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Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

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Heavy Ion Collisions at Relativistic Energies: Testing a Nuclear Matter at High Baryon and Isospin Density

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Heavy Ion Collisions at Relativistic Energies: Testing a Nuclear Matter at High Baryon and Isospin Density

HIC → probing:
- different densities
- high momenta
- covariant structure: genuine rel. effects
- limits of the hadronic picture

Differential Flows

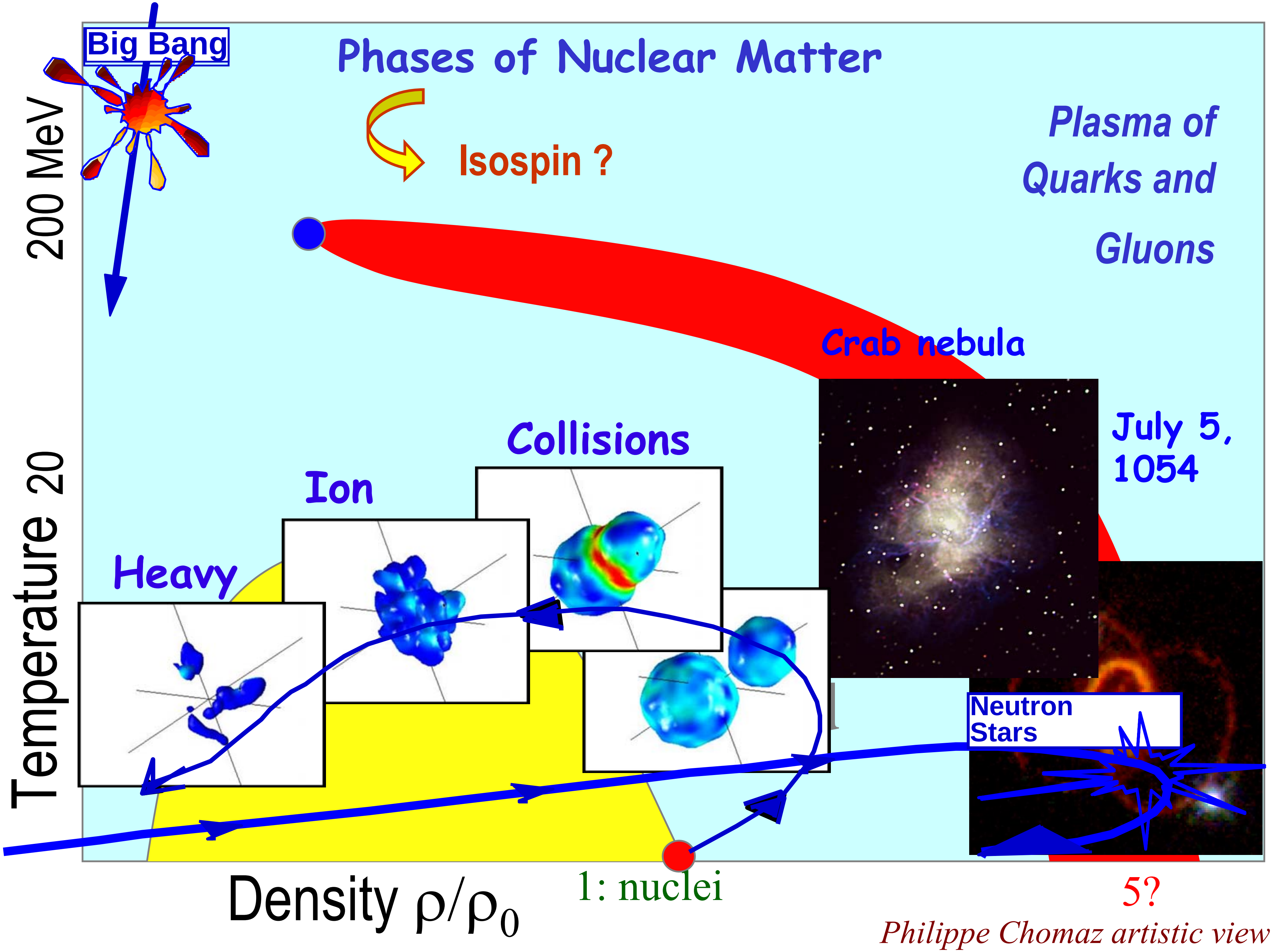
Pion/Kaon Production

Deconfinement Precursors?

Mean Fields
Effective Masses
In-medium cross sections

} Self-energies → Relativistic Transport Dynamics

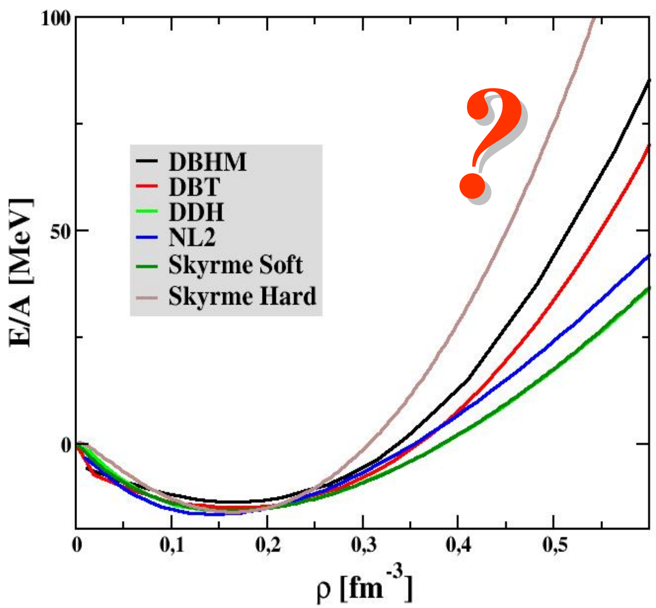
ICTP, May 06, ditoro@lns.infn.it



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

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

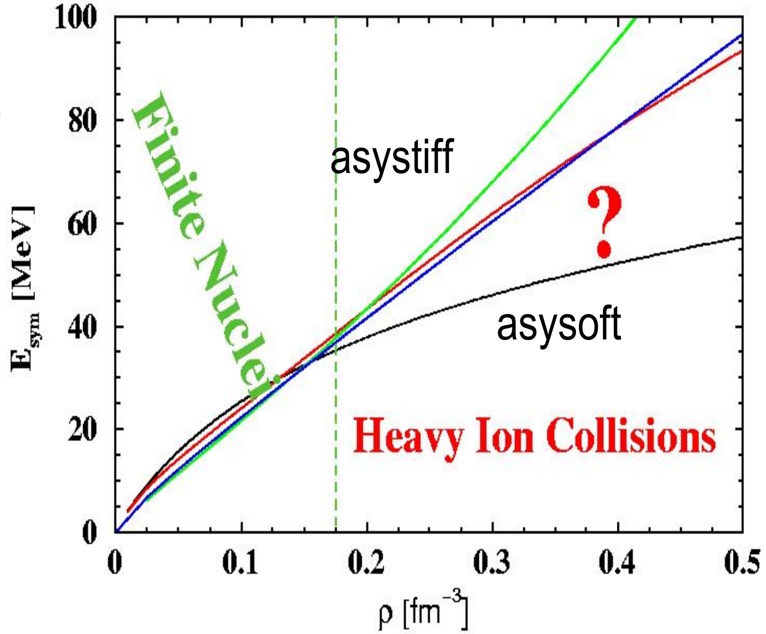
(less compression)

soft EoS

κ≈200 MeV

(more compression)

…iso-vector sector



Symmetry energy

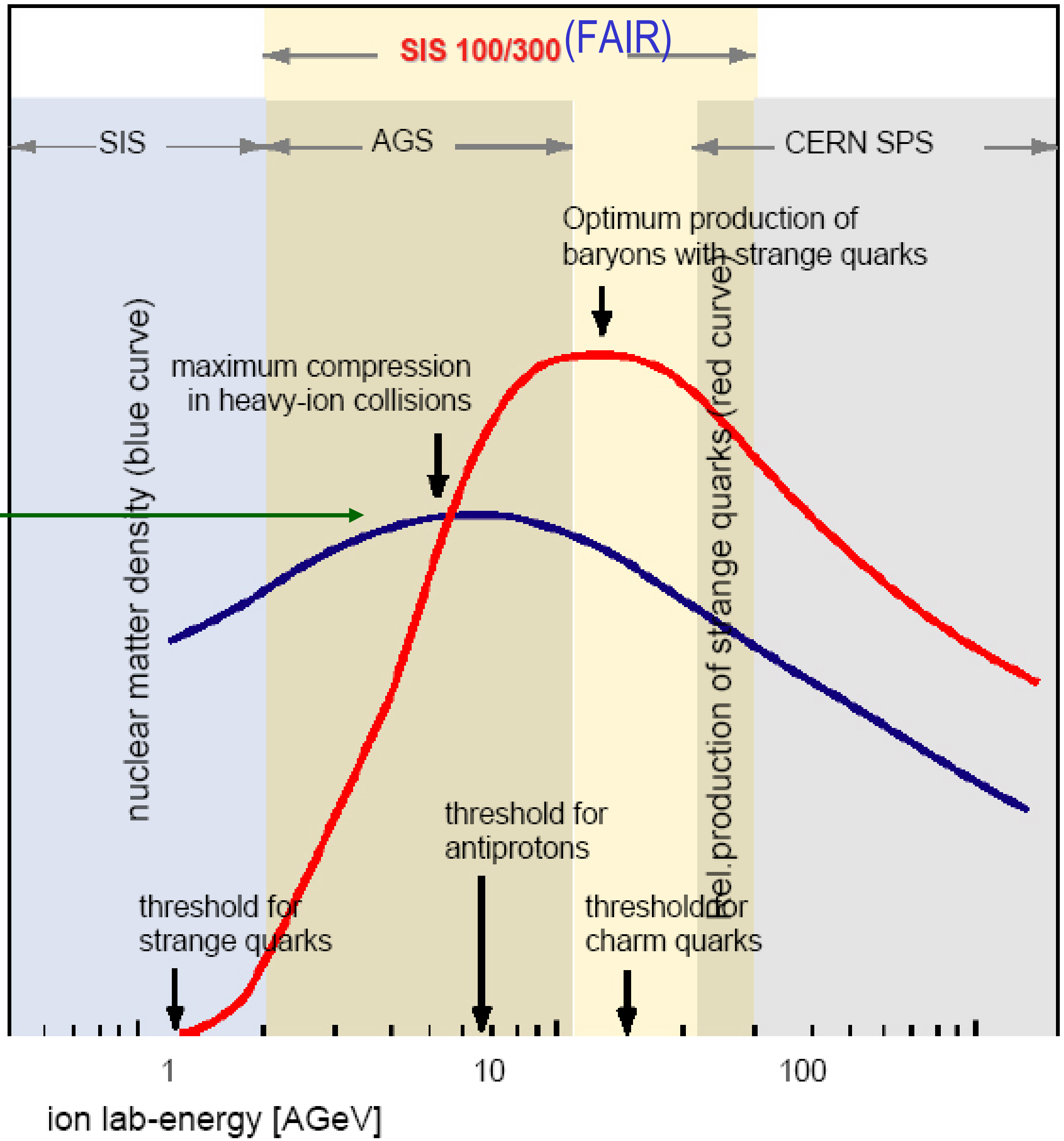
E_{sym} from second derivative of E/A with
respect to asymmetry (N-Z)/(N+Z)

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

High density symmetry energy→ neutron star: - structure (mass/radius, hybrid)
- cooling (proton fraction→direct URCA)

Physics at High Baryon (and Isospin?) Density

~4-5 ρ_0

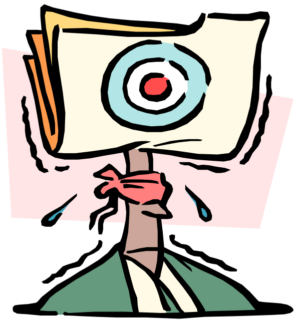


Quantum Hadrodynamics (QHD)

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 → Isoscalar; Scalar, Vector → Isovector



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

⊕ Attraction & Repulsion → Saturation

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

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

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

No linear

No perturbative

QHD Equation of State

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

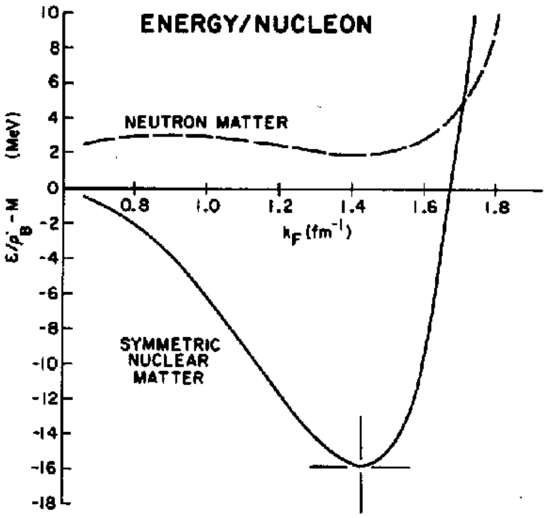
QHD-I

f_σ f_ω

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

f_σ f_ω f_ρ f_δ

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



QHD-I

- ✓ soft EoS (K=220 MeV)
- ✓ E_{bind}=-16 MeV
- ✓ $\rho_0(fm^{-3})\approx 0.15$
- ✓ 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 $\quad f_{\rho,\delta} \equiv \left(\frac{g_{\rho,\delta}}{m_{\rho,\delta}}\right)^2$

