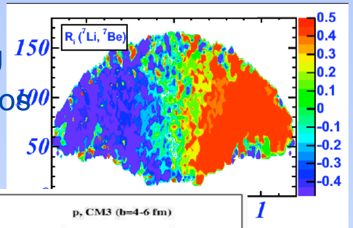
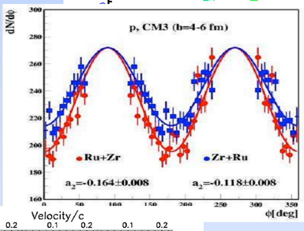
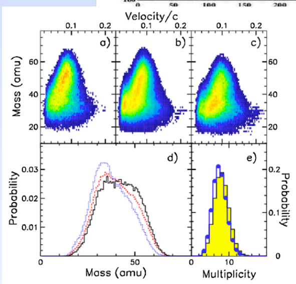
Constraining the Symmetry Energy

Lassa @ MSU
Imbalance ratios

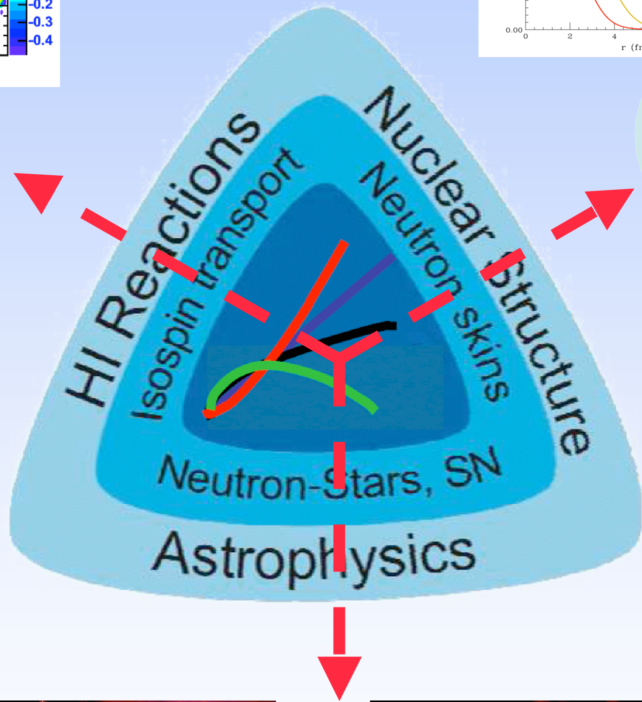


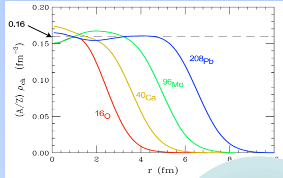
FOPI @ GSI
Elliptic flow

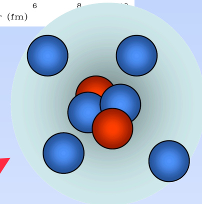


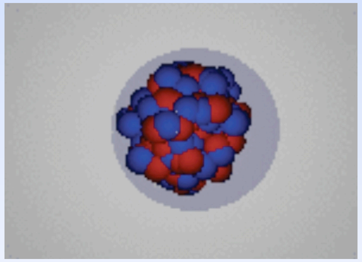


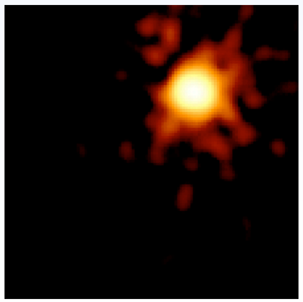
Chimera @ LNS
Competitiion Inc. Fusion / DIC









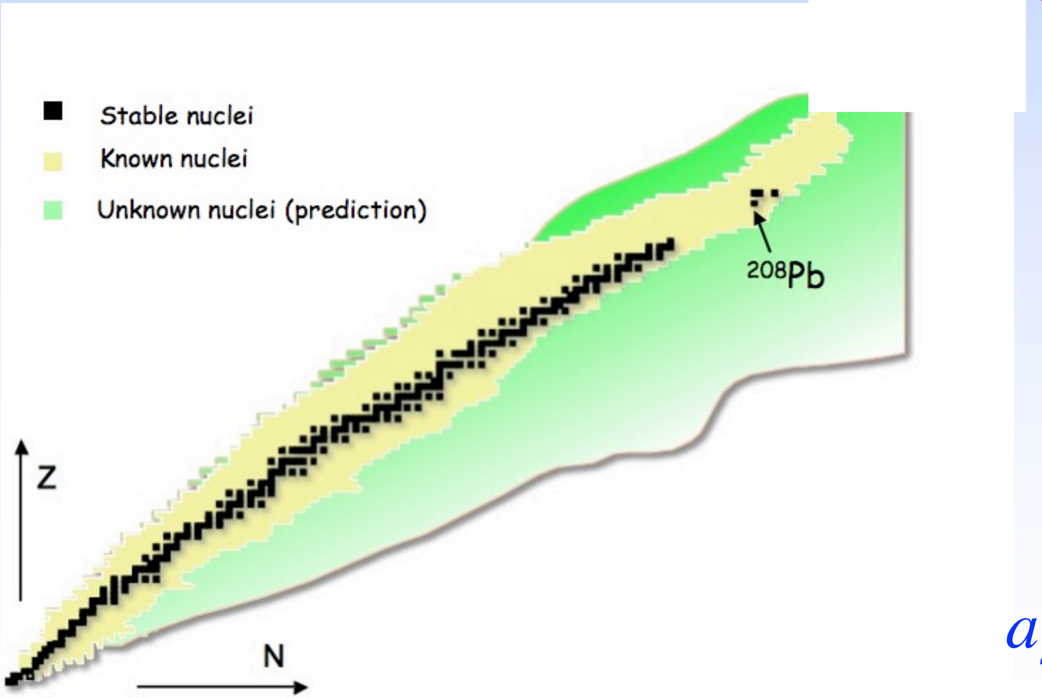


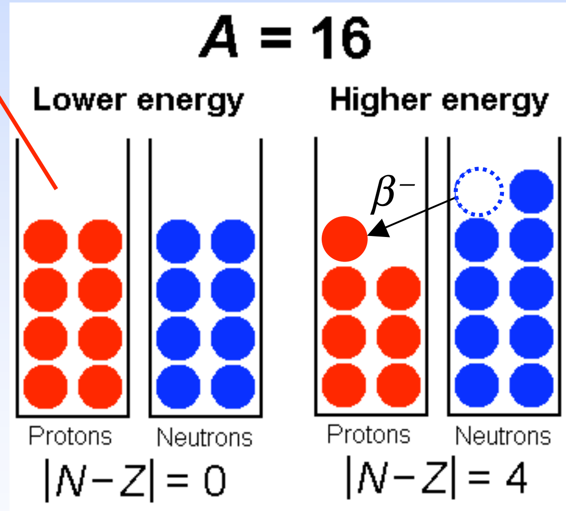
G. Verde
INFN, Italy

Symmetry energy in finite nuclei

Bethe-Weiszacker

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





$$a_{sym} = a_{sym}^{Volume} \cdot A - a_{sym}^{Surface} \cdot A^{2/3}$$

Systematics of $a_{sym}^{Surface}$ probes $E_{sym}(\rho)$

P. Danielewicz, Nucl. Phys. A727 (2003) 233

The EoS of asymmetric nuclear matter

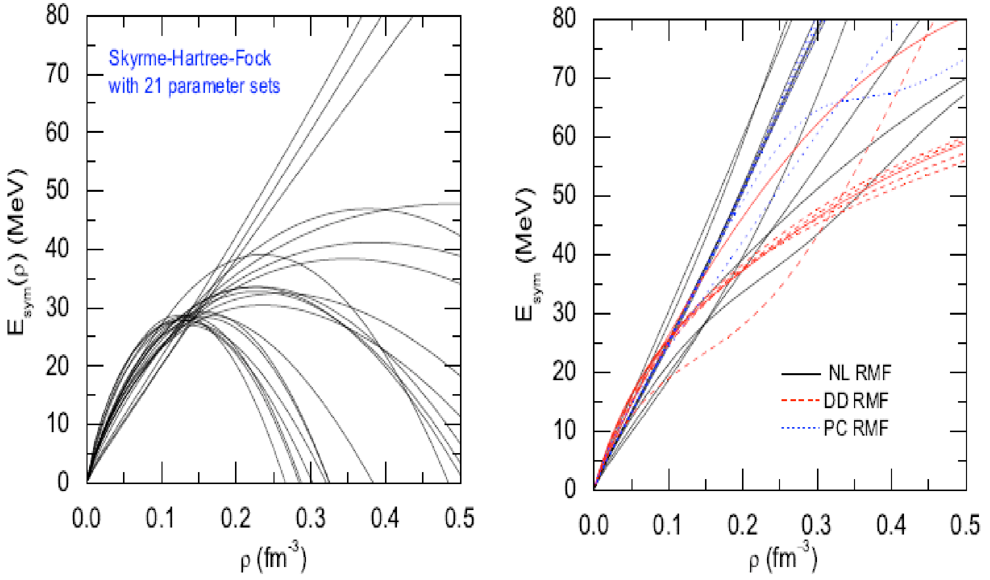
From finite nuclei…

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

… to infinte nuclear matter: how does E depend on density and δ?

$$E(\rho,\delta) = E\left(\rho,\delta=0\right) + \boxed{E_{sym}(\rho)} \cdot \delta^2 + O\left(\delta^4\right) \qquad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

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

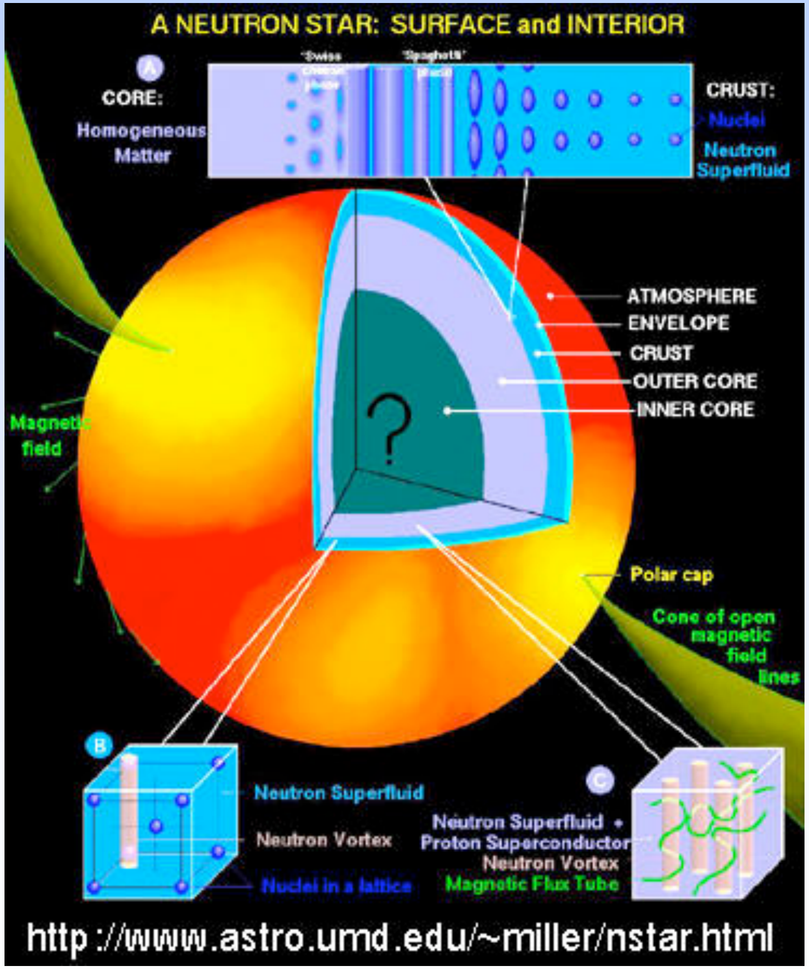


???

Many approaches… large uncertainties….

Microscopic many-body, phenomenological, variational, …

Neutron stars

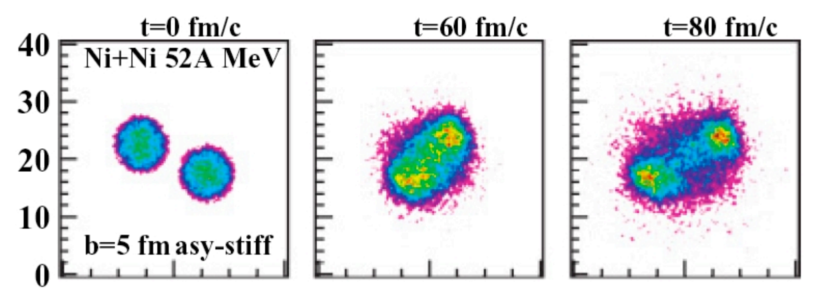


- Radii
- Frequencies of crustal vibrations
- Composition and thickness of inner crust
- URCA processes
- Phases within the star

Nusym10: Several talks to learn from

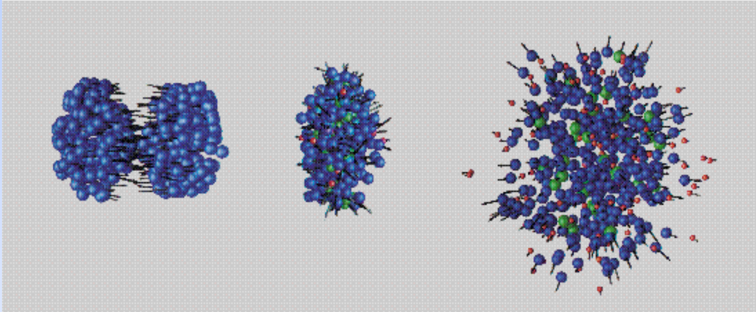
How to produce density gradients of asymmetric nuclear matter?

Intermediate energies: E/A=20-100 MeV



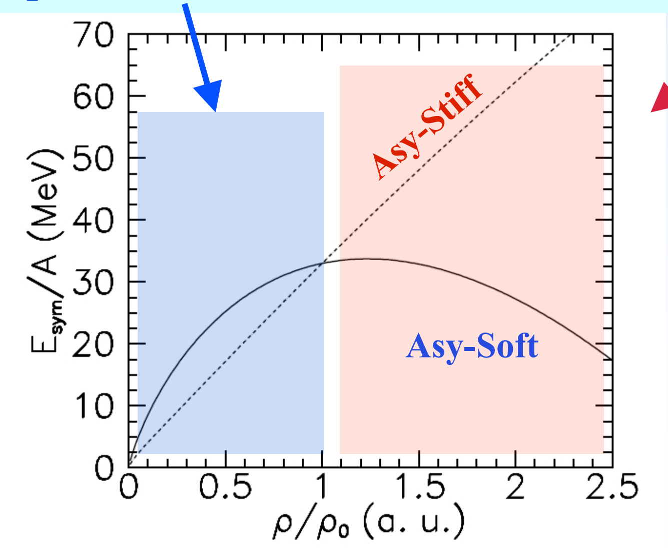
SMF - Baran, Colonna, Di Toro, Greco

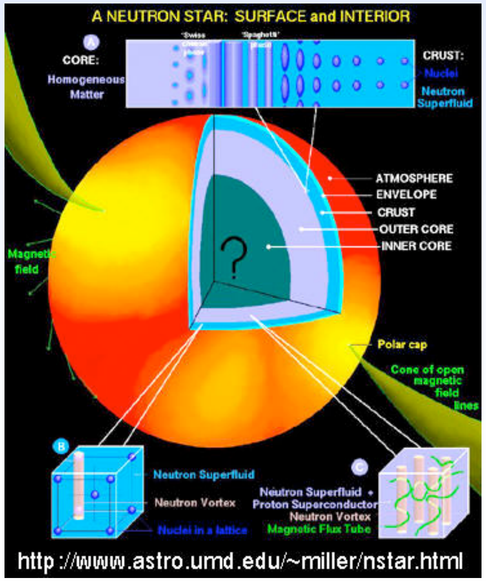
High energies: E/A>200 MeV



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

CSR, GSI/Fair, FRIB, Riken, …





Outline

- Probes at Intermediate energies: sub-saturation density Asy-EoS ($\rho<\rho_0$)
- Probes at high energies: supra-saturation density Asy-EoS ($\rho>\rho_0$)

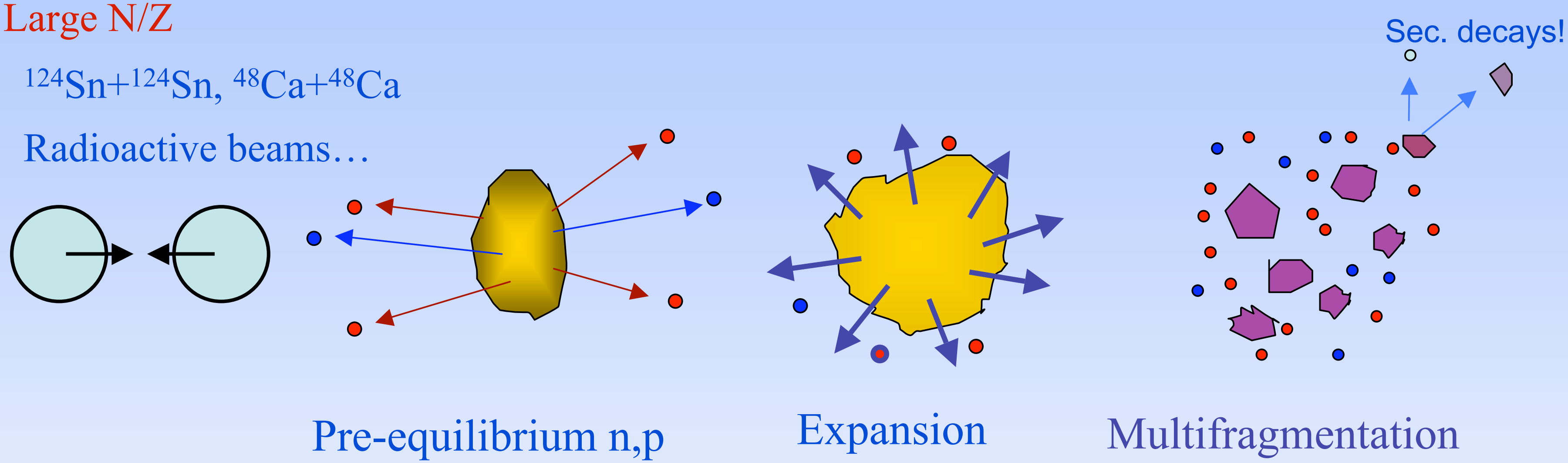
$\rho_0 \sim 0.17\ fm^{-3}$

Probes in HIC at intermediate energies

Large N/Z

$^{124}Sn+^{124}Sn$, $^{48}Ca+^{48}Ca$

Radioactive beams…



- Prompt dipole γ emission (Baran)
- n/p emissions (Famiano)
- Two-particle correlations (Chajecki)

- Collective flow (Yennello)
- Neck fragmentation

- Isospin fractionation
- Isoscaling (Kowalski, Trautmann)

Isospin transport: N/Z diffusion, migration, transparency (Lehaut)

Strategies

Measured observables

VS

Calculated observables in reaction models

INPUT: $V_{sym}(\rho)$ (asy-stiff, asy-soft), $V_{sym}(\rho,k)$

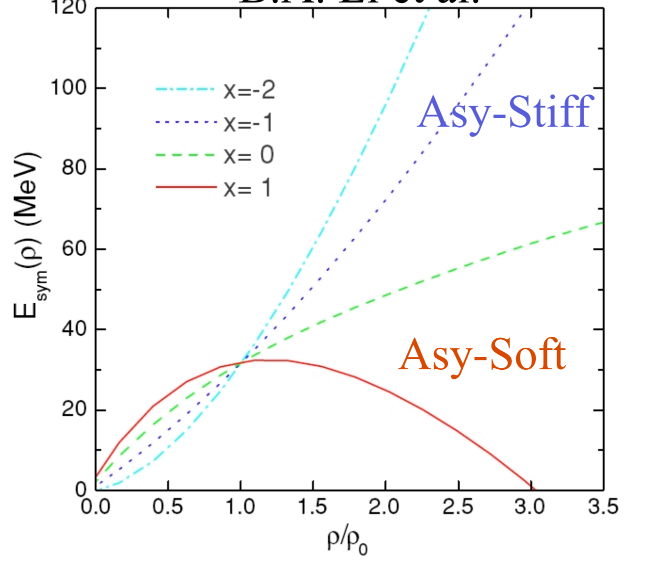
Nucleon-nucleon cross section: σ_{NN}

Comparisons provide constraints on $E_{sym}(\rho)$

Typical $E_{sym}(\rho)$ parameterizations

Symmetry potential is repulsive on neutrons and attractive on protons

B.A. Li et al.

