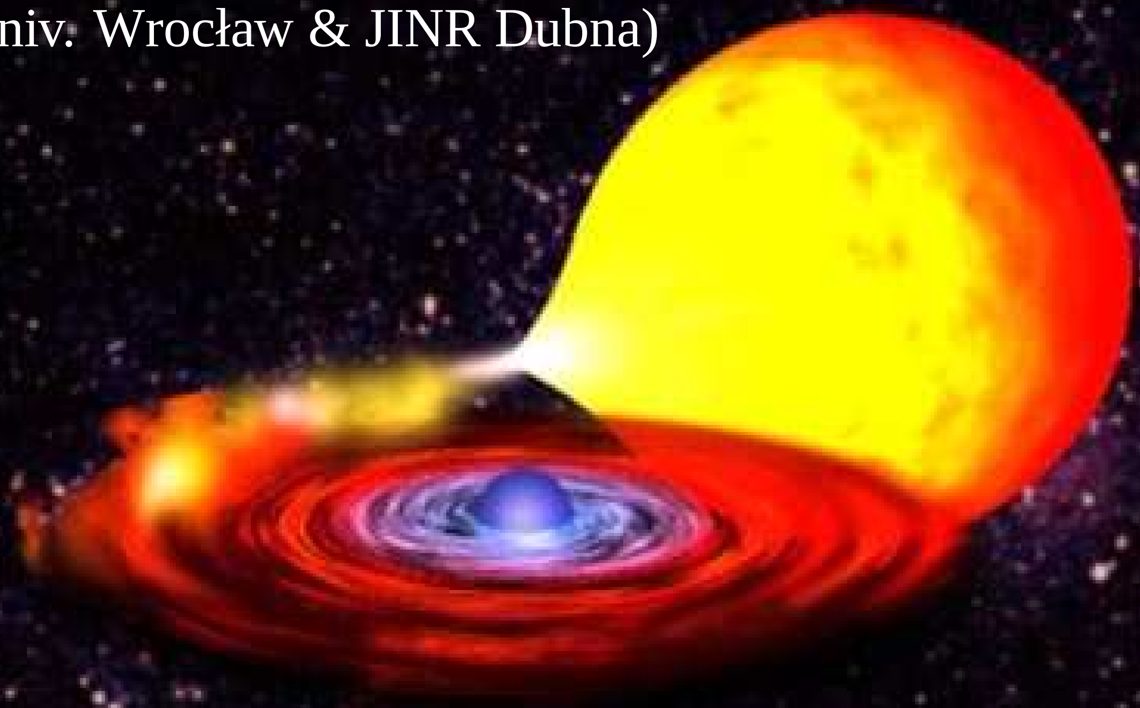
Probing the Dense Matter EoS with Compact Stars

David Blaschke (Univ. Wrocław & JINR Dubna)



GSI Darmstadt, July 17th, 2010

Probing Dense Matter with Compact Stars

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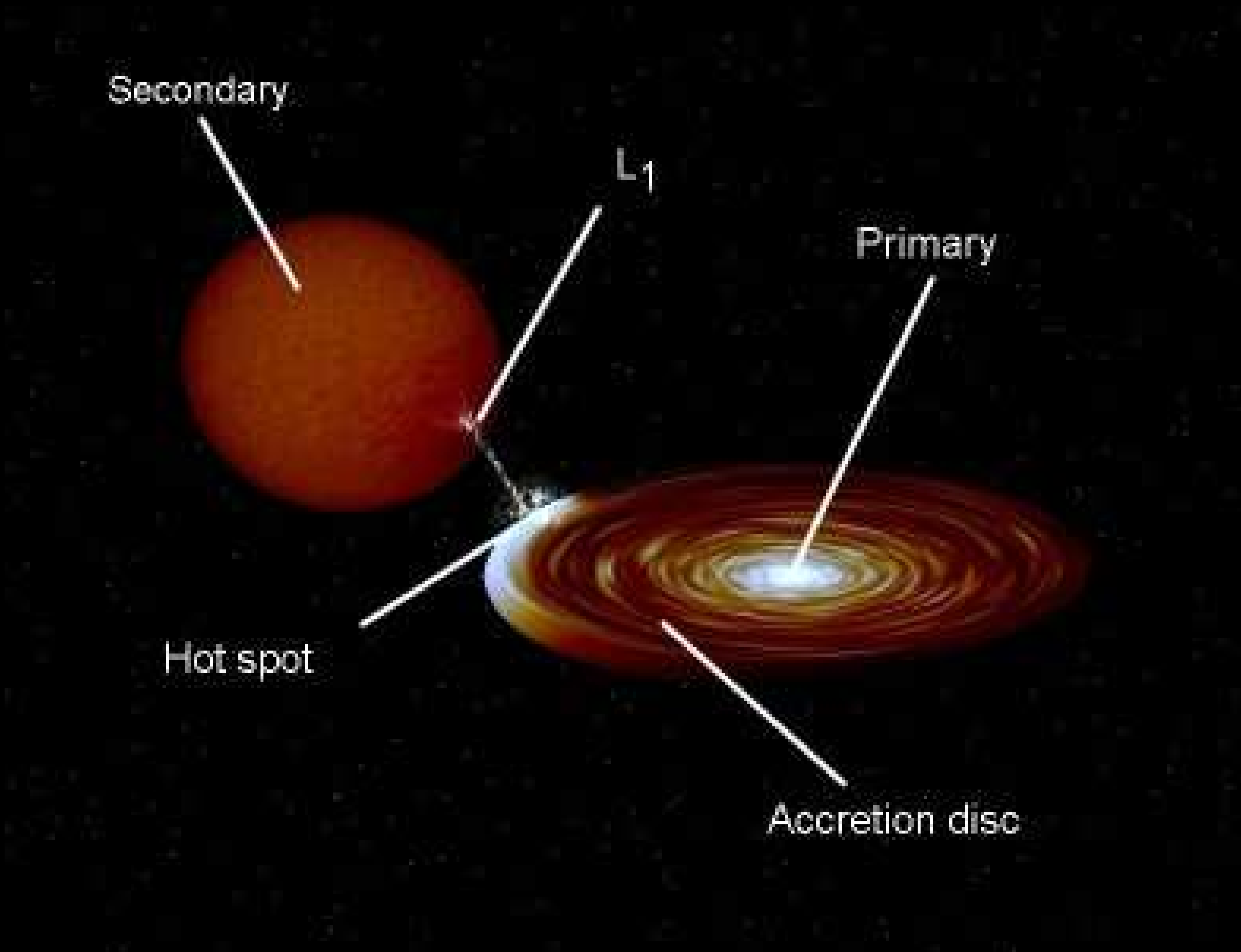
T. Klähn, R. Łastowiecki, D. Zabłocki (Wrocław),
F. Sandin (Luleå),
H. Grigorian (Dubna & Yerevan),
D.N. Voskresensky (Moscow & Darmstadt),
S.B. Popov (Moscow)

- M-R constraints from qLMXB's & RXJ 1856
- EoS for dilute nuclear matter with clusters
- EoS for dense quark matter $\longrightarrow$ Hybrid EoS
- Towards a new EoS for Supernovae and HIC

GSI Darmstadt, July 17th, 2010

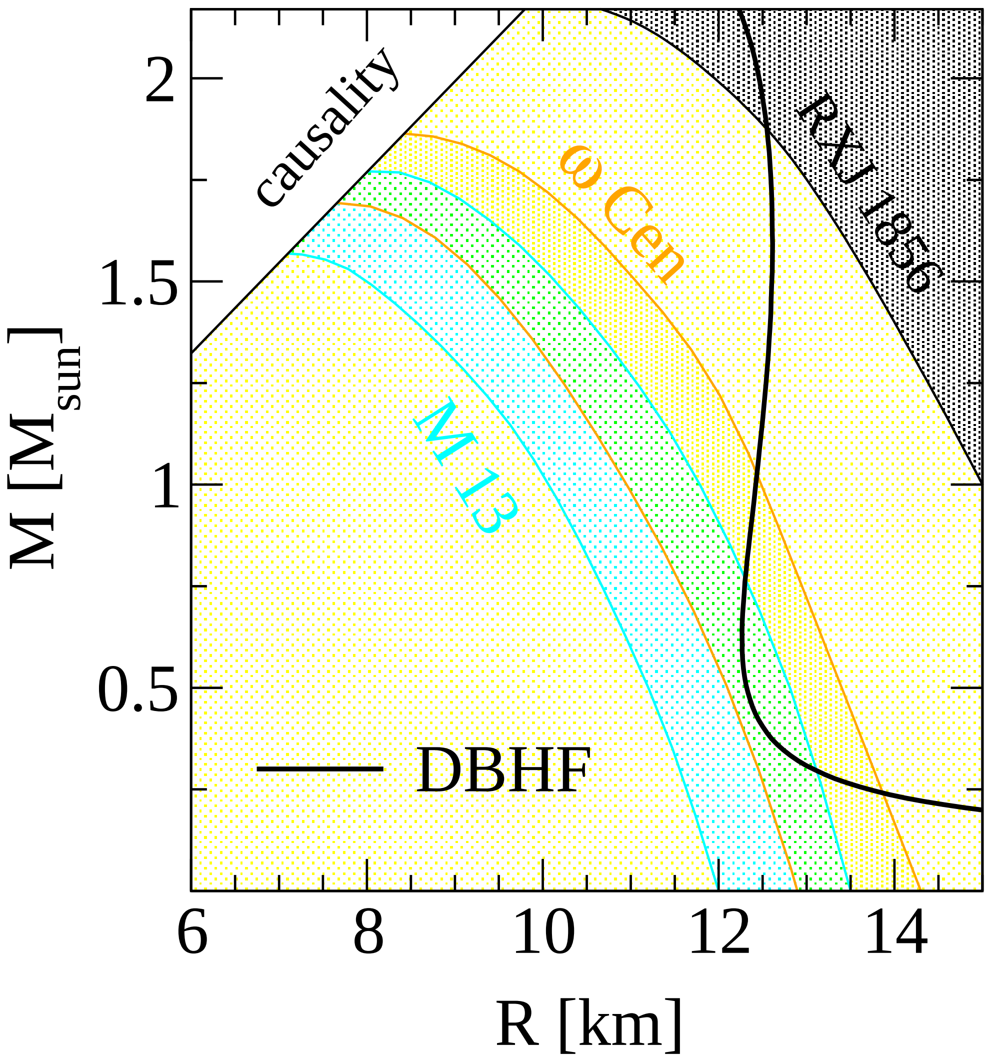
Quiescent Low-Mass X-ray Binaries (qLMXBs)



- When the LMXB is accreting, we mostly observe X-rays from the disc
- In some sources ("transients") accretion can stop - and then we see only the neutron star

System names: LMXB's, Soft X-ray transients, Neutron star binaries

M-R constraints from qLMXB's and M7



- Distance measured
- Spectrum measured (ROSAT, XMM, Chandra)
- Luminosity measured

→ effective temperature $T_{\rm eff}$:

$$F = \sigma T_{\rm eff}^4 (R_\infty / D)^2$$

→ photospheric radius:

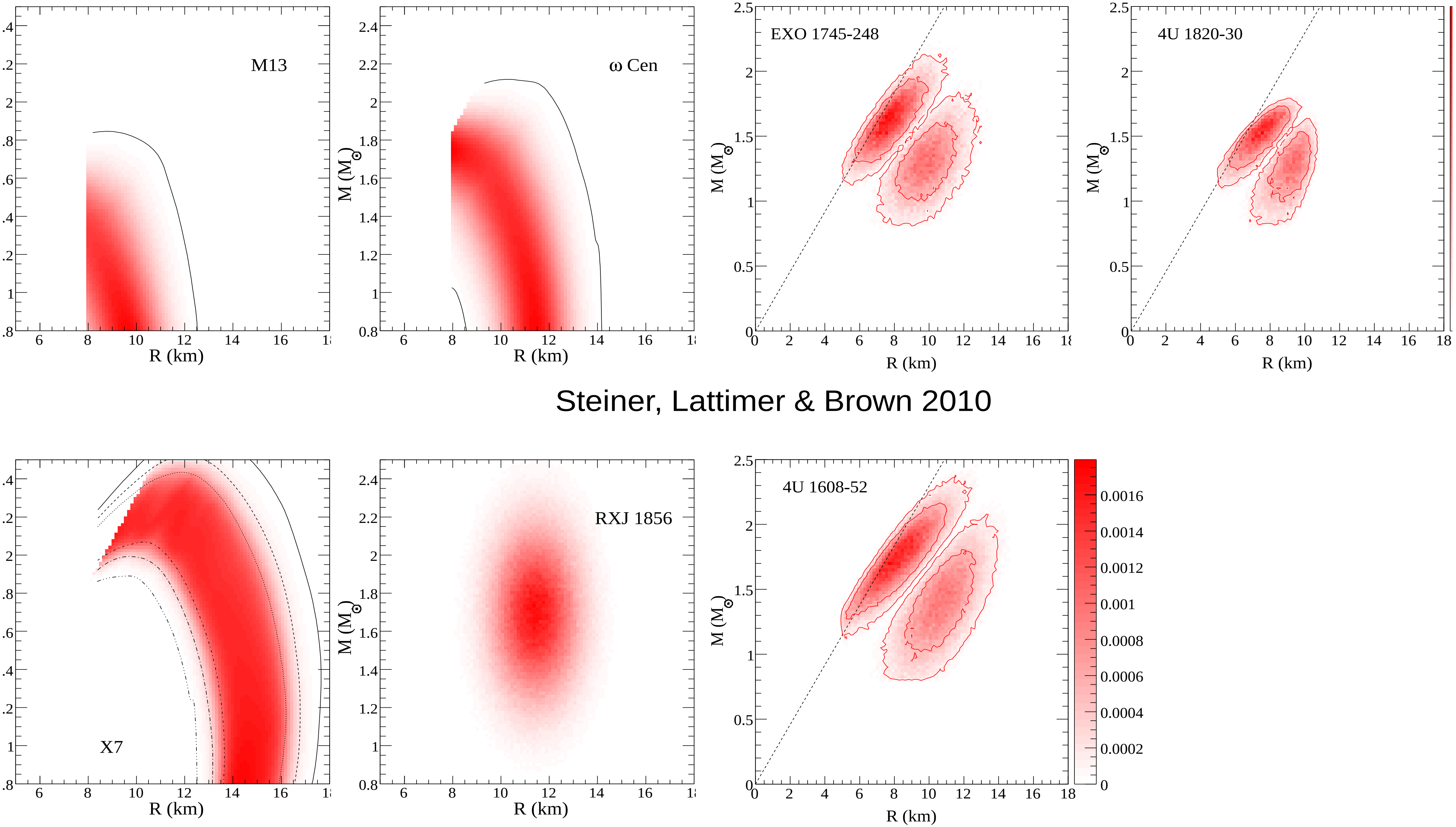
$$R_\infty = R/\sqrt{1 - R_S/R}\,, \quad R_S = 2GM$$

