ISOSPIN DYNAMICS IN HEAVY ION COLLISIONS:

…from the Coulomb Barrier to the Quark-Gluon-Plasma

V.Baran, M.Colonna, M.Di Toro, G.Ferini, Th.Gaitanos, V.Giordano, V. Greco, Liu Bo, M.Zielinska-Pfabe, S. Plumari, V.Prassa, C.Rizzo, J.Rizzo, B.Sapienza and H.H.Wolter

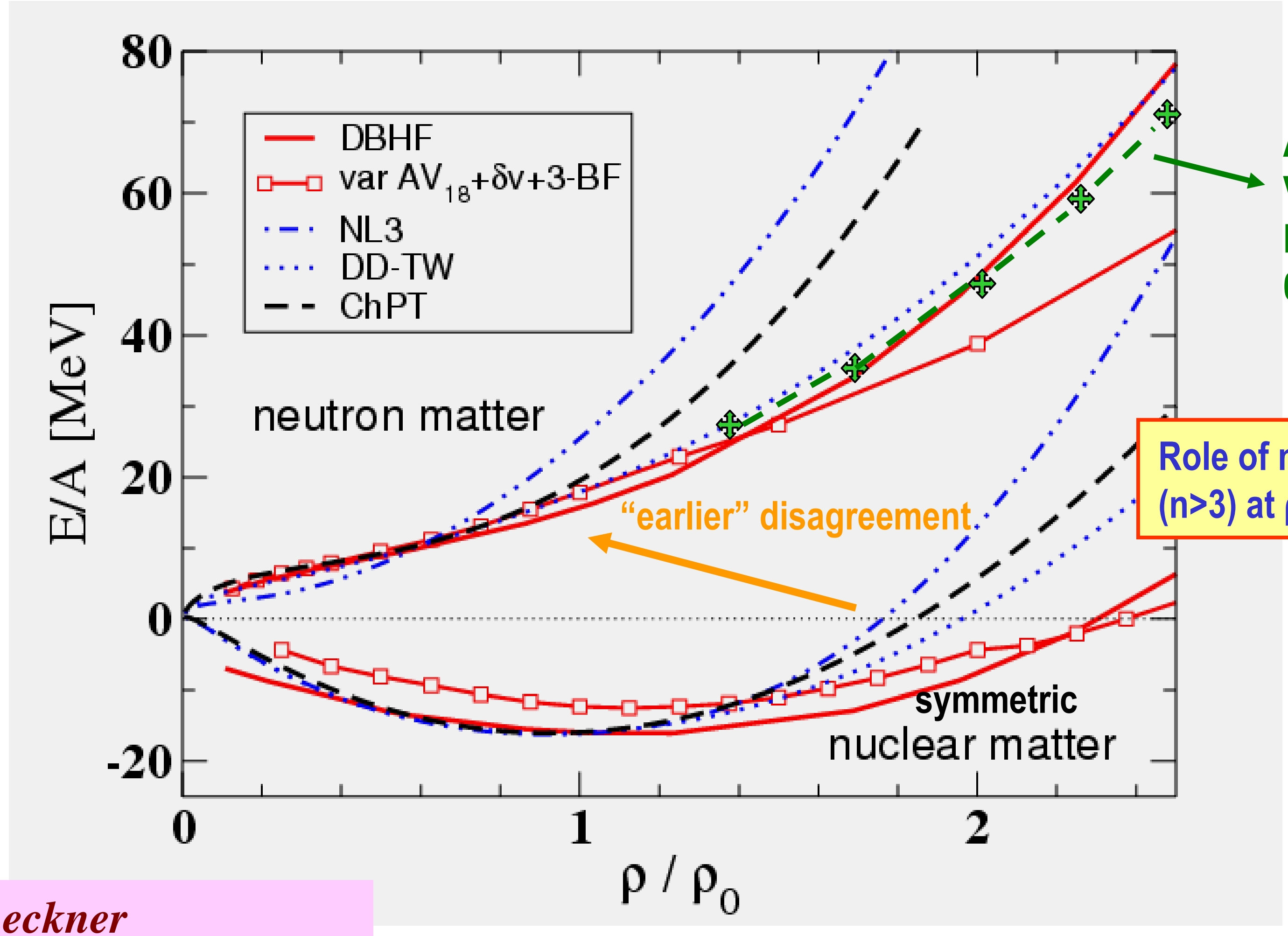
LNS-Catania, NIPNE-HH Bucharest, Smith College Mass., IHEP Beijing, Univ. of Munich, Giessen, Thessaloniki…….and with the contribution of a very lively Etna mountain!

From the Phys.Dept. Jan.2002

Etna Double-Face, Aug.07

Erice "Nuclear Physics" School, Sept.08, ditoro@lns.infn.it

EOS of Symmetric and Neutron Matter



“earlier” disagreement

AFDMC
V8’+3body
Fantoni et al
0807.5043

Role of n-body forces
(n>3) at $\rho > 2\rho_0$

Dirac-Brueckner
Variational+3-body(non-rel.)
RMF(NL3)
Density-Dependent couplings
Chiral Perturbative

Ch.Fuchs, H.H.Wolter, WCI Final Report
EPJA 30 (2006)

Iso-Tracer (1): Isospin Transport and Chemical Potentials

currents

$$j_n = D_n^{\rho}\nabla\rho + D_n^{I}\nabla I$$

$$j_p = D_p^{\rho}\nabla\rho + D_p^{I}\nabla I$$

drift

$$D_q^{\rho} \propto \left(\frac{\partial\mu_q}{\partial\rho}\right)_{I,T}$$

diffusion

$$D_q^{I} \propto \left(\frac{\partial\mu_q}{\partial I}\right)_{\rho,T} \rightarrow (q = n, p)$$

Isospin chemical potential

$$\boxed{\mu_n - \mu_p = 4E_{sym}(\rho)\ I}$$

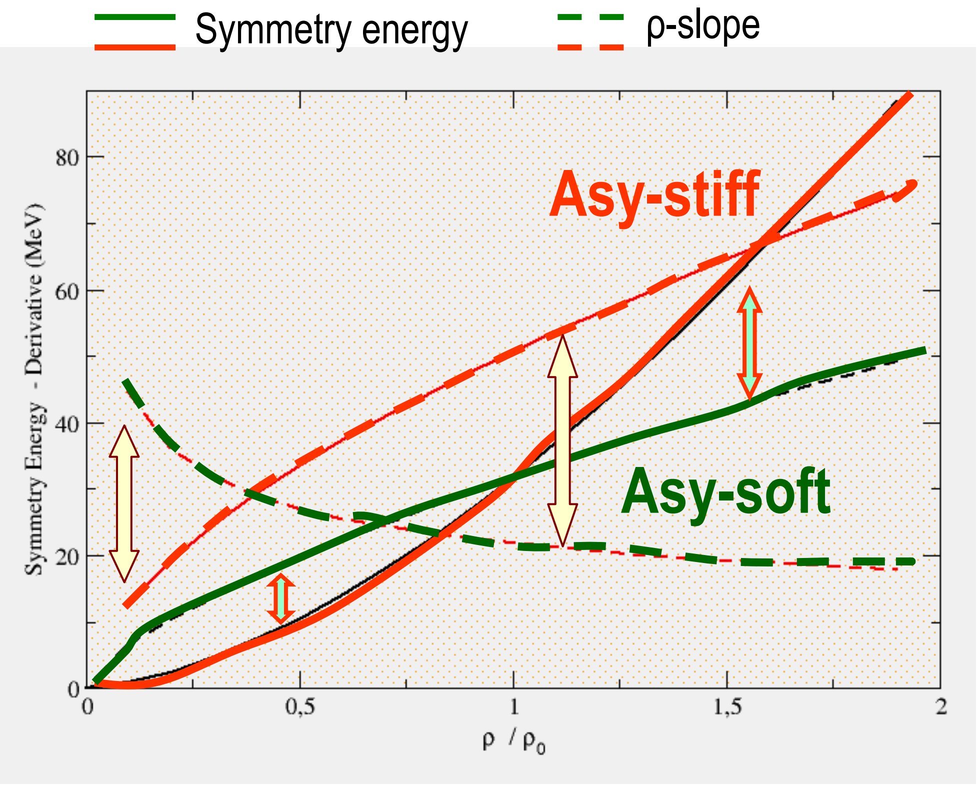
$$\boxed{j_n - j_p \propto E_{sym}(\rho)\nabla I + \frac{\partial E_{sym}(\rho)}{\partial\rho} I\nabla\rho}$$

Diffusion

Drift

$$\boxed{E/A\ (\rho) = E_s(\rho) + E_{sym}(\rho)I^2}$$

I=(N-Z)/A



Direct Access to Value and Slope of the Symmetry Energy at ρ !

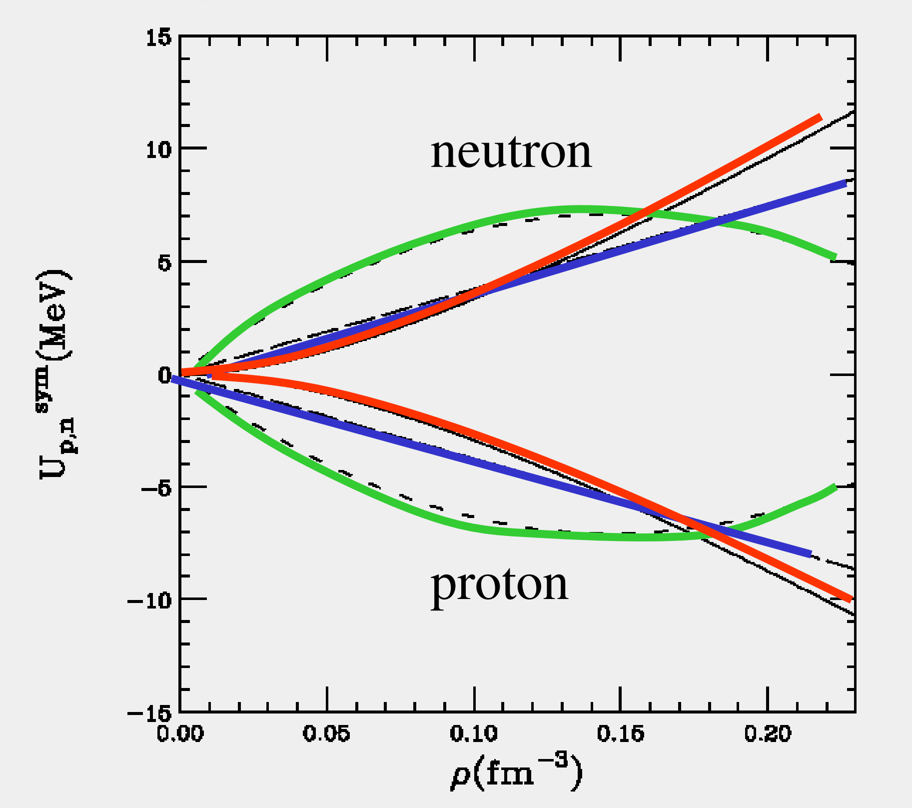
Iso-Tracer (2): Symmetry Potentials and Effective Masses

Density dependence

Momentum dependence

$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$$

^{124}Sn "asymmetry" I= 0.2

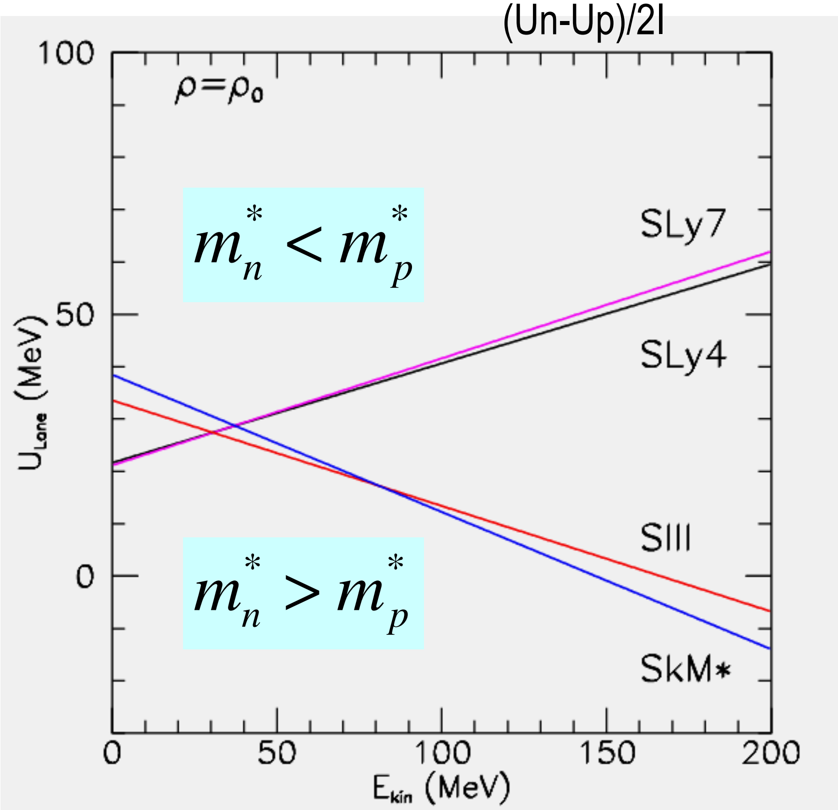


Asy-stiff

Asy-soft

Lane Potentials

(Un-Up)/2I



$$m_n^* < m_p^*$$

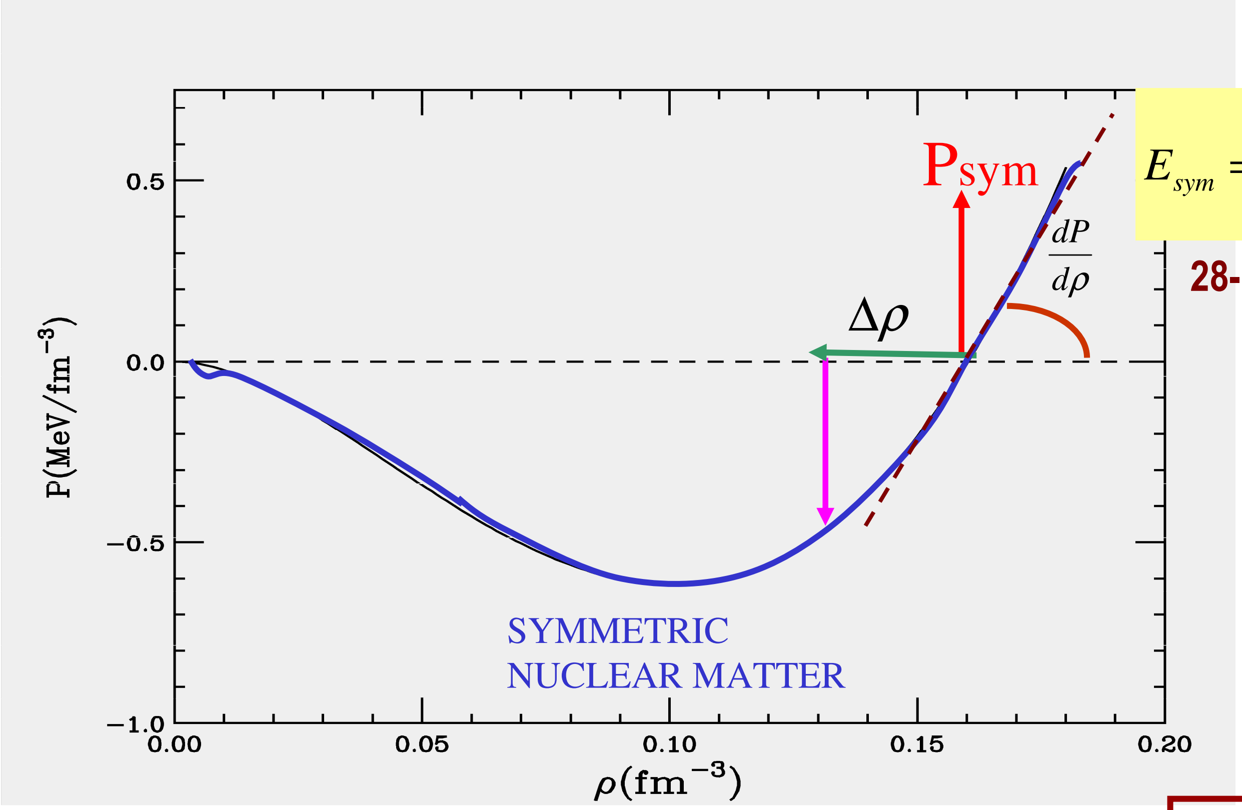
$$m_n^* > m_p^*$$

Nucleon emission, Flows, Particle production….

Phys.Rep.410(2005)335-466

Near Saturation Properties

SYMMETRY PRESSURE → **SHIFT of** $\rho_0(I), K_{NM}(I)$



Expansion around ρ_0

$$E_{sym} = a_4 + \frac{L}{3}\left(\frac{\rho_B-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B-\rho_0}{\rho_0}\right)^2$$

28-32MeV **Slope** **Curvature**

Saturation density shift

$$\Delta\rho(I) = \rho_0(I) - \rho_0(0) = -\frac{P_{sym}}{\left.\frac{dP}{d\rho}\right|_{\rho_0}} \equiv -\frac{3\rho_0 L}{K_{NM}(0)} I^2$$

Central density of Heavy Exotic Nuclei ?

Compressibility shift

$$\Delta K_{NM}(I) = (K_{sym} - 6L)I^2 < 0$$

Exotic Monopole?

Stable nuclei:
nucl-ex/0709.3132:Notre Dame-Osaka exp.
GMR in 112-124Sn→ ΔK = -550±100 MeV
→Very stiff : L ~ +100MeV!

Esym ≈ $(\rho/\rho_0)^\gamma$
L~3$a_4\gamma$→γ≥1

→n-skin thickness?

STOCHASTIC MEAN FIELD TRANSPORT EQUATION: VLASOV + NN-COLLISIONS and PAULI CORRELATIONS

Fluctuations

$$\frac{df(r,p,t)}{dt} = \frac{\partial f(r,p,t)}{\partial t} + \{f,h\} = I_{coll}[f] + \delta I_{coll}$$

$$h = \frac{p^2}{2m} + U[f]$$

$$\underbrace{w^{+}(1-f)}_{\text{gain}} - \underbrace{w^{-}f}_{\text{loss}}$$

Self-Consistent Mean Field ⟺ Equation of State

Phys.Rep. 389 (2004) 263 **Phys.Rep. 410 (2005) 335**

Coulomb Barrier

Isospin Equilibration: Dynamical Dipole in Fusion Reactions

$E_{sym}(\rho)$ Sensitivity

Value ($<\rho_0$)

Restoring Force → Centroid, Yield

Neutron Emission

Reaction Mechanism

NN cross sections

Anisotropy

Damping

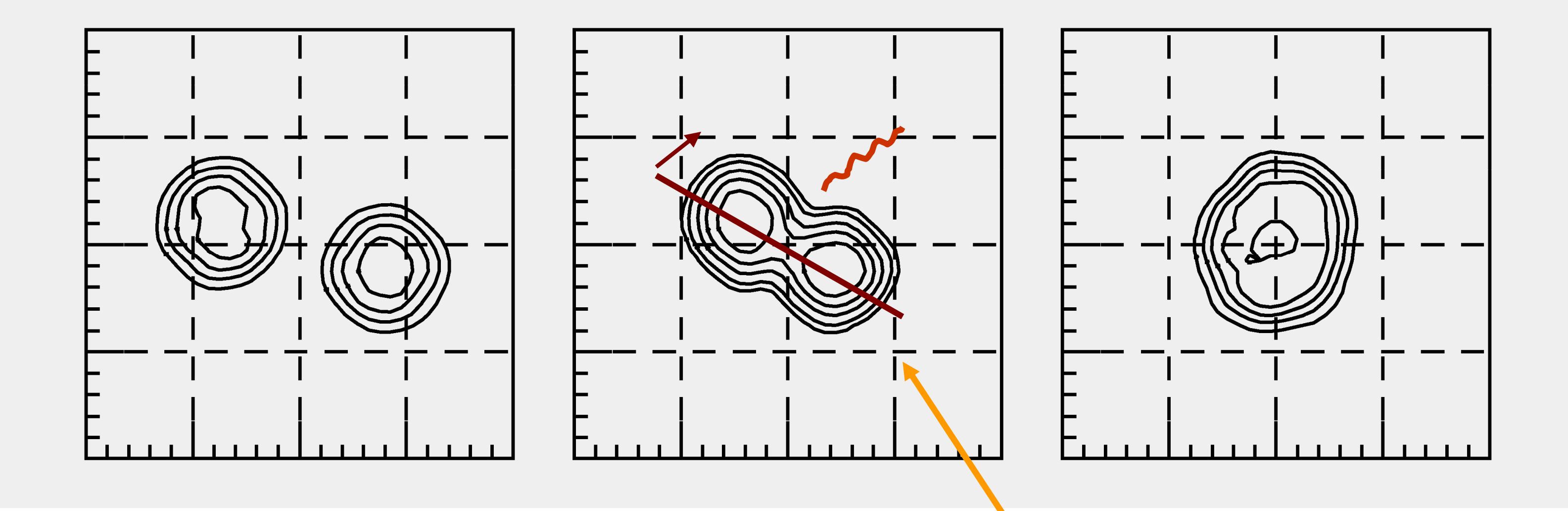
Pre-equilibrium Dipole Radiation

Charge Equilibration Dynamics:

Stochastic → Diffusion

vs.

