Study of the Nuclear Symmetry Energy: Future theoretical directions

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Excellence Cluster

Quest for the density dependence of Nuclear Symmetry Energy (NSE)
- now for more than 20 years of intensive research,
- still not well known, esp. at higher density
- but important for very asymmetric nuclear systems (exotic nuclei), and in astrophysics

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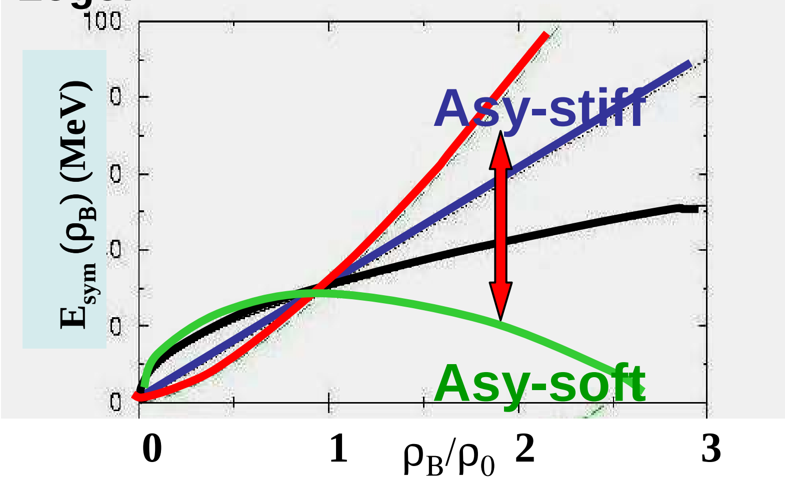
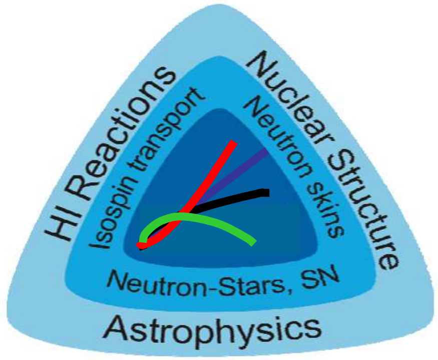


Why?
Since cannot be reliably calculated, one needs to look for observables in nuclear physics and astrophysics,
strong interdependence of theory and experiment,

-- experiments and observations: future prospects bright (see talks of E. Brown, G. Verde, Y. Leifels and Bill Lynch).

-- theory: more expansion desirable, esp. in Europe challenges in theory:

- microscopic calculation: effective forces and many-body theory
- theoretical interpretation of experiments
  a) nuclear structure beyond mean field
  b) HIC: transport approach
  c) astropysics: structure of NS and dynamics of CCSN



Note 1: the NSE is a rather simple, stationary concept (a piece of the nuclear EoS)
the way to study it involve much more complex systems
(finite, dynamical, non-equilibrium)

Note 2: all the above also true for the EOS in general, i.e. for symmetric nuclear
matter. However, the NSE is a subdominant component of the EoS,
and thus more difficult to observe and more difficult to calculate.

We are now in the quantative era of the study of the NSE!

This talk: try to identify the challenges in the theoretical treatments of the NSE
and the possible future directions:
illustrative and incomplete, qualitative, highly personal,
but not supposed to be a summary.

Evolved during workshop but special distracting event

Symmetry energy reviewed extensively in the past


A way forward in the study of the symmetry energy: experiment, theory, and observation

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(Dated: March 30, 2014)

The symmetry energy describes how the energy of nuclear matter rises as one goes away from equal numbers of neutrons and protons. This is very important to describe neutron rich matter in astrophysics. This article reviews our knowledge of the symmetry energy from theoretical calculations, nuclear structure measurements, heavy ion collisions, and astronomical observations. We then present a roadmap to make progress in areas of relevance to the symmetry energy that promotes collaboration between the astrophysics and the nuclear physics communities.

PACS numbers: 21.65.Cd, 21.65.Mn, 26.60.-c, 26.50.+x

I. INTRODUCTION

The liquid-drop formula of Bethe and Weizsäcker [1, 2] models the nucleus as an incompressible quantum drop consisting of Z protons, N neutrons, and mass number $A = Z + N$. In particular, the nuclear binding energy is expressed in terms of a handful of empirical parameters that capture the physics of a quantum drop. That is,

$$B(Z,N) = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \ldots \quad (1)$$

The volume term a_V represents the binding energy per nucleon of a large symmetric drop in the absence of long-range Coulomb forces. In turn, the next three terms denote binding-energy corrections resulting from the development of a nuclear surface, the Coulomb repulsion among protons, and the Pauli exclusion principle and strong interactions that favor symmetric ($N = Z$) systems. Although refinements to the mass formula have been made to account for the emergence of nuclear shells, the structure of this 75 year-old formula has remained practically unchanged.

In the thermodynamic limit in which both the number of nucleons and the volume are taken to infinity but their ratio remains fixed at the saturation density, the binding energy per nucleon may be written as

$$\varepsilon(\alpha) \equiv -\frac{B(Z,N)}{A} = -a_V + J\alpha^2, \quad (2)$$

where $J \equiv a_A$ and $\alpha = (N-Z)/A$ is the neutron-proton asymmetry. Note that we have neglected long-range Coulomb forces (which would render the drop unstable) and have assumed that both Z and N are individually conserved. Such a simple expression suggests that the binding energy per nucleon of a large symmetric drop of density $\rho_0 \approx 0.15\,\mathrm{fm}^{-3}$ is $a_V \approx 16$ MeV and that there is an energy cost of $J \approx 32$ MeV in converting all protons into neutrons. However, in reality the liquid drop is not incompressible, so the semi-empirical mass formula, while highly insightful, fails to describe the response of the liquid drop to density fluctuations. This information is contained in the equation of state (EOS) which dictates the dependence of the energy per nucleon on both the density and the neutron-proton asymmetry.[1] Following Eq. (2), we may write the equation of state of asymmetric matter as

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}(\rho,\alpha=0) + S(\rho)\alpha^2 + \ldots \quad (3)$$

where $\mathcal{E}(\rho,\alpha=0)$ is the EOS of symmetric nuclear matter and $S(\rho)$ is the symmetry energy:

$$S(\rho) = \frac{1}{2}\left(\frac{\partial^2 \mathcal{E}(\rho,\alpha)}{\partial \alpha^2}\right)_{\alpha=0} \approx \mathcal{E}(\rho,\alpha=1) - \mathcal{E}(\rho,\alpha=0). \quad (4)$$

Although the value of the symmetry energy at a density of $\rho \approx 0.1\,\mathrm{fm}^{-3}$ is fairly well constrained by the masses of heavy nuclei, at present its density dependence is poorly known. Note that the EOS of asymmetric matter is mainly characterized by the density dependence of the symmetry energy ($\partial S/\partial\rho$) which is essential for the understanding of the structure of neutron-rich nuclei, particle yields in heavy-ion collisions, and properties of neutron stars. To characterize the

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[1] The EOS and therefore the symmetry energy, are defined without model-dependent concepts. They include the effects of all kind of correlations in nuclear matter, such as the cluster correlations that are important at low densities.

.... difficult to say something new

What do we want to know about the NSE?

$$E(\rho_B,\delta)/A = E_{nm}(\rho_B) + E_{sym}(\rho_B)\delta^2 + O(\delta^4) + \dots \qquad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

2 ways to define:

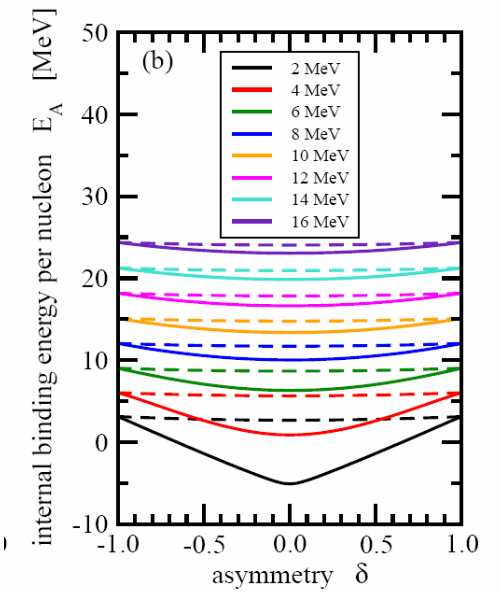
$$E_{sym}(\rho) = \tfrac{1}{2}\frac{\partial^2}{\partial\delta^2}E(\rho,\delta)\Big|_{\delta=0}$$

$$E_{sym}(\rho) = E(\rho,\delta=1) - E(\rho,\delta=0)$$

not necessarily the same: → higher orders in δ
→ change of composition,
e.g. clusterization stronger in SNM

with (solid) and without (dashed) clusters

physics independent of definitions.
but dependent on how this SE is used: Astro (y), HIC (no)



Need further information about the NSE, because of non-static systems

$$U(\rho,k;\delta) = \underbrace{U_0(\rho,k) + U_{sym}(\rho,k)(\tau\delta)}_{U_\tau(\rho,k)} + \dots$$

$$\frac{m^*_\tau}{m} = \left(1 + \frac{m}{\hbar^2 k}\frac{\partial U_\tau}{\partial k}\right)^{-1}$$

$$\sigma_{NN}^{(in-med)}(k;\rho)$$

Connected in a microscopic theory, or in a energy density functional.

