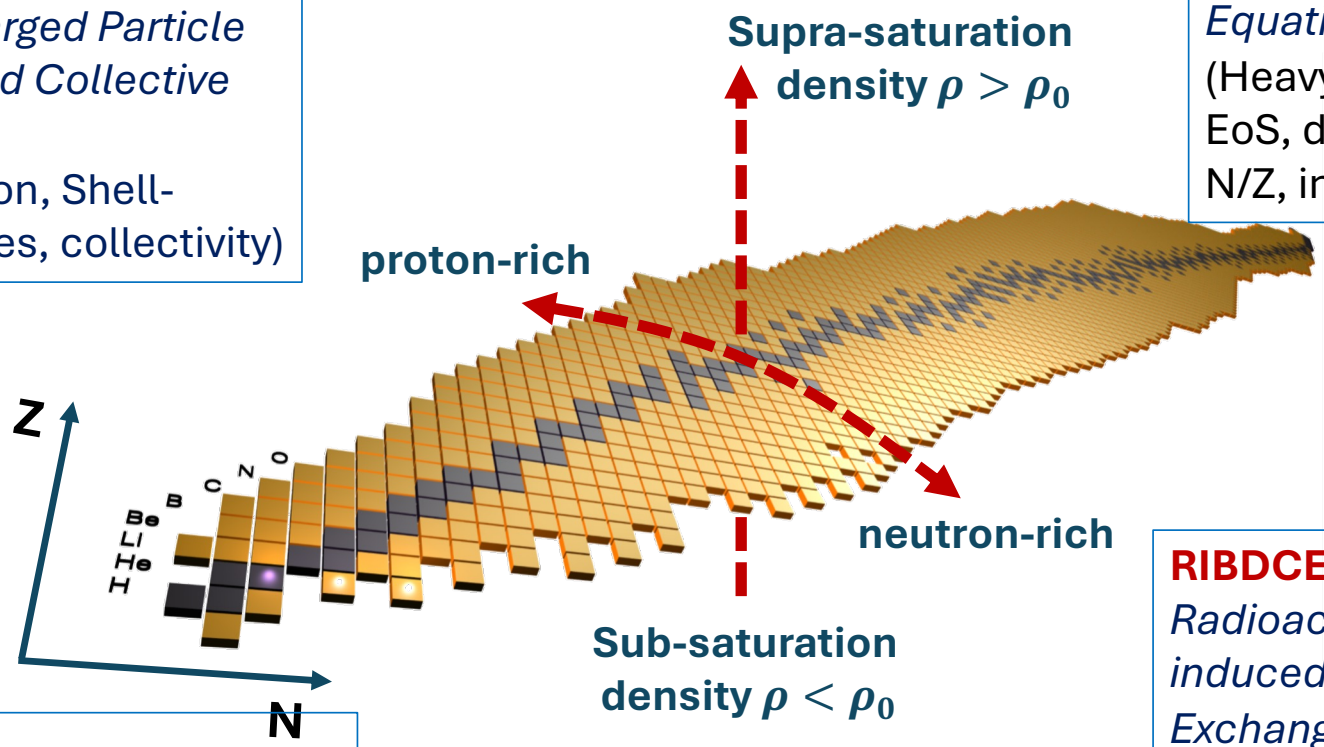
NUSDAF: Nuclear Structure, Dynamics and Astrophysics at FRIB

An INFN-FRIB synergic project - 5 initiatives (4 exper + 1 theor)

GASPEC
Gamma and Charged Particle Spectroscopy and Collective excitations
(Spin, Deformation, Shell-model at drip-lines, collectivity)

SYMEOS
Symmetry Energy and Equation of State
(Heavy-ion collisions and EoS, density, temperature, N/Z, in-medium structure)



NUSYC
Nucleosynthesis and Clustering
(low σ, r- and rp-process, clusters in exotic nuclei, ...)

RIBDCE
Radioactive Ion Beam induced Double-Charge Exchange
(low σ, 0^o measurements, few-body, 3-body forces, light clusters, $0\nu\beta\beta$ decays)

NUSDAF: Nuclear Structure, Dynamics and Astrophysics at FRIB

An INFN-FRIB synergic project - 5 initiatives (4 exper + 1 theor)

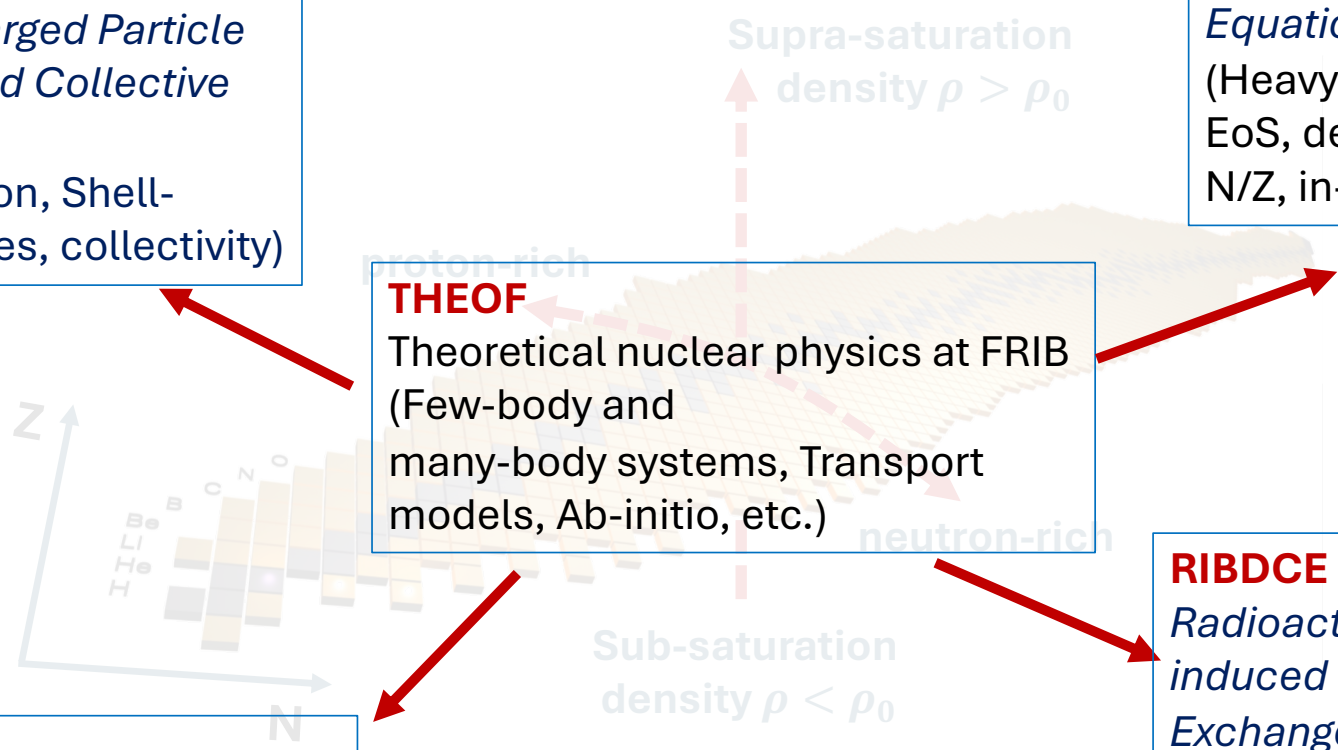
GASPEC
Gamma and Charged Particle Spectroscopy and Collective excitations
(Spin, Deformation, Shell-model at drip-lines, collectivity)

SYMEOS
Symmetry Energy and Equation of State
(Heavy-ion collisions and EoS, density, temperature, N/Z, in-medium structure)

THEOF
Theoretical nuclear physics at FRIB
(Few-body and many-body systems, Transport models, Ab-initio, etc.)

NUSYC
Nucleosynthesis and Clustering
(low σ, r- and rp-process, clusters in exotic nuclei, ...)

RIBDCE
Radioactive Ion Beam induced Double-Charge Exchange
(low σ, 0^{o} measurements, few-body, 3-body forces, light clusters, $0\nu\beta\beta$ decays)



NUSDAF: Nuclear Structure, Dynamics and Astrophysics at FRIB

An INFN-FRIB synergic project - 5 initiatives (4 exper + 1 theor)

Relevance to NuSym

GASPEC
Gamma and Charged Particle Spectroscopy and Collective excitations
(Spin, Deformation, Shell-model at drip-lines, collectivity)
→ **PDR, GMR, …**

SYMEOS
Symmetry Energy and Equation of State
(Heavy-ion collisions and EoS, density, temperature, N/Z, in-medium structure)

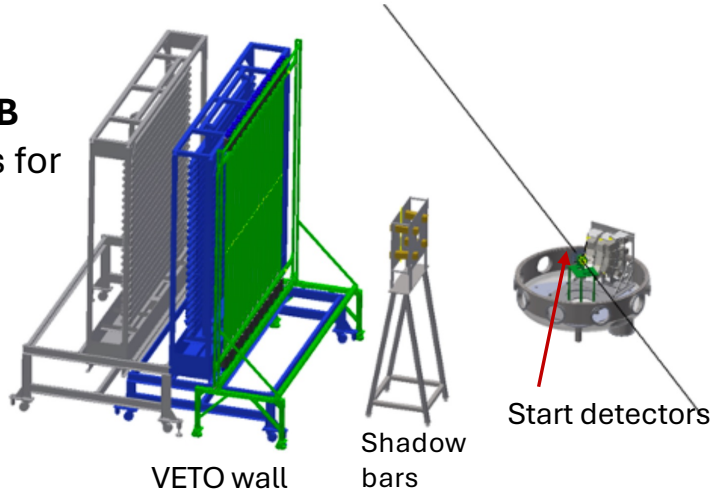
THEOF
Theoretical nuclear physics at FRIB
(Few-body and many-body systems, Transport models, Ab-initio, etc.)

NUSYC
Nucleosynthesis and Clustering
(low σ, r- and rp-process, clusters in exotic nuclei, …)

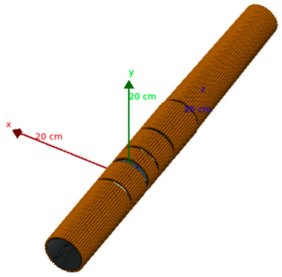
RIBDCE
Radioactive Ion Beam induced Double-Charge Exchange
(low σ, 0° measurements, few-body, **3-body forces, light clusters**, $0\nu\beta\beta$ decays)

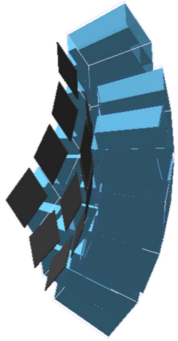
Experimental synergy: multi-purpose setups

LANA n det @ FRIB
Liquid Scintillators for n-γ discrimination



Fiber Array @ FRIB





HiRA - Blocks of Silicon strips and CsI(Tl)

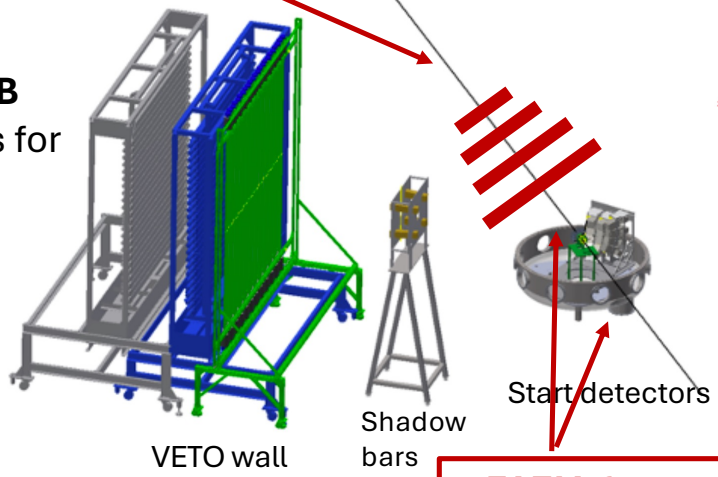
Presently existing setup at FRIB

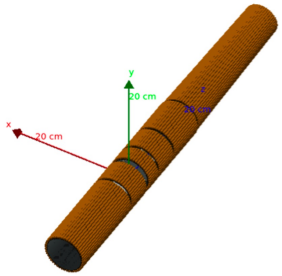
Experimental synergy: multi-purpose setups

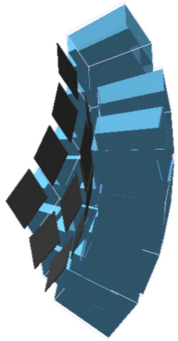
+ 4-5 Si-CsI(Tl) Chimera rings
Improve reaction plane and b

Fiber Array @ FRIB

LANA n det @ FRIB
Liquid Scintillators for
n-γ discrimination







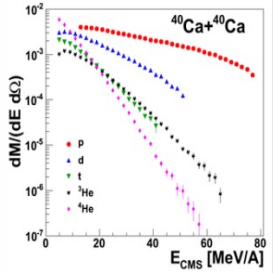
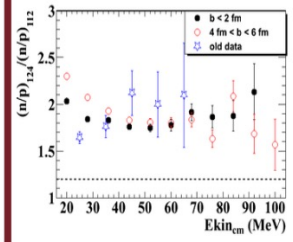
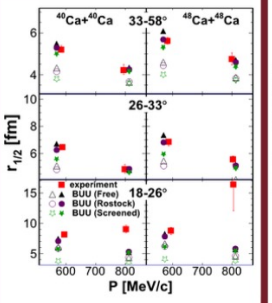
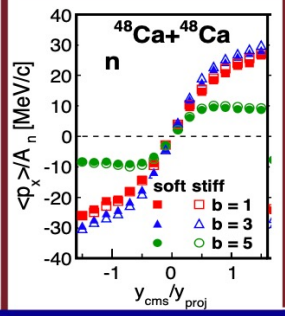
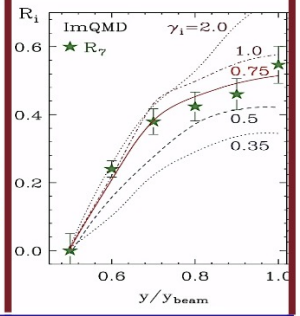
HiRA - Blocks of Silicon strips and CsI(Tl)

+ FARCOS blocks
Increase correlators
(Silicon strips and CsI(Tl))

+ FAZIA forward & backward
N/Z in spectators and participants (OSCAR?)

