PSR J1614-2230 AND THE COMPSTAR EOS FOR QUARK MATTER

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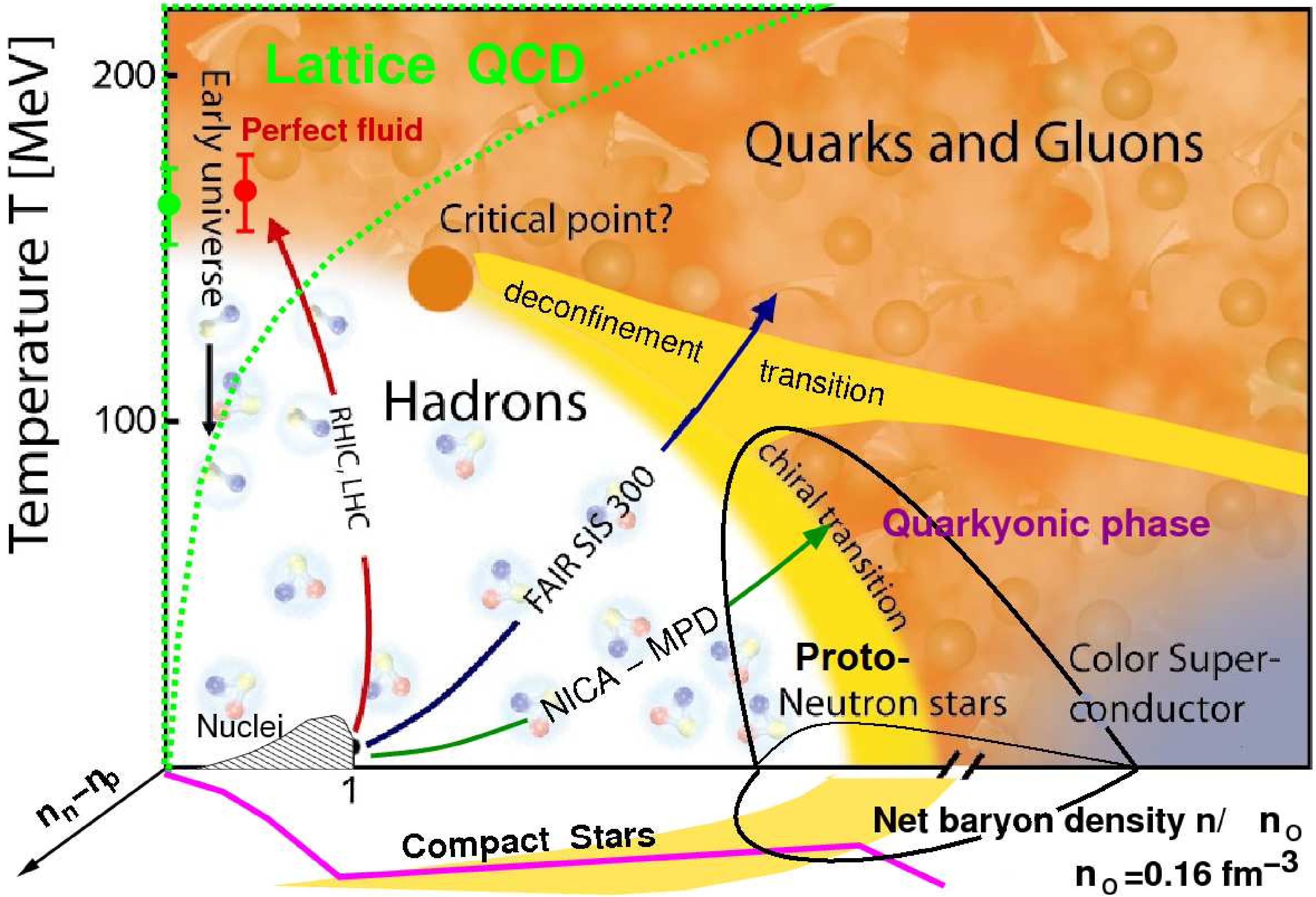
- Cold dense matter EoS - constraint from PSR J1614-2230
- Color superconducting quark matter and hybrid stars
- Supernovae and HIC in the QCD phase diagram - hybrid models at finite T,n
- CompOSE - CompStar Online Supernova EoS

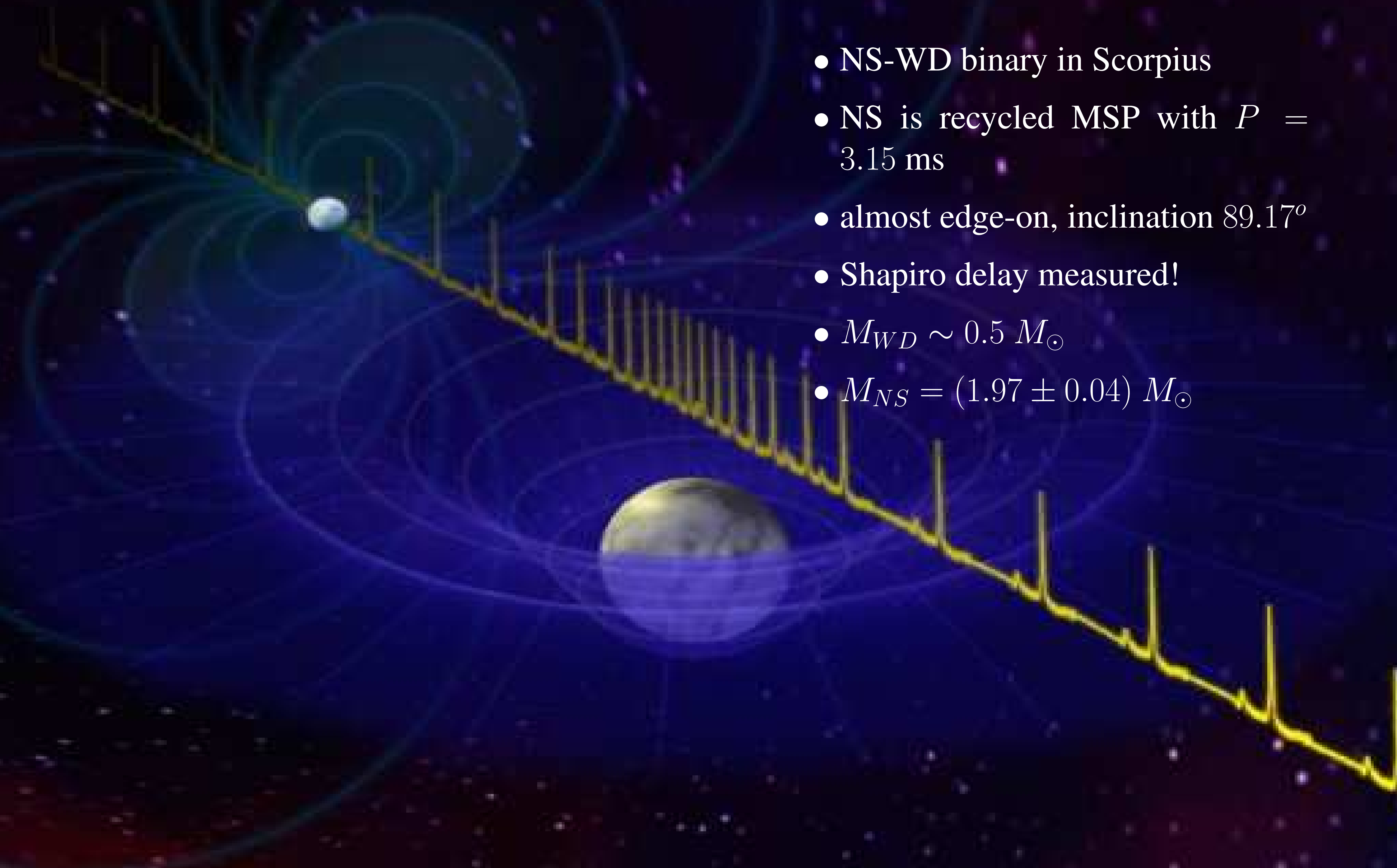
52[nd] Cracow School of Theoretical Physics, Zakopane 25.05.2012

Extreme States of Matter - The Phase Diagram



NICA White Paper, `http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome`

PSR J1614-2230 - A new constraint for the Compact Star EoS



- NS-WD binary in Scorpius
- NS is recycled MSP with $P = 3.15$ ms
- almost edge-on, inclination 89.17^o
- Shapiro delay measured!
- $M_{WD} \sim 0.5\ M_\odot$
- $M_{NS} = (1.97 \pm 0.04)\ M_\odot$

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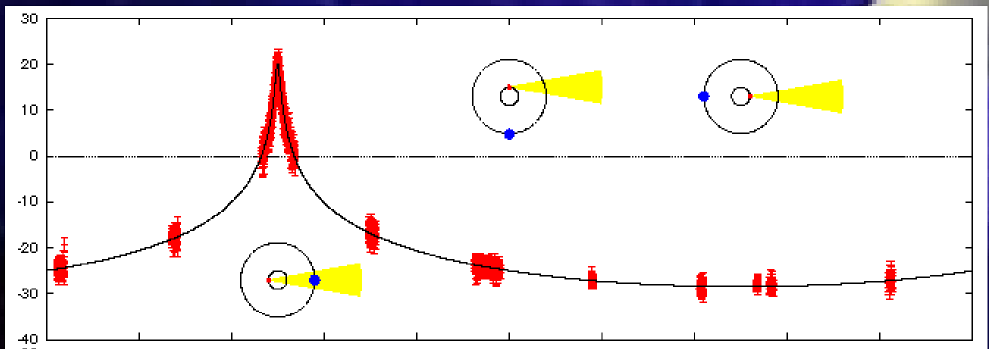

Demorest et al., Nature 467, 1081 (2010)

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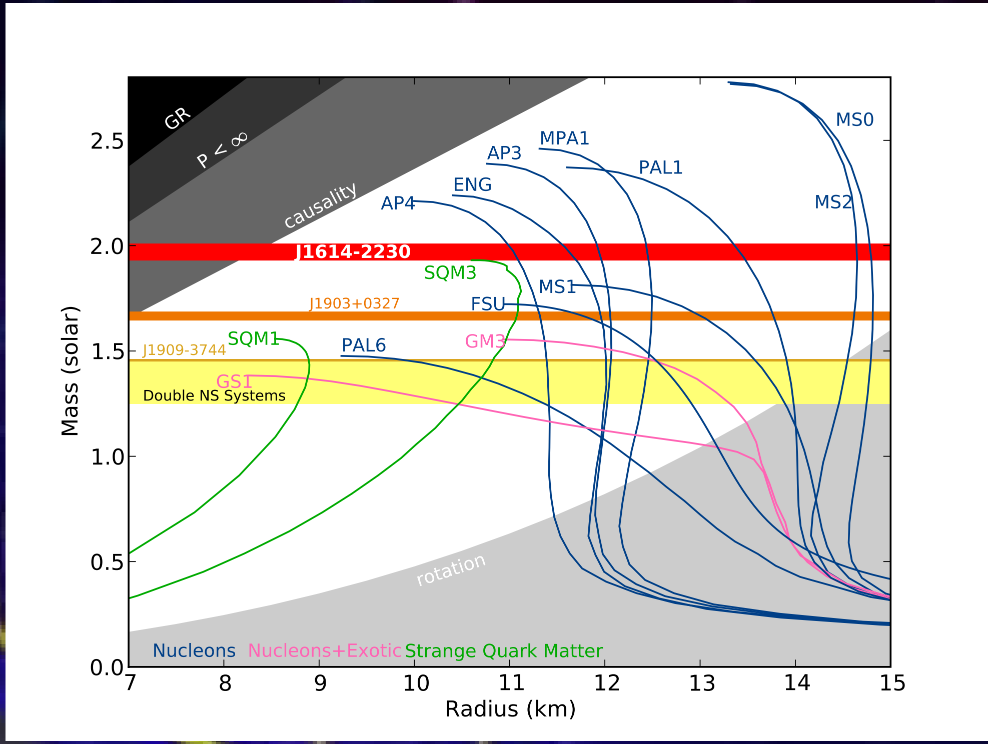

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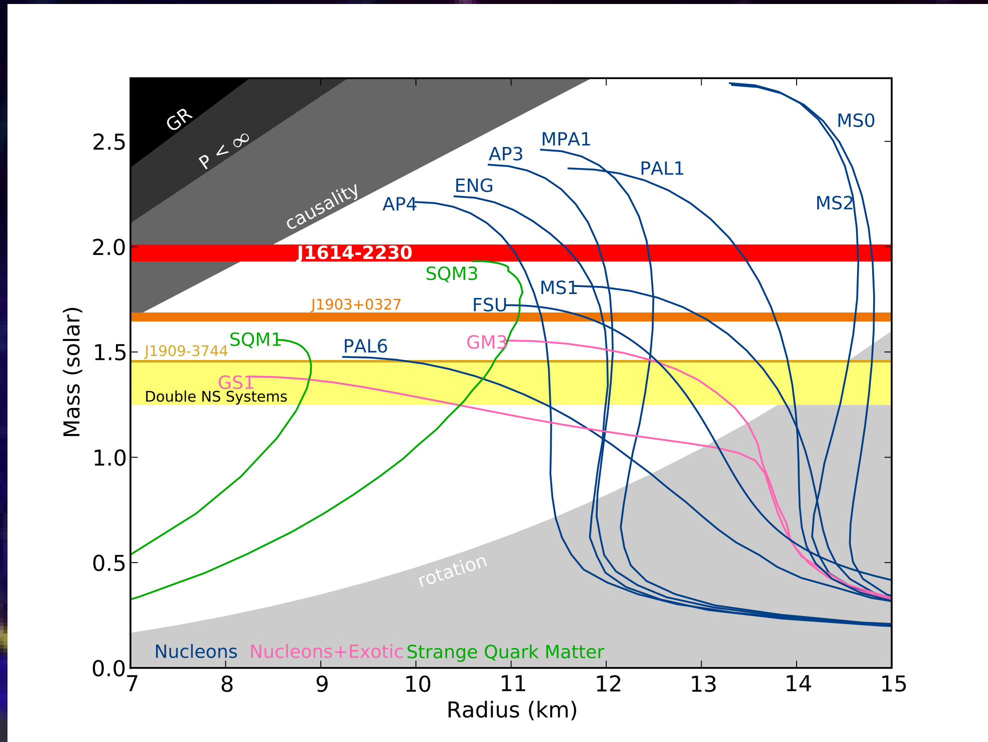
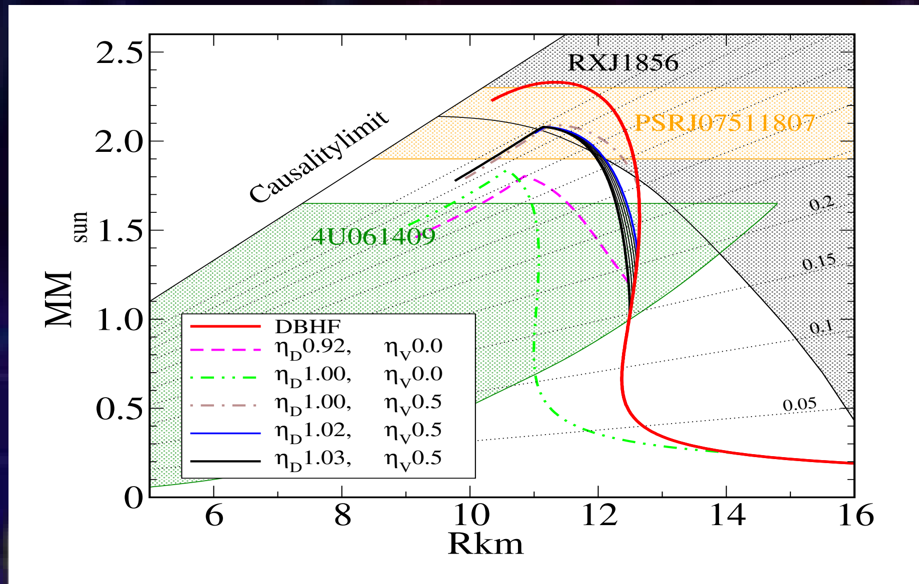