→ redshift $z = 1/\sqrt{1 - R_S/R} - 1 \approx R_S/(2R)$

Object	R_∞ [km]	Reference
RXJ 1856	16.8	Trümper et al. (2004)
ωCen	13.6 ± 0.3	Gendre et al. (2003)
M13	12.8 ± 0.4	Gendre et al. (2004)

Lower limit from RXJ 1856 incompatible with ω Cen and M13 ?

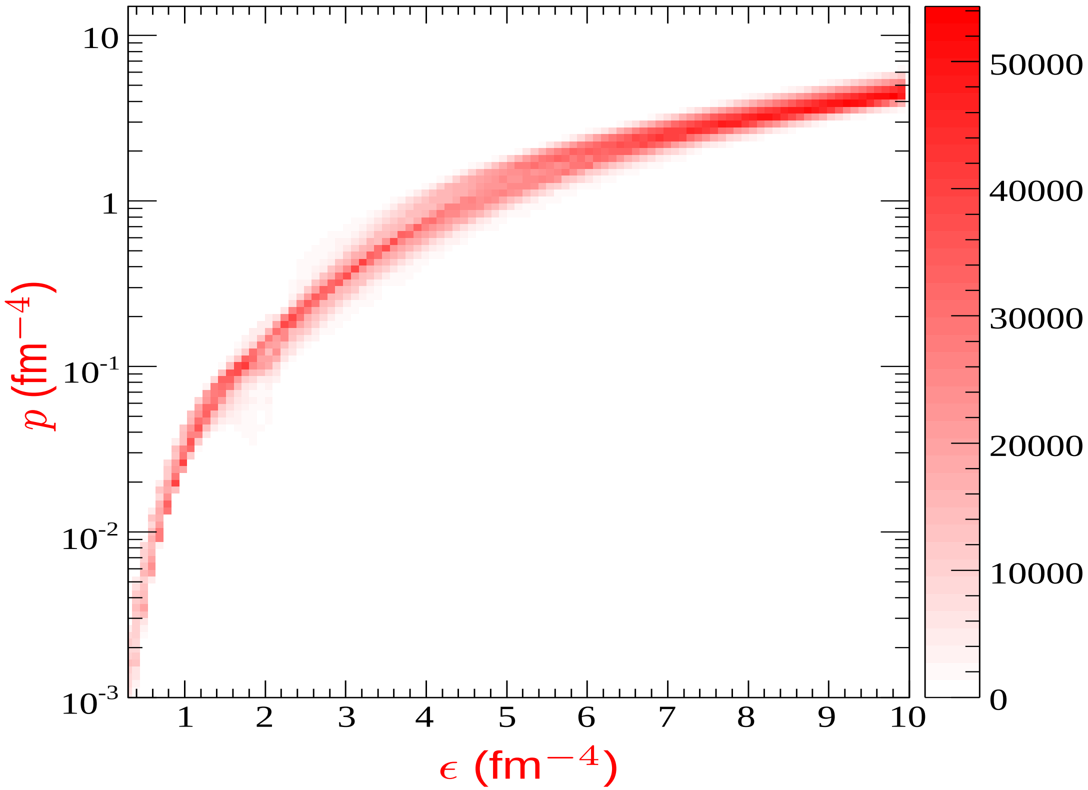
M-R Probability Distributions

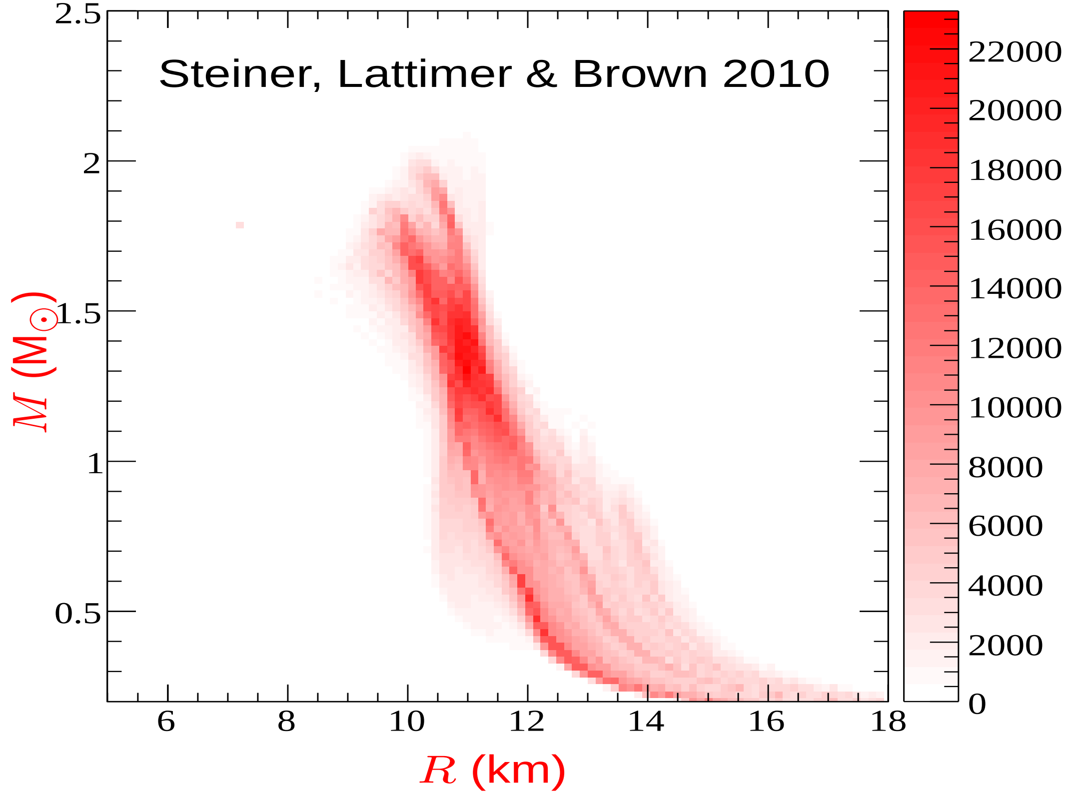


Steiner, Lattimer & Brown 2010

Bayesian TOV Inversion

- $n < 0.5n_s$: EOS is BBP and NV
- $0.5n_s < n < n_1$: EOS is determined by K, K', S_v, γ
- $n_1 < n < n_2$: EOS is polytropic with γ_1; $n > n_2$: EOS is polytropic with γ_2
- M and R probability distributions for 7 neutron stars treated equally ($0.8\ \mathrm{M}_\odot < M < 2.5\ \mathrm{M}_\odot$; $5\ \mathrm{km} < R < 18\ \mathrm{km}$)
- Assume all prior model parameters are uniformly distributed





“Measuring” the EoS with Compact Stars: M-R → P(e)

Equation of State and Stability of Compact Stars

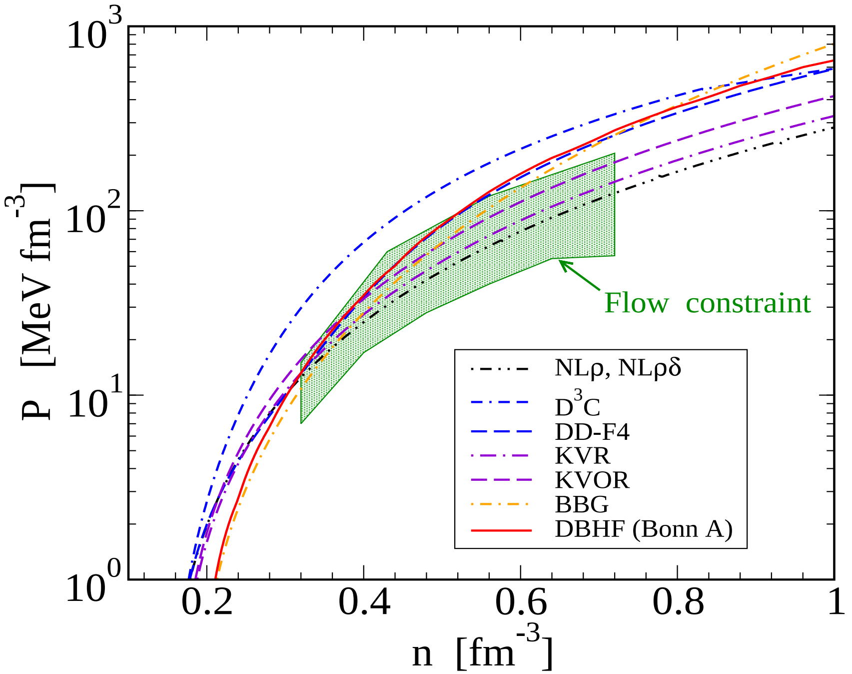
Tolman-Oppenheimer-Volkoff Equations

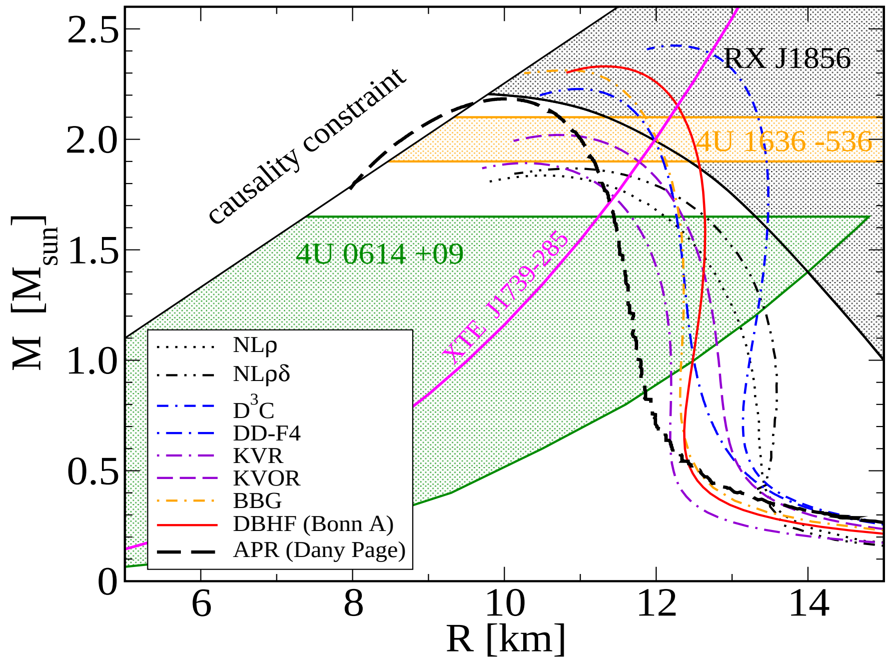
1. Stability: General Relativistic Hydrostatic Equilibrium

$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1+\frac{P(r)}{\varepsilon(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{m(r)}\right)\left(1-\frac{2Gm(r)}{r}\right)^{-1}$$

