The Density Dependence of the Symmetry Energy from Heavy Ion Collisions

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TUM LMU Excellence Cluster Universe

MLL

Int. Symposium „Advancves of Nuclear Many-Body Theory“ in honor of Peter Ring‘s 70th birthday

Primosten, Croatia, June 7-10, 2011

Peter Ring and I have been together in Munich for many years, even though at competing universities.

Many thanks for sympathy and encouragement

Some recent pictures.

Points to discuss

I. Density (and momentum) dependence of the nuclear Symmetry Energy (SE); uncertainties, importance, astrophysics

II. Situation from many-body theory, particularly in the RMF theory

III. Study of Symmetry Energy in heavy ion collisions,
choice of asymmetry and density regime.
theoretical tool: transport theory

IV. Discuss specific examples:
$< \rho_0$, isospin transport, Fermi energies
$> \rho_0$ momentum distributions („flow“), meson production

V: What do we know?

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

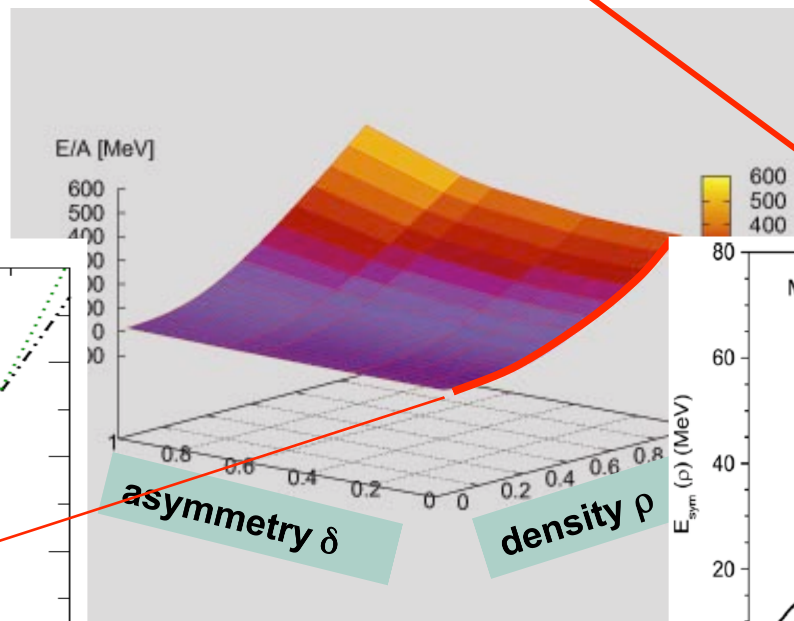
Equation-of-State and Symmetry Energy

symmetry energy

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

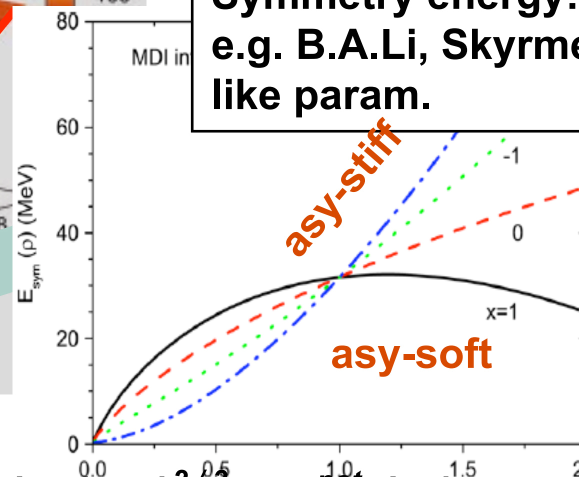
density-asymmetry dep. of nucl.matt.
$$E(\rho_B,\delta)/A = E_{nm}(\rho_B) + E_{sym}(\rho_B)\delta^2 + O(\delta^4) + \ldots \qquad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$a_S = E_{sym}(\rho_0)$$

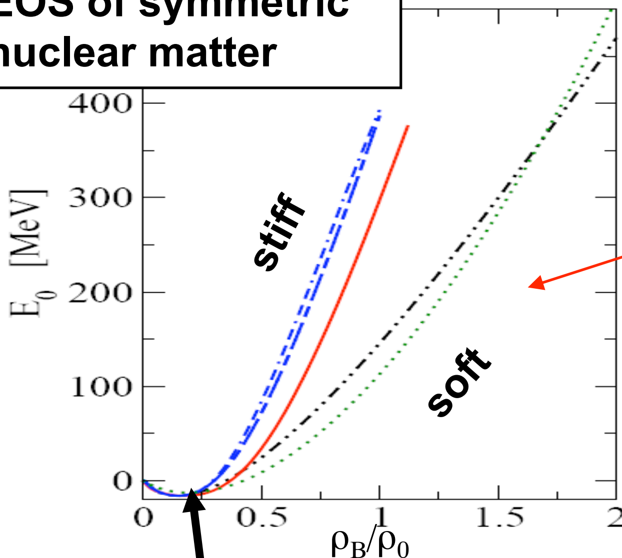


rather unknown

Symmetry energy: e.g. B.A.Li, Skyrme-like param.



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 :

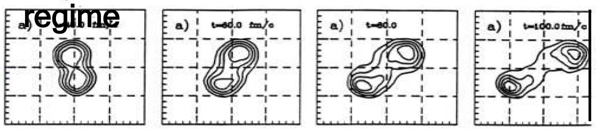
$$E_{sym}(\rho) = J + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

Importance of Nuclear Symmetry Energy

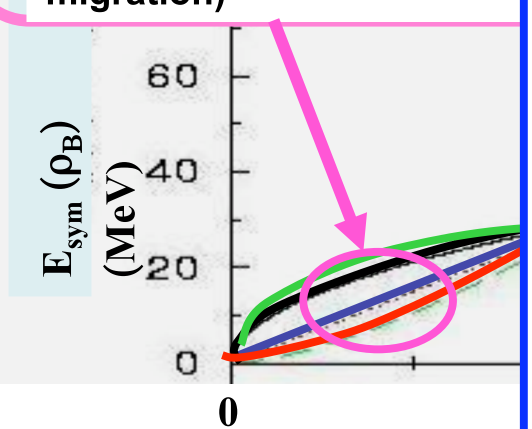
$$E(\rho_B, I)/A = E(\rho_B) + E_{sym}(\rho_B) I^2 + O(I^4) + \ldots$$

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

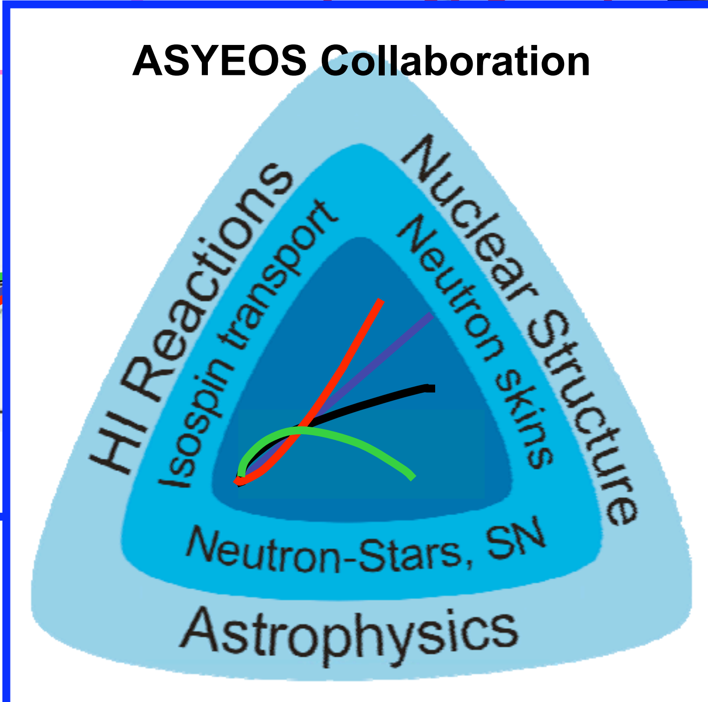
heavy ion collisions in the Fermi energy regime



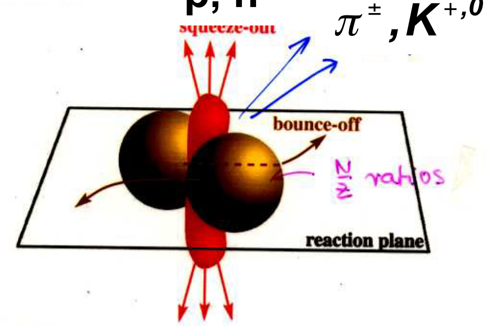
Isospin Transport properties, (Multi-)fragmentation (diffusion, fractionation, migration)



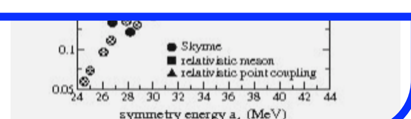
supernovae, neutron stars)



rel. Heavy ion collisions



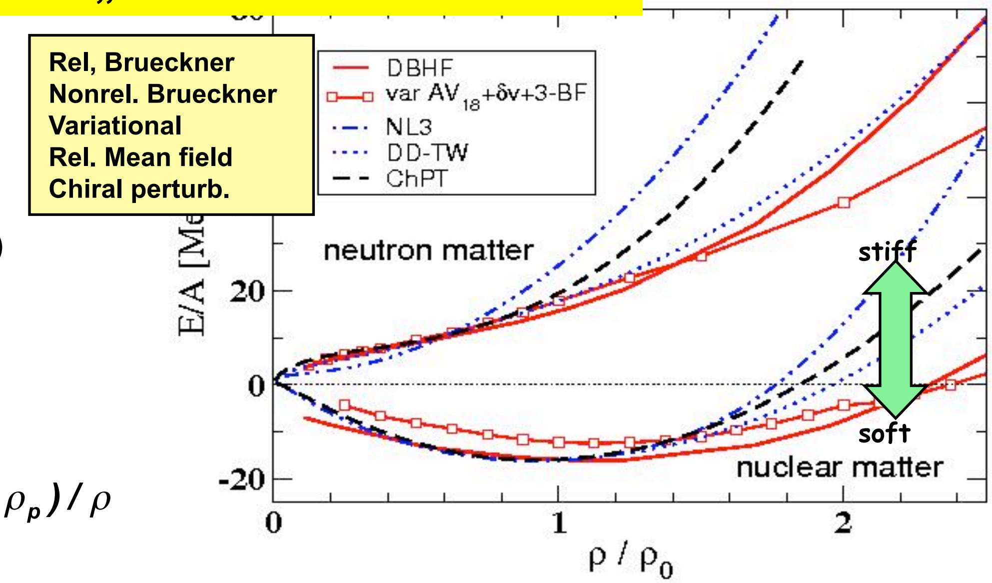
Nuclear structure (neutron skin thickness, Pygmy DR, IAS)
Slope of Symm Energy



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)

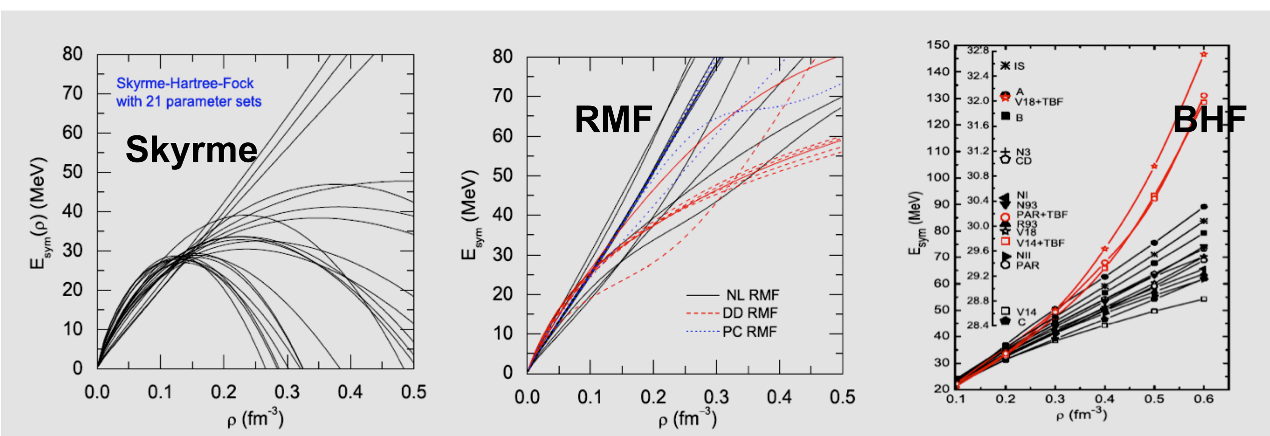


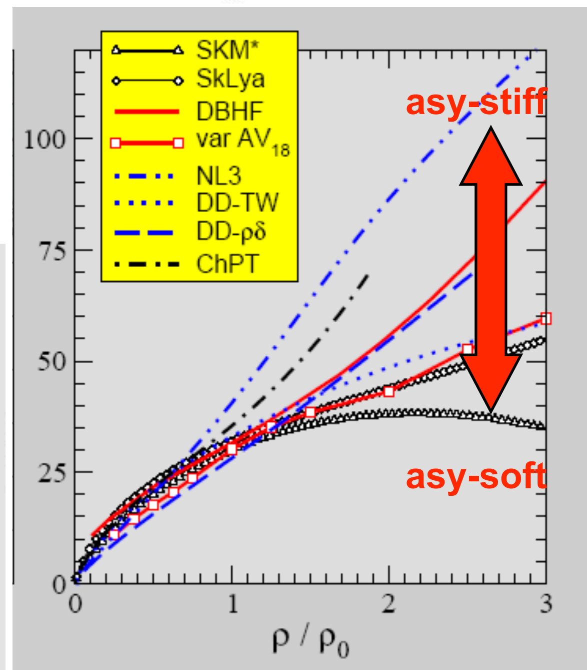
The symmetry energy as the difference between symmetric and neutron matter:

$$E(\rho,\delta) = E(\rho) + E_{sym}(\rho)\delta^2 + ...; \quad \delta = (\rho_n - \rho_p)/\rho$$

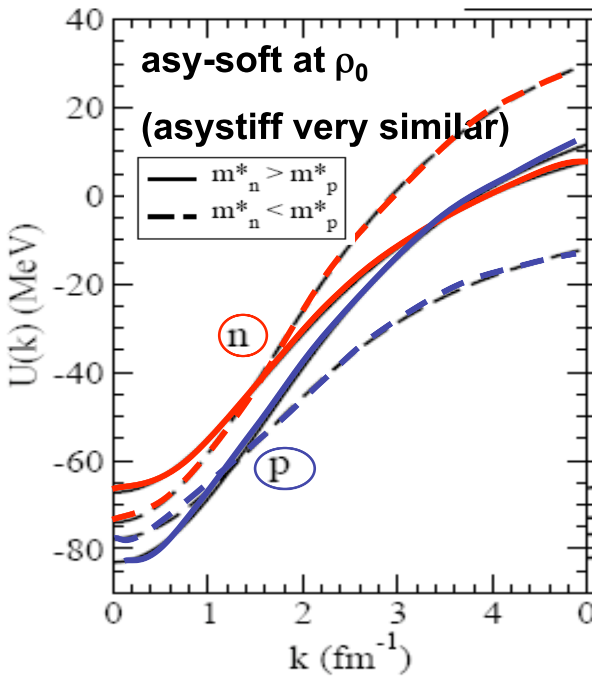
$$E_{sym} = E_{neutr.matt} - E_{nucl.matt}$$

many more in: B.A. Li et al., Phys. Rep. 464 (2008)





Momentum Dependence of the Symmetry Energy



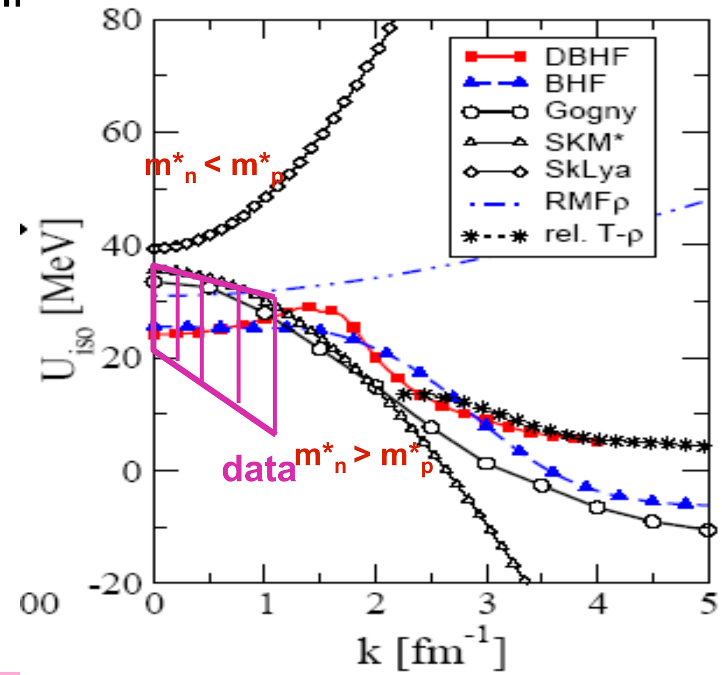
$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$$

Different proton/ neutron effective masses

-> crossing around Fermi momentun

Isovector (Lane) potential: momentum dependence

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

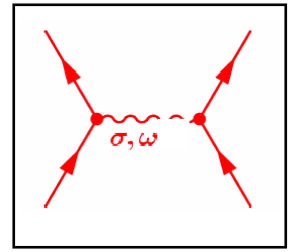


Why is symmetry energy so uncertain??
->In-medium ρ mass, and short range tensor correlations (B.A. Li, PRC81 (2010));
-> effective mass scaling (Dong, Kuo, Machleidt, arxiv 1101.1910)

Hadronic field theory → Quantenhadrodynamics (QHD)

σω-model: however, not sufficient for nuclear matter properties:

extensions neccesary; many choices



$$L = \overline{\Psi}\left[i\gamma_\mu \left(\partial^\mu + i g_\omega \omega^\mu \qquad \right) - \left(m - g_\sigma \sigma \qquad \right) \right] \Psi + L^{mes}$$

Full Lorentz structure:

	isoscalar	isovector
scalar	σ	δ
vector	ω	ρ

isovector mesons: symmetry energy

V. Greco, et al., PLB562(03)215

non-linear meson self-interactions

Boguta,Bodmer,NPA292(77)413

$$L_\sigma^{mes} = \frac{1}{2}\left(\partial^\mu \sigma \, \partial_\mu \sigma - m_\sigma^2 \right) - \frac{b_3}{3}\sigma^3 - \frac{b_4}{4}\sigma^4$$

density dependent coupling vertices

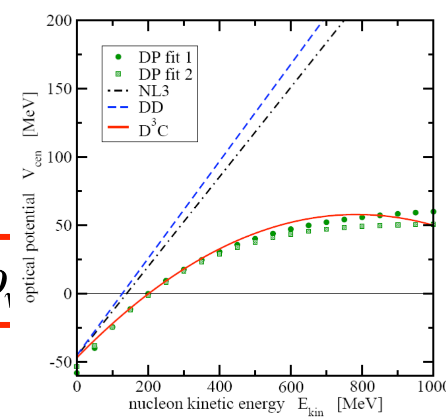
Fuchs,Lenske,Wolter, PRC52(95)3043

$$\Gamma_\omega(\hat{\rho}) \qquad \Gamma_\rho(\hat{\rho})$$

density dependent derivative coupling (D3C)

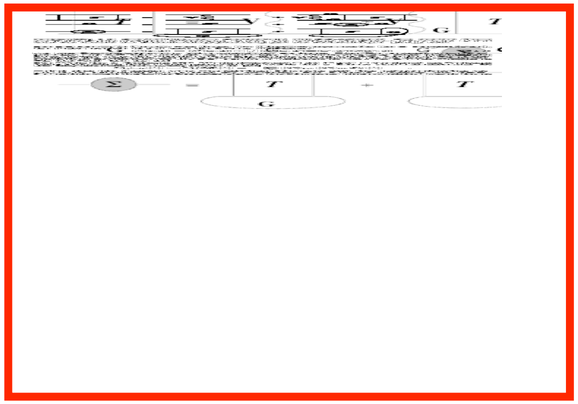
Typel,PRC71(05)064301

$$\Gamma_\mu = \gamma^\nu \left(g_{\nu\mu} + Y(\omega_{\cdots}\right.$$

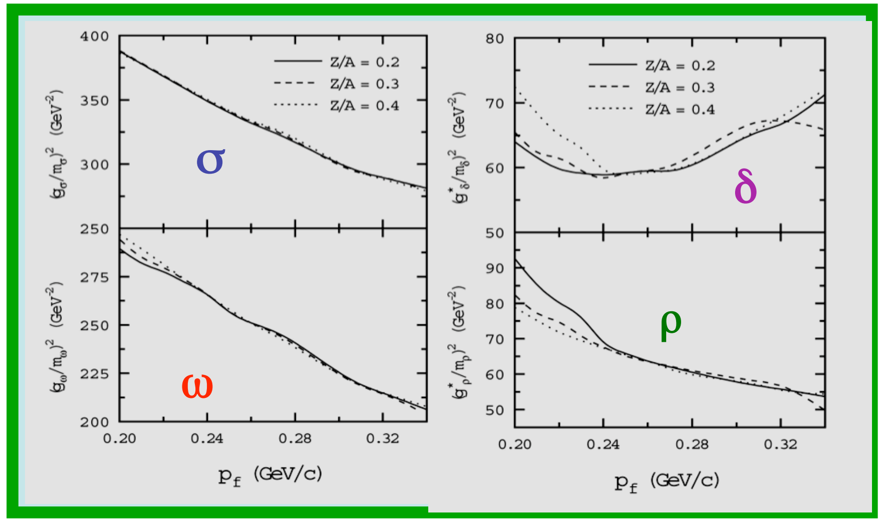


Justification for contribution of δ−meson: a_0(980,S=1,I=1) very heavy!