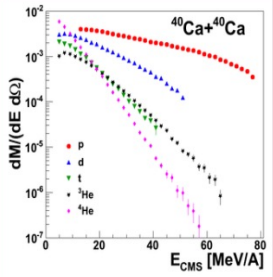
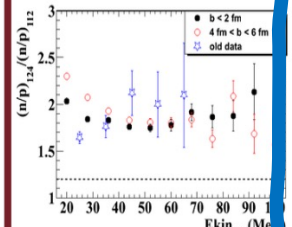
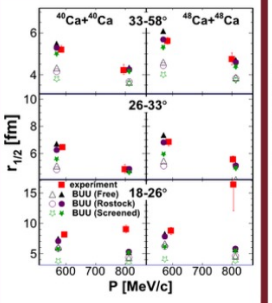
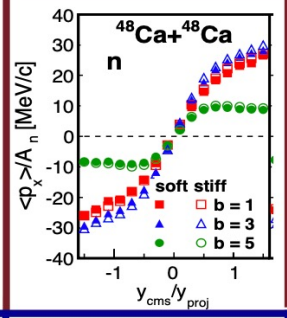
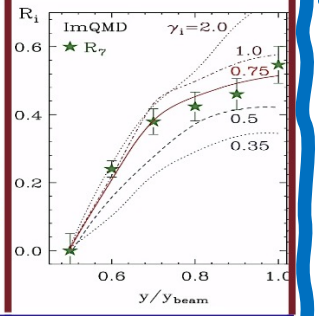
1. Campaigns of HIC experiments (A+A at E/A=150 – 350 MeV)
2. Double-charge exchange experiments: (t,3p), (18Ne,18O), etc., impact on $0\nu\beta\beta$
3. Nuclear astrophysics: invariant mass spectroscopy rp-process nuclei

SYMEOS: Symmetry energy and EoS

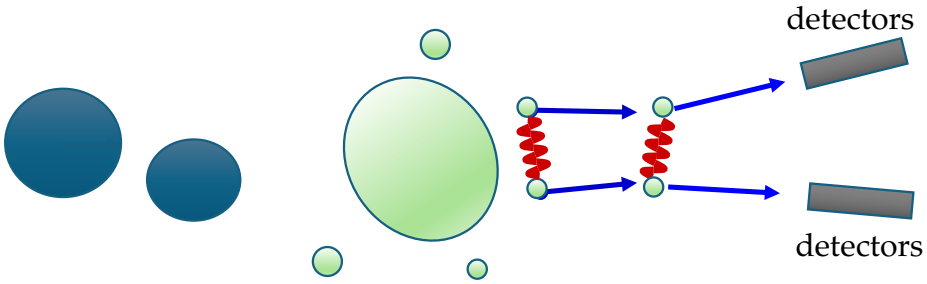
Observables	Spectra	(Double-) ratios	Femtoscopy	Flow	Isospin diffusion
Transport model ingredients ↓					
Symmetry energy		✔		✔	✔
Effective mass		✔		?	?
Cross section	✔	✔	✔	✔	✔
Cluster production	✔	✔	✔	✔	✔

SYMEOS: Symmetry energy and EoS

INFN

Observables	Spectra	(Double-) ratios	Femtoscopy	Flow	Isospin diffusion
Transport model ingredients ↓					
Symmetry energy		✔		✔	✔
Effective mass		✔		?	?
Cross section	✔	✔	✔	✔	✔
Cluster production	✔	✔	✔	✔	✔

Proton-Proton femtoscopy

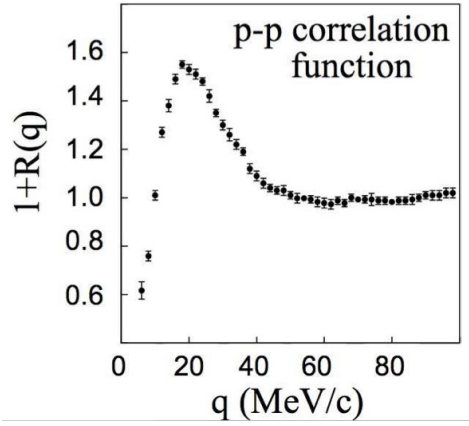


Final State Interactions + Quantum statistics (if identical)

$$1 + R(q) = k \cdot \frac{Y_{coinc}(q)}{Y_{evt.mixing}(q)}$$

Intensity interferometry / Femtoscopy

q = mom. of relative motion

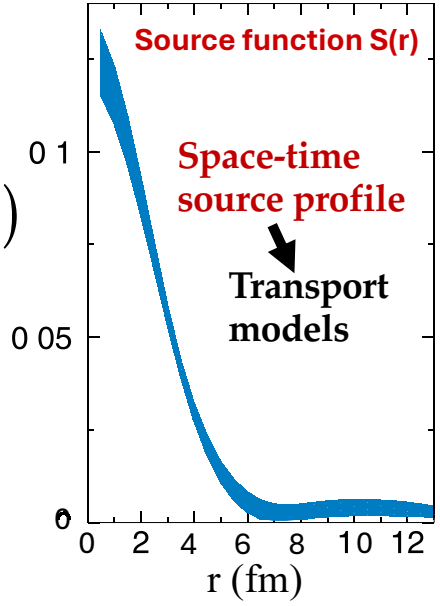


Koonin-Pratt Eq.

$$R(\vec{q}) = \int d\vec{r} \cdot S(\vec{r}) \cdot K(\vec{r}, \vec{q})$$

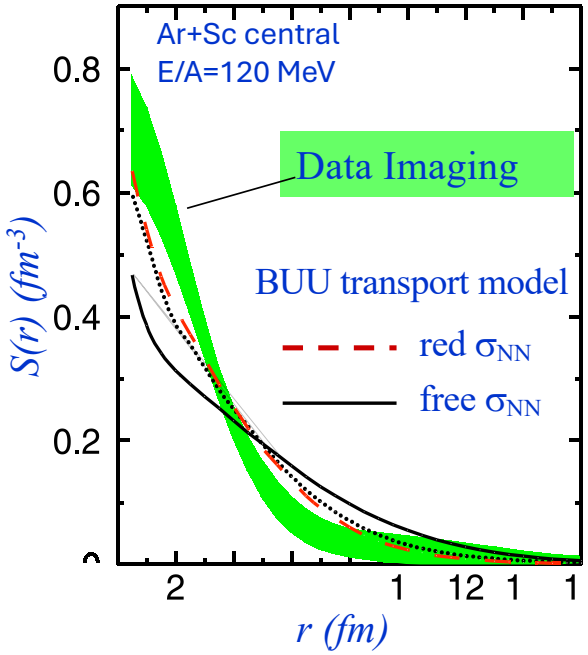
Imaging – Danielewicz

New technique! Deblurring by P. Nzabahimana and Danielewicz!

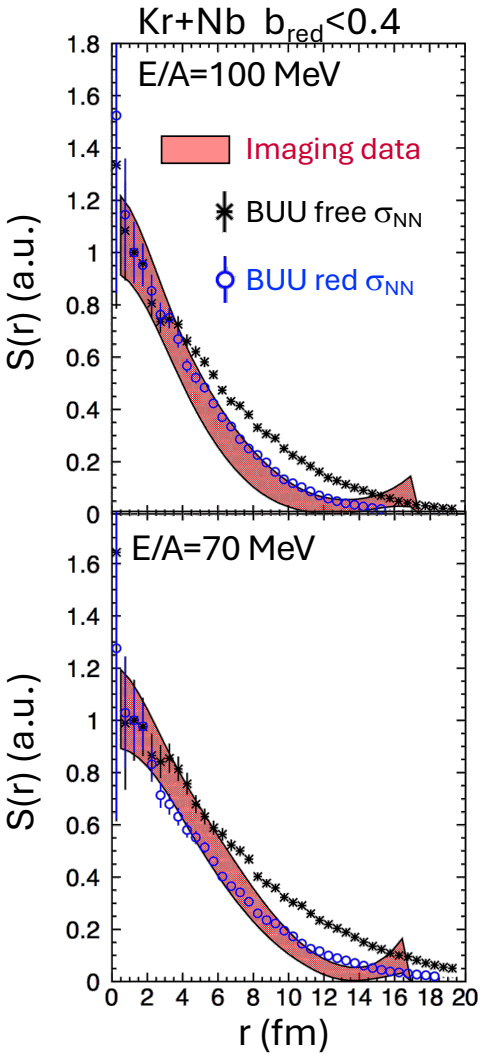


pp Femtoscopy and transport models

NN collision cross section



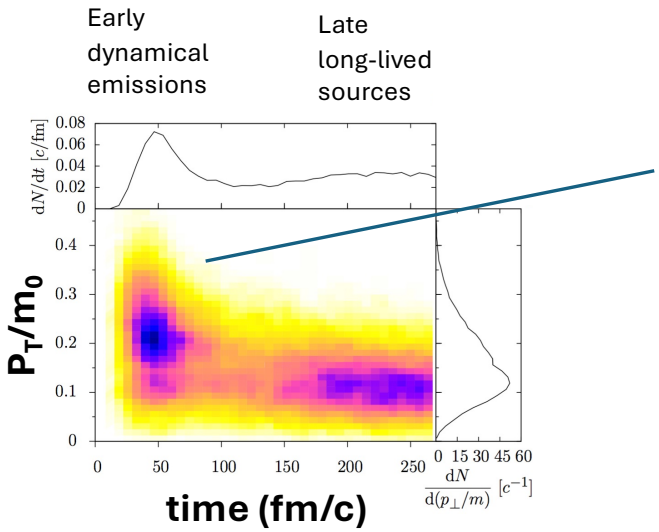
G. Verde, P. Danielewicz et al. PRC67, 034606 (2002)
B. Barker, PhD thesis @ NSCL (2014)
P. Nzabahimana, P. Danielewicz, G. Verde (2024) TBS



Significant sensitivity to σ_{NN}

Imaging sources at different emission stages

Xe+Au E/A=50 MeV (Central)



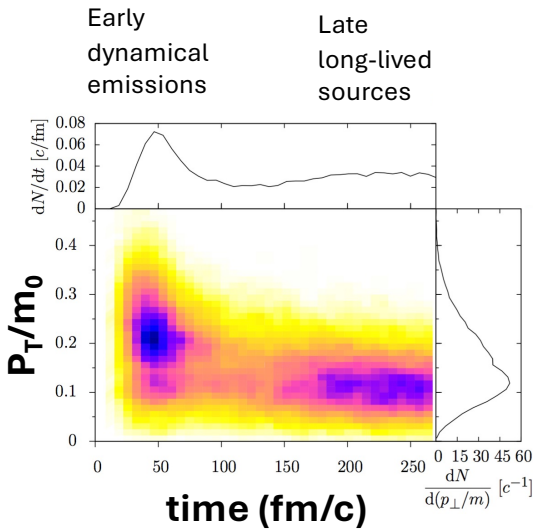
High PT protons emitted at early dynamical stage

BUU simualtions

G. Verde, B. Barker, P. Danielewicz

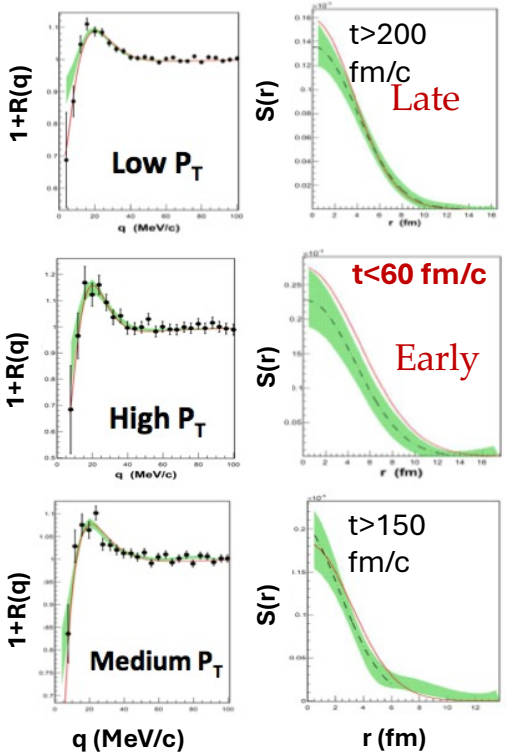
Imaging sources at different emission stages

