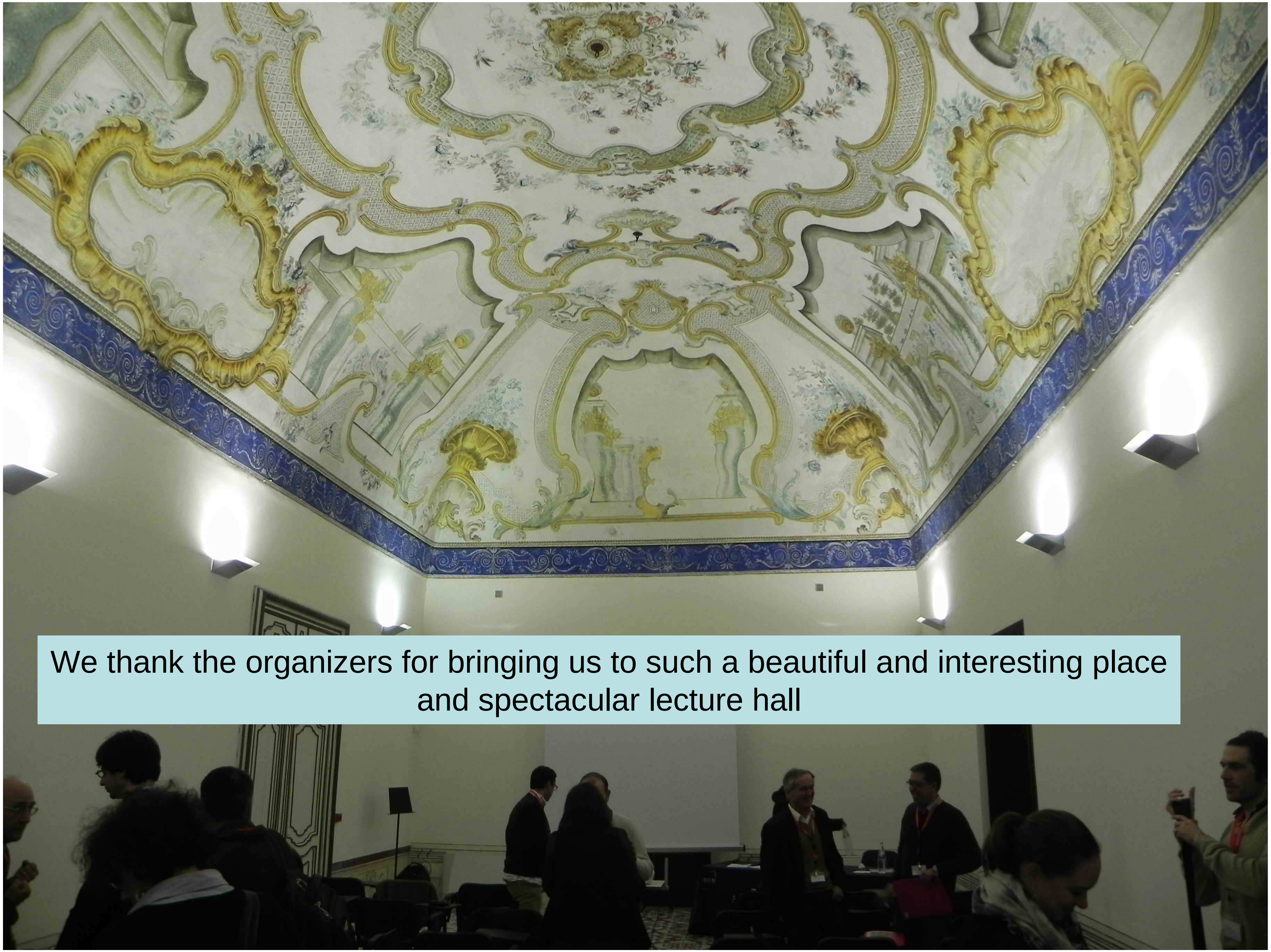
Concluding Remarks

Hermann Wolter, Univ. of Munich

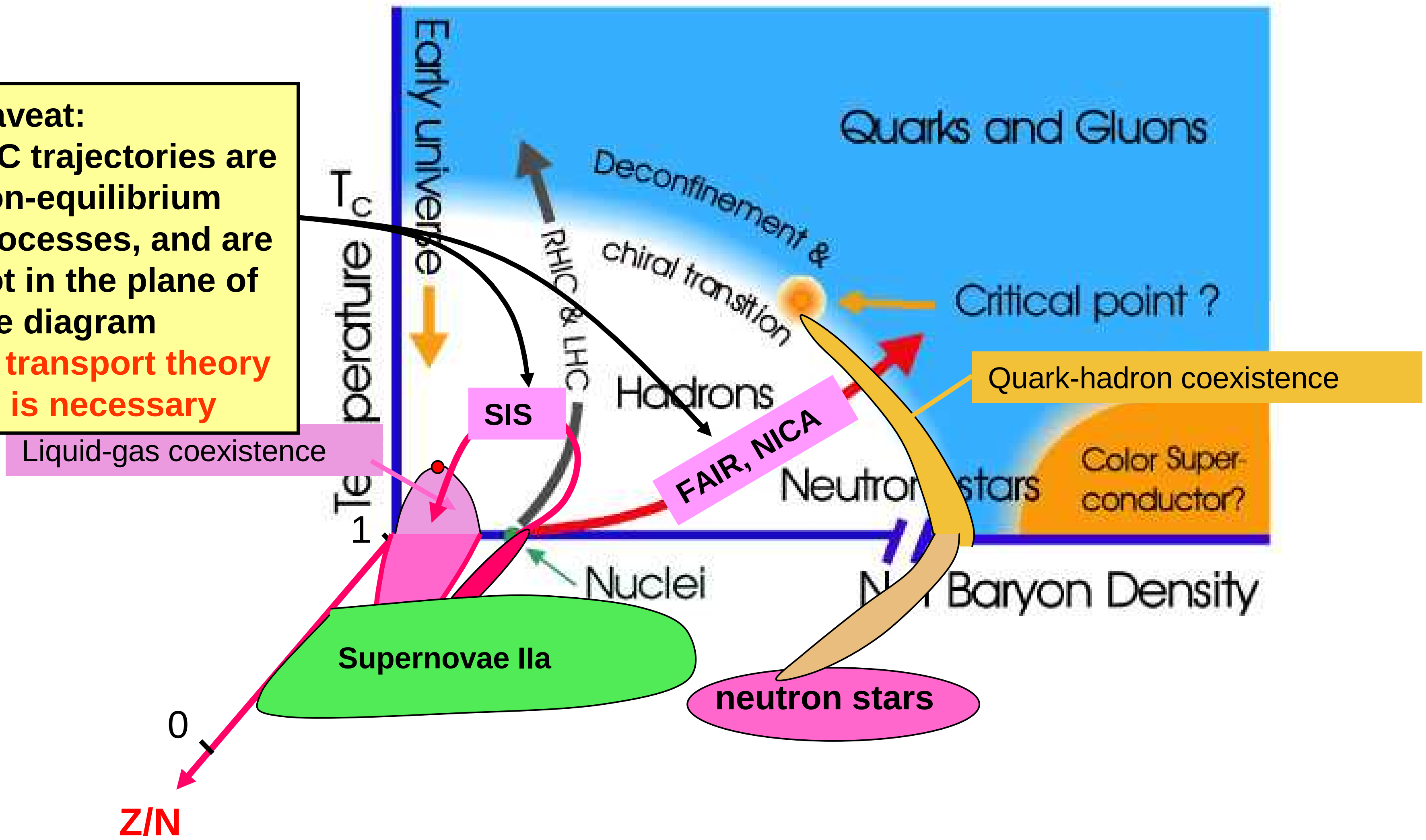
Asy-EoS 2015 Int. Workshop on the Nuclear Symmetry Energy and Reaction Mechanisms,
Piazza Armerina, Sicily, March 3-6, 2015


We thank the organizers for bringing us to such a beautiful and interesting place
and spectacular lecture hall

Our general aim in Heavy Ion Reactions:

The Phase Diagram of Strongly Interacting Matter

Caveat:
HIC trajectories are non-equilibrium processes, and are not in the plane of the diagram
→ transport theory is necessary



Isospin degree of freedom

Transport theory: 2 families

1. Boltzmann-Uehling-Uhlenbeck (BUU)

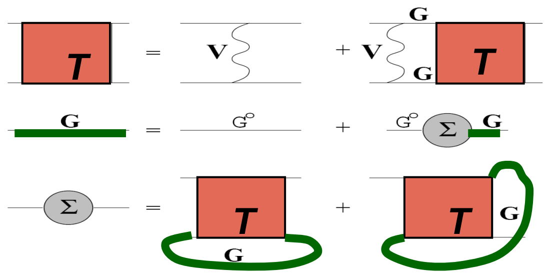
$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\vec{\nabla}^{(r)} f - \vec{\nabla} U(r)\,\vec{\nabla}^{(p)} f(\vec{r},\vec{p};t) = \int d\vec{v}_2\, d\vec{v}_{1'}\, d\vec{v}_{2'}\, v_{21}\,\sigma_{12}(\Omega)\,(2\pi)^3\,\delta(p_1+p_2-p_{1'}-p_{2'})\left[f_{1'} f_{2'}(1-f_1)(1-f_2) - f_1 f_2 (1-f_{1'})(1-f_2{}')\right]$$

Derived:

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

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

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



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

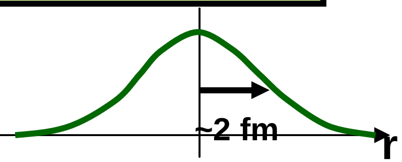
$$A(x,p) \propto \frac{2\Gamma(x,p)}{(p^{*2}-m^{*2}) + \Gamma^2(x,p)} \quad \xrightarrow{\text{QPA}} \quad \propto \delta(p^{*2}-m^{*2})\,\Theta(p^{*0})$$

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

2. Molecular Dynamics (QMD)

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

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



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

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

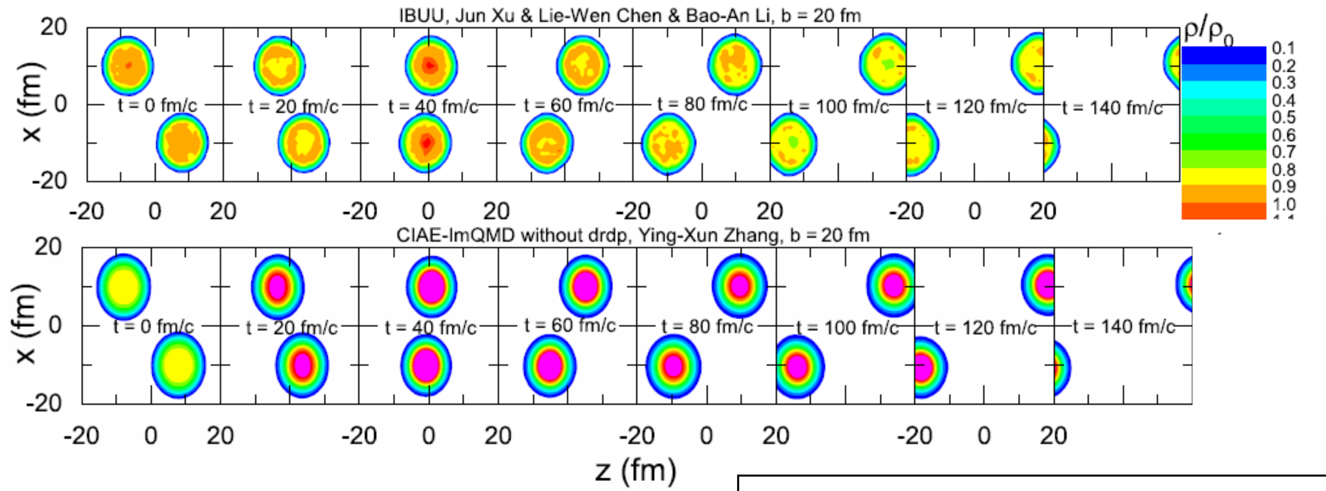
Code Comparison Project: Trento, ECT*, 2006 and 2009 Shanghai, Jan. 2014, Lanzhou 2014

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

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

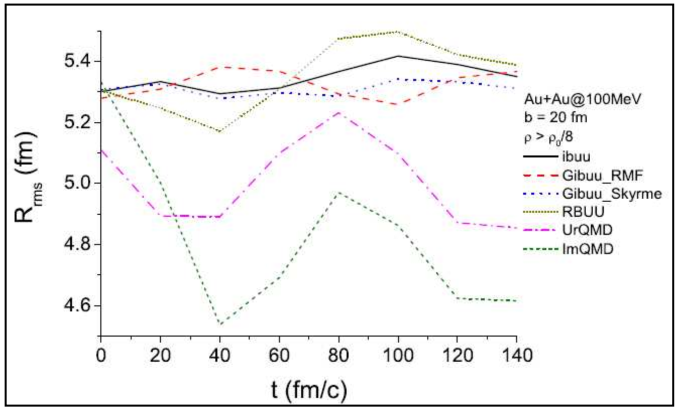
1. step: Initialize colliding nuclei. usually not exact ground states

free propagation (large impact parameter)



→ nuclei oscillate, influences dynamical evolution in collision, part. at lower incident energies

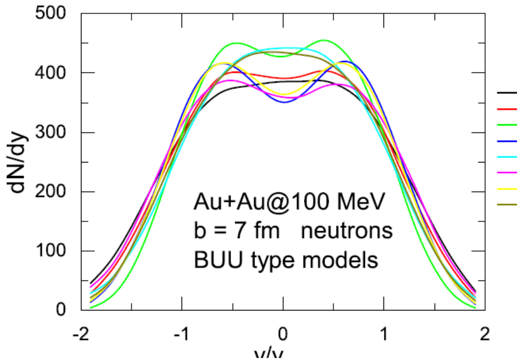
→ construct better gs, e.g. Thomas-Fermi



