EoS for Quark-Hadron Matter and Supernova Applications

David Blaschke

Institute for Theoretical Physics, University of Wroclaw, Poland

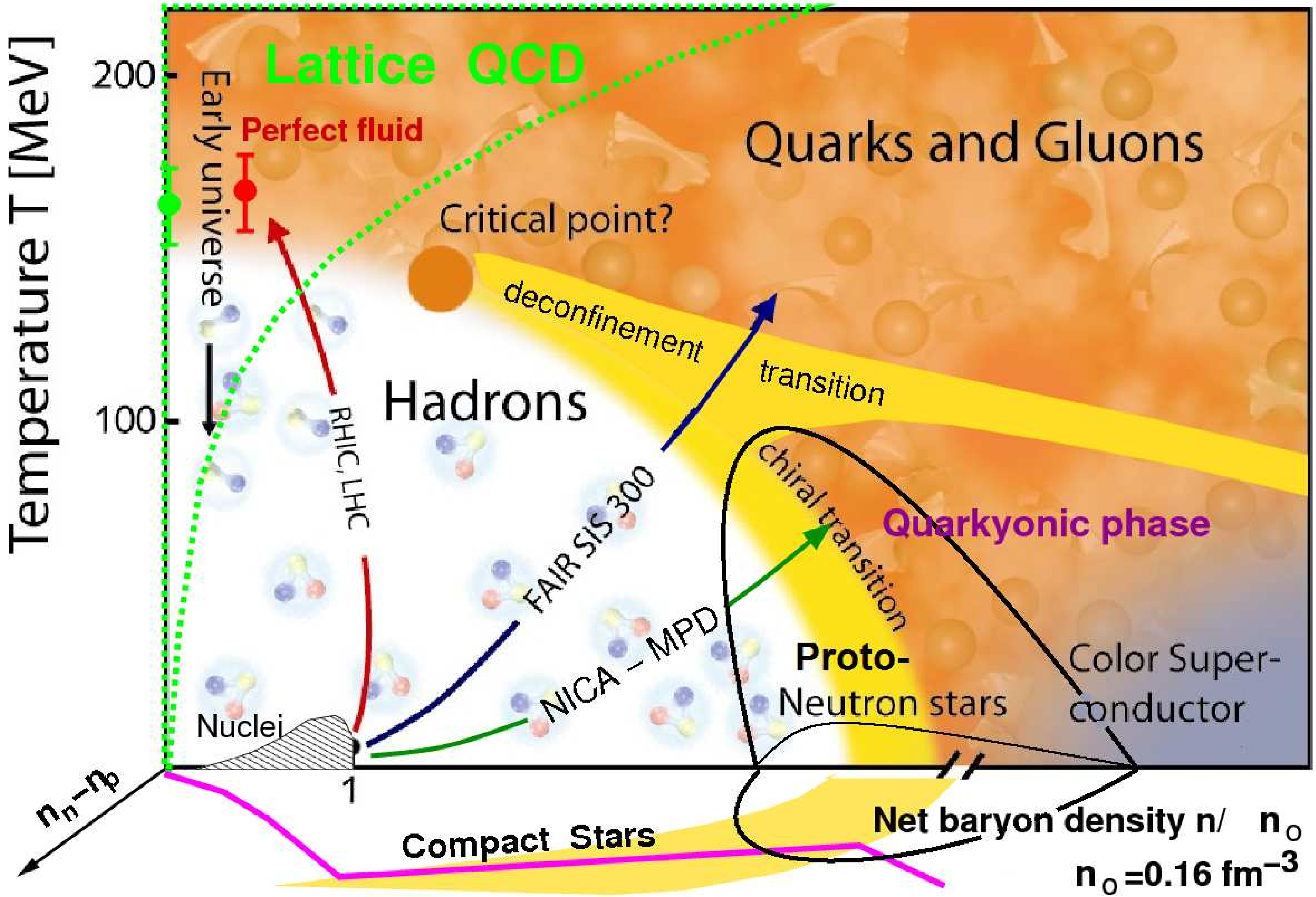
Bogoliubov Laboratory for Theoretical Physics, JINR Dubna, Russia

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

Uniwersytet Wrocławski | JINR DUBNA | HadronPhysics2 | Ministerstwo Nauki i Szkolnictwa Wyższego | РФФИ | comp star

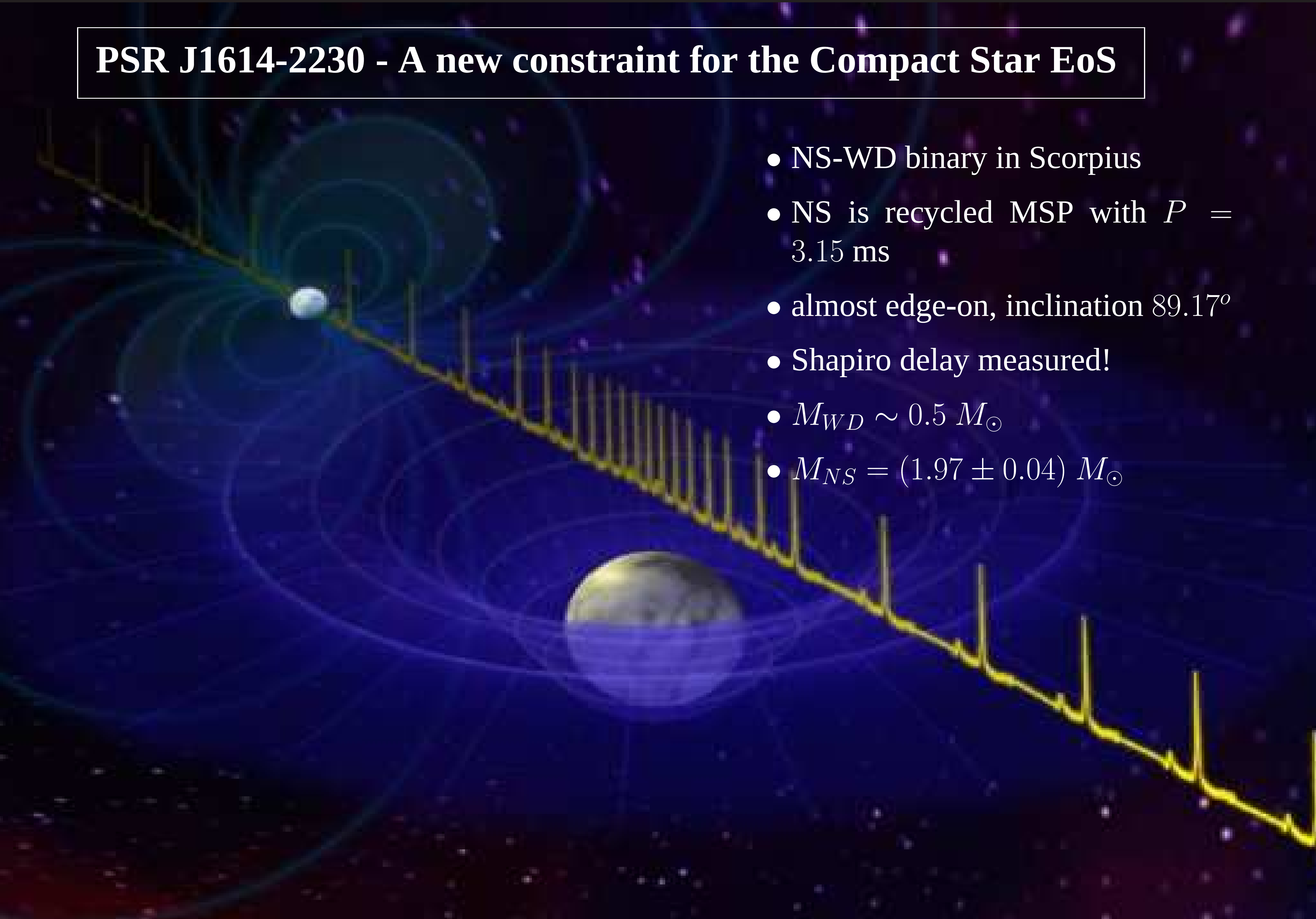
NPP 2010, Moscow, 01.12.2010

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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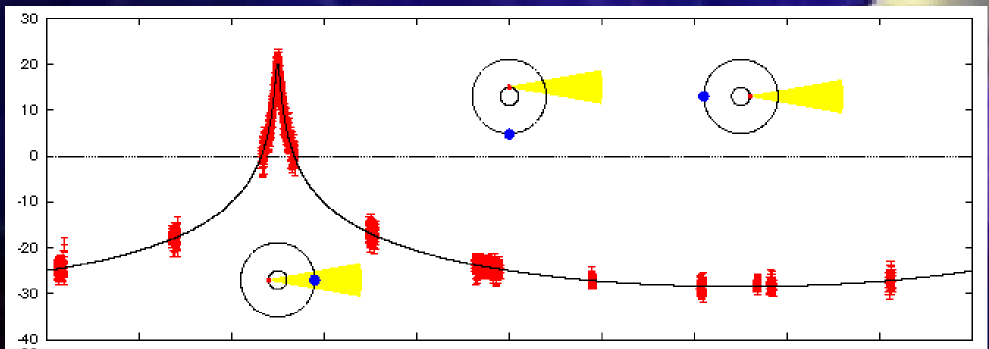

Demorest et al., Nature 467, 1081 (2010)

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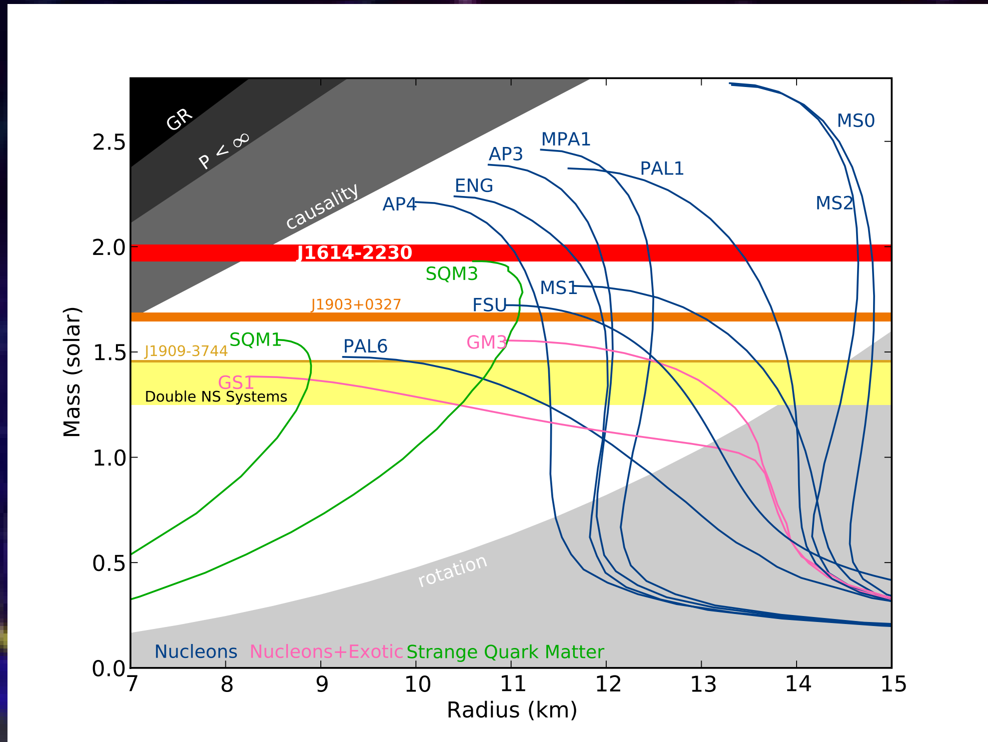

