Flow and Correlations

Recent Experimental Results on the Symmetry Energy and Reaction Dynamics

Alan McIntosh
Texas A&M University

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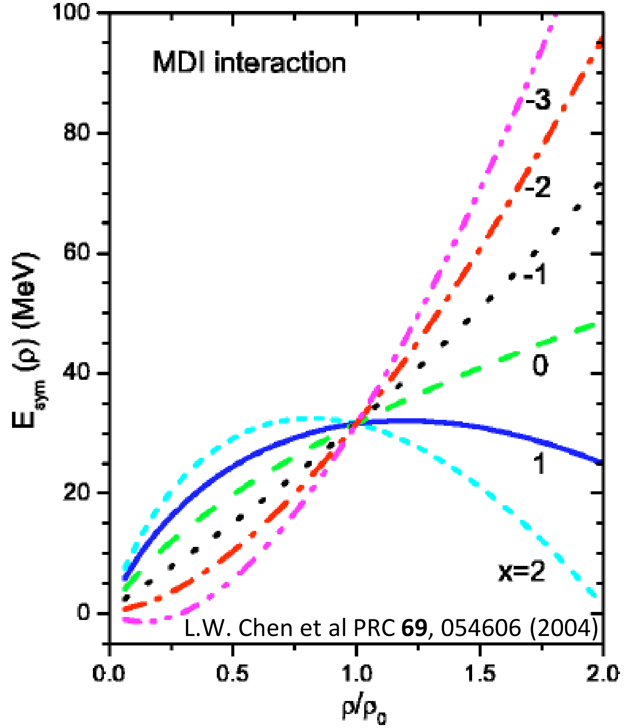
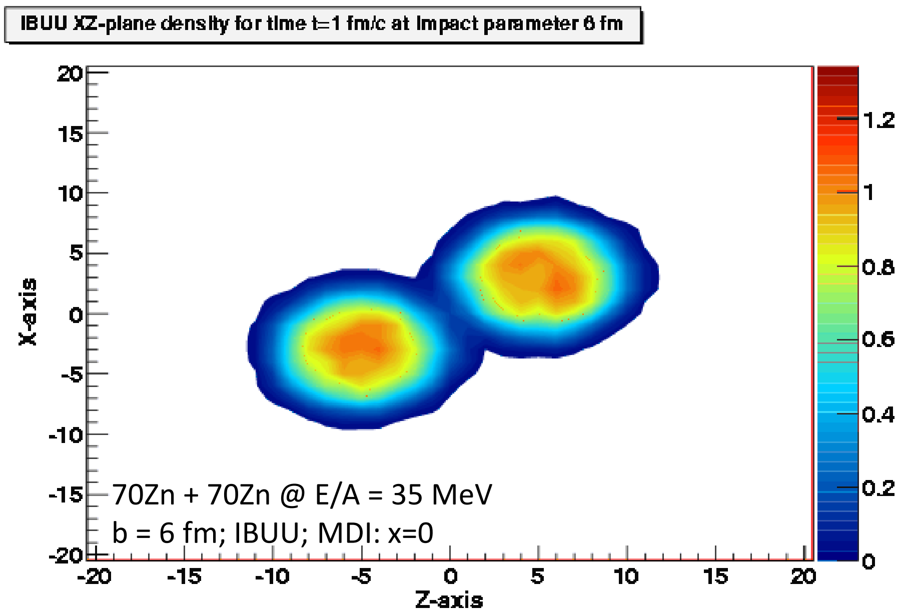




"Stiff" and "Soft" are relative, and have meaning within a particular model.

- Extraction of information on $E_{sym}(\rho)$
  - Experimental Data ↔ Theoretical Transport Model Calculations
- Reaction dynamics are critical
  - Mid-rapidity or neck emission
  - Emission from transiently deformed shapes.

<u>Directed Flow</u> <u>of Light Charged Particles and Intermediate-Mass Fragments</u>

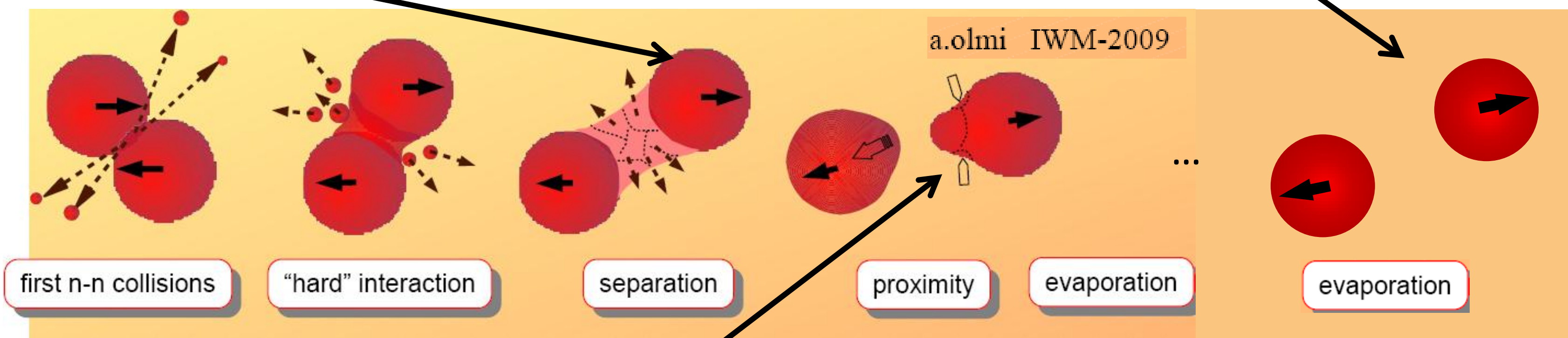
Sensitive to $E_{sym}(\rho)$ – Model Dependent

- Dependence of Flow on Fragment N/Z
- Differential Flow (^3He:^3H)
- Dependence of Flow on impact parameter

<u>Statistical Decay</u>

Careful **reconstruction** of **equilibrated** source is needed. Info on $E_{sym}(\rho)$ from:

- Caloric Curves (asymmetry, coulomb)
- Isoscaling



<u>Correlations</u> <u>Between Observables for Dynamically Produced Fragments</u>

→ May provide useful new constrains for models

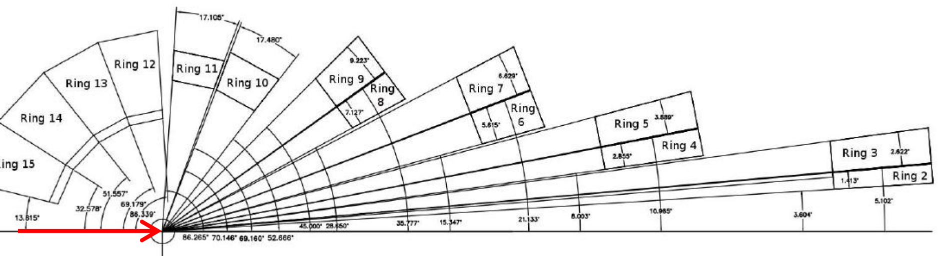
- Alignment
- Fragment Size
- Fragment Composition
- Yield
- Velocity Damping
- Breakup Timescale

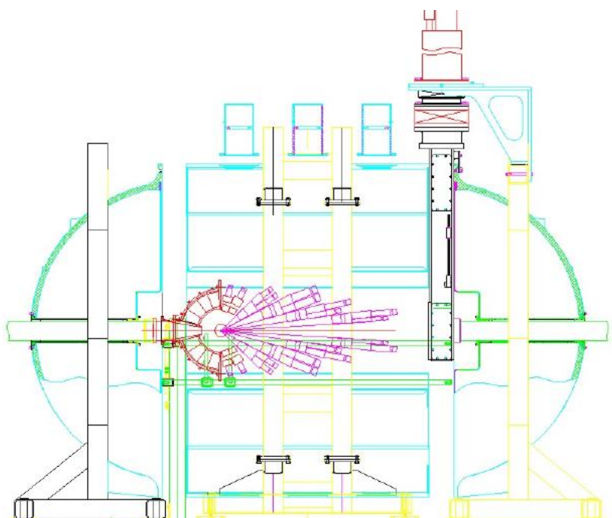
Experimental Descriptions

$^{70}Zn + ^{70}Zn$, $^{64}Zn + ^{64}Zn$, $^{64}Ni + ^{64}Ni$
@ E/A = 35 MeV

TAMU NIMROD-ISiS Array

- Nearly 4π coverage
- Isotopic Resolution for Z ≤ 17
- Free Neutron Multiplicity



