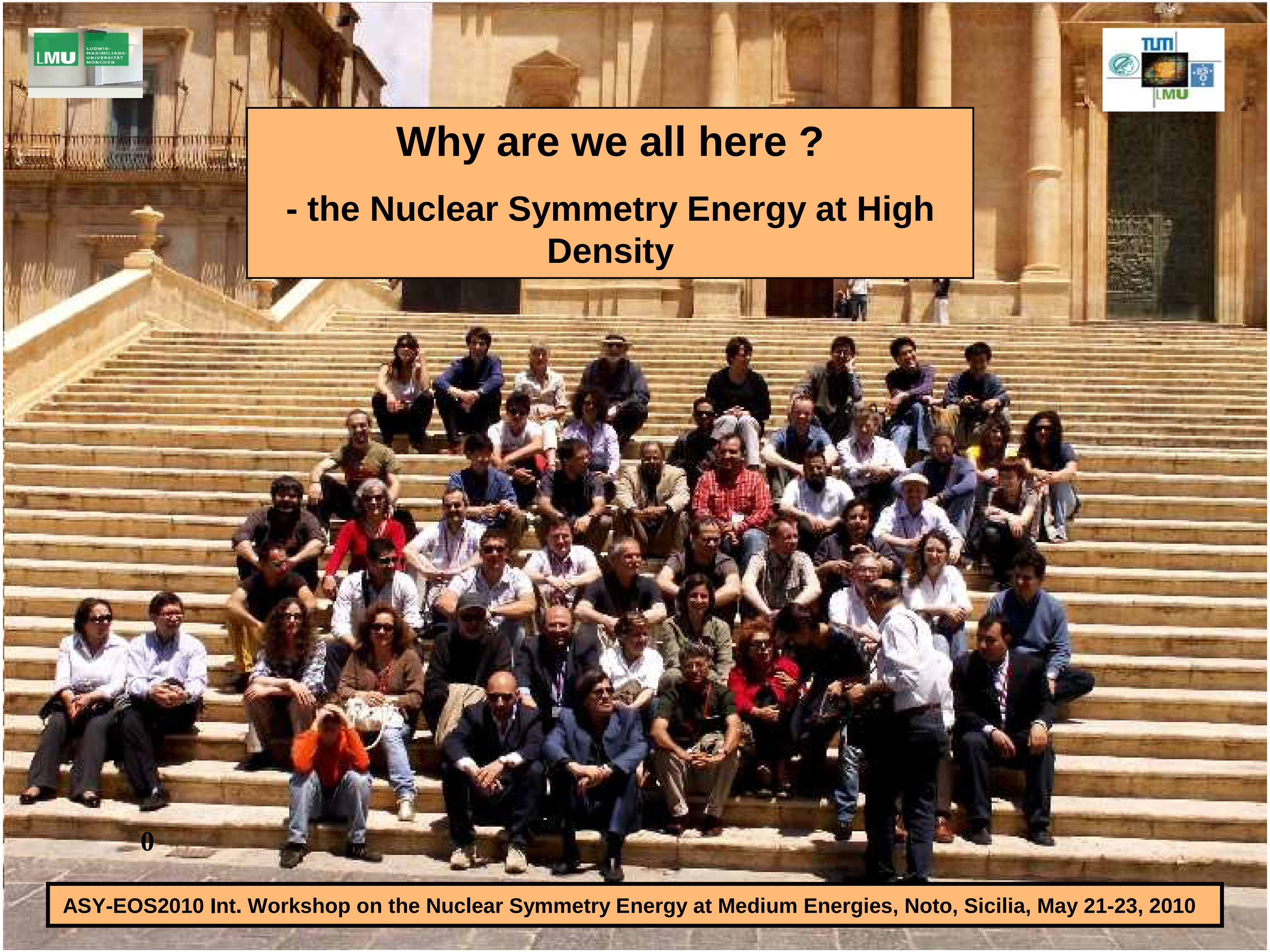
Why are we all here ?

- the Nuclear Symmetry Energy at High Density



ASY-EOS2010 Int. Workshop on the Nuclear Symmetry Energy at Medium Energies, Noto, Sicilia, May 21-23, 2010

Why are we all here ?

- the Nuclear Symmetry Energy at High Density

looking both ways

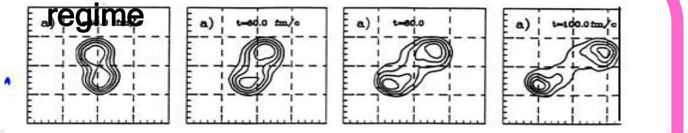
Hermann Wolter, LMU München

So, why are we all here ???

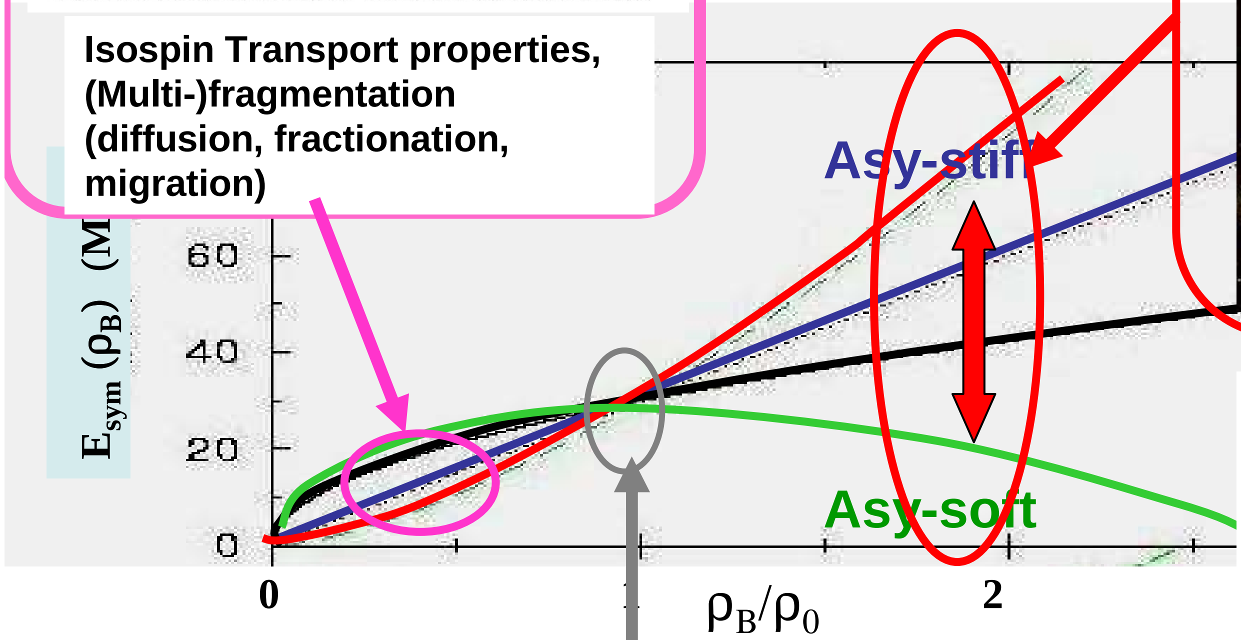
$$E(\rho_B, I)/A = E(\rho_B) + E_{sym}(\rho_B) I^2 + O(I^4) + \ldots$$

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

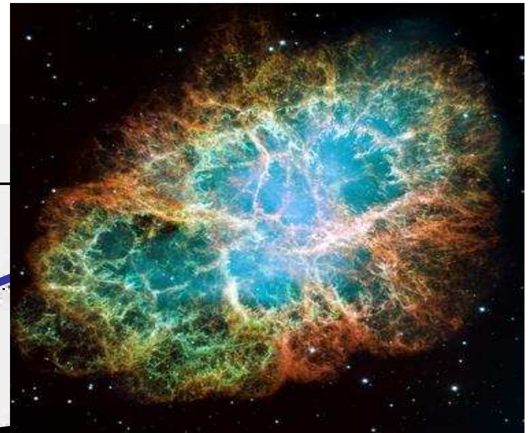
heavy ion collisions in the Fermi energy regime



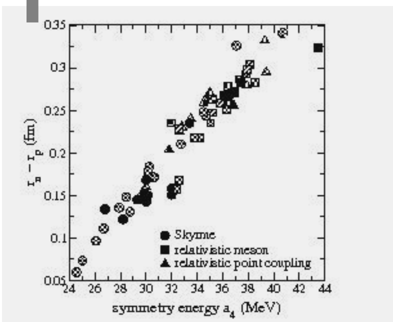
Isospin Transport properties, (Multi-)fragmentation (diffusion, fractionation, migration)

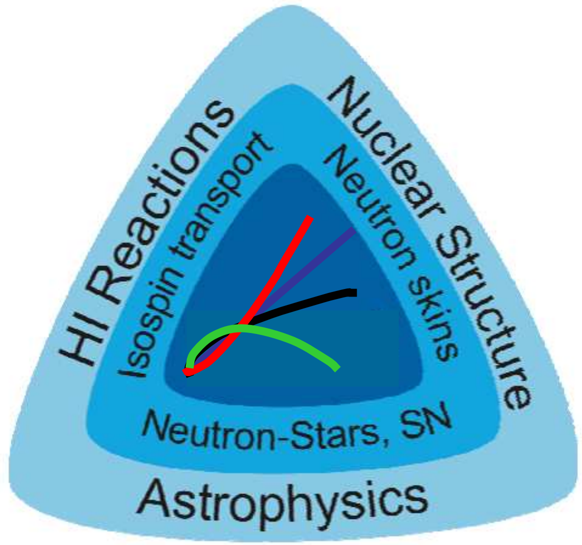


Suprasaturation densities supernovae, nucleosynthesis (rel. HIC, neutron stars)

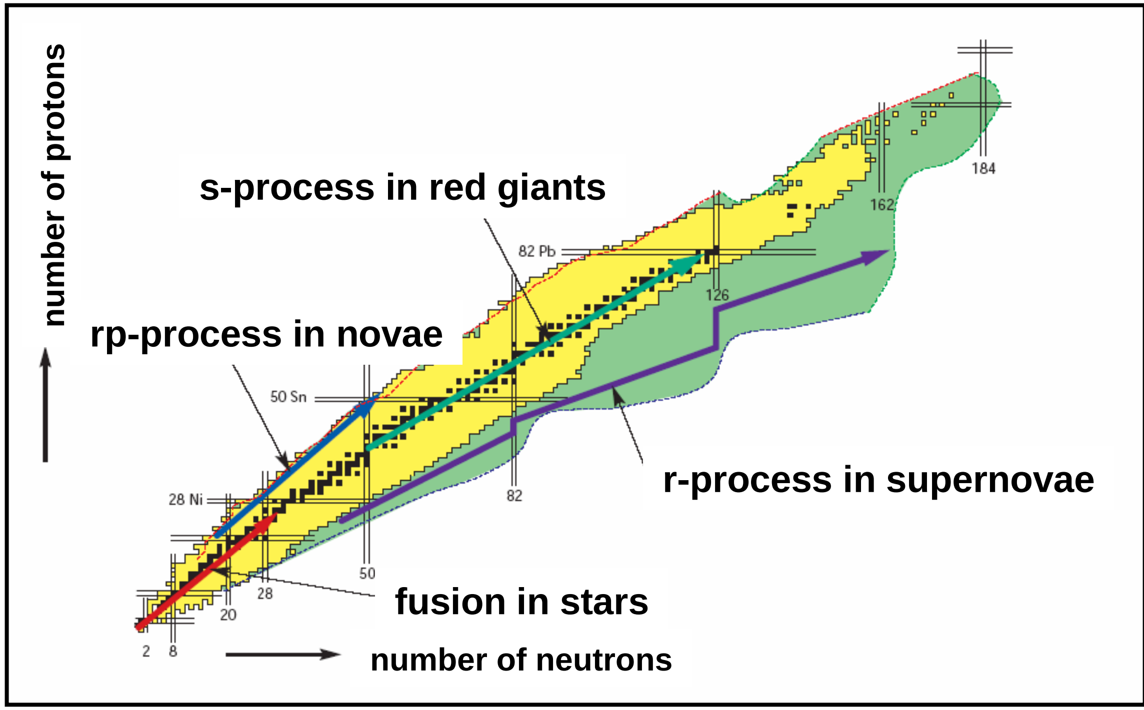


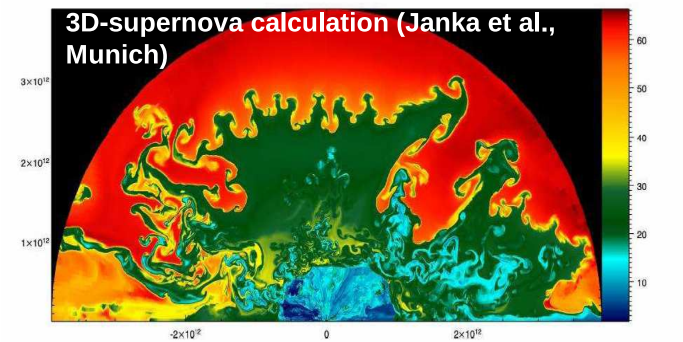
Nuclear structure (neutron skin thickness, Pygmy DR, IAS)
Slope of Symm Energy