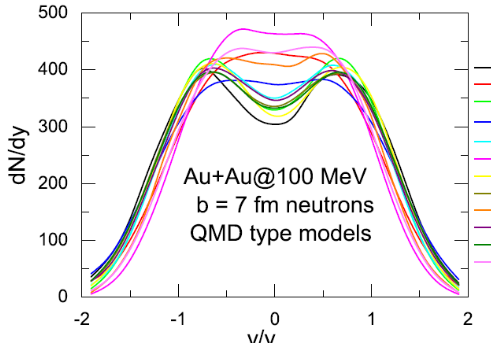
Examples of results: Au+Au, PRELIMINARY

E/A=100 MeV

BUU models

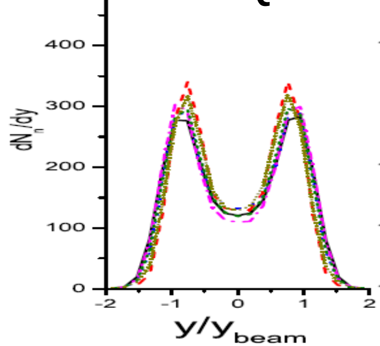


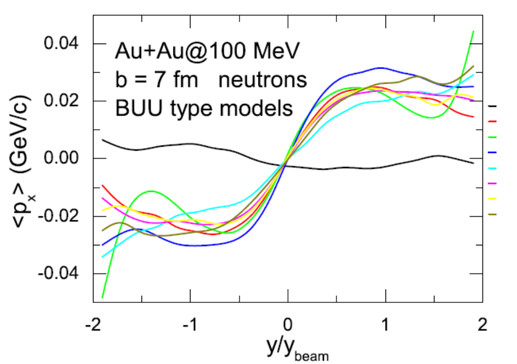
QMD models

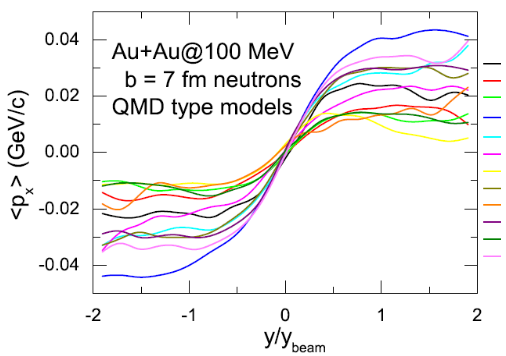


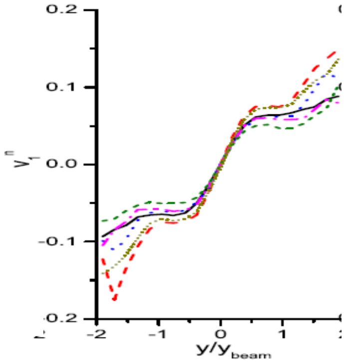
E/A=400 MeV

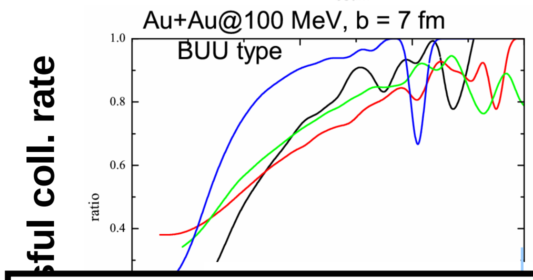
BUU and QMD models

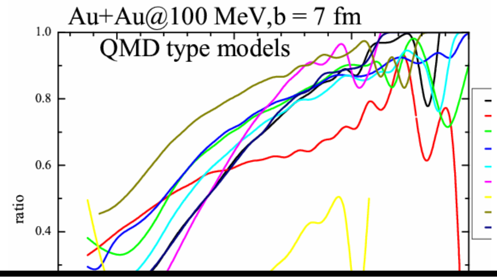


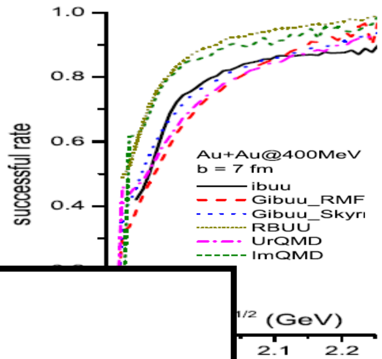








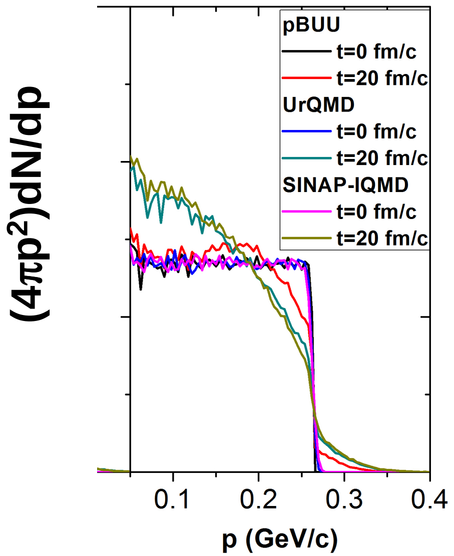


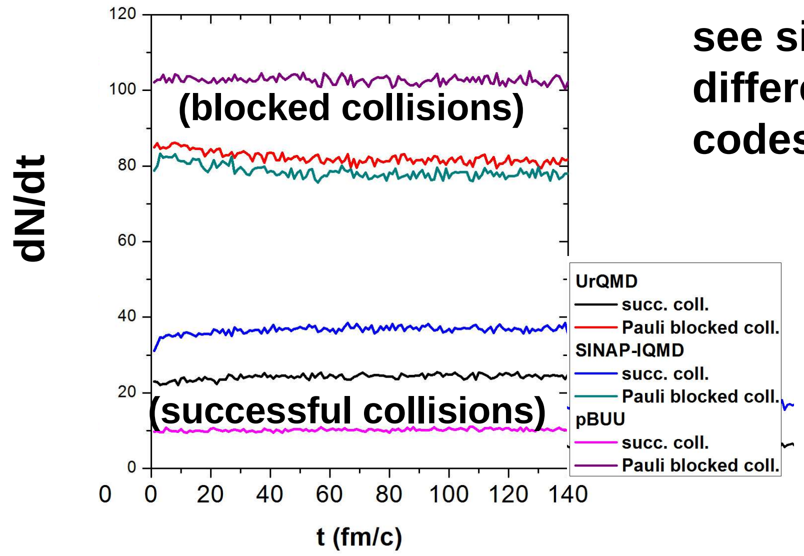


- → considerable differences
- → partly due to initialization, but mainly to collision term
- → no essential difference between BUU and QMD models
- → 100 MeV sensitive region for flow because of competition between mf and collisions, better at higher energy

Transport Calculations in a (periodic) Box

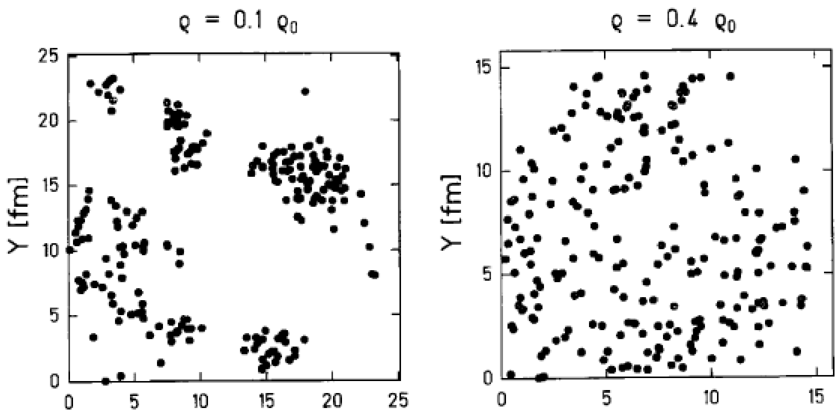
test collision routine and Pauli blocking under controlled conditions; reveal important features of the semiclassical approach.
One effect: Initialization, T=0. →Fermi statistics is lost quickly!





see significant differences between codes!

Broader applications:
1. Intialization in spinodal region: fragment formation, check of fluctuations
2. Intialize not in ground state: check of equilibration



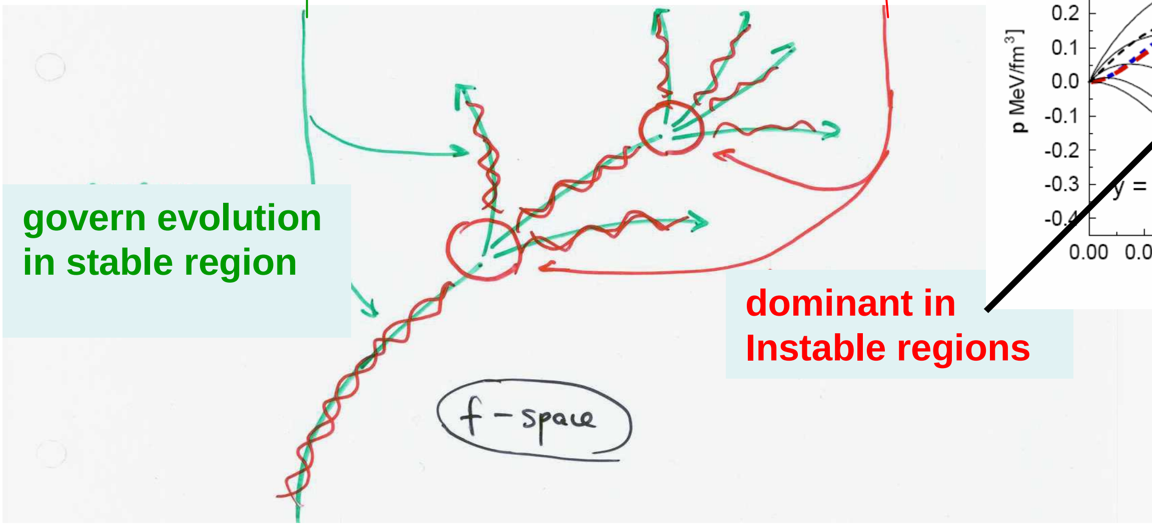
Fluctuations in Phase Space

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

Mean field evolution (dissipative)　　Fluctuations

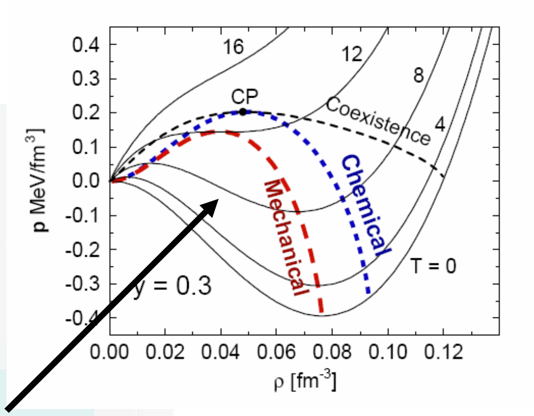
Boltzmann-Langevin eqn.

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



govern evolution in stable region

dominant in Instable regions



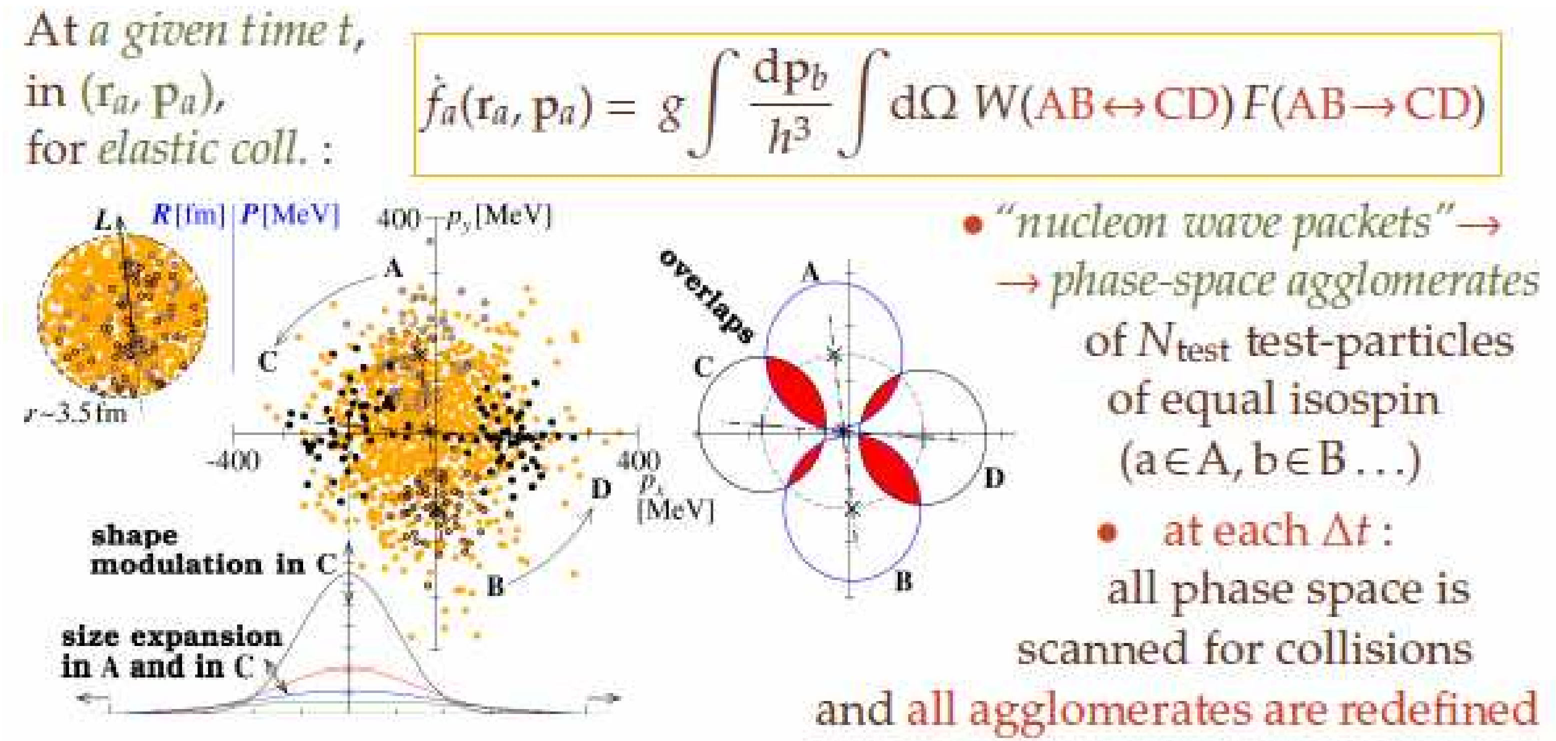
Origin of fluctuations: → **initial state correlations** (how important and realistic?)
→ **higher order correlations**
→ **collisions** (diss.-fluct. theorem)

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

- Stochastic Mean-Field (SMF) model :
  Fluctuations are projected on the coordinate space

P. Napolitani
M. Colonna

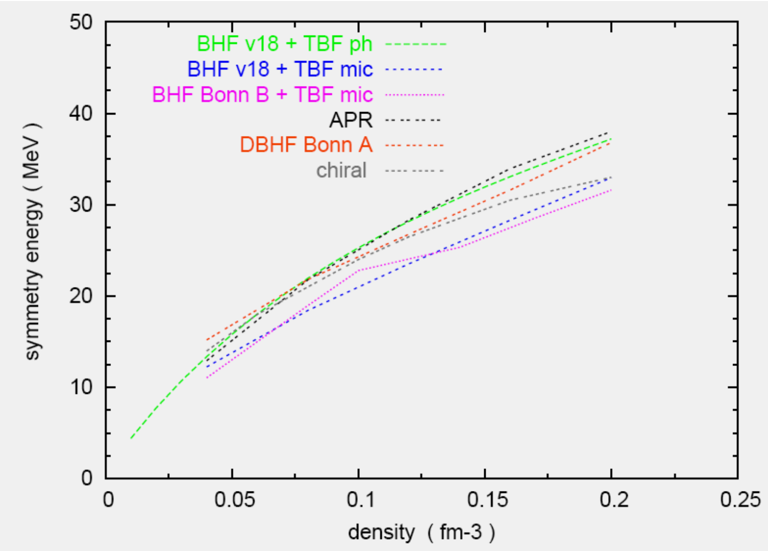
- Boltzmann-Langevin One Body (**BLOB**) model :
  fluctuations implemented in full phase space

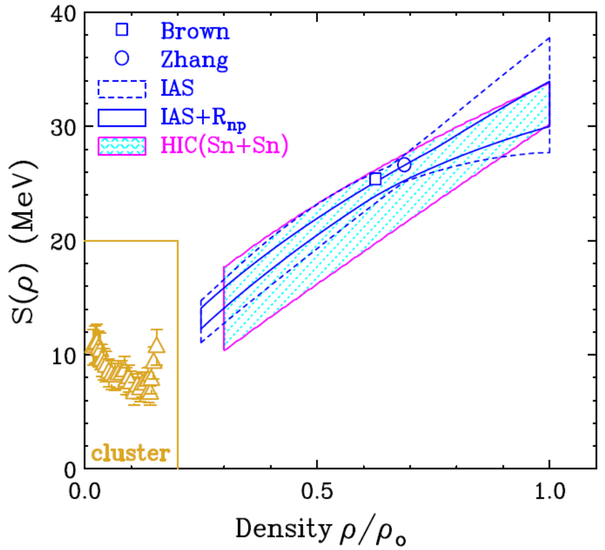


- Clouds of test particles (nucleons) are moved once a collision happens
- Shape modulation of the packet ensures Pauli blocking is respected

