Observables for the High-Density Symmetry Energy from Heavy Ion Collisions

Hermann Wolter
Ludwig-Maximilians-Universität München (LMU)

HIM-Meeting, Pohang, Korea, APRIL 13, 2012

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LMU Excellence Cluster Universe

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Munich at Eastern 2012

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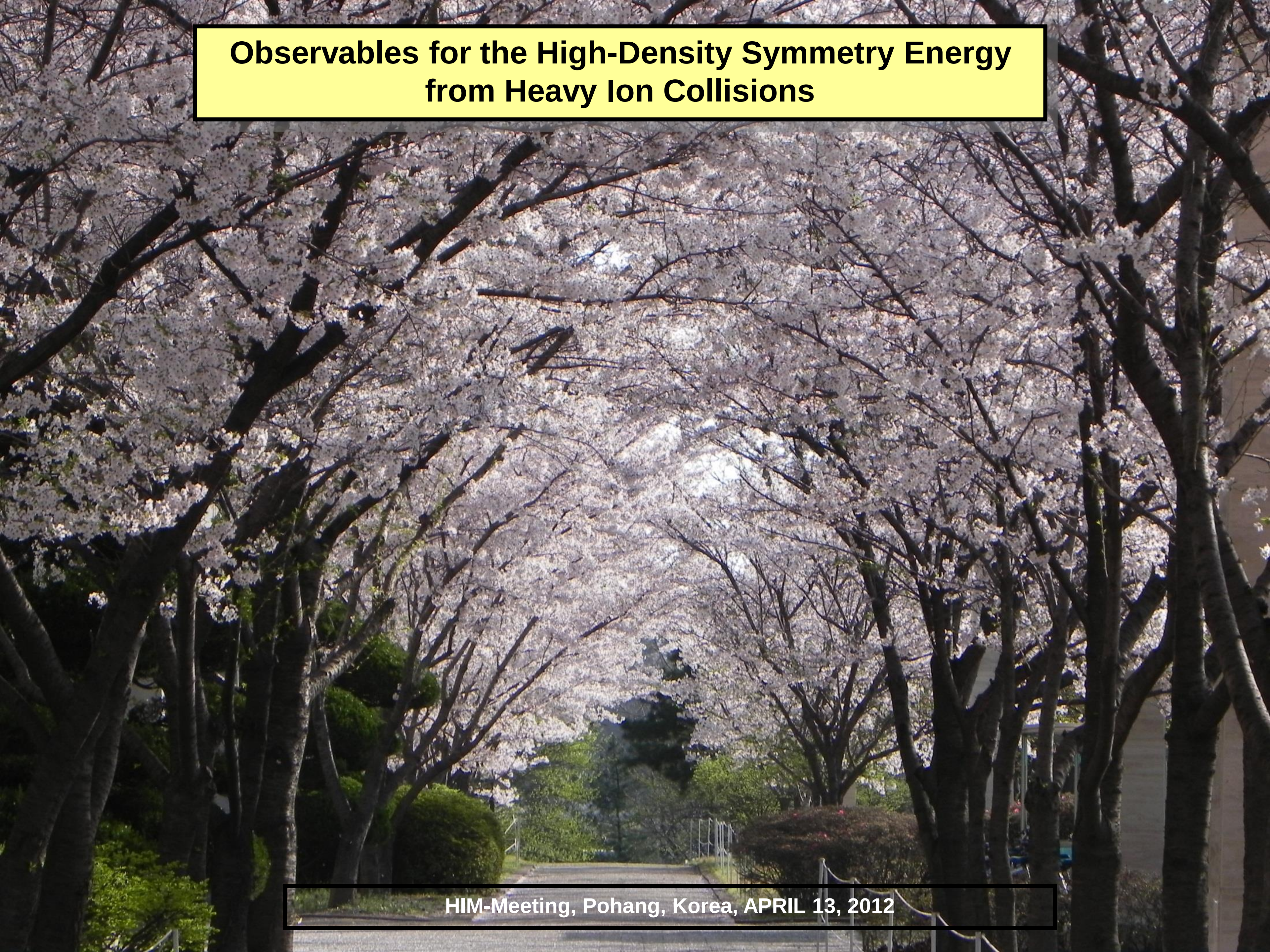

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Points to discuss

I. **Motivation:**
The nuclear Symmetry Energy: density (and momentum) dependence,
uncertainties from many-body theory,
importance, astrophysics

II. Study of Symmetry Energy in heavy ion collisions,
choice of asymmetry and density regime.
non-equilibrium: transport theory

III. Discussion of observables in the regime $\rho \geq \rho_0$
possible obervables
correlation and consistency between observables
sparse data: projects like KORIA important

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collaborators:
Massimo Di Toro, Maria Colonna, V. Greco, Lab. Naz. del Sud, Catania
Theodoros Gaitanos, Univ. of Giessen
Vaia Prassa, Georgios Lalazissis, Univ. Thessaloniki
Malgorzata Zielinska-Pfabe, Smith Coll., Mass., USA

Equation-of-State and Symmetry Energy

symmetry energy

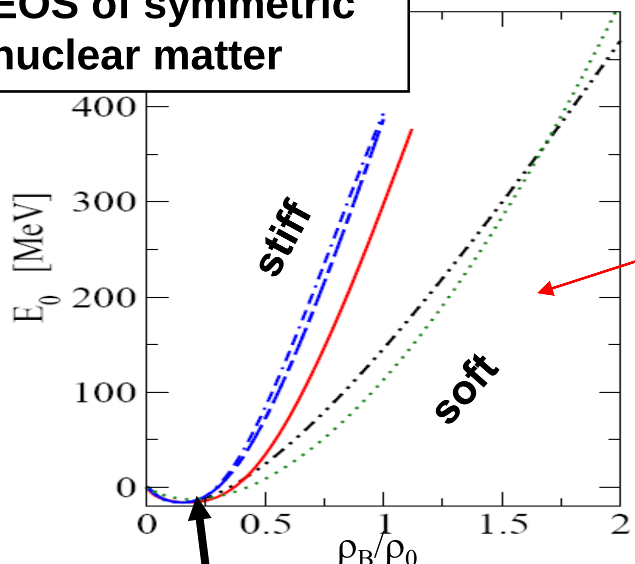
BW mass formula
$$E(A,Z)/A = a_v - a_s A^{-1/3} - a_C Z(Z-1)A^{-4/3} - a_s (N-Z)^2/(N+Z)^2 + \delta_{pair}$$

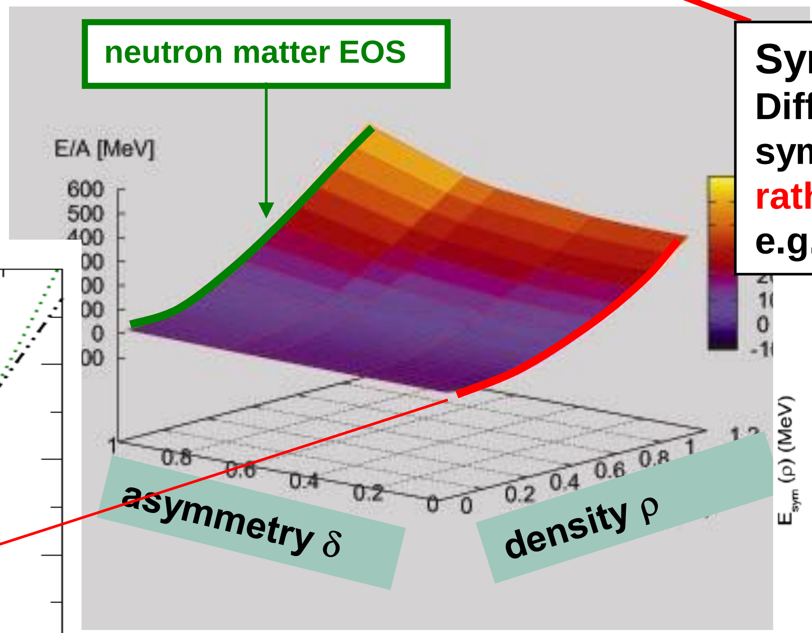
density-asymmetry dep. of nucl.matt.
$$E(\rho_B,\delta)/A = E_{nm}(\rho_B) + E_{sym}(\rho_B)\delta^2 + O(\delta^4) + \ldots \qquad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

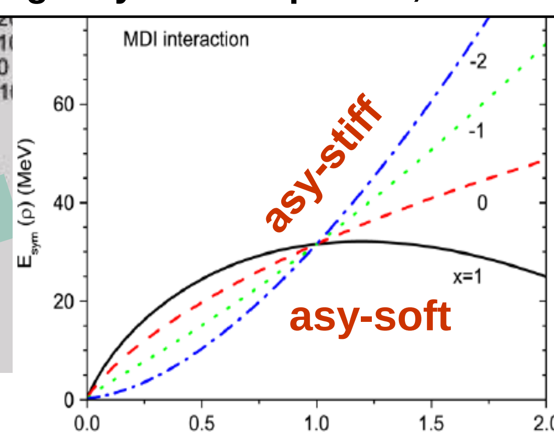
$$a_S \approx E_{sym}(0.6\rho_0)$$

Symmetry energy:
Diff. between neutron and symm matter,
rather unknown,
e.g. Skyrme-like param.,B.A.Li

EOS of symmetric nuclear matter







saturation point

Fairly well fixed! Soft!

