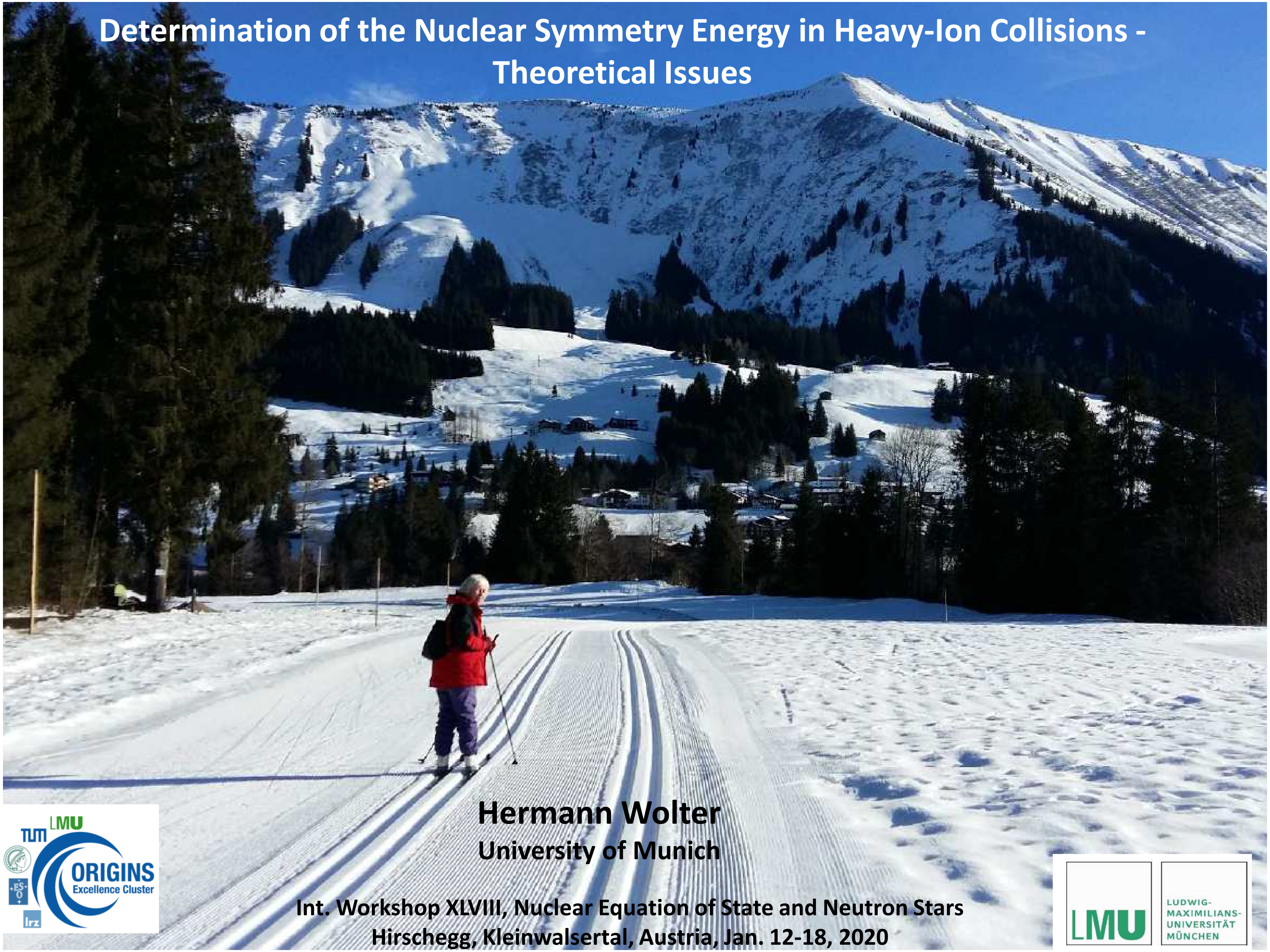
# Determination of the Nuclear Symmetry Energy in Heavy-Ion Collisions - Theoretical Issues



**Hermann Wolter**
**University of Munich**

**Int. Workshop XLVIII, Nuclear Equation of State and Neutron Stars**
**Hirschegg, Kleinwalsertal, Austria, Jan. 12-18, 2020**

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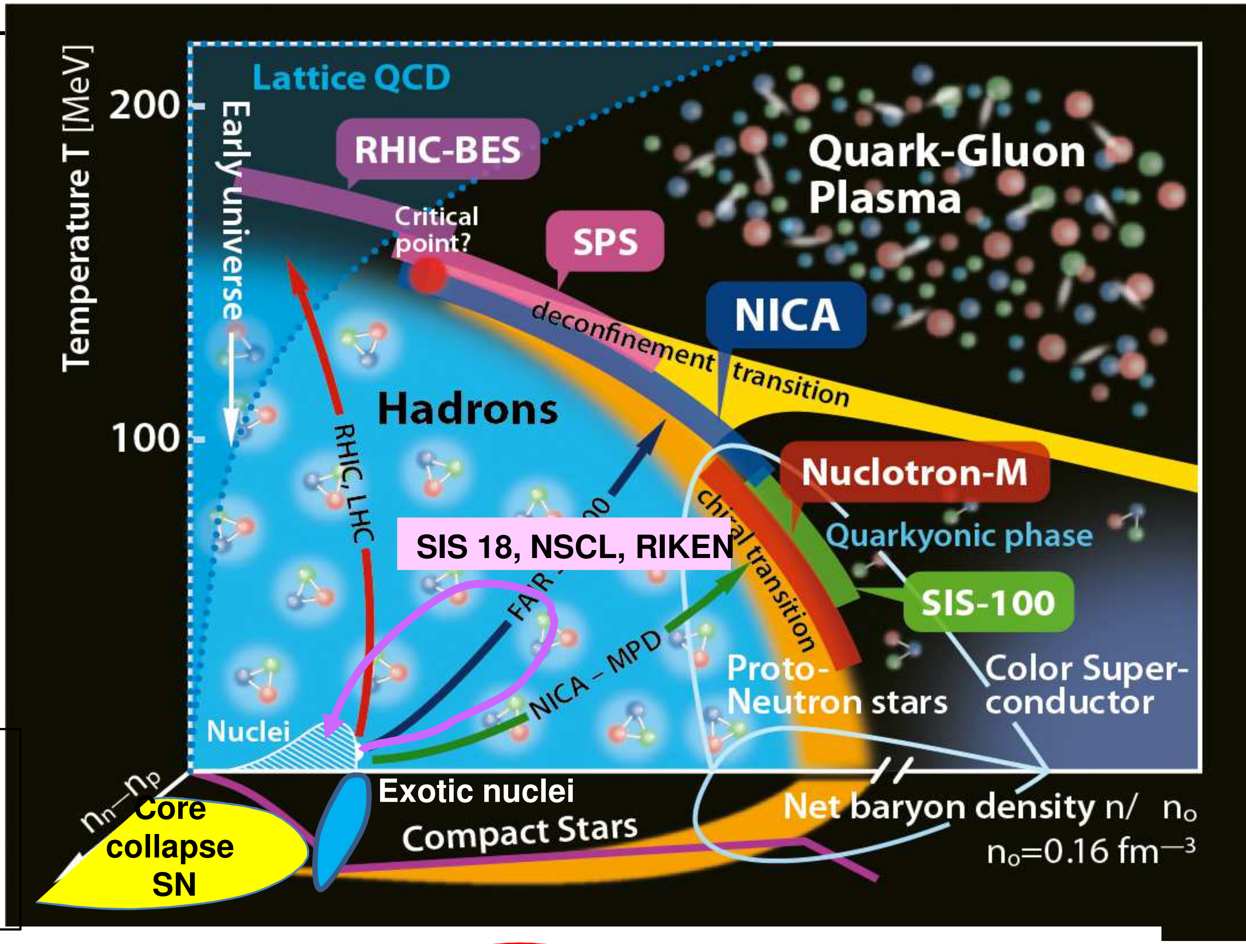
Aim of Heavy-Ion Collisions (HIC): Determine the Phase Diagram of Strongly Interacting Matter




**Asymmetry axis --> search for symmetry energy**

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

**Extensive efforts by:**

- **Microscopic theory**
- **Neutron star observations, NS mergers, NICER**
- **HI experiments in the hadronic and partonic regime,**
  **only way to investigate dense ,mildly neutron-rich matter in the lab**

Note: HIC trajectories are non-equilibrium processes
→ transport theory is necessary
but should check its robustness

**Plan:**
**Some theoretical issues in the transport decription of heavy-ion collisions (HIC).**

- not: comparison to experimental data (talks of Bill Lynch, Arnauld LeFevre, Abdou Chbihi)

