Sequential clustering in transport dynamics

by A. Le Fèvre[1], Y. Leifels[1], J. Aichelin[2], Ch. Hartnack[2]
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- The FRIGA clustering approach.
- The achievements of the static approach.
- Spectator versus fireball cluster formation: cold-static versus hot-expanding-sequential clustering.
- Sequential FRIGA: new developments and results.

FRIGA: a clusterisation approach…

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

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

FRIGA: a clusterisation approach…

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* Applicable from the Fermi energy domain (50 A.MeV, multi-fragmentation) up to (ultra-)relativistic energies (spectator - participant decay).
* Prediction of (light and heavy) (hyper)isotope yields and full phase space distribution.

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Simulated Annealing Clusterization Algorithm (SACA): The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :

a) Take the positions and momenta of all nucleons at time t.

b) Combine them in all possible ways into fragments or leave them as single nucleons.

c) Neglect the interaction among clusters.

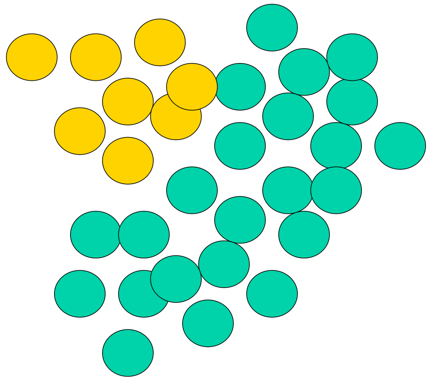
d) **Choose that configuration which has the highest binding energy.**

Simulations show: Clusters chosen that way at early times are the pre-fragments of the final state clusters, because fragments are not a random collection of nucleons at the end but initial-final state correlations.

FRIGA: a clusterisation approach…

Steps:

1) Pre-select good «candidates» for fragments according to proximity criteria: coordinate and momentum space coalescence = Minimum Spanning Tree (**MST**) procedure.



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

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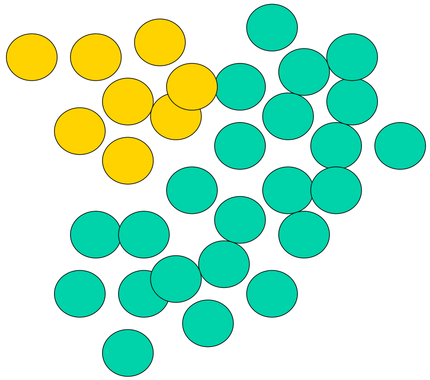
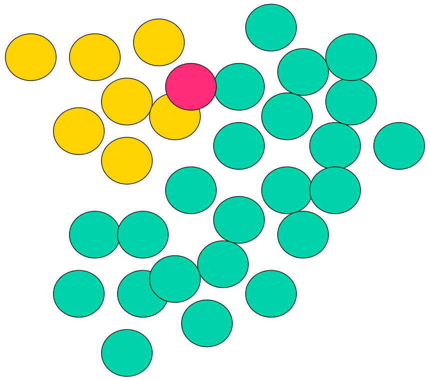
2) Take randomly 1 nucleon out of one fragment





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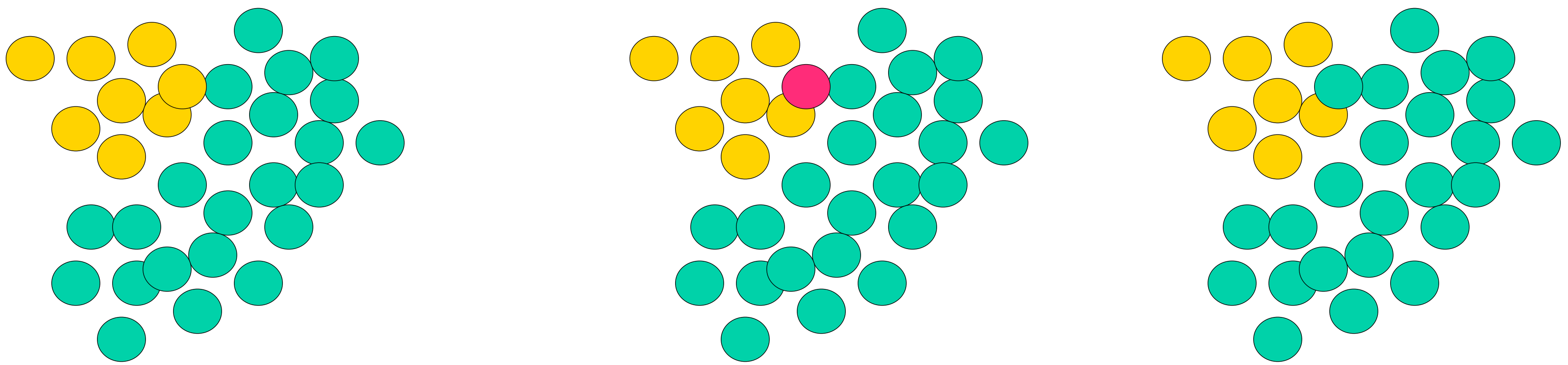

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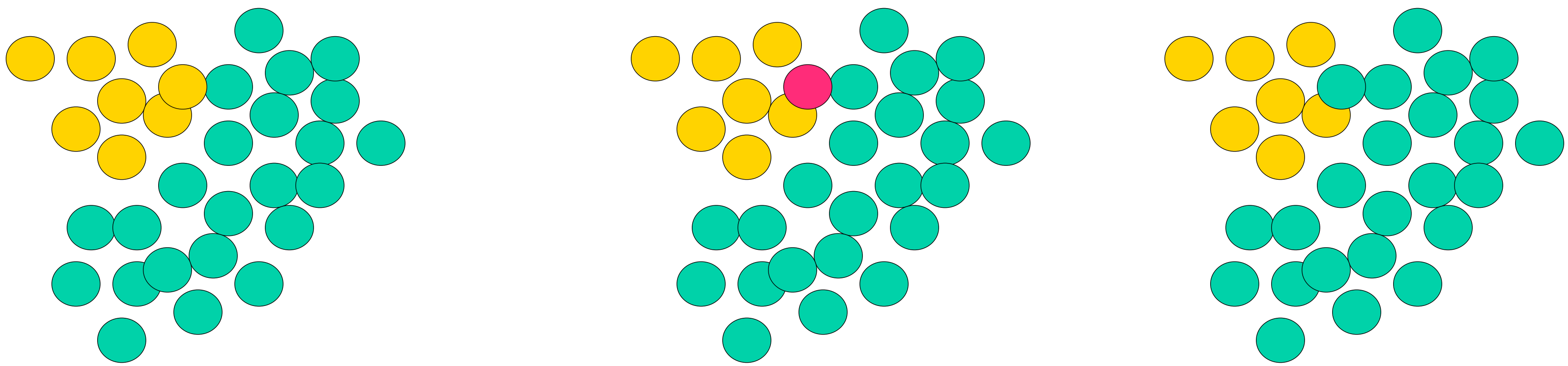

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If $E' < E$ take the new configuration

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: a clusterisation approach…

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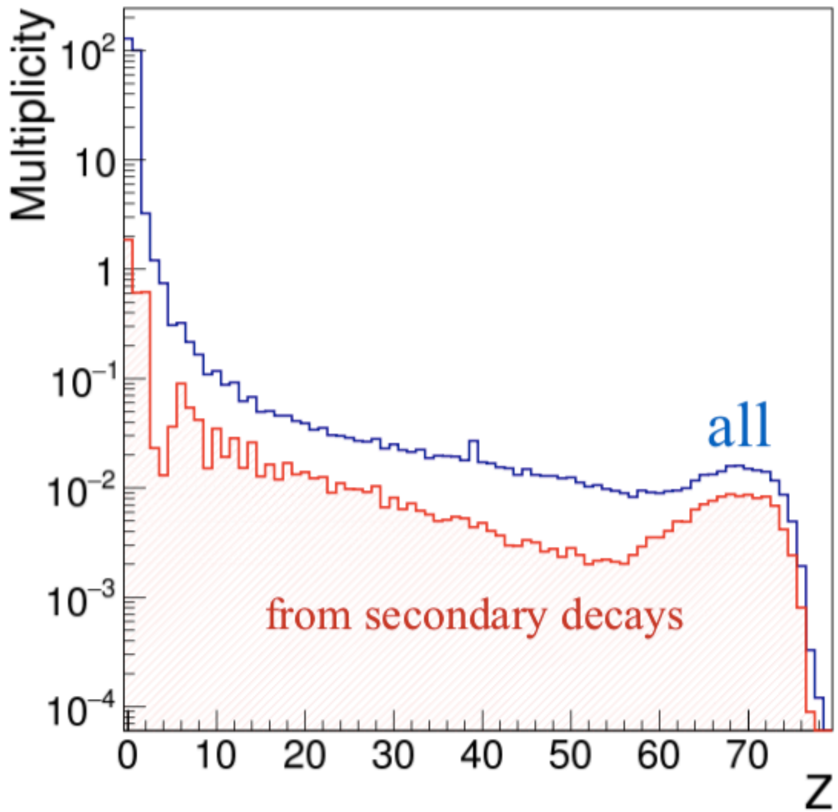
⑧ Rejection of « non-existing » isotopes and hyper-clusters.

Influence of the secondary decays on light isotope yields

An example: Au+Au @ 600 A.MeV (min. bias), b<6 fm (passing time = 2 t_{pass}) from BQMD*+FRIGA



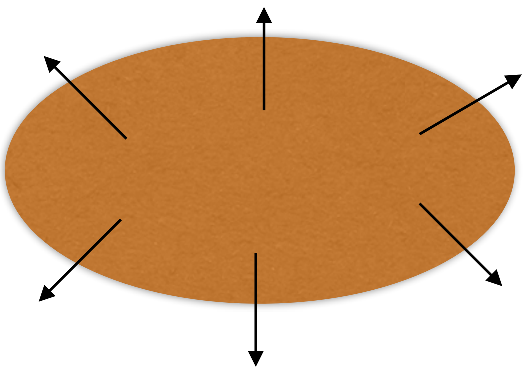
*: J. Aichelin. Phys. Reports 202, 233 (1991).