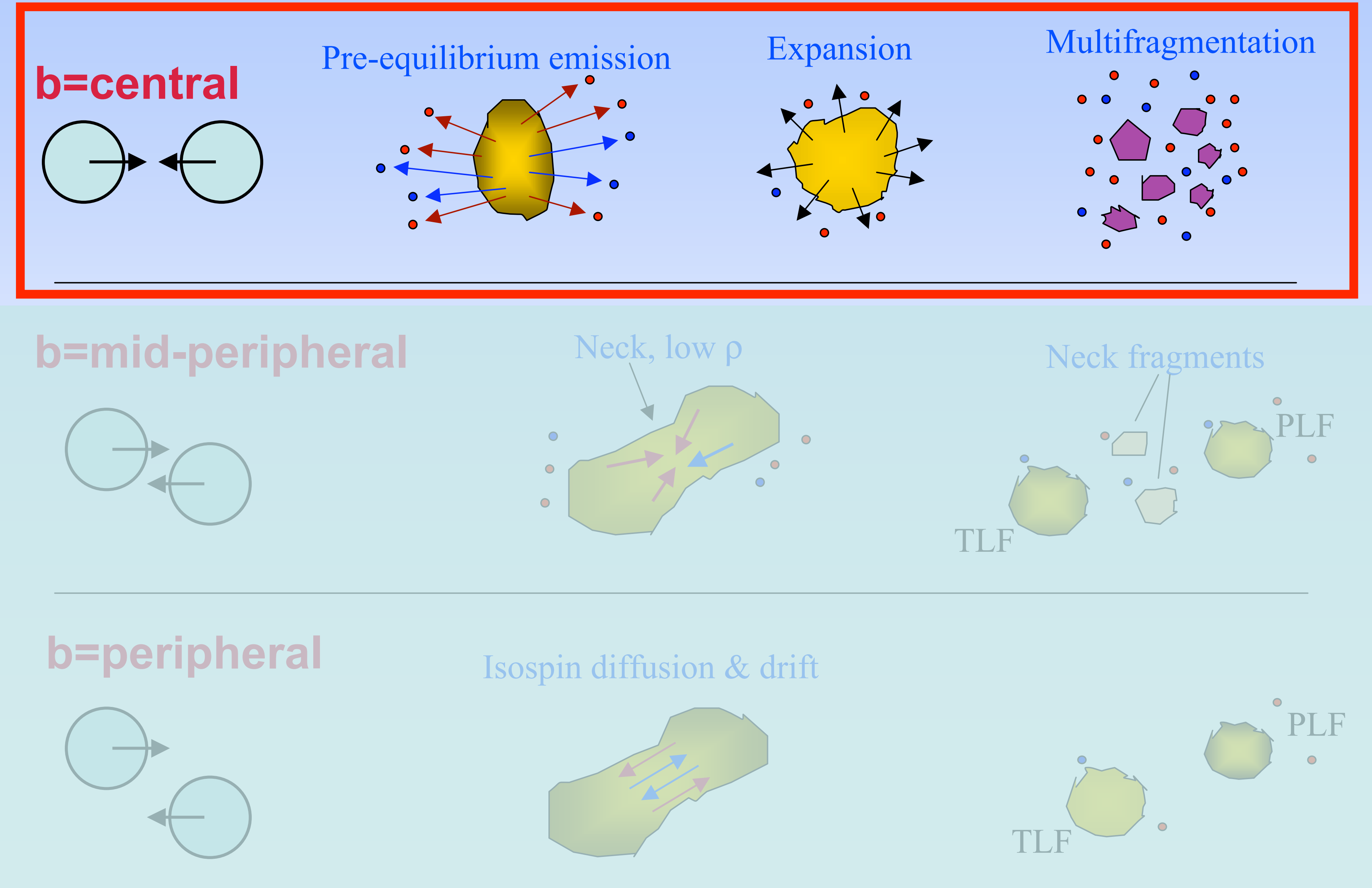


$$E_{sym}(\rho) = E_{sym}^{kin}(\rho) + E_{sym}^{pot}(\rho) = a \cdot \left(\frac{\rho}{\rho_0}\right)^{2/3} + b \cdot \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

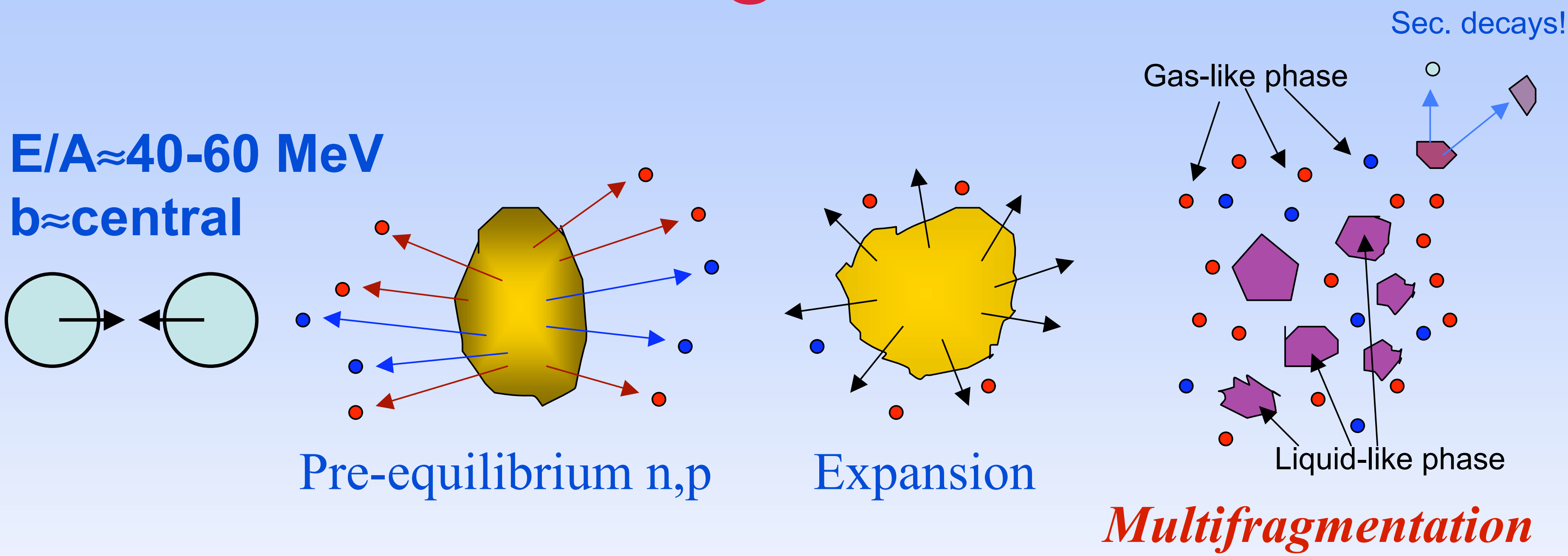
$\gamma=2$ ~ Super stiff

$\gamma=0.3$ ~ Super soft

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



Multifragmentation

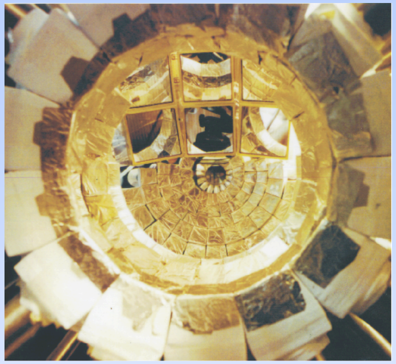


Isospin sensitive phenomena

- **Isoscaling**
- **Isospin fractionation**

Isotopic effects in multifragmentation

LASSA

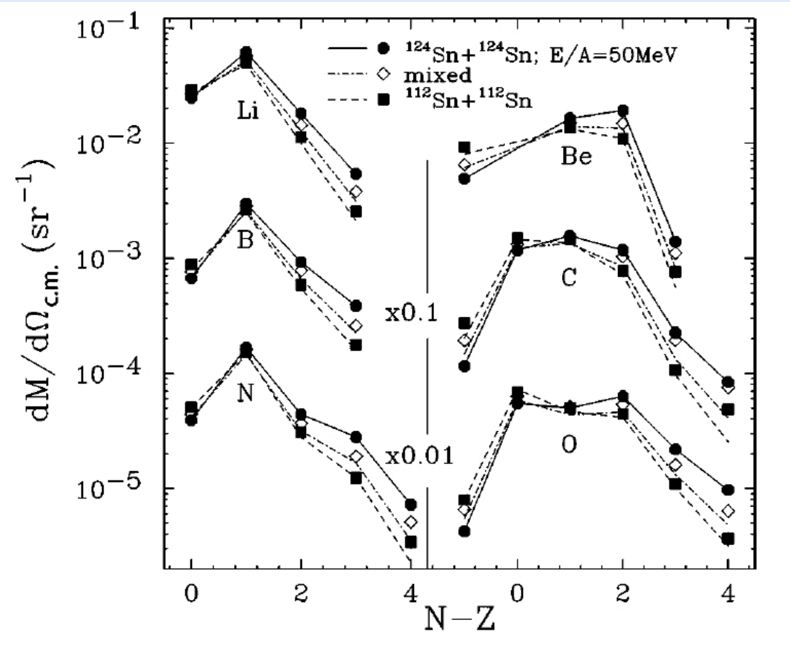


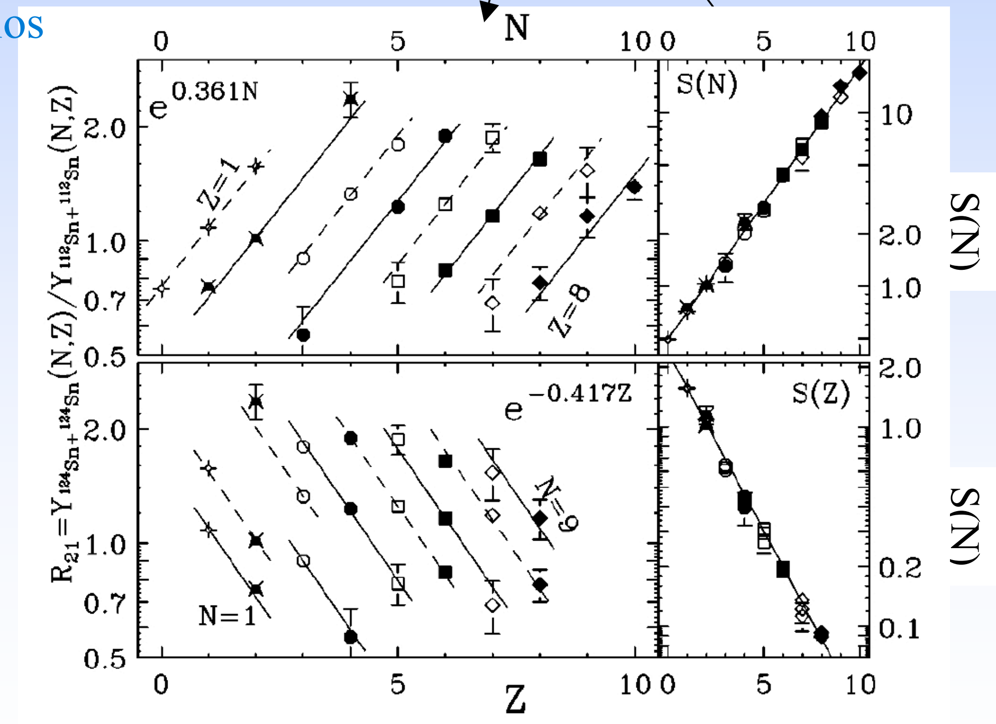
$^{112,124}Sn+^{112,124}Sn$ E/A=50 MeV Central

$$R_{12}(N,Z)=\frac{Y^{124+124}(N/Z)}{Y^{112+112}(N/Z)} \propto \exp(\alpha \cdot N+\beta \cdot Z)$$

Amplify isotopic effects with ratios

$$S(N)=R_{21}\cdot exp(-\beta Z)$$





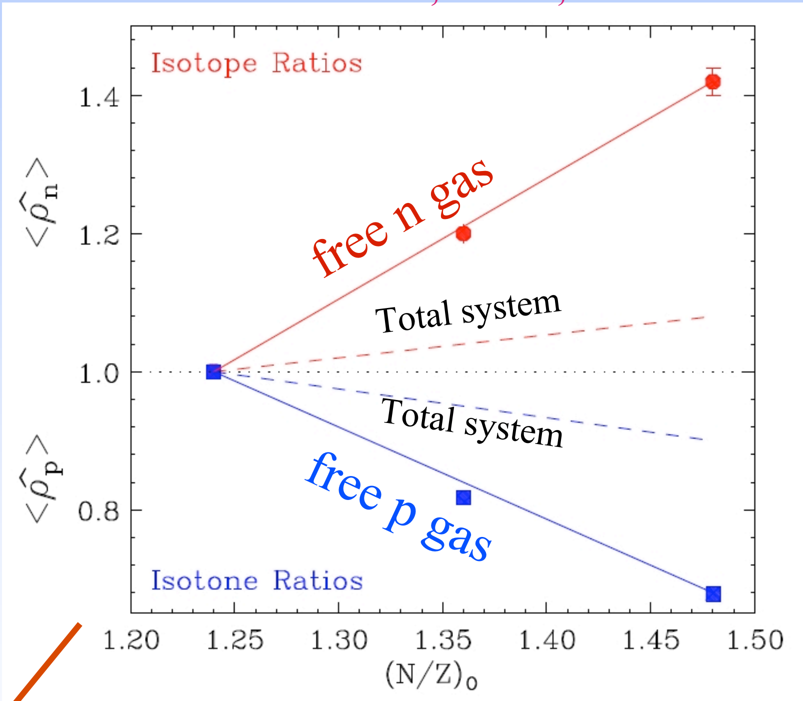
Isoscaling

Tsang et al, PRL86, 5023 (2001)

Isospin fractionation

$$R_{12}(N,Z) = \frac{Y^{124+124}(N/Z)}{Y^{112+112}(N/Z)} \propto \exp(\alpha \cdot N + \beta \cdot Z)$$

H. Xu et al., PRL75, 716



Grand-Canonical Ensamble

$$R_{21} \propto \exp\left[(\Delta\mu_n/T)\cdot N + (\Delta\mu_p/T)\cdot Z\right] \propto (\hat{\rho}_n)^N (\hat{\rho}_p)^Z$$

$$\alpha = \Delta\mu_n/T \qquad \beta = \Delta\mu_p/T$$

Densities of free neutrons and protons (gas)

$$\hat{\rho}_n = \left[\frac{\rho_{free,n}^{124+124}}{\rho_{free,n}^{112+112}}\right] \qquad \hat{\rho}_p = \left[\frac{\rho_{free,p}^{124+124}}{\rho_{free,p}^{112+112}}\right]$$

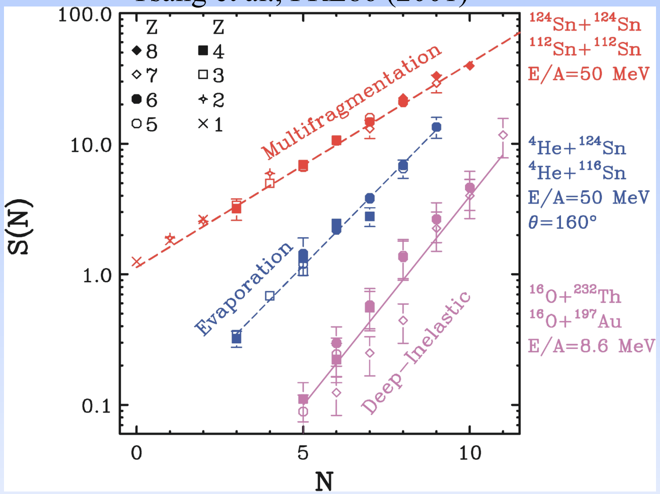
N/Z gas phase > N/Z liquid phase

Experimental signal of **isospin fractionation** in the coexistence region of asymmetric nuclear matter

Mueller & Serot, PRC52, 2072 (1995)

Isoscaling and the symmetry energy

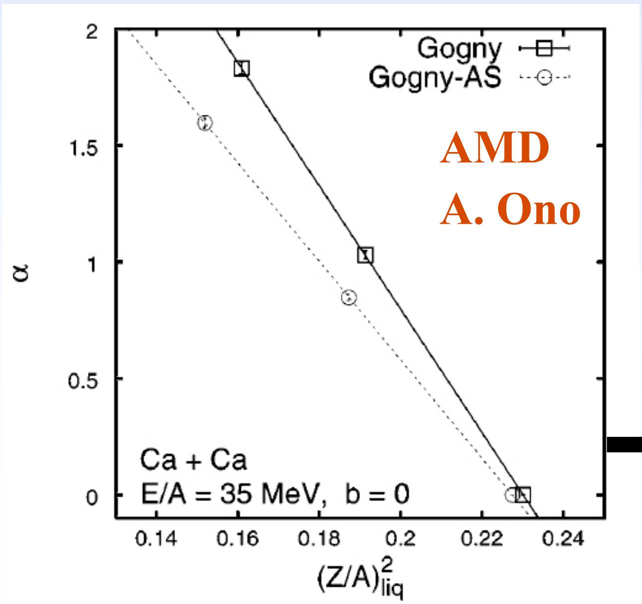
Tsang et al., PRL86 (2001)



$$R_{12}(N,Z) = \frac{Y^{124+124}(N/Z)}{Y^{112+112}(N/Z)} \propto \exp(\alpha \cdot N + \beta \cdot Z)$$

Link to symmetry energy and temperature

$$\alpha = \frac{4C_{sym}}{T} \cdot \left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2} \right)$$



Predicted in statistical and dynamical models

M.B. Tsang et al., PRC64, 054615 (**SMM**)

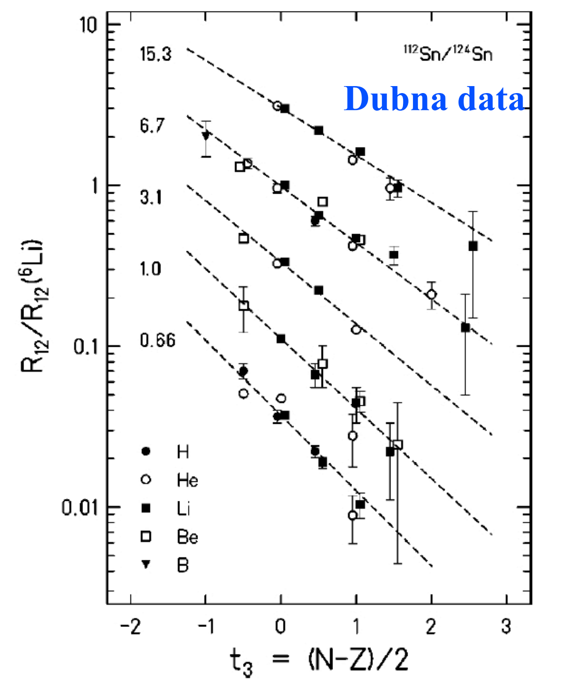
A. Ono, PRC68, 051601(R) (**AMD**)

