Opportunities for HIC at FRIB and GANIL energies: symmetry energy and in-medium correlations

Giuseppe Verde (INFN-Catania & L2I Toulouse)

outline

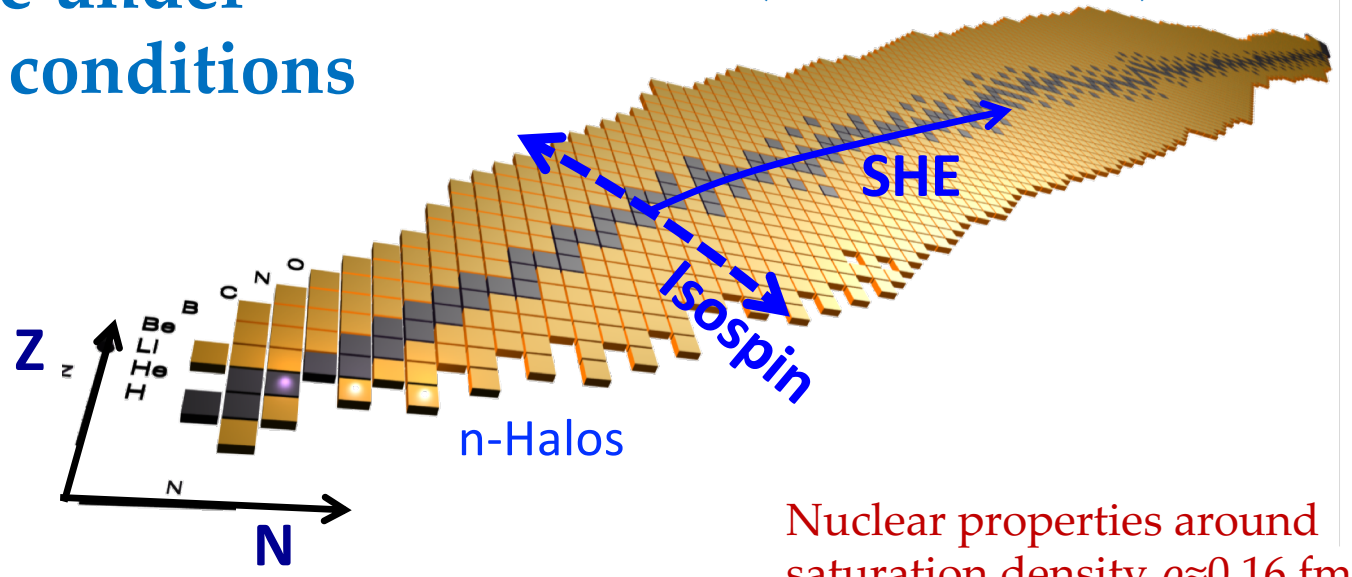
- HIC as a tool for dynamical investigations of nuclear structure: interplays of EoS and nuclear properties

  This is also an introduction to the talks by Arnaud, Luigi and Simone

- Isospin diffusion and drift at GANIL: some results from INDRA-VAMOS and INDRA-FAZIA
- In-medium nuclear structure effects on dynamics: particle-particle correlations, cluster states, resonances
- A word on perspectives: FRIB

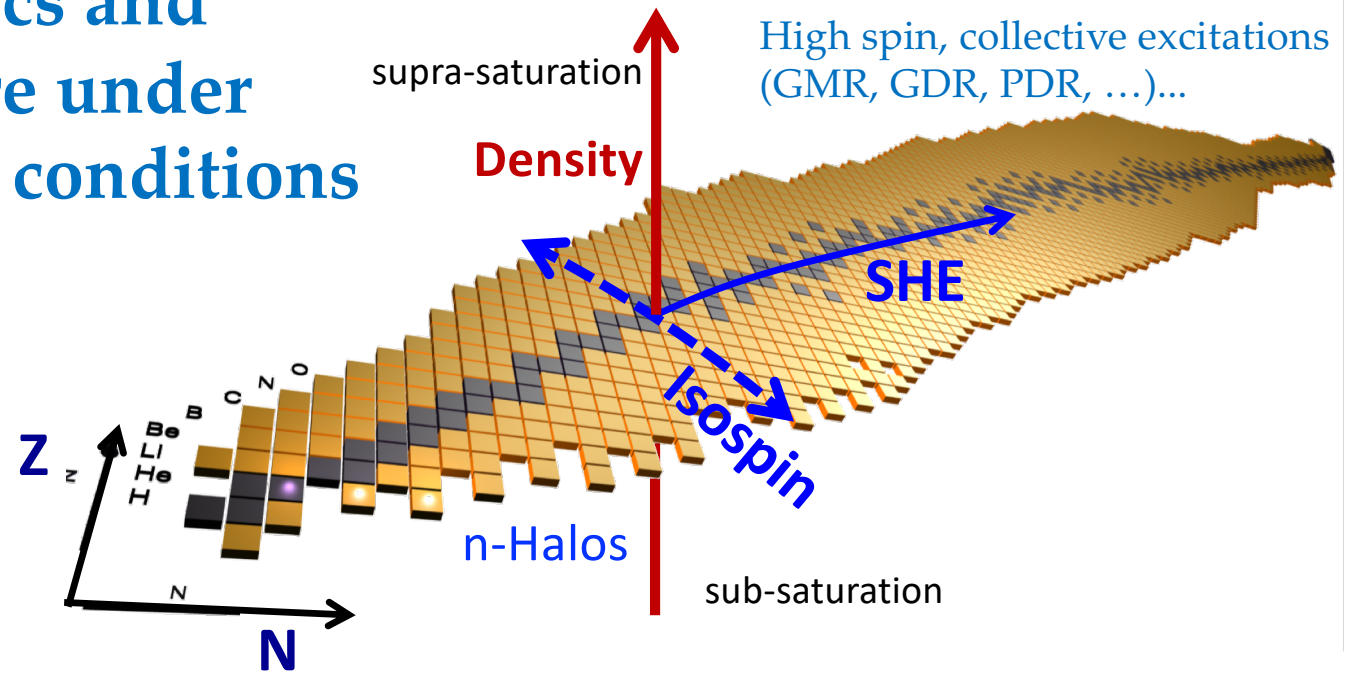
Dynamics and Structure under extreme conditions

Extreme conditions: deformations, High spin, collective excitations (GMR, GDR, PDR, …)...



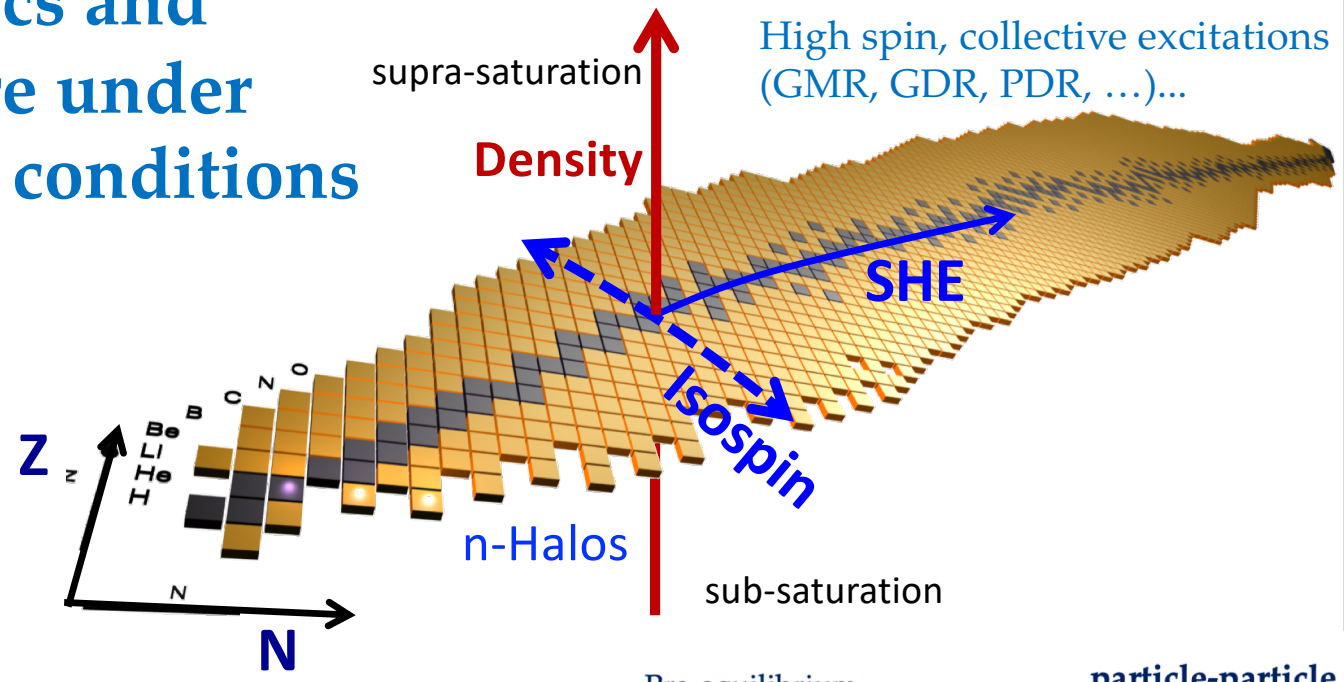
Nuclear properties around saturation density $\rho \approx 0.16$ fm^{-3}

Dynamics and Structure under extreme conditions

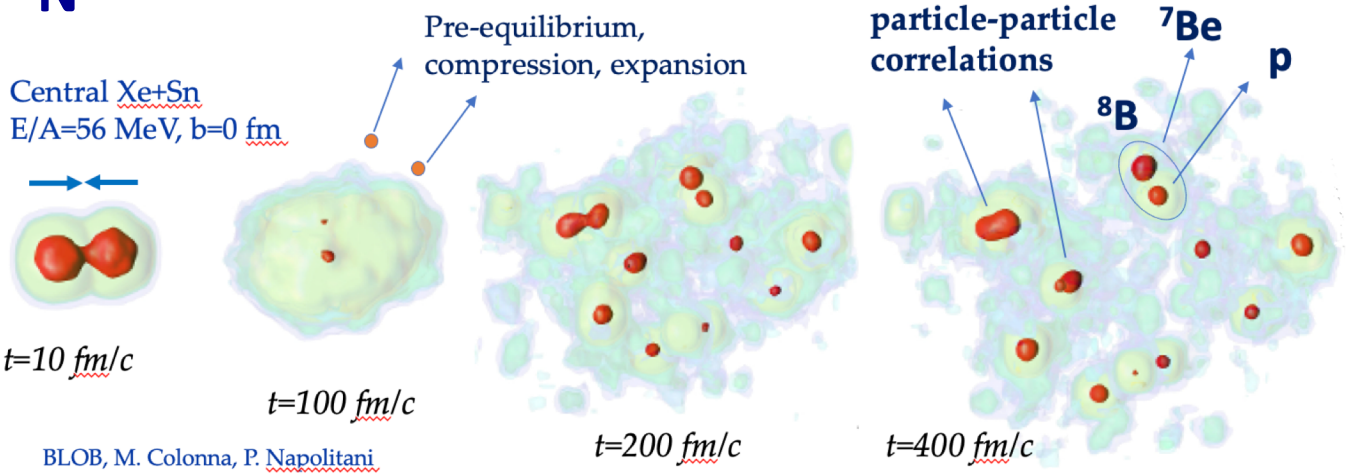


Dynamics and Structure under extreme conditions

Extreme conditions: deformations, High spin, collective excitations (GMR, GDR, PDR, …)...