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

$E_{sym}^{pot}(\rho)$ often parametrized as $C(\rho/\rho_0)^{\gamma}$

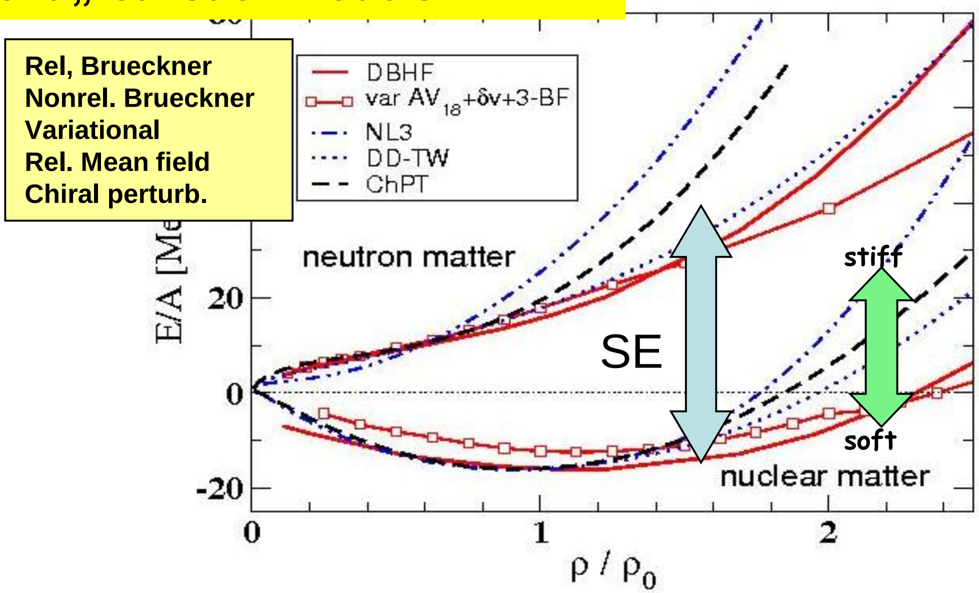
useful around $\rho=\rho_0$. Expansion around ρ_0 :

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

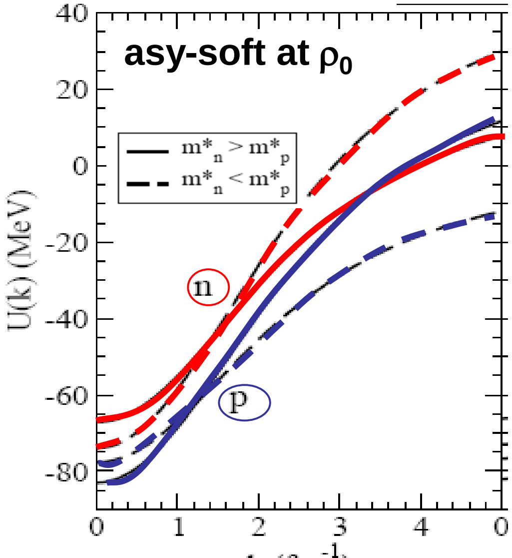
The Nuclear Symmetry Energy in different „realistic“ models

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

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



SE ist also momentum dependent → effective mass

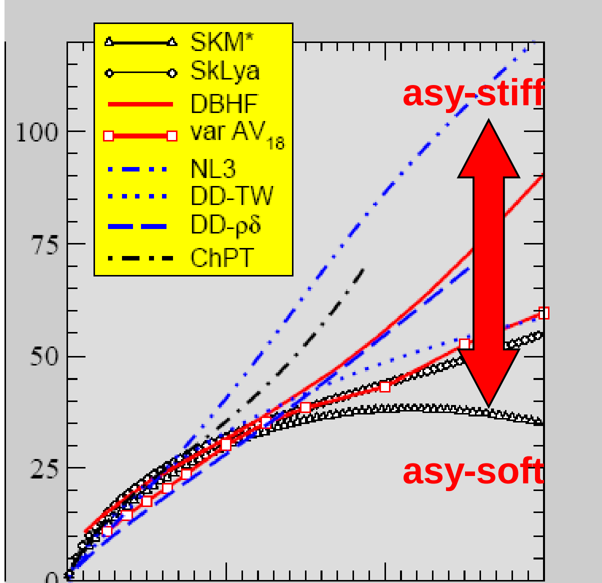


$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$$

Different proton/neutron effective masses

Isovector (Lane) potential: momentum dependence

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



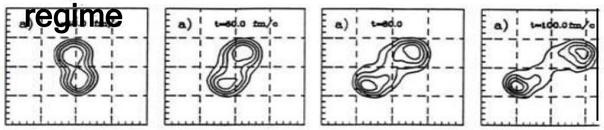
Why is symmetry energy so uncertain??
->In-medium ρ mass, and short range tensor correlations (B.A. Li, PRC81 (2010));
-> effective mass scaling (Dong, Kuo, Machleidt, arxiv 1101.1910)

Importance of Nuclear Symmetry Energy

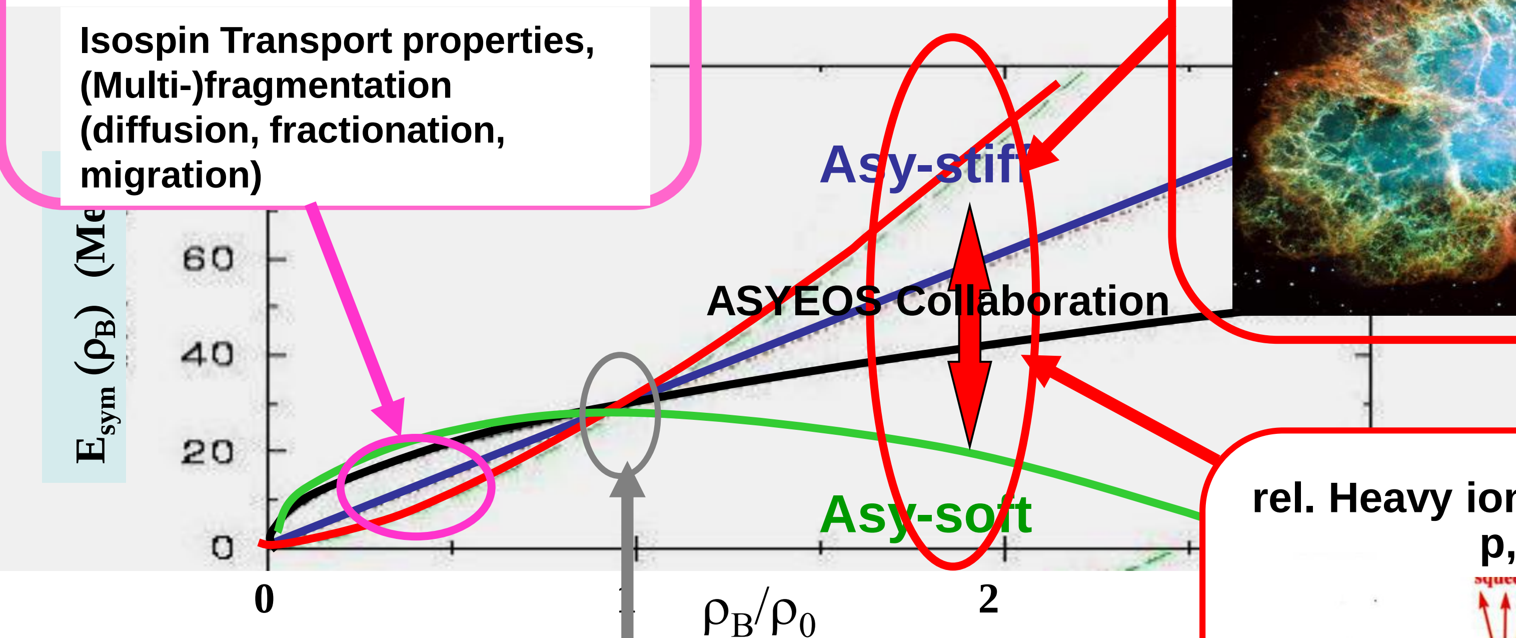
$$E(\rho_B, I)/A = E(\rho_B) + E_{sym}(\rho_B) I^2 + O(I^4) + \dots$$

$$I = \frac{N-Z}{N+Z}$$

heavy ion collisions in the Fermi energy regime

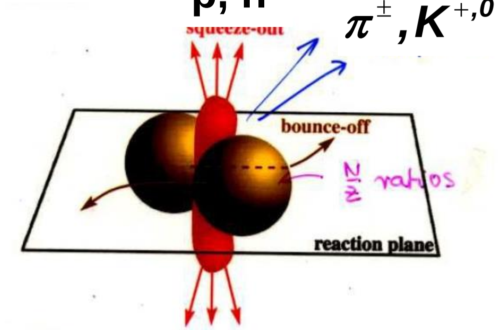


Isospin Transport properties, (Multi-)fragmentation (diffusion, fractionation, migration)

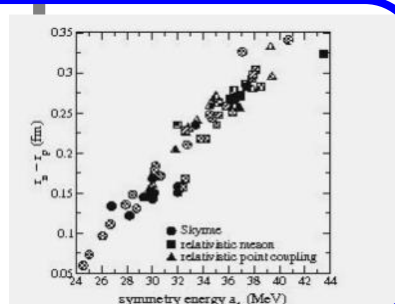


supernovae,neutron stars)

rel. Heavy ion collisions



Nuclear structure (neutron skin thickness, Pygmy DR, IAS)
Slope of Symm Energy



Importance of Nuclear Symmetry Energy

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

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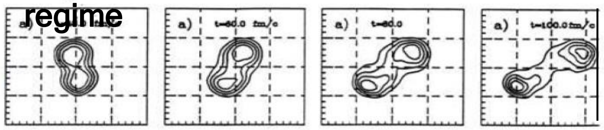

