Properties of symmetric and asymmeteric nuclear matter within DBHF theory

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ANL EOS workshop

August 2008

Outline

Introduction

Relativistic dynamics

Dirac-Brueckner-Hartree-Fock

Nuclear bulk properties

Proton-neutron mass splitting

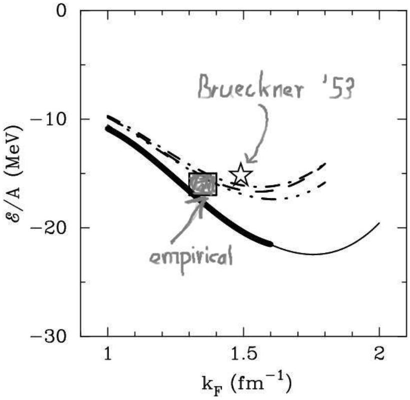
DBHF versus BHF

Chiral condensate

Heavy ion reactions

Summary

Quest for the EOS

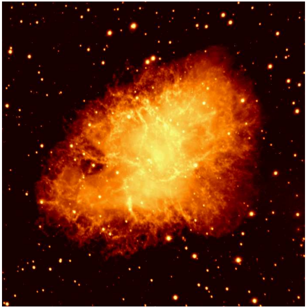


- EOS at high density ?
- EOS at extreme isospin ?

Creation of super-dense mattter

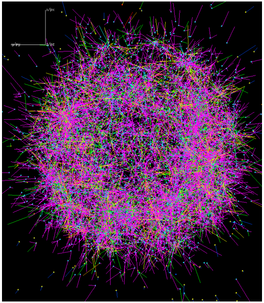
One has to compress by

Gravitation



$\rho \simeq 10\rho_0$

Kinetic energy



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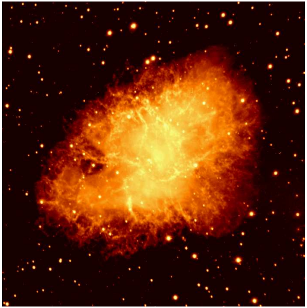

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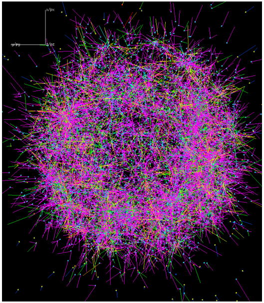

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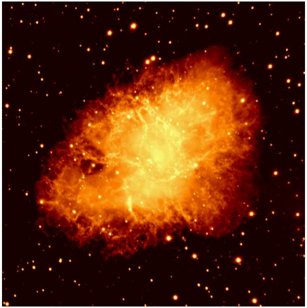

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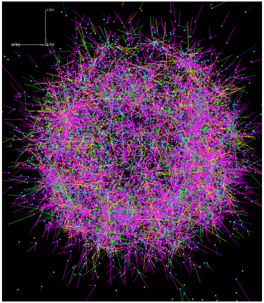

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Overview models

- Ab inito approaches
  Brueckner-Hartree-Fock (BHF), Relativistic Brueckner (DBHF)
  variational appr., Quantum Monte Carlo
  realistic NN-interaction, no parameters
- Effective field theory
  Density functionals, ChPT
  peturbativ, scale arguments (m_π / M, k_F / M), few parameters (< 2)
- Empirical density functionals
  Skyrme, Relativistic Mean Field
  many parameters (6-10), high precison fits to finite nuclei
- Relativistic versus non-relativistic approaches

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Relativity in nuclear systems?

Relevance of relativity:

$k_{\rm F}/M \simeq 1/4 \rightarrow$ velocity $v \simeq 1/4c$
$\rightarrow$ moderate corrections from relativistic kinematics

But:

- Relativistic dynamics: new scale
  RMF, Hadronic many-body theory (DBHF), QCD sum rules

  $$\rightarrow \quad \Sigma_{\rm s} \simeq -350 \text{ MeV}, \Sigma_0 \simeq +300 \text{ MeV}$$

- Cancellation in mean field potential $U_{\rm s.p.} \simeq \Sigma_{\rm o} + \Sigma_{\rm s} \simeq -50$ MeV
- Large spin-orbit force $U_{\rm S.O.} \propto (\Sigma_{\rm o} - \Sigma_{\rm s})\vec{L} \cdot \vec{S} \simeq +750$ MeV

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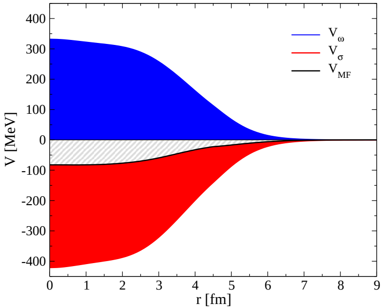
Known from phenomenology

boson-exchange, RMF:
large scalar/vector fields
$\Longrightarrow$ large SO force



Is the new scale universal?

relation to NN-scattering ?
large fields as a consequence of Lorentz symmetry ?
relation to chiral condensate ?

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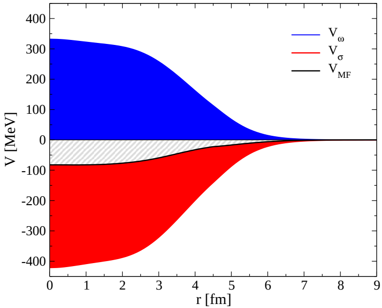

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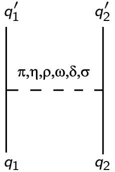
One-boson exchange potentials