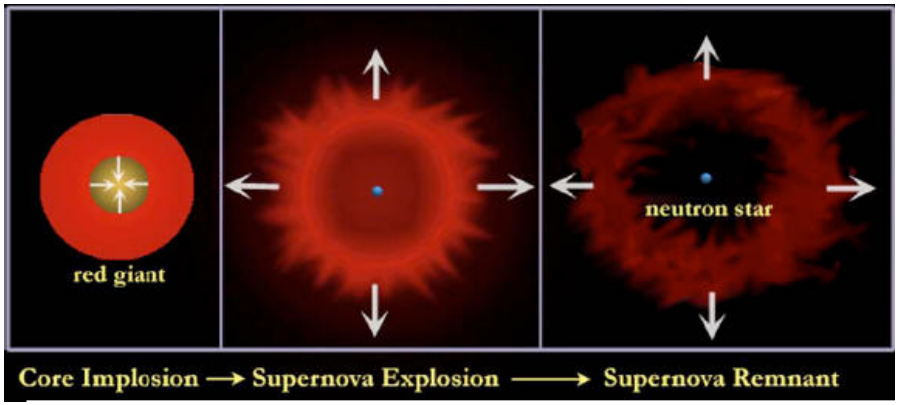
HIC at E/A=20-100



Important astrophysical implications

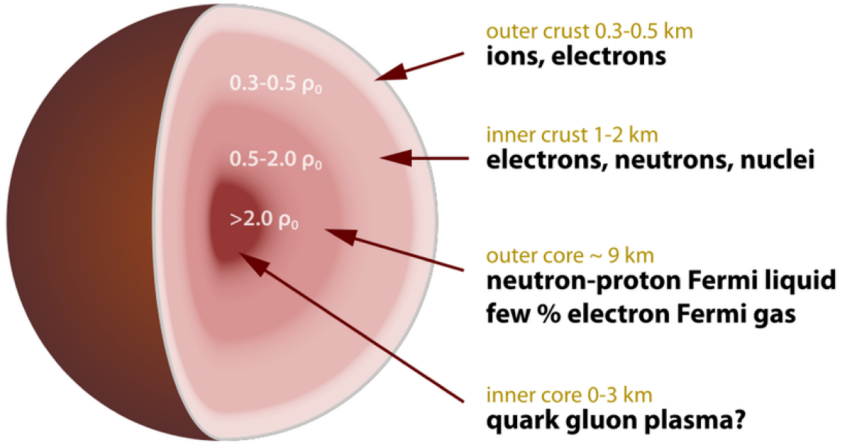
Type II supernovae explosions

- **neutrinosphere**

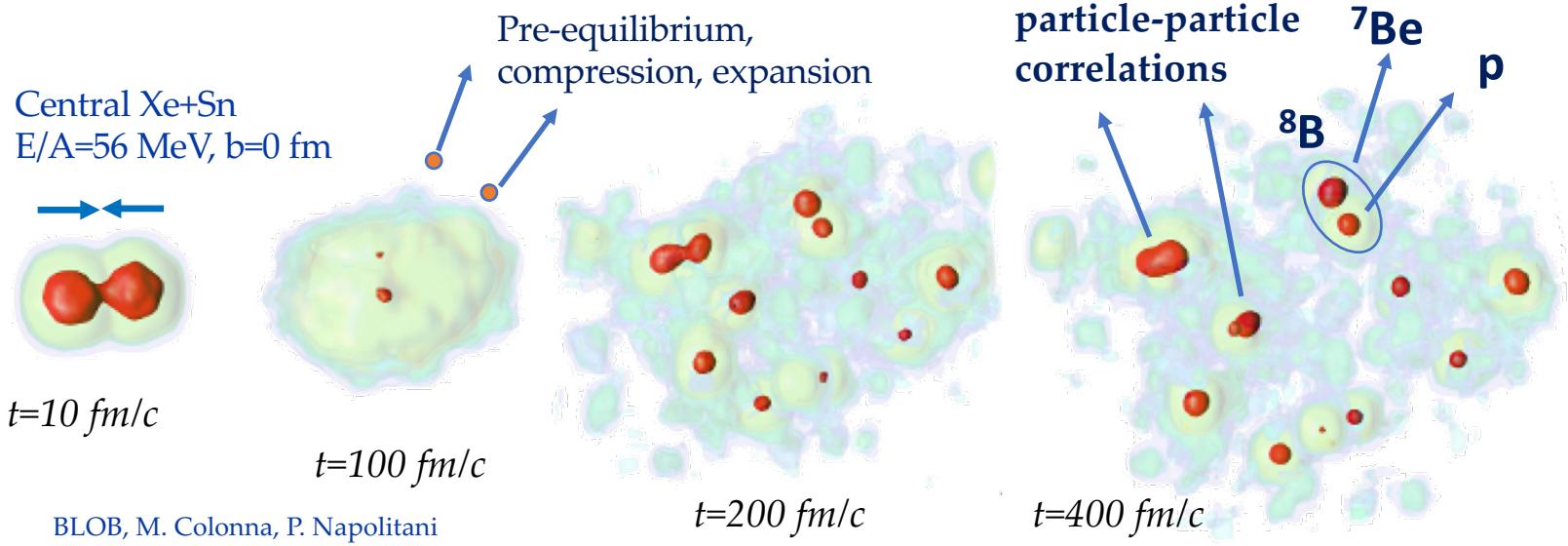


Neutron stars

- **Binary mergers, tydal deformabilities, GW, R vs M investigations…**



Dilute and warm matter at GANIL energies



Collective properties

EoS, Symmetry Energy, phase transitions

Femtoscopic properties

Correlations, Resonance decays in the medium, clustering.

in-medium dynamics ⟷ structure

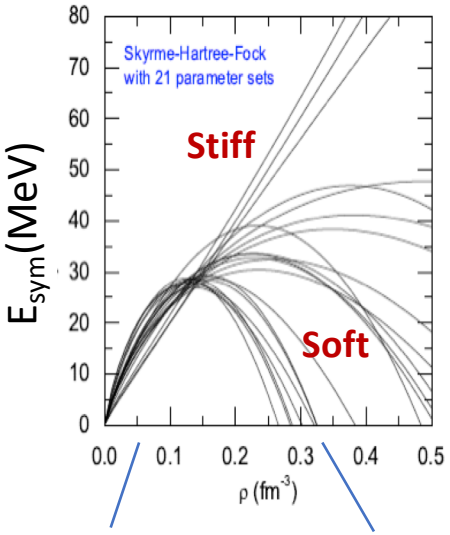
Density dependence of the symmetry energy

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\cdot\delta^2 + O(\delta^4)$$

Asymmetry term

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \neq 0$$

$$\rho = \rho_n + \rho_p$$



E/A=20-100 MeV
GANIL, LNS

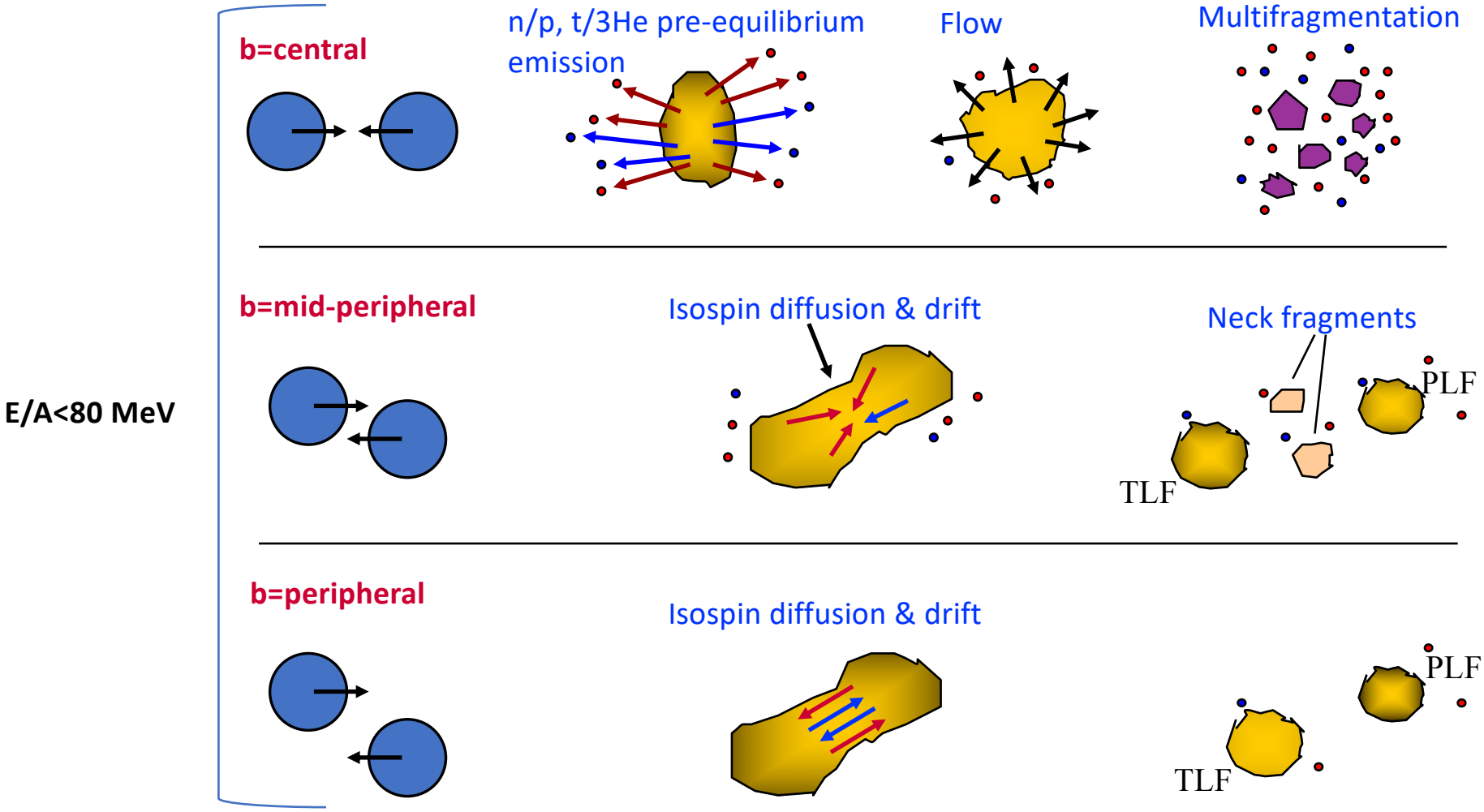
E/A>100 MeV
FRIB, FAIR, RIKEN

B.A. Brown, Phys. Rev. Lett. 85, 5296 (2000)
ZH Li, U. Lombardo, PRC74 047304 (2006)

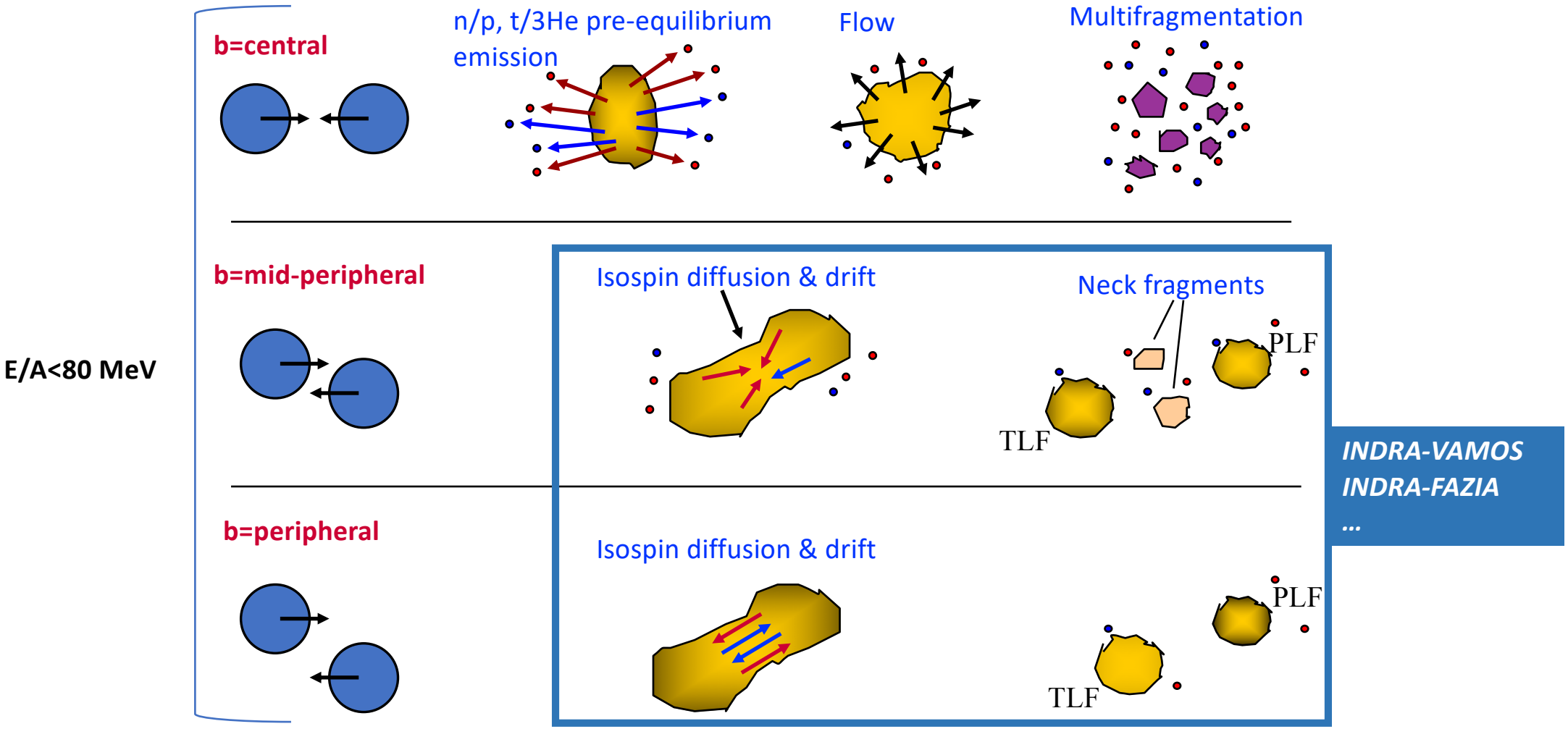
Many approaches… large uncertainties….