Xe+Au E/A=50 MeV (Central)



BUU simualtions

Experimental data (LASSA @ MSU)



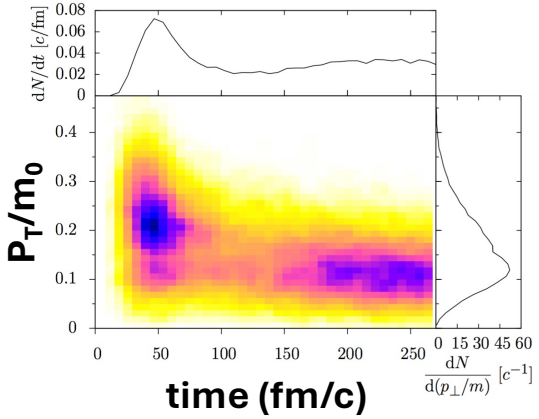
G. Verde, B. Barker, P. Danielewicz

Imaging sources at different emission stages

Xe+Au E/A=50 MeV (Central)

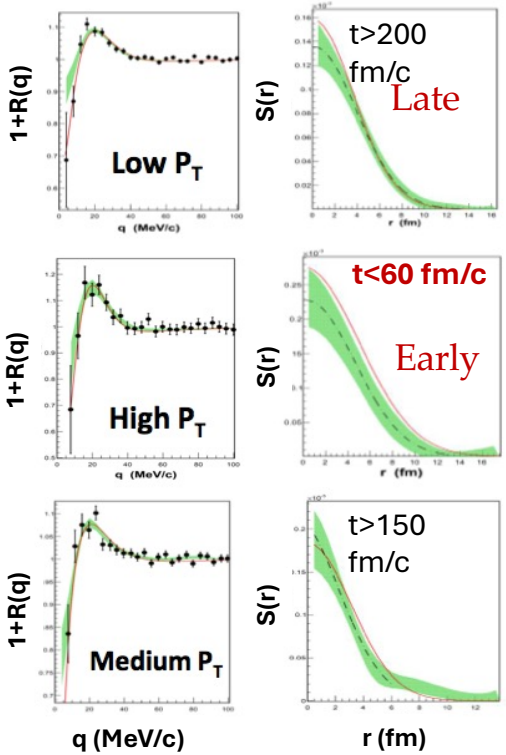
Early dynamical emissions

Late long-lived sources

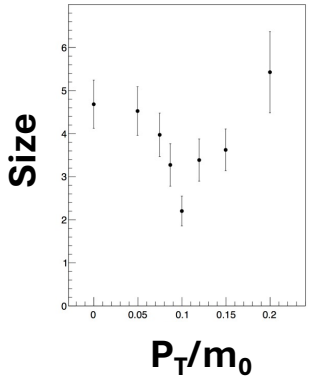


BUU simualtions

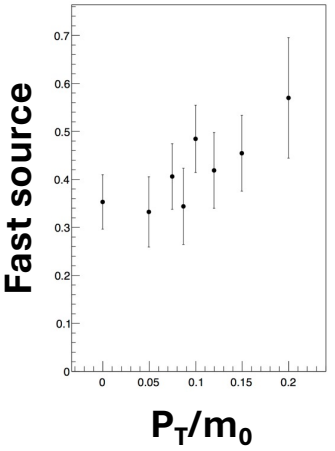
Experimental data (LASSA @ MSU)