Also: Composition of asymmetric matter: important for astrophysical applications

Special representations of the SE:

$$E(\rho_B,\delta)/A = E_{nm}(\rho_B) + E_{sym}(\rho_B)\delta^2 + O(\delta^4) + \dots$$

$$E_{sym}(\rho) = S + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

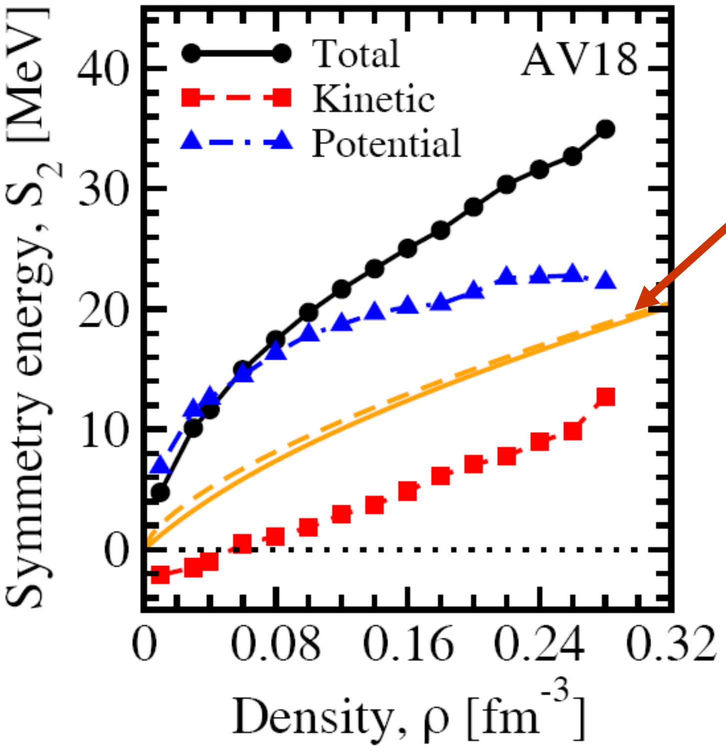
expansion around ρ_0

$$\Rightarrow \frac{1}{3}\varepsilon_F(\rho/\rho_0)^{2/3} + E_{sym}^{pot}(\rho)$$

split into kin. and pot. symm energy

$$E_{sym}^{pot} = C(\rho/\rho_0)^{\gamma}$$

polynomial behavior implies continuity between low and high densities: not necessarily so



kinetic energy in a theoy with correlations not Fermi Gas

a question of mapping microscopic theories to phenomenological approaches

$$\Sigma(k,\rho) \Leftrightarrow \{m^*, U(\rho)\}$$

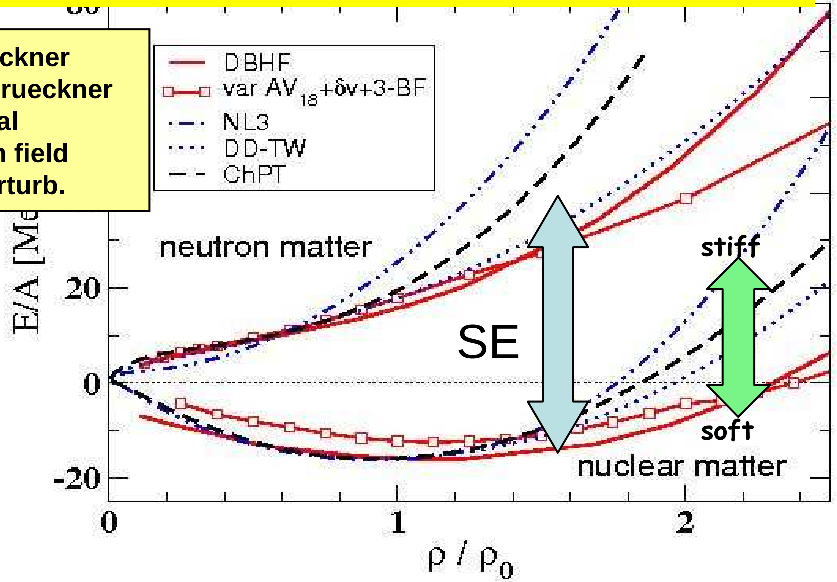
Carbone, et al., EPJA50;13

The Nuclear Symmetry Energy in „realistic“ models

The EOS of symmetric and pure neutron matter in different many-body approaches

C. Fuchs, H.H. Wolter, EPJA 30(2006)5,(WCI book)

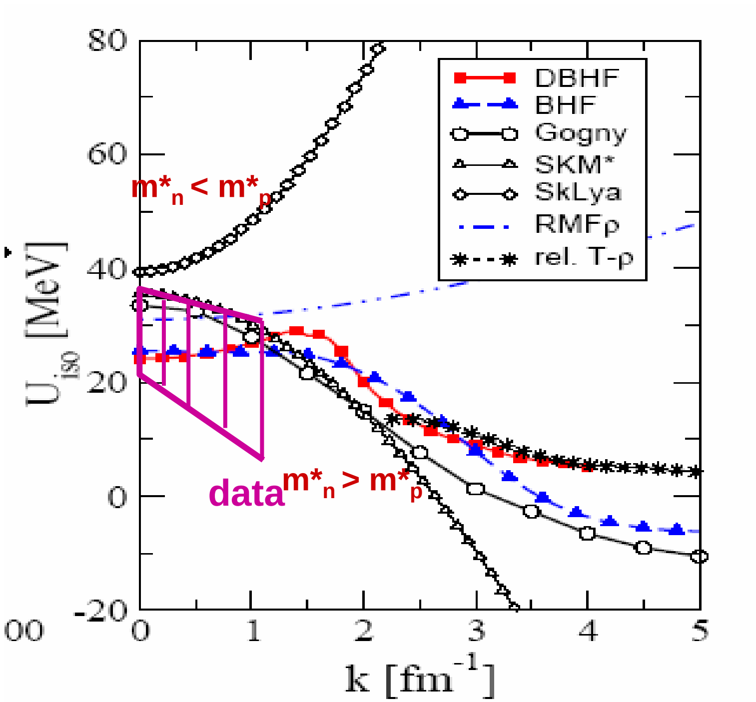
Rel, Brueckner
Nonrel. Brueckner
Variational
Rel. Mean field
Chiral perturb.



The symmetry energy as the difference between symmetric and neutron matter:

$$E_{sym} = E_{neutr.matt} - E_{nucl.matt}$$

SE ist also momentum dependent → effective mass

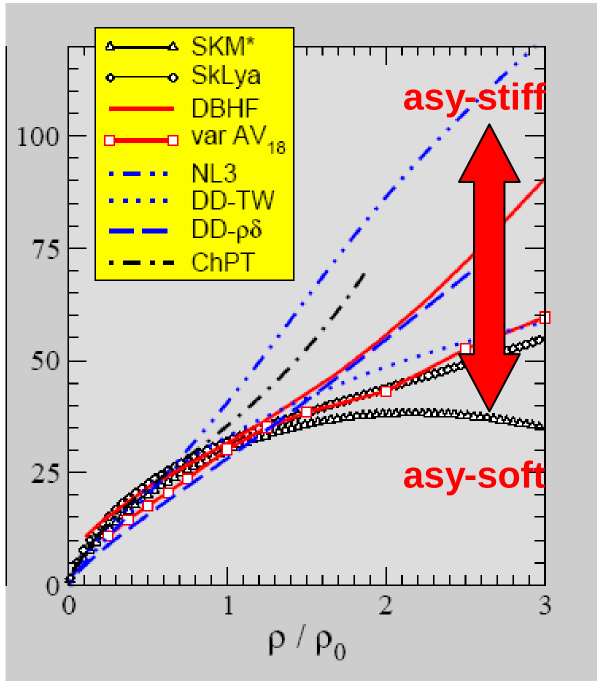


Different proton/neutron effective masses

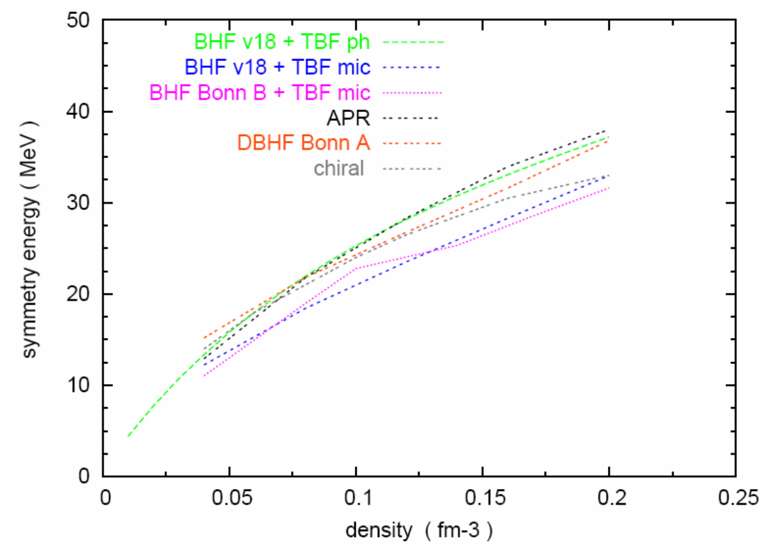
$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$$

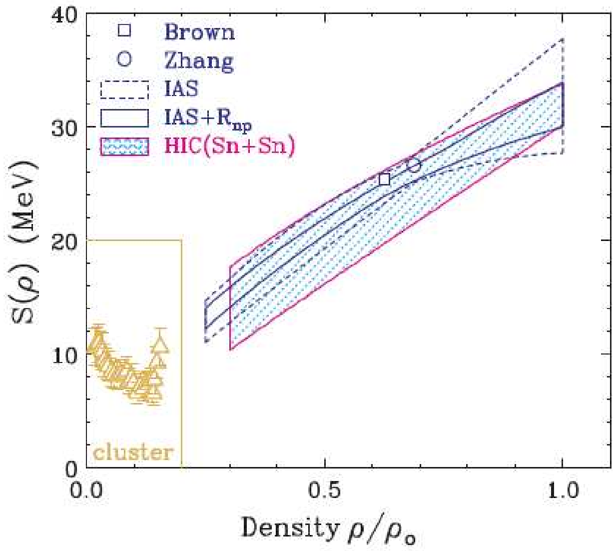
Isovector (Lane) potential: momentum dependence

$$U_{Lane}(k) = \frac{1}{2\beta}(U_{neutr} - U_{prot})$$



More work has been done since then: Review by Marcello Baldo



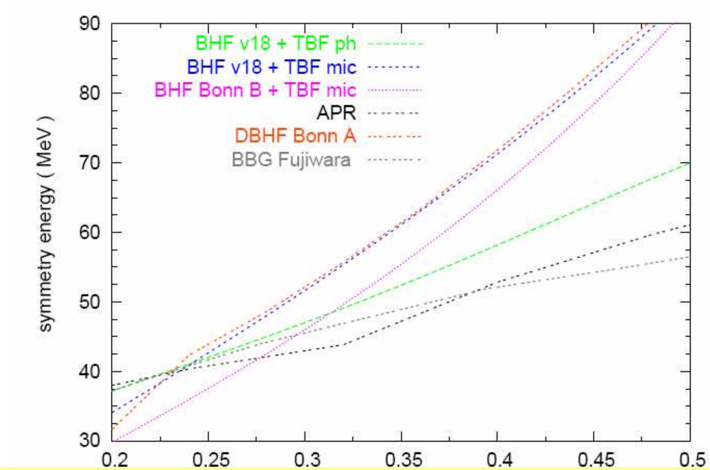


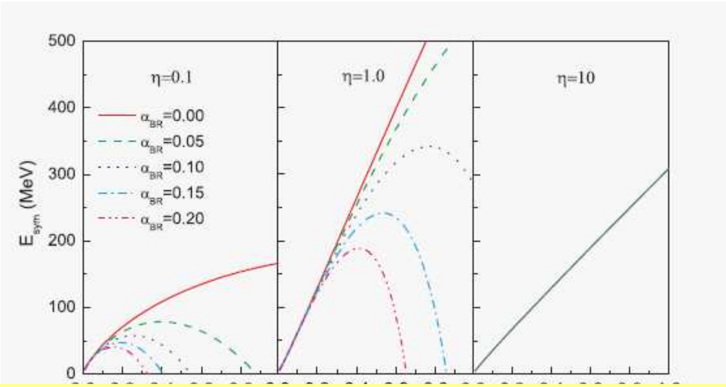
Horowitz, et al., JPhysG, 2014

Low density symmetry energy behave similarly and are consistent with analyses from nuclear structure and HIC.