NEWTON EINSTEIN CORRECTIONS GENERAL REL. THEORY

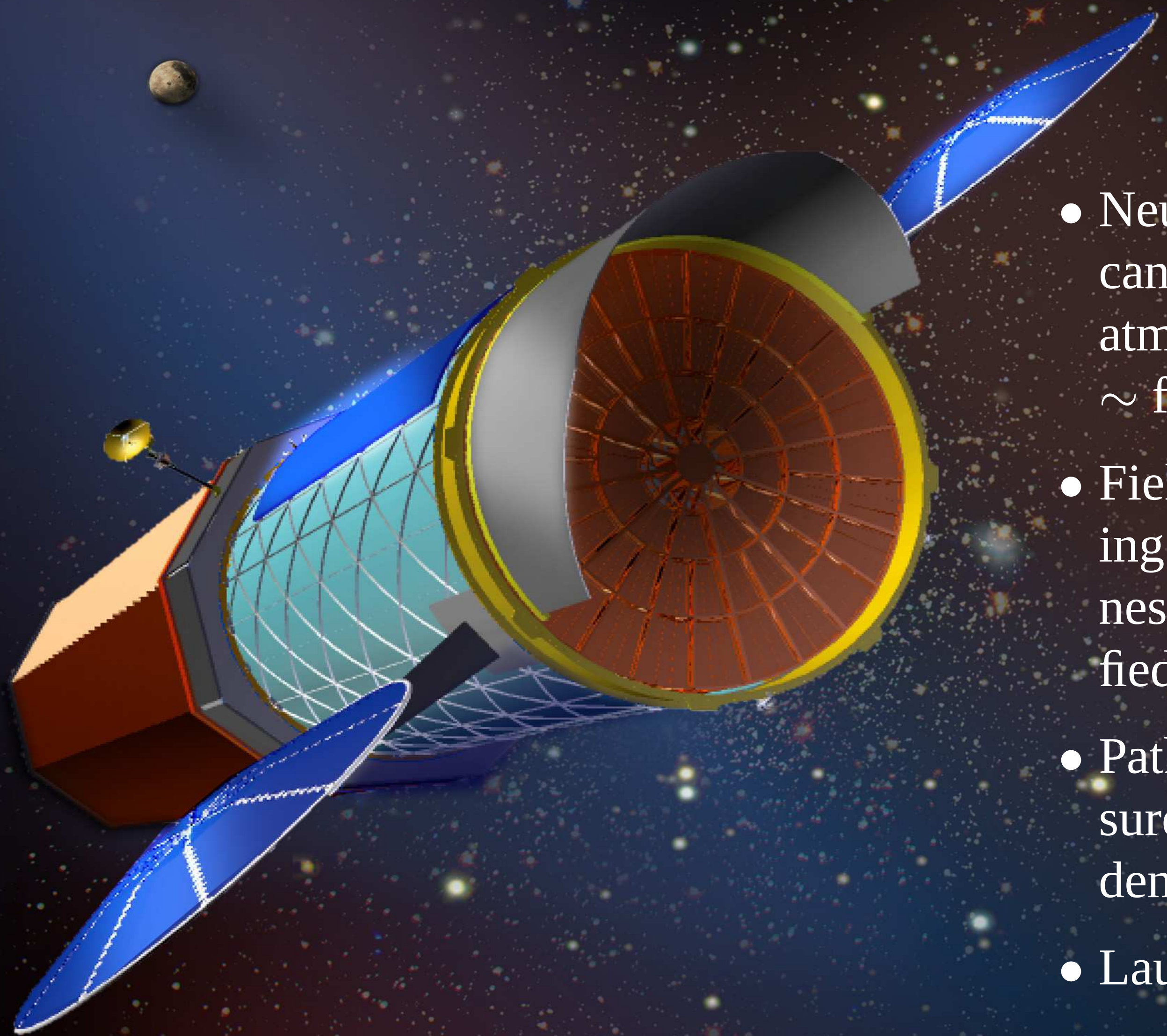
2. Mass Distribution: $m(R) = \int_0^R \varepsilon(r)\, 4\pi\, r^2\, dr$





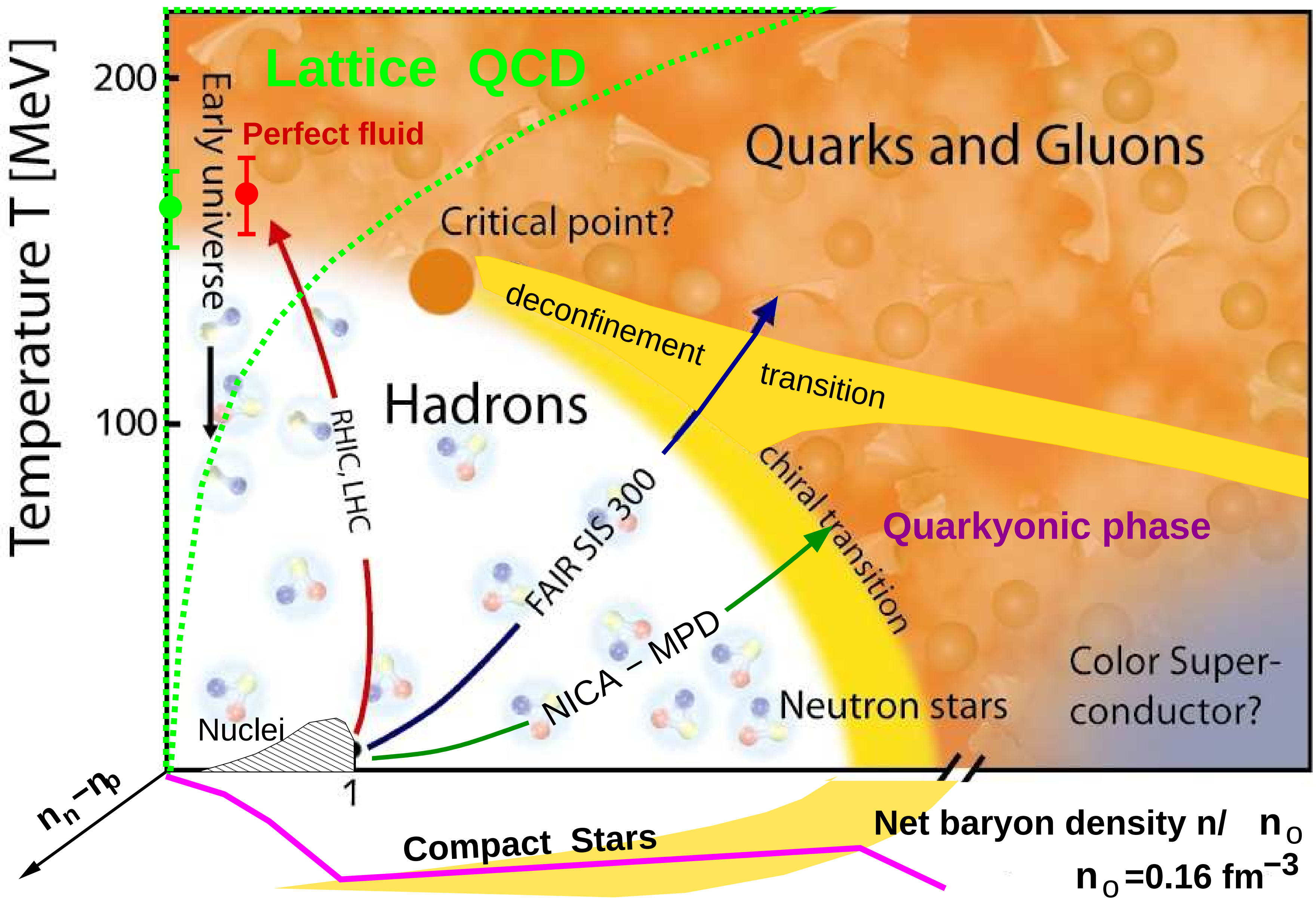
Klähn, D.B., Typel, Fuchs, Faessler, Grigorian, Miller, Röpke, Trümper, et al: PRC 74, 035802 (2006)

The Proposed International X-Ray Observatory (IXO)



- Neutron Star Masses and Radii can be measured from H-atmosphere neutron stars with $\sim$ few % accuracy with IXO
- Field sources are most promising targets due to their brightness, but they must be identified first
- Path: simultaneous M-R measurements determine the cold dense matter EoS
- Launch 2021 (NASA)

Extreme States of Matter - The Phase Diagram



L. McLerran and R. Pisarski, NPA 796 (2007) 83

Motivation and Tasks

EoS for Supernova and Merger Simulations: Wide range of parameters!

- $10^{-8} \leq n/n_0 \leq 10$
- $0 \leq T \leq 200$ MeV
- $0 \leq Y_p \leq 0.6$; $\beta = 1 - 2Y_p$

Commonly used EsoS:

- Lattimer-Swesty, NPA 535 (1991):
  Skyrme-type model LD modeling of nuclei embedded in nucleon gas
- Shen, Toki et al., Prog. Theor. Phys. 100 (1998):
  RMF model (TM1), α particles with excluded volume procedure

Recent development:

- Horowitz-Schwenk, NPA 776 (2006): virial expansion, nucleons and α's
  uses experimental data for BE and scattering phase shifts, exact limit for low densities $n/n_0 < 10^{-3}$

Tasks of the present work:

- medium effects on light clusters from quantum statistical approach
- realistic description of high-density matter (DD-RMF)
- thermodynamics, liquid-gas phase transition (instability region)

Theory of nuclear matter with clusters (I)

Total nucleon density:

$$n_\tau(T,\tilde\mu_p,\tilde\mu_n) = \frac{1}{\Omega}\sum_1 \langle a_1^\dagger a_1\rangle \delta_{\tau,\tau_1} = 2\int \frac{d^3k_1}{(2\pi)^3}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi} f_{1,Z}(\omega) S_1(1,\omega)$$

Distribution functions: $f_{A,Z}(\omega) = \left(\exp\left\{\beta\left[\omega - Z\tilde\mu_p - (A-Z)\tilde\mu_n\right]\right\} - (-1)^A\right)^{-1}$

Cluster decomposition of nucleon densities

$$n_p^{\mathrm{tot}}(T,\tilde\mu_p,\tilde\mu_n) = \frac{1}{\Omega}\sum_{A,\nu,K} Z f_{A,Z}[E_{A,\nu}^{\mathrm{qu}}(K;T,\tilde\mu_p,\tilde\mu_n)]$$

$$n_n^{\mathrm{tot}}(T,\tilde\mu_p,\tilde\mu_n) = \frac{1}{\Omega}\sum_{A,\nu,K} (A-Z) f_{A,Z}[E_{A,\nu}^{\mathrm{qu}}(K;T,\tilde\mu_p,\tilde\mu_n)]$$

Mass fractions of clusters: $X_{A,Z} = \frac{A}{\Omega n}\sum_{\nu,K} f_{A,Z}[E_{A,\nu}^{\mathrm{qu}}(K;T,\tilde\mu_p,\tilde\mu_n)]$

Thermodynamical potential F by integration of $\mu(n)$ [inverted $n(\mu)$]

$\longrightarrow$ all thdyn. functions (EoS)

$$F(T,n,Y_p^{\mathrm{s}})/\Omega = \int_0^n dn'\, \tilde\mu(T,n',Y_p^{\mathrm{s}})$$

Typel, Röpke, Klähn, D.B., Wolter, Phys. Rev. C 81, 015803 (2010)

Theory of nuclear matter with clusters (II)

Single-nucleon quasiparticle dispersion in effective mass approximation:

$$E_\tau^{\rm qu}(k) = \Delta E_\tau^{\rm SE}(0) + \frac{k^2}{2m_\tau^*} + \mathcal{O}(k^4)$$

From density-dependent RMF theory follows

$$E_{n,p}^{\rm qu}(0) = \sqrt{[m - \Sigma_{n,p}(T,n,\pm\delta)]^2 + k^2} + \Sigma_{n,p}^0(T,n,\pm\delta)$$

$\Sigma_{n,p}$ – scalar self energy; $\Sigma_{n,p}^0$ time component of vector self energy

$$\Delta E_{n,p}^{\rm SE}(k) = \Sigma_{n,p}^0(T,n,\pm\delta) - \Sigma_{n,p}(T,n,\pm\delta)\ ;\ \ m_{n,p}^* = m - \Sigma_{n,p}(T,n,\pm\delta)$$

Quasiparticle energies for clusters from A-particle Schrödinger equation in perturbation theory

