

# GENERALIZED BETH-UHLENBECK EoS FOR THE NONIDEAL QUARK PLASMA

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## Punchline:

- **Hagedorn:** “A system of interacting elementary particles can be reformulated as a system of noninteracting resonances”  $\longrightarrow$  **Resonance Gas**
- **Bound states** can be treated as a new species  $\implies$  **chemical picture**
- **Physical picture:** there are also scattering states!  
EoS with bound and scattering states: **Beth-Uhlenbeck EoS** (1936/37)
- Generalized Beth-Uhlenbeck EoS includes the **Mott transition:**  
bound states  $\implies$  resonances in the scattering continuum



# PARTITION FUNCTION FOR QUANTUM CHROMODYNAMICS (QCD)

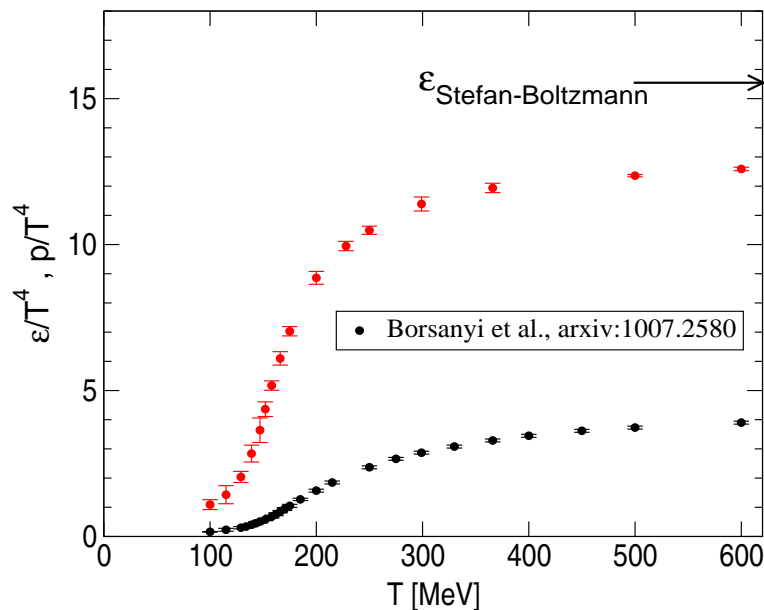
- Partition function as a Path Integral (imaginary time  $\tau = i t, 0 \leq \tau \leq \beta = 1/T$ )  $\Rightarrow$  PS I

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

- QCD Lagrangian, non-Abelian gluon field strength:  $F_{\mu\nu}^a(A) = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} [A_\mu^b, A_\nu^c]$

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

- **Numerical evaluation:** Lattice gauge theory simulations (hotQCD, Wuppertal-Budapest)



- Equation of state:  $\varepsilon(T) = -\partial \ln Z[T, V, \mu] / \partial \beta$

- Phase transition at  $T_c = 155$  MeV

- **Problem:** Interpretation ?