Napolitani and Colonna, PLB 2013

SE: Microscopic many-body calculations: Marcello Baldo, NuSYM14



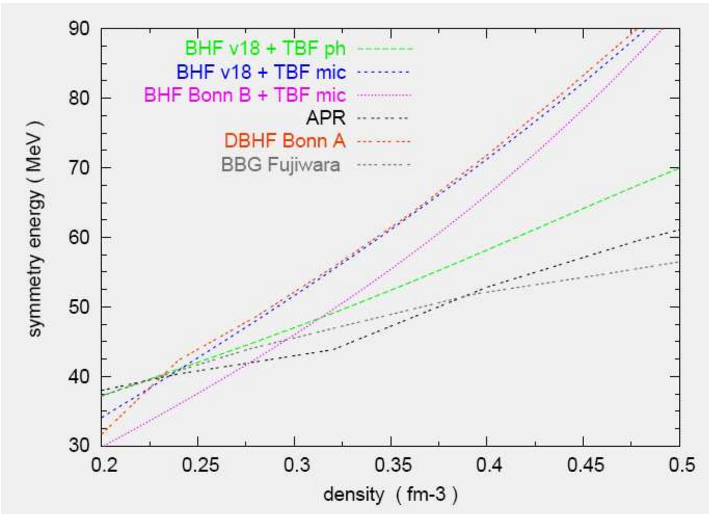


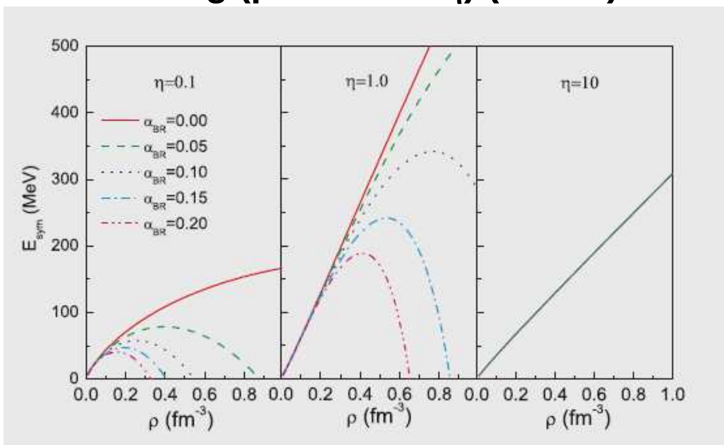
J. Phys. G: Nucl. Part. Phys. 41 (2014) 093001

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

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

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

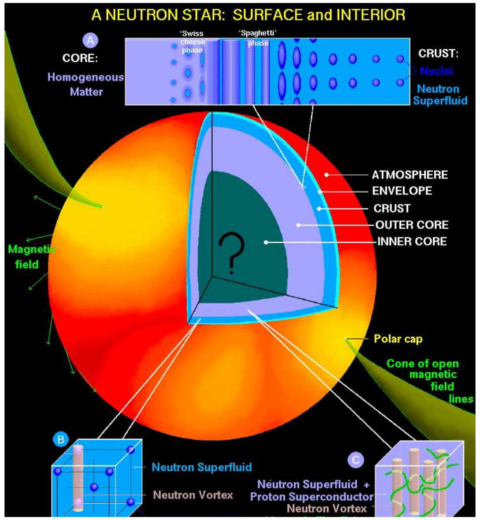


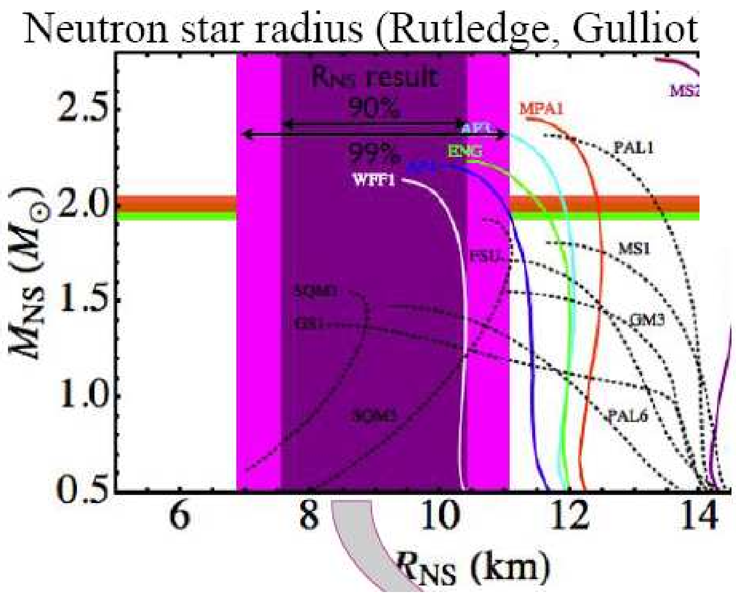


further work required! Investigation heavy ion collisions

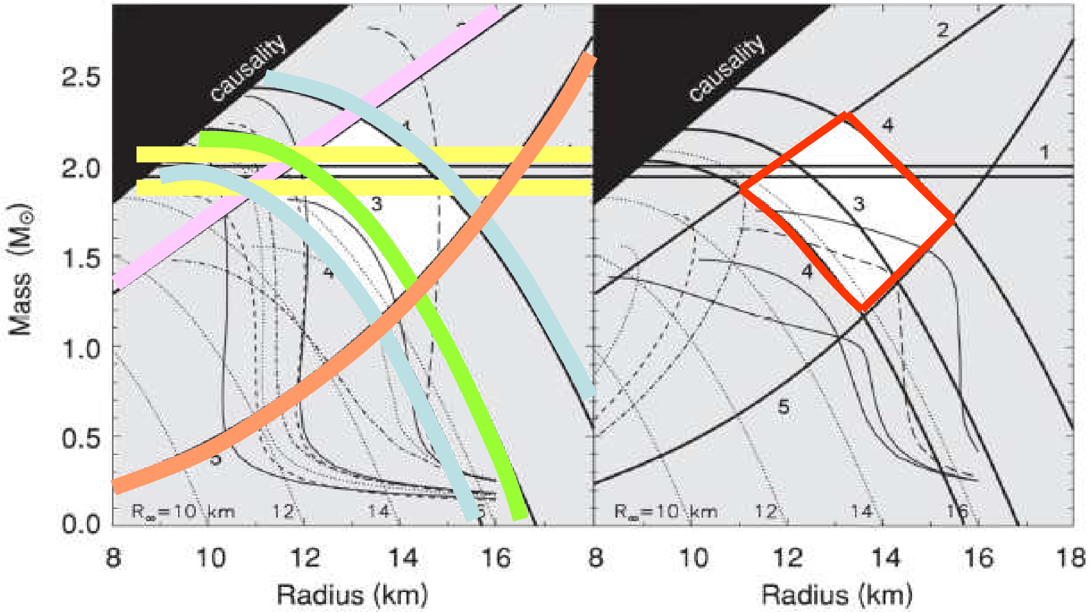
Constraints on EoS from Astrophysical Observation

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





Trümper Constraints (Universe Cluster, Irsee 2012)



1 Largest mass J1614 - 2230
(Demorest et al. 2010)

2 Maximum gravity XTE 1814 – 338
(Bhattacharyya et al. 2005)

3 Minimum radius RXJ1856 - 3754
(Trümper et al. 2004)

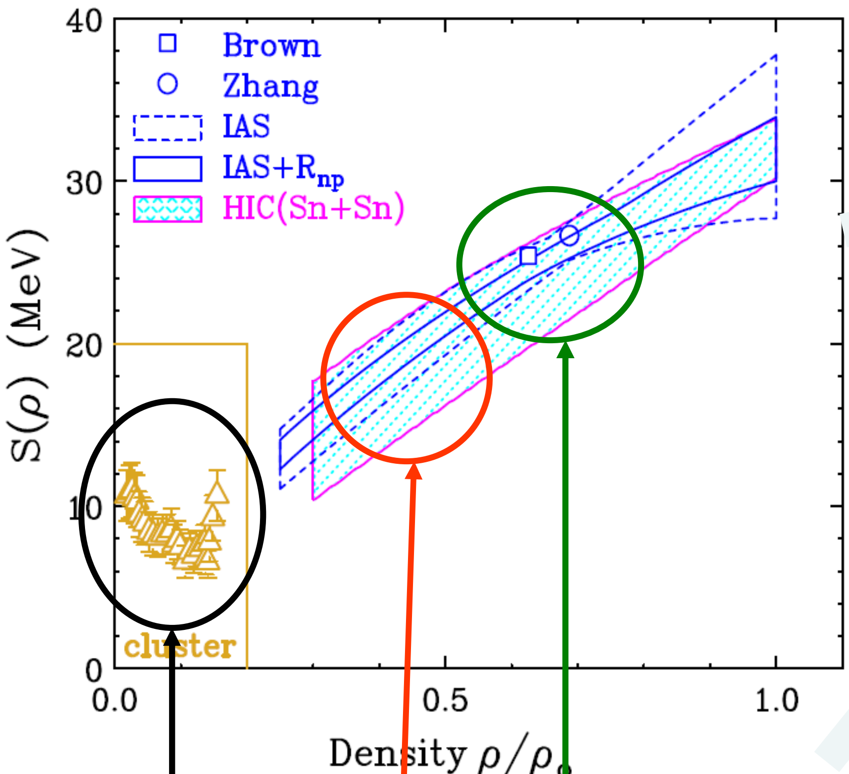
4 Radius, 90% confidence limits LMXB 47 Tuc
(Heinke et al. 2006)

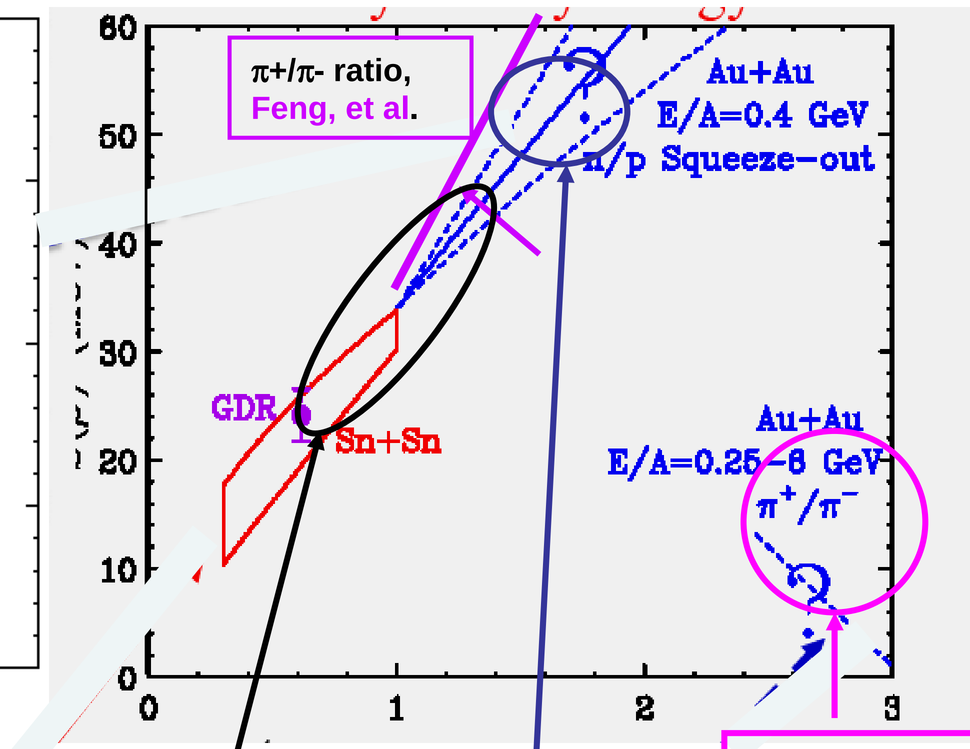
5 Largest spin frequency J1748 – 2446
(Hessels et al. 2006)

Increasingly stringent constraint on many EoS models

Present constraints on the symmetry energy from HIC

discuss for different density regions





very low density, clusterization

fragmentation, liquid-gas PT

around ρ_0, masses, collective excitations

pre-equilibrium emission of nucleons and light clusters

collective flow

pion, kaon,.. production

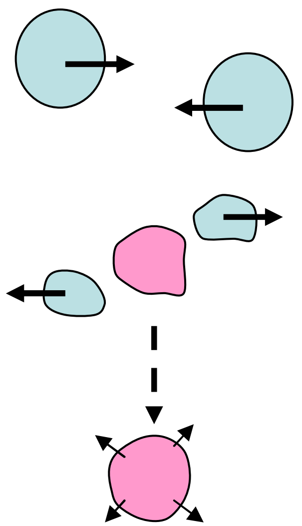
talks C. Hagel, C. Horowitz

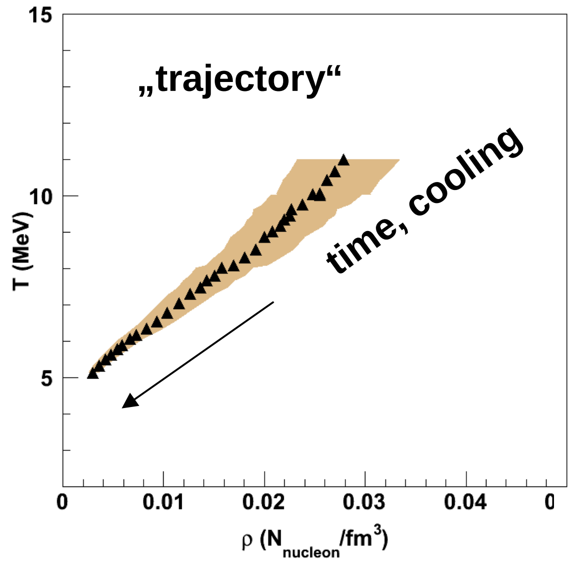
Contributions to the workshop from all these fields!
almost impossible to summarize in a finite time

Investigation of very low density NSE in Heavy ion collisions

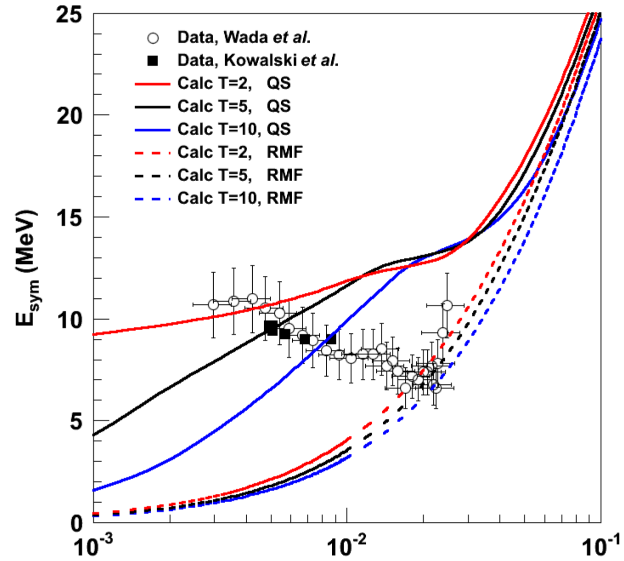
C. Hagel

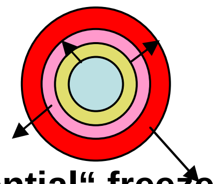
e.g. experiment 64Zn+(92Mo,197Au) at 35 AMeV
S. Kowalski, J. Natowitz, et al.,PRC75 014601 (2007)
J. Natowitz, G. Röpke, S. Typel, .. PRL 104, 202501 (2010)