Bonn and CD-Bonn potentials

$$V(\mathbf{q}',\mathbf{q}) = \sum_{\alpha=s,ps,v} \bar{V}_\alpha(\mathbf{q}',\mathbf{q})\; \mathcal{F}^2_\alpha(\mathbf{q}',\mathbf{q};\lambda_\alpha)$$



$$-i\bar{V}_\alpha(q',q) = \frac{\bar{u}(-\mathbf{q}')\,\kappa_2^{(\alpha)}\,u(-\mathbf{q})P_\alpha\;\bar{u}(\mathbf{q}')\,\kappa_1^{(\alpha)}\,u(\mathbf{q})}{(q'-q)^2 - m_\alpha^2}, \quad u_\lambda(\mathbf{q}) = \sqrt{\frac{E+M}{2M}}\begin{pmatrix}1\\ \frac{2\lambda|\mathbf{q}|}{E+M}\end{pmatrix}\chi_\lambda$$

Dirac structure $\kappa^{(s)} = g_s\mathbf{1}$, $\kappa^{(ps)} = g_{ps}\frac{\not{q}'-\not{q}}{2M}i\gamma_5$, $\kappa^{(v)} = g_v\gamma^\mu + \frac{f_v}{2M}i\sigma^{\mu\nu}$

→ various scales and spin-isospin structure associated with meson exchange,
long range=OPE, short/intermediate range = heavy mesons

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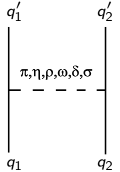

$$-i\bar{V}_\alpha(q', q) \;=\; \frac{\bar{u}(-\mathbf{q}') \; \kappa_2^{(\alpha)} u(-\mathbf{q}) P_\alpha \;\; \bar{u}(\mathbf{q}') \; \kappa_1^{(\alpha)} u(\mathbf{q})}{(q' - q)^2 - m_\alpha^2}, \qquad u_\lambda(\mathbf{q}) = \sqrt{\frac{E + M}{2M}} \begin{pmatrix} 1 \\ \frac{2\lambda|\mathbf{q}|}{E+M} \end{pmatrix} \chi_\lambda$$

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Non-relativistic potentials

Low energy expansion of OBE potential

$$V(\mathbf{q}', \mathbf{q}) = \sum_{\alpha=1,5} [V_\alpha + V'_\alpha \tau_1 \cdot \tau_2] \, O_\alpha$$

$$O_1 = 1,$$
$$O_2 = \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2,$$
$$O_3 = (\boldsymbol{\sigma}_1 \cdot \mathbf{k})(\boldsymbol{\sigma}_2 \cdot \mathbf{k}),$$
$$O_4 = \frac{i}{2}(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \mathbf{n},$$
$$O_5 = (\boldsymbol{\sigma}_1 \cdot \mathbf{n})(\boldsymbol{\sigma}_2 \cdot \mathbf{n}),$$

$$\mathbf{k} = \mathbf{q}' - \mathbf{q},$$
$$\mathbf{P} = \frac{1}{2}(\mathbf{q}' + \mathbf{q}),$$
$$\mathbf{n} = \mathbf{q} \times \mathbf{q}' = \mathbf{P} \times \mathbf{k},$$

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\end{aligned}$$

Non-relativistic potentials

- Nijm 93 and Nijmegen I/II

  long range part due to OPE, approximate OBE amplitudes
- Argonne v_{18}

  long range part due to OPE, intermediate and short range parametrized via operators O_α and strength functions V_α
- Idaho potential

  Chiral effective field theory, N^3LO, D. Entem and R. Machleidt, (29 free model parameters)
- V_{lowk}

  Derivation of an effective low-momentum potential V_{lowk} from modern NN potentials (out-integration of high-momentum modes, $\Lambda \simeq 2fm^{-1}$, and use of renormalization group methods)

Projection onto covariant operators

$|\mathrm{LSJ}\rangle \rightarrow$ partial wave helicity basis $\rightarrow$ plane wave helicity basis $\rightarrow$ Covariant basis

Choice of basis

- **Fermi covariants** $\Gamma_m = \{\mathrm{S}, \mathrm{V}, \mathrm{T}, \mathrm{P}, \mathrm{A}\}$

  $\mathrm{S} = \mathbf{1} \otimes \mathbf{1}, \quad \mathrm{V} = \gamma^\mu \otimes \gamma_\mu, \quad \mathrm{T} = \sigma^{\mu\nu} \otimes \sigma_{\mu\nu}, \quad \mathrm{P} = \gamma_5 \otimes \gamma_5, \quad \mathrm{A} = \gamma_5 \gamma^\mu \otimes \gamma_5 \gamma_\mu$

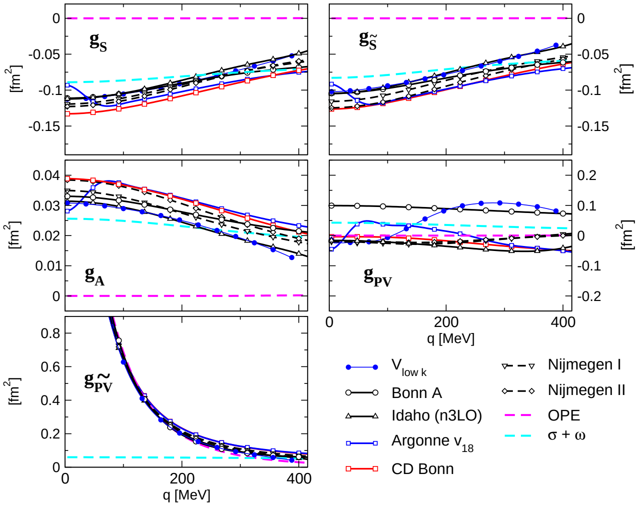
- **Pseudovector choice** (Tjon and Wallace) $\quad \Gamma_m = \{\mathrm{S}, \tilde{\mathrm{S}}, (\mathrm{A} - \tilde{\mathrm{A}}), \mathrm{PV}, \widetilde{\mathrm{PV}}\}$

  Exchange covariants $\tilde{\Gamma}_m = \tilde{\mathrm{S}} \Gamma_m, \quad \tilde{\mathrm{S}} u(1)_\sigma u(2)_\tau = u(1)_\tau u(2)_\sigma$

