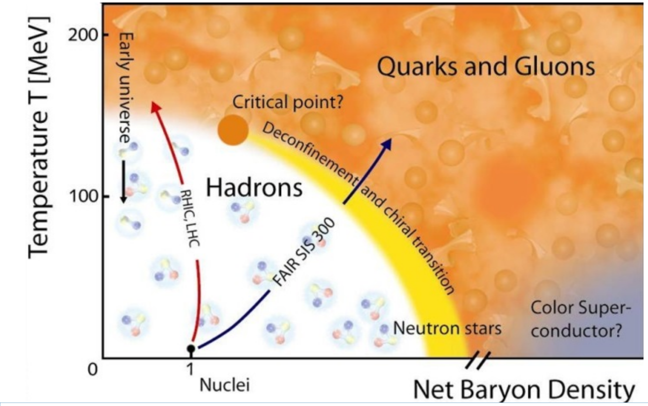

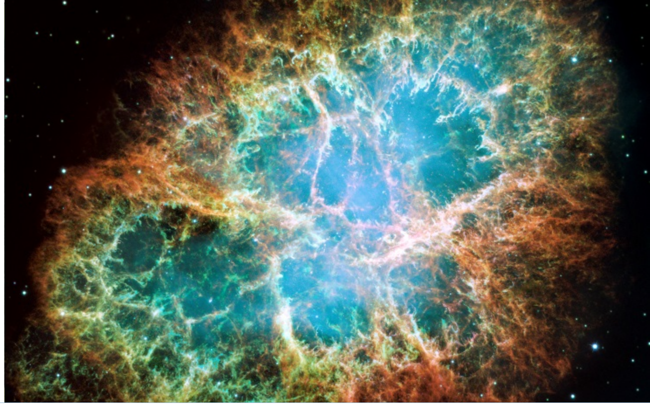

Relevance of cluster formation in heavy ion collisions and the fragmentation code FRIGA

Cold nuclei and hot matter

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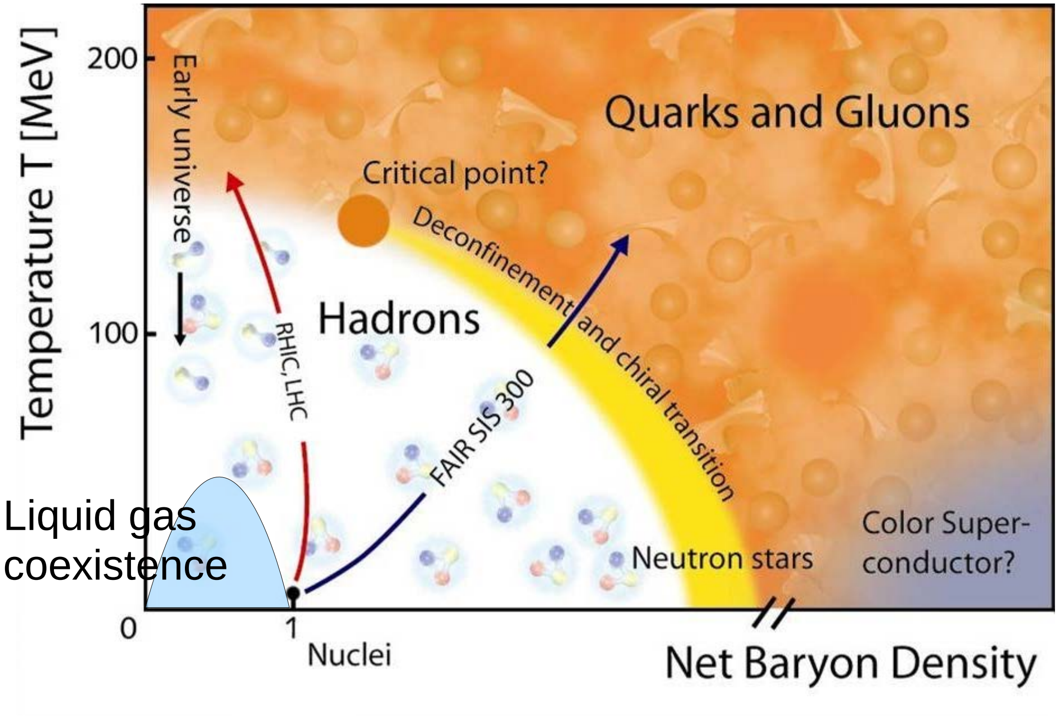
CBM Symposium
3.10.2018

Outline

- Heavy ion reactions between 0.1 - 10AGev
- Introduction to transport models
- Characteristic observables
- Relevant quantities and comparison to experimental data
  - Equation of state of nuclear matter
  - Dependencies to other input parameters
  - Importance of cluster formation
- FRIGA
  - Introduction
  - Benchmarking BQMD + FRIGA
  - Benchmarking IQMD + FRIGA
  - Hyper nuclei
- Summary and Outlook

Phase diagram of QCD matter

How to explore nuclear matter under extreme conditions?



- heavy ion collisions tool to explore characteristics of compressed nuclear matter in the laboratory
- need microscopic transport models to interpret the data

Microscopic models – two approaches

Boltzmann-Vlasov-like (BUU/HSD)

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

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

Molecular dynamics like (QMD/AMD)

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

$$\dot{r}_i = \{r_i, H\};\ \dot{p}_i = \{p_i, H\}$$

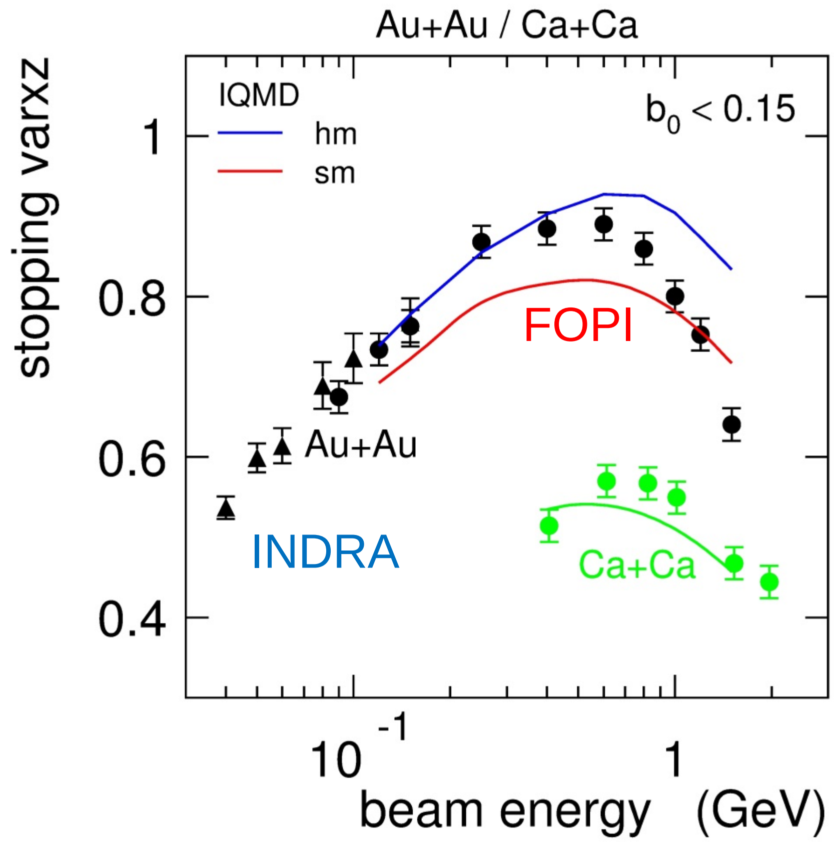
$$H = \sum_i t_i + \sum_{i,j} V(r_i - r_j)$$

Time-dependent Hartree Fock plus stochastic NN collisions

physical input:
mean field (potential),
σ_{inmed}, spectral functions $\rightarrow$ **transport code** $\rightarrow$ observables

“technical input”: discretization, averaging (coarse graining), Pauli blocking, etc.
Code comparison project: H. Wolter, M. Colonna, J. Xu et al.

1. Stopping



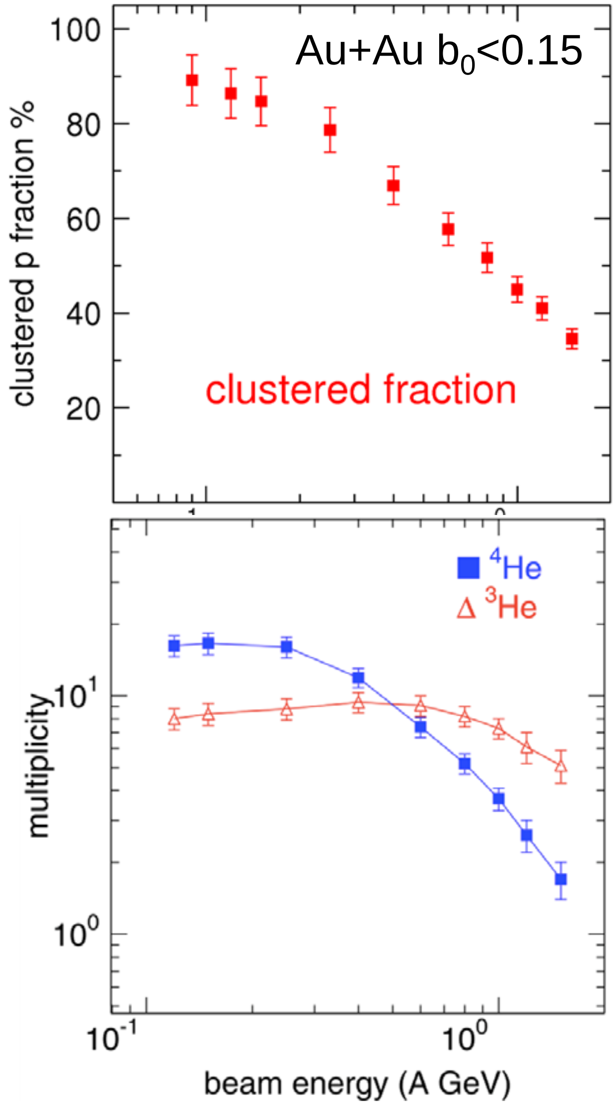
Data: FOPI+Indra, A.Andronic et al.
Eur.Phys. J.30 (2006) 31-46
IQMD, C. Hartnack et al. EPJ A1 (1997) 151

- Stopping deduced from phase space distributions

$$\text{var xz} = \frac{\sigma^2_{y_x}}{\sigma^2_{y_z}}$$

- measured 0.12 – 1.5 (2.0) AGeV for Au+Au to Ca+Ca
- depending on energy (maximum at 0.5AGeV)
- sensitive to in-medium cross sections

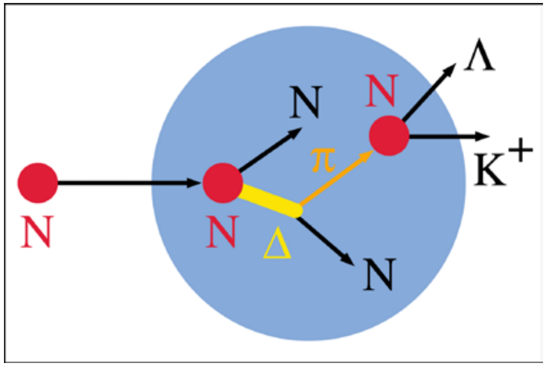
2. Formation of clusters



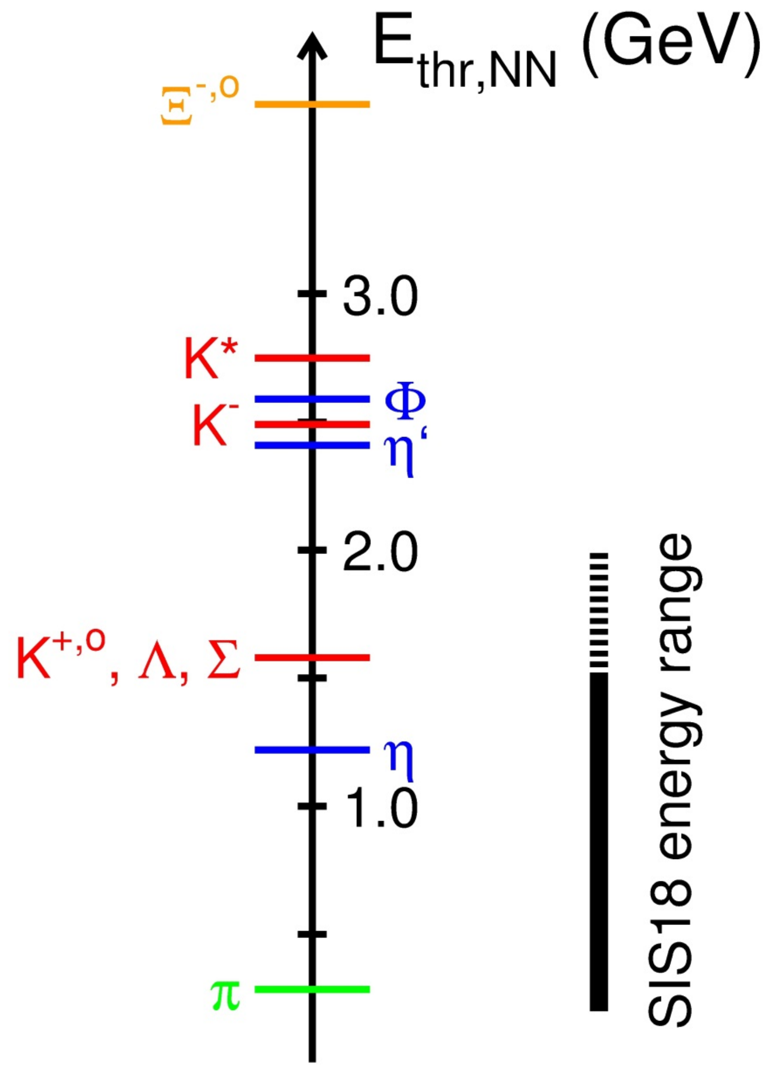
- high degree of cluster formation in most central collisions
- yields cannot be described by coalescence
  - neutron capture of ^{3}He enhances α yield at low energies
- cluster production influences phase space distribution of other particles

3. Particle production

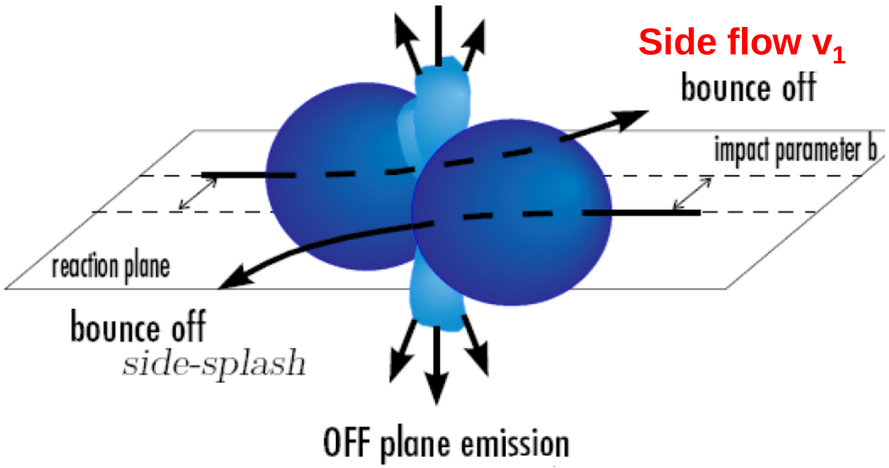
Possible at energies below to the threshold in NN system



- multi-step processes can cumulate the energy needed
- intermediate resonances used as an energy reservoir
- production at high densities due to short life time of resonances
- probing density (number of binary collisisons)

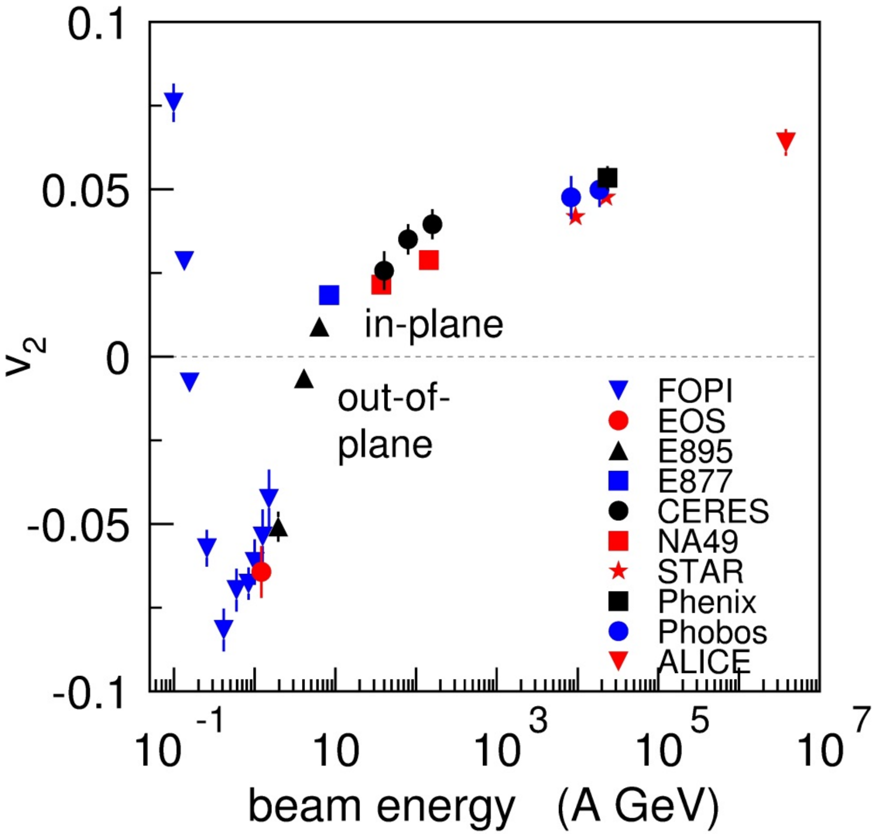


4. Flow



$$\frac{dN}{d\phi} \sim 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi)$$

$$\phi = \phi_R - \varphi$$



Predicted by Hydrodynamics

H. Stoecker et al., PRC 285(1982) 349

Discovery at Bevalac

H.A. Gustafsson, et al., Phys. Rev. Lett. 52 (1984) 1590.
R.E. Renfordt, et al., Phys. Rev. Lett. 53 (1984) 763.