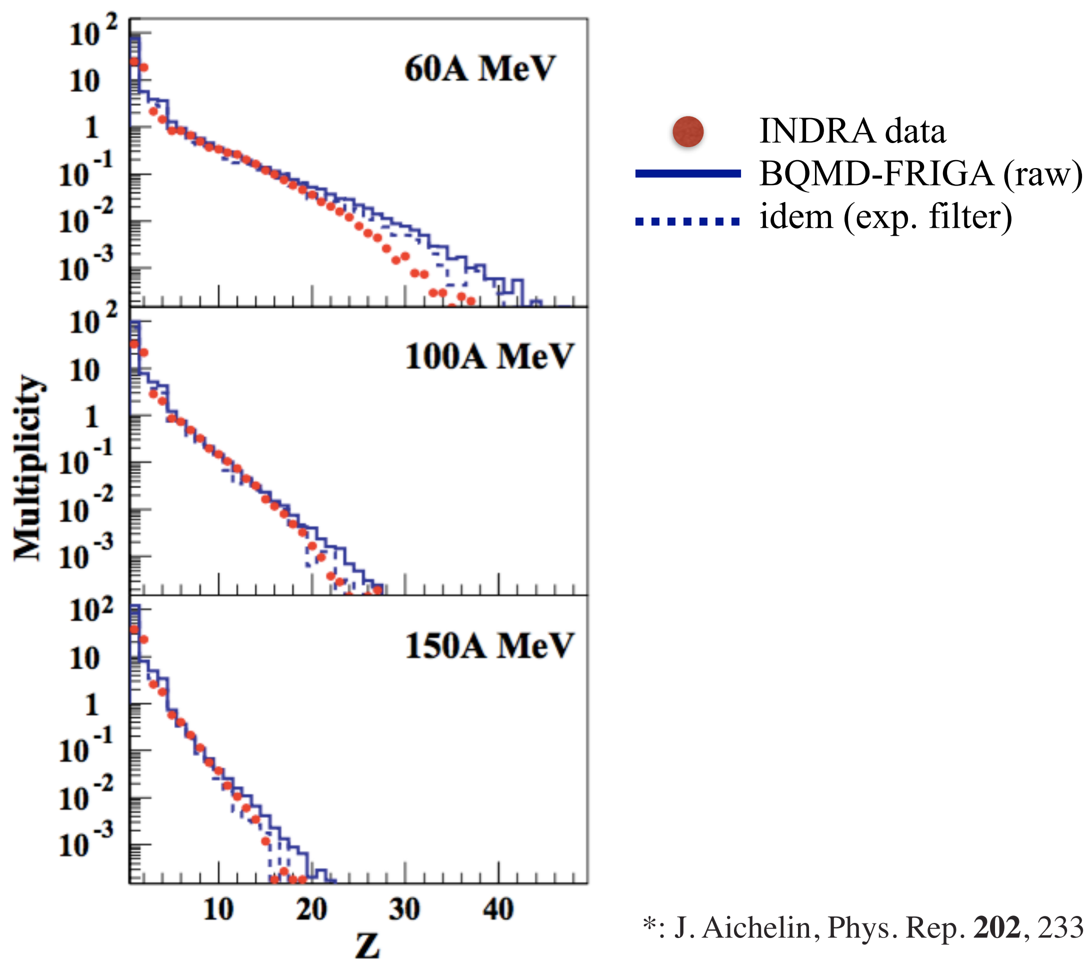
Some successful applications at intermediate energies

INDRA central Au+Au

K. Zbiri et al., PHYSICAL REVIEW C **75**, 034612 (2007)

BQMD*+FRIGA
($t = 2\ t_{pass}$)





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Some successful applications at intermediate energies

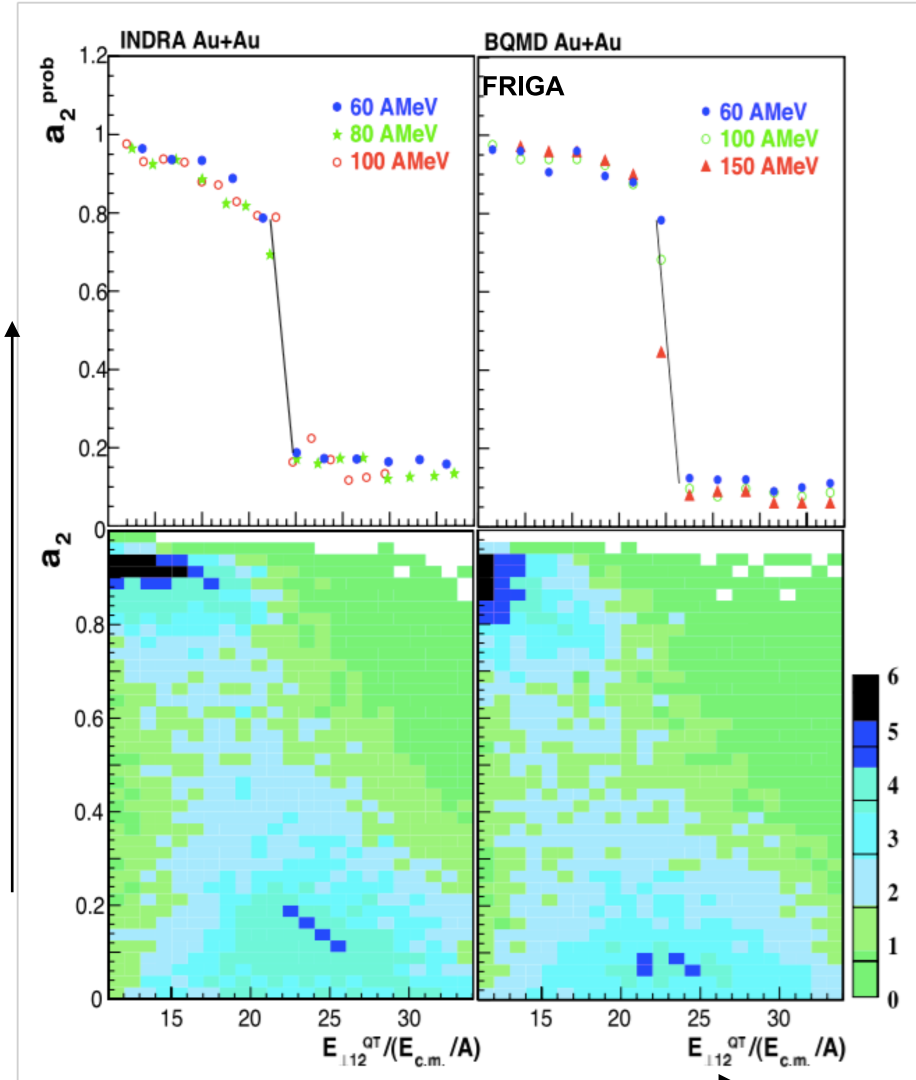
INDRA Au+Au excitation function
A. Le Fèvre and J. Aichelin - PRL 100, 042701 (2008)

BQMD*+FRIGA
($t = 2\ t_{pass}$)

=> Bimodality** =
a mechanical instability
(critical phenomenon, metastability)

fragment size asymmetry
$a_2 = (Z_1 - Z_2)/(Z_1 + Z_2)$

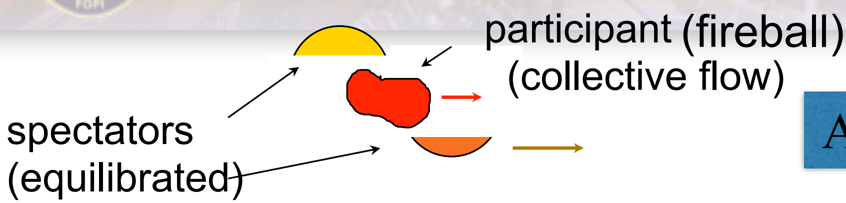
=> sufficient fluctuations
necessary in transport models



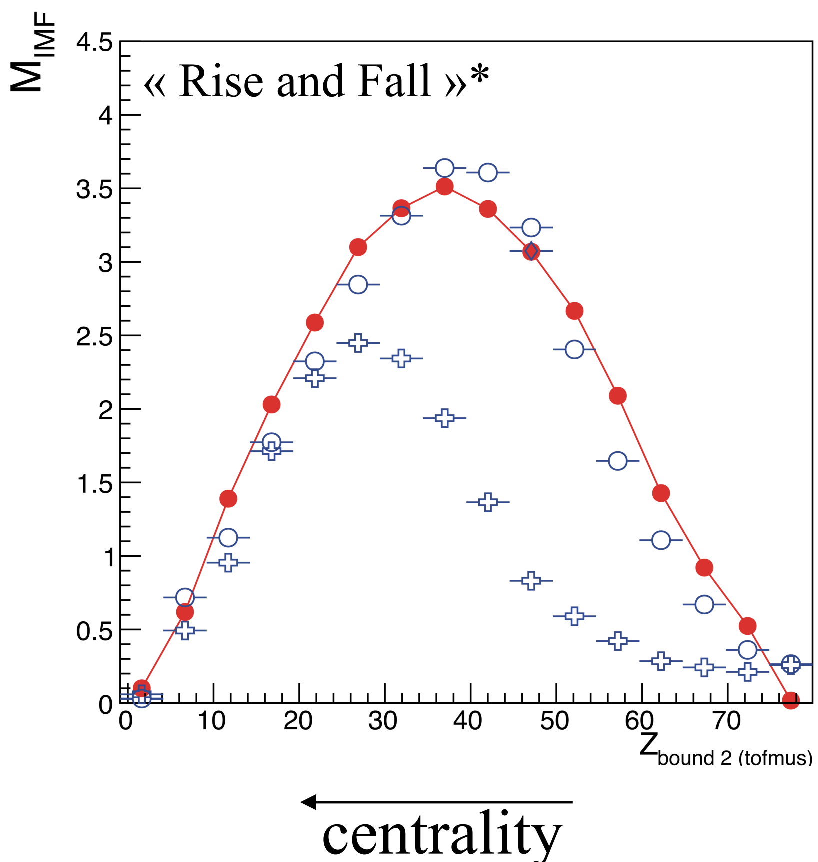
centrality

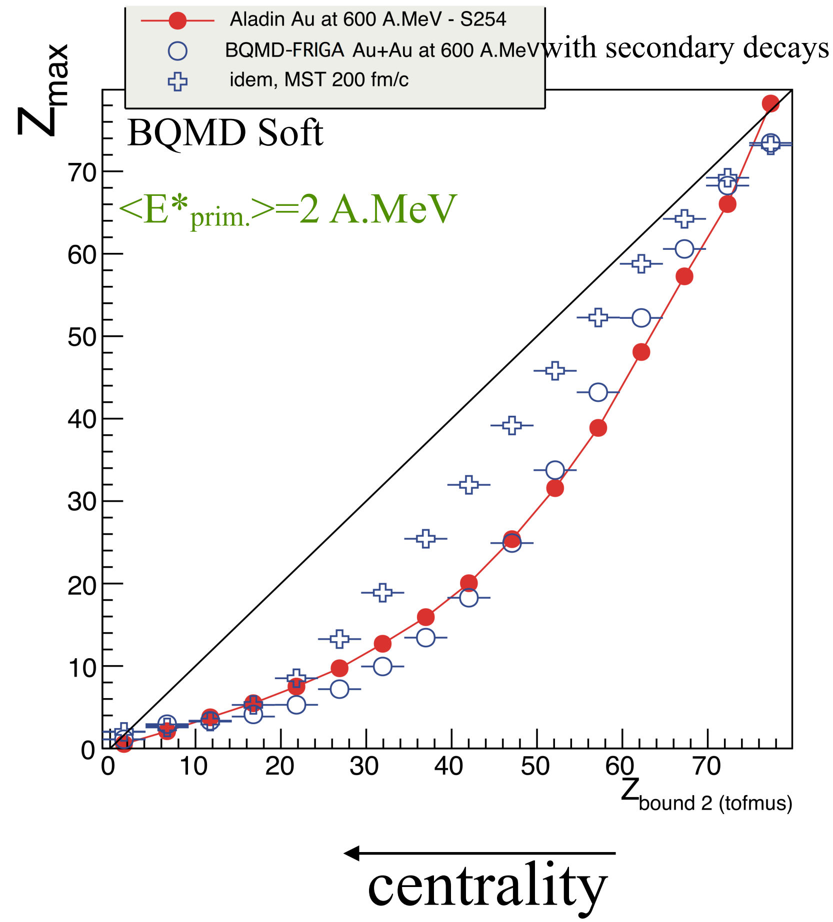
*: J. Aichelin, Phys. Rep. **202**, 233 (1991).
**: also found in Xe+Sn system in
M. Pichon et al, INDRA-ALADIN Coll.,
Nuclear Physics A 779 (2006) 267–296

