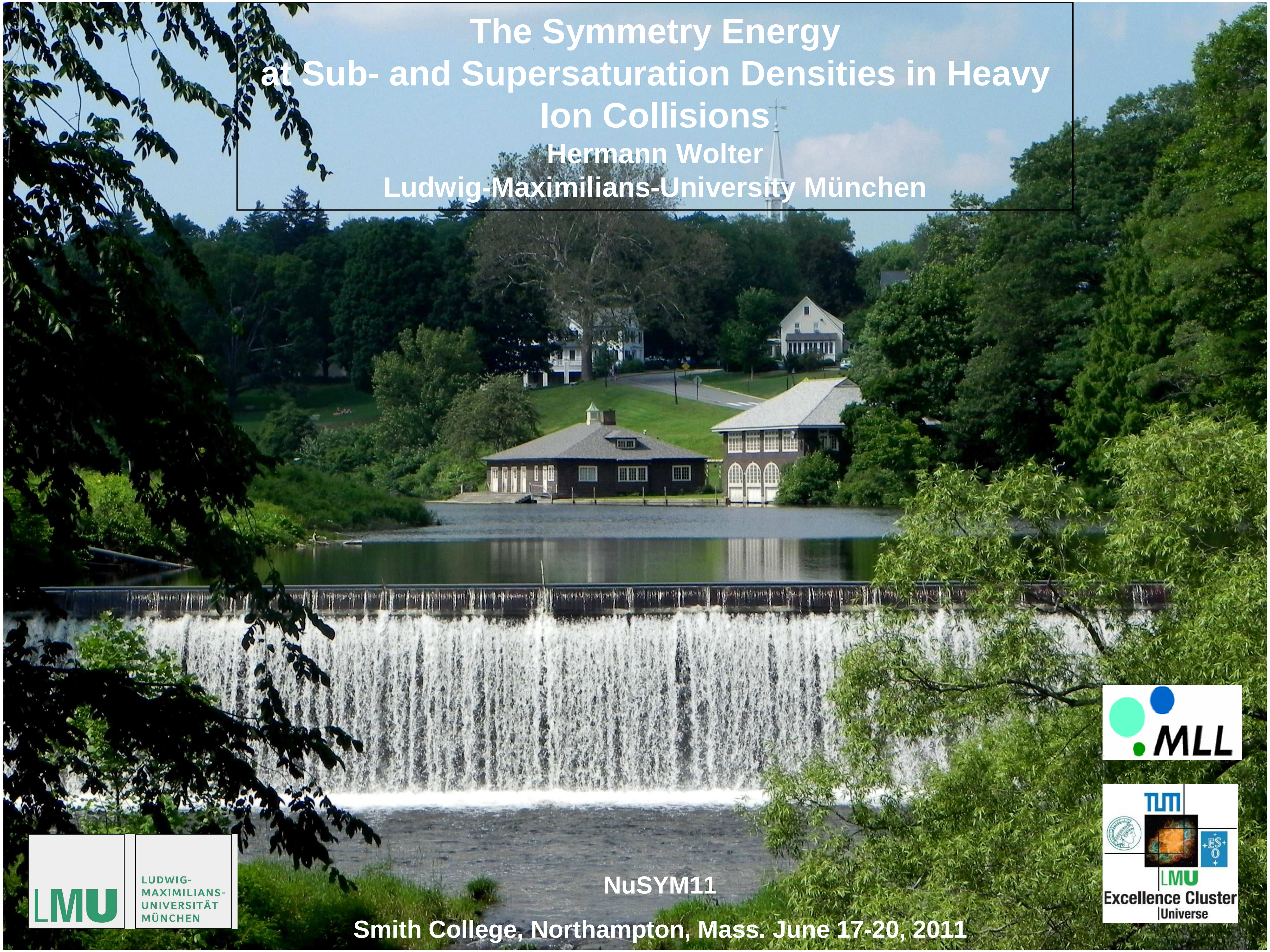


The Symmetry Energy at Sub- and Supersaturation Densities in Heavy Ion Collisions

Hermann Wolter
Ludwig-Maximilians-University München

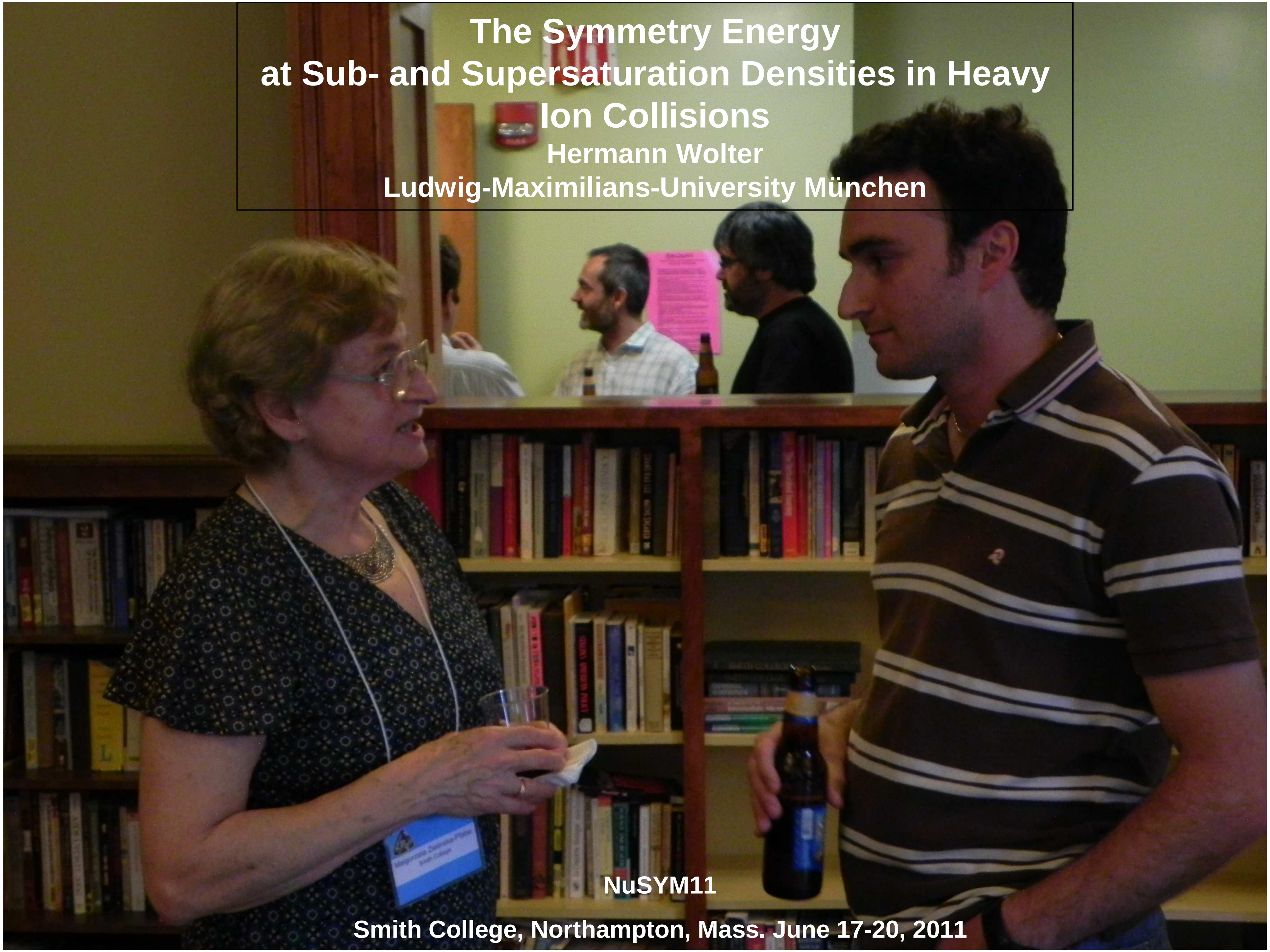
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

MLL

TUM LMU Excellence Cluster Universe

NuSYM11

Smith College, Northampton, Mass. June 17-20, 2011



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Points to discuss

→ explore the symmetry over a large range of densities with many probes

→ a satisfactory consistent picture (between different observables and between different groups) has not yet been achieved: it is better at subsaturation density but still lacking at suprasaturation)

→ the momentum dependence of the symmetry energy (difference in neutron and proton effective masses) has to be considered for a reliable interpretation (and is still controversial)

I report on work of the Catania reaction theory group and associated members:

Massimo Di Toro, Maria Colonna, Vincenzo Greco, Joseph Rizzo, Carmelo Rizzo, Valentina Giordano, Lab. Naz. del Sud, Catania

Virgil Baran, University of Bucharest, Romania

Malgorzata Zielinska-Pfabe, Smith Coll., USA

Theodoros Gaitanos, Univ. of Giessen

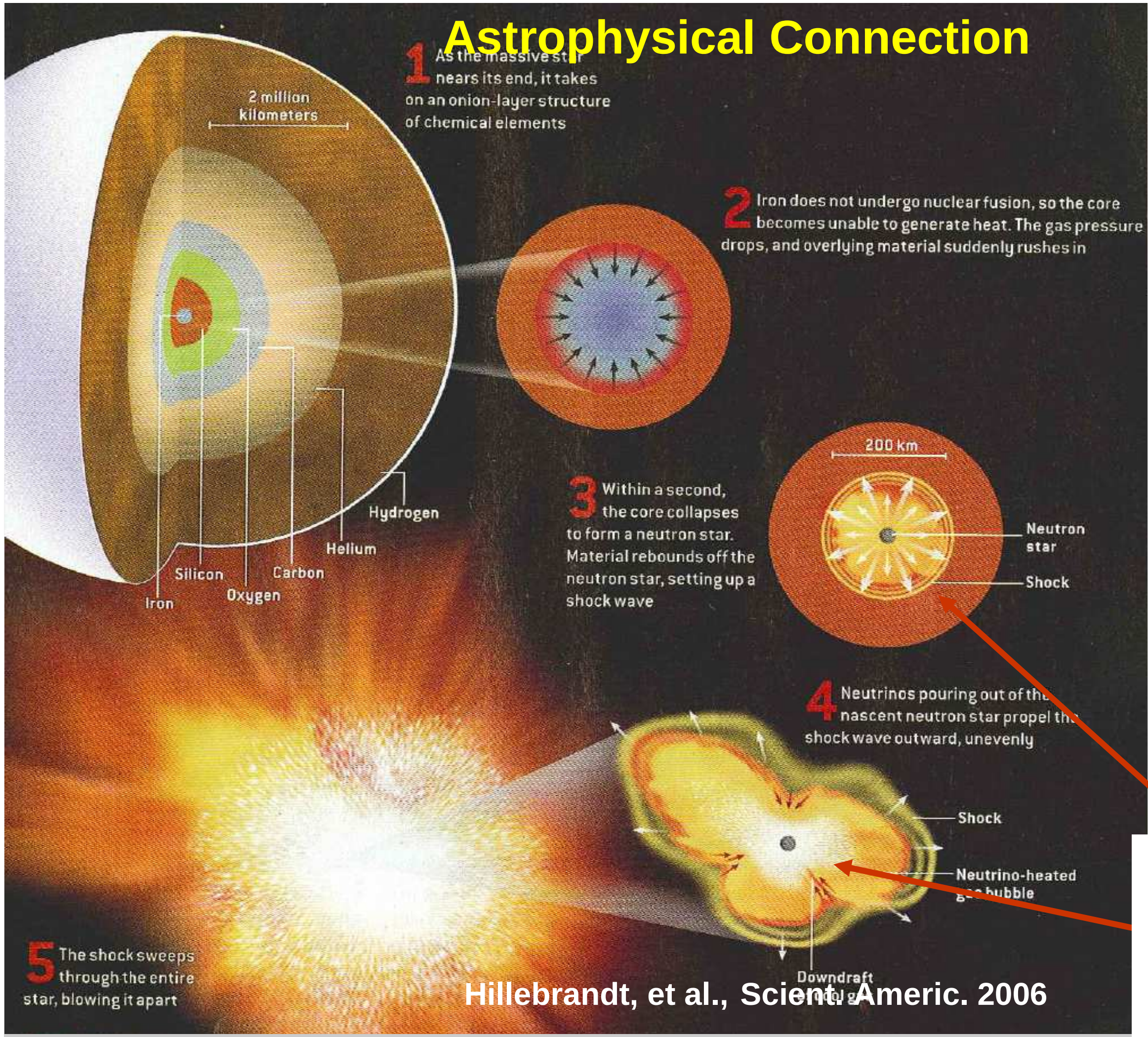
Vaia Prassa, Georgios Lalazissis, Aristotle Univ. Thessaloniki, Greece

Tatiana Mikhailova, Dubna, Russia

Plan:

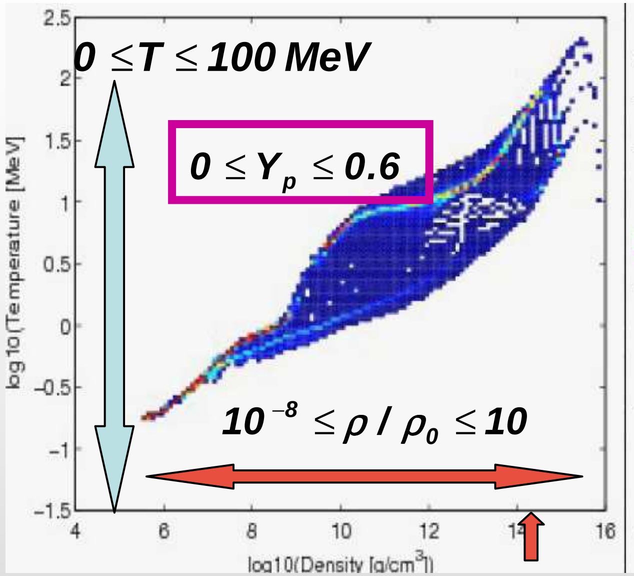
- Relevance of symmetry energy to astrophysics
- Overview over different probes at different energies
- Analysis of important and illustrative cases

Astrophysical Connection



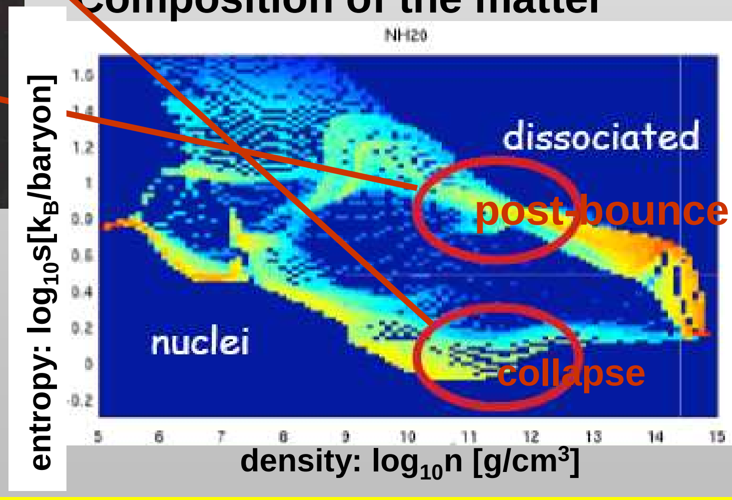
Hillebrandt, et al., Scient. Americ. 2006

