Formation of hypernuclei in relativistic ion collisions

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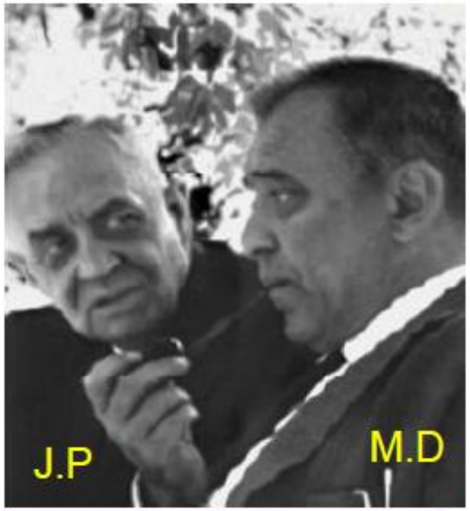
OAC *(Kolymbari, Chania), Crete, Greece*

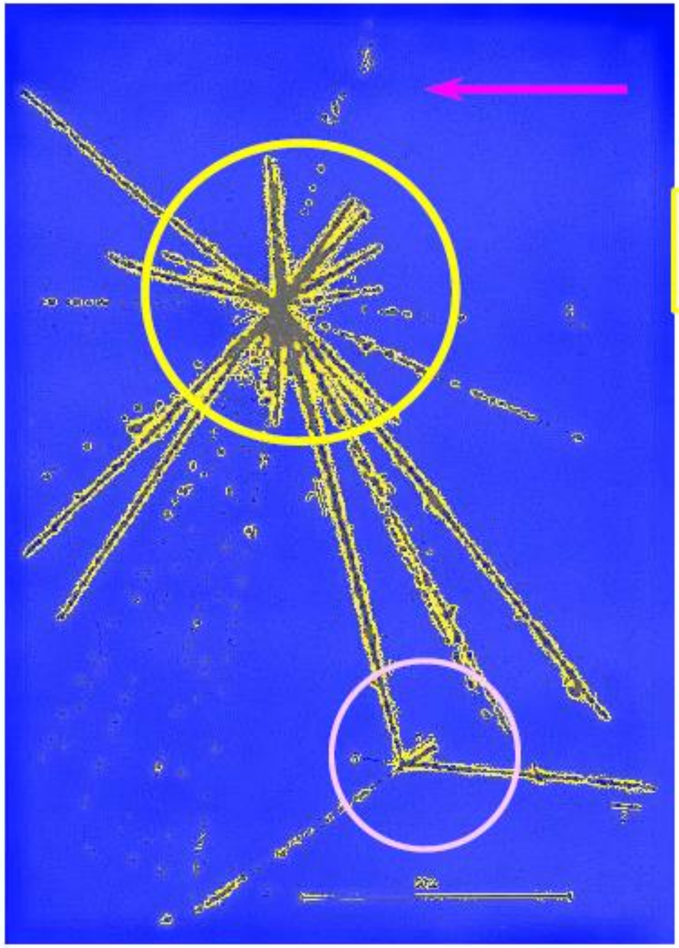
July 6-14 , 2016

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

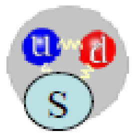
From the first star, 21 Tracks => $9\alpha + 11H + 1\ {}_{\Lambda}X$

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.**

Hyperons: Baryons with Strangeness

Lambda



Λ^0=(uds)

$m(\Lambda^0)$ = 1115.683 +/- 0.006 MeV

S = - 1

Quark	Symbol	charge (e)	Strangeness (S)
Up	(u)	2/3	0
Down	(d)	-1/3	0
Strange	(s)	-1/3	-1
Charm	(c)	2/3	0
Bottom	(b)	-1/3	0
Top	(t)	2/3	0

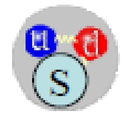
lifetimes of ~1×10^{-10} s

with the exception of Σ^0

whose lifetime is

shorter than 1×10^{-19} s

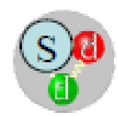
Sigma



Σ^0=(uds)

$m(\Sigma^0)$ = 1192.642 +/- 0.024 MeV

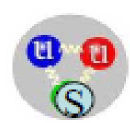
S = - 1



Σ^-=(dds)

$m(\Sigma^-)$ = 1197.449 +/- 0.030 MeV

S = - 1

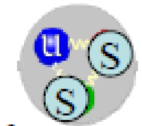


Σ^+(uus)

$m(\Sigma^+)$ =1189.37 +/- 0.07 MeV

S = - 1

Cascade or Xi



Ξ^0=(uss)

$m(\Xi^0)$ = 1314.86 +/- 0.2 MeV

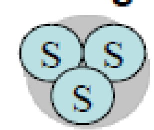
S = - 2

Ξ^-=(dss)

$m(\Xi^-)$ = 1321.71 +/- 0.07 MeV

S = - 2

Omega



Ω^-=(sss)

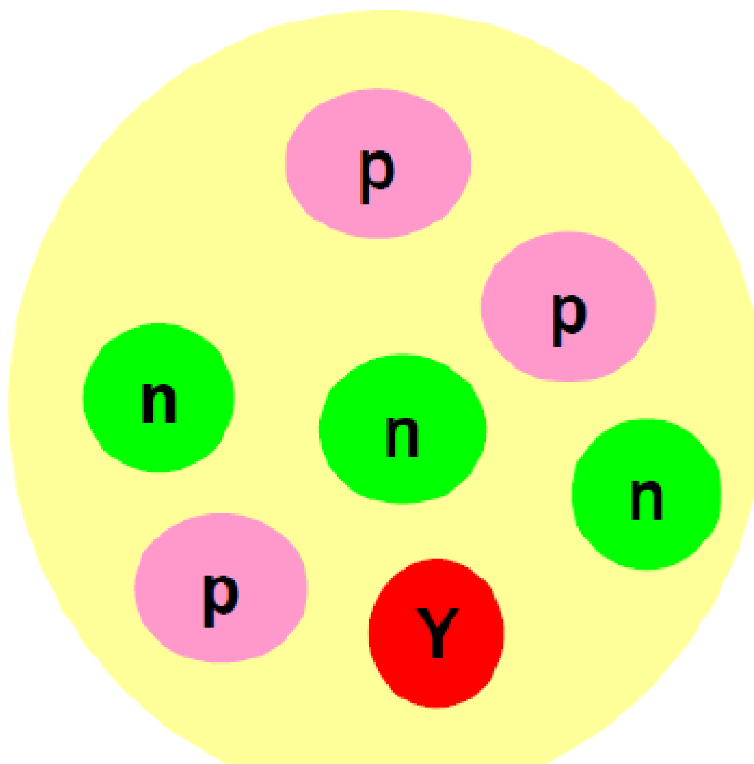
$m(\Omega^-)$ = 1672.45 +/- 0.29 MeV

S = - 3

lifetime of ~ 8.2×10^{-11} s

Hypernucleus: Hyperons Bound in Nuclei

Hypernucleus: consists of nucleons (n, p) + hyperon (Y)



Notation:

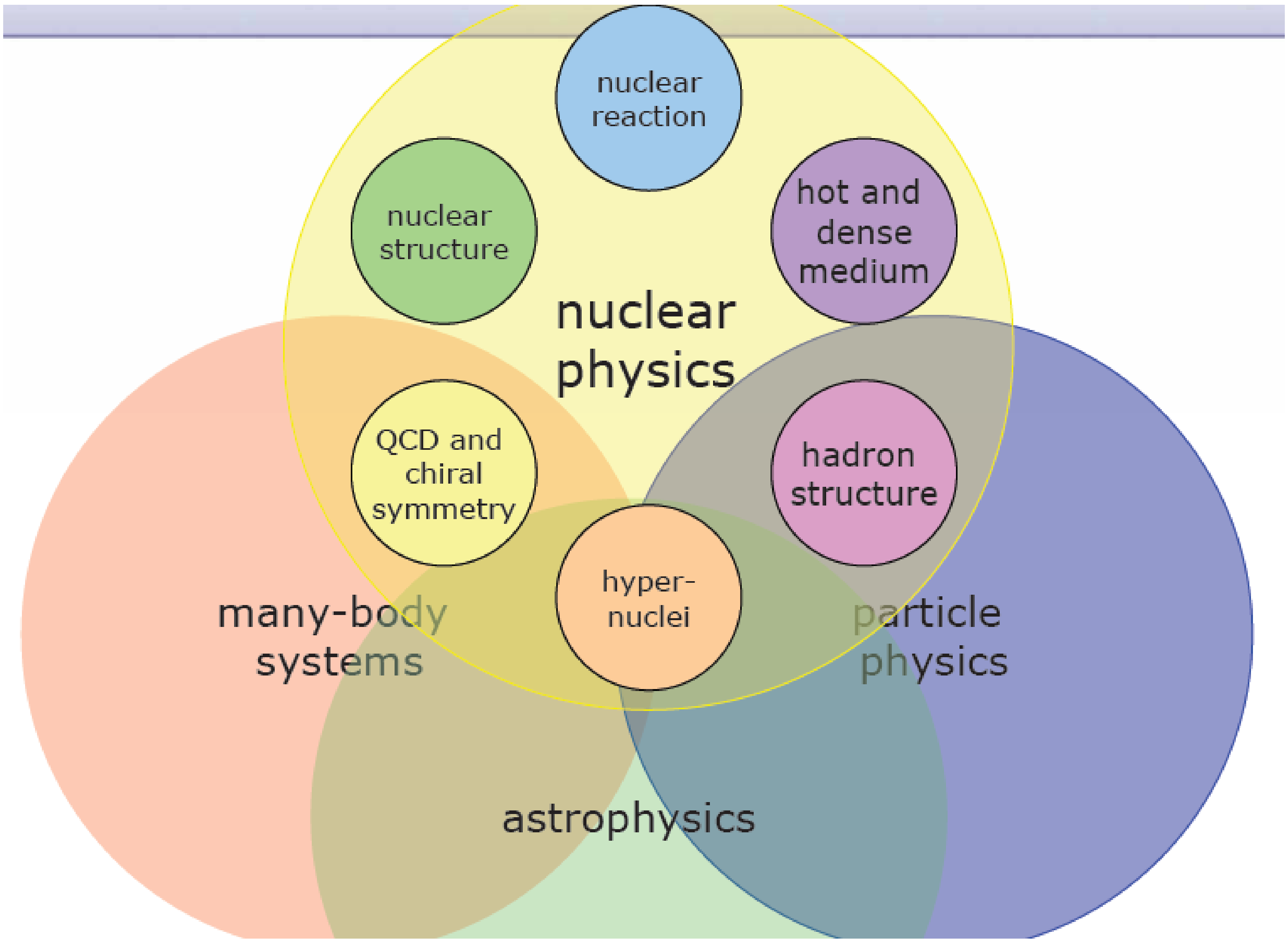
$${}^{A}_{Y}Z$$

Y = Hyperon

$Z = Z_p + (N_Y \cdot q_Y)$

$A = N_n + N_p + N_Y$

Hypernuclei within the research fields



Why hypernuclei ?

QCD theory development

Micro-laboratory with protons, neutrons, and hyperons;

YN & YY interaction can be investigated (strangeness sector of hadronic EoS); ...

Astrophysics

Hyperons are important for cosmology, physics of neutron stars , "strange stars", black holes, ...

