Correlations and space-time probes in Heavy-Ion collisions

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Chimera & Farcos groups, INFN-CT, INFN-LNS, Un. Of Catania

OUTLINE:

- The Asy-EoS and the role of space-time probes
- Experimental probes with Chimera and Correlation measurements
- Conclusions and perspectives

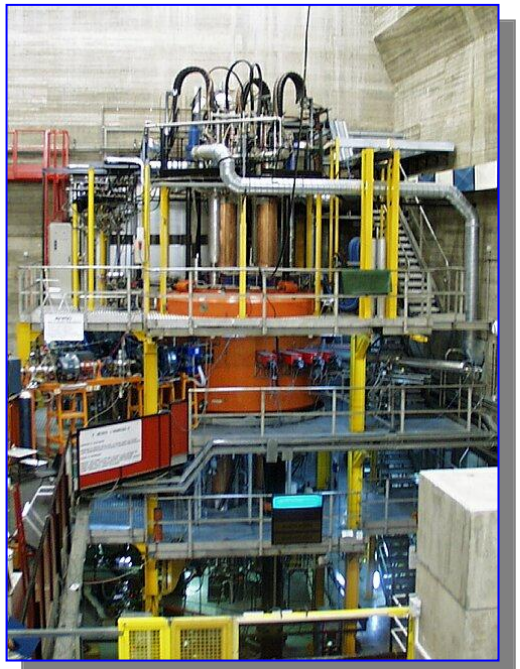
Zimanyi School 2012
Budapest 3-7 Dec, 2012

Istituto Nazionale di Fisica Nucleare, Catania and LNS

Catania

LNS

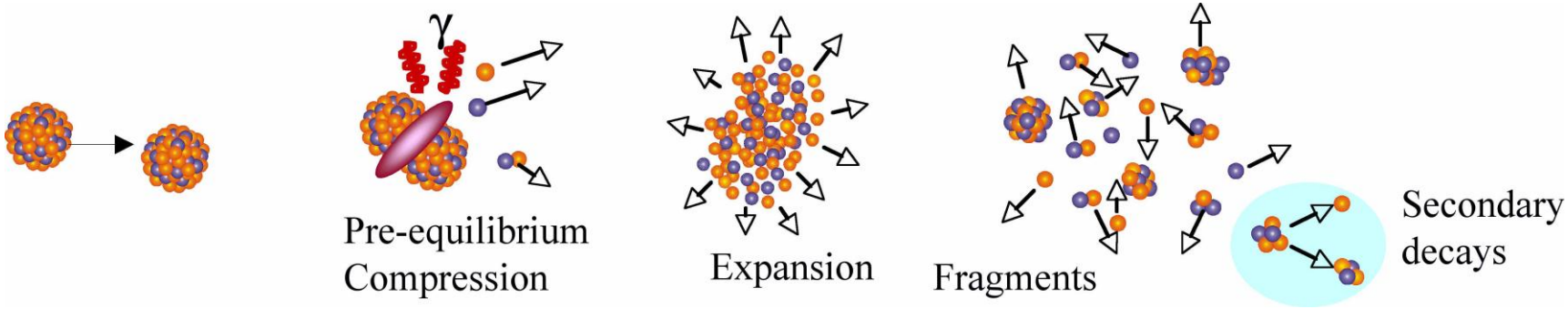
Tandem (15 MV) **EA ≤ 10 MeV**



K800

Superconducting Cyclotron

Intermediate energies: E/A=20-100 MeV
Medium Energies: E/A=100-1500 MeV



Dynamics/Thermodynamics

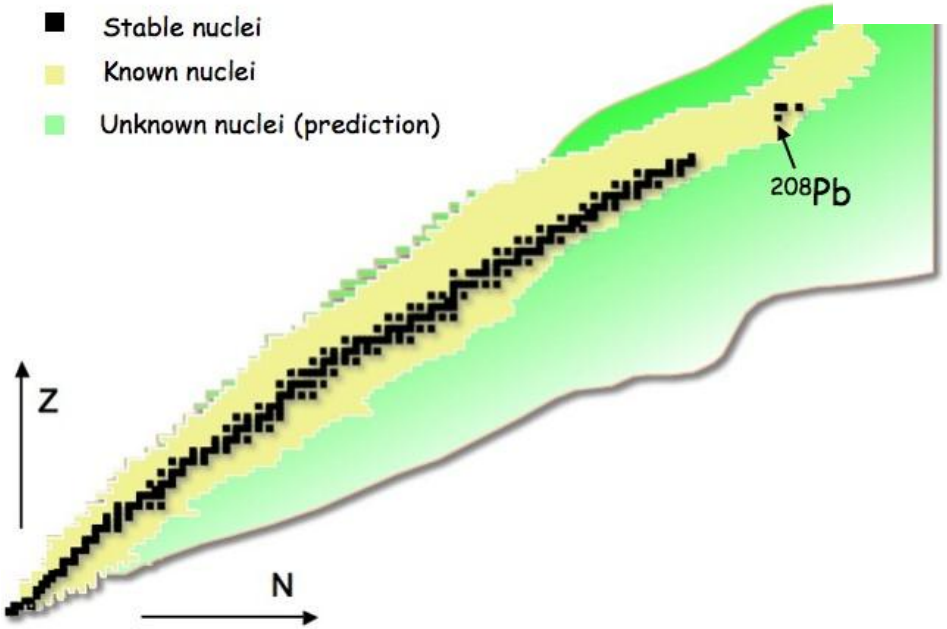
EoS, **Asy-EoS**

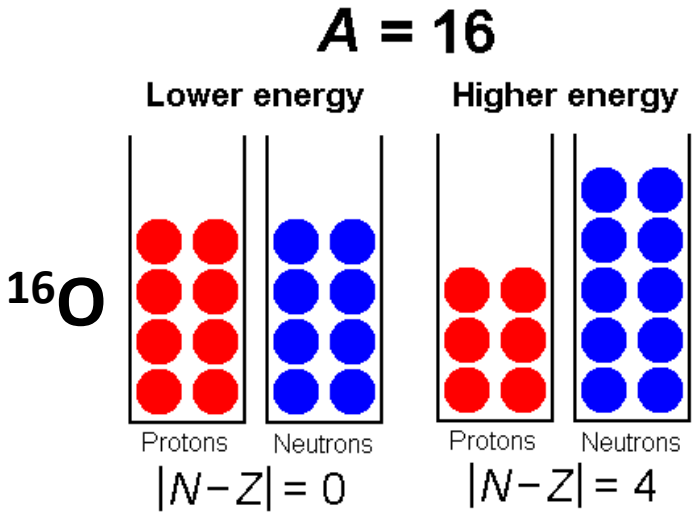
Space-time probes required (Two-particle correlations, Femtoscopy, emission chronology, time-scales, etc.)

Symmetry energy in finite nuclei

Bethe-Weiszacker

$$E(A,Z) = -a_v A + a_s A^{2/3} + a_C \frac{Z(Z-1)}{A^{1/3}} + a_{sym} \frac{(N-Z)^2}{A} + \ldots$$



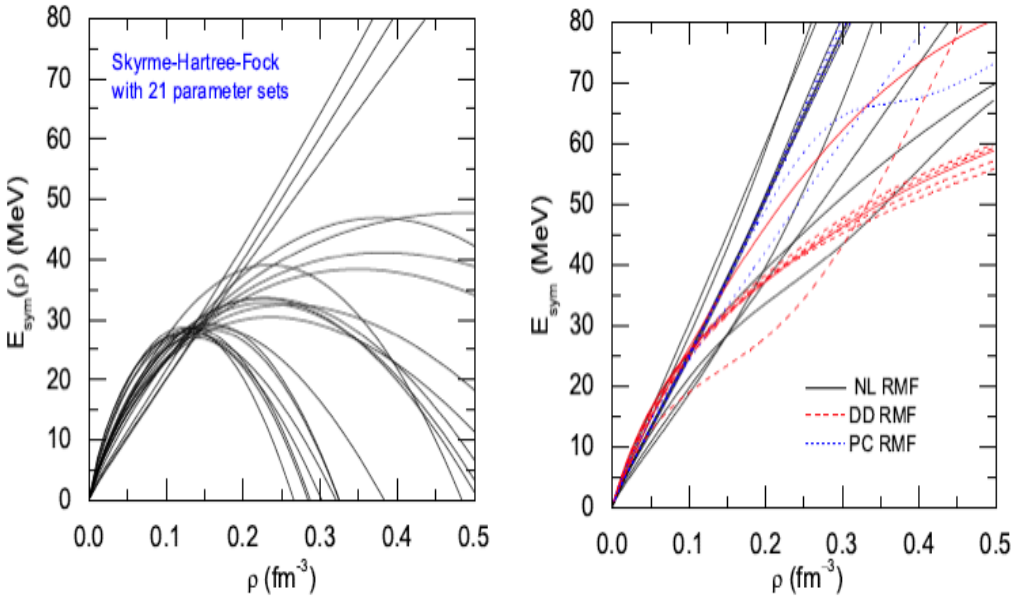


The EoS of asymmetric nuclear matter

Infinite nuclear matter: how does E depend on density?

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

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



???

Many approaches… large uncertainties….

Microscopic many-body, phenomenological, variational, …

Typical parameterizations

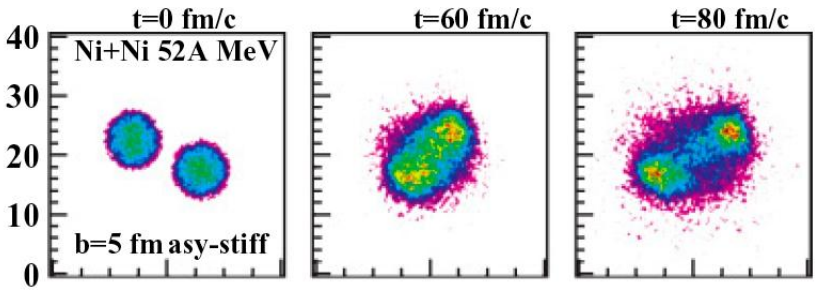
$$E_{sym}(r) \propto \left(\frac{r}{r_0}\right)^g$$