→ Extract the symmetry energy C_{sym}

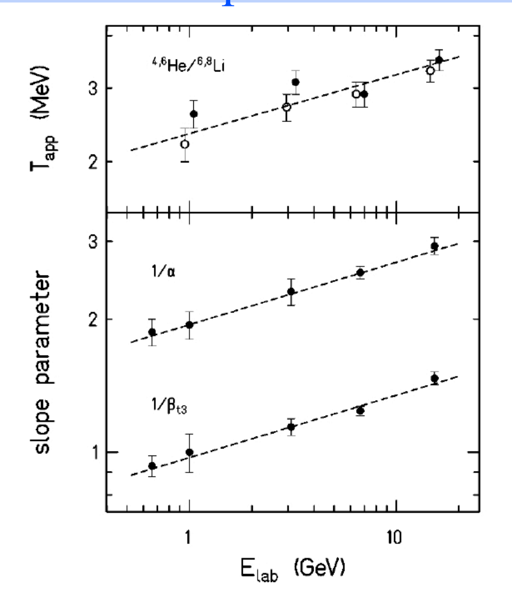
Isoscaling in LCP-induced reactions

A.S. Botvina et al., PRC65, 044619 (2002)

p,d,α+^{112,124}Sn   E=0.6-1.53 GeV



Temperatures



α-slope decreases with E_{lab}: temperature effect

Grand-canonical

$\alpha = \Delta\mu / T$

$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z_1}{A_1}\right)^2 - \left(\frac{Z_2}{A_2}\right)^2\right]$$

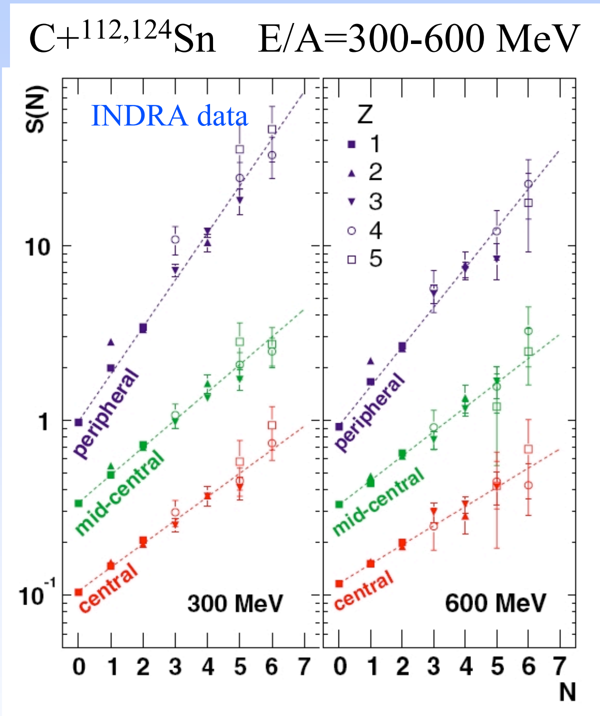
Symmetry energy in statistical models

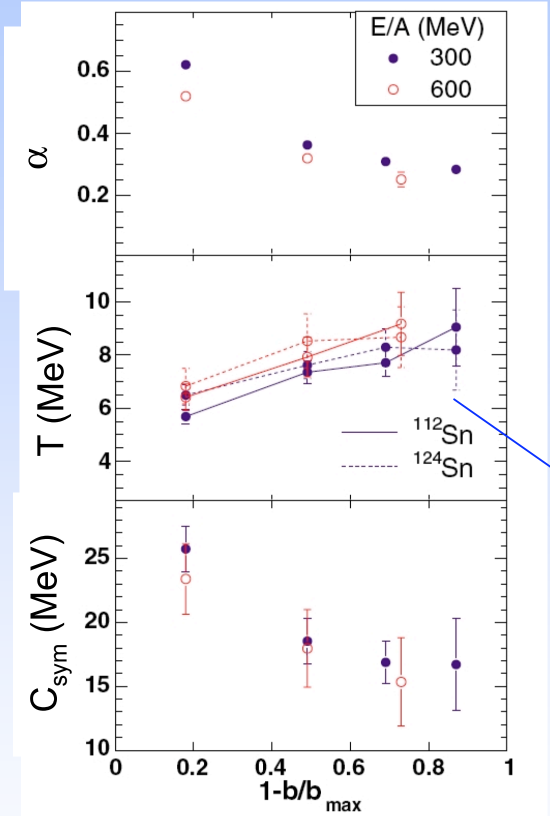
$$M(A,Z) \propto \exp\left(-\frac{F_{AZ}}{T}\right) \qquad E_{A,Z}^{sym} = C_{sym}\cdot(A-2Z)^2/A$$

Experimental data consistent with: C_{sym}~22.5 MeV

Isoscaling in spectator decay - Indra@GSI

A. Le Fevre et al., PRL94, 162701 (2005)





α-slope decreases with E_{lab}

$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z_1}{A_1}\right)^2 - \left(\frac{Z_2}{A_2}\right)^2\right]$$

Slow increase of T cannot explain decreasing α

- Symmetry energy decreases up to C_{sym}<15 MeV…
- Chemical freeze-out in expanded source (low ρ)

$E_{sym}(\rho)$ and clustering at very low densities

^{64}Zn+^{92}Mo,^{197}Au E/A=35 MeV

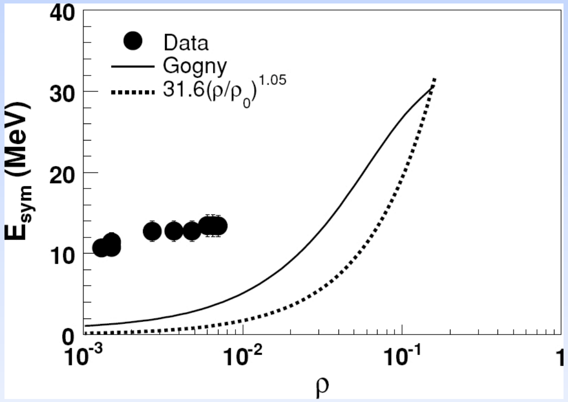
Velocity gated isoscaling analysis

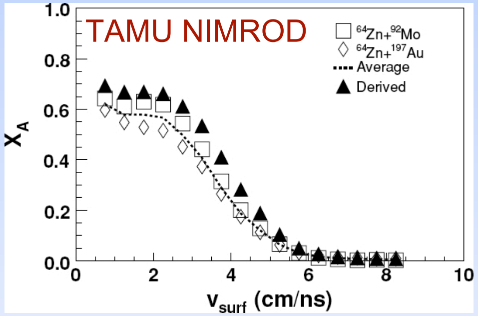
$$\alpha = \frac{4F_{sym}}{T}\left[\left(\frac{Z_1}{A_1}\right)^2 - \left(\frac{Z_2}{A_2}\right)^2\right]$$

High v ==> high ρ

Low v ==> low ρ

S. Kowalski et al., PRC75, 014601 (2007)





Strong α-clustering at low density observed

$E_{sym}(\rho)$ at $\rho < 0.05\text{-}0.01\rho_0$ higher than mean-field model expectations (talk by W. Kowalski)

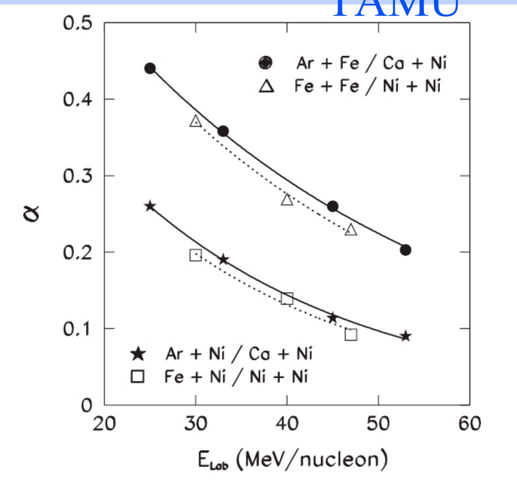
Include clustering at low ρ in EoS models

Horowitz et al.

Isoscaling and C_{sym} at Fermi energies

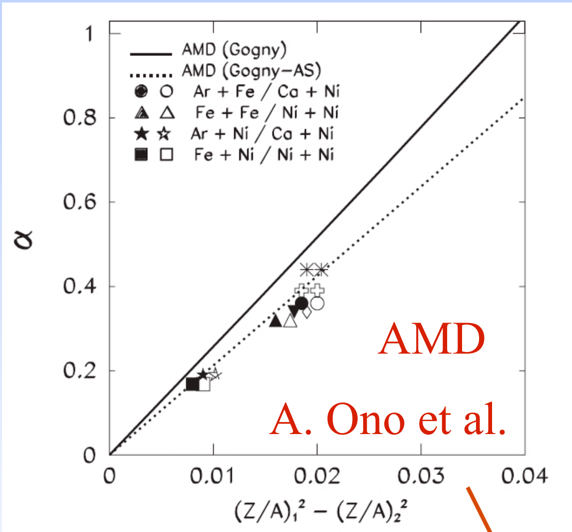
^{40}Ar,^{40}Ca,^{58}Ni,^{58}Fe+^{58}Ni,^{58}Fe
E/A=25-53 MeV

TAMU

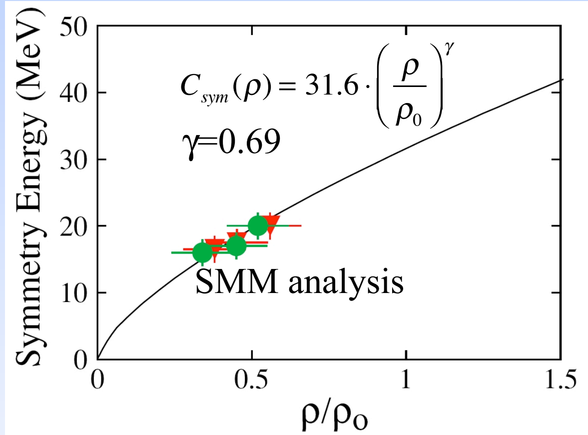


$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z_1}{A_1}\right)^2 - \left(\frac{Z_2}{A_2}\right)^2\right]$$

AMD simulations - A. Ono et al., PRC68, 051601 (R) (2003)



D. Shetty et al. PRC76, 024606 (Yennello's group @ TAMU)

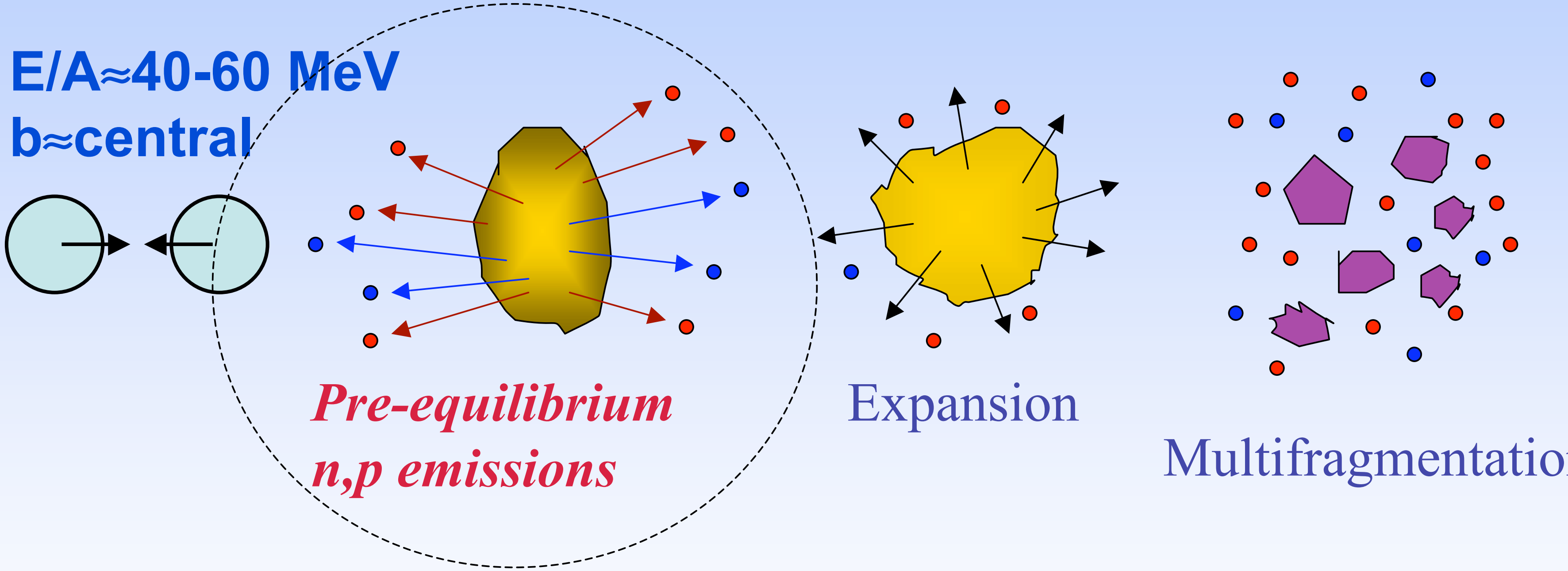


Consistent picture dynamical and statistical analysis

- α-slope decreases with E_{lab}: temperature only cannot explain

Expansion ==> Decreasing C_{sym} at lower ρ

$E_{sym}(\rho)$ from pre-equilibrium nucleons

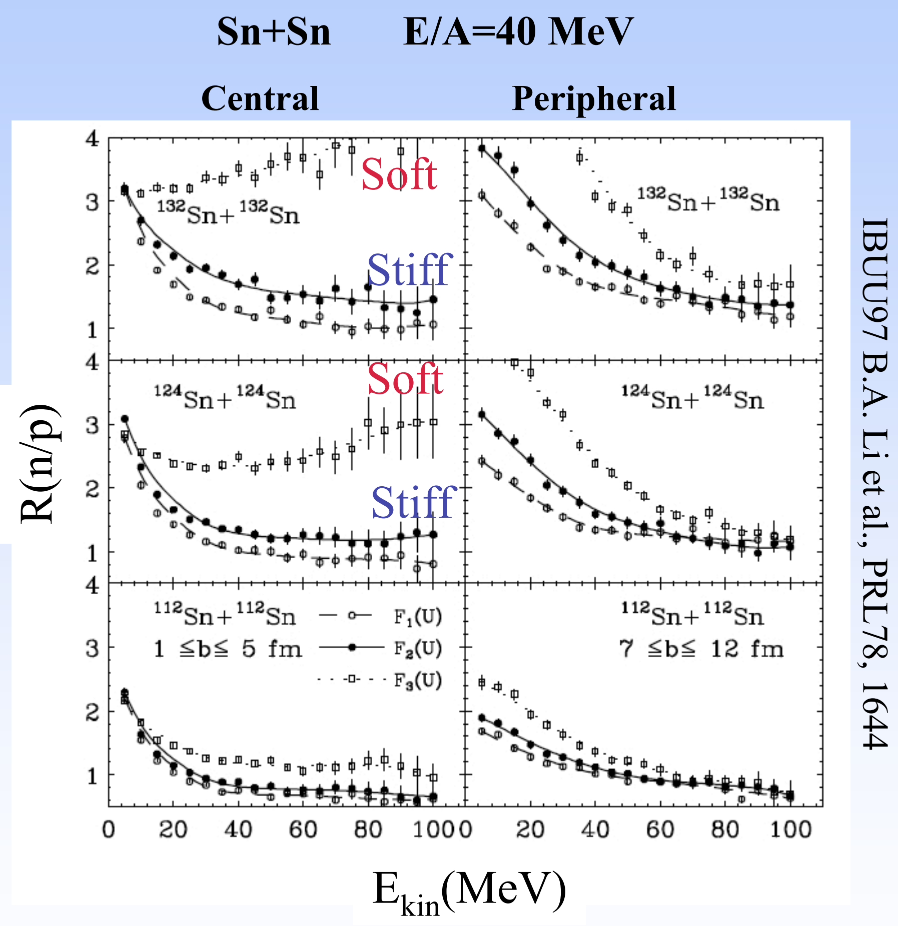


- Neutron/proton ratios and double ratios
- Two-nucleon correlation functions (HBT)

Neutron/Proton yield ratios

$$R(n/p) = \frac{Y_n(E_{kin})}{Y_p(E_{kin})}$$

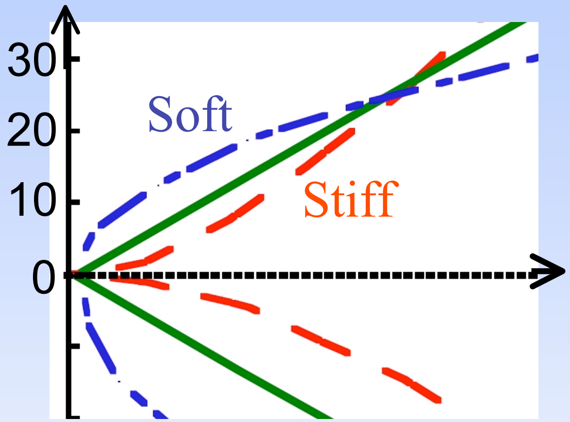
- R(n/p) sensitive to $E_{sym}(\rho)$
- Soft E_{sym} emits more neutrons at high E_{kin}



IBUU97, no mom-dependent interaction

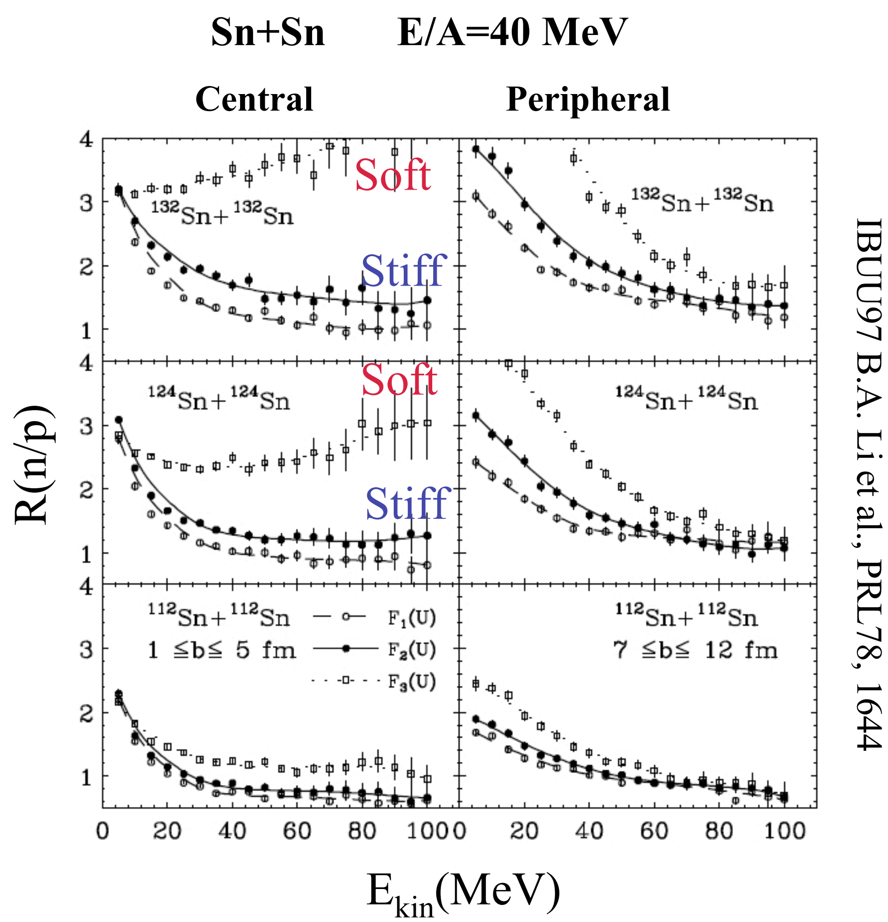
Pre-equilibrium n/p and $E_{sym}(\rho)$

Sub-saturation density



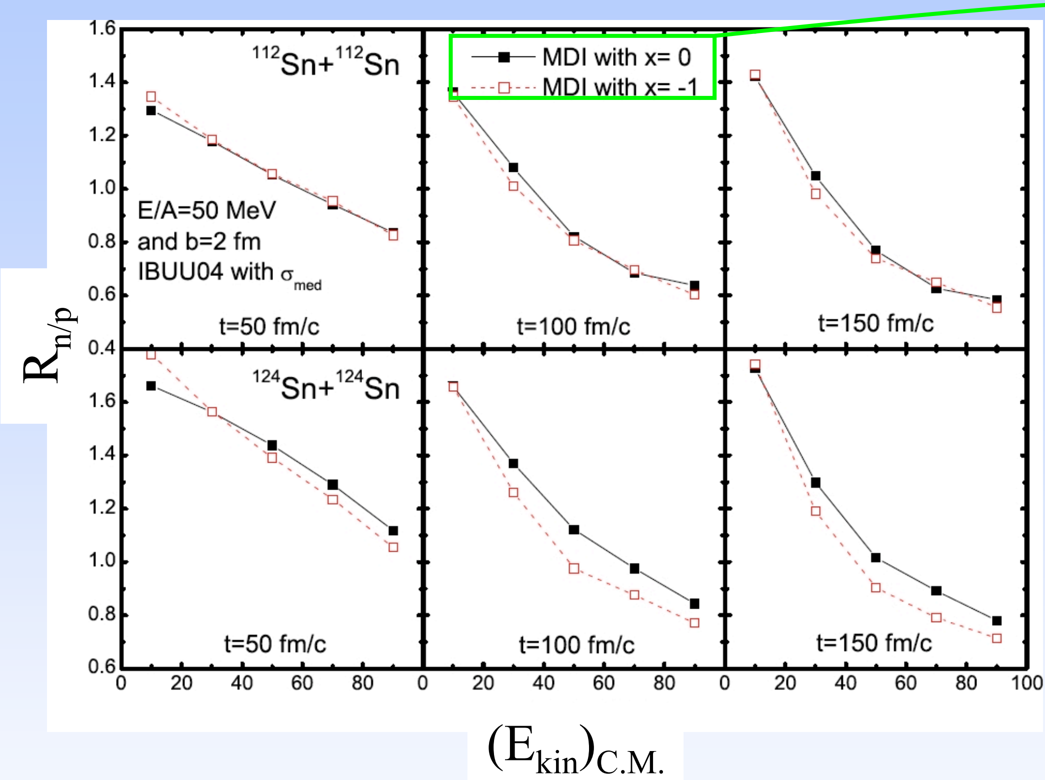
- V_{asy}(Soft) > V_{asy}(Stiff)
  more repulsion with V_{asy}(Soft)