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

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

- Hadron resonance gas

# PARTITION FUNCTION FOR QUANTUM CHROMODYNAMICS (QCD)

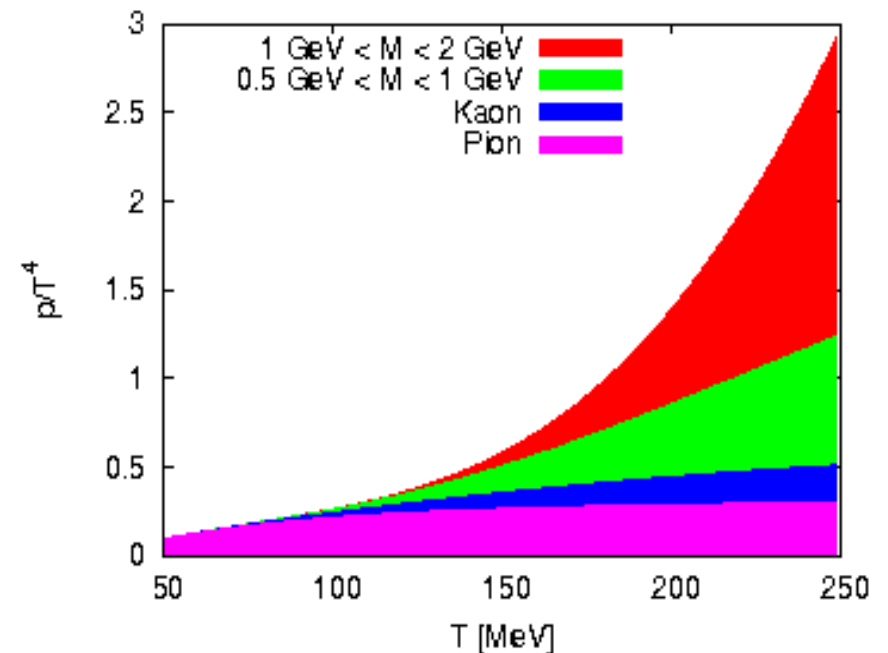
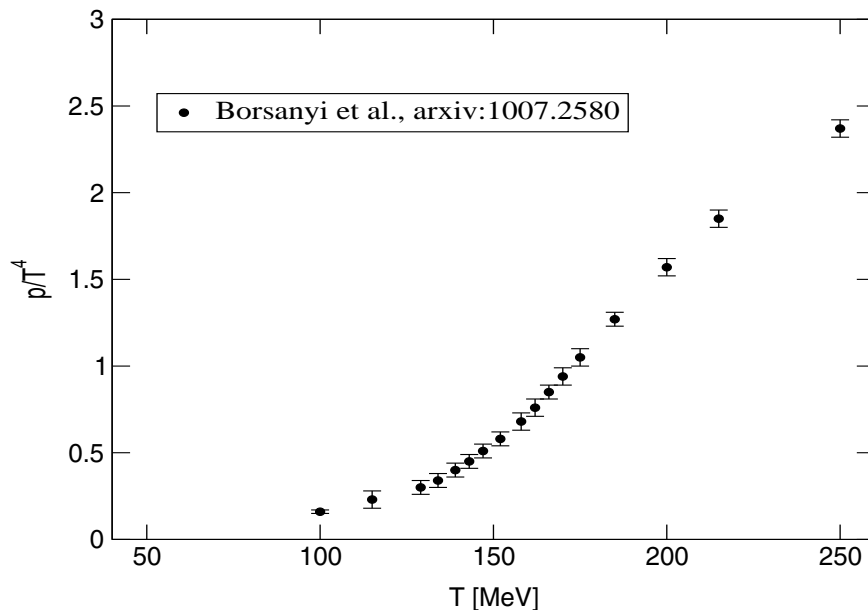
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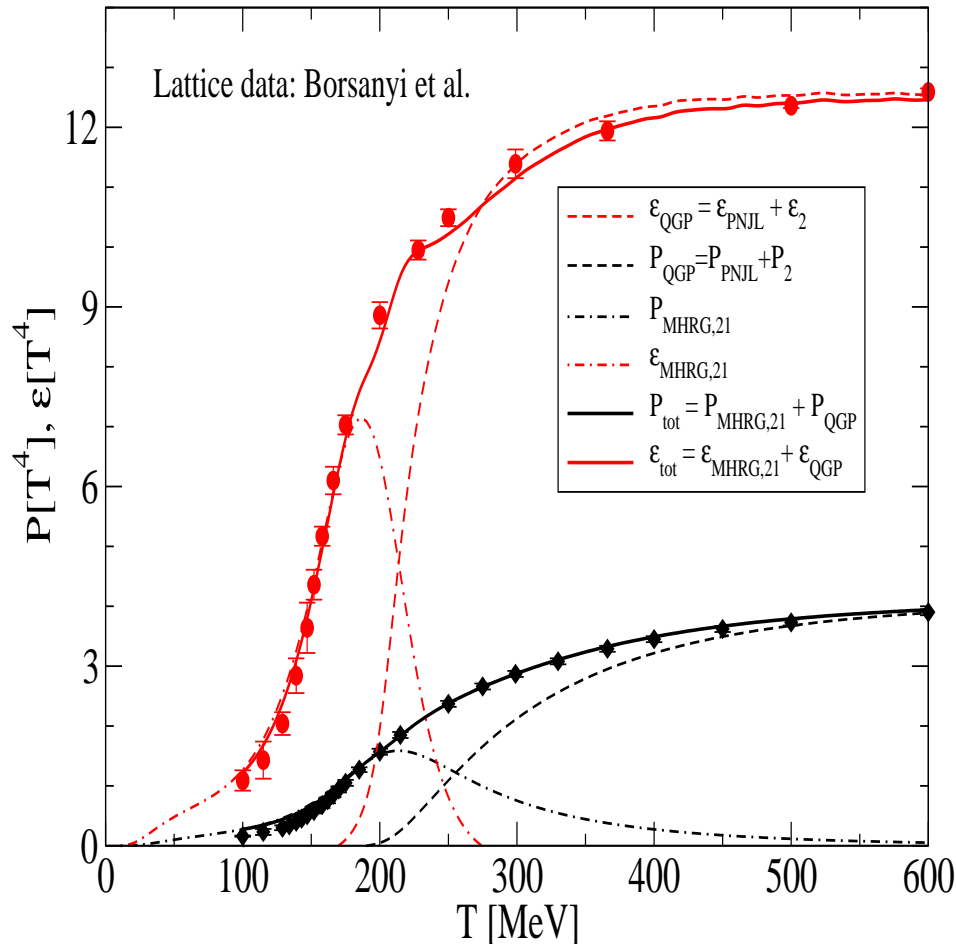
$$\mathcal{L}_{QCD}(\psi, \bar{\psi}, A) = \bar{\psi}[i\gamma^\mu(\partial_\mu - igA_\mu) - m - \gamma^0\mu]\psi - \frac{1}{4}F_{\mu\nu}^a(A)F^{a,\mu\nu}(A)$$

- Numerical evaluation: Lattice gauge theory simulations (hotQCD, Wuppertal-Budapest)



# HYBRID APPROACH: PNJL & MOTT-HAGEDORN RESONANCE GAS

$$P_{\text{tot}}(T, \{\mu_j\}) = P_{\text{PNJL}}(T, \{\mu_i\}) + \sum_{r=M,B} \delta_r g_r \int ds A_r(s, m_r; T) \int \frac{d^3p}{(2\pi)^3} T \ln \left\{ 1 + \delta_r \exp \left( \frac{\sqrt{p^2 + s} - \mu_r}{T} \right) \right\}$$



**Spectral function** for hadronic resonances:

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

Ansatz motivated by chemical freeze-out model:

$$\Gamma_r(T) = \tau_r^{-1}(T) = \sum_h \lambda \langle r_r^2 \rangle_T \langle r_h^2 \rangle_T n_h(T)$$

Apparent phase transition at  $T_c \sim 165$  MeV

Hadron resonances present up to  $T_{\text{max}} \sim 250$  MeV

**Blaschke & Bugaev, Fizika B13, 491 (2004)**

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

**Blaschke, Prorok & Turko, in preparation**

**Hadronic states above  $T_c$  ! See also: Ratti, Bellwied et al., arXiv:1109.6243 [hep-ph]**

# CHIRAL MODEL FIELD THEORY FOR QUARK MATTER

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

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

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

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

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

- Bosonization (Hubbard-Stratonovich Transformation)

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

- Collective quark fields: Mesons ( $M_M$ ) and Diquarks ( $\Delta_D$ ); Gluon mean field:  $\Phi$
- 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**