Collective → Dipole Oscillations of the Di-nuclear System ⇒ Fusion Dynamics



$$D_0 = \frac{Z_1 Z_2}{A}\left(\frac{N_1}{Z_1} - \frac{N_2}{Z_2}\right)(R_1 + R_2)$$

Initial Dipole

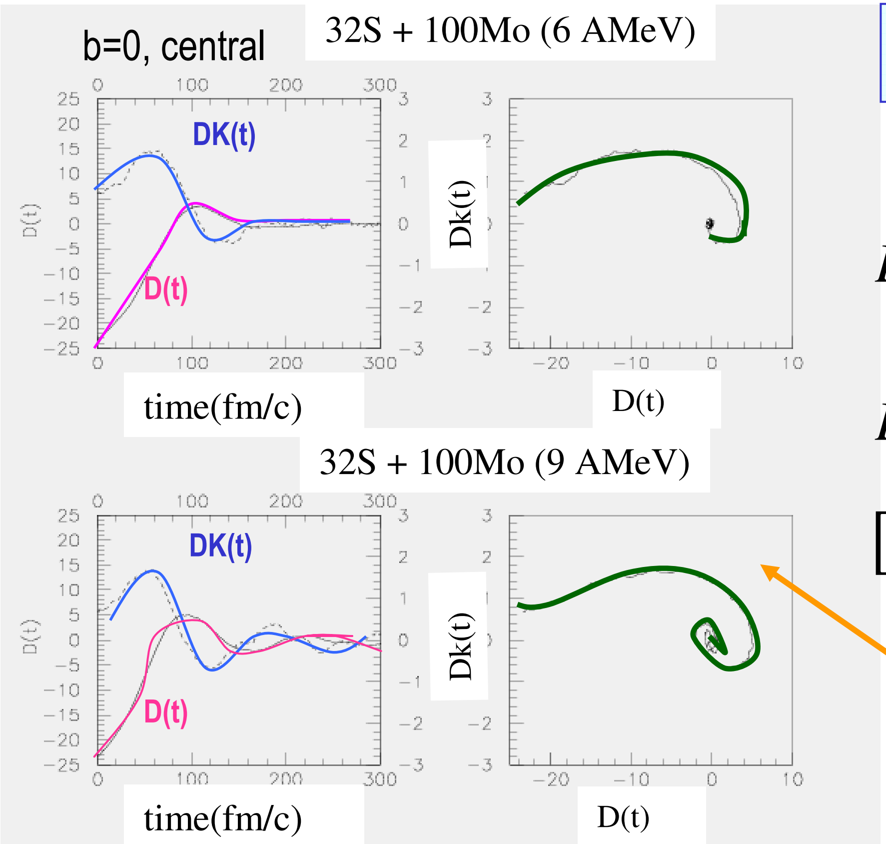
D(t) : bremss.
dipole radiation

CN: Statistical
GDR

…tilting lighthouse!

Cooling on the way to Fusion

Pre-equilibrium dipole emission



D.Pierroutsakou et al. PRC71(2005)

$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$

$$DK(t) \equiv P_p - P_n \rightarrow P_{p,n} \equiv \frac{1}{Z,N}\Sigma p_i^{p,n}$$

$$\left[D, DK\right] = i\hbar$$

SPIRALS → Collective Oscillations!

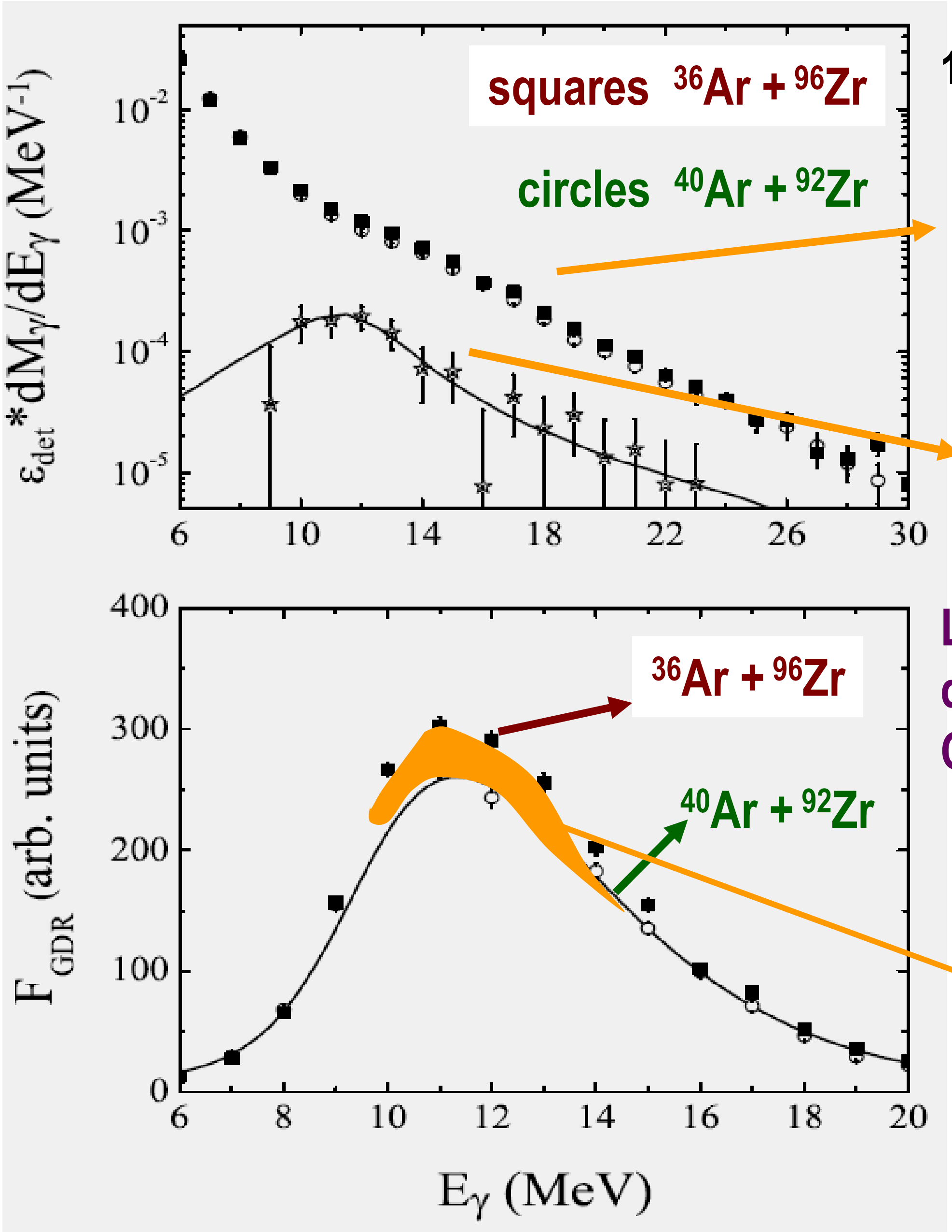
TDHF: C.Simenel, Ph.Chomaz, G.de France

Bremsstrahlung:
Quantitative estimations

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|D''(\omega)\right|^2$$

V.Baran, D.M.Brink, M.Colonna, M.Di Toro, PRL.87(2001)

D.Pierroutsakou et al., New Medea Exp. at LNS-Catania,



16AMeV Fusion events: same CN selection

(np)-bremsstrahlung-subtracted spectra
at θ_γ=90° vs. Beam Axis

Difference

Linearized spectra:
divided by the no-GDR
CN evaporation component

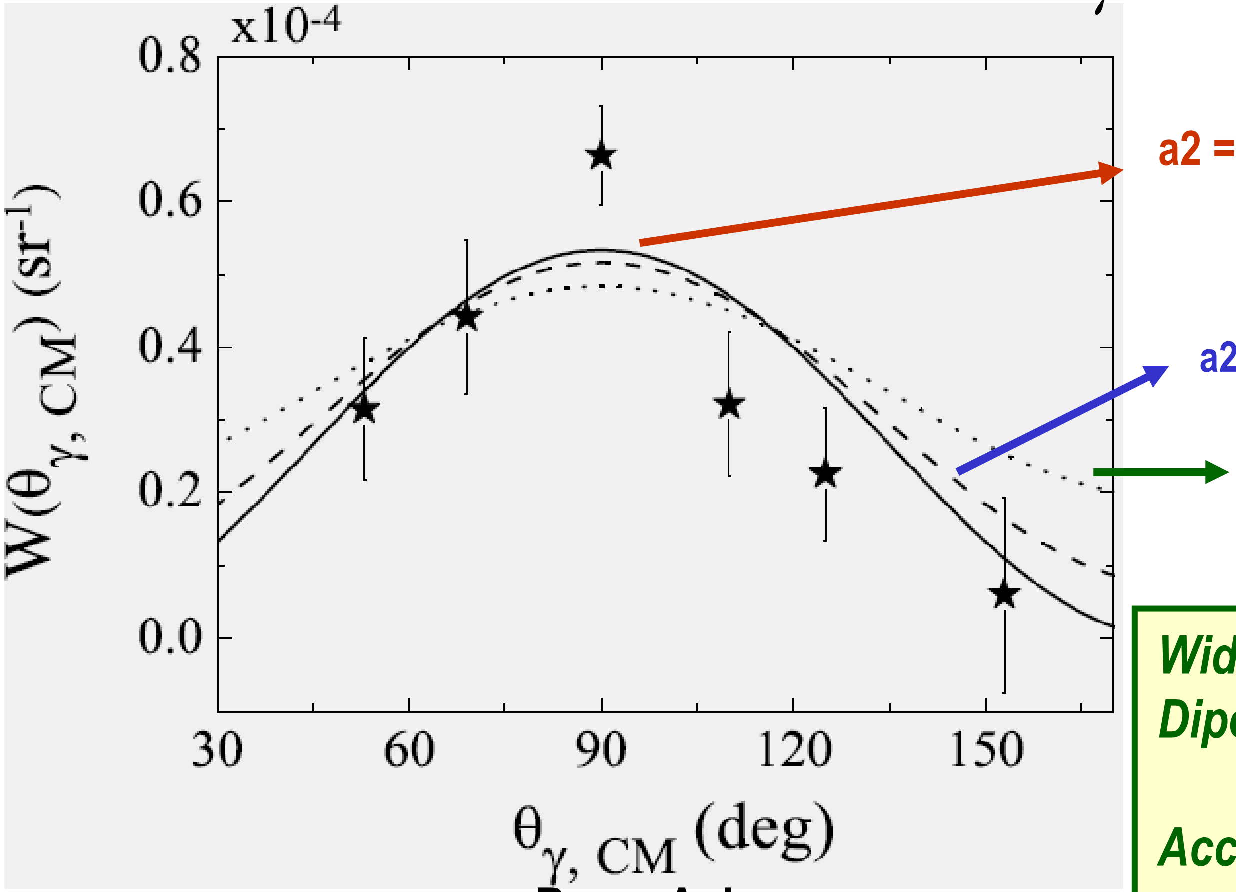
θ_γ-study of the extra-yield with MEDEA

B.Martin et al., PLB 664 (2008) 47

Dipole Angular Distribution of the Extra-Yield: Anisotropy!!

36Ar+96Zr vs. 40Ar+92Zr: 16AMeV Fusion events:
same CN selection

$$W(\vartheta_\gamma) = W_0[1 + a_2 P_2(\cos\vartheta_\gamma)]$$



vs Beam Axis

a2 = -1→Pure Dipole oscillation along the Beam Axis→ ~ $\sin^2\theta_\gamma$

a2 = -0.8

a2 = -0.5

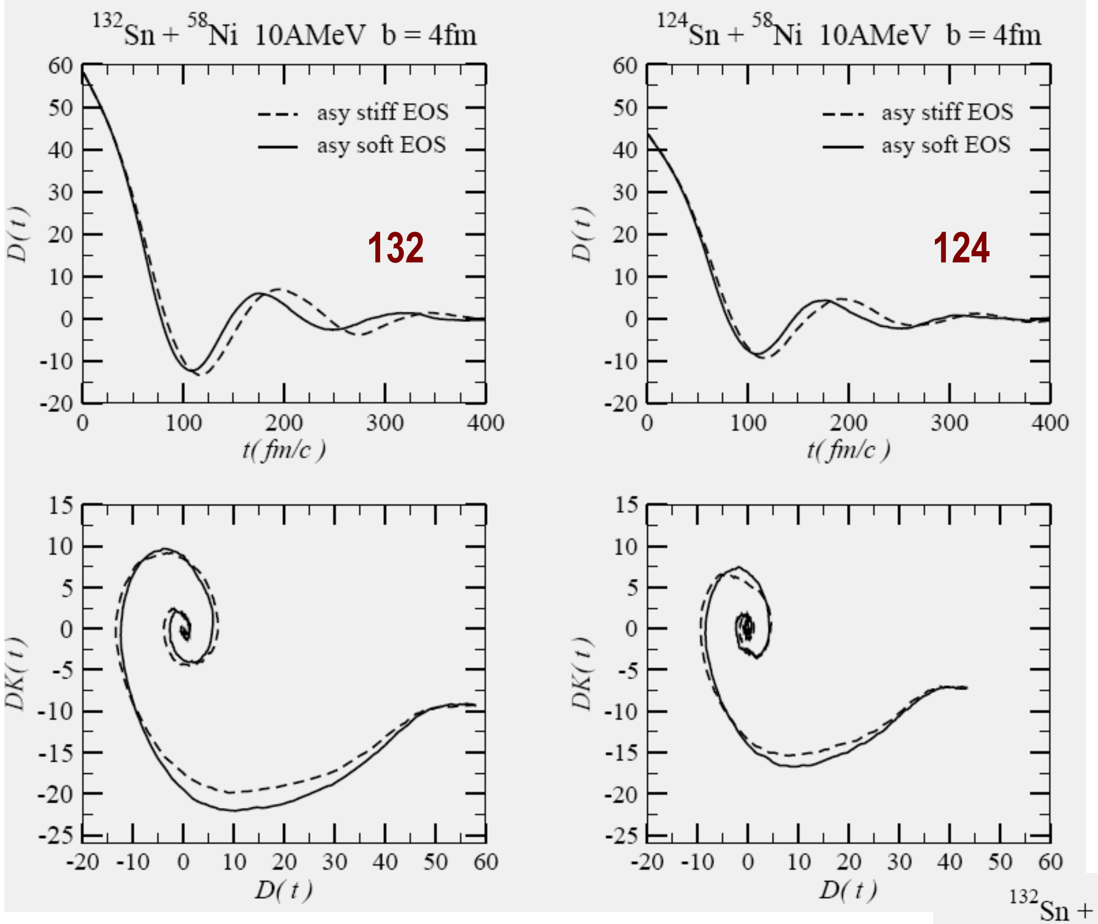
Widening: rotation of the Prompt Dipole Axis vs the Beam Axis

↓

Accurate Angular Distrib. Measure: Dipole Clock!

B.Martin et al., PLB 664 (2008) 47

The “Monster” ^{132}Sn Dynamical Dipole: Symmetry Energy



10AMeV, b=4fm

Prompt Dipole Oscillations

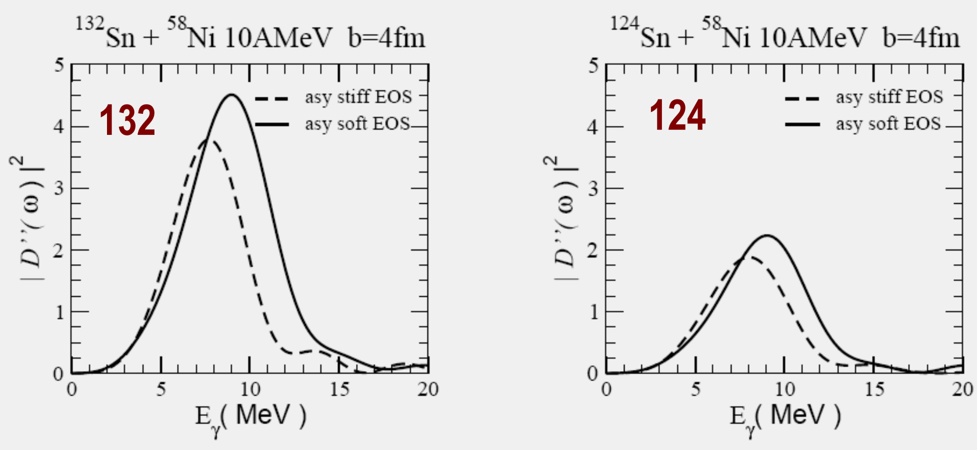
—— Asy soft

- - - - Asy stiff

Phase Space Correlations

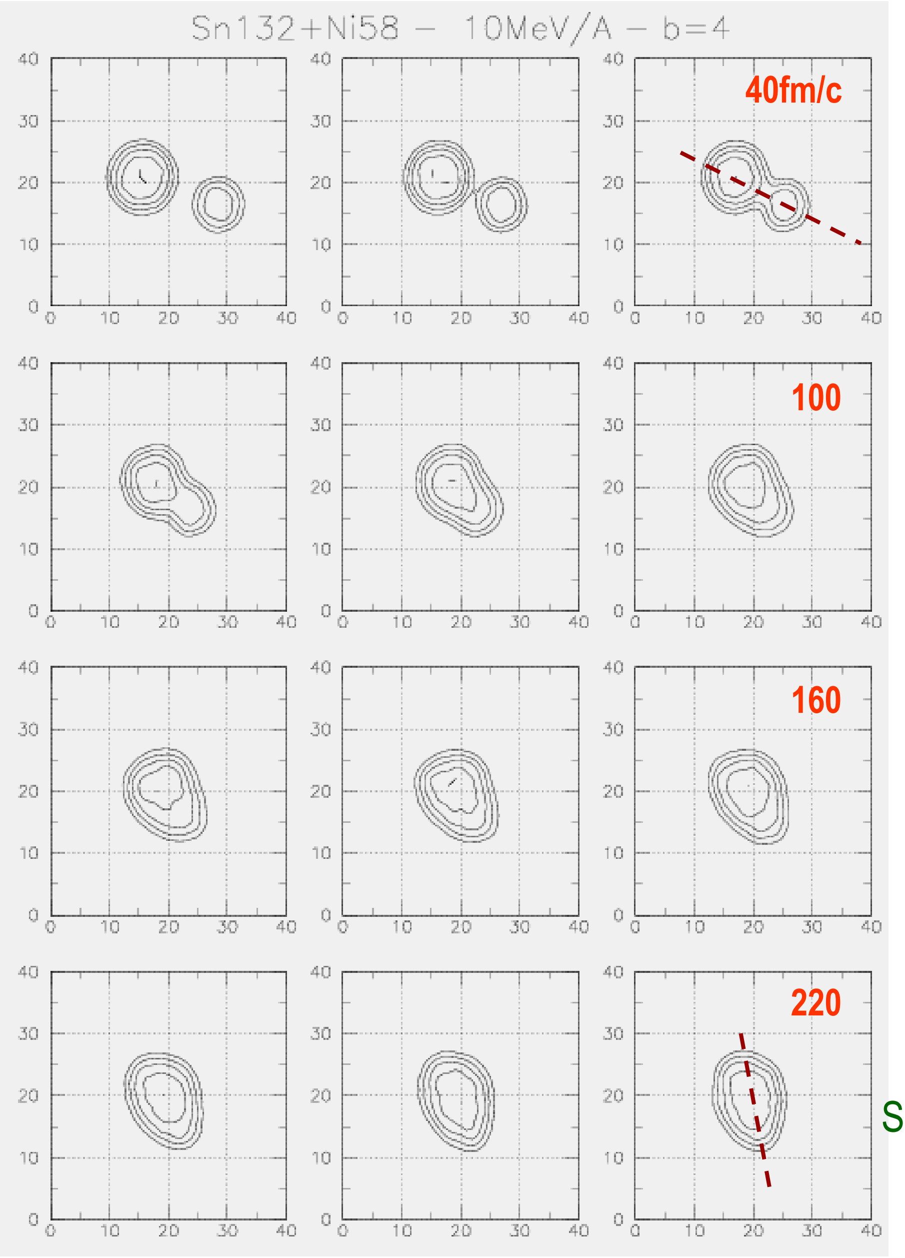
Power Spectrum

ASYSOFT: *Larger Yield (25%)*
Larger Centroid Energy
Larger Width



arXiv:0807.4118[nucl-th]

Density Plots on the Reaction Plane: Rotation of the Oscillation Axis vs the Beam Axis

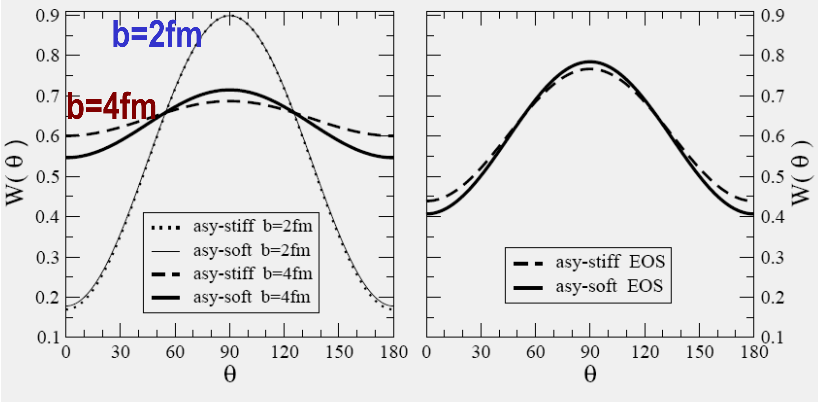


132Sn:
The Monster Dipole
Case

Weighted anisotropies:

$$W(\theta) = \sum_{i=1}^{t_{max}} \beta_i W(\theta, \Phi_i)$$

$$P(t) = \int_{t_0}^{t} \mid D''(t) \mid^2 dt / P_{tot}$$



Total Angular Distribution

Still emitting,..although damped

arXiv:0807.4118[nucl-th]

Fermi Energies

Multifragmentation at the Fermi Energies

$E_{sym}(\rho)$ Sensitivity: expansion phase, dilute matter

Isospin Distillation + Radial Flow

Low Density Slope

Value: Symmetry Potentials

Asy-soft more effective

Asy-soft: compensation
N-repulsion vs Z-coulomb
→Flat N/Z vs kinetic energy

Stochastic mean field (SMF) calculations

(fluctuations projected on ordinary space)

