E. De Filippo (INFN Catania) (***NEWCHIM***  *collaboration)*

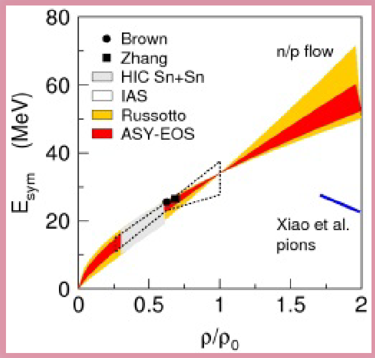
Experimental observables and transport models: a challenge in HIC from low to high energy regime

Transport models are the main way to extract dynamical information from Heavy Ion Collisions, in particular when looking at the EOS symmetry energy constraints as a function of density.

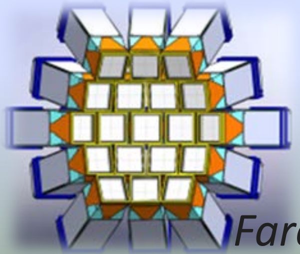
Transport 2017 - MSU

Main topics

Observables at low and Fermi Energy regime: some examples and open problems



Results of the **AsyEos@GSI experiment** : how these results have contributed to improve the theory for interpretation of data. Open problems and new perspectives

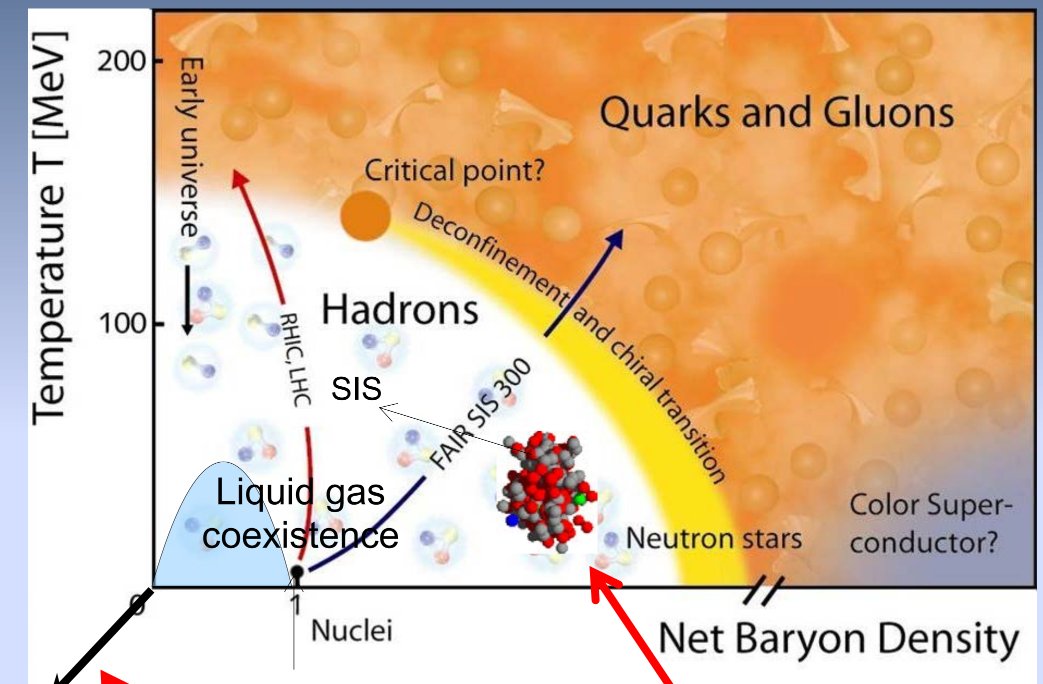


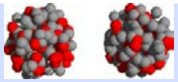
Farcos

Particle and IMF correlations: experimental improvements and status of the FARCOS correlator array project.

The nuclear EOS describes the relation among energy, pressure, density, temperature and isospin asymmetry. It is a fundamental ingredient in nuclear physics (exotic nuclei, heavy ion collisions, …) and astrophysics (neutron stars, supernovae, …)

Nuclear matter phase diagram (schematic)



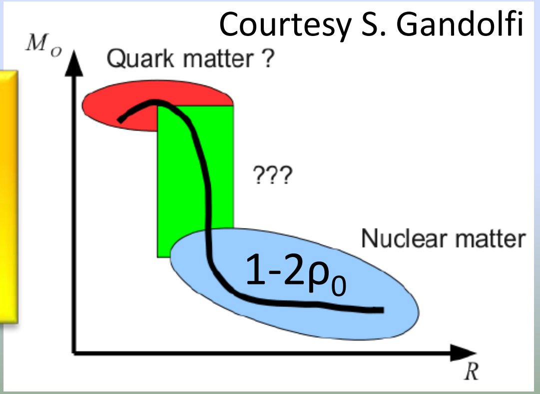


Heavy ion collisions (HIC): Why and how they provide information on density dependence of Symmetry term of EOS ?

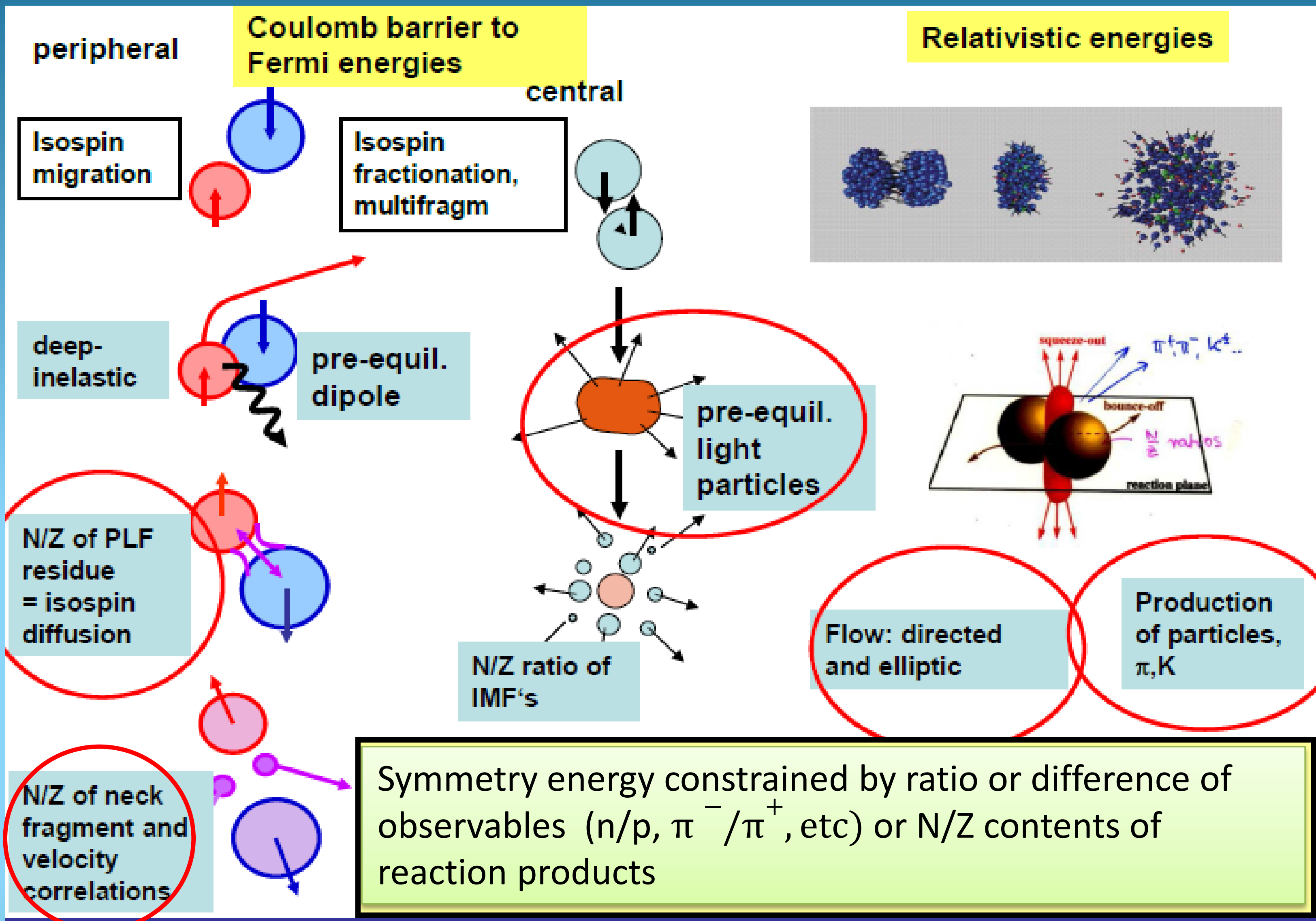
With HIC large density variations (density gradients) in nuclear matter can be obtained in a short timescale.

Isospin asymmetry

Relevance of symmetry energy in astrophysical objects



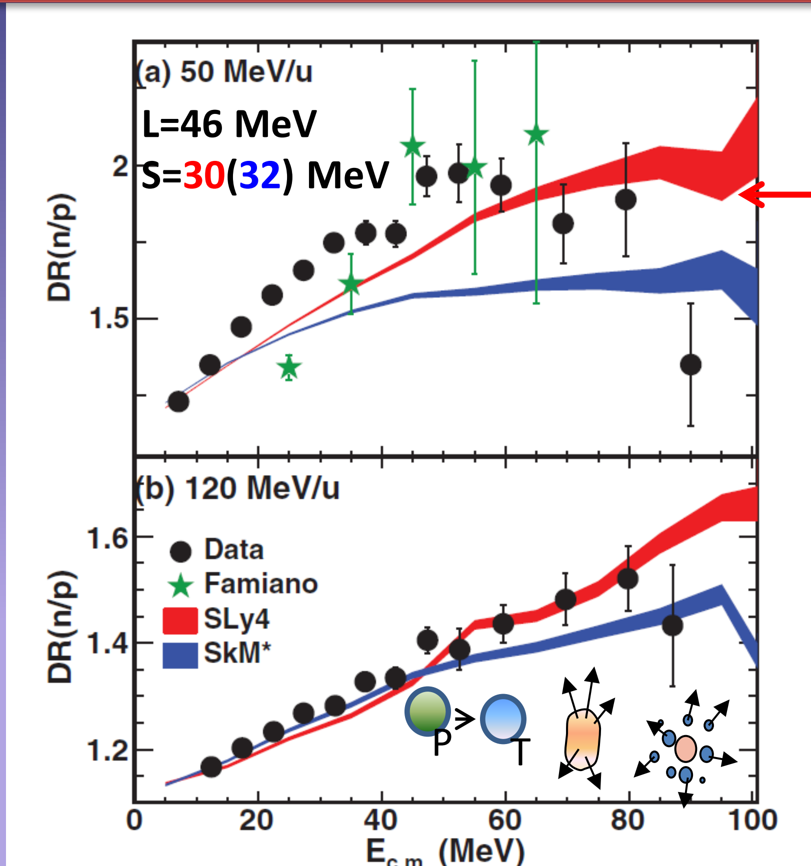
From Nusym2016 introductory lecture by Hermann Wolter



Symmetry energy constrained by ratio or difference of observables (n/p, π^-/π^+, etc) or N/Z contents of reaction products

Symmetry energy at low density: momentum dependence of the nucleonic mean-field potential (an example with MSU data)

$$DR_{n/p} = \frac{R_{n/p}\left(^{124}Sn + ^{124}Sn\right)}{R_{n/p}\left(^{112}Sn + ^{112}Sn\right)}$$



SkM* $m_n^* > m_p^*$ — ImQMD

SLy4 $m_n^* < m_p^*$ — ImQMD

More repulsive potential for neutrons

Coupland et al., Phys. Rev C94 011601 (2016)