Dirac-Brueckner (DB)

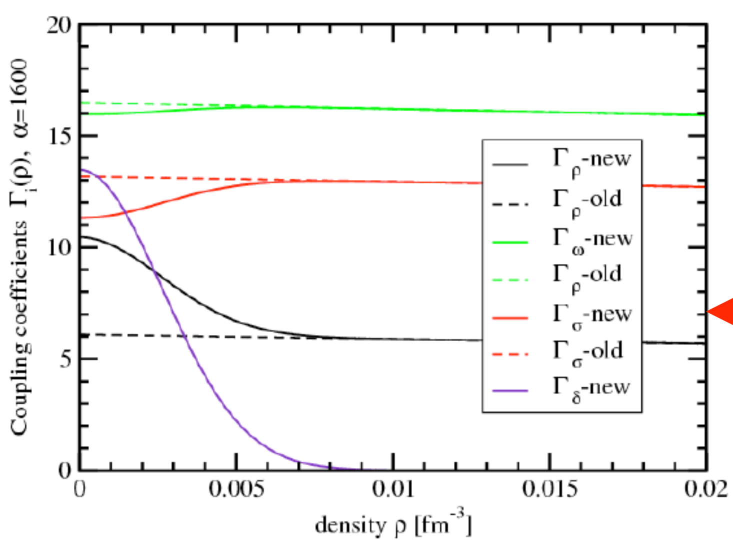


deJong, Lenske, PRC58(98)890



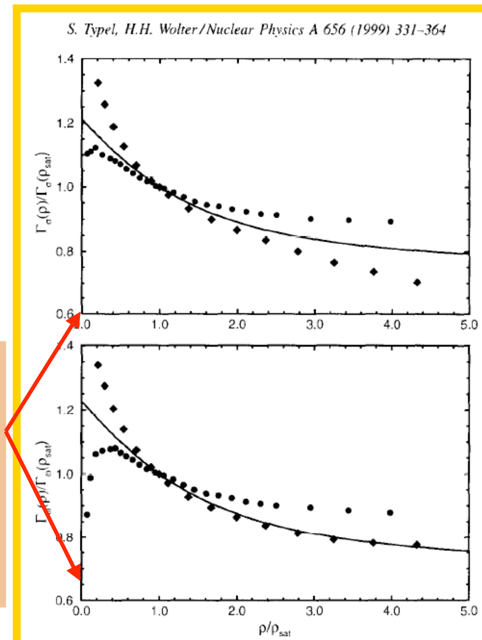
Decomposition of DB self energy

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



empirical fit of coupling coefficients (solid line)

Typel,Wolter NPA656(99)



Additional constraint at ρ=0 from free NN scattering (Voskresenskaya, Typel)

δ meson necessary!

Dynamic effects of δ–meson:

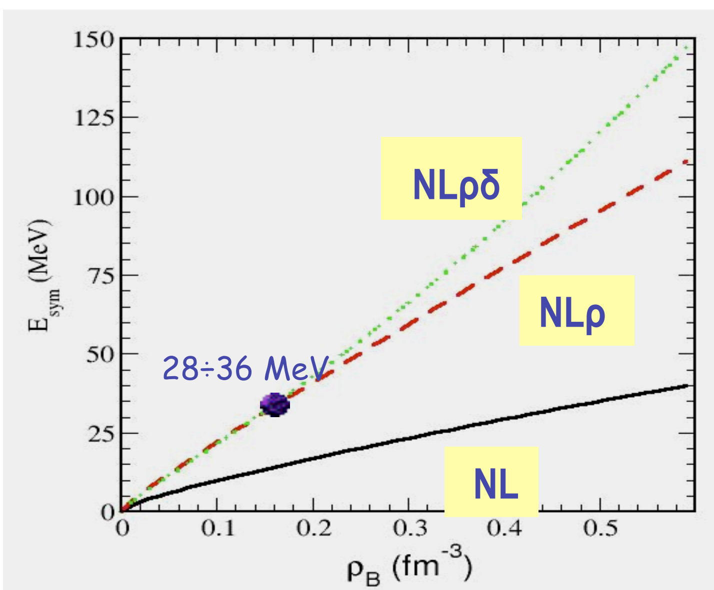
	isoscalar	isovector
scalar	σ	δ
vector	ω	ρ

A cancellation between scalar and the isovector sector, similarly as for the isoscalar vector parts in potential

$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^{*2}} + \frac{1}{2}\left[f_\rho - f_\delta \left(\frac{M^*}{E^*} \right)^2 \right] \rho_B$$

No δ → $f_\rho \cong 1.5\, f_\rho^{FREE}$ **NLρ**

$f_\delta = 2.5\ fm^2$ → $f_\rho \cong 5 f_\rho^{FREE}$ **NLρδ**



Liu, Greco, et al., PRC65(02)045201

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**

2. $\rho<\rho_0$: **Isospin transport in Fermi energy central and peripheral collisions, (multi-)fragmentation,**

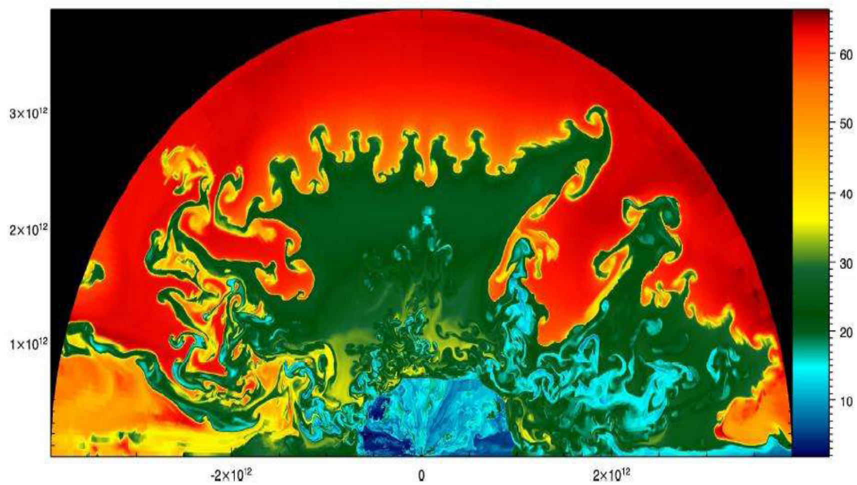
3. $\rho\sim\rho_0$: **structure and low energy excitations of (asymmetric) nuclei: skin thickness, Pygmy resonances, IAS,**

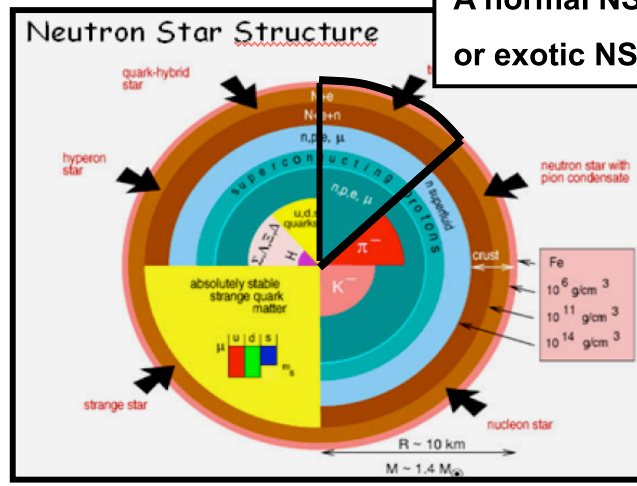
4. $\rho>\rho_0$: **Relativistic heavy ion collisions: light cluster emission, flow and particle production,**

5. $\rho>>\rho_0$: **Ultrarelativistic HI collisions, Dependence of mixed and deconfinement phase on asymmetry?**

mainly discuss these

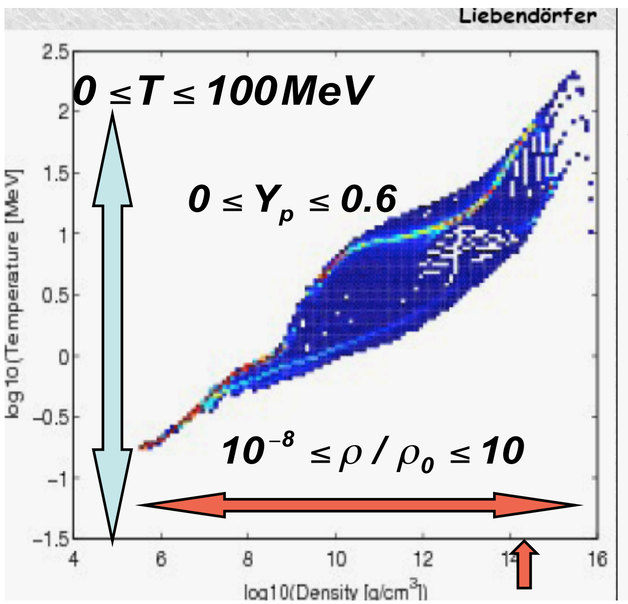
Astrophysics: Supernovae and neutron stars



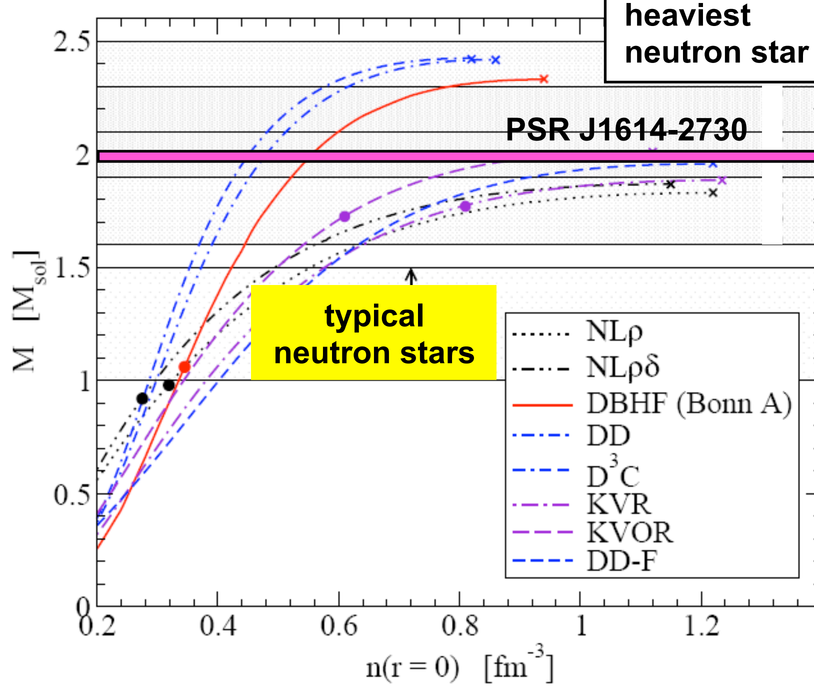


A normal NS (n,p,e)

or exotic NS?

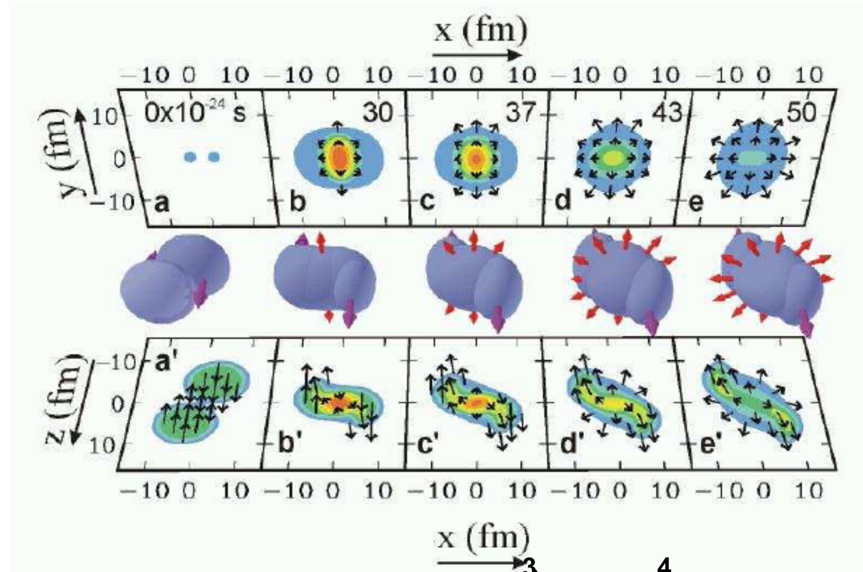


Supernova evolution: range of densities and temperatures and asymmetries:



Determination of nuclear SE in heavy ion collisions

→ Transport theory



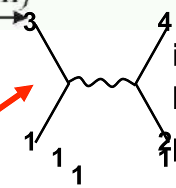
central quantitiy:
1-body phase space distribution f(r,p,t)
Wigner transform of one-body density

→equation of motion in semiclass. approx: Vlasov equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\vec{\nabla}^{(r)} f - \vec{\nabla}^{(r)} U(r)\, \vec{\nabla}^{(p)} f = 0$$

EOS

isoscalar and isovector (~10%)



isospin dependent, pp,nn,pn

In-medium!!!

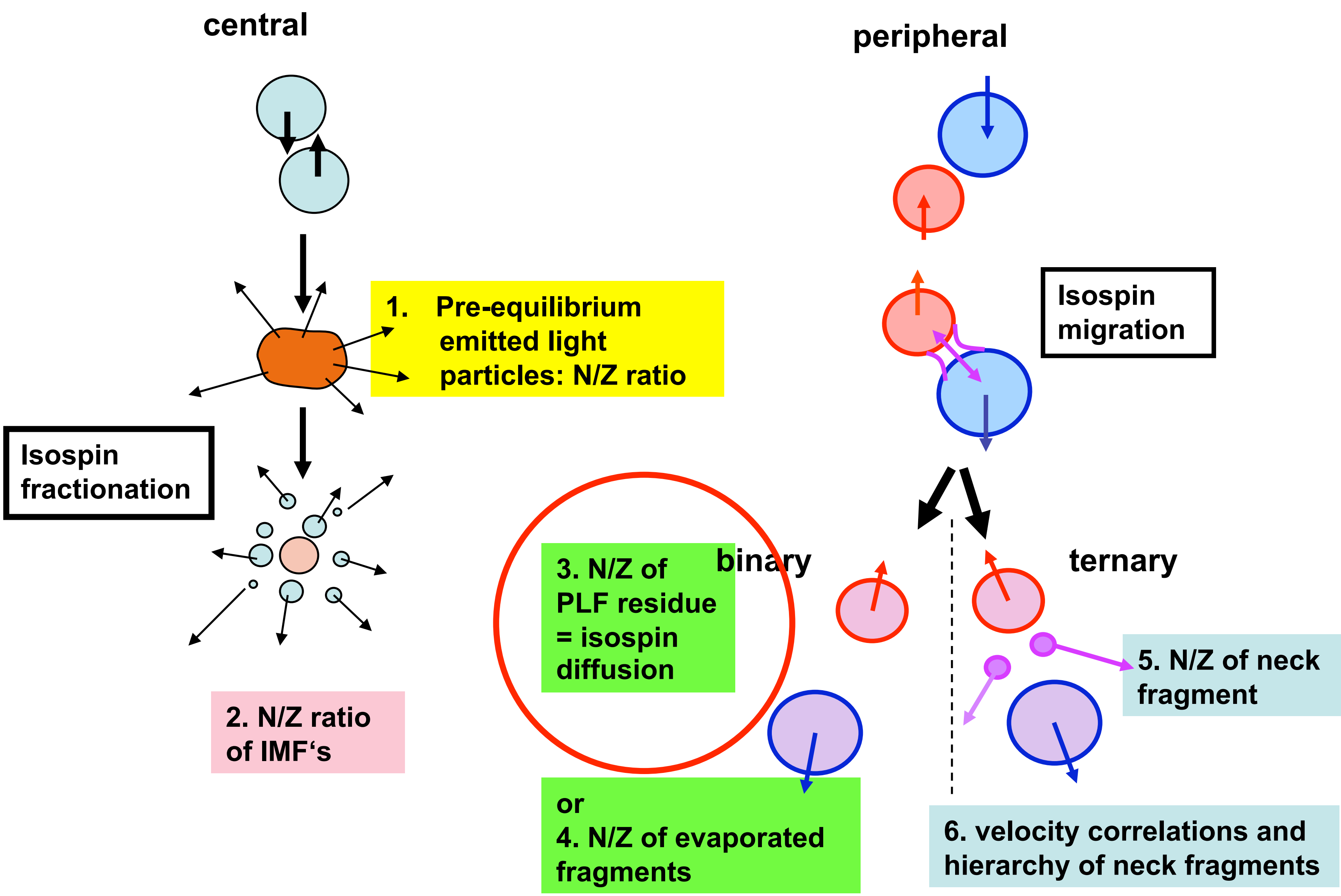
$$I_{coll} = \int d\vec{v}_2\, d\vec{v}_{1'} d\vec{v}_{2'} v_{12}\, \sigma(\Omega)\, (2\pi)^3 \delta(p_1 + p_2 - p_{1'} - p_{2'}) \times \left[f_{1'} f_{2'} (1-f_1)(1-f_2) - f_1 f_2 (1-f_{1'})(1-f_2') \right]$$

2-body collisions | gain term | loss term

Boltzmann-Ühling-Uhlenbeck, Landau-Vlasov

1) Approximation to a much more complicated non-equilibrium quantum transport equation (Kadanoff-Baym) by neglecting finite width of particles (quasi-particle approximation)
2) Coupled transport eqs. for neutrons and protons
3) Isovector effects are small relative to isoscalar quantities
4) Relativistic transport equations: RMF models
5) Inelastic collisions (particle production; mesons π,K)

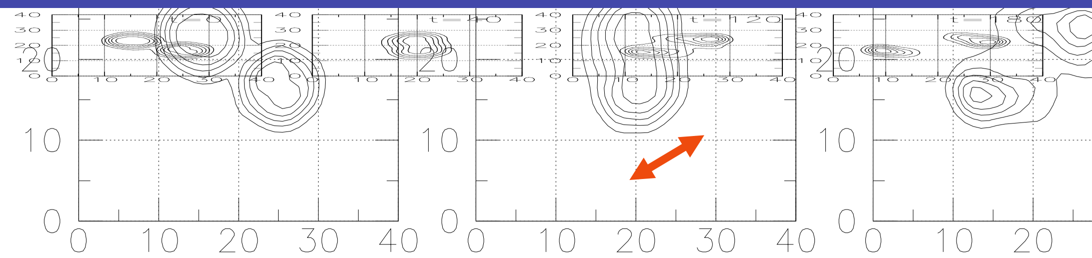
Isospin Effects in the Fermi energy domain