γ ~ 2 ~ Asy-Stiff

γ < 0.5 ~ Asy-Soft

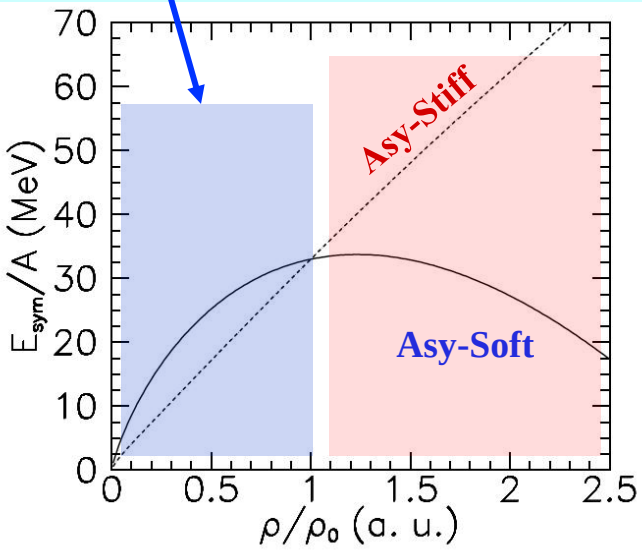
Producing density gradients in the lab

Intermediate energies: E/A=20-100 MeV

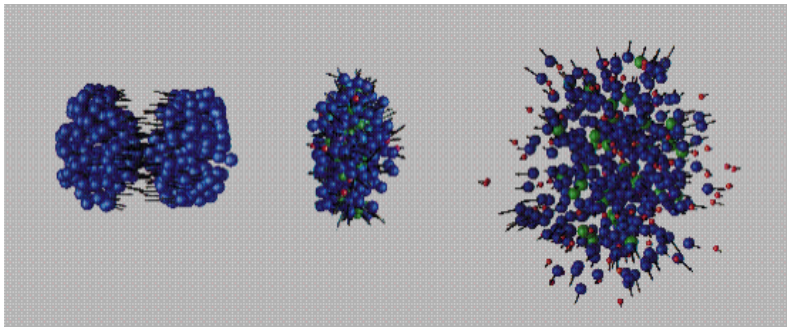


SMF - Baran, Colonna, Di Toro, Greco

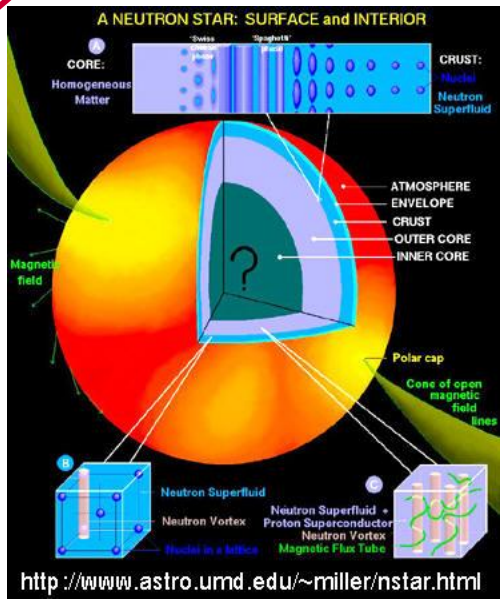
Ganil, Eurisol, Frib, Lns, Nscl, Spiral2, Tamu, …



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!!!

Isolating symmetry energy effects

- Symmetry energy effects are small!

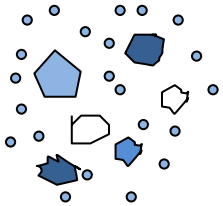
$$E(r,\delta) \approx E(r,\delta=0) + E_{sym}(r)\times\delta^2$$

Enhance effects by increasing δ^2 factor ~ $(N-Z)^2/A^2$

  - Reactions with same Ebeam and different N/Z

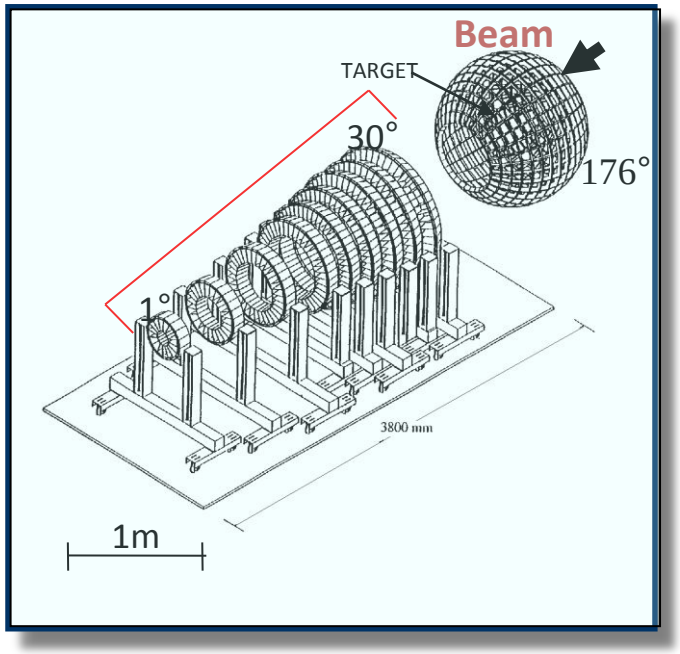
112Sn + 112Sn

112Sn + 124Sn



Chimera @ INFN-LNS

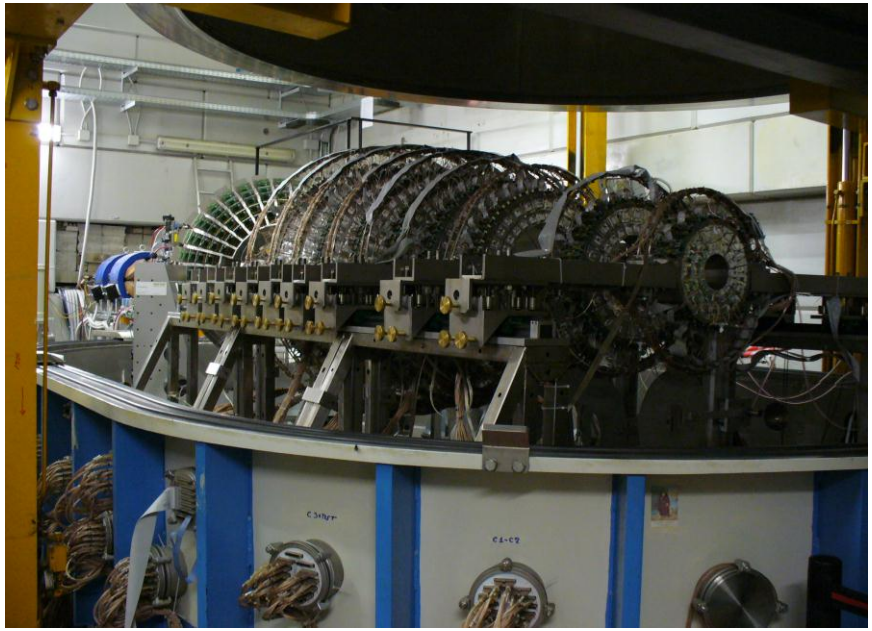
1192 Si-CsI(Tl) Telescopes



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

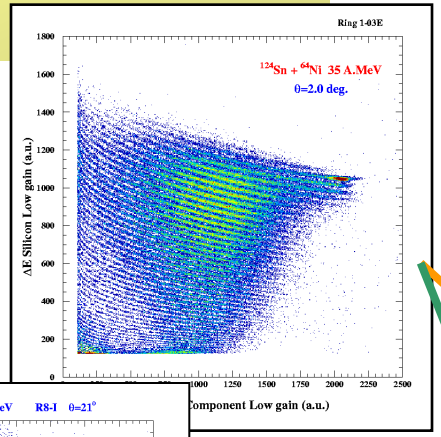


- Z identification up to beam charge (ΔE-E)
- Z and A identification by ΔE-E up to $Z \leq 9$
- Z and A identification in CsI up to $Z \leq 4$
- Mass identification with low energy threshold (< 0.3 MeV/u) by ToF
- Z identification for particles stopping in Si (pulse shape)

Particle identification in Chimera

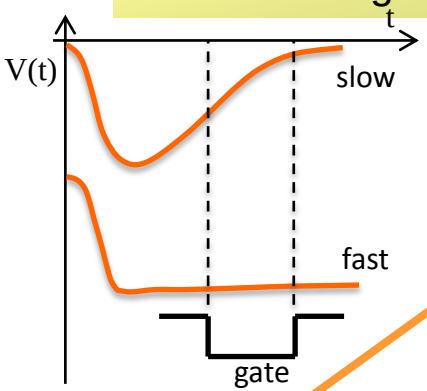
ΔE(Si)-E(CsI)

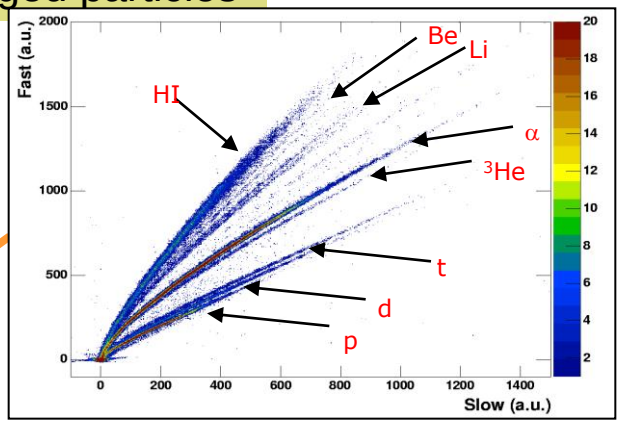
Charge Z for particles punching throught the Si detector

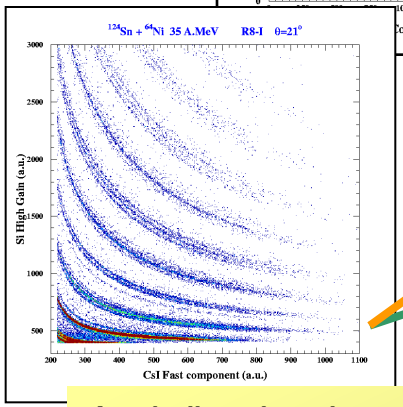


PSD in CsI(Tl)

Z and A for light charged particles







Si

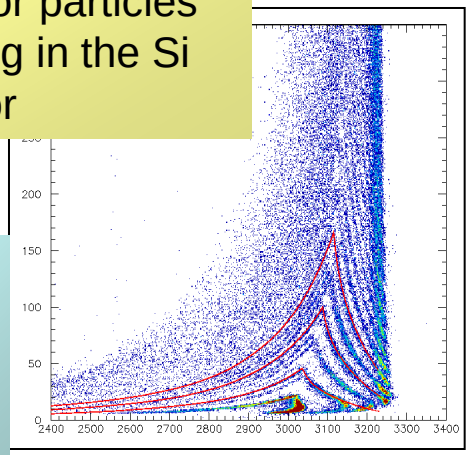
~300 μm

CsI(Tl)