Ranges of density, temperature, asymmetry in SN event



Liebendörfer, et al., NIX XI, 2010

Composition of the matter



Symmetry energy plays an essential role in astrophysics

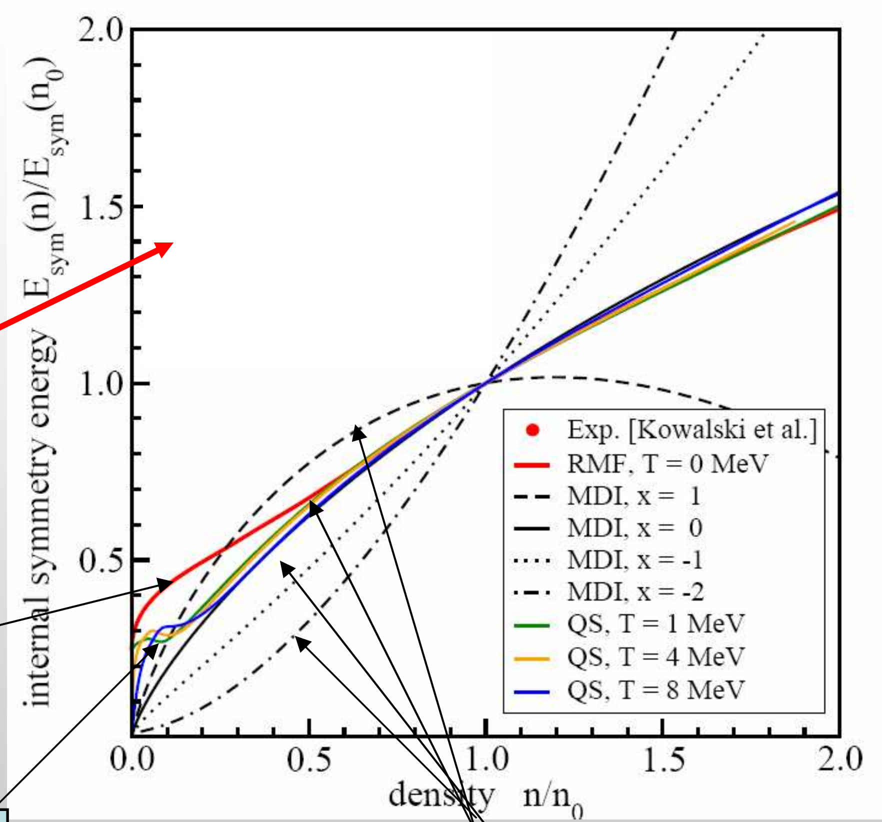
not uniform, but light and heavy clusters (nuclei embedded in the medium)

EOS for use in Supernovae (and neutron stars):
Cf. talk of Maria Voskresenskaya (+ S. Typel, G. Röpke, et al.)

Thermal Green Fct (quantumstatistical) model for medium dependence of clusters

+ gen RMF model (with explicit cluster degrees of freedom)

+ heavy nucleus in the medium (in Wigner-Seitz cell approx)



Comparison to low low densitiy SE determined in heavy ion collisions (Natowitz et al., PRL 104 (2010))

Single nucleus approx. (Wigner-Seitz), RMF

Quantum Statistical model , T=1,4,8 MeV)

Parametrization of nuclear symmetry energy of different stiffness (momentum dependent Skyrme-type) (B.A. Li)

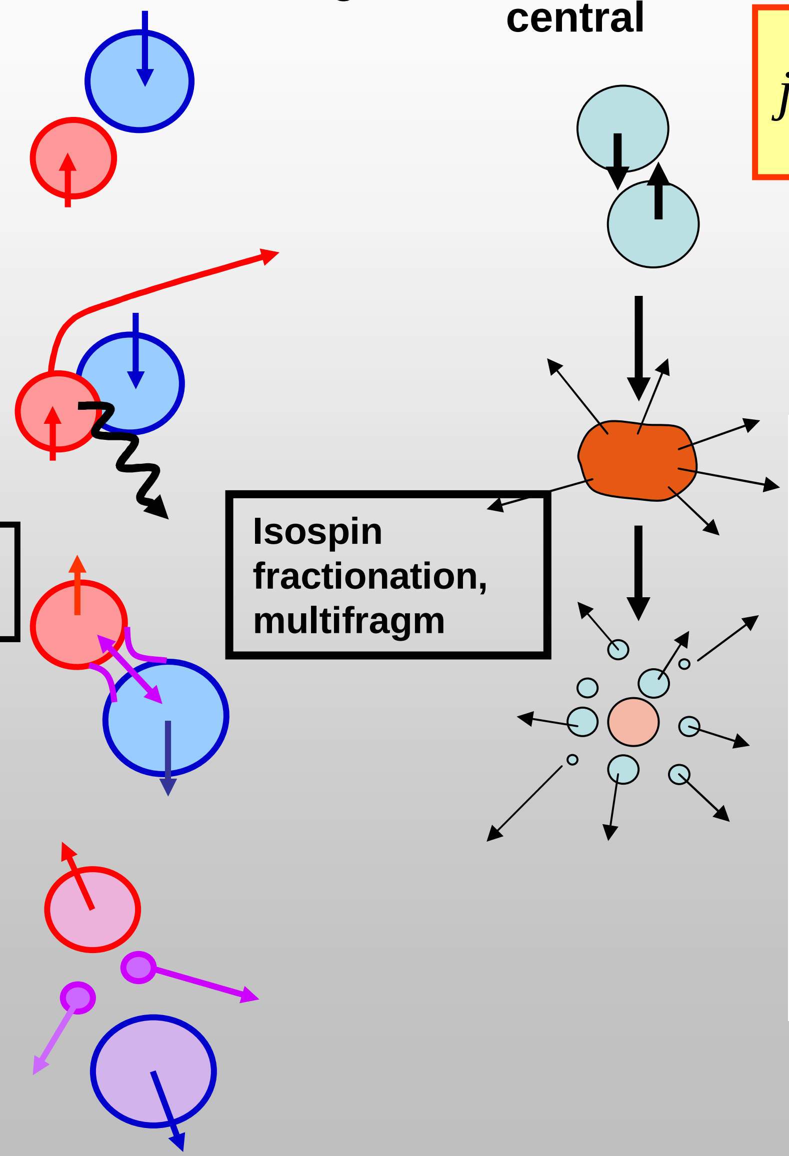
The symmetry energy is finite at low density and temperatures!

Reaction Mechanisms in Heavy Ion Collisions

Coulomb barrier to Fermi energies

peripheral

central



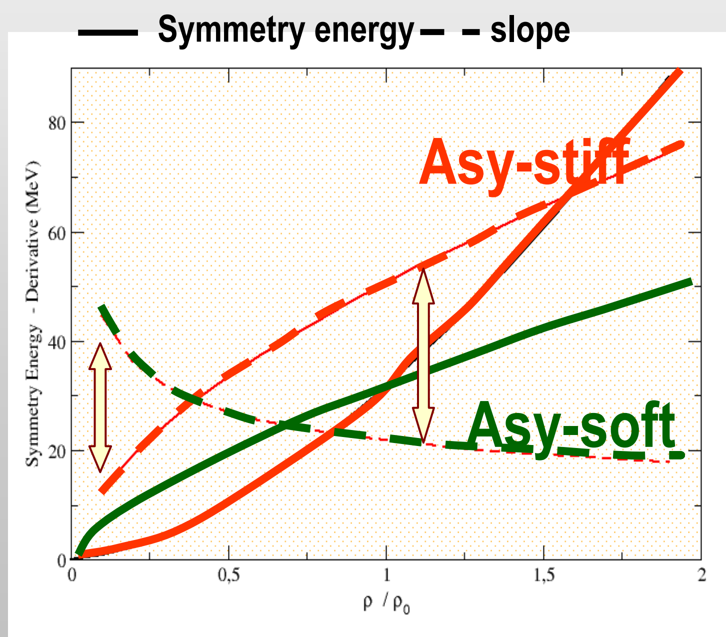
Isospin migration

Isospin fractionation, multifragm

Proton and neutron currents

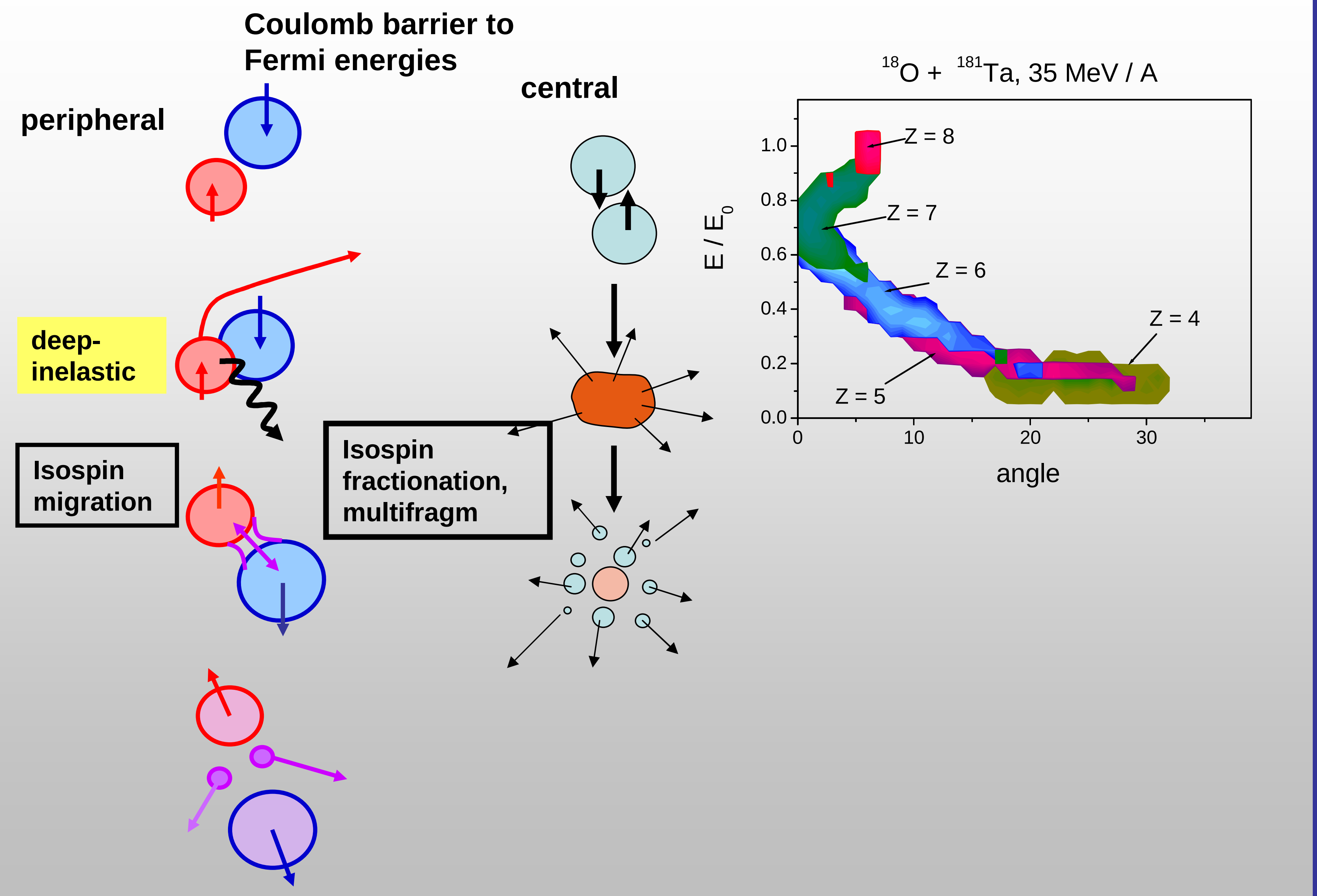
$$j_n - j_p \propto E_{sym}(\rho)\nabla I + \frac{\partial E_{sym}(\rho)}{\partial \rho} I\nabla\rho$$

"Diffusion" "Drift"