Effettive mass splitting not well constrained yet

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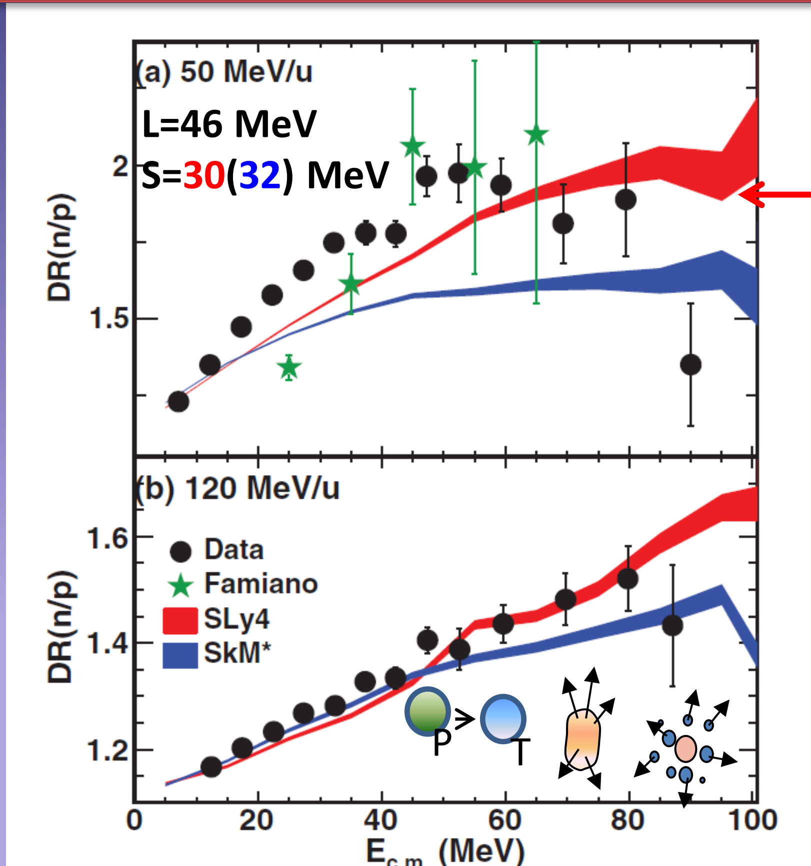

Coupland et al., Phys. Rev C94 011601 (2016)

SkM* $m_n^* > m_p^*$ ImQMD

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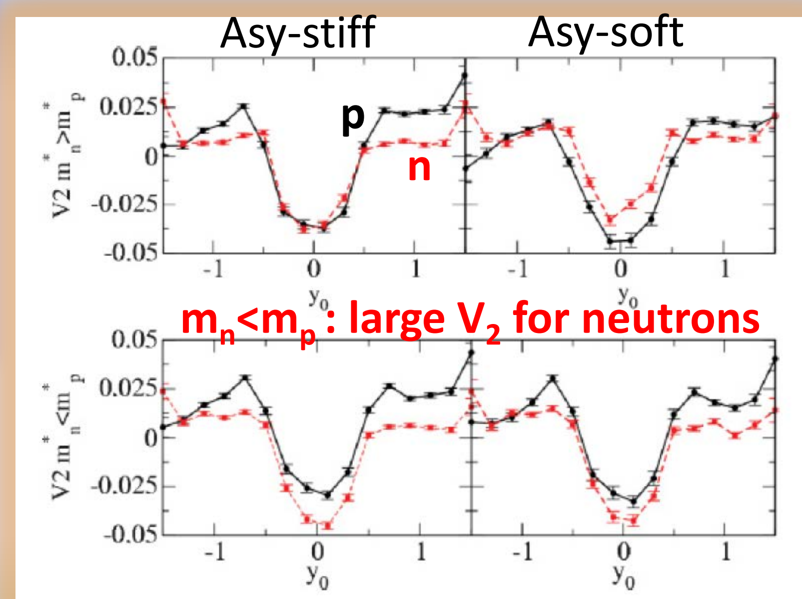
More repulsive potential for neutrons

SMF model: Impact of mass-splitting on Elliptic Flow Au+Au@400 A.MeV

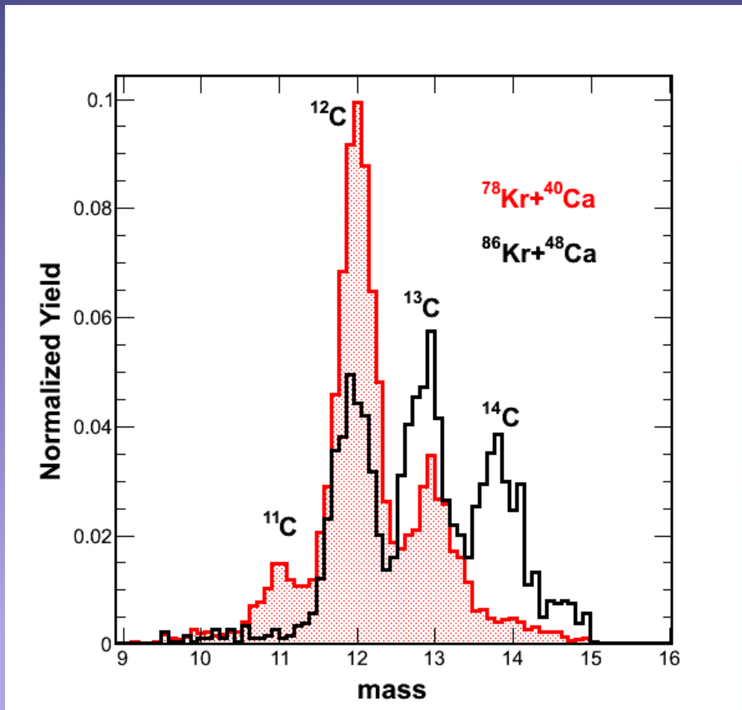


$m_n < m_p$: large V_2 for neutrons

Effettive mass splitting not well constrained yet

V. Giordano, M. Colonna et al., Phys. Rev C81 044611 (2010)

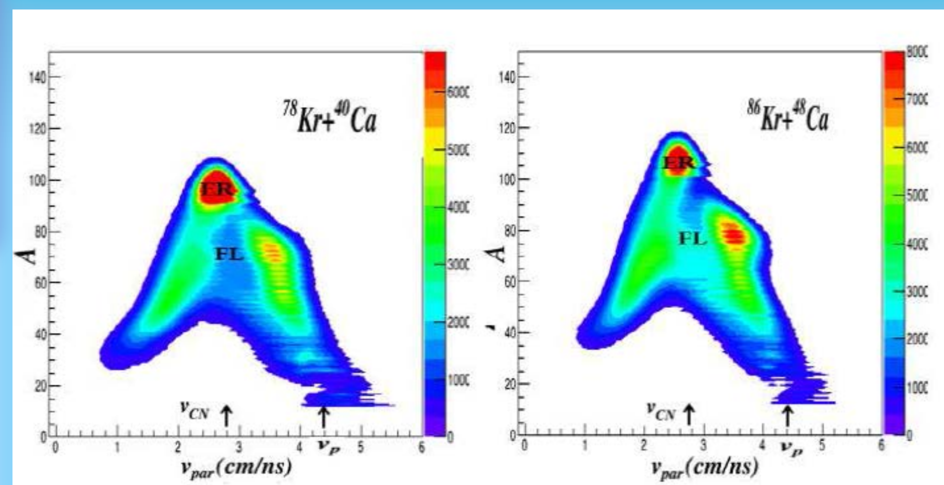
Isospin influence on reaction mechanisms at low energies (E/A<15 A.MeV)



The ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca @10 A.MeV reactions (ISODEC experiment)

Evaporation residues, fission-like fragment and total reaction cross sections.

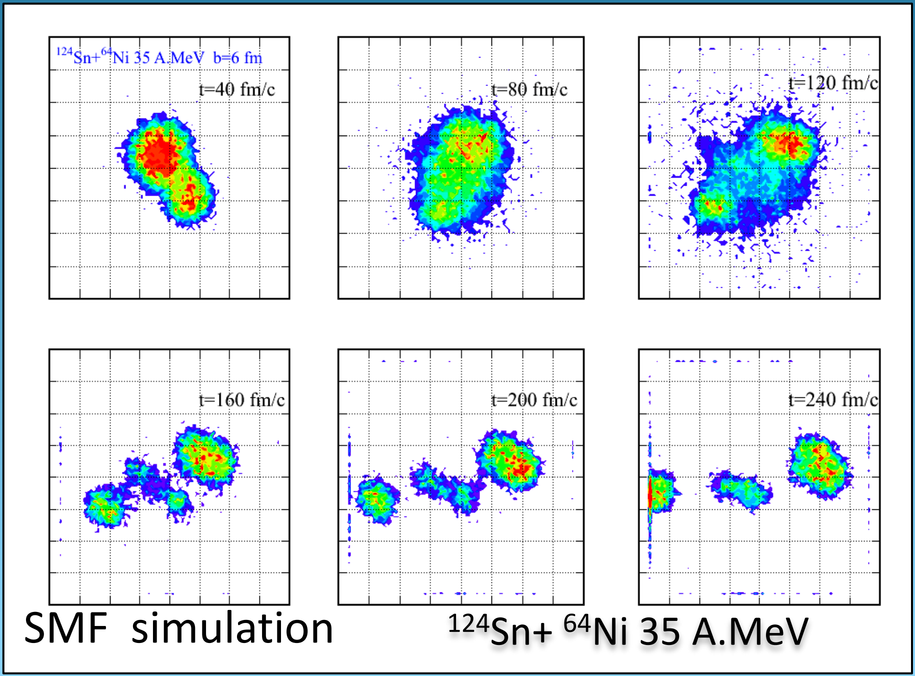
	σ_{ER} (mb)	σ_{FL} (mb)	σ_{ER}/σ_{FL}	σ^{qp}_{reac} (mb)
^{78}Kr+^{40}Ca	455±70	790±120	0.58	2390±250
^{86}Kr+^{48}Ca	400±60	560±85	0.71	2520±260



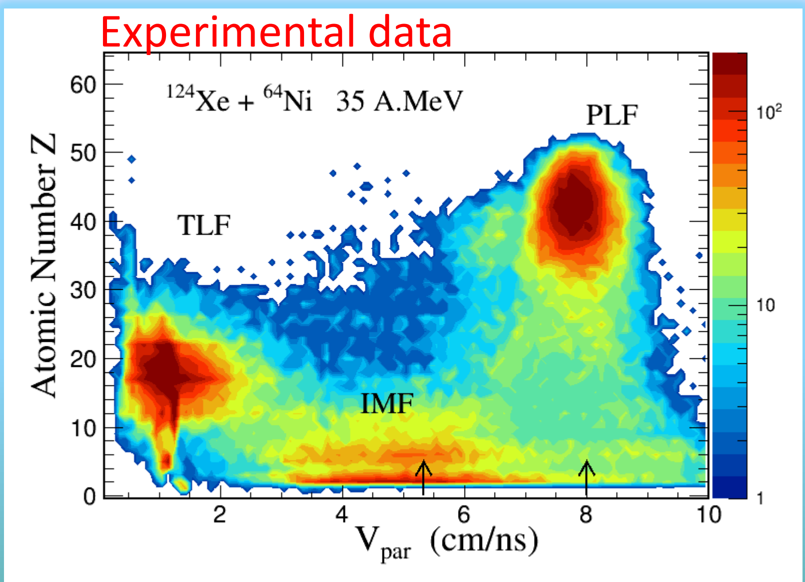
Comparison with stochastic transport models (SMF, BLOB, ..) can look at interplay among CN formation, fission, deep-inelastic processes , quasi-fission, etc for systems with different isospin → (**exotic beams, Spes - Spiral2 interplay**)