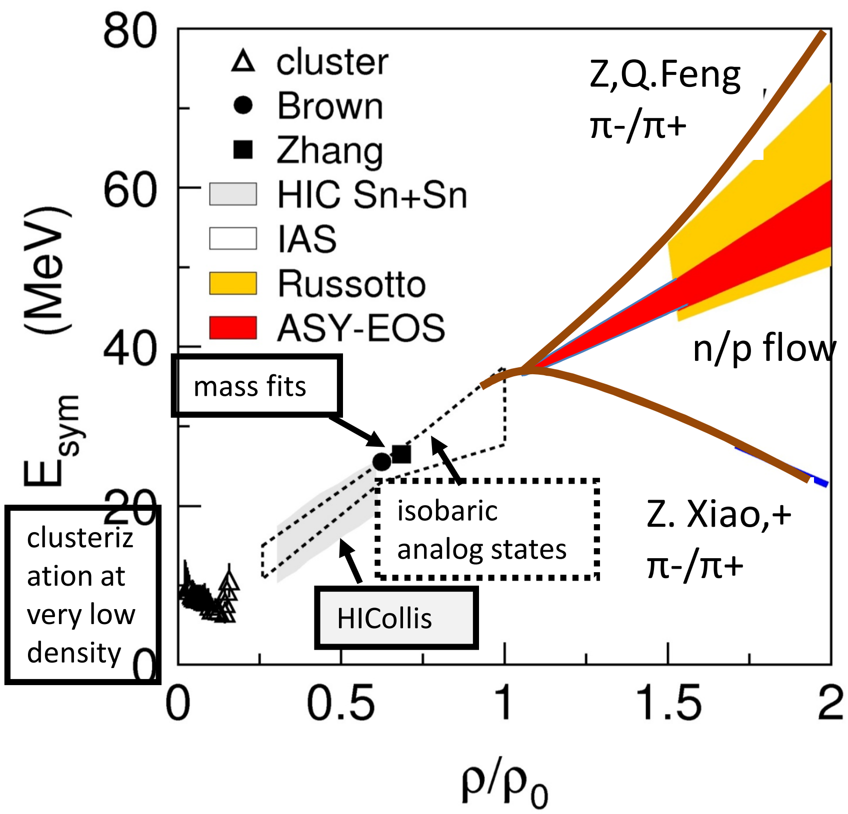
- Transport theory:
  approximations, physical ingredients, equation-of-state (EoS)
  beyond mean field: fluctuations and correlations

- Robustness of transport model results:
  benchmark calculations under controlled conditions:
  box calculations with periodic boundary conditions.

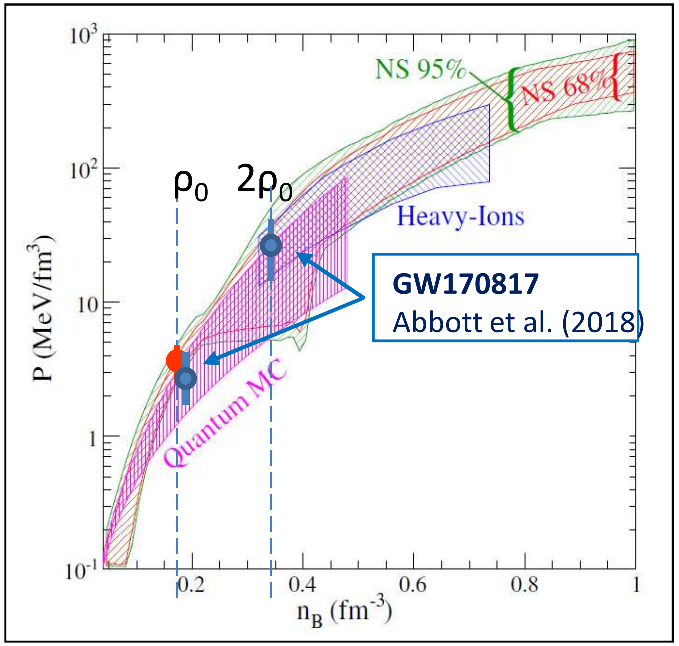
- see also: Workshop „Challenges to transport theory for heavy-ion collisions“.
  May 20-24, 2019, ECT*, Trento

# Present state and successes of transport analyses of HIC:

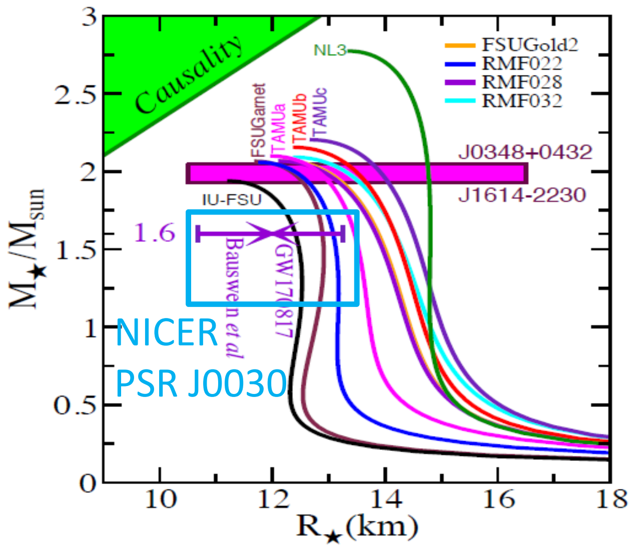
from nuclear physics




comparison to many-body calc and astrophysics




constraints from NS masses, radii and mergers



## Remarks on derivation of transport theory for HIC
(e.g. P. Danielewicz, Ann. Phys. 152, 239 (1984), and Transport 2019 workshop, ECT*)

Real-time Green function method: non-equilibrium, many-body

$$G_1(r_1,t_1;r_1',t_1') \leftrightarrow G_2(r_1,t_1,r_2,t_2;r_1',t_1',r_2',t_2') \leftrightarrow G_3(1,2,3;1',2',3') \leftrightarrow \cdots$$ BBGKY-Hierarchy

non-equilibrium-> 2 indep. Greenfcts

Truncation on 1-body leveland definition of self energy $\Sigma$

$$iG_1(1,1') = \int d2d2'd3'\, G_1(1,2)\langle 23'|V|2'3'\rangle G_2(2'3';1'3')$$

$$\approx \int d2d2' G_1(1,2)\Sigma(2,2')G_1(2',1')$$

This neglects higher order correlation effects,

they have to re-introduced: - in the form of fluctuations (for fragment production)

- explicitely (for light clusters)

Quasi-particle approx.: under slow spatial and temporal changes of the system the Wigner transform of $G^<$ becomes a 1-body phase space density

$$f(r,p;t) = \int dr' e^{ipr'} G_1^<(r+\tfrac{r'}{2}, r-\tfrac{r'}{2};t), \quad r = \tfrac{1}{2}(r_1+r_2),\ r' = (r_1-r_2)$$

This obeys an evolution equation of the Boltzmann-Vlasov type:
Mean field evolution plus collision term

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

## Physics ingredients in the transport equation

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

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

$\bar{f}_i := (1-f_i)$ Pauli blocking factors,

a) mean field, EOS,
energy density functional

$$\varepsilon(\rho,\delta)=E_0(\rho)+E_{sym}(\rho)\delta^2+\cdots$$

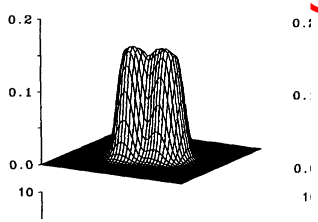
⟹ potential,
momentum-dependent

$$U(r,p;\rho,\delta)=\frac{\partial\varepsilon(\rho,\delta)}{\partial f(r,p)}=U_0(r,p;\rho,\delta)+U_{sym}(r,p;\rho,\delta)\,\delta+\cdots$$

↳ effective mass $m^*$ p/n eff. mass splitting $m_n^*-m_p^*$

How to choose EDF:
usual: model with parameters, e.g. Skyrme functional, Relativistic mean field (RMF)
determine EOS by comparison with experiment
„ab-initio“: Brückner theory, Brückner G-matrix: $U=\int G\bullet f;\ \sigma^{in-med}=|G|^2$

Temperature $U(r,p;\rho,\delta,T)$?? but non-equilibrium!
in the Brückner approach is taken (partly) into account
by the folding with the non-equilibrium $f$.
C. Fuchs, et al., NPA 601 (1996) 473 and 505



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

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$$\varepsilon(\rho,\delta) = E_0(\rho) + E_{sym}(\rho)\delta^2 + \cdots$$

⟹ potential, momentum-dependent

$$U(r,p;\rho,\delta) = \frac{\partial \varepsilon(\rho,\delta)}{\partial f(r,p)} = U_0(r,p;\rho,\delta) + U_{sym}(r,p;\rho,\delta)\,\delta + \cdots$$

↳ effective mass $m^*$ p/n eff. mass splitting $m_n^* - m_p^*$

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b) collisions $\sigma_{NN}^{in-med}$ medium-modified elast, cross sect., e.g. Brueckner *G*-Matrix ,

inelastic collisions: e.g. $NN \leftrightarrow N\Delta \leftrightarrow N\Lambda K$

↳ $\Delta \leftrightarrow N\pi$

transfer of asymmetry $\frac{n}{p} \to \frac{\Delta^{-,0}}{\Delta^{+,++}} \to \frac{\pi^-}{\pi^+}$

Coupled transport eqs.

$$Df^{(N)} = I_{coll}(NN \leftrightarrow NN) + I_{coll}(NN \leftrightarrow N\Delta)$$

$$Df^{(\Delta)} = I_{coll}(NN \leftrightarrow N\Delta + I_{decay}(\Delta \to N\pi)$$

$$Df^{(\pi)} = I_{coll}(\pi N \leftrightarrow \pi N) + I_{coll}(N\pi \leftrightarrow \Delta)$$

new physics input:
π,Δ potentials and
inelastic cross sections

Transport eq.:dissipative mean field dynamics, deterministic in principle

# In practice two main transport approaches

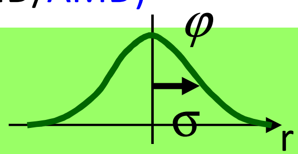
Boltzmann-Vlasov-like (BUU)