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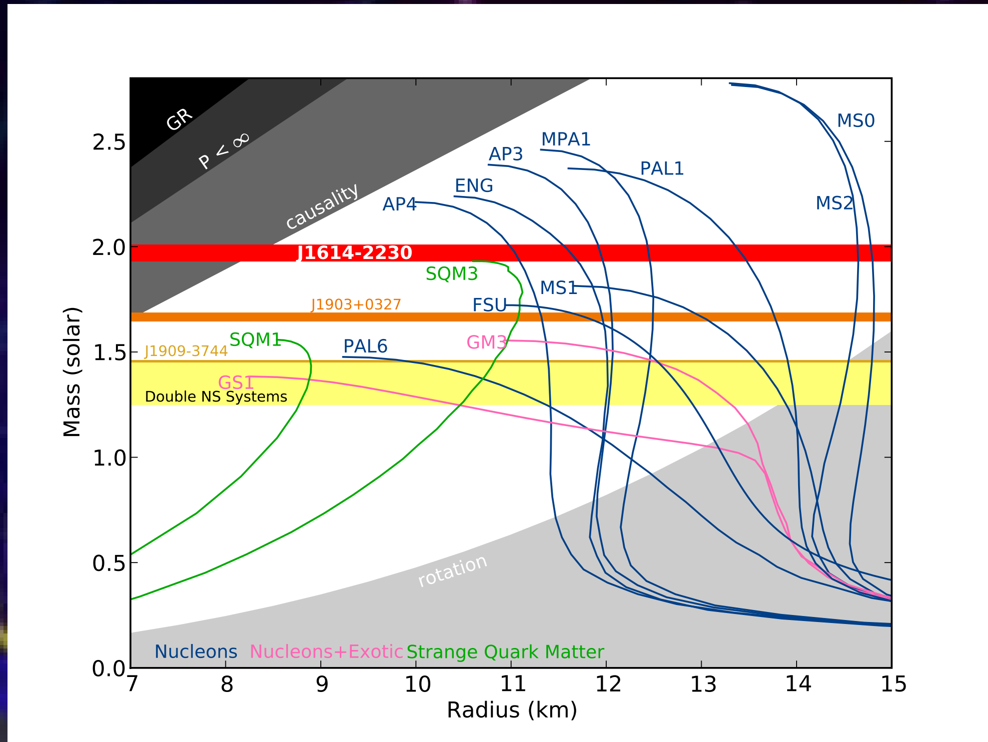

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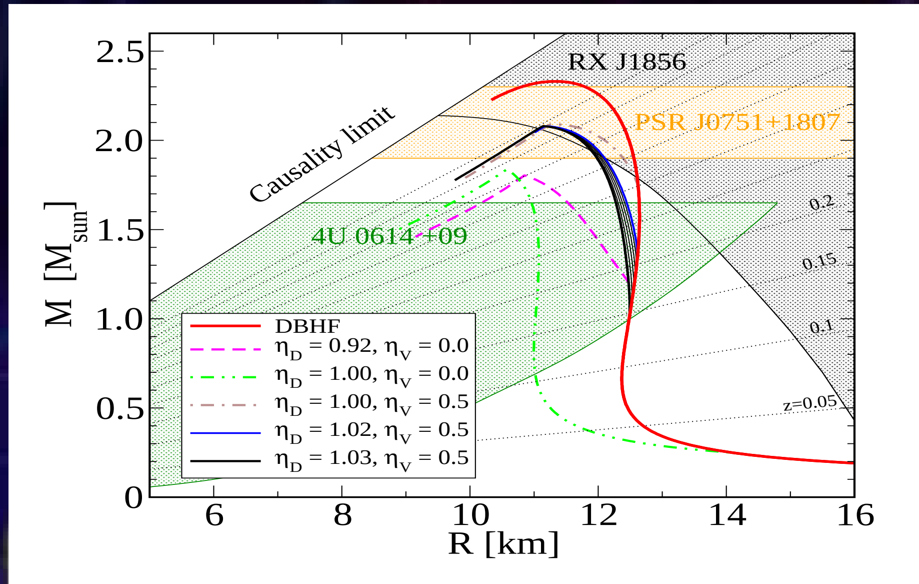
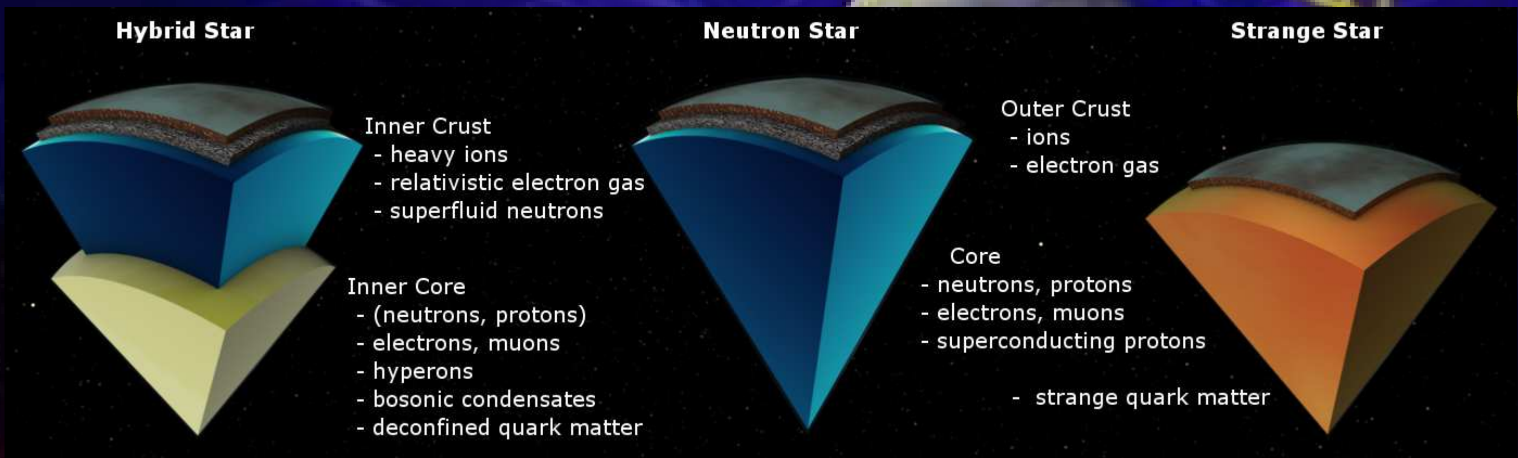
Some “soft” EoS are now ruled out !

What about hybrid stars? Strong constraints for quark matter!

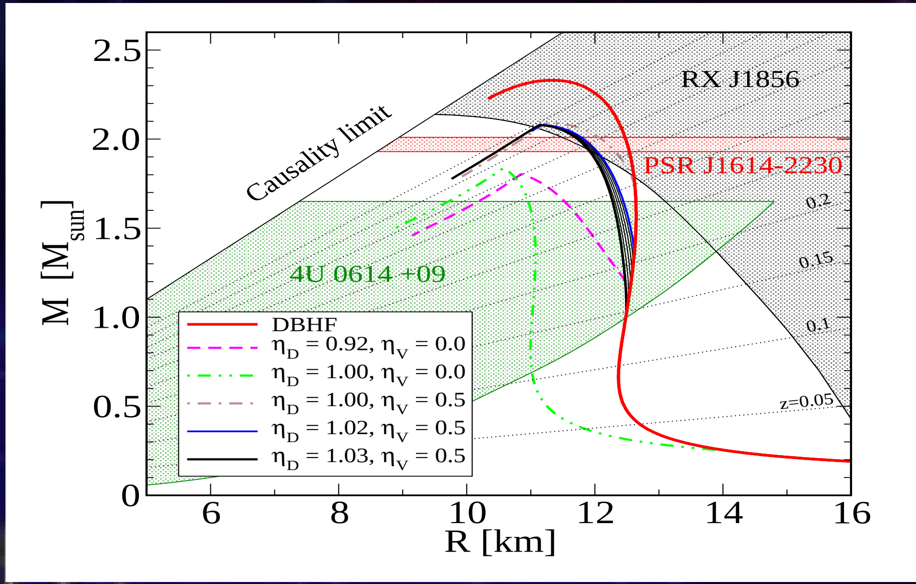
PSR J1614-2230 - A new constraint for the Compact Star EoS



Klähn et al., PLB 654, 170 (2007)



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



CompStar, in preparation (2010)

State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield “stiffening”

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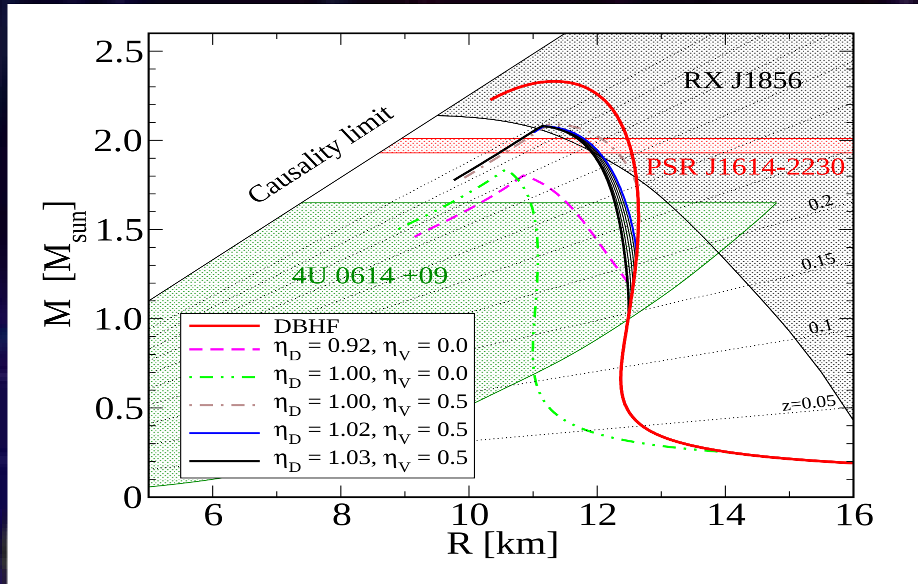

