# COMPACT STARS IN THE QCD PHASE DIAGRAMM VI

(Cosmic matter in heavy-ion collision laboratories?)



# The High-Density Symmetry Energy in Heavy ion Collisions and Compact stars

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LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Excellence Cluster Universe

Subtitle of CSQCD VI: Cosmic matter in heavy ion collision laboratories?

Aim and outline of this talk:

- Discuss investigation of EoS, relevant for astrophysics, in heavy ion collisions
- non-equlibrium processes→ transport theory (hydrodynamics?)
- issues in transport theory
- Application at very low and supersaturation densities
- status of knowledge of symmetry energy (in the hadronic sector)

Collaborators:

Heavy ion collisions:
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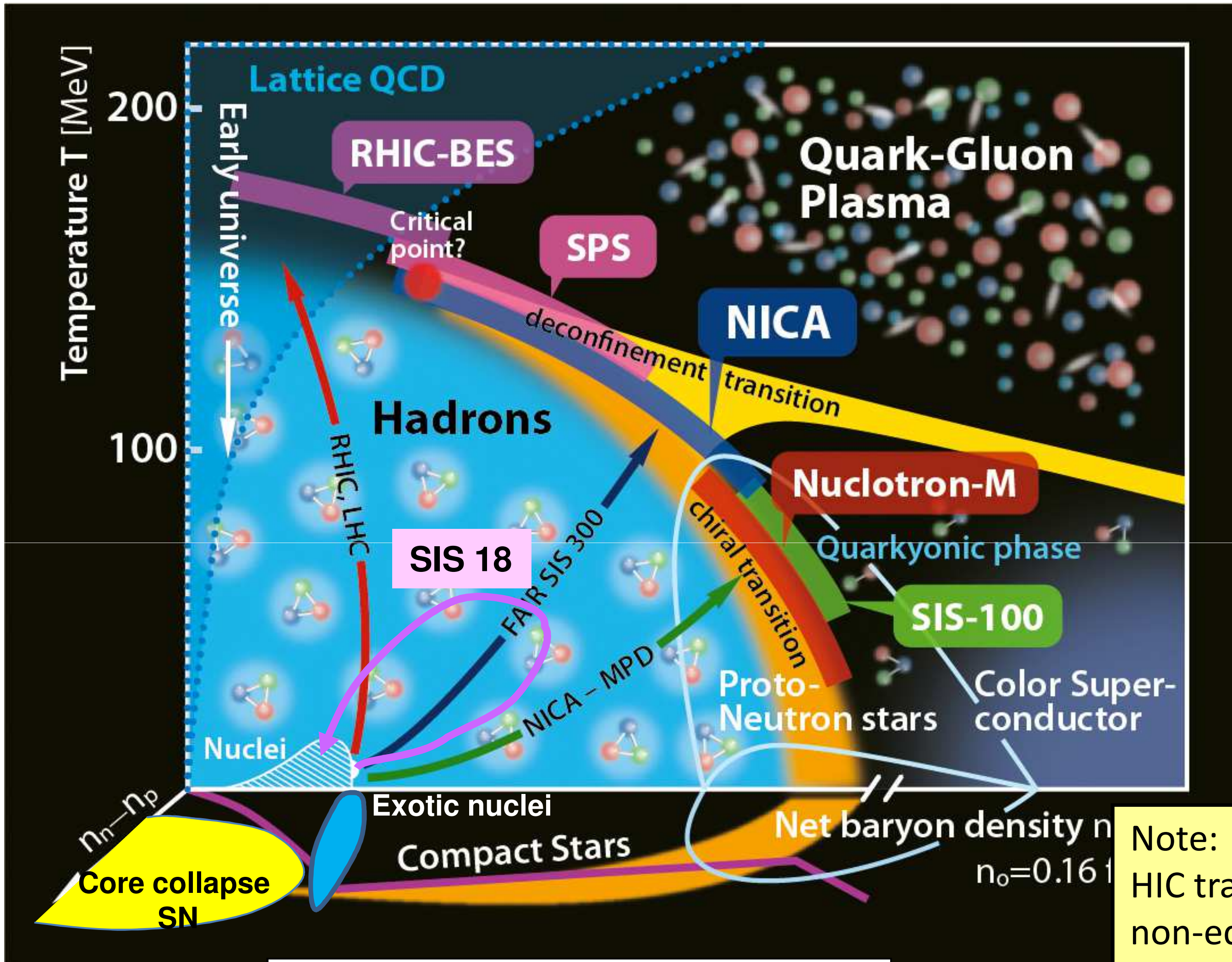
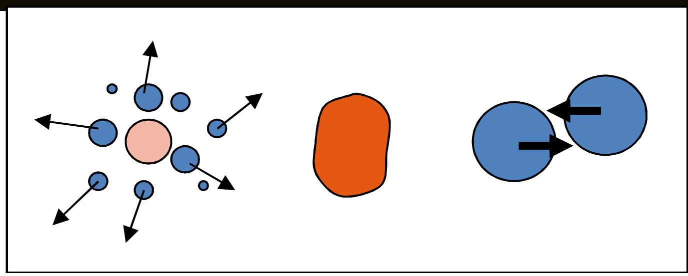
Aim in Heavy Ion Reactions: The Phase Diagram of Strongly Interacting Matter



Note:
HIC trajectories are non-equilibrium processes, and are not necessarily in this diagram
→ transport theory is necessary

# Equation-of-State and Symmetry Energy

symmetry energy

BW mass formula

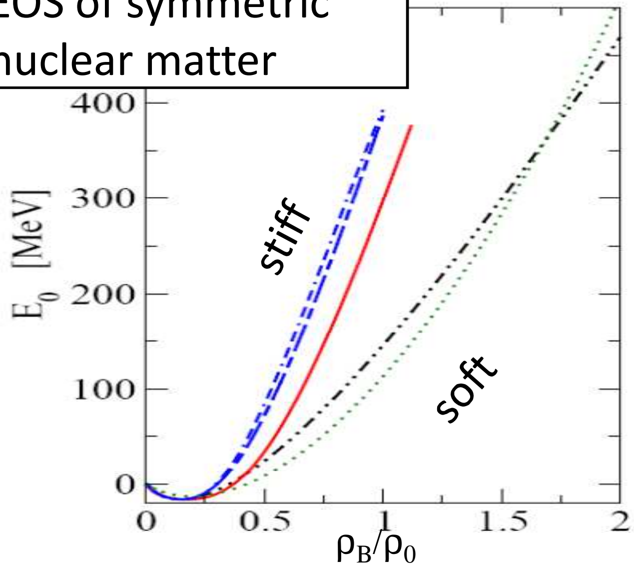
$$E(A,Z)/A = a_v - a_s A^{-1/3} - a_C Z(Z-1)A^{-4/3} - a_s (N-Z)^2/(N+Z)^2 + \delta_{pair}$$

density-asymmetry dep. of nucl.matt.

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

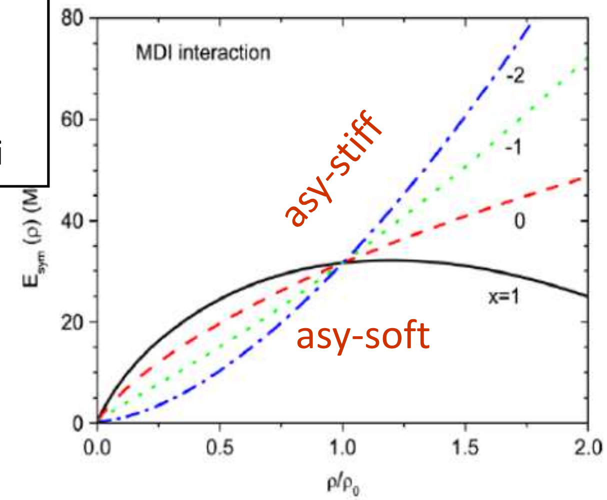
$$a_S \approx E_{sym}(\rho_0)$$

EOS of symmetric nuclear matter




Fairly well fixed! Soft!

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




**Parametrizations around $\rho_0$ :**

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

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

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

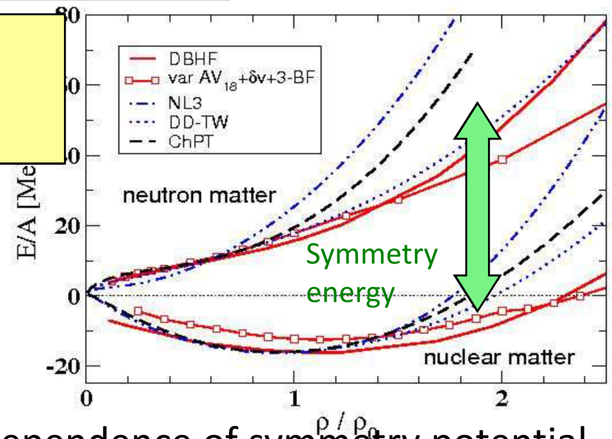
# Equation-of-State and Symmetry Energy: Microscopic Results

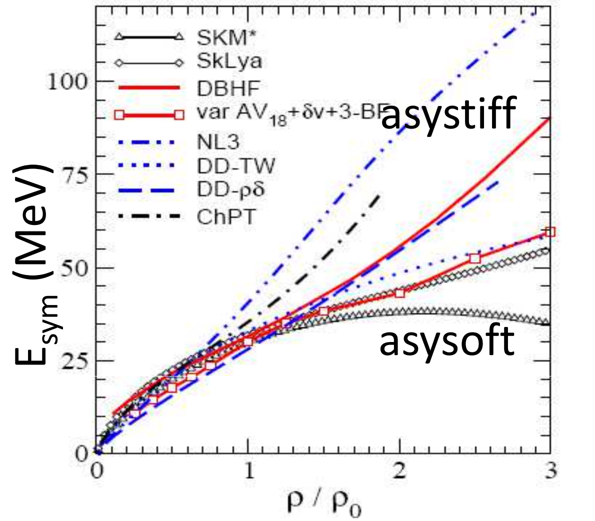
density-asymmetry dep. of nucl.matt.

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

## Many-Body calculations:

Rel, Brueckner
Variational
Rel. Mean field
Chiral perturb.

