The Symmetry Energy at very low, low, and high densities in Heavy Ion Colisions

or

All you ever wanted to know about the Symmetry Energy, but …

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Excellence Cluster Universe

International Collaborations in Nuclear Theory (ICNT):
Program 2013: „Symmetry Energy in the Context of New Radioactive Beam Facilities and Astrophysics“
FRIB, East Lansing, July 15. – Aug. 9. 2013

Points to discuss:

- **Definition of the Nuclear Symmetry Energy (NSE)**
  in nuclei, nuclear matter and astrophysics
- **NSE in microscopic calculations (also at very low densities with correlations)**
- **Investigation of the NSE in Astrophysics and Heavy ion collisions (HIC)**
- **Transport theory: approximations and implementations**
  fluctuations, formation of fragments

NSE at various densities in HIC

- $\rho \ll \rho_0$: **clustered matter**
- $\rho \lesssim \rho_0$: **barrier to Fermi Energy regime, isospin transport**
  ex.: isospin diffusion, pre-equilibrium emission
  constraints
- $\rho > \rho_0$: **reaction mechanism, observables**
  flow, particle production (pion, Kaon)

This is supposed to be an informal talk, and it can only touch on many questions!

Definitions of the Symmetry Energy

Equation-of-State and Symmetry Energy

BW mass formula

$$E(A,Z)/A = a_v - a_s A^{-1/3} - a_C Z(Z-1)A^{-4/3} - a_s(N-Z)^2/(N+Z)^2 + \delta_{pair}$$

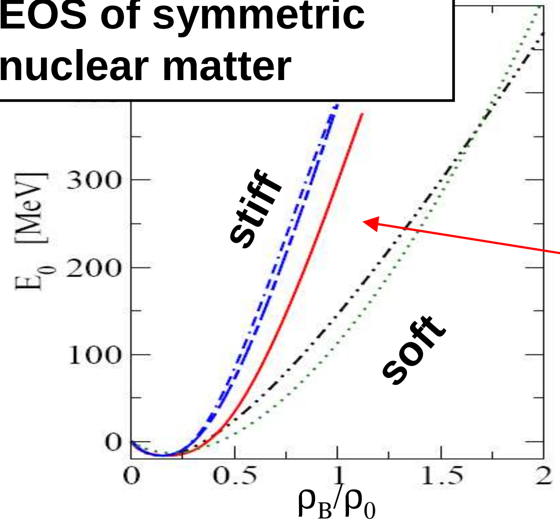
symmetry energy

density-asymmetry dep. of nucl.matt.

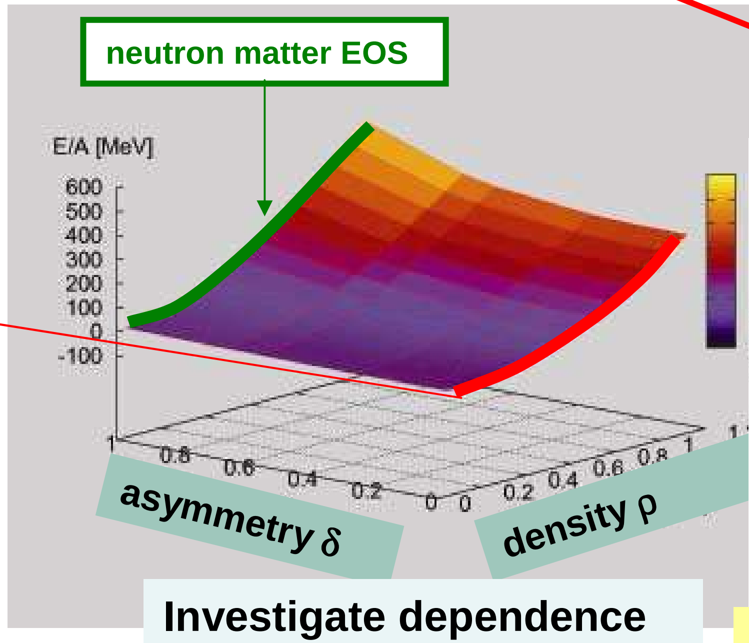
$$E(\rho_B,\delta)/A = E_{nm}(\rho_B) + E_{sym}(\rho_B)\delta^2 + O(\delta^4) + \ldots \qquad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Symmetry energy:
Diff. neutron and symm matter

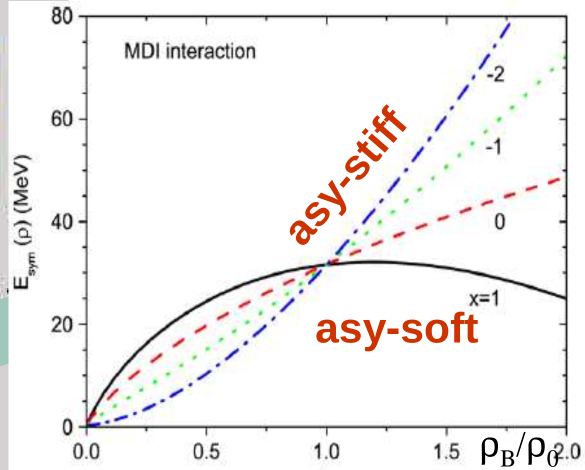
EOS of symmetric nuclear matter



Fairly well fixed! Soft



Investigate dependence in large part of (ρ,δ)-plane



Rather uncertain!
esp. at high density
Isovector tensor correlations?

Question: 2nd deriv

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

or finite diff

$$E_{sym}(\rho) = E(\rho,\beta=-1) - 2E(\rho,\beta=0) + E(\rho,\beta=1)$$

quadratic over a large interval of β?

1.5 Representations of Symmetry Energy

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

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

Parametrizations:

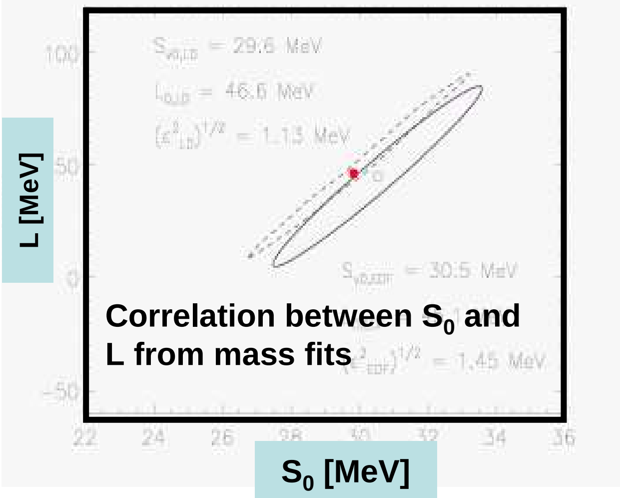
2. polynomial behaviour $\qquad E_{sym}^{pot} = C\,(\rho/\rho_0)^{\gamma}$

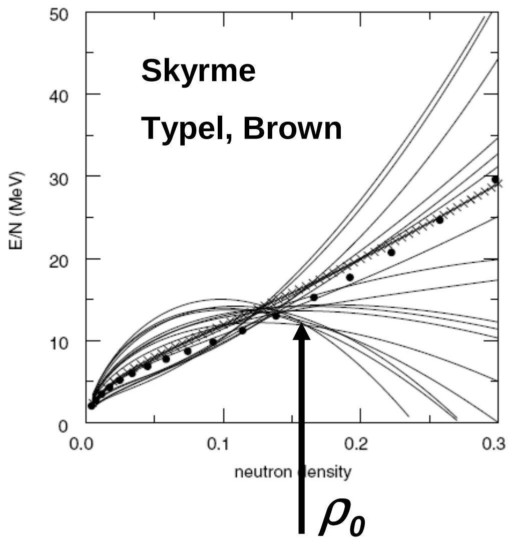
3. Expansion around ρ_o $\qquad E_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$

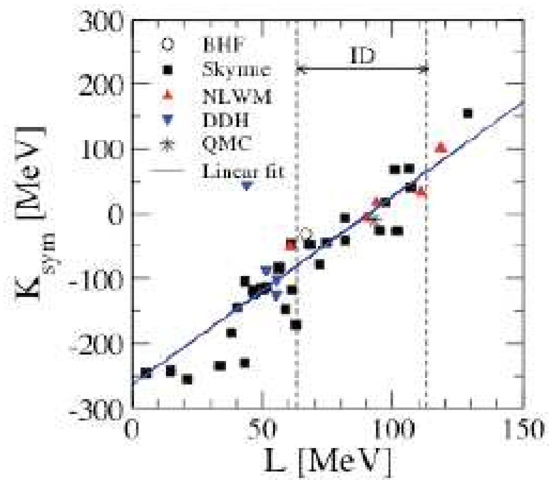
Relation between γ and L

correlations

Lattimer, Lim, arXiv 1203.4286







Correlation between L and K_{sym} ?

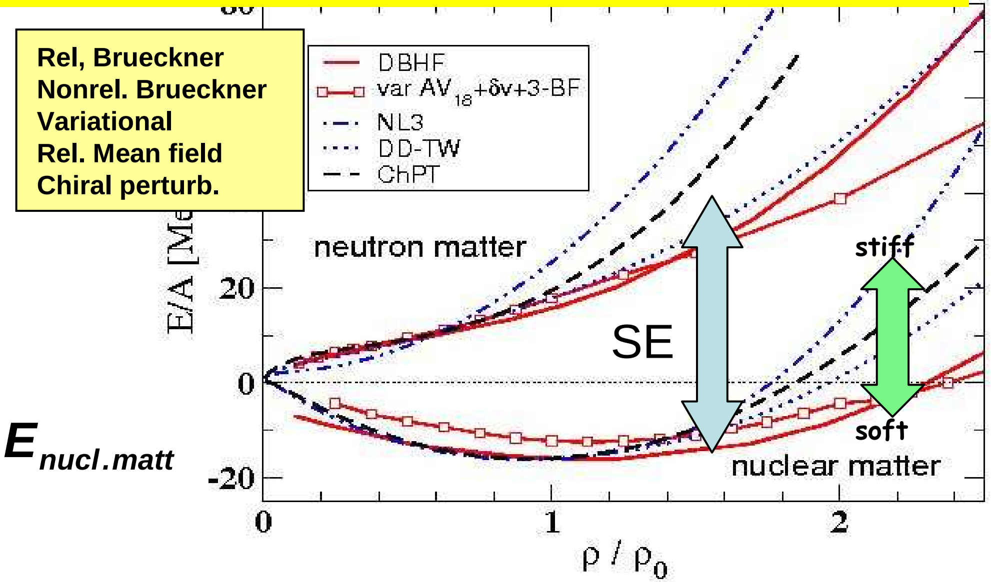
The Nuclear Symmetry Energy in different „realistic“ models

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

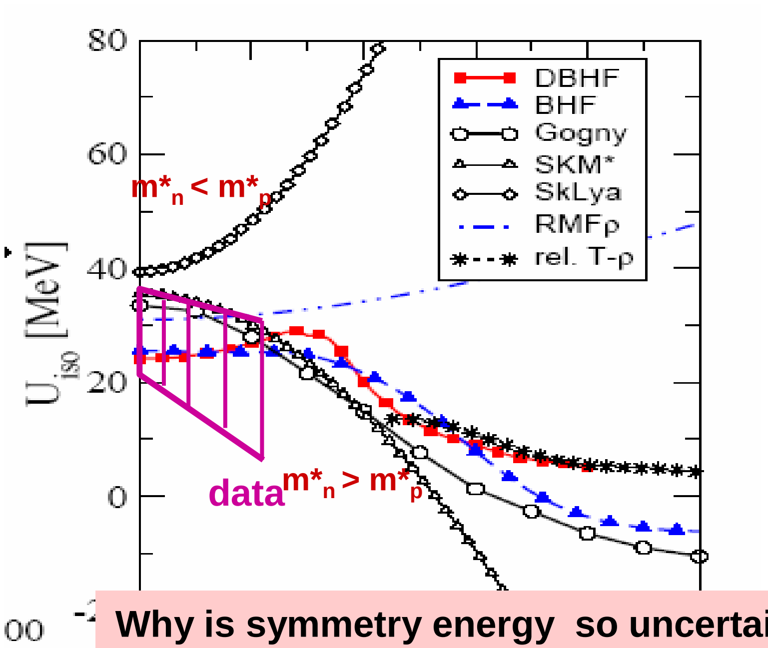
C. Fuchs, H.H. Wolter, EPJA 30(2006)5,(WCI book)

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

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



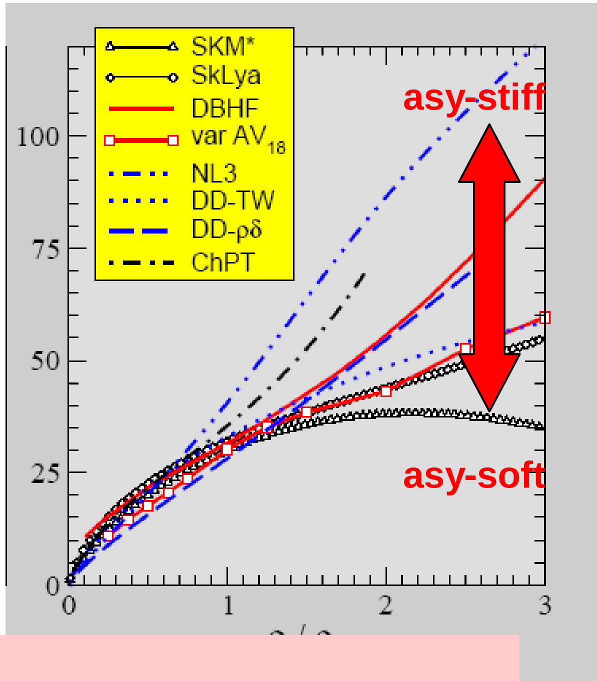
SE ist also momentum dependent → effective mass



Different proton/neutron effective masses

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

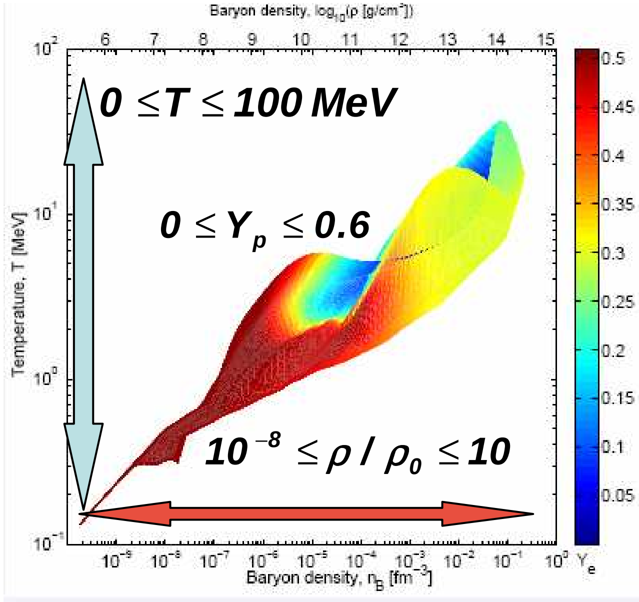
Isovector (Lane) potential: momentum dependence



Why is symmetry energy so uncertain??
->In-medium ρ mass, and short range tensor correlations (Xu, BA. Li, PRC81 (2010) 064612);

Very low density matter in Astrophysics

In Supernova simulations the Equation-of-State appears for a wide range of Densities, temperatures and asymmetries.



T. Fischer, GSI Darmstadt

In particular also at very low densities, where correlations become important.

Various commonly used EoS‘s treat this in a phenomenological manner (e.g. Lattimer,Swesty; Shen, Toki; Shen, Horowitz, Teige))
There exists an exact low density limit, the Virial Theorem (Horowitz, Schwenk)

Attempted Improvements: **(S.Typel, G. Röpke, T. Klähn, D. Blaschke, HHW, PRC 81, 015803 (2010))**

-**medium effects on light clusters, quantum statistical approach**

-**description of low to high density clustered matter in dens.-dep. rel. mean field model (DD-RMF)**

Theoretical approach:

Typel, Röpke, Klähn, Blaschke, Wolter,PRC81,015803(2010)

Quantumstatistical model (QS)

-Includes medium modification of clusters (Mott transition)

-Includes correlations in the continuum (phase shifts)

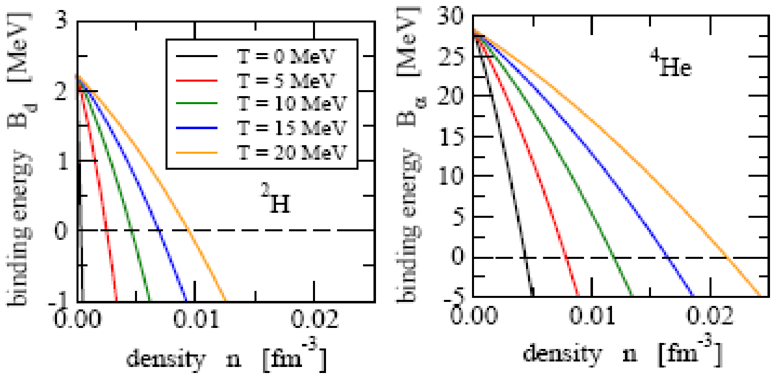
-needs good model for quasi-particle energies in the mean field

Generalized Rel. Mean Field model (RMF)

-Good description of higher density phase, i.e. quasiparticle energies

-Includes cluster degrees of freedom with parametrized density and temperature dependent binding energies

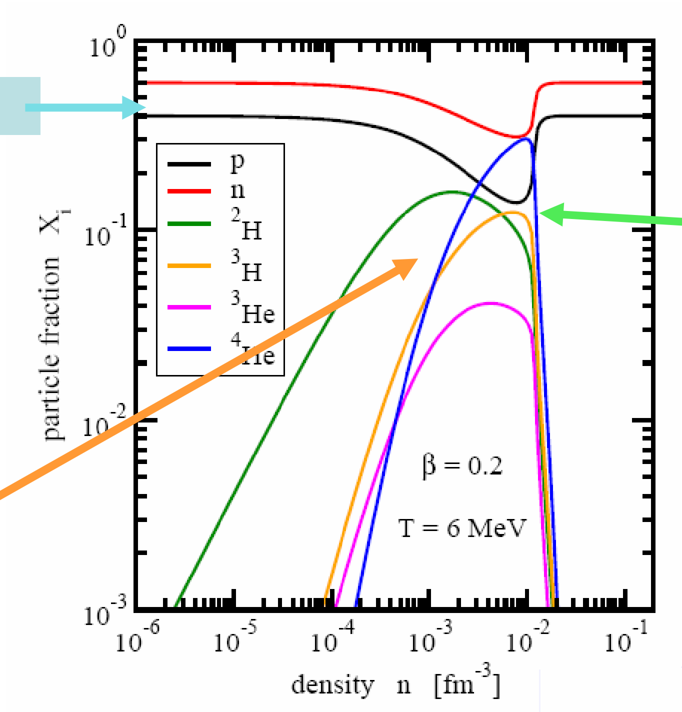
-Heavier clusters treated in Wigner-Seitz cell approximation (



Global approach from very low to high densities

Particle Fractions

very low density: p,n



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

here heavier nuclei (embedded into a gas) become important, not yet fully implemented

Increasing density: clusters arise: deuteron first, but then α dominates

S.Typel, G. Röpke, et al.,PRC 81 (2010)

