Formation of hypernuclei in relativistic ion collisions

Alexander Botvina

Frankfurt Institute for Advanced Studies,
Frankfurt am Main (Germany) and
Institute for Nuclear Research, Moscow (Russia)

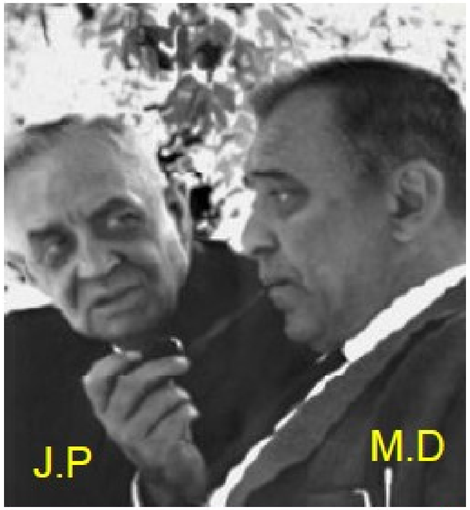
(Collaboration with M.Bleicher, E.Bratkovskaya, K.Gudima,
J.Pochodzalla, J.Steinheimer)

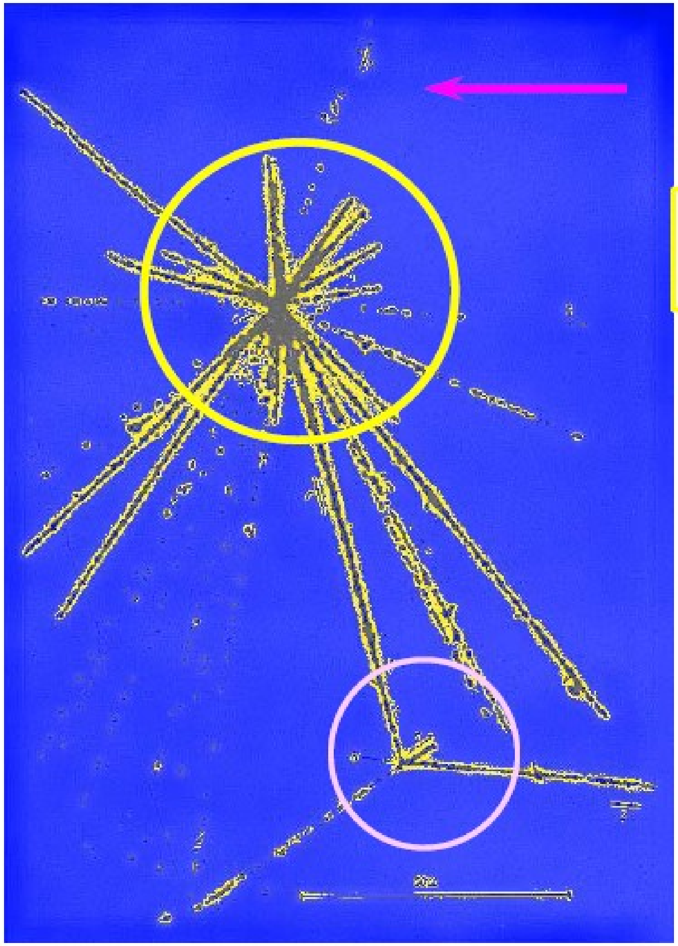
SQM2015,
JINR, Dubna, Russia
July 6-11, 2015

Discovery of a Strange nucleus: Hypernucleus

M. Danysz and J. Pniewski, Philos. Mag. 44 (1953) 348

First-hypernucleus was observed in a stack of photographic emulsions exposed to cosmic rays at about 26 km above the ground.





Incoming high energy proton from cosmic ray

colliding with a nucleus of the emulsion, breaks it in several fragments forming a star. **Multifragmentation !**

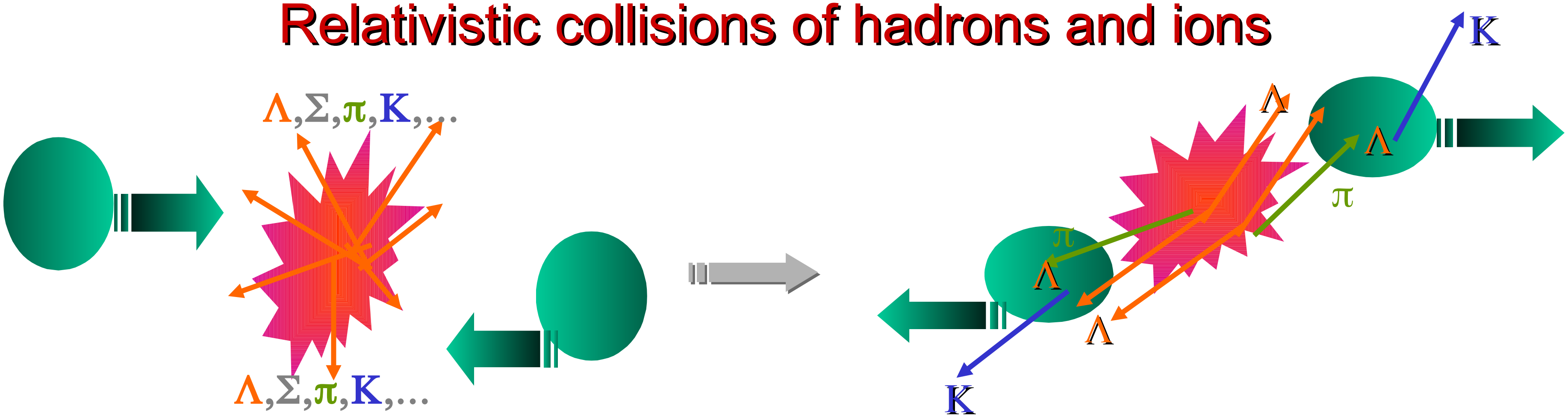
All nuclear fragments stop in the emulsion after a short path

From the first star, 21 Tracks => $9\alpha + 11H + 1\ {}_{\Lambda}X$

The fragment ${}_{\Lambda}X$ disintegrates later , makes the bottom star. Time taken ~ 10^{-12} sec (typical for weak decay)

This particular nuclear fragment, and the others obtained afterwards in similar conditions, were called **hyperfragments or hypernuclei.**

Relativistic collisions of hadrons and ions

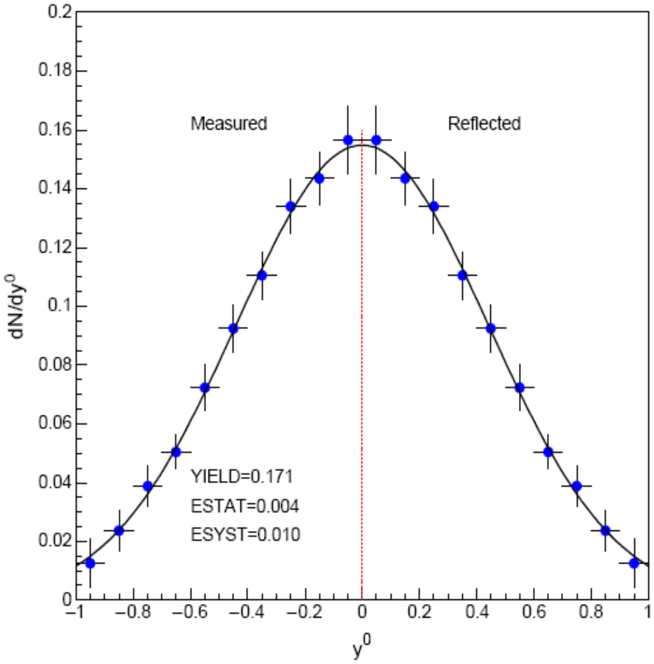


Production of hypermatter in relativistic HI and hadron collisions

- Production of strange particles and hyperons by “participants”,
- Rescattering and absorption of hyperons by excited “spectators”

X. Lopez / Progress in Particle and Nuclear Physics 53 (2004) 149–151

Reconstructed Λ rapidity distribution for central ($\sigma_{\text{geo}} = 350$ mb) Ni + Ni reactions at 1.93 A GeV.



Central collisions of relativistic ions

Production of $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{H}$ in central 11.5 GeV/c Au+Pt heavy ion collisions

PHYSICAL REVIEW C 70, 024902 (2004)

(AGS)

Rapidity	1.6–2.6
p_t(GeV/c)	0–1.5

coalescence mechanism

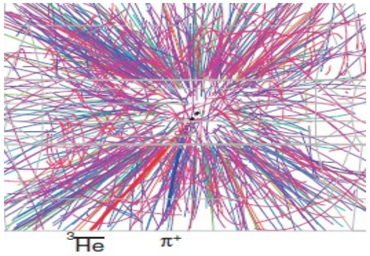
N_{event}	13.5×10^{9}	$^{3}_{\Lambda}\mathrm{H}$
N_{count}	1220 ± 854	

STAR collaboration (RHIC):

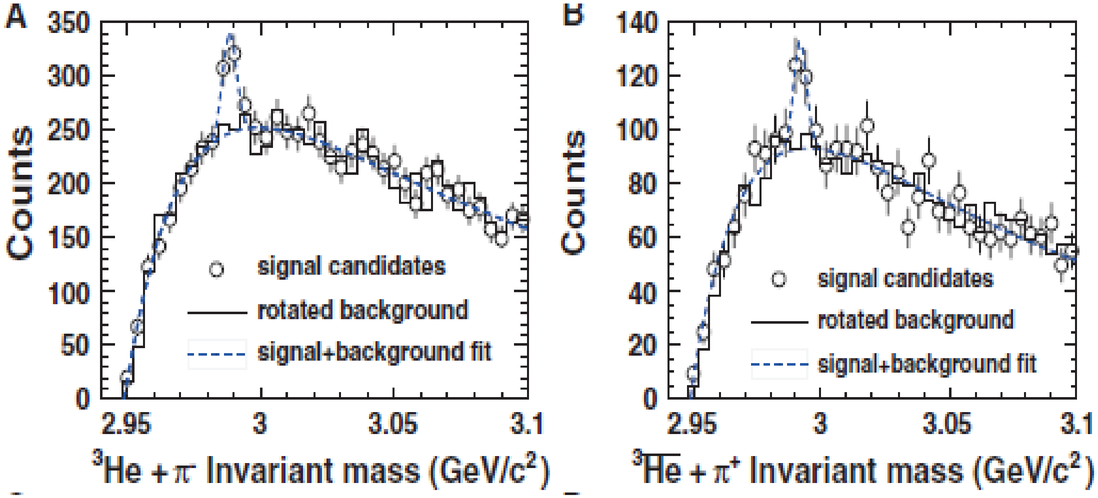
Science, 238 (2010) 58

Au + Au collisions at 200 A GeV

gas-filled cylindrical Time Projection Chamber



70 ± 17 antihypertritons ($^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$) and 157 ± 30 hypertritons ($^{3}_{\Lambda}\mathrm{H}$).



