Isospin dependent EoS (Asy-EoS) with Heavy-ion collision probes

G. Verde INFN-CT

for the Chimera & Farcos group

OUTLINE:

- The Asy-EoS and the density dependence of the symmetry energy
- Experimental probes by the Chimera group (GSI and LNS experiments)
- Future perspectives for sub-saturation and supra-saturation density research

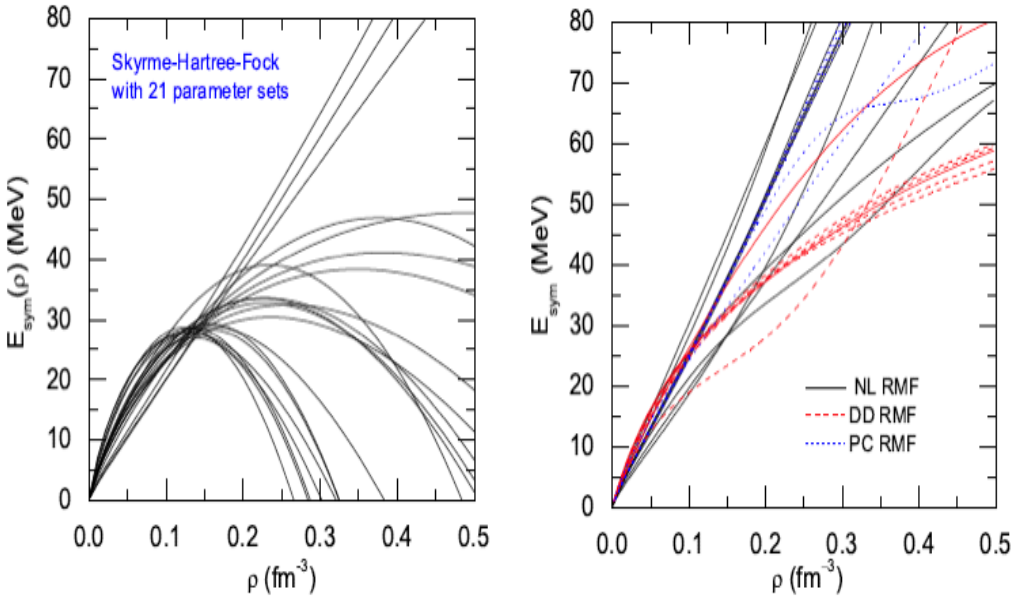
Italy-Japan meeting
Milano 19-23 Nov, 2012

The EoS of asymmetric nuclear matter

Infinite nuclear matter: how does E depend on density?

$$E(r,d) = E(r,d=0) + E_{sym}(r) \times d^2 + O(d^4) \qquad d = \frac{r_n - r_p}{r_n + r_p}$$

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



???

Many approaches… large uncertainties….

Microscopic many-body, phenomenological, variational, …

Typical parameterizations

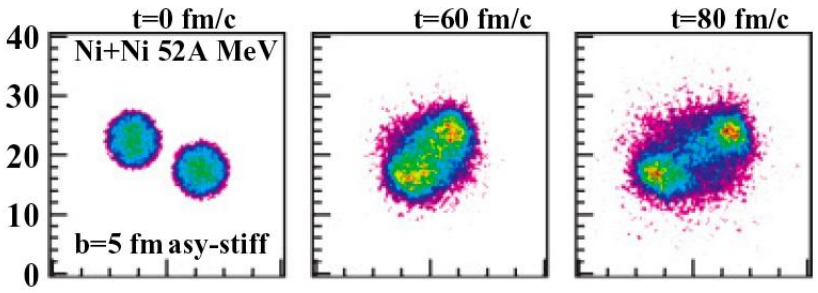
$$E_{sym}(r) \propto \left(\frac{r}{r_0}\right)^g$$

γ ~ 2 ~ Asy-Stiff

γ < 0.5 ~ Asy-Soft

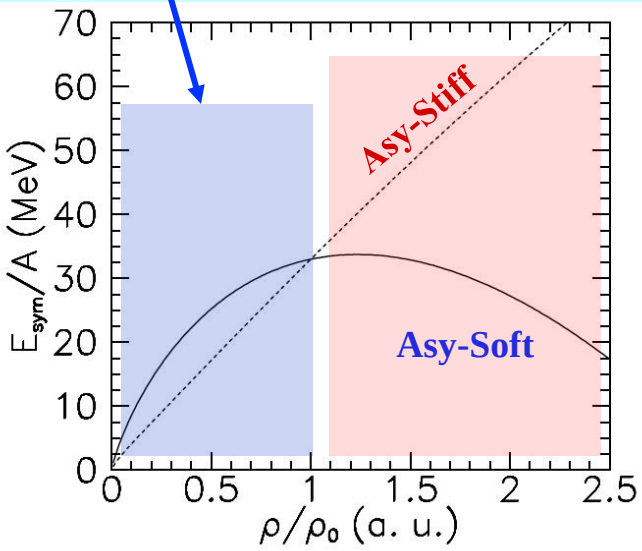
Producing density gradients in the lab

Intermediate energies: E/A=20-100 MeV

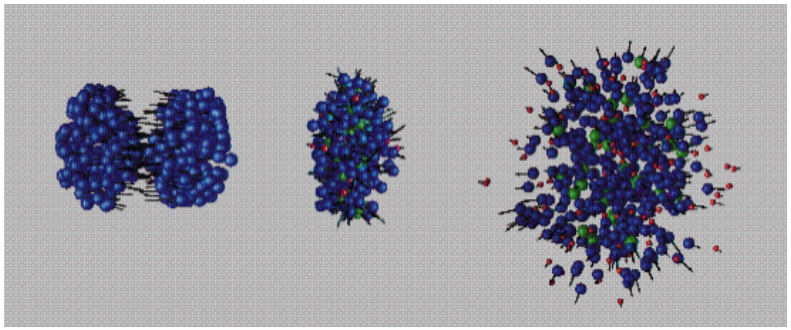


SMF - Baran, Colonna, Di Toro, Greco

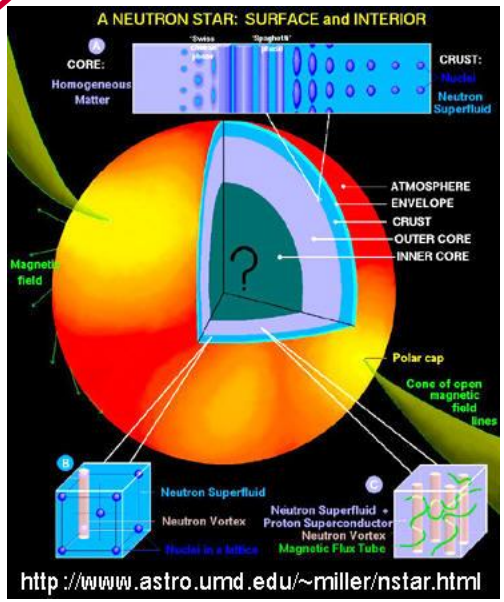
Ganil, Eurisol, Frib, Lns, Nscl, Spiral2, Tamu, …



High energies: E/A>200 MeV



CSR, GSI/Fair, NSCL/FRIB, Riken, …



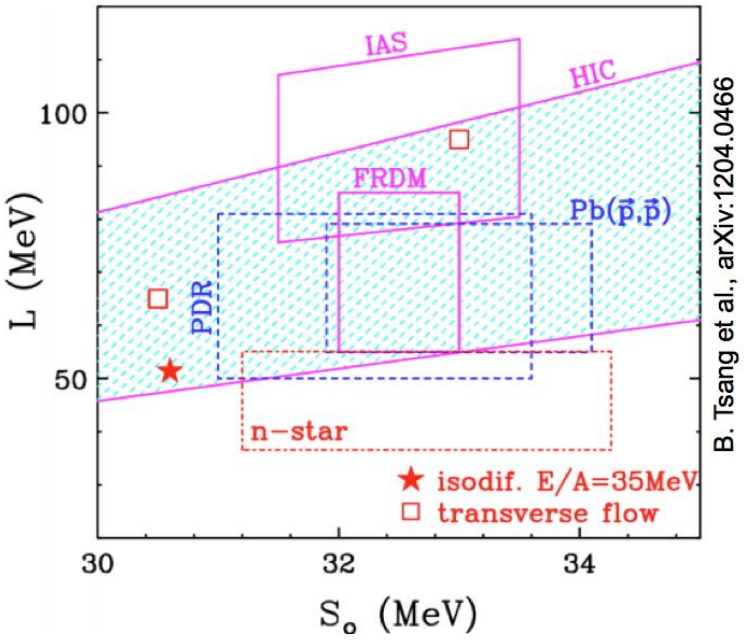
Neutron Stars

- Radii
- Frequencies of crustal vibrations
- Composition, thickness of inner crust
- URCA processes
- Phases within the star

Densities ~ $0.01\rho_0$ - $6\rho_0$ – Large Gradients!!!

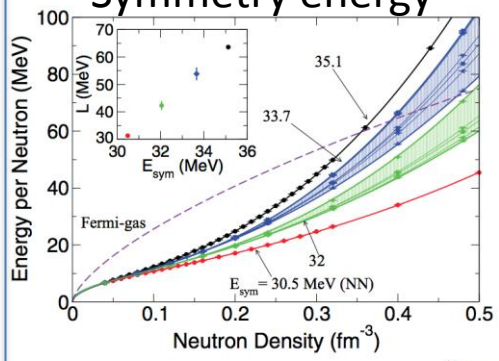
Constraints on $E_{sym}(\rho)$

Status of laboratory experiments

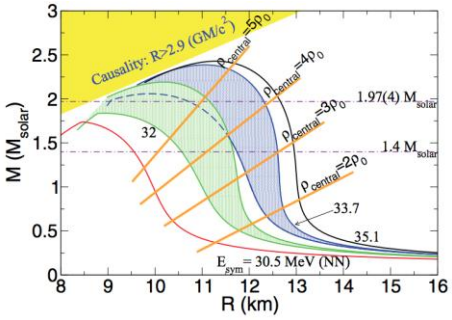


$$E_{sym}(\rho) = S_0 + \frac{L}{3}\frac{\rho-\rho_0}{\rho_0} + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots$$

Symmetry energy



S. Gandolfi et al., Physical Review C**85**, 032801(R)



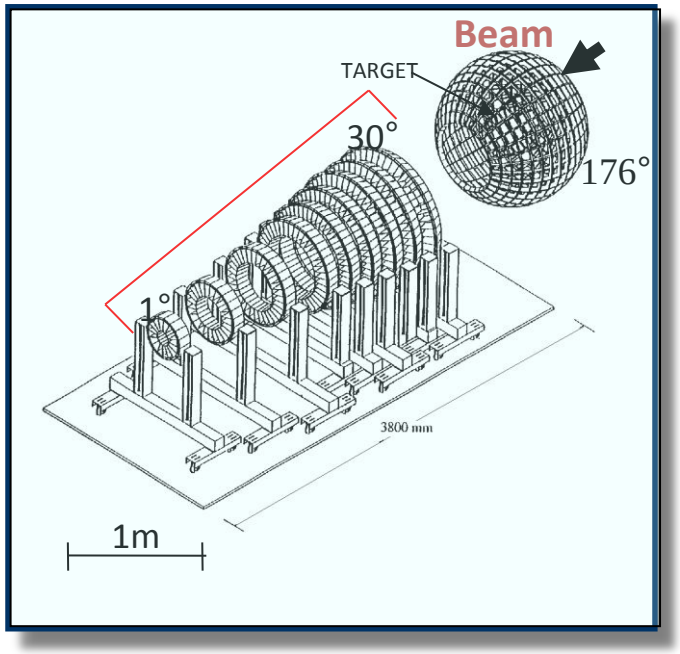
Neutron star Radii and Masses

Still large error bars in laboratory measurements:

→ Need to reduce uncertainties in HIC experiments

Chimera @ INFN-LNS

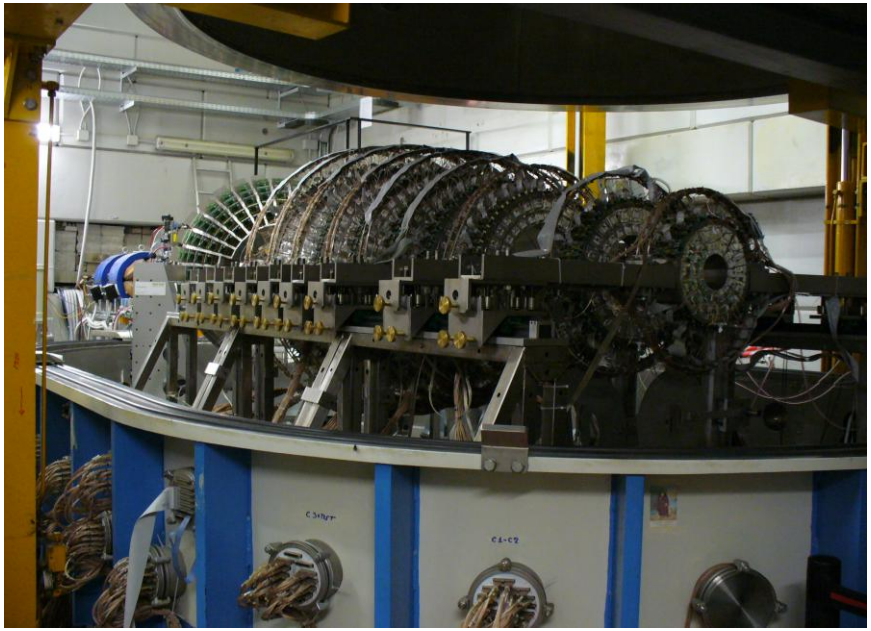
1192 Si-CsI(Tl) Telescopes



18 rings in the range $1° \leq \theta \leq 30°$

17 rings in the range $30° \leq \theta \leq 176°$ (sphere)