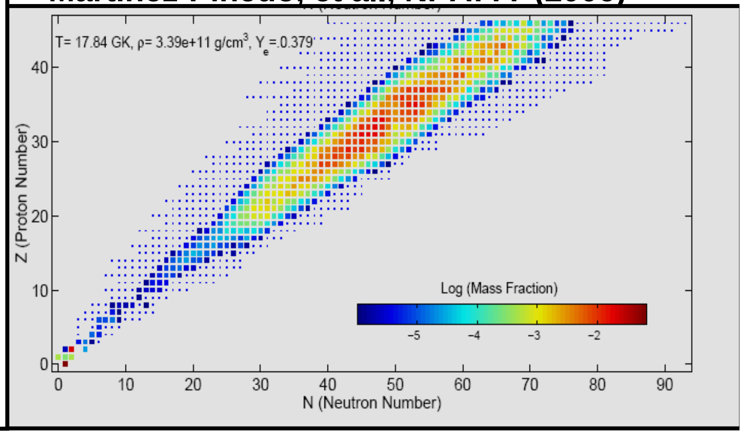


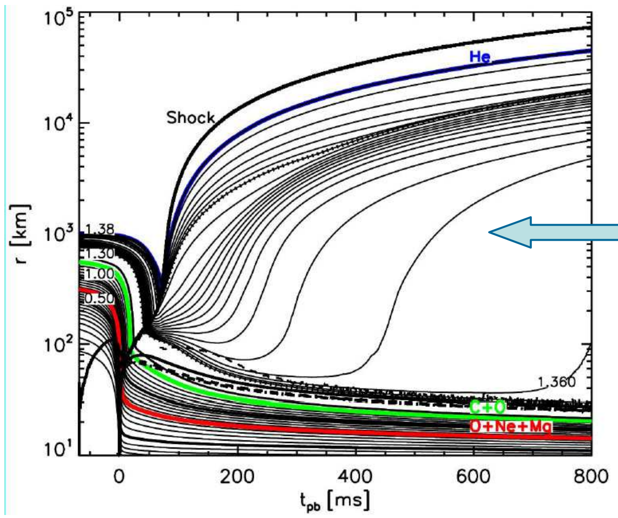
If Supernovae did not occur, would we be here?





Abundances in core collapse supernovae
Martinez-Pinedo, et al., NPA777 (2006)

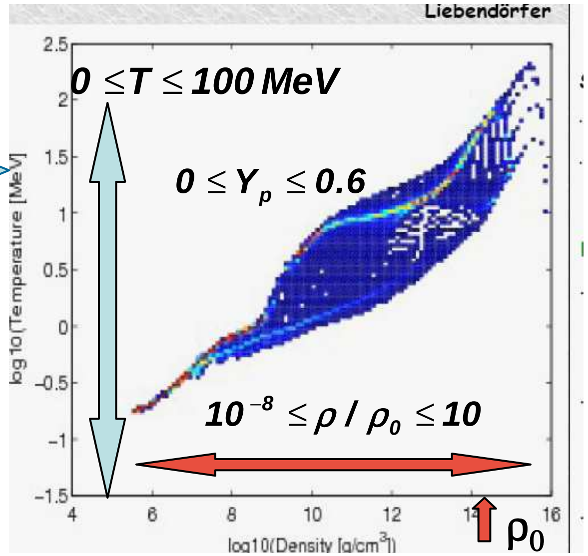




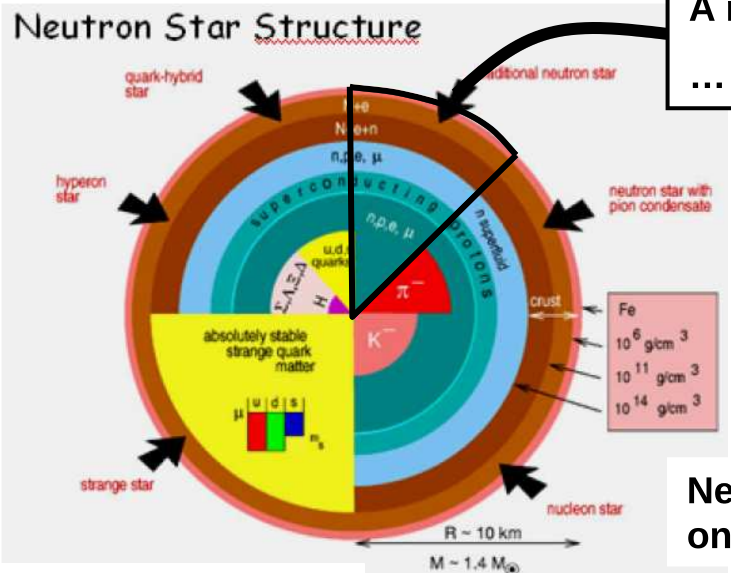
Density, temperature and aymmetry range in a SN

Shock front in a core-collapse SN

All depend on dens. dep. of Symmetry energy



Neutron stars: a laboratory for the high-density symmetry energy

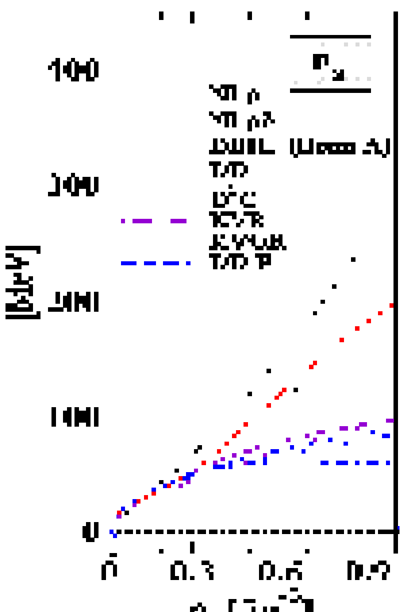


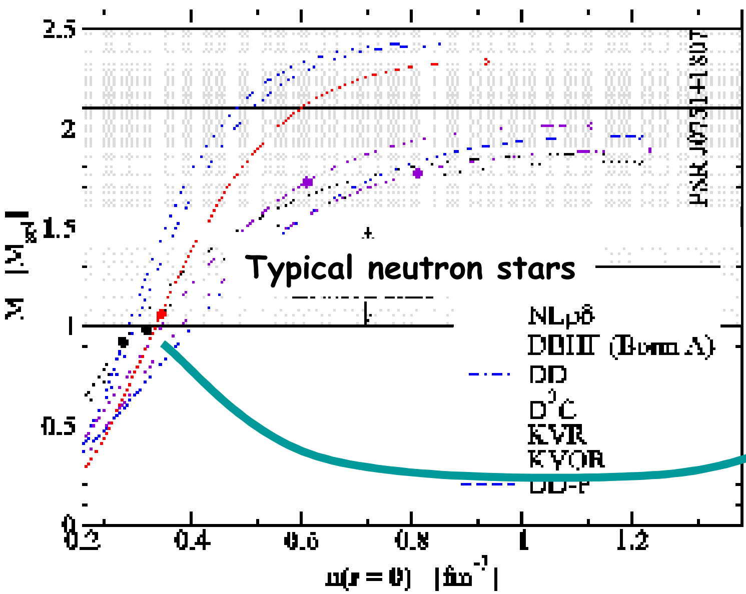
A normal NS (n,p,e)

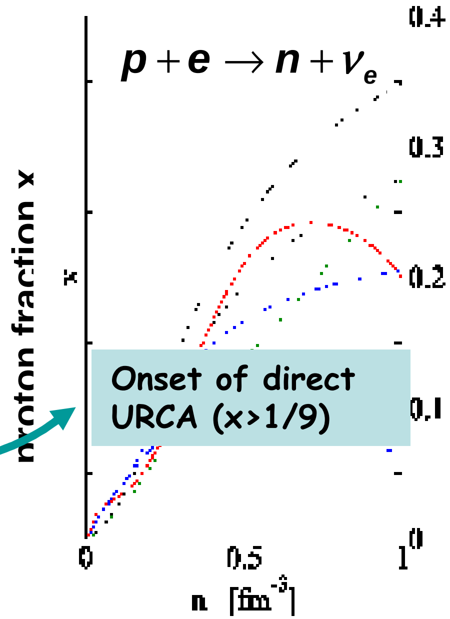
… or exotic NS ??

Neutron star mass dep. on Symmetry Energy

Fast cooling of NS: direct URCA process



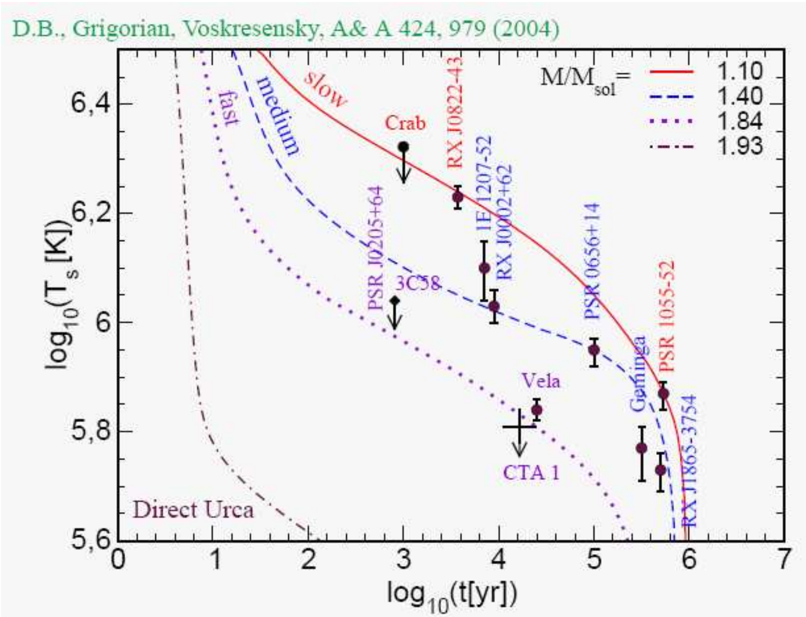




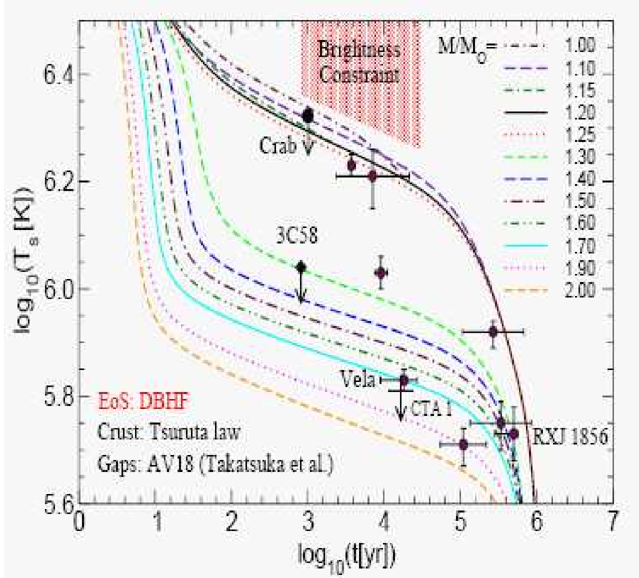
Klähn, Blaschke, Typel, Faessler, Fuchs, Gaitanos,Gregorian, Trümper, Weber, Wolter, Phys. Rev. C74 (2006) 035802