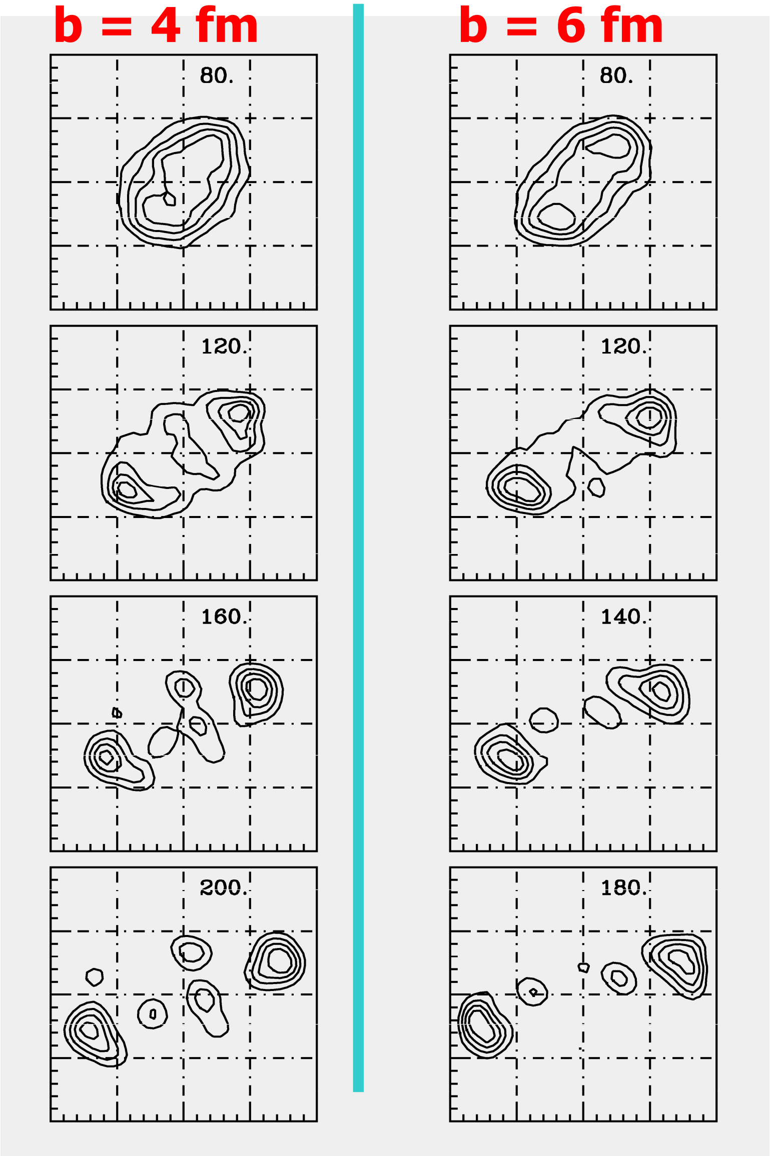
Central collisions

Ni + Au, E/A = 45 MeV/A

Isospin Distillation + Radial Flow

Semi-Central

Sn124 + Sn124, E/A = 50 MeV/A



Isospin Migration + Alignement

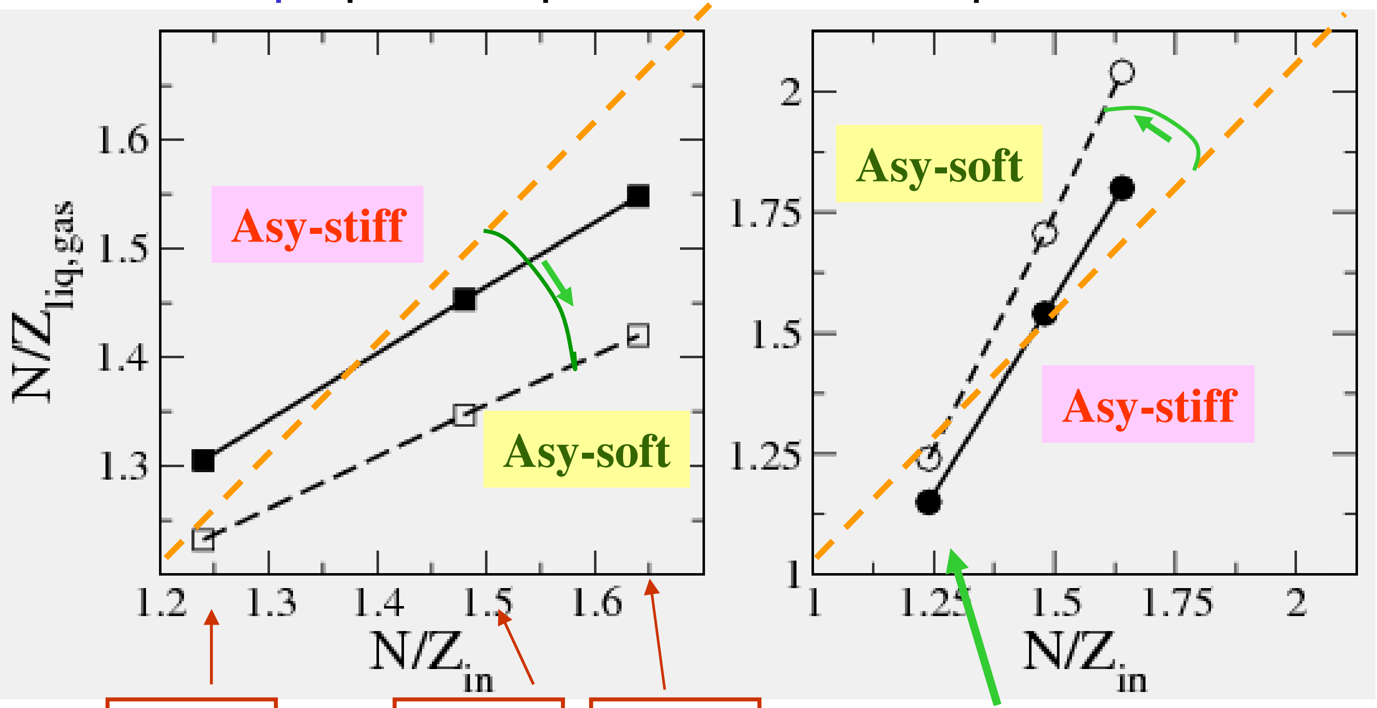
ISOSPIN DISTILLATION

- Sn112 + Sn112
- Sn124 + Sn124
- Sn132 + Sn132

E/A = 50 MeV, b=2 fm

1200 events for each reaction

Liquid phase: n-depletion **Gas phase: n-enrichement**



112,112

112,124

124,124

ASY-SOFT MORE EFFECTIVE

With Asy-stiff in the (112,112) case:
- N/Z (gas) below bisectrix
- N/Z (gas) < N/Z (liquid)

→ large proton emission

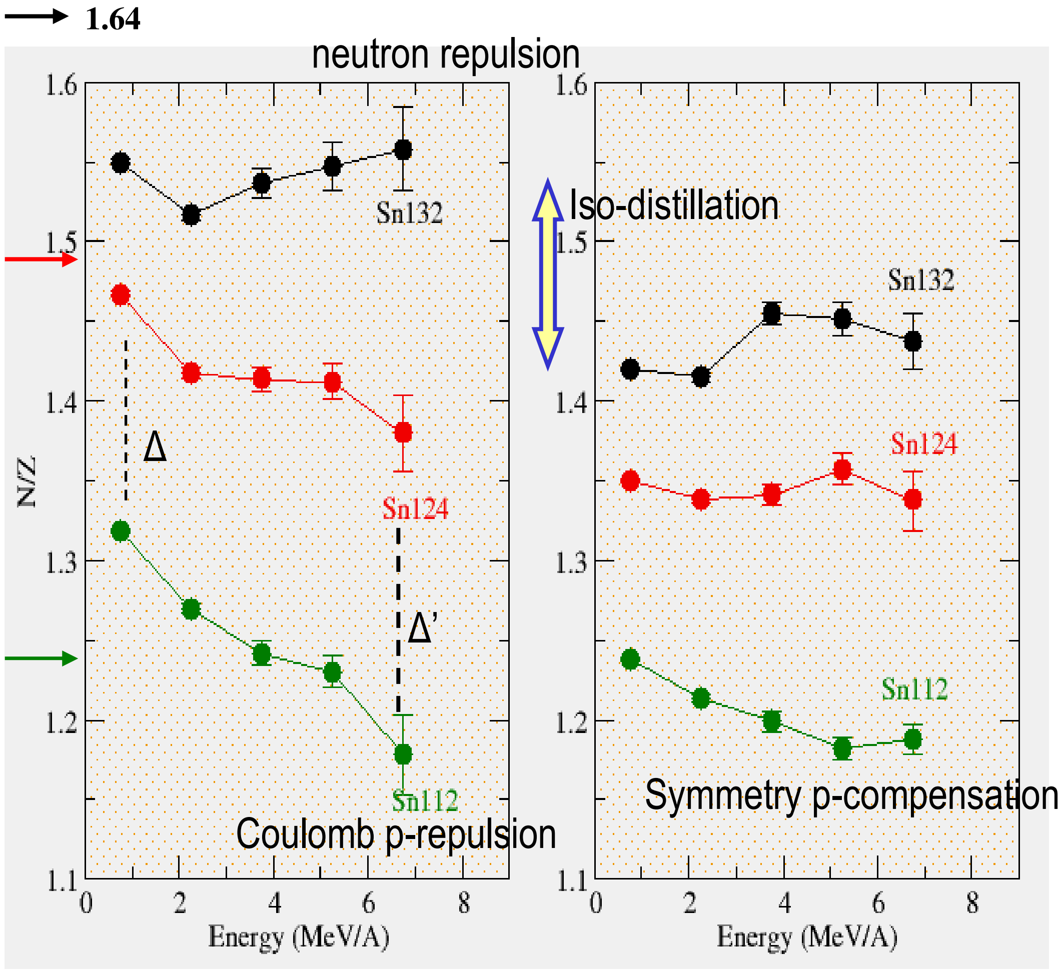
M.Colonna et al., INPC-Tokyo , NPA 805 (2008)

Isospin content of IMF in central collisions

N/Z: N = Σi Ni , Z = Σi Zi $3 \le Z_i \le 10$

Isospin Distillation (spinodal mechanism)
+ Radial Flow
+ Symmetry Potentials

Asy-stiff **Asy-soft**



neutron repulsion

Iso-distillation

Coulomb p-repulsion

Symmetry p-compensation

New Observables:

N/Z vs fragment energy

Proton/neutron repulsion:
** n-rich clusters emitted at larger energy in n-rich systems (Δ'>Δ)*
** flat spectra with Asy-soft*

Primary fragment properties

M.Colonna et al., INPC-Tokyo , NPA 805 (2008)

Neck-fragmentation at the Fermi Energies

$E_{sym}(\rho)$ Sensitivity: density gradient around normal density

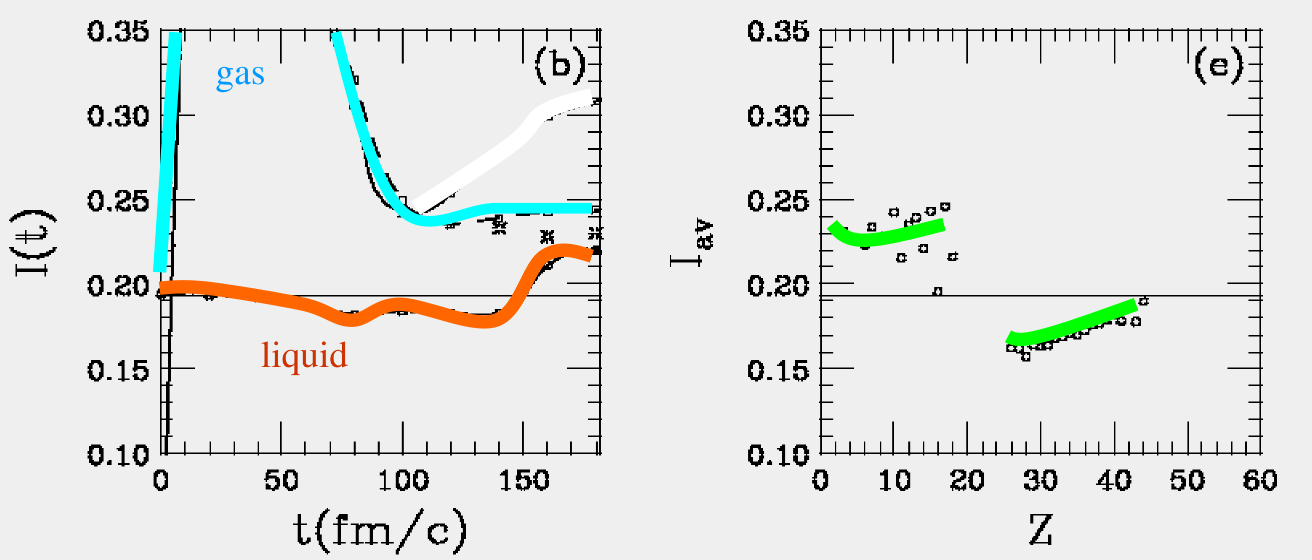
Isospin Migration + Hierarchy

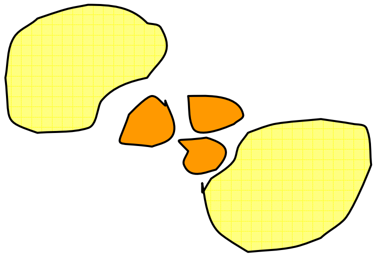
Slope just below ρ_0

Asy-stiff more effective

IMF Mass, N/Z vs alignement/$v_{transverse}$:
→ *time sequence of mechanisms:*
Spinodal → neck instabilities
→ *fast fission→ cluster evaporation*

Semi-peripheral collisions

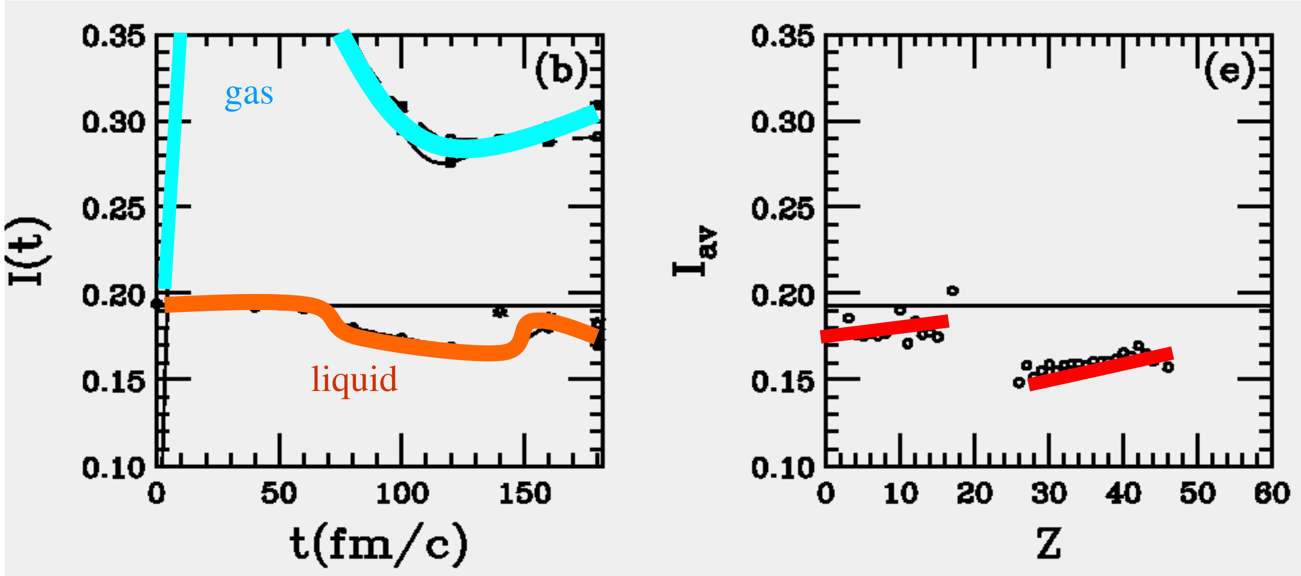




Asy-stiff:
neutron enrichment of neck IMFs

^{124}Sn+ ^{124}Sn 50 AMeV: average asymmetry

Isospin migration



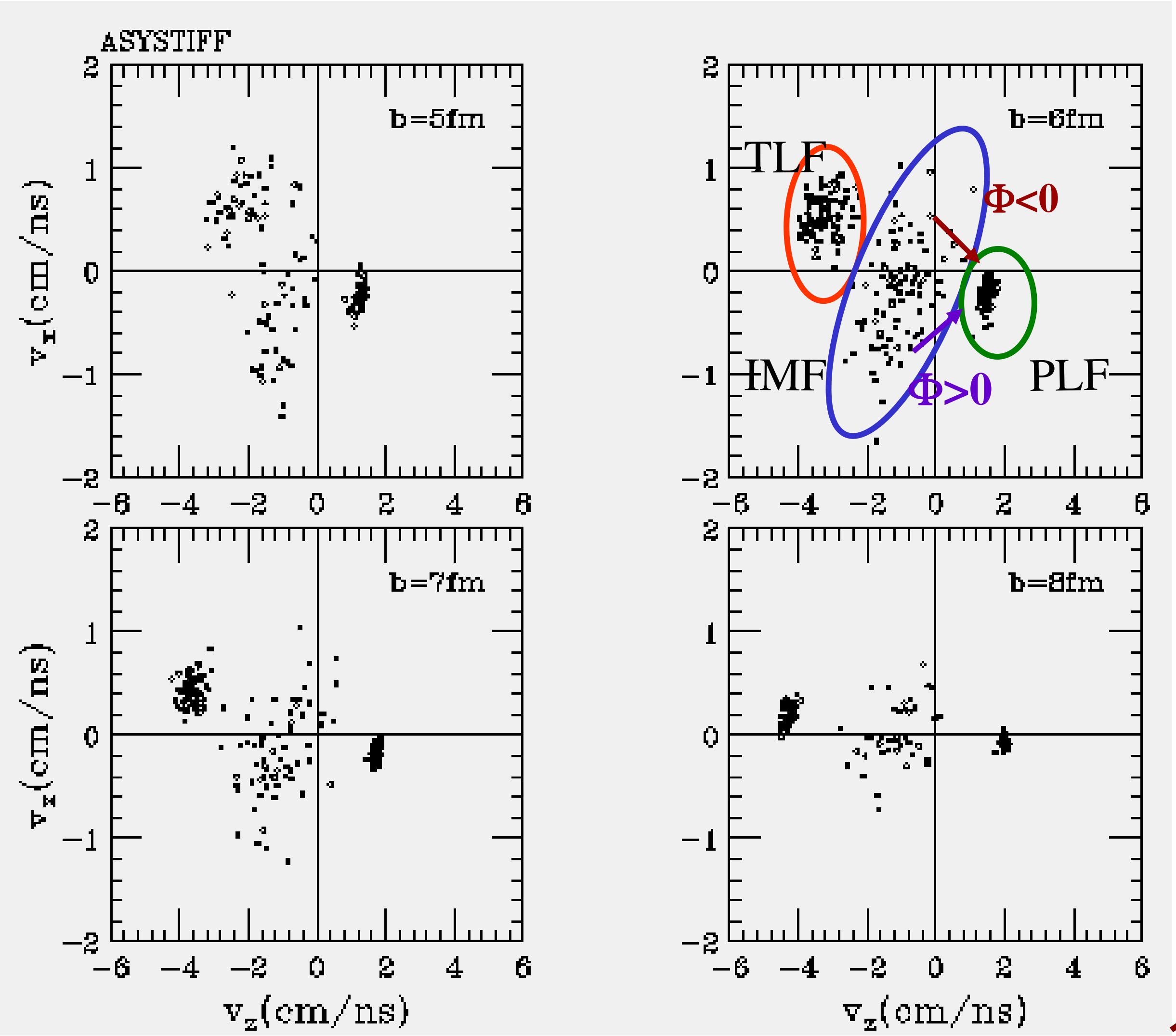
Asy-soft

V.Baran et al.,
NPA703(2002)603
NPA730(2004)329

NECK FRAGMENTS: V_z-V_x CORRELATIONS

^{124}Sn + ^{64}Ni
35 AMeV

vs. 4π CHIMERA data



Deviations from Viola systematics

Alignement + centroid at $\Phi_{plane} \geq 0$

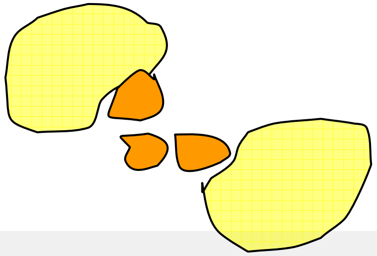
$\Downarrow$

Clear Dynamical Signatures !

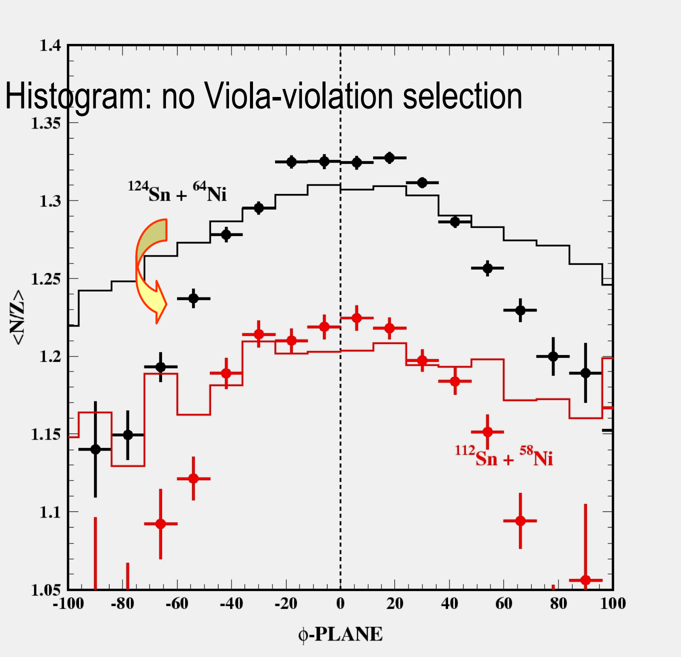
Large dispersion along transversal direction, v_x → time hierarchy ?

