Matter @ High Densities in Compact Stars & CBM

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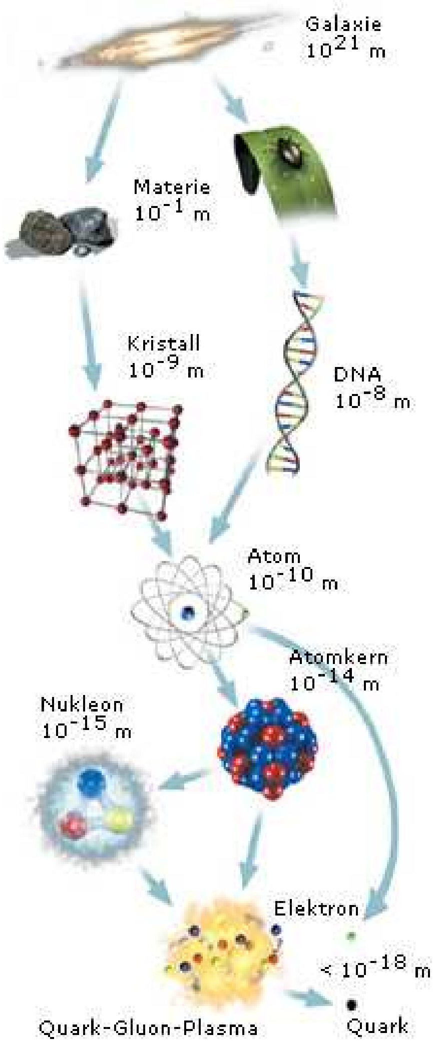
- Introduction: Many-particle Systems and Quantum Field Theory
- Partition function for QCD: Lattice Simulations vs. Resonance Gas
- Bound states and Mott effect, Color superconductivity
- Application 1: J/ψ suppression in Heavy-Ion Collisions
- Application 2: Quark Matter in Compact Stars and in CBM @ FAIR
  - Masses and Cooling behaviour
  - Flow constraint and phase diagram
- Conclusions / Outlook

Many Particle Systems & Quantum Field Theory



Elements	Bound states	System
humans, animals	couples, groups, parties	society
molecules, crystals	(bio)polymers	animals, plants
atoms	molecules, clusters, crystals	solids, liquids, ...
ions, electrons	atoms	plasmas
nucleons, mesons	nuclei	nuclear matter
quarks, anti-quarks	nucleons, mesons	quark matter

Highly Compressed Matter ⇔ Pauli Principle

Partition function: $Z = \mathrm{Tr}\left\{e^{-\beta(H-\mu_i Q_i)}\right\}$

Partition function for Quantum Chromodynamics (QCD)

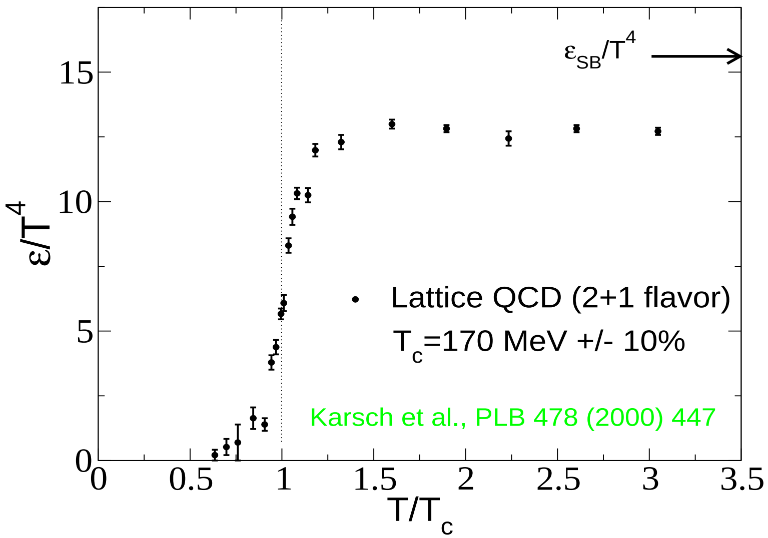
- Partition function as a Path Integral (imaginary time $\tau = i\,t$, $0 \le \tau \le \beta = 1/T$) $\Rightarrow$ PS I

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A \exp\left\{-\int_0^\beta d\tau \int_V d^3x\ \mathcal{L}_{QCD}(\psi,\bar{\psi},A)\right\}$$

- QCD Lagrangian, non-Abelian gluon field strength: $F^a_{\mu\nu}(A) = \partial_\mu A^a \nu - \partial_\nu A^a_\mu + g\ f^{abc}[A^b_\mu, A^c_\nu]$

$$\mathcal{L}_{QCD}(\psi,\bar{\psi},A) = \bar{\psi}[i\gamma^\mu(\partial_\mu - igA_\mu) - m - \gamma^0\mu]\psi - \frac{1}{4}F^a_{\mu\nu}(A)F^{a,\mu\nu}(A)$$

- Numerical evaluation: Lattice gauge theory simulations (Bielefeld group)

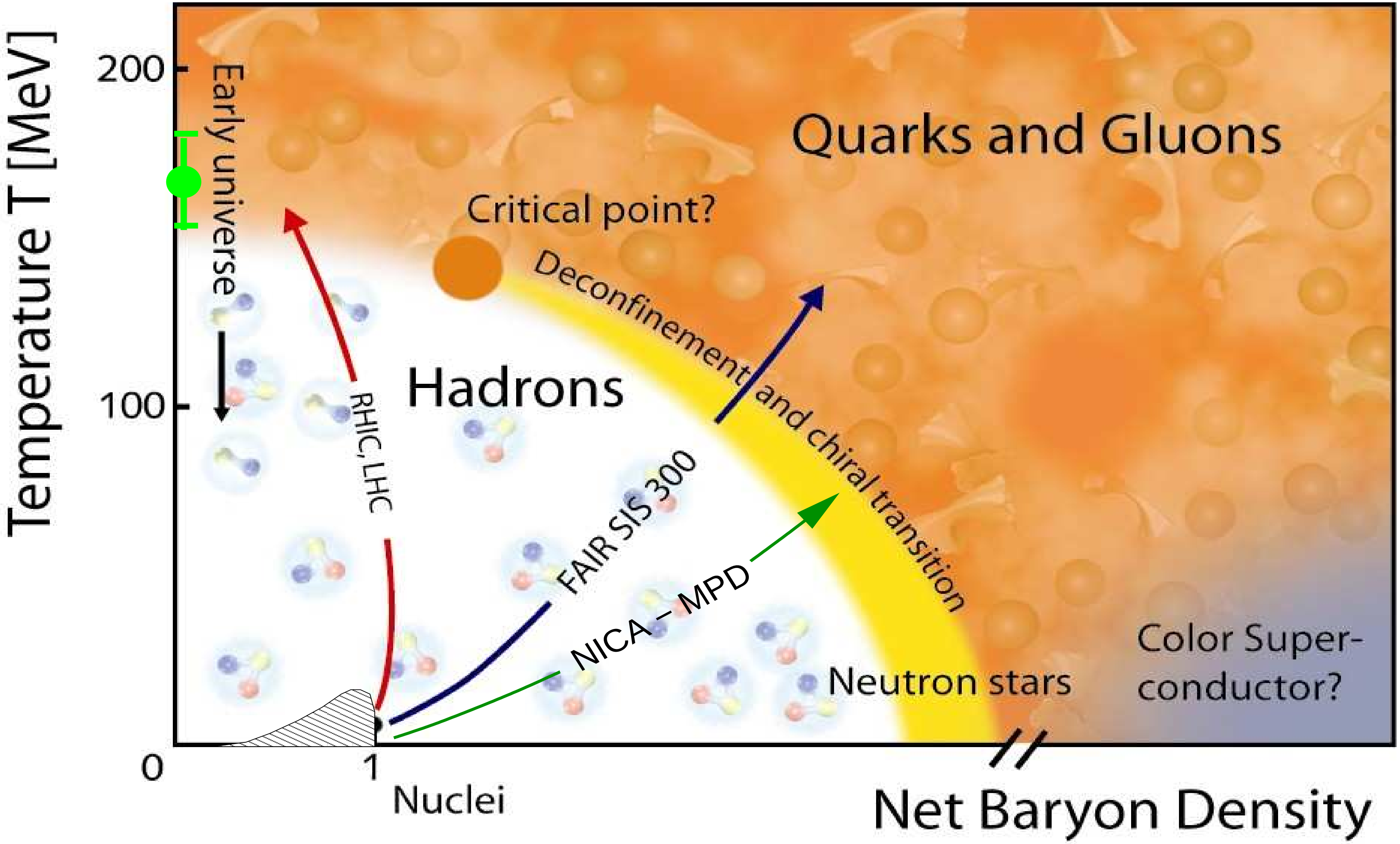


- Equation of state: $\varepsilon(T) = -\partial \ln Z[T,V,\mu]/\partial\beta$
- Phase transition at $T_c = 170$ MeV
- Problem: Interpretation ?

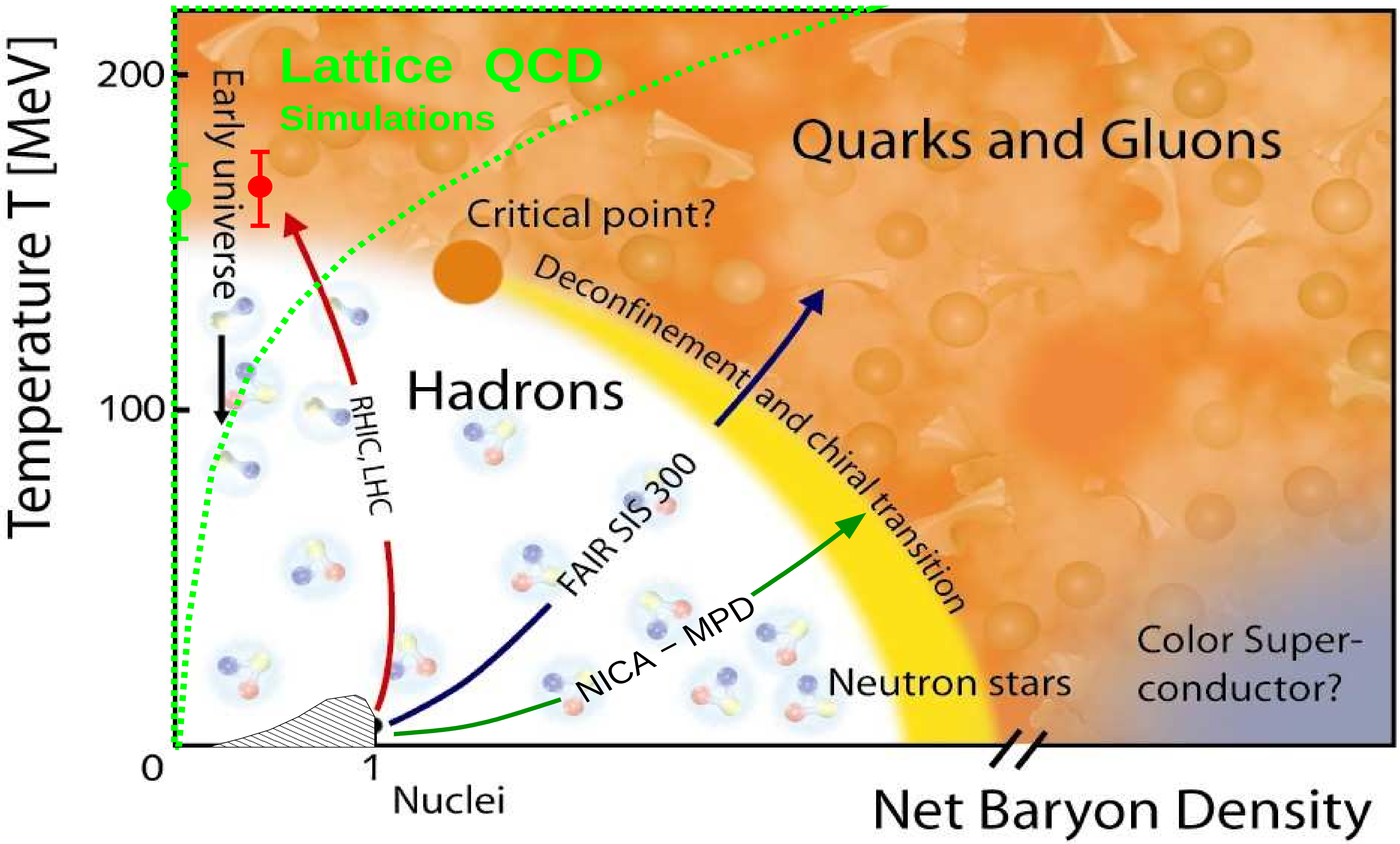
$\varepsilon/T^4 = \frac{\pi^2}{30}N_\pi \sim 1$ (ideal pion gas)

$\varepsilon/T^4 = \frac{\pi^2}{30}(N_G + \frac{7}{8}N_Q) \sim 15.6$ (quarks and gluons)

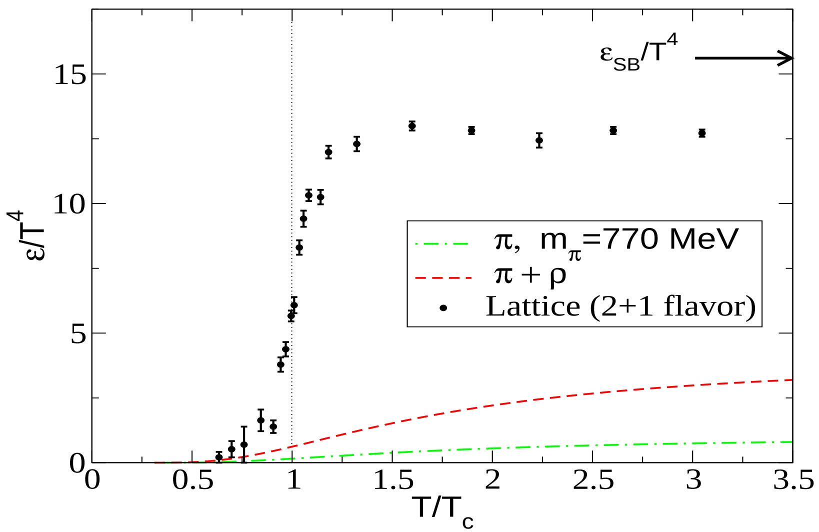
PHASEDIAGRAM OF QCD: LATTICE SIMULATIONS



PHASEDIAGRAM OF QCD: LATTICE SIMULATIONS



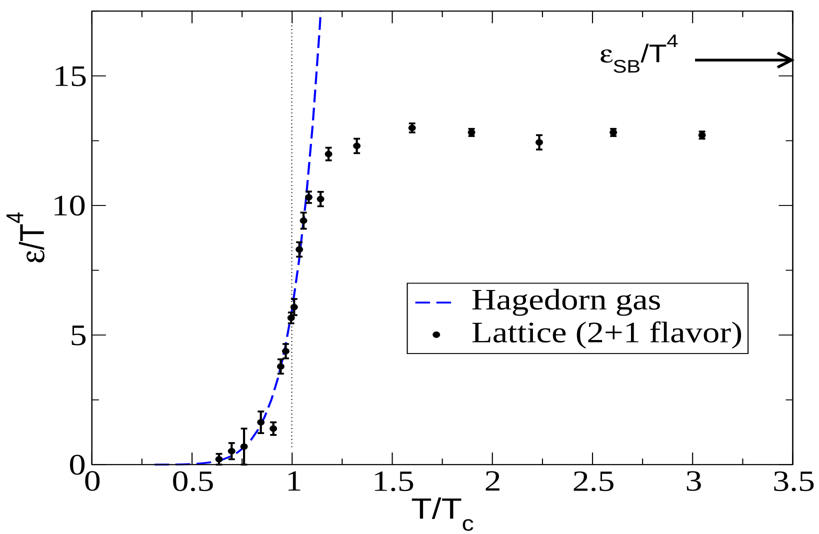
Lattice QCD EoS vs. resonance gas



Ideal hadron gas mixture ...

$$\varepsilon(T) = \sum_{i=\pi,\rho,\ldots} g_i \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+m_i^2}}{\exp(\sqrt{p^2+m_i^2}/T)+\delta_i}$$

missing degrees of freedom below and above T_c



Resonance gas ...

Karsch, Redlich, Tawfik, Eur.Phys.J. C29, 549 (2003)

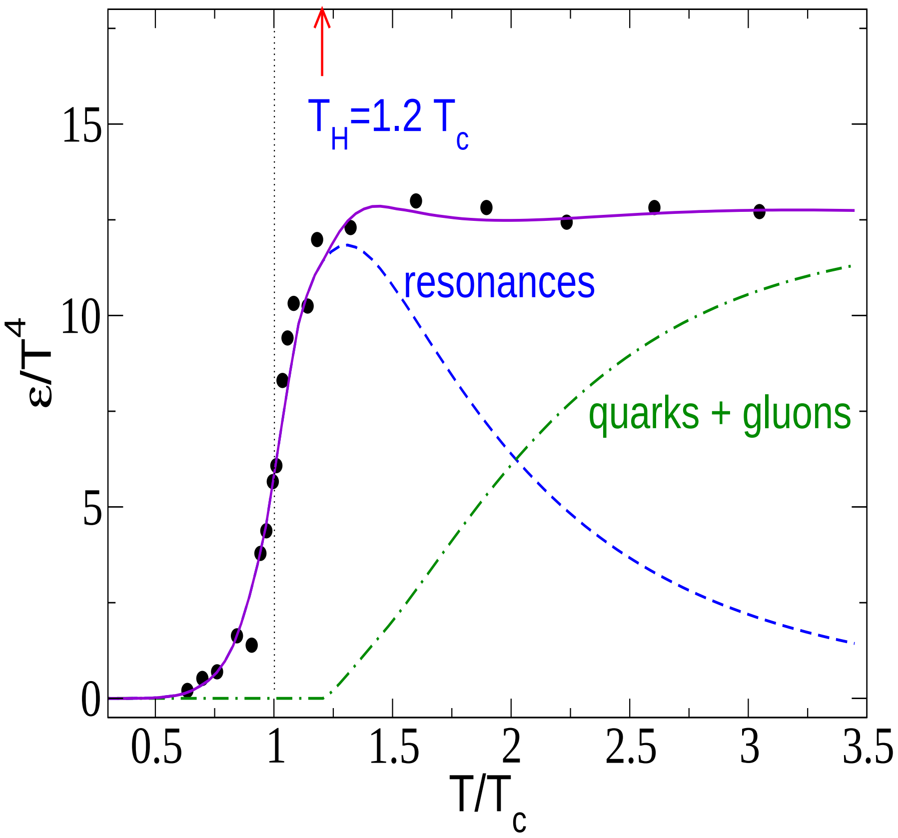
$$\begin{aligned} \varepsilon(T) &= \sum_{i=\pi,\rho,\ldots} \varepsilon_i(T) \\ &+ \sum_{r=M,B} g_r \int dm\, \rho(m) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+m^2}}{\exp(\sqrt{p^2+m^2}/T)+\delta_r} \end{aligned}$$

$\rho(m) \sim m^\beta \exp(m/T_H)$ ... Hagedorn mass spektrum

too many degrees of freedom above T_c

LATTICE QCD EOS AND MOTT-HAGEDORN GAS

$$\varepsilon_{\rm R}(T,\{\mu_j\}) = \sum_{i=\pi,K,\ldots} \varepsilon_i(T,\{\mu_i\}) + \sum_{r=M,B} g_r \int_{m_r} dm \int ds\, \rho(m) A(s,m;T) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+s}}{\exp\left(\frac{\sqrt{p^2+s}-\mu_r}{T}\right)+\delta_r}$$



Hagedorn mass spectrum: $\rho(m)$

Spectral function for heavy resonances:

$$A(s,m;T) = N_s \frac{m\Gamma(T)}{(s-m^2)^2 + m^2\Gamma^2(T)}$$

Ansatz with Mott effect at $T = T_H = 180$ MeV:

$$\Gamma(T) = B\Theta(T-T_H)\left(\frac{m}{T_H}\right)^{2.5}\left(\frac{T}{T_H}\right)^{6}\exp\left(\frac{m}{T_H}\right)$$