RMF Symmetry Energy: $\delta - contrib.$

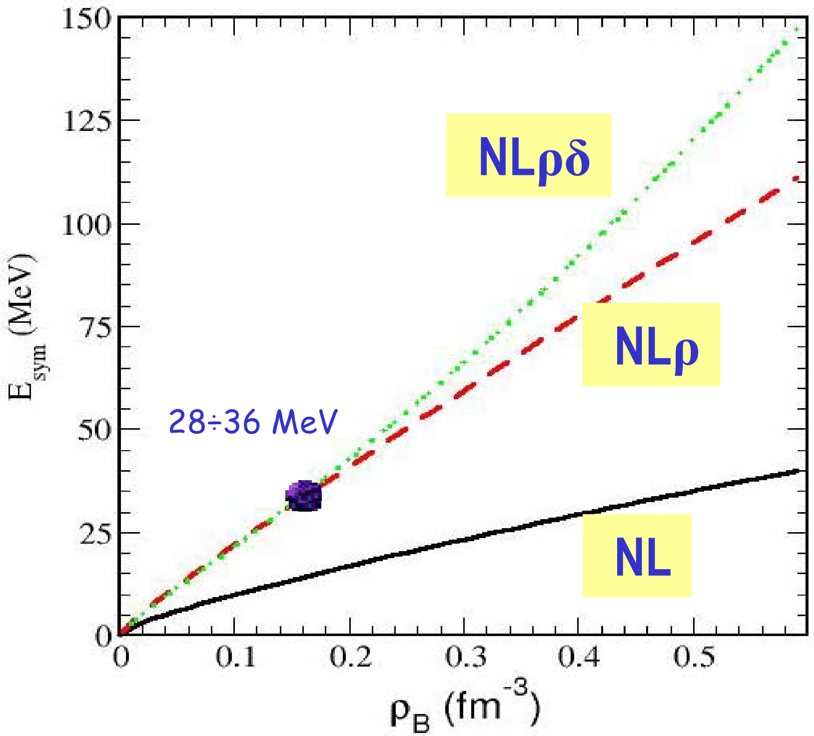
$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^{*2}} + \frac{1}{2}\left[f_\rho - f_\delta \left(\frac{M^*}{E^*} \right)^2 \right] \rho_B$$

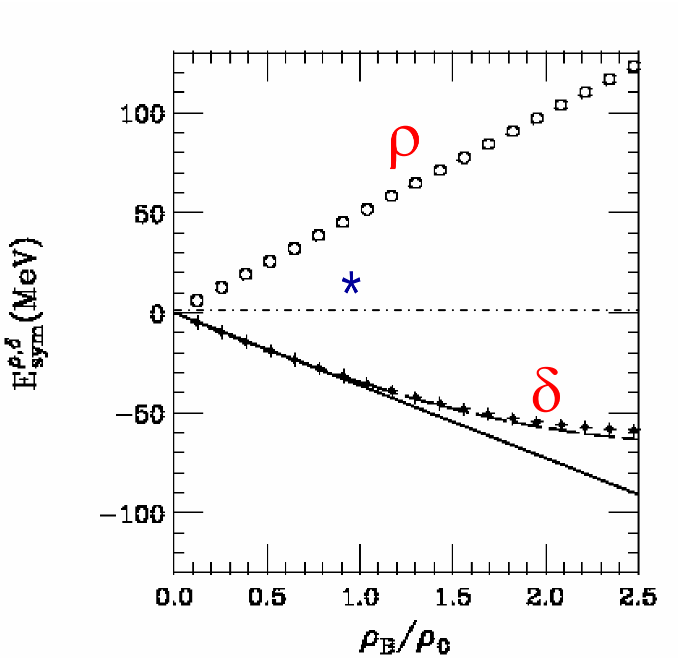
No δ → $f_\rho \cong 1.5\, f_\rho^{FREE}$

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

$a_4 = E_{sym}(\rho_0)$ 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

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

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

$$\Sigma_s(n,p) = f_\sigma \sigma(\rho_s) \mp f_\delta \rho_{s3}$$

$$\Sigma^{\mu}(n,p) = f_\omega j^{\mu} \mp f_\rho j_3^{\mu}$$

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

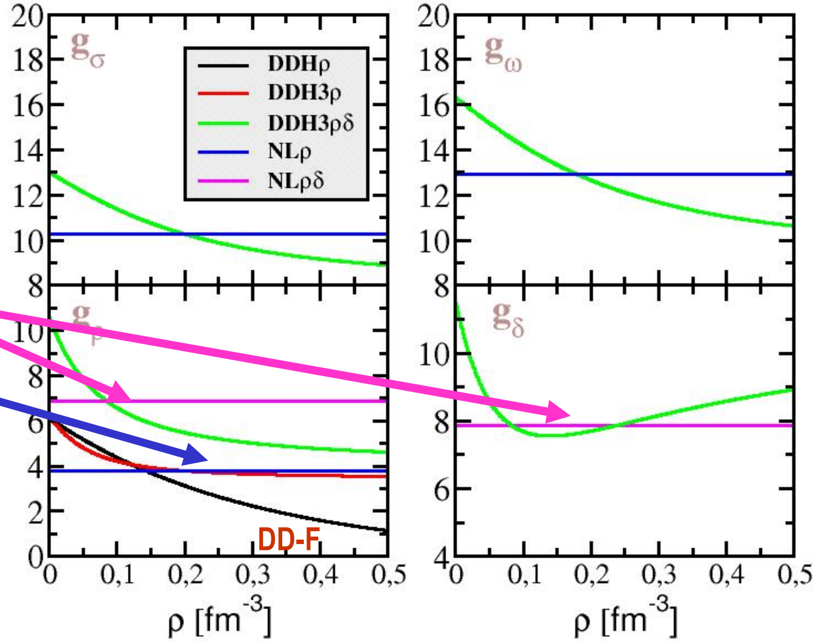
Phys.Rep.410(2005)335-466

σ,ω,ρ,δ couplings

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

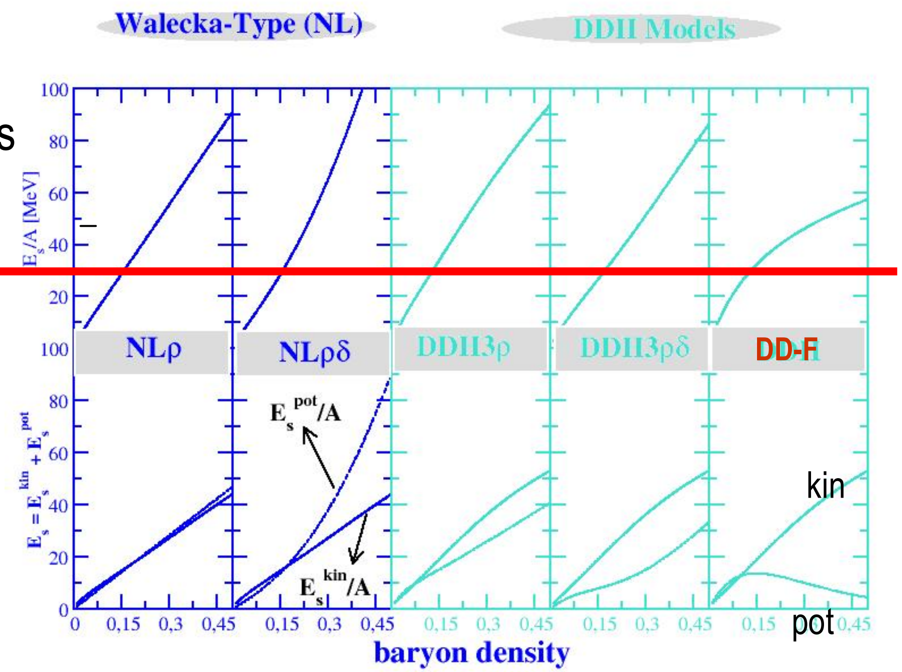
NL$\rho\delta$

NLρ



Symmetry energies

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



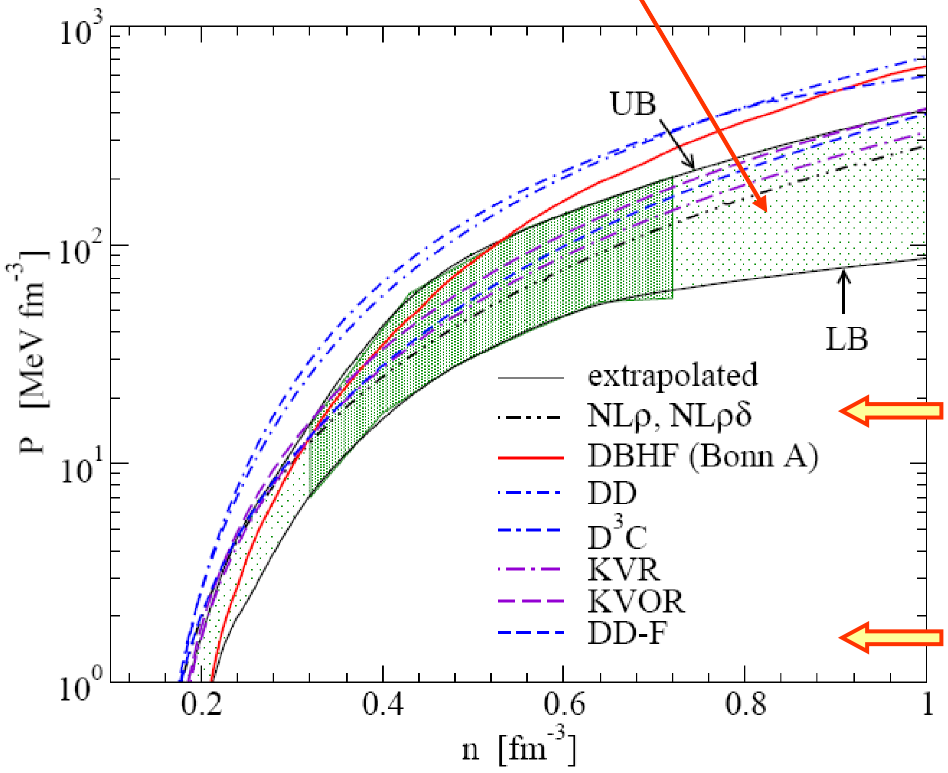
Gaitanos, Di Toro, Typel, Baran, Fuchs, Greco, Wolter, NPA 732 (04) 24

Collection of EOS "Realistic" Covariant Models

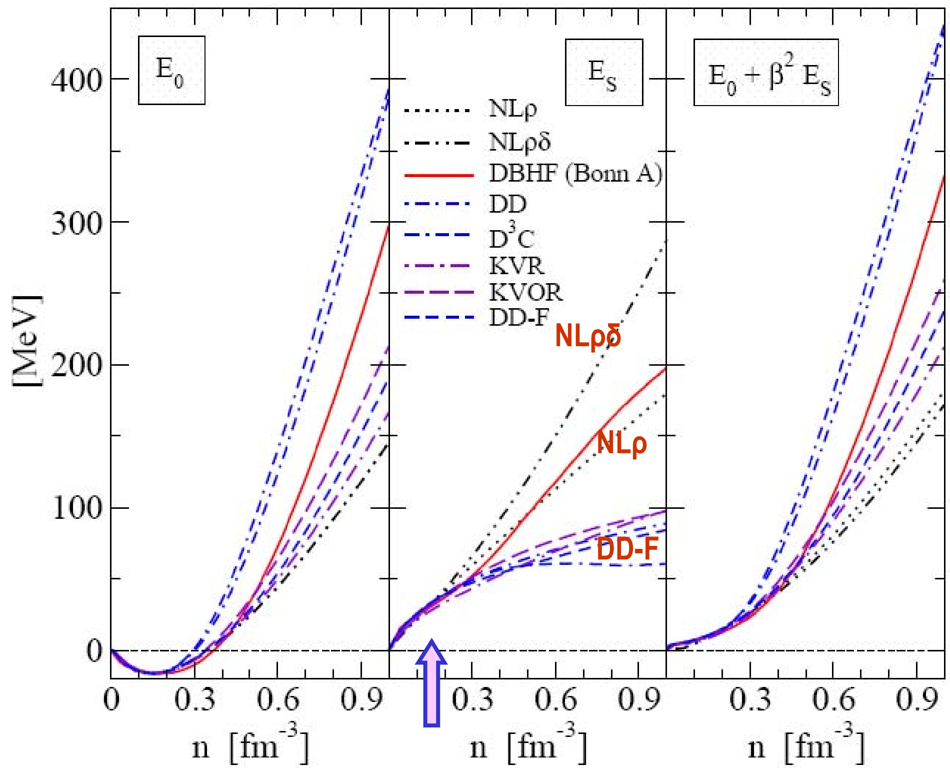
compact stars & heavy ion data
T.Klaen et al. nucl-th/0602038

Pressure

Exp boundaries (flow, kaon multiplicities)