Comparing experimental results to model predictions…

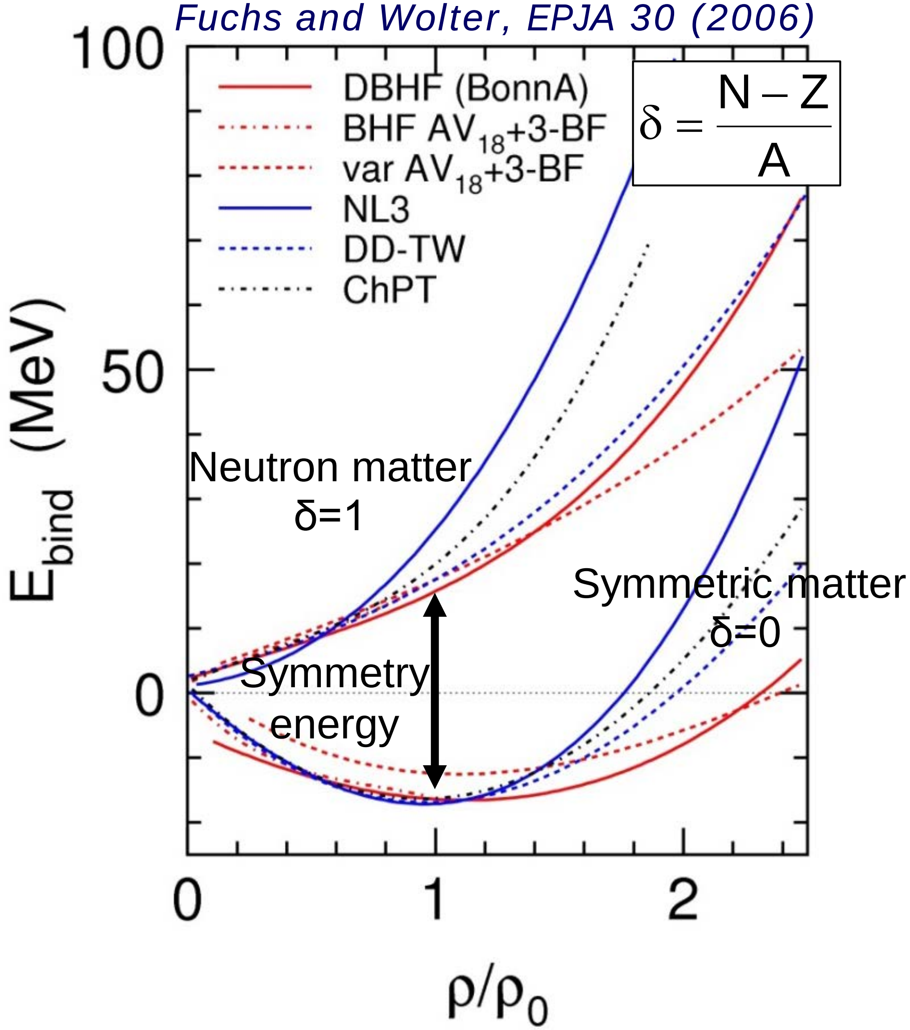
Yield information on

- **nuclear matter equation of state**
  - *momentum dependence*
  - *symmetry energy*

$$E(\rho, \delta, T) = E_{SN}(\rho, T) + \delta^2 E_{sym}(\rho, T) + \cdots$$

- in-medium cross sections
  - *scattering and production*
- in-medium characteristics of particles
  - *effective masses/potentials, spectral functions*
  - *decay widths*

Fuchs and Wolter, EPJA 30 (2006)



Equation of state for symmetric nuclear matter

Infinite symmetric nuclear matter N=Z

- ground state properties: ρ_0 = 0.16 N/fm^3 and E(ρ_0) = -16 MeV
- expansion in density:

$$E(\rho, T=0, \delta=0) = E_0 + \frac{K}{18\rho^2}(\rho-\rho_0)^2 + \ldots$$

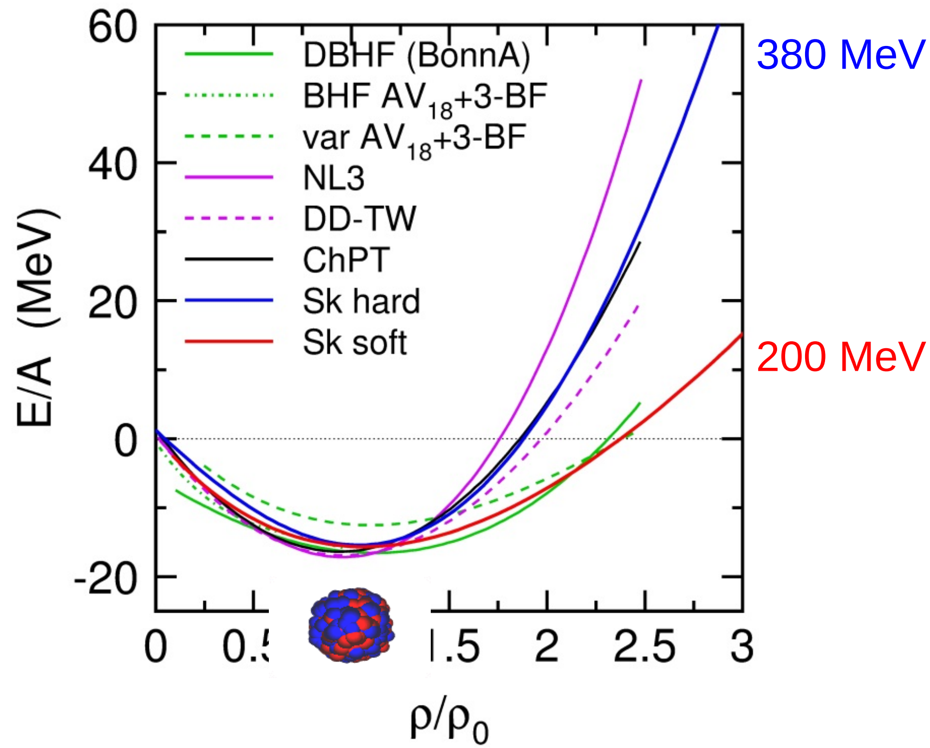
- K is the compression modulus

In the IQMD model

$$U(\rho) = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma}$$

- 3 parameters: 2 fixed by g. s. condition
- 3rd parameter: compression modulus
- artificial link between curvature and ground state behavior

Fuchs and Wolter, EPJA 30 (2006)



J. Piekarewicz, PRC 69 (04) 041301,
RMF: K=248 MeV
G. Colò et al.,PRC 70 (04) 024307
Skyrme HF: K=230 MeV
S. Shlomo et al. Eur. Phys. J. A 30, 23 (06)
K=240±20 MeV
D.H. Youngblood et al., PRC 80, 064318 (09):
K=231±5 MeV

Symmetry energy

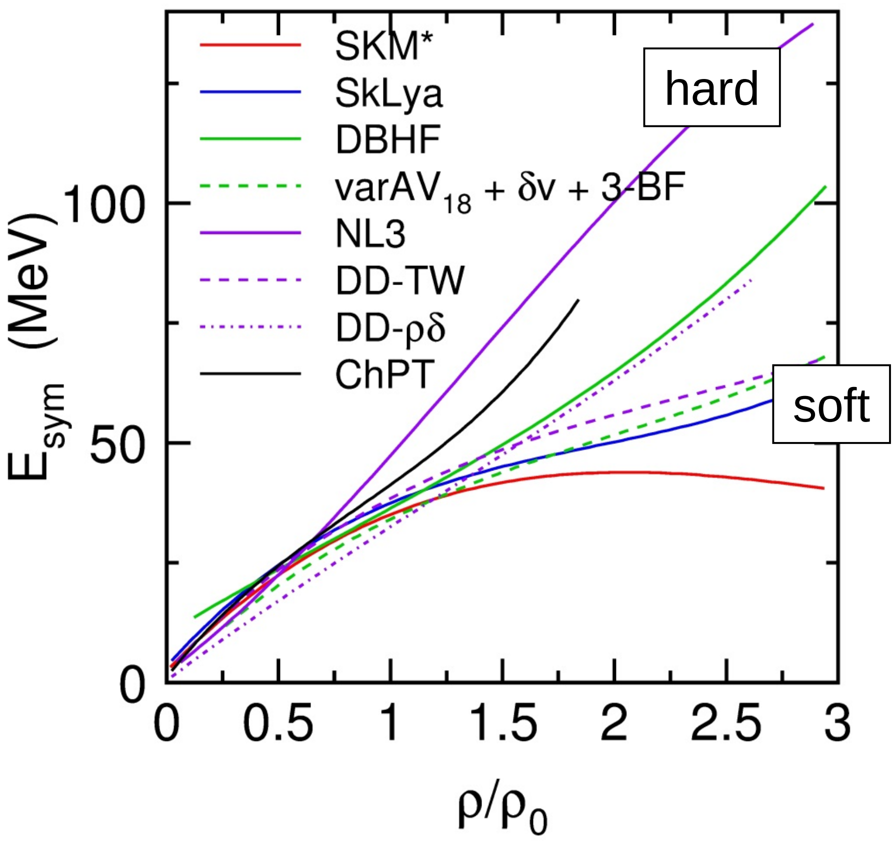
$$E_{sym}(\rho) = E_{sym,0} + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \dots$$

Largely unconstrained at high densities → related to uncertainty of three-body and tensor forces at high density

In IQMD

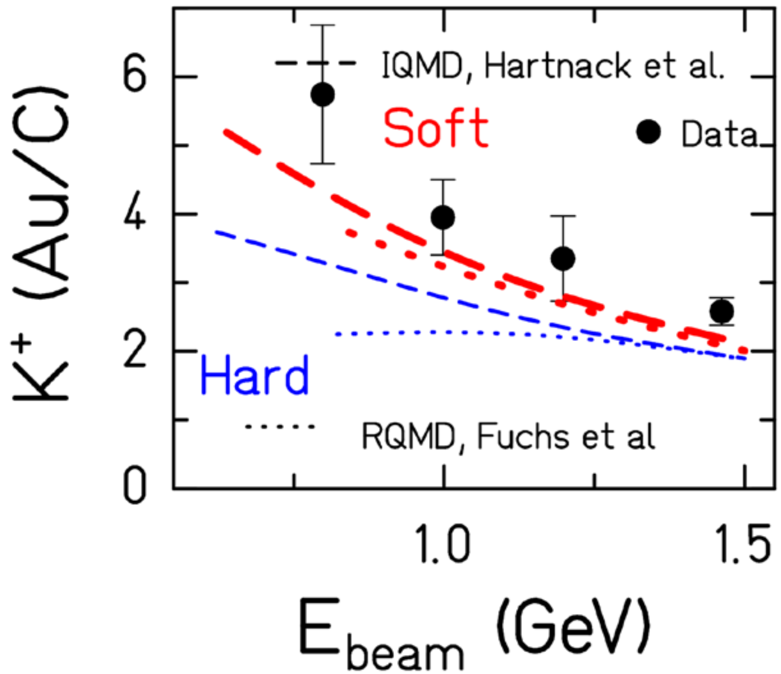
$E_{sym}=S_0\cdot(\rho/\rho_0)^{\gamma}$

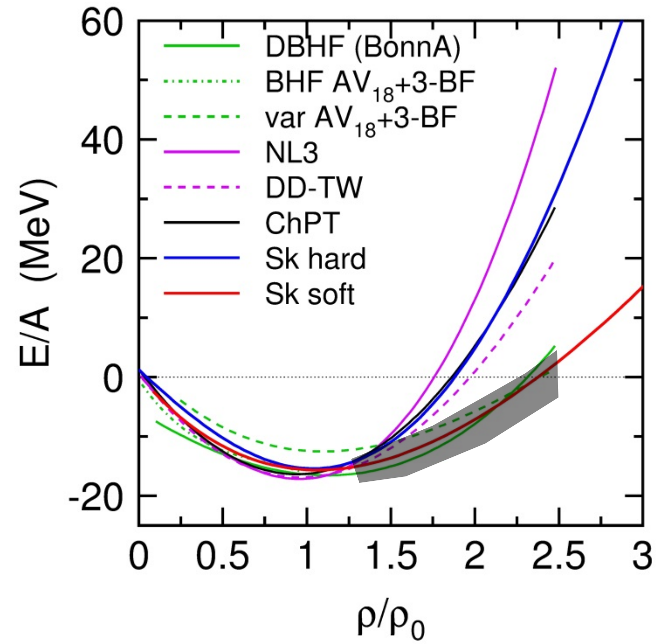
Fuchs and Wolter, EPJA 30 (2006)



Compressibility of symmetric nuclear matter: Kaon production

C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (2006) 012302

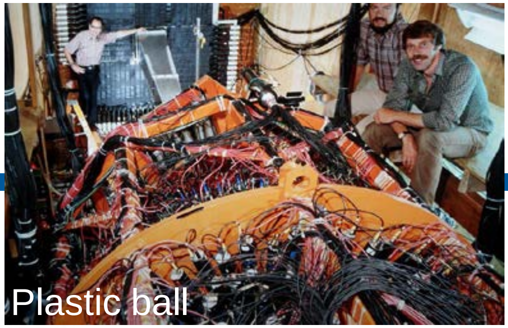


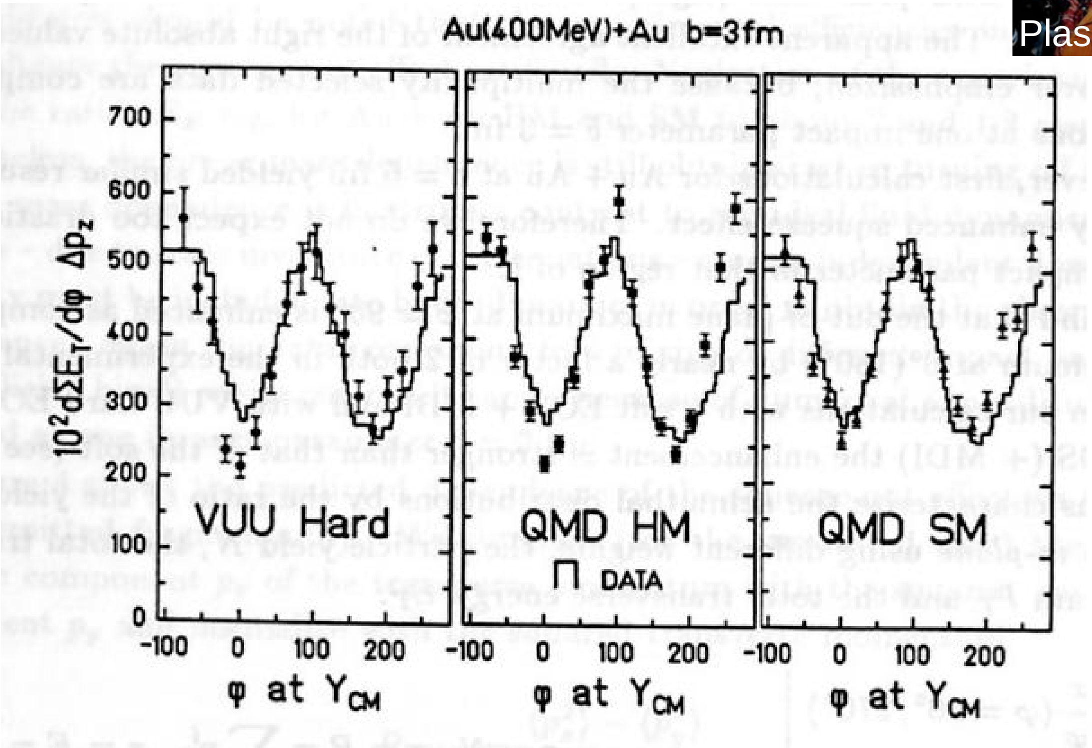


- Kaon production
  ∝ density reached
  ∝ compressibility
  soft EOS yields more Kaons

- results are independent on production cross sections and mechanisms and on the in-medium properties of kaons
- sensitivity to compressibilty largest below threshold
- relevant density ~$2\rho_0$

Compressibility of symmetric matter: Directed flow at Plastic Ball



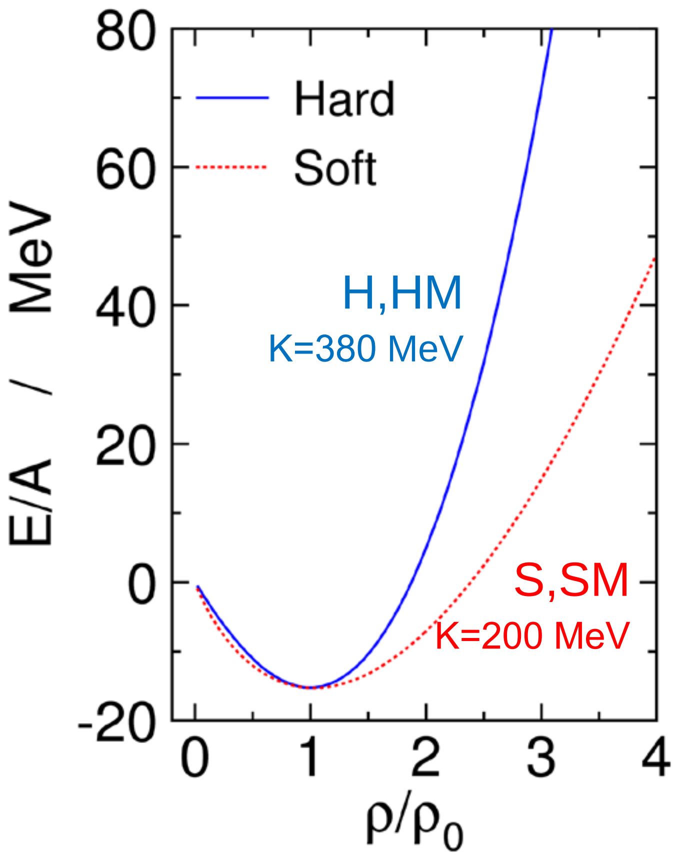


- IQMD comparison to Plastic Ball data favors a soft EOS with mdi (C. Hartnack GSI-Report-93-05, Mod. Phys. Lett. A 09, 1994)
- ambiguities between Skyrme part and mdi contribution
- influence of cross sections