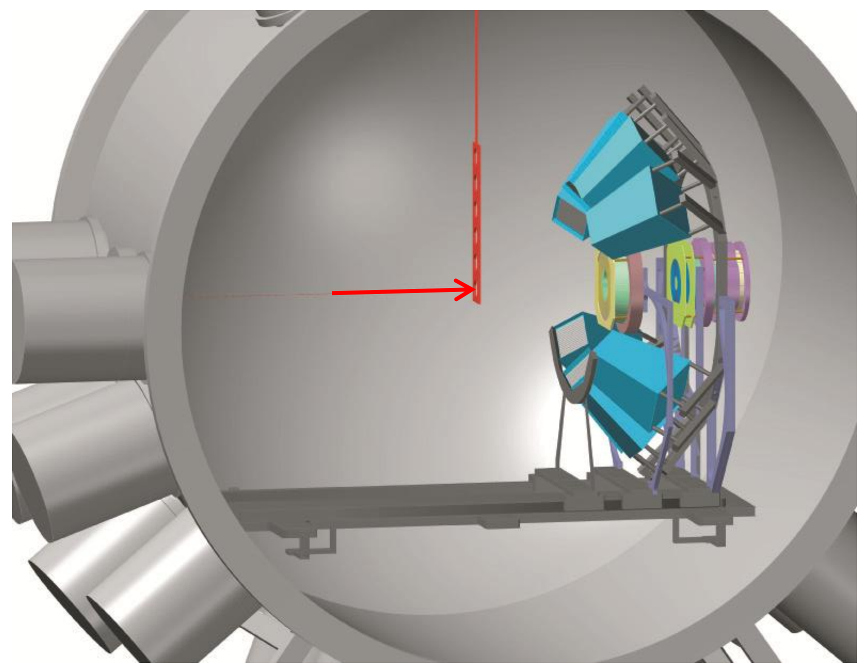


S. Wuenschel *et al.*, NIMA **604**, 578 (2009).

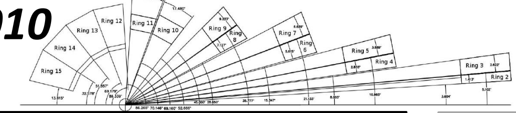
$^{124,136}Xe + ^{112,124}Sn$
@ E/A = 50 MeV

Indiana University FIRST-LASSA Array

- Selection of 2.8° ≤ θ_{lab} ≤ 6.6° (for this analysis)
- High Angular Resolution (0.1°)
- Isotopic Resolution for Z ≤ 14



T. Paduszynski et al., NIMA **547**, 464 (2005)



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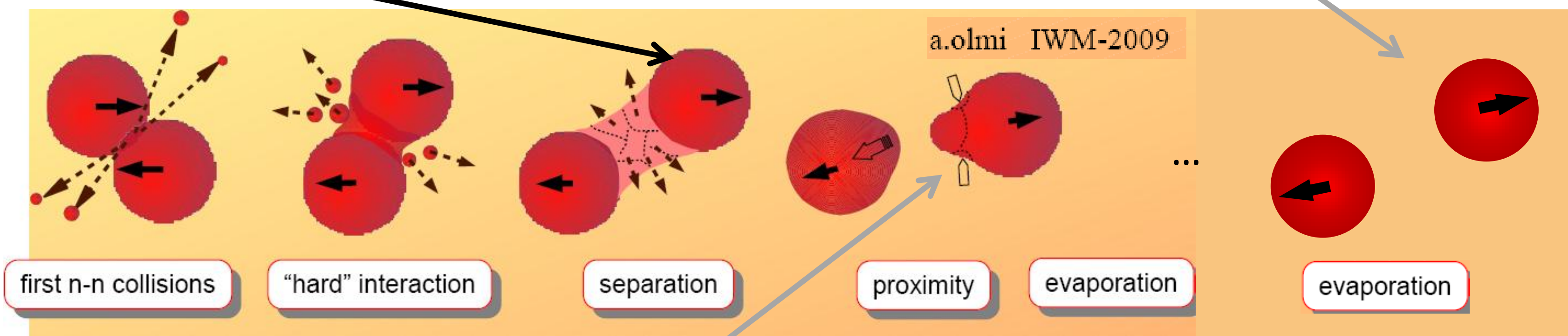

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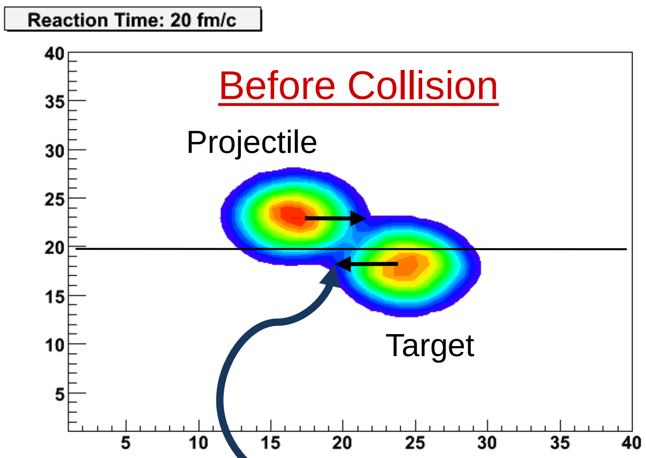
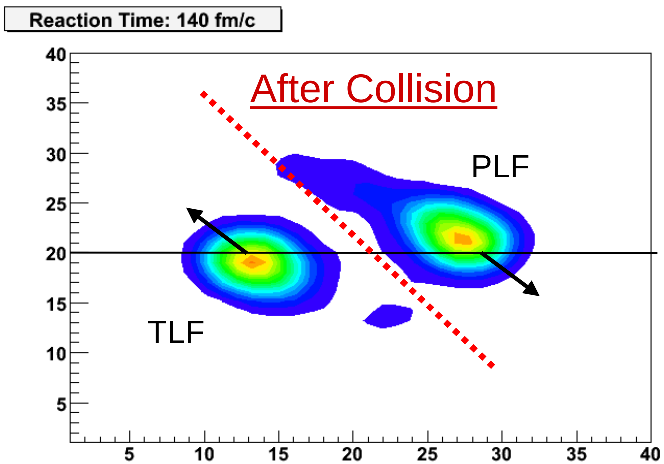
- Yield
- Dissipation
- Decay Timescale