Demorest et al., Nature 467, 1081 (2010)

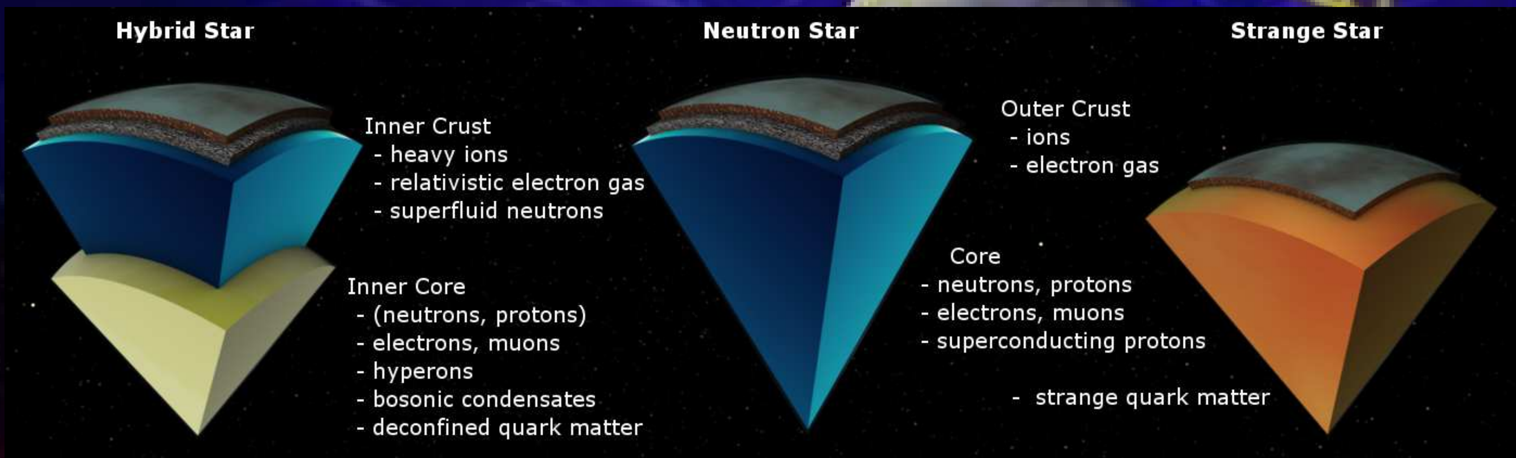
Some "soft" EoS are now ruled out !

What about hybrid stars? Strong constraints for quark matter!

PSR J1614-2230 - A new constraint for the Compact Star EoS



Klähn et al., PLB 654, 170 (2007)



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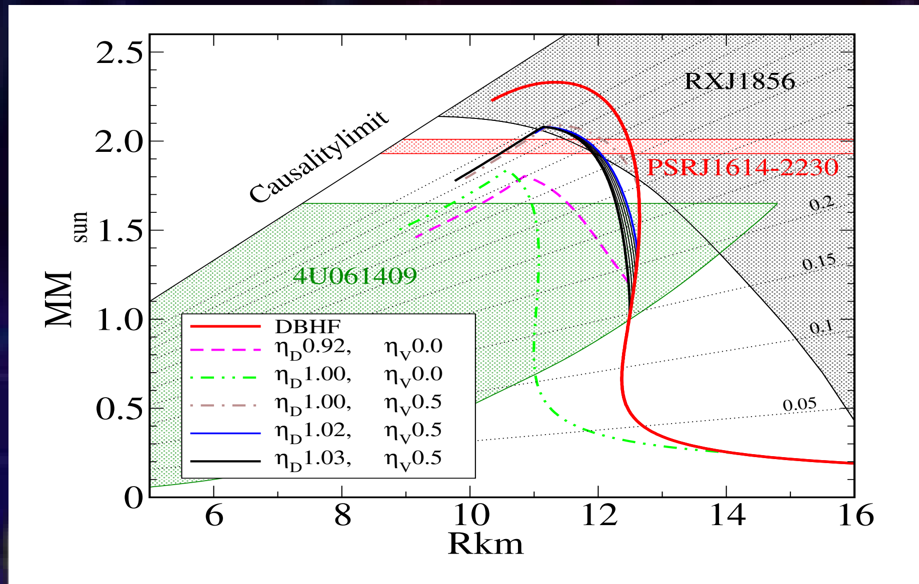
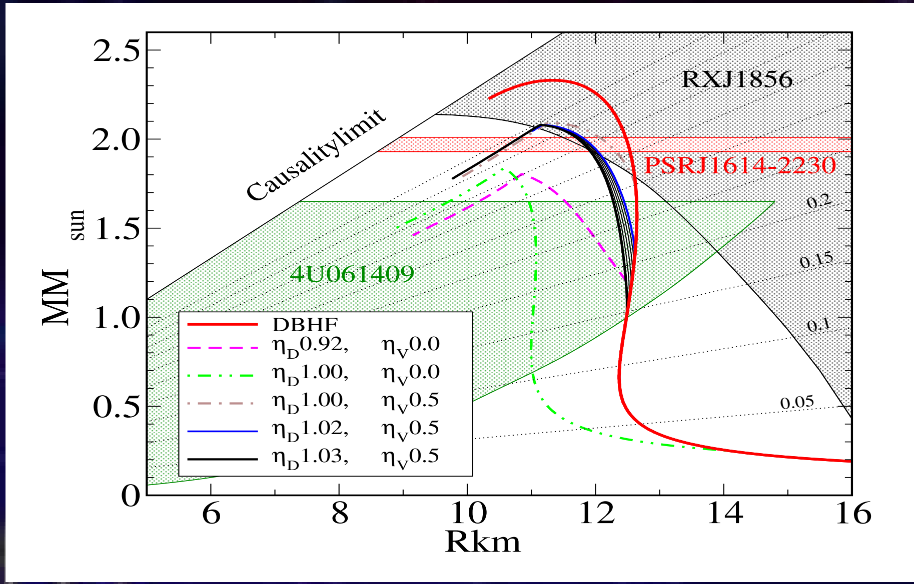


CompStar, in preparation (2010)

State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield "stiffening"

PSR J1614-2230 - A new constraint for the Compact Star EoS



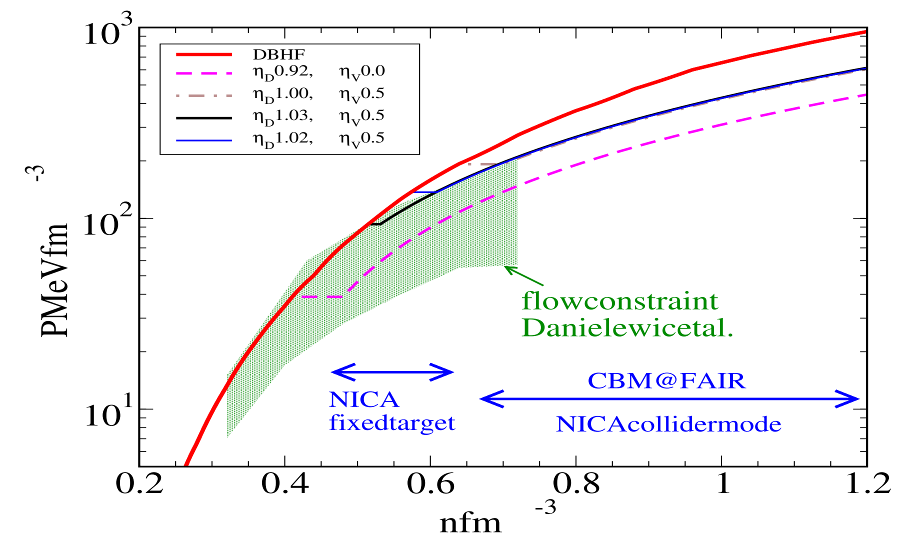
State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield "stiffening"

Constraints from heavy-ion collisions:

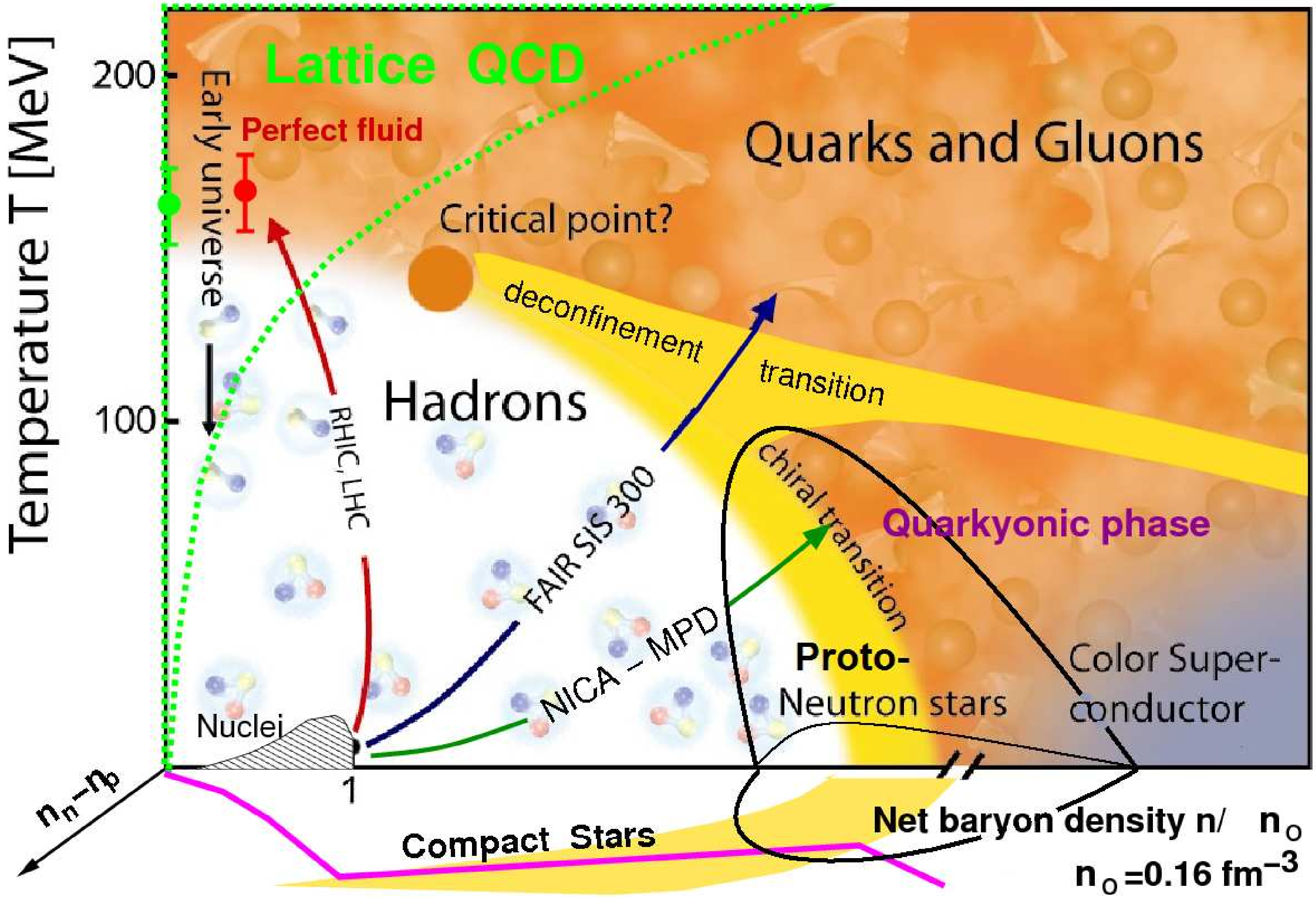
- Flow constraint at high densities
- Not too early onset of quark matter

$\Longrightarrow$ **QCD phase diagram**



Klähn et al., PLB (2007), arxiv:1101.6061

Extreme States of Matter - The Phase Diagram



NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

Chiral Model Field Theory for Quark Matter

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

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp\left\{-\int^{\beta} d\tau \int_V d^3x[\bar{\psi}[i\gamma^\mu\partial_\mu - m - \gamma^0(\mu + \lambda_8\mu_8 + i\lambda_3\phi_3]\psi - \mathcal{L}_{\rm int} + U(\Phi)]\right\}$$

Polyakov loop: $\Phi = N_c^{-1}{\rm Tr}_c[\exp(i\beta\lambda_3\phi_3)]$ Order parameter for deconfinement

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

$$\mathcal{L}_{\rm int} = \sum_{M=\pi,\sigma,\dots} G_M(\bar{\psi}\Gamma_M\psi)^2 + \sum_D G_D(\bar{\psi}^C\Gamma_D\psi)^2 - K[{\rm det}_f(\bar{q}(1+\gamma_5)q) + {\rm det}_f(\bar{q}(1-\gamma_5)q)]$$