Isopin transport

isospin transport through „neck“ in peripheral collisions

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

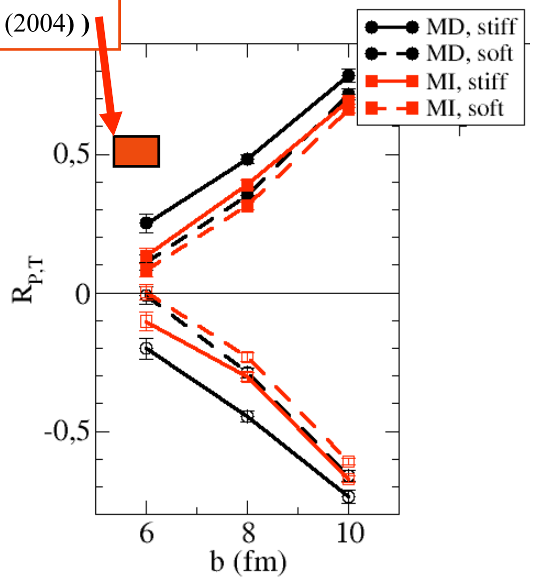


Imbalance (or Rami, transport) ratio:
β asymmetry of residue (i=PLF,TLF)
(also for other isospin sens.quantities)

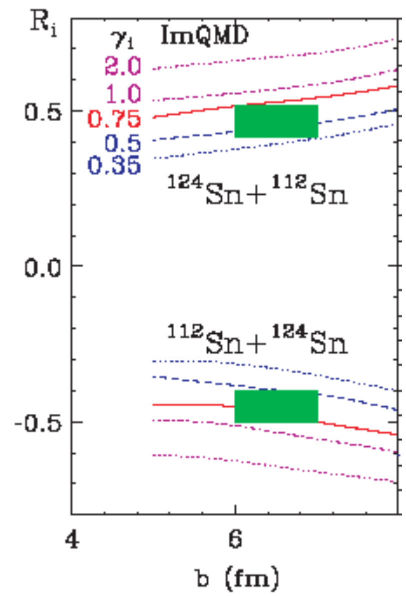
$$R_i = \frac{\beta_i^{mix} - \frac{1}{2}(\beta_i^{HH} + \beta_i^{LL})}{\frac{1}{2}(\beta_i^{HH} - \beta_i^{LL})}$$

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

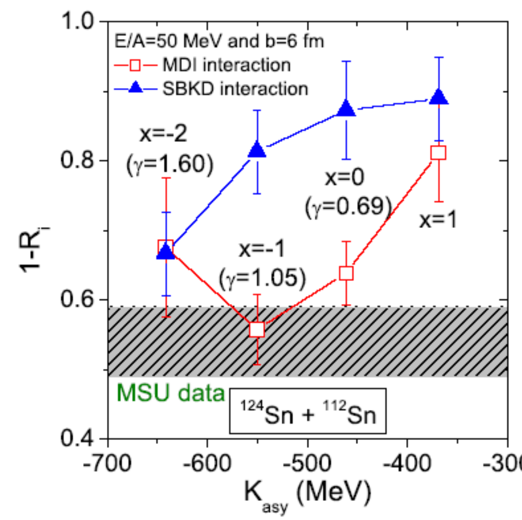
experimental data
(B. Tsang et al.
PRL 92 (2004))



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



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



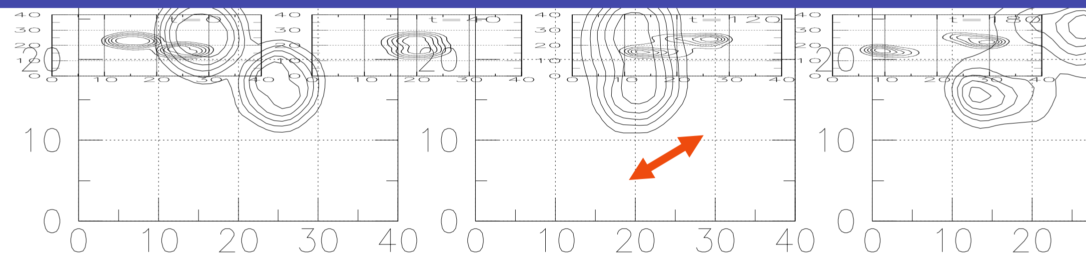
L.W.Chen, C.M.Ko, B.A.Li, PRL 94, 032701 (2005)

points toward a moderately stiff (γ~1) SE, but disagreement in detail

Isopin transport

isospin transport through „neck“ in peripheral collisions

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



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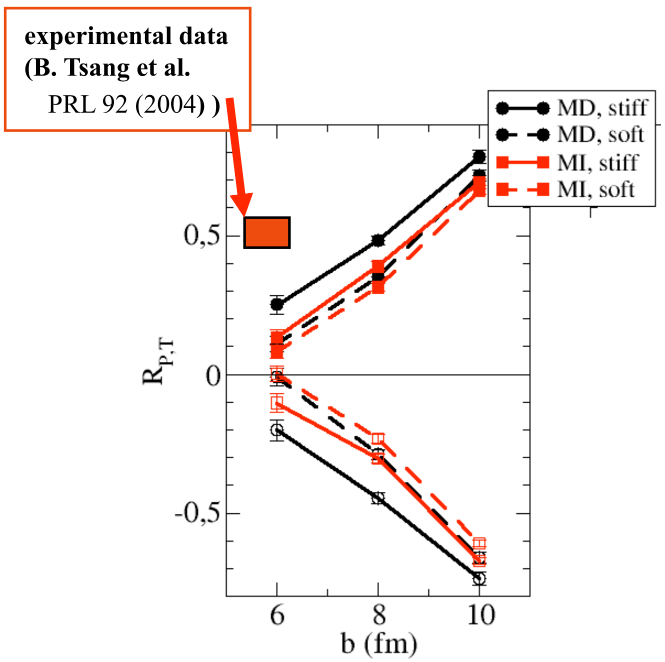
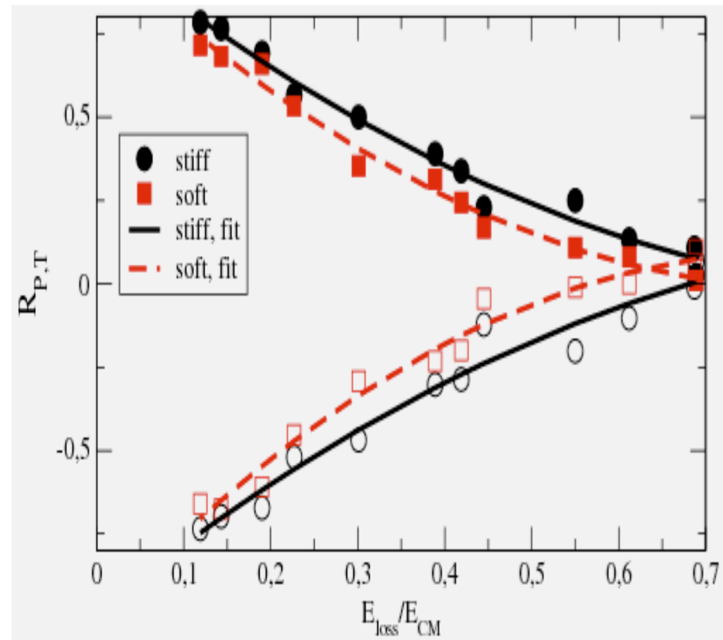


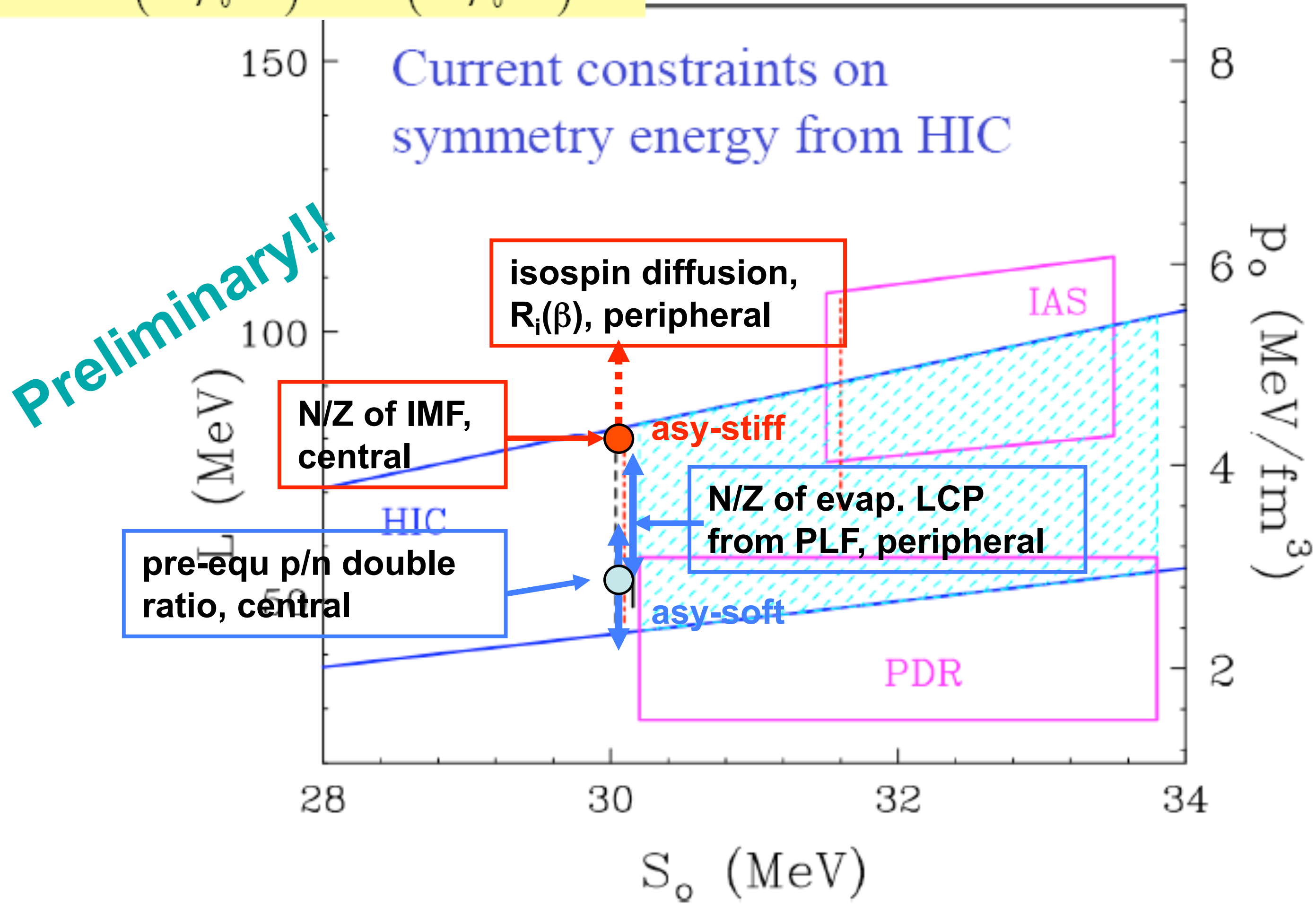
J.Rizzo, et al., Nucl. Phys. A806 (2008) 79



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

Comparison to contraints from MSU (Contribution of B. Tsang)

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



Current state of knowledge:

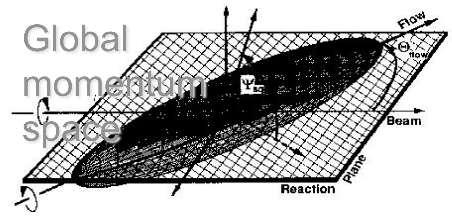
Generally consistent with each other , but still rather uncertain. More work necessary, especially also on consistency of codes

Heavy Ion Collisions at Relativistic Energies: "Flow"

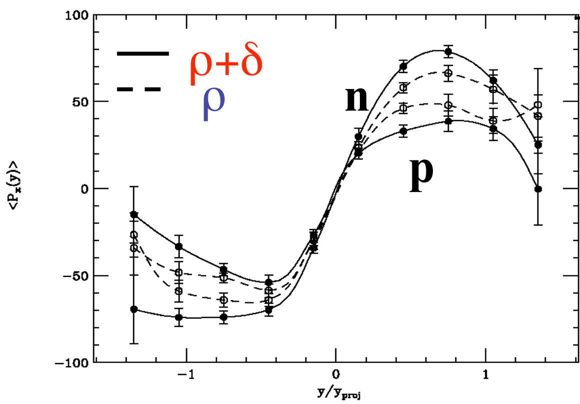
Fourier analysis of momentum tensor : „flow"

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

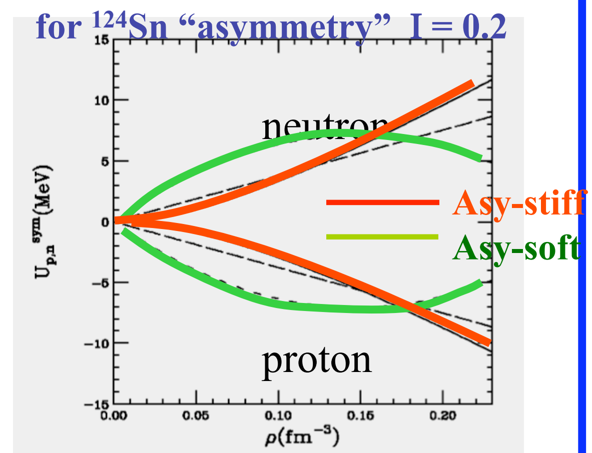
v_1: sideward flow | v_2: elliptic flow



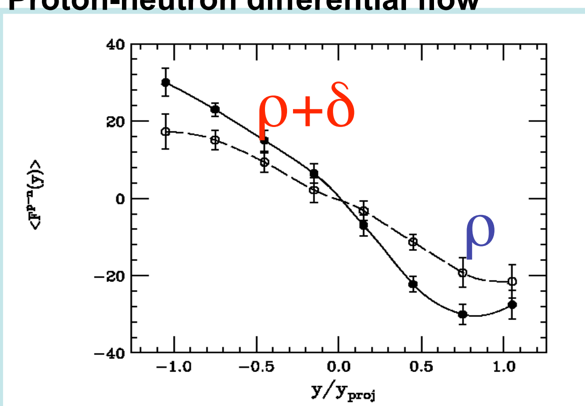
$^{132}Sn + {}^{132}Sn$ @ 1.5 AGeV b=6fm



Proton/neutron potentials



Proton-neutron differential flow



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

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

- **dynamical boosting of vector contribution**

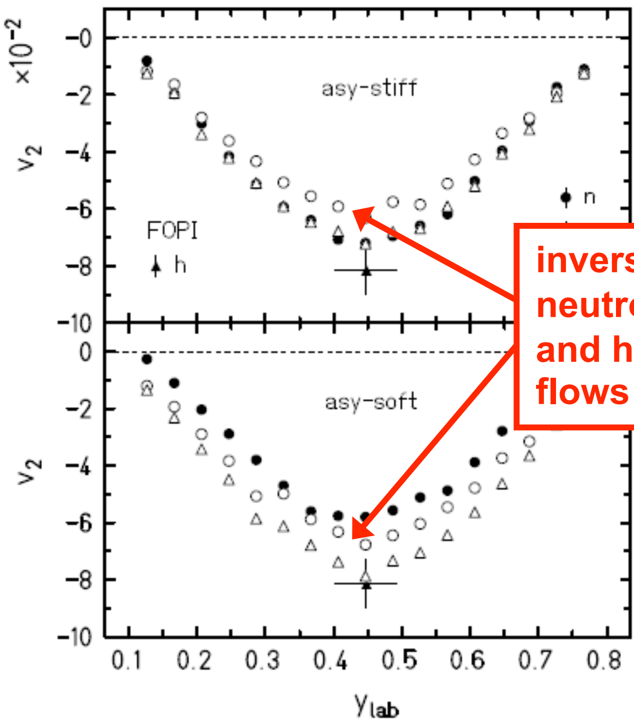
$$\frac{d\vec{p}^{\,*}_p}{d\tau} - \frac{d\vec{p}^{\,*}_n}{d\tau} \simeq 2\left[\gamma f_\rho - \frac{f_\delta}{\gamma}\right]\vec{\nabla}\rho_3 = \frac{4}{\rho_B}E^*_{sym}\vec{\nabla}\rho_3$$

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

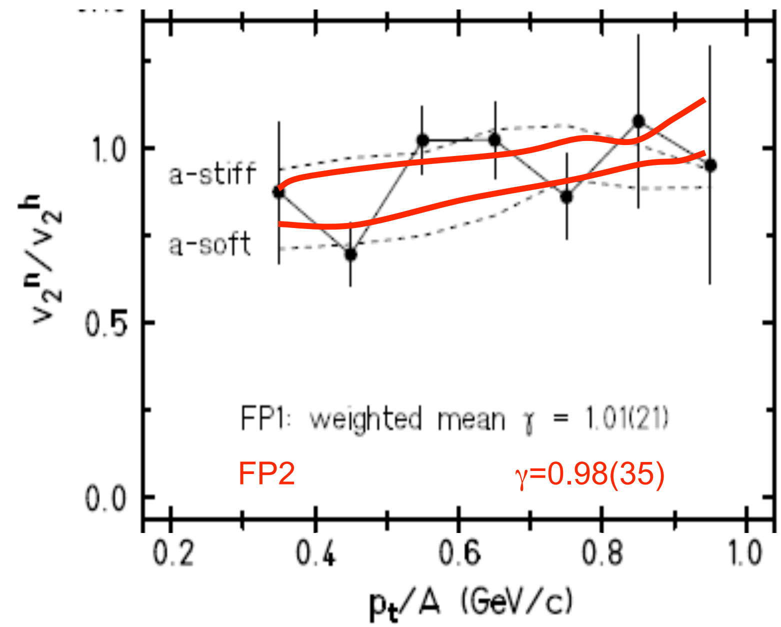
and analogously for elliptic flow

ASY-EOS: Hunting the high density symmetry energy with v_2

Russotto, et al., PLB 697, 471 (2011)



inversion of neutron and hydrogen flows



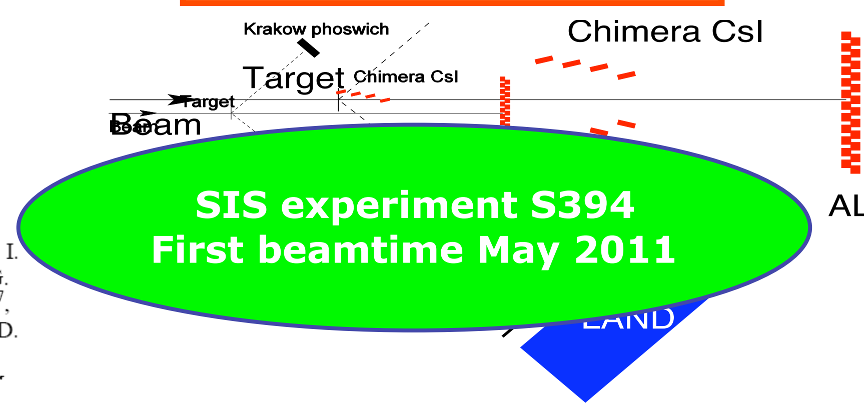
Indication of an asy-stiff symmetry energy at suprasaturation density

Constraining the Symmetry Energy at Supra-Saturation Densities With Measurements of Neutron and Proton Elliptic Flows

Co-Spokespersons: R.C. Lemmon[1] and P. Russotto[2]

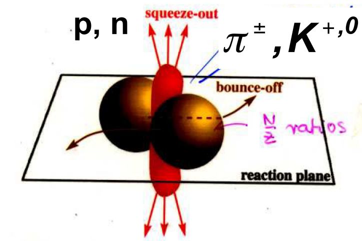
Collaboration

F. Amorini[2], A. Anzalone[17], T. Aumann[3], V. Avdeichikov[12], V. Baran[23], Z. Basrak[4], J. Benlliure[13], I. Berceanu[11], A. Bickley[14], E. Bonnet[6], K. Boretzky[3], R. Bougault[30], J. Brzychczyk[8], B. Bubak[22], G. Cardella[7], S. Cavallaro[2], J. Cederkall[12], M. Chartier[5], M.B. Chatterjee[16], A. Chbihi[6], M. Colonna[17], D. Cozma[11], B. Czech[10], E. De Filippo[7], K. Fissum[12], D. Di Julio[12], M. Di Toro[2], M. Famiano[27], J.D. Frankland[6], E. Galichet[18], I. Gasparic[4], E. Geraci[15], V. Giordano[2], P. Golubev[12], L. Grassi[15], A.