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

Dynamics of the 1-body phase space distribution function $f$ with 2-body dissipation,
solution by test particle method
in principle deterministic,
in practice stochastic simulation

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)
plus stochastic NN collisions

No quantum correlations,
but classical N-body correlations, damped by the smoothing. by wp width

Both BUU and QMD do not naturally have the correct fluctuations and no quantum correlations (except Pauli correlations in AMD))

fluctuations and correlations are effects beyond a 1-body theory,
- but become important in description of HIC, and have to be reintroduced

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

correlations ⟺ fluctuations

**correlations** ⇩ Light-cluster (LC) formation
Short-range correlations (SRC)

**fluctuations** ⇩ Intermediate-mass fragment (IMF) formation

**a large fractions of particles in clusters, e.g.**

Partitioning of protons

| | Xe + Sn 50 MeV/u | Au + Au 250 MeV/u |
|---|---|---|
| p | ≈10% | 21% |
| $\alpha$ | ≈20% | 20% |
| d, t, $^3$He | ≈10% | 40% |
| $A > 4$ | ≈60% | 18% |

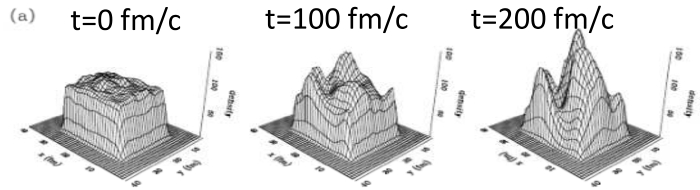
INDRA data, Hudan et al., PRC67 (2003) 064613.

FOPI data, Reisdorf et al., NPA 848 (2010) 366.

**LC's are not stabilized by the mean field but by few-body correlations.**

**Introduce as explicit degrees of freedom,**

**Fluctuation in the instable region are amplified and stabilized by the mean field**



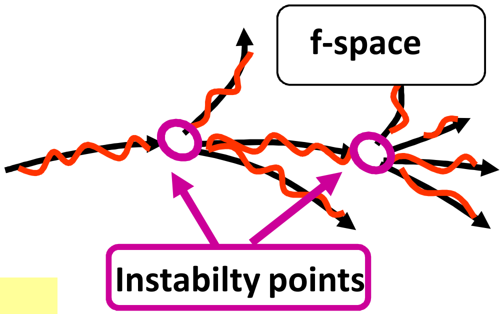

**BUU calculation in a box with initial conditions inside the instability region: $\rho=\rho_0/3$, T=5 MeV, $\delta=0$**

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

**Inject fluctuations with amplitudes motivated by physical (not numerical) principles.**

**We will see that fluctuations are also important in stable situations**

# Methods to introduce fluctuations




**BUU:** phase space distribution *f* is a statistical quantity with fluctuations, where the av. value <*f*> is determined by the BUU eq.

$$f = \bar{f} + \delta f \quad ; \quad \langle \delta f \rangle = 0, \quad \langle \delta f \delta f \rangle = \sigma^2$$

***f*** now obeys the Boltzmann-Langevin eq. (BL) $\frac{df}{dt} = I_{coll} + I_{fluct}$

The amplitude and spectrum of the fluctuations is the critical question. How to specify?

- \- fluctuation-dissipation theorem, is given by the 2-body collisions
- \- general thermal statistical fluctuations of a Fermi system, since fluctuations also arise from the neglected higher order correlations $\sigma^2(r,p) = \bar{f}(r,p)(1-\bar{f}(r,p))$

Implementations in BUU: minimize numerical noise (many TPs)

- SMF (stochastic mean field): project on density fluctuations (Colonna)
- BLOB (Boltzmann-Langevin One-Body dynamics)

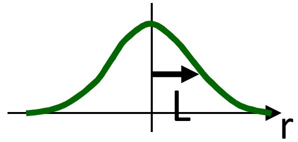
Move $N_{TP}$ test particles simultaneously (in p-space) to simulate fluctuation connected to NN collisions (Napolitani)

- Fokker-Planck-eq. , apply locally , invoking the dissipation-fluctuation theorem (Hao Li, PD)

⇒ ensure global conservation laws

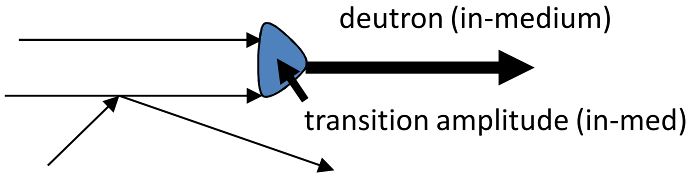
**QMD:** fluctuations are given by classical molecular dynamics but controlled by wave packet width L:

„empirical“: $L^2 \sim 2fm^2$



## Methods to introduce light cluster (LC) correlations:

pBUU (Danielewicz)
LC as explicit degrees of freedom



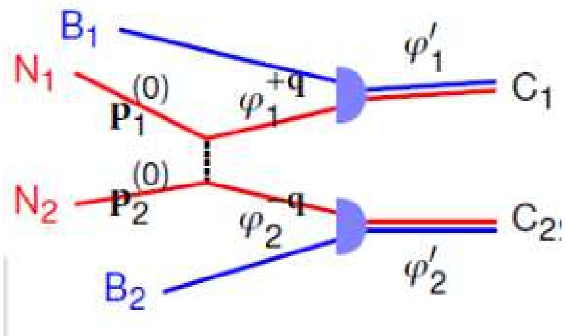

→ coupled transport equations for LC

Medium modification of properties and transition amplitudes of light clusters in heavy ion reactions
C. Kuhrts, et al,..PRC63 (2001), Typel, Röpke,et al., PRC81 (2010)

**Continue for heavier clusters, like t, $^3$He, α**
**--> coupled transport eqs. but increasingly complicated collision terms and unknown amplitudes**
**not (yet) included α partilcle**

AMD (Ono)

1. formation of clusters in terms of overlap with cluster wave function
2. put wave packets into the configuration of the cluster, satisfying Pauli principle , but propagate as nucleons
3. include also cluster-cluster collisions to form bigger clusters



**Plan:**

**Some theoretical issues in the transport decription of heavy-ion collisions (HIC).**

- not: comparison to experimental data (talks of Bill Lynch, Arnauld LeFevre, Abdou Chbihi)

- Transport theory:
  approximations, physical ingredients, equation-of-state (EoS)
  beyond mean field: fluctuations and correlations

- robustness of transport model results:
  benchmark calculations under controlled conditions:
  box calculations with periodic boundary conditions.

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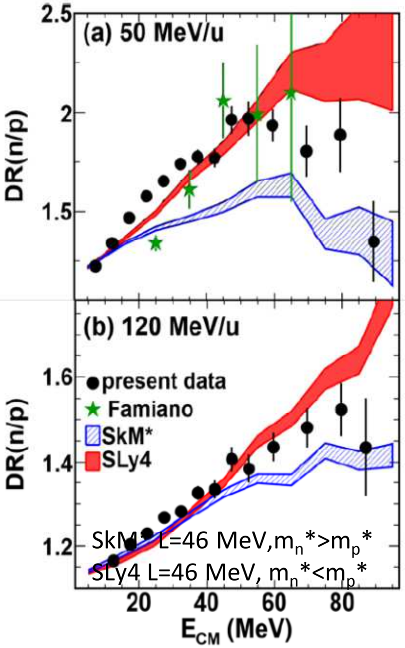
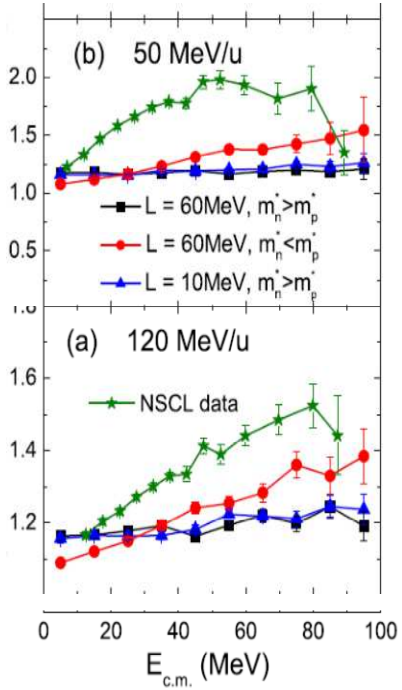
Solving the Transport theory by simulations: A need for more consistency.
Examples

double ratio of n/p pre-equilibrium emiss.