Neutron star cooling: a test of the symmetry energy

Temperature - age plot: characterizes compact star matter properties



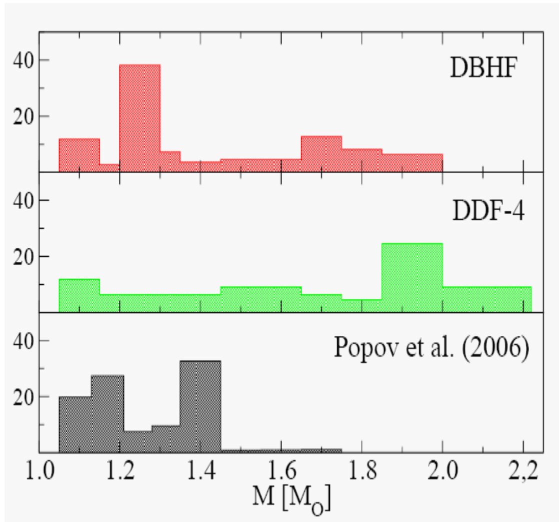
e.g. for DBHF EOS)



A given symmetry energy behavior leads to a distribution of NS masses:

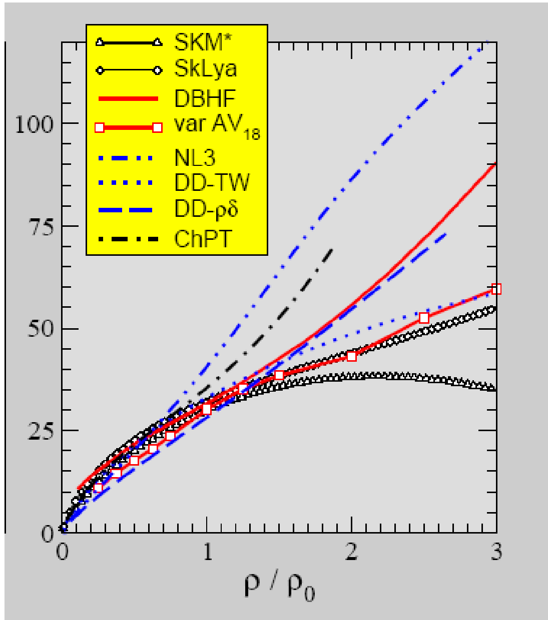
Comparison to mass distribution from population synthesis models (Popov et al., A&A 448 (2006)

plus other neutron star observables; consistency far from obvious

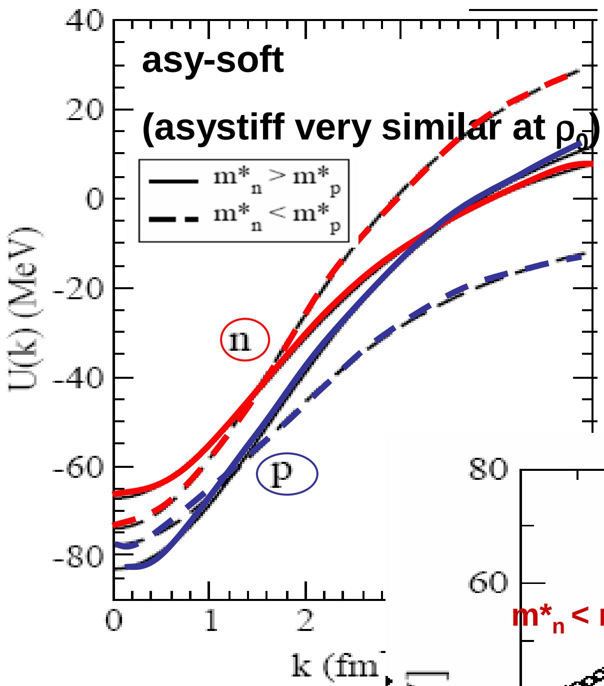


D. Blaschke, Compstar workshop, Caen, 10

Symmetry Energy in different „realistic“ models



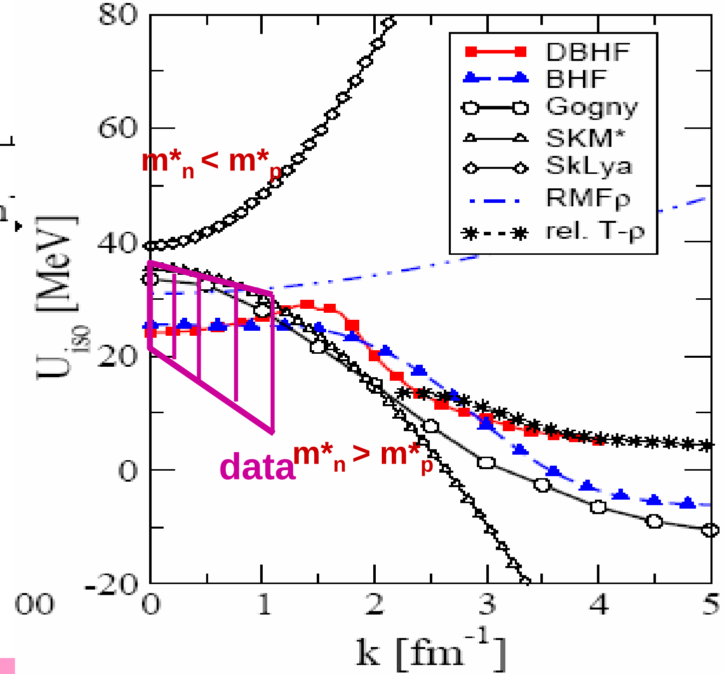
C. Fuchs, H.H. Wolter, EPJA 30(2006)5



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

Different proton/neutron effective masses

-> crossing around Fermi momentum!



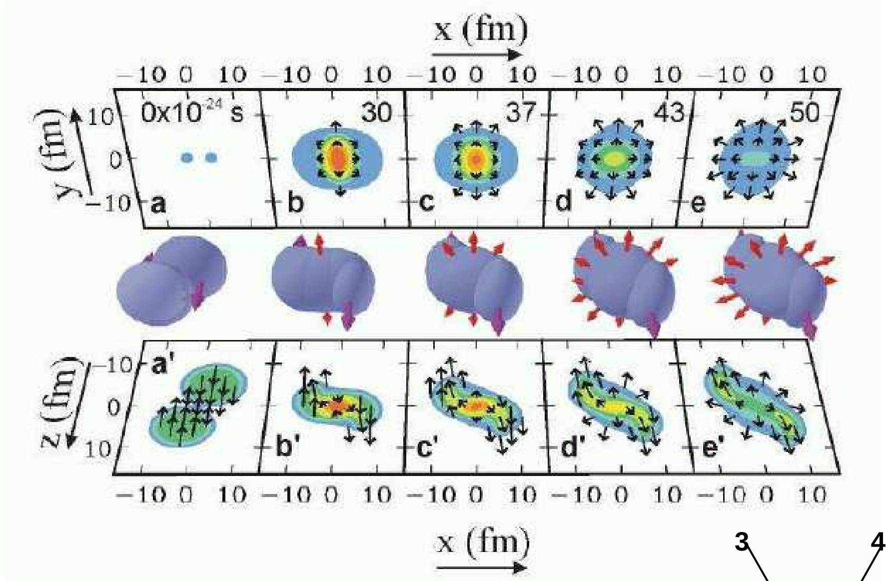
Isovector (Lane) potential: momentum dependence

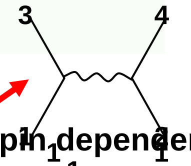
$$U_{Lane}(k) = \frac{1}{2I}(U_{neutr} - U_{prot})$$

Why is symmetry energy so uncertain??
->In-medium ρ mass, and short range tensor correlations (B.A. Li, arXiv0910:4803);
->see talk by Fiorella Burgio

Test of symmetry energy in heavy ion collisions

→ Transport theory





non-relativistic: BUU

2-body collisions

isospin dependent, pp,nn,pn

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\nabla f - \nabla U \nabla_p f = I_{coll}[f,\sigma] = \frac{1}{(2\pi)^{3/2}} \iiint dp_2 dp_3 dp_4 \, v_{12} \frac{d\sigma}{d\Omega}_{12\to 34} \delta(p_1 + p_2 - p_3 - p_4)$$

$$[(1-f)(1-f_2) f_3 f_4 - f\, f_2 (1-f_3)(1-f_4)]$$

Vlasov eq.; mean field

loss term

gain term

EOS

isoscalar and isovector (~10%)

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

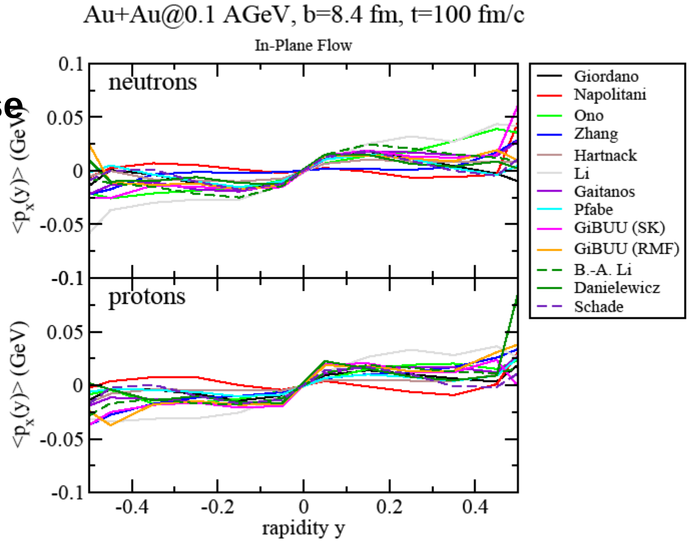
2) **Isovector effects are small relative to isoscalar quantities**

3) **Method to solve exact enough??**

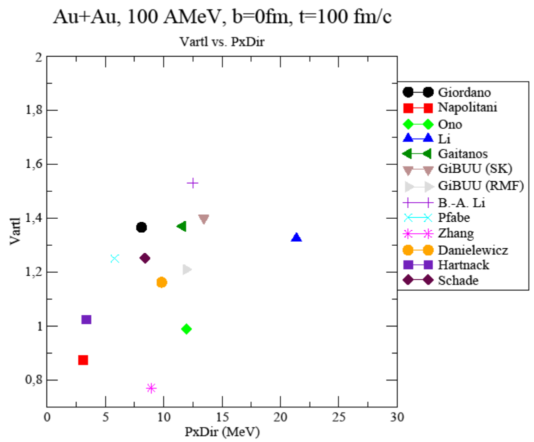
Code Comparison Project:
Workshop on Simulations of Heavy Ion Collisions at Low and Intermediate Energies, ECT*, Trento, May 11-15, 2009

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

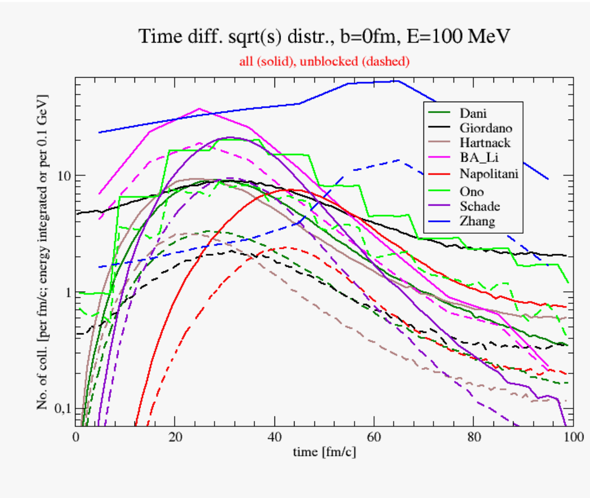
transverse flow



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



time distribution of collisions (energy integrated)



→ agreement for flow is not really good enough to make detailed conclusions, correlations

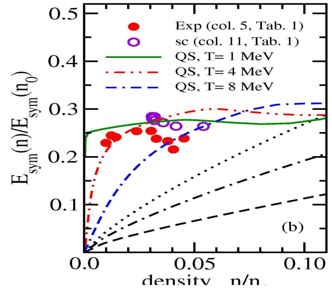
→ symmetry effects are order of magnitude smaller: hope that differences are less sensitive (?)