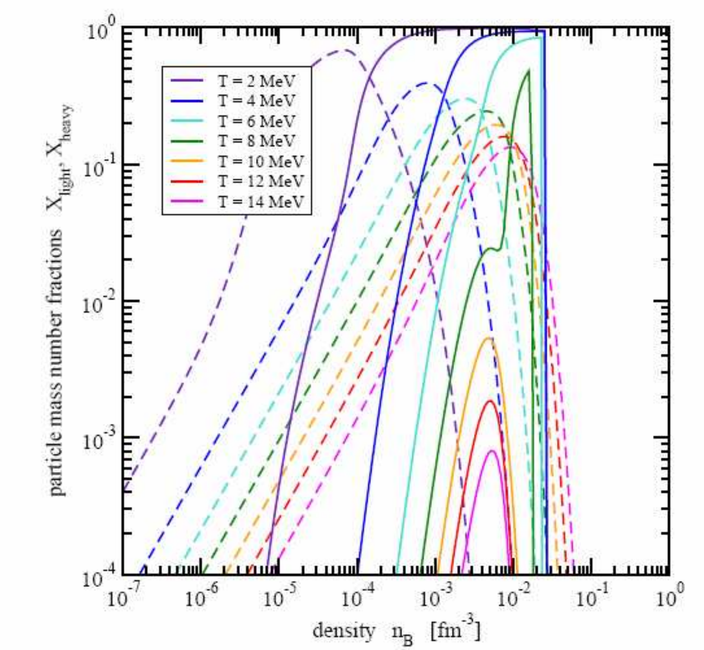
Calculation in RMF of heavy cluster in Wigner-Seitz cell in beta-equilibrium

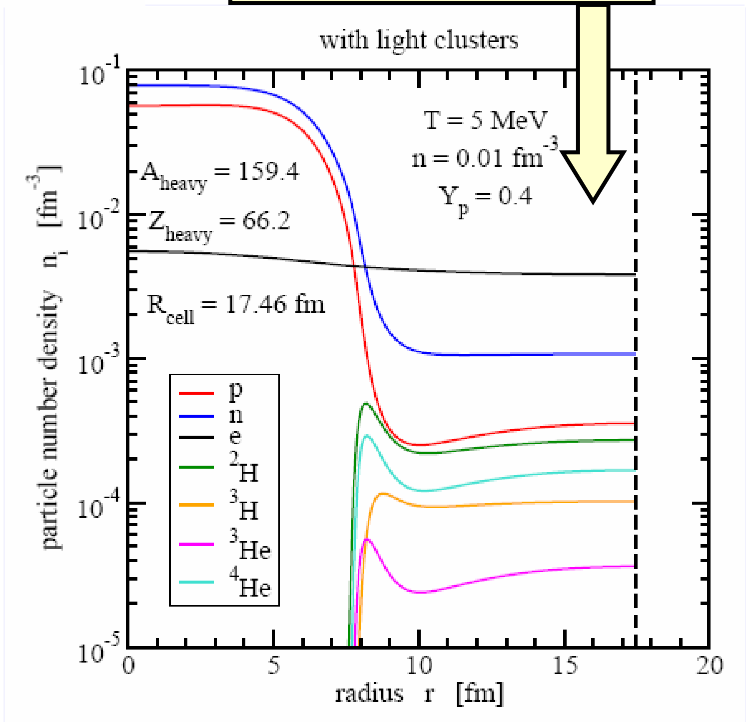
Heavier clusters (nuclei)

(......) light

(——) heavy

fraction



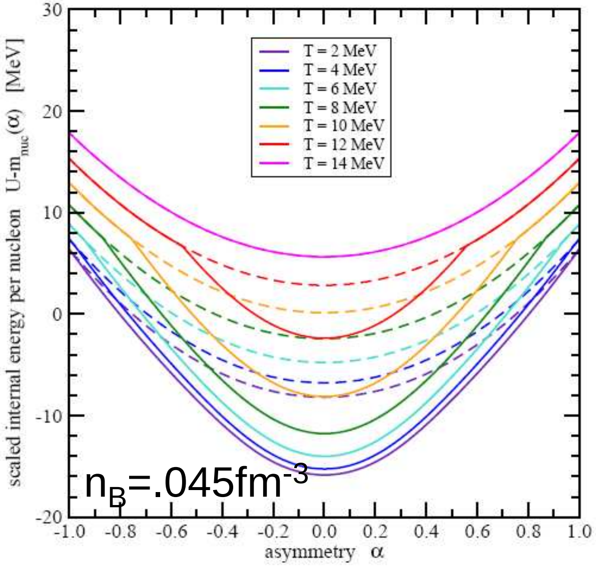


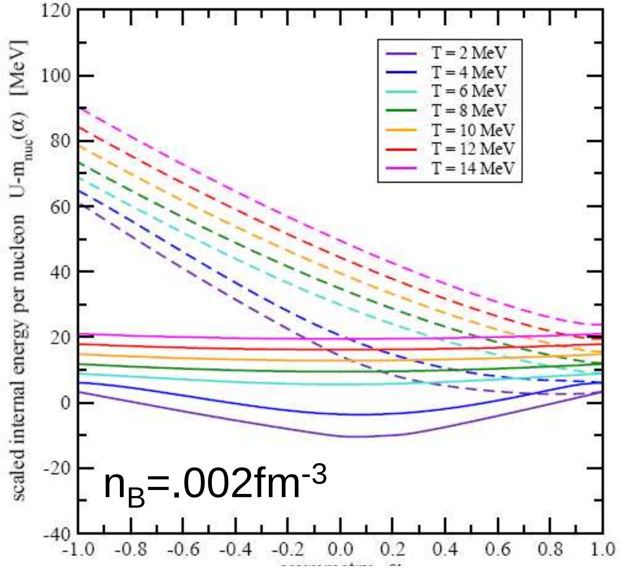
Symmetry Energy in Nuclear and Stellar Matter

Nuclear Matter (w/o clusters) without (-----) and with (———) liquid-gas phase transition

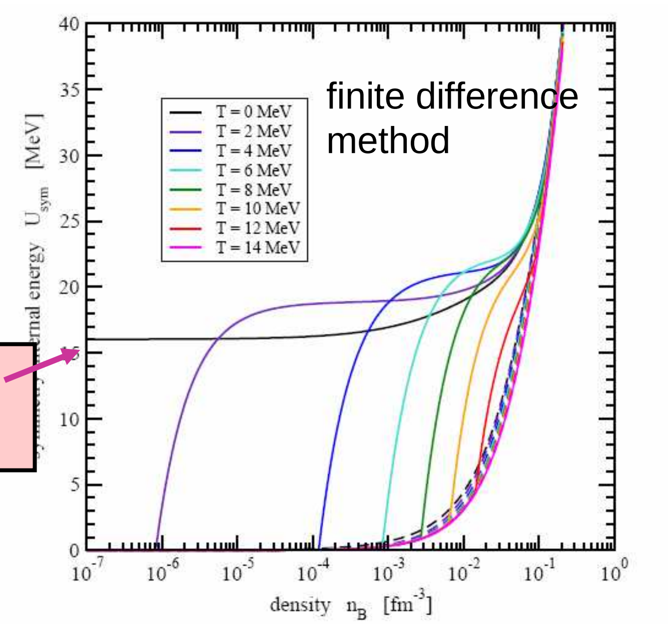
Stellar Matter (with electrons and with clusters) without (------) and with Coulomb contrib removed (———)

Internal Energy

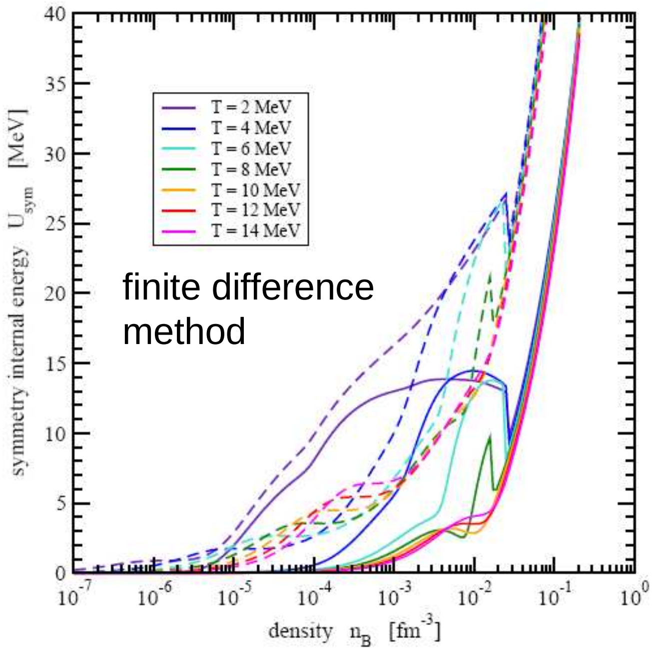




Symmetry Energy

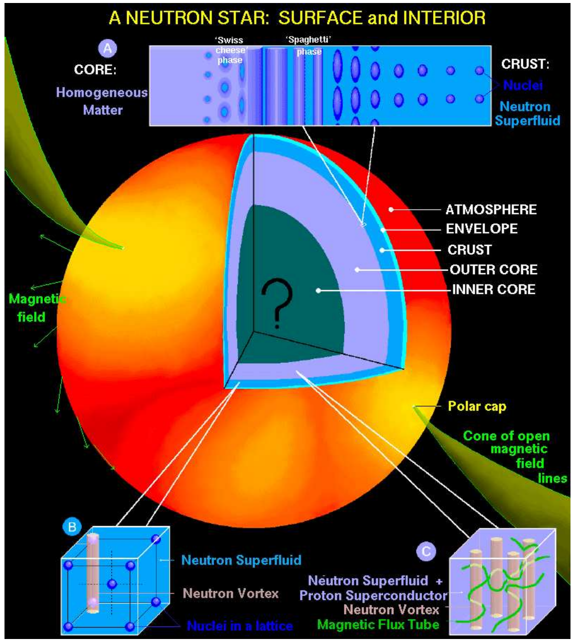


finite at T=0 due to PT



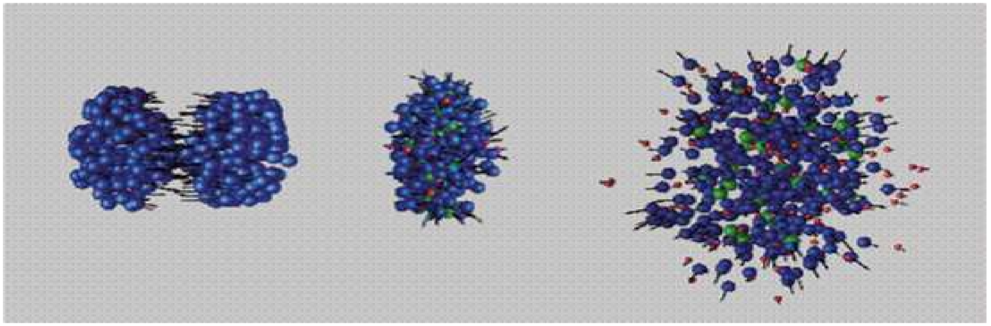
Constraints on EoS via Astrophysical Observation and Laboratory Experiments

Model for structure of NS



Simple (in some parts) and equilibrated system, but difficult to observe

Heavy ion collisions

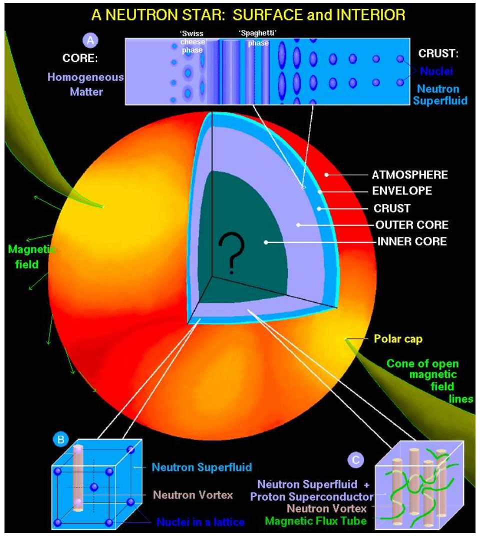


Complex system not in equilibrium, but managable in the lab

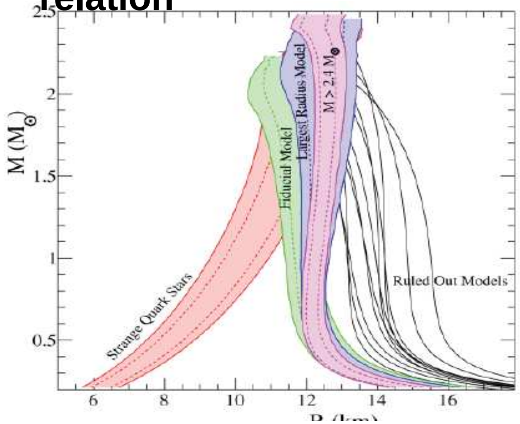
The Symmetry Energy in Astrophysics

Constraints on EoS from Astrophysical Observation

Observations of:
masses
radii (X-ray bursts)
rotation periods

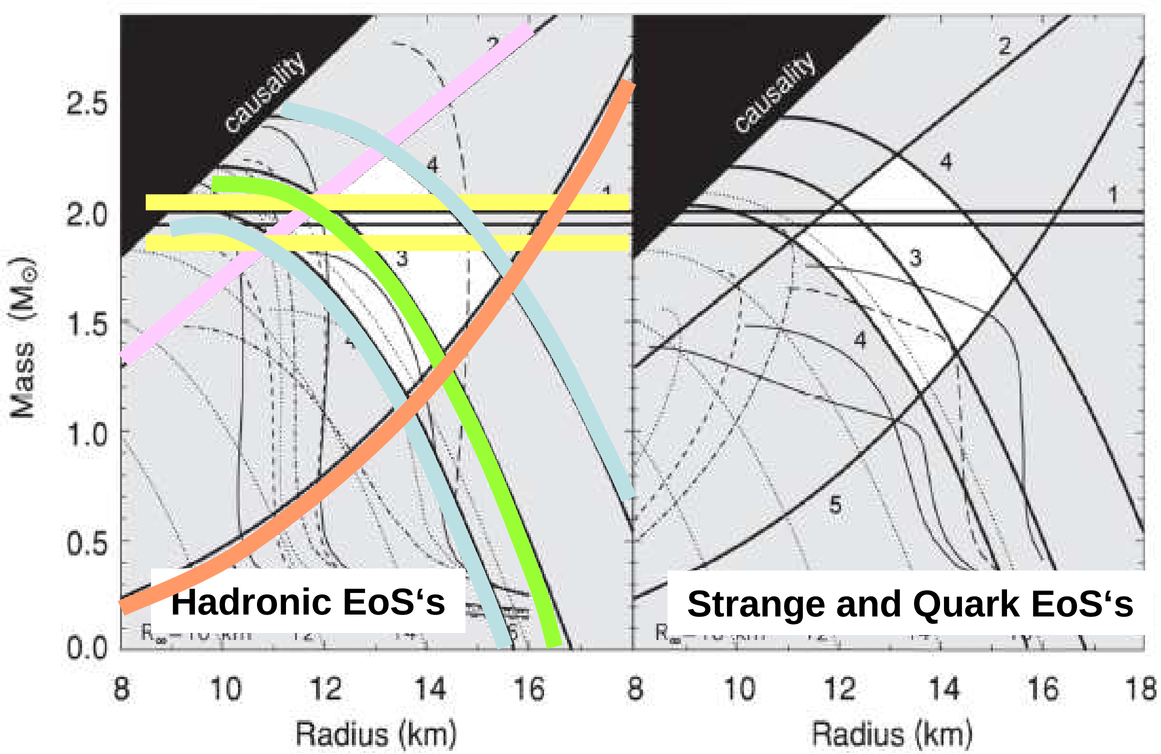


Neutron star mass-radius relation



Steiner, Lattimer, arXiv 1205.6871

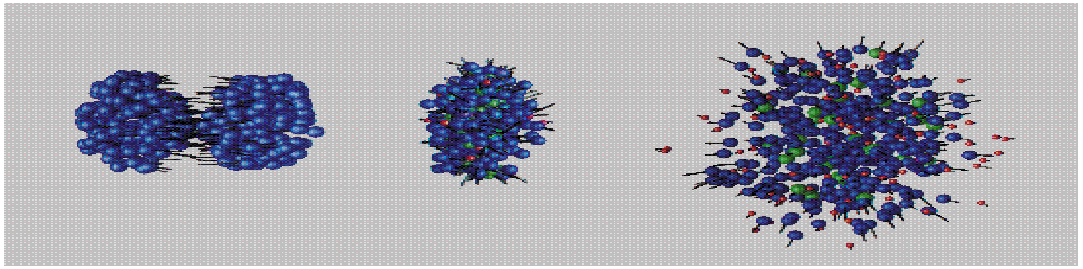
Trümper Constraints (Universe Cluster, Irsee 2012)



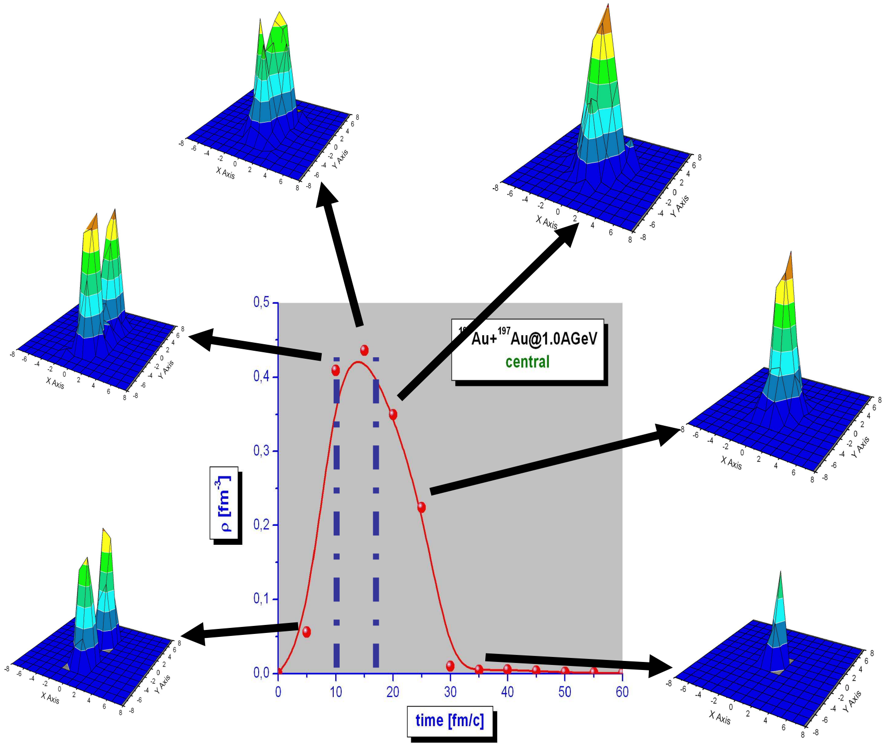
Stringent constraint on many EoS models

Transport Theory for Heavy Ion Collisions

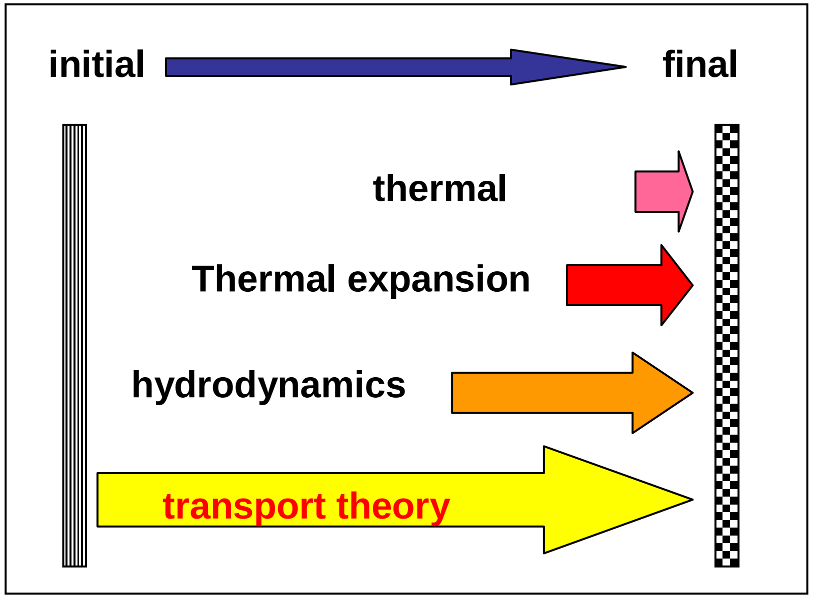
Heavy ion collisons



non-equilibrium



Levels of description of evolution from initial to final state:



Transport equations

Boltzmann-Ühling-Uhlenbeck (BUU)

$$\frac{\partial f}{\partial t}+\frac{\vec{p}}{m}\vec{\nabla}^{(r)}f-\vec{\nabla}U(r)\,\vec{\nabla}^{(p)}f(\vec{r},\vec{p};t)=\int d\vec{v}_2\,d\vec{v}_{1'}\,d\vec{v}_{2'}\,v_{21}\,\sigma_{12}(\Omega)(2\pi)^3\,\delta(p_1+p_2-p_{1'}-p_{2'})\left[f_{1'}f_{2'}(1-f_1)(1-f_2)-f_1f_2(1-f_{1'})(1-f_2')\right]$$

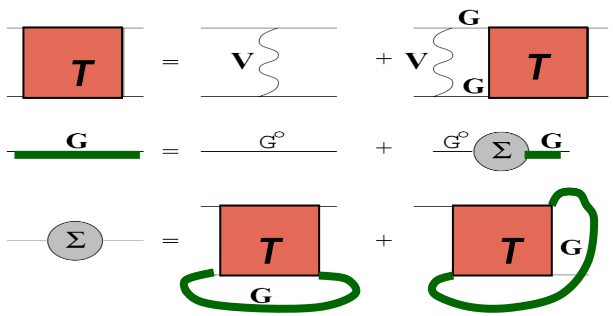
Can be derived:

→ **Classically from the Liouville theorem**

→ **Semiclassically from THDF**

} **collision term added (and fluctuations)**

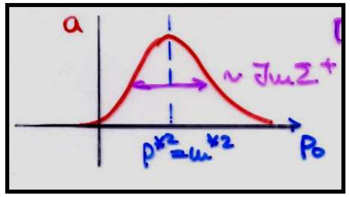
→ **From non-equilibrium theory (Kadanoff-Baym)**
collision term included
mean field and in-medium cross sections consistent, e.g. from BHF



Spectral fcts, off-shell transport, quasi-particle approx.

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

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



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

Dirac-Brueckner (DB) self energies and in-medium cross sections

Decomposition of DB self energy

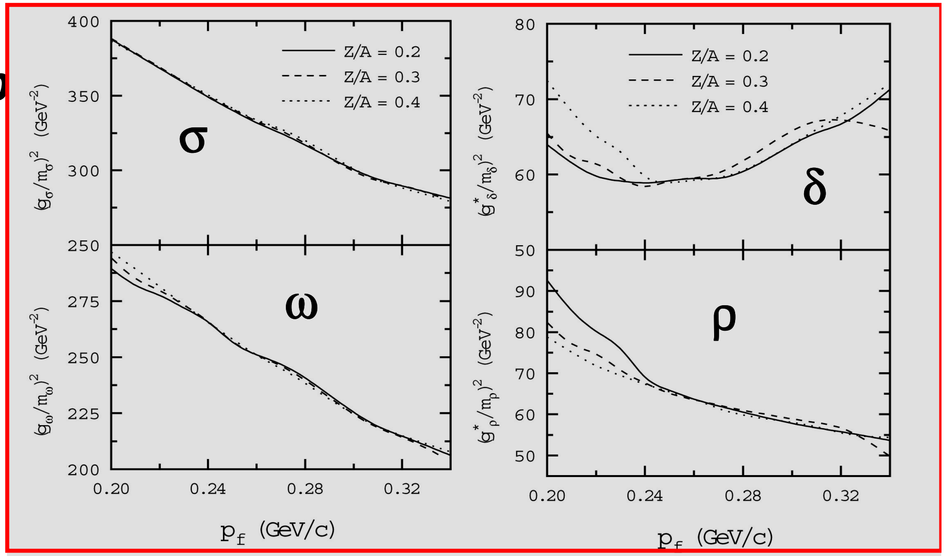
$$\Sigma_{n,p}(p) = \Sigma^{s}_{n,p}(p) - \gamma^{0}\Sigma^{0}_{n,p}(p) + \vec{\gamma}\vec{p}\,\Sigma^{v}_{n,p}(p$$

Represent as density (and momentum) dependent coupling coeff.

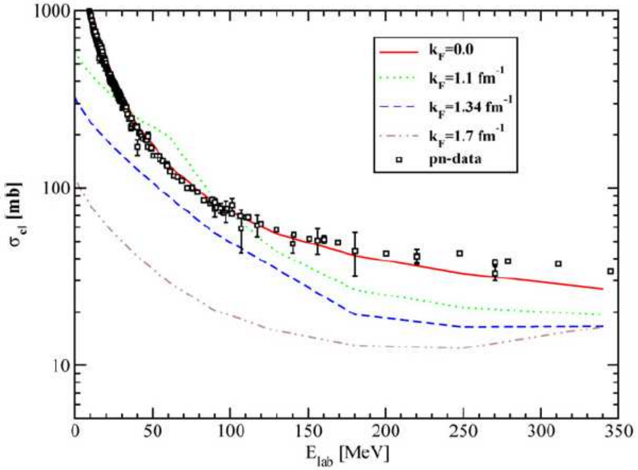
$$\Gamma_{\alpha}(\rho_B, p) = \frac{\Sigma^{\alpha}(\rho_B, p)}{\rho_{\alpha}(\rho_B)};\ \alpha = \{\sigma, \omega, \rho, \delta\}$$

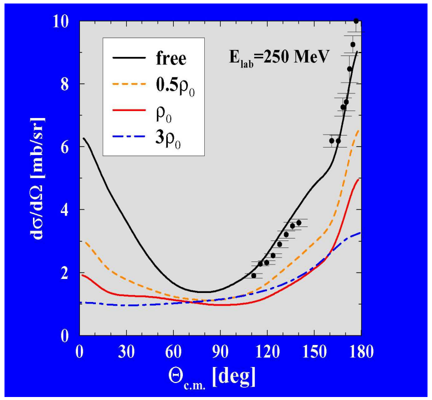
can be used in DD-RMF approach (e.g. Typel, Wolter NPA656, 331 (1999)

deJong, Lenske, PRC 58 (98) 890



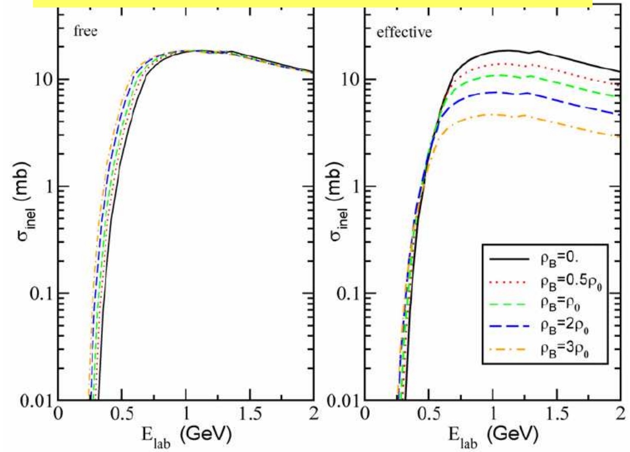
elastic np from DBHF:





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

NN → NΔ, from DBHF



terHaar, Malfliet, PRC 36 (87) 1611

Characterization of Codes for Transport Calculations

Realizations of transport codes:

1. Testparticle methods (BUU)

$$f(r,p;t) = \frac{1}{N_{TP}} \sum_{i=1}^{AN_{TP}} \delta(r - r_i(t))\, \delta(p - p_i(t))$$

Simulate continuous phase space distribution by many test particles per nucleon (N_{TP}= 50-200).

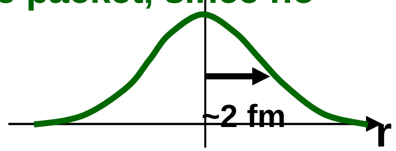
variants: - Gaussian test particles: smoother distributions with fewer testparticles

- include fluctuations: explicit, reduced N_{TP},, Brownian force

- non-relativistic (Skyrme-type) or relativistic (RMF) density functionals

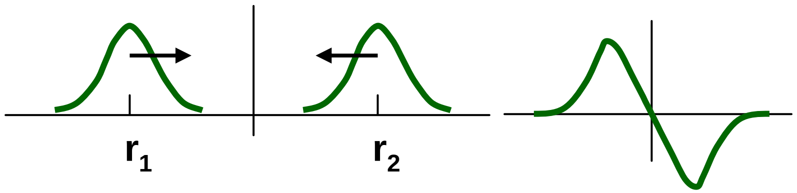
2. Quantum molecular dynamics (QMD)

Gaussian particles with large width to smooth fluctuations, but not a wave packet, since no antisymmetrization (thus similar to BUU with N_{TP}=1), but event generator.



variants: - different density funtionals and inclusion of isospin often denoted by different names: e.g. IQMD, ImQMD, (isospin dependence)

- antisymmetrization of wave packets included (AMD, FMD)
Particle coordinates loose meaning as WP approach each other.
reduction of wp in collision term



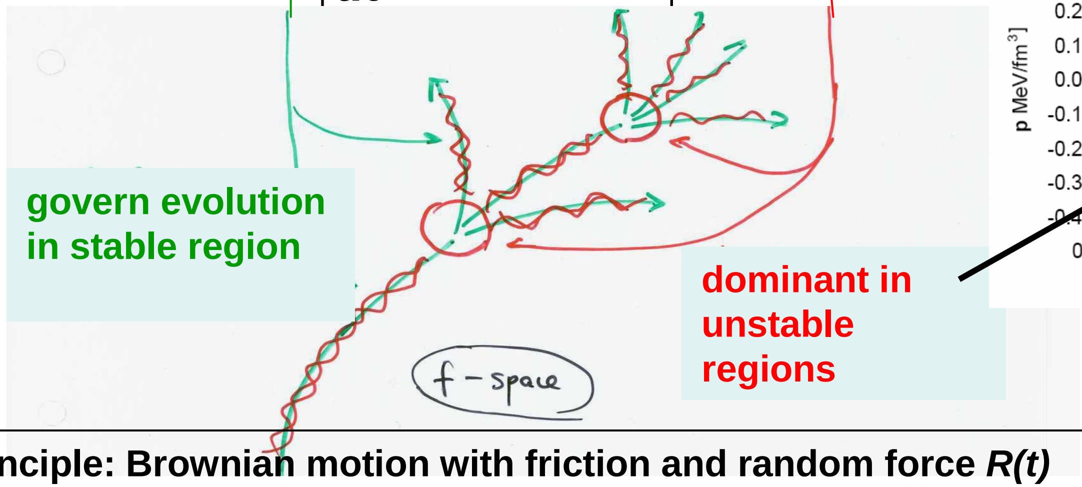
Fluctuations in Phase Space

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

Mean field evolution (dissipative)

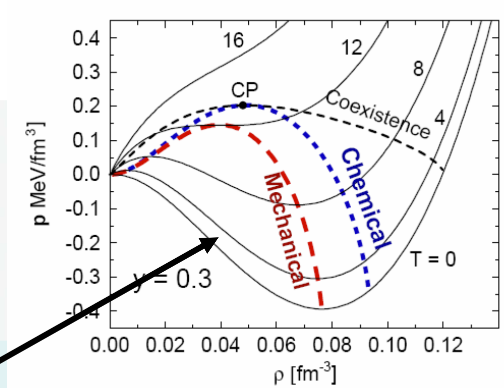
Fluctuations (higher orger correlations)

Boltzmann-Langevin eqn. $$\boxed{\frac{df}{dt} = I_{coll} + I_{fluc}}$$



govern evolution in stable region

dominant in unstable regions



General principle: Brownian motion with friction and random force *R(t)*

$$m\frac{dv}{dt} = -\gamma v + R(t)$$

$$\Rightarrow \quad \langle R(t)R(t')\rangle = 2\gamma T\,\delta(t-t')$$

Fluctuation-Dissipation theorem (Einstein relation)
→Dissipation (collisions) and Fluctuations necessarily connected!

Origin of fluctuations: → initial state correlations (how important and realistic?)
→ higher order correlations
→ collisions (diss.-fluct. theorem)

The last two are not contained in BUU and have to be reintroduced, i.e. the Boltzmann-Langevin eq. has to be solved, at least approximatively

Fluctuations in QMD?

Classical Molecular Dynamics (CMD) has classical many body correlations:
2-body potential V_{ij}, classical eq.-of-motion, trajectories

QMD (without collisions): smeared-out classical molecular dynamics,
smearing (=width of Gaussians) much larger than size of nucleon.

mean field $$U_i(r_i) = \sum_j \int dr_j V_{ij}(r_i - r_j)\,\rho_j(r_j) = \int dr_j V_{ij}(r_i - r_j)\,\rho(r_j)$$

same as in BUU

Thus in propagation little difference between QMD and BUU.

Difference in collision term:

QMD: collision moves one nucleon, large fluctuation, „event“
BUU: collision moves one test particle → much smaller fluctuation
(attempt to simulate this in BUU (Bertsch): move N_{TP} neighboring TPs)
→ therefore explicit fluctuation neccessary (see above)
QMD: uncertainity in defining collisions.
cf. AMD, wave packet distance looses meaning, when nucleons are close
spreading of wave packet not taken into account

Expect that differences between QMD and BUU have origin in collision term

Fragment recognition algorithm in BUU:

1. „density cut“: find contours of density ρ_c ~1/10 ρ_0

   Fragments have non-integer mass and charge numbers. Distribute to neighboring integer masses.

2. Test particle distribution sampling:

   choose A out of N_{TP}*A test particles with correct global properties. Treat these as nucleons and do coalescence or spanning tree algorithm (as in QMD): two particles belong to the same cluster if their distance in phase space is below a limit $r_{12}<r_0$, $p_{12}<p_0$; r_0, p_0 parameters

   Do this many times (~1000), and generate a distribution

   → Reconstruct many body correlations consistent with the single particle distribution

Ex.: 4 „events“ with fluctuations

458 M. Colonna et al./Nuclear Physics A 642 (1998) 449-460

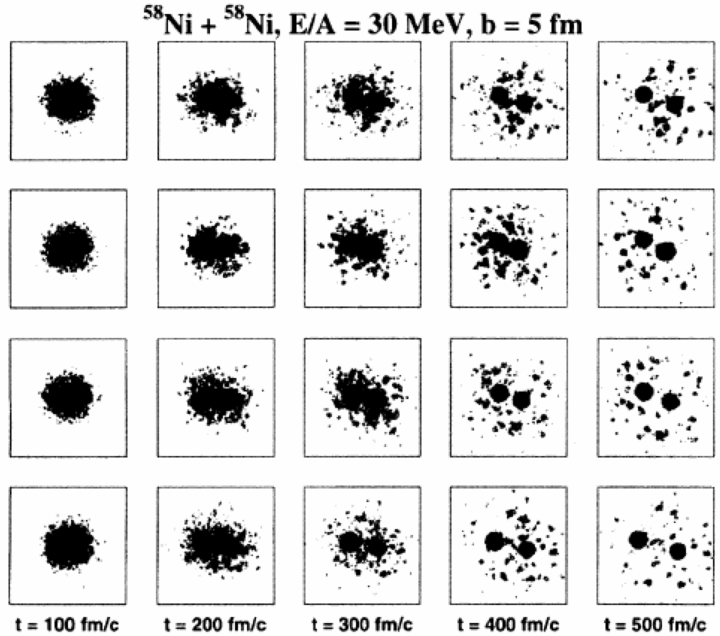
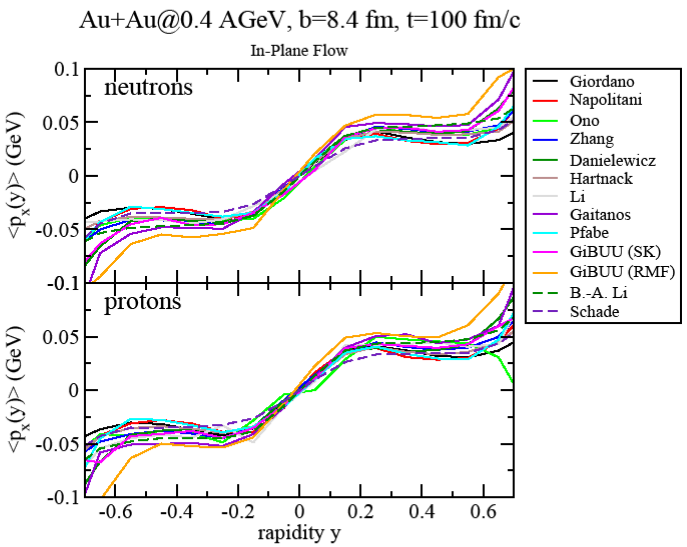


Fig. 3. Same as Fig. 1, but in the case of the binary events obtained in the collision Ni + Ni at 30 MeV/A, b = 5 fm.