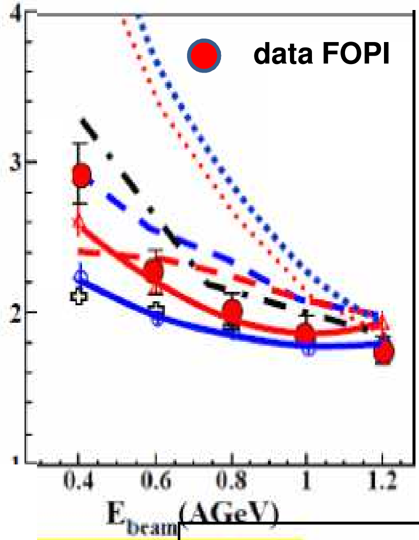
D.D.S.Coupland, et al., PRC94, 011601(R) (2016)

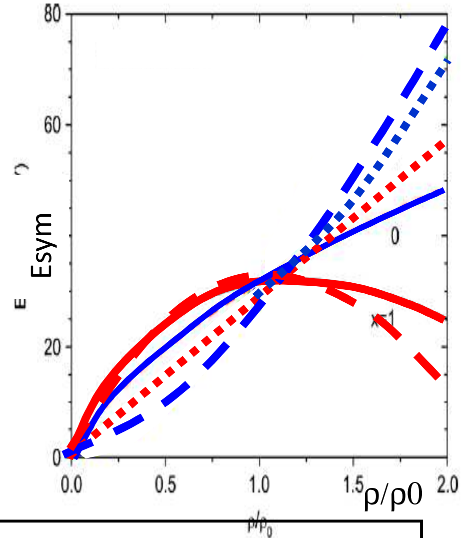



H.J.Kong, et al., PRC91,047601 (2015)




ratio of pion yields, Au+Au,0.4-1.2 GeV/A




various models
blue: stiffer symm energy
red: softer symm energy
→ no consensus, even on ordering

**Reasons for differences often not clear, since calculations slightly different in the physical parameters.**
**→ therefore comparison of calculations with same physical input,**
**i.e. under controlled conditions**

## Transport Model Evaluation Project

Comparison of all major transport codes under controlled and as far as possible identical conditions.
Steps:

**1. Full heavy ion collisions (Au+Au)**

**a) high energy ~1 AGeV: attention to $\pi$,K production (Trento 2004)**

**E. Kolomeitsev, et al., J. Phys. G 31 (2005) S741**

**b) intermediate energy , 100, 400 AMeV, attention to flow and NN collision rates (Trento 2009 and Shanghai 2014)**

**J. Xu et al., Phys. Rev. C 93, 064609 (2016)**

**-> considerable discrepancies, but difficult to disentangle reasons**

**2. Calculations of nuclear matter (box with periodic boundary conditions) test separately ingredients in a transport approach:**

**a) collision term without and with blocking (Cascade) (MSU 2017)**

**Y.X. Zhang, et al., Phys. Rev. C 97, 034625 (2018)**

**b) $\pi$, $\Delta$ production in Cascade (Busan 2018)**

**A. Ono, et al., Phys. Rev. C 100, 044617 (2019)**

**c) $\pi$,$\Delta$ production in a full HIC : Sn+Sn, 270 AMeV, close to submission**

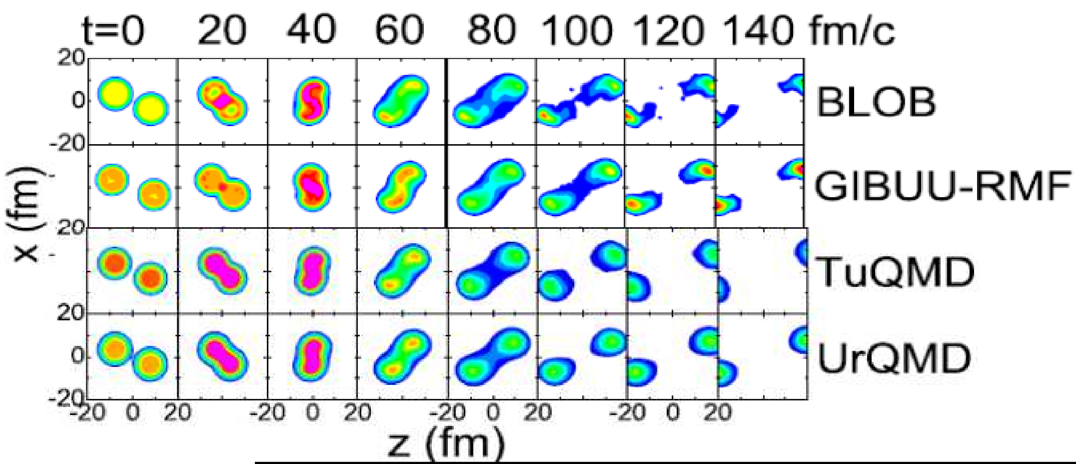
**d) mean field propagation (Vlasov), in preparation**

**e) instabilities , fragmentation ….. planned**

→ up to 19 codes of BUU- and QMD-type, 1 AMD code
→ non-rel. and relativistic codes
→ BUU codes with explicit fluctuations: SMF, BLOB
→ many new Chinese codes: QMD-XXX: much activity in China, originally closely related

# homework 1: full heavy ion collision with identical physics input

Au+Au at b=7fm (midcentral)
100 and 400 AMeV,
selected contour plots;
different evolution apparent

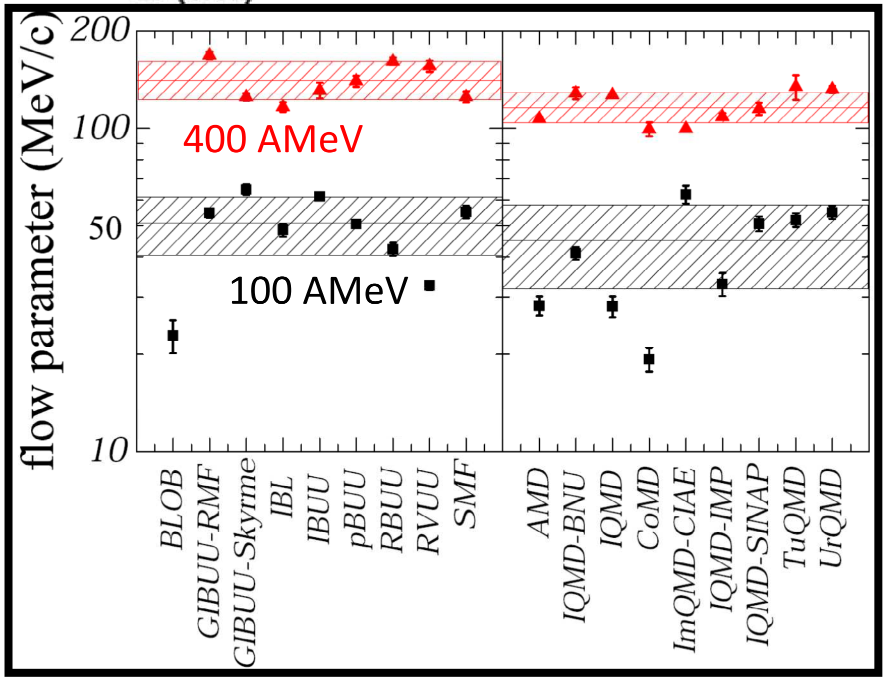



**Differences between codes seen in**
**- initialization,**
**- density evolution**
**- collision rates and blocking of collisions**
**-->differences in observables**

quantify spread of simulations by value of flow parameter =slope of transverse flow at midrapidity
BUU and QMD approx. consistent

uncertainity

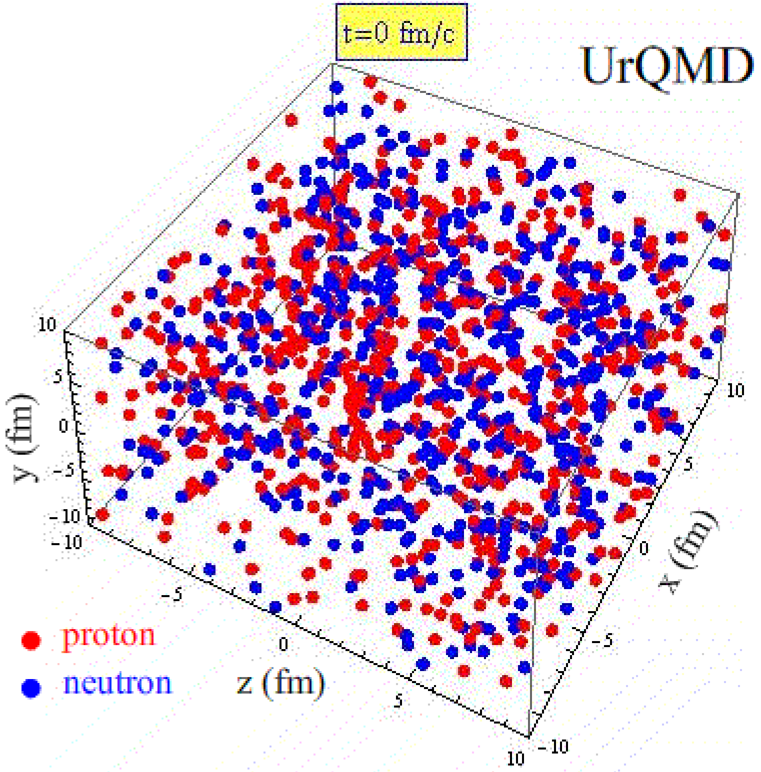
100 AMeV: ~30%
400 AMeV: ~13%




**Difficult to disentangle origin of discrepancies, since effects interact**

# Box calculation comparison

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




Useful for many reasons:

- check thermodynamical consistency of calculation
- check consistency of simulation:
  (often exact limits from kinetic theory)
- check different aspects of simulation separately
  Cascade: only collisions
  without/with blocking
  Vlasov: only mean field propagation
  Strategies for particle production, e.g. pions
  etc

