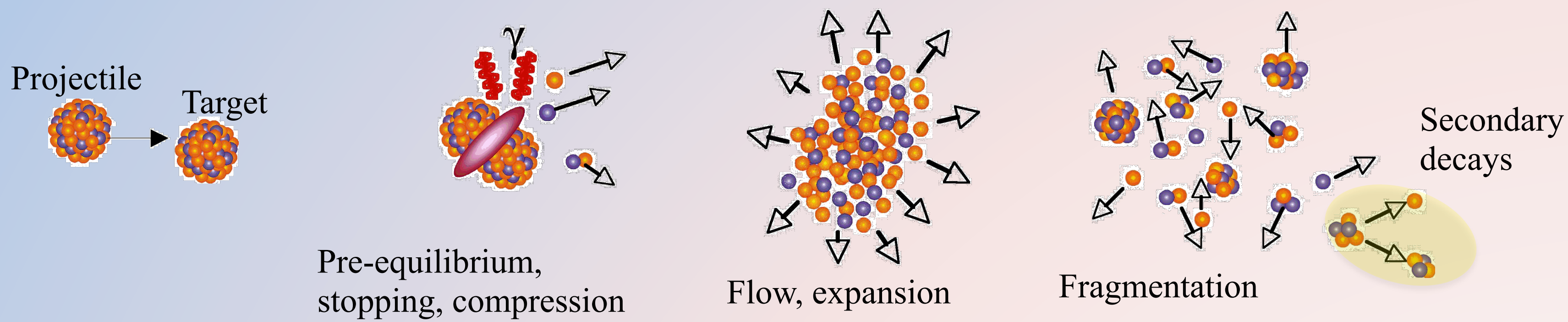
Reaction dynamics – Intermediate energies

G. Verde, IPN Orsay



- **Dynamical evolution ↔ Nuclear Structure**
- **Unique terrestrial means to explore the nuclear EoS**
  - → nuclear interaction, astrophysics, symmetry energy, clusters
  - → Low density: E/A<100 MeV– high density: GSI energies
- **Production of exotic unbound states**
  - → Interplays structure/dynamics (particle-particle correlations)

The nuclear EoS – some history - 1

Nuclear interaction ≈ van der Waals

$$E(\rho, T, \delta = 0)$$

Symmetric nuclear matter

$$P = \rho^2 \frac{\partial (E/A)}{\partial \rho}\Big|_{S=const}$$

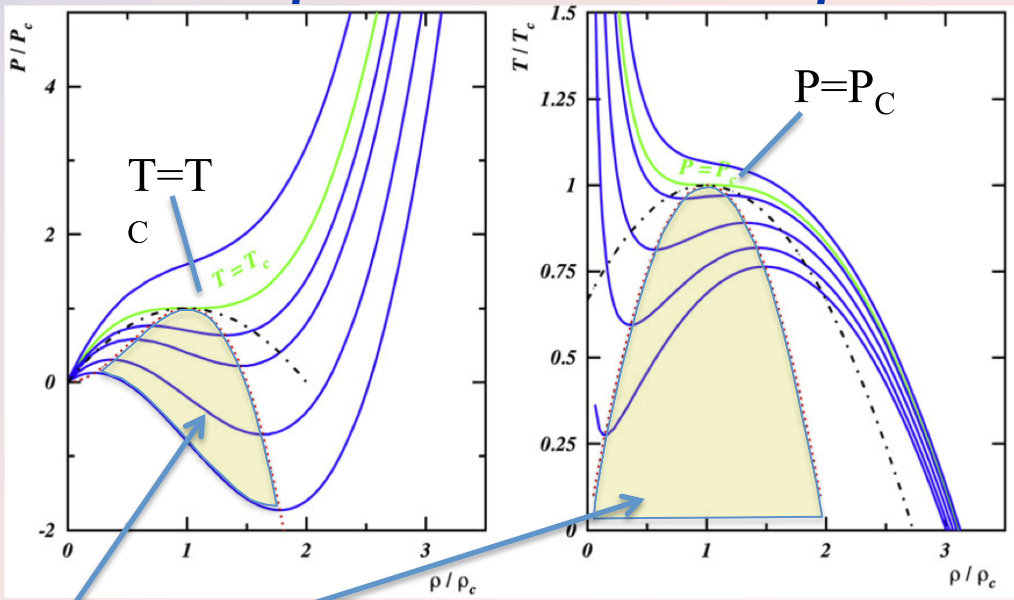
Pressure

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

$$K \propto \frac{\partial P}{\partial \rho}\Big|_{S=const}$$

Compressibility

P vs ρ **T vs ρ**

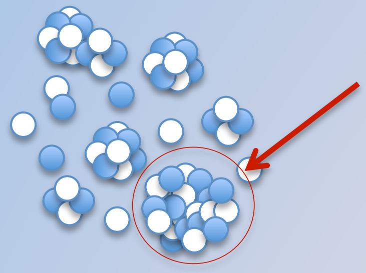


Borderie, Rivet, Prog.Part.Nucl.Phys. 61 (2008)

Spinodal instability region (K<0)

- Liquid-gas coexistence region at $\rho<\rho_0$ and T<15 MeV – Multifragmentation extensively addressed over the last 20 years…

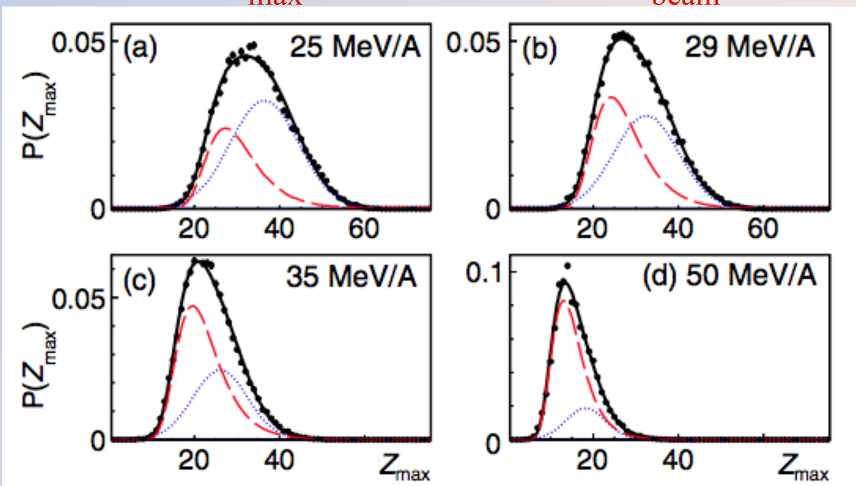
Recent highlights from INDRA studies



Z_{max} = Order parameter of the phase transition
Distribtuion and Fluctuations

Xe+Sn E/A=25-50 MeV Central
Indra@ GANIL

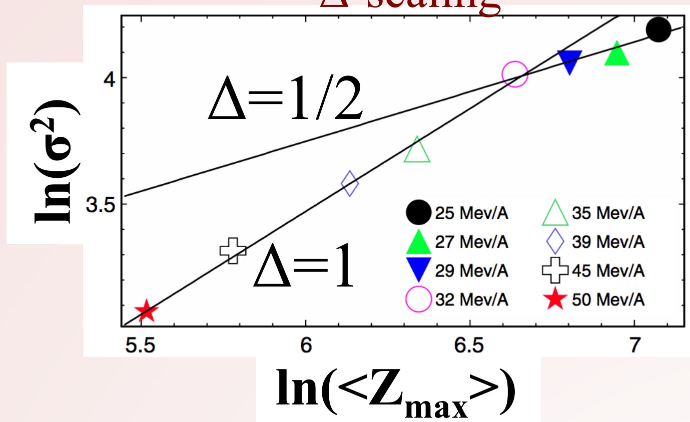
Z_{max} distributions vs E_{beam}



$$P(Z_{max}) = \eta\, f_{Gauss}(Z_{max}) + (1-\eta)\, f_{Gumbel}(Z_{max})$$

$$\sigma^2 \propto \langle Z_{max} \rangle^{2\Delta}$$

Δ-scaling



D. Gruyer et al., PRL 110, 172701 (2013)

- Analogy with **<u>Out-of equilibrium</u> cluster aggregation** models

E/A~ 32 MeV → Transition towards "rapid fragmentation" over shorter time-scales → **interplay of stopping and radial flow**

Asymmetric nuclear matter

$$E\left(\rho, T, \delta \neq 0\right)$$

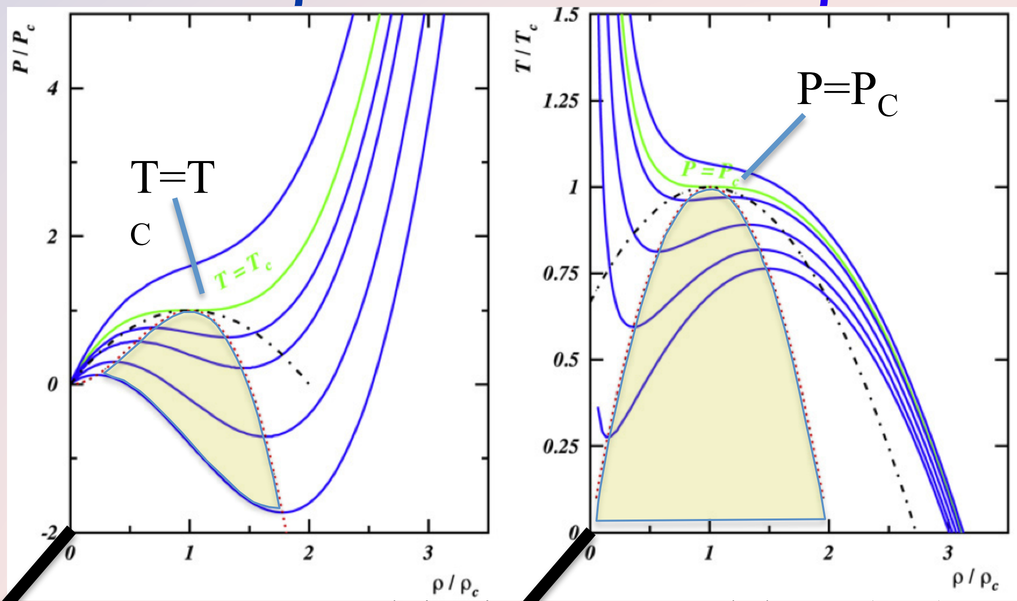
Asymmetric nuclear matter

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

$$P = \rho^2 \left.\frac{\partial (E/A)}{\partial \rho}\right|_{S=const}$$

$$K \propto \left.\frac{\partial P}{\partial \rho}\right|_{S=const}$$

P vs ρ **T vs ρ**



Borderie, Rivet, Prog.Part.Nucl.Phys. 61 (2008)