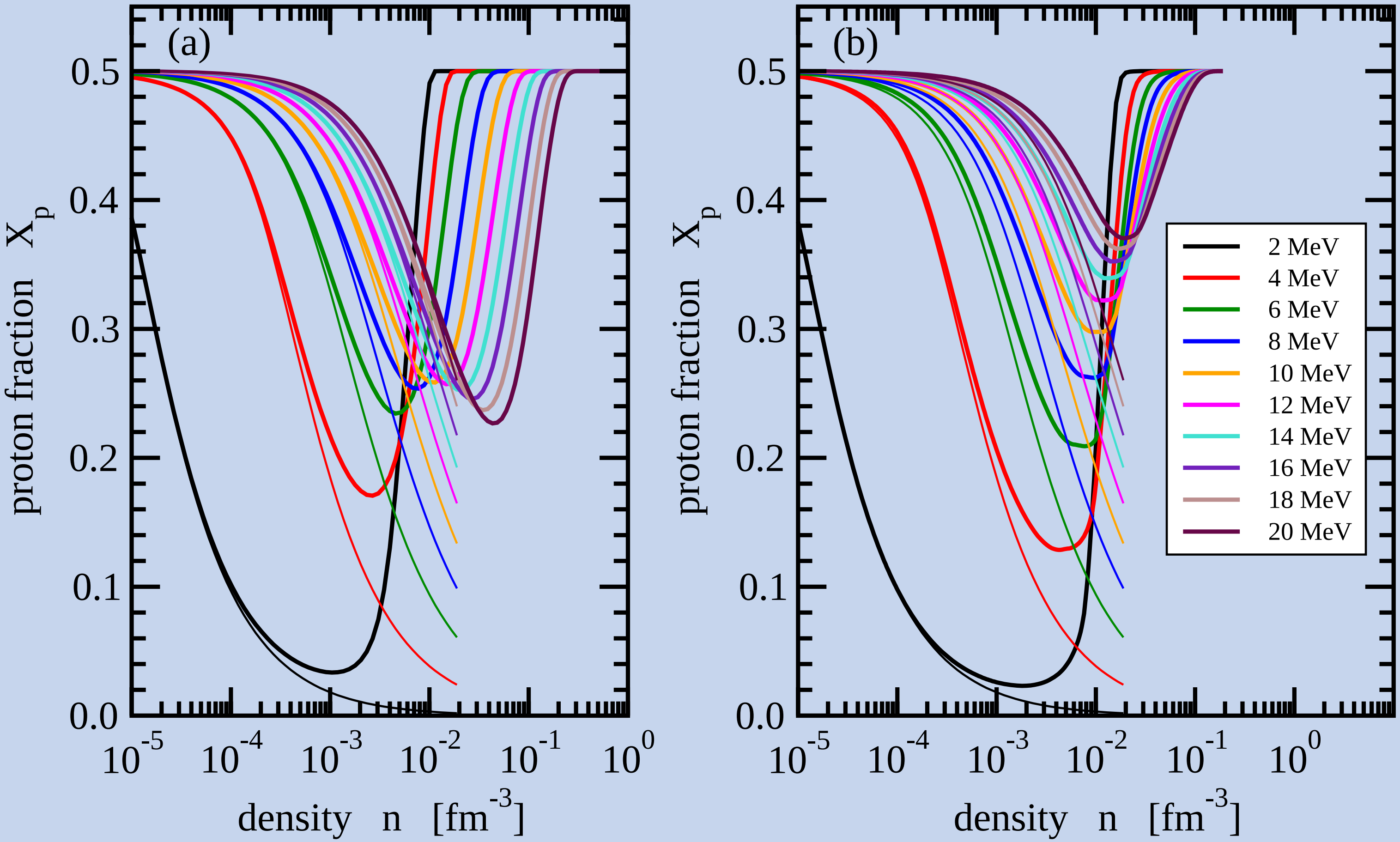
$$E_{A,\nu}^{\rm qu}(K) = E_{A,Z}^{\rm qu}(K) = E_{A,Z}^{(0)} + \frac{K^2}{2Am} + \Delta E_{A,Z}^{\rm SE}(K) + \Delta E_{A,Z}^{\rm Pauli}(K) + \Delta E_{A,Z}^{\rm Coul}(K) + \dots$$

Important effect for cluster binding energy in medium: Pauli shift:

$$\Delta E_{A,Z}^{\rm Pauli}(K) \approx \Delta E_{A,Z}^{\rm Pauli}(0)\ \exp\left(-\frac{K^2}{g_{A,Z}}\right)\ \ ;\ \ g_i(T,n,Y_p) = \frac{g_{i,1} + g_{i,2}T + h_{i,1}n}{1 + h_{i,2}n}$$

Typel, Röpke, Klähn, D.B., Wolter, Phys. Rev. C 81, 015803 (2010)

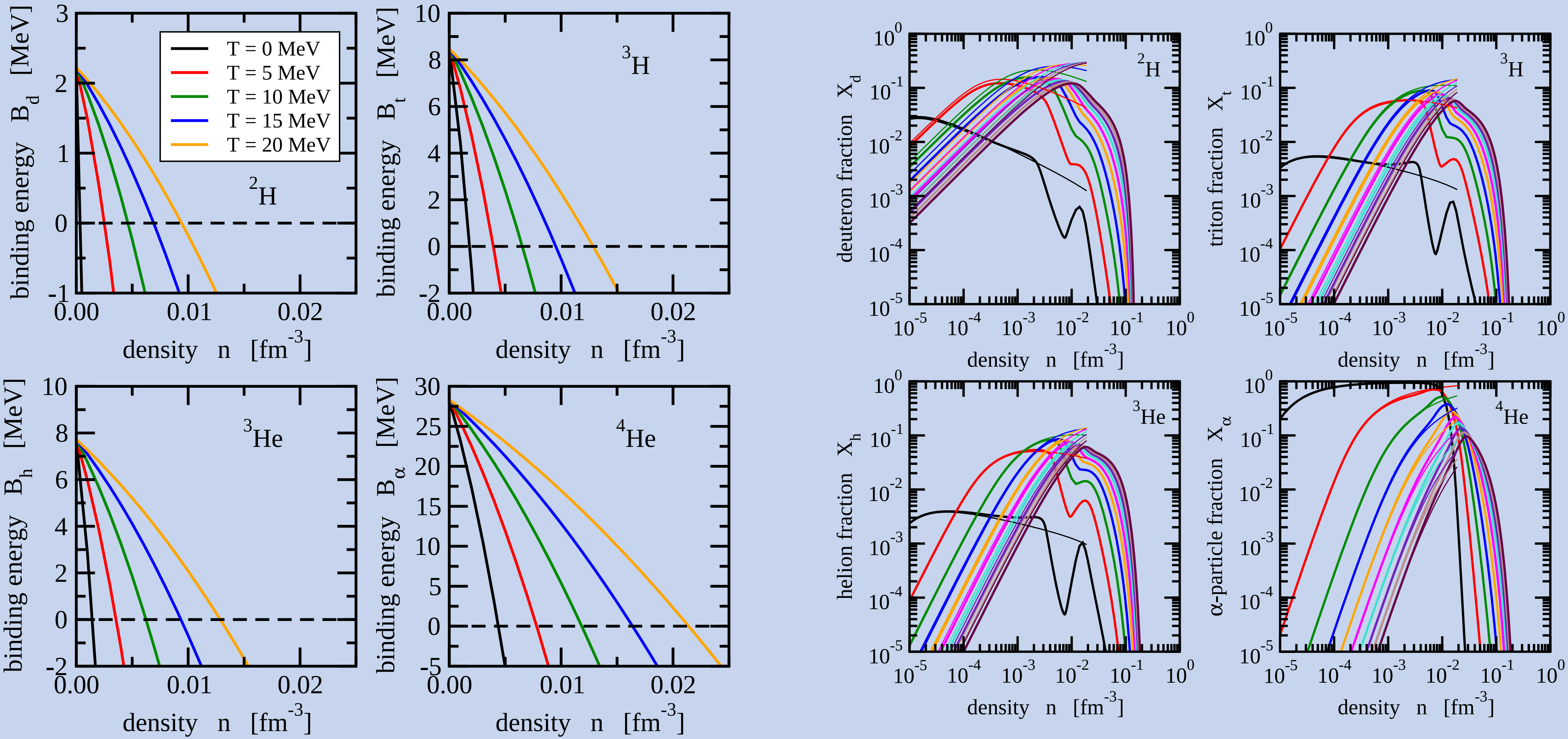
Proton fraction (dissociation degree) in nuclear matter



Proton fraction X_p in symmetric nuclear matter in generalized RMF model (a) and quantum statistical approach (b). Thin lines show the nuclear statistical equlibrium (NSE) model for comparison.

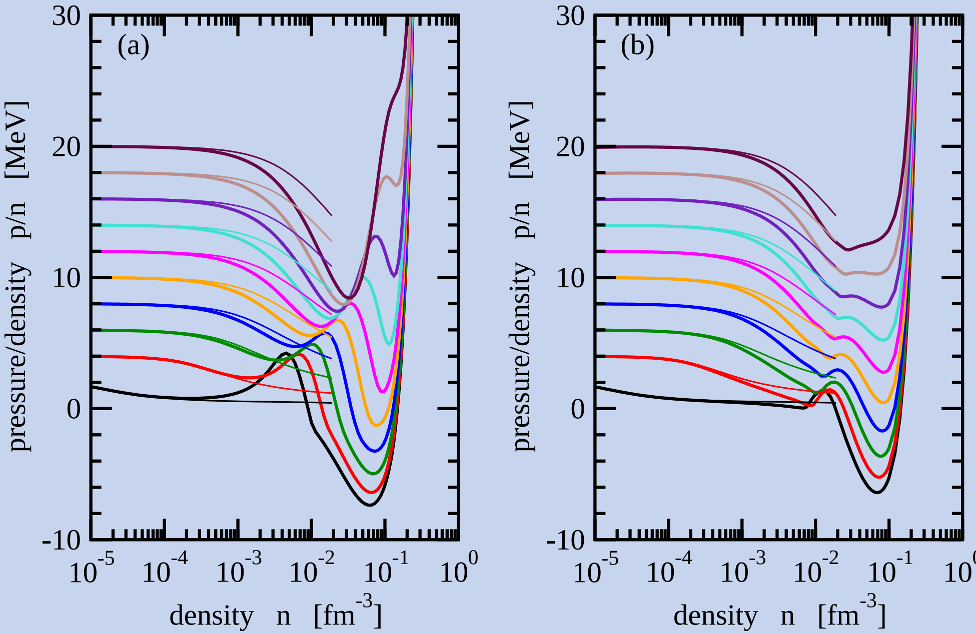
Typel, Röpke, Klähn, D.B., Wolter, arxiv:0908.2344; Phys. Rev. C 81, 015803 (2010)

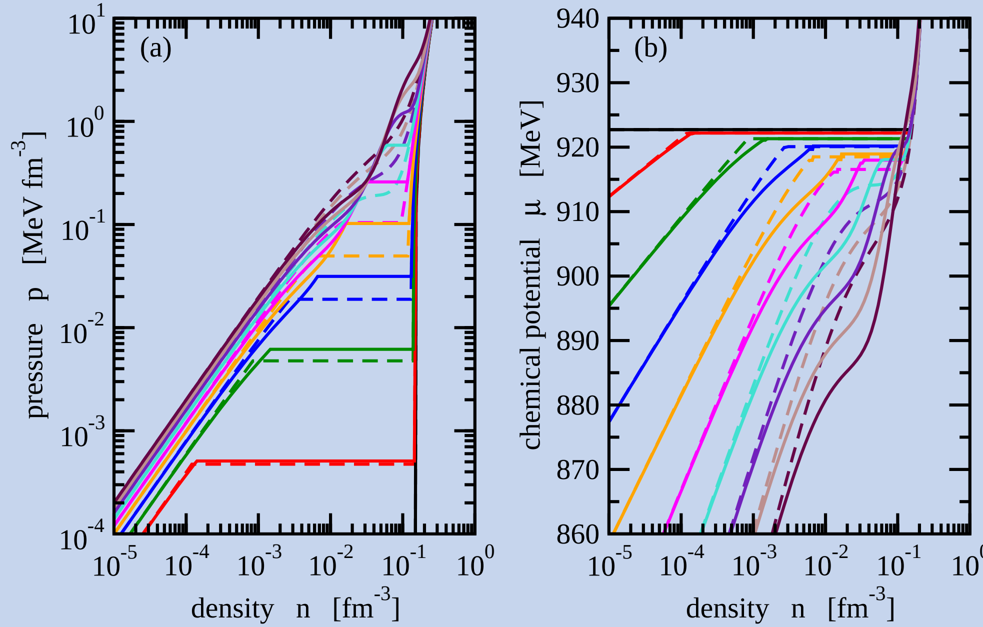
Cluster binding energies and fractions in nuclear matter



Typel, Röpke, Klähn, D.B., Wolter, arxiv:0908.2344; Phys. Rev. C 81, 015803 (2010)