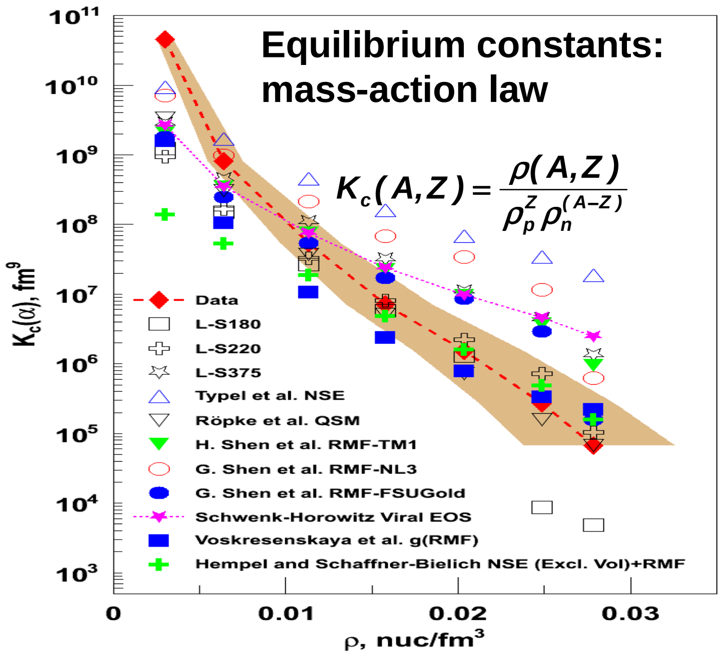


symmetry energy



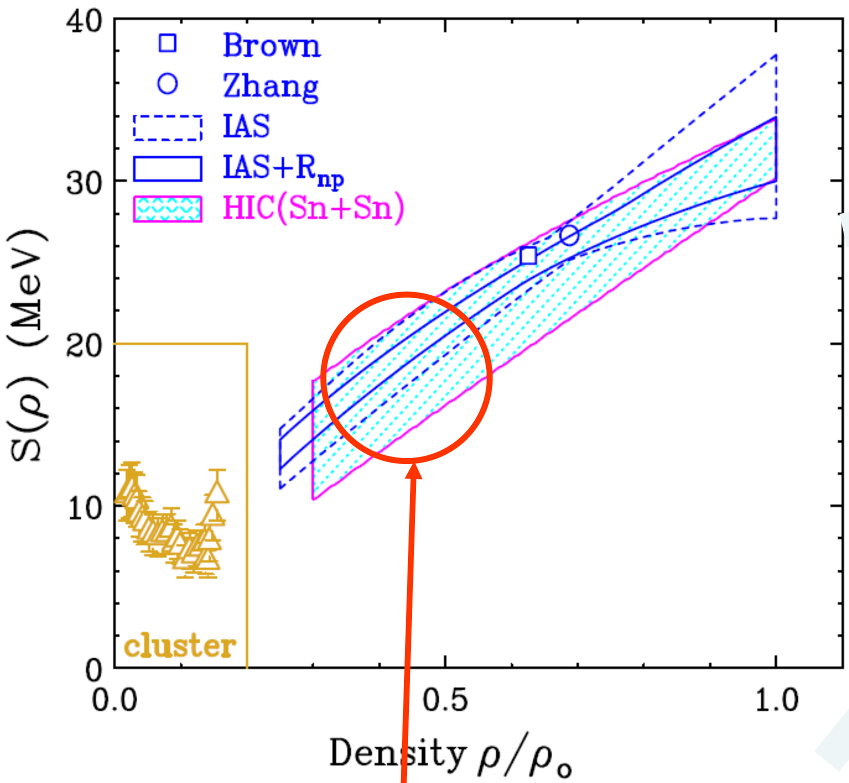


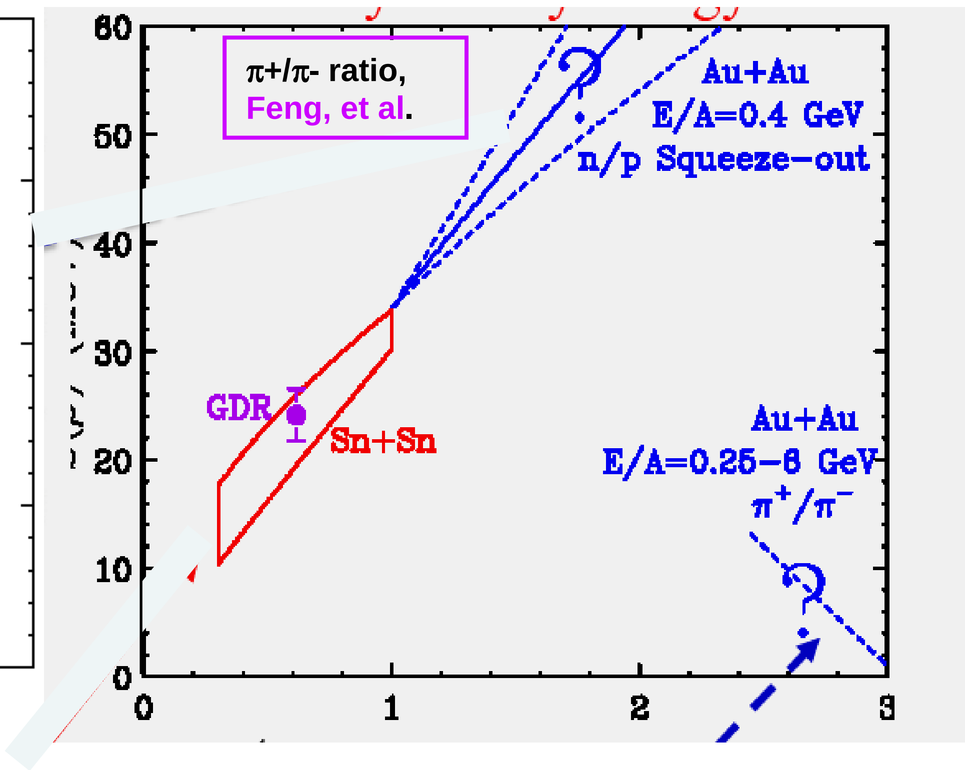
„differential“ freeze-out analysis:
source reconstruction,
analysis in terms of v_{surf}~time of emission
determination of thermodyn. properties as fct of v_{surf}
determination of symmetry energy



Assumptions need to be checked in transport calculations.

Present constraints on the symmetry energy from HIC
discuss for different density regions



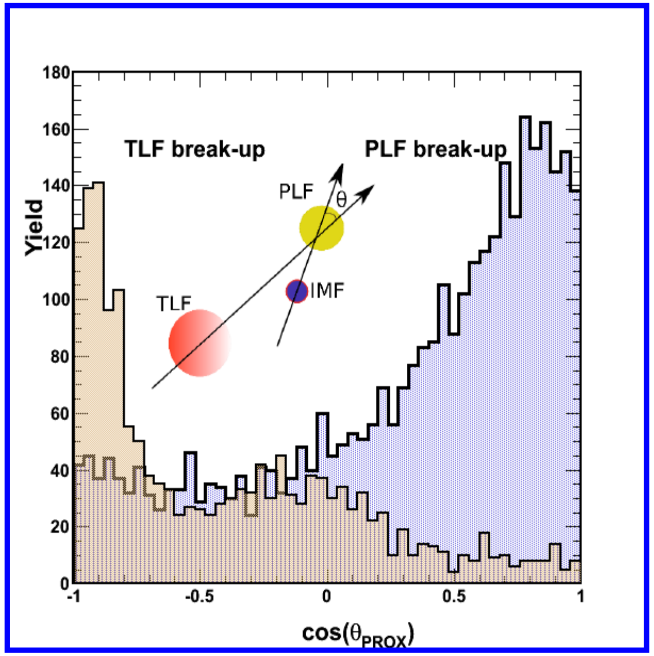


fragmentation,
liquid-gas PT

Region of low densitiy symmetry energy:
→importance of fluctuations: Langevin terms
Colonna, Napolitani

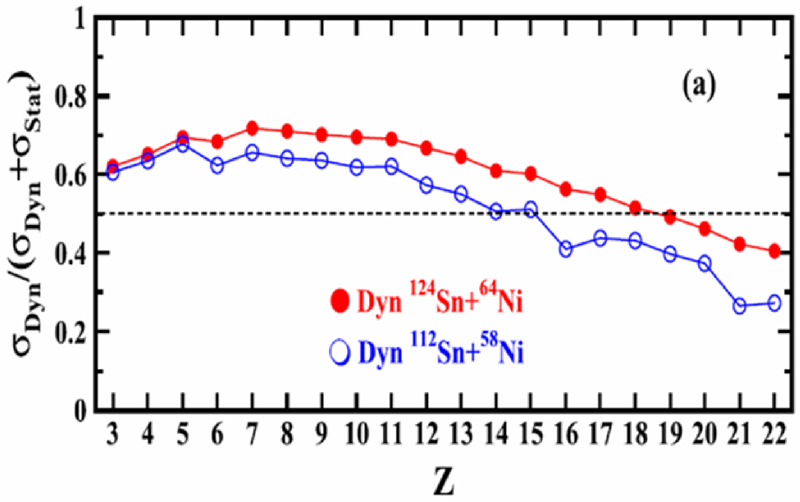
- isospin transport (migration, fractionation): Colonna
- isospin diffusion, neck neutron enrichment
- multifragmentation, freeze out approximation
- dynamical fission

E. De Filippo: Dynamical fission at low energies
Break-up of PLF in vicinity of TLF.



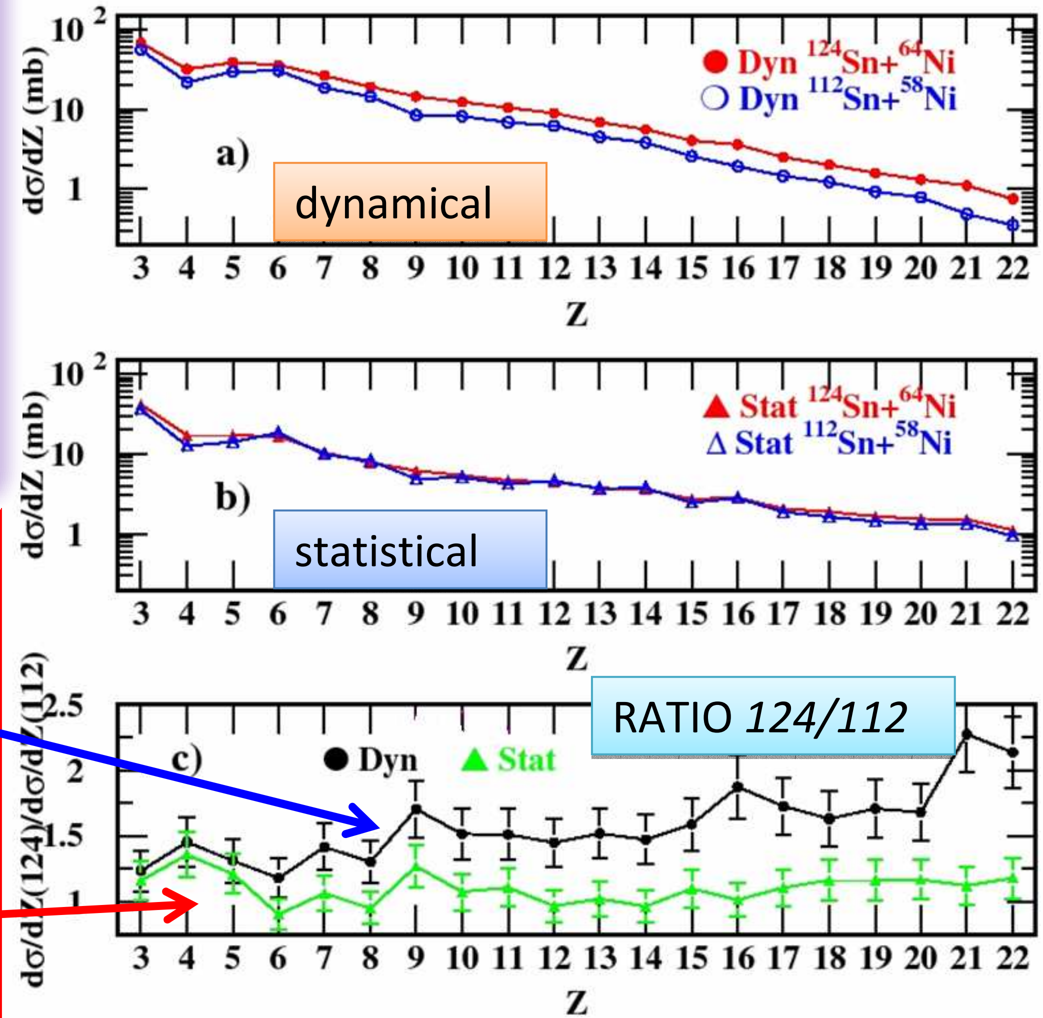
Comparison of IMFs cross sections for $^{124}Sn+^{64}Ni$ and $^{112}Sn+^{58}Ni$

Ratio of $\sigma_{dyn}/(\sigma_{dyn}+\sigma_{stat})$ as a function of IMFs charge Z for the two systems.



P. Russotto et al. , Phys. Rev. C91, 014610 (2015)

Cross-sections



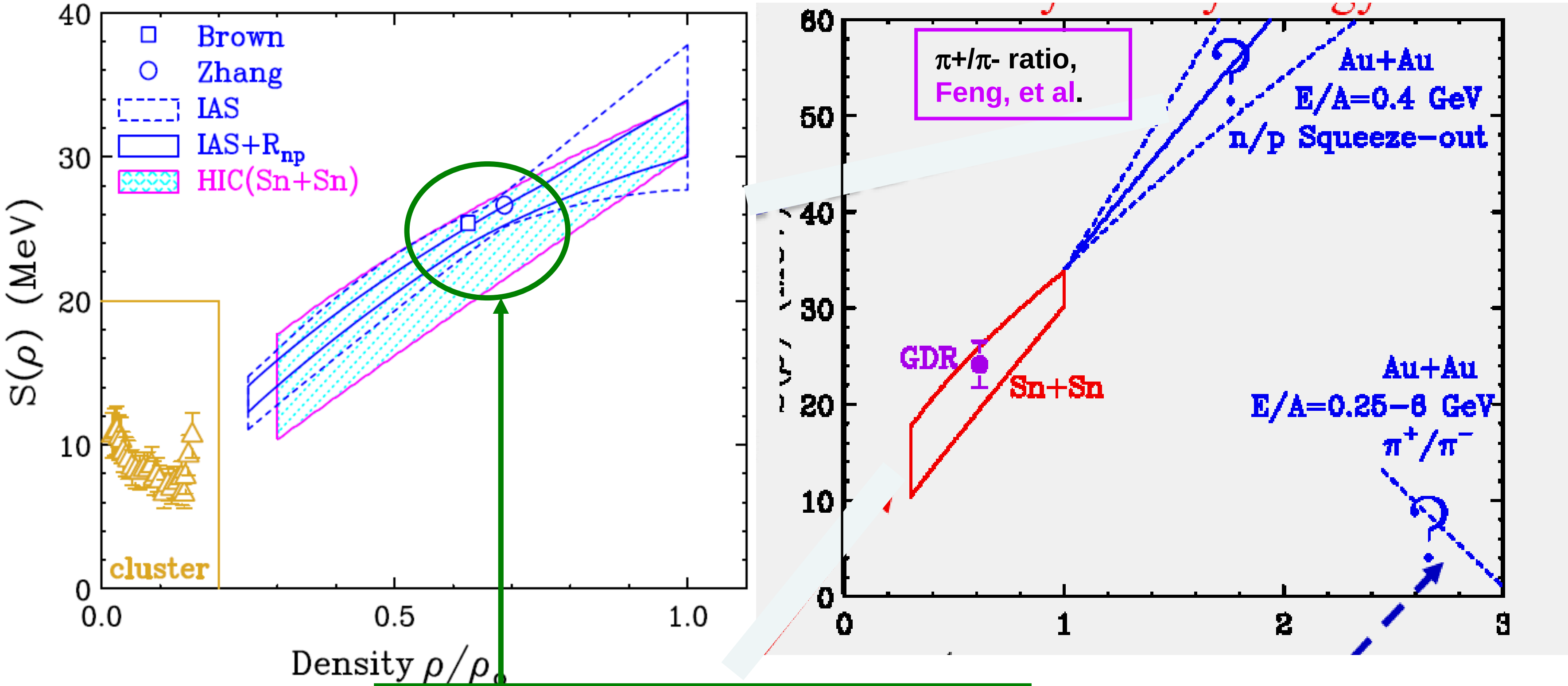
•Dynamical component: enhanced for the neutron rich

•Statistical component: almost equal (A ratio: ~1.1 close to the mass ratio between the systems)

DeFilippo

see also A.B. McIntosh et al. PRC 81 034603 (2010)

Present constraints on the symmetry energy from HIC
discuss for different density regions