Nuclear physics

Phenomenology: extention of nuclear charts into strangeness, exotic nuclei, limits of nuclear stability

Structure theory -- new degree of freedom for investigating interaction of baryons in nuclei (hyperons - without Pauli blocking)

Reaction theory – new probe for fragmentation of nuclei, phase transitions and EoS in hypermatter and finite hypernuclei

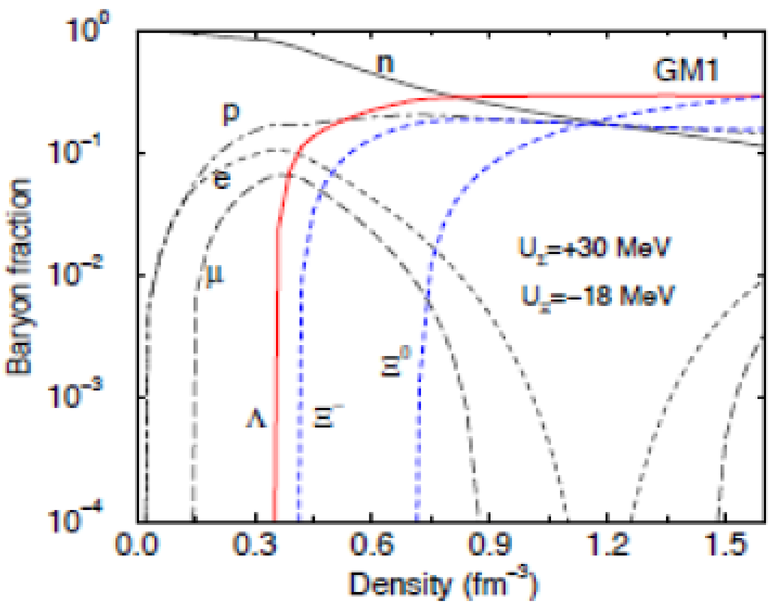
5 decades of hyperons in neutron stars

NEUTRON STAR MODELS

A. G. W. Cameron
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
Received June 17, 1959

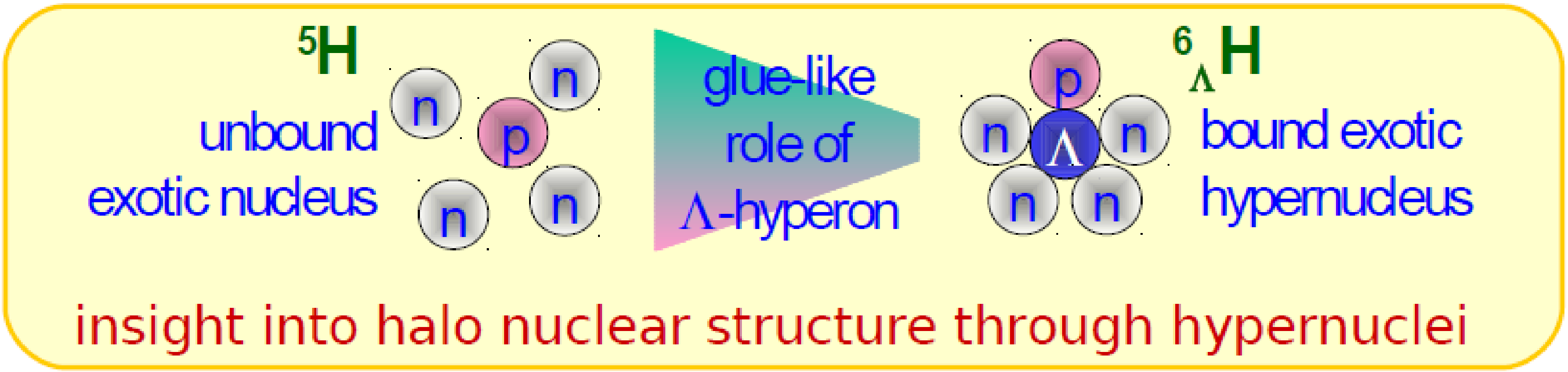
Another reason why the writer has not taken into account complications inherent in using a relativistic equation of state is that no such things as pure neutron stars can be expected to exist. The neutrons must always be contaminated with some protons and sometimes with other kinds of nucleons (hyperons or heavy mesons).

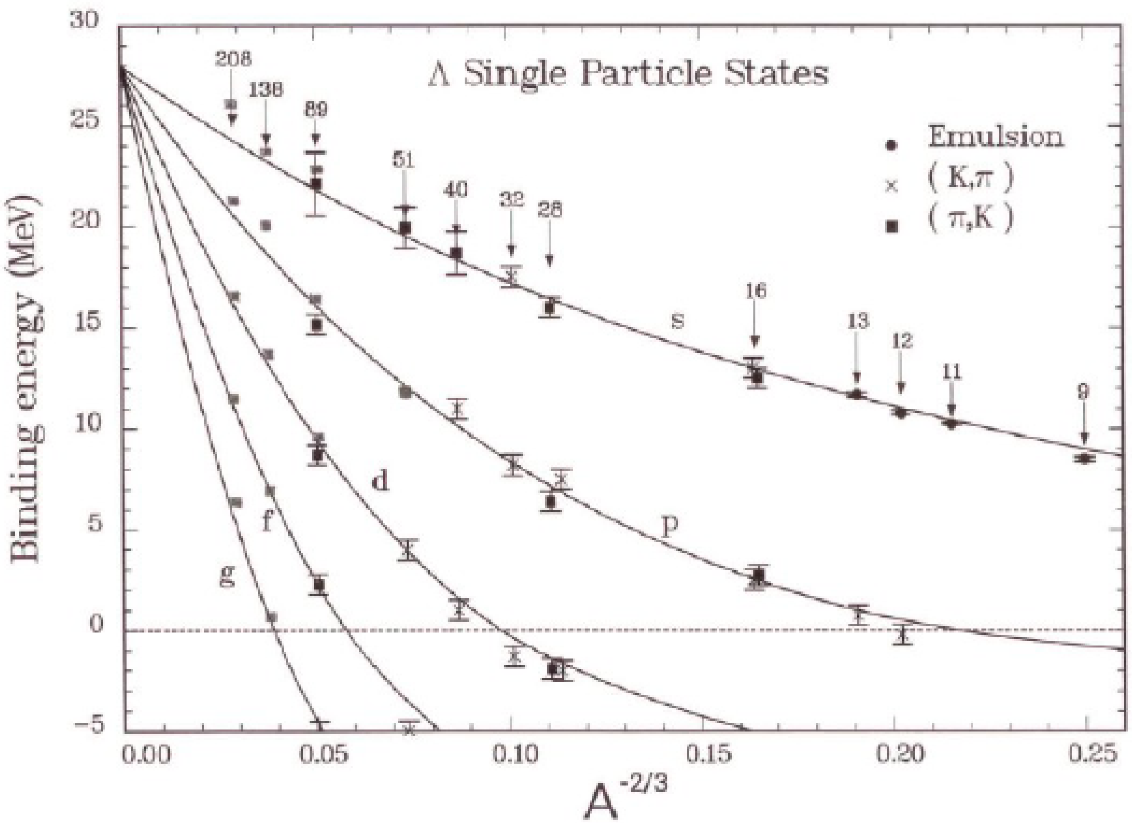
Alastair G.W. Cameron, Astrophysical Journal, vol. 130, p.884 (1959)



J. Schaffner-Bielich, Nucl. Phys. A804 (2008) 309

n-rich hypernucleus is a doorway to n-star

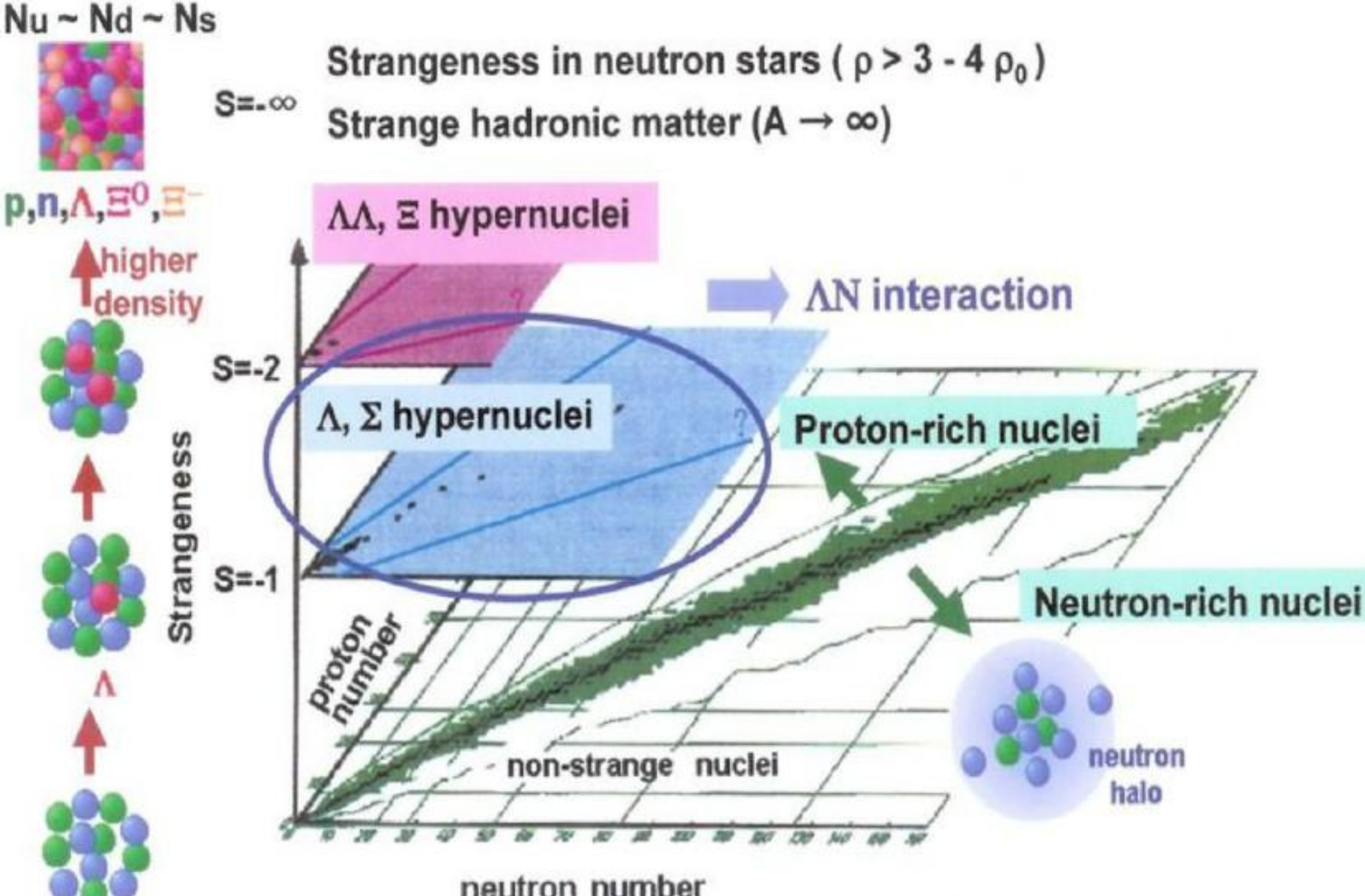




Hyperon can be put deep inside – no Pauli blocking

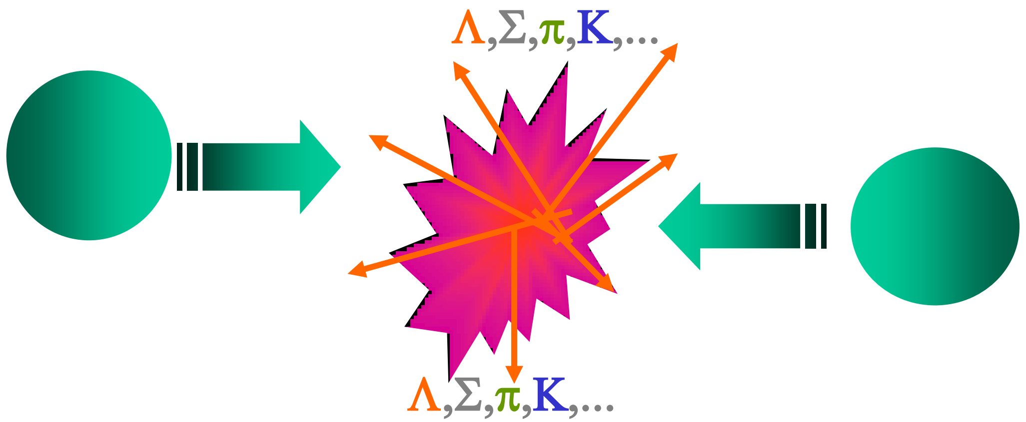
In heavy nuclei effects of the additional hyperon binding will be larger:

Production of nuclei beyond the drip lines



3-dimensional nuclear chart

Relativistic collisions of hadrons and ions



Production of hypernuclei in central HI collisions:

- Production of strange particles and hyperons in hadron collisions,
- Rescattering and coalescence/capture of produced baryons.

