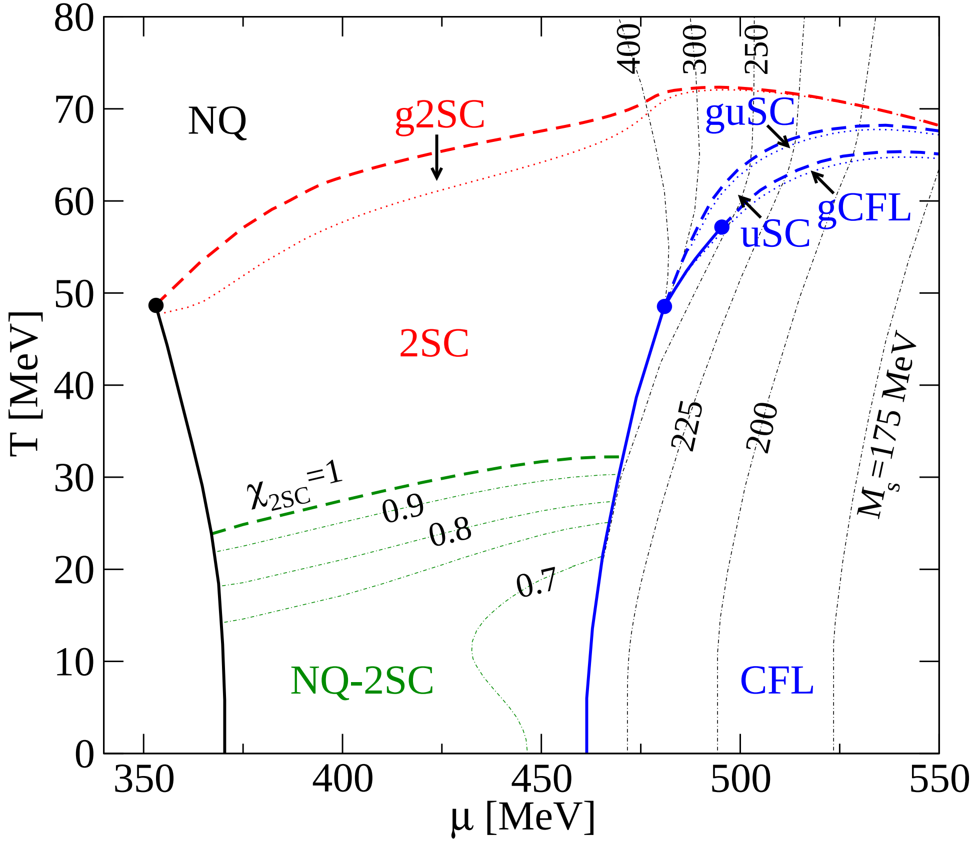
Dynamical quark masses and diquark gaps at $T = 0$ for intermediate diquark coupling $G_D = 0.75\ G_S$



Dispersion relations for $G_D = 0.75\ G_S$, $T = 0$, $\mu = 465$ MeV (left), $G_D = 1.0\ G_S$, $T = 59$ MeV, $\mu = 500$ MeV (right)

Rüster et al, PRD 72 (2005) 034004; Blaschke et al, PRD 72 (2005) 065020

Three-flavor Quark Matter Phase Diagram



The phases are:

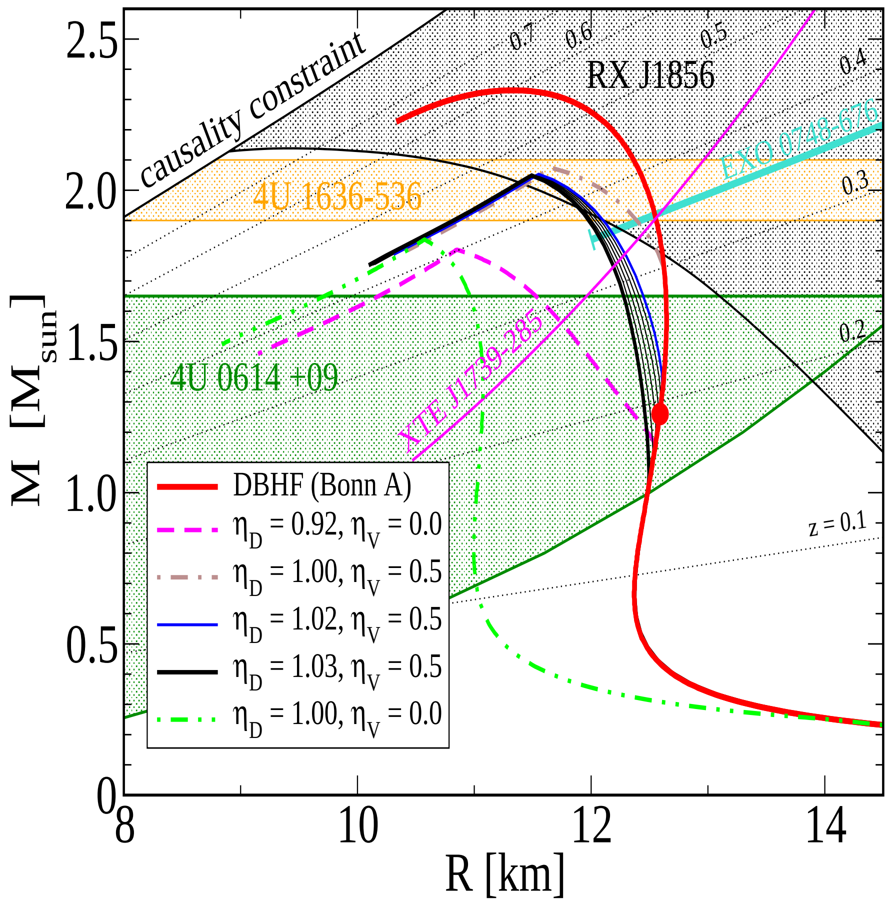
- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$, $0 \leq \chi_{2SC} \leq 1$;
- 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq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

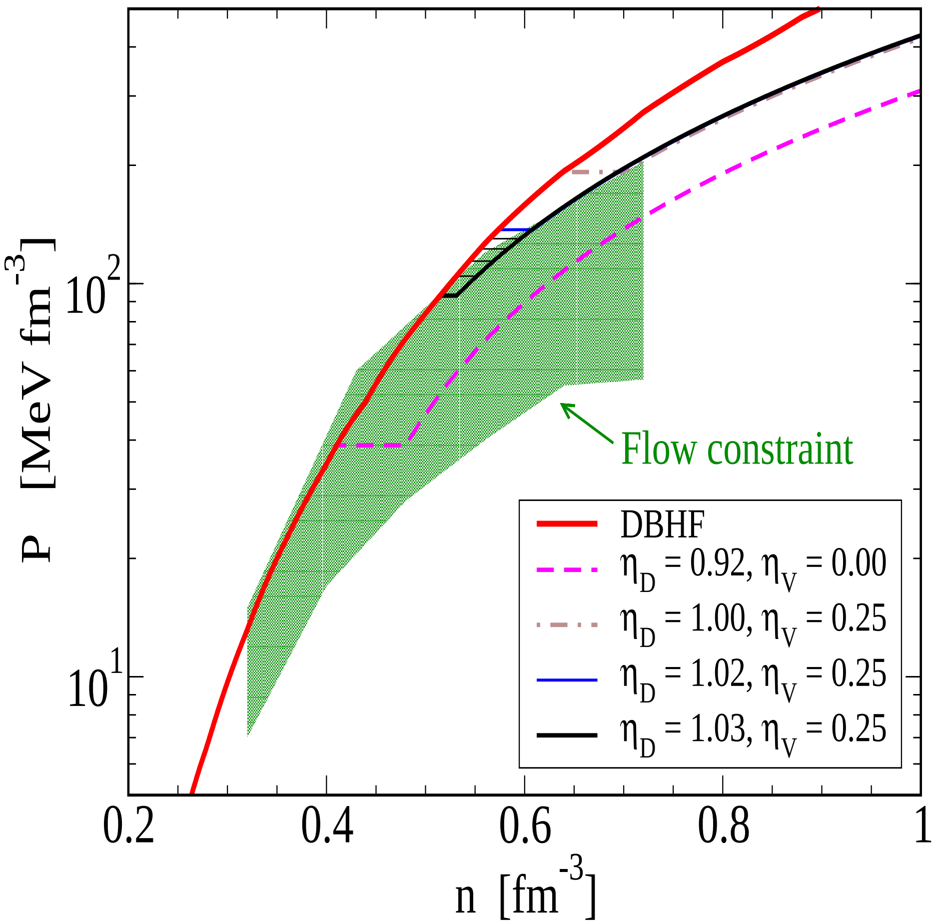
Result:

- 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.

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

Mass-Radius constraint and Flow constraint (II)

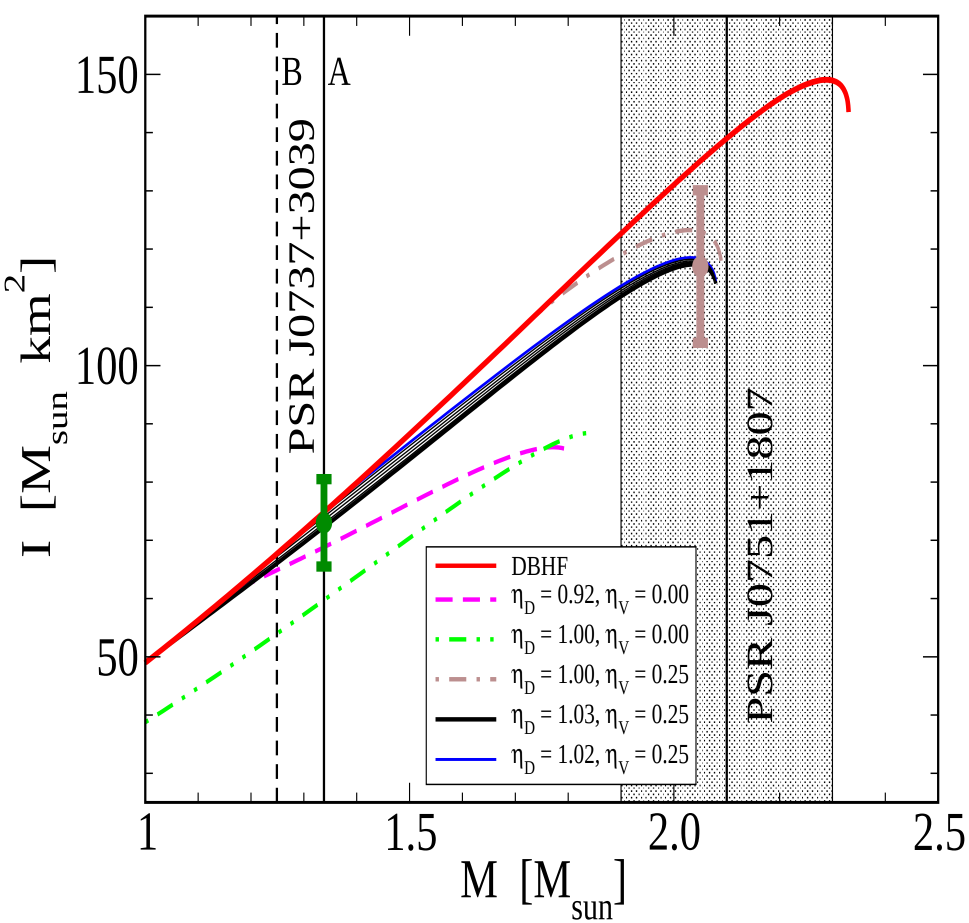


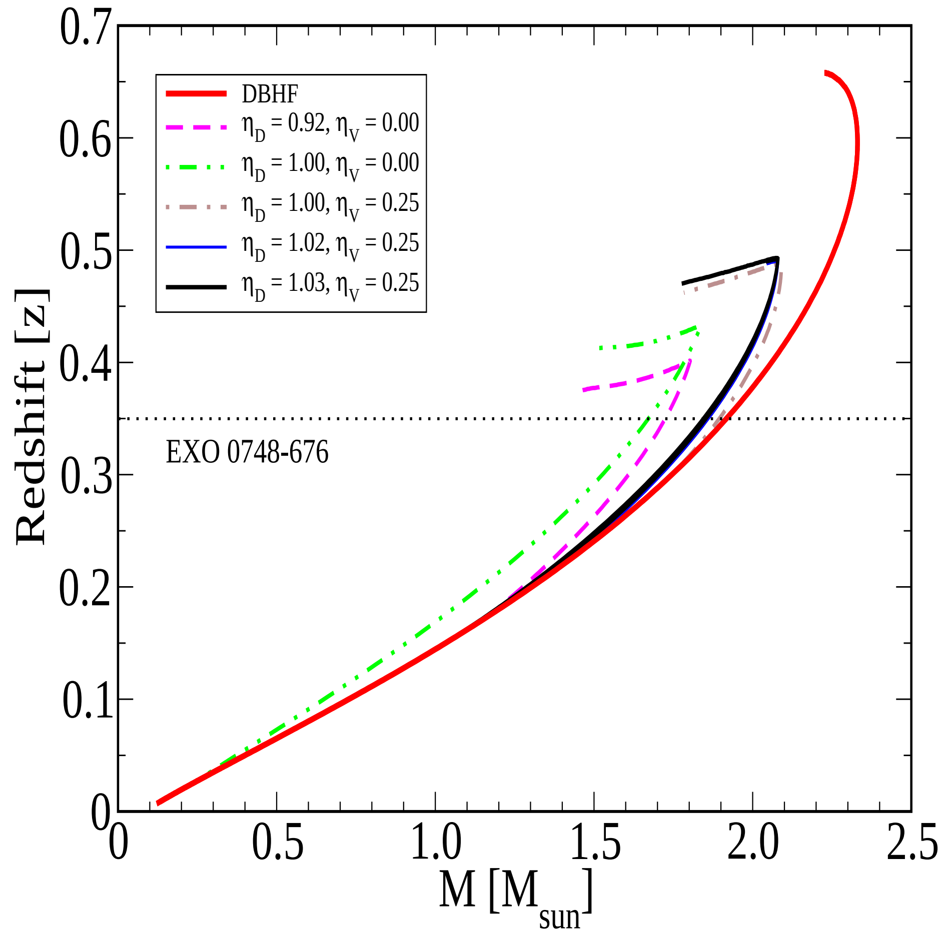


- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff quark matter EoS;
  Note: DU problem of DBHF removed by deconfi nement! and: CFL core Hybrids unstable!
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !
  Note: Quark matter removes violation by DBHF at high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