δ δ

Mueller & Serot, PRC52, 2072 (1995)
H. Xu et al., PRL75, 716 (2000)

Highlights from symmetry energy

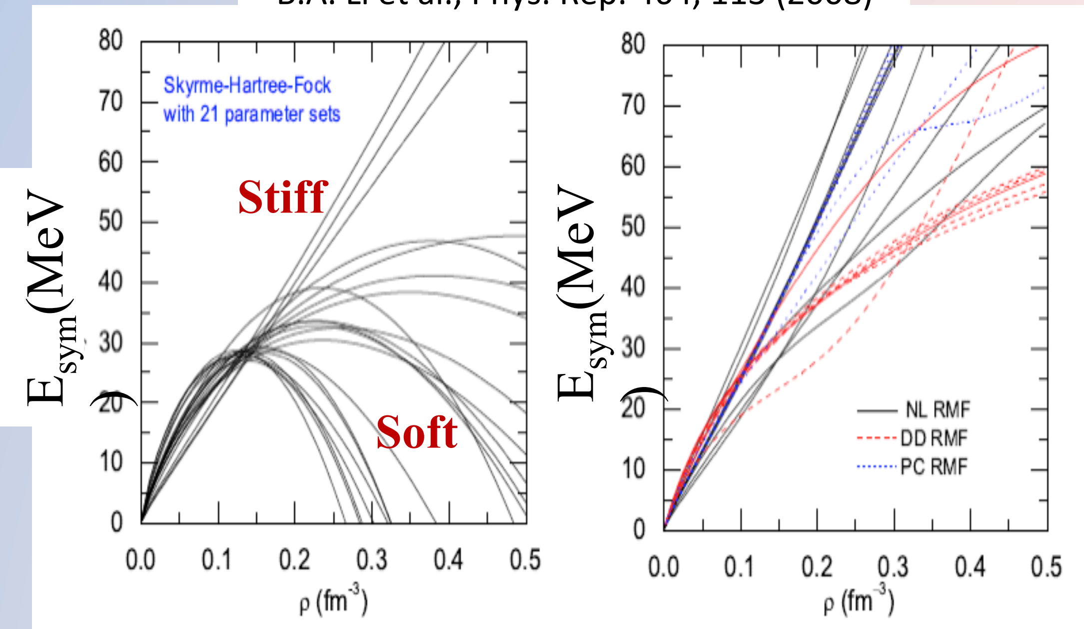
$$E(\rho,\delta) = E(\rho,\delta=0) + \boxed{E_{sym}(\rho)\cdot\delta^2} + O(\delta^4)$$

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

Asymmetry term

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

B.A. Li et al., Phys. Rep. 464, 113 (2008)



Many approaches… large uncertainties….

Microscopic many-body, phenomenological, variational, …

Especially at high densities (three-body forces)

ZH Li, U. Lombardo, PRC74 047304 (2006)

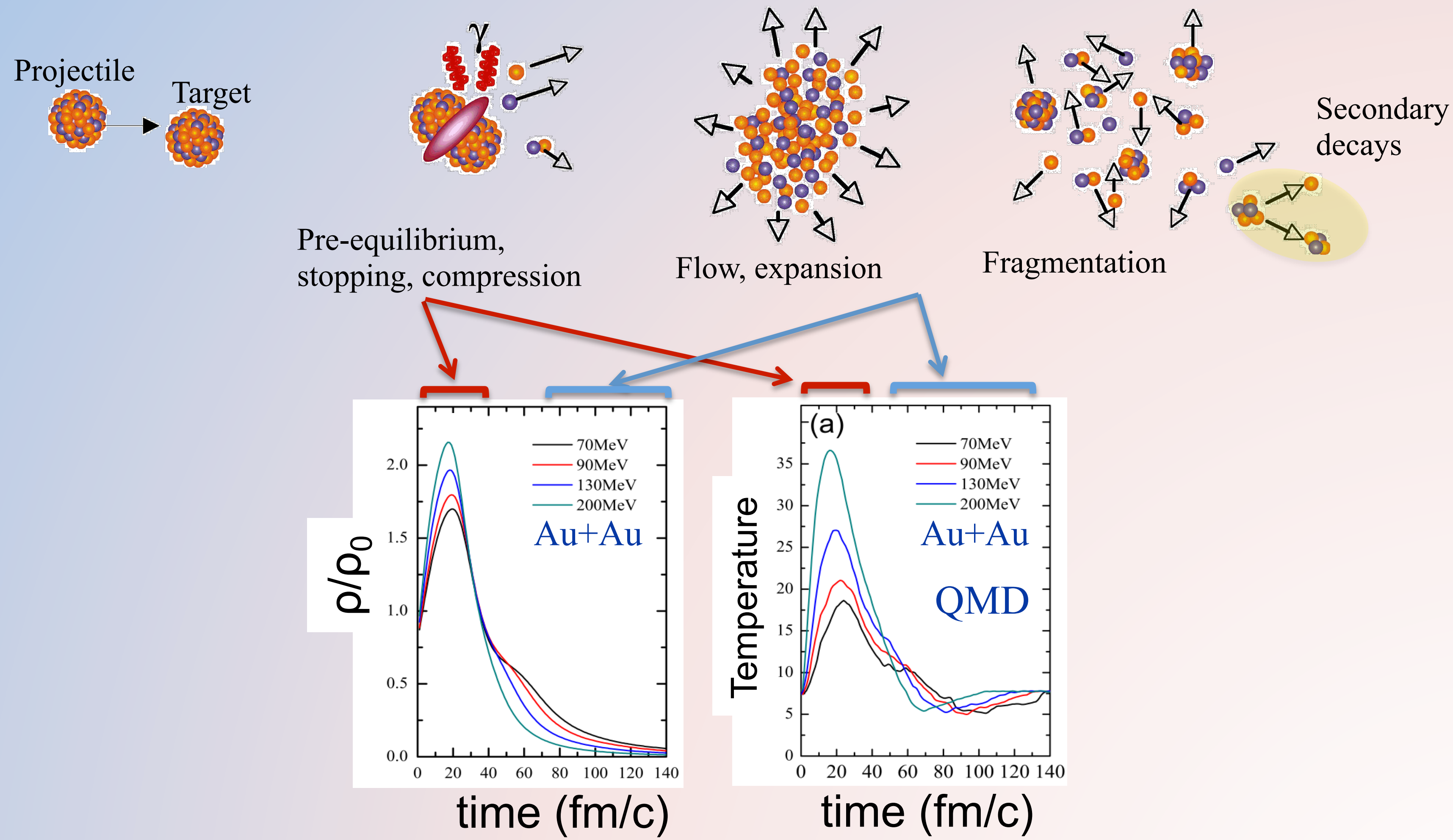
Brown, Phys. Rev. Lett. 85, 5296 (2001)
Fuchs and Wolter, EPJA 30, 5 (2006)

Enhance small Esym effects:

→ **RIB facilities** (SPES, Spiral2, Eurisol): increase δ

→ **SIB at high intensities: increase statistics**

Nuclear densities away from saturation in the LAB



EoS *under laboratory controlled conditions*

Transport models: obseravbles ↔ EoS, Interaction

Enhance <u>small</u> Symmetry Energy effects: two experimental directions

- **<u>N/Z</u> → RIB facilities:**
  - increase N/Z of beams →larger ***δ*** → larger Esym effects

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

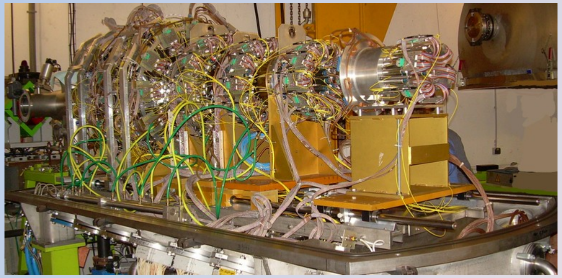
- **<u>Intensity</u> → SIB facilities (high intensity)**
  - Increase statistics → search for small effects
  - Reference points with symmetric systems and high quality beams
  - Study of specific key observables: particle-particle correlations (intensity interferometry)
  - Opportunity of producing secondary exotic beams

Enhance small Symmetry Energy effects: two experimental directions

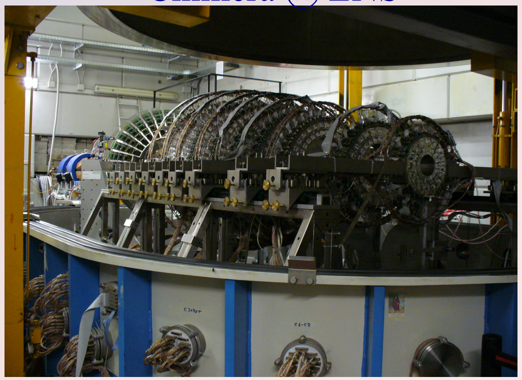
- High isotopic resolution
- 4pi coverage and high granularity
- High Energy and Angular resolution: correlations
- Low identification thresholds
  - Reaction mechanism studies at low beam energies
- Fast and digital electronics, increase DAQ rate (intensity)
- Wide (A,Z) ranges: speed-up calibrations and data analysis
- Neutron detection: source reconstruction, probes of $E_{sym}(\rho)$

