Scuola di Fisica Nucleare Teorica "Raimondo Anni"
Secondo Corso

Equazione di Stato ad Alta Densita' Barionica

I. Dinamica della collisioni di ioni relativistici
II. Osservabili sensibili all'EOS.
Potenziale di Simmetria.

Otranto, Maggio 2006 – ditoro@lns.infn.it

Collisioni di Ioni Pesanti ad energie relativistiche: Test di Materia Nucleare ad Alta Densita' Barionica e di Isospin

Collisioni "violente" di nuclei ad energie "Intermedie" →

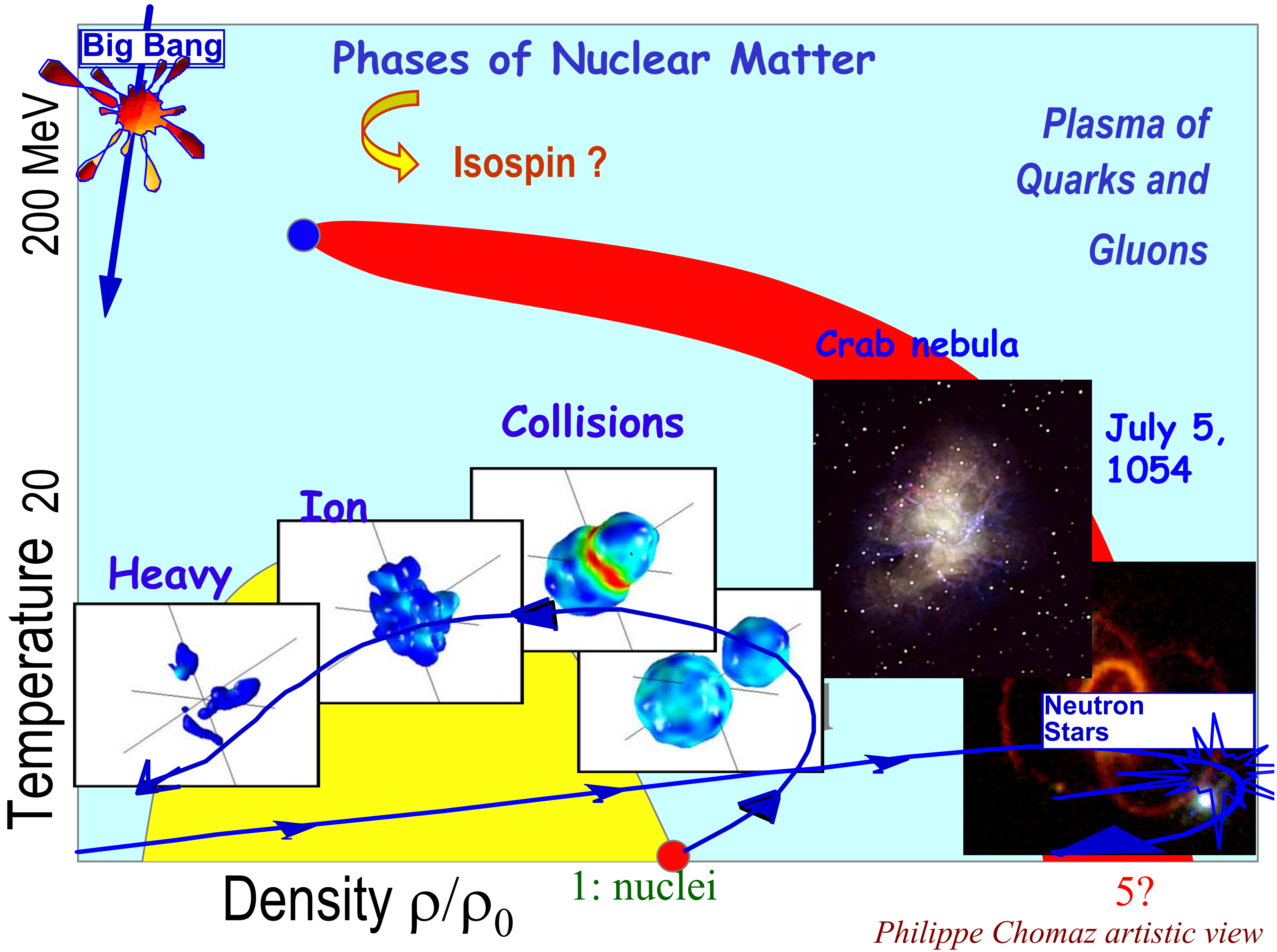
- varie regioni di densita'
- alti impulsi
- struttura covariante: "puri" effetti relativistici
- limiti della descrizione adronica

Campo Medio
Masse effettive
Sezioni d'urto nel mezzo

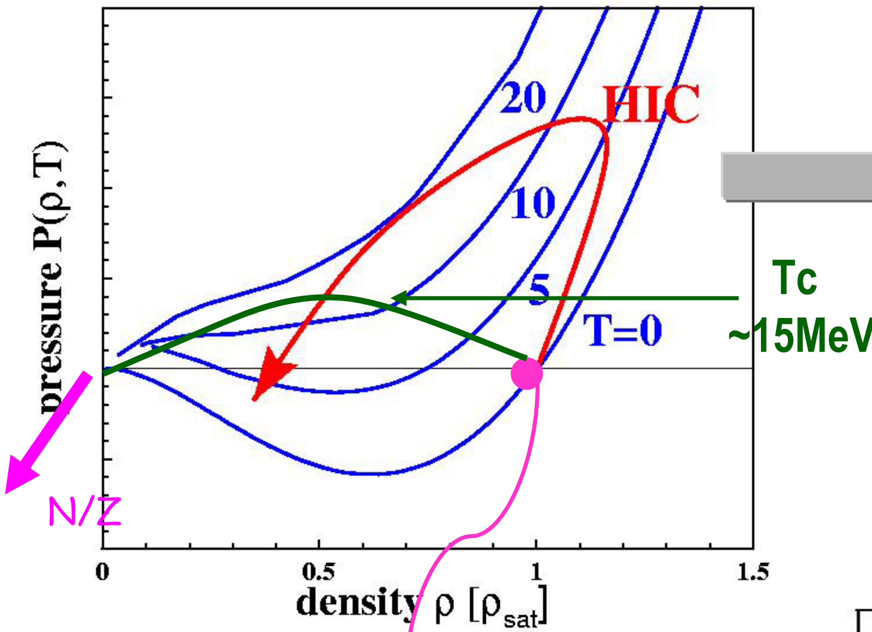
} **Self-energies** → **Equazioni del Trasporto Relativistiche Autoconsistenti**

Osservabili sensibili all'Equazione di Stato

Produzione di Frammenti
Flussi Collettivi
Produzione di Pioni/Kaoni
Trasparenza di Isospin
Segnali Precursori del Deconfinamento?


Big Bang
Phases of Nuclear Matter
Isospin ?
Plasma of Quarks and Gluons
200 MeV
Temperature 20
Crab nebula
July 5, 1054
Collisions
Ion
Heavy
Neutron Stars
Density ρ/ρ_0
1: nuclei
5?
Philippe Chomaz artistic view

Terrestrial Labs.



Ground state
T, P=0 MeV
ρ_{sat} = 0.15 fm^{-3}
E/A = -16 MeV

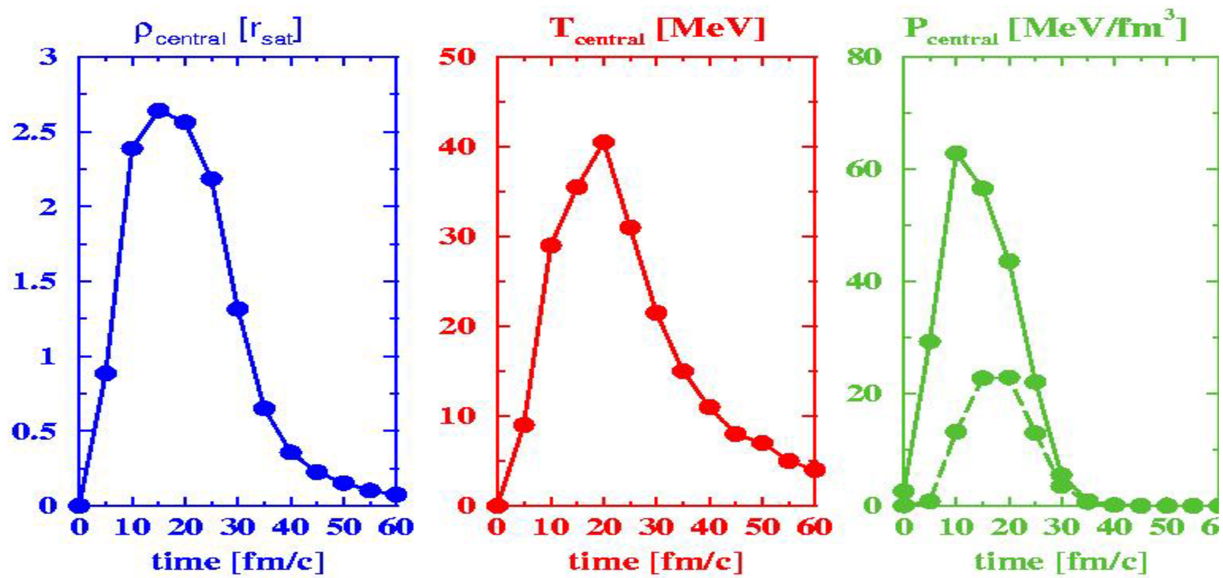
E_{beam}=0.1-10 GeV/N

Heavy Ion Collisions(HIC)

Explore matter under **extreme** Conditions

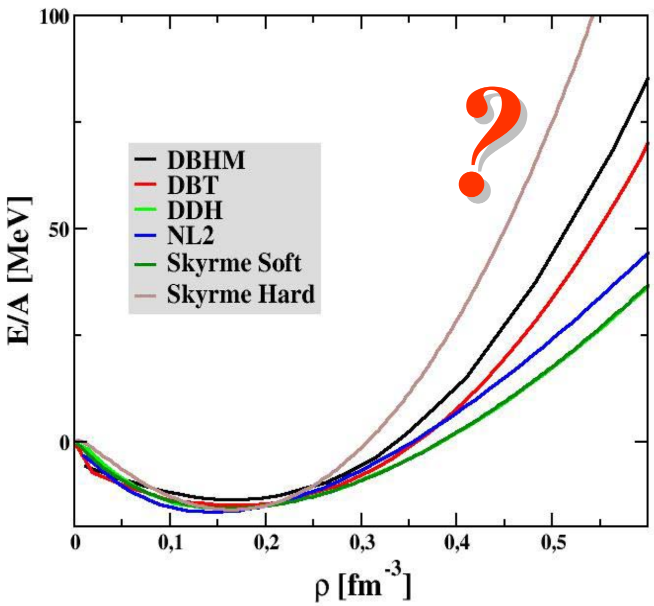
$\rho=(2-3)*\rho_{sat}, T>>T_c$ and isospin

Au (E_{beam}=0.6 GeV/nucleon) + Au – central



The Nuclear EOS Uncertainties

...iso-scalar sector



Binding energy/nucleon

$E/A = T^{00}$ (from 00-component of energy-momentum tensor)

hard EoS

κ≈380 MeV

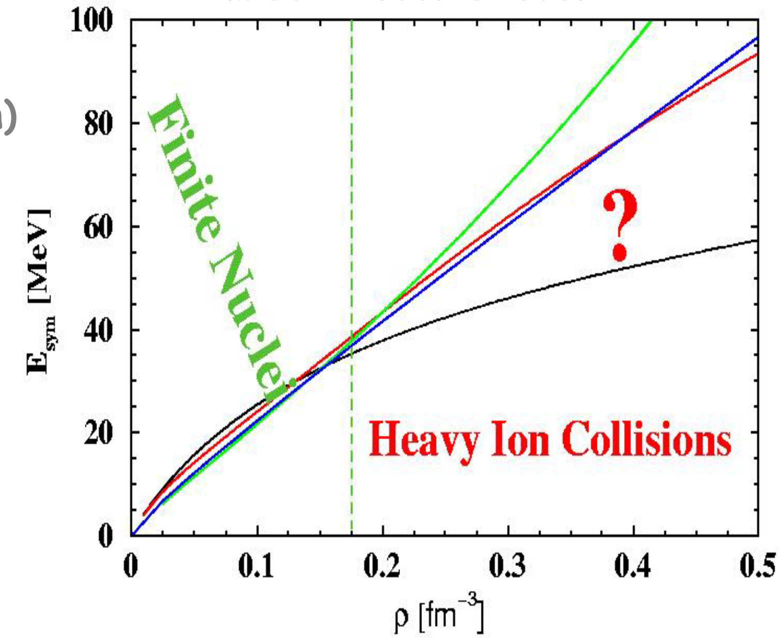
(less compression)

soft EoS

κ≈200 MeV

(more compression)

...iso-vector sector



Symmetry energy

E_{sym} from second derivative of E/A with respect to asymmetry (N-Z)/(N+Z)

Nuclear matter at supra-normal densities not fixed (crucial differences between models)

High density symmetry energy→ neutron star: - structure (mass, hybrid)

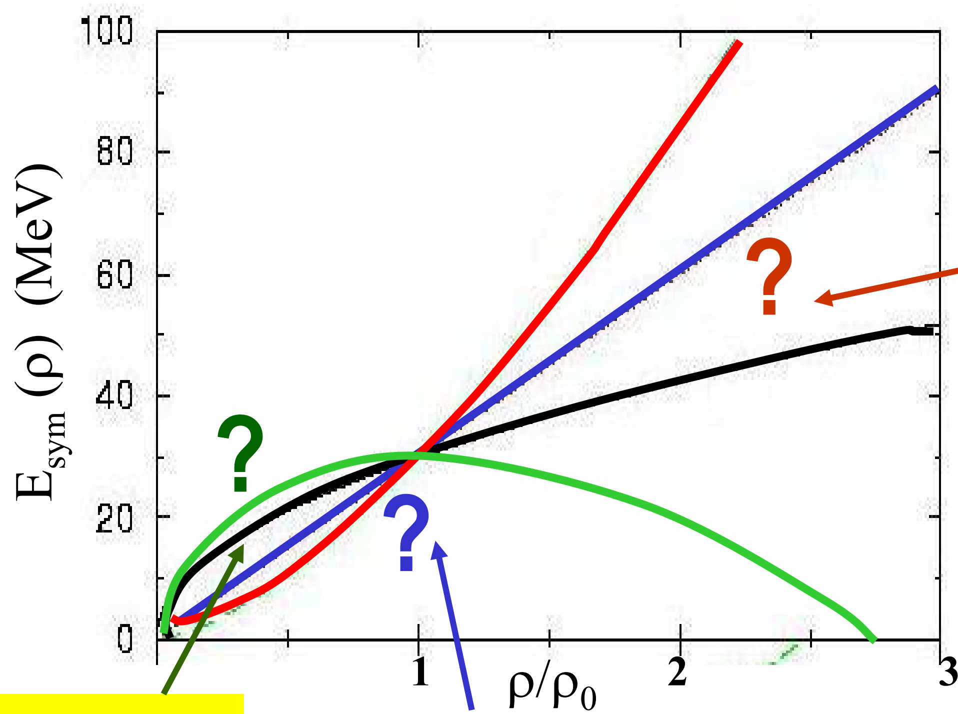
- cooling (proton fraction→direct URCA)

Symmetry Energy

$$\varepsilon(\rho,\rho_3)=\varepsilon(\rho)+\rho E_{sym}(\rho)\left(\frac{\rho_3}{\rho}\right)^2+O(\ )^4+\ldots$$

$$\rho=\rho_p+\rho_n$$
$$\rho_3=\rho_p-\rho_n$$

$$I\equiv \rho_3/\rho$$



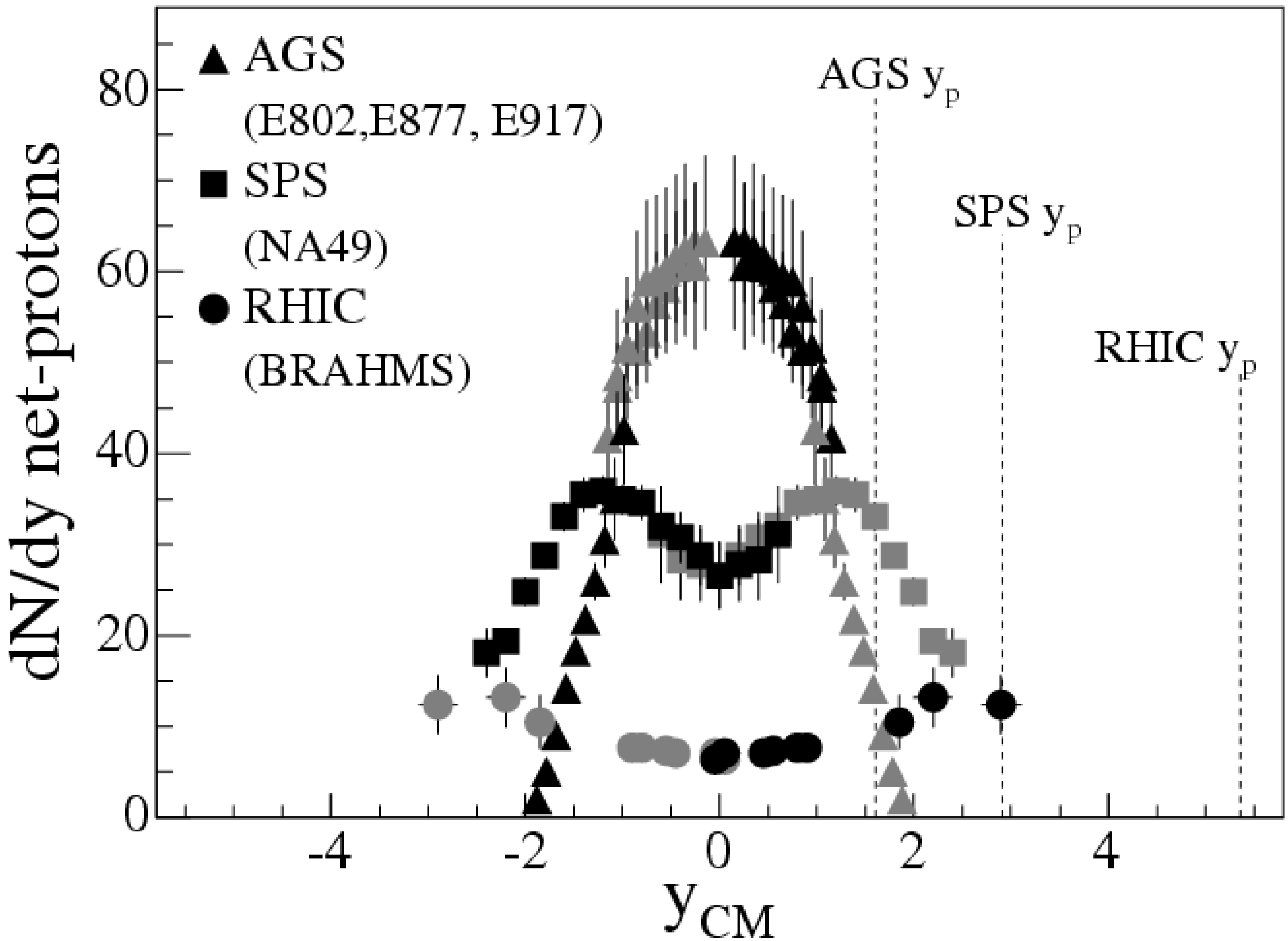
Neutron Stars
-formation
-mass/radius
-cooling
-"structure"

Neutron star crust, merging

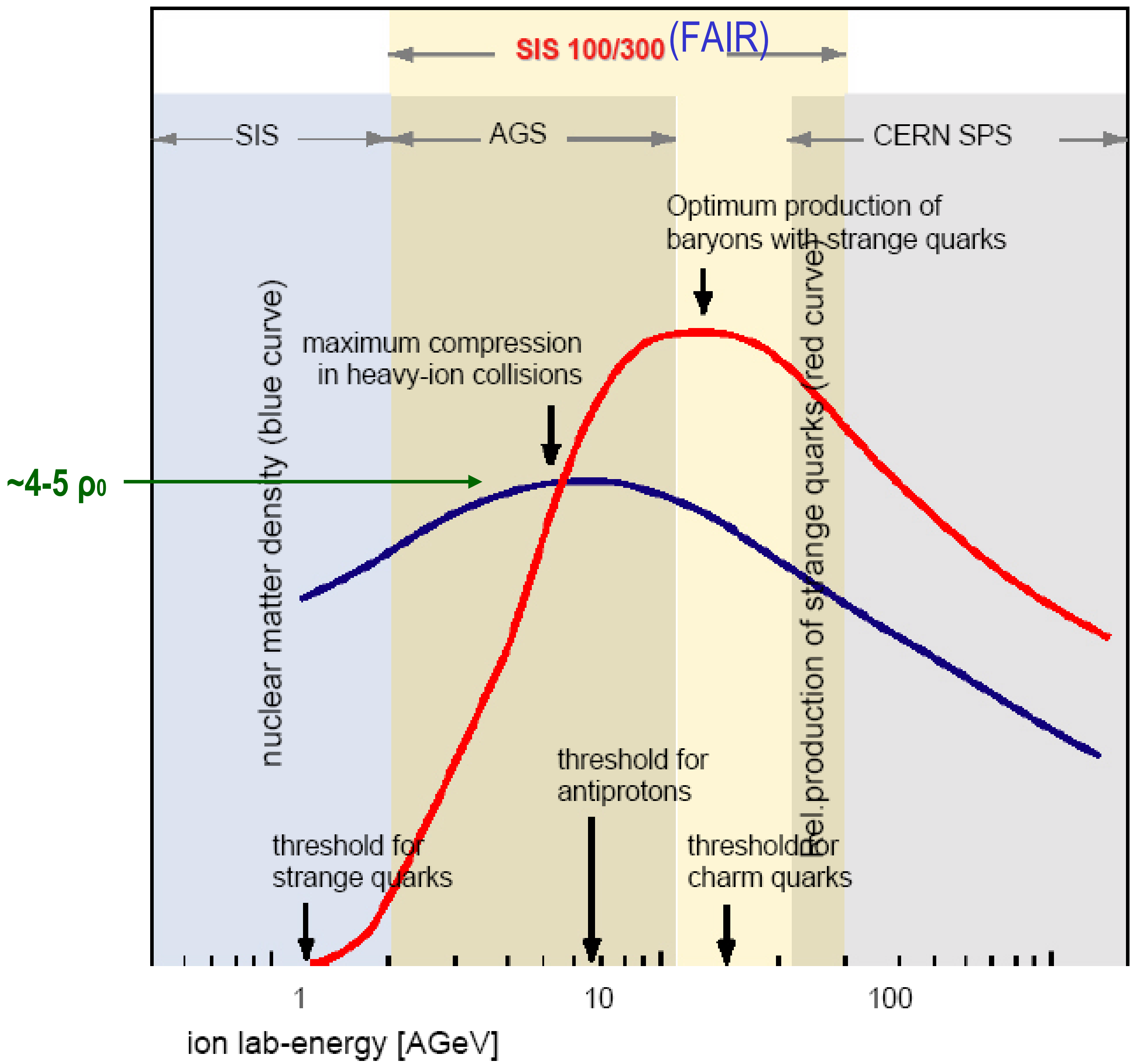
Nuclear structure
Giant Dipole
Neutron skin

Phys.Rep.410(2005)335-466

Why Intermediate Energies?
Proton stopping at mid-rapidity: Au+Au central



Physics at High Baryon (and Isospin?) Density

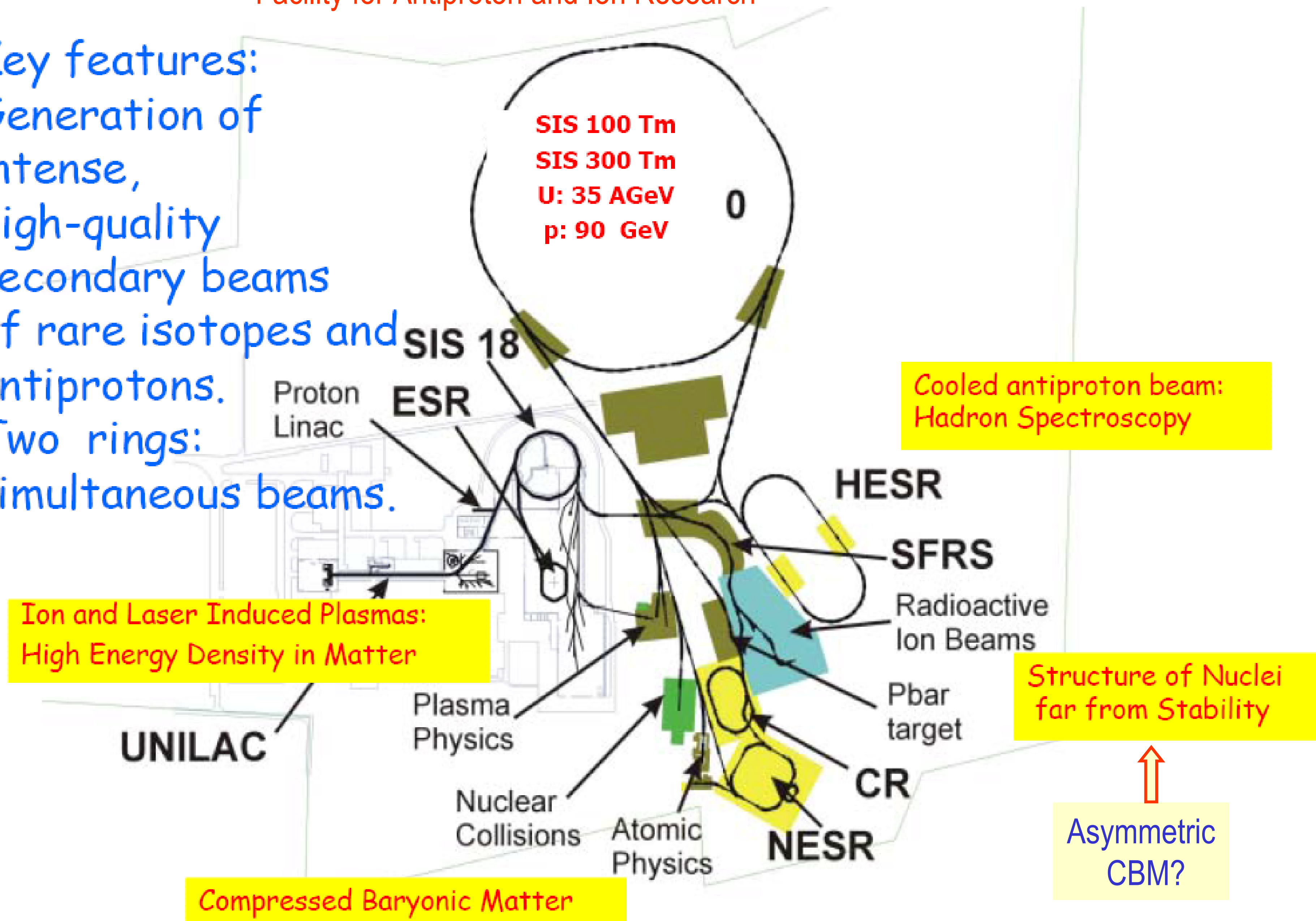


The future international accelerator facility FAIR

GSI

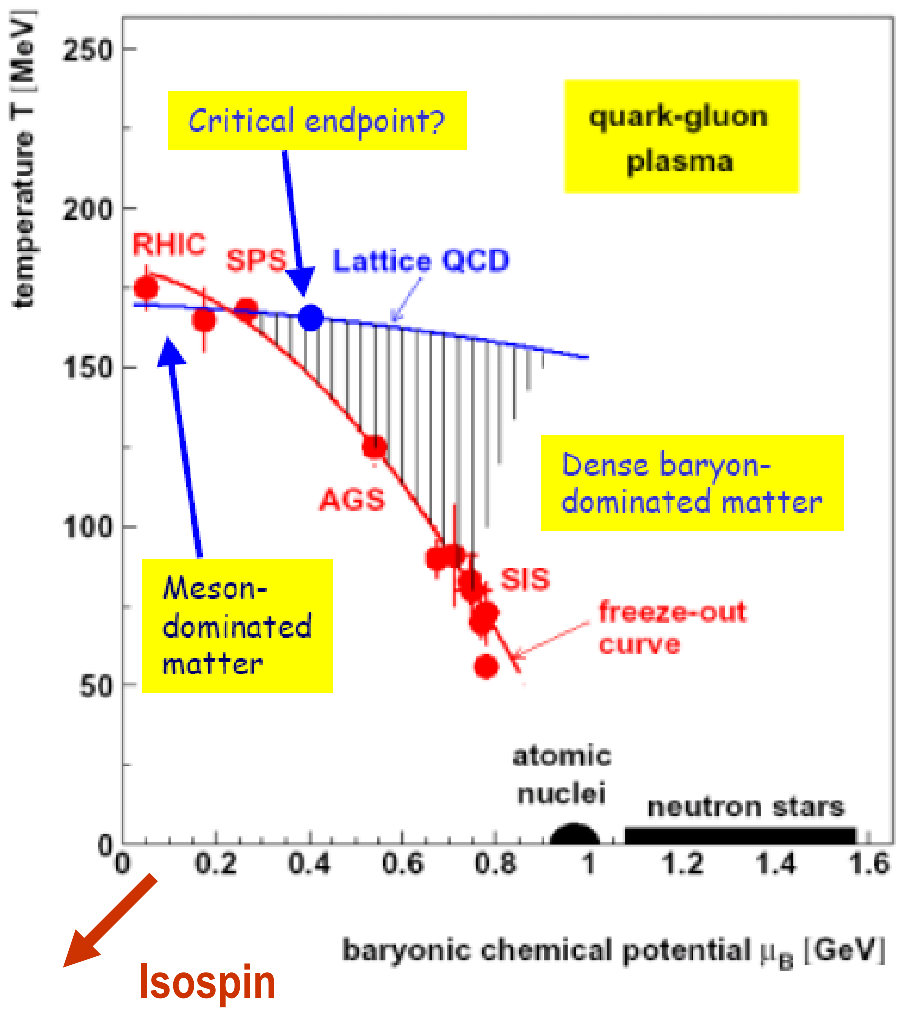
Facility for Antiproton and Ion Research

Key features:
Generation of intense, high-quality secondary beams of rare isotopes and antiprotons.
Two rings: simultaneous beams.



The QCD phase diagram

B.Friman,GSI



To map out the QCD phase diagram need:

High, intermediate and low energies

At E = 10 - 45 AGeV:

- Probe matter at high baryon densities
- Open charm near threshold
- Strangeness maximum
- Dileptons: ρ, ω, ϕ, J/Ψ in matter
- Collective flow
- Chiral restoration
- Deconfinement
- Critical end point?