High granularity and efficiency up to 94% 4π

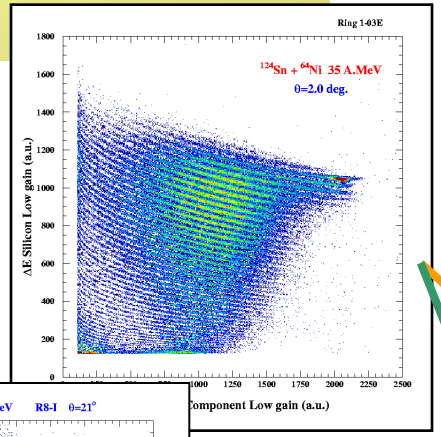


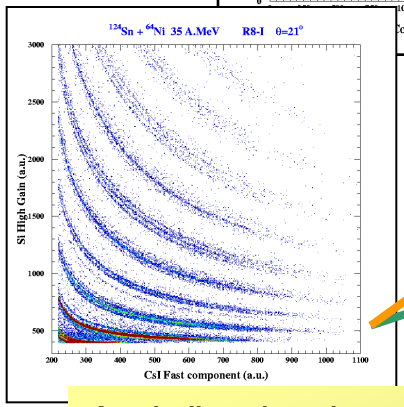
- Z identification up to beam charge (ΔE-E)
- Z and A identification by ΔE-E up to $Z \leq 9$
- Z and A identification in CsI up to $Z \leq 4$
- Mass identification with low energy threshold (< 0.3 MeV/u) by ToF
- Z identification for particles stopping in Si (pulse shape)

Particle identification in Chimera

ΔE(Si)-E(CsI)

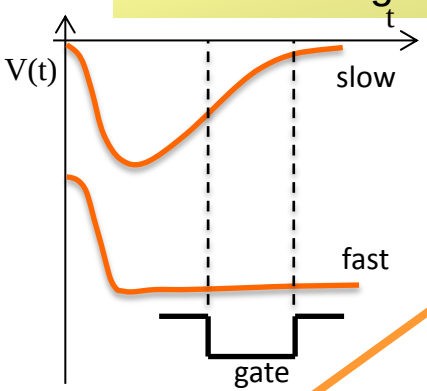
Charge Z for particles punching throught the Si detector

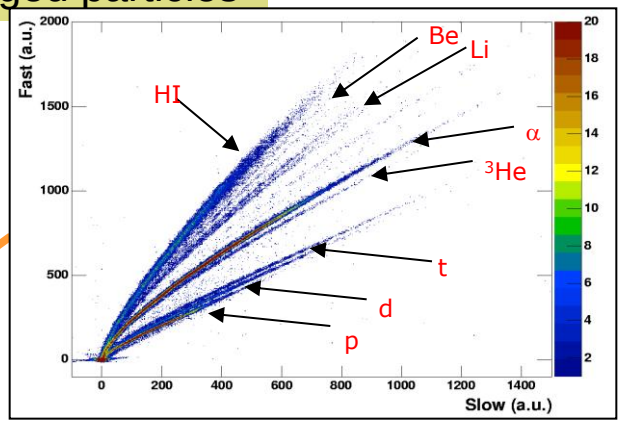


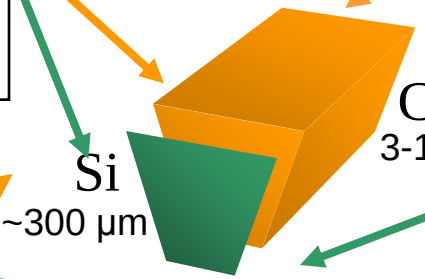


PSD in CsI(Tl)

Z and A for light charged particles

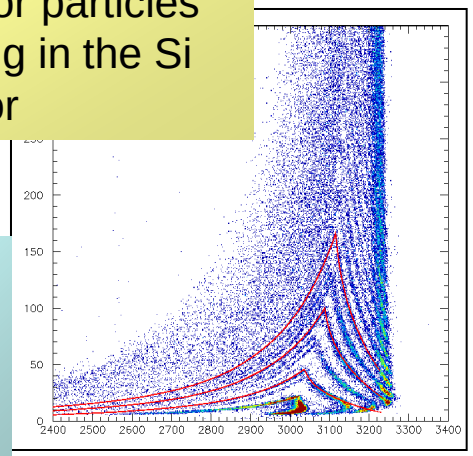






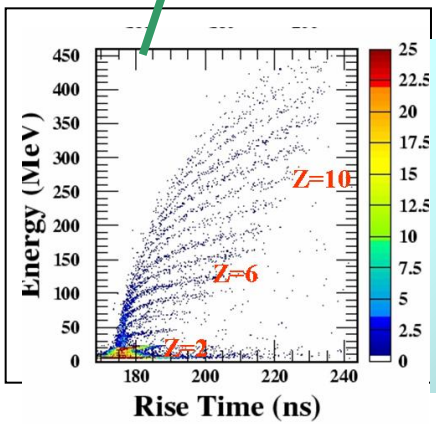
ΔE(Si)-ToF

Mass for particles stopping in the Si detector



ΔE(Si)-E(CsI)

Charge Z and A for light ions (Z<9) punching throught the Si detector

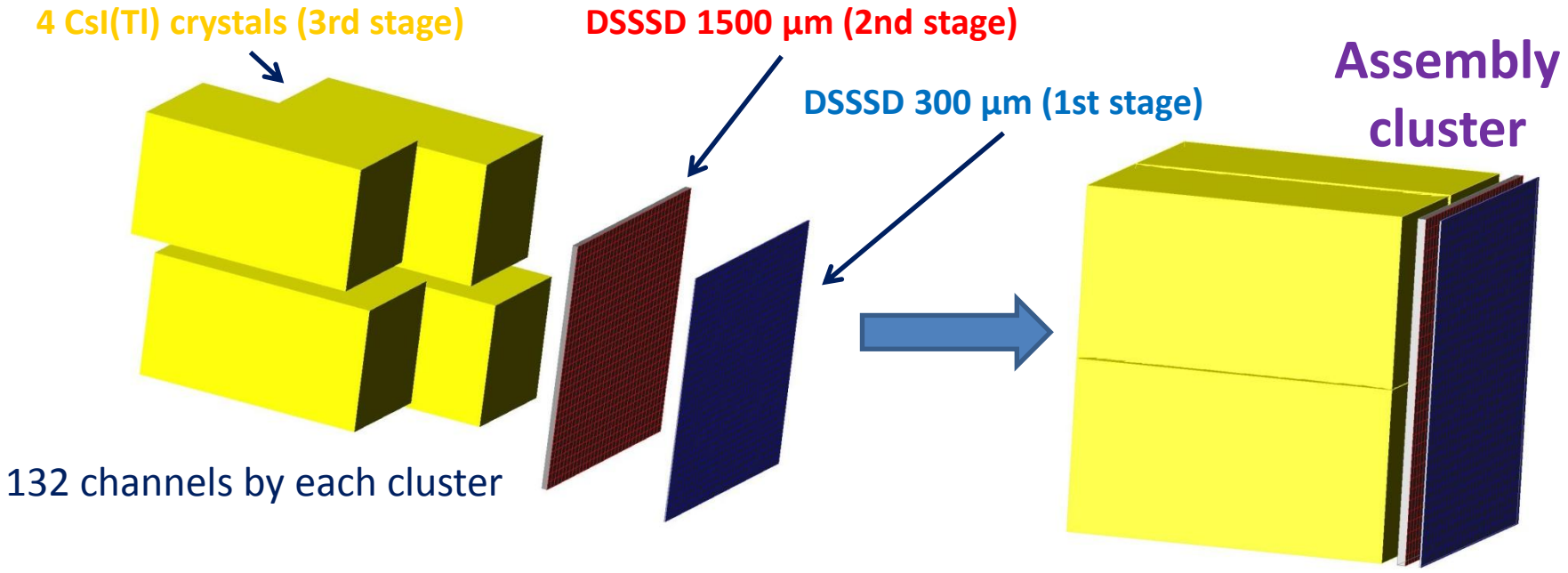


E(Si)-Rise time

Charge Z for particle stopping in Si detectors (NEW)

FARCOS add-in: *Femtoscopy*

- Based on (62x64x64 mm^3) clusters
- 1 square (0.3x62x62 mm^3) DSSSD 32+32 strips
- 1 square (1.5x62x62 mm^3) DSSSD 32+32 strips
- 4 60x32x32 mm^3 CsI(Tl) crystals



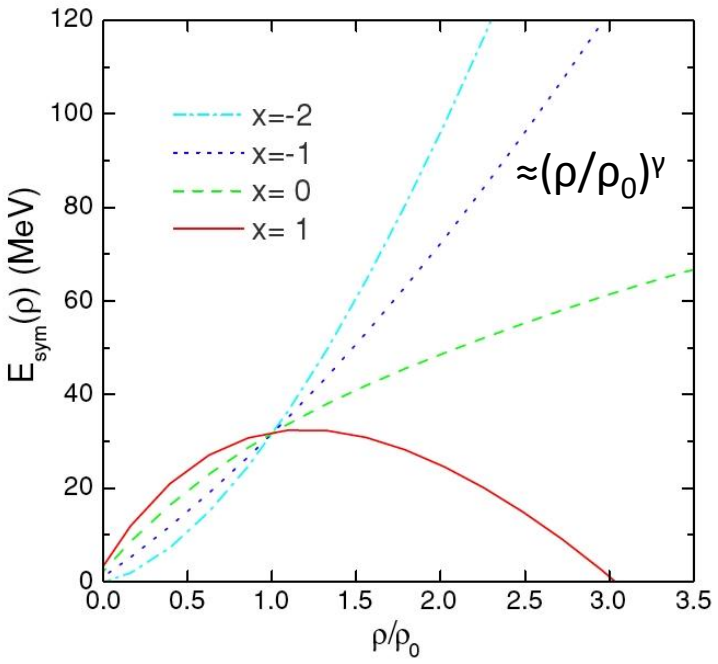
Fully reconfigurable (more Si layers, neutron detection, …)

Probes of the symmetry energy

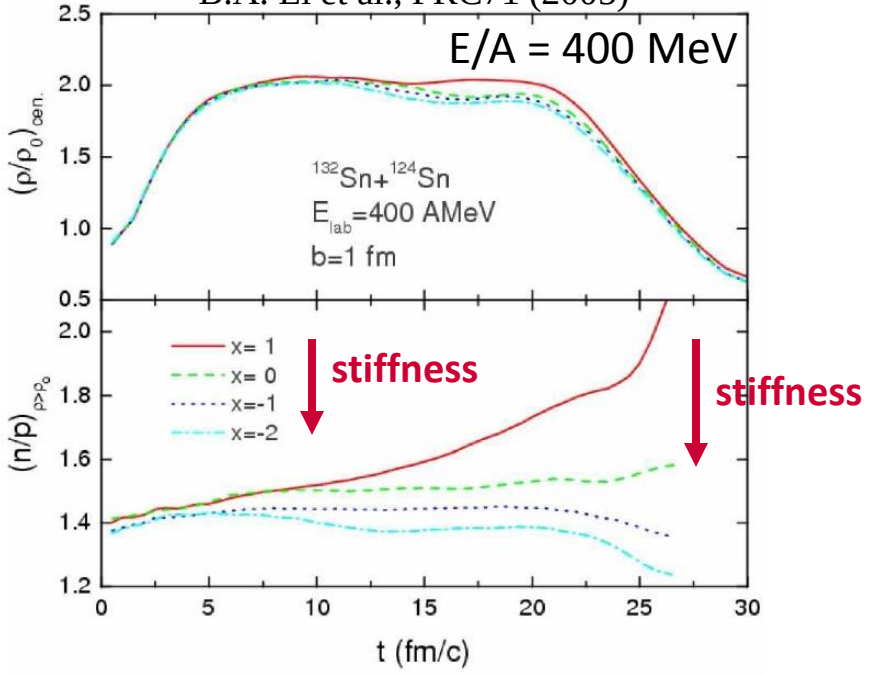
- Probes at Intermediate energies: sub-saturation density ($\rho<\rho_0$)
  - Isospin diffusion and drift
  - Neutron-proton pre-equilibrium emission spectra
  - nn, np, pp correlation functions

- Probes at GSI energies: supra-saturation density ($\rho>\rho_0$)
  - π^+/π- and K^+/K^0 emission ratios
  - n/p elliptic flow
  - n/p pre-equilibrium emission and correlation functions

Effects of the E_{sym} at high density



B.A. Li et al., PRC71 (2005)



- **N/Z of high density regions sensitive to $E_{sym}(\rho)$**
- High $\rho>\rho_0$: asy-stiff more repulsive on neutrons