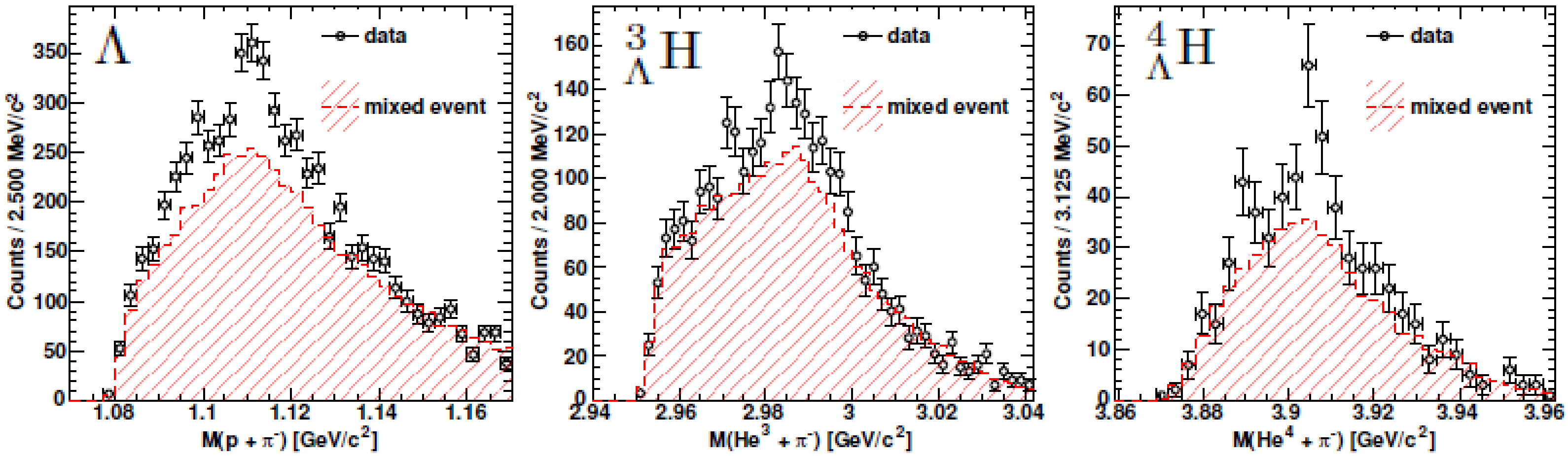
Production of hypernuclei in peripheral HI collisions: The HypHI project at GSI

T.Saito, (for HypHI),
NUFRA2011 conference, and
Nucl. Phys. A881 (2012) 218;
Nucl. Phys. A913 (2013) 170.

T.R. Saito[a,b,c], D. Nakajima[a,d], C. Rappold[a,c,e], S. Bianchin[a], O. Borodina[a,b], V. Bozkurt[a,f], B. Göküzüm[a,f], M. Kavatsyuk[g], E. Kim[a,h], Y. Ma[a,b], F. Maas[a,b,c], S. Minami[a], B. Özel-Tashenov[a], P. Achenbach[b], S. Ajimura[i], T. Aumann[a], C. Ayerbe Gayoso[b], H.C. Bhang[f], C. Caesar[a], S. Erturk[f], T. Fukuda[j], E. Guliev[h], Y. Hayashi[k], T. Hiraiwa[k], J. Hoffmann[a], G. Ickert[a], Z.S. Ketenci[f], D. Khaneft[a,b], M. Kim[h], S. Kim[h], K. Koch[a], N. Kurz[a], A. Le Fevre[a,l], Y. Mizoi[j], M. Moritsu[k], T. Nagae[k], L. Nungesser[b], A. Okamura[k], W. Ott[a], J. Pochodzalla[b], A. Sakaguchi[m], M. Sako[k], C.J. Schmidt[a], M. Sekimoto[n], H. Simon[a], H. Sugimura[k], T. Takahashi[n], G.J. Tambave[g], H. Tamura[o], W. Trautmann[a], S. Voltz[a], N. Yokota[k], C.J. Yoon[h], K. Yoshida[m],

C. Rappold et al.,
Phys. Rev. C88 (2013) 041001:
Λnn bound state ?

Projectile fragmentation: ^{6}Li beam at 2 A GeV on ^{12}C target



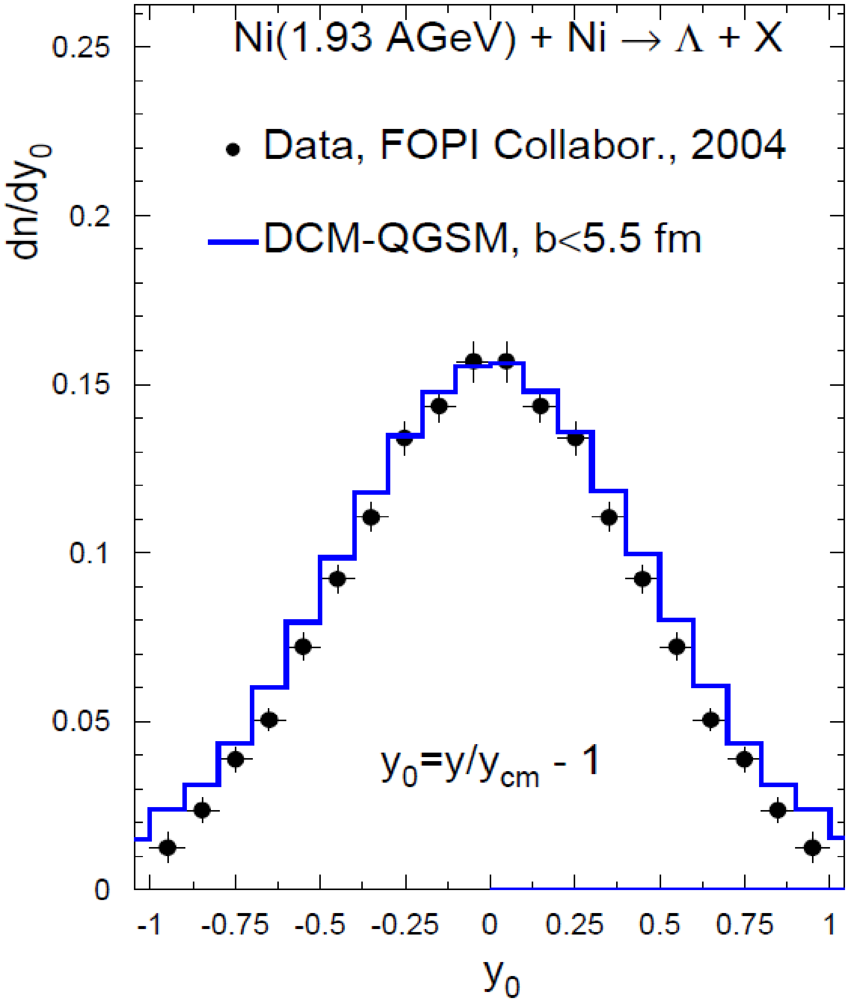
For the first, they have also observed a large correlation of $^{2}\mathrm{H} + \pi^{-}$
i.e., considerable production of Λn bound states

Theoretical descriptions of strangeness production within transport codes

old models : *INC, QMD, BUU*	e.g., Z.Rudy, W.Casing et al., *Z. Phys.A351(1995)217*
GiBUU model: *(+SMM)*	Th.Gaitanos, H.Lenske, U.Mosel , *Phys.Lett. B663(2008)197,* *Phys.Lett. B675(2009)297*
PHSD model:	E.Bratkovskaya, W.Cassing, … *Phys. Rev. C78(2008)034919*
DCM (INC) : *(+QGSM+SMM)*	JINR version: K.K.Gudima et al., *Nucl. Phys. A400(1983)173, …* *Phys. Rev. C84 (2011) 064904*
UrQMD approach:	S.A. Bass et al., *Prog. Part. Nucl. Phys. 41 (1998)255.* M.Bleicher et al._*J. Phys.G25(1999)1859, …* , J.Steinheimer ...