Box calculations are an important tool to understand transport simulations

They should lead to an improvement and development of transport approaches:

## homework 2: Collision term in box calculations

collision probability

no blocking

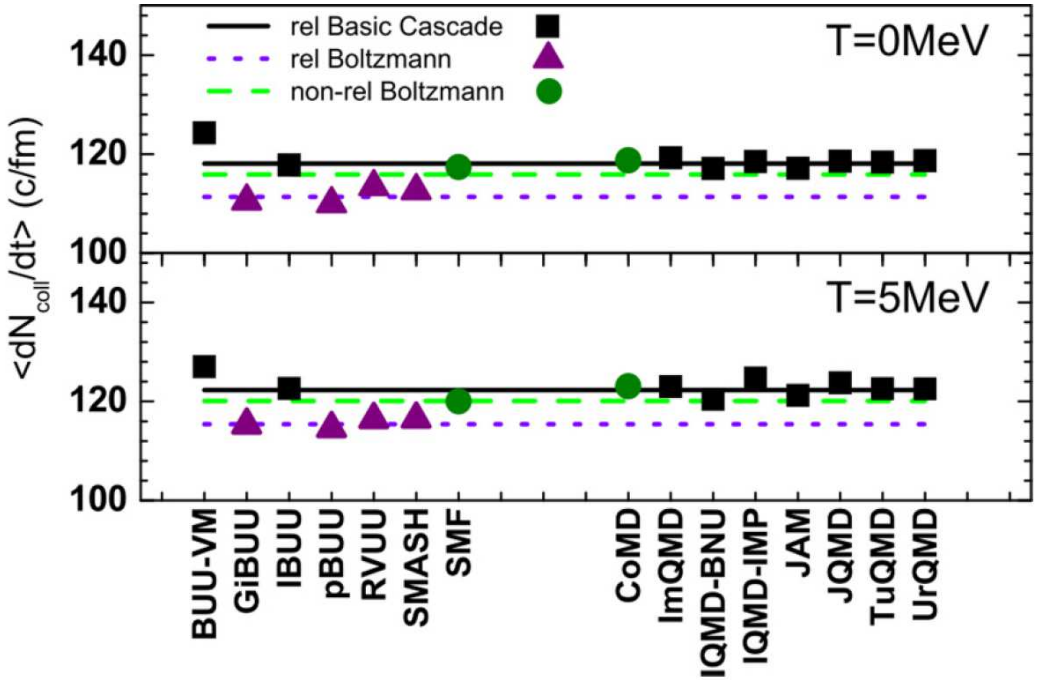
$$I_{coll} = \int d\vec{p}_2 d\vec{p}_{1'} d\vec{p}_{2'}\, v_{21}\, \sigma_{12}^{in-med}(\Omega)\,(2\pi)^3 \delta(p_1 + p_2 - p_{1'} - p_{2'}) \left[ f_{1'} f_{2'} (1-f_1)(1-f_2) - f_1 f_2 (1-f_{1'})(1-f_{2'}) \right]$$

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

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

$$\frac{dN_{\rm coll}}{dt} = \frac{A}{2\rho} g^2 \int \frac{d^3p\, d^3p_1}{(2\pi\hbar)^6} v_{\rm rel}\, \sigma^{\rm med} f(p)\, f(p_1) = \frac{1}{2} A\, \rho\, \langle v_{\rm rel}\, \sigma^{\rm med} \rangle\ .$$

($v_{rel}$ and average depend on treatment of relativity)




**good agreement with corresponding exact result**
**collision probability generally ok**
**( small deviations can be understood, higher order correlations between collisions)**

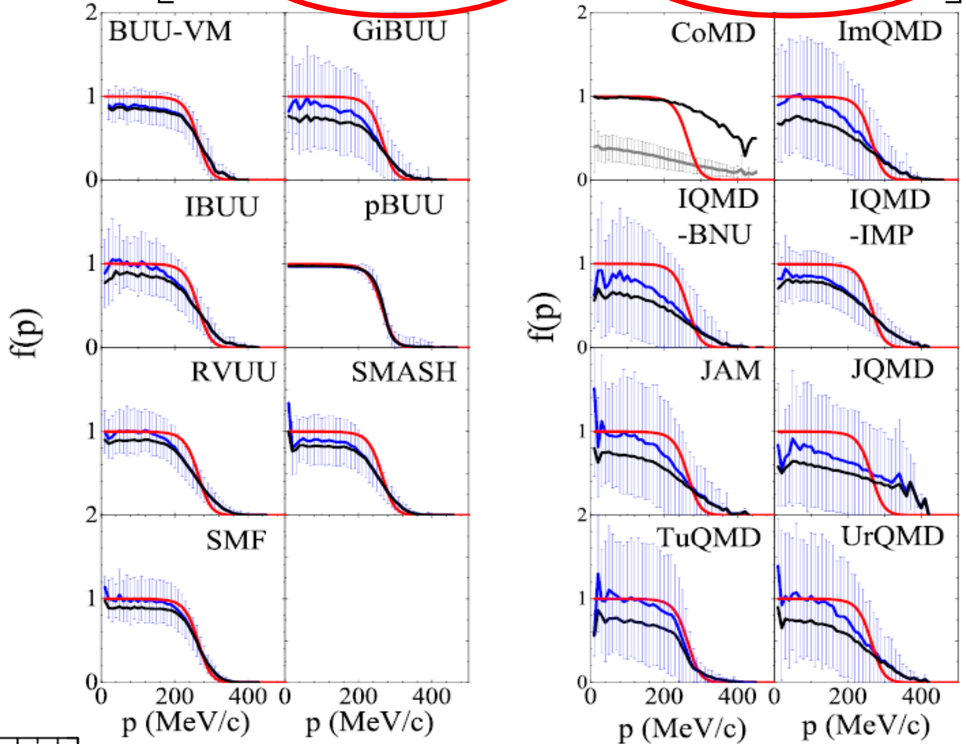
## Test of collision integral: Cascade calculation in a **box** **with Pauli blocking**

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

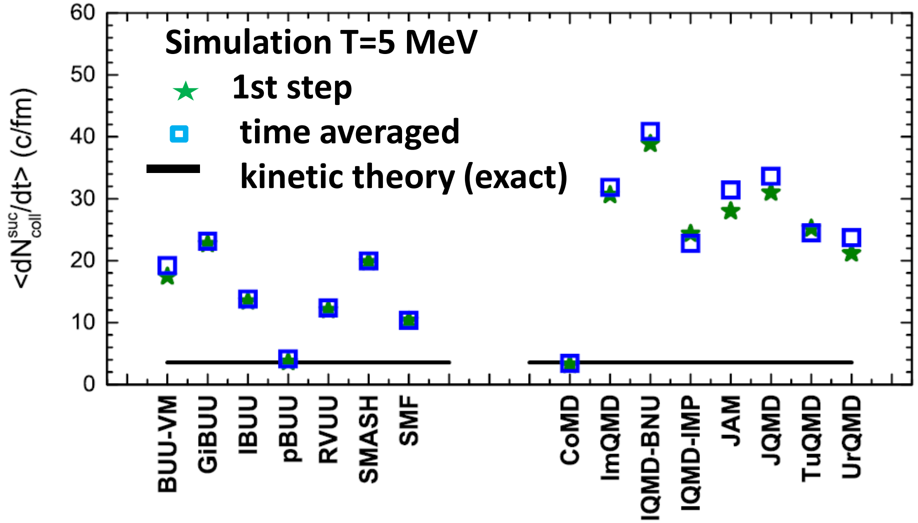
**Sampling of occupation prob.**
**in comp. to prescribed FD distribution (red):**
**-> large fluctuation, depending on code**

**width and averages of calculated occupation numbers in different codes**

- red line: **prescribed occupation**
- blue line: **average calculated occupation**
- black line: **average of f<1 occupation (used for the blocking)**




**Collision rates**



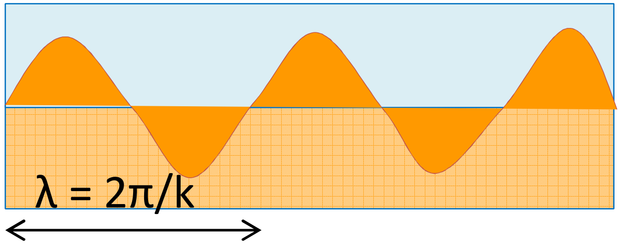

- **almost all codes have too little blocking, i.e. allow too many collisions,**
- **QMD codes more, because of larger fluctuations**

- **Fluctuations influence dynamics of transport calculations.**
- **Codes differ in treatment of fluctuations**
- **Proper treatment of fluctuations in transport under debate (as discussed above).**

## homework 2: Box simulations: test of m.f. dynamics, Vlasov (in preparation)

-- Symmetric matter --
- Only mean-field potential
- No surface terms
- Compressibility K=240 and 500 MeV