- Bosonization (Hubbard-Stratonovich Transformation)

$$Z[T,V,\mu] = \int \mathcal{D}M_M\mathcal{D}\Delta_D^\dagger\mathcal{D}\Delta_D\ {\rm e}^{-\sum_{M,D}\frac{M_M^2}{4G_M} - \frac{|\Delta_D|^2}{4G_D} + \frac{1}{2}{\rm Tr}\ \ln S^{-1}[\{M_M\},\{\Delta_D\},\Phi] + U(\Phi) + V_{\rm KMT}}$$

- Collective quark fields: Mesons (M_M) and Diquarks (Δ_D); Gluon mean field: Φ
- 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 $\Omega(T,\mu) = -T \ln Z[T,\mu]$

$$\Omega(T,\mu) = \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} + \frac{K\ \phi_u+\phi_d+\phi_s}{16G_S^3} - \frac{(\mu^*-\mu)^2}{4G_V}$$
$$- T\sum_n \int \frac{d^3p}{(2\pi)^3}\frac{1}{2}\mathrm{Tr}\ln\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right) + U(\Phi) + \Omega_e - \Omega_0.$$

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

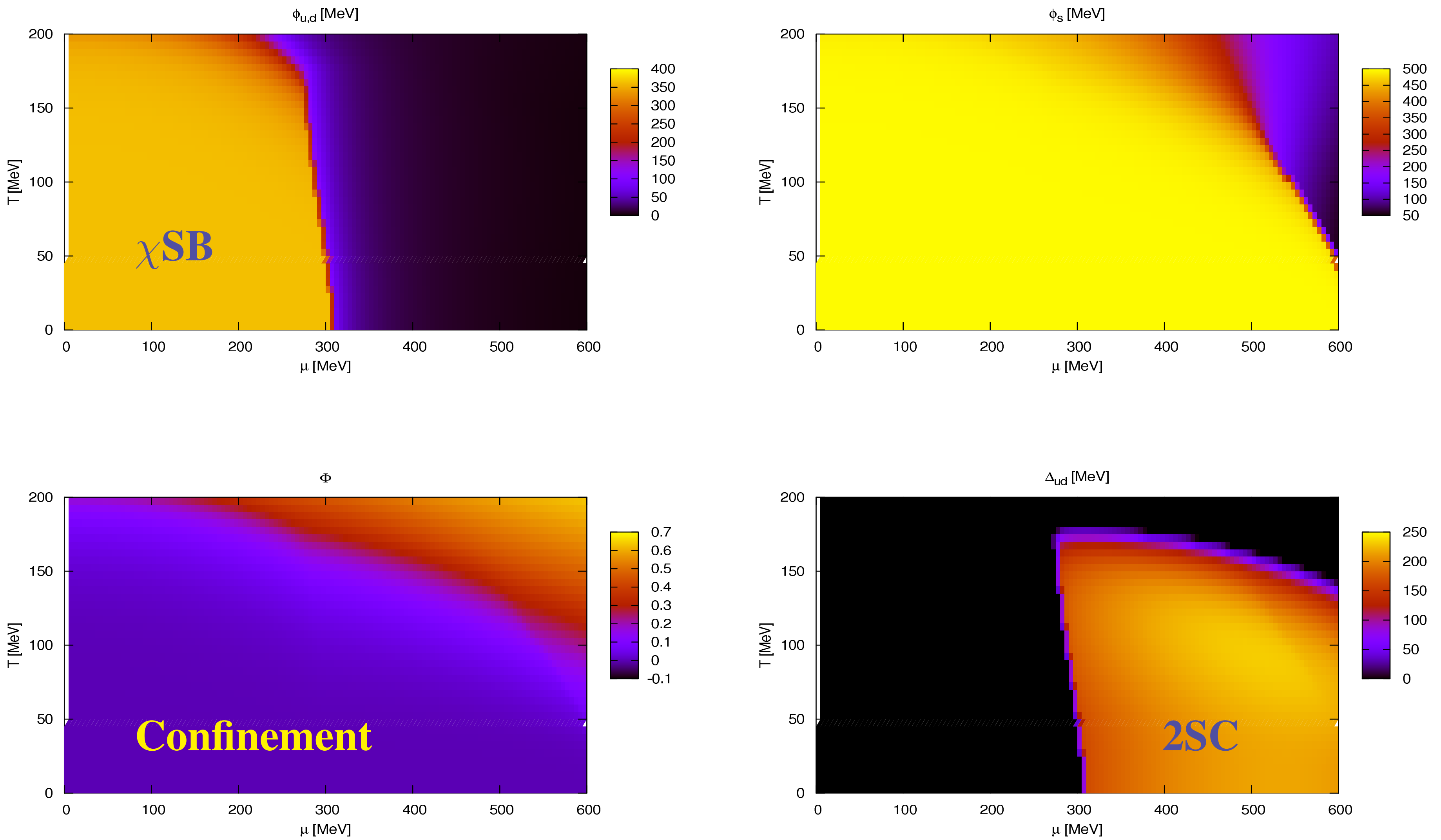
Fermion Determinant (Tr ln D = ln det D): $\ln\det[\beta\ S^{-1}(i\omega_n,\vec{p})] = 2\sum_{a=1}^{18}\ln\{\beta^2[\omega_n^2+\lambda_a(\vec{p})^2]\}$.

Result for the thermodynamic Potential (Meanfield approximation)

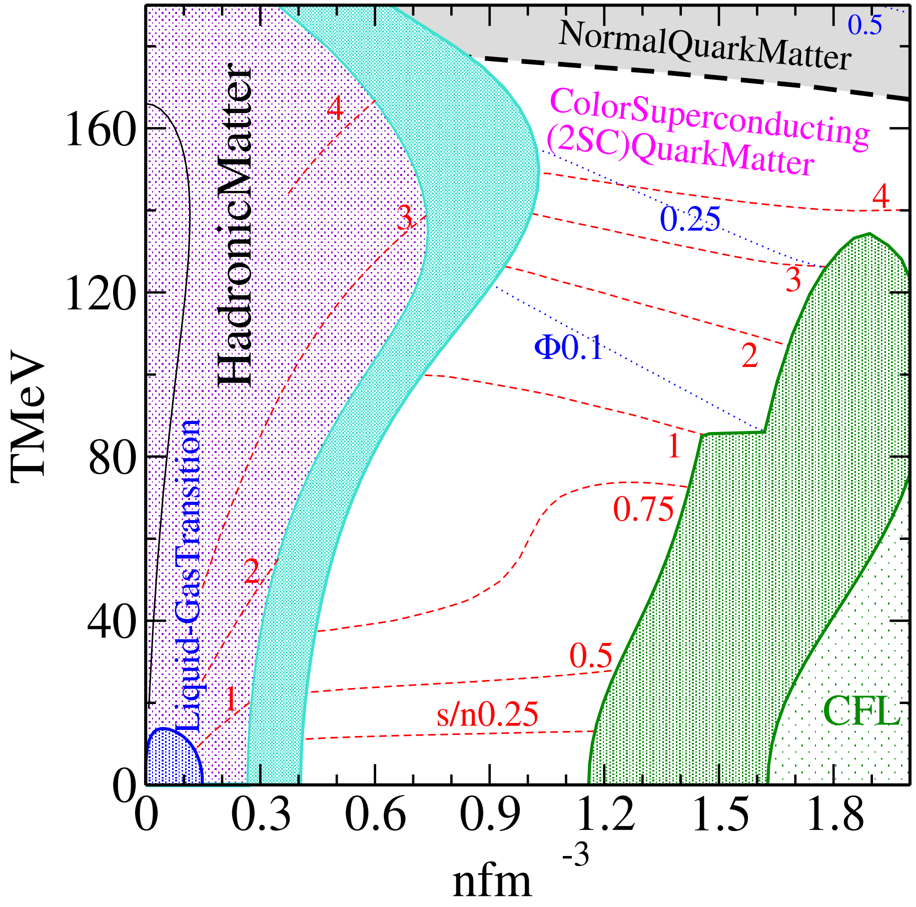
$$\Omega(T,\mu) = \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} + \frac{K\ \phi_u+\phi_d+\phi_s}{16G_S^3} - \frac{(\mu^*-\mu)^2}{4G_V}$$
$$- \int \frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left[\lambda_a + 2T\ln\left(1+e^{-\lambda_a/T}\right)\right] + U(\Phi) + \Omega_e - \Omega_0.$$

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.

Phases of QCD @ Extremes: no Color Neutrality



Phase Diagram for Symmetric Matter (HIC)

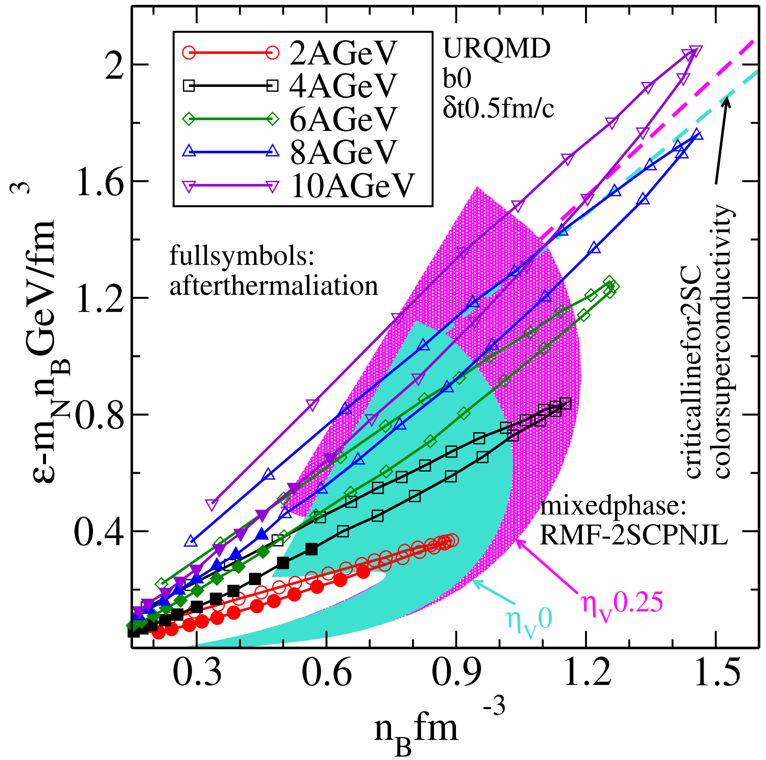


DB, Sandin, Skokov, NICA WhitePaper (2009)

- Critical density for chiral restoration $n_\chi \geq 1.5\, n_0$ increasing (!) with low T
- Almost crossover (masquerade!), i.e. small density jump, small latent heat/ time delay in heavy-ion coll.!
- High $T_c \approx 0.9 T_d$ for 2SC phase due to Polyakov loop.
- 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 $T \leq 100$ MeV

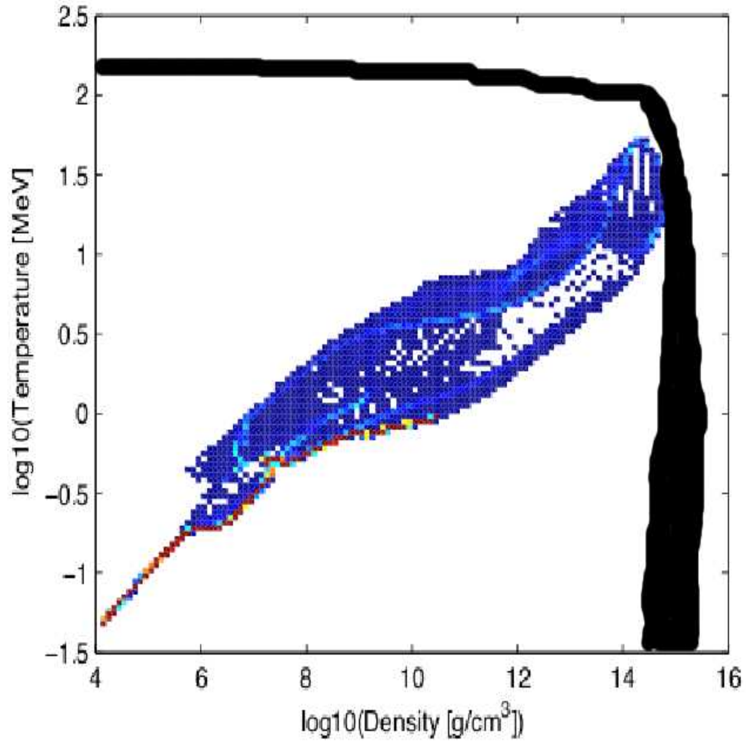
Exploring the QCD Phase Diagram: Trajectories

Heavy-Ion Collisions:



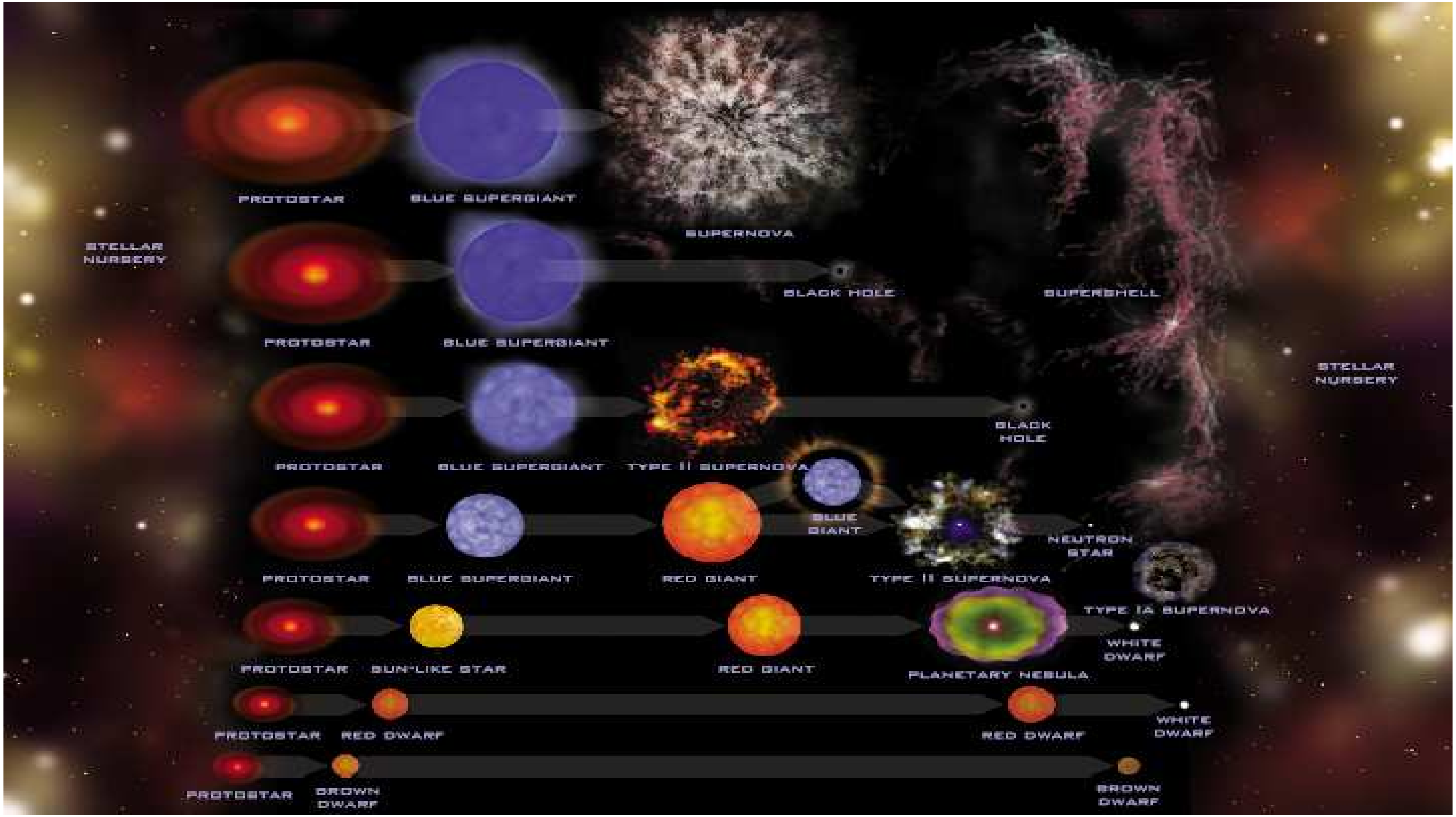
D.B.,Skokov, Sandin, NICA WhitePaper (2009)