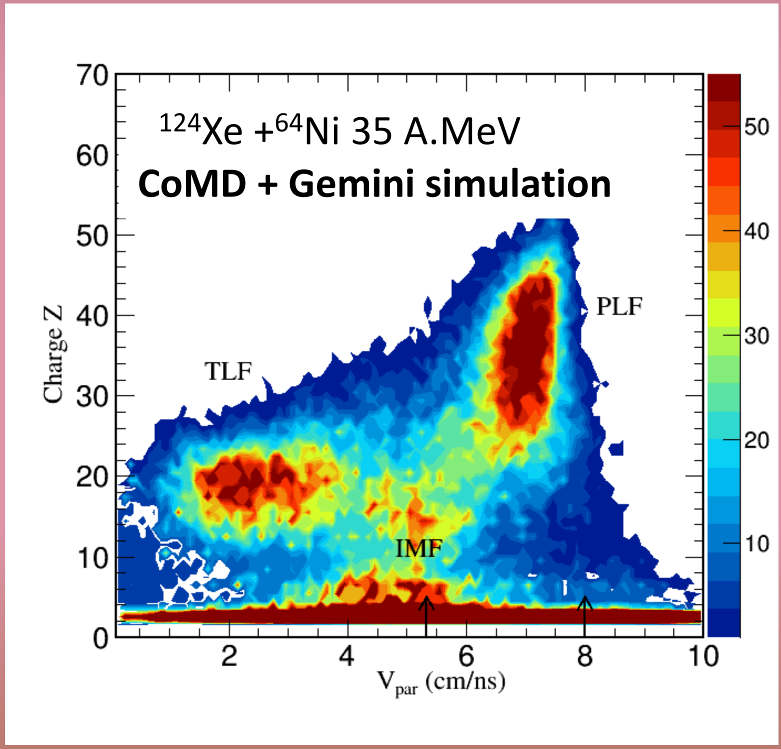
To be submitted to PRC
LOI at SPES@LNL ^{92,94}Kr

IMFs in semi-peripheral reactions: a challenge for transport models

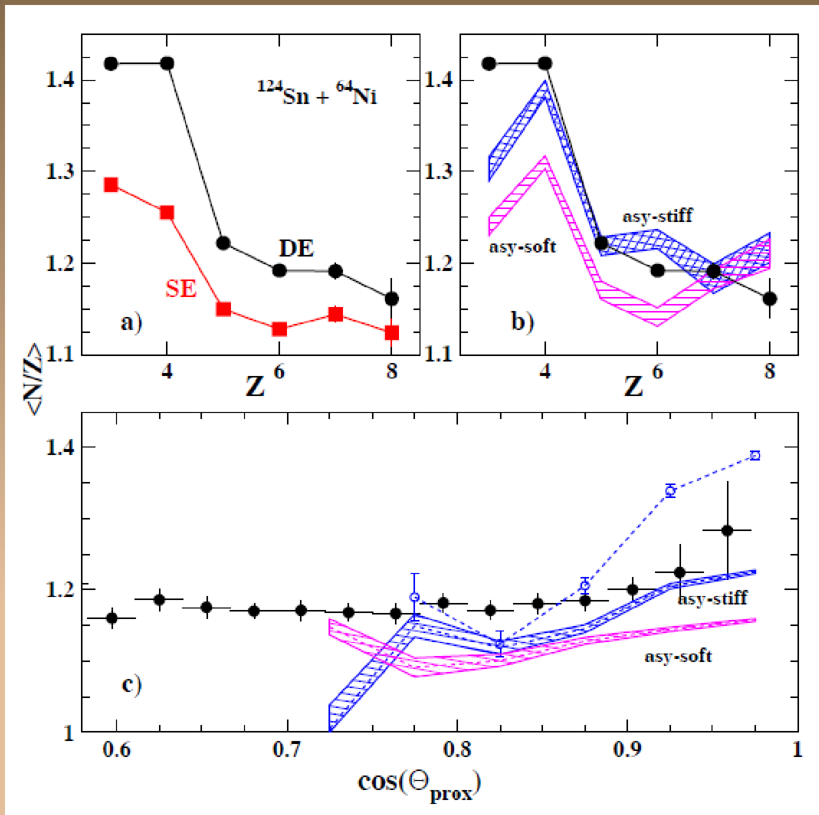


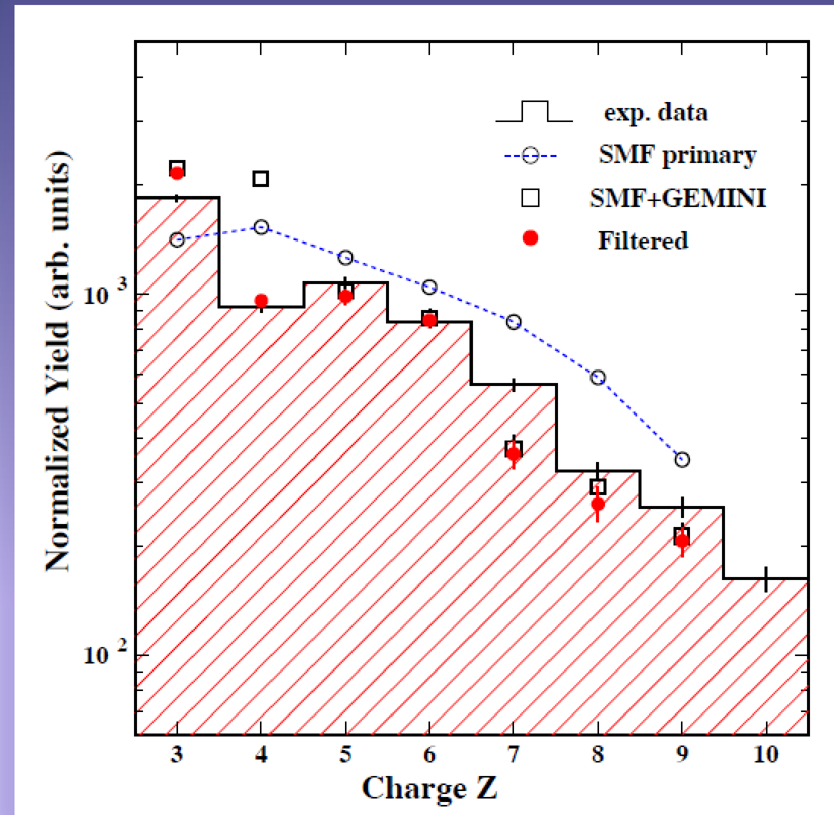
1) The "**neck**" emission where light IMFs (Z<≈9) are produced at midrapidity due to the rupture of a piece of nuclear matter a low density ("neck"). This is a **FAST** process (<100 fm/c)



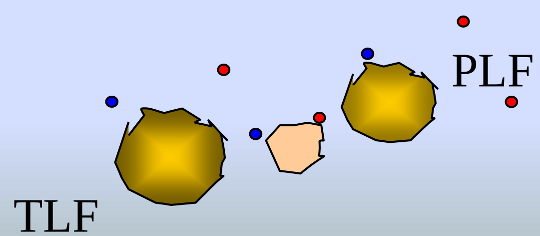


Properties of dynamically emitted fragments: SMF and Chimera data





E.d.F et al., Phys. Rev C86 014610 (2012)



- ❑ Good reproduction of reactions dynamics
- ❑ Asy-stiff (L=75 MeV) better reproduce the N/Z content of IMFs
- ❑ Open problems →

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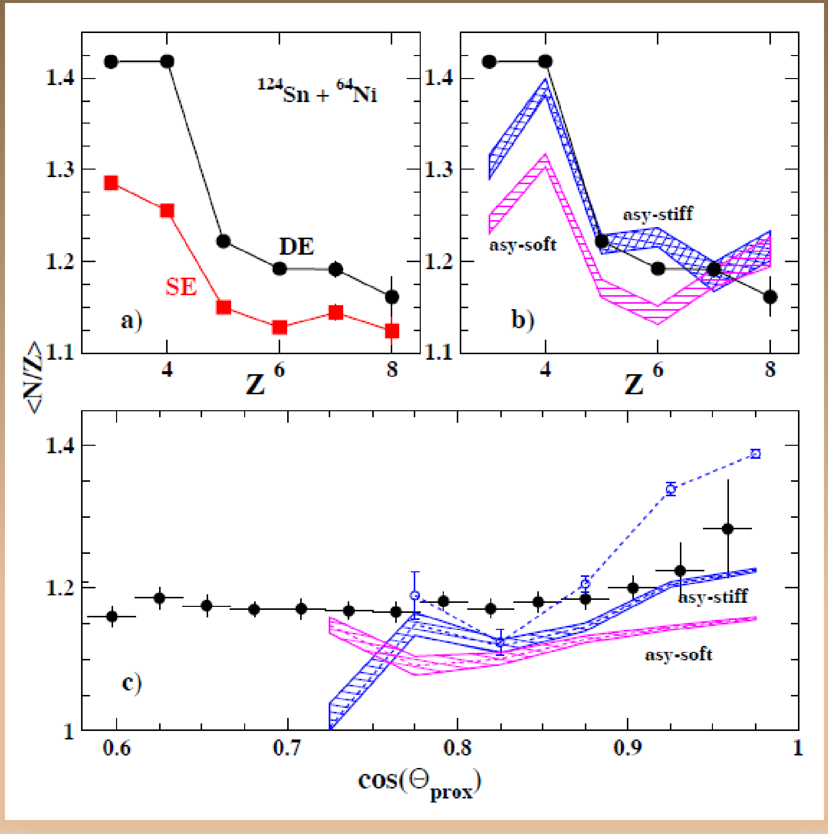

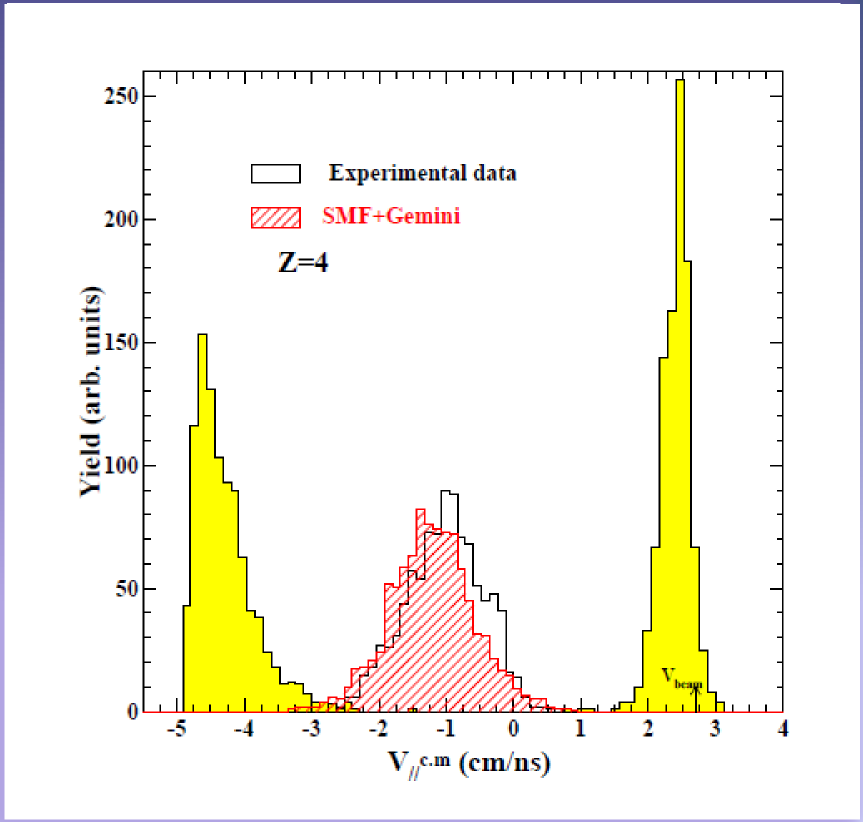

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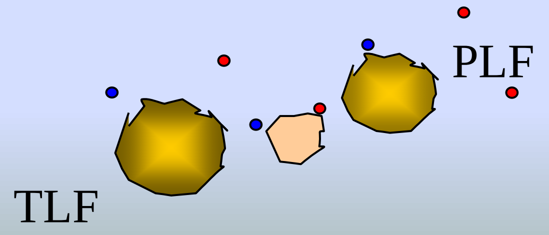