- **Experiments with large N/Z asymmetries to enhance effects of Esym → RIBs at FRIB**
- **Isolate regions where N/Z is large: neck at GANIL energies**

Symmetry energy probes at GANIL/NSCL energies

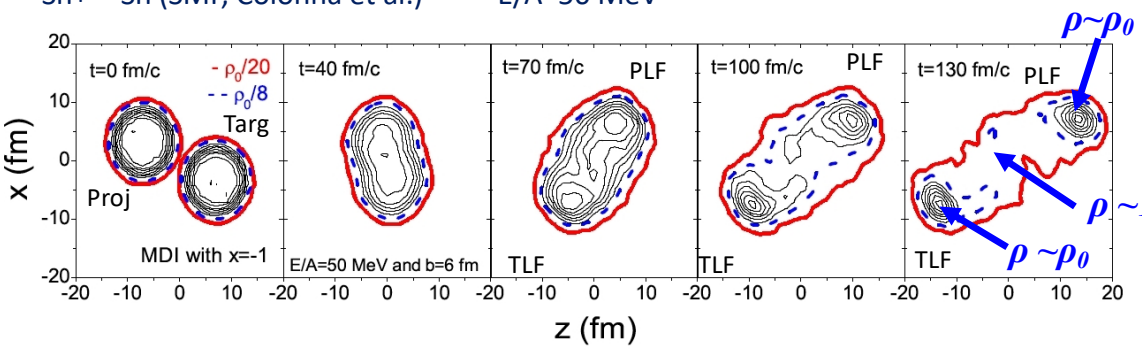


Symmetry energy probes at GANIL/NSCL energies



Isospin drift and diffusion

^{112}Sn+^{112}Sn (SMF, Colonna et al.) E/A=50 MeV

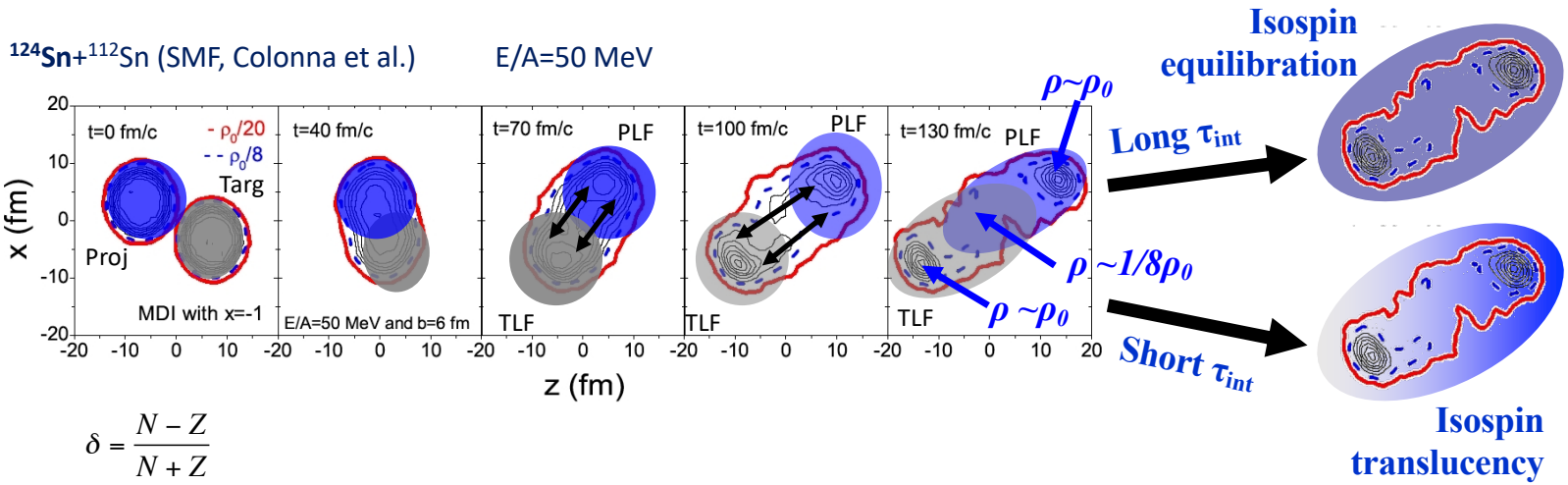


Neutron drift towards low density neck

Isospin drift

Colonna et al.; Danielewicz et al.

Isospin drift and diffusion

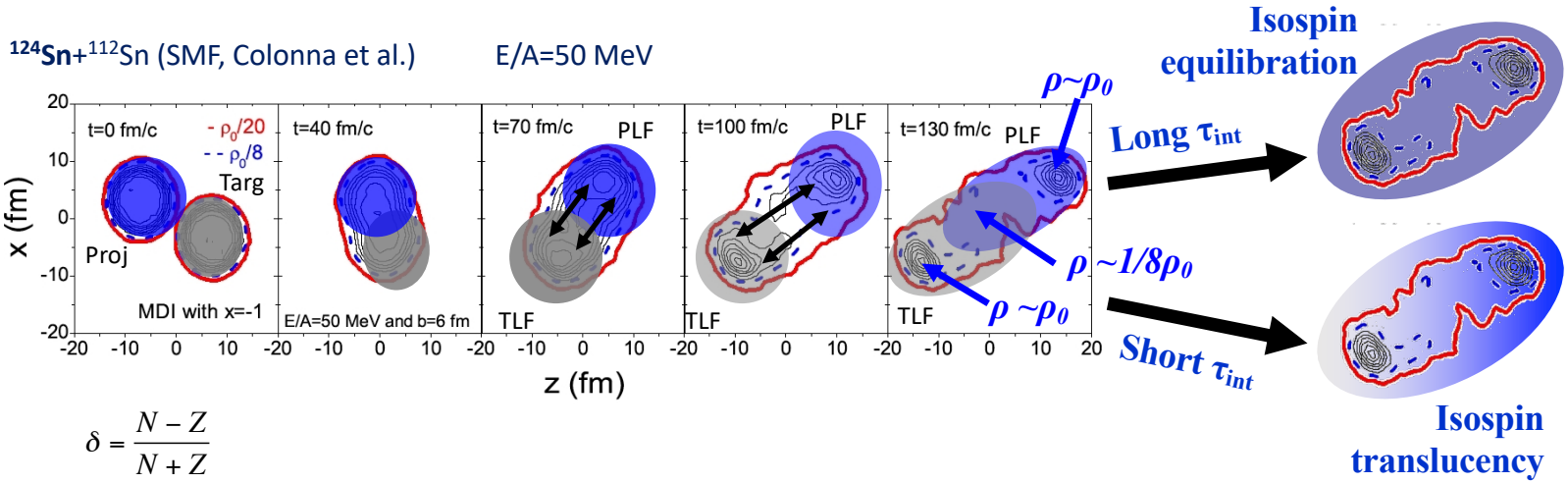


$$\delta = \frac{N - Z}{N + Z}$$

Isospin drift **Isospin diffusion**

Colonna et al.; Danielewicz et al.

Isospin drift and diffusion



$$\delta = \frac{N - Z}{N + Z}$$

Isospin drift **Isospin diffusion**

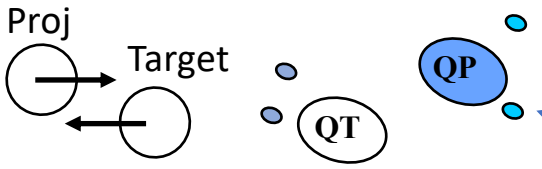
$$j_n - j_p = \left(D_n^{\rho} - D_p^{\rho}\right)\nabla\rho - \left(D_n^{\delta} - D_p^{\delta}\right)\nabla\delta$$

$$\propto \frac{\partial E_{sym}}{\partial \rho} \qquad \propto E_{sym}$$

Probing $E_{sym}(\rho)$ Via comparisons to transport models

Colonna et al.; Danielewicz et al.

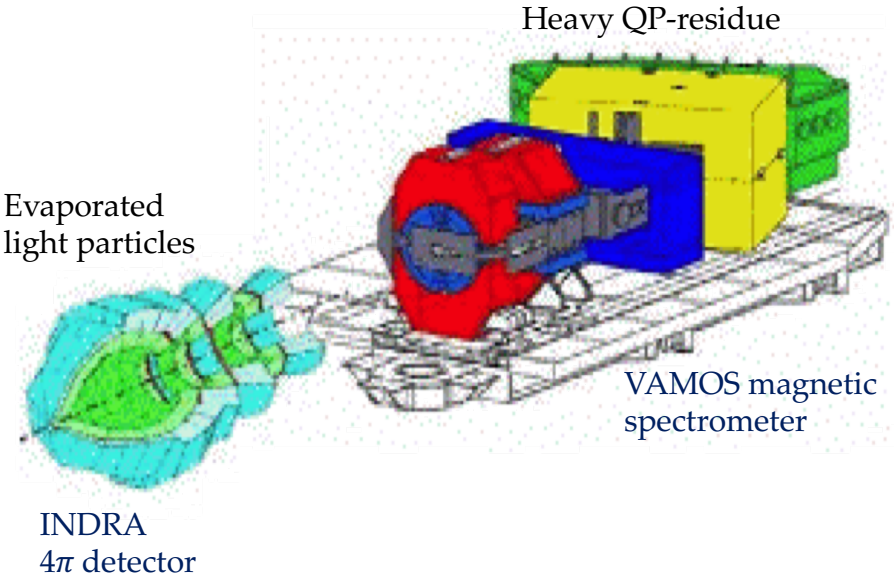
INDRA-VAMOS campaign on E_{sym}

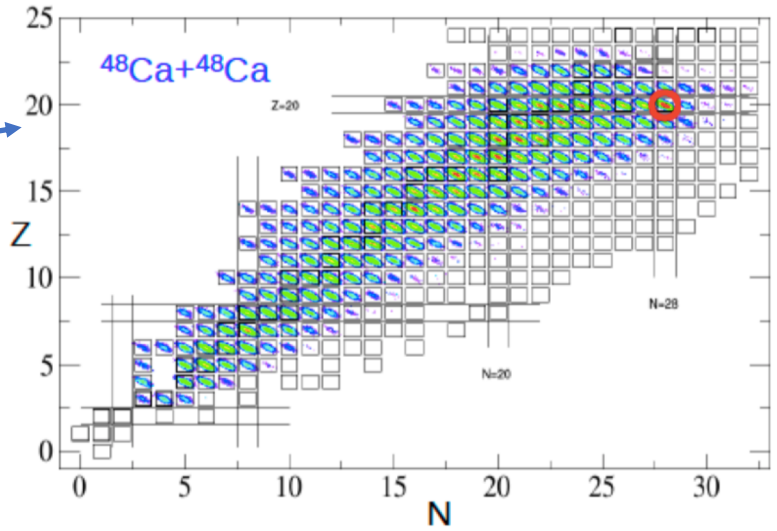


$^{40,48}Ca + ^{40,48}Ca$ @ E/A = 35 MeV

Direct detection of residue produced in the decay of excited quasi-projectile:

coincidences INDRA-VAMOS





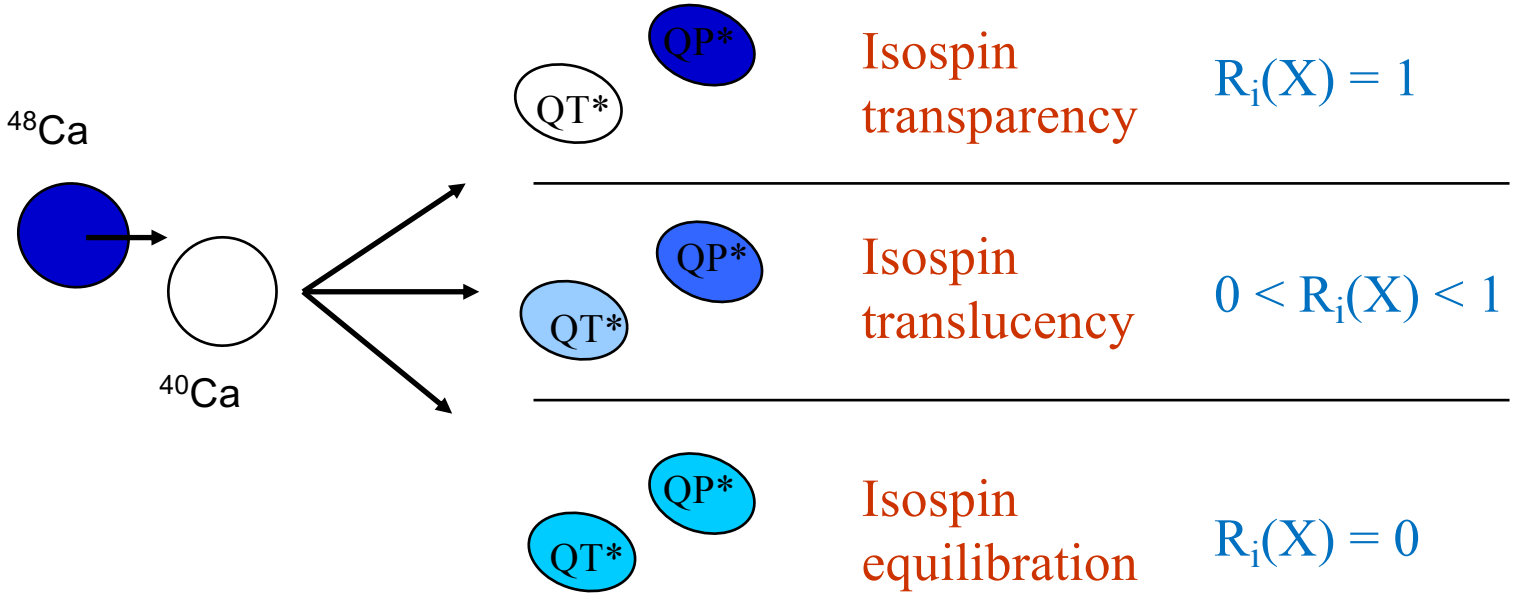
INDRA-VAMOS (2007)