Supernova Explosions (15 $M_\odot$):

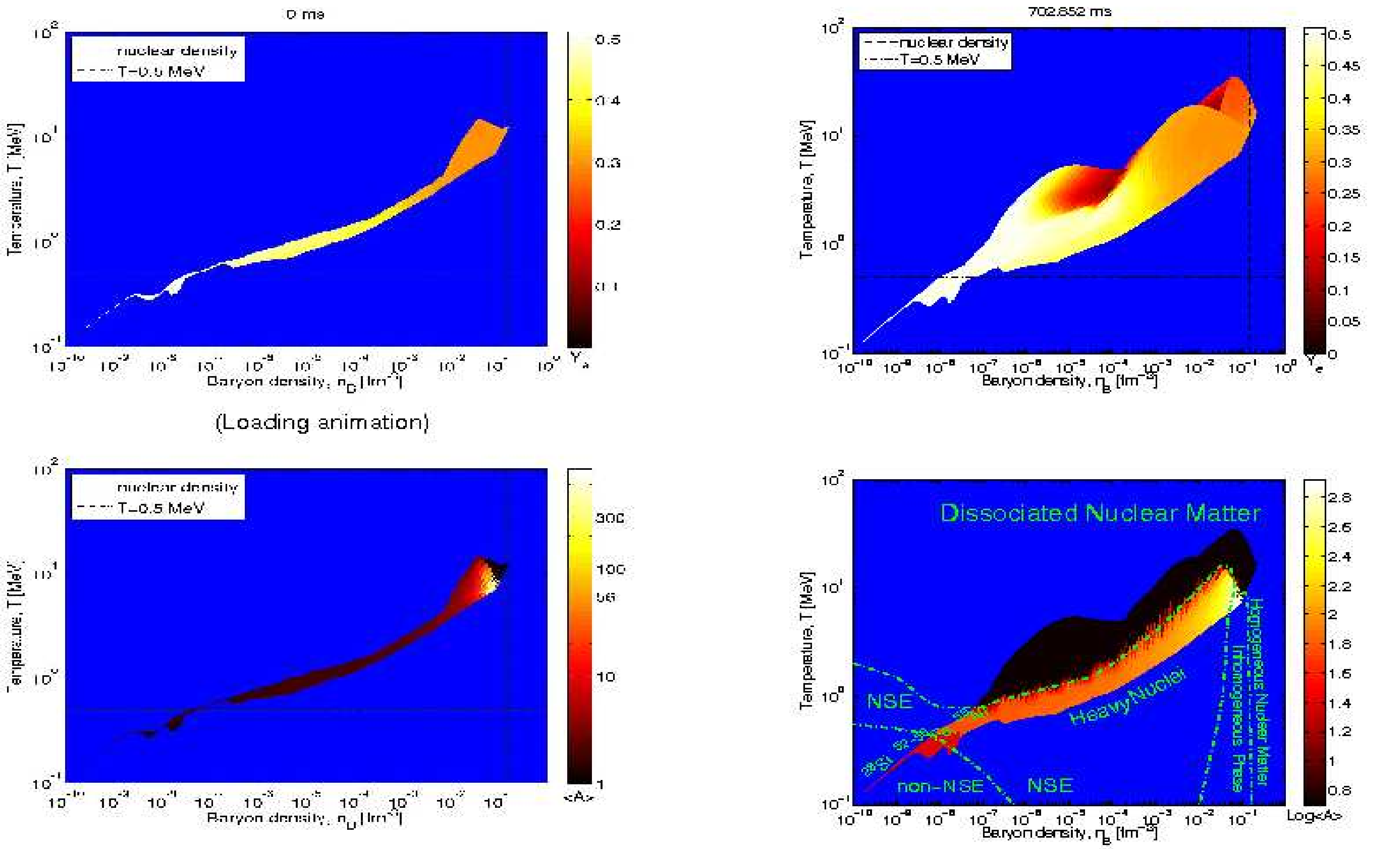


Liebendoefer et al. (2005)
Sagert et al., PRL 102 (2009)

SUPERNOVAE - COMPACT STARS - BLACK HOLES

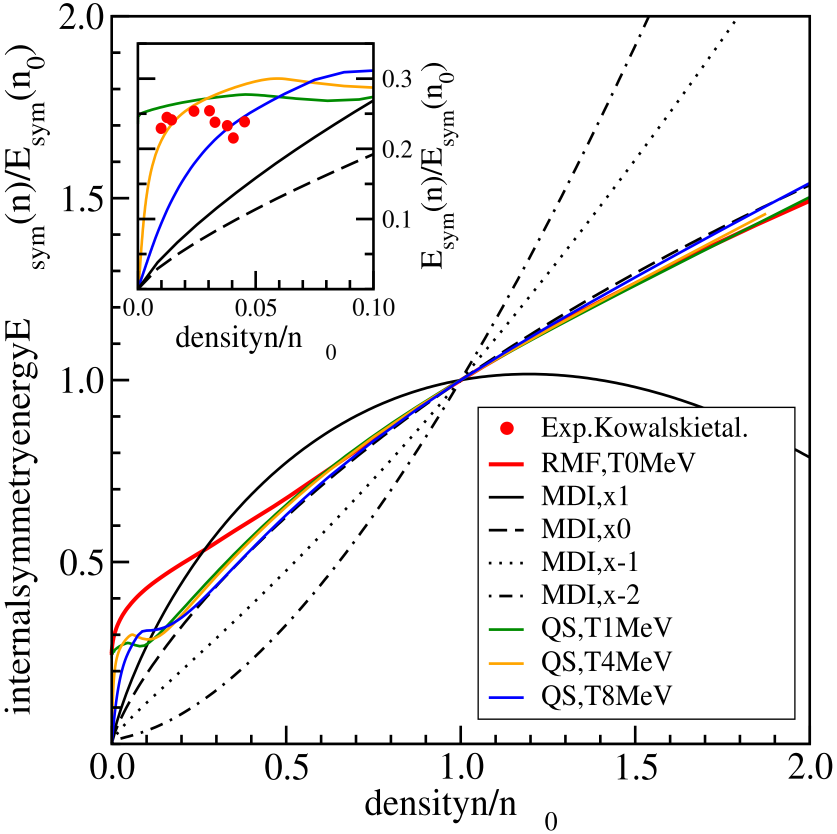


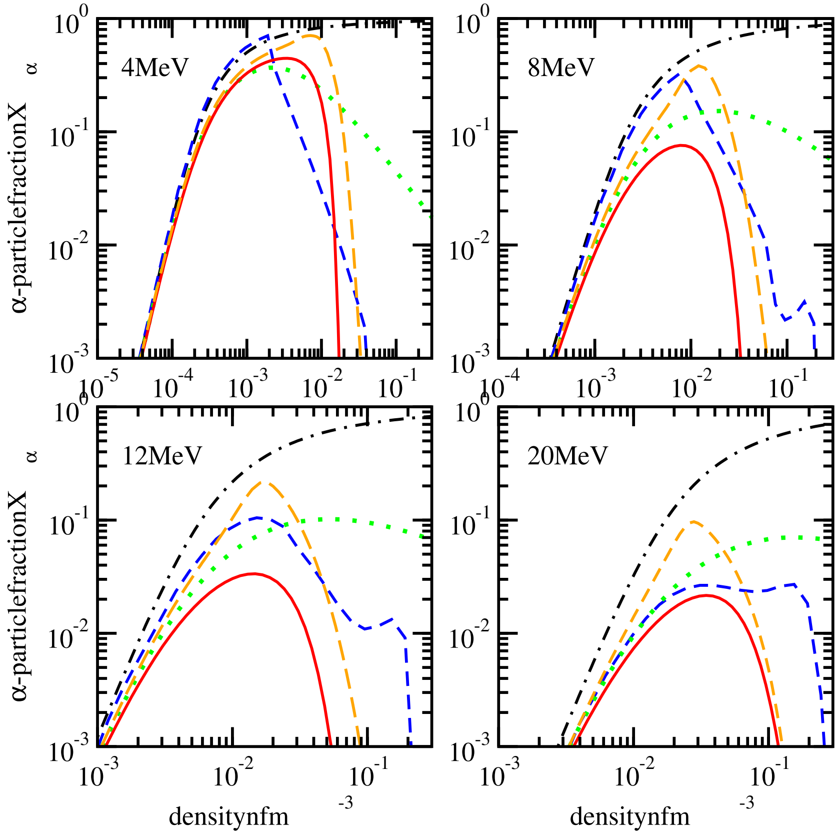
SUPERNOVA POSTBOUNCE EVOLUTION IN THE PHASE DIAGRAM



T. Fischer, D.B., et al., Yad. Fiz. 75 (2012) [arxiv:1103.3004]

TOWARDS NEW SUPERNOVA EOS: CLUSTERS AT LOW-DENSITIES





- Clusters important in plunge phase of SN collapse ($0.01 < n/n_0 < 0.1$)
- Low-density symmetry energy with clusters describes experiment (Kowalski et al.)

Typel, Röpke, Klähn, D.B., Wolter, Phys. Rev. C81 (2010); arxiv:0908.2344 [nucl-th]
Natowitz et al. (12 coauthors), Phys. Rev. Lett. (2010); arxiv:1001.1102 [nucl-th]

BAG VS. PNJL MODEL IN THE PHASE DIAGRAM

Figure: The MIT bag model[a], $Y_p \simeq 0.3$

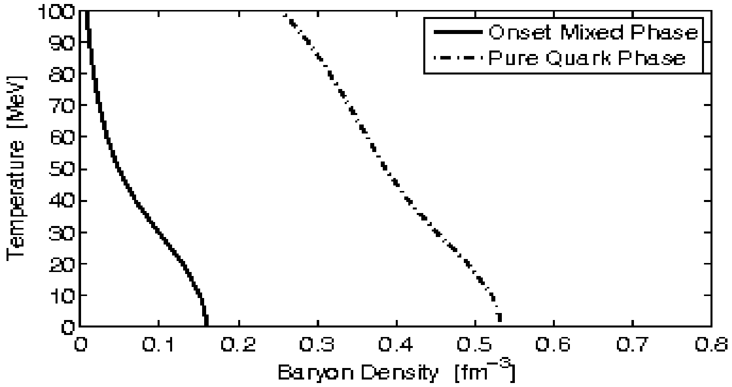
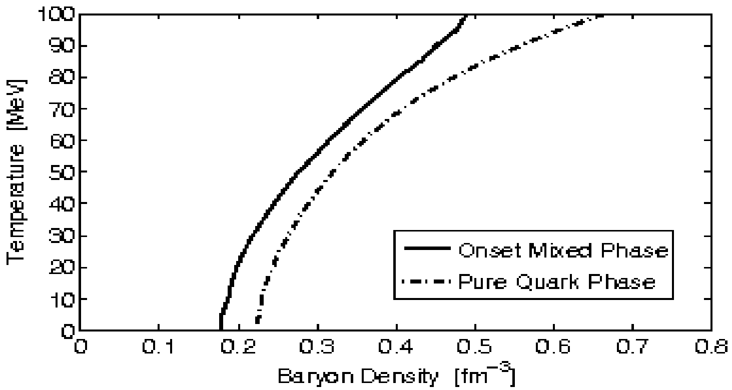


Figure: The PNJL model[b], $Y_p \simeq 0.3$



[a] Sagert et al. (2009)
[b] Sandin and Blaschke (2008)

Quark matter descriptions and the mixed phase

1. The MIT bag model

   (Fermi-gas, the bag pressure B defines confinement)

   $$B^{1/4} = 145, \ldots, 200 \text{ MeV}$$

2. The PNJL model

   (Based on the QCD Lagrangian)

- Similar critical densities:

  $n_c(T \simeq 0) \simeq 0.17\,\text{fm}^{-3}$ (MIT bag)

  $n_c(T \simeq 0) \simeq 0.18\,\text{fm}^{-3}$ (PNJL)

- Different behavior of the critical density for finite T

  $n_c(T)$ reduces for increasing T (MIT bag)

  $n_c(T)$ increases for increasing T (PNJL)

3. The problem: the transition from quarks confined in hadrons to the quark-gluon plasma at finite T and n_B

$\longrightarrow$ Construction of the coexistence region/mixed phase

(Maxwell construction, Gibbs conditions)

$\longrightarrow$ Thermodynamics

(required for use in astrophysical applications)