Liquid-gas phase transition in symmetric nuclear matter



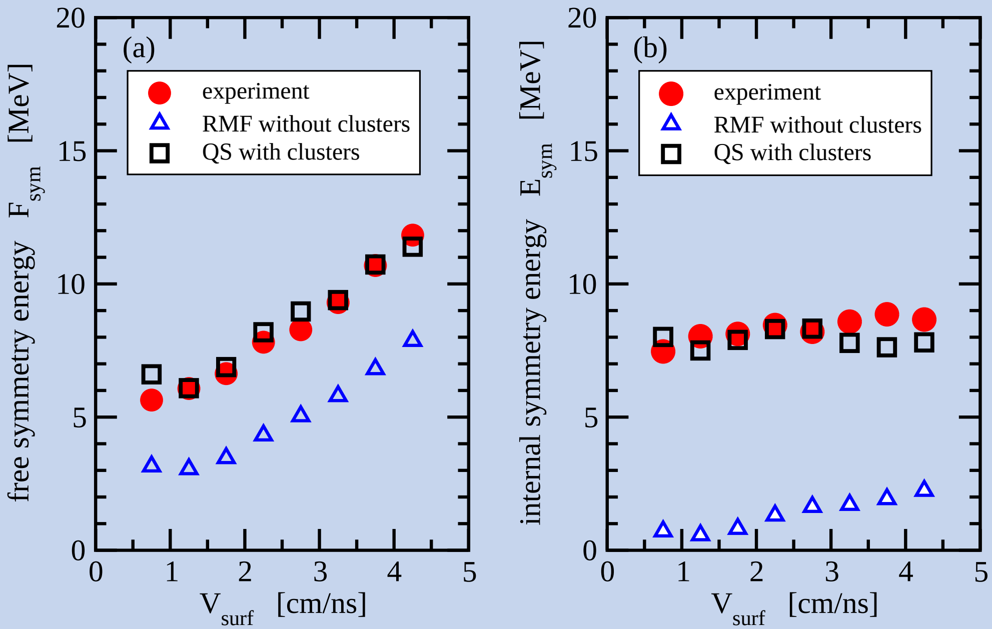


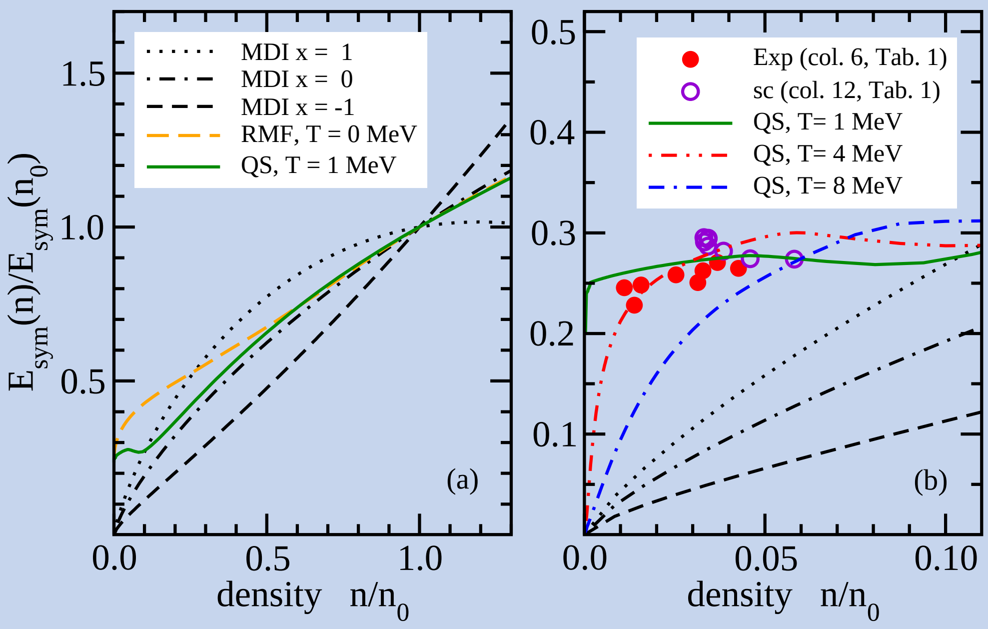
Typel, Röpke, Klähn, D.B., Wolter, arxiv:0908.2344; Phys. Rev. C 81, 015803 (2010)

Nuclear matter symmetry energy with clusters

Nuclear (internal) symmetry energy:

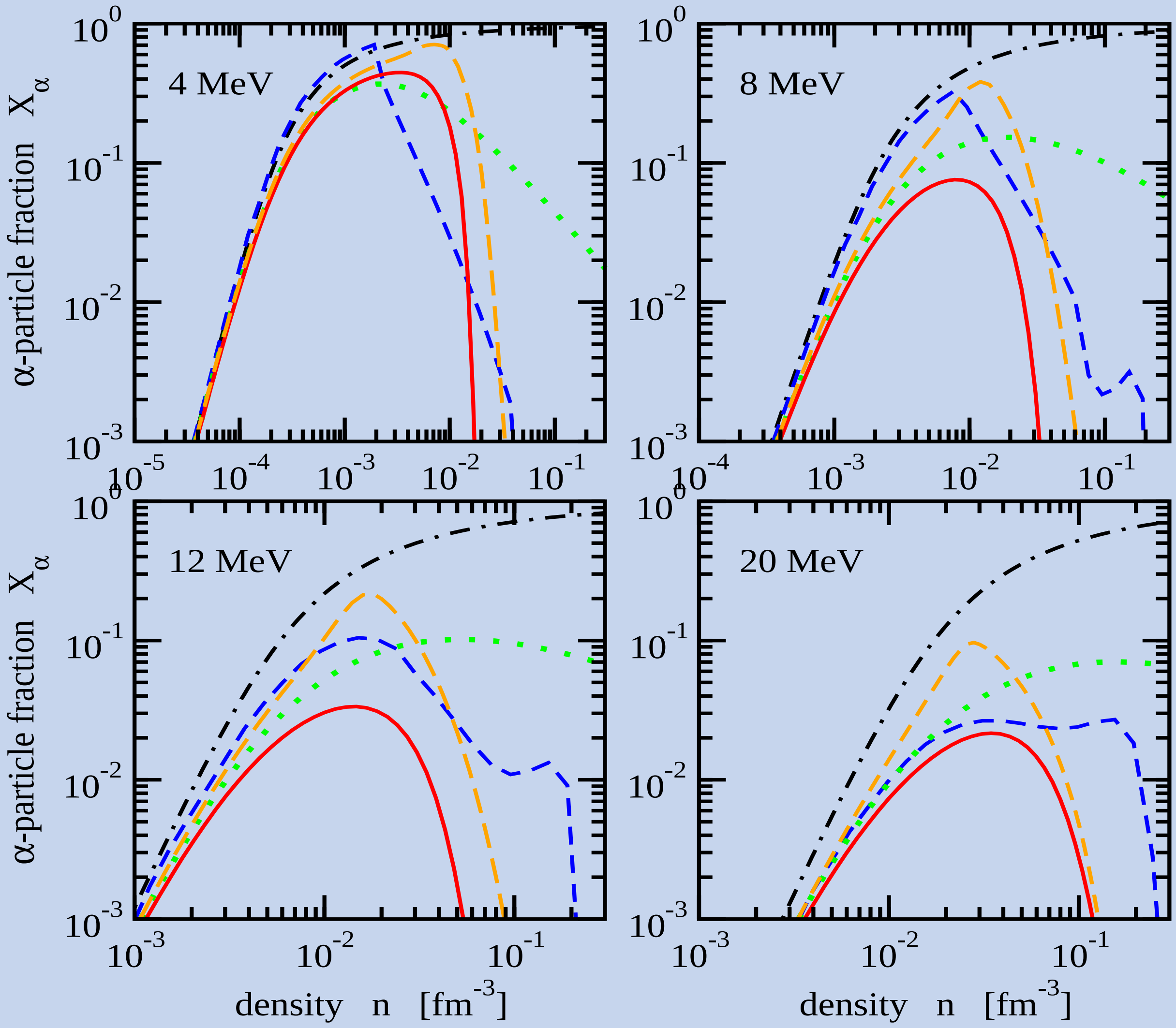
$$E_{\rm sym}(n,T) = \frac{E(n,1,T)+E(n,-1,T)}{2} - E(n,0,T)$$





Natowitz, Röpke, Typel, D.B., ..., Wolter, arxiv:1001.1102 [nucl-th]; PRL (2010).

Comparison with standard SN EoS (Shen et al.)

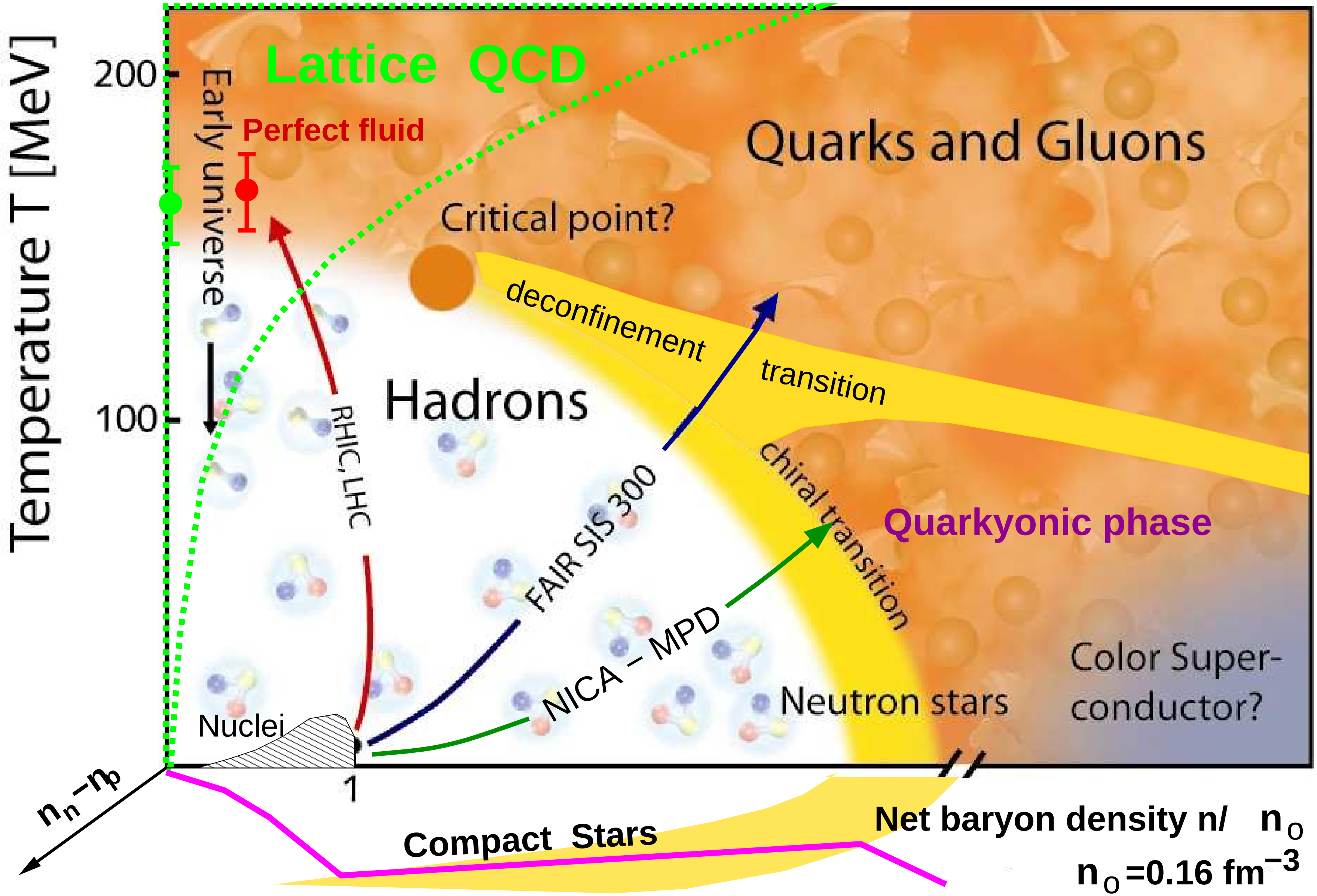


- virial expansion (dash-dotted)
- NSE (dotted)
- Shen et al. (short-dashed)
- generalized RMF (long-dashed)
- quantum statistics (solid)

α particle fractions in symmetric nuclear matter as functions of density at four temperatures.