However, at high densities large differences. -- 3-body forces? (Baldo); scaling with density?

-- short range tensor force (cut-off r_c) and in-medium mass scaling (parameter η) (B.A.Li)



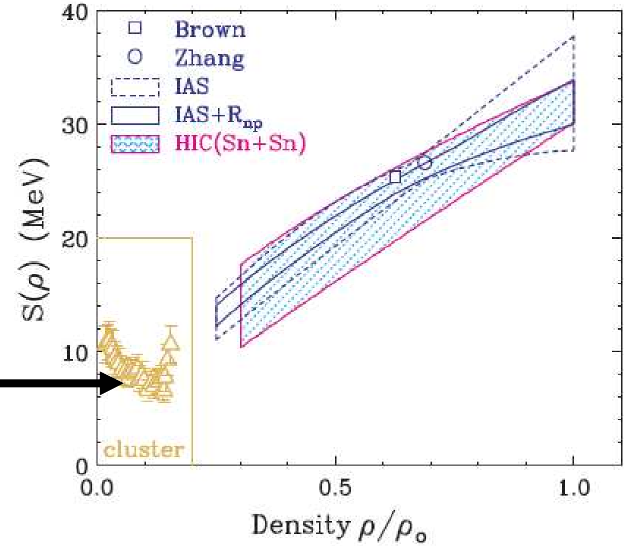


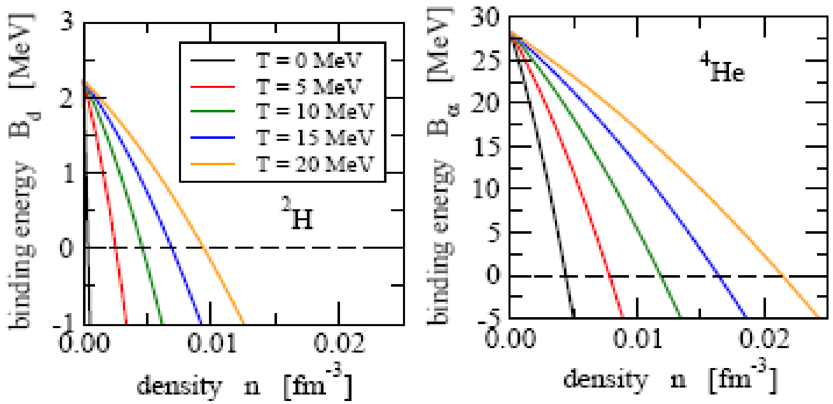
further work requred!

Note: attempts to derive directly from QCD (QM-BB, QCD sum rules, holographic QCD, Skyrmions)

Symmetry energy at very low density (< 0.1 ρ_0) determined by cluster correlations
(Typel, et al., PRC81,015803(2010))

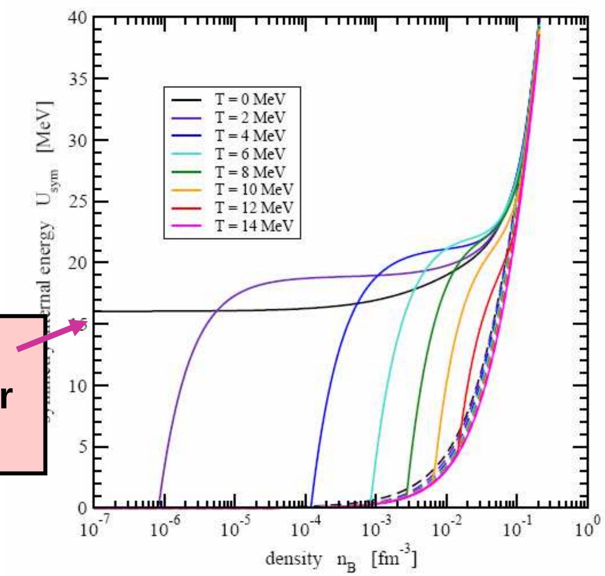
RMF model with explicit cluster degrees of freedon
with thermal Green function approach to calculate medium modifications of clusters:
NSE at $\rho \rightarrow 0$ finite, because cluster low density symmetric matter gains energy by cluster formation

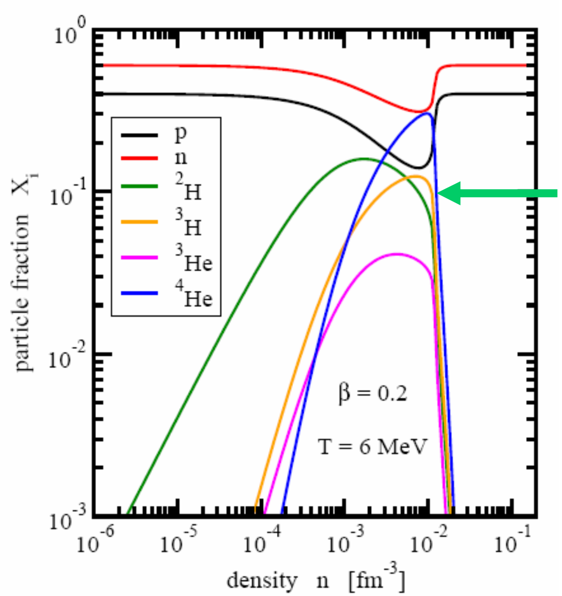




Symmetry Energy

finite at T=0 due to cluster correlations



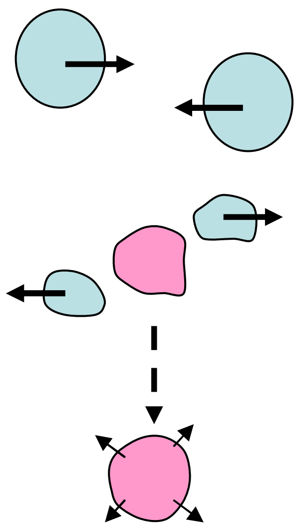


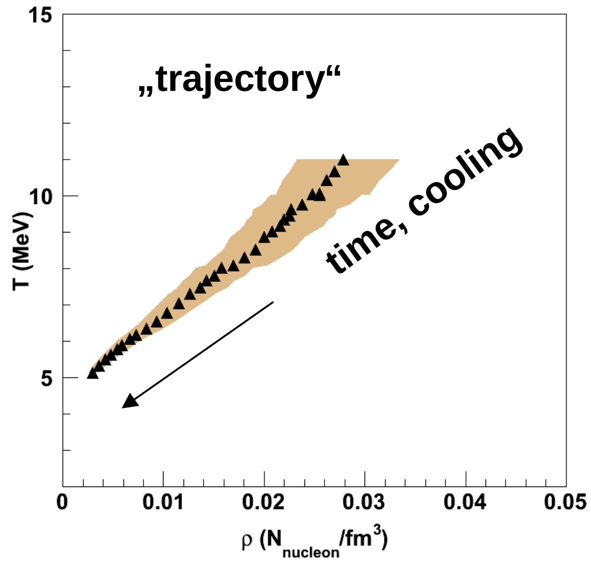
Mott density: clusters melt, homogeneous p,n matter;

here heavier nuclei (embedded into a gas) become important

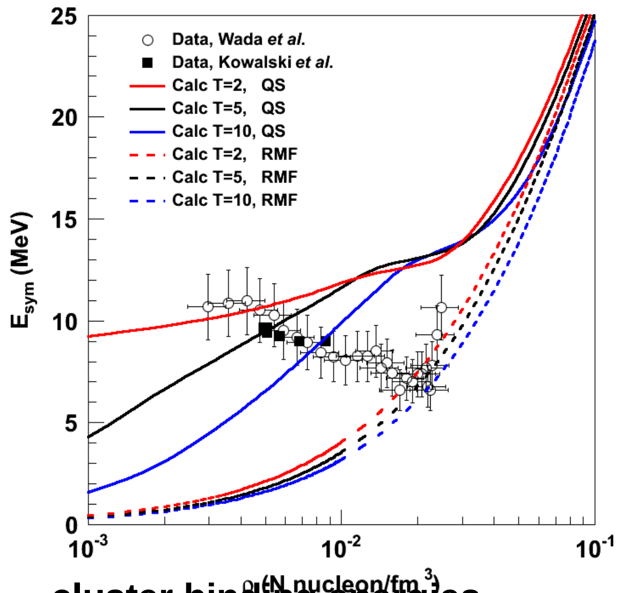
Investigation of very low density NSE in Heavy ion collisions

e.g. experiment 64Zn+(92Mo,197Au) at 35 AMeV
S. Kowalski, J. Natowitz, et al.,PRC75 014601 (2007)
J. Natowitz, G. Röpke, S. Typel, .. PRL 104, 202501 (2010)

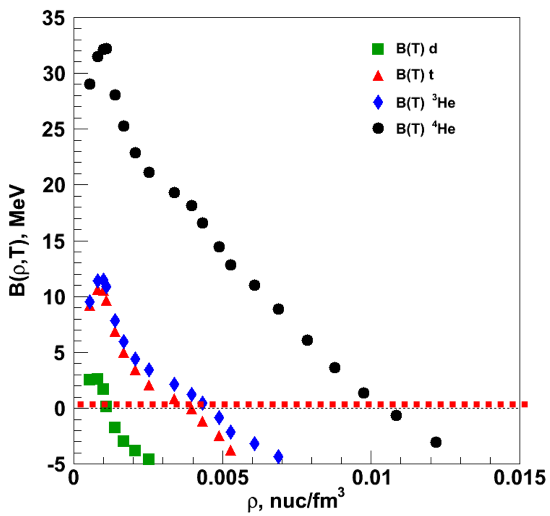


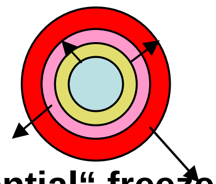


symmetry energy



cluster binding energies



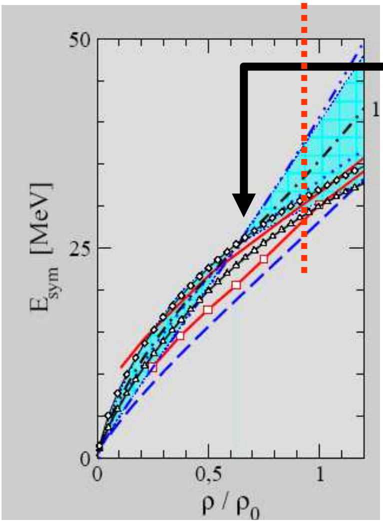


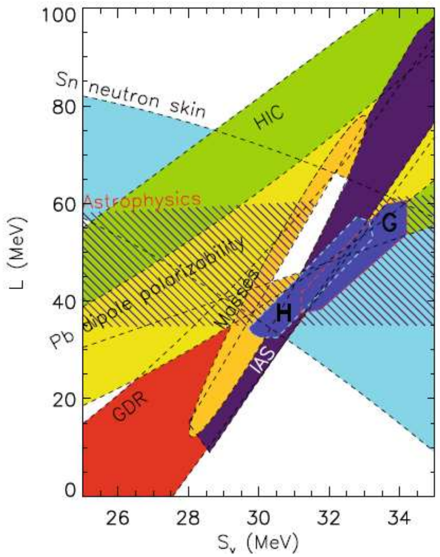
„differential“ freeze-out analysis:
source reconstruction,
analysis in terms of v_{surf}~time of emission
determination of thermodyn. properties as fct of v_{surf}
determination of symmetry energy

Assumptions need to be checked in transport calculations.