T. Fischer, D.B., et al., Yad. Fiz. 75 (2012) [arxiv:1103.3004]

EVOLUTION OF CENTRAL MASS ELEMENTS IN SHEN/PNJL PHD

Figure: 20 $M_\odot$, non-exploding model

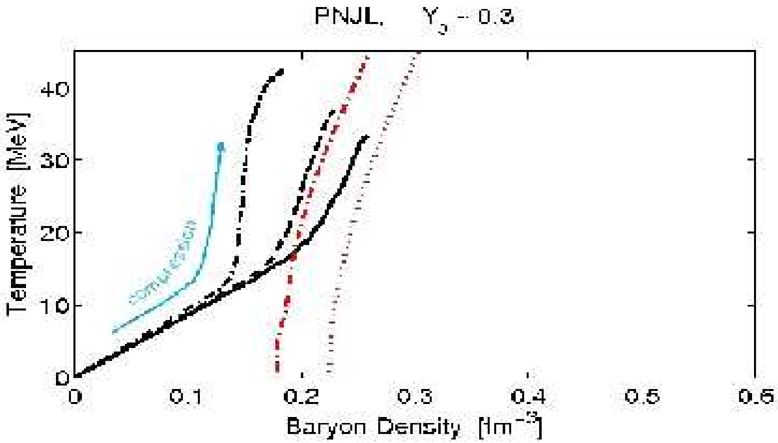
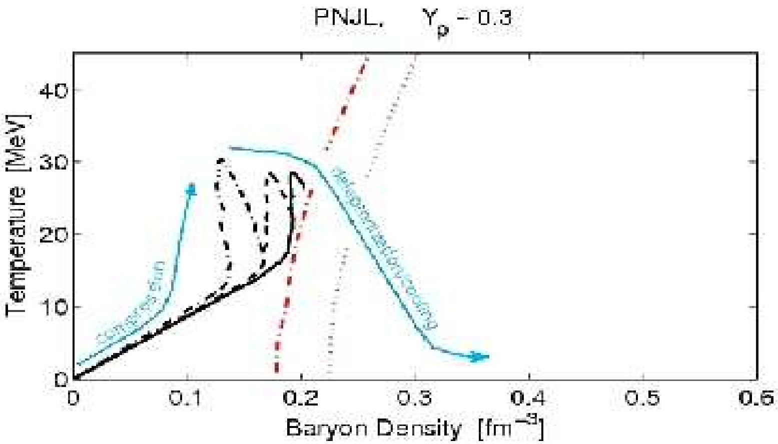
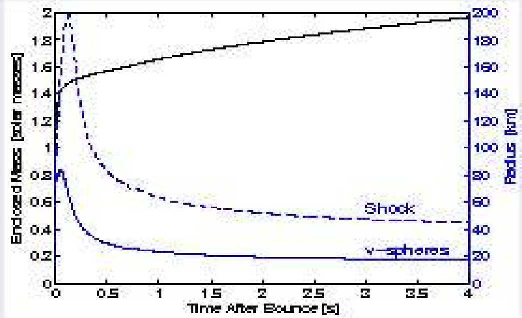


Figure: 20 $M_\odot$, ν-driven explosion

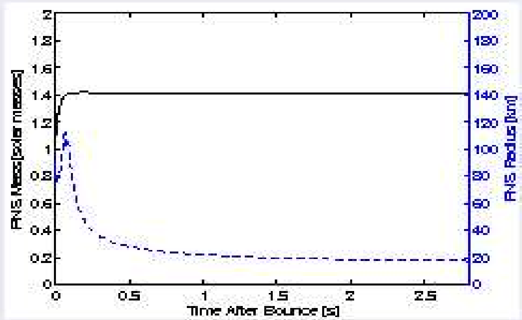


The appearance of quark matter in PNSs

1. Non-exploding models
   - Central n_B and T increase on timescale $\sim$ 1 second
   - Continued rise of the enclosed mass



2. Explosion models



T. Fischer, D.B., et al., Yad. Fiz. 75 (2012) [arxiv:1103.3004]

PHASE DIAGRAM / COMPACT STARS FOR SHEN/BAG MODEL

Figure: (MIT bag) $Y_p \simeq 0.1$, $Y_p \simeq 0.3$, $Y_p \simeq 0.5$

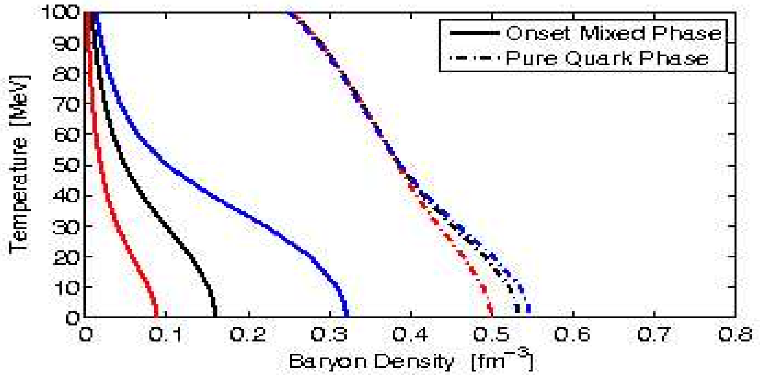
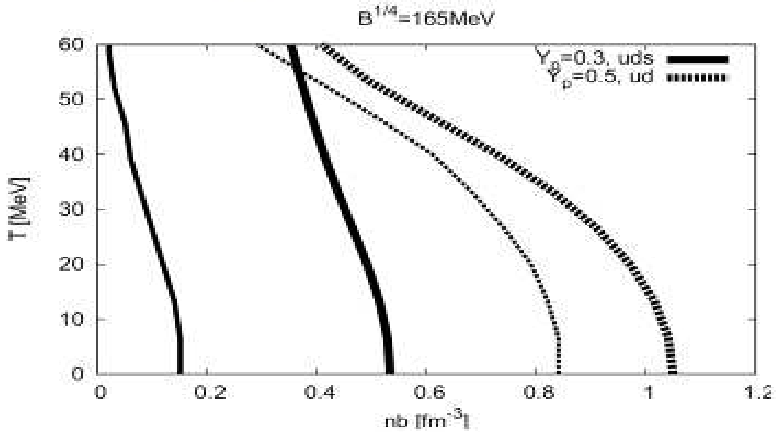


Figure: The MIT bag model

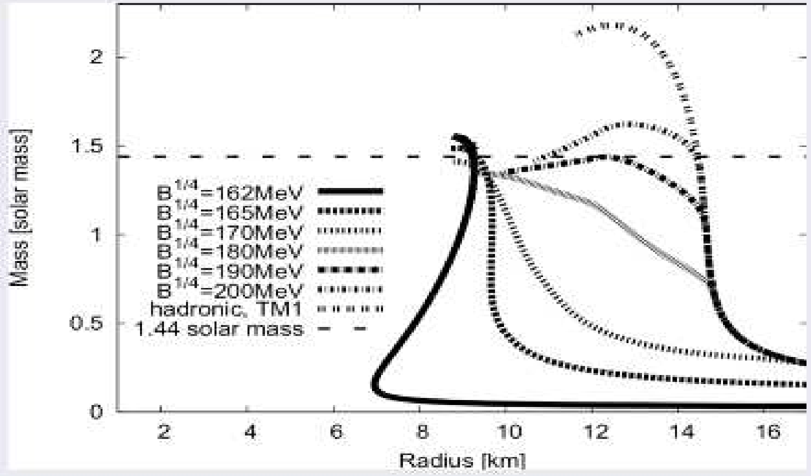


Requirements of the model and dependencies

1. Isospin asymmetry

$$n_c = n_c(T, Y_p)$$

2. Maximum Mass (Mass-Radius relation)



3. Consistent with data from heavy-ion collisions

4. Timescales to establish equilibrium (production of strangeness)

$$u + d \leftrightarrow u + s$$

$m_u \simeq m_d \simeq 0$, $m_s \simeq 100$ MeV

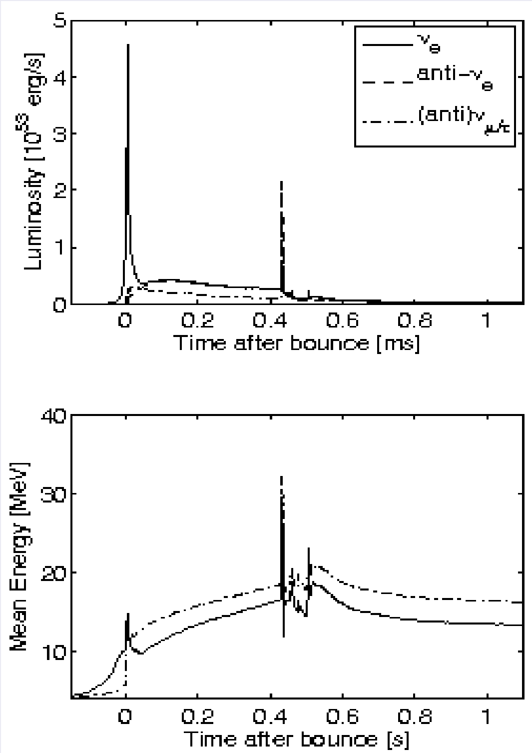
T. Fischer, D.B., et al., Yad. Fiz. 75 (2012) [arxiv:1103.3004]

EXTRA NEUTRINO BURST FROM QUARK-HADRON TRANSITION

The neutrino observables

1. No direct signal form the phase transition
2. Shock crossing over the neutrinospheres

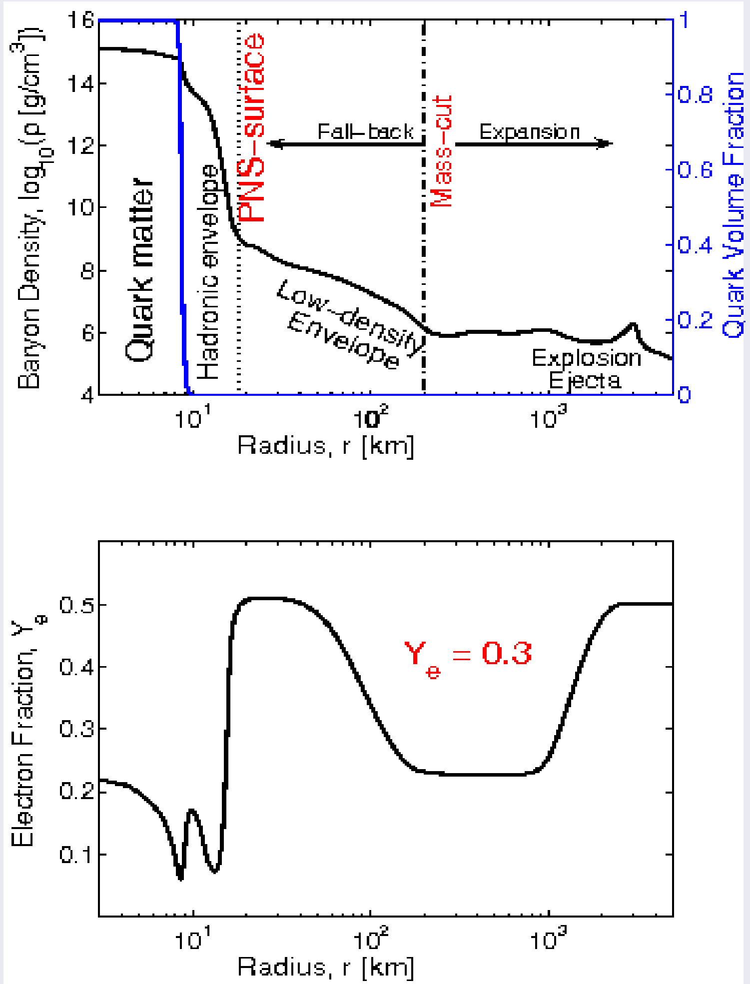
⟶ Neutrino burst dominated by $\bar{\nu}_e$



3. Detection of the "QCD-burst" (ICEC,SK)[a]

[a] Dasgupta et al. (2010)

QCD degrees of freedom: possible site for the r-process



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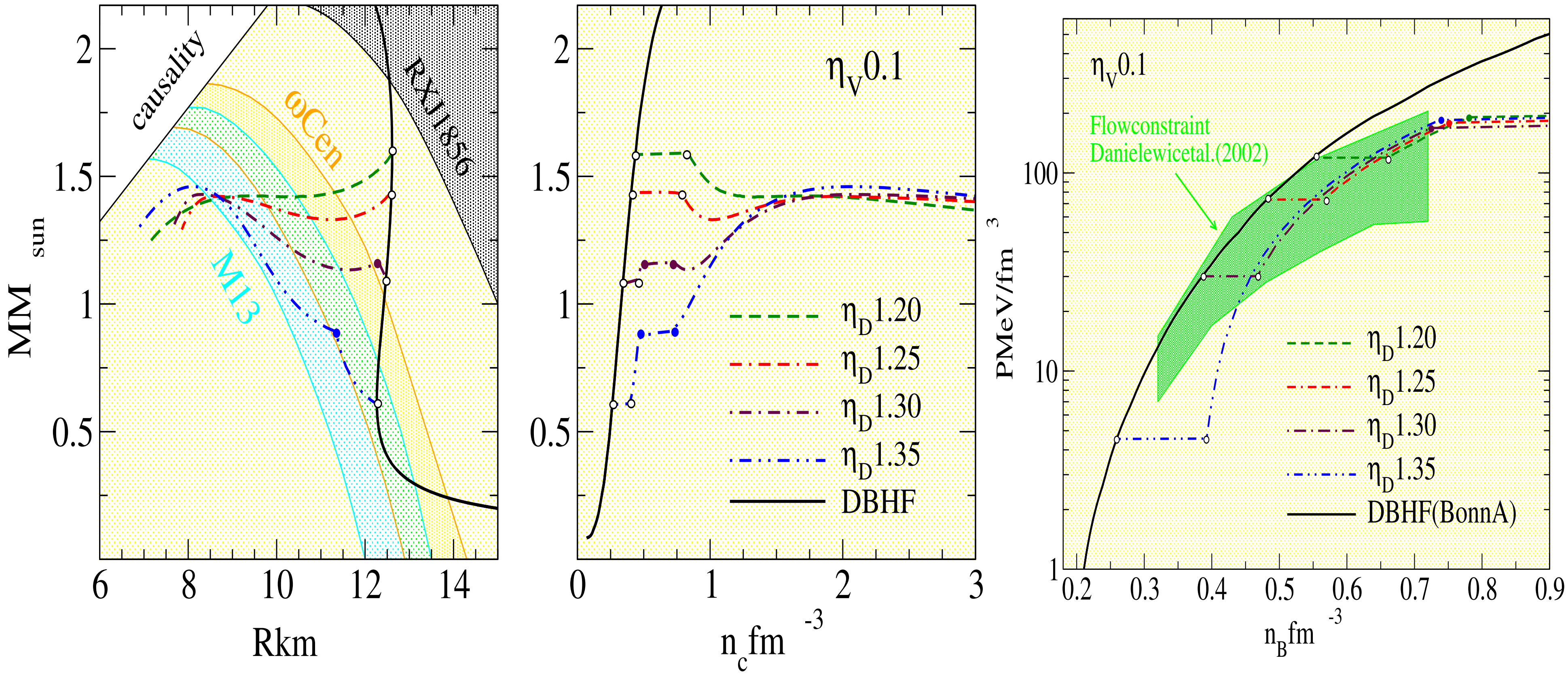
HYBRID-EOS ROBUST? ROLE OF KMT DET - TWINS!