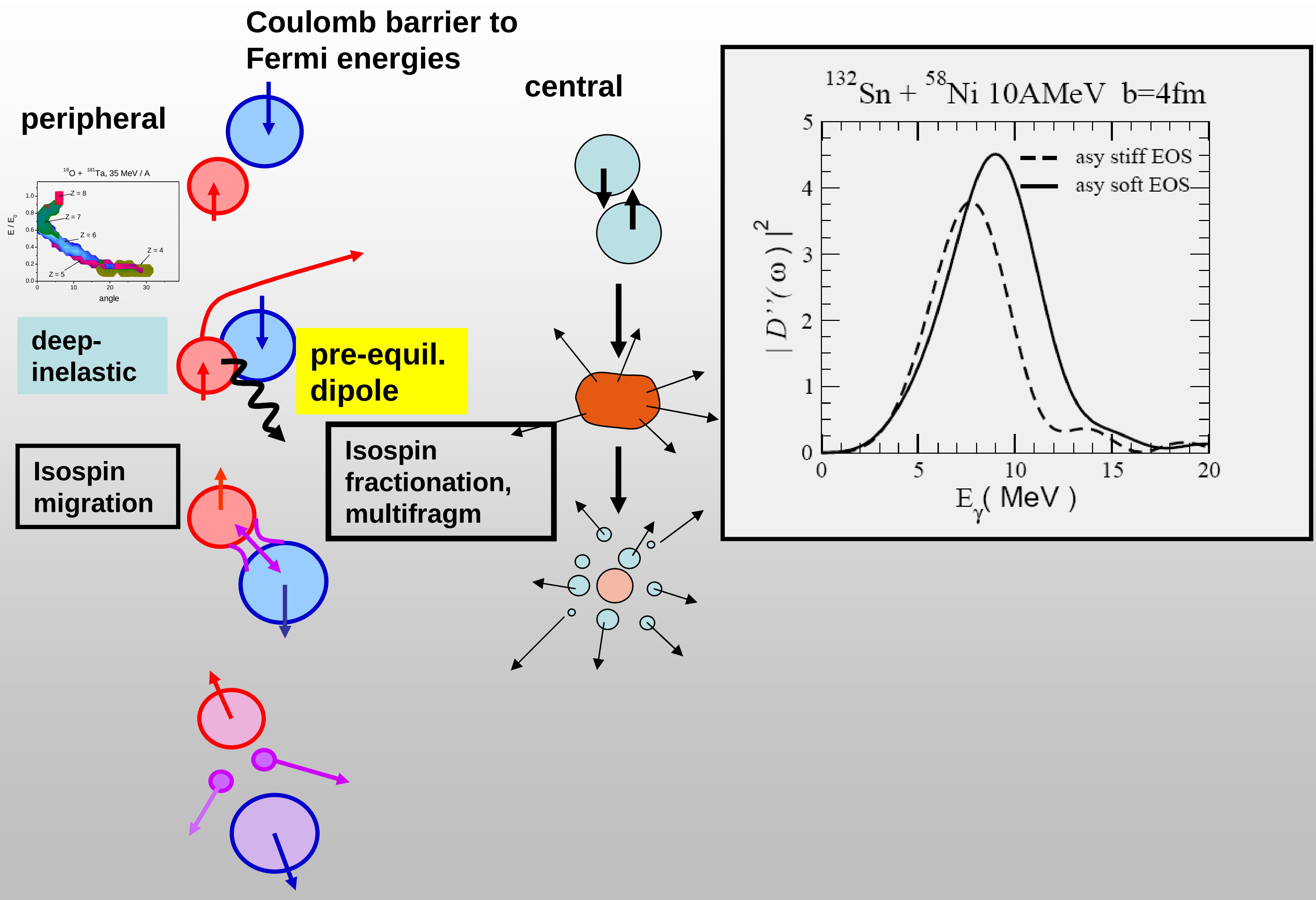


Sensitive to Sym. Energy and slope depending on observable

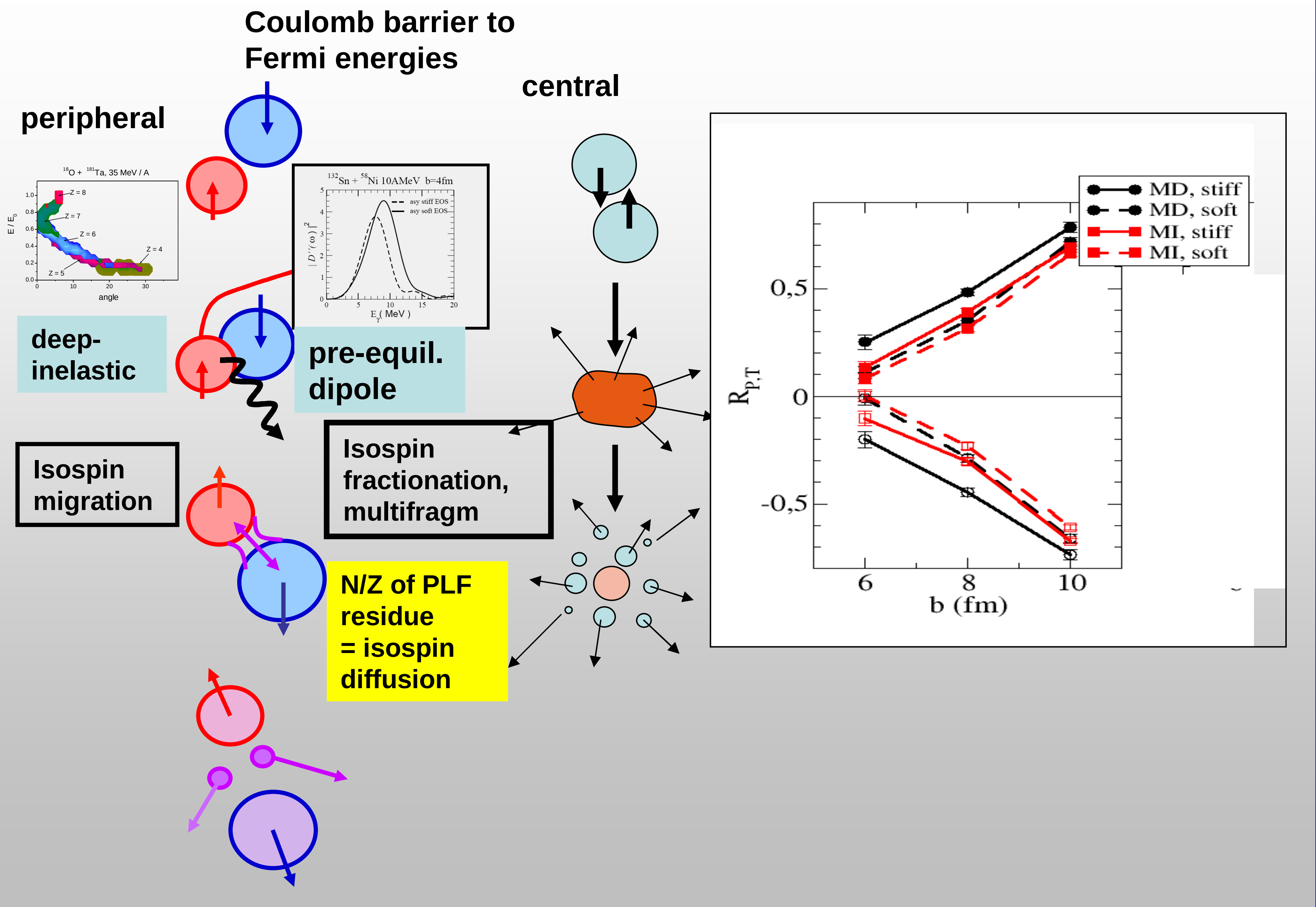
Reaction Mechanisms in Heavy Ion Collisions



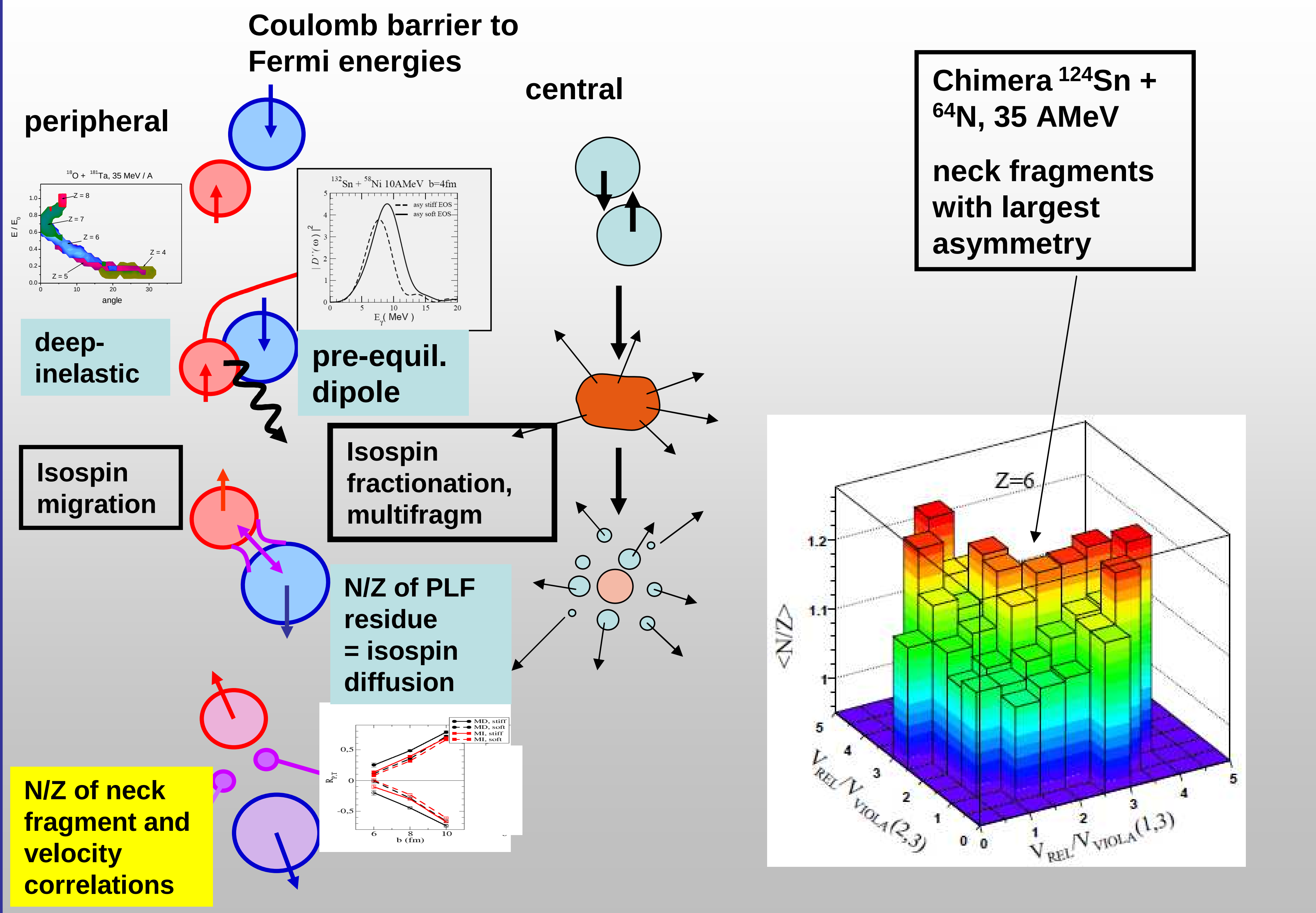
Reaction Mechanisms in Heavy Ion Collisions



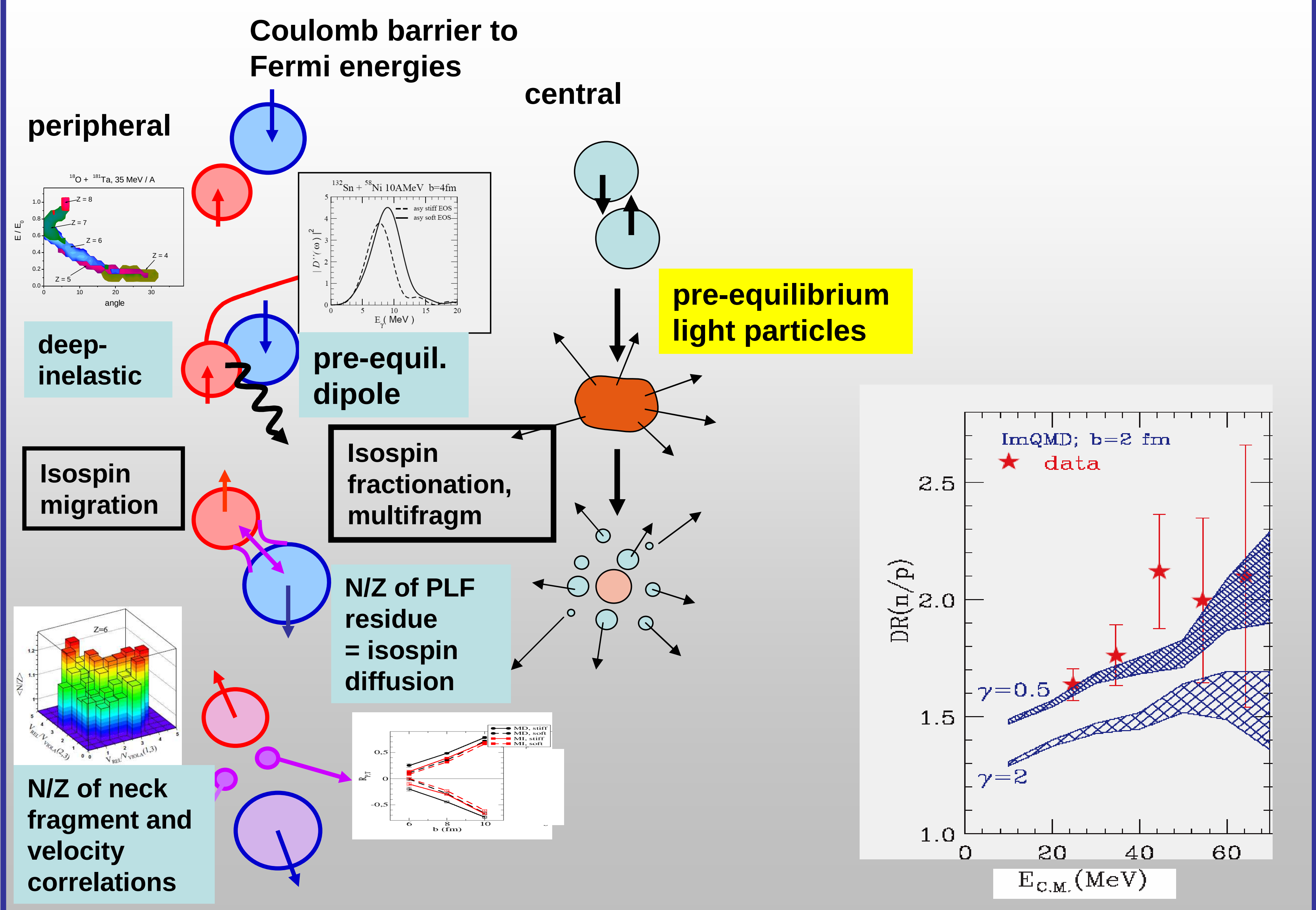
Reaction Mechanisms in Heavy Ion Collisions