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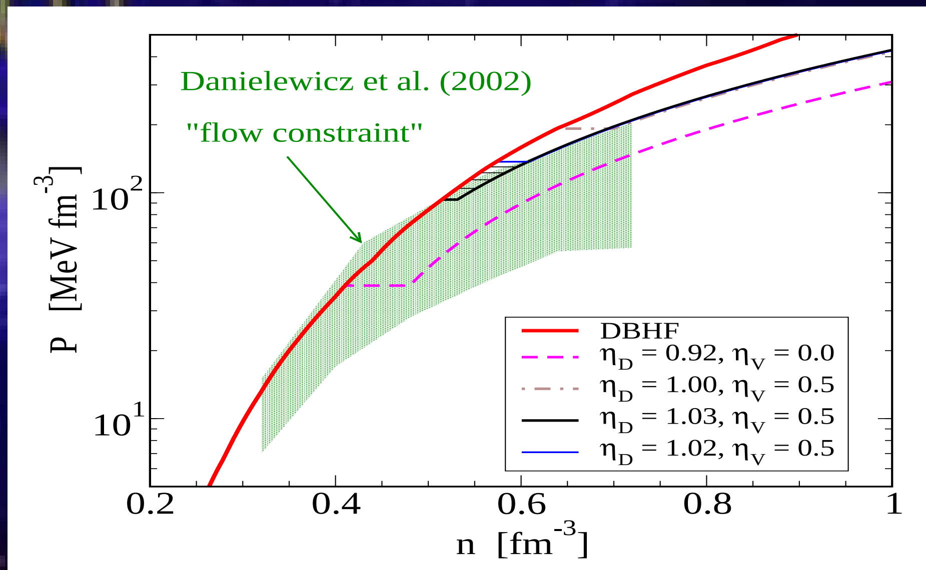


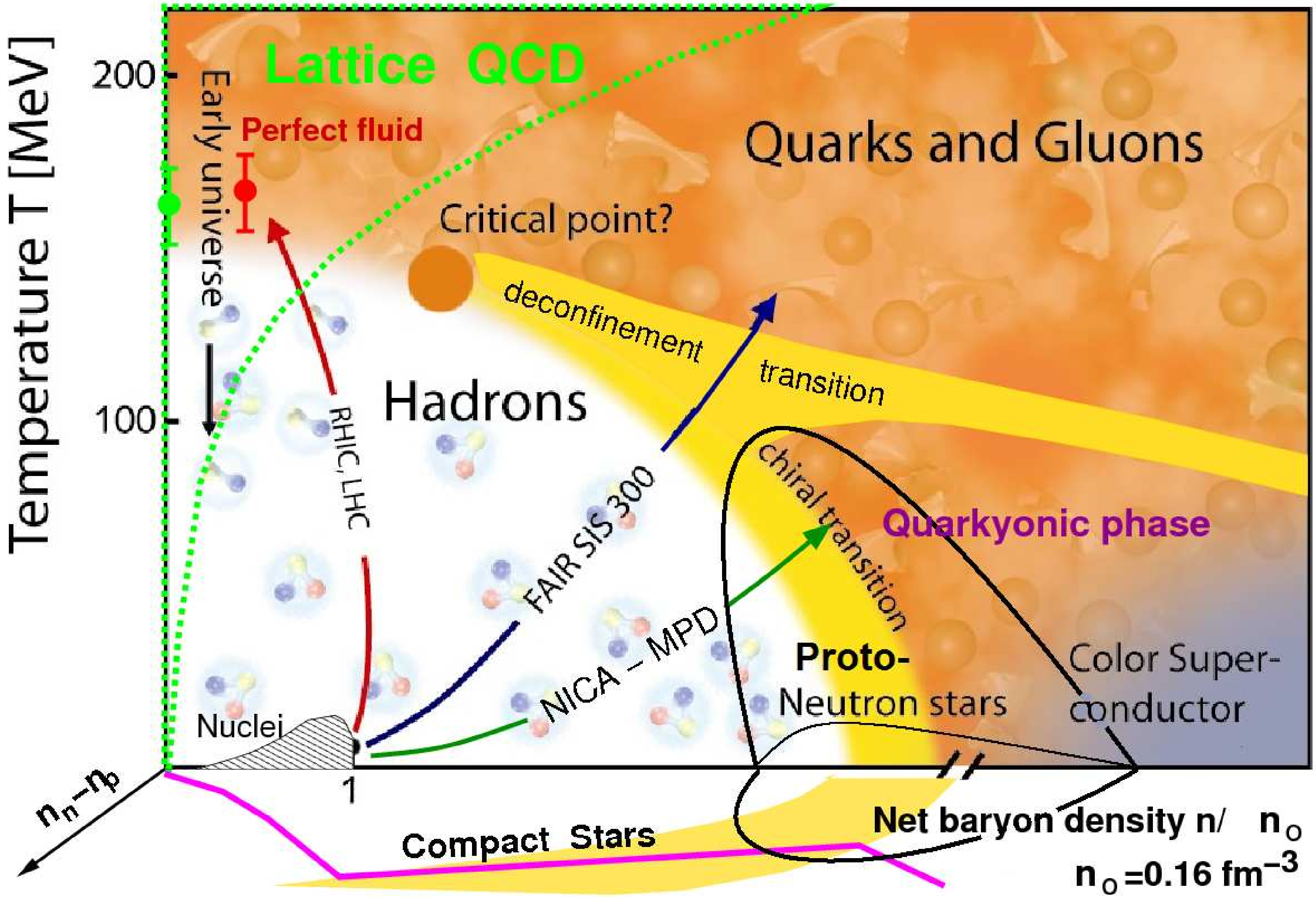
Constraints from heavy-ion collisions:

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

$\Longrightarrow$ **QCD phase diagram**

Klähn et al., PLB 654, 170 (2007)

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)

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

- Bosonization (Hubbard-Stratonovich Transformation)

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

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

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

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

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

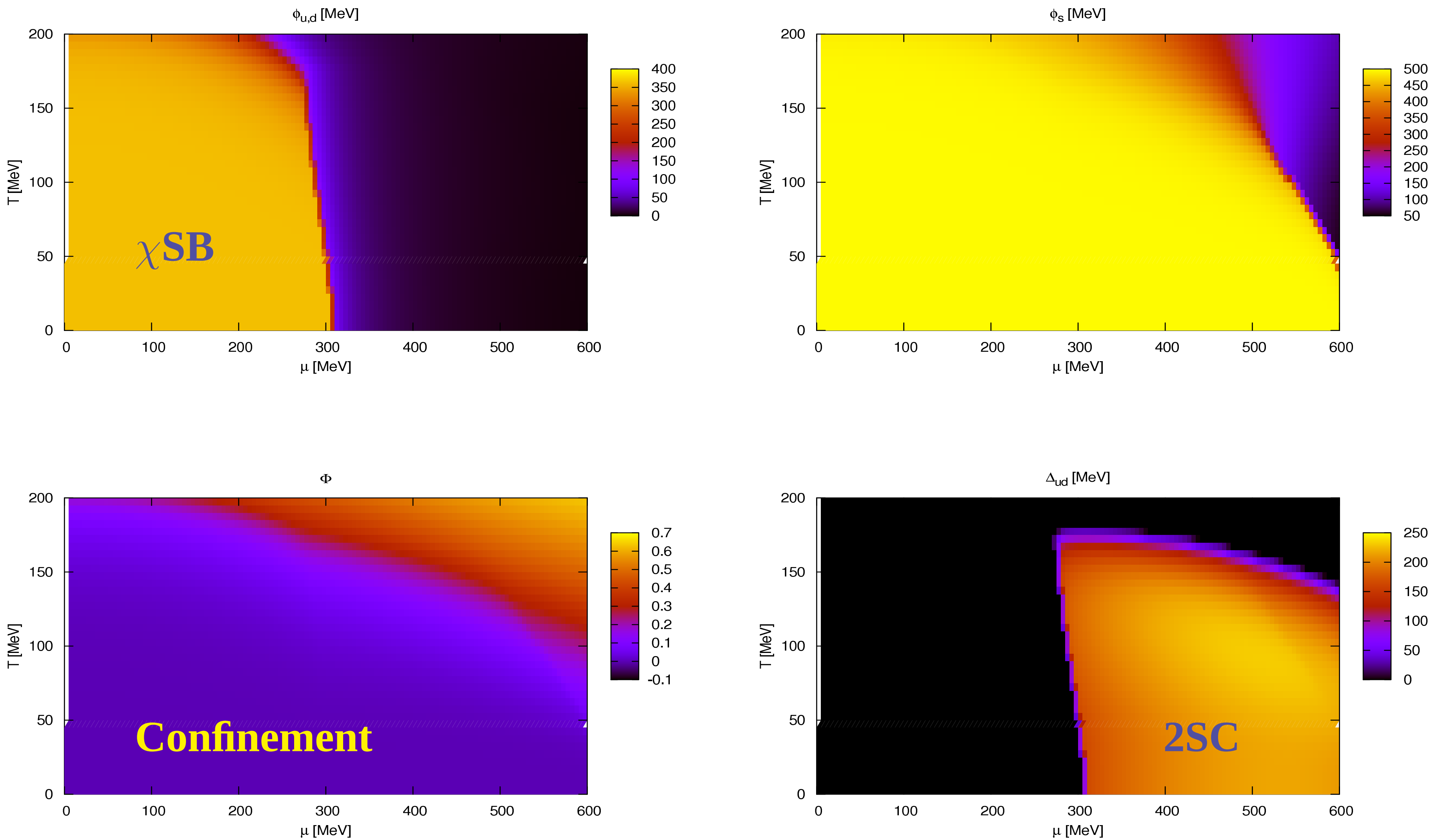
Fermion Determinant (Tr ln D = ln det D): $\ln\det[\beta\, S^{-1}(i\omega_n,\vec{p})] = 2\sum_{a=1}^{18} \ln\{\beta^2[\omega_n^2 + \lambda_a(\vec{p})^2]\}$.