E.De Filippo et al. (Chimera Coll.) PRC 71 (2005)

Non-equilibrium Effects in Fragmentation - IMF hierarchy vs. $v_\perp$: Isospin Tracer



124Sn+124Sn 50AMeV semicentral



Chimera data: see E.De Filippo, P.Russotto
INPC-Tokyo, NPA 805 (2008)

low $v_\perp \rightarrow$ more PLF-correlated $\rightarrow \Phi$-plane ≈ 0
large N/Z
Viola-violation
larger masses

Time Hierarchy: Early Formation
via fast Spinodal Mechanism for
Light Fragments $\rightarrow$ Large v_{transv}
$\rightarrow$ Low alignement
$\rightarrow$ Low N/Z

MULTI-MODALITY Fragmentation
…….just in one shot

ISOSPIN: Tracer of a "Continuous" Series of Bifurcations →
from multi- to neck-fragmentation up to PLF dynamical fission

Imbalance Ratios: Isospin Equilibration at Fermi Energies

$E_{sym}(\rho)$ Sensitivity: asymmetry gradients

Isospin Diffusion

(Overdamped Dipole Oscillation)

Value below ρ_0

Asy-soft more effective

Interaction time selection→Centrality(?),
Kinetic Energy Loss

Caution: Disentangle isoscalar and isovector effects!

Rami imbalance ratio:

Mass(A) ≈ Mass(B) ; N/Z(A) ≠ N/Z(B)

$$R = \frac{2AB - (AA) - (BB)}{(AA) - (BB)}$$

A dominance → +1

mixing → 0

B dominance → -1

Isospin Observables: isoscaling $\alpha(\beta), \frac{N}{Z}, \frac{t}{^{3}He}, \frac{\pi^-}{\pi^+} \ldots$

vs. Centrality (fixed y) → Kinetic Energy Loss

vs. Rapidity (fixed centrality)

vs. Transverse momentum (fixed y, centrality) ?

Isospin equilibration: Imbalance ratios

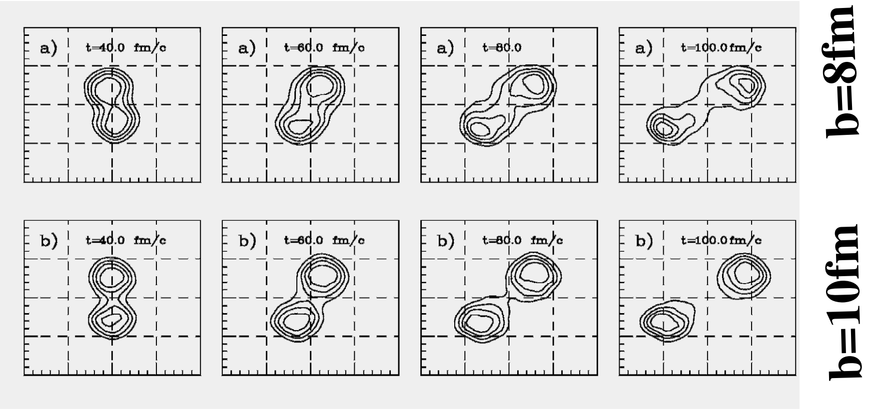
B. Tsang et al. PRL 92 (2004)

M : ^{124}Sn + ^{112}Sn

L: ^{112}Sn + ^{112}Sn

H: ^{124}Sn + ^{124}Sn

@ 35, 50 Mev/A



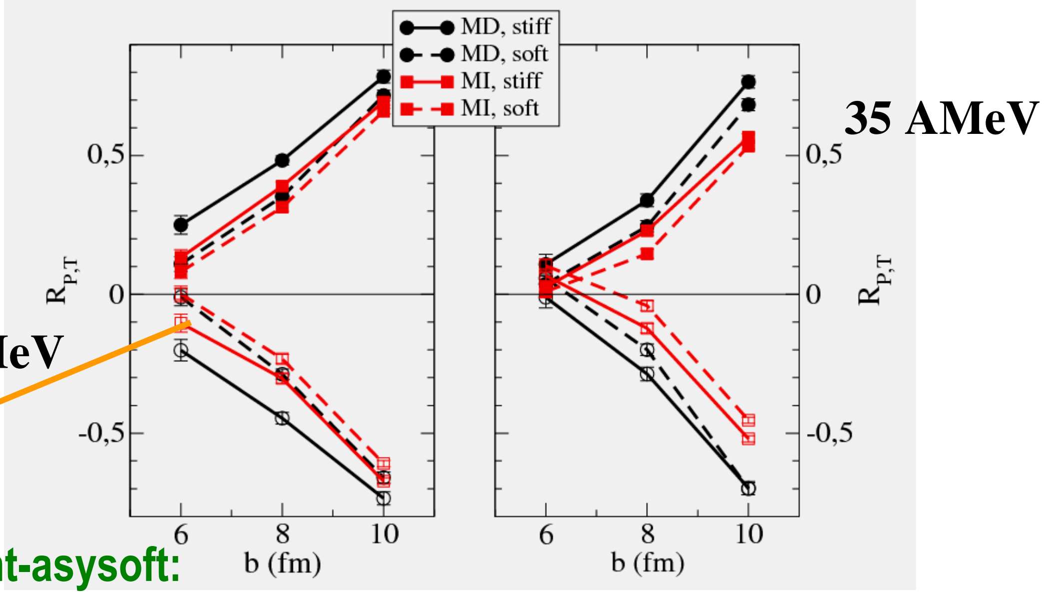
SMF simulations

$$R_P = \frac{2I_P^M - I_P^{124-124} - I_P^{112-112}}{I_P^{124-124} - I_P^{112-112}} ; R_T = \frac{2I_T^M - I_T^{124-124} - I_T^{112-112}}{I_T^{124-124} - I_T^{112-112}}$$

I = (N-Z)/A
of PLF or TLF

Smaller R values for:
- ✓ Asy-soft
- ✓ MI interaction
- ✓ Lower beam energy

50 AMeV



Mom. Independent-asystiff ≈ Mom. Dependent-asysoft:
Compensation of isoscalar/isovector effects

J.Rizzo et al. NPA806 (2008) 79

Imbalance ratios: isoscalar vs. isovector effects

$$R^x_{P,T} = \frac{2(x^M - x^{eq})}{(x^H - x^L)}$$

$$x^{eq} = \frac{1}{2}(x^H + x^L).$$

If: $$\beta^M_{P,T} = \beta^{eq} + (\beta^{H,L} - \beta^{eq})\ e^{-t/\tau}$$

Overdamped dipole oscillation

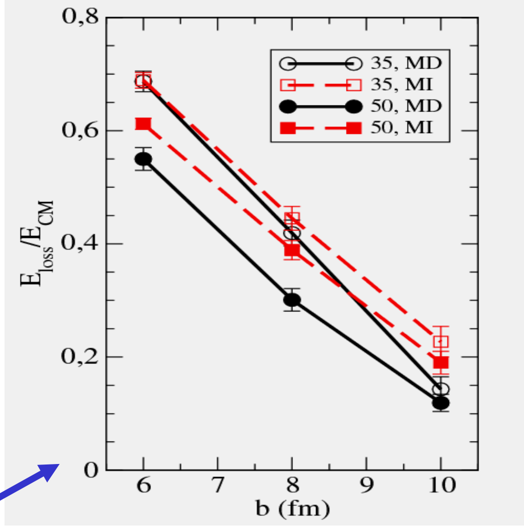
$$R^\beta_{P,T} = \pm e^{-t/\tau}$$

$\tau \longrightarrow$ symmetry energy

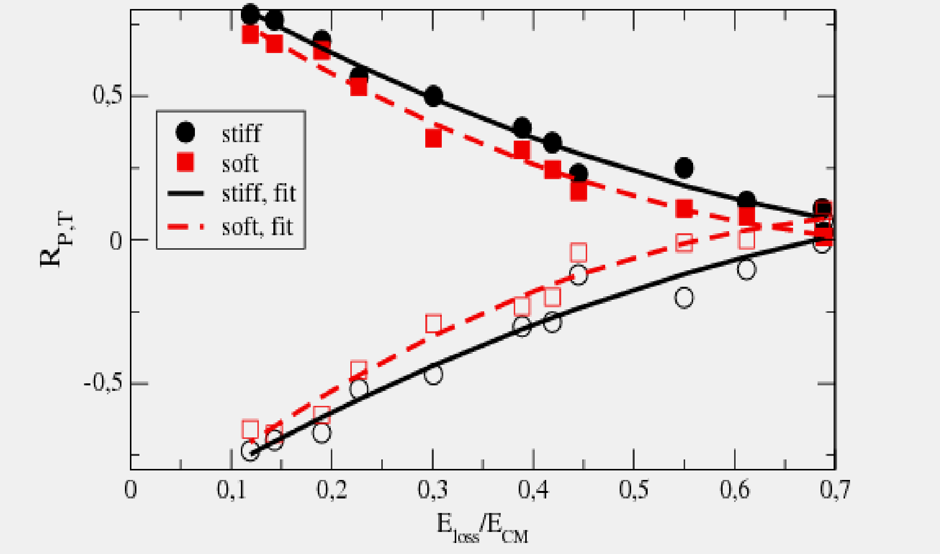
tcontact $\longrightarrow$ dissipation

$\beta = I = (N-Z)/A$

Kinetic energy loss - or PLF(TLF) velocity - as a measure of dissipation (time of contact)



$$E_{loss} = E_{cm} - \frac{E_{kin} + E^{Coul}_{pot}}{A_{PLF} + A_{TLF}}$$



R dependent only on the isovector part of the interaction !

Intermediate Energies

Multifragmentation at High Energies

$E_{sym}(\rho)$ Sensitivity: compression phase

Isospin Distillation + Radial Flow

High Density Slope

Value: Symmetry Potentials

Asy-stiff more effective

Larger N-repulsion with Asy-stiff
→Flat N/Z vs kinetic energy

Problem: large radial flow → few heavier clusters survive, with memory of the high density phase

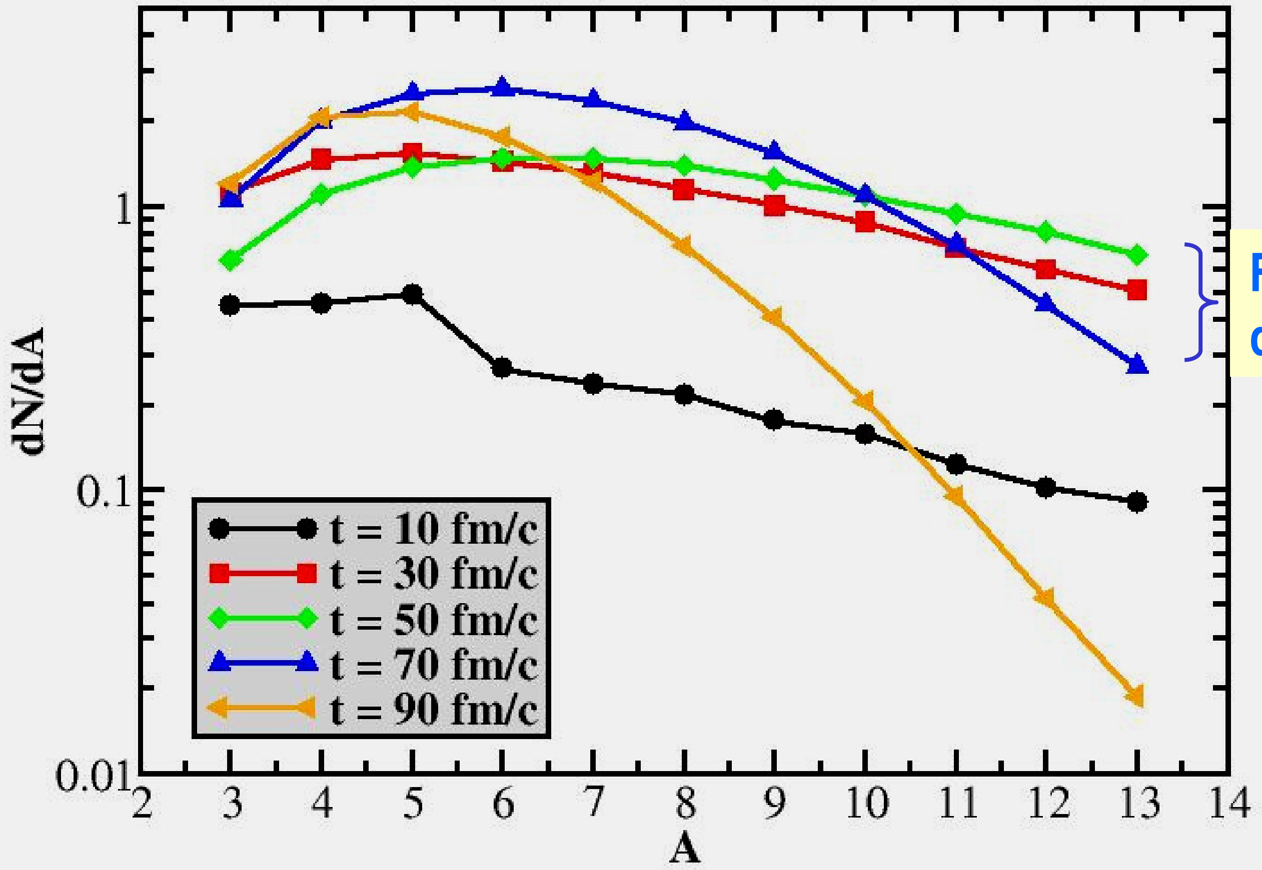
Stochastic RBUU +
Phase Space Coalescence

Time-evolution of fragment formation

(E. Santini et al., NPA756(2005)468)

Au+Au 0.4 AGeV Central

Z=3,4



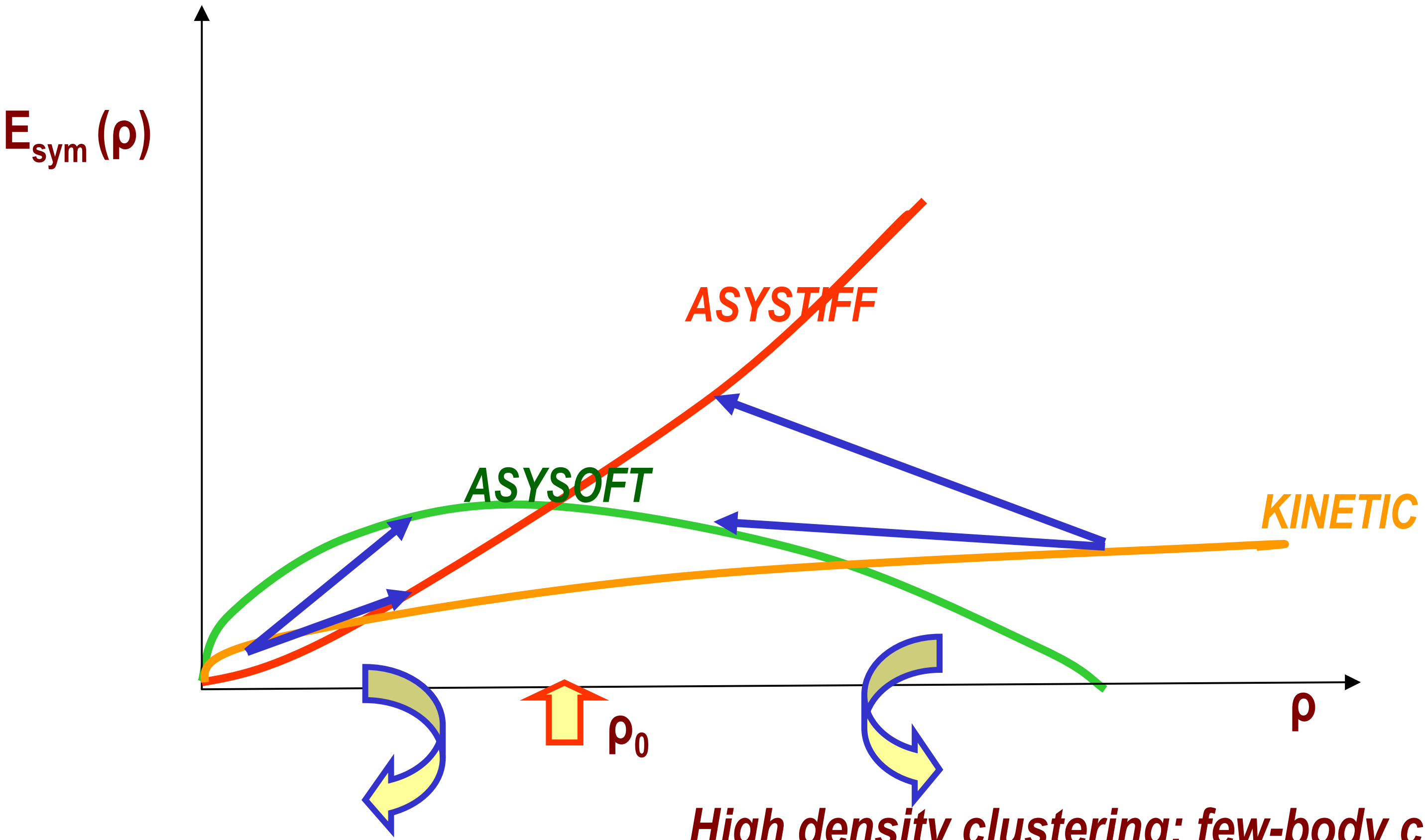
Fast clusterization in the high density phase

Heavier fragments: “relics” of the high density phase

⇓

Isospin Content vs. Symmetry Term ?

The Isospin "Ballet" in Multifragmentation



High density clustering: few-body correlations
and p.s. coalescence

Low density clustering: spinodal mechanism

↓

Asysoft: more symmetric clusters,
larger neutron distillation
combined to a larger pre-eq neutron emission

↓

Asystiff: more symmetric clusters, combined
to a larger fast neutron emission

Isospin content of Fast Nucleon/Cluster emission, Isospin Flows

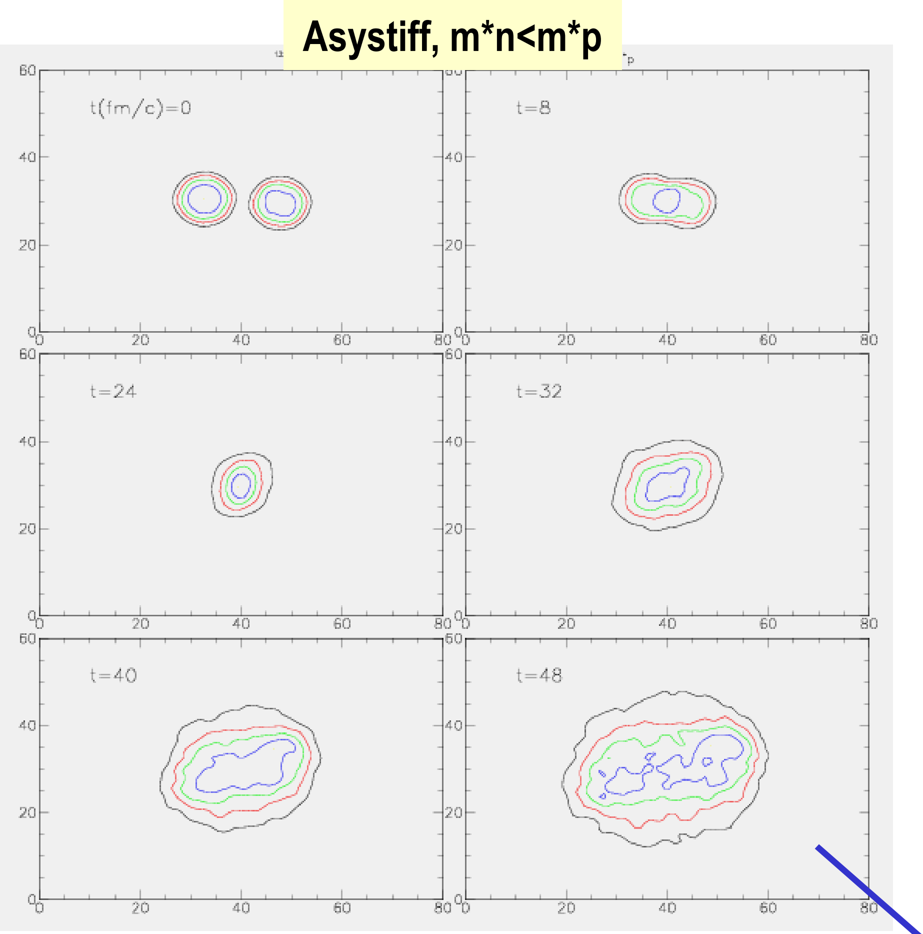
$E_{sym}(\rho)$ Sensitivity: stiffness and symmetry potentials

Neutron/Proton Effective Mass Splitting

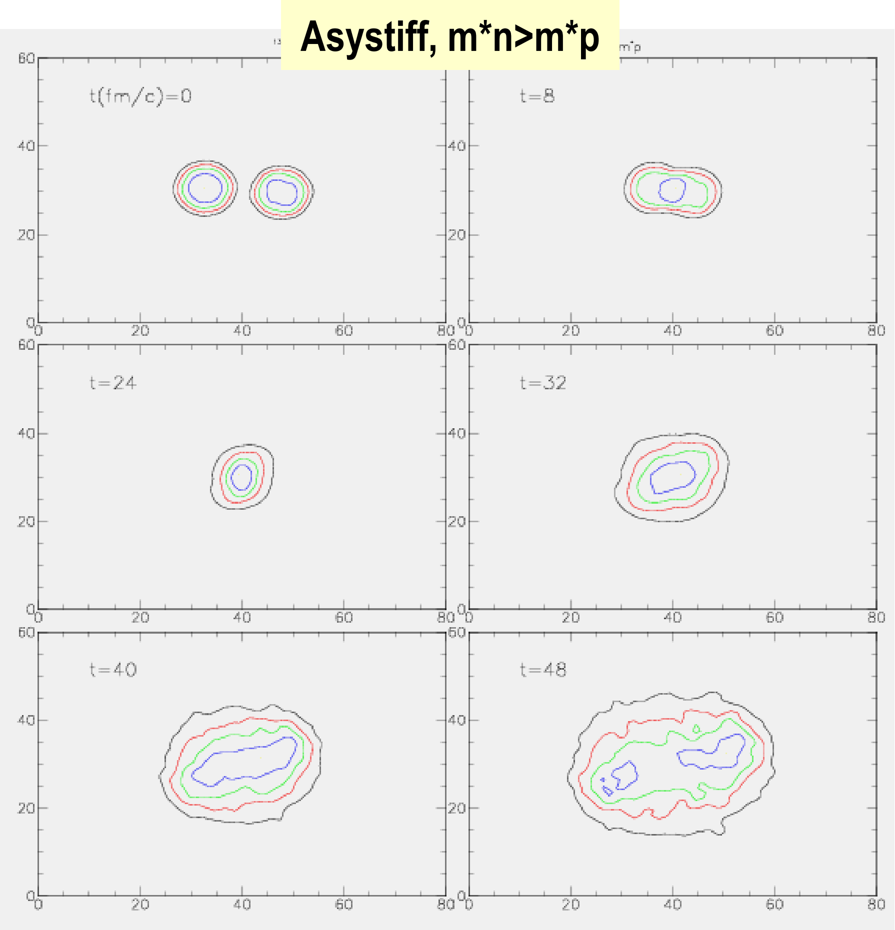
High p_t selections:
- *source at higher density*
- *squeeze-out : v_2*
- *high kinetic energies*