4π and high (angle, isotopic) resolution arrays

Indra @ GANIL, GSI

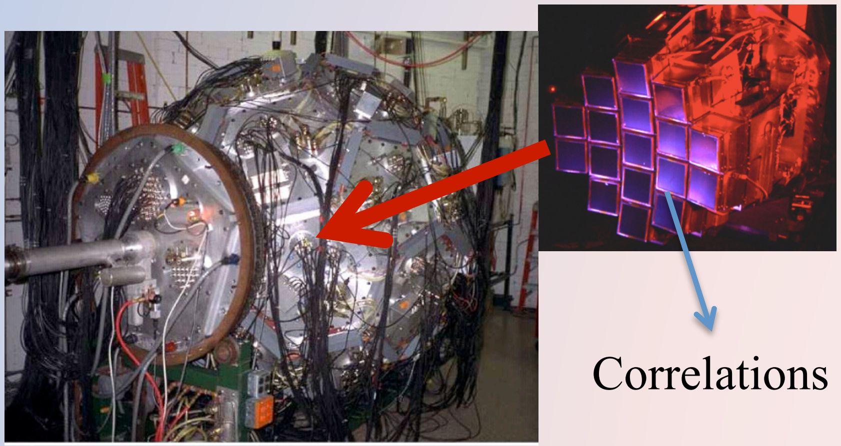


Chimera @ LNS



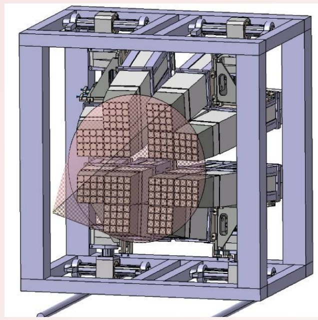
Analog pulse shape : Si and CsI(Tl)

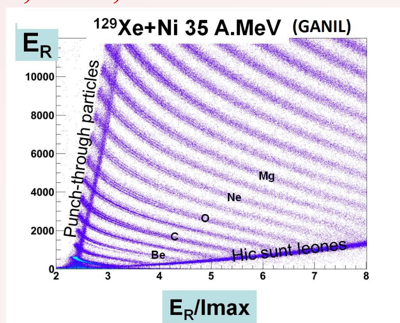
MSU 4pi + HiRA Si-Strip array



Correlations

Fazia @ LNL, LNS, GANIL



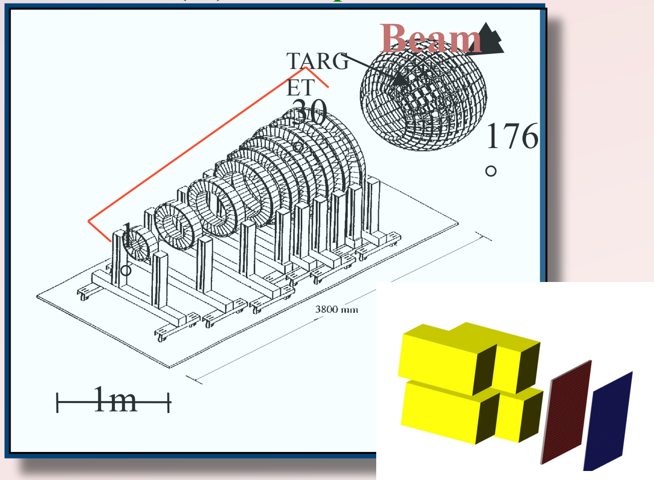


Digital pulse shape : Si and CsI(Tl)

Coupling to segmented arrays for correlations

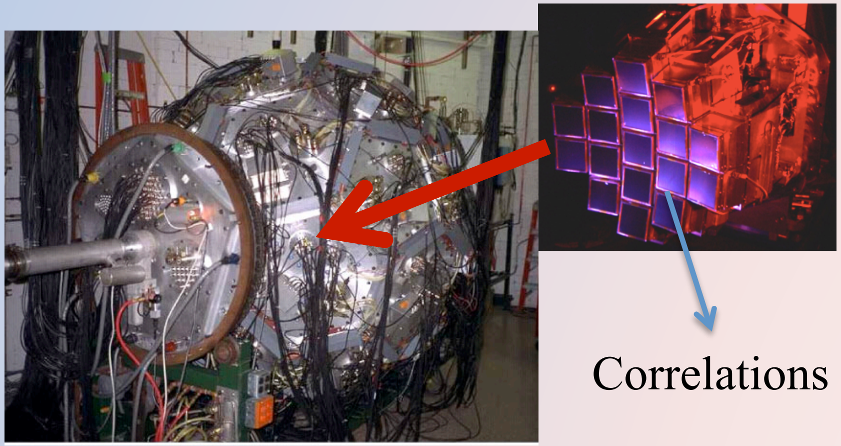
CHIMERA-PS & FARCOS

1192 Si-CsI(Tl) Telescopes



Farcos @ CT
(GET electronics)

MSU 4pi + HiRA Si-Strip array

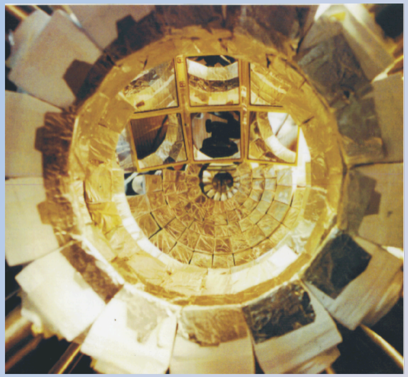


Correlations

…also Indra and Fazia + Correlators

The importance of SIB studies

LASSA + Miniball

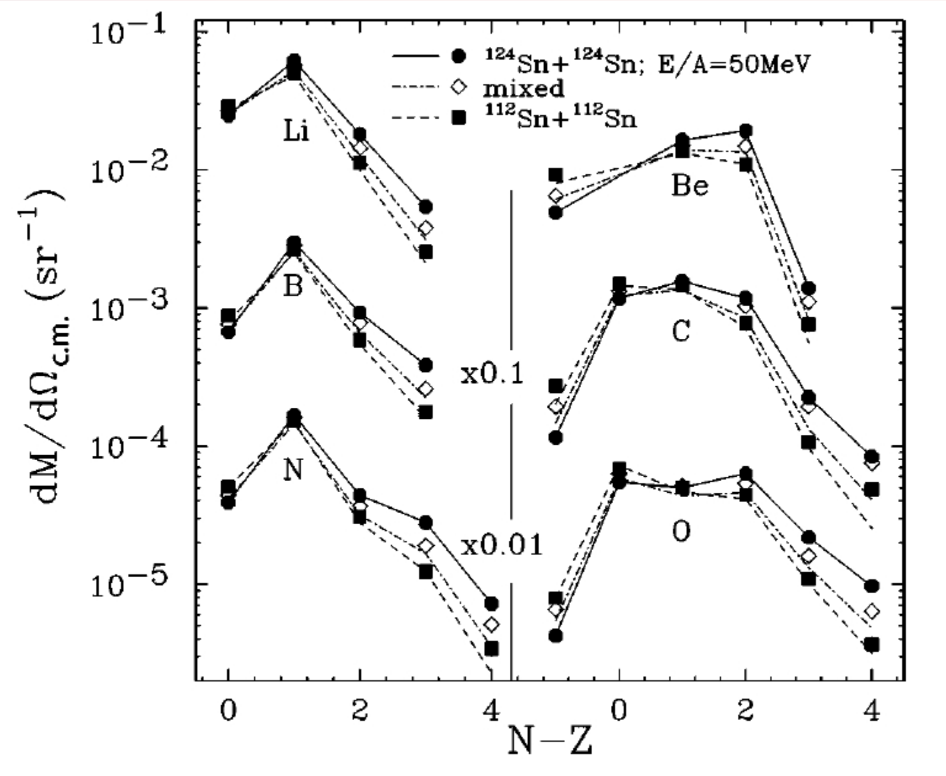


NSCL-MSU

E/A=50 MeV, Central collisions

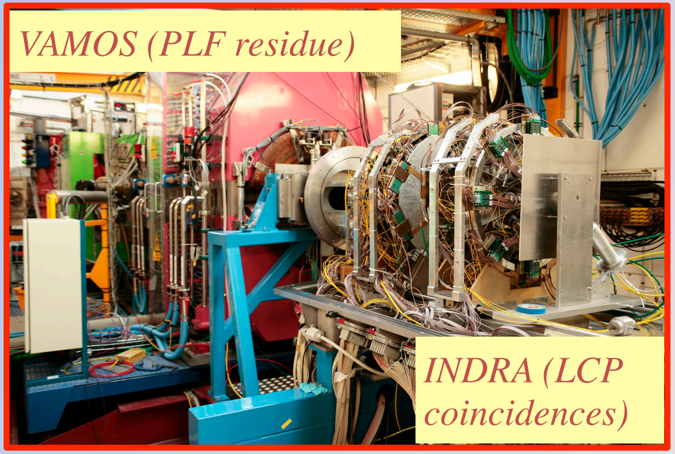
$^{112}Sn+^{112}Sn$,	$^{112}Sn+^{124}Sn$	$^{124}Sn+^{124}Sn$
N/Z = 1.24	N/Z=1.36	N/Z=1.48
n-poor + n-poor	mixed	n-rich + n-rich

- Isotopic effects of Esym are small
- Require thin targets
- **Two directions required:**
  - ✧ **SIB**: increase statistics
  - ✧ **RIB**: increase N/Z effects