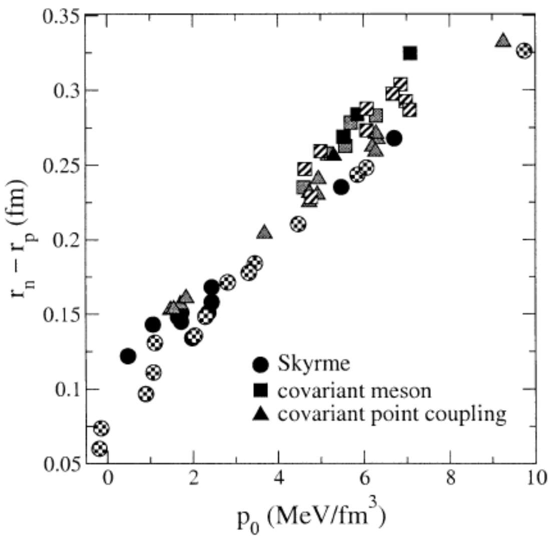


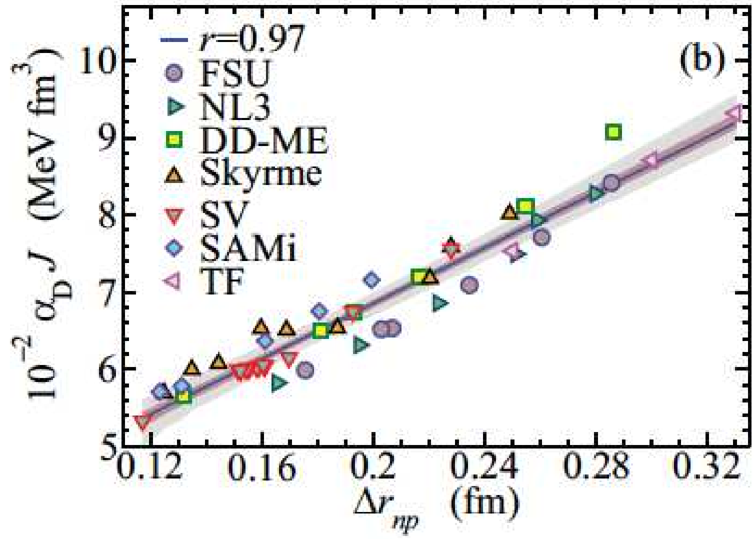
around ρ_0: Masses,
Giant resonances: IVGDR, PDR, ISGDR
Dipole radiation
Clustering in skin
Correlations (S←→L)

Correlations (X. Roca-Maza)

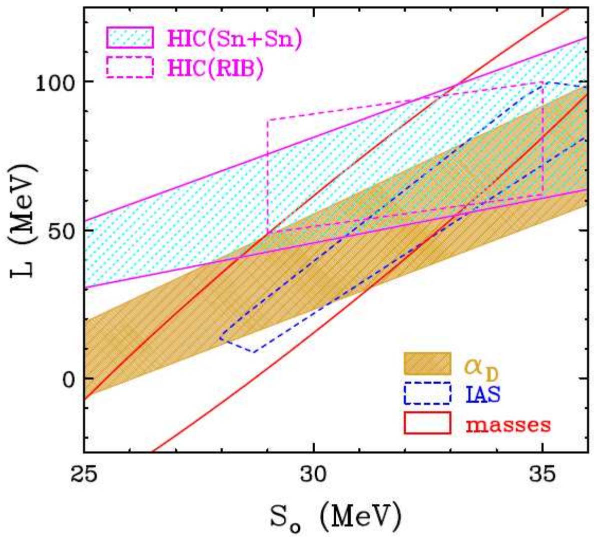
distinguish between

1) correlations between model parameters and an observable, or between observables e.g.



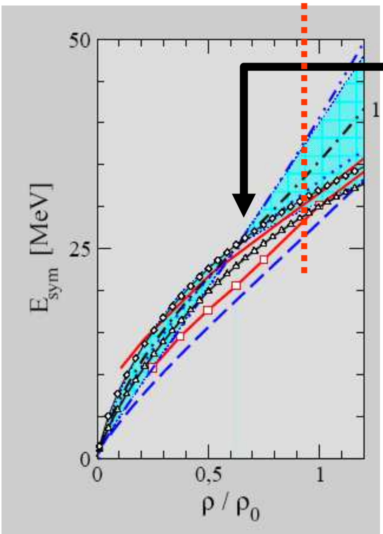


2) and correlations between model parameters, e.g. S_0 and L



C.J.Horowitz, et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 093001

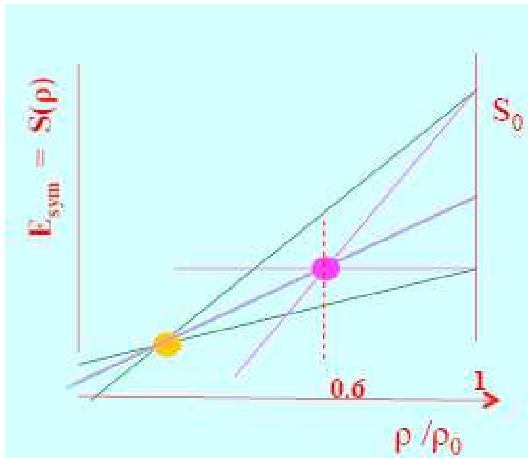
Correlations between model parameters, e.g.



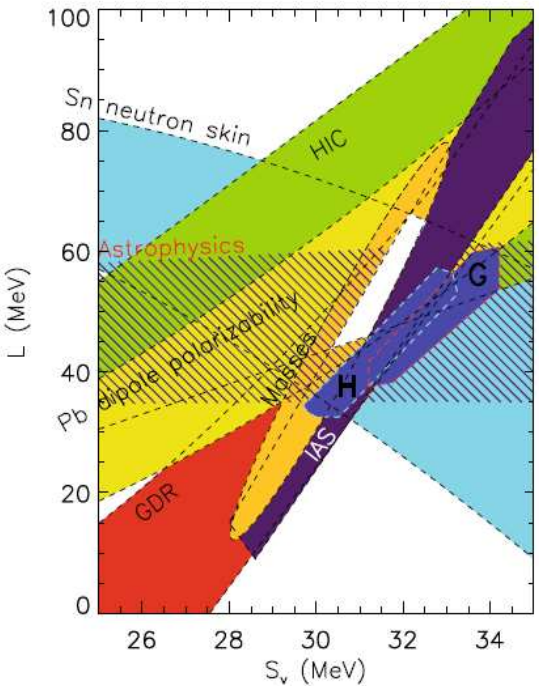
-- e.g. SE that fit nuclear masses cross below saturation density,
(some average densitiy of a finite nucleus)

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

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



(from M. Colonna)



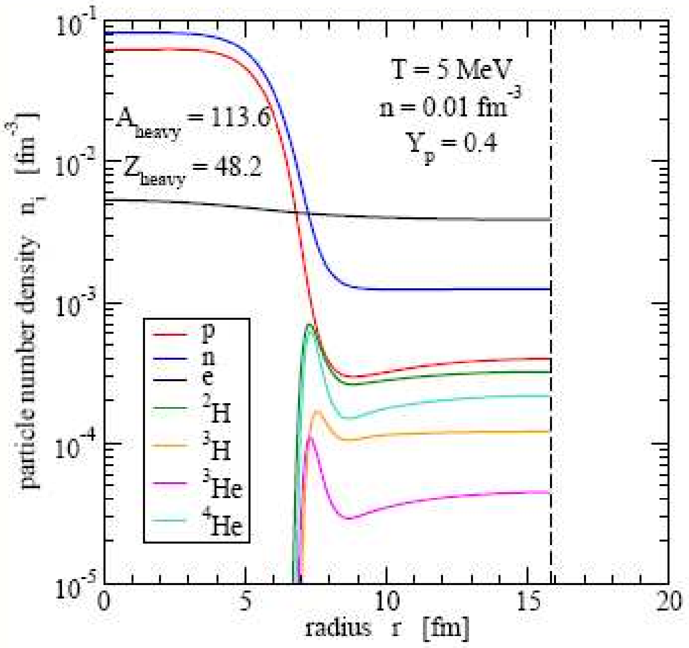
--different observables are sensitive to different densities
(or ranges of densities) and thus induce different correlations

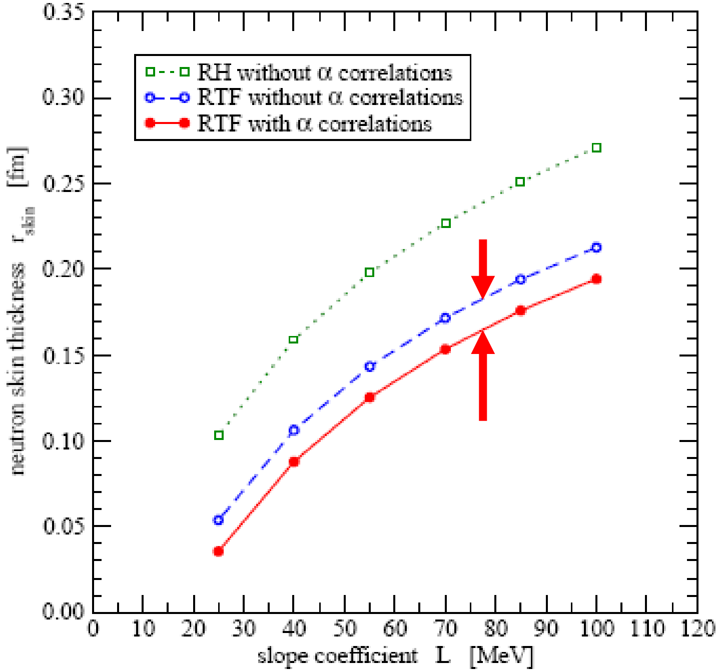
-- crossing point will hopefully fix S and L, which are
independent

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

Neutron Skins with Cluster Correlations

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation
  $\Rightarrow$ enhanced cluster probability at surface of heavy nuclei, effects for **heavy nuclei in vacuum at zero temperature**?



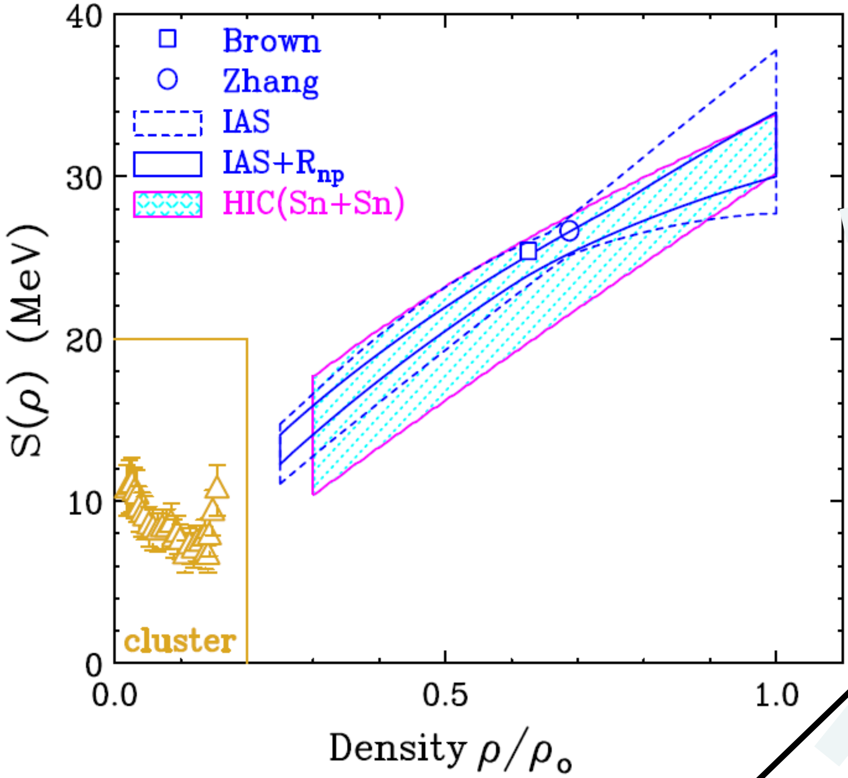


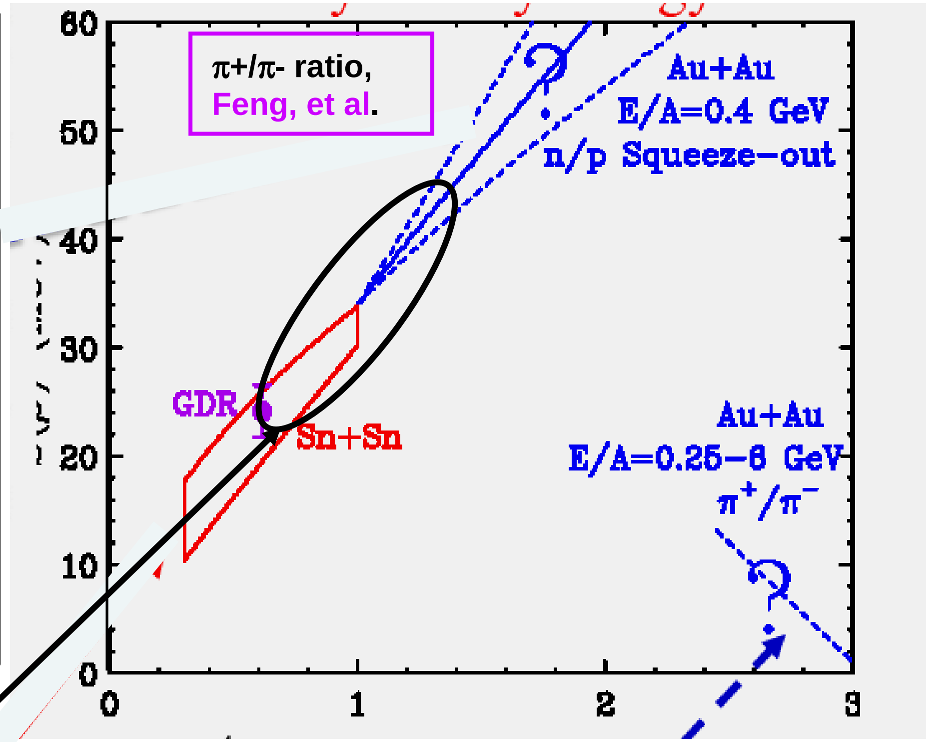
important effect for determination of L via measuerement of skin thickness