# CHIRAL MODEL FIELD THEORY FOR QUARK MATTER

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

$$Z[T, V, \mu] = \int \mathcal{D}\bar{q}\mathcal{D}q \exp \left\{ - \int^{\beta} d\tau \int_V d^3x [\bar{q}(i\gamma^\mu \partial_\mu - m_0 - \gamma^0 \mu)q + \sum_{M=\pi,\sigma} G_M (\bar{q}\Gamma_M q)^2] \right\}$$

- Couplings:  $G_\pi = G_\sigma = G_S$  (chiral symmetry)
- Vertices:  $\Gamma_\sigma = \mathbf{1}_D \otimes \mathbf{1}_f \otimes \mathbf{1}_c$ ;  $\Gamma_\pi = i\gamma_5 \otimes \vec{\tau} \otimes \mathbf{1}_c$
- Bosonization (Hubbard-Stratonovich Transformation)

$$\exp [G_S (\bar{q}\Gamma_\sigma q)^2] = \text{const.} \int \mathcal{D}\sigma \exp \left[ \frac{\sigma^2}{4G_S} + \bar{q}\Gamma_\sigma q \sigma \right]$$

- Integrate out quark fields  $\rightarrow$  bosonized partition function

$$Z[T, V, \mu] = \int \mathcal{D}\sigma \mathcal{D}\pi \exp \left\{ -\frac{\sigma^2 + \pi^2}{4G_S} + \frac{1}{2} \text{Tr} \ln S^{-1}[\sigma, \pi] \right\}$$

- Systematic evaluation: **Mean fields** + **Fluctuations**
  - Mean-field approximation: **order parameters** for phase transitions (gap equations)
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## MEAN FIELD PLUS (GAUSSIAN) FLUCTUATIONS

- Separate the mean-field part of the quark determinant

$$\text{Tr} \ln S^{-1}[\sigma, \pi] = \text{Tr} \ln S_{\text{MF}}^{-1}[m] + \text{Tr} \ln [1 + (\sigma + i\gamma_5 \vec{\tau} \vec{\pi}) S_{\text{MF}}[m]]$$

- Mean-field quark propagator

$$S_{\text{MF}}(\vec{p}, i\omega_n; m) = \frac{\gamma_0(i\omega_n + \mu) - \vec{\gamma} \cdot \vec{p} + m}{(i\omega_n + \mu)^2 - E_p^2}$$

- Expand the logarithm:  $\ln(1 + x) = -\sum_{n=1}^{\infty} (-1)^n x^n / n = x - x^2/2 + \dots$
- Thermodynamic potential in Gaussian approximation

$$\begin{aligned} \Omega(T, \mu) &= -T \ln Z(T, \mu) = \Omega_{\text{MF}}(T, \mu) + \Omega_{\text{M}}^{(2)}(T, \mu) + \dots \\ \Omega_{\text{M}}^{(2)}(T, \mu) &= \frac{N_M}{2} \int \frac{d^2 p}{(2\pi)^3} \frac{1}{\beta} \sum_n e^{i\nu_n \eta} \ln [1 - 2G_S \Pi_M(\vec{p}, i\nu_n)] \quad , \quad N_\sigma = 1, \quad N_\pi = 3 \end{aligned}$$

- Mesonic polarization loop

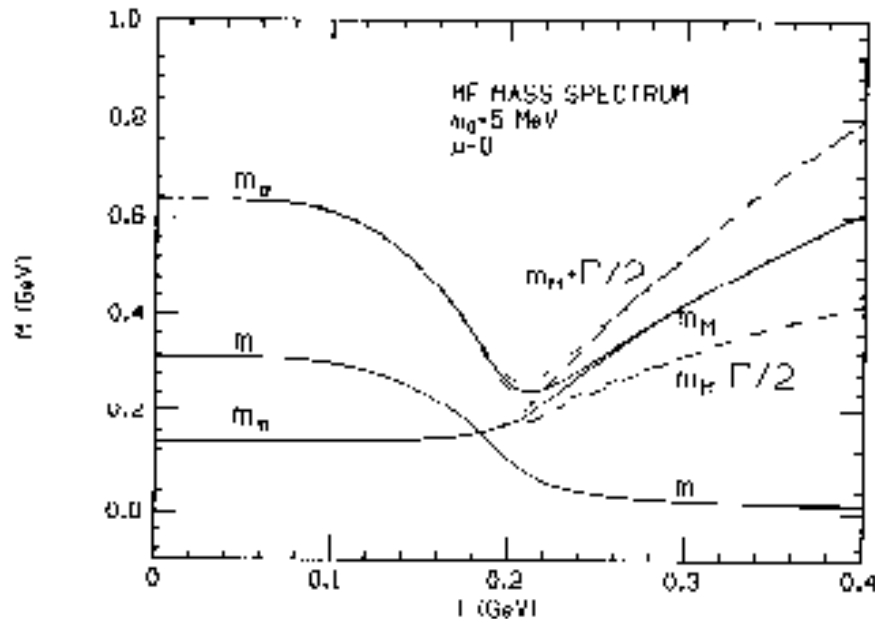
$$\Pi_M(\vec{p}, i\nu_n) = -\frac{1}{\beta} \sum_{n'} e^{i\nu_{n'} \eta} \int \frac{d^2 k}{(2\pi)^3} \text{Tr} \left[ \Gamma_M S_{\text{MF}}(-\vec{k}, -i\omega_{n'}) \Gamma_M S_{\text{MF}}(\vec{k} + \vec{p}, i\omega_{n'} + i\nu_n) \right]$$