3-12 cm

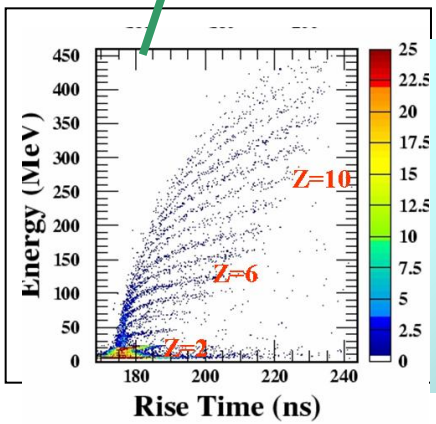
ΔE(Si)-ToF

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

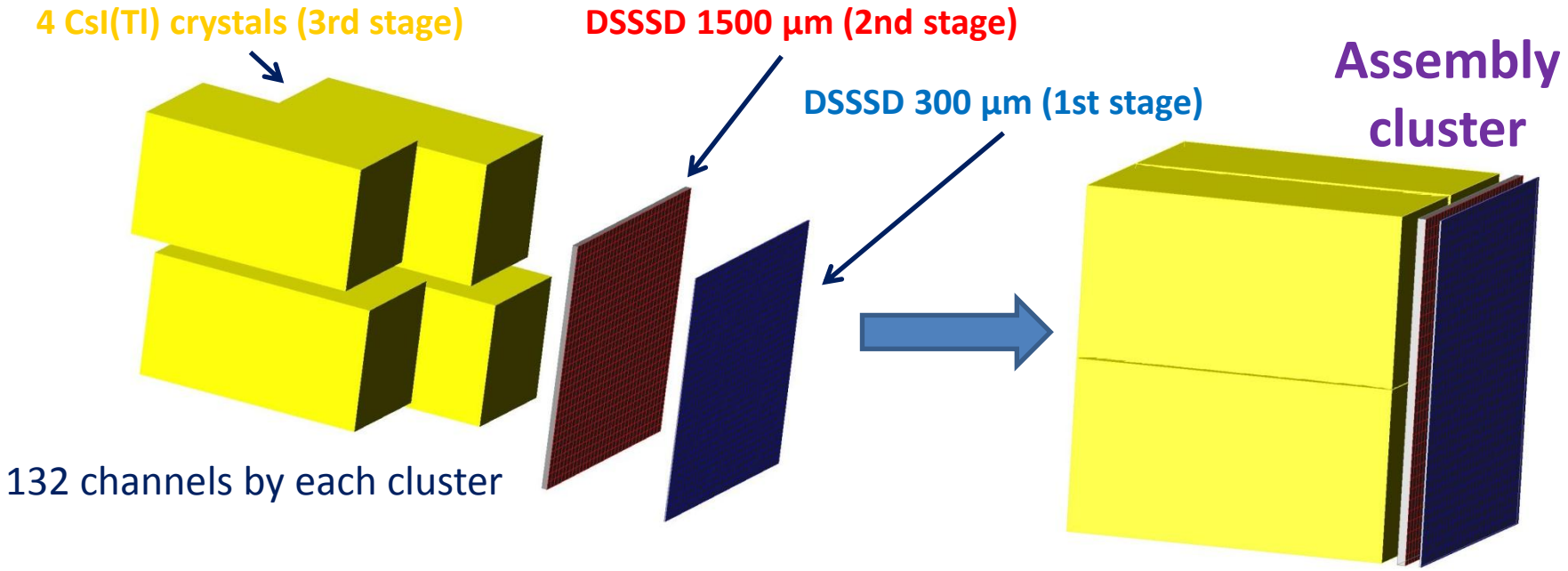


E(Si)-Rise time

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



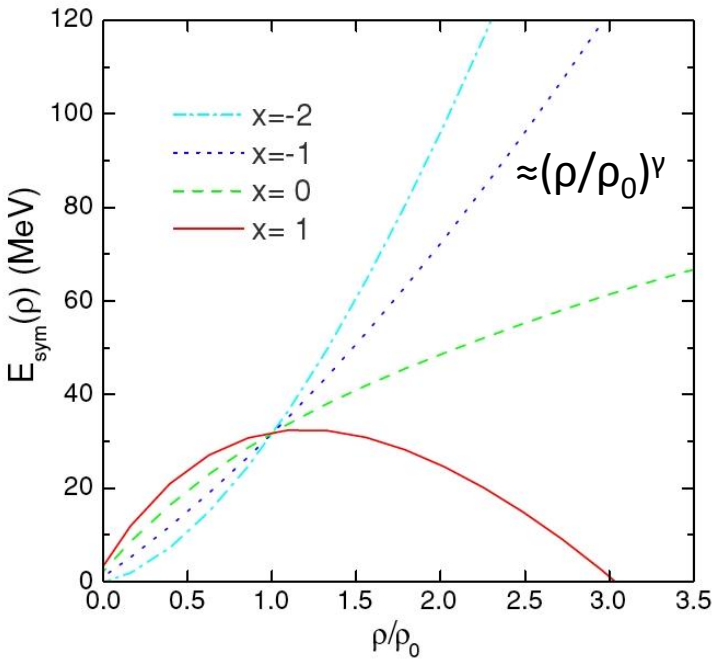
Talk by Emanuele Pagano

Probes of the symmetry energy

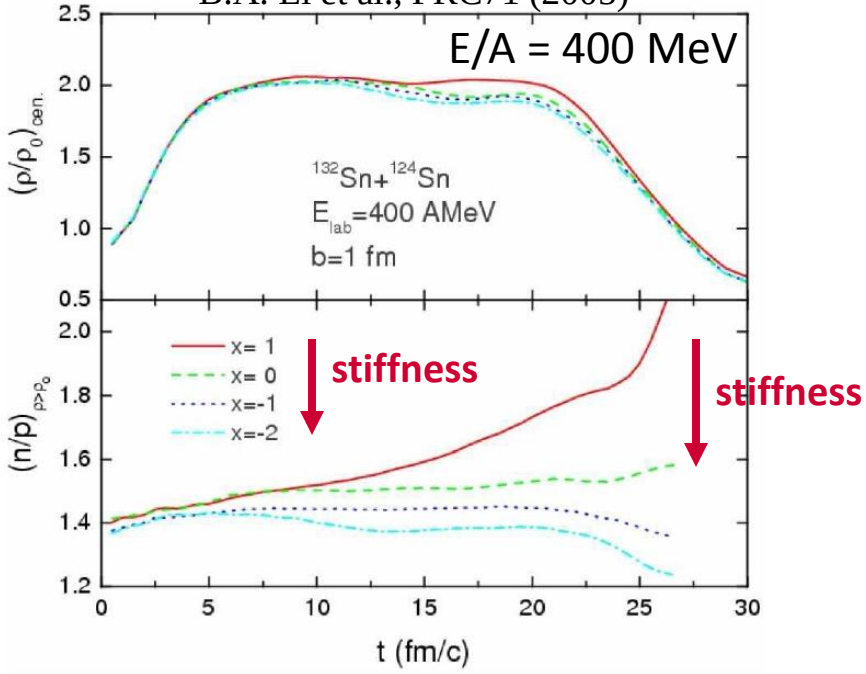
- Probes at Intermediate energies: sub-saturation density ($\rho<\rho_0$)
  - Isospin diffusion and drift
  - Neutron-proton pre-equilibrium emission spectra
  - nn, np, pp correlation functions

- 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

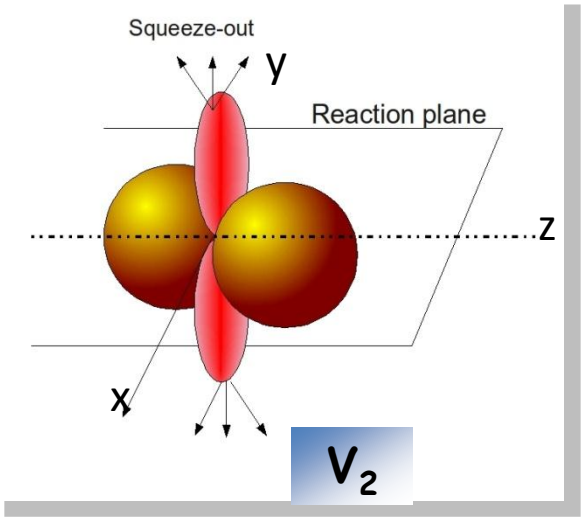
Elliptic flow in HIC at medium energies

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

Y=rapidity, p_t=transverse momentum

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

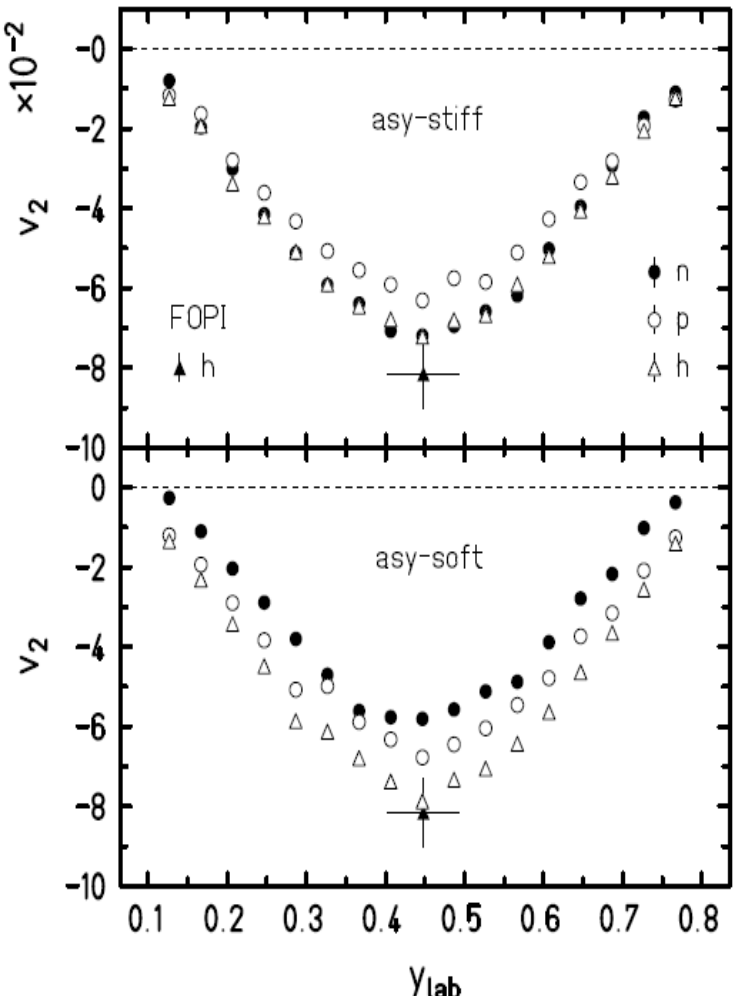
Elliptic flow: competition between in plane (V_2>0) and out-of-plane ejection (V_2<0)