Defining Transverse Flow

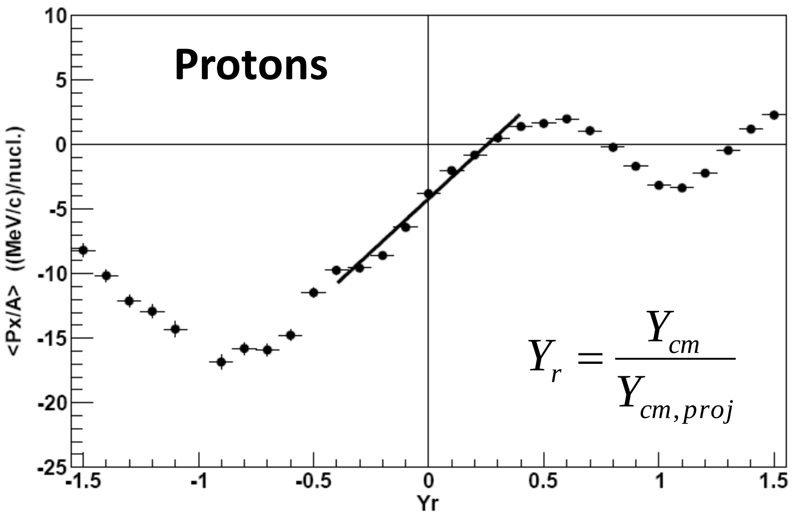




Attractive Mean Field
- Isospin-dependent part

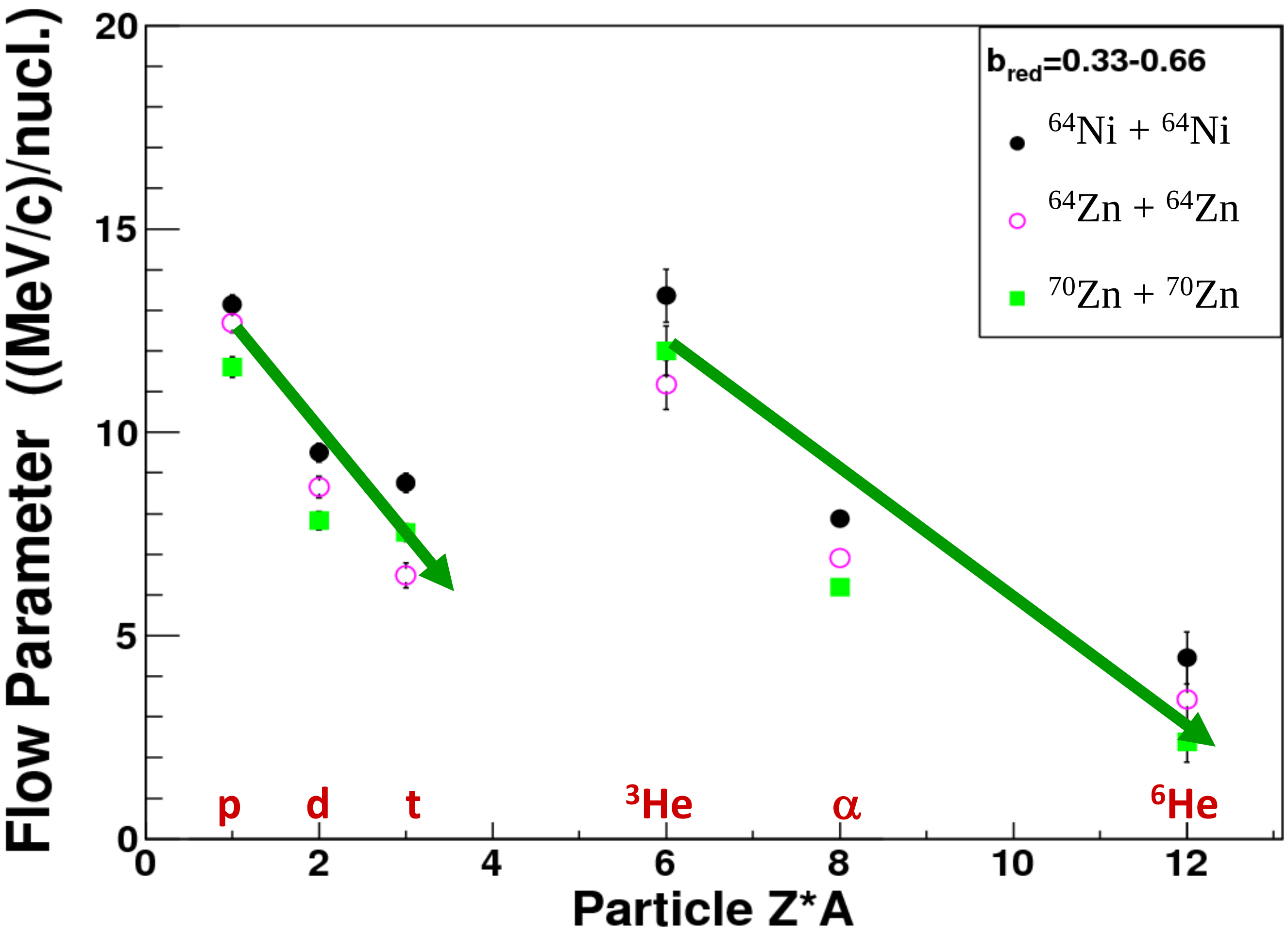
Repulsive NN-collisions
Repulsive Coulomb

$$F = \frac{\partial \langle P_x / A \rangle}{\partial Y_r}$$



$$Y_r = \frac{Y_{cm}}{Y_{cm,proj}}$$

Flow of Light Charge Particles



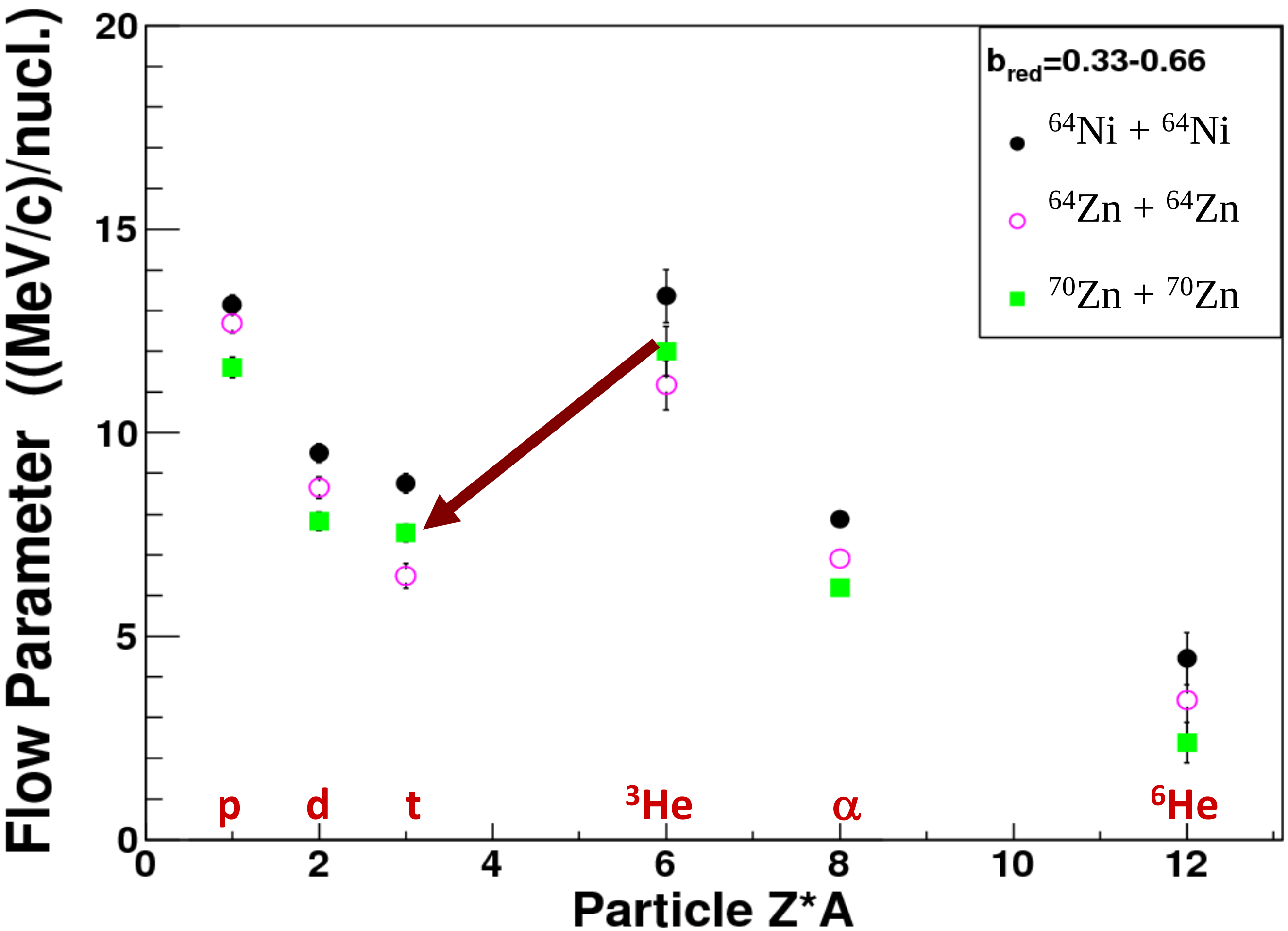
<u>Experimental Details</u>

- TAMU Cyclotron Institute
- NIMROD-ISiS Detector
- 35 MeV/u (Fermi Energy)

- Strong Isotopic Trends
- ↓ Flow with ↑ n-rich

Kohley *et al.* Phys. Rev. C **83**, 044601 (2011)

Flow of Light Charge Particles



Kohley *et al.* Phys. Rev. C **83**, 044601 (2011)

Experimental Details
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- 35 MeV/u (Fermi Energy)

- Strong Isotopic Trends
- ↓ Flow with ↑ n-rich

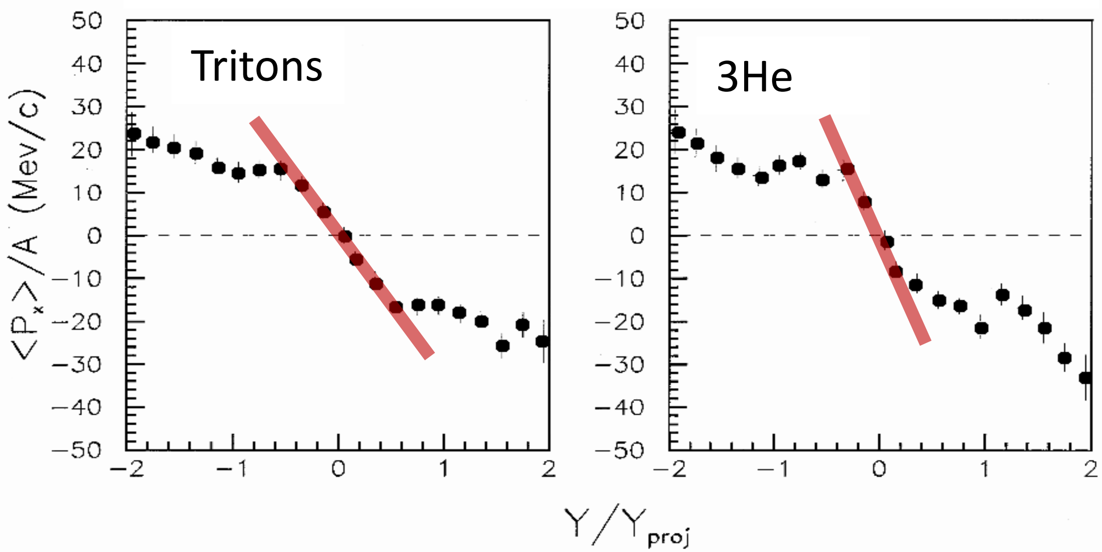
- Isobaric Effects (A=3)