Source size



% of dynamical early emissions



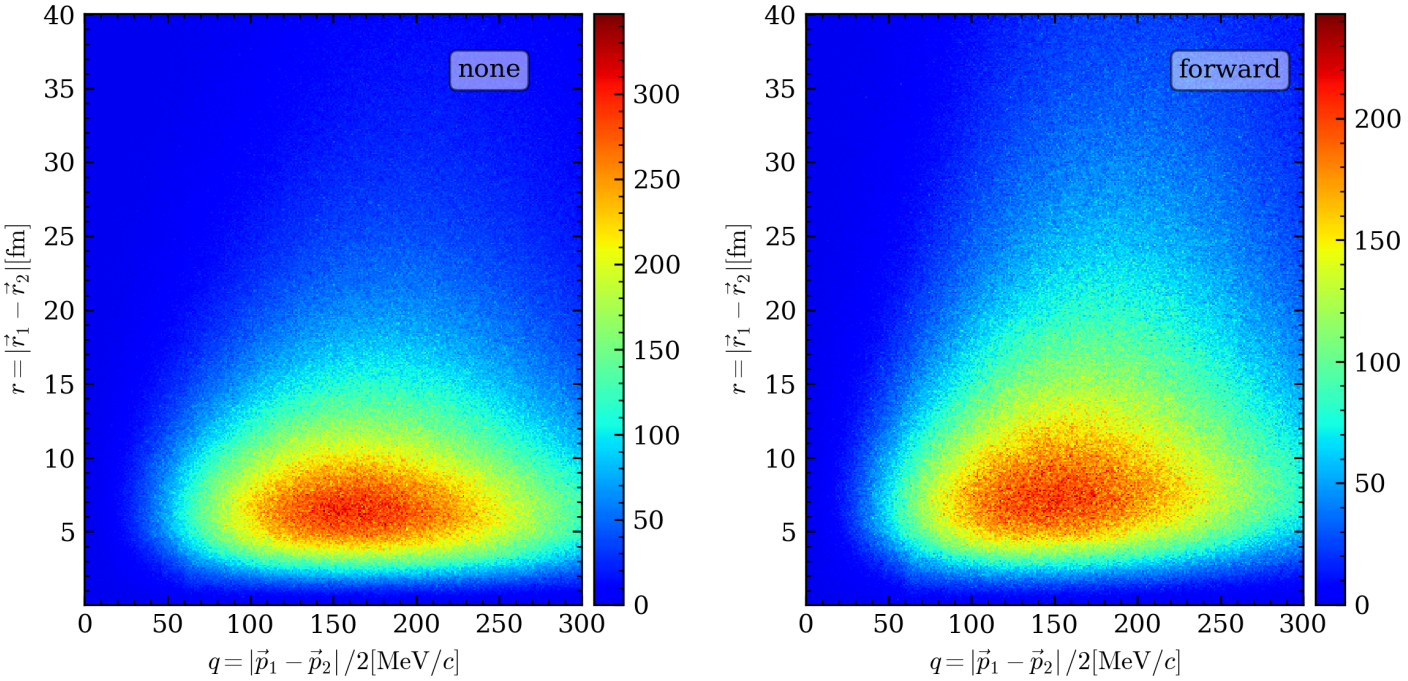
G. Verde, B. Barker, P. Danielewicz

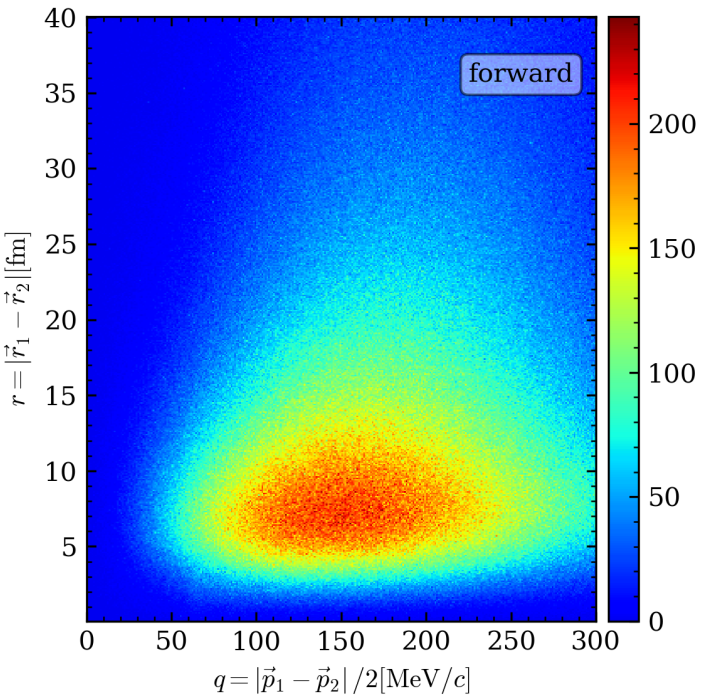
AMD – ^{58}Ni+^{58}Ni -central

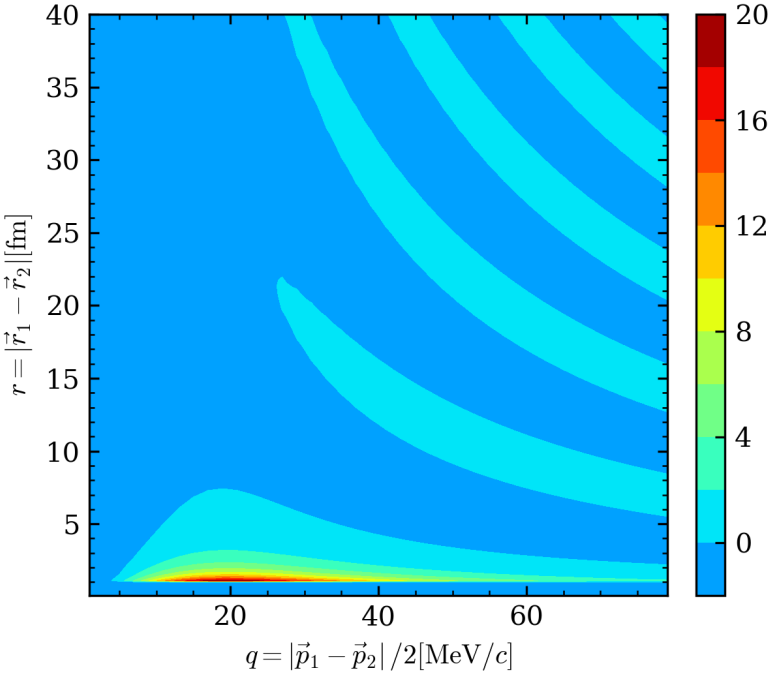
K. Chi Tam, WMU
G. Verde

November 2023

Forward : allow the first particle to propagate for dt
None: no such correction



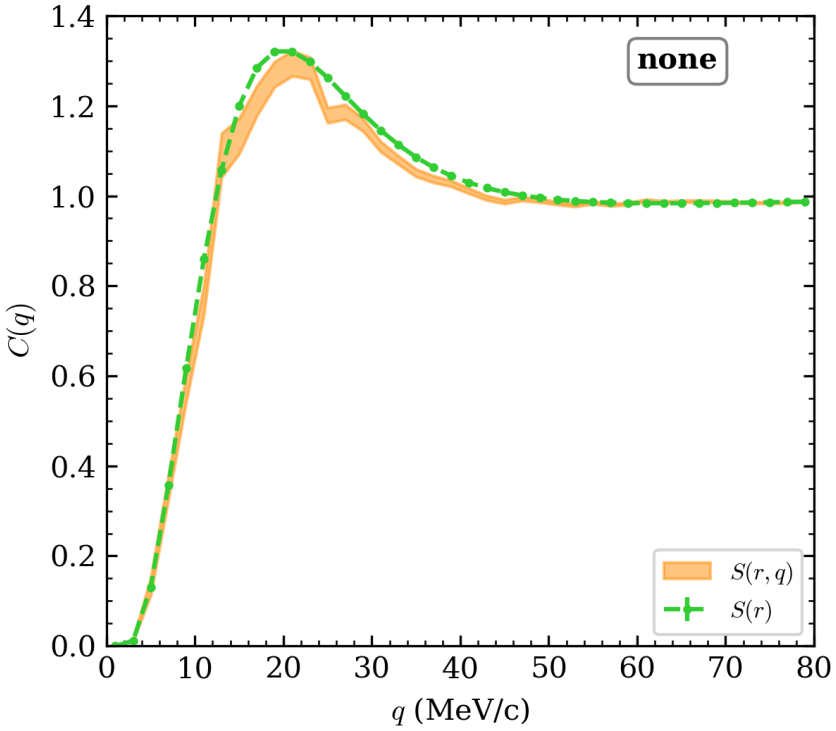


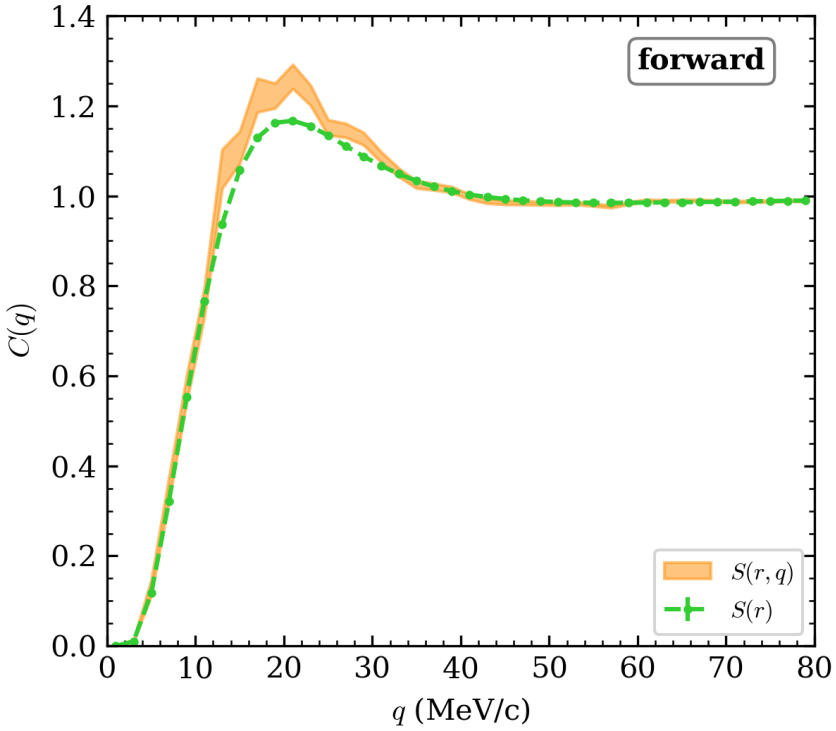


$$S(r,q) = N(r,q)/r^2$$

$$|\Psi(r,q)|^2 = \mathcal{K}(r,q) + \mathbf{I}$$

$$C(q) = 4\pi \int \mathrm{d}r r^2 S(r,q)(\mathcal{K}(r,q) + \mathbf{I})$$

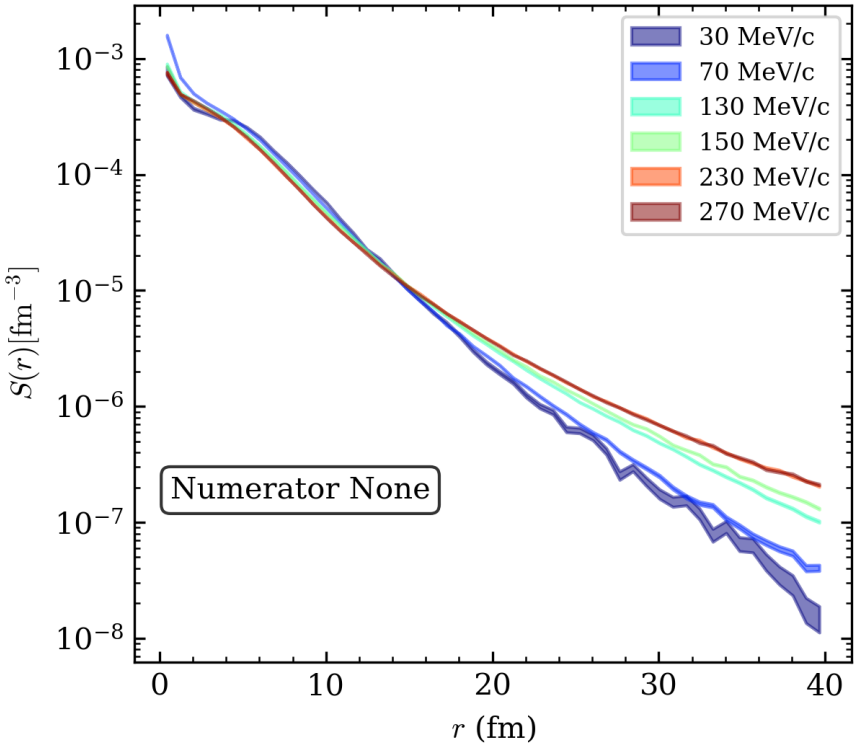


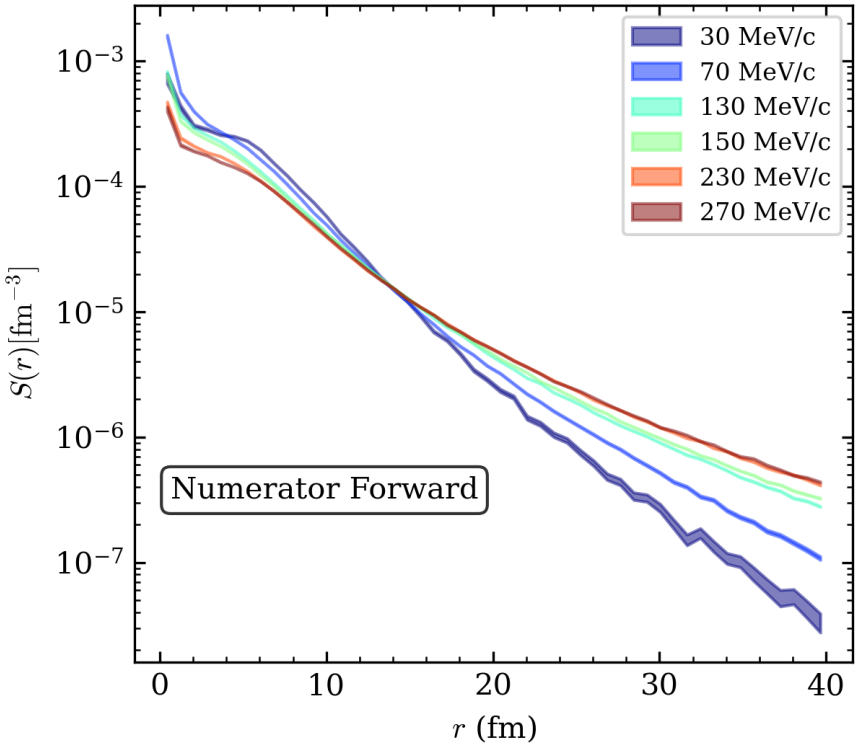


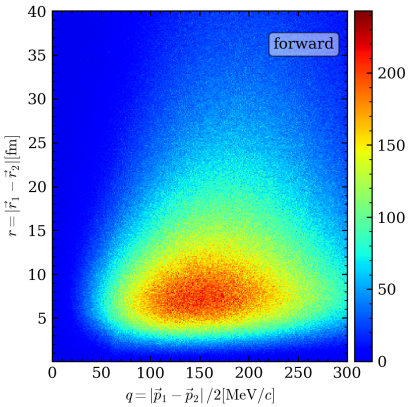
$$\bar{S}(r) \approx \sum S(r,q)$$

$$C(q) = 4\pi \int \mathrm{d}r r^2 S(r,q)(\mathcal{K}(r,q) + \mathbf{I})$$

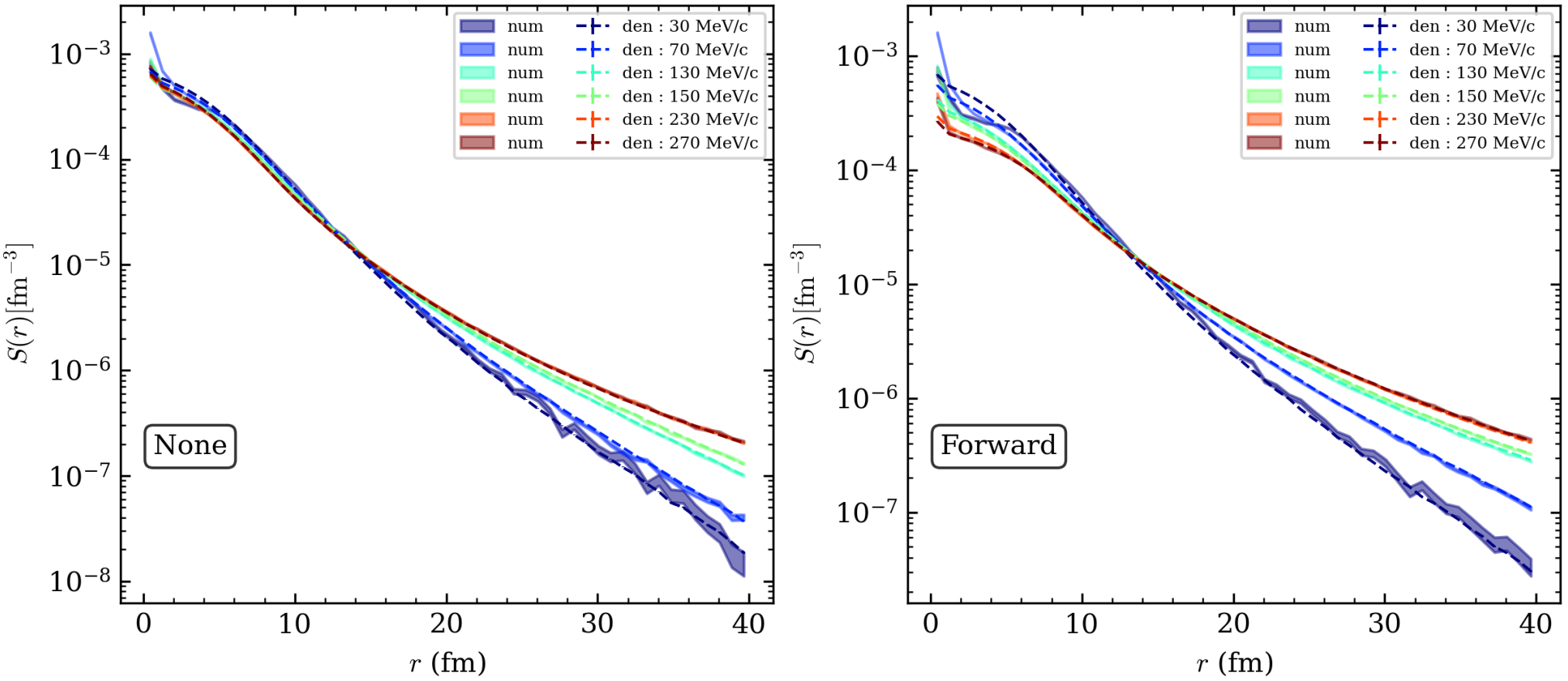
$$C(q) = 4\pi \int \mathrm{d}r r^2 \bar{S}(r)(\mathcal{K}(r,q) + \mathbf{I})$$





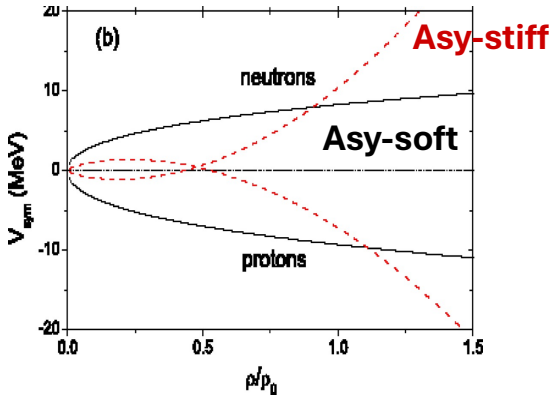


- sampled real pair (r, q) histogram, lets call it $N(r,q)$
- $S(r,q) \propto \frac{N(r,q)}{r^2}$
- Slice the histogram, for each q, we get a $S(r)$, normalized as usual.
- 50 bins in r.


num
num
num
num
num
num
den : 30 MeV/c
den : 70 MeV/c
den : 130 MeV/c
den : 150 MeV/c
den : 230 MeV/c
den : 270 MeV/c
None
Forward
$S(r)[\mathrm{fm}^{-3}]$
r (fm)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
10
20
30
40

pp, np, nn Femtoscopy Vs transport models

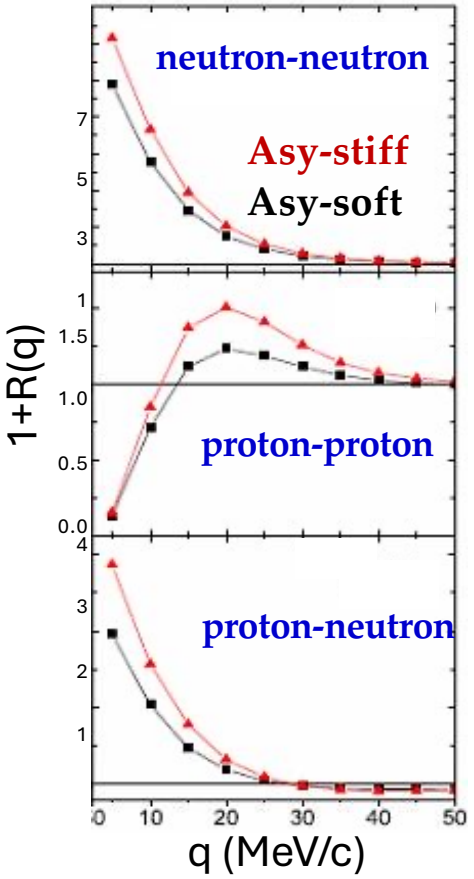
Density and momentum dependence of the symmetry energy



L.W. Chen et al., PRL 90, 162701 (2003) Esym
L.W. Chen et al., PRC 69, 054606 (2004) Esym and Mom. Dep.

Need for important experimental plans on n-p correlations!