132Sn+124Sn 400AMeV Central → nucleon, cluster Yield Ratios

Free nucleons vs 3H, 3He clusters: phase space coalescence,
200 events, 6000 Montecarlo samplings



Asystiff, m*n<m*p



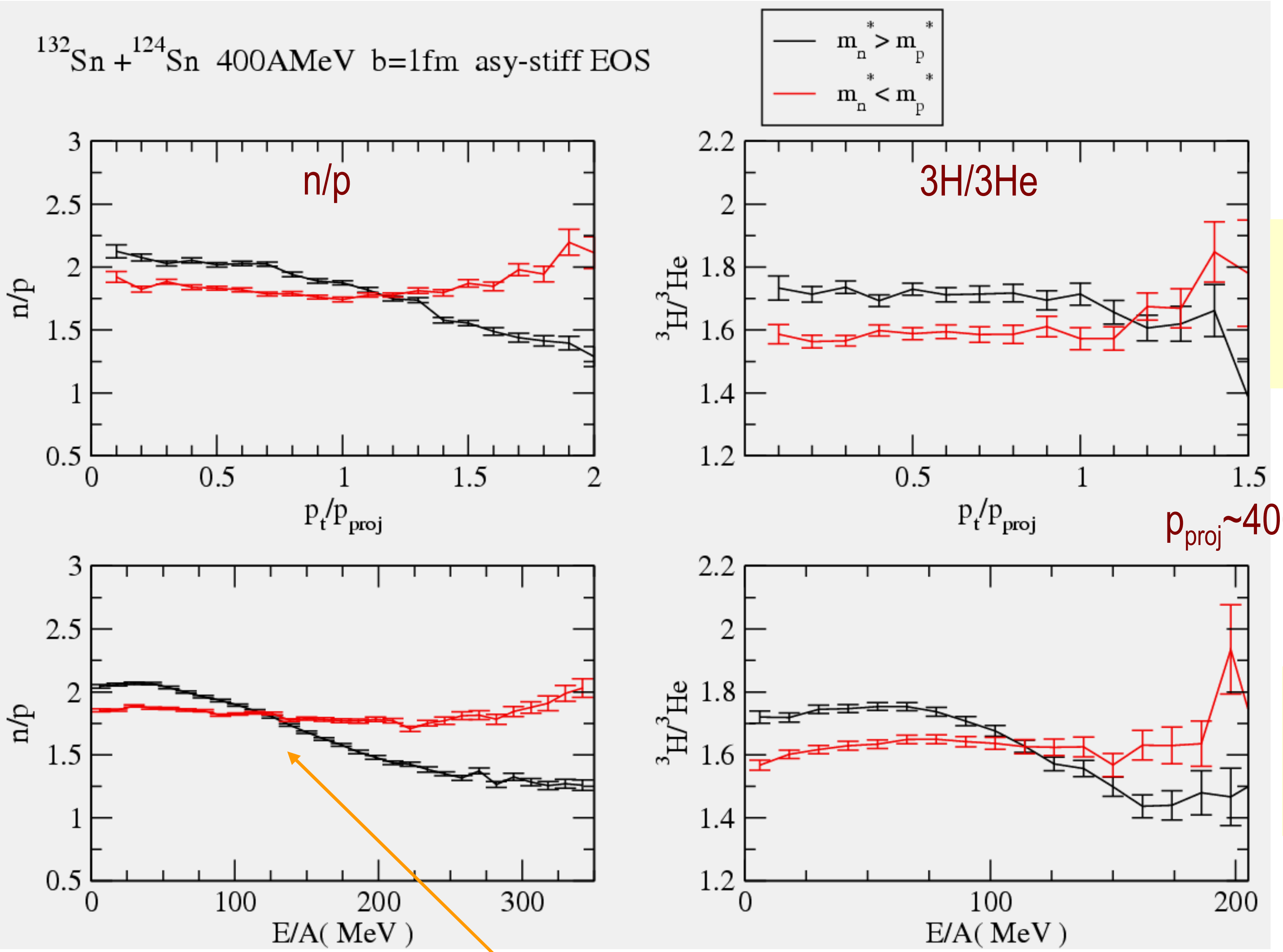
Asystiff, m*n>m*p

Same “global”
reaction dynamics:
Radial (squeeze-out) flows

Freeze-out time: saturation of N_{coll} → ~50fm/c

Valentina Giordano, Master Thesis 2008

132Sn+124Sn 400AMeV Central → Yield Ratios : Asy-stiff + mass splitting



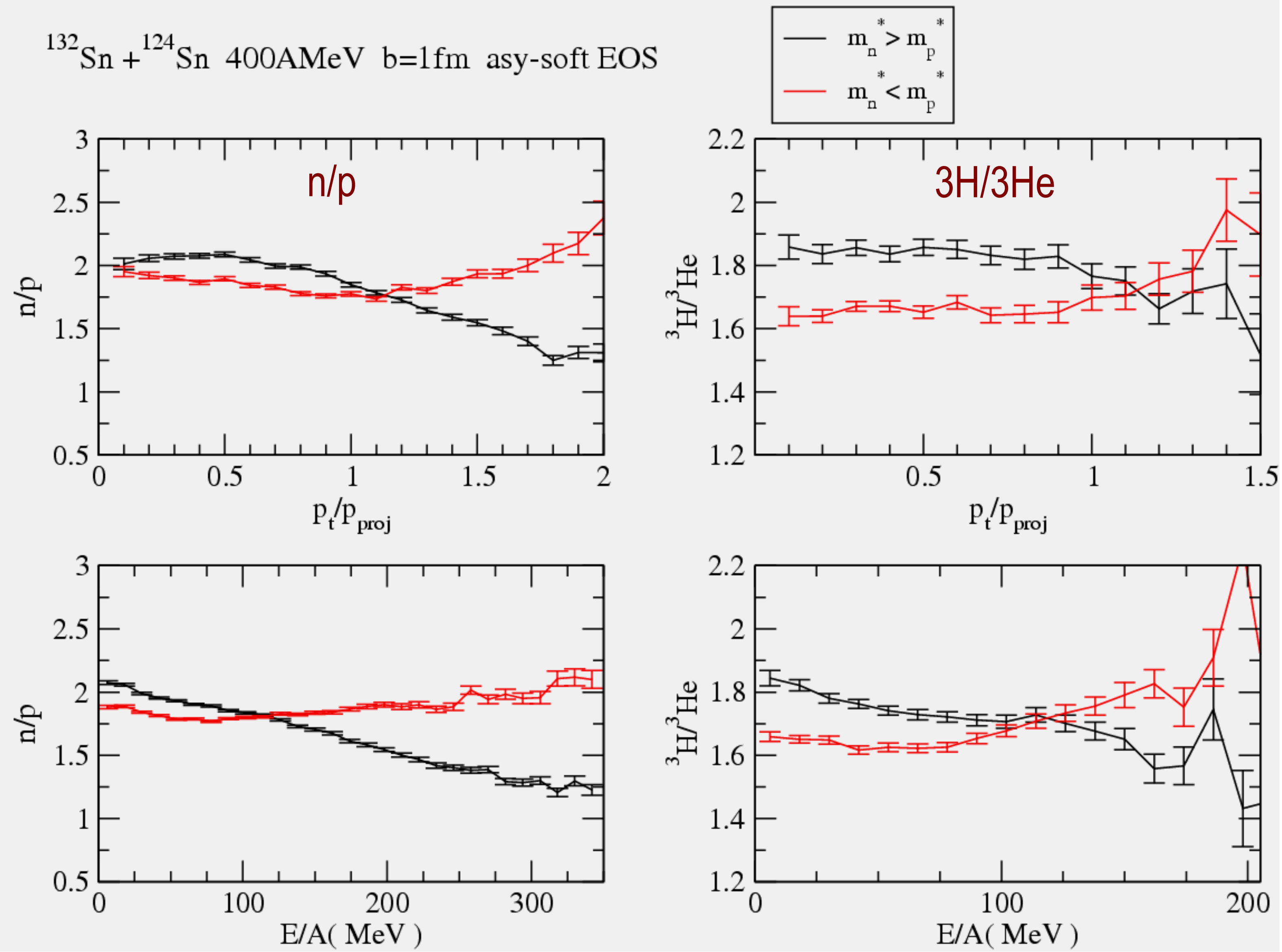
vs. $p_{transverse}$
mid-rapidity
$|y^0|<0.3$

p_{proj}~400Mev/c

vs.
kinetic
energy

Crossing of the symmetry potentials for a matter at $\rho\approx1.7\rho_0$

132Sn+124Sn 400AMeV Central → Yield Ratios : Asy-soft + mass splitting

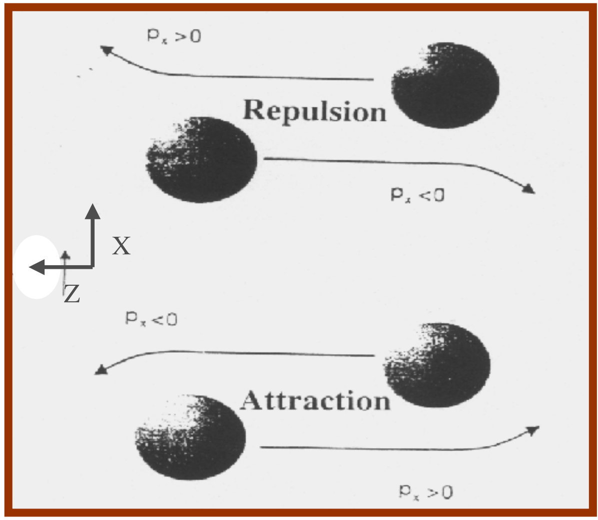


vs. $p_{transverse}$
mid-rapidity
$|y^0|<0.5$

vs.
kinetic
energy

Collective flows

In-plane



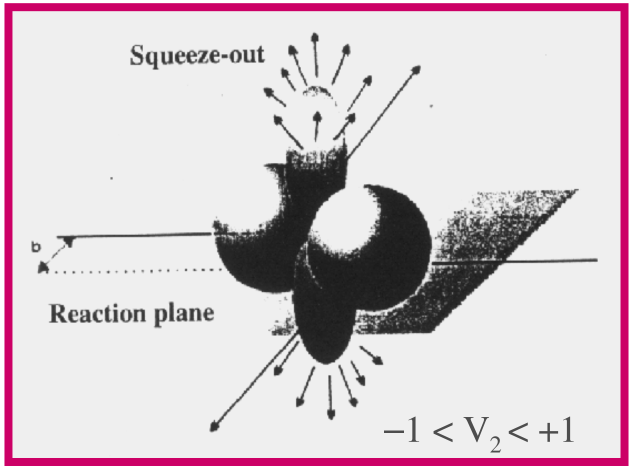
y = *rapidity*

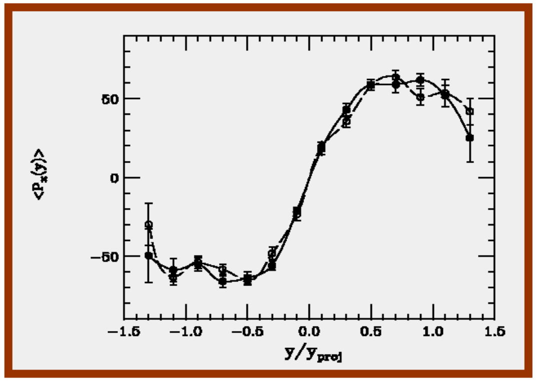
p_t = *transverse momentum*

$$V_1(y,p_t)=\langle p_x\rangle/\langle p_t\rangle_y$$

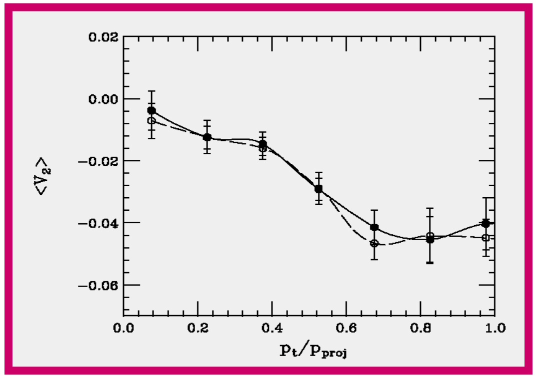
$$V_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_x^2+p_y^2}\right\rangle_y$$

Out-of-plane





$$V_2\begin{cases}=-1 & \text{full out}\\ =\ \ 0 & \text{spherical}\\ =+1 & \text{full in}\end{cases}$$



$V_1^{p-n}(p_t)=V_1^p(p_t)-V_1^n(p_t)$ ← **Isospin** → $V_2^{p-n}(p_t)=V_2^p(p_t)-V_2^n(p_t)$

$$<v_{Differential}(y,p_t)>\equiv\frac{1}{N+Z}\sum\tau_i v_i(y,p_t)$$

$$\tau_i=+1(n),-1(p)$$

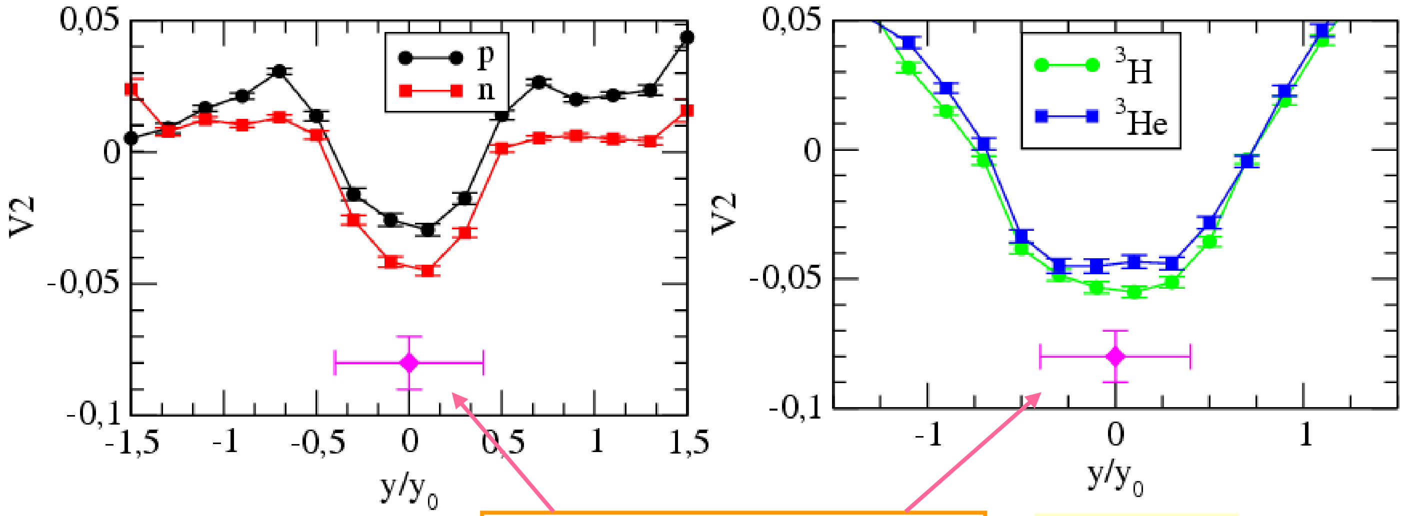
+ : isospin fractionation

-- : missed neutrons, smaller

Flow Difference vs.Differential flows

197Au+197Au 400AMeV SemiCentral → nucleon, cluster Elliptic Flows

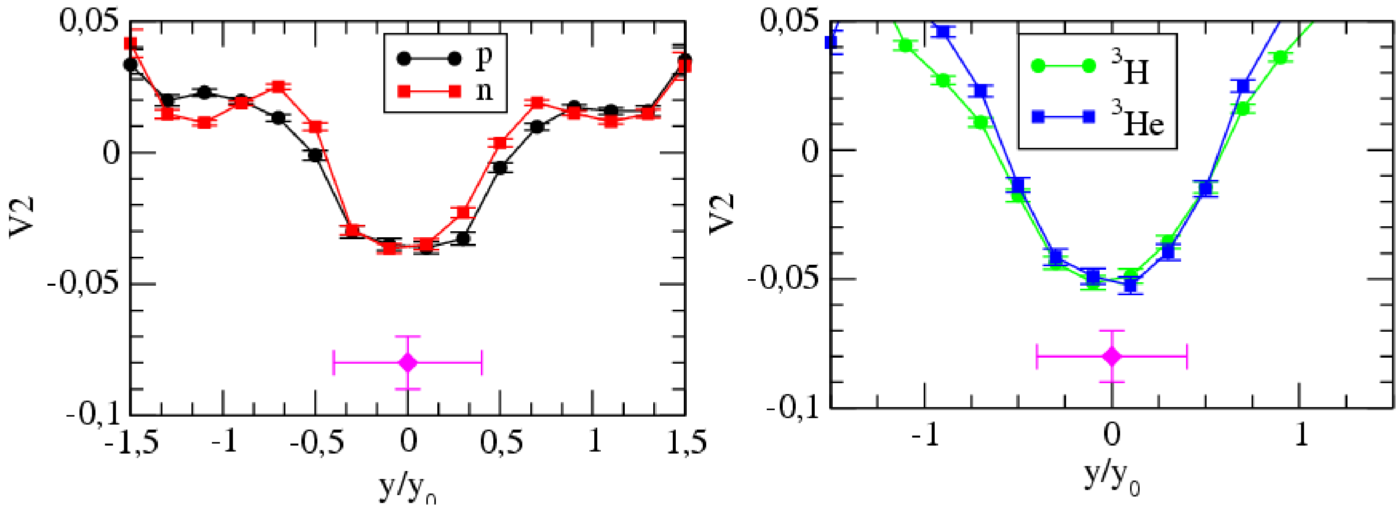
Asy-stiff
m*n < m*p



FOPI(LAND) Z=1 point

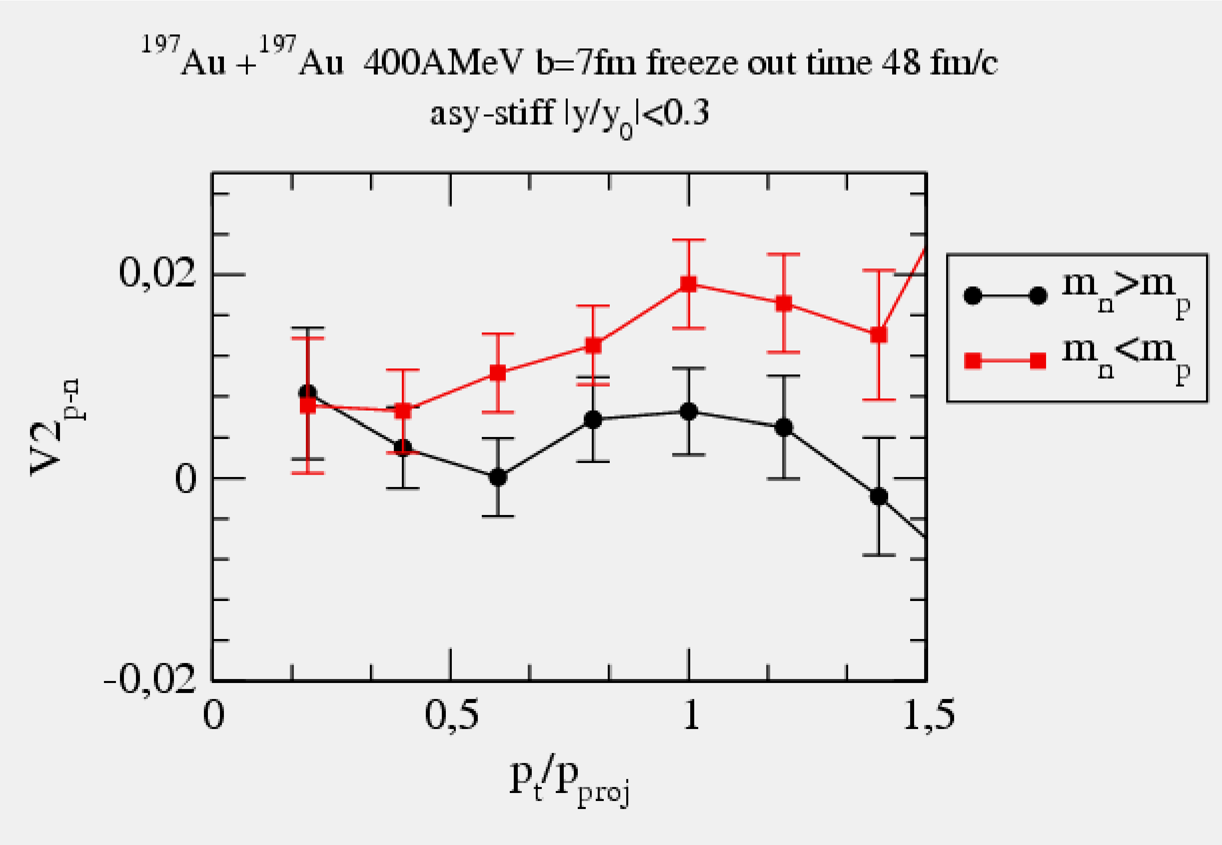
no filters

Asy-stiff
m*n > m*p



Au+Au 400AMeV Semicentral

Elliptic proton-neutron flow difference vs p_t at mid-rapidity



Relativistic Energies

Compressed Baryon Matter

Covariant Mean Field Dynamics

↓

Quantum Hadrodynamics (QHD) → Relativistic Transport Equation (RMF)