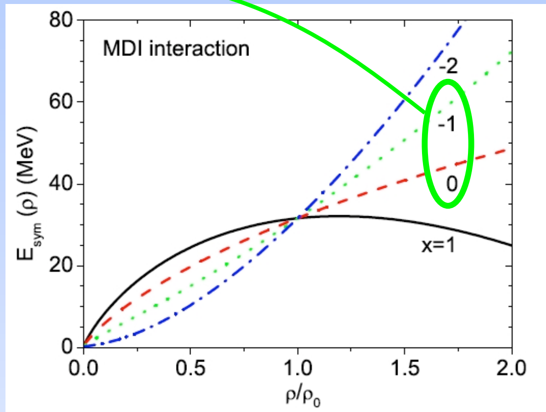
  Larger effects on n/p ratios



IBUU97, no mom-dependent interaction

IBUU04 predictions on R(n/p) - MDI+$\sigma_{NN,med}$





MDI: V_{asy} decreases at high k ==>*smaller isospin effects (10-15%)*

- Momentum dependent interaction important

Small effects need to be isolated!!

Double n/p ratios: advantages

Enhance effects due to symmetry energy only

^{124}Sn+^{124}Sn

^{112}Sn+^{112}Sn

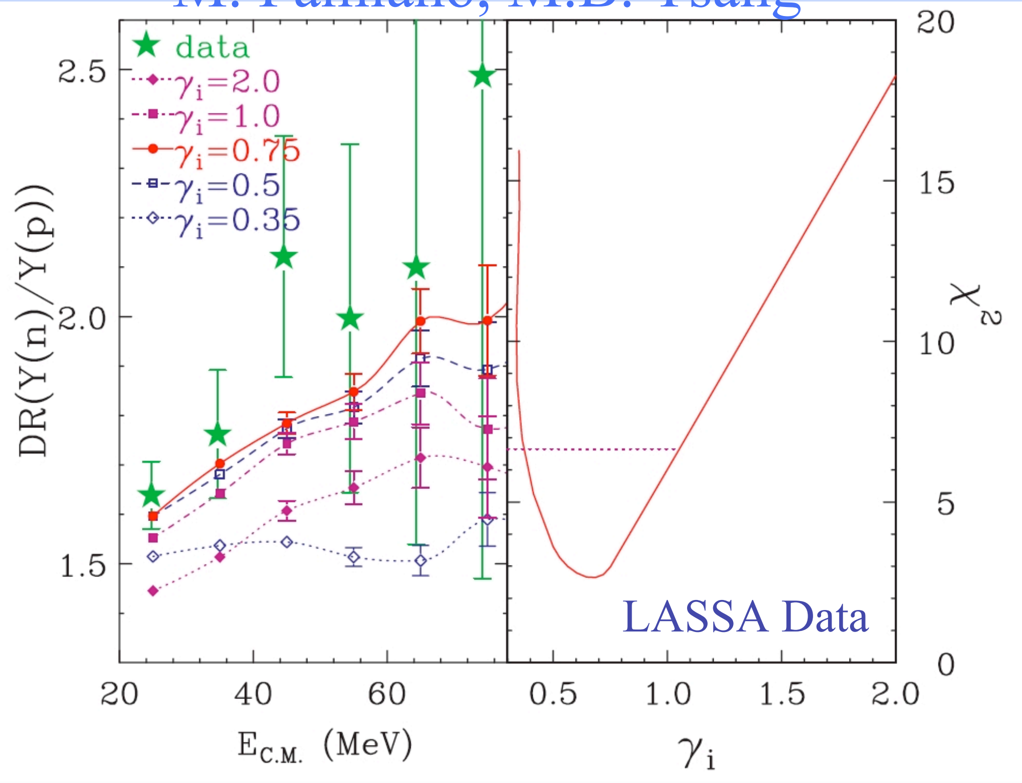
$$DR(n/p) = \frac{\left[Y(n)/Y(p)\right]^{124+124}}{\left[Y(n)/Y(p)\right]^{112+112}}$$

Remove secondary non-E_{sym} effects (Coulomb, secondary decays, detection efficiency problems, …)

Neutron/proton ratios and $E_{sym}(\rho)$

$^{112,124}Sn+^{112,124}Sn$ E/A=50 MeV

M. Famiano, M.B. Tsang



Comparisons to ImQMD

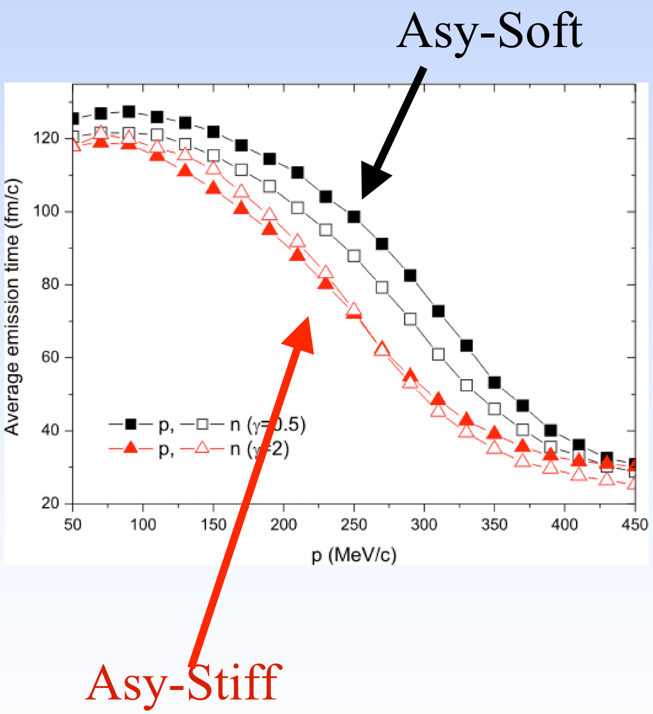
$$E_{sym}(\rho) = \frac{Cs,k}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{Cs,p}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

χ^2 analysis provides $\gamma \approx 0.7$

M.B. Tsang et al., PRL102, 122701 (2009)

pp, nn, np correlation functions

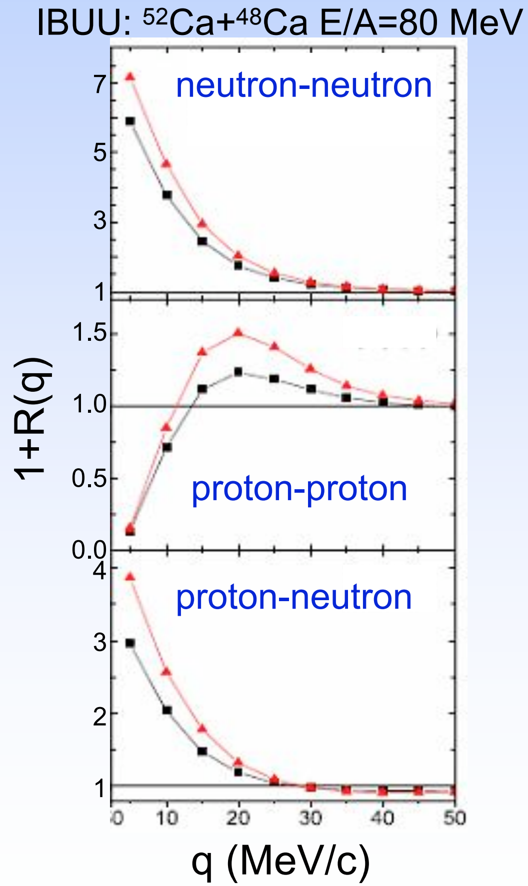
Emmission times of
neutrons and protons



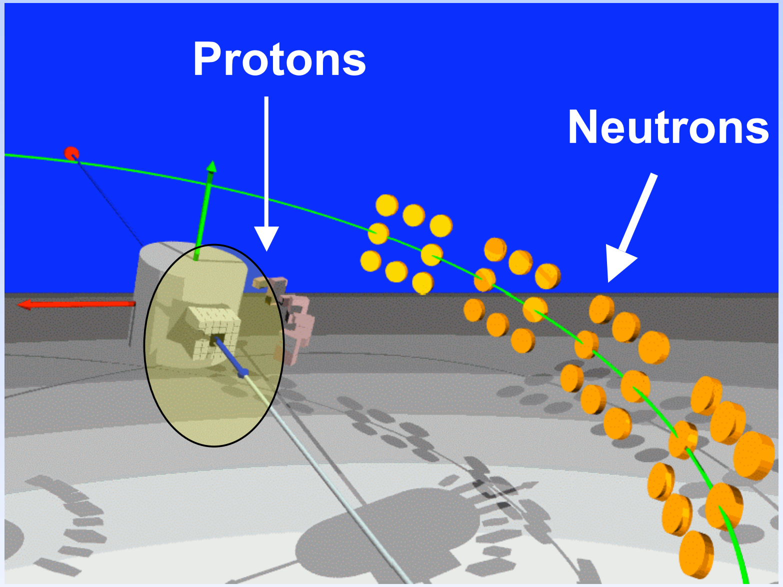
Lie-Wen Chen et al., PRL (2003), PRC(2005)

Talk by Z. Chajecki, Poster by M. Kilburn

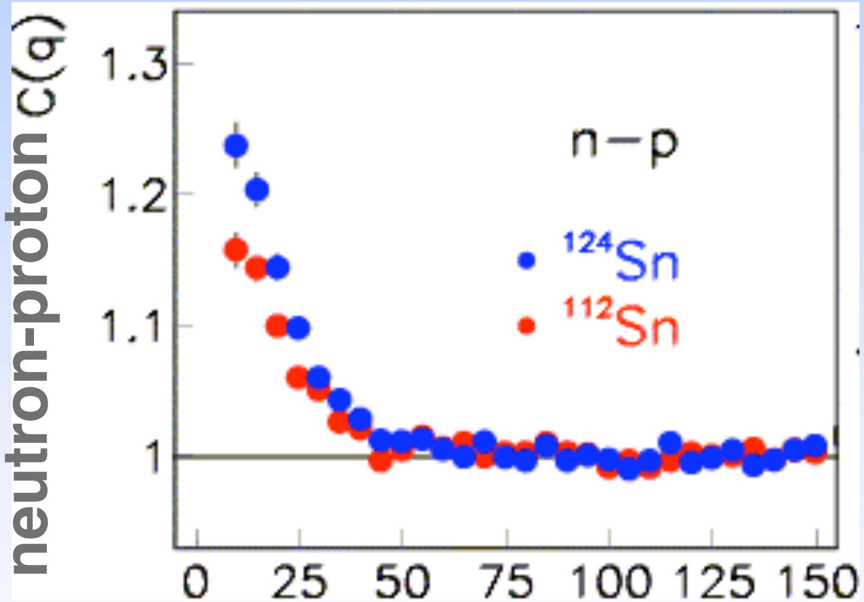
Correlation functions



Neutron-proton correlation functions



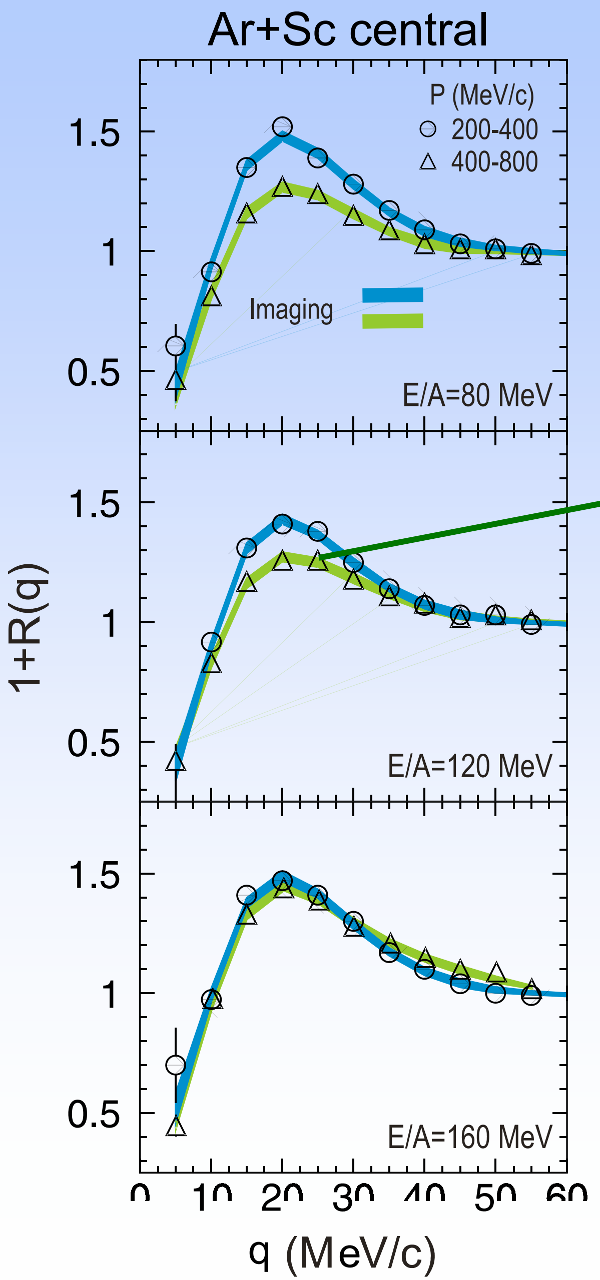
Ghetti *et al,* PRC 69 (2004) 031605



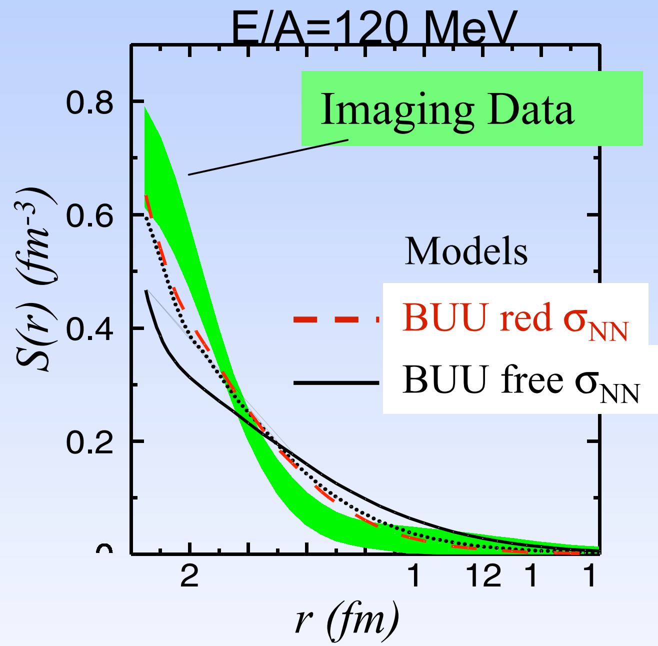
Emission chronology sensitive to Asy-EOS

Difficult experiments!!!

Imaging and transport



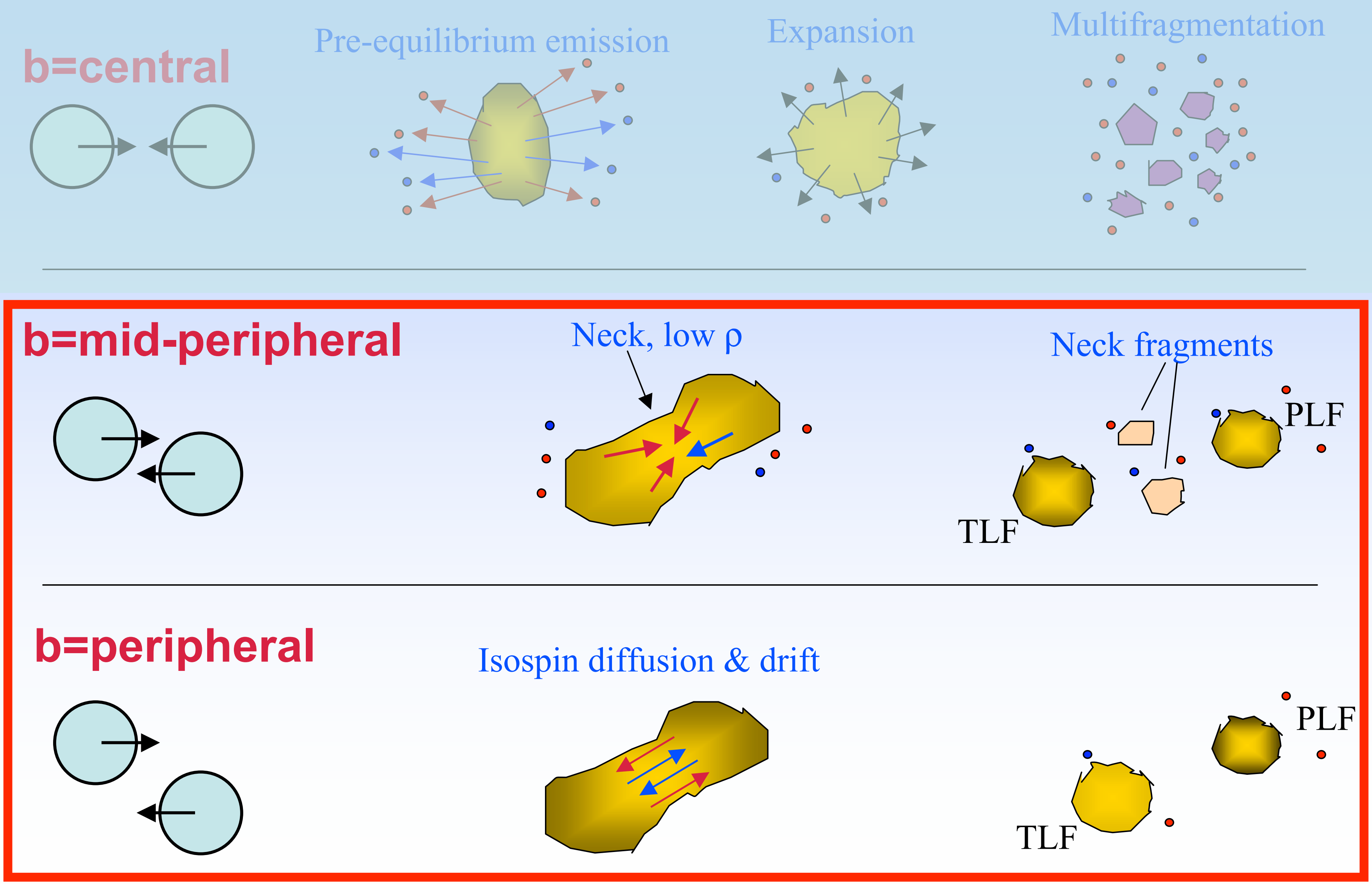
G. Verde et al., Phys. Rev. C67, 034606 (2003)