# GENERALIZED BETH-UHLENBECK EoS: NJL MODEL RESULTS

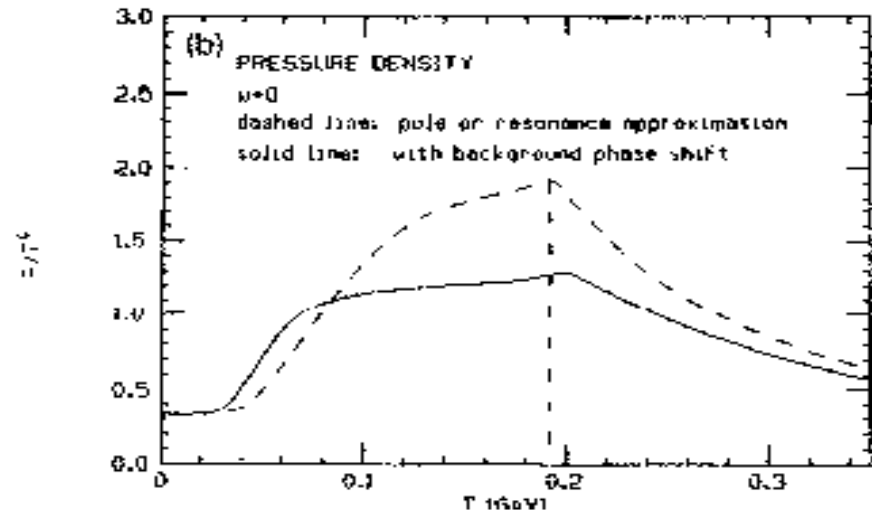
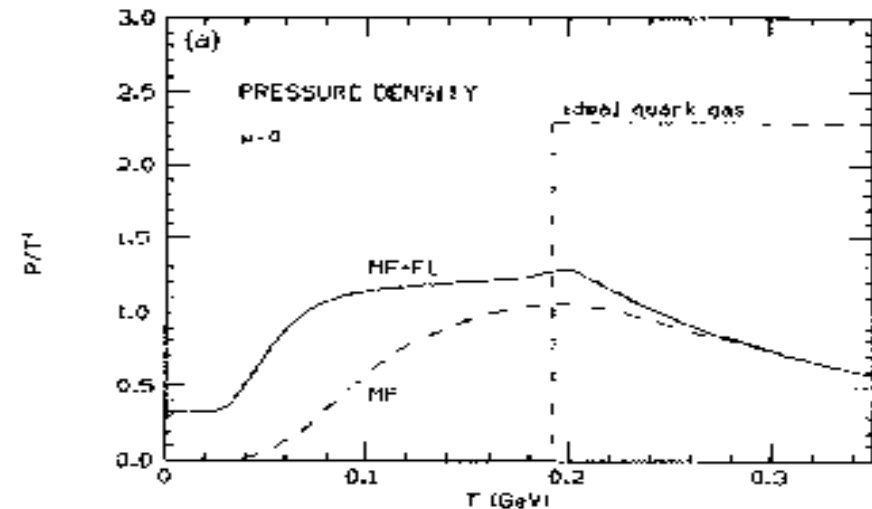
Generalized Beth-Uhlenbeck approach:

- Deuterons in nuclear matter  
Schmidt, Röpke, Schulz, Ann. Phys. (1990)
- Mesons in quark matter  
Hüfner, Klevansky, Zhuang, Voß, Ann. Phys. (1994)