Symmetric Matter | Symmetry Energy | Neutron Matter



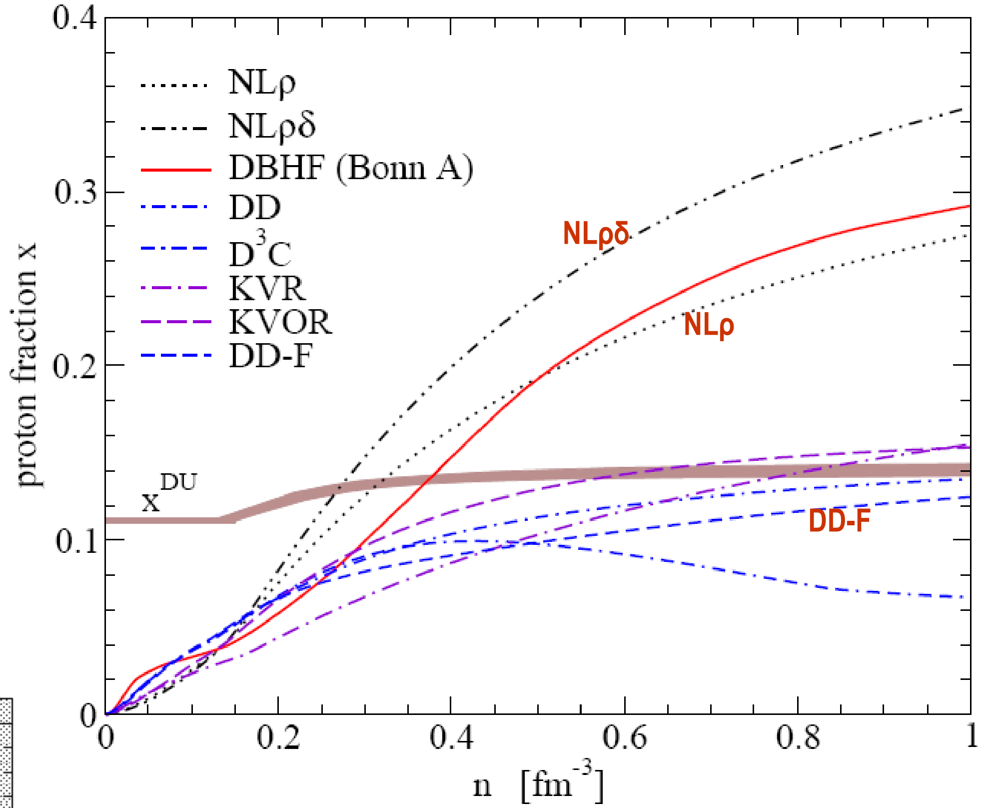
Slope at normal density:
Isospin transport at Fermi energies

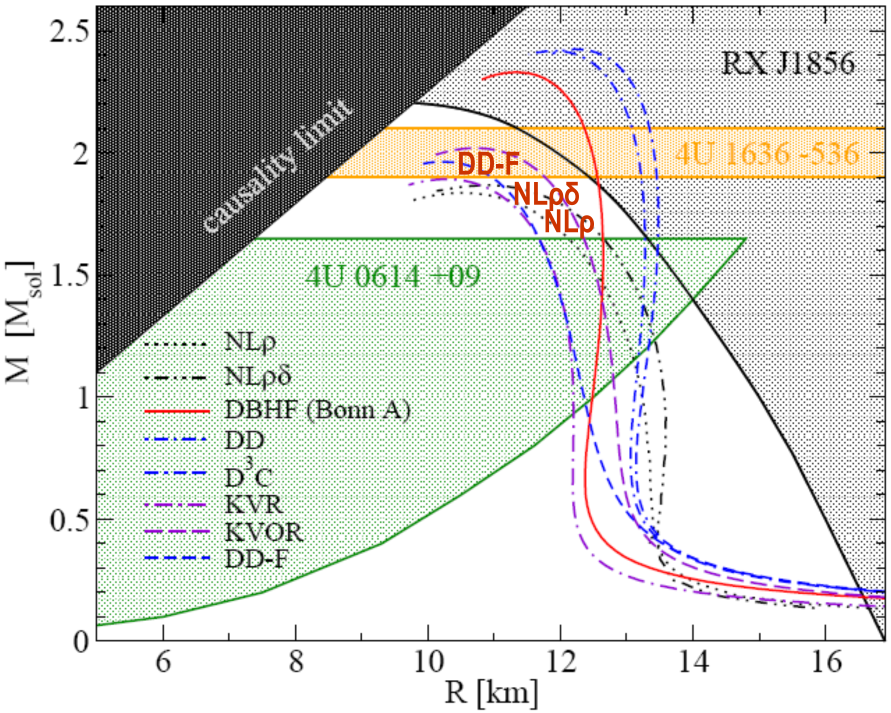
Soft Symm Matter, Stiff (super-stiff) Symmetry Energy

Soft Symm Matter, Soft Symmetry Energy

Neutron Star (npeμ) properties

Direct URCA threshold





Mass/Radius relation

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

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, Landau-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

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

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

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

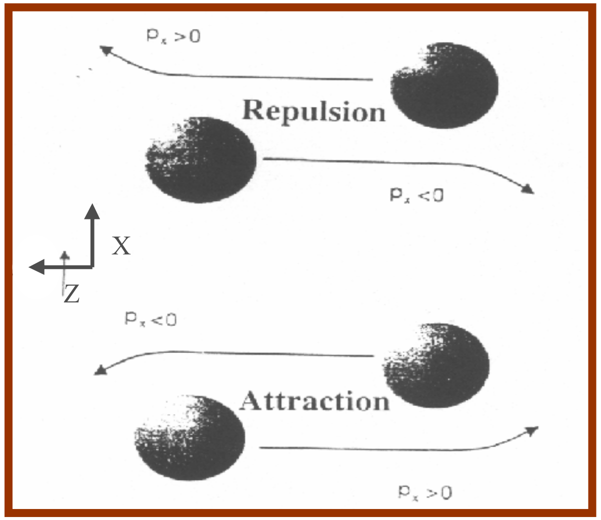
- E*/M* boosting of the vector contributions

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

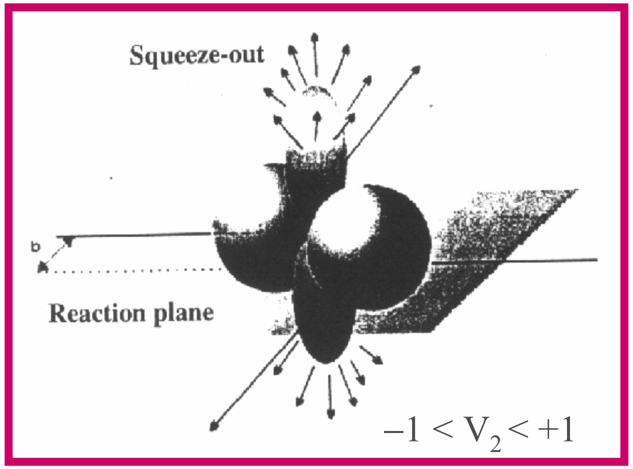
→ in medium reduced Cross Sections

Collective flows

In-plane



Out-of-plane

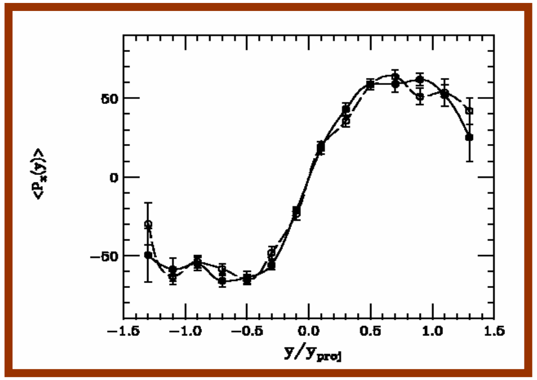


$$V_1(y, p_t) = \langle p_x \rangle / \langle p_t \rangle$$

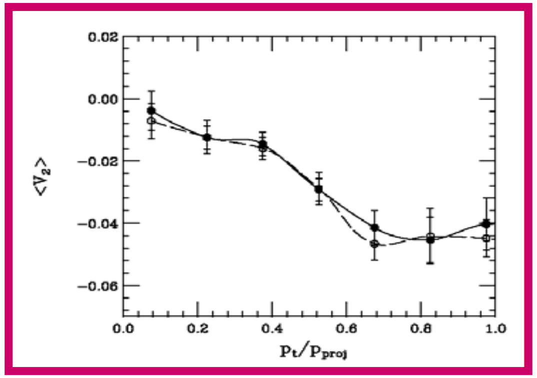
y = rapidity

p_t = transverse momentum

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



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



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

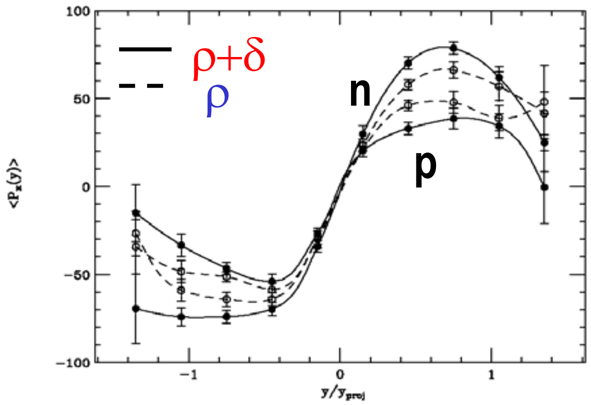
Isospin

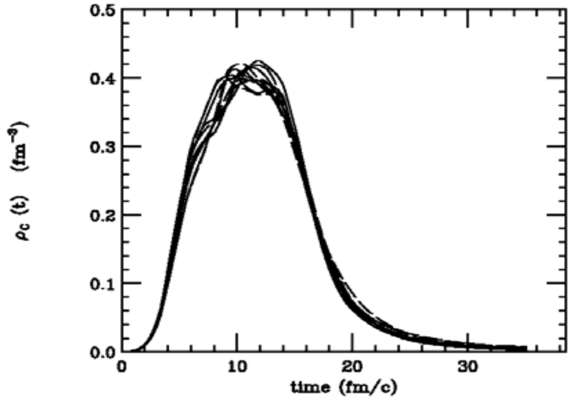
Differential flows

$$V_2^{p-n}(p_t) = V_2^p(p_t) - V_2^n(p_t)$$

Differential Transverse Flow

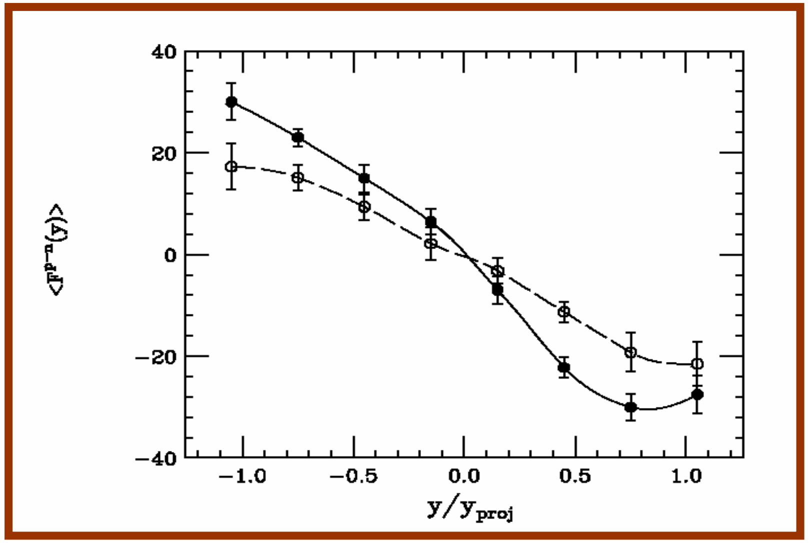
$^{132}Sn + {}^{132}Sn$ @ 1.5 AGeV b=6fm





- Sensitivity to the isovector part of the mean field

  → E_{sym} around $\rho \approx 3\text{–}4\rho_0$



o NLH-ρ

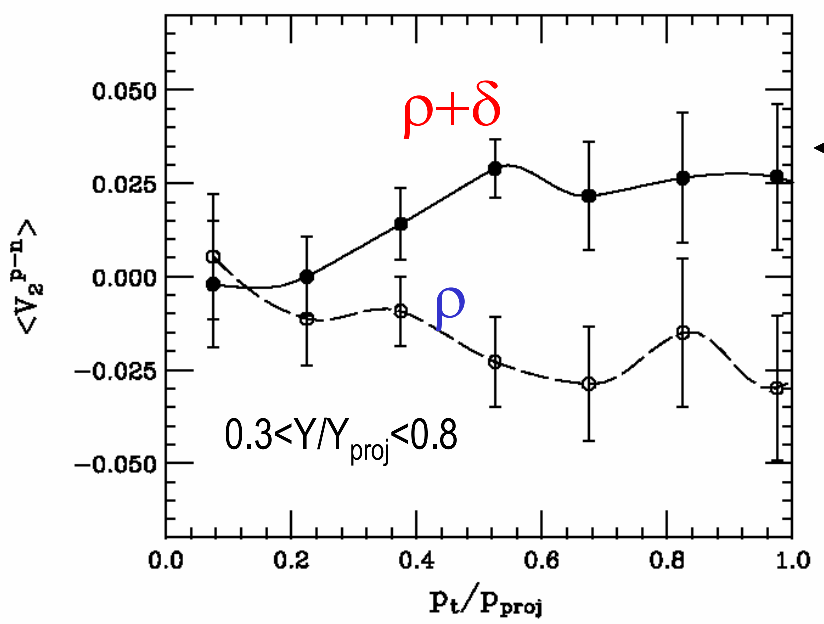
• NLH-(ρ+δ)