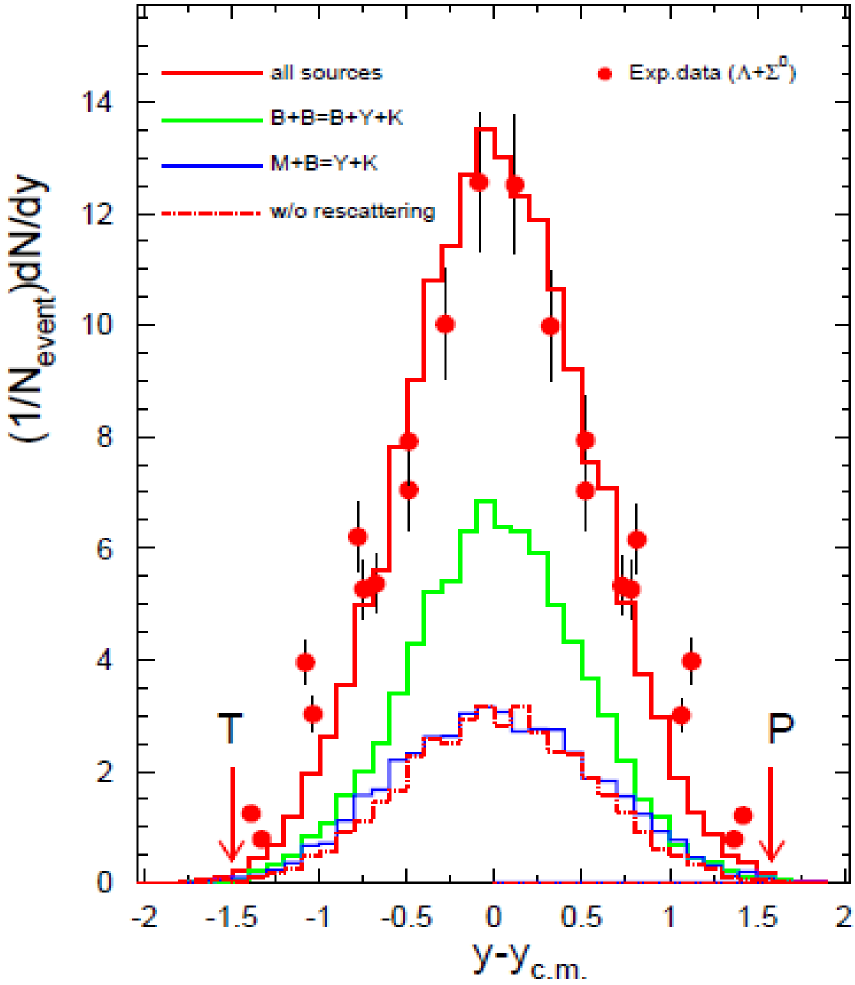
Main channels for production of strangeness in individual hadron- nucleon collisions: BB→BYK , Bπ—>YK, … (like $p+n \rightarrow n+\Lambda+K^+$, and secondary meson interactions, like $\pi+p \rightarrow \Lambda+K^+$). Rescattering of hyperons is important for their capture by spectators. Expected decay of produced hyperons and hypernuclei: 1) mesonic $\Lambda \rightarrow \pi+N$; 2) in nuclear medium nonmesonic $\Lambda+N \rightarrow N+N$.

Verification of the transport models



X. Lopez / Progress in Particle and Nuclear Physics 53 (2004) 149–151

DCM: PRC **84** (2011) 064904



S.Albergo et al., E896: PRL88(2002)062301

Au(11 A GeV/c)+Au

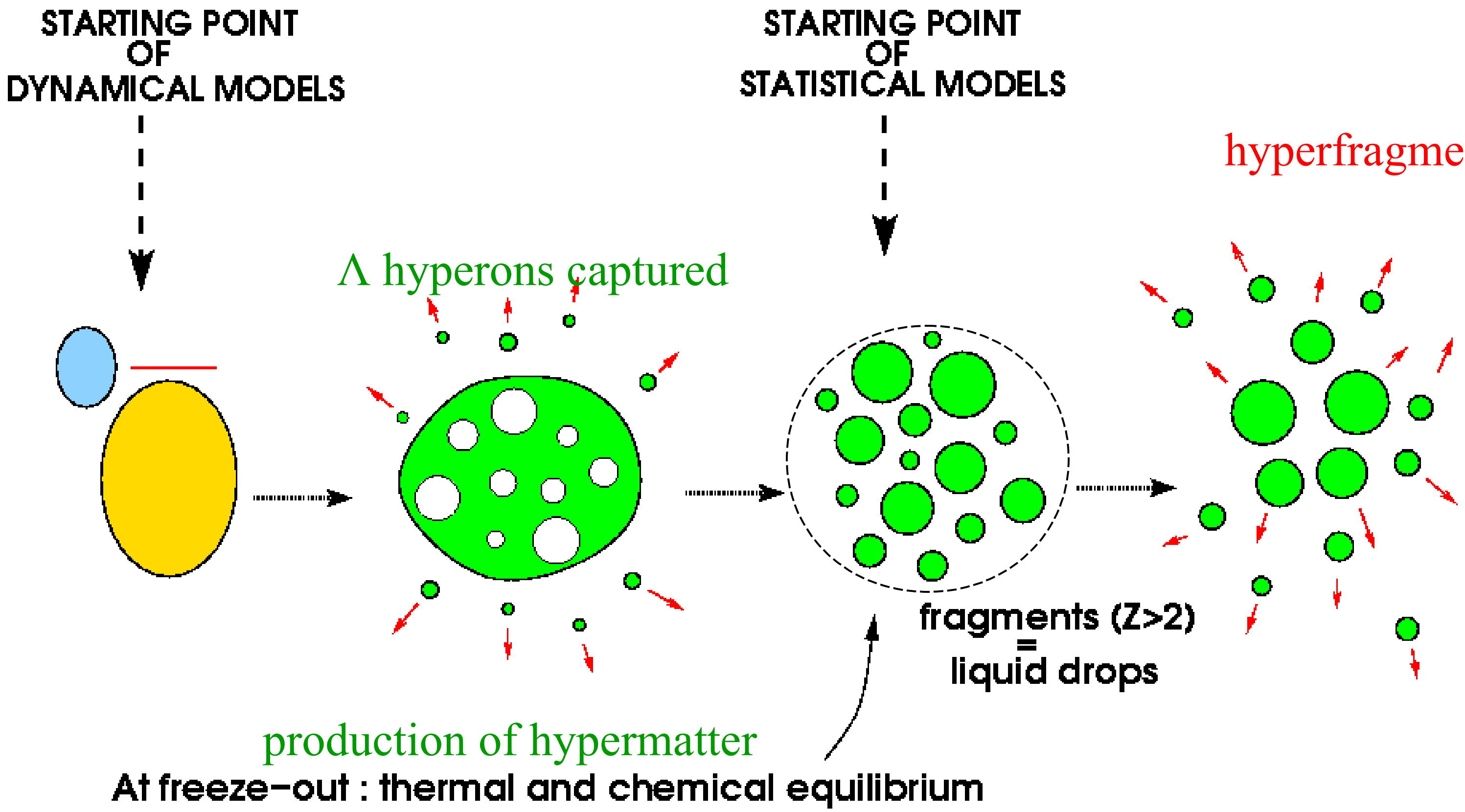
A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

Generalization of the statistical de-excitation model for nuclei with Lambda hyperons

In these reactions we expect analogy with

multifragmentation in intermediate and high energy nuclear reactions

+ nuclear matter with strangeness



hyperfragments

Λ hyperons captured

production of hypermatter

Physical picture of peripheral relativistic HI collisions:

nucleons of projectile interact with nucleons of target, however, in peripheral collisions many nucleons (spectators) are not involved. All products of the interactions can also interact with nucleons and between themselves. The time-space evolution of all nucleons and produced particles can be calculated with transport models.

All strange particles: Kaons, Lambda, Sigma, Xi, Omega
are included in the transport models

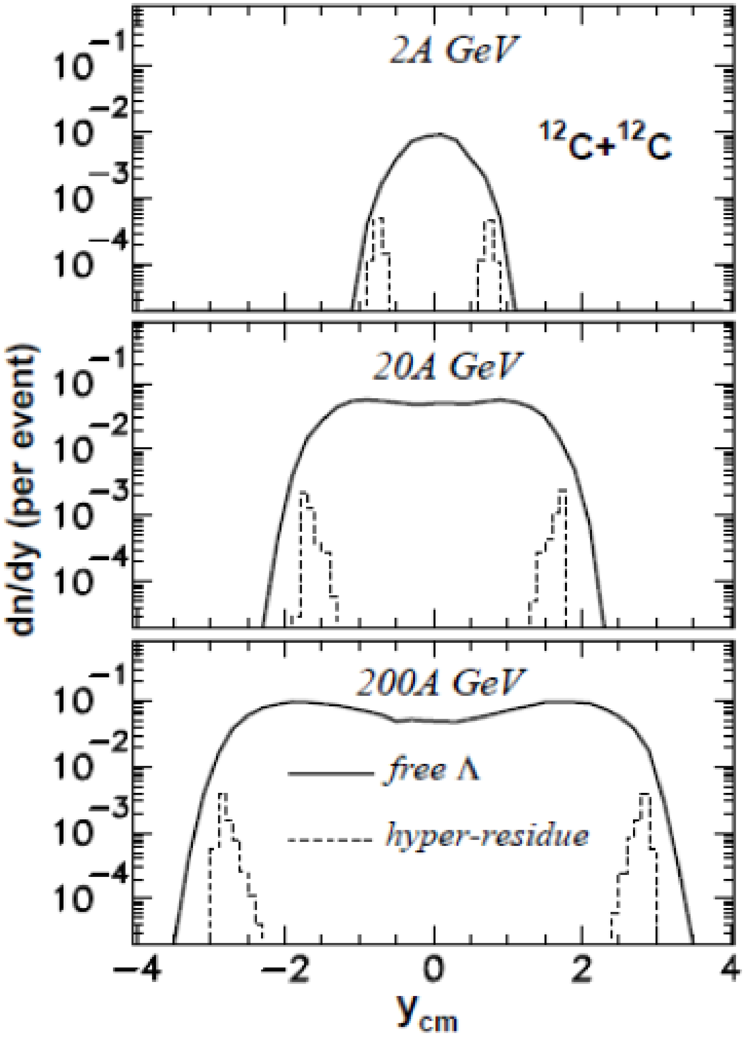
ABSORPTION of LAMBDA :

The residual spectator nuclei produced during the non-equilibrium stage may capture the produced Lambda hyperons if these hyperons are (a) inside the nuclei and (b) their energy is lower than the hyperon potential in nuclear matter (~30 MeV). In the model a depletion of the potential with reduction of number of nucleons in nucleus is taken into account by calculating the local density of spectator nucleons.

Rapidity distribution of free hyperons and hyper-residues in relativistic ion collisions (DCM calculations)

A.S.Botvina, K.K.Gudima, J.Pochodzalla PRC 88 (2013) 054605

Wide distributions of produced Lambda-hyperons up to spectator rapidities at all incident energies. A stochastic process related to secondary interactions leads to the hyperon capture by residues.



The evolution to a double peak distribution with increasing energy tell us that the Lambda production is mainly caused by secondary processes too.