Mean Fields
Effective Masses
In-medium cross sections

⟺ *Self-Energies*

Phys.Rep.410(2005)335-466

RBUU transport equation

Wigner transform ∩ Dirac + Fields Equation ➡ *Relativistic Vlasov Equation*
+ Collision Term…

$$\left[\frac{p_i^{*\mu}}{M_i^*}\partial_\mu + \left(\frac{p^*_{\nu i}}{M_i^*}\mathcal{F}_i^{\mu\nu} + \partial^\mu M_i^*\right)\partial_\mu^{(p^*)}\right] f_i(x,p^*) = \mathcal{I}_c$$

$$k_i^{*\mu} \equiv k_i^\mu - \Sigma_i^\mu$$

$$m_i^* \equiv M - \Sigma_{s,i}$$

drift

mean field

$$F^{\mu\nu} = \partial^\mu \Sigma^\nu - \partial^\nu \Sigma^\mu$$

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\cdot\vec{\nabla}_r f + \vec{\nabla}_r U \cdot \vec{\nabla}_p f = I_{coll}$$

Non-relativistic Boltzmann-Nordheim-Vlasov

"Lorentz Force"→ Vector Fields
pure relativistic term → ***Large Isospin Flows above 1AGeV***

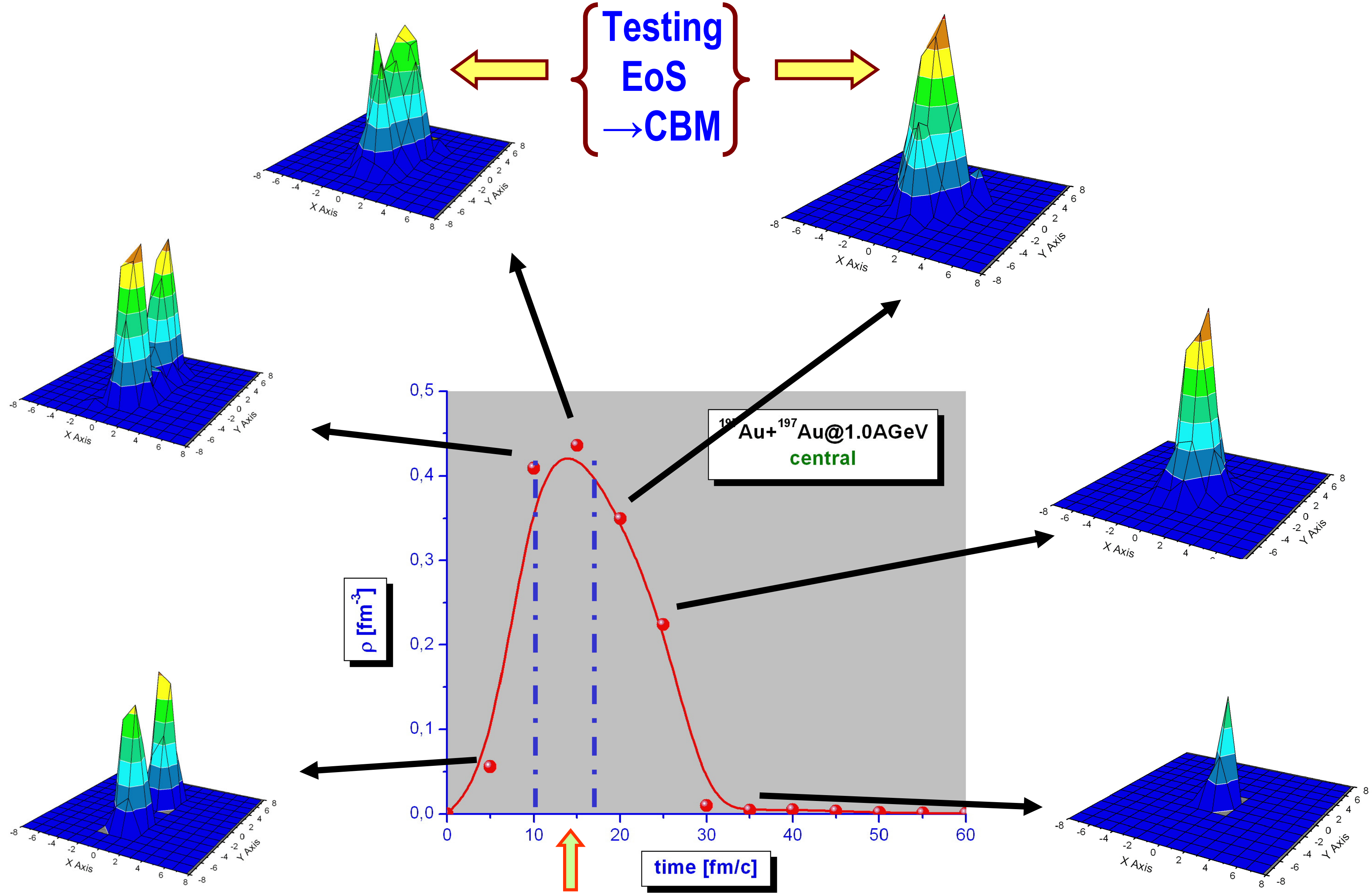
Collision term:

$$\mathcal{I}_c = \frac{g}{(2\pi)^3}\int \frac{dp_2^*}{p_2^{*0}}\frac{dp_3^*}{p_3^{*0}}\frac{dp_4^*}{p_4^{*0}}\int d\Omega\,(p^* + p_2^*)^2\,\frac{d\sigma}{d\Omega}\,\delta^4(p^* + p_2^* - p_3^* - p_4^*)$$
$$\times\{f_3 f_4[1-f][1-f_2] - f f_2[1-f_3][1-f_4]\}$$

Self-Energy contributions to the inelastic channels!

Au+Au 1AGeV central: Phase Space Evolution in a CM cell

Testing
EoS
→CBM



K production

Quantum Hadrodynamics (QHD) → Relativistic Transport Equation (RMF)

NN scattering $\xrightarrow{\text{OBE}}$ nuclear interaction from meson exchange:
main channels (plus correlations)

$$\underbrace{\underset{\text{Scalar}}{\sigma(0^+,0)}\qquad\underset{\text{Vector}}{\omega(1^-,0)}}_{\text{Isoscalar}}\qquad\underbrace{\underset{\text{Scalar}}{\delta(0^+,1)}\qquad\underset{\text{Vector}}{\rho(1^-,1)}}_{\text{Isovector}}$$

Nuclear interaction by Effective Field Theory
as a covariant Density Functional Approach

- Attraction & Repulsion ➡ **Saturation**

$$L=\overline{\Psi}\left[\gamma_\mu\left(i\partial^\mu-g_\omega\hat{V}^\mu\right)-\left(M-g_\sigma\hat{\Phi}\right)\right]+\frac{1}{2}\left(\partial^\mu\hat{\Phi}\partial_\mu\hat{\Phi}-m_\sigma^2\hat{\Phi}^2\right)-\frac{1}{4}\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}+\frac{1}{2}m_\omega^2\hat{V}_\mu\hat{V}^\mu$$

$$\sigma:\ \left(\partial_\mu\partial^\mu+m_\sigma^2\right)\hat{\Phi}=g_\sigma\overline{\psi}\psi=g_\sigma\hat{\rho}_S$$

$$\omega:\ \partial_\mu\hat{W}^{\mu\nu}+m_\omega^2\hat{V}^\nu=g_\omega\overline{\psi}\gamma^\nu\psi=g_\omega J^\nu$$

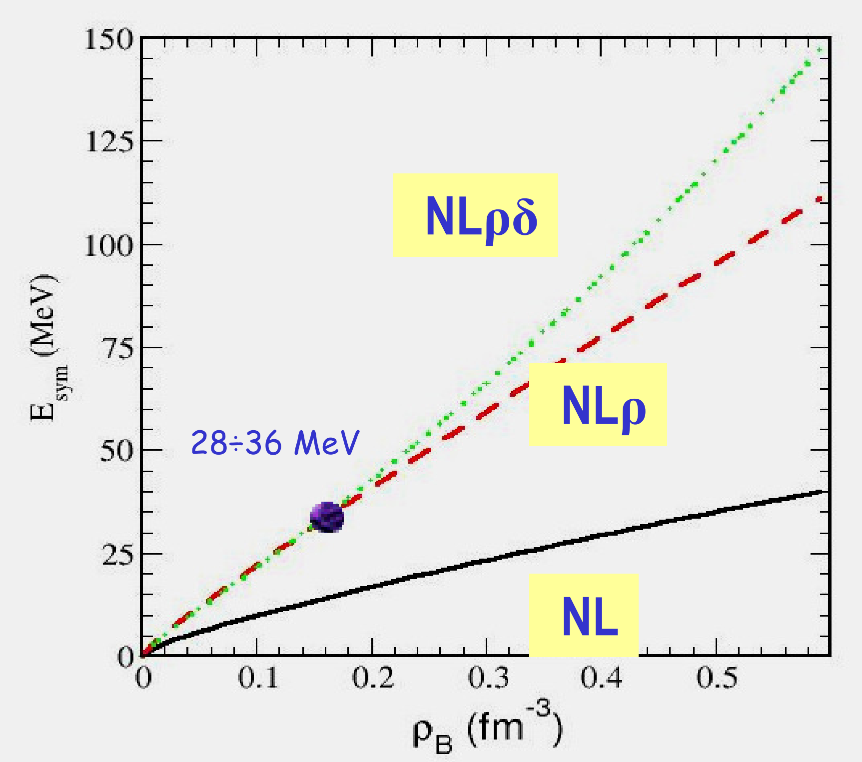
Relativistic structure also in isospin space !

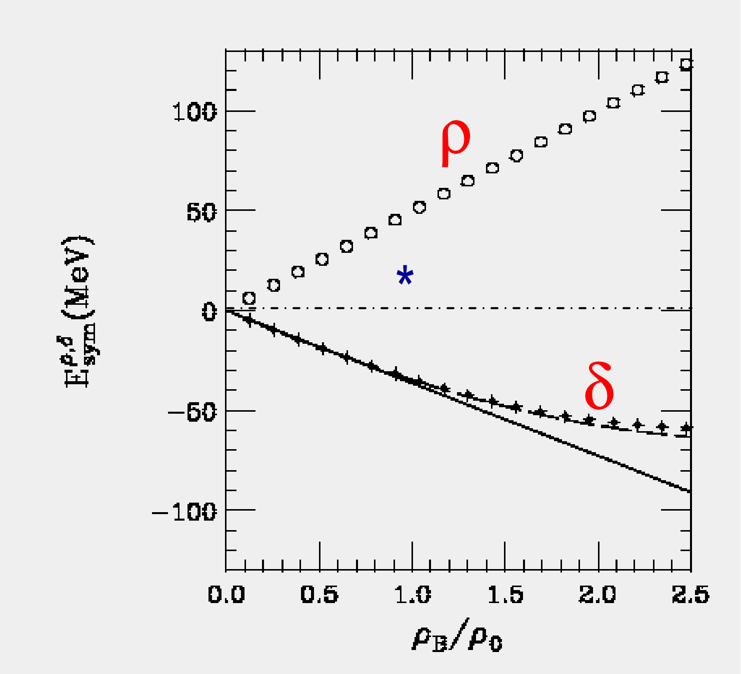
E_{sym} = kin. + (ρ–vector) – (δ–scalar)

RMF Symmetry Energy: the δ - mechanism

$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^{*2}} + \frac{1}{2}\left[f_\rho - f_\delta \left(\frac{M^*}{E^*} \right)^2 \right] \rho_B$$

$$f_{\rho,\delta} \equiv \left(\frac{g_{\rho,\delta}}{m_{\rho,\delta}} \right)^2$$





Liu Bo et al., PRC65(2002)045201

Constant Coupling Expectations

Self-Energies: kinetic momenta and (Dirac) effective masses

$$k_i^{*\mu} \equiv k_i^{\mu} - \Sigma_i^{\mu}$$

$$m_i^{*} \equiv M - \Sigma_{s,i}$$

$$\boxed{\begin{aligned} \Sigma_s(n,p) &= f_\sigma \sigma(\rho_s) \mp f_\delta \rho_{s3} \\ \Sigma^\mu(n,p) &= f_\omega j^\mu \mp f_\rho j_3^\mu \end{aligned}}$$

Upper sign: n

$$(\rho, j)_3 \equiv (\rho, j)_p - (\rho, j)_n$$

$$\rho_{B3} \equiv \rho_{Bp} - \rho_{Bn} < 0, n - rich$$

Dirac dispersion relation: single particle energies

$$\varepsilon_i + M = +\Sigma_i^0 + \sqrt{k^2 + m_i^{*2}}$$

→

n-rich:

- **Neutrons see a more repulsive vector field, increasing with f_ρ and isospin density**
- **m*(n)<m*(p)**

Chemical Potentials (zero temp.)

$$\mu_i = \sqrt{k_F^{\ 2} + m_i^{*2}} + f_\omega \rho_B \mp f_\rho \rho_{B3}$$

→

asymmetry parameter

$$\mu_n - \mu_p \approx \left[4E_{sym}(kin) + 2\rho_B f_\rho\right]\alpha$$

Isospin Flows at Relativistic Energies

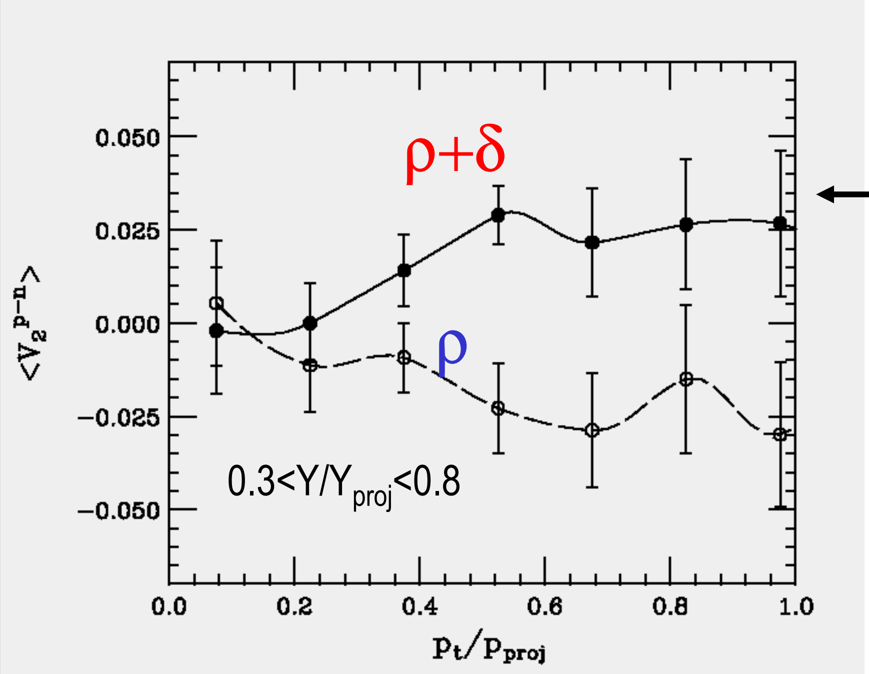
$E_{sym}(\rho)$: Sensitivity to the Covariant Structure

Enhancement of the Isovector-vector contribution via the Lorentz Force

High p_t selections: source at higher density
→ Symmetry Energy at 3-4ρ_0

Elliptic flow Difference

132Sn+132Sn, 1.5AGeV, b=6fm: NL-ρ & NL-(ρ +δ)



- Difference at high p_t ⇔ first stage

High p_t neutrons are emitted “earlier”

Equilibrium (ρ,δ) dynamically broken:
Importance of the covariant structure

approximations

$$\frac{d\vec{p}_p^{\,*}}{d\tau} - \frac{d\vec{p}_n^{\,*}}{d\tau} \simeq 2\left[\gamma f_\rho - \frac{f_\delta}{\gamma}\right]\vec{\nabla}\rho_3 = \frac{4}{\rho_B}E^*_{sym}\vec{\nabla}\rho_3$$

$$2\left[f_\rho - f_\delta\frac{M^*}{E_F^*}\right] = \frac{4}{\rho_B}E_{sym}^{pot}$$

Dynamical boosting of the vector contribution

V.Greco et al., PLB562(2003)215

Meson Production at Relativistic Energies: π^-/π^+, K^0/K^+

$E_{sym}(\rho)$: Sensitivity to the Covariant Structure

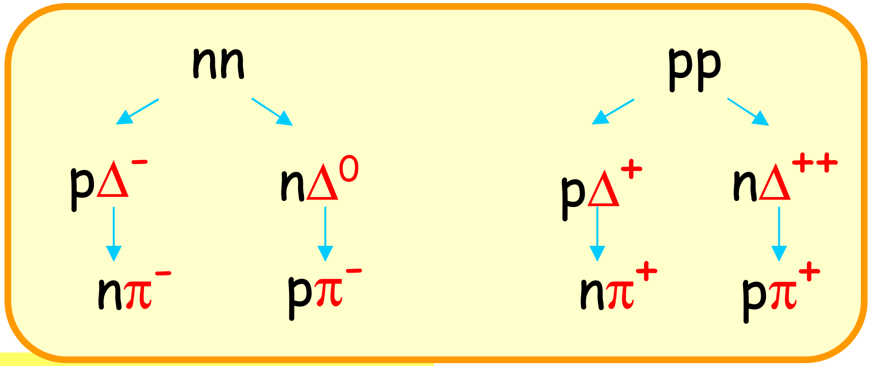
Self-energy rearrangement in the inelastic vertices with different isospin structure → *large effects around the thresholds*

High p_t selections: source at higher density
→ *Symmetry Energy at 3-4*ρ_0

PION PRODUCTION

G.Ferini et al., NPA 762 (2005) 147, NM Box
PRL 97 (2006) 202301, HIC

Main mechanism $NN \Rightarrow N\Delta \searrow \pi N$



n→p "transformation"

$$\boxed{\Rightarrow \frac{\pi^-}{\pi^+}}$$

Vector self energy more repulsive for neutrons and more attractive for protons

1. C.M. energy available: "threshold effect"

$$\varepsilon_{n,p} = E^*_{n,p} + f_\omega \rho_B \mp f_\rho \rho_{B3} \longrightarrow \begin{array}{l} s_{nn}(NL) < s_{nn}(NL\rho) < s_{nn}(NL\rho\delta) \\ s_{pp}(NL) > s_{pp}(NL\rho) > s_{pp}(NL\rho\delta) \end{array}$$

π(-) enhanced
π(+) reduced

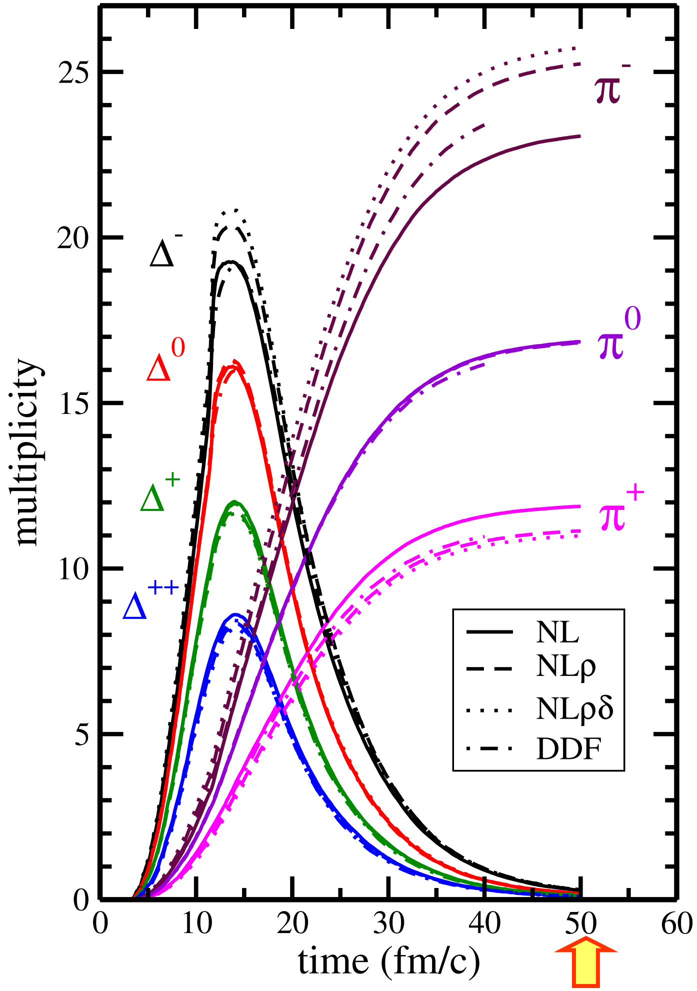
2. Fast neutron emission: "mean field effect"

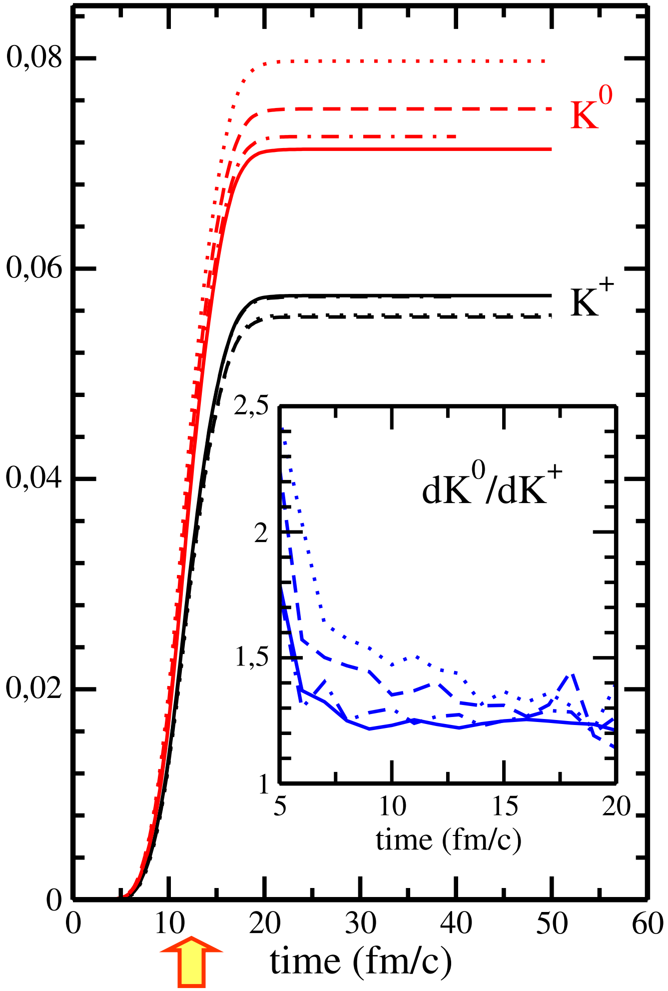
$$\boxed{\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow \Rightarrow decrease: NL \rightarrow NL\rho \rightarrow NL\rho\delta}$$