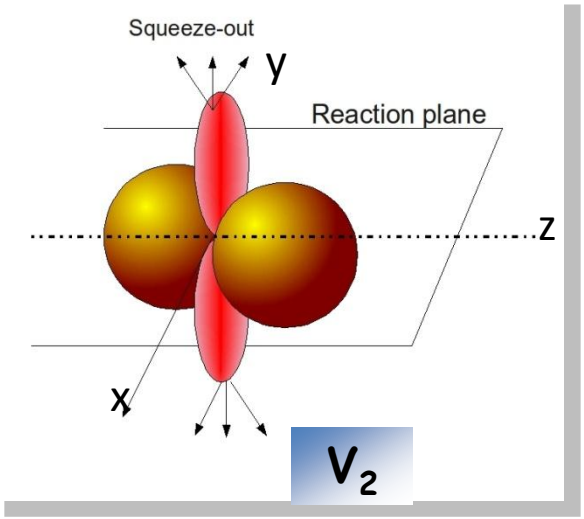
Elliptic flow in HIC at medium energies

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

Y=rapidity, p_t=transverse momentum

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

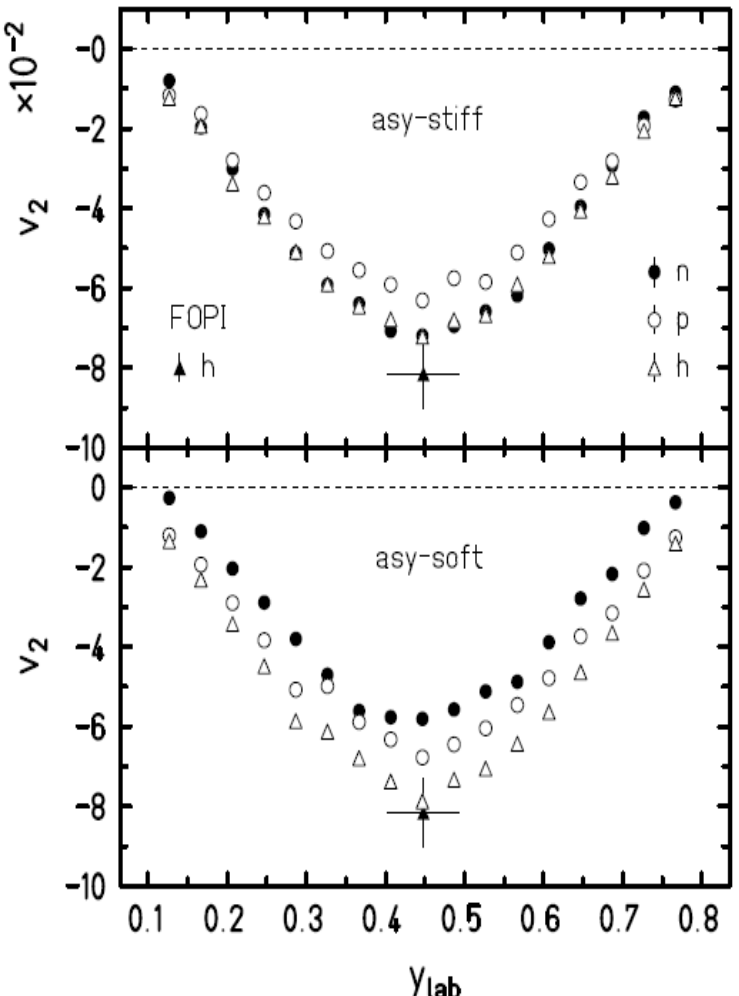
Elliptic flow: competition between in plane (V_2>0) and out-of-plane ejection (V_2<0)



Qingfeng Li, J. Phys. G31 1359-1374 (2005)
P.Russotto et al., Phys. Lett. B 697 (2011)

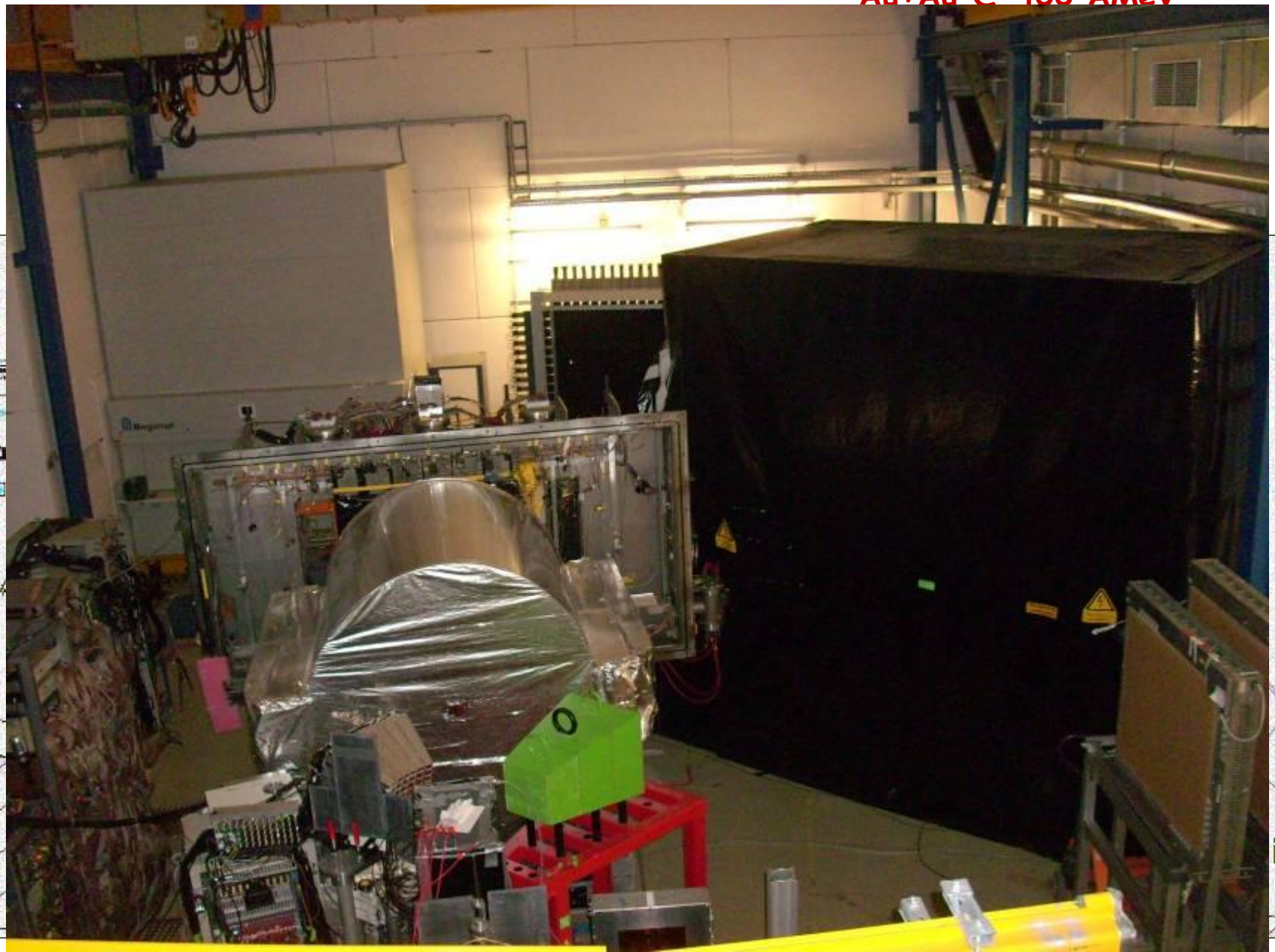
UrQMD vs. FOPI data:
Au+Au @ 400 A MeV

5.5<b<7.5 fm



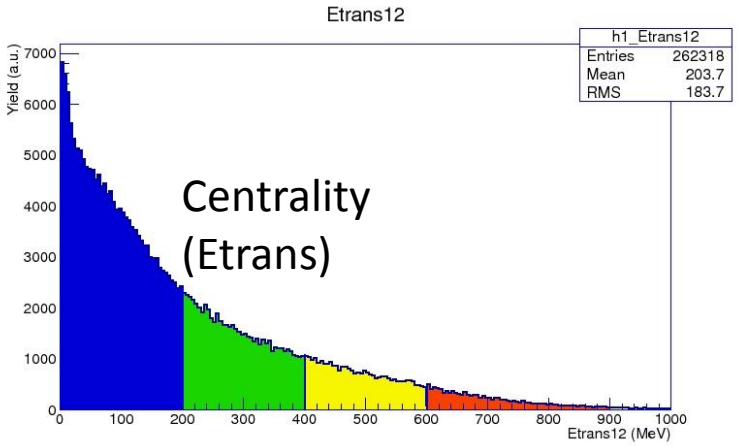
ASY-EOS S394 experiment @ GSI Darmstadt (Germany)

Au+Au @ 400 AMeV



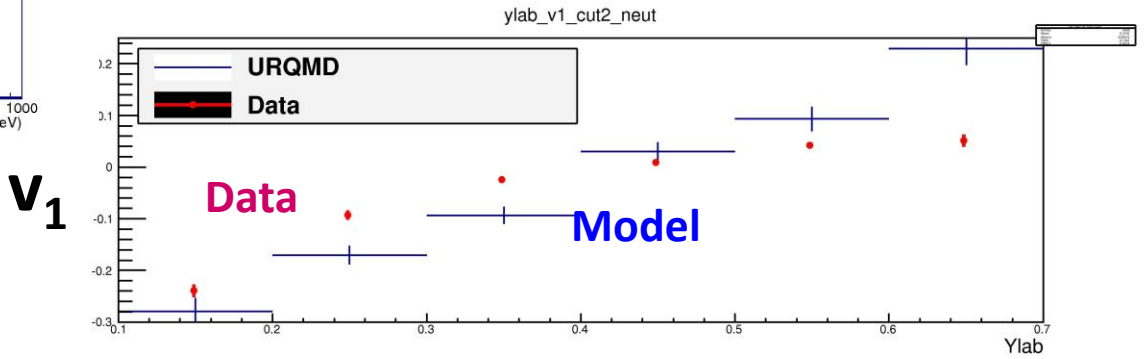
itted)

Preliminary results on neutron flow



Centrality (Etrans)

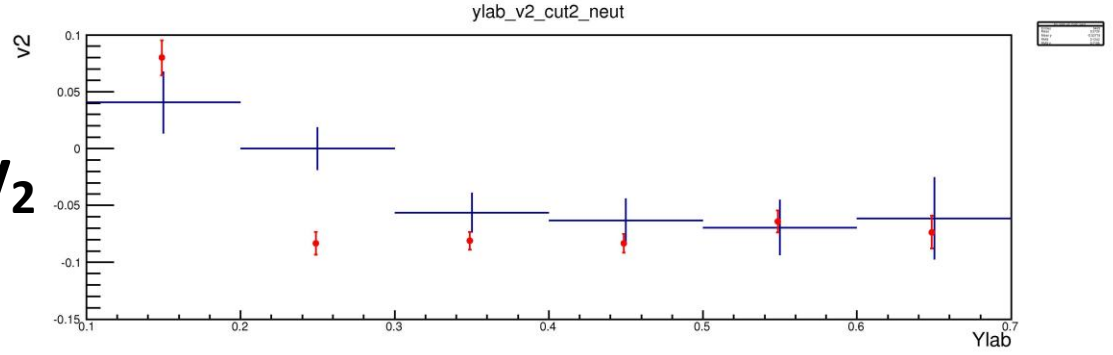
Au+Au @ 400 AMeV



v_1

Data

Model



v_2

y_{lab}

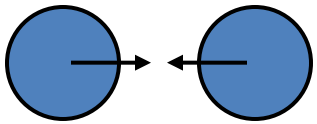
preliminary

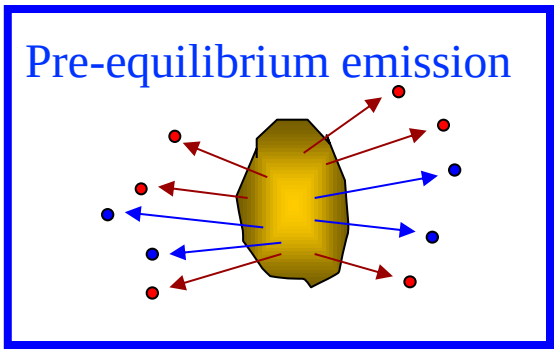
g32new

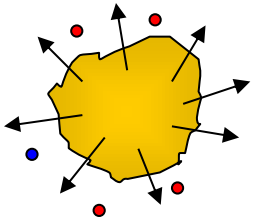
P. Russotto, INFN-CT

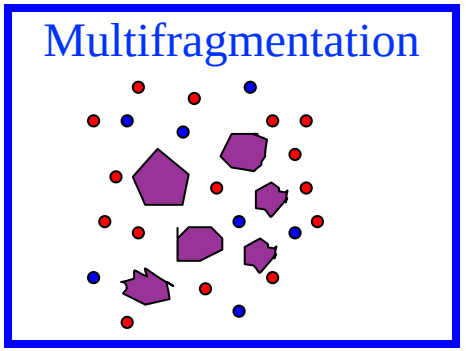
HIC at Fermi energies: $E_{sym}(\rho)$ at $\rho<\rho_0$

b=central









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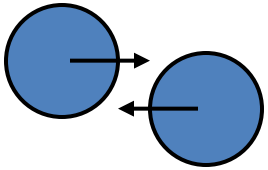
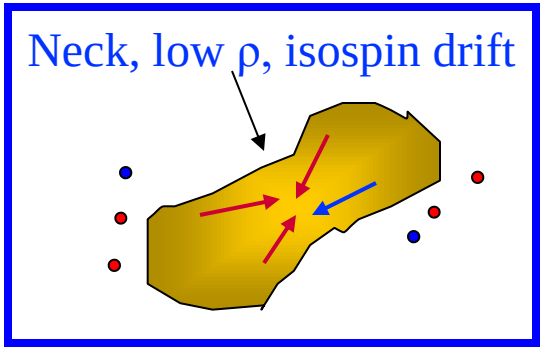
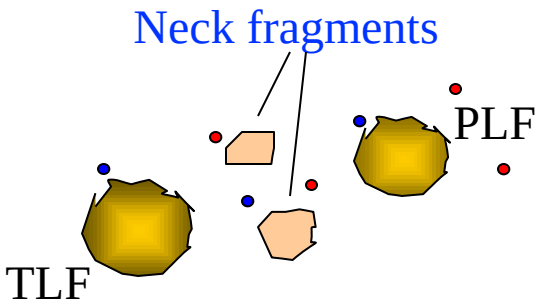
b=mid-peripheral