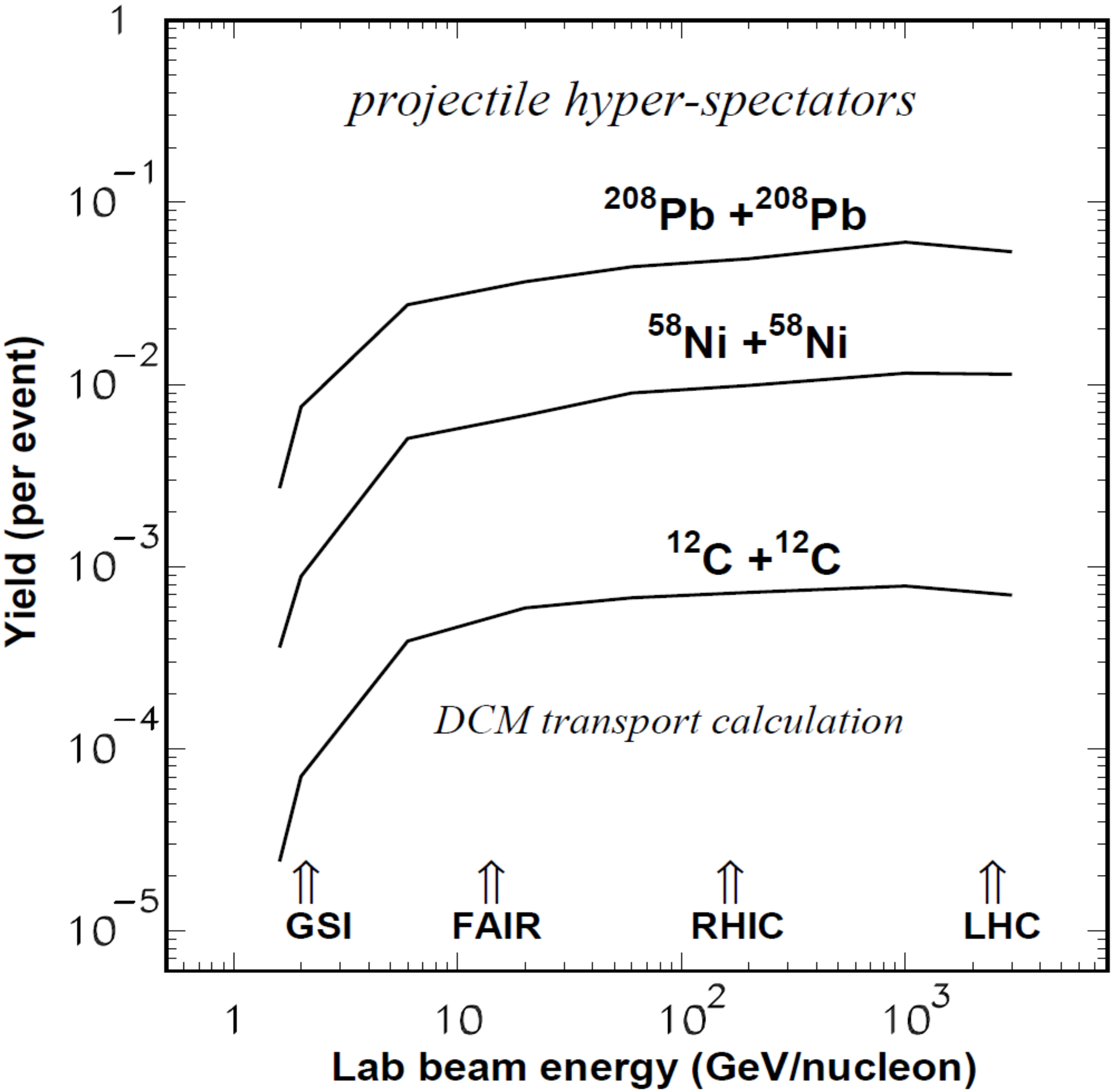
Yield of hypernuclei in peripheral collisions

A.S.Botvina, K.K.Gudima, J.Pochodzalla (PRC88, 054605, 2013)

Threshold behavior with saturation at high energies (for single hypernuclei)

Yield is integrated over all impact parameters.

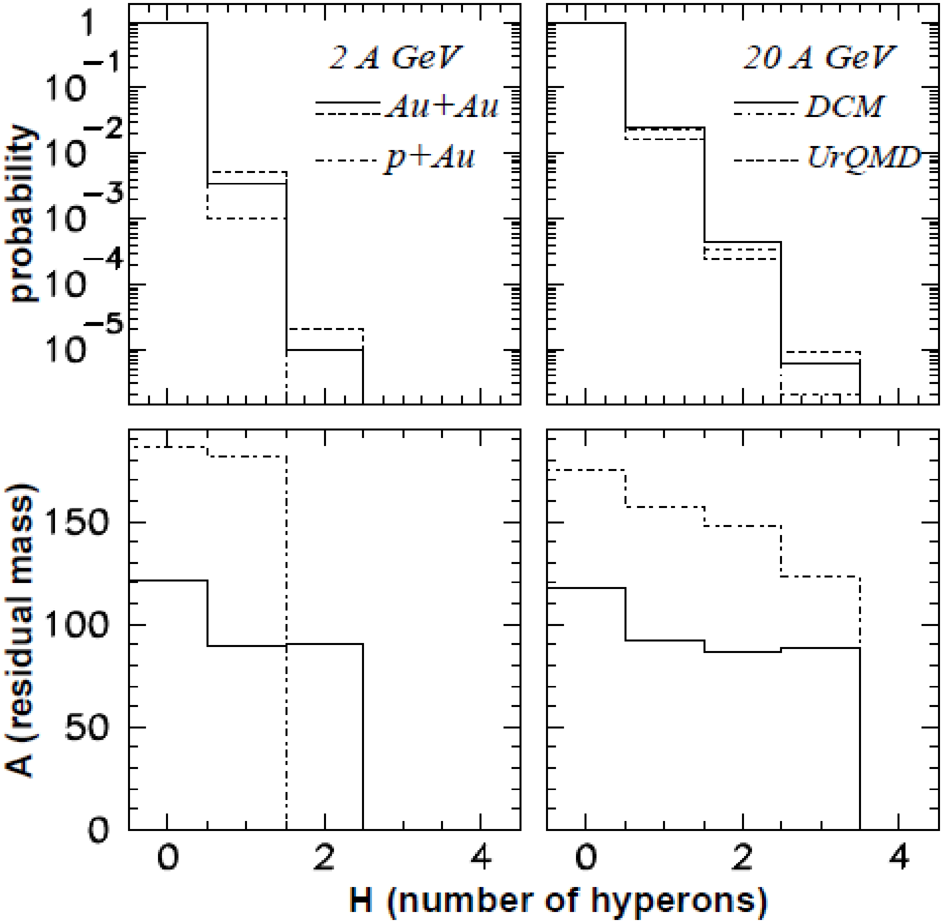
Reactions can be studied at GSI/FAIR and JINR/NICA facilities as well as on operating RHIC and LHC (fixed target experiments).



A.S.Botvina, K.K.Gudima, J.Steinheimer, M.Bleicher, I.N.Mishustin. PRC 84 (2011) 064904

projectile residuals produced after non-equilibrium stage

total yield of residuals with single hyperons ~1% , with double ones ~0.01%, at 2 GeV per nucleon, and considerably more at 20 GeV per nucleon



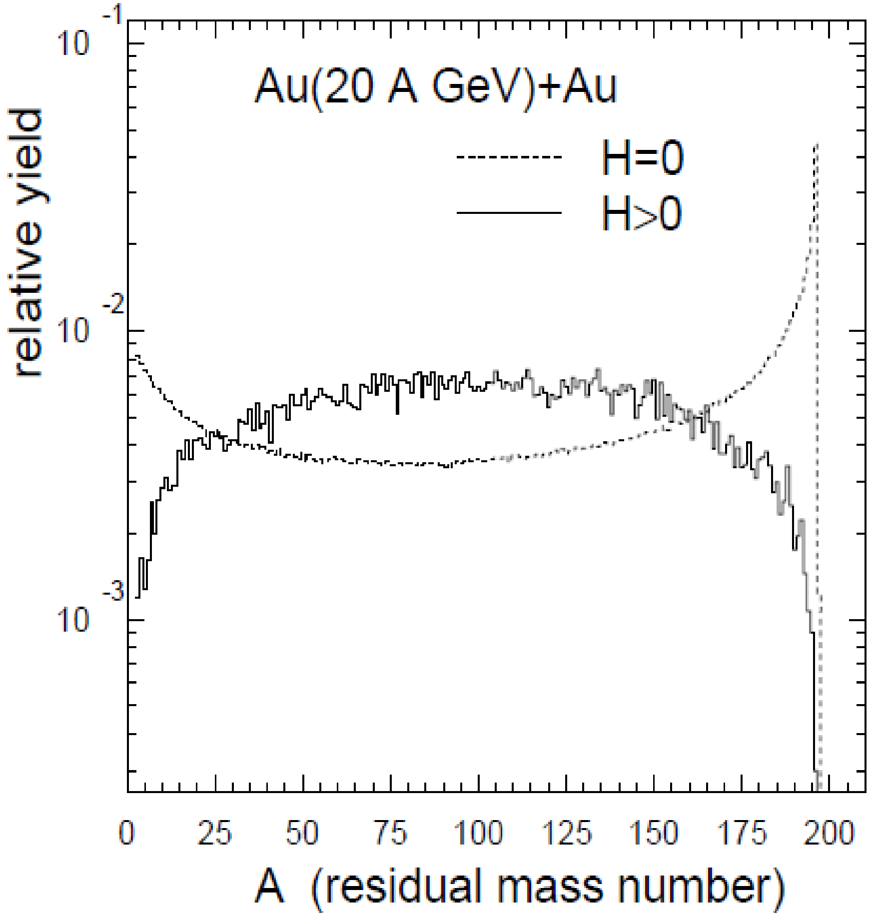
Integrated over all impact parameters

Formation of multi-strange nuclear systems (H>2) is possible!

The disintegration of such sytems can lead to production of exotic hypernuclei.