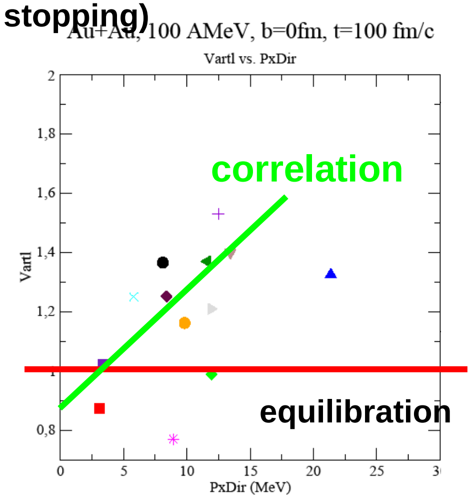
Code Comparison Project:
Workshop on Simulations of Heavy Ion Collisions at Low and Intermediate Energies, ECT*, Trento, May 11-15, 2009

→ using same reaction and physical input (not neccessarily very realistic, no symm energy))
→ include major transport codes
→ obtain estimate of „systematic errors“

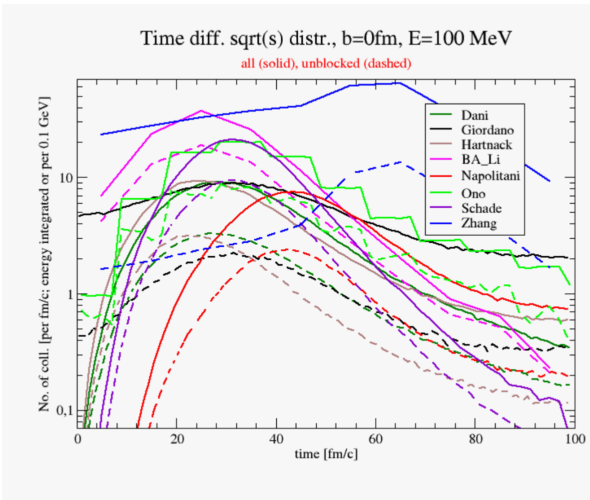
transverse flow



Correlation between transv flow and Vartl (ratio of long and transv stopping)



time distribution of collisions (energy integrated)



→ agreement for flow and other one-body observables reasonable,
but perhaps not really good enough to make detailed conclusions

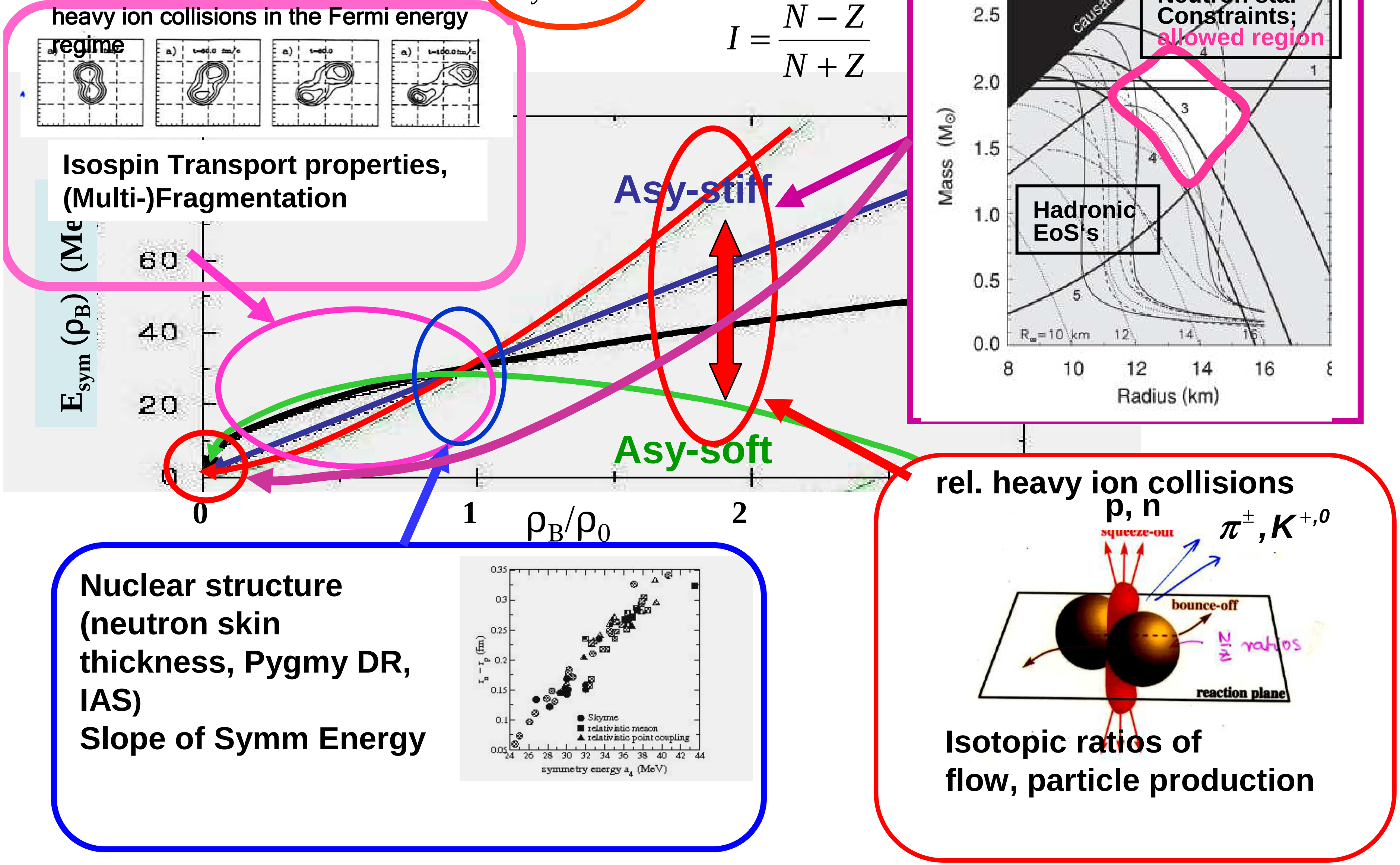
→ symmetry effects are order of magnitude smaller: hope that differences are less sensitive (?)

→ origin of differences: collisions ?

The Symmetry Energy in Various Density Regimes

Investigations on the Nuclear Symmetry Energy

$$E(\rho_B, I)/A = E(\rho_B) + E_{sym}(\rho_B) I^2 + O(I^4) + \ldots \qquad I = \frac{N-Z}{N+Z}$$

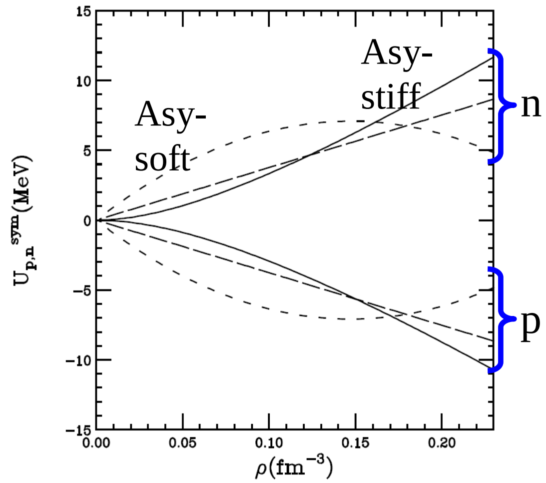


Strategies for the determination of the SE in HIC

Potential energy in nuclear matter:

E/A~-16 MeV = T(3/5 ε_F ~21 MeV) + U → U~37 MeV

Usym ~ 8 MeV → small effect



Thus use differences or ratios of isospin dependent observables, to eliminate As much as possible uncertainties in the isoscalar sector.
Of course, no guarantee. Establish that global description of reaction is correct.

I arrived at this point during the lecture.

The remaining slides will perhaps be discussed in an afternoon session

The Symmetry Energy at very low densities

A statistical analysis to determine Symmetry Energy at very low densities

S. Kowalski, J. Natowitz, et al.,PRC75 014601 (2007)

^{64}Zn+(^{92}Mo,^{197}Au) at 35 AMeV

Central collisions, reconstruction of fireball

Determination of thermodyn. conditions as fct of $v_{surf}=v_{emission}-v_{coul}$
~time of emission with specified conditions of density and temperature:

→ temperature: isotope temperatures, double ratios H-He

$$T_{\mathrm{HHe}} = \frac{14.3}{\ln[\sqrt{(9/8)}(1.59 R_{V_{\mathrm{surf}}})]},$$

→ densities ρ_p, ρ_n, from yield ratios and bound clusters

$$\rho_p = 0.62 \times 10^{36} T^{3/2} e^{-19.8/T} Y(^4\mathrm{He})/Y(^3\mathrm{H}).$$

→ Isoscaling analysis

(B.Tsang, et al.,)

$$R_{12} = \frac{Y_2(N,Z)}{Y_1(N,Z)} \cong \left(e^{\frac{\Delta\mu_n}{T}}\right)^N \left(e^{\frac{\Delta\mu_n}{T}}\right)^Z \cong e^{\alpha N + \beta Z}$$

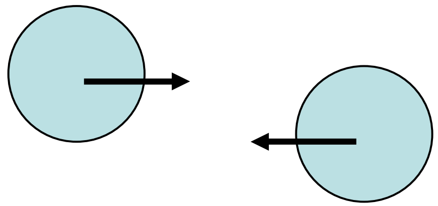
Isoscaling coefficients α and β

→ Symmetry free energy

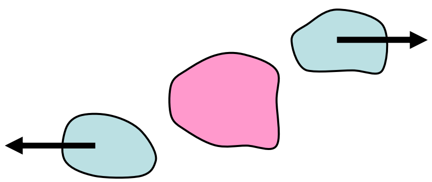
$$\boxed{\alpha = \frac{4F_{sym}}{T}\left(\left(\frac{Z_1}{A_1}\right)^2 - \left(\frac{Z_2}{A_2}\right)^2\right)}$$

$$E_{sym} = F_{sym} + T S^{(NSE)}$$

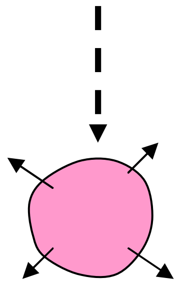
Scheme of Kowalski Interpretation



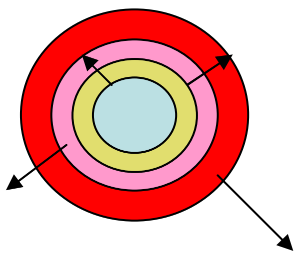
64Zn+(92Mo,197Au) at 35 AMeV,
i.e. two systems for isoscaling analysis



3-source fit and complete reconstruction of participant, i.e N,Z of source



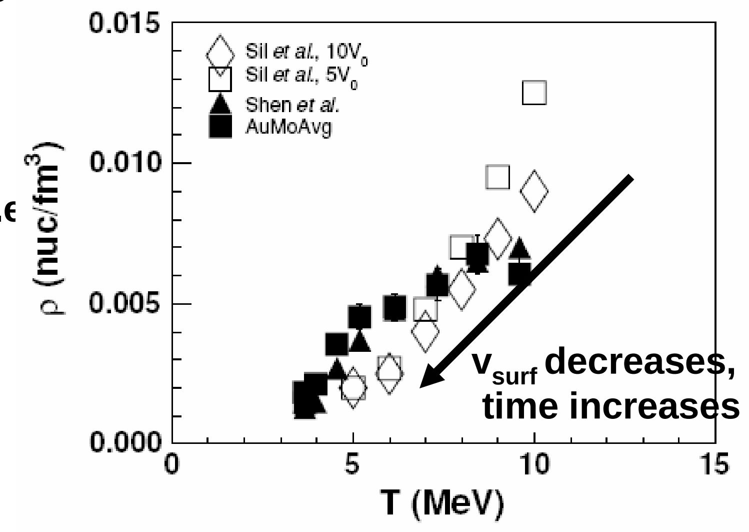
Participant emits light clusters (p,n,d,t,3He,α) and cools
Earlier emitted particles have higher temperature and higher initial velocity =$v_{surf,,}$,which is measured



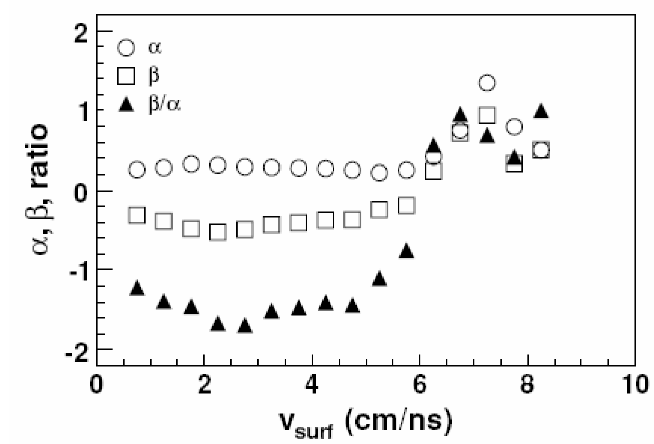
Interpret results by thermodynamics as a function of v_{surf} ,

i.e. each shell is a piece of equilibrated dilute matter, of which T, ρ are determined

Extracted ρ-T relation for emitting sourse

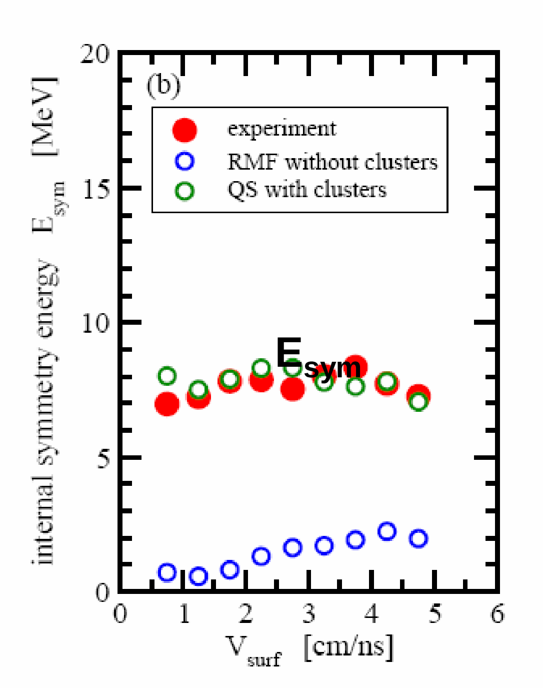


Isoscaling coefficients



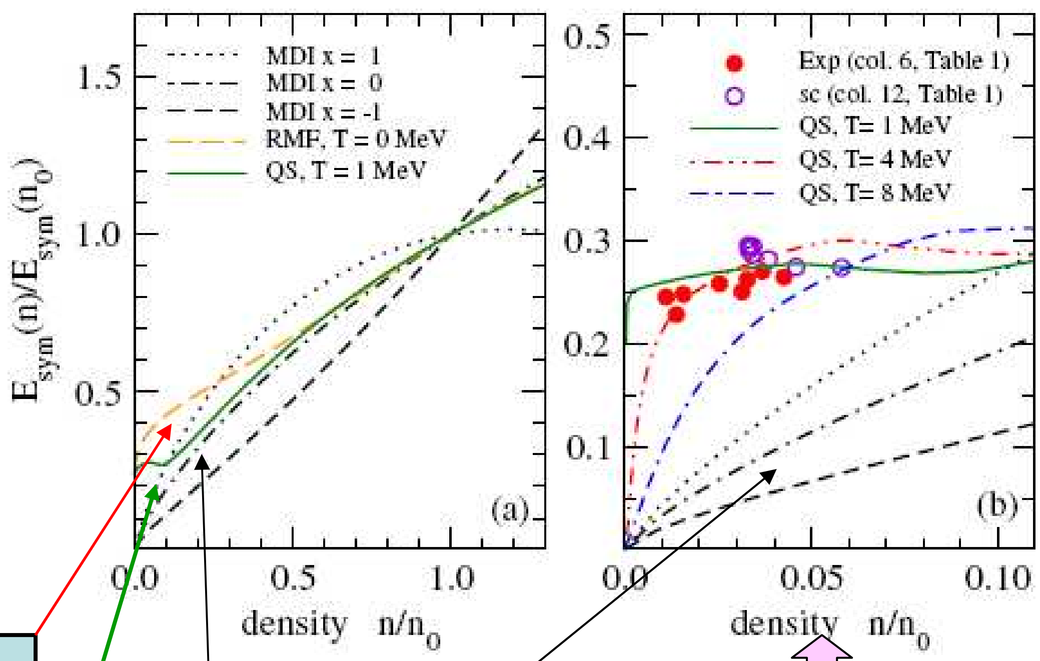
Comparision of low-density symmetry energy to experiment:

J. Natowitz, G. Röpke, S. Typel, … HHW, PRL 104, 202501 (2010)



complete density range

low densities



Single nucleus approx. (Wigner-Seitz), RMF

Quantum Statistical model , T=1 MeV)

Parametrization of nuclear symmetry energy of different stiffness (B.A. Li)

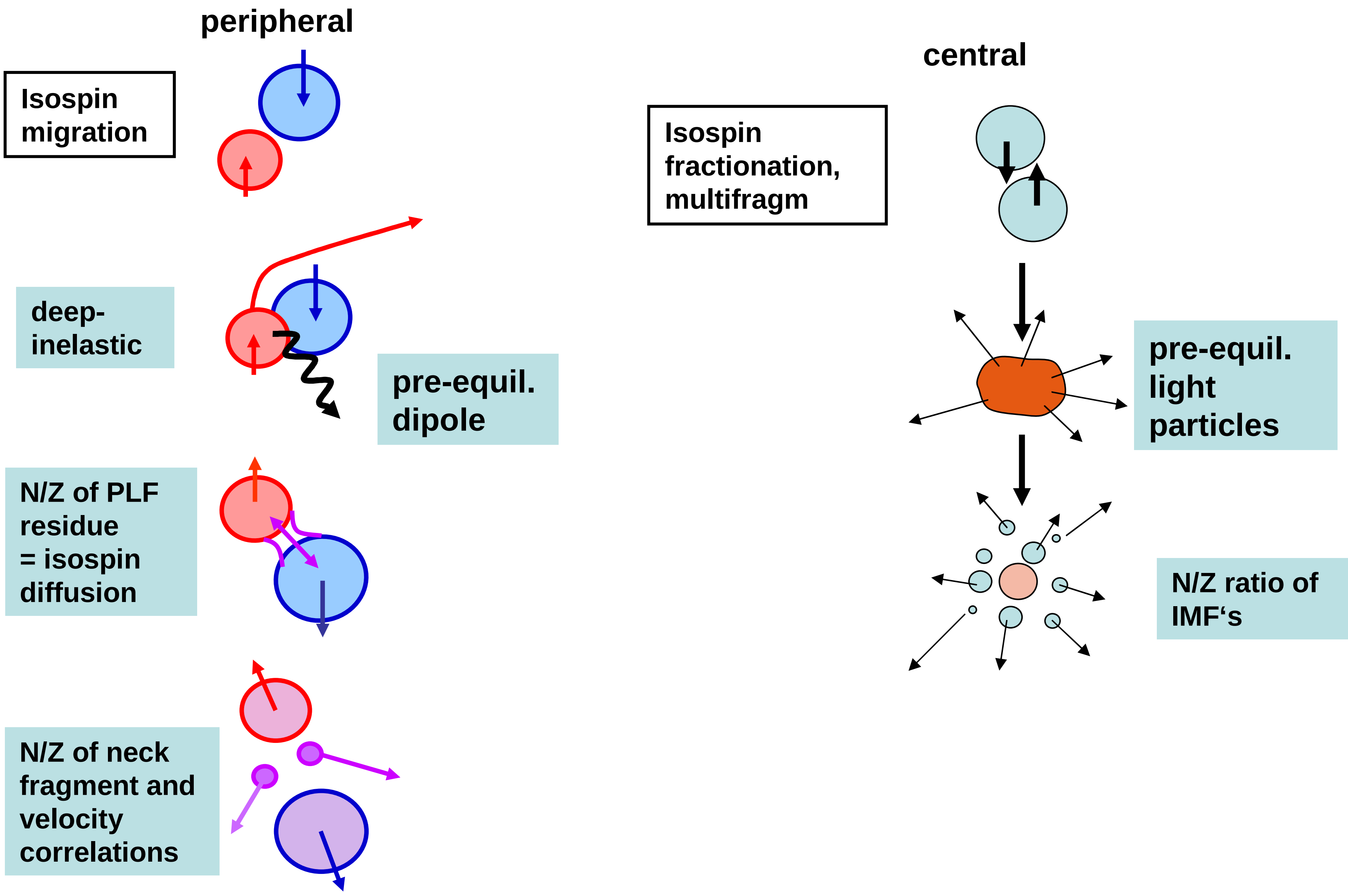
Successfully reproduce the experimentally deduced symmery energy at low density.