P. Marini et al., Phys. Lett. B 756, 194 (2016)
Q. Fable et al., Phys. Rev. C 106, 024605 (2022)
Q. Fable et al., Phys. Rev. C 107, 014604 (2023)

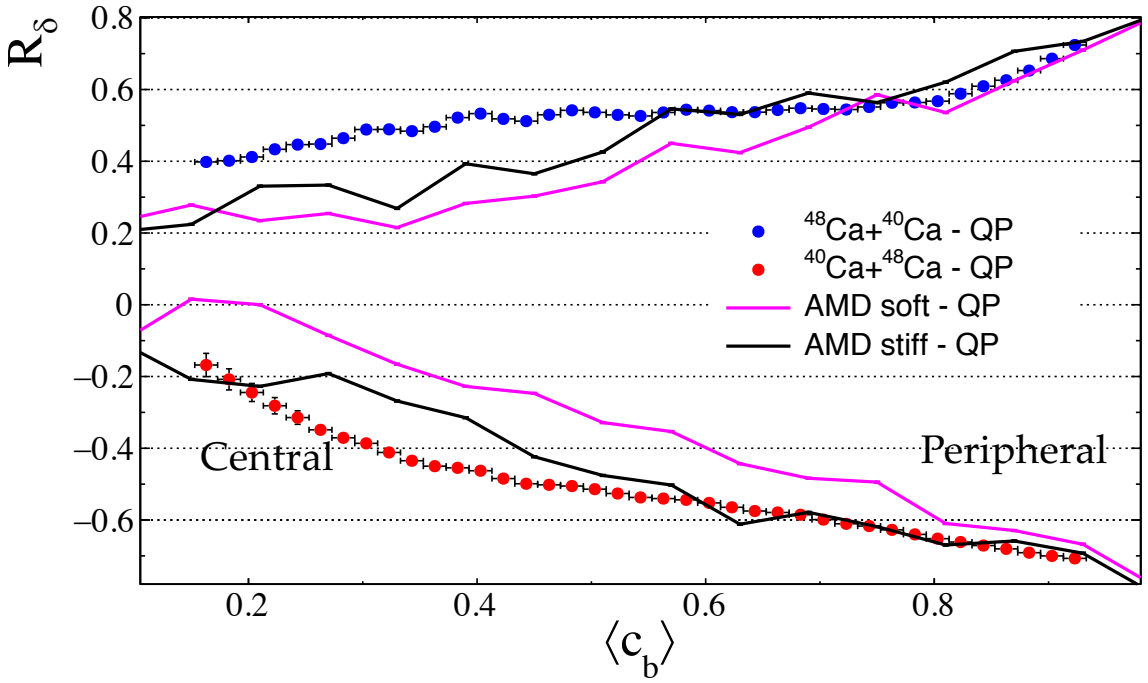
Isospin diffusion and imbalance ratios

$^{40}Ca+^{40}Ca$	$^{40}Ca+^{48}Ca$	$^{48}Ca+^{40}Ca$	$^{48}Ca+^{48}Ca$
PP	MIX	MIX	NN

X=N/Z of emitter → $R_i(X) = \frac{2X - X^{NN} - X^{PP}}{X^{NN} - X^{PP}}$



Isospin diffusion - data vs AMD sims → E_{sym}?



Not there yet…
More work required on the transport model side

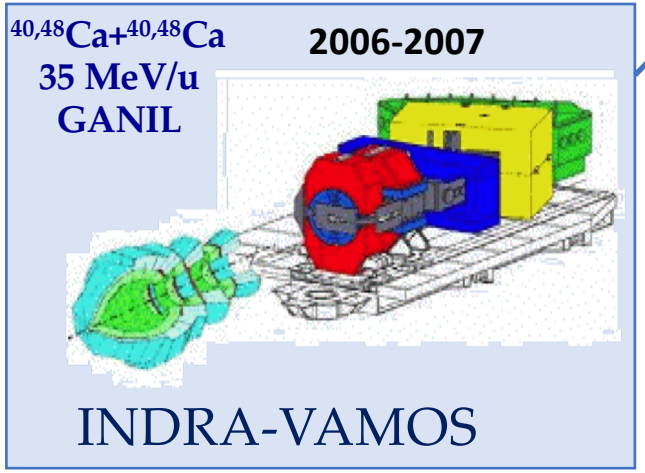
Towards equilibration

Q. Fable, A. Chbihi. G. Verde, J. Frankland, et al., PRC under submission process

Towards FAZIA…

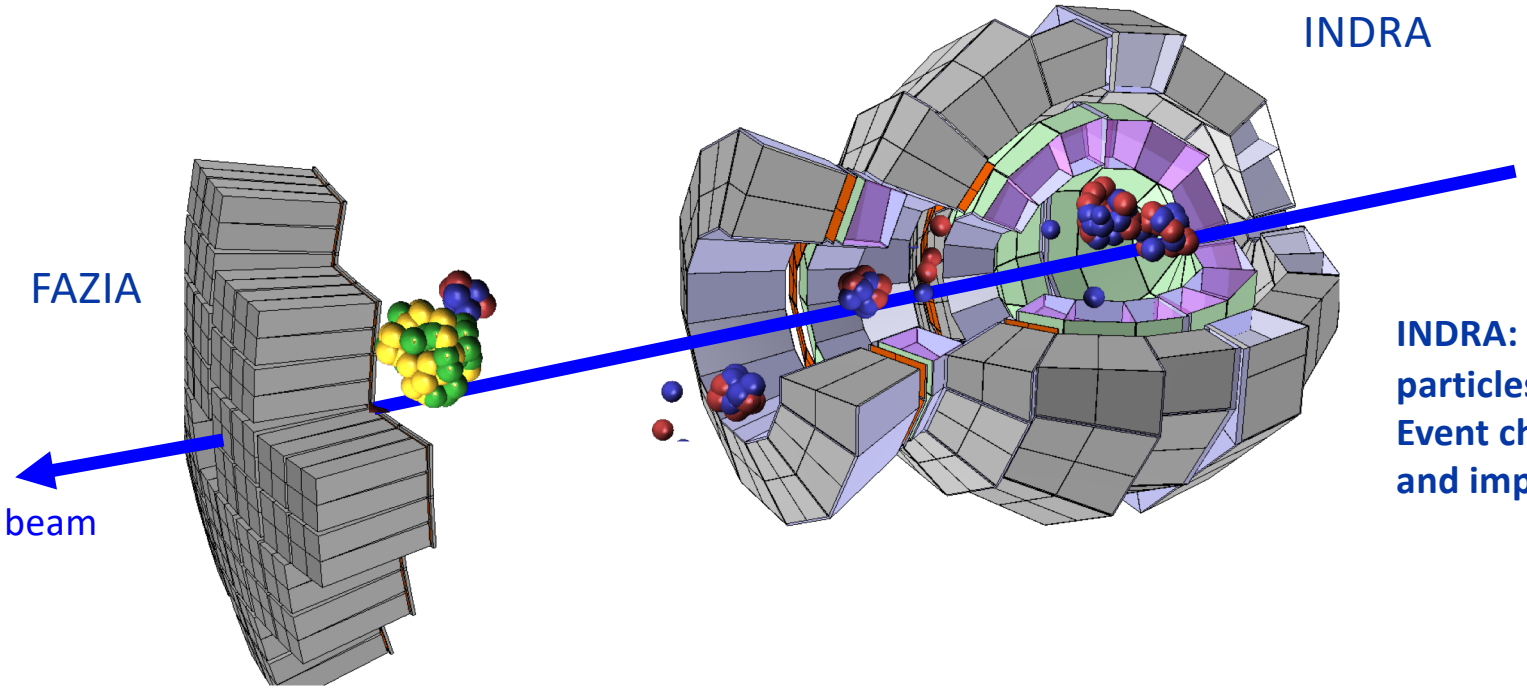
Limitations

- Need to run at several $B\rho$ values (long beam times)
- Difficult analysis: efficiency in patching spectra…
- Only one fragment detcted in VAMOS → most peripheral and less dissipative events are better isolated…



A. Chbihi, G. Verde

FAZIA-INDRA campaigns @ GANIL (≈ 2019-2024)



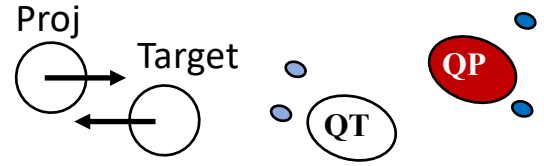
INDRA: fragments and particles at θ > 14°
Event characterization and impact parameter

12 Blocks (192 telescopes)
full Z & A identification for 1≤Z<25 at θ < 14°
Symmetry energy
Correlations

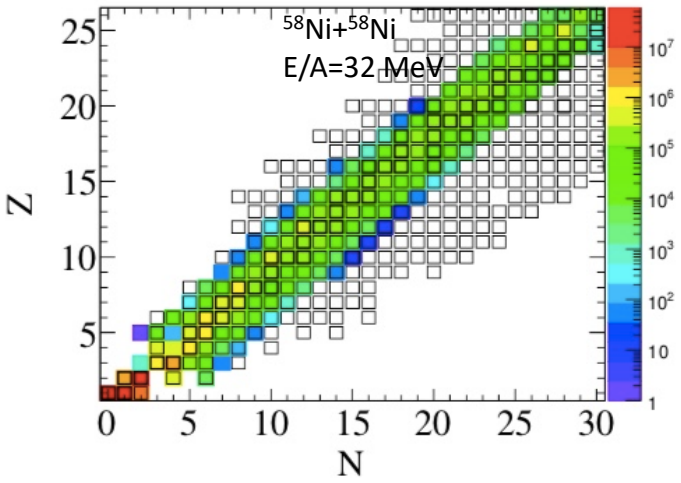
S. Valdrè's talk

INDRA-FAZIA: 1st campaign (2018)

^{58,64}Ni+^{58,64}Ni, E/A=32-52 MeV



Z-N identification Z=1-25

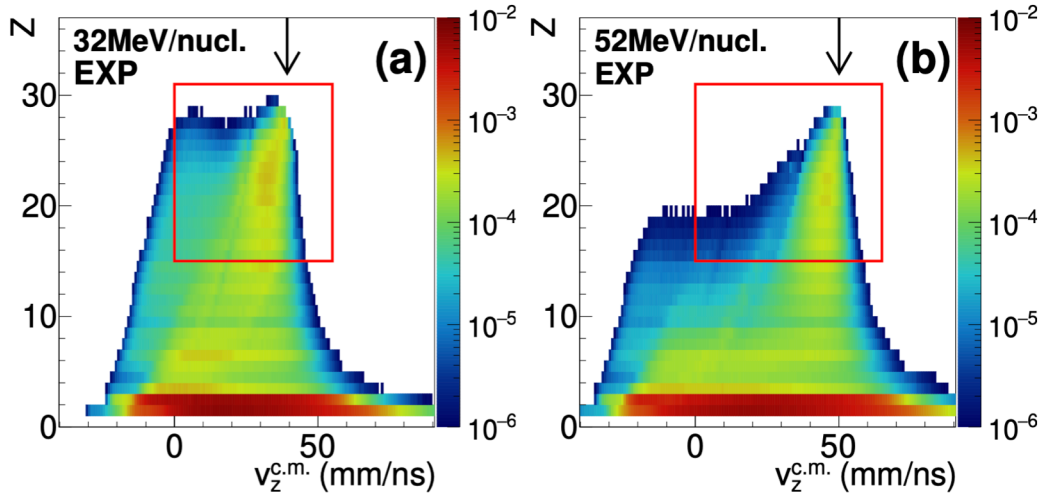


C. Ciampi et al., Phys. Rev. C 106, 024603 (2022)

FAZIA → Projectile fragments $(Z, A, \vec{p})$ for $\theta < 14^{o}$

INDRA → Coincident particles $(Z, A, \vec{p})$ for $\theta \geq 14^{\circ}$ and Z=1-4