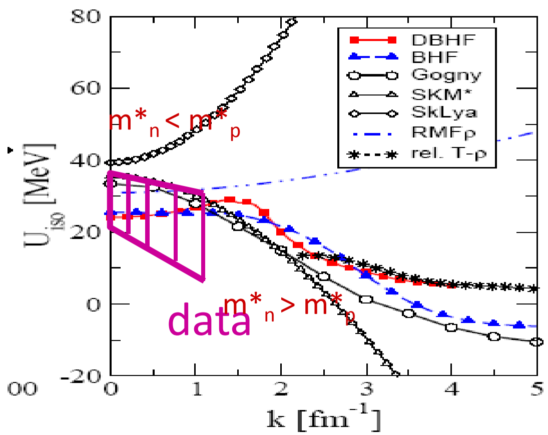



C. Fuchs, H.H. Wolter, EPJA 30(2006)5

Momentum dependence of symmetry potential
(isoscalar and isovector effective mass)

$$U(\rho,k;\delta) = \frac{\partial \varepsilon(\rho,\delta)}{\partial f(\rho,k)} = \underbrace{U_0(\rho,k) + U_{sym}(\rho,k)(\tau\delta)}_{U_\tau(\rho,k)} + \ldots \qquad \frac{m^*_\tau}{m} = \left(1 + \frac{m}{\hbar^2 k}\frac{\partial U_\tau}{\partial k}\right)^{-1}$$

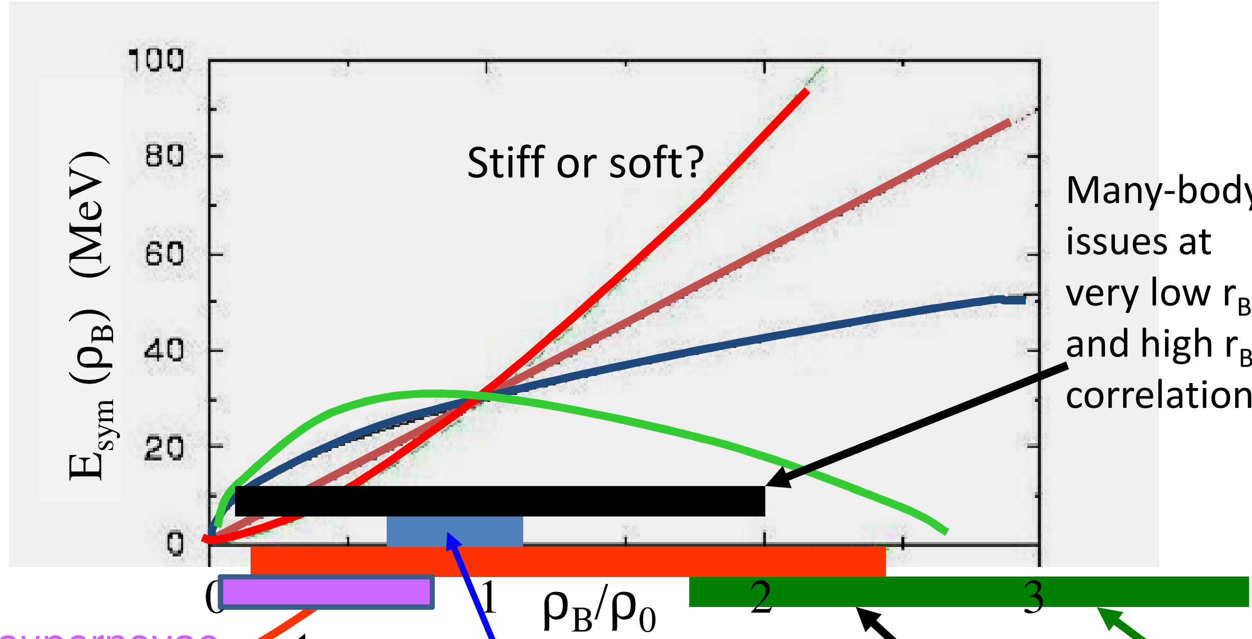



**effective mass splitting also uncertain from many-body theories and not very constrained from data on optical potentials.**

Why is symmetry energy so uncertain??
→ Short range isovector tensor correlations; 3-body forces

# The Search for the Nuclear Symmetry Energy

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




Many-body calculations issues at very low $r_B$(clustering) and high $r_B$ (short range correlations)

Core collapse supernovae

heavy ion collisions

nuclear structure

neutron stars $\rho \sim 2\text{–}4\ \rho_0$

$$E_{sym}(\rho_B) = S_0 + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2 + \ldots$$

$E_{sym}(\rho_B)$

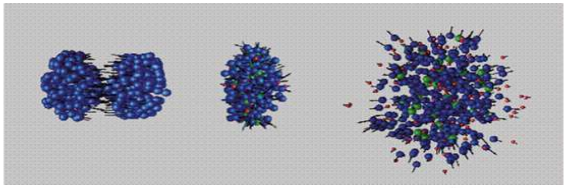
**Cosmic matter in the laboratory**

→ Discuss transport approach
→ and applications to learn about the symmetry energy

# HIC one way to obtain information on the EoS - but complex processes

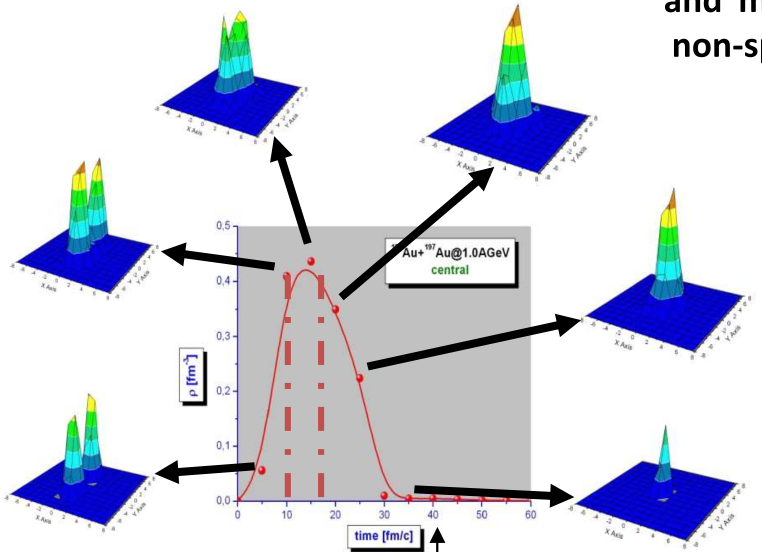
**Fermi energies: (multi)-fragmentation in central collisions**

**Intermediate energies: several 100 MeV/A to several GeV/A**
**Vaporization, production of new particles, like pions, strangeness (kaons, hyperons), etc,**

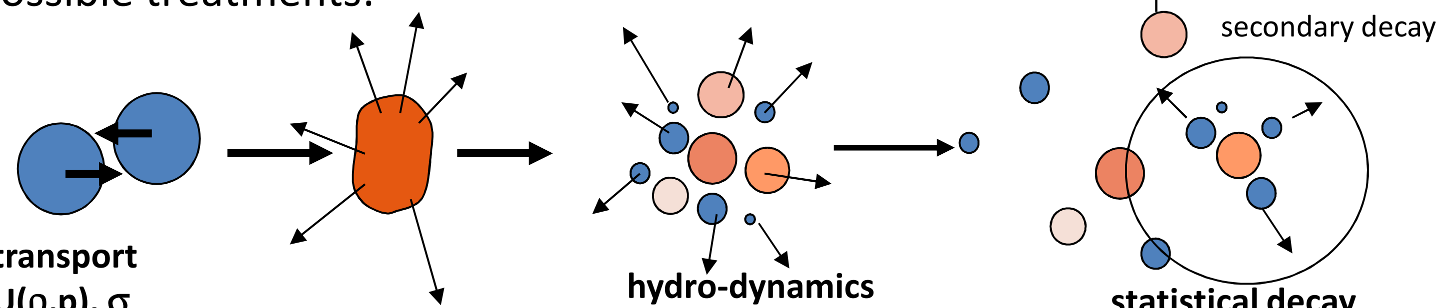


**evolution in coordinate space**

**and momentum space: non-sphericity**




Possible treatments:




**transport**
**U(ρ,p), σ**
**quasi-particle picture**
**full non-equilibrium**

**hydro-dynamics**
**EoS ε(P)**
**local equilibrium**

**statistical decay**
**$V_{freeze-out}$, $E_{exc}$,A,Z**
**global equilibrium**

# Transport theory based on a chain of approximations

**Martin-Schwinger hierarchy in many-body densities, real time formalism**
**truncation, introduction of self energies (1-body quantities),**
**irreversability**

**Quantum transport theory: Kadanoff-Baym theory**

**Semiclassical approximation :**
**Wigner transform, treat as phase space probabilities**
**Gradient approximation (separation of short and long scales)**

**Quasi-particle approximation**
**Spectral function→ delta function with effective momenta and masses**
**neglect off-shell effects (or treat approximately)**

→ kinetic equation

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

$$\int d\vec{p}_2 d\vec{p}_{1'} d\vec{p}_{2'}\, v_{21}\sigma_{12}^{in-med}(\Omega)\,(2\pi)^3\delta(p_1+p_2-p_{1'}-p_{2'})\left[f_{1'}\,f_{2'}\bar{f}_1\bar{f}_2-f_1\,f_2\,\bar{f}_{1'}\bar{f}_{2'}\right]$$

Pauli blocking factors,
main quantum ingredienet

$\bar{f}_i := (1-f_i)$

Mean field evolution (Vlasov) + uncorr. 2-body collisions (Boltzmann)
+ Pauli-blocking of final states (Uehling-Uhlenbeck)

physical input:
mf potential U(r,p), momentum dependent
$\sigma^{in\text{-}med}$ in-medium cross sections

Obtainable
e.g. from Bruecker theory

# Two families of transport approaches, fluctuations

## Boltzmann-Vlasov-like (BUU/BL/BLOB)

$$\left(\frac{\partial}{\partial t}+\frac{\vec{p}}{m}\vec{\nabla}^{(r)}-\vec{\nabla}U(r)\vec{\nabla}^{(p)}\right)f(\vec{r},\vec{p};t) = I_{coll}[\sigma^{in-med}]+\delta I_{fluct}$$

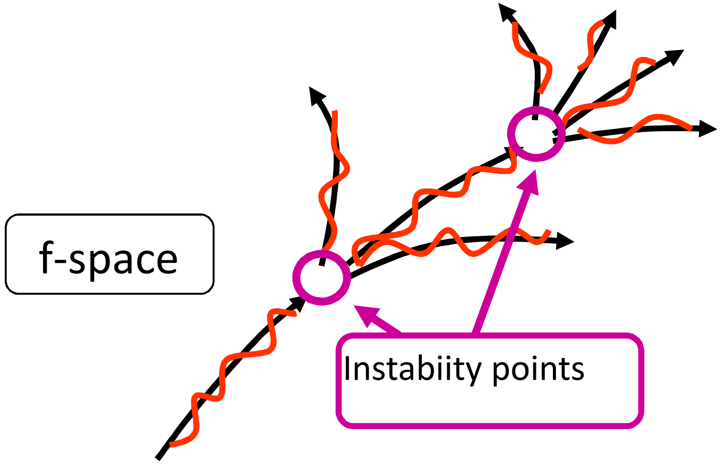
Dynamics of the 1-body phase space distribution function f with 2-body dissipation

fluctuations around diss. solution

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

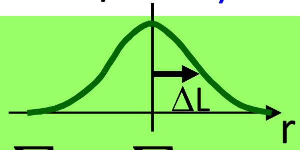
$$\boxed{\frac{df}{dt}=I_{coll}+I_{fluc}}$$

Boltzmann-Langevin eq.




## Molecular-Dynamics-like (QMD/AMD)

$$|\Phi\rangle = A\prod_{i=1}^{A}\varphi(r;r_i,p_i)|0\rangle$$




$$\dot{r}_i=\{r_i,H\};\quad \dot{p}_i=\{p_i,H\};\quad H=\sum_i t_i+\sum_{i,j}V(r_i-r_j)$$

TD-Hartree(-Fock)
(or classical molecular dynamics with extended particles)
plus stochastic NN collisions
No quantum fluctuations,
but classical N-body fluctuations, damped by the smoothing.