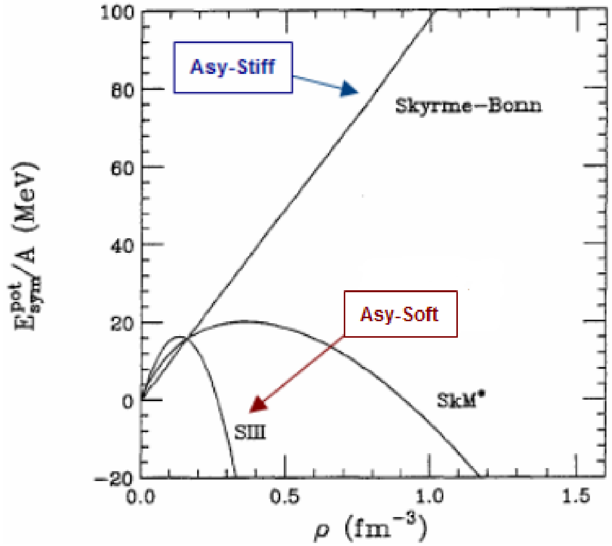
Fragments are moving differently in HICs depending on their N/Z.
(It's not just a mass or charge effect)

^{3}H-^{3}He Flow

Motivation: t/3He flow as surrogate for n/p flow

BNV Simulation





M. Di Toro *et al.*, Prog. Part. Nucl. Phys. **42,** 125 (1999).

L. Scalone *et al.*, Phys. Lett. B **461,** 9 (1999).

Stiff $E_{sym}(\rho)$	**^{3}He > ^{3}H**
Soft $E_{sym}(\rho)$	**^{3}He=^{3}H**

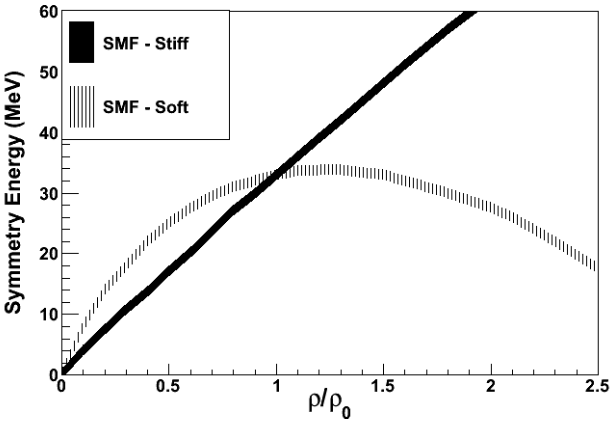
Stiff symmetry potential drives neutrons into the low density neck.
This motion is counter to the net nucleon flow
"Stiff" → Larger flow of 3He than tritons for "stiff"

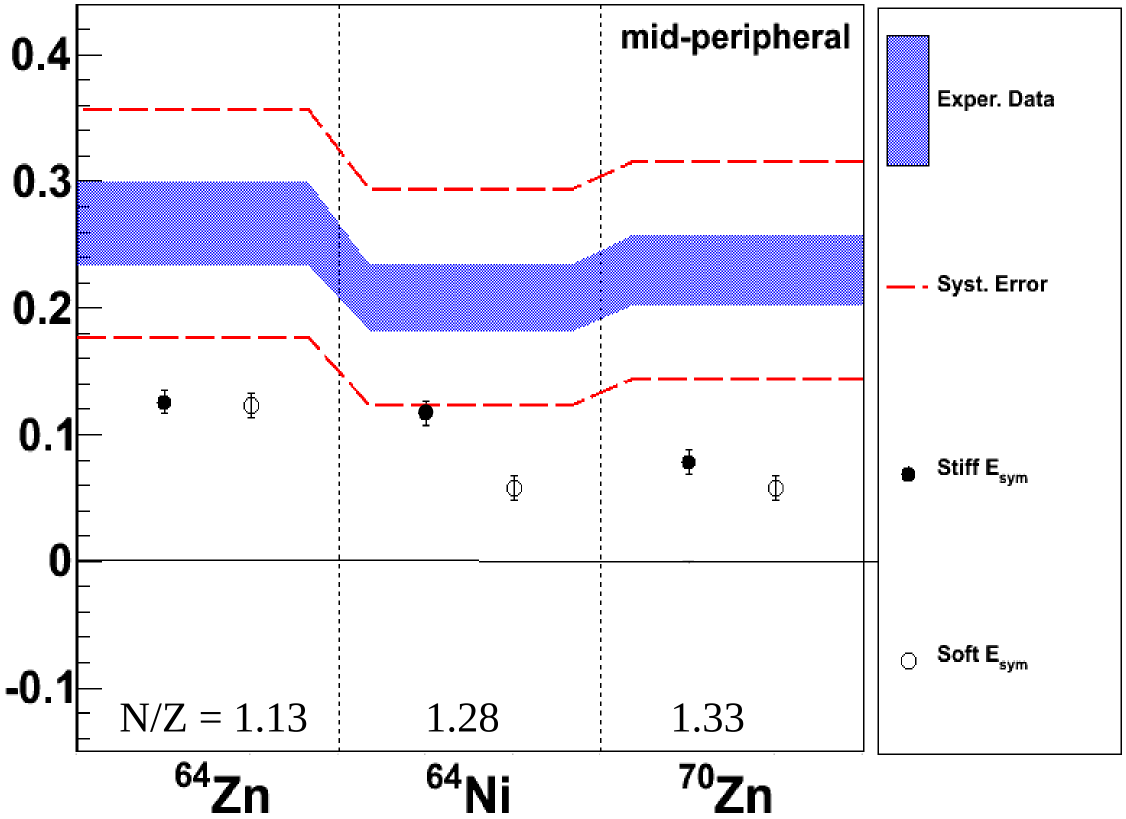
^3H-^3He Flow

Stochastic Mean-Field (SMF)

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

$$R_{^3He\text{-}^3H} = \frac{F^{^3He} - F^{^3H}}{F^{^3He} + F^{^3H}}$$

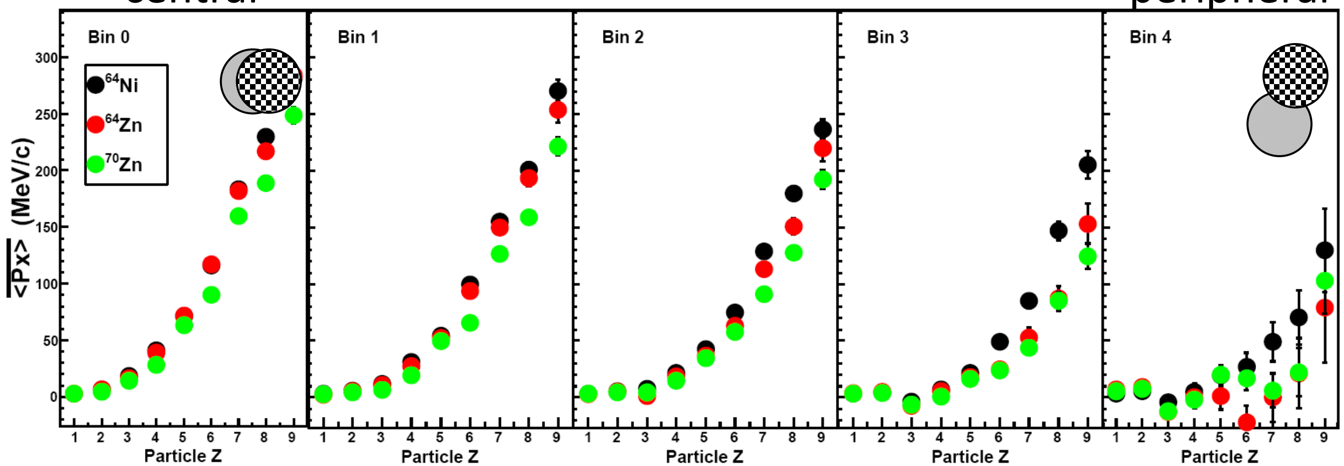




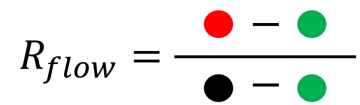
- Transverse flow is movement of particles following the PLF and TLF.
- Stiff symmetry energy propels neutrons away from the PLF and TLF into the neck, decreasing the flow for neutron-rich species.