Central collisions of relativistic ions

Production of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ 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

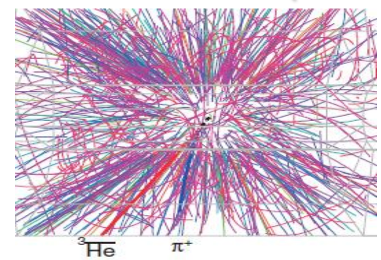
N_{event}	13.5×10^{9}	$^{3}_{\Lambda}H$
N_{count}	1220±854	

STAR collaboration (RHIC):

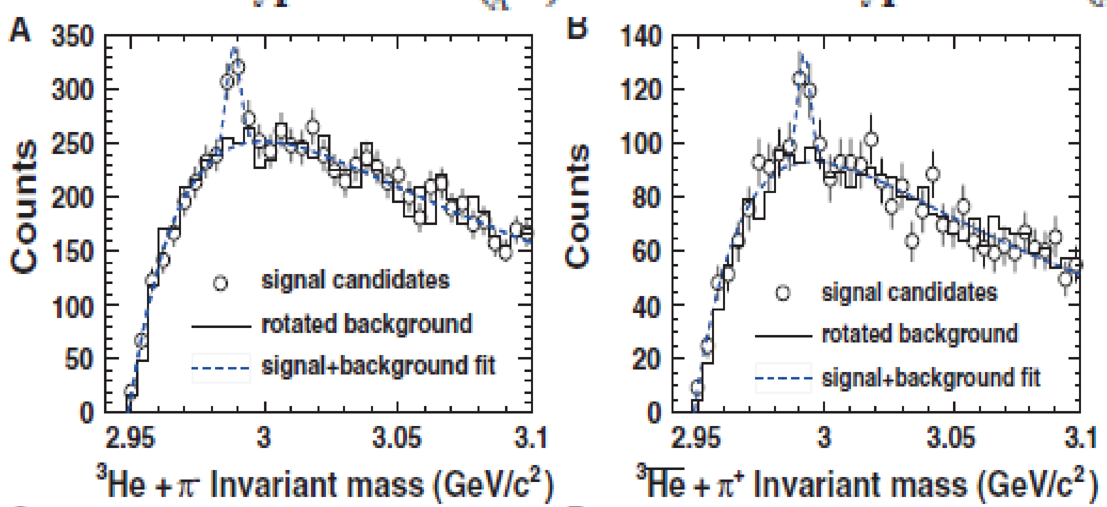
Science, 238 (2010) 58

Au + Au collisions at 200 A GeV

gas-filled cylindrical Time Projection Chamber



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



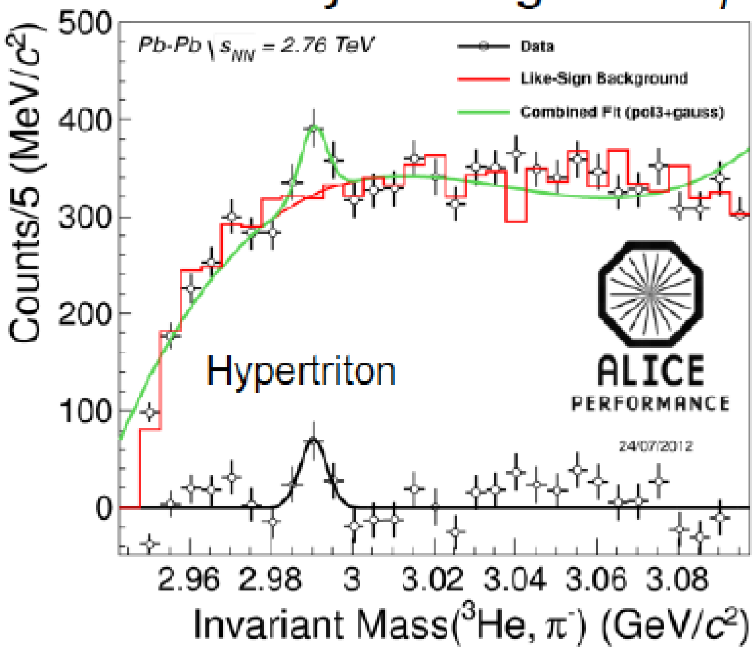
B. Doenigus et al., Nucl. Phys. A904-905 (2013) 547c

ALICE's observation for (anti-)hypertriton

Hypertriton

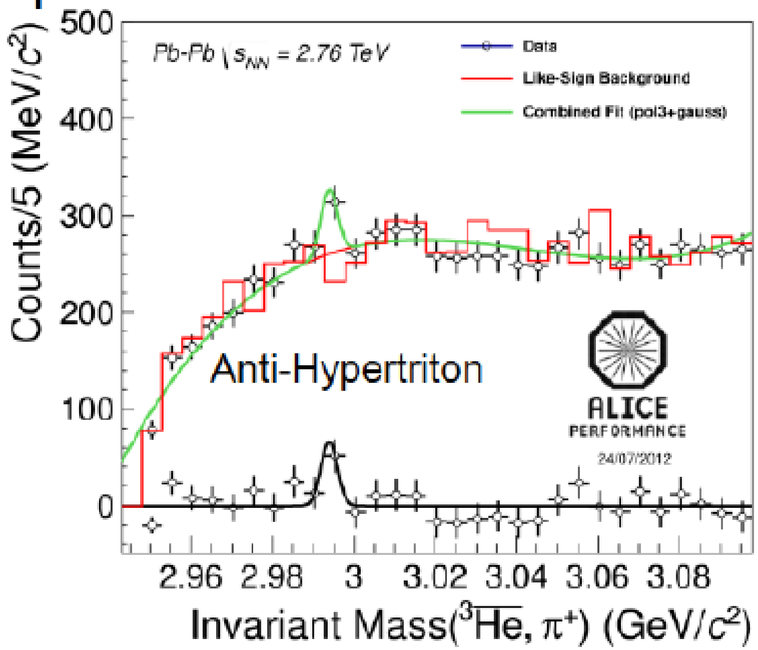
Signal of the hypertriton from the 2011 run

→ currently working on the p_T spectra extraction



μ = (2.990 ± 0.001) GeV/c^2

σ = (3.35 ± 0.7)x10^{-3} GeV/c^2



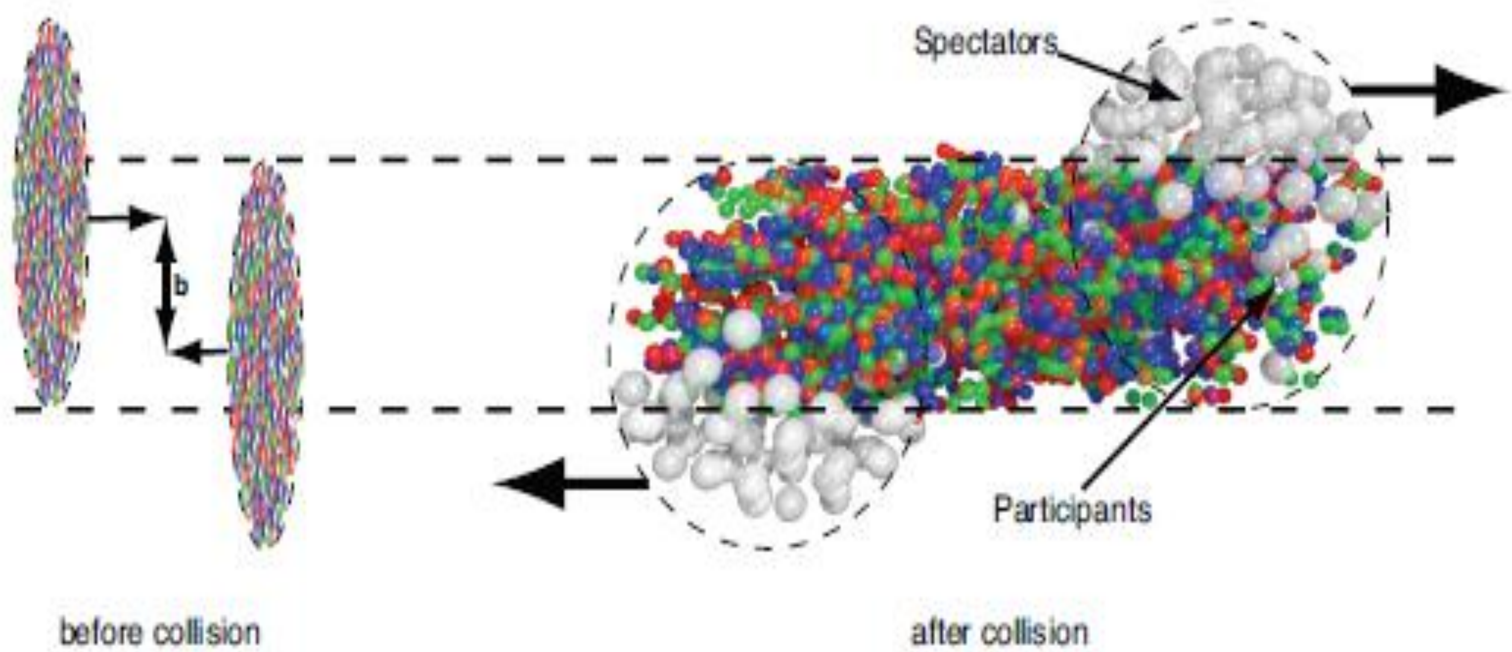
μ = (2.993 ± 0.001) GeV/c^2

σ = (2.00 ± 1.2)x10^{-3} GeV/c^2

UrQMD PHSD DCM GiBUU

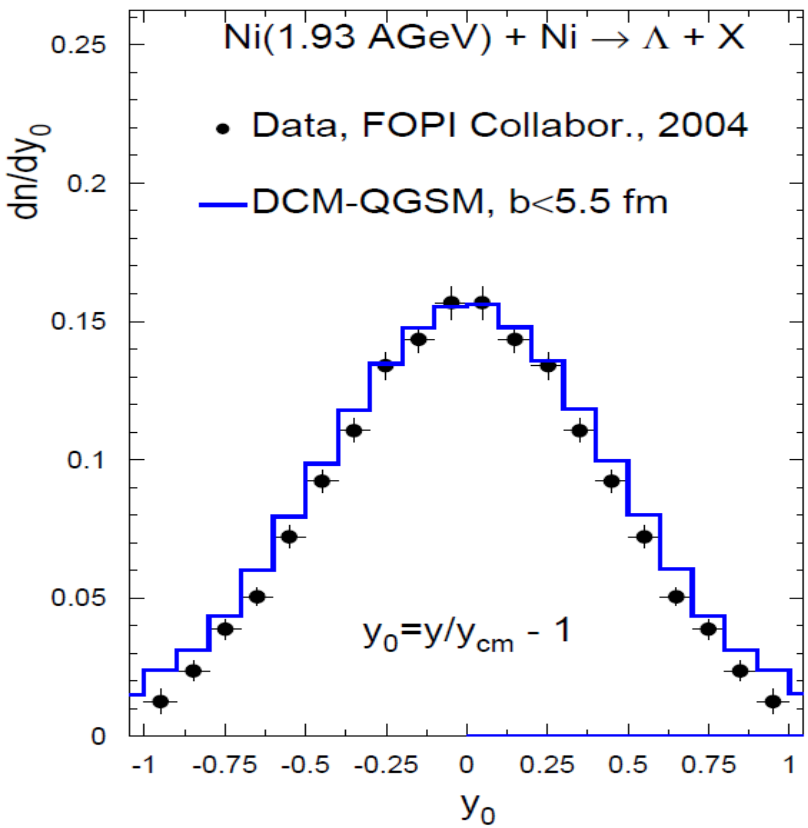
Production of hypermatter in peripheral HI and hadron collisions

- Production of strange particles and hyperons by "participants",
- Secondary production and rescattering of hyperons,
- Coalescence or capture of produced baryons by excited "spectators".



Peripheral collisions. All transport modes predict similar picture: Hyperons can be produced can be produced at all rapidities, in participant and spectator kinematic regions.

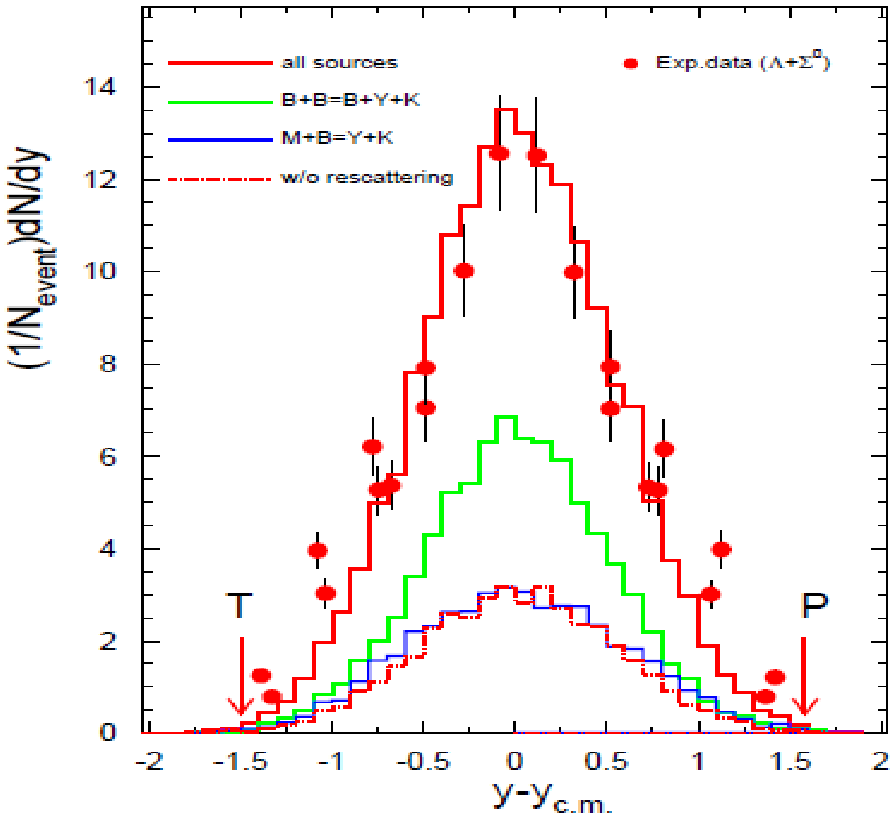
Wide rapidity distribution of produced Λ!