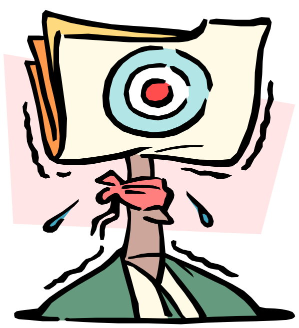
Quantum Hadrodynamics (QHD)

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

$\sigma(0^+,0)$ $\omega(1^-,0)$ $\delta(0^+,1)$ $\rho(1^-,1)$

Scalar Vector Scalar Vector

Isoscalar Isovector



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

⊕ Attraction & Repulsion → Saturation

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

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

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

No linear

No perturbative

QHD Equation of State

$$\varepsilon = \sum_{i=n,p} 2\int \frac{d^3k}{(2\pi)^3} E_i^*(k) n_i(k) + \frac{1}{2}\frac{g_s^2}{m_\sigma^2}\rho_s^2 + \frac{1}{2}\frac{g_\omega^2}{m_\omega^2}\rho_B^2$$

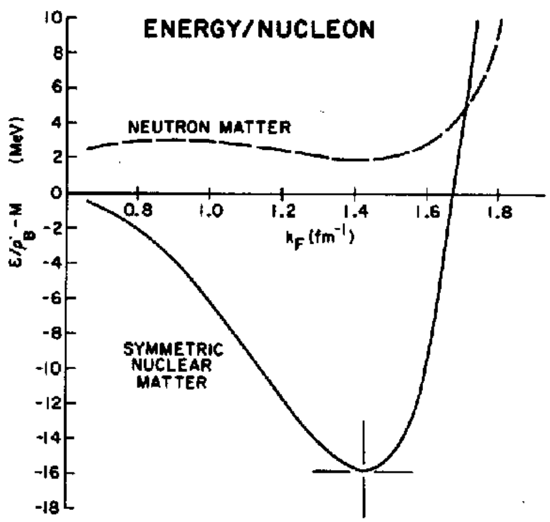
QHD-I

$\mathbf{f}_\sigma$ $\mathbf{f}_\omega$

$$\varepsilon = \sum_{i=n,p} 2\int \frac{d^3k}{(2\pi)^3} E_i^*(k) n_i(k) + \frac{1}{2}\underbrace{m_\sigma^2\Phi^2 + U(\Phi)}_{\mathbf{f}_{\sigma\ldots}} + \frac{1}{2}\frac{g_\omega^2}{m_\omega^2}\rho_B^2 + \frac{1}{2}\frac{g_\rho^2}{m_\rho^2}\rho_{B3}^2 + \frac{1}{2}\frac{g_\delta^2}{m_\delta^2}\rho_{S3}^2$$

$\mathbf{f}_\omega$ $\mathbf{f}_\rho$ $\mathbf{f}_\delta$

- Self-interacting terms (NL models)
- Charged effective mesons (QHD-II)



QHD-I

- ✓ soft EoS (K=220 MeV)
- ✓ E_{bind}=-16 MeV
- ✓ ρ_0(fm^{-3})≈0.15
- ✓ m*/M=0.75
- ✓ a_4=30.7 MeV

Isospin degrees of freedom in QHD

- $\sigma - \omega$ model → Only kinetic contribution to E_{sym}
- Charged mesons :

$\vec{\delta}[a_0(980)]$	(scalar isovector)
$\vec{\rho}\ (770)$	(vector isovector)

$$N:\left[\gamma_\mu i\partial^\mu - g_V\gamma_0 V^0 - g_\rho\gamma_0\tau_3 b^0 - \left(M - g_S\Phi - g_\delta\tau_3\delta_3\right)\right]\Psi = 0$$

→ Splitting n & p M^*

$$\vec{\rho}:\quad b_0 = \frac{g_\rho}{m_\rho^2}\left(\rho_p - \rho_n\right)$$

$$\vec{\delta}:\quad \delta_0 = \frac{g_\delta}{m_\delta^2}\left(\rho_{sp} - \rho_{sn}\right)$$

Relativistic structure also in isospin space !

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

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

RMF Symmetry Energy: $\delta - contrib.$

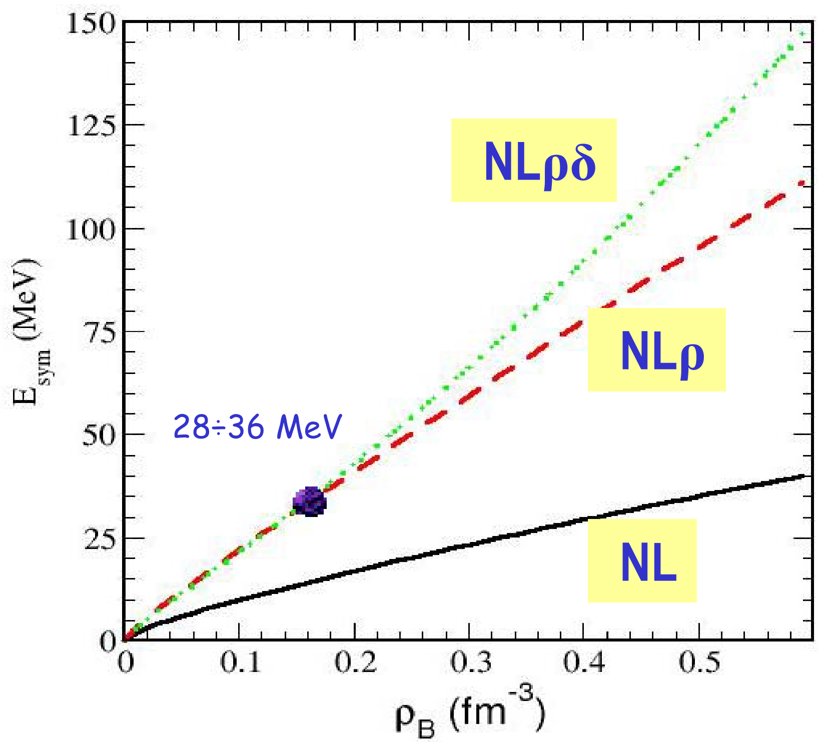
$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^{*2}} + \frac{1}{2}\left[f_\rho - f_\delta\left(\frac{M^*}{E^*}\right)^2\right]\rho_B$$

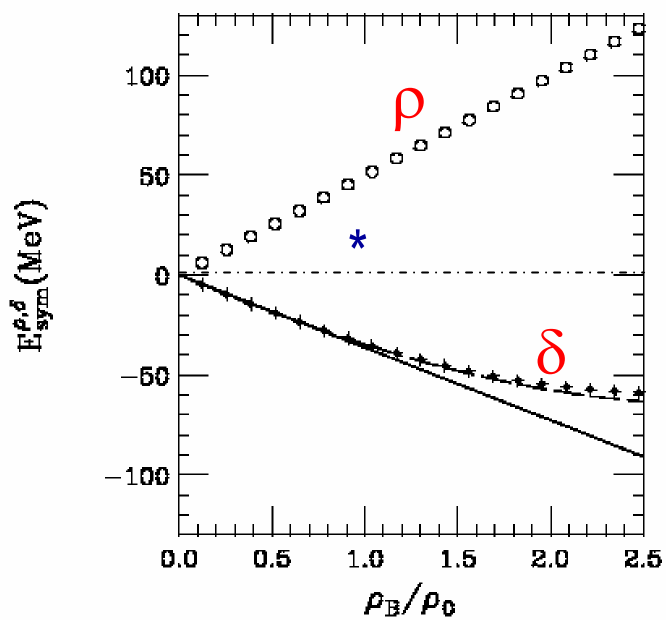
No δ → $f_\rho \cong 1.5\, f_\rho^{FREE}$

$f_\delta = 2.5\ fm^2$ → $f_\rho \cong 5 f_\rho^{FREE}$

$a_4 = E_{sym}(\rho_0)$ fixes (f_ρ, f_δ)

DBHF, DHF: $f_\delta \approx 2.0 \div 2.5\ fm^2$





PRC65(2002)045201

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

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

Chemical Potentials (zero temp.) $\mu_i = \sqrt{k_F{}^2 + m_i^{*2}} + f_\omega \rho_B \mp f_\rho \rho_{B3}$

Symmetry Energy

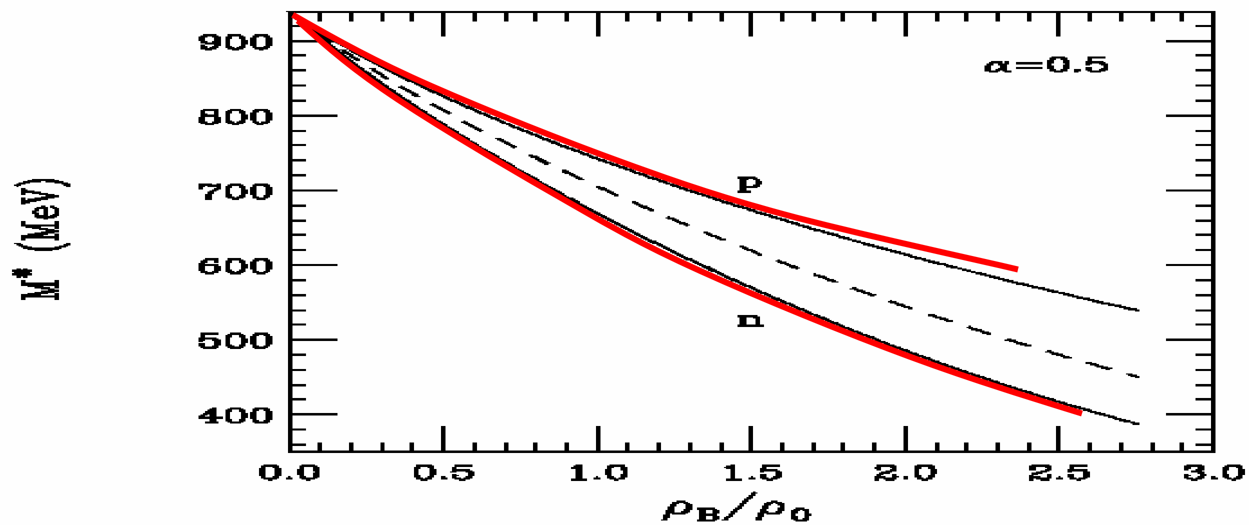
$$\mu_n - \mu_p = 4E_{sym} I$$

$$I \equiv \frac{\rho_n - \rho_p}{\rho}$$

Asymmetry parameter

Effective Mass Splitting: Dirac Masses

Minimal Effective Field Approach: $(\sigma, \omega, \delta, \rho)$



$$m_D^*(q) = m - \Sigma_s(\sigma) \pm f_\delta \rho_{S3}$$

$$\rightarrow +n, -p$$

$$\rho_3 \equiv \rho_p - \rho_n, < 0 \Rightarrow n - rich$$

RMF–(ρ+δ)

RMF-ρ

Splitting sign $(m_D^*(n) - m_D^*(p))$

Agree {
- RMFT, DHF(V. Greco et al., PRC63, PRC64 (2001))
- DBHF (F. Hofmann et al., PRC64 (2001))
- SLy (E. Chabanat et al., NPA 627 (1997)) non rel.

Disagree {
- BHF (W.Zuo, PRC60 (1999) 24605)
- "Old" Skyrme

non rel.

PRC65(2002)045201

Phys.Rep.410(2005)335-466

DIRAC OPTICAL POTENTIAL

Dispersion relation $$(E-\Sigma_0)^2 = p^2 + (m-\Sigma_s)^2$$

$$\downarrow$$

$$\varepsilon + m \Rightarrow \sqrt{k_\infty^2 + m^2}$$

$$\longrightarrow \quad V_{opt} = \Sigma_0 - \Sigma_s + \frac{1}{2m}\left(\Sigma_s^2 - \Sigma_0^2\right) + \frac{\Sigma_0}{m}\varepsilon$$

$\longrightarrow$ RMF

Schroedinger mass

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

$$m_S^* = \frac{m}{1+\frac{\Sigma_0}{m}} \approx m - \Sigma_0 = m_D^* + (\Sigma_s - \Sigma_0)$$

~50 MeV

Dirac mass $$m_D^* = m - \Sigma_s$$

Asymmetric Matter

$(\sigma, \omega, \rho, \delta)$

$$\Sigma_0 \Rightarrow \Sigma_0 \mp f_\rho \rho_{B3}$$

$$\Sigma_s \Rightarrow \Sigma_s \mp f_\delta \rho_{S3}$$

upper signs: neutron

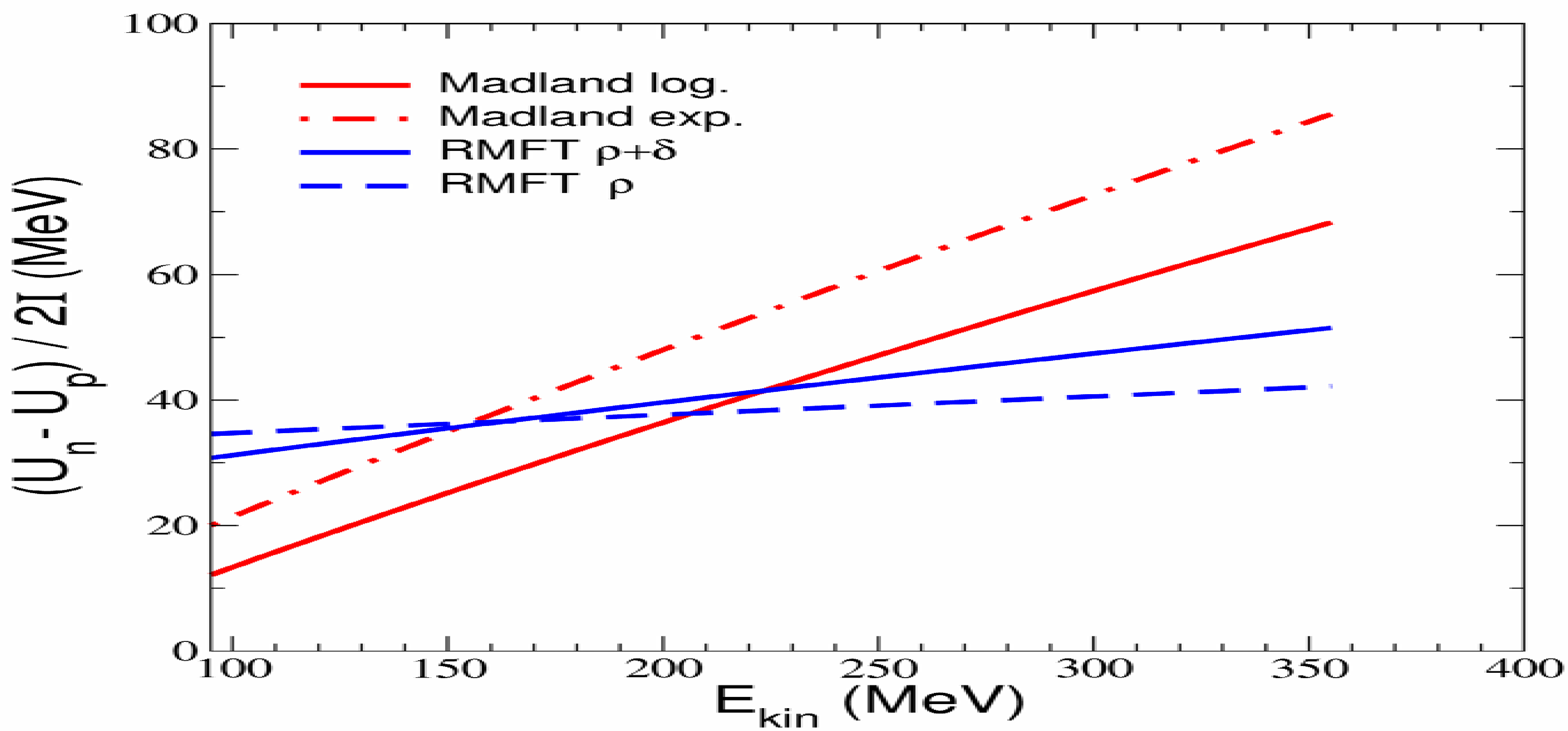
$$\rho_{B3} \equiv \rho_{Bp} - \rho_{Bn} < 0, n-rich$$

$$m_S^*(n,p) = m_{Dsym}^* + (\Sigma_s - \Sigma_0)_{sym} \pm \rho_{B3}\left(f_\rho - \frac{m_D^*}{E_F^*} f_\delta\right) \rightarrow \boxed{\begin{array}{c} m_D^*(n) < m_D^*(p) \\ m_S^*(n) < m_S^*(p) \end{array}}$$

Phys.Rep.410(2005)335-466, MSU-RIA05 nucl-th/0505013 AIP Conf. 791(2005)70-82

DIRAC LANE POTENTIAL

$$\frac{U_n - U_p}{2\beta} = E_{sym,pot}(\rho_0) + f_\rho \frac{\rho_0}{m}\varepsilon \quad \begin{cases} \xrightarrow{\rho} + 0.04\varepsilon \\ \xrightarrow{\rho+\delta} + 0.12\varepsilon \end{cases}$$



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BEYOND RMF: k-dependence of the Self-Energies

$$f(\sigma,\omega,\rho,\delta) \equiv f_i(\rho_B,k) \qquad \Leftrightarrow \qquad \text{DBHF}$$

Schroedinger mass

$$m_S^* = m_D^* + (\Sigma_s - \Sigma_0) + (m - \Sigma_s)\Sigma_s' - (m + \varepsilon - \Sigma_0)\Sigma_0'$$

$$\Sigma_0' \equiv \frac{d\Sigma_0}{d\varepsilon} < 0$$ High momentum saturation of the optical potential

$$\Sigma_s' \equiv \frac{d\Sigma_s}{d\varepsilon} < 0$$ High momentum increase of the Dirac Mass

Asymmetric Matter

$$m_D{}^*(n) < m_D{}^*(p)$$

but

$$m_S{}^*(n) >,< m_S{}^*(p)$$

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Analysis of DB self energies

Decomposition of DB self energy

$$\Sigma(p) = \Sigma^s(p) - \gamma^0\Sigma^0(p) + \bar{\gamma}\cdot\bar{p}\Sigma^v.$$

Density (and momentum) dependent coupling coeff. (at k_F)

$$\left(\frac{g_\sigma^*}{m_\sigma}\right)^2 = -\frac{1}{2}\frac{\Sigma_n^s(\bar{p}_f)+\Sigma_p^s(\bar{p}_f)}{\rho_n^s+\rho_p^s}$$

$$\left(\frac{g_\omega^*}{m_\omega}\right)^2 = -\frac{1}{2}\frac{\Sigma_n^0(\bar{p}_f)+\Sigma_p^0(\bar{p}_f)}{\rho_n^v+\rho_p^v}$$

$$\left(\frac{g_\delta^*}{m_\delta}\right)^2 = -\frac{1}{2}\frac{\Sigma_n^s(\bar{p}_f)-\Sigma_p^s(\bar{p}_f)}{\rho_n^s-\rho_p^s}$$

$$\left(\frac{g_\rho^*}{m_\rho}\right)^2 = -\frac{1}{2}\frac{\Sigma_n^0(\bar{p}_f)-\Sigma_p^0(\bar{p}_f)}{\rho_n^v-\rho_p^v},$$

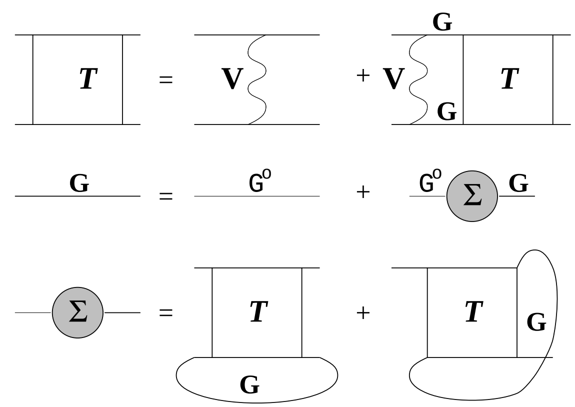
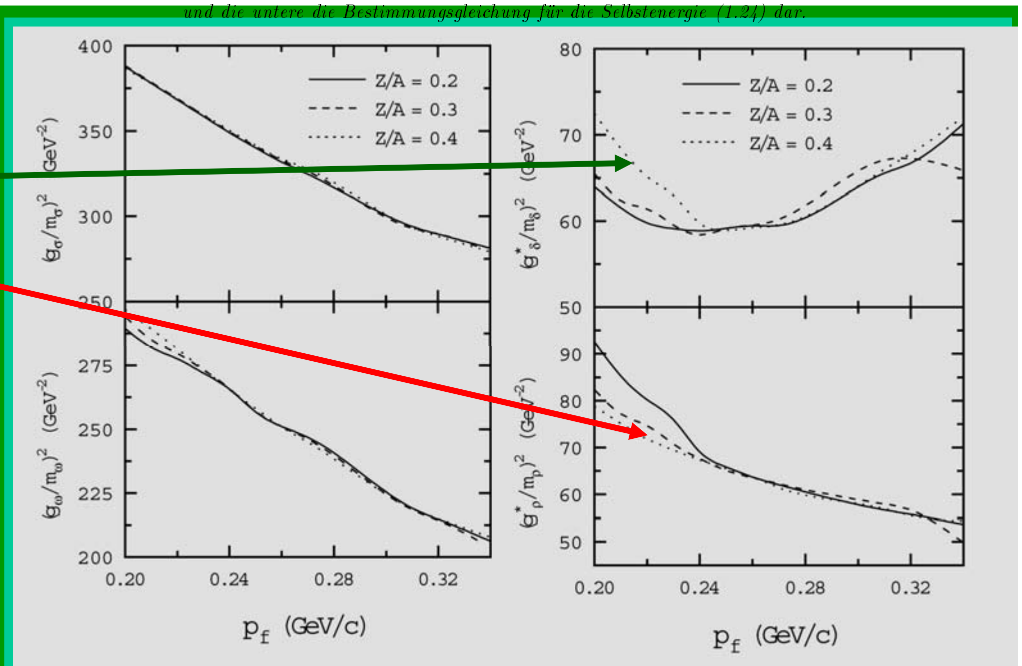


Abbildung 1.2: *Diagrammatische Darstellung der DB-Methode. Die oberste Reihe stellt die Bethe-Salpeter-Gleichung (1.23), die mittlere die Dyson-Gleichung (1.25) und die untere die Bestimmungsgleichung für die Selbstenergie (1.24) dar.*

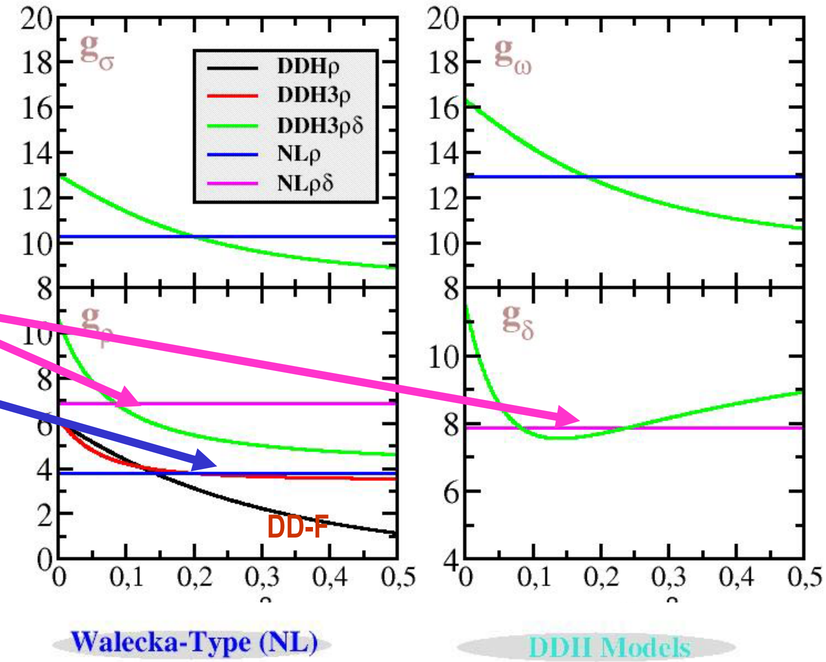


deJong, Lenske, PRC 58 (98) 890

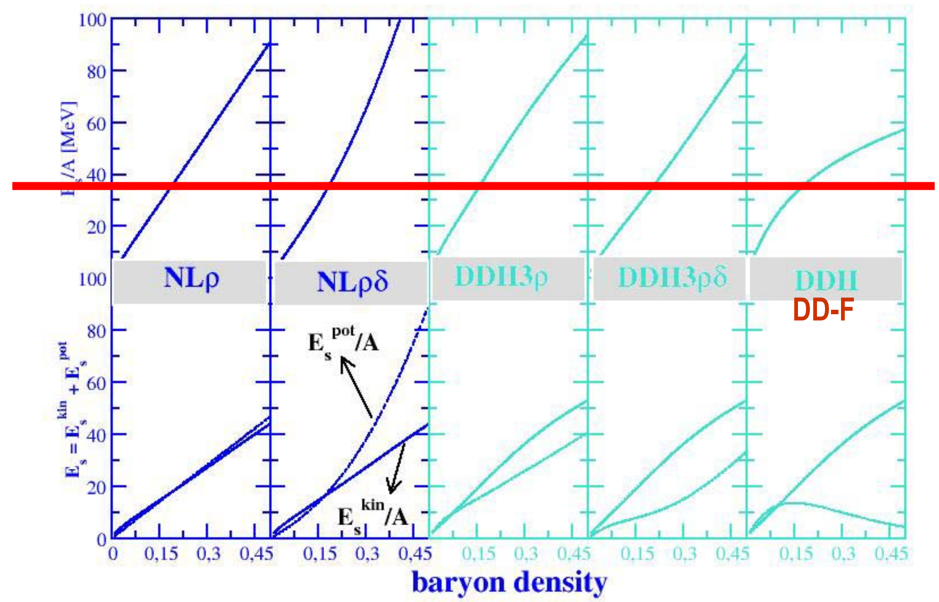
A $\rho\delta$ parametrization of the isovector dependence

$\mathbf{NL}\rho\delta$

$\mathbf{NL}\rho$



$a_4 = E_{sym}(\rho_0) \approx 33\,\mathrm{MeV}$



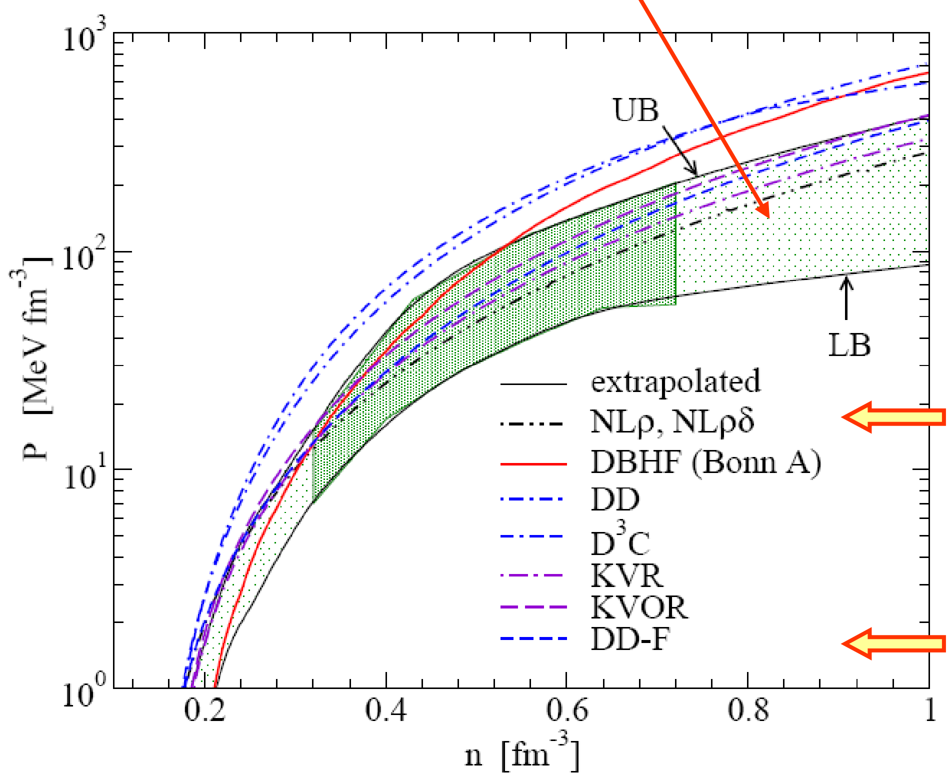
Gaitanos, Di Toro, Typel, Baran, Fuchs, Greco, Wolter, NPA 732 (04) 24

Collection of EOS "Realistic" Covariant Models

compact stars & heavy ion data
T.Klaen et al. Nucl-th/0602038

Pressure

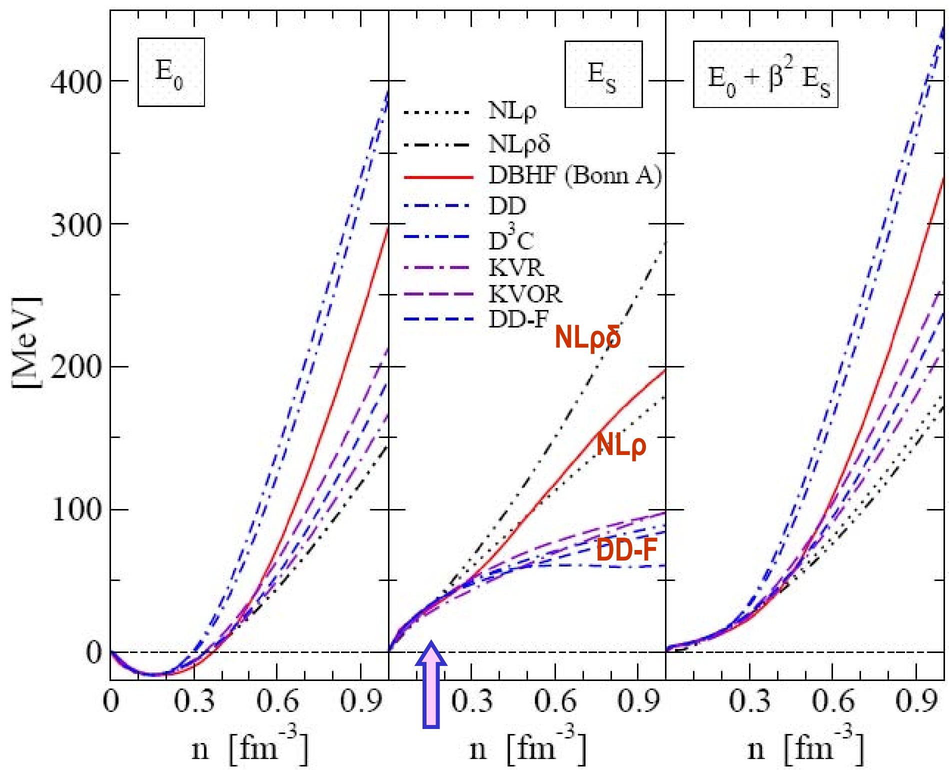
Exp boundaries (flow, kaon multiplicities)