Imaged *S(r) vs BUU S(r)*

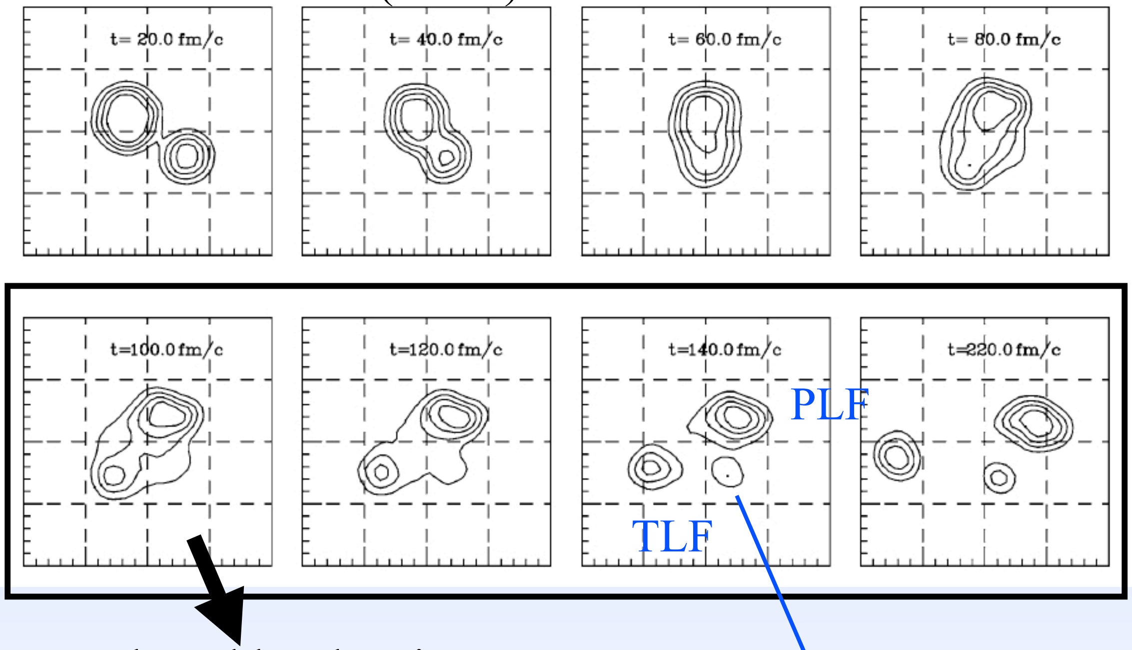
Two-nucleon correlation functions as a probe of in-medium isospin dependent σ_{NN}????

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

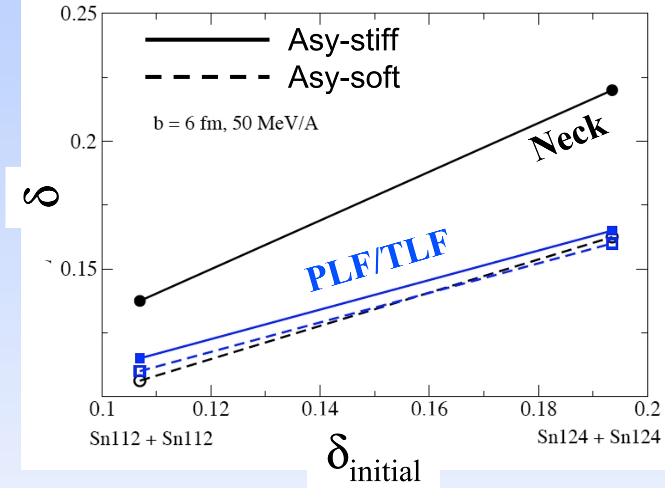


Neck emision and isospin drift

BNV simulations (Baran)

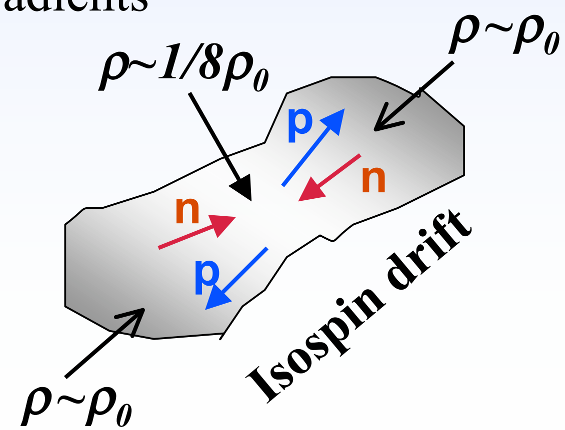


n-enrichment in the neck



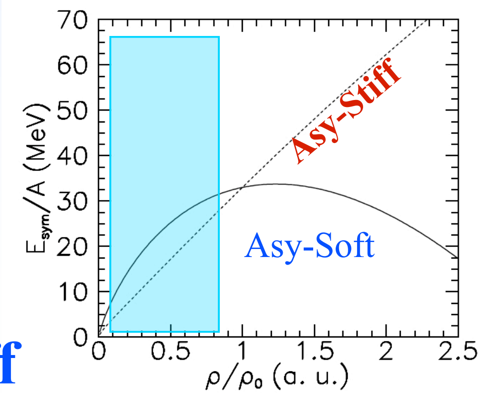
Induced by density gradients

Neck fragments neutron rich



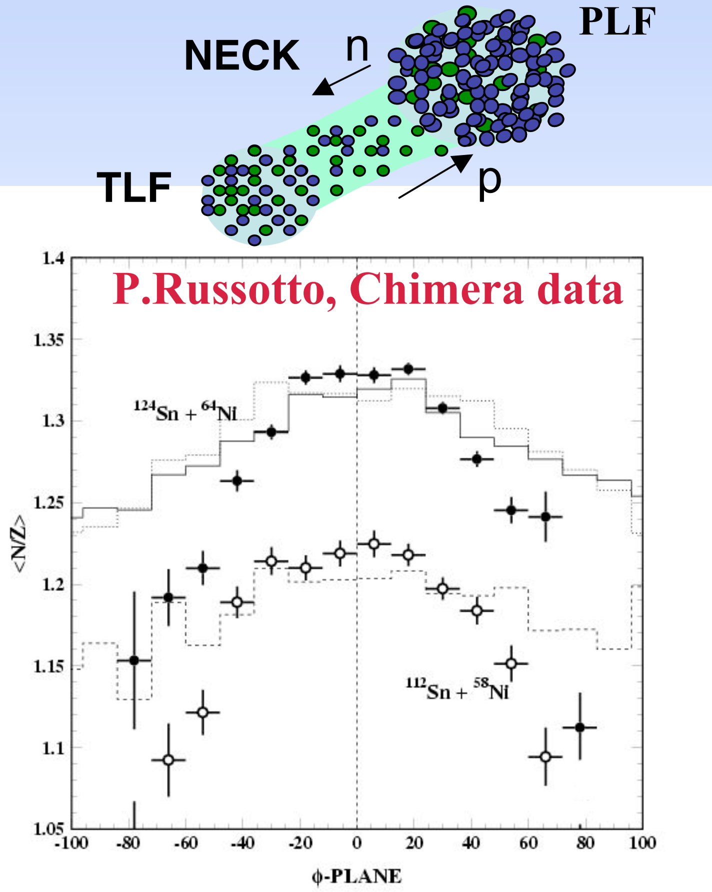
Drift $\propto \dfrac{\partial E_{sym}}{\partial \rho}$

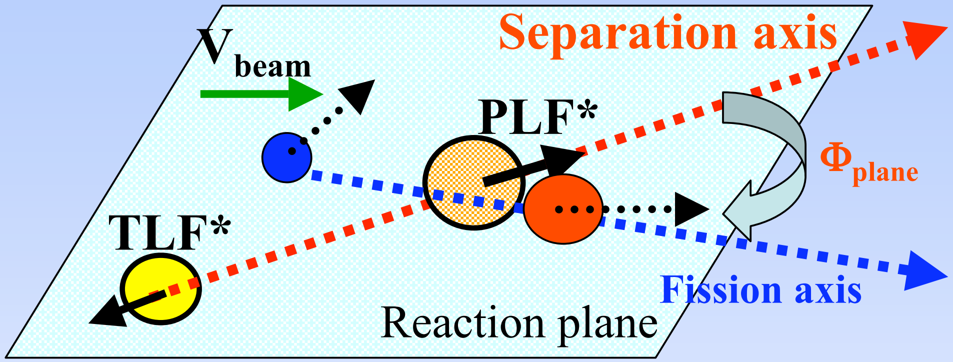
More drift with Asy-Stiff

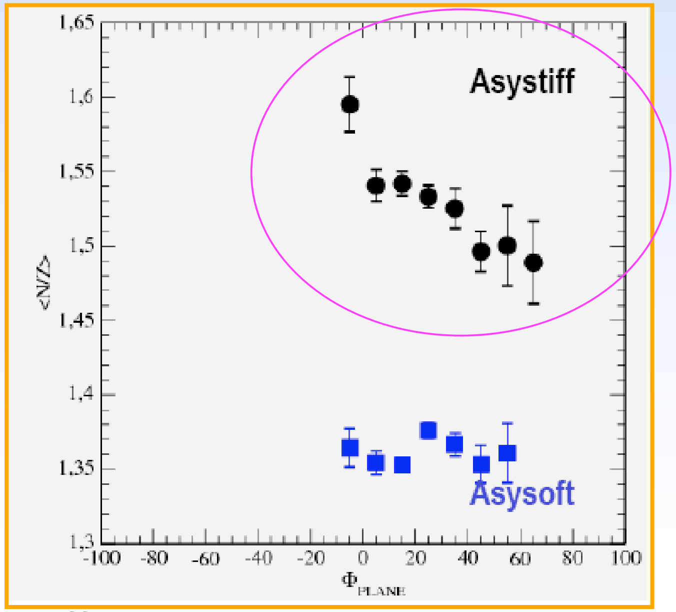


Neck alignment vs N/Z properties

$^{124}Sn+^{64}Ni$ E/A=35 MeV

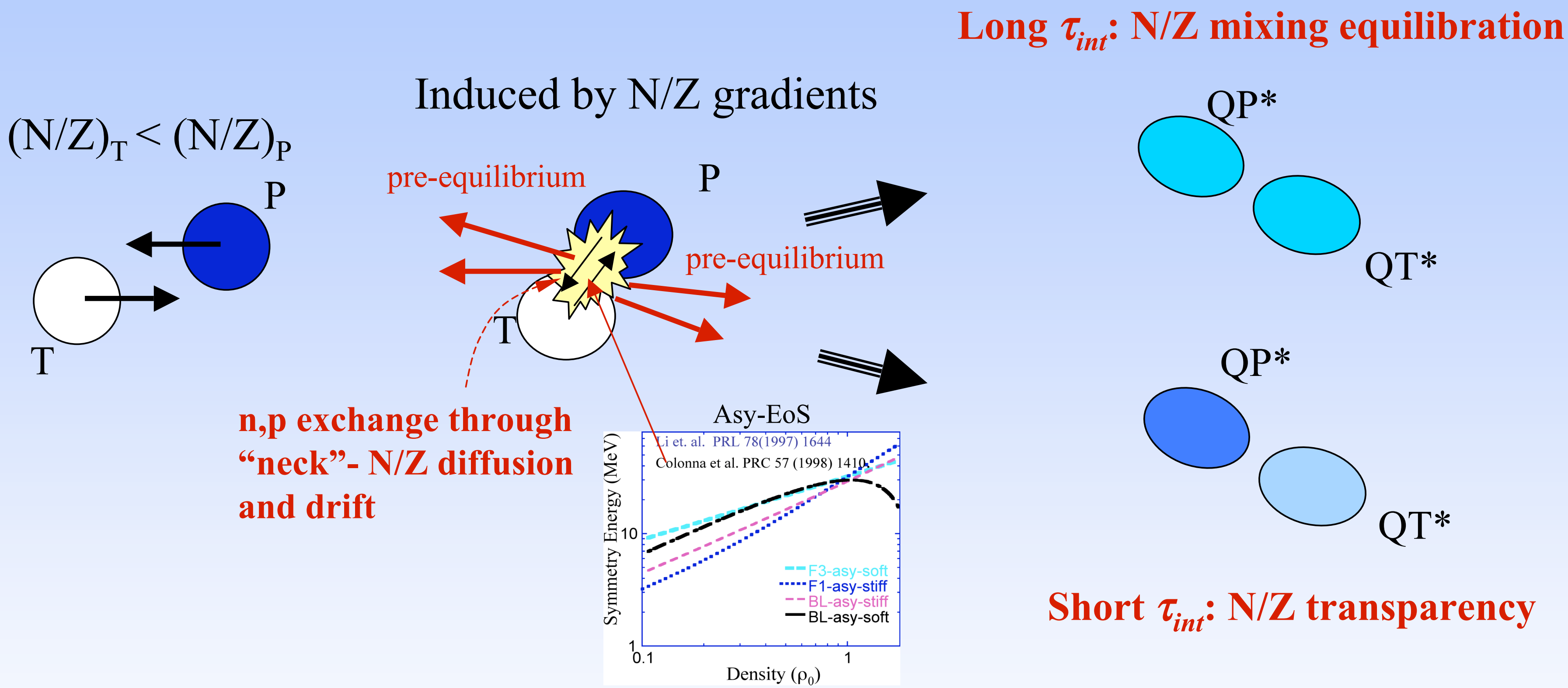






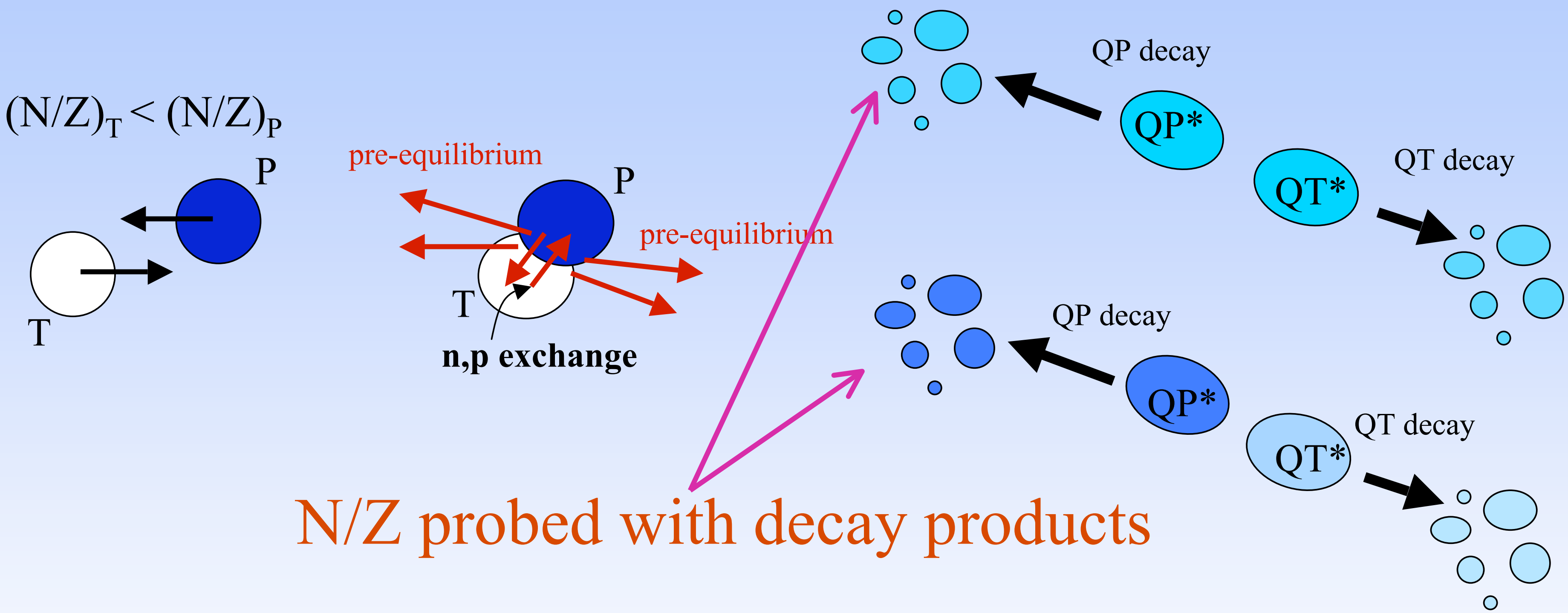
Asystiff: more isospin migration to the "neck" fragments (BNV simulations)

Isospin diffusion



- *Interaction time* τ_{int} determined by **beam energy** and **impact parameter**

Experimental Probes of isospin diffusion



N/Z probed with decay products

Need to measure observables $X \propto \delta^* = (N-Z)/(N+Z)$

- X = Reconstructed $(N/Z)_{QP}$ — Indra @ GANIL
- X = α-slope from isoscaling — Lassa @ MSU
- X = $Y(^7Li)/Y(^7Be)$ — Lassa @ MSU

Isospin diffusion/equilibration: Indra Data

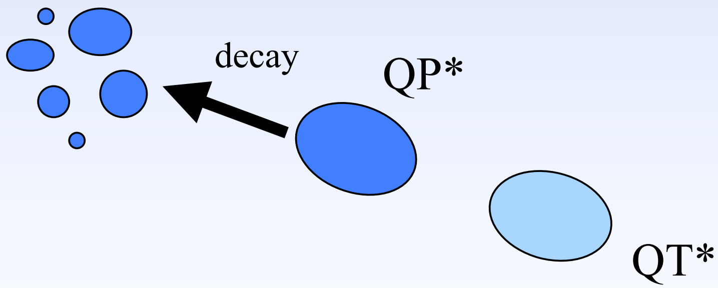
^{58}Ni+^{58}Ni E/A=52, 74 MeV

^{58}Ni+^{197}Au E/A=52, 74 MeV

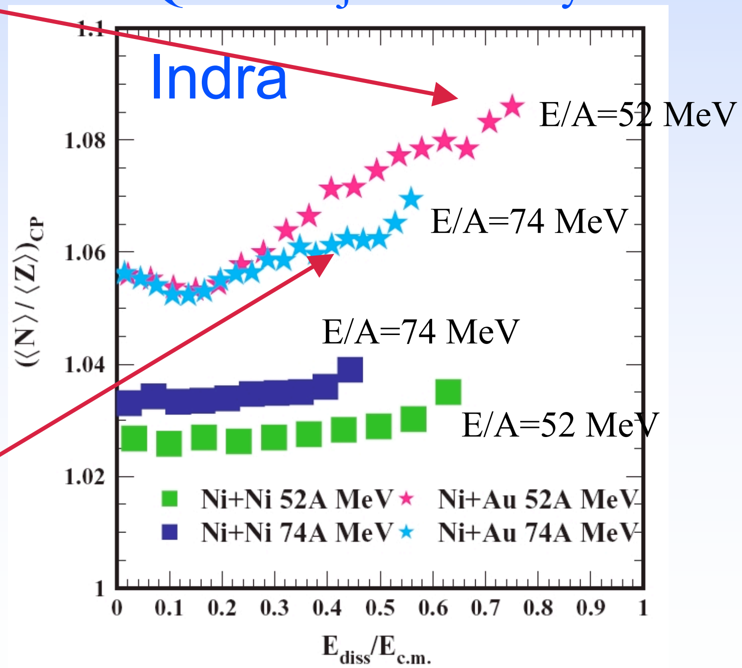
$$E_{\rm diss} = E_{\rm c.m.} - \frac{1}{2}\mu V_{\rm rel}^2$$