→agreement is somewhat better at 400 AMeV: mean field effects are smaller

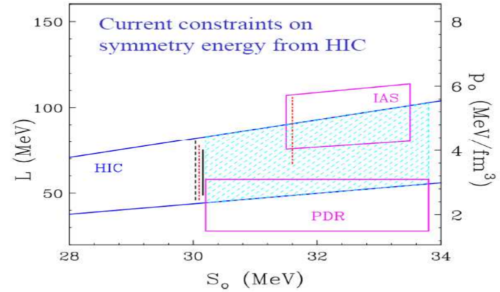
→ look for origin of differences: collisions ??

Investigation of the Symmetry Energy in Different Density Ranges

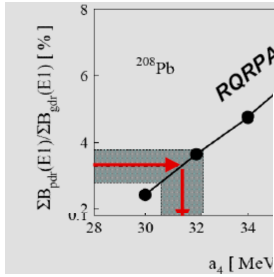
1. $\rho \ll \rho_0$: **expanding fireball in Fermi-energy heavy ion collisions.**
   cluster correlations at low density and temperature
   → not here



2. $\rho < \rho_0$: **Isospin transport in Fermi energy central**
   and peripheral collisions, (multi-)fragmentation,
   → short comments here, talk by Yenello



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



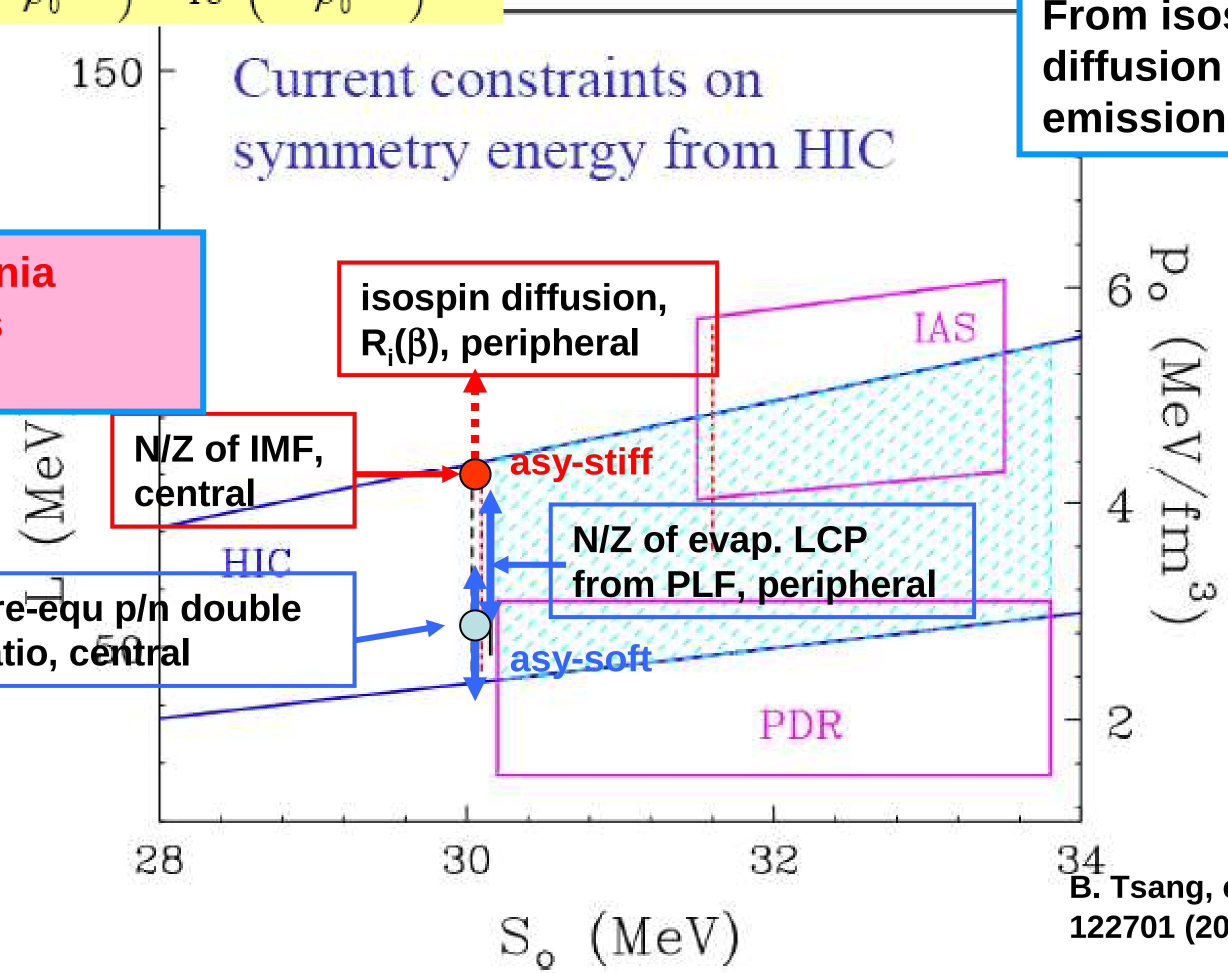
Strength of Pygmy Dipole Resonance PDR

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

5. $\rho \gg \rho_0$: **Ultrarelativistic HI collisions, Dependence of mixed**
   and deconfinement phase on asymmetry?
   → talk by Di Toro

Comparison of SE determinations at lower energy

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



From isospin diffusion and p/n emission ratios

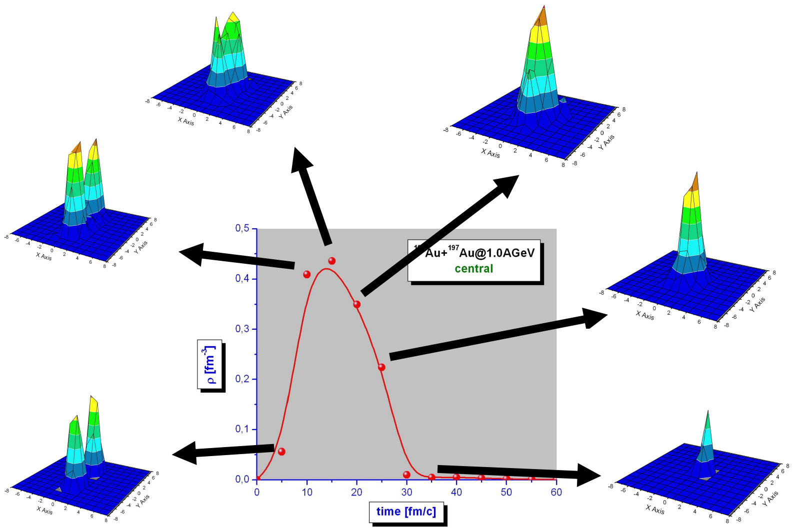
Note: for Catania results: Limits approximate!

B. Tsang, et al., PRL 102, 122701 (2009)

Current state:

Generally consistent with each other , but still uncertainties. More work necessary, also on consistency of codes

High density symmetry energy in relativistic heavy ion collisions



→Au+Au 1AGeV central: phase space evolution in a CM cell

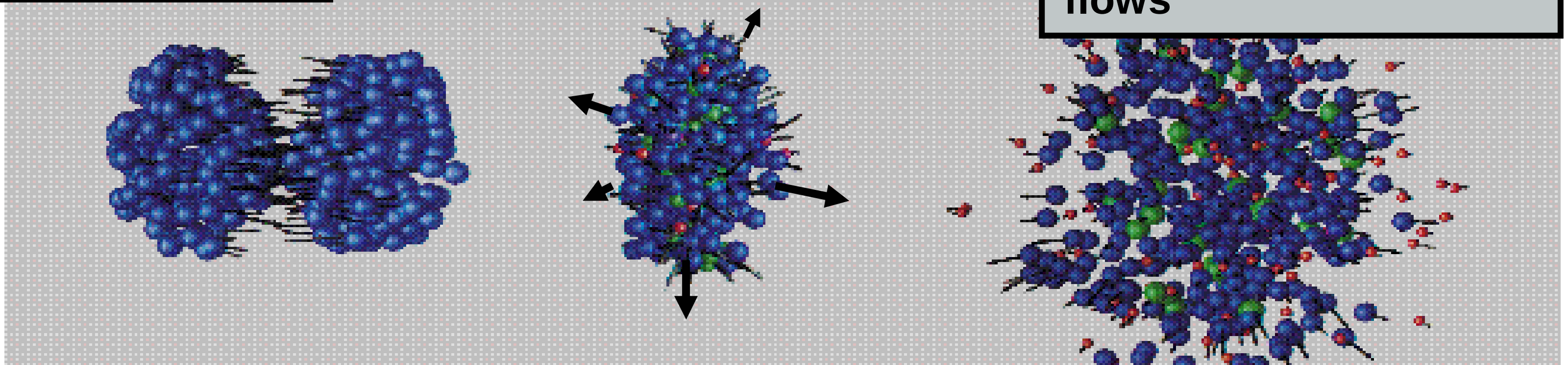
→High densities about 2.5 ρ_0

→Non-spherical momentum distribution, non-equilibrium even at highest densities

Three types of Observables:

1. Pre-equilibrium emission of p, n, light clusters

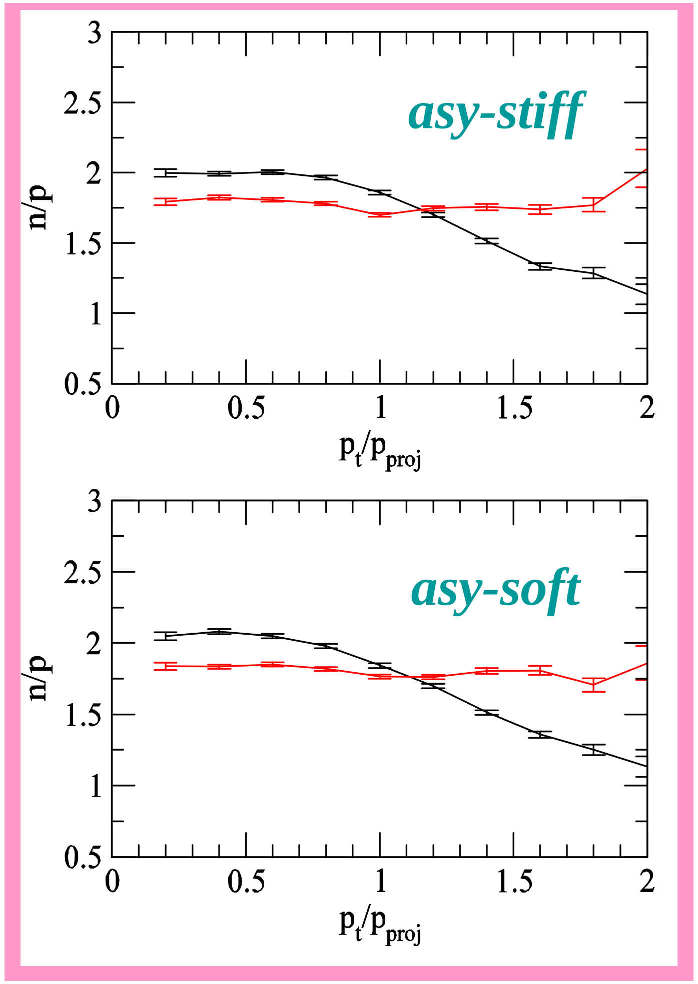
2. Differential and difference of collective flows