S. Typel, arXiv 1403.2851

Present constraints on the symmetry energy from HIC

discuss for different density regions



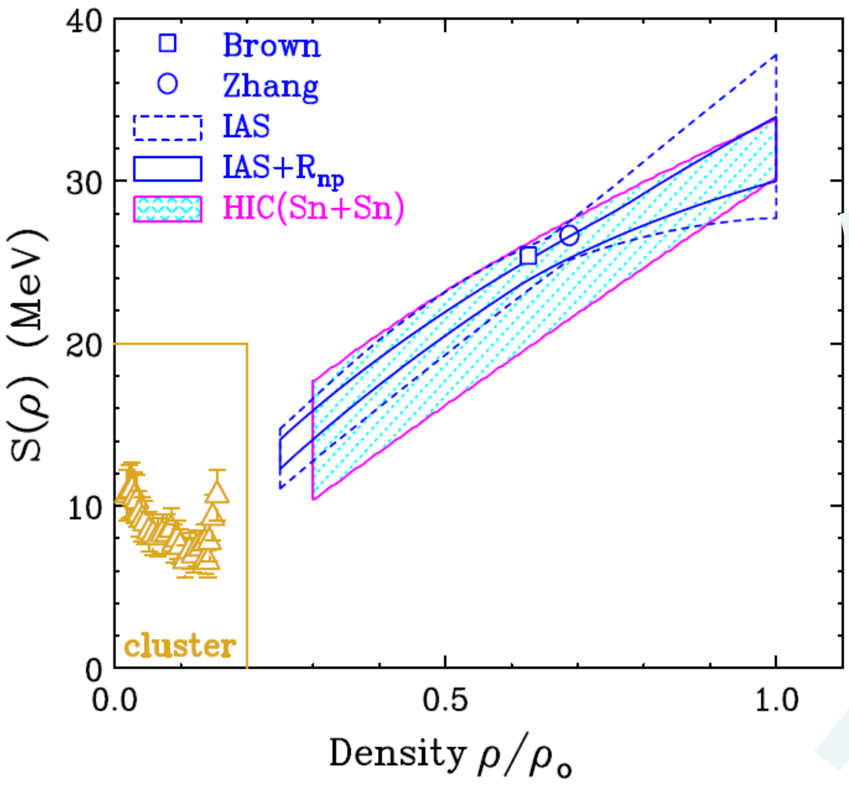


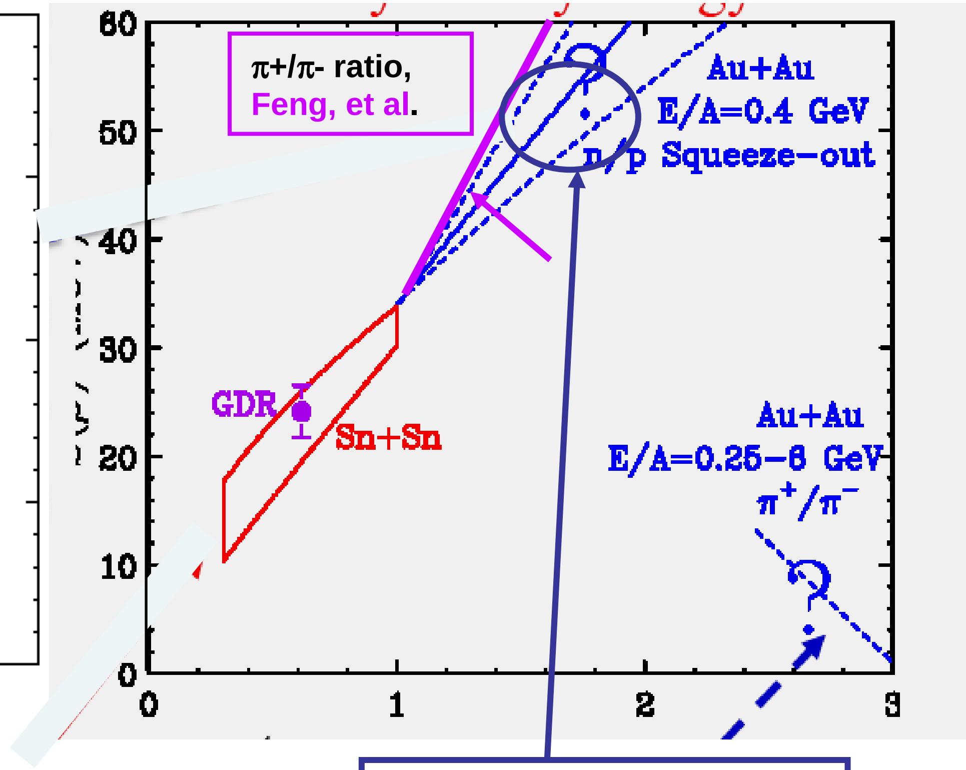
pre-equilibrium emission of nucleons and light clusters

- discussed in my previous talk and extensively in open discussion,
- a promising probe of the symmetry energy and the effective mass splitting
- but needs a reliable treatment of light cluster production in collisions

Present constraints on the symmetry energy from HIC

discuss for different density regions





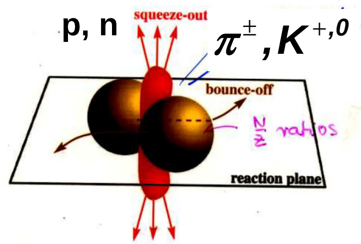
collective n/p flow
ASYEoS Experiment

symmetric EOS: LeFevre

Momentum distributions, “Flow”

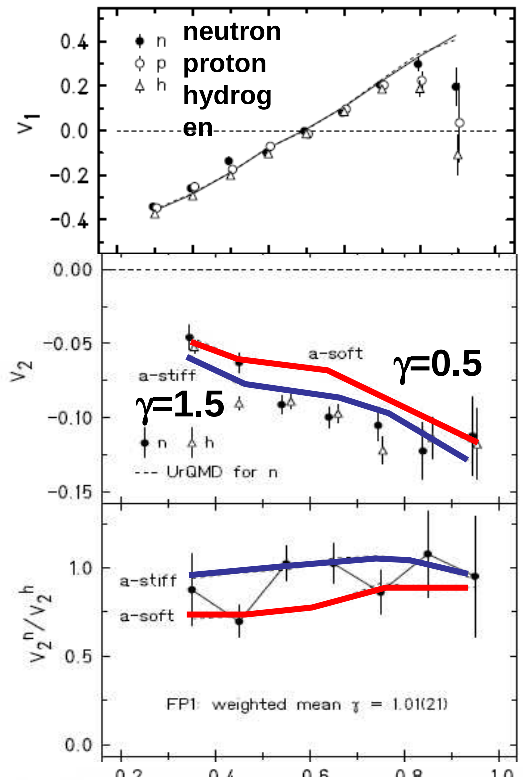
Au+Au @ 400 AMeV, FOPI-LAND

prediction



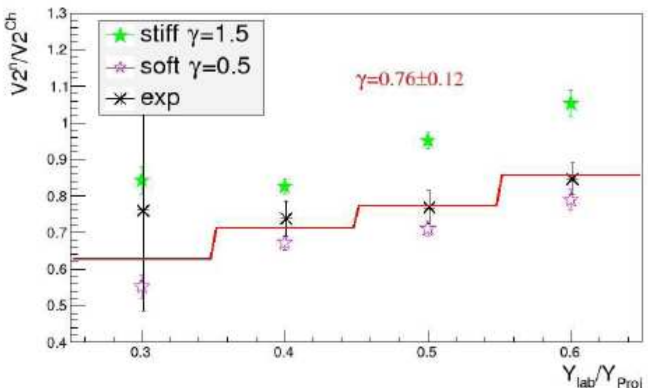
- **Directed flow** not very sensitive to SE (involves many different densities)

- **Elliptic flow** in this energy region probe of high density



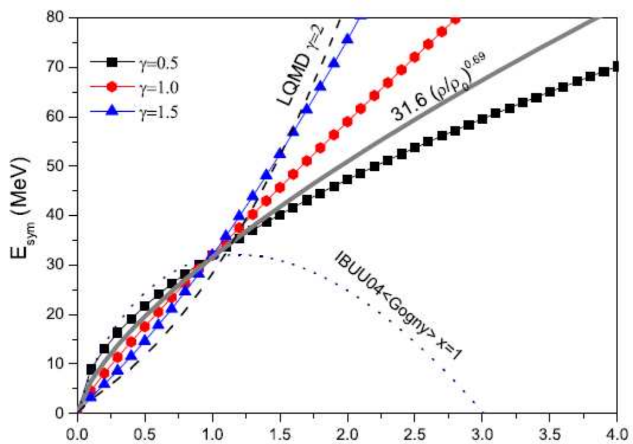
(Russotto, et al., PLB 697, 471 (11))

preliminary result from new experiment ASY-EOS (Russotto, IWM_EC workshop Catania 2014)



γ=0.7±0.2
L=70±13 (FP1)

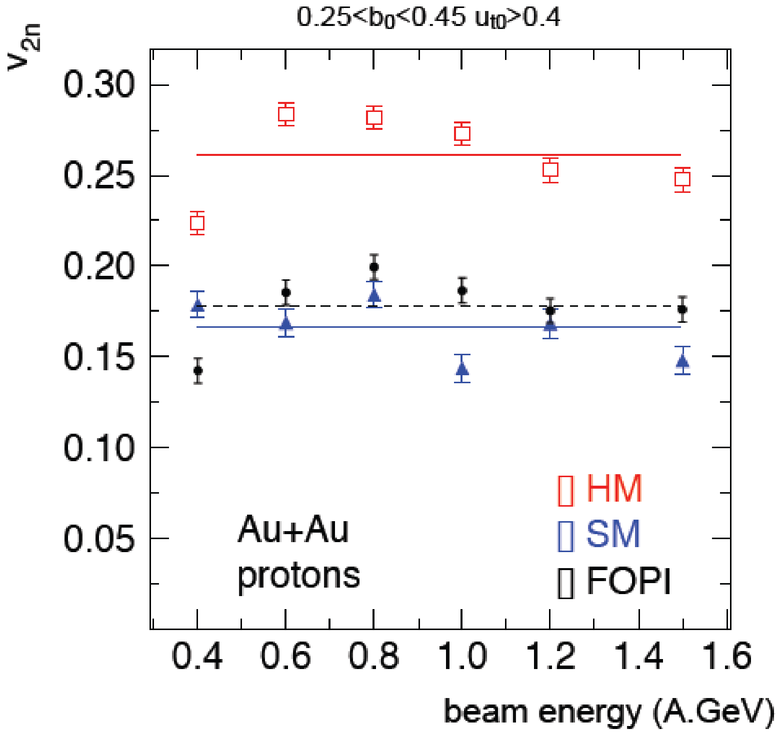
not very precise (yet) but indicates rather stiff SE, γ~1

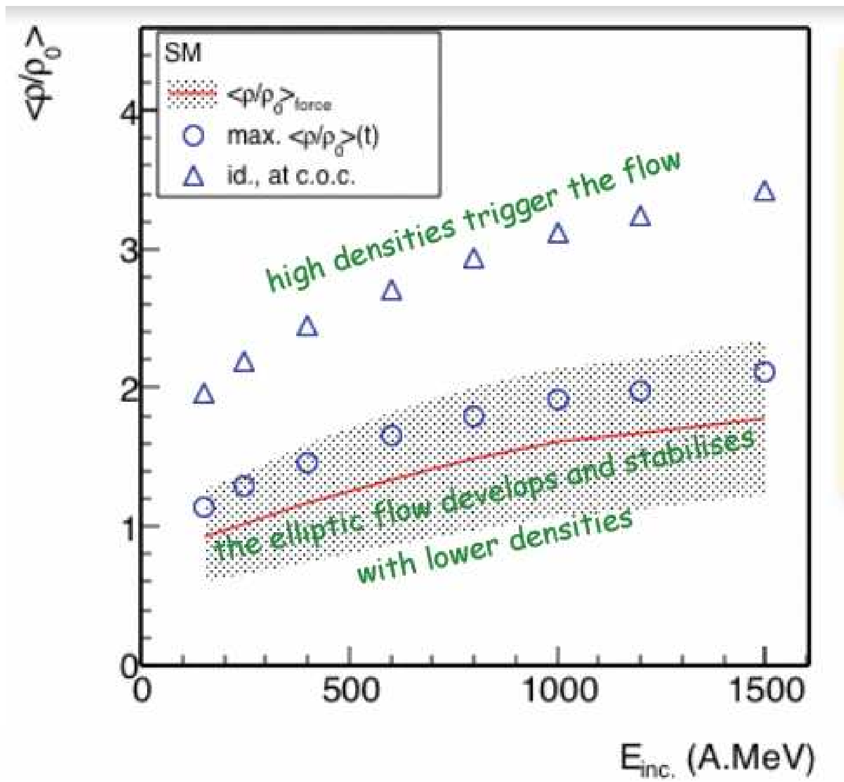


A major advance in the search for the high density Symmetry Energy!

A. Le Fevre: Analysis of extensive FOPI data on flow with IQMD:
strong constraint of the symmetric EOS
extension of earlier work by P. Danielewicz, et al., Science

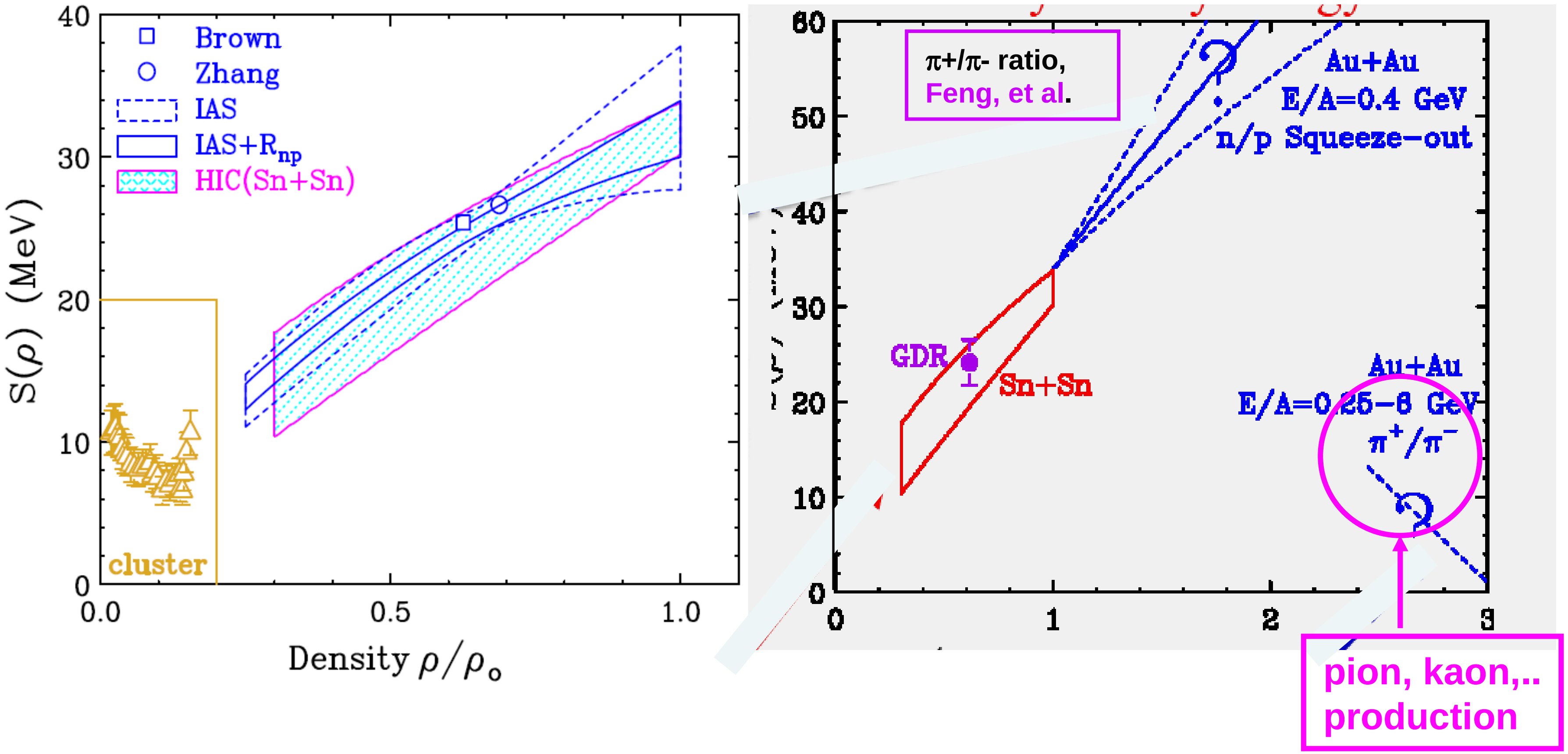
Complete shape of $v_2(y_0)$:
a new observable:
$v_{2n} = |v_{20}| + |v_{22}|$,
from fit
$v_2(y_0) = v_{20} + v_{22} \cdot y_0^2$





Present constraints on the symmetry energy from HIC

discuss for different density regions



Particle Production

Inelastic collisions: Production of particles and resonances: Coupled transport equations

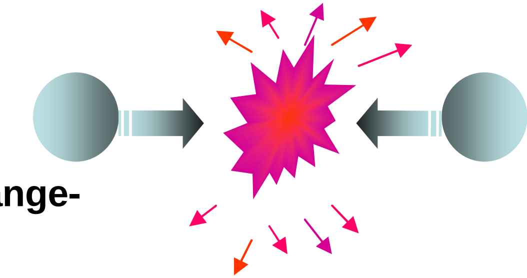
$$\frac{d}{dt} f_N(x_\mu) = I_{coll}(\sigma_{NN\to NN}, f_N;\ \sigma_{NN\to N\Delta} f_\Delta;....)$$

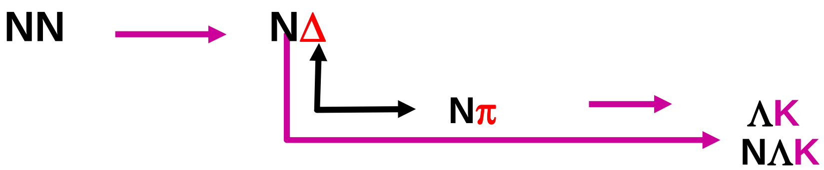
$$\frac{d}{dt} f_\Delta(x_\mu) = I_{coll}(\sigma_{\Delta N\to NYK} f_Y f_K;....)$$

etc.

e.g. pion and kaon production;

coupling of Δ and strange-ness channels.