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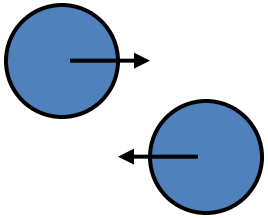
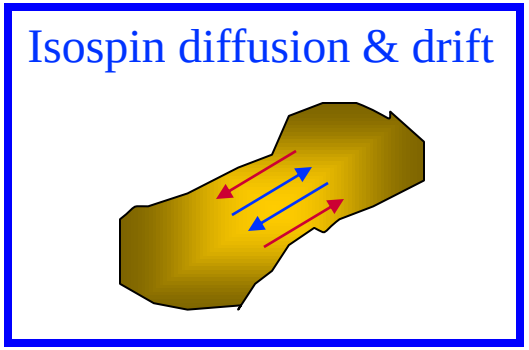
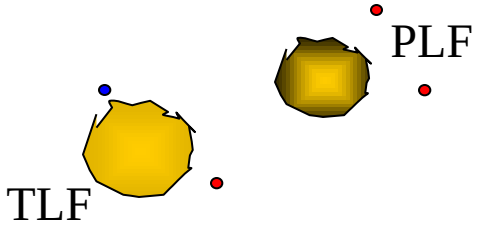
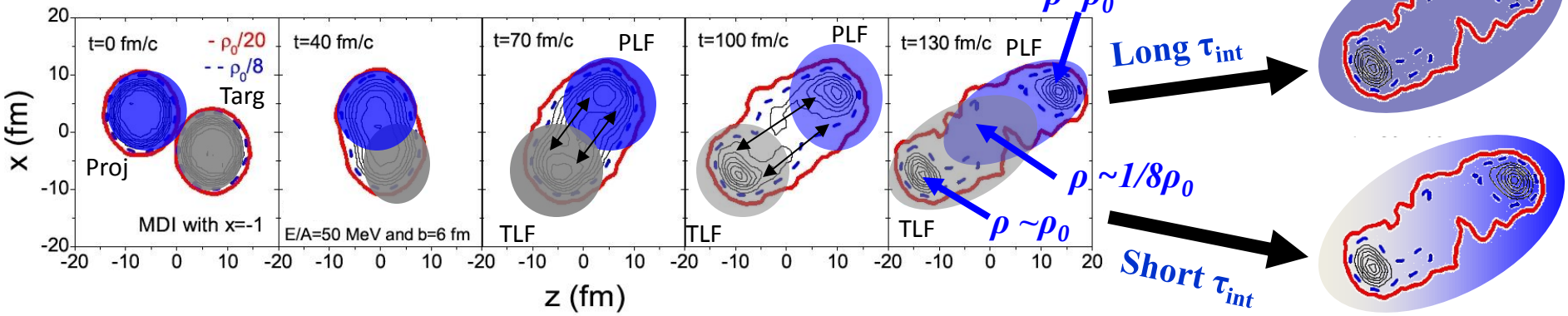
b=peripheral



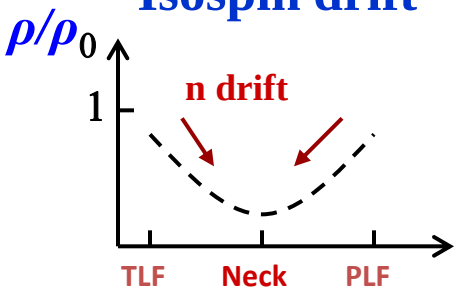




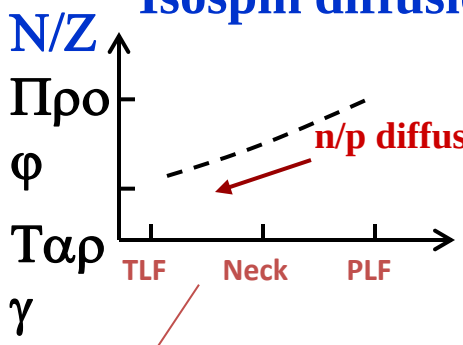
Isospin drift & diffusion



Isospin drift



Isospin diffusion

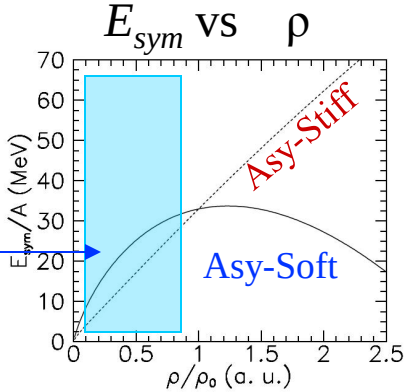


$$d = \frac{N - Z}{N + Z}$$

$$j_n - j_p = \left(D_n^r - D_p^r\right)\nabla r - \left(D_n^d - D_p^d\right)\nabla d$$

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

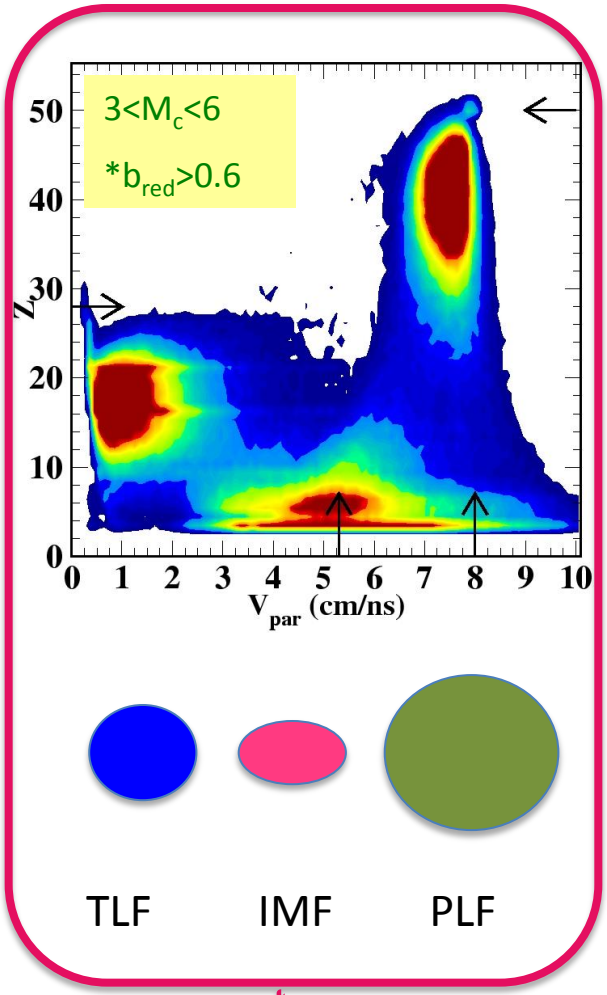
Low $\rho<\rho_0$

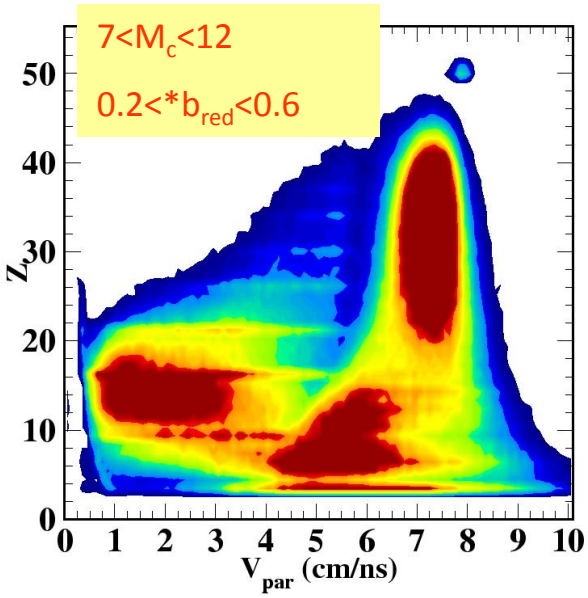


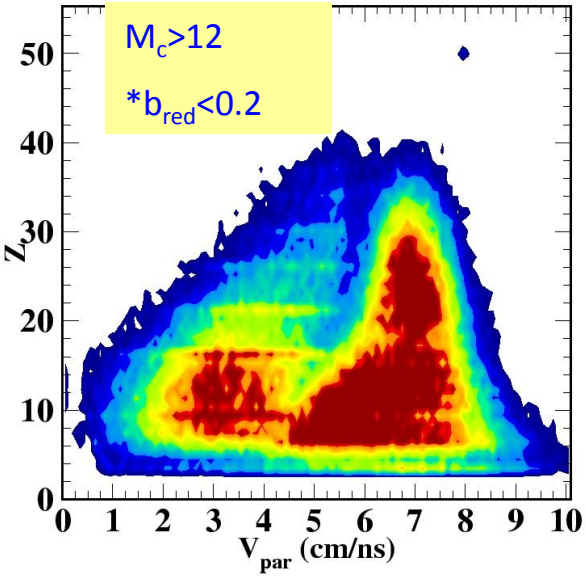
Colonna et al.; Danielewicz et al.

Event characterization with Chimera

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







Characterize IMF emission IMF times

Time-scales from three-fragment correlations

seq. statistical emission from PLF

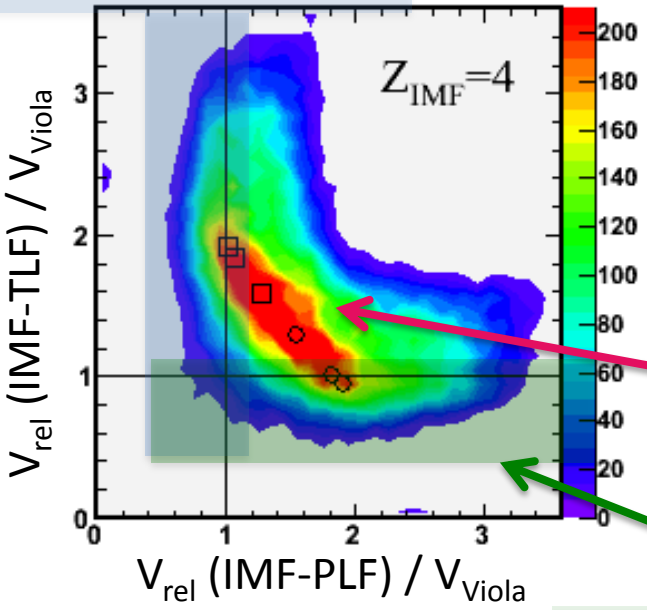
PLF

IMF intermediate

TLF

$$V_{Viola} = \sqrt{\frac{2 * E_C}{m}}$$

$$E_C = 0.755 \frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} + 7.3$$



IMF

V_{rel} (IMF - TLF)

V_{rel} (IMF - PLF)

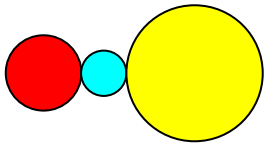
TLF

PLF

Dynamical emission from neck

seq. statistical emission from TLF

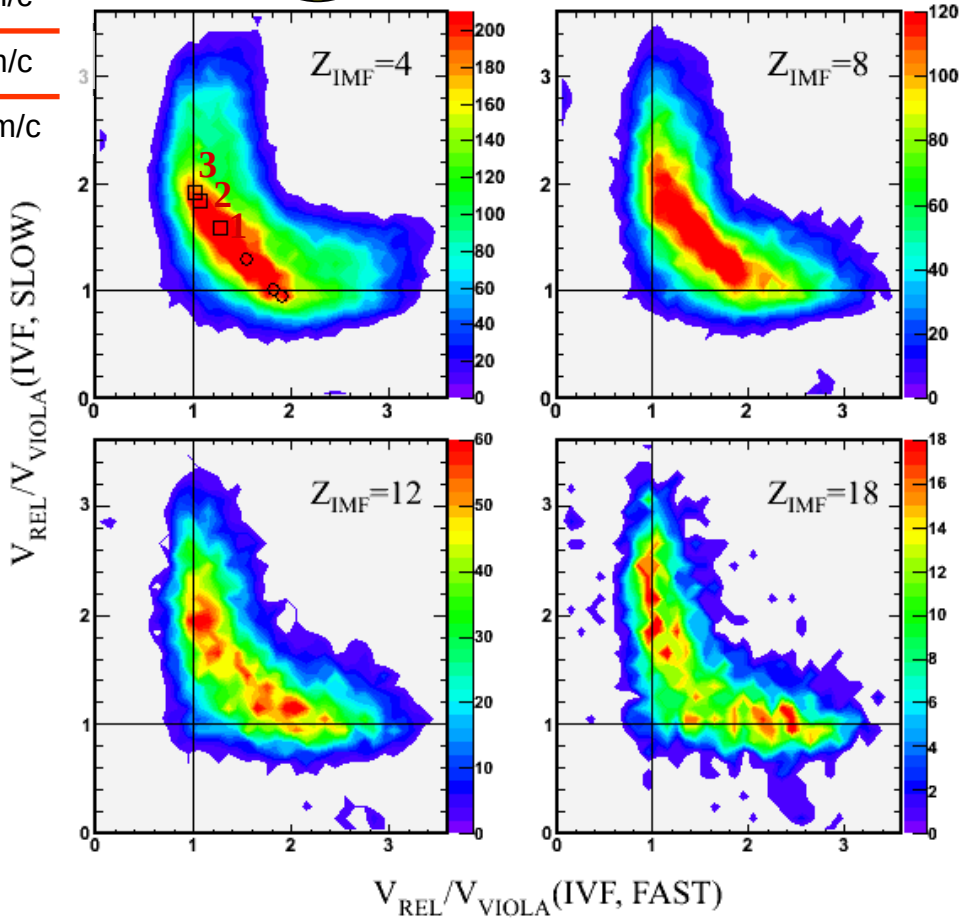
Emission time-scales and chronology



Simultaneous

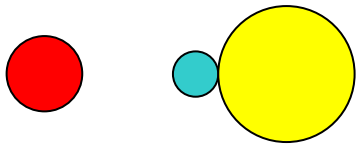
E. De Filippo, P. Russotto, A. Pagano
Phys. Rev. C (2012)