Soft Symm Matter, Stiff (super-stiff) Symmetry Energy

Soft Symm Matter, Soft Symmetry Energy

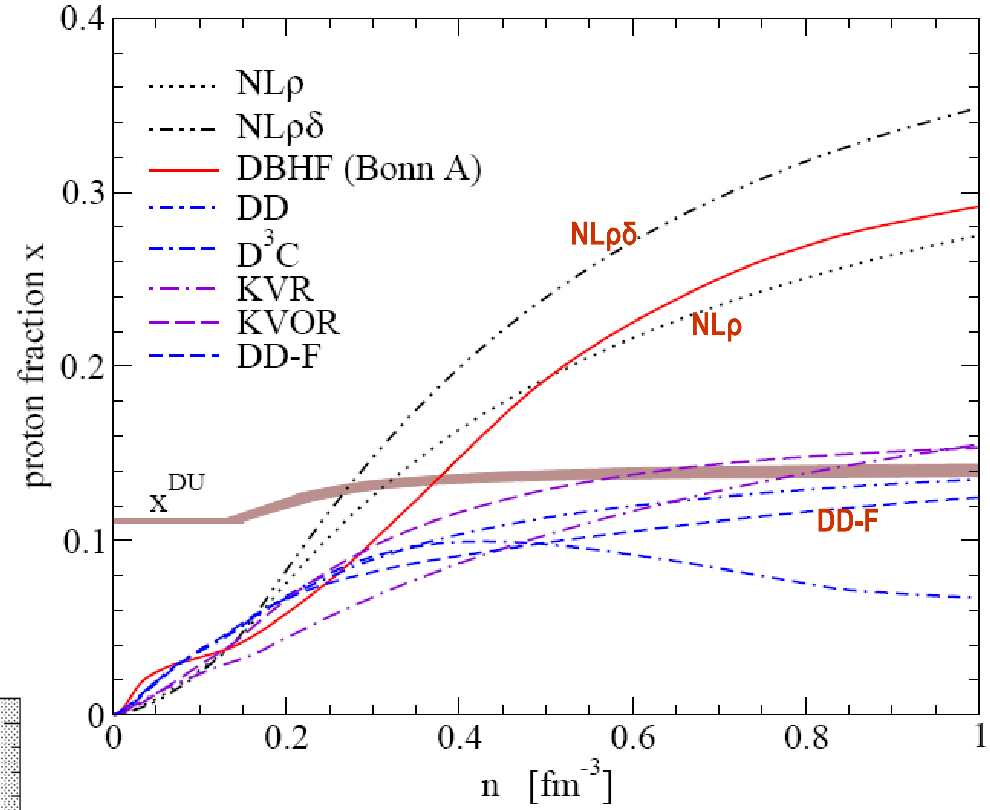
Symmetric Matter | Symmetry Energy | Neutron Matter

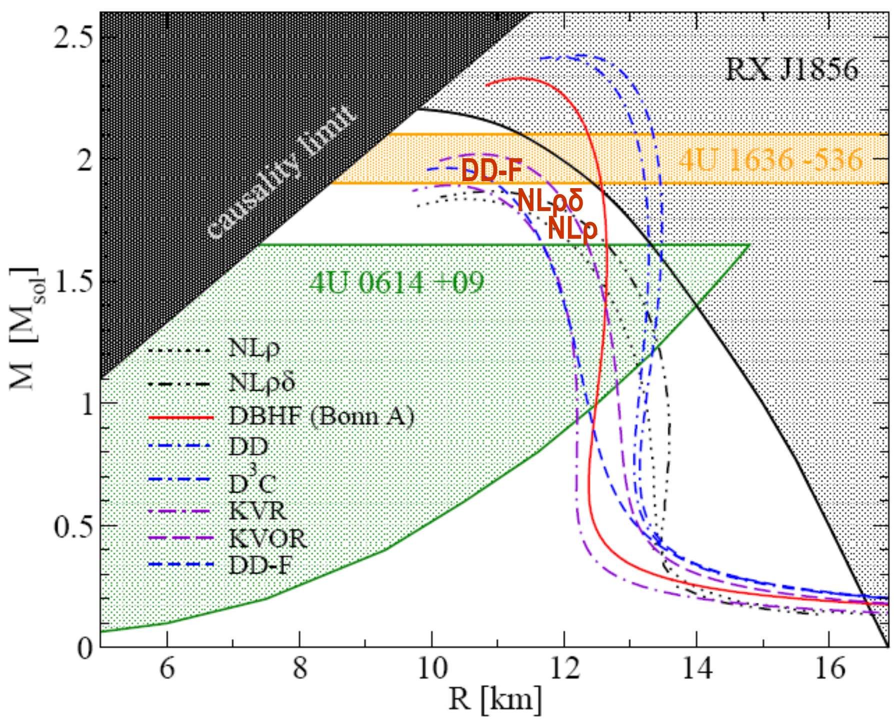


Slope at normal density:
Isospin transport at Fermi energies

Neutron Star (npeμ) properties

Direct URCA threshold





Mass/Radius relation

RBUU transport equation

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

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

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

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

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

drift

mean field

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

Non-relativistic Boltzmann-Nordheim-Vlasov

"Lorentz Force"→ Vector Fields
pure relativistic term

Collision term:

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

Relativistic Landau Vlasov Propagation

Discretization of f(x,p*)→ Test particles represented by covariant Gaussians in xp-space

$$f(x,p^*) = \sum_{i=1}^{AN_{test}} \int_{-\infty}^{+\infty} d\tau \;\; g(x - x_i(\tau))g(p^* - p_i^*(\tau))$$

→ Relativistic Equations of motion for x^μ and $p^{*\mu}$ for centroids of Gaussians

$$\frac{d}{d\tau}x_i^\mu = \frac{p_i^*(\tau)}{M_i^*(x_i)} \;,$$

$$\frac{d}{d\tau}p_i^{*\mu} = \frac{p_{i\nu}^*(\tau)}{M_i^*(x_i)}\mathcal{F}_i^{\mu\nu}\left(x_i(\tau)\right) + \partial^\mu M_i^*(x_i)$$

u_ν Test-particle 4-velocity → Relativity: - momentum dependence always included due to the Lorentz term $\left(u_\nu F^{\mu\nu}\right)$

- E*/M* boosting of the vector contributions

Collision Term: local Montecarlo Algorithm imposing an average Mean Free Path plus Pauli Blocking

→ in medium reduced Cross Sections

Rel. Transport 1

1 ONE-BODY DENSITY MATRIX (4x4 + ISOSPIN)

$$\boxed{\rho_{\alpha\beta}(x_1, x_2) \equiv \langle \bar{\Psi}_\alpha(x_1)\, \Psi_\beta(x_2) \rangle}$$

2 WIGNER TRANSFORM $\quad x = \frac{1}{2}(x_1 + x_2)$

$$R = (x_1 - x_2)$$

$$\boxed{F_{\alpha\beta}(x, P) \equiv \frac{1}{(2\pi)^4} \int d^4R\; e^{-iPR} \rho_{\alpha\beta}\left(x + \frac{R}{2}, x - \frac{R}{2}\right)}$$

⇒ scalar density $\quad \rho_s(x) \equiv \langle \bar{\Psi} \Psi \rangle = \int d^4p\; \mathrm{Tr}\left[F(x,p)\right]$

vector current $\quad j_\mu(x) \equiv \langle \bar{\Psi} \gamma_\mu \Psi \rangle = \int d^4p\; \mathrm{Tr}\left[\gamma_\mu F(x,p)\right]$

3 EQ.-OF-MOTION FOR $F(x,p)$: $\boxed{(\sigma, \omega)}$

$$\left[\gamma_\mu(\partial^\mu - 2ip^\mu) + 2im\right] F(x,p) = 2i\, e^{-\frac{i}{2}\Delta} \left(\Sigma_s - \gamma_\mu \Sigma^\mu\right) F$$

$$\Delta \equiv \underbrace{\partial^p_\mu}_{\text{on } F(x,p)}\; \underbrace{\partial^\mu_x}_{\text{on fields}}$$

⇒ FIRST ORDER EXPANSION

$$\Rightarrow \boxed{\left\{ \frac{i}{2}\left[\gamma_\mu \partial^\mu - \Delta\left(\Sigma_s - \gamma_\mu \Sigma^\mu\right)\right] + \left[\gamma_\mu \underbrace{(p^\mu - \Sigma^\mu)}_{p^{*\mu}} - \underbrace{(m - \Sigma_s)}_{m^*}\right] \right\} F(x,p) = 0}$$

Rel. Transport 2

4 REAL PART

$$(\gamma_\mu p^{*\mu} - m^*) F(x,p) = 0$$

$\Rightarrow$ MASS SHELL CONSTRAINT $\quad [(\gamma_\mu p^{*\mu} + m^*)] \times$ left

$$\boxed{(p^{*2} - m^{*2}) F = 0}$$

$8 \to 7$ variables

$\Rightarrow$ LORENTZ COMPONENTS OF $F(x,p)$

$\to$ tensor ~ 0

$$F(x,p) = F_s(x,p) + \gamma_\mu F^\mu(x,p) + \frac{1}{2}\sigma_{\mu\nu} F^{\mu\nu}(x,p) +$$

$$+ \underbrace{\gamma^5 A(x,p)}_{\substack{\text{pseudoscalar} \\ =0}} + \underbrace{\gamma^5 \gamma_\mu A^\mu(x,p)}_{\substack{\text{axial vector} \\ =0}}$$

locally spin-saturated

$$\Rightarrow \quad p^{*\mu} F_s = m^* F^\mu$$

$$\boxed{F^\mu(x,p) \equiv p^{*\mu} \underbrace{f(x,p)}_{\text{SCALAR}}} \Rightarrow J_\mu(x)$$

$$f(x,p) \equiv \frac{F_s}{m^*} \Rightarrow \rho_s(x)$$

5 IMAGINARY PART

$$\partial_\mu F^\mu + \Delta(\Sigma_\mu F^\mu) - \Delta(\Sigma_s F_s) = 0$$

$$(x_\mu, p_\mu) \Rightarrow (x_\mu, p^*_\mu)$$

$$\boxed{\Rightarrow p^*_\mu \partial^\mu_{(x)} f(x,p^*) + \left[\underbrace{p^*_\nu F^{\mu\nu}}_{\substack{\text{Lorentz force} \\ \text{FROM VECTOR FIELD}}} + \underbrace{m^* \partial^\mu m^*}_{\substack{\text{force FROM} \\ \text{SCALAR FIELD}}}\right] \partial^{(p^*)}_\mu f(x,p^*) = 0}$$

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

6 RELATIVISTIC VLASOV EQUATION

$$\boxed{\frac{p^*_\mu}{m^*}\partial^\mu_{(x)} f(x,p^*) + \left[\frac{p^*_\nu}{m^*}F^{\mu\nu} + \partial^\mu m^*\right]\partial^{(p^*)}_\mu f(x,p^*) = 0}$$

① NON RELATIVISTIC $\Downarrow$ $\qquad\Downarrow\qquad\qquad\Downarrow$

$\partial_t f + \frac{\vec{p}}{m}\vec{\nabla} f$ $\qquad$ pure relativistic term $\qquad$ $-\vec{\nabla}U\cdot\vec{\nabla}^{(p)} f$

② LIOUVILLE THEOREM

$$\Rightarrow \left[\frac{\partial x^\mu}{\partial \tau}\partial^{(x)}_\mu + \frac{\partial p^{*\mu}}{\partial \tau}\partial^{(p^*)}_\mu\right] f(x,p^*) = 0$$

$$\frac{d}{d\tau} f\left[x(\tau), p^*(\tau)\right] = 0$$

CONSTANT ALONG $x(\tau)$, $p^*(\tau)$ P.S. TRAJECTORIES

WITH

$$\left\{\begin{array}{l} \dfrac{\partial x^\mu}{\partial \tau} = \dfrac{p^{*\mu}}{m^*} \\[2ex] \dfrac{\partial p^{*\mu}}{\partial \tau} = p^*_\nu \dfrac{F^{\mu\nu}}{m^*} + \partial^\mu_{(x)} m^* \end{array}\right.$$

$\xRightarrow{\text{MASS SHELL}}$ $dx_\mu{}^2 = d\tau^2$

$\Downarrow$

EIGENTIME OF THE "PARTICLES"

$\Rightarrow$ TEST PARTICLE APPROACH

+ PROPAGATION BY A SYSTEM TIME

MEAN FIELD PROPAGATION :

"GENUINE" RELATIVISTIC EFFECTS FROM THE LORENTZ STRUCTURE OF THE FIELDS

1 SCALAR AND BARYON DENSITIES (σ, ω)

$$\Sigma_s = f_\sigma \, \rho_s(x) = f_\sigma \int d^4p^* \, m^*(x) \, f(x, p^*)$$

$$\Sigma_\mu = f_\omega \, j_\mu(x) = f_\omega \int d^4p^* \, p^*_\mu \, f(x, p^*)$$

$$\Rightarrow \Sigma_0 = f_\omega \, \rho_B(x) \quad ; \quad \rho_B(x) = \int d^4p^* \, p^*_0 \, f(x, p^*)$$

$$\boxed{\rho_s(x) \simeq \frac{m^*}{\underset{\searrow E^* = \sqrt{p^{*2} + m^{*2}}}{p_0^*}} \rho_B = \frac{\rho_B}{\gamma} < \rho_B \quad \text{AT HIGH DENSITIES (MOMENTA)}}$$

2 LORENTZ BOOSTING OF THE VECTOR FIELD CONTRIBUTION TO THE "FORCE" ACTING ON THE PARTICLE

$$\frac{d\vec{p}^*}{d\tau} = f_\omega \frac{p^*_\nu}{m^*} \left(\vec{\nabla} j_\nu - \partial_\nu \vec{j} \right) - f_\sigma \vec{\nabla} \rho_s$$

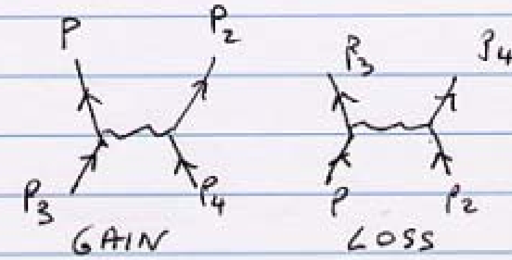
$$\simeq f_\omega \frac{E^*}{m^*} \vec{\nabla} \rho_B - f_\sigma \vec{\nabla} \rho_s \simeq \Big(f_\omega \underbrace{\frac{E^*}{m^*}}_{\gamma} - \underbrace{\frac{m^*}{E^*}}_{\frac{1}{\gamma}} f_\sigma \Big) \vec{\nabla} \rho_B$$

(neglecting $\partial_i j_k$)

$\Rightarrow$ ENHANCED EFFECT OF ρ-MESON FIELD (ISOVECTOR-VECTOR) ON NEUTRON VS PROTON DYNAMICS AT HIGH MOMENTA

COLLISION TERM

$$\frac{d}{d\tau} f(x,p^*) = I_{COLL}[f]$$



⇒ STOSSZAHLANSATZ ⊕ LOCAL $\quad N_{COLL}(1,2) \sim f_1(x,p_1^*)\, f_2(x,p_2^*)$

$$I_{COLL}[f] = \int \frac{d^3p_2^*}{E_2^*}\,\frac{d^3p_3}{E_3^*}\,\frac{d^3p_4}{E_4^*}\, W(p^*p_2^*\,|\,p_3^*p_4^*)$$

$$\cdot\Big[\underbrace{f_3 f_4}_{\text{GAIN}}(1-f)(1-f_2) - \underbrace{f f_2}_{\text{LOSS}}(1-f_3)(1-f_4)\Big]$$

PAULI BLOCKING

$$W(p^*p_2^*\,|\,p_3^*p_4^*) \approx \frac{d\sigma}{d\Omega}(s,t)\,\delta^4(p+p_2-p_3-p_4)$$

$$s = (p+p_2)^2 = (p_3+p_4)^2$$

SIMULATION : MONTECARLO ALGORITHM

PROBABILITIES GIVEN BY IN-MEDIUM REDUCED CROSS SECTIONS

Rel. Transport 6

INELASTIC COLLISIONS : ISOSPIN EFFECTS

$$p_1 + p_2 = p_3 + p_4$$

$$\rightarrow p_1^* + \Sigma_1 + p_2^* + \Sigma_2 = p_3^* + \Sigma_3 + p_4^* + \Sigma_4$$

REFERENCE FRAME $\vec{p}_1^* + \vec{p}_2^* \simeq \vec{p}_3^* + \vec{p}_4^* = 0$ $(\Delta\vec{\Sigma} \simeq 0)$

$$\Rightarrow E_1^* + \Sigma_1^0 + E_2^* + \Sigma_2^0 = E_3^* + \Sigma_3^0 + E_4^* + \Sigma_4^0$$

$$> m_3^* + \Sigma_3^0 + m_4^* + \Sigma_4^0$$

THRESHOLD

NEUTRON RICH SYSTEM : $\Sigma_n^0 \uparrow$ (like $\Sigma_{\Delta^-}^0$)

$\Sigma_p^0 \downarrow$ (like $\Sigma_{\Delta^{++}}^0$)

$\Rightarrow$ $nn \rightarrow p\Delta^-$ vs $pp \rightarrow n\Delta^{++}$

$\sim$ $2(E_n^* + \Sigma_n^0) > m_p^* + m_{\Delta^-}^*$ $\qquad$ $2(E_p^* + \Sigma_p^0) > m_n^* + m_{\Delta^{++}}^*$

$\sim 2m^*$ (symmetric matter) $\qquad$ $\sim 2m^*$ (symmetric matter)

$\Downarrow$ $\qquad$ $\Downarrow$

INCREASING $\qquad$ DECREASING

$NL \rightarrow NL\rho \rightarrow NL\rho\delta$ $\qquad$ $NL \rightarrow NL\rho \rightarrow NL\rho\delta$

$\rightarrow$ LARGER π^-/π^+ AND ISOVECTOR CHANNELS DEPENDENCE

Fragment Formation in Central Collisions at Relativistic Energies

Au+Au, Zr+Zr, Ni+Ni at 400 AMeV → Central

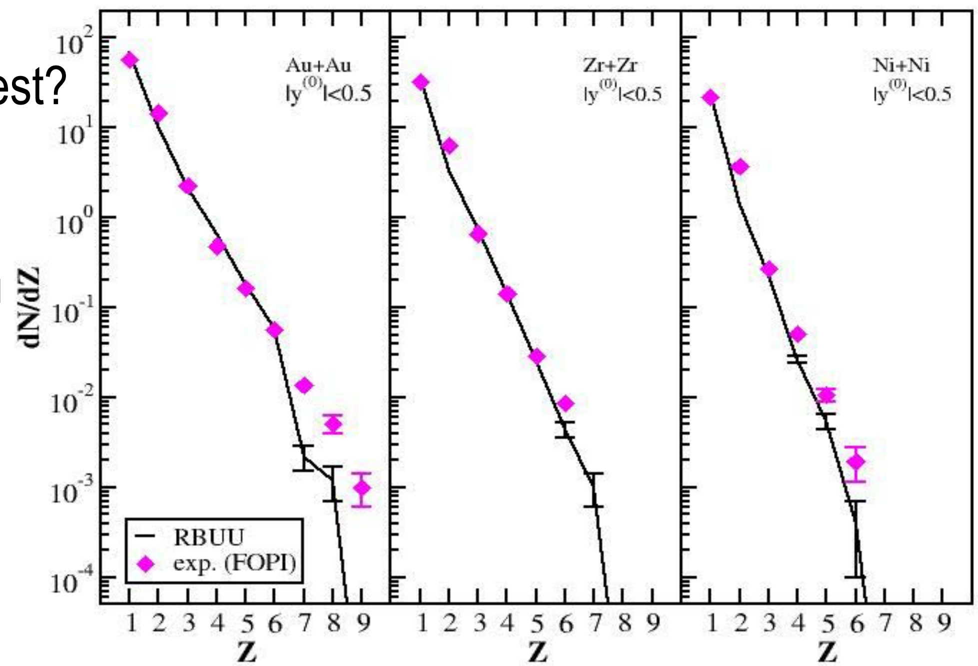
Stochastic RBUU + Phase Space Coalescence

➢ *Global fit to experimental charge distributions*

Size dependence: the lightest is the hottest?

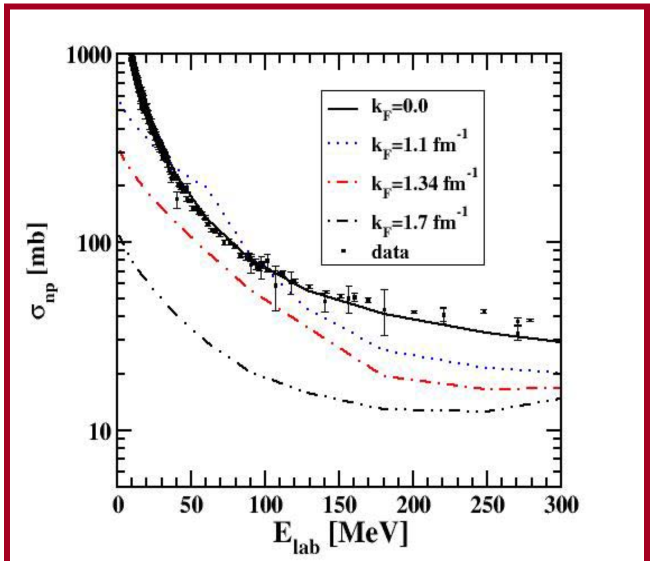
No but

Fast clusterization in the high density phase



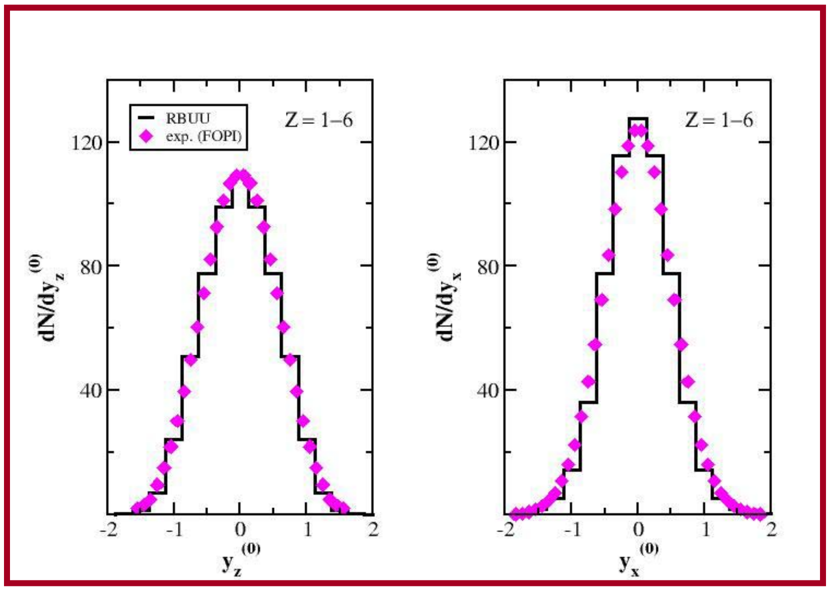
E.Santini et al., NPA756(2005)468

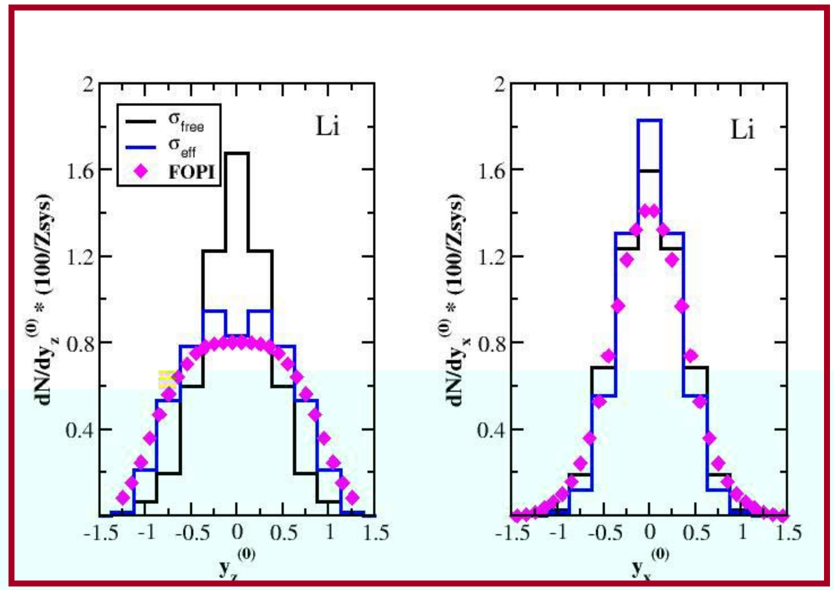
In-medium effects of σ_{NN} on stopping



C.Fuchs at al.,PRC64(2001)024003

Fragment
z- and x- rapidity distributions

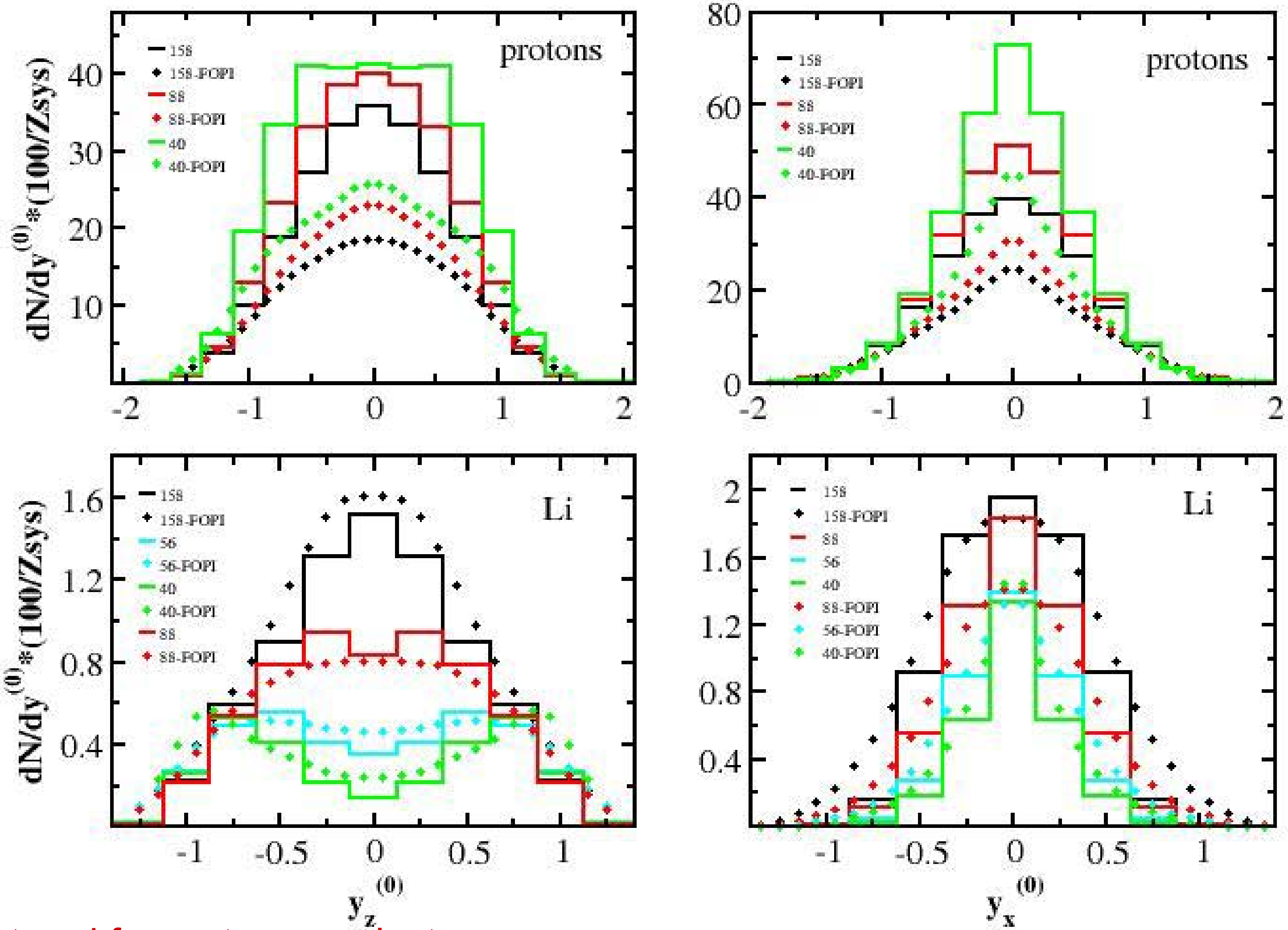




(E. Santini et al., NPA756(2005)468)

Transparency properties of protons & clusters

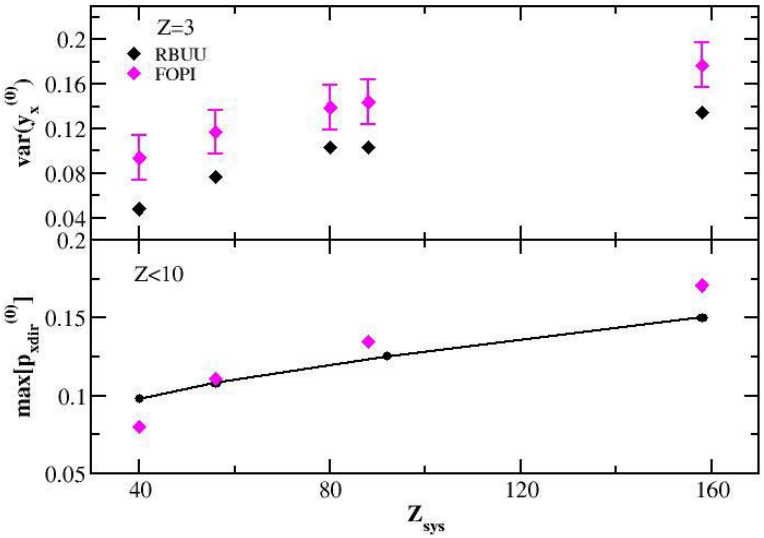
(E. Santini et al., NPA756(2005)468)



Opposite trend for protons vs clusters:
correlation between fragment multiplicity and stopping