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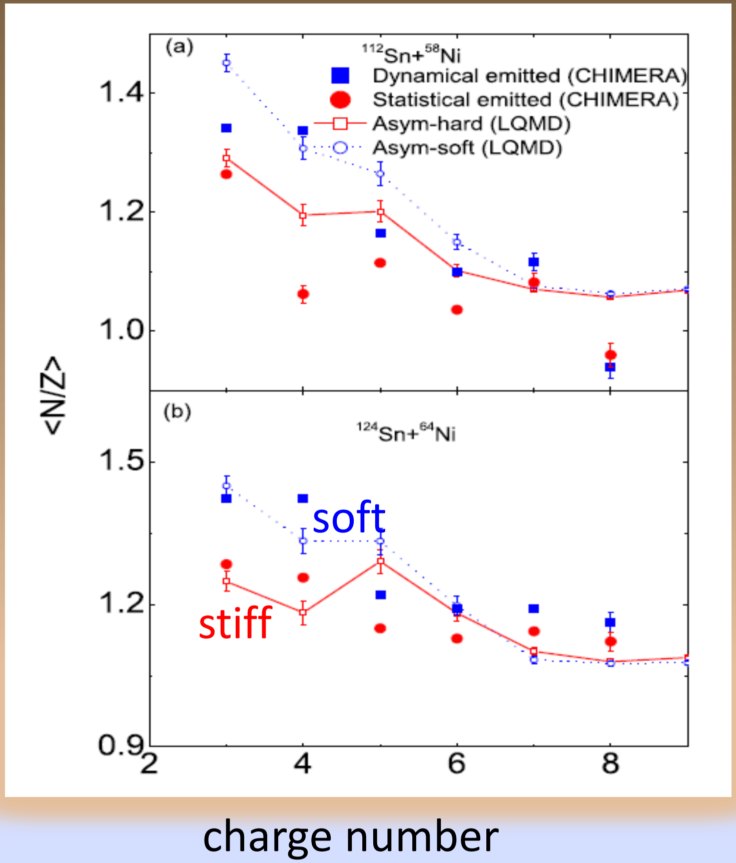

LQMD calculations for Sn+Ni reaction at 35 A.MeV:

More neutron rich particles for a asy-soft case in neck fragmentation dynamics

Zhao-Qing Feng , PRC94,014609 (2016)

Effect of symmetry energy at low density ?

Problems of data reproduction by using different models: need different observables at same times both in experiment and theory.

Need coherent results by different models

Some experimental signatures:

Clear distinction of dynamical (DE) and statistical emission (SE)

Production of DE light IMFs at low densities $\rho \approx 1/3\ \rho_0$

N/Z enrichment for dynamical emitted fragments

Link between IMFs emission time-scale, isotopic composition and phace-space alignments

Enhanced IMF production for neutron rich systems

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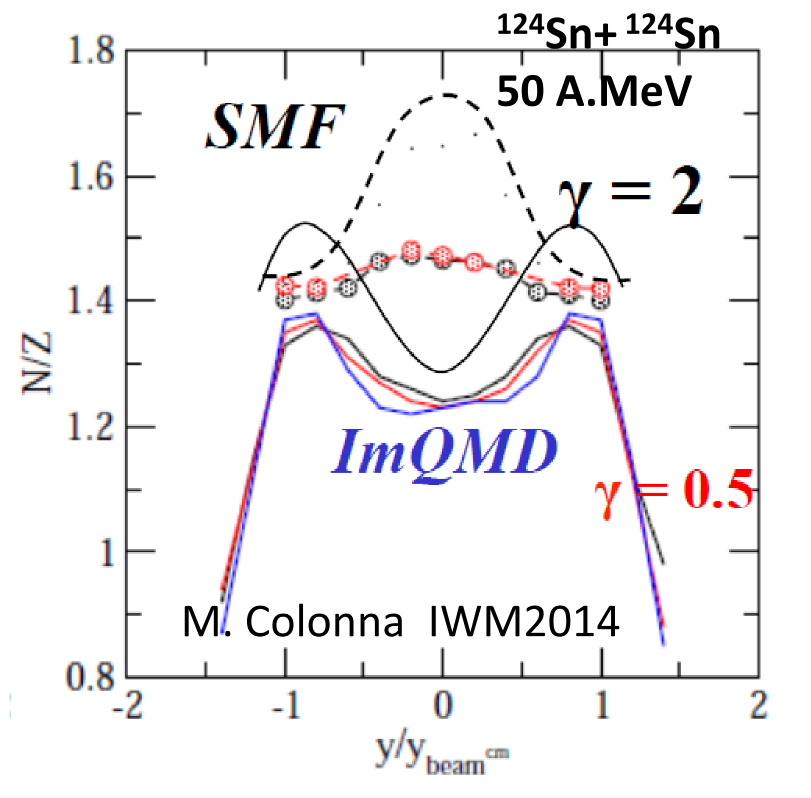

charge number

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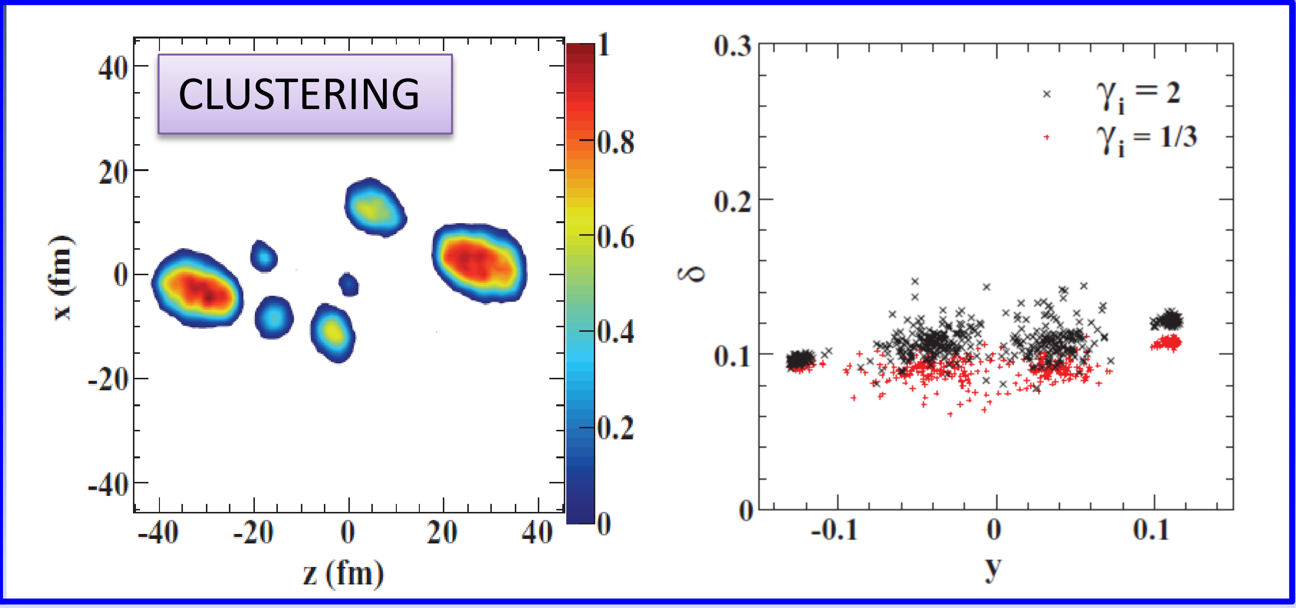
Open problems:

Effect of early cluster productions: influence on dynamics



pBUU model: *D. Coupland et al. Phys. Rev. C84 054603 (2011)*

Reduced **isospin migration and diffusion** through the neck.

Less sensitivity to EOS parametrization

Open problems:

At which density does cluster formation appear ? (see L. Qin et al. ….)

Inclusion of cluster formation as "ingredient" in transport models (AMD [Ono] has cluster production)

Realistic production of light fragments in the models

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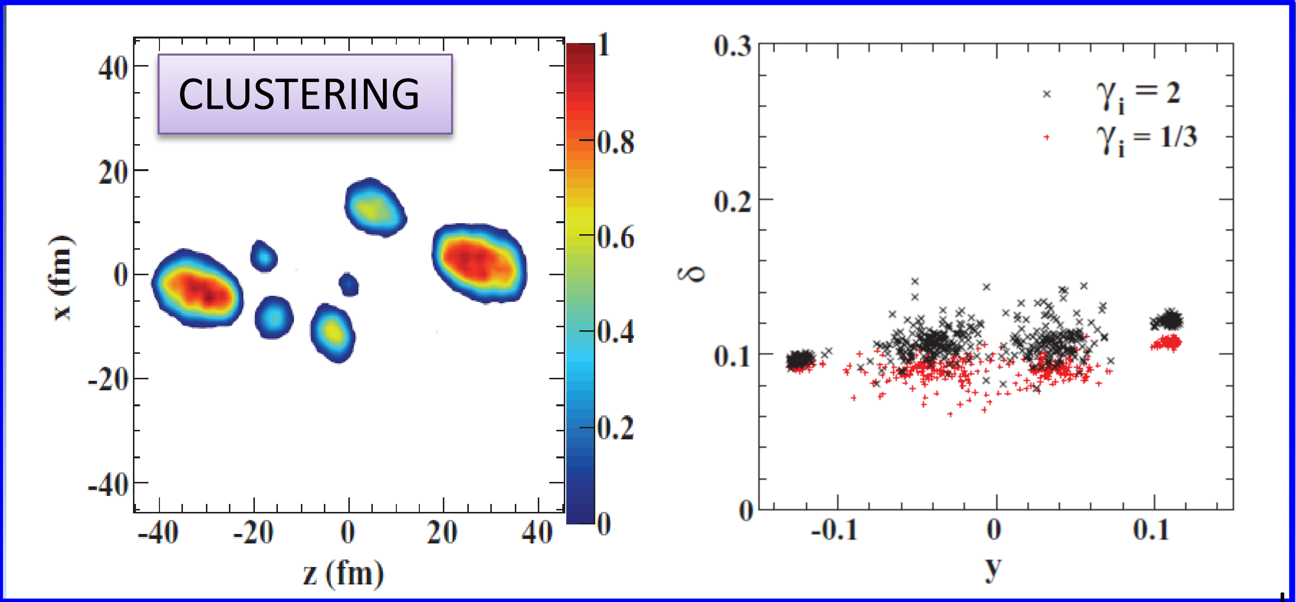

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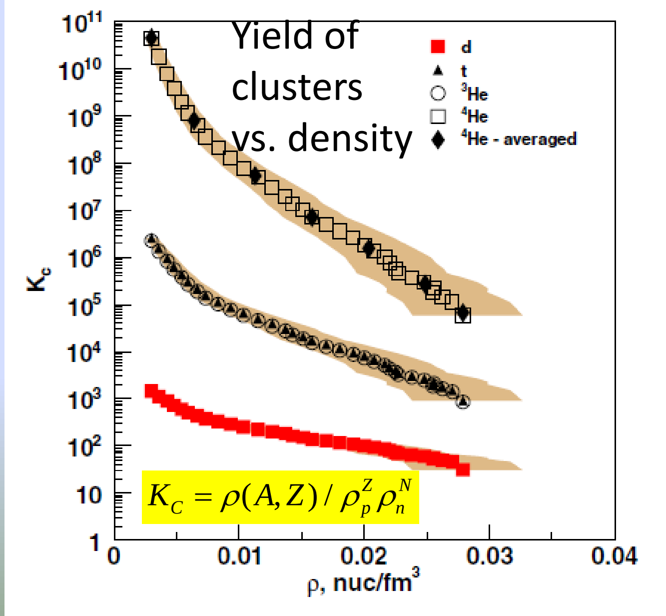