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

Hybrid Stars that masquerade as Neutron Stars*

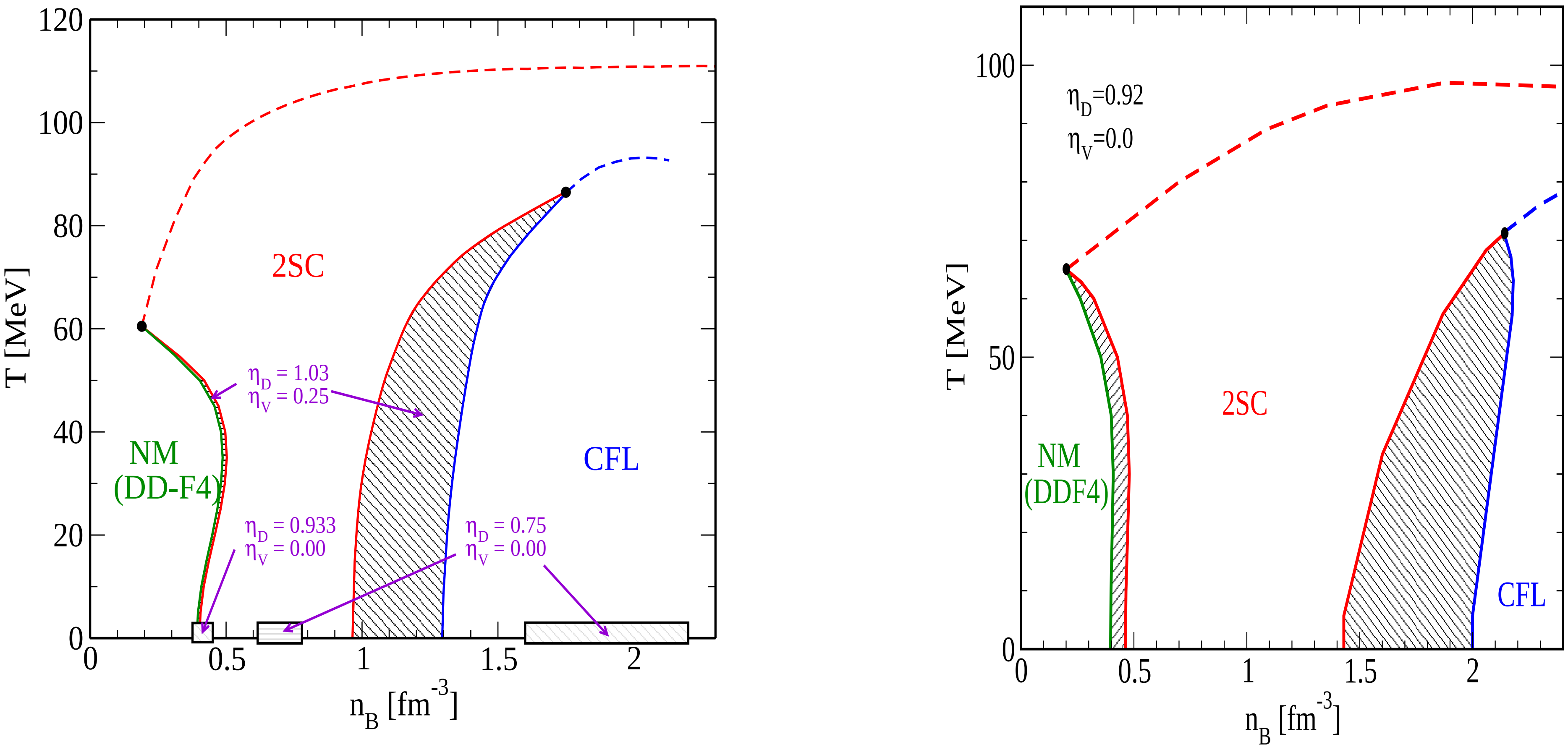




- Moment of Inertia ⇒ objects with large masses necessary
- Surface redshift ⇒ large values (> 0.5) troublesome for quark matter

* **Alford et al., ApJ 629, 969 (2005); Klähn et al., PLB567, 160 (2007), [nucl-th/0609067]**

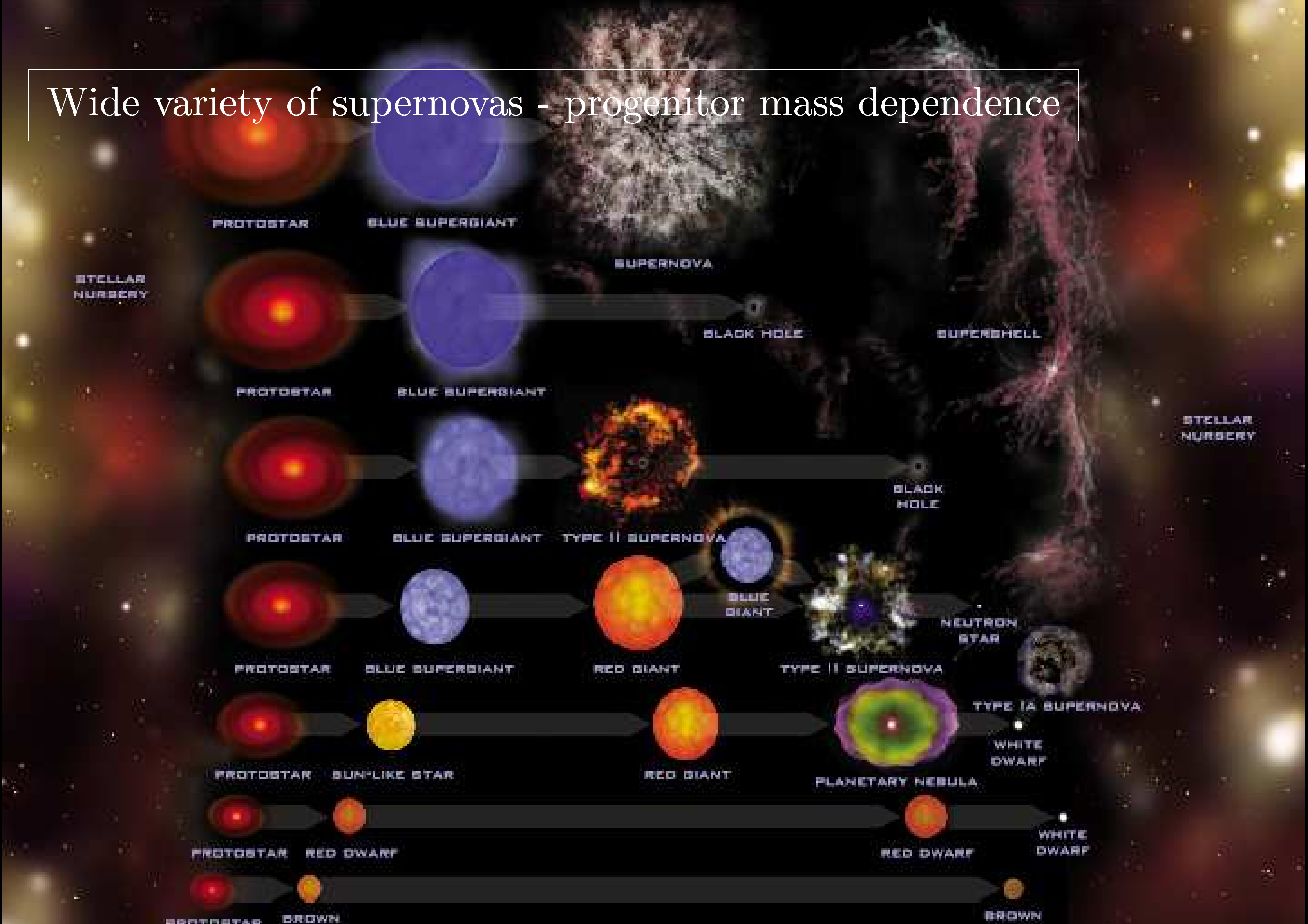
Phase diagrams for the CBM experiment



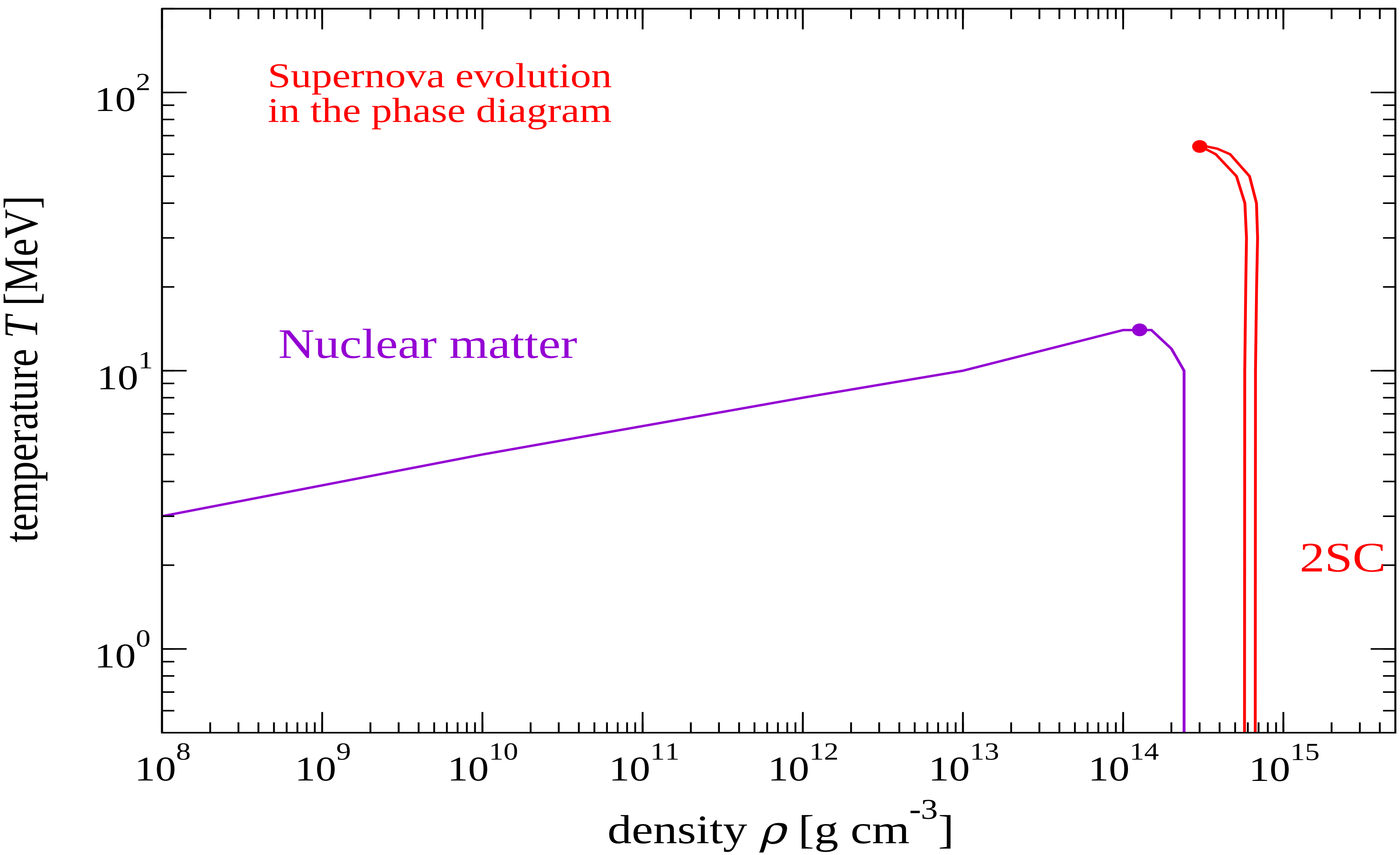
Phase diagrams for isospin-symmetric matter, for hybrid star maximum mass $M_{max} = 2.1\ M_\odot$ (left-hand side) and $M_{max} = 1.7\ M_\odot$ (right-hand side).