Directly related to τ_{int}

Long τ_{int}: Large E_{diss}
N/Z equilibration



Quasi-Projectile Decay

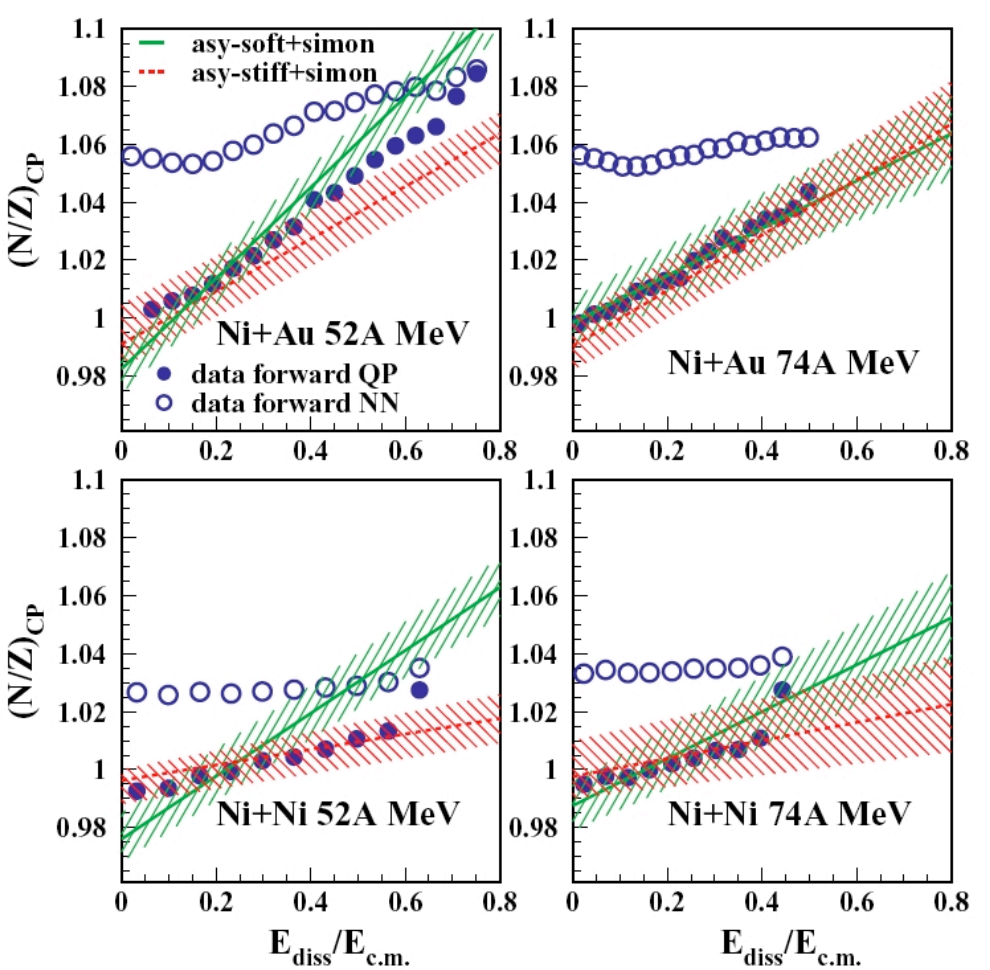


Short τ_{int}: Small E_{diss}
N/Z translucency

E. Galichet et al., PRC79, 064614 (2009)

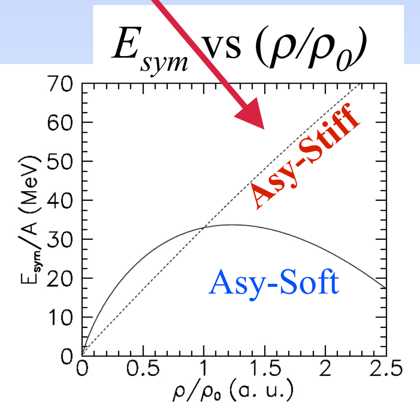
Probing $E_{sym}(\rho)$

Comparisons to SMF



E. Galichet et al., PRC79, 064615 (2009)

Data closer to Asy-Stiff parameterization



$$E_{sym}^{pot}(\rho) \propto \left(\frac{\rho}{\rho_0}\right)^{\gamma} \qquad \gamma = 1$$

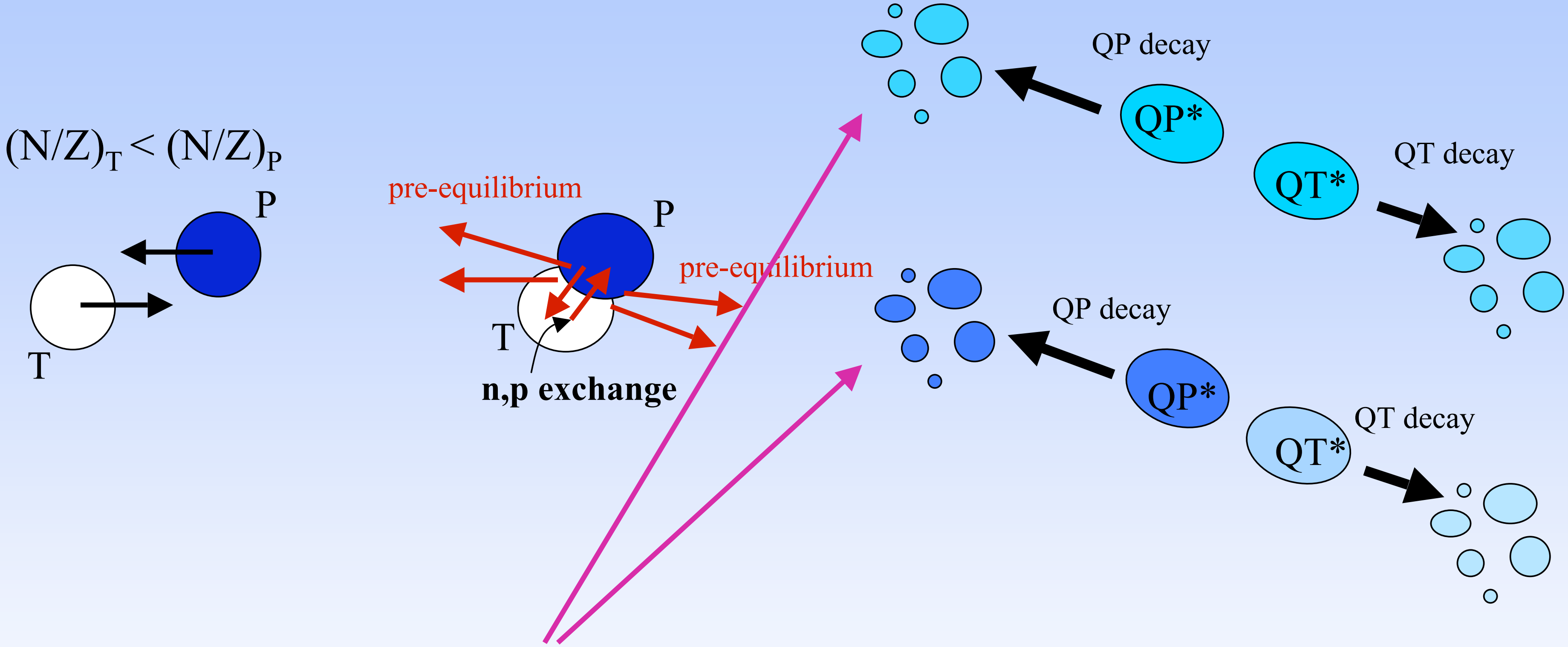
More about N/Z equilibration/transparency and stopping

Talk by G. Lehaut, Indra data

Stay tuned…

G. Lehaut et al., PRL104, 232701 (2010)

Isospin diffusion: Lassa Data



Observables $X \propto \delta^* = (N-Z)/(N+Z)$

- X = α-slope from isoscaling — Lassa @ MSU
- X = $Y(^7Li)/Y(^7Be)$ — Lassa @ MSU

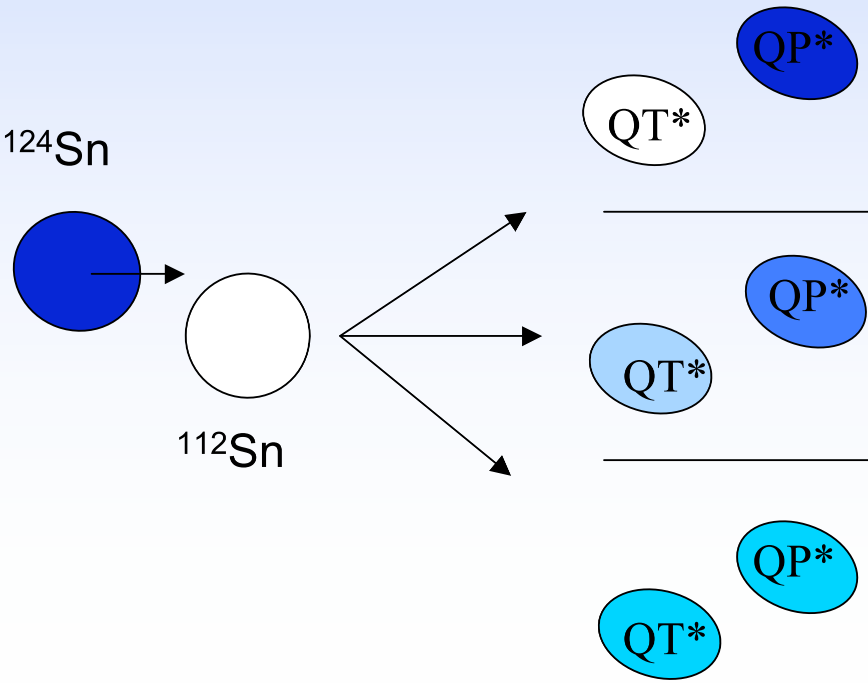
Isospin imbalance ratios

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

$$R_i(X) = \frac{2X - \alpha^{124+124} - \alpha^{112+112}}{\alpha^{124+124} - \alpha^{112+112}}$$

$X=Y(^7Li)/Y(^7Be)$

$X=\alpha$-slope isoscaling



Isospin transparency	$R_i(X) = 1$
Isospin translucency	$0 < R_i(X) < 1$
Isospin equilibration	$R_i(X) = 0$

Advantages

Elegant way to show isospin diffusion effects

Remove effects due to Coulomb, Pre-equilibrium, Secondary decays, detector efficiency

Enhances isospin sensitive effects

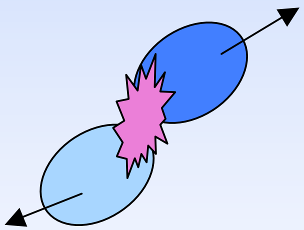
Allows comparing to model predictions even using different observables $X \propto \delta = (N-Z)/(N+Z)$

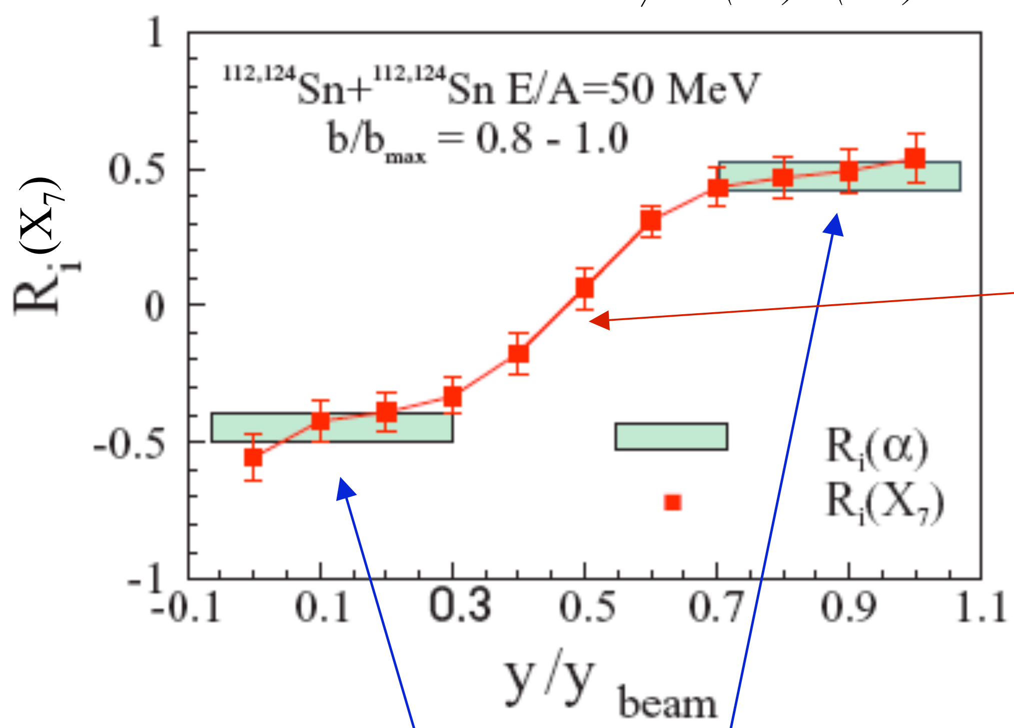
Imbalance ratios vs rapidity

$^{112,124}Sn+^{112,124}Sn$ E/A=50 MeV

$X_7 = Y(^7Li)/Y(^7Be)$

Lassa Data





N/Z stopping at mid-rapidity

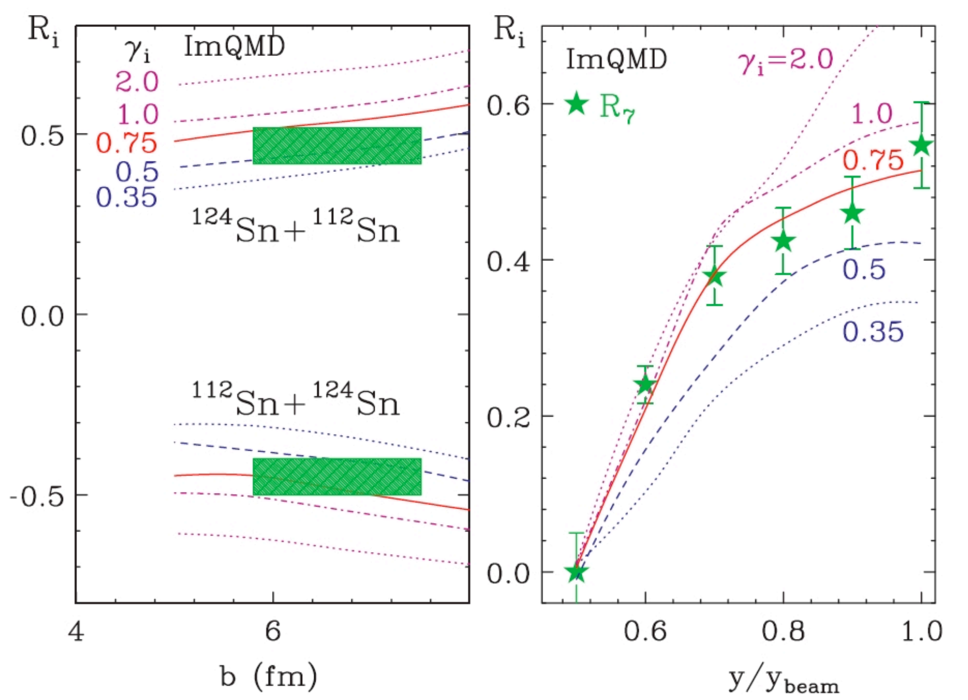
N/Z translucency at target and projectile rapidity

Probing $E_{sym}(\rho)$ with ImQMD

$^{112,124}Sn+^{112,124}Sn$ E/A=50 MeV

Cluster formation accounted for

$R_i(\alpha)$ $R_i(X_7)$



$$E_{sym}(\rho) = \frac{Cs,k}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{Cs,p}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

b=6 fm γ≈ 0.45-1.0

b=7 fm γ≈ 0.35-0.8

M.B. Tsang et al., PRL102, 122701 (2009)

Towards a consistent picture

Same $E_{sym}(\rho)$ parameterization for multiple probes

$$E_{sym}(\rho)=12.5\cdot(\rho/\rho_0)^{2/3}+17.5\cdot(\rho/\rho0)^{\gamma} \qquad 0.4 < \gamma < 1$$

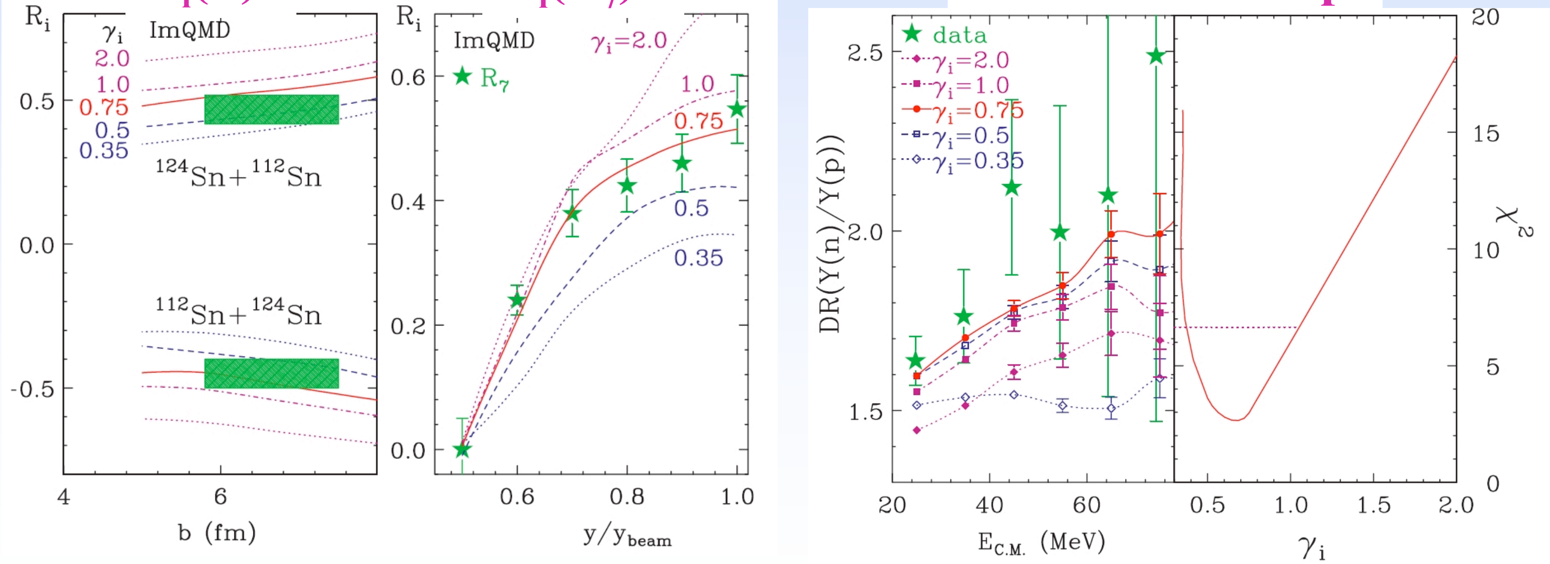
IsoDiffusion from isoscaling

Rapidity dependence of IsoDiffusion

Double n/p ratios at pre-equilibrium

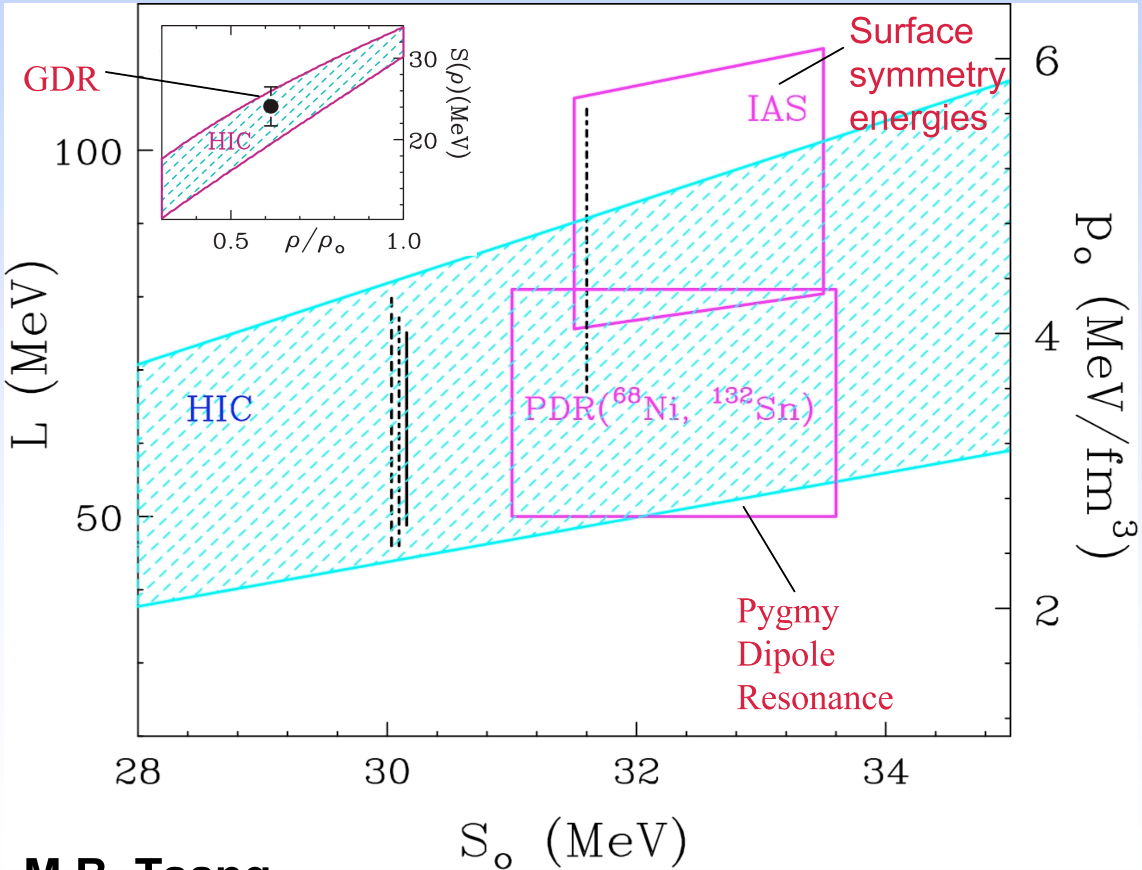
M.B. Tsang et al., PRL102, 122701 (2009)