Momentum dependent interaction in IQMD

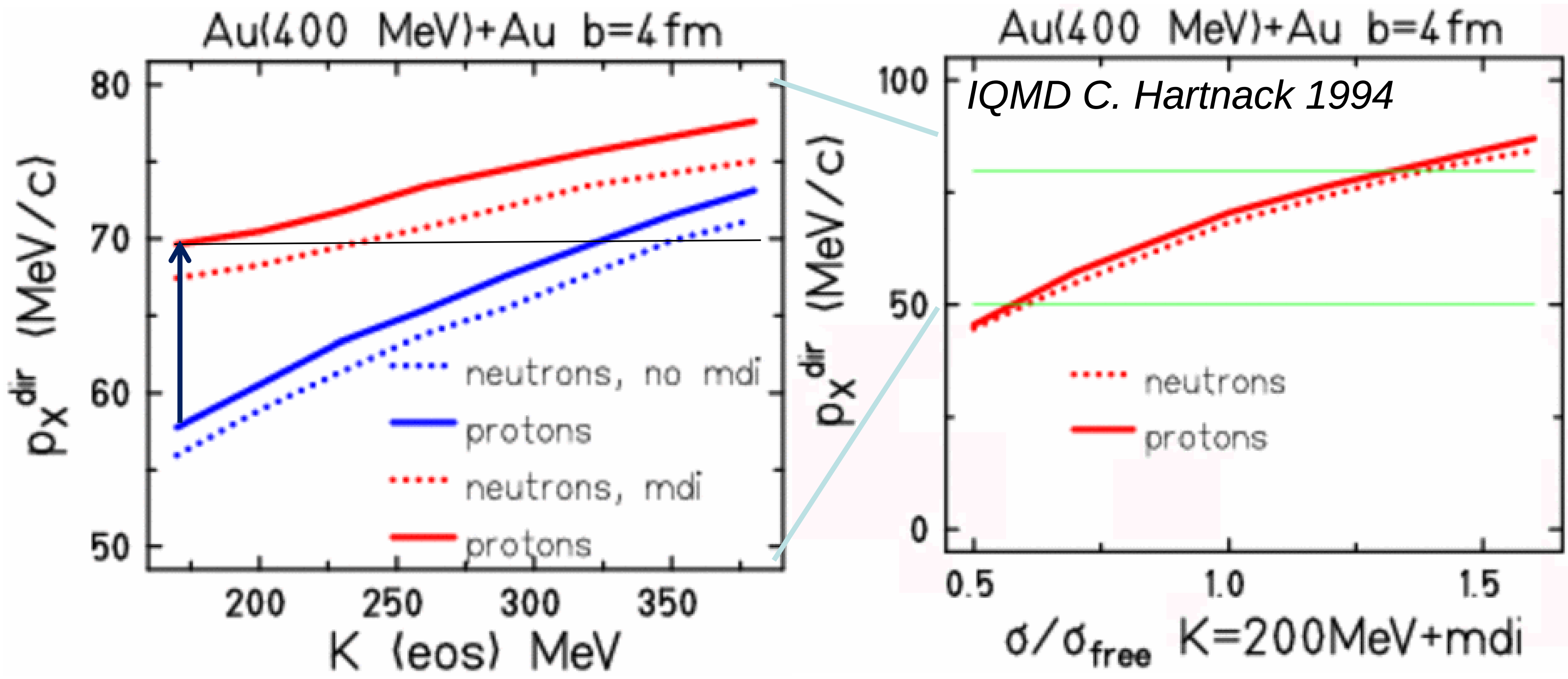
$$U(\rho) = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma}$$
$$+ \underbrace{\delta \cdot \ln^2(\epsilon \cdot (\Delta\vec{p})^2 + 1)\left(\frac{\rho_{int}}{\rho_0}\right).}_{U_{mdi}}$$

- optical potential linear in density
- parameters fitted to experimental pN data
- a soft EOS with mdi (SM) shows the same density dependence as a soft EOS without mdi (S)



IQMD, C. Hartnack et al. EPJ A1 (1997) 151

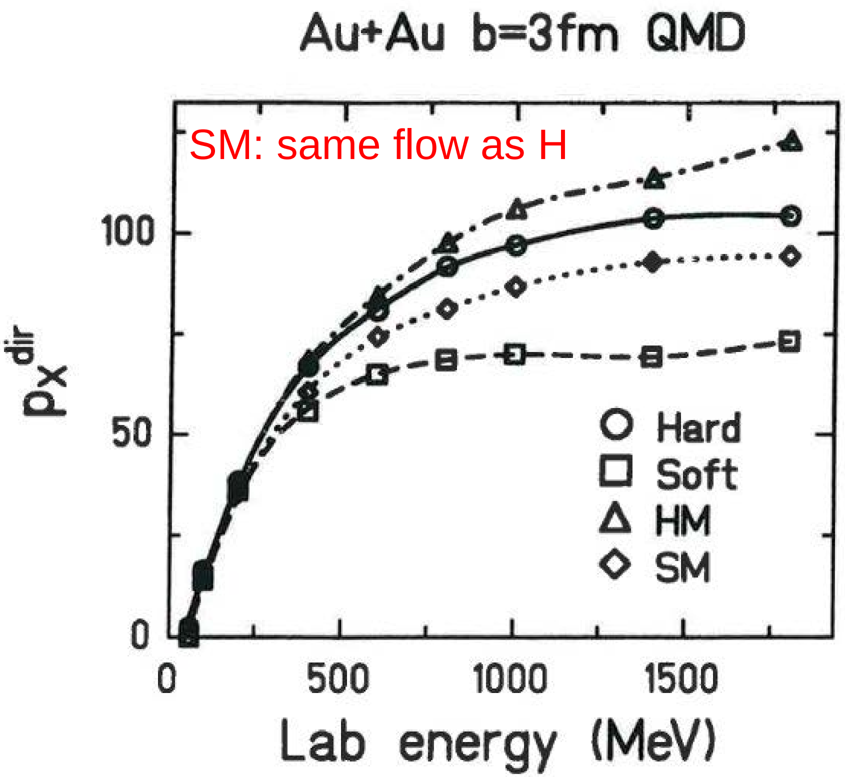
Directed flow depends on the EOS and…



Effect of mdi similar to the influence of EOS …
effects of other ingredients also strong

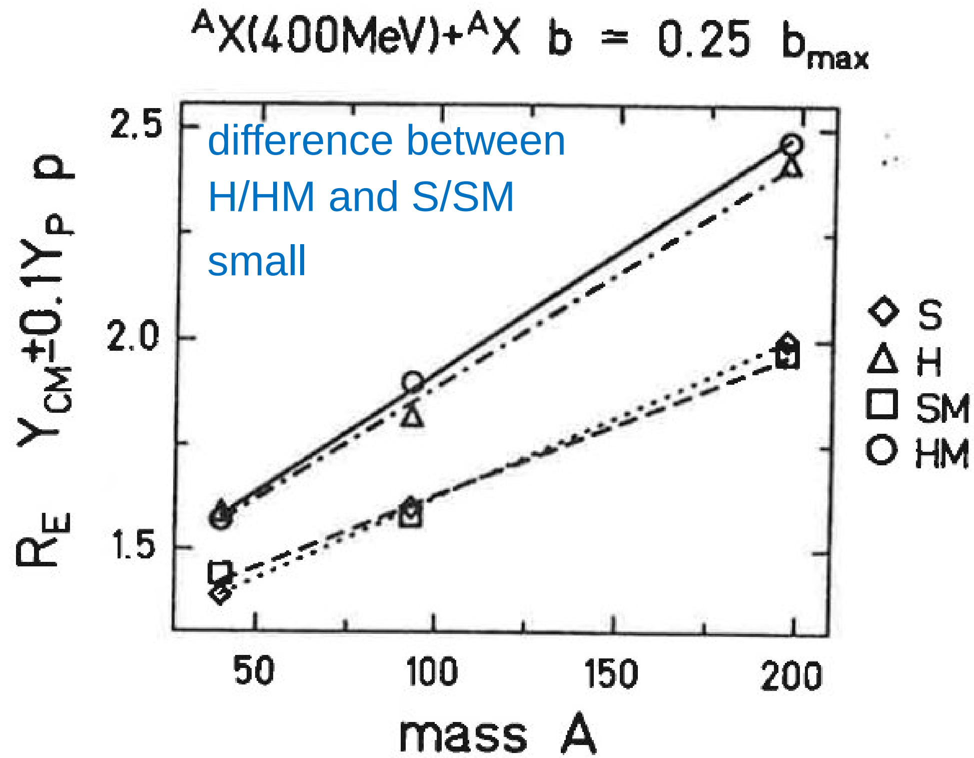
Luckily there is more than just one observable…

Directed flow



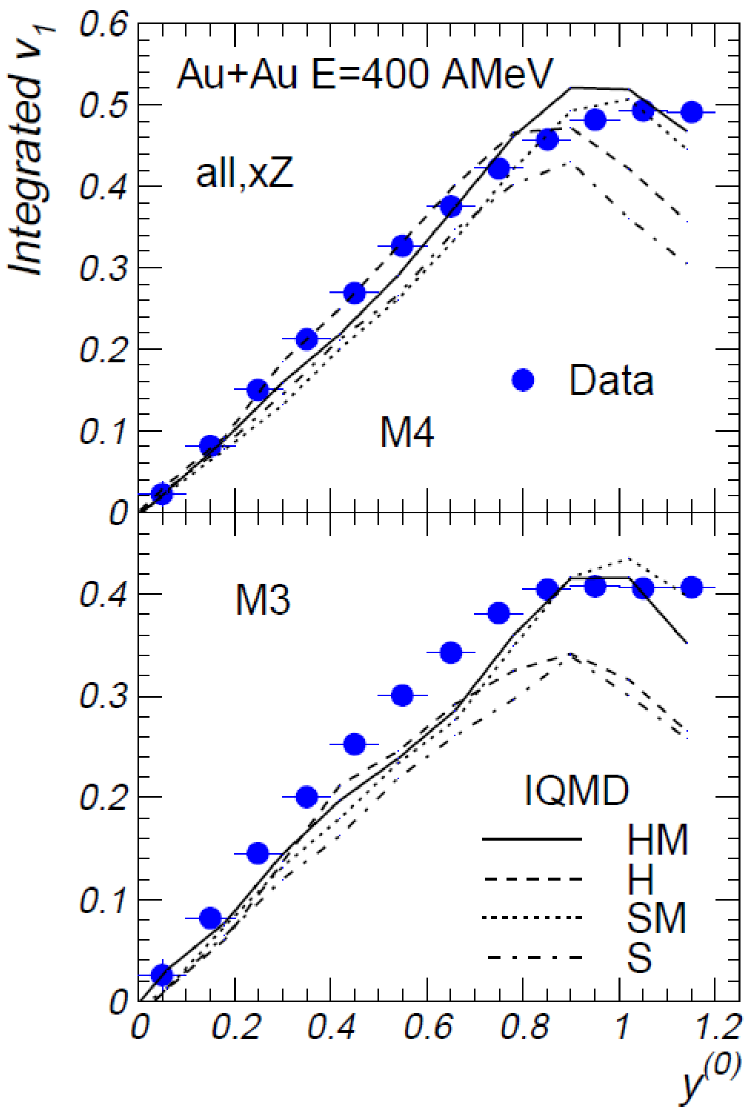
Elliptic flow ratio

at mid-rapidity



C. Hartnack GSI-Report 93-05

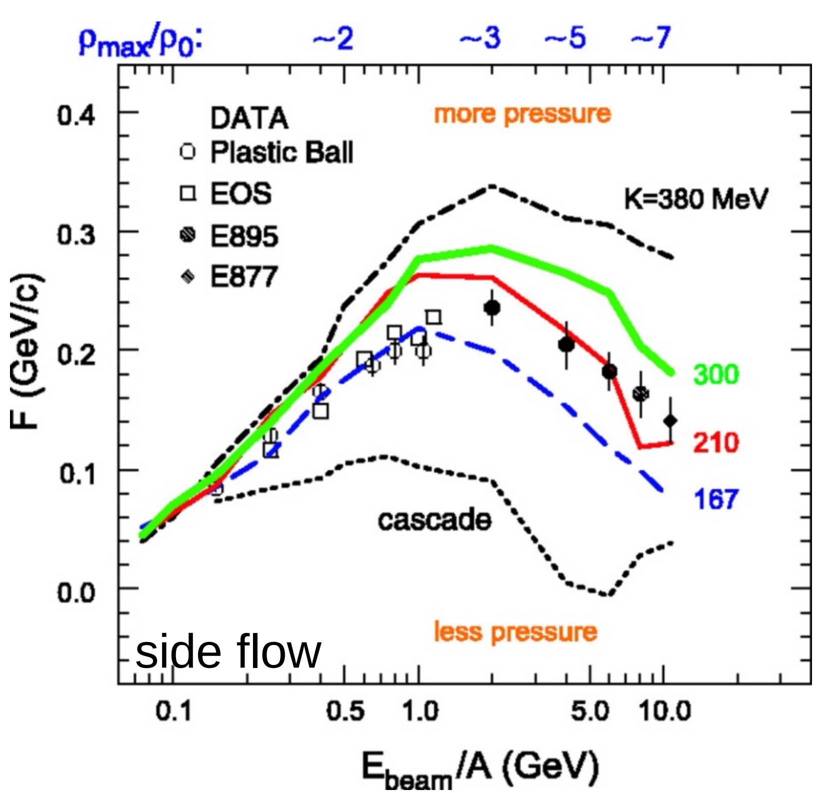
Directed flow data in comparison to IQMD

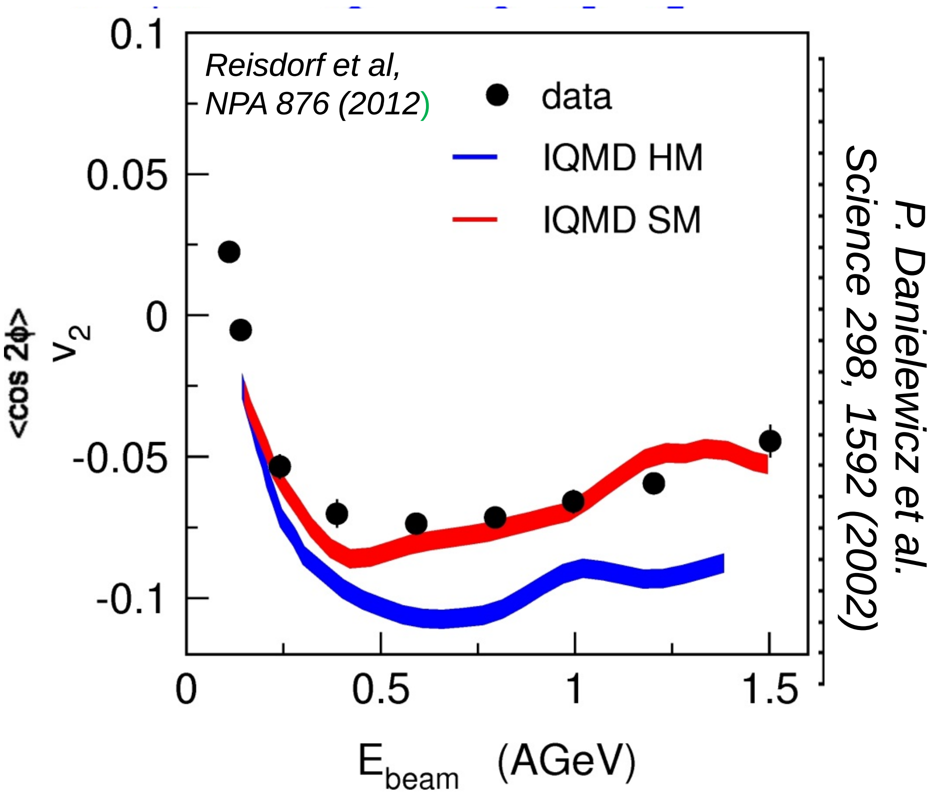


A. Andronic et al. PRC 67 (2003)034907

- all charged particles weighted with Z
- semi-central collisions
- **no conclusions can be drawn**

Compressibility of symmetric nuclear matter: Directed flow of protons

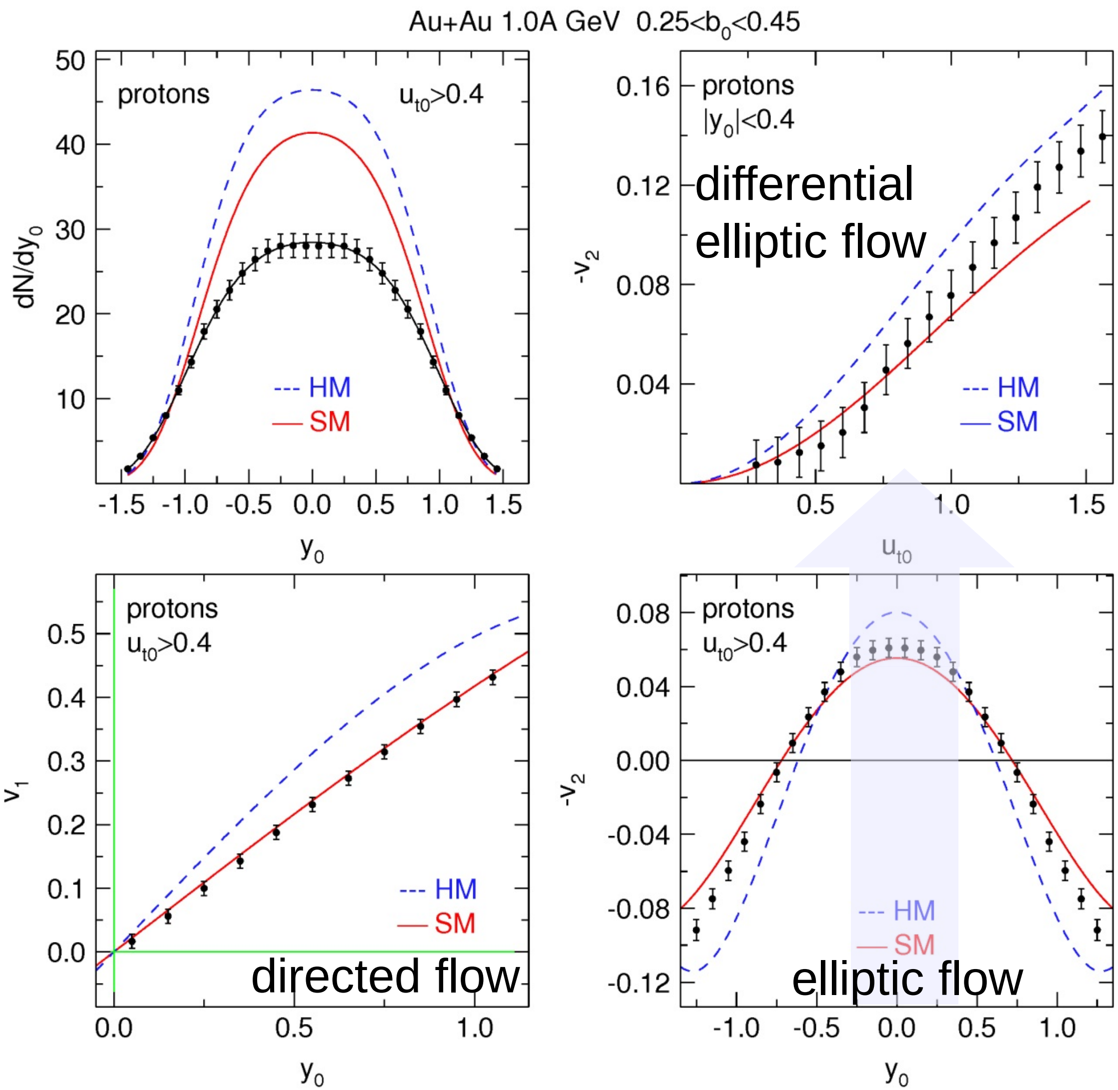




- quote of the authors: additional constraints needed on momentum dependence of NN potential and in-medium cross sections and symmetry potential
- newer data on elliptic flow in agreement with a soft EOS (SM)

  → most available data and Kaon production is reasonably described by this model (input parameters constrained with experimental data)