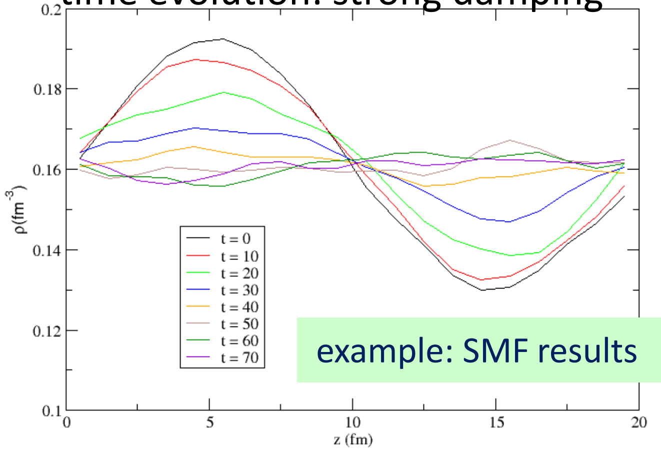
1. Density oscillations in the stable regime, time evolution of $\rho(z)$;




$\rho(z,t=t_0)= \rho_0 + a_\rho \sin(k_i z)$

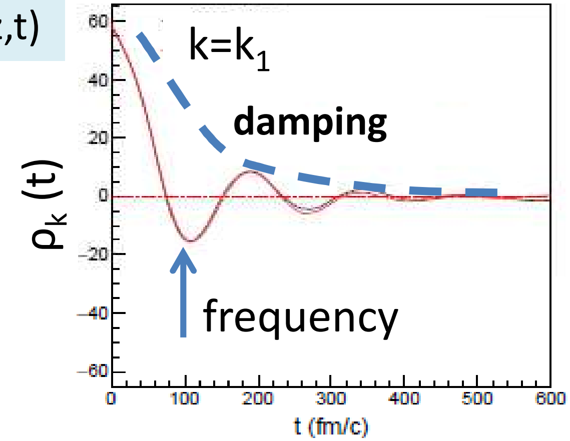
$k_i = n_i\, 2\pi/L, \quad a_\rho = 0.2\, \rho$

time evolution: strong damping



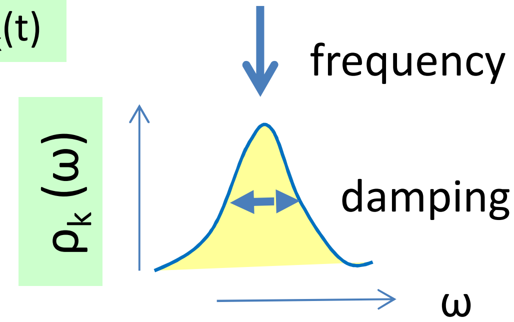

2. Fourier transform in space, modes

$\rho_k(t) = \int dz \sin(kz)\, \rho(z,t)$




3. Fourier transform in time: extract response funct., compare to exact result

$\rho_k(\omega) = \int dt \cos(\omega t)\, \rho_k(t)$

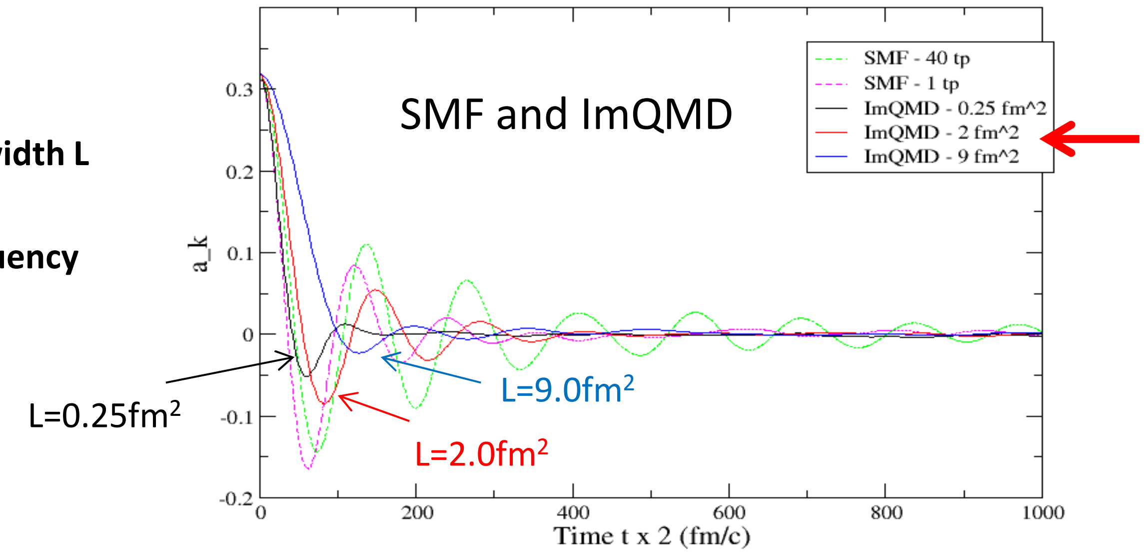



**Maria Colonna**

**Increasing fluctuation with:**

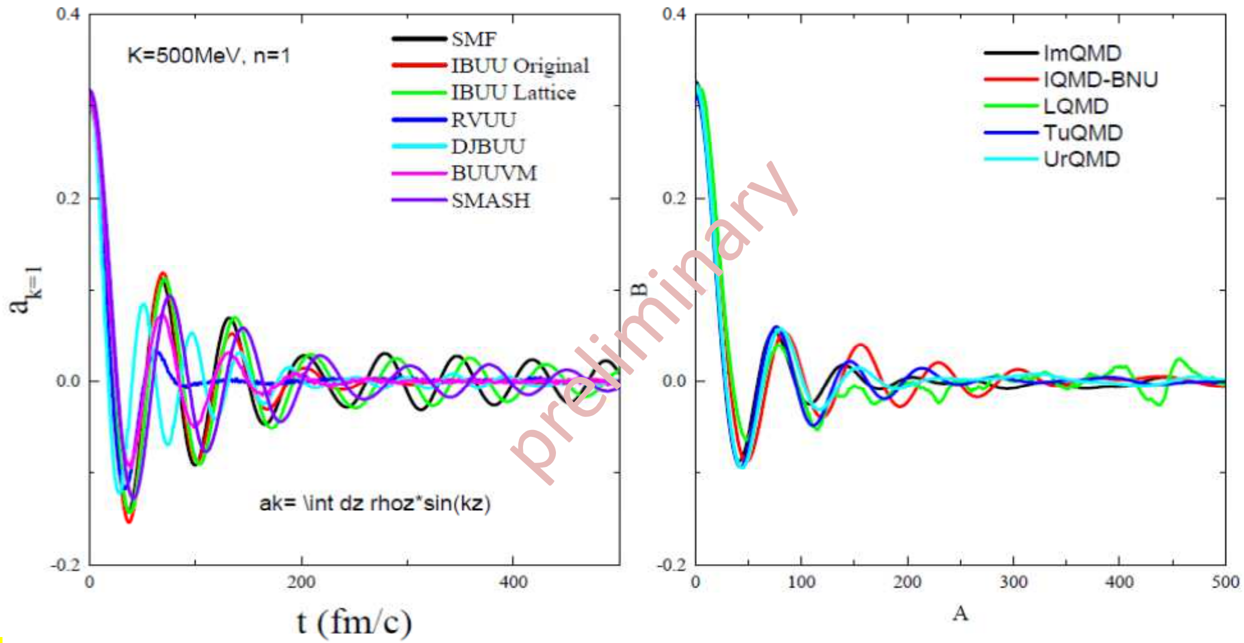
**SMF(BUU) decreasing TP no.**
**QMD (ImQMD) decreasing width L**

**--> increase damping**
**increase somewhat frequency**




all codes in the comparison

differences in frequency connected with effect of fluctuations on the calculation of the forces (gradients of potentials)




Fluctuations influence the mf dynamics. The effect will be much stronger in a regime of instabilty (spinodal region)

# homework 3: Pion production in a box

**A. Ono, et al., Phys. Rev. C 100, 044617 (2019)**

**Box calculation, $\rho=\rho_0$, T=60 MeV, asymmetry $\delta$=0., 0.2**
**Cascade calculation: no m.f., no Pauli-blocking, standard x-sections and widths**

$$NN \leftrightarrow N\Delta, \quad \Delta \leftrightarrow N\pi$$

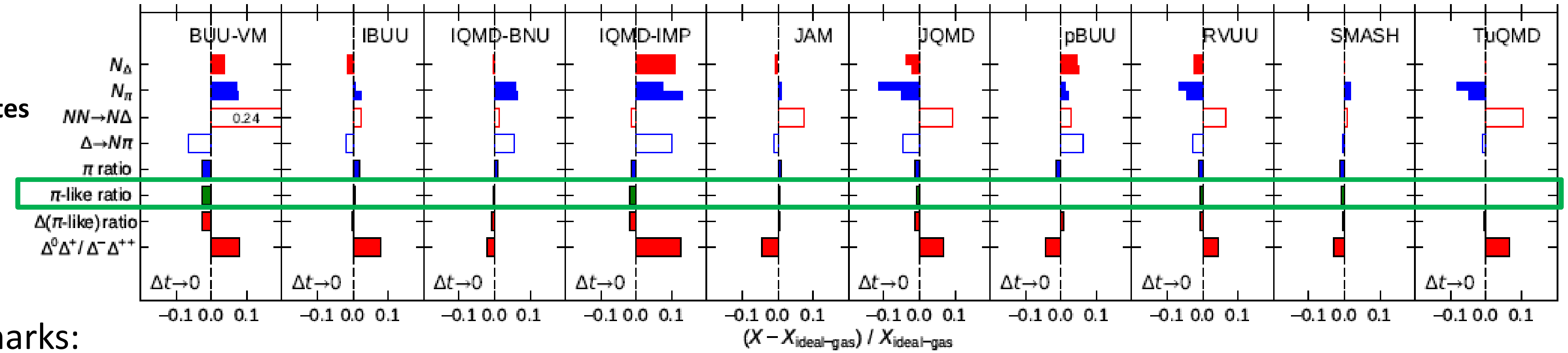
**Comparison of results of different codes to exact limit (Boltzmann equilibrium distributions)**