1 40 fm/c
2 80 fm/c
3 120 fm/c



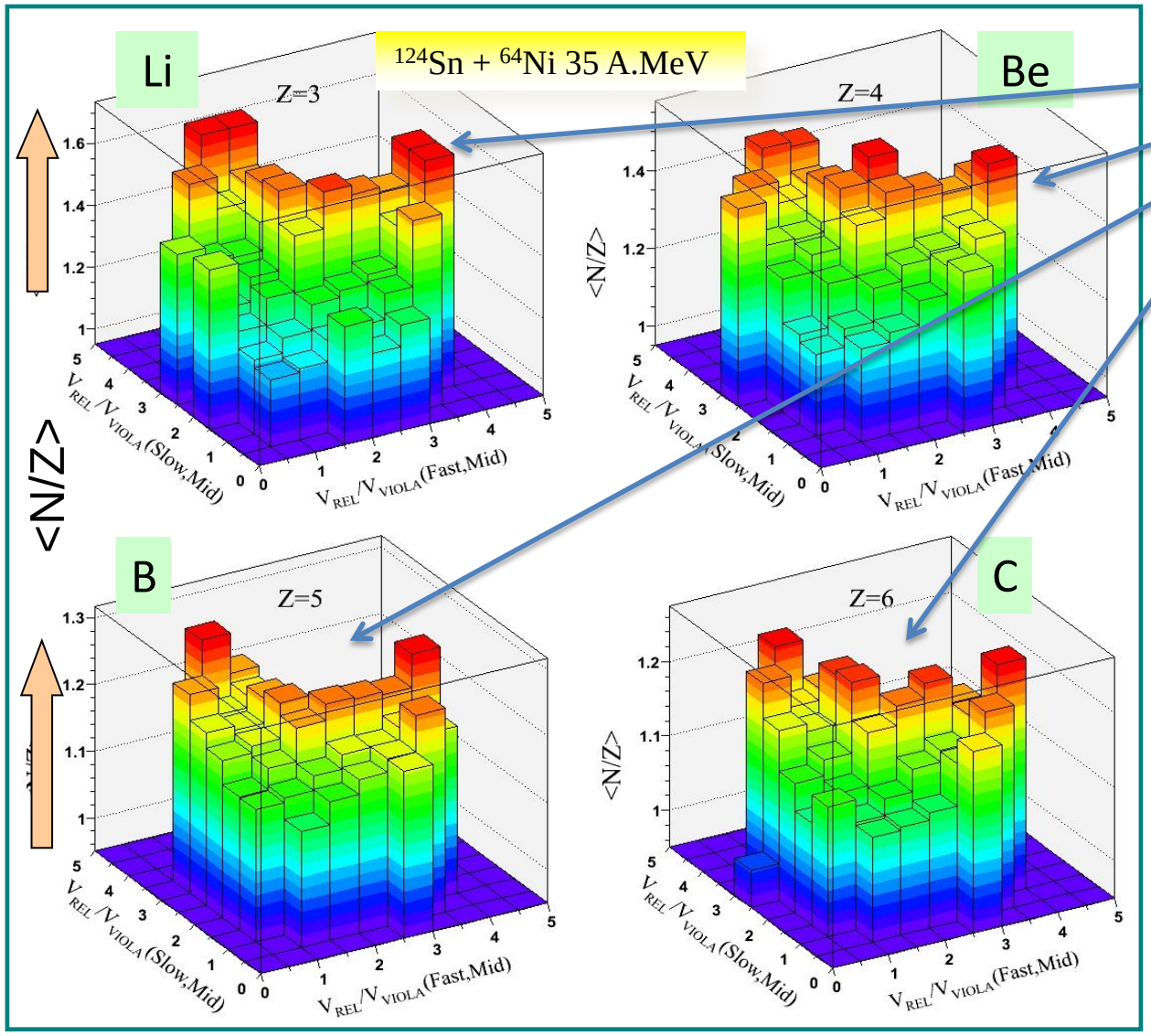
Light fragments: shorter time-scales compared to heavier

~40 fm/c vs ~120 fm/c



Sequential

Isospin chronology



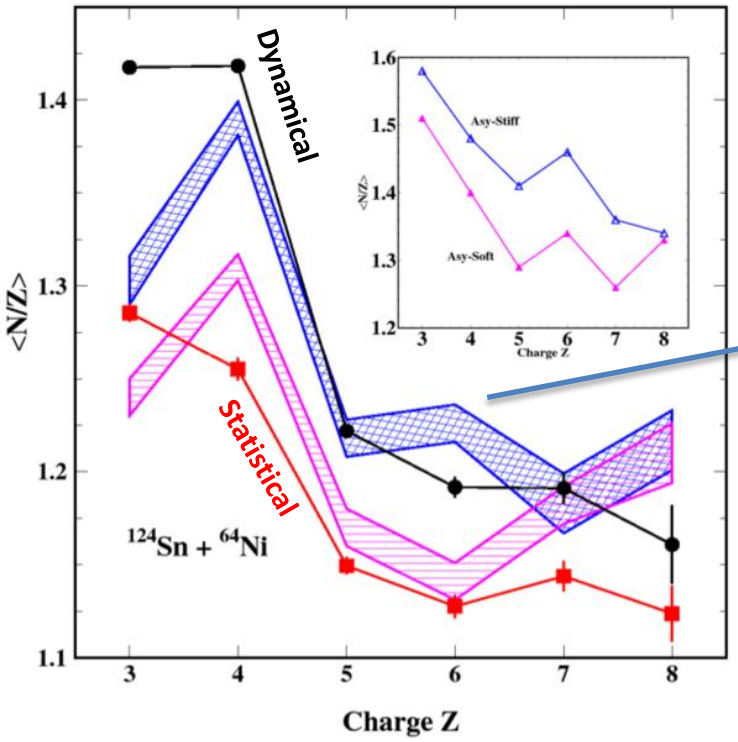
Dynamical emissions: more neutron rich

neutron enrichment in neck emissions & sensistivity to $E_{sym}(\rho)$

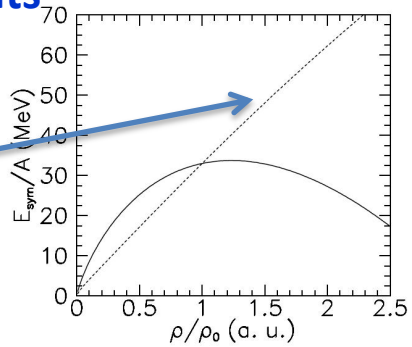
E. De Filippo, A. Pagano, P. Russotto et al. PRC (2012)

Sensitivity to symmetry energy

P. Russotto, E. De Filippo, A. Pagano



"Quasi"-Asy-Stiff (γ~0.8) more consistent with experimental results



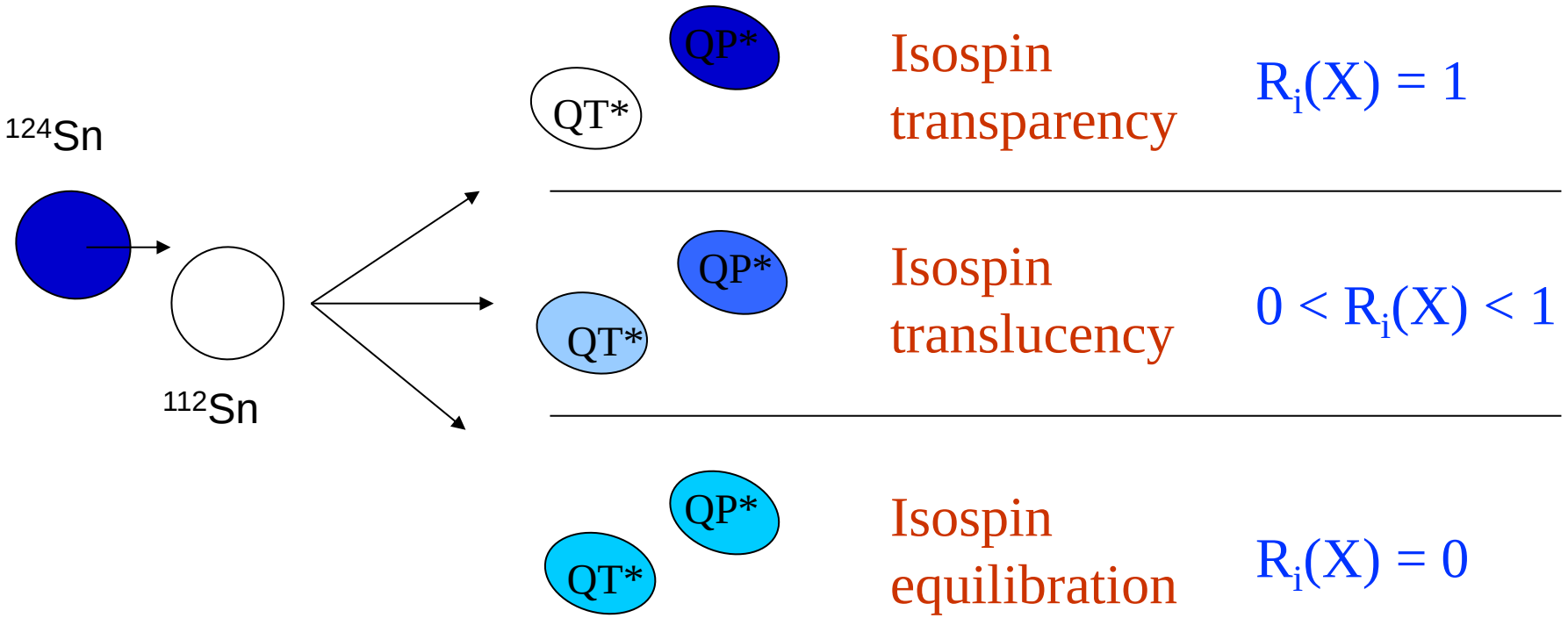
E. De Filippo, A. Pagano, P. Russotto et al., Phys. Rev. C (2012)

Isospin diffusion and imbalance ratios

$^{112}Sn+^{112}Sn$	$^{112}Sn+^{124}Sn$	$^{124}Sn+^{112}Sn$	$^{124}Sn+^{124}Sn$
PP	MIX	MIX	NN

X=Y(^{7}Li)/Y(^{7}Be)
Sensitive to N/Z of emitter

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



Isospin transparency — $R_i(X) = 1$

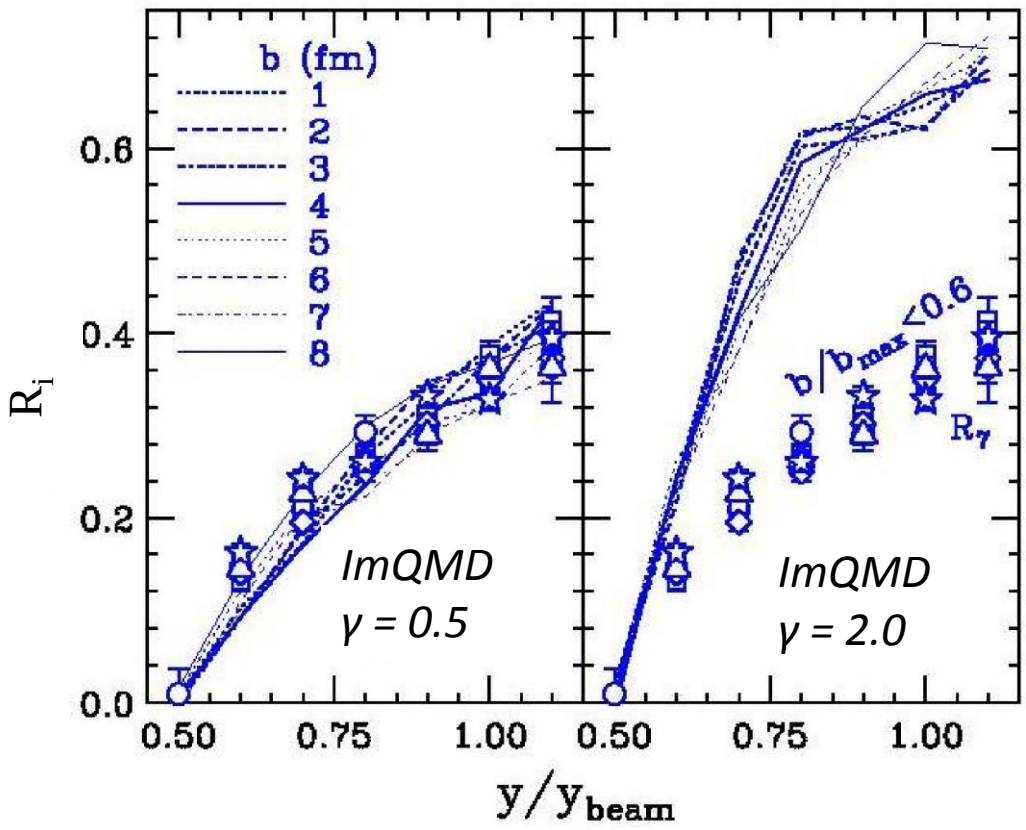
Isospin translucency — $0 < R_i(X) < 1$

Isospin equilibration — $R_i(X) = 0$

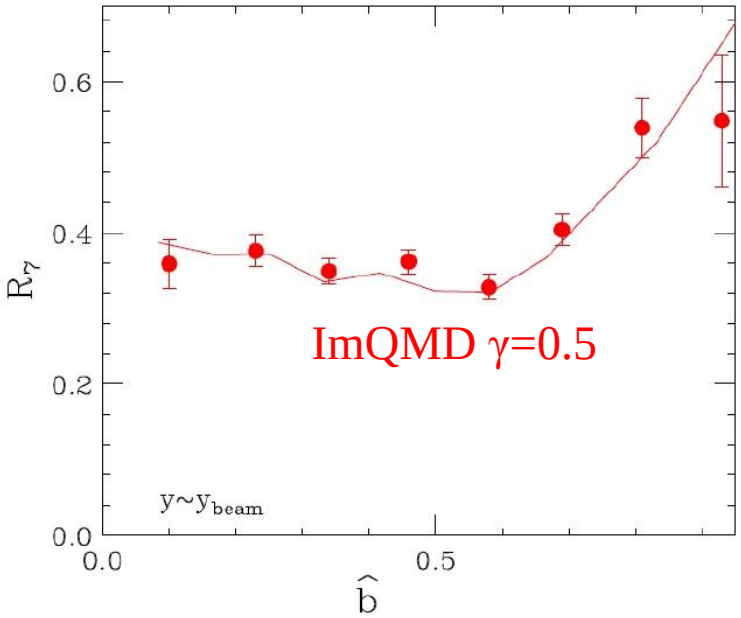
Isospin diffusion: Chimera-MSU coll.