Masses of projectile residuals produced after DCM

different hyper-residuals (with large cross-section) can be formed
(from studies of conventional matter: expected temperatures - up to 5-8 MeV)



6b : H=0

200mb: H>0

Momentum distribution of Lambda captured in the spectators

(Connection of the potential capture and the coalescence)

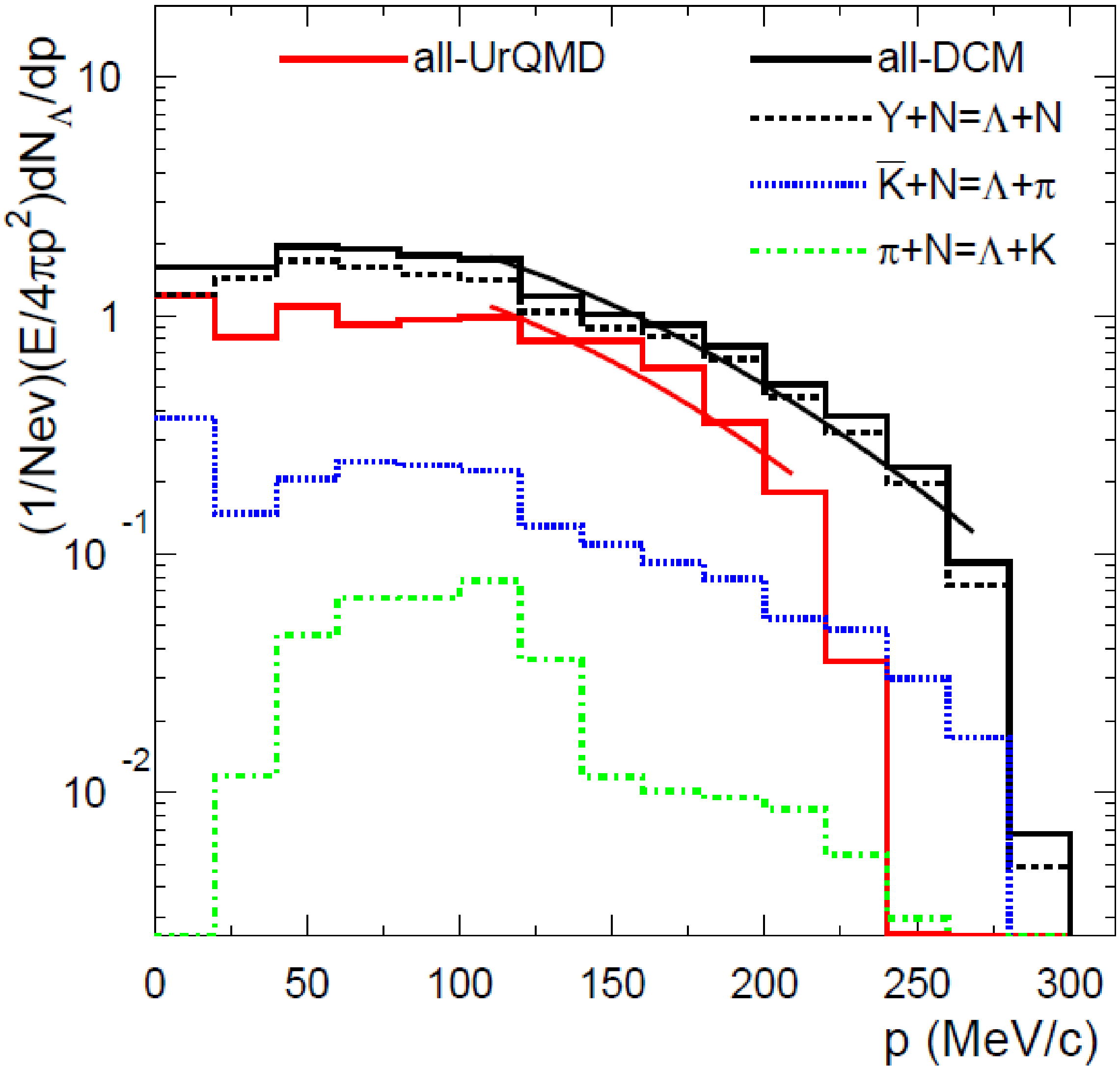
Coalescence of baryons

momenta:

$$|P_i - P_0| \leq P_c$$

coordinates:

$$|X_i - X_0| \leq X_c$$



A.Botvina, J.Steinheimer, E.Bratkovskaya, M.Bleicher, J.Pochodzalla, PLB742(2015)7

Coalescence of Baryons (CB) Model :

Development of the coalescence for formation of clusters of all sizes

1) Relative velocities between baryons and clusters are considered,
if ($|\mathbf{V}b-\mathbf{V}_A|$)<$\mathbf{V}c$ the particle b is included in the A-cluster.
2) Step by step numerical approximation.

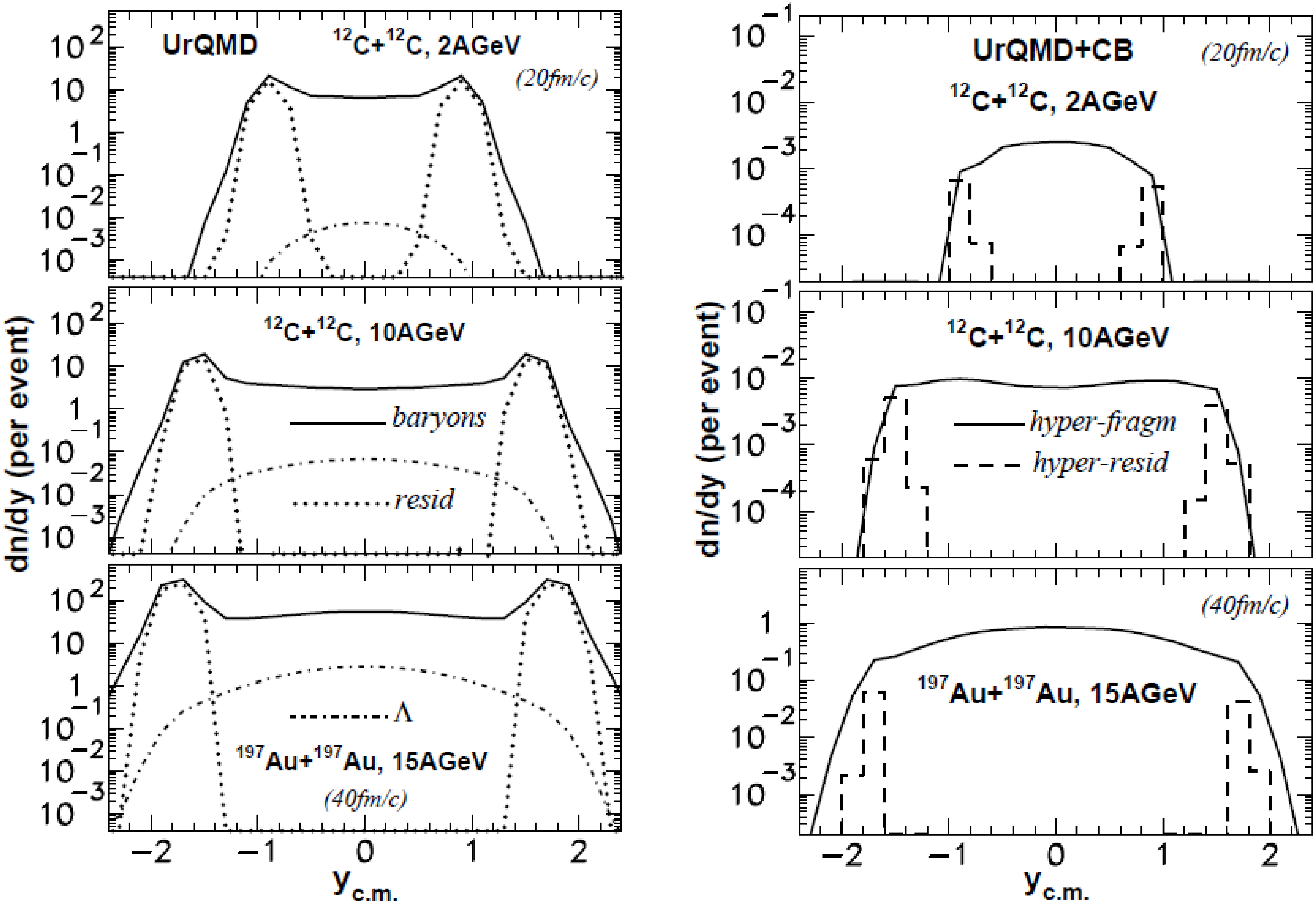
3) In addition, coordinates of baryons and clusters are considered,
if $|\mathbf{X}b-\mathbf{X}_A|$<R*A**(1/3) the particle b may be included in A-cluster.
4) Spectators' nucleons are always included in the residues.

Combination of transport UrQMD and HSD models with CB:

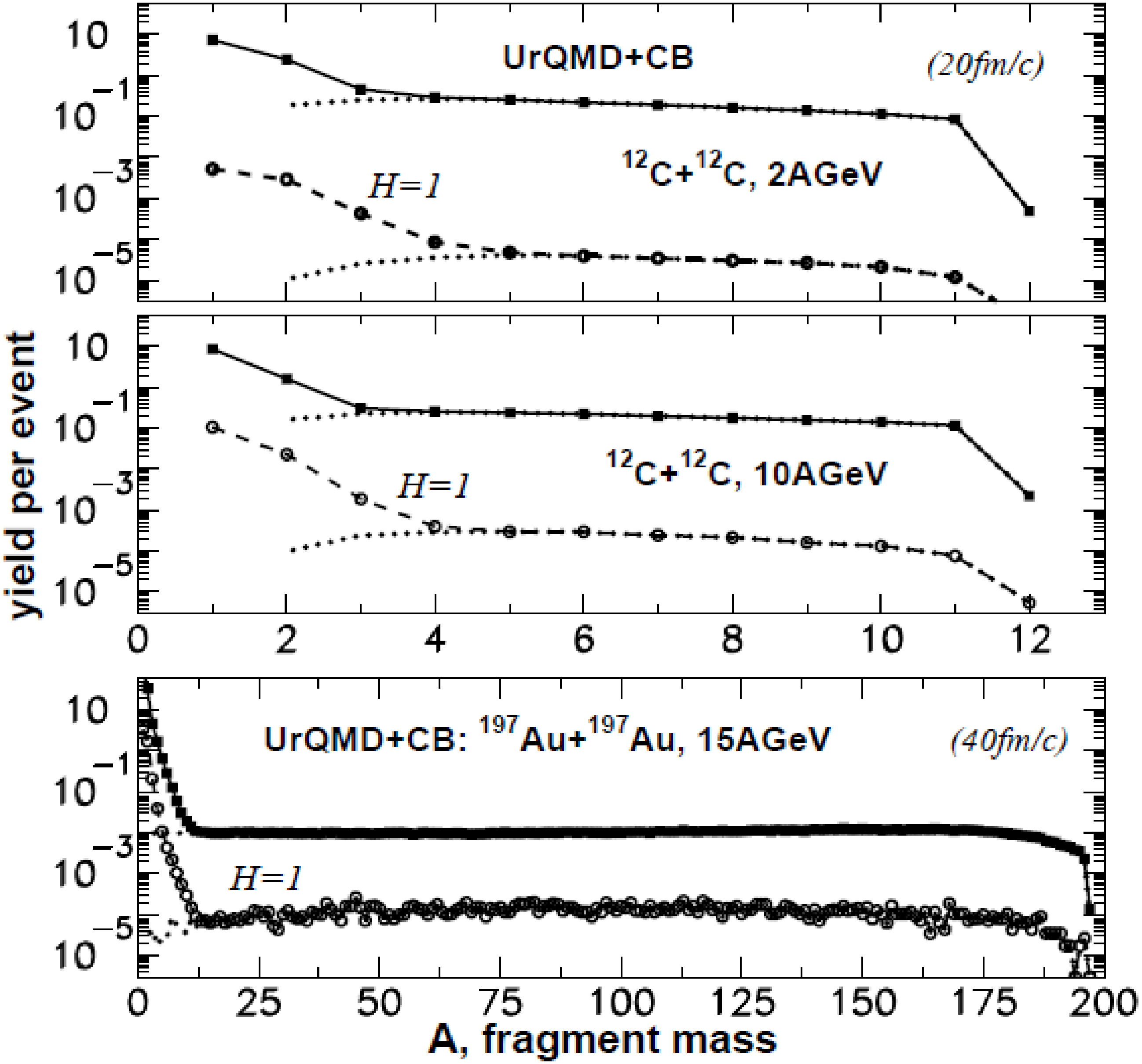
Investigation of fragments/hyperfragments at all rapidities !
(connection between central and peripheral zones)