**no. of $\pi$, $\Delta$**

**reaction rates**

**pion and $\Delta$ ratios**

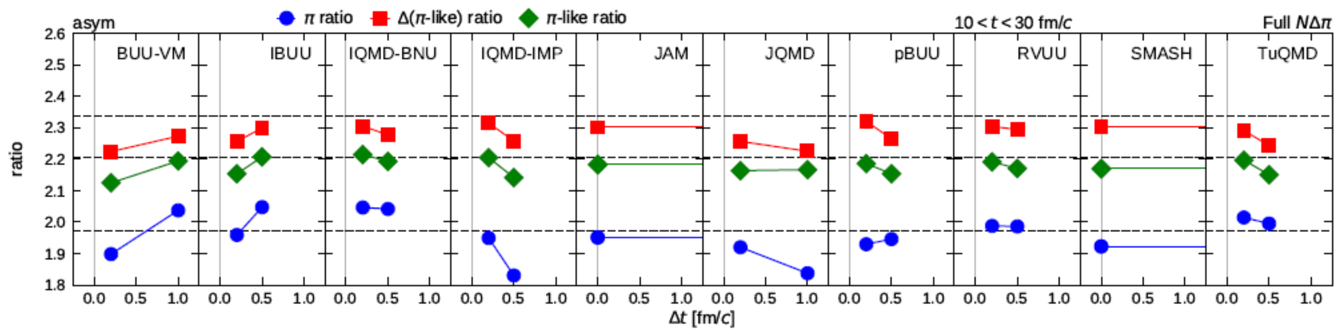
**isospin violation**




remarks:

1. **time step in the solution is important. Results extrapolated to $\Delta$t-> 0**
2. **Differences in no. of $\pi$,$\Delta$; mostly understood from strategies in handling the sequence of collisions, this may result in unphysical isospin violations**
3. **simulation and Boltzmann statistics may be different, because of higher order correlations between collisions**
4. **The pion-like ratio (green) corresponds to the $\pi-/\pi+$ ratio in a HIC. A good correspondece between the codes**

Still valid in non-equilibrium?




**the same comparison (in a different representation) for earlier time (box not equilibrated) shows larger differences (green diamonds).**

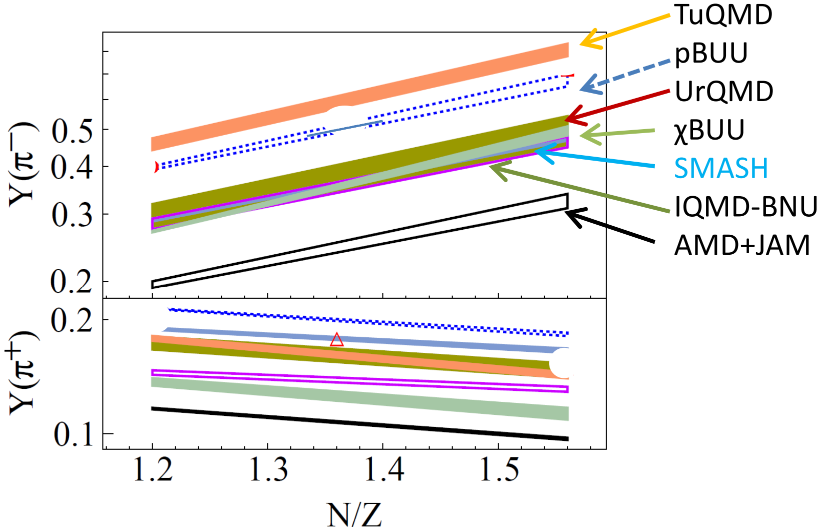
## Pion production in HIC:

SπRIT experiment, B. Lynch talk, to be submitted soon
Sn+Sn @270 AMeV, b=3 fm

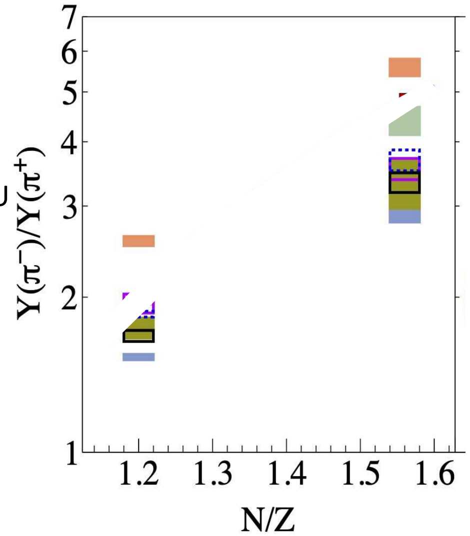
132Sn+124Sn (N/Z=1.56)
112Sn+124Sn (N/Z=1.36)
108Sn+112Sn (N/Z=1.2)

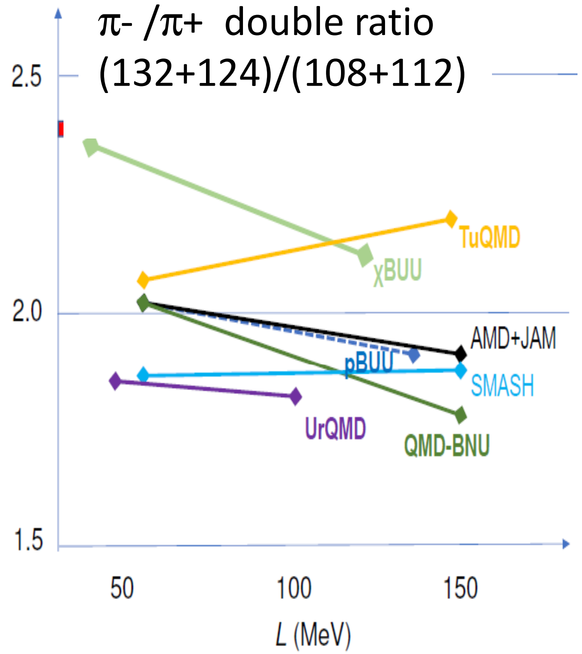
predictions of codes prior to the data

π- and π+ Yields




π- /π+ single ratios



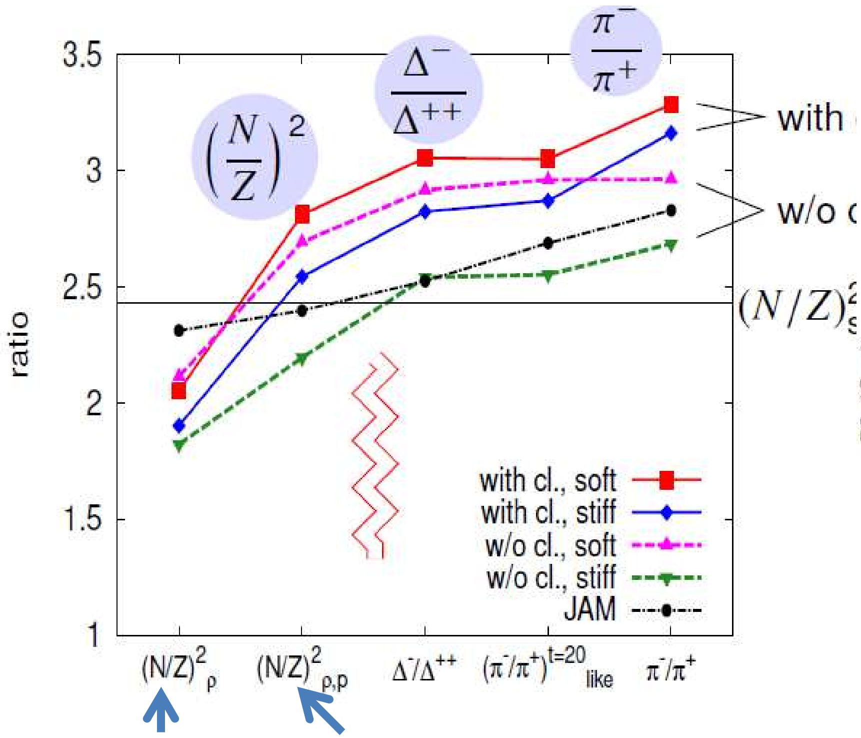

upper and lower boundaries of bands and squares:
--> stiff and soft symmetry energies for each code

Differences between codes is larger than difference between stiff and soft SE for each code!
Need to understand better.