Collective flows in Au+Au at 1.0A GeV



W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

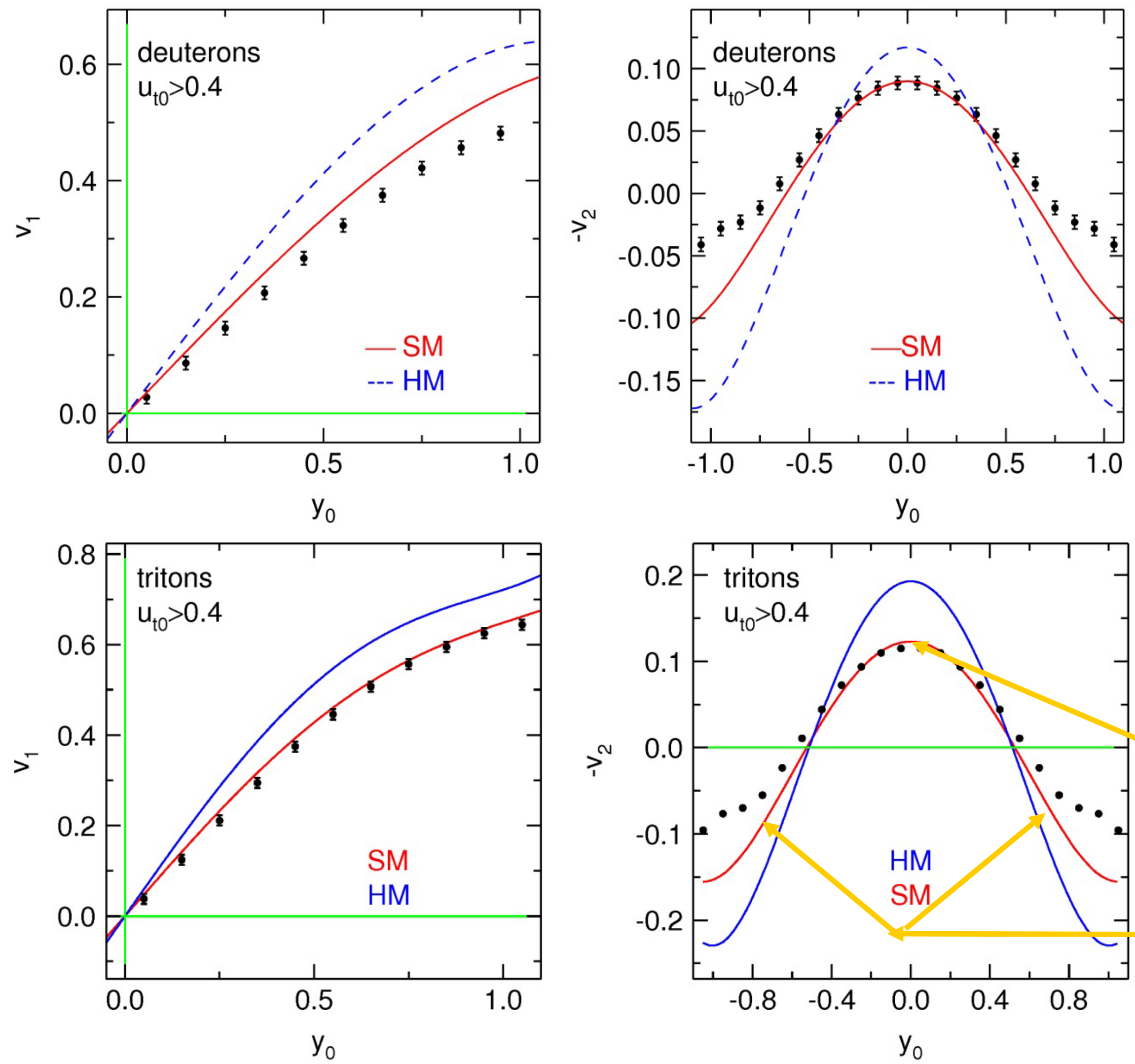
All flow results

- Au+Au 0.4 – 1.5AGeV
  Ru+Ru/Zr+Zr
- directed flow
- elliptic flow
- protons
- d, t, ^{3}He, α

are reasonably well described by IQMD transport code employing **a SM EOS for symmetric matter**

Collective flow of light charged particles

Au+Au 400A MeV 0.25<b0<0.45

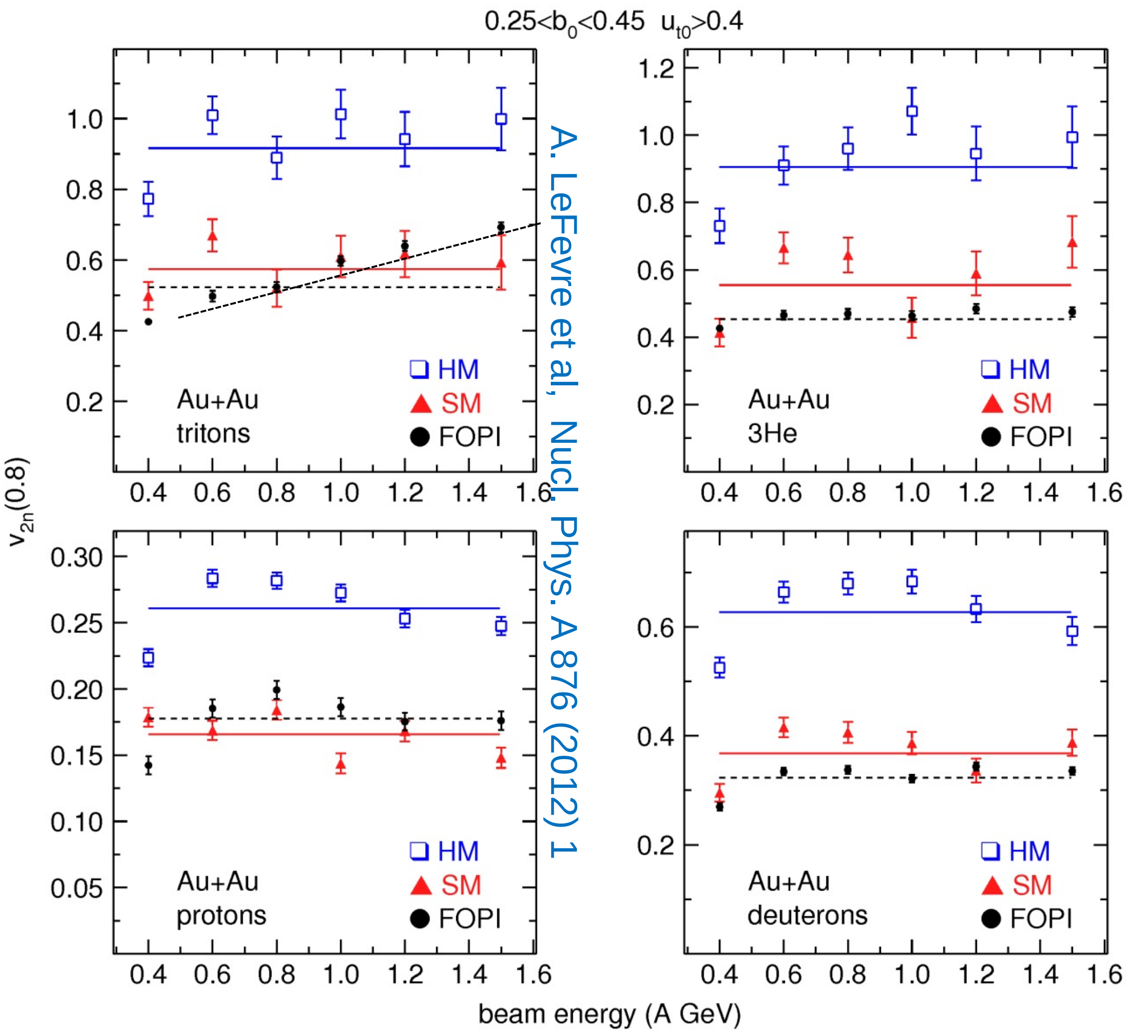


- composite particles are less influenced by thermal noise, larger flows
- flow pattern of clusters described by IQMD SM despite mismatch in the overall yields
- mismatch in the region of target/projectile rapidity point to insufficient description of clusterization

$$v_2(Y^{(0)}) = v_{20} + v_{22} \cdot Y^{(0)2}$$

$$v_{2n} = |v_{20}| + |v_{22}|$$

Elliptic flow of light charged clusters



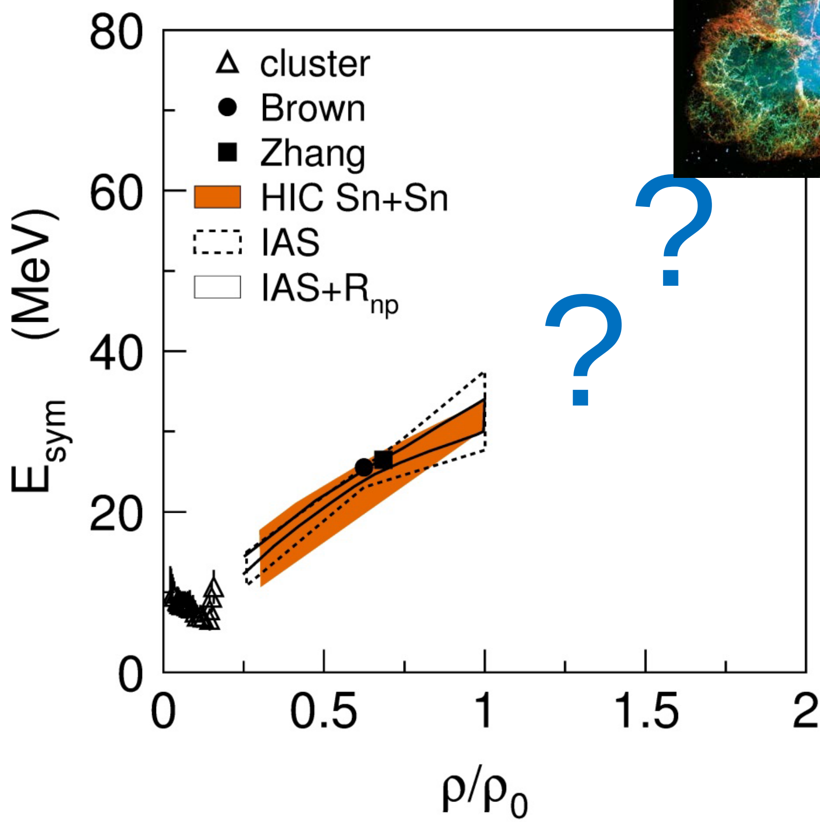
A. LeFevre et al, Nucl. Phys. A 876 (2012) 1

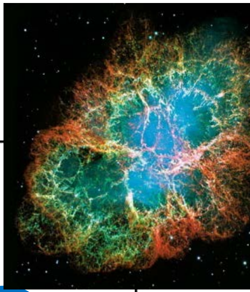
- influence of clusterisation is partially removed by using this observable
- isotopically resolved elliptic flow is described by IQMD employing an SM EOS
- huge difference for the two types of EOS (SM and HM)
- much larger than the experimental error bars
- promising observable to constrain the EOS for symmetric matter

Constraining the symmetry energy

Sensitive observables that are or will be more extensively explored :

- neutron stars...
- nuclear masses
- neutron skins
- cluster formation at low densities
- fragmentation of nuclei
- isospin diffusion und isospin drift between nuclei of different N/Z in peripheral HIC
- neutron/proton, t/^{3}He spectra and collective flows
- π-/π+ multiplicities and spectra





cluster/HIC Sn+Sn/ IAS:
Horrowitz et al. JPhG 41 (2014)
Brown: arXiv:1308.3664

Symmetry energy at supra-normal densities

Differential elliptic flow v_2 of n/p

UrQMD* (Q. Li et al.) predicts

"hard" E_{sym} protons unchanged

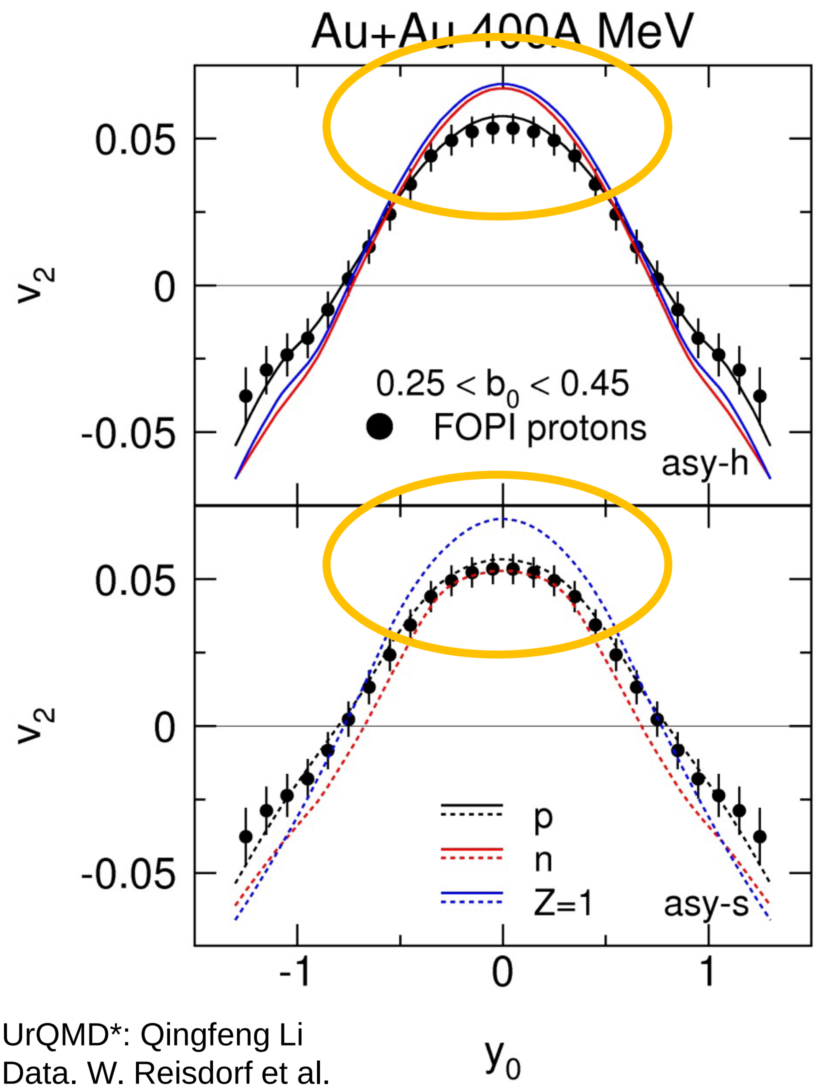
"soft" E_{sym} neutron and proton flow inverted

Model independence investigated in

M.D. Cozma et al., arXiv:1305.5417

P. Russotto et al., PLB 267 (2010)

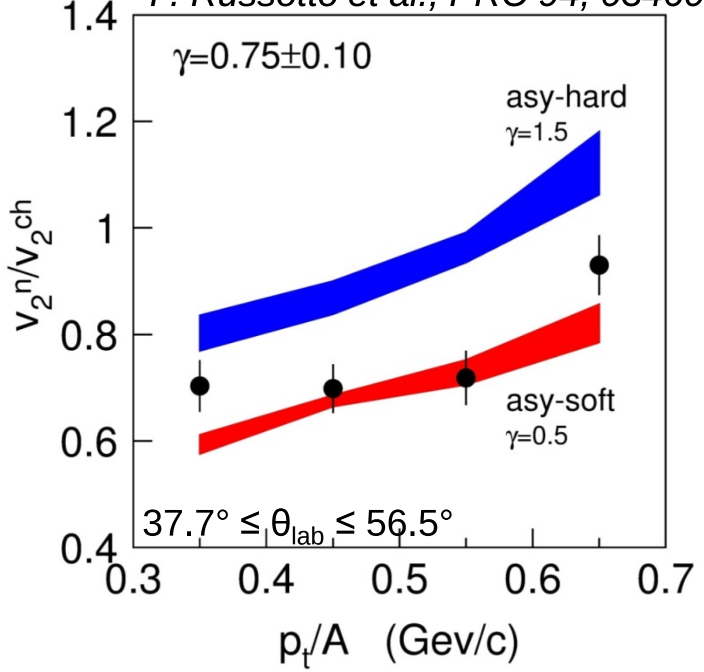
Y. Wang et al.,PRC 89, 044603 (2014)

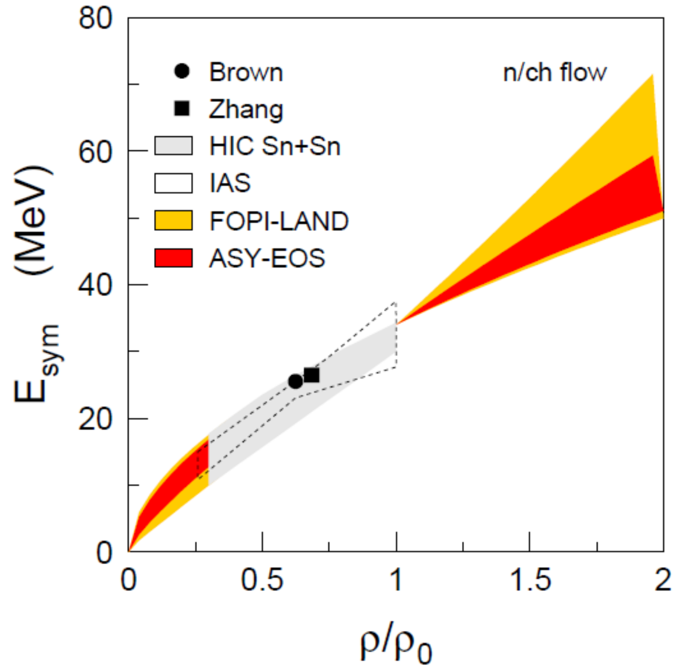


UrQMD*: Qingfeng Li
Data. W. Reisdorf et al.

Elliptic flow ratio of neutrons and charged particles

P. Russotto et al., PRC 94, 034608 (2016)





- parametrization for SE used in UrQMD* model:

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22\text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

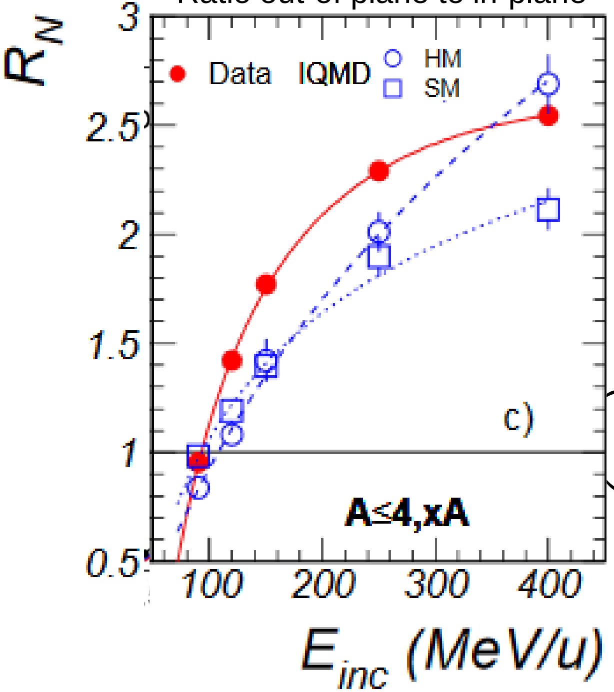
- systematic errors corrected: $\gamma = 0.72 \pm 0.19$
- slope parameter: $L = 72 \pm 13$ MeV, $E_{sym}(\rho_0) = 34$ MeV
- slope parameter: $L = 63 \pm 11$ MeV, $E_{sym}(\rho_0) = 31$ MeV
- clusterization important

But… what about the clusters and fragments…?