Result for the thermodynamic Potential (Meanfield approximation)

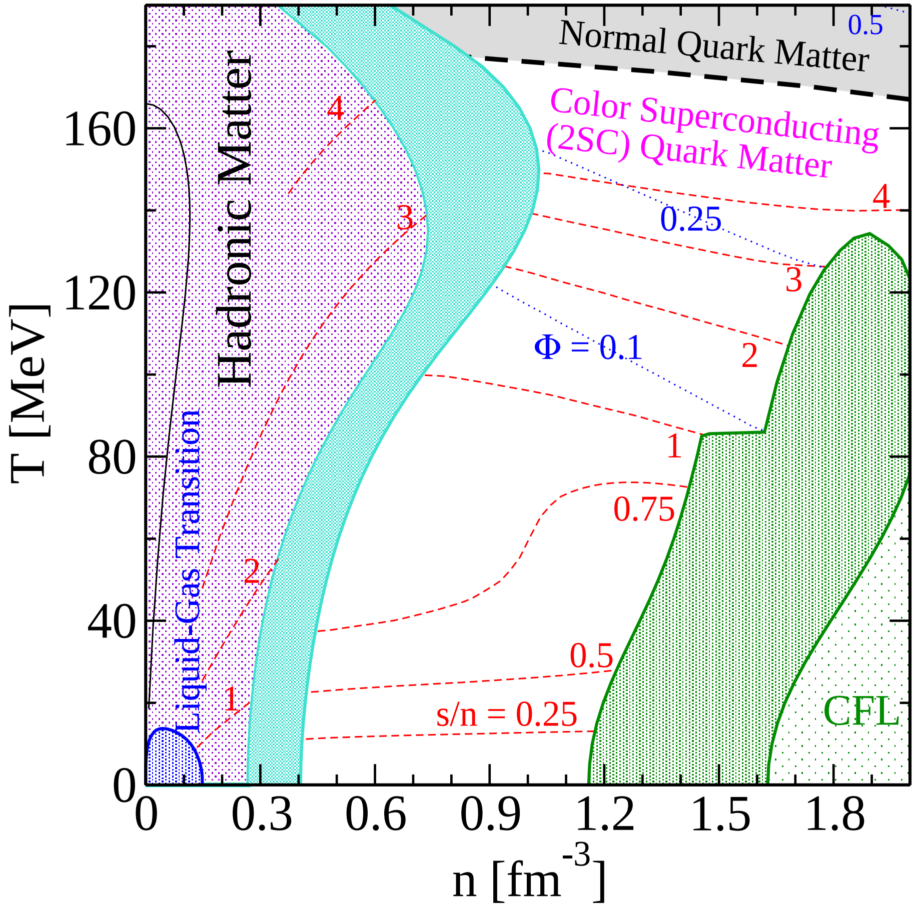
$$\Omega(T,\mu) \;=\; \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} - \int \frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left[\lambda_a + 2T\ln\left(1+e^{-\lambda_a/T}\right)\right] + \Omega_e - \Omega_0 .$$

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.

PHASES OF QCD @ EXTREMES: NO COLOR NEUTRALITY



Phase Diagram for Symmetric Matter (HIC)

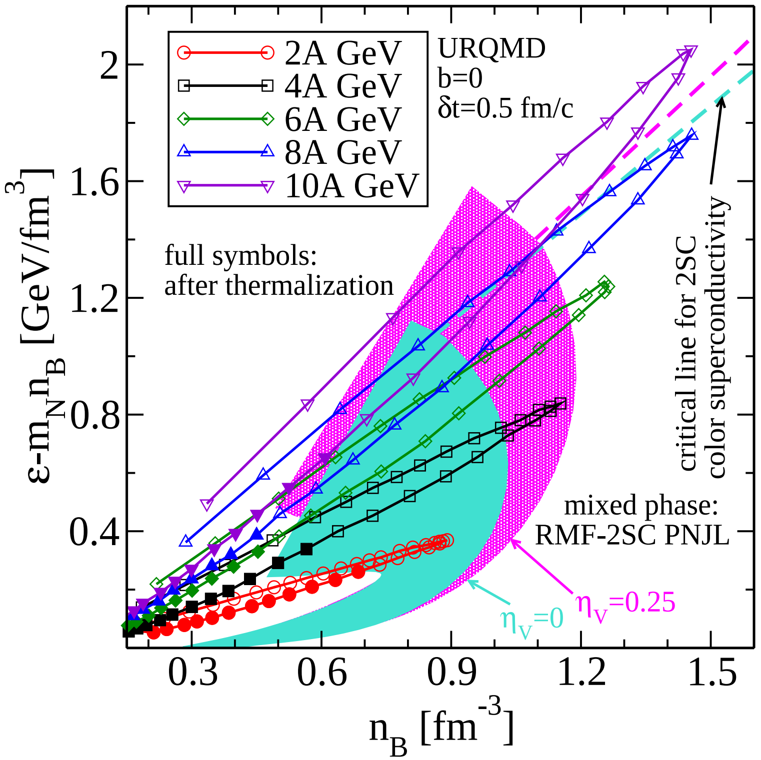


DB, Sandin, Skokov, NICA WhitePaper (2009)

- 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

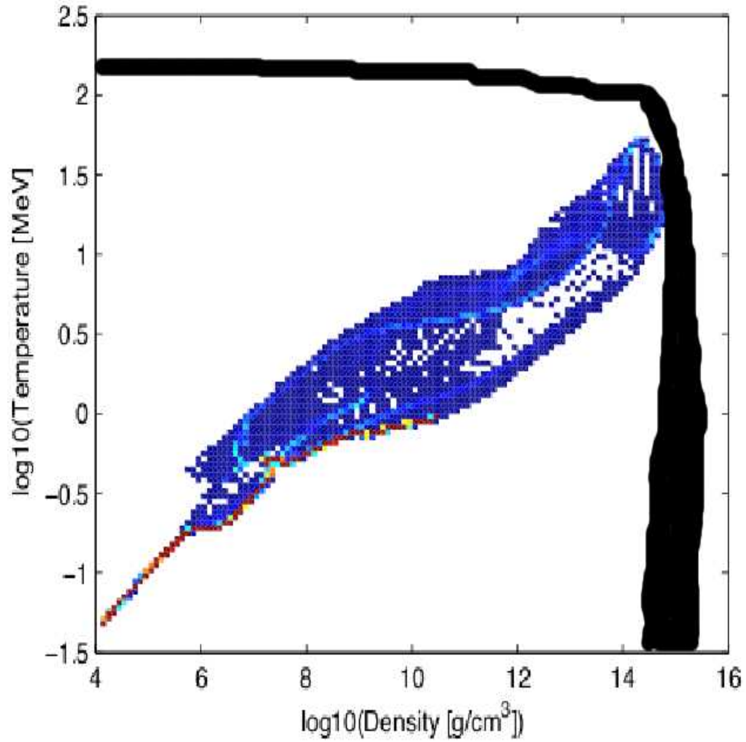
EXPLORING THE QCD PHASE DIAGRAM: TRAJECTORIES

Heavy-Ion Collisions:



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

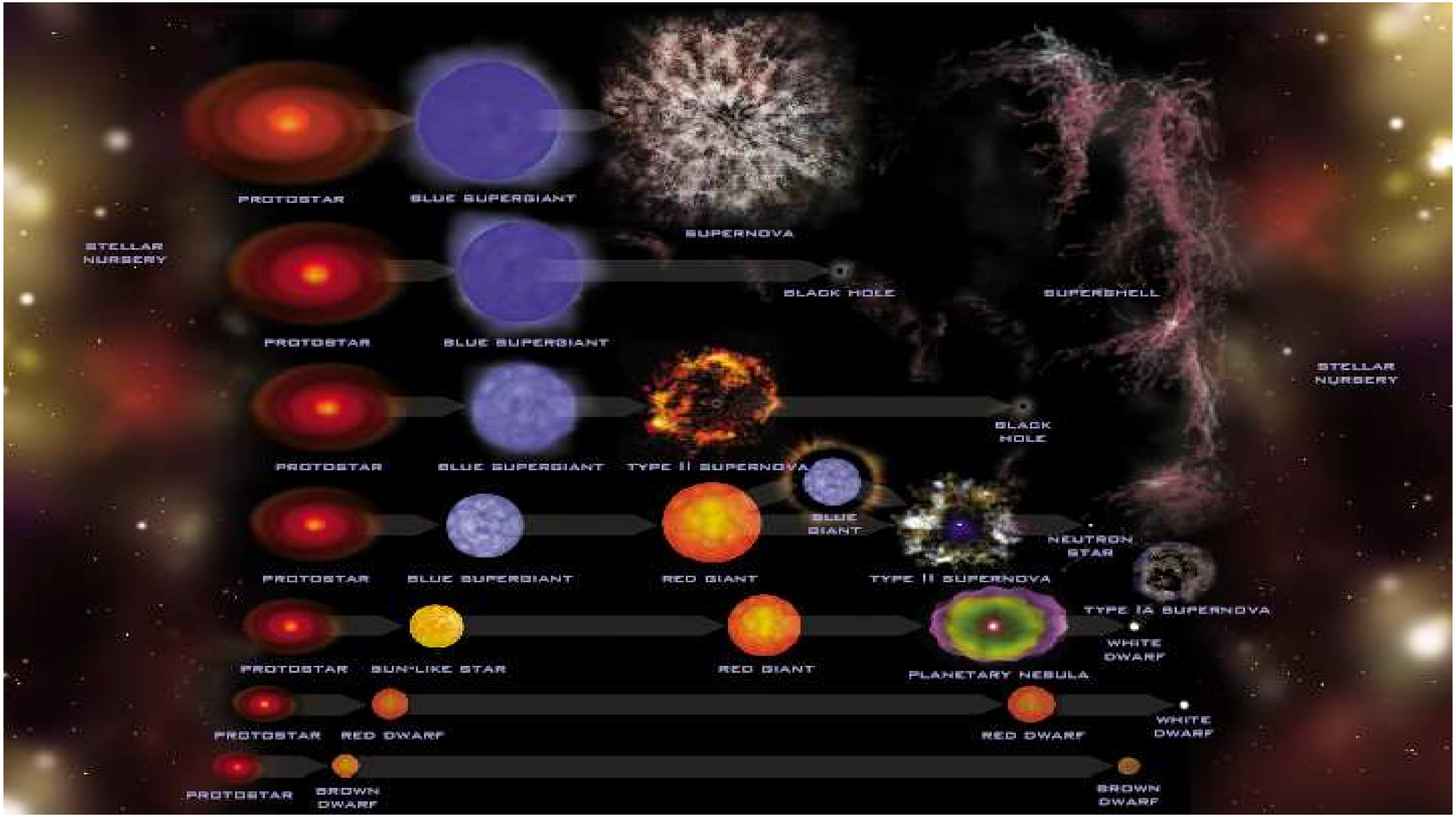
Supernova Explosions (15 $M_\odot$):