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

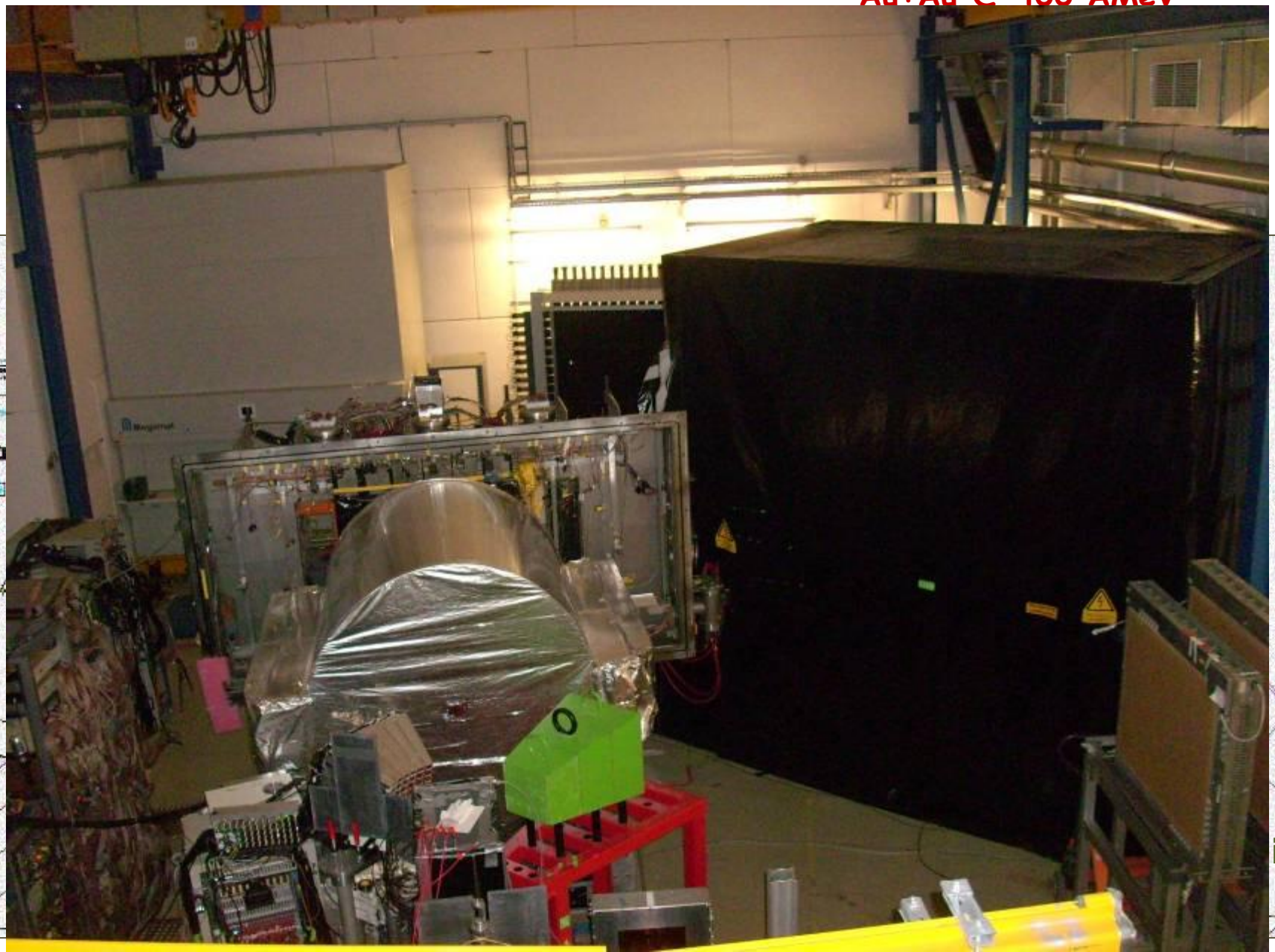
UrQMD vs. FOPI data:
Au+Au @ 400 A MeV

5.5<b<7.5 fm



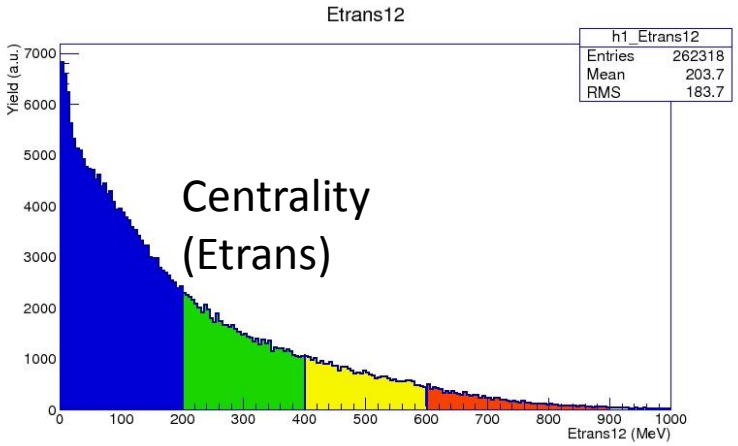
ASY-EOS S394 experiment @ GSI Darmstadt (Germany)

Au+Au @ 400 AMeV



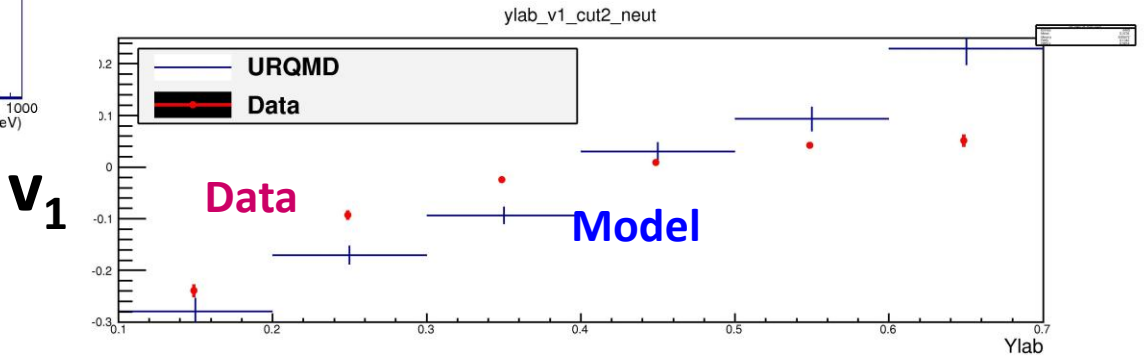
itted)

Preliminary results on neutron flow



Centrality (Etrans)

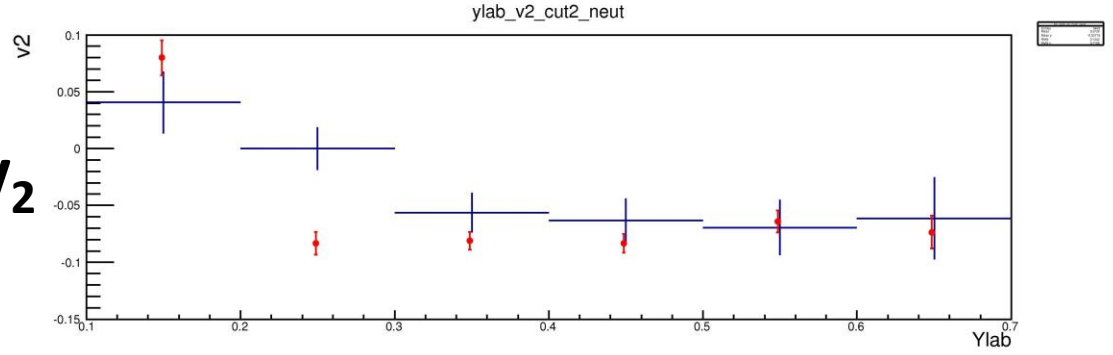
Au+Au @ 400 AMeV



v_1

Data

Model



v_2

y_{lab}

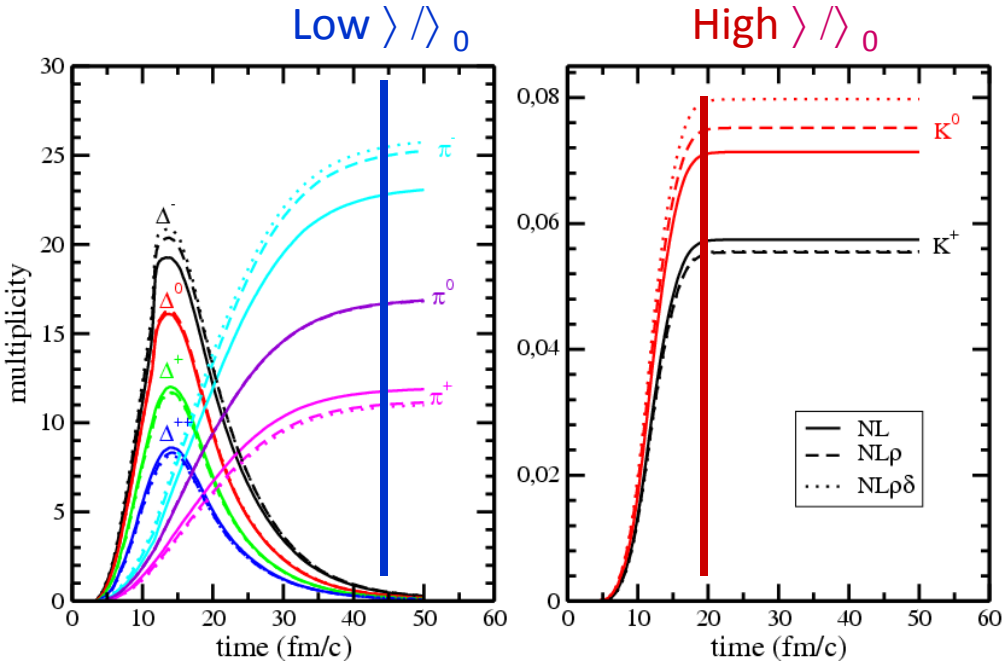
preliminary

g32new

P. Russotto, INFN-CT

Pion and Kaon freeze-out in HIC

π^+, π^-



K^+, K^0

RBUU, Ferini et al., PRL97, 202301

Warning with pions:

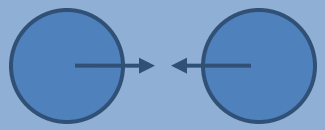
- Strongly interacting in medium
- Freeze-out at late times (low ⟩ /⟩ 0)
- Difficult to isolate π+ and π- produced in the high density stage

Kaons: more sensitive probes?

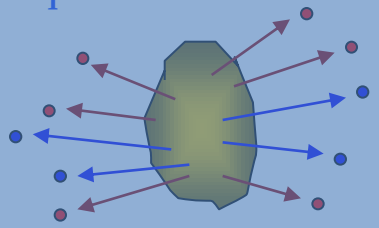
- Higher thresholds
- Weakly interacting in medium
- Freeze-out already at 20 fm/c: more reliable as high ρ probes