Some successful applications in the spectator regime

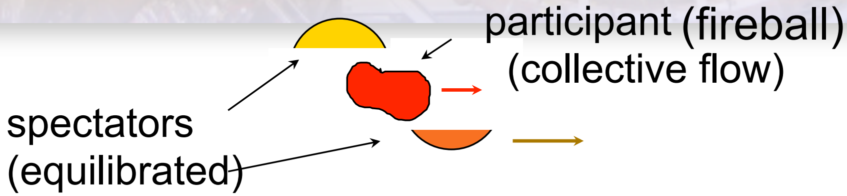


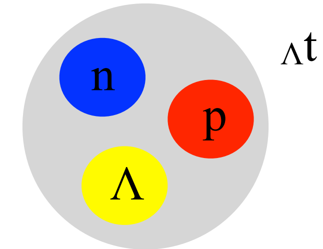
ALADiN Au+Au @ 600 A.MeV (S254 exp., 2003)





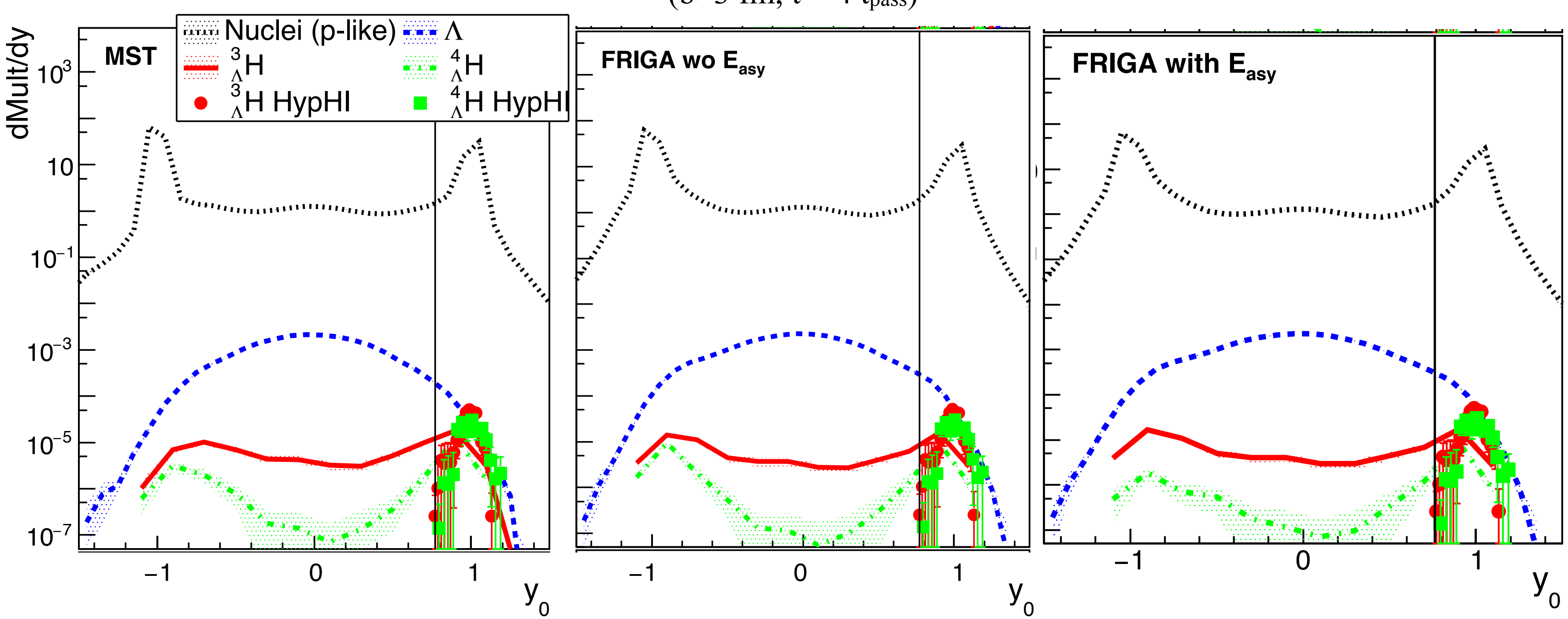
Some successful applications in the spectator regime (hypernuclei)





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

IQMD*+FRIGA
^{6}Li+^{12}C @ 2A.GeV
(b>3 fm, t = 4 t_{pass})



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

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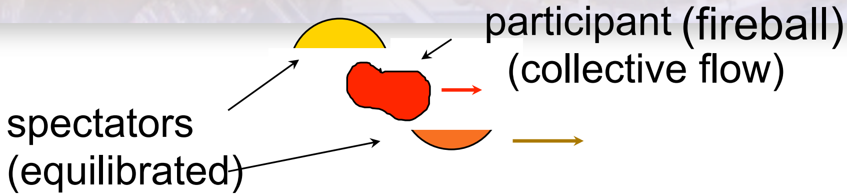

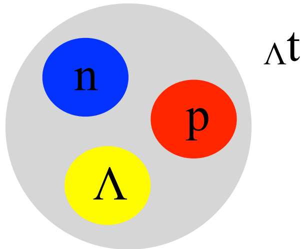

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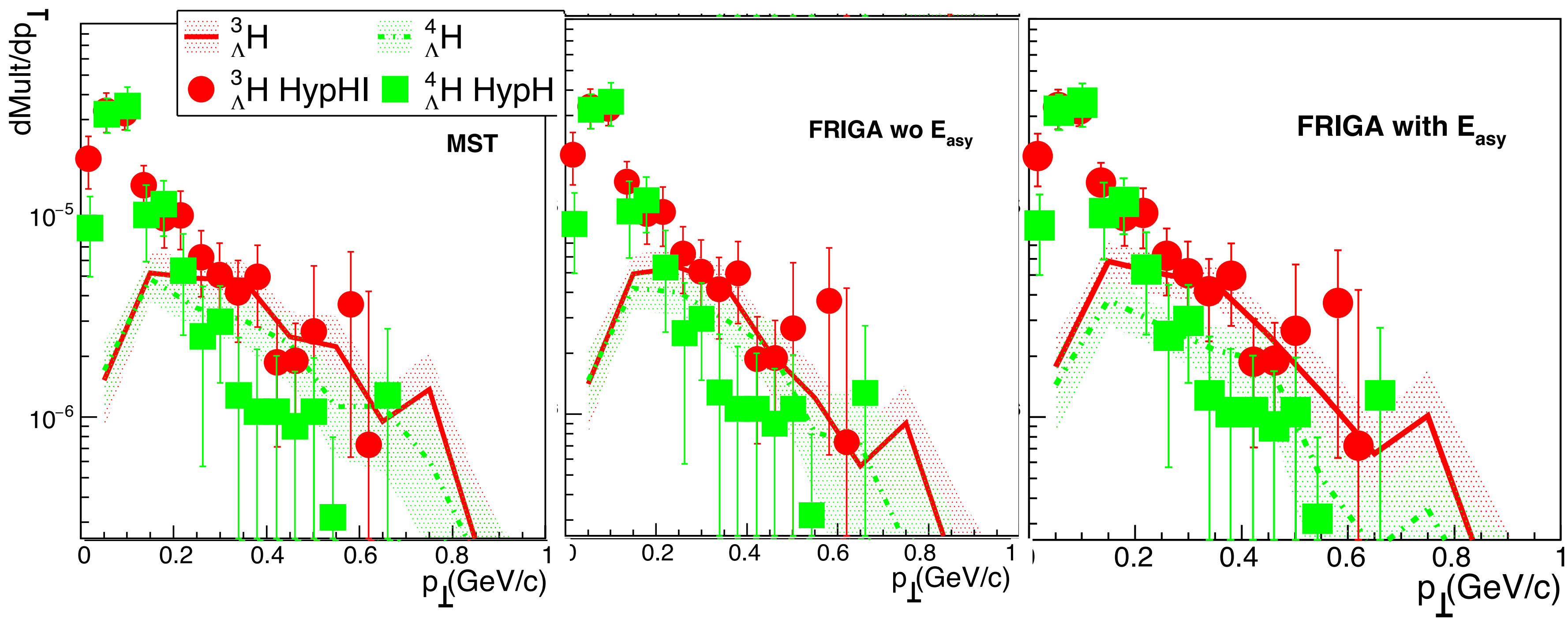

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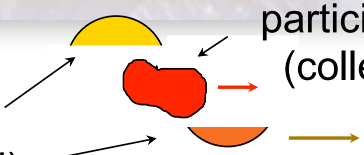
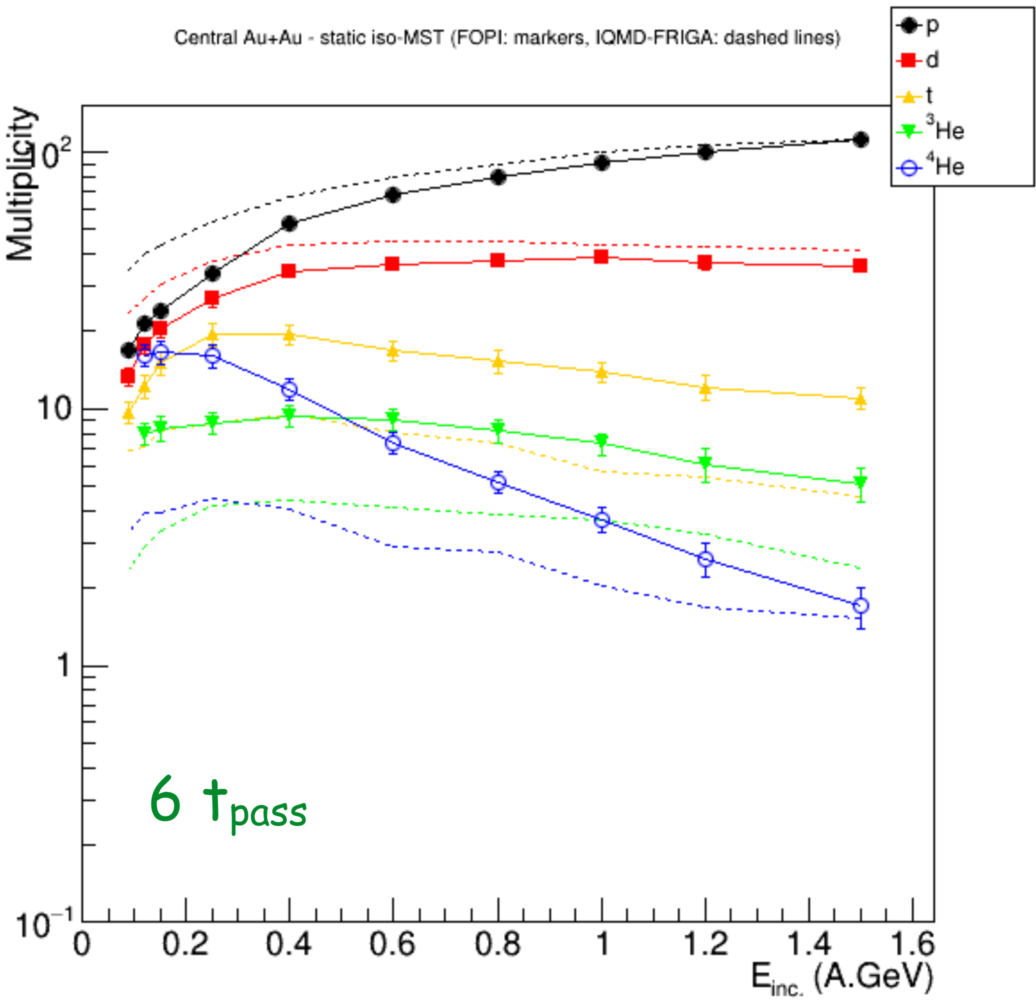
The fireball regime with the static approach