No width below T_H: Hagedorn resonance gas

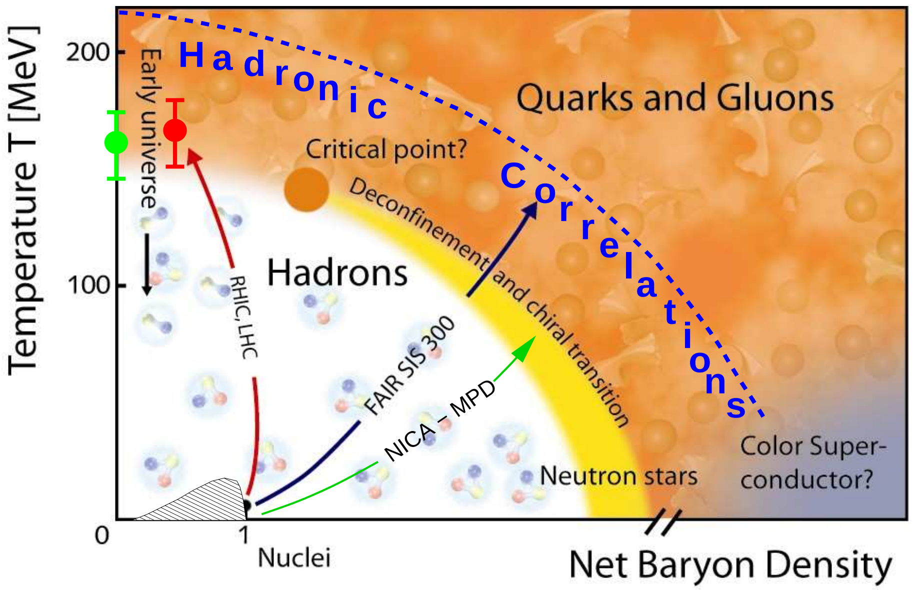
Apparent phase transition at $T_c \sim 150$ MeV

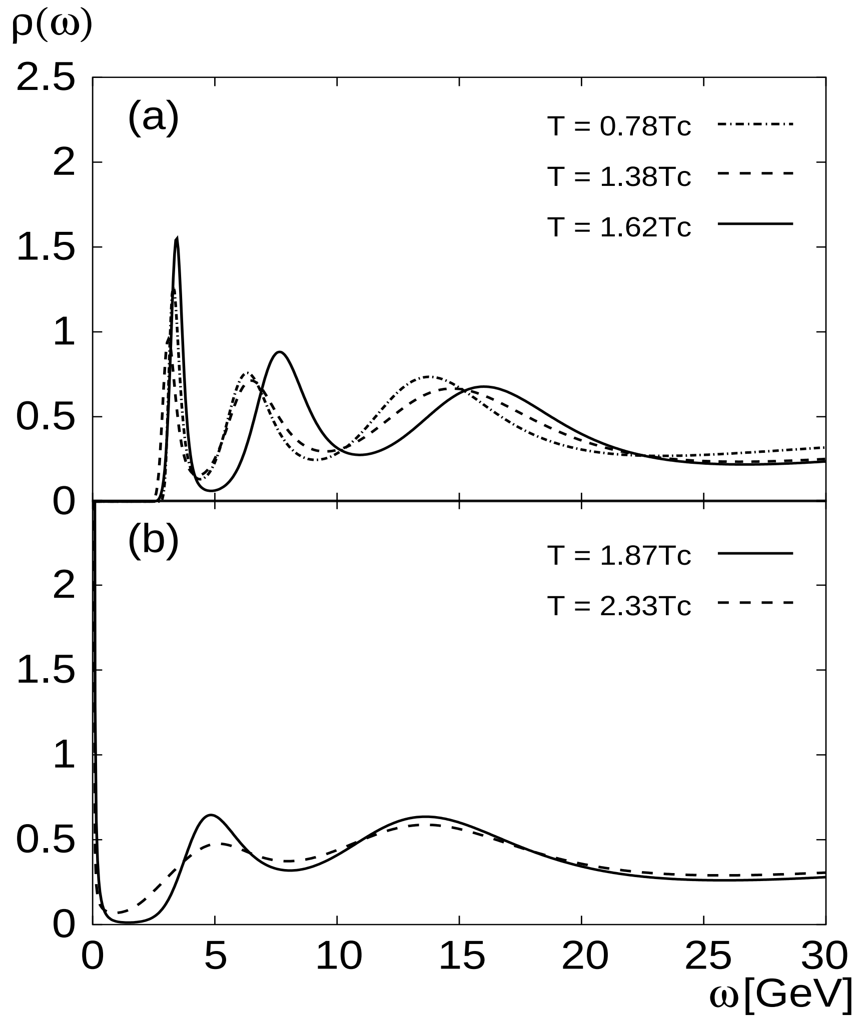
Blaschke & Bugaev, Fizika B13, 491 (2004)

Prog. Part. Nucl. Phys. 53, 197 (2004)

Blaschke & Yudichev, in preparation

Hadronic Correlations above T_c: Lattice QCD





Hadron correlators $G_H \Longrightarrow$ spectral densities $\rho_H(\omega, T)$

$$G_H(\tau, T) = \int_0^\infty d\omega \rho_H(\omega, T) \frac{\cosh(\omega(\tau - T/2))}{\sinh(\omega/2T)}$$

Maximum entropy method

Karsch et al. PLB 530 (2002) 147

Result:

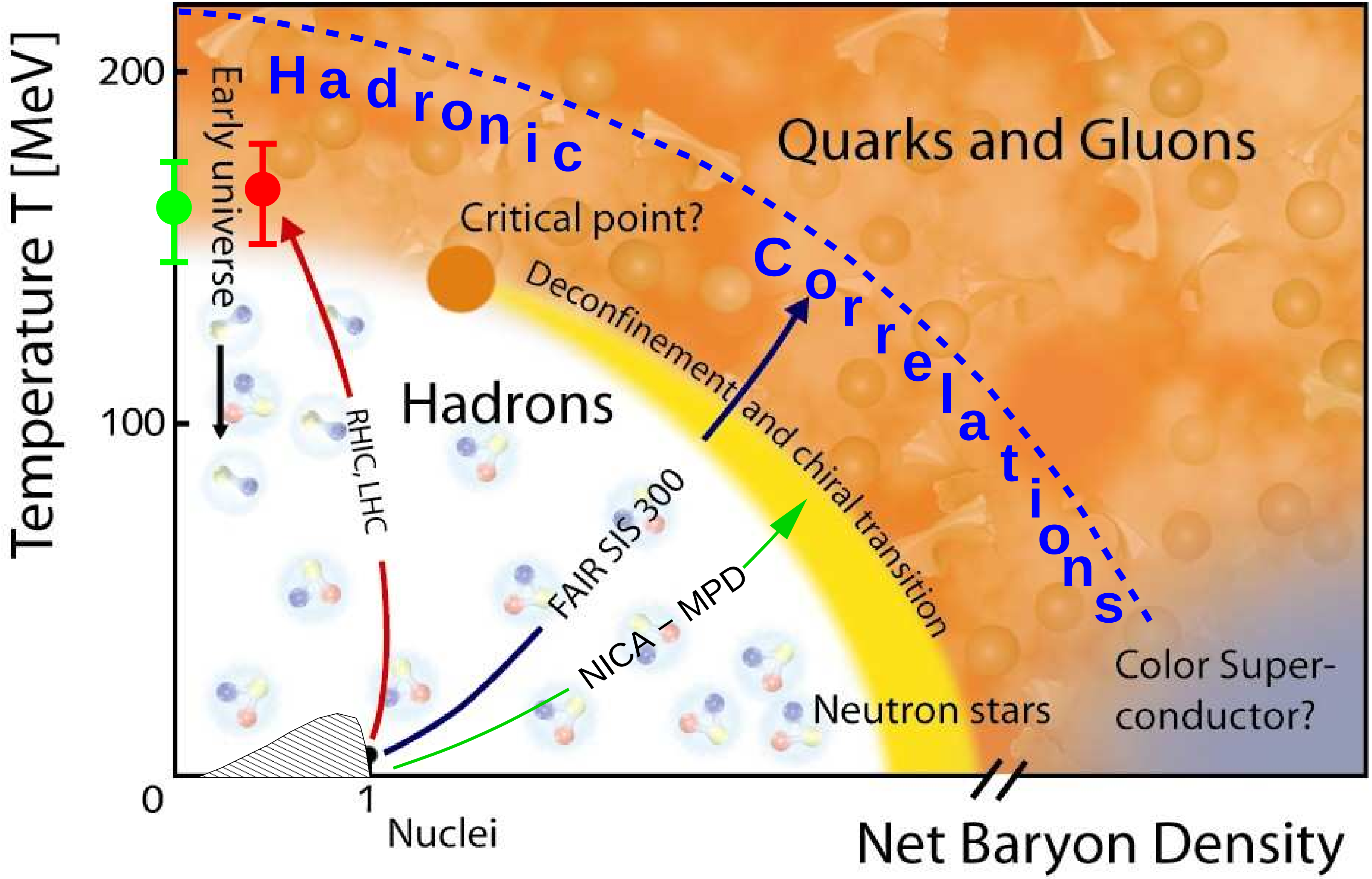
Correlations persist above T_c !

Karsch et al. NPA 715 (2003)

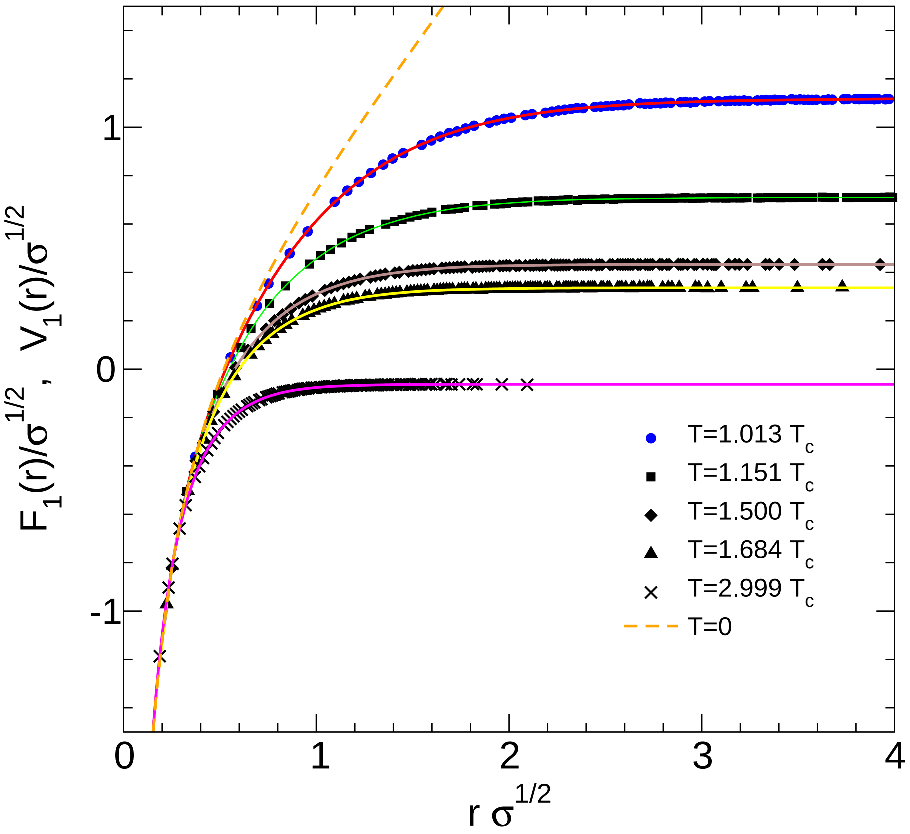
J/ψ and η_c survive up to $T \sim 1.6 T_c$

Asakawa, Hatsuda; PRL 92 (2004) 012001

Hadronic Correlations in the Phasediagram of QCD



HEAVY QUARK POTENTIAL FROM LATTICE QCD



Blaschke, Kaczmarek, Laermann, Yudichev, EPJC 43, 81 (2005); [hep-ph/0505053]

Color-singlet free energy F_1 in quenched QCD

$$\langle \mathrm{Tr}[L(0)L^\dagger(r)]\rangle = \exp[-F_1(r)/T]$$

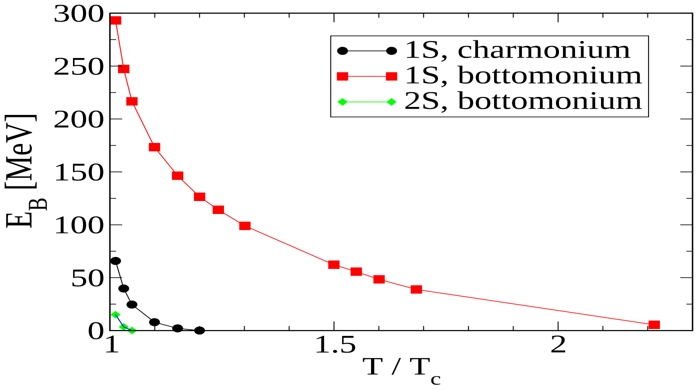
Long- and short- range parts

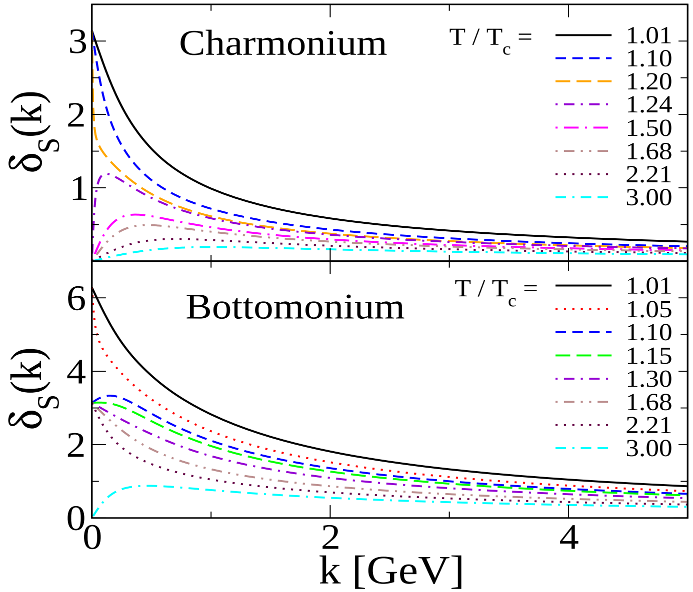
$$F_1(r,T) = F_{1,\mathrm{long}}(r,T) + V_{1,\mathrm{short}}(r)e^{-(\mu(T)r)^2}$$

$$\begin{aligned}
F_{1,\mathrm{long}}(r,T) &= -\frac{q^2(T)}{2^{3/4}\Gamma(3/4)}\sqrt{\frac{r}{\mu(T)}}K_{1/4}\left[(\mu(T)r)^2\right] \\
&\quad + q^2(T)\frac{\Gamma(1/4)}{2^{3/2}\Gamma(3/4)\mu(T)}, \\
V_{1,\mathrm{short}}(r) &= -\frac{4}{3}\frac{\alpha(r)}{r}, \\
\alpha(r) &= \frac{4\pi}{11}\left(\frac{1}{\ln(r^2/c^2)} - \frac{r^2}{r^2-c^2}\right).
\end{aligned}$$

Quarkonium ($Q\bar{Q}$)	1S	1P$_1$	2S
Charmonium ($c\bar{c}$)	J/ψ(3097)	χ_{c1}(3510)	ψ' (3686)
Bottomonium ($b\bar{b}$)	Υ (9460)	χ_{b1} (9892)	Υ' (10023)

SCHROEDINGER EQN: BOUND & SCATTERING STATES





Quarkonia bound states at finite T:

$$[-\nabla^2/m_Q + V_{\rm eff}(r,T)]\psi(r,T) = E_B(T)\psi(r,T)$$

Binding energy vanishes $E_B(T_{\rm Mott}) = 0$: Mott effect

Scattering states:

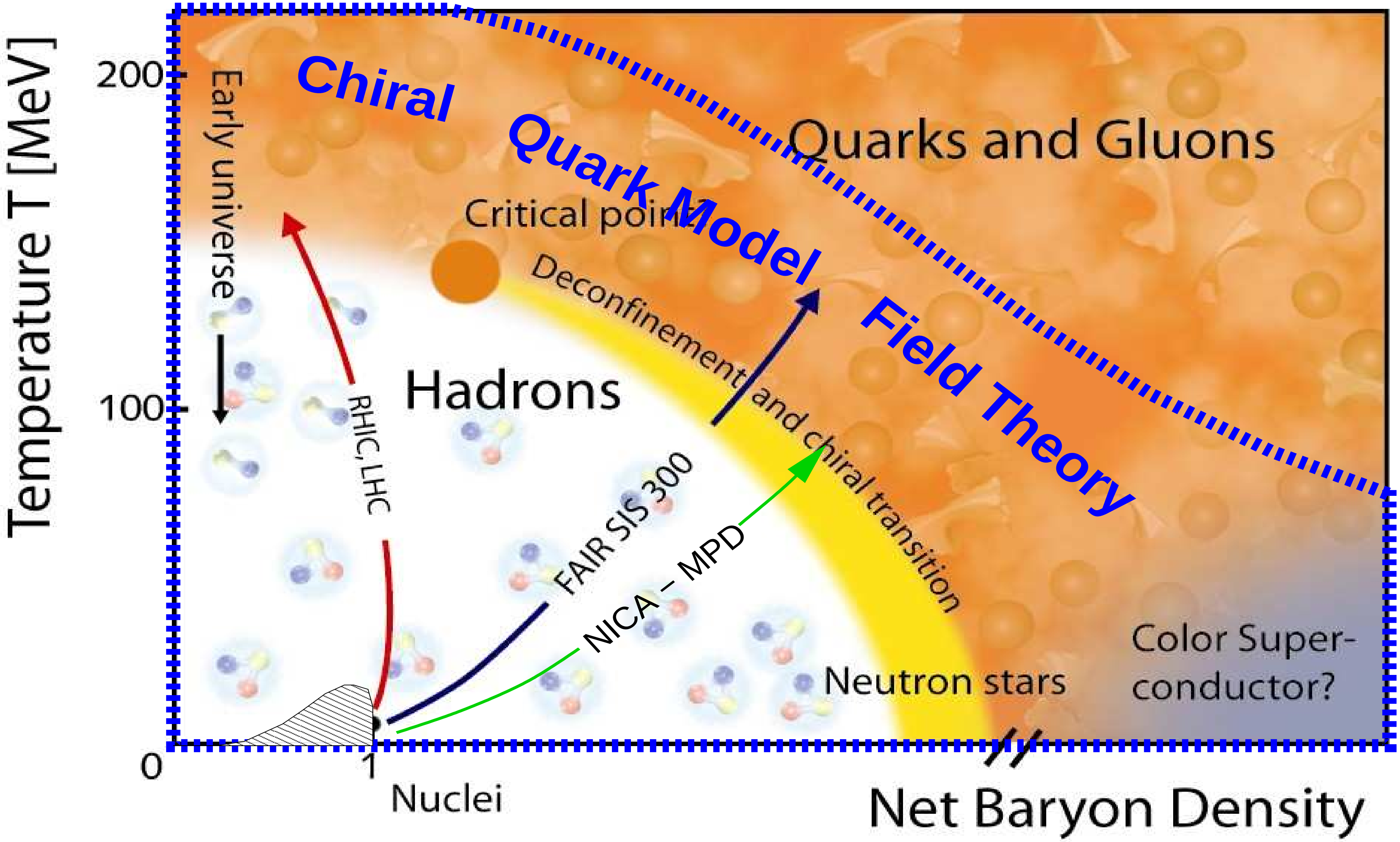
$$\frac{d\delta_S(k,r,T)}{dr} = -\frac{m_Q V_{\rm eff}}{k}\sin(kr + \delta_S(k,r,T))$$

Levinson theorem:

Phase shift at threshold jumps by π when bound state $\rightarrow$ resonance at $T = T_{\rm Mott}$

Blaschke, Kaczmarek, Laermann, Yudichev EPJC 43, 81 (2005); [hep-ph/0505053]

PHASEDIAGRAM OF QCD: CHIRAL MODEL FIELD THEORIES



Chiral Model Field Theory for Quark Matter

- Partition function as a Path Integral (imaginary time $\tau = i\,t$)

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

- Current-current interaction (4-Fermion coupling)

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

- Bosonization (Hubbard-Stratonovich Transformation)

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

- Collective (stochastic) fields: Mesons (M_M) and Diquarks (Δ_D)
- Systematic evaluation: Mean fields + Fluctuations
  - Mean-field approximation: order parameters for phase transitions (gap equations)
  - Lowest order fluctuations: hadronic correlations (bound & scattering states)
  - Higher order fluctuations: hadron-hadron interactions

NJL model for neutral 3-flavor quark matter

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

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

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

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

Fermion Determinant (Tr ln D = ln det D): $\ln\det[\beta\, S^{-1}(i\omega_n,\vec{p})] = 2\sum_{a=1}^{18}\ln\{\beta^2[\omega_n^2+\lambda_a(\vec{p})^2]\}$.