Typel, Röpke, Klähn, D.B., Wolter, arxiv:0908.2344; Phys. Rev. C 81, 015803 (2010)

Extreme States of Matter - The Phase Diagram



L. McLerran and R. Pisarski, NPA 796 (2007) 83

Quantum Field Theory for chiral Quark Matter

- Partition function for chiral Quark Field theory coupled to Polyakov-loop potential

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp\left\{ - \int^{\beta} d^4x \{ \bar{\psi}[i\gamma^\mu\partial_\mu - m - \gamma^0(\mu + i\lambda_3\phi_3)]\psi - \mathcal{L}_{\rm int} + U[\Phi(\phi_3)] \} \right\}$$

- Current-current coupling (4-fermion interaction) and KMT determinant

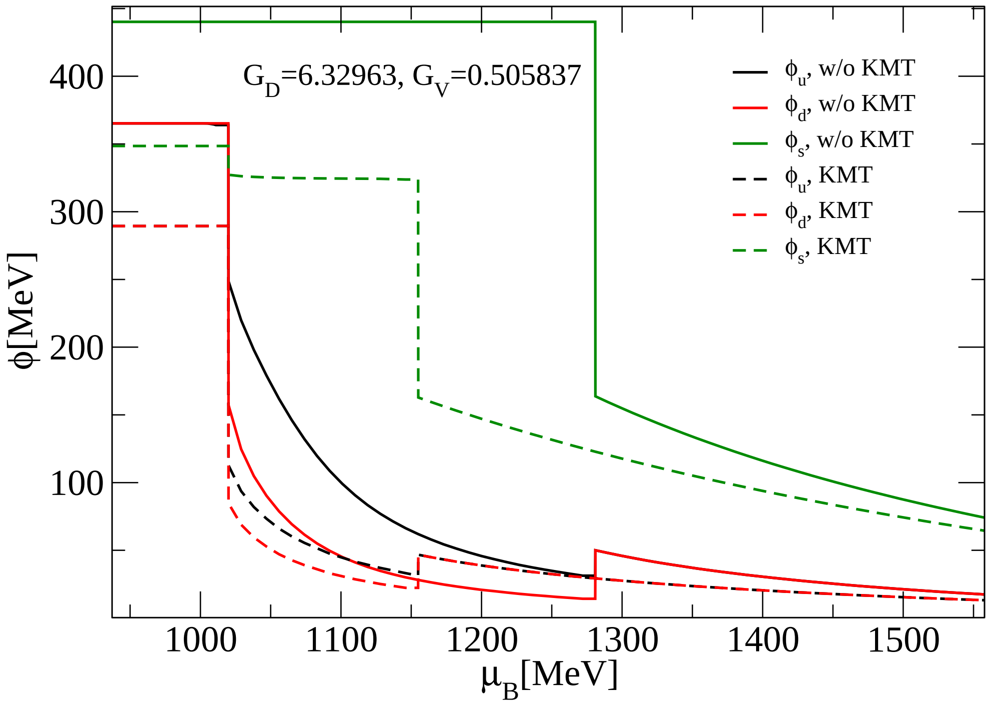
$$\mathcal{L}_{\rm int} = \sum_{M=\pi,\sigma,\dots} G_M(\bar{\psi}\Gamma_M\psi)^2 + \sum_D G_D(\bar{\psi}^C\Gamma_D\psi)^2 + \mathcal{L}_{\rm det}$$

- Bosonisation (Hubbard-Stratonovich Transformation)

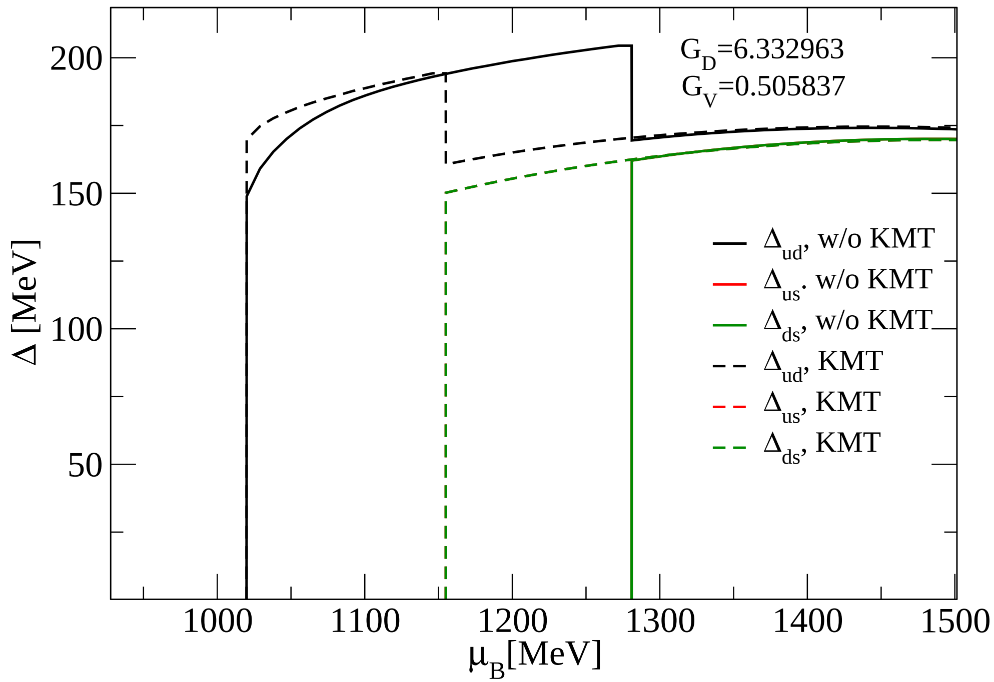
$$Z[T,V,\mu] = \int \mathcal{D}\phi_M \mathcal{D}\Delta_D^\dagger \mathcal{D}\Delta_D \exp\left\{ -\frac{\phi_M^2}{4G_M} - \frac{|\Delta_D|^2}{4G_D} - \frac{K\phi_u\phi_d\phi_s}{16G_S^3} + \frac{1}{2}{\rm Tr}\ \ln S^{-1} + U[\Phi(\phi_3)] \right\}$$

- 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

Chiral and Diquark Gaps w/wo KMT determinant



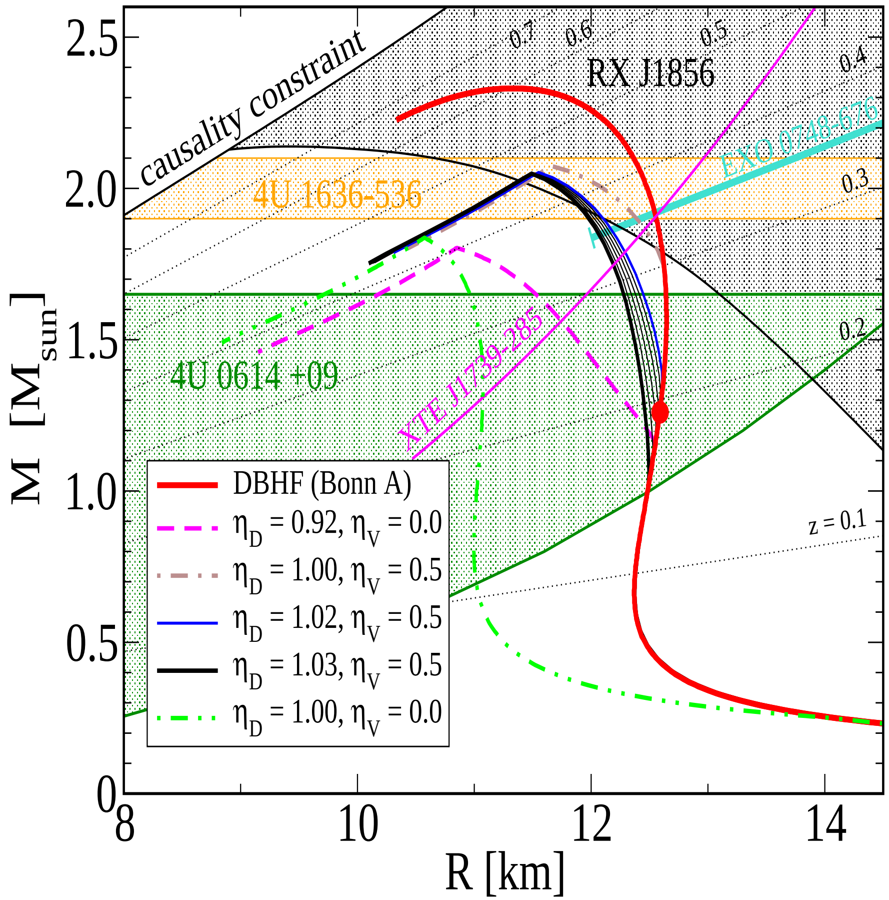
Dynamical quark masses with and without KMT determinant interaction at $T = 0$; pion properties and quark mass fixed at $\mu = 0$

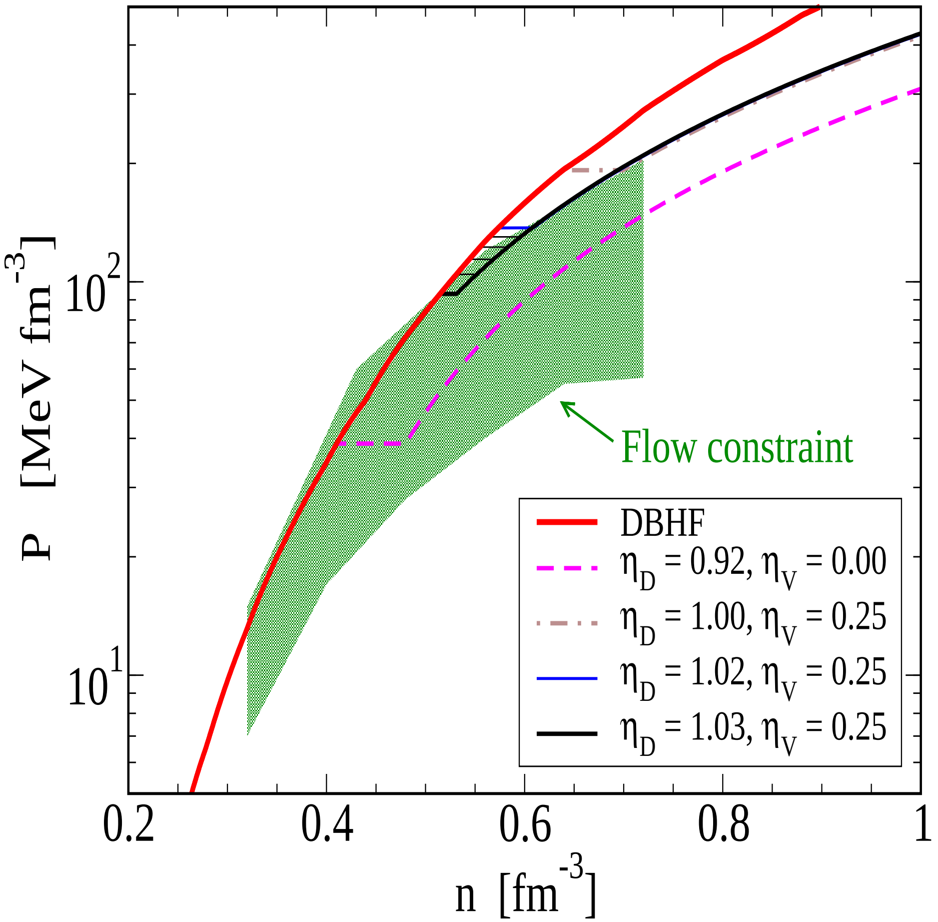


Diquark condensates with and without KMT determinant at $T = 0$, strong diquark coupling case

Rüster et al, PRD 72 (2005) 034004; Blaschke et al, PRD 72 (2005) 065020; Łastowiecki et al. (in prep.)

Mass-Radius constraint and Flow constraint, w/o KMT det.