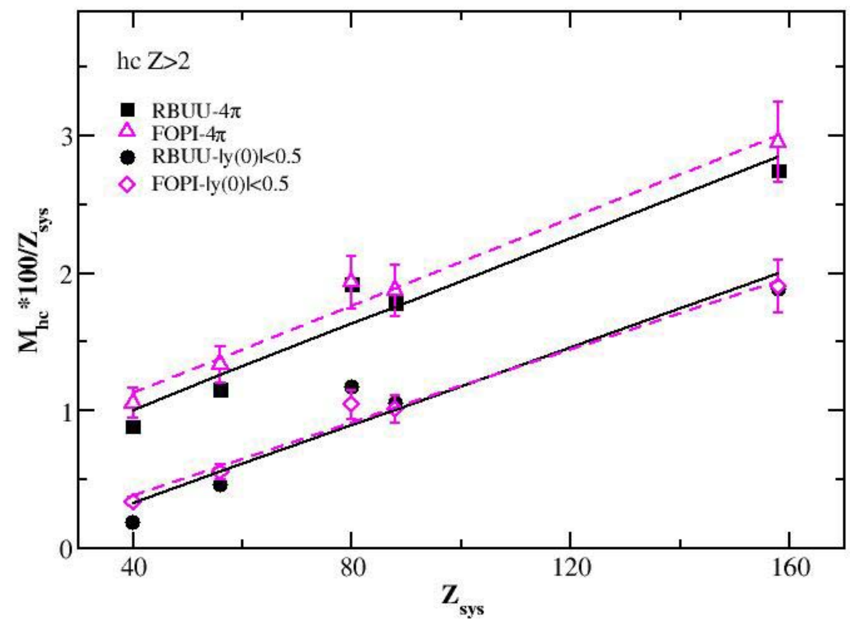
Deuteron coalescence problem: protons overestimated (but not Z=1-6)

System size behaviour of clusters



Li-stopping correlation

Z=1-10 cluster directed flow



Size (Z_sys^2)-dependence of heavy cluster multiplicity

$\Downarrow$

Seeds: two-body correlations

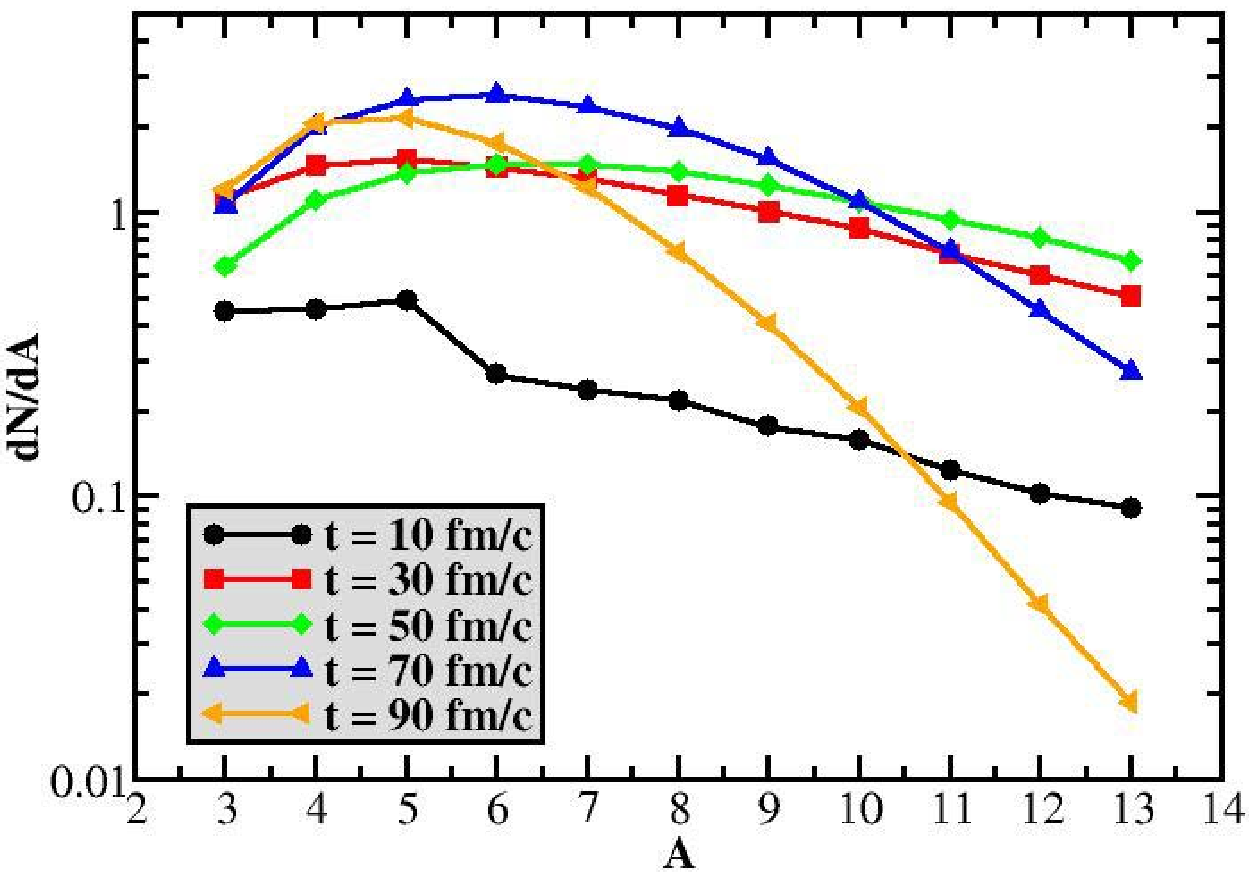
(E. Santini et al., NPA756(2005)468)

Time-evolution of fragment formation

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

Au+Au 0.4 AGeV Central

Z=3,4



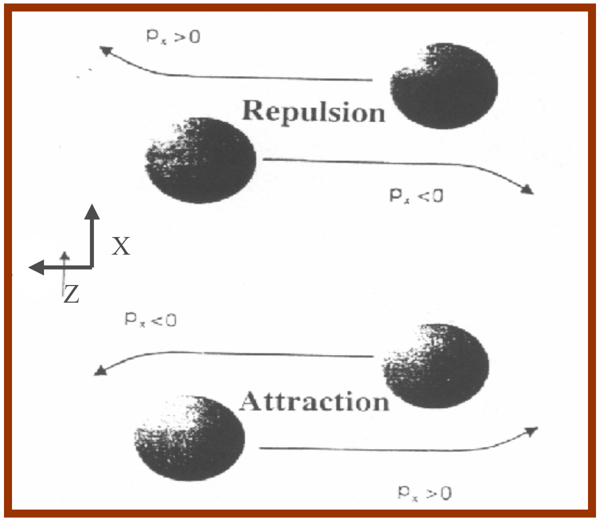
Heavier fragments: “relics” of the high density phase

$\Downarrow$

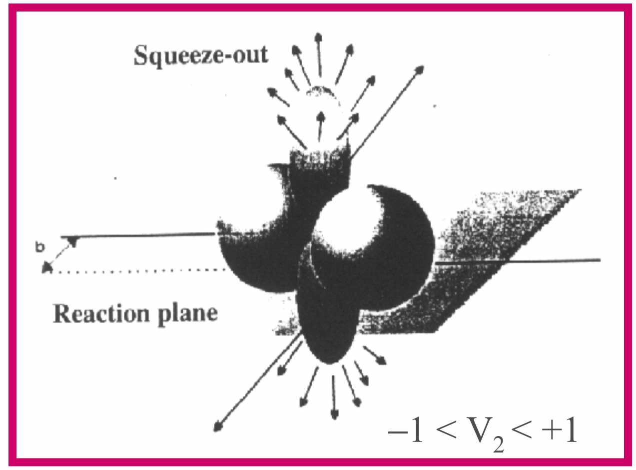
Isospin Content vs. Symmetry Term ?

Collective flows

In-plane



Out-of-plane

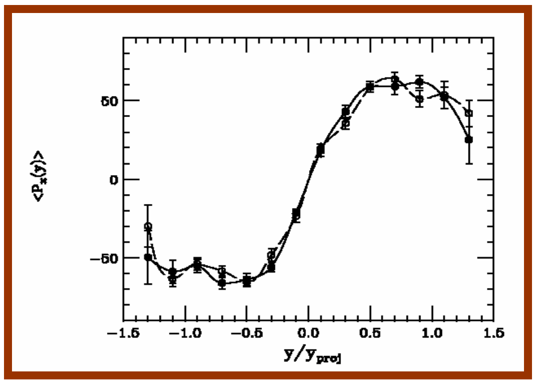


$$V_1(y, p_t) = \langle p_x \rangle / \langle p_t \rangle$$

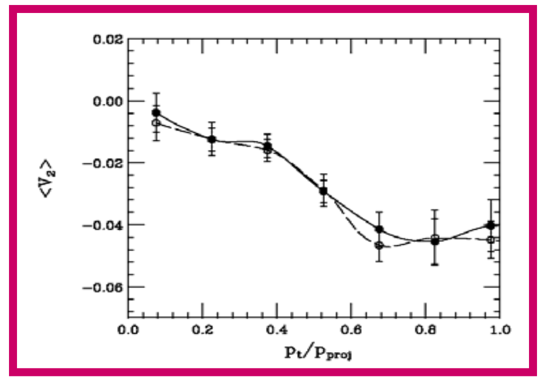
y = *rapidity*

p_t = *transverse momentum*

$$\mathrm{V}_2(p_t) = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$



$$\mathrm{V}_2 \begin{cases} = -1 & \text{full out} \\ = \ \ 0 & \text{spherical} \\ = +1 & \text{full in} \end{cases}$$



$$V_1^{p-n}(y, p_t) = V_1^{p}(p_t) - V_1^{n}(p_t)$$

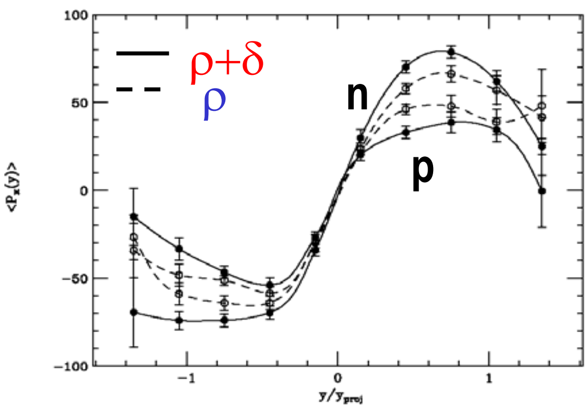
Isospin

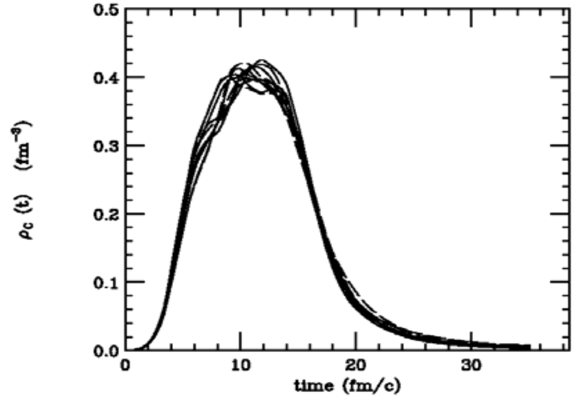
$$\mathrm{V}_2^{\mathrm{p-n}}(p_t) = \mathrm{V}_2^{\mathrm{p}}(p_t) - \mathrm{V}_2^{\mathrm{n}}(p_t)$$

Differential flows

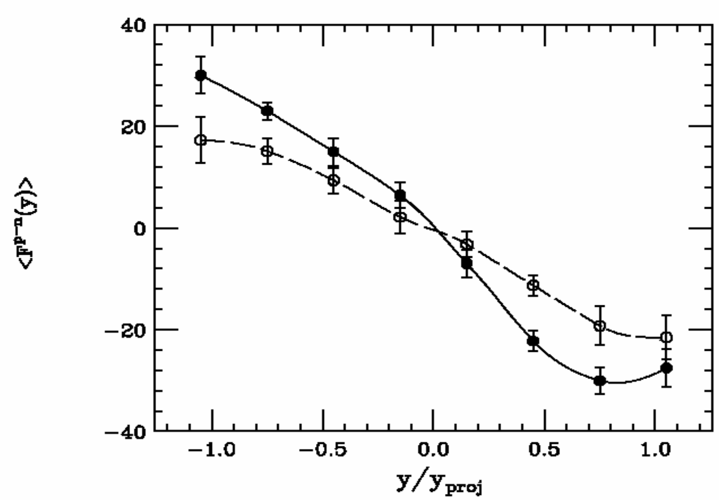
Differential Transverse Flow

$^{132}Sn + ^{132}Sn$ @ 1.5 AGeV b=6fm





- Sensitivity to the isovector part of the mean field
  → E_{sym} around $\rho \approx 2\rho_0$



o NLH-ρ

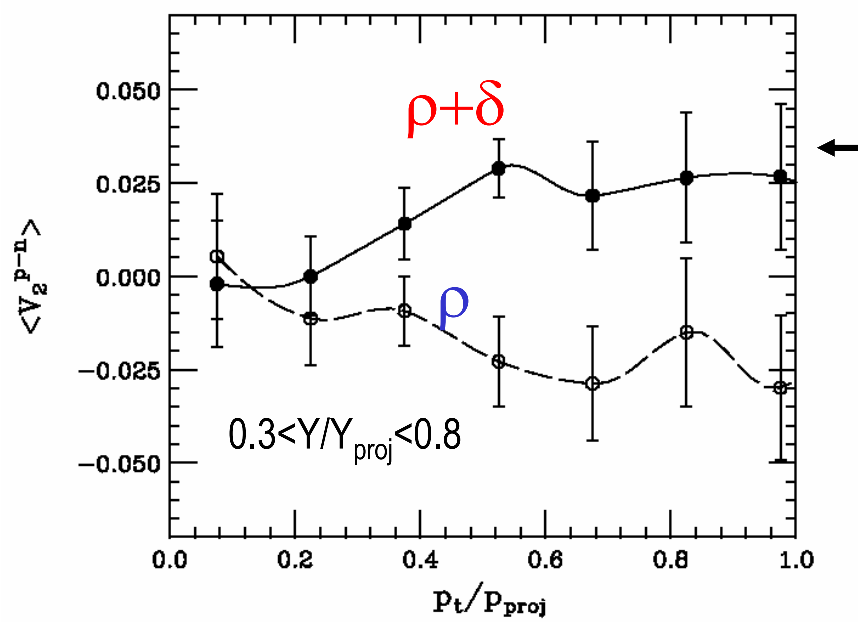
• NLH-(ρ+δ)

Greater E_{sym}

stiffer $< F^{p-n} >$

Elliptic flow

132Sn+132Sn, 1.5AGeV, b=6fm: Test with NL-ρ & NL-($\rho+\delta$)



- Difference at high p_t ⟺ first stage

High p_t neutrons are emitted "earlier"

Equilibrium (ρ,δ) dynamically broken
Importance relativistic structure

approximations

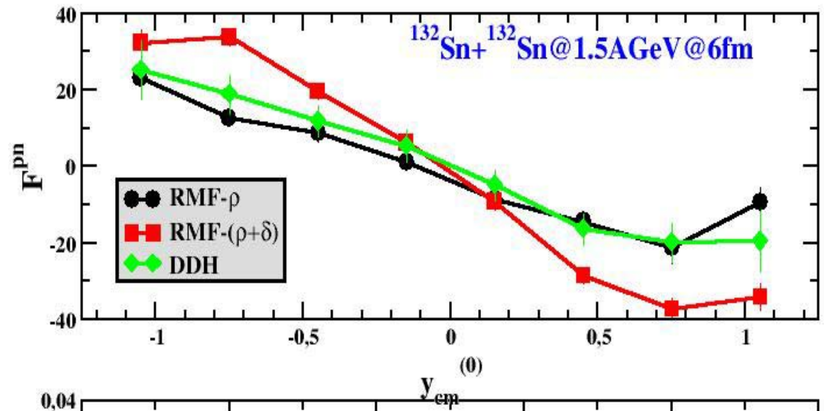
$$\frac{d\vec{p}_p^{\,*}}{d\tau} - \frac{d\vec{p}_n^{\,*}}{d\tau} \simeq 2\left[\gamma f_\rho - \frac{f_\delta}{\gamma}\right]\vec{\nabla}\rho_3 = \frac{4}{\rho_B}E^*_{sym}\vec{\nabla}\rho_3$$

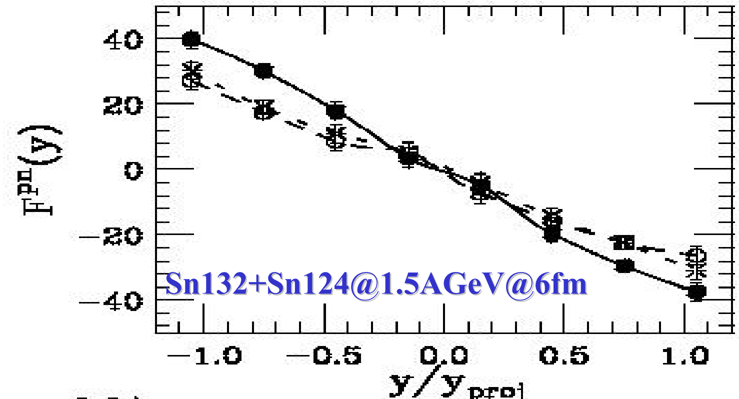
$$2\left[f_\rho - f_\delta\frac{M^*}{E_F^*}\right] = \frac{4}{\rho_B}E_{sym}^{pot}$$

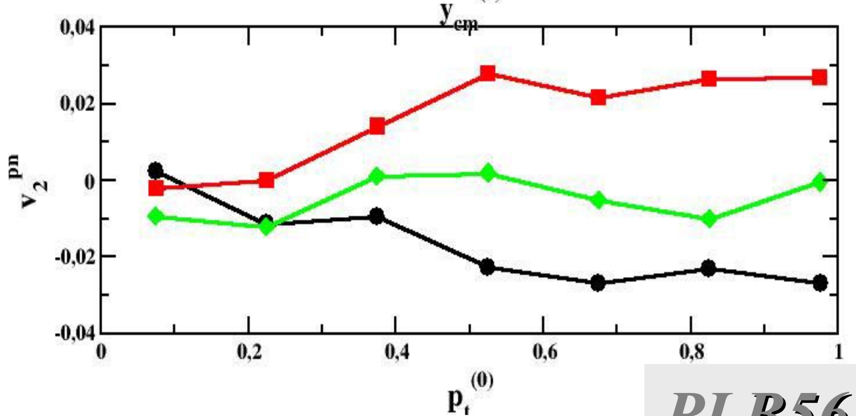
Dynamical boosting of the vector contribution

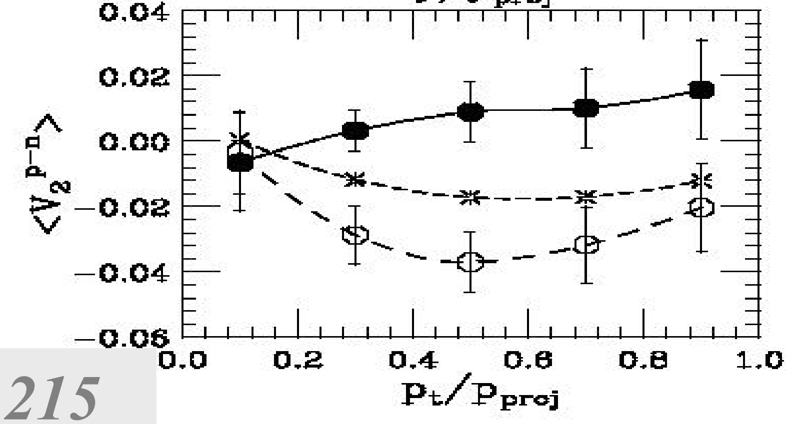
PLB562(2003)

Not just a symmetry energy effect: DDH →density dep. f_ρ to reproduce the same symmetry term of NLρδ









*PL**B562**(2003)215*

Strong isospin dependence of isospin flow

→ ***Pt-dependence: Chronometer of collision (high pt's reflect earlier high compression)***

→ ***NLρδ: more I-Flow due to Lorentz decomposition of iso-vector channel:*** $\frac{d\vec{p}_p^{\,*}}{d\tau} - \frac{d\vec{p}_n^{\,*}}{d\tau} \approx 2\left[\gamma f_\rho - \frac{f_\delta}{\gamma}\right]\nabla\rho_I$

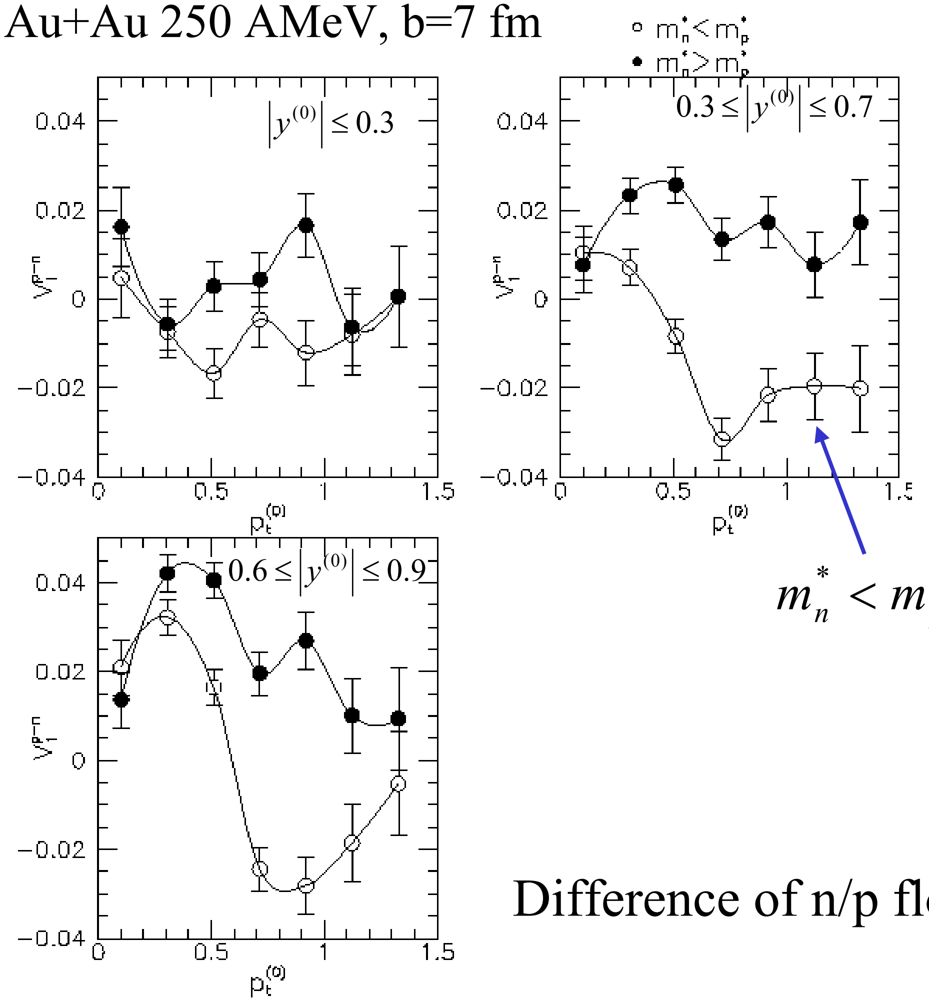
ρ-meson enhanced by γ   δ-meson suppressed by scalar density

One needs neutron (light isobars) detection from experiments!

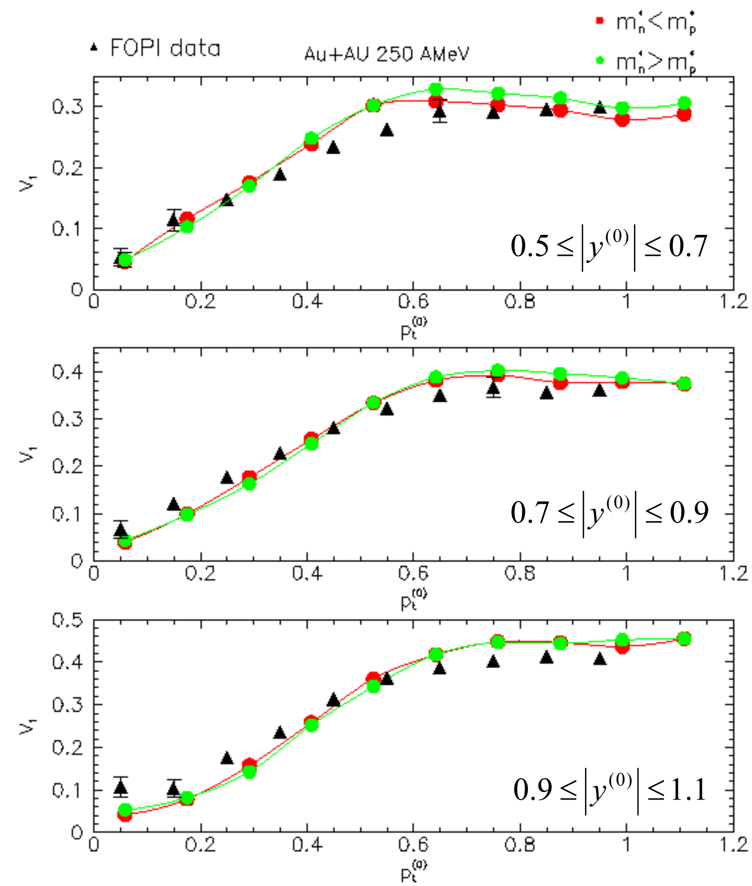
Effective Mass Sensitivity: Differential Transverse Flows

Non-relativistic with both mass-splitting

Au+Au 250 AMeV, b=7 fm



$m_n^* < m_p^*$



Difference of n/p flows

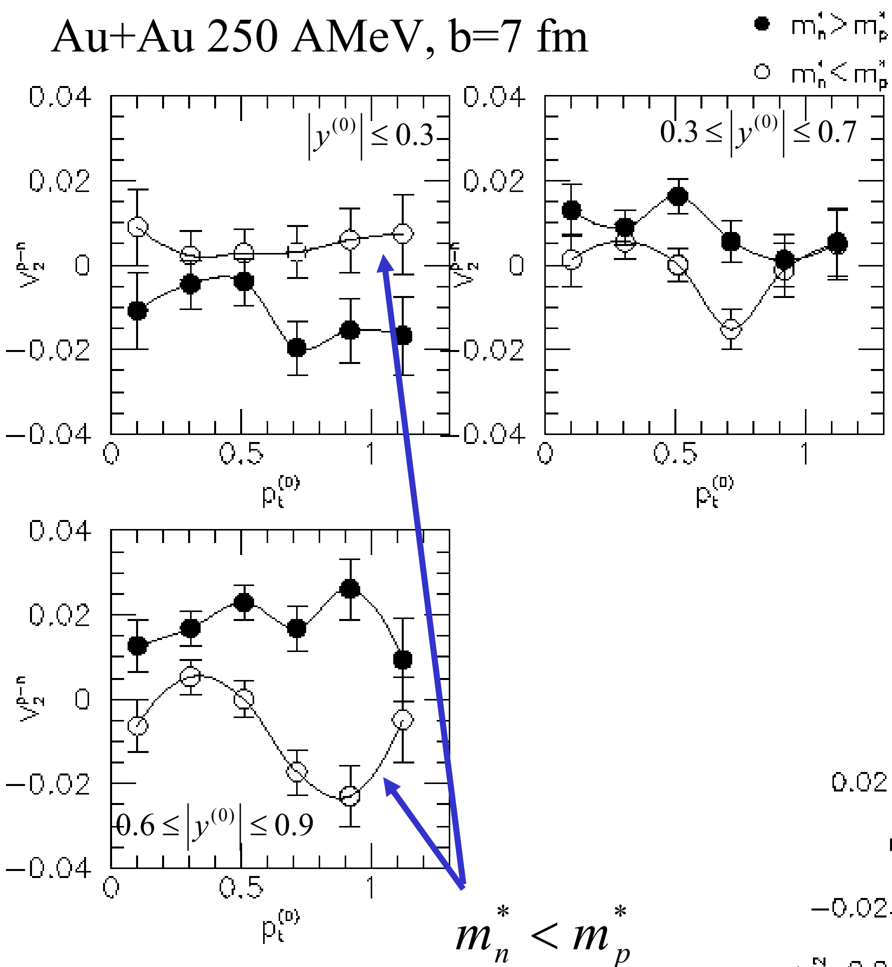
Larger effects at high momenta

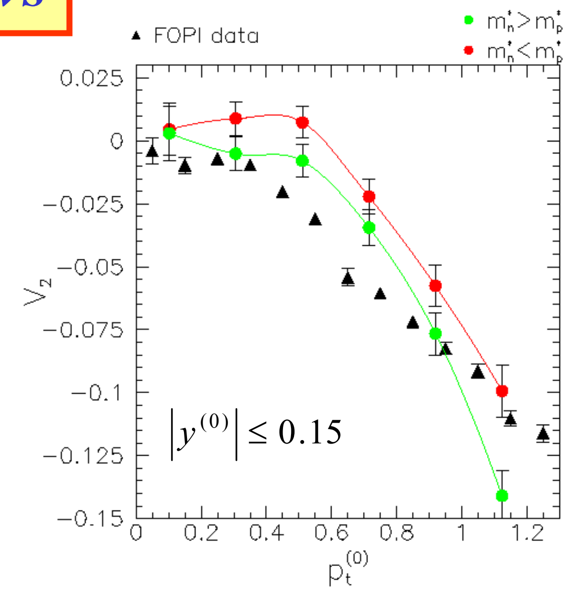
Z=1 data
M3 centrality
6<b<7.5fm

Triton vs. ^{3}He Flows?