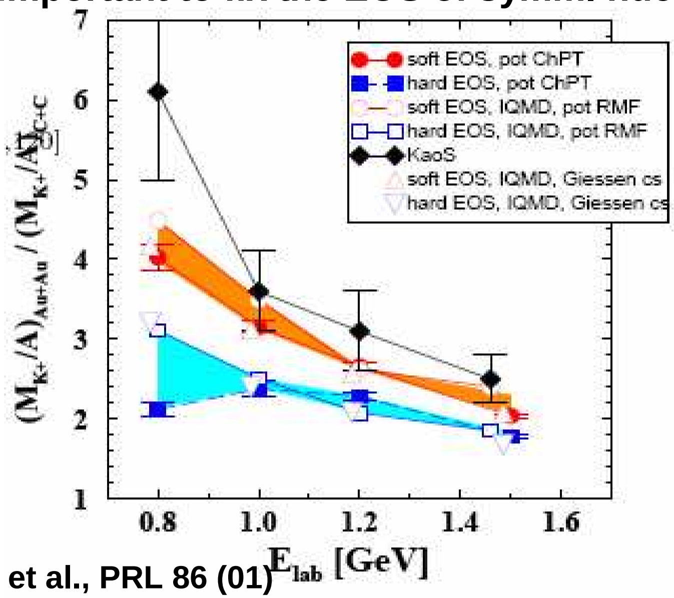


Many new potentials, elastic and inelastic cross sections needed, Δ dynamics in medium

What can one learn from different species?

- **pions**: production at all stages of the evolution via the Δ-resonace
- **kaons** (strange mesons with high mass): subthreshold production, probe of high density phase
- **ratios** of π^+/π^- and K^0/K^+: → probe for symmetry energy

Important to fix the EOS of symm. nucl. matter



Fuchs, et al., PRL 86 (01)

Particle production as probe of symmetry energy

Two effects:

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

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 assumption 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

$$\sigma = \sigma_{inel}\left(\sqrt{s_{in}} - \sqrt{s_{in}}\right)$$

Detailed analysis gives

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

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

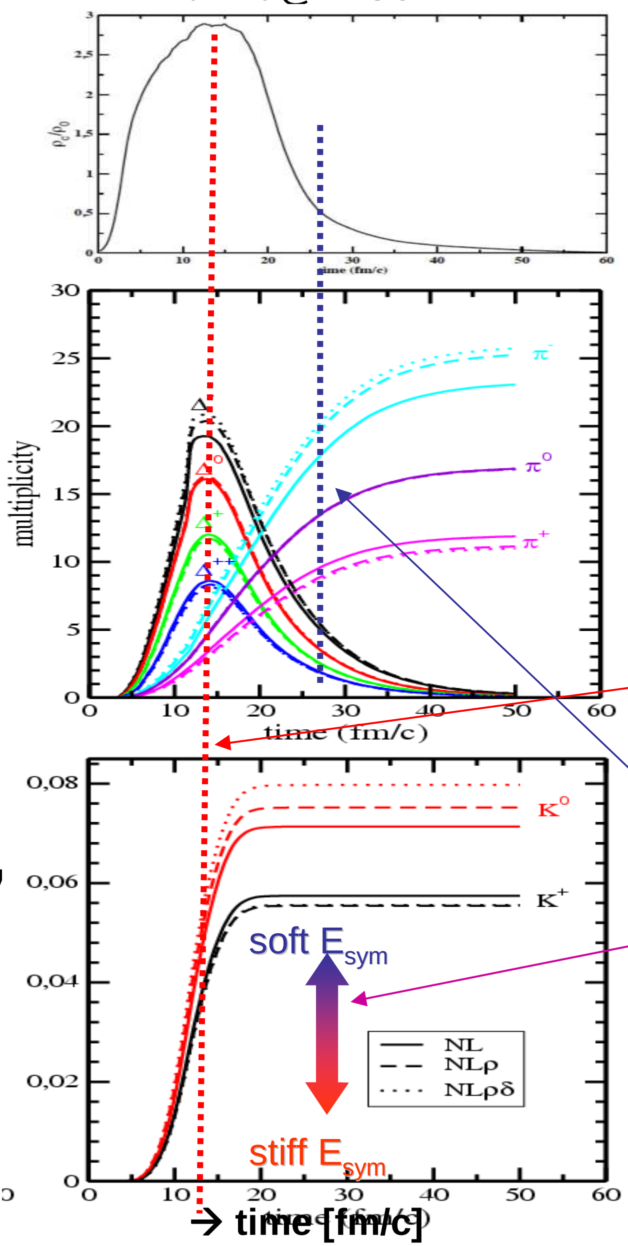
Dynamics of particle production (Δ,π,K) in heavy ion collisions

Au+Au@1AGeV

Central density

π and Δ multiplicity

$K^{0,+}$ multiplicity



→ time [fm/c]

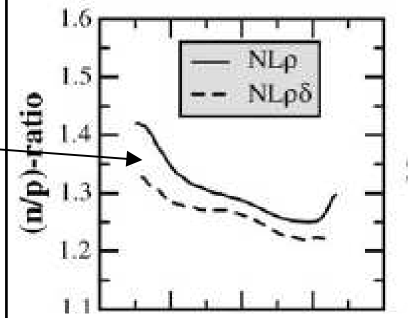
Dependence of ratios on asy-stiffness

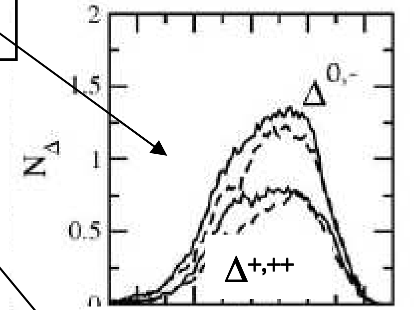
n/p

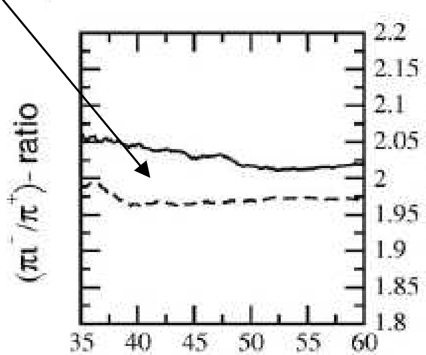
→ $\Delta^{0,-}/\Delta^{+,++}$

→ π^-/π^+

Au+Au, 0.6AMeV





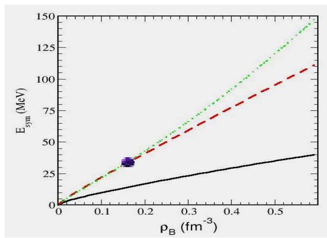


time [fm/c]

Δ and K: production in high density phase

Pions: low and high density phase

Sensitivity to asy-stiffness



NLρδ

NLρ

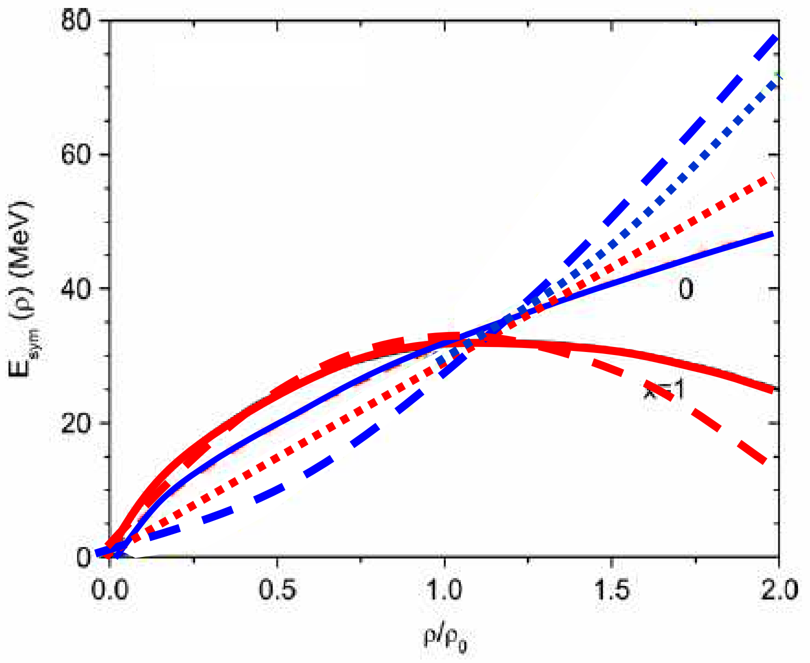
NL

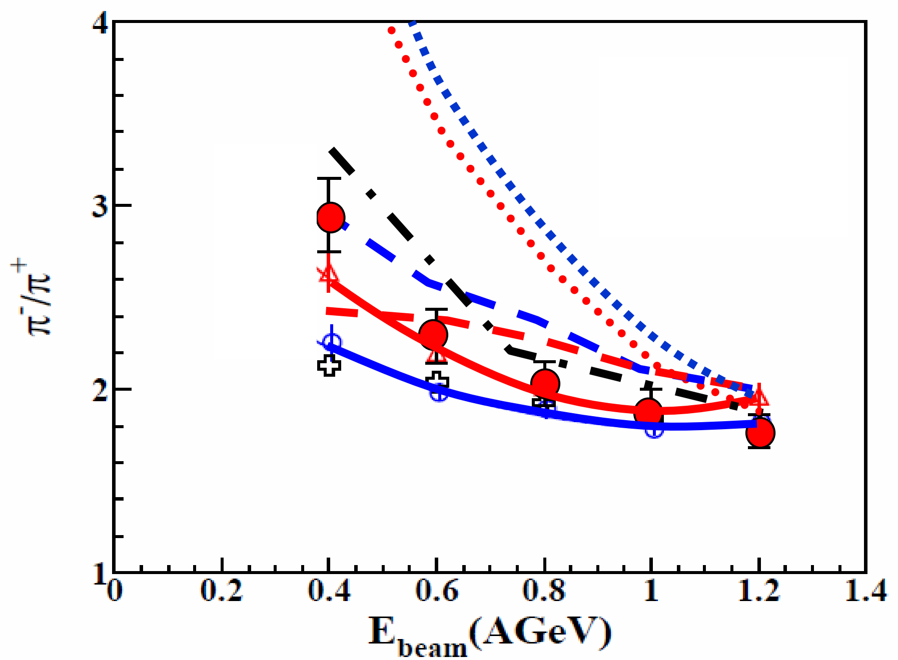
G.Ferini et al.,PRL 97 (2006) 202301

Pion ratios in comparison to FOPI data

Au+Au, semi-central

solid blue	MDI, x=0, mod. soft	Xiao,.. B.A.Li, PRL 102 (09)
solid red	MDI, x=1, very soft	Xiao,.. B.A.Li, PRL 102 (09)
dotted blue	NLρδ, stiff	Ferini, Gaitanos,.. NPA 762 (05)
dotted red	NLρ, linear	Ferini, Gaitanos,.. NPA 762 (05)
dashed blue	γ=2, stiff	Feng,… PLB 683 (10)
dashed red	SIII, very soft	Feng,… PLB 683 (10)
black dash-dot	small dep. on SE	J. Hong, P.Danielewicz
red circle	FOPI exp (NPA 781, 459 (07))	





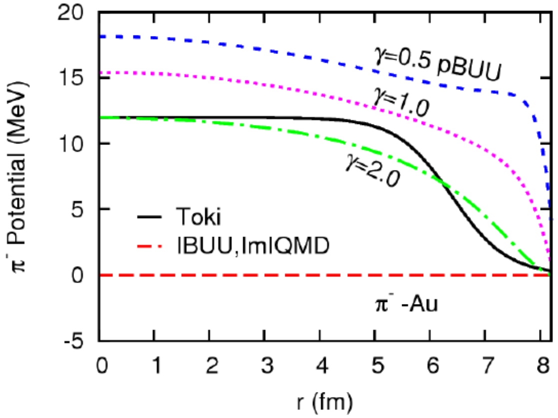
Contradictory results, trend with asy-stiffness differs

P. Danielewicz

π vs Baryon Optical Potentials

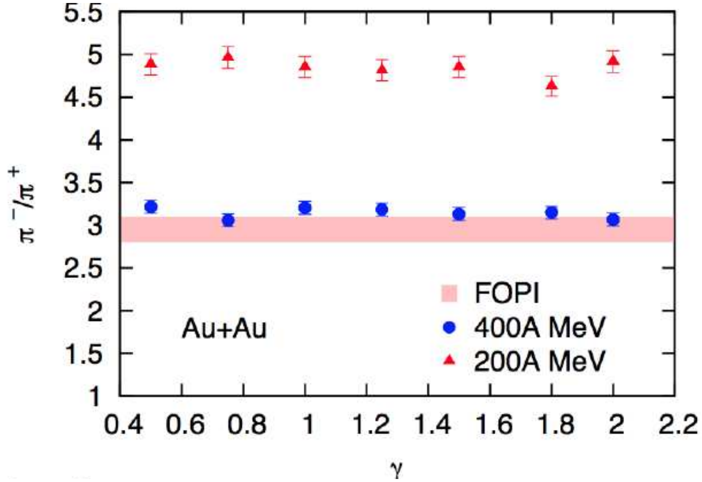
$$\Delta \longleftrightarrow N + \pi \qquad U_\Delta \overset{?}{=} U_N + U_\pi$$

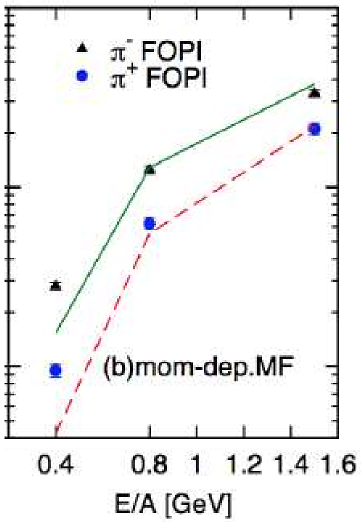
Symmetry-Energy Derived π Potential

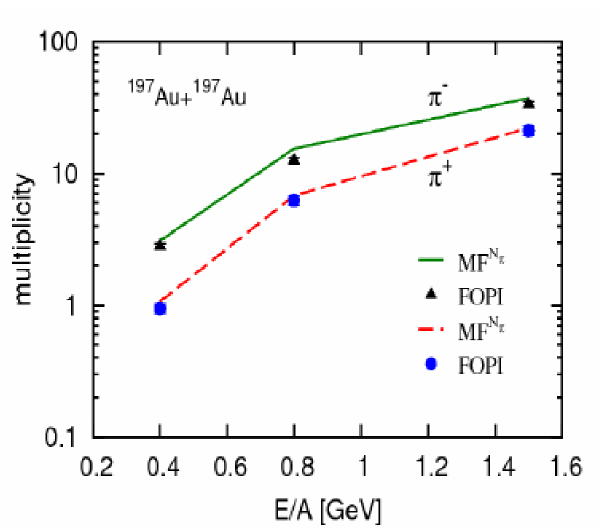


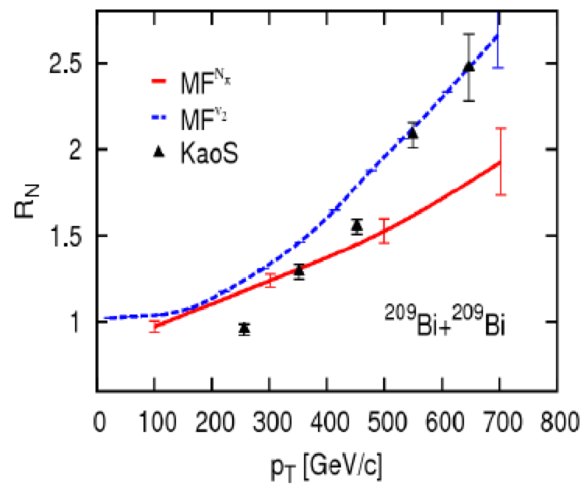
Jun Hong&PD PRC90(14)024605 Nucl density: Thomas-Fermi