Symmetry energy around saturation density:
Determination from nuclear structure and low energy heavy ion collisions

Correlations between characteristic quantities of the SE: e.g. S, L, K_{sym} and experimental observables (e.g. neutron skin, polarizability, isospin diffusion,…)





-- e.g. SE that fit nuclear masses cross below saturation density, (some average densitiy of a finite nucleus)

-- induces a correlation between value and slope at ρ_0, within the model., eg. in lin. approx.

$$S(\rho=2\rho_0/3) = J - \frac{L}{9} + \frac{K_{\rm sym}}{162} + \ldots \approx J - \frac{L}{9}$$

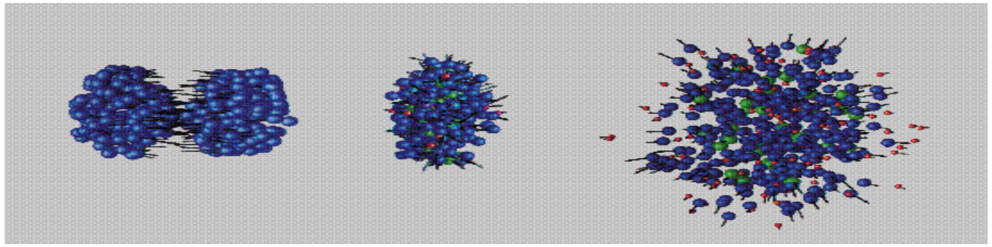
--different observables are sensitive to different densities (or ranges of densities) and thus induce different correlations

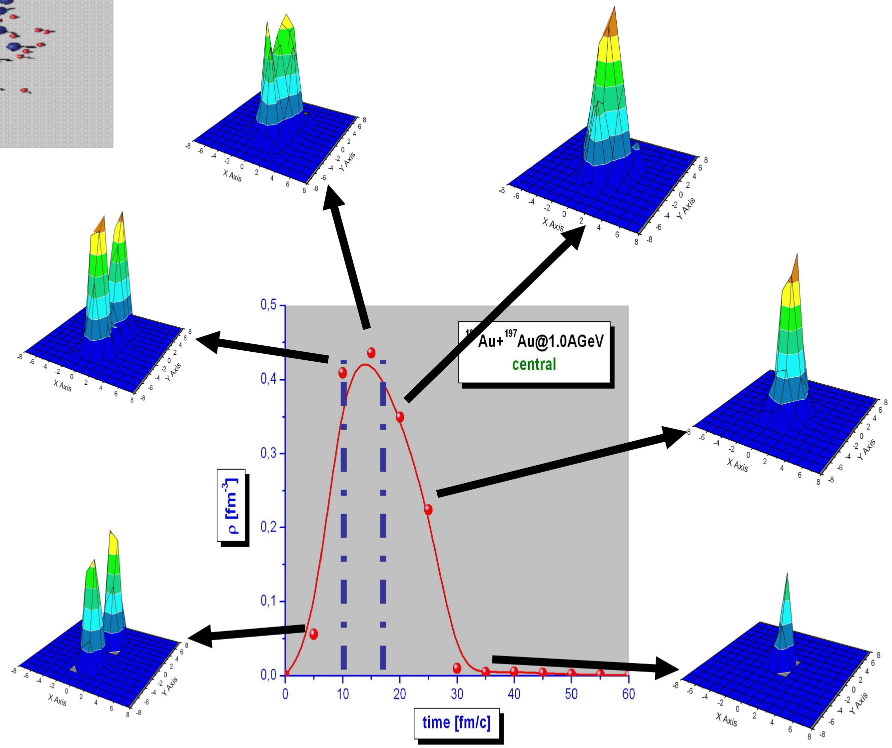
-- crossing point will hopefully fix S and L, which are independent
(not easy to see, how neutron skin of Sn induces anti-correlation, in contrast to 208Pb)

-- Represents an extrapolation using a model with different density dependences
in some cases a wide extrapolation, eg. in NS

Use models beyond mf models for this extrapolation, since observables are sensitive to correlations.

Heavy Ion Collisions: Transport Theory





→ **Transport approaches neccessary if system is not always in equilibrium.**
→ **Many observbles are determined during the evolution and not only at the end.**
→ **Especially interesting questions, like the high density phase, occur when the system is still not equilibrated.**
→ **Reliable transport approaches crucial to extract physics from heavy ion experiments**

Transport equations: 2 families

1. Boltzmann-Uehling-Uhlenbeck (BUU)

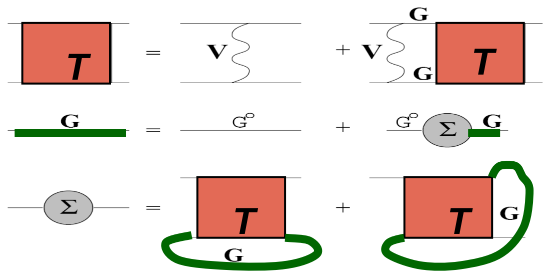
$$\frac{\partial f}{\partial t}+\frac{\vec p}{m}\vec\nabla^{(r)}f-\vec\nabla U(r)\,\vec\nabla^{(p)}f(\vec r,\vec p;t)=\int d\vec v_2\, d\vec v_{1'}\, d\vec v_{2'}\, v_{21}\,\sigma_{12}(\Omega)\,(2\pi)^3\,\delta(p_1+p_2-p_{1'}-p_{2'})\left[f_{1'}f_{2'}(1-f_1)(1-f_2)-f_1f_2(1-f_{1'})(1-f_2')\right]$$

Derived:

→Classically from the Liouville theorem or semiclassically from THDF, collision term added (and fluctuations)

→ From non-equilibrium theory (Kadanoff-Baym); collision term included

mean field and in-medium cross sections consistent, e.g. from BHF



$$\Sigma_{s,\mu}(k;\rho)\approx Tr\,(T\,f\,);\qquad \sigma_{NN}^{(in-med)}(k;\rho)\approx\left|T^2\right|$$

Spectral fcts, off-shell transport, quasi-particle approx. (QPA)

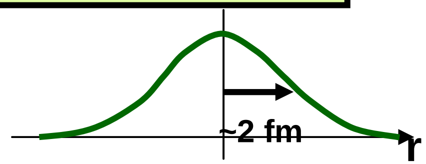
$$A(x,p)\propto\frac{2\,\Gamma(x,p)}{(p^{*2}-m^{*2})+\Gamma^2(x,p)}\quad \xrightarrow{\text{QPA}}\quad \propto\delta(p^{*2}-m^{*2})\,\Theta(p^{*0})$$

$$\Gamma(x,p)=m^*\,Im\,\Sigma_s^{+}-p_\mu{}^*\,Im\,\Sigma^{+\mu}$$

2. Molecular Dynamics (QMD)

$$\frac{dr_i}{dt}=\{r_i,\mathcal{H}\};\qquad \frac{dp_i}{dt}=\{p_i,\mathcal{H}\};\qquad H=\sum_i t_i+\sum_{i<j}V_{ij}$$

classical molecular Dynamics with Gaussian particles to reduce fluctuations + collision term



2b) Antisymmetrized MD (AMD,FMD) Gaussians are antisymmetrized wp collision term with stochastic features (wave packet splitting)

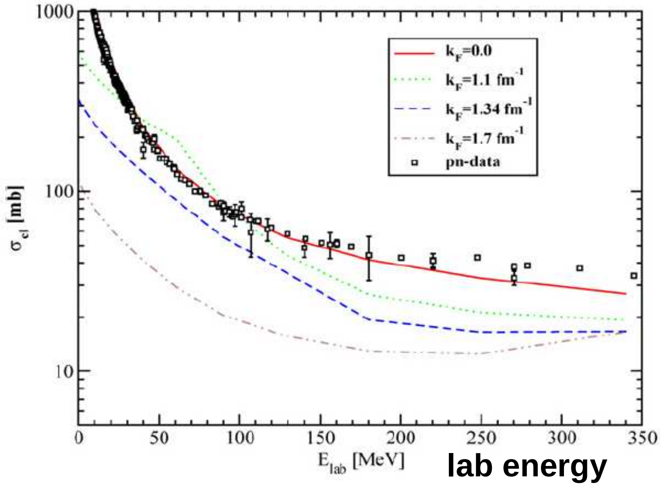
Transport theory is on a well defined footing, in principle – but in practice?

Examples of microscopic input into transport calculations:

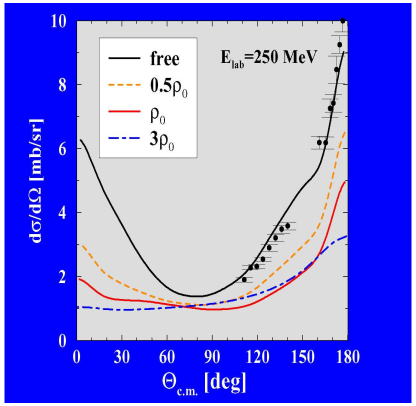
In-medium cross sections

density and angular dependence

elastic np from DBHF:



lab energy



cm scatt. angle

[17] C. Fuchs, et al., Phys. Rev. C 64 (2001) 024003.