Central
Au+Au:
IQMD-FRIGA (dashed lines)
vs
FOPI data (markers)*

static
iso-MST*



*$\Delta r_{pp} < 2.5$ fm
$\Delta r_{nn,np} < 3.8$ fm

*: *W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427*

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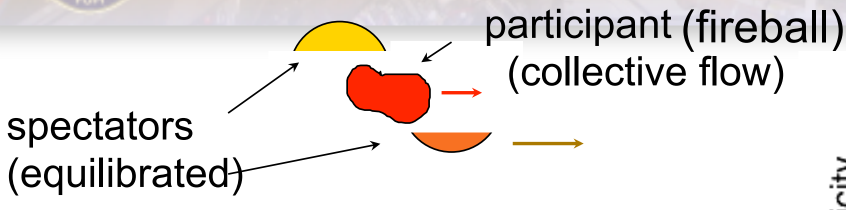

Central
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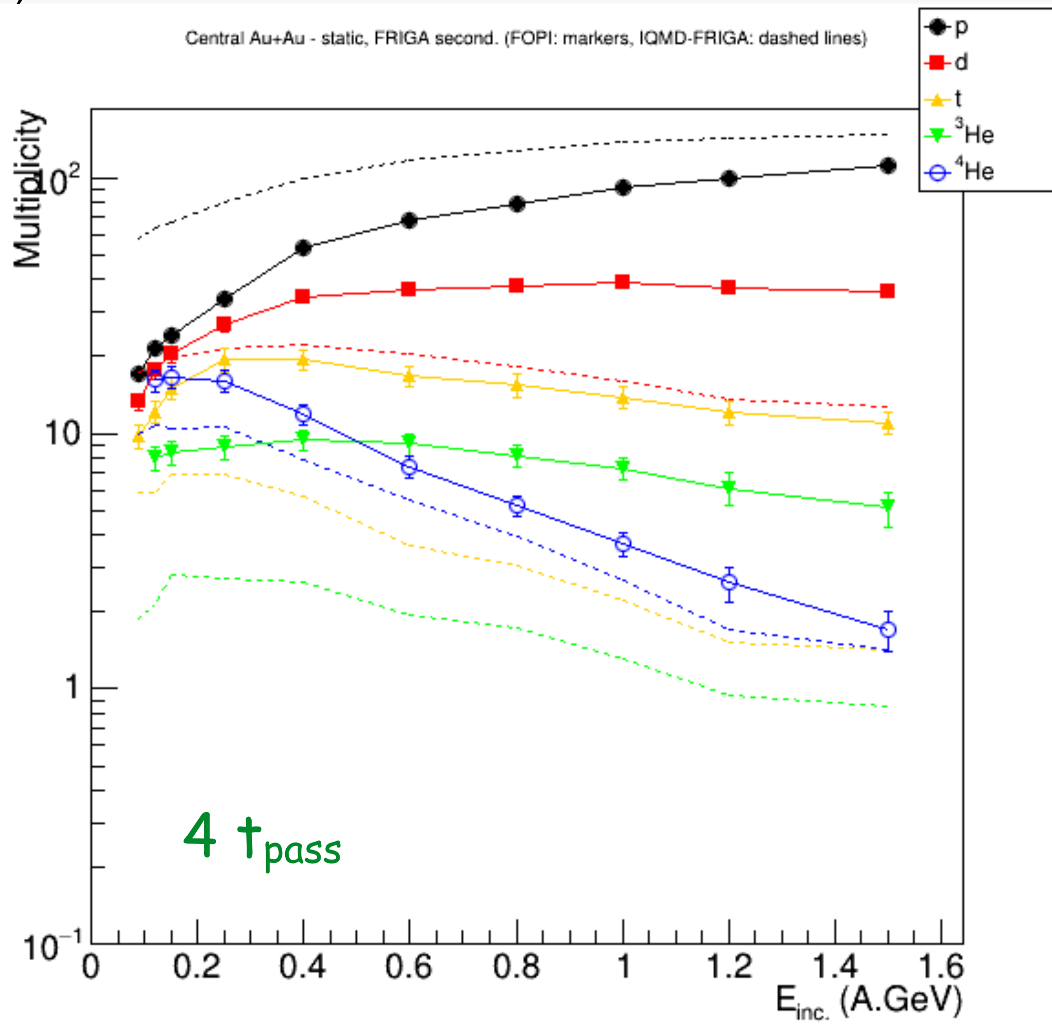
static
FRIGA
(with B_{asy}, second.)



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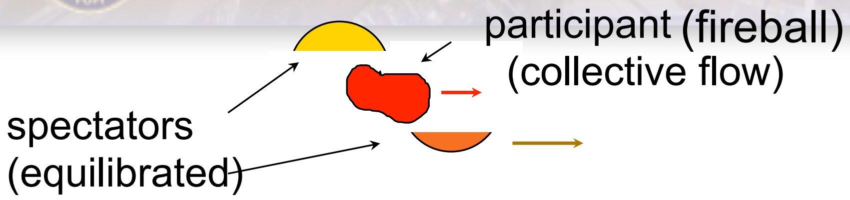
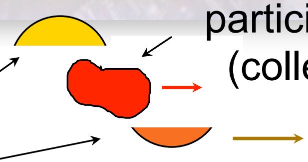


➲ In central collisions, the static/instantaneous FRIGA strategy (including asymmetry and structure binding energies) provides inaccurate light isotope yields

➲ Reversely, the MST static coalescence approach is more reliable at the highest SIS energies.

*: W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427

The fireball regime with the static approach



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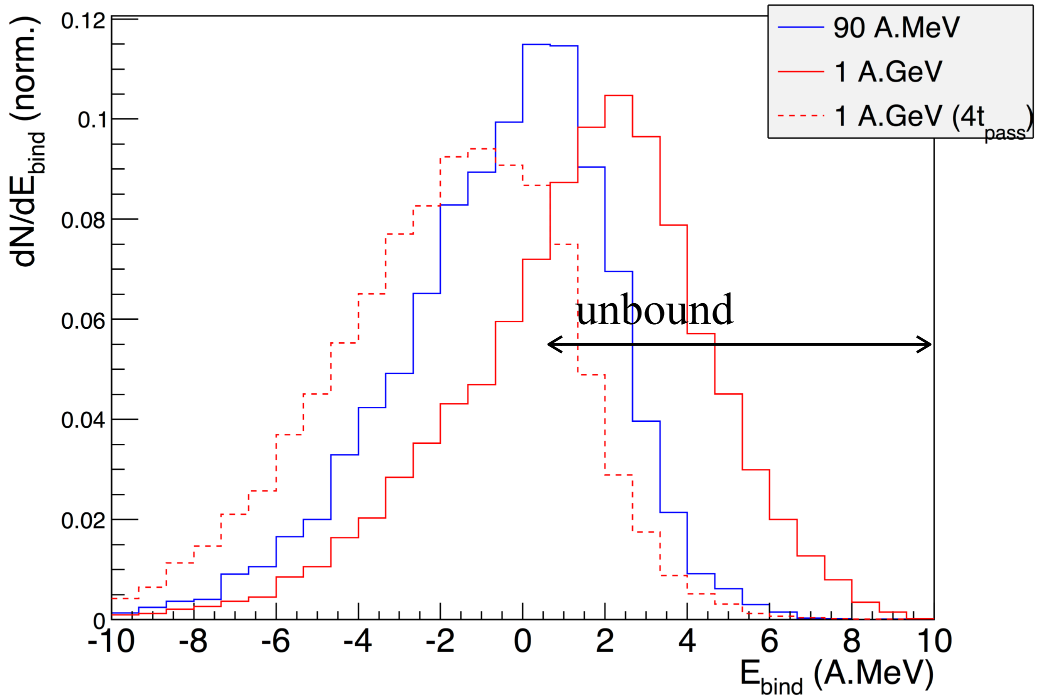
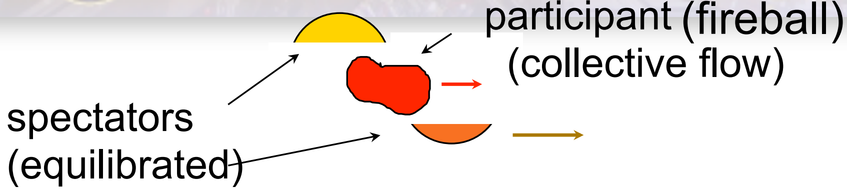


Binding energy of early (2 t_{pass}) tritons identified with coalescence (MST)

B_{asy} on
B_{struct} on

The fireball regime with the static approach

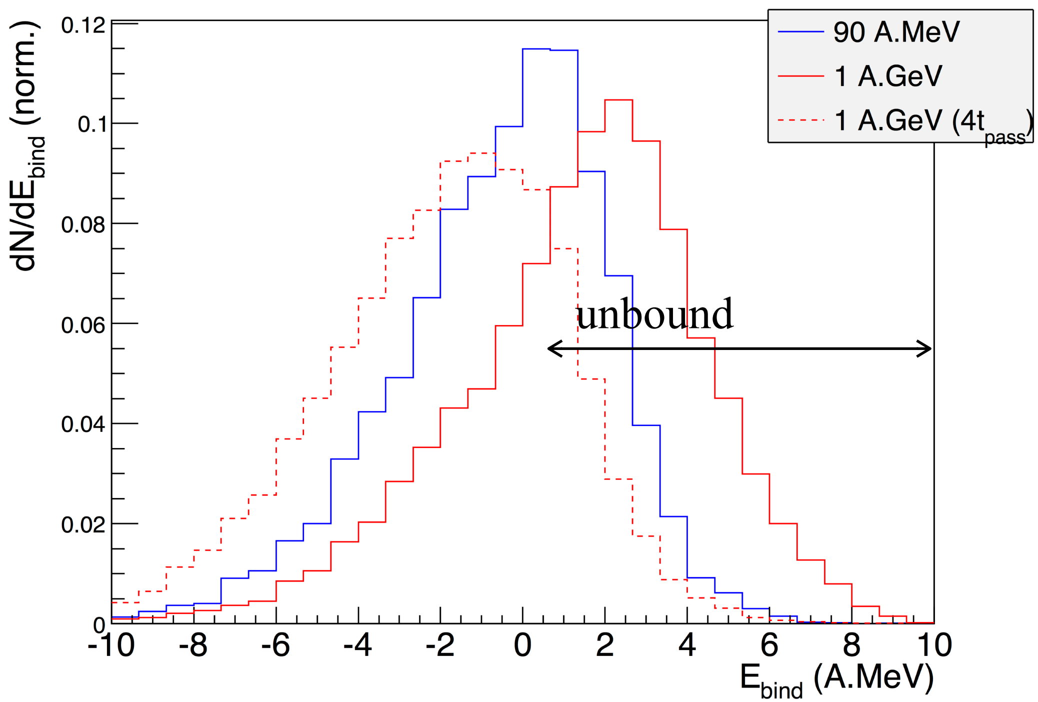


Central Au+Au: IQMD-FRIGA

1- On the contrary of the rather cool central source of intermediate energies (and spectator), in the hot fireball, early pre-fragments are mostly hot and unbound.