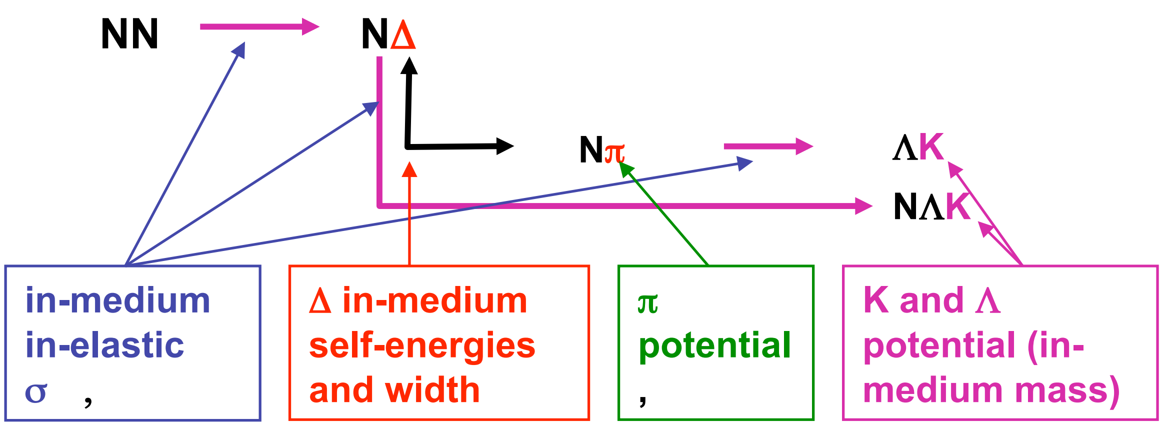


High-density Symmetry Energy: Flow and particle production

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
2. Threshold effect, in medium effective masses:
→ m^*_{N}, m^*_{Δ}, contribution of symmetry energy; m^*_K, models for K-potentials

$$\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$

$$decrease : NL \rightarrow NL\rho \rightarrow NL\rho\delta$$

$$\sigma = \sigma\left(s_{in} - s_{th}\right) \quad \frac{\pi^-}{\pi^+}\uparrow \; increase\; NL \rightarrow NL\rho\delta$$

s_{th} independent of isospin, „too simple“ model of Δ self energies

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

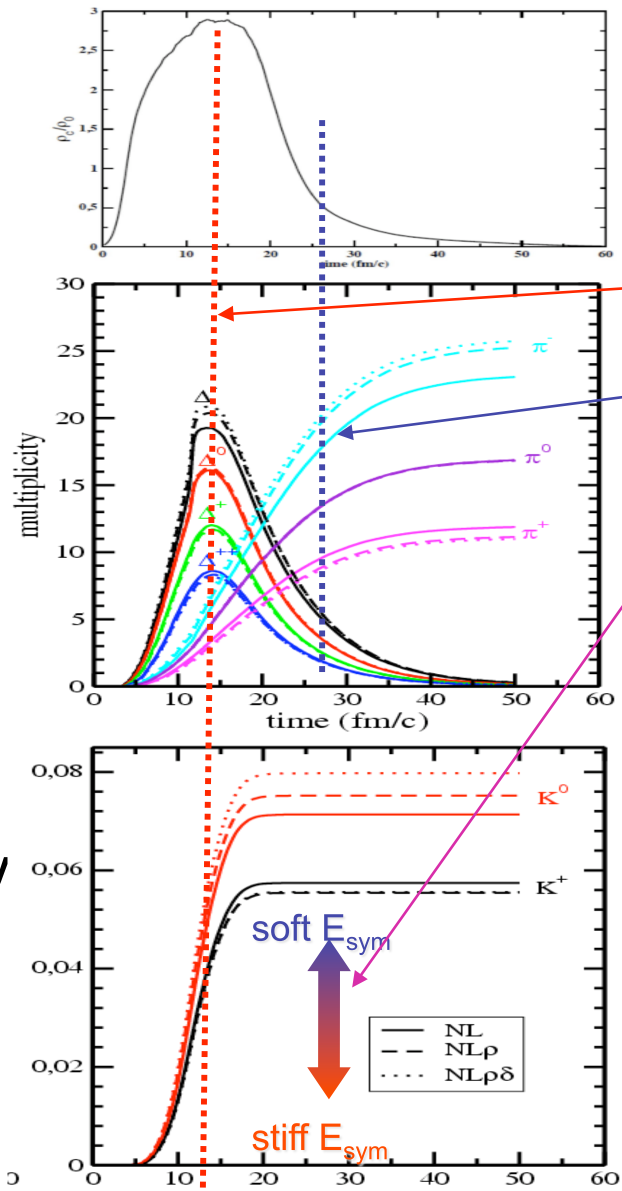
Dynamics of particle production (Δ,π,K) in heavy ion collisions

Au+Au@1AGeV

Central density

π and Δ multiplicity

$K^{0,+}$ multiplicity

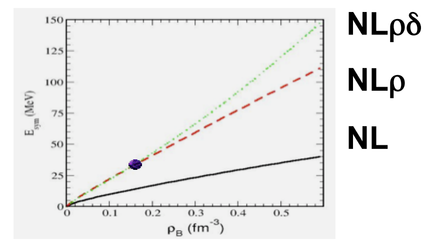


→ time [fm/c]

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

→ $\Delta^{0,-}/\Delta^{+,++}$

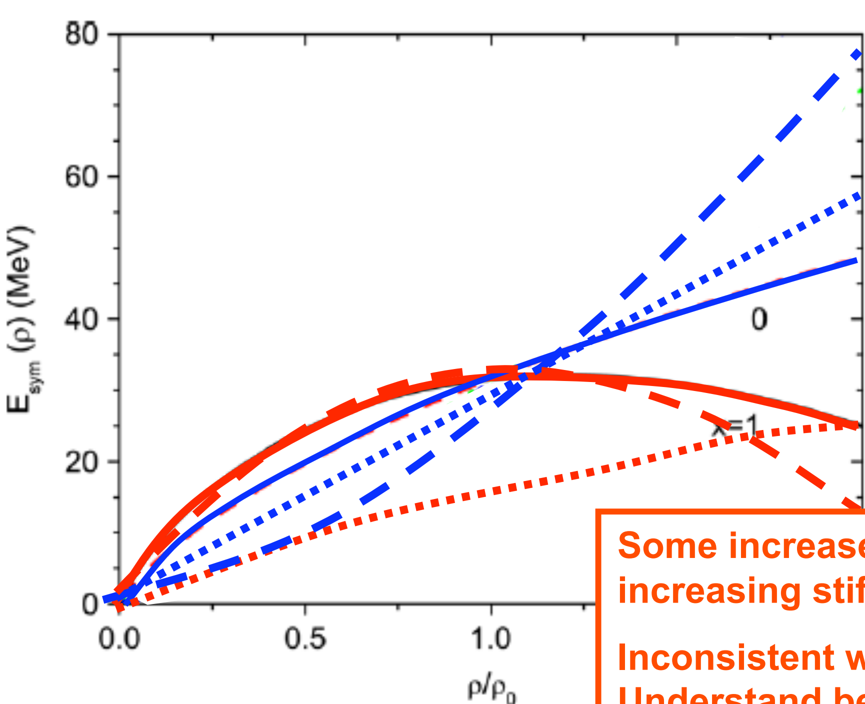
→ π^-/π^+, K^0/K^+

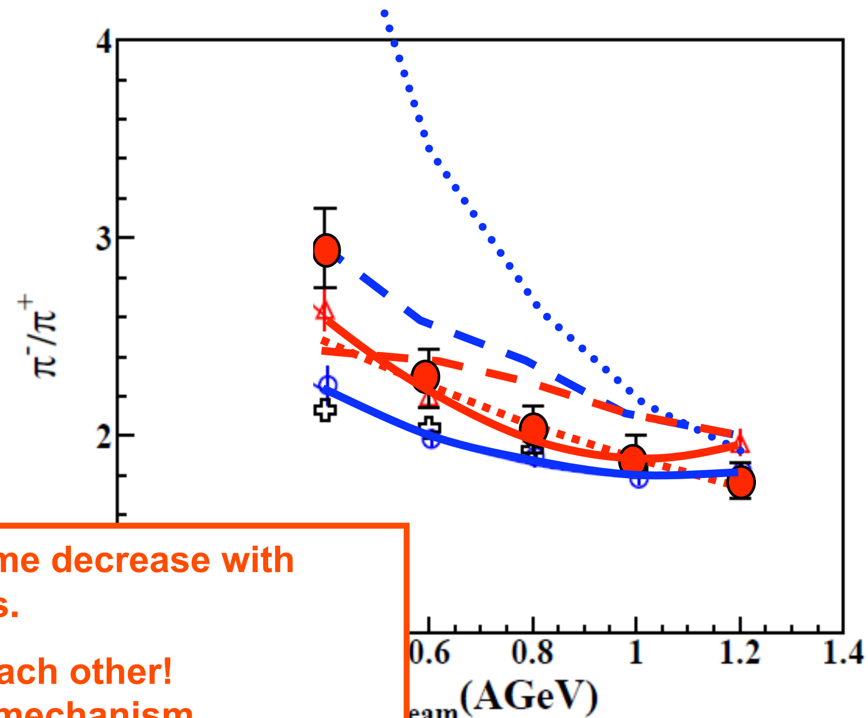
→ n/p ratio governs particle ratios

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

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

blue solid	MDI, x=0, mod. soft	Xiao,.. B.A.Li, PRL 102 (09)
red solid	MDI, x=1, very soft	
blue dotted	NLδ, stiff	Ferini, Gaitanos,.. NPA 762 (05)
red dotted	NL, soft, no Esym	
blue dashed	γ=2, stiff	Feng,… PLB 683 (10)
red dashed	SIII, very soft	
red circle	FOPI, exp	

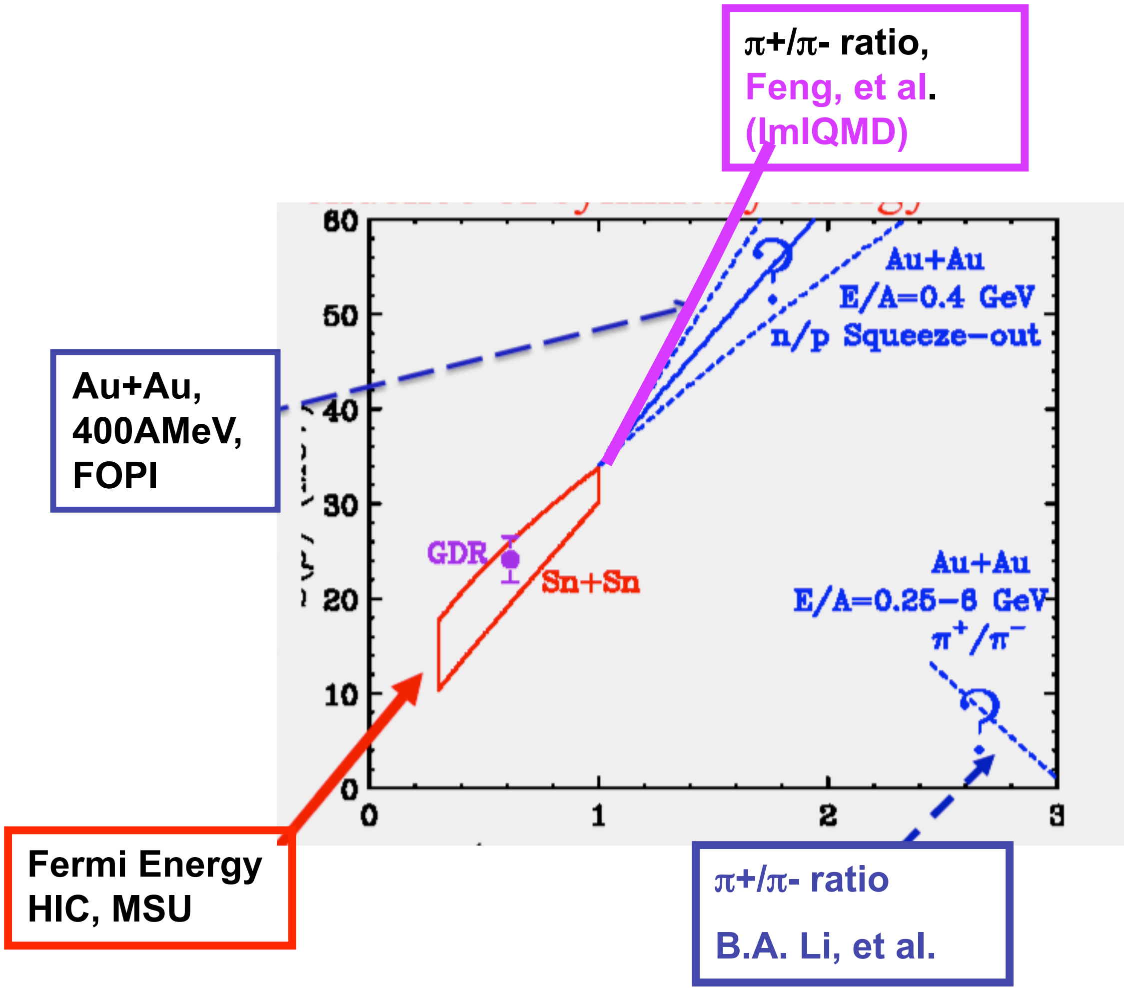




Some increase, some decrease with increasing stiffness.

Inconsistent with each other!
Understand better mechanism,
esp. Δ dynamics!

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!

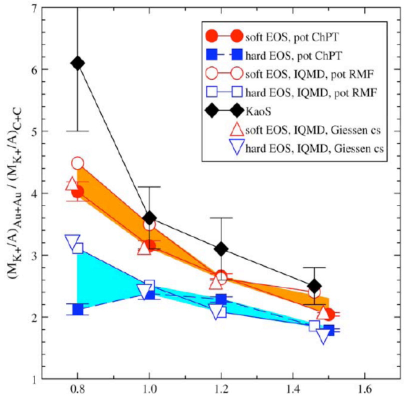
Summary and Outlook

- **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.**
- **Constraints come from neutron star observables and from HIC both at sub-saturation (Fermi energy regime) and supra-saturation densities (relativistic collisions).**
- **At subsaturation densities the constraints become increasingly stringent (γ~1),**
  but constraints are largely lacking at supra-saturation densities.
- **Observables for the suprasaturation symmetry energy**
  N/Z of pre-equilibrium light clusters,
  difference flows, (first hints -> ASYEOS)
  part. production rations π^-/π^+, K^0/K^+ (FOPI,HADES)
- **More work to to in exp. (more data)**
  and theory (consistency of transport codes, π,Δ dynamics)
- **Nuclear symmetry energy: an interesting field that connects areas of nuclear structure, reactions and astrophysics**

Thank you, and all the best to Peter in the future!

backup

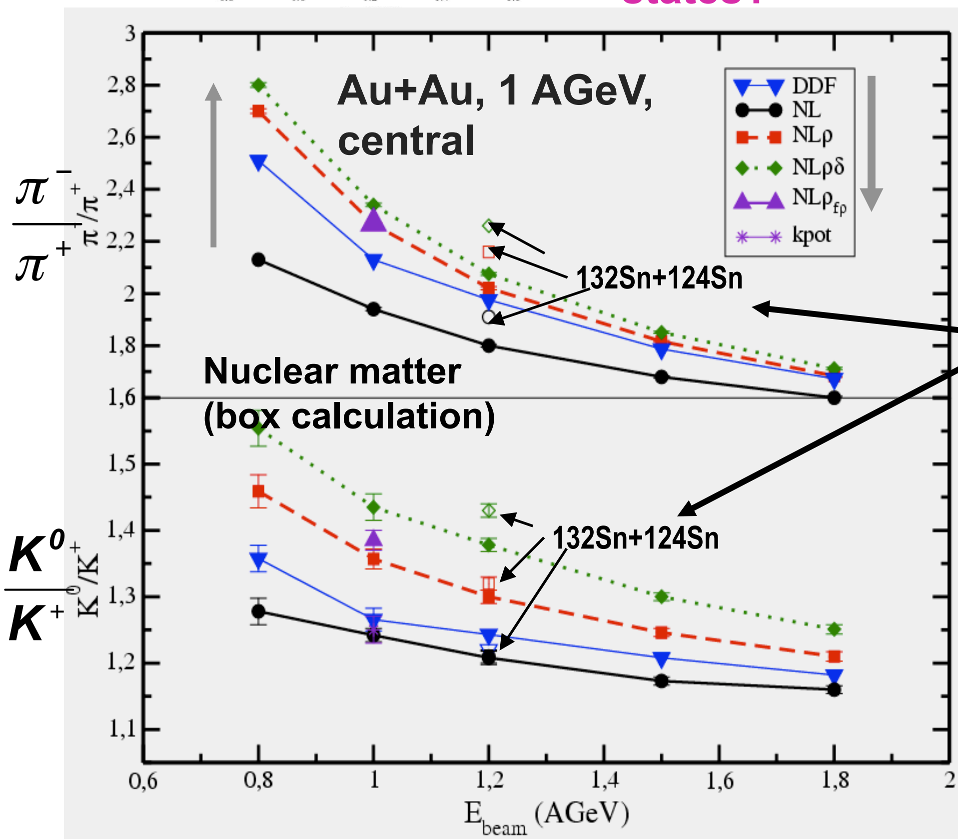
Kaons as a probe for the EOS – also for the Symmetry Energy?



Kaons are a <u>more sensitive and clean</u> probe of the high density EOS. Demonstrated by Fuchs, et al., PRL 86 (01), C.M. Ko & J. Aichelin, PRL55(85) 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?