Pseudovector choice

$$\hat{V}^{\mathrm{I}}(|\mathbf{q}|, \theta) = g^{\mathrm{I}}_{\mathrm{S}}(|\mathbf{q}|, \theta)\, \mathrm{S} - g^{\mathrm{I}}_{\tilde{\mathrm{S}}}(|\mathbf{q}|, \theta)\, \tilde{\mathrm{S}} + g^{\mathrm{I}}_{\mathrm{A}}(|\mathbf{q}|, \theta)\, (\mathrm{A} - \tilde{\mathrm{A}})$$
$$+ g^{\mathrm{I}}_{\mathrm{PV}}(|\mathbf{q}|, \theta)\, \mathrm{PV} - g^{\mathrm{I}}_{\widetilde{\mathrm{PV}}}(|\mathbf{q}|, \theta)\, \widetilde{\mathrm{PV}}$$

Lorentz invariant amplitudes



Self-energy in Hartree-Fock approximation

$$\Sigma_{\alpha\beta}(k,k_F) = -i\int_F \frac{d^4q}{(2\pi)^4}\; G^D_{\tau\sigma}(q)\; V^A(k,q)_{\alpha\sigma;\beta\tau}$$

Dirac propagator $\quad G^D(q) = [\not{q} + M]2\pi i\delta(q^2 - M^2)\Theta(q_0)\Theta(k_F - |\mathbf{q}|)$

$$\Sigma(k,k_\mathrm{F}) = \Sigma_\mathrm{s}(k,k_\mathrm{F}) - \gamma_0\,\Sigma_\mathrm{o}(k,k_\mathrm{F}) + \boldsymbol{\gamma}\cdot\mathbf{k}\,\Sigma_\mathrm{v}(k,k_\mathrm{F}),$$

$$\begin{aligned}
\Sigma_\mathrm{s} &= \frac{1}{4}\int^{k_F}\frac{d^3|\mathbf{k}|}{(2\pi)^3}\frac{M}{E_\mathbf{q}}\left[4g_\mathrm{S} - g_{\tilde{\mathrm{S}}} + 4g_\mathrm{A} - \frac{(k^\mu - q^\mu)^2}{4M^2}g_{\widetilde{\mathrm{PV}}}\right]\\
\Sigma_\mathrm{o} &= \frac{1}{4}\int^{k_F}\frac{d^3|\mathbf{q}|}{(2\pi)^3}\left[g_{\tilde{\mathrm{S}}} - 2g_\mathrm{A} + \frac{E_\mathbf{k}}{E_\mathbf{q}}\frac{(k^\mu - q^\mu)^2}{4M^2}g_{\widetilde{\mathrm{PV}}}\right]\\
\Sigma_\mathrm{v} &= \frac{1}{4}\int^{k_F}\frac{d^3|\mathbf{q}|}{(2\pi)^3}\frac{|\mathbf{k}|\cdot|\mathbf{q}|}{|\mathbf{k}|^2 E_\mathbf{q}}\left[g_{\tilde{\mathrm{S}}} - 2g_\mathrm{A} + \frac{k_z}{q_z}\frac{(k^\mu - q^\mu)^2}{4M^2}g_{\widetilde{\mathrm{PV}}}\right]
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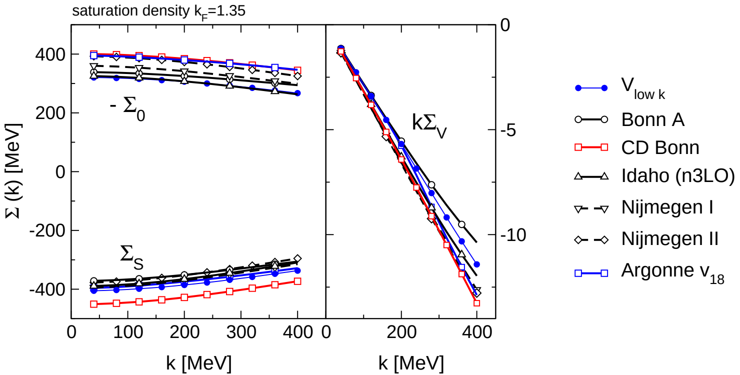
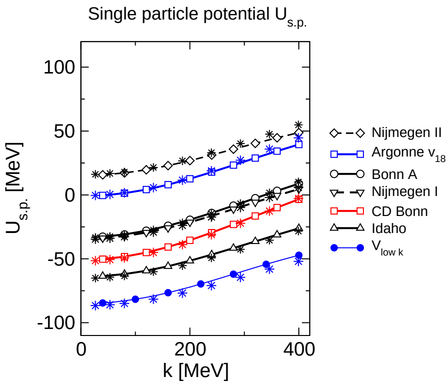
Large scalar/vector fields

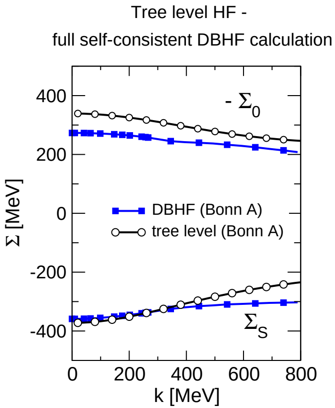


Mapping of NN potentials on relativistic operator basis
→ large scalar/vector fields → universal feature of NN interaction

O. Plohl, C.F., van Dalen, PRC 73 (2006) 014003

Role of short range correlations





$$U_{s.p.}(k) = \frac{M}{E_{\mathbf{k}}} \langle \bar{u}(k)|\Sigma|u(k)\rangle$$
$$= M\Sigma_{\rm s}/E_{\mathbf{k}} - \Sigma_{\rm o} + \Sigma_{\rm v}\mathbf{k}^2/E_{\mathbf{k}}$$

What generates the scale in chiral EFT?