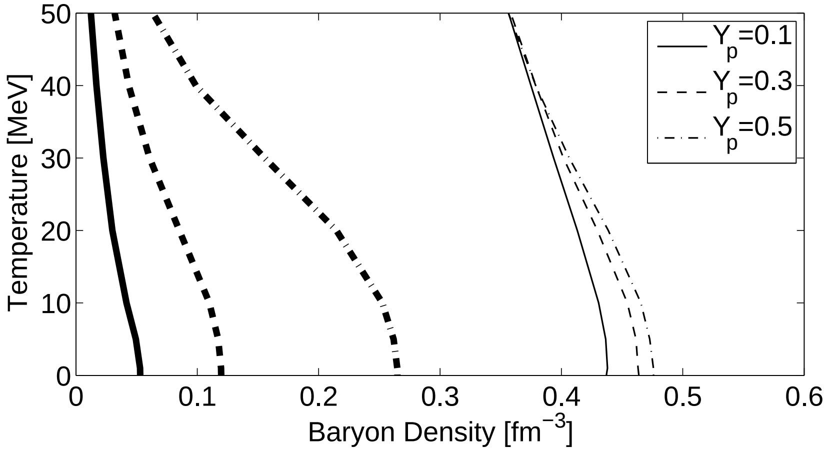
Liebendoefer et al. (2005)

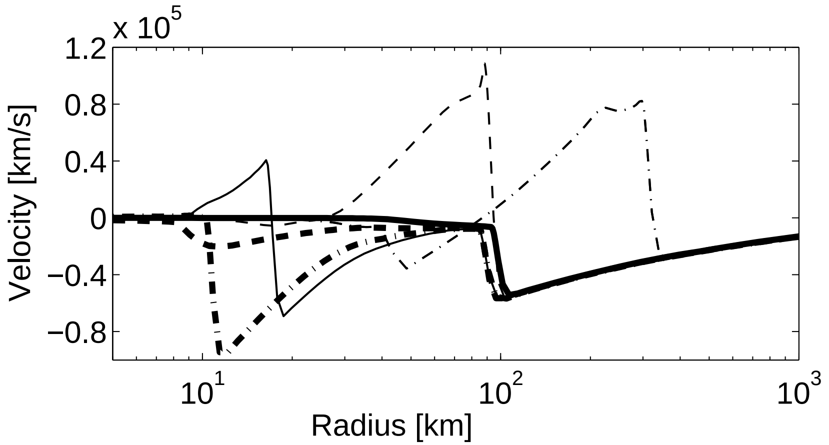
Sagert et al., PRL 102 (2009)

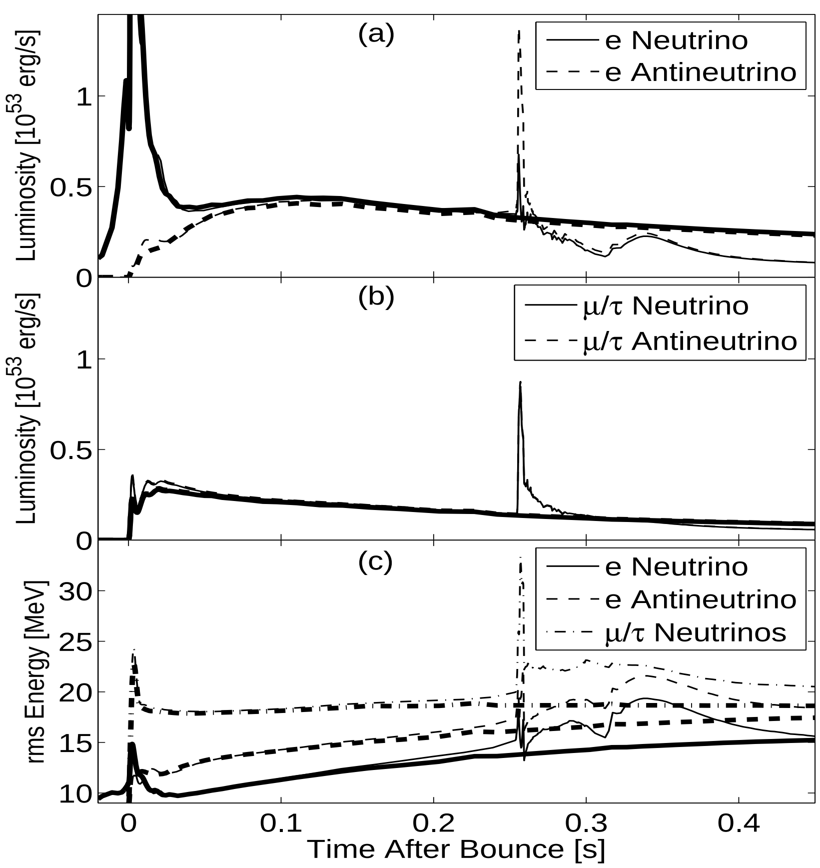
SUPERNOVAE - COMPACT STARS - BLACK HOLES



QUARK MATTER IN SUPERNOVA COLLAPSE: THE “FIRST SHOT”



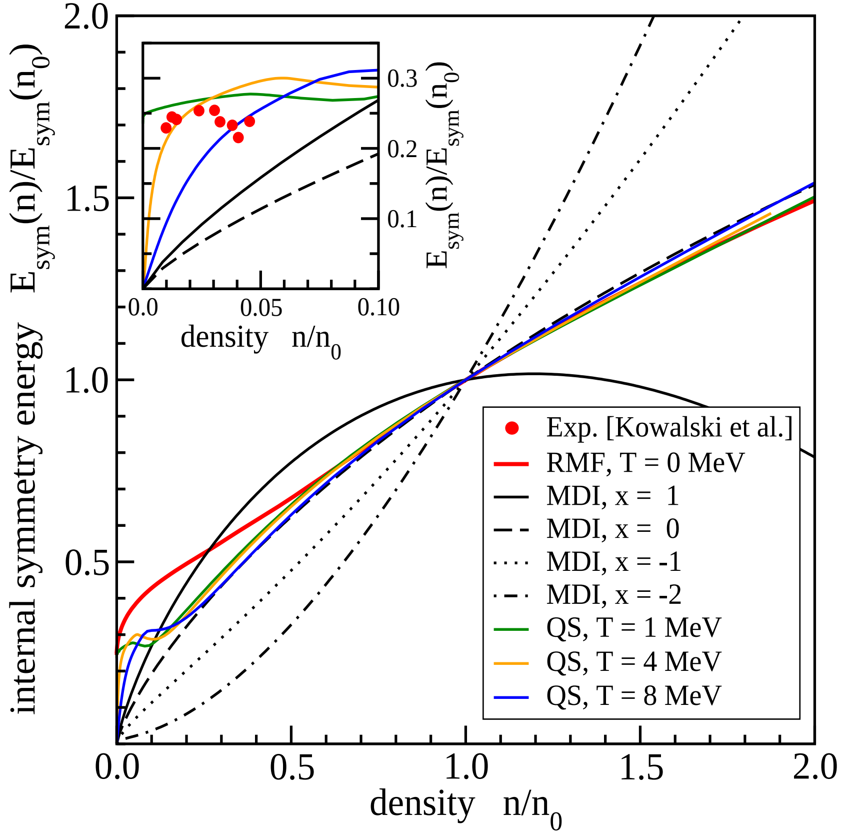


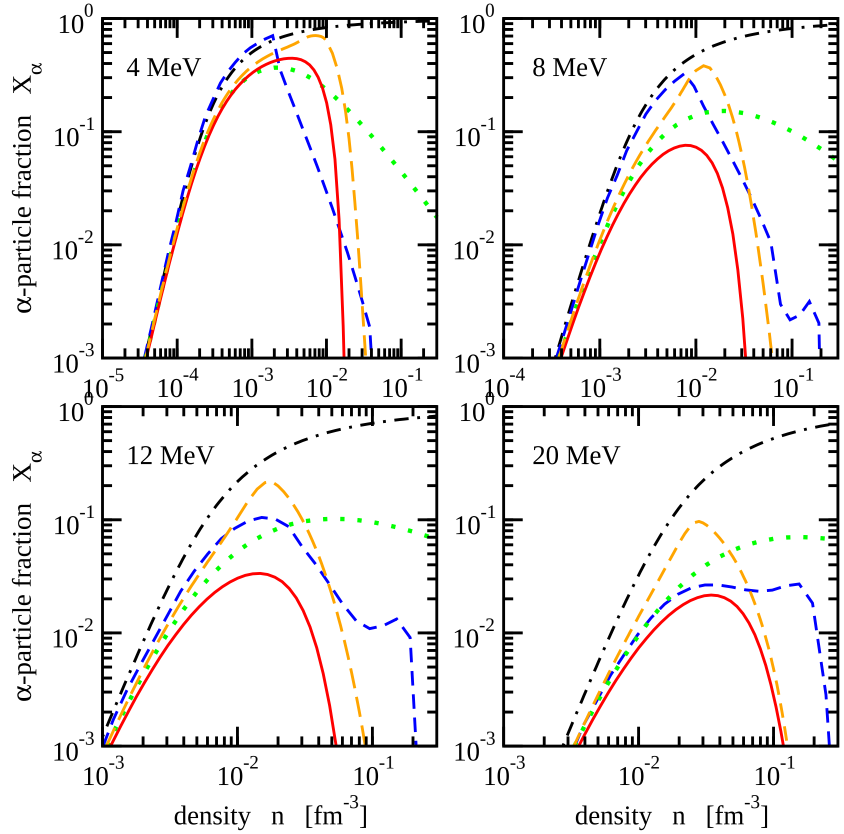


- Shen et al. + Bag model: $M^{\rm PNS}_{\rm onset} < M_\odot$, **but:** $M^{\rm PNS}_{\rm max} \sim 1.4 M_\odot$
- Phase transition: second shock, second neutrino pulse **but:** heavy progenitors $\rightarrow$ BH

Sagert, Hempel, Pagliara, Schaffner-Bielich, Fischer, Liebendörfer, Mezzacappa, PRL 102 (2009)

TOWARDS NEW SUPERNOVA EOS: CLUSTERS AT LOW-DENSITIES

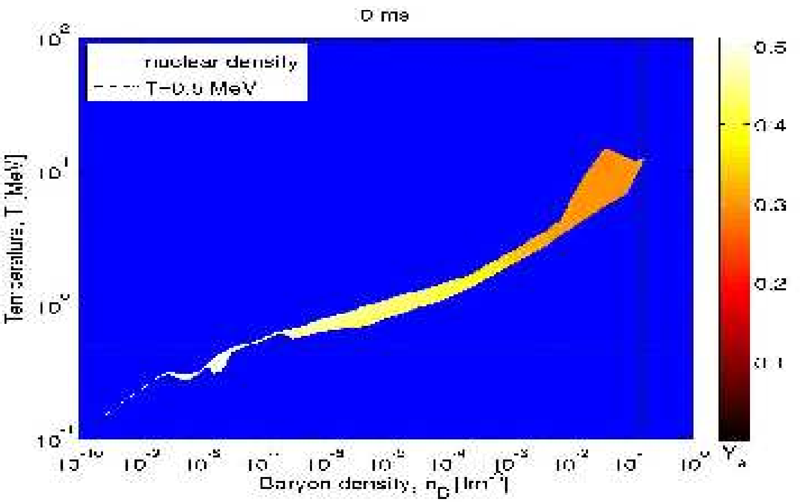


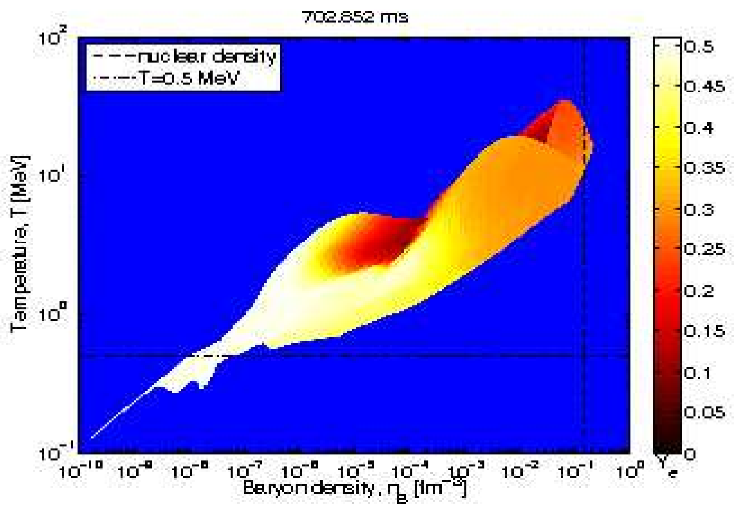


- Clusters important in plunge phase of SN collapse ($0.01 < n/n_0 < 0.1$)
- Low-density symmetry energy with clusters describes experiment (Kowalski et al.)