- ambiguities due to different fragment species
- fragments much more sensitive to dynamical effect
- clusters formation is omnipresent in HIC, important for analysis (observables depend on degree of cluster formation)

Elliptic flow

Ratio out-of plane to in-plane



FOPI: Stoicea et al. (1996)

FRIGA

Fragment **R**ecognition **I**n **G**eneral **A**pplications

- Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm)
- So far applied with various transport models: BQMD, IQMD, pHSD.
- Prediction of (light and heavy) (hyper)isotope yields and full phase space distribution.

Germanic mythological goddess Frigg/Friga, spinning the clouds

A. LeFevre, J. Aichelin, E. Bratkovskaya, C. Hartnack, V. Kireyeu, Y. Leifels

Model used

Transport : **IQMD** *(C. Hartnack et al., Eur. Phys. J. A 1 (1998) 151)*

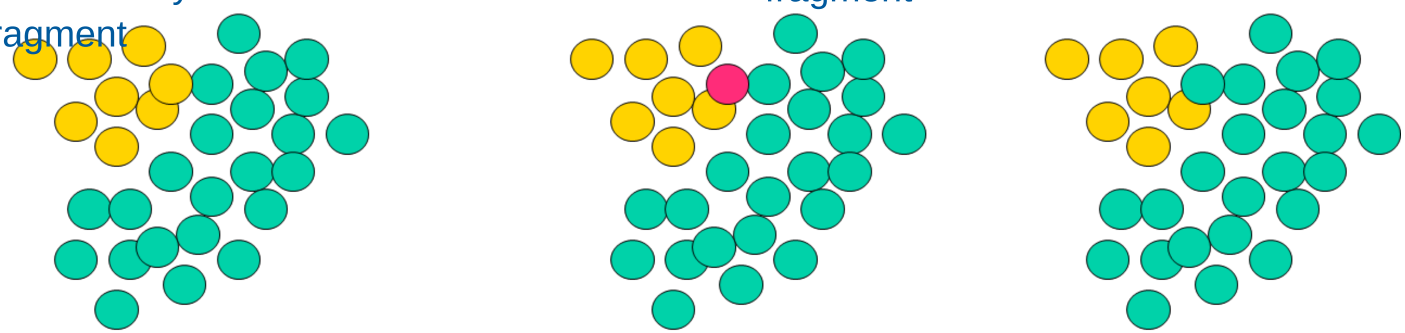
+ Clustering algorithm: **FRIGA** *(A. Le Fèvre et al, 2016 J. Phys.: Conf. Ser. 668 012021)*

- simulated annealing with Minimum Spanning Tree coalescence as 1st step
  + overall cluster binding energy minimization

$$E_{\text{bind}} = E_{\text{kin}} + E_{\text{Coul}} + E_{\text{m.f.}} + E_{\text{Yuk.}}^{\text{surf.}} + E_{\text{asy}}^{\text{pot}} + E_{\text{struct}}$$

- veto of unstable isotopes
- ^{3}He+n; secondary decay of excited primary clusters (GEMINI);

1. Preselect fragments with MST
2. Take randomly 1 nucleon out of 1 fragment
3. Place it randomly in another fragment



$E=E^1_{\text{kin}} + E^2_{\text{kin}} + V^1 + V^2$

$E'=E^{1'}_{\text{kin}} + E^{2'}_{\text{kin}} + V^{1'} + V^{2'}$

If $E' < E$ take the new configuration

If $E' > E$ take the old with a probability depending on E'-E

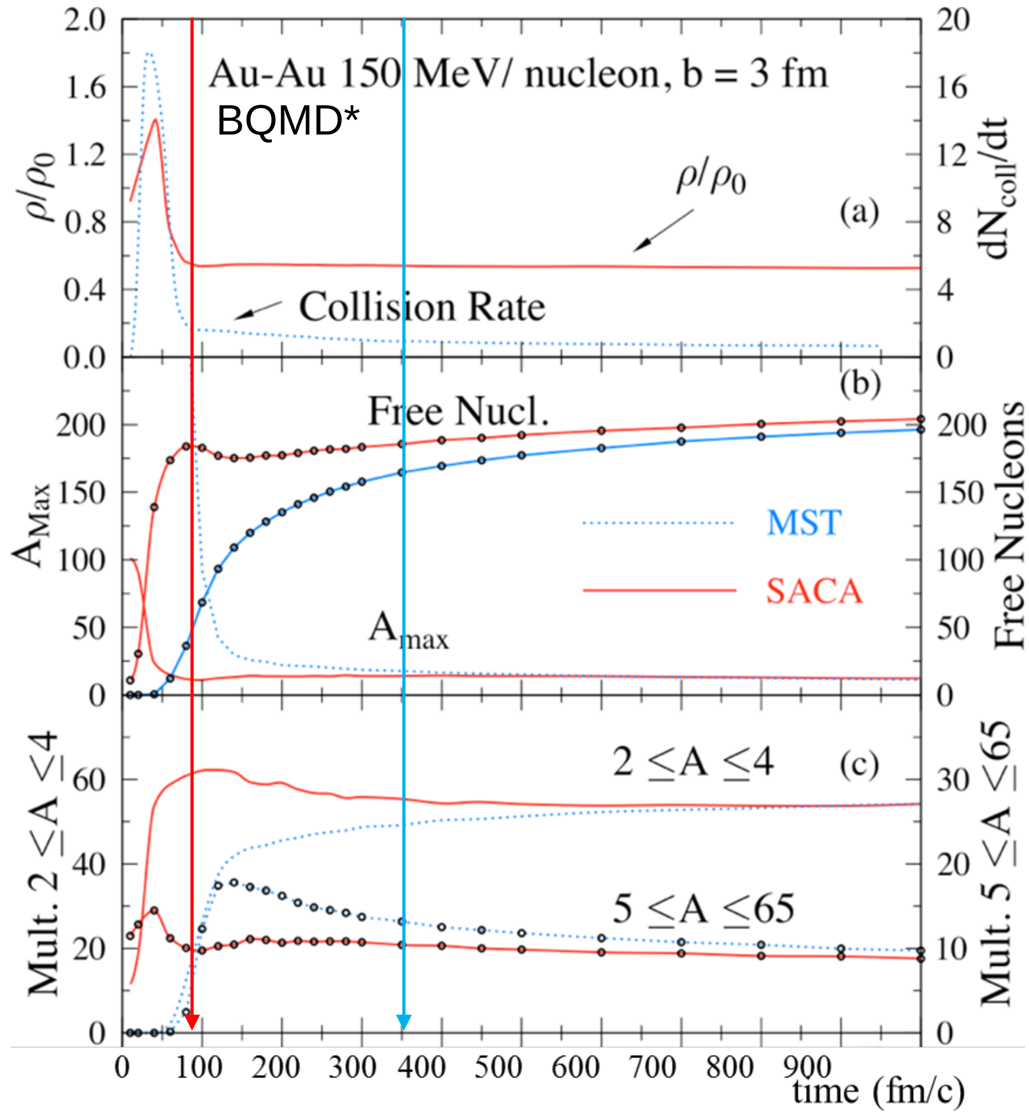
Repeat this procedure very many times... (Metropolis procedure)

It leads automatically to **the most bound configuration**.

FRIGA vs Minimum spanning tree

Unlike FRIGA, MST is not able to describe the early formation of fragments.
➞ MSTs applied at later times (typically 200-400 fm/c

Advantage of FRIGA
Fragment partitions reflect the early dynamical conditions (Coulomb, density, flow details, strangeness…), which is particularly important for hyper nucleus formation.

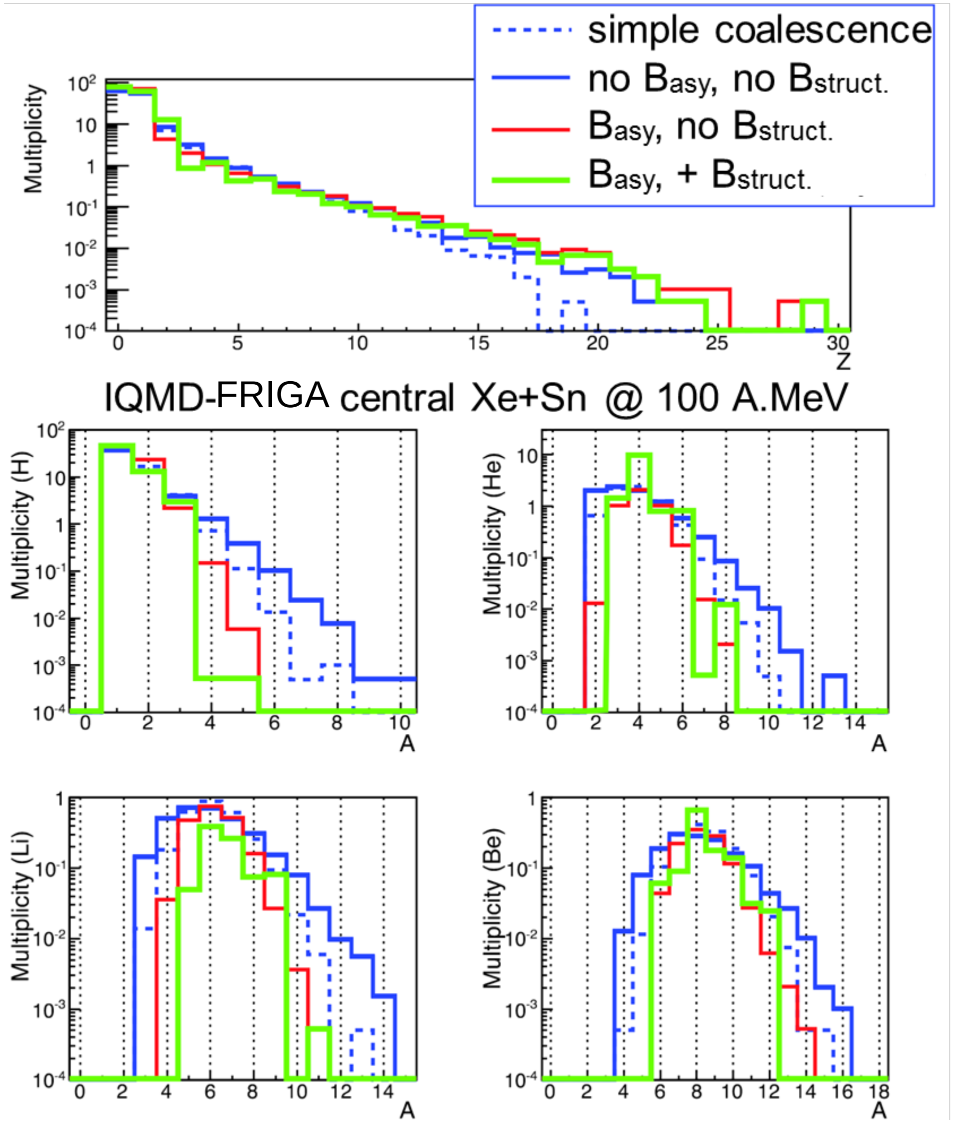


* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

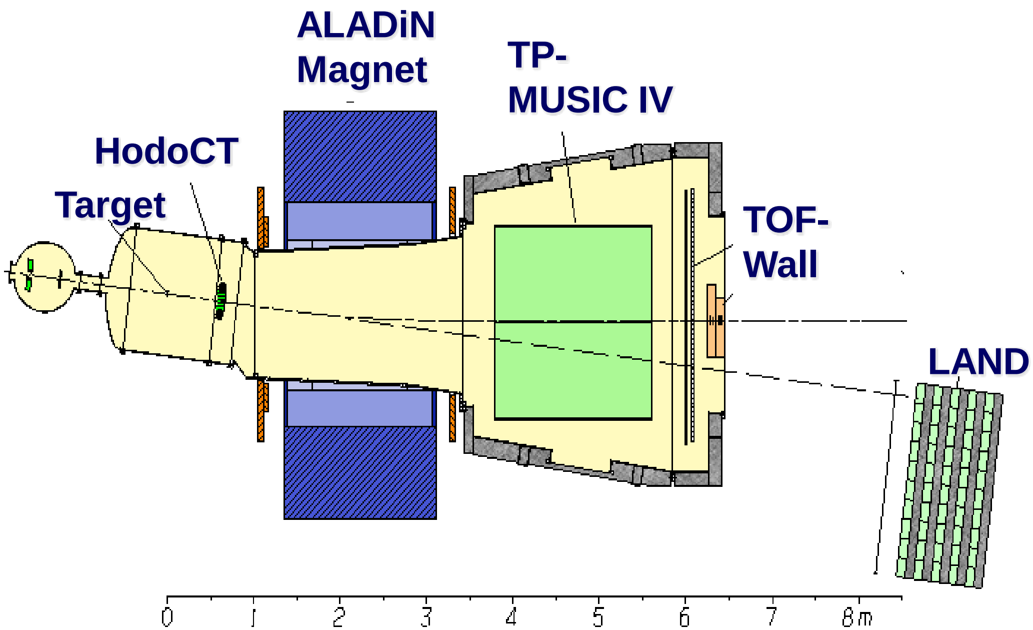
Clustering with FRIGA

- MST at 200 fm/c
- FRIGA at 2-3 t_{pass} (time of nuclei to pass each other completely without deceleration)

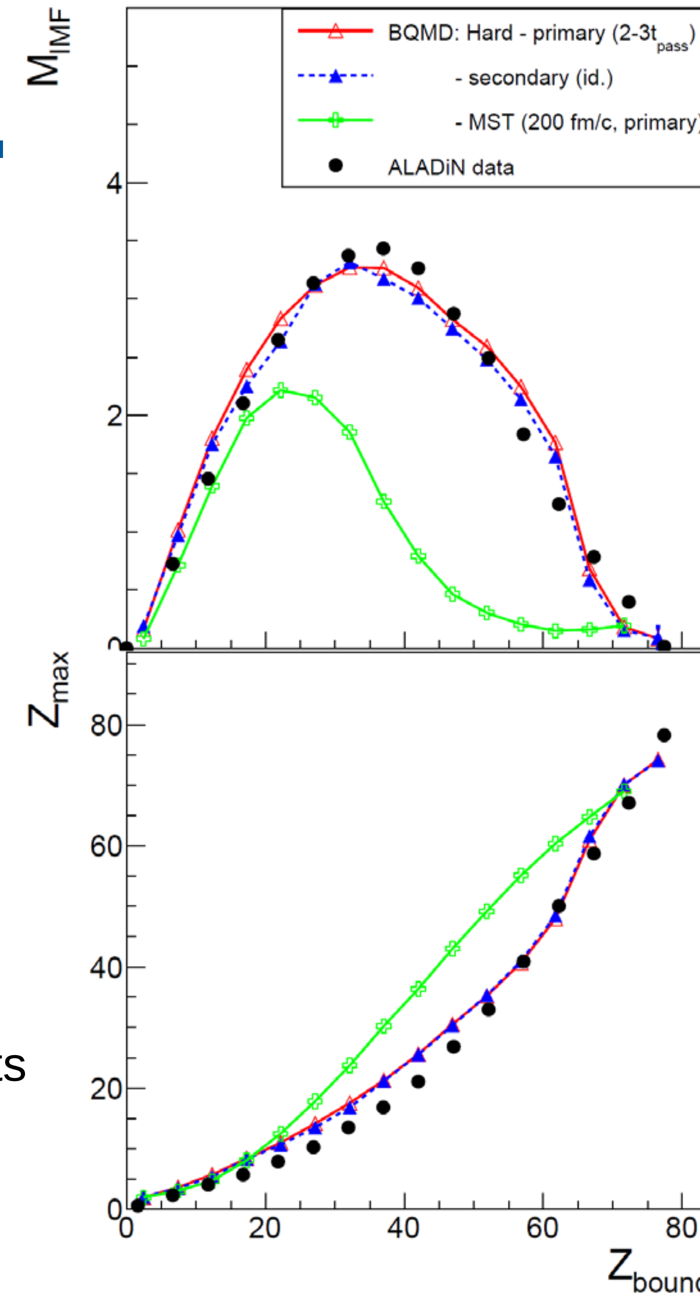
- Less heavy fragments are produced with MST
- MST shows broader distribution
- Symmetry energy narrows distributions at around N=Z
- Structure effects small and underestimate binding energies for small clusters



Benchmarking BQMD+FRIGA with ALADIN data



- Projectile fragmentation of ^{197}Au+Au at 600 MeV/u
- M_{imf} multiplicity of intermediate mass fragments (Z≥2) measured in forward direction
- Z_{bound} sum of charges detected at small polar angles (measures impact parameter)

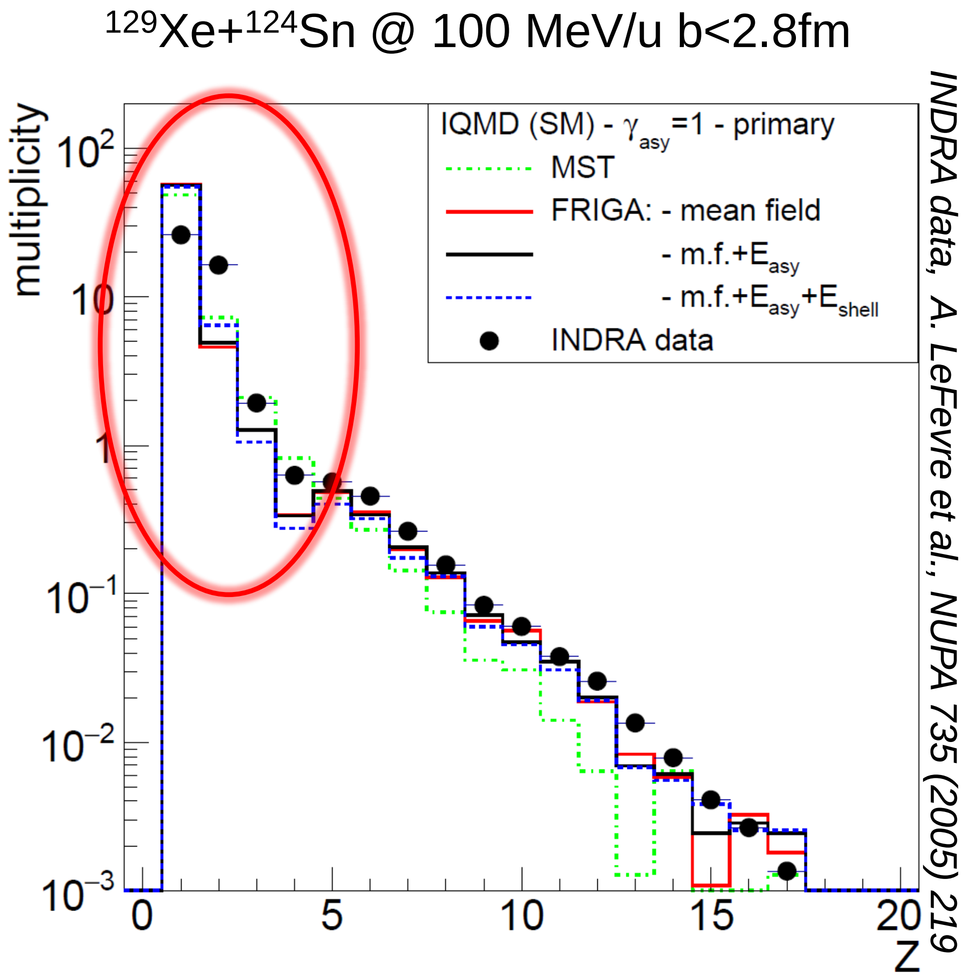


ALADIN S254 measured by the ALADIN2000 collaboration

Clustering with IQMD+FRIGA

- MST at 200 fm/c
- FRIGA at 2-3 t_{pass} (time of nuclei to pass each other completely without deceleration)