Result for the thermodynamic Potential (Meanfield approximation)

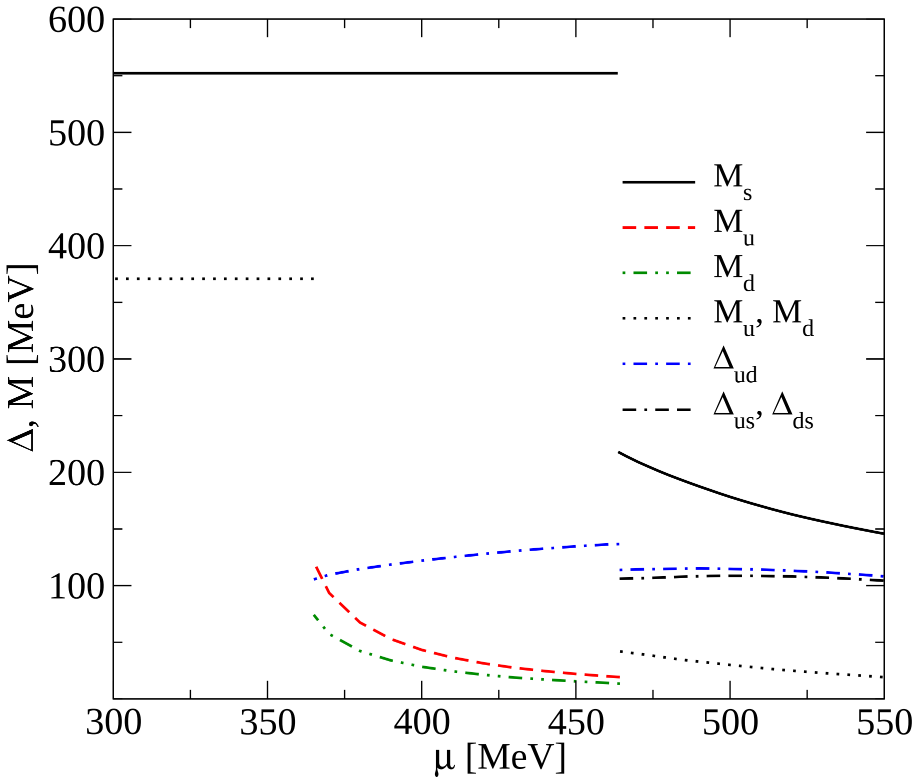
$$\Omega(T,\mu) \;=\; \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} - \int \frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left[\lambda_a + 2T\ln\left(1+e^{-\lambda_a/T}\right)\right] + \Omega_e - \Omega_0.$$

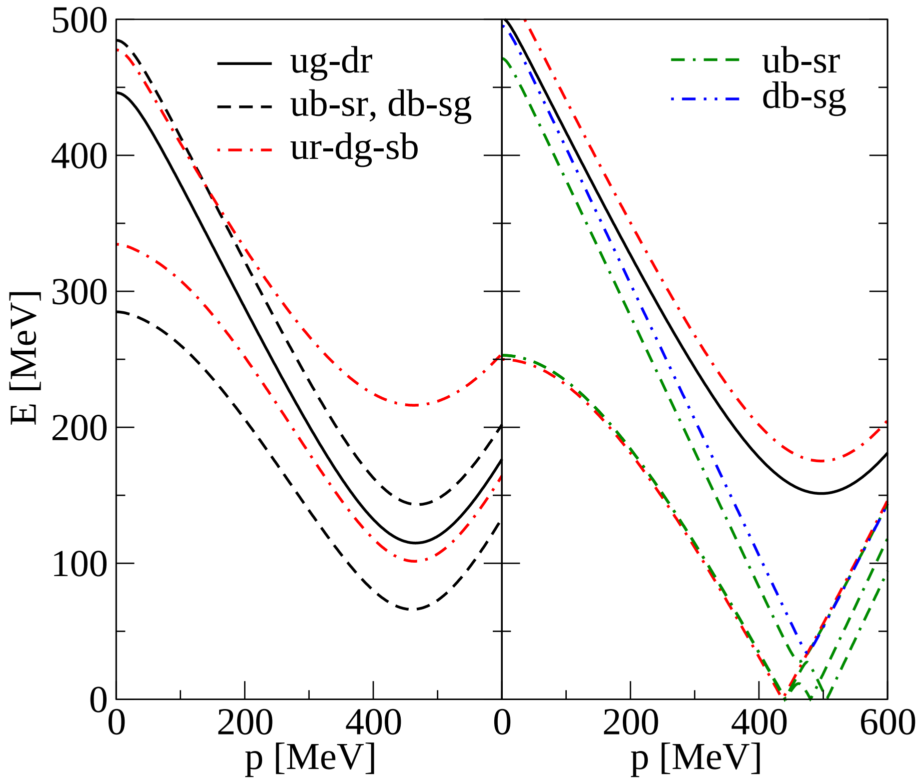
Color and electric charge neutrality constraints: $n_Q = n_8 = n_3 = 0$, $n_i = -\partial\Omega/\partial\mu_i = 0$,
Equations of state: $P = -\Omega$, etc.

ORDER PARAMETERS: MASSES AND DIQUARK GAPS

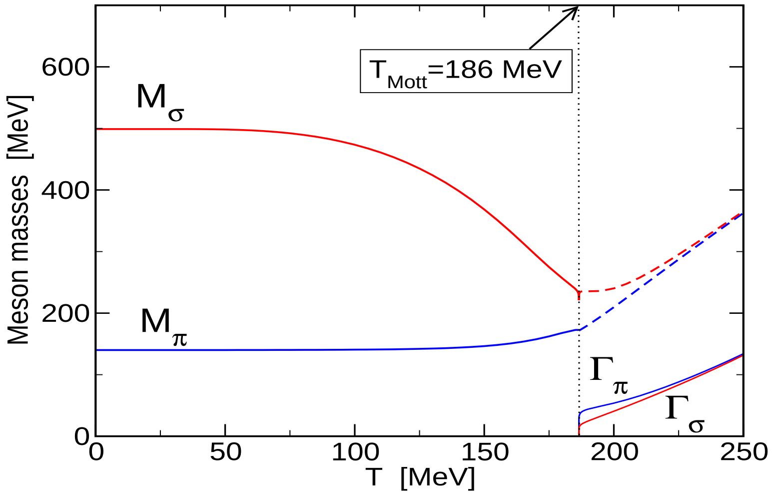
Masses (M) and Diquark gaps (Δ) as a function of the chemical potential at $T = 0$

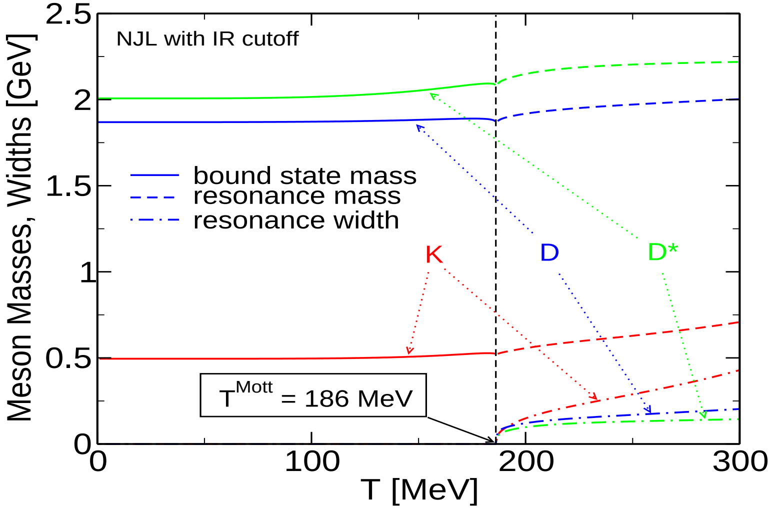
Left: Gap in excitation spectrum ($T = 0$)
Right: 'Gapless' excitations ($T = 60$ MeV)



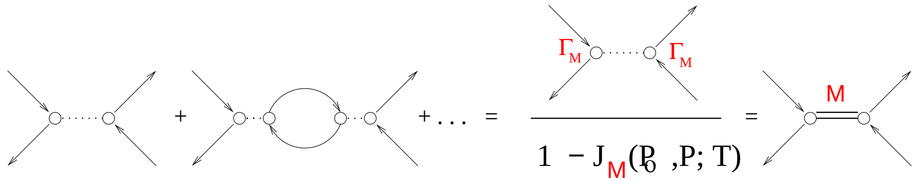


MOTT EFFECT: NJL MODEL PRIMER





RPA-type resummation of quark-antiquark scattering in the mesonic channel M,



defines Meson propagator

$$D_M(P_0, P; T) \sim [1 - J_M(P_0, P; T)]^{-1},$$

by the complex polarization function J_M
$\rightarrow$ Breit-Wigner type spectral function

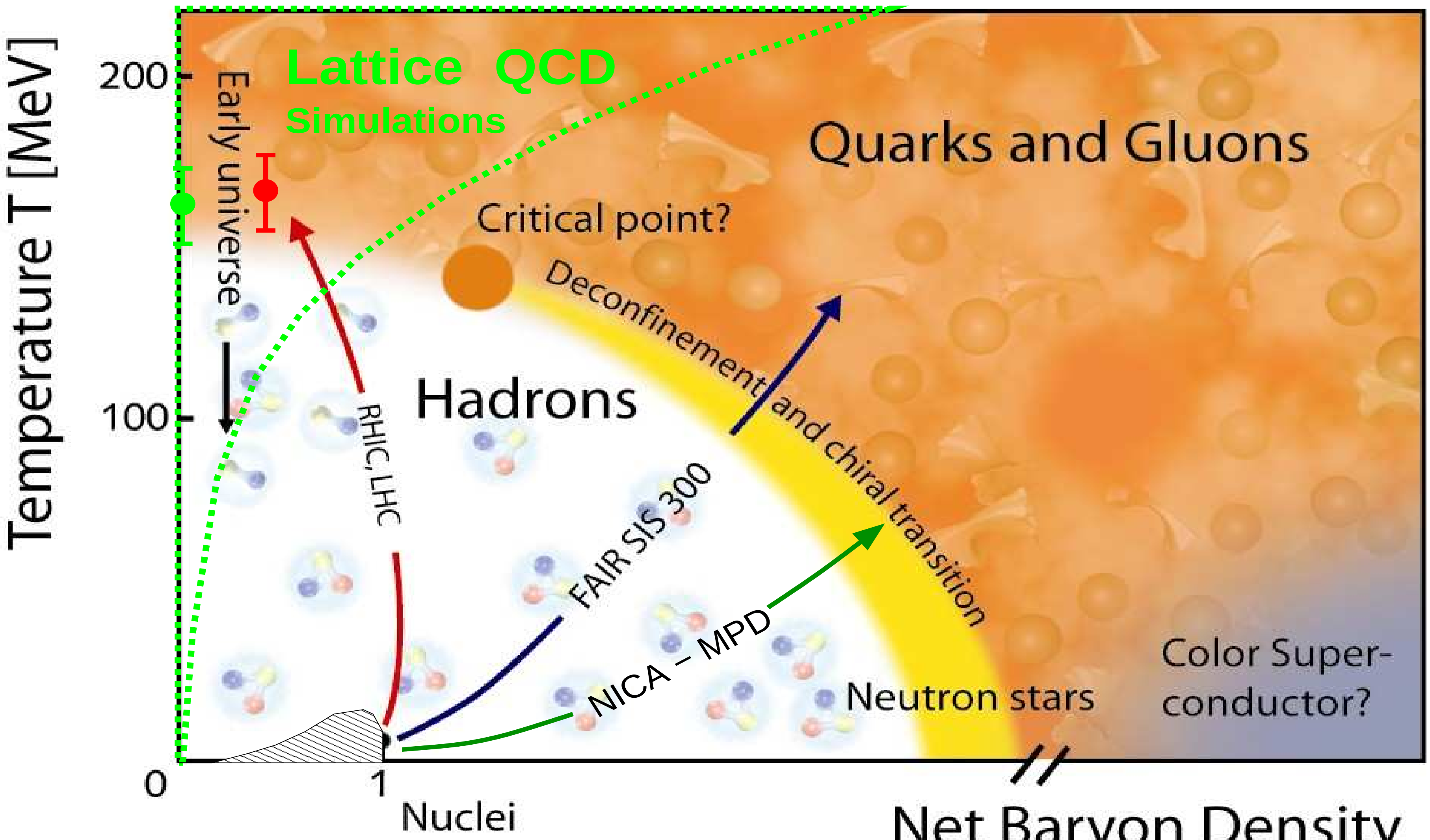
$$\mathcal{A}_M(P_0, P; T) = \frac{1}{\pi} \text{Im } D_M(P_0, P; T)$$
$$\sim \frac{1}{\pi} \frac{\Gamma_M(T) M_M(T)}{(s - M_M^2(T))^2 + \Gamma_M^2(T) M_M^2(T)}$$

For $T < T_{\text{Mott}}$: $\Gamma \rightarrow 0$, i.e. bound state
$\mathcal{A}_M(P_0, P; T) = \delta(s - M_M^2(T))$

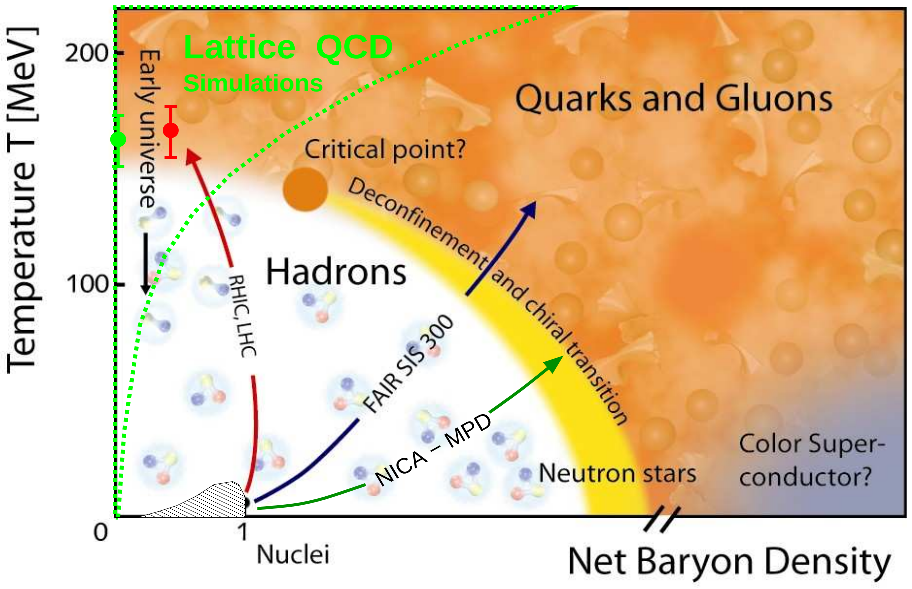
Light meson sector:
Blaschke, Burau, Volkov, Yudichev: EPJA **11** (2001) 319

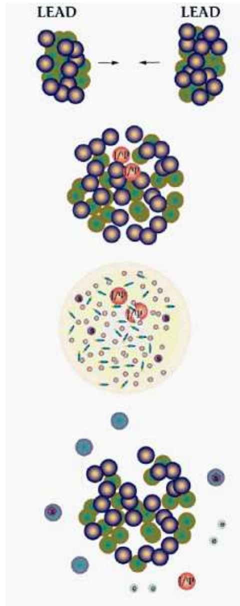
Charm meson sector:
Blaschke, Burau, Kalinovsky, Yudichev,
Prog. Theor. Phys. Suppl. **149** (2003) 182

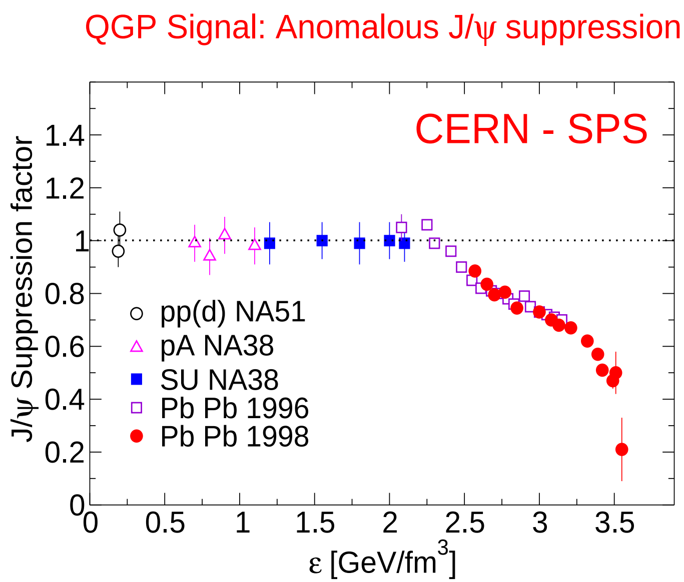
PHASEDIAGRAM OF QCD: HEAVY-ION COLLISIONS

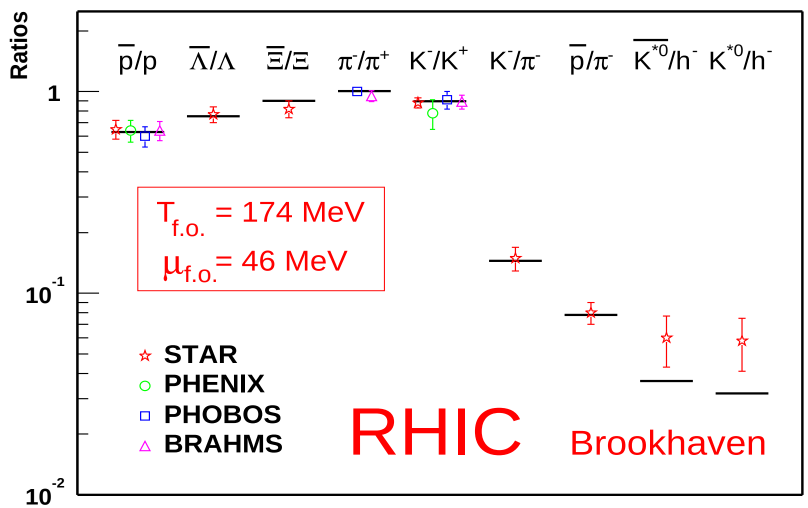


PHASEDIAGRAM OF QCD: LATTICE VS. HEAVY-ION COLLISIONS









Statistical model describes composition of hadron yields in Heavy-Ion Collisions with few freeze-out parameters.