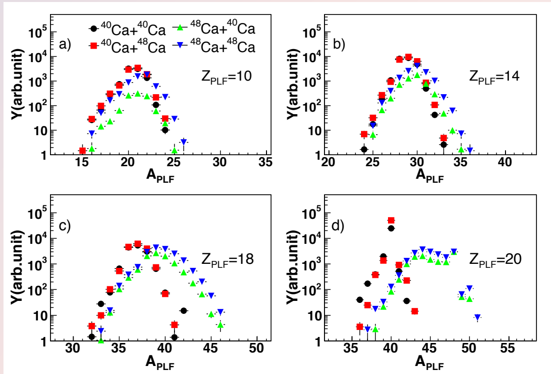
Need high intensities/statistics

Probing small effects with SIB



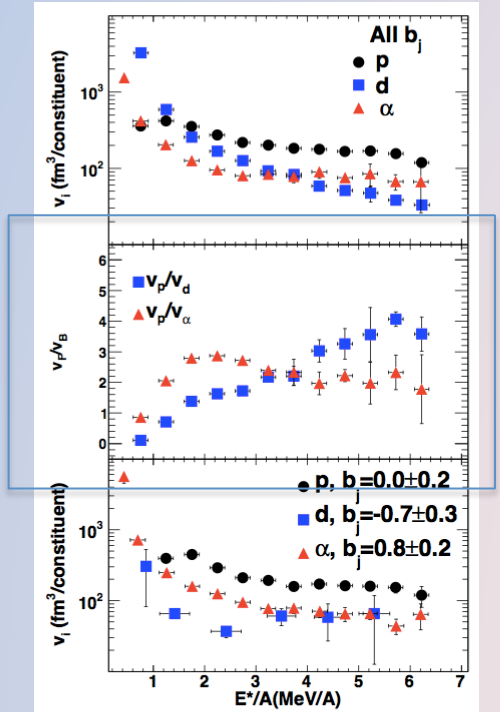
Indra-Vamos experiment
40,48Ca+40,48Ca E/A=35 MeV

Vamos → **high quality isotopic distributions for heavy-fragments!**



Limitations:

- Acceptance;
- No multiparticle detection *(→FAZI)*



- Coincidence with LCP in Indra:

  Determine E*, T and Densities of PLF

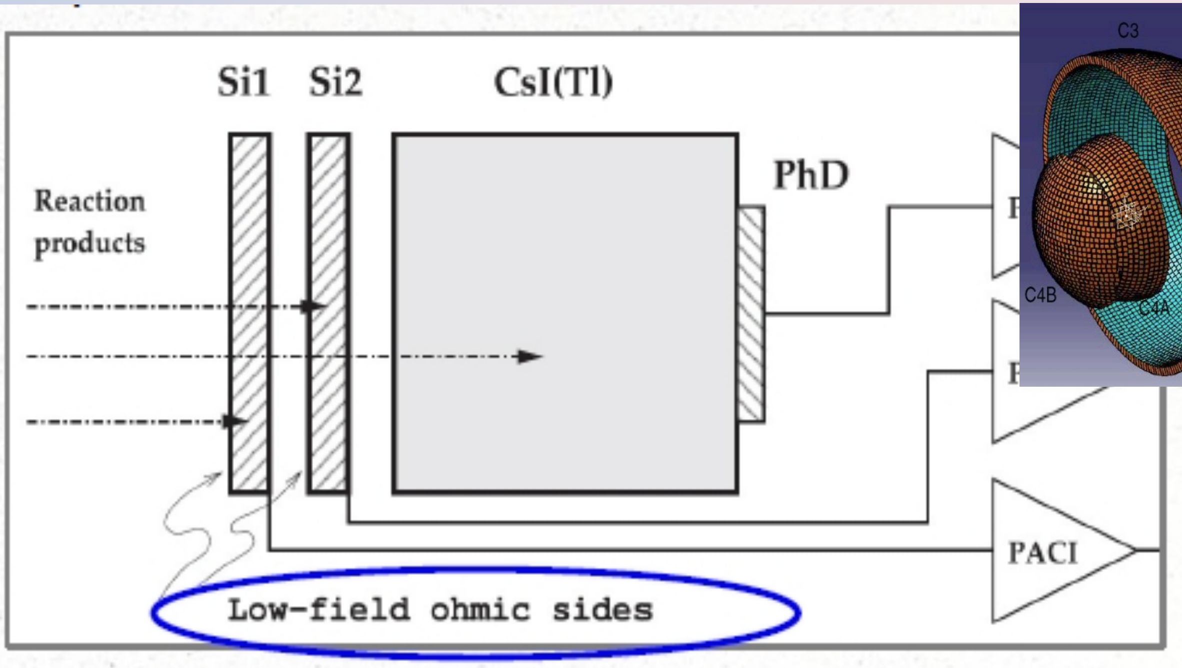
- Boson Volumes << Fermion Volumes: Signals of boson condensation and fermion quenching?

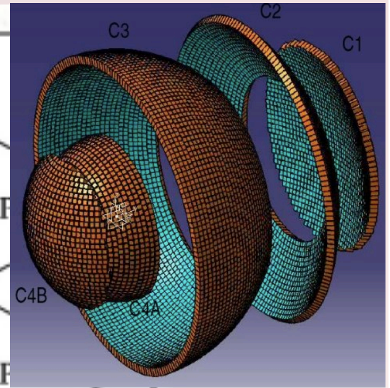
P. Marini, H. Zheng, M. Boisjoli, G. Verde, A. Chbihi et al., to be submitted soon

Fazia telescopes and capabilities

Silicons
20x20mm2
nTD type
ρ~3-4000 ohm*cm
300 and 500 μm
7deg cut off <100>

CsI(Tl)
20x20mm2
tapered
1500-2000ppm Tl-doping
Uniform doping
10 cm thick

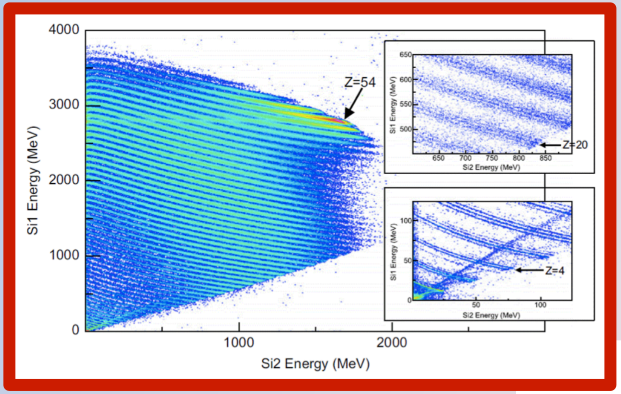


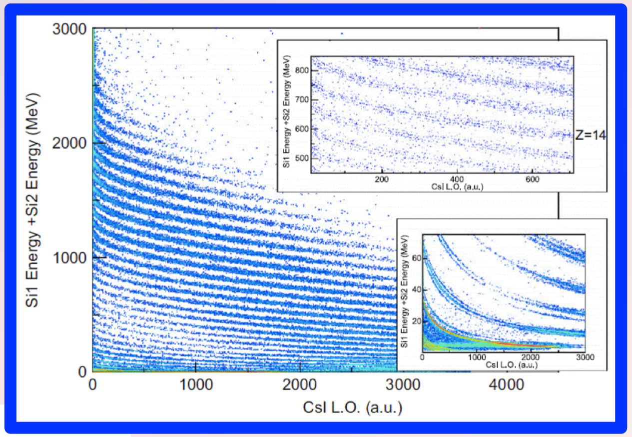


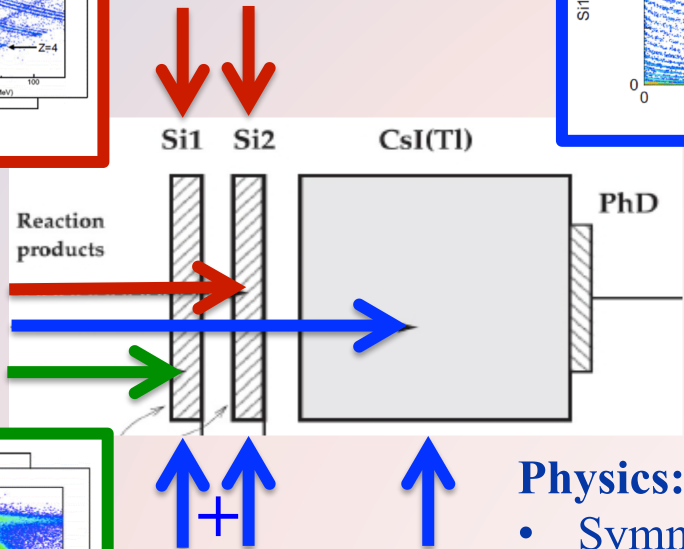
IPN Orsay: Front-End Electronics

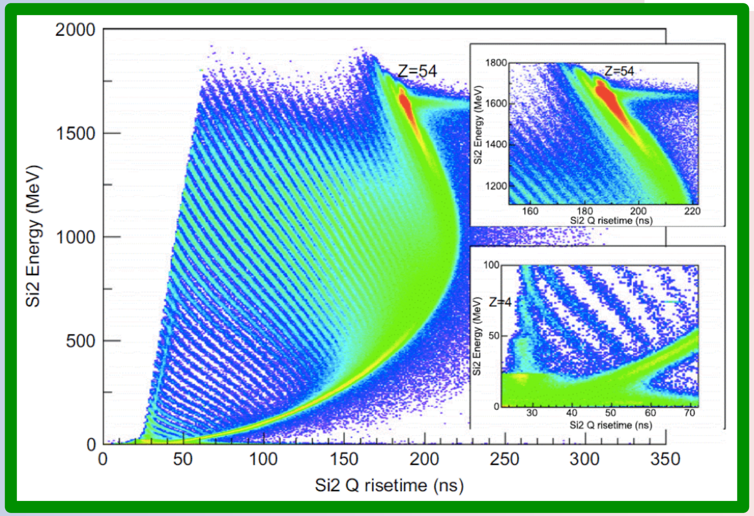
- Digitalization of signals (Si and CsI(Tl) + wide dynamic range
- Low identification thresholds → Low energy HIC…
- Geometric flexibility → Stand alone mode or Coupling to 4π, Spectrometers, Si-Strip correlators…