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

b=central

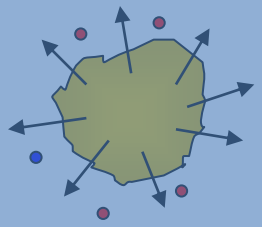


Pre-equilibrium emission

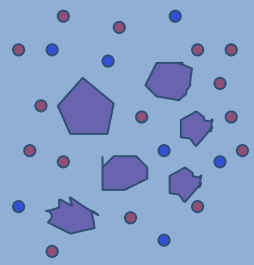


2

Expansion

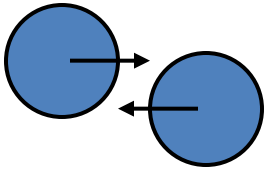


Multifragmentation

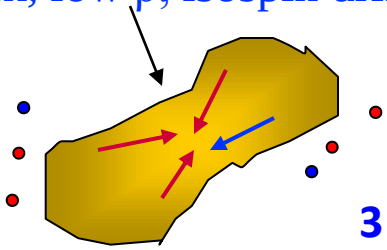


1

b=mid-peripheral

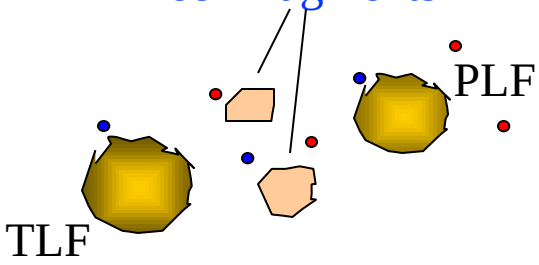


Neck, low ρ, isospin drift

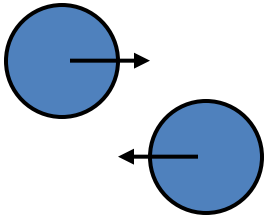


3

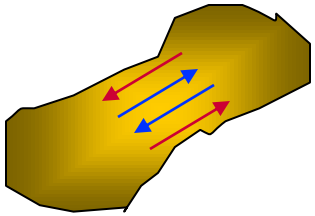
Neck fragments



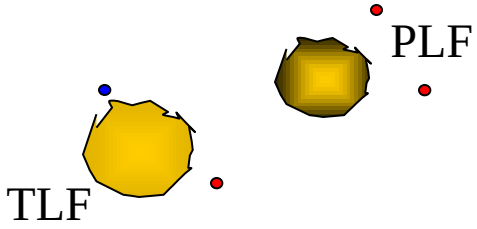
b=peripheral



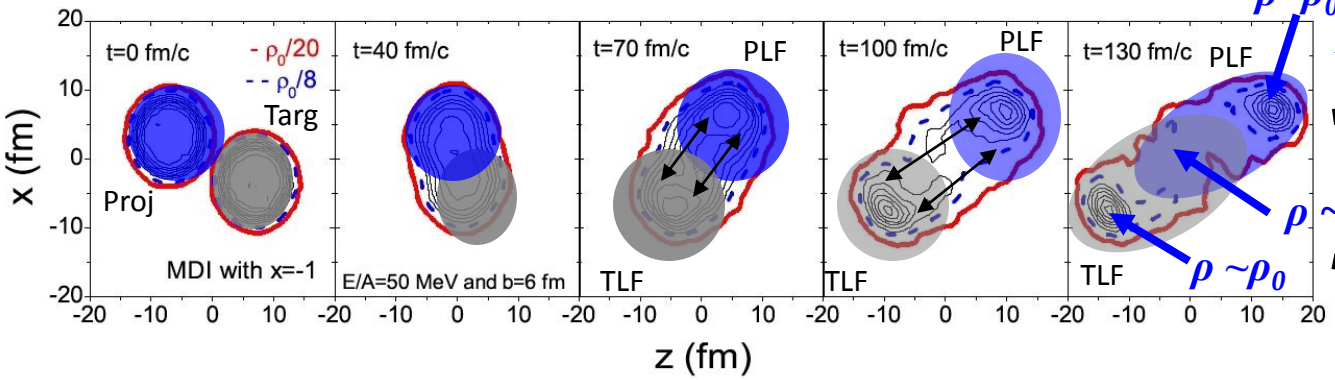
Isospin diffusion & drift

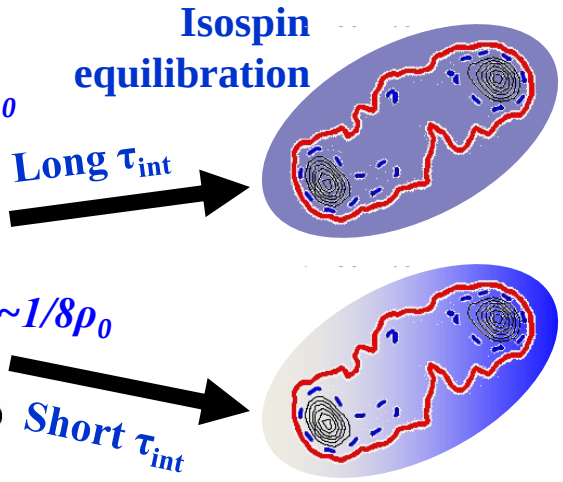


4

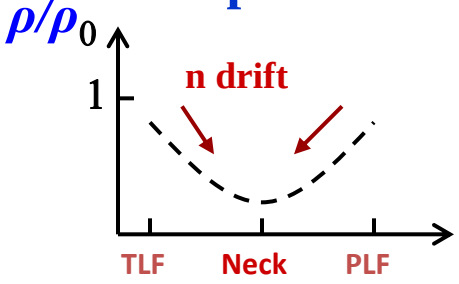


Isospin drift & diffusion

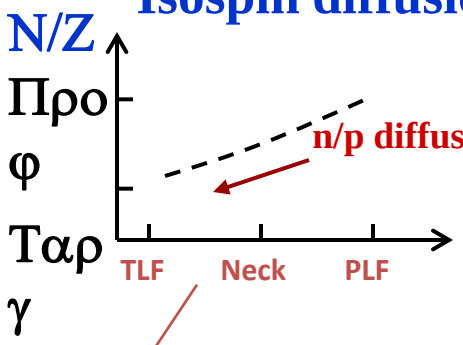




Isospin drift



Isospin diffusion

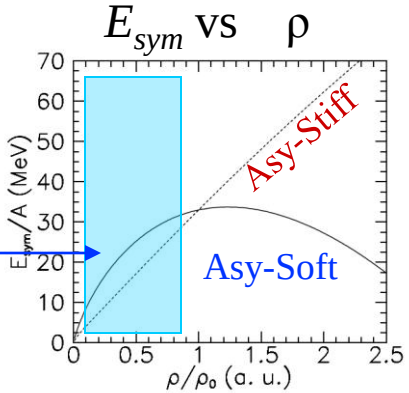


$$d = \frac{N - Z}{N + Z}$$

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

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

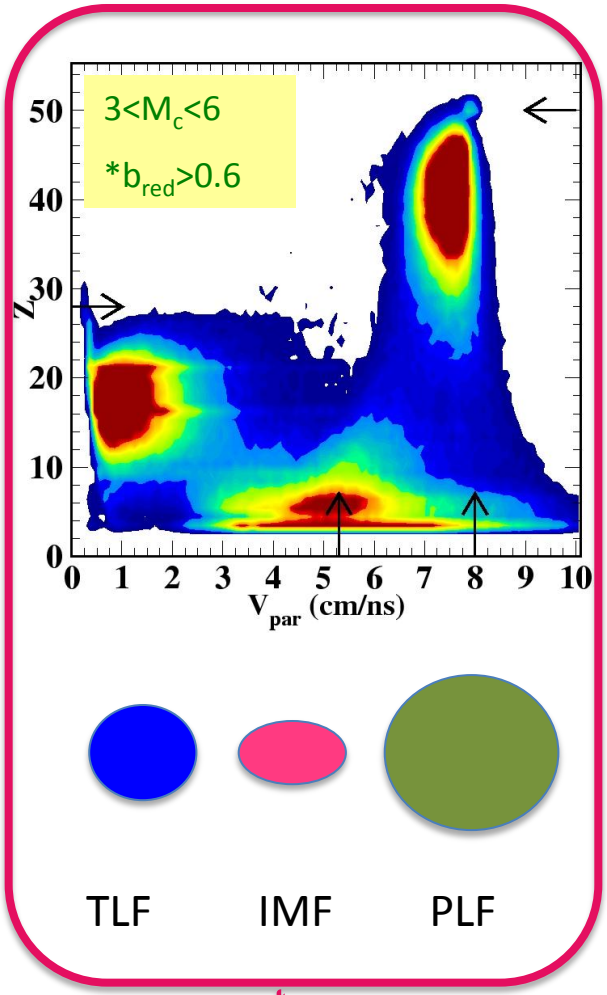
Low $\rho<\rho_0$

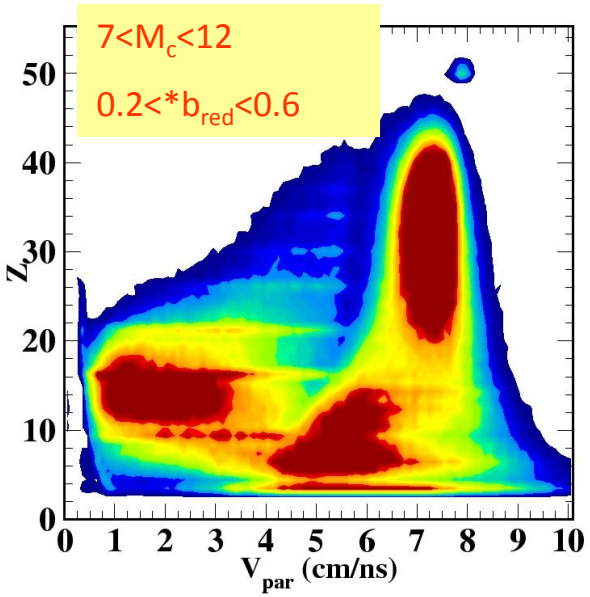


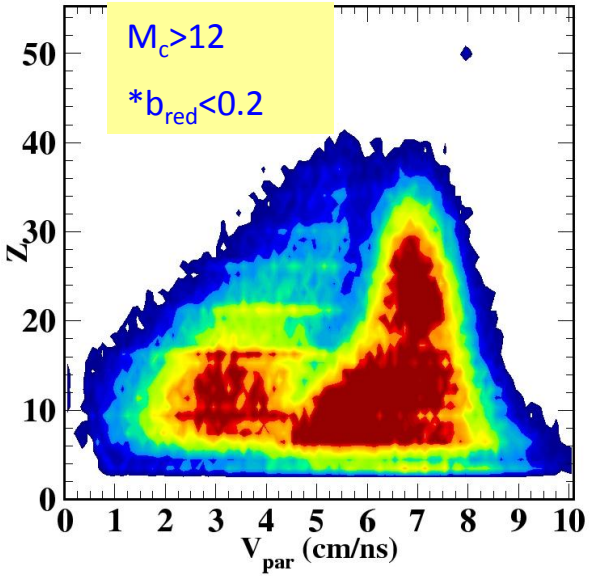
Colonna et al.; Danielewicz et al.