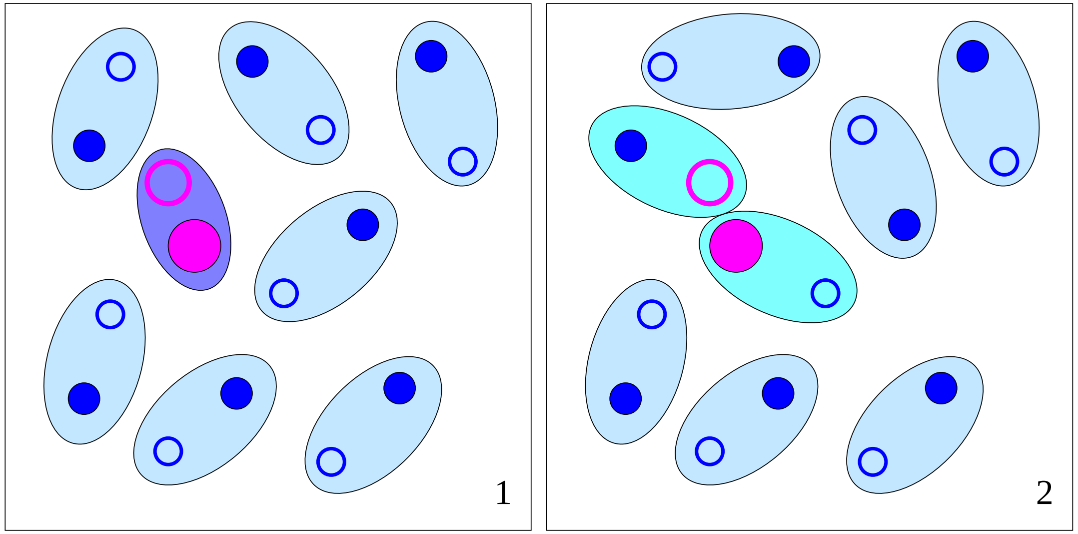
$$\ln Z[T,V,\{\mu\}] = \pm V \sum_i \frac{g_i}{2\pi^2} \int_0^\infty dp\, p^2 \ln[1 \pm \lambda_i \exp(-\beta\varepsilon_i(p))]$$

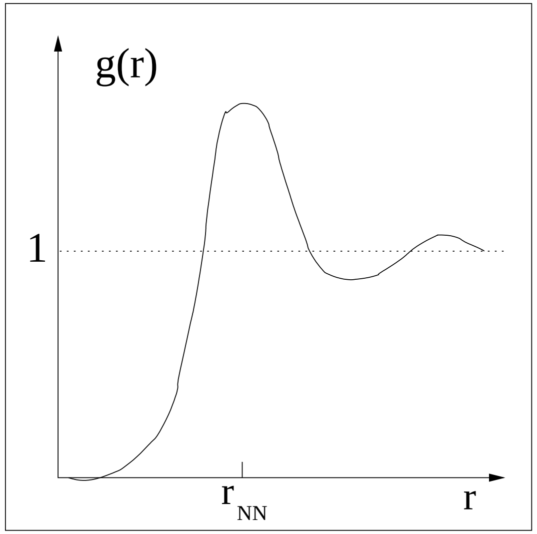
$$\lambda_i(T,\{\mu\}) = \exp[\beta(\mu_B B_i + \mu_S S_i + \mu_Q Q_i)]$$

Braun-Munzinger, Redlich, Stachel, in *QGP III* (2003)

A SNAPSHOP OF THE sQGP

The Picture: String-flip (Rearrangement) $\Longleftrightarrow$ Pair correlation



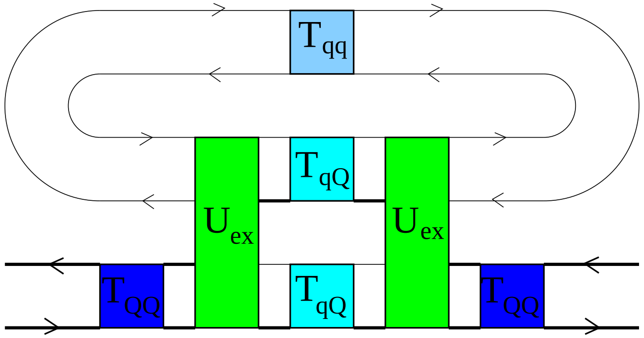


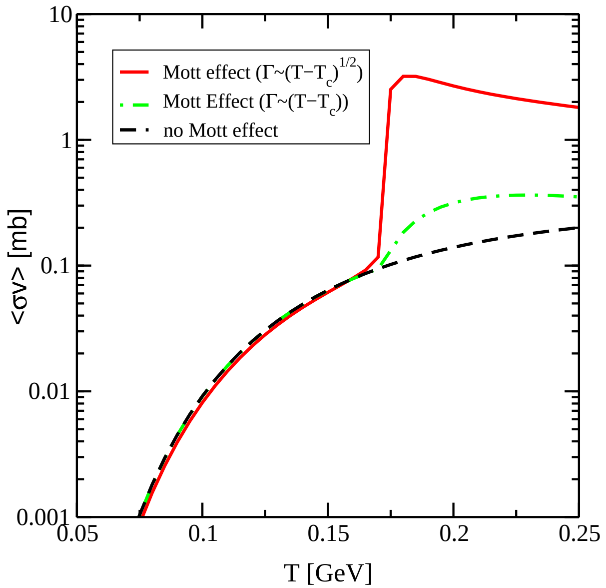
Horowitz et al. PRD (1985), D.B. et al. PLB (1985), Röpke, Blaschke, Schulz, PRD (1986)

Thoma, Quark Matter '05; [hep-ph/0509154]

- Strong correlations present: hadronic spectral functions above T_c (lattice QCD)
- Finite width due to rearrangement collisions (higher order correlations)
- Liquid-like pair correlation function (nearest neighbor peak)

QUANTUM KINETIC APPROACH TO J/ψ BREAKUP





Inverse lifetime for Charmonium states

$$\tau^{-1}(p) = \Gamma(p) = \Sigma^{>}(p) \mp \Sigma^{<}(p)$$

$$\Sigma^{\gtrless}(p,\omega) = \int_{p'}\int_{p_1}\int_{p_2}(2\pi)^4\delta_{p,p';p_1,p_2}\,|\mathcal{M}|^2\,G_\pi^{\lessgtr}(p')\,G_{D_1}^{\gtrless}(p_1)\,G_{D_2}^{\gtrless}(p_2)$$

$G_h^{>}(p) = [1 \pm f_h(p)]A_h(p)$ and $G_h^{<}(p) = f_h(p)A_h(p)$

$$\tau^{-1}(p) = \int \frac{d^3\mathbf{p}'}{(2\pi)^3}\int ds' \quad f_\pi(\mathbf{p}',s')\;A_\pi(s')v_{\rm rel}\;\sigma^*(s)$$

In-medium breakup cross section

$$\sigma^*(s) = \int ds_1\;ds_2\;A_{D_1}(s_1)\;A_{D_2}(s_2)\;\sigma(s;s_1,s_2)$$

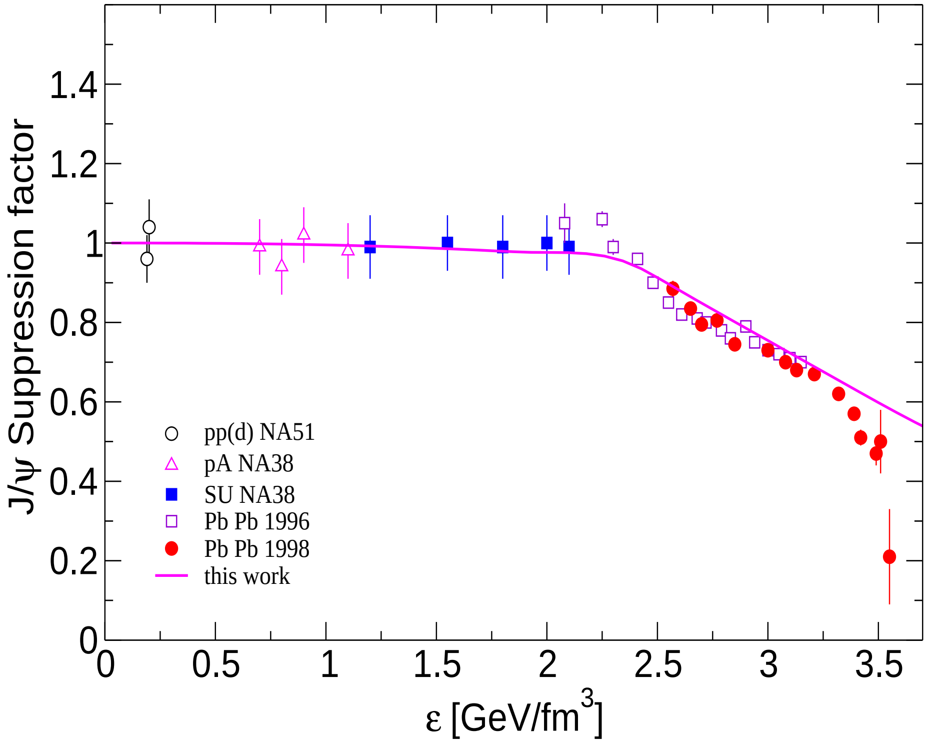
Medium effects in spectral functions A_h and $\sigma(s;s_1,s_2)$

$$A_h(s) = \frac{1}{\pi}\frac{\Gamma_h(T)\;M_h(T)}{(s-M_h^2(T))^2+\Gamma_h^2(T)M_h^2(T)} \longrightarrow \delta(s-M_h^2)$$

resonance $\Leftarrow$ Mott-effect $\Leftarrow$ bound state

Blaschke et al., Heavy Ion Phys. 18 (2003) 49

"ANOMALOUS" J/ψ SUPPRESSION IN MOTT-HAGEDORN GAS



Survival probability for J/ψ

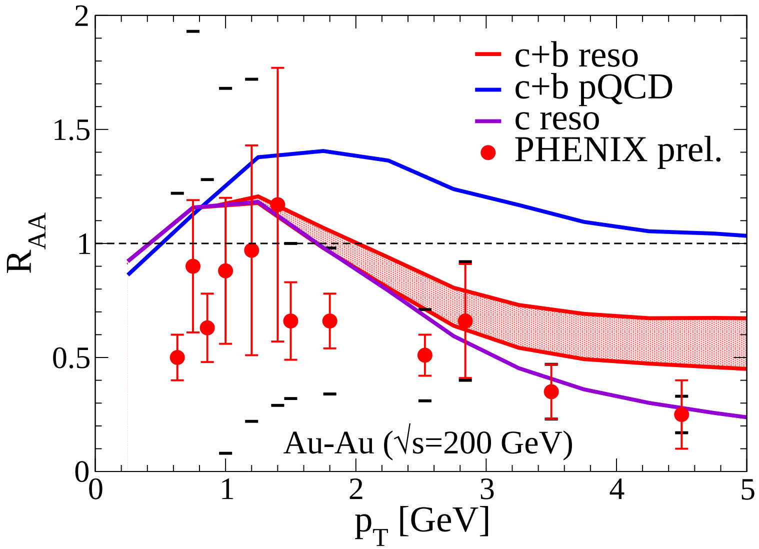
$$S(E_T)/S_N(E_T) \;=\; \exp\left[-\int_{t_0}^{t_f} dt\; \tau^{-1}(n(t))\right]$$

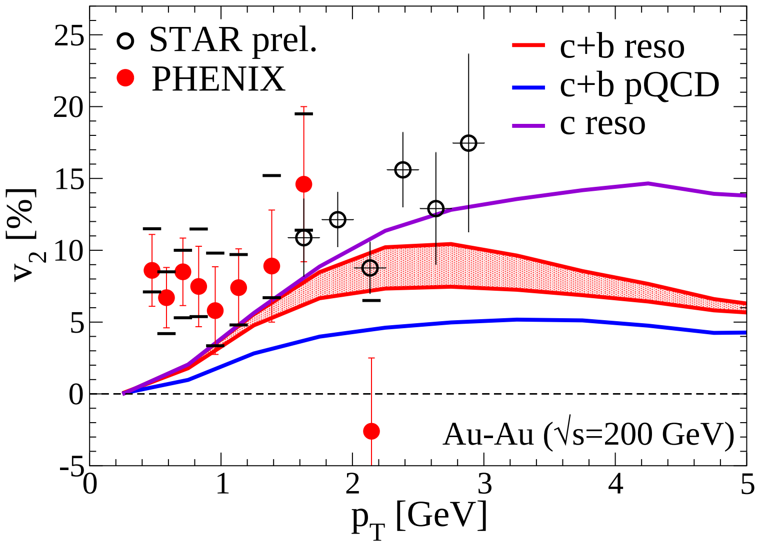
Threshold: Mott effect for hadrons

Blaschke and Bugaev, Prog. Part. Nucl. Phys. 53 (2004) 197

In progress: full kinetics with gain processes (D-fusion), HIC simulation

CHARM AND CHARMONIUM PRODUCTION @ RHIC

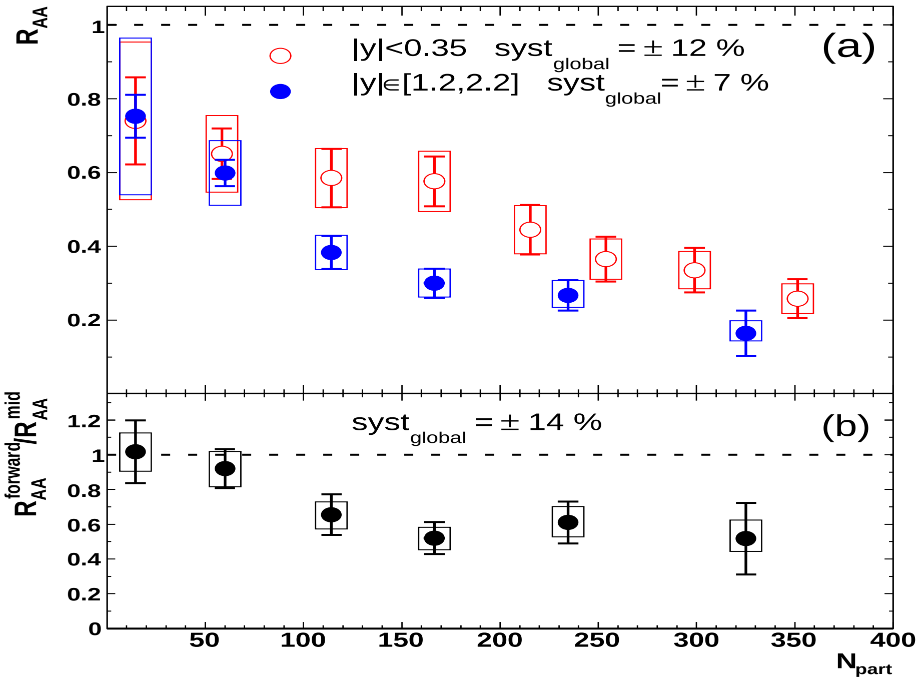




Hees, Greco, Rapp, PRC 73, 034913 (2006)

Nuclear modification factor R_{AA} and elliptic flow v_2 of semileptonic $D-$ and $B-$ meson decay-electrons in $b = 7$ fm Au-Au ($\sqrt{s} = 200$ GeV) collisions at RHIC $\Longleftarrow$

J/ψ suppression in forward stronger than in central rapidity: signal for charmonium regeneration? $\downarrow$

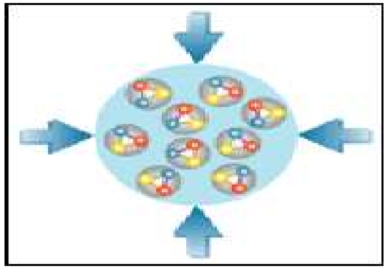


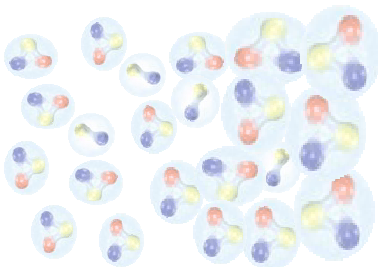
Adare et al. (PHENIX Collaboration); nucl-ex/0611020

Charm and charmonium production @ FAIR-CBM

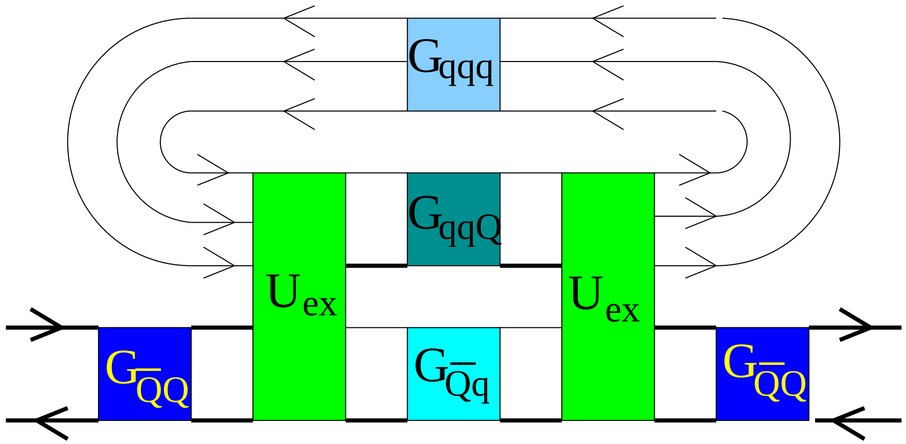
J/ψ dissociation process in dense baryonic matter at FAIR-CBM: spectral functions for open charm hadrons (D-meson, Λ_c) are essential inputs!

$\Longleftarrow$

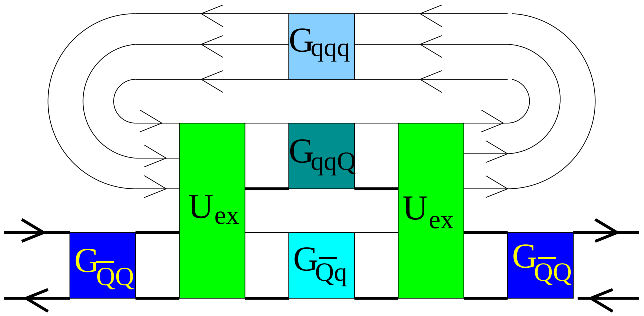


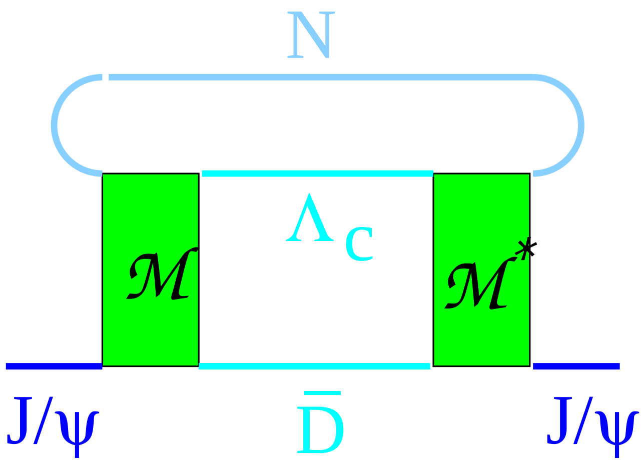


D-meson spectral function in cold dense nuclear matter from a G-matrix approach $\downarrow$



QUANTUM KINETICS OF J/ψ DISSOCIATION @ CBM ($\mu_B \neq 0$)

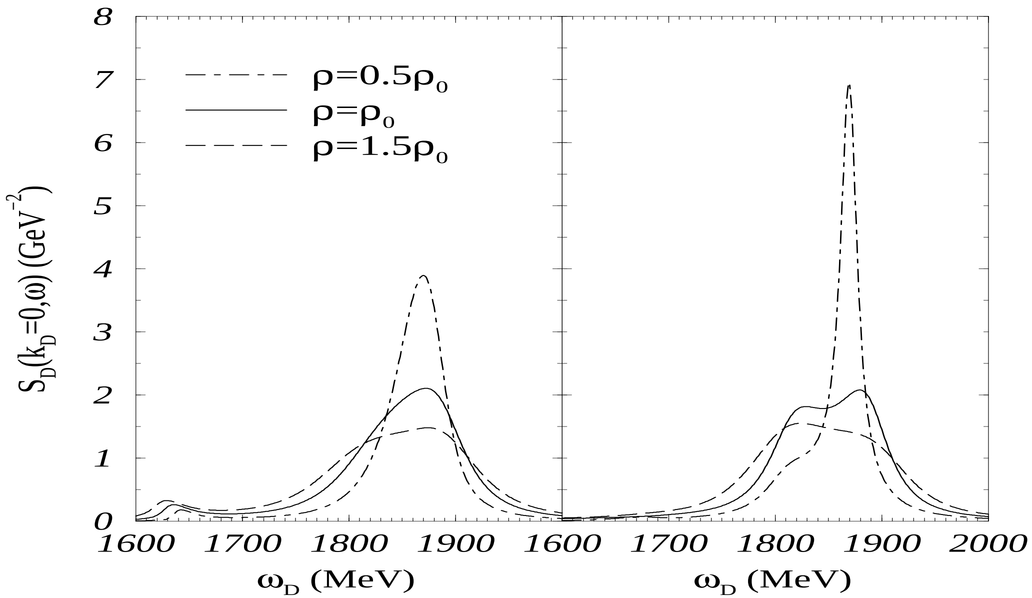




Charmonium lifetime in a dense nuclear medium ($f_D \approx 0$)

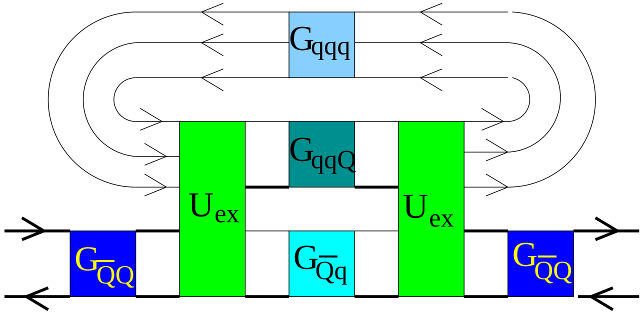
$$\tau^{-1}(p) \;=\; \int_{p'}\int_{p_2}\int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} \left|\mathcal{M}\right|^2 f_N(p')\; A_N(p')\; A_\Lambda(p_1)\; A_D(p_2)$$