$$R_i(x) = \frac{2x - X_{B+B} - X_{A+A}}{X_{B+B} - X_{A+A}} \qquad x = X_7 = Y(^7Li)/Y(^7Be)$$

$^{112,214}Sn+^{112,124}Sn$ E/A=35 MeV



Z.Y. Sun, M.B. Tsang, W.G. Lynch, G. Verde et al, PRC82 051603 (2010)

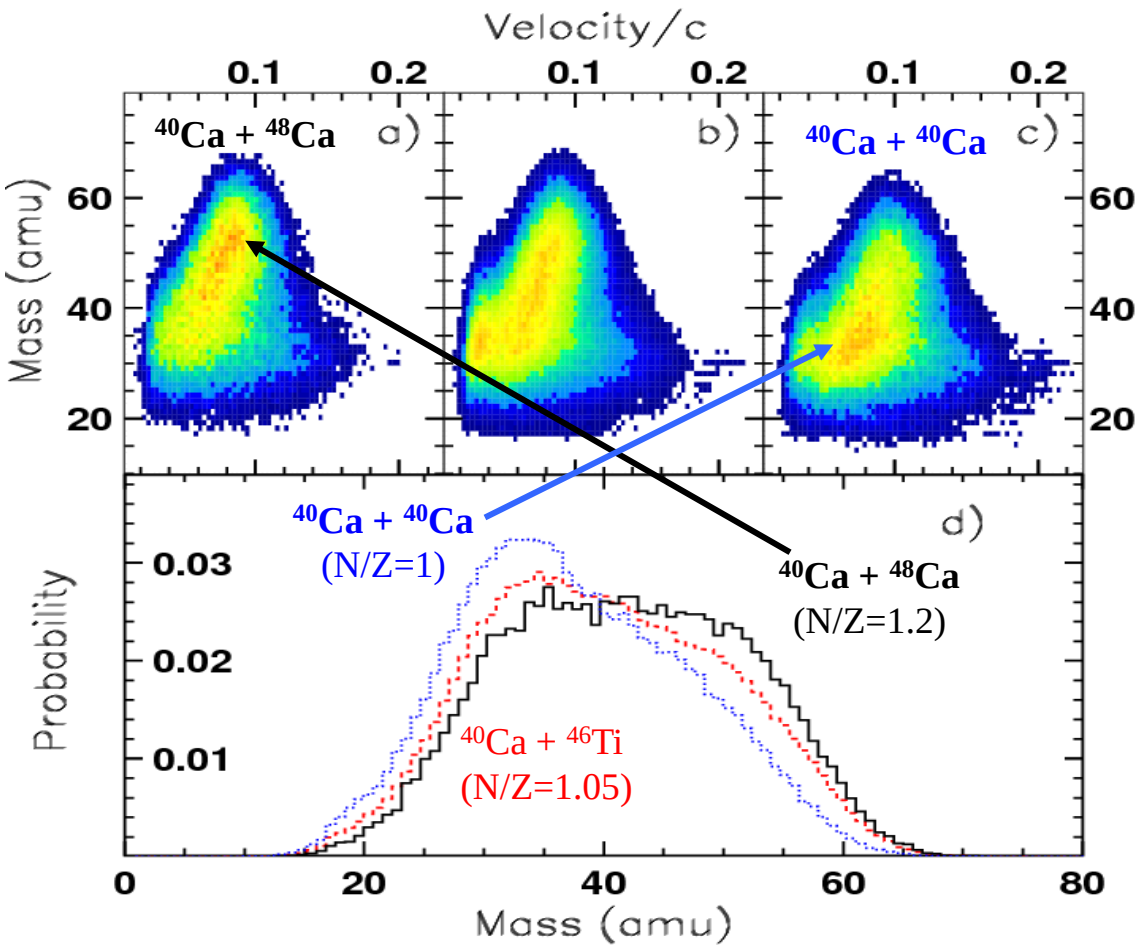


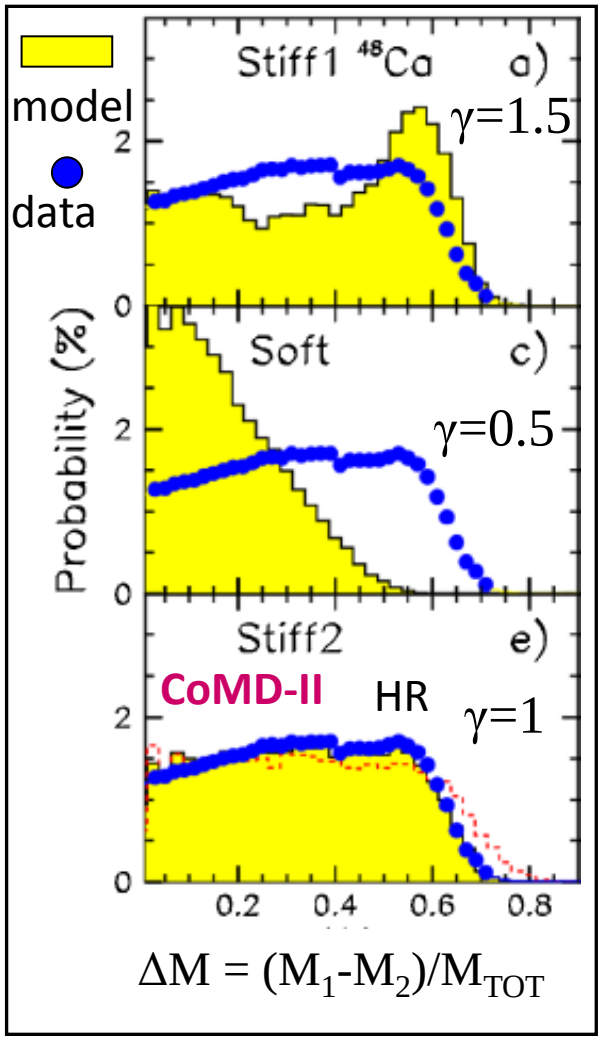
N/Z translucency persists in central collision

Isospin diffusion excludes very stiff $E_{sym}(\rho) \propto (\rho/\rho_0)^{2.0}$

N/Z effects at sub-Fermi energies

$^{40}Ca + {}^{48}Ca, {}^{40}Ca, {}^{46}Ti$ E/A = 25 MeV





Phys. Rev Lett. 102 112701 (2009)

I. Lombardo

M1 = Largest frament Mass

N/Z effects at low energies

ISODEC: ^{78,86}**Kr** + ^{40,48}**Ca** → CN: ^{118,134}**Ba*** (~ 250 MeV)

S.Pirrone (INFN – Catania), J.P.Wieleczko (GANIL- Caen), M.La Commara (Univ.& INFN – Napoli), G.Politi (Univ. &INFN – Catania)

Topics to be addressed

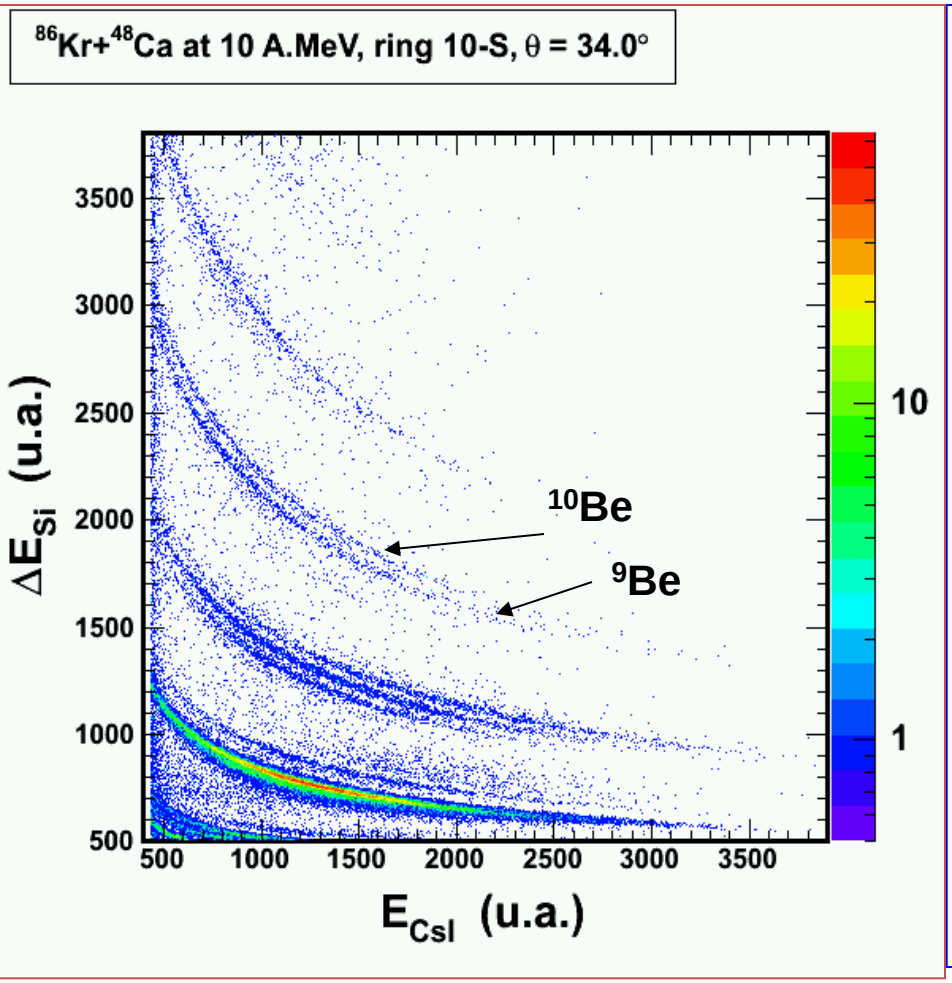
- N/Z effects on CN formation and decay: complex fragments production?
- Links to level density parameter (N/Z-dependence), fission barriers, viscosity, spectroscopy
- interplay between nuclear structure and reaction mechanism

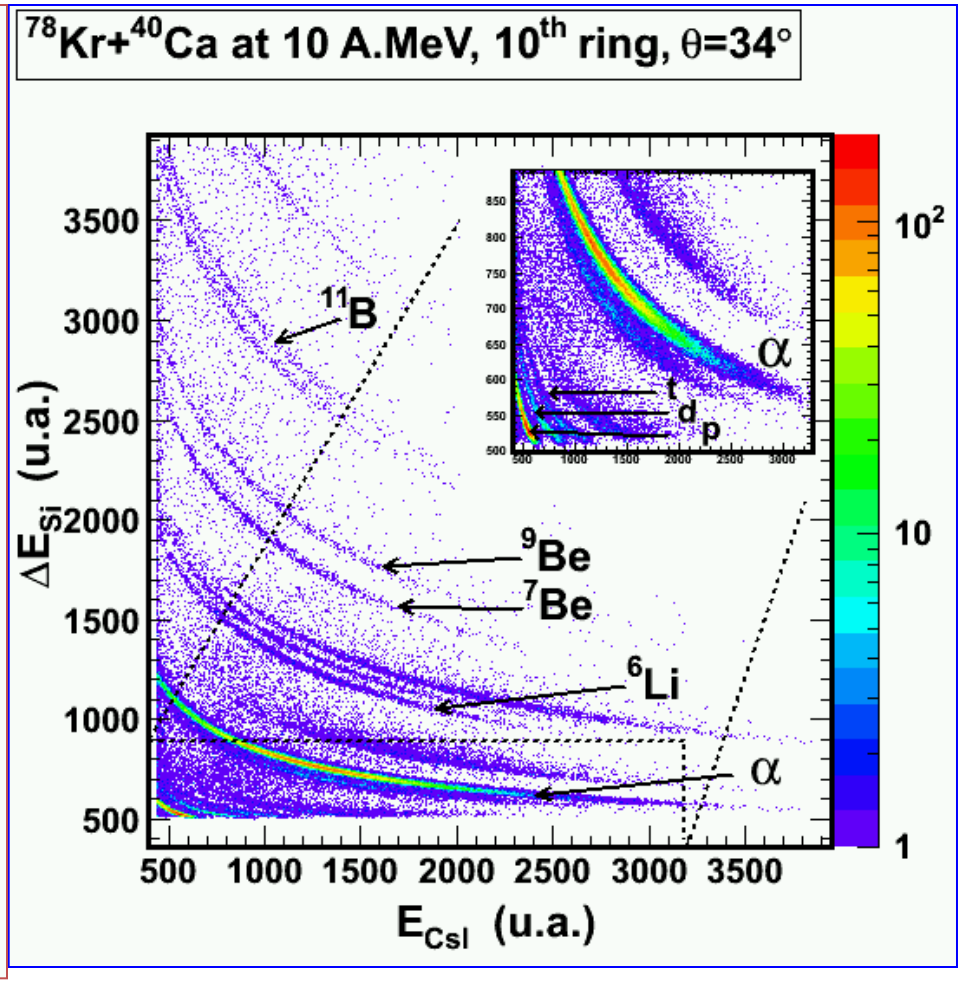
Collaboration INFN-GANIL.
LoI presented at Spes with radioactive beams (larger N/Z asymmetries)