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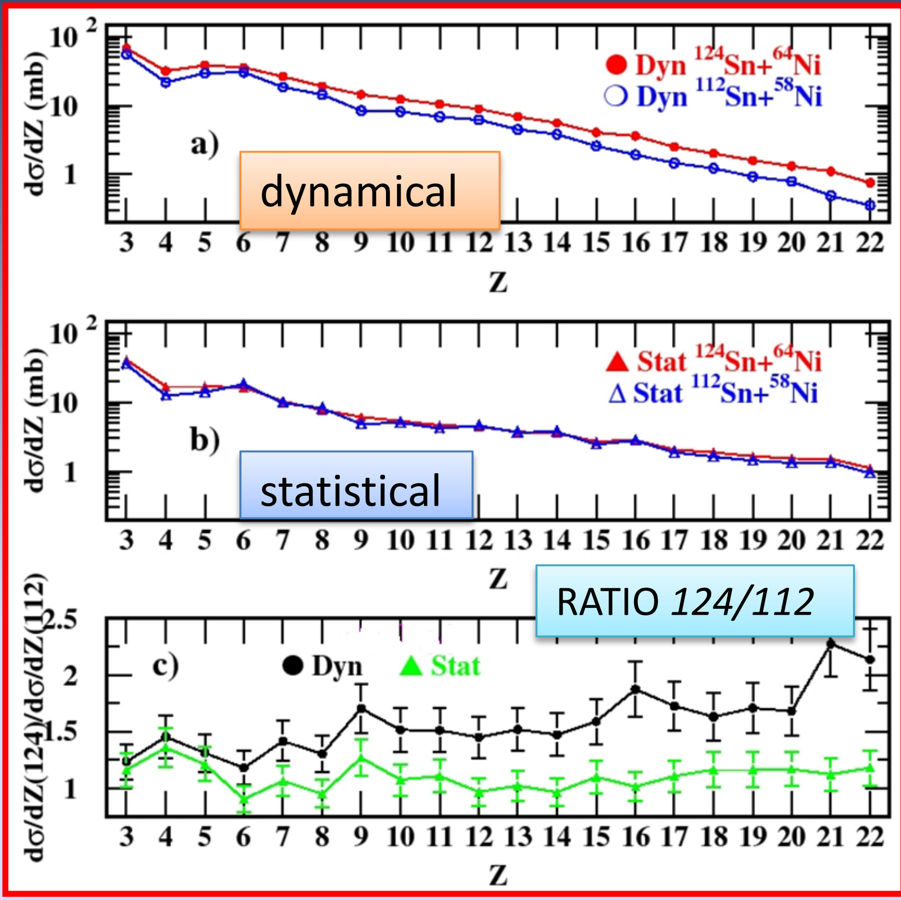
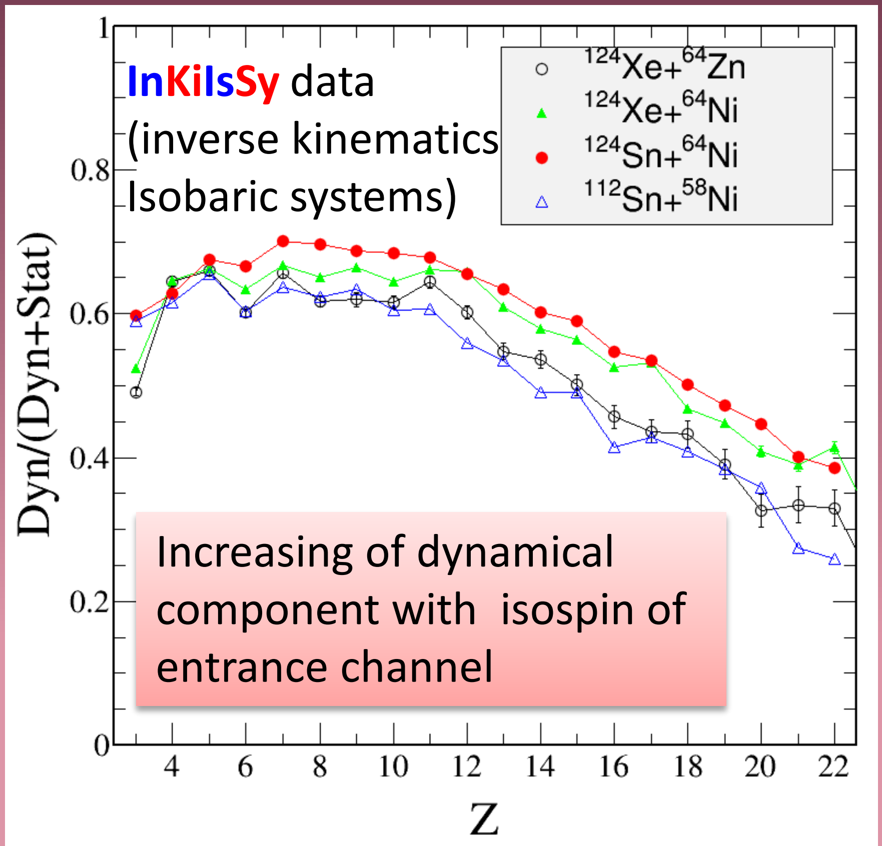
Isospin dependence on projectile break-up



P. Russotto et al. , Phys. Rev. C91, 014610 (2015)

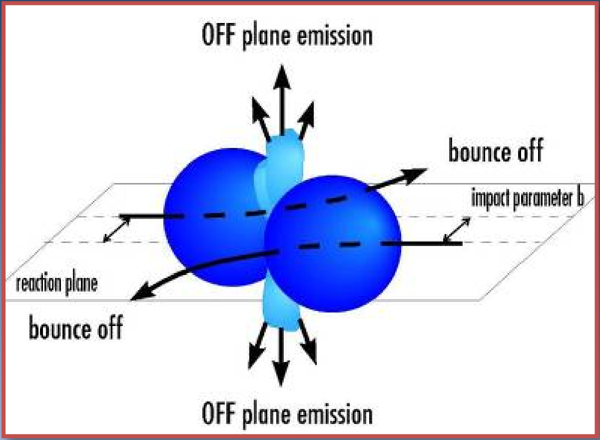


to be submitted

Main experimental signature:
Probability of dynamical emission enhanced for neutron rich system

Open problems:
Calculations need to follow the full range of times scale involved and the whole IMF mass spectrum

HIGH DENSITIES: COLLECTIVE FLOWS



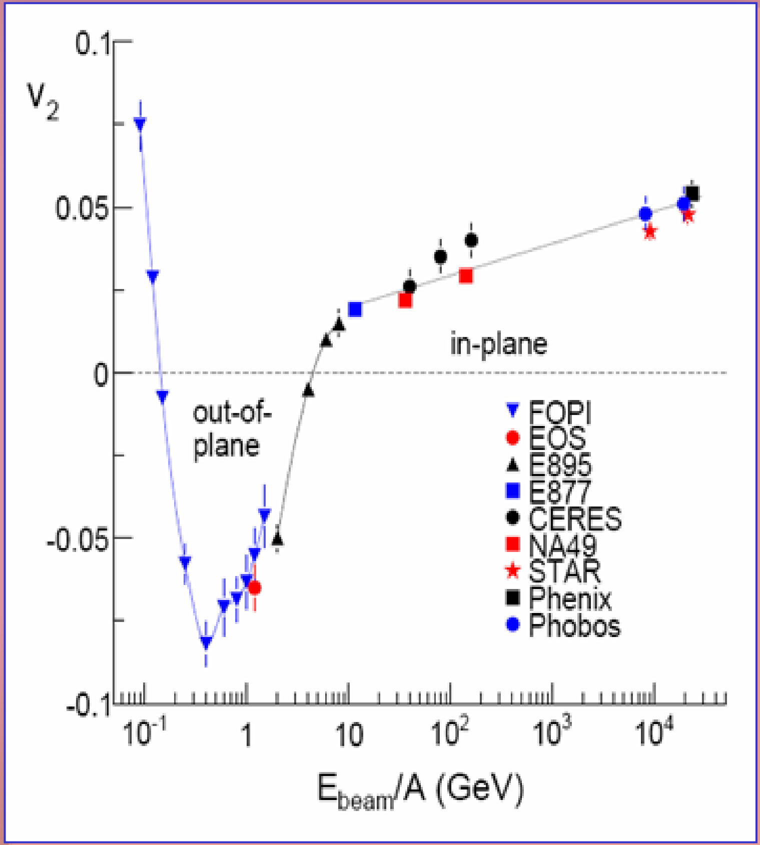
$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

Transverse flow

$$V_1(y,p_t)=\left\langle\frac{p_x}{p_t}\right\rangle$$

Elliptic flow

$$V_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$



Elliptic flow: competition between in plane (**$V_2>0$**) and out-of-plane ejection (**$V_2<0$**)

Transverse flow: *it provides information on the azimuthal anisotropy in the reaction plane*

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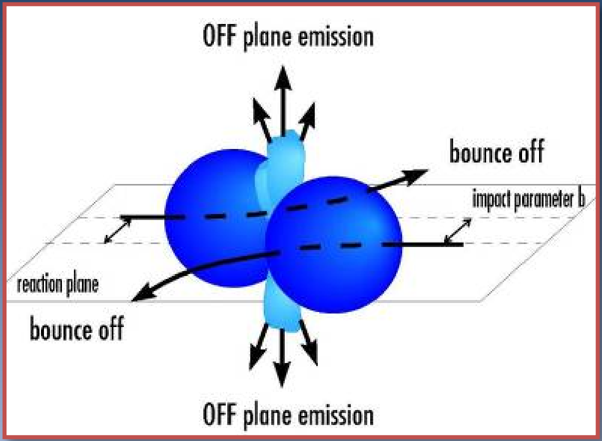

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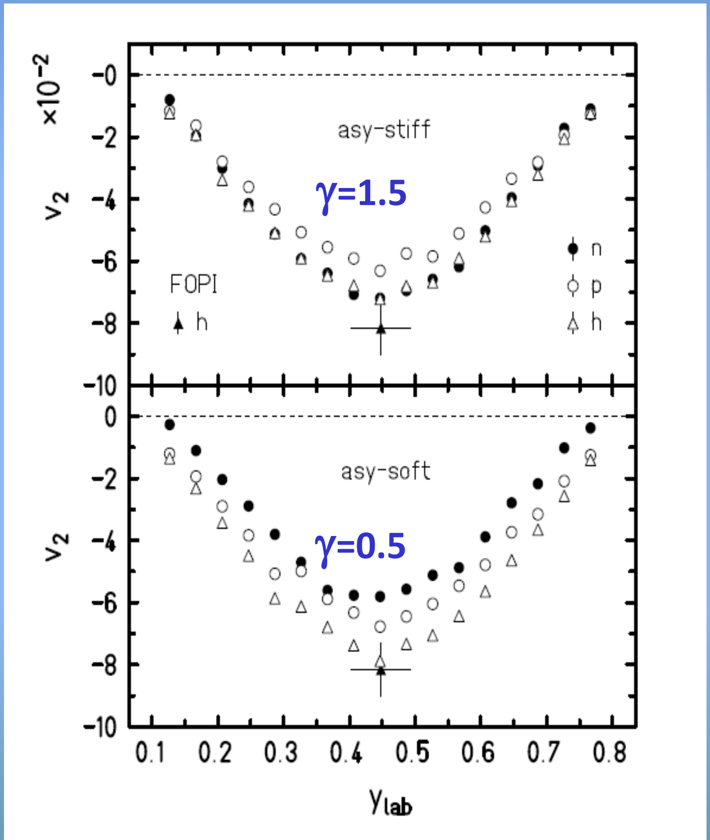