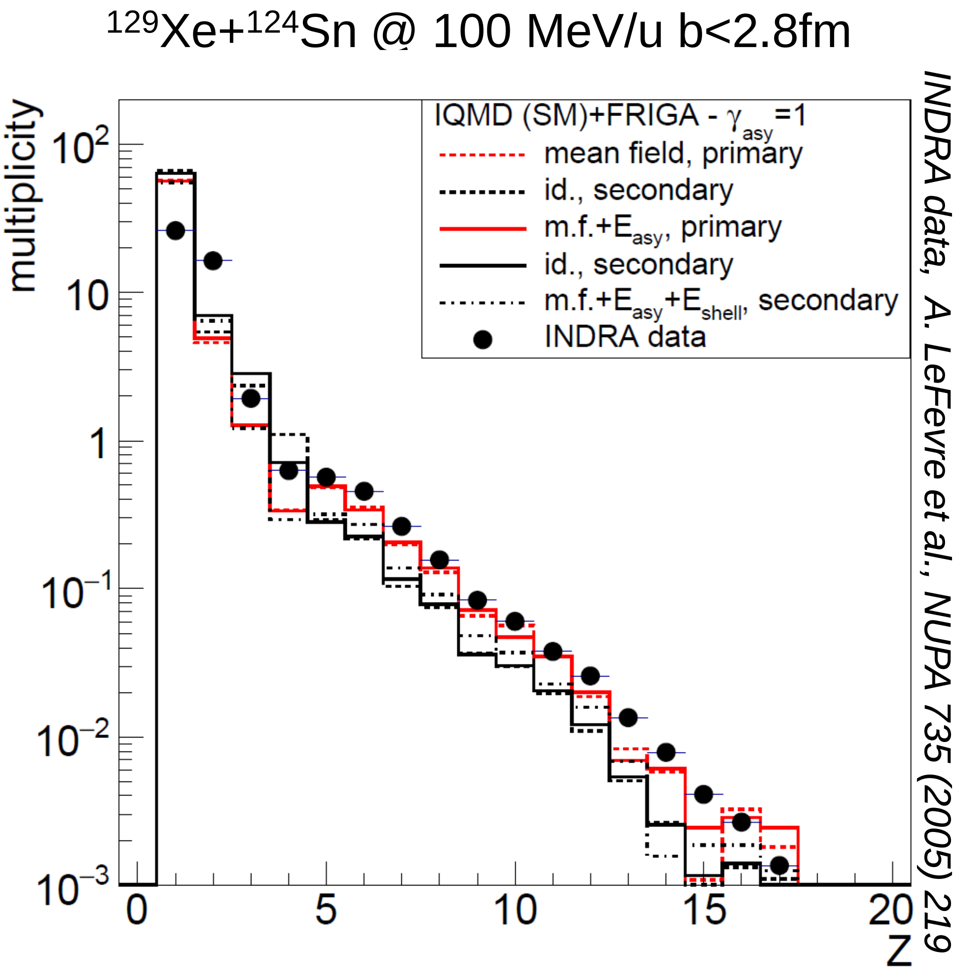
- Less heavy fragments are produced with MST but more light fragments
- Structure effects small and underestimate binding energies for small clusters



Clustering with FRIGA after secondary decays

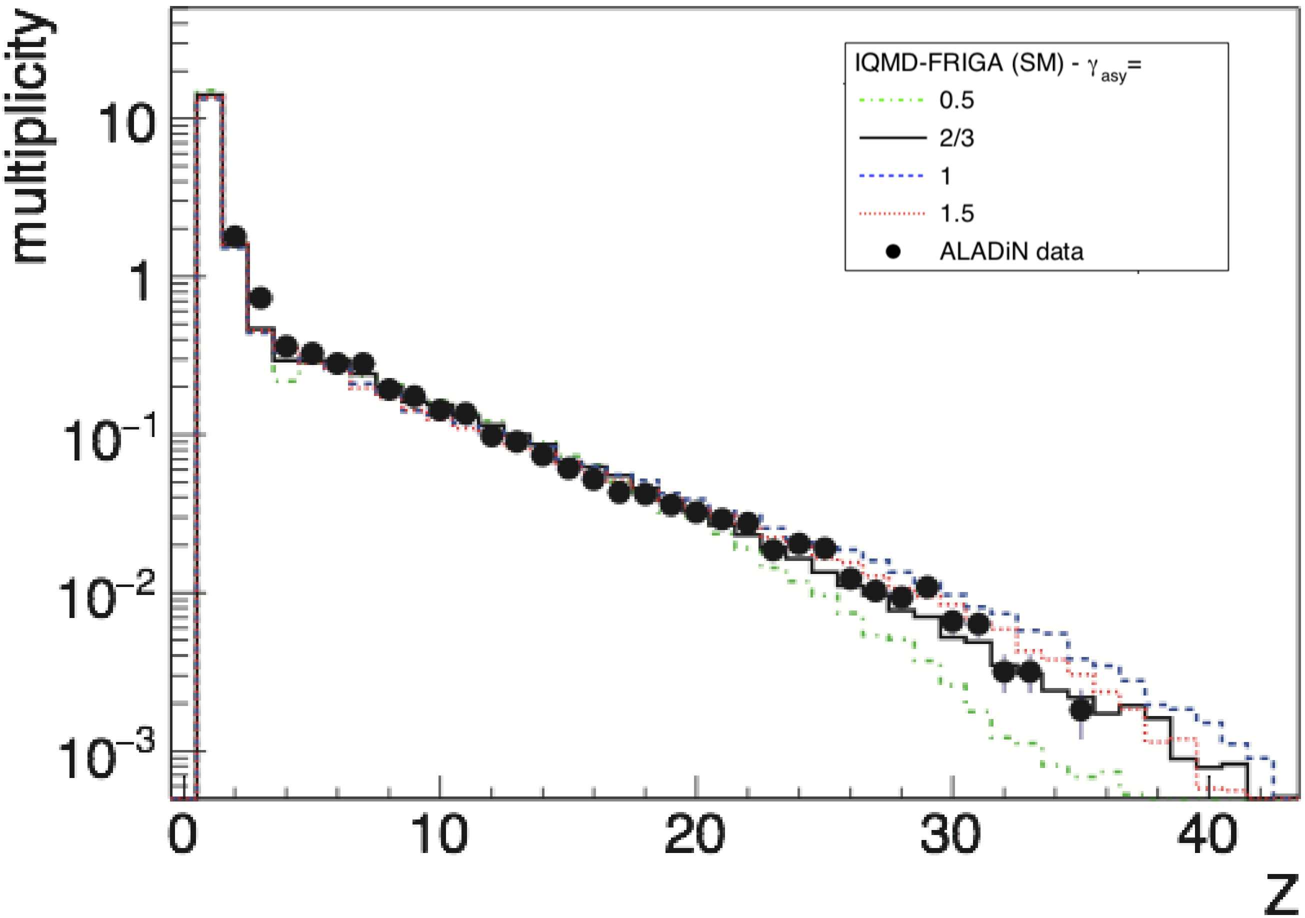
- MST at 200 fm/c
- FRIGA at 2-3 t_{pass} (time of nuclei to pass each other completely without deceleration)
- after secondary decays

- IQMD SM does not produce enough (heavy) clusters



Clustering with IQMD SM - revisited

^{197}Au+ ^{197}Au 600 MeV/u b=8 fm

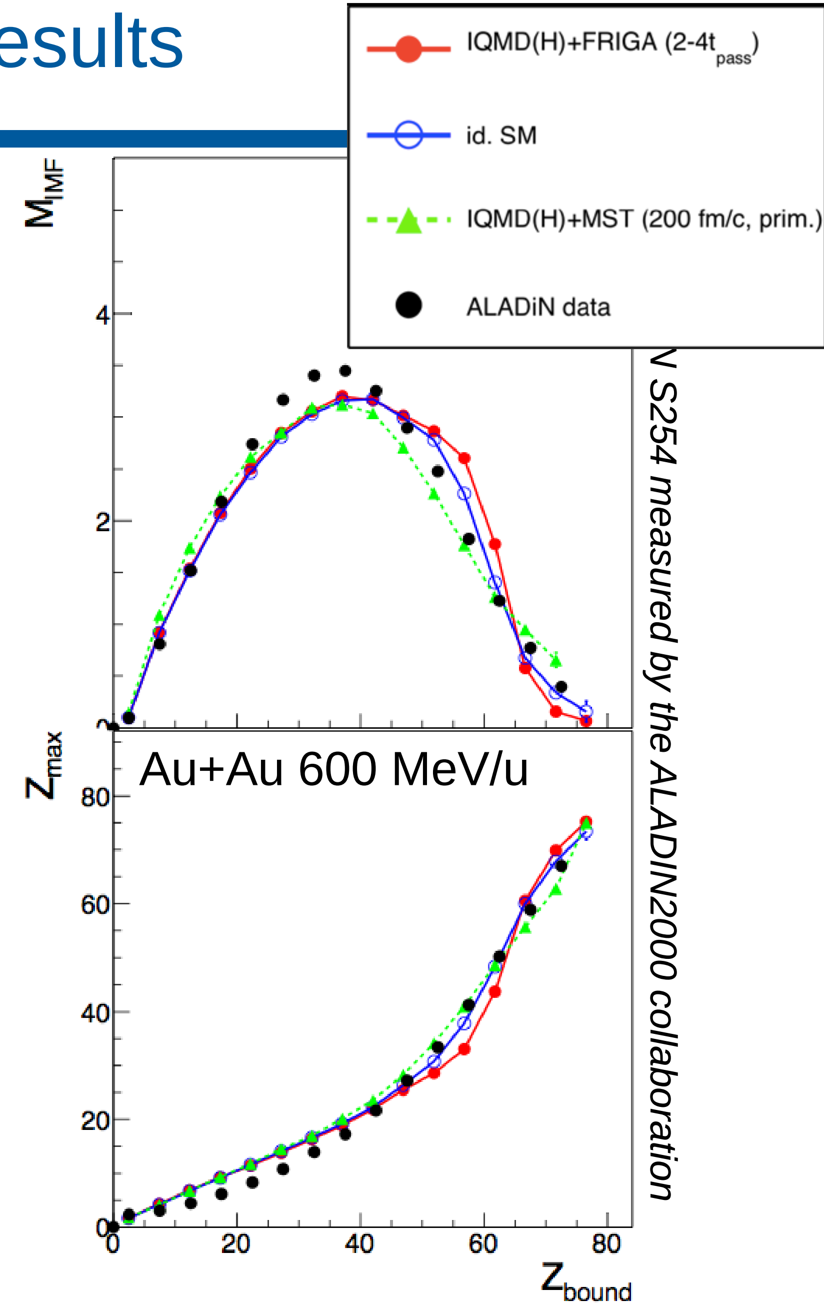


R. OGUL et al. PHYSICAL REVIEW C ***83****, 024608 (2011)*

- Possible to describe fragment yields with IQMD SM

Benchmarking IQMD+FRIGA results

- IQMD modifications
  - smaller Gaussian package width: 4.33 fm^2
  - reduction of Fermi momentum during initialization
- cluster multiplicity stable upto 200 fm/c
- SM and H EOS yield similar results



Reconstruction of hyper nuclei

Soft EOS
with m.d.i.
no Kaon pot.

FRIGA ingredients:

1 Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei). We consider the strange quark as inert as a first approach ⇒ $U(N\Lambda) = 2/3 \cdot U(NN)$

2 Surface effect correction: Yukawa term.

And optionally:

3 Symmetry energy E_{asy}

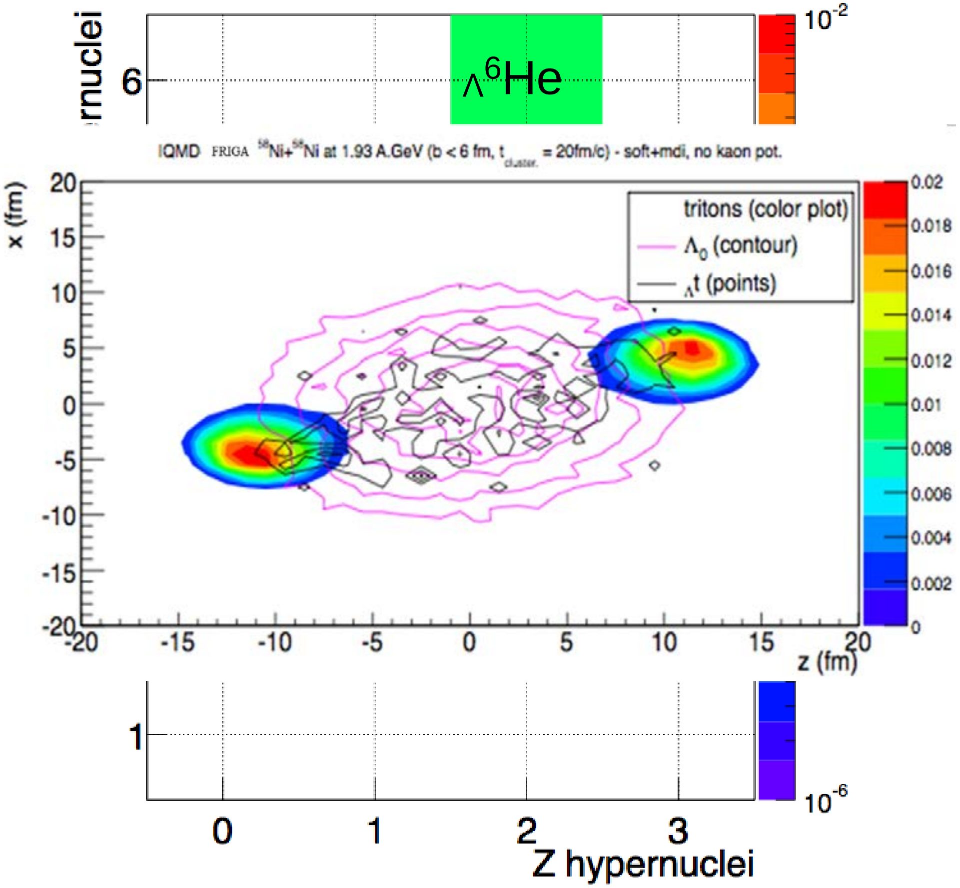
4 ~~Extra « structure » energy (N,Z,ρ) – $B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$~~

5 ~~^3He+n recombination.~~

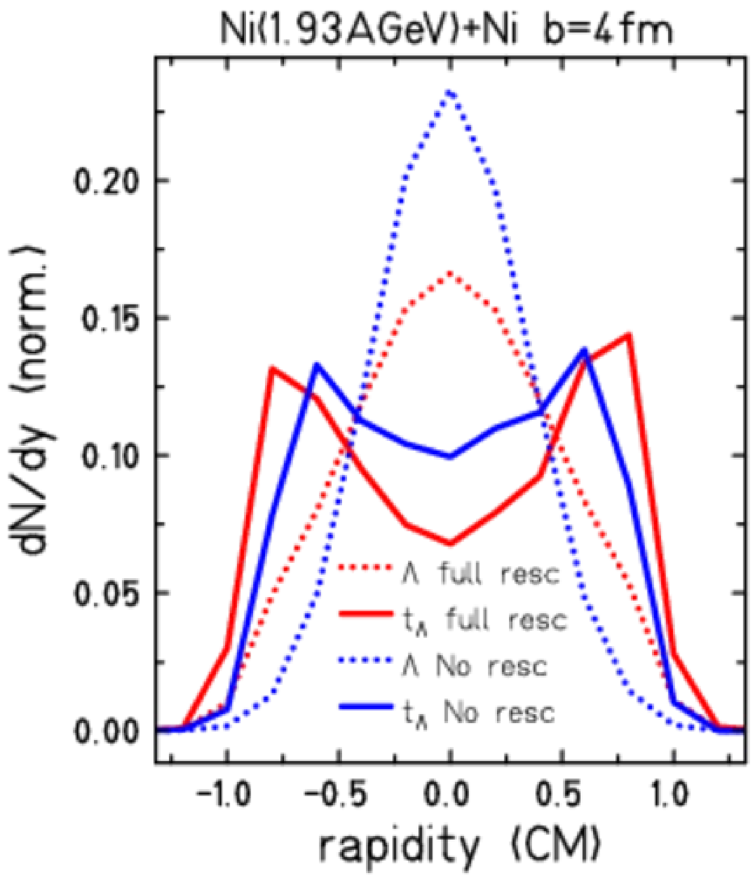
6 ~~Secondary decay: GEMINI.~~

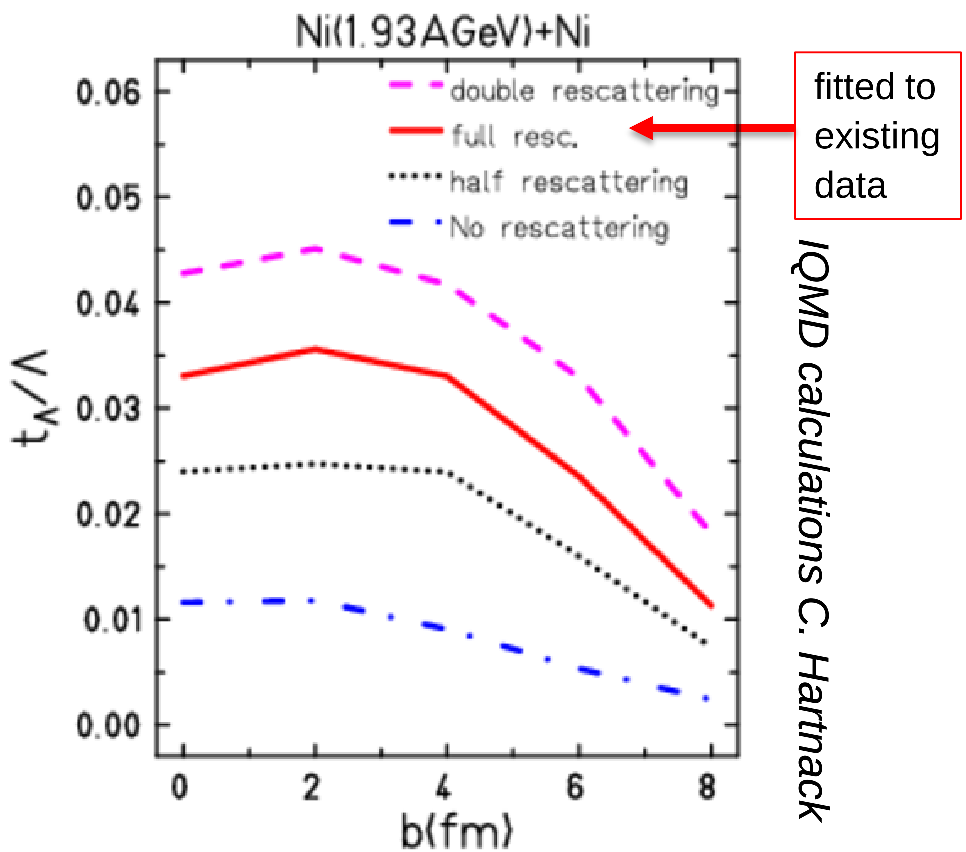
7 Rejection of « non-existing » isotopes and hyper-clusters.