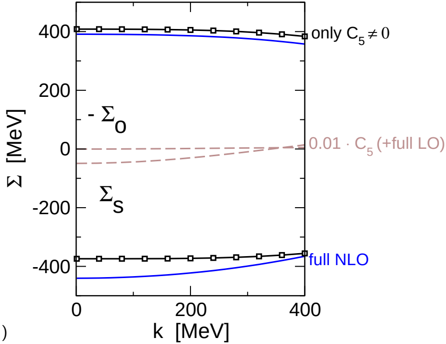
LO

$V = -\frac{g_A^2}{4f_\pi^2}\frac{\vec{\sigma}_1\cdot\vec{k}\,\vec{\sigma}_2\cdot\vec{k}}{q^2+m_\pi^2}, \quad V = C_S + C_T\vec{\sigma}_1\cdot\vec{\sigma}_2$

NLO

leading order 2π exchange

$V = \ldots + C_5(-i\vec{S}\cdot(\vec{q}\times\vec{q}\,')+\ldots + C_7(..)$



Large scalar/vector fields → NLO contact terms (strength of LEC C_5 is dictated by P-wave NN scattering)
→ Effective nucleon mass $M^* = M + \Sigma_S$ → short-distance physics

O. Plohl, C.F., PRC 74 (2006) 034325

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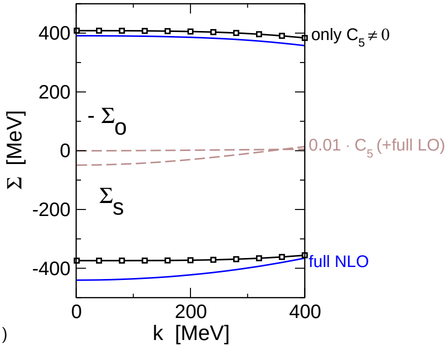

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Relativistic Brueckner

- N+OBEP ($V = \sigma, \omega, \pi, \rho, \eta, \delta$)
- 2-N correlations in hole-line expansion
- self-consistent sum of ladder diagrams

Dyson-Equation:

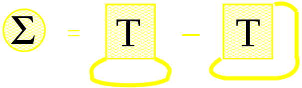
$$G = G_0 + G_0 \Sigma G$$

Bethe-Salpeter-Equation:

$$T = V + i \int VGGQT$$

Self Energy:

$$\Sigma(\rho, k) = \sum_{q \epsilon F} < q | T(q,k) | q > = \Sigma_S - \gamma_0 \Sigma_0 + \vec{\gamma} \cdot \vec{k} \Sigma_V$$



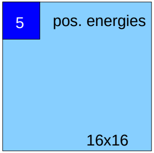
Technicalities/approximations

- 3-dim. reduction of BSE: Thompson eq.
- angle averaged Pauli operator
- Quadratic approx. to s.p. potential: $\Sigma_{S,0}(k_F)$
  Brockmann/Machleidt 90, Envik et al., Sammarunca et al.,...

$$U_{s.p.}(k) = = \frac{m^*}{E^*} \sum_{q \epsilon F} < kq|T(q,k)|kq >= \frac{m^* \Sigma_S}{\sqrt{\mathbf{k}^2 + (M + \Sigma_S)^2}} - \Sigma_0$$

- Projection on covariant amplitudes: $\Sigma_{S,0,V}(k_F, k)$
  Horowitz/Serot 87, Malfliet et. al., Tübingen
- Include negative energy states
  Weigel et al., DeJong/Lenske

PV choice reduces on-shell ambiguities



- On-shell: Equal *ps* and *pv* matrix elements
- *ps* couples to negative enrgy states:

$$< \bar{u}|P|u > = < \bar{u}|PV|u > \quad , \quad < \bar{v}|P|u > = 1, < \bar{v}|PV|u > = 0$$

- Different contributions to Σ:

$$tr[\widetilde{P}G(q)] >> tr[\widetilde{PV}G(q)]$$

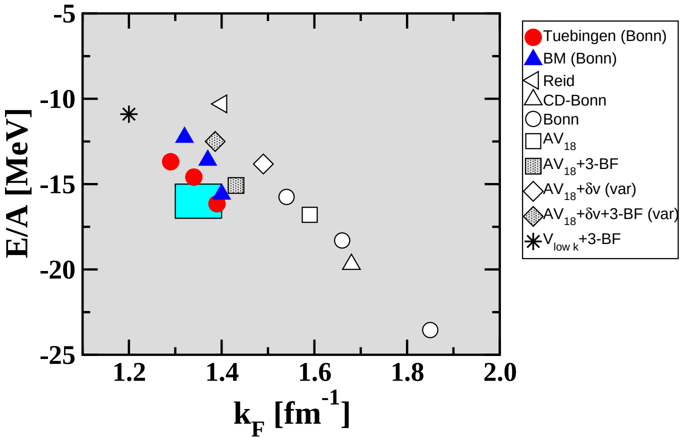
- critical for 1-π-exchange:
  pv coupling removes spurious contributions to Σ_S and Σ_0
- Only possible in Tjon&Wallace basis

Isospin asymmetric matter

- Coupled channel problem for the *np* channel
- 6 instead of 5 independent helicity/covariant amplitudes

$$
\begin{aligned}
T_{nn} &= V_{nn} + i \int V_{nn} Q_{nn} G_n G_n T_{nn} \\
T_{pp} &= V_{pp} + i \int V_{pp} Q_{pp} G_p G_p T_{pp} \\
T_{np}^{D} &= V_{np}^{D} + i \int V_{np}^{D} Q_{np} G_n G_p T_{np}^{D} + i \int V_{np}^{X} Q_{pn} G_p G_n T_{np}^{X} \\
T_{np}^{X} &= V_{np}^{X} + i \int V_{np}^{X} Q_{pn} G_p G_n T_{np}^{D} + i \int V_{np}^{D} Q_{np} G_n G_p T_{np}^{X}
\end{aligned}
$$

Model comparision: nuclear matter



see e.g. C.F. arXiv:0711.3367

Bulk properties (with Bonn A)