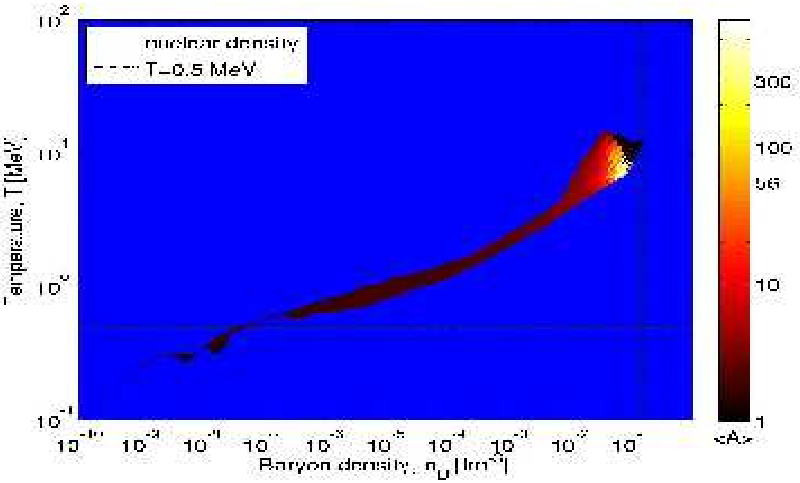
Typel, Röpke, Klähn, D.B., Wolter, Phys. Rev. C81 (2010); arxiv:0908.2344 [nucl-th]
Natowitz et al. (12 coauthors), Phys. Rev. Lett. (2010); arxiv:1001.1102 [nucl-th]

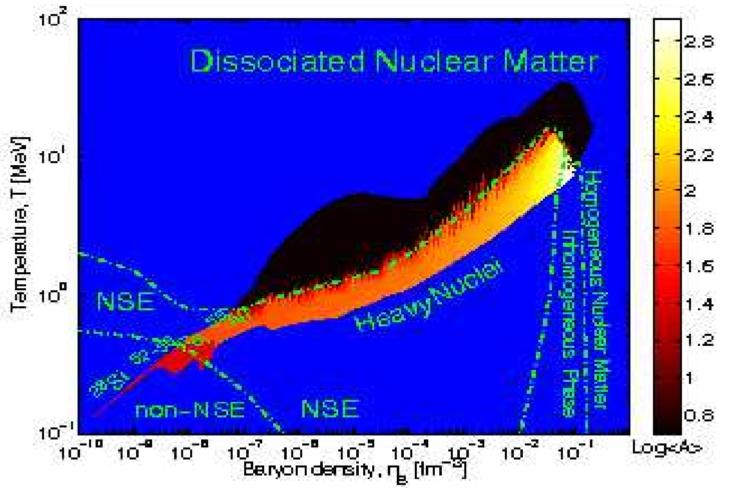
SUPERNOVA POSTBOUNCE EVOLUTION IN THE PHASE DIAGRAM





(Loading animation)





Bag vs. PNJL model in the phase diagram

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

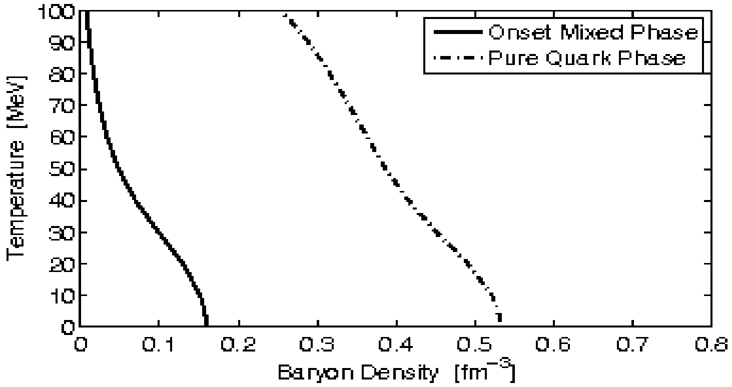
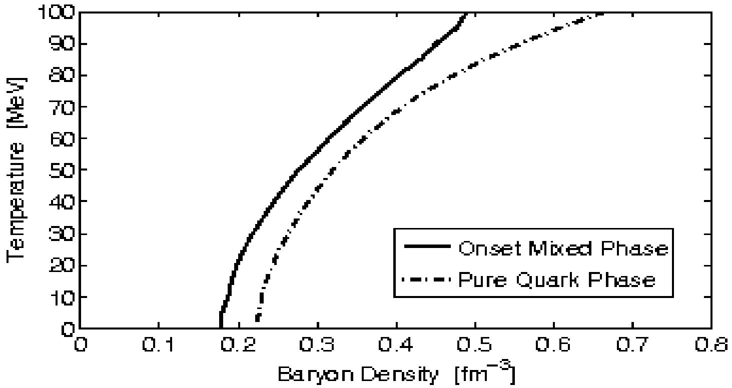


Figure: The PNJL model[b], $Y_p \simeq 0.3$



[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)

EVOLUTION OF CENTRAL MASS ELEMENTS IN SHEN/PNJL PHD

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

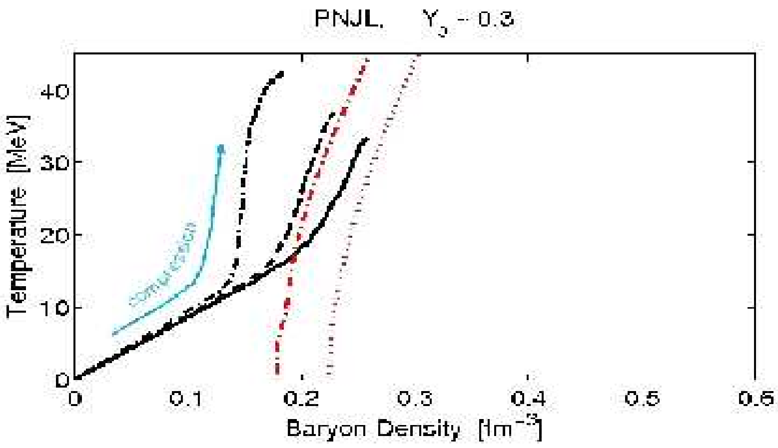
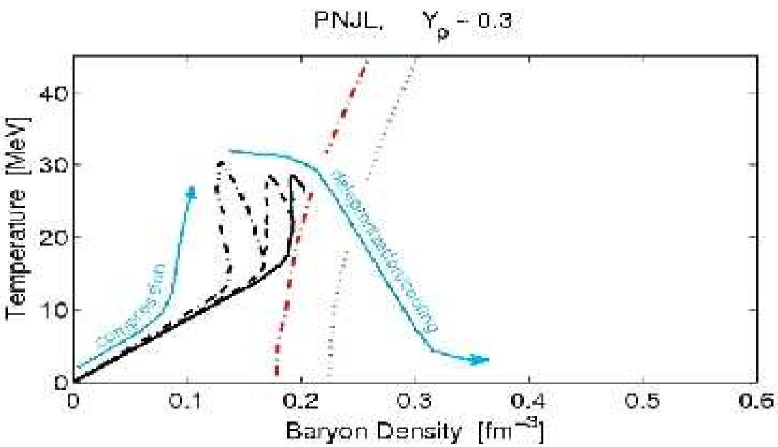
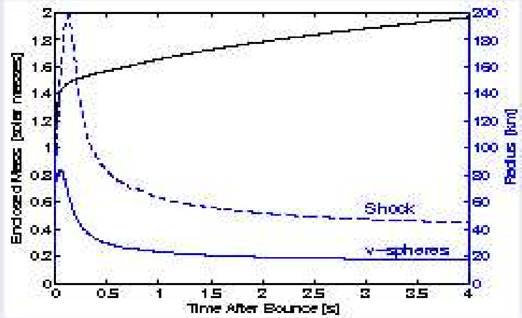


Figure: 20 $M_\odot$, ν-driven explosion

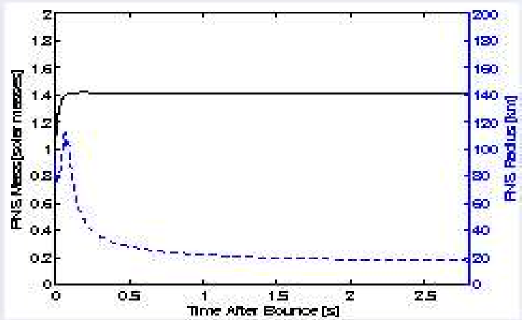


The appearance of quark matter in PNSs

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



2. Explosion models



Phase diagram / compact stars for Shen/Bag model

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

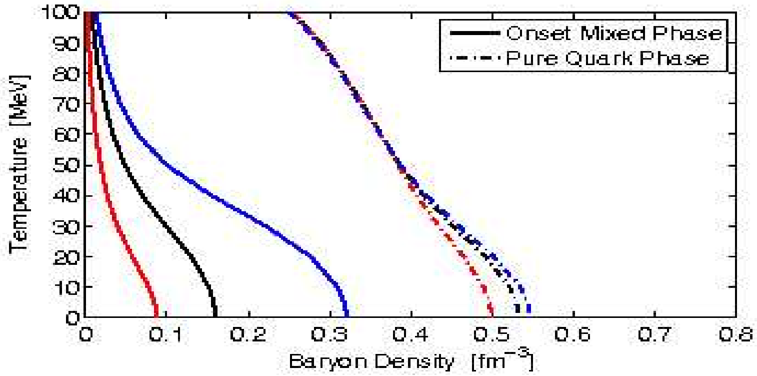
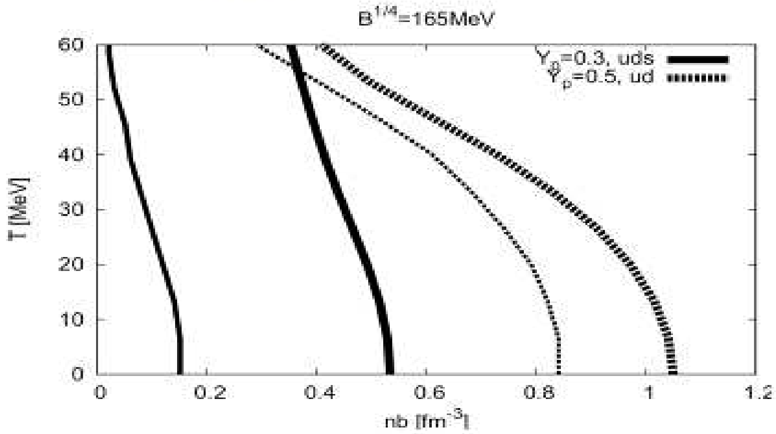