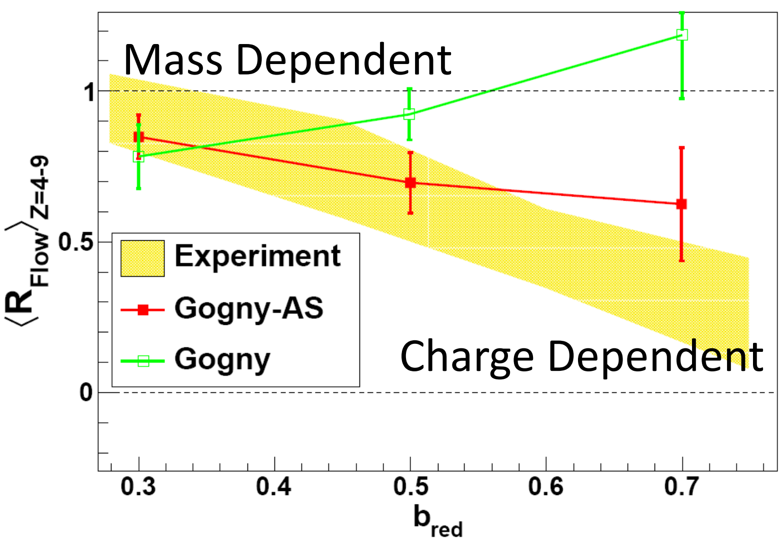
IMF Flow

central peripheral



$$R_{\mathrm{flow}} = \frac{\overline{\langle Px \rangle}_{^{64}\mathrm{Zn}} - \overline{\langle Px \rangle}_{^{70}\mathrm{Zn}}}{\overline{\langle Px \rangle}_{^{64}\mathrm{Ni}} - \overline{\langle Px \rangle}_{^{70}\mathrm{Zn}}}$$





Kohley *et al.,* Phys. Rev. C **82**, 064601 (2010)

Violent Collisions

The heavier systems have more NN collisions (repulsive)

→ Lower E_{bal} and *lower flow* than the lighter system

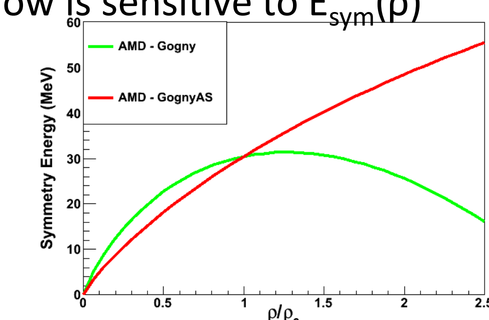
Peripheral Collisions

Smaller interaction volume

→ Less mean-field component, but same Coulomb

Charge-dependent flow

Mean-field is isospin dependent, so the competition between mass-dependent and charge dependent flow is sensitive to $E_{sym}(\rho)$

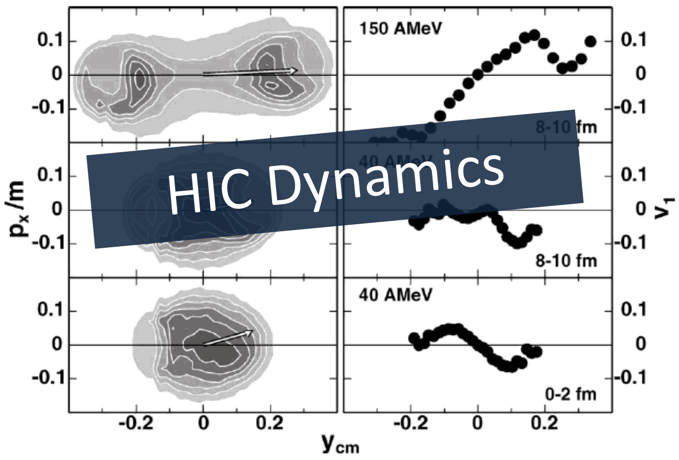


AMD+GEMINI

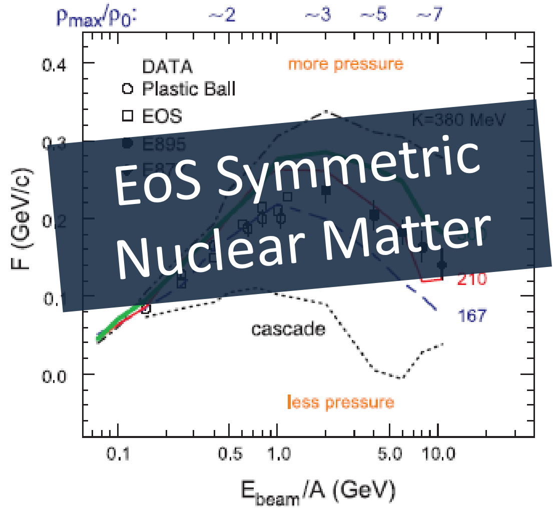
Molecular dynamics model coupled with statistical decay.

A. Ono and H. Horiuchi, Prog. Part. Nucl. Phys. ***53,*** *501, (2004).*

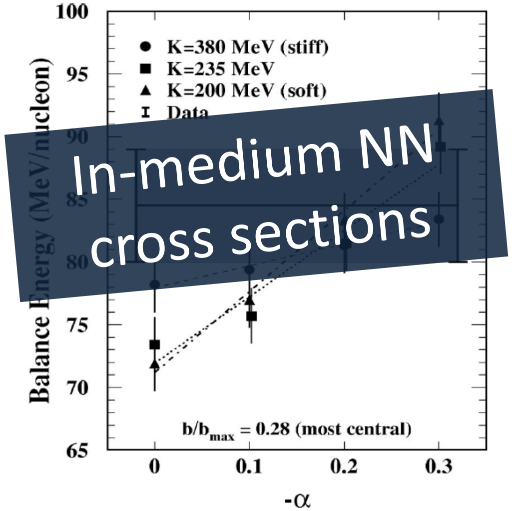
Usefulness/Importance of Flow Measurements



J. Lukasik *et al.*, PLB (2005)



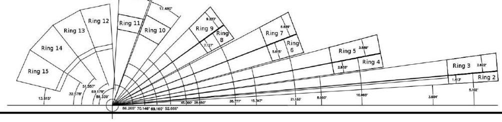
P. Danielewicz *et al.*, Science (2002)



D.J. Magestro et al., (2000)

Probe of EoS for asymmetric nuclear matter.

- ***IMF flows***
- ***LCP flows (Ex. 3H-3He)***
- *Balance energy*
- *π+/π- flows*
- *N/P flows*



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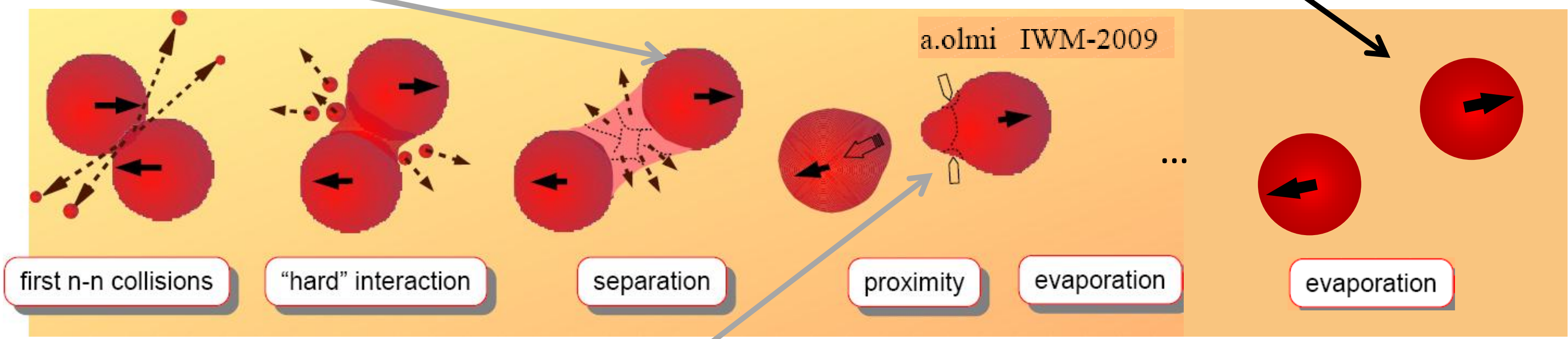