Symmetry energy is finite at very low density!

The Symmetry Energy at Low Densities

Dynamical Interpretations of Low Energy Heavy Ion Collisions

Coulomb barrier to Fermi energies

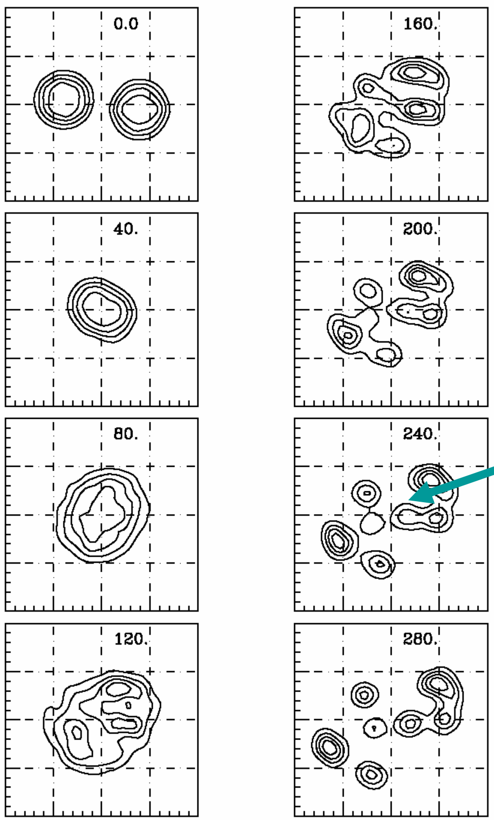


Isospin dynamics at Fermi energies

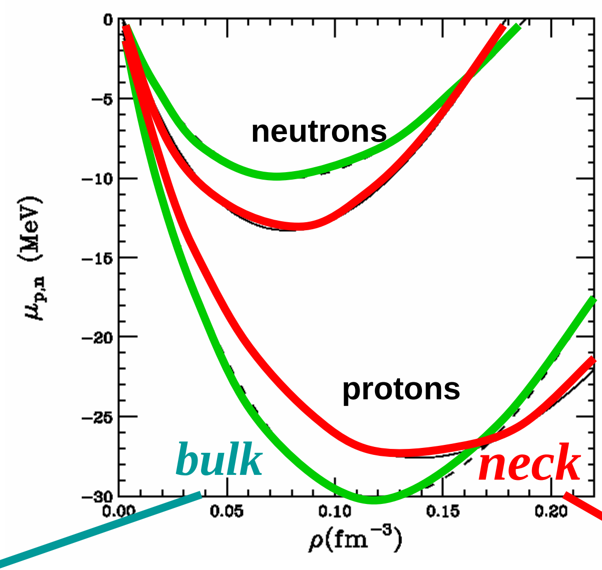
V.Baran et al.,
NPA703(2002)603
NPA730(2004)329

$^{124}Sn+^{124}Sn$, 50 AMeV

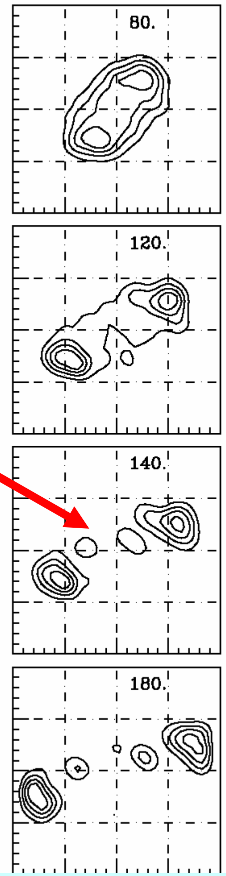
Central collision, b=2 fm

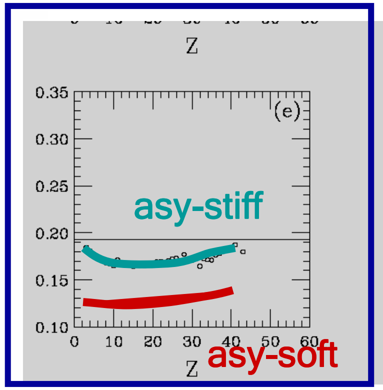


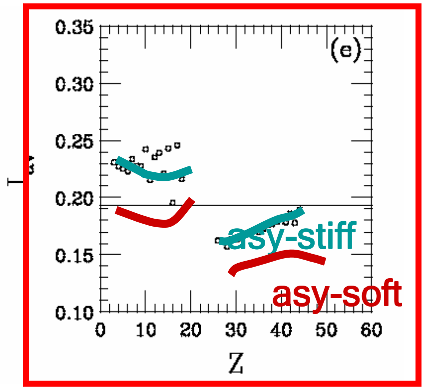
Chemical potential: isosoft, isostiff



Peripheral collision, b=6 fm







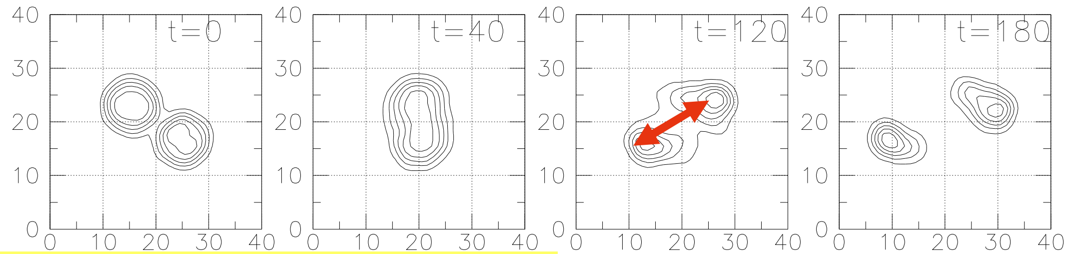
Multifragmentation: Isospin fractionation at low densities

Neck-fragmentation: Isospin migration at interface with normal density

Isopin diffusion

isospin transport through „neck“ in peripheral collisions

$^{124}Sn(H)+^{112}Sn(L)$



Imbalance (or Rami, transport) ratio:

β asymmetry of residue (i=PLF,TLF)
(also for other isospin sens.quantities)

$$R_i = \frac{\beta_i^{mix} - \frac{1}{2}(\beta_i^{HH} + \beta_i^{LL})}{\frac{1}{2}(\beta_i^{HH} - \beta_i^{LL})}$$

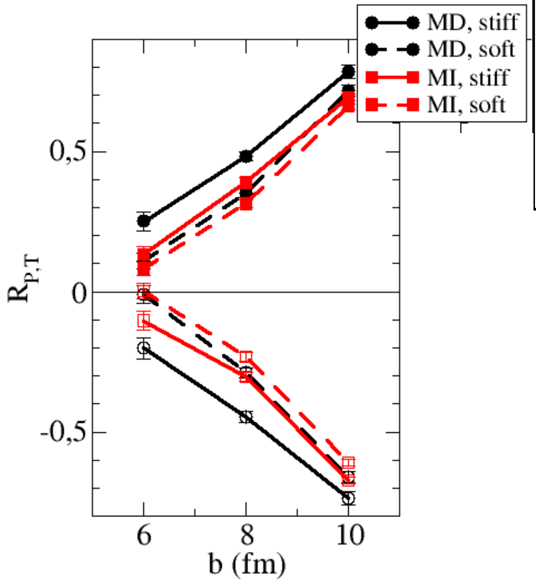
Limiting values:
***R*=0 complete equilibration**
***R*=+-1, complete transparency**

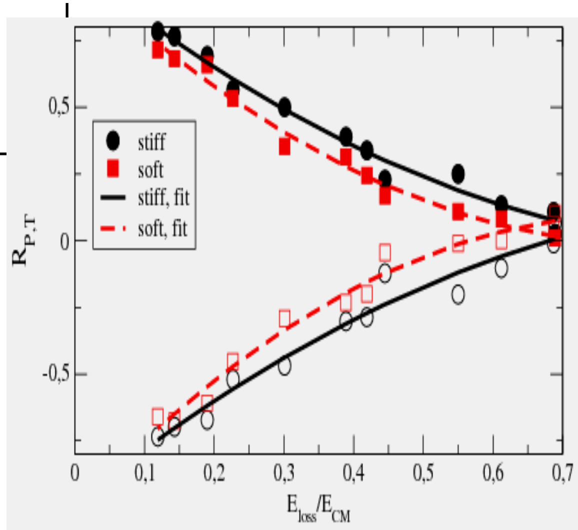
Simple equil. model

$$\beta^M_{P,T} = \beta^{eq} + (\beta^{H,L} - \beta^{eq})\ e^{-t/\tau},$$

$$R^{\rho}_{P,T} = \pm e^{-t/\tau}$$

Ratio det. by interact. and relax. times



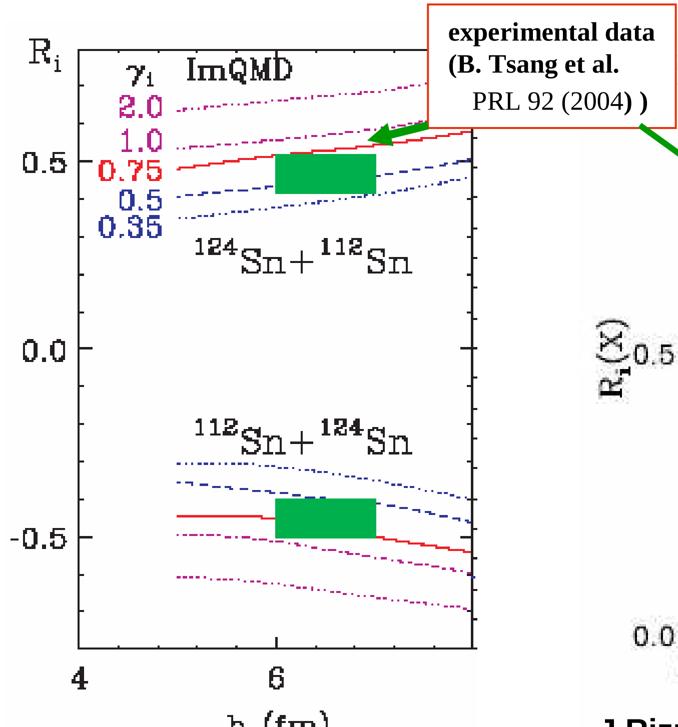


J.Rizzo, et al., Nucl. Phys. A806 (2008) 79

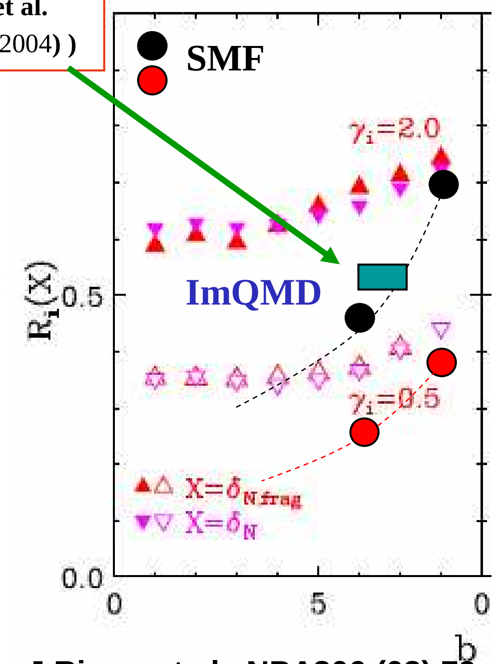
more equlibration (lower R) for longer interaction time ~ correlation with total energy loss

Transport Ratios for Projectile/Target Residues: ^{112,124}Sn + ^{112,124}Sn, 50 MeV

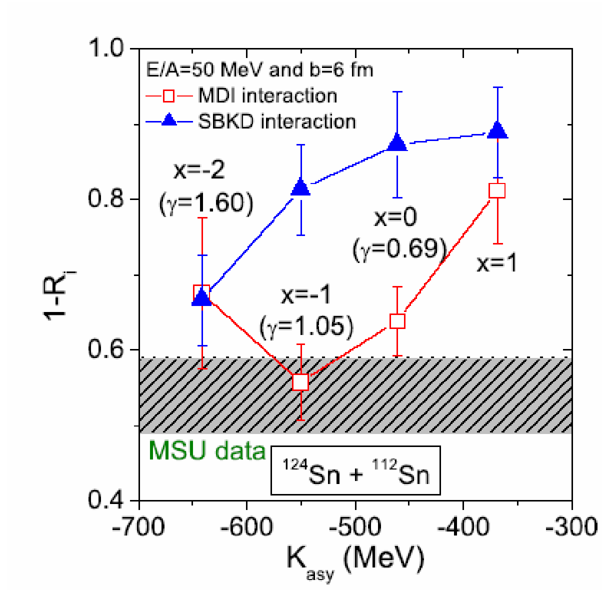
Comparison to other calculation:



M.B. Tsang, et al., PRL 102 (2008)



J.Rizzo, et al., NPA806 (08) 79



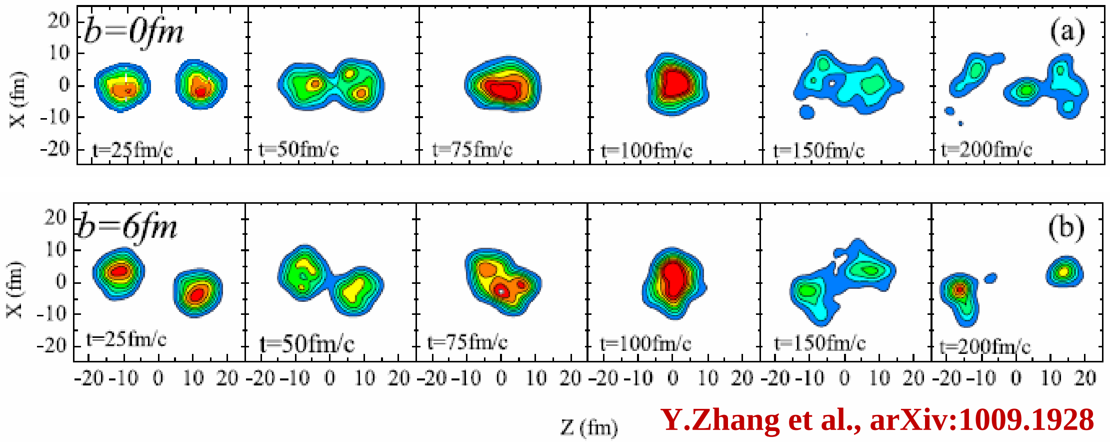
L.W.Chen, C.M.Ko, B.A.Li, PRL 94, 032701 (2005)

1. Qualitative agreement, but not quantitative
2. different impact parameter dependence
3. perhaps related to different procedures to solve transport eq. (BUU vs. QMD)

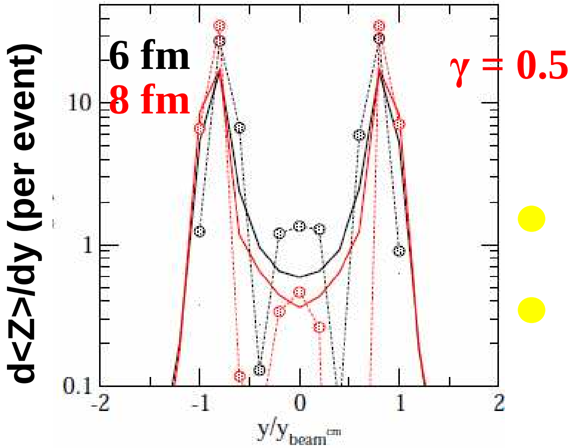
Analysis of differences BNV – QMD

→ more `explosive´ dynamics:
more `transparency´

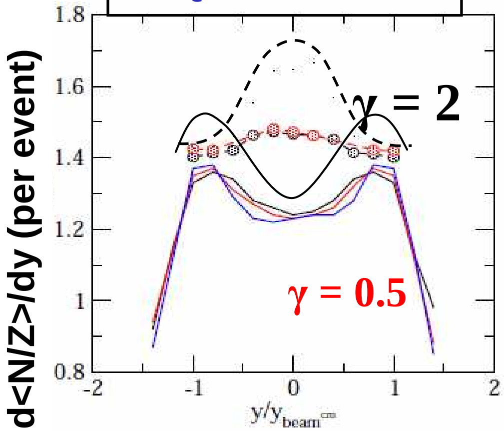
ImQMD calculations, ^{112}Sn +^{112}Sn, 50 AMeV



Y.Zhang et al., arXiv:1009.1928



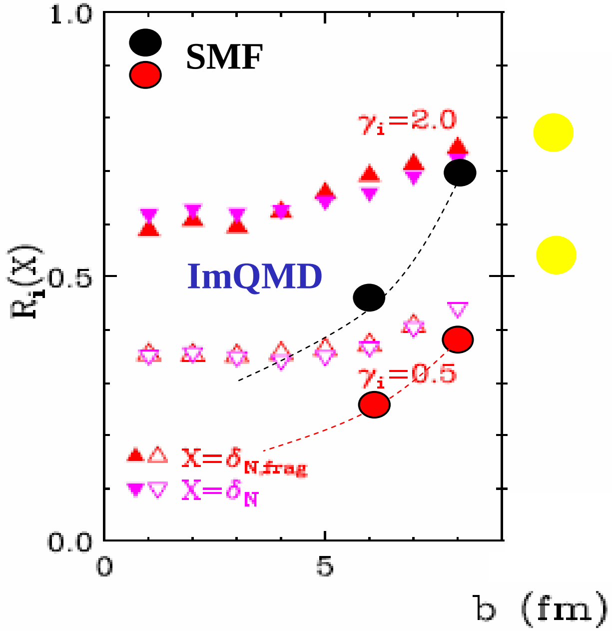
SMF = dashed lines
ImQMD = full lines



Much less isospin migration in ImQMD, Other sources of dissipation: Fragment emission, fluctuation?

→Less dependence on impact parameter.