- Mass - radius constraints from quiescent LMXB's and RXJ 1856 ⇒ Small AND large stars? NJL with KMT allows for mass twins! Direct transition DBHF-CFL possible!
- Flow constraint ⇒ PT not too early! No direct DBHF-CFL trans.!

D.B., Klähn, Łastowiecki, Sandin, J. Phys. G 37, 094063 (2010); arxiv:1002.1299 [nucl-th]

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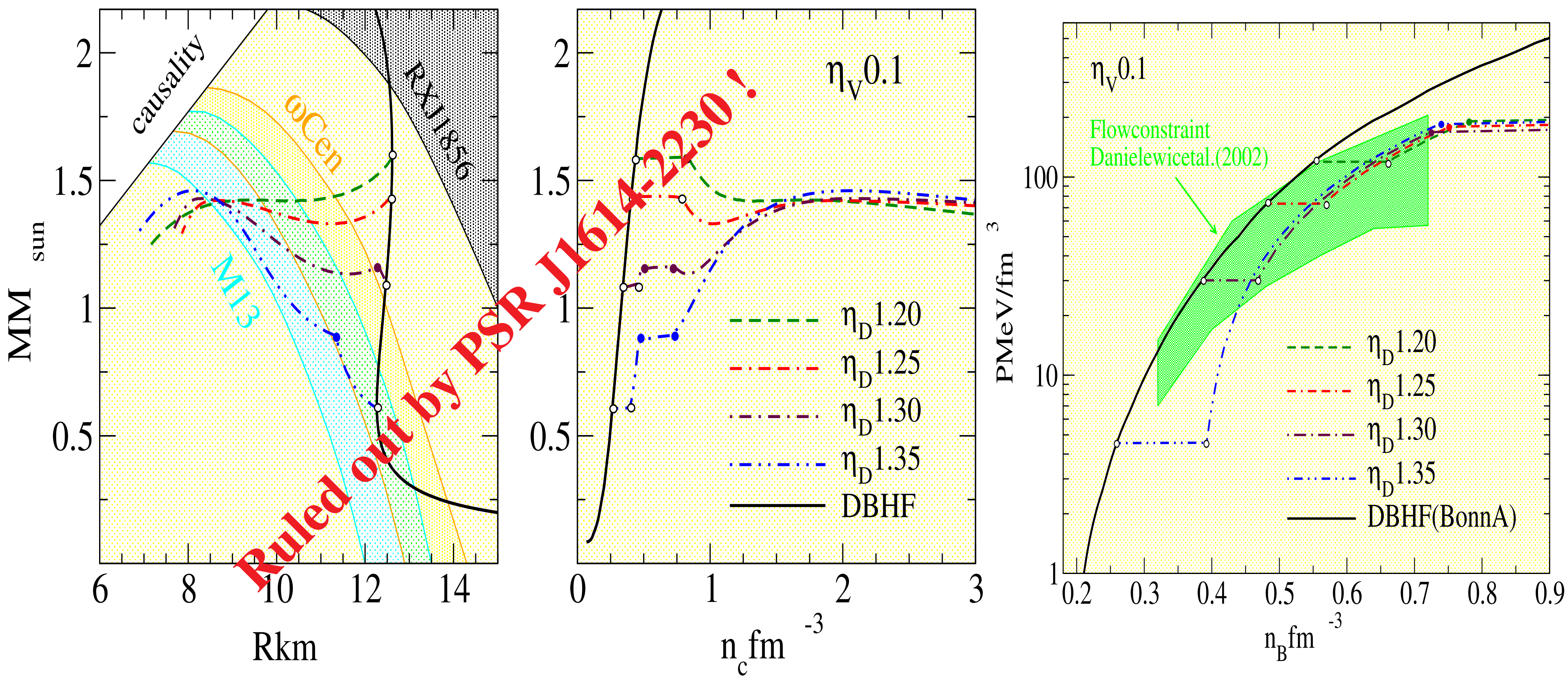

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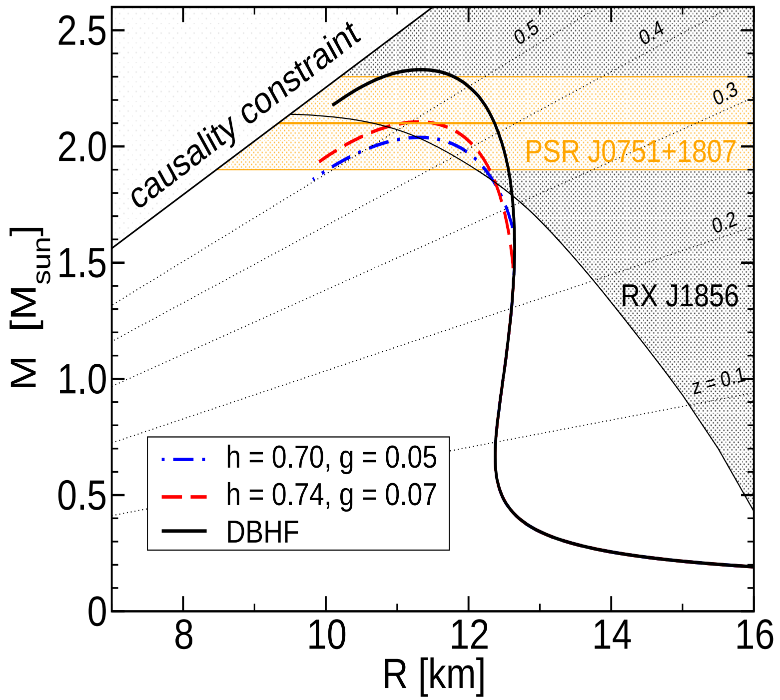
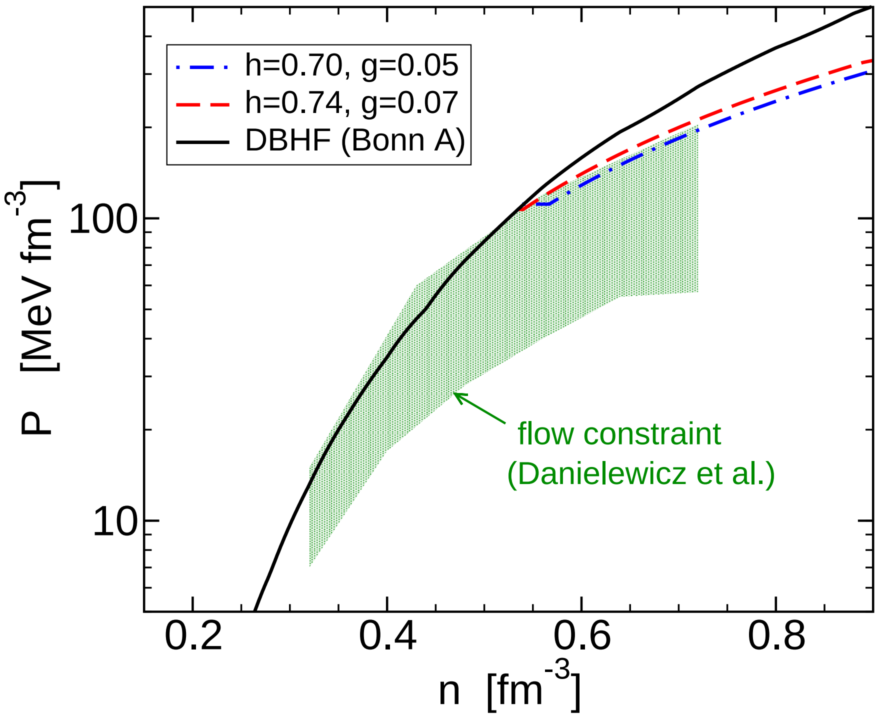
Hybrid-EoS Robust? Constraints & Covariant NCQM





- Covariant, nonlocal interaction model:

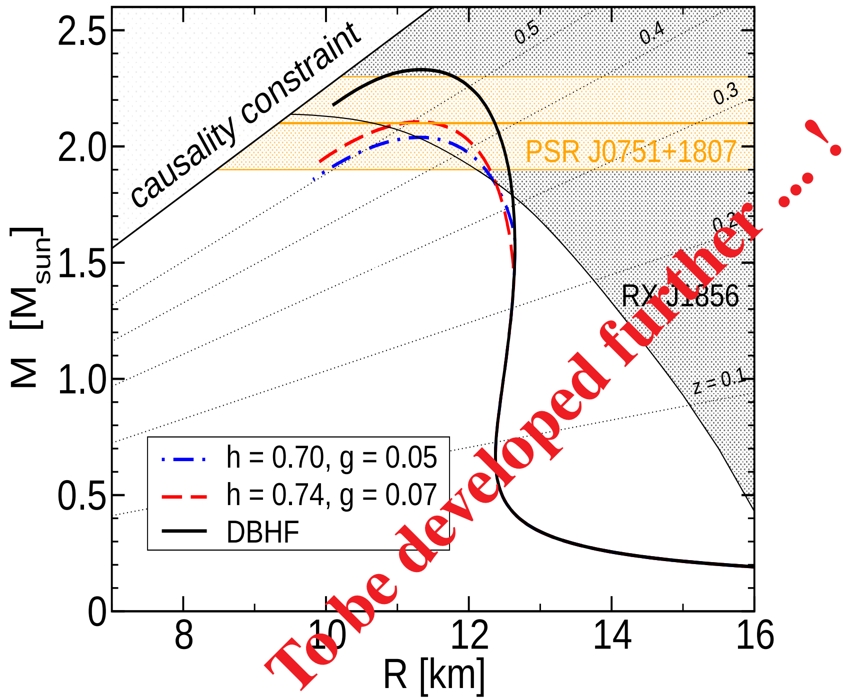
$$\mathcal{L}_{\rm int} = -\int d^4x \,\left\{ \frac{G_S}{2} j_S^f(x) j_S^f(x) + \frac{H}{2}\left[j_D^a(x)\right]^\dagger j_D^a(x) + \frac{G_V}{2} j_V^\mu(x)\, j_V^\mu(x) \right\}$$

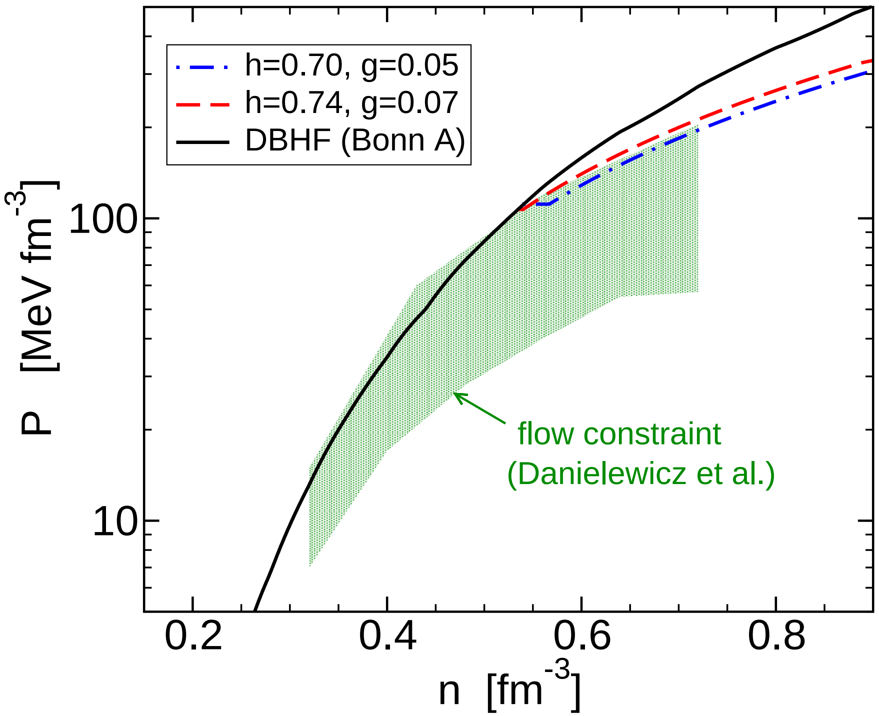
- Nonlocal currents, e.g.

$$j_S^f(x) = \int d^4z \; g(z)\; \bar{\psi}(x+\tfrac{z}{2})\;\Gamma_f\,\psi(x-\tfrac{z}{2})\,,$$

D.B., Gomez-Dumm, Grunfeld, Klähn, Scoccola, PRC 75, 065804 (2007); [arxiv:nucl-th/0703088]
Recent developments: Radzhabov et al., arxiv:1012.0664; Horvatic et al., arxiv:1012.2113