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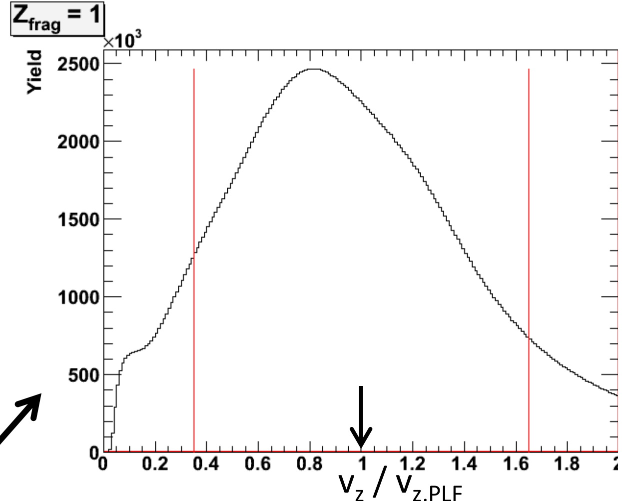
- Dissipation
- Decay Timescale

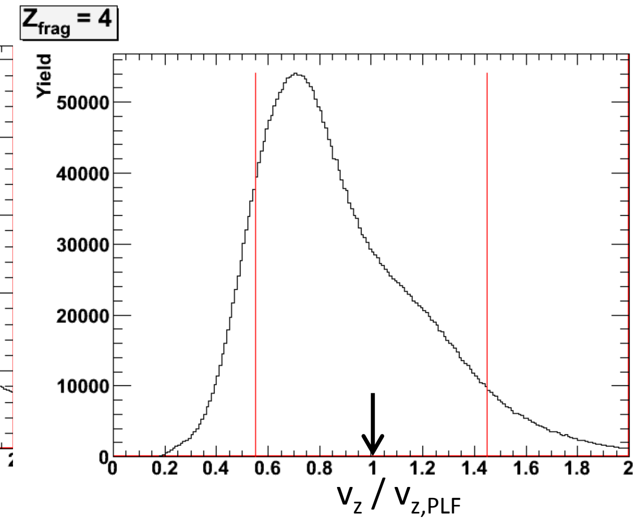
Source Selection

S. Wuenschel et al., PRC**79**, 061602 (2009)
J.C. Steckmeyer et al., NPA**686**, 537 (2001)

Remove particles that clearly do not belong (on average) to a statistically emitting projectile-like source

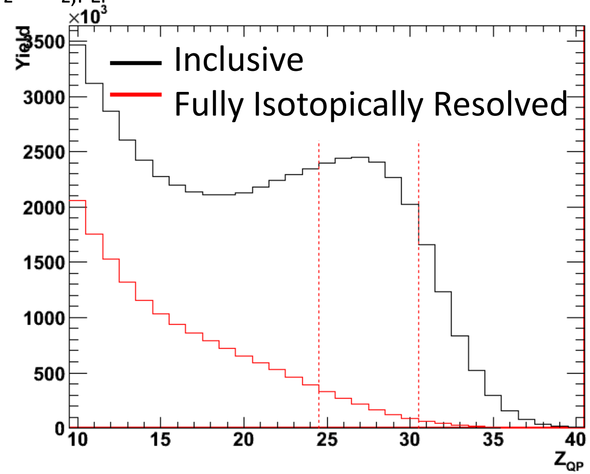
$$Z = 1: \quad 0.35 \le {}^{v_z}/_{v_{z,PLF}} \le 1.65$$
$$Z = 2: \quad 0.40 \le {}^{v_z}/_{v_{z,PLF}} \le 1.60$$
$$Z \ge 3: \quad 0.55 \le {}^{v_z}/_{v_{z,PLF}} \le 1.45$$





Select events with a well-measured QP:

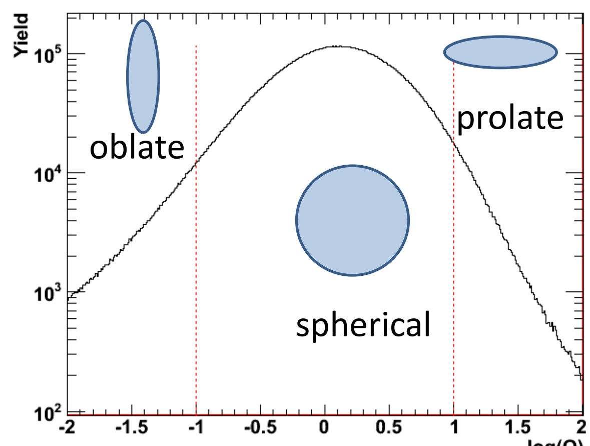
$$25 \le \sum Z \le 30$$



Select events with near-zero average momentum quadrupole.

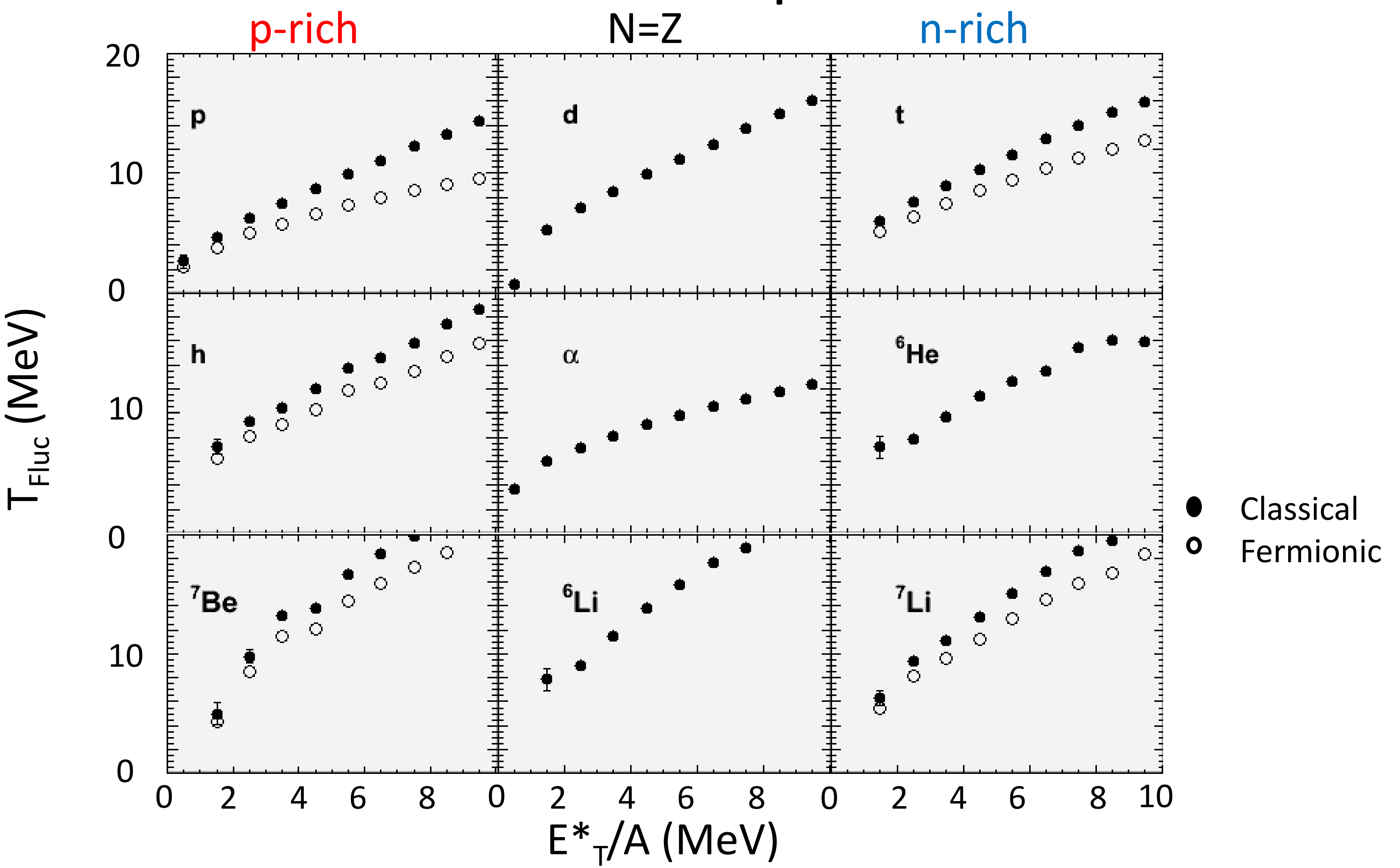
$$-1 \le \log Q \le 1$$

$$Q = \frac{\sum {p_{z,i}}^2}{\frac{1}{2}\sum {p_{T,i}}^2}$$



-- preliminary --

Fluctuation Temperature



Classical: $${\sigma_{xy}}^2 = 4m^2{T_{cl}}^2$$

Fermionic: $${\sigma_{xy}}^2 = \frac{16m^2{\epsilon_f}^2}{35}\left(1 + \frac{7}{6}\pi^2\left(\frac{T}{\epsilon_f}\right)^2\right)$$