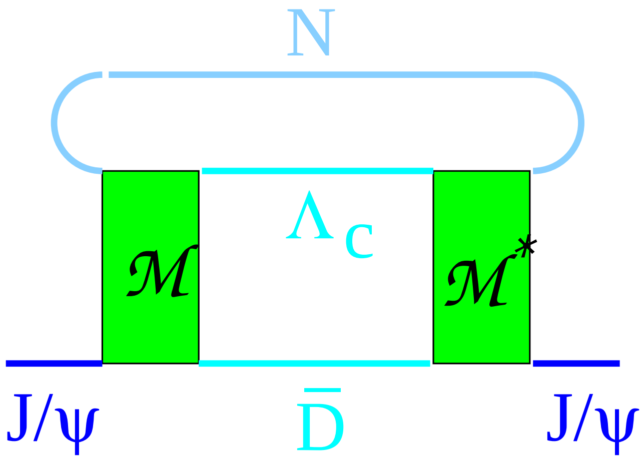
Medium effects in hadronic spectral functions A_h and $\sigma(s;s_1,s_2)$
D-meson spectral function in cold dense nuclear matter from a G-matrix approach ↓ ($N,\ \Lambda_c$ similar)



Tolos et al., EPJC (2005); nucl-th/0501151

QUANTUM KINETICS OF J/ψ DISSOCIATION @ CBM ($\mu_B \neq 0$)

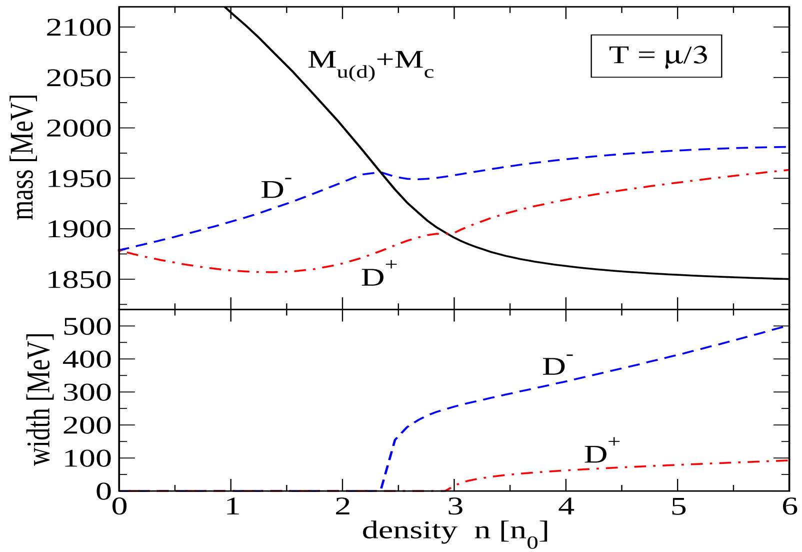




Charmonium lifetime in a dense nuclear medium ($f_D \approx 0$)

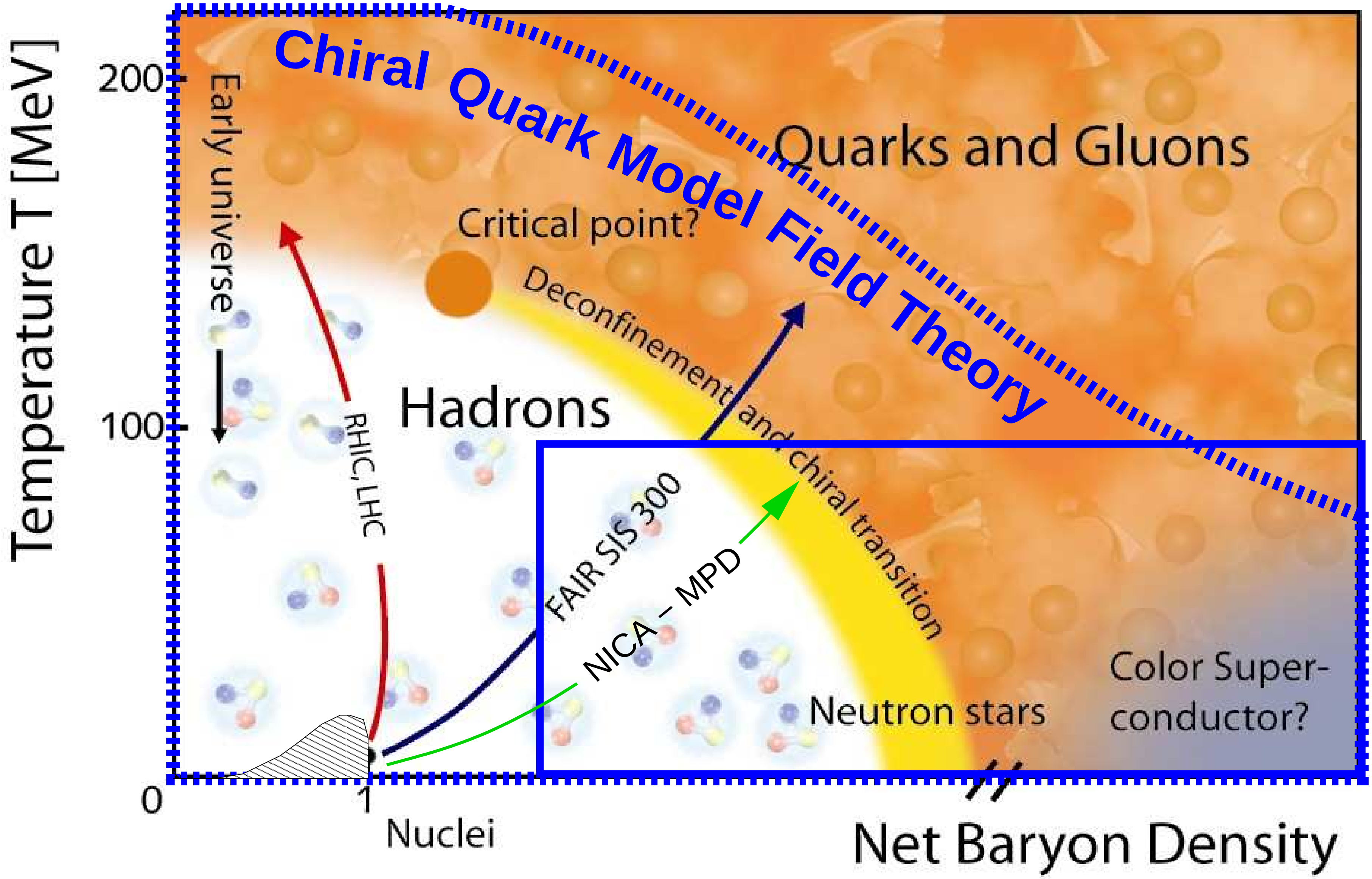
$$\tau^{-1}(p) \;=\; \int_{p'}\int_{p_2}\int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} \left|\mathcal{M}\right|^2 f_N(p')\; A_N(p')\; A_\Lambda(p_1)\; A_D(p_2)$$

Medium effects in hadronic spectral functions A_h and $\sigma(s; s_1, s_2)$
D-meson spectral function in hot, dense quark matter from a NJL model approach ↓ (N, Λ_c similar)

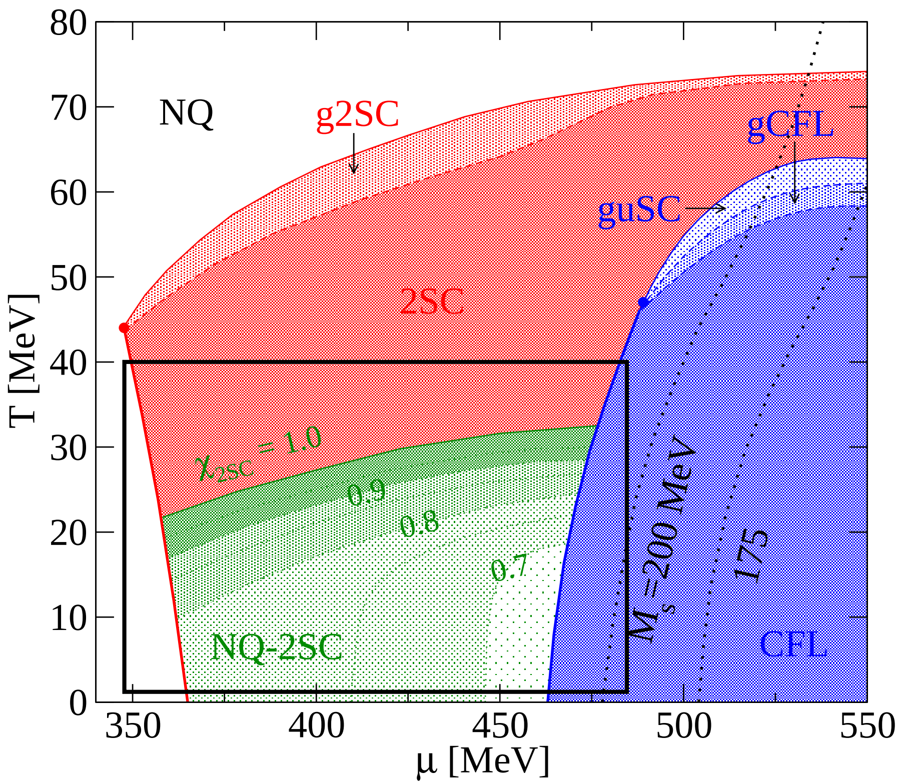


D.B., P. Costa, Yu. Kalinovsky, in preparation

PHASEDIAGRAM OF DEGENERATE QUARK MATTER



QUARK MATTER IN COMPACT STARS



Rüster et al: PRD 72 (2005) 034004
Blaschke et al: PRD 72 (2005) 065020
Abuki, Kunihiro: NPA 768 (2006) 118

The phases are characterized by 3 gaps:

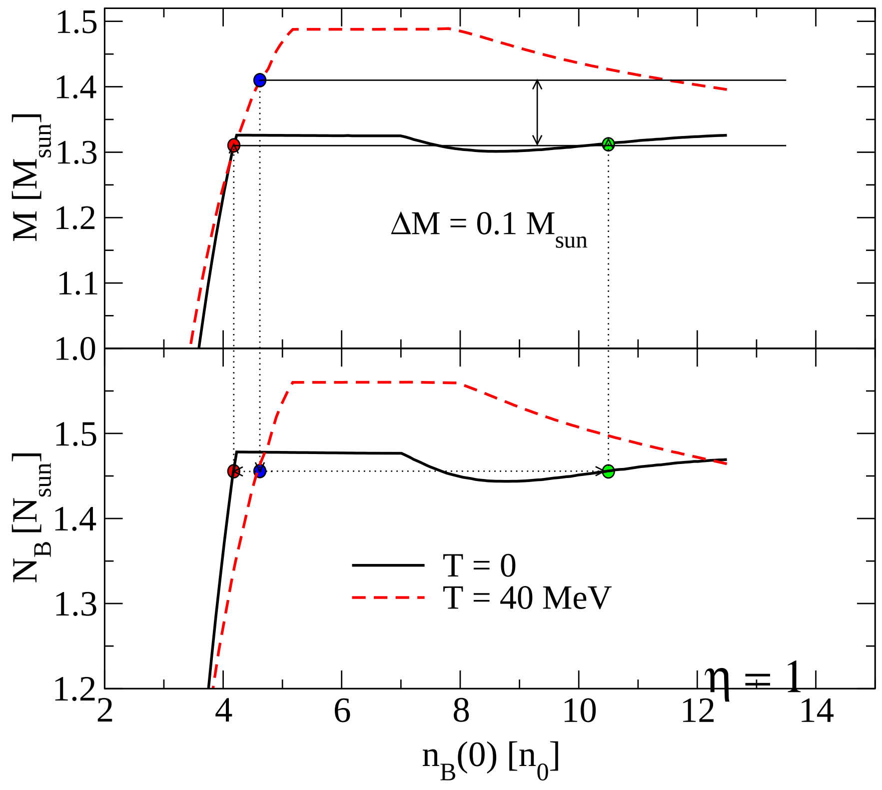
- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$, 0$\leq \chi_{2SC} \leq$1;
- 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq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

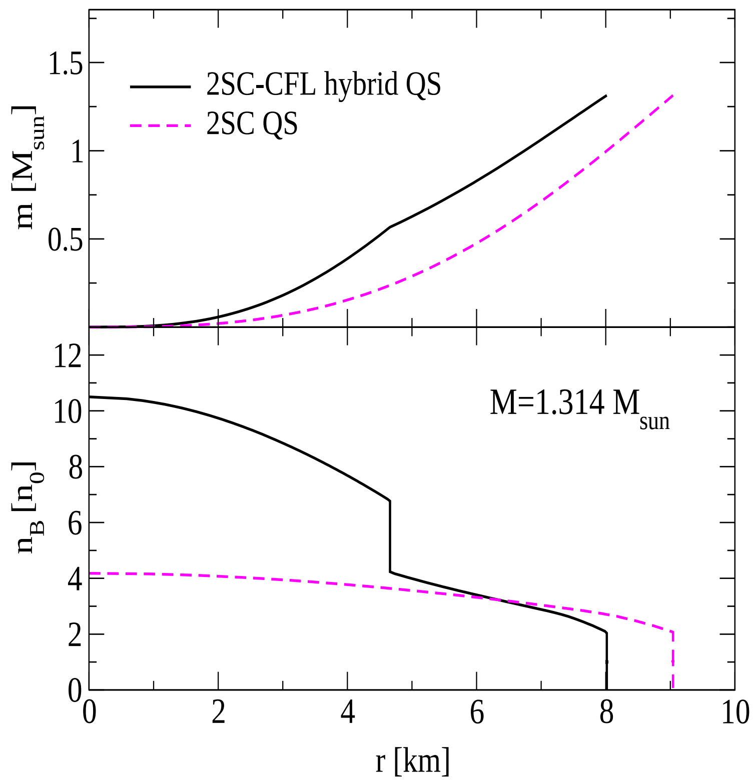
Result:

- 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, $\eta = 1$, changes?.

$\Longrightarrow$ Zhuang (DM 12, 17)

2SC-CFL twin configurations, energy release





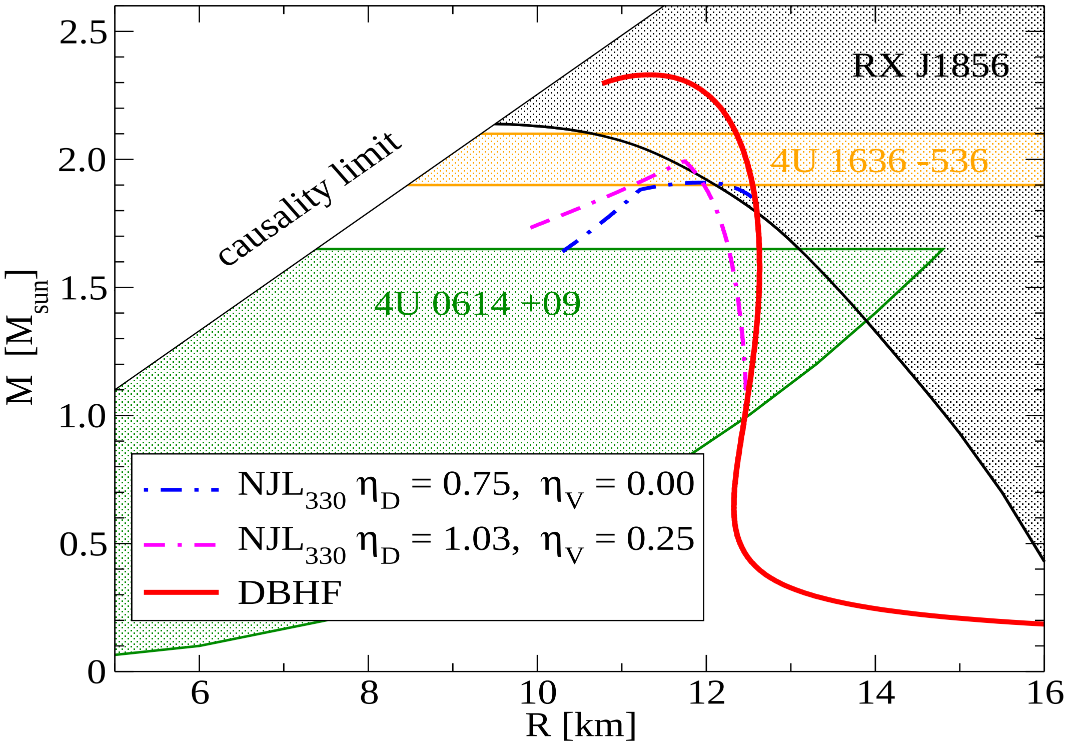
Energy release: $\Delta E \sim 0.1\ \mathrm{M}_\odot \mathrm{c}^2 \sim 10^{52}$ erg.

See also: Aguilera et al: A&A 416, 991 (2004), DB et al: NPA 736, 203 (2004)

Caution: CFL core unstable against adding a hadronic shell!

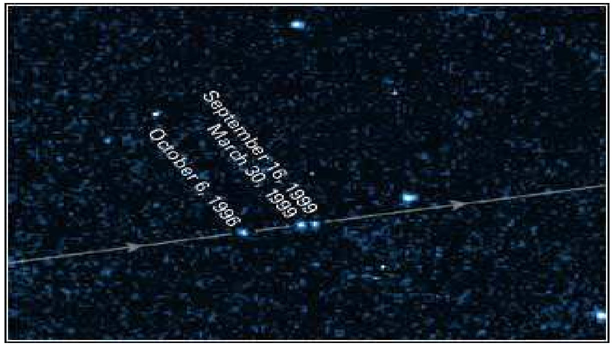
Quark matter in compact stars: Mass-Radius constraint

Solve TOV Eqn. → Hybrid stars fulfill constraint!

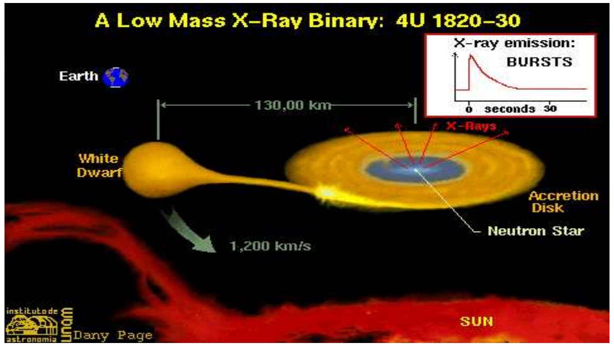


Klähn et al: Constraints on the high-density EoS ...
PRC 74 (2006); [nucl-th/0602038], [astro-ph/0606524]

- Isolated Neutron star RX J1856: M-R constraint from thermal emission

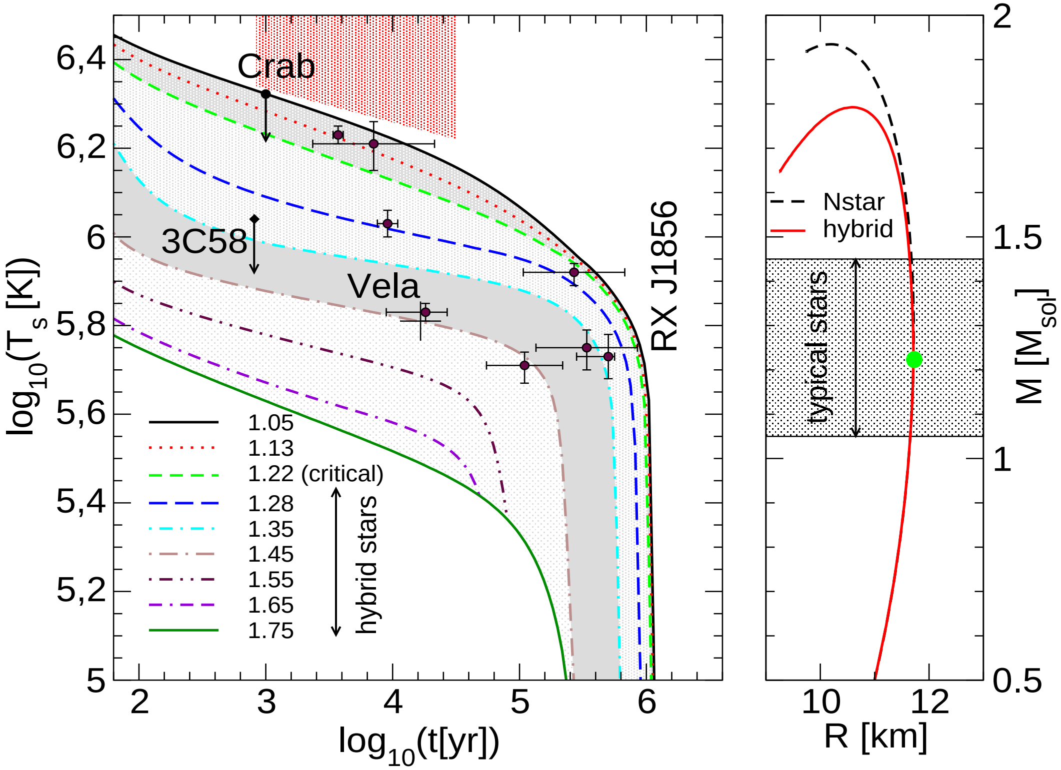


- Low-mass X-ray binary 4U 1636: Mass constraint from ISCO obs.