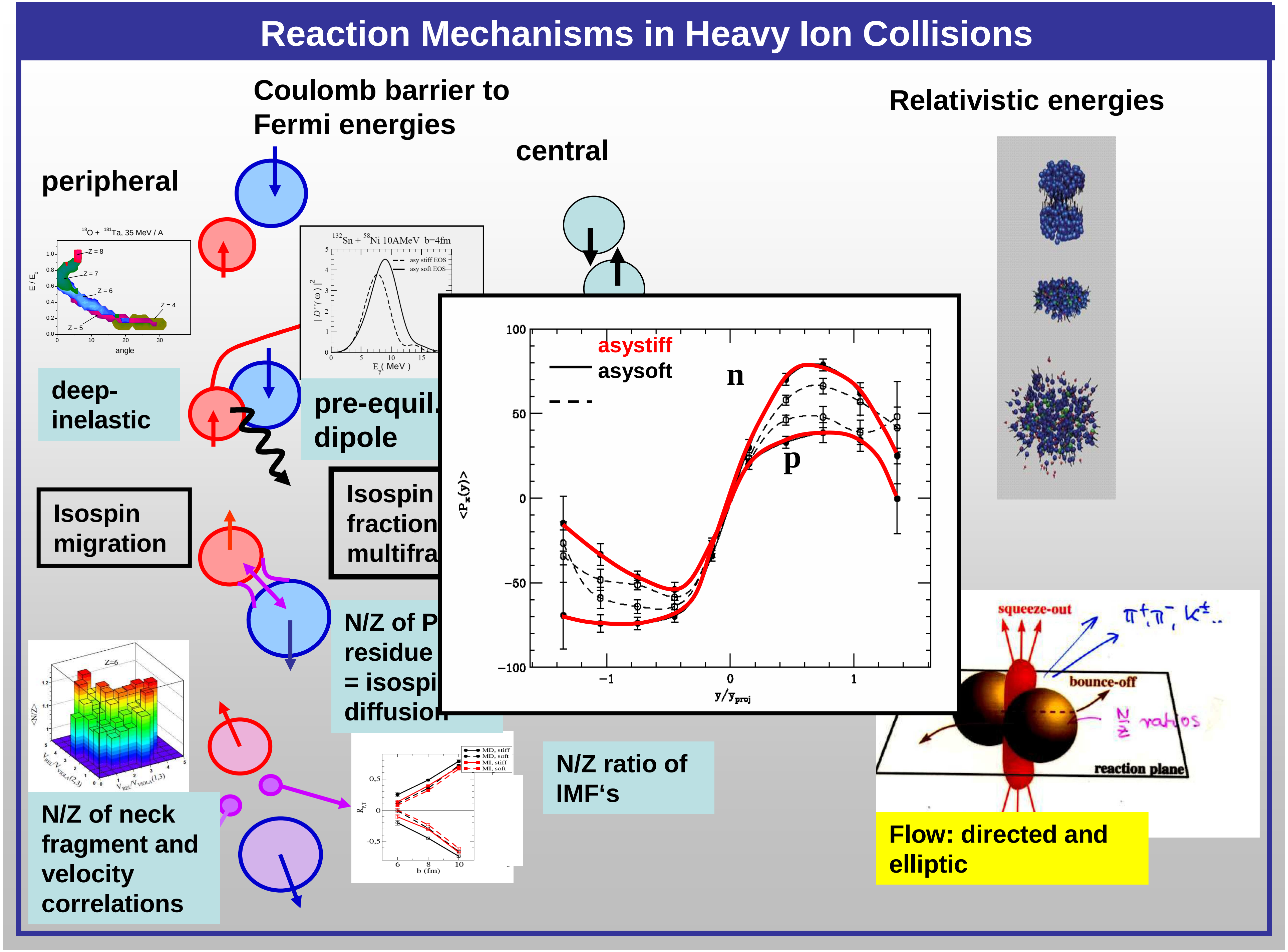


Reaction Mechanisms in Heavy Ion Collisions

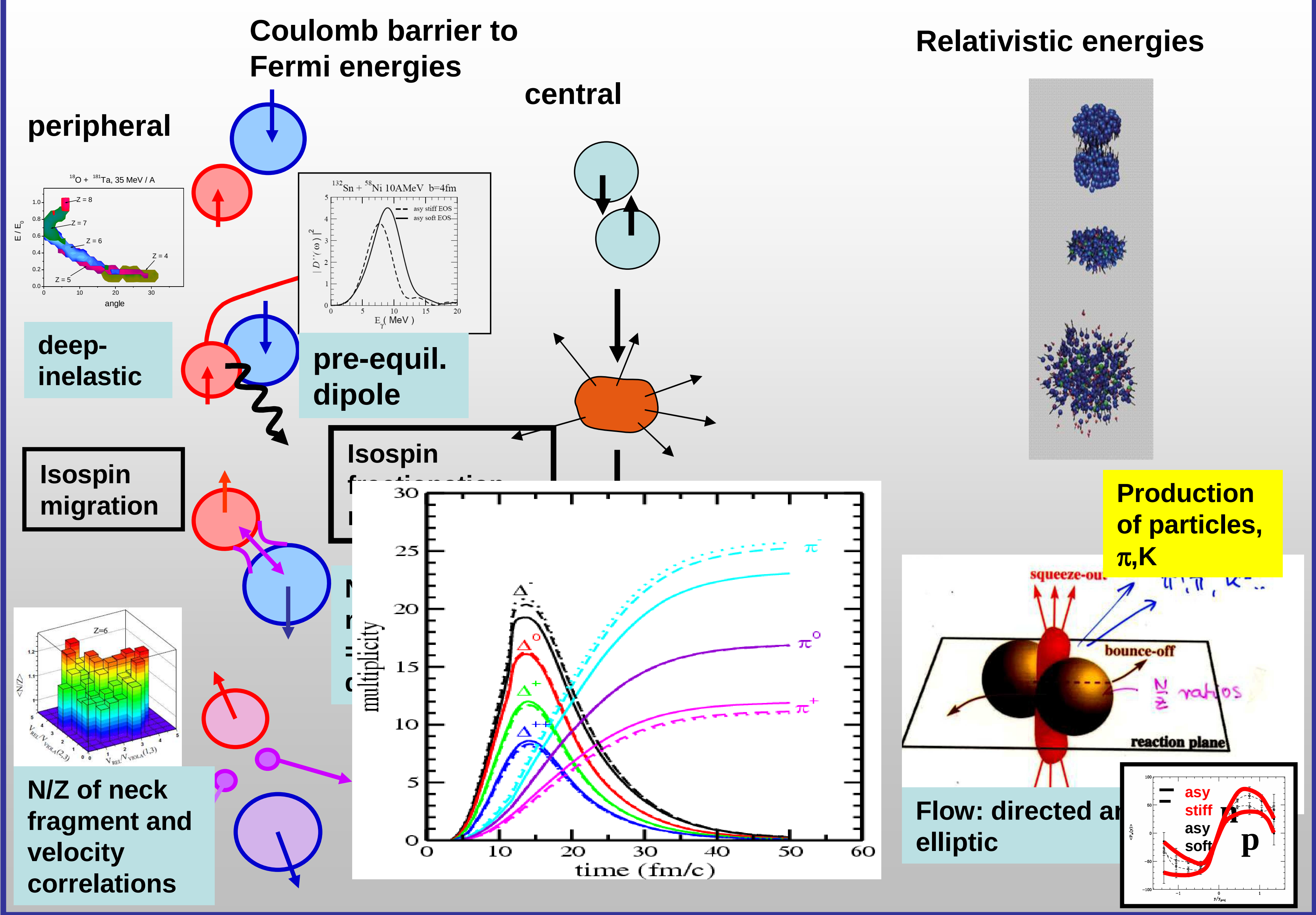


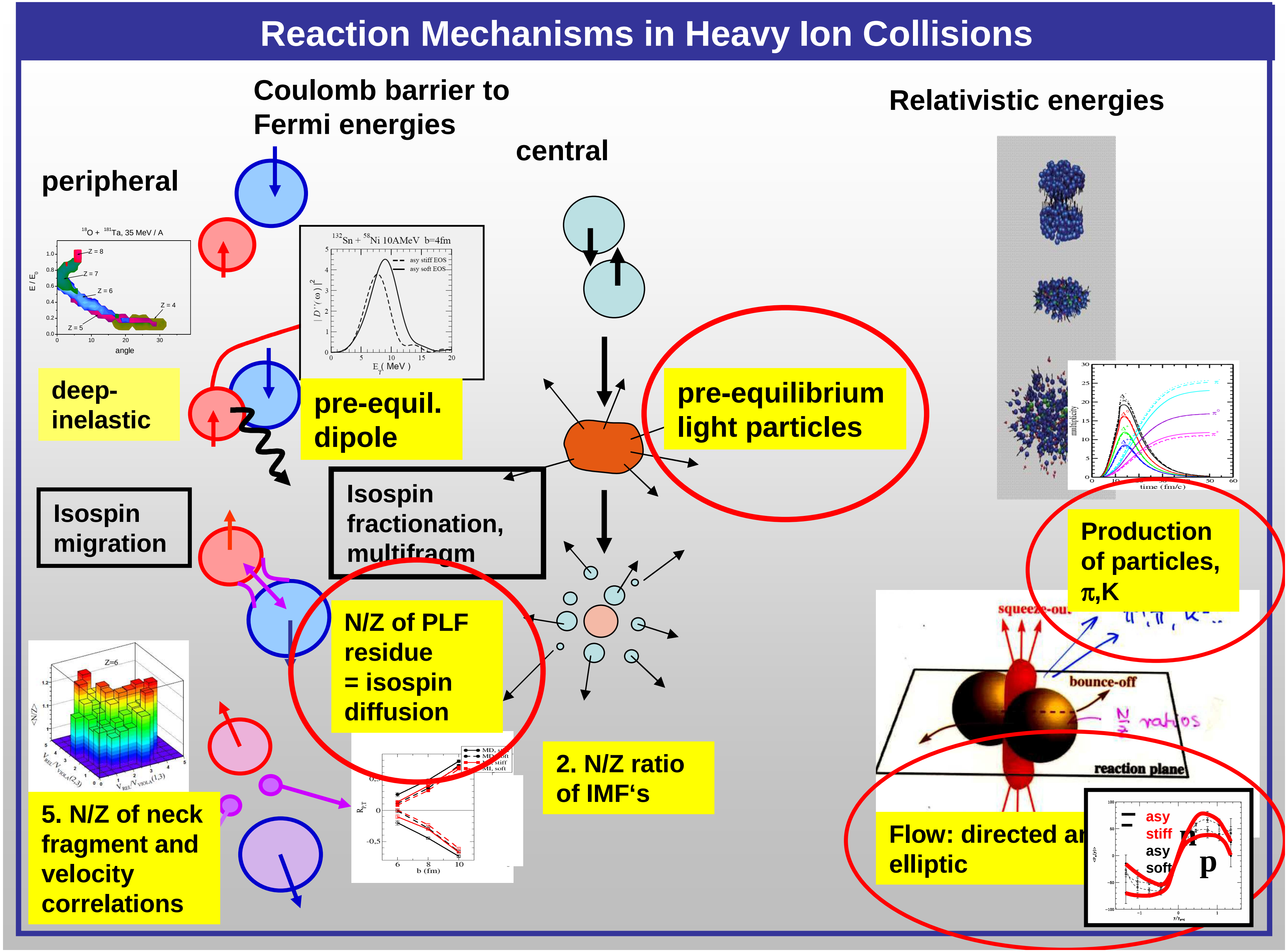
Reaction Mechanisms in Heavy Ion Collisions




Reaction Mechanisms in Heavy Ion Collisions
Coulomb barrier to Fermi energies
peripheral
central
Relativistic energies
deep-inelastic
pre-equil. dipole
Isospin migration
Isospin fraction multifra
N/Z of P residue = isospi diffusion
N/Z of neck fragment and velocity correlations
N/Z ratio of IMF's
Flow: directed and elliptic
asystiff
asysoft
n
p
squeeze-out
bounce-off
reaction plane

Reaction Mechanisms in Heavy Ion Collisions




Reaction Mechanisms in Heavy Ion Collisions
Coulomb barrier to
Fermi energies
central
Relativistic energies
peripheral
angle
132Sn + 58Ni 10AMeV b=4fm
asy stiff EOS
asy soft EOS
deep-
inelastic
pre-equil.
dipole
pre-equilibrium
light particles
Isospin
migration
Isospin
fractionation,
multifragm
Production
of particles,
π,K
N/Z of PLF
residue
= isospin
diffusion
2. N/Z ratio
of IMF's
squeeze-out
bounce-off
reaction plane
5. N/Z of neck
fragment and
velocity
correlations
Flow: directed and
elliptic
b (fm)
time (fm/c)
multiplicity
asy
stiff
asy
soft
p

Transport Description of Heavy Ion Collisions

one-body pase space density: f(**r**,**p**;t)

$$\frac{\partial f}{\partial t}+\frac{\vec{p}}{m}\nabla f-\nabla U\,\nabla_p f=I_{coll}[f,\sigma] \; + \; \delta I_{fluc}$$

Vlasov eq.; mean field

2-body hard collisions

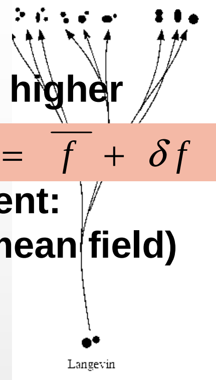
$$=\frac{1}{(2\pi)^{3/2}}\iiint dp_2 dp_3 dp_4\, v_{12}\frac{d\sigma}{d\Omega}_{12\to 34}\,\delta(p_1+p_2-p_3-p_4)$$

$$[(1-f)(1-f_2)f_3 f_4 - f\,f_2(1-f_3)(1-f_4)]$$

loss term gain term

Fluctuations from higher order corr.; $f = \overline{f} + \delta f$

stochastic treatment:
SMF (stochastic mean field)



Relativistic BUU eq.

$$\boxed{\left[p^{*\mu}\partial_\mu^{(r)}+(p^*_\nu F^{\mu\nu}+m^*\partial^\mu_{(r)}m^*)\,\partial_\mu^{(p^*)}\right]f(r,p^*)=I_{coll}}$$

effective mass $m^* = m - \Sigma_s$;

Kinetic momentum $p^*_\mu = p_\mu - \Sigma_\mu$

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

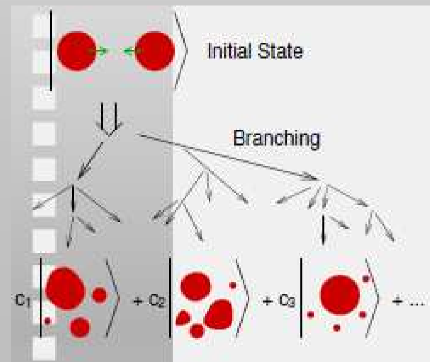
Quantum molecular dynamics QMD

$$|\Phi(Z)\rangle = \det_{ij}\left[\exp\left\{-\nu\left(\mathbf{r}_j-\frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2\right\}\chi_{\alpha_i}(j)\right]$$

Stochastic equation of motion for the wave packet centroids Z:

(stochastic NN collisions)

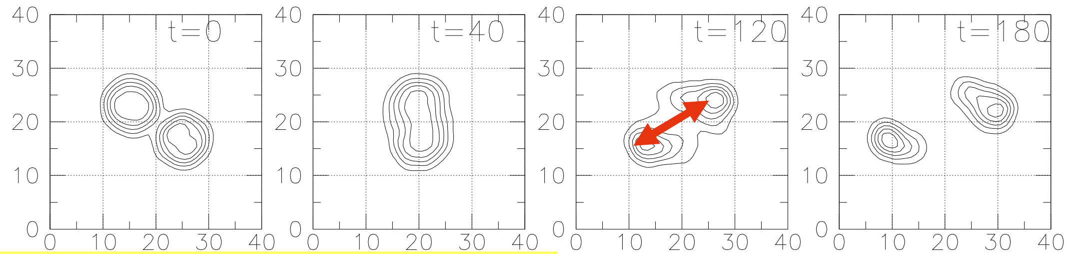
$$\frac{d}{dt}\mathbf{Z}_i = \{\mathbf{Z}_i,\mathcal{H}\}_{\mathrm{PB}} + \Delta\mathbf{Z}_i(t) + (\mathrm{NN\ collisions})$$



Isopin diffusion

isospin transport through „neck“ in peripheral collisions

$^{124}Sn(H)+^{112}Sn(L)$

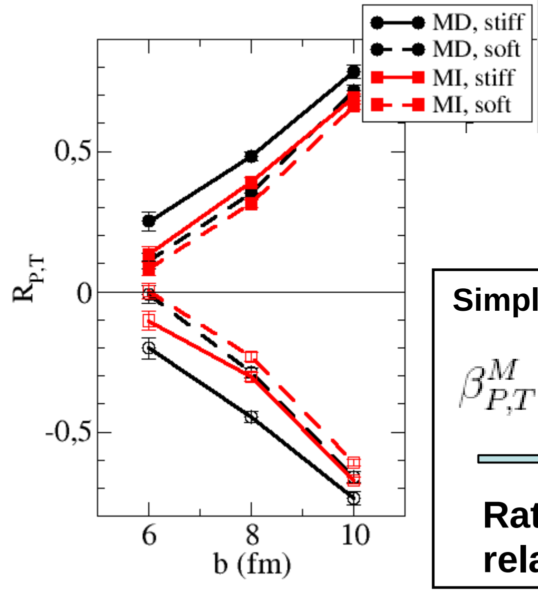


Imbalance (or Rami, transport) ratio:

β asymmetry of residue (i=PLF,TLF)
(also for other isospin sens.quantities)

$$R_i = \frac{\beta_i^{mix} - \frac{1}{2}(\beta_i^{HH} + \beta_i^{LL})}{\frac{1}{2}(\beta_i^{HH} - \beta_i^{LL})}$$

Limiting values:
***R*=0 complete equilibration**
***R*=+-1, complete transparency**



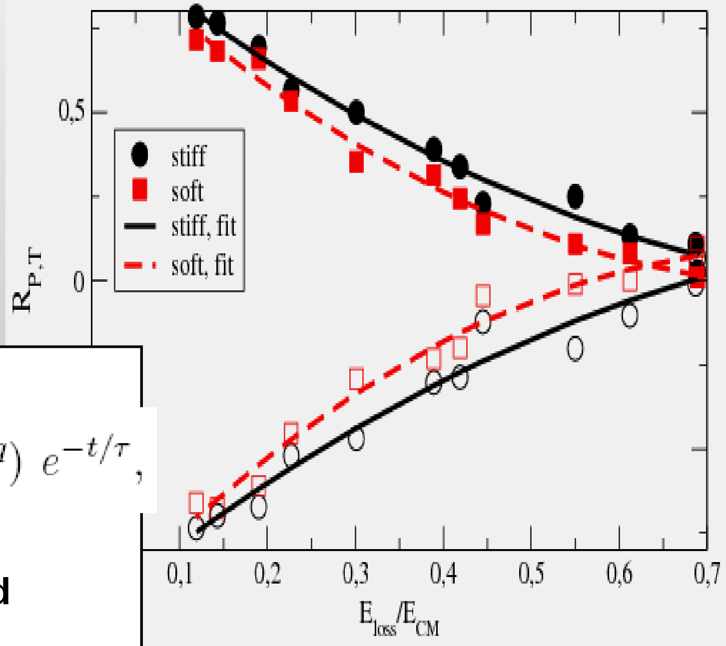
J.Rizzo, et al., Nucl. Phys. A806 (2008) 79

Simple equil. model

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

$$\Longrightarrow \quad R^{\rho}_{P,T} = \pm e^{-t/\tau}$$

Ratio det. by interact. and relax. times

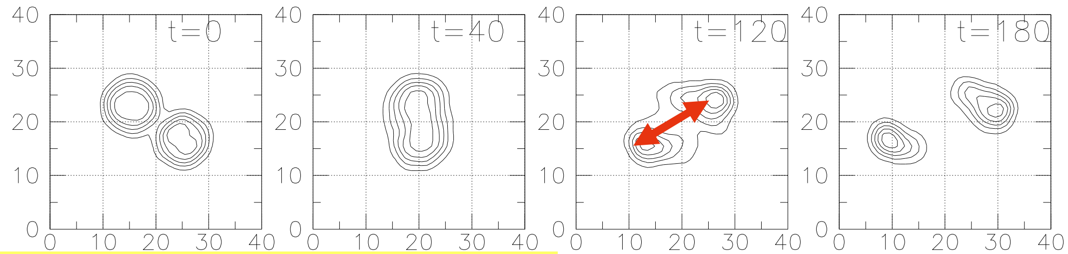


more equlibration (lower R) for longer interaction time ~ correlation with total energy loss

Isopin transport

isospin transport through „neck“ in peripheral collisions

$^{124}Sn(H)+^{112}Sn(L)$



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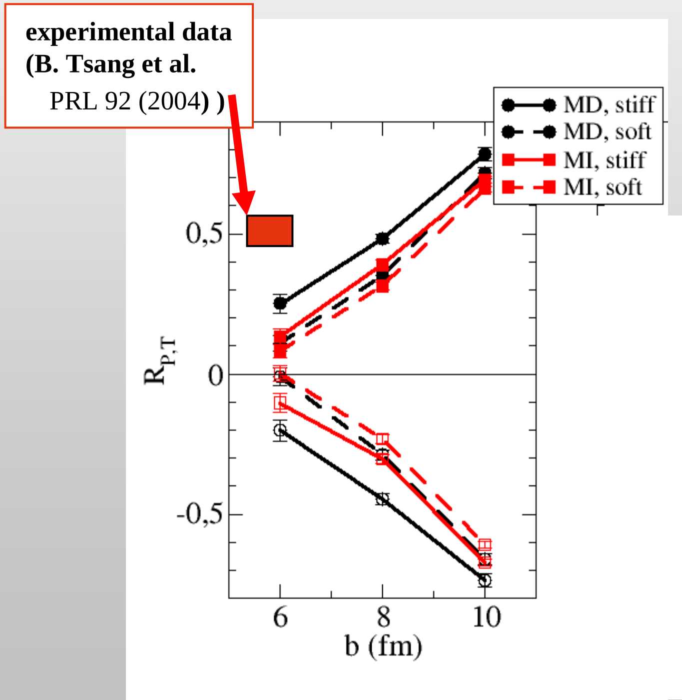
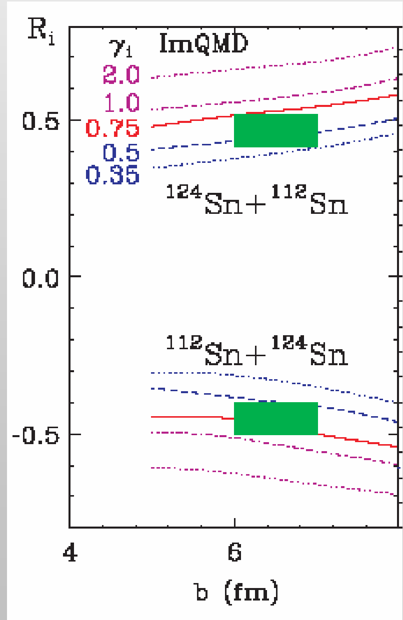
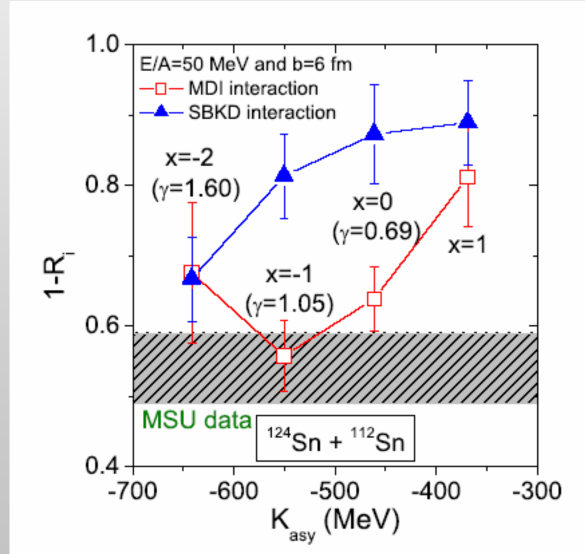


J.Rizzo, et al., Nucl. Phys. A806 (2008) 79



M.B. Tsang, et al., PRL 102 (2008)



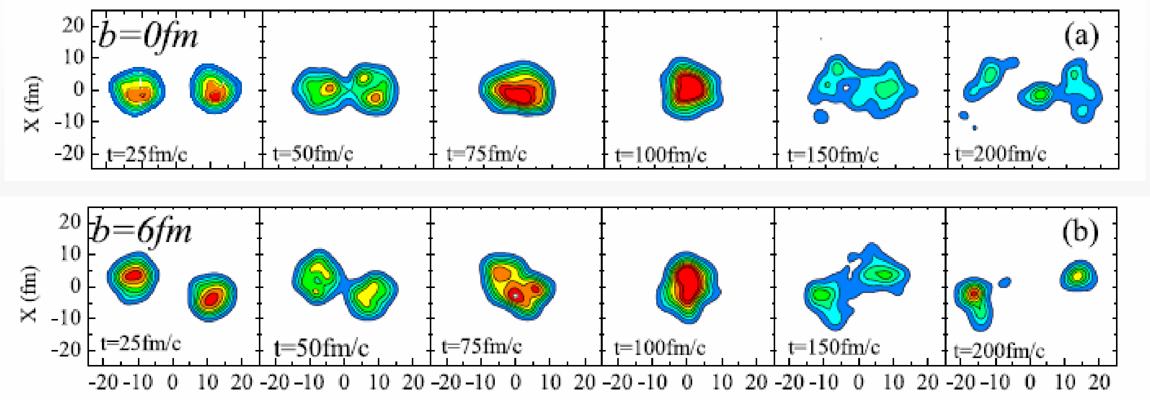
L.W.Chen, C.M.Ko, B.A.Li, PRL 94, 032701 (2005)

points toward a moderately stiff (γ~1) SE, but disagreement in detail

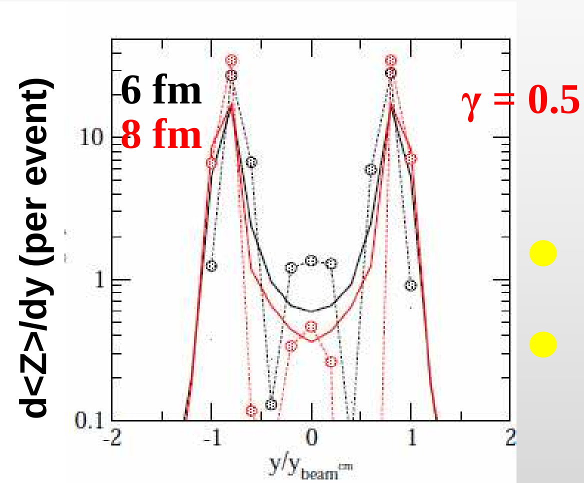
Analysis of differences BNV – QMD

→ more `explosive´ dynamics:
more `transparency´

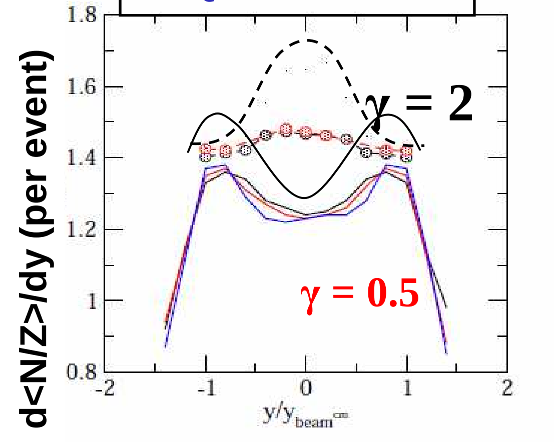
ImQMD calculations, $^{112}Sn + ^{112}Sn$, 50 AMeV



Y.Zhang et al., arXiv:1009.1928



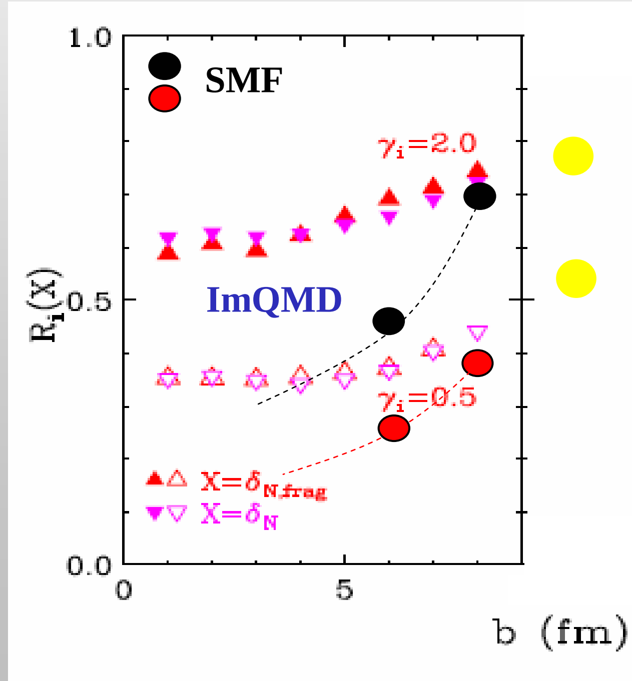
SMF = dashed lines
ImQMD = full lines



Much less isospin migration in ImQMD, Other sources of dissipation: Fragment emission, fluctuation?

→Less dependence on impact parameter.

Similar conclusions in comparison with Antisymmetrized Mol. Dynamics (AMD): Colonna, Ono, Rizzo, PRC (2011)



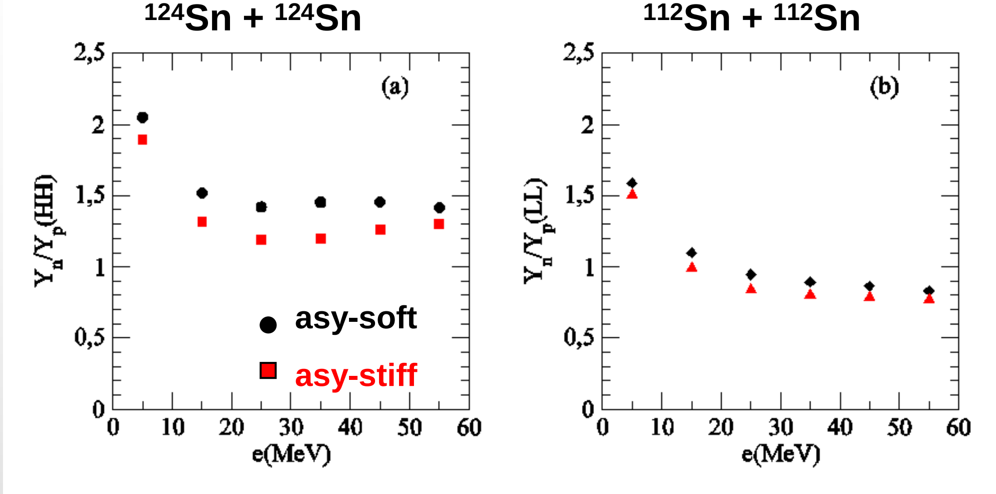
Model dependence of imbalance ratio!