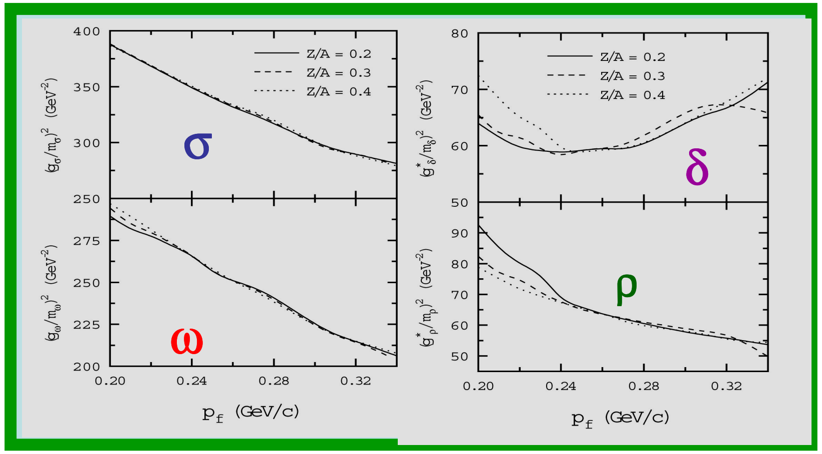
Decomposition of DB self energy

$$\Sigma(p) = \Sigma^s(p) - \gamma^0\Sigma^0(p) + \bar{\gamma}\cdot\bar{p}\Sigma^v.$$

Density (and momentum) dependent coupling coeff.

$$\Gamma_i^2(k,\rho) = \left(\frac{g_i}{m_i}\right)^2 = \frac{\Sigma_i(k,\rho)}{\rho_i}$$

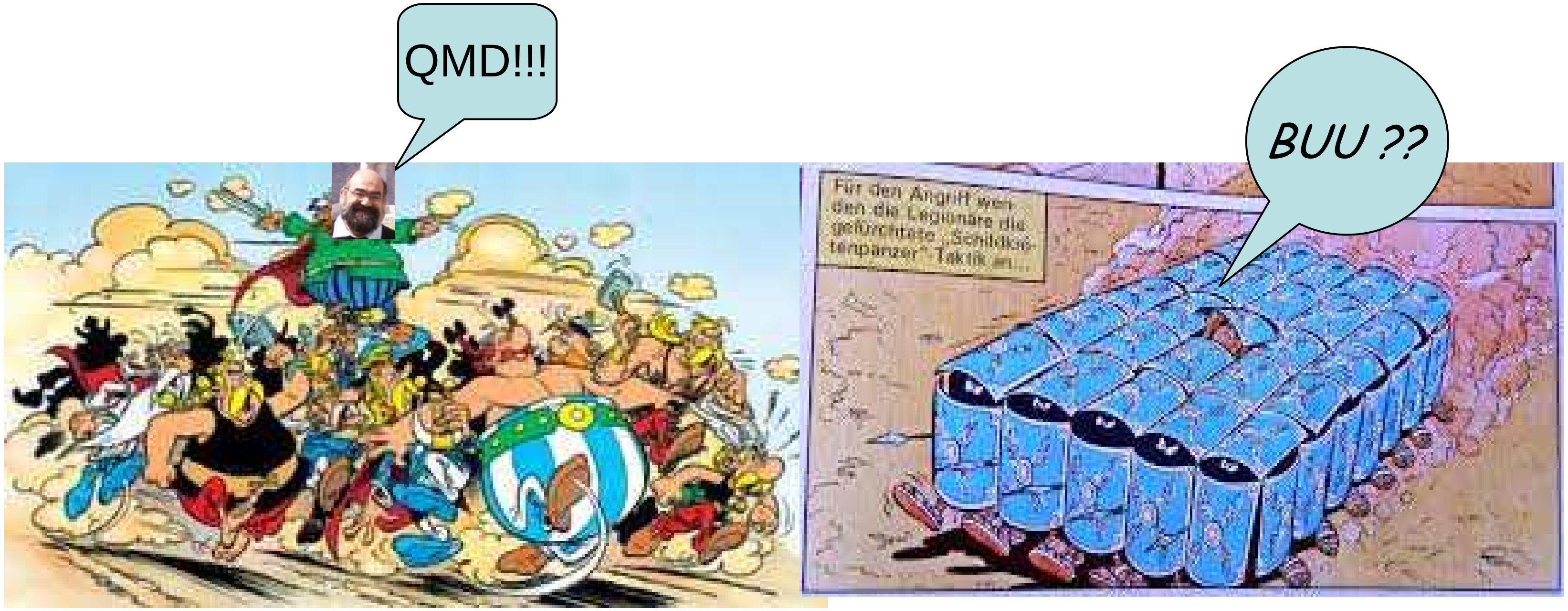
$$i = \sigma, \omega, \rho, \delta$$



Motivation for density dep. RMF model

and inclusion of δ-meson (J^π=0+,T=1)

Practical transport approaches: somestimes a „fight“ between MD and Boltzmann models:



BUU: Ideal procedure: solve BUU eq. with N_{TP}→inf, and add flucuation term
into a Boltzmann-Langevin eq. with physically determined fluctation strength.
approximations: „gauged“ numerical noise, BOB, statistical fluctuations (SMF)
Bauer-Bertsch-method (collisions of swarms of TP, BLOB)

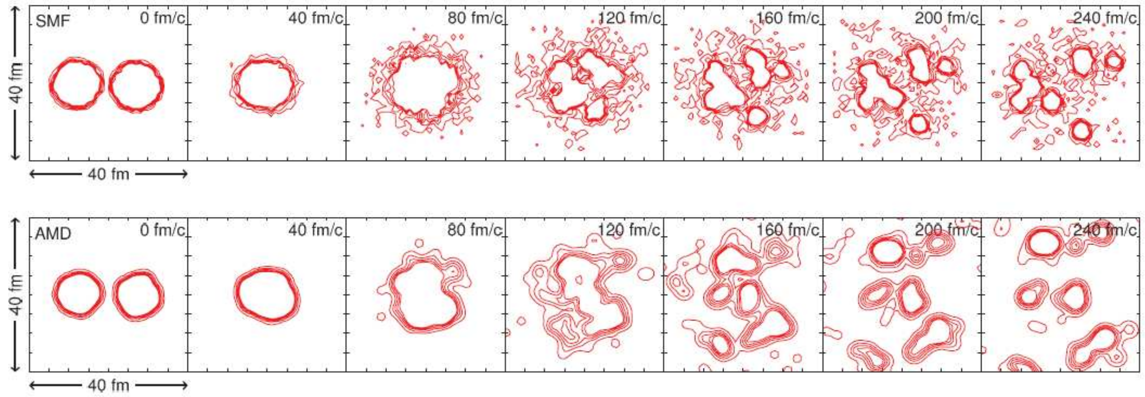
$$\boxed{\frac{df}{dt} = I_{coll} + I_{fluc}}$$

MD-models: fluctuation inherent, but determined by a parameter for width of wp

→ Issues now discussed intensively
differences mainly in nature and amount of fluctuations

Comparison of simulations: SMF-AMD: (Rizzo, Colonna,Ono, PRC76(2007); Colonna et al., PRC82 (2010))

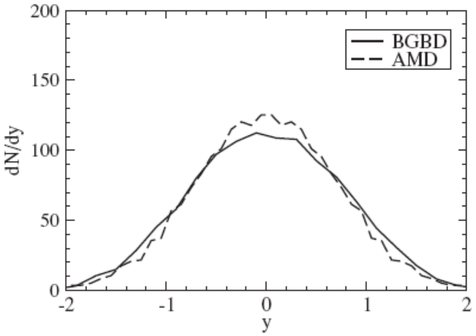
112Sn+112Sn,
50 AMeV



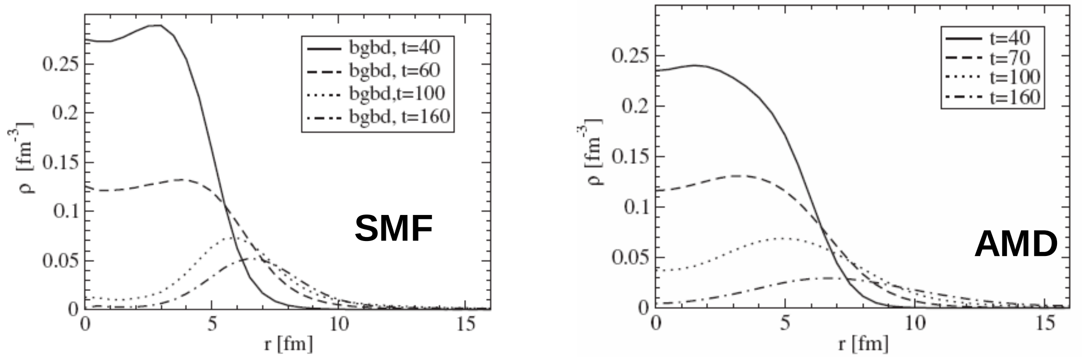
SMF (BGBD)

AMD

Stopping: similar

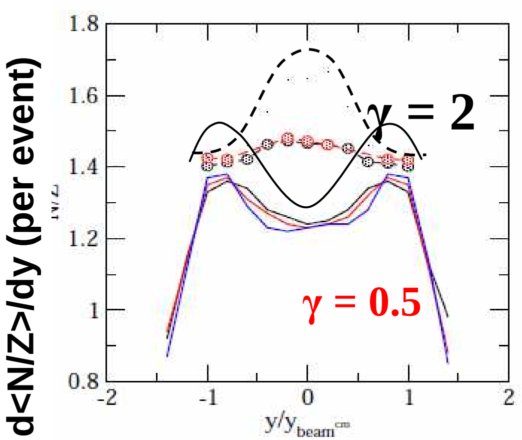


Radial density at different times: SMF more bubble like



Comparison, SMF-ImQMD: more transparency in QMD
(M. Colonna, X.Y.Zhang)

SMF = dashed lines
ImQMD = full lines



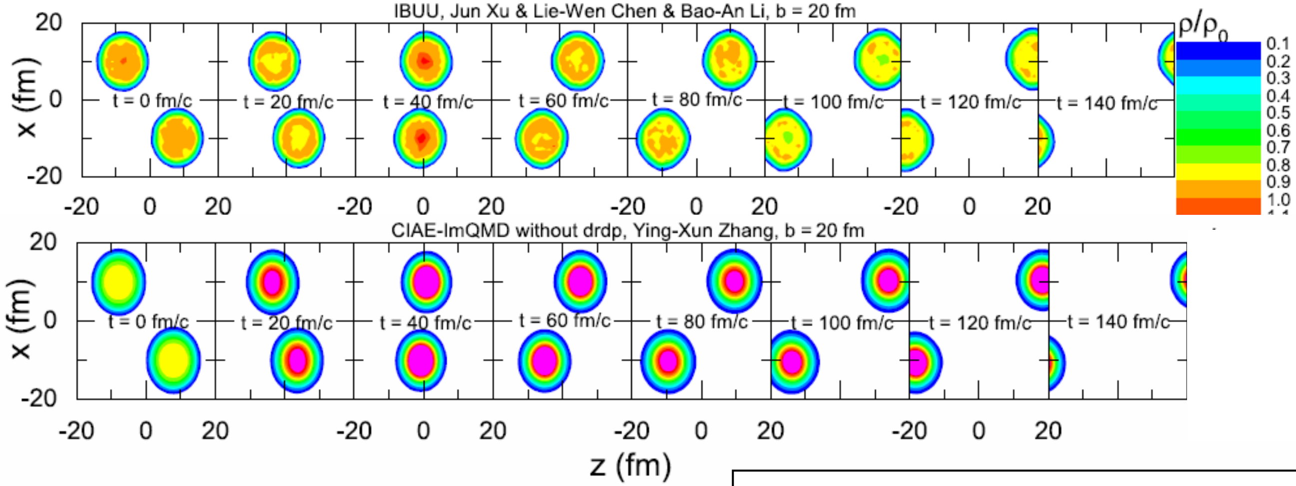
Code Comparison Project: Trento, ECT*, 2006 and 2009
Shanghai, Jan. 2014, (Lanzhou 2014)

check consistency of transport codes in calculations with same system (Au+Au), E=100,400 AMeV, identical (simple) physical input (mean field (EOS) and cross sections)