IQMD+FRIGA 1.9GeV/u Ni+Ni



Influence of Lambda re-scattering



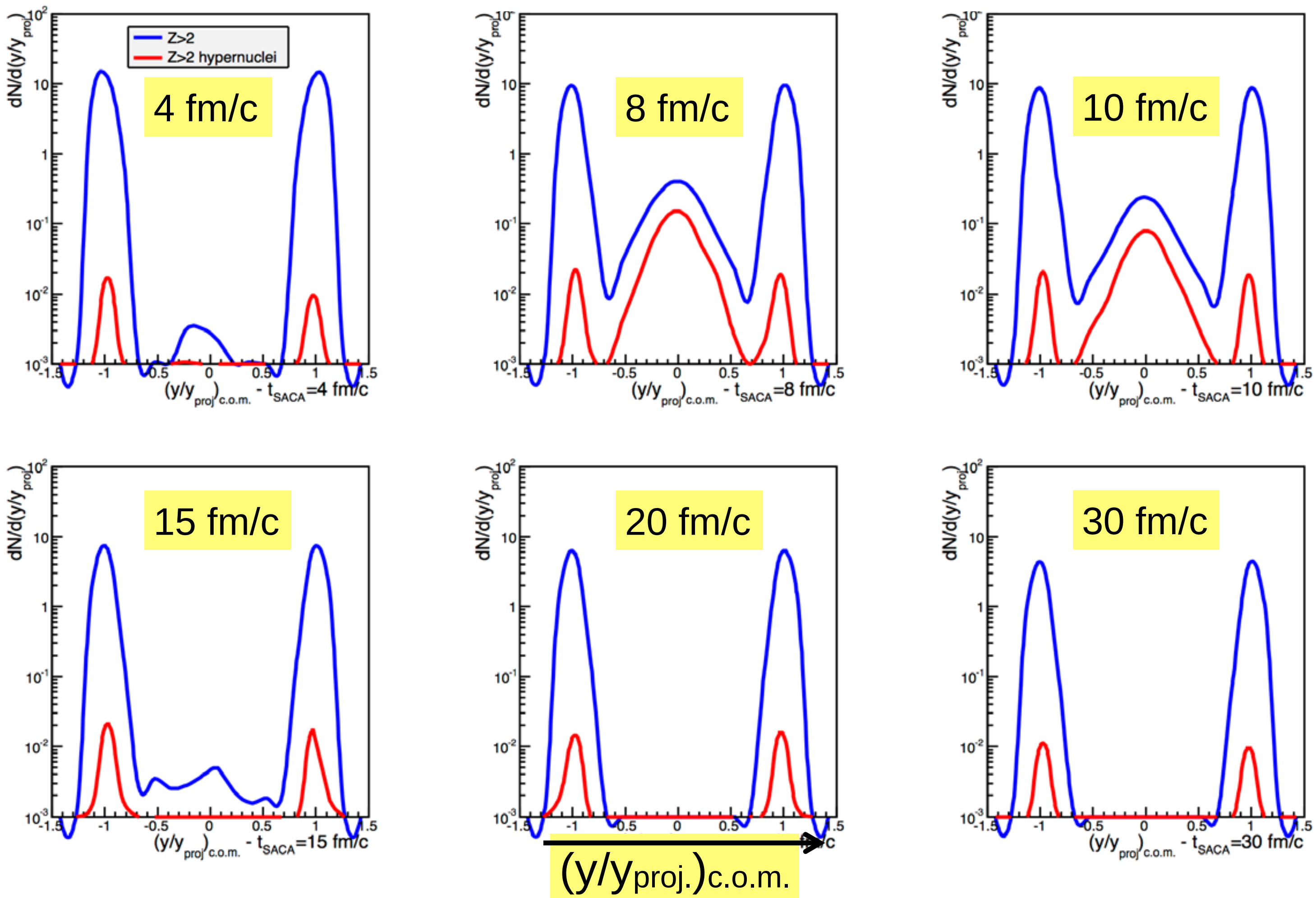


- rescattering changes rapidity distribution of hyperons
- and consequently the overlapp region between hyperons and spectator nucleons
- huge influence on yields on hyper nuclei

Clusterisation time influence on rapidity distributions

HSD+FRIGA Au+Au @ 11.45 GeV/u, b=6fm, passing time 7.5 fm/c

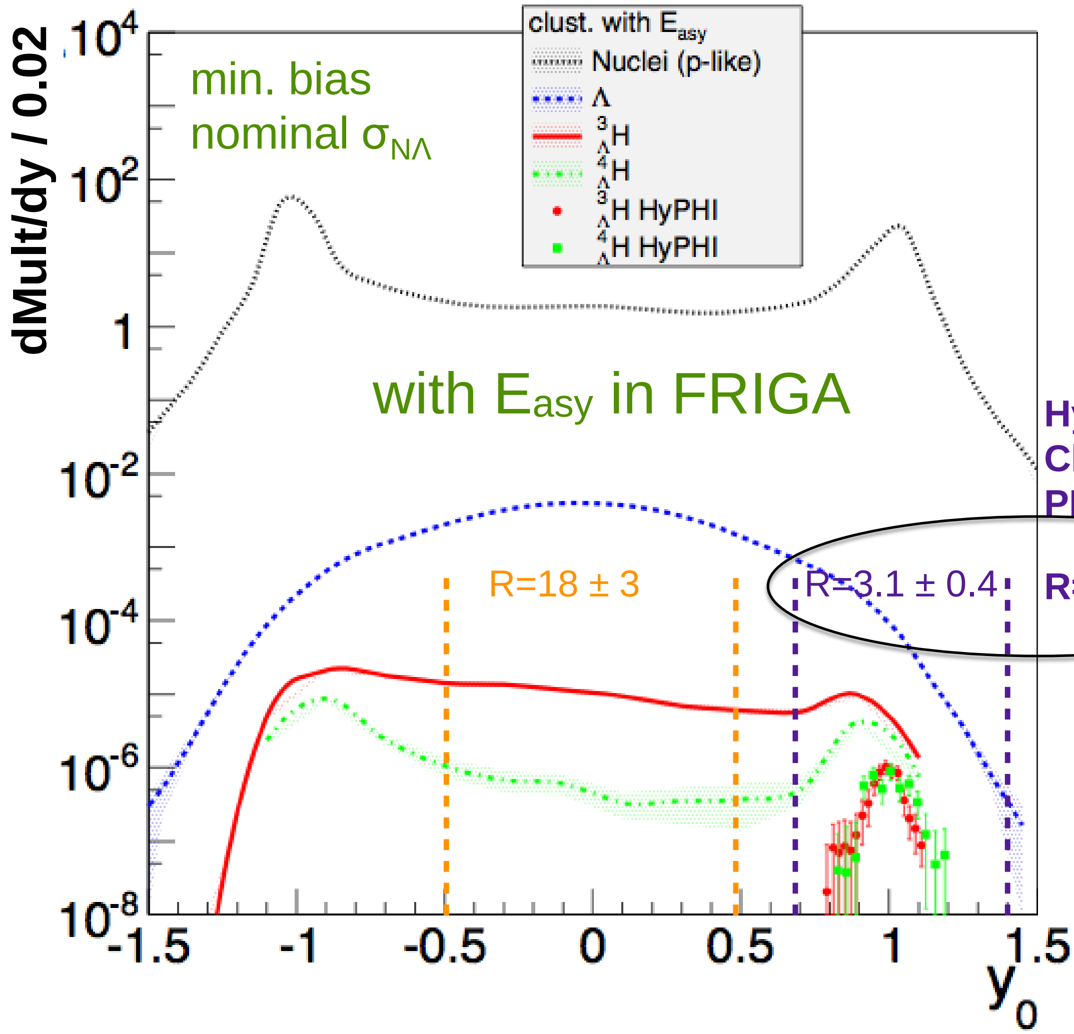
heavy
(Z>2)
hypernuclei



HYPHI@GSI results in comparison to IQMD+FRIGA

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
(t = 2 t_{pass})

$R=Y(_{\Lambda}^{3}H)/Y(_{\Lambda}^{4}H)$



HyPHI @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13:

R=1.4 ± 0.8

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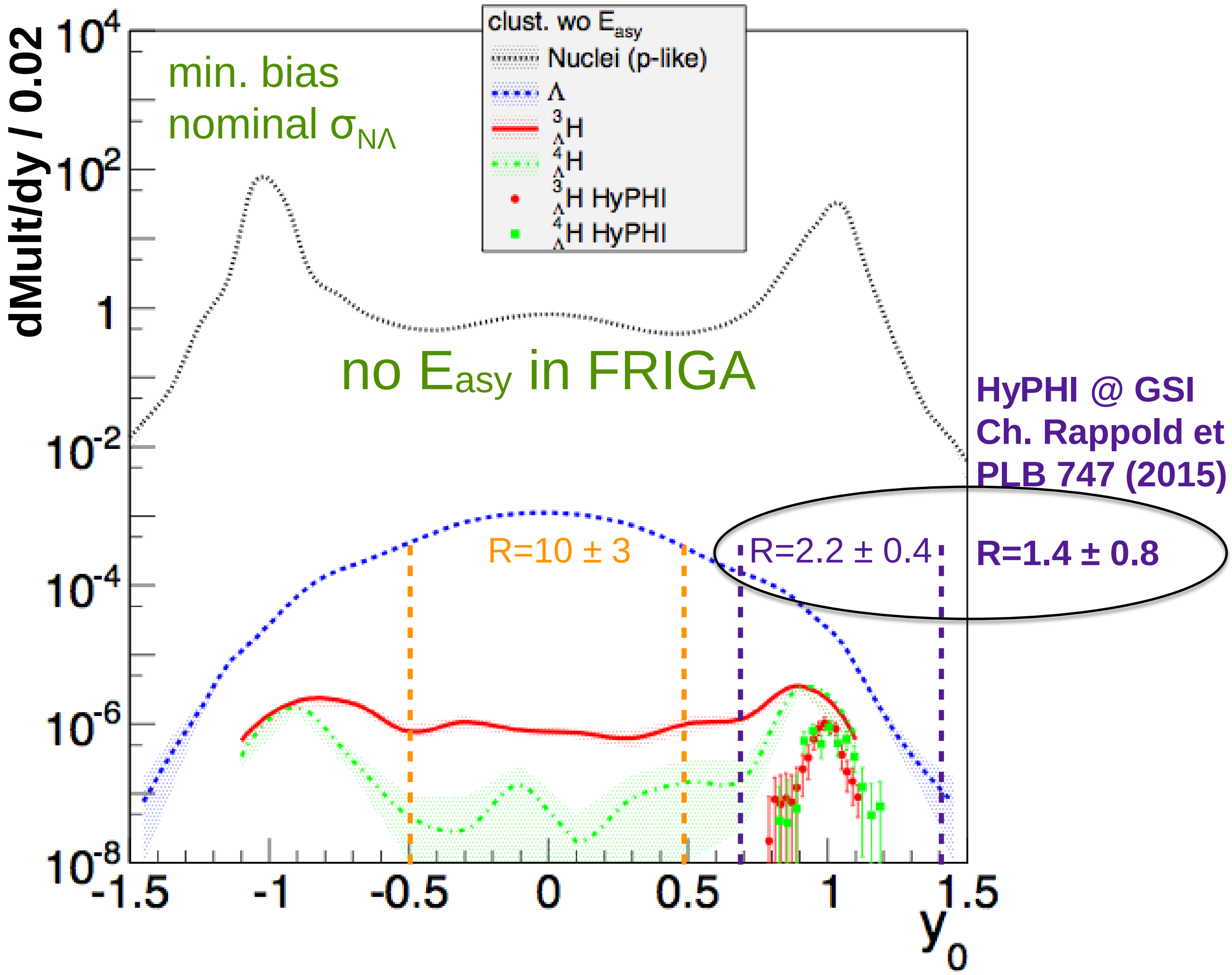

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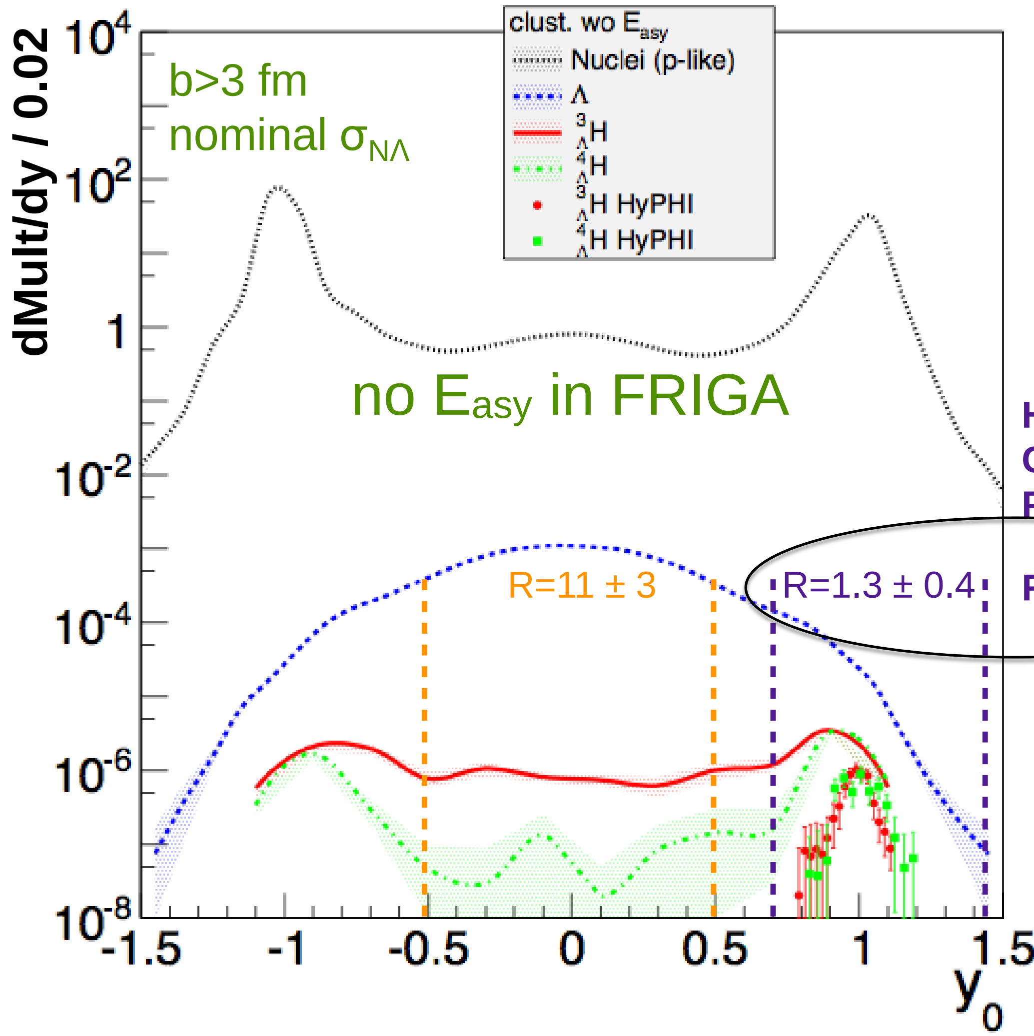

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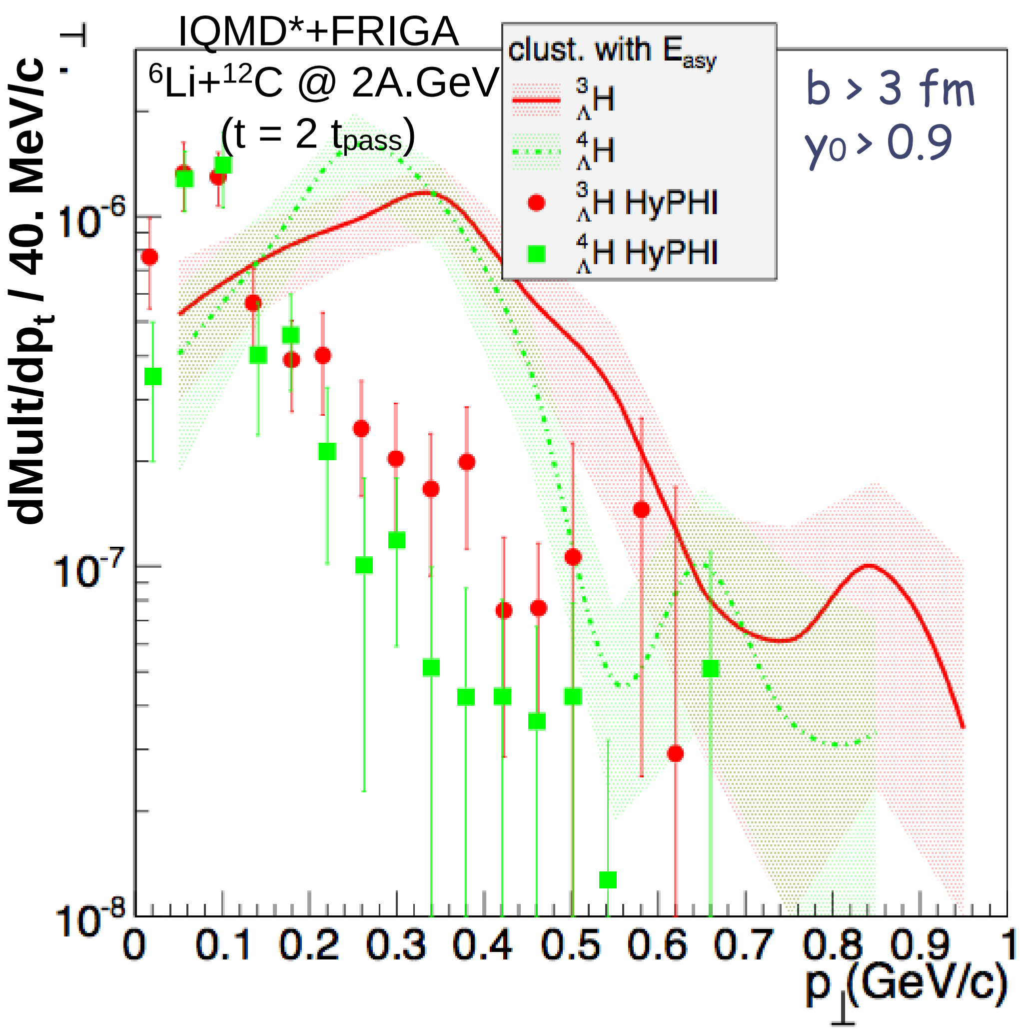