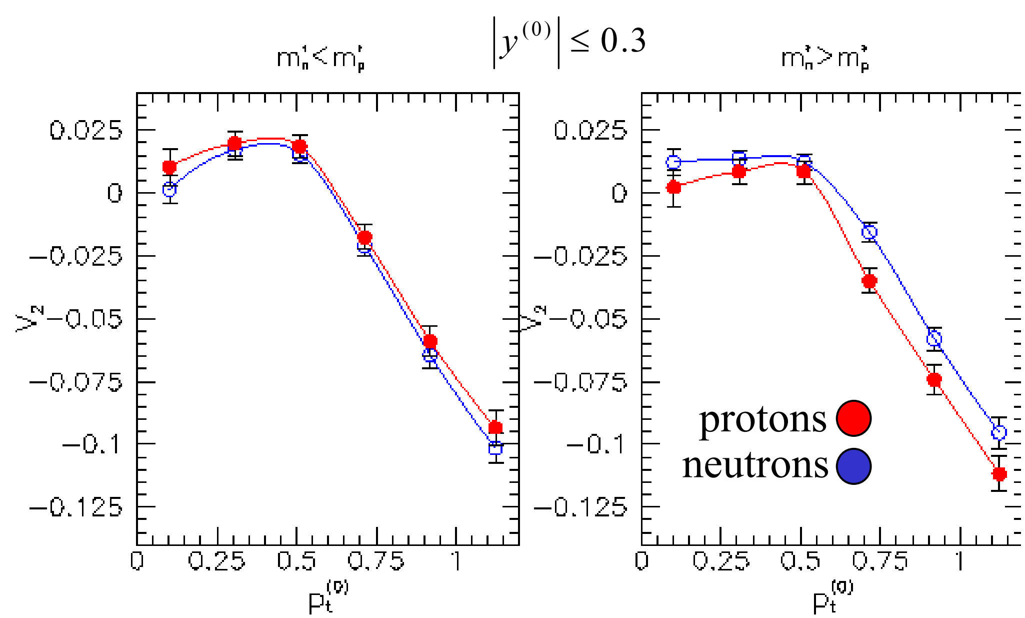
MSU/RIA05,nucl-th/0505013 , AIP Conf.Proc.791 (2005) 70

Differential Elliptic Flows





Z=1 data, M3 centrality, 6<b<7.5fm



m*n<m*p : larger neutron squeeze out at mid-rapidity

Momentum Dependence and Effective Masses: Fast Nucleon Emission

Non-relativistic with both mass-splitting

Skyrme-like parametrization $\varepsilon = \varepsilon_{kin} + \varepsilon(A', A'') + \varepsilon(B', B'') + \varepsilon(C', C'')$

$$\varepsilon(A', A'') = \left(A' + A''\beta^2\right)\frac{\rho^2}{\rho_0}$$

$$\varepsilon(B', B'') = \left(B' + B''\beta^2\right)\left(\frac{\rho}{\rho_0}\right)^{\sigma}\rho$$

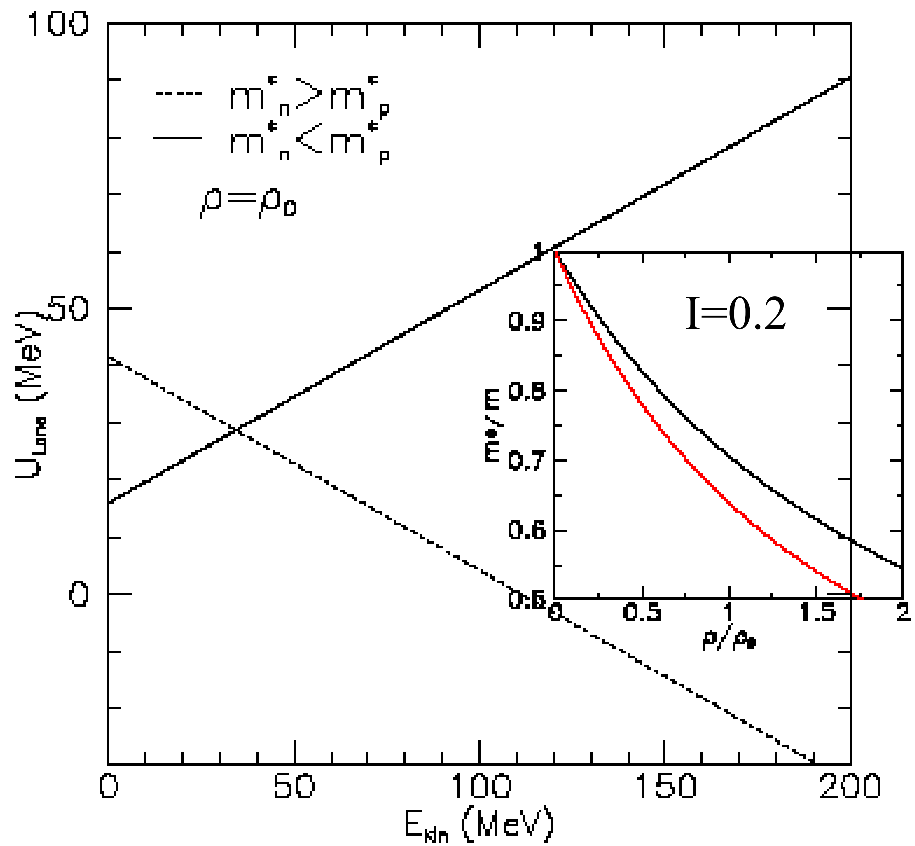
$$\varepsilon(C', C'') = C'(\mathrm{I}_{nn} + \mathrm{I}_{pp}) + C''\mathrm{I}_{np}$$

$$I_{\tau\tau'} = \int d\vec{p}\,d\vec{p}' f_\tau(\vec{r},\vec{p}) f_{\tau'}(\vec{r},\vec{p}') g(\vec{p},\vec{p}')$$

$$g(\vec{p},\vec{p}') = 1 - \frac{(\vec{p}-\vec{p}')^2}{\Lambda^2}$$

GBD extension

Correspondence to Skyrme parameters



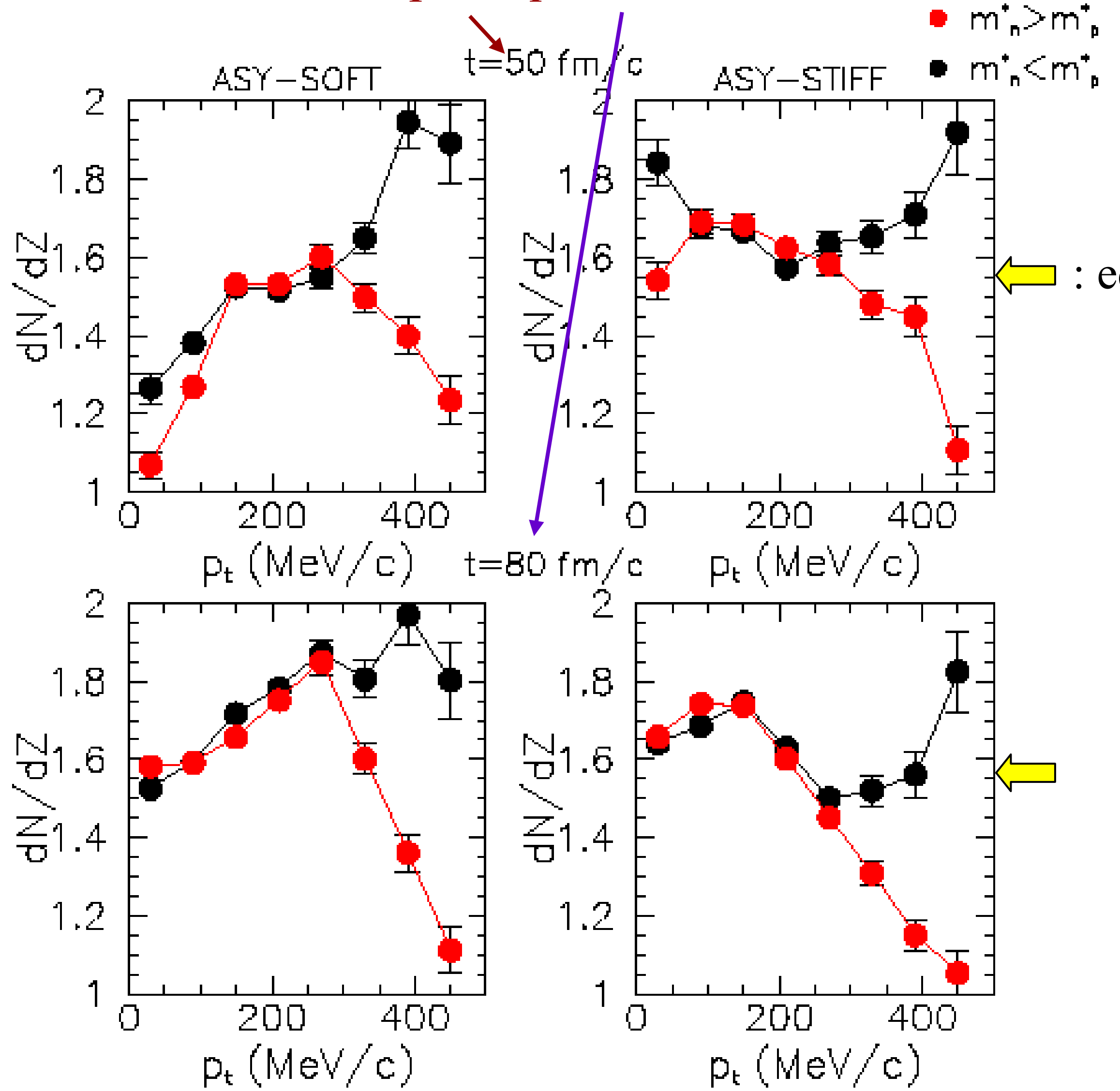
Lane Potential

NPA732(2004)202, nucl-th/0505013, PRC 72 (2005) 064609

Pre-equilibrium emission

Gas asymmetry vs. p_t $(\rho < \rho_0 / 8)$
different times: end of pre-eq., freeze out

$^{132}Sn+^{124}Sn$, 100 AMeV, b=2 fm, $y^{(0)} \leq 0.3$



: equil.asymmetry

Enhanced effects
at higher energy

$m^*_n < m^*_p$
$m^*_n > m^*_p$

Light isobar (3H/3He) yields?

J.Rizzo et al.,
PRC 72 (2005) 064609

PION PRODUCTION

NPA762(2005) 147

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

nn → $p\Delta^-$ → $n\pi^-$; nn → $n\Delta^0$ → $p\pi^-$

pp → $p\Delta^+$ → $n\pi^+$; pp → $n\Delta^{++}$ → $p\pi^+$

n→p "transformation"

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

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

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

π(-) enhanced
π(+) reduced

2. Fast neutron emission: "mean field effect"

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

Compensation in "open" systems: HIC

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

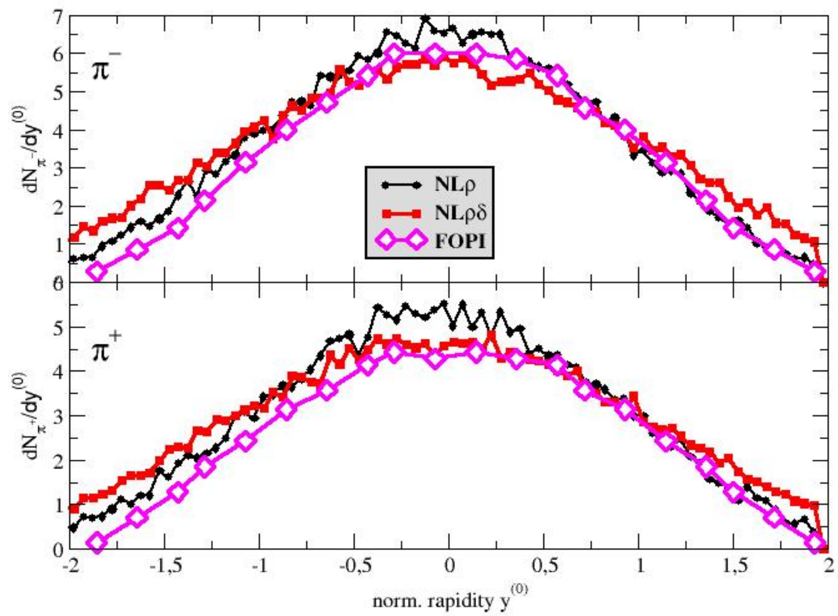
3. Pion absorption

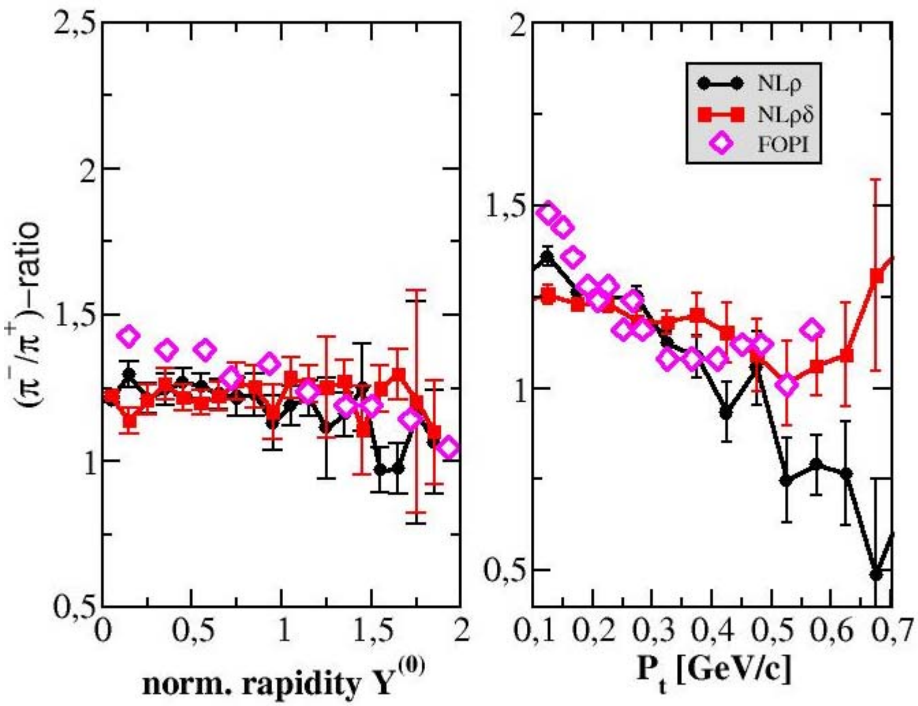
At low energies pi(-) more absorbed since more energy is available in their production

Pion production at SIS energies: 96Ru+96Ru at 1.53AGeV

Central selection

N/Z=1.18, still some Iso-EOS sensitivity





NLρδ more efficient in “transforming” neutrons into protons at high density, producing π−

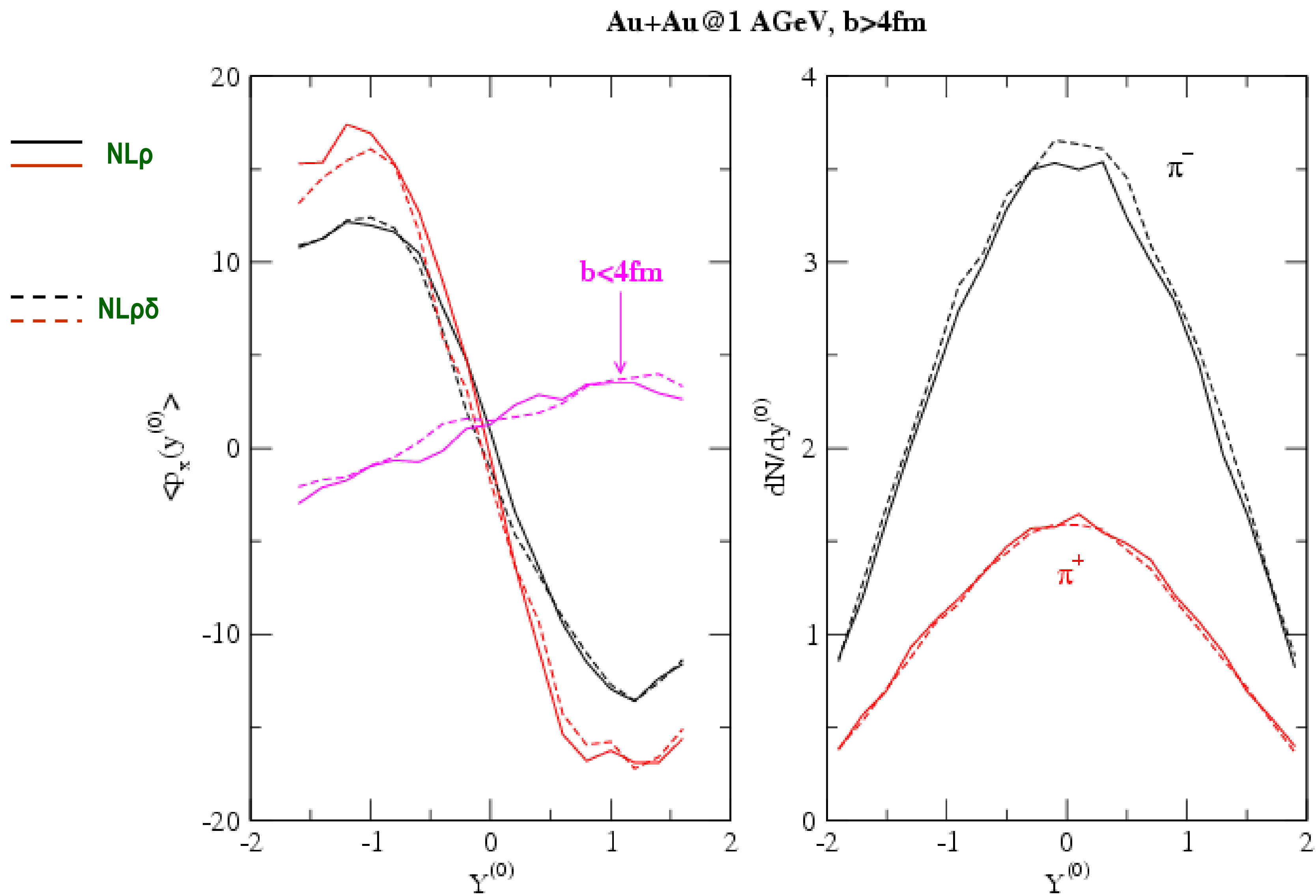
Coulomb effect:
less π+ present in the high density region

NPA732(2004)24

Pion Flows

Semiperipheral: antiflows (shadowing)

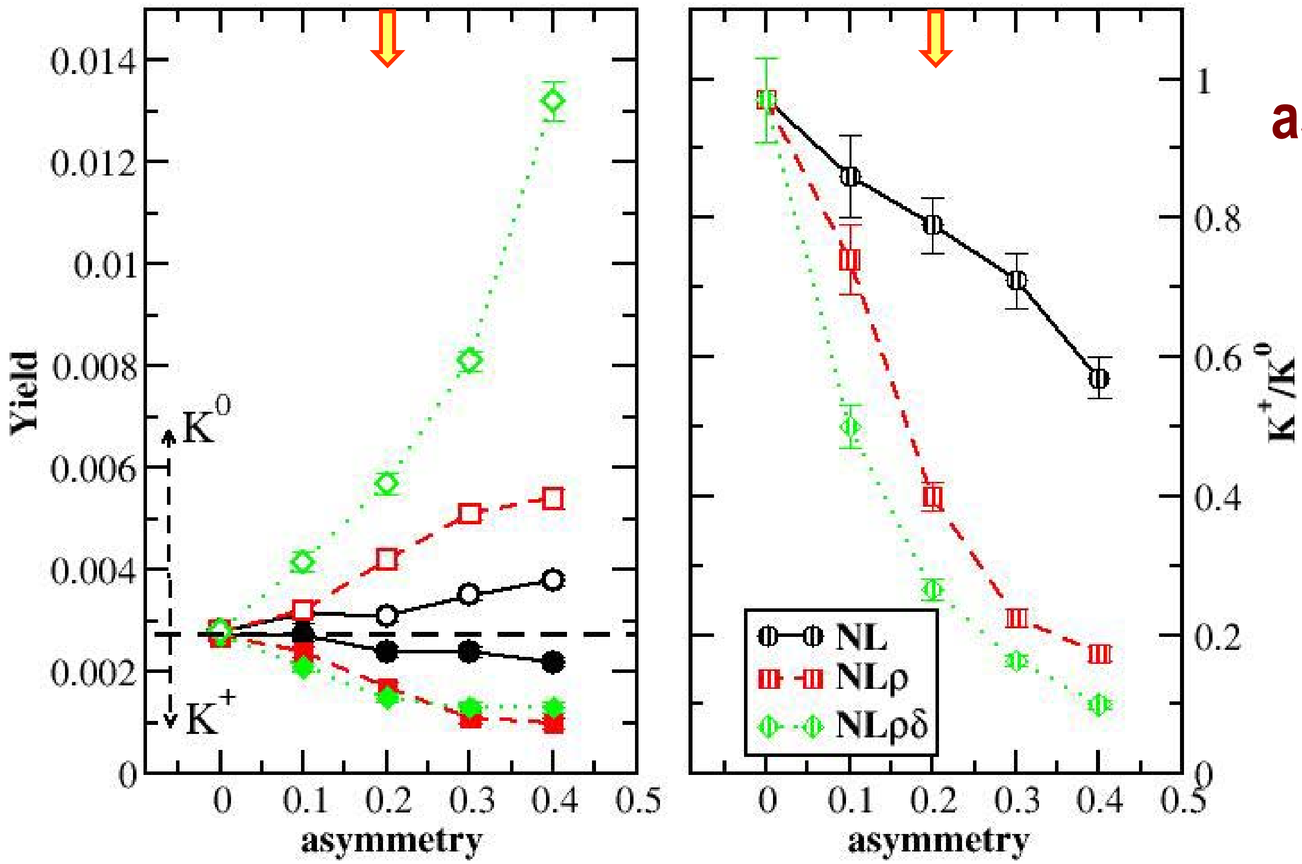
More inclusive data→
Not large Iso-EOS effects



Isospin effects on Kaon Production: Nuclear Matter Box Results

NPA762(2005) 147

Density and temperature like in Au+Au 1AGeV at max.compression

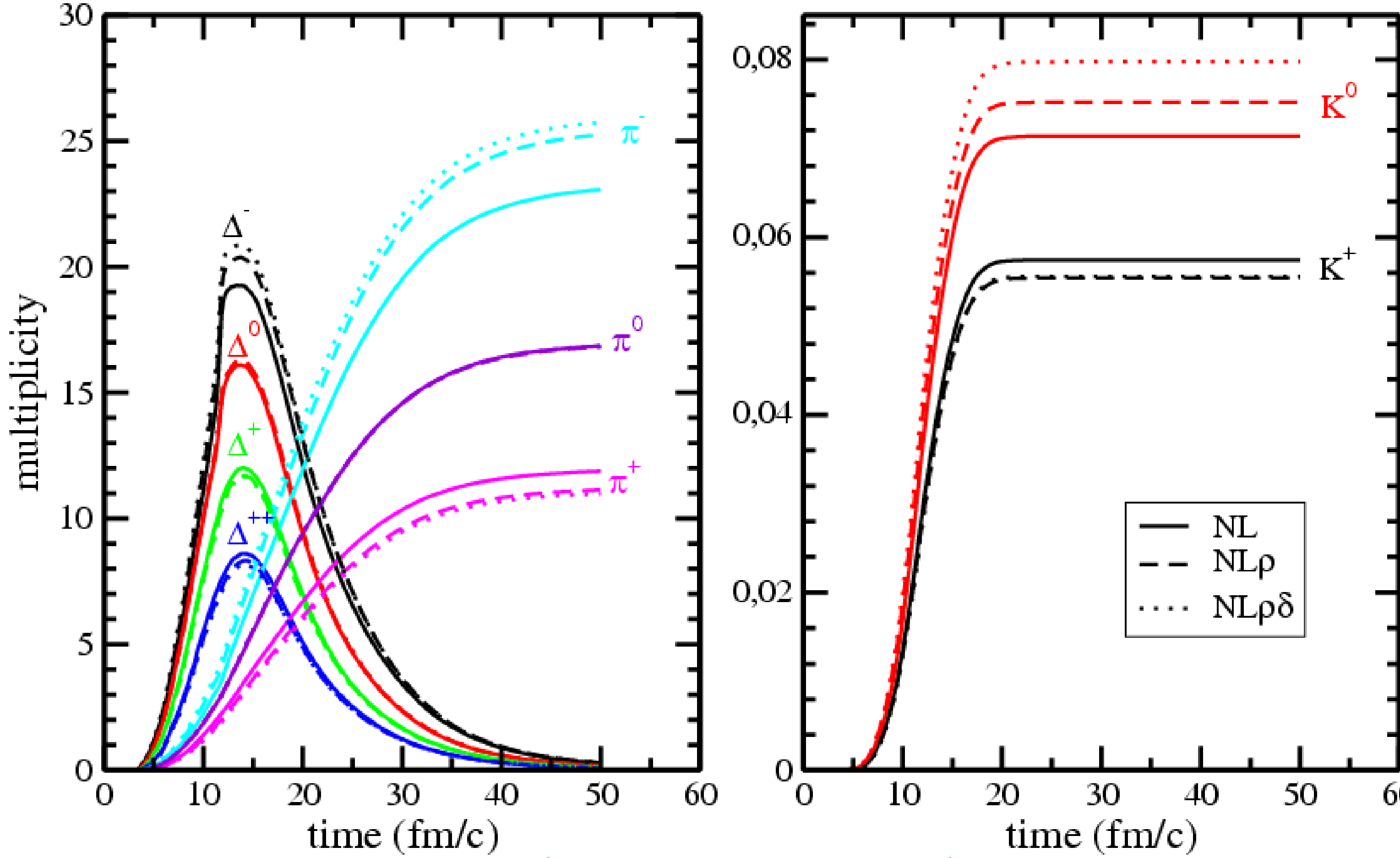


vs. asymmetry

Large isospin effects: - no neutron escape

- Δ's in chemical equilibrium→less n-p "transformation"

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



Pions: compensation

Kaons:

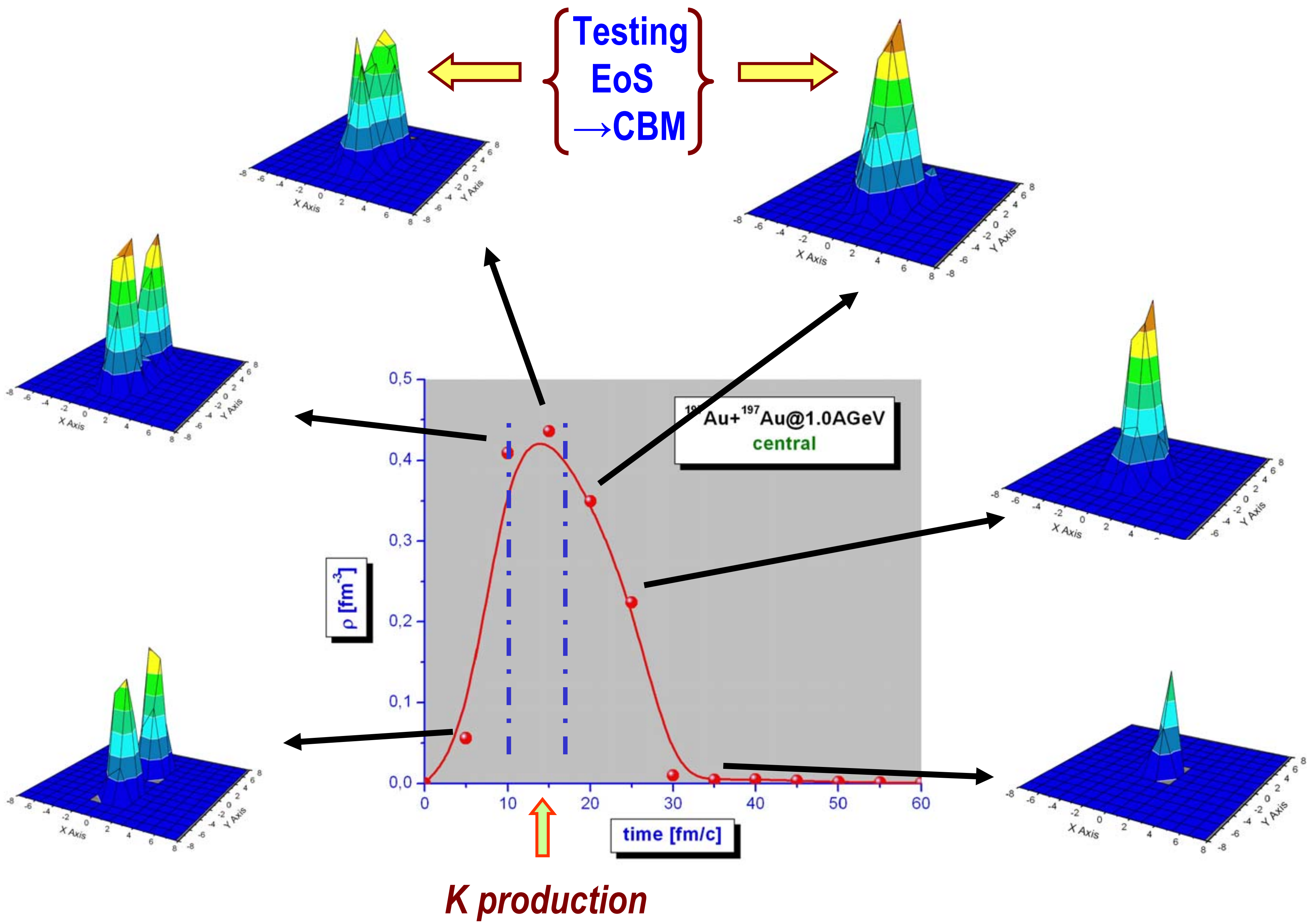
- early production: high density phase

- isovector channel effects →

but mostly coming from second step collisions…

→ reduced asymmetry of the source

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



Kaon production in "open" system: Au+Au 1AGeV, central
Main Channels

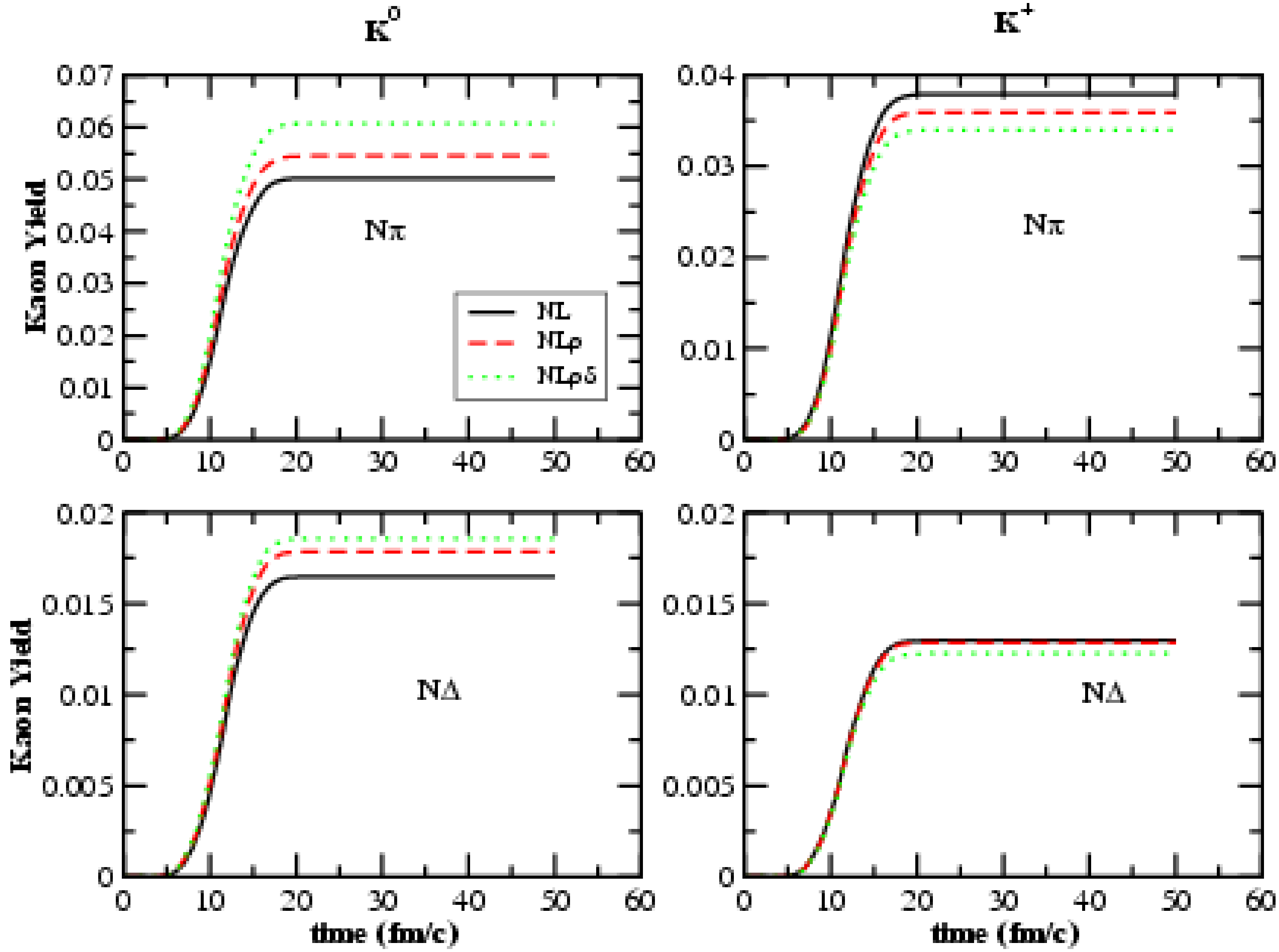
$NN \rightarrow BYK$

$N\Delta \rightarrow BY$

$\Delta\Delta \rightarrow BYK$

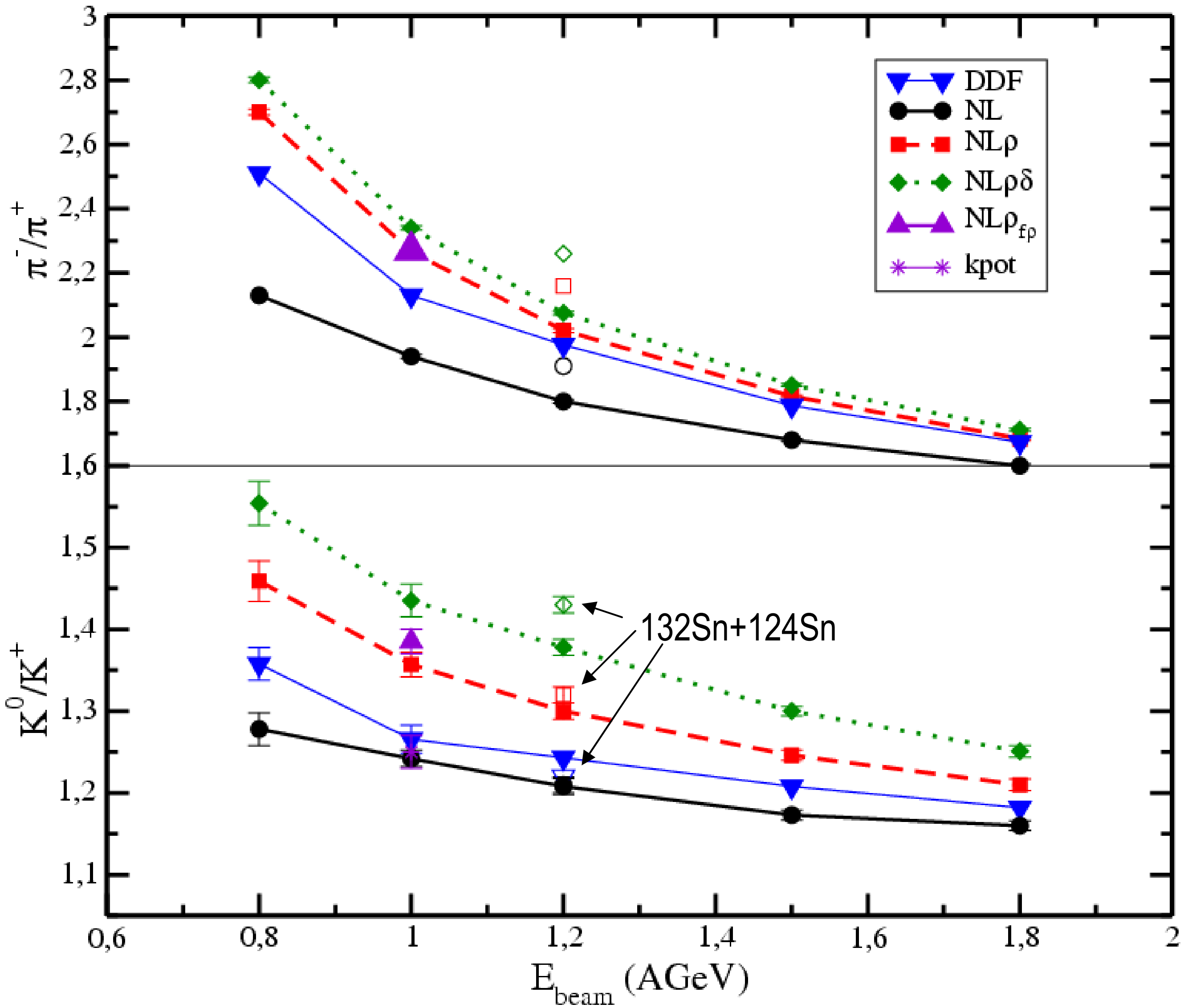
$\pi N \rightarrow YK$

$\pi\Delta \rightarrow YK$



opposite contribution of the δ-coupling

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



Kaons:
~15% difference between DDF and NLρδ

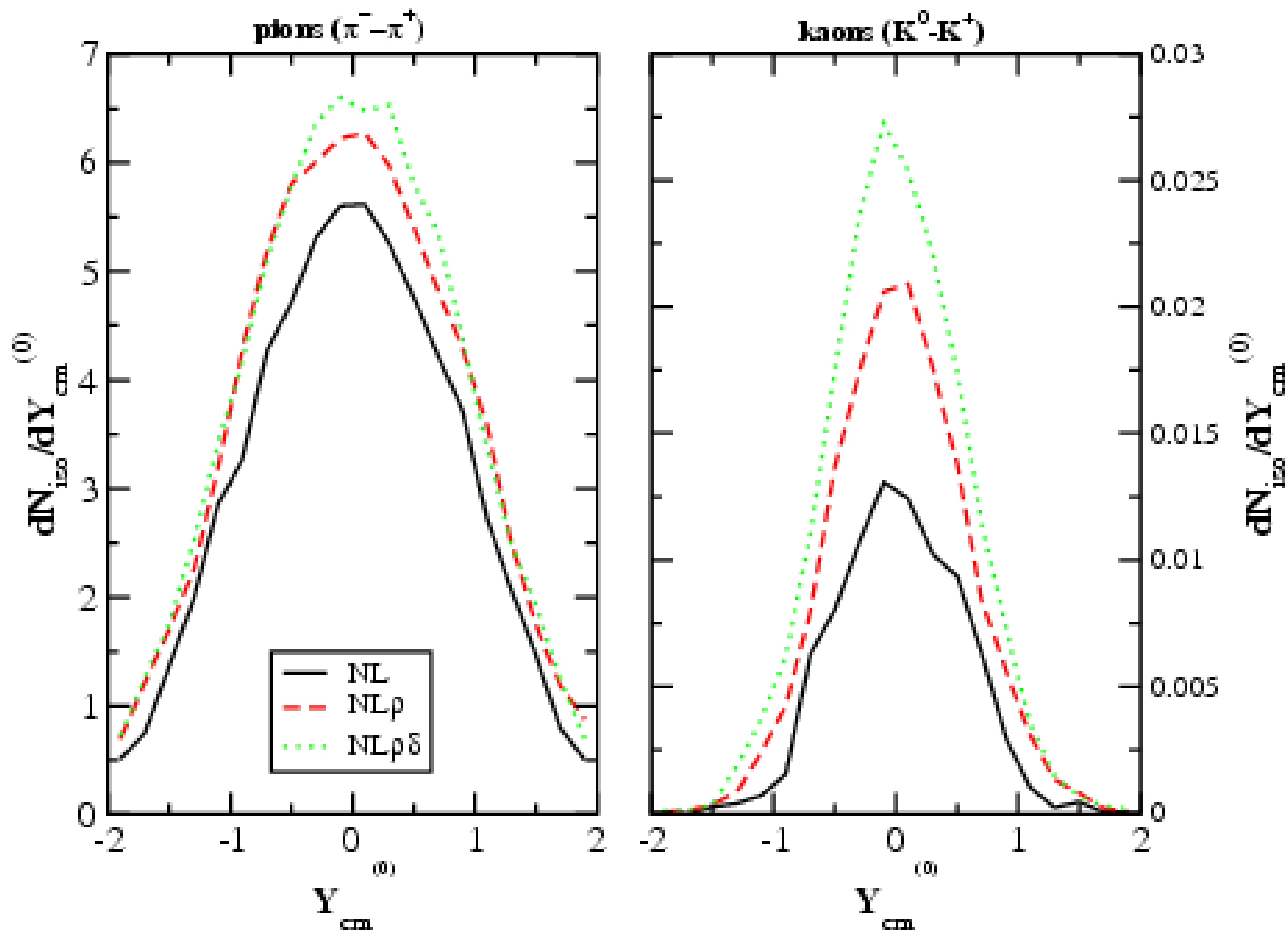
No sensitive to the K-potential

Pions: less sensitivity ~10%, but larger yields

Inclusive multiplicities

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

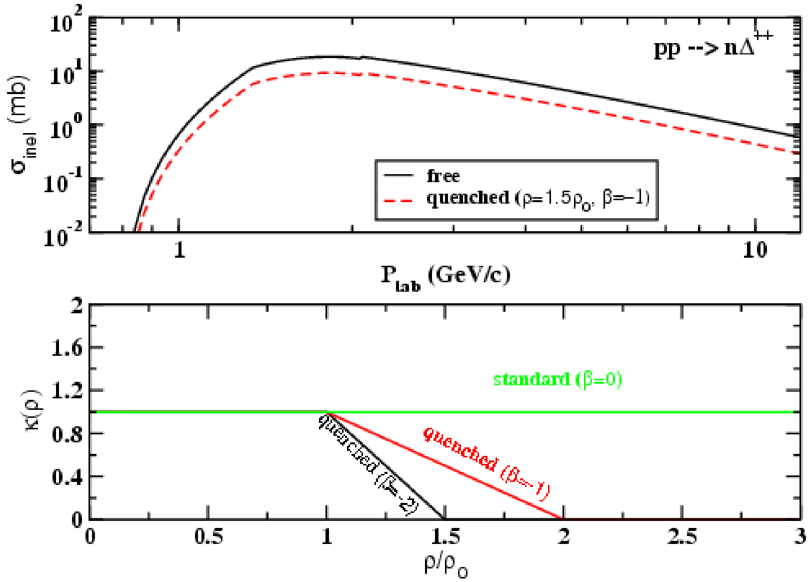
"differential"- rapidity distributions

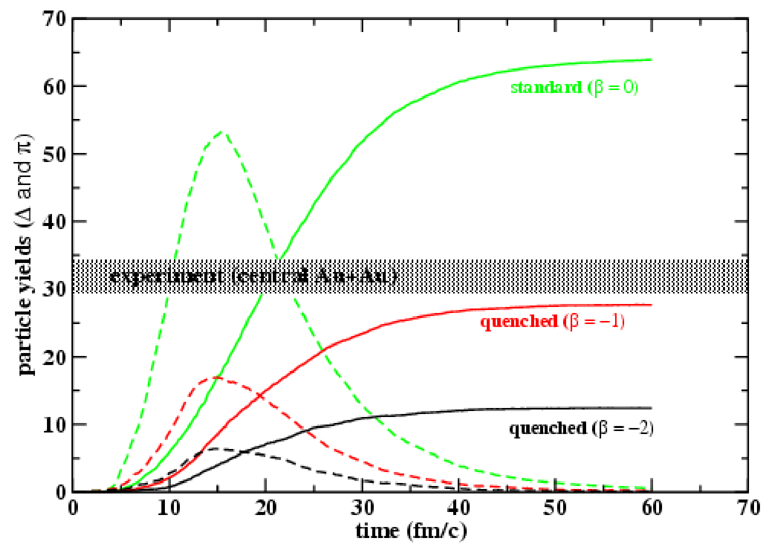


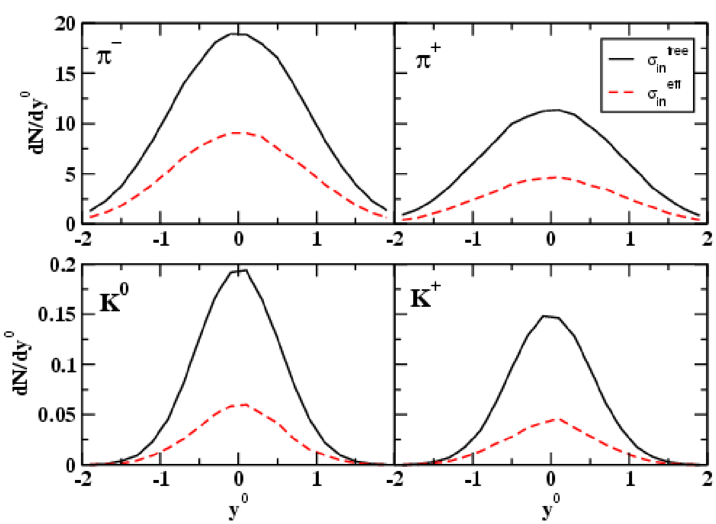
rather sensitive observable for Kaons

Reduced in-medium inelastic cross sections

V.Prassa et al. nucl-th/0510035







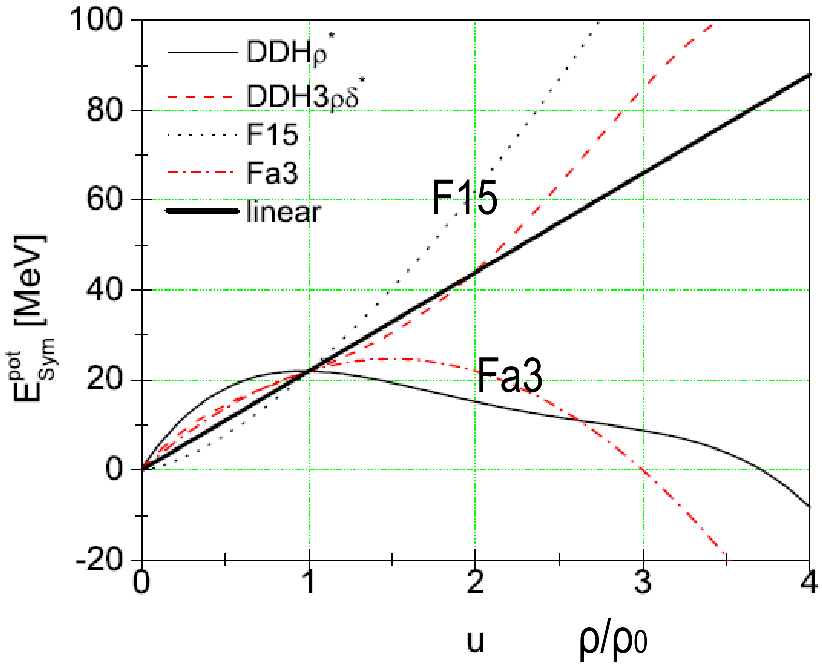
particle ratio	free σ_{inel}	in-medium $\sigma_{inel}(\beta = -1)$
(π^-/π^+)	1.65 (± 0.22)	1.9 (± 0.24)
(K^+/K^0)-ratio	0.76 (± 0.09)	0.75 (± 0.08)

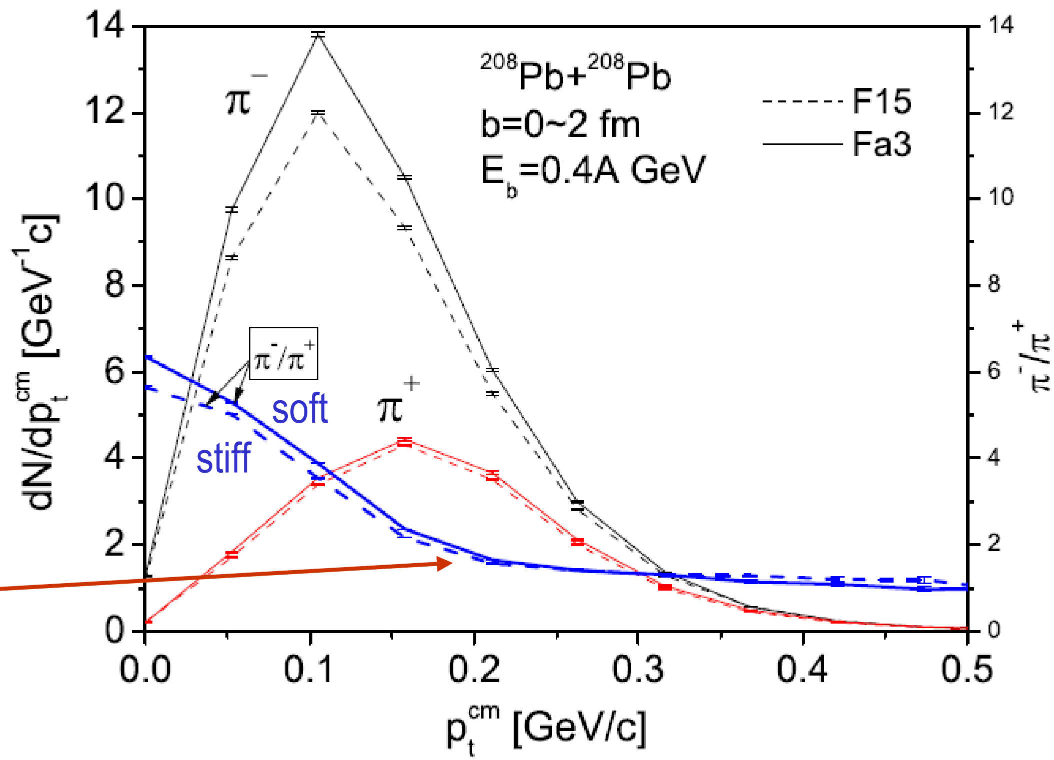
K-ratio: robust EOS signal

Pions produced everywhere,
Kaons only at high densities

UrQMD : not covariant symmetry term

208Pb+208Pb at 0.4AGeV



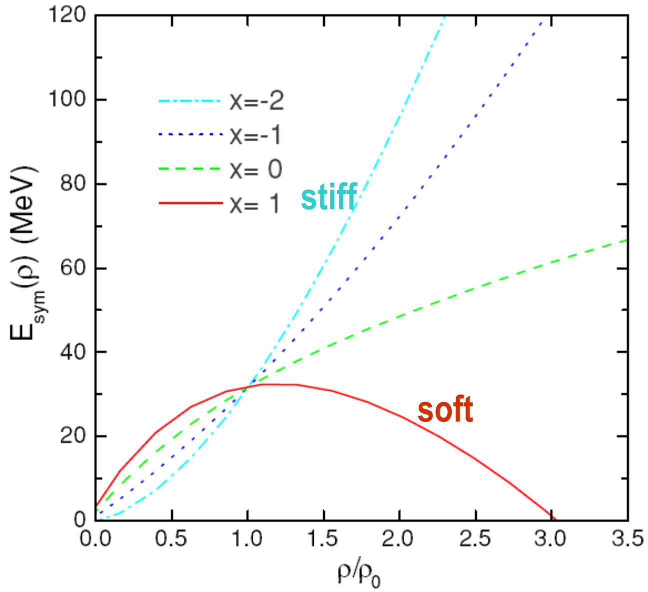


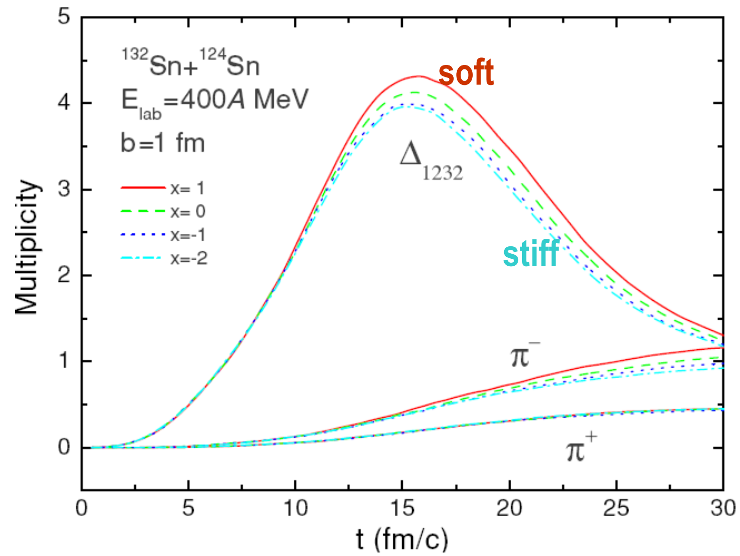
Inelastic channels less important but still crossing at high p_t

Q.Li et al. PRC 72 (2005) 034613

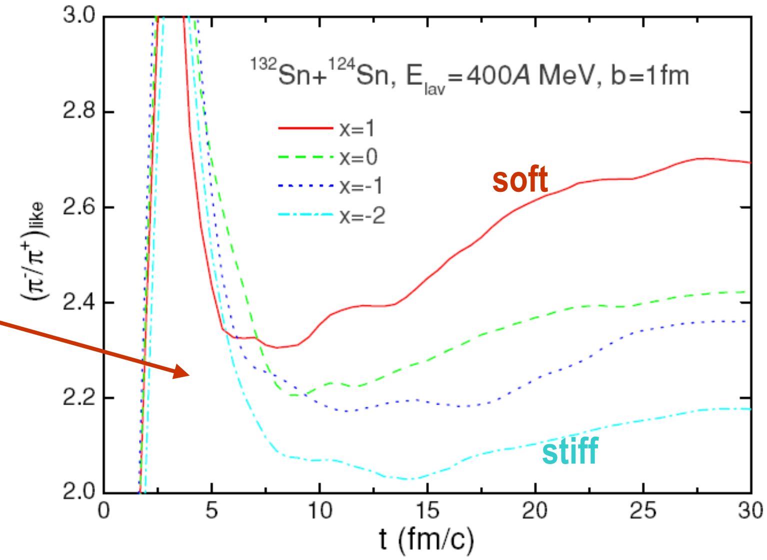
IBUU : not covariant symmetry term

132Sn+124Sn at 0.4AGeV





fluctuations



π(-)/π(+) always decreasing with the iso-stiffness?

Bao-An Li PRC 71 (2005) 014608

ISOSPIN EFFECTS IN REACTIONS

Mass(A)=Mass(B) ; N/Z(A) = N/Z(B)

Rami imbalance ratio:

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

A dominance → +1

mixing → 0

B dominance → -1

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

vs. Centrality (fixed y)

vs. Rapidity (fixed centrality)

vs. Transverse momentum (fixed y, centrality) ?

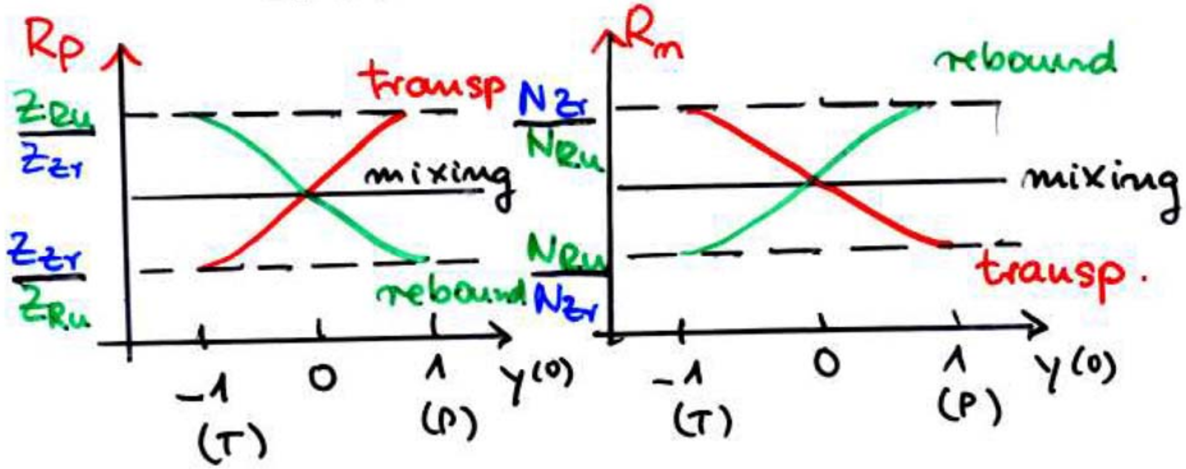
STOPPING and ISOSPIN TRACING METHOD (FOPI)

Ru + Zr System

$$\left.\begin{array}{ll} {}^{96}_{40}Zr_{56} & N/Z = 1.4 \\ {}^{96}_{44}Ru_{52} & N/Z = 1.18 \end{array}\right\} \quad \frac{Z_{Zr}}{Z_{Ru}} = 0.91 ; \quad \frac{N_{Zr}}{N_{Ru}} = 1.08$$

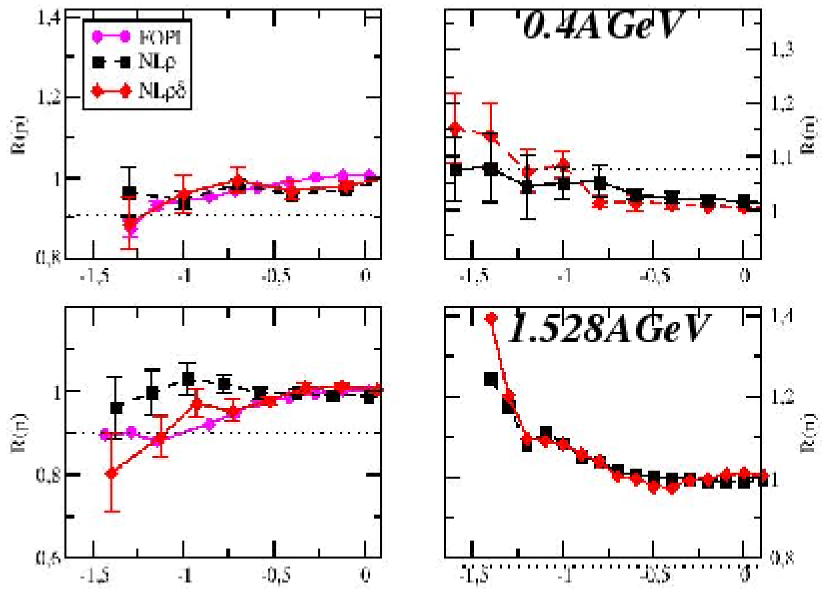
Isospin tracing Ratio

$$R_i = \frac{Y_i^{RuZr}}{Y_i^{\underset{(P)}{Zr}\,\underset{(T)}{Ru}}} \quad ; \; i = p, n, d, t, {}^3He, \pi^\pm, \ldots$$

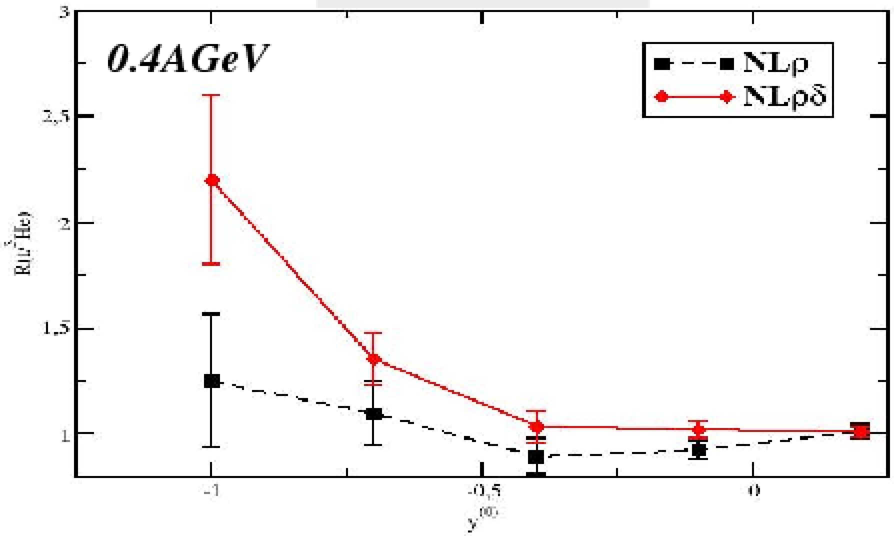


Isospin transparency@SIS

protons **neutrons**

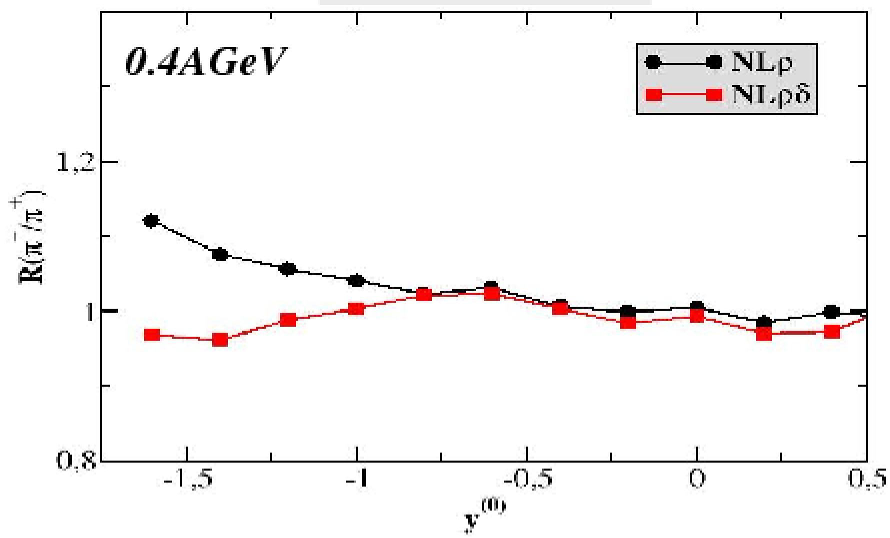


t / ³he



Target rapidity

π^-/π^+

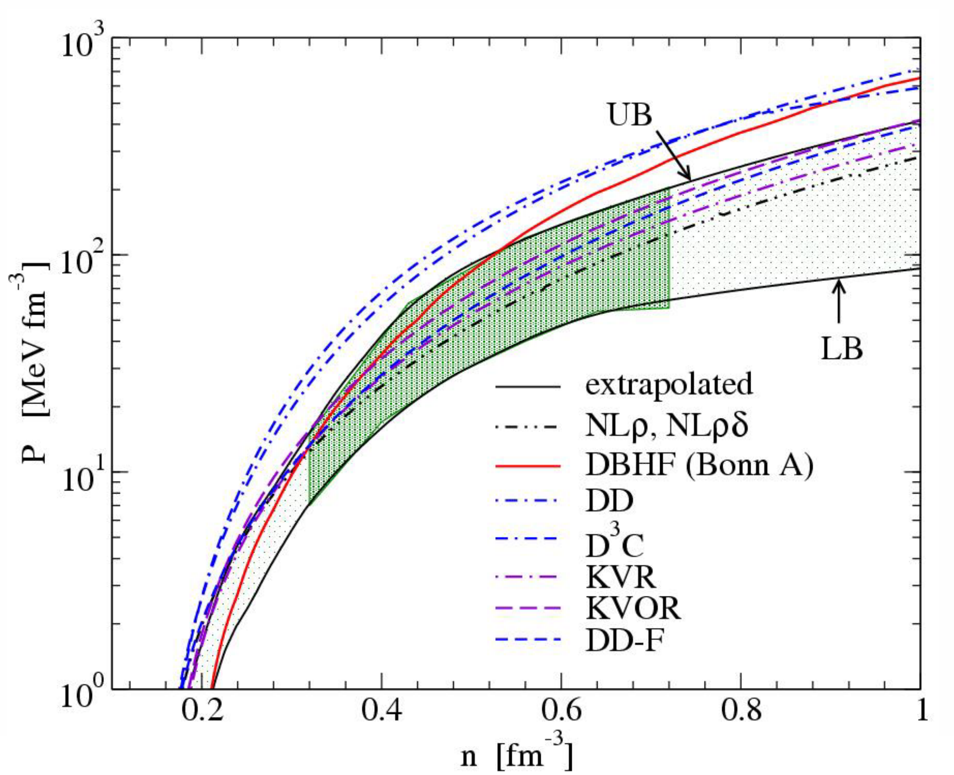


Mixed systems Ru(Zr)+Zr(Ru)

A=96, n-poor(n-rich)+inverse

$$R(n, p, \pi, fragments, ..) = \frac{N_y^{Ru+Zr}}{N_y^{Zr+Ru}}$$

Gaitanos et al. PLB595 (2004)



EOS softening at high baryon density?