$R_i(\alpha)$ **$R_i(X_7)$** **Double ratios n/p**



IBUU04: γ=0.7-1.05 from $R_i(\alpha)$ only -- agreement

Consistent constraints from different communities



M.B. Tsang

$$S_0 = E_{sym}(\rho_0)$$

Strength at $\rho=\rho_0$

$$L = 3\rho_0 \left|\frac{dE_{sym}(\rho)}{d\rho}\right|_{\rho_0} = \left(\frac{3}{\rho_0}\right) p_0$$

Slope

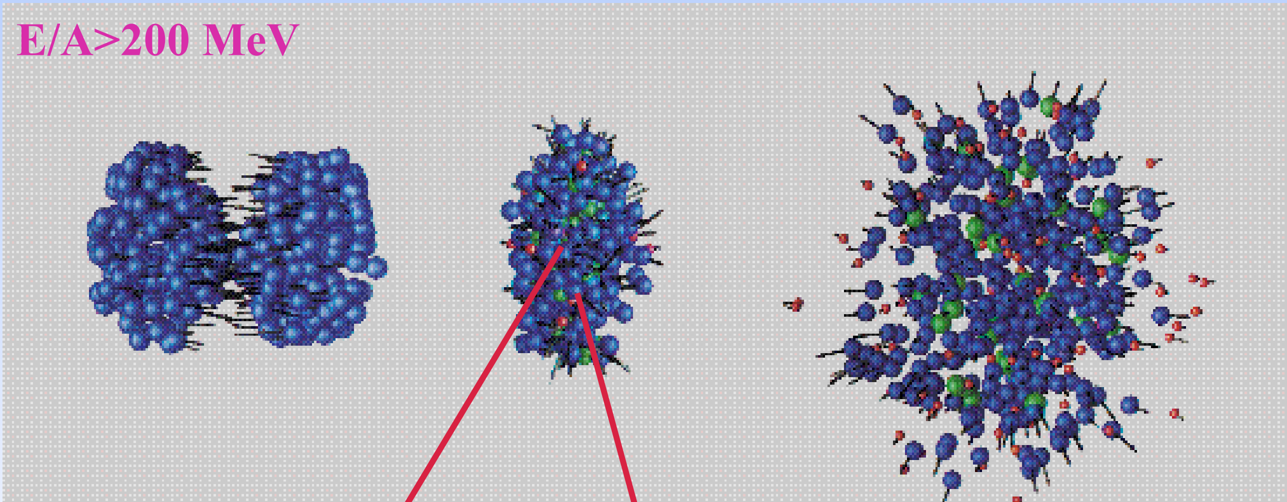
$$K_{sym} = 9\rho_0^2 \left|\frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\right|_{\rho_0}$$

Curvature

Conclusions: sub-saturation densities

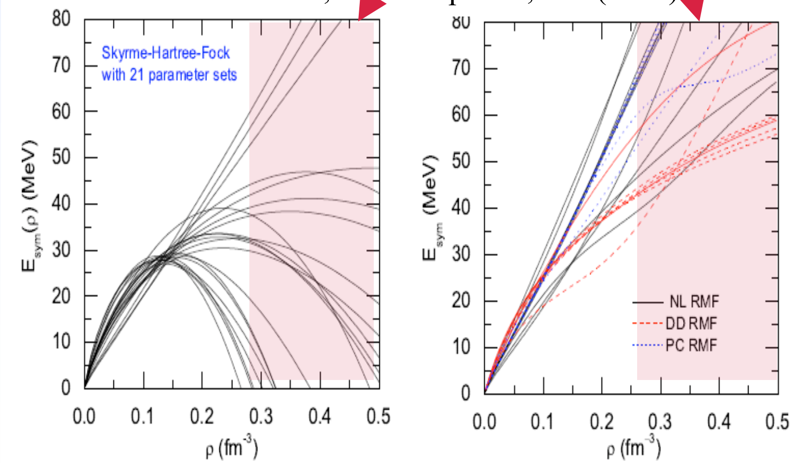
- Important progress has been made
  - Consistent analyses of γ=0.4-1.0 from isoscaling, isospin diffusion, n/p pre-equilibrium emissions
  - Different communities and one language
- The work we need to do: extend the systematics, reduce error bars, improve detectors
- Explore σ_{NN}, momentum dependence and m*/m splitting
- Understand model discrepancies
- Enhance E_{sym} signals with future RIB facilities (high N/Z asymmetries): FRIB, Riken, Eurisol, Spiral2, …

Studying $E_{sym}(\rho)$ at supra-saturation densities



GSI, CSR, Riken, NSCL, FRIB, Fair …

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

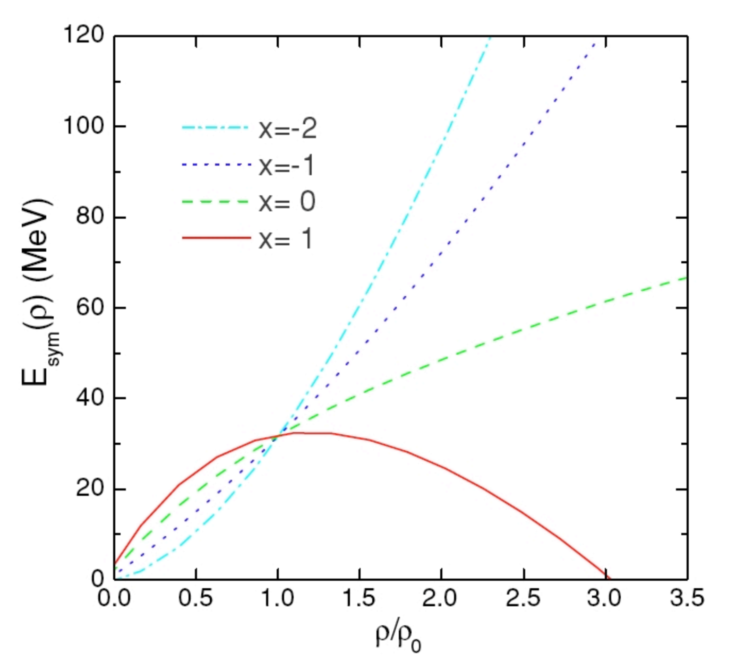


Largely unconstrained

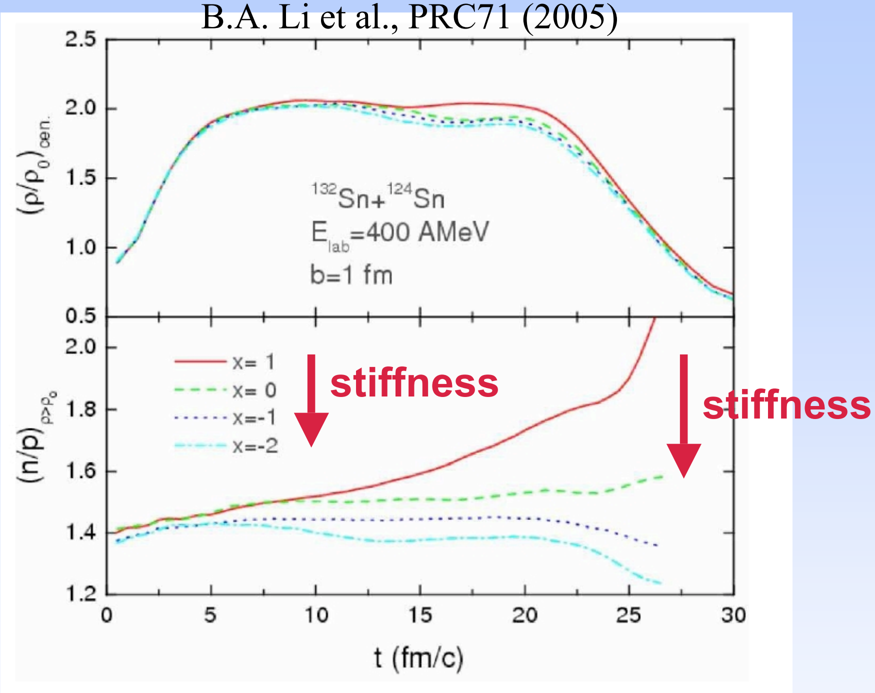
SEP by M.B. Tsang et al.,

CoSymE by Z. Basrak et al.

Effects of the E_{sym} at high density



B.A. Li et al., PRC71 (2005)



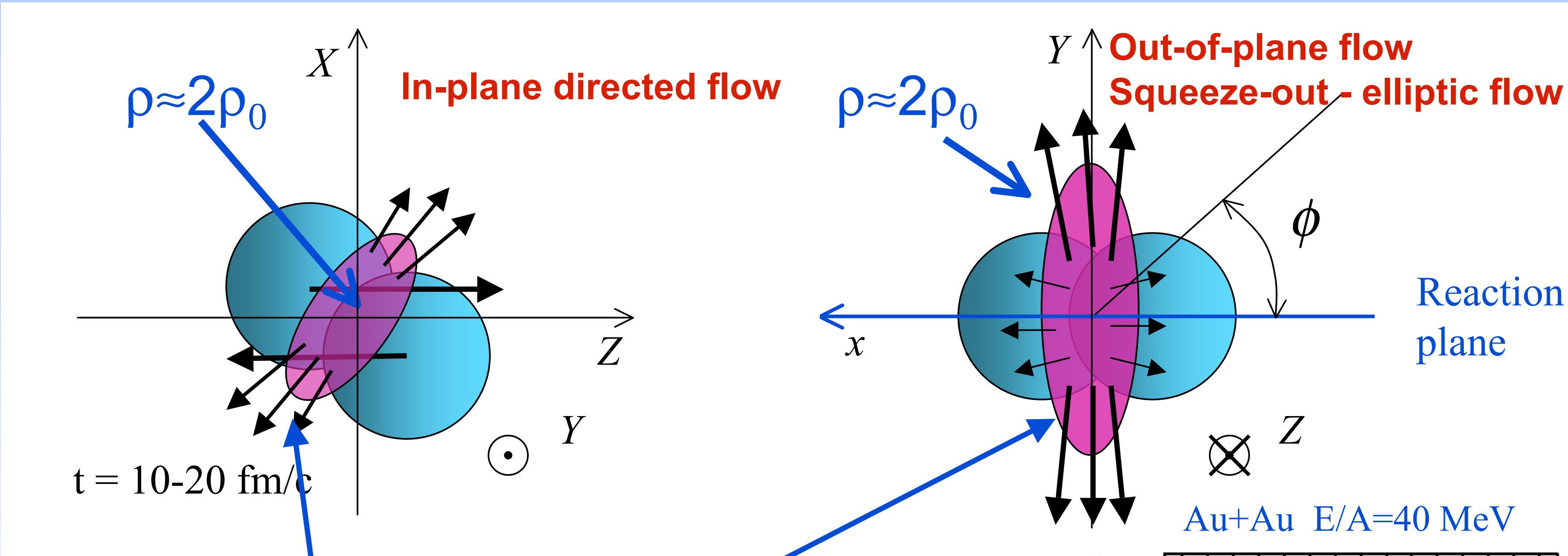
- **N/Z of high density regions sensitive to $E_{sym}(\rho)$**
- High ρ/ρ_0 : asy-stiff more repulsive on neutrons - opposite of sub-saturation trend

Probes at supra-saturation

1. n/p directed and elliptic flow
2. Particle production in high density regions: p^-/p^+ and K^0/K^+
3. n/p and t/^{3}He spectra squeezed-out of participant region (ρ~2-3ρ0)

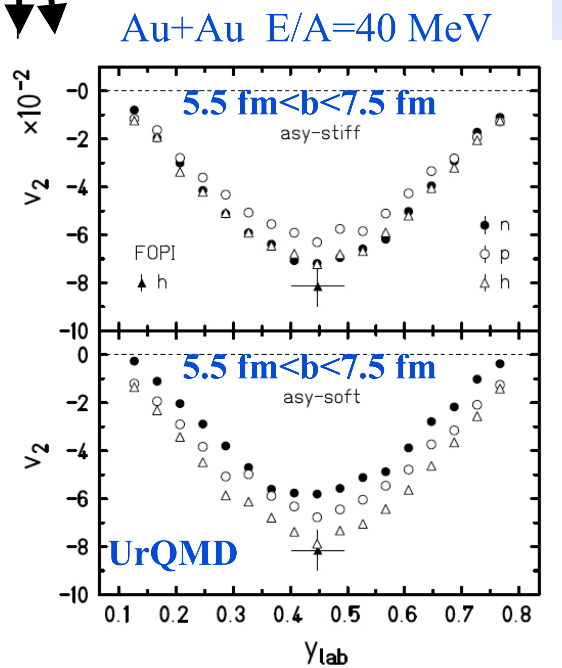
Caution with momentum dependent interaction

Directcted and Elliptic flow



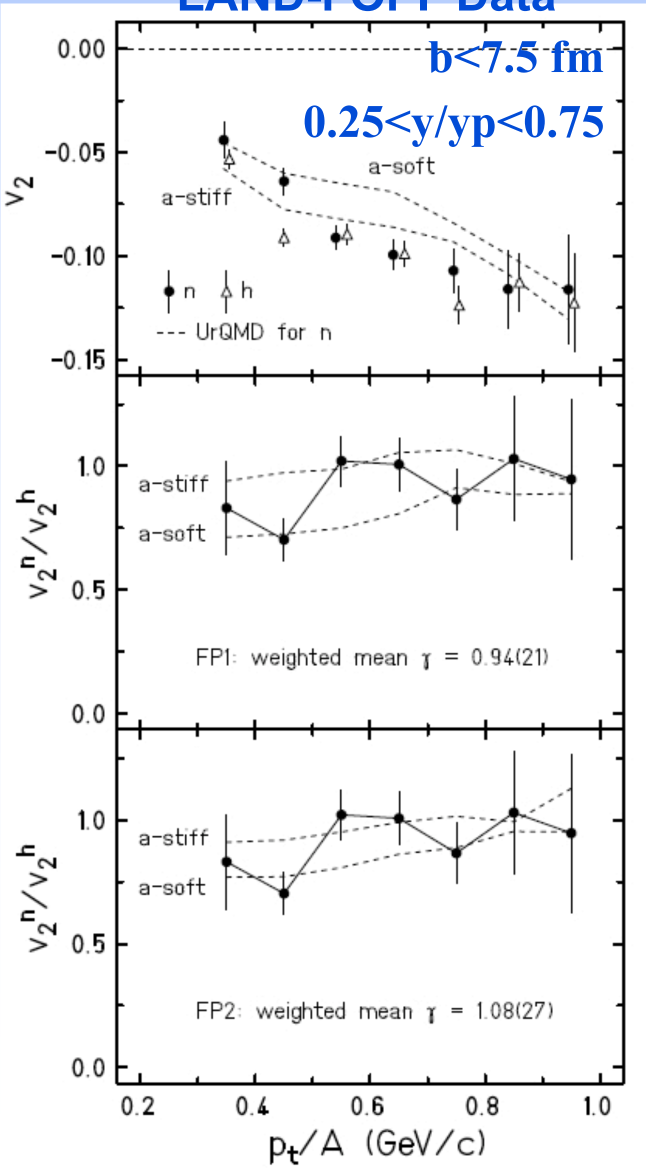
$dN/d\phi = 1 + 2\mathbf{v_1}\cos(\phi) + 2\mathbf{v_2}\cos(2\phi)$

Squeeze-out of neutrons sensitive to $E_{sym}(\rho)$



n/p elliptic flow

LAND-FOPI Data



UrQMD simulations

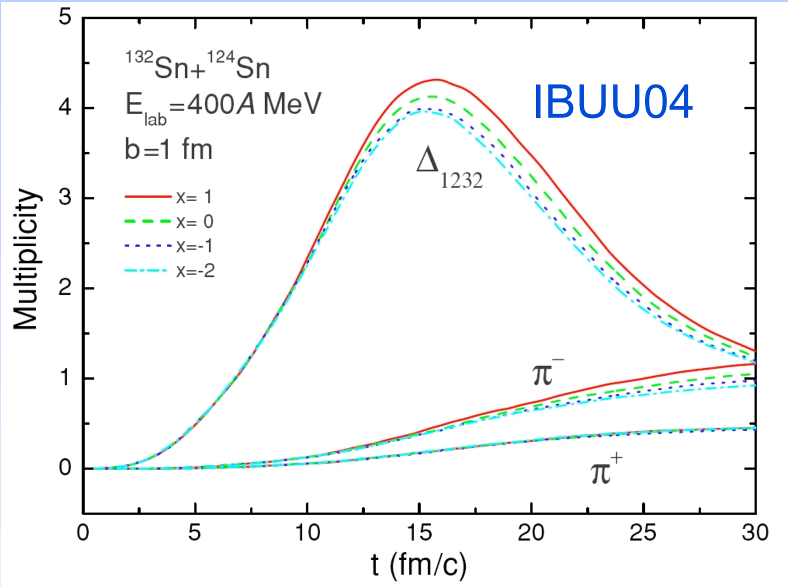
$$E_{sym}(\rho) = E_{sym}^{kin}(\rho) + E_{sym}^{pot}(\rho)$$

$$E_{sym}^{pot}(\rho) = 22MeV \cdot \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

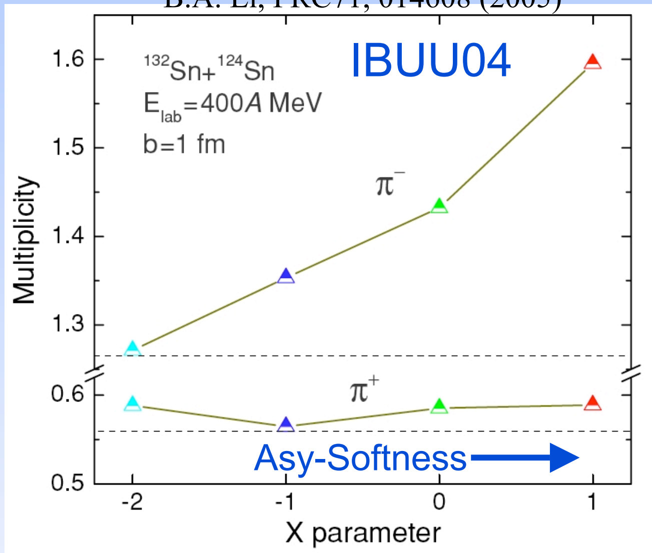
$\gamma = 1.0 \pm 0.3$

P.Russotto et al., 2010, Submitted for publication

Meson production: Pions



B.A. Li, PRC71, 014608 (2005)