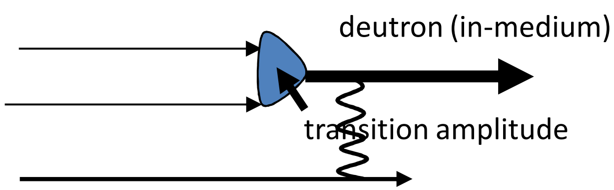
However, more fluctuations than BUU, since dof are nucleons and not test particles:
→ amount controlled by width of single particle packet ΔL

## The issue in fragment and cluster formation in HIC collisions:

correlations ⇔ fluctuations

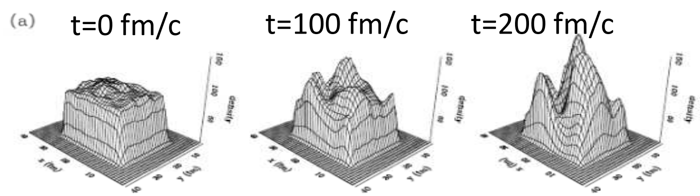
| correlations ⇓ | fluctuations ⇓ |
|---|---|
| light cluster (LC) formation | Intermediate mass fragment (IMF) formation |

LC's are not stabilized by the mean field but by many body correlations. Introduce as explicit degrees of freedom, generated by the collision term




(P. Danielewicz and Q. Pan, PRC 46 (1992))
(d,t,3He, but no $\alpha$!)

Fluctuation in the instable region are Amplified and stabilized by the mean field




BUU calculation in a box with initial conditions inside the instability region: $\rho=\rho_0/3$, T=5 MeV, $\delta=0$

(V.Baran, et al., Phys.Rep.410,335(05))

Maybe the way to deal with the hadron-quark phase transition in transport approaches

## Particle Production

**Inelastic collisions: Production of particles and resonances**

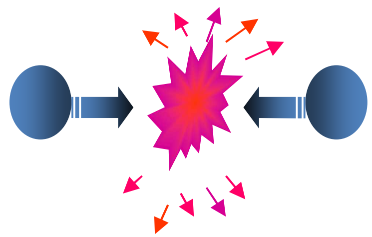
$NN \rightarrow N\Delta$

$N\pi \rightarrow \Lambda K$

$N\Lambda K$

e.g. pion and kaon production;

coupling of $\Delta$ and strange-ness channels.



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

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

*etc.*

Coupled transport equations

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

What can one learn from different species?

- pions: production at all stages of the evolution via the $\Delta$-resonace
- kaons (strange mesons with high mass): subthreshold production, probe of high density phase
- ratios of $\pi^+/\pi^-$ and $K^0/K^+$:

→ probe for symmetry energy

symmetry energy effects on $\pi,\Delta$ production

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

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

2. Threshold effect, in medium effective masses:

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

→ can be competing effects!

# Code Comparison Project

## Boltzmann-Vlasov-like (BUU/BL/BLOB)

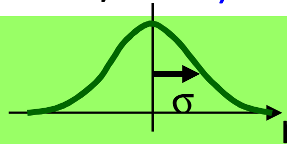
$$\left(\frac{\partial}{\partial t}+\frac{\vec{p}}{m}\vec{\nabla}^{(r)}-\vec{\nabla}U(r)\,\vec{\nabla}^{(p)}\right)f(\vec{r},\vec{p};t) = I_{coll}[\sigma^{in-med}, f_i]$$

Dynamics of the 1-body phase space
distribution function f
with 2-body dissipation

6-dim integro-differential, non-linear eq.

## Molecular-Dynamics-like (QMD/AMD)

$$|\Phi\rangle = A\prod_{i=1}^{A}\varphi(r;r_i,p_i)|0\rangle$$




$$\dot{r}_i=\{r_i,H\};\quad \dot{p}_i=\{p_i,H\};\quad H=\sum_i t_i+\sum_{i,j}V(r_i-r_j)$$

TD-Hartree(-Fock (AMD))
(or classical molecular dynamics with extended particles)
plus stochastic NN collisions

6A-dim many body problem

→ very complex, simulate solutions
introduces many technical details

physical input (EOS, $\sigma_{inmed}$, $\pi\Delta$ physics, ..) → **transport code** → observables

→ unique? code independent?

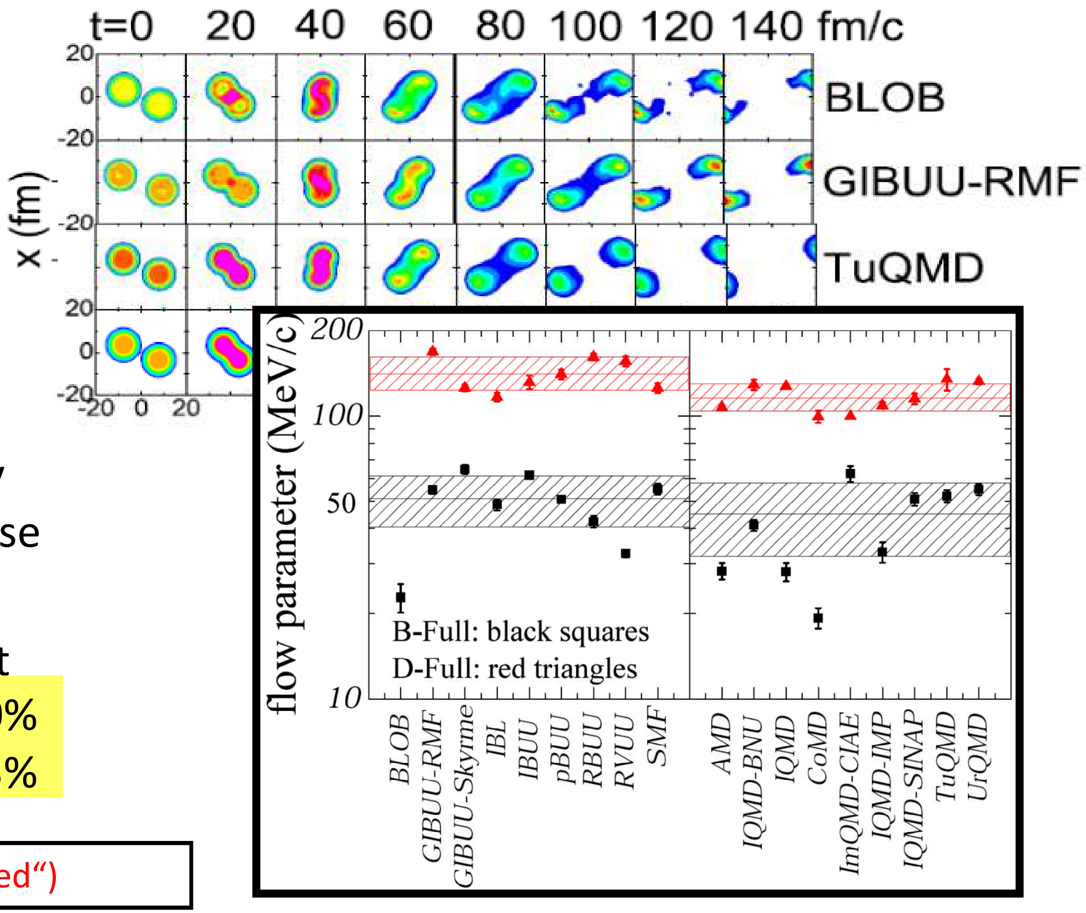
→Transport Code Evaluation (Comparison) Project

# Code Comparison Project (1st stage):

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

idea: establish sort of theoretical systematic error of transport calculations
(and hopefully to reduce it )
published: J. Xu, et al. (31 authors); PRC 93, 044609 (2016)

HIC at b=7m (midcentral)
selected contour plots;
different evolution apparent
→compare collision numbers,
blocking,  and observables




quantify spread of simulations by value of „flow“=slope of transverse momentum at midrapidity

BUU and QMD approx. consistent

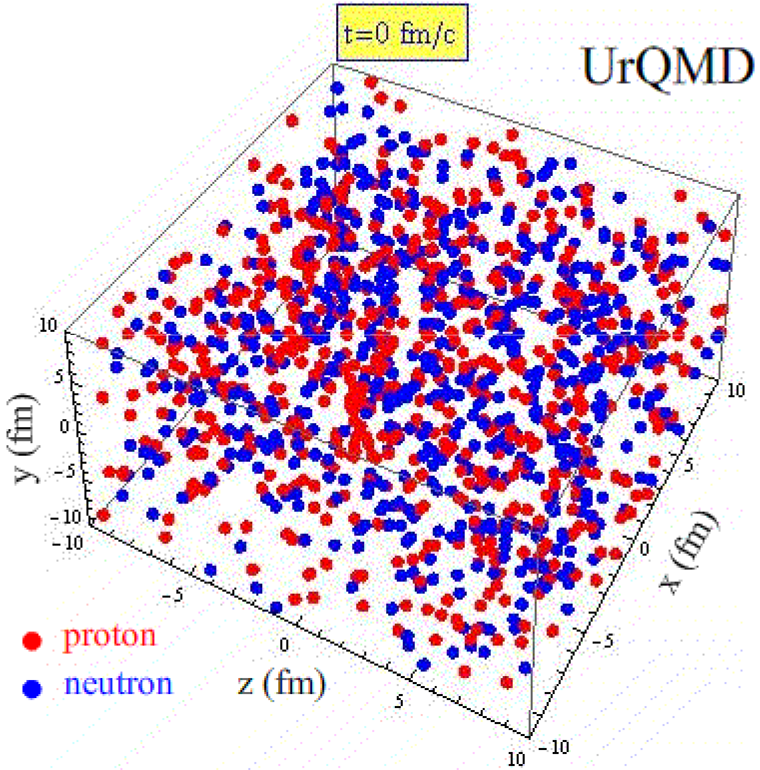
uncertainity

100 AMeV: ~30%
400 AMeV: ~13%

Understand differences better („entangled“)

## 2nd stage: Box calculation comparison

simulation of the static system of infinite nuclear matter,
→ solve transport equation in a periodic box




Useful for many reasons:

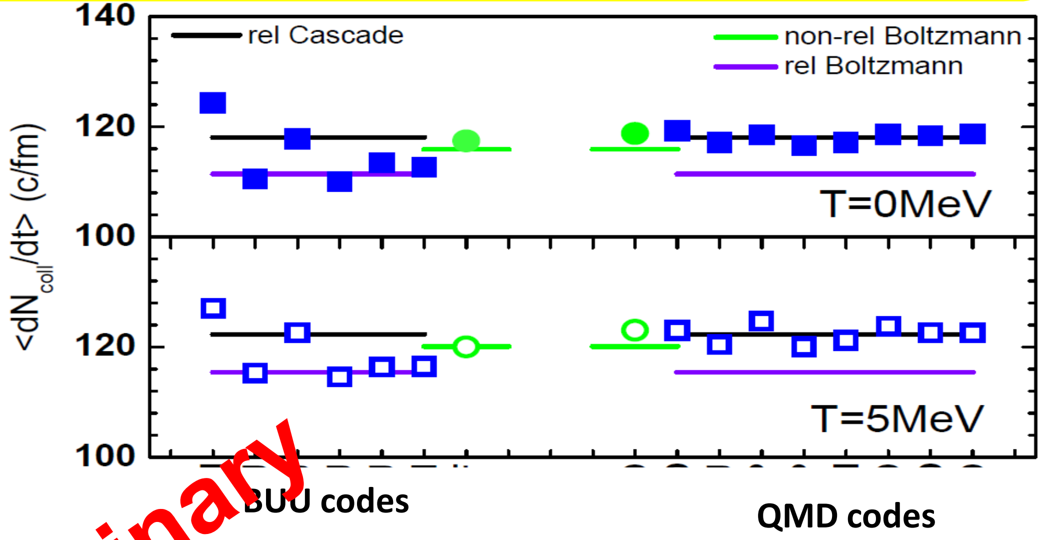
- check consistency of calculation
  e.g. EoS energy dens ε vs. pressure P
- check consistency of simulation:
  collision numbers, blocking
  (exact limits from kinetic theory)
- check aspects of simulation separately
  Cascade: only collisions
  without/with blocking
  Vlasov: only mean field propagation
- check ingredients of particle production
  e.g. pion production

$$I_{coll} = \int d\vec{p}_2 d\vec{p}_{1'} d\vec{p}_{2'}\, v_{21}\, \sigma_{12}^{in-med}(\Omega)\, (2\pi)^3 \delta(p_1 + p_2 - p_{1'} - p_{2'}) \left[ f_{1'} f_{2'} \bar{f}_1 \bar{f}_2 - f_1 f_2 \bar{f}_{1'} \bar{f}_{2'} \right]$$

## Check of Collision term

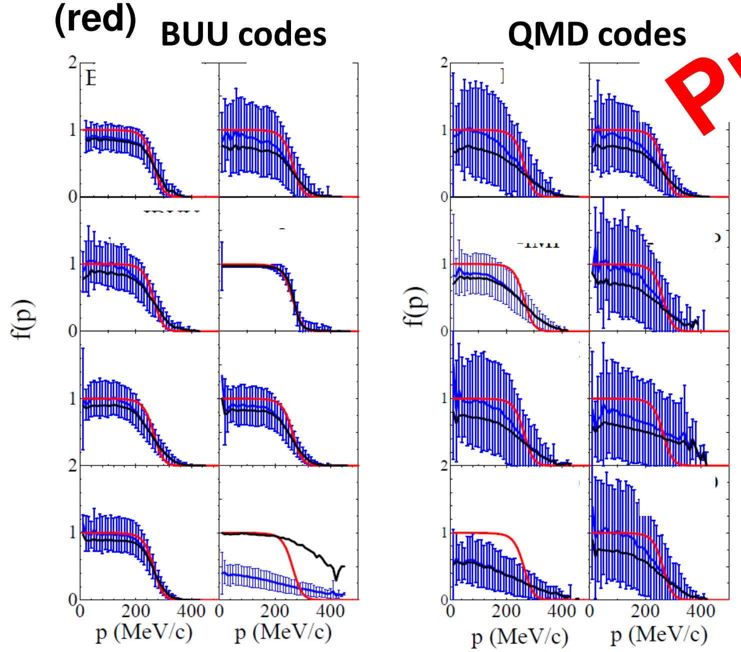
Collision rates in a cascade box calculation (w/o mean field, T=0 and 5 MeV)

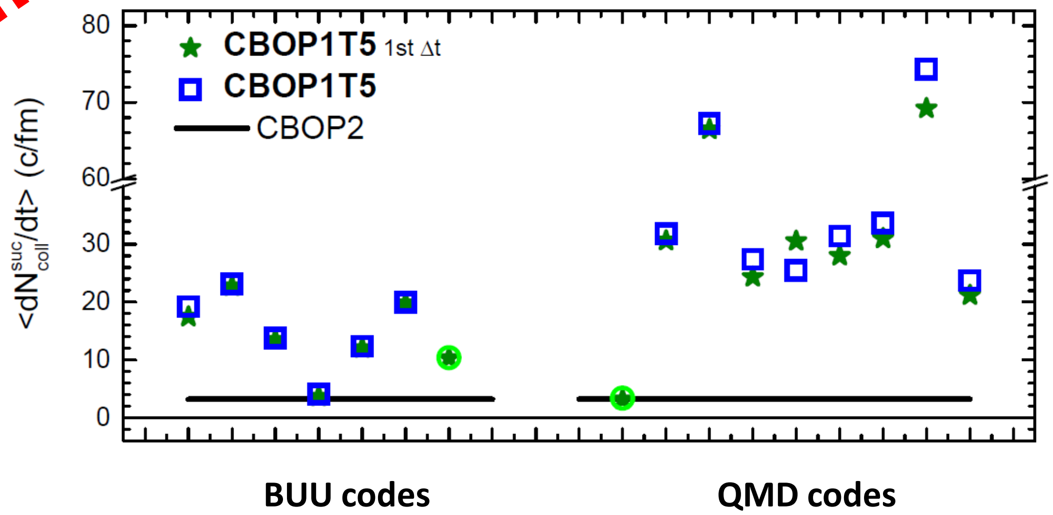
**without blocking**
**Comparison to exact limit ok**




Preliminary

**with blocking**
**Sampling of occupation prob. in comp. to prescribed FD distribution (red)**




(Note: Code names removed because of preliminary nature of figure)

**--> characteristically different fluctuation in BUU and QMD models**

Check of π,Δ production in box cascade calculation

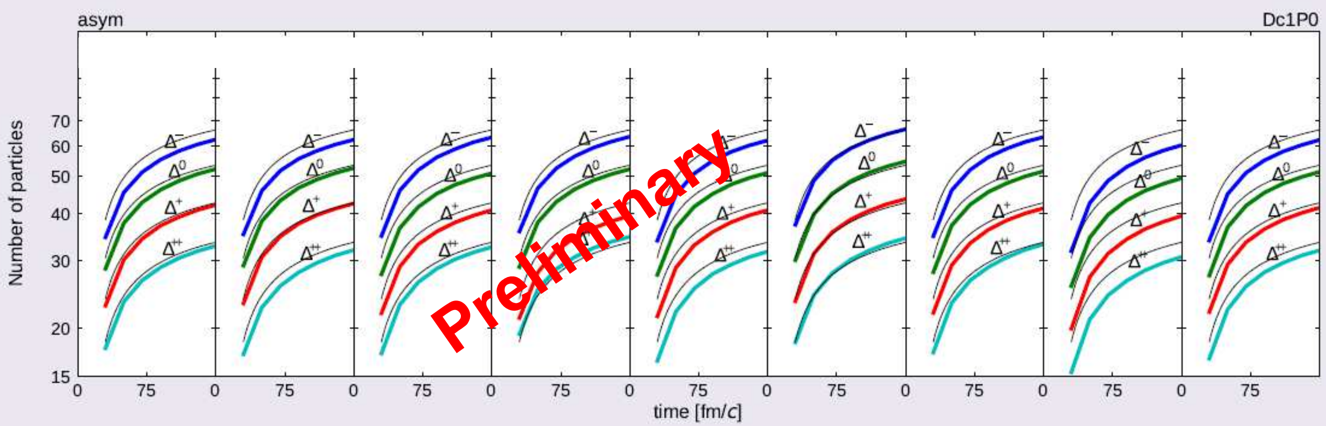
- Constant Δ mass $M_\Delta = 1.232$ GeV.
- Constant $\sigma(NN \to N\Delta) = 40$ mb for $\sqrt{s} > M_N + M_\Delta$.

$NN \to N\Delta$

no pions

—— kinetic solution

Time evolution of numbers of nucleons and Deltas




pions and Δ

Δ mass distribution

$NN \leftrightarrow N\Delta$

$\Gamma[\Delta \to N\pi] = 0.115$ GeV

(very preliminary figure removed)

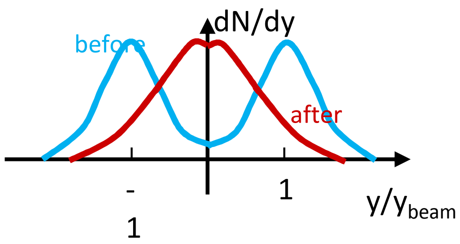
# Transport theory ←→ Experiments (Observables)

Transport theory calculates *f(r,p;t)*, or *{$r_i(t)$,$p_i(t)$}* i.e. full information about the complete evolution,

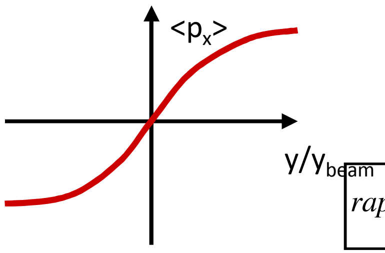
Experiment measures $f(r \to \infty, p; t \to \infty)$, i.e. asymptotic momentum distribution, of nucleons, and also of newly produced particles (p, K, ...) (inel. cross sections) and of clusters (in principle many-body observables)

**characteristic observables: „primary“ observables**

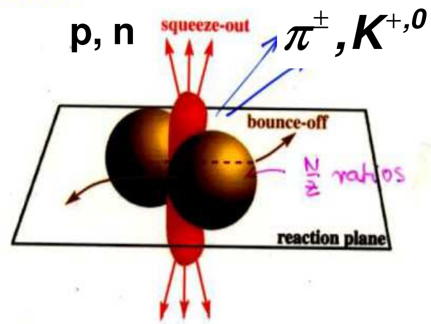
Rapidity distribution (stopping)




Transverse flow (compression)




$$rapidity \qquad y = \frac{1}{2}\ln\frac{1+\beta_z}{1-\beta_z}$$




E.g. „flow“ (Fourier decomp. of azimuthal momentum distrib. )

$$N_\tau(\Theta; y, p_t) = N_0(1 + v_1^\tau(y, p_t)\cos\Theta + v_2^\tau(y, p_t)\cos 2\Theta + \ldots$$

$v_1$: directed flow | $v_2$: elliptic flow

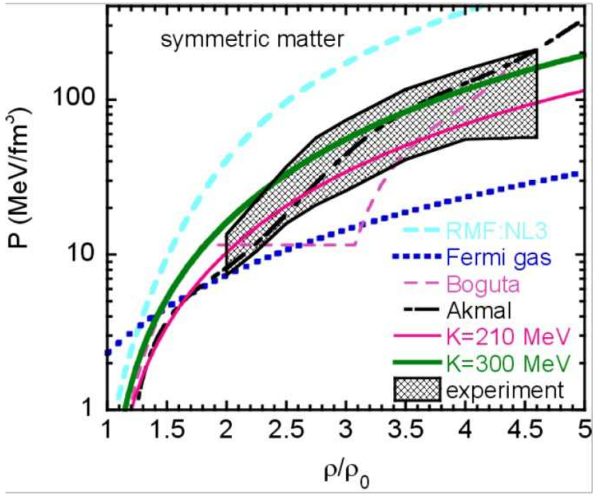
**For symmetry energy discuss p/n ratios or differences of observables $v_i^n / v_i^p$ ; $v_i^n - v_i^p$**