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

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

Au(11AGeV/c)+Au



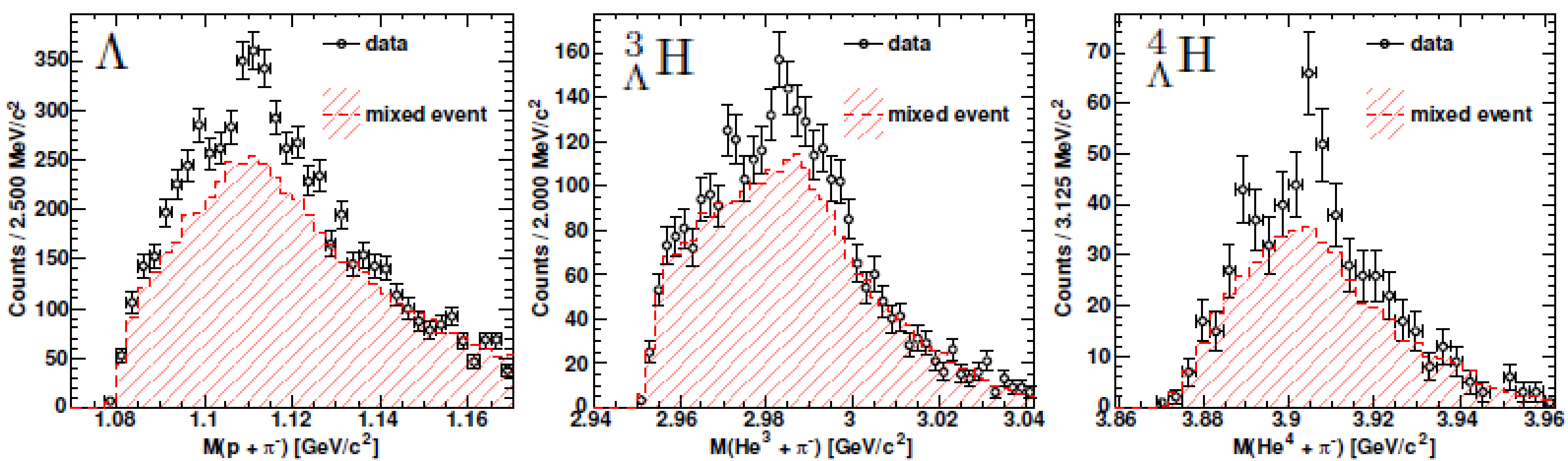
Production of hypernuclei in peripheral HI collisions: The HypHI project at GSI

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

Λ-hyperon lifetime in very heavy hypernuclei produced in the $p+U$ interaction

The recoil shadow method for the detection of fission fragments has been used to investigate delayed fission of very heavy Λ hypernuclei produced in the p-U interaction at the projectile energy of 1.5 GeV. From the measured distribution of delayed fission events in the shadow region and the calculated momenta of hypernuclei leaving the target the lifetime of the Λ hyperon in very heavy hypernuclei was determined to be $\tau = 2.40 \pm 60$ ps. The comparison of the number of delayed fission events with that of the prompt events leads to an estimation of the cross section for the production of Λ hypernuclei in $p+U$ collisions at 1.5 GeV of $\sigma_{Hv} = 150^{+150}_{-80}$ μb. [S0556-2813(97)04506-8]

H. Ohm et al., PRC 55 (1997) 3062

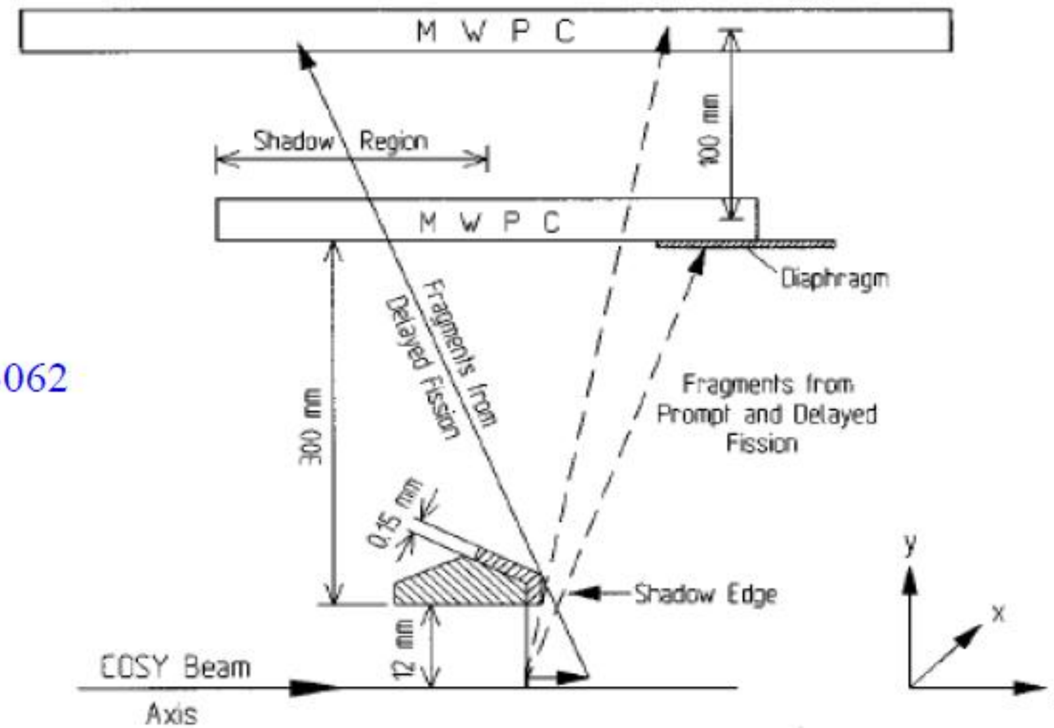


FIG. 1. Schematic presentation of the experimental setup. The thickness of the target holder is enhanced in the drawing to show the details. The real distances are given.

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, et al. …
… *Phys.Lett. B663(2008)197, Phys.Lett. B675(2009)297*

DCM /INC+QGSM (+SMM) JINR version : K.K.Gudima, V.D.Toneev et al.,
Nucl. Phys.A400(1983)173, ... Phys. Rev. C84 (2011) 064904

PHSD model E. Bratkovskaya, W. Cassing ... *Phys. Rev. C78 (2008) 034919*

UrQMD approach: S.A. Bass et al., *Prog. Part. Nucl. Phys. 41 (1998) 255.*
(Frankfurt Uni) 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—>n+Λ+K^+, and secondary meson interactions, like π+p→Λ+K^+). Rescattering of hyperons is important for their capture by spectators. Capture of Λ takes place in the nuclear potential well (approximately 2/3 of the nucleon potential).

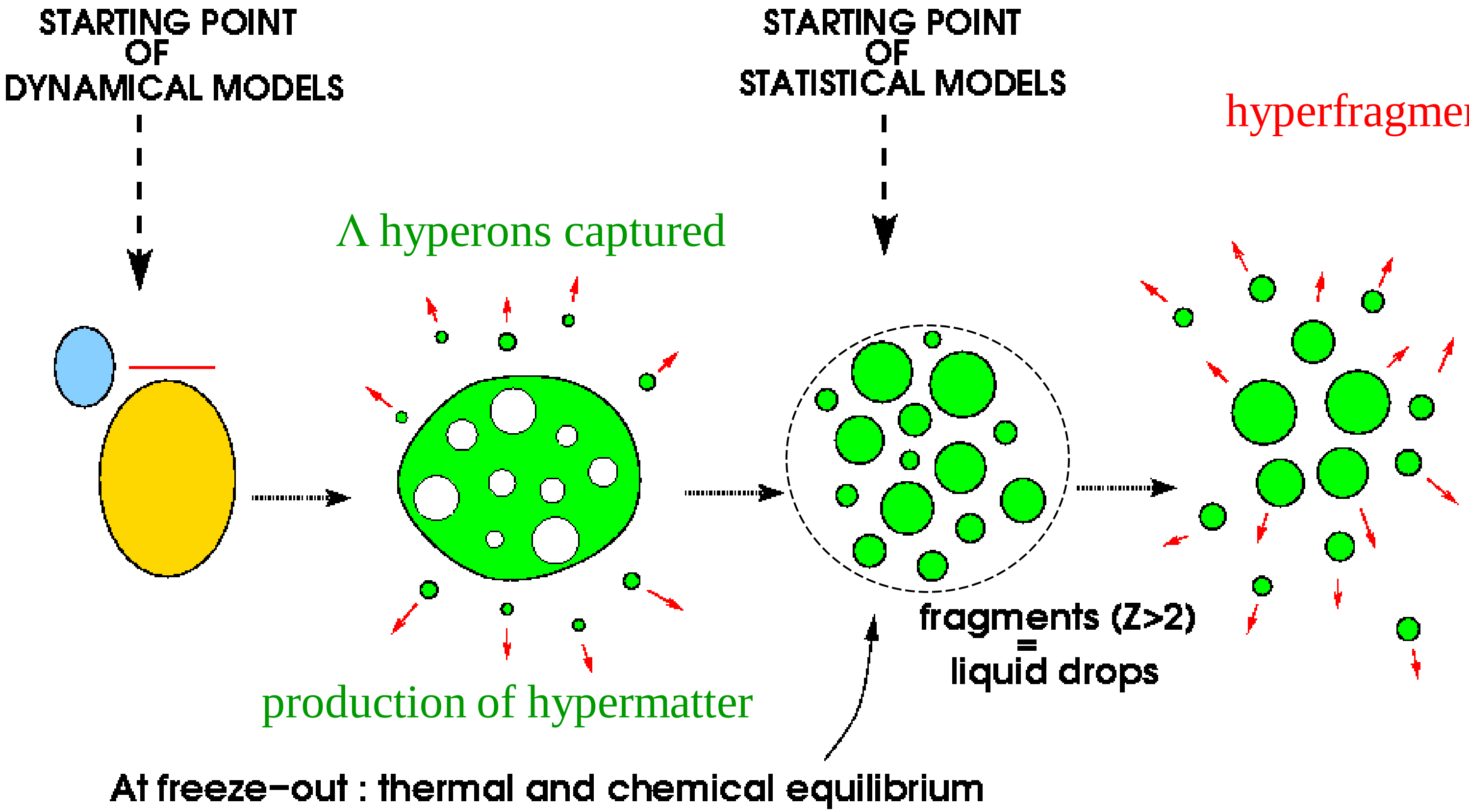
A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