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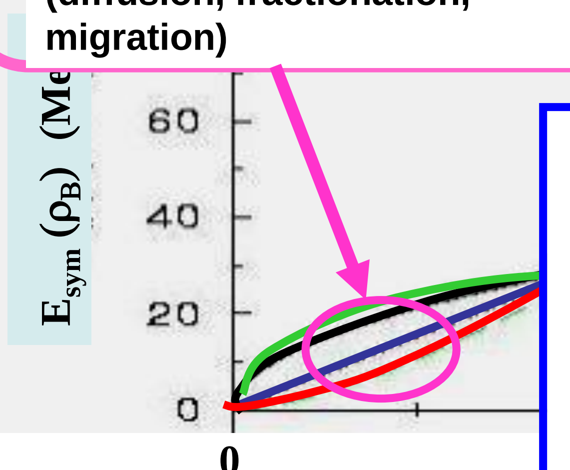
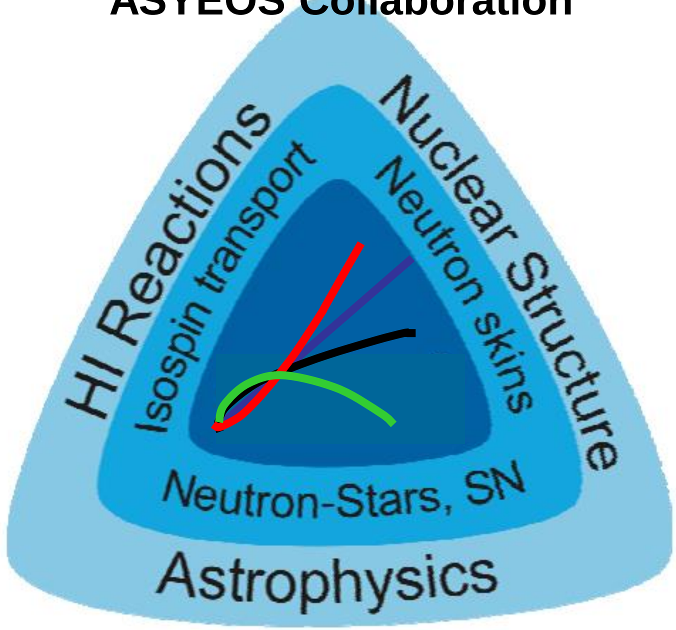
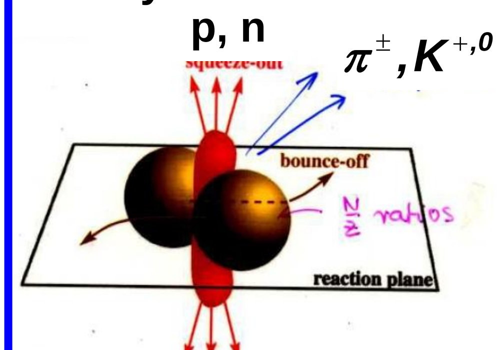


supernovae,neutron stars)

ASYEOS Collaboration

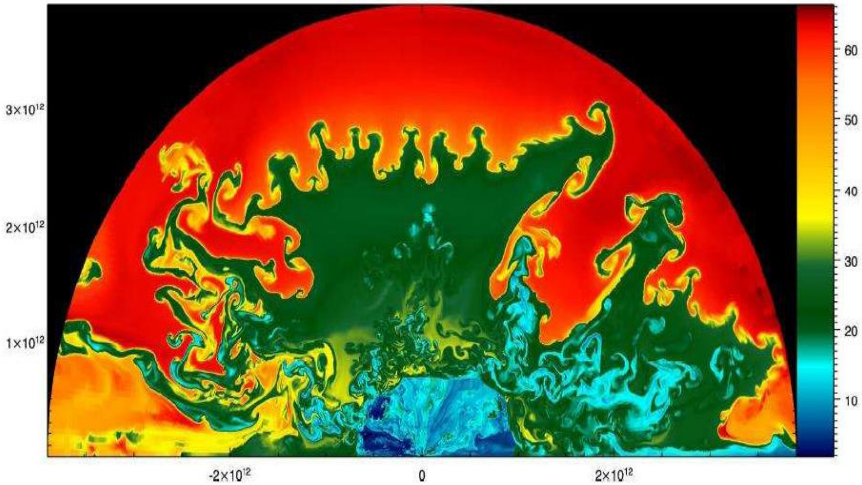


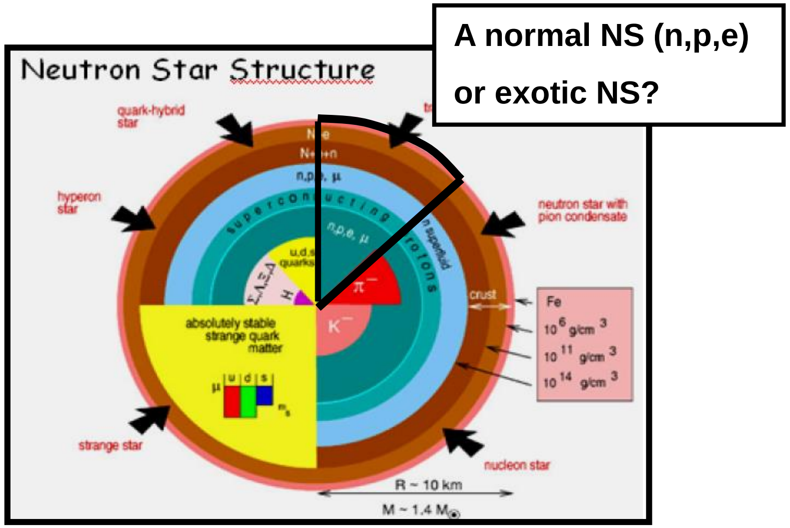
. Heavy ion collisions

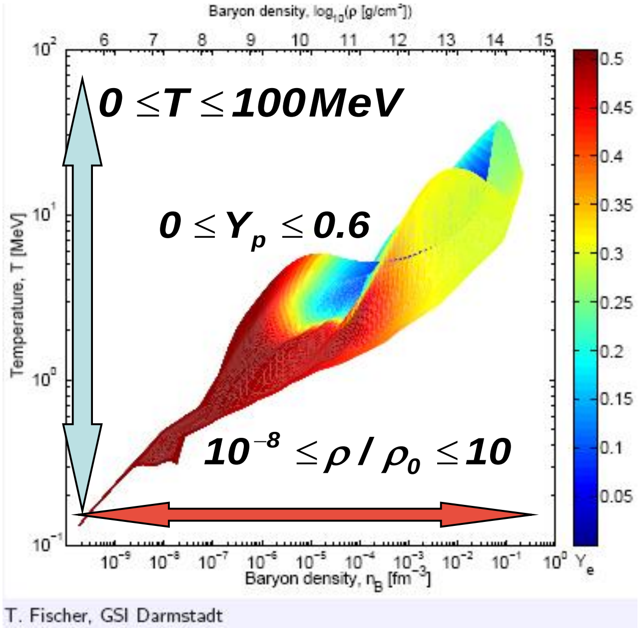


Nuclear structure (neutron skin thickness, Pygmy DR, IAS)
Slope of Symm Energy

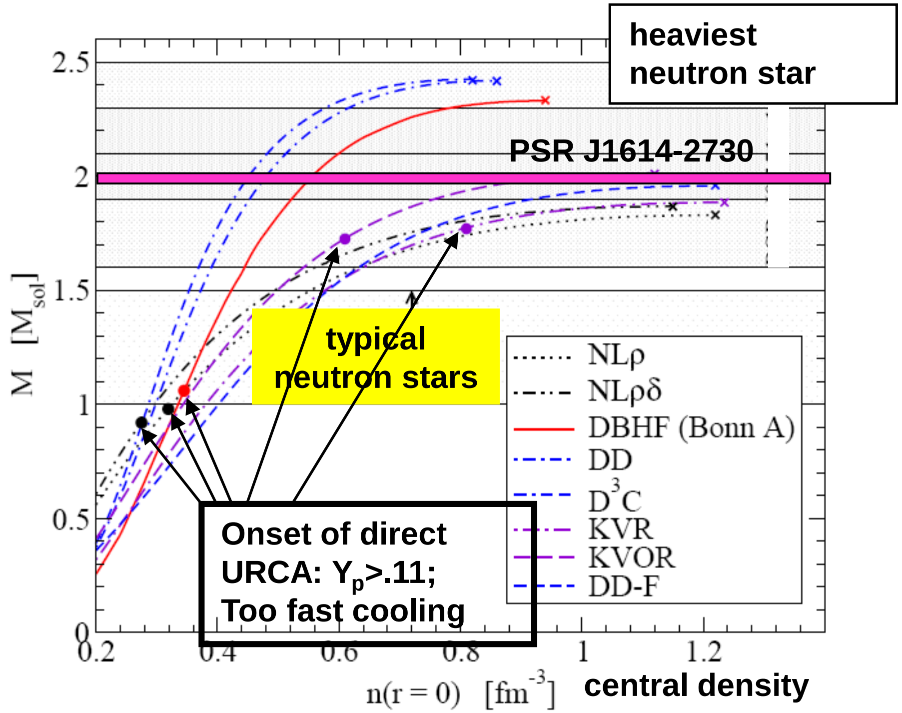
Astrophysics: Supernovae and neutron stars





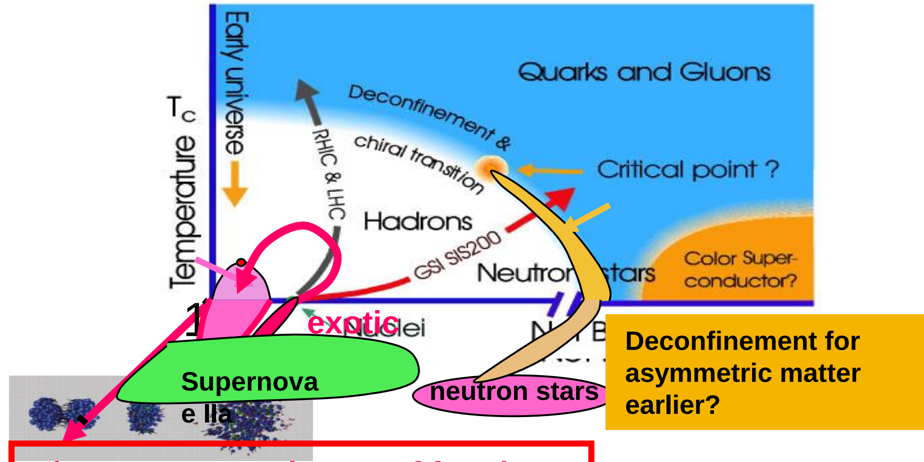


Supernova evolution: range of densities and temperatures and asymmetries:



Determination of nuclear SE in heavy ion collisions

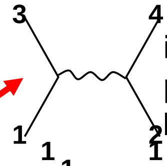
→ Transport theory



Z/N, asymmetry degree of freedom

→equation of motion in semiclass. approx: BUU equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\vec{\nabla}^{(r)} f - \vec{\nabla}^{(r)} U(r)\, \vec{\nabla}^{(p)} f = I_{coll}$$



isospin dependent, pp,nn,pn In-medium!