**„Secondary“ observables**
**particle production, e.g. pions, strangeness**

**NN → NΔ**
**NΔ → Nπ → ΛK**
**NΔ → NΛK**

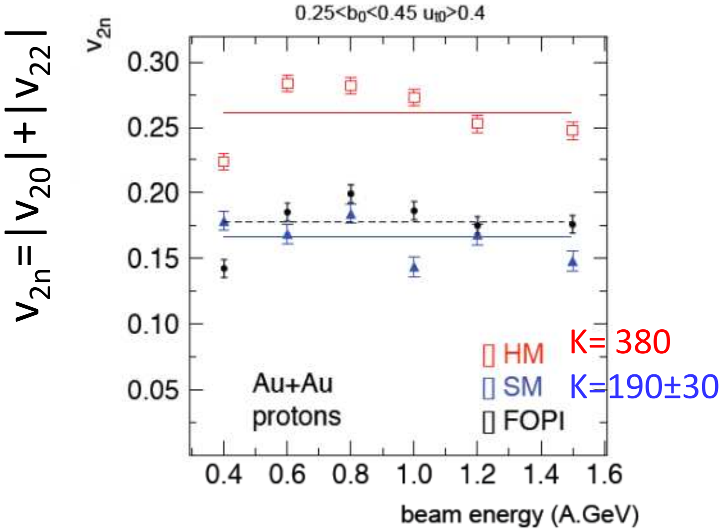
# Constraints on EOS of symmetric nuclear matter

(P.Danielewicz, et al., Science 298(02)1592)

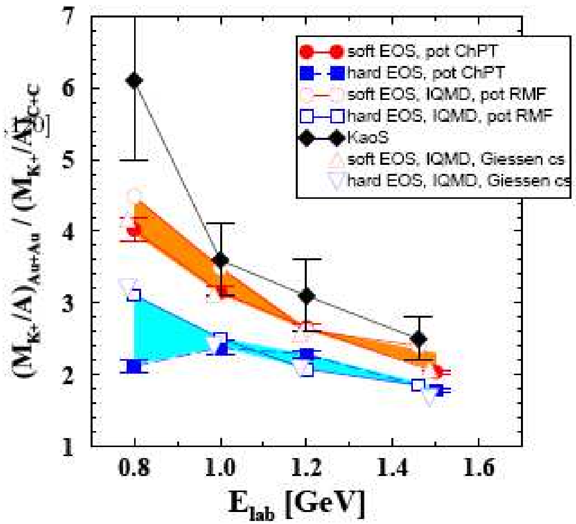



- analysis of elliptic and directed flow for E=.15 to 10 AGeV
- using a particular model (purely hadronic) , shaded area constraint in this model
- densities in the range from 2 – 4.5(?) $\rho_0$
- eliminates some extreme models

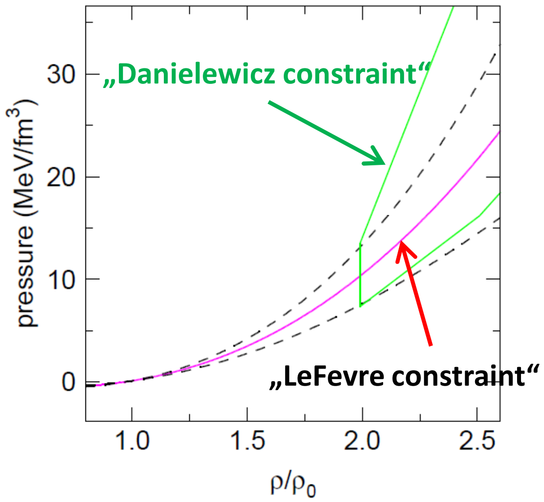
**Recent analysis:**
**LeFevre, et al, NPA945 (2016) 112**




C. Fuchs, PPNP56(06)




ratio of K+ production in heavy (Au+Au, compression) relative to light system (C+C,small compres-sion)




**Both favor a rather soft EoS,**
**where the momentum dependence of the potential is important**

# Isospin sensitive Observables in Heavy Ion Collisions

peripheral

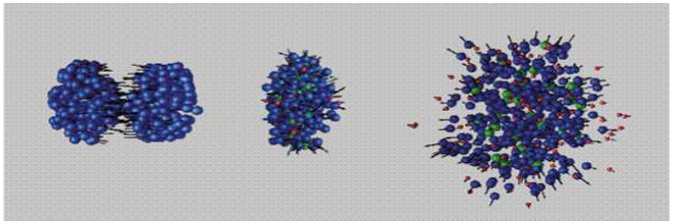
Coulomb barrier to Fermi energies

central

Relativistic energies

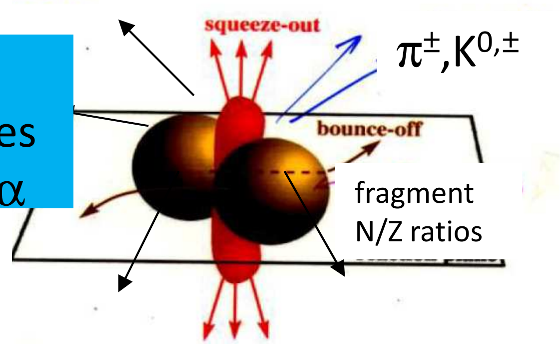
Isospin migration

Isospin fractionation, multifragm



N/Z of PLF residue = isospin diffusion

pre-equil. light particles n,p,d,t,$^{3}$He,$\alpha$




N/Z of neck fragment and velocity correlations

N/Z ratio of IMF's

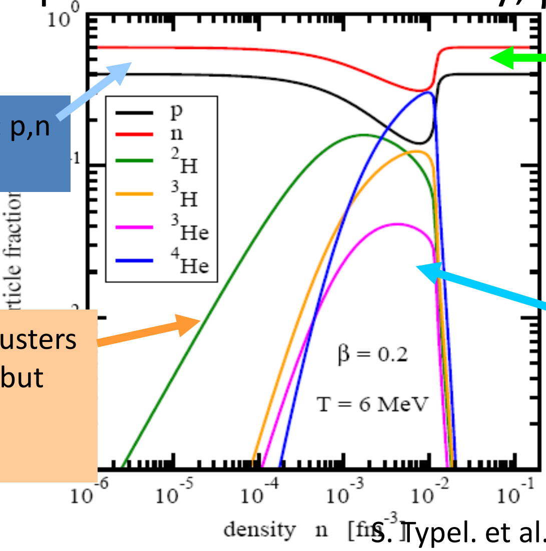
Flow: directed and elliptic

Production of particles, $\pi$,K

Symmetry energy effects are small absolutely (about 10%)
→ use differences or ratios of isospin dependent observables, to eliminate uncertainties in the isoscalar sector.

# Clustering of very dilute nuclear matter

composition as fct of density; β=0.2, T=6 MeV




very low density: p,n

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

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

here heavier nuclei (embedded into a gas) become important here

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

Can this be investigated in heavy ion collisions?

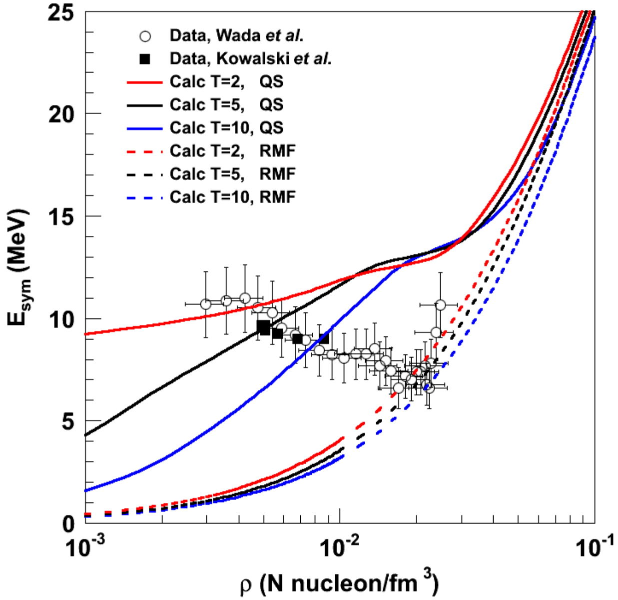
Semi-central heavy ion collisions, ($^{64}$Zn+$^{92}$Mo,$^{197}$Au at 35MeV/A) and time-resolved measurement of light fragments from decay of fireball:

S. Kowalski +, PRC75 014601 (2007)

J. Natowitz, G. Röpke+ PRL 104, 202501 (2010)

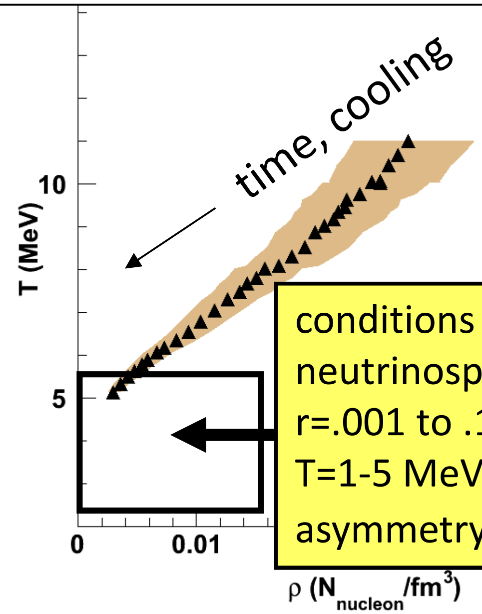
determine „trajectory“ of evolution density and temp. of expanding source using statistical models

extract symmetry energy and compare with quantumstat. calculation of clustered matter




Should be verified in dynamical description.

Relevance for Supernovae physics? ν-opacity of neutrinisphere?
HIC ⟺ Femto-Nova?