$(Z, \vec{p})$ for $\theta \geq 14^{\circ}$ and Z ≥5



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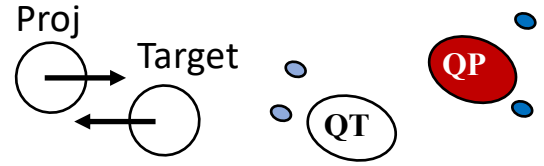
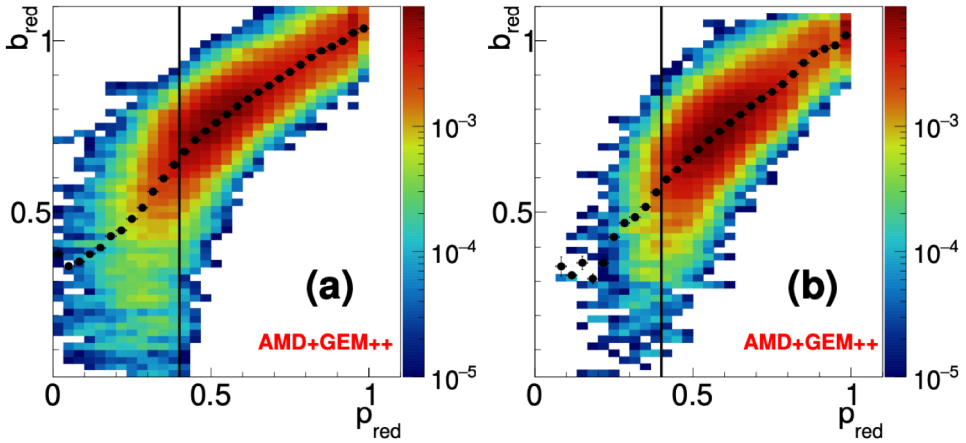


Impact parameter determination (AMD+GEMINI)



$$b_{red} = \frac{b}{b_{max}} \qquad p_{red} = \left(\frac{p_z^{QP}}{p_{beam}}\right)_{c.m.}$$

FAZIA → Projectile fragments $(Z, A, \vec{p})$ for $\theta < 14^{o}$

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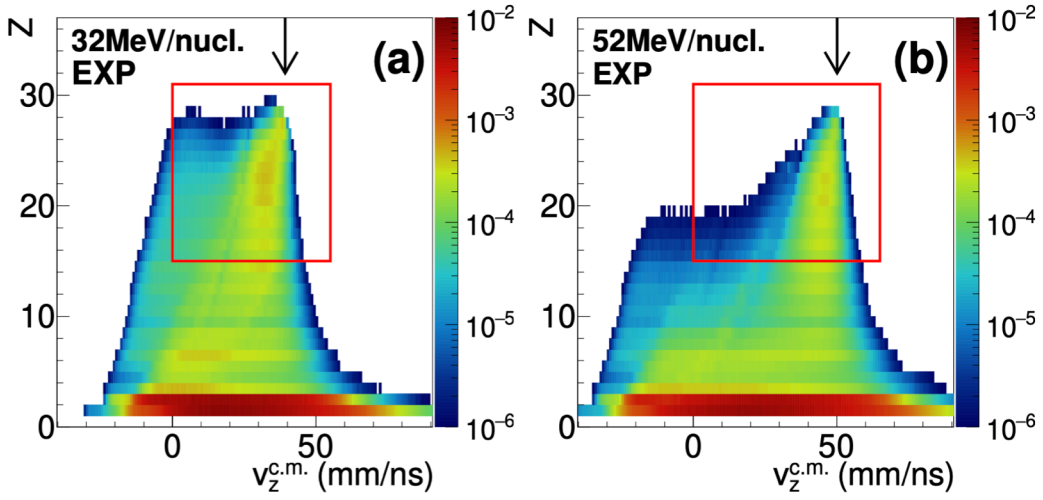
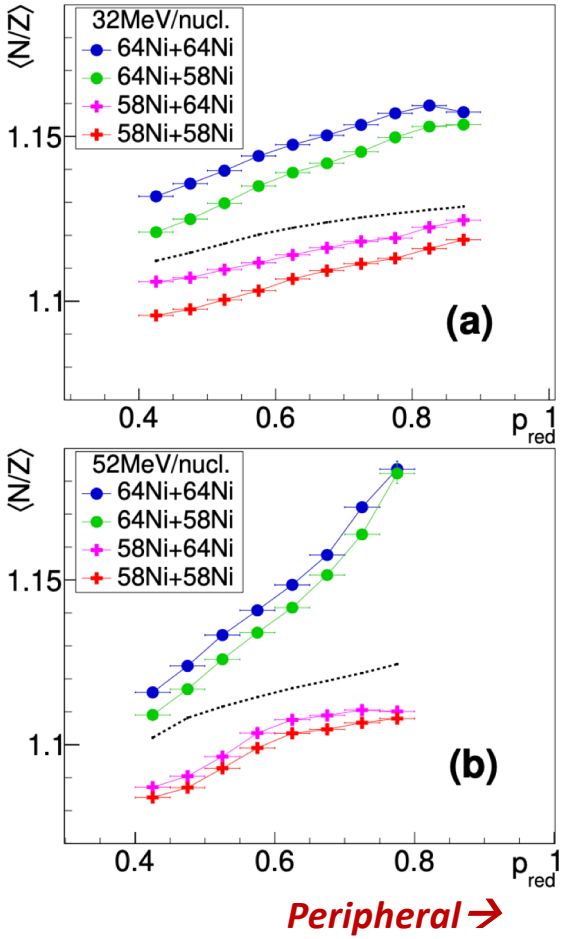
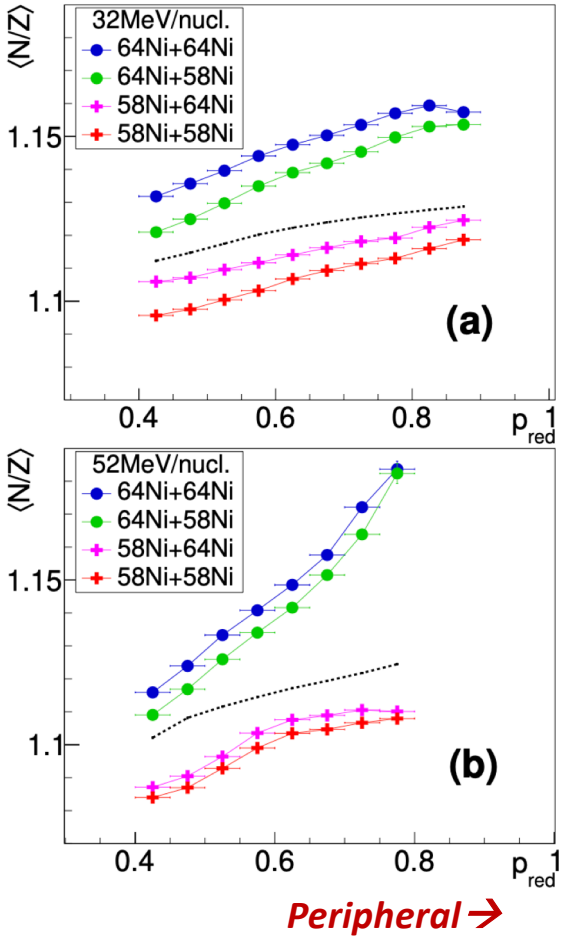


Isospin diffusion with INDRA-FAZIA



C. Ciampi et al., Phys. Rev. C 106, 024603 (2022)

Isospin diffusion with INDRA-FAZIA



C. Ciampi et al., Phys. Rev. C 106, 024603 (2022)

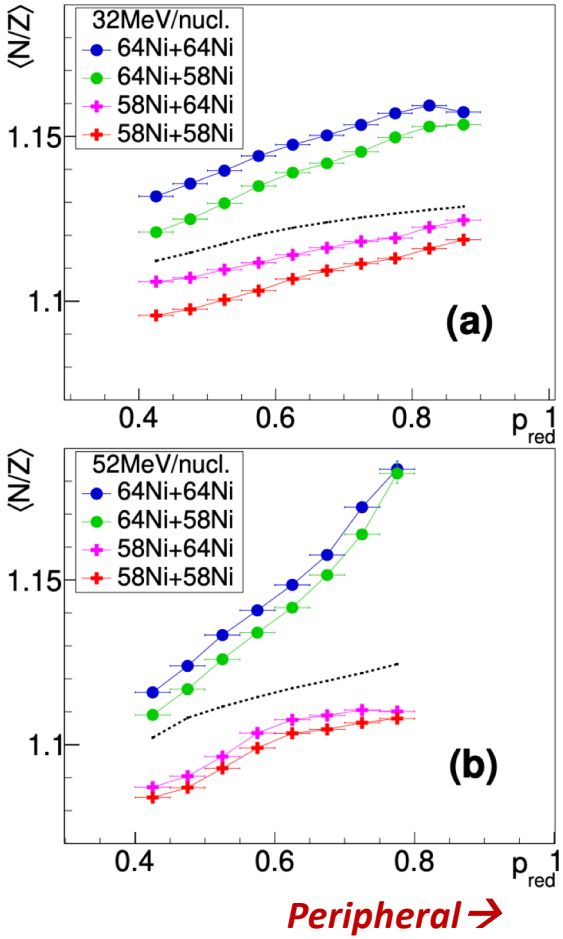
Isospin imbalance ratios

X=N/Z of emitter →

$$R_i(X) = \frac{2X - X^{NN} - X^{PP}}{X^{NN} - X^{PP}}$$

- R = 1, -1 Isospin transparency
- R = 0 Isospin equilibration/stopping
- 0 < R < 1 Depends on dissipation, time-scales and symmetry energy

Isospin diffusion with INDRA-FAZIA



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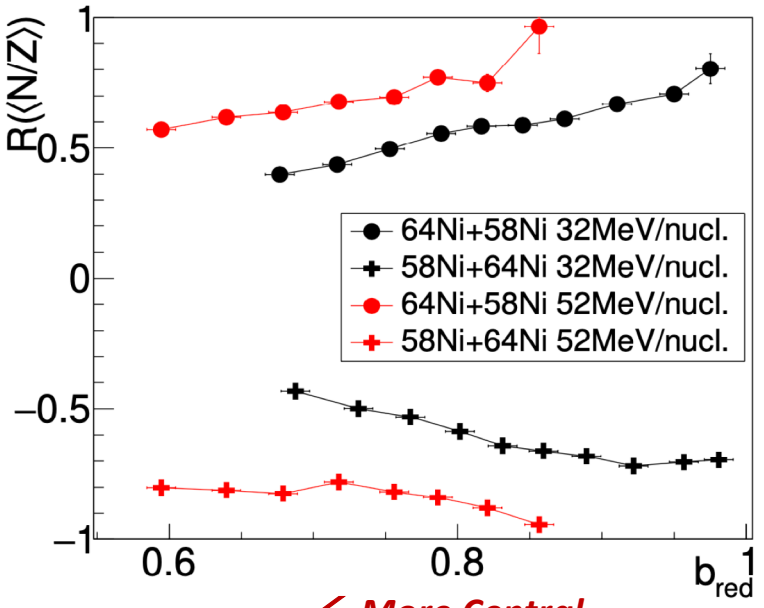
Isospin imbalance ratios

X=N/Z of emitter →

$$R_i(X) = \frac{2X - X^{NN} - X^{PP}}{X^{NN} - X^{PP}}$$

Towards more isospin equilibration →

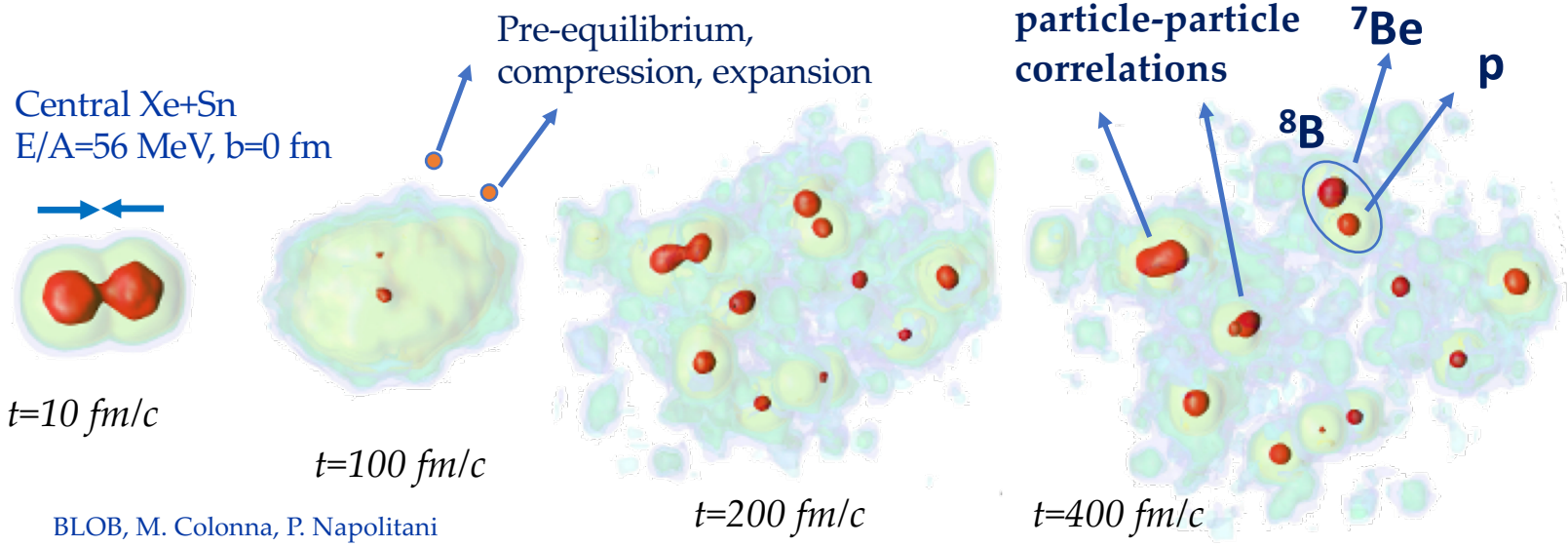
Depending on time-scales of dissipation (Ebeam and impact parameter)



Transport models Vs isospin diffusion in INDRA-FAZIA?