IMF Isotopic Identification

PSD in Silicon

ΔE-E , Si-CsI(Tl)





n-rich **n-poor**

S.Pirrone EPJ Web of Conf. 17 (2011) 16010

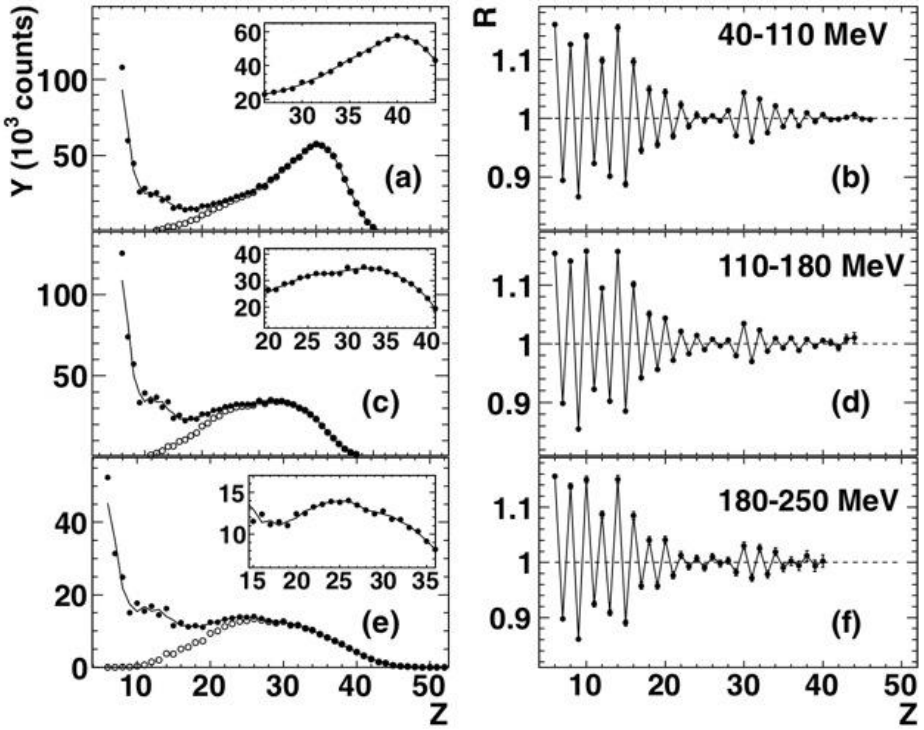
G.Politi et al 2011 EPJ Web of Conf. 21 (2012) 02003

PRELIMINARY

Staggering effects

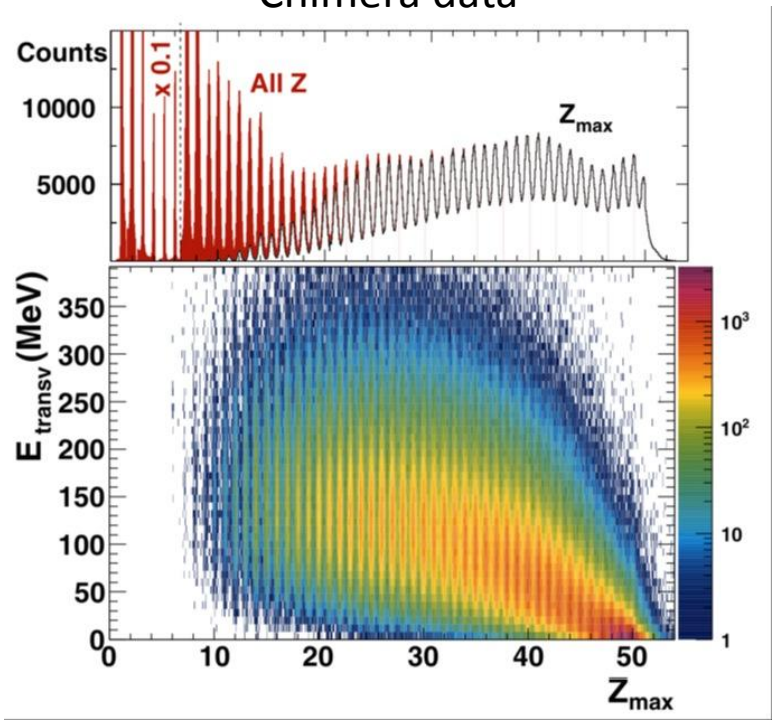
112Sn + 58Ni E/A = 35 MeV

Even-odd staggering
in charge distribution



Centrality

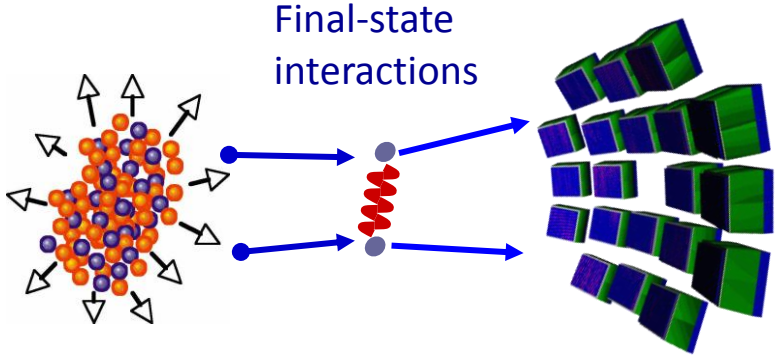
Chimera data



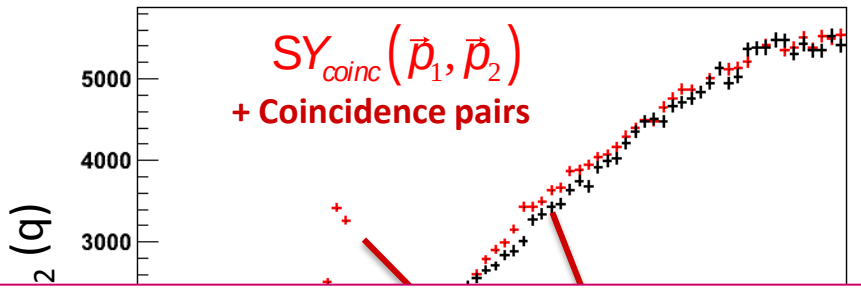
No centrality dependence observed: final decays dominate

G. Casini et al., PRC (2012)

Femtoscopy

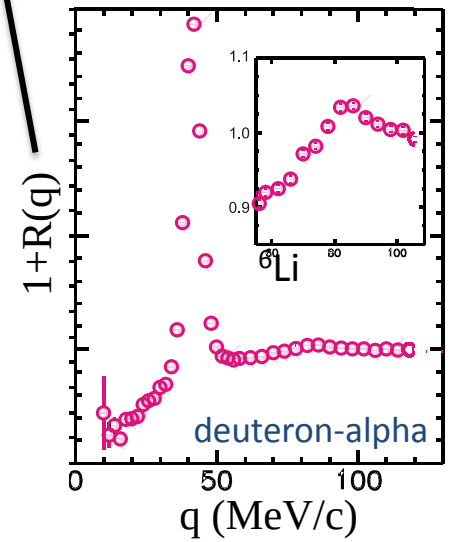


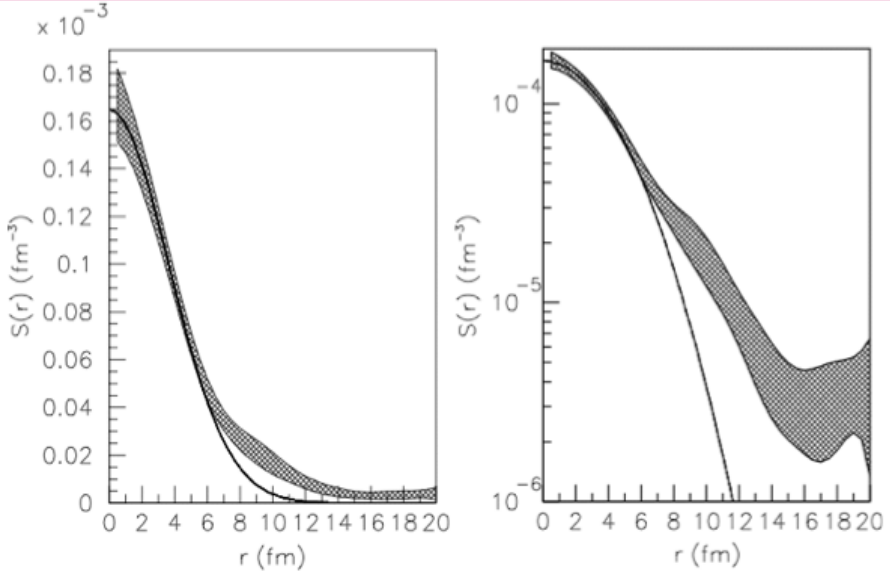
Deuteron-Alpha correlations



Imaging: Profile of emitting sources… space-time !images!

$$1+R(q)=k\times\frac{SY_{coinc}(\vec{p}_1,\vec{p}_2)}{SY_{evt.mixing}(\vec{p}_1,\vec{p}_2)}$$





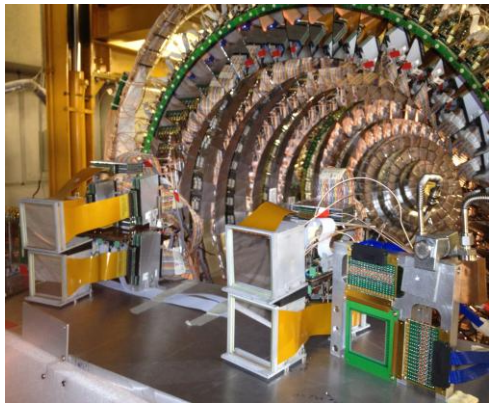
n at

High

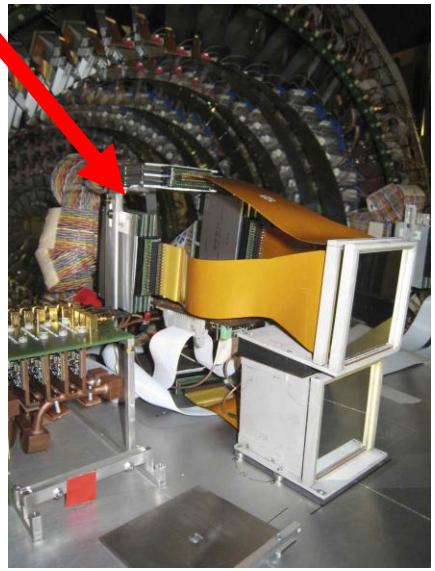
→ L

E.V. Pagano, G. Verde et al.