Central collisions at Fermi energies: Ratios of emitted pre-equilibrium particles

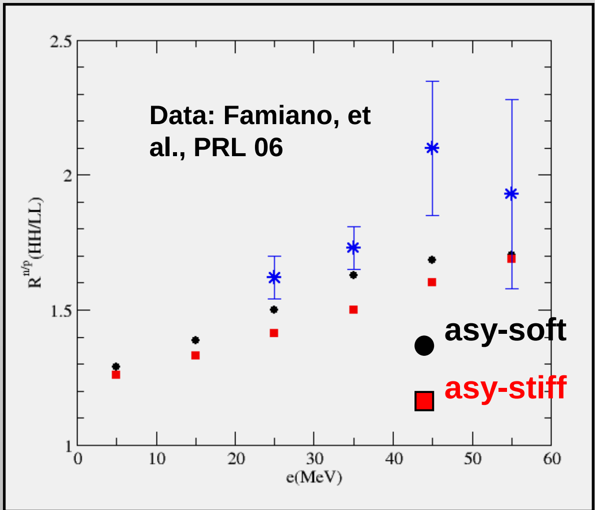
Early emitted neutrons and protons reflect difference in potentials in expanded source, esp. ratio Y(n)/Y(p).

more emission for asy-soft, since symm potential higher

protons vs. neutrons



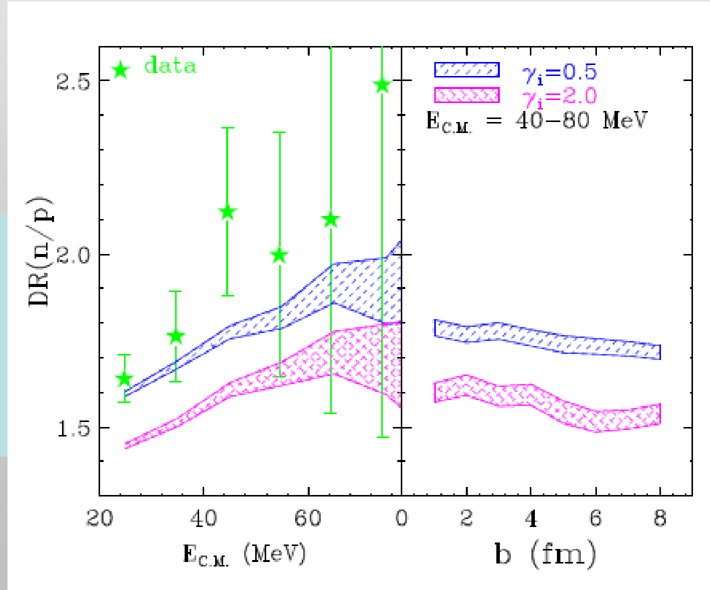
„Double Ratios“ $\dfrac{^{124}\text{Sn} + {}^{124}\text{Sn}}{^{112}\text{Sn} + {}^{112}\text{Sn}}$



SMF simulations, V.Baran 07

softer symmetry energy closer to data

qualitatively as seen in ImQMD, but quantitatively weaker dependence on SymEn

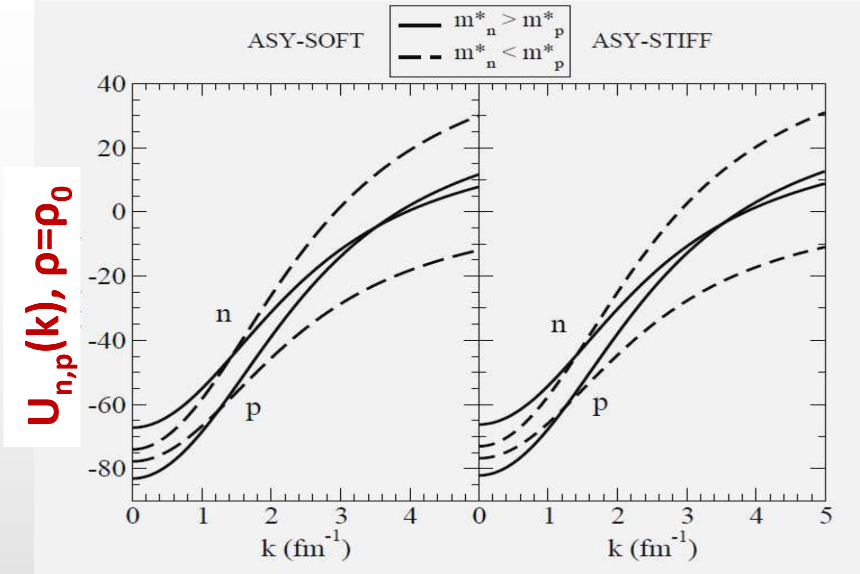


Y. Zhang, et al., arXiv (2011)

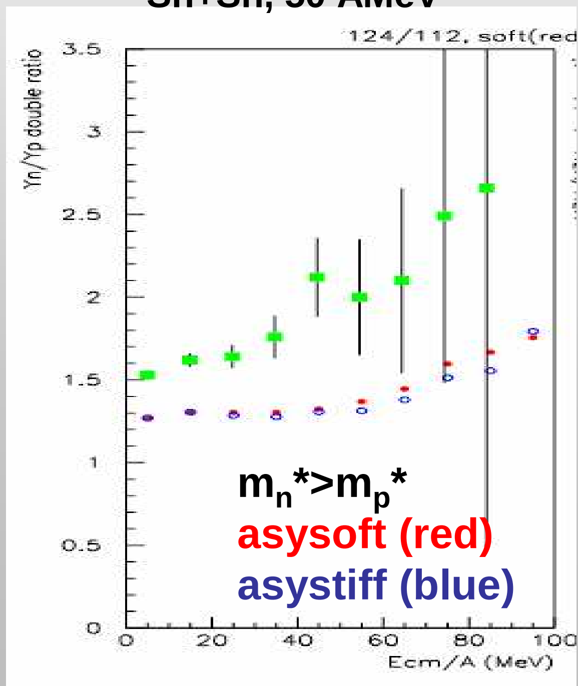
Momentum Dependence and Effective Mass Splitting

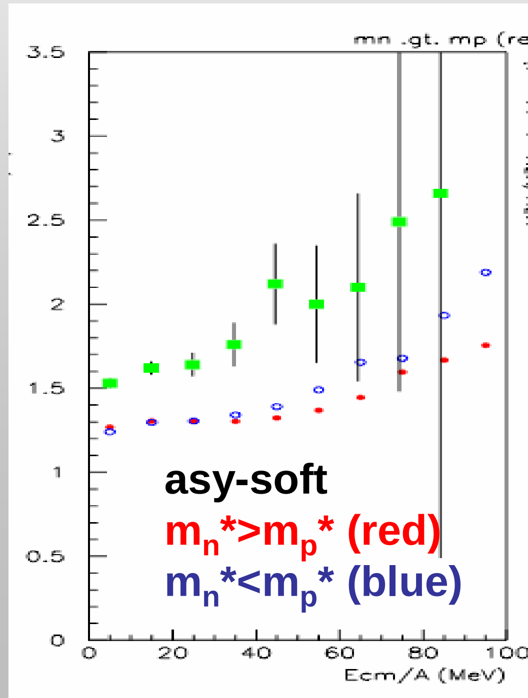
$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$$

At high momentum m* splitting effect larger than asy-stiffness



Sn+Sn, 50 AMeV





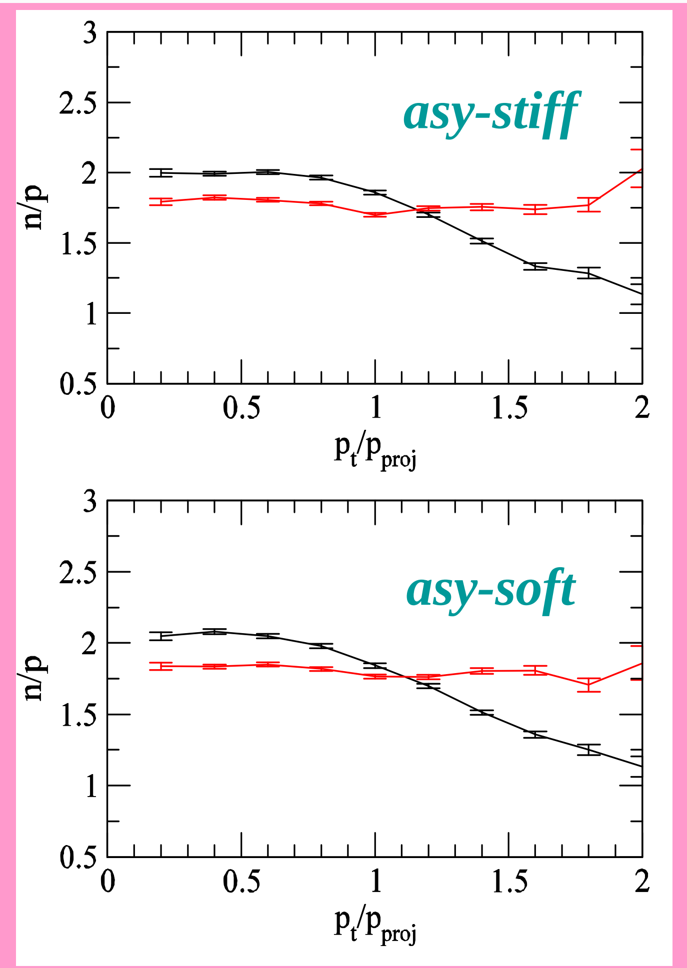
Effect of momentum dependence of symmetrymenergy as large as effect of asy-EOS itself.

Momentum dependence here rather strong

M. Zielinska-Pfabe, IWM08

Pre-equilibrium nucleon and light cluster emission at higher energy

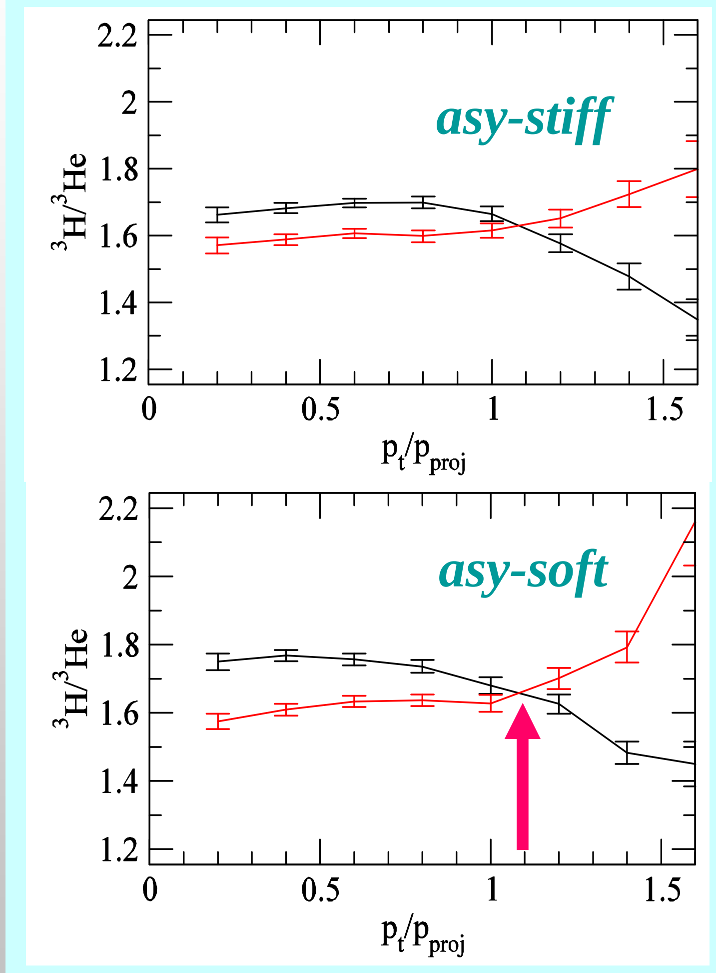
n/p ratio yields



$^{197}Au+^{197}Au$
600 AMeV
b=5 fm,
y(0)≤0.3

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

Light isobar $^3H/^3He$ yields



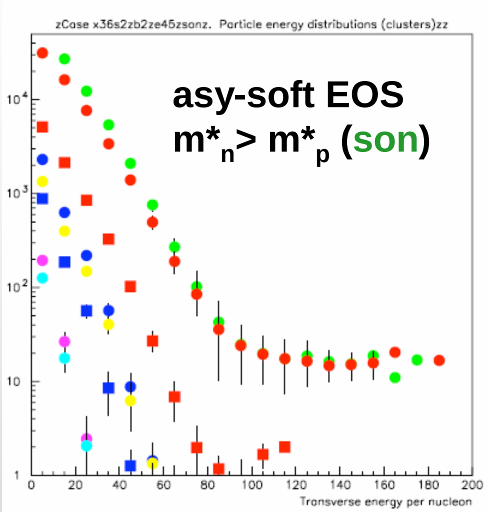
Observable very sensitive at high p_T
to the mass splitting and not to the asy-stiffness

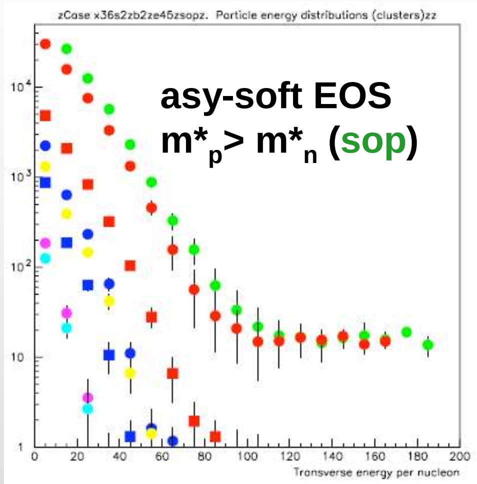
Crossing of
the symmetry potentials for
a matter at $\rho \approx 1.7 \rho_0$

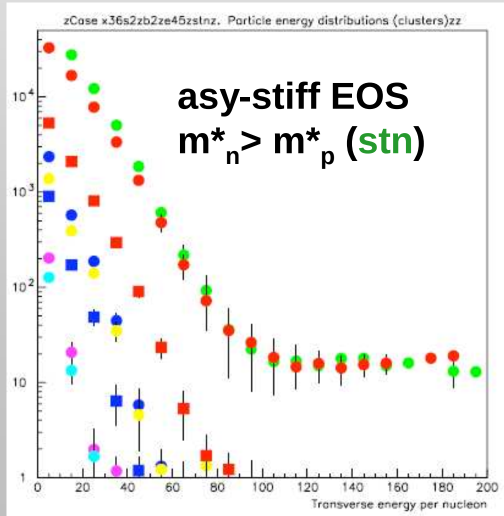
V.Giordano, M.Colonna et al., PRC 81(2010)