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

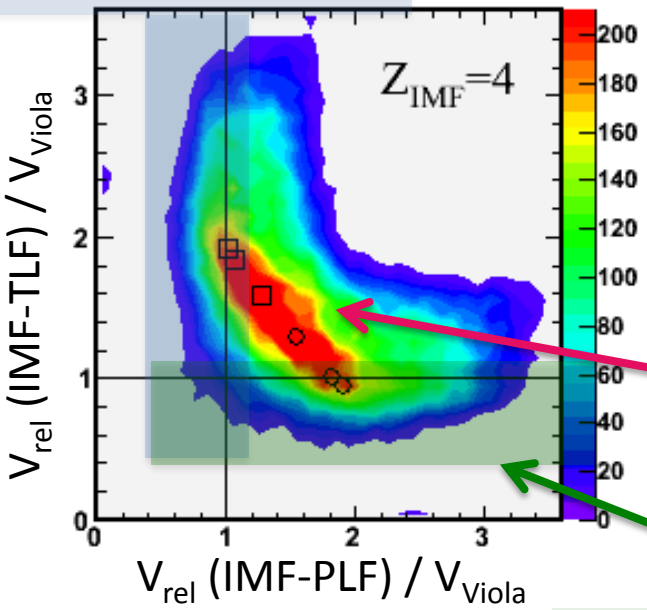
PLF

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

$V_{rel}(IMF - TLF)$

$V_{rel}(IMF - PLF)$

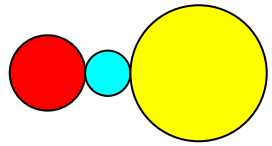
TLF

PLF

Dynamical emission from neck

seq. statistical emission from TLF

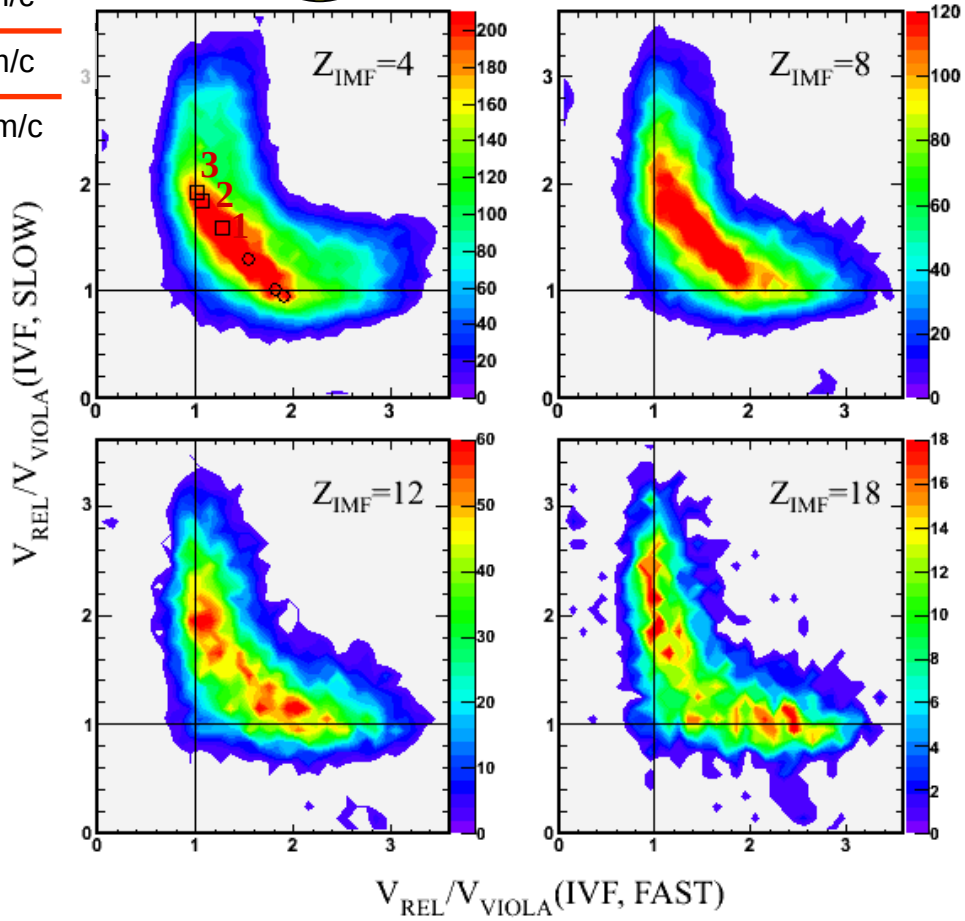
Emission time-scales and chronology



Simultaneous

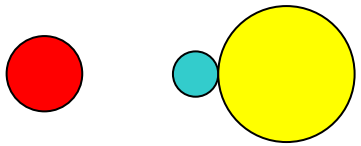
E. De Filippo, P. Russotto, A. Pagano
Phys. Rev. C (2012)

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



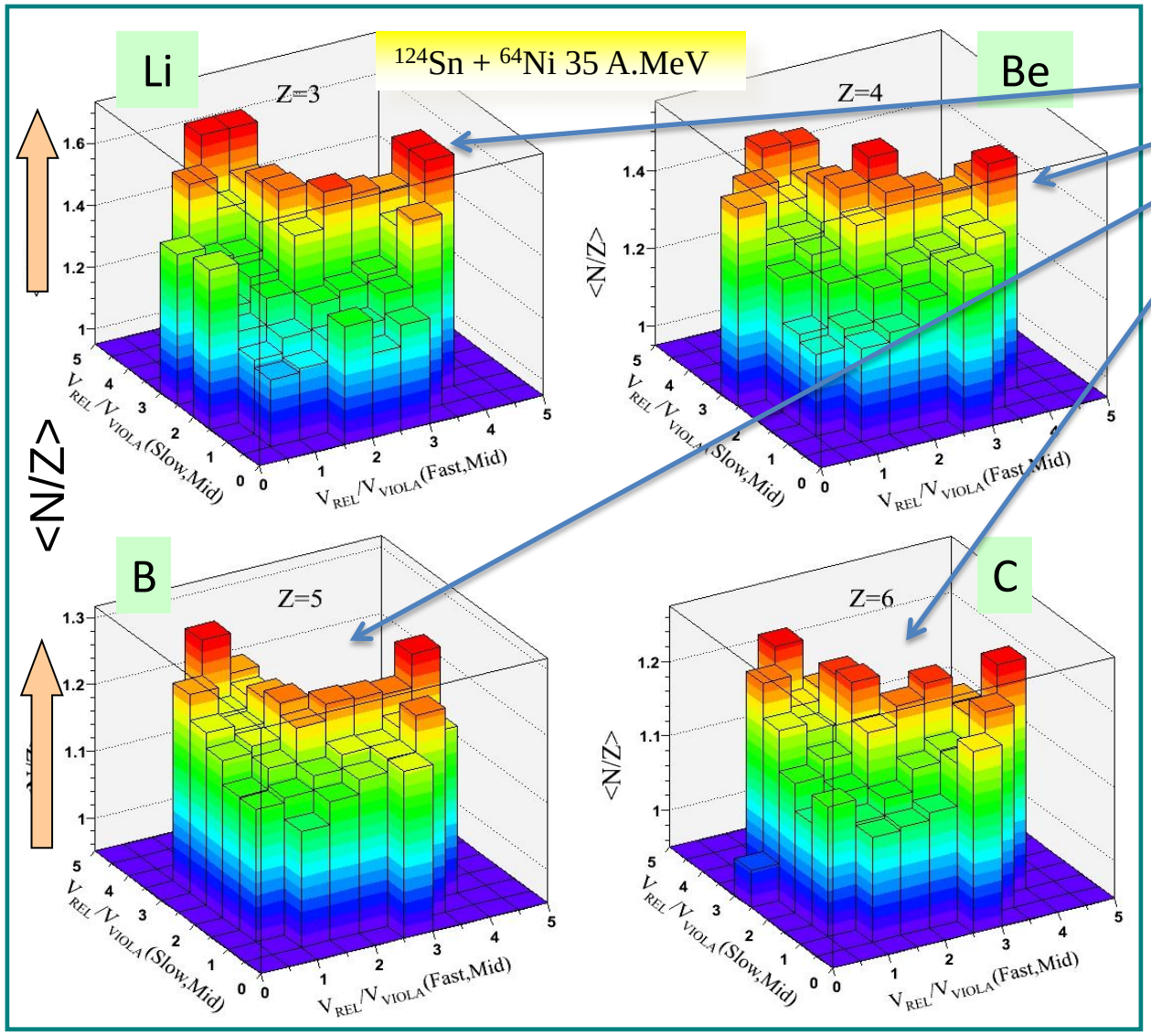
Light fragments: shorter time-scales compared to heavier

~40 fm/c vs ~120 fm/c



Sequential

Isospin chronology



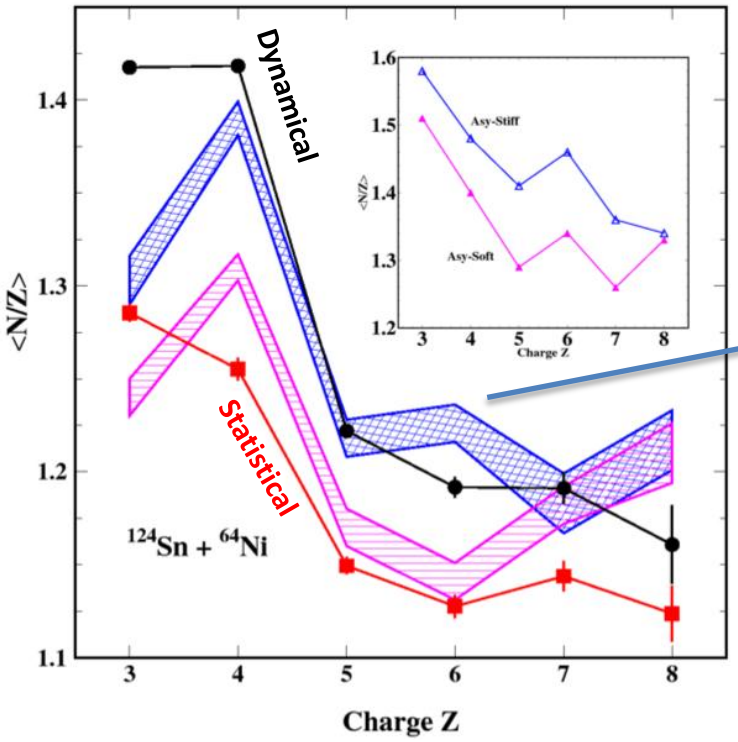
Dynamical emissions: more neutron rich

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

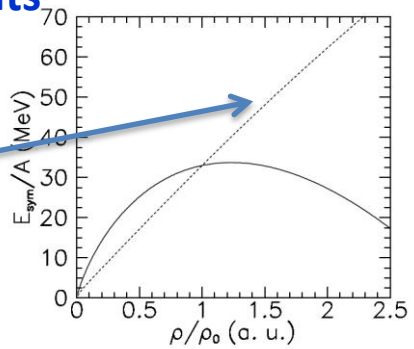
E. De Filippo, A. Pagano, P. Russotto et al. PRC (2012)

Sensitivity to symmetry energy

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



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



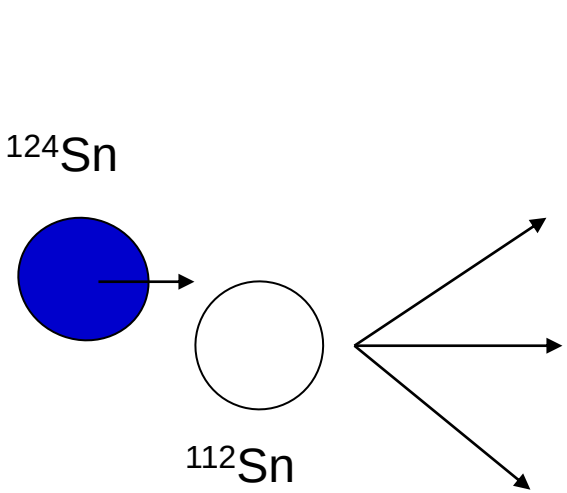
E. De Filippo, A. Pagano, P. Russotto et al., Phys. Rev. C (2012)

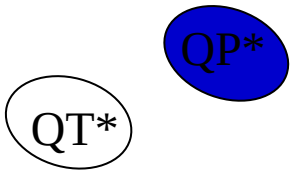
Isospin diffusion and imbalance ratios

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

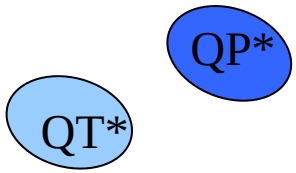
X=Y(^{7}Li)/Y(^{7}Be)
Sensitive to N/Z of emitter