Correlation functions



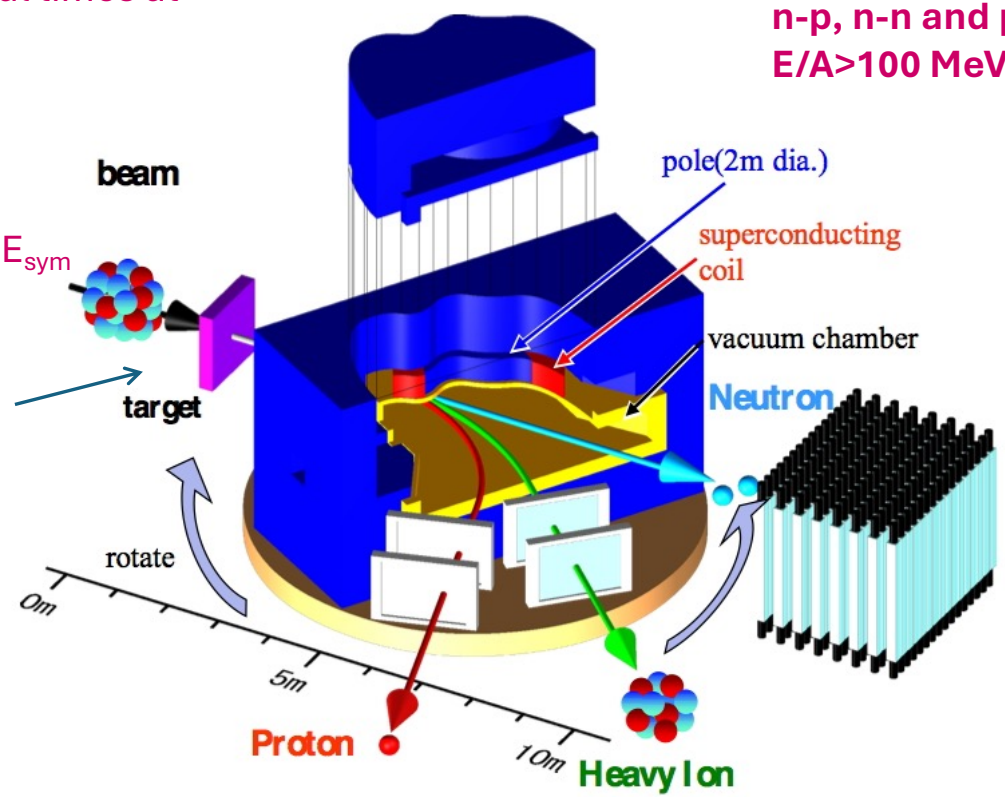
Hopefully with future TPCs coupled to charged particle and neutron detectors

Perspectives discussed several times at Riken (Samurai)

FRIB: time to do it!

RIBs to increase sensitivity to E_{sym}

n-p, n-n and p-p correlations at E/A>100 MeV



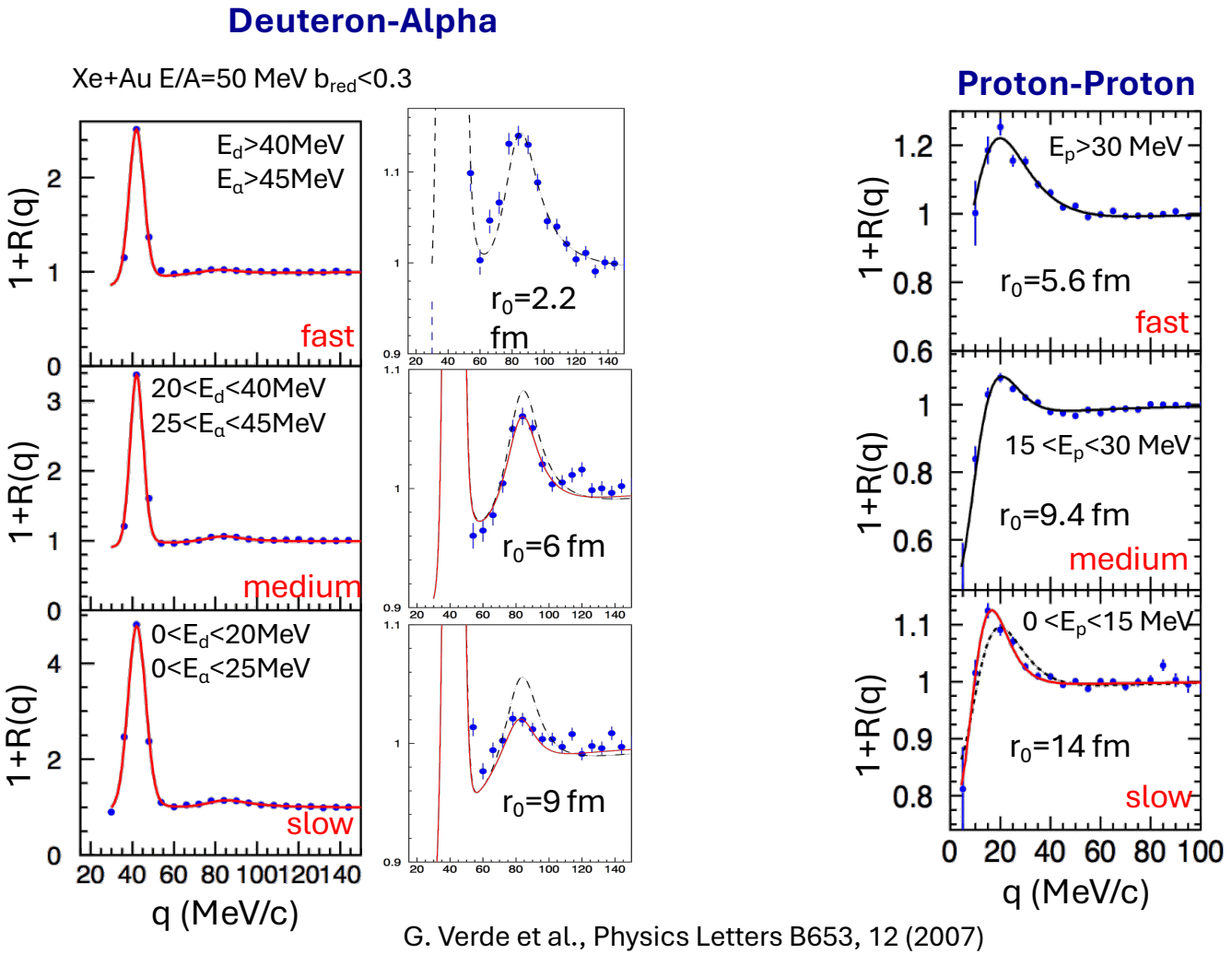
Samurai Image - Courtesy of T. Nakamura

Additional charged particle detectors with high energy and isotopic resolution

Clusters and emission hierarchy

- Velocity gated correlations suggest that different particles may come at different times (hierarchy)
- Early work by R. Ghetti et al.

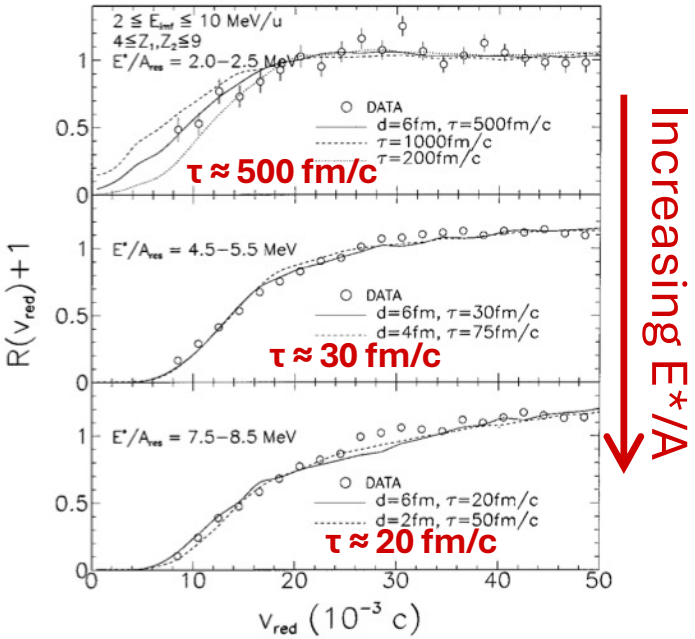
Different particles → different sources



G. Verde et al., Physics Letters B653, 12 (2007)

Fragment-Fragment correlations in spectactor matter and phase transitions

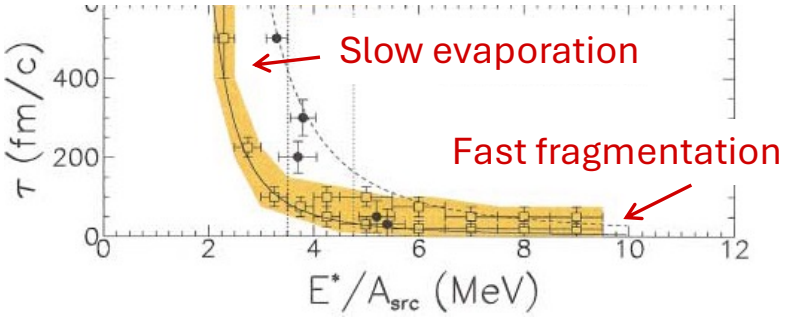
π^-, p + Au 8.0, 8.2, 9.2, 10.2 GeV/c

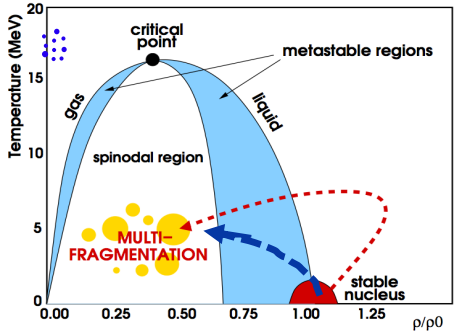


ISiS data @ Brookhaven

L. Beaulieu et al., PRL84 (2000) 5971

In memory of Vic Viola

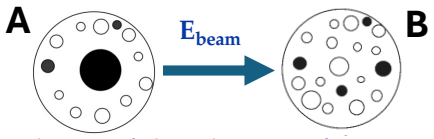




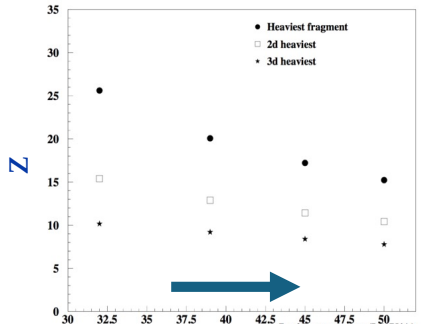
Dynamical approach to isospin effects on phase transitions

Time-scales and "tomography" of fragment emission

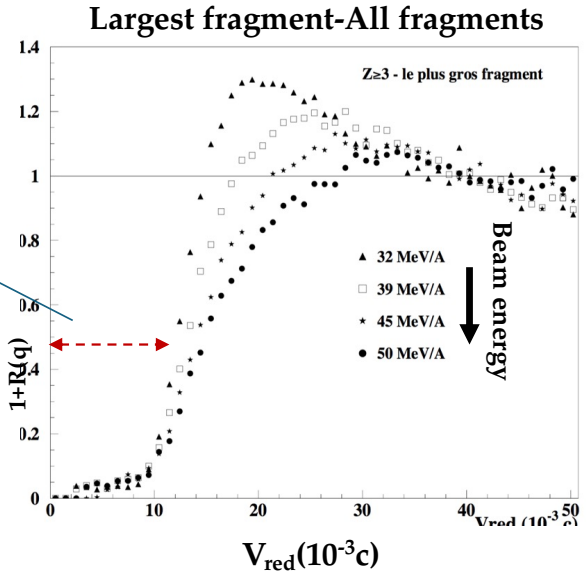
Xe+Sn (central) – Indra data
E/A=32, 39, 45, 50 MeV



Charge of the 3 heaviest fragments



τ < 50 fm/c

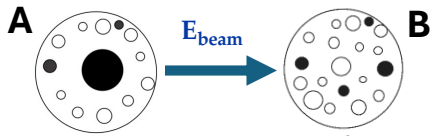


Emission times decrease with beam energy

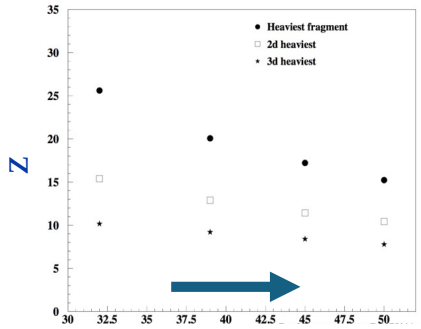
S. Salou, PhD thesis, GANIL
G. Verde, A. Chbihi, Int. J. Mod. Phys. E, Special-Topics Issue on Nuclear Particle Correlations and Cluster Physics