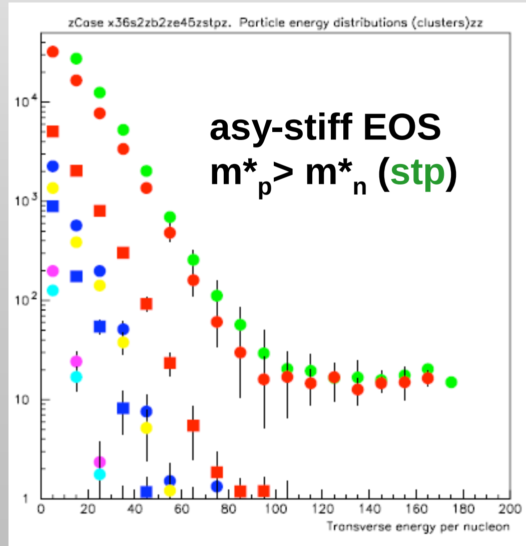
Emission of light clusters

Particle Yields ^{136}Xe + ^{124}Sn, 32 AMeV









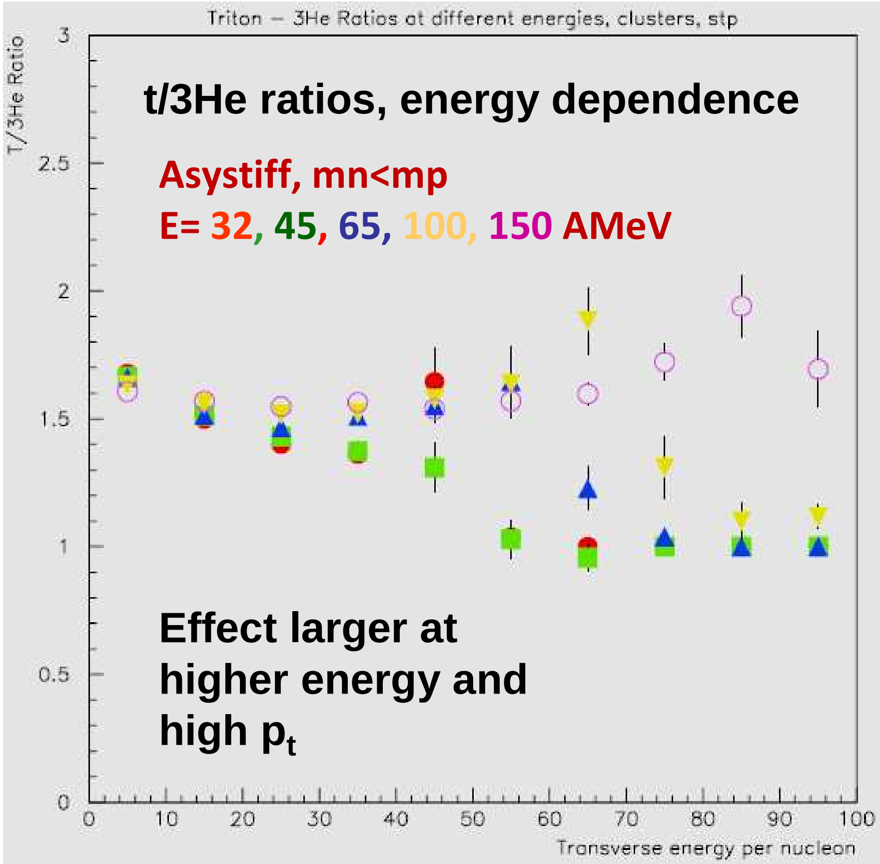
- n
- p
- d
- t
- ^{3}He
- α
- ^{7}Li
- ^{7}Be

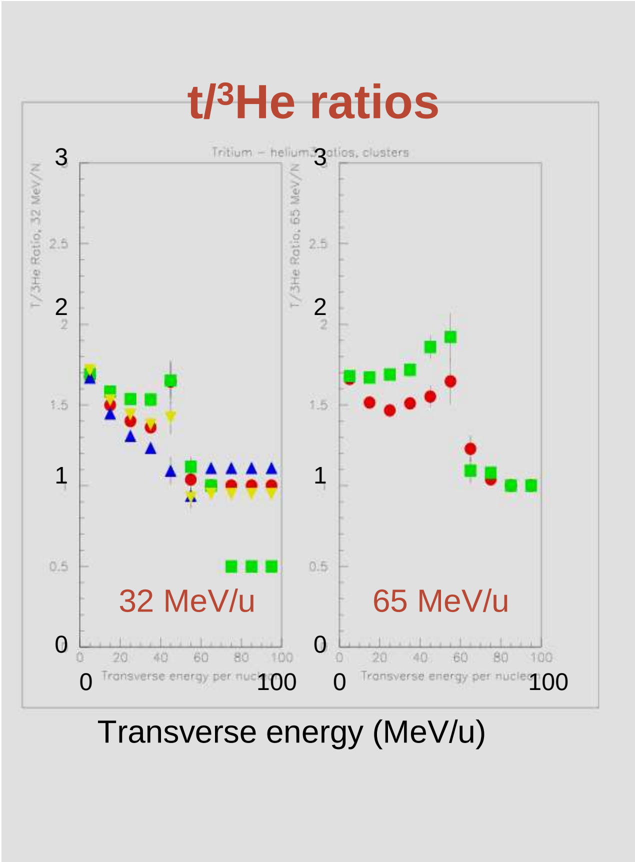
M. Zielinska-Pfabe, IWM09

n/p and t/³He ratios as functions of transverse energy

136Xe+124Sn

M. Zielinska-Pfabe, IWM09





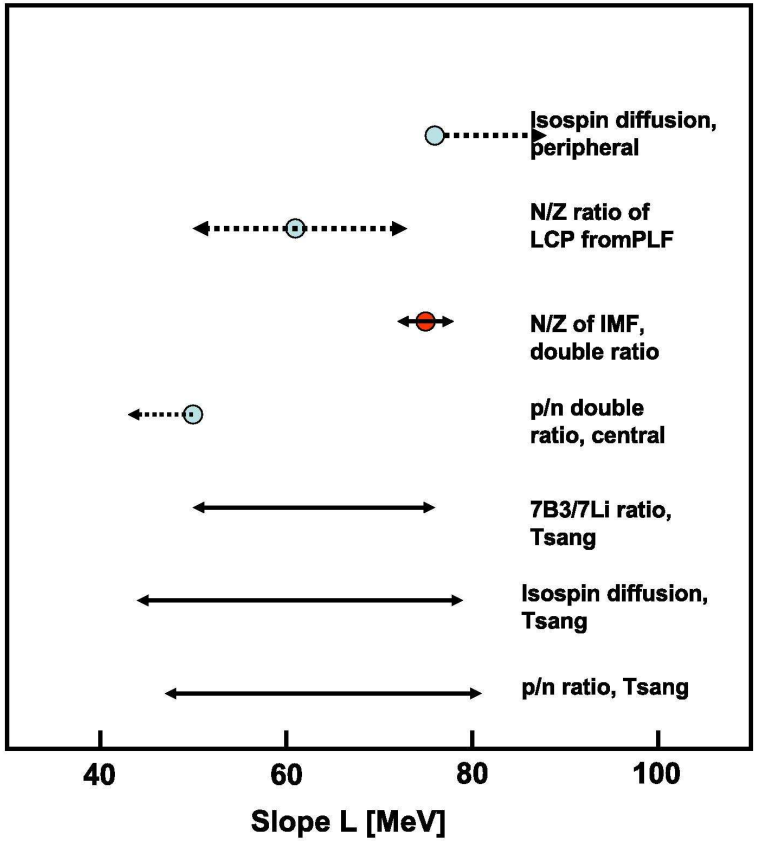
green asy-soft EOS $m^*_p > m^*_n$ (sop)
red asy-stiff EOS $m^*_p > m^*_n$ (stp)
blue asy-stiff EOS with $m^*_n > m^*_p$,(stn)
yellow asy-soft EOS with $m^*_n > m^*_p$ (son)

sop and stp n accelerate more than p, the ratio goes up. (There is a limit for first chance emission (beam+ Fermi)).
stn and son decrease only. For t/³He goes down about beam energy (prob. statistics).

More sensitivity to effective mass than to symmetry energy!

Slope of Symmetry Energy

Comparison of results for symmetry energy slope extracted from Fermi energy collisions



Catania results, qualitative S_0=30 MeV

M.B.Tsang, et al., PRL102,122701(09)

Agreement in general but differences in detail.

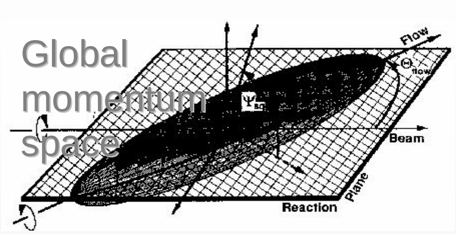
Point to different dynamics in the different approaches which should be better understood, as e.g. in Colonna et al., PRC 81 (2011)

Heavy Ion Collisions at Relativistic Energies: "Flow"

Fourier analysis of momentum tensor : „flow"

$$N(\theta, y, b) = N_0(1 + v_1(y,b)\cos\theta + v_2(y,b)\cos 2\theta + ..)$$

v_1: directed flow | v_2: elliptic flow



To investigate symmetry energy:

differences of flow (more sensitive for clusters):

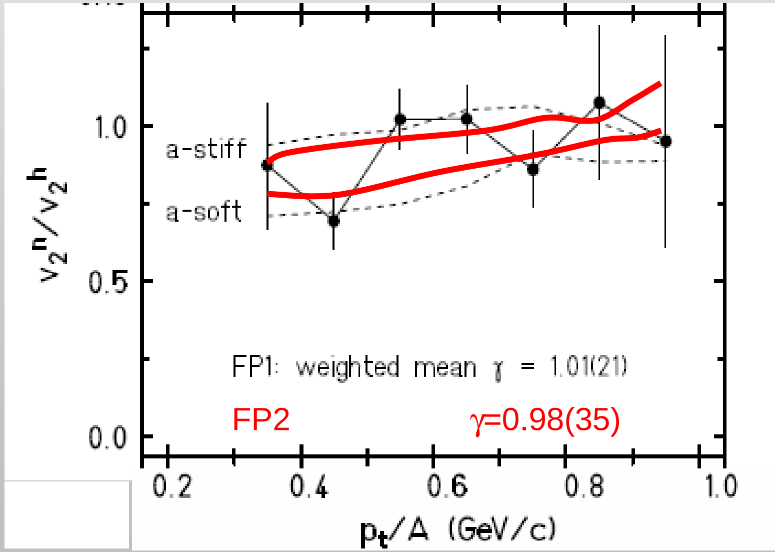
$$\langle p_x^t/A\rangle - \langle p_x^{^3\mathrm{He}}/A\rangle = \frac{1}{N_t}\sum_{i=1}^{N_t} p_x^i/A - \frac{1}{N_{^3\mathrm{He}}}\sum_{i=1}^{N_{^3\mathrm{He}}} p_x^i/A.$$

or differential flow

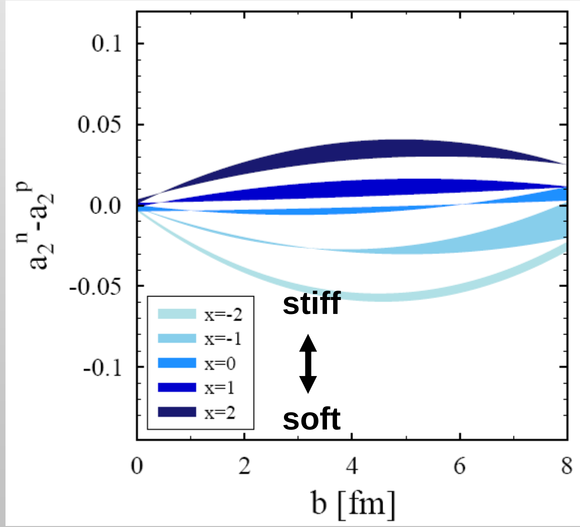
$$\langle p_x^{t\text{-}^3\mathrm{He}}/A\rangle = \frac{N_t}{N_t + N_{^3\mathrm{He}}}\langle p_x^t/A\rangle - \frac{N_{^3\mathrm{He}}}{N_t + N_{^3\mathrm{He}}}\langle p_x^{^3\mathrm{He}}/A\rangle,$$

(analogous for v_1, v_2, ..)

Au+Au @ 400 AMeV, FOPI-LAND



Russotto, et al., PLB 697, 471 (2011)

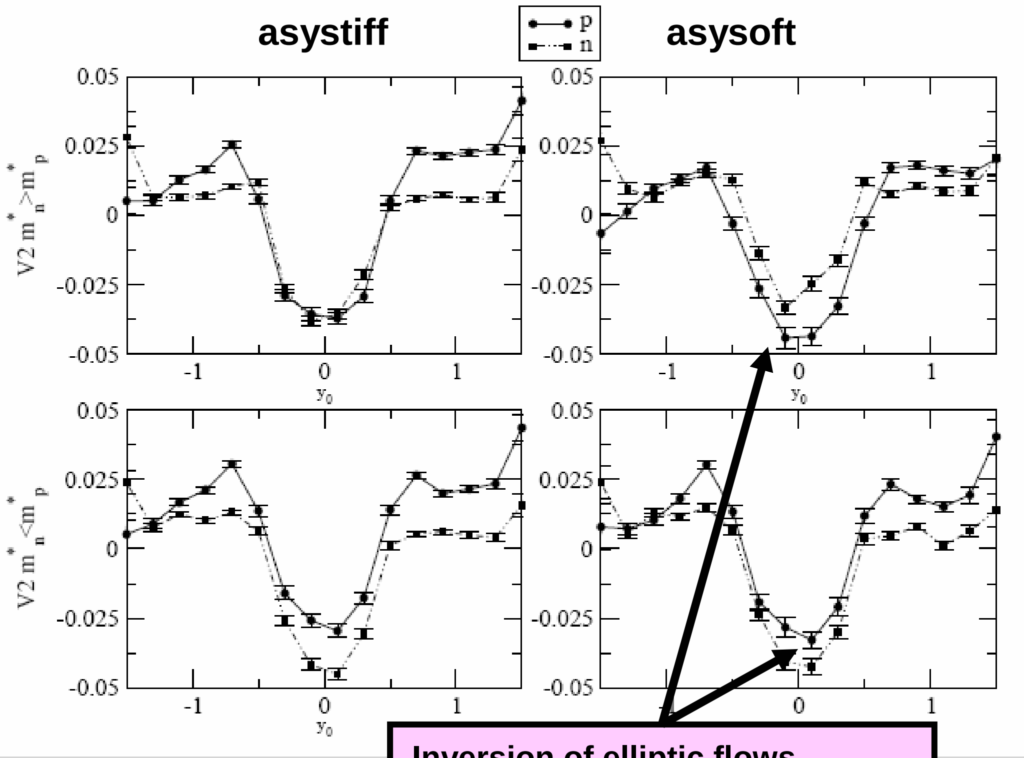


Recent study by Cozma, arxiv 1102.2728

band: soft vs. stiff eos of symmetric matter,
→ robust probe

Differential elliptic flow

Au+Au, 400 AMeV



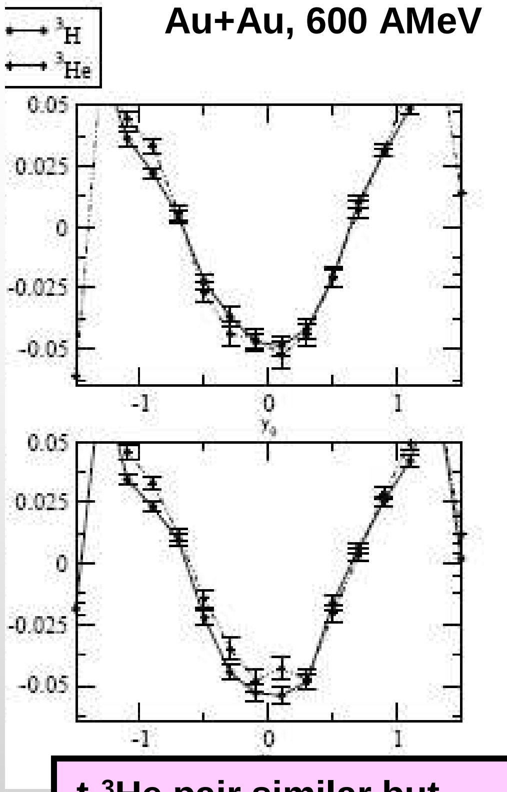
$m^*_n > m^*_p$

$m^*_n < m^*_p$

V.Giordano, M.Colonna et al., arXiv 1001.4961, PRC81(2010)