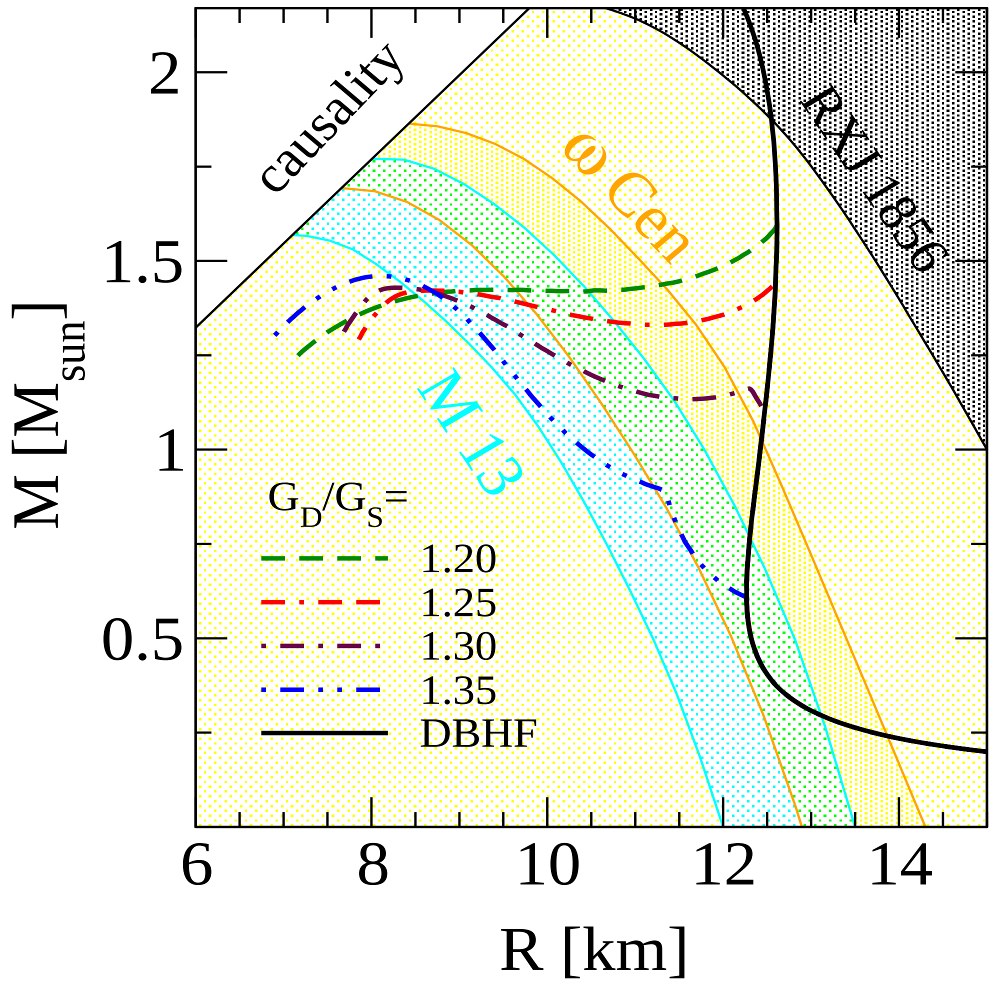


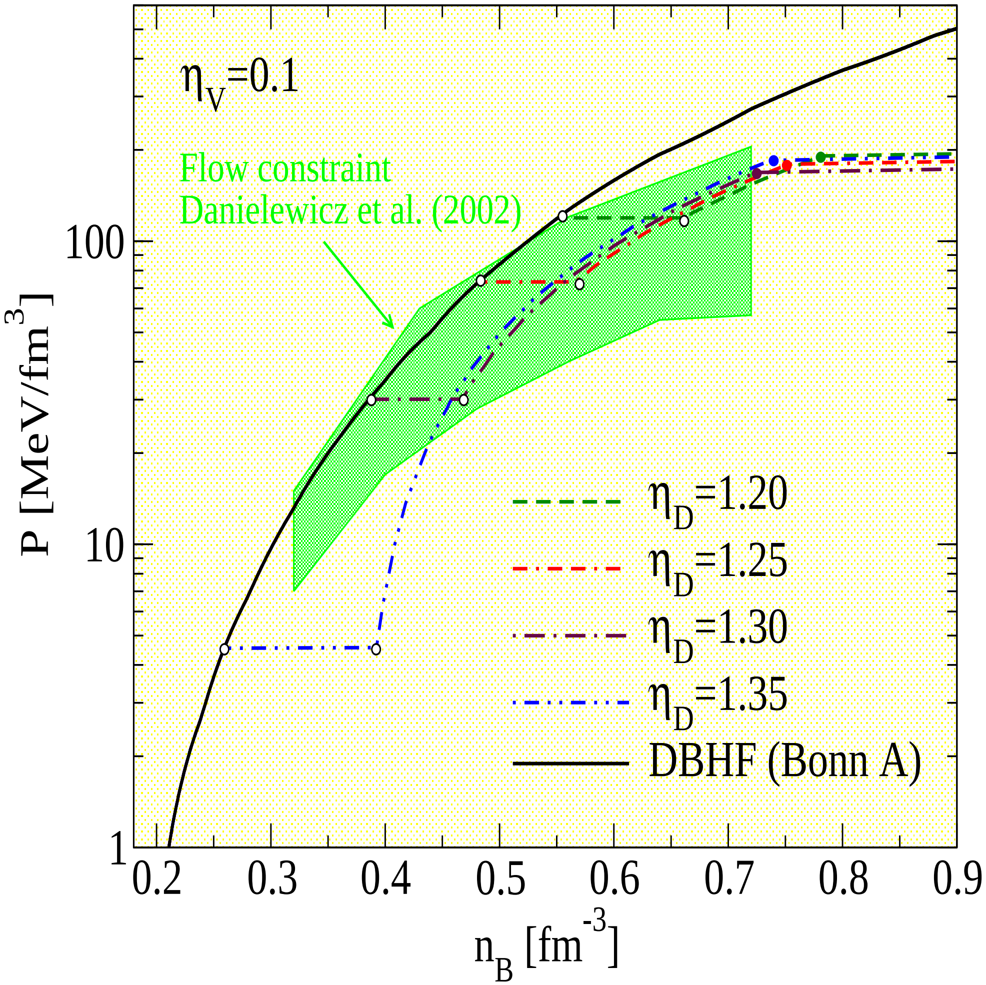


- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) ⇒ stiff quark matter EoS;
  Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!
- Flow in Heavy-Ion Collisions ⇒ not too stiff EoS !
  Note: Quark matter removes violation by DBHF at high densities

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

Mass-Radius constraint and Flow constraint with KMT det.

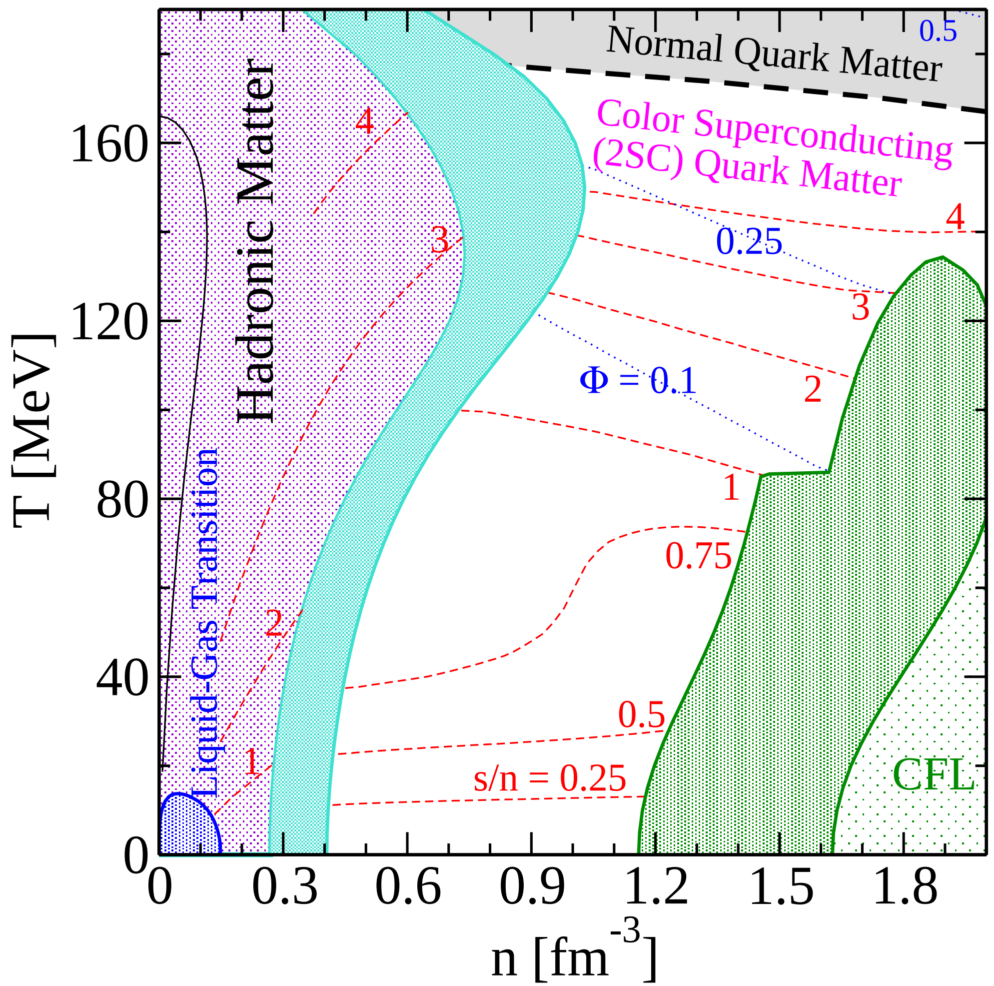


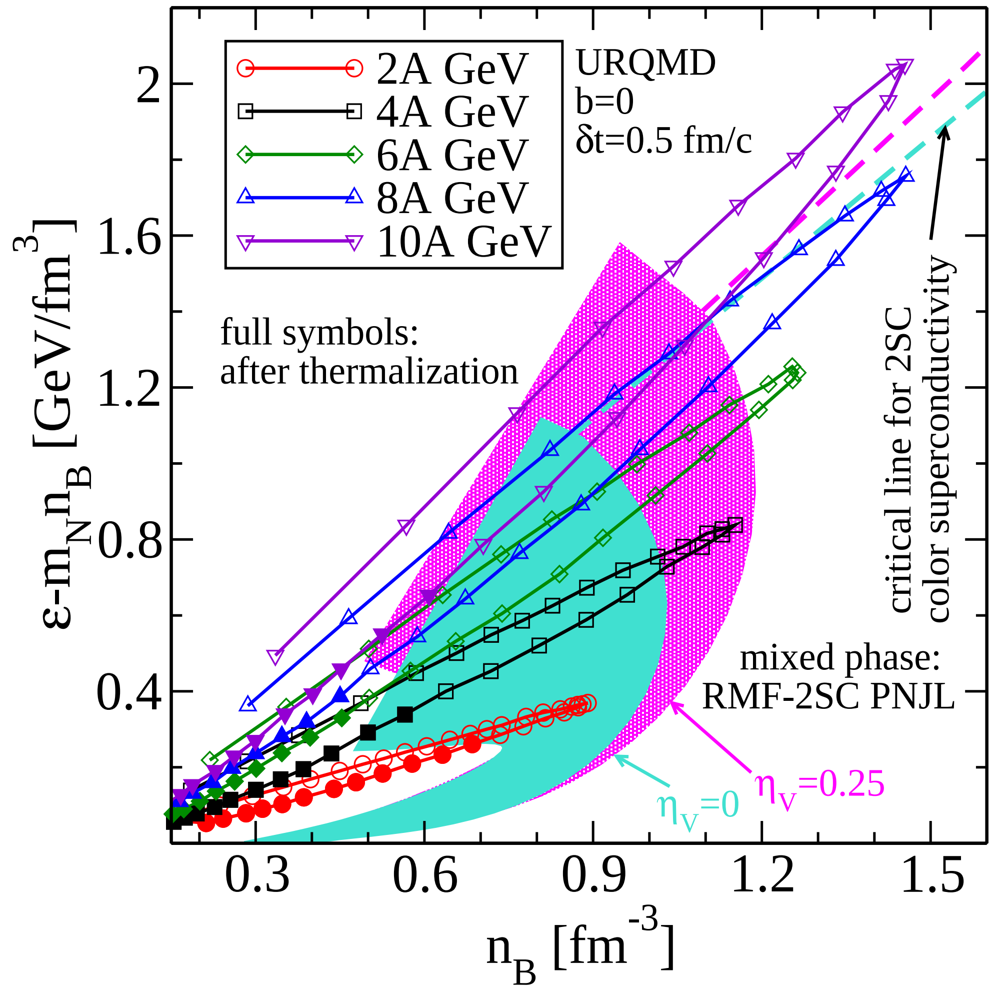


- Mass twins ($\sim 1.5\ M_\odot$) possible: $R \sim 8$ km and $R \sim 12$ km;
  Note: DU problem of DBHF removeable by deconfinement! and: CFL core Hybrids stable!
- Flow in Heavy-Ion Collisions ⇒ not too stiff EoS !
  Note: Quark matter removes violation by DBHF at high densities

D.B., Klähn, Łastowiecki, Sandin, arxiv:nucl-th/1002.1299; J. Phys. G 37 (2010) in press.