From Soft to Stiff from lower to upper curves:
Stiffer iso-EOS→larger ratio!
Threshold dominates mean field effect; larger at lower energies

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!
→Exp.: double ratio data by FOPI (Lopez, et al., PRC75 (07)

G.Ferini et al.,PRL 97 (2006) 202301, V. Prassa, et al., NPA 832 (2010)

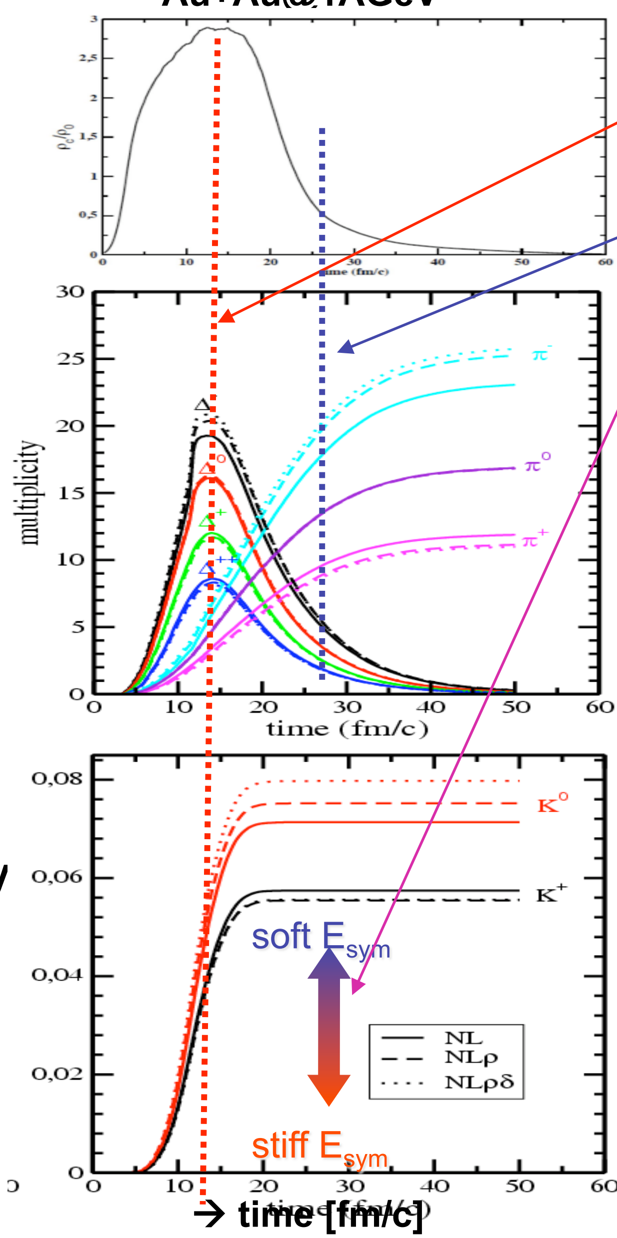
Dynamics of particle production (Δ,π,K) in heavy ion collisions

Au+Au@1AGeV

Central density

π and Δ multiplicity

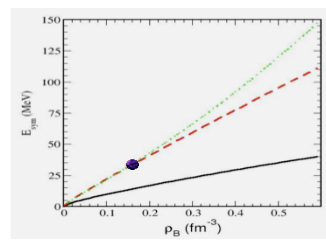
$K^{0,+}$ multiplicity



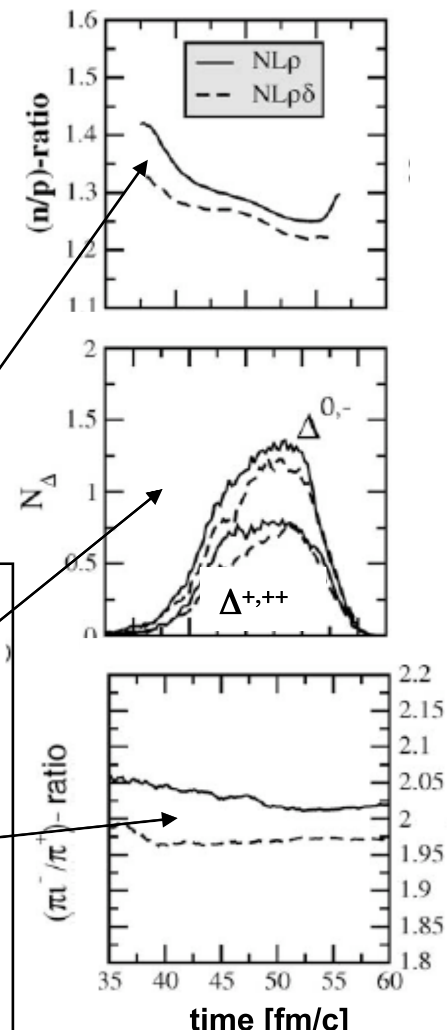
Δ and K: production in high density phase

Pions: low and high density phase

Sensitivity to asy-stiffness



Au+Au, 0.6AMeV



Dependence of ratios on asy-stiffness

n/p

→ $\Delta^{0,-}/\Delta^{+,++}$

→ π^-/π^+

→ n/p ratio governs particle production effects

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

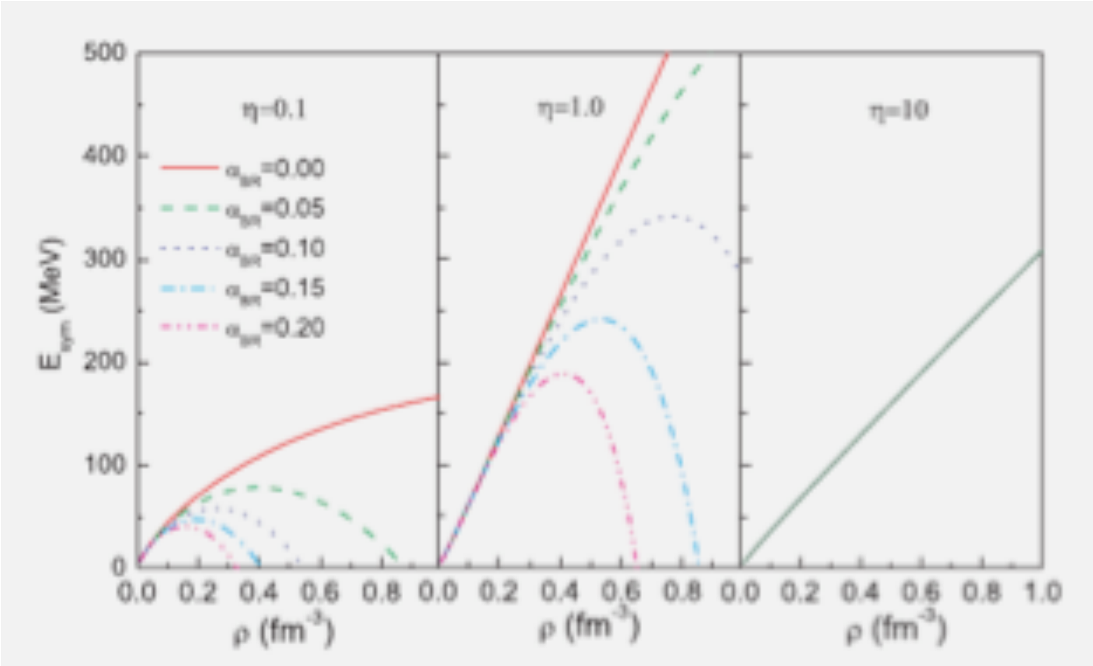
Why is the symmetry energy so uncertain at high densities?

- In-medium properties of the short-range tensor force in the n-p (T=0) channel, controlled by the in-medium rho-meson mass
- Isospin-dependence of short-range nucleon-nucleon correlations
- Effects of many-body forces

$$\bar{V}_T = \int \Theta(r_{ij} - r_c)\left[V_T^{\pi}(r_{ij}) + V_T^{\rho}(r_{ij})\right]dr_{ij};\ r_c = \eta\left(\frac{3}{4\pi\rho}\right)^{1/3}$$

$$m_{\rho}^{*} / m_{\rho} = 1 - \alpha_{BR} \cdot \rho / \rho_0$$

Brown-Rho scaling of ρ mass



Changes of SE without changing the isoscalar potential

B.A. Li, et al., PRC 81, 064612 (2010)

around normal density: Structure

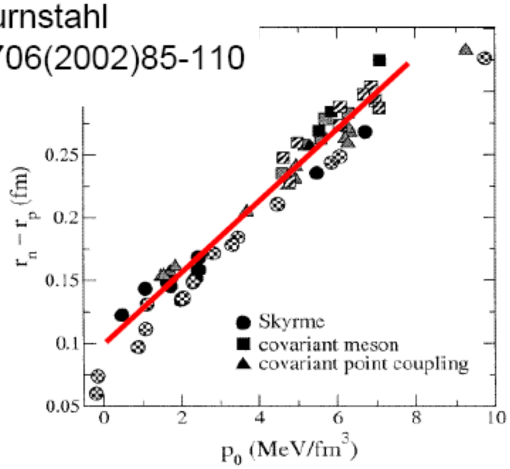
Expansion of SE around ρ_0:

$$E_{sym} = a_4 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

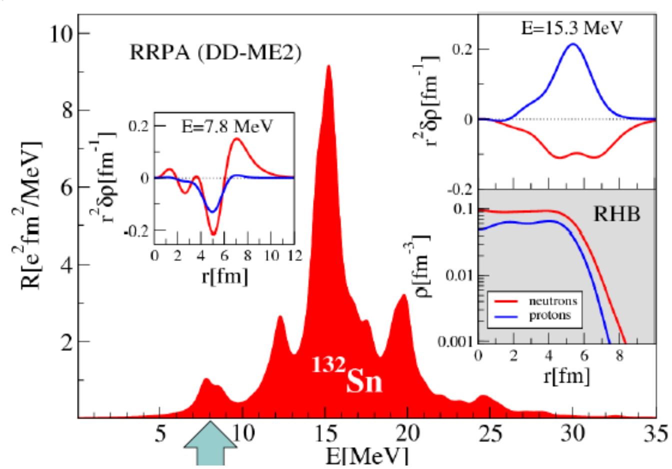
Symmetry pressure

$$P_{sym} = \frac{1}{\rho_0}\frac{dE_{sym}}{d\rho}$$

R.J.Furnstahl
NPA 706(2002)85-110

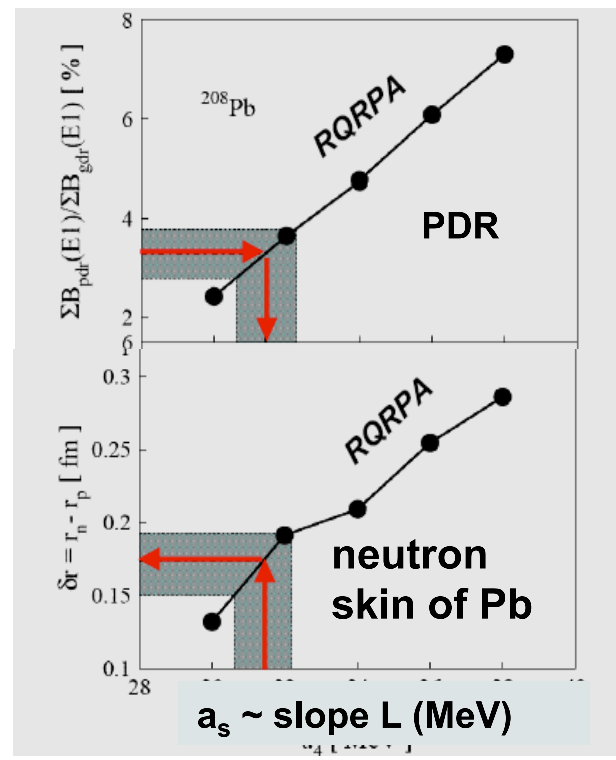


strong linear correlation between neutron skin thickness and SE slope L~p_0 (or also a_4)



strong correlation between Dipole strength of Pygmy resonance and SE slope L

→ possibility to determine slope of SE, but also neutron skin thickness



N. Paar, D. Vretenar, and P. Ring, Phys. Rev. Lett. 94, 182501 (2005)

Transport approaches

Transport theory describes the non-equilibrium aspects of the temporal evolution of a collision. The central quantitiy is the phase space density (coordinate and momentum distribution).

Demonstrate two aspects:

1. **Evolution in coordinate space:**

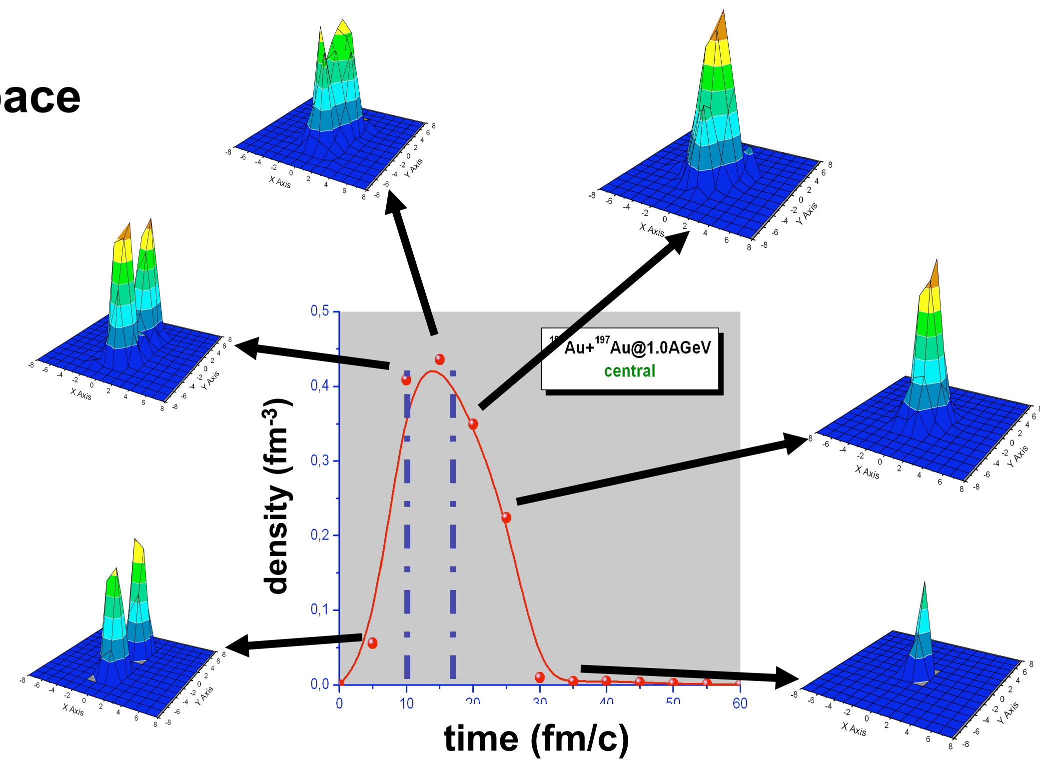
   → **movies curtesy T. Gaitanos, T.Chossy**

2. **Evolution in momentum space**

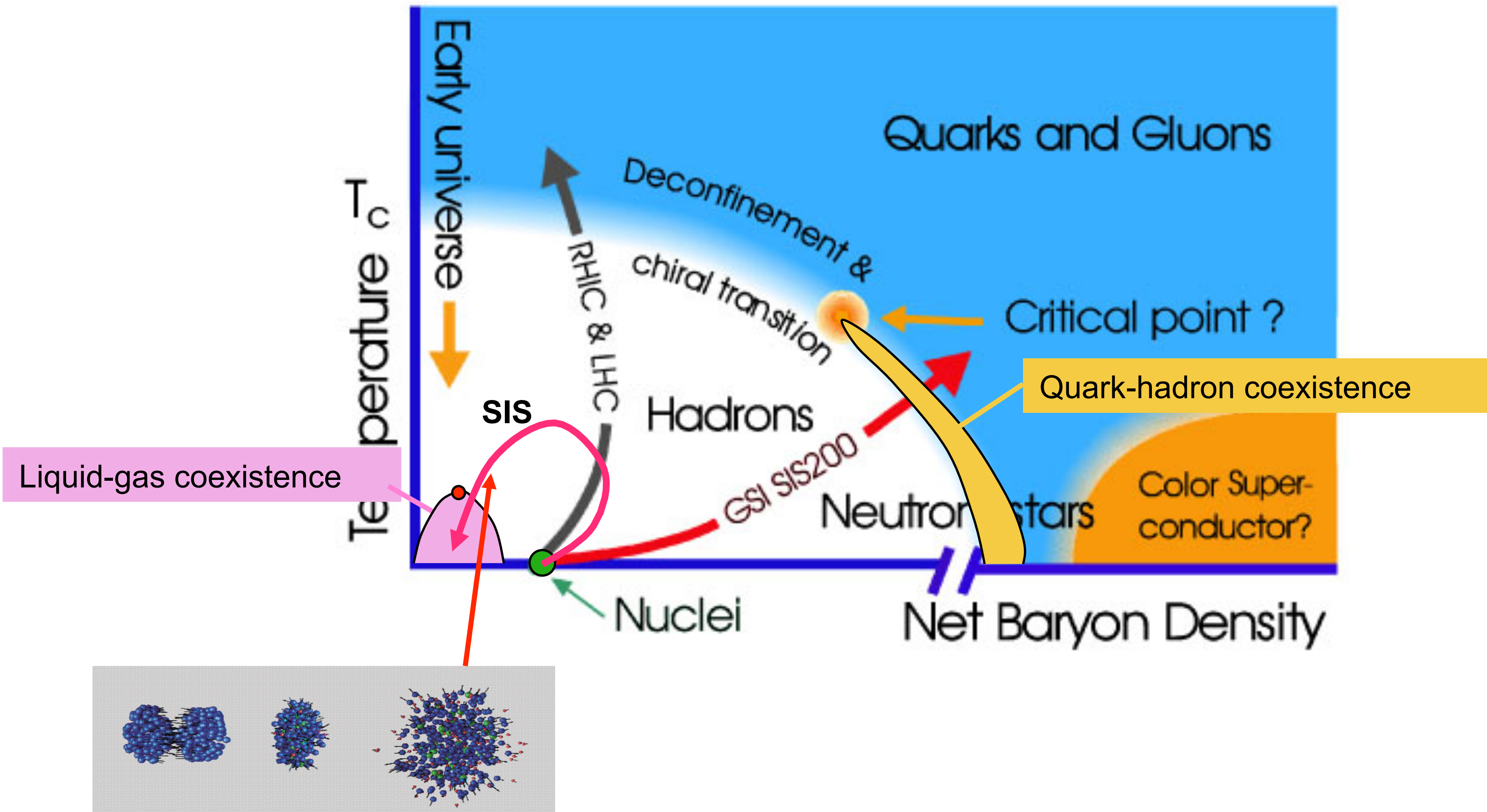
non-equilibrium,

non-sphericity of local momentum distributions

→ **Transport theory!!!**

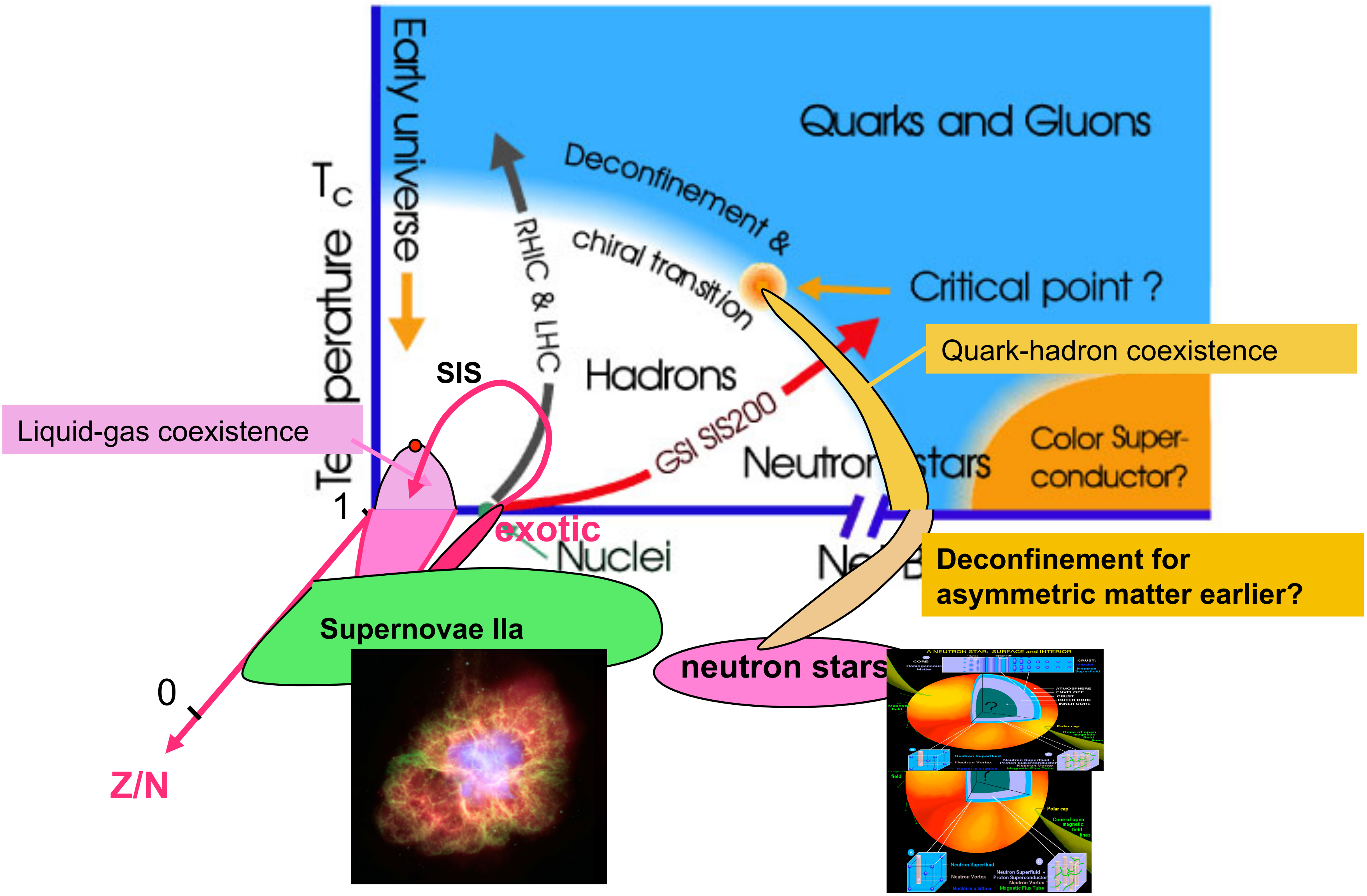


Extreme States of Strongly interacting Matter



Extreme States of Strongly interacting Matter

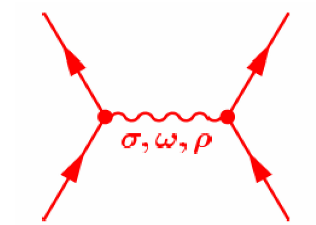
Asymmetry degree of freedom



II.3 Relativistic transport theory

„Quantumhadrodynamics“ (QHD) effective field theory

$$L = \overline{\Psi}\left[\gamma_\mu\left(i\partial^\mu - g_\omega\omega^\mu\right) - \left(m - g_\sigma\sigma\right)\right]\Psi + L^{mes}$$



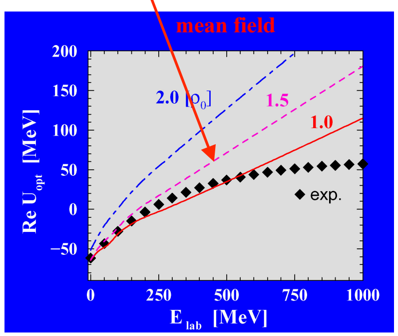
Relativistic Transport Eq.