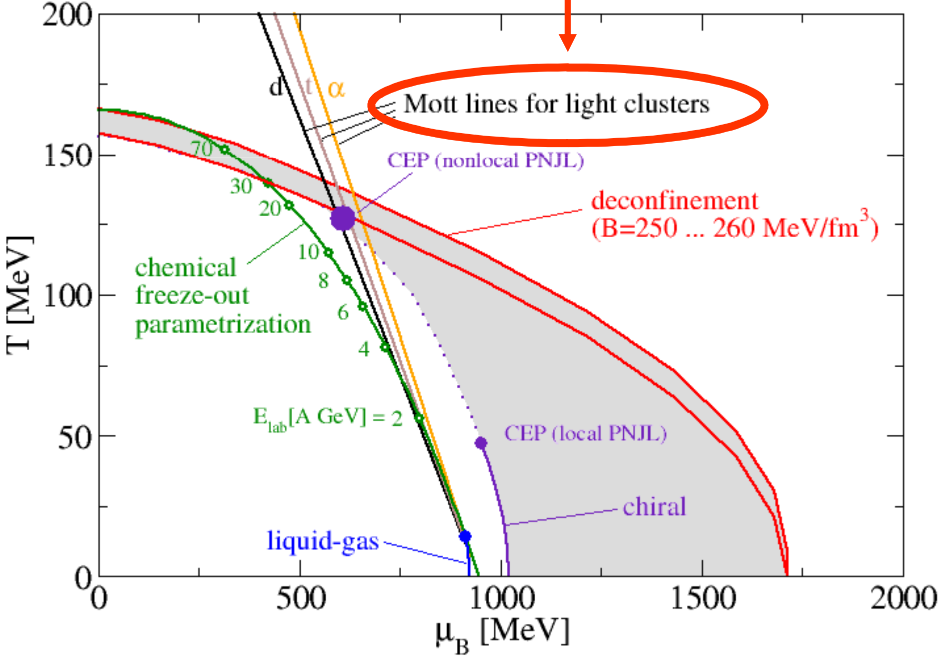

conditions of neutrinosphere:
r=.001 to .1 r$_{o,,}$
T=1-5 MeV
asymmetry $Y_e$=0.1 – 0.25

Cluster production can also be important at high energies/densities, e.g. NICA White paper, EPJA 52:

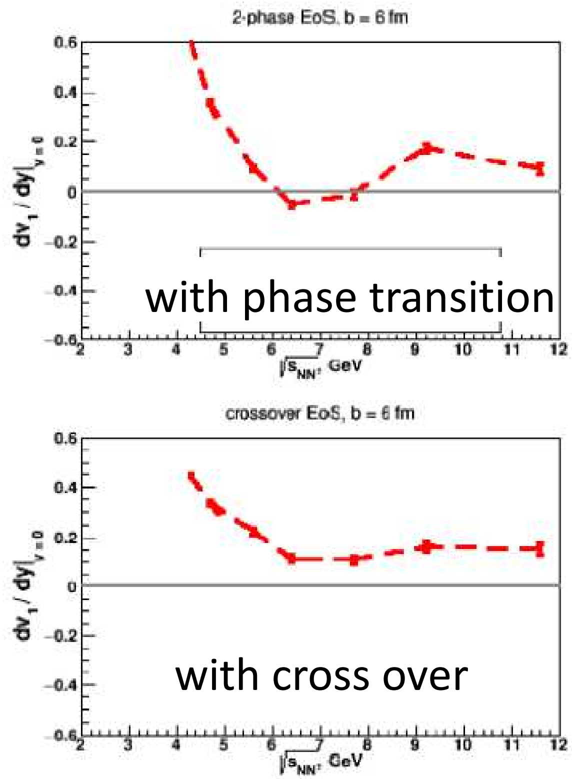
# #34 Light cluster production at NICA

N.-U. Bastian[1], P. Batyuk[2], D. Blaschke[1,2,3], P. Danielewicz[4], Yu. B. Ivanov[3,5], Iu. Karpenko[6,7], G. Röpke[3,8,a], O. Rogachevsky[2], H. H. Wolter[9]

light clusters can be present at high densities near the deconfinment phase transition




3-fluid hydro, Au+Au, deuteron flow




Flow of light custers traces early pressure distribution, not affected by rescattering on pions and light hadrons

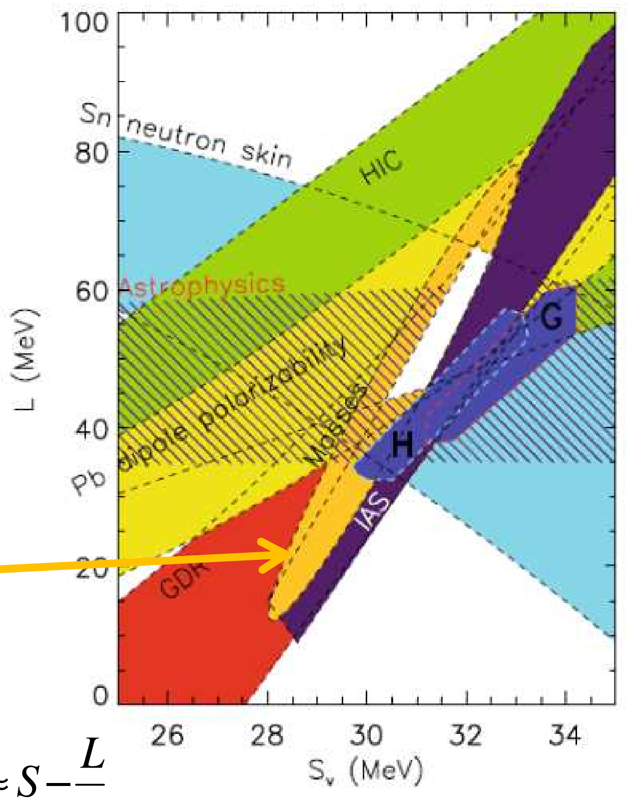
# Constraints on the Symmetry Energy as correlation $S_0$ vs. L

Limits on the value around saturation density

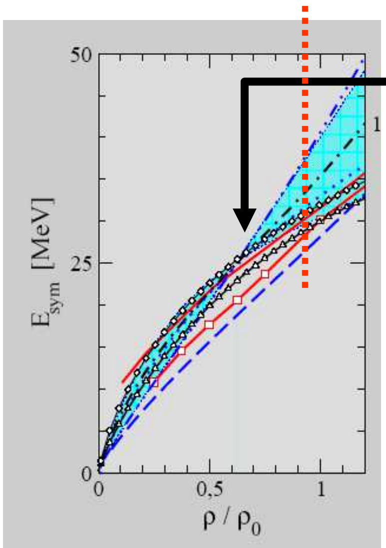
$$E_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

A consensus towards a rather narrow region in the parameter space is seen.

But includes correlation between parameters due to extrapolation to $\rho_0$, e..g. masses




J.Lattimer, A. Steiner, EPJA 50, 40 (2014)




$$S(\rho = \tfrac{2}{3}\rho_0) = S - \frac{L}{9} + \frac{K_{sym}}{162} + \ldots \approx S - \frac{L}{9}$$

-- 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 $\rho_0$, within the model., eg. in lin. approx.

# The Symmetry Energy at High Density

Au+Au @ 400 AMeV
new experiment ASY-EOS
P. Russotto et al., Phys. Rev. C 94, 034608 (2016)

$$N(\Theta; y, p_t) = N_0(1 + v_1 \cos\Theta + v_2 \cos 2\Theta + \ldots)$$

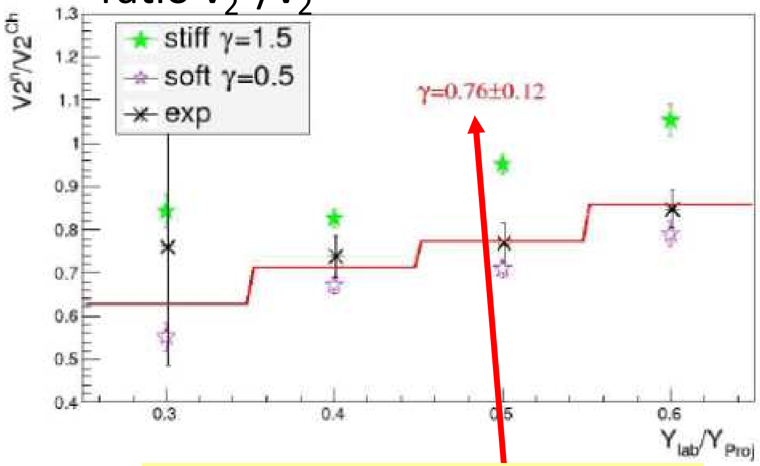
ratio of neutron to hydrogen flow
- Elliptic flow $v_2$ in this energy region good probe of high density

analysis of density dependence of SE in terms of power law exponent $\gamma$

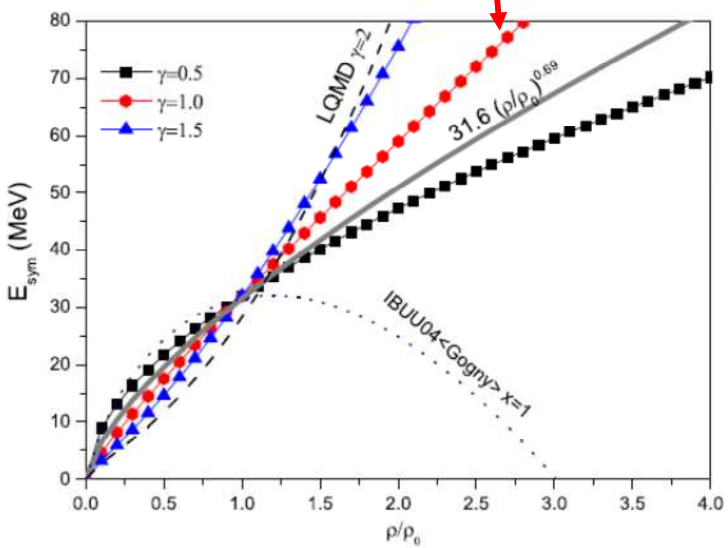
$$E_{sym}(\rho) = \tfrac{1}{3}\varepsilon_F\left(\frac{\rho}{\rho_0}\right)^{2/3} + C\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