Phase diagrams for the CBM and NICA experiments

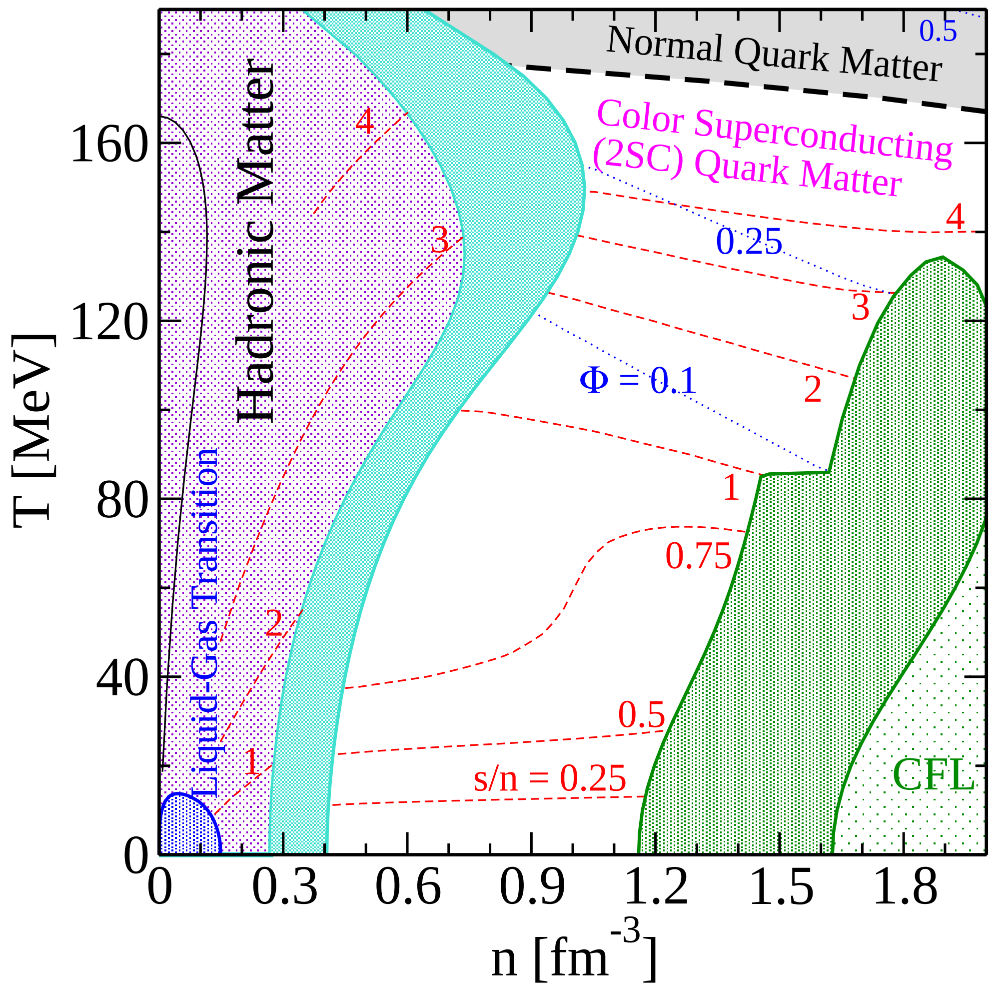


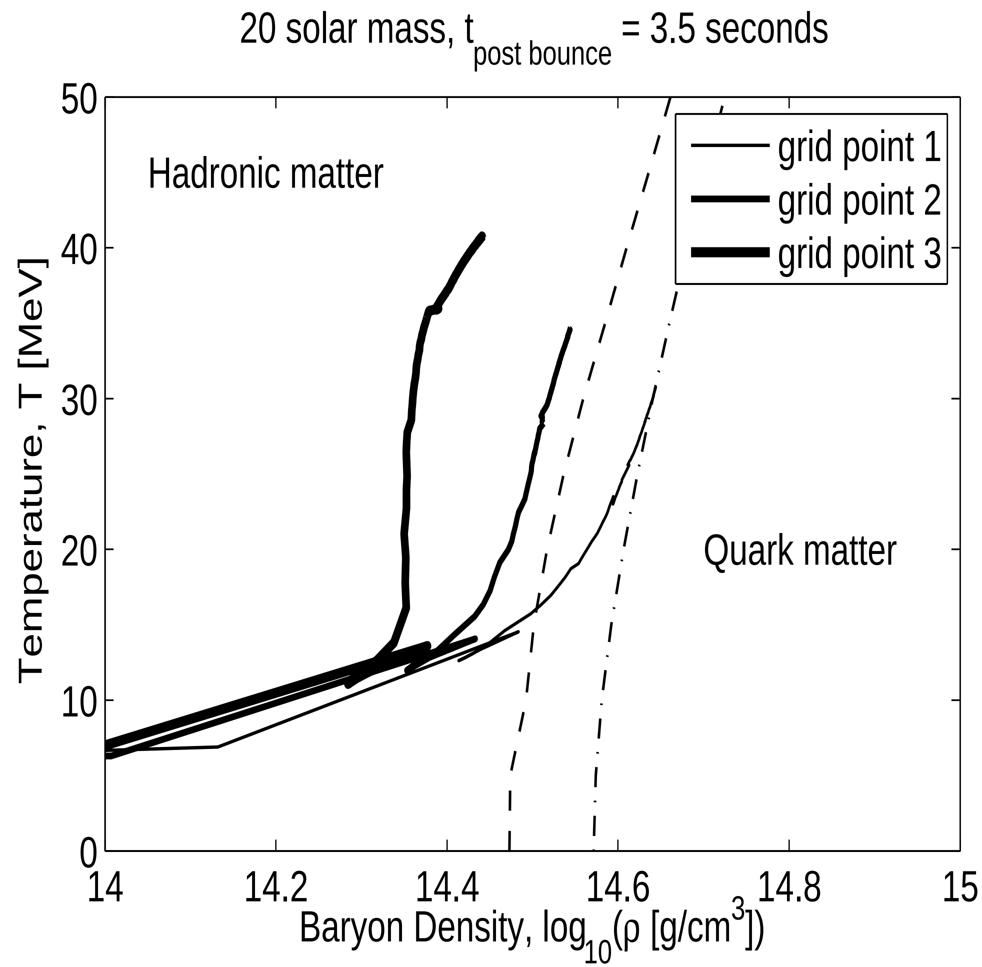


Phase diagram for isospin-symmetric matter (left); trajectories for heavy-ion collisions (right)

D.B., F. Sandin, V. Skokov, S. Typel, Acta Phys. Pol. Supp. 3, 741 (2010).

Phase diagram and EoS for SN collapse



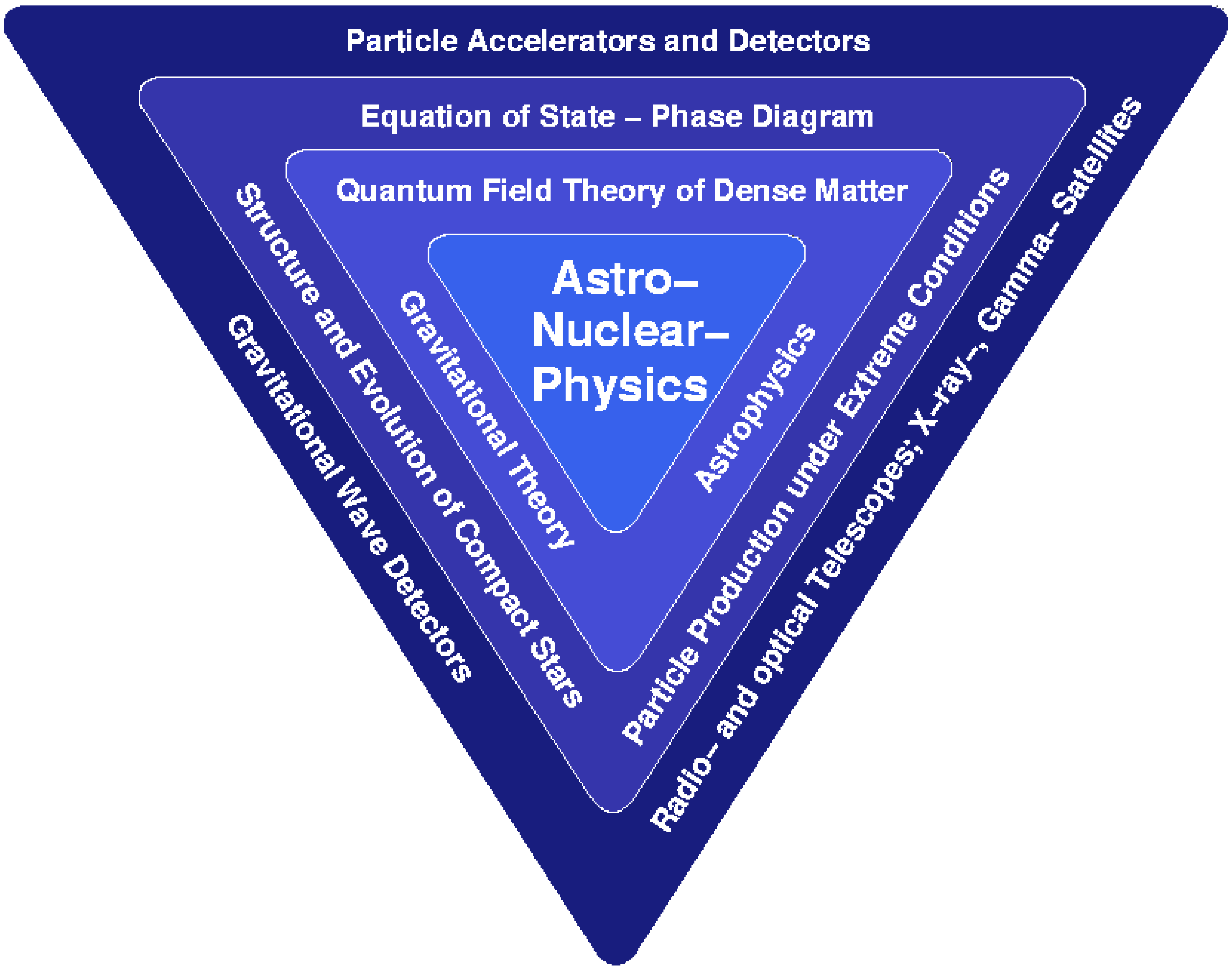


Phase diagram for isospin-symmetric matter, extension to asymmetric matter and EoS for SN collapse; calculations in progress (right-hand side)!

F. Sandin, T. Fischer, D.B., M. Liebendörfer, S. Typel, in preparation. → CompStar Coll.

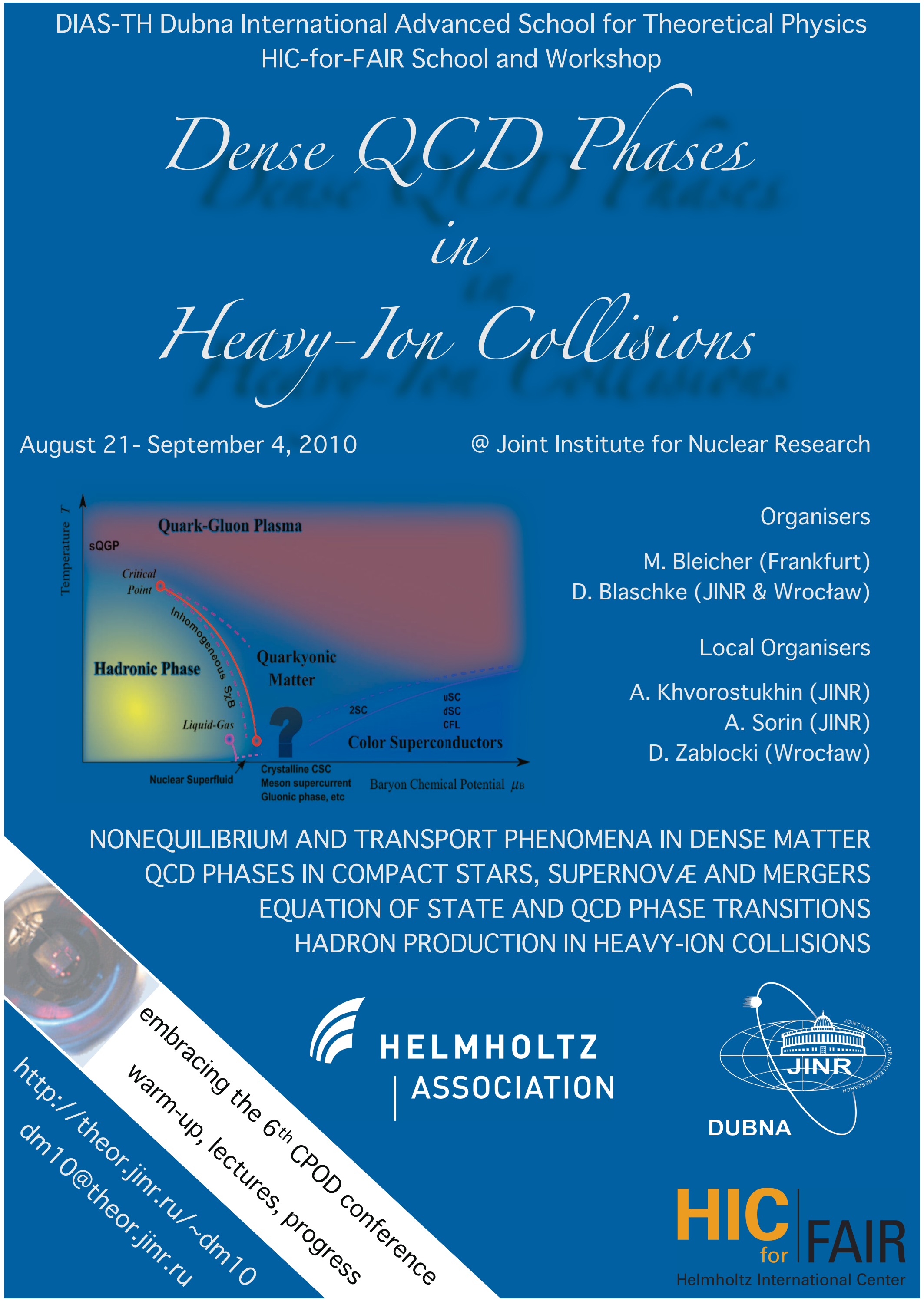
For bag model, see: I. Sagert et al., Phys. Rev. Lett. **102**, (2009) → CompStar Coll.

New ways to understand Dense QCD Matter



http://www.esf.org/compstar

CompStar **O**nline **S**upernova EoS **T**ables → coming soon!



Invitations

HIC-for-FAIR School
"Dense Matter in Heavy-Ion Collisions",
Dubna, Russia, Aug. 21- Sept. 4, 2010
(site in preparation)

CPOD 2010 - 6th Int. Conf.
"Critical Point and Onset of Deconfinement"
Dubna, Russia, Aug. 23-29, 2010
http://theor.jinr.ru/cpod

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