EOS

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

isoscalar and isovector (~10%) 2-body collisions gain term loss term

1) Approximation to a much more complicated non-equilibrium quantum transport equation (Kadanoff-Baym) by neglecting finite width of particles

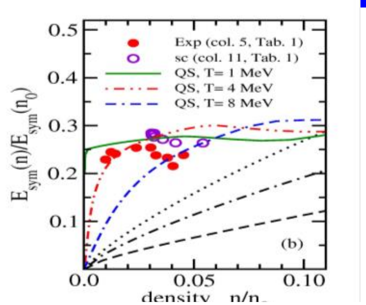
2) Coupled transport eqs. for neutrons and protons

3) Isovector effects are small relative to isoscalar quantities

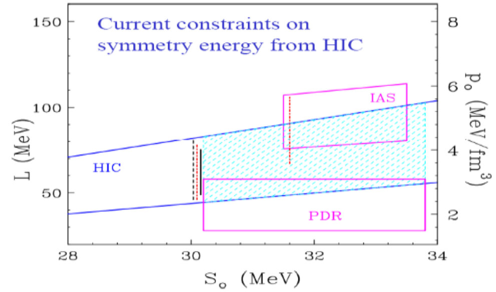
4) Relativistic transport equations: Walecka-type (RMF) models

5) Inelastic collisions (particle production; mesons π,K)

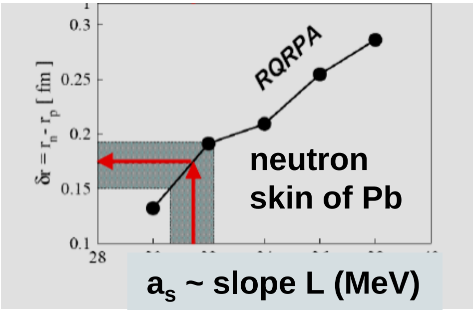
Investigation of the Symmetry Energy in Different Density Ranges



1. $\rho << \rho_0$: expanding fireball in Fermi-energy heavy ion collisions.
   cluster correlations at low density and temperature
   → talk by C. Horowitz and my talk on monday



2. $\rho < \rho_0$: Isospin transport in Fermi energy central
   and peripheral collisions, (multi-)fragmentation,
   → see talks by Betty Tsang

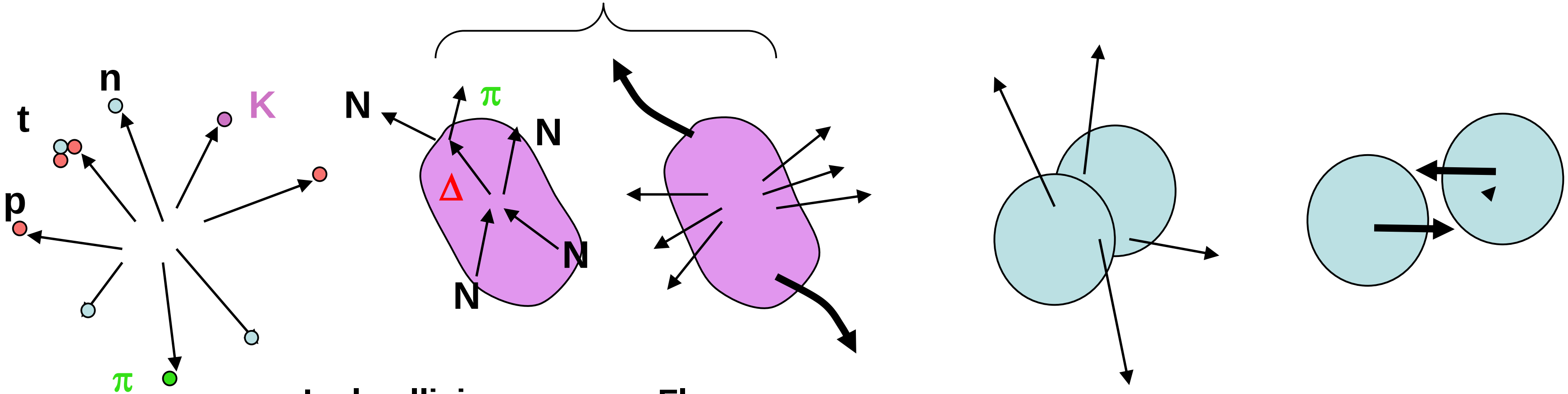


3. $\rho \sim \rho_0$: structure and low energy excitations of (asymmetric)
   nuclei: skin thickness, Pygmy resonances, IAS,
   →talk by Betty

4. $\rho > \rho_0$: Intermediate energy heavy ion collisions:
   light cluster emission,
   flow and particle production,
   → more here

5. $\rho >> \rho_0$: Ultrarelativistic HI collisions,
   dependence of mixed and deconfinement phase on asymmetry?
   → not here, e..g. DiToro, et al.,

Sketch of reaction mechanism at intermediate energies and observables



disintegration

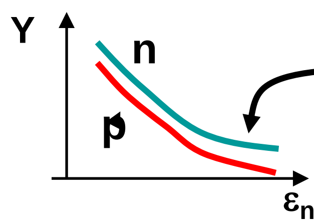
Inel.collisions
Particle product.
NN->NΔ->NΛK
Nπ

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

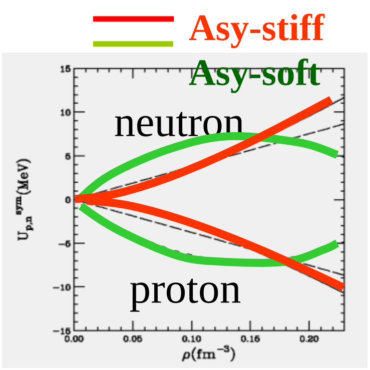
Pre-equilibr emiss.
(first chance,
high momenta)

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)

diff # p,n
(asymmetry of
system)

Pion production

nn -> Δ^- p
$n\pi^-$

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

diff. force on n,p

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

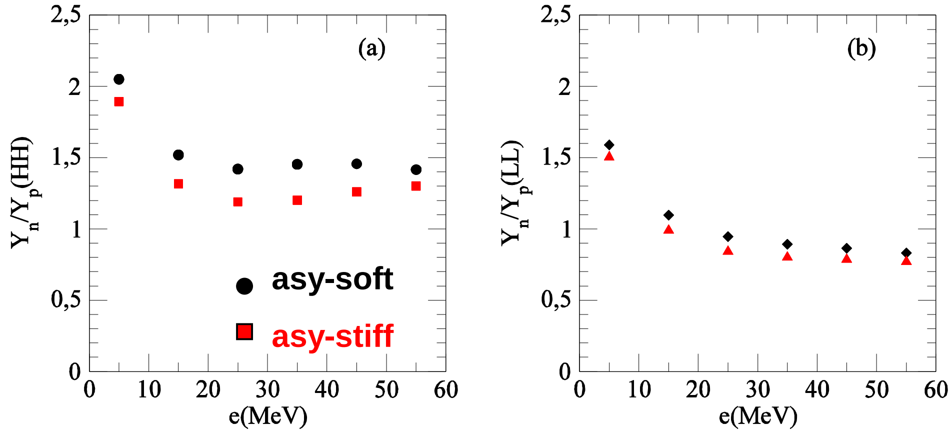
Ratios of emitted pre-equilibrium particles

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

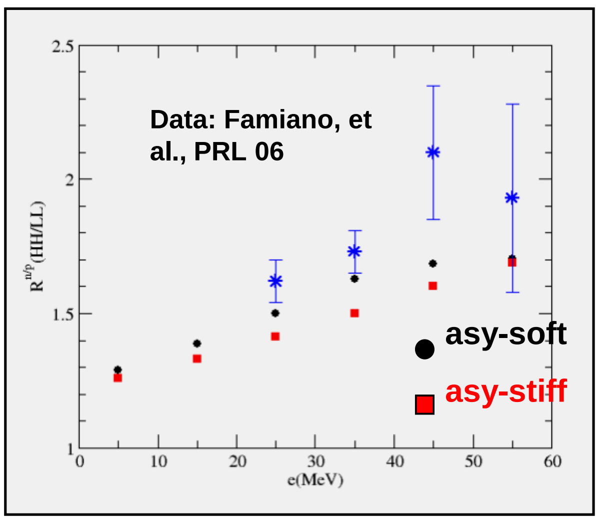
more neutron emission for asy-soft, since symm potential higher

protons vs. neutrons

^{124}Sn + ^{124}Sn $\qquad$ ^{112}Sn + ^{112}Sn



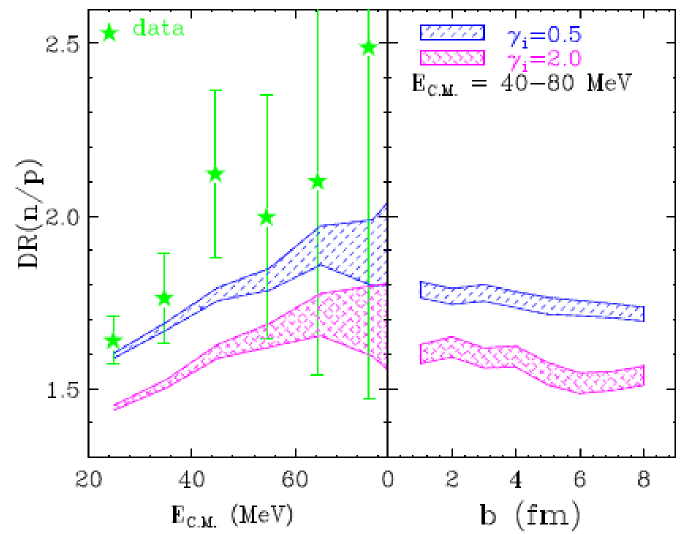
„Double Ratios“ $\dfrac{^{124}\text{Sn} + {}^{124}\text{Sn}}{^{112}\text{Sn} + {}^{112}\text{Sn}}$



SMF simulations, M.Pfabe IWM09

softer symmetry energy closer to data

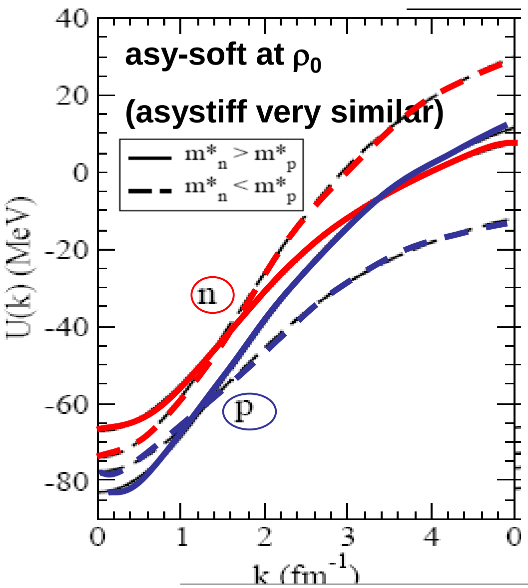
qualitatively as seen in ImQMD, but quantitatively weaker