QUARK MATTER IN COMPACT STARS: COOLING CONSTRAINT

Quark matter in compact stars: color superconducting

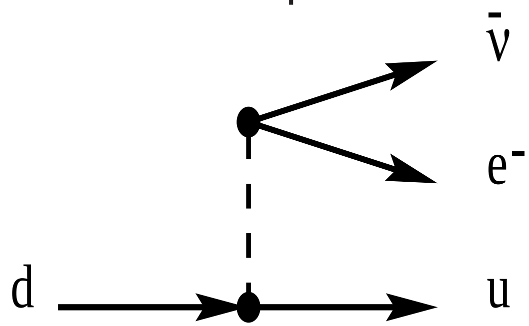


Popov et al: Neutron star cooling constraints ...
PRC 74, 025803 (2006); [nucl-th/0512098]

- Neutrinos carry energy off the star, Cooling evolution (schematic) by

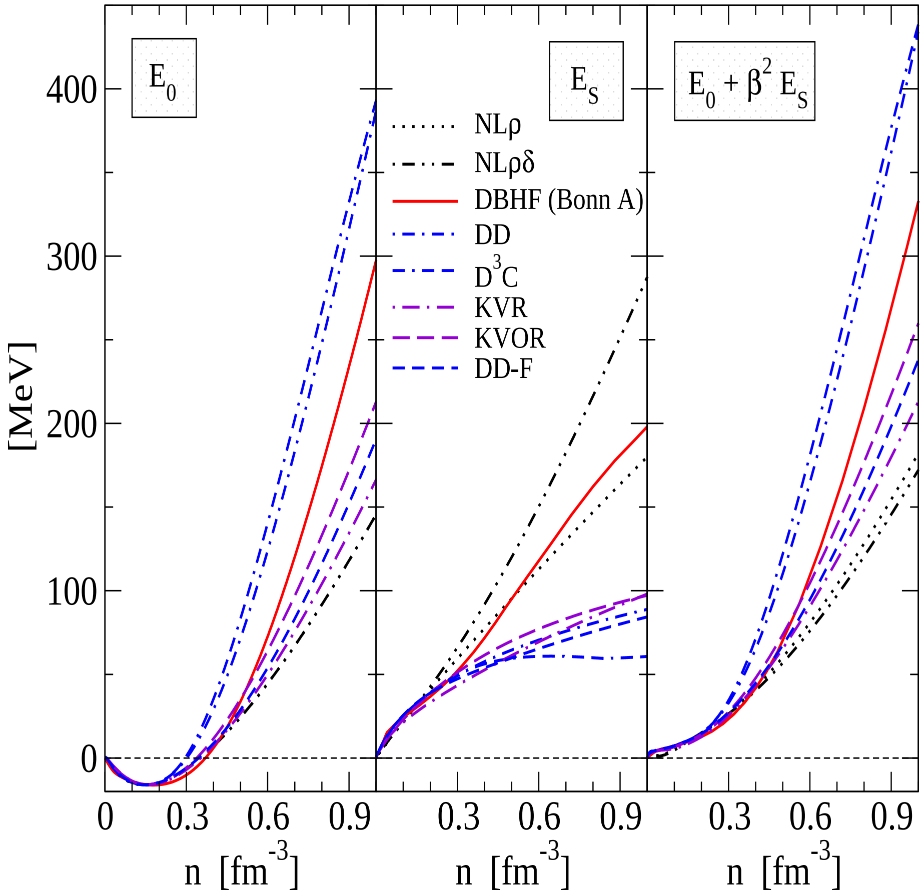
$$\frac{dT(t)}{dt} = -\frac{\epsilon_\gamma + \sum_{j=Urca,...}\epsilon_\nu^j}{\sum_{i=q,e,\gamma,...} c_V^i}$$

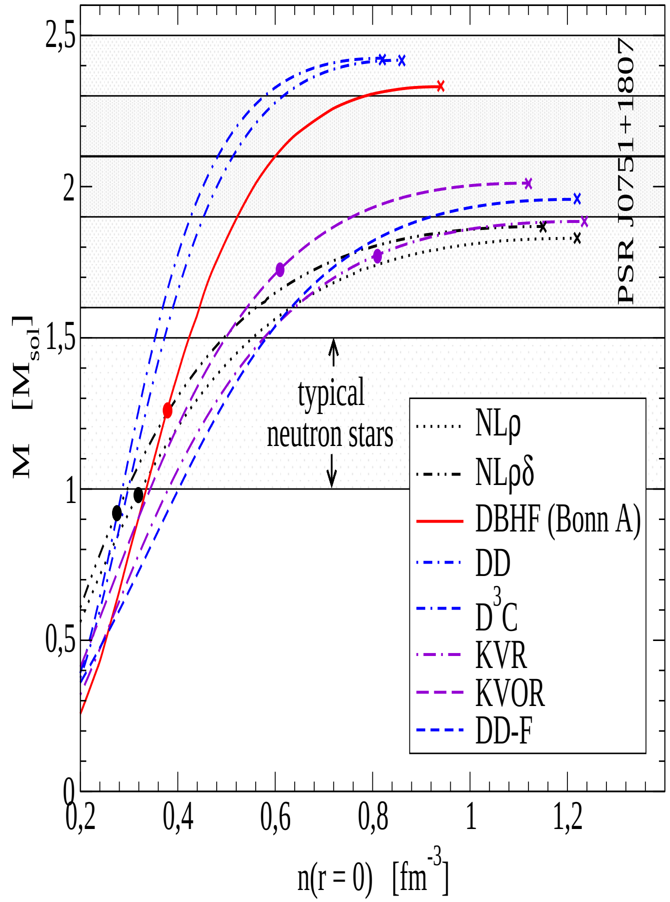
- Most efficient process: Urca



- Exponential suppression by pairing gaps! $\Delta \sim 10 \ldots 100$ keV

DU THRESHOLD AND 'HADRONIC' NEUTRON STARS

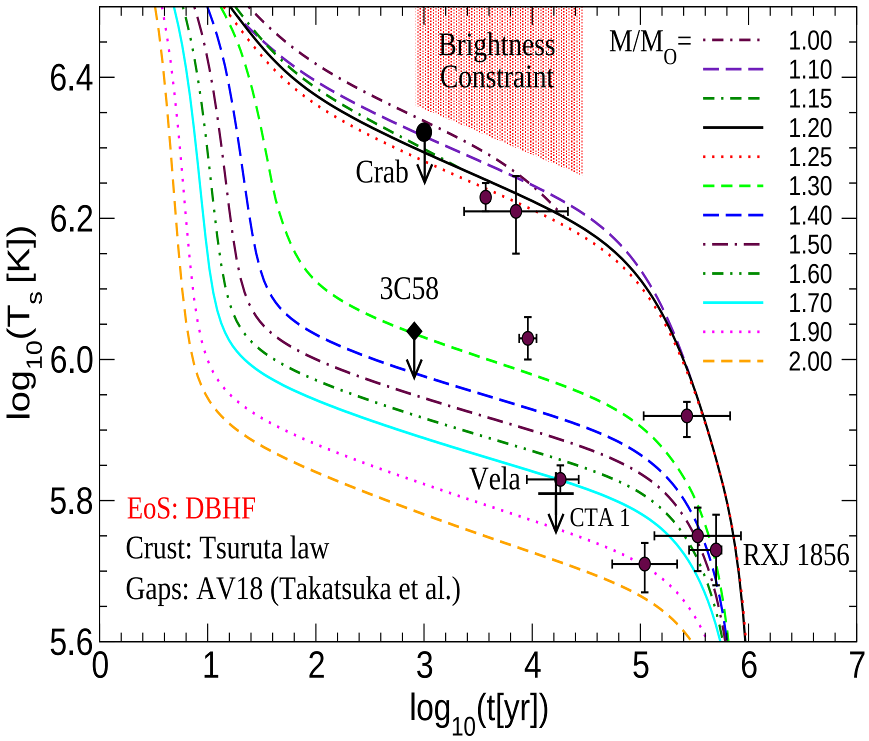


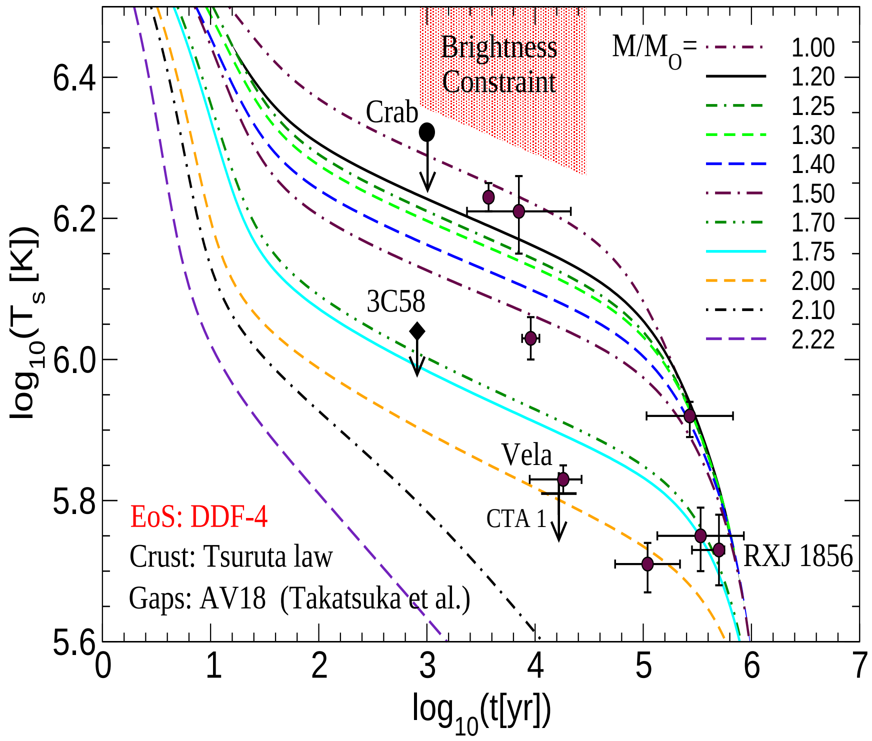


DU threshold for most hadronic EoS active in neutron stars with typical masses !

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

DU threshold and 'hadronic' neutron stars (II)

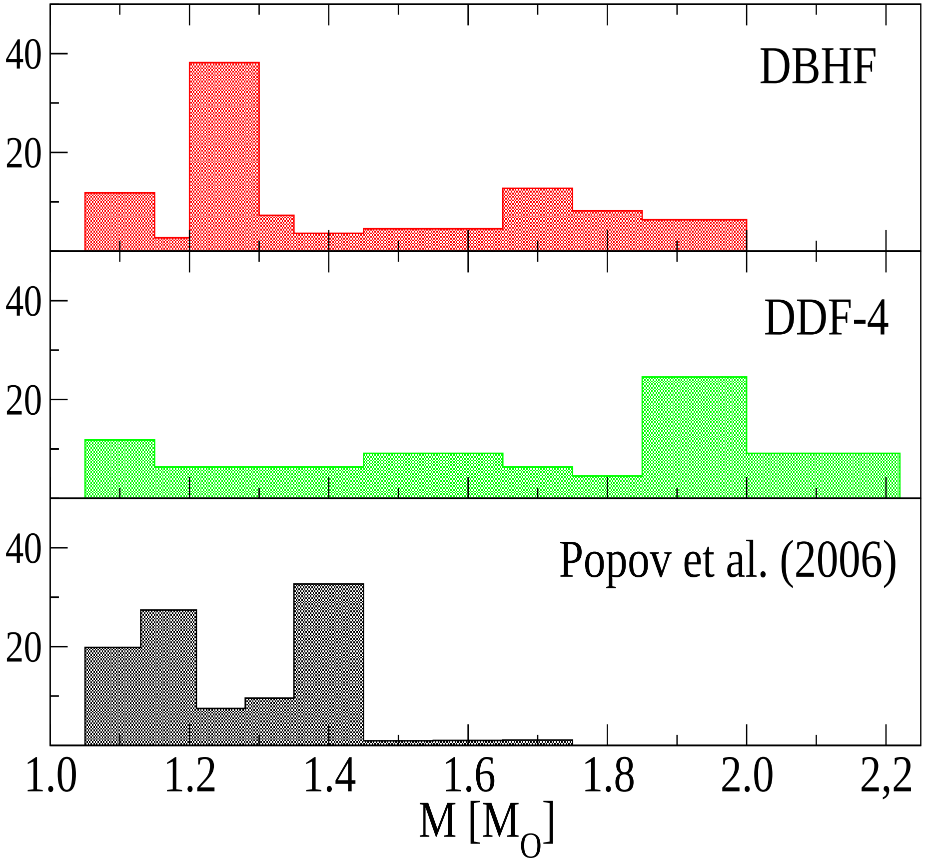




- DU threshold $\Rightarrow$ sensitivity to tiny mass variations;
- Description of Vela not possible with typical masses !

S. Popov et al., PRC 74 (2006); D.B. and H. Grigorian, PPNP (2007) [astro-ph/0612092]

DU THRESHOLD AND 'HADRONIC' NEUTRON STARS (III)

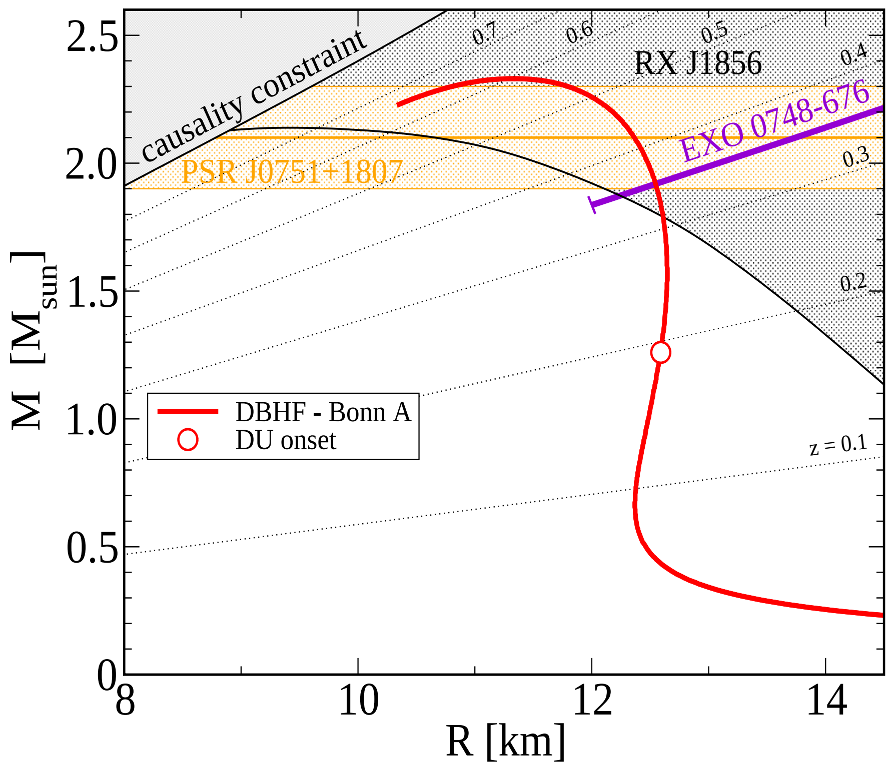


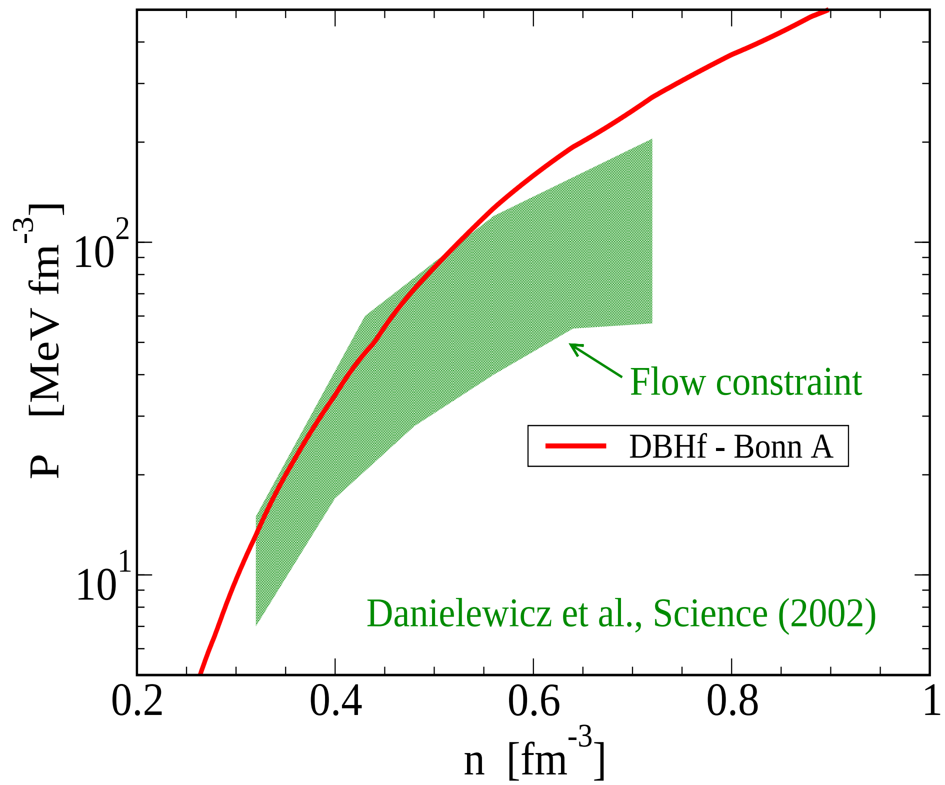
Mass population from Cooling

- 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, PPNP (2007); [astro-ph/0612092]

Mass-Radius constraint and Flow constraint (I)