Similar conclusions in comparison with Antisymmetrized Mol. Dynamics (AMD): Colonna, Ono, Rizzo, PRC (2011)

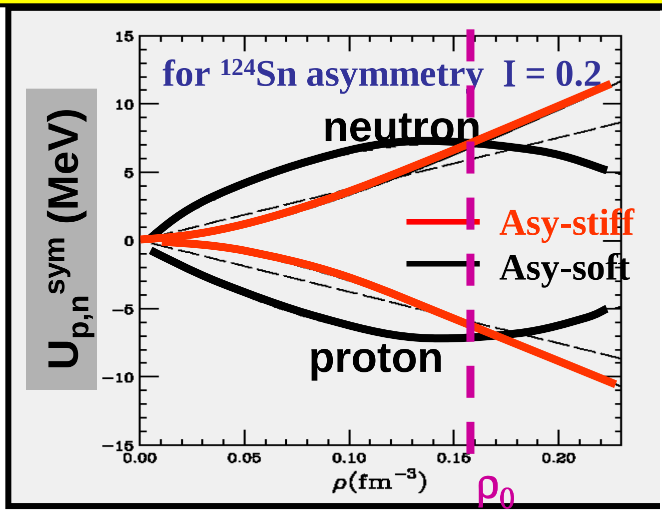


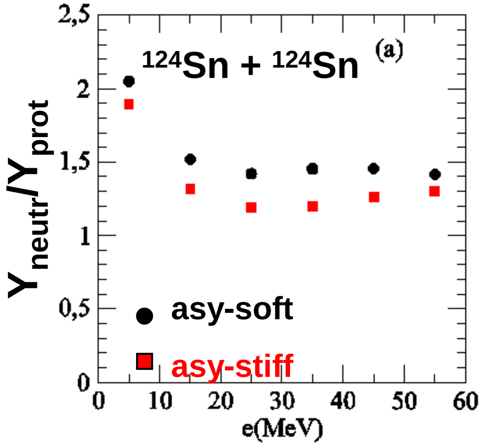
Influence on imbalance ratio!

Pre-equilibrium particle emission: n/p ratio

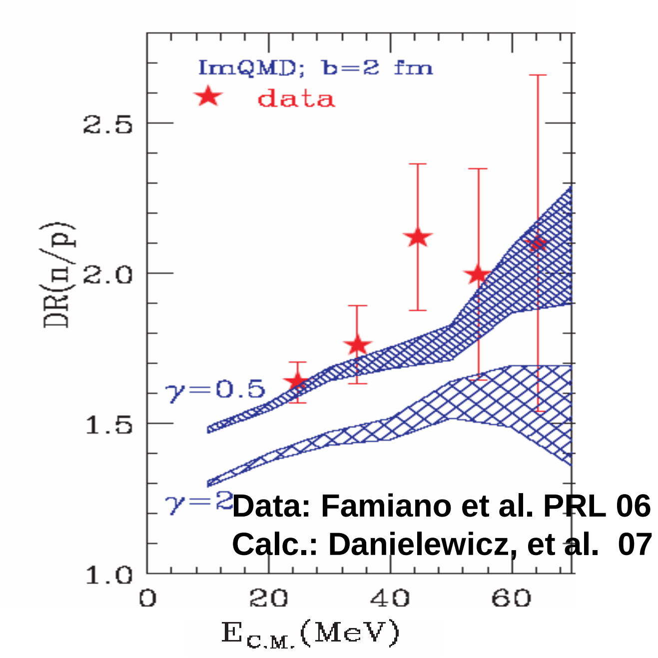
Early emitted neutrons and protons reflect difference in potentials in expanded source, esp. ratio Y(n)/Y(p).

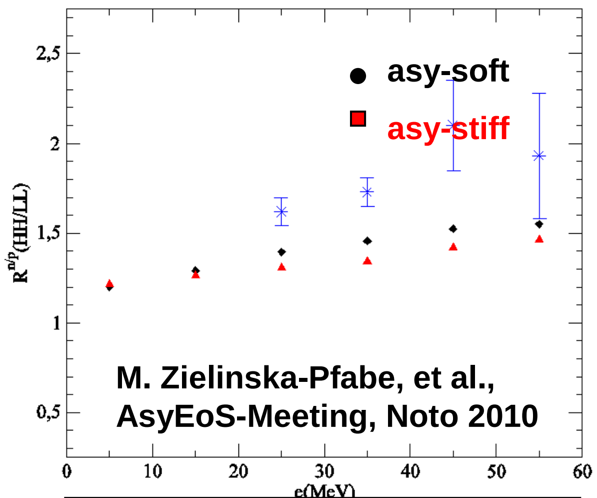
more emission for asy-soft, since symm potential higher



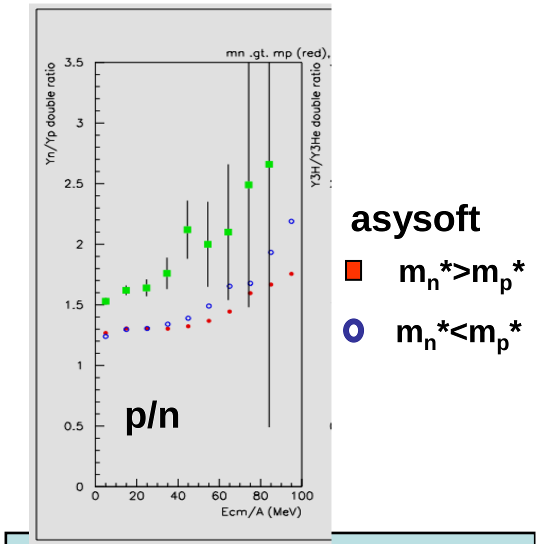


„Double Ratios“ $\frac{^{124}\text{Sn} + ^{124}\text{Sn}}{^{112}\text{Sn} + ^{112}\text{Sn}}$





Similar qualitatively but smaller effect



Effect of mass splitting of same magnitude

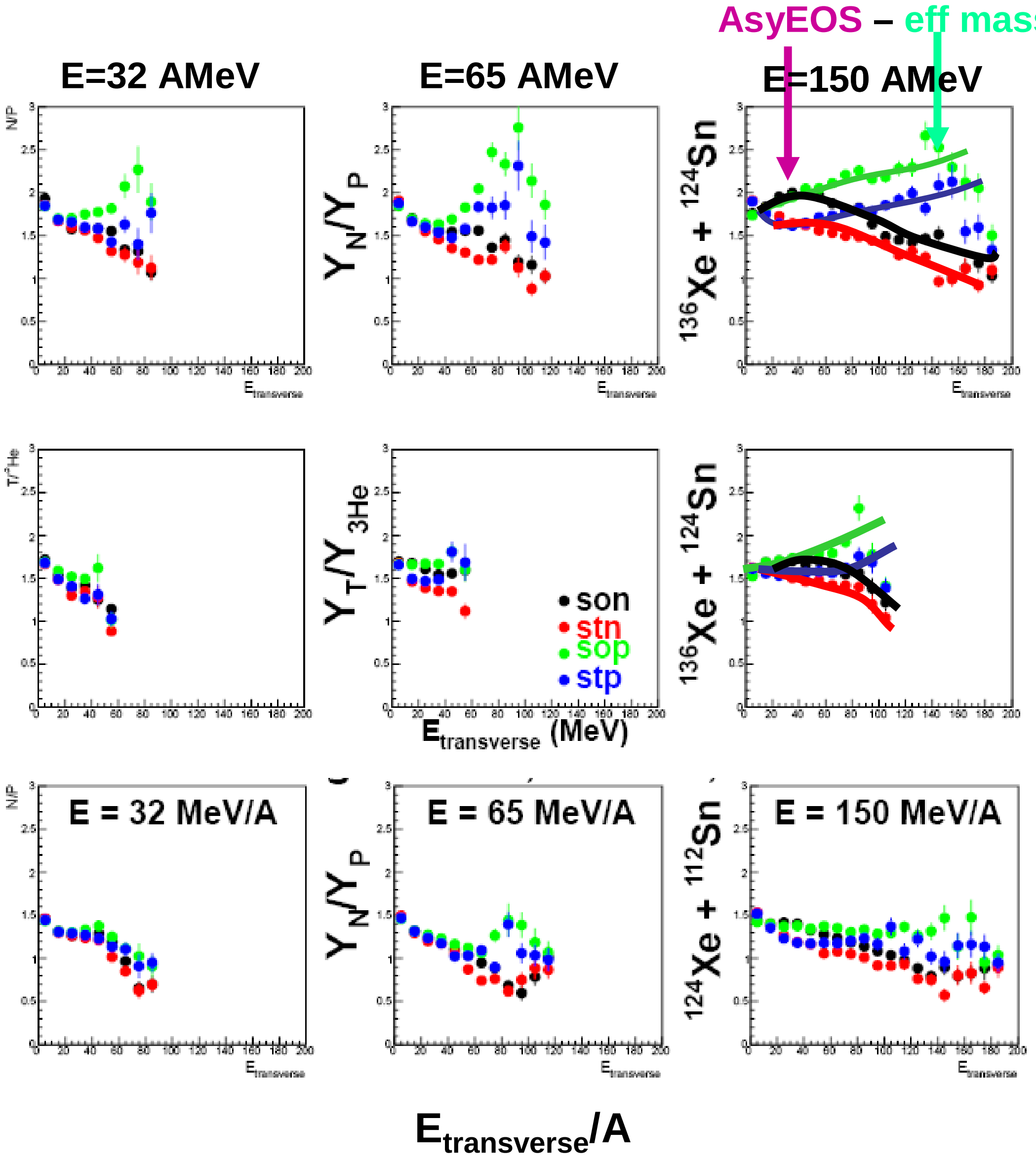
→ A promising observable, but theoretical discrepancies→systematic study usefull

Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,.,150 AMeV ,
Single yield ratios

Single ratio n/p
neutron rich

Single ratio t/3He
neutron rich

Single ratio n/p
neutron poor



Possibility to separate density and momentum dependence of symmetry energy

Effects smaller For light clusters t/He

Smaller neutron excess: effects smaller

son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

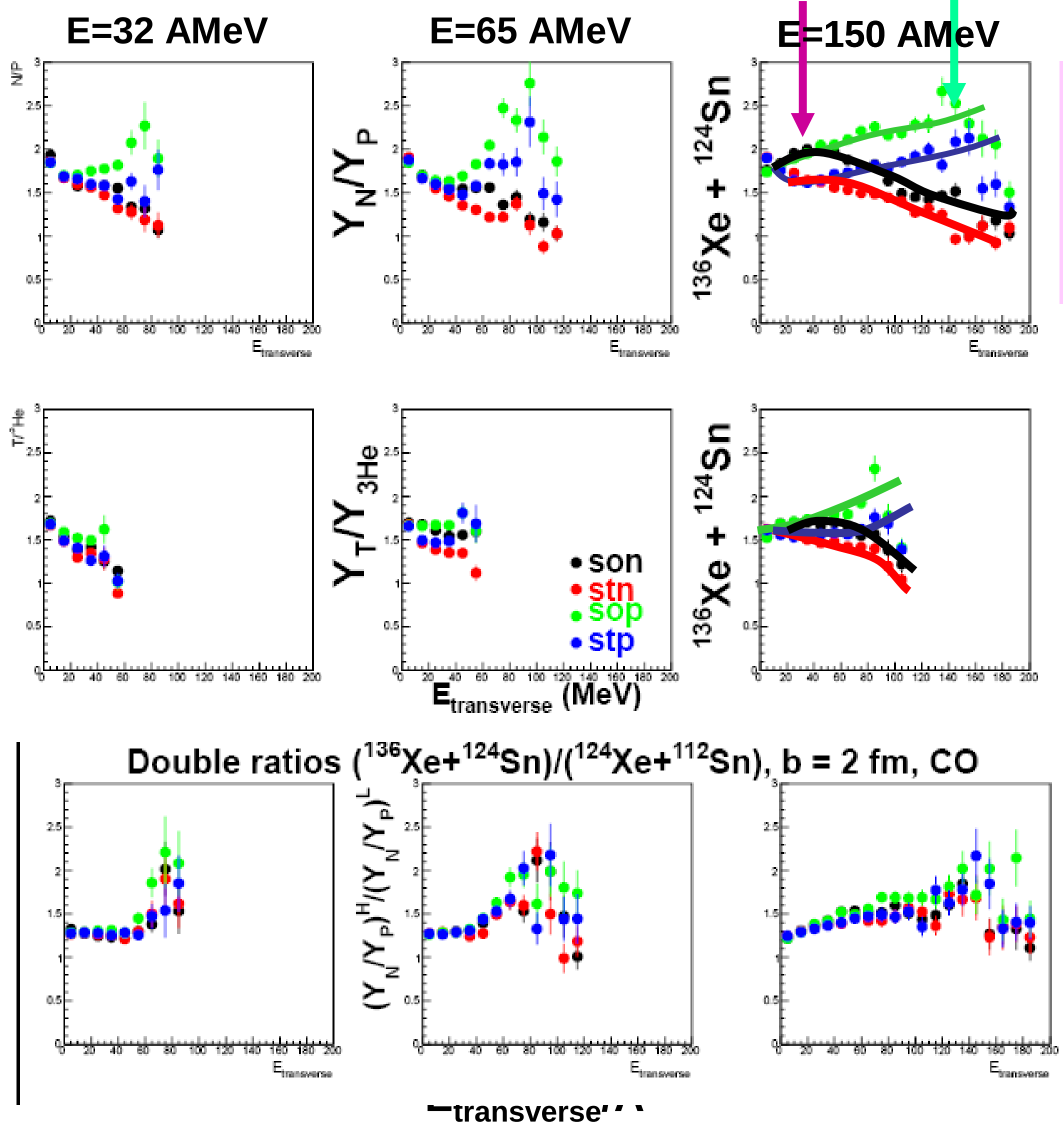
Study of Light Fragment Emission: ^{136,124}Xe+^{124,112}Sn, E = 32,.,150 AMeV ,
Single yield ratios

AsyEOS – eff mass dominates

Single ratio **n/p**
neutron rich

Single ratio **t/3He**
neutron rich

Double ratio n/p
neutron rich
neutron poor



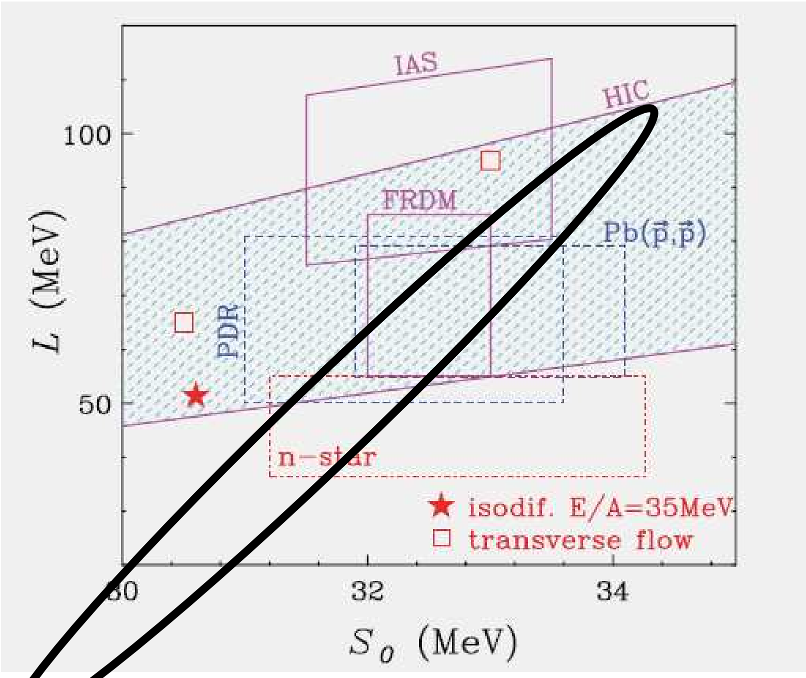
Possibility to separate density and momentum dependence of symmetry energy

Effects smaller For light clusters t/He

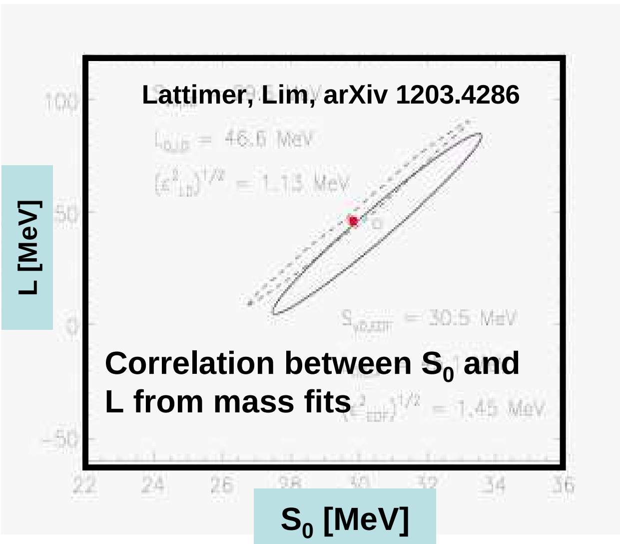
Double ratio also shows effect but less sensitive to symmetry energy

son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

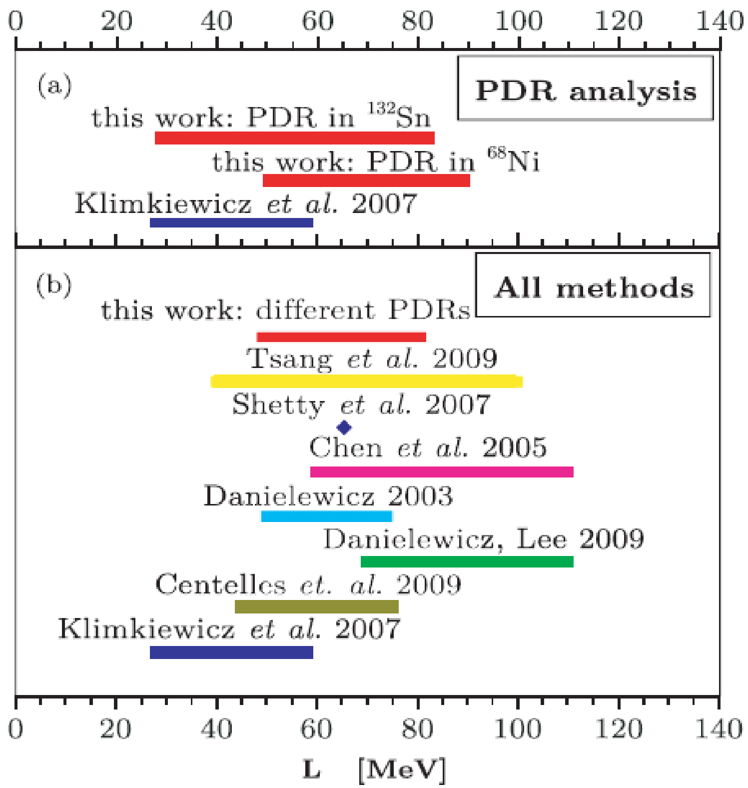
Contraints of SE for $\rho \leq \rho_0$ from Fermi energy collisions



M.B.Tsang, et al., PRC86,015803(2012)



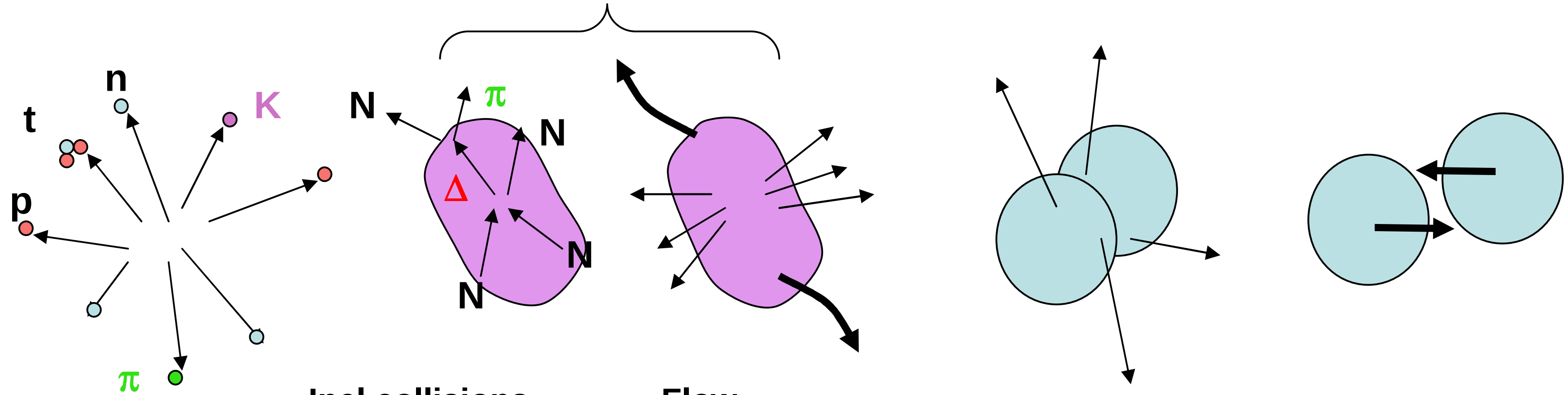
Determinations of L from structure and reactions