Big step forward in constraining the high-density symmetry energy

ratio $v_2^n/v_2^{charged}$




not very precise (yet) but indicates rather stiff SE, $\gamma$~1



# Particle Production

## Inelastic collisions: Dynamics of production of particles and resonances

NN → NΔ → Nπ → ΛK

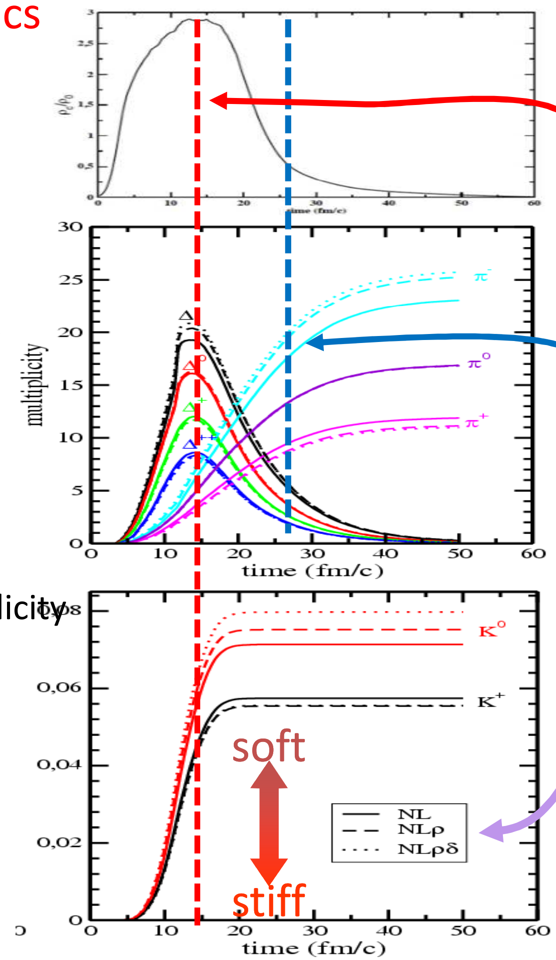
NΔ → NΛK

Dynamics

Central density

π and Δ multiplicity

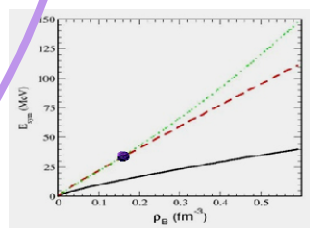
$K^{0,+}$ multiplicity




Δ and K: production in high density phase

Pions: low and high density phase

Sensitivity to asy-stiffness




G. Ferini et al., Nucl. Phys. A 762, 147 (2005)

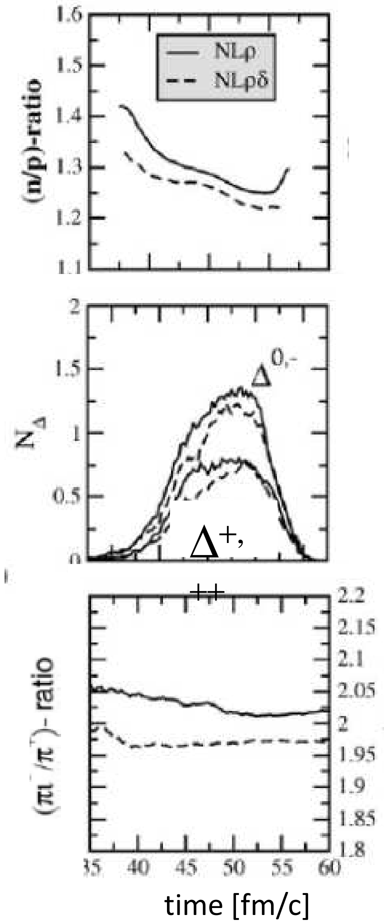
Dependence on asy-stiffness

n/p ratio

Y($\Delta^{0,-}$) vs.Y($\Delta^{+,++}$)

$\pi^-/\pi^+$

Au+Au, 0.6AMeV



# Results for pion ratios

NN → NΔ → Nπ → ΛK

NΔ → NΛK

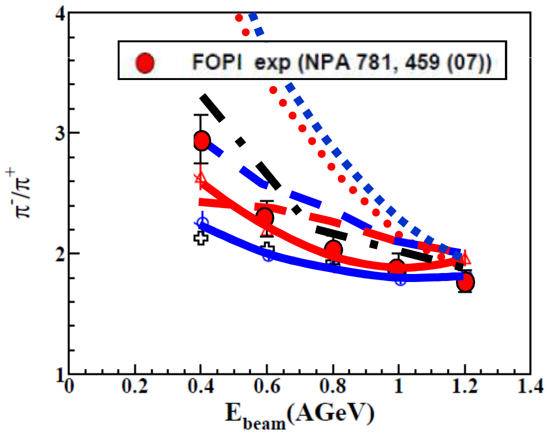
(π,Δ,K) dynamics: many new physical ingredients

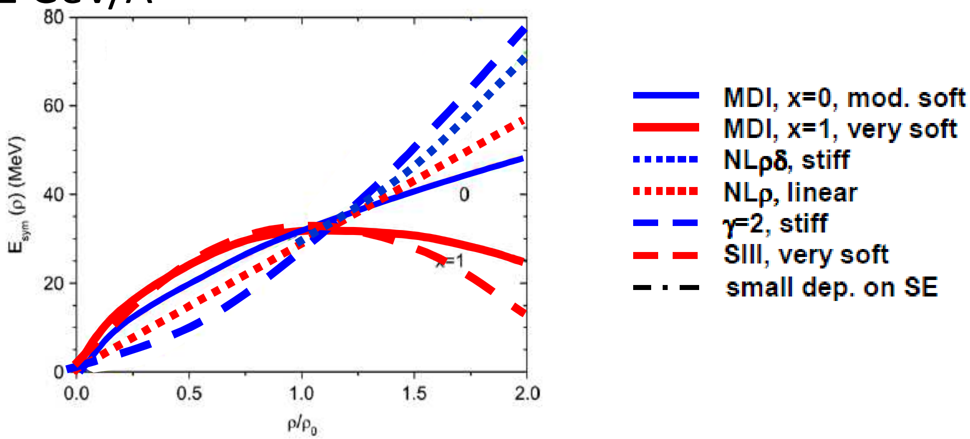
→ potentials $U_p$, $U_D$, $U_K$ → effective masses in medium, threshold effects

→ inelastic cross sections, e.g. NN→NΔ, in medium

→ Δ Resonances with decay widths, mass distributions, spectral fcts,
more general: off-shell transport

FOPI exp, Au+Au, 0.4-1.2 GeV/A



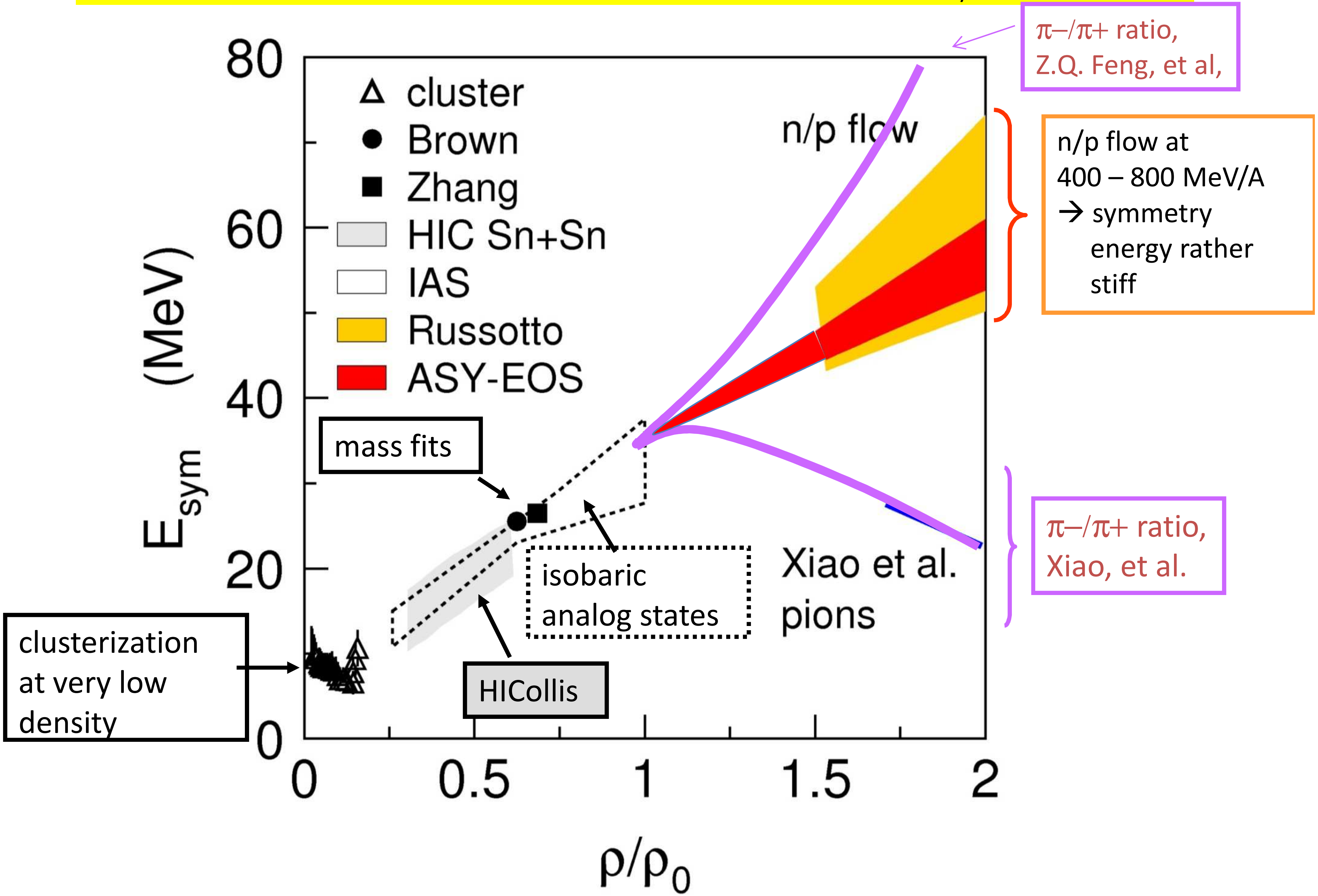

→ present situation of analysis unsatisfactory

→ check of (π,Δ) physics in box calculations

→ more sensitivity in spectral distributions, Sprit experiment (MSU-RIKEN)

→ reconsider Kaons, more direct probe of high density region

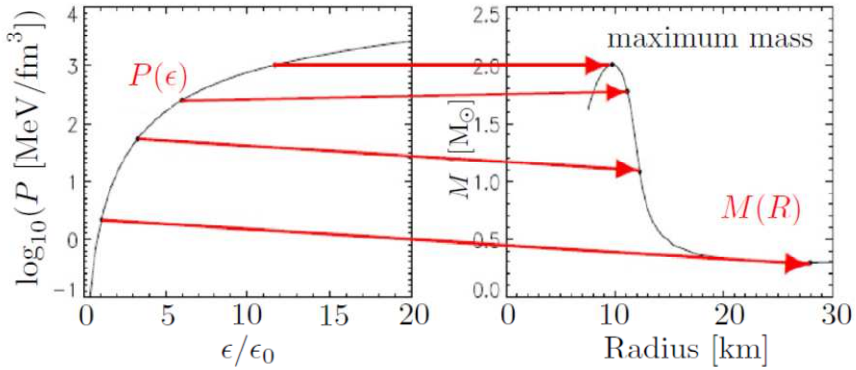
# Present Constraints on the Symmetry Energy (shown as $E_{sym}(\rho/\rho_0)$)



# Testing models of the high-density symmetry energy in NS

ı (Tolmann-Oppenheimer-Volkov TOV):

$$\frac{\partial P}{\partial r} = -\frac{m\rho}{r^2}\left(1+\frac{4\pi\, r^3\, P}{m}\right)\left(1+e+\frac{P}{\rho}\right)\left(1-\frac{2m}{r}\right)^{-1}$$