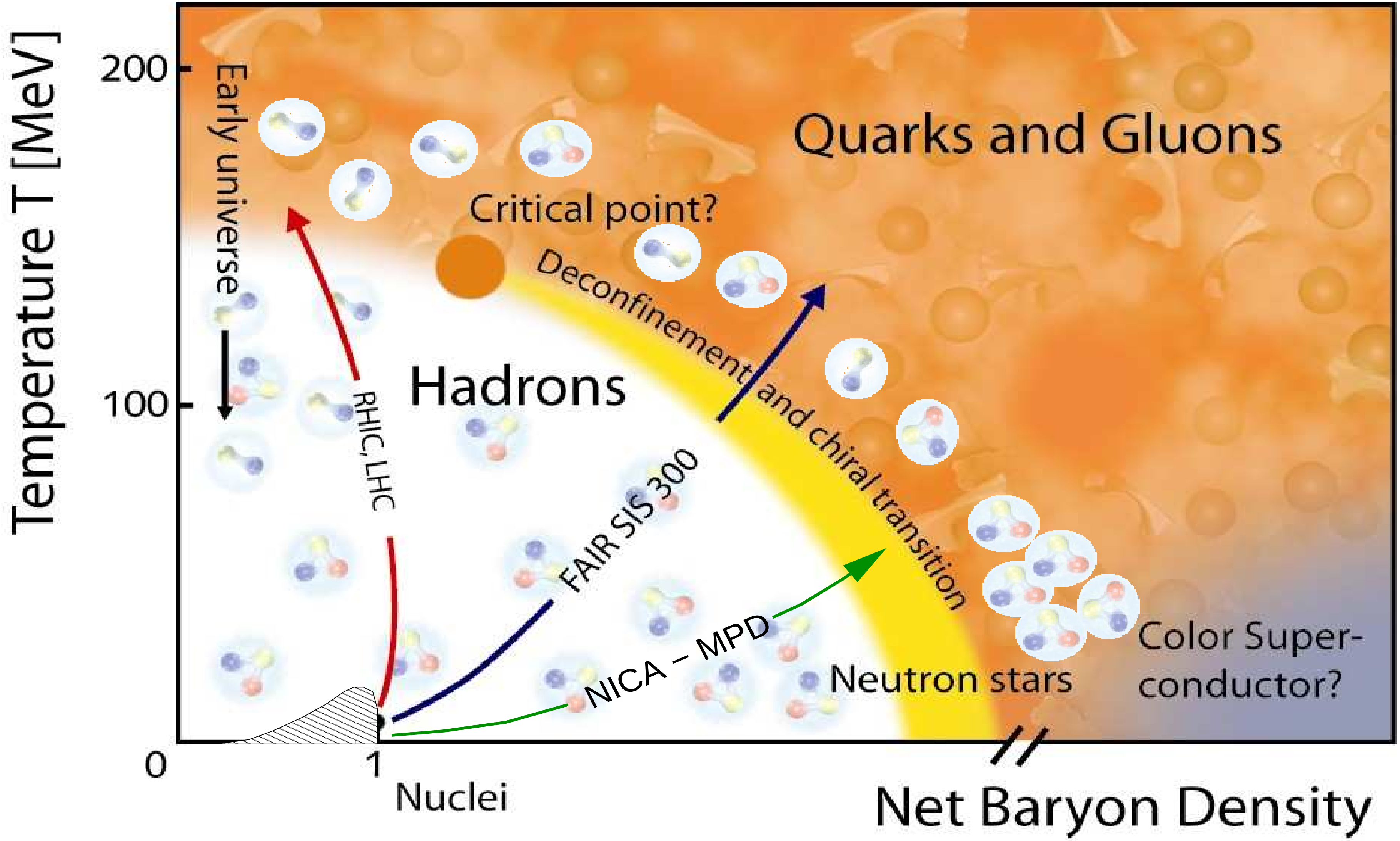




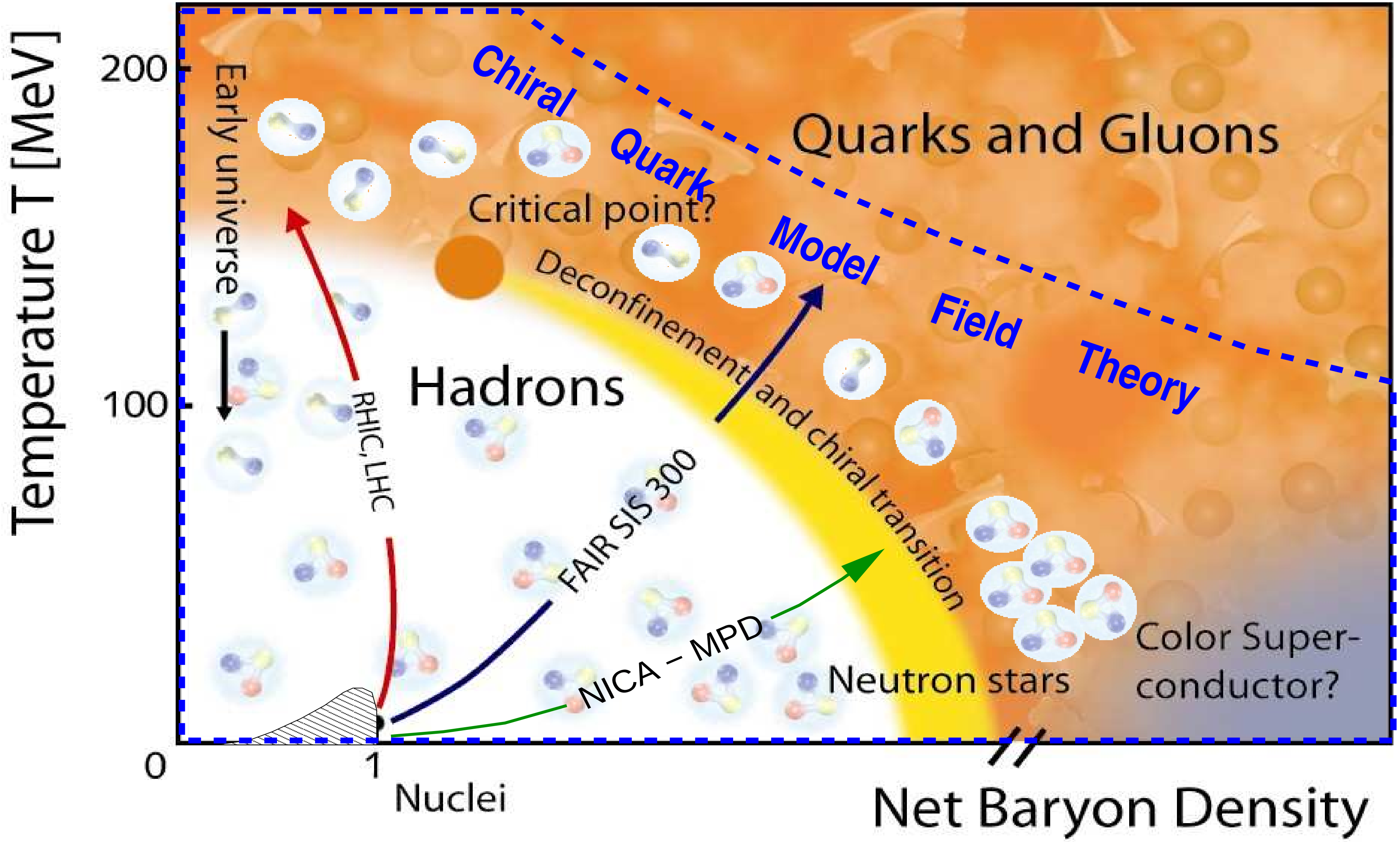
- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;
  But: DBHF has DU onset in typical mass regon!
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS ! But: DBHF violates at high densities

Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Röpke, Trümper, [arxiv:nucl-th/0609067]

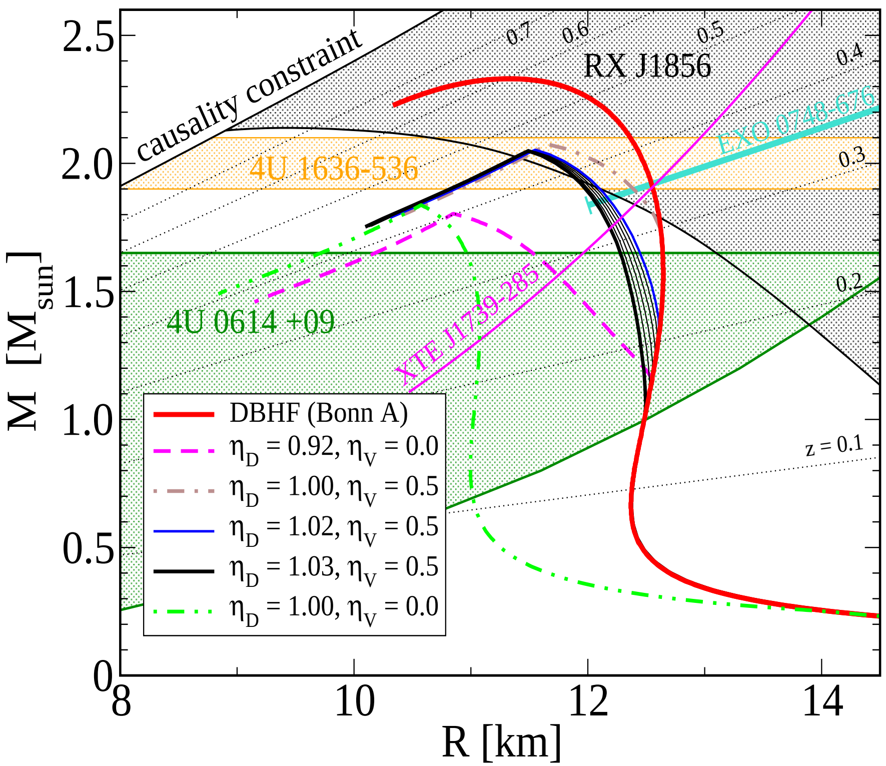
QUARK SUBSTRUCTURE AND PHASE DIAGRAM

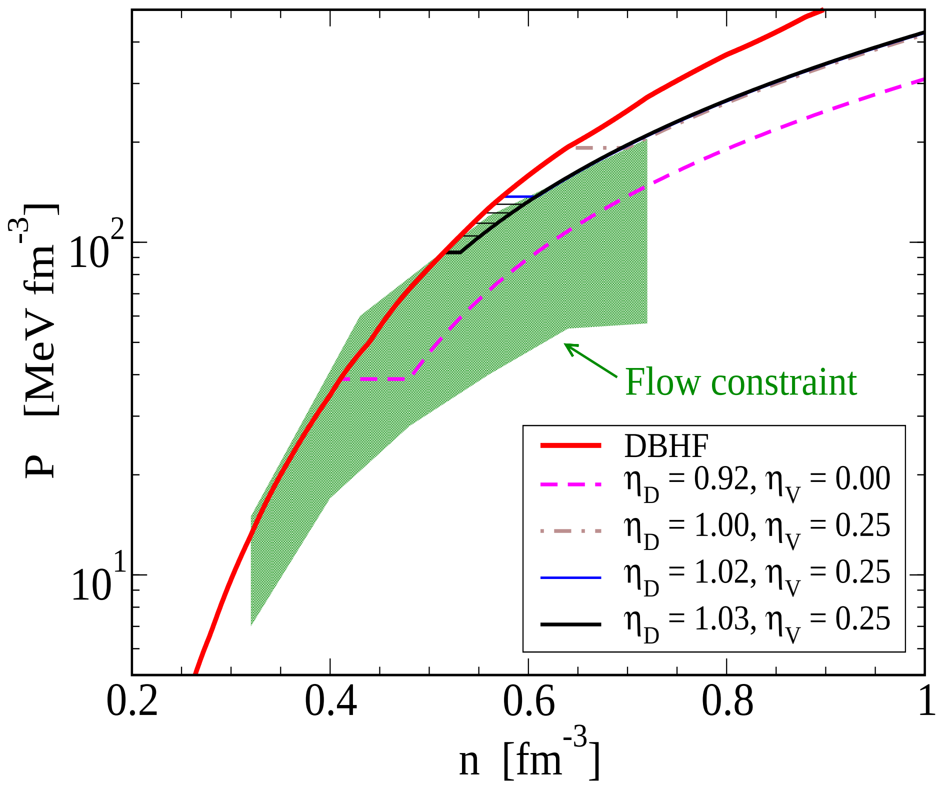


PHASE DIAGRAM OF QCD: CHIRAL QUARK MODELS



Mass-Radius constraint and Flow constraint (II)

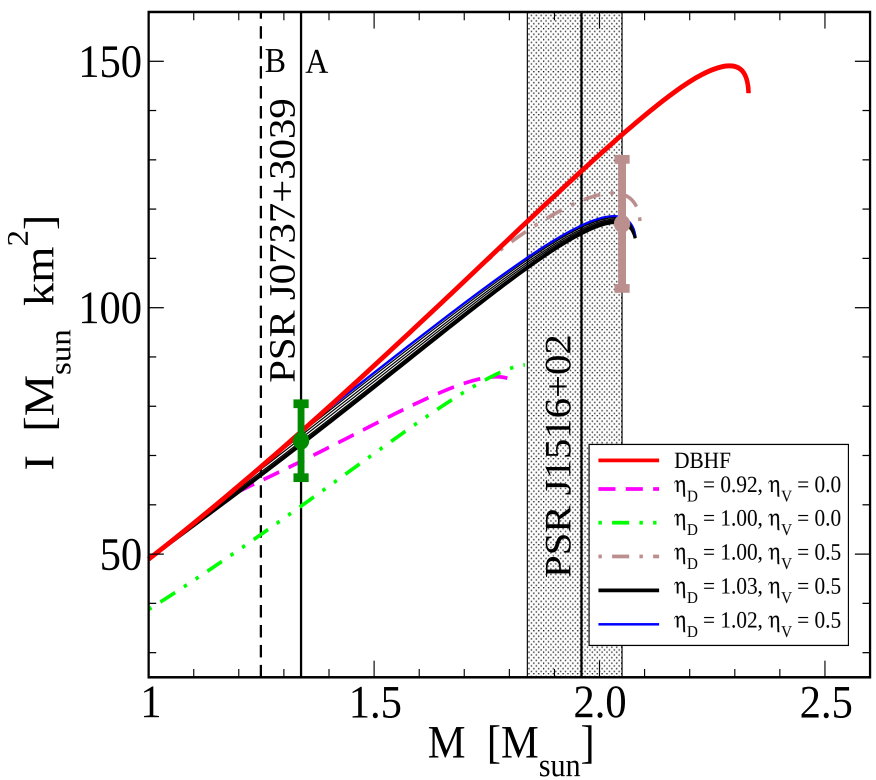


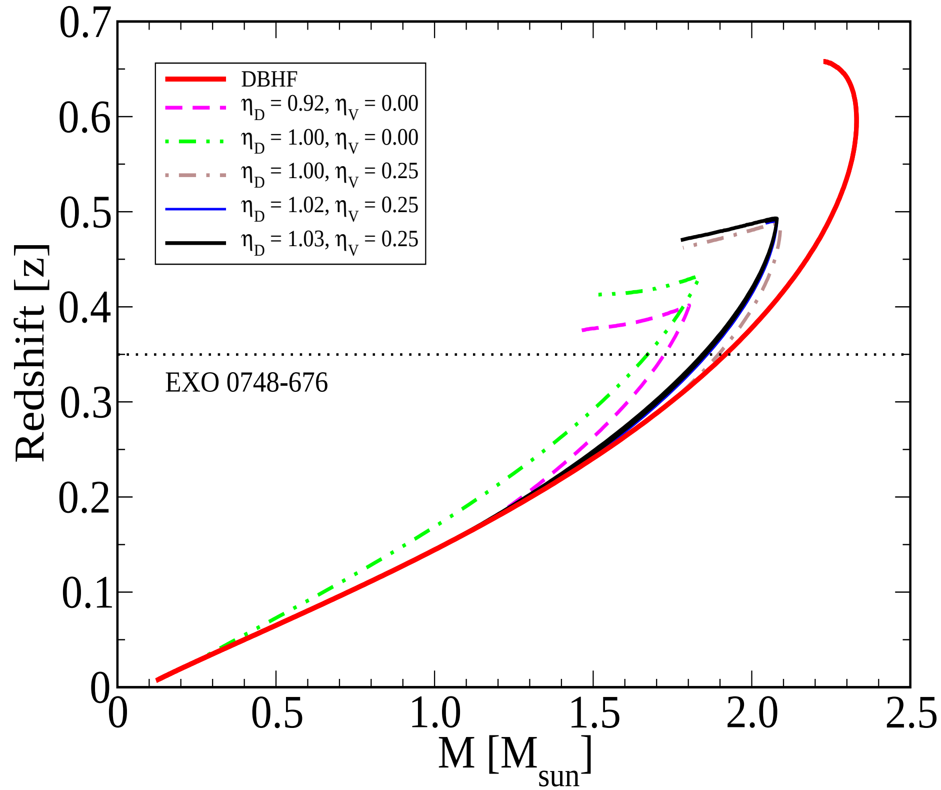


- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff quark matter EoS;
  Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !
  Note: Quark matter removes violation by DBHF at high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

Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Röpke, Trümper, [arxiv:nucl-th/0609067]

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., PLB (2007); nucl-th/0609067**

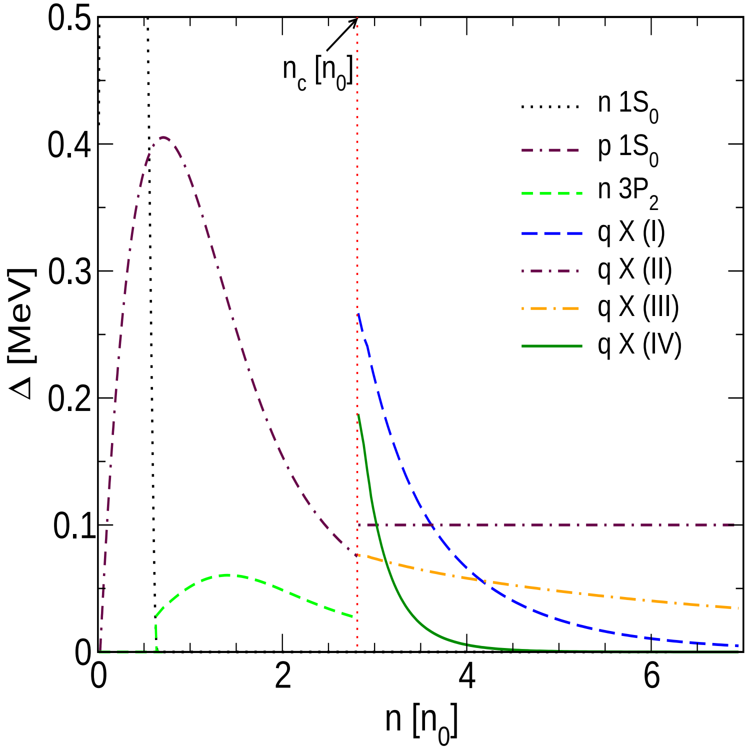
Hybrid Star Cooling with 2SC Quark Matter

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

Ansatz 2SC + X phase:

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

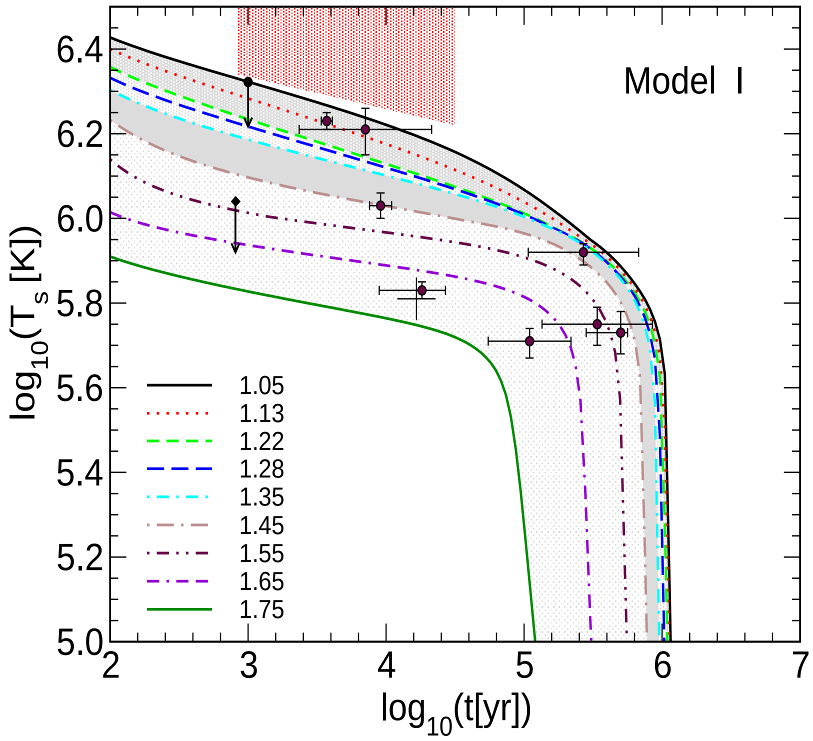
Model	Δ_0 [MeV]	α
I	1	10
II	0.1	0
III	0.1	2
IV	5	25

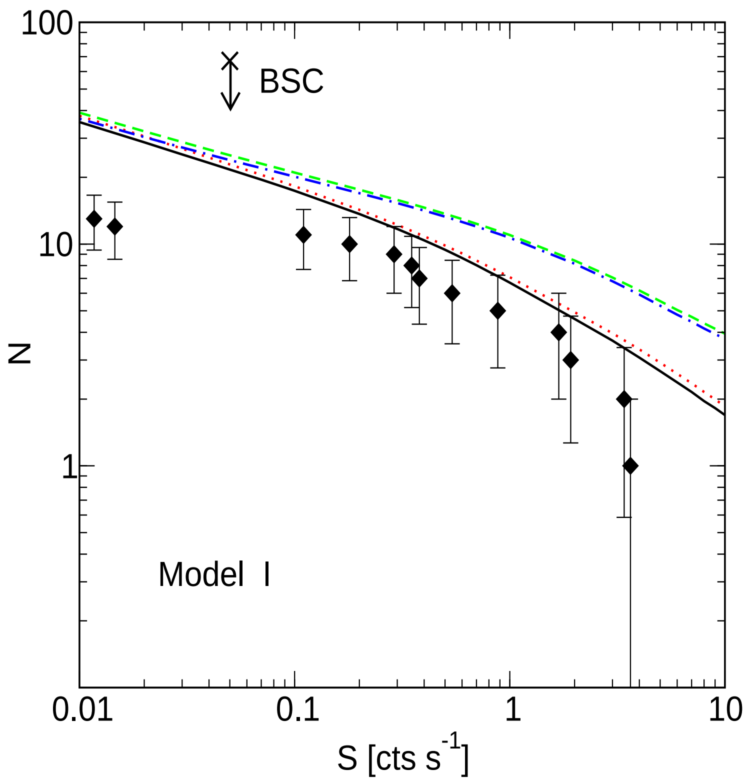


Pairing gaps for hadronic phase
(**AV18 - Takatsuka et al. (2004)**)
and 2SC + X phase