A.Botvina, J.Steinheimer, E.Bratkovskaya, M.Bleicher, J.Pochodzalla, PLB742(2015)7

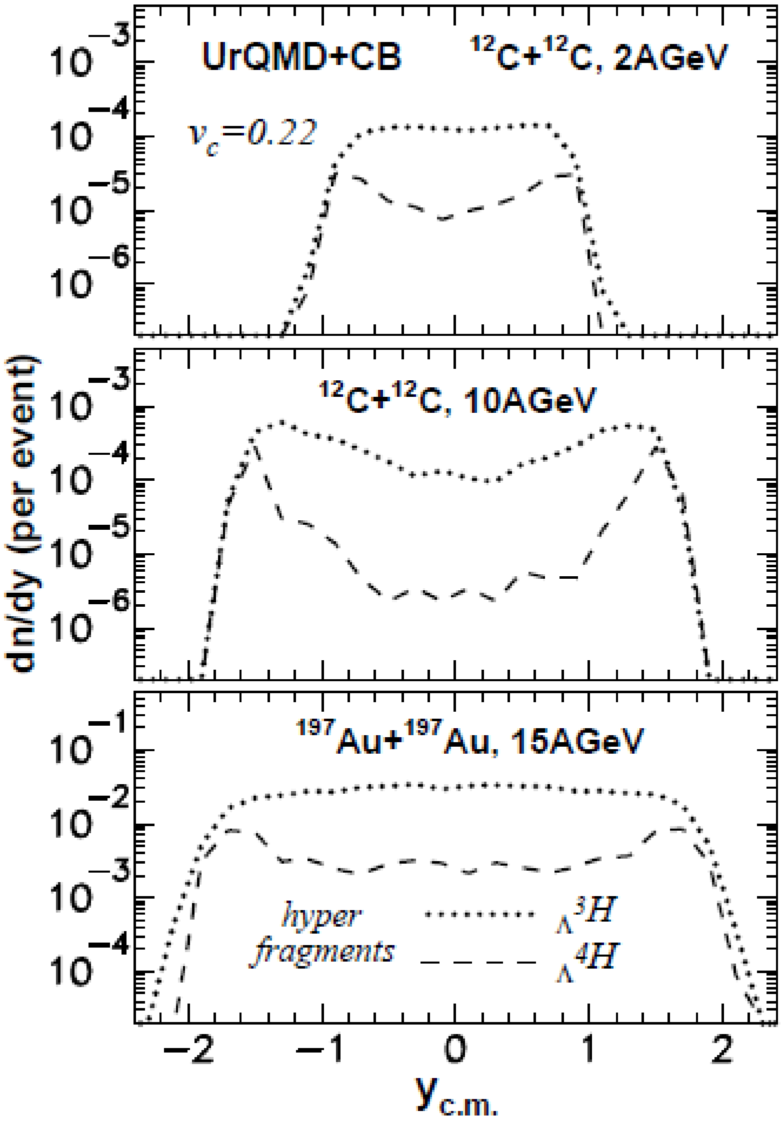
baryons, Lambdas, hyper-fragments, hyper-residues

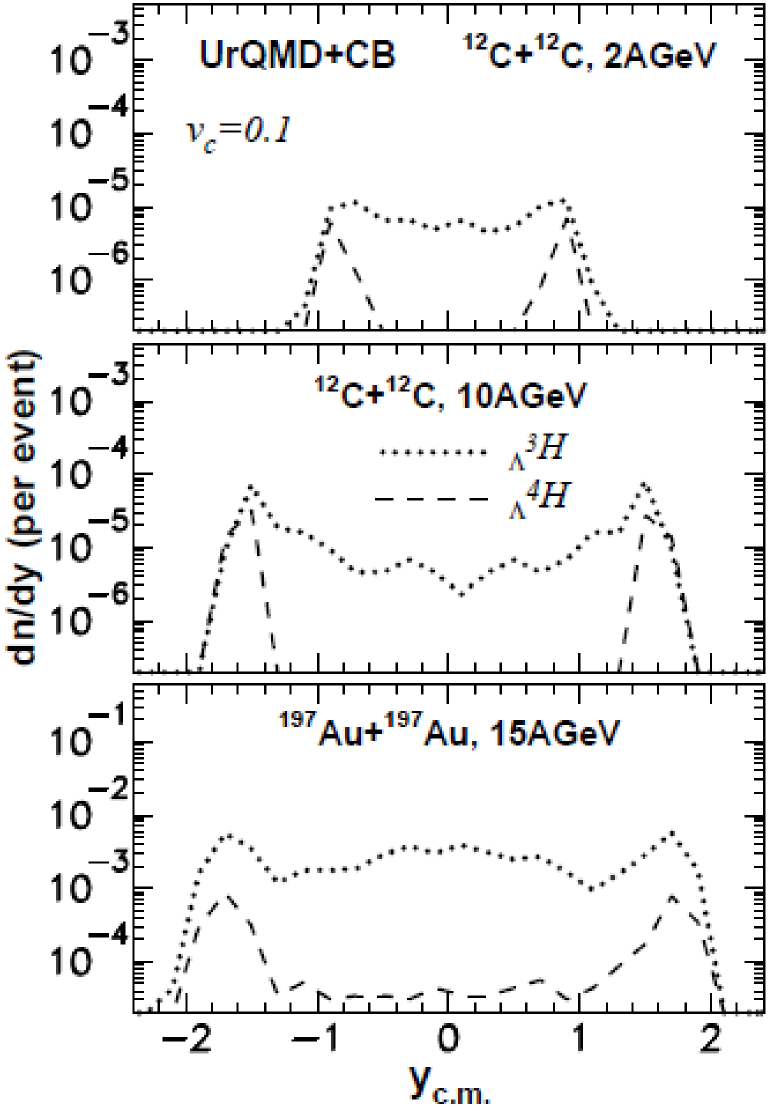


normal fragments and hyper-fragments (with residue contribution)



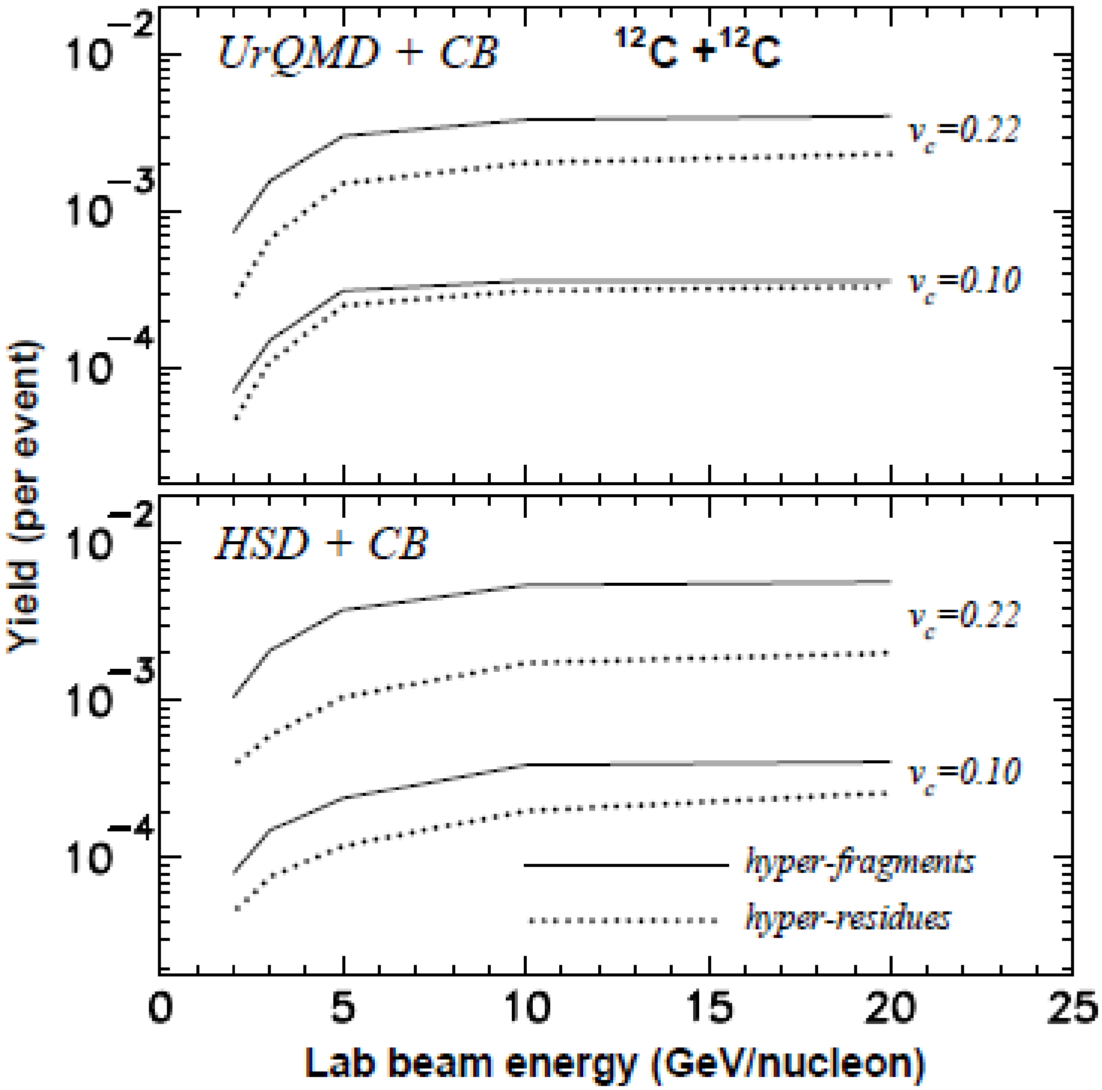
light hyper-fragments





A.Botvina, J.Steinheimer, E.Bratkovskaya, M.Bleicher, J.Pochodzalla, PLB742(2015)7