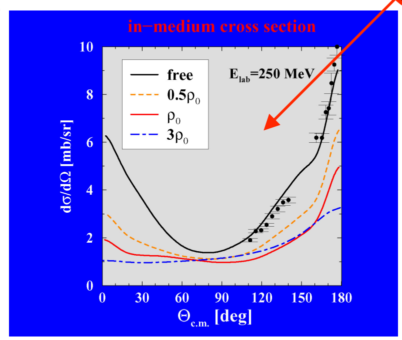
$$\left[p^{*\mu}\partial^x_\mu + \left(p^*_\nu F^{\mu\nu} + m^*\partial^\mu_x m^*\right)\partial^{p^*}_\mu\right] f(x,p^*) = I_{coll}(f,\sigma)$$

ffective mass $m^* = m - \Sigma_s$

Kinetic momentum $p^*_\mu = p_\mu - \Sigma_\mu$

Field tensor $F^{\mu\nu} = \partial^\mu\Sigma^\nu - \partial^\nu\Sigma^\mu$





consistency between self-energies and in-medium cross sections !

e.g. in Dirac BHF $T = V + VQGGT$ *Bethe – Salpeter – Eq.*

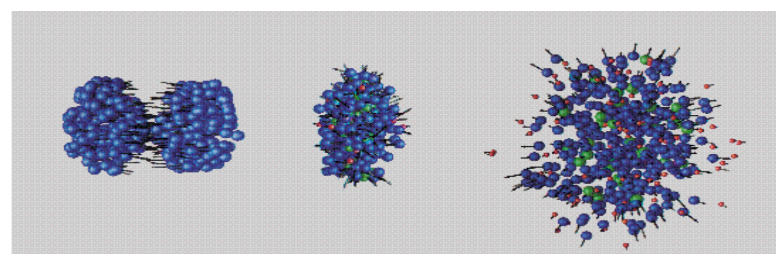
$$\Sigma \approx Re\,Trace(T f); \quad \sigma \approx T^2$$

extensions: fluctuations: fluctuation-dissipation theorem

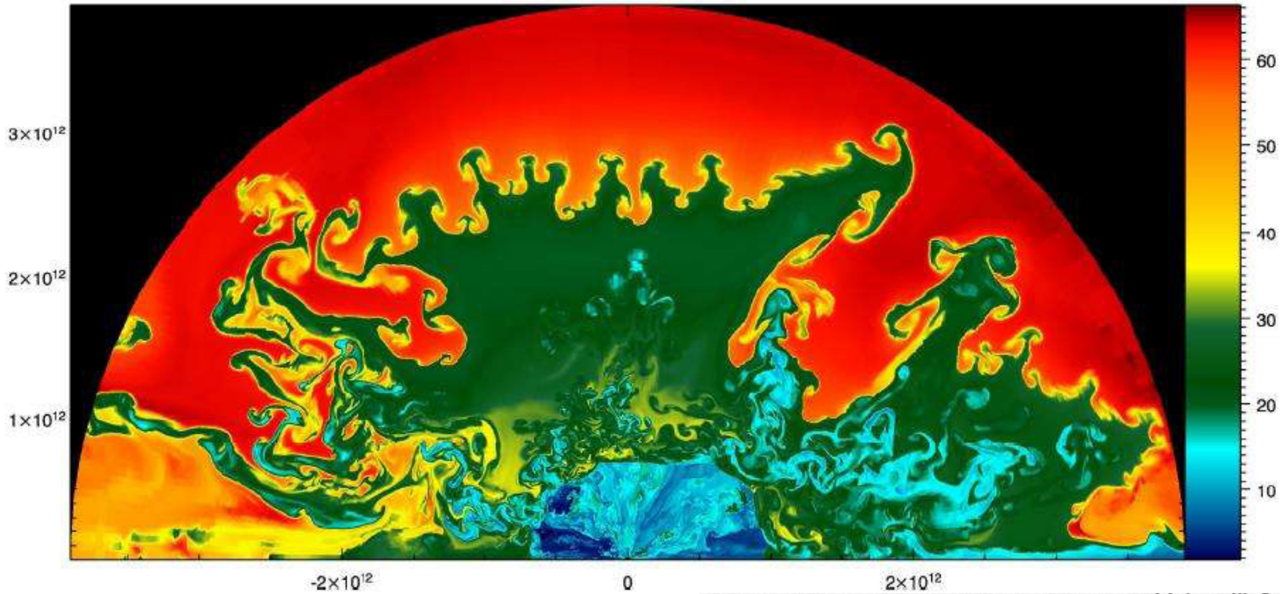
instabilities, liquig-gas phase transition

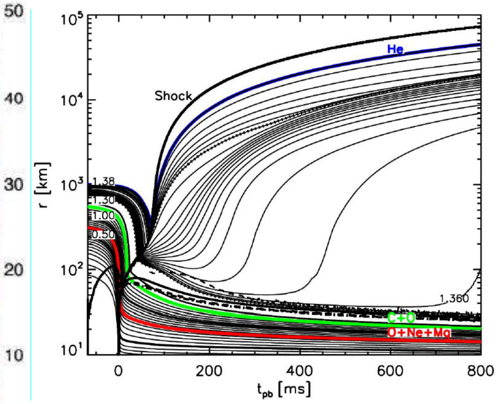
propagation of particles with finite width

(spectral function): Kadanoff-Baym Eqs.

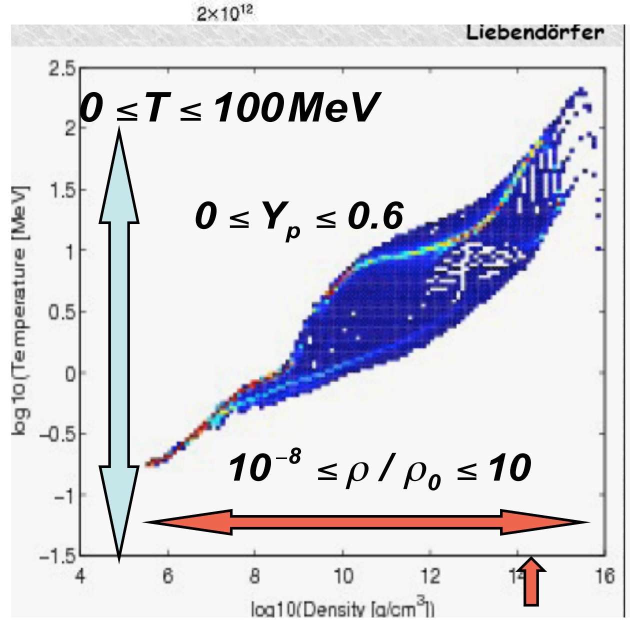


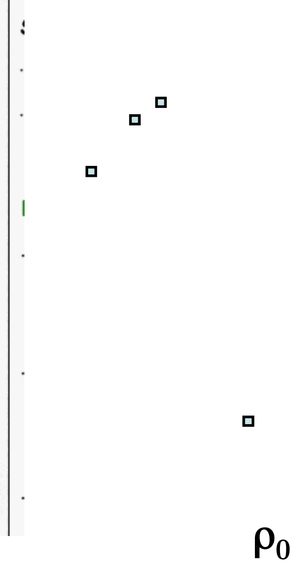
I.7 Importance of Symmetry energy: Supernovae



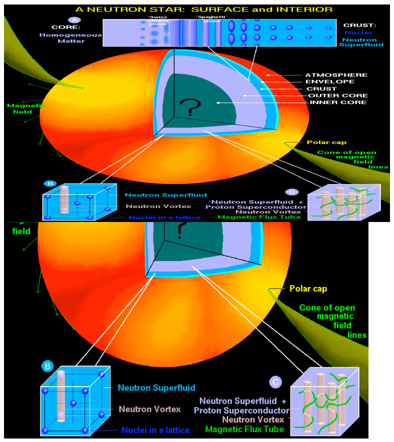


Supernova evolution: range of densities and temperatures and asymmetries:





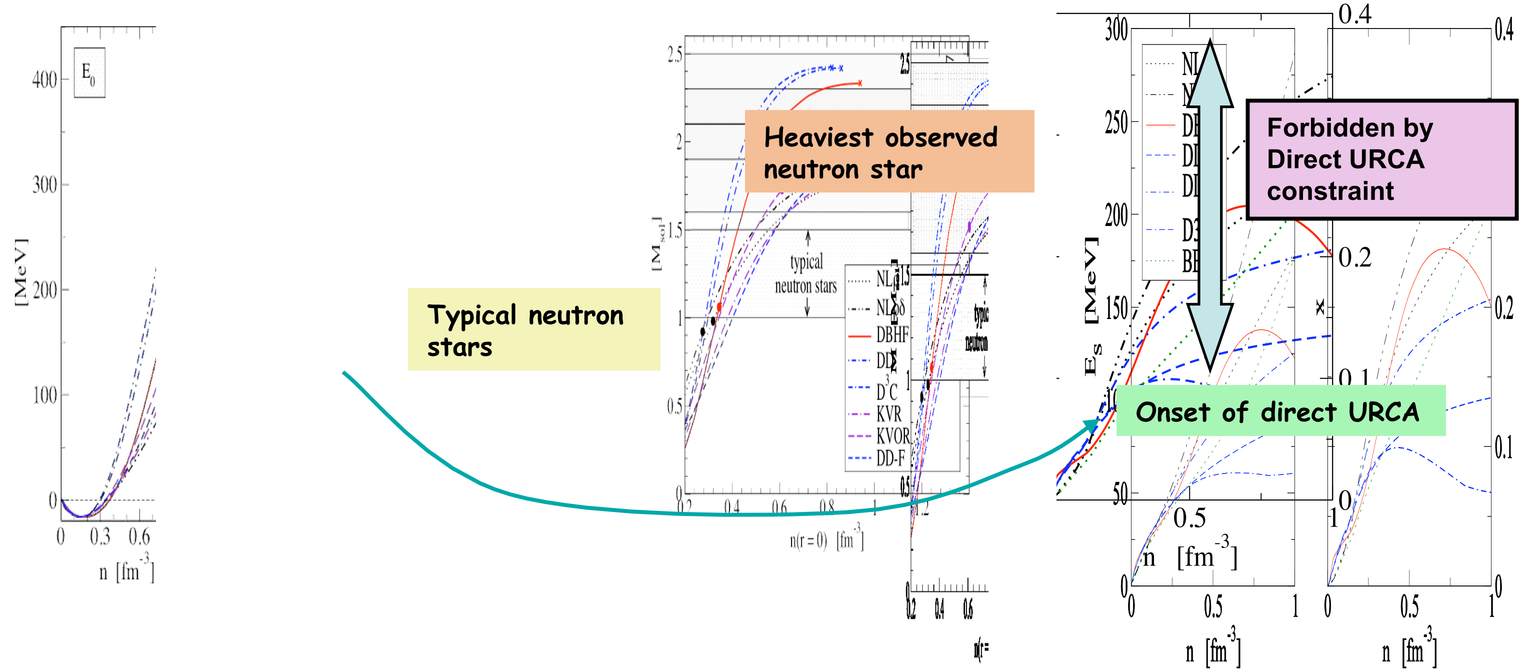
I.8 Importance of Symmetry energy: neutron stars



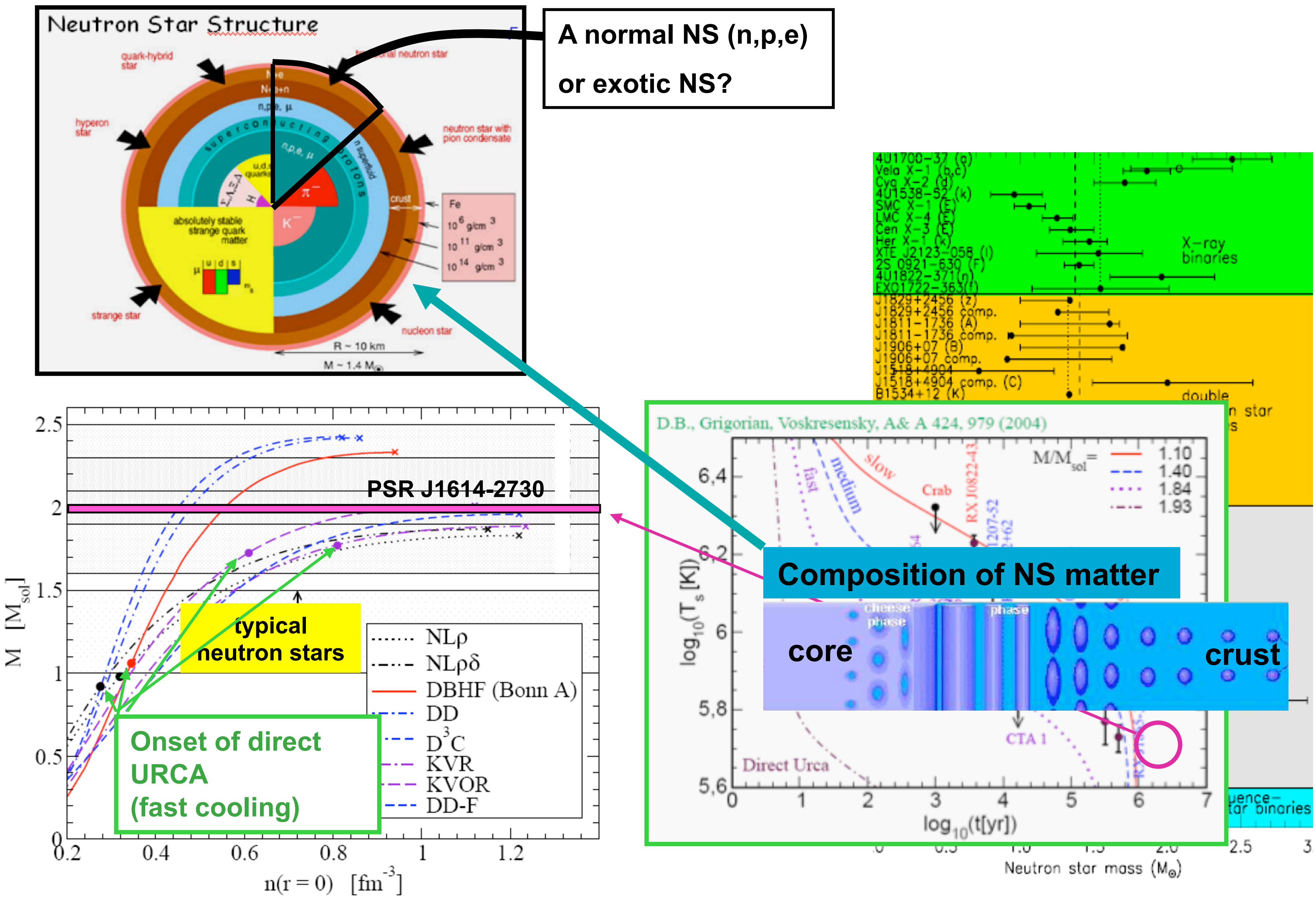
dependence of maximum neutron star mass on symmetry energy.

However, other constraints, e.g. coling due to URCA process

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

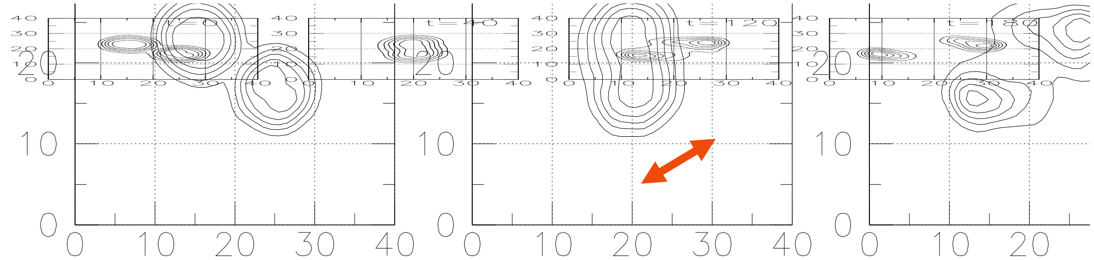


Neutron Stars: a Laboratory for the High-Density Equation-of-State



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

3. Peripheral collisions: Isospin Equilibration through Neck:



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

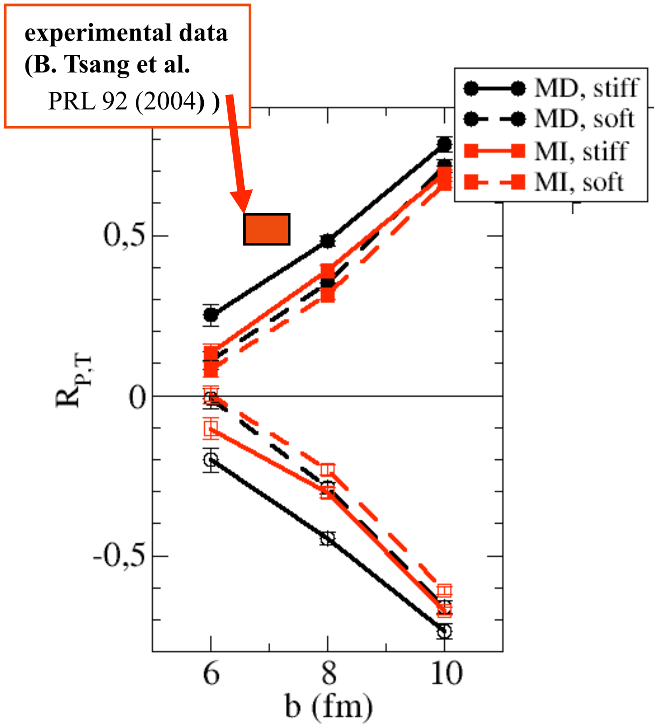
***R*=+-1, complete trasnparency**

Discussed extensively in the literature (talk by B. Tsang)