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

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

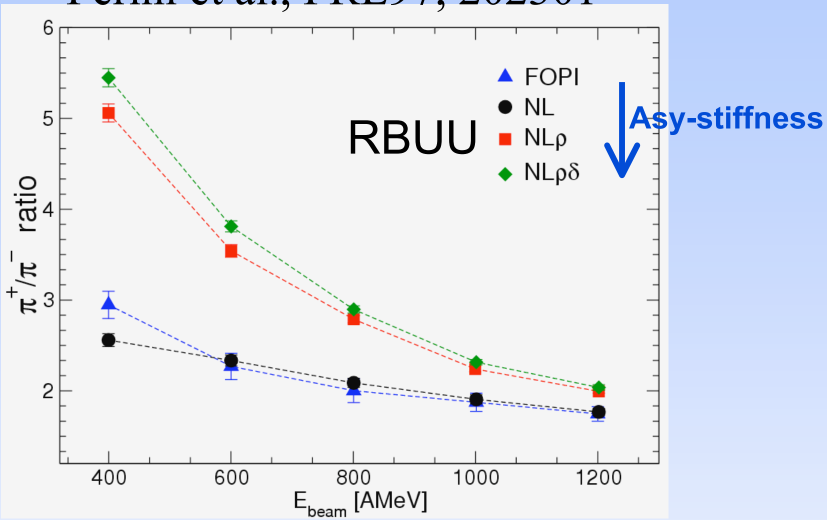
π-/π+ sensitive to $E_{sym}(\rho)$ at high ρ

NN collisions in high density regions

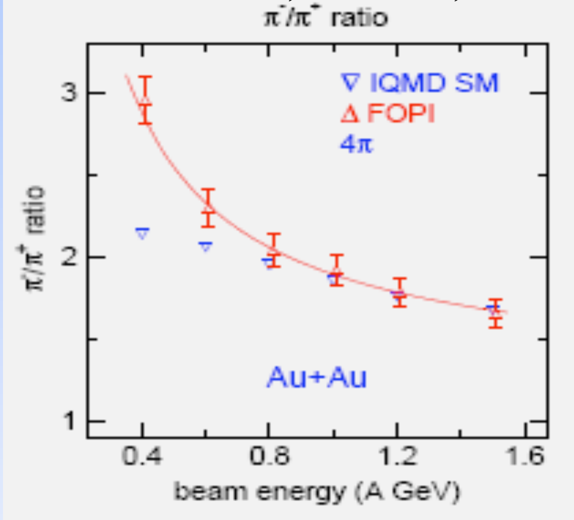
π–/π+ reflecting the $(N/Z)_{dense}$

Pion controversial results….

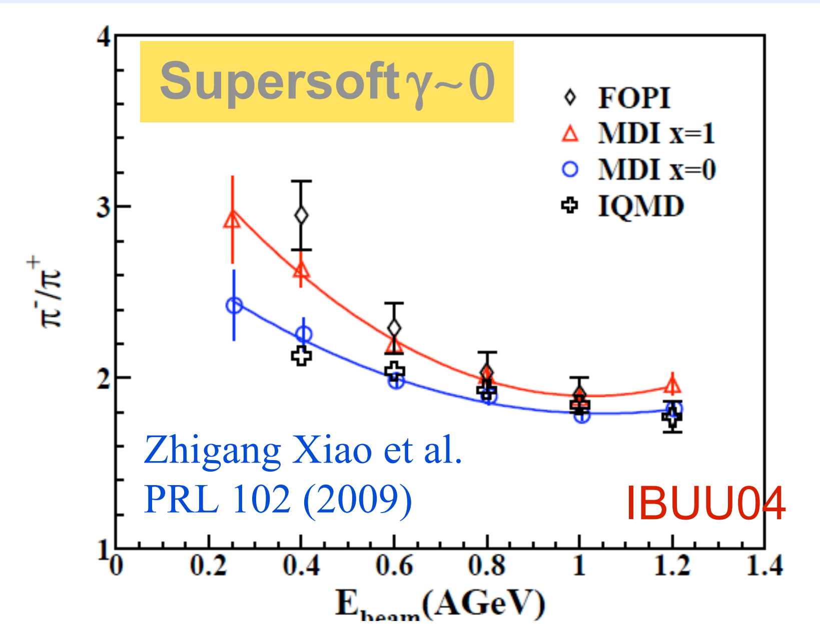
Ferini et al., PRL97, 202301

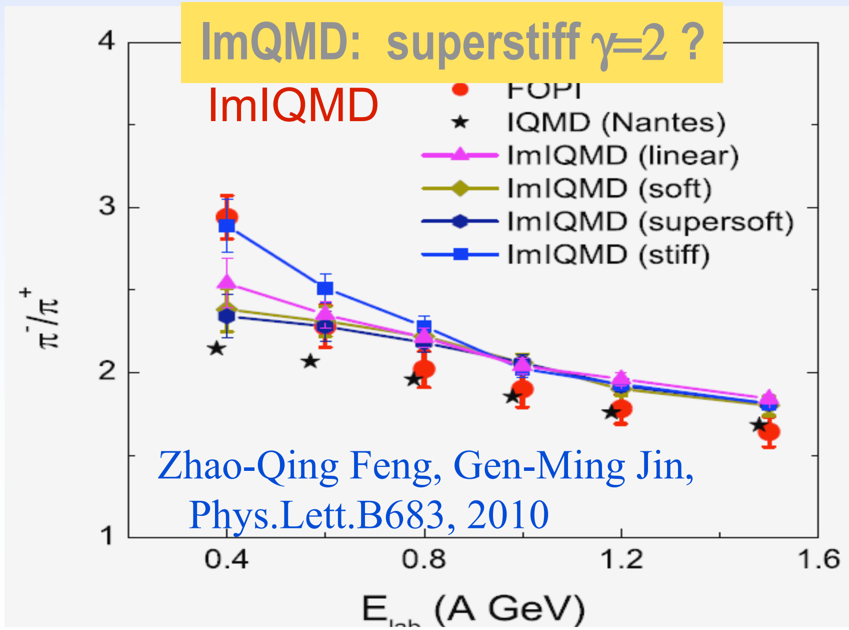


Reisdorf et al., NPA781, 459



Talk by Y. Leifels

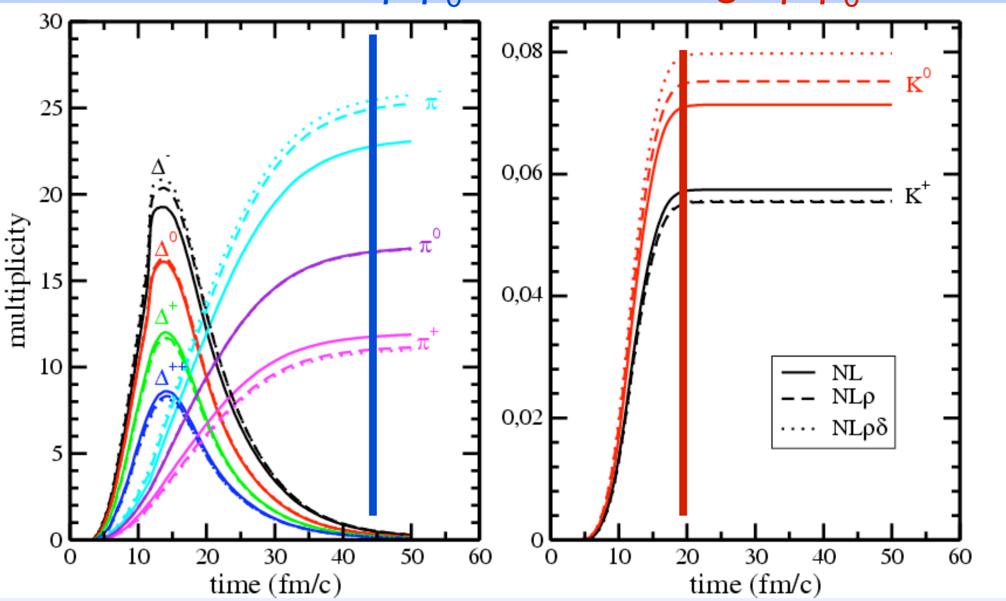




Pion and Kaon freeze-out in HIC

Low ρ/ρ_0 High ρ/ρ_0

π^+,π^-



K^+,K^0

RBUU, Ferini et al., PRL97, 202301

Warning with pions:

- Strongly interacting in medium
- Freeze-out at late times (low ρ/ρ_0)
- Difficult to isolate π+ and π- produced in the high density stage

Kaons: more sensitive probes?

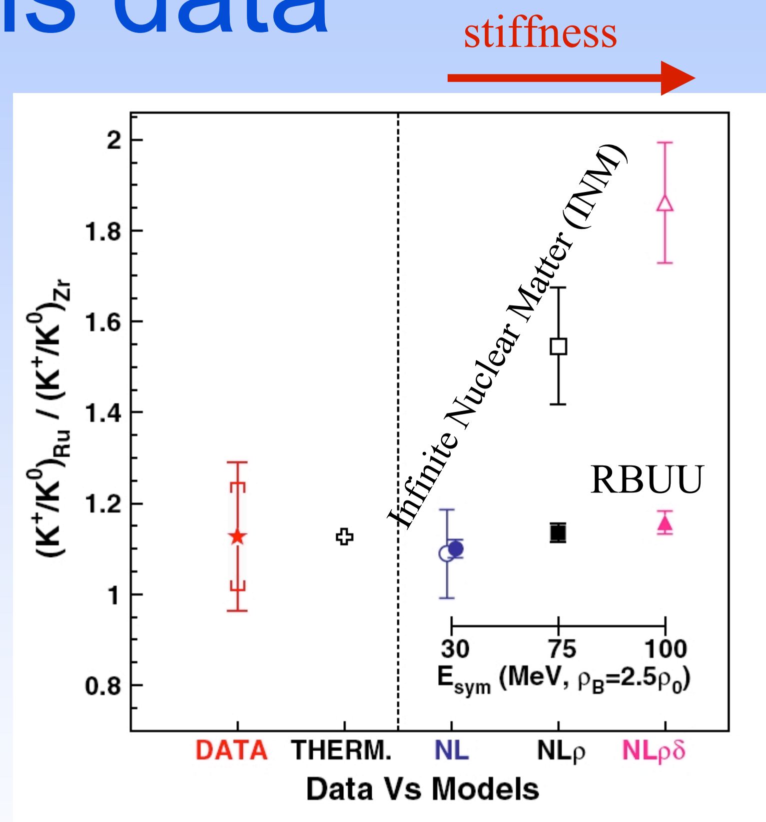
- Higher thresholds
- Weakly interacting in medium
- Freeze-out already at 20 fm/c: real high density region probes

Kaons data

$^{96}Ru+^{96}Ru$, $^{96}Zr+^{96}Zr$

E/A=1.529 GeV

FOPI



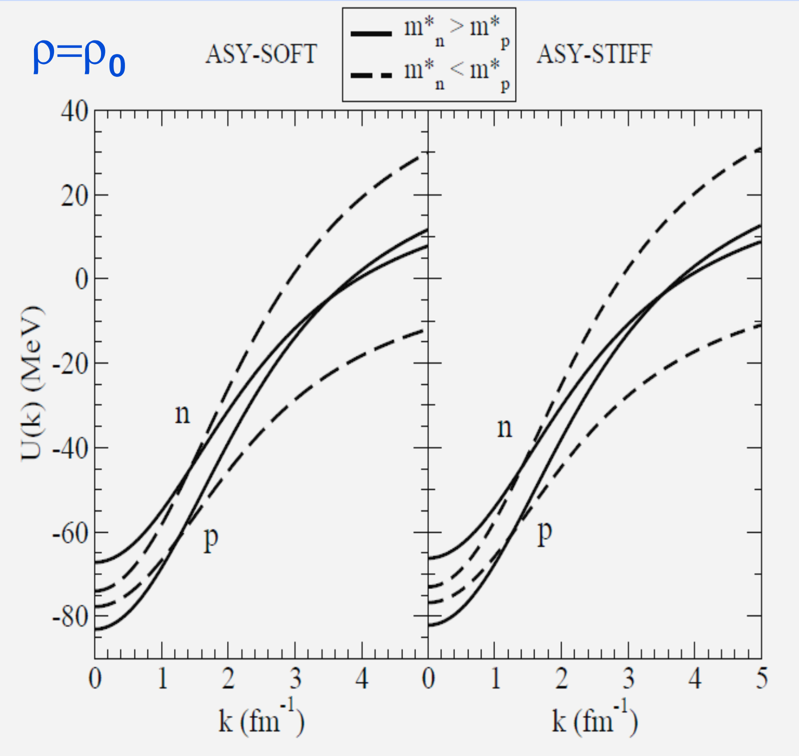
RMF calculations

INM: T=60 MeV and $\rho_B=2.5\rho_0$

RBUU: transport simulation

Need for new data… Kaons as a promising probe of the high density regions

Caution with momentum dependence in $U_{sym}(\rho,k)$

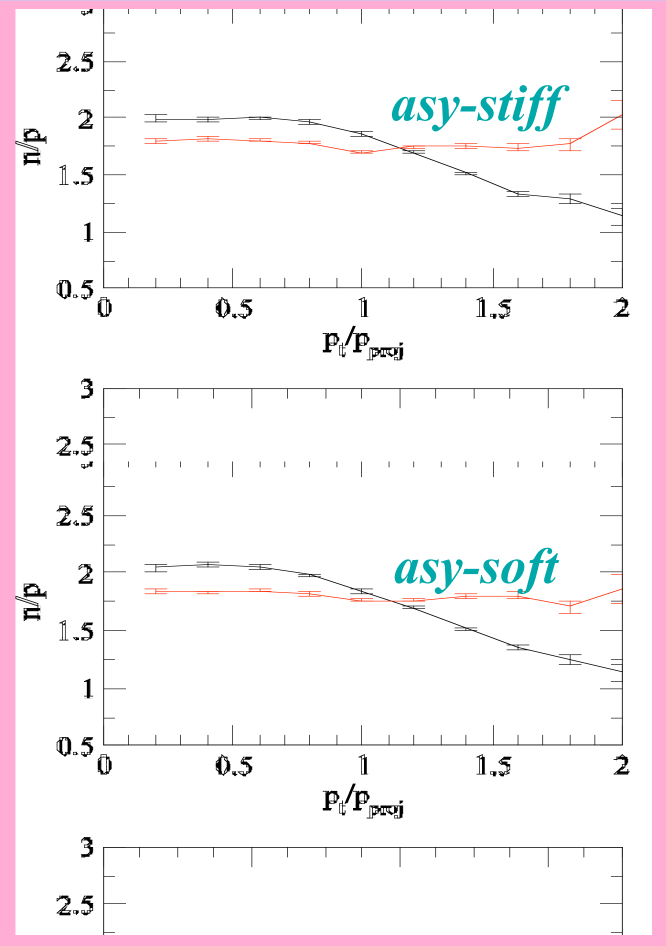


$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k} \frac{\partial U_q}{\partial k} \right]^{-1}$$

Important for: nucleon emission, flow, particle production (π^-/π^+,...)

Effective n/p mass splitting and high Pt

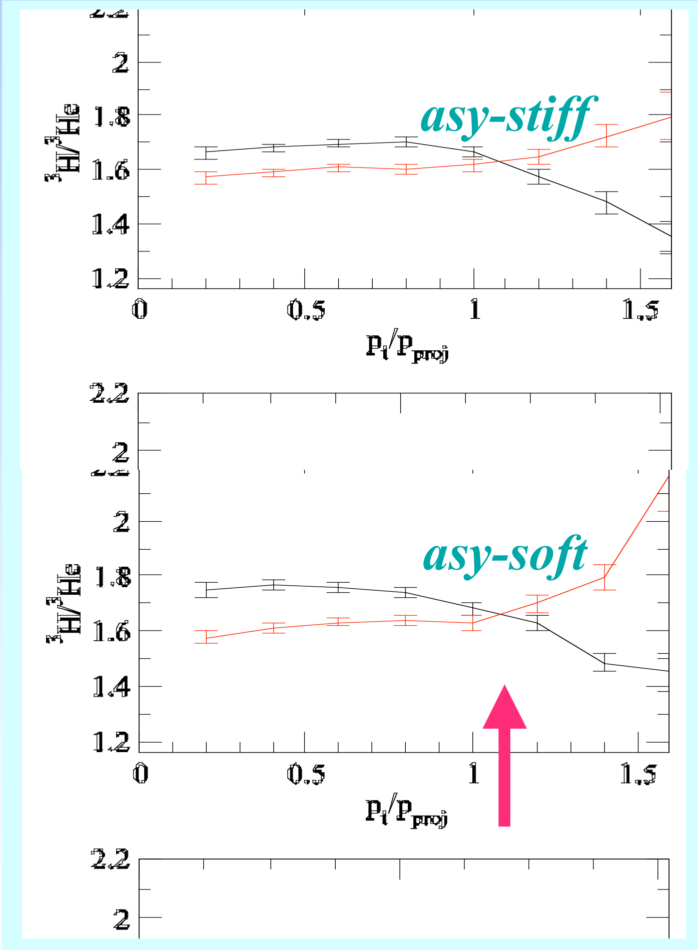
n/p ratio



$^{197}Au+^{197}Au$
400 AMeV
b=5 fm,
$y^{(0)} \leq 0.3$

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

Light isobar $^3H/^3He$



n/p at high pt sensitive to m*/m only!

E. Greco, INPC2010

V.Giordano et al. PRC81(2010)

Conclusions on supra-saturation density

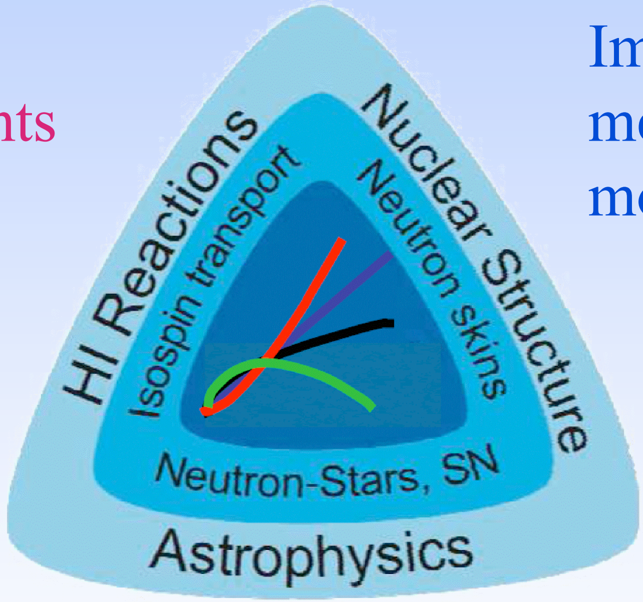
- Elliptic flow analysis

  $\gamma = 1.0 \pm 0.3$ …waiting for the next GSI experiment

- n/p ratios vs Pt to constrain (m*/m) splitting?
- Pion and Kaon production probes need more work: experimens and models - better understand Δ-dynamics and role of $E_{sym}(\rho)$
- Future projects: Need for better data, larger systematics (E_{inc}, N/Z) at Riken, Fair, FRIB, CSR, …

Where are we? where do we go from here?

Significant achievements



Improvements in measurements and modelling required

Encouraging and stimulating for future challenges

Different communities working together

Acknowldgements

- All the scientific community: wonderful results and passionate dedication in their work
- The organizers for bringing us here
- The participants for coming, sharing their ideas
- Help by colleagues at CT, MSU, GANIL, GSI