Some compensation in "open" systems, HIC, but "threshold effect" more effective, in particular at low energies

⇒ **No evidence of Chemical Equilibrium!!**

Pion/Kaon production in “open” system: Au+Au 1AGeV, central





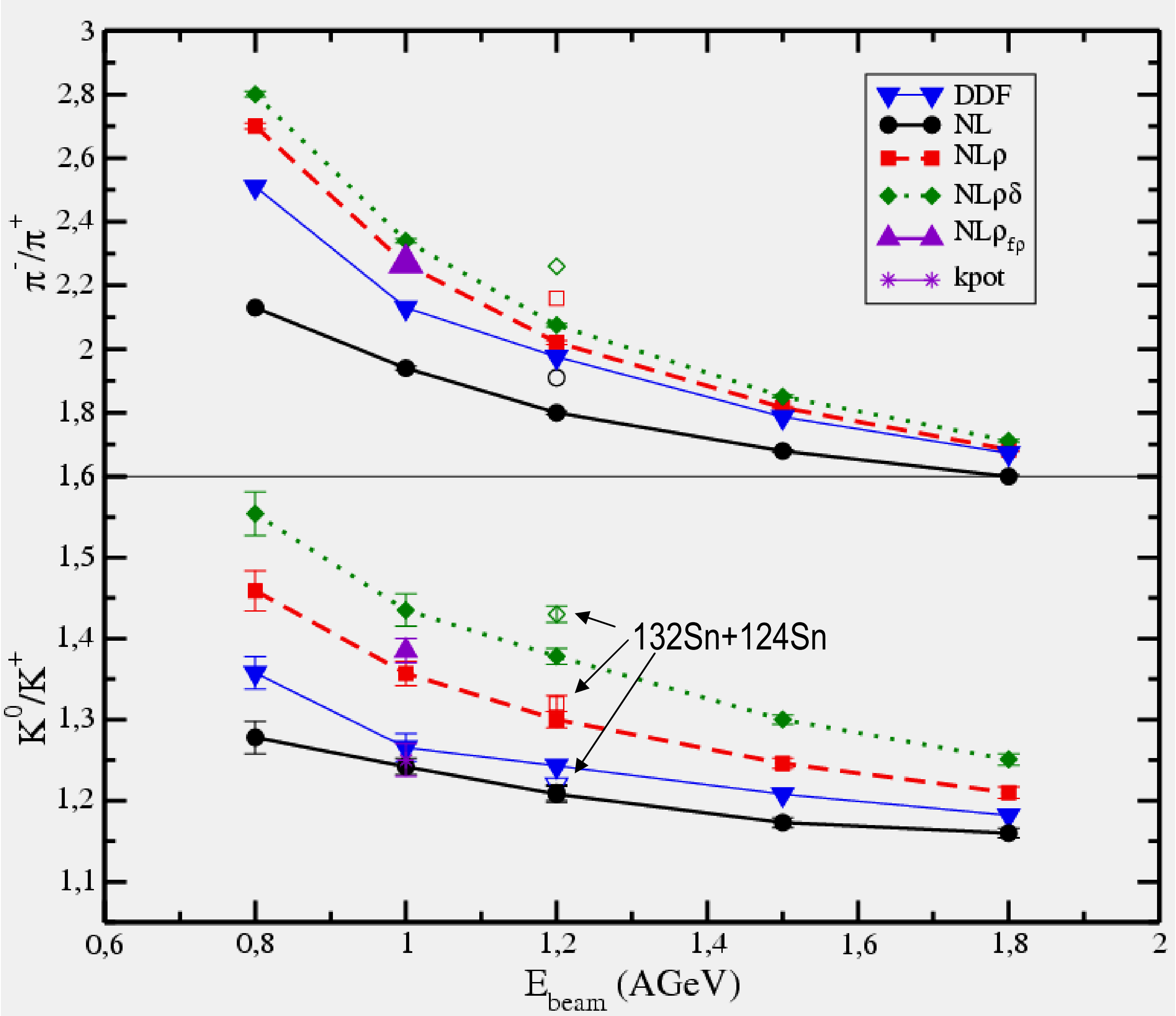
Pions: large freeze-out,
compensation

Kaons:

- **early production: high density phase**
- **isovector channel effects →**
  but mostly coming from second step collisions…
  → reduced asymmetry of the source

G.Ferini et al.,PRL 97 (2006) 202301

Au+Au central: π and K yield ratios vs. beam energy



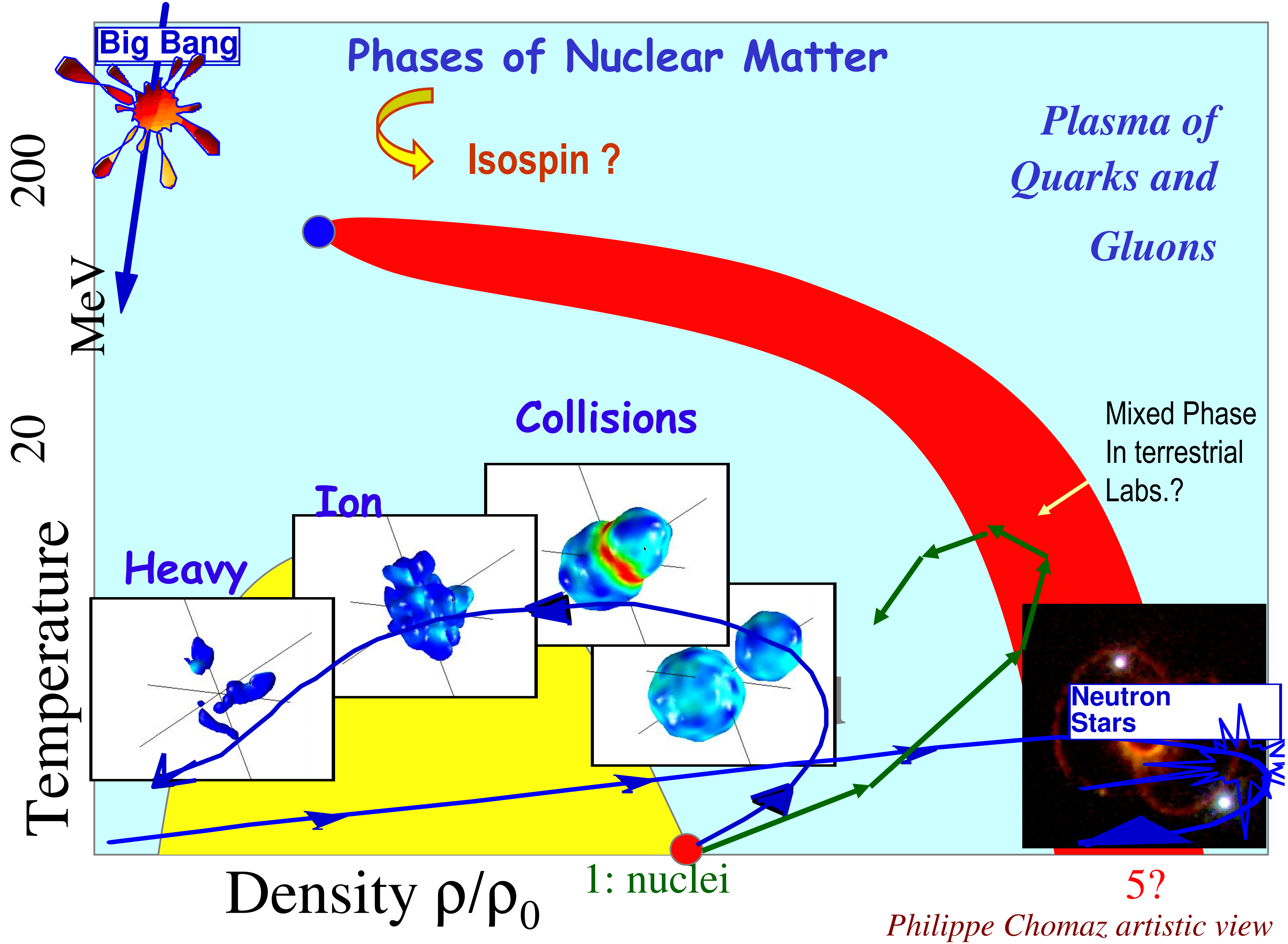
Kaons:
~15% difference between DDF and NLρδ

Inclusive multiplicities

Pions: large effects at lower energies

G.Ferini et al.,PRL 97 (2006) 202301

Phases of Nuclear Matter



Big Bang

Isospin ?

Plasma of Quarks and Gluons

Collisions

Heavy

Ion

Mixed Phase
In terrestrial
Labs.?

Neutron
Stars

Temperature 20 MeV 200

Density ρ/ρ_0

1: nuclei

5?

Philippe Chomaz artistic view

Testing deconfinement with RIB's?

$$\mu_B^H(\rho_B^H,\rho_3^H,T)=\mu_B^Q(\rho_B^Q,\rho_3^Q,T)$$
$$\mu_3^H(....)=\mu_3^Q(....)$$
$$P^H(\rho_B^H,\rho_3^H,T)=P^Q(\rho_B^Q,\rho_3^Q,T)$$

Mixed Phase →

$$\rho_B=(1-\chi)\rho_B^H+\chi\rho_B^Q$$
$$\rho_3=(1-\chi)\rho_3^H+\chi\rho_3^Q$$

(T,ρ_B,ρ_{B3}) binodal surface

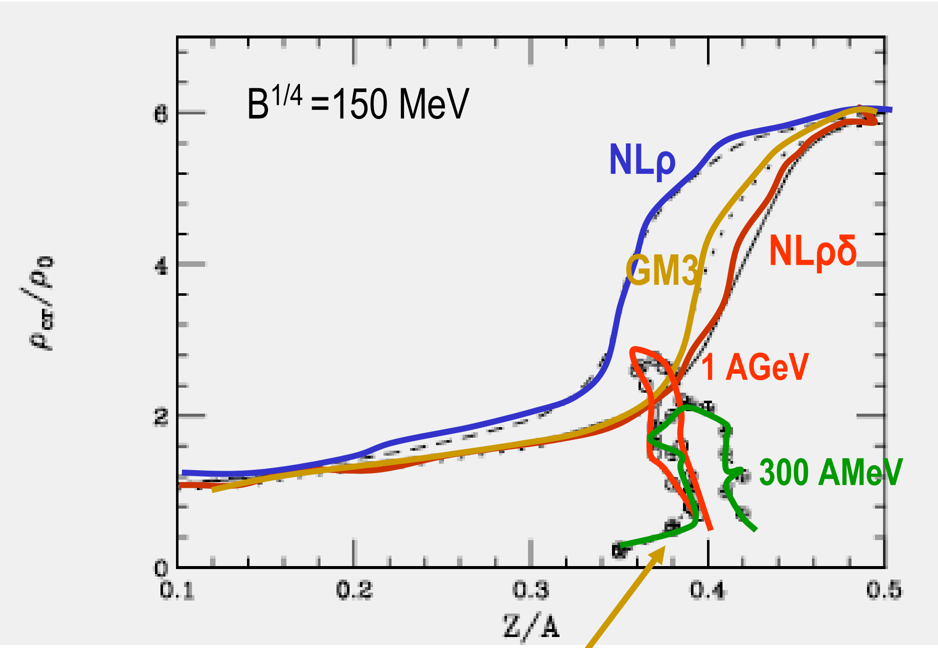
Hadron-RMF

Quark-
Bag model
(two flavors)

ρ_{trans} ⇨ onset of the mixed phase
→ decreases with asymmetry

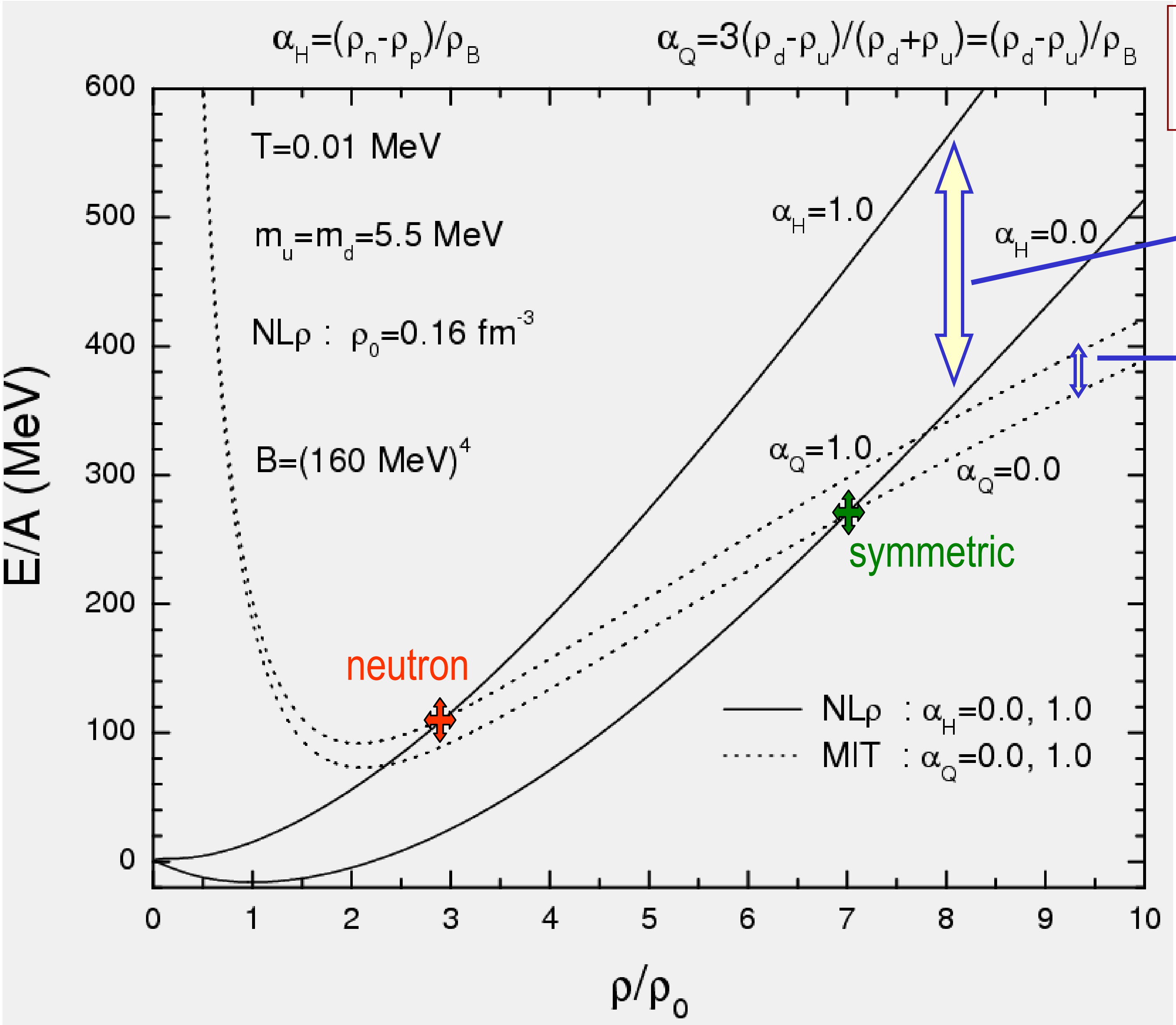
Signatures?

NPA775(2006)102-126



132Sn+124Sn, semicentral

EoS of Symmetric/Neutron Matter: Hadron (NLρ) vs MIT-Bag → Crossings

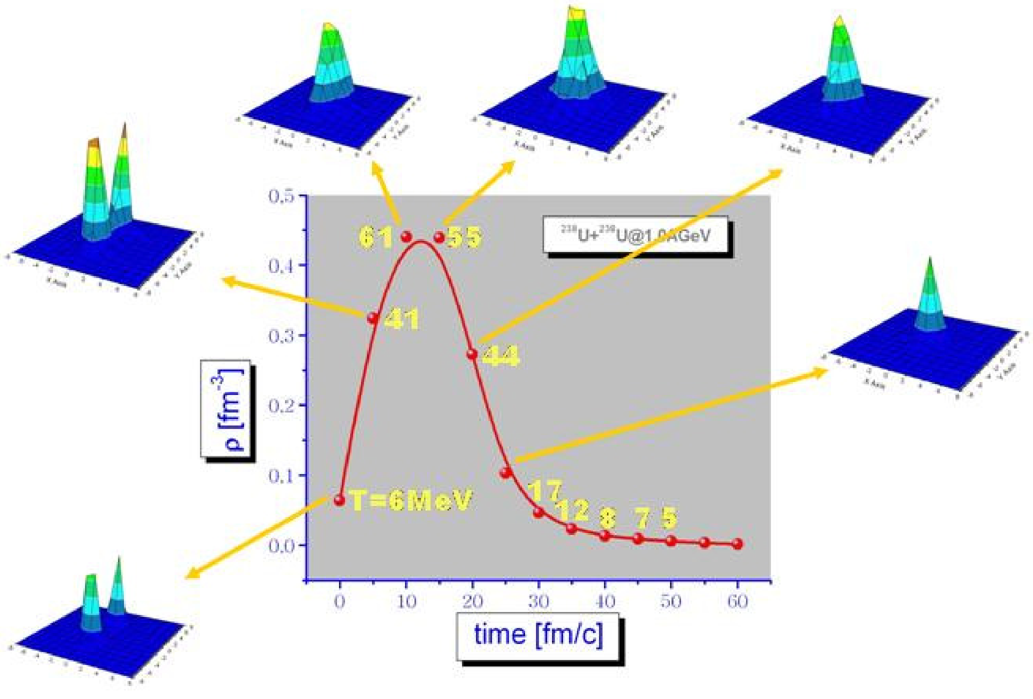


Symmetry energies

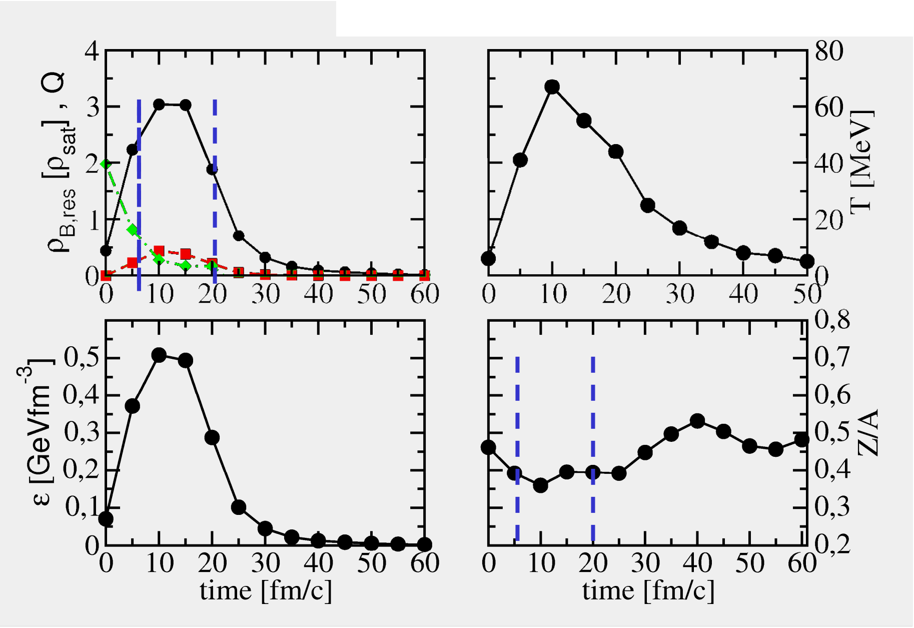
hadron

Quark:
Fermi only

System Size Dependence & Equilibration (U+U)



In a C.M. cell

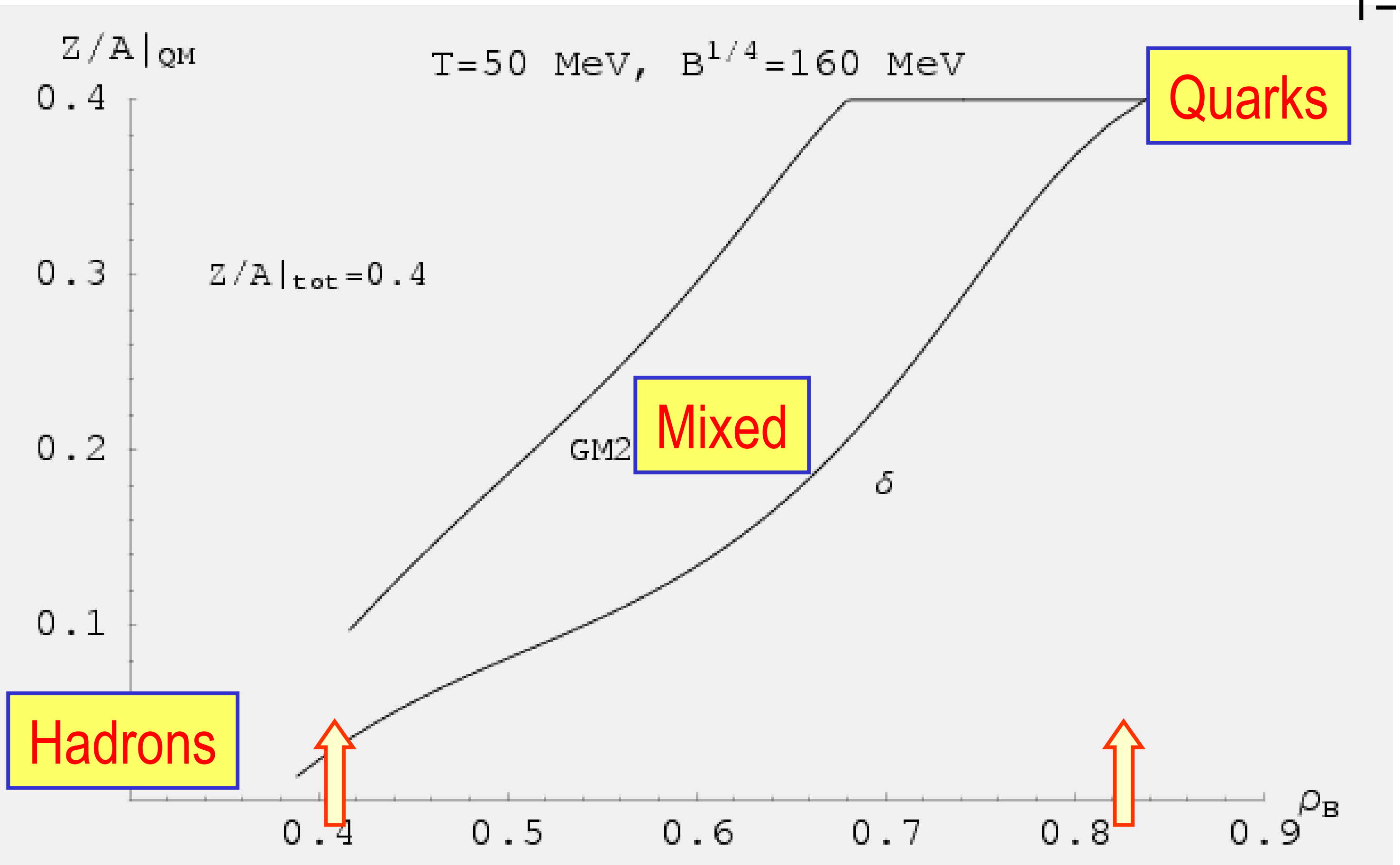


$$^{238}U + ^{238}U, 1AGeV\ , \quad b = 7\ fm$$

Exotic matter over 10 fm/c ?