D. B., F. Sandin, S. Typel, in preparation.

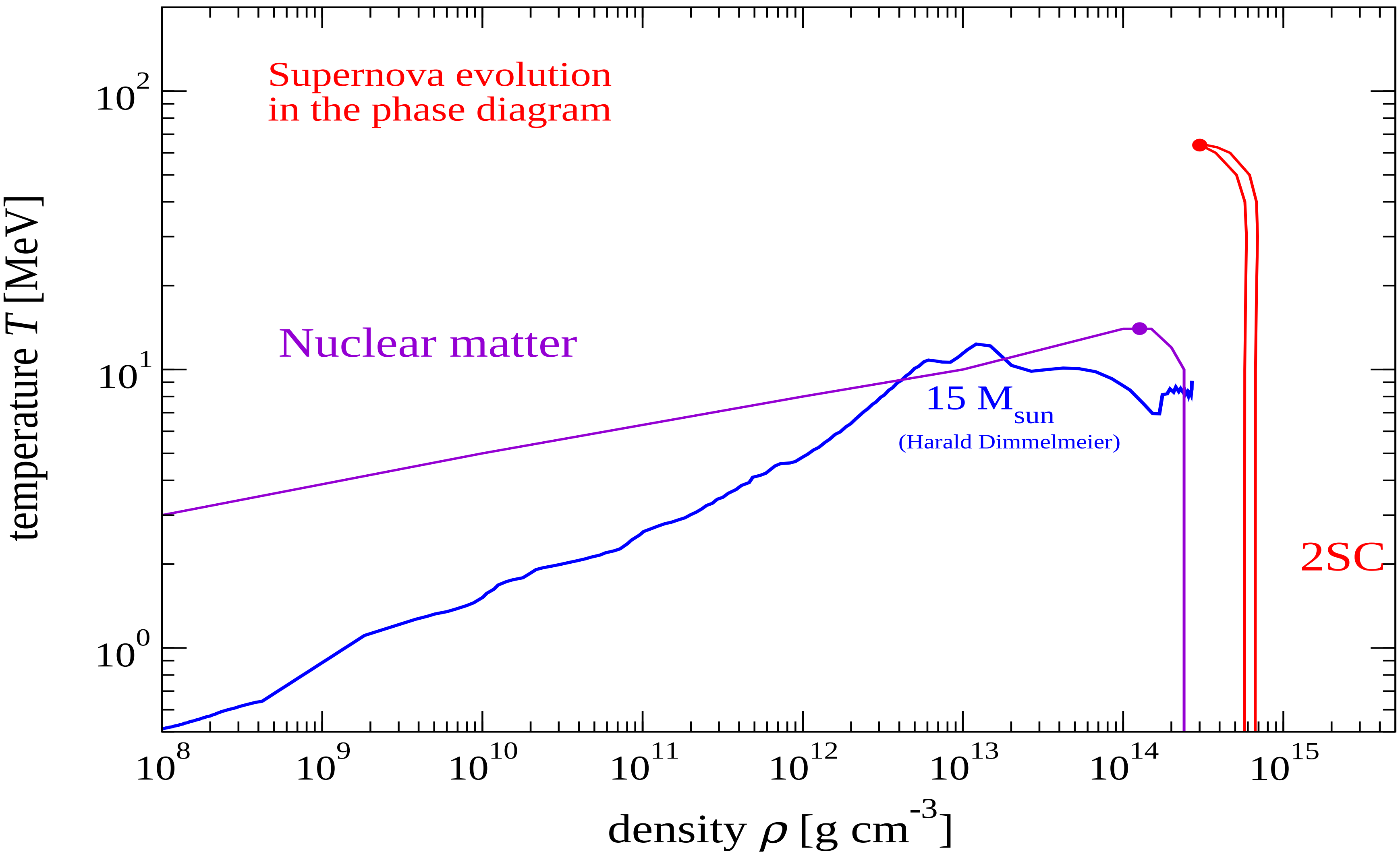
Wide variety of supernovas - progenitor mass dependence



Supernova Collapse in the Phase Diagram



Supernova Collapse in the Phase Diagram (II)



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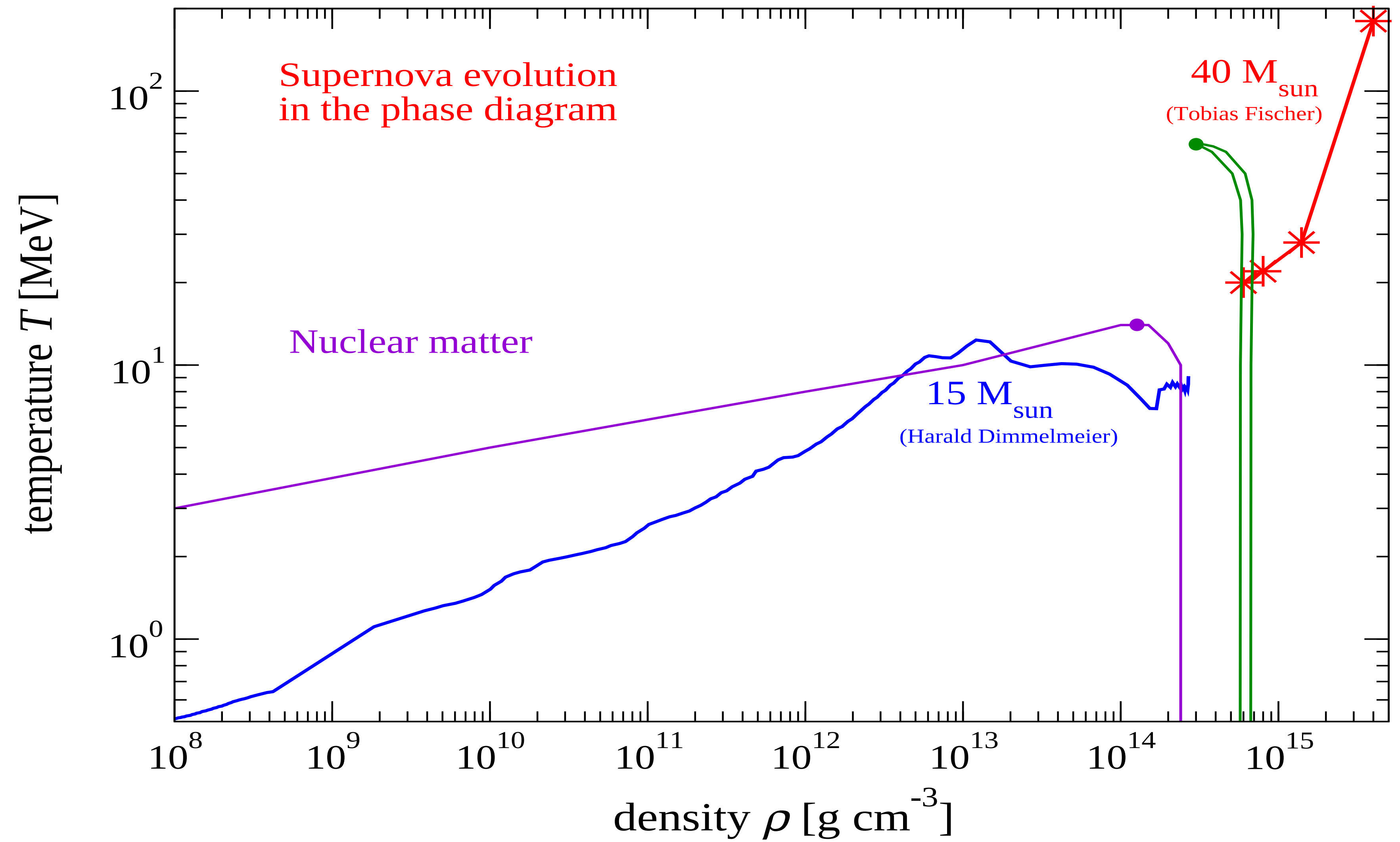
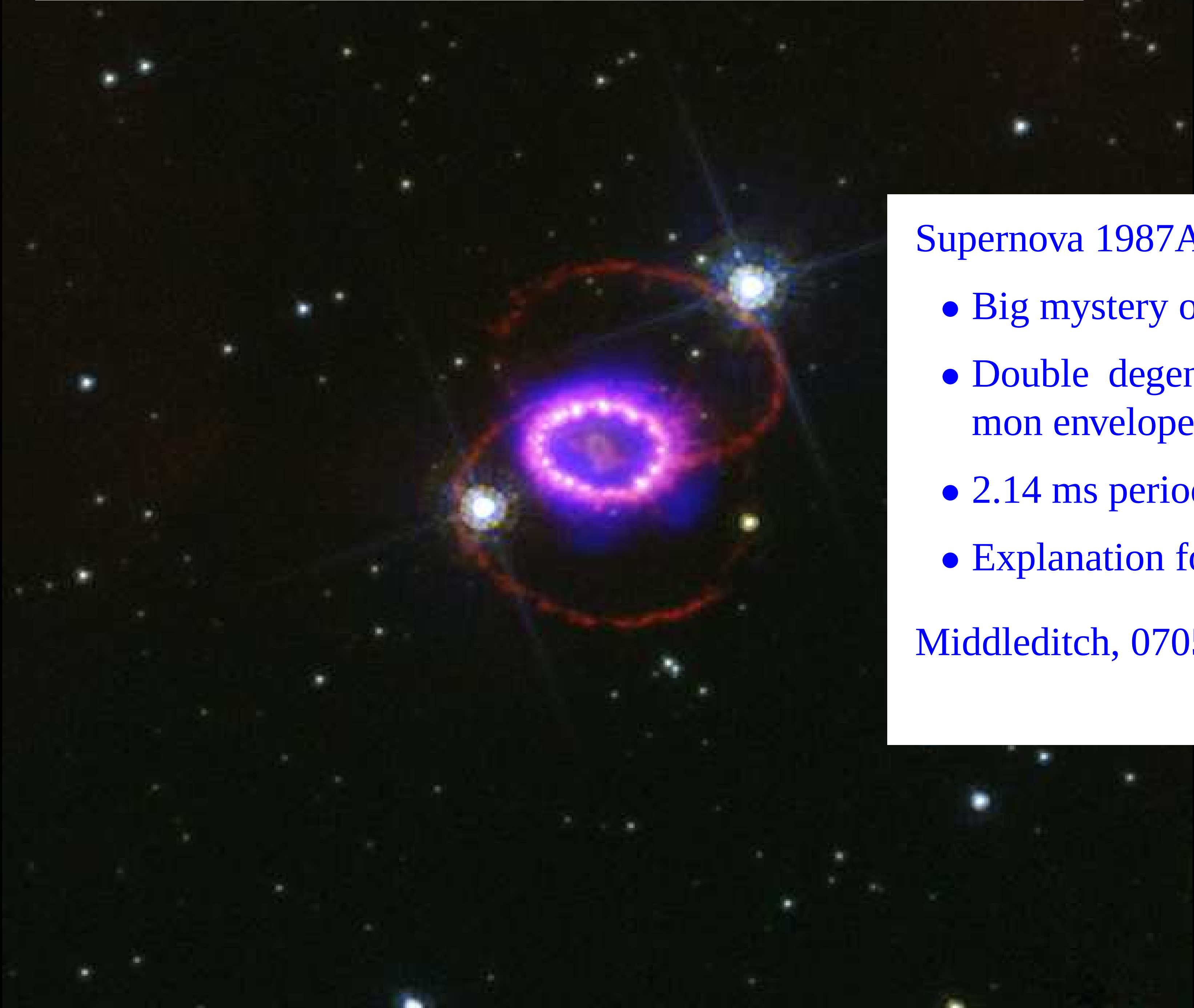


Equation of State for Supernova Applications

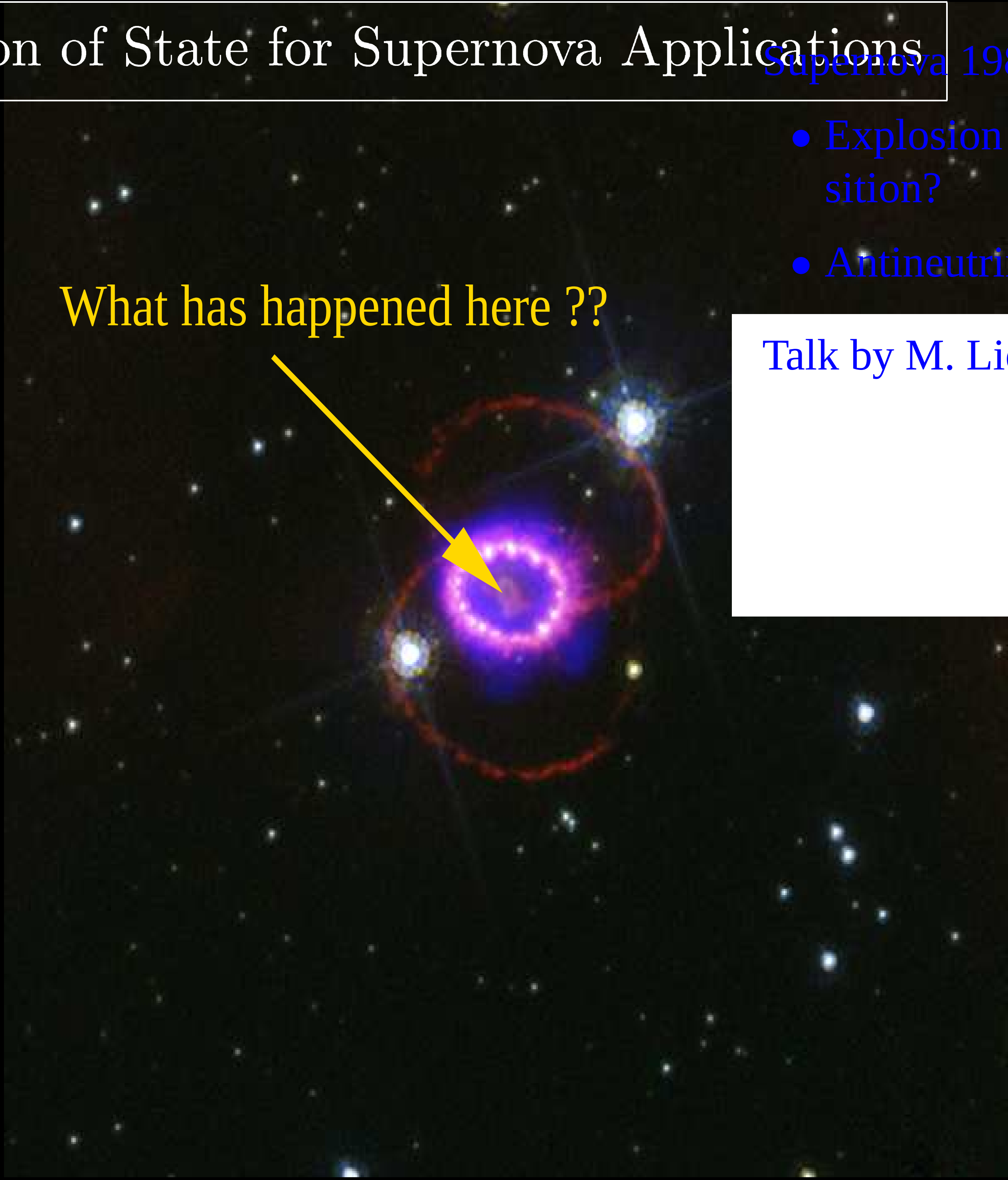


Supernova 1987A - 20 years later:

- Big mystery of rings!
- Double degenerate core in common envelope?
- 2.14 ms periodic signal
- Explanation for 99% of GRB ?

Middleditch, 0705.3846 [astro-ph]

Equation of State for Supernova Applications



Supernova 1987A - 20 years later:

- Explosion powered by QCD transition?
- Antineutrino burst signal?