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

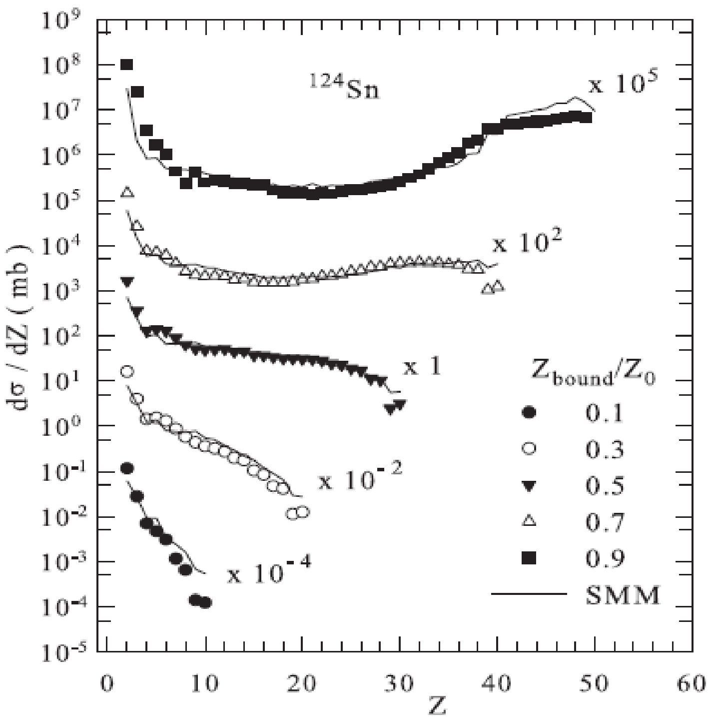


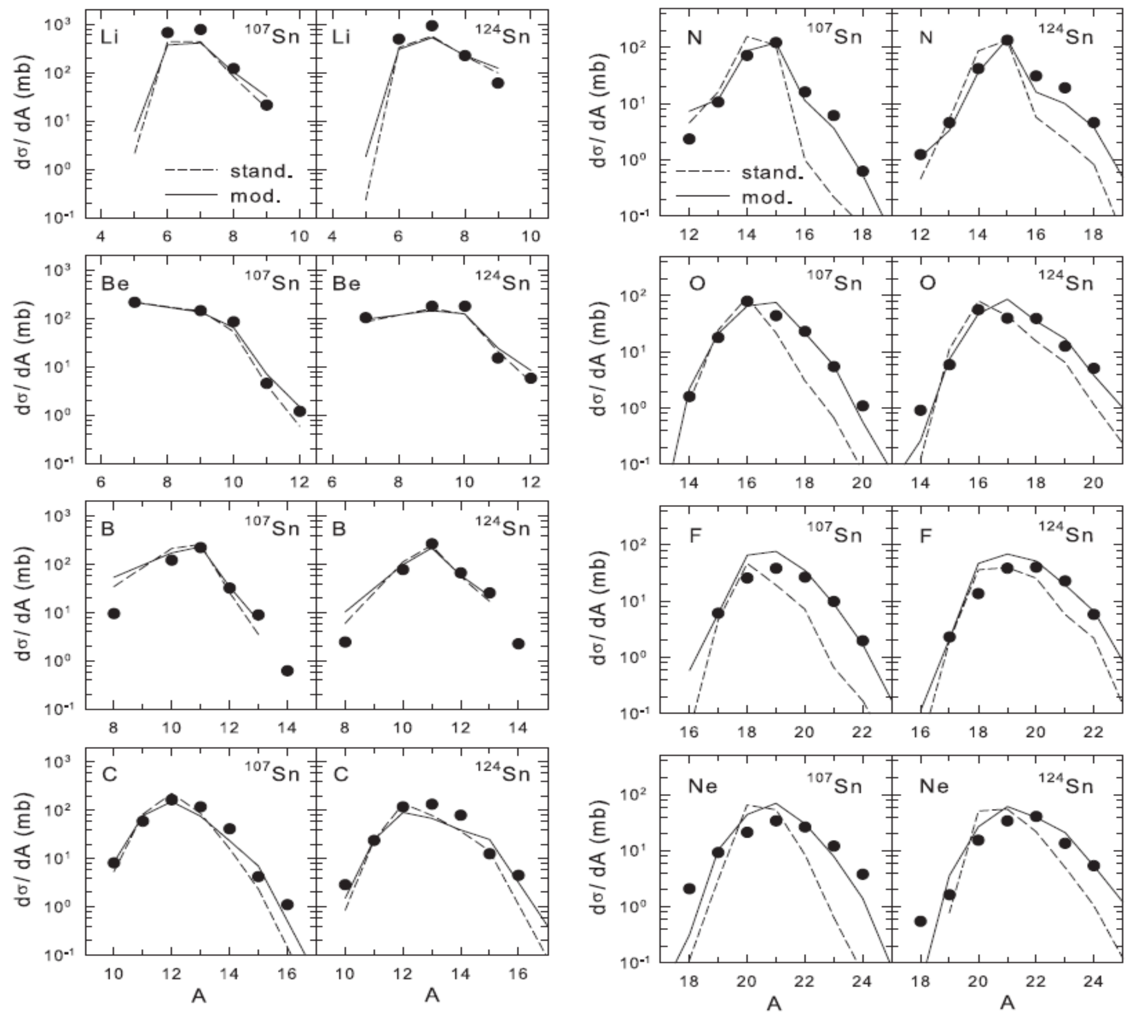
R.Ogul et al. PRC **83,** 024608 (2011) **ALADIN@GSI**

Isospin-dependent multifragmentation of relativistic projectiles

124,107-**Sn**, 124-**La** (600 A MeV) + **Sn** → projectile (multi-)fragmentation

Very good description is obtained within Statistical Multifragmentation Model, including fragment charge yields, isotope yileds, various fragment correlations.





Statistical (chemical) equilibrium is established at break-up of hot projectile residues ! In the case of strangeness admixture we expect it too !

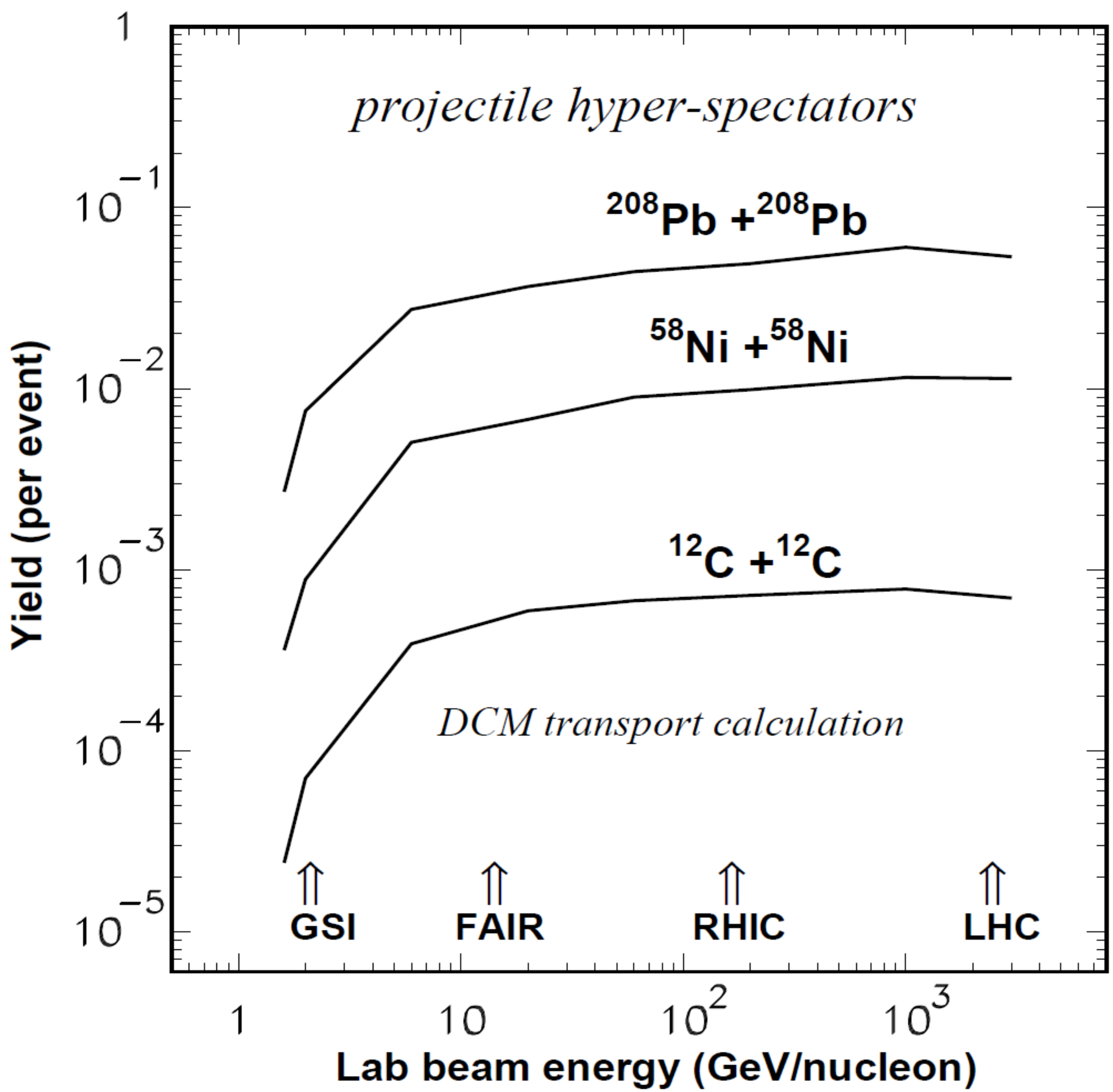
Yield of hypernuclei in peripheral collisions

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 expe-riments).

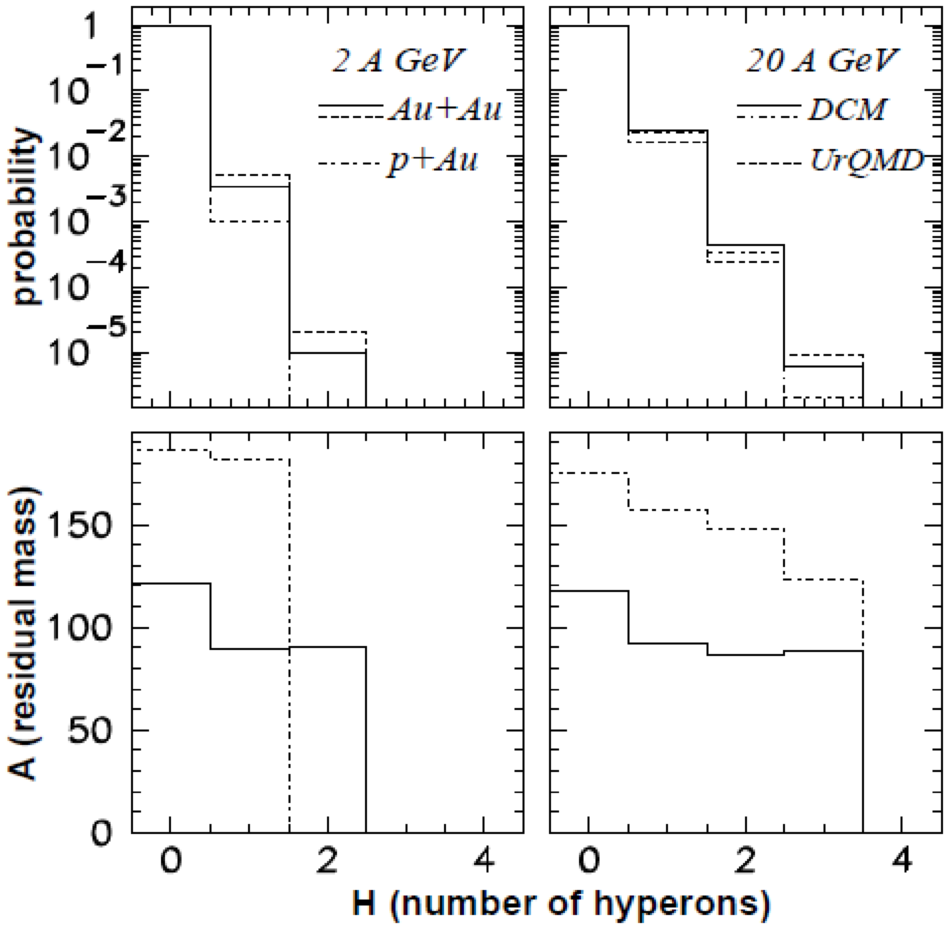


A.S.Botvina, K.K.Gudima, et al. PRC 84 (2011) 064904

Capture of many hyperons in HI is a natural process

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



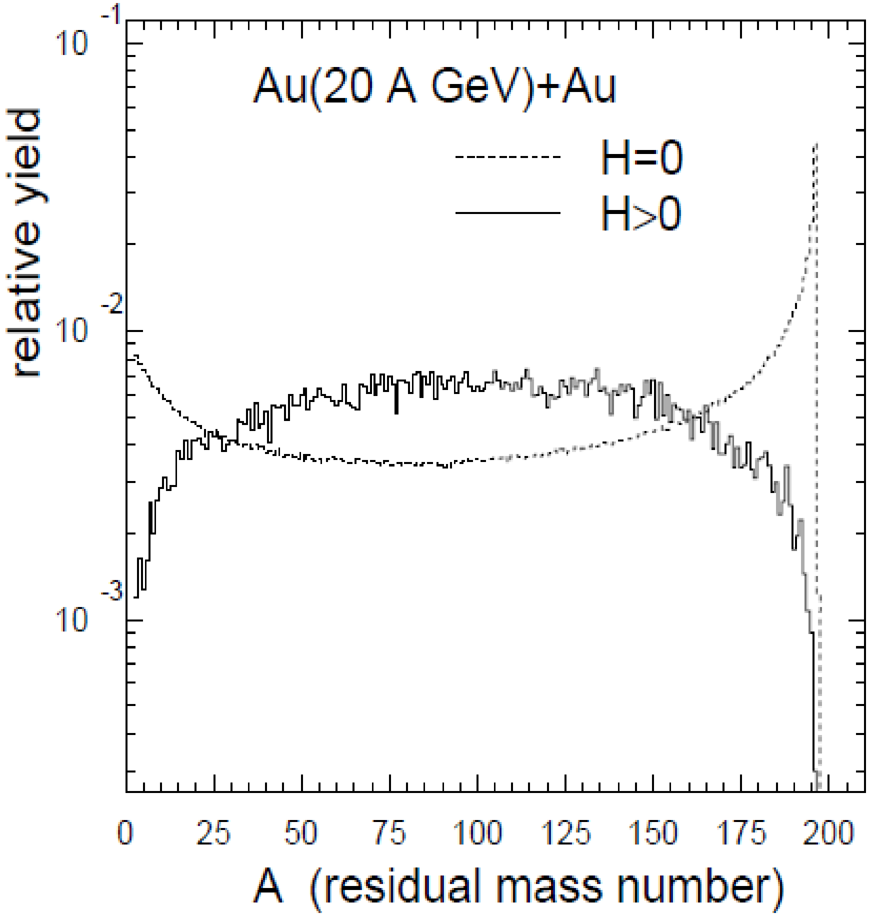
Integrated over all impact parameters

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)