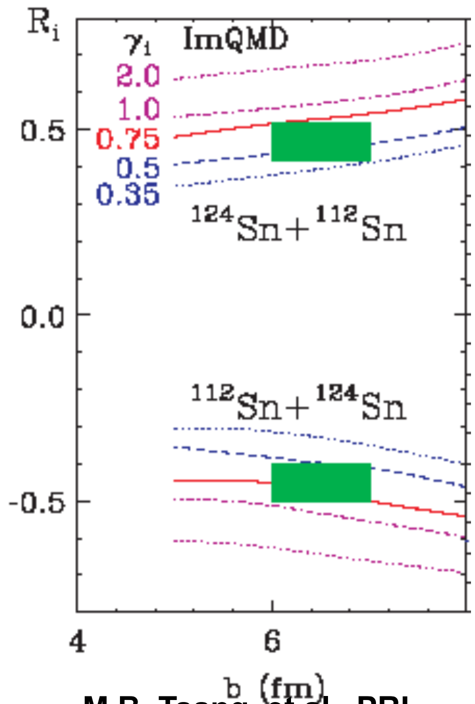
→ Momentum dependence important

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

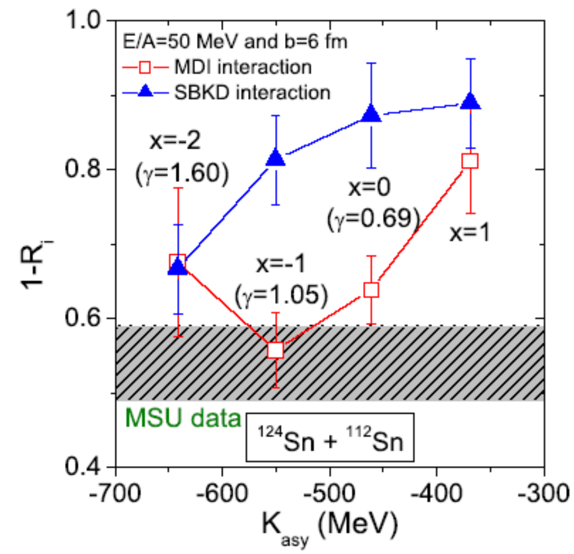
Comparison to other calculation:



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



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



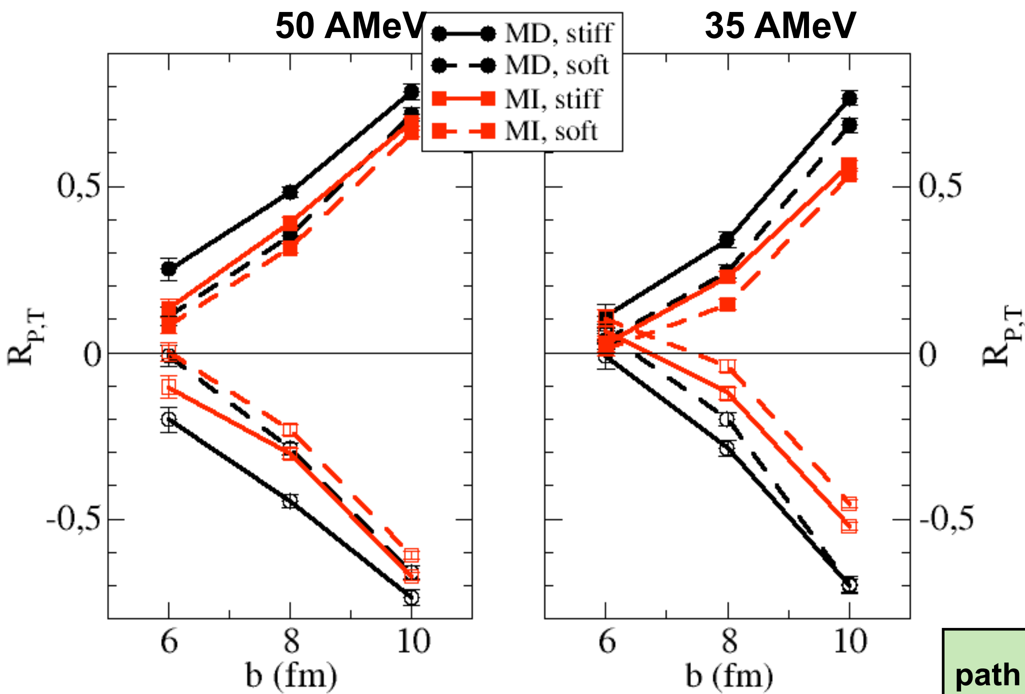
L.W.Chen, C.M.Ko, B.A.Li, PRL 94, 032701 (2005)

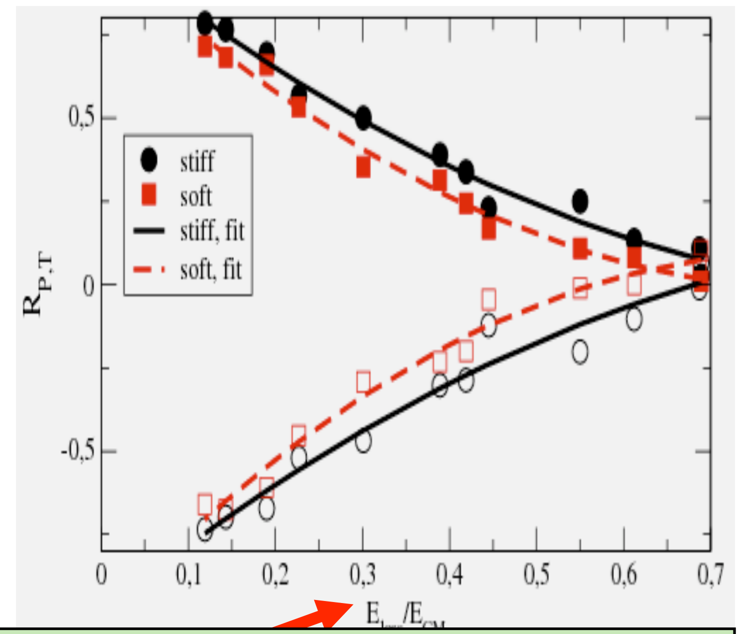
1. disagreement with MSU calculation and also with B.A. Li $(\gamma \approx 1)$
3. much stronger impact parameter dependence
3. question still open

3. Peripheral collisions: Isospin Equilibration through Neck

Imbalance Ratios for Projectile/Target Residues: $^{112,124}Sn + {}^{112,124}Sn$

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





More equlibration (lower R) for MI interaction and lower energy, i.e. longer interaction time

Correlation with total energy loss = measure of interaction time

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

path towards equilibrium for observable x, e.g. R_i

$$\beta_{1,2}(t) - \beta_{eq} = (\beta_{1,2}(0) - \beta_{eq})e^{-t/\tau};$$

$$\beta_{eq} = \tfrac{1}{2}(\beta_1 + \beta_2)$$

$$\Rightarrow R^{\beta}_{1,2} = \pm e^{-t/\tau}$$

t → contact time, τ → dissipation time for obs. β

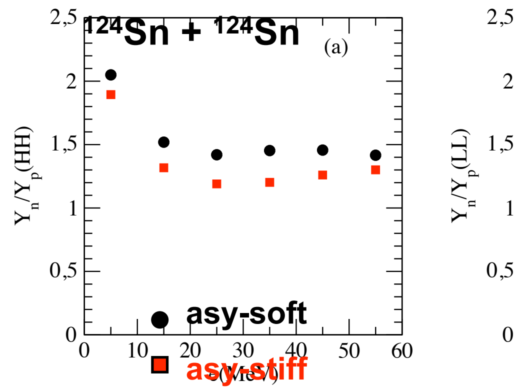
→ universal curve (for each asy_EOS)

III.7 Central Collisions: Ratios of emitted pre-equilibrium particles

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

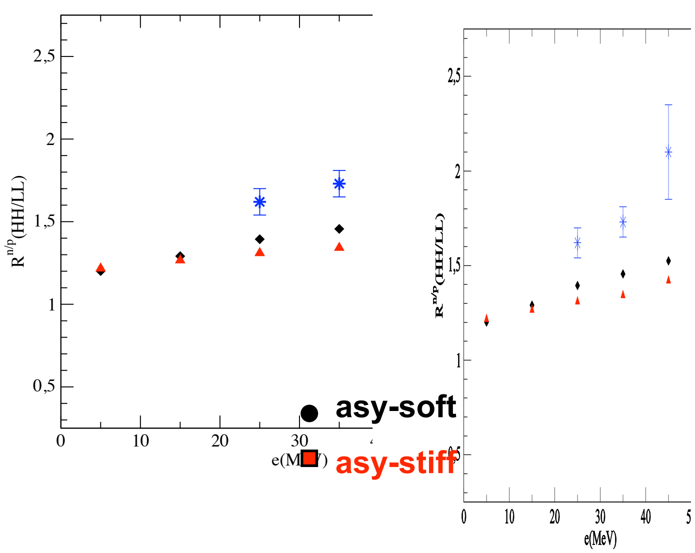
more emission for asy-soft, since symm potential higher

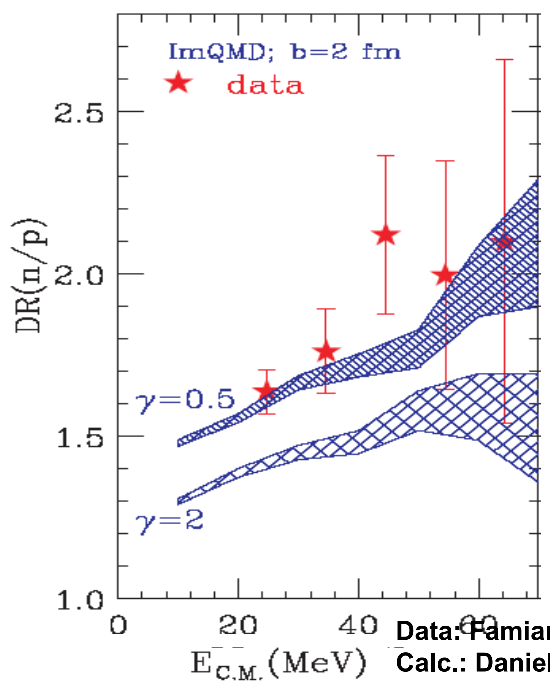
But magnitude of calculation too low



„Double Ratios“

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





Data: Famiano et al. PRL 06
Calc.: Danielewicz, et al. 07

softer symmetry energy closer to data

Differential directed and transverse flow

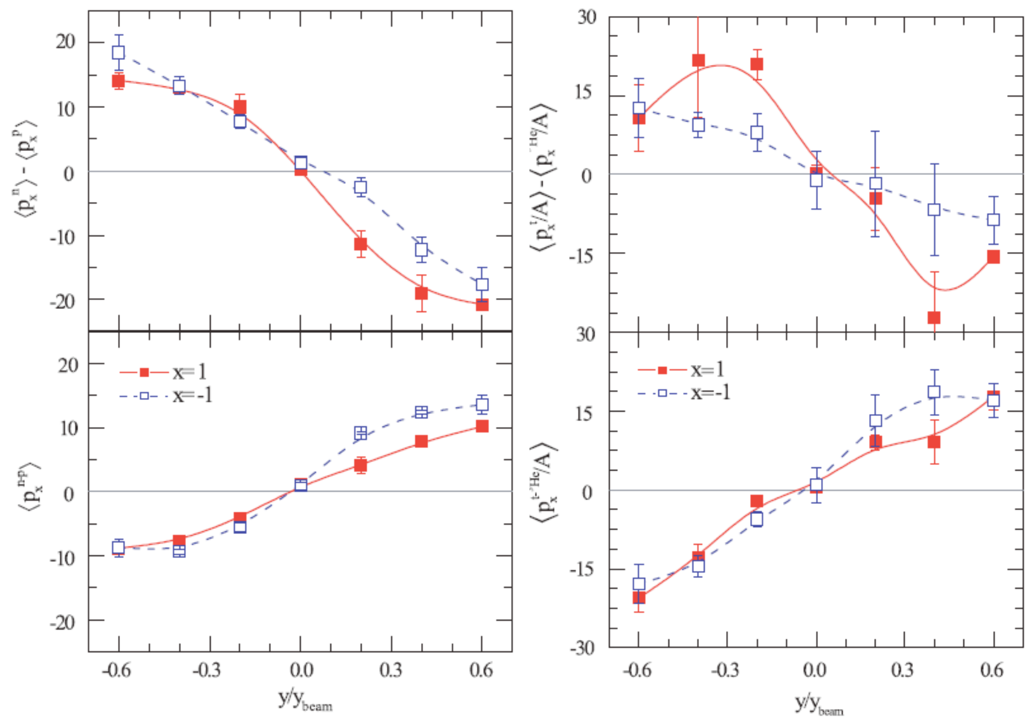
n vs p

t vs ^{3}He

difference

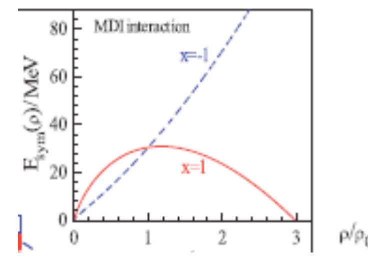
vs

differential flow



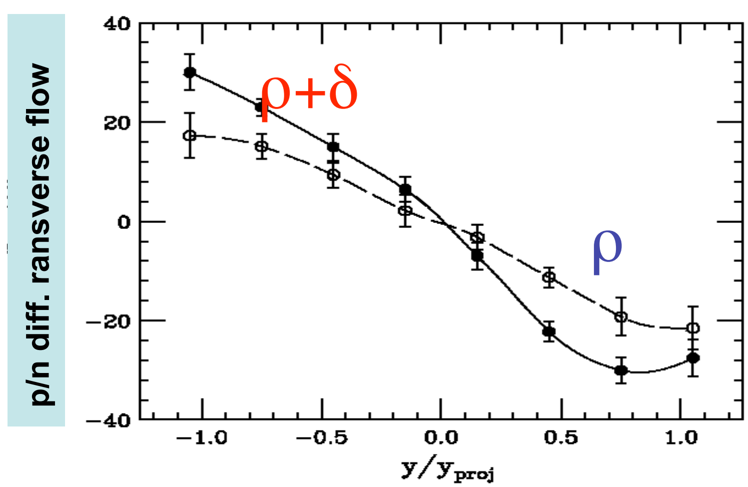
132Sn+124Sn

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 $E_{sym} \Rightarrow$ ***stiffer*** F_{np}

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

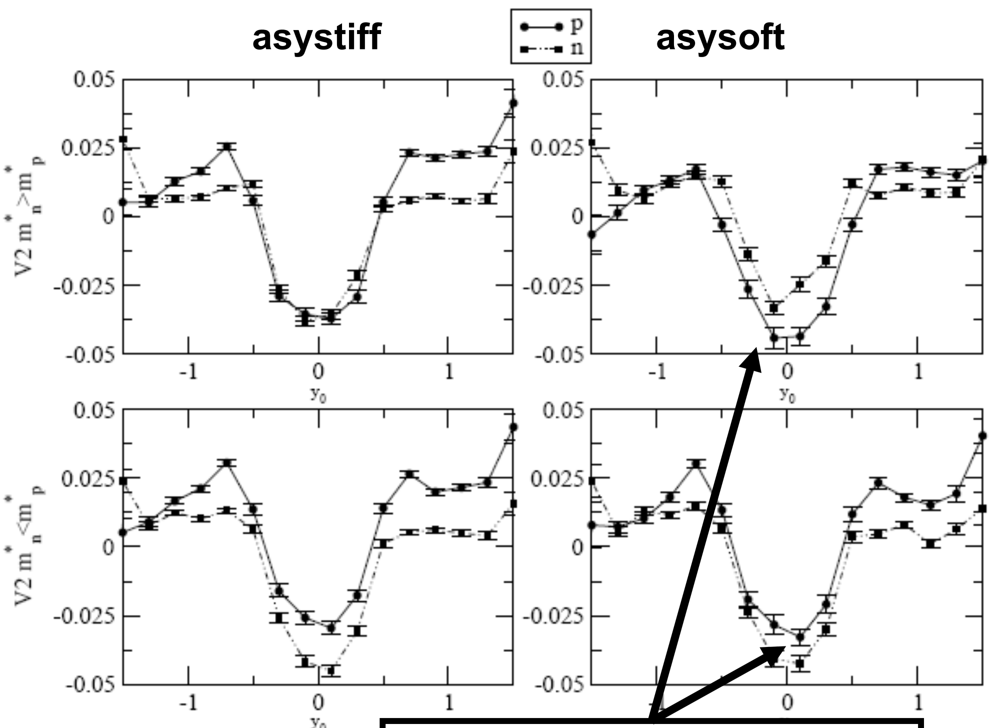
Differential elliptic flow

Au+Au, 400 AMeV

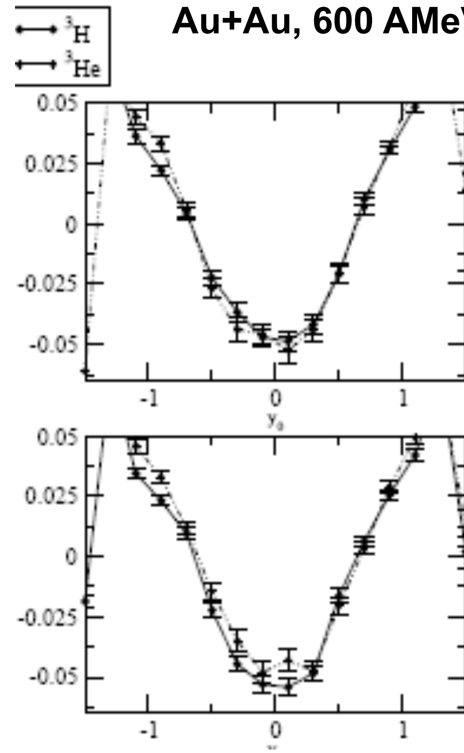
asystiff **asysoft**

$m^*_n > m^*_p$

$m^*_n < m^*_p$



Au+Au, 600 AMeV



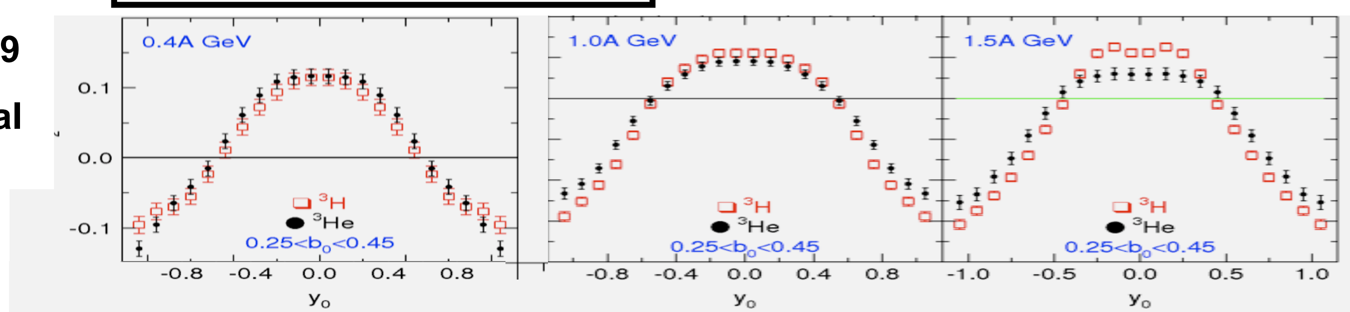
Inversion of elliptic flows because of inversion of potentials with effective mass