Talk by M. Liebendörfer

General Relativistic Cooling Equations

The energy flux per unit time $l(r)$ through a spherical slice at distance r from the center is:

$$l(r) = -4\pi r^2 k(r) \frac{\partial (T e^{\Phi})}{\partial r} e^{-\Phi} \sqrt{1 - \frac{2M}{r}}.$$

The factor $e^{-\Phi}\sqrt{1 - \frac{2M}{r}}$ corresponds to relativistic corrections of time and distance scales.
The equations for energy balance and thermal energy transport are:

$$\frac{\partial}{\partial N_B}(l e^{2\Phi}) = -\frac{1}{n}(\epsilon_\nu e^{2\Phi} + c_V \frac{\partial}{\partial t}(T e^{\Phi}))$$

$$\frac{\partial}{\partial N_B}(T e^{\Phi}) = -\frac{1}{k}\frac{l e^{\Phi}}{16\pi^2 r^4 n}$$

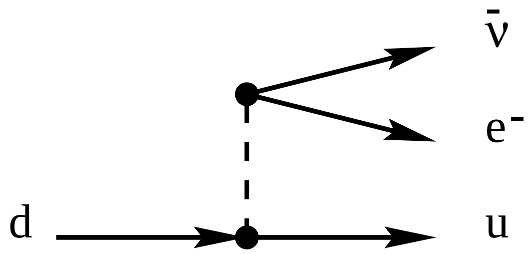
where $n = n(r)$ is the baryon number density, $N_B = N_B(r)$ is the total baryon number in the sphere with radius r and

$$\frac{\partial N_B}{\partial r} = 4\pi r^2 n (1 - \frac{2M}{r})^{-1/2}$$

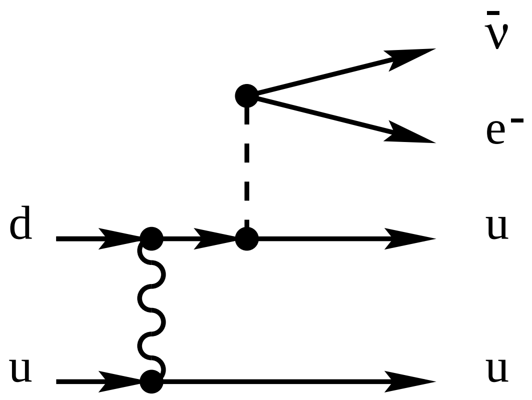
F. Weber: Pulsars as Astrophys. Labs ... (1999); D.B., Grigorian, Voskresensky, A& A 368 (2001) 561.

Neutrino processes in quark matter: Emissivities

- Quark direct Urca (QDU) the most effi cient processes
  $d \to u + e + \bar{\nu}$ and $u + e \to d + \nu$
  $\epsilon_\nu^{\rm QDU} \simeq 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\rm QDU}\, T_9^6$ erg cm^{-3} s^{-1},
  Compression $u = n/n_0 \simeq 2$, strong coupling $\alpha_s \approx 1$



- Quark Modifi ed Urca (QMU)and Quark Bremsstrahlung (QB)
  $d + q \to u + q + e + \bar{\nu}$ and $q_1 + q_2 \to q_1 + q_2 + \nu + \bar{\nu}$
  $\epsilon_\nu^{\rm QMU} \sim \epsilon_\nu^{\rm QB} \simeq 9.0 \times 10^{19} \zeta_{\rm QMU}\, T_9^8$ erg cm^{-3} s^{-1}.



Quark PBF

- Suppression due to the pairing
  QDU : $\zeta_{\rm QDU} \sim \exp(-\Delta_q/T)$
  QMU and **QB** : $\zeta_{\rm QMU} \sim \exp(-2\Delta_q/T)$ for $T < T_{{\rm crit},q} \simeq 0.57\, \Delta_q$

- $e + e \to e + e + \nu + \bar{\nu}$
  $\epsilon_\nu^{ee} = 2.8 \times 10^{12}\, Y_e^{1/3} u^{1/3} T_9^8$ erg cm^{-3} s^{-1},
  becomes important for $\Delta_q/T >> 1$

FLOWERS, ITOH, APJ 250 (1981) 750; SCHAAB, VOSKRESENSKY, SEDRAKIAN, WEBER, WEIGEL, A & A 321 (1997)591
YAKOVLEV, LEVENFISH, SHIBANOV, PHYS. USP. 169 (1999) 825; BAIKO, HAENSEL, ACTA PHYS. POLON. B 30 (1999) 1097
BLASCHKE, GRIGORIAN, VOSKRESENSKY , ASTRON. & ASTROPHYS. 368 (2001) 561; JAIKUMAR, PRAKASH, PLB 516 (2001) 345
JAIKUMAR, ROBERTS, SEDRAKIAN, PRC 73 (2006) 034012; WANG, WANG, WU, PRC 74 (2006) 014021

Hybrid Star Cooling with 2SC Quark Matter

2SC phase: 1 color (blue) is unpaired
(mixed superconductivity)

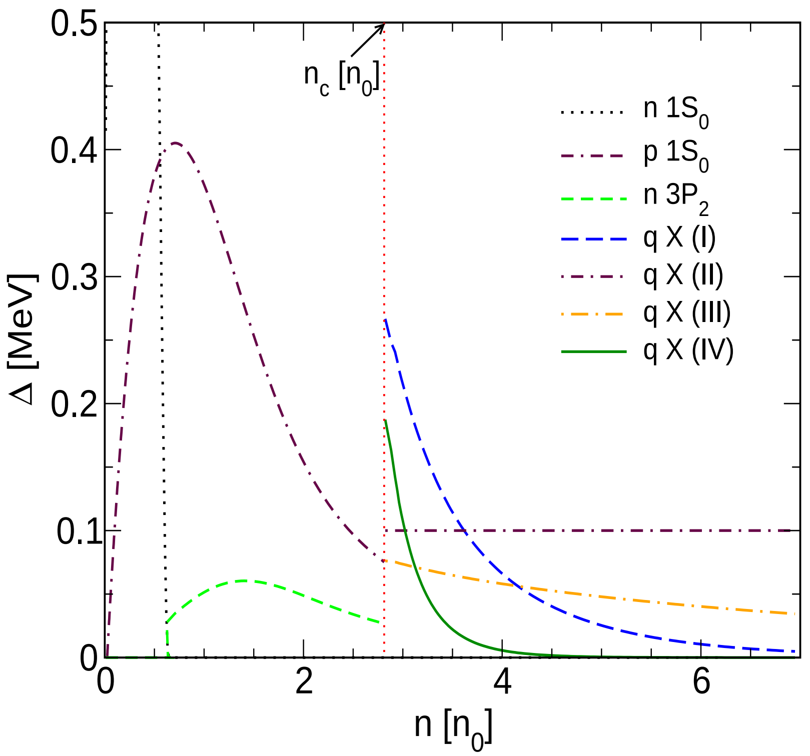
Ansatz 2SC + X phase:

$$\Delta_X(\mu) = \Delta_0 \exp[\alpha(1 - \mu/\mu_c)]$$

Grigorian, D.B., Voskresensky, PRC 71 (2005)

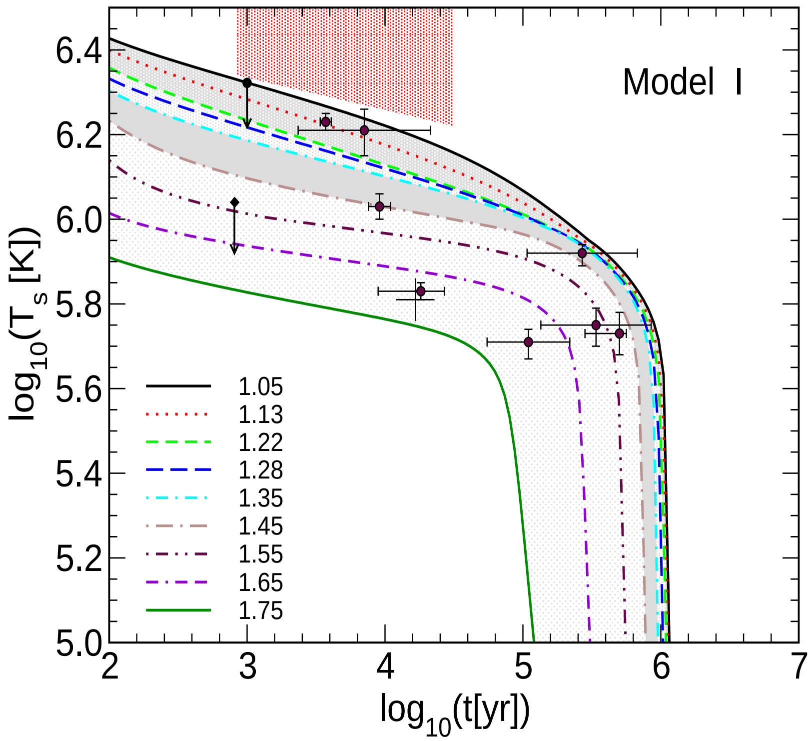
Model	Δ_0 [MeV]	α
I	1	10
II	0.1	0
III	0.1	2
IV	5	25

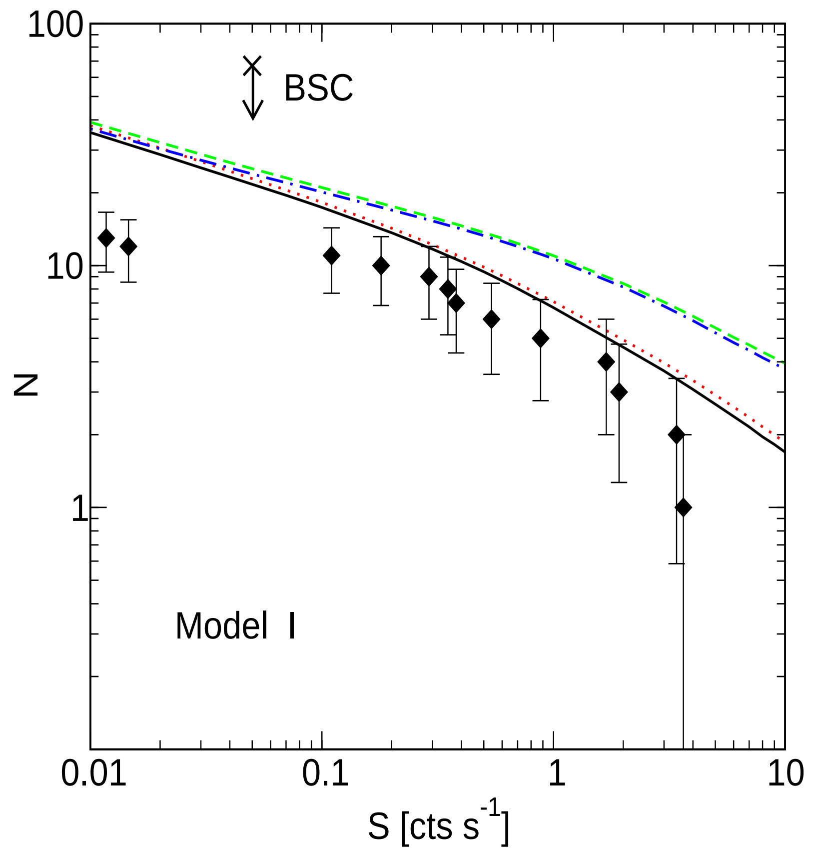
Popov, Grigorian, D.B., PRC 74 (2006)



Pairing gaps for hadronic phase
AV18 - Takatsuka et al. (2004)
and 2SC + X phase

Hybrid Star Cooling with 2SC Quark Matter





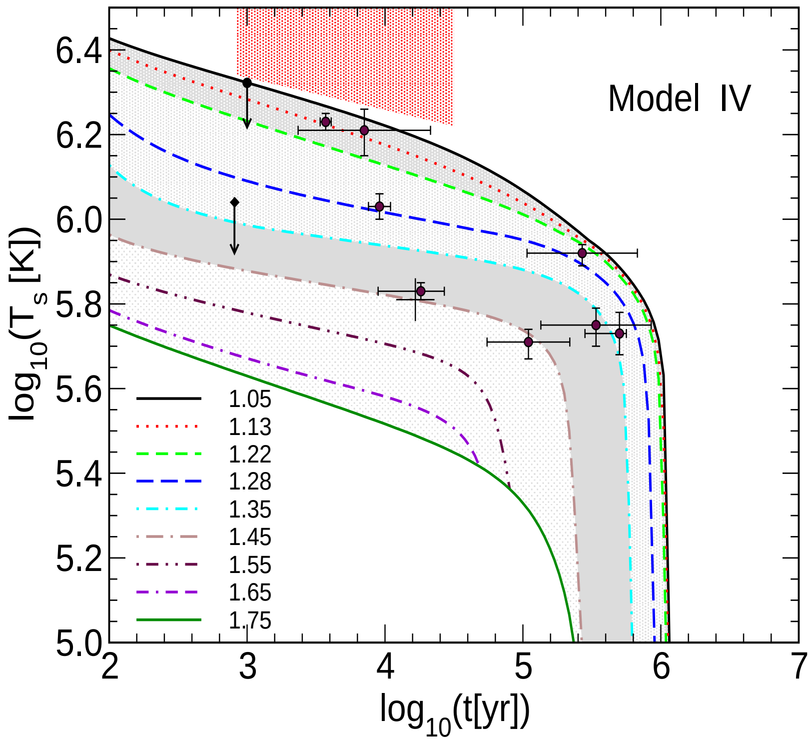
2SC + X phase, $\Delta_0 = 1$ MeV, $\alpha = 10$