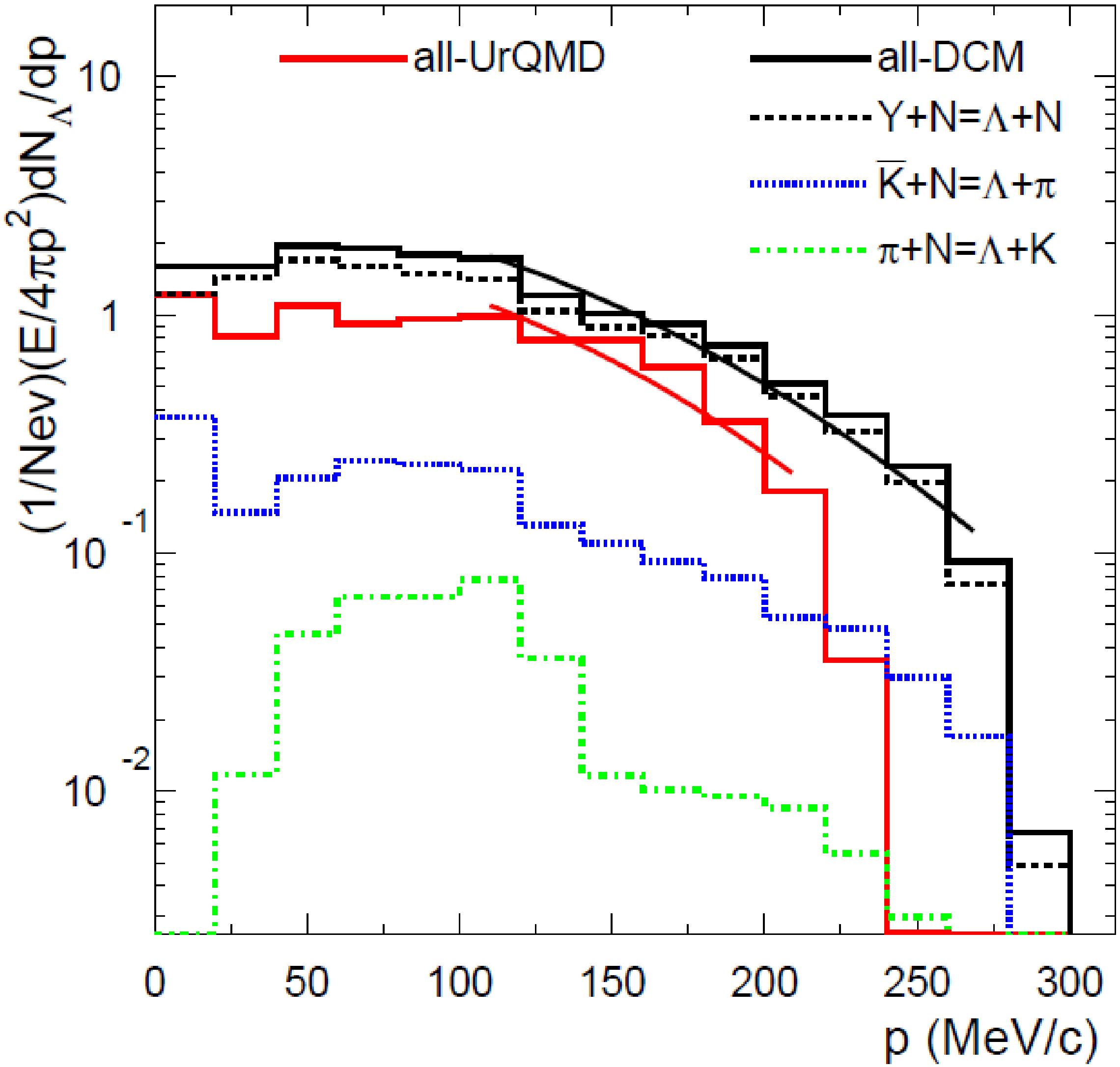
Coalescence of baryons

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.

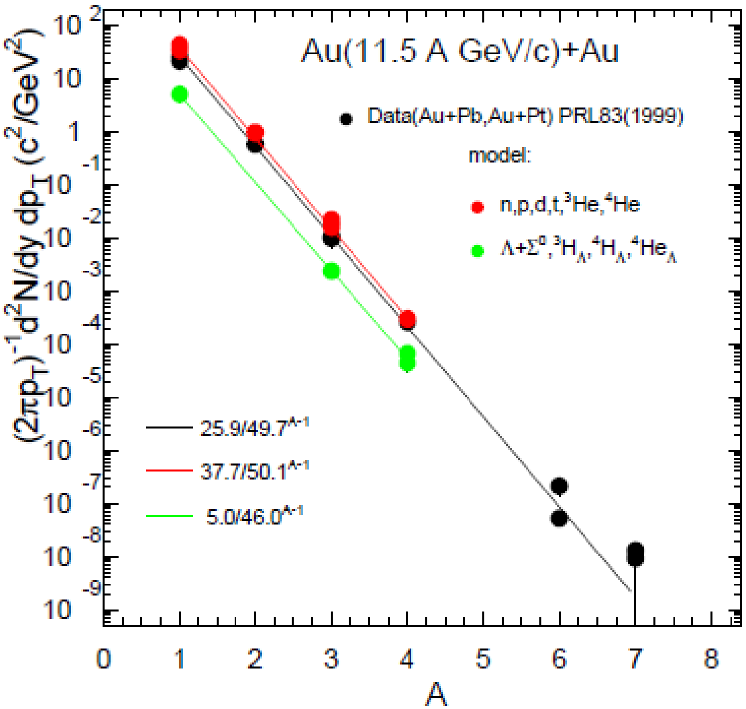
Combination of transport UrQMD and HSD models with CB:

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

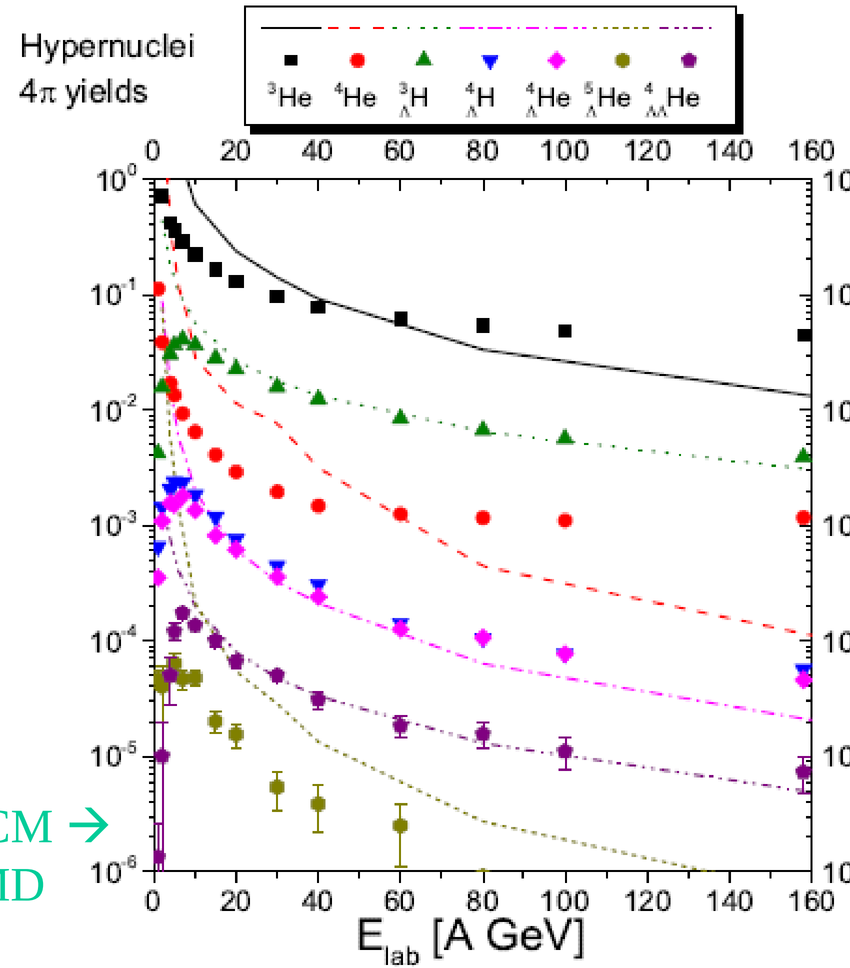
Production of light nuclei in central collisions : Au+Au

DCM and UrQMD calculations - J.Steinheimer et al., Phys. Lett. B**714**, 85 (2012)

DCM versus experiment :
coalescence mechanism



Also predictions for hybrid approach :
UrQMD + thermal hydrodynamics

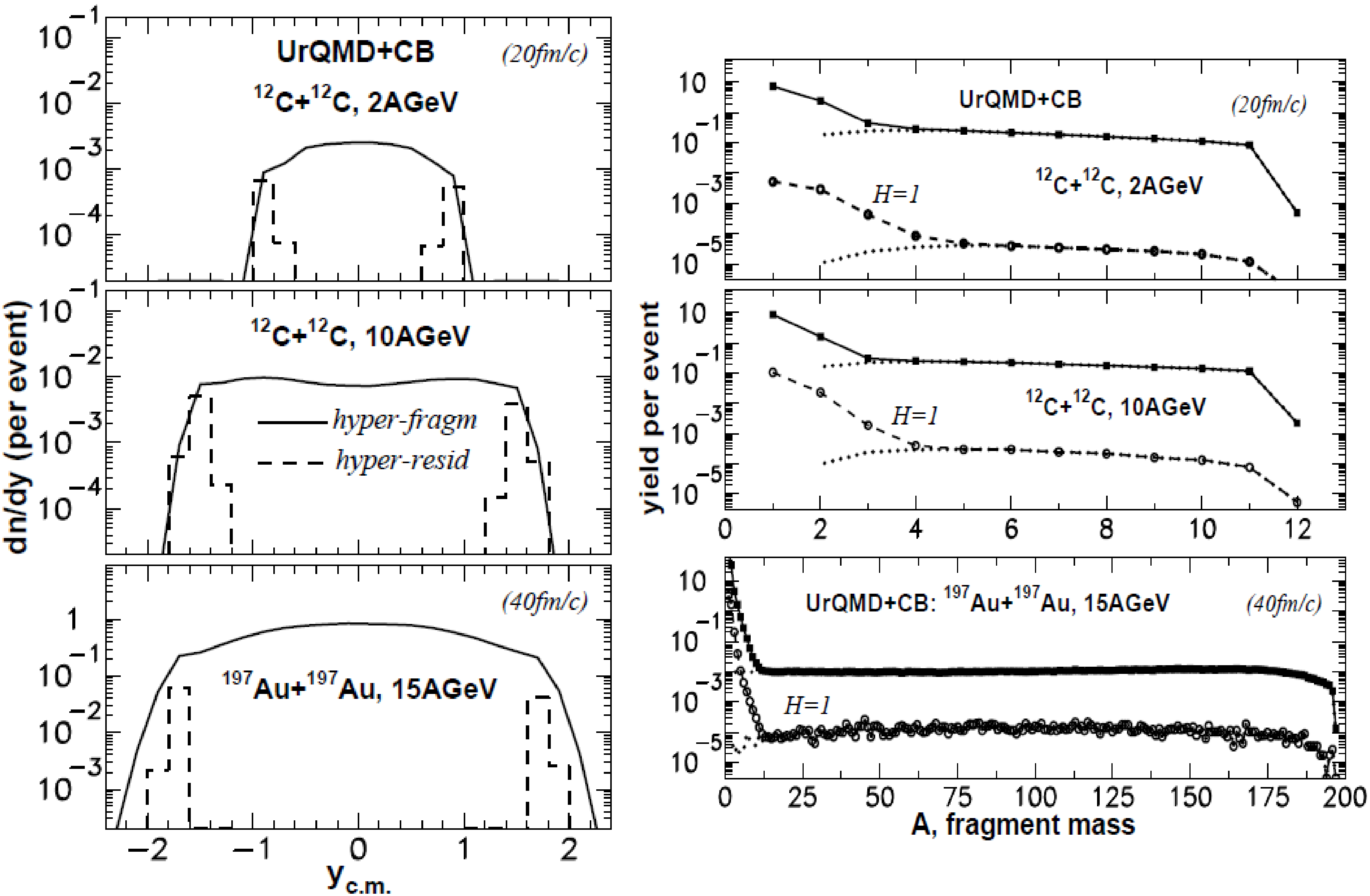


It is not possible to produce big nuclei !