FAZIA performances/perspectives







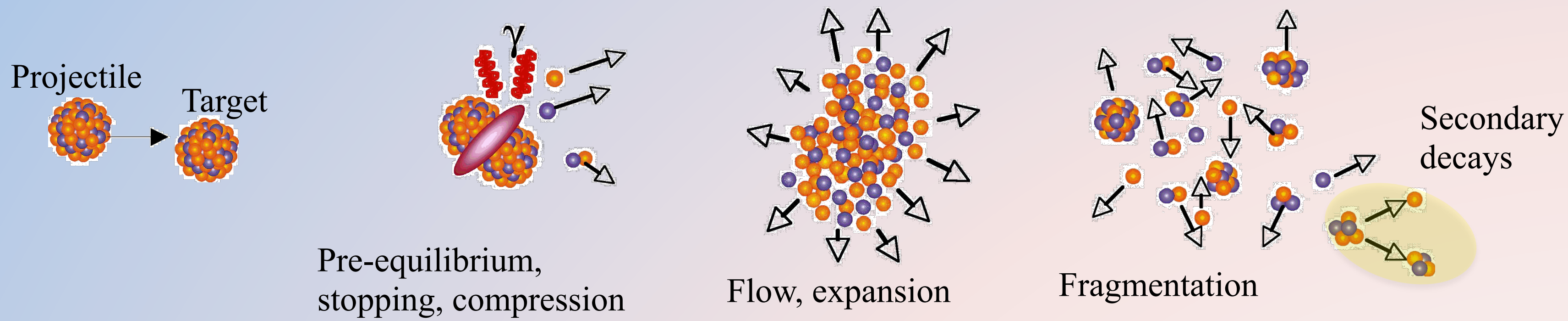


Physics: low and intermediate E/A

- Symmetry energy, dynamics
- Femtoscopy and correlations
- CN decay
- DIC/Fission
- Interplays dynamics/structure

Next experiment w demonstrator
LNS-Catania December 2014

The importance of RIB studies



- **Proj and target N/Z asymmetry (ex.: ^{124}Sn+^{124}Sn vs ^{112}Sn+^{112}Sn)**
  - enhancement of isotopic N/Z effects (increasing as $(N-Z)^2/A^2$) → Asy-EoS

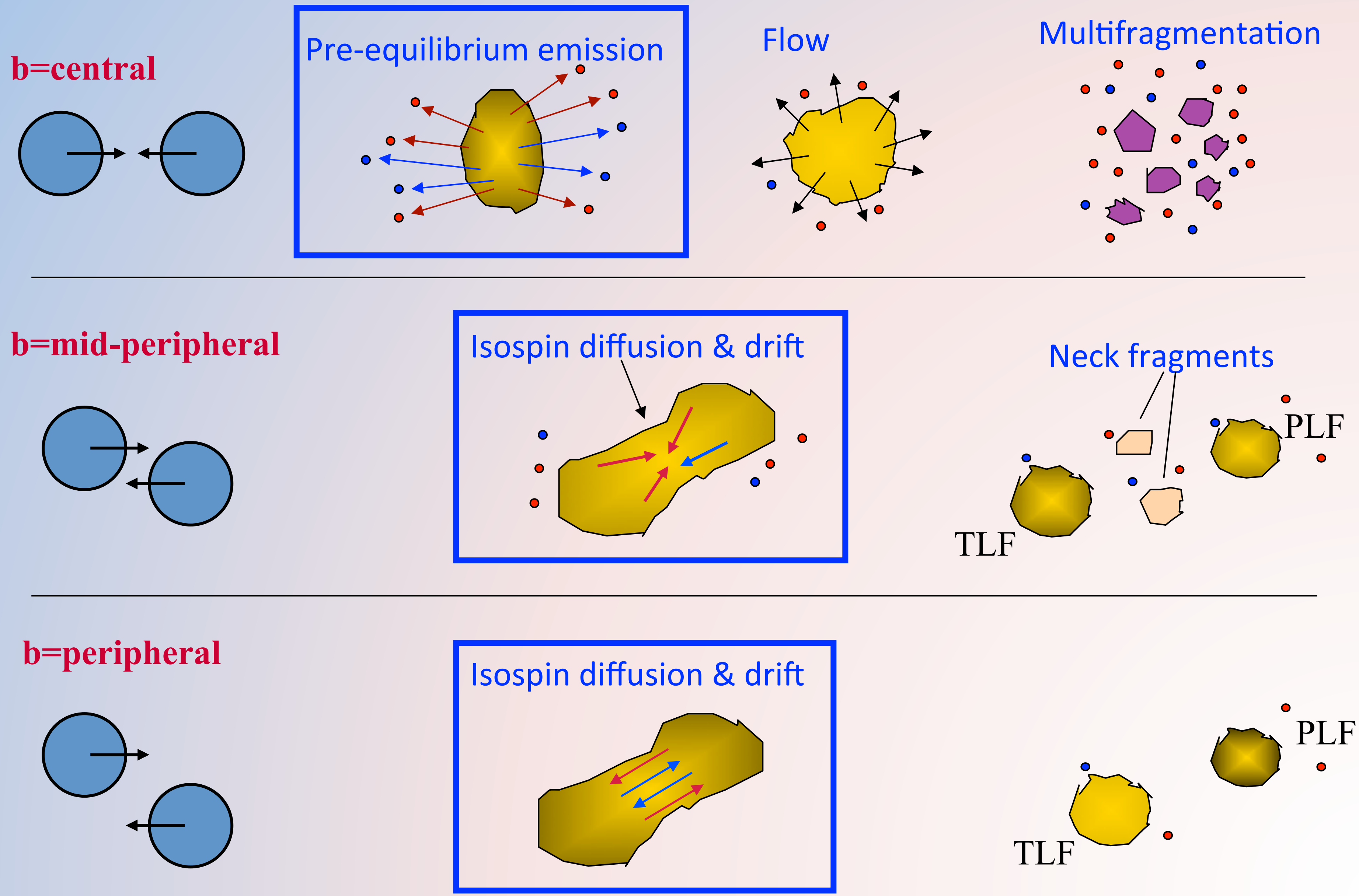
Exotic beams: ex. 74Kr vs 92Kr → amplification factor 15 !!

…and important interplays dynamics/structure

→ enhance effects on observables

→ improve comparisons to models

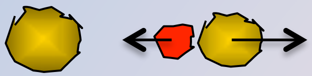
Highlights of E_{sym} observables (SIB@EU)



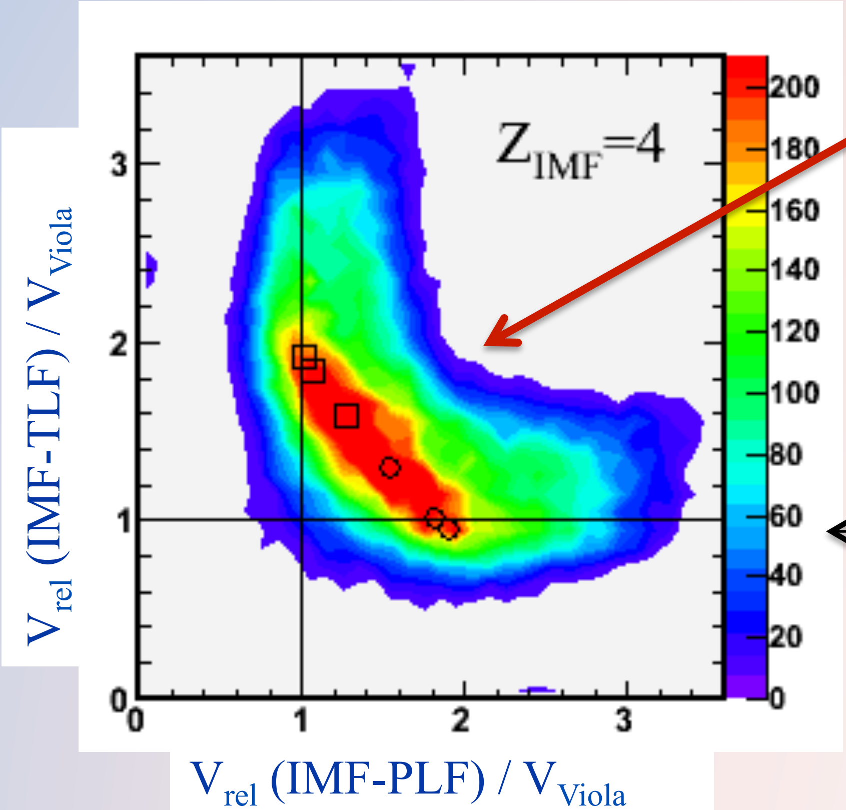
Neck emissions Vs. PLF/TLF fission

$^{124}Sn+^{64}Ni$ @ 35 MeV/u   Chimera @ LNS

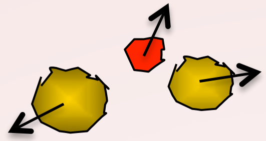
Three-fragment correlations

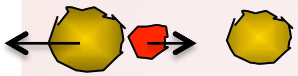


PLF fission – long time-scales
t>100 fm/c



Neck emission
Fast time-scales
t<100 fm/c





TLF fission –
long time-scales
t>100 fm/c

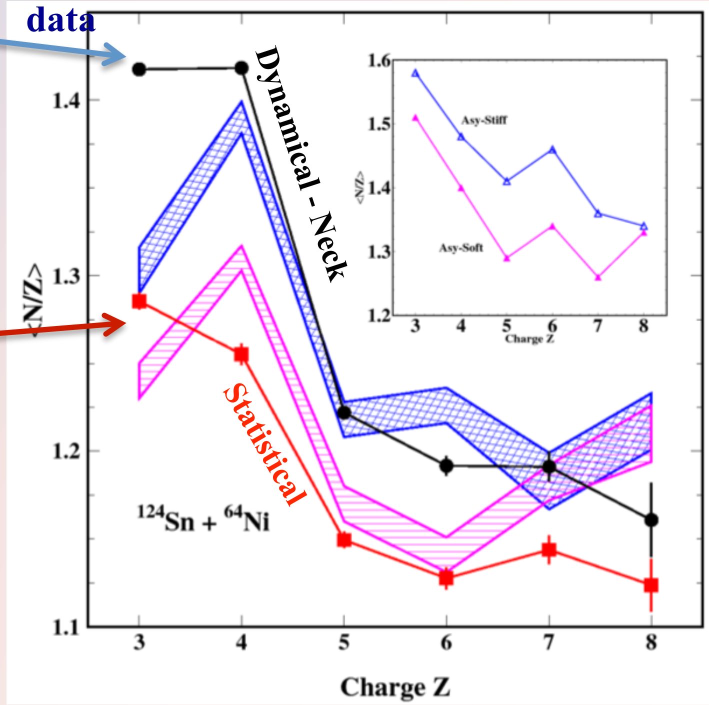
E. De Filippo et al., Phys. Rev. C (2012)