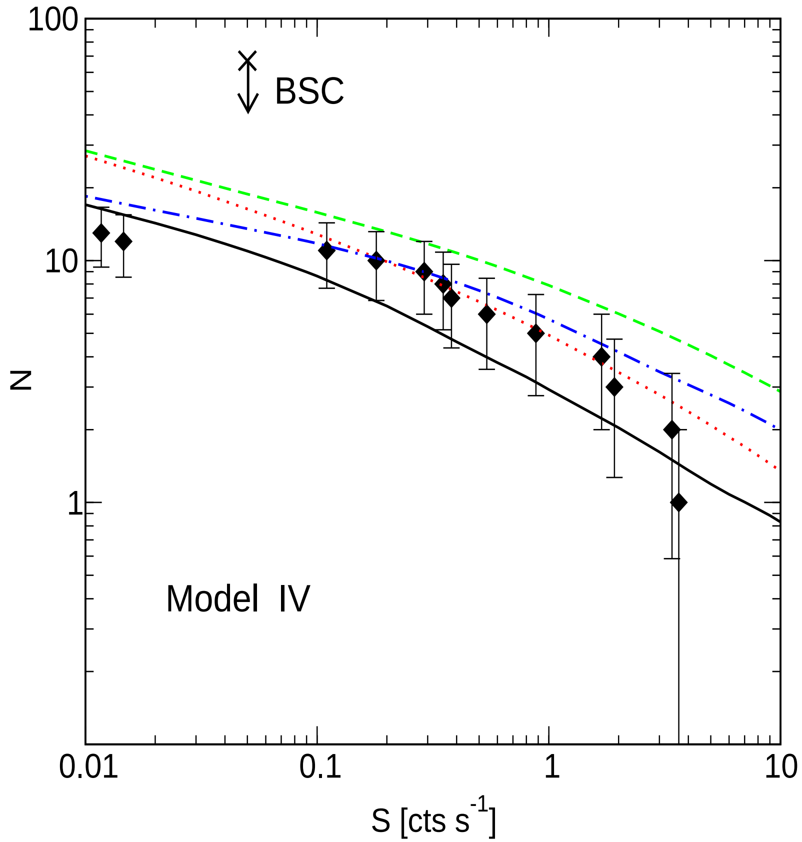
Too large mass for Vela required

Log N - Log S test fails

Popov, Grigorian, D.B., PRC 74 (2006)

Hybrid Star Cooling with 2SC Quark Matter





2SC + X phase, $\Delta_0 = 5$ MeV, $\alpha = 25$

Temperature-age and Vela mass OK

Log N - Log S test passed

Popov, Grigorian, D.B., PRC 74 (2006)

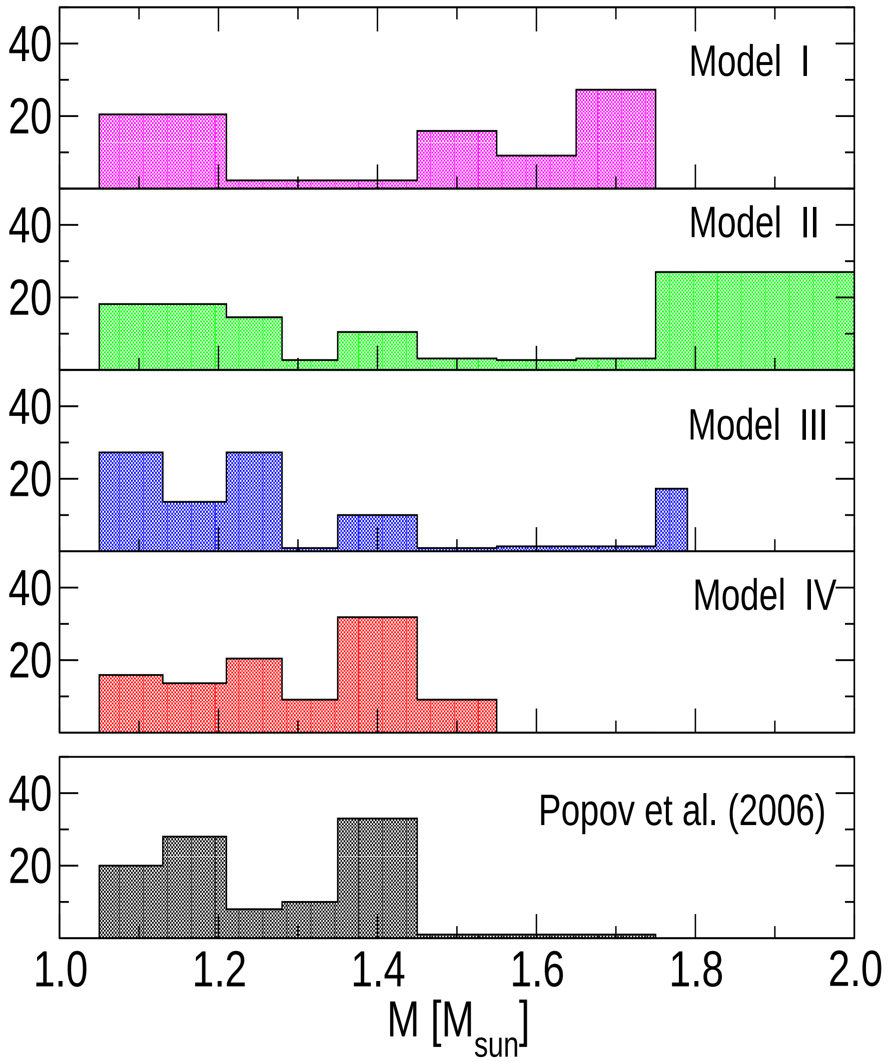
Hybrid Star Cooling with 2SC Quark Matter

Hybrid star cooling passes all modern tests:

- Temperature - age
- Log N - Log S
- Brightness constraint
- Vela mass (Population sysnthesis)

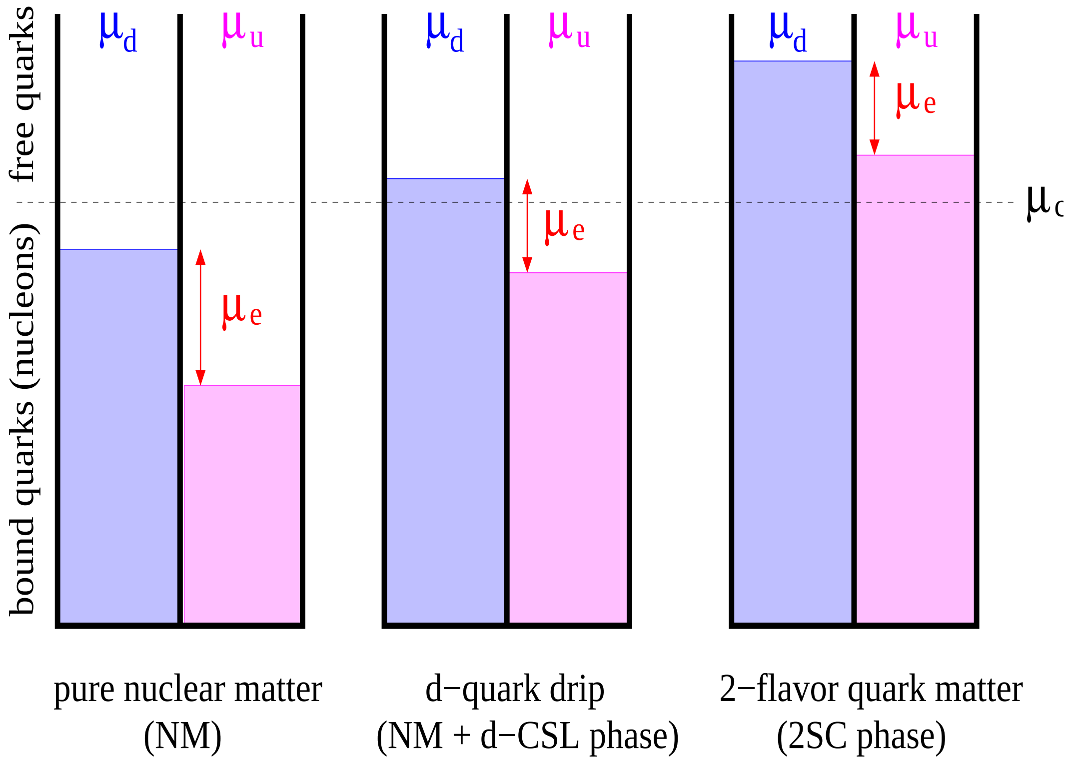
Popov, Grigorian, D.B., PRC 74 (2006)

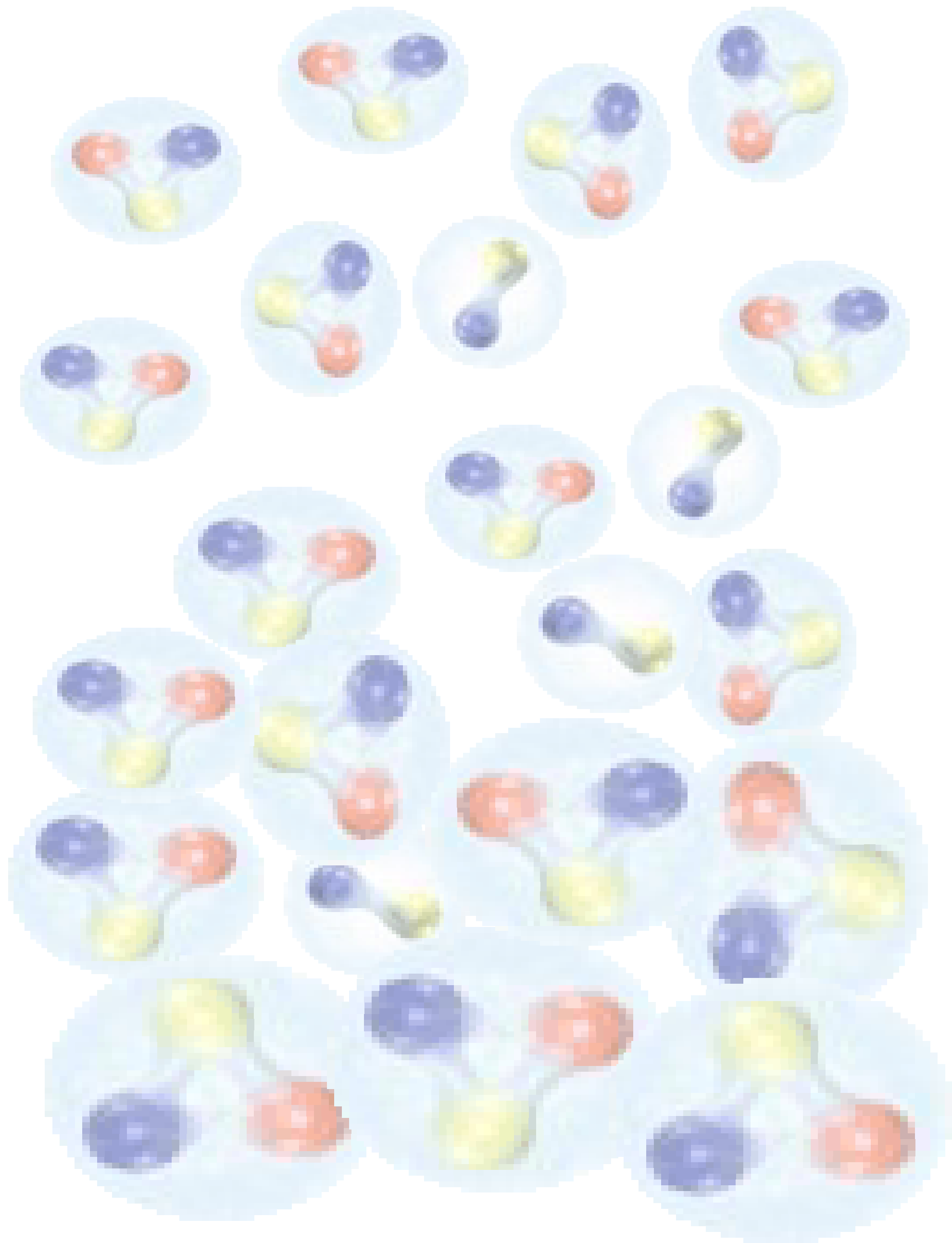
D.B., H. Grigorian, PPNP (2007)



d-quark 'dripline' and single-flavor (d-CSL) phase

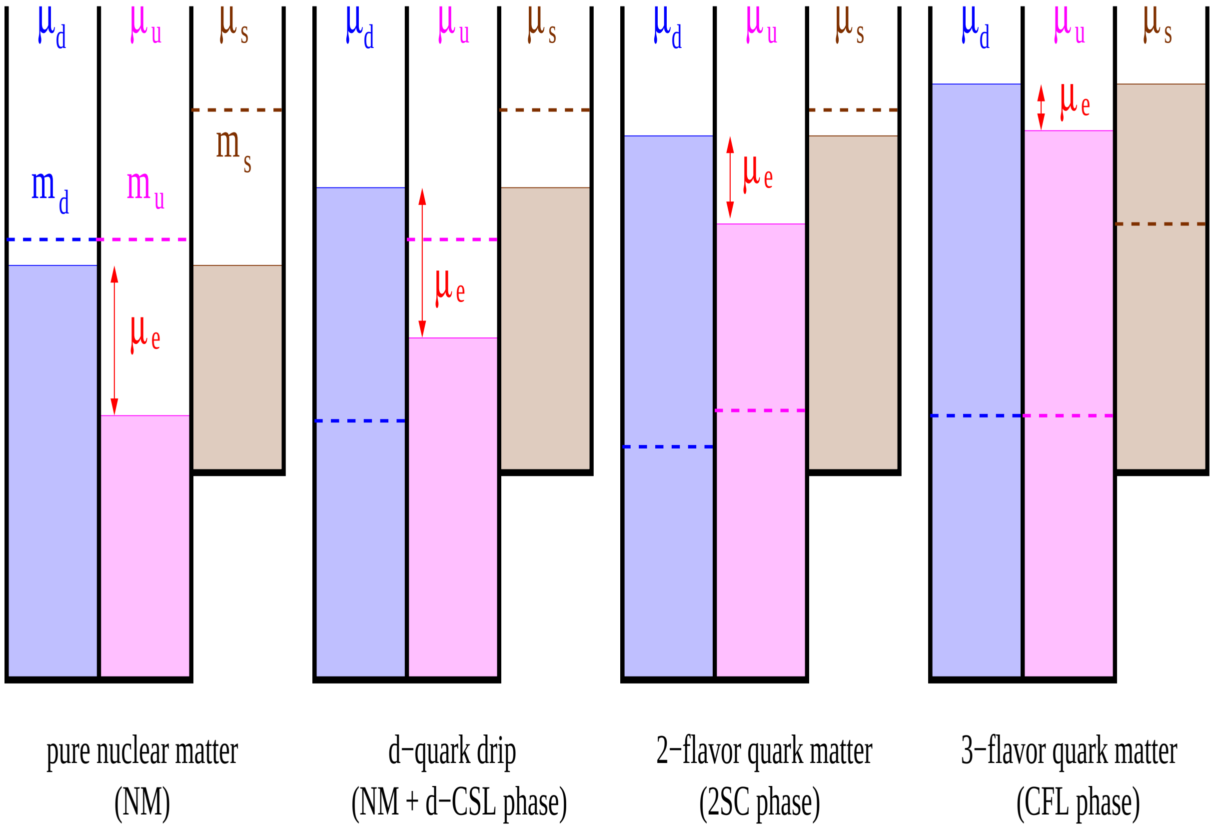
Sequential 'deconfinement' of quark flavors