*P. Zhuang et al. / Nuclear Physics A 576 (1994) 525–552*



*P. Zhuang et al. / Nuclear Physics A 576 (1994) 525–552*



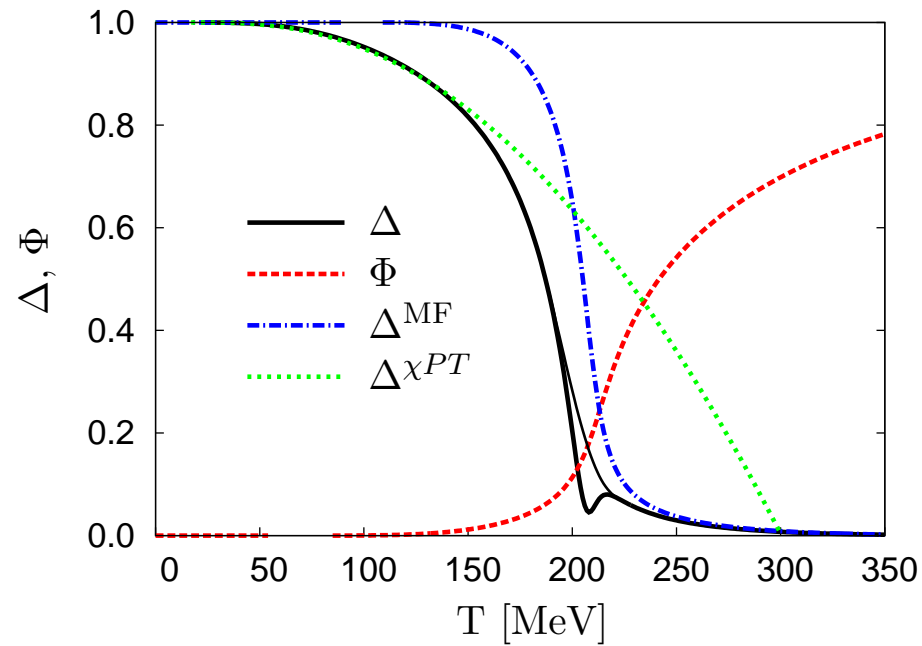


# GEN. BETH-UHLENBECK EOS: NONLOCAL PNJL RESULTS

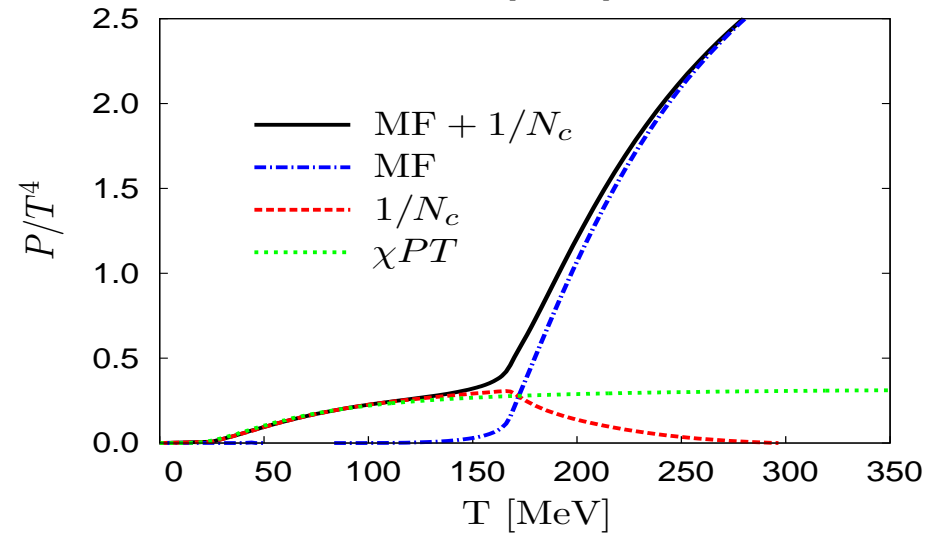
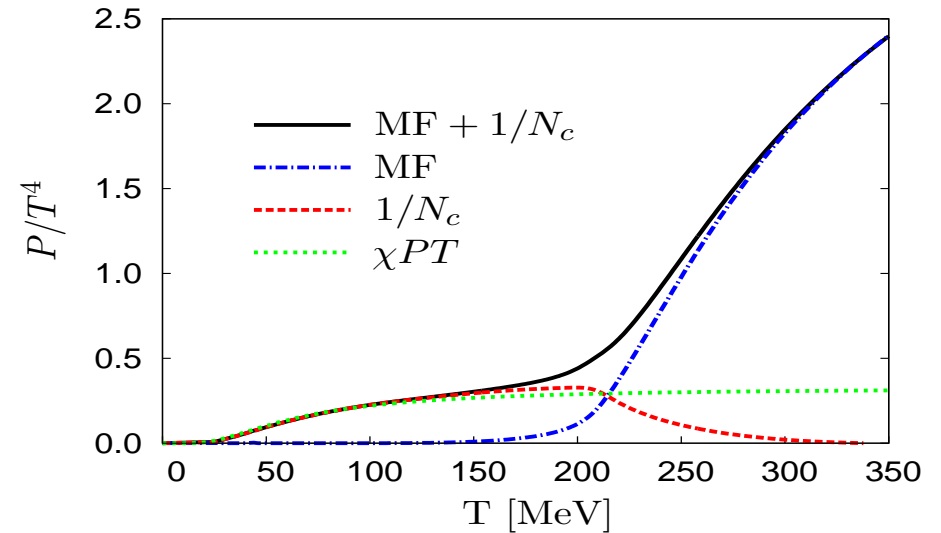
Nonlocal PNJL model beyond meanfield:

Blaschke et al., *Yad. Fiz.* 71 (2008)

Radzhabov et al., *PRD* 83 (2011) 116004



PL-Potential with  $T_0 = 270$  MeV (upper panel),  
and  $T_0 = 208$  MeV (lower panel)  $\implies$



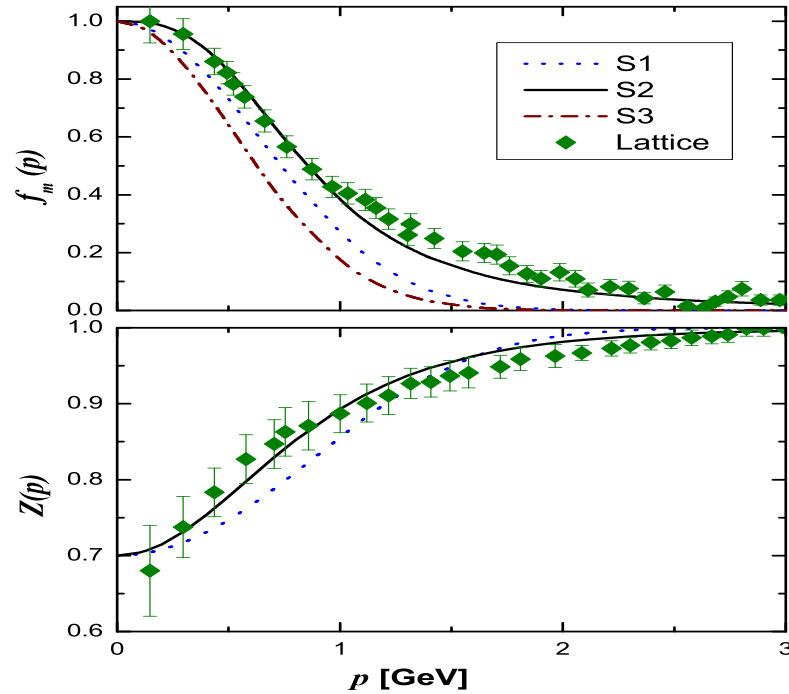
# NONLOCAL PNJL MODEL VS. LATTICE QCD

$$S_E = \int d^4x \left\{ \bar{\psi}(x) (-i\gamma_\mu D_\mu + \hat{m}) \psi(x) - \frac{G_S}{2} [j_a(x)j_a(x) - j_P(x)j_P(x)] + \mathcal{U}(\Phi[A(x)]) \right\},$$