- Saturation properties:

$$\rho_{sat} = 0.184\ fm^{-3} \quad E_B = -16.15 \quad K = 230\ MeV \quad M^* = 637\ MeV$$

- Symmetry energy:

$$E_{sym} = 31.6\ MeV \ \ @ \ \ \rho = 0.160\ fm^{-3}$$

- Maximal neutron star mass:

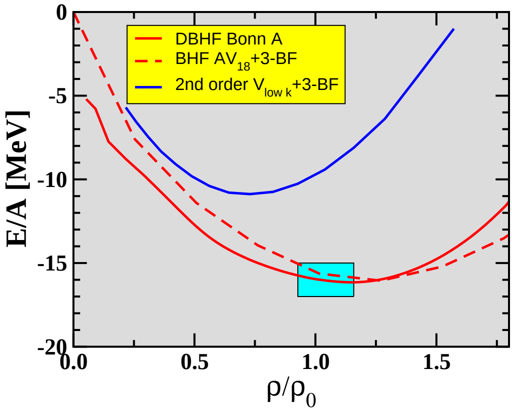
$$M = 2.33\ M_\odot$$

Gross-Boelting, C.F., Faessler, NPA 648 (1999) 105

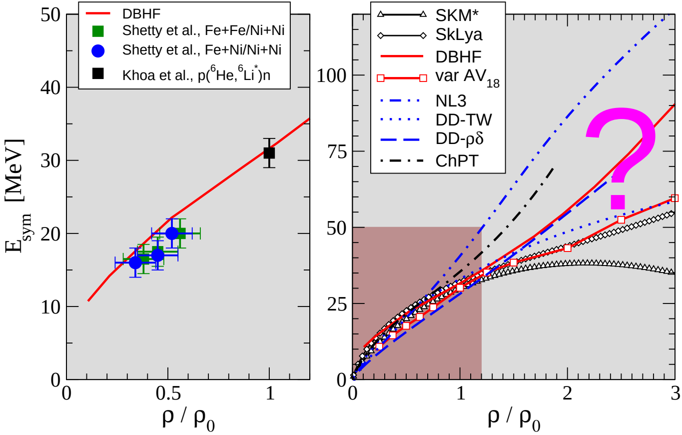
van Dalen, C.F., Faessler, NPA 744 (2004) 227

Model comparison: EOS

Perturbative treatment with $V_{low\ k}$+3-BFs (Bogner et al, NPA 763 (2005) 59)
BHF with AV_{18}+3-BFs (Catania group)



Model comparison: symmetry energy



$$E(\rho,\beta) = E(\rho) + E_{\text{sym}}(\rho)\beta^2 + \mathcal{O}(\beta^4) + \cdots \qquad \beta = Y_n - Y_p$$

Effective nucleon mass

Different definitions are used!

- Non-relativistic mass:

$$m^*_{NR} \quad = \quad \left[M + \frac{1}{k}\frac{d}{dk} U_{s.p.} \right]^{-1} = |\mathbf{k}|[dE/d|\mathbf{k}|]^{-1}$$

parameterizes non-locality in space (k-mass) and time (e-mass)

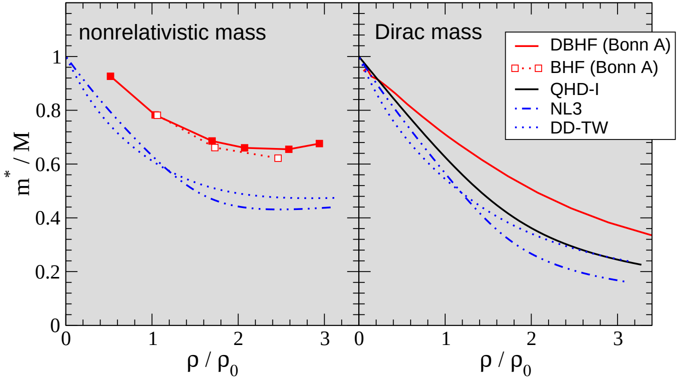
Mahaux et al., Müther, Frick,..

- Dirac mass:

$$m^*_D = M + \Sigma_S \quad , U_{s.p.} \simeq \frac{m^*_D}{E^*}\Sigma_S + \Sigma_0$$

scalar part of self energy

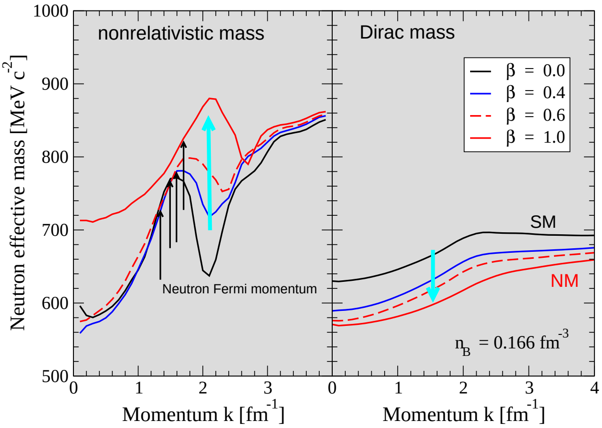
Effective nucleon mass



Proton-neutron mass splitting

- BHF: $m^*_{NR,n} > m^*_{NR,p}$
- RMF: $m^*_{D,n} < m^*_{D,p}$; $m^*_{NR,n} < m^*_{NR,p}$ $(\rho + \delta)$
  Baran, Di Toro et al., Phys. Rep. 410 ('05) 335
- DBHF with Σ extracted by fit method: $m^*_{D,n} > m^*_{D,p}$
  Alonso & Sammarunca, PRC 67 ('03) 054301
- DBHF with projection method: $m^*_{D,n} < m^*_{D,p}$
  de Jong & Lenske, PRC 58 ('98) 890; van Dalen, C.F., Faessler, NPA 744 ('04) 227
- non-rel. mass in DBHF: $m^*_{NR,n} > m^*_{NR,p}$
  van Dalen, C.F, Faessler, PRL 95 (2005) 022302