3. Particle production, π,K

Fast (pre-equilibrium) nucleon and light cluster emission
→ talk by M. Zielinska-Pfabe

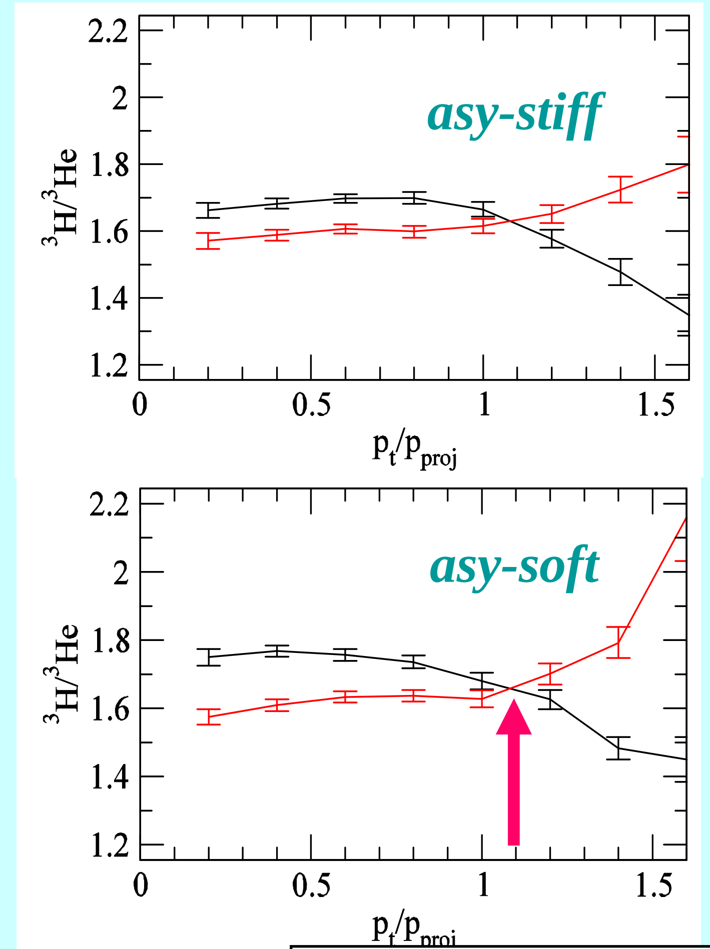
n/p ratio yields



^{197}Au+^{197}Au
600 AMeV
b=5 fm,
y(0)≤0.3
(squeeze-out)

- $m^*_n > m^*_p$
- $m^*_n < m^*_p$

Light isobar ^{3}H/^{3}He yields



Crossing of the symmetry potentials for a matter at $\rho \approx 1.7\, \rho_0$

Observable very sensitive at high p_T to the mass splitting and not to the asy-stiffness

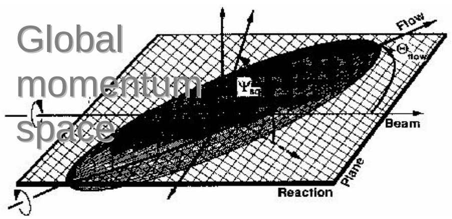
V.Giordano, M.Colonna et al., arXiv 1001.4961, to appear PRC

Heavy Ion Collisions at Relativistic Energies: "Flow"

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



or transverse flow

$$\langle p_x/A\rangle(y) \equiv \frac{1}{N(y)}\sum_{i=1}^{N(y)} p_x^i/A(y),$$

To investigate symmetry energy:

differences of flow (more sensitive for clusters):

$$\langle p_x^t/A\rangle - \langle p_x^{^3\mathrm{He}}/A\rangle = \frac{1}{N_t}\sum_{i=1}^{N_t} p_x^i/A - \frac{1}{N_{^3\mathrm{He}}}\sum_{i=1}^{N_{^3\mathrm{He}}} p_x^i/A.$$

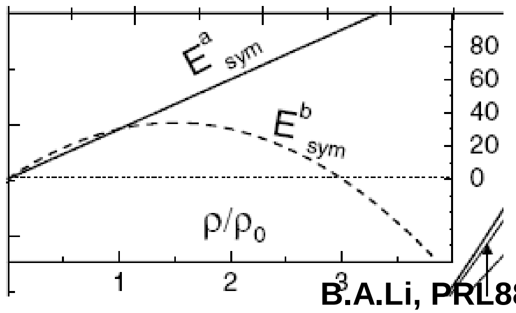
or differential flow

$$\langle p_x^{t\text{-}^3\mathrm{He}}/A\rangle = \frac{1}{N_t + N_{^3\mathrm{He}}}\left(\sum_{i=1}^{N_t} p_x^i/A - \sum_{i=1}^{N_{^3\mathrm{He}}} p_x^i/A\right)$$

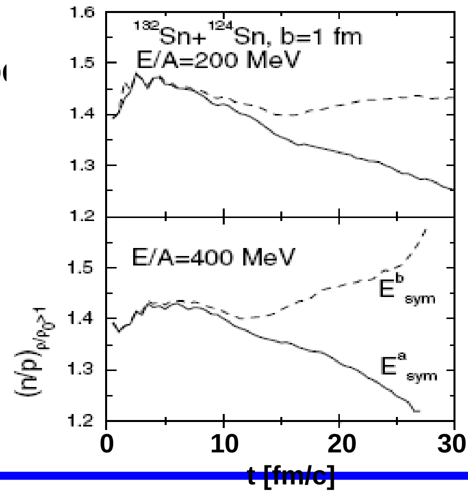
(analogous for v_1, v_2, ..)

$$= \frac{N_t}{N_t + N_{^3\mathrm{He}}}\langle p_x^t/A\rangle - \frac{N_{^3\mathrm{He}}}{N_t + N_{^3\mathrm{He}}}\langle p_x^{^3\mathrm{He}}/A\rangle,$$

Effects in flow complimentary with resp pre-equilibrium emission:



B.A.Li, PRL88(02)



Stiffer SE emits more pre-eq neutrons, thus residual system is less neutron rich

→ Isospin fractionation at high energies

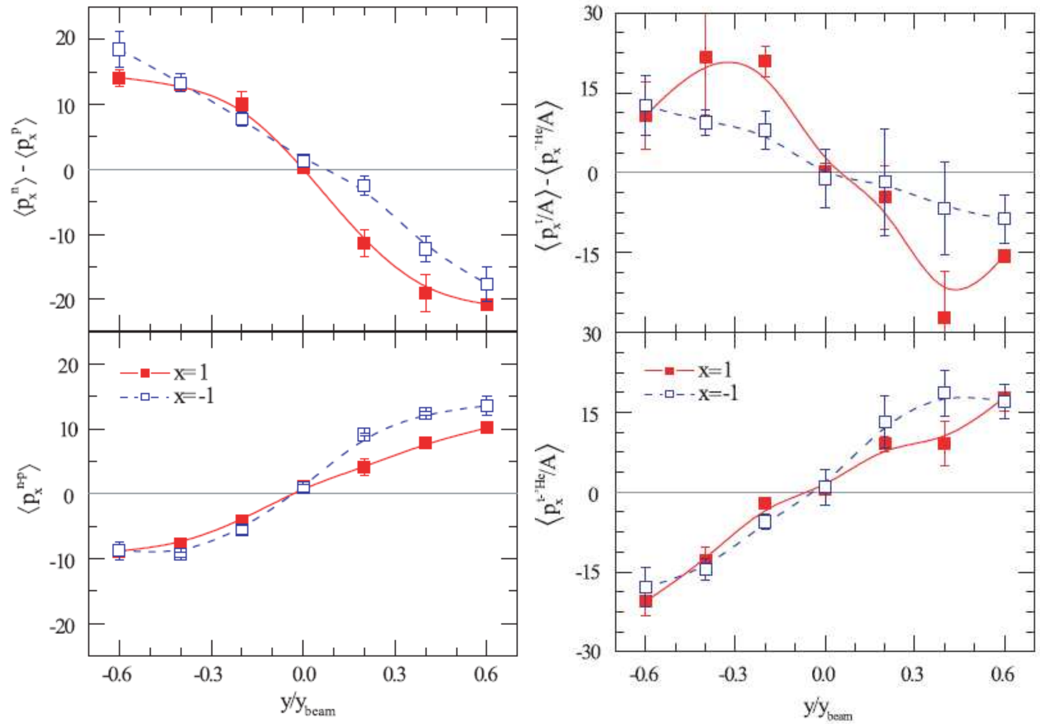
Differential directed and transverse flow

n vs p　　　t vs ^{3}He

difference

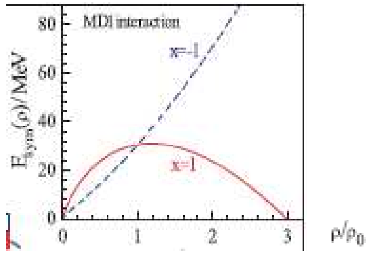
vs

differential flow



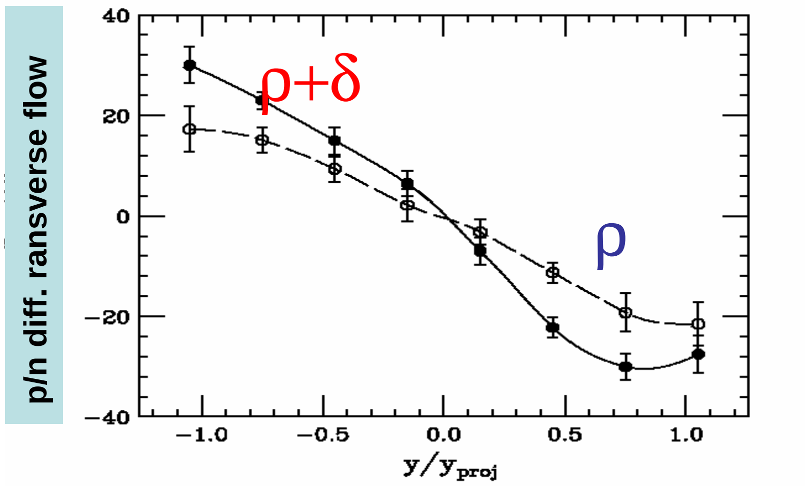
132Sn+124Sn

400 AMeV, b=5fm



Coulomb effects dominate,
→difference flow negative,
more for soft SE

G.C.Yong, et al. PRC80 (09)



132Sn+132Sn, 1.5 AGeV, b=6fm

RMF model for SE, ρ– and δ-meson

$$\frac{d\vec{p}^{\,*}_p}{d\tau} - \frac{d\vec{p}^{\,*}_n}{d\tau} \simeq 2\left[\gamma f_\rho - \frac{f_\delta}{\gamma}\right]\vec{\nabla}\rho_3 = \frac{4}{\rho_B}E^*_{sym}\vec{\nabla}\rho_3$$