Nonlocal currents

$$j_a(x) = \int d^4z g(z) \bar{\psi}\left(x + \frac{z}{2}\right) \Gamma_a \psi\left(x - \frac{z}{2}\right)$$

$$j_P(x) = \int d^4z f(z) \bar{\psi}\left(x + \frac{z}{2}\right) \frac{i\overleftrightarrow{\partial}}{2\kappa_p} \psi\left(x - \frac{z}{2}\right)$$



Parappilly et al., Phys. Rev. D

Formfactors fitted to Lattice results

$$g(q) = \frac{1 + \alpha_z}{1 + \alpha_z f_z(q)} \frac{\alpha_m f_m(q) - m \alpha_z f_z(q)}{\alpha_m - m \alpha_z}$$

$$f(q) = \frac{1 + \alpha_z}{1 + \alpha_z f_z(q)} f_z(q)$$

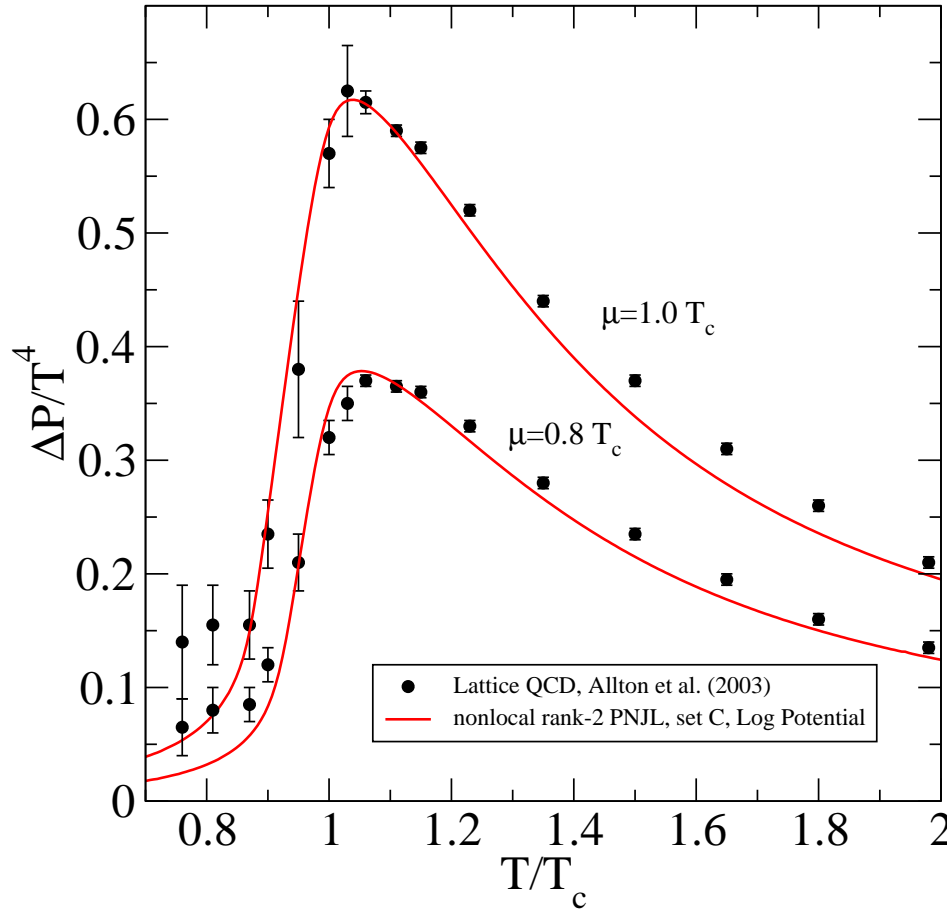
$$f_m(q) = \left[ 1 + (q^2/\Lambda_0^2)^{3/2} \right]^{-1}$$

$$f_z(q) = \left[ 1 + (q^2/\Lambda_1^2) \right]^{-5/2}.$$

Noguera, Scoccola, PRD 78, 114002 (2008)

# NONLOCAL PNJL MODEL VS. LATTICE QCD (II)

$$\Omega^{\text{MFA}} = -\frac{4T}{\pi^2} \sum_c \int_{p,n} \ln \left[ \frac{(\rho_{n,\vec{p}}^c)^2 + M^2(\rho_{n,\vec{p}}^c)}{Z^2(\rho_{n,\vec{p}}^c)} \right] + \frac{\sigma_1^2 + \kappa_p^2 \sigma_2^2}{2G_S} + \mathcal{U}(\Phi, T)$$



Mass function and WF renormalization

$$M(p) = Z(p) [m + \sigma_1 g(p)]$$

$$Z(p) = [1 - \sigma_2 f(p)]^{-1}.$$

Finite  $T, \mu$  formalism: Matsubara

$$(\rho_{n,\vec{p}}^c)^2 = [(2n + 1)\pi T - i\mu + \phi_c]^2 + \vec{p}^2,$$

Polyakov-loop potential:

Dexheimer-Schramm, arXiv:0910.1312

$$\mathcal{U}(\Phi, T, \mu) = (a_0 T^4 + a_1 \mu^4 + a_2 T^2 \mu^2) \Phi^2 + a_3 T_0^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)$$