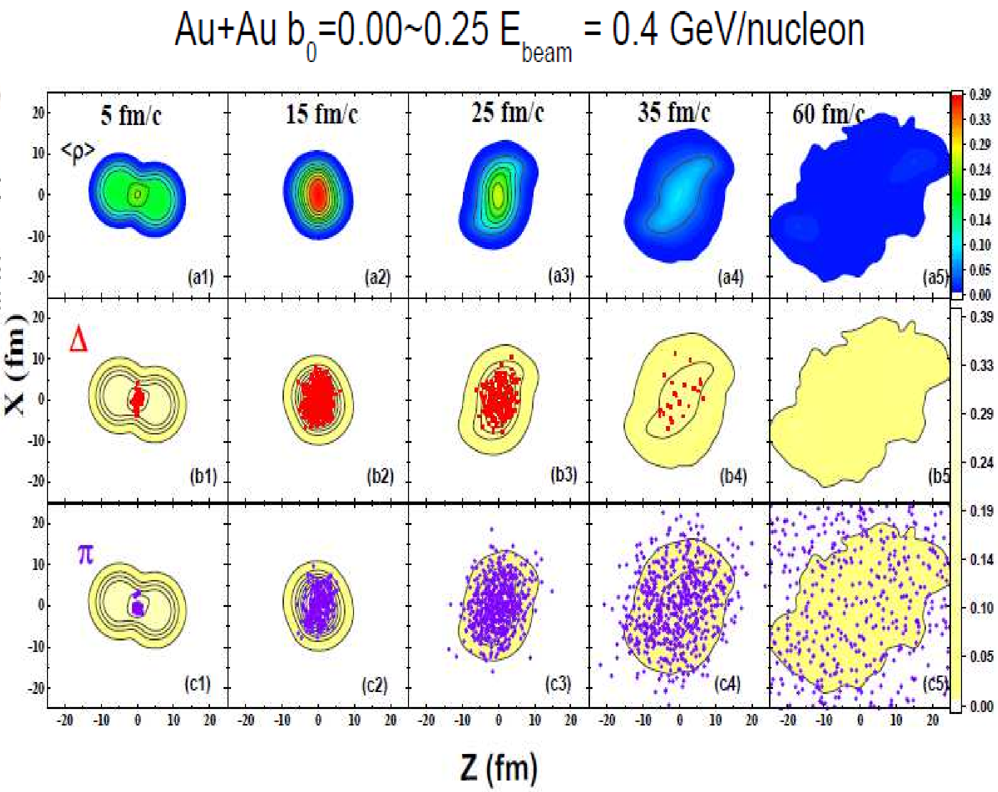
Predictions for SpiRIT exp:

also spectra are not very sensitive

further selection of pion production improves sensitivity (Ono, priv. commun.)




high density and momentum regions



Comment: consider Kaon production again:

NN → NΔ → Nπ → ΛK

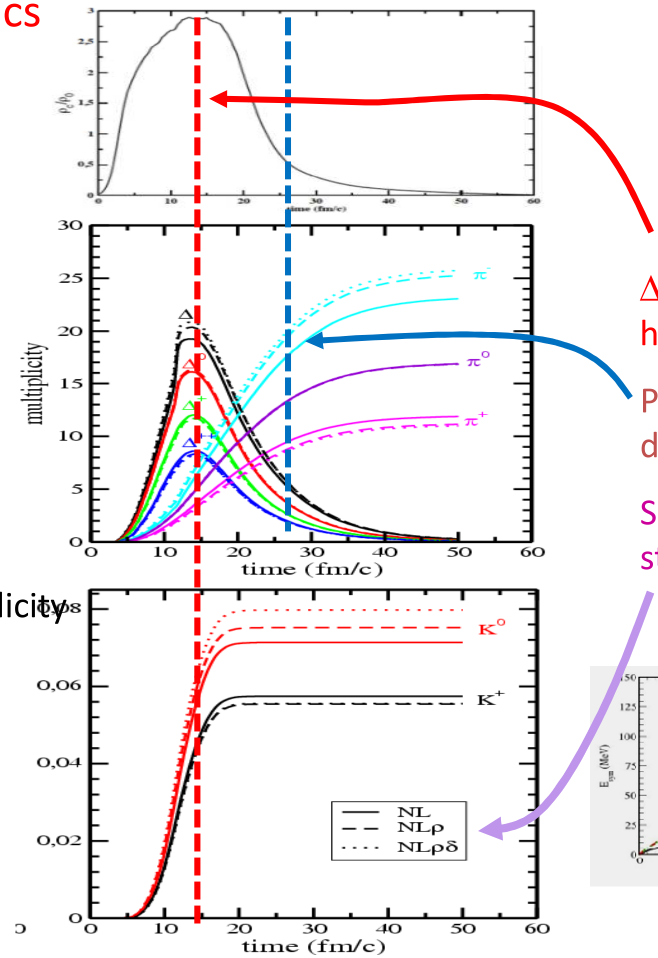
NΔ → NΛK

Dynamics

Central density

π and Δ multiplicity

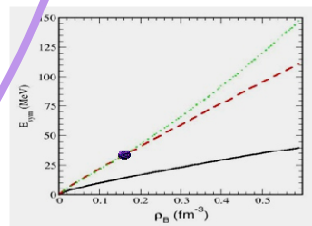
$K^{0,+}$ multiplicity




Δ and K: production in high density phase

Pions: low and high density phase

Sensitivity to asy-stiffness



NLρδ

NLρ

NL

stiffer

softer

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

## Conclusions:

- Transport theory neccessary to interpret HICs
- Allow to investigate the EoS, particularly the symmetry energy, away from saturation
- Important successes, but also
  - questions about effects beyond mean field dynamics
  - consistency of predictions of different codes (implementations)

Review of foundation, ingredients and extensions of transport approach

- ❑ Momentum (temperature?) dependence of potential,
- ❑ In-medium cross sections, elastic, inelastic, treatment of collision term
- ❑ Fluctuations (fragment production, but also blocking, mean field damping)
- ❑ Few-body correlations (Light cluster production, important probes for the symmetry energy and the state of the system), short-range correaltions

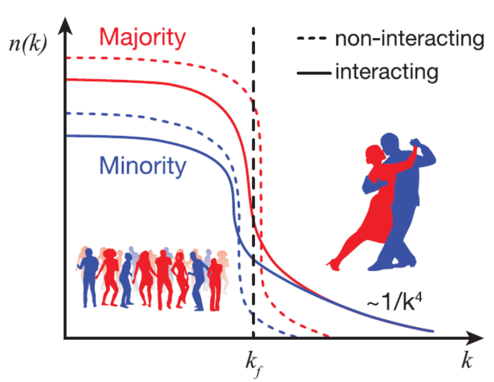
Transport model evaluation project:

- ➢ Estimate systematical theoretical uncertainity of transport analyses
- ➢ Study effects on results (e.g. fluctuations, higher-order correlations, etc.)
- ➢ pion production is interesting but needs better understanding

# Thank you for the attention !

## Role of Short-Range-Correlations

High momentum tail due to short range correlations.
In asymmetric nuclear matter, this is different for neutrons and protons, for $k<k_F$, but similar for $k>k_F$. -> Symmetry energy effect.
Could be important in HIC in particle production.



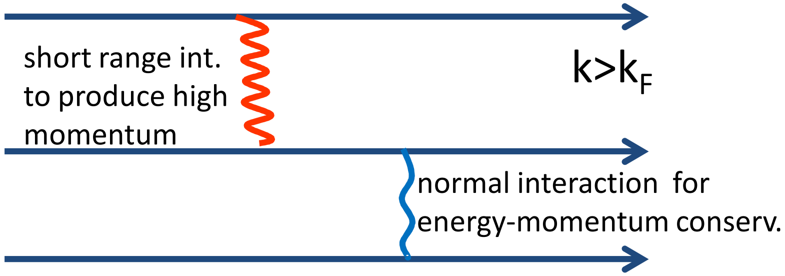

Current debate, how to take into account in transport:

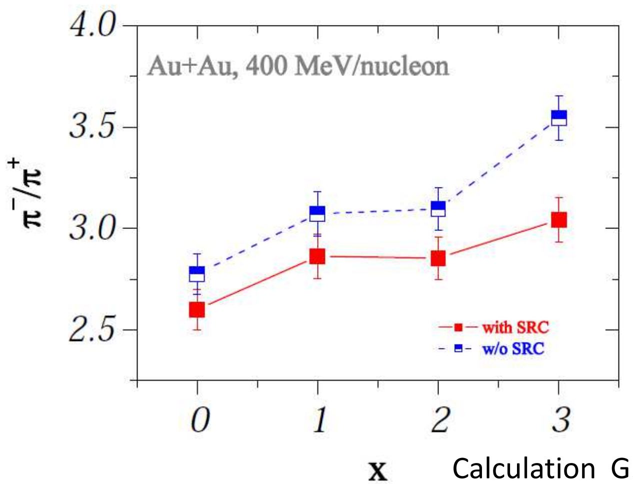
1. Initialize momentum distribution with high momentum tail, e.g. GC Yong, PLB 765 (2017) 104
   Should be quickly lost due to collisions and is not regenerated.
2. Subtract correlation energy from mean field potential, e.g. B.A.Li+, PRC 91, 044601 (2015).

$$E_{\rm sym}(\rho)=\eta\cdot E^{\rm kin}_{\rm sym}({\rm FG})(\rho)+\left[S_0-\eta\cdot E^{\rm kin}_{\rm sym}({\rm FG})(\rho_0)\right]\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

   argument: determination of $U_{sym}$ more realistic, since correlation energy not assumed as symmetry energy.
   but: but does not affect kinetic energy and produces no high momentum tails

3.? Treat explicitely in 3-body collision, in a sense similar to problem of LC production.




Calculation G.C.Yong