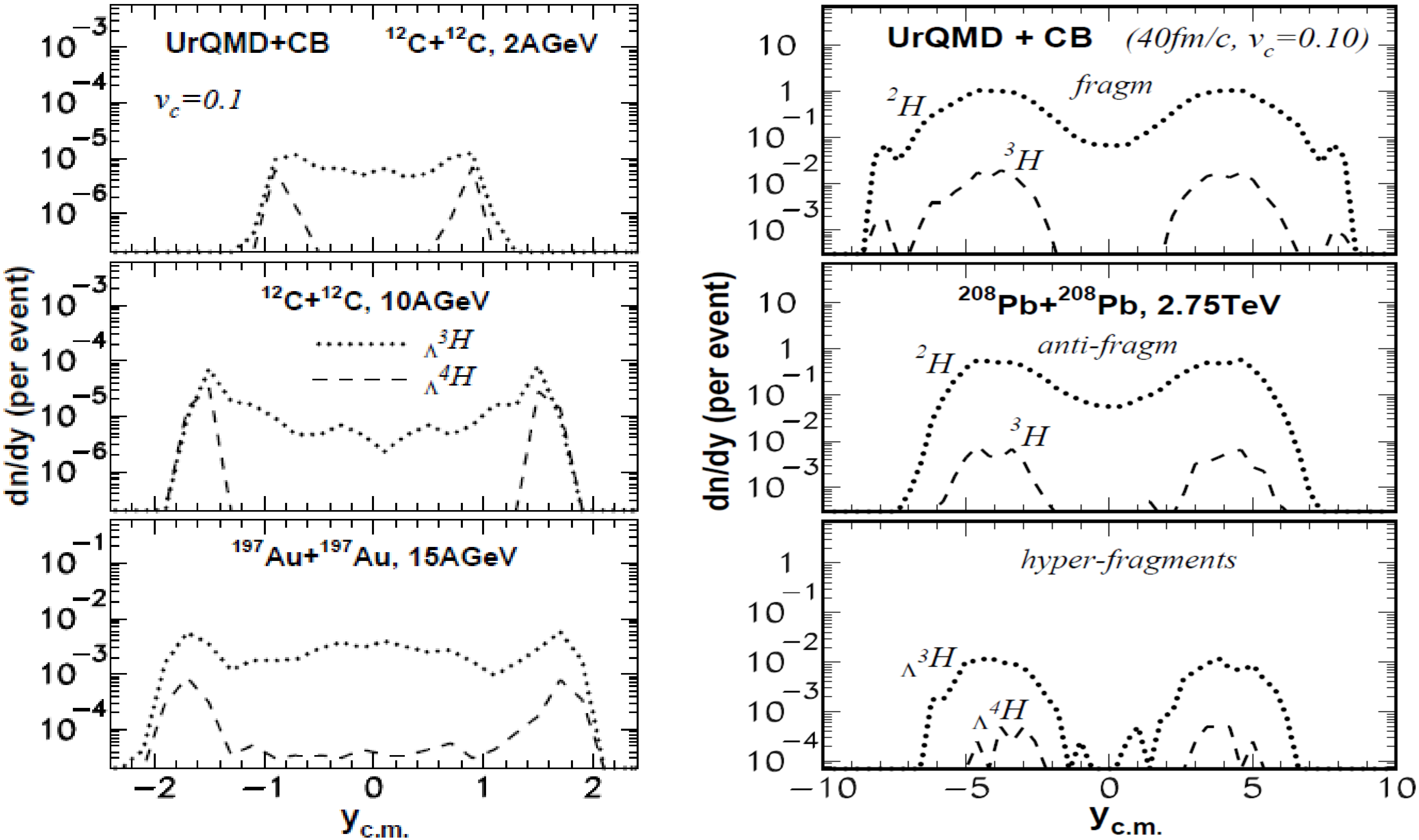
Symbols - DCM →
Lines - UrQMD

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

normal fragments, hyper-fragments, hyper-residues

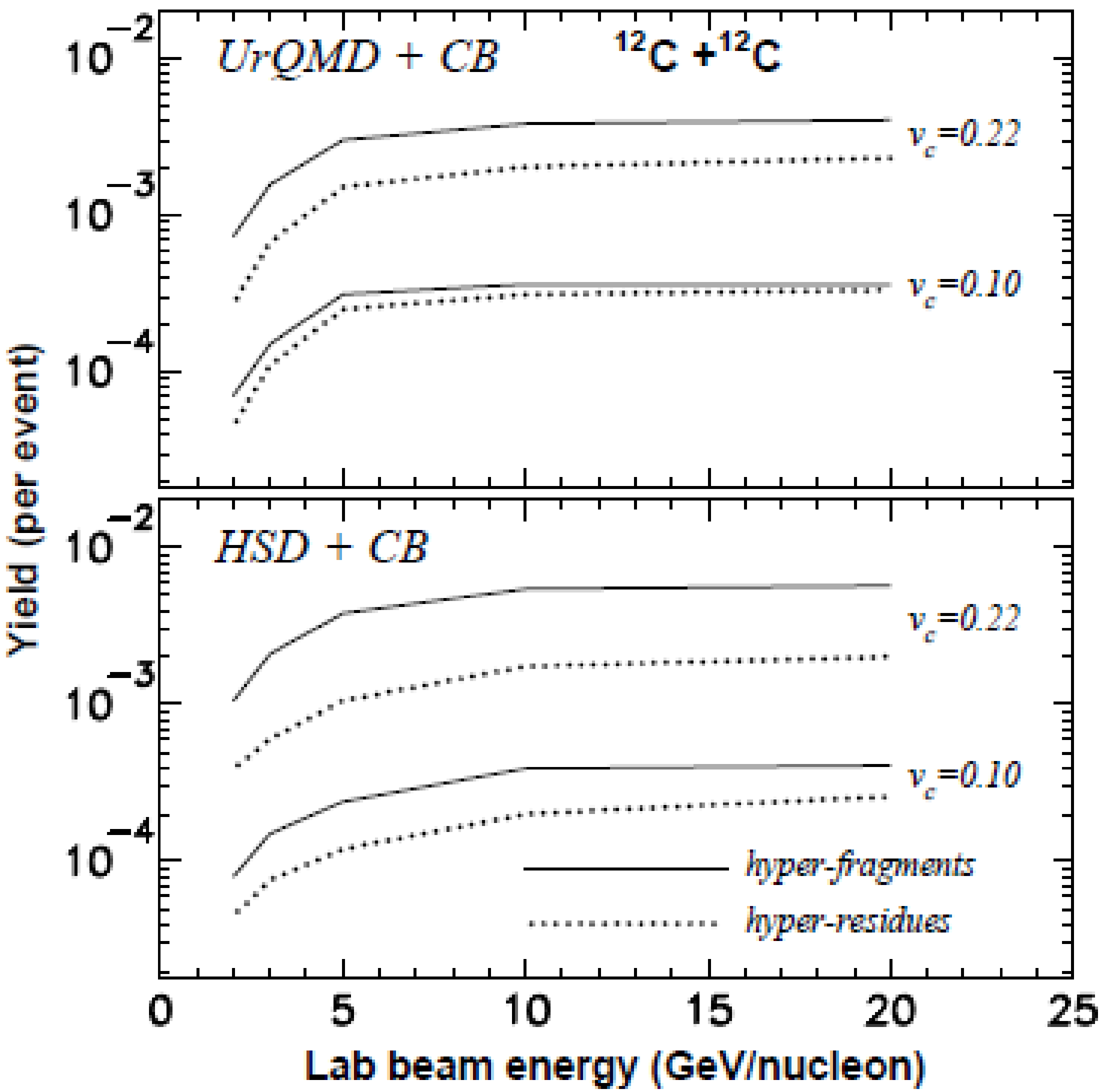


Because of the secondary interactions the maximun of the fragments production is shifted from the midrapidity. Secondary products have relatively low kinetic energies, therefore, they can produce clusters with higher probablity (even for light fragments/hyper-fragments).



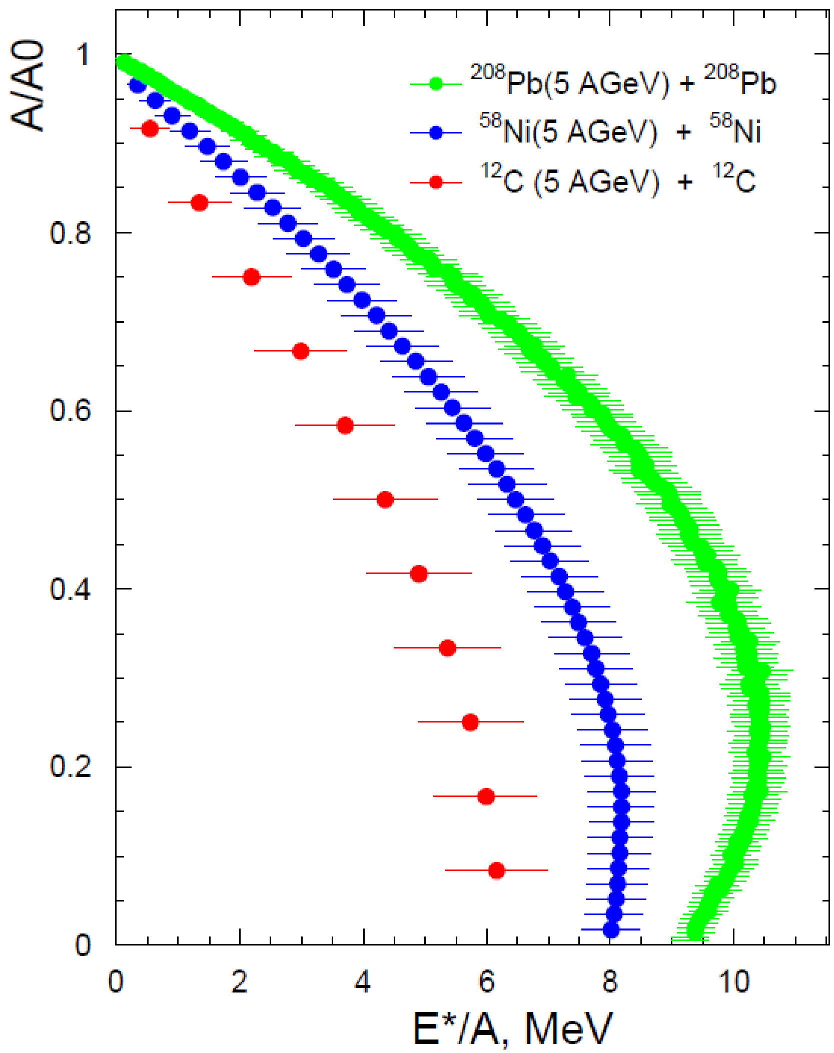
A.Botvina, J.Steinheimer, E.Bratkovskaya, M.Bleicher, J.Pochodzalla, PLB742(2015)7

Transport models are consistent (UrQMD, HSD)



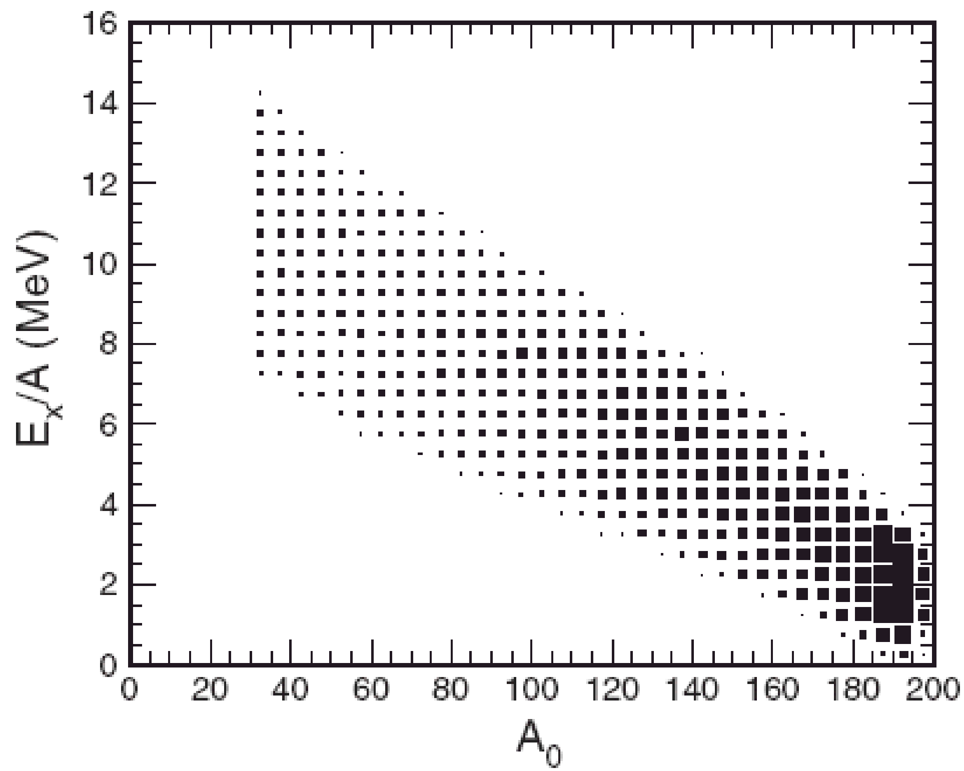
Excitation energies of the residual nuclei