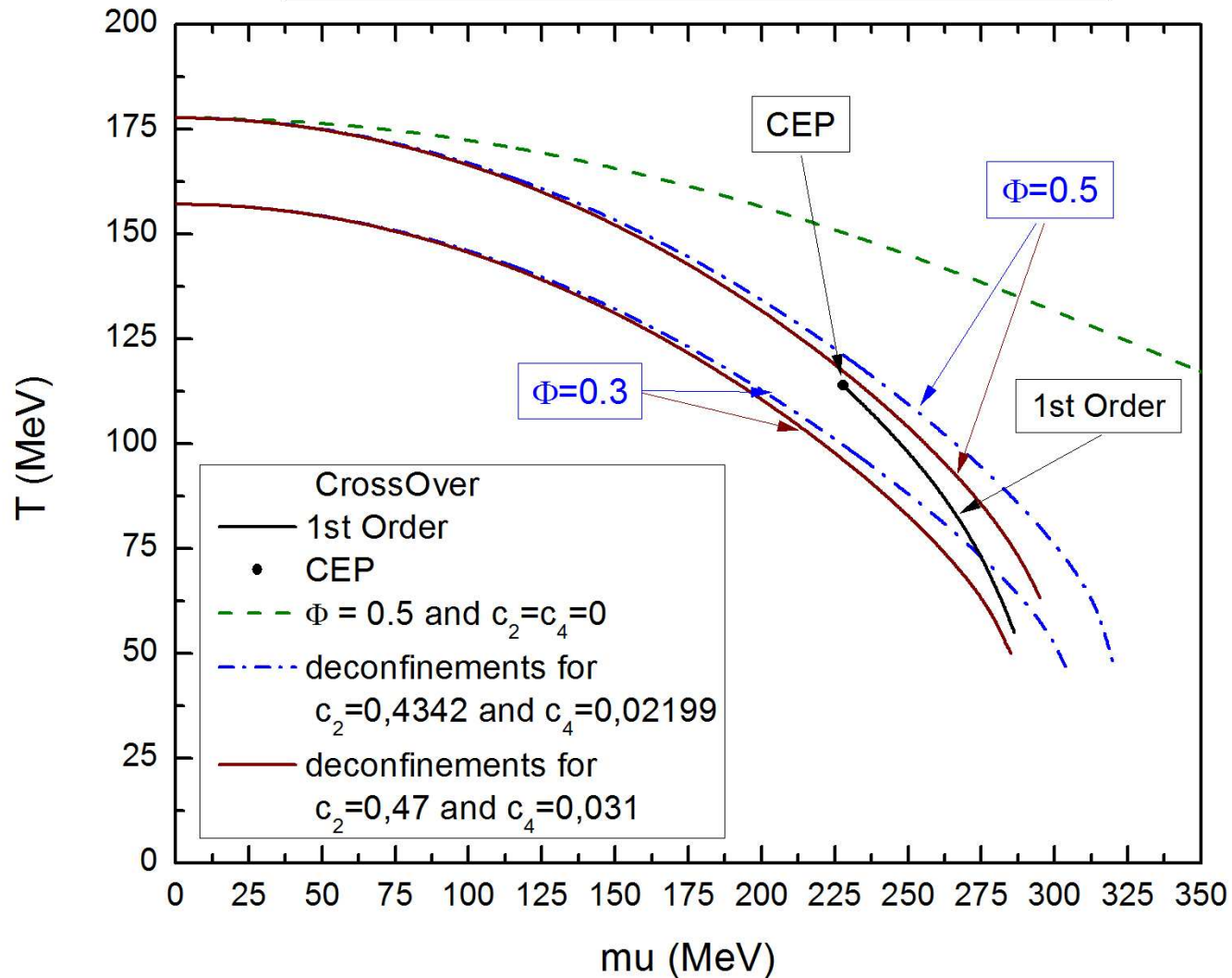
Parameters:

$$a_0 = 1.85, a_1 = 1.44 \times 10^{-3}, a_2 = 0.08, a_3 = 0.40$$

Contrera, D.B., in preparation

# NONLOCAL PNJL MODEL: PHASE DIAGRAM AND CP

Phase diagram - Set C - with  $\mu$  dependence



CEP Parameters:

$$T_{CP} = 128.6 \text{ MeV}$$

$$\mu_{CP} = 223.3 \text{ MeV}$$

$$\mu/T|_{CEP} = 1.74$$

Gustavo Contrera, D.B.,  
in preparation (2011)

## FROM DIQUARKS TO BARYONS (I)

The inverse diquark propagator is then obtained from

$$(S_D^A)^{-1}(k_0, k) = \frac{1}{4G_D} - \Pi_D^A(k_0, k) \quad , \quad \Pi_D^A(k_0, k) = \int \frac{d^4q}{(2\pi)^4} S_Q(q) \Sigma^A(k) S_Q(q - k) \Sigma^A(k)$$

Propagator can be expressed via the spectral density after analytic continuation

$$S_D^A(z, k) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{\varrho_D^A(\omega, k)}{z - \omega} \quad , \quad \varrho_D^A(\omega, k) = \lim_{\varepsilon \rightarrow 0} \frac{8G_D^2 \text{Im}\Pi_D^A(\omega + i\varepsilon, k)}{[1 - 2G_D \text{Re}\Pi_D^A(\omega + i\varepsilon, k)]^2 + [2G_D \text{Im}\Pi_D^A(\omega + i\varepsilon, k)]^2}$$

Similar, baryon propagator and spectral density

$$S_B^{-1}(P_0, P) = \frac{1}{G_B} - \Pi_B(P_0, P) \quad , \quad \Pi_B(P_0, P) = \sum_{A=2,5,7} \int \frac{dk^4}{(2\pi)^4} S_Q^{11,A}(P - k) S_D^A(k)$$

Further details:

**Wang, Wang, Rischke, PLB (2011); arXiv:1008.4029 [nucl-th]**

**Zablocki, Blaschke, Buballa, in preparation (2011)**

## THERMODYNAMIC POTENTIAL IN TERMS OF PHASE SHIFT

Integrating the spectral density over the coupling constant leads to

$$\int_0^G \frac{dg}{g^2} \rho_B^g(\omega, \mathbf{P}) = \frac{i}{2} \log \left( \frac{\frac{1}{G} - \Pi_B(\omega + i\delta, \mathbf{P})}{\frac{1}{G} - \Pi_B(\omega - i\delta, \mathbf{P})} \right) \equiv \delta_B(\omega, \mathbf{P}).$$