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

HYBRID STAR COOLING WITH 2SC QUARK MATTER (II)





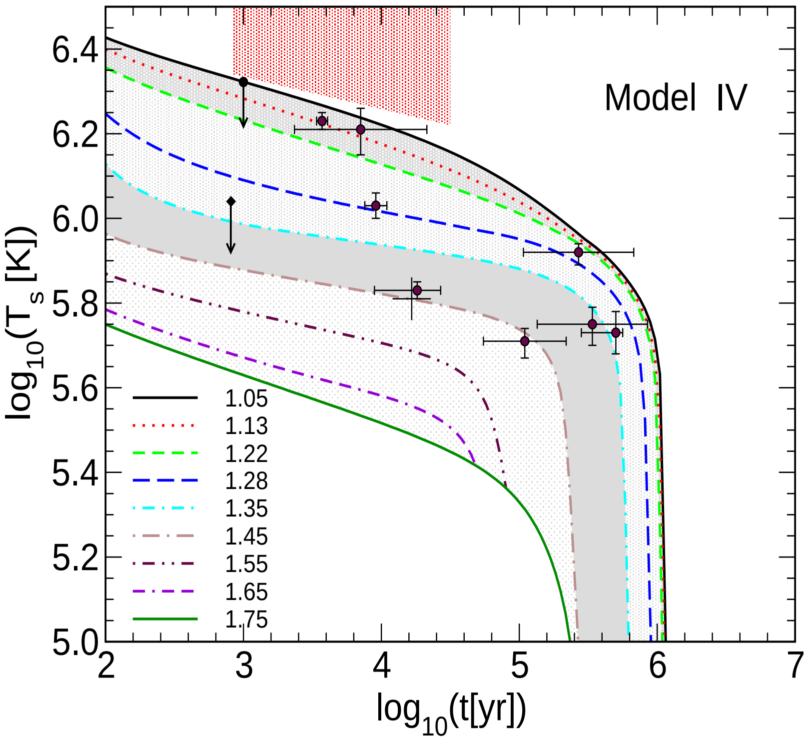
2SC + X phase, $\Delta_0 = 1$ MeV, $\alpha = 10$

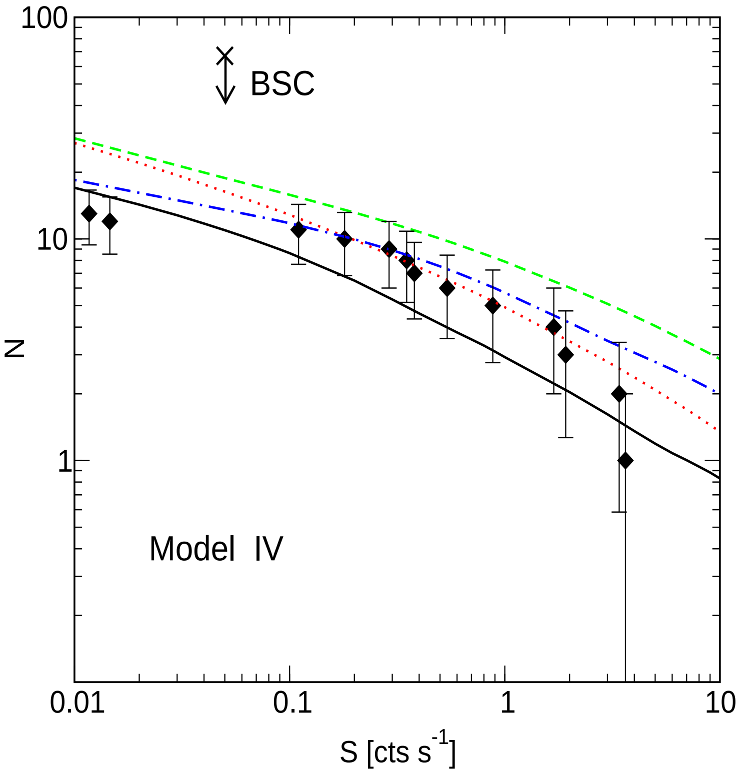
Too large mass for Vela required

Log N - Log S test fails

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

Hybrid Star Cooling with 2SC Quark Matter (III)





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

Temperature-age and Vela mass OK

Log N - Log S test passed

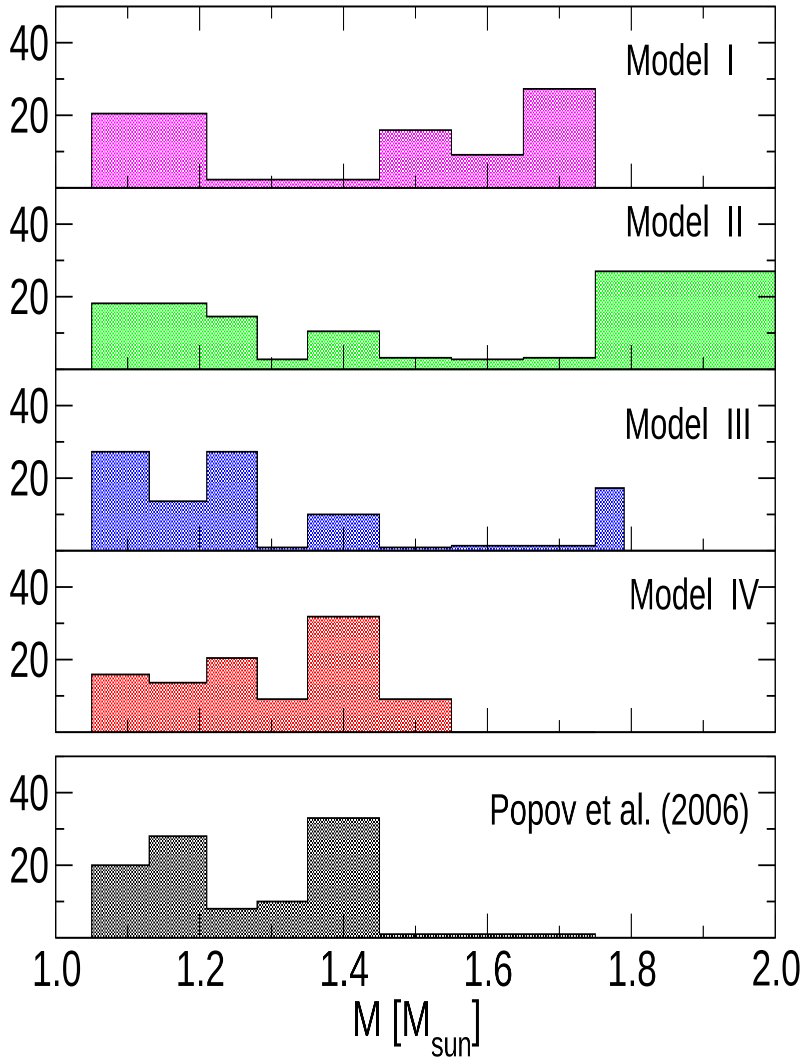
Popov, Grigorian, D.B., PRC 74 (2006)

Hybrid Star Cooling with 2SC Quark Matter (IV)

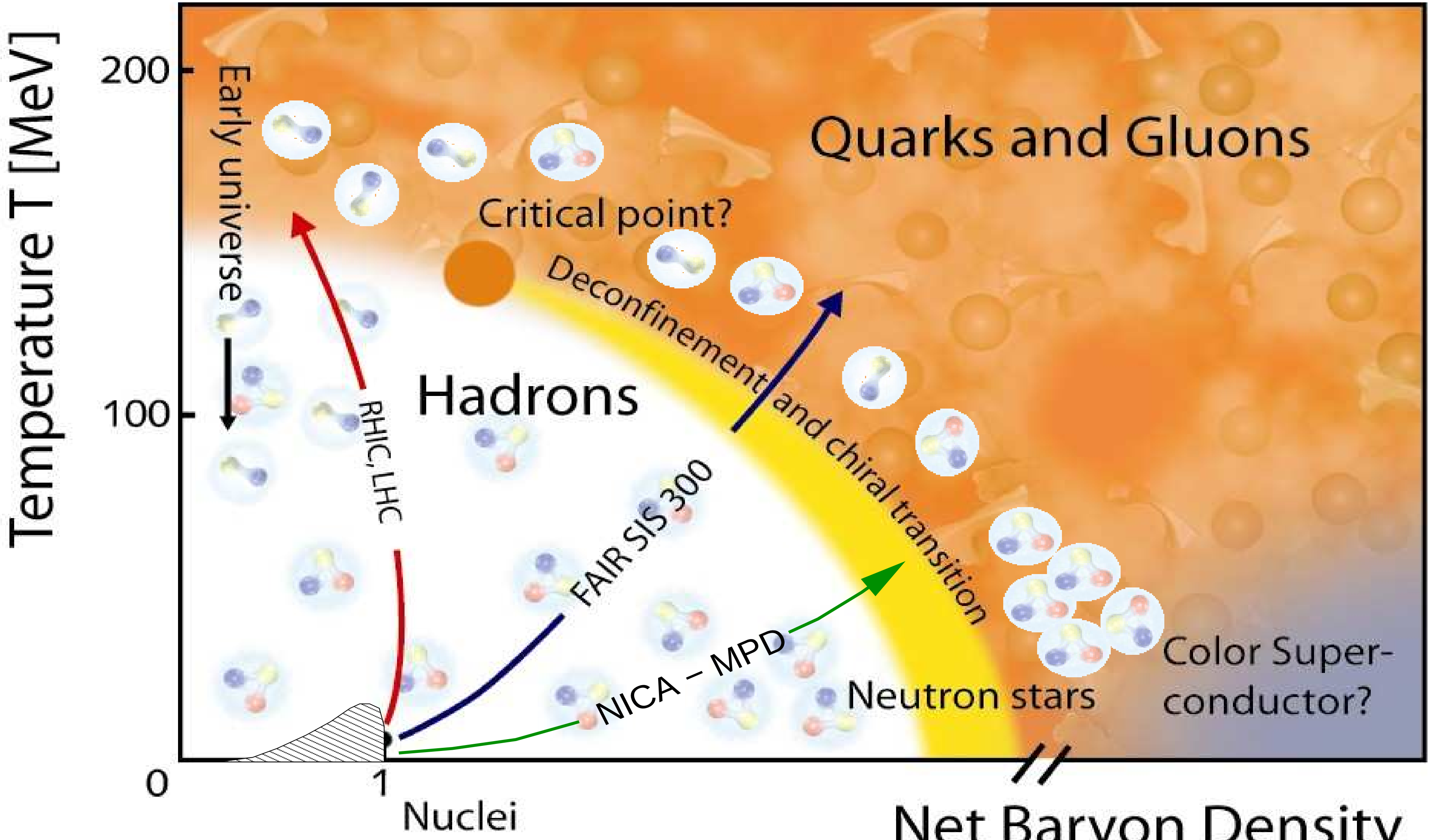
Hybrid star cooling passes all modern tests:

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

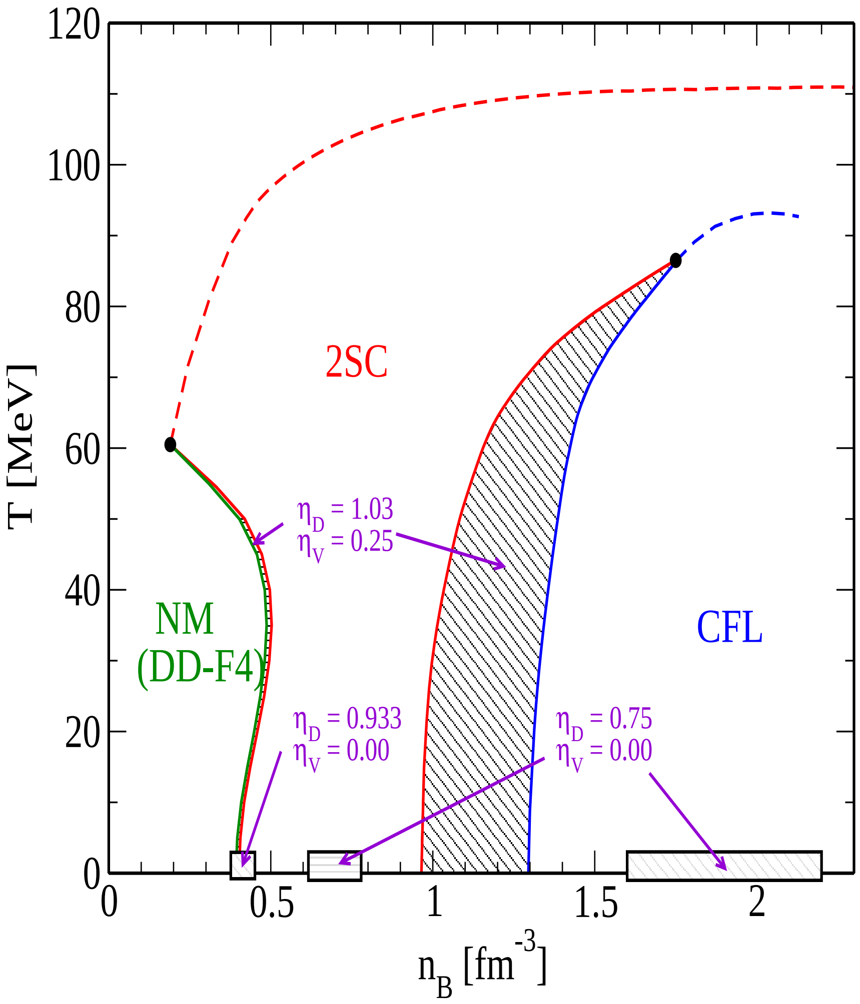
Popov, Grigorian, D.B., PRC 74 (2006)
D.B., H. Grigorian, D.B., PPNP 59 (2007)
astro-ph/0612092



Quark Substructure and Phase Diagram



Phase Diagram for Symmetric Matter (HIC)



- Critical density for deconfinement in heavy-ion collisions $n_{dec} \geq 3\ n_0$
- Almost crossover (masquerade!), i.e. no density jump, no latent heat/ time delay!
- 2SC - CFL phase transition at $n \geq 6\ n_0$ with density jump and latent heat/ time delay!
  Provided the temperature can be kept low $T \leq 70$ MeV

Klahn, Sandin, Typel, D.B., in preparation

Summary

- Mott-Hagedorn model as alternative interpretation of Lattice data
- Microscopic formulation of the hadronic Mott effect within a chiral quark model
- Mesonic (hadronic) correlations important for $T > T_c$ (and $\mu > \mu_c$)
- Step-like enhancement of threshold processes due to Mott effect
- Large neutron star masses: EoS at high densities needs to be stiff! QM - superconducting!
- Hybrid stars 'masquerade' as neutron stars: Cooling observables!

Plans for the Future

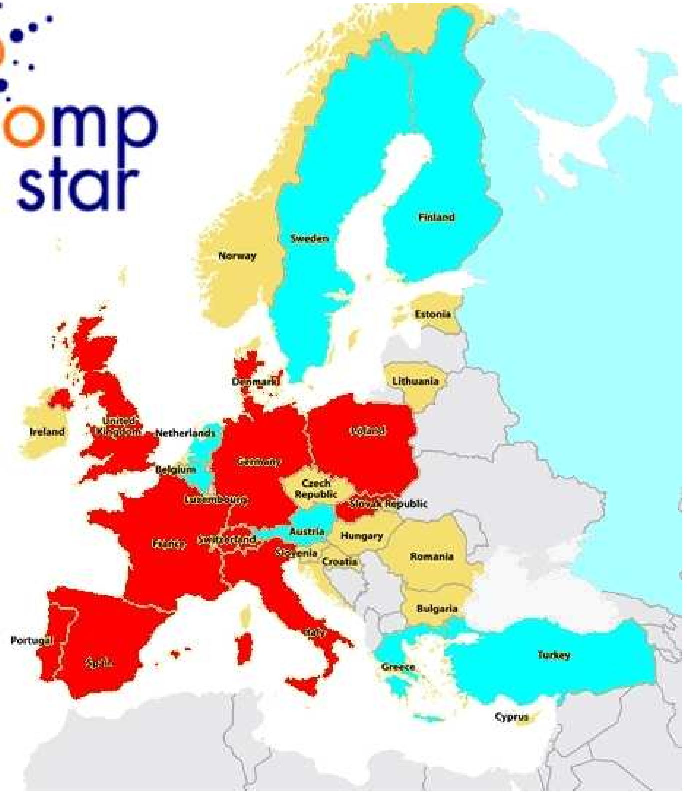
- Bridge Lattice QCD and Phenomenology: spectral functions
- Calculate J/ψ breakup with baryon impact $\Longrightarrow$ CBM @ FAIR GSI
- Mott effect in dense baryonic matter: nucleon dissociation!
- EoS for hot, dense matter with Mott-effect, encoded in hadronic spectral functions

Thanks to:

Deborah Aguilera, Jens Berdermann, Michael Buballa, Fiorella Burgio, Christian Fuchs, Daniel Gomez Dumm, Hovik Grigorian, Gabriela Grunfeld, Davor Horvatic, Dubravko Klabucar, Thomas Klähn, Gevorg Poghosyan, Sergey Popov, Gerd Röpke, Fredrik Sandin, Norberto Scoccola, Joachim Trümper, Stefan Typel, Dima Voskresensky, a.m.m.

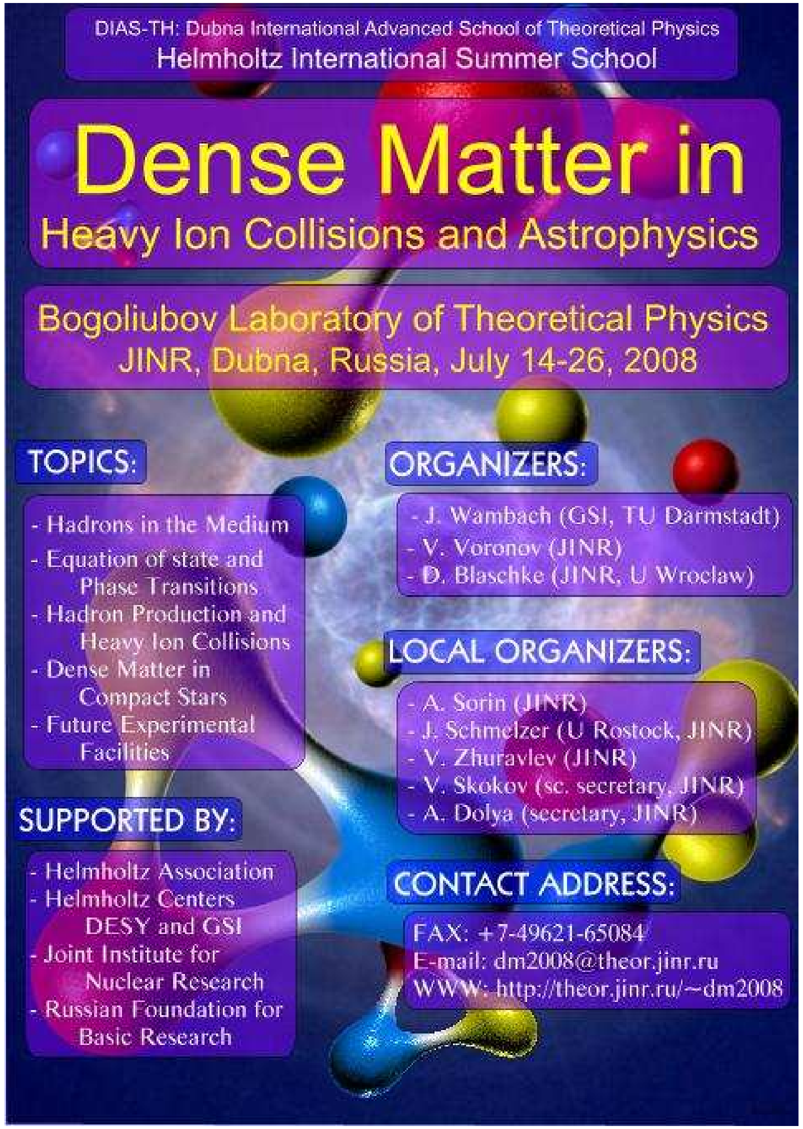
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

comp star



ESF Research Networking Programme "CompStar", 2008 - 2013

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

"Quarkonia in Hot and Dense Matter"

Trento, Italy, May 25-29, 2009

http://www.ect.it

ESF Research Networking Programme

"CompStar" (2008-2013)

http://www.esf.org/compstar

http://compstar-esf.org

Invitation ... to Wroclaw