A. Carbone, et al., PRC81, 043101 (2010)

The Symmetry Energy at Supra-Saturation Densities

Sketch of reaction mechanism at intermediate energies and observables



disintegration

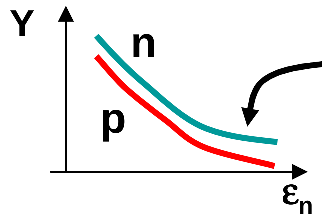
Inel.collisions
Particle product.
NN->NΔ–>NΛK
Nπ

Flow,
In-plane, transverse
Squeeze-out, elliptic

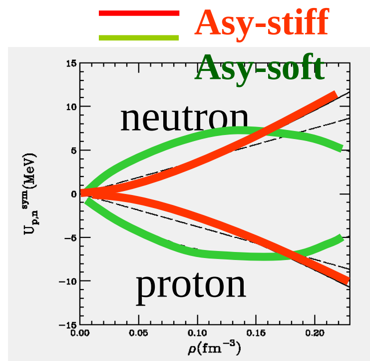
Pre-equilibr emiss.
(first chance,
high momenta)

Yield and spectra of light part.

residual source
more symm. n/p



e.g.asy-stiff
n preferential
n/p



flow

Differential p/n
flow
(or t/3He)

Pion production

nn -> Δ^- p
$n\pi^-$

pp -> Δ^{++} n π^-/π^+
$p\pi^+$ (asystiff)

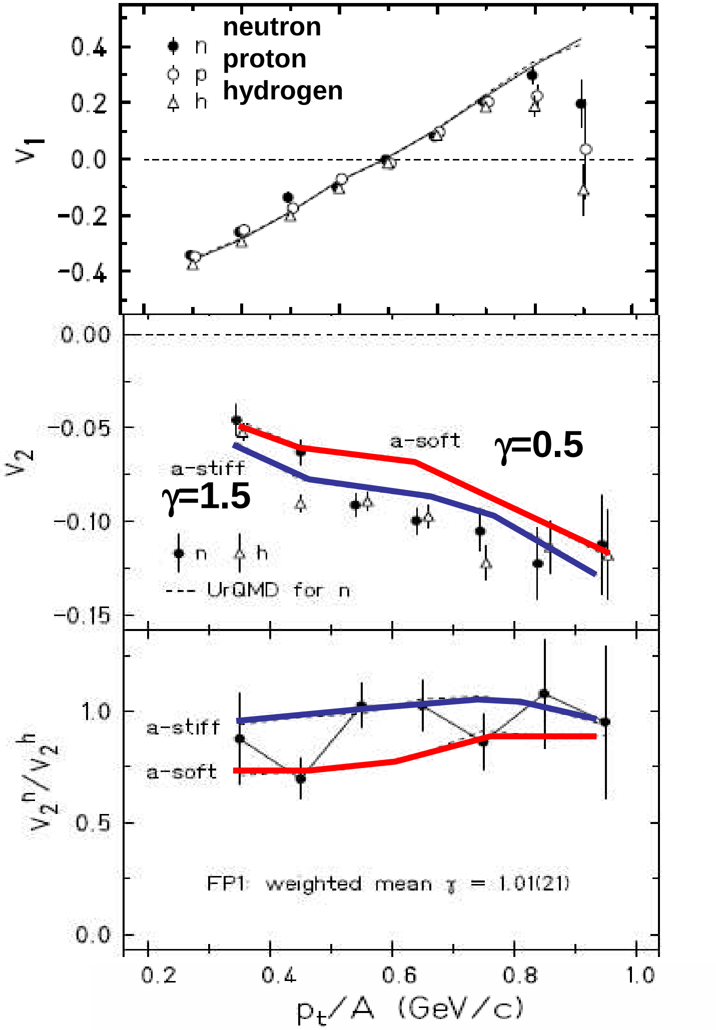
diff # p,n
(asymmetry of
system)

diff. force on n,p

Reaction mechanism can be tested with several observables: Consistency required!

First measurement of isospin flow

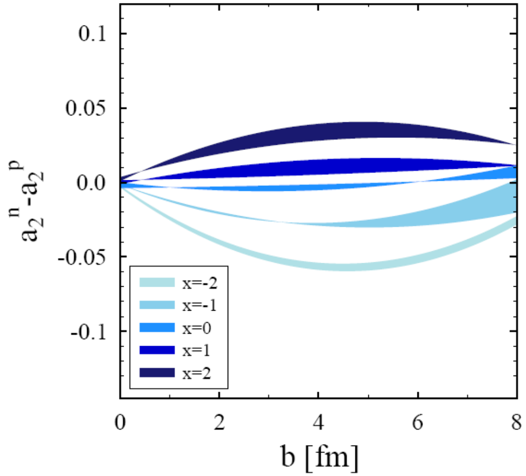
Au+Au @ 400 AMeV, FOPI-LAND **(Russotto, et al., PLB 697, 471 (11))**



directed flow (v1) not very sensitive,

but elliptic flow (v2), originates in compressed zone

determines a rather stiff symmetry energy (γ~1)



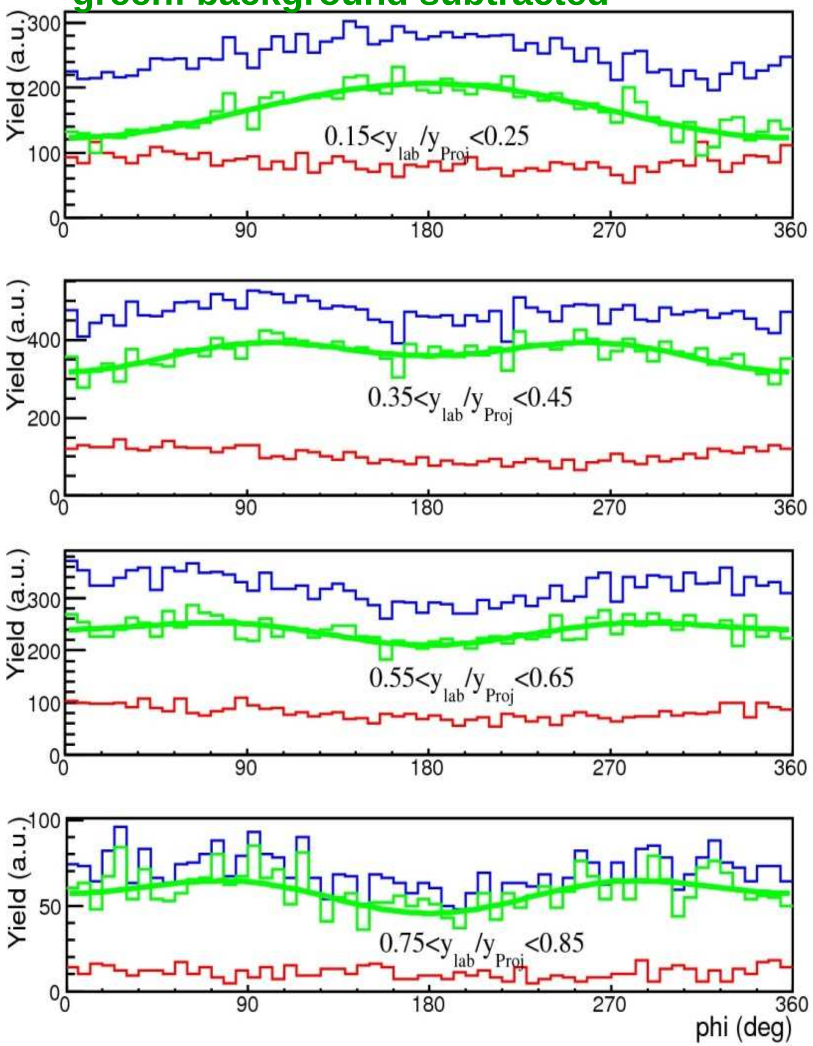
Each band: soft vs. stiff eos of symmetric matter, (Cozma, arXiv 1102.2728)
→ robust probe

ASYEOS experiment at GSI
May 2011, being analyzed

ASYEOS Experiment

preliminary

Azimuthal distributions,
green: background subtracted

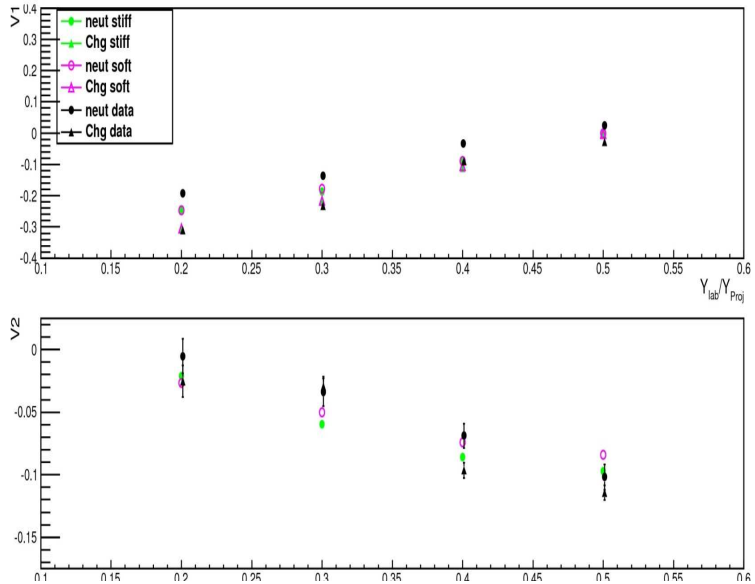


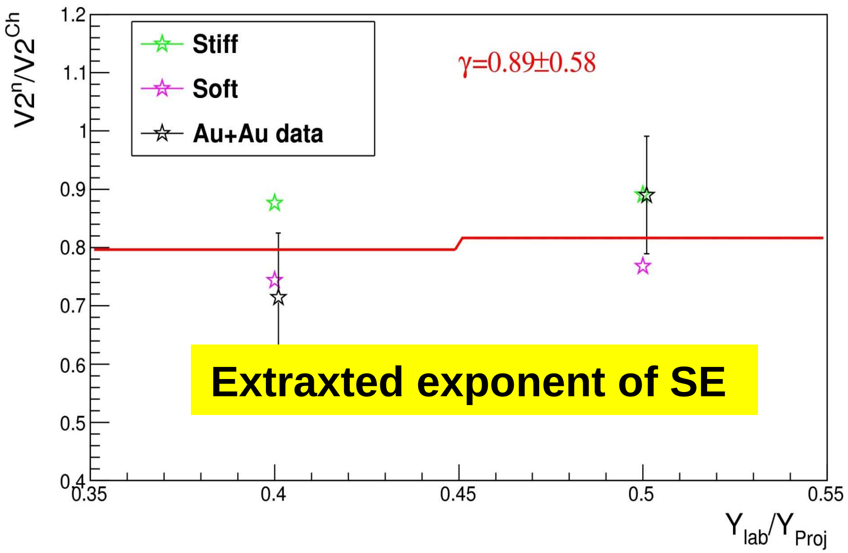
P. Russoto, Thexo Meeting, ECT, Trento, 8.-12.7.13

Au+Au @ 400 AMeV

b< 7.5 fm

Elliptic flow coefficients (neutrons and Z=1)

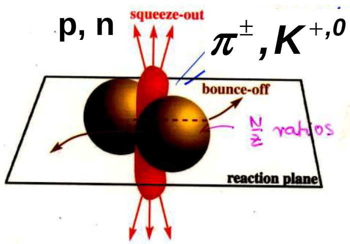




Particle production as probe of symmetry energy

Difference in neutron and proton potentials

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

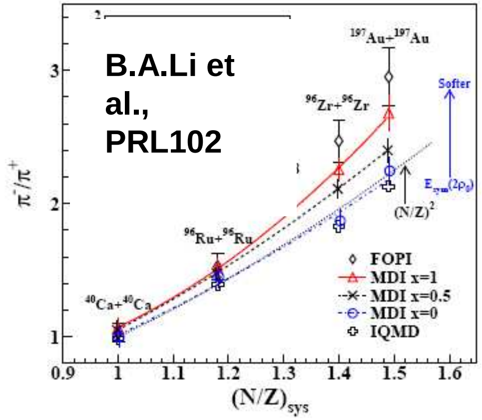


NN → NΔ

NΔ → Nπ → ΛK

NΔ → NΛK

in-medium in-elastic σ,	Δ in-medium self-energies and width	π potential,	K and Λ potential (in-medium mass)



Two limits:

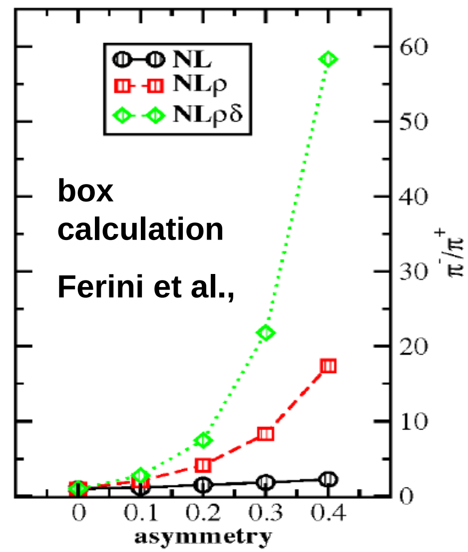
1. isobar model (yield determined by CG-Coeff of Δ->Nπ

$$\pi^- / \pi^+ = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

2. chemical equilibrium

$$\pi^- / \pi^+ \propto exp\frac{2(\mu_n - \mu_p)}{T} = exp\frac{8\delta E_{sym}(\rho)}{T}$$

-> π–/π+ hould be a good probe!



Particle production as probe of symmetry energy

Two effects:

1. Mean field effect: U_{sym} more repulsive for neutrons, and more for asystiff
→ pre-equilibrium emission of neutron, reduction of asymmetry of residue

$$\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$
decrease with asy – stiffness

2. Threshold effect, in medium effective masses:

Canonical momenta have to be conserved. To convert to kinetic momenta, the self energies enter

$$I_{coll} = \int d\vec{v}_2\, d\vec{v}_{1'} d\vec{v}_{2'} v_{12} \sigma_{inel}(\Omega)(2\pi)^3 \delta(p_1 + p_2 - p_{1'} - p_{2'}) \times \left[f_{1'} f_{2'} (1-f_1)(1-f_2) - f_1 f_2 (1-f_{1'})(1-f_2') \right]$$

In inelastic collisions, like nn->pΔ⁻, the selfenergies may change. Simple assumtion about self energies of Δ..

$$\Sigma_i(\Delta^-) = \Sigma_i(n),$$
$$\Sigma_i(\Delta^0) = \frac{2}{3}\Sigma_i(n) + \frac{1}{3}\Sigma_i(p),$$
$$\Sigma_i(\Delta^+) = \frac{1}{3}\Sigma_i(n) + \frac{2}{3}\Sigma_i(p),$$
$$\Sigma_i(\Delta^{++}) = \Sigma_i(p),$$

Yield of pions depends on

$$\sigma = \sigma_{inel}(s_{in} - s_{th})$$

Detailed analysis gives

$$\frac{\pi^-}{\pi^+}\uparrow \textit{ increase with asy – stiffness}$$

Competing effects!
Not clear, whether taken into account in all works.
Assumptions may also be too simple.