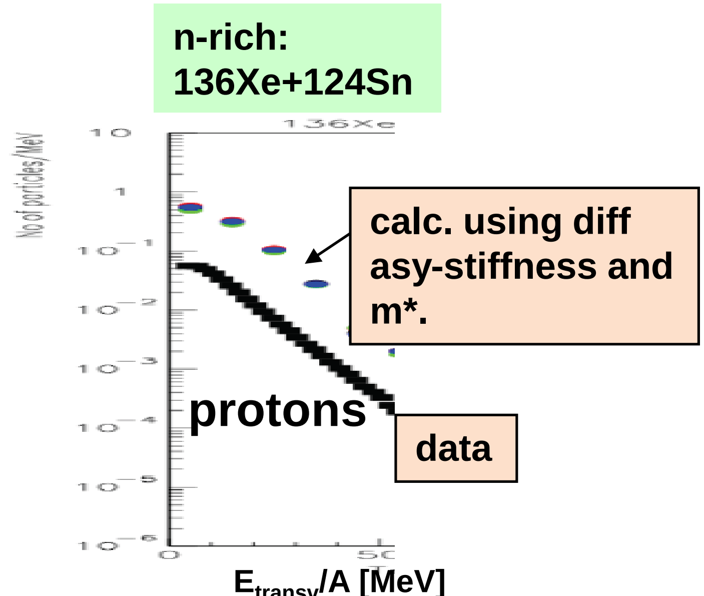


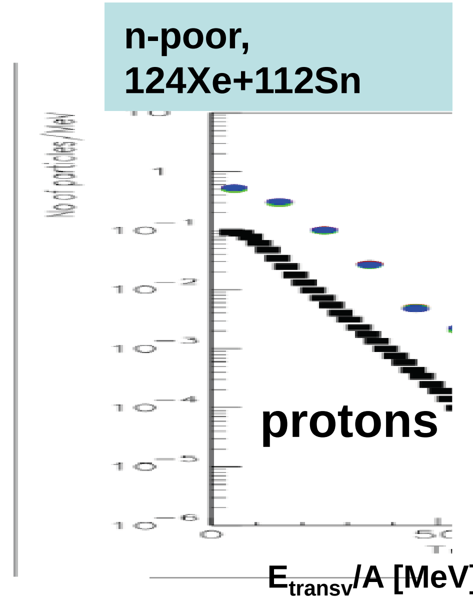
B.Tsang, et al., PRL102, 122701 (09)

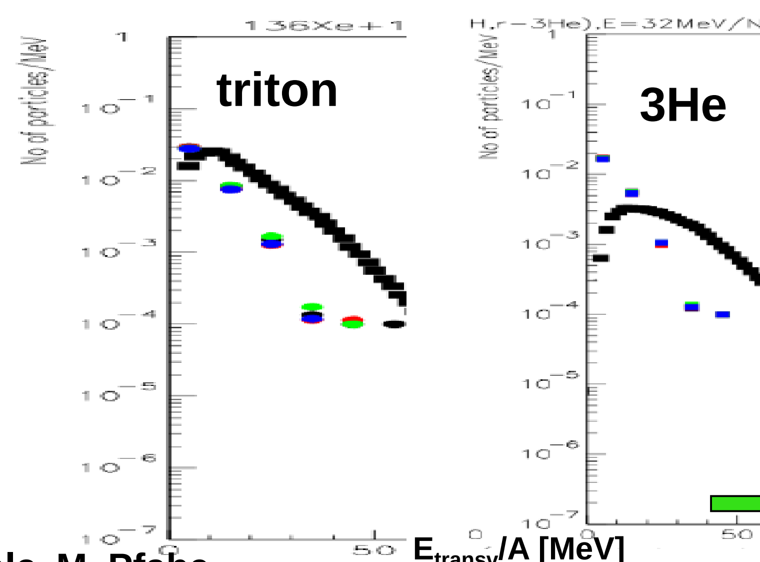
Check density and momentum dependence of symmetry energy in detail:

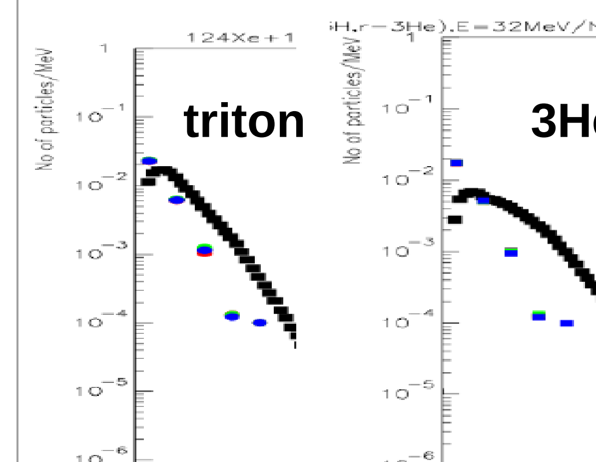
^{136,124}Xe+^{124,112}Sn, E = 32,…,150 AMeV data R. Bougault (Ganil, IWM11)