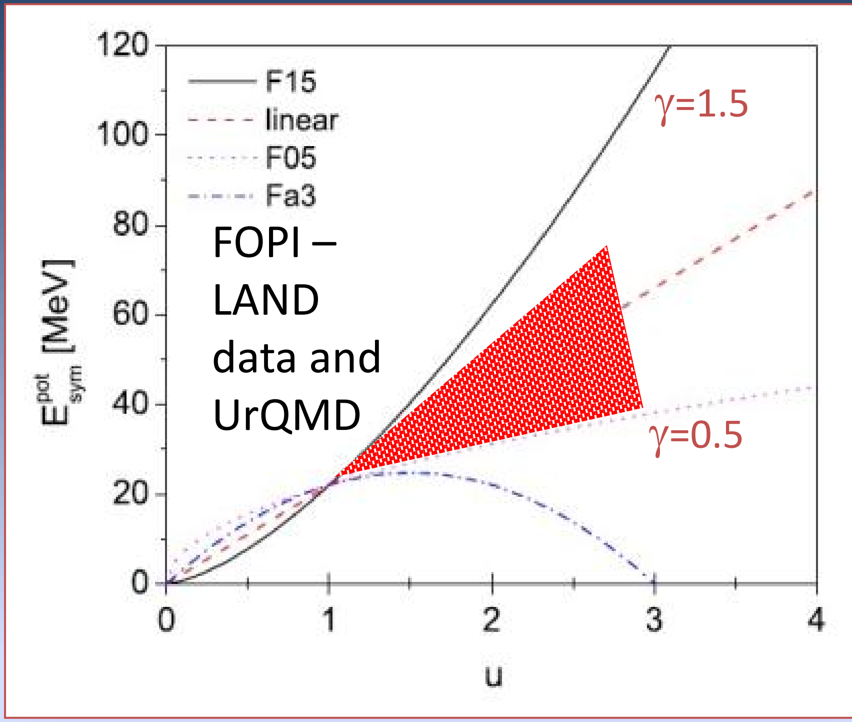
Elliptic flow from FOPI /LAND experiment Au+Au 400 A.MeV

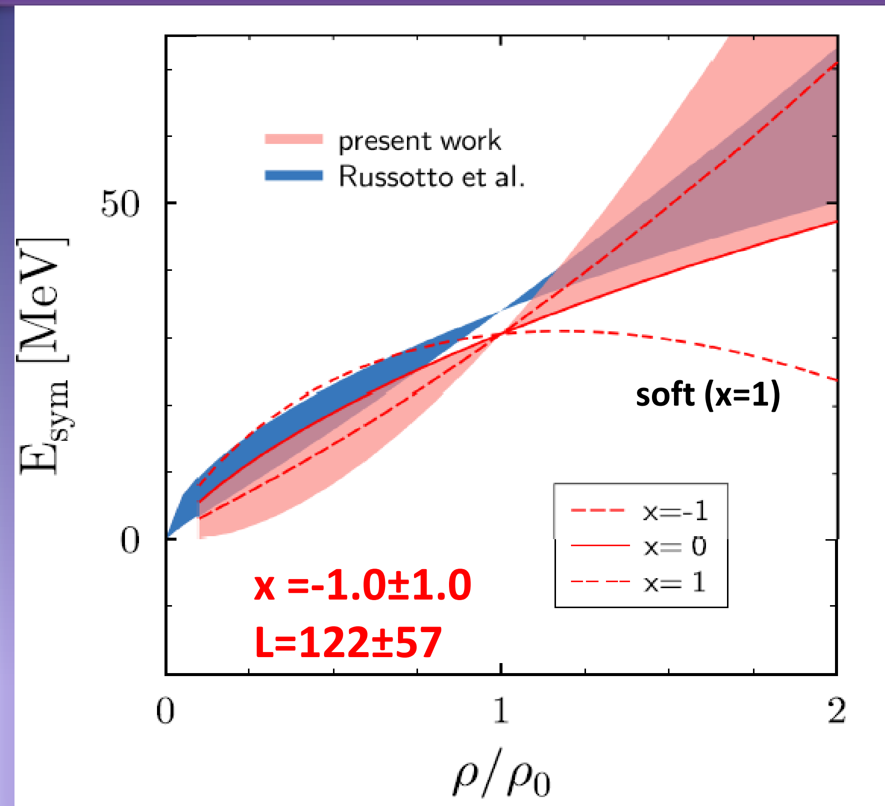
UrQMD model: Au+Au @ 400 AMeV
5.5<b<7.5 fm

Qingfeng Li, J. Phys. G31 1359-1374 (2005)

P. Russotto et al., Phys. Lett. **B697,** 471 (2011)

UrQMD vs. Tubingen QMD: searching for model invariance





UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS
momentum independent power-law parameterization of the symmetry energy

$$\gamma = 0.9 \pm 0.4$$

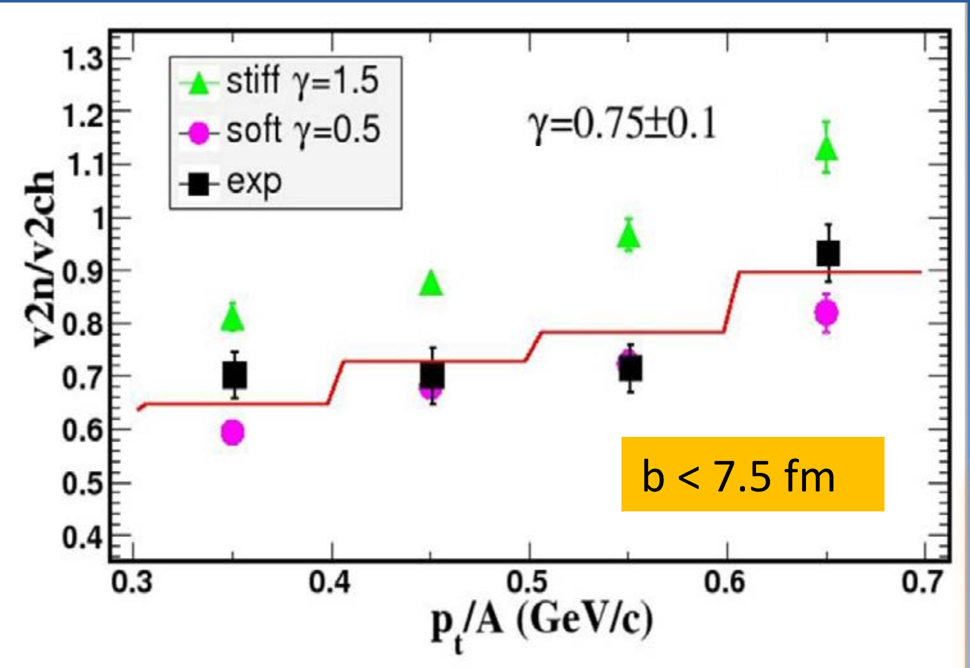
L=83±26

Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

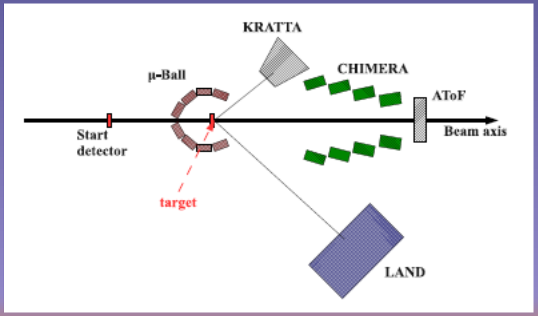
Tübingen-QMD:
density dep. of NNECS
asymmetry dep. of NNECS
soft vs. hard EoS
width of wave packets
momentum dependent (Gogny inspired) parameterization of the symmetry energy

M.D. Cozma et al. , PLB 700, 139 (2011);
PRC 88 044912 (2013)

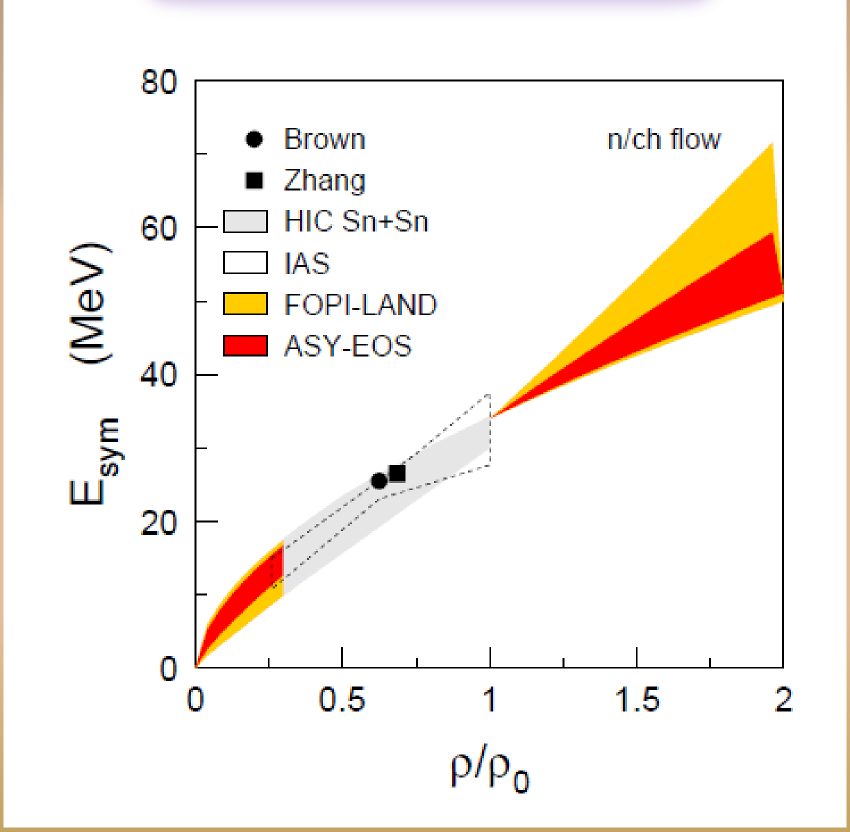
Flow ratios of neutrons/Charged particles in comparison with UrQMD predictions



ASYEOS data,
Phys. Rev. C94, 014609 (2016)



HIC: (mainly Sn+Sn . . .)
M.B. Tsang et al., PRC 86, 015803 (2012)
Neutron skin thickness, binding energies,….:
B.A. Brown, PRL 111, 232502 (2013); Zhang and Chen, Phys. Lett. B 726 (2013).
FOPI DATA : P.Russotto et al., Phys. Lett. B 697 (2011) : **γ = 0.9 ± 0.4 ; L=83±26**
ASYEOS DATA (with final corrections):
γ = 0.72± 0.19 ; L=72±13