*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

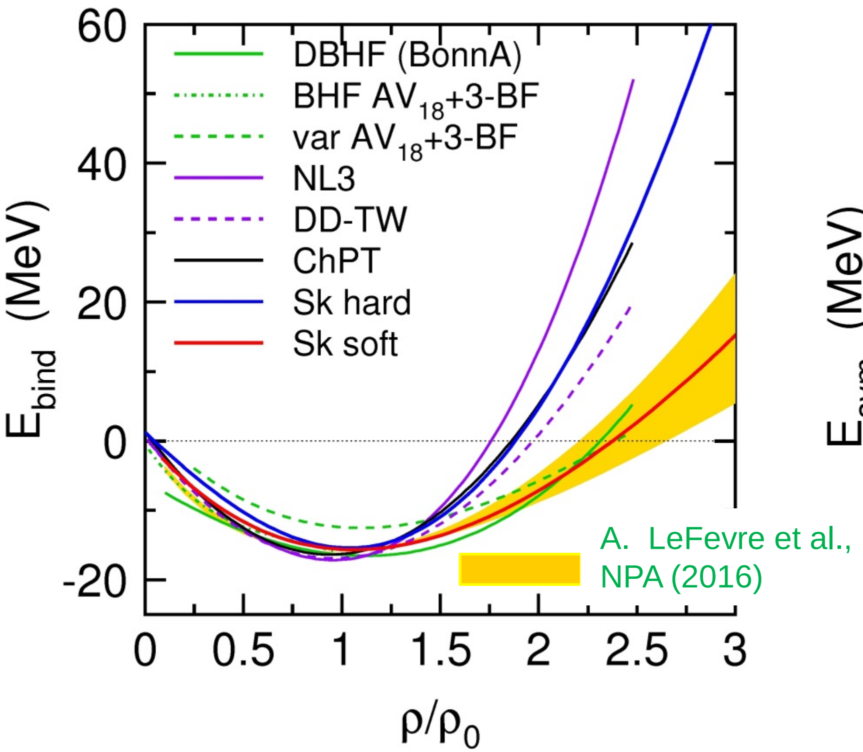
- formation of heavy hyper-nuclei predominantly in the spectator region
- crucially ingredient is the ΛN re-scattering cross section
- cluster multiplicity in the mid-rapidity region depends on the clusterization time
- in contrast to spectator region (relatively stable)
- multiplicity of the HYPHI data overpredicted
- different slopes of transverse momentum spectra of $^3_\Lambda$H and $^4_\Lambda$H reproduced

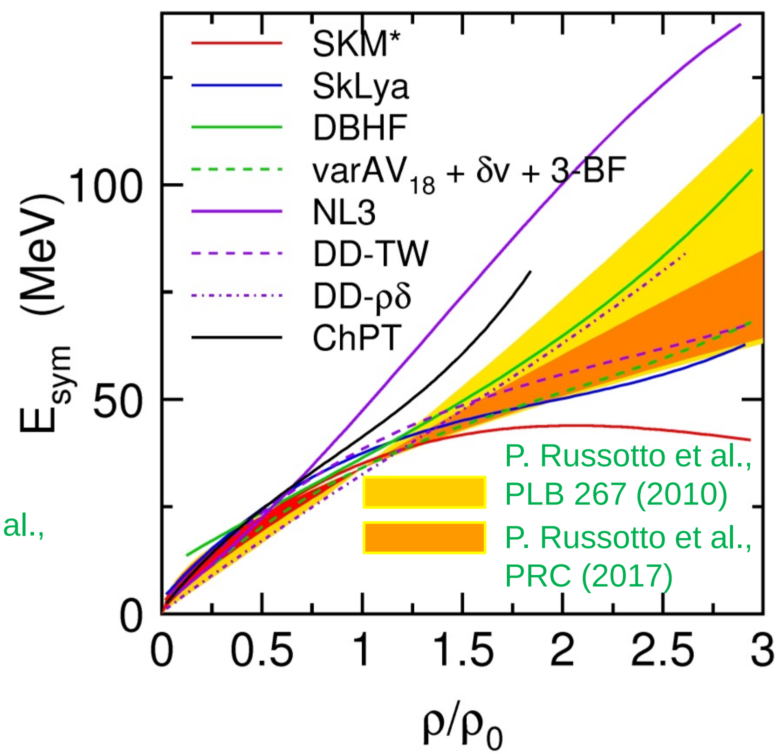
Summary

- Cluster formation is omnipresent in heavy ion collisions
  - Cluster have a larger sensitivity to dynamics
  - and influence all observables
- Understanding of production needed for more stringent constraints on equation of state and symmetry energy, important for reaction dynamics and formation mechanisms
- Dynamical creation of clusters during transport would be the most elegant approach
- Advantage of FRIGA
  - minimazation of cluster binding energies - relatively fast
  - allows for clusterization at early times to preserve the dynamics at this stage
    - the final state of FRIGA is a classical bound state (no Fermi motion)
- Experimental data
  - production of heavy clusters in the projectile/spectator region
  - light clusters in particular in the mid-rapidity region
- First results on cluster production with IQMD SM available, needs benchmarking

- Hyper nuclei production might be a very important tool to study the mechanisms of fragmentation and production of clusters
- more data (with larger phase space coverage) urgently needed

Outlook – Constraining the EOS with I/UrQMD





- Equation of state of symmetric nuclear matter from comparison of FOPI data with IQMD
- the symmetry energy as extracted from ASY-EOS results with UrQMD*

Outlook

- Pressure in a neutron star

$$(P_{NN}^{sym}(K_0) + P_{asy}(L))\delta$$

$\delta = 0.9(5\%protons + degeneratee^{-})$

- L as from AsyEOS at 1-2ρ_0

  L = 63 ± 11 MeV
  for $E_{pot}^{asy}(\rho_0)$=19 MeV)
  or L = 72 ± 13 MeV
  for $E_{pot}^{asy}(\rho_0)$=22 MeV

  [Russotto et al. PRC94(2016)034608]

- K_0 as from FOPI flow data

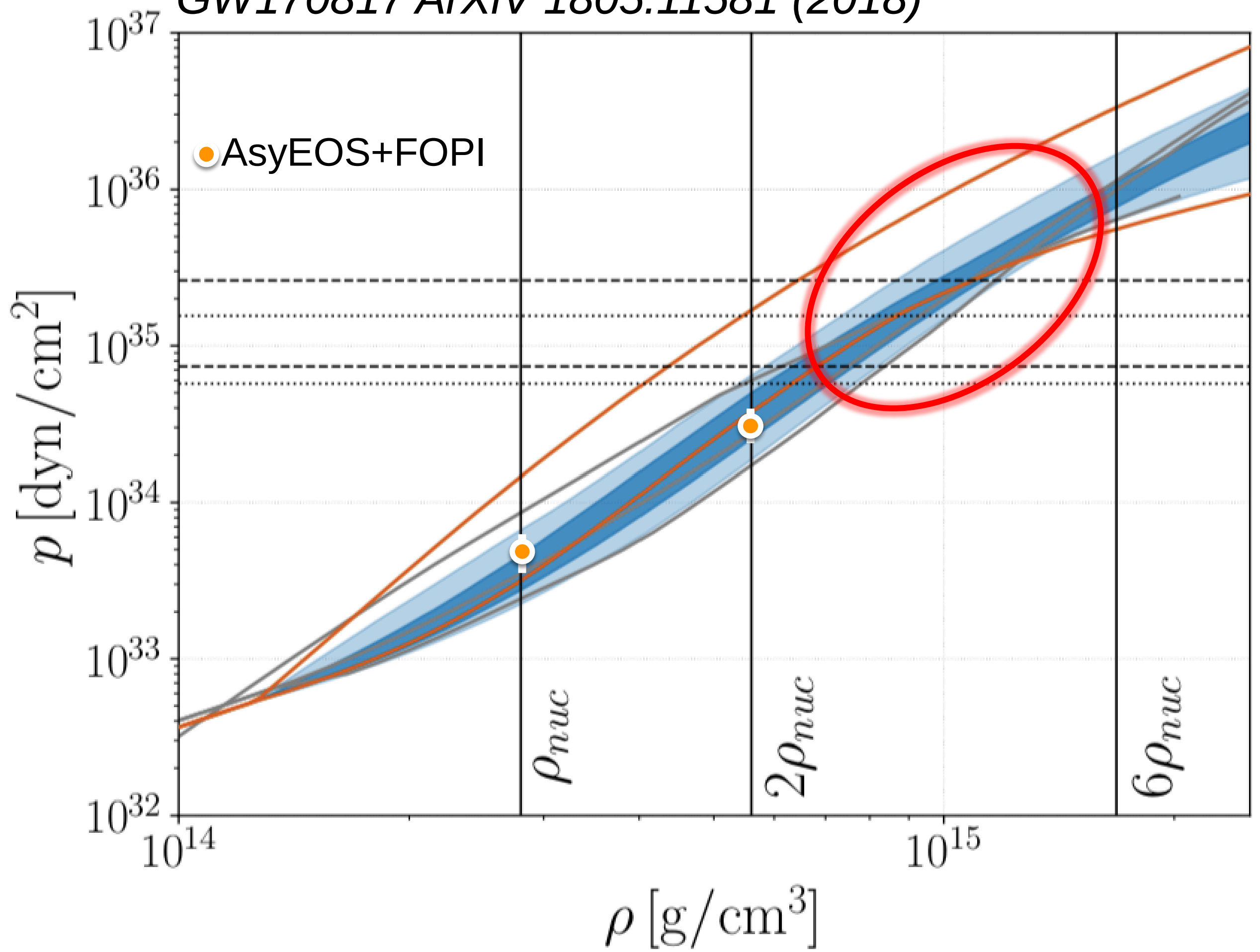
$IQMD -> K_0 = 190 \pm 30 MeV$

[A. Le Fèvre et al., NPA945(2016)112-133]

$\mathrm{UrQMD} -> \mathrm{K}_0 = 220 \pm 40\mathrm{MeV}$

[Y. Wang et al., PLB-778(2018)207-212]

GW170817 ArXiV 1805.11581 (2018)



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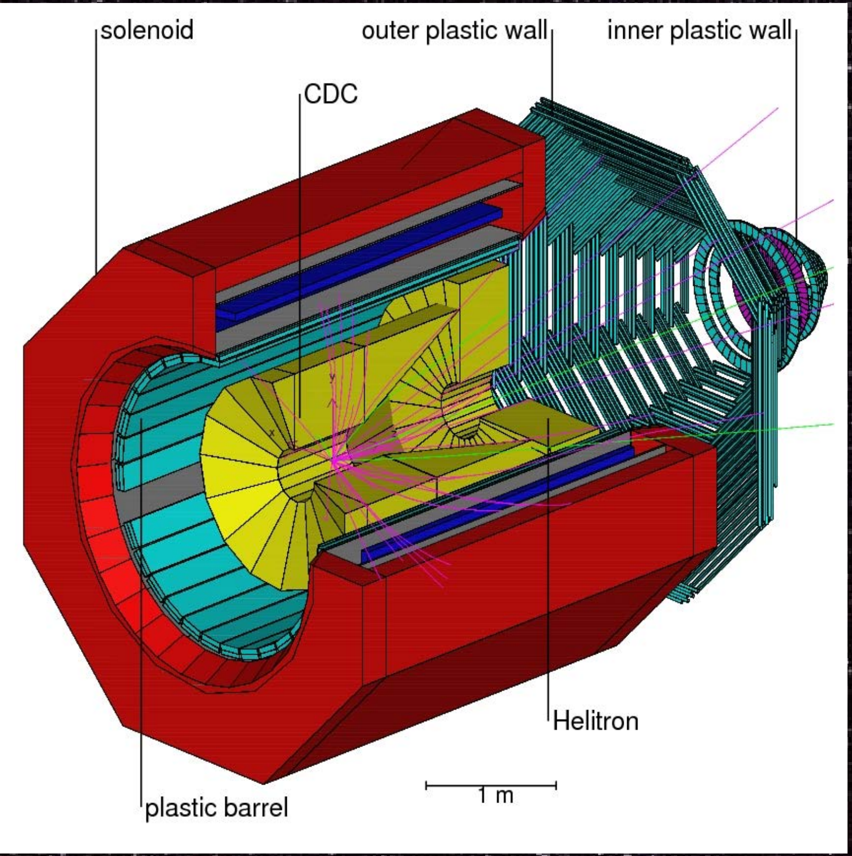
A. Andronic, R. Averbeck, Z. Basrak, N. Bastid, M.L. Benabderramahne, M. Berger, P. Bühler, R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, J. Frühauf, F. Fu, P. Gasik, O. Hartmann, N. Herrmann, K.D. Hildenbrand, B. Hong, T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis, M. Kirejczyk, R. Münzer, P. Koczon, M. Korolija, R. Kotte, A. Lebedev, K.S. Lee, Y. Leifels, A. LeFevre, P. Loizeau, X. Lopez, M. Marquardt, J. Marton, M. Merschmeyer, M. Petrovici, K. Piasecki, F. Rami, V. Ramillien, A. Reischl, W. Reisdorf, M.S. Ryu, A. Schüttauf, Z. Seres, B. Sikora, K.S. Sim, V. Simion, K. Siwek-Wilczynska, K. Suzuki, Z. Tyminski, J. Weinert, K. Wisniewski, Z. Xiao, H.S. Xu, J.T. Yang, I. Yushmanov, V. Zimnyuk, A. Zhilin, Y. Zhang, J. Zmeskal



IPNE Bucharest, Romania, ITEP Moscow, Russia CRIP/KFKI Budapest, Hungary, Kurchatov Institute Moscow, Russia, LPC Clermont-Ferrand, France, Korea University, Seoul, Korea, GSI Darmstadt, Germany, IReS Strasbourg, France, FZ Rossendorf, Germany, Univ. of Heidelberg, Germany , Univ. of Warsaw, Poland, RBI Zagreb, Croatia, IMP Lanzhou, China, SMI Vienna, Austria, TUM, Munich, Germany, T.Yamazaki(RIKEN)

and to the ASYEOS collaboration

authors of proposal 2009

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

List from the Proposal

Collaboration

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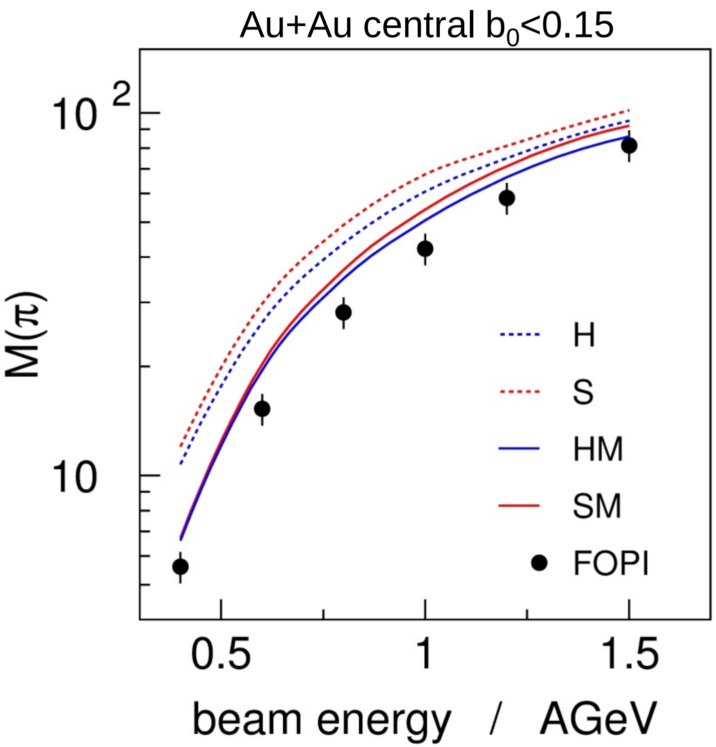
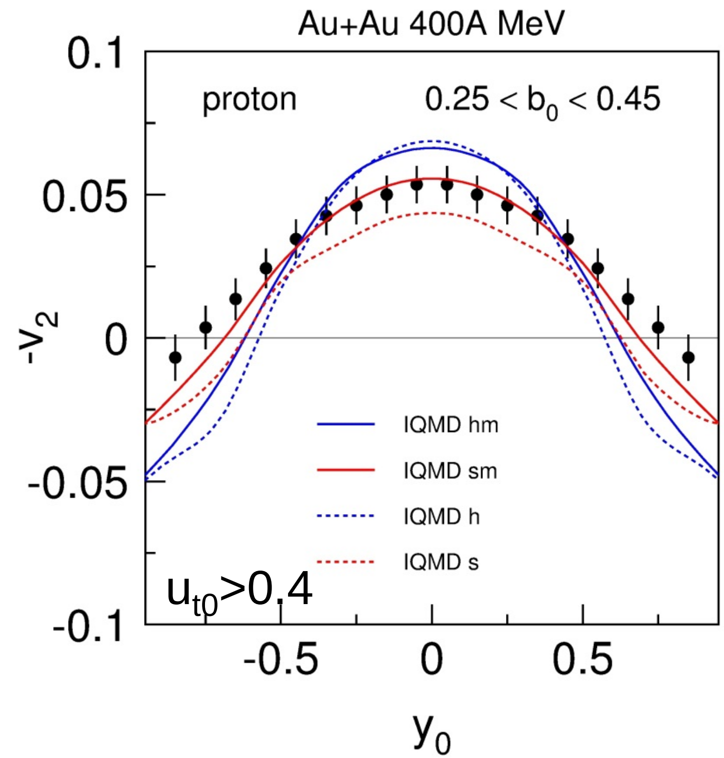
Confining the input parameters of IQMD





Choice in IQMD for

- σ_{NN},
- momentum dependence of optical potentials,
- prescription of Pauli blocking and detailed balance etc.

describes most of the data