Figure: The MIT bag model

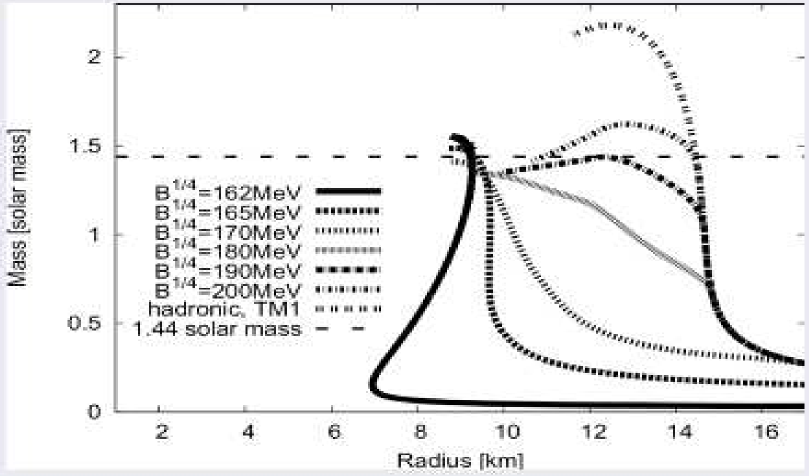


Requirements of the model and dependencies

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)

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

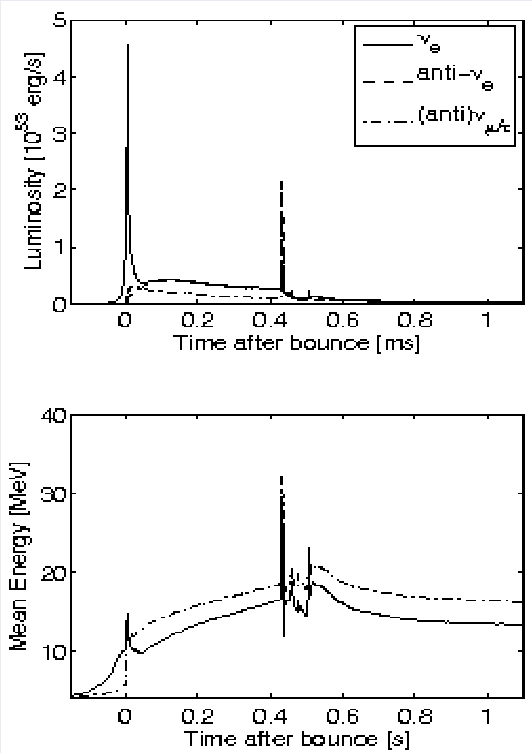
$m_u \simeq m_d \simeq 0$, $m_s \simeq 100$ MeV

EXTRA NEUTRINO BURST FROM QUARK-HADRON TRANSITION

The neutrino observables

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

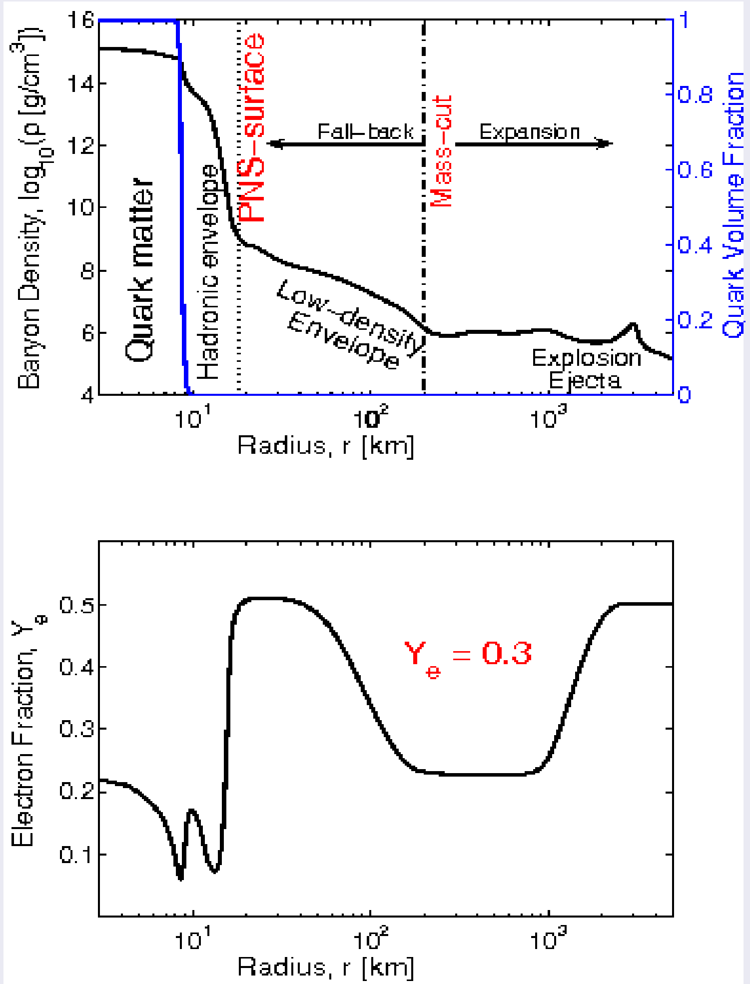
⟶ Neutrino burst dominated by $\bar{\nu}_e$



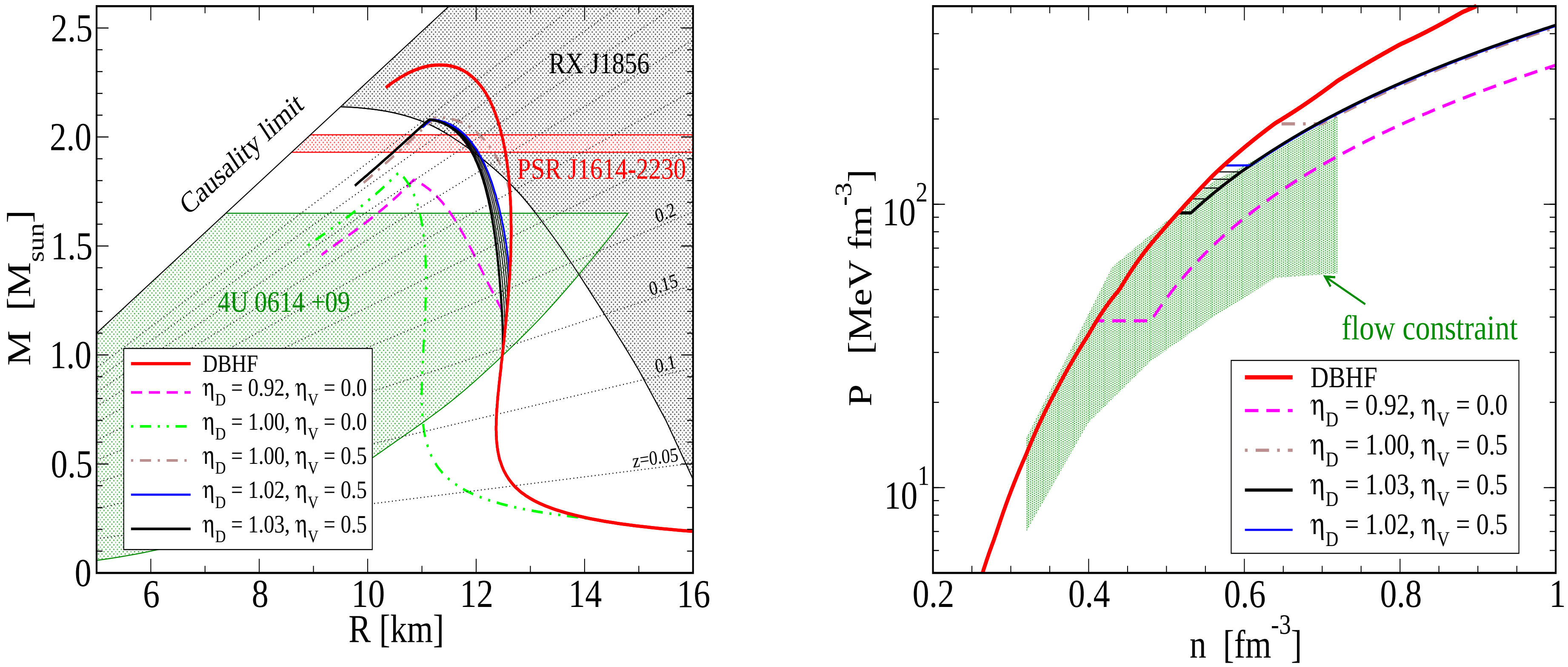
3. Detection of the "QCD-burst" (ICEC,SK)[a]

[a] Dasgupta et al. (2010)