Transport models are consistent (UrQMD, HSD)

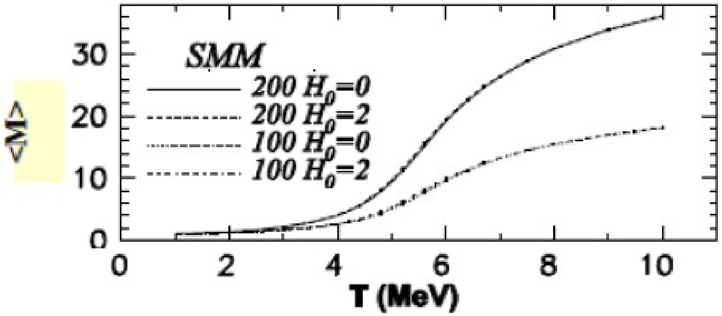


Multifragmentation of excited hyper-sources

H_0 is the number of hyperons
in the system

General picture depends weakly on strangeness content (in the case it is much lower than baryon charge)

Mean multiplicity



However, there are essential differences in properties of produced fragments !

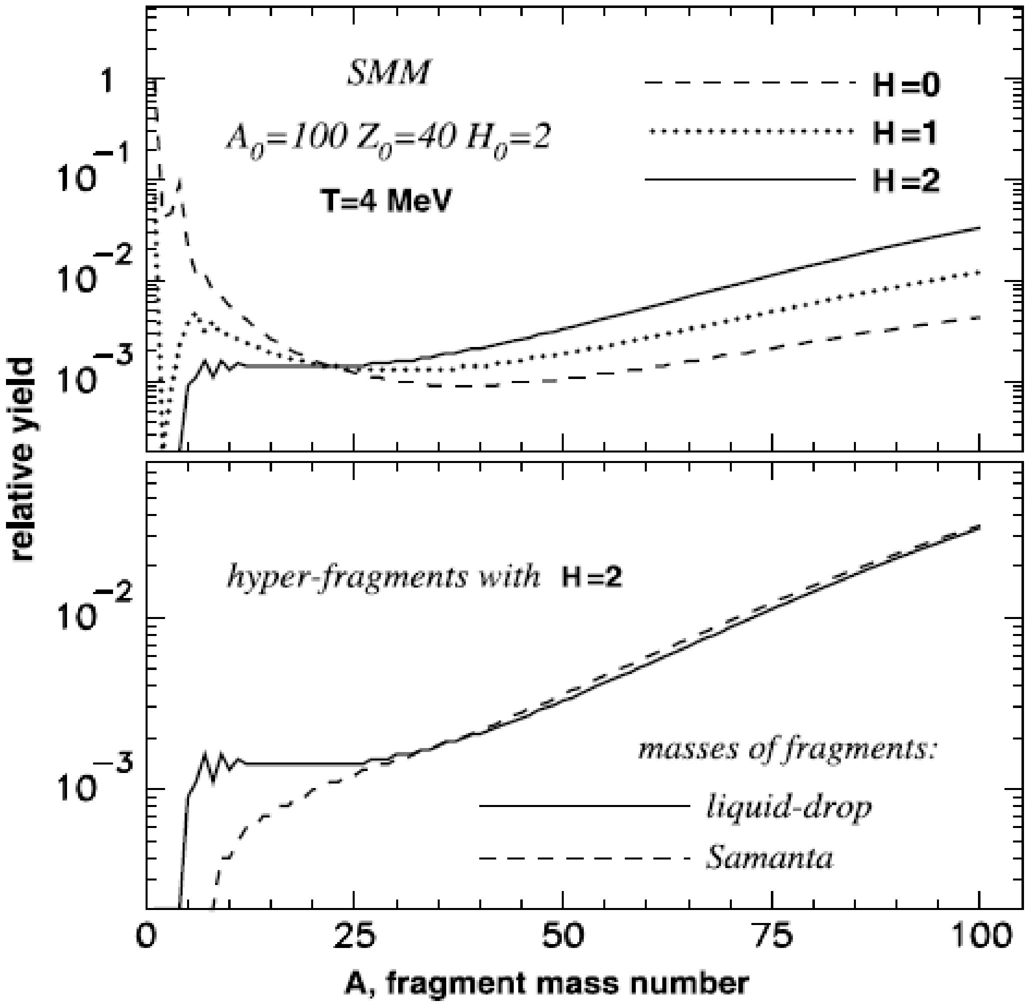
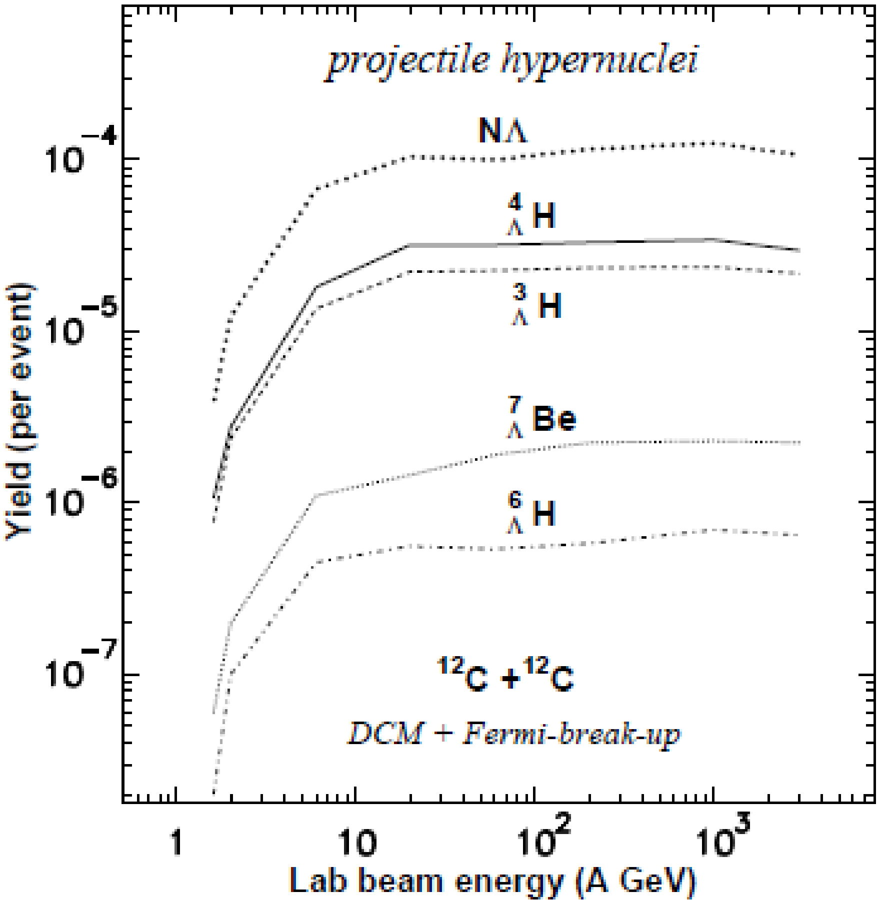
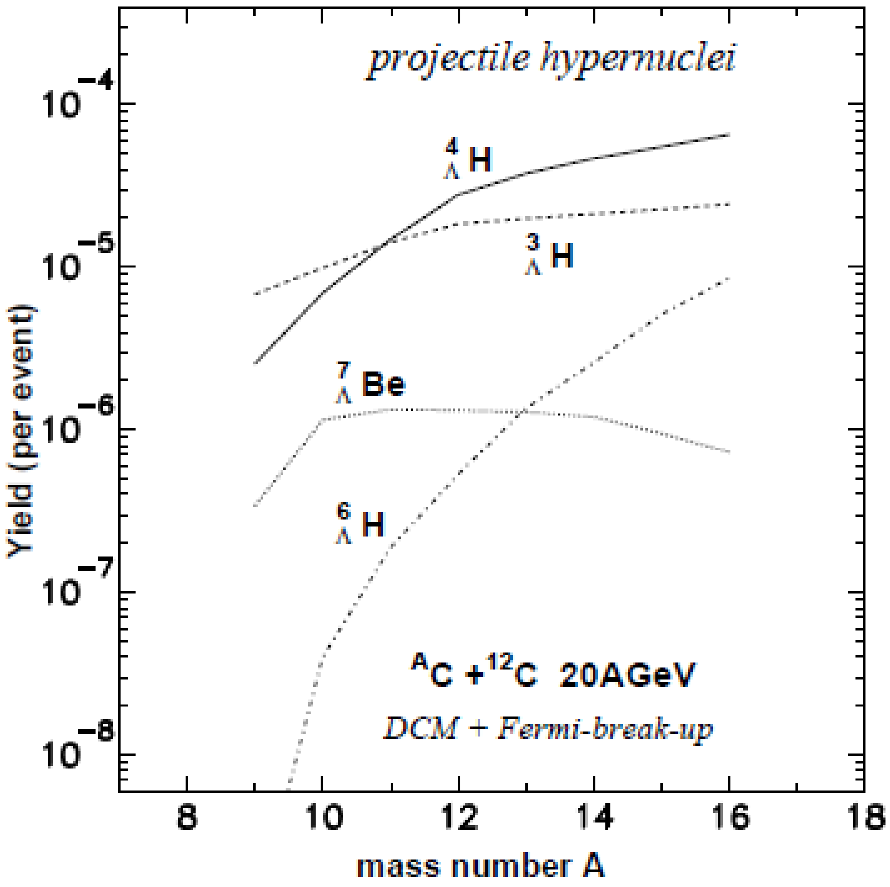


Fig. 3. Multifragmentation of an excited double-strange system with mass number 100 and charge 40, at temperature 4 MeV. Top panel – yield of fragments containing 0, 1, and 2 Λ hyperons. Bottom panel – effect of different mass formulae with strangeness on production of double hyperfragments [13].