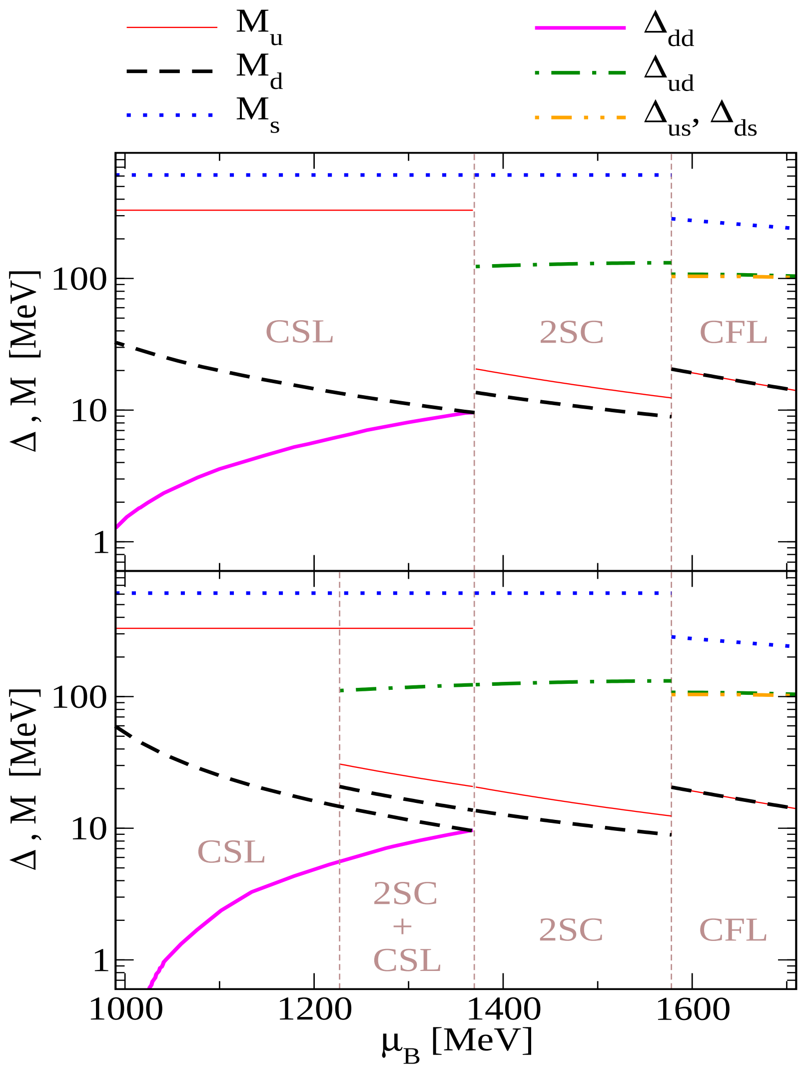




D.B., F. Sandin, T. Klähn, J. Berdermann, arXiv:0807.0414 [nucl-th]

Sequential deconfinement in asymmetric NS matter





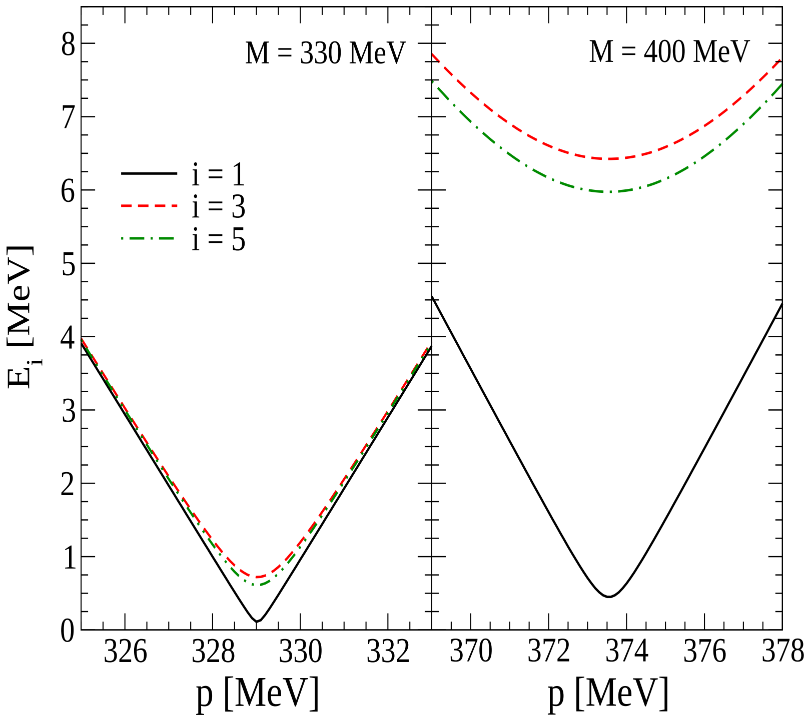
D.B., F. Sandin, T. Klähn, J. Berdermann, arXiv:0807.0414 [nucl-th]

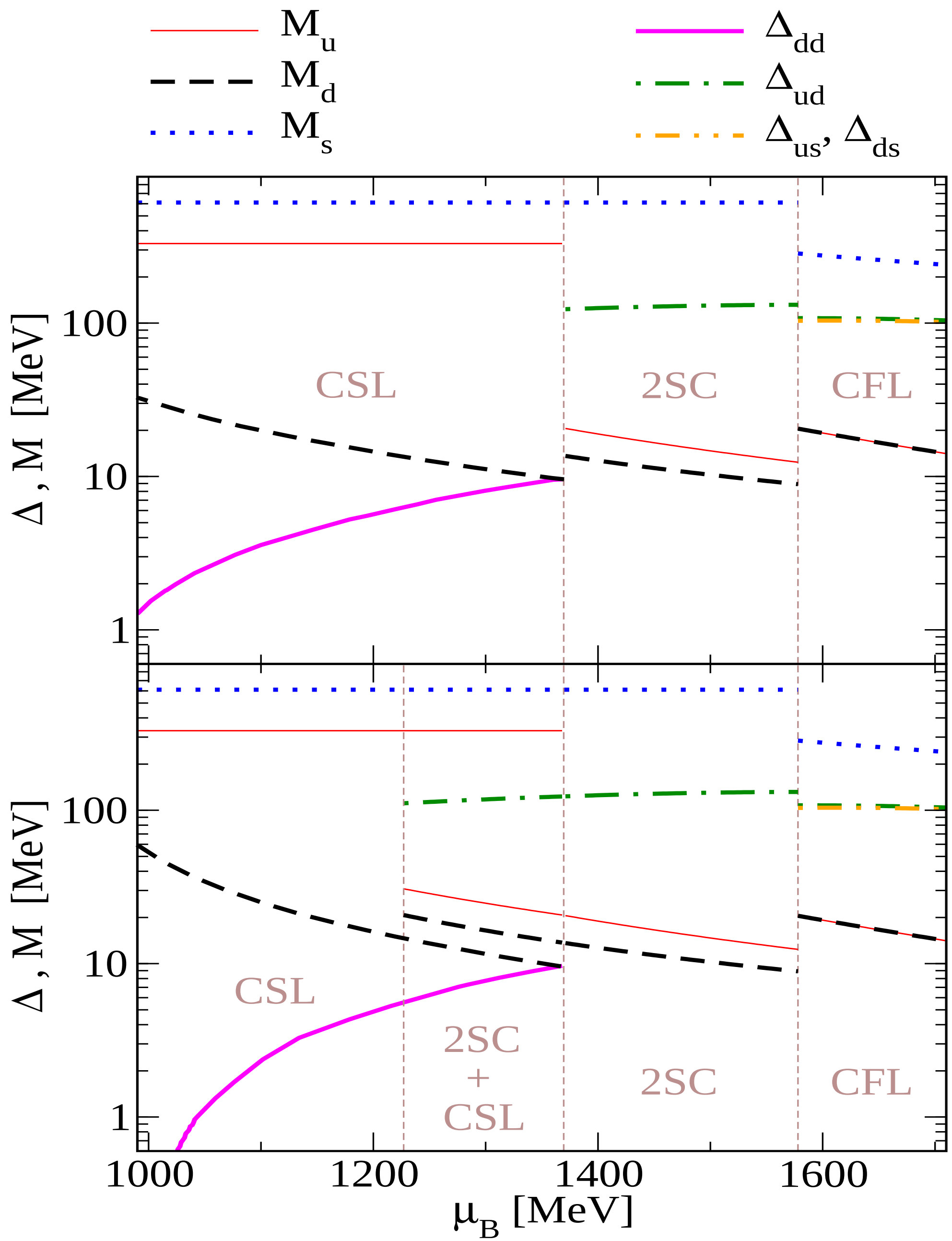
Single-flavor (d-CSL) phase in competition

Ansatz: isotropic Color-spin-locking (CSL)

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

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

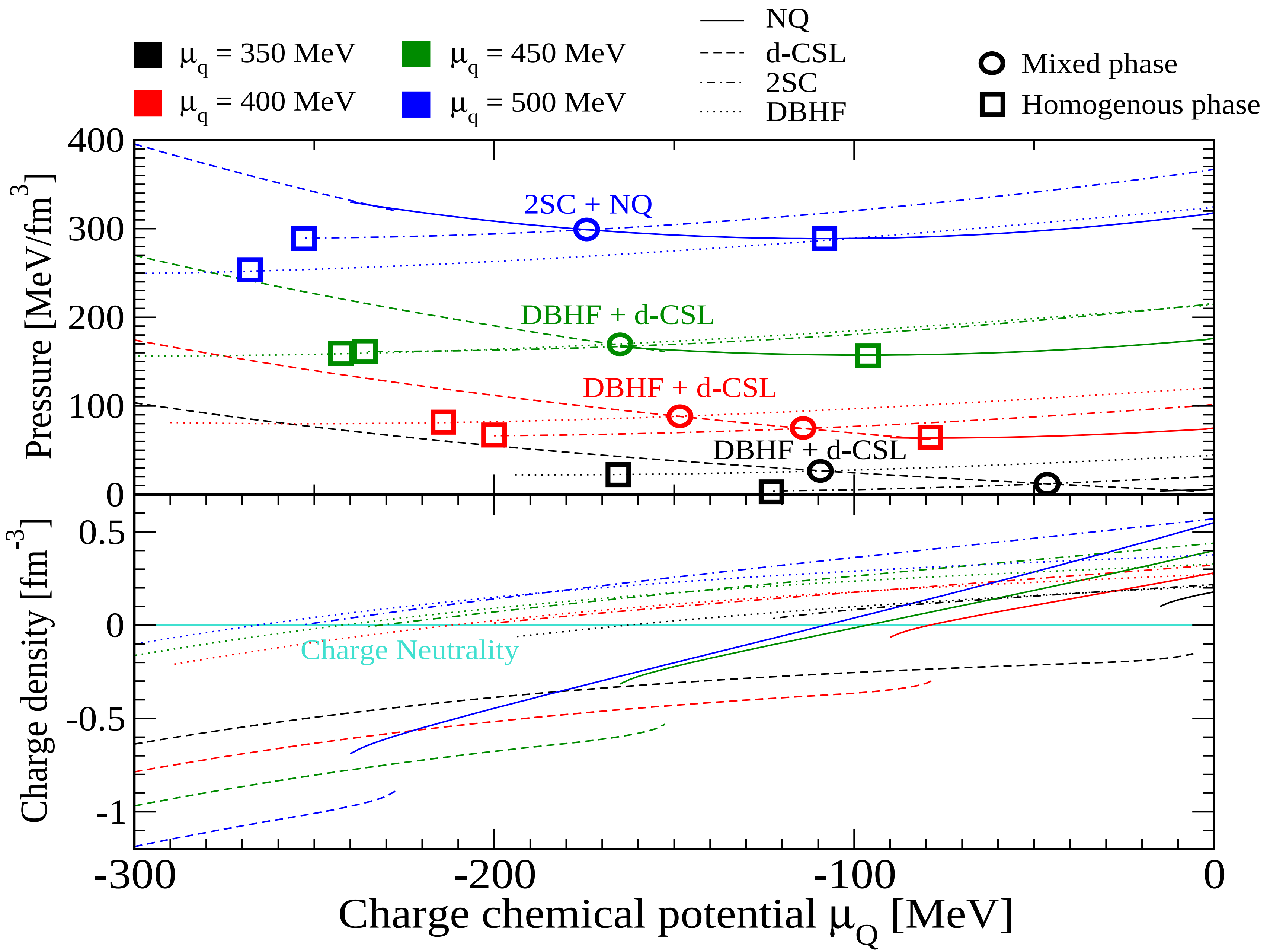




See also:

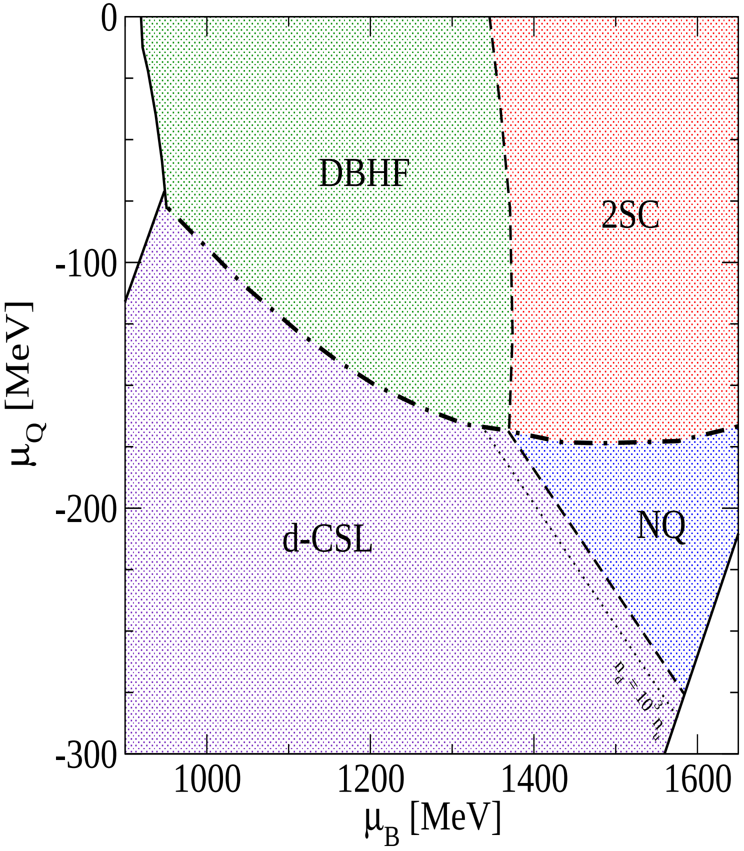
Schmitt, Wang, Rischke, PRD 66, 114010 (2002)

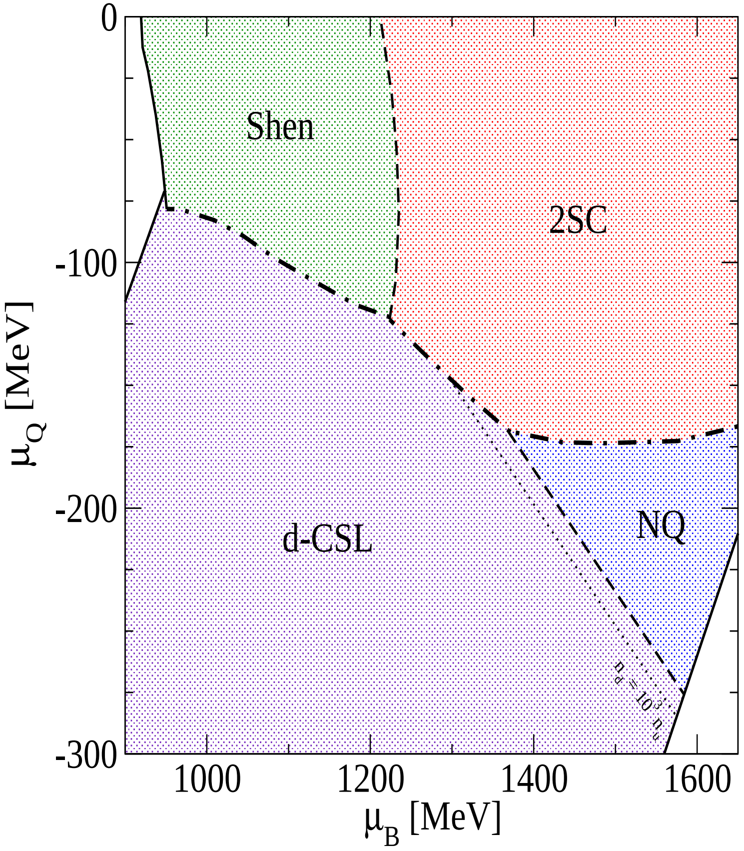
Global charge neutrality: quark-nuclear hybrid



d-CSL: single-flavor phase in competition

Dash-dotted lines: border between oppositely charged phases

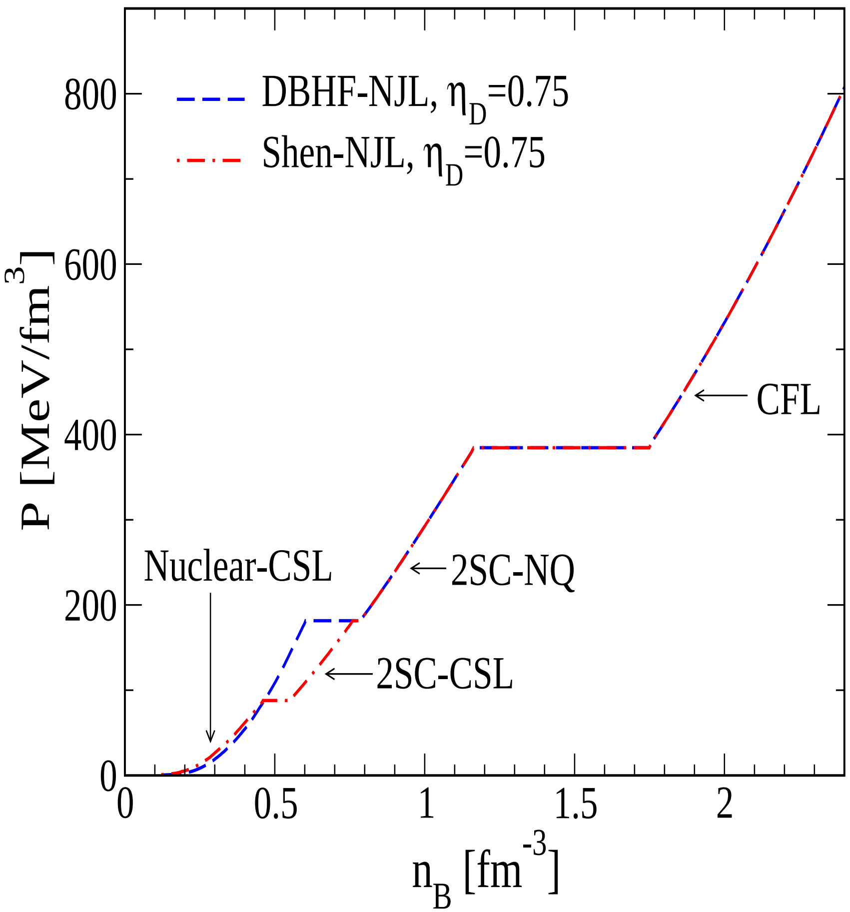




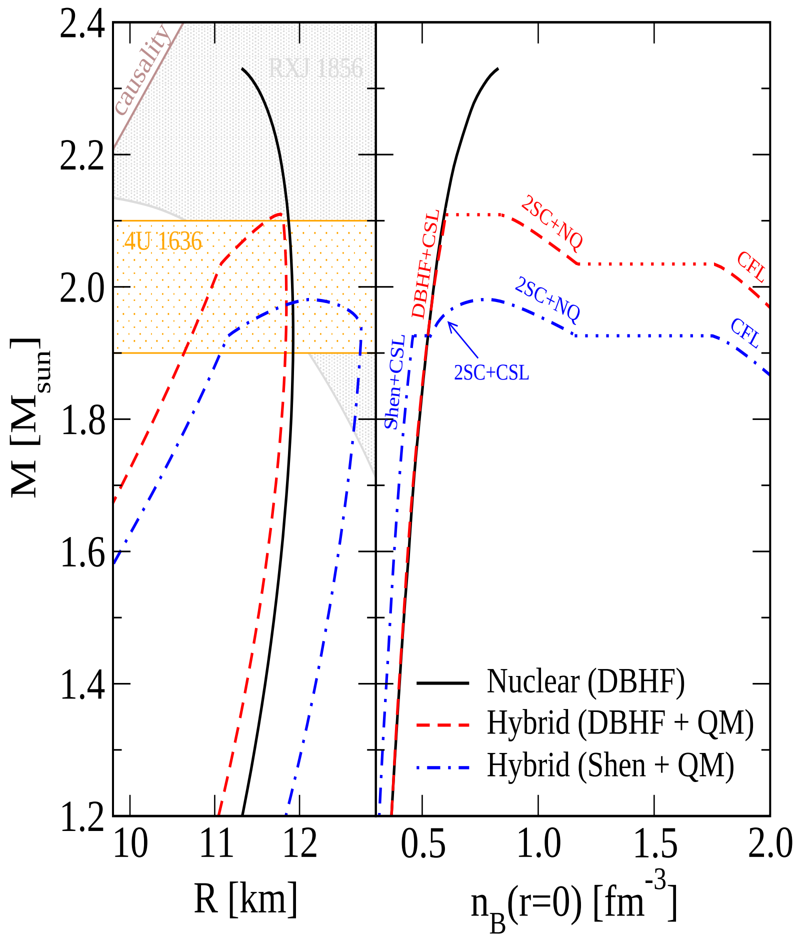
D.B., F. Sandin, T. Klähn, J. Berdermann, in preparation.

d-CSL: single-flavor phase in neutron stars

Equation of state



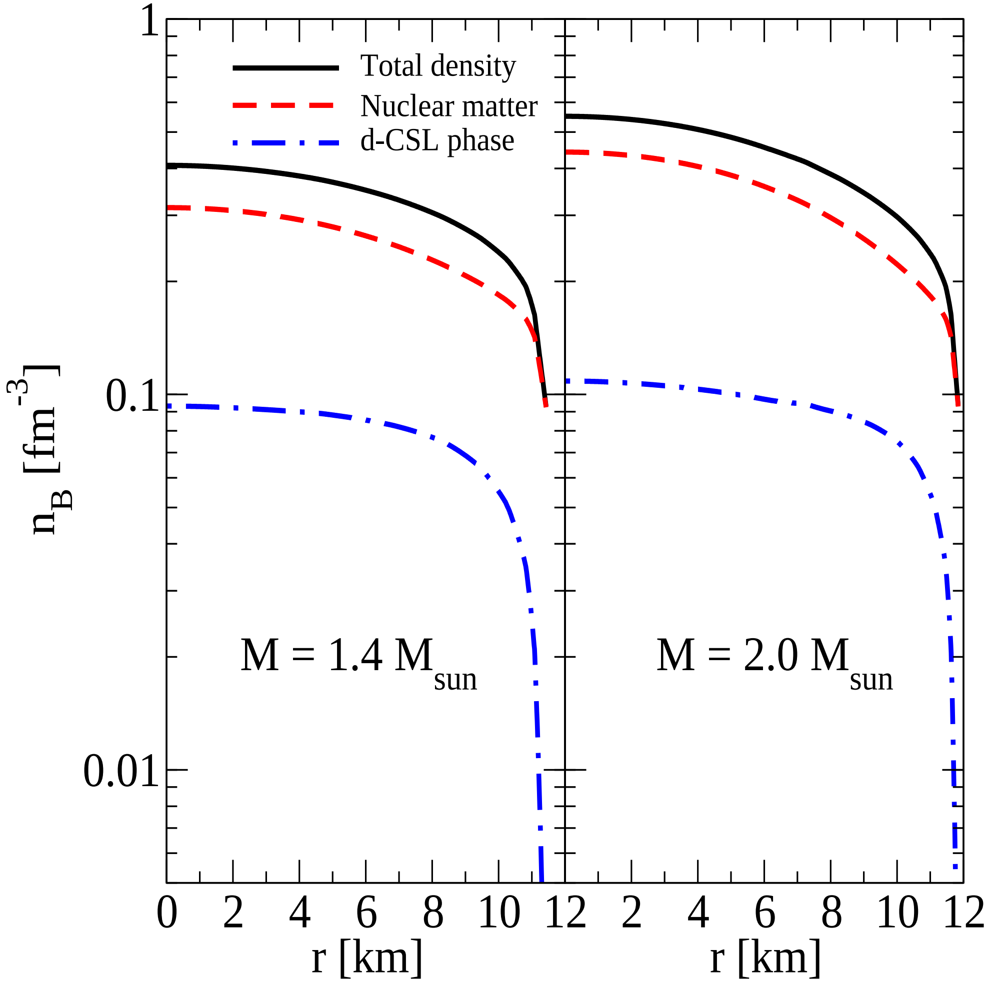
Configuration Sequences



D. B., F. Sandin, T. Klähn, J. Berdermann, arXiv:0807.0414 [nucl-th]

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

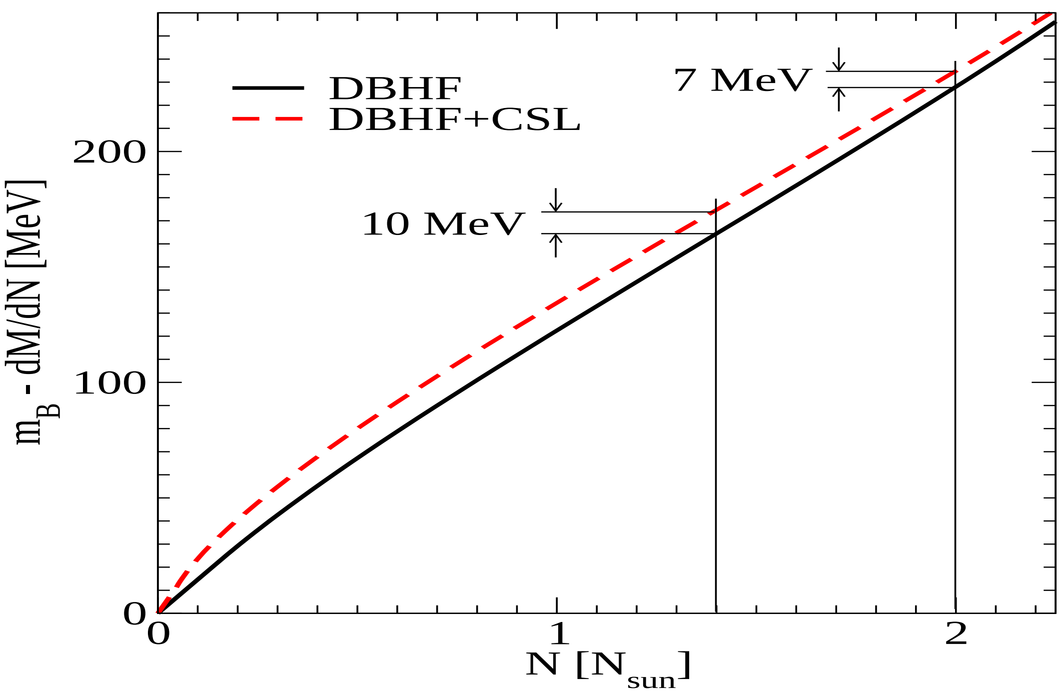
d-quark drip at crust-core boundary: Candidate for "deep crustal heating" (DCH) process?