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

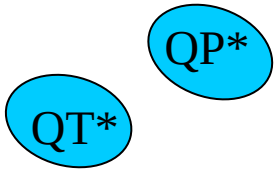




Isospin transparency — $R_i(X) = 1$



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



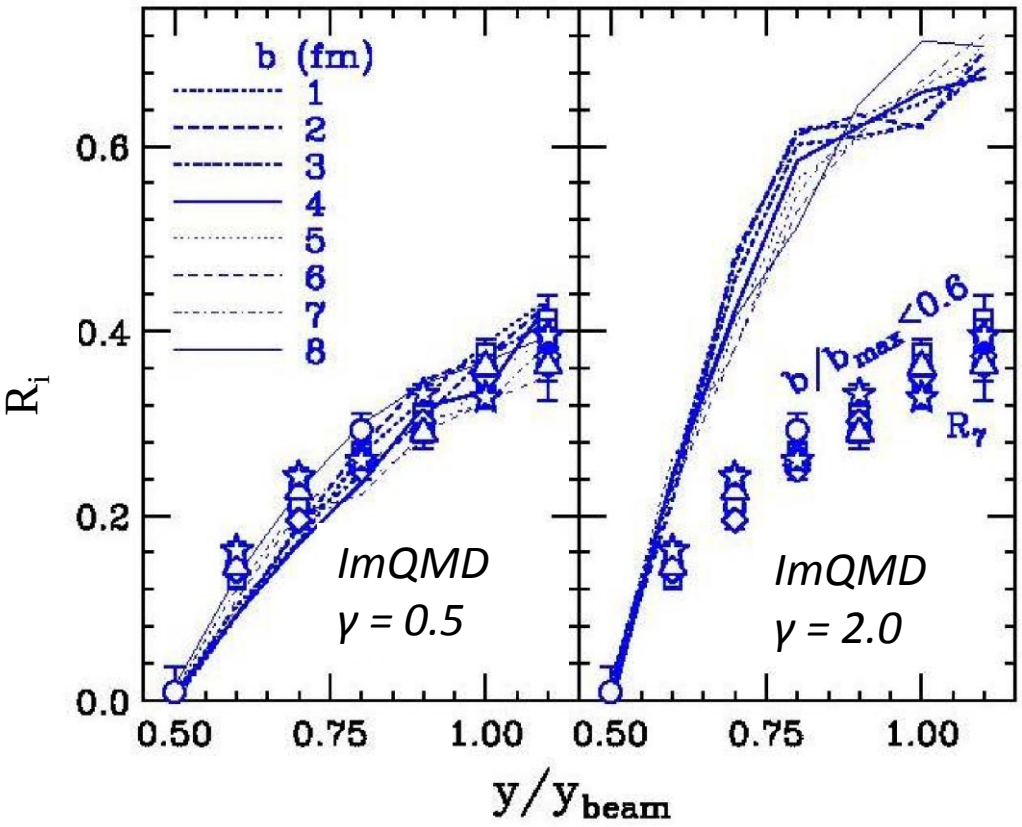
Isospin equilibration — $R_i(X) = 0$

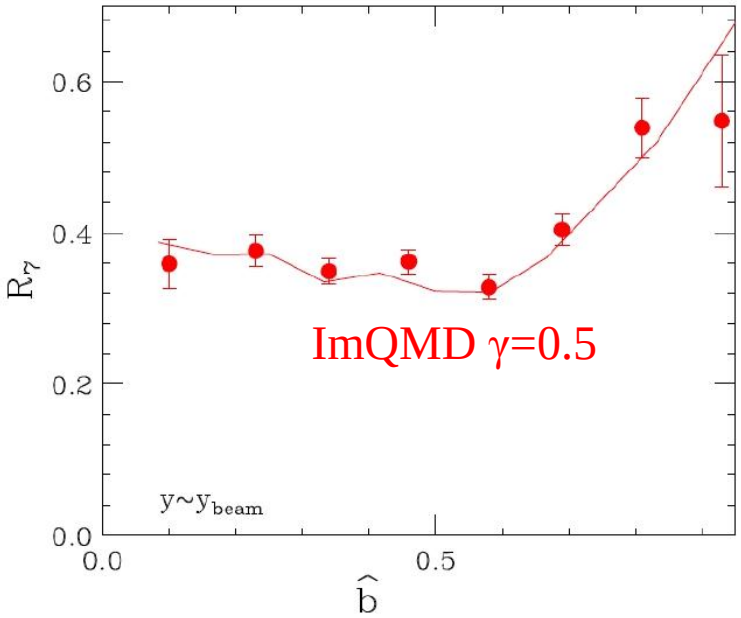
Isospin diffusion: Chimera-MSU coll.

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

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

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

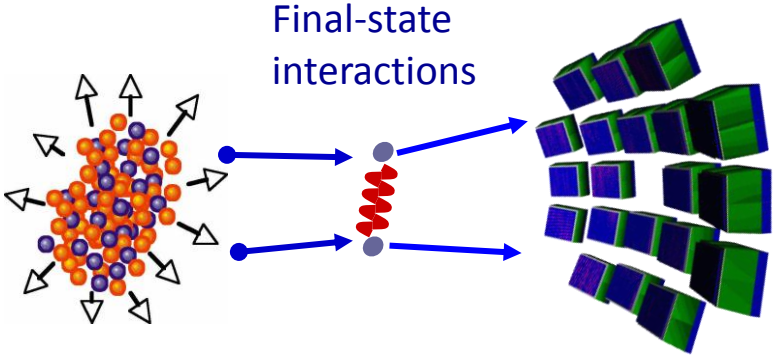


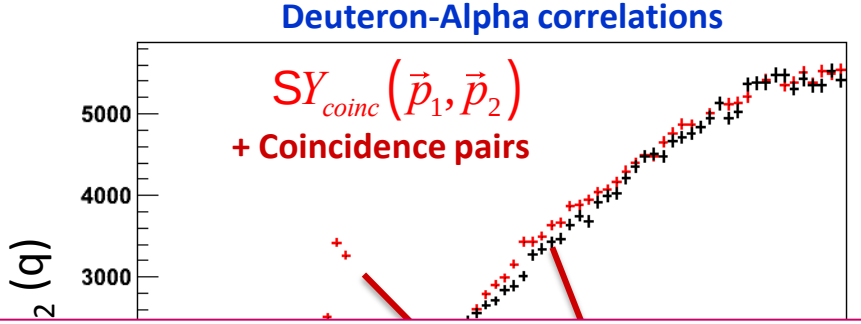


N/Z translucency persists in central collision

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

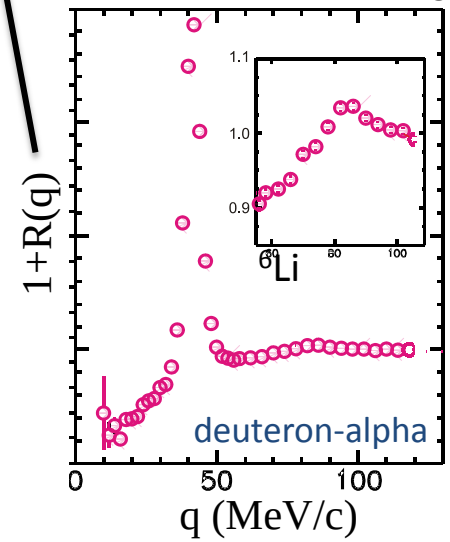
Femtoscopy

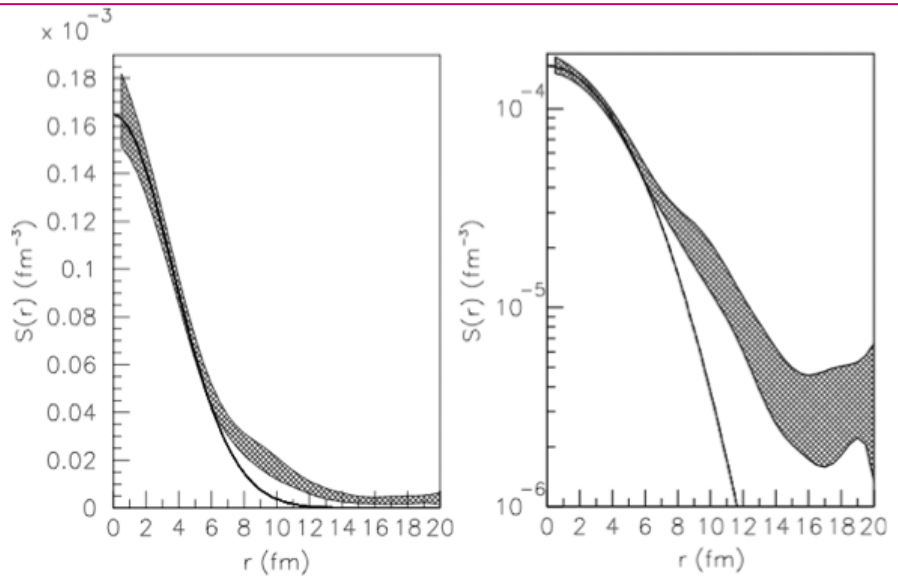




Imaging: Profile of emitting sources… space-time !images!