Greater E_{sym}

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

Elliptic flow

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



- Difference at high p_t ⇔ first stage

High p_t neutrons are emitted "earlier"

Equilibrium (ρ,δ) dynamically broken
Importance relativistic structure

approximations

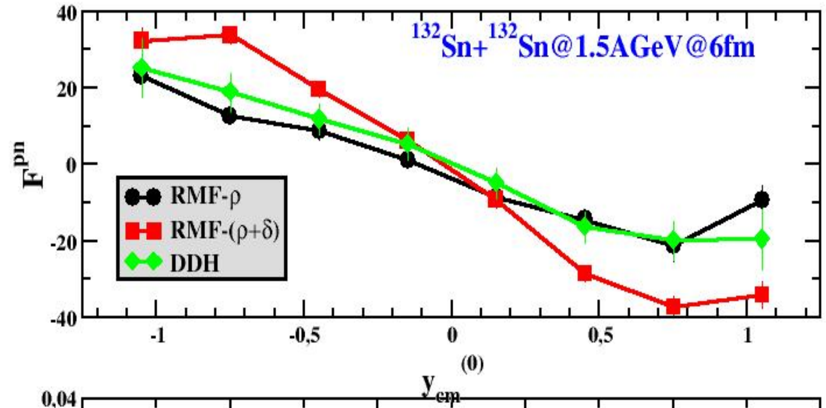
$$\frac{d\vec{p}_p^{\,*}}{d\tau} - \frac{d\vec{p}_n^{\,*}}{d\tau} \simeq 2\left[\gamma f_\rho - \frac{f_\delta}{\gamma}\right]\vec{\nabla}\rho_3 = \frac{4}{\rho_B}E_{sym}^{*}\vec{\nabla}\rho_3$$

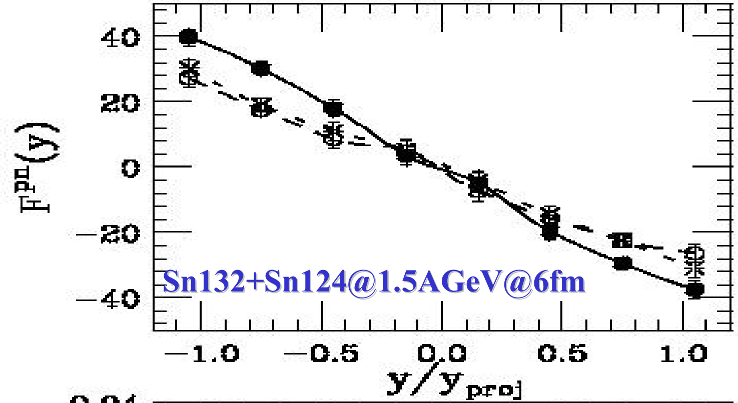
$$2\left[f_\rho - f_\delta \frac{M^*}{E_F^*}\right] = \frac{4}{\rho_B}E_{sym}^{pot}$$

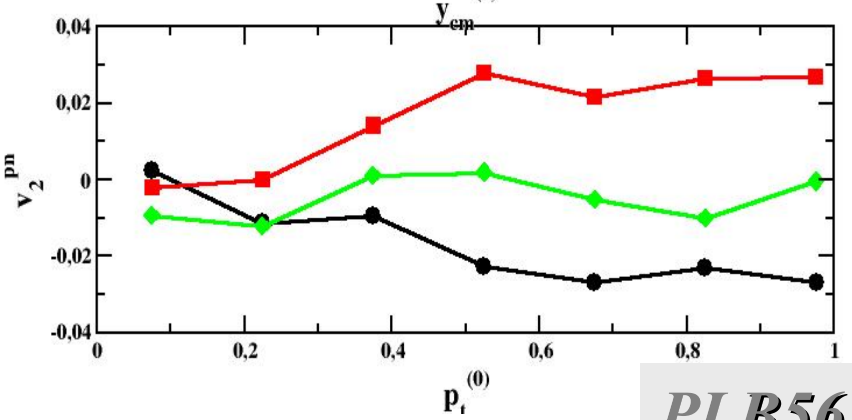
Dynamical boosting of the vector contribution

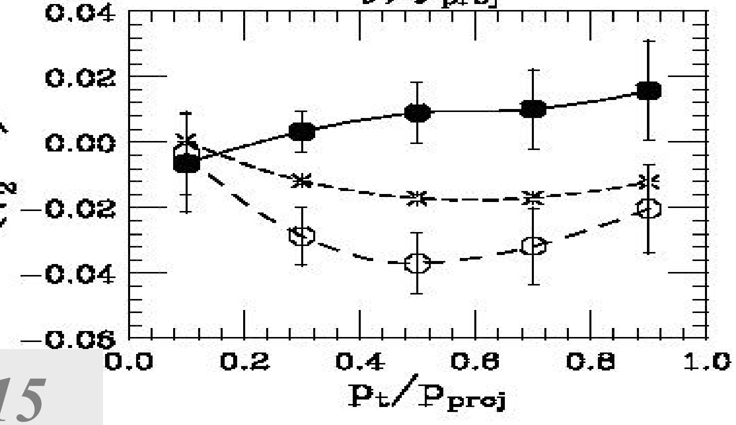
PLB562(2003)

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









PLB562(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:* $\frac{d\vec{p}_p^{\,*}}{d\tau} - \frac{d\vec{p}_n^{\,*}}{d\tau} \approx 2\left[\gamma f_\rho - \frac{f_\delta}{\gamma}\right]\vec{\nabla}\rho_i$

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

One needs neutron (light isobars) detection from experiments!

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

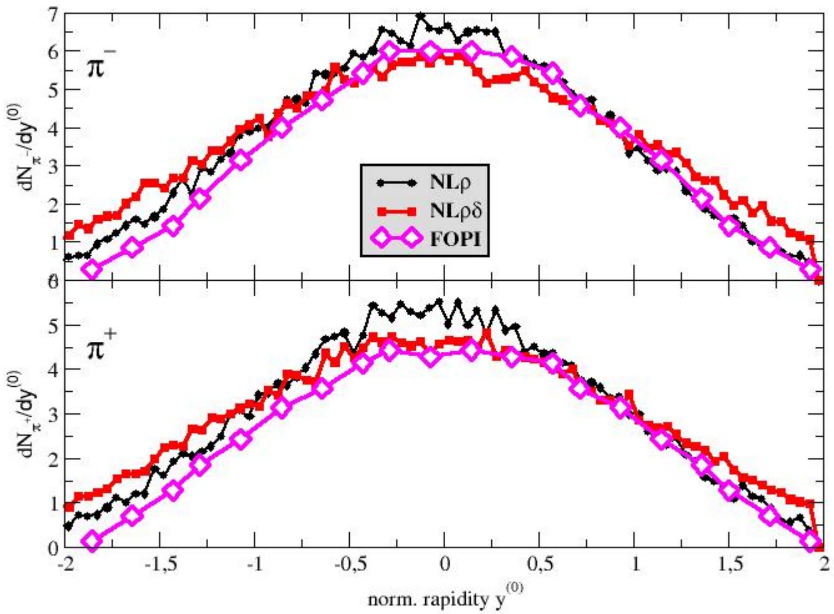
3. Pion absorption

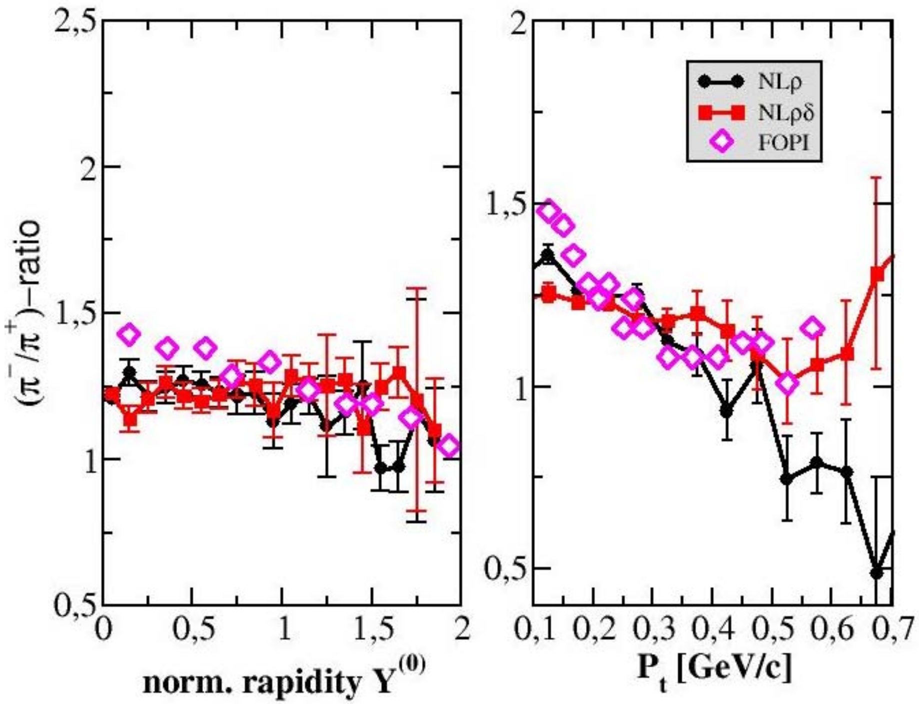
At low energies pi(-) more absorbed since more energy is available in their production

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

Central selection

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



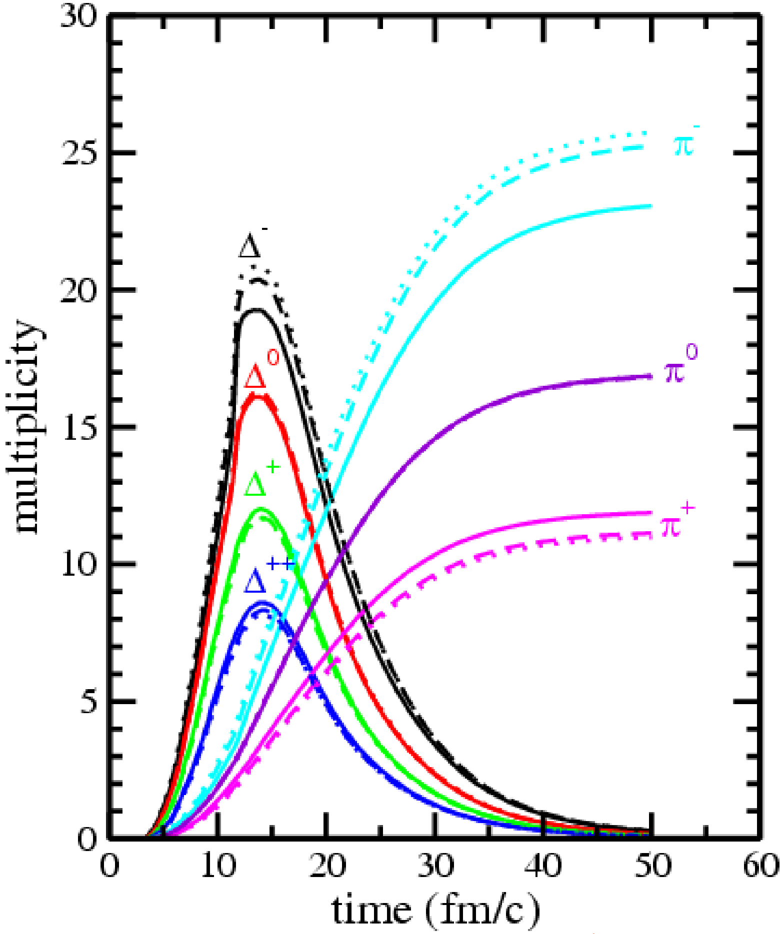


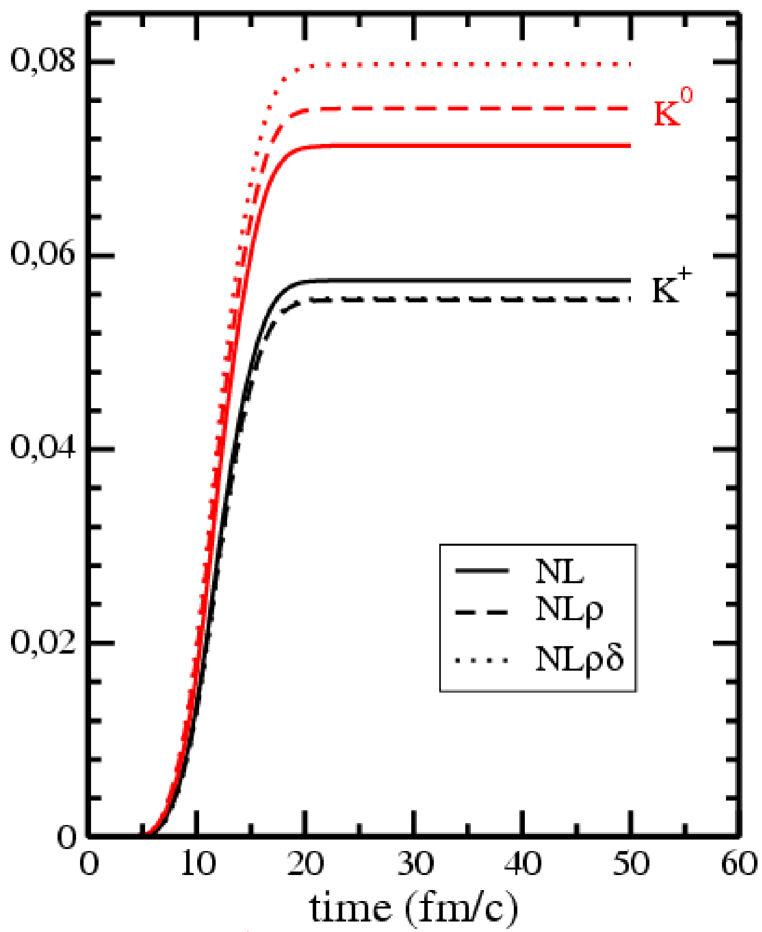
NLρδ more efficient in "transforming" neutrons into protons at high density, producing π–