2- In a fireball, the hot expanding medium needs more time to generate clusters than the spectator regime (fast clustering from a rather cold non expanding medium)

➲ Invalidity of static/instantaneous FRIGA as an early « afterburner » in the fireball regime. Better alternative: follow the process of cluster formation up to a relatively longer time.



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Clustering in the fireball regime: what says the experiment?

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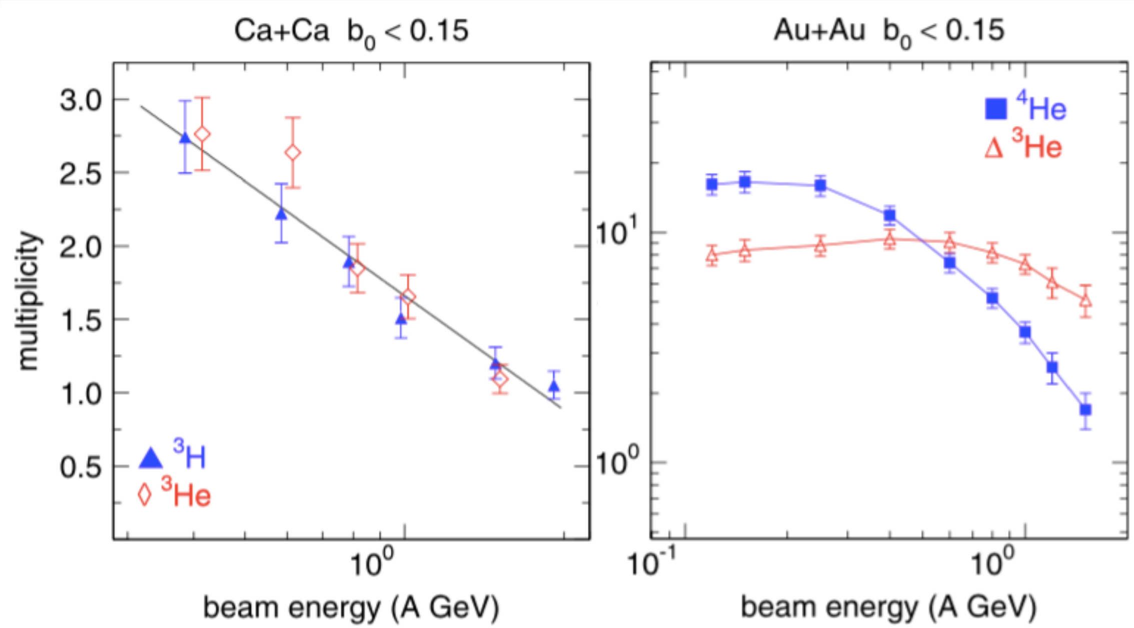

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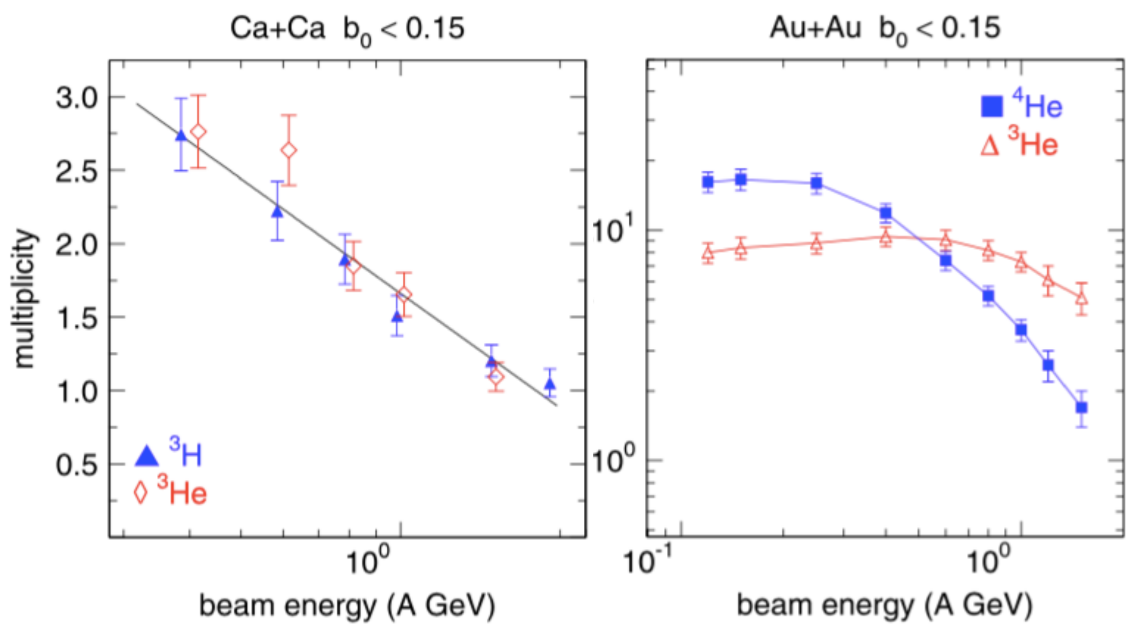

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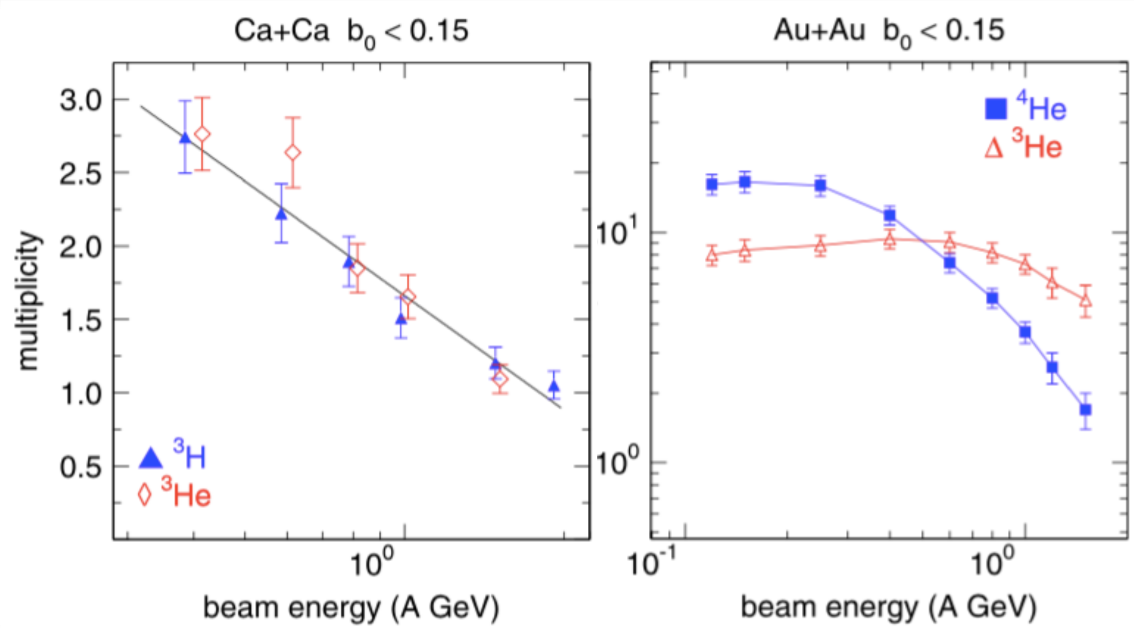
FOPI Collaboration / Nuclear physics A 848 (2010) 366-427

A high degree of clusterisation even at high energies: extrapolation of FOPI@GSI trend -> clustered fraction >10% up to 4A GeV. Persistence of a significant probability to clusterize at freeze-out up to an available energy per nucleon more than two orders of magnitude higher than typical nucleonic binding energies

➲ Signal of local cooling accompanying the fireball expansion

➲ Strong constraint on the associated entropy.



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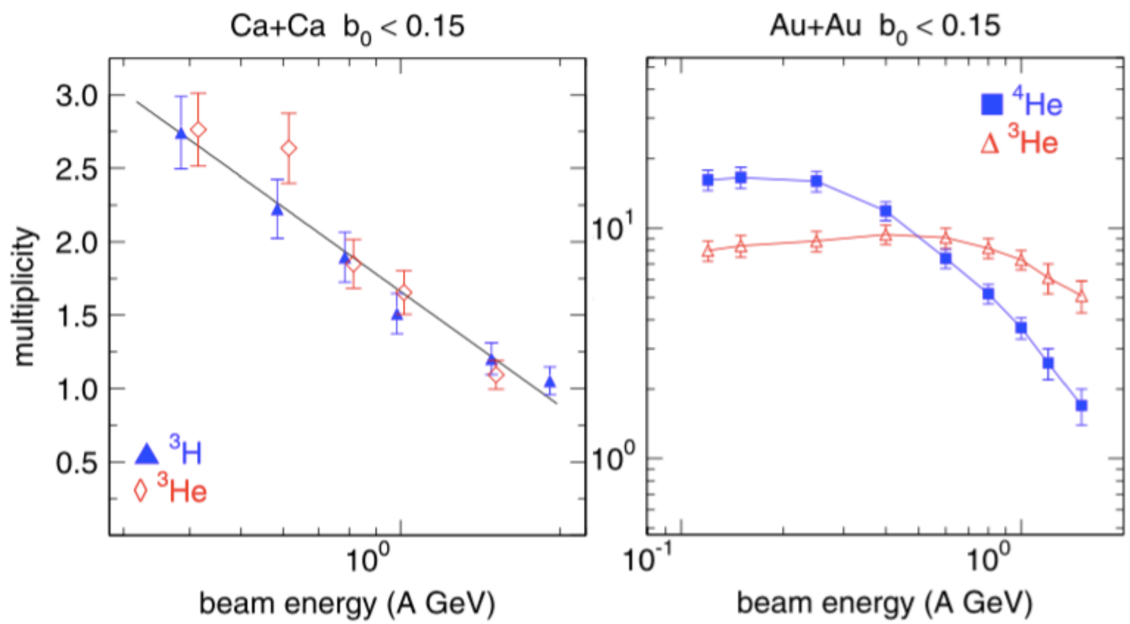

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An interpretation: Increased stopping (right panels) <-> increased compression <-> increasing radial flow developed thereafter in the expansion phase coupled to increased cooling **('droplet formation')**

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3) Process with MST/FRIGA free hadrons only.