A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

Production of light hypernuclei in relativistic ion collisions





One can use exotic neutron-rich and neutron-poor projectiles, which are not possible to use as targets in traditional hyper-nuclear experiments, because of their short lifetime. Comparing yields of hypernuclei from various sources we can get info about their binding energies and properties of hyper-matter.

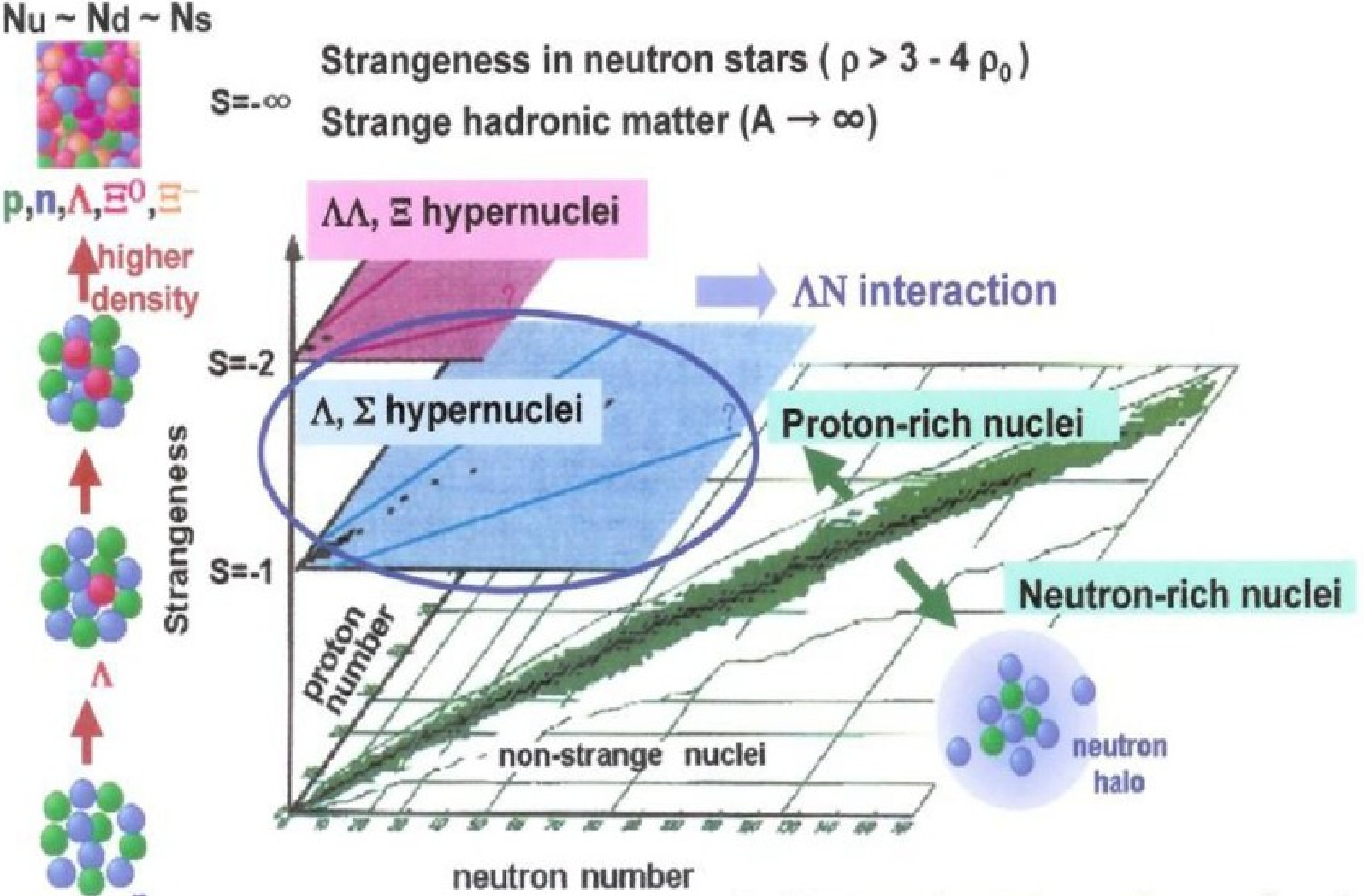
A.S.Botvina, K.K.Gudima, J.Pochodzalla, PRC 88, 054605, 2013

Conclusions

Collisions of relativistic ions and hadrons with nuclei are promising reactions for novel research of hypernuclei and exotic nuclei. These processes are theoretically confirmed with various models.

Mechanism of formation of hypernuclei in peripheral reactions:
Strange baryons (Λ, Σ, Ξ, …) produced in particle collisions are transported to the spectator residues and are captured in nuclear matter. These strange systems are excited and after decay of such systems hypernuclei of all sizes (and isospin), including exotic weakly-bound states, multi-strange nuclei, and those beyond the drip-lines can be produced.

Advantages over other reactions producing hypernuclei: there is no limit on sizes and isotope content of produced nuclei; probability of their formation is very high; a large strangeness can be deposited in nuclei.
After decay of such hypernuclei exotic normal nuclei can be obtained.
Correlations (unbound states) and lifetimes can be naturally studied.
EOS of hypermatter at subnuclear density can be investigated.



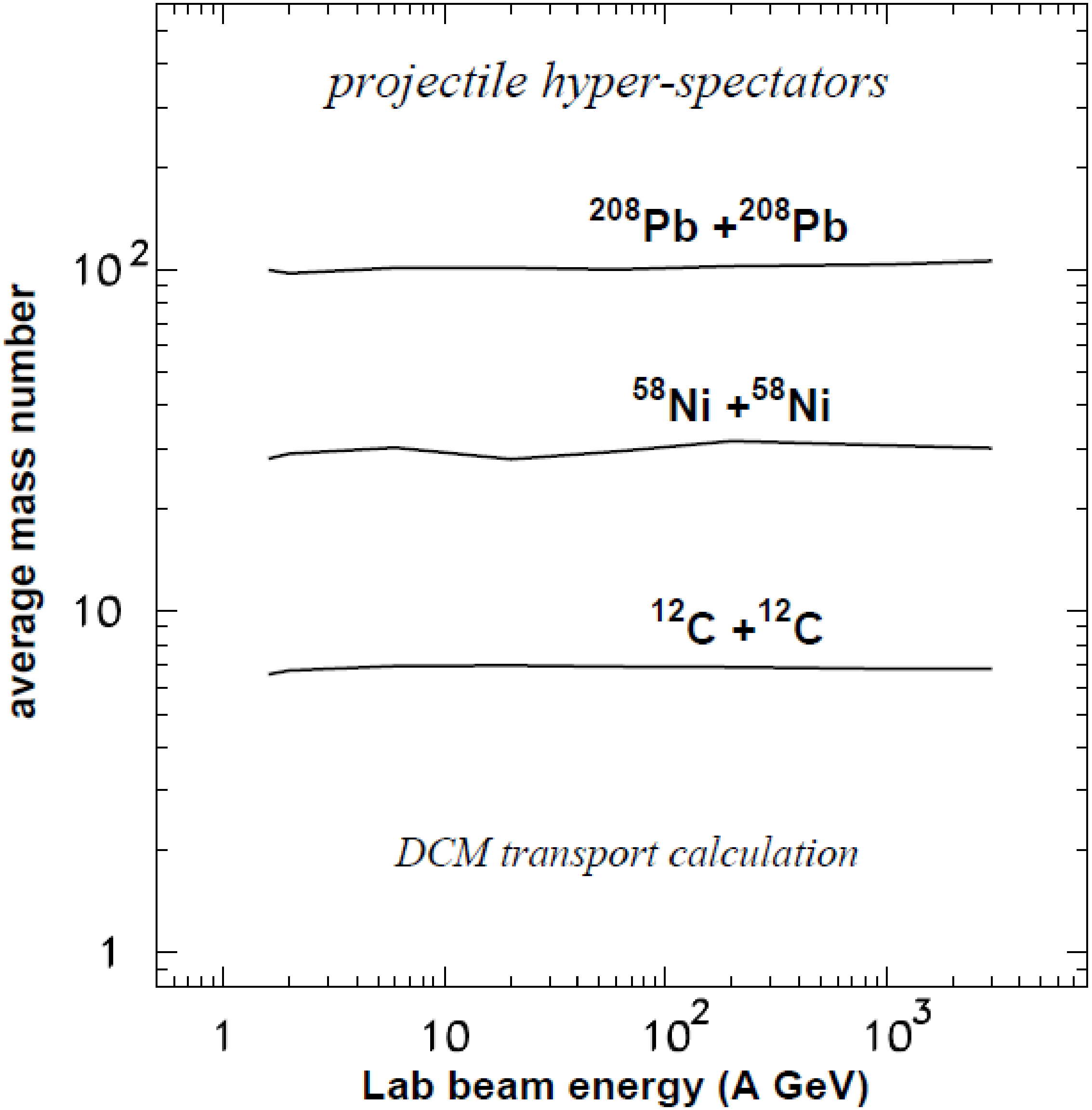
Strangeness in neutron stars ($\rho > 3 - 4\ \rho_0$)

Strange hadronic matter ($A \rightarrow \infty$)

3-dimensional nuclear chart

Yield of hypernuclei in peripheral collisions

A.S.Botvina, K.K.Gudima, J.Pochodzalla (PRC)



Description of elementary interactions in DCM transport code