$${\sigma_M}^2 = \frac{3}{2}\frac{T}{\epsilon_f}$$

Isoscaling of Fragments from Reconstructed Quasi-Projectiles

^{78,86}Kr + ^{58,64}Ni @ E/A = 35 MeV

Isoscaling over a very wide range of nuclides:
$1 \leq Z \leq 17$

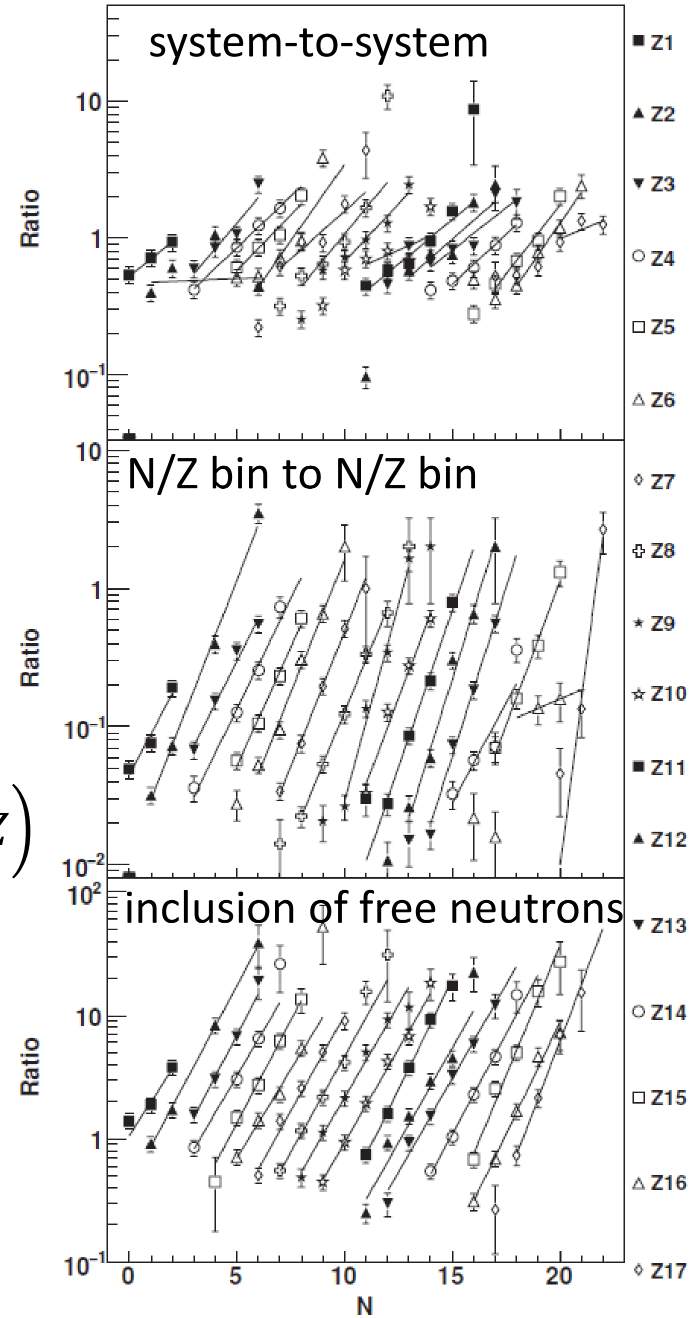
$$Y(N,Z) \propto exp\left(\left(-G(N,Z) + \mu_n N + \mu_p Z\right)/T\right)$$

$$R_{12}(N,Z) = \frac{Y_1(N,Z)}{Y_2(N,Z)} \propto exp\left(\frac{\mu_{n,2} - \mu_{n,1}}{T} N - \frac{\mu_{p,2} - \mu_{p,1}}{T} Z\right)$$

$$R_{12}(N,Z) \propto exp(\alpha N - \beta Z)$$

$$\frac{C_{sym}}{T} = \frac{\alpha}{\Delta}$$

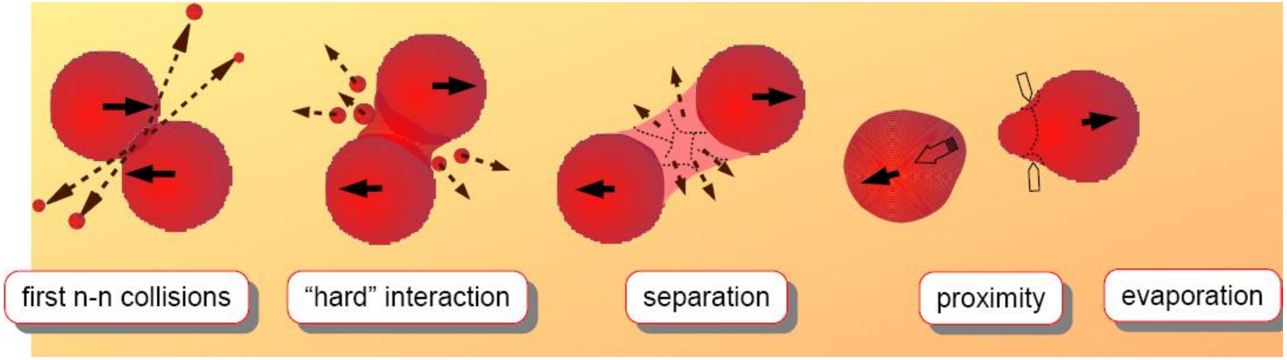
Careful source characterization is an integral part of this analysis!



S. Wuenschel et al., PRC **79**, 061602 (2009)
see also P. Marini et al., submitted to PRC

M.B. Tsang et al., PRC **64**, 054615 (2001)

- Challenge: to form a description of the heavy ion collisions that respects the dynamical and statistical evolution of the system



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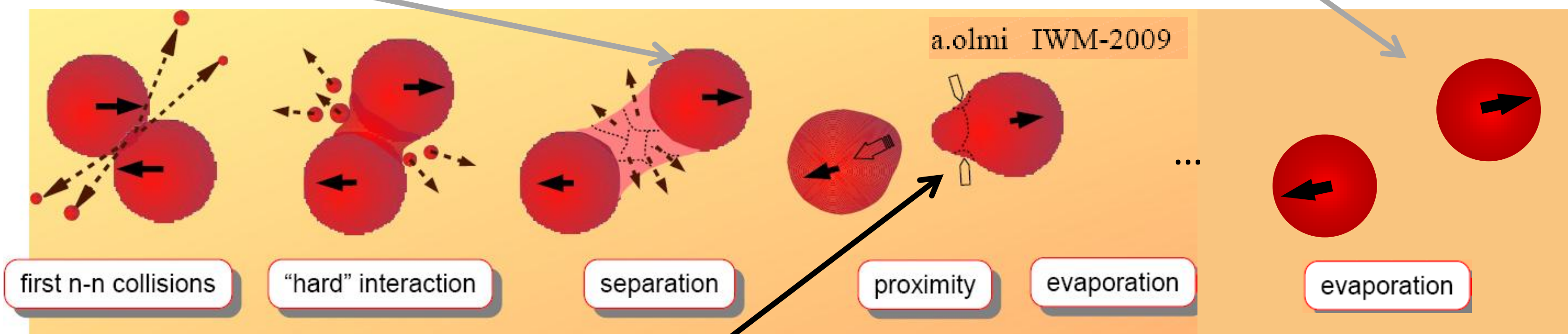