Stiffer E_{sym} ⇒ stiffer F_{np}

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

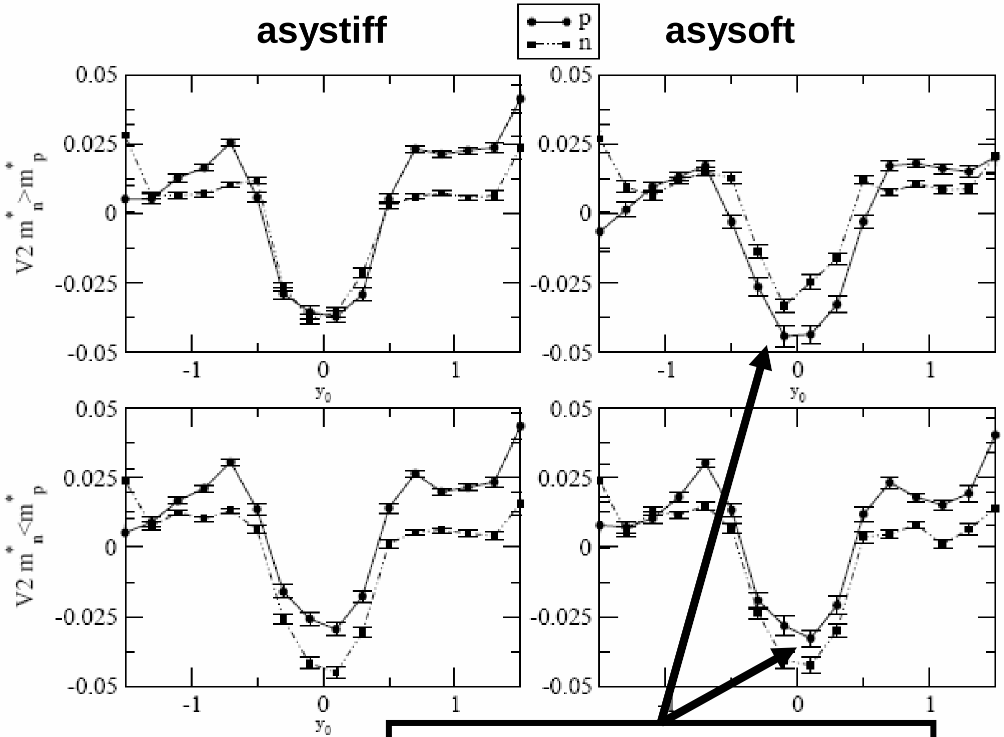
Differential elliptic flow

Au+Au, 400 AMeV

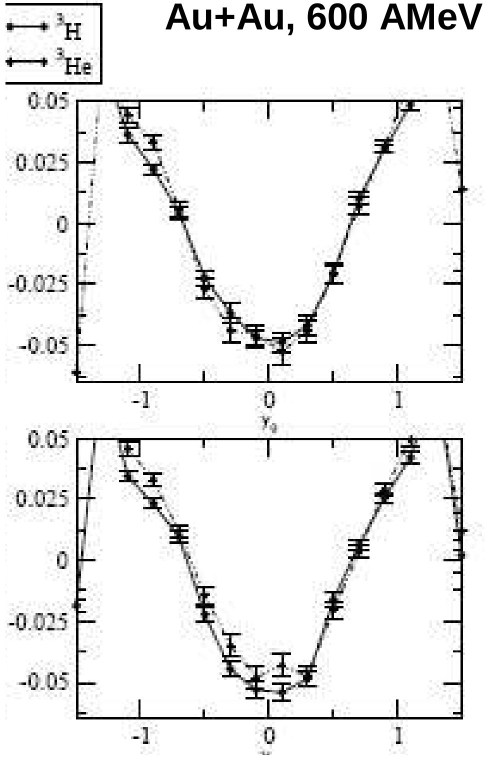
asystiff　　asysoft

$m^*_n > m^*_p$

$m^*_n < m^*_p$



Au+Au, 600 AMeV



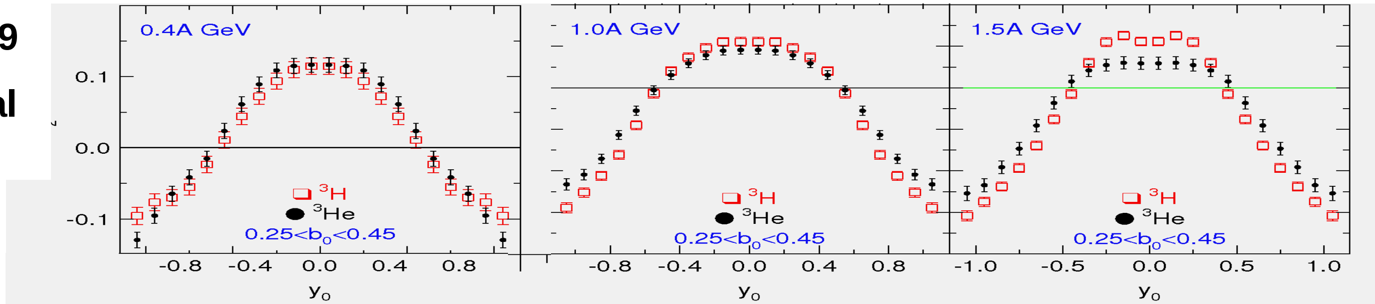
V.Giordano, M.Colonna et al., arXiv 1001.4961, to appear PRC

Inversion of elliptic flows because of inversion of potentials with effective mass

t-^{3}He pair similar but weaker

W. Reisdorf, ECT*, May 09

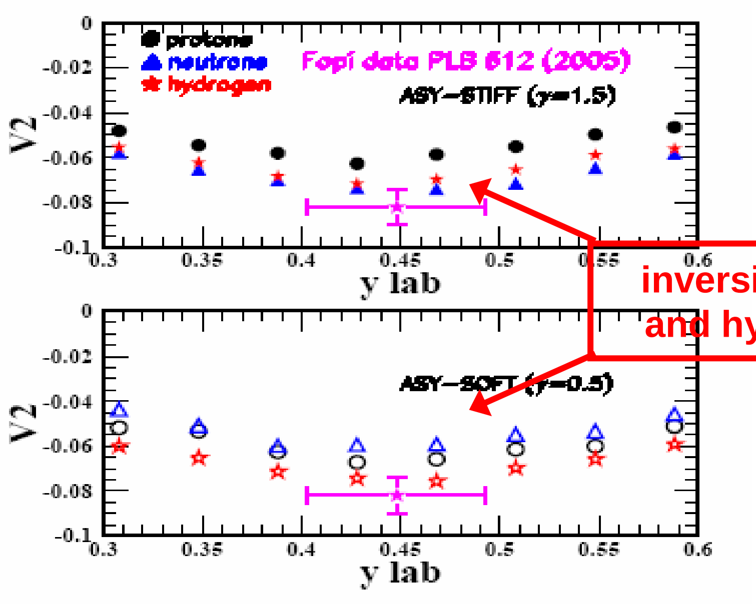
Indication of experimental effect



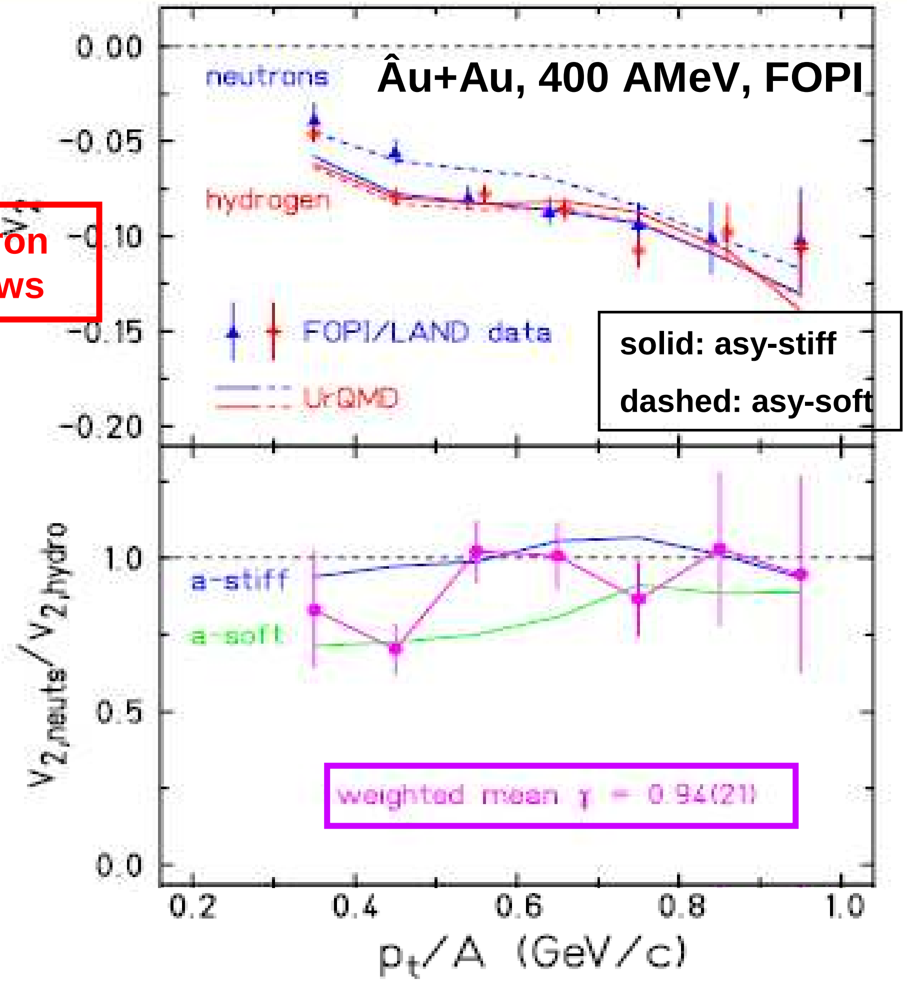
Elliptic flow perhaps more sensitive, since determined by particles that are emitted perp to the beam direction

ASYEOS: Hunting the high density SE with v_2

Early FOPI data (Y. Leifels)



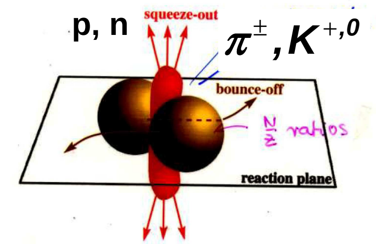
UrQMD calc.
W. Trautmann, …,Q.F. Li, …P. Russotto
PPNP 62 (425)



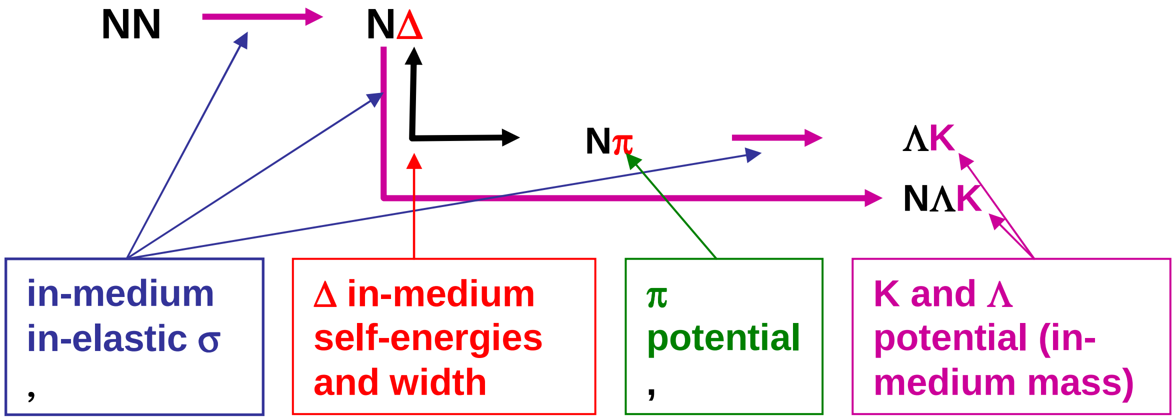
Indication of a asy-stiff Symmetry energy at suprasaturation density