Hybrid-EoS Robust? Constraints & Covariant NCQM





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D.B., Gomez-Dumm, Grunfeld, Klähn, Scoccola, PRC 75, 065804 (2007); [arxiv:nucl-th/0703088]
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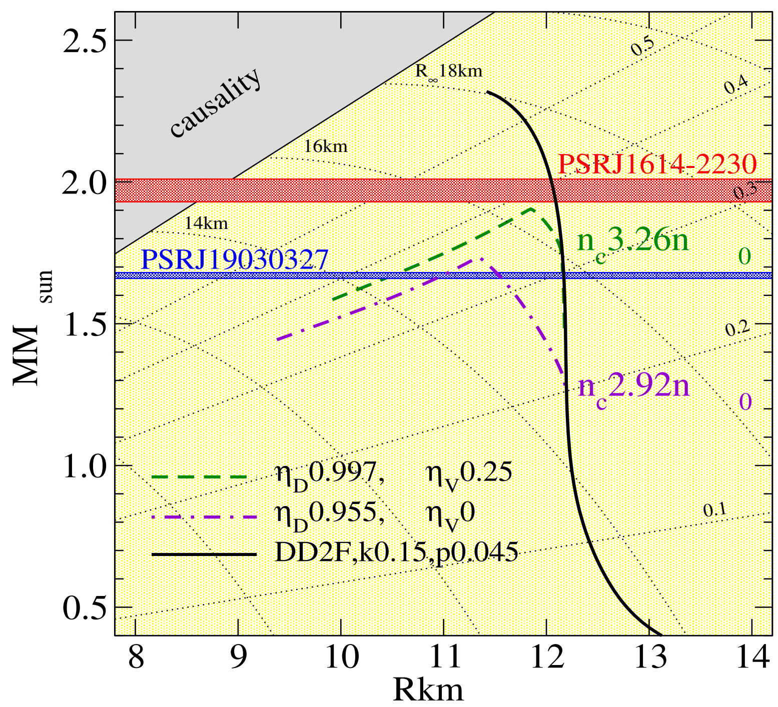
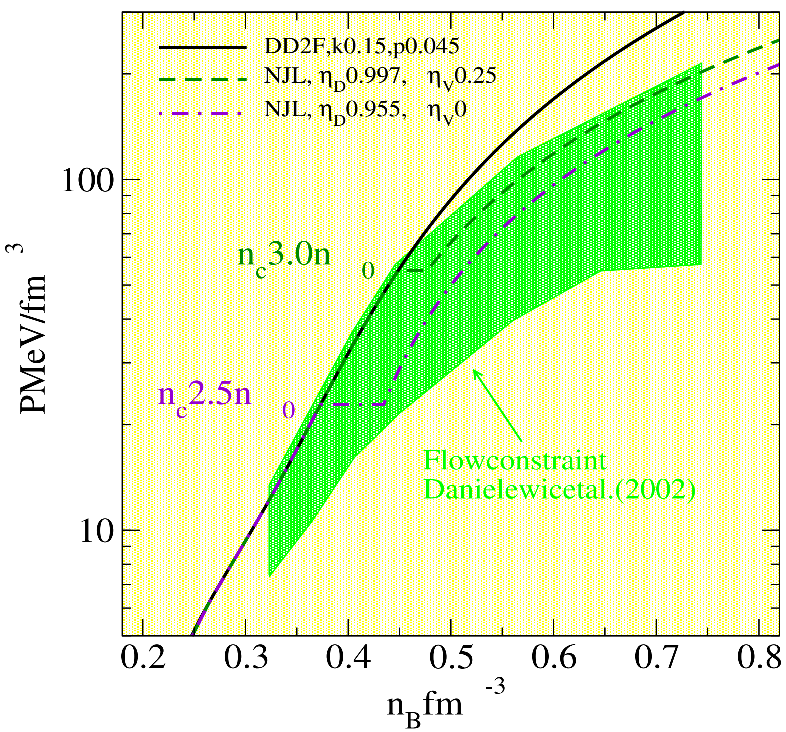
Mass-Radius constraint and Flow constraint

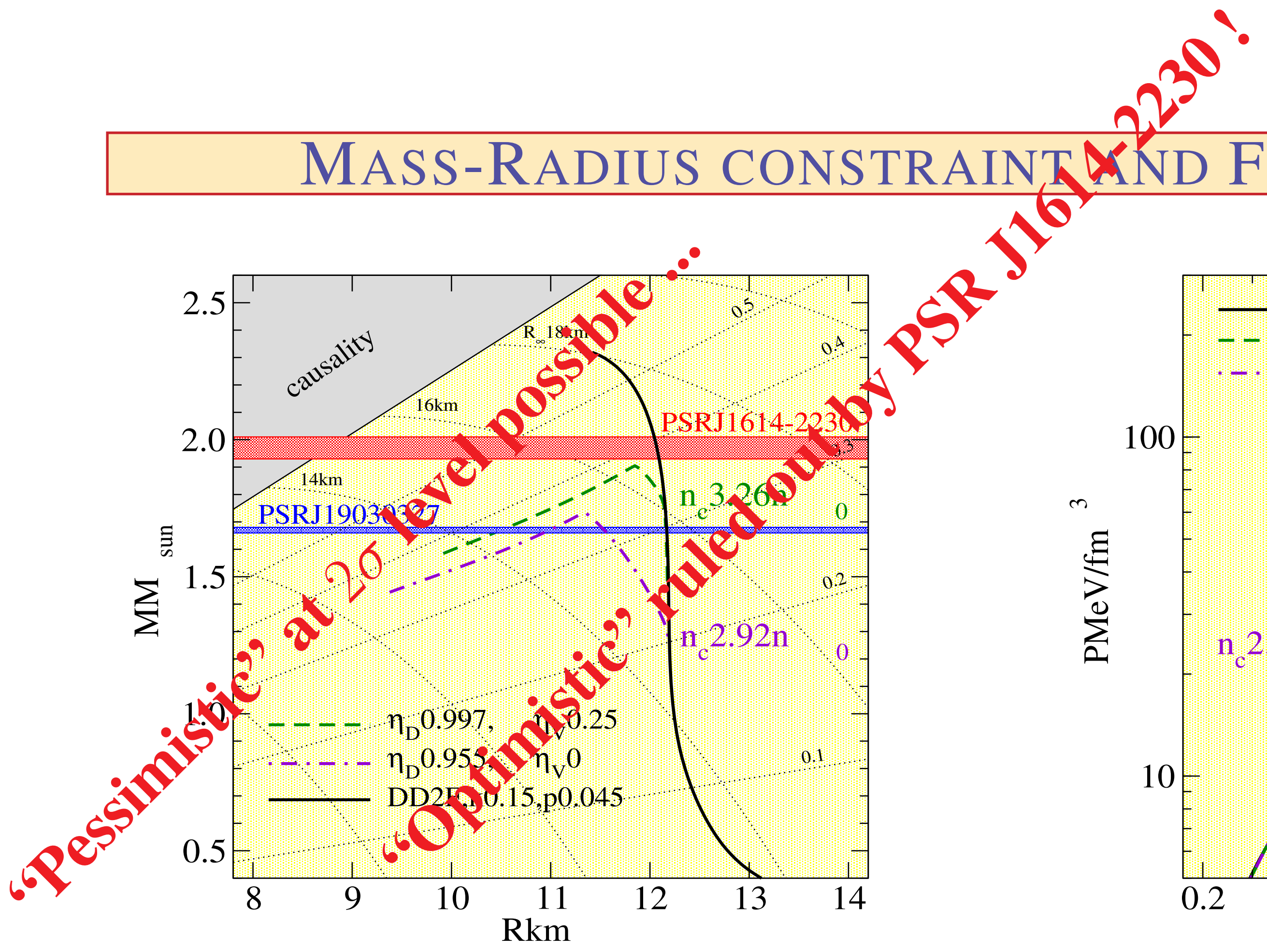


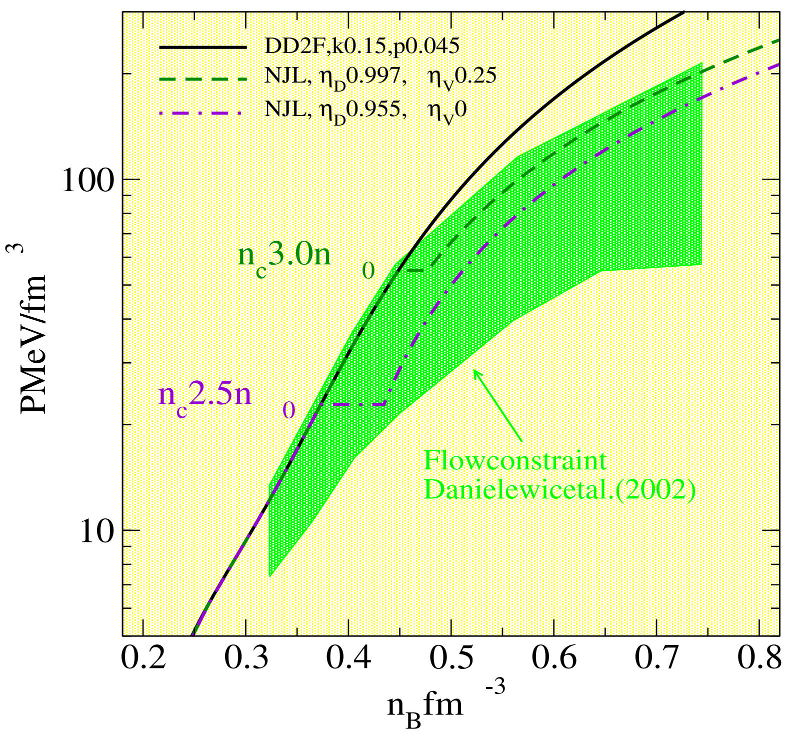


- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !

Sandin et al., CompOSE project (2009-10); See also:
Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Röpke, Trümper, PLB 654, 170 (2007)

Mass-Radius constraint and Flow constraint





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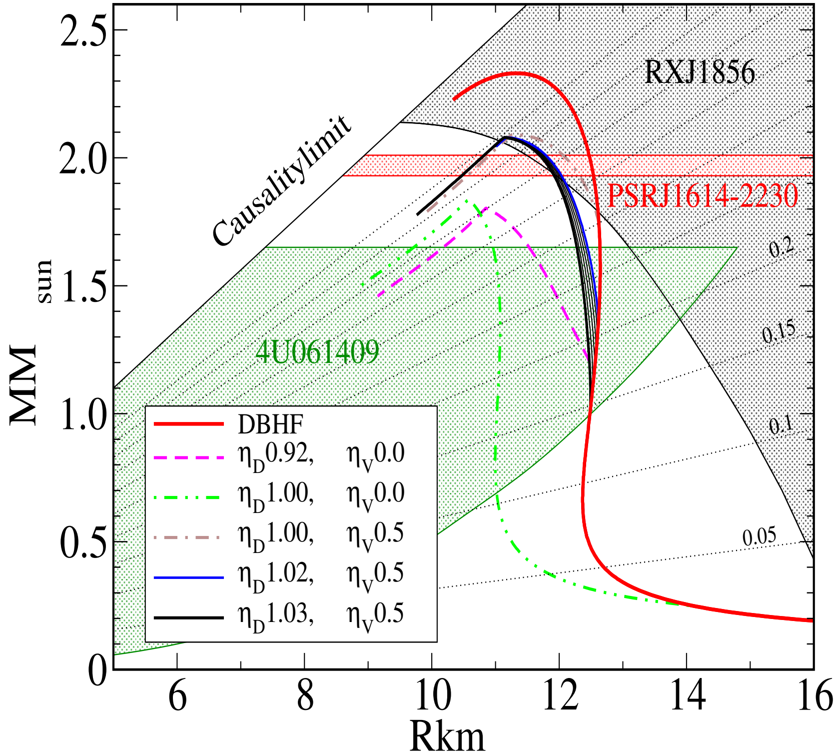

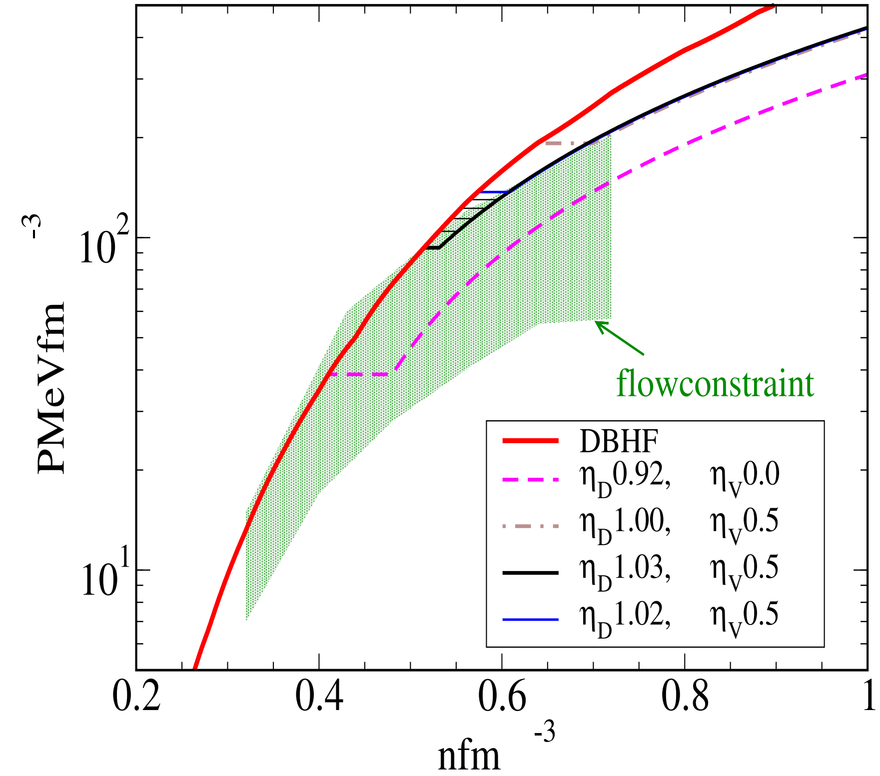

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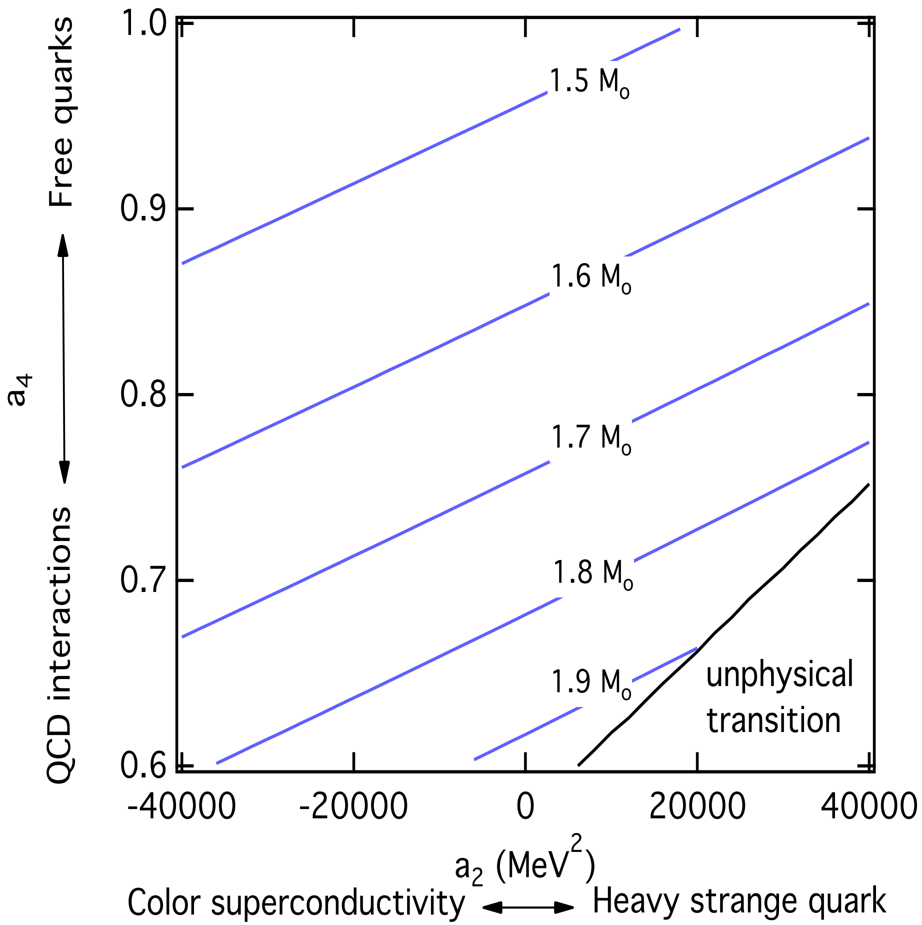
Constraints from PSR J1614-2230 for Quark Matter EoS