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

NPA732(2004)24

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



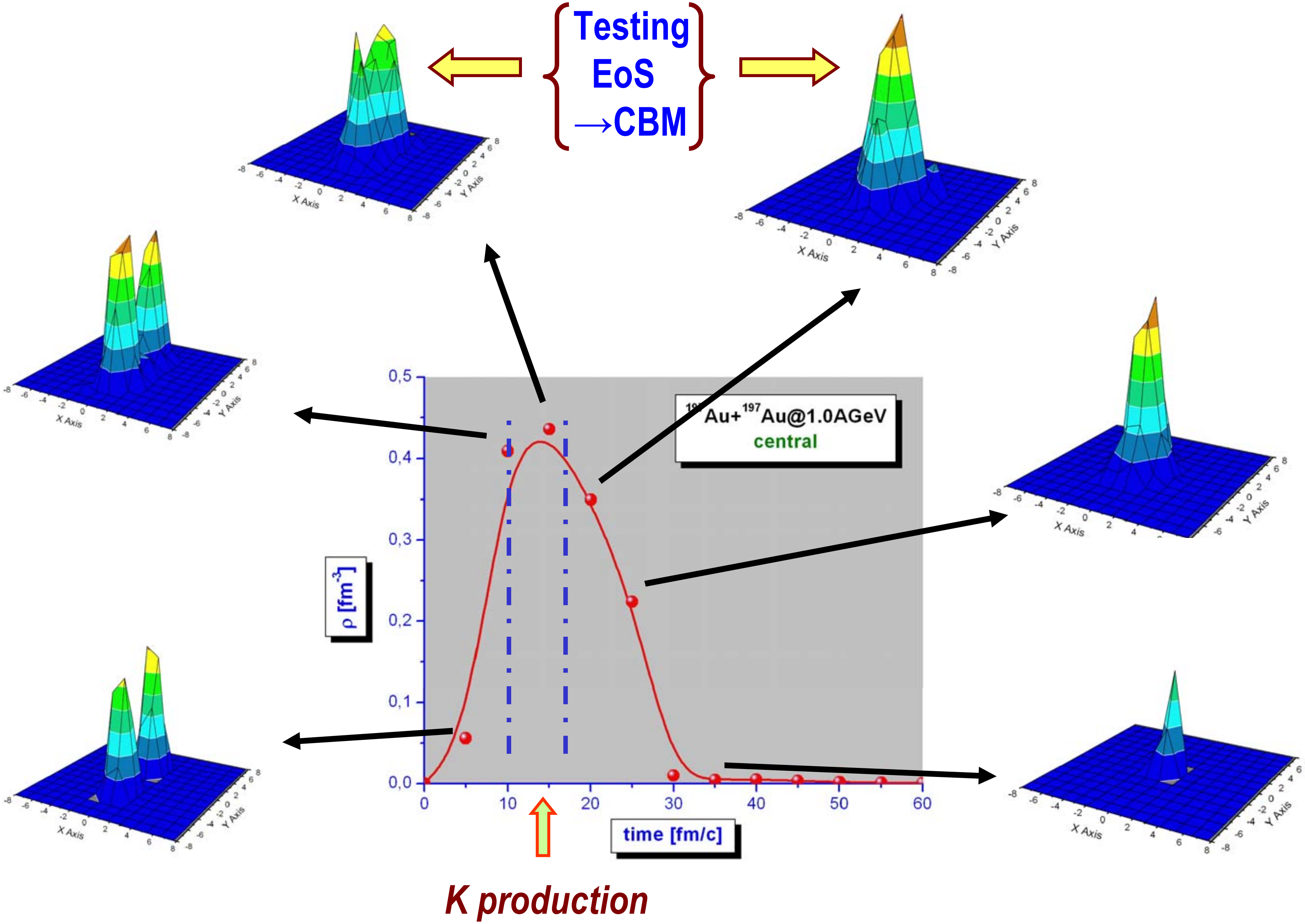


Pions: compensation

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

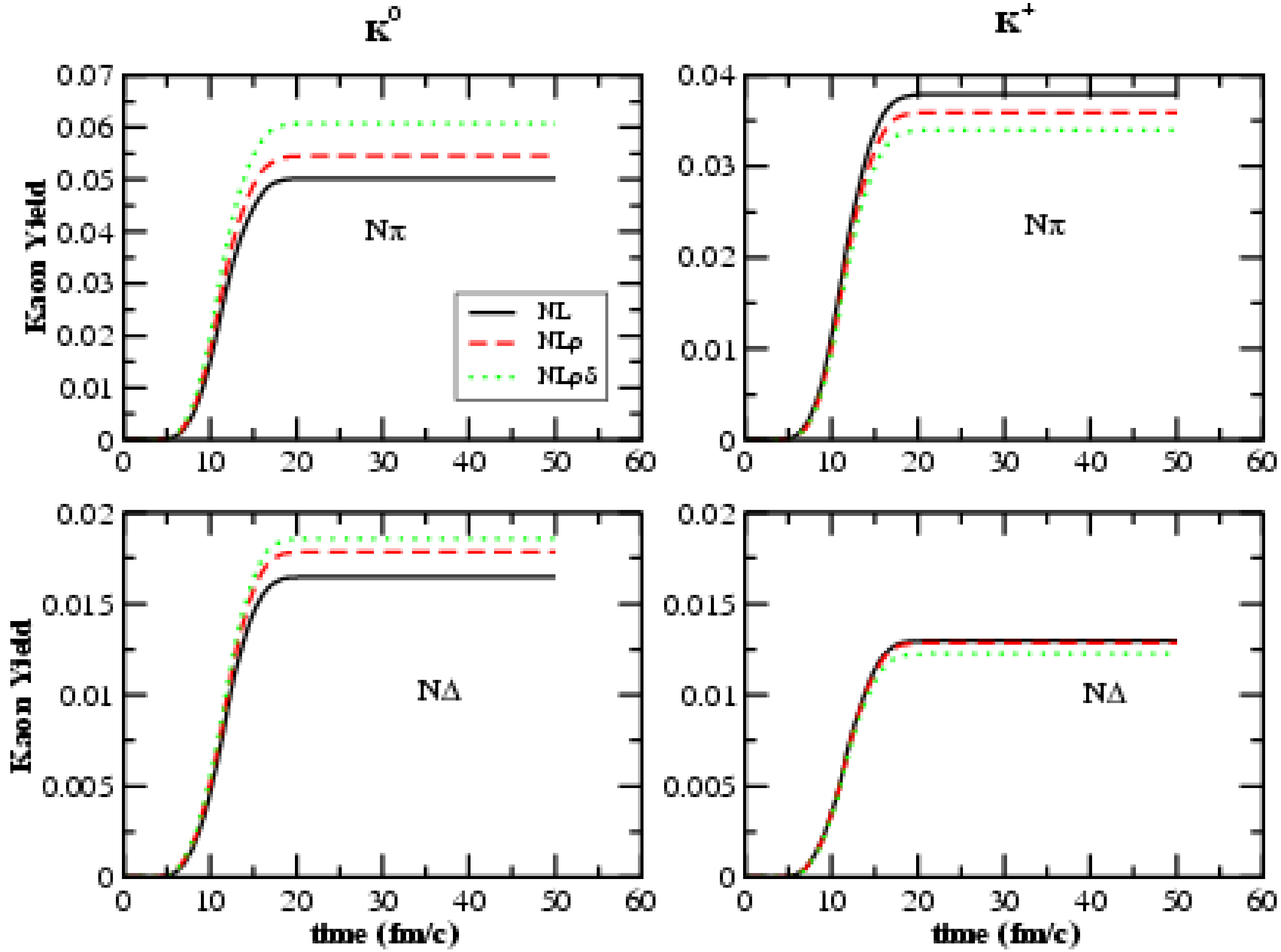
NN → BYK

NΔ → BY

ΔΔ → BYK

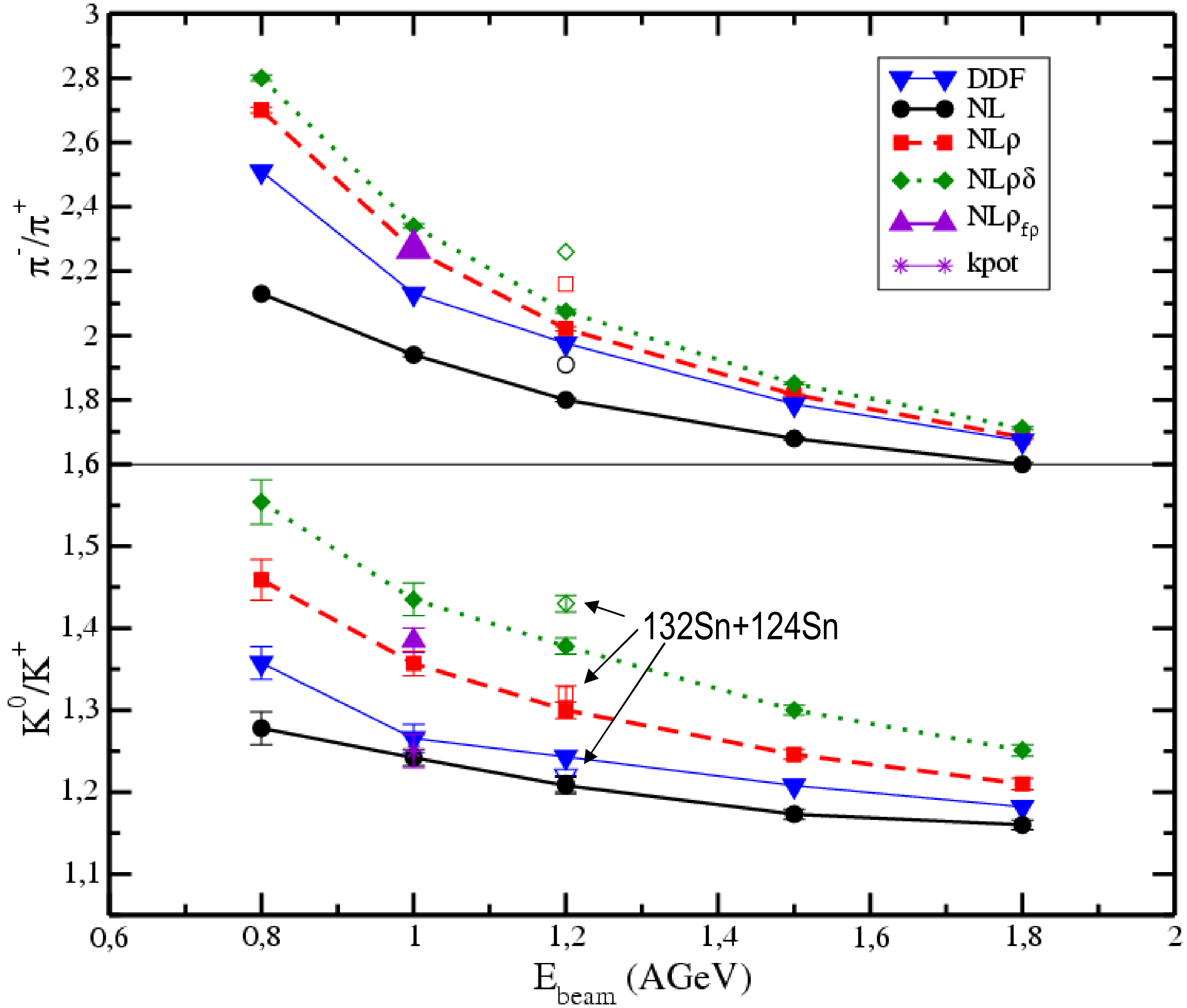
πN → YK

πΔ → 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

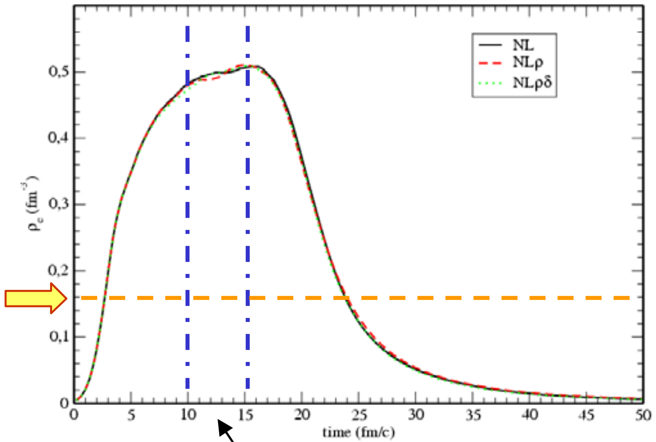
No sensitive to the K-potential

Pions: less sensitivity ~10%, but larger yields

Inclusive multiplicities

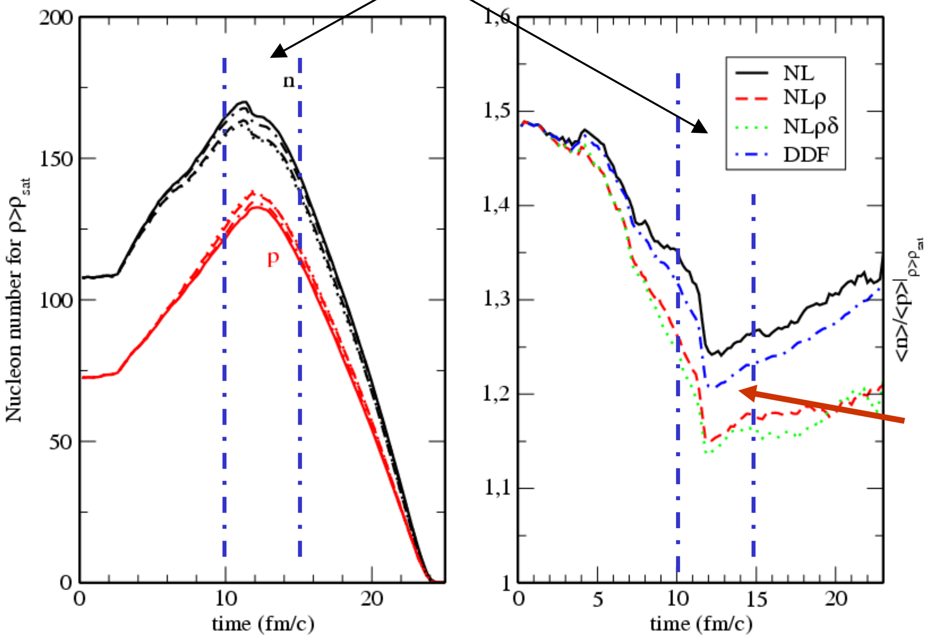
Au+Au 1AGeV: density and isospin of the Kaon source

"central" density