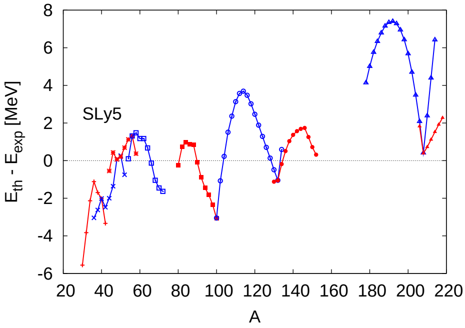
Proton-neutron mass splitting



van Dalen, C.F., Faessler, PRL 95 (2005) 022302

Guidance for phenomenology

SkLy5: mass splitting $m_n^* < m_p^*$ (in contrast to BHF/DBHF)



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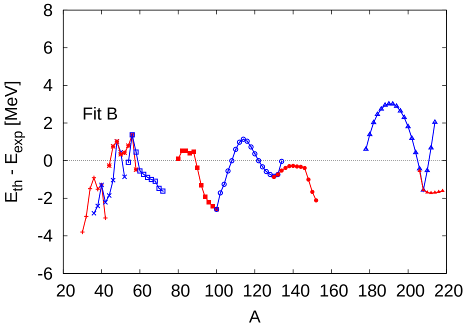
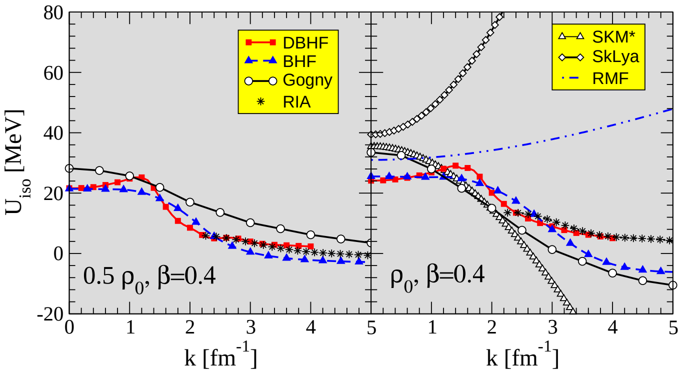


new fit, small change of parameters: $m_n^* > m_p^*$ $(\kappa_V = 0.3)$

Lesinski et al., PRC 74 (2006) 044315

Isovector optical potential: $U_{iso} = (U_n - U_p)/2\beta$



DBHF: van Dalen, C.F., Faessler, PRC 72 (2005) 065803

BHF: Zuo et al. PRC 72 (2005) 014005

RIA: Chen, Ko, Li, PRC 72 (2005) 064606

Main differences between DBHF/BHF

- vector/scalar density
  $\rho_B \propto a^\dagger a - b^\dagger b$
  $\rho_S \propto a^\dagger a + b^\dagger b$
- dressed interaction:
  $\langle u|V|u\rangle \mapsto \langle u^*|V|u^*\rangle$
- quenching of tensor force by m^*/M
  iterated OPE is less important for satuation
- New scale: large scalar/vector fields
- effective inclusion of 3-body forces:
  box diagramms, intermediate Δ
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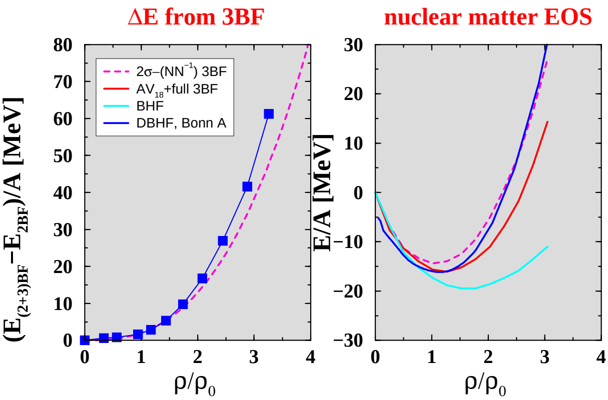
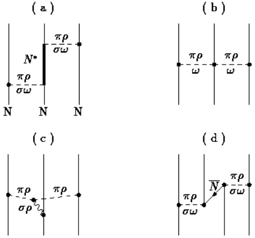
3-body forces



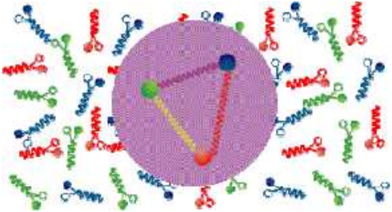


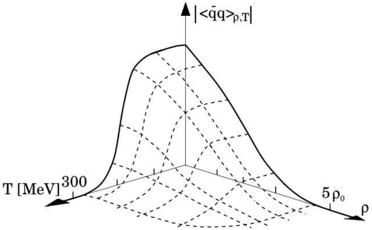
Zuo et al., NPA 418 (2002) 706

Connection to QCD

- scalar condensate: $\langle \bar{q}q \rangle \sim (-250\ MeV)^3$
- naive QCD sum rule interpretation:

$$\frac{\langle \bar{q}q \rangle_{\rho_B}}{\langle \bar{q}q \rangle_0} = \frac{M^*}{M}$$





In-medium chiral condensate

Hellmann-Feynman:

$$\frac{\langle \bar{q}q \rangle_{\rho_N}}{\langle \bar{q}q \rangle_0} = 1 - \frac{\rho_N}{m_\pi^2 f_\pi^2} \left[\sigma_N + m \frac{d}{dm} \frac{E}{A} \right]$$

pion-nucleon sigma-term $\quad \sigma_N = m \frac{dM}{dm} =< N|m\bar{q}q|N >$

Problem: unknown quark mass dependence

$$\sum_{\sigma,\omega,\pi,\rho} \left[\frac{\partial E}{\partial m_i} \frac{dm_i}{dm} + \frac{\partial E}{\partial g_i} \frac{dg_i}{dm_i} + \cdots \right] = ???$$

see e.g. Brockmann, Weise, PLB 367 (1996)