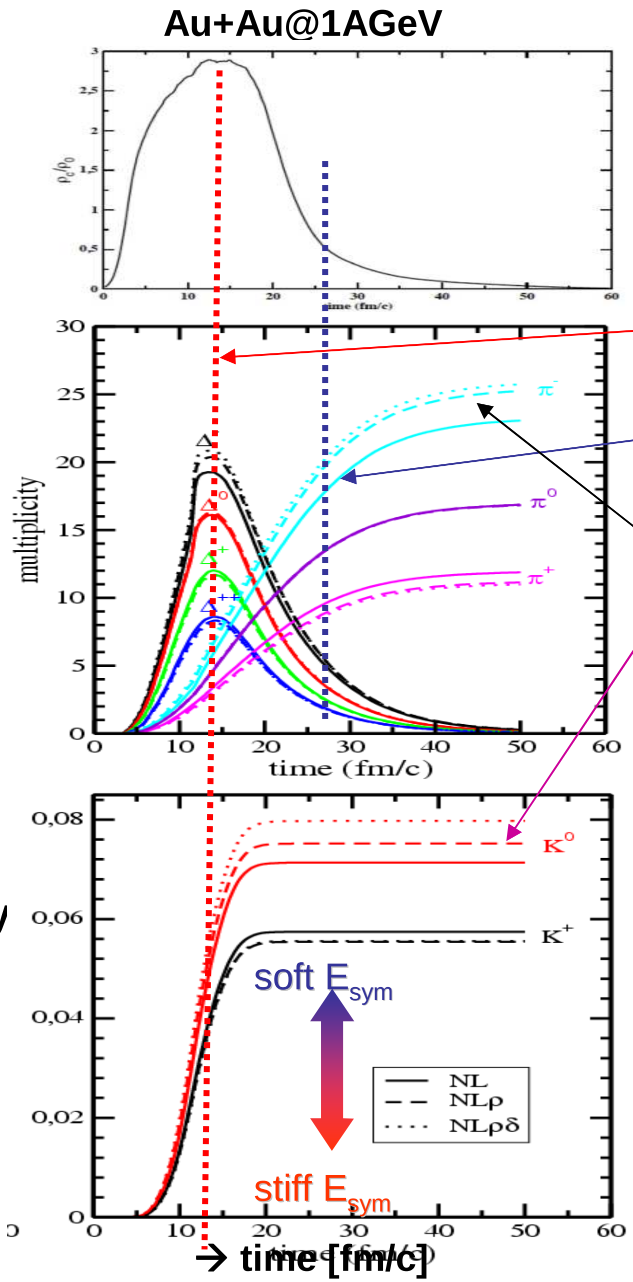
G.Ferini et al.,PRL 97 (2006) 202301

Dynamics of particle production (Δ,π,K) in heavy ion collisions

Central density

π and Δ multiplicity

$K^{0,+}$ multiplicity



Δ and K: production in high density phase

Pions: low and high density phase

Sensitivity to asy-stiffness

Dependence of ratios on asy-stiffness

n/p

→ $\Delta^{0,-}/\Delta^{+,++}$

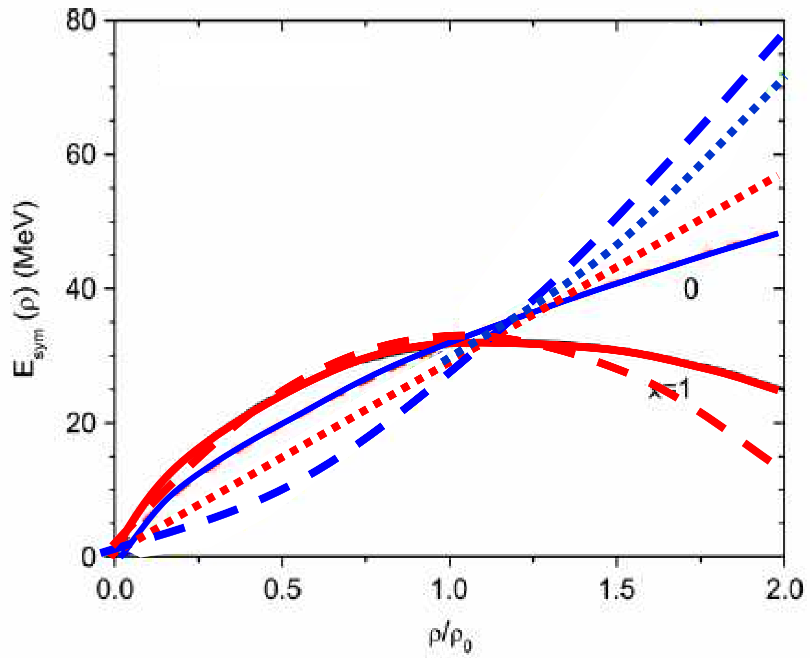
→ π^-/π^+, K^0/K^+

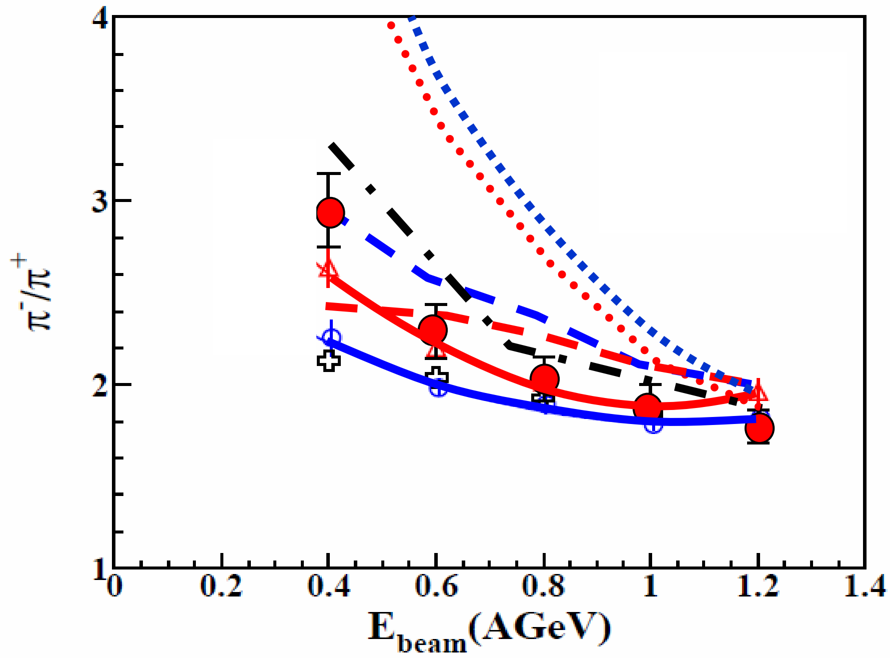
→ n/p ratio governs particle ratios

G.Ferini et al.,PRL 97 (2006) 202301

Pion ratios in comparison to FOPI data (W.Reisdorf et al. NPA781 (2007) 459)

MDI, x=0, mod. soft MDI, x=1, very soft	Xiao,.. B.A.Li, PRL 102 (09)
NLρδ, stiff NLρ, linear	Ferini, Gaitanos,.. NPA 762 (05)
γ=2, stiff SIII, very soft	Feng,… PLB 683 (10)
small dep. on SE	J. Hong, P.Danielewicz APCTP workshop
FOPI, exp	

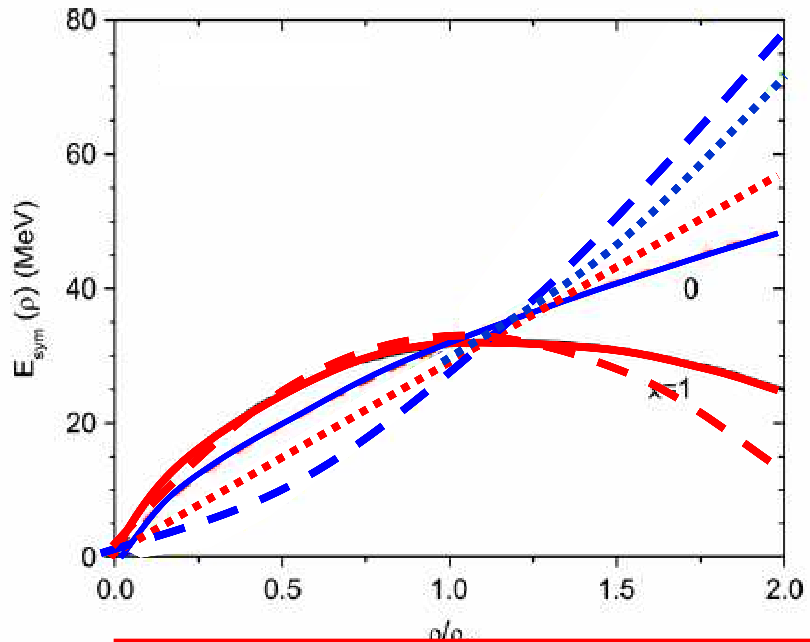


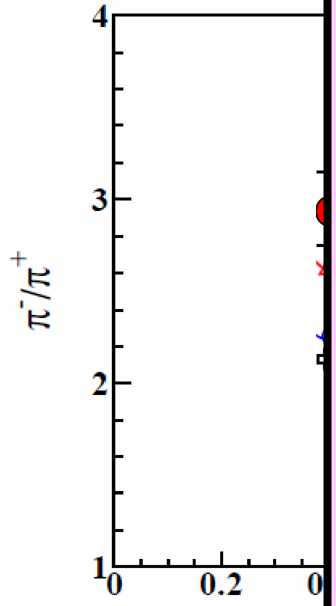


Contradictory results of different calculations;

Pion ratios in comparison to FOPI data (W.Reisdorf et al. NPA781 (2007) 459)

solid blue	MDI, x=0, mod. soft	Xiao,.. B.A.Li, PRL 102 (09)
solid red	MDI, x=1, very soft	
dotted blue	NLρδ, stiff	Ferini, Gaitanos,.. NPA 762 (05)
dotted red	NLρ, linear	
dashed blue	γ=2, stiff	Feng,… PLB 683 (10)
dashed red	SIII, very soft	
dash-dot black	small dep. on SE	
red circle	FOPI, exp	





Contradictory results of different calculations;

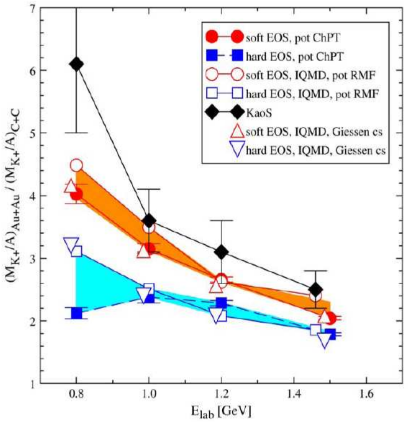
Possible causes:

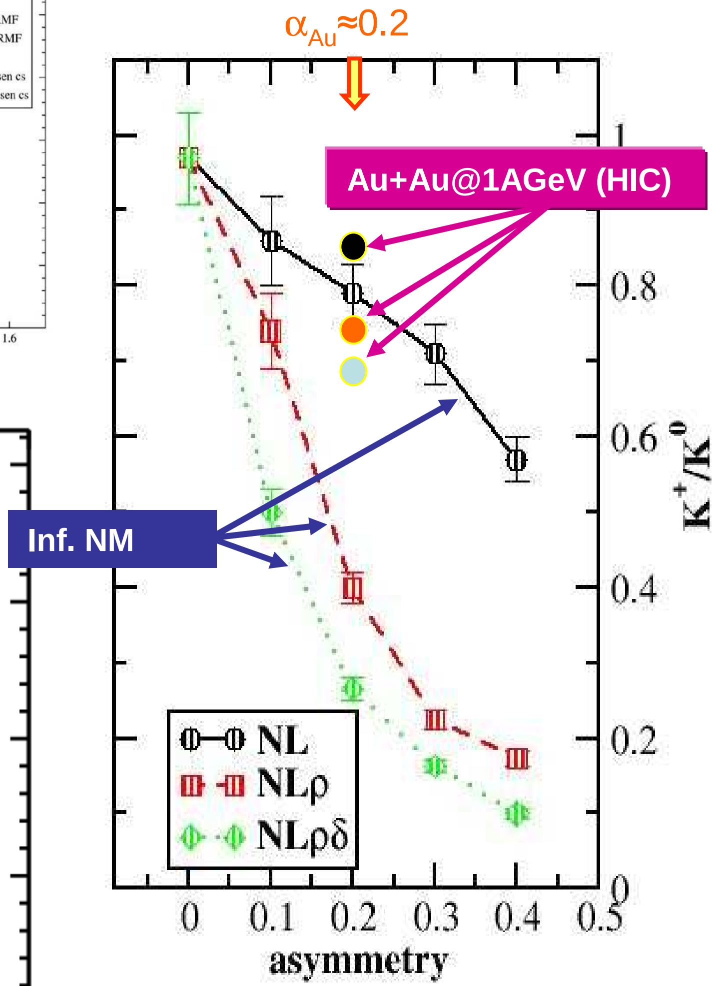
- **Pion are created via Δ's. Δ dynamics in medium (potential, width, etc) largely unknown.**
- **Threshold and mean field effects**
- **Pion potential: U_π=0 in most calculations. OK?**
- **differences in simulations, esp. collision term**
- **Urgent problem to solve!!!**

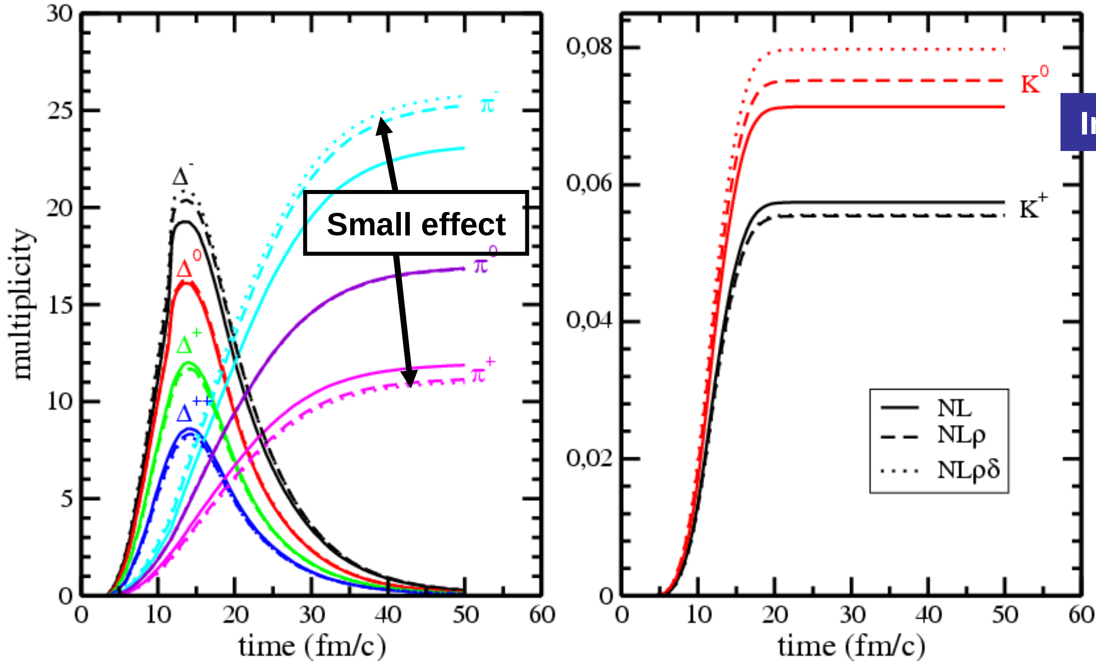
Strangeness production in HIC: Kaons

Kaons were a decisive observable to determine the symmetric EOS;

perhaps also useful for SE?
Kaons are closer to threshold, come only from high density, have large mean free path, small width:



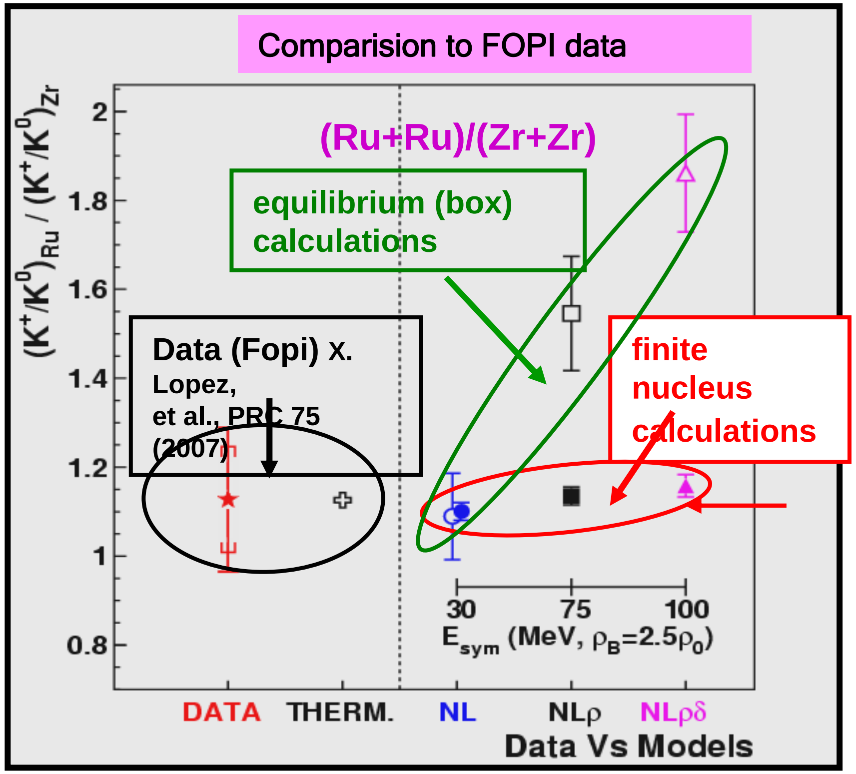




Larger (or equally large) effect for kaons, which come directly from high density region

Dynamic reduction of asymmetry in HIC, thus reduction of sensitivity rel. to nuclear matter

Kaon ratios in HIC

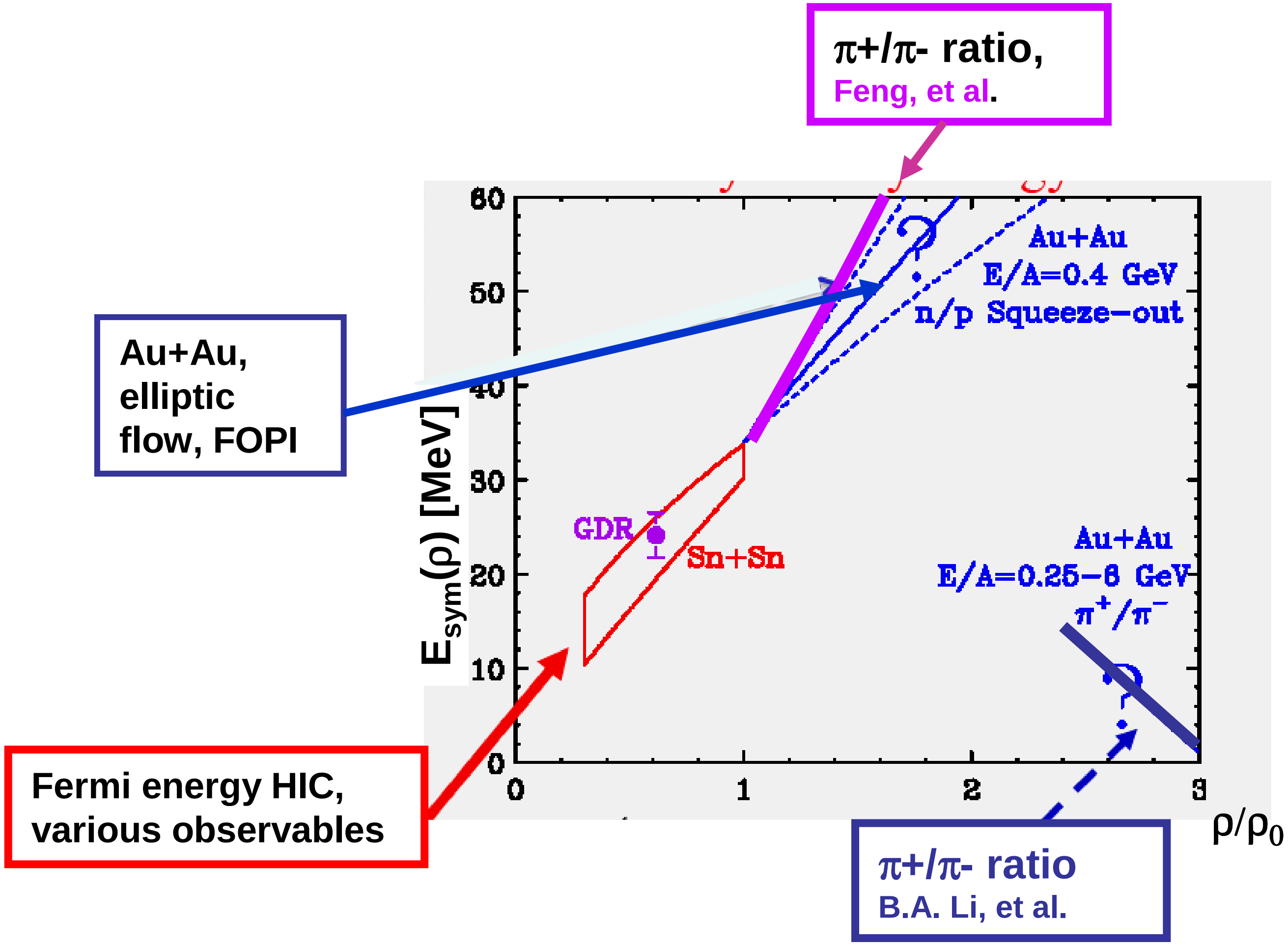


G. Ferini, et al., NPA762(2005) 147

single ratios more sensitive

• enhanced in larger systems

Present constraints on the symmetry energy from heavy ion collisions



Moving towards a determination of the symmetry energy in HIC

but at higher density few data
and some difficulty with consistent results of simulations for pion observables.

Conclusion:

There is a lot to know about the symmetry energy …

and anyway, this talk was only to start of a discussion

I thank you for the attention
and I look forward to an exciting workshop