DCM



ALADIN analysis: Au+Au at 1 A GeV data (GSI)

H.Xi et al.,
Z.Phys. A359(1997)397



De-excitation of hot light hypernuclear systems

A.Sanchez-Lorente, A.S.Botvina, J.Pochodzalla, Phys. Lett. B697 (2011)222

For light primary fragments (with $A \leq 16$) even a relatively small excitation energy may be comparable with their total binding energy. In this case we assume that the principal mechanism of de-excitation is the explosive decay of the excited nucleus into several smaller clusters (the secondary break-up). To describe this process we use the famous Fermi model [105]. It is analogous to the above-described statistical model, but all final-state fragments are assumed to be in their ground or low excited states. In this case the statistical weight of the channel containing n particles with masses m_i $(i = 1, \ldots, n)$ in volume V_f may be calculated in microcanonical approximation:

$$\Delta\Gamma_f^{\rm mic} \propto \frac{S}{G}\left(\frac{V_f}{(2\pi\hbar)^3}\right)^{n-1}\left(\frac{\prod_{i=1}^n m_i}{m_0}\right)^{3/2}\frac{(2\pi)^{(3/2)(n-1)}}{\Gamma(\frac{3}{2}(n-1))}\left(E_{\rm kin} - U_f^C\right)^{(3/2)n-5/2}, \qquad (58)$$

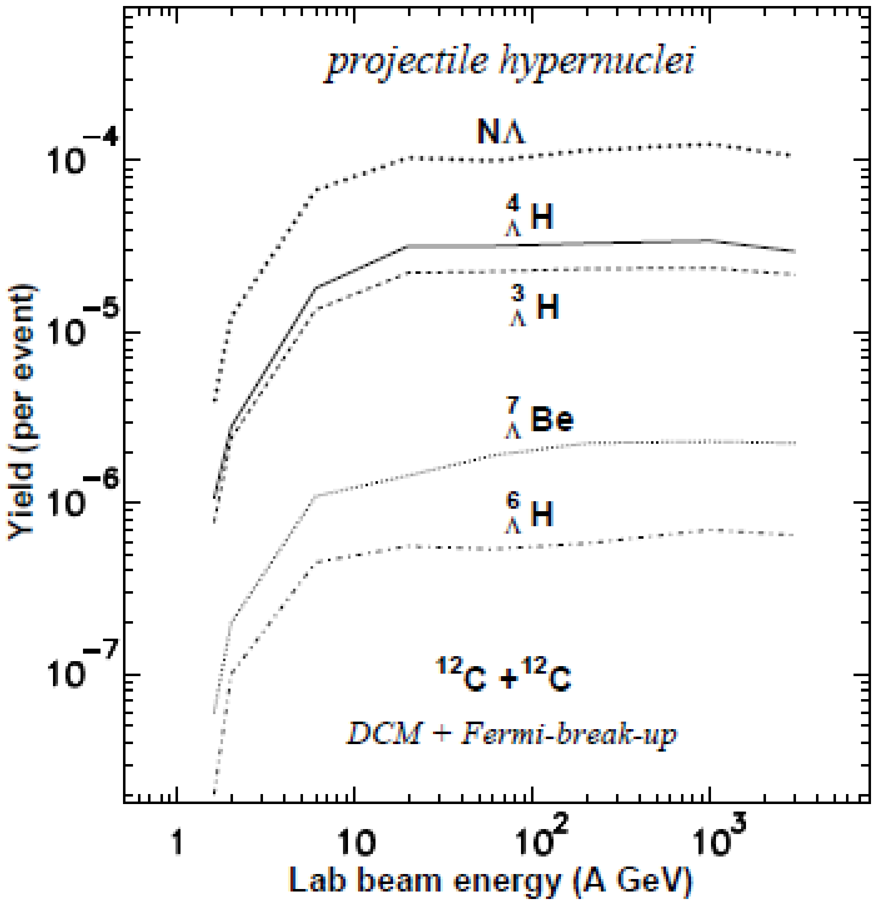
where $m_0 = \sum_{i=1}^n m_i$ is the mass of the decaying nucleus, $S = \prod_{i=1}^n (2s_i + 1)$ is the spin degeneracy factor (s_i is the ith particle spin), $G = \prod_{j=1}^k n_j!$ is the particle identity factor (n_j is the number of particles of kind j). $E_{\rm kin}$ is the total kinetic energy of particles at infinity which is related to the prefragment excitation energy E_{AZ}^* as

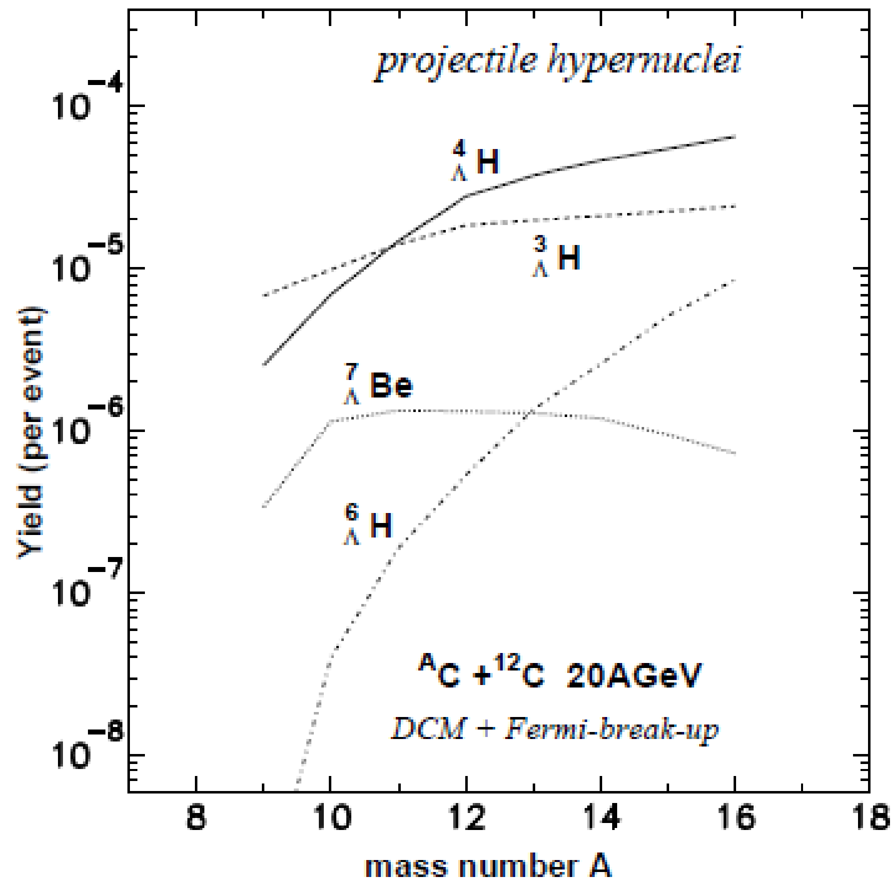
$$E_{\rm kin} = E_{AZ}^* + m_0 c^2 - \sum_{i=1}^n m_i c^2. \qquad (59)$$

U_f^C is the Coulomb interaction energy between cold secondary fragments given by Eq. (49), U_f^C and V_f are attributed now to the secondary break-up configuration.

Generalization of the Fermi-break-up model: new decay channels with hypernuclei were included ; masses and spins of hypernuclei and their excited states were taken from available experimental data and theoretical calculations

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

Experiments on hypernuclei at GSI/FAIR (current and future)

Peripheral collisions relativistic light and heavy ions

HypHI collaboration (in past)

-- Super-FRS (normal and proton-rich hypernuclei)

-- R3B (neutron-rich hypernuclei)

Semi-peripheral and central collisions

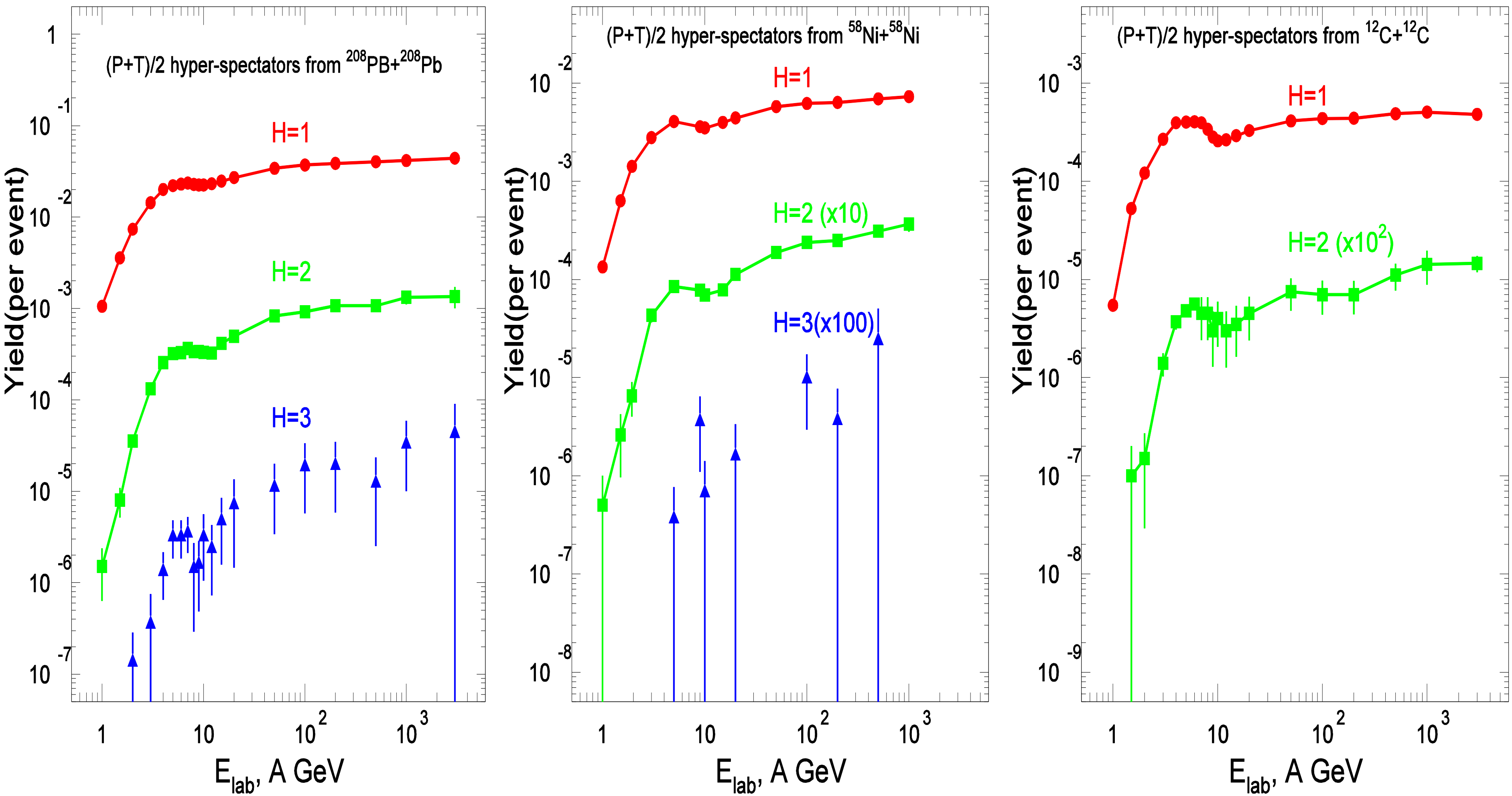
FOPI collaboration (in past)

-- CBM collaboration

Sub-threshold region (<1.6 A GeV) is important for future FRS experiments with projectile-like hypernuclei

Preliminary DCM predictions:

Heavy nuclei | **Medium nuclei** | **Light nuclei**



Conclusions

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

Mechanisms of formation of hypernuclei in peripheral reactions: Strange baryons (Λ, Σ, Ξ, …) produced in particle collisions can be transported to the spectator residues and captured in nuclear matter. Another mechanism is the coalescence of baryons leading to light clusters, including anti-matter, will be effective at all rapidities. These exotic systems are presumably excited and after their decay novel hypernuclei of all sizes (and isospin), including exotic weakly-bound states, multi-strange nuclei, anti-nuclei can be produced.

Advantages over other reactions: in the spectator matter there is no limit on sizes and isotope content of produced exotic nuclei; probability of their formation may be high; a large strangeness can be deposited in nuclei.
Correlations (unbound states) and lifetimes can be naturally studied.
EOS of hypermatter at subnuclear density can be investigated.