Özel, Psaltis, Ransom, Demorest, Alford, arxiv:1010.5790 [astro-ph] (2010)

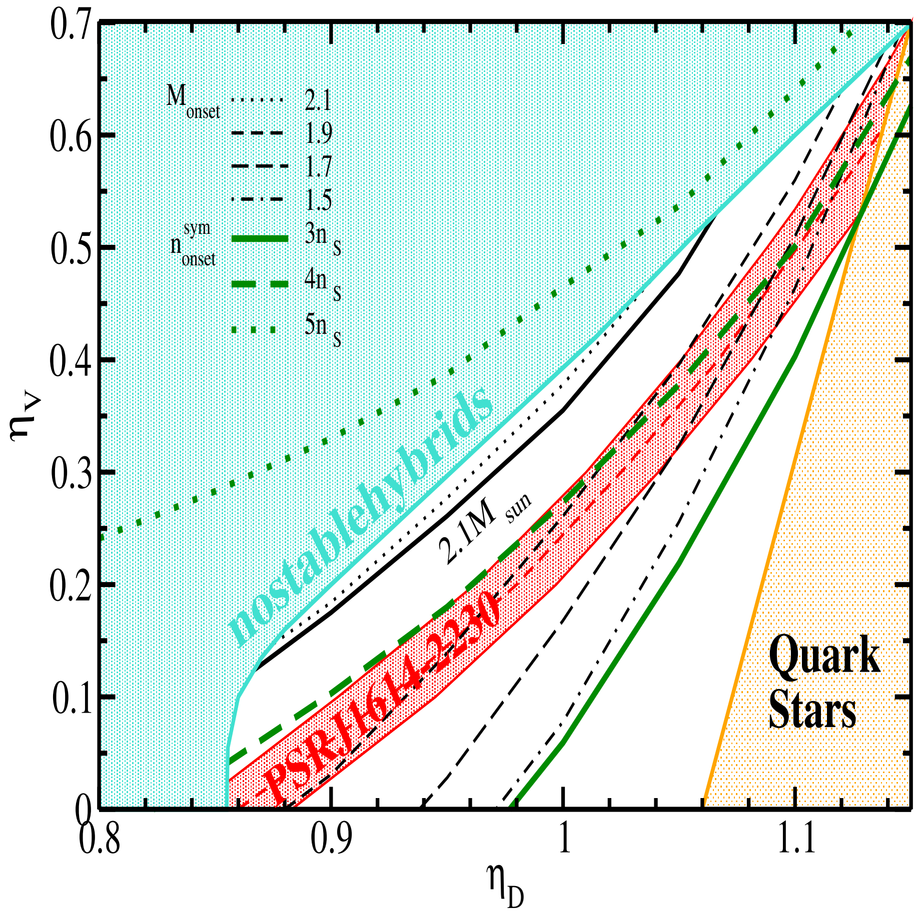
Phenomenological Quark Matter EoS:

$$\Omega_{\rm QM} = -\frac{3}{4\pi}a_4\mu^4 + \frac{3}{4\pi^2}a_2\mu^2 + B_{\rm eff}$$

If the critical density for chiral restoration/deconfinement is reached in the compact star core, then $M_{\rm J1614} = 1.97 \pm 0.04\ M_\odot$ implies the following:

- Quark matter is strongly interacting, QCD corrections (a_4) important
- Quark matter is color superconducting: $a_2 \leq 0$

CONSTRAINTS FROM PSR J1614-2230 FOR QUARK MATTER EOS

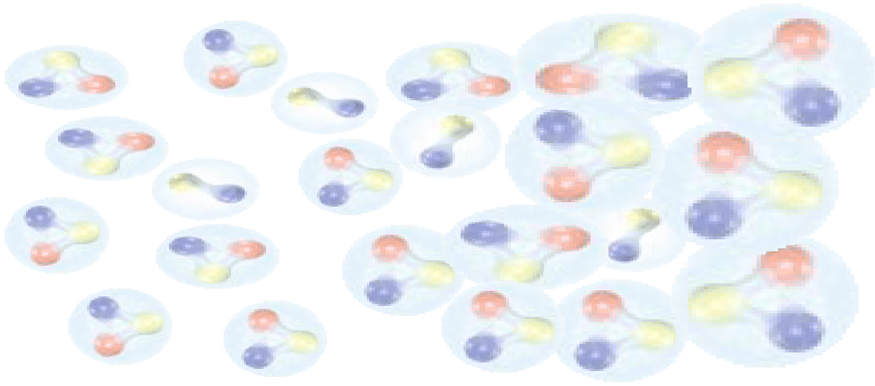


DB, Klähn, Łastowiecki, Miller; in prep. (2010)

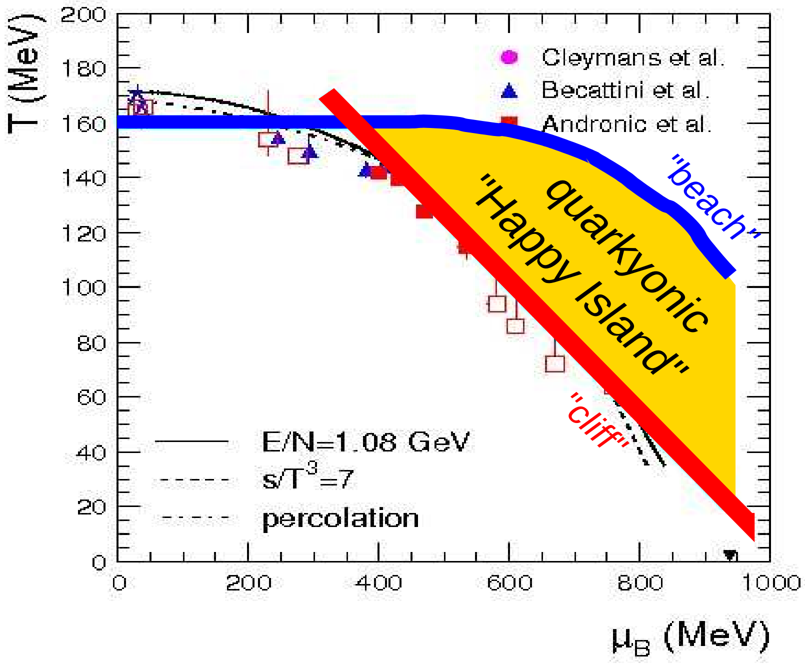
$M_{J1614} = 1.97 \pm 0.04\ M_\odot$ implies the following:

- KMT interaction term cannot be admitted without a compensating effect (Fierz'd KMT, change of gluon condensate (bag pressure), ...)
- If PSR J1614 is a hybrid star it must be in the 2SC phase ! No strange quarks (CFL phase) admitted !
- A maximum star mass $M_{\max} \sim 1.9\ M_\odot$ requires that the critical density for chiral restoration/deconfinement in symmetric matter is $n_\chi \geq 4\ n_0$
- Conversely: Onset of (CSC) quark matter in compact stars at 1.5 $M_\odot$ requires $n_\chi \sim 3\ n_0$ in symmetric matter, but would fulfill the Demorest constraint only for extreme η_D and η_V.

What happens on “Happy Island”?



Andronic et al., arxiv:0911.4806



“beach”: hadron resonances $\longrightarrow$ QGP

“cliff”:

- (unmodified) vacuum bound state energies
- fast chemical equilibration

Explanation:

Strong medium dependence of rates
for flavor (quark) exchange processes

Reason:

- lowering of thresholds
- increase of hadron size (Pauli principle)
  $\rightarrow$ geometrical overlap (percolation)

D.B., Berdermann, Cleymans, Redlich,
Part. Nucl. Phys. Lett. (2011), arxiv:1102.2908;
Few Body Syst. (2011) arxiv:1109.5391

COMPOSE - COMPSTAR ONLINE SUPERNOVA EOS

Reference manual
version 1.0

CompOSE

CompStar Online Supernovæ Equations of State

fertilising the fields of nuclear physics and astrophysics

www.compstar-esf.org/compose[*]
compose@compstar-esf.org[†]

European Science Foundation
Research Networking Program
CompStar

November 22, 2010

General Requirements:

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

New Developments:

- Dissolution of clusters due to Pauli blocking
- Realistic high-density modeling: DD-RMF/3FSC PNJL
- Thermodynamics of 1^{st} order PT; pasta phases

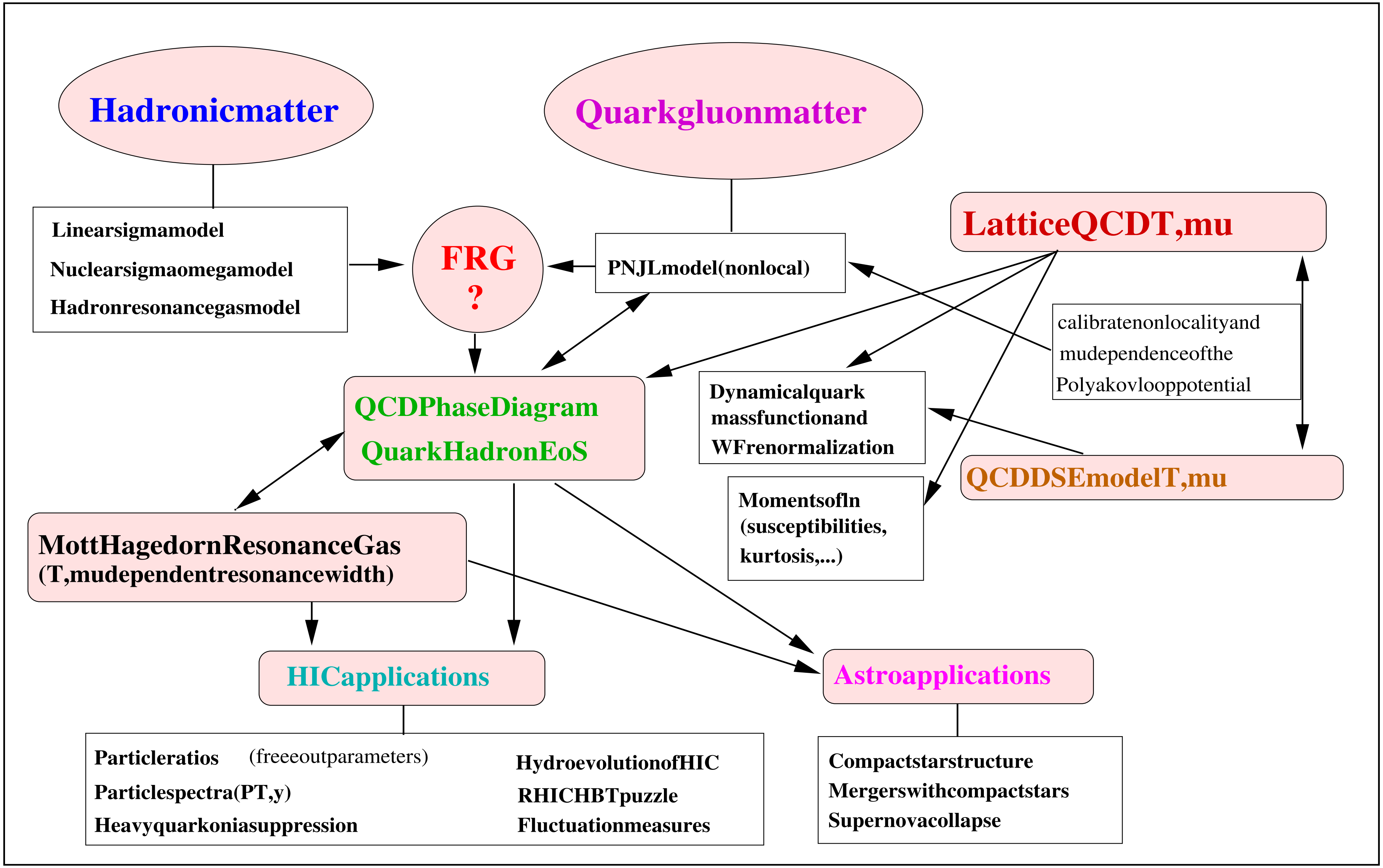
I. For Contributors:

- How to prepare EoS tables
- How to submit EoS tables
- Extending CompOSE

II. For Users:

- Hadronic EoS: Statistical, Skyrme, DBHF, ...
- Quark Matter EoS: Bag, PNJL, ...
- Phase transition: Maxwell, Gibbs, Pasta, ...

ROADMAP FOR PHASE DIAGRAM AND EOS RESEARCH



Summary

- Hadron production in HIC $\rightarrow$ Triple point in QCD phase diagram!
- Compressed nuclear matter: **quarkyonic phase** (QP)! Coexisting chiral symm. + conf.
- Here: PNJL model as microscopic formulation of the QP
- Prospects for HIC (CBM & NICA) and Supernovae: color superconducting (quarkyonic) phases accessible!

Outlook: next steps ...

- Walecka model as limit of PNJL model: chiral transition effects in nuclear EoS
- Beyond meanfield: mesons and baryons in the PNJL, higher clusters: sextetting
- Astrophysics: Maximum mass & cooling of quarkyonic stars; quarkyonic supernovae
- HIC: signals of CSC phase transition (dilepton enhancement?)

INVITATION: CONTRIBUTE TO THE NICA WHITE PAPER

Draft v 3.03

June 20, 2010

SEARCHING for a QCD MIXED PHASE at the

NUCLOTRON-BASED ION COLLIDER FACILITY

(NICA White Paper)

http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

http://theor.jinr.ru

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INVITATION: VISIT WROCŁAW & UNIVERSITY