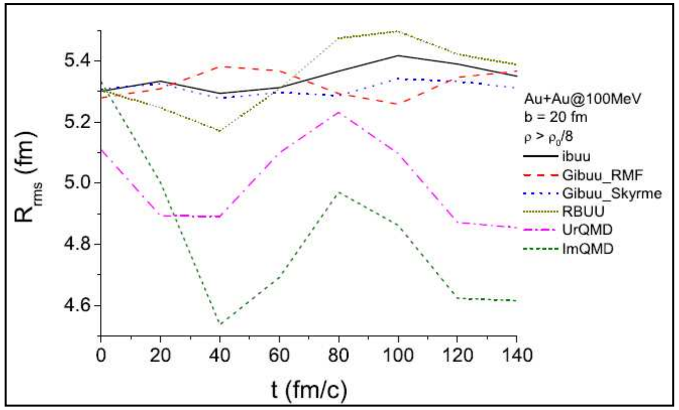
idea: establish sort of theoretical systematic error or transport calculations (and hopefully to reduceit)

1. step: Initialize colliding nuclei. usually not exact ground states

free propagation (large impact parameter)



→ nuclei oscillate, influences dynamical evolution in collision, part. at lower incident energies
→ construct better gs, e.g. Thomas-Fermi



Examples of results: Au+Au, PRELIMINARY

E/A=100 MeV

BUU models **QMD models**

E/A=400 MeV

BUU and QMD models

Graphs eliminated, since results are preliminary
and are still under review of the participating code owners.
It is planned to make them available publicly in the near future

- → considerable differences
- → partly due to initialization, but mainly to collision term
- → no essential difference between BUU and QMD models
- → 100 MeV sensitive region for flow because of competition between mf and collisions, better at higher energy

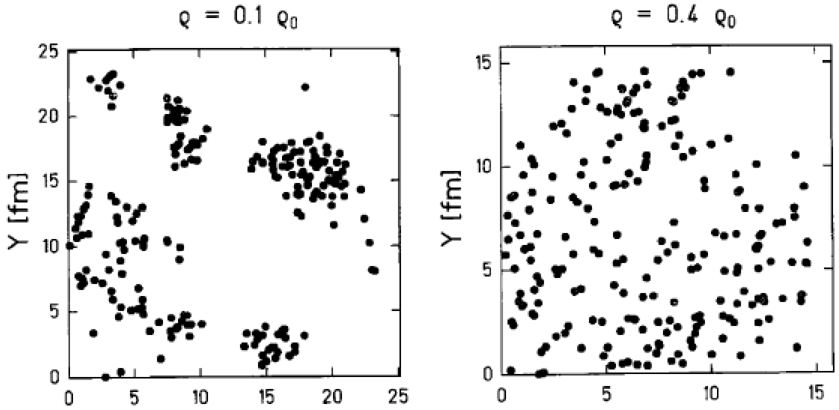
Treansport Calculations in a (periodic) Box

test collision routine and Pauli blocking under controlled conditions;
reveal important features of the semiclassical approach.
One effect: Initialization, T=0. → Fermi statistics is lost quickly!

see significant differences between codes!

Graphs eliminated, since results are preliminary
and are still under review of the participating code owners.
It is planned to make them available publicly in the near future

Broader applications:
1. intialization in spinodal region: fragment formation, check of fluctuations
2. intialize expanded or two interpenetrating Fermi system (two Fermi spheres): check of equilibration
3. others
→ interesting for a detailed study



Fluctuations in Phase Space

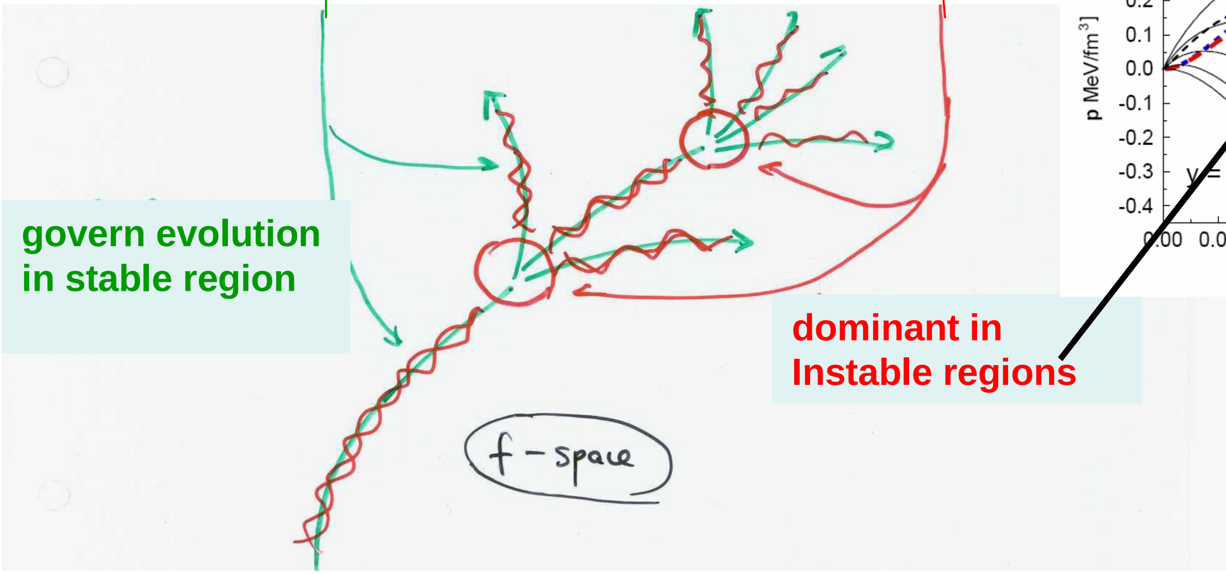
$$f(r,p,t) = \bar{f}(r,p,t) + \delta f(r,p,t)$$

Mean field evolution
(dissipative,deterministic)

Fluctuations
(from collisions and higher order correlations)

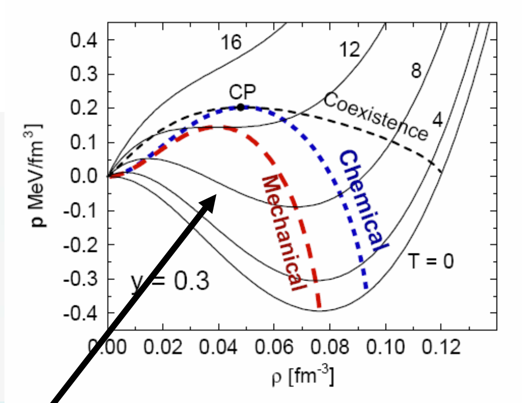
Boltzmann-Langevin eqn.

$$\boxed{\frac{df}{dt} = I_{coll} + I_{fluc}}$$



govern evolution
in stable region

dominant in
Instable regions

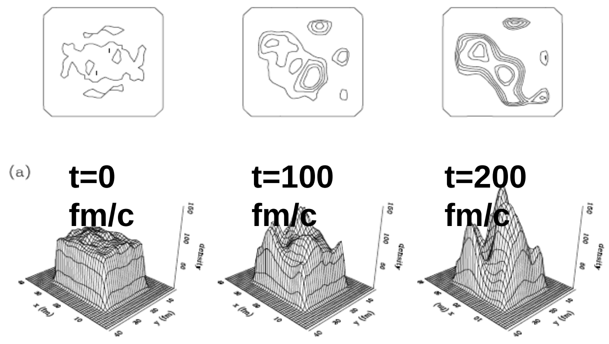


Fragment and light clusters in transport calculation

A fragment represents a many-body correlation,
which is not contained in approaches for the one-body density. How to describe anyway?

Distinguish Intermediate mass fragments (IMF) and Light Clusters (LC:d,t,^{3}He,α)

a) IMF's: formation dominated by mean field,
which favors matter at normal density
e.g. BUU calculation in a box (periodic boundary conditions) with initial conditions inside the instability region: $\rho=\rho_0/3$, T=5 MeV, $\beta=0$

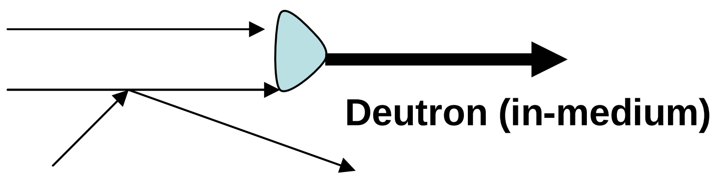


b) Light clusters (LC:d,t,^{3}He,α)

Correlation dominated (esp.Pauli-Correlation). not good in BUU and MD models,
except(!) for AMD: can define realistic wave functions for LC with reasonable BE;

Solution for BUU models:

LC distribution functions as explicit degrees of freedom coupled to nucleon distribution functions by 3-body collisions
of type NNN→ND
→ P. Danielewicz and Q. Pan, PRC 46 (1992)
(d,t,^{3}He, but no α!) coupled transport equations



Caveat: Medium properties of LC: see discussion of low density matter,

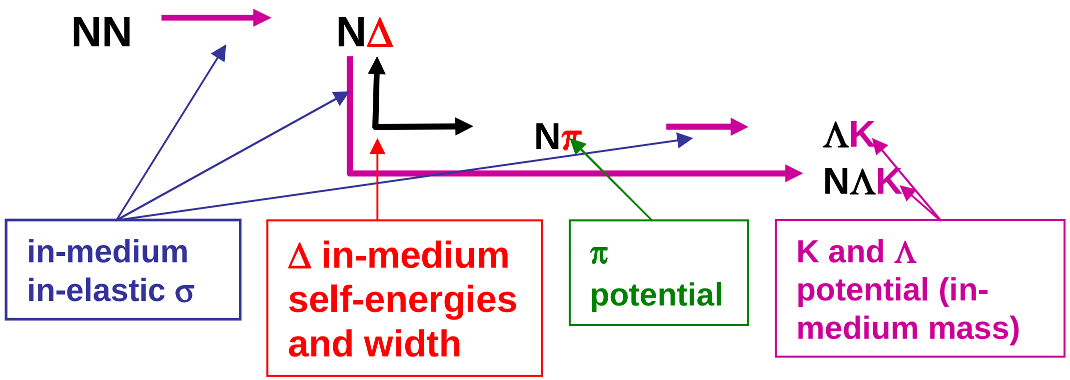
refs.: C. Kuhrts, Beyer, Danielewicz,..PRC63 (2001) 034605, Typel, Röpke, et al., PRC81 (2010)

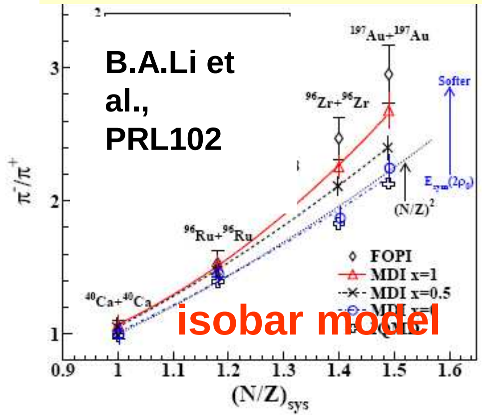
Particle production: pions, Kaons, ….