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



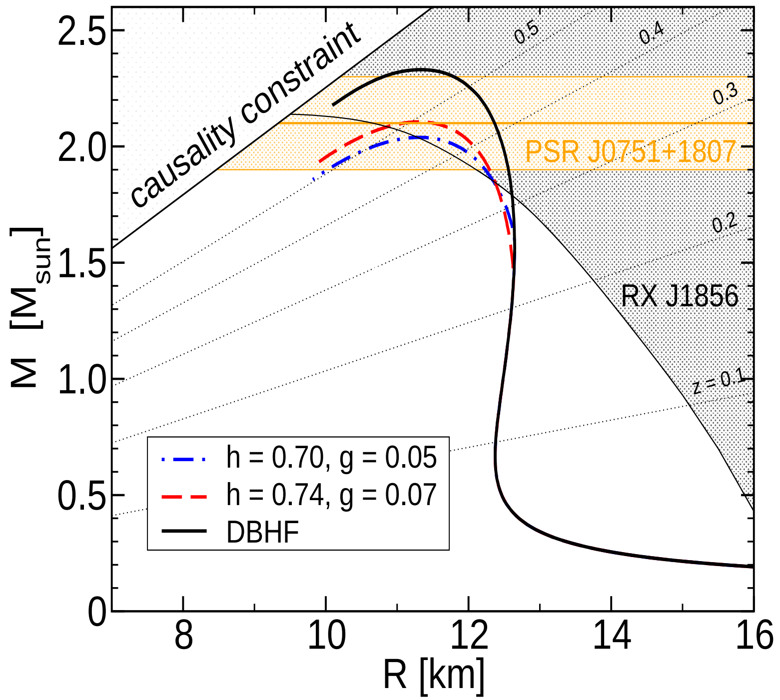
Mass-Radius constraint and Flow constraint

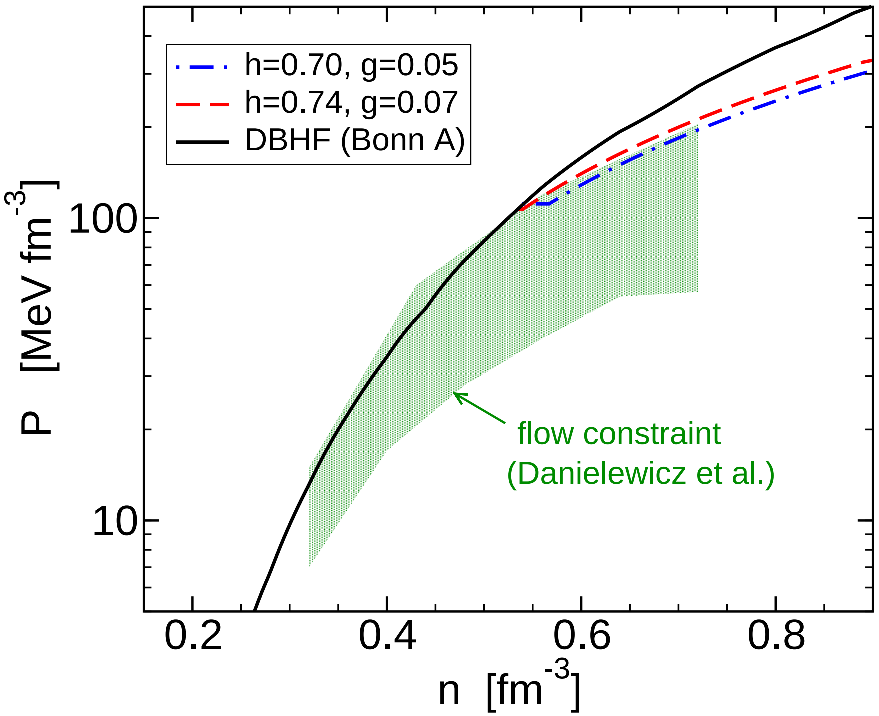


- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !

Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Röpke, Trümper, PLB 654, 170 (2007); [arxiv:nucl-th/0609067]

HYBRID-EOS ROBUST? CONSTRAINTS & COVARIANT NCQM





- Covariant, nonlocal interaction model:

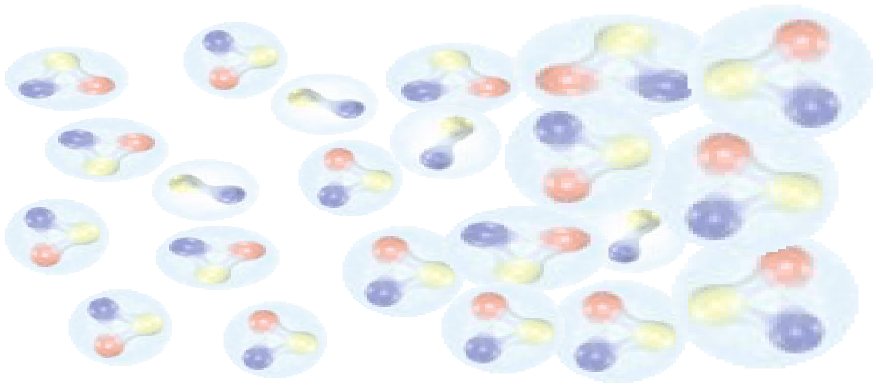
$$\mathcal{L}_{\rm int} = -\int d^4x \ \left\{ \frac{G_S}{2} j_S^f(x) j_S^f(x) + \frac{H}{2} \left[j_D^a(x)\right]^\dagger j_D^a(x) + \frac{G_V}{2} j_V^\mu(x)\, j_V^\mu(x) \right\}$$

- Nonlocal currents, e.g.

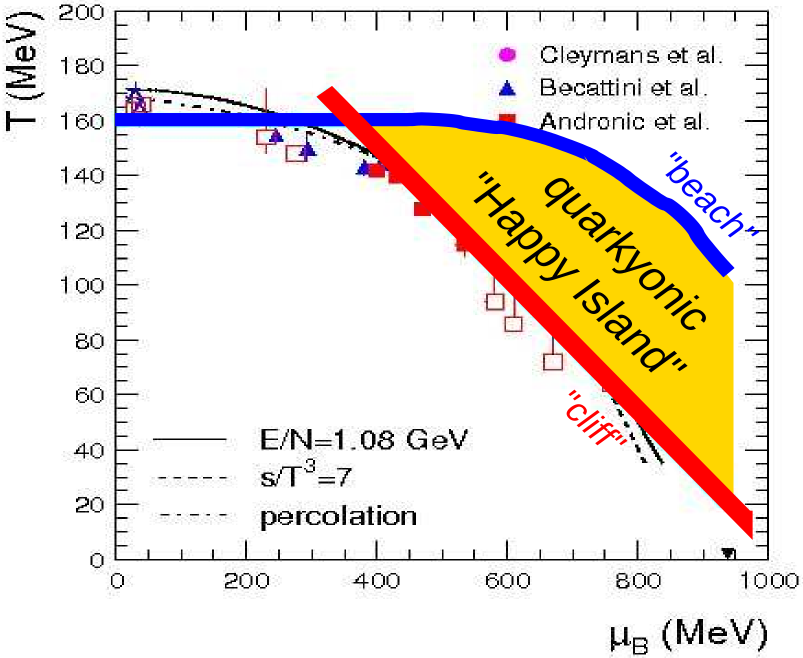
$$j_S^f(x) = \int d^4z \ g(z) \ \bar{\psi}(x + \tfrac{z}{2}) \ \Gamma_f \, \psi(x - \tfrac{z}{2}) \,,$$

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

What happens on "Happy Island"?



Andronic et al., arxiv:0911.4806



"beach": later

"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)

CompOSE - CompStar Online Supernova EoS

Reference manual
version 1.0

CompOSE

CompStar **O**nline **S**upernovæ **E**quations 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

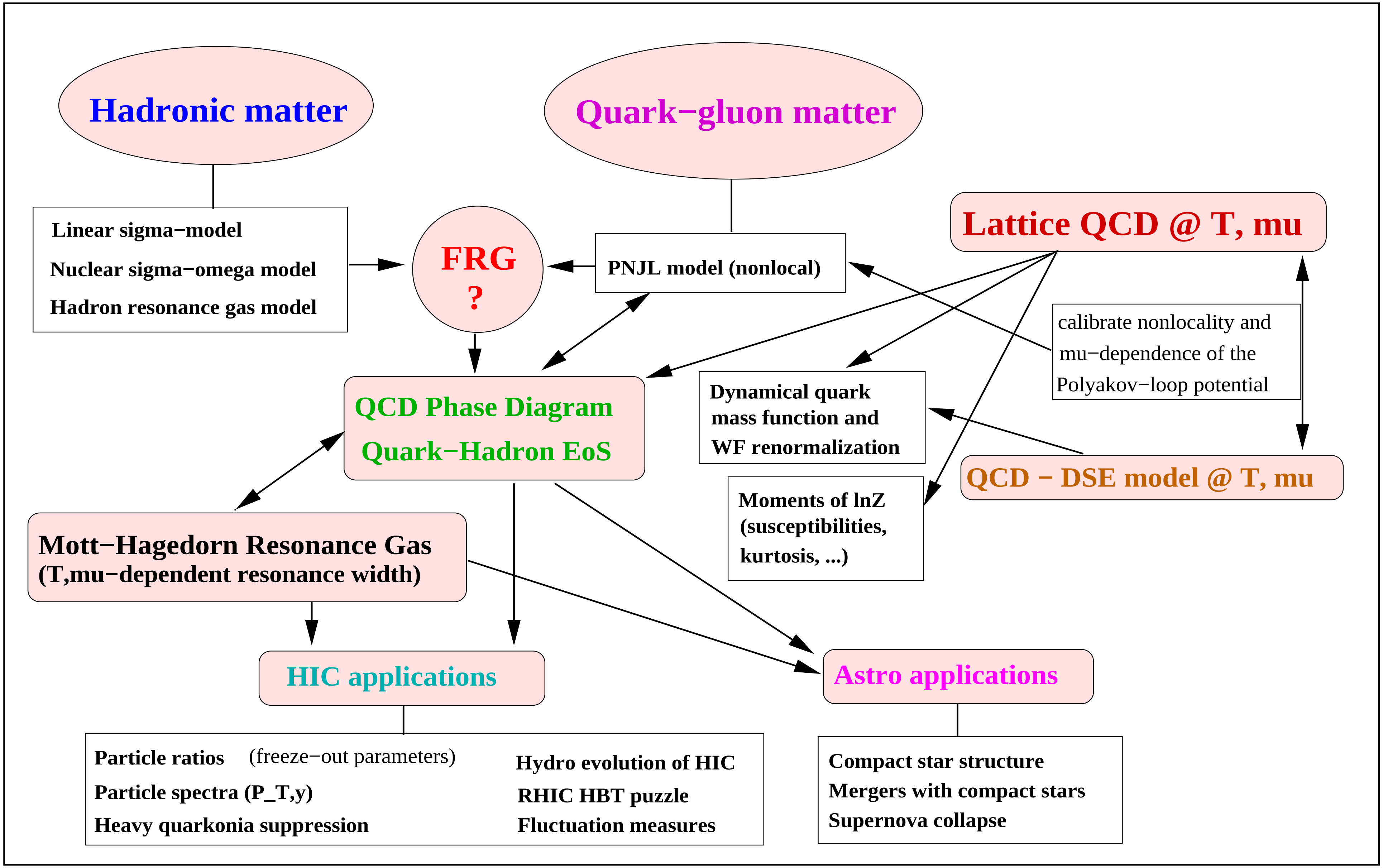
I. For Contributors:

- 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?)

THREE DAYS ON HAPPY ISLAND - WROCLAW, MAY 2011