→ asymmetric matter?

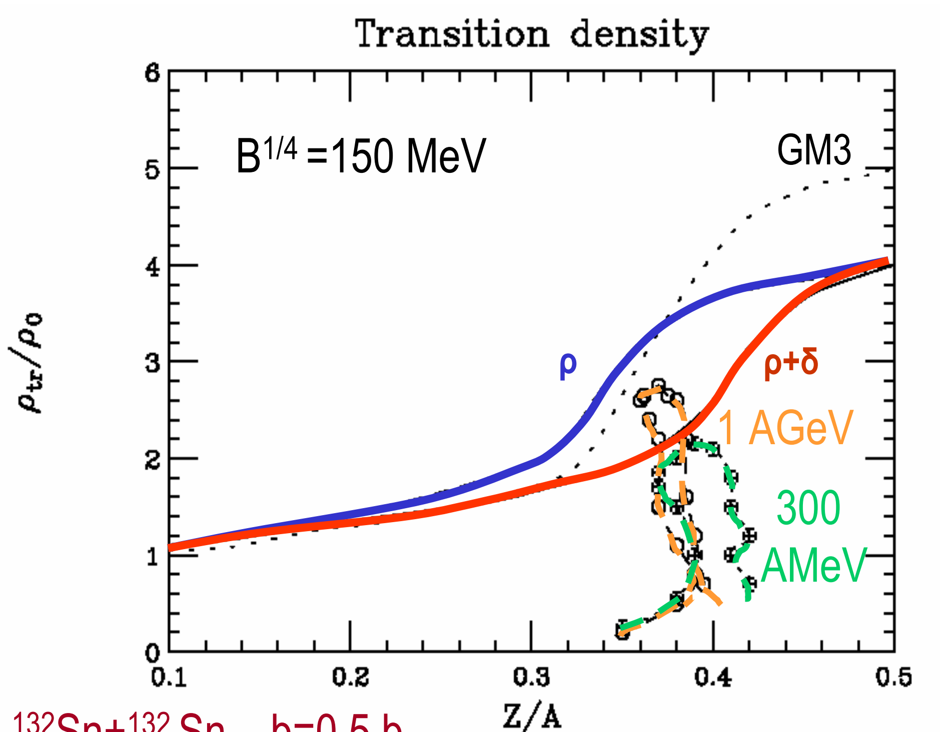
Testing deconfinement with RIB's?

(T,ρ_B,ρ_{B3}) binodal surface → Hadron-RMF; → Quark-bag model

ρ_{trans} ⇨ onset of the mixed phase

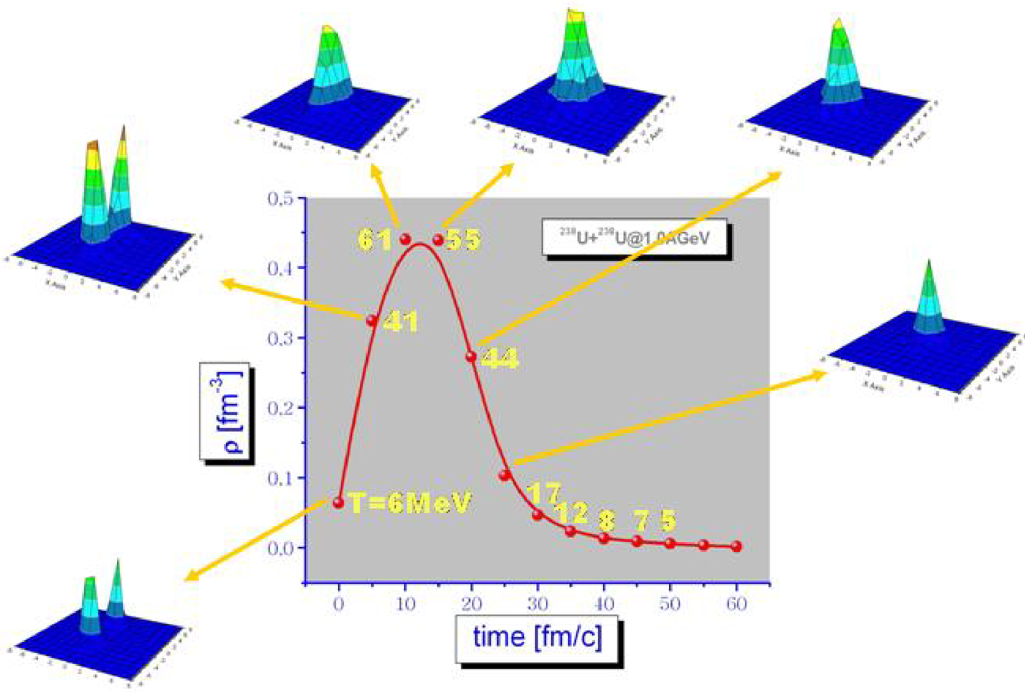
Signatures?

NPA722(2003), nucl-th/0602052→NPA2006

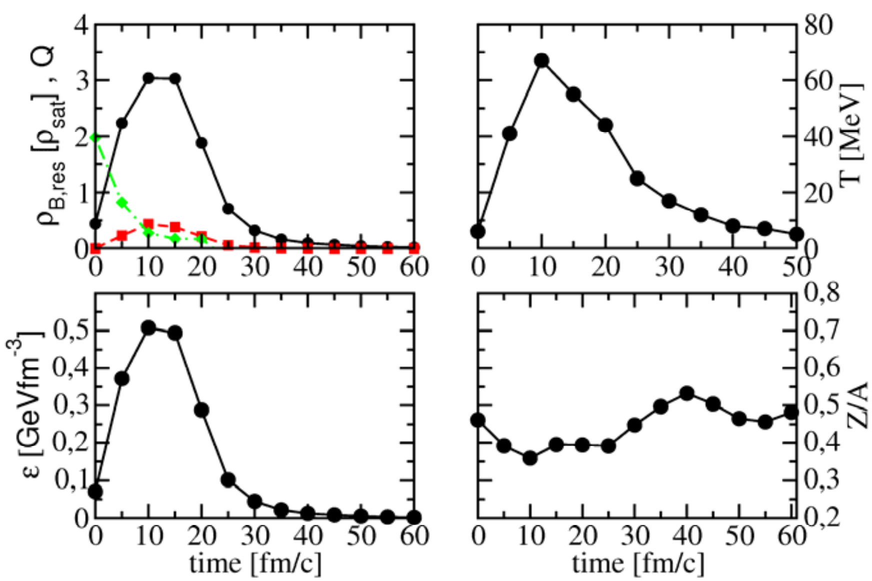


$^{132}Sn+^{132}Sn$ b=0.5 b_{max}

System Size Dependence & Equilibration (U+U)



In a C.M. cell



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

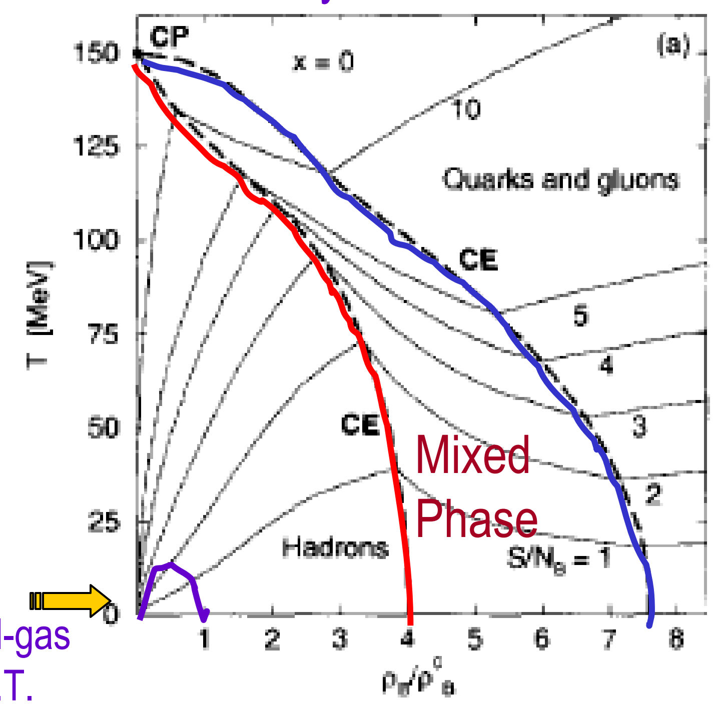
Exotic matter over 10 fm/c ?

Transition to deconfined phase at high baryon density

H.Mueller NPA618(1997)

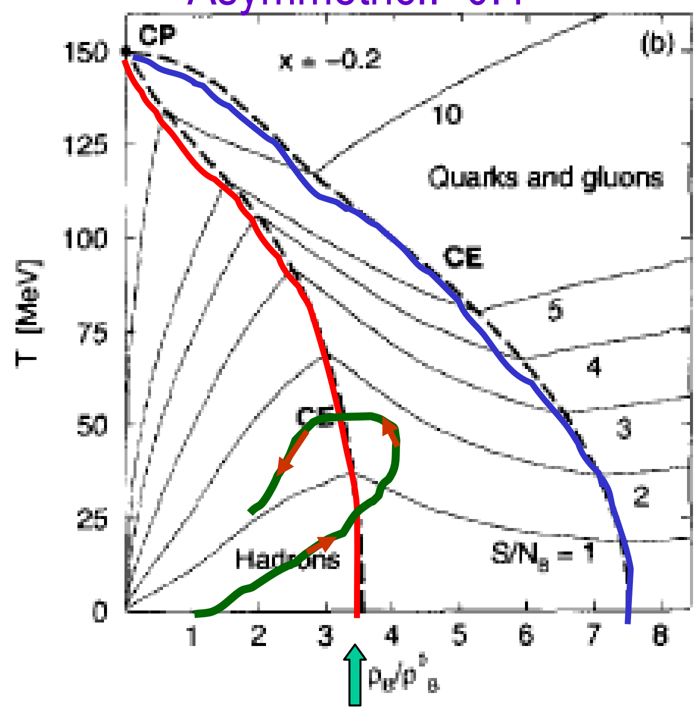
Hadron EOS : QHD
Quark EOS: MIT-Bag Model

Symmetric



liquid-gas
P.T.

Asymmetric:I=0.4



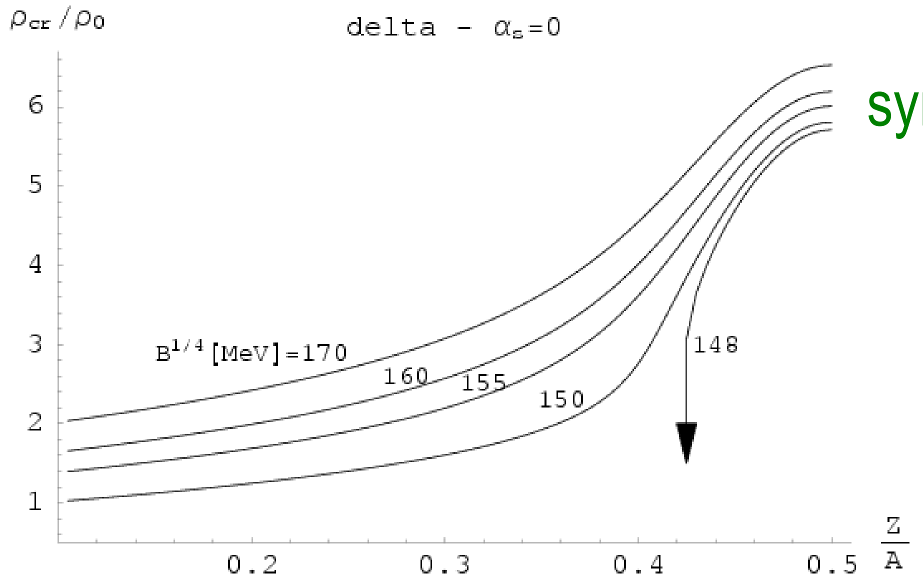
Reduced transition density

1. Earlier transition at high isospin density
2. Worse model choice? Hadron: rho-meson only, Quark: B1/4=190MeV
   large Bag-Pressure

Lower Boundary of the Binodal Surface vs. NM Asymmetry

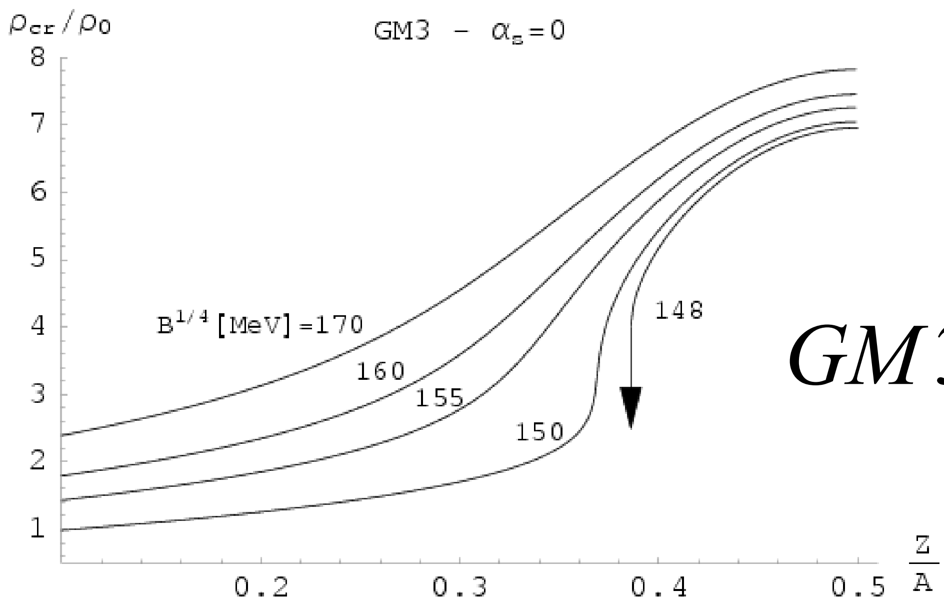
$$Hadron : NL\rho\delta$$

vs. Bag-constant choice



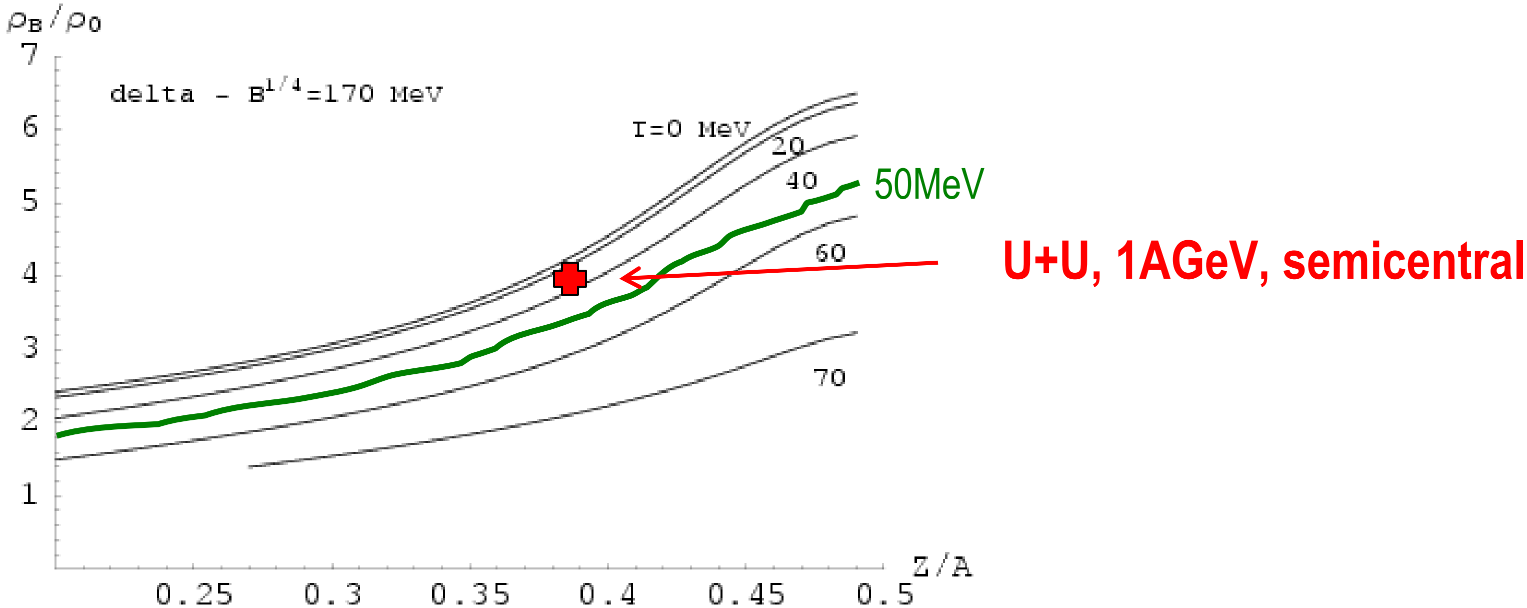
symmetric

Proton-fraction

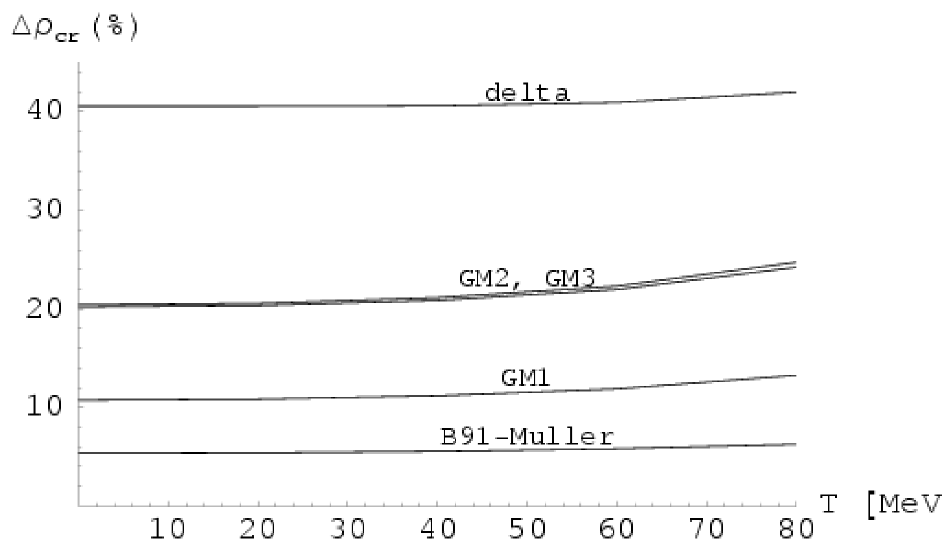


$$GM3 \Leftrightarrow NL\rho$$

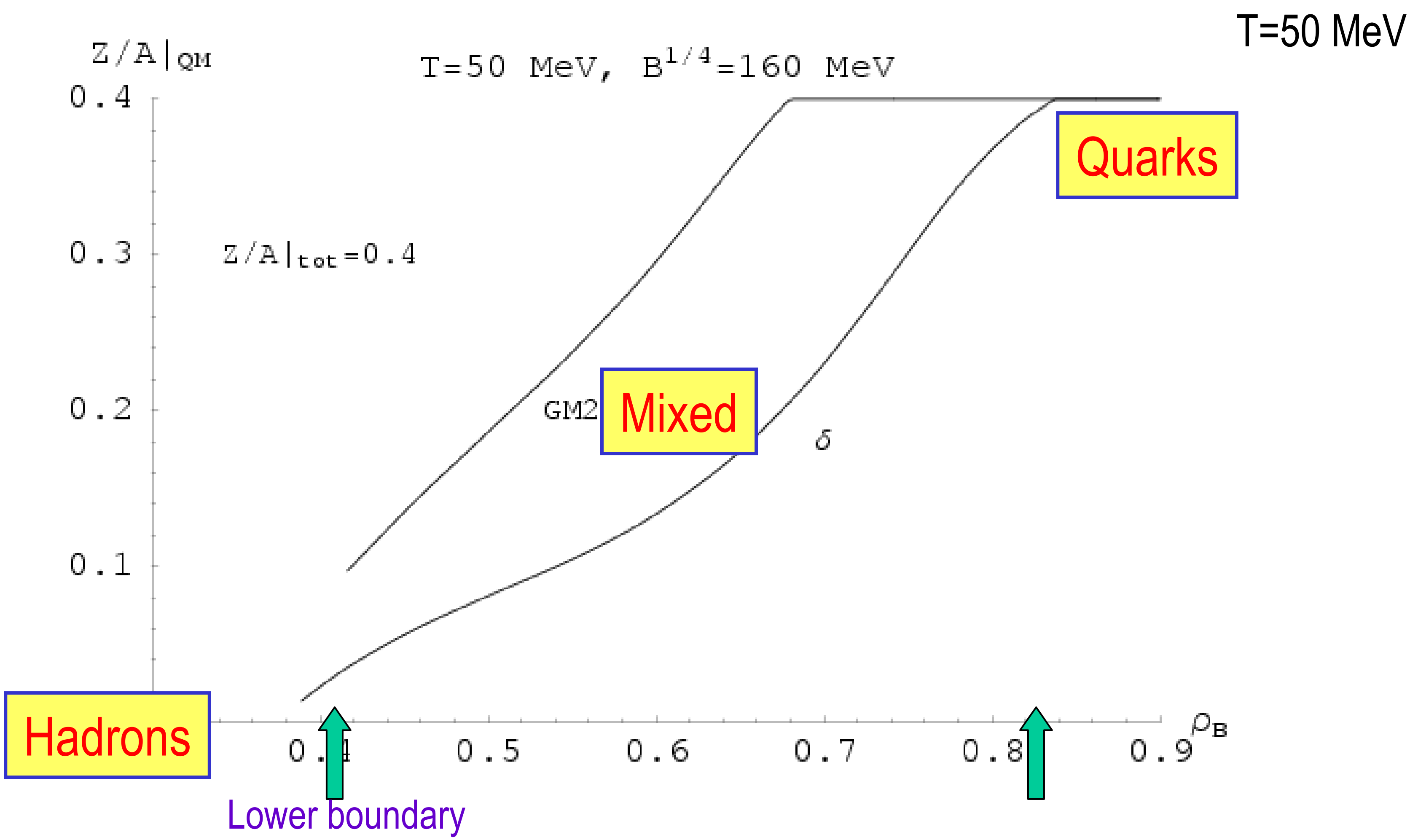
Temperature variation of the crossing density



Reduction of the crossing density vs. T:
delta-meson very efficient!



Isospin content of the Quark Clusters in the Mixed Phase



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

ISOSPIN IN RELATIVISTIC HIC: EOS – SENSITIVE OBSERVABLES

1. *Fragments in Central Collisions: N/Z*
2. *n – p collective flows* ⟶ *light isobar flows*
3. *Kaon Yields , (π^-/π^+) ? , flows?*
4. *Iso – stopping*
5. *Deconfinement precursors*

Genuine relativistic effects: - boosting of vector potentials
- baryon and scalar densities
  (vector vs. scalar field competition)
- Dirac masses

People: M.Colonna, M.Di Toro, **G.Ferini,** Ch.Fuchs,
Th.Gaitanos, V.Greco, Liu Bo, **V.Prassa,**
E.Santini, **S.Yildirim** and H.H.Wolter
+ **A.Drago, A.Lavagno**

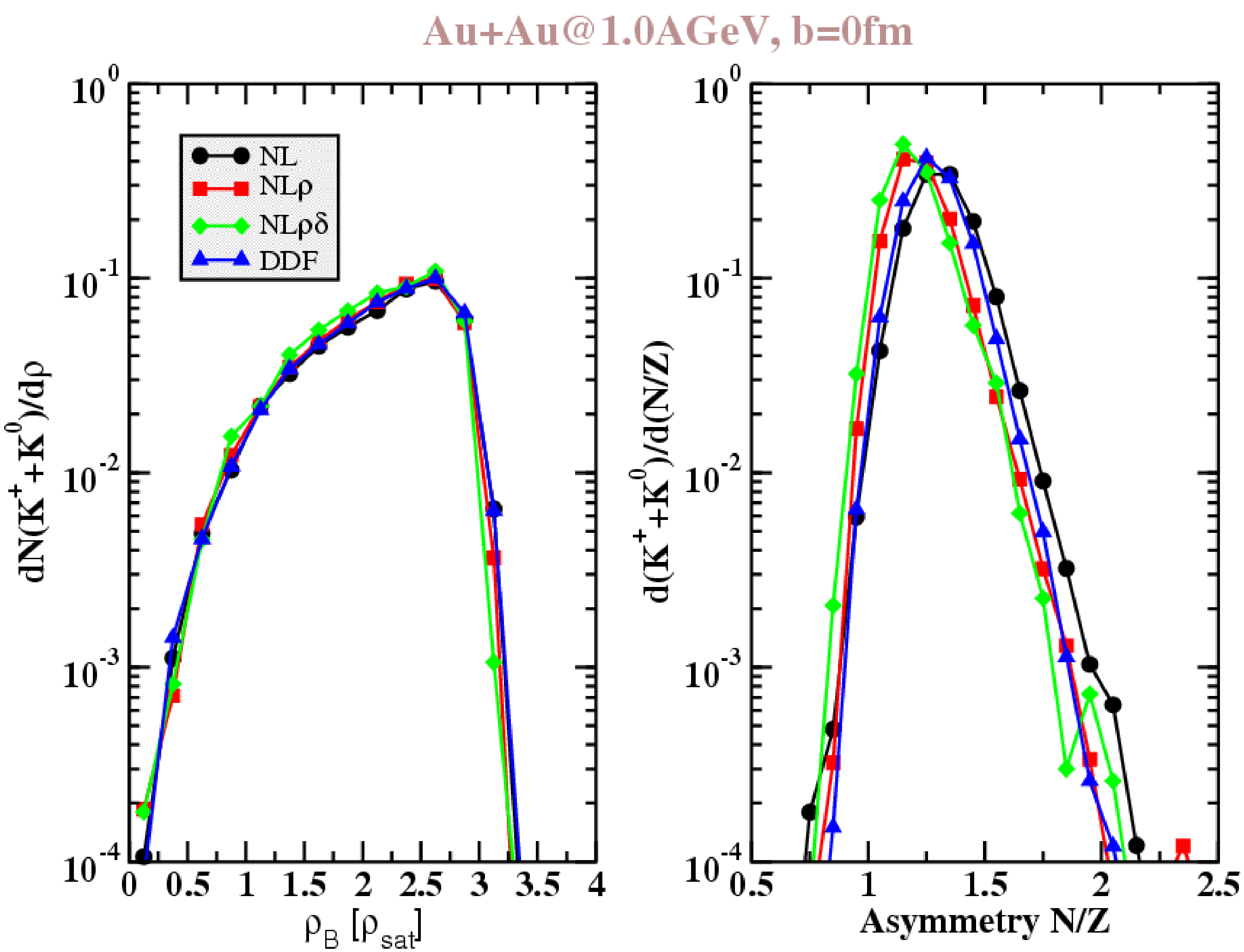
Relativistic Transport Dynamics

Effective Lagrangian → Transport Equations → Event simulation

Hadronic: High Baryon and Isospin Densities → New Physics?
- **Pion, proton multiplicities (saturation?)**
- **Meson, baryon spectra vs. transverse momentum**
- **Elliptic Flows (EOS softening?)**
- **Isospin structure of particles at high p_t**

Partonic: beyond "Cascade"
- **Hadronization (coalescence) dynamics**
- **Hydro limit**
- **Collective flows**
- **Spinodal mechanism for hadronization**

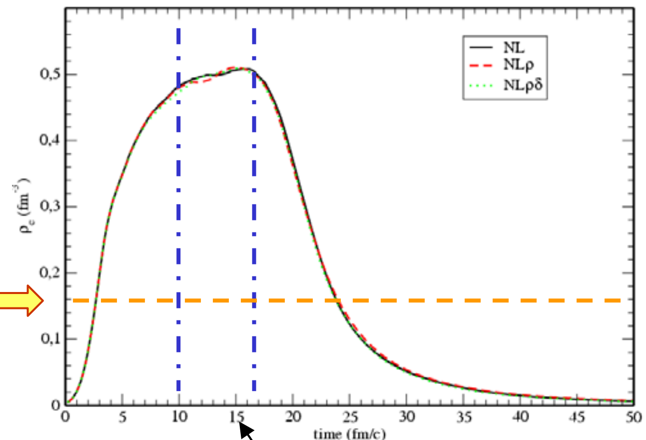
Au+Au 1AGeV: density and asymmetry of the Kaon source