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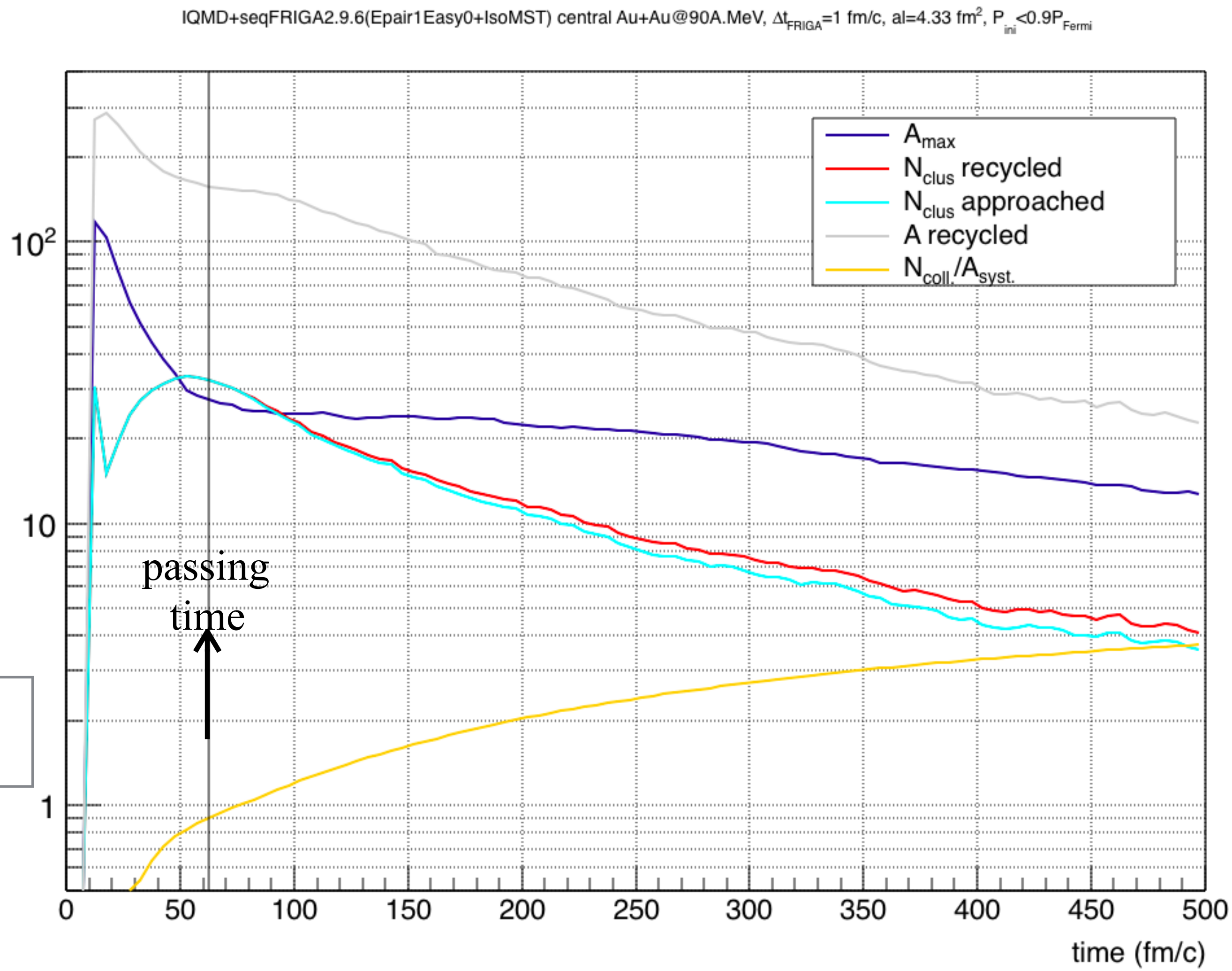
Central
Au+Au:
IQMD-FRIGA

90A MeV



General trend with IQMD:
A_{max} leak after 250 fm/c

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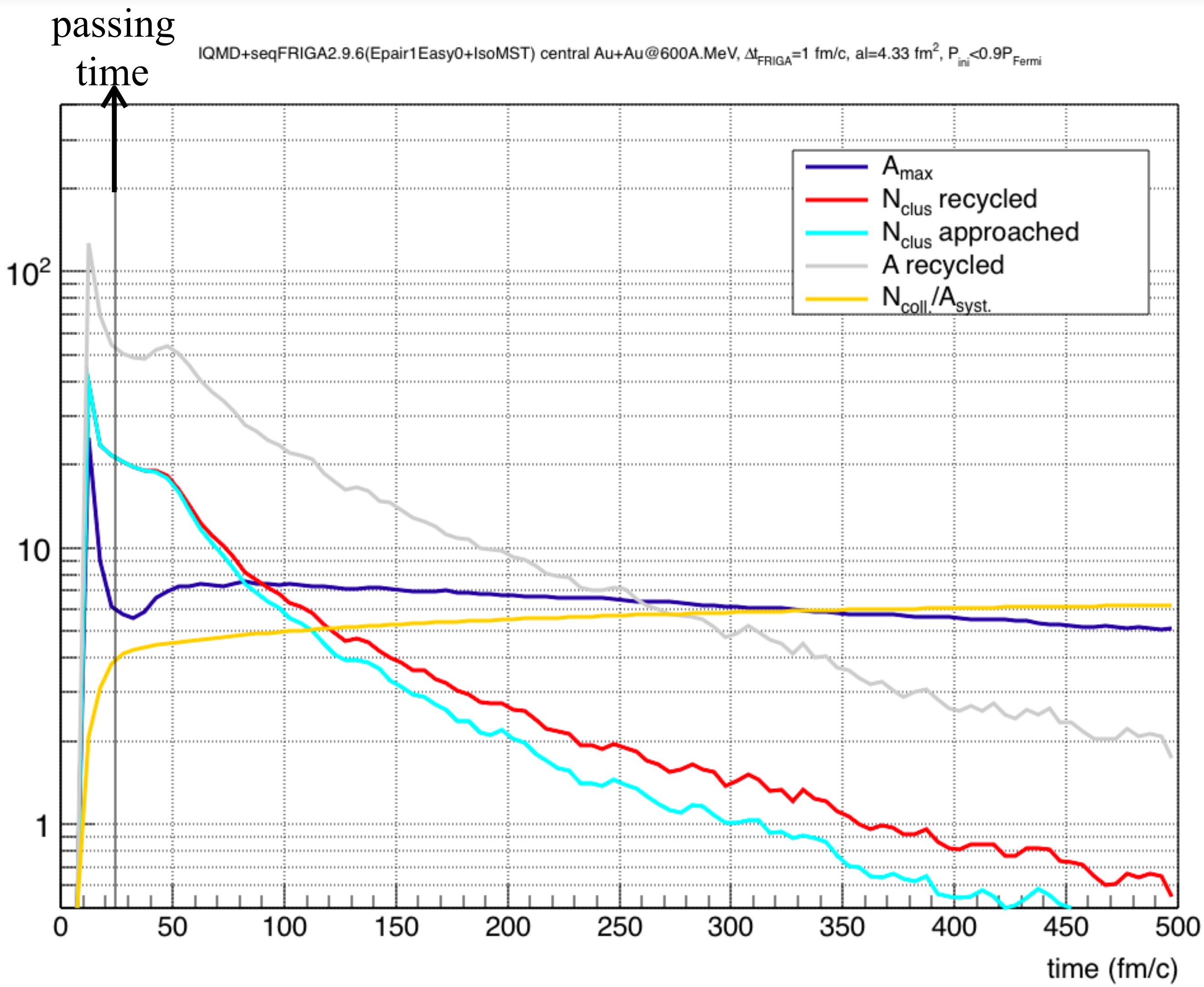

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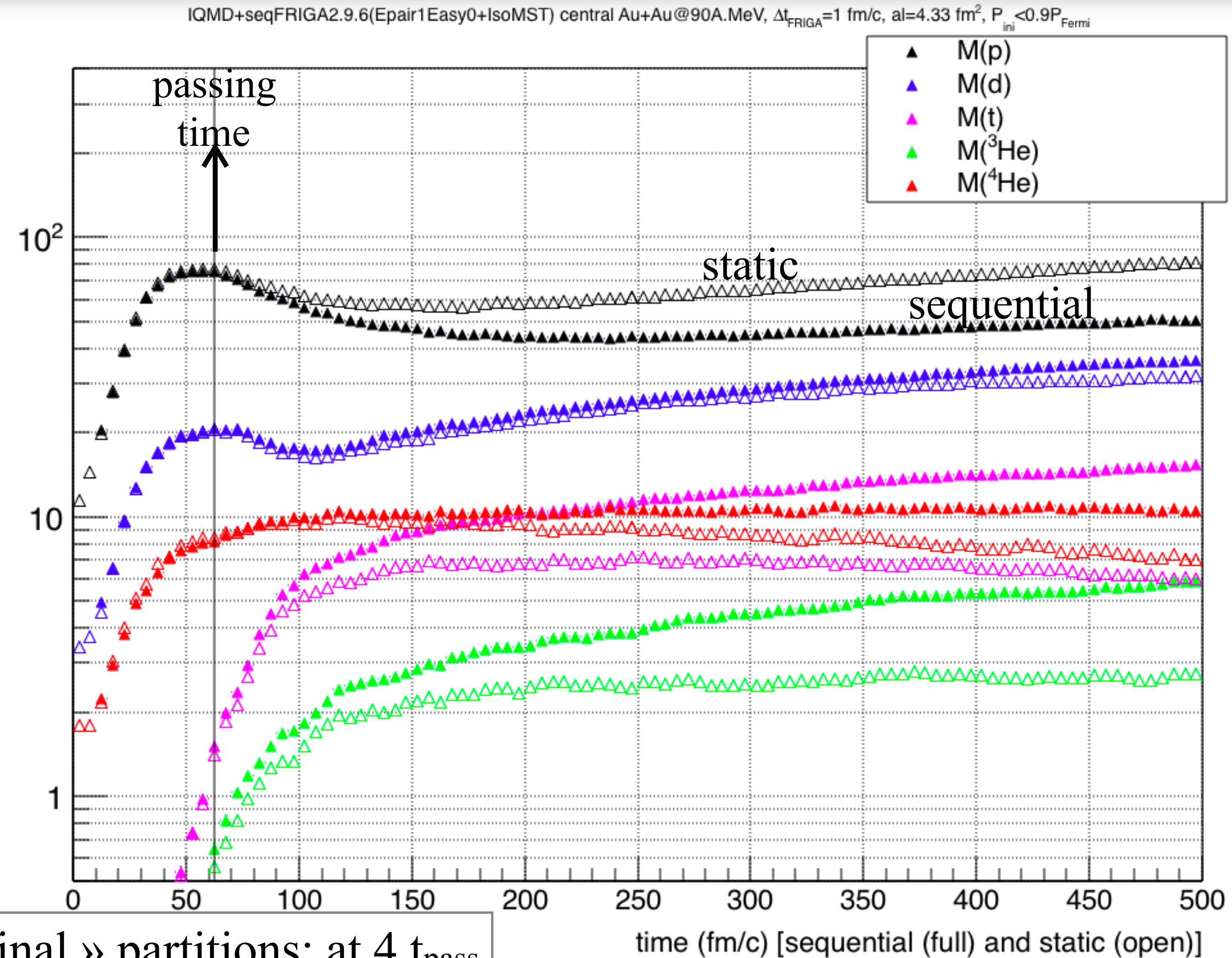