Particularly interesting in view of the search for the high density symmetry energy

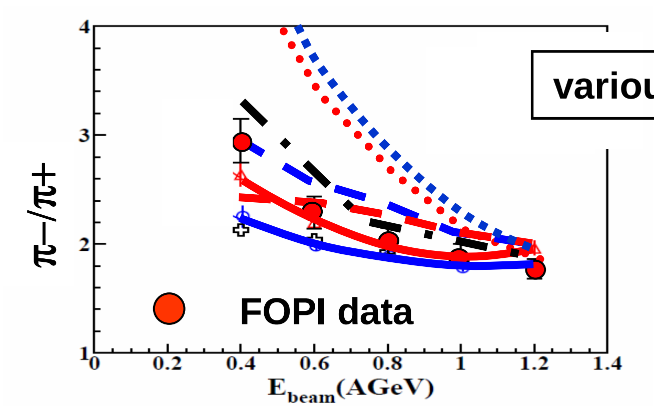
1. „direct effects“: difference in proton and neutron (or light cluster) emission and momentum distribution
2. „secondary effects“: production of particles, isospin partners $\pi^{-,+}$, $K^{0,+}$

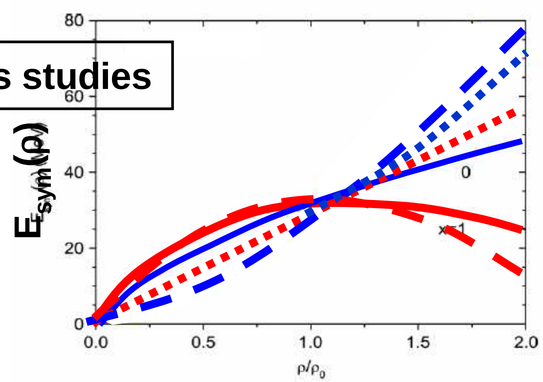
in two limits π^-/π^+ should be a good probe!

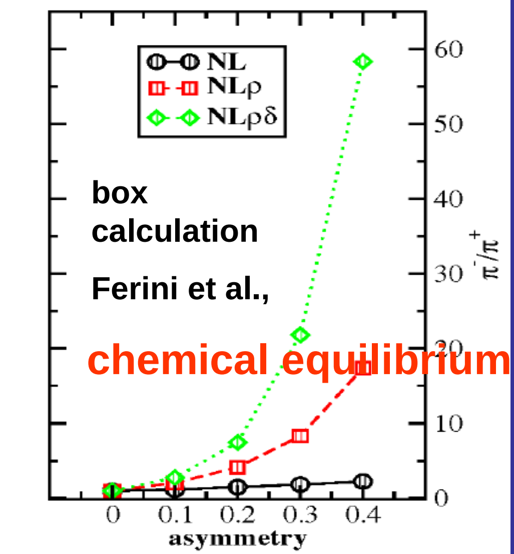




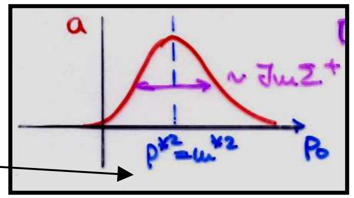
various studies







consistent dynamical spectral functions necessary, „Off-shell transport“
usual treatment: sample spectral fct

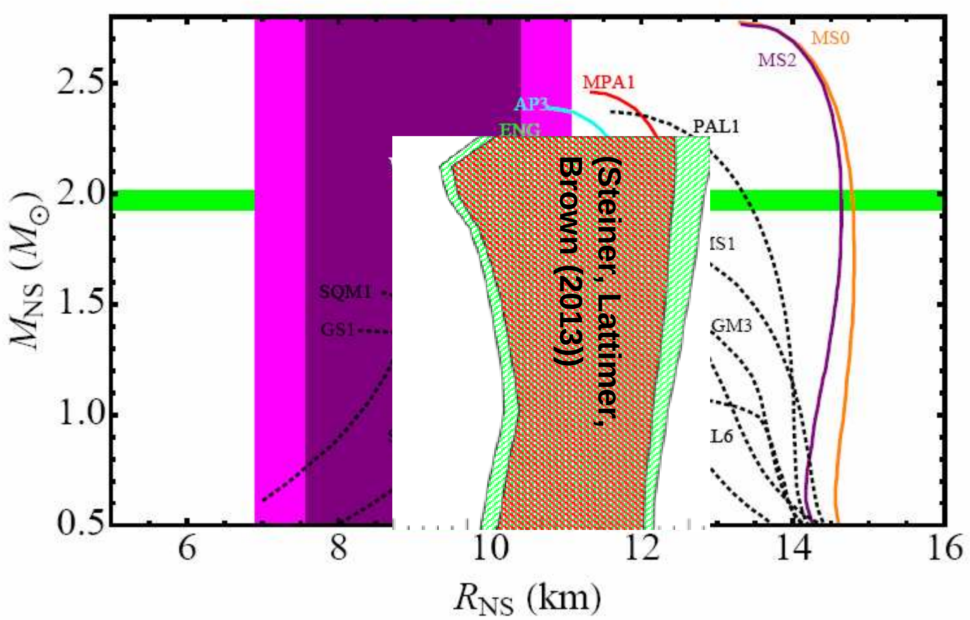


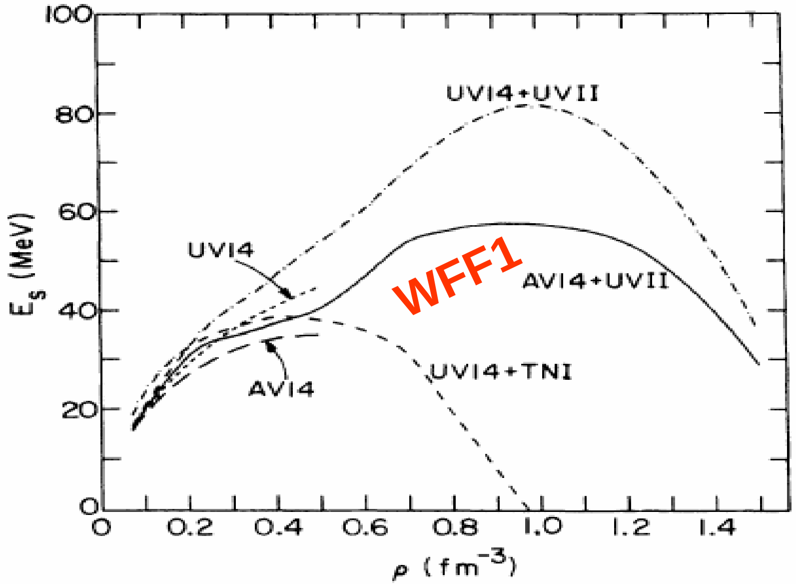
Mass-radius relation of neutron stars and NSE

Rutledge+Guillot:

ApJ v.772 (2013)

$$R_{\mathrm{NS}} = 9.1^{+1.3}_{-1.5}\ \mathrm{km}\ (90\%\text{-confidence})$$



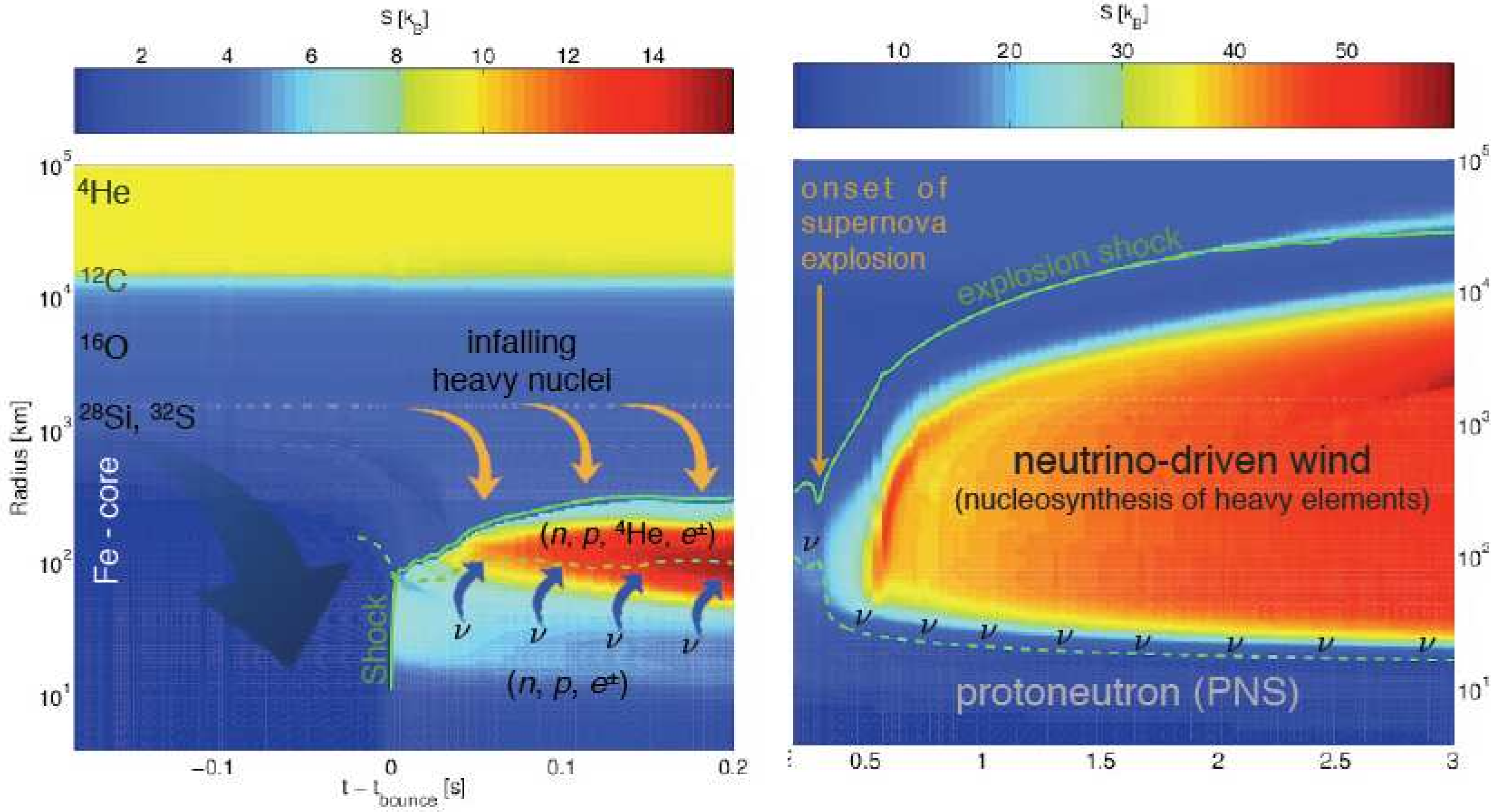


Small radii together with 2 solar mass NS seemed to imply a special behavior of the NSE (soft at ~ 2ρ_0 and stiffer afterwards, like WFF1.