Time interval of Kaon production

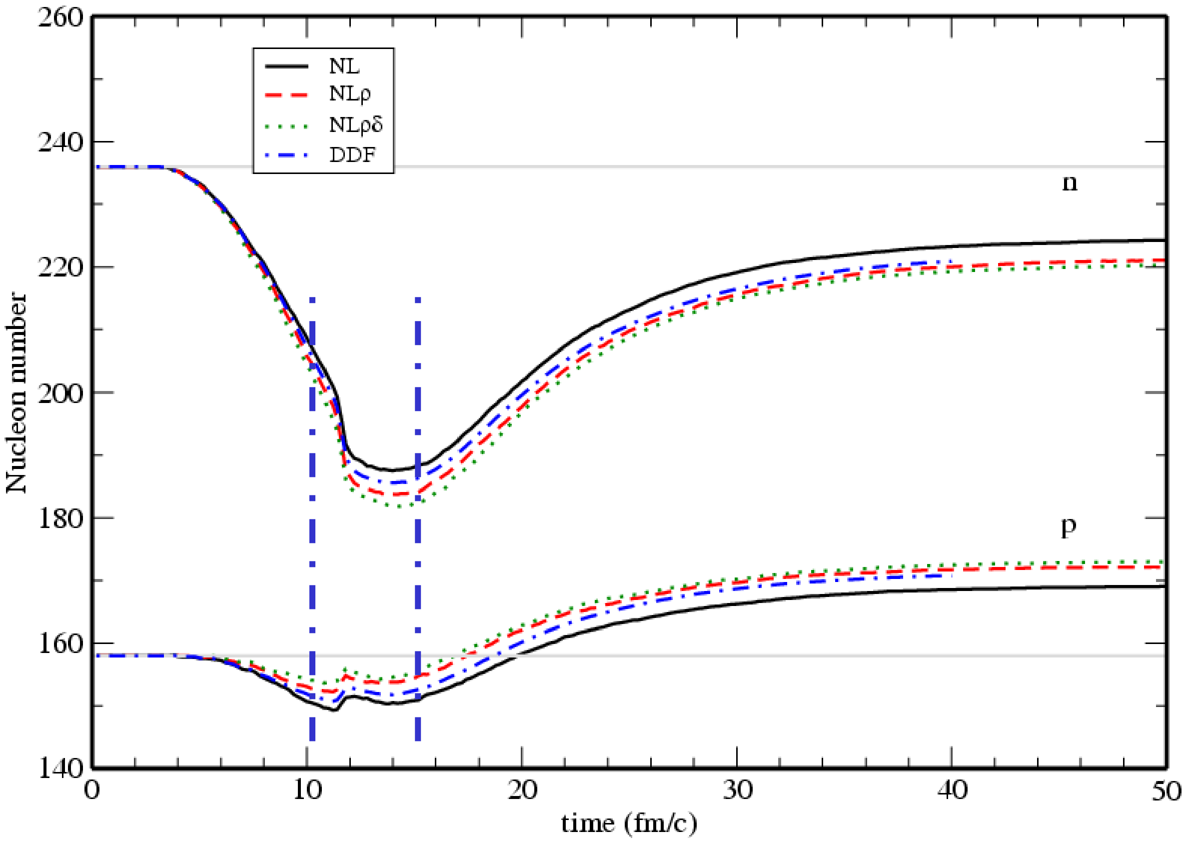
n,p at
High density



n/p at
High density

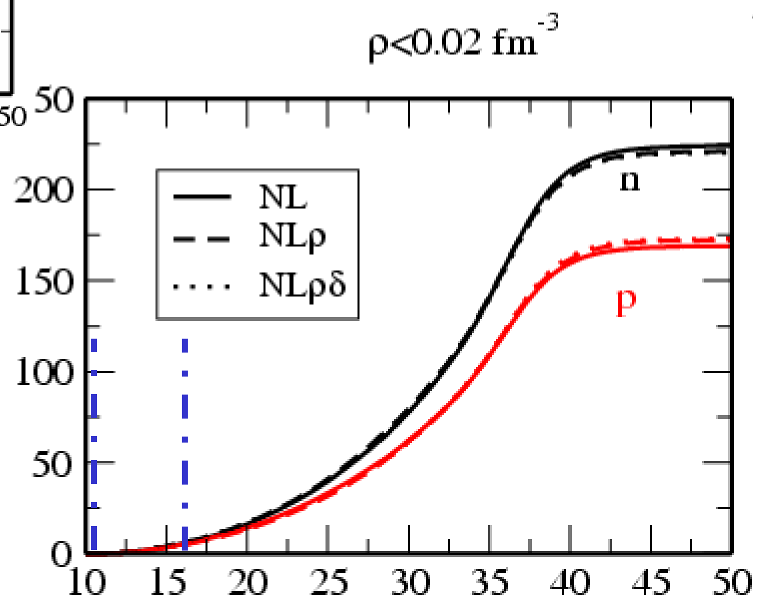
Drop:
Competition of fast neutron emission
and
Inelastic channels:
n→p *transformation*

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

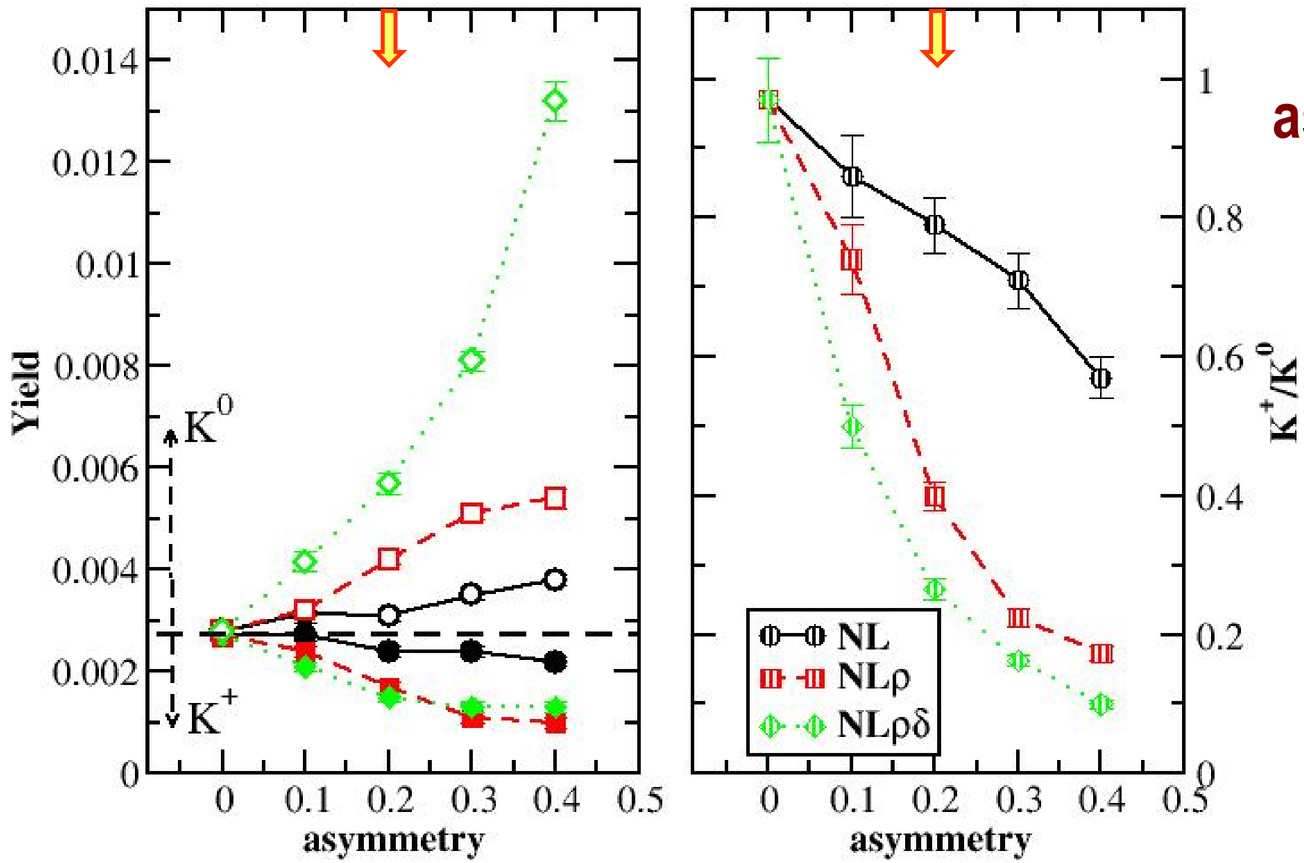
Check:
π-/π+, free n/p, K(0)/K(+) vs. emission time (p_t)

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

Nuclear Matter Box Results

NPA762(2005) 147

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

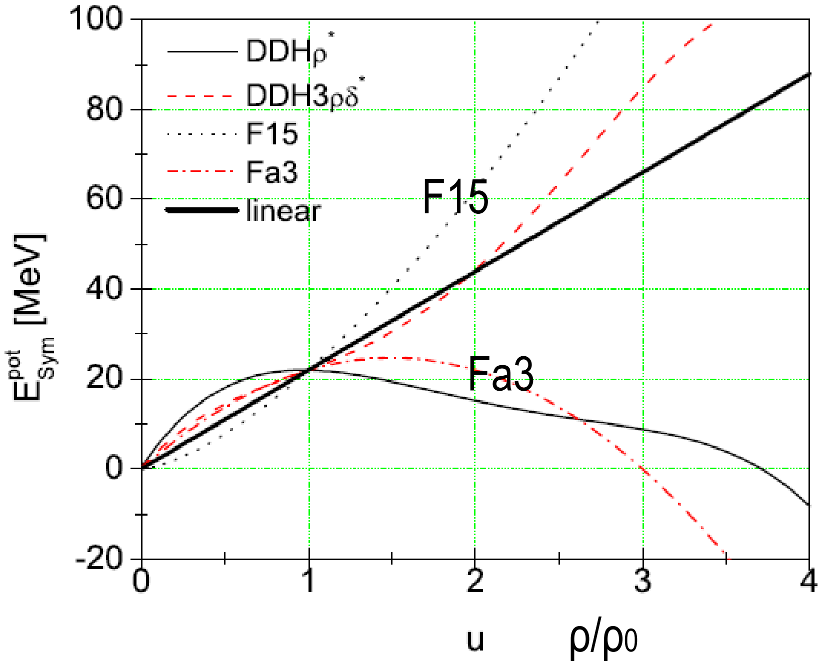


vs. asymmetry

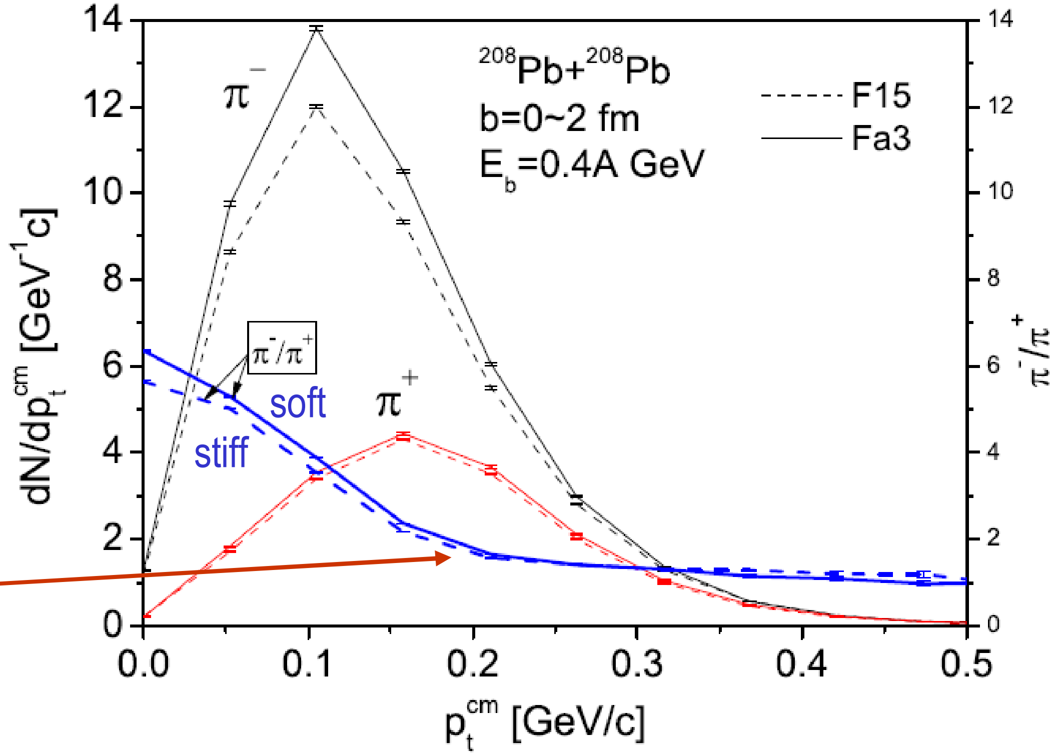
Larger isospin effects: - no neutron escape