The **in-medium phase shift**  $\delta_{\mu,T}(\omega, \mathbf{P})$  is the argument of the dynamic pair susceptibility

$$\frac{\frac{1}{G} - \Pi_B(\omega \pm i\delta, \mathbf{P})}{|\frac{1}{G} - \Pi_B(\omega, \mathbf{P})|} = e^{\mp i\delta_B(\omega, \mathbf{P})}.$$

Thermodynamical potential in Beth-Uhlenbeck type form

$$\begin{aligned} \Omega_B^{(2)}(T, \mu) &= -d_B \int_{-\infty}^{\infty} \frac{d\omega}{\pi} \frac{d\mathbf{P}}{(2\pi)^3} \tilde{f}_B(\omega) \delta_B(\omega, \mathbf{P}), \\ &= d_B \int_0^{\infty} \frac{d\omega}{\pi} \frac{d\mathbf{P}}{(2\pi)^3} [1 - f_B(\omega) - f_{\bar{B}}(\omega)] \delta_B(\omega, \mathbf{P}), \\ &= d_B \int_0^{\infty} \frac{d\omega}{\pi} \frac{d\mathbf{P}}{(2\pi)^3} \left\{ \omega + T \ln[1 + e^{-(\omega-3\mu)/T}] + T \ln[1 + e^{-(\omega+3\mu)/T}] \right\} \frac{\partial \delta_B(\omega, \mathbf{P})}{\partial \omega}, \end{aligned}$$

Pole approximation  $\rightarrow$  Walecka model:  $\Omega_{\text{tot}} = \Omega_{\text{MF}} + \Omega_B^{(2)}$

See also [Abuki, NPA 791 \(2007\) 117](#) and [Zablocki, D.B., Buballa, in prep. \(2011\)](#)

# 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\\*](http://www.compstar-esf.org/compose*)  
[compose@compstar-esf.org](mailto:compose@compstar-esf.org)<sup>†</sup>

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<sup>st</sup> 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, ...

# 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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## SUMMARY

- Generalized Beth-Uhlenbeck approach as microphysical basis to account for hadron dissociation (Mott effect) at extreme temperatures and densities
- Benchmark: pion and sigma Mott effect within NJL model, revised within nonlocal PNJL model
- Nonlocal PNJL model calibrated with lattice quark propagator data, EoS at finite  $T$  and  $\mu$ , Phase diagram with critical point
- Application of GBU to interpret chemical freeze-out as Mott-Anderson localization
- Effective GBU model description: Mott-Hagedorn resonance gas + PNJL model describes Lattice QCD thermodynamics

## OUTLOOK: NEXT STEPS ...

- Walecka model as limit of PNJL model: chiral transition effects in nuclear EoS
- Prospects for HIC (CBM & NICA) and Supernovae: color superconducting (quarkyonic) phases accessible!

48th Karpacz Winter School of Theoretical Physics

# Cosmic Matter in Heavy-Ion Collision Laboratories

Łądek Zdrój, Poland, February 4-11, 2012

## Lecturers

P. Haensel (Warsaw):

*Dense matter and compact stars*

J.-P. Blaizot (Saclay):

*Matter under extreme conditions*

H. Satz (Bielefeld):

*Analysis of matter in QCD*

W. Florkowski (Cracow):

*Ultrarelativistic heavy-ion collisions*

M. Gaździcki (Frankfurt/Kielce):

*Energy scan programs in HIC*

G. Martinez-Pinedo (Darmstadt):

*Supernovae and the origin of heavy elements*

## Contact

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Nuclear Astrophysics  
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## Invitations:

Karpacz Winter School on Theoretical Physics

“Cosmic Matter in Heavy-Ion Collision Laboratories”

Łądek Zdrój, Poland, February 4-11, 2012

<http://www.ift.uni.wroc.pl/~karp48>

International Conference

“CompStar:

the physics and astrophysics of compact stars”

Tahiti, June 4-8, 2012

<http://compstar-esf.org>

Helmholtz International Summer School

“Dense Matter in HIC & Astrophysics”

Dubna, Russia, 2012

<http://theor.jinr.ru/meetings>

CompStar School & Workshop

“EoS in Compact Star Astrophysics & HIC”

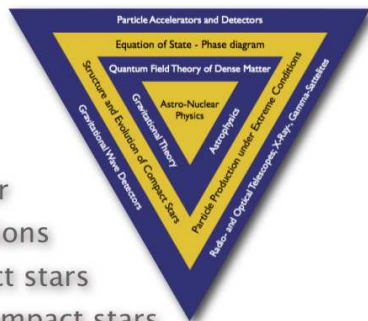
Zadar, Croatia, September 2012

<http://compstar-esf.org>

**CompStar: the physics and astrophysics of compact stars**

**Tahiti, June 4-8, 2012**

astrochemistry  
 neutrino physics  
 superdense matter  
 supernova explosions  
 physics of compact stars  
 astrophysics of compact stars  
 gravitational waves from compact stars



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**Invitations:**

Karpacz Winter School on Theoretical Physics  
 “Cosmic Matter in Heavy-Ion Collision Laboratories”

Lądek Zdròj, Poland, February 4-11, 2012  
<http://www.ift.uni.wroc.pl/~karp48>

International Conference  
 “CompStar:  
 the physics and astrophysics of compact stars”

Tahiti, June 4-8, 2012  
<http://compstar-esf.org>

Helmholtz International Summer School  
 “Dense Matter in HIC & Astrophysics”  
 Dubna, Russia, 2012  
<http://theor.jinr.ru/meetings>

CompStar School & Workshop  
 “EoS in Compact Star Astrophysics & HIC”  
 Zadar, Croatia, September 2012  
<http://compstar-esf.org>

IT'S FUN TO INVESTIGATE HOT & DENSE STATES OF MATTER !!