Neck and symmetry energy/Chimera

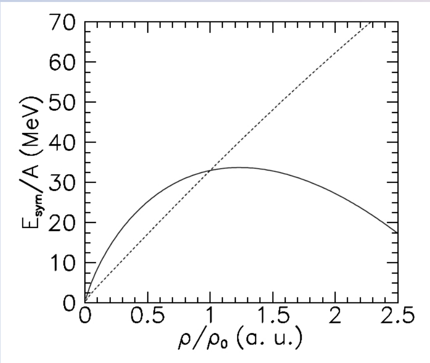
N/Z content of neck fragment (dynamical fast emission)

N/Z content of statistical emission by PLF and TLF

SMF Simulations Vs Experimental data



E. De Filippo et al., Phys. Rev. C (2012)



$$E_{sym}(\rho) \propto \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

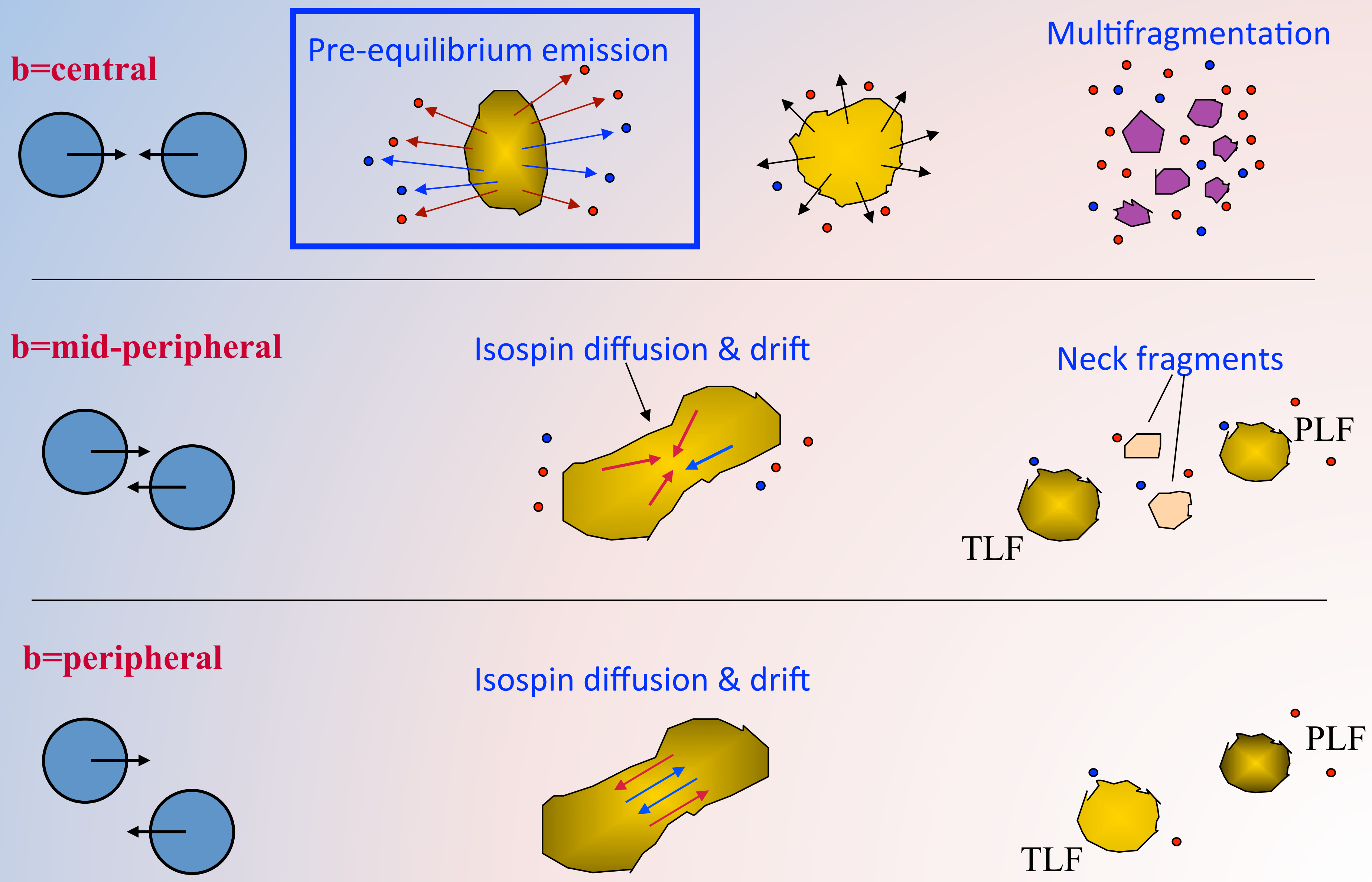
Data consistent with $\gamma \approx 0.8$

SMF: Stochastic Mean Field calculations by M. Colonna et

Extension to lower energy domains

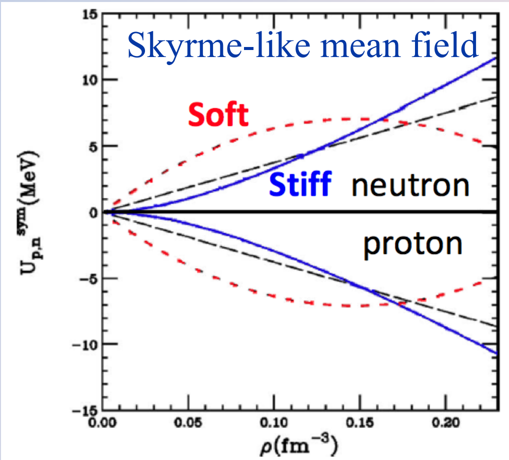
- Time-scales (Chimera) and chronometry (Gruyer@Indra) → probes emission ordering with heavy fragments
- Sequential PLF and TLF fission studies at lower energies with SIB and RIB facilities
- Onset of neck dynamics vs E/A and vs N/Z
- Coincidences with light particles and gammas…

Highlights: pre-equilibrium emissions



Dynamical n and p emissions at pre-equilibrium

V. Baran et al., Phys. Rep. 410 (2005)
B.A. Li et al., PLB 634, 378 (2006)
Y. Zhang et al., PLB664, 145 (2008)



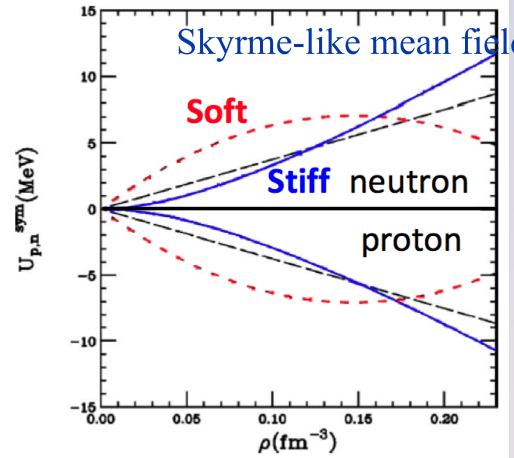
Asy-Soft more repulsive for neutrons

- Single-particle neutron/ proton energy spectra
- Two-particle correlation functions
  - nn, pp, np
  - tt, $^3He^3He$,t^3He
  - …