Look at ratios: p/n, t/3He, etc

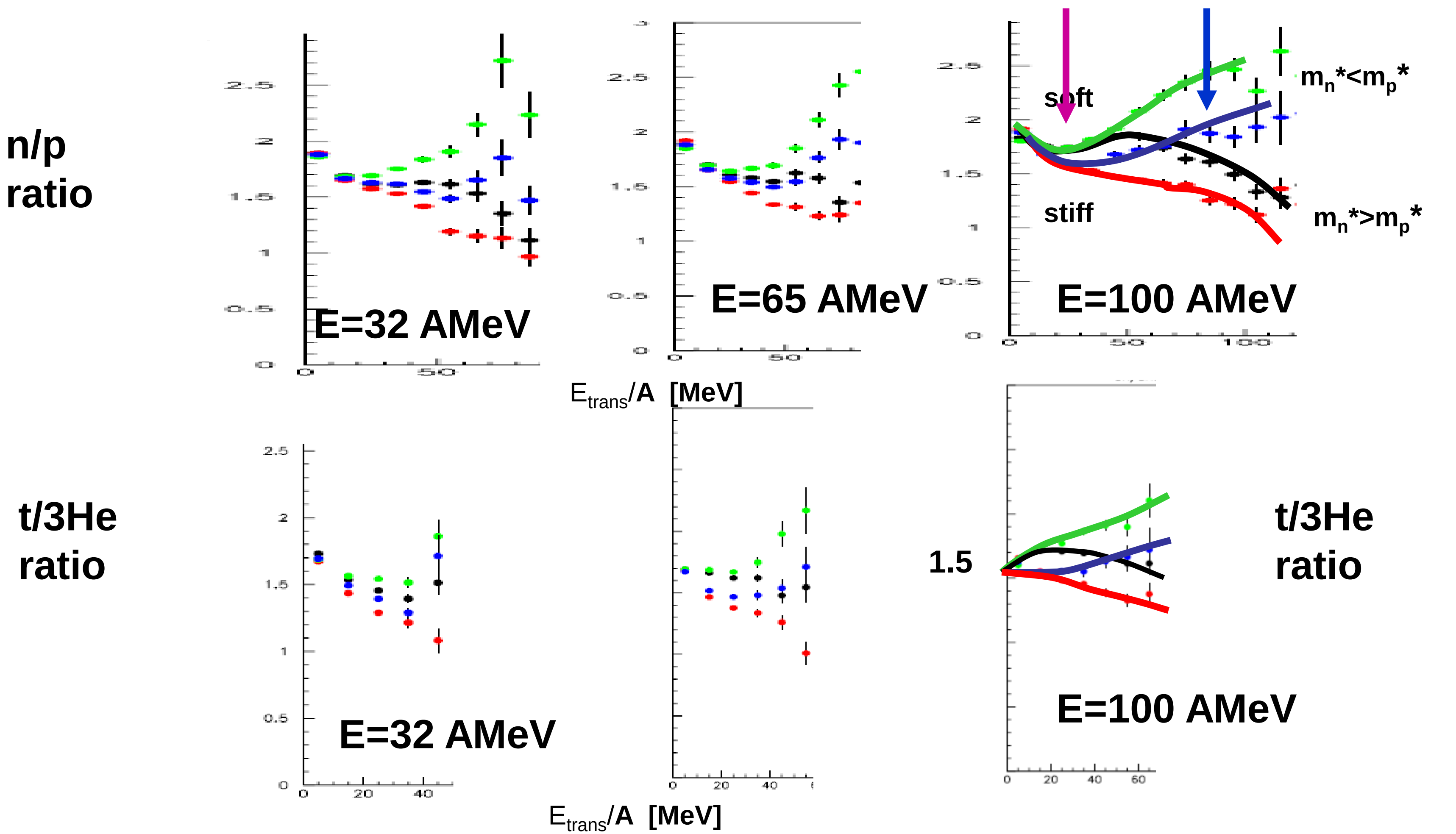
prelim. calc. M. Pfabe

Check momentum dependence of SE:
^{136,124}Xe+^{124,112}Sn, E = 32,…,150 AMeV

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

Yield ratios 136Xe+124Sn, central

Asy-EOS – eff mass dominates



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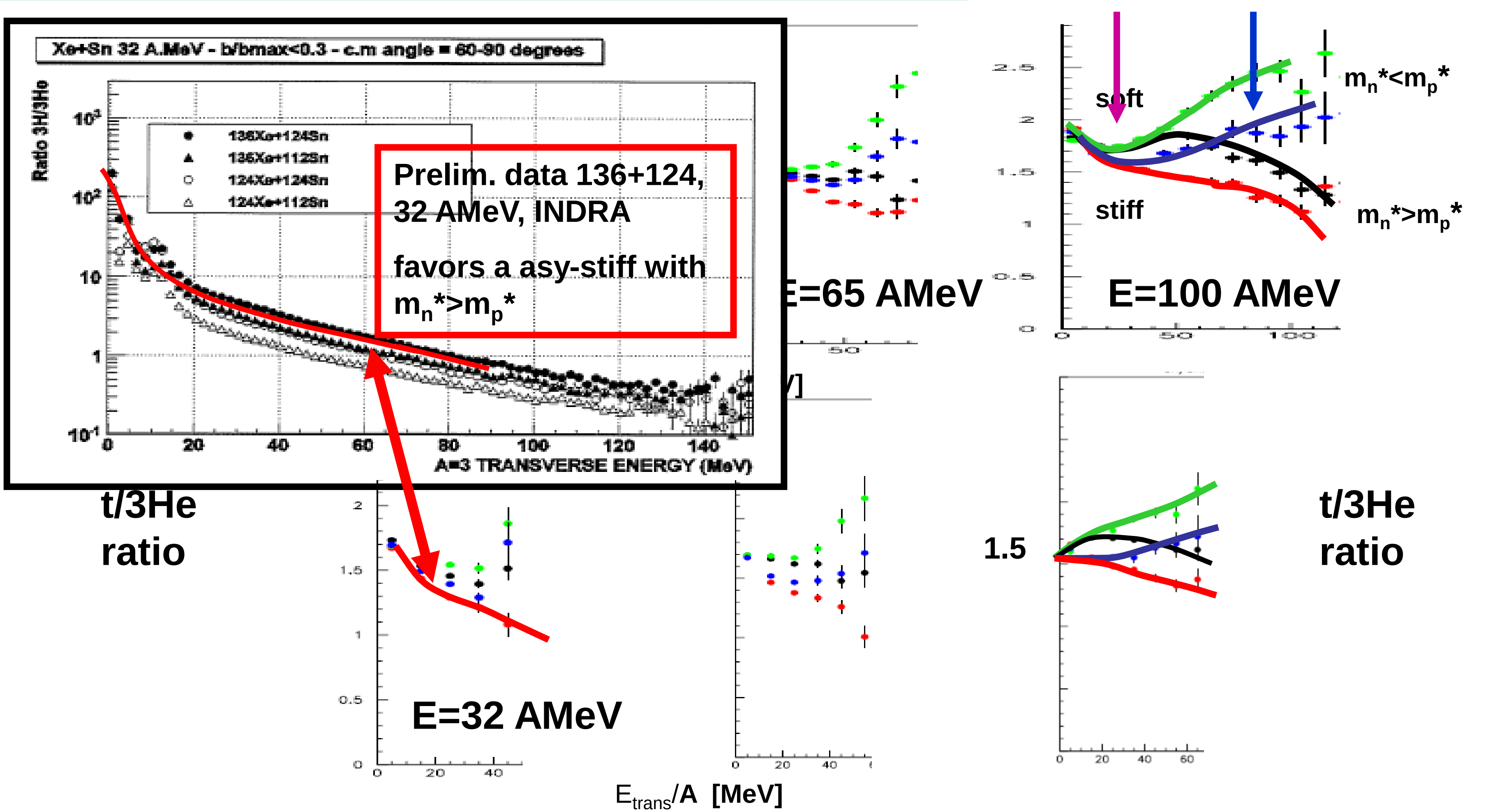
^{136,124}Xe+^{124,112}Sn, E = 32,…,150 AMeV
data R. Bougault (Ganil, prelim, IWM11)

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

Comparison of yield ratios 136Xe+124Sn, central



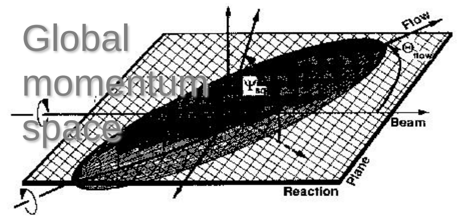
The single t/3He ratios seem to be a promising observable, double ratios under study

"Flow", Momentum distribution of emitted particles

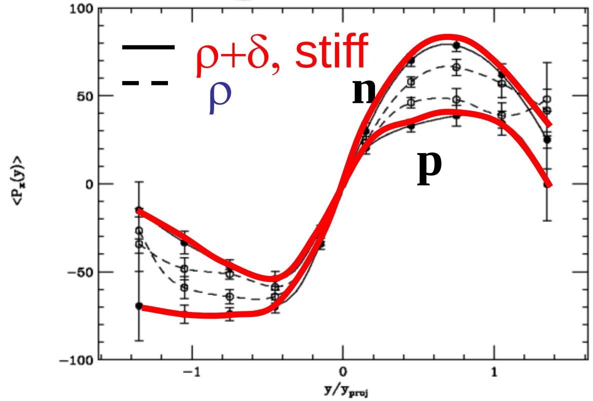
Fourier analysis of momentum tensor : „flow"

$$N(\theta, y, b) = N_0(1 + v_1(y,b)\cos\theta + v_2(y,b)\cos 2\theta + ..)$$

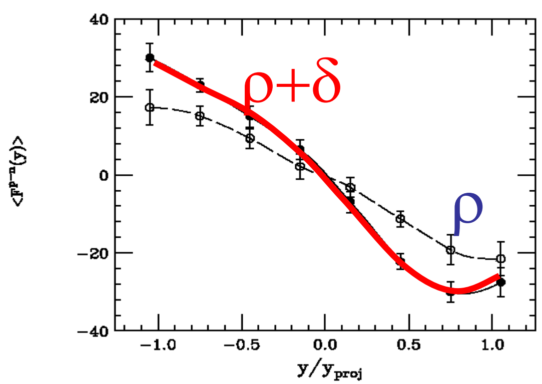
v_1: sideward flow | v_2: elliptic flow



$^{132}Sn + ^{132}Sn$ @ 1.5 AGeV b=6fm



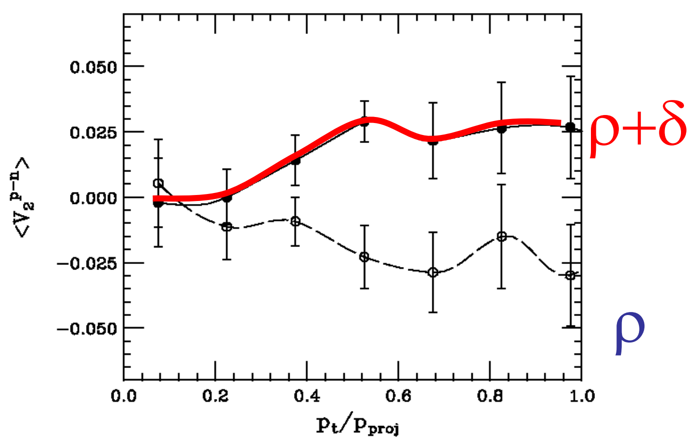
Proton-neutron differential flow



$$F^{x}_{n-p}(y) = \frac{1}{N(y)}\sum_{i=1}^{N(y)}(p_i^x w_i),$$

$$w_i = +1(-1)\ for\ neutron\ (proton)$$

differential elliptic flow

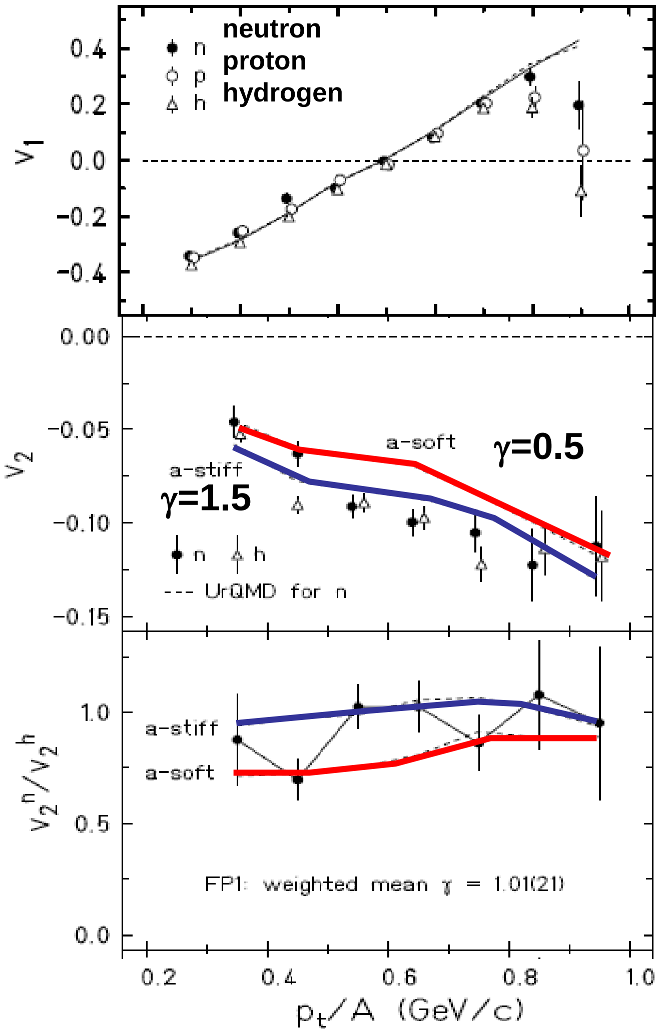


Elliptic flow more sensitive, since particles emitted perpendicular

T. Gaitanos, M. Di Toro, et al., PLB562(2003)

First measurement of isospin flow

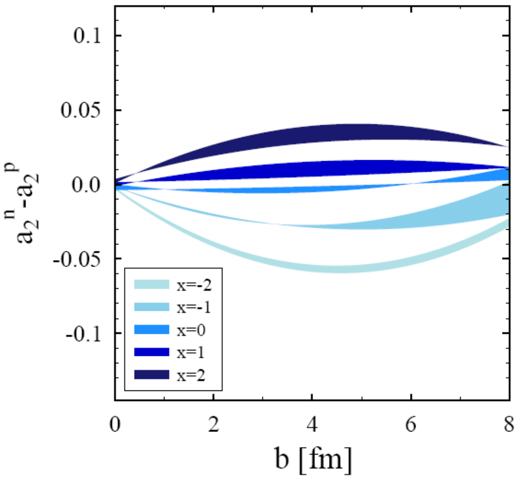
Au+Au @ 400 AMeV, FOPI-LAND (Russotto, et al., PLB 697, 471 (11))



directed flow (v1) not very sensitive,

but elliptic flow (v2), originates in compressed zone

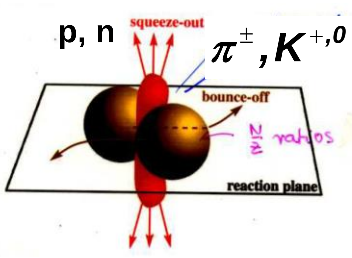
determines a rather stiff symmetry energy (γ~1)