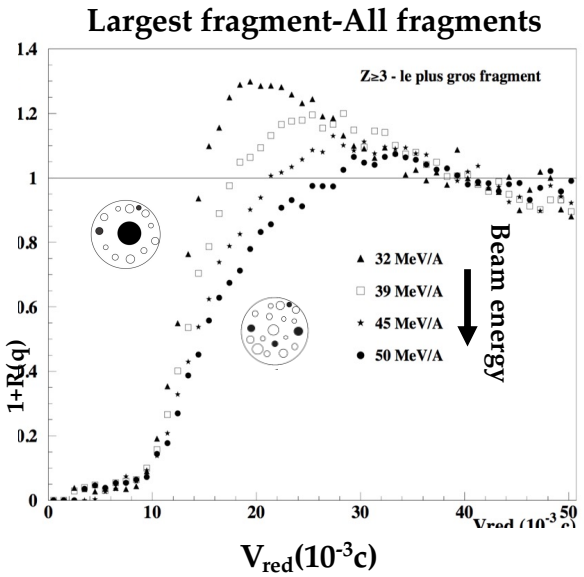
Time-scales and "tomography" of fragment emission

Xe+Sn (central) – Indra data
E/A=32, 39, 45, 50 MeV



Charge of the 3 heaviest fragments





Emission times decrease with beam energy

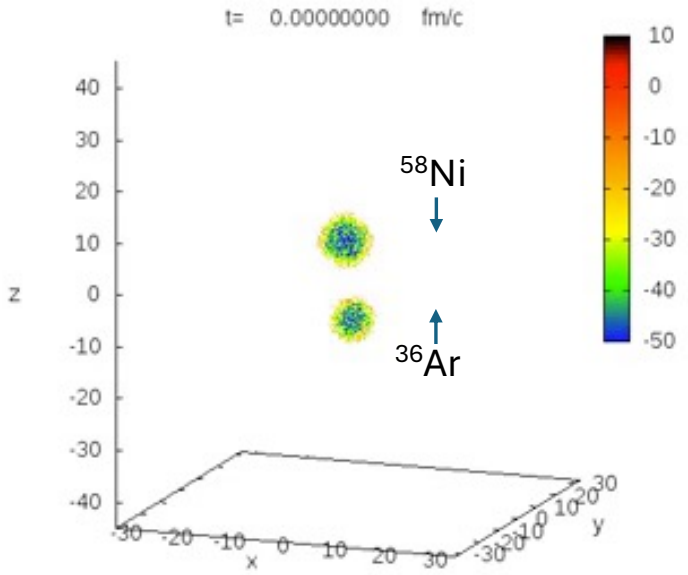
- **from asymmetric splitting** (sequential/evaporation-like) **to homogeneous and simultaneous** in-medium fragmentation
- Tests of cluster emission in transport models (D. Dell'Aquila, GV)

S. Salou, PhD thesis, GANIL
G. Verde, A. Chbihi, Int. J. Mod. Phys. E, Special-Topics Issue on Nuclear Particle Correlations and Cluster Physics

Projectile jet fragmentation

BLOB (P. Napolitani, M. Colonna)

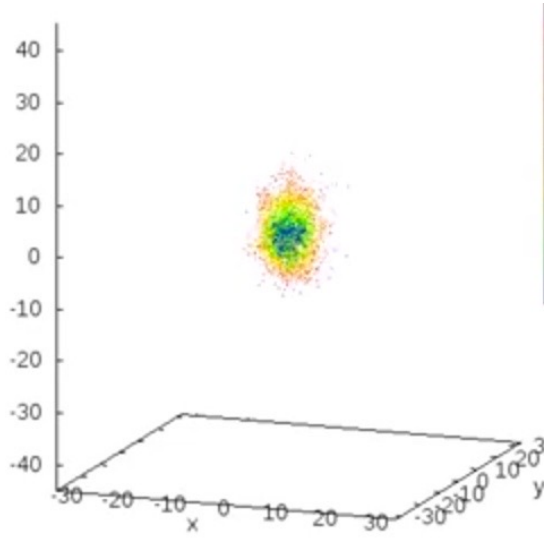
$^{36}Ar + {}^{58}Ni$ E/A=40 MeV



Projectile jet fragmentation

BLOB (P. Napolitani, M. Colonna)

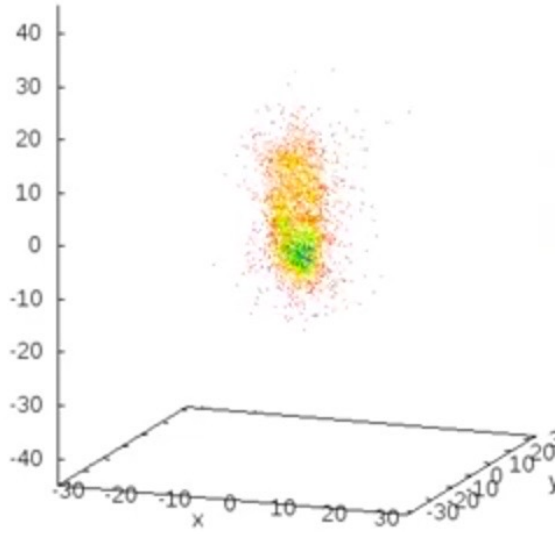
$^{36}Ar + ^{58}Ni$ E/A=40 MeV



Projectile jet fragmentation

BLOB (P. Napolitani, M. Colonna)

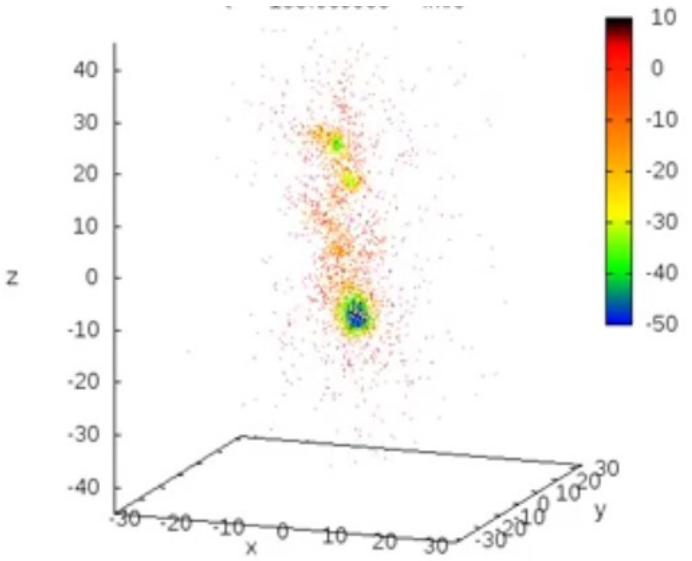
$^{36}Ar + {}^{58}Ni$ E/A=40 MeV

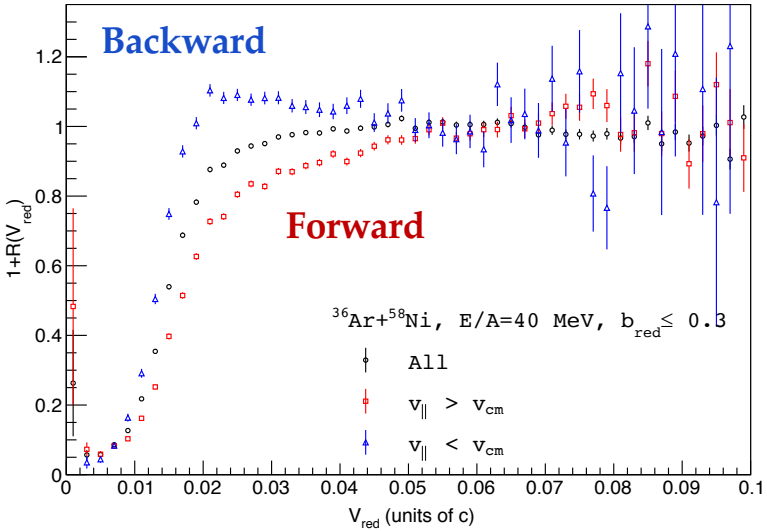


Projectile jet fragmentation

BLOB (P. Napolitani, M. Colonna)

$^{36}Ar + ^{58}Ni$ E/A=40 MeV



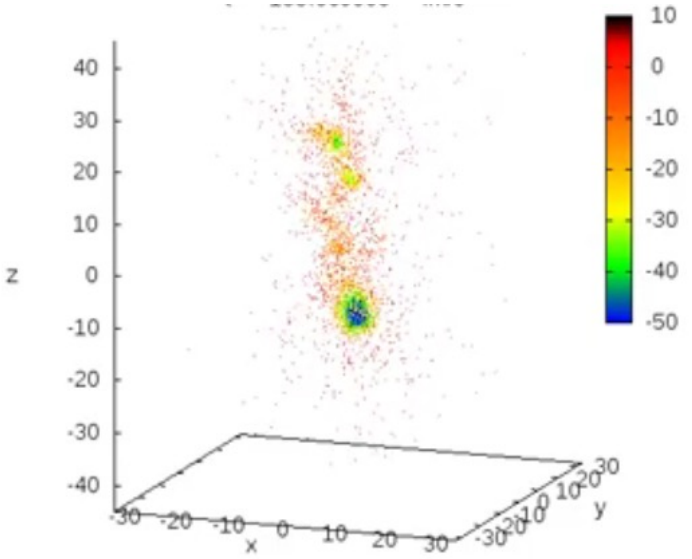


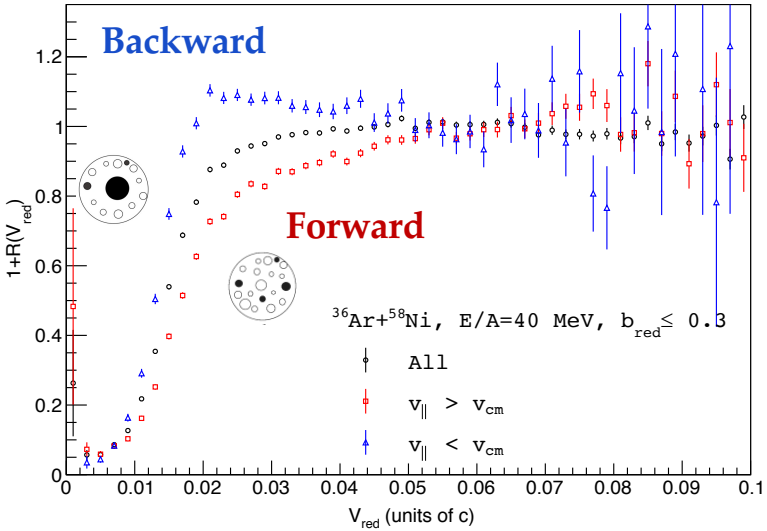
L. Francalanza, D. Dell'Aquila et al.

Projectile jet fragmentation

BLOB (P. Napolitani, M. Colonna)

$^{36}Ar + ^{58}Ni$ E/A=40 MeV



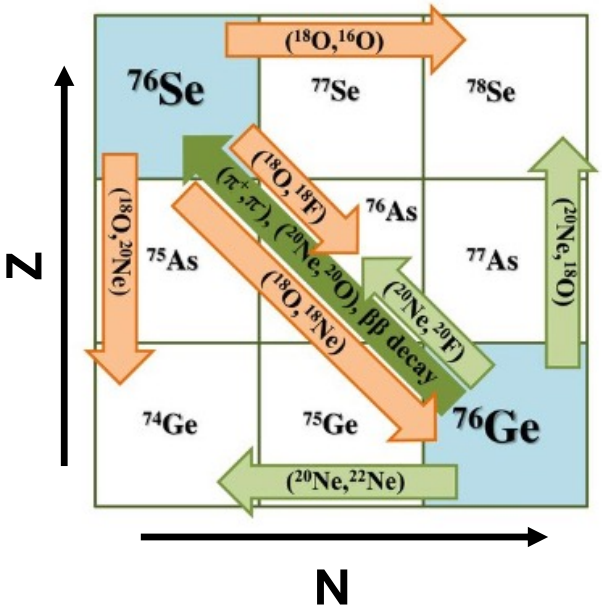


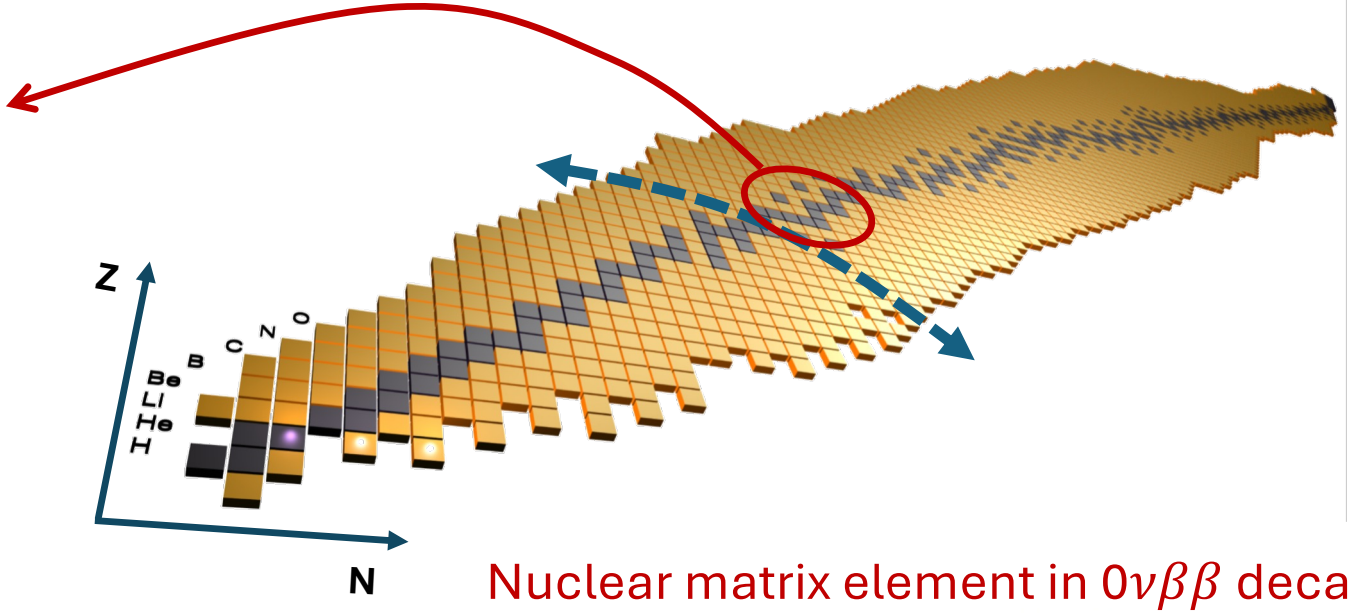
- **Forward projectile region**: fast emission + homogeneous fragmentation patterns
- **Backward target region**: longer emission times and asymmetric charge fragmentation pattern