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

UrQMD : not fully covariant symmetry term



208Pb+208Pb at 0.4AGeV

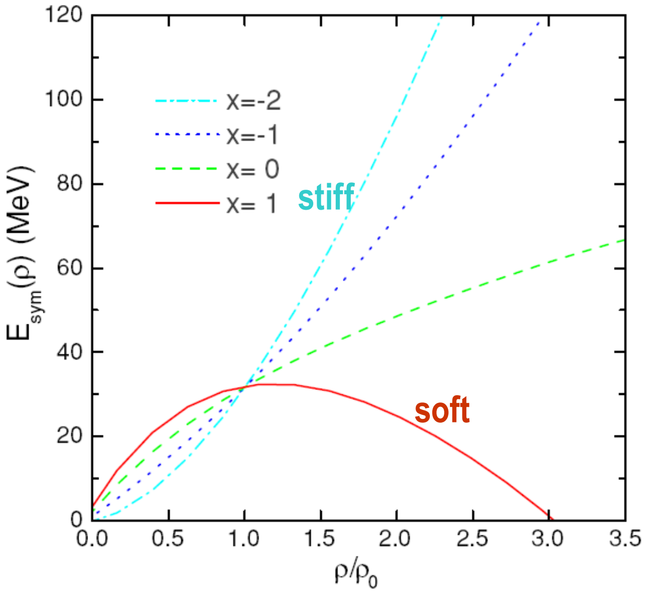


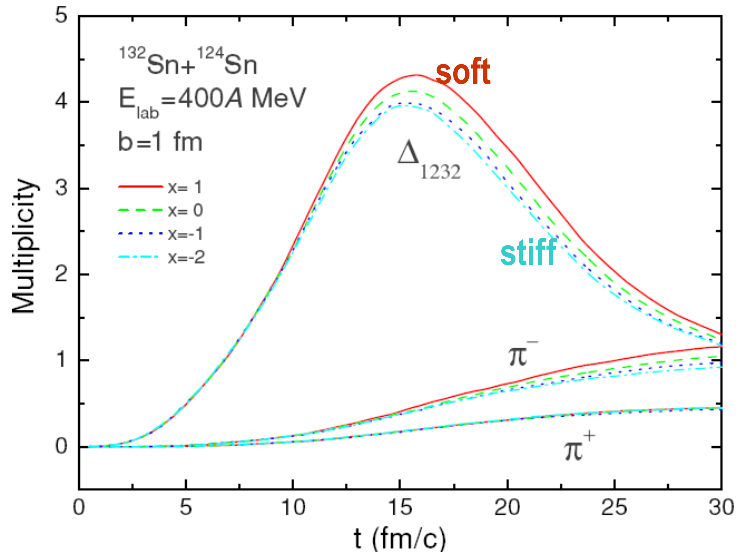
Inelastic channels less important
but still crossing at high p_t

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

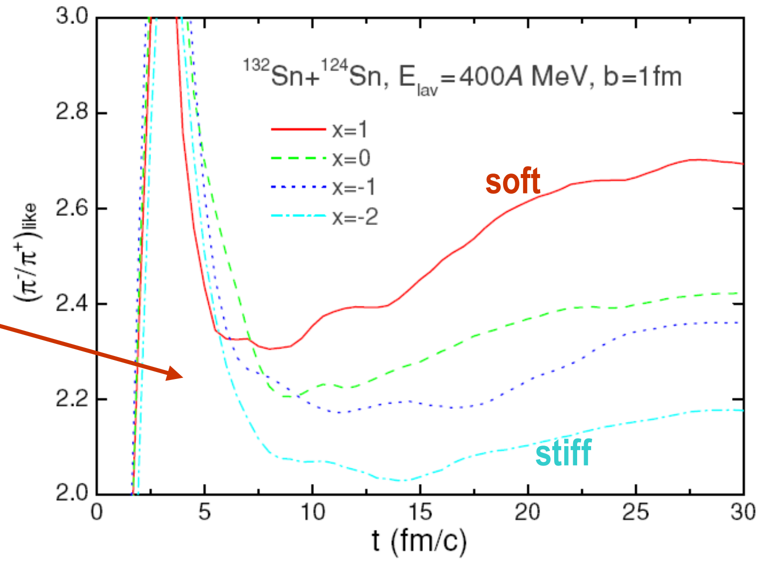
IBUU : not fully covariant symmetry term

132Sn+124Sn at 0.4AGeV





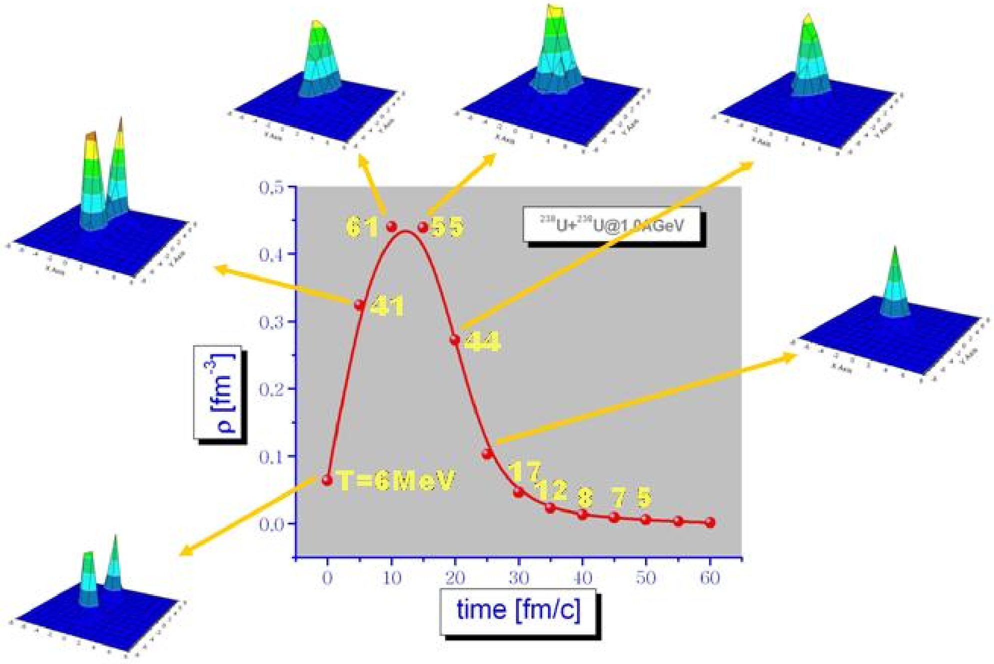
fluctuations



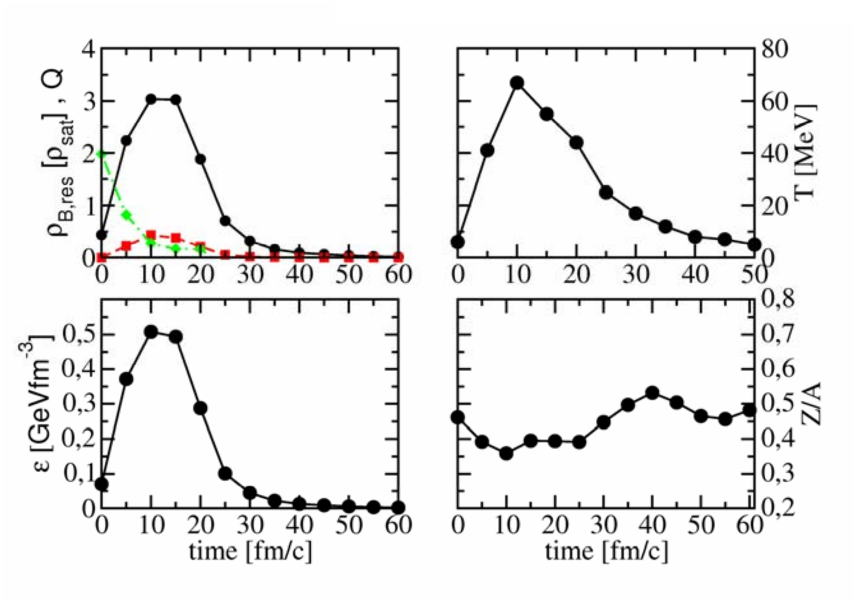
π(-)/π(+) always decreasing with the iso-stiffness?

Bao-An Li PRC 71 (2005) 014608

System Size Dependence & Equilibration (U+U)



In a C.M. cell



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

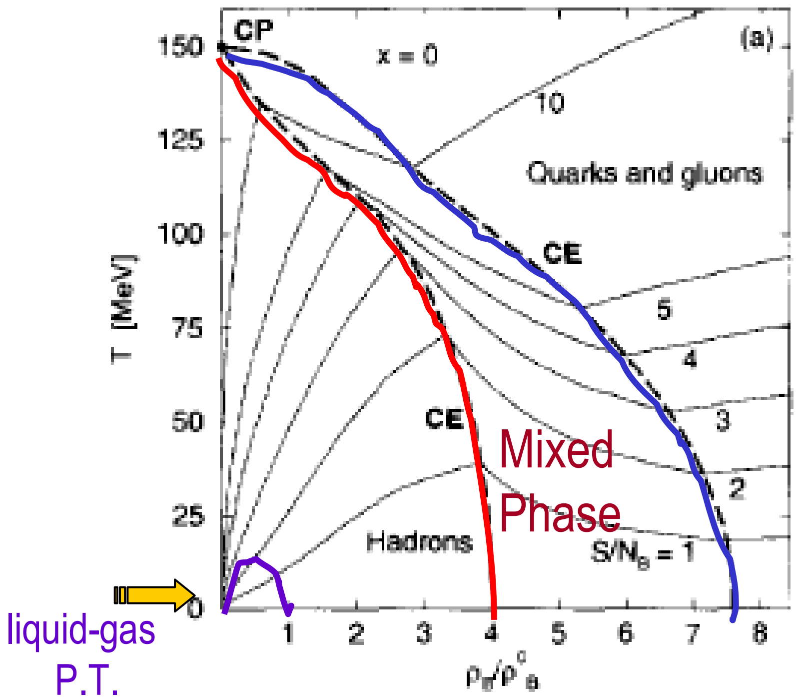
Exotic matter over 10 fm/c ?