Isospin content of the Quark Clusters in the Mixed Phase

T=50 MeV



Lower boundary

Signatures? Neutron migration to the quark clusters (instead of a fast emission)

NPA775(2006)102

Symmetry Energy in the Quark Phase?

Isospin Extension of the NJL Effective Lagrangian (two flavors)

Mass (Gap) - Equation

$$\boxed{\begin{aligned} &M_i = m_i - 4G_1\Phi_i - 4G_2\Phi_j , i \neq j \in (u,d) \\ &\Phi_u =< \bar{u}u >, \Phi_d =< \bar{d}d > \end{aligned}}$$

$$G_1 = (1-\alpha)G_0$$
$$G_2 = \alpha G_0$$

M.Buballa, Phys.Rep. 407 (2005)

α : flavor mixing parameter → α = ½ , NJL, Mu=Md
α → 0 , small mixing, favored → physical η mass
α → 1 , large mixing

$$M_u = m - 4G_0\Phi_u + 4\alpha G_0(\Phi_u - \Phi_d)$$
$$M_d = m - 4G_0\Phi_u + 4(1-\alpha)G_0(\Phi_u - \Phi_d)$$

Neutron-rich matter at high baryon density:
$|\Phi_d|$ decreases more rapidly due to the larger ρ_d

$\rightarrow (\Phi_u - \Phi_d) < 0$

$$\alpha \rightarrow 0 \Rightarrow M_u > M_d \Rightarrow M_p^* > M_n^*$$
$$\alpha \rightarrow 1 \Rightarrow M_u < M_d \Rightarrow M_p^* < M_n^*$$

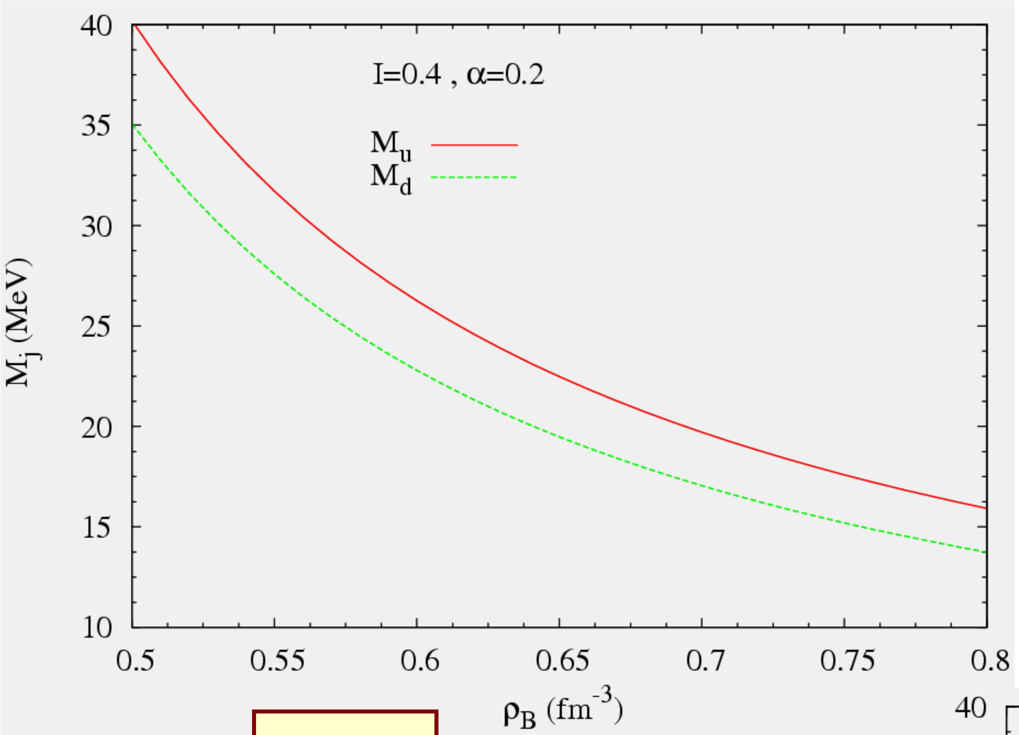
α in the range 0.15 to 0.25……

Iso-NJL

Very n-rich matter: I=N-Z/A=0.4

Masses in the Chiral Phase

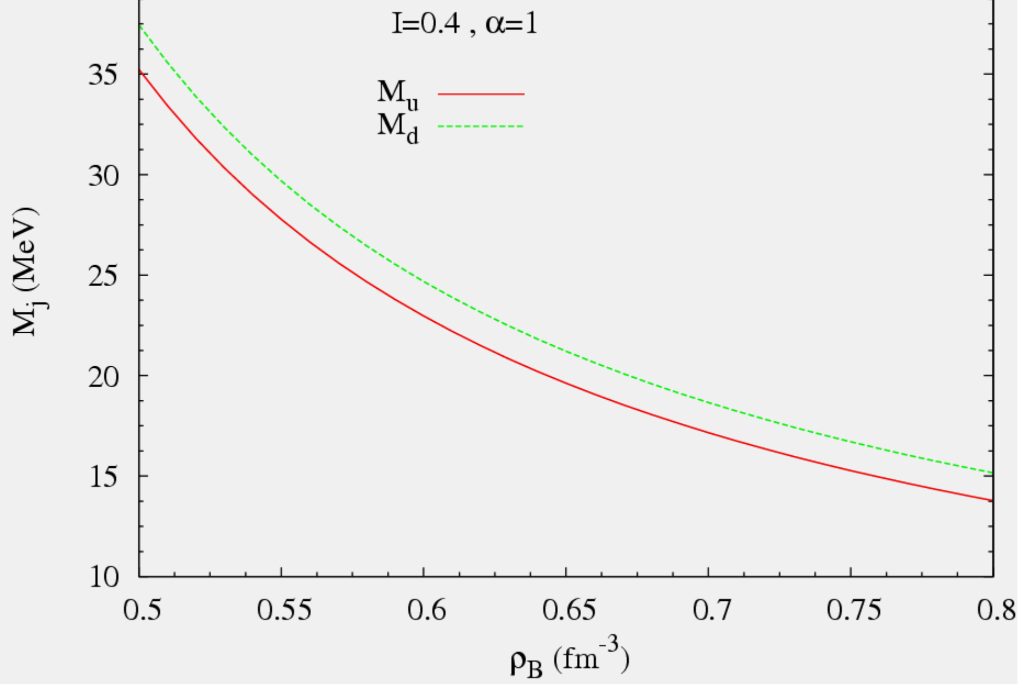
Solutions of the Iso-Gap Equation
S.Plumari, Thesis 2008



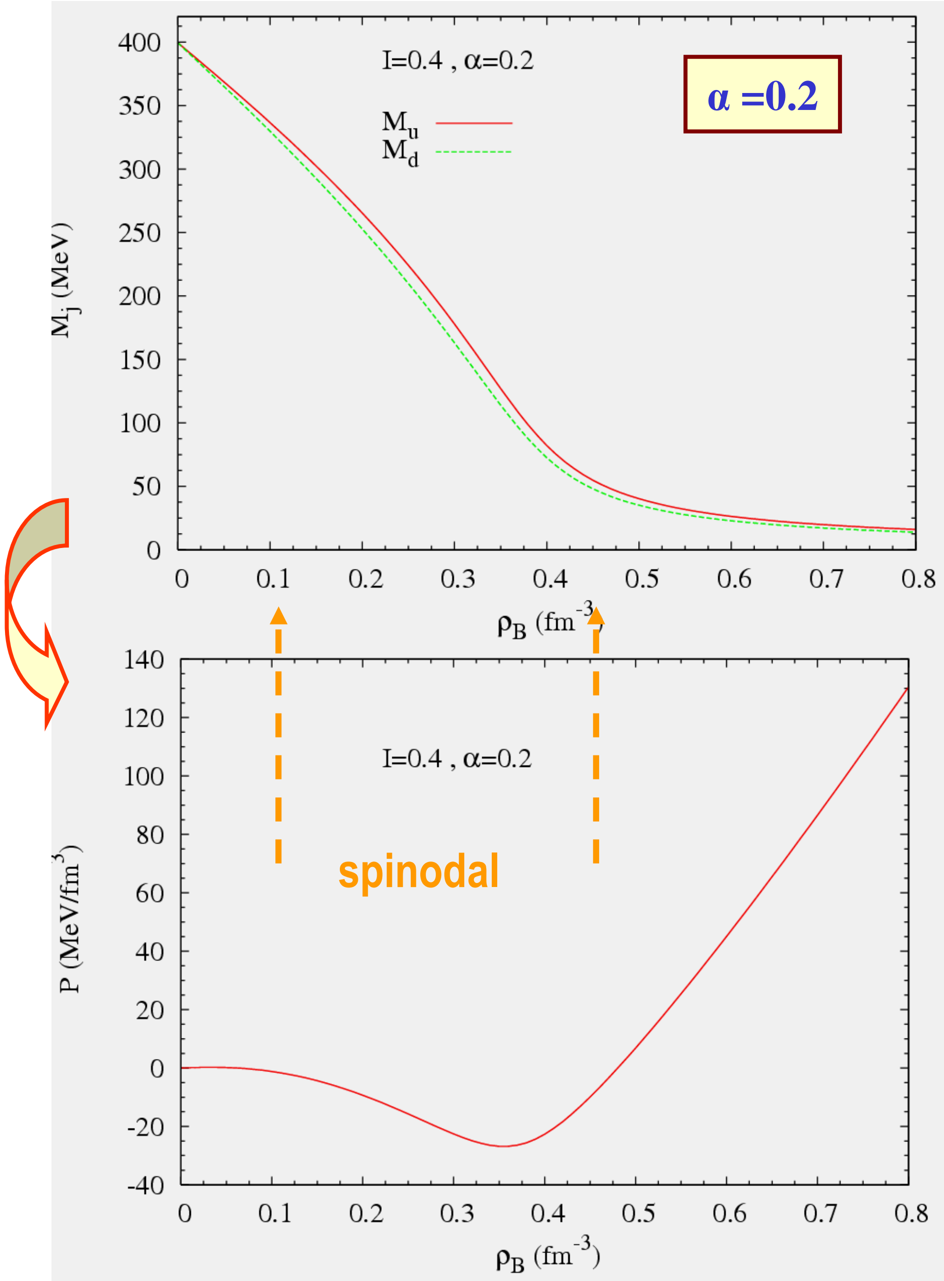
α =0.2

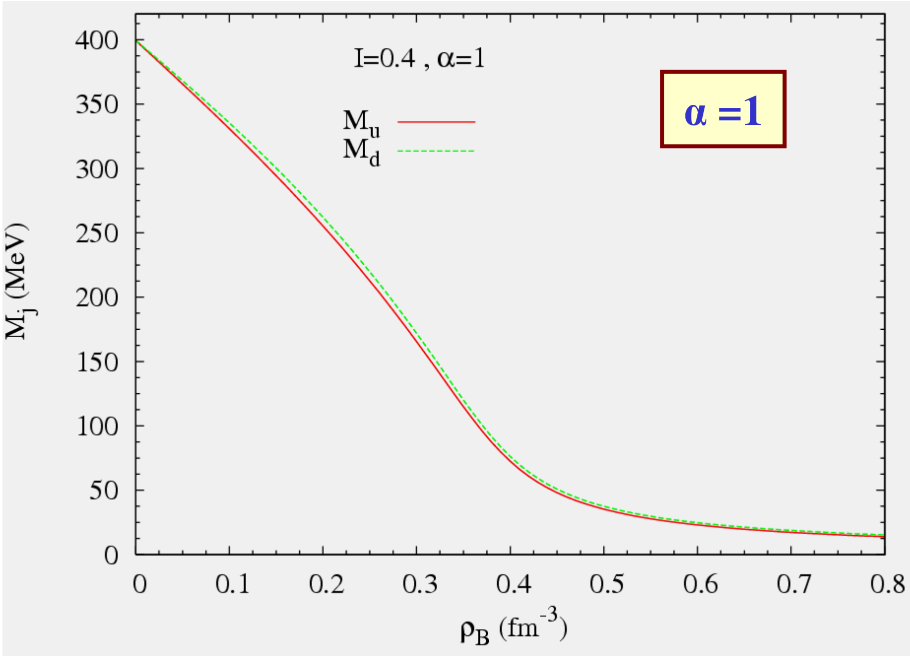
m = 6MeV
Λ = 590MeV
$G_0\Lambda^2$=2.435
→
M_{vac}=400MeV
<qbarq>=(-241.5MeV)^3
m_π=140.2MeV
f_π=92.6MeV

α =1

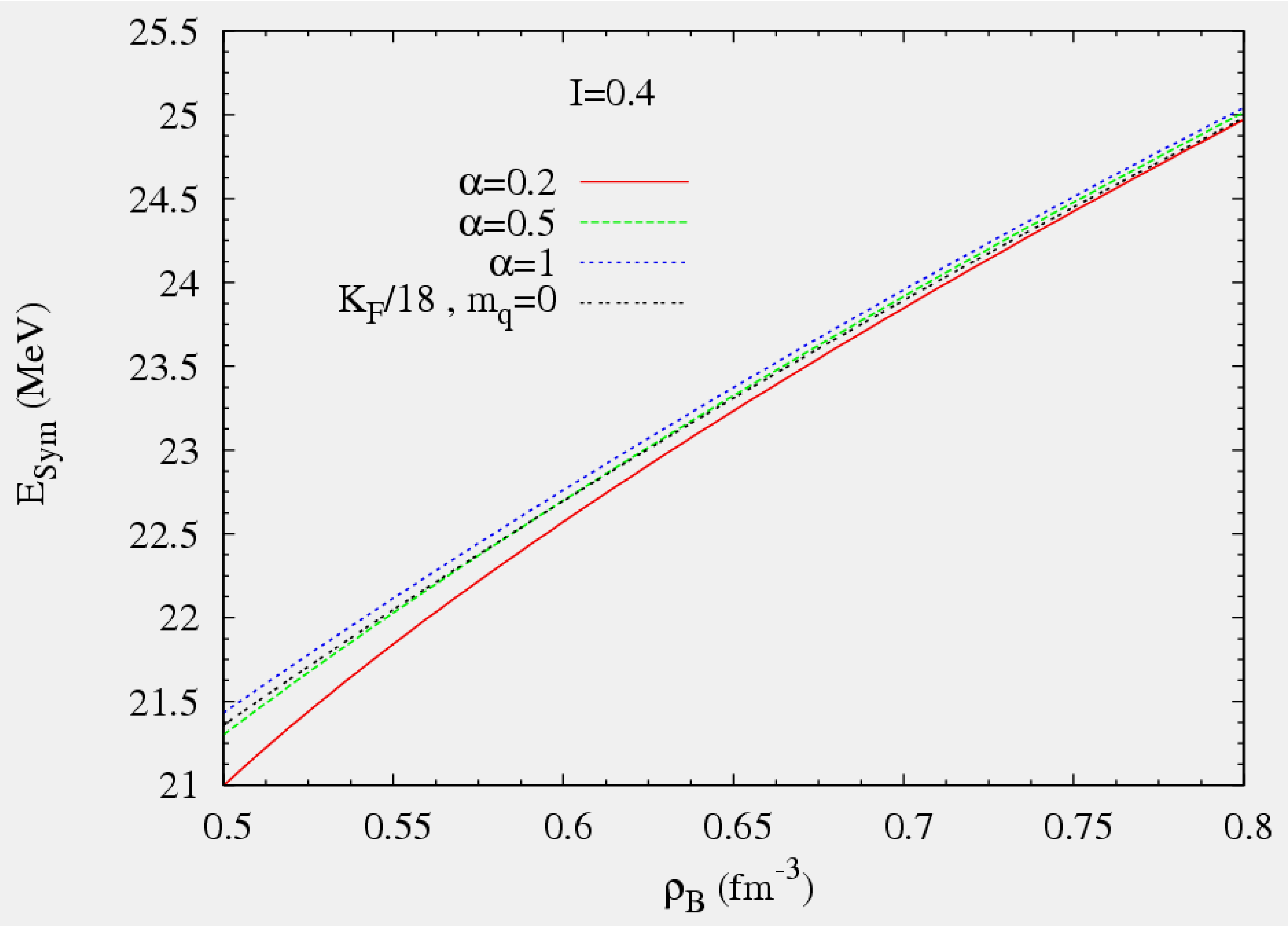


Iso-NJL: u-d mass splitting vs flavor mixing



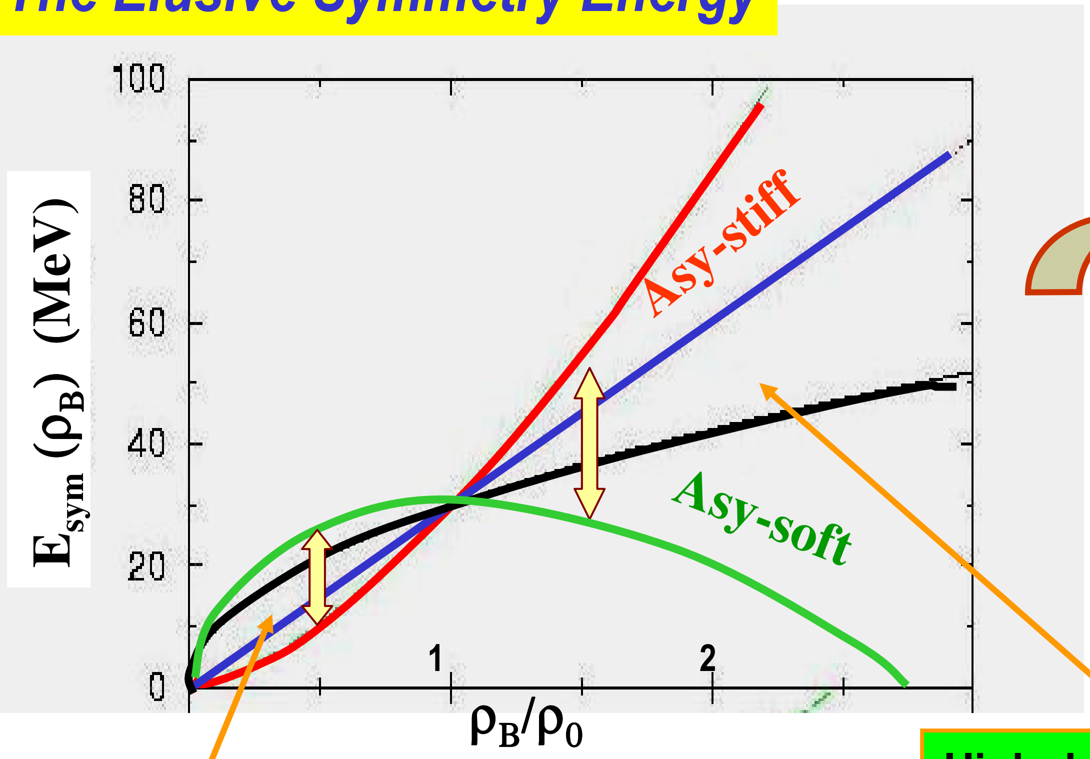


Symmetry Energy in the Chiral Phase: something is missing



….only kinetic contribution

The Elusive Symmetry Energy



AWAY FROM SATURATION:
HEAVY ION DYNAMICS

Subsaturation density (Low to Fermi energies):

Isospin Equilibration: Dynamical Dipole

Imbalance Ratios

- Mid-rapidity fragmentation

- Isospin Flows: V1 effects

.......RIBs at Fermi Energies are welcome!

High density (Intermediate energies):
Isospin effects on
- fragment production in central collisions
- "squeeze-out" nucleons and clusters
- meson production

lack of data, but….SAMURAI at RIKEN
CHIMERA+LAND at GSI

Signals of Deconfinement?

...FAIR Beams?