Diskussion by A. Steiner seems to make this conclusion less stringent.
However, a non-polynomial behavior of $E_{sym}(\rho)$ is seen also in other cases (e.g.DB)

The NSE energy in Core-Collapse Supernovae (CCSN)

Workshop: Simulating the Supernova neutrinosphere with heavy ion collision, Trento, ECT*; April 2014



→ core collapse → post bounce evolution (mass accretion)

(proto)neutron star deleptonization →

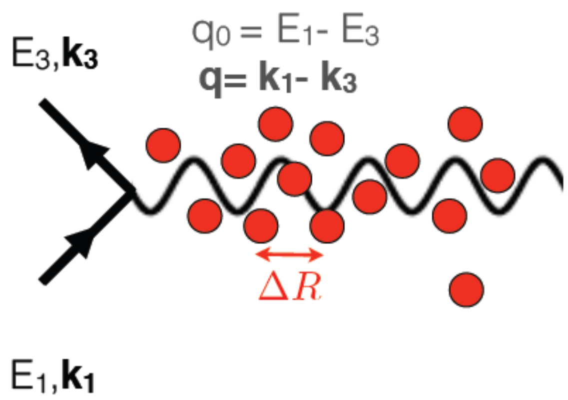
conditions of neutrinosphere:
densities 1/1000 to 1/10 ρ_o
temperature T=4-5 MeV
asymmetry Y_e=0.1 – 0.25

Main processes:

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Correlations & Neutrino Scattering

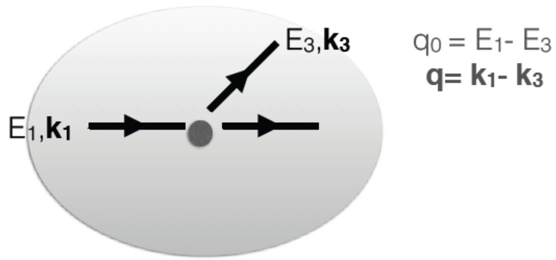
- Neutrinos “see” more than one particle in the medium.
- Nature of spatial and temporal correlations between nuclei, nucleons and electrons affect the scattering rate.



At small q_0 and $\mathbf{q}$ the neutrino cannot resolve single particles.

Sawyer (1975, 1989)
Iwamoto & Pethick (1982)
Horowitz & Wherberger (1991)
Raffelt & Seckel (1995)

Neutrinos Scatter From Fluctuations of Density & Spin



direct interface with nuclear physics

Differential Scattering/Absorption Rate:

$$\frac{d\Gamma(E_1)}{d\cos\theta \, dq_0} = \frac{G_F^2}{4\pi^2} (E_1 - q_0)^2 \left[(1+\cos\theta) \, S_V^{\mathrm{RPA}}(q_0, q) + (3 - \cos\theta) \, S_A^{\mathrm{RPA}}(q_0, q)\right]$$

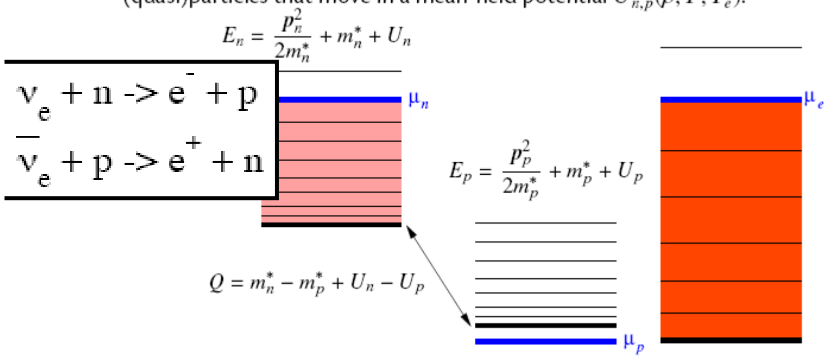
spectrum of density fluctuations

spectrum of spin fluctuations

(S. Reddy)

Neutrino opacities and neutrino spectra dependent on low density symmety energy

Most of Equations of State treat neutrons and protons as "non-interacting" (quasi)particles that move in a mean-field potential $U_{n,p}(\rho, T, Y_e)$.



- ν_e absorption opacity affected by final state electron blocking

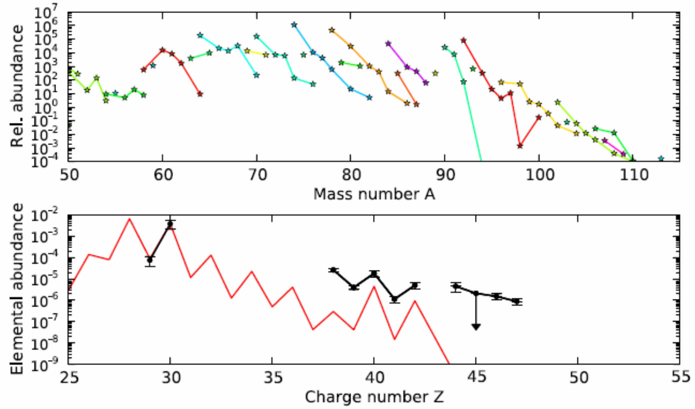
$$\chi(E_\nu) \propto (E_\nu + \Delta m^* + \Delta U)^2 \exp\left(\frac{E_\nu + \Delta m^* + \Delta U - \mu_e}{kT}\right), \quad \Delta U = U_n - U_p$$

- $\bar{\nu}_e$ absorption affected by energy threshold (ΔU).

$$\chi(E_\nu) \propto (E_\nu - \Delta m^* - \Delta U)^2 \quad E_\nu > \Delta m^* + \Delta U$$

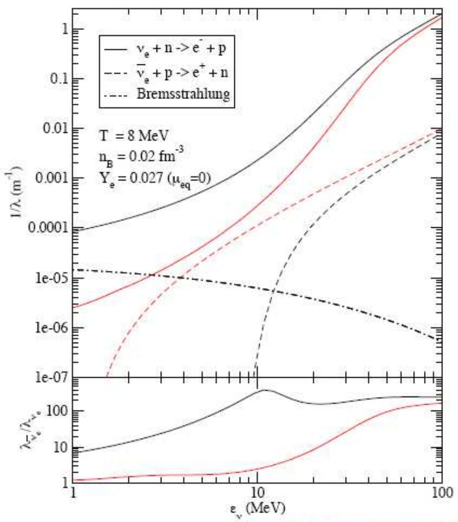
- larger symmetry energy (larger ΔU) implies: i) the larger the energy difference between ν_e and $\bar{\nu}_e$; ii) smaller electron flavor luminosities.

Nucleosynthesis



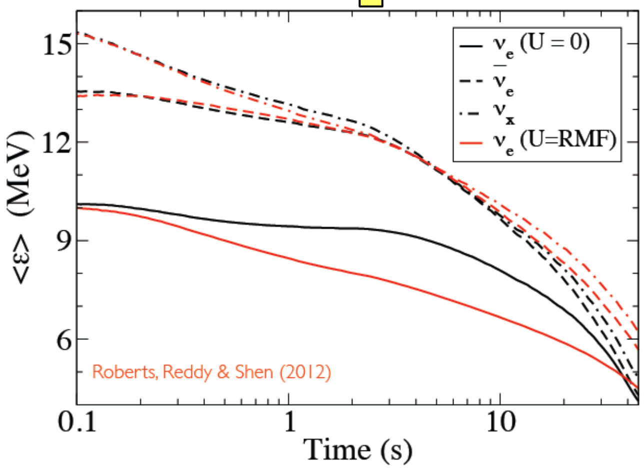
- Elements between Zn and Mo, including ^{92}Mo, are produced
- Mainly neutron-deficient isotopes are produced
- No elements heavier than Mo ($Z = 42$) are produced.

- Energy shift helps overcome electron final state blocking.
- Enhances ν_e absorption
- Larger energy needed to produce neutrons suppresses anti-ν_e absorption.



Roberts, Reddy & Shen (2012)

solid=with symm energy shift, dashed without



Time evolution of electron neutrino spectrum could be a useful diagnostic

(S. Reddy)

Interesting to consider Homework from ECT* workshop:

1. Use transport model (calibrated on HIC data) to simulate warm matter at low density in box calculation and extract dynamical neutrino response functions

2. Check freeze-out densities from coalescence and particle correlation methods. (Re-)analyze more data sets of HIC.

3. Explore themodynamical conditions of freeze-out configuration for larger N/Z to come closer to neutrinosphere conditions

4. Improve light cluster description in transport codes

5. Establish a kind of collaboration:
   - website,
   - white paper for the Texas low energy community meeting,
   - another workshop in about 2 years

Important point:
Opportunity, where nuclear physics can make a concrete contribution to an important astrophysical problem!

Final Remarks:

NSE: a field of strong exchange between theory and experiment

largest uncertainties at very low ($\rho<0.1\rho_0$) and at high density ($\rho>2\rho_0$)
(clusters) (strongly correlated)

mapping of microscopic models to phenomenological approaches
(both in nuclear structure and in transport calculation):
(e.g. effective masses, mean field potentials, kinetic energies, medium cross sections, medium modification of clusters)

development of transport approaches:
fluctuations and fragmentation
dynamical role of light clusters

Direct confrontation with astrophysical questions:
NS, e.g. mass radius relation and other observables
CCSN: neutrino opacities in the ν-sphere

many things to do in the future