High-density Symmetry Energy: Particle Production

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



1. Mean field effect: U_{sym} more repulsive for neutrons, and more for asystiff

→ pre-equilibrium emission of neutron, reduction of asymmetry of residue

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

2. Threshold effect, in medium effective masses:

→ m^*_N, m^*_Δ, contribution of symmetry energy; m^*_K, models for K-potentials

$$\boxed{\sigma = \sigma\left(s_{in} - s_{th}\right)} \quad \frac{\pi^-}{\pi^+}\uparrow \ \textit{increase with asy-stiffness}$$

s_{thres} independent of isospin, due to simple model of Δ self energies

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

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

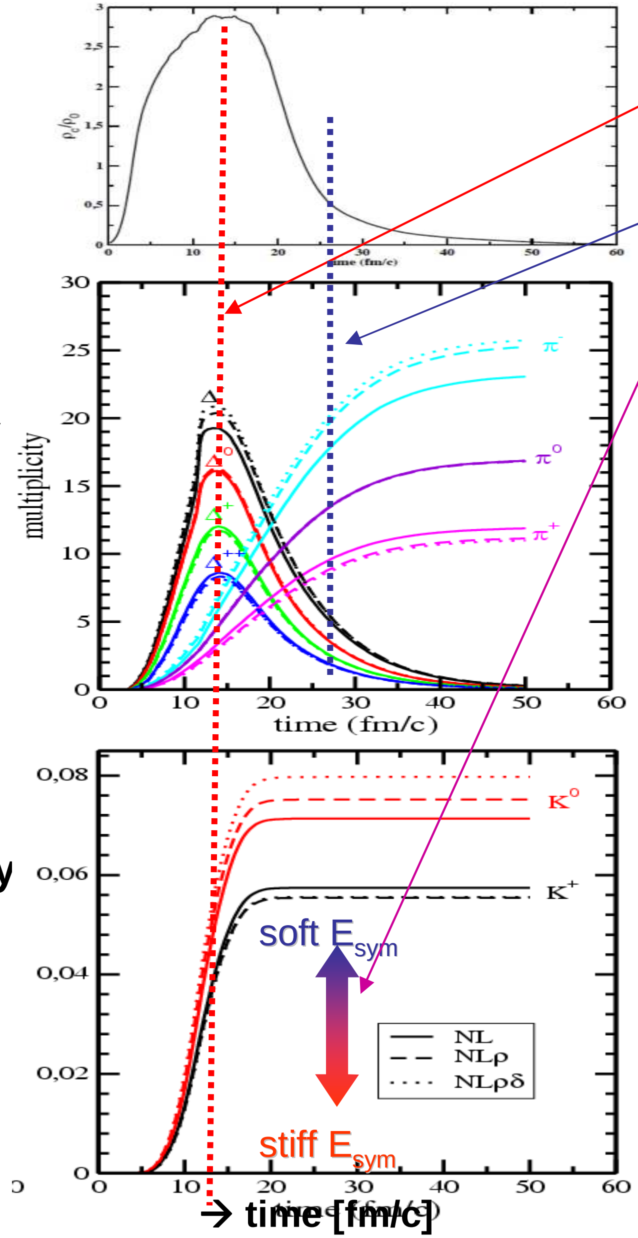
Dynamics of particle production (Δ,π,K) in heavy ion collisions

Au+Au@1AGeV

Central density

π and Δ multiplicity

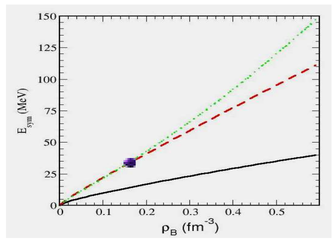
$K^{0,+}$ multiplicity



Δ and K: production in high density phase

Pions: low and high density phase

Sensitivity to asy-stiffness



Dependence of ratios on asy-stiffness

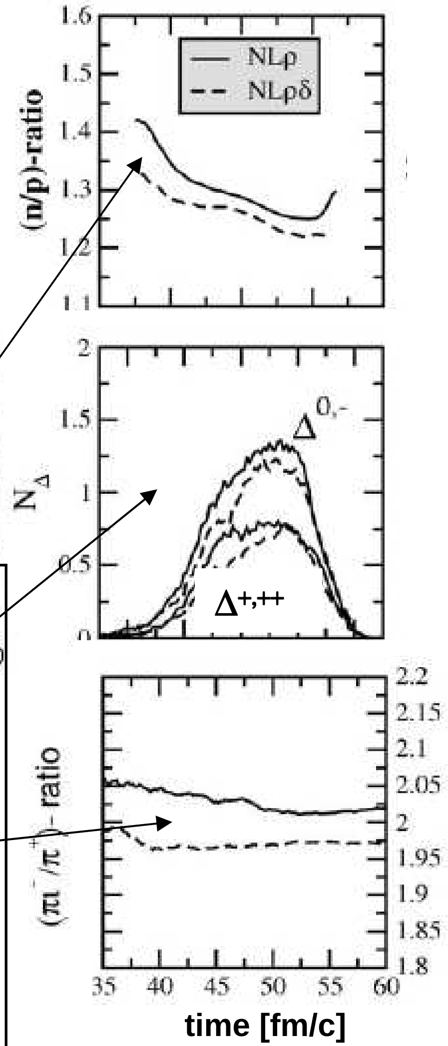
n/p

→$\Delta^{0,-}/\Delta^{+,++}$

→ π^-/π^+

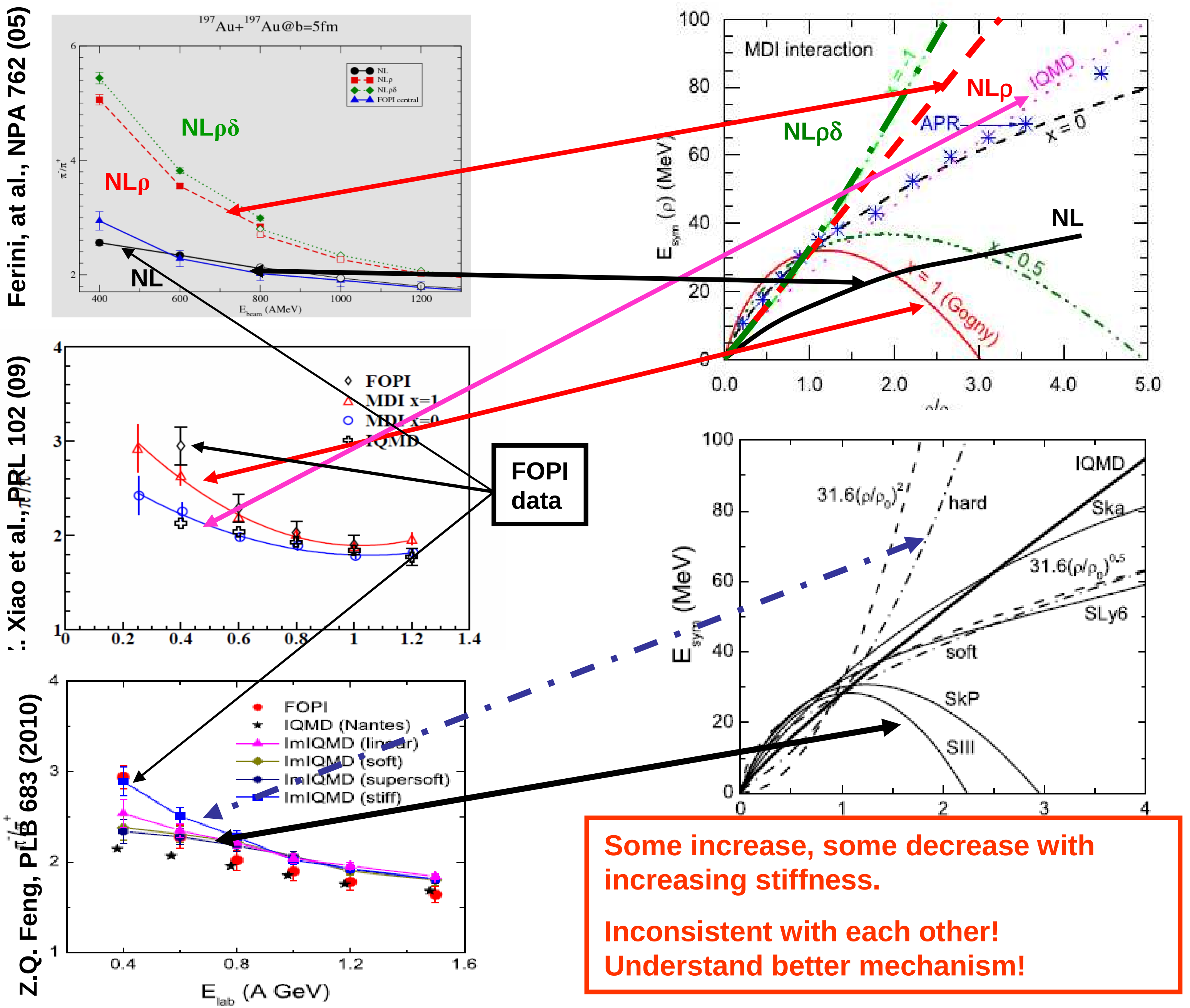
→ n/p ratio governs particle production effects

Au+Au, 0.6AMeV



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

Pion Ratios in Comparison to FOPI data (W.Reisdorf et al. NPA781 (2007) 459)



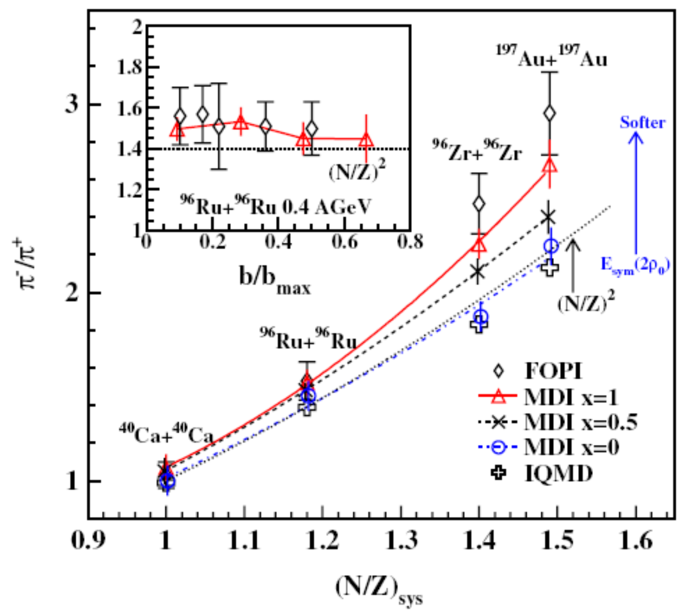
models for symmetry energy (SE)

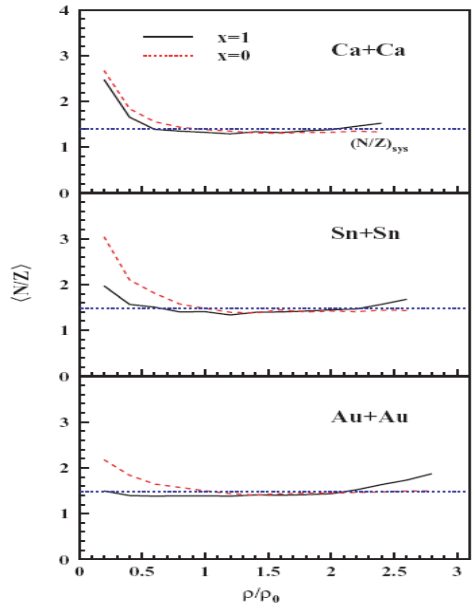
Some increase, some decrease with increasing stiffness.

Inconsistent with each other! Understand better mechanism!