L. Francalanza, D. Dell'Aquila et al.

RIBDCE: Radioactive Ion Beam induced Double-Charge Exchange reactions

DCE Reactions - 2n ↔ 2p





Nuclear matrix element in $0\nu\beta\beta$ decay

$$1/T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) = G_0 \left| M^{\beta\beta\,0\nu} \right|^2 \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2$$

Experiments and methodology

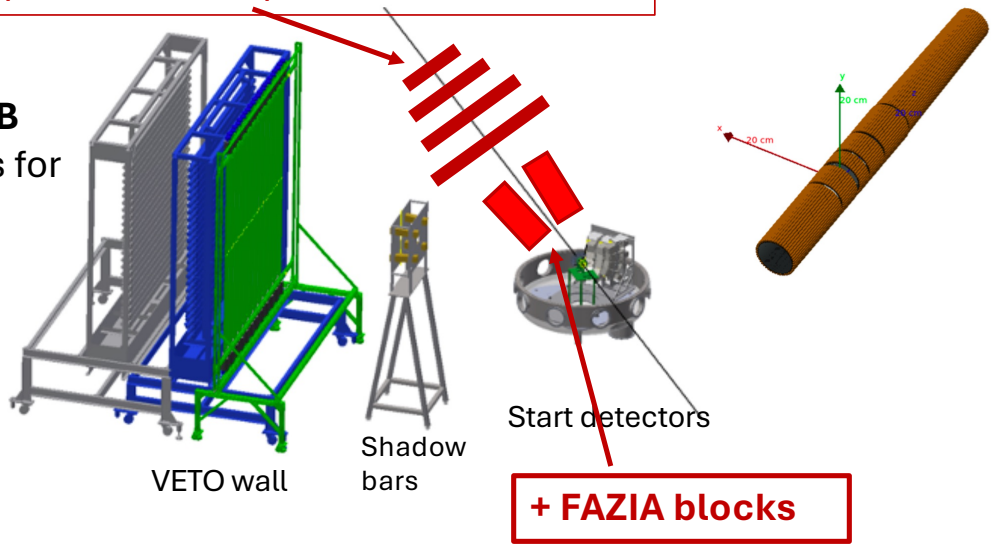
Measure DCE cross sections – very small and at $\theta \approx 0^o$!

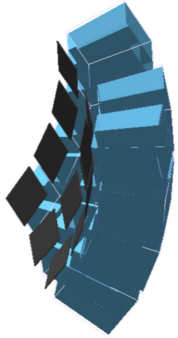
RIBDCE: Radioactive Ion Beam induced Double-Charge Exchange reactions

+ 4-5 Si-CsI(Tl) Chimera rings
Improve reaction plane and b

Fiber Array @ FRIB

LANA n det @ FRIB
Liquid Scintillators for n-γ discrimination





HiRA - Blocks of Silicon strips and CsI(Tl)

+ FARCOS blocks
Increase correlators (Silicon strips and CsI(Tl))

FAZIA and CHIMERA to detetct the double-charge exchanging probe:

- t + 3He → 3 n + 3 p (detected with FAZIA and Chimera blocks)
- Detection of ^{18}O in (^{18}Ne,^{18}O) reactions induced by ^{18}Ne @ FRIB

NUSYC: synergy with SYMEOS and RIBDCE

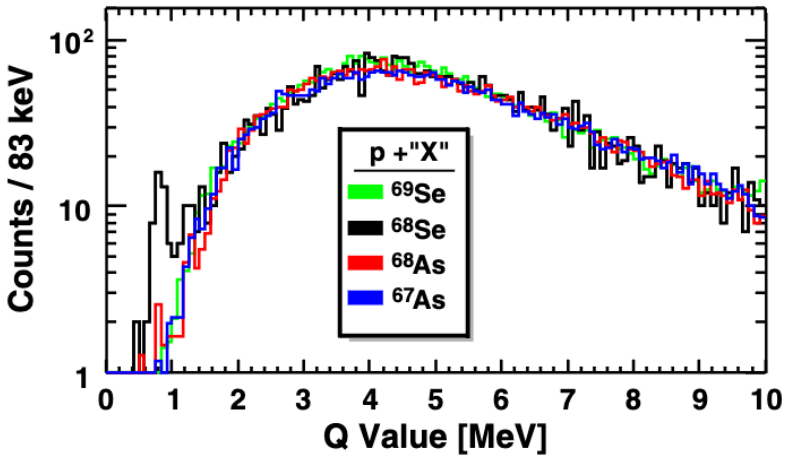
Detectors: same as SYMEOS and RIBDCE

Decay of p-rich nuclei → relevant for rp-process

Ground-State Proton Decay of ^{69}Br and Implications for the ^{68}Se Astrophysical Rapid Proton-Capture Process Waiting Point

A. M. Rogers, M. A. Famiano, W. G. Lynch, M. S. Wallace, F. Amorini, D. Bazin, R. J. Charity, F. Delaunay, R. T. de Souza, J. Elson, A. Gade, D. Galaviz, M.-J. van Goethem, S. Hudan, J. Lee, S. Lobastov, S. Lukyanov, M. Matoš, M. Mocko, H. Schatz, D. Shapira, L. G. Sobotka, M. B. Tsang, and G. Verde

Phys. Rev. Lett. **106**, 252503 – Published 24 June 2011

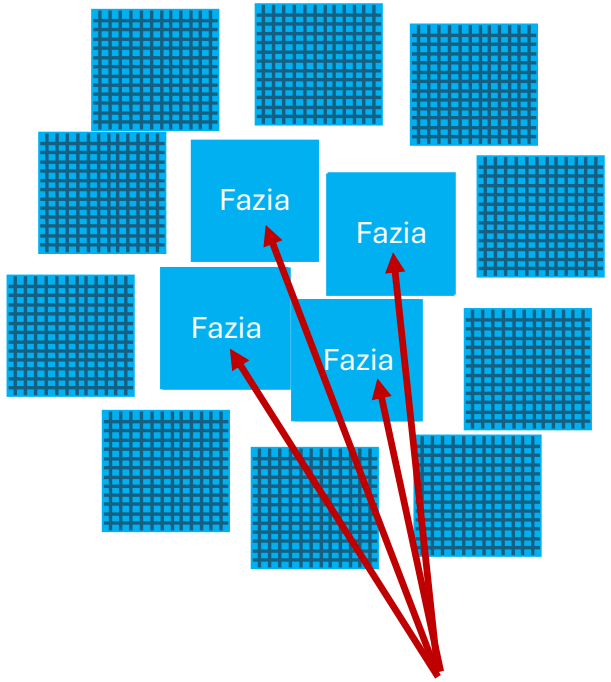


HiRA Si-strip

+

S800 magnetic spectrometer

Si-strip/CsI(Tl) detectors for LCP
HiRA(FRIB) and FARCOS (INFN)

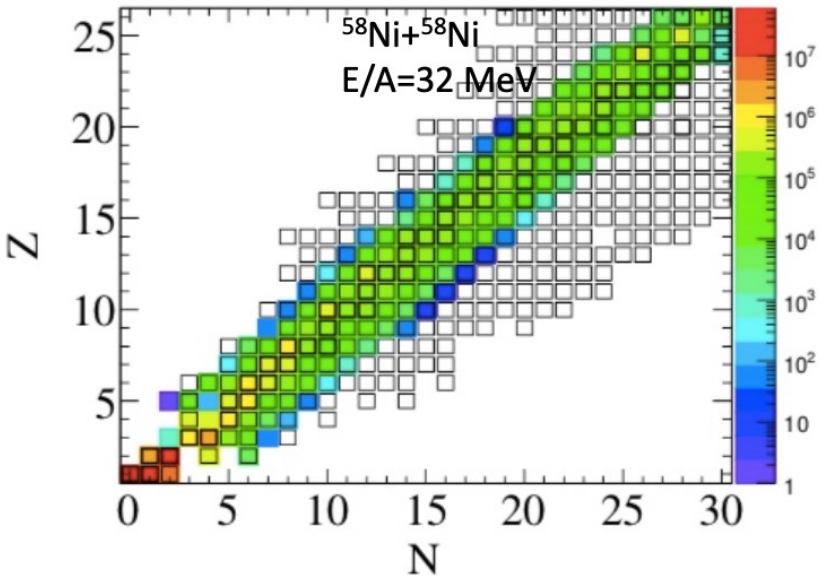


FAZIA in place of a magnetic spectrometer
(high A and Z resolution up to Z=30)

NUSYC: synergy with SYMEOS and RIBDCE

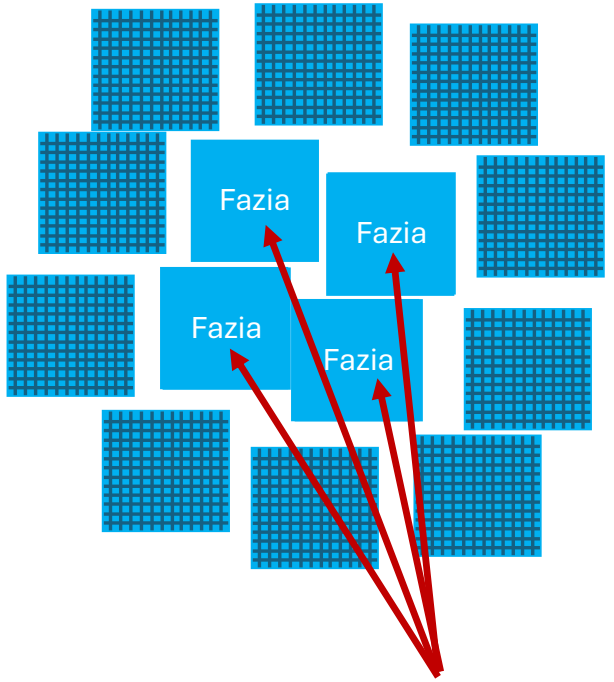
Detectors: same as SYMEOS and RIBDCE

Decay of p-rich nuclei → relevant for rp-process



C. Ciampi, FAZIA Coll.

Si-strip/CsI(Tl) detectors for LCP
HiRA(FRIB) and FARCOS (INFN)



FAZIA in place of a magnetic spectrometer
(high A and Z resolution up to Z=30)

INFN Management – FRIB meeting

INFN Visit to FRIB
Facility for Rare Isotope Beams (FRIB)
9/4 - 9/5/2024
AGENDA

Start	Duration	Agenda Item	Presenter
Wednesday, 4 September 2024 Rm. 2311			
9:15 AM	0:15	Arrival to FRIB (640 S Shaw Lane, East Lansing, MI 48824) Katie to escort to 2311	
9:30 AM	0:30	Welcome and FRIB Overview	Glasmacher
10:00 AM	0:30	Overview of INFN and its nuclear physics organization and program	Bettoni, Ciuchini, Giubellino
10:30 AM	0:15	*Break*	
10:45 AM	0:30	Overview of INFN FRIB connections and plans	Verde
11:15 AM	0:15	Opportunities to study the nuclear equation of state at FRIB	Brown
11:30 AM	0:15	Nuclear astrophysics program at FRIB	Spyrou
11:45 AM	0:15	Opportunities with gamma-ray spectroscopy at FRIB	Gade
12:00 PM	1:15	Hosted Lunch at FRIB	
1:15 PM	0:15	Theory connections	D. Lee
1:30 PM	0:30	FRIB's Graduate Program	Hergert
2:00 PM	1:00	Discussions	
3:00 PM	1:30	FRIB Tour	Glasmacher
4:30 PM			

Synergic efforts needed

INFN-IN2P3 exchanges soon

My opinion: include GSI in near future - both science case and R&D for new detectors (TPCs?)