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





n at

High

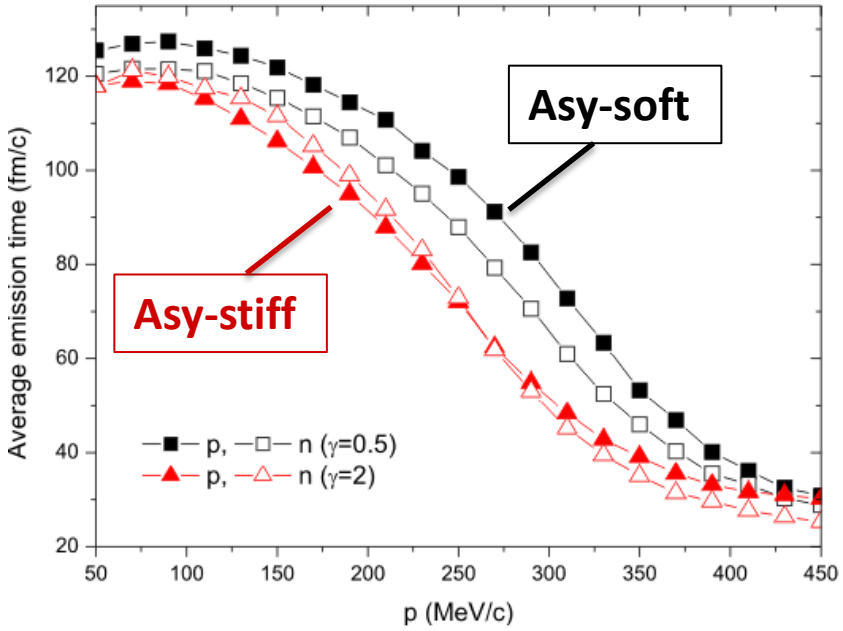
→ L

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

NN correlations and symmetry energy

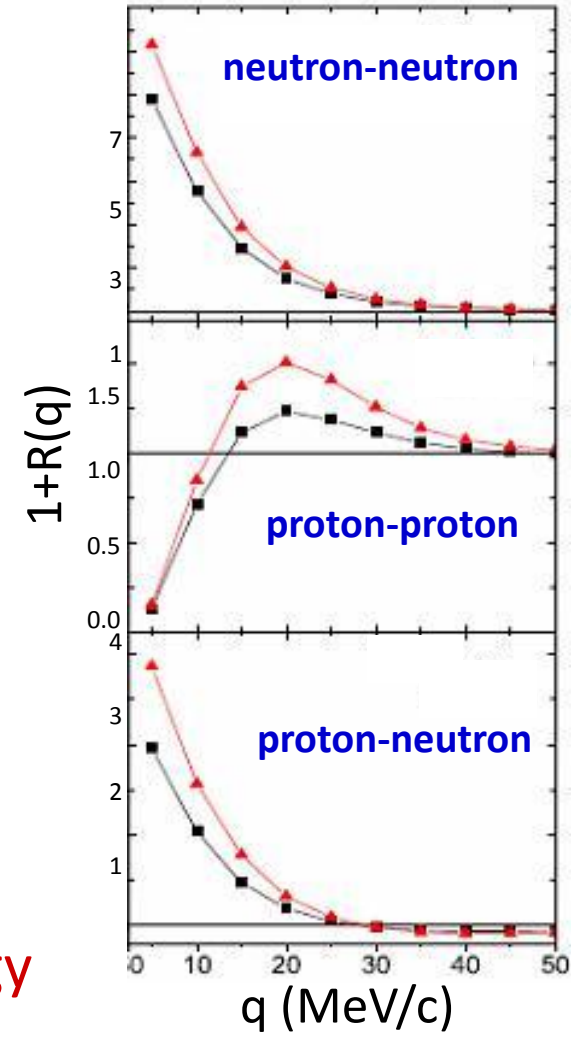
IBUU simulations

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



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

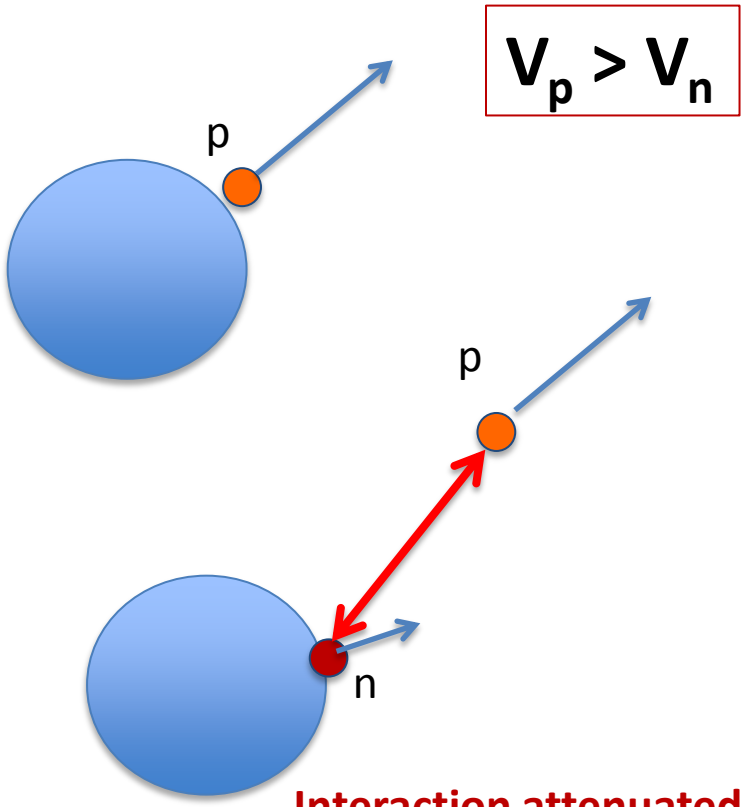
Correlation functions



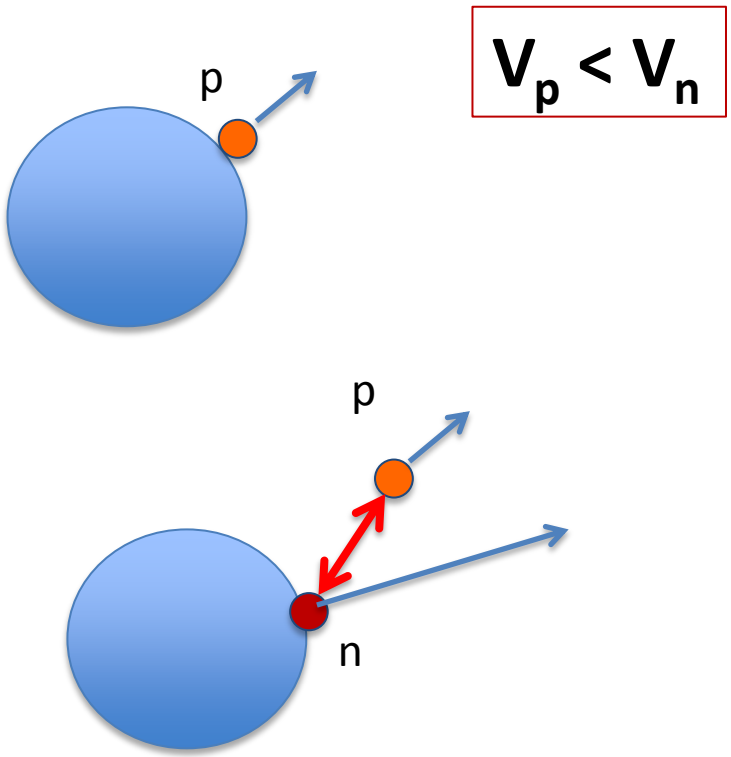
Proton/neutron emission times sensitive to density dependence of the symmetry energy

Neutron-proton emission chronology

Time delay between emissions Δt≠0 - Example: p emitted first



Interaction attenuated



Stronger interaction
"particle catch-up"

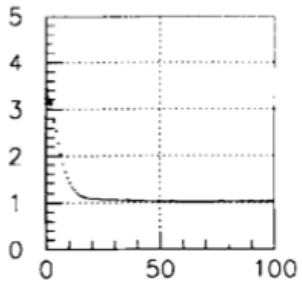
“Lednicky’s recipe”: p-n correlations

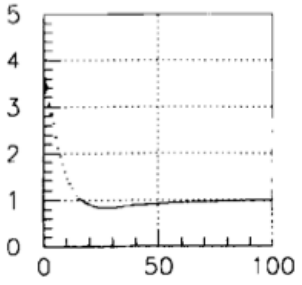
p first -100 fm/c

n first +100 fm/c

$1+R_+(q)$

Proton faster

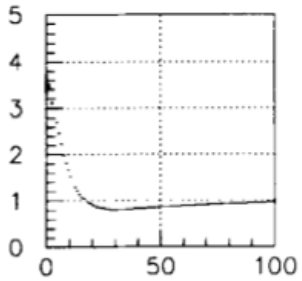


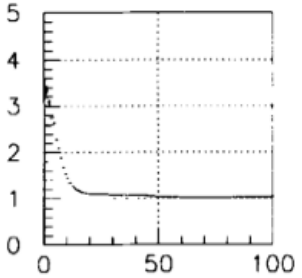


R. Lednicky et al., Phys. Lett. B373, 30 (1996)

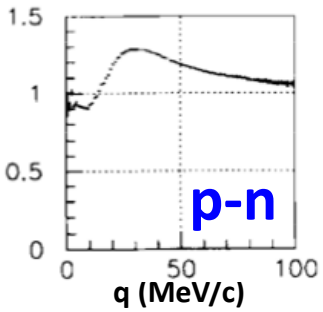
$1+R_-(q)$

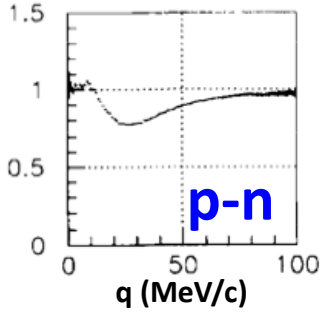
Neutron faster





Ratio +/-



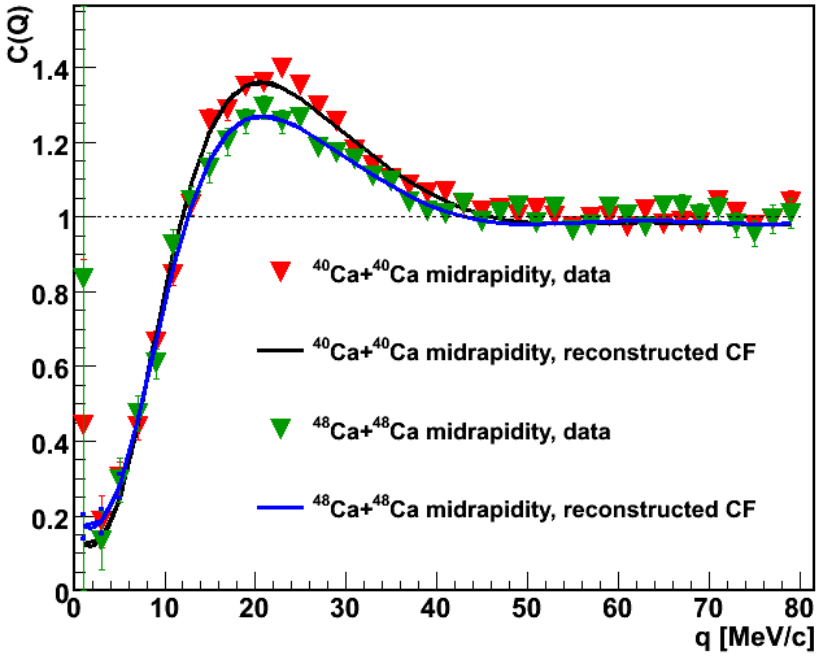


R+/R- ratios tell who is emitted first →Chronology →$E_{sym}(\rho)$

Some preliminary N/Z effects on p-p

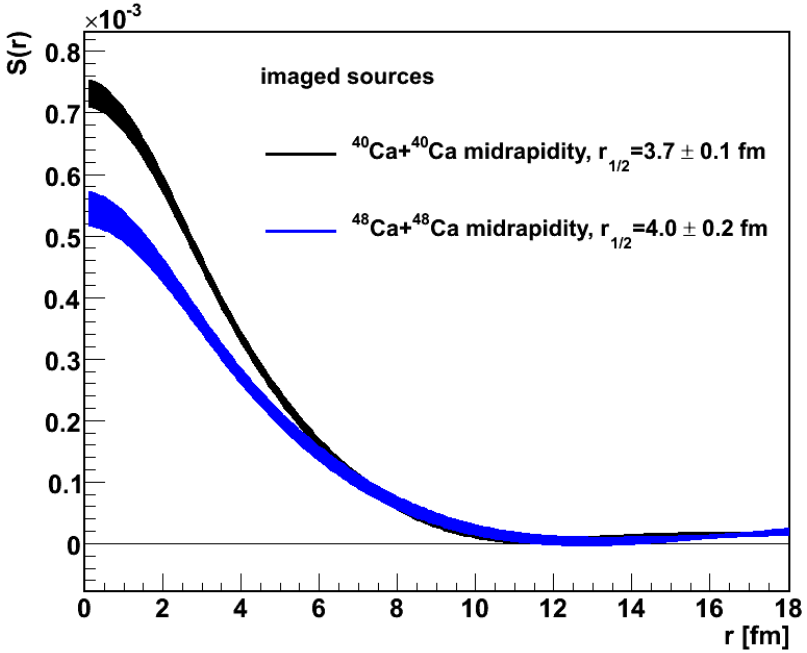
^{48}Ca+^{48}Ca vs ^{40}Ca+^{40}Ca

E/A=80 MeV - Central



Correlations

R ^{48}Ca+ ^{48}Ca > R ^{40}Ca+ ^{40}Ca



Emitting sources

Larger size for more n-rich system:

→ N/Z effect? Size effect? Asy-EoS? σ_{NN}

Z. Chajecki, et al. Phys. Rev. C (2012)

Conclusions

- Probes of symmetry energy - high density:
  - GSI energies: n/p flow Chimera-LAND@GSI
  - π^+/π- and K^+/K^0 emission ratios: future perspectives at RIKEN (SAMURAI/TPC,…)
- Space-time probes of symmetry energy - 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 → promising probes

Acknowledgements

All the Chimera, Farcos, Exochim groups

Special acknowledgements to students and postdocs

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