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Solution:

Determine E from chiral EFT NN interaction
Quark mass dependence known up to NLO

Epelbaum, Glöckle, Meissner, EPJA **18**, 499 (2003)

Exact calculation at NLO

Hartree-Fock
Brückner-Hartree-Fock

O. Plohl, C.F., NPA 798 (2008) 75

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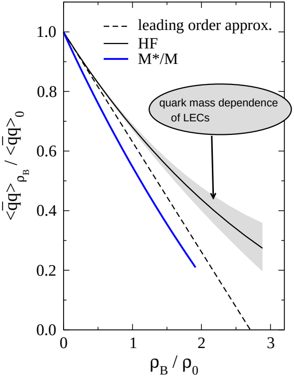
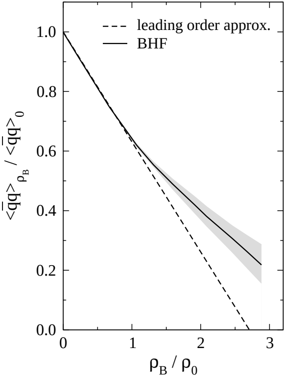
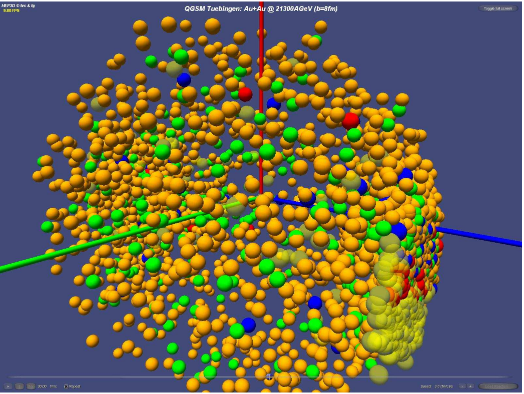




- decoupling of condensate and effective mass
- condensate driven by long-distance physics
- effective mass driven by short-distance physics

Probing dense matter by HICs



$Au + Au$, $\sqrt{s} = 200$ AGeV, QGSM Tübingen

- Advantage:
  On earth experiments
- Disdvantages:
  Short time scale, non-equlibrium
  Heated matter
  Small asymmetries
  Surface effects
- Observables:
  Collective flow
  Particle production

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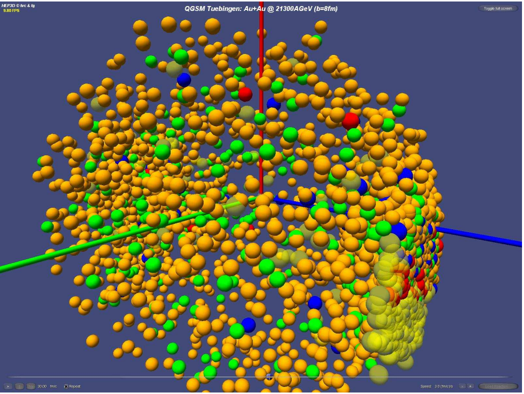

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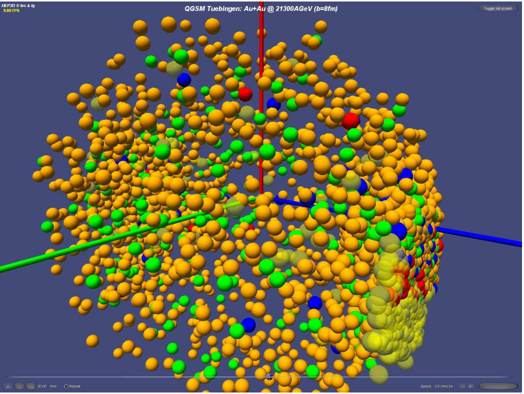

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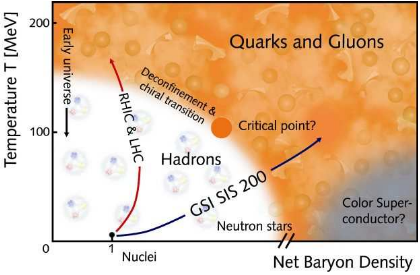
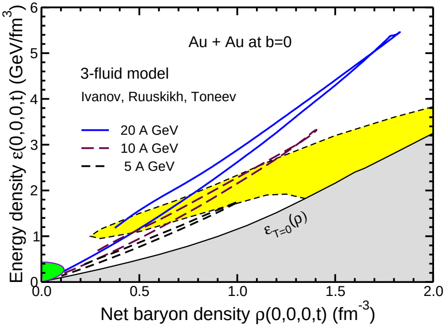
Densities at CBM/FAIR





- DOFs, phase transition?
- SIS: symmetric nuclear matter up to 3 ρ_0

see e.g. CBM Physics Book: Collision Dynamics

Subthreshold kaon production

- Subthreshold particle production: $E_{Lab} < E_{thr}$:
  $K^+(u\bar{s})$: $NN \longmapsto N\Lambda K^+$ $E_{thr} = 1.58$ GeV
  $\pi N \longmapsto \Lambda K^+$
  $K^-(\bar{u}s)$: $NN \longmapsto NNK^+K^-$ $E_{thr} = 2.5$ GeV
- Energy provided by multistep collisions:
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- $K^+(u\bar{s})$: strangeness conservation:
  (almost) no final state interaction
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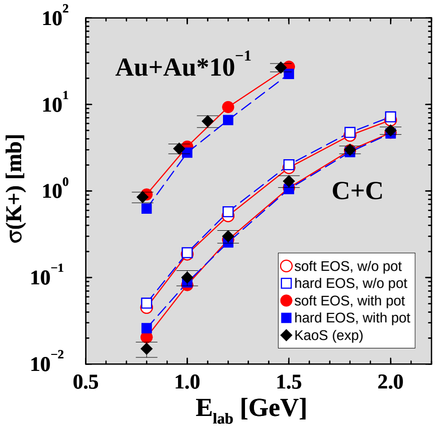
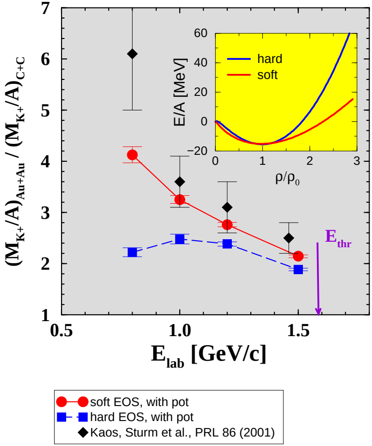
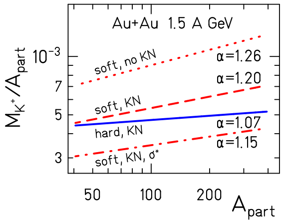
RQMD transport calculations