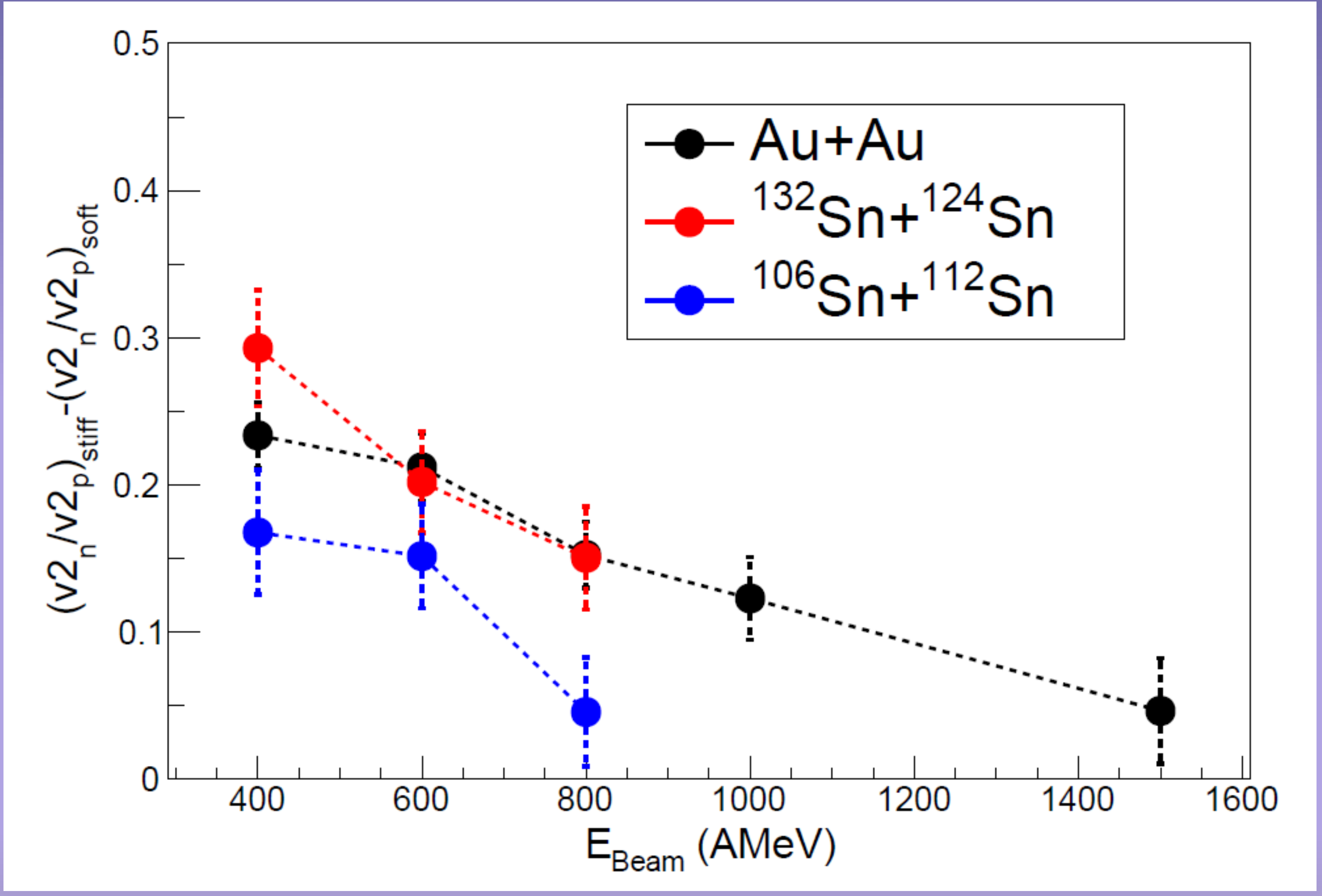


OUTLOOK: UrQMD prediction for some interesting beams (and δ^2)

$^{197}Au+^{197}Au$ @ 400, 600, 800, 1000,1500 AMeV (0.039+0.039)

$^{132}Sn+^{124}Sn$ @ 400, 600, 800 AMeV (0.059+0.037)

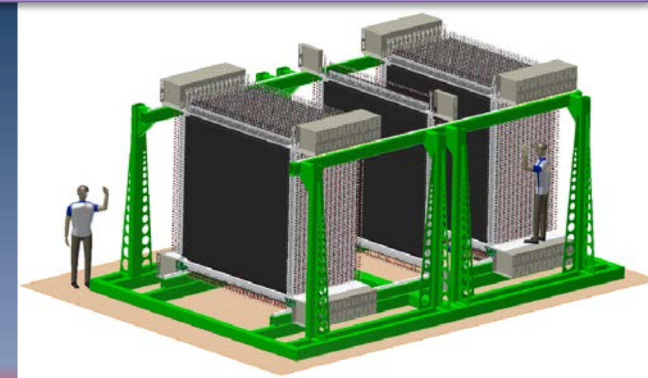
$^{106}Sn+^{112}Sn$ @ 400, 600, 800 AMeV (0.003+0.011)

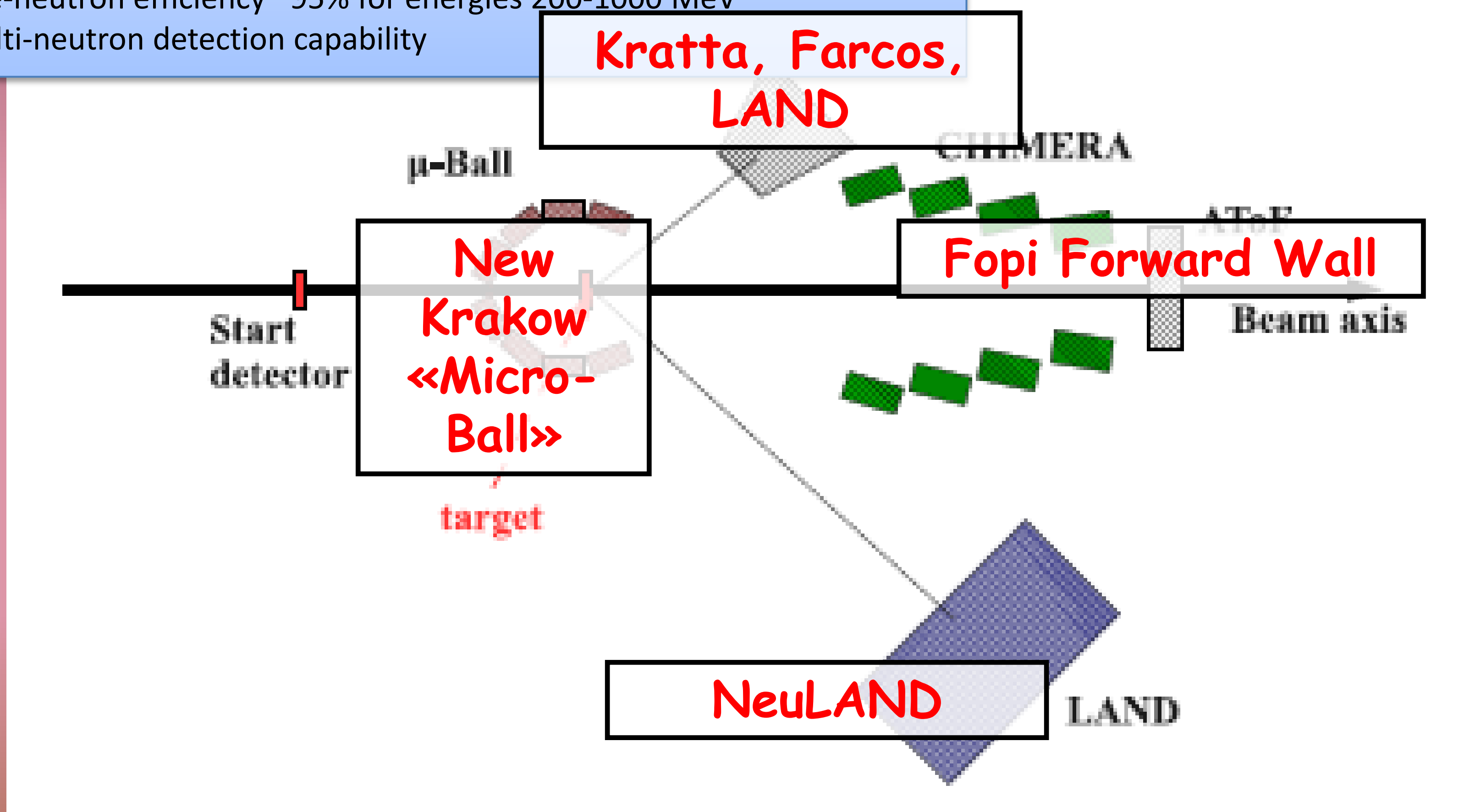


OUTLOOK: PROJECTS FOR FUTURE EXPERIMENTS AT GSI/FAIR

NeuLAND @ FAIR/GSI

- TDR finalized in Oct 2011 and submitted
- total volume 2.5x2.5x3 m^3
- each bar readout by two PMT
- 3000 modules (plastic scintillator bars) 250x5x5 cm^3
- 30 double planes with 100 bars each, bars in neighboring planes
- mutually perpendicular
- $\sigma_t \leq 150$ ps and $\sigma_{x,y,z} \leq 1.5$ cm
- one-neutron efficiency ~95% for energies 200-1000 MeV
- multi-neutron detection capability

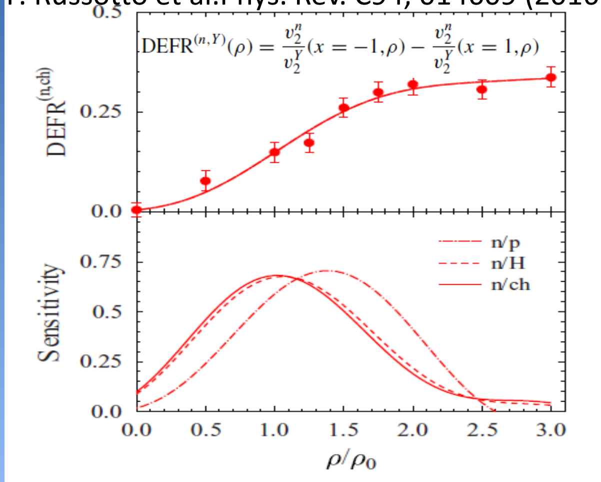




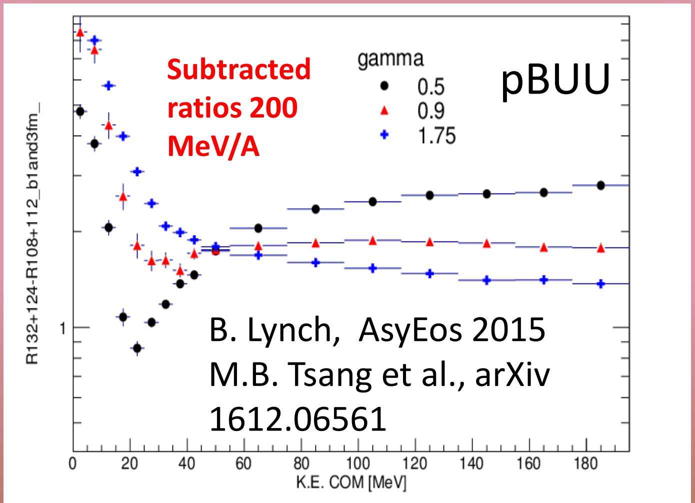
Open problems … or opportunities ?

Sensitivity of observables to density. TuQMD calculations

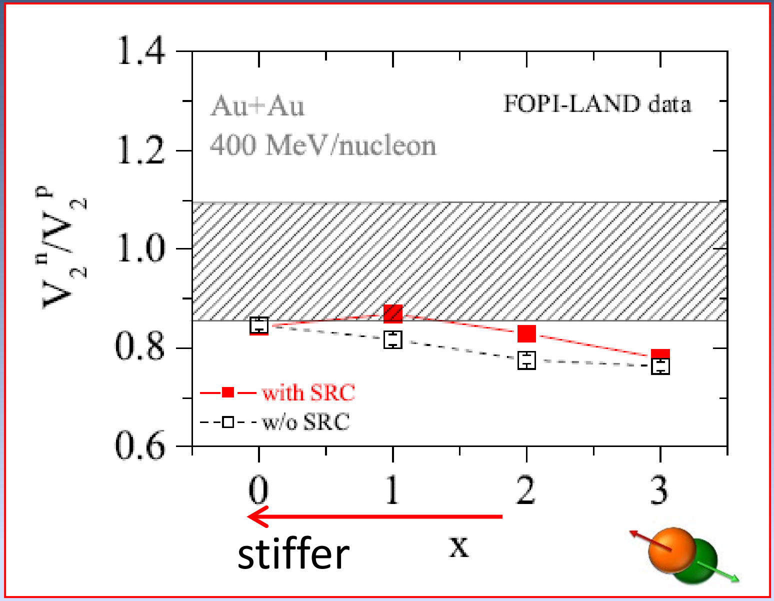
P. Russotto et al.Phys. Rev. C94, 014609 (2016)