→ **independence of pion ratio on SE**







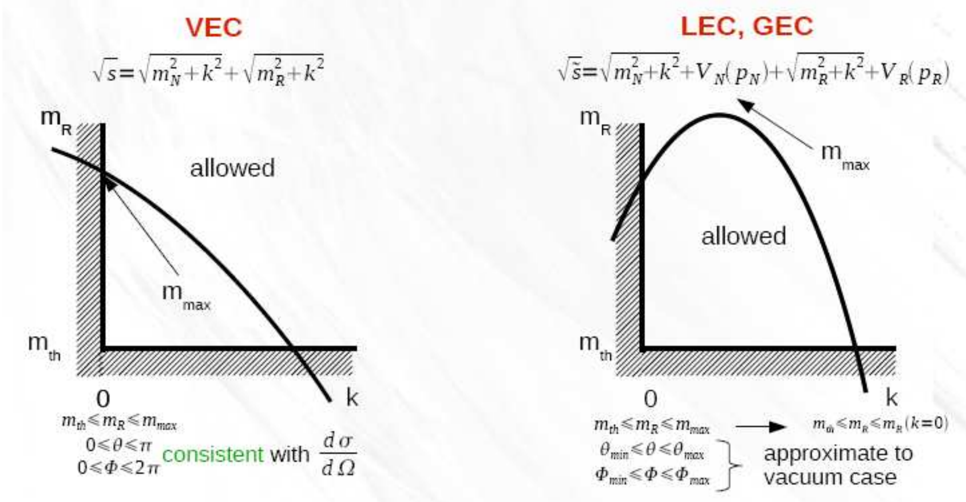


but does not fit pion data→ U_π(p) modiified (softened) for low momenta → inconsistent with ell. flow

D. Cozma

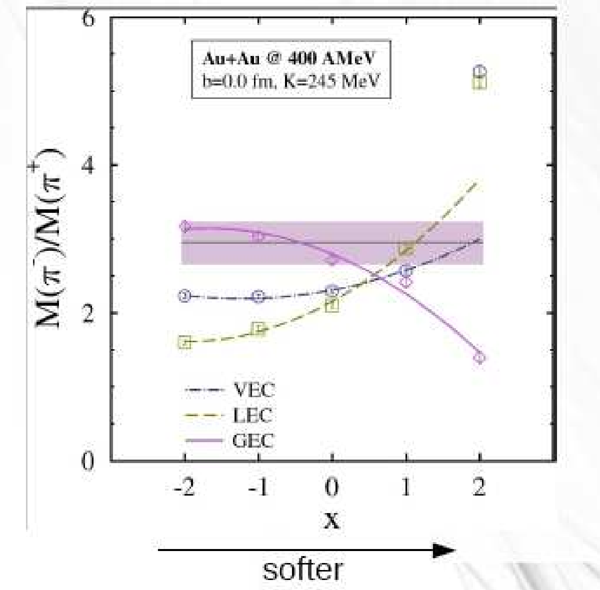
Threshold condition for NN→NR

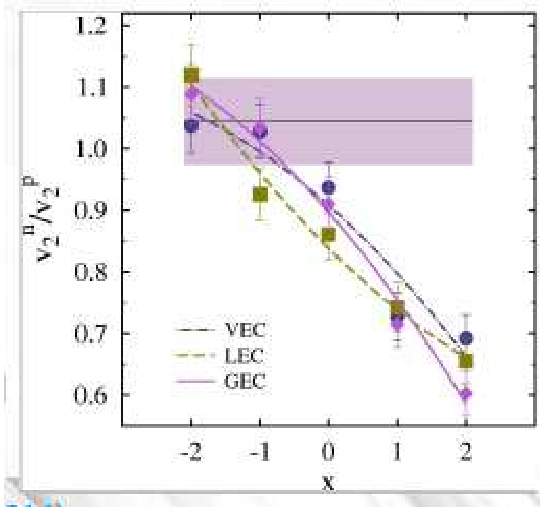
$$\sqrt{p_1^2+m_1^2}+U(p_1)+\sqrt{p_2^2+m_2^2}+U(p_2)=\sqrt{p'^2_1+m'^2_1}+U(p'_1)+\sqrt{p'^2_2+m'^2_2}+U(p'_2)$$

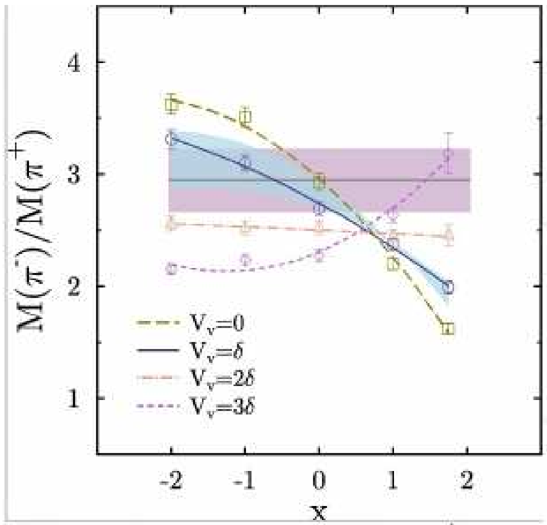


$$V(\Delta^{++})=V_s+\frac{3}{2}V_v$$
$$V(\Delta^{+})=V_s+\frac{1}{2}V_v$$
$$V(\Delta^{0})=V_s-\frac{1}{2}V_v$$
$$V(\Delta^{-})=V_s-\frac{3}{2}V_v$$

$$V_s=\frac{1}{2}(V_n+V_p)$$
$$\delta=\frac{1}{3}(V_n-V_p)$$





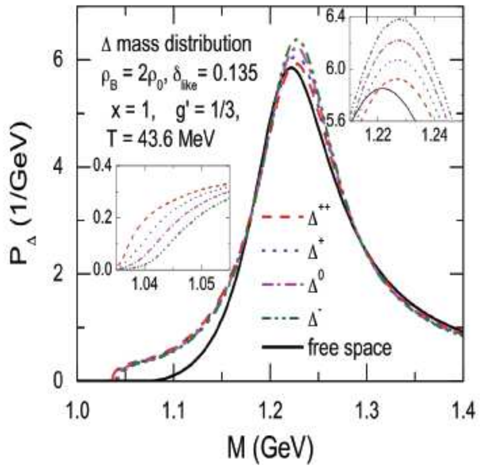


strong dependence on assumption on threshold condition
consistency with flow can be achieved for stiff SE and GEC

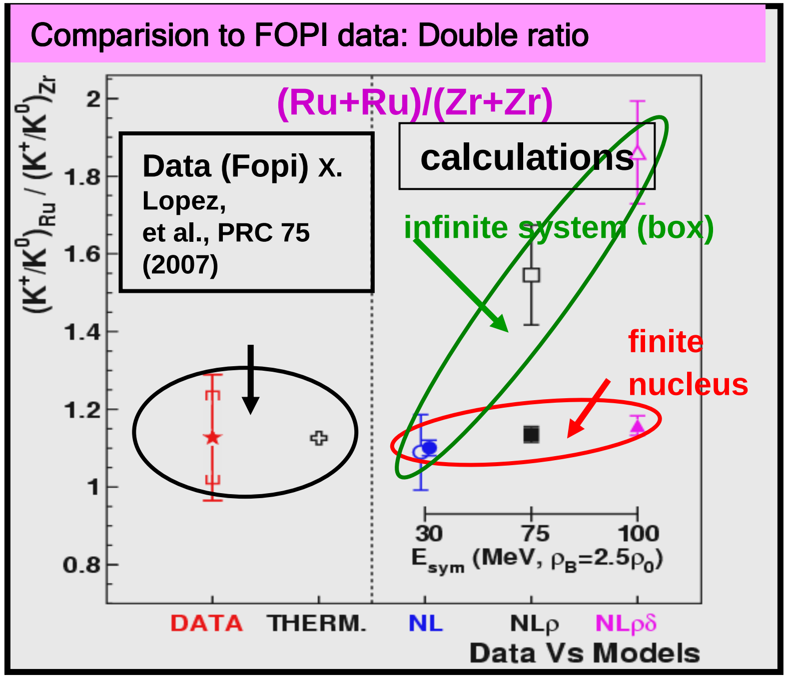
however, strongly dependent on assumption on isovector Δ potential

pion production decisively depending on implementation of threshold condition and in-medium potentials of π and Δ

more generally: transport theory of particles with finite width,
„off-shell“ transport,
see Mosel (GiBUU) and Cassing (HSE) groups; not systematically investigated



Δ spectral function

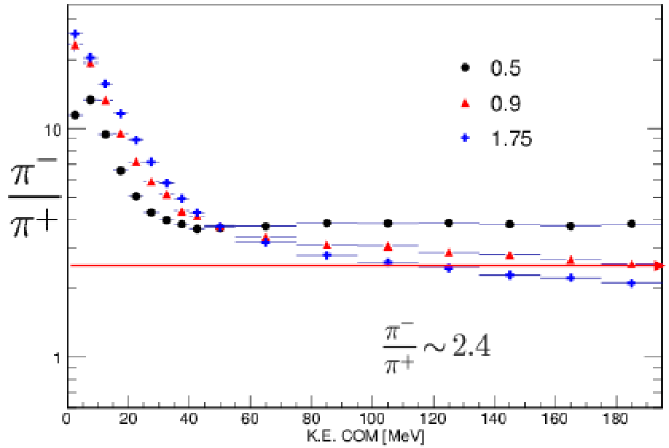


antistrange Kaons should be considered as an alternative, since small interaction with nuclear medium
single rations sensitive to SE

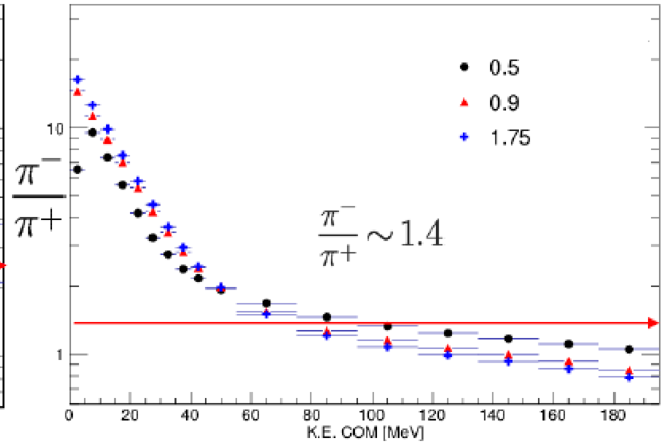
G. Ferini, et al., NPA762(2005) 147

Spectra of pion ratios seem to be more sensitive:
Planned experiment at Sπrit (MSU, Riken) 300 MeV: R. Shane, J. Estee
calculations with pBUU (P. Danielewicz)

$^{132}Sn+^{124}Sn$ and b=3fm

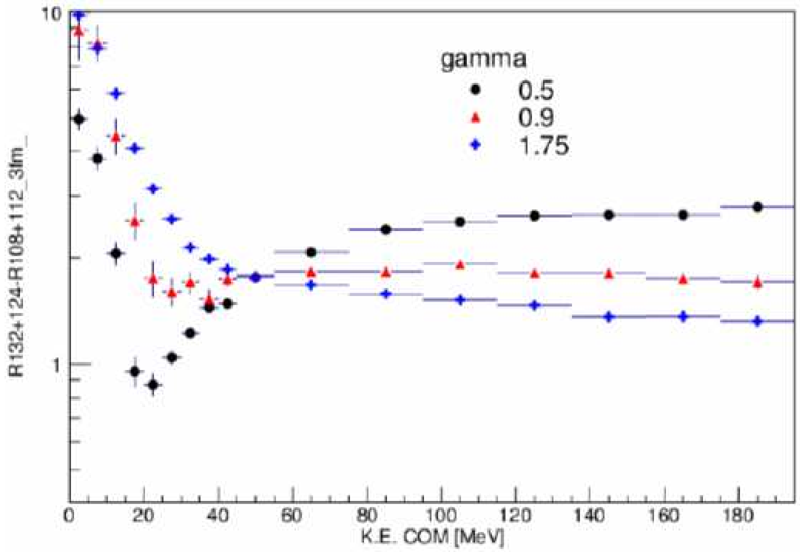


$^{108}Sn+^{112}Sn$ and b=3fm



new sugg. observable

$$\Delta R_{(132+124)-(108+112)}\left(\pi^-/\pi^+\right) = R_{132+124}\left(\pi^-/\pi^+\right) - R_{108+112}\left(\pi^-/\pi^+\right)$$



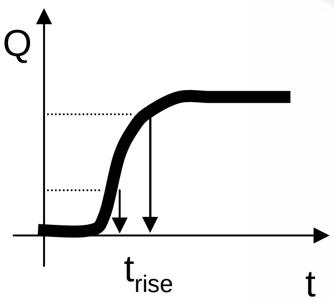
High energy pions (Better understood)

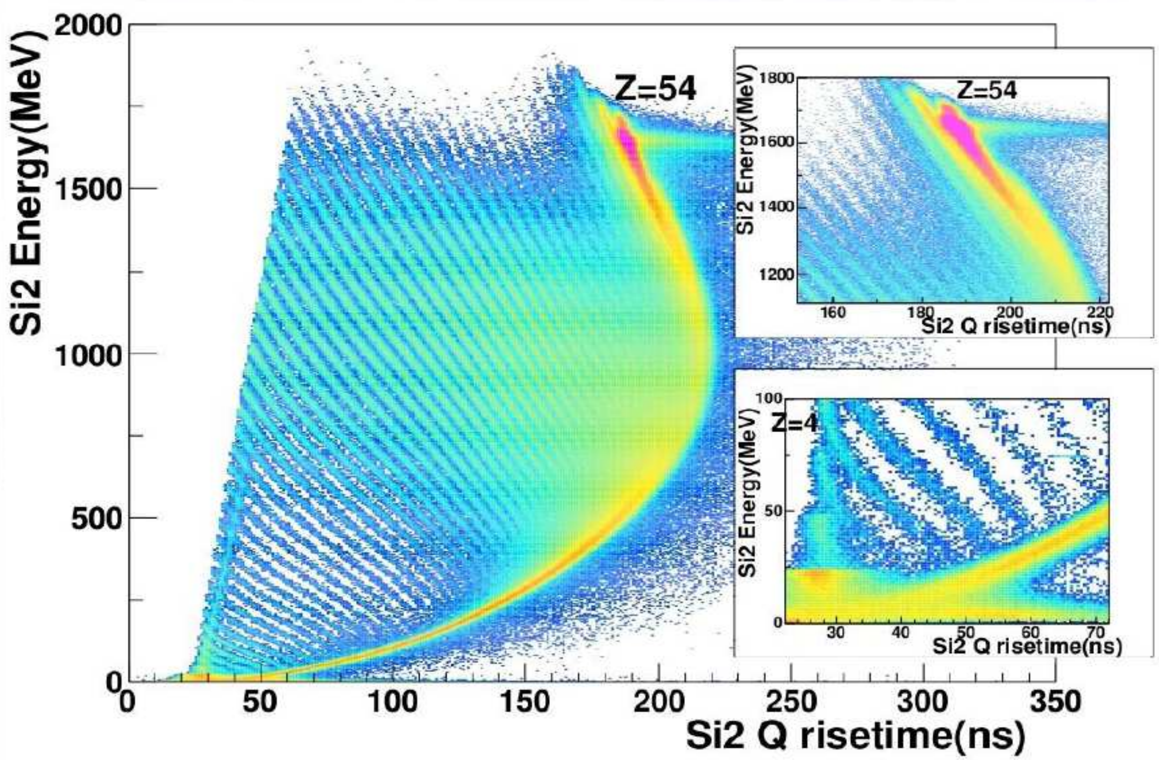
- produced early in high density regions
- less likely to be absorbed and exchange charge

Impressive experimental devolopments: ex.: FAZIA (O. Lopez); FARCOS (Tririro)
VAMOS-INDRA (Fable)

FAZIA Phase 1 : Pulse Shape Analysis

Some results at the end of phase 1:
Pulse Shape Analysis from E – Charge Rise Time





S.Carboni et al., NIMA 664 (2012) 251

Final Remarks:

ASY-EoS: a field of strong exchange between theory and experiment

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

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

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

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

many things to do in the future


with many thanks to the organizers for the great organization and nice treatment