t-^{3}He pair similar but weaker

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

W. Reisdorf, ECT*, May 09

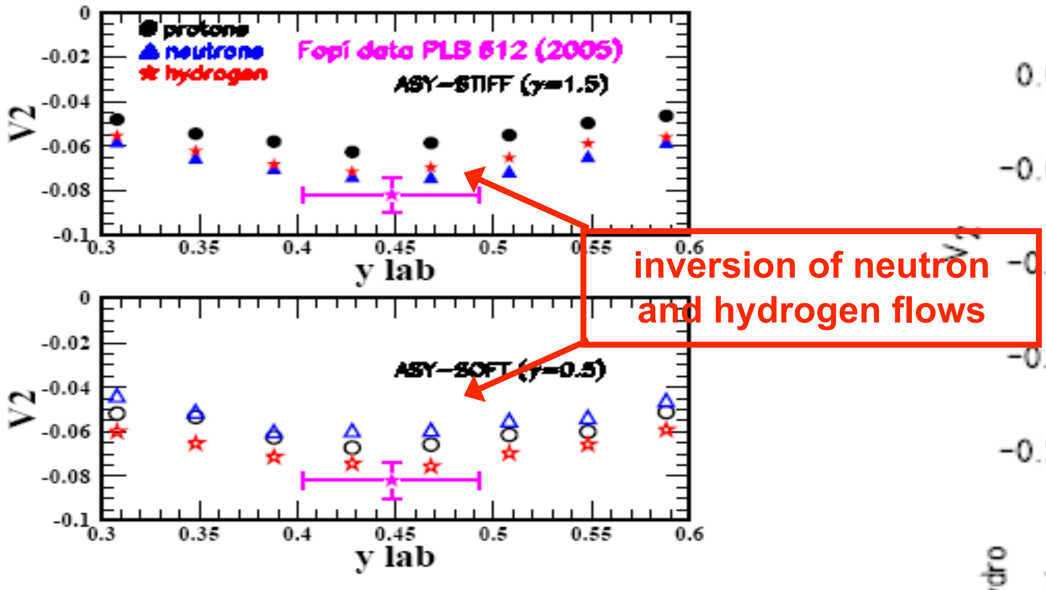
Indication of experimental effect



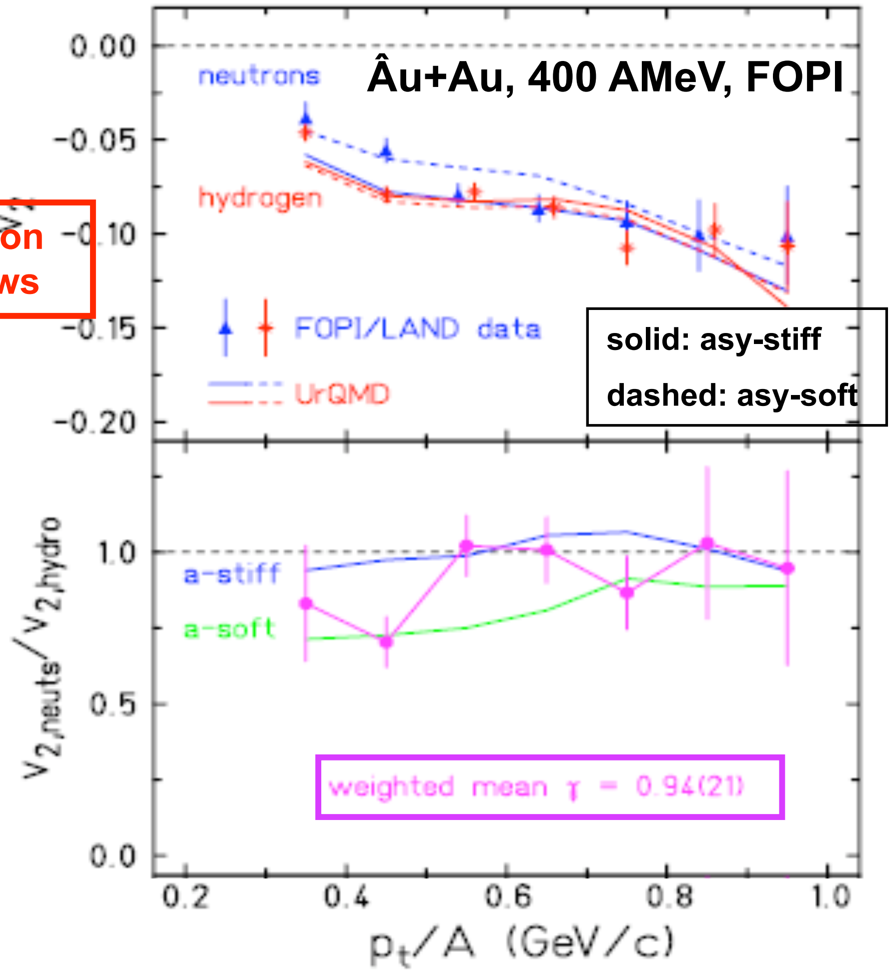
Elliptic flow perhaps more sensitive, since determined by particles that are emitted perp to the beam direction

ASYEOS: Hunting the high density SE with v_2

Early FOPI data (Y. Leifels)



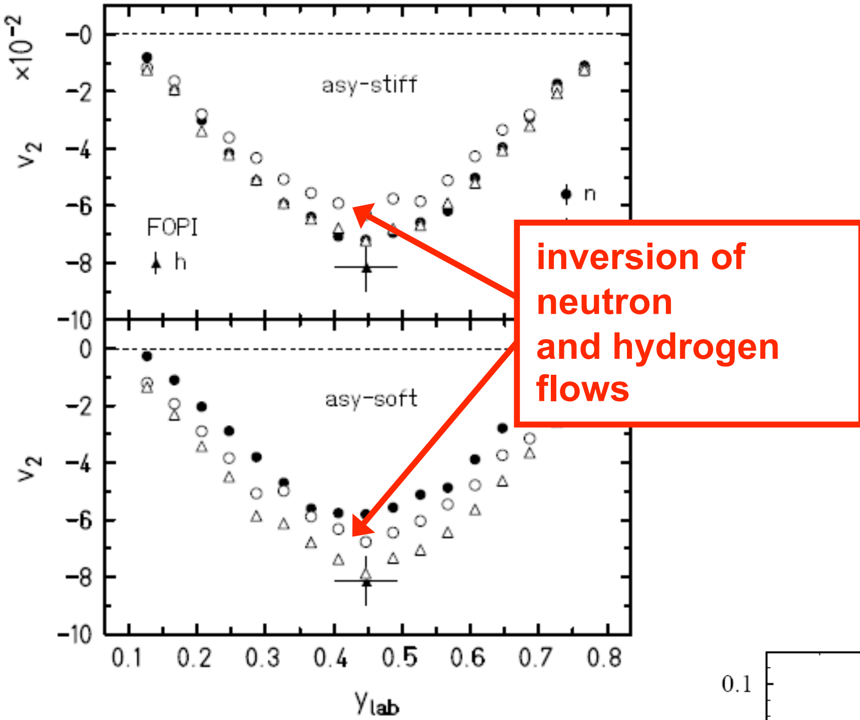
UrQMD calc.
W. Trautmann, …,Q.F. Li, …P. Russotto
PPNP 62 (425)

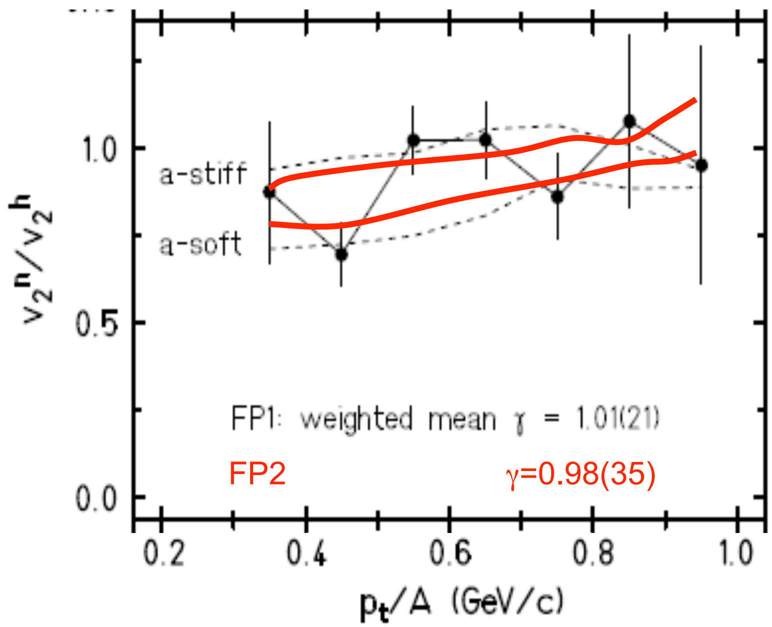


Indication of a asy-stiff Symmetry energy at suprasaturation density

ASY-EOS: Hunting the high density symmetry energy with v_2

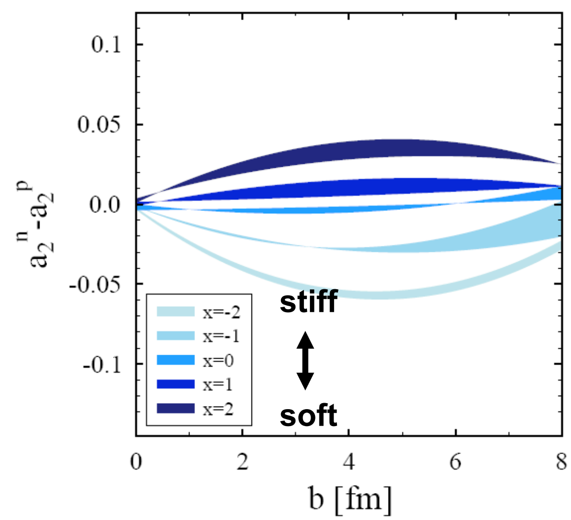
Russotto, et al., PLB 697, 471 (2011)

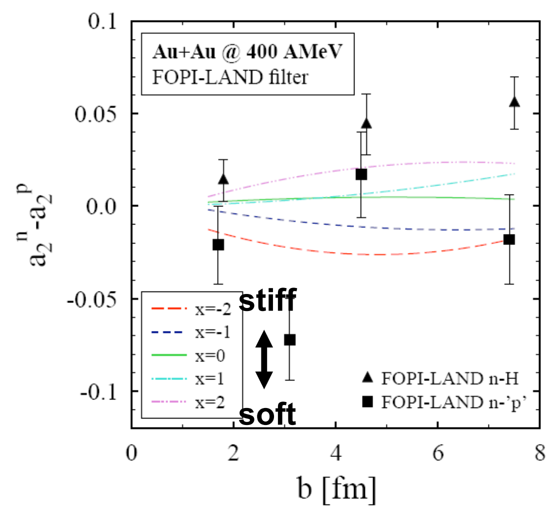




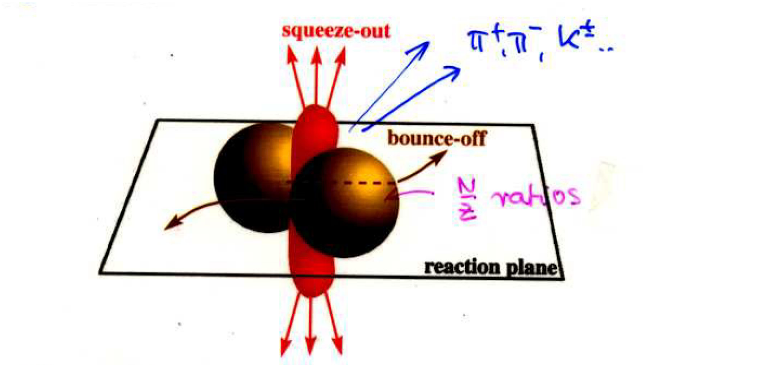
Recent study by Cozma, arxiv 1102.2728

band: soft vs. stiff eos of symmetric matter

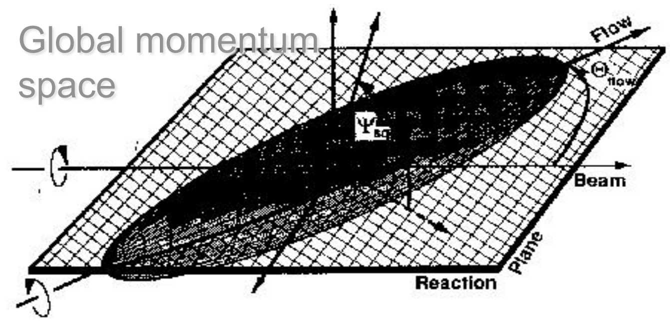




Observables



Analysis of momentum tensor : „flow“



$$Flow: N(\Theta; y, p_t, b) = N_0 (1 + \boxed{v_1(y, p_t)} \cos\Theta + \boxed{v_2(y, p_t)} \cos 2\Theta + \ldots$$

V1: Sideward flow

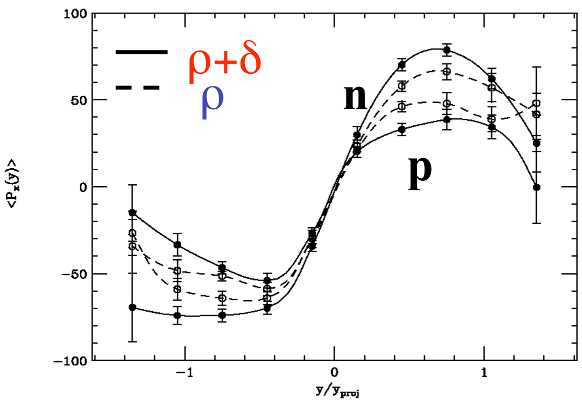
V2: Elliptic flow

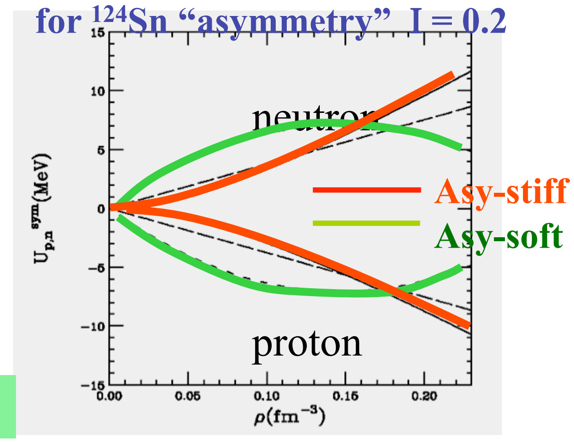
Yields of produced particles,

in particular ratios of isospin partners

Asymmetric matter: Differential directed and elliptic flow

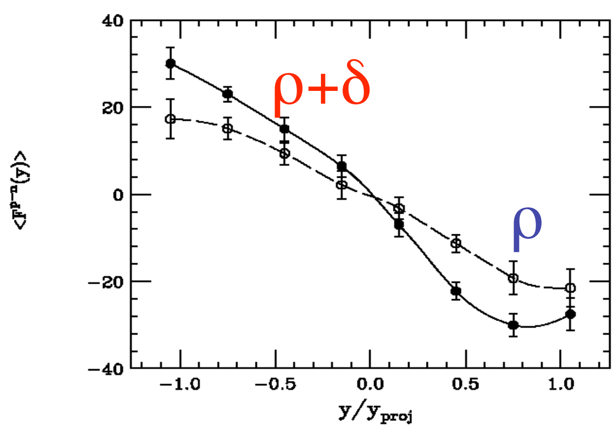
$^{132}Sn + {}^{132}Sn$ @ 1.5 AGeV b=6fm

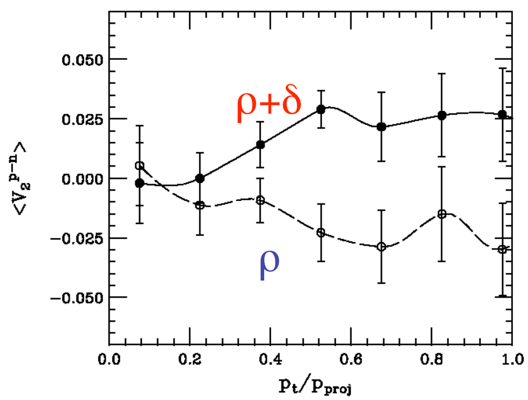




differential elliptic flow

differential directed flow





Proton-neutron differential flow

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

$$w_i = +1(-1)\; f\; omeutron\;(proton)$$

and analogously for elliptic flow

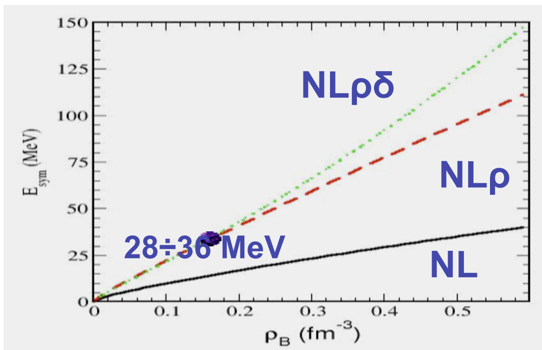
- Difference at high p_t ⟺ first stage , dynamical boosting of vector contribution

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

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

Probing the symmetry energy with flow in HIC: Iso-flows

RMF model with ρ and σ mesons:



$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^{*2}} + \frac{1}{2}\left[f_\rho - f_\delta\left(\frac{M^*}{E^*}\right)^2\right]\rho_B$$

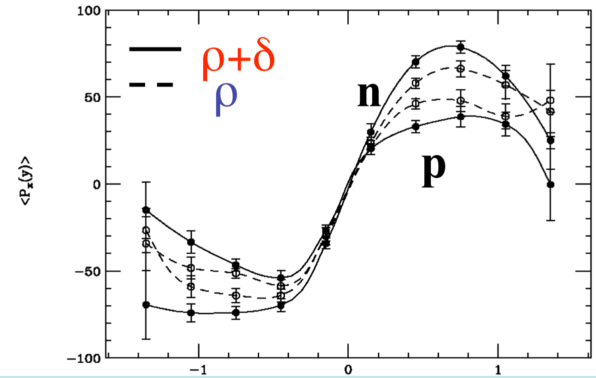
Proton-neutron differential flow

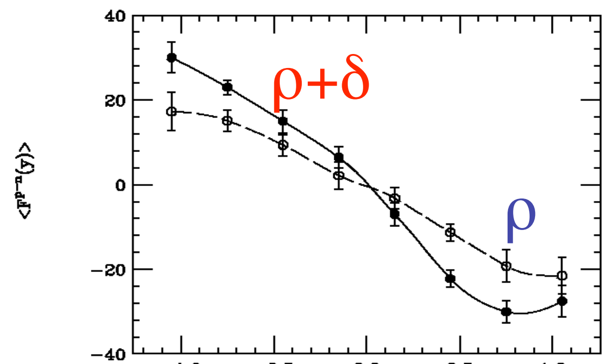
$$F^x_{n-p}(y) = \frac{1}{N(y)}\sum_{i=1}^{N(y)}(p_i^x w_i),$$

$$w_i = +1(-1)\, f\, omeutron\,(proton)$$

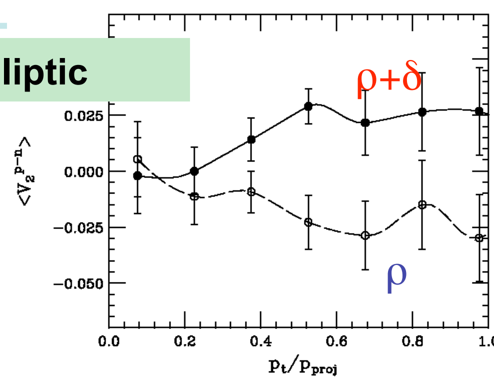
and analogously for elliptic flow

Greater $E_{sym} \Rightarrow$ stiffer F_{np}





differential elliptic flow

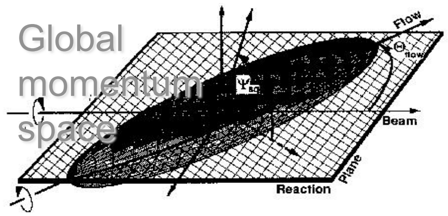


Heavy Ion Collisions at Relativistic Energies: "Flow"

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):

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

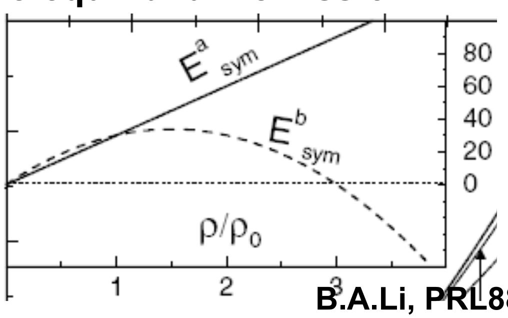
or differential flow

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

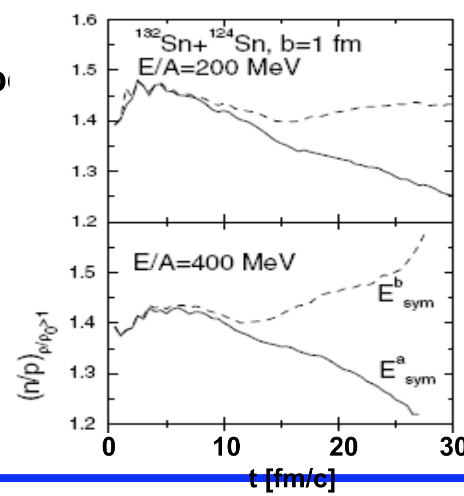
(analogous for v_1, v_2, ..)

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

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