- Very clear signals from data on how isospin diffusion depends on centrality and dissipation
- Working on transport models and on their capability of reproducing data… still under way: important for $E_{sym}(\rho)$
  - impact parameter filters
  - sensitivity of observables to impact paramter
  - Clustering, cluster-cluster correlations

The other side of the coin: structure and clustering



Collective properties

EoS, Symmetry Energy, phase transitions (liquid-gas)

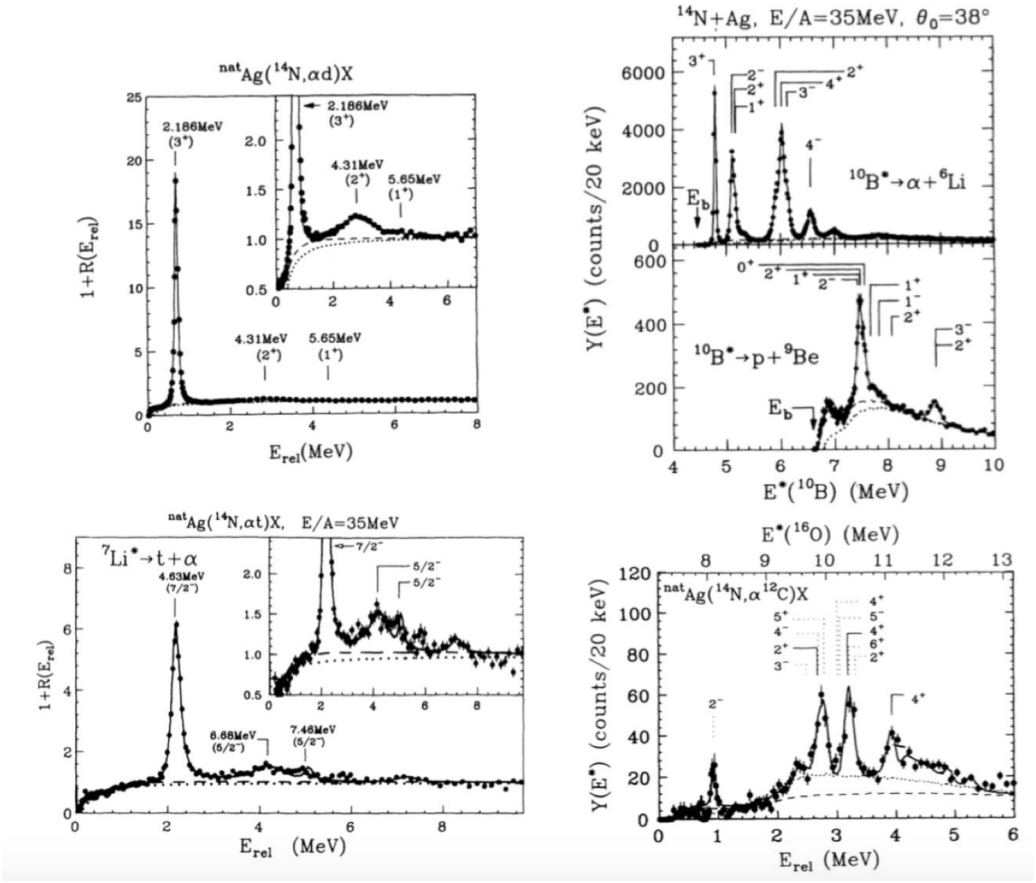
Femtoscopic properties

Correlations, Resonance decays, clustering, **in-medium properties**
Tools for nuclear structure in HIC!

W.P. Tan et al., PRC69, 061304(R) (2004)

In-medium resonance decays

N + Ag E/A=35 MeV
NSCL data – T.K. Nayak et al., PRC45, 132 (1992)



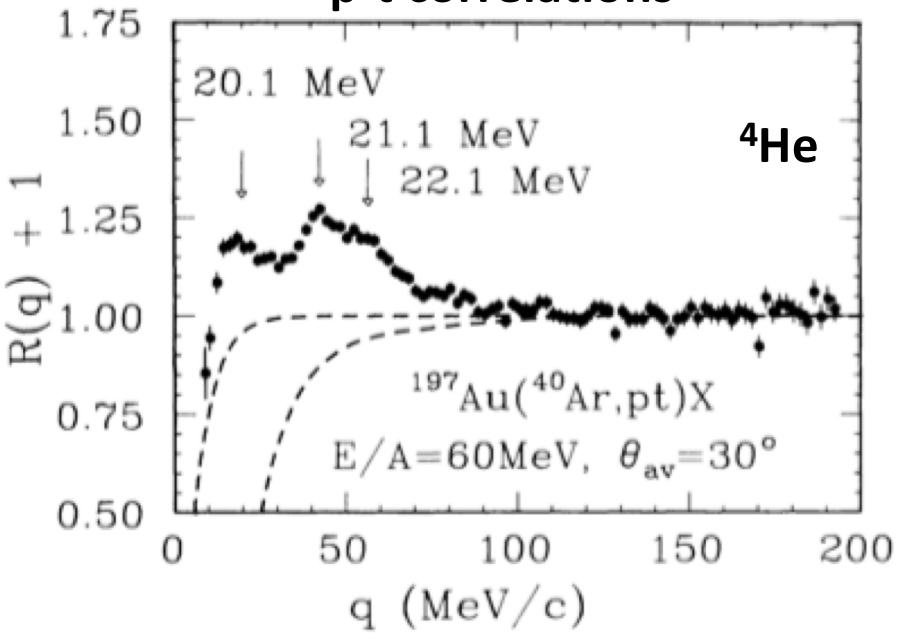
^{5}Li → α + p
^{8}Be → α + α
^{12}N → ^{11}C + p
^{10}B → ^{6}Li+α, ^{8}Be+d, ^{9}Be+p
^{12}C → ^{8}Be+ α, α+α+α
...other many cases...

Plenty of resonances in one single experiment

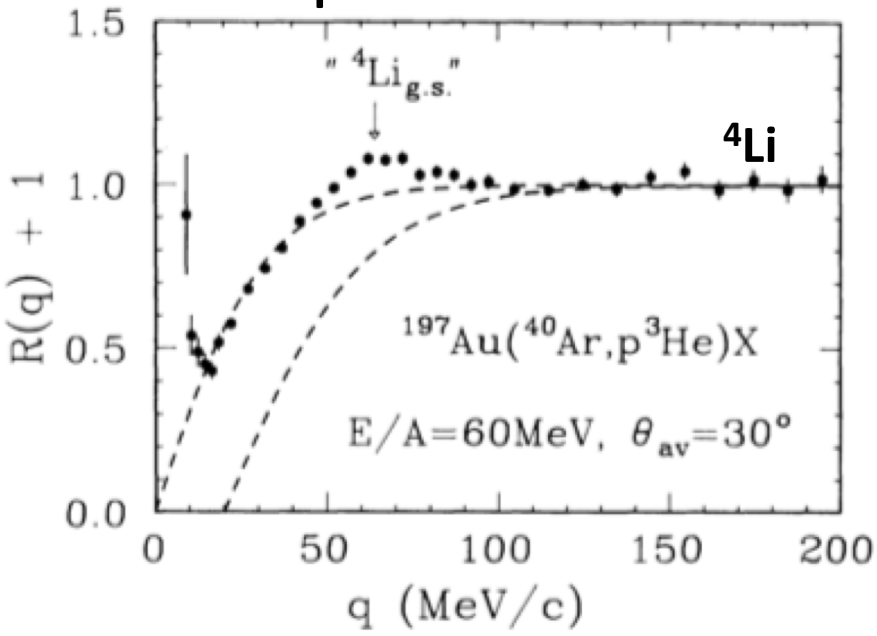
HIC as a tool for nuclear structure
and
Structure as a tool to improve models

An interdisciplinary case: ^{4}Li – ^{4}He

p-t correlations



p-^{3}He correlations



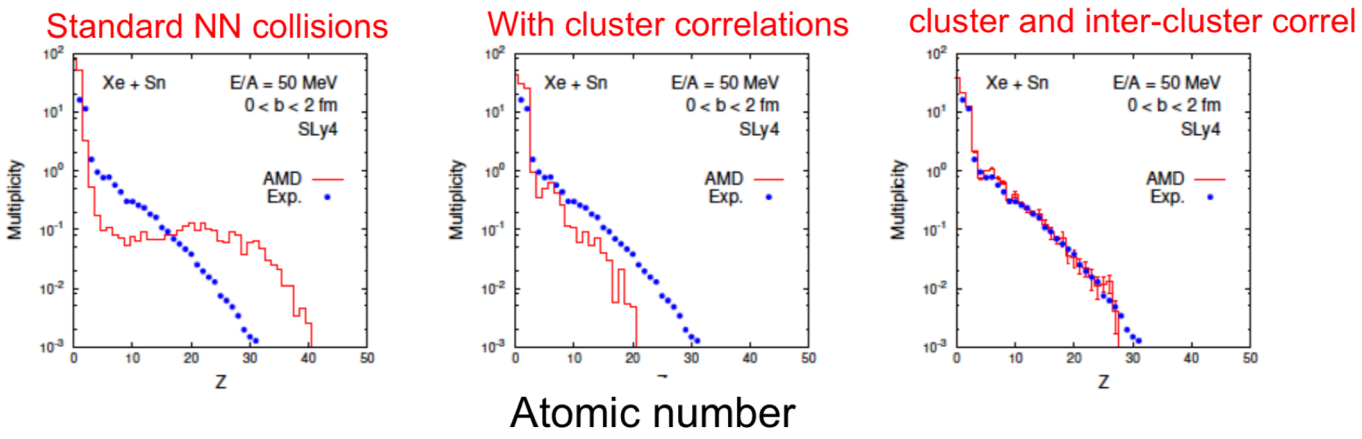
Hope to learn about few body nuclear interaction from measurements at low and high energies

→ proton-cluster correlations @ HADES see M. Stefaniak at recent WPCF 2023

Clusters and their correlations in models Vs data

INDRA data

A. Ono, Journal of Physics: Conference Series **420** (2013) 012103

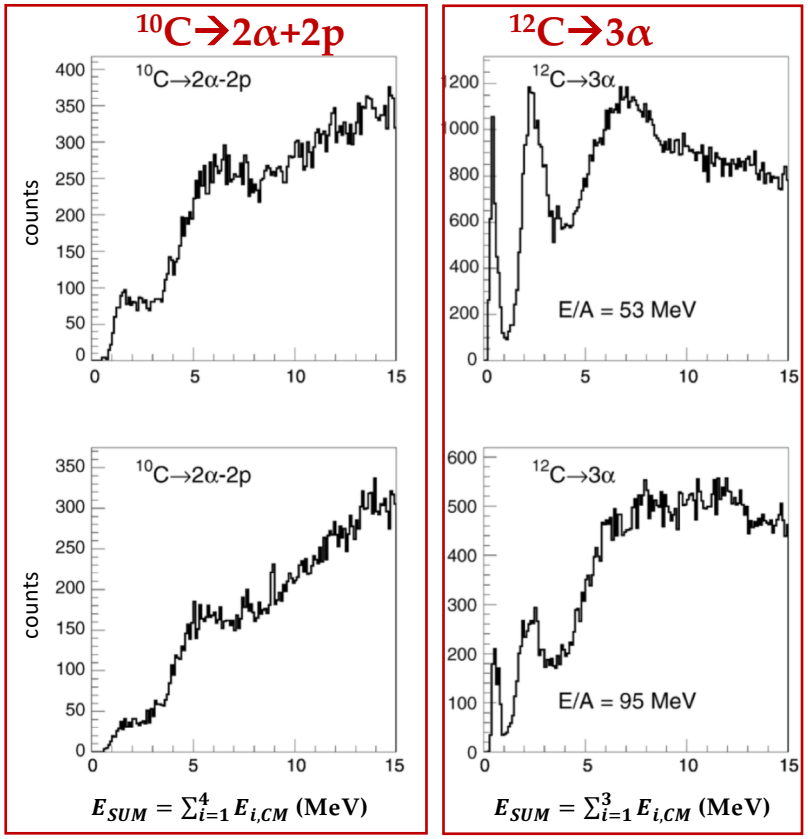


- Data better described reproduced if cluster formation and cluster-cluster correlations included
- Study cluster-cluster correlations experimentally