NL→ DDF→NLρ→NLρδ : more neutron escape and more n→p *transformation* (less asymmetry in the source)

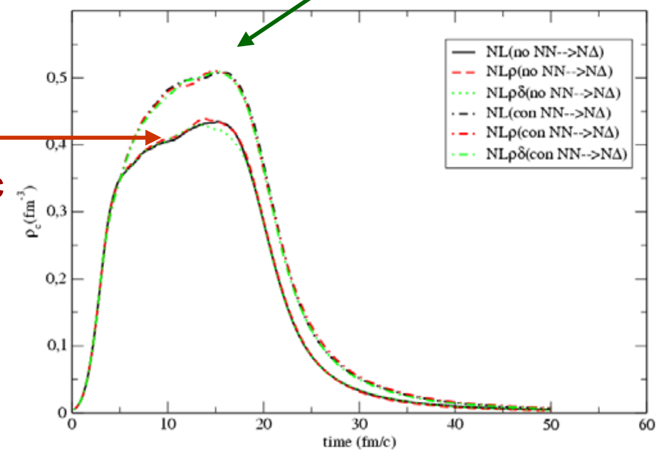
Au+Au 1AGeV: density and isospin of the Kaon source

"central" density



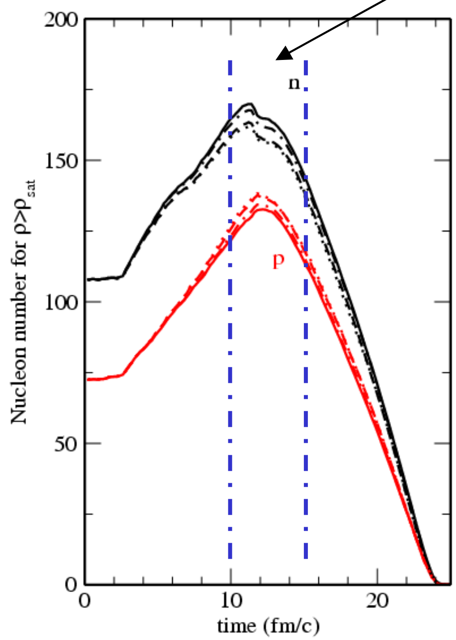
Higher baryon density with inelastic channels

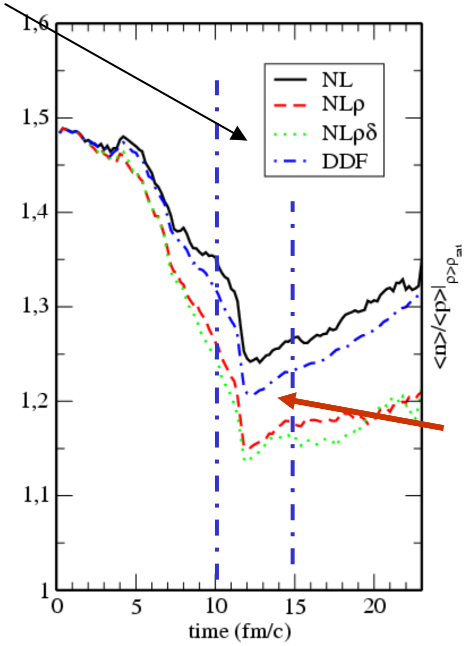
only elastic



Time interval of Kaon production

n,p at High density





n/p at High density

Drop:

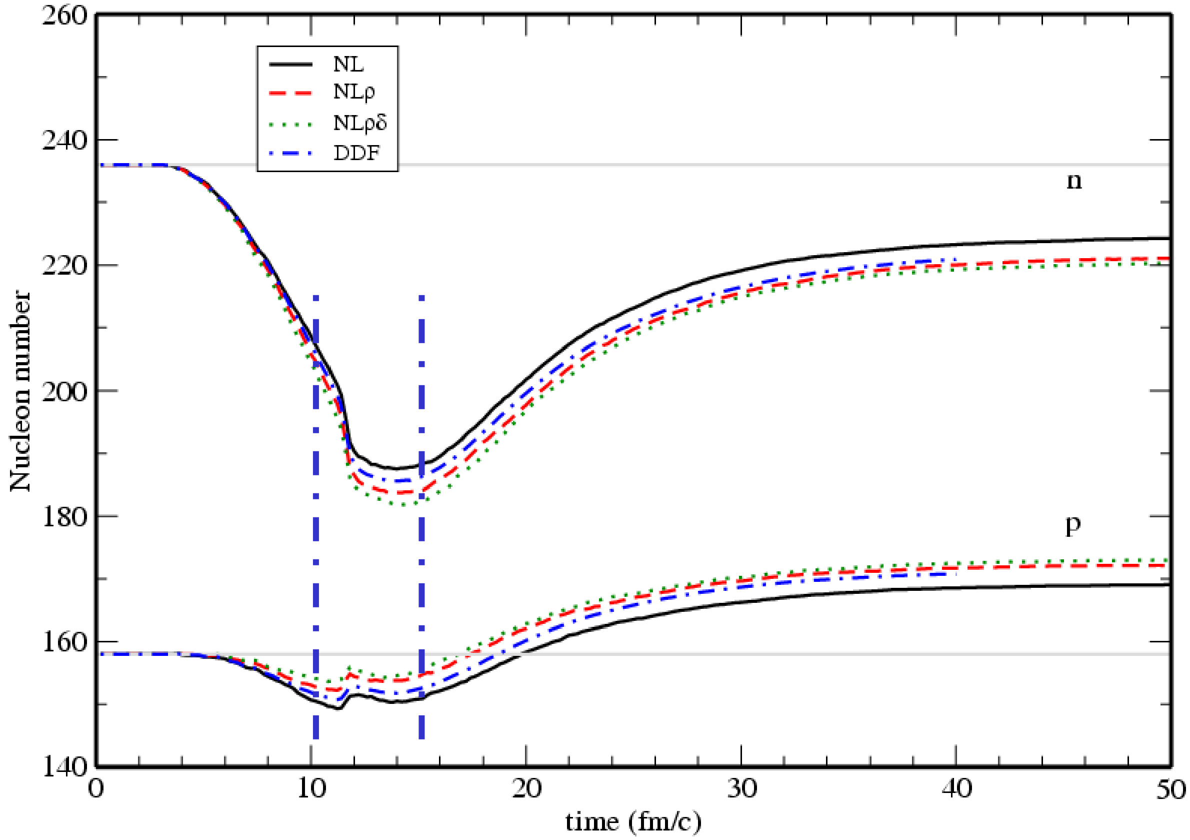
Competition of fast neutron emission

and

Inelastic channels:

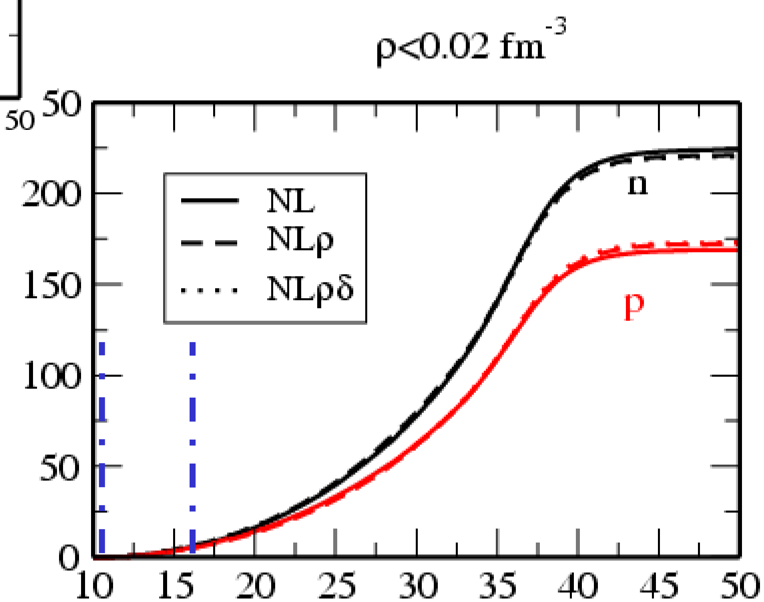
n⟶p *transformation*

Au+Au 1AGeV: time evolution of the total number of nucleons



Large n→p transformation
at early times:
Less asymmetry in the Kaon source

f_ρ increasing sequence
NL<DDF<NLρ<NLρδ

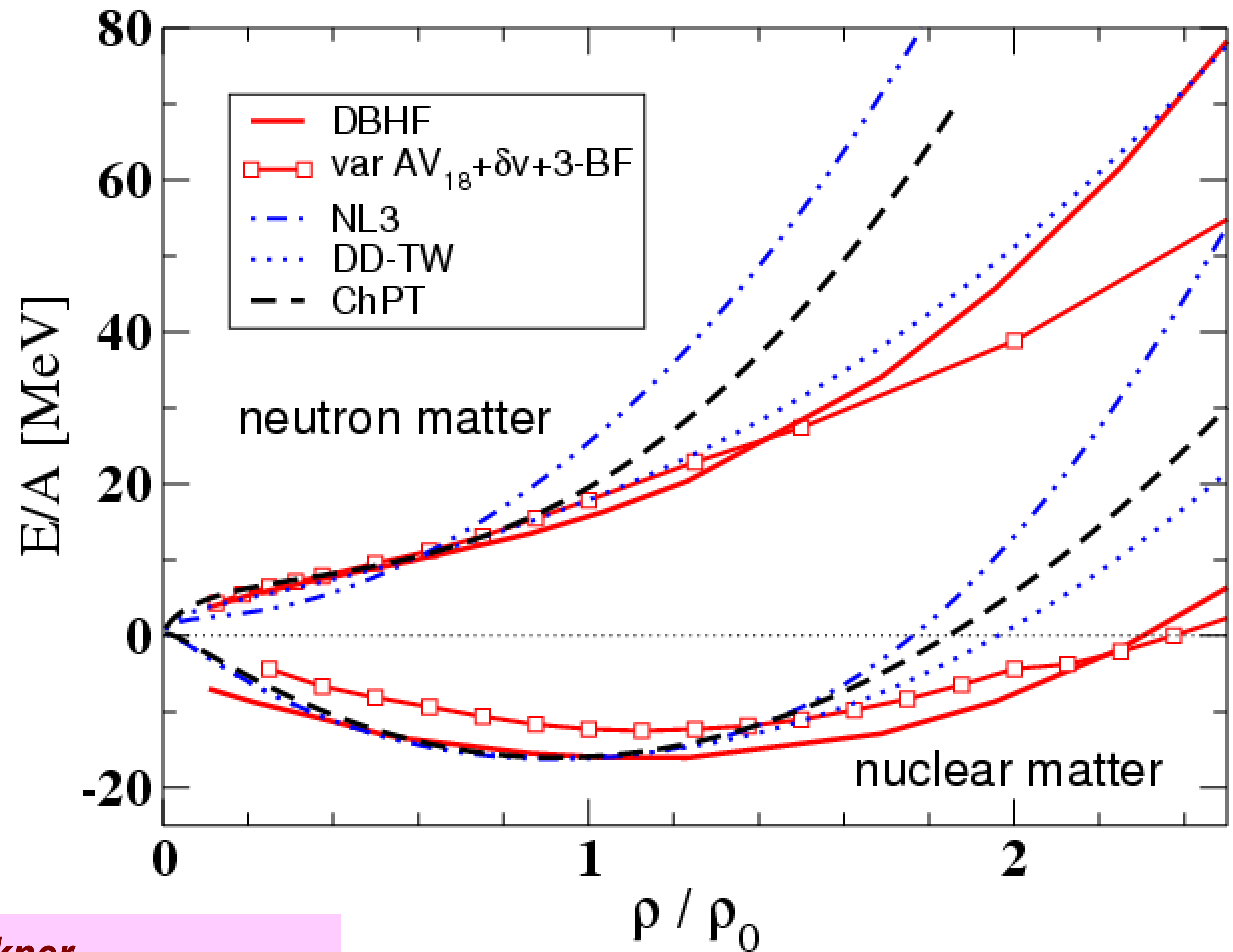


Free nucleons

Check:
π-/π+, n/p, K(0)/K(+) vs emission time (P_t)

→ **Different behavior at lower energies, reduced inelastic competition**

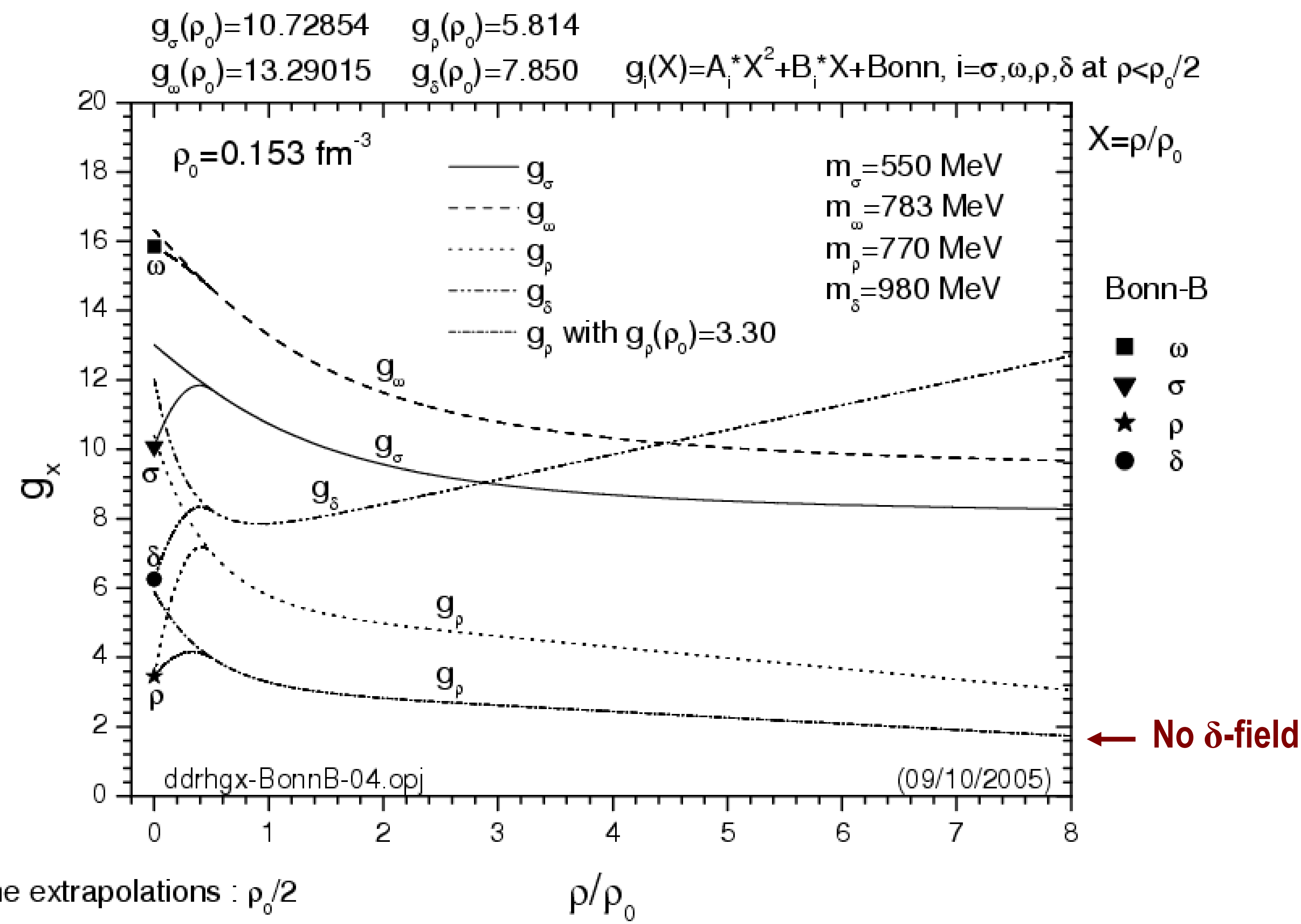
EOS of Symmetric and Neutron Matter



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

Ch.Fuchs, WCI Final Report 2006

DBHF-density dependent effective couplings

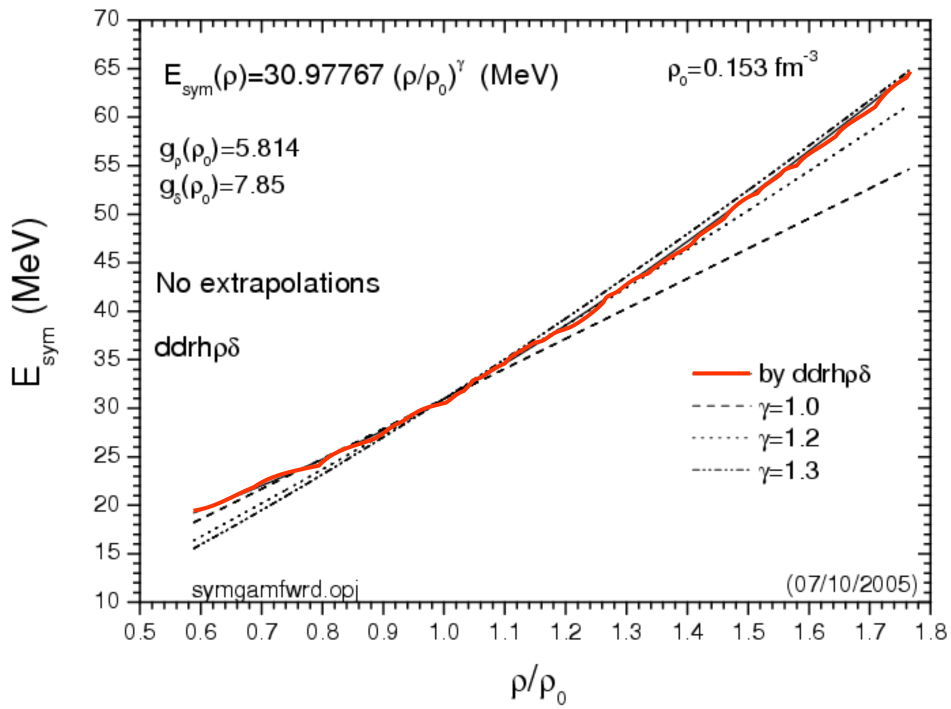


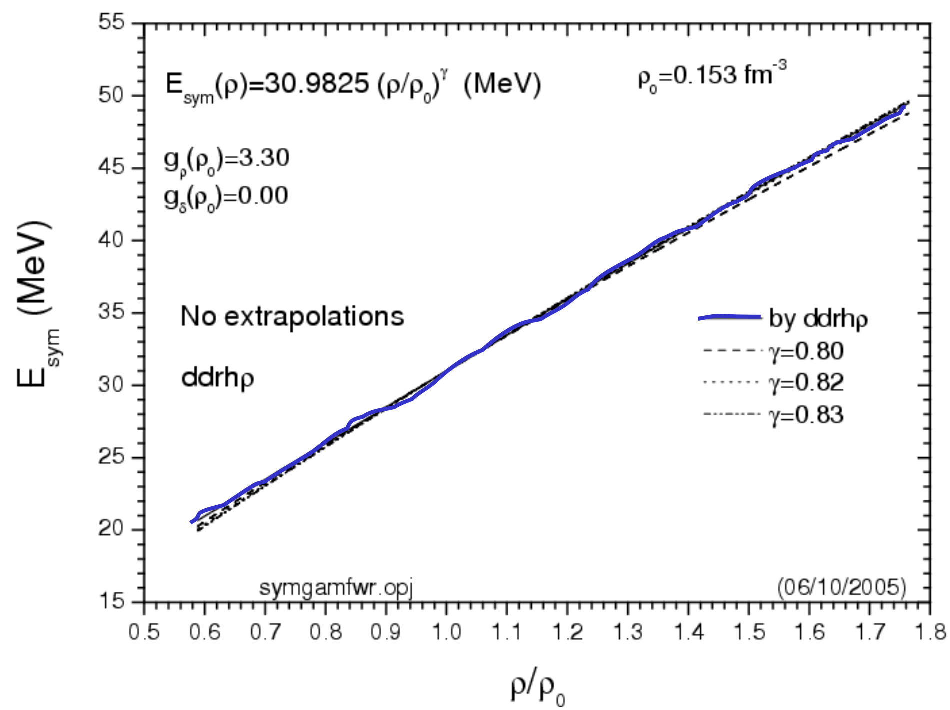
The extrapolations : $\rho_0/2$

Liu Bo calcs.

Symmetry energy around saturation (1)

RMF calculation with Density dependent couplings

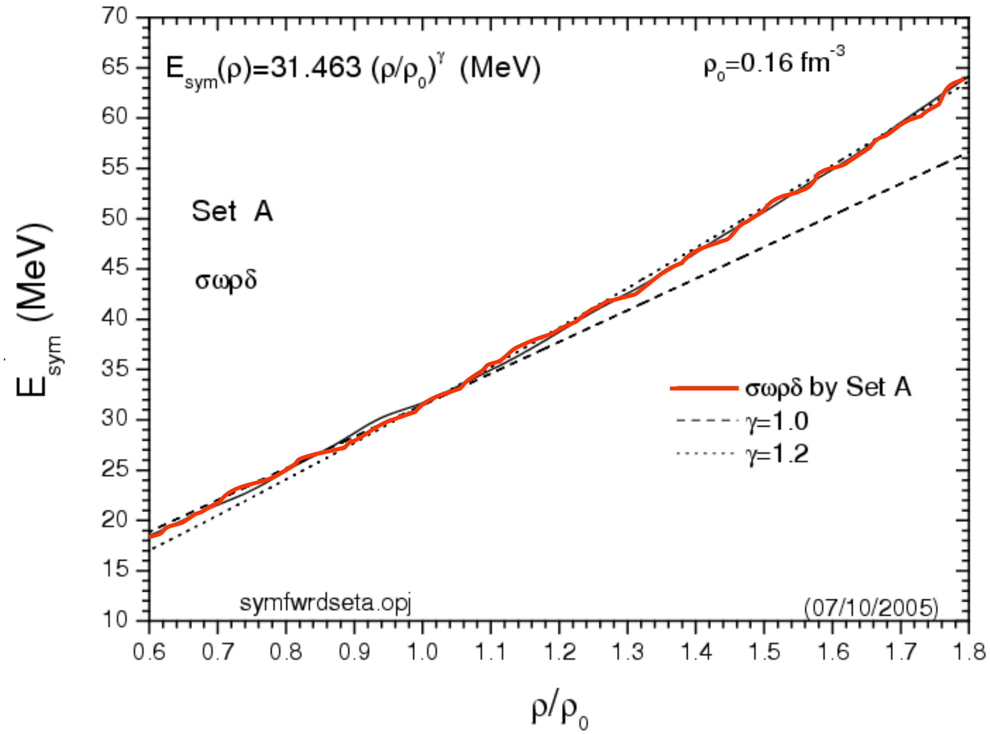


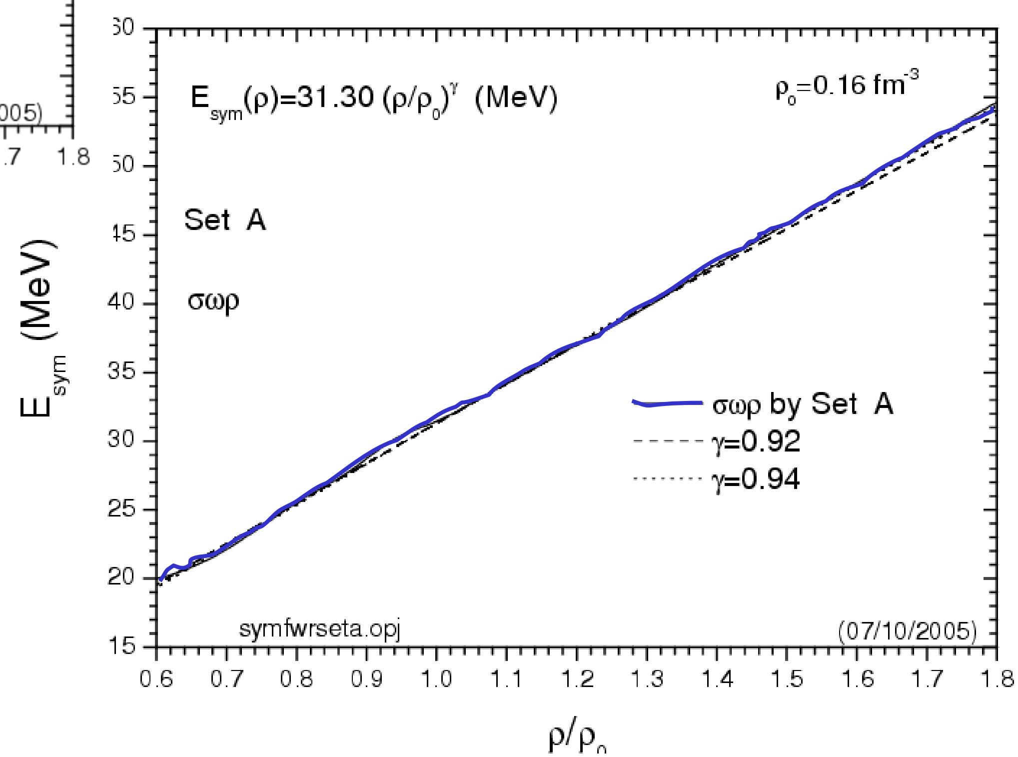


Liu Bo calcs.

Symmetry energy around saturation (2)

RMF calculation with constant couplings

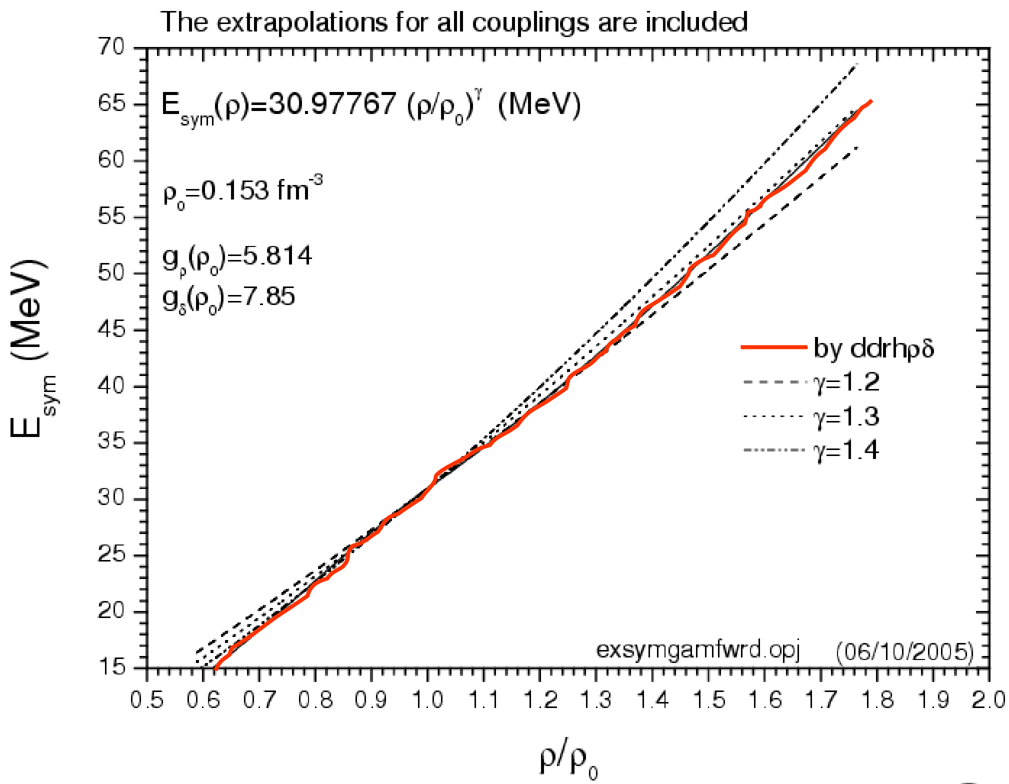


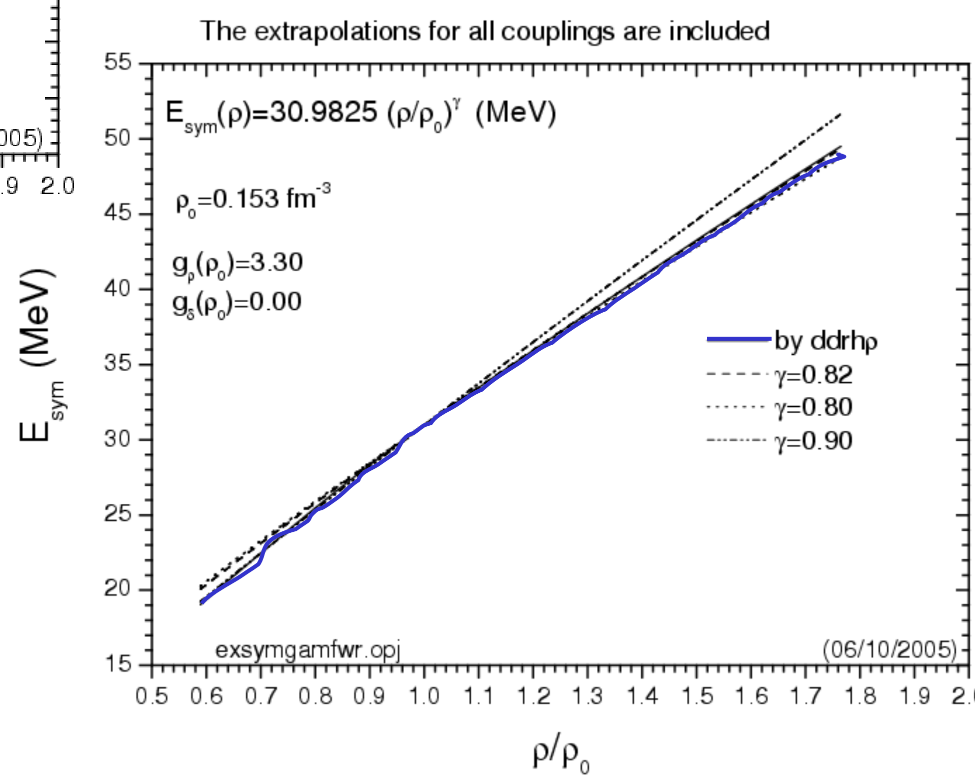


Liu Bo calcs.

Symmetry energy around saturation (3)

Density dependent couplings with free value extrapolations





Liu Bo calcs.