→ ***Femtoscopy***

Neutron-proton pre-equilibrium emissions

V. Baran et al., Phys. Rep. 410 (2005)
B.A. Li et al., PLB 634, 378 (2006)
Y. Zhang et al., PLB664, 145 (2008)

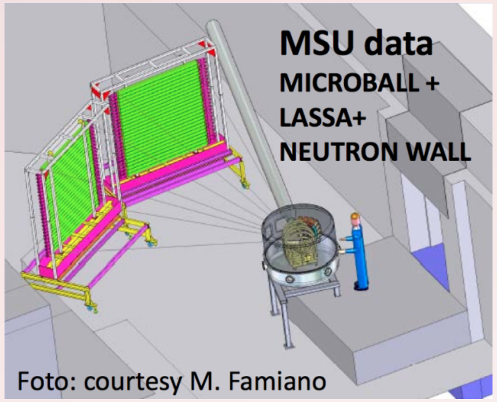


Asy-Soft more repulsive for neutrons

^{112}Sn+^{112}Sn, ^{124}Sn+^{124}Sn   E/A=50 MeV

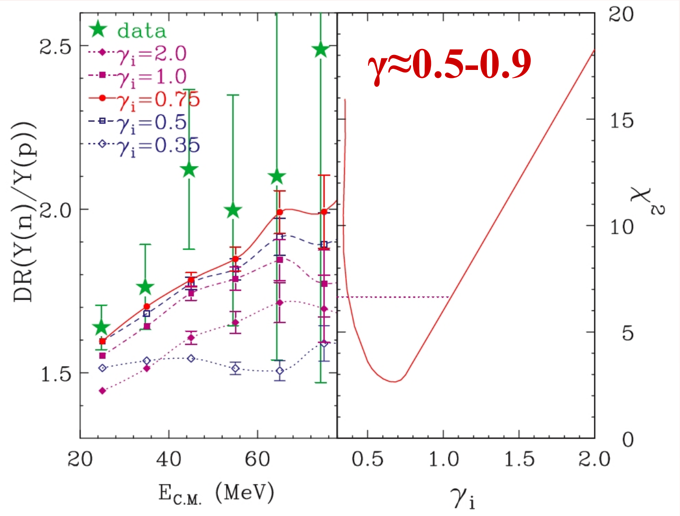
Lassa and Neutron Wall
@ NSCL, MSU

Neutron detection:
need n-γ discrimination



M. Famiano et al., PRL97, 052701 (2006)

ImQMD simulations Vs Data

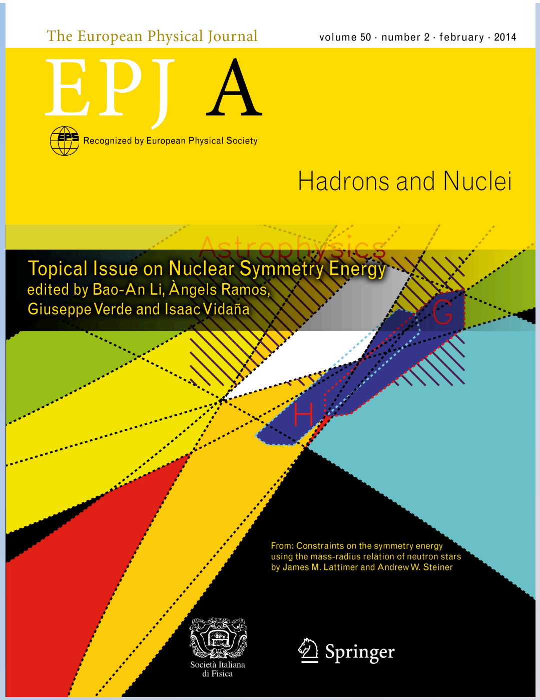


$$E_{sym} \propto \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

M.B. Tsang et al., PRL102, 122701 (2009)

$$\frac{\textbf{Y(n)/Y(p) in 124Sn+124Sn}}{\textbf{Y(n)/Y(p) in 112Sn+112Sn}}$$

Double ratios: enhance N/Z effects & reduce systematic errors and efficiency problems



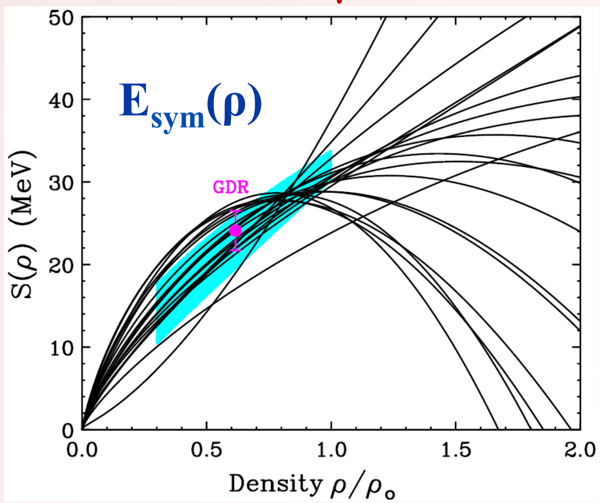
Eur. Phys. Journal A 50
Feb 2014

Edited by:
B.A. Li, A. Ramos,
G. Verde, I. Vidana

Status on symmetry energy

40 contributions from:
Heavy-Ion collisions, Hadron Physics, Astrophysical studies, Theory, Experiments, New facilities, etc.

Heavy-ion collision dynamics
$0.4 < \gamma < 1$

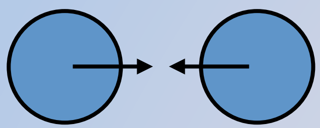


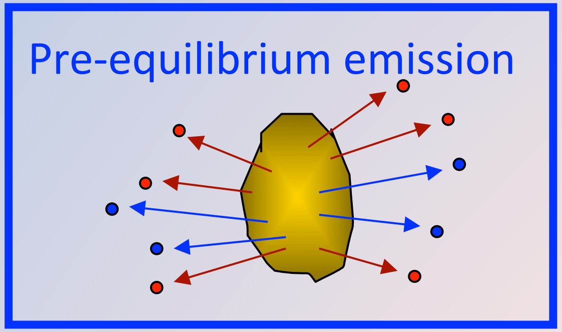
Need for future investigations

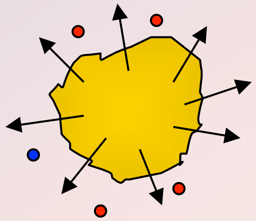
- **Better constraints:**
  - → Reduce error bars (SIB and RIB expt.)
  - → Improve comparison to transport theories
- **New perspectives from Correlations and Femtoscopy**
- **High densities (GSI energies) need special attention**

Symmetry energy and femtoscopy

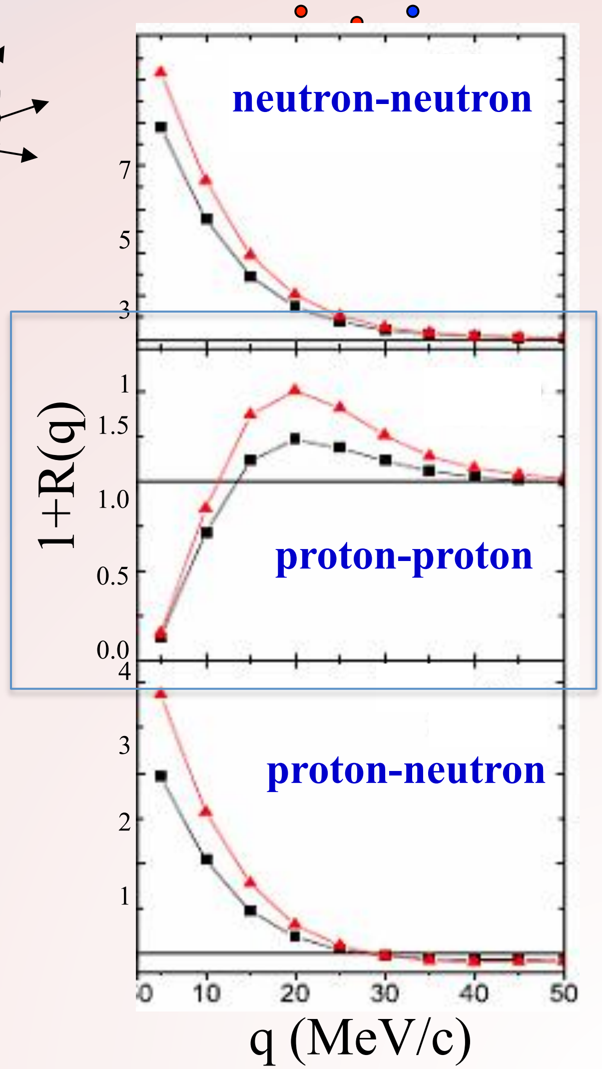
b=central



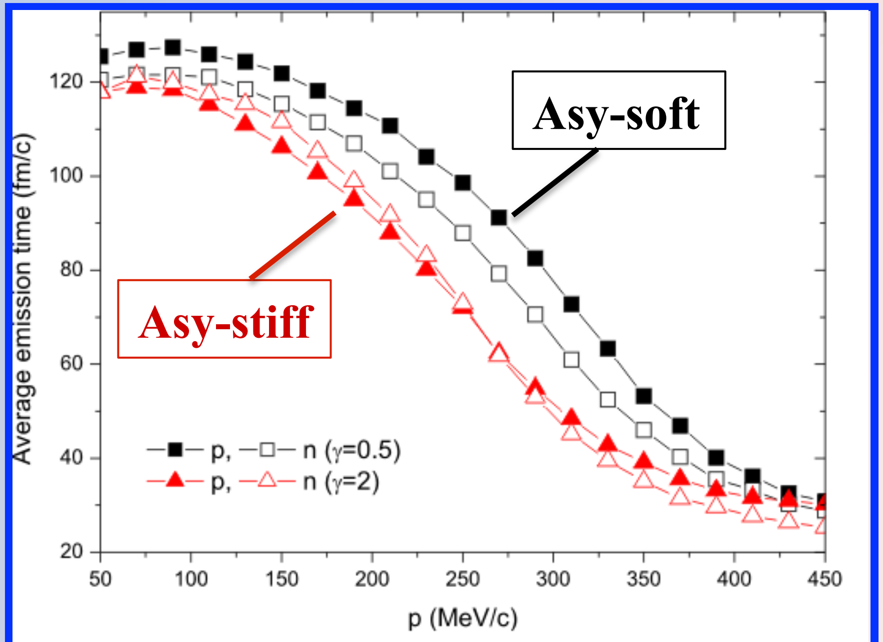




Correlation functions



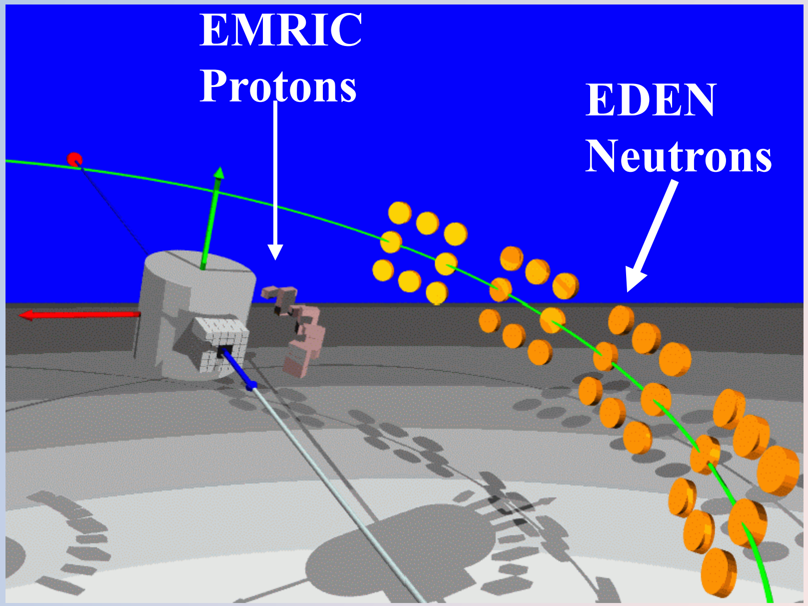
Neutron/proton emission times vs. E_{sym}