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

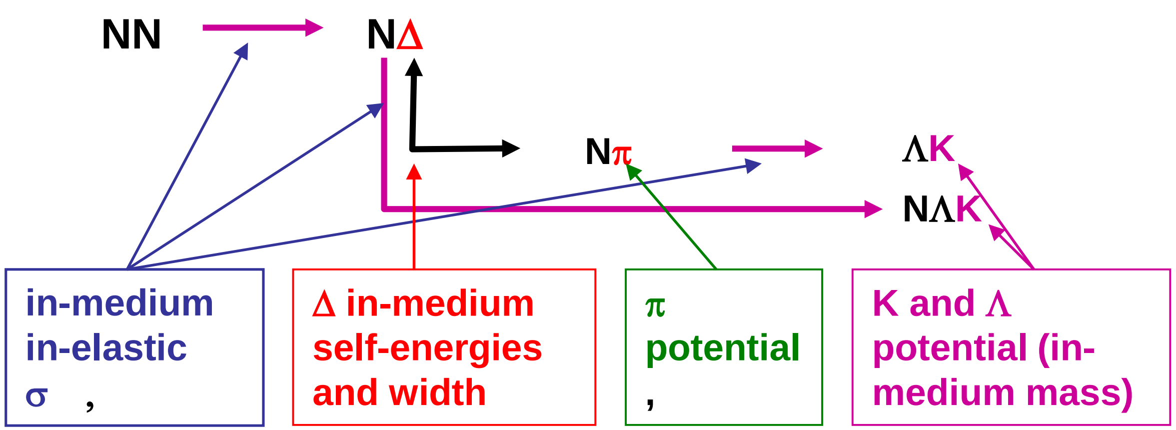
new ASYEOS experiment at GSI May 2011, being analyzed

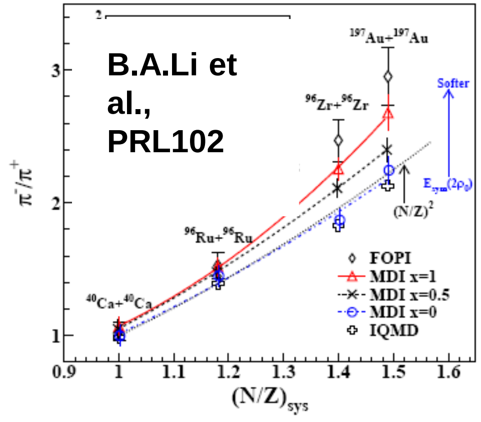
Particle production as probe of symmetry energy



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 $\pi^{-,+}$, $K^{0,+}$





Two limits:

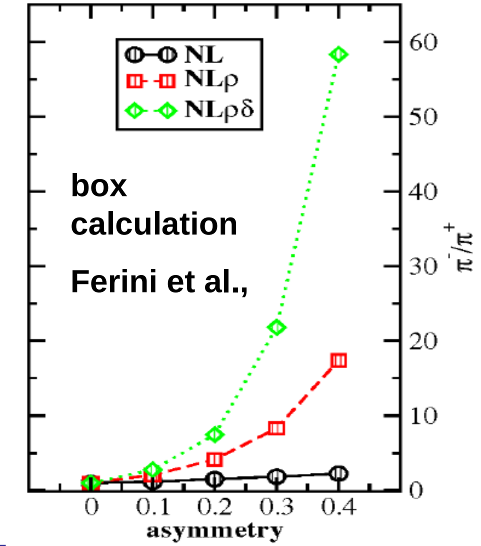
1. isobar model (yield determined by CG-Coeff of Δ->Nπ)

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

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:

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

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

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

$$\frac{\pi^-}{\pi^+}\uparrow$$ *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

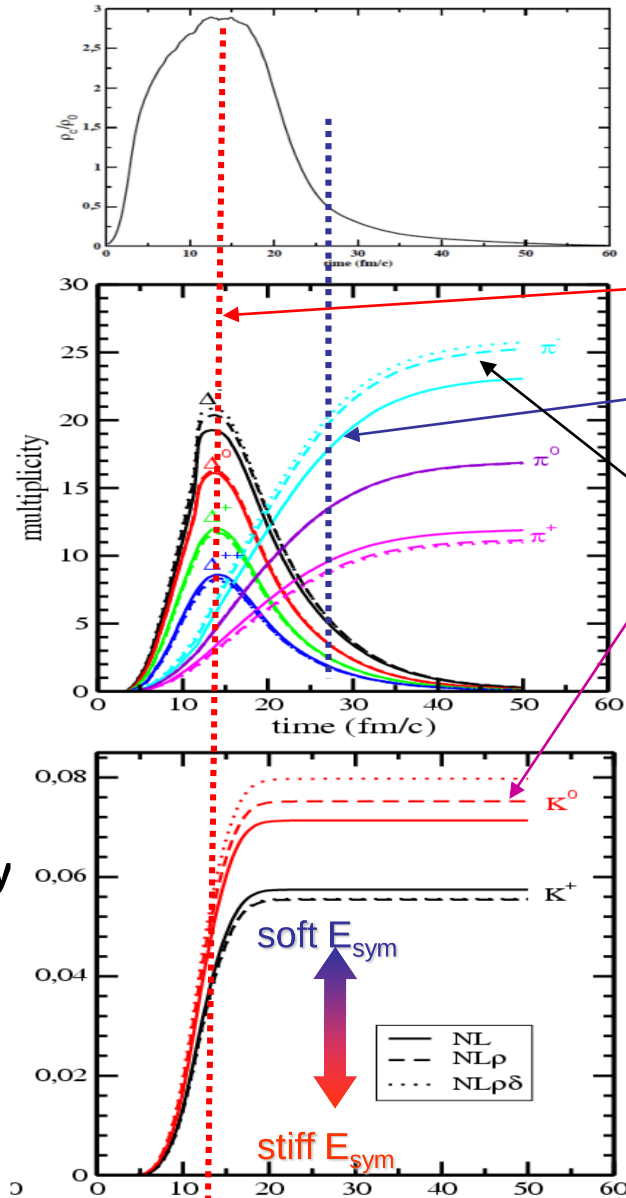
Dynamics of particle production (Δ,π,K) in heavy ion collisions