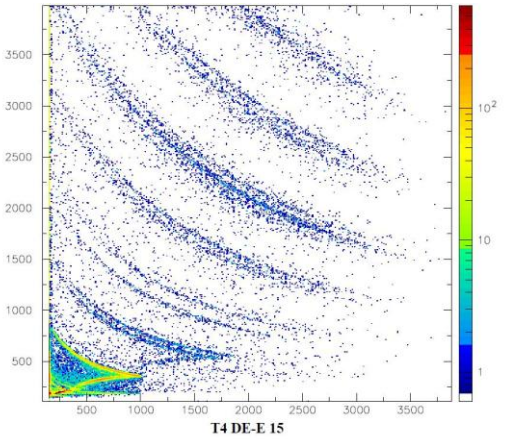
FARCOS@Chimera: first prototypes (4 telescopes)



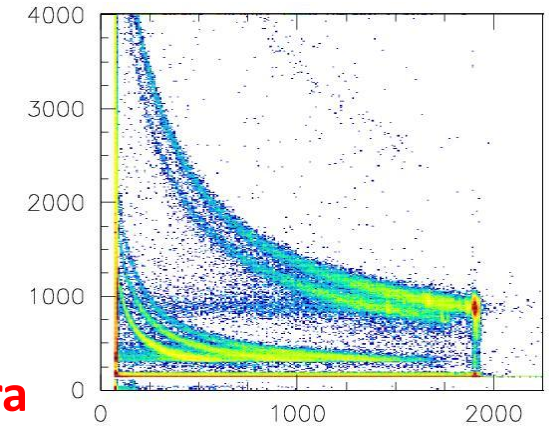
Pre-amplifier boxes



Si-Si matrix



Si-CsI(Tl) matrix



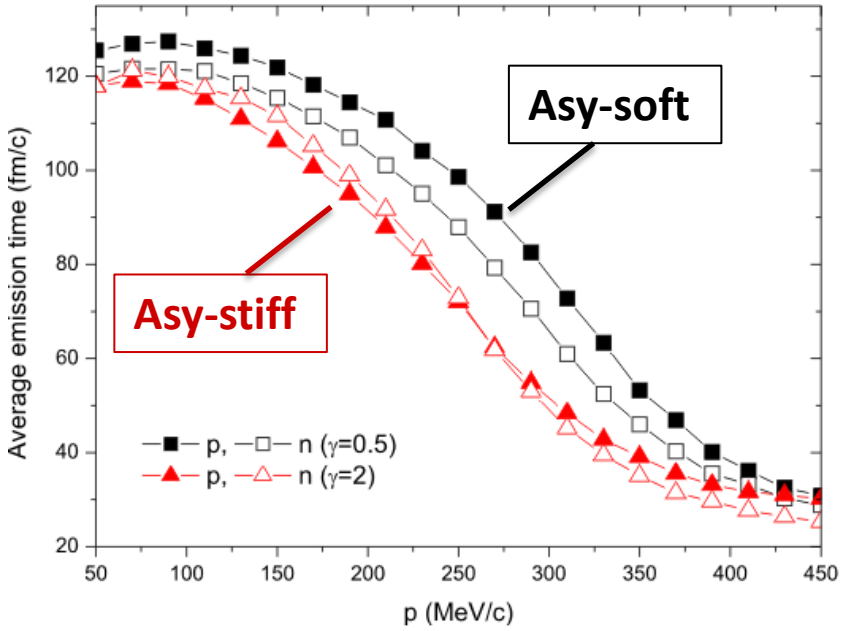
Preliminary results… analysis underway

Spring 2013: first experiments Farcos+Chimera

NN correlations and symmetry energy

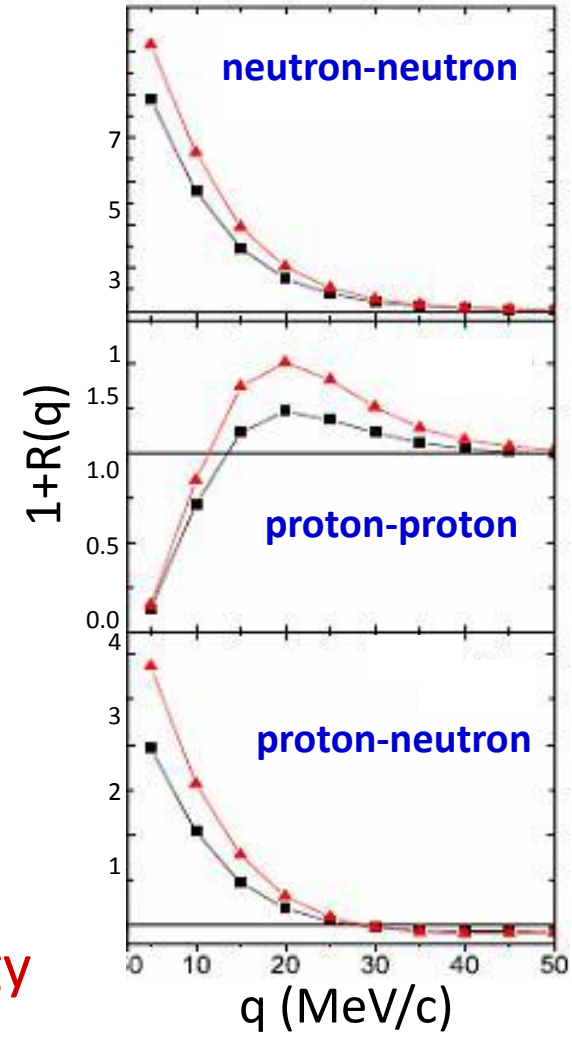
IBUU simulations

$^{52}Ca+^{48}Ca$ E/A=80 MeV Central collisions



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

Correlation functions

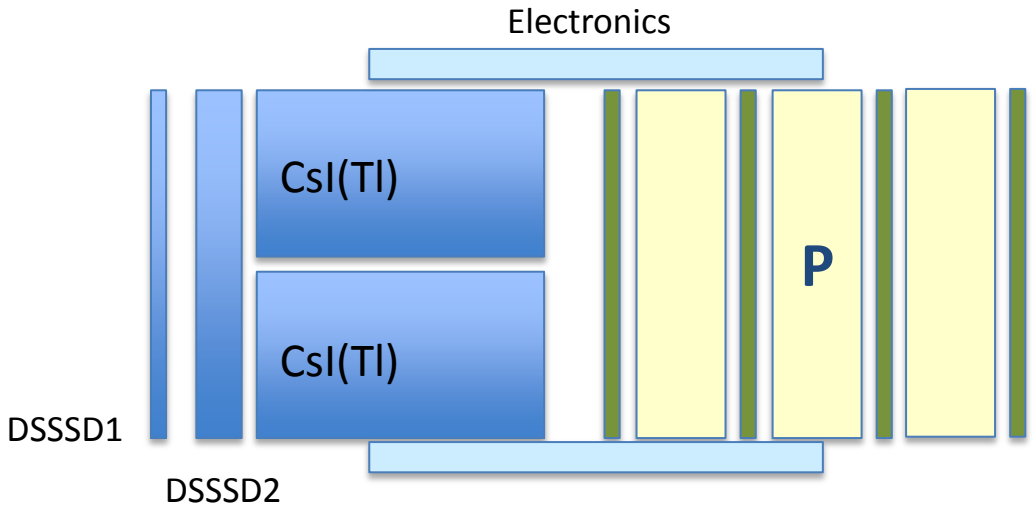


Proton/neutron emission times sensitive to density dependence of the symmetry energy

Extensions to neutron detection

- Working group formed (L. Francalanza, A. Pagano et al.)
- Simulations and tests for integration into Chimera and Farcos telescopes

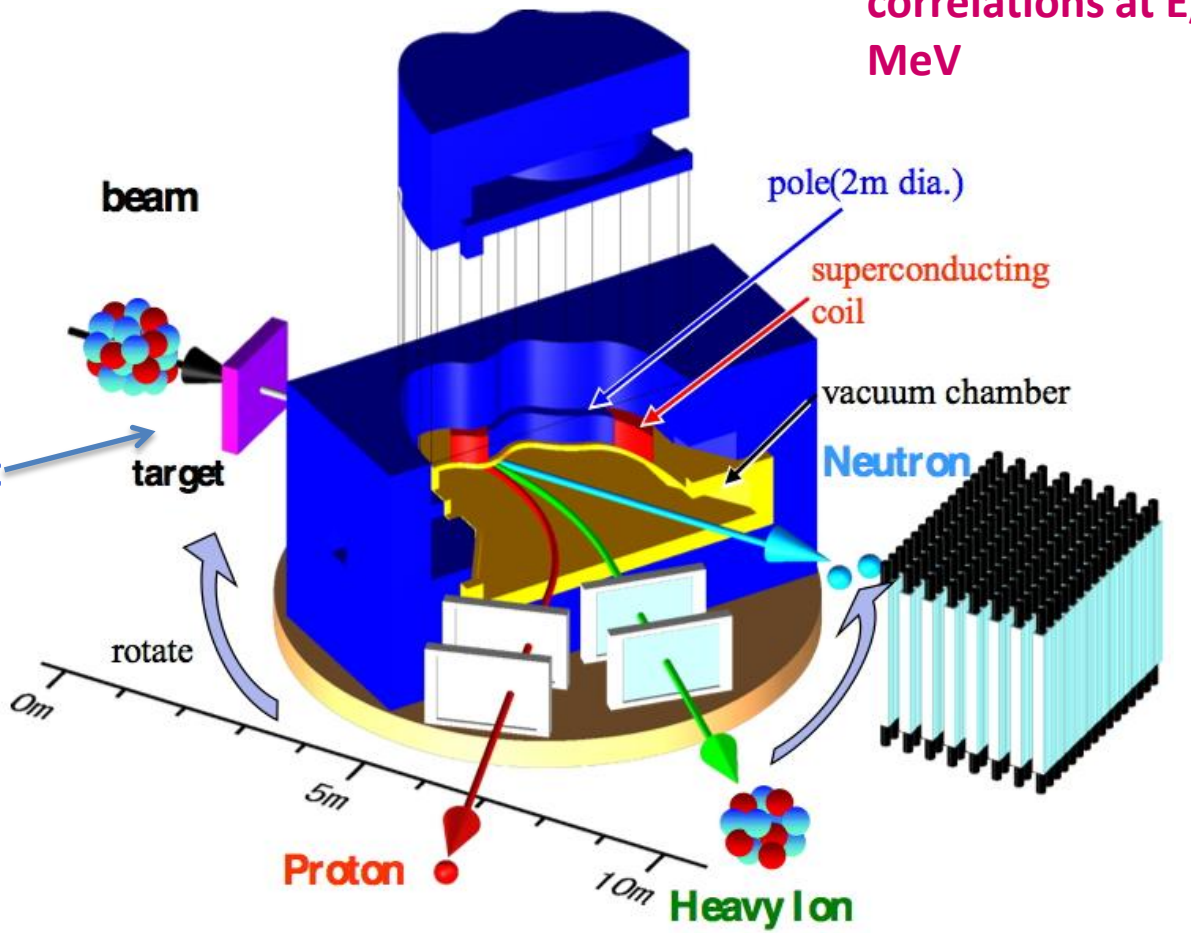
…just a schematic example:



…under study

Possible perspectives at Riken

n-p, n-n and p-p correlations at E/A>300 MeV



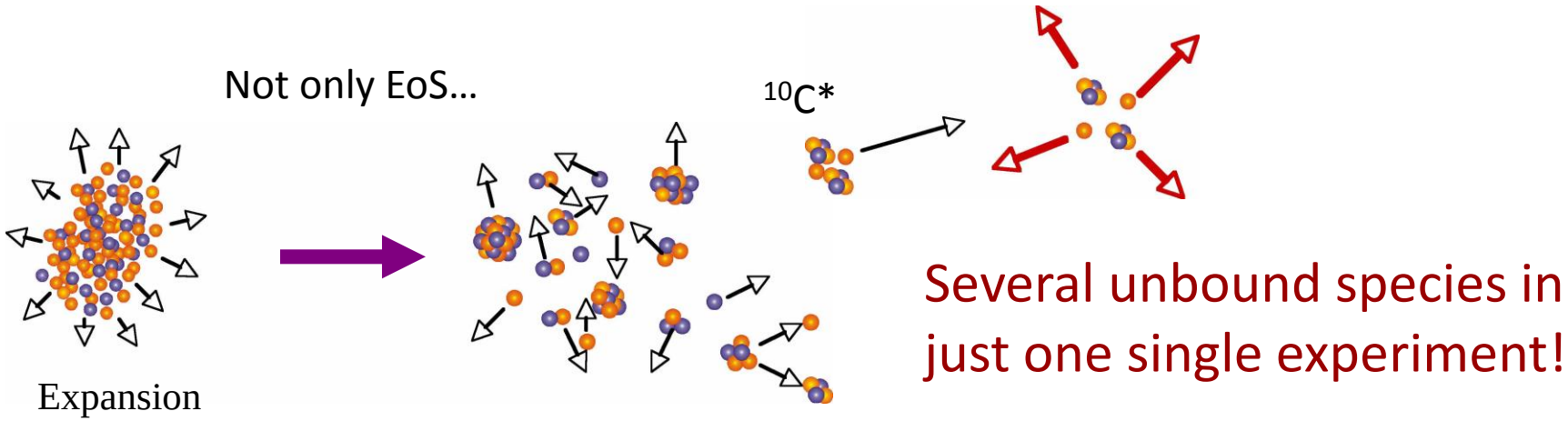
Detector for event characterization

Nebula

Outside user charged particle detectors

Informal discussions
G.V. and T. Nakamura

Non-femtoscopic correlations: particle decay spectroscopy



HIC and correlations as a spectroscopic tool

- Cluster states in stable and exotic nuclei
- BEC, Hoyle (A. Raduta et al., Phys. Lett. B705, 65, 2011)
- Branching ratios for exotic decays (sequential and multi-body breakup) →F. Grenier et al., Nucl. Phys. A811 (2008) 233

Conclusions

- Probes of symmetry energy at high density:
  - GSI energies: n/p flow Chimera-LAND@GSI
  - π^+/π- and K^+/K^0 emission ratios: future perspectives at RIKEN (SAMURAI/TPC,…)
- Probes of symmetry energy at low density:
  - Intermediate energies: Isospin diffusion and drift;
    - → range of symmetry energies (γ~0.6-0.9)
    - → still large error bars…
- Femtoscopy and neutron observables as a promising probe for future projects (both sub- and supra-saturation densities)

Acknowledgements

All the Chimera, Exochim, Farcos groups

Special acknowledgements to students and postdocs

…one more word about symmetry and asymmetry

Mt. Fuji @ Tokyo

Mt. Etna @ Catania

WPCF IX – IX Workshop on Particle Correlations and Femtoscopy

- Intensity interferometry, HBT in nuclear and particle physics, particle correlations in resonance decays
- **Synergy between High Energy and Intermediate Energy Heavy-ion collisions**

INFN-LNS Catania
October 28-November 1, 2013

ANSiP-2013 – Advanced School and Workshop on Nuclear Physics Signal Processing

- Signal processing in nuclear physics
- Training in new analog and digital
- Synergy with technologic research

Acireale (CT)
November 18-22 1, 2013