Inversion of elliptic flows because of inversion of potentials with effective mass

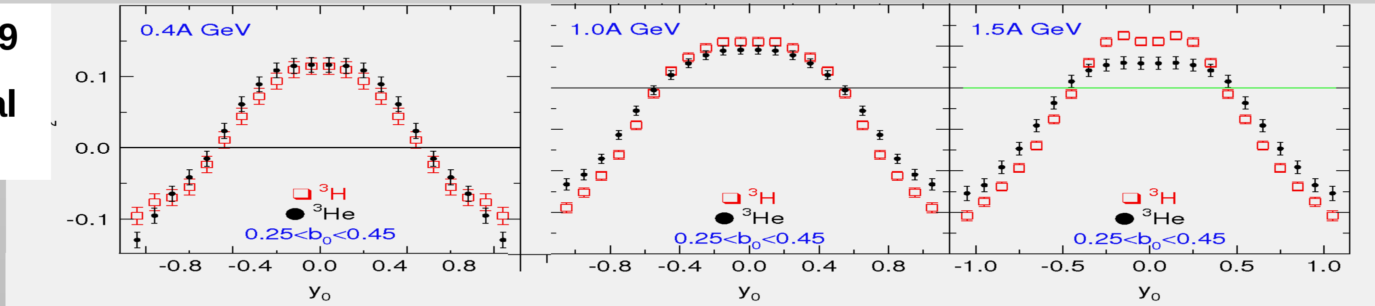
Au+Au, 600 AMeV



t-^{3}He pair similar but weaker

W. Reisdorf, ECT*, May 09

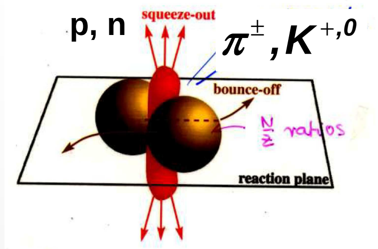
Indication of experimental effect



Elliptic flow more sensitive, since determined by particles that are emitted perp to the beam direction

Particle production as probe of symmetry energy

Difference in neutron and proton potentials



1. „direct effects“: difference in proton and neutron (or light cluster) emission and momentum distribution
2. „secondary effects“: production of particles, isospin partners $\pi^{-,+}$, $K^{0,+}$

NN → NΔ → Nπ → ΛK

NΔ → NΛK

in-medium in-elastic σ ,	Δ in-medium self-energies and width	π potential ,	K and Λ potential (in-medium mass)

1. Mean field effect: U_{sym} more repulsive for neutrons, and more for asystiff
→ pre-equilibrium emission of neutron, reduction of asymmetry of residue

$$\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$

decrease with stiffer asyEOS

2. Threshold effect, in medium effective masses:
→ m^*_{N}, m^*_{Δ}, contribution of symmetry energy; m^*_K, models for K-potentials

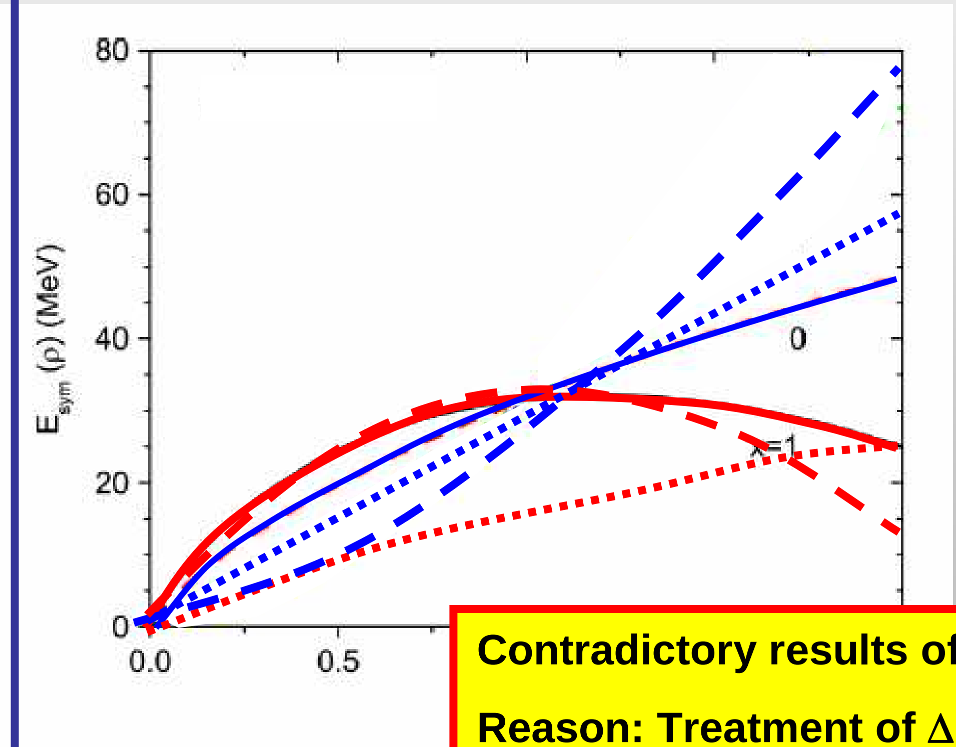
$$\sigma = \sigma\left(s_{in} - s_{th}\right)$$

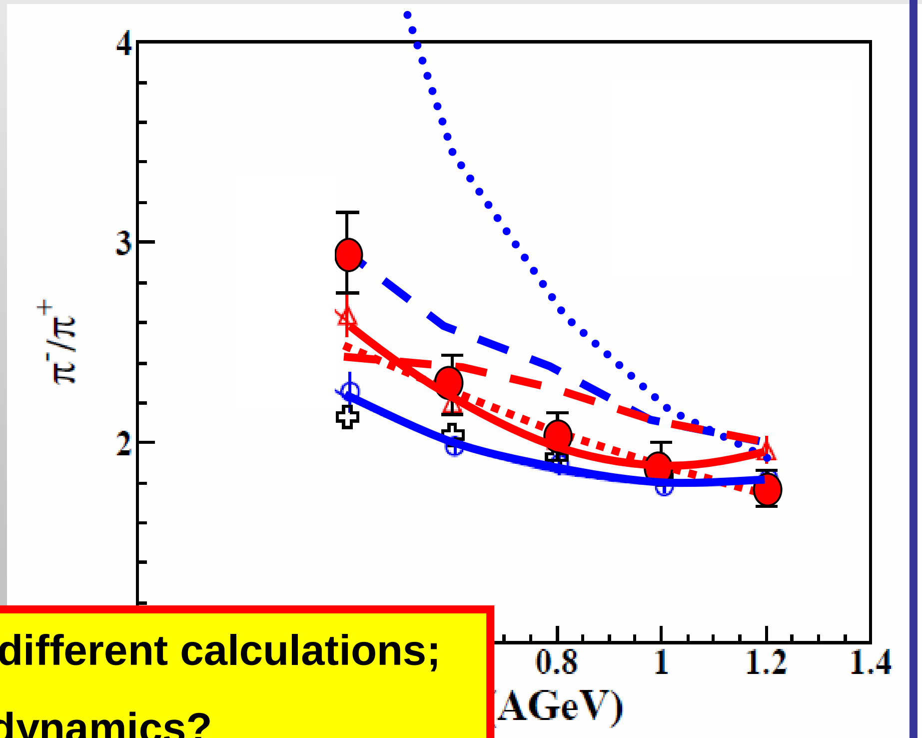
$$\frac{\pi^-}{\pi^+}\uparrow \textit{ increase with asy-stiffness}$$

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

Pion ratios in comparison to FOPI data (W.Reisdorf et al. NPA781 (2007) 459)

- MDI, x=0, mod. soft — Xiao,.. B.A.Li, PRL 102 (09)
- MDI, x=1, very soft — Xiao,.. B.A.Li, PRL 102 (09)
- NLδ, stiff — Ferini, Gaitanos,.. NPA 762 (05)
- NL, soft, no Esym — Ferini, Gaitanos,.. NPA 762 (05)
- γ=2, stiff — Feng,… PLB 683 (10)
- SIII, very soft — Feng,… PLB 683 (10)
- FOPI, exp

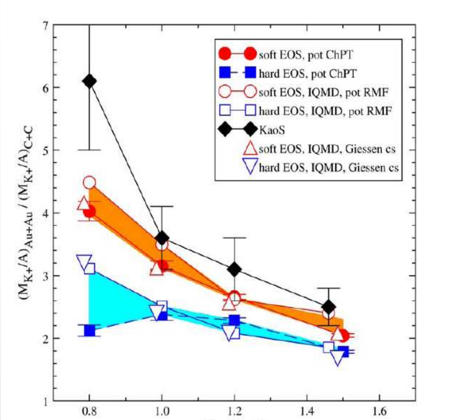




Contradictory results of different calculations;

Reason: Treatment of Δ dynamics?

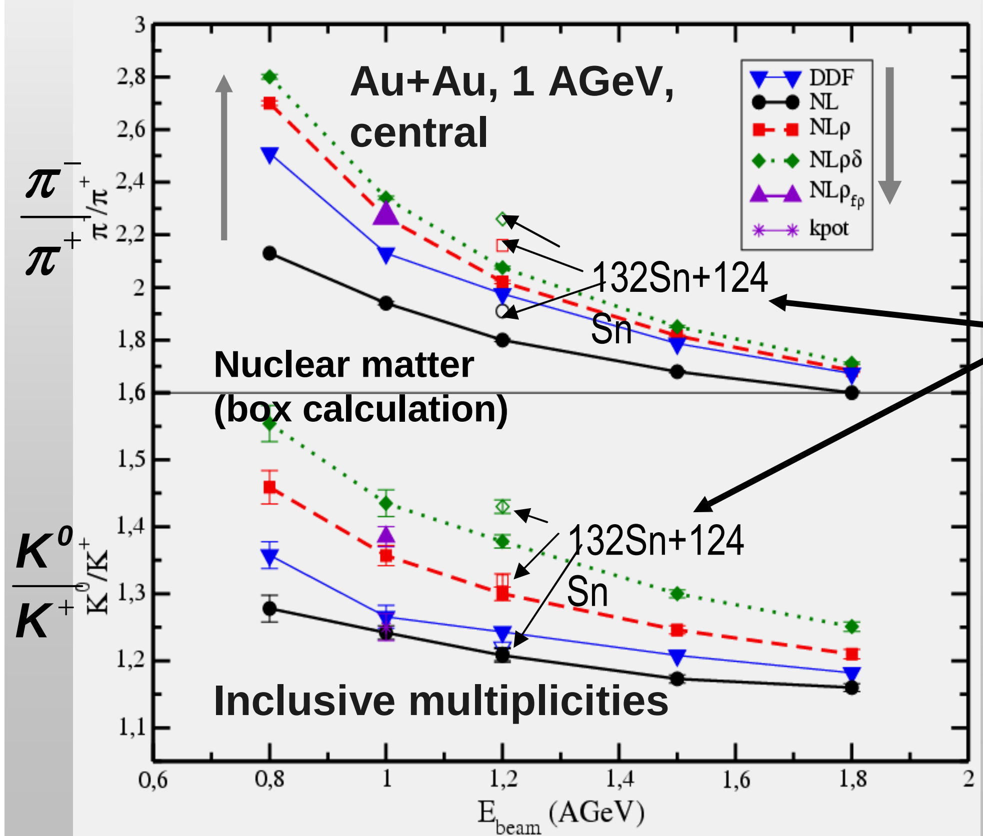
Kaons a good probe for the EOS – also for the Symmetry Energy?



Kaons are a <u>more sensitive and clean</u> probe of the high density EOS. Demonstrated by Fuchs, et al., PRL 86 (01), C.M. Ko & J. Aichelin, PRL55(85) for symmetric matter in comparison with KAOS data.

Kaons are closer to threshold, come only from high density, have large mean free path, small width:

Also a probe for the symmetry energy for ratio of different charge states, K^0/K^+?



From soft to stiff from lower to upper curves:
Stiffer asy-EOS→larger ratio!
Threshold dominates mean field effect; larger at lower energies

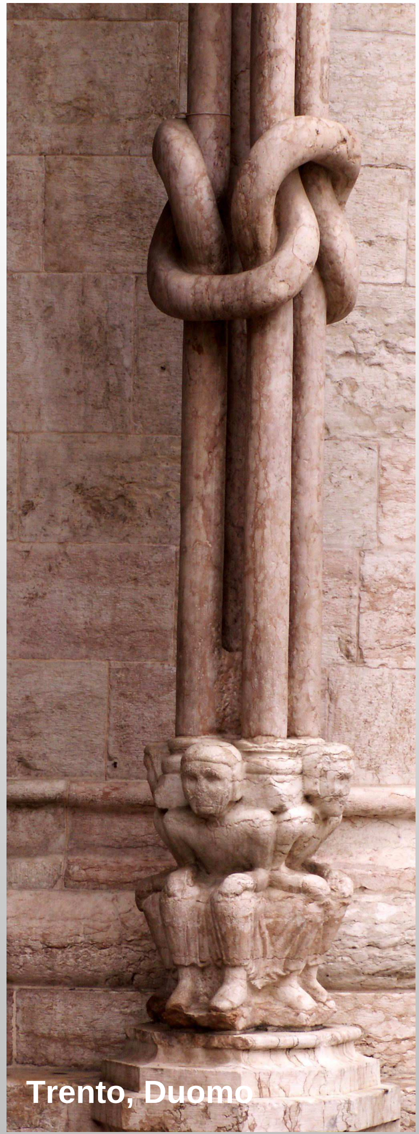
Effect reduced in finite nuclei (pre-equil emission reduces asymmetry)

Kaon ratio still a bit more sensitive probe:
~15% difference betw. very soft and stiff
→small but perhaps measurable!
→double ratio data by FOPI (Lopez, et al., PRC75 (07)

G.Ferini et al.,PRL 97 (2006) 202301, V. Prassa, et al., NPA 832 (2010)

Summary and Outlook:

- Investigated different probes for the Symmetry Energy in heavy ion collisions with transport theory at different energy (density) ranges
- Explore the sensitivity to the ingredients (asy-EOS, momentum dependence of SymEn, medium, esp. isospin dependence of cross sections)
- Still considerable differences between different codes. Continue code comparison initiative (?)
- Consistent description of many observables mandatory, also from structure and astrophysics
- Many knotty problems!



Thank you!