Haensel and Zdunik,A& A **227**, 431 (1990)
Ushomirsky and Rutledge, MNRAS **325**, 1157 (2001)

Page and Cumming,ApJ **635**, L157 (2005): Superbursts & Strange Stars
Stejner and Madsen,A& A **458**, 523 (2006): SS + Transient Cooling

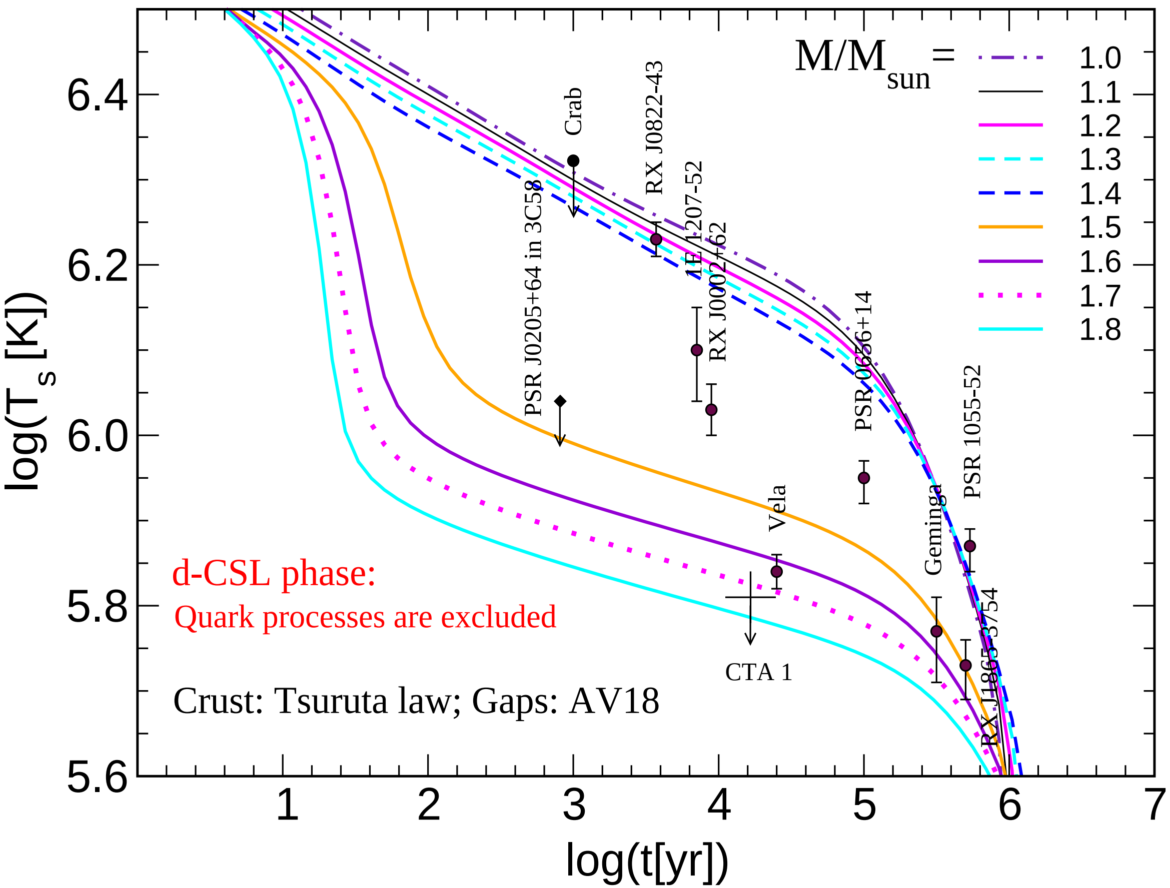
Shternin, Yakovlev, Haensel and Potekhin, MNRAS **382**, L43 (2007): KS1731



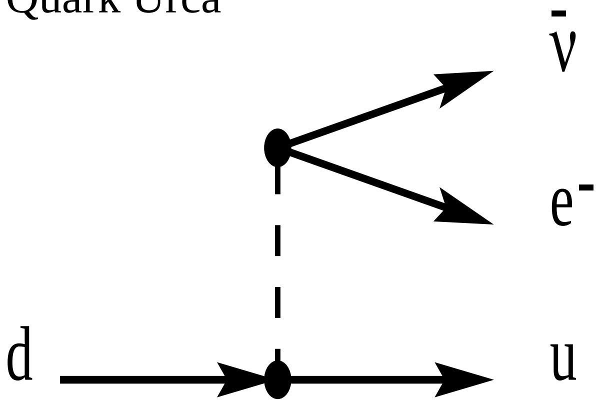
D. B., F. Sandin, T. Klähn, J. Berdermann, arXiv:0807.0414 [nucl-th]

d-CSL: single-flavor phase in neutron stars

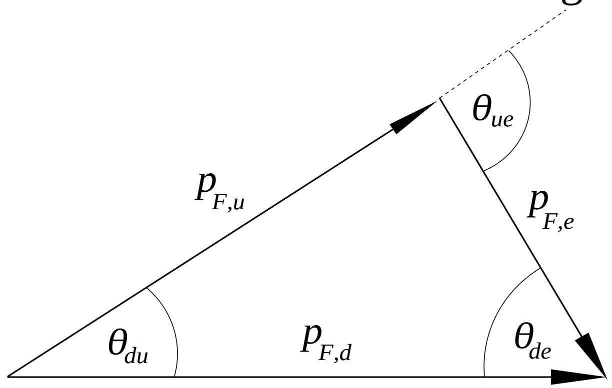
Cooling: processes in single-flavor quark matter are blocked!



Quark Urca



Momentum conservation triangle



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

D. B., F. Sandin, H. Grigorian, 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 coupling lowers phase transition density
- vector meanfield stiffens quark matter EoS

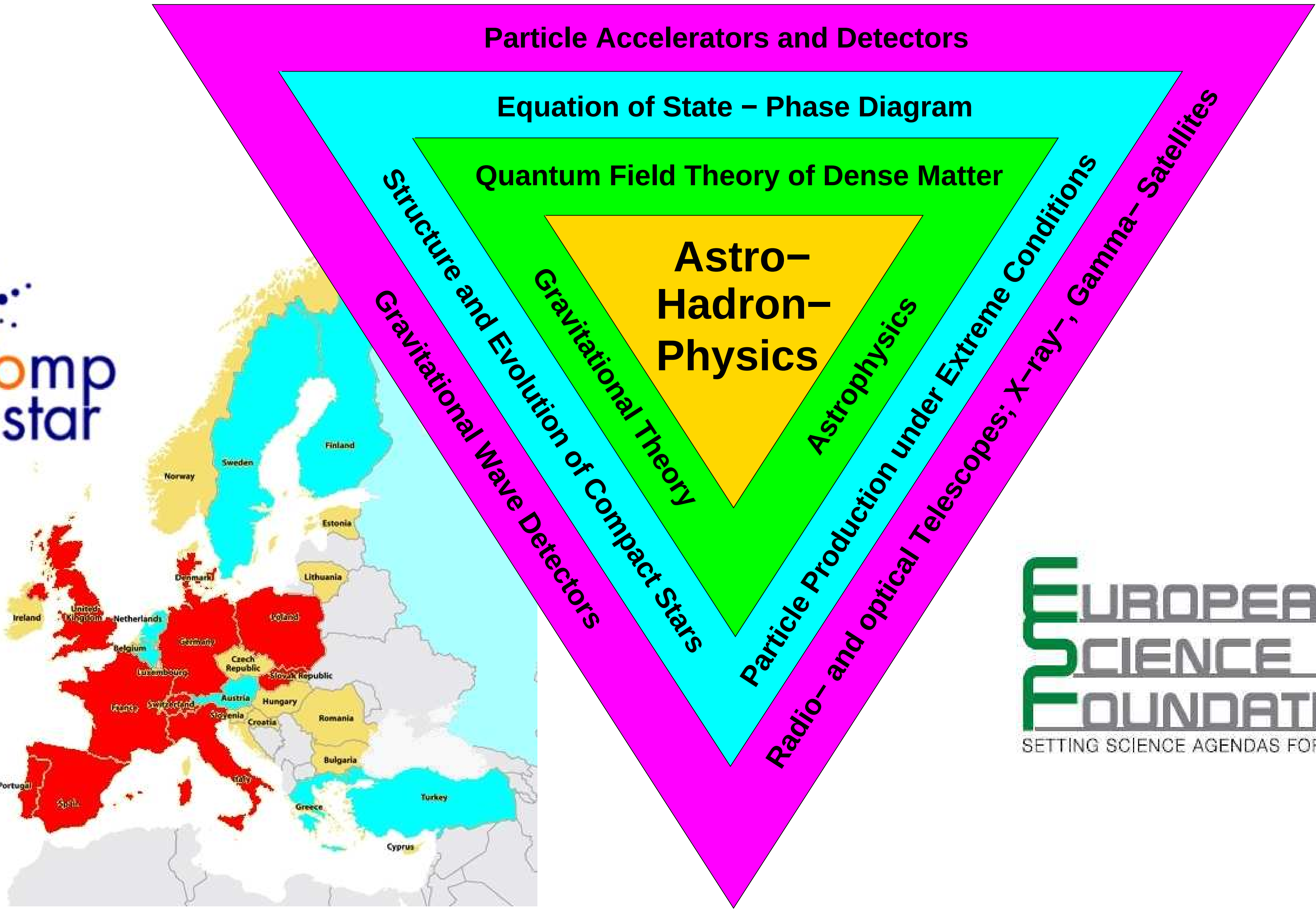
Global charge neutrality: d-CSL + DBHF hybrid

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

Next steps

- apply to superbursts, X-ray transients, high-mass supernovae
- extend to inhomogeneous phases: surface tension and Coulomb effects

New ways to understand Dense Matter



comp star

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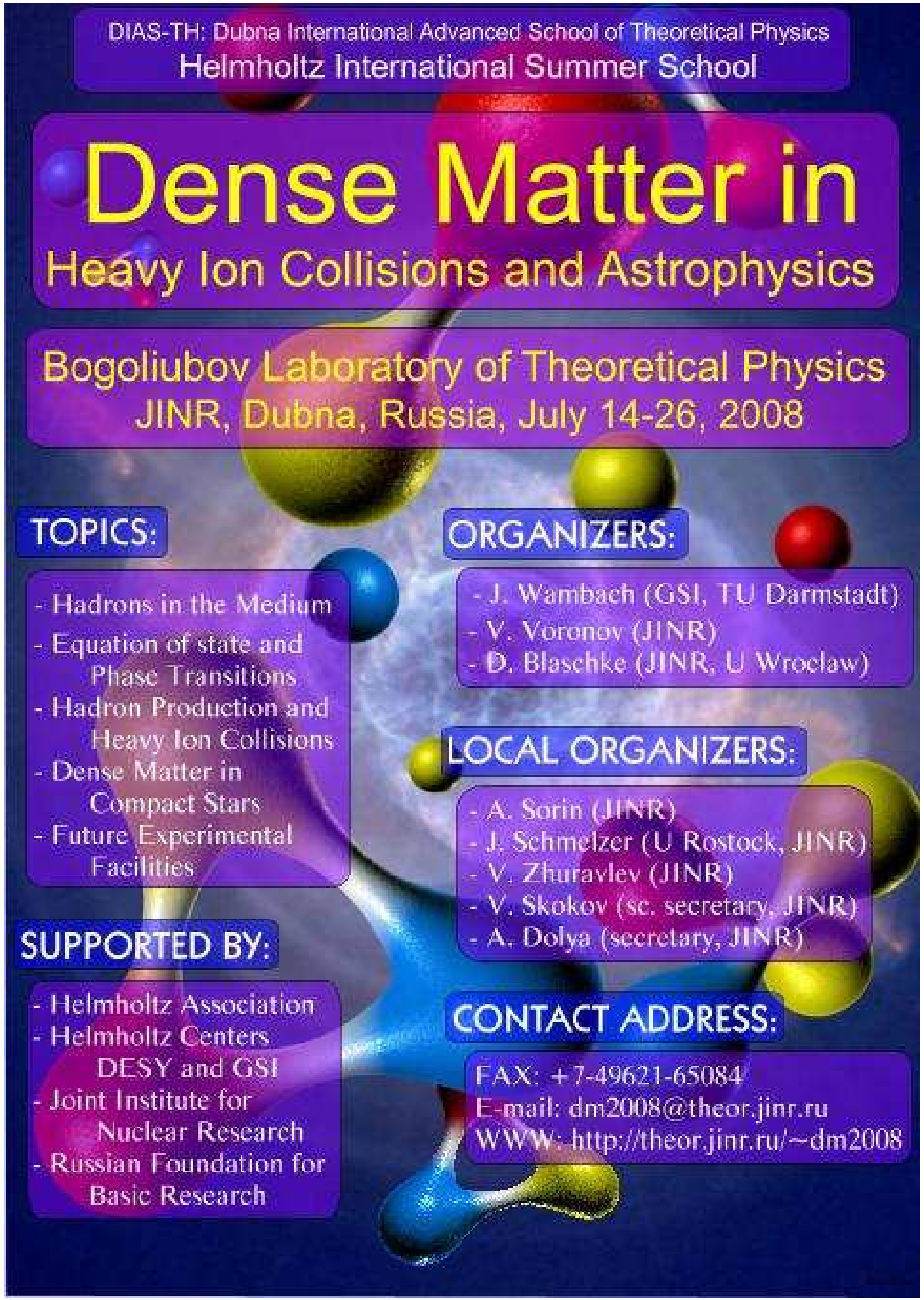

Invitations

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

XXIV. Max Born Symposium
"Quantum Statistics and Field Theory"
Wroclaw, Poland, September 25-27, 2008
http://www.ift.uni.wroc.pl/~mborn24

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

THANKS FOR YOUR ATTENTION!