Au+Au@1AGeV

Central density

π and Δ multiplicity

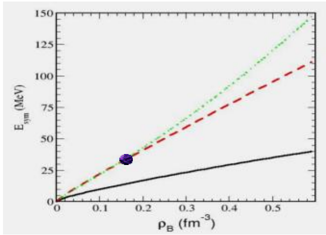
$K^{0,+}$ multiplicity



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

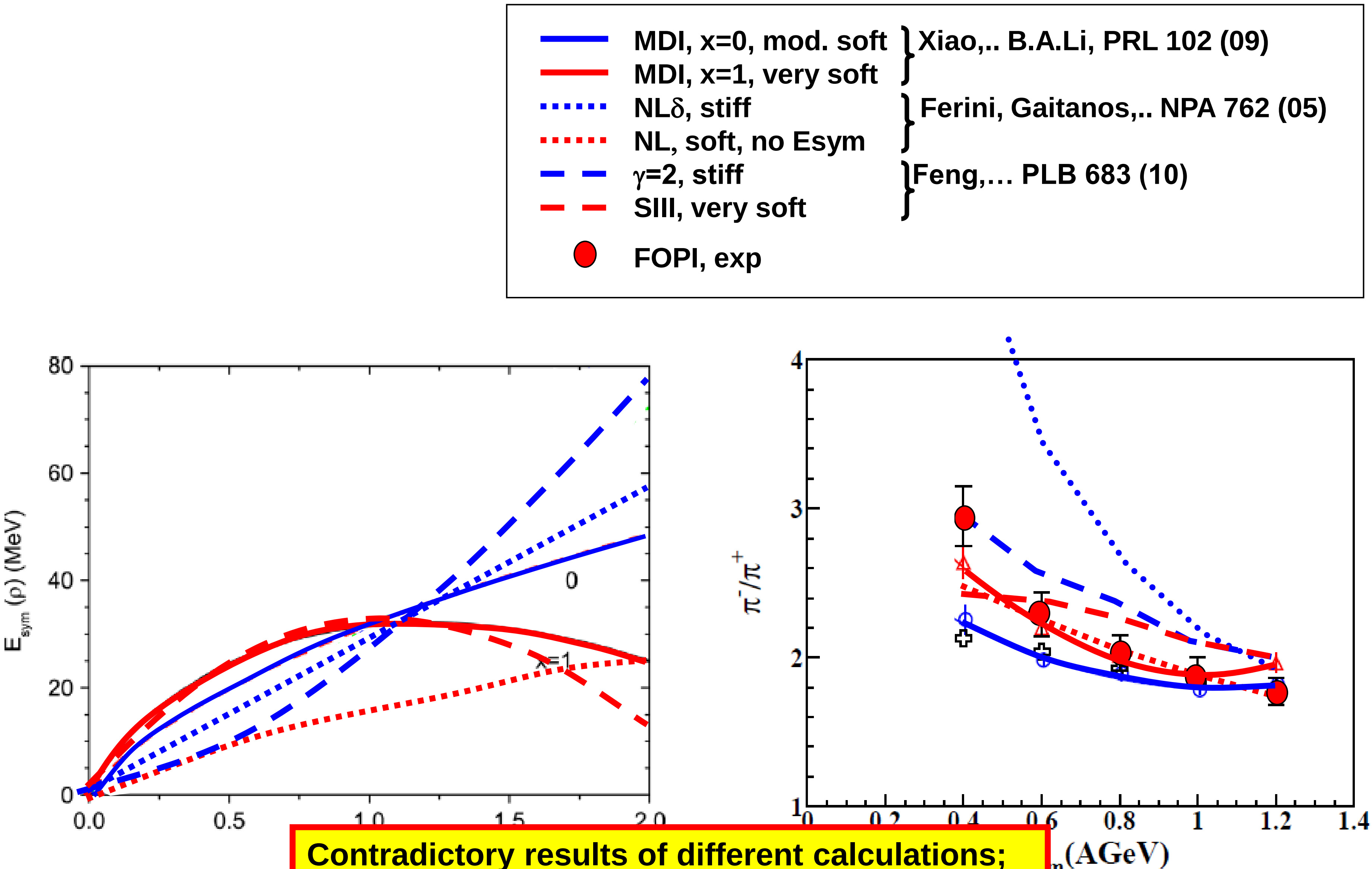
→ $\Delta^{0,-}/\Delta^{+,++}$

→ π^-/π^+, K^0/K^+

→ n/p ratio governs particle ratios

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

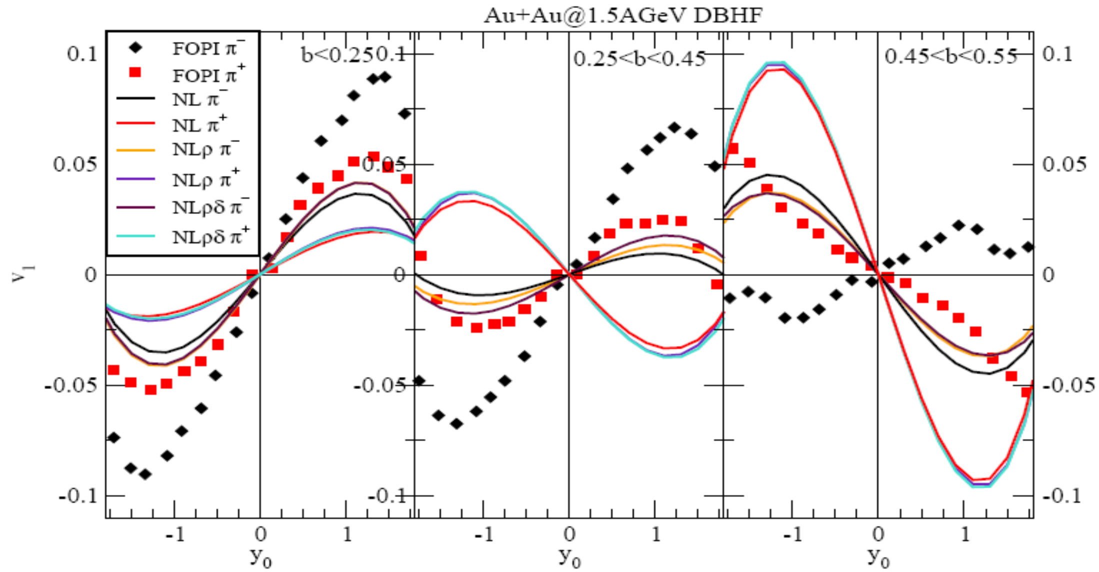
Pion ratios in comparison to FOPI data (W.Reisdorf et al. NPA781 (2007) 459)



Contradictory results of different calculations;

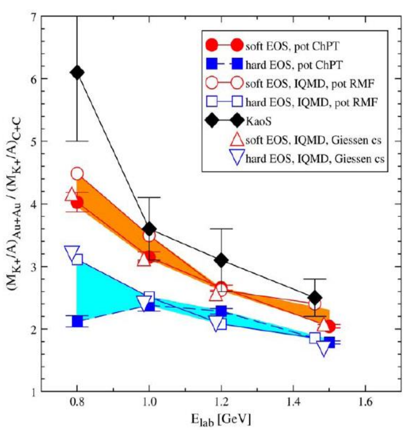
Other pion observables, or kaons

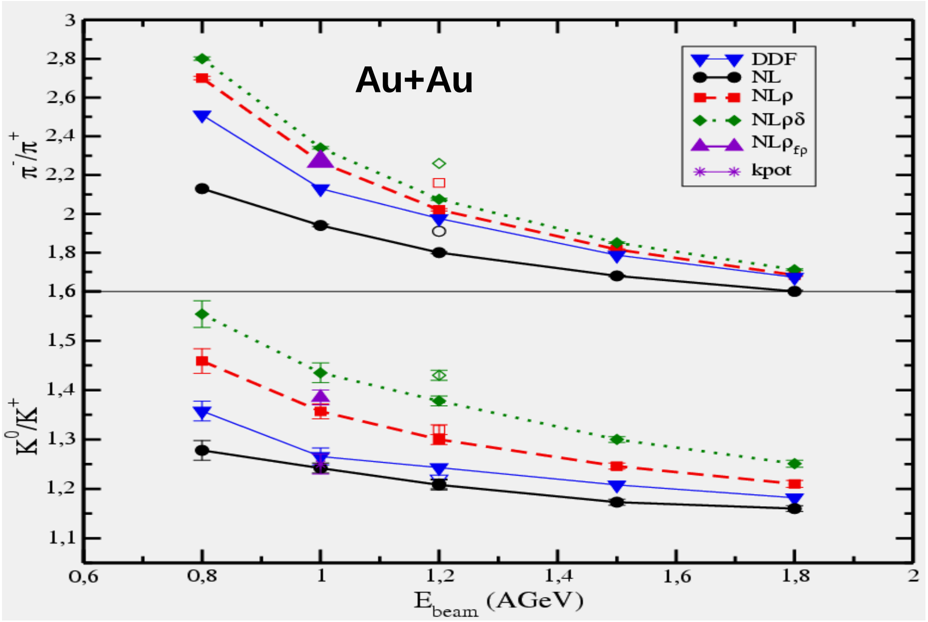
perhaps other pion observables: flow



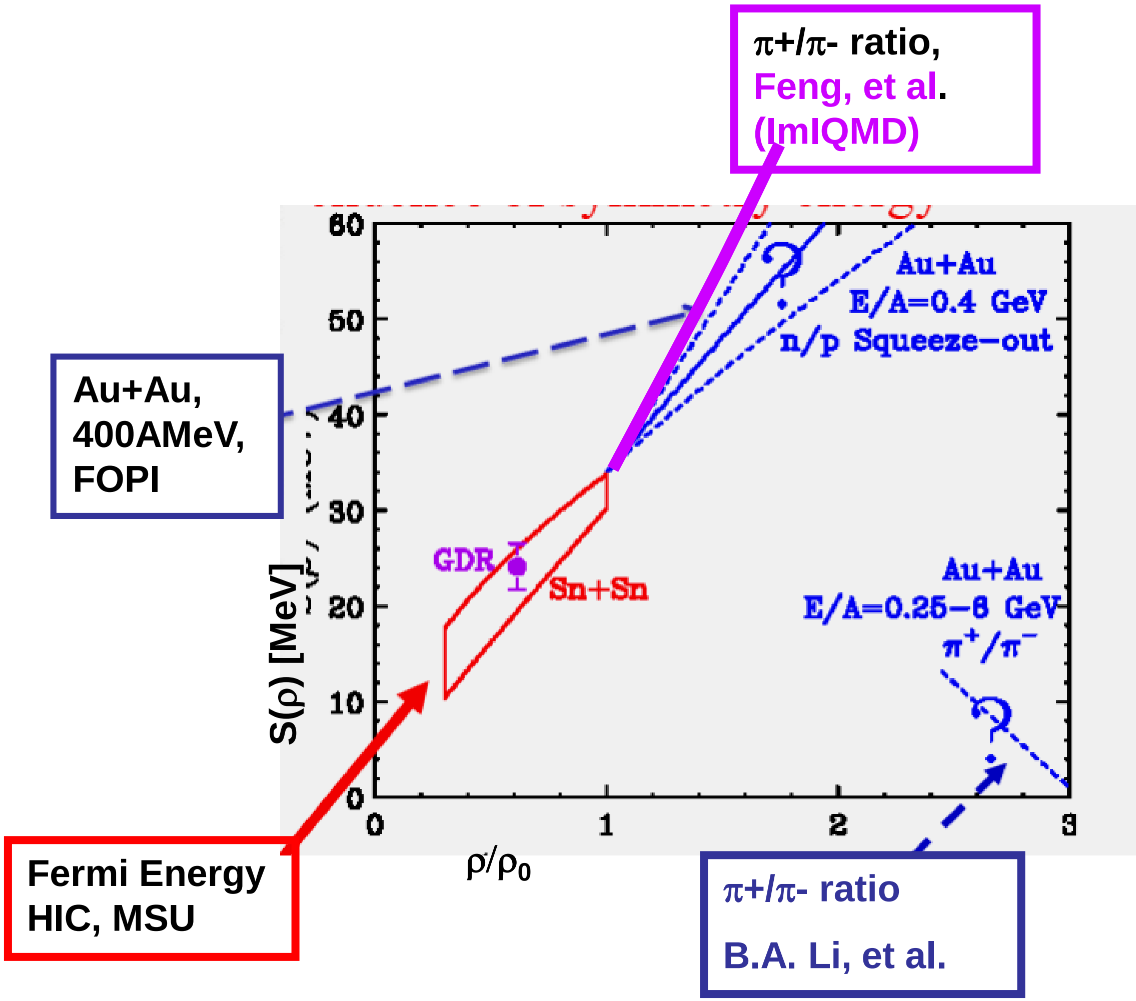
or kaon ratios:

Kaons were a decisive observable to determine the symmetric EOS.





Present constraints on the symmetry energy



Moving towards a better determination of the symmetry energy

Large uncertainties at higher density

Conflicting theoretical conclusions for pion observables.

Work in exp. and theory necessary!

Summary and Outlook:

•While the EOS of symmetric NM is now fairly well determined, the density (and momentum) dependence of the Symmetry Energy is still rather uncertain, but important for exotic nuclei, neutron stars and supernovae.

• Different probes for the Symmetry Energy in heavy ion collisions with transport theory at different energy (density) ranges

• Explore the sensitivity of observables to the ingredients (asy-EOS, momentum dependence of SymEn, medium, esp. isospin dependence of cross sections.
Consistent description of many observables mandatory, also from structure and astrophysics

• High density region particularly open. Experimental constraints very important.

Thank you!