3- and 4-particle correlations in HIC: INDRA

^{12}C+^{24}Mg E/A=53 and 95 MeV, INDRA data

F. Grenier et al., Nucl. Phys. A811, 233 (2008)



F. Grenier et al., Nucl. Phys. A811, 233 (2008)

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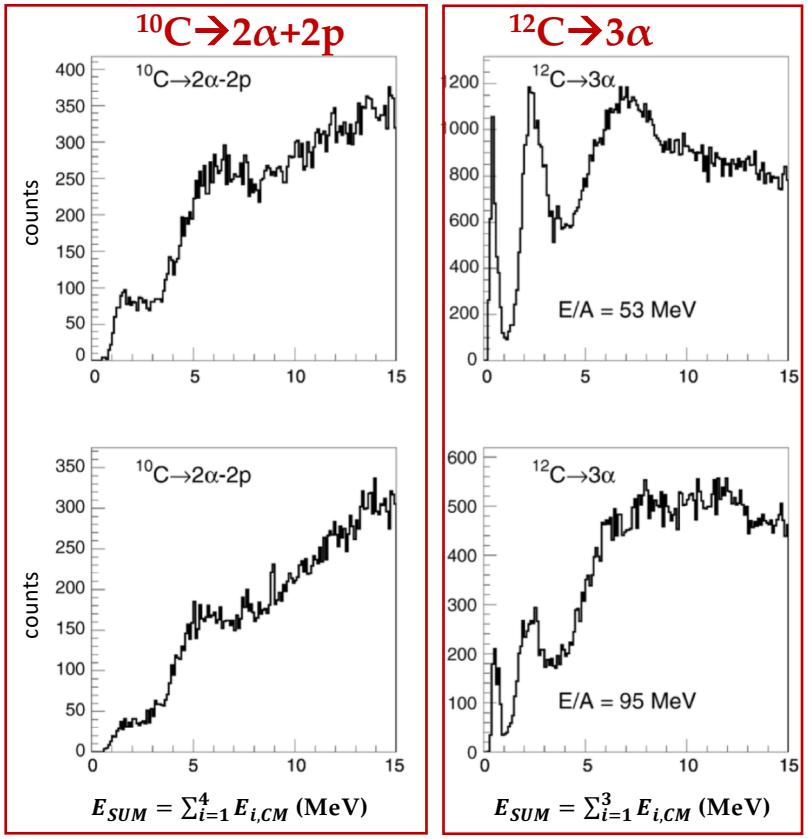


^{10}C decay

^{10}C* → ^{6}Be+α → (2p+α)+α

^{10}C* → ^{8}Be+p+p → (α+α)+p+p

^{10}C* → ^{9}B+p → (p+α+α)+p

^{10}C* → p+p+α+α **Direct**

^{12}C decay

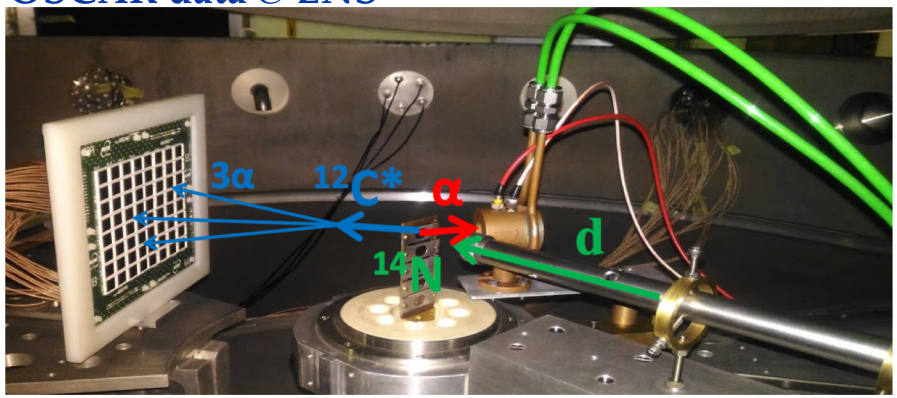
^{12}C* → ^{8}Be+α → (α +α)+α

^{12}C* → α + α+ α **Direct**

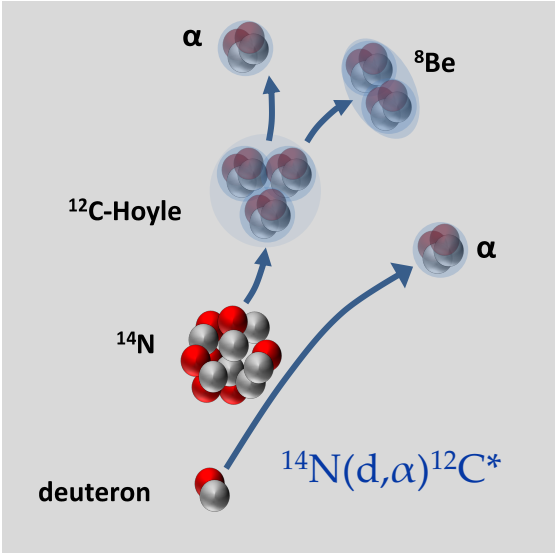
Strong contribution

Direct reaction measurements: ^{12}C Hoyle state decay

OSCAR data @ LNS



D. Dell'Aquila, I. Lombardo, G. Verde et al., Physical Review Letters 119, 132501 (2017)



Contraddictiry results when running experiments with direct reactions: No direct three-body decay found!

In-medium effects on nuclear structure?

L. Redigolo's talk

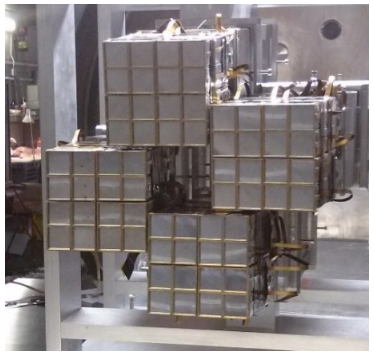
Stay tuned !