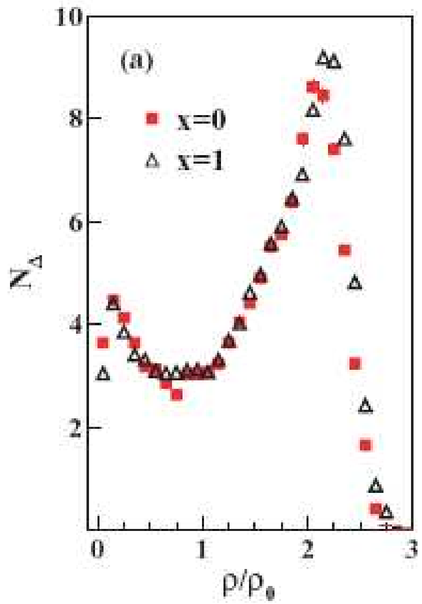
Further study of π^-/π^+ ratio: system dependence

M Zhang, et al., PRC80(2009) and Z. Xiao, PRL102 (09)



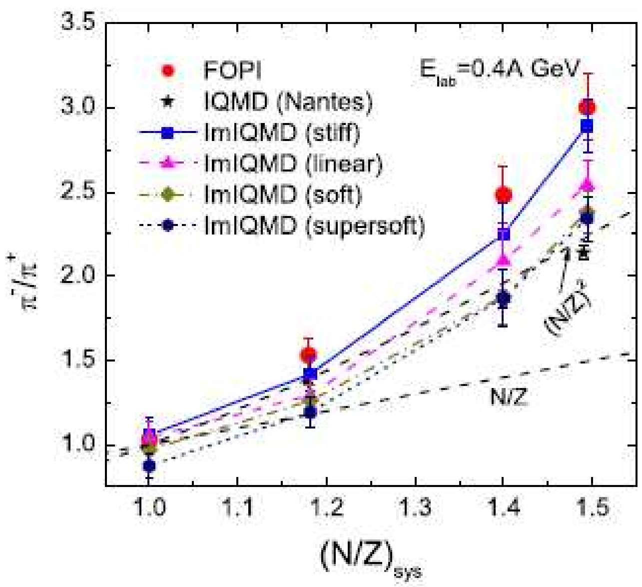


Crossing of <N/Z> ratio with density for different asystiffness (ok!)



Δ mostly produced in high density region except a few first chance collisions (ok!)

Z.Q. Feng at al., PLB 683 (2010)

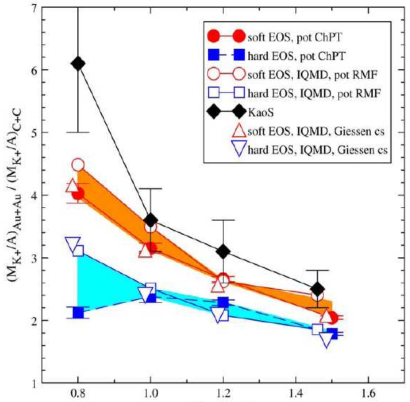


Ratio enhanced relative to isobar model $\sim(N/Z)^2$, due to isospin fractionation
→ medium effect (ok!)

But also contradiction with respect to systen dependence

Δ dynamics has to be checked in detail.

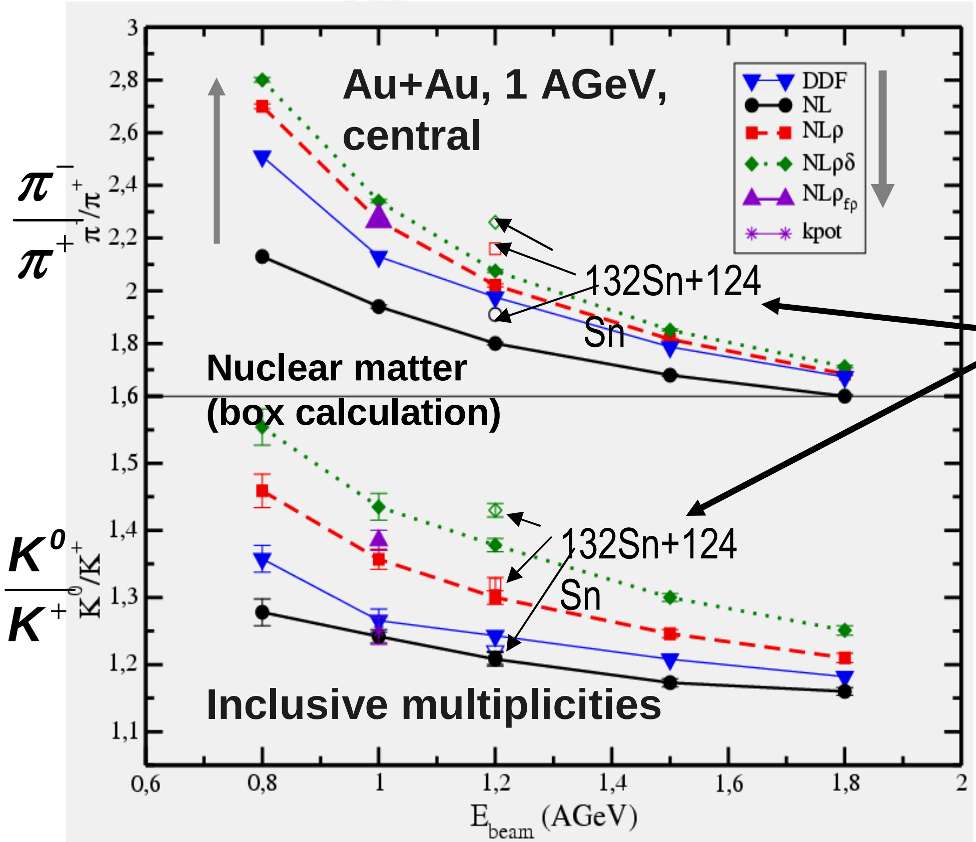
Kaons as a probe for the EOS – also for the Symmetry Energy?



C.M. Ko & J. Aichelin, PRL55(85): Kaons are a <u>more sensitive and clean</u> probe of the high density EOS. Demonstrated by Fuchs, et al., PRL 86 (01), and other groups for symmetric matter in comparison with KAOS data.

Kaons are closer to threshold, come only from high density, have large mean free path, small width:

Also a probe for the symmetry energy for different charge states?



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

From Soft to Stiff from lower to upper curves:
Stiffer iso-EOS→larger ratio!
Opposite to mean field effect!

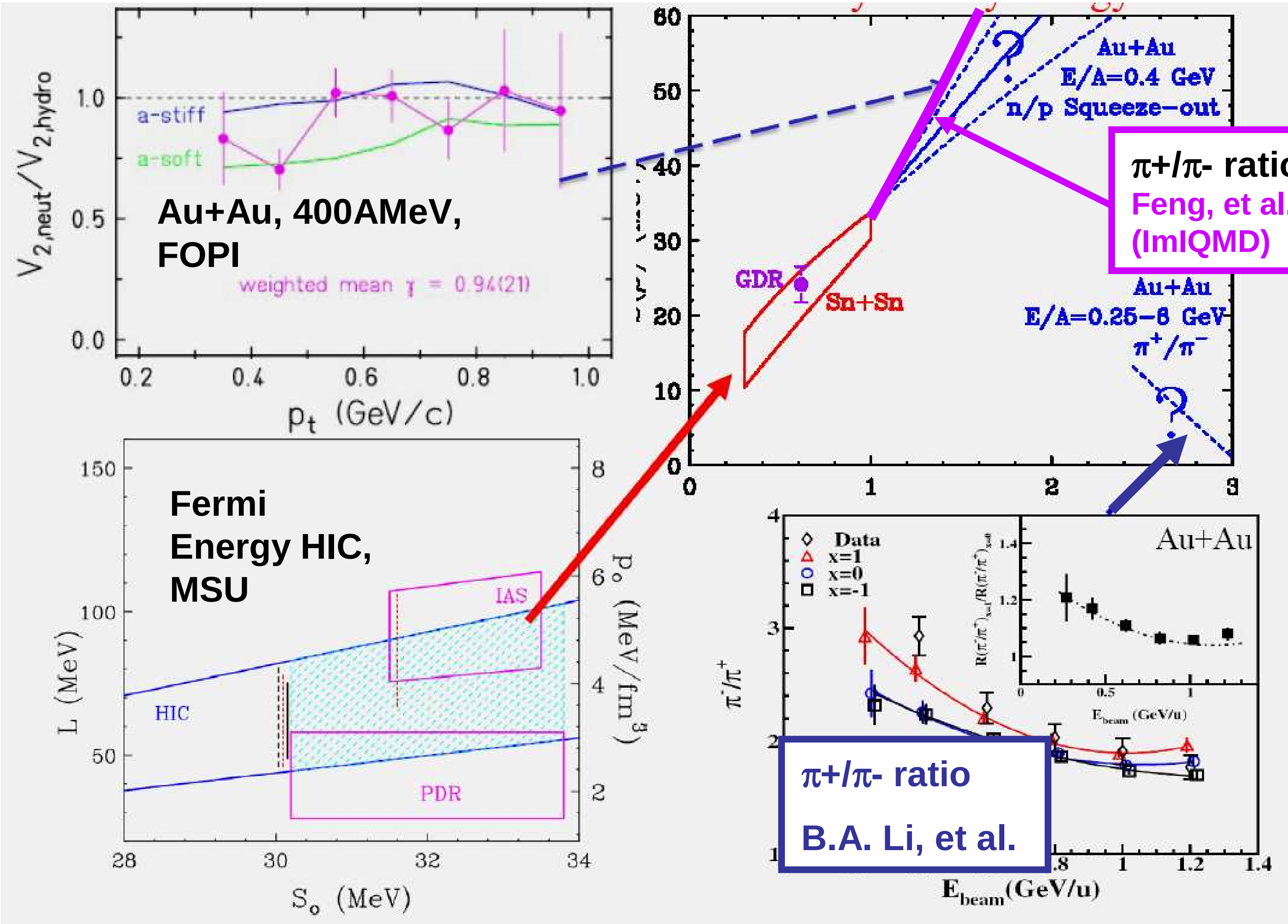
Effect reduced in finite nuclei (pre-equil emission reduces asymmetry)

Kaons ratio still a bit more sensitive probe:
~15% difference betw. very soft and stiff
→ small but perhaps measurable!

Larger effects at lower energies
"Threshold effect" dominant

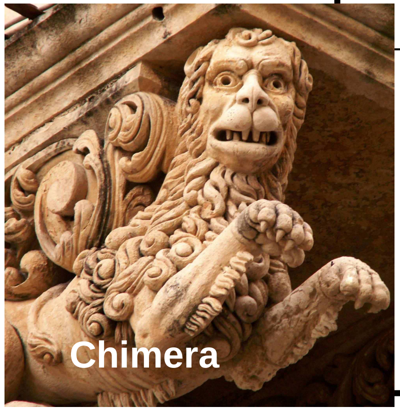
→ Talk by V. Prassa !

Present constraints on the high density symmetry energy



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.
- Constraints come from neutron star observables and from HIC both at subsaturation (Fermi energy regime) and suprasaturation densities (relativistic collisions).
- At subsaturation densities the constraints become increasingly stringent (γ~1),
  but constraints are largely lacking at suprasaturation densities.
- Observables for the suprasaturation symmetry energy
  - N/Z of pre-equilibrium light clusters (no data?)
  - difference flows (first hints -> ASYEOS)
  - part. production rations π^-/π^+ (good data, FOPI)
    K^0/K^+ (first data, HADES?)



To Do:

- exp: more data
- theory: ->accuracy and consistency of transport codes; continue comparison projects
  -> π,Δ dynamics, self energies of Δ more realistic
  -> threshold effects more microscopic

Special thanks to my collaborators:

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Theo Gaitanos, Univ. of Giessen

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Thank you for attention!

Villa Romana del Tellaro (near Noto)