Best compromise for « final » partitions: at 4 t_{pass}

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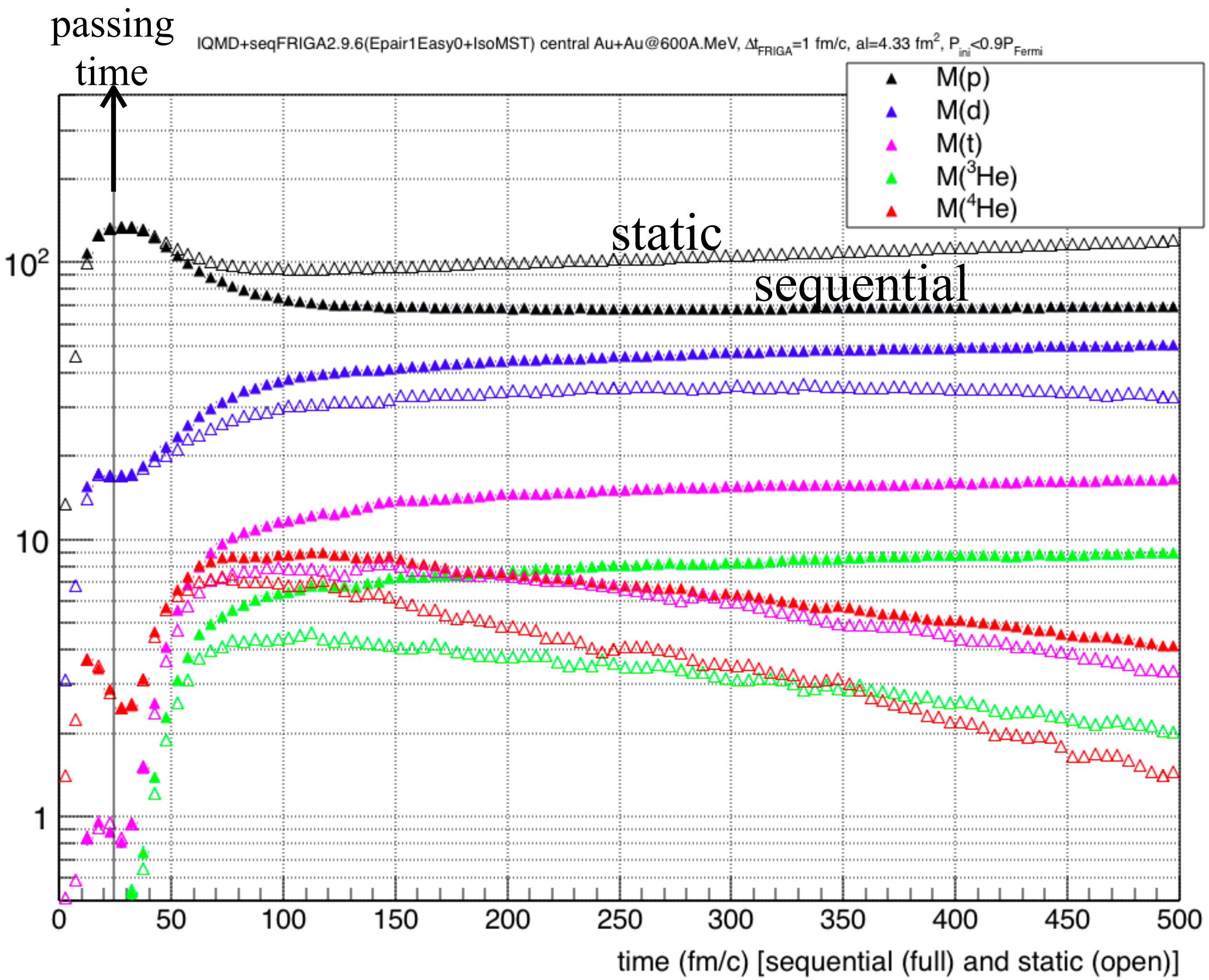
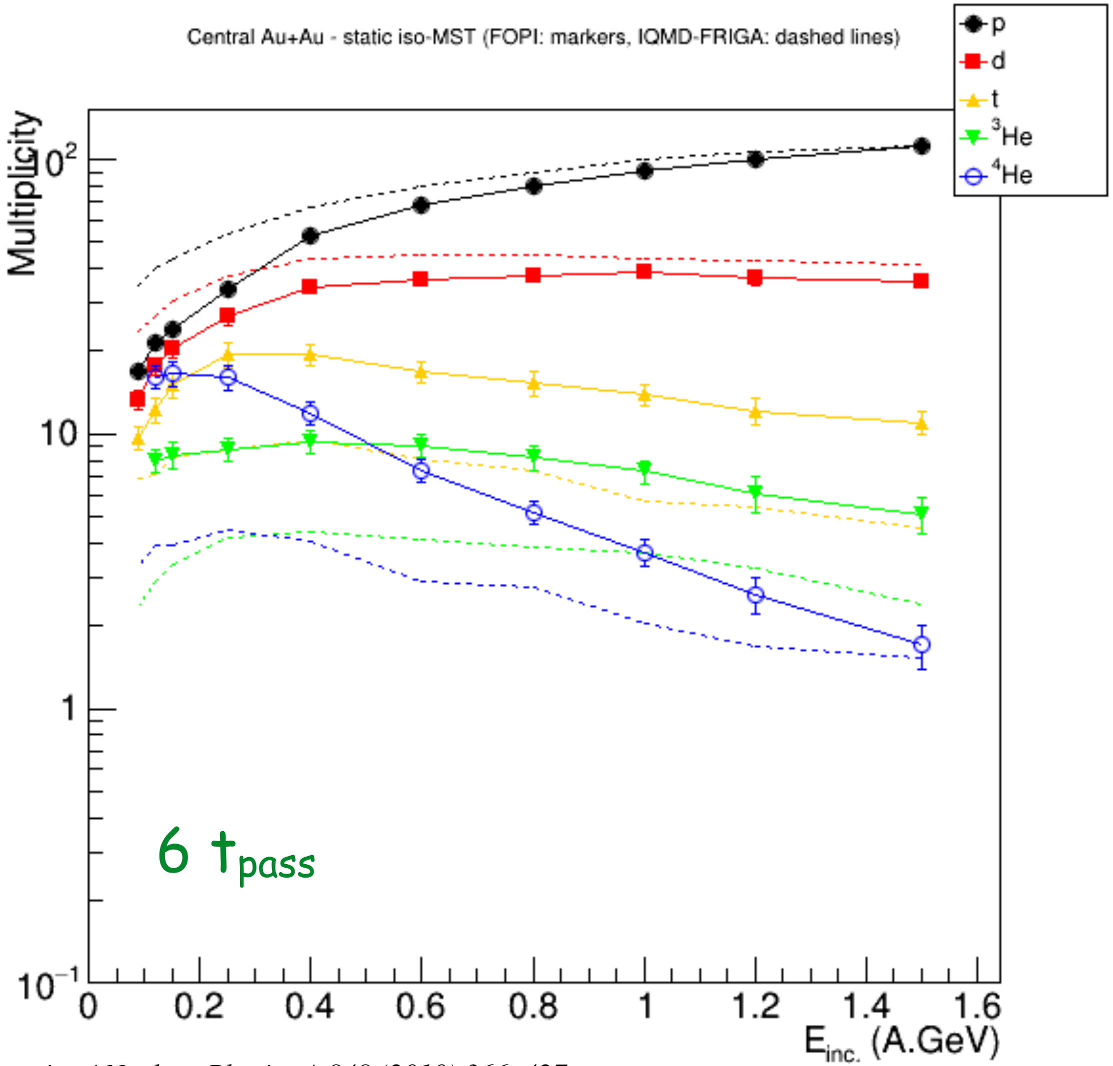


HELMHOLTZ
ASSOCIATION

A new non-static approach: « sequential » FRIGA

Central
Au+Au:
IQMD-FRIGA (dashed lines)
vs
FOPI data (markers)*

static
iso-MST*



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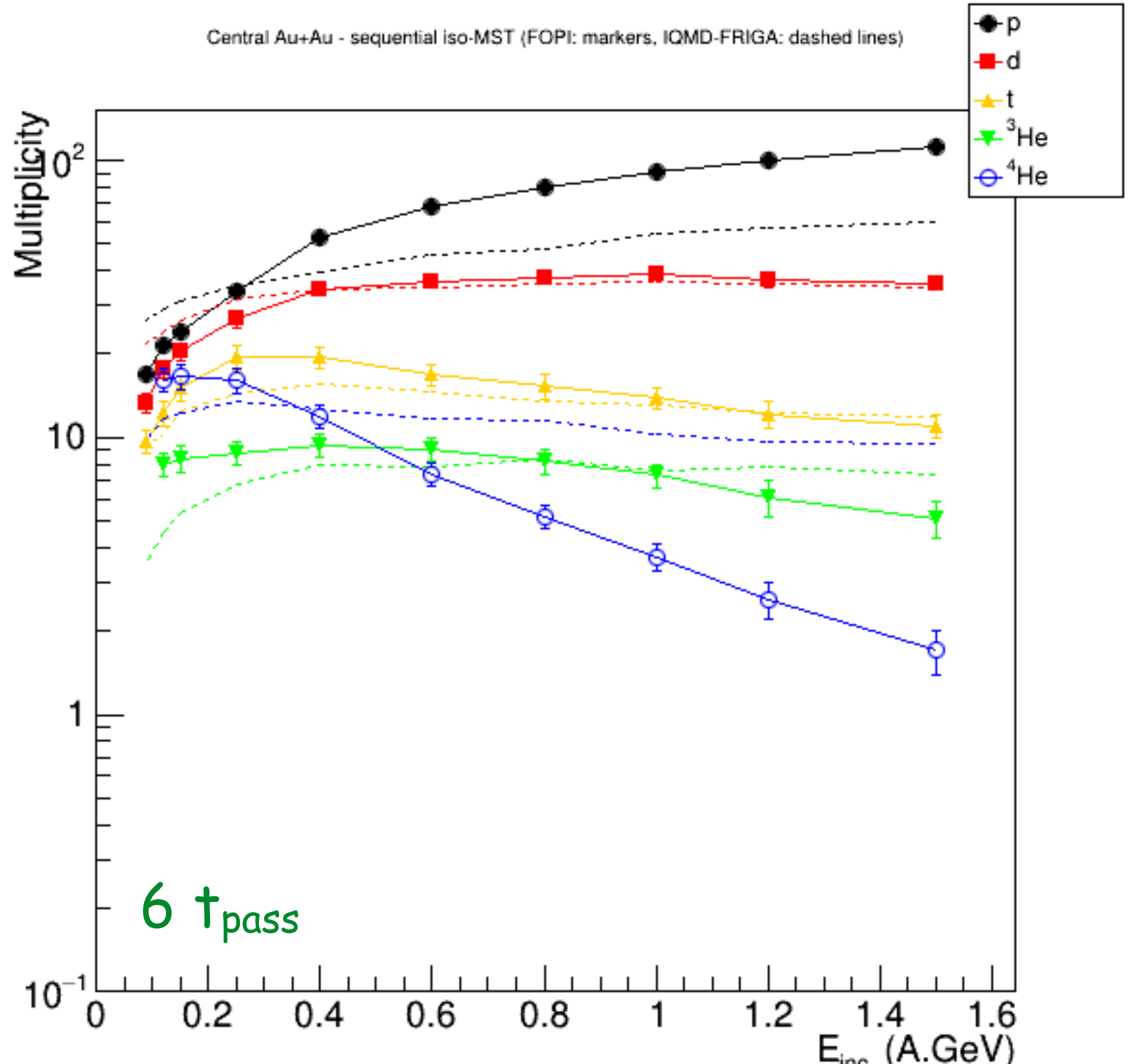