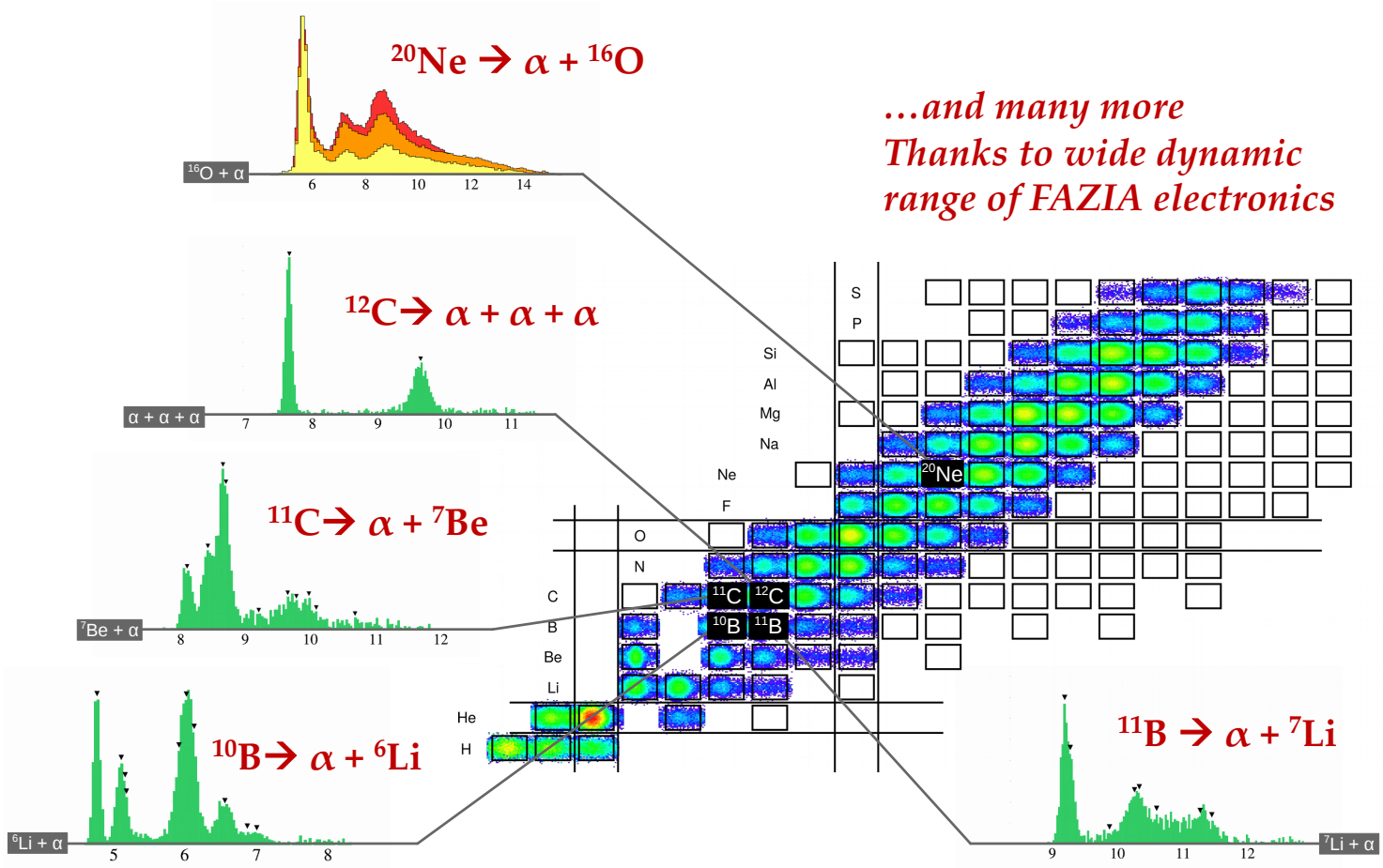
Cluster correlations with FAZIA

FAZIACOR @ LNS

G. Verde & D. Gruyer,
FAZIA collaboration
(just 4 blocks)

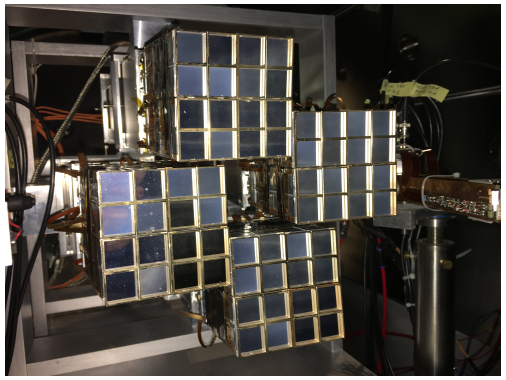
$^{20}Ne+^{12}C$ at 25 MeV/u





…and many more
Thanks to wide dynamic range of FAZIA electronics

In-medium clustering with FAZIA



FAZIACOR @ LNS

G. Verde, D. Gruyer, FAZIA Collaboration

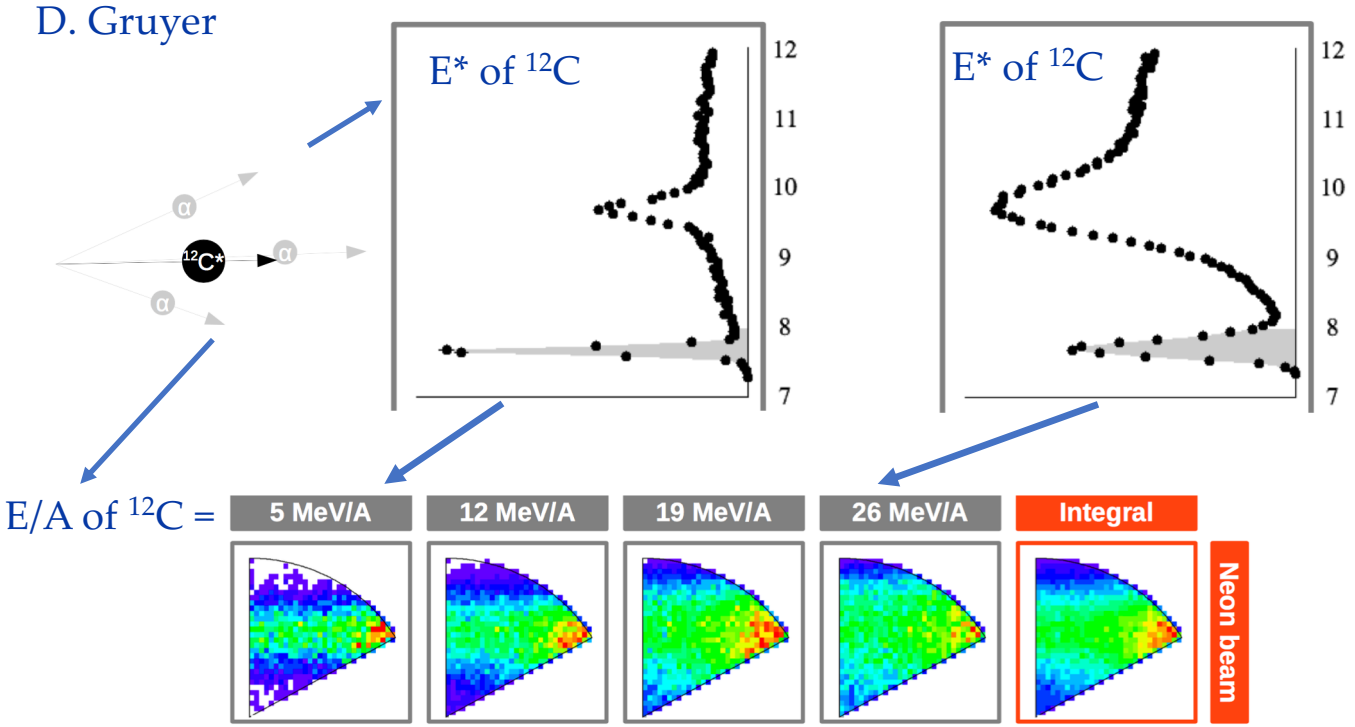
$^{32}S + ^{12}C$ E/A=25, 50 MeV

$^{36}S + ^{12}C$ E/A=25, 50 MeV

$^{20}Ne + ^{12}C$ E/A=25, 50 MeV

Preliminary data on the Hoyle state

D. Gruyer



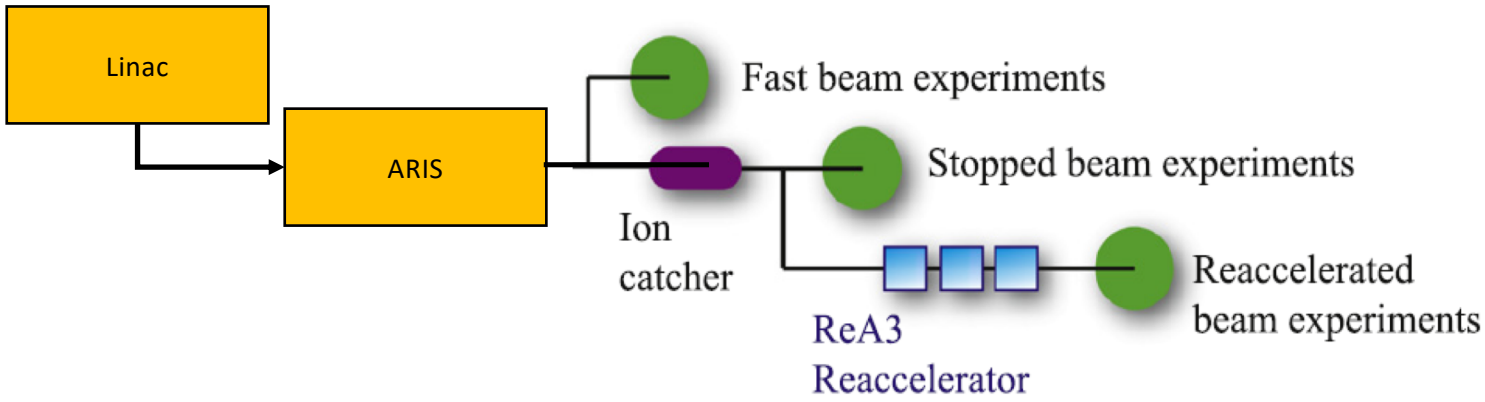
Slow ^{12}C – high dissipation

- → **Almost only sequential decay**
- → **Negligible background**
- → **Agreement with direct reactions**

Fast ^{12}C – low dissipation

- → **direct decay: Puzzle: effects of dynamical medium on clustering? need more data**

FRIB facility and perspectives at higher energies



- **Fast beams**: Furthest reach towards neutron-rich nuclei – exploit variety of direct reactions, neutron, charged-particle and γ-ray spectroscopy, time-of-flight mass measurements, ***HIC***
- **"Stopped"** beams: Precision decay measurements (β, βn, βp, α, isomer, p, 2p …), high-precision mass spectrometry, laser spectroscopy, tests of fundamental symmetries
- **Reaccelerated beams**: Direct reactions, fusion, capture reactions, Coulomb excitation around the Coulomb barrier (no chemistry limitation unlike with ISOL)

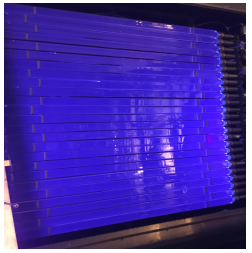
New proposal 23058 @ PAC2 FRIB

^{56,70}**Ni** + ^{58,64}Ni

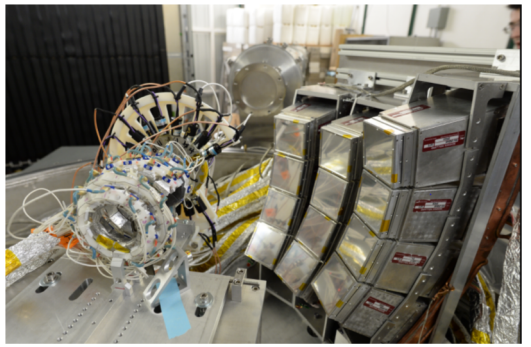
E/A = 175 MeV

Constraining the density and momentum dependence of the symmetry energy and n/p effective masses

Neutron Wall



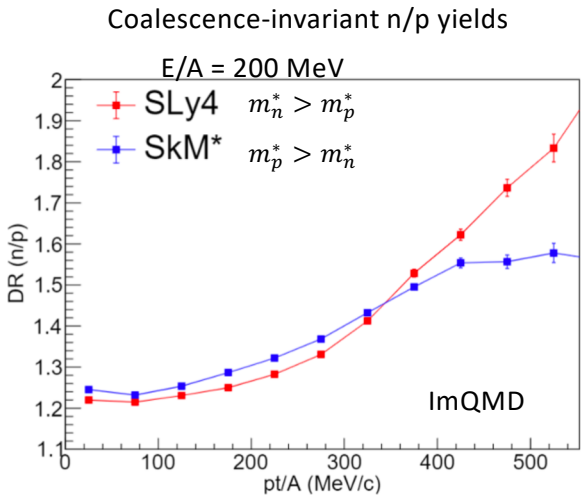
Veto Wall



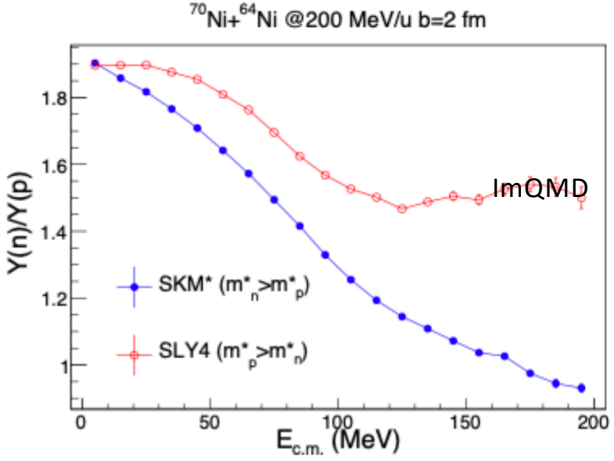
µBall HiRA

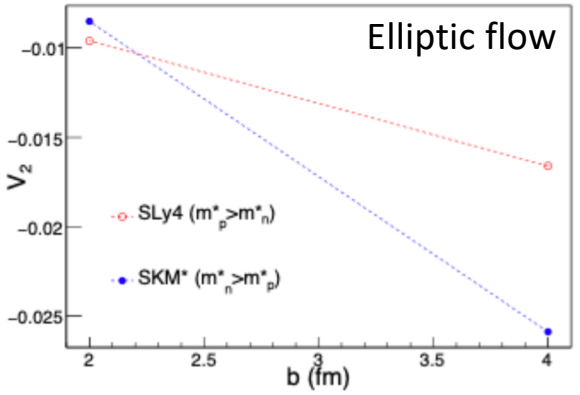
Neutron/proton elliptic flow and yield ratios

ImQMD simulations

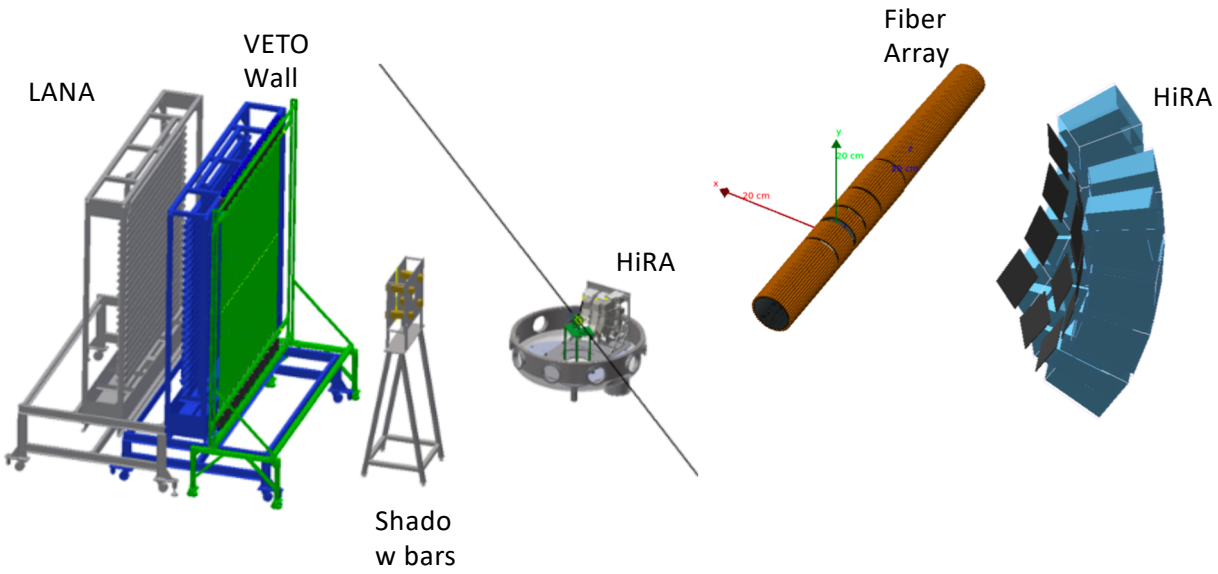


$$DR\ (n/p) = \frac{Y(^{70}Ni + {}^{64}Ni)}{Y(^{56}Ni + {}^{58}Ni)}$$





New proposal 23058 @ PAC2 FRIB

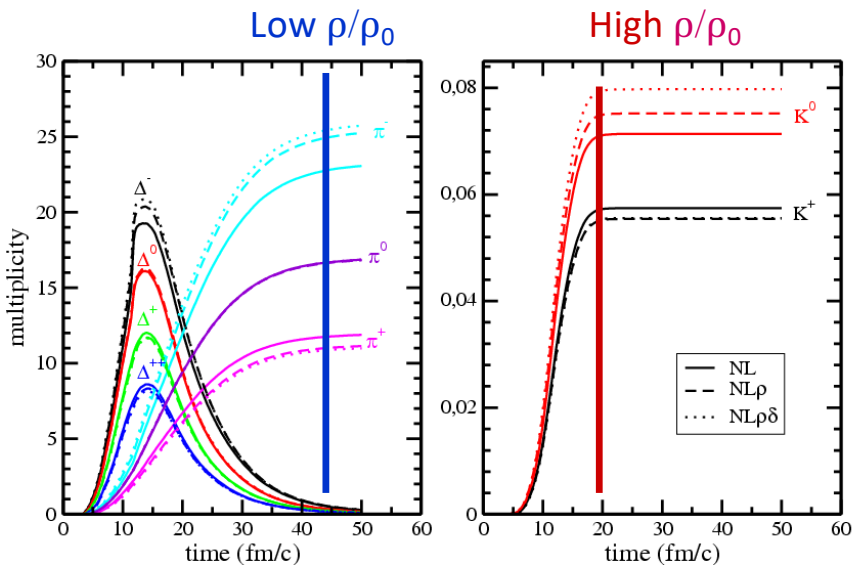


Towards higher energies/densities – GSI/FAIR

- High density EoS and symmetry energy → most relevant for neutron stars and gravitation waves from binary mergers
- Plans are ongoing at HADES, CBM and results from the ASYEOS experiment are already available (**see talk by A. Le Fevre**)
- More observables need to be measured:
  - Pion ratios (pi+/pi- sensitive to the Esym)
  - Kaon ratios (K+/K0) to probe the highest density regions, but difficult to measure at GSI energies

Towards higher energies/densities – GSI/FAIR

π^+, π^-



K^+,K^0 (best to probe higher densities)

RBUU, Ferini et al., PRL97, 202301

Summary

- HIC as a unique tool to study astrophysically phenomena in compact star physics (neutrinosphere in supernovae, neutron stars, GW, …) → role of E_{sym} and nuclear transport
- Isospin diffusion and drift with direct detection of QP remnants by FAZIA: clear signals of isospin transparency and equilibration - important advances expected from transport models
- Interplays of dynamics and structure with multi-resonance decay studies: relevant to deduce Esym from transport models and a tool for nuclear structure studies (in-medium vs «in-vacuum»…)
- Future perspectives offered by FRIB and GSI/FAIR exotic beams… discussions are under way between collaborations – open to welcome collaborators