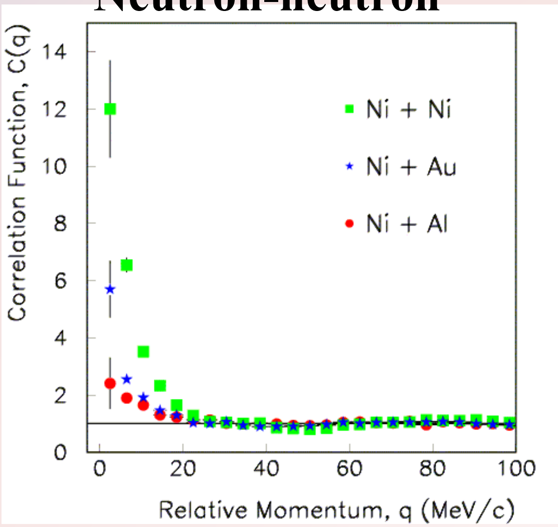
Lie-Wen Chen et al., PRL (2003); PRC(2005)

Past experiences on nucleon-nucleon correlations

Ghetti *et al,* PRL 91 (2003) 092701



Neutron-neutron



Difficult experiments

- Low detection efficiency
- Background from cross-talk

Unique tools still not explored enough:

- High angular resolution and solid angle coverage for correlations
- Large array for event characterization (impact parameter, etc.)
- n and p detection in same telescopes (future perspective…)
- tt, 3He3He and t3He same as nn, pp and np????

Plans on dynamics studies

- Need all energy range E/A=5-100 MeV (low and high!)
- Need both SIB and RIB experiments

E/A<15 MeV: "low E"

- Dominated by Mean-Field dynamics
- …but fluctuations and correlations important
- **TDHF with fluctuations and correlations**
- DIC and width of Z and A distributions for PLF and TLF fragments
- CN formation and decay
- Cluster effects on dynamics

E/A>10 MeV: "intermediate E"

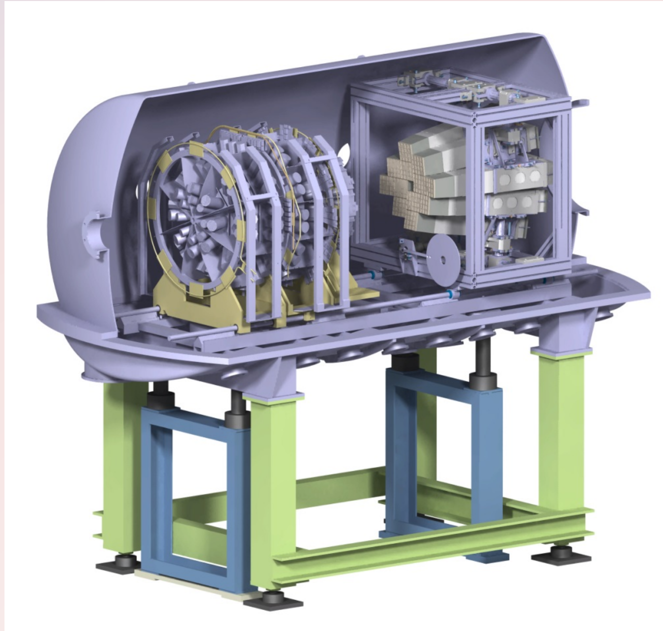
- Mean-Field + NN collision dynamics
- EoS, Symmetry Energy
- Transport properties
- **Binary mechanisms (~ DIC) at peripheral**
- Neck dynamics
- Flow, stopping, transparency
- Clusters, boson condensates, correlations

Opportunities with SIB and RIB facilities

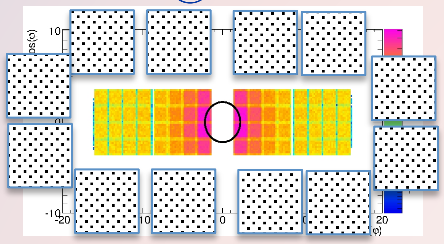
4pi detectors + FAZIA (GANIL, LNS, LNL)

→Ex.: INDRA-FAZIA: high isotopic resolution at forward acceptance

→isospin diffusion, symmetry energy

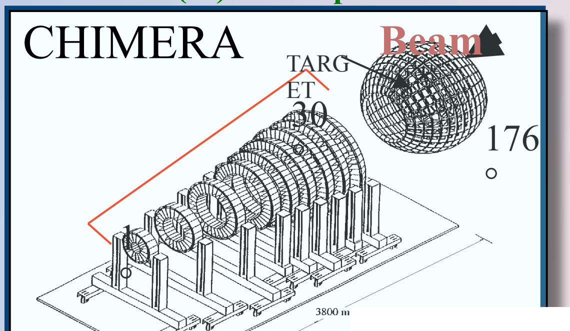


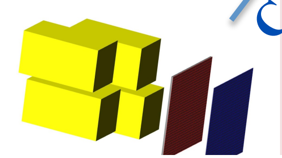
FAZIA @ LNS 2015



Fazia Acceptance

1192 Si-CsI(Tl) Telescopes





Silicon-strip Correlators

Correlations

4pi detectors + Si-Strip Correlators (LNS,GANIL,LNL)

→ Ex.: Indra/Chimera+FAZIA, Correlators (Farcos,Must2,…)

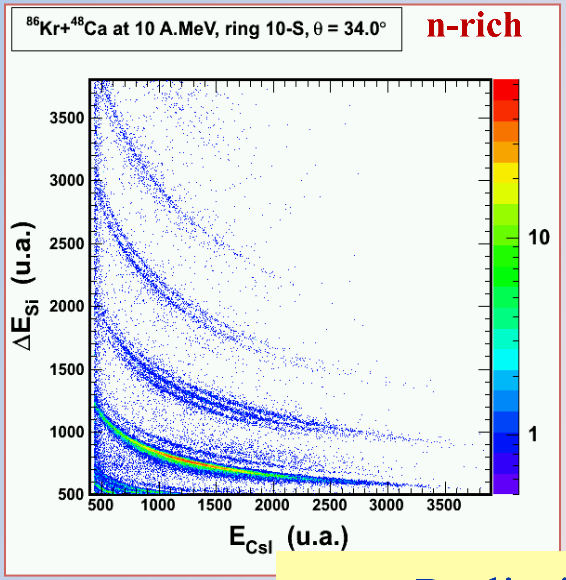
→ Imaging and Femtoscopy

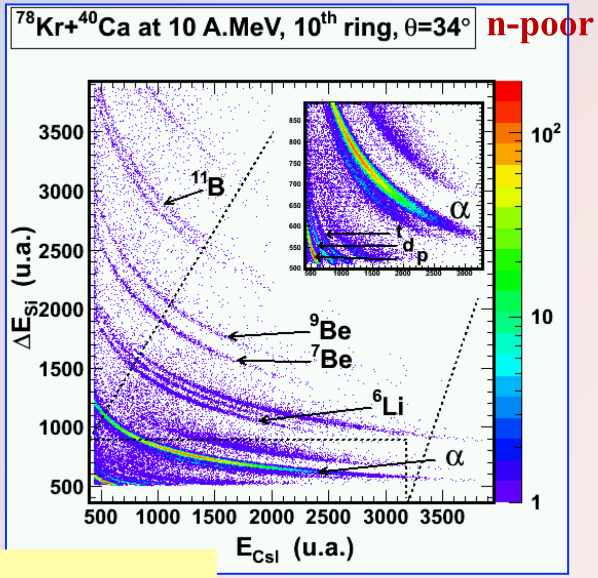
→ FAZIA: pp, tt, 3He3He, IMF-IMF

→ Si-strips: Resonance correlations ($d\alpha$, $\alpha\alpha$, $\alpha\alpha\alpha$, $p\alpha$, p-IMF, α-IMF,…)

Fragment observables

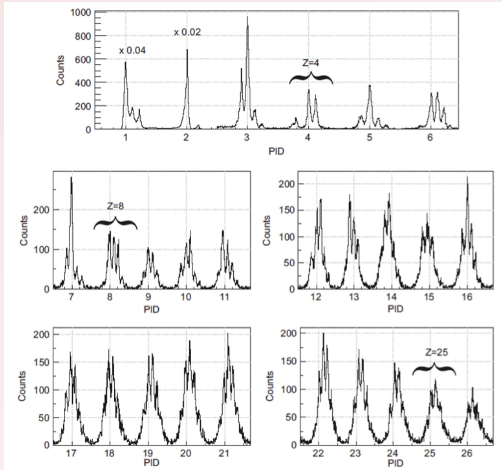
Chimera @ LNS





Preliminary

FAZIA increased capabilities: isotopic resolution and low thresholds



- High intensity to detect heavier evaporated fragments (low prob.)
- Widths of charge and mass PLF/TLF distributions in DIC
  → probe mean field models + correlations/fluctuations (ex. TDHF +correlations)
- Tandem facilities (ALTO, LNS, LNL, …)

Conclusions

- Present status of dynamics and EoS research
  - Important advances in technologies
  - Constraints on symmetry energy: lots of progress $0.4<\gamma<1.0$, but need to reduce uncertainties
- Future perspectives:
  - Unexplored phenomena soon accessible (resolution, SIB and RIB facilities, high intensities)
  - Relevance of isospin and space-time probes (diffusion, correlations) at low E/A (CN, DIC, fission) and intermediate E/A (E_{sym}, clusters)
  - Probes of dynamics/structure interplays