New perspectives and advances with PIONS ratios



Short range correlations may influence results



Gao-Chan Yong, Phys. Rev. C ***93****, 044610 (2016)*

F. Zhang, Gao-Chan Yong, EPJA ***52****, 350 (2016)*

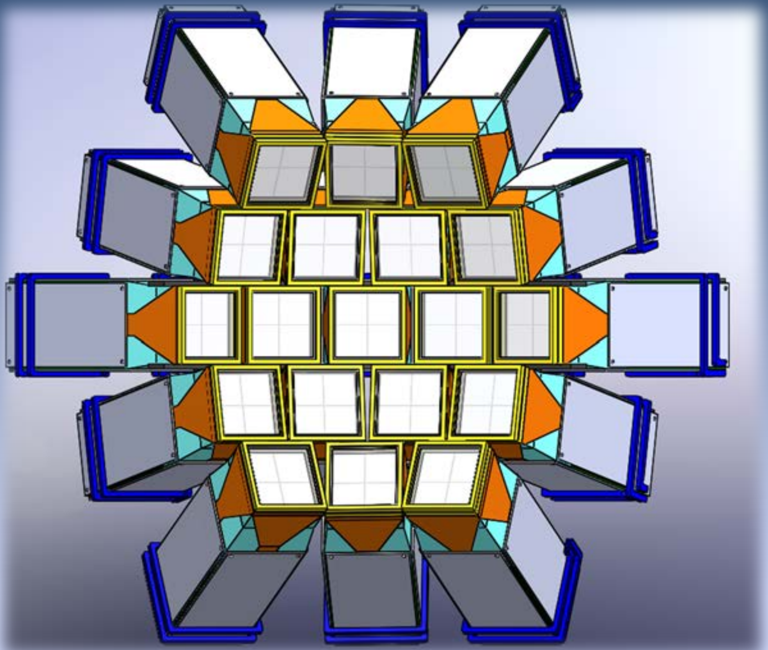
Possibility to look simultaneously to flow data and pions data in future experiments:

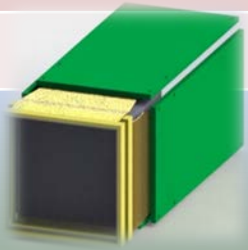
SπRIT TPC, new AsyEos@R3B projects ?

Experimental PERSPECTIVES in CHIMERA group : The FARCOS project

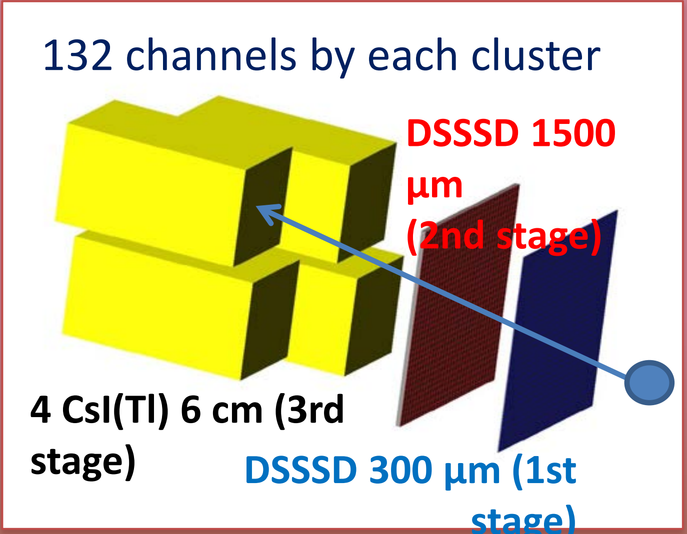
Starting prototype: 4 telescopes : NEWCHIM (2015-2019 final planning 20 telescopes)

Year	Tel.	Operation
2015	6	test acq. GET for FARCOS construction of 2 telescopes purchase of final GET electronics
2016	10	test dual gain module test GET electronic +DAQ Study of alignment system
2017	14(10)	test new asic pre-amplifiars final design modular support implementation asic pre-amplifier new DAQ VME+ GET running First experiments with new Chimera+Farcos front-end
2018	18(?)	Construction of new telescopes
2019	20+2	20 telescopes ready
. . . . .		

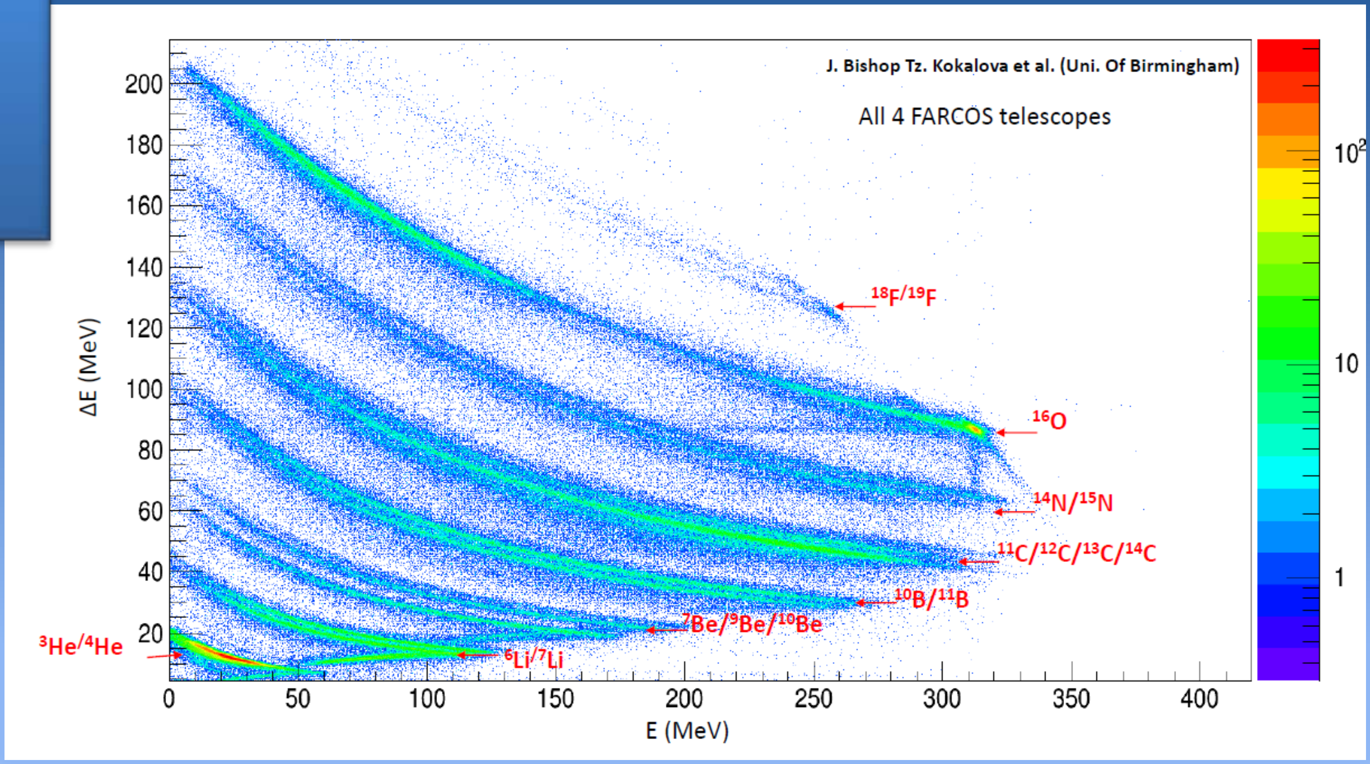




Final cost prediction: ≈< 1 M€



SIKO experiment
University of Birmingham & CHIMERA collaboration



High energy and angular resolution (Δϑ<1°)
Low thresholds (<1 MeV/A):
Pulse-shape on first Si layer for low energy experiments
High counting rate (1KHz)
Large Dynamic range (20MeV to 2GeV)
Flexibility, Modularity, Trasportability
Easy coupling to 4π detectors or spectrometers
Integrated Electronics (GET)

Dynamical processes in projectile break-up and IMF production at 20 A.MeV studied with the CHIMERA and FARCOS devices. CHIFAR: CHImera-FARcos (approved LNS-PAC proposal) **spokes: E.V. Pagano, E.d.F., P. Russotto**

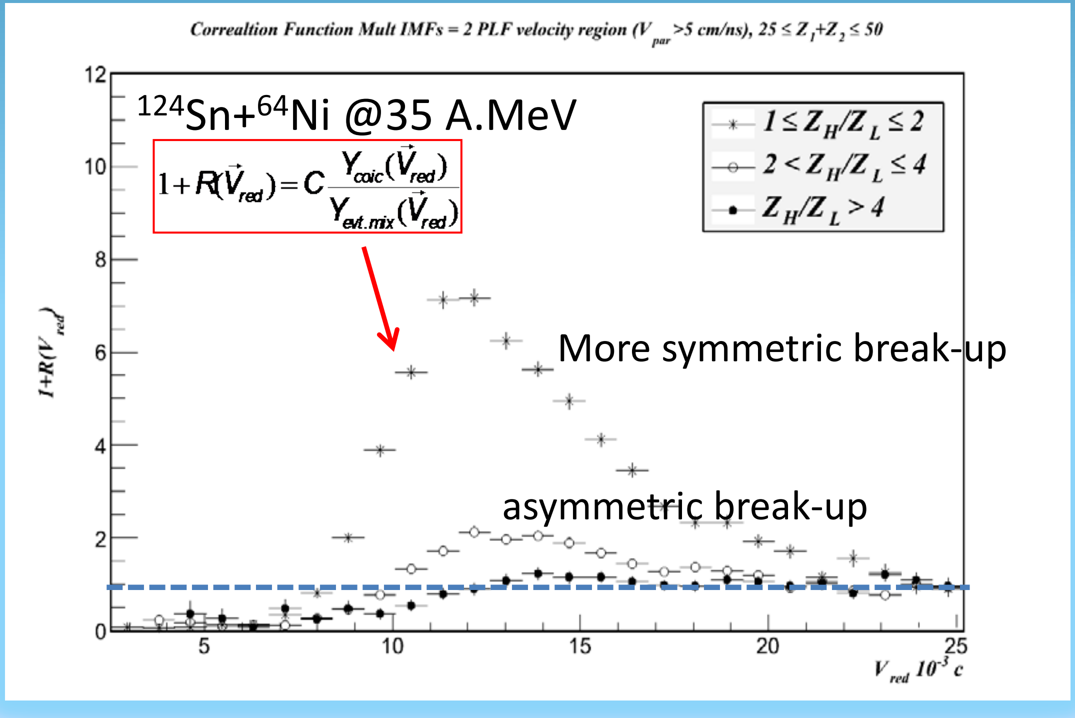
Dynamical processes in projectile break-up and Intermediate Mass Fragments production at **20 A.MeV** beam incident energy studied with the CHIMERA and **FARCOS** devices

CHIMERA + 8 FARCOS telescopes

^{124}Xe, ^{124}Sn + ^{64}Ni, ^{64}Zn

^{112}Sn+^{58}Ni @ 20A.MeV

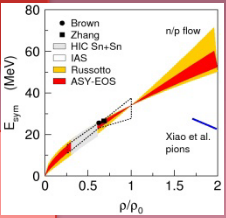
IMF-IMF correlations function



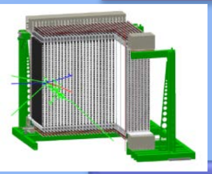
See E.V. Pagano talk

SUMMARY

Transport models are a fundamental tool to learn about the behaviour of the nuclear effective interaction and EOS and at same time reactions dynamics that can be compared with experimental results.
More work on code consistency needed yet. Results (not a review) at low and intermediate energies have been shown.



The AsyEos (S394) experiment results that have given a stringent constraint for the symmetry energy at supra-saturation density, contributing also to improve the understanding of models by careful comparison of data with transport codes.



New experiments like SπIRIT TCP or NeuLand@R3B at GSI or should improve accuracy in observable measurements, giving new results for flows and particles ratios (like p, n, light clusters, π^-, π^+, Kaons, etc) possibly looking simultaneously at different observables by using stable and radiactive beams.