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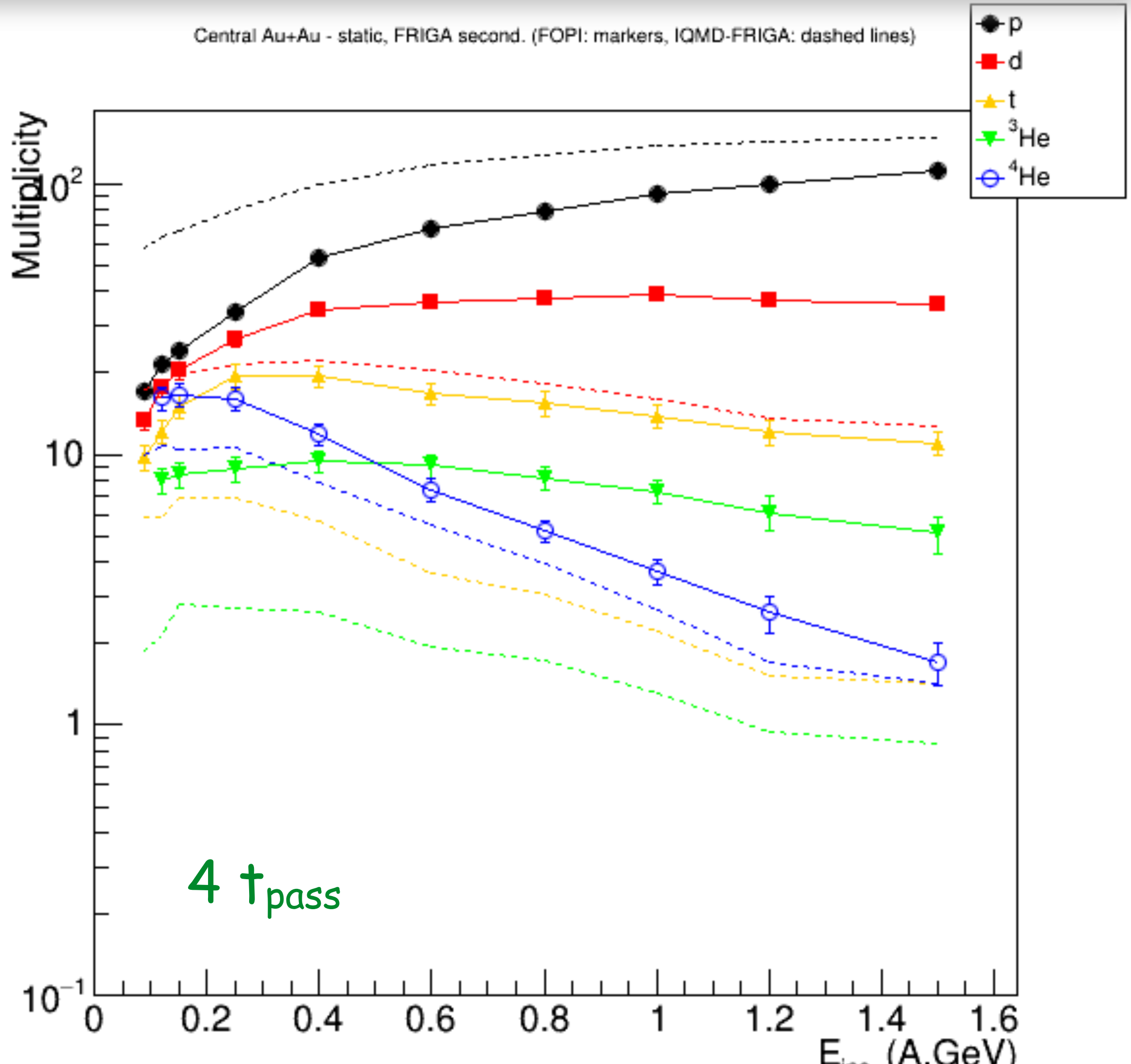
static
FRIGA
(with B_{asy}, second.)



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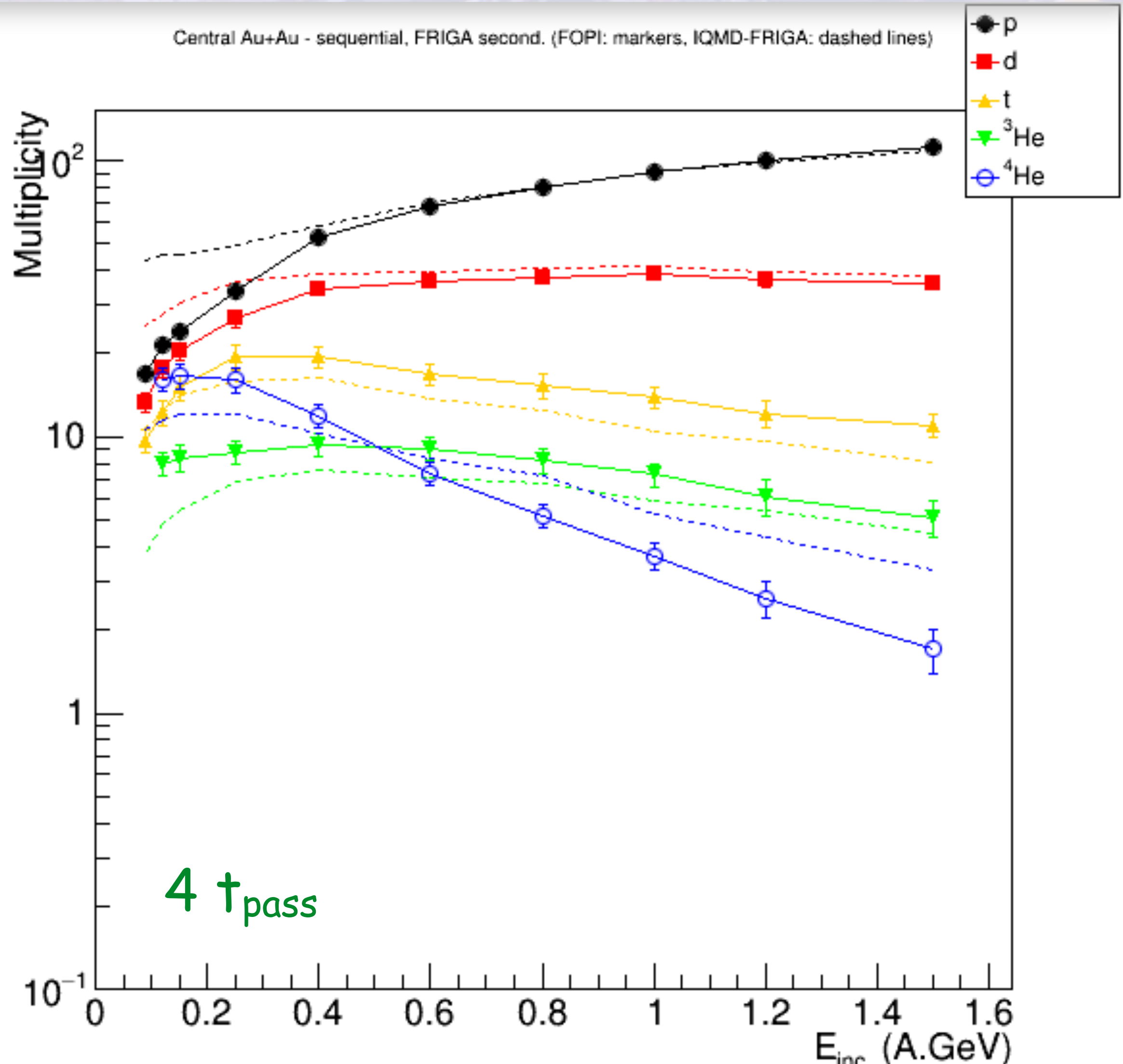

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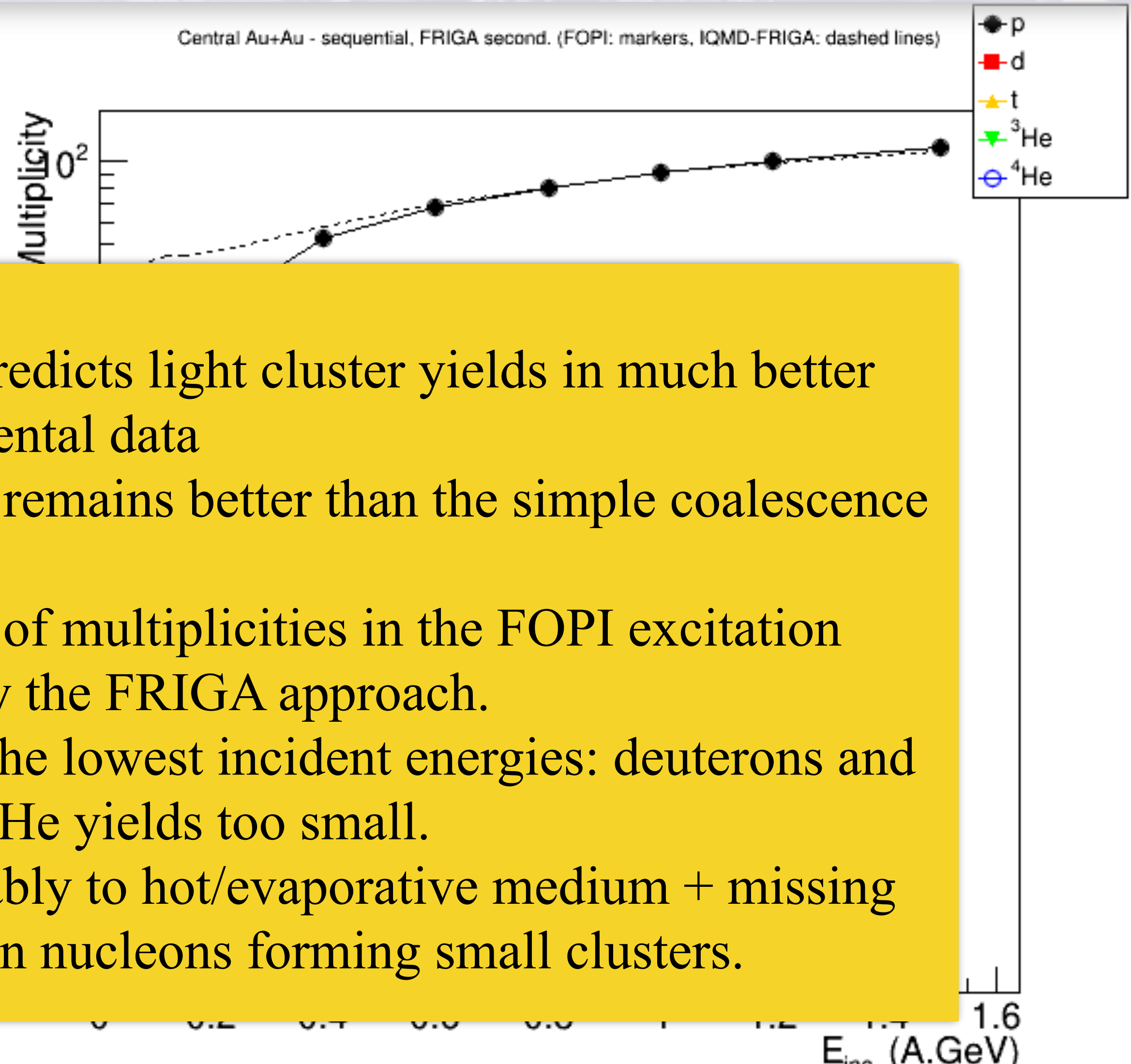
vs
FOPI data



➲ Sequential strategy: predicts light cluster yields in much better agreement with experimental data

➲ The FRIGA approach remains better than the simple coalescence method.

➲ The ^{3}He/^{4}He crossing of multiplicities in the FOPI excitation function is only found by the FRIGA approach.

➲ Still discrepancies at the lowest incident energies: deuterons and proton yields too large, ^{4}He yields too small.

➲ IQMD creates a probably to hot/evaporative medium + missing quantum binding between nucleons forming small clusters.

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