Transition to deconfined phase at high baryon density

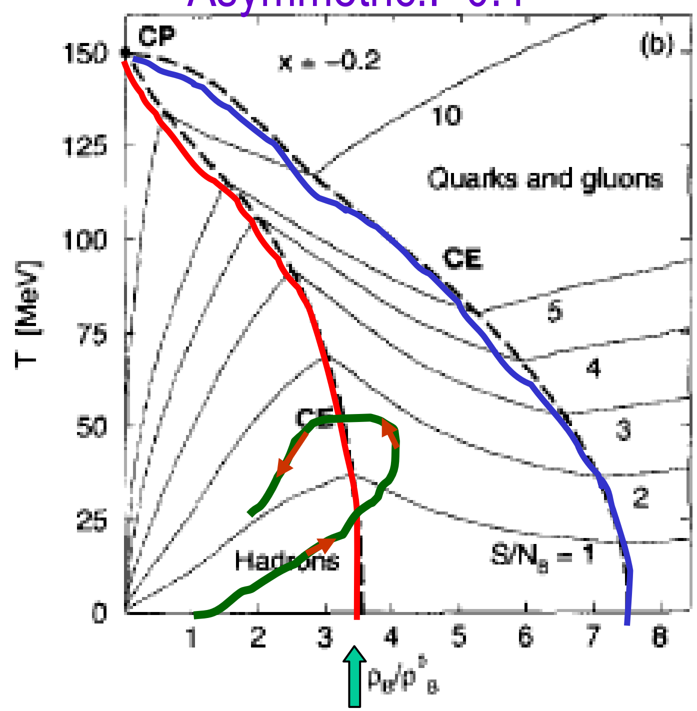
H.Mueller NPA618(1997)

Hadron EOS : QHD
Quark EOS: MIT-Bag Model

Symmetric



Asymmetric:I=0.4



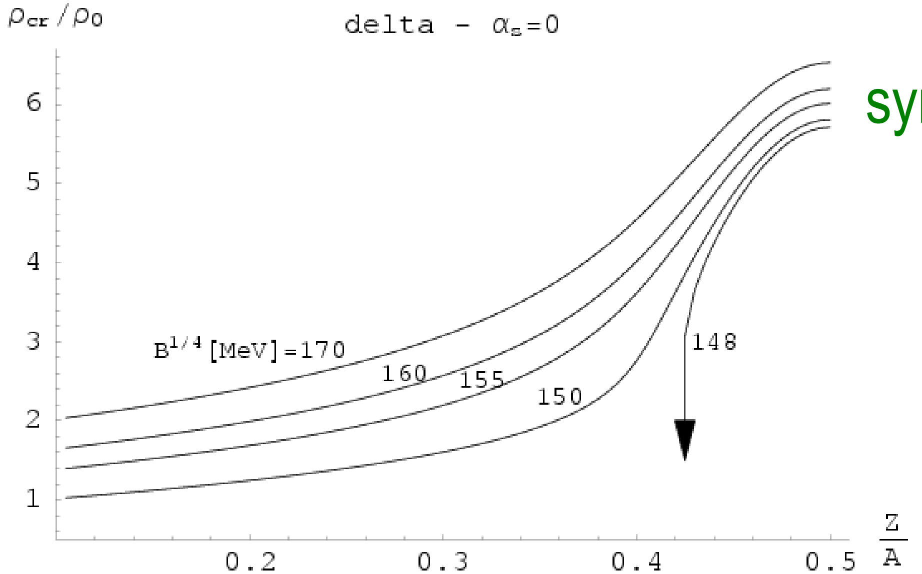
Reduced transition density

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

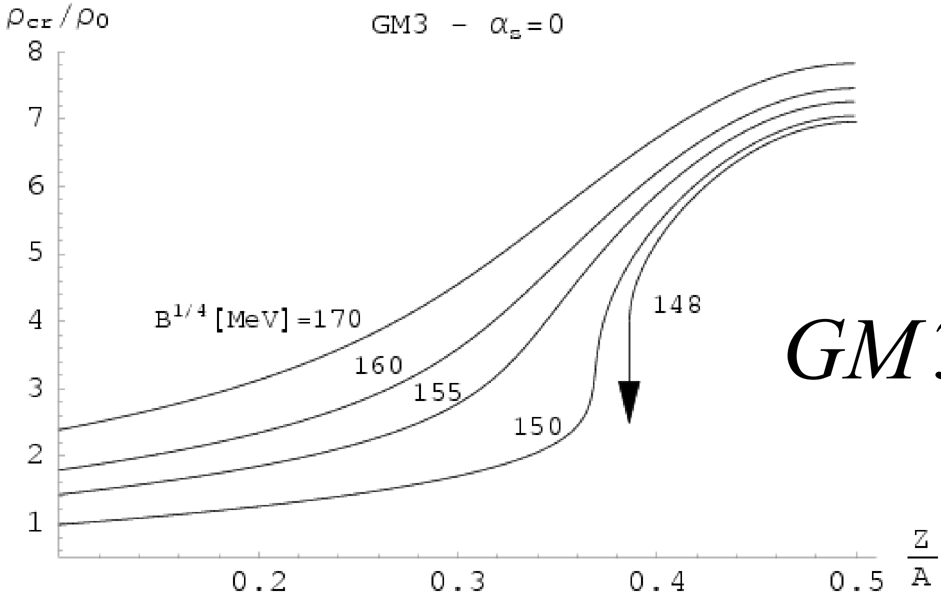
$$Hadron : NL\rho\delta$$

vs. Bag-constant choice



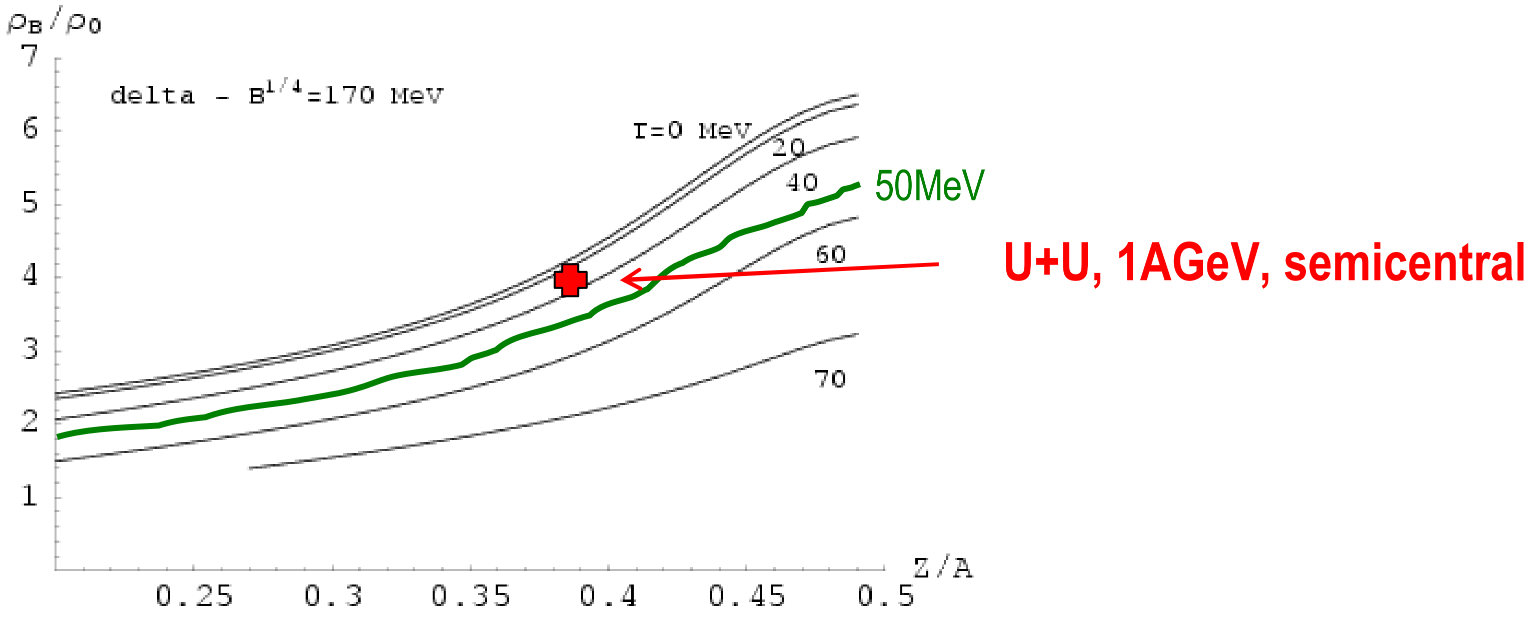
symmetric

Proton-fraction

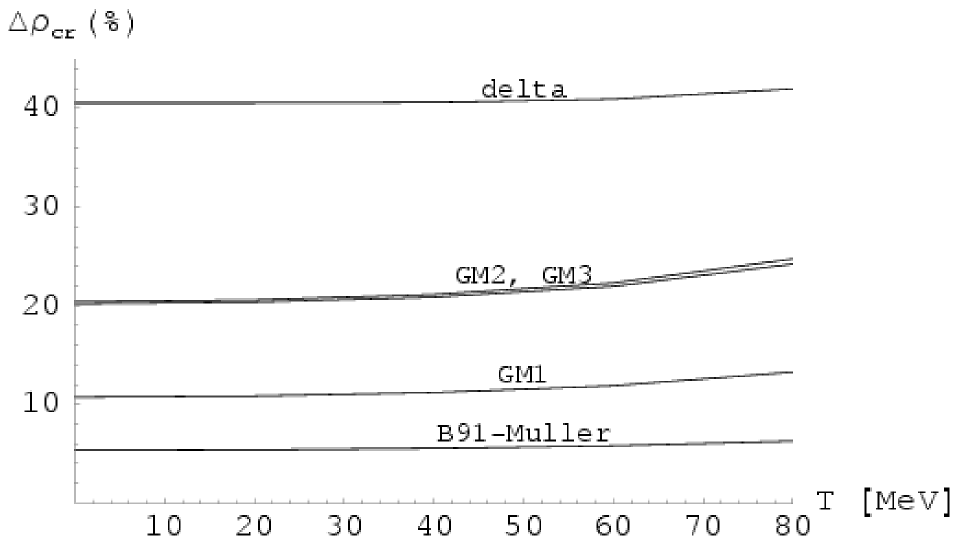


$$GM3 \Leftrightarrow NL\rho$$

Temperature variation of the crossing density

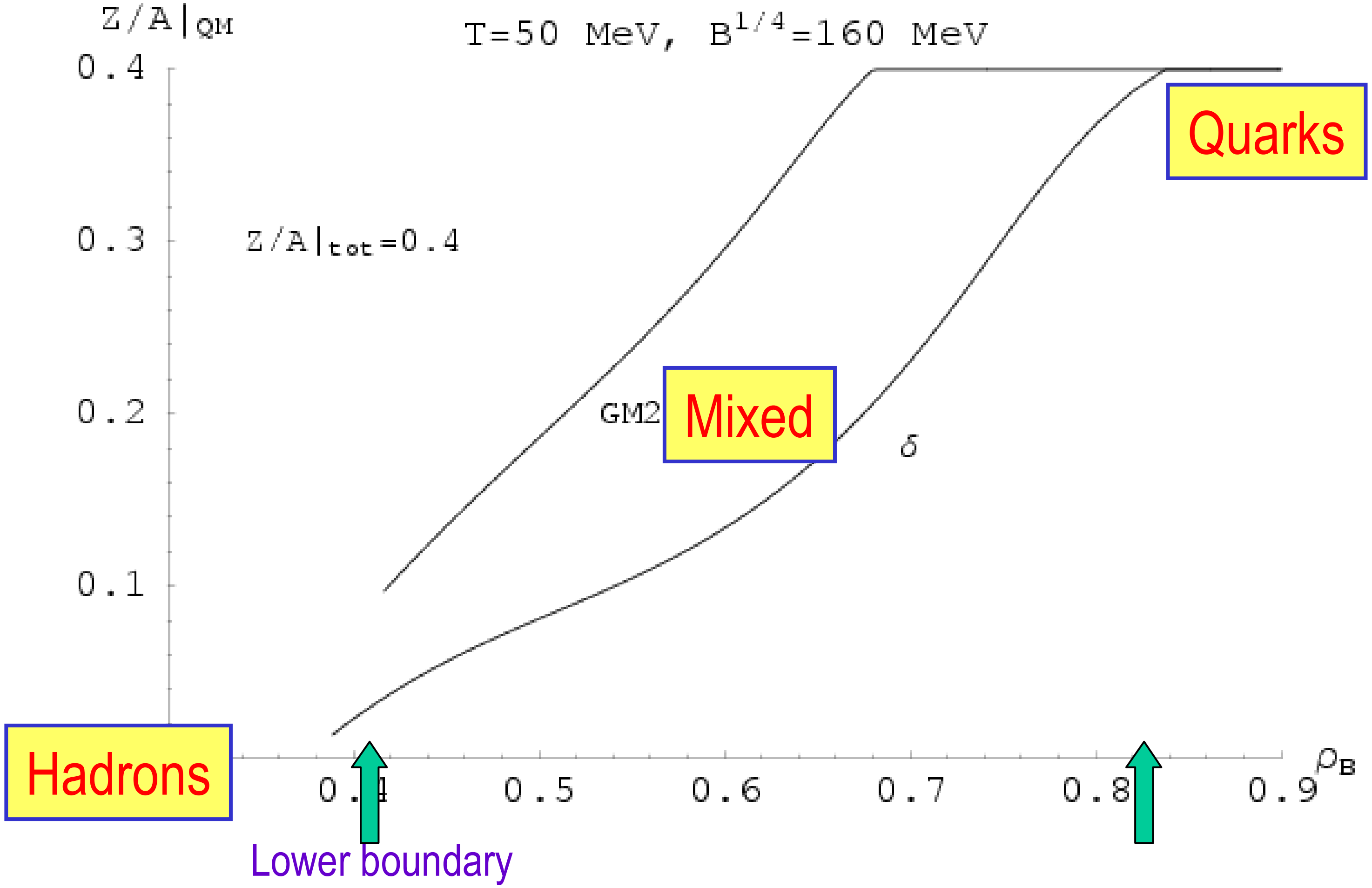


Reduction of the crossing density vs. T:
delta-meson very efficient!



Isospin content of the Quark Clusters in the Mixed Phase

T=50 MeV



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

nucl-th/0602052→NPA2006

ISOSPIN IN RELATIVISTIC HIC: EOS - SENSITIVE OBSERVABLES

1. *n – p collective flows* ⟶ *light isobar flows*
2. *Kaon Yields , (π^-/π^+) ? , flows?*
3. *Deconfinement precursors*

Violent Collisions of Relativistic Radioactive Beams?

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

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