Workshop on Particle Correlations and Femtoscopy

Toulouse (France), November 4-8, 2024

17th Edition

Both low and high energy physics in femtoscopy and resonance decays

Space still available for talks (especially students and postdocs)

Postdoc positions at INFN

- 15 postdoc positions in theoretical nuclear and particle physics
- 20 postdoc positions in experimental nuclear and particle physics

Contact us if interested

backup

NUSDAF – Nuclear Structure, Dynamics and Astrophysics at FRIB

- A synergic collaborative effort between INFN groups and FRIB
- FRIB beams complimentary to EU beams → key to physics case

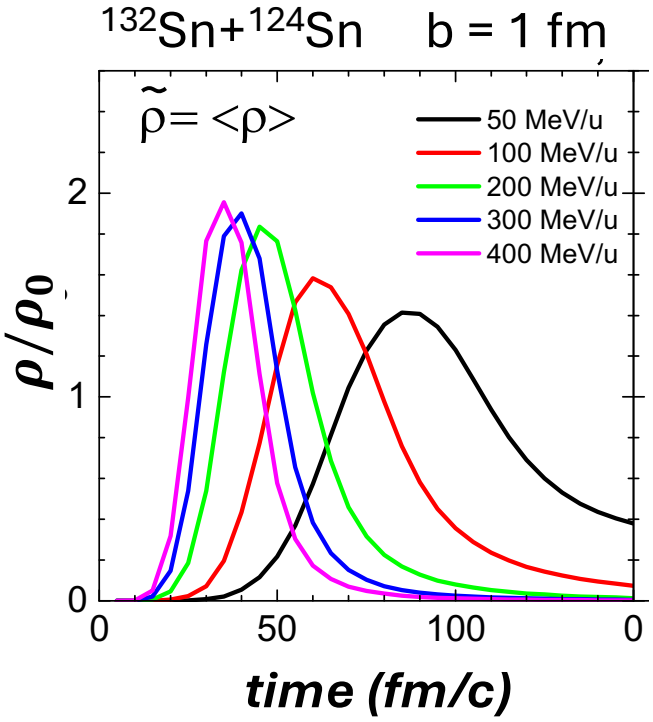
Five initiatives:

1. **SYMEOS** - Symmetry Energy and Equation of State
2. **RIBDCE** – Radioactive Ion Beam induced Double-Charge Exchange
3. **NUSYC** – Nucleosynthesis and Clustering
4. **GASPEC** – Gamma and charged-particle Spectroscopy, Collective Excitations in exotic nuclei
5. **THEOF** – Theoretical nuclear physics at FRIB

Over 100 INFN FTEs' participating in the project

SYMEOS and THEOF

Key role played by transport models → THEOF initiative



ImQMD simulations

TMEP Initiative
Transport Model Evaluation Project
a theory synergy between FRIB, INFN, GSI and other institutes

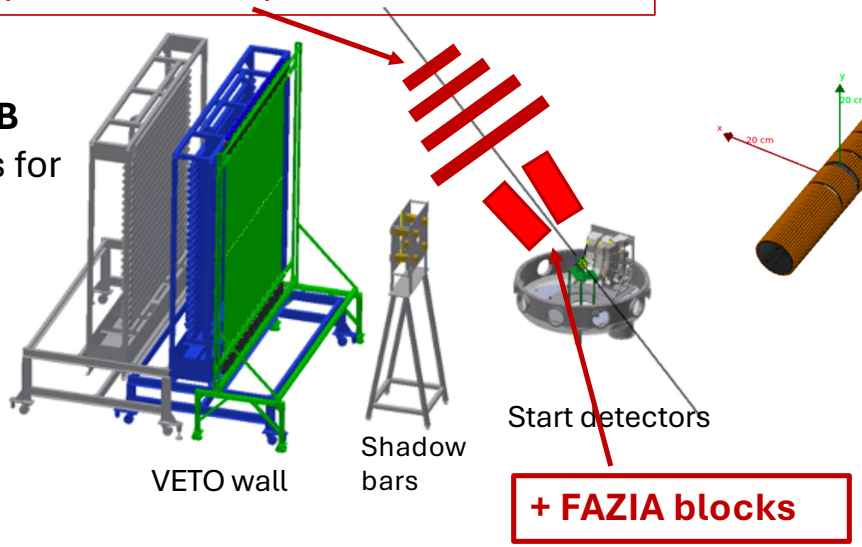
- Achieved density increases with beam energy and with mass of colliding nuclei
- FRIB-400: additional observables to be probed
  - Meson production: π^+/π^-, K^+/K^0
  - FRIB-TPC project + ancillary (FAZIA blocks

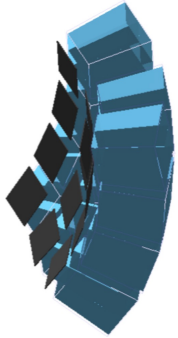
RIBDCE: Radioactive Ion Beam induced Double-Charge Exchange reactions

+ 4-5 Si-CsI(Tl) Chimera rings
Improve reaction plane and b

Fiber Array @ FRIB

LANA n det @ FRIB
Liquid Scintillators for n-γ discrimination





HiRA - Blocks of Silicon strips and CsI(Tl)

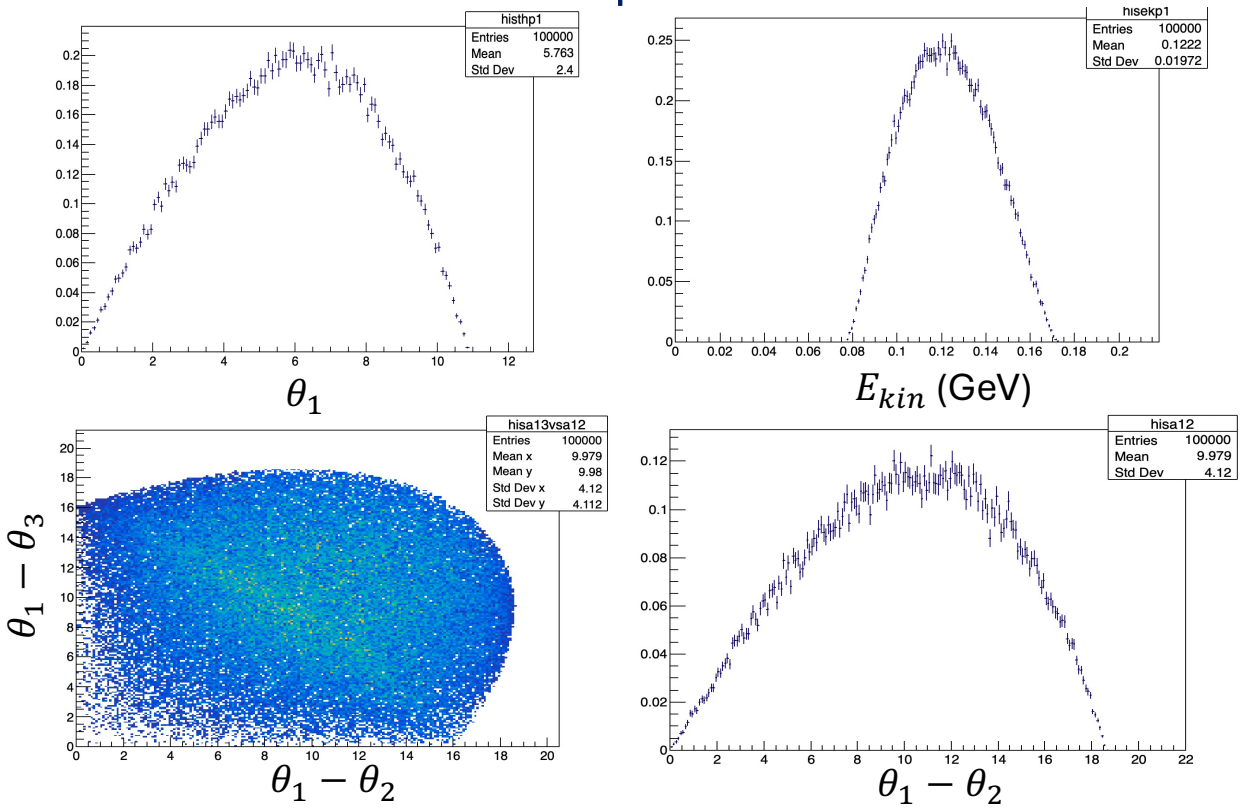
+ FARCOS blocks
Increase correlators (Silicon strips and CsI(Tl))

First case: the most basic DCE reaction, (t,3p)

$t + {}^{3}He \rightarrow 3\,n + 3\,p$ 3p detected with FAZIA blocks

RIBDCE: Radioactive Ion Beam induced Double-Charge Exchange reactions

t + ^{3}He → 3n + 3p E/A = 150 MeV



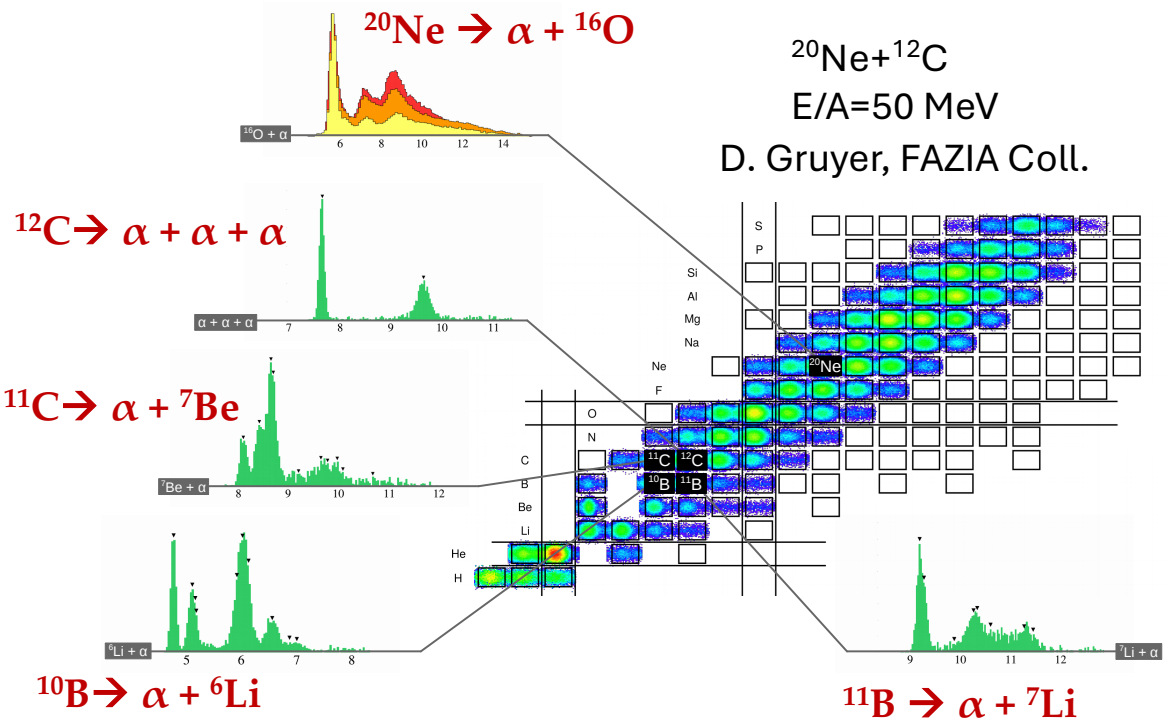
3-proton correlations in FAZIA @ FRIB

- DCE
- FSI, 3-body forces, ^{3}Li ?, …
- Important implications on the EoS (synergy)

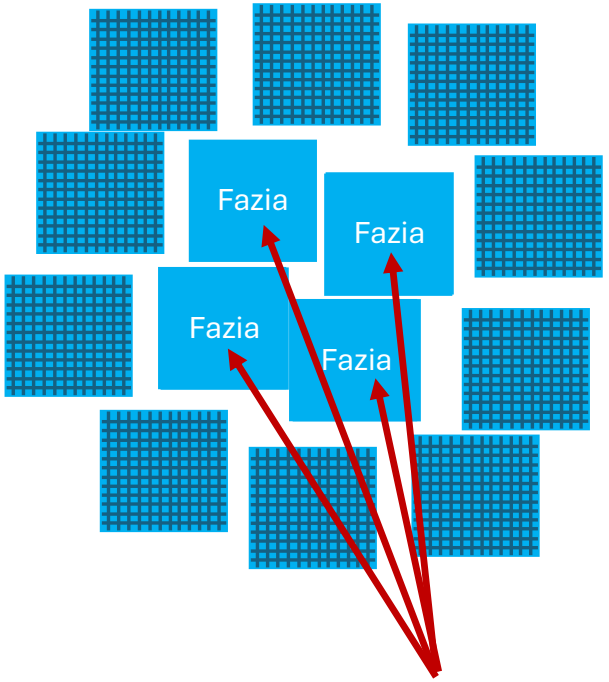
NUSYC: synergy with SYMEOS and RIBDCE

Mult—particle Invariant Mass Spectroscopy

Femtoscopy and Resonance decays in exotic nuclei



Si-strip/CsI(Tl) detectors for LCP
HiRA(FRIB) and FARCOS (INFN)



FAZIA in place of a magnetic spectrometer
(high A and Z resolution up to Z=30)