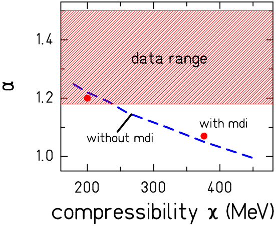


Data: Sturm et al., KaoS Coll., PRL 86 (2001) 39

Conclusions from KaoS data





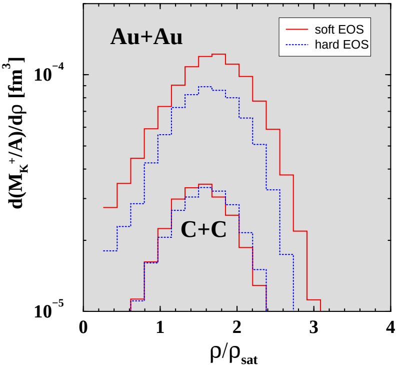


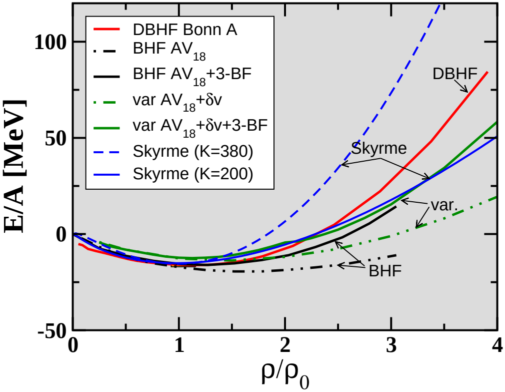
C.F. et al., PRL 86 (2001) 1974

C.F.,Prog. Part. Nucl. Phys. 56 (2006) 1

Hartnack et al. PRL 96 (2006) 012302

Density range tested by K^+ @ SIS





e.g. Au+Au @ 0.8 AGeV $<\rho/\rho_0>= 1.53$

Below $2.5 \div 3\rho_0$ EOS is soft!

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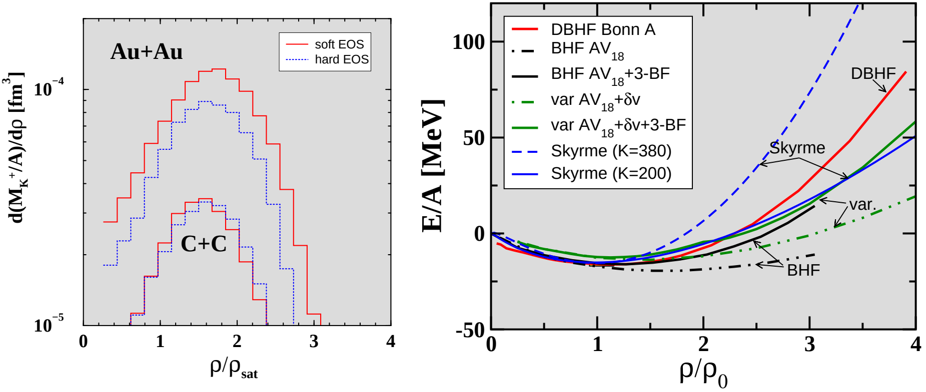

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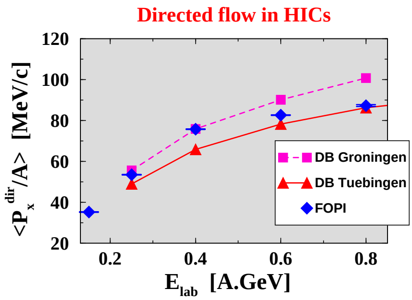
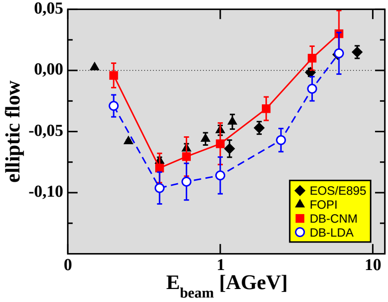
Directed/elliptic flow

RBUU transport: e.g. Gaitanos et al., EPJA 12 (2001) 421; C.F., Gaitanos, NPA 714 (2003) 634





Large non-equilibrium effects:

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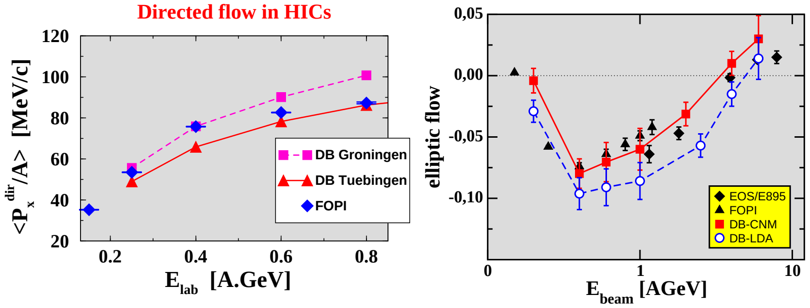

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  $\longrightarrow$ new scale: large fields
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