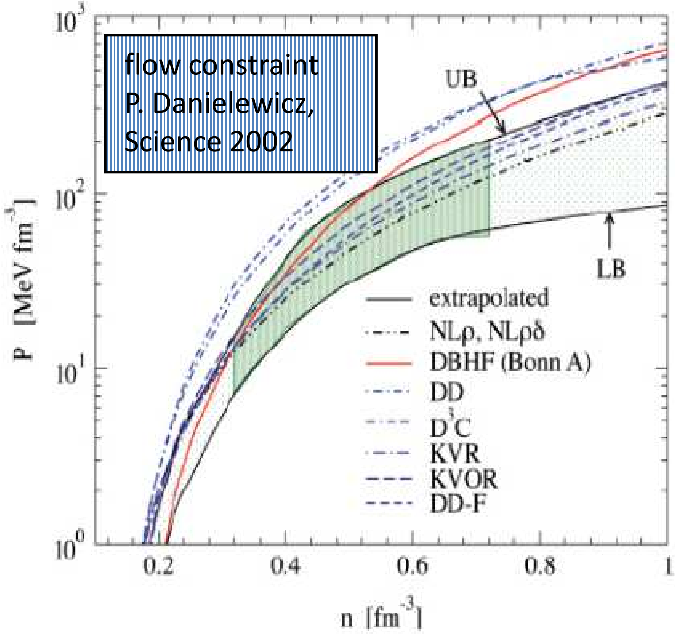



**Testing of EoS's constrained by HIC in NS not often performed systematically. One example:**

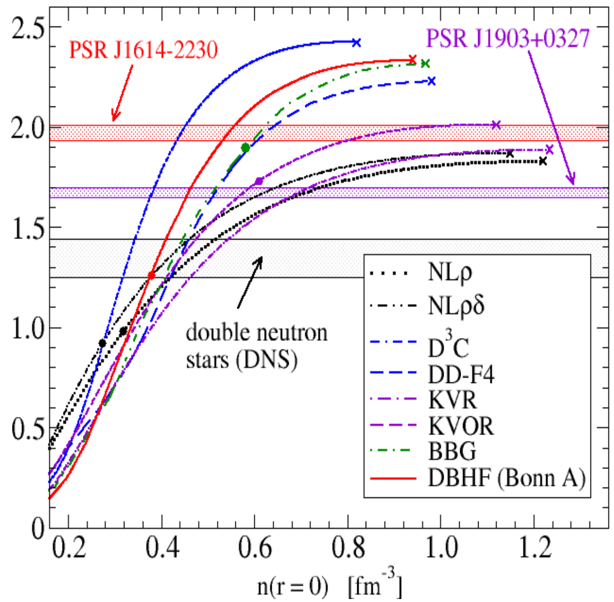

T. Klähn,[1,2,*] D. Blaschke,[3,4,†] S. Typel,[3] E. N. E. van Dalen,[2] A. Faessler,[2] C. Fuchs,[2] T. Gaitanos,[5] H. Grigorian,[1,6] A. Ho,[7] E. E. Kolomeitsev,[8] M. C. Miller,[9] G. Röpke,[1] J. Trümper,[10] D. N. Voskresensky,[3,11] F. Weber,[7] and H. H. Wolter[5]



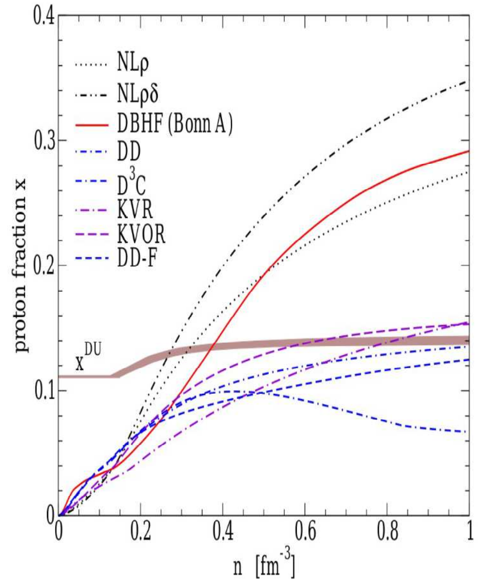
PHYSICAL REVIEW C 74, 035802 (2006)


nuclear matter EoS

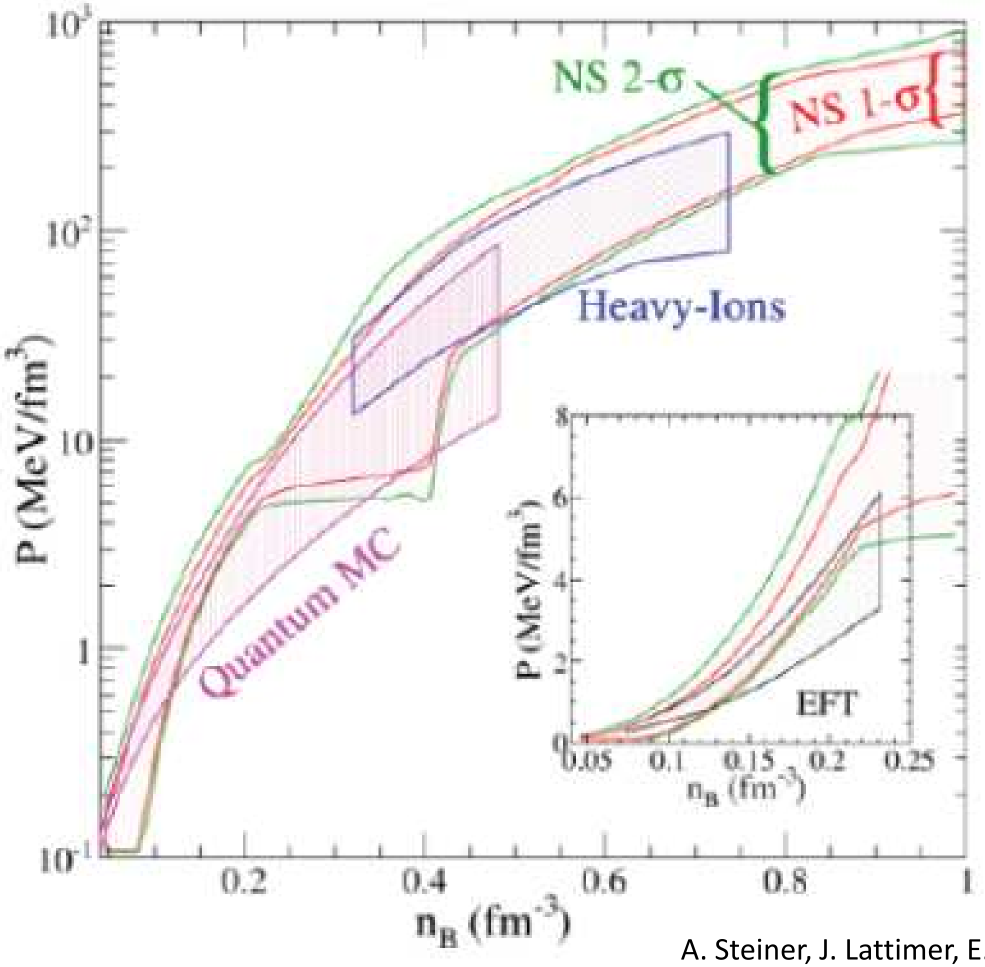



central density vs. mass




proton fraction
and URCA constraint

Synopsis of constraints from neutron stars, HIC and microscopic calculations
(for neutron star matter, i.e. β-equilibrium)




A. Steiner, J. Lattimer, E.D. Brown, APJLett 765 (2013)

Conclusions:

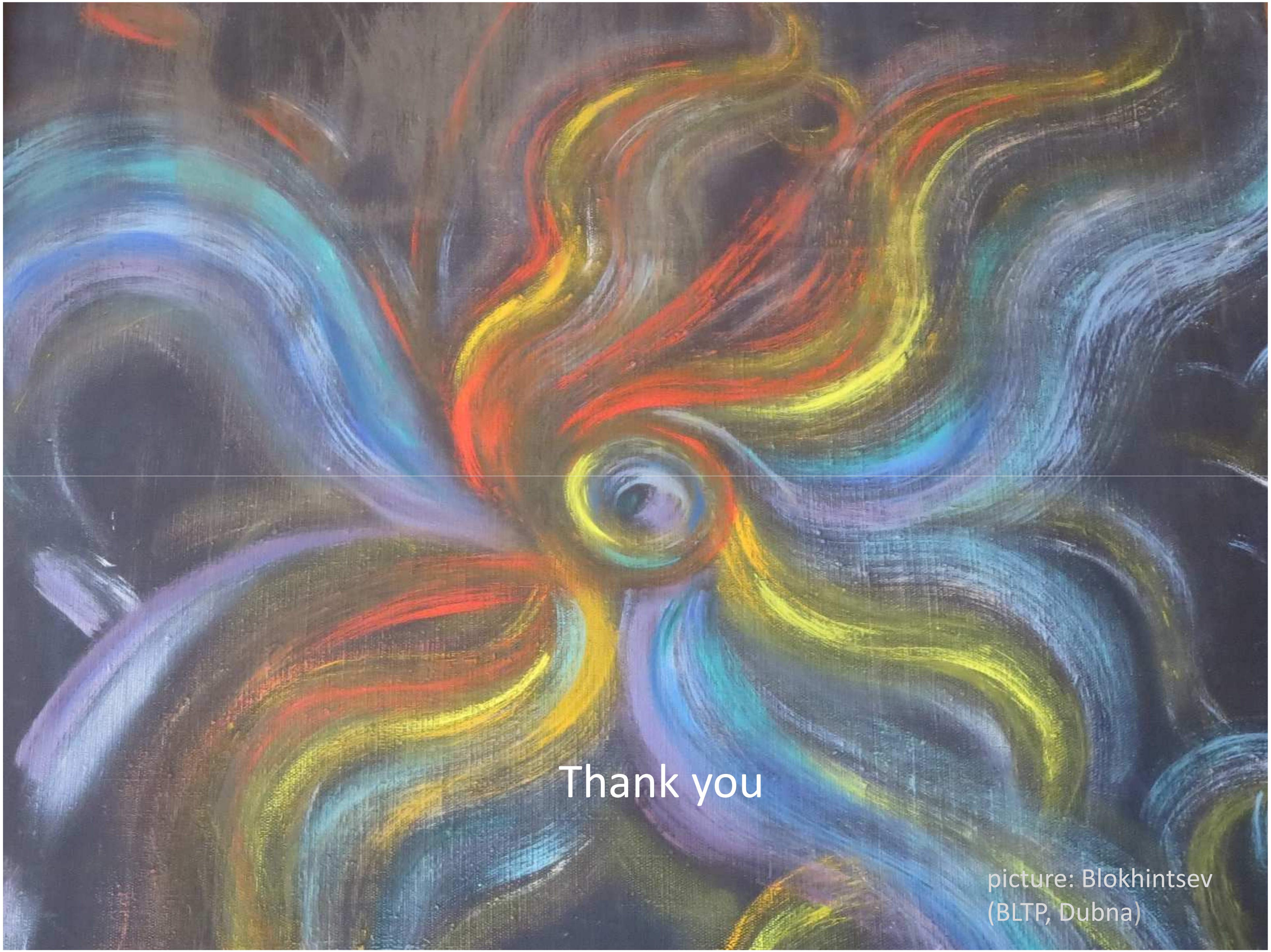
- Heavy ion collisions important to investigate the EoS in a wide range of densities

- Non-equilibrium processes, therefore transport theories are necessary to extract EoS.
  EoS does not enter directly, rather potentials and cross sections

- Transport theories are well developed, but also open problems
  fluctuations , finite size effects,
  change of degrees of freedom, homogeneous <->clustered matter, hadron<->quark mat

- Symmetry energy in hadronic sector starting to converge,
  but more work needed in the high density region

- HIC important for investigation of NICA, FAIR , J-PARK energy regime


Thank you
picture: Blokhintsev
(BLTP, Dubna)