Alan McIntosh, Ph.D. Thesis, 2010
Indiana University

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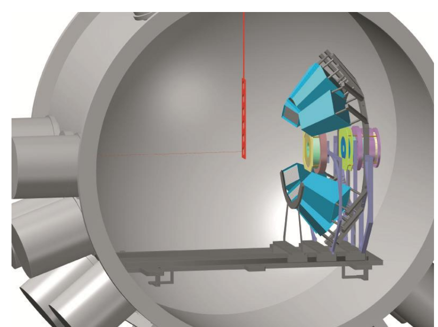
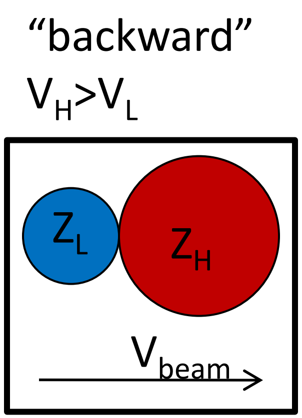
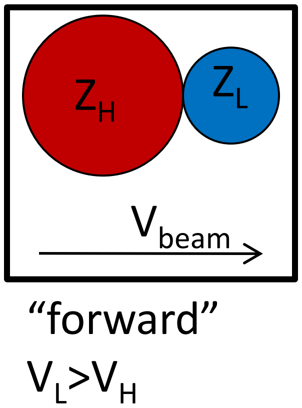
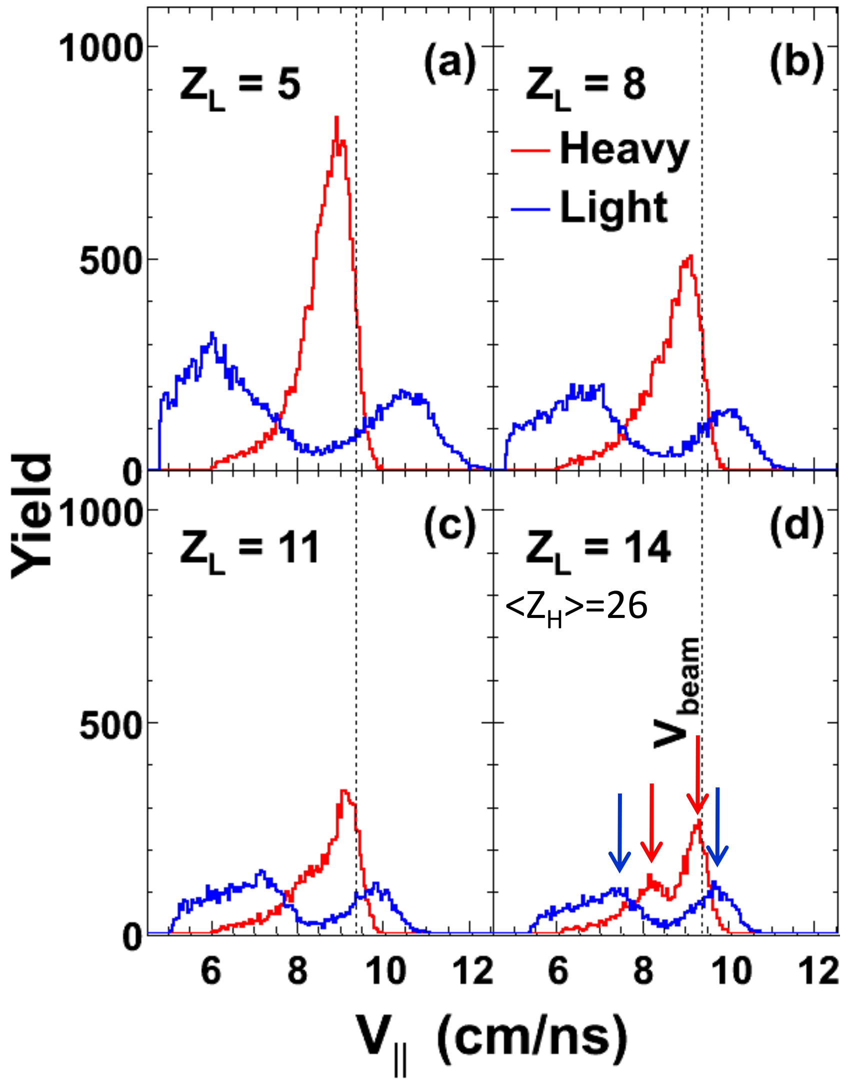


Out-of-equilibrium fragment production

Recoil Effects Between Z_{Heavy} and Z_{Light}

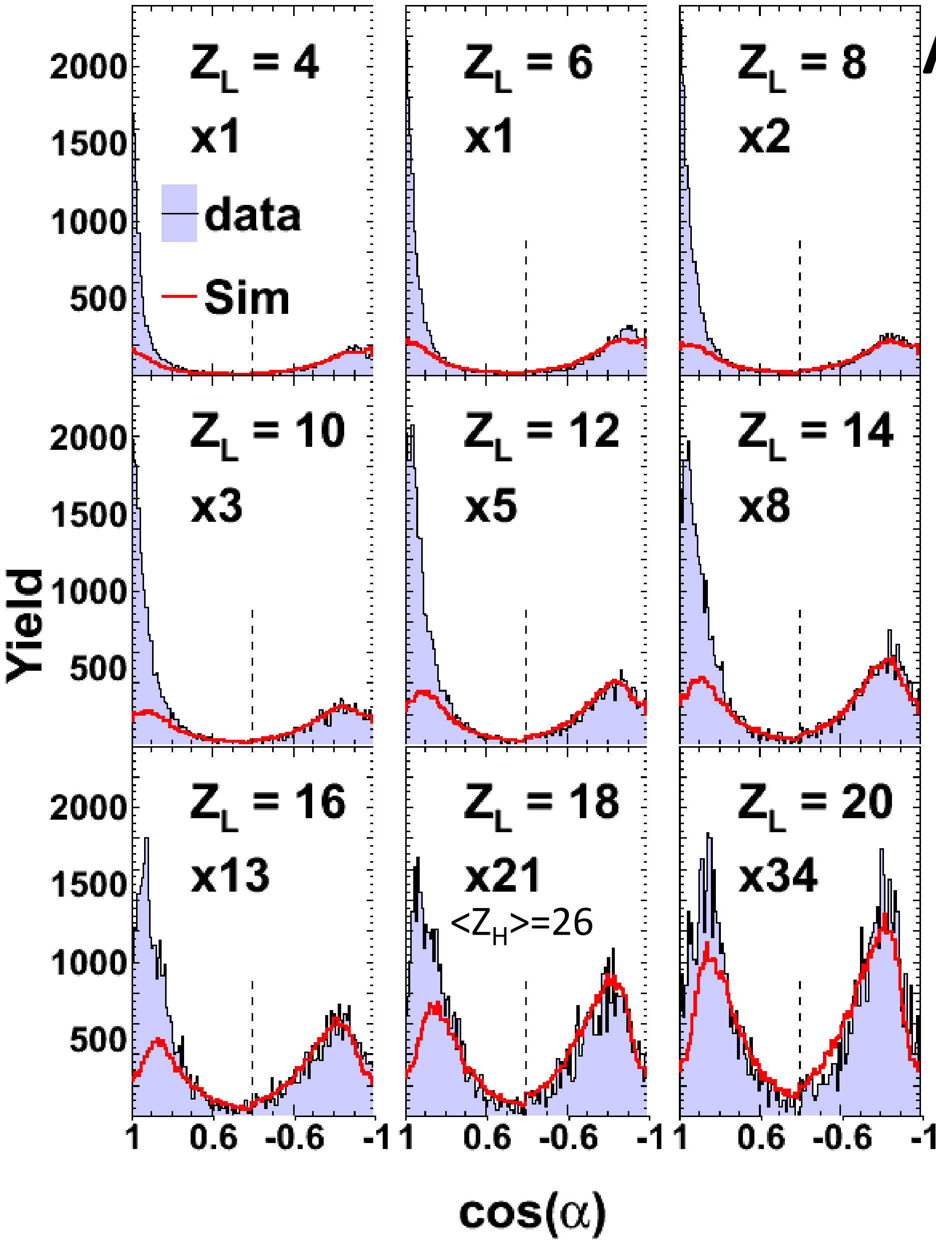


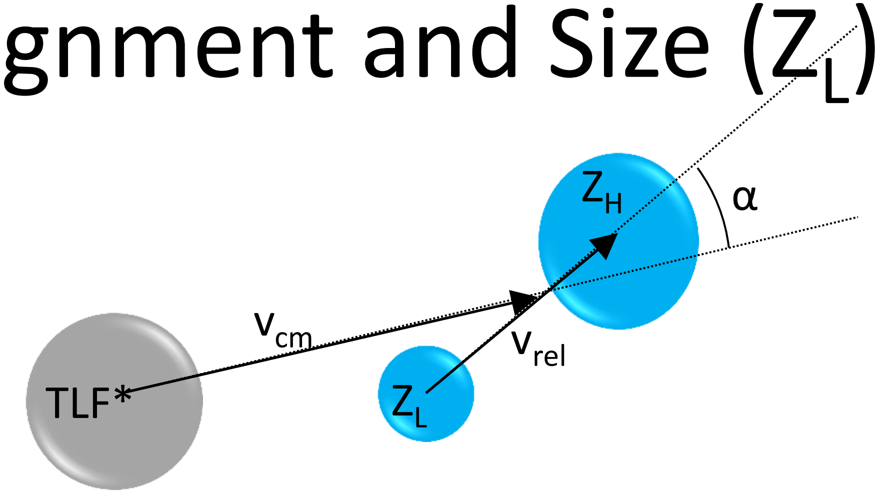




- Select events with at least **2 fragments** ($Z_H \geq 21$, $Z_L \geq 4$)
- $3° \leq \theta_{lab} \leq 7°$ selects only "forward" and "backward" break-up
- Light fragment (Z_L) is peaked forward of mid-velocity
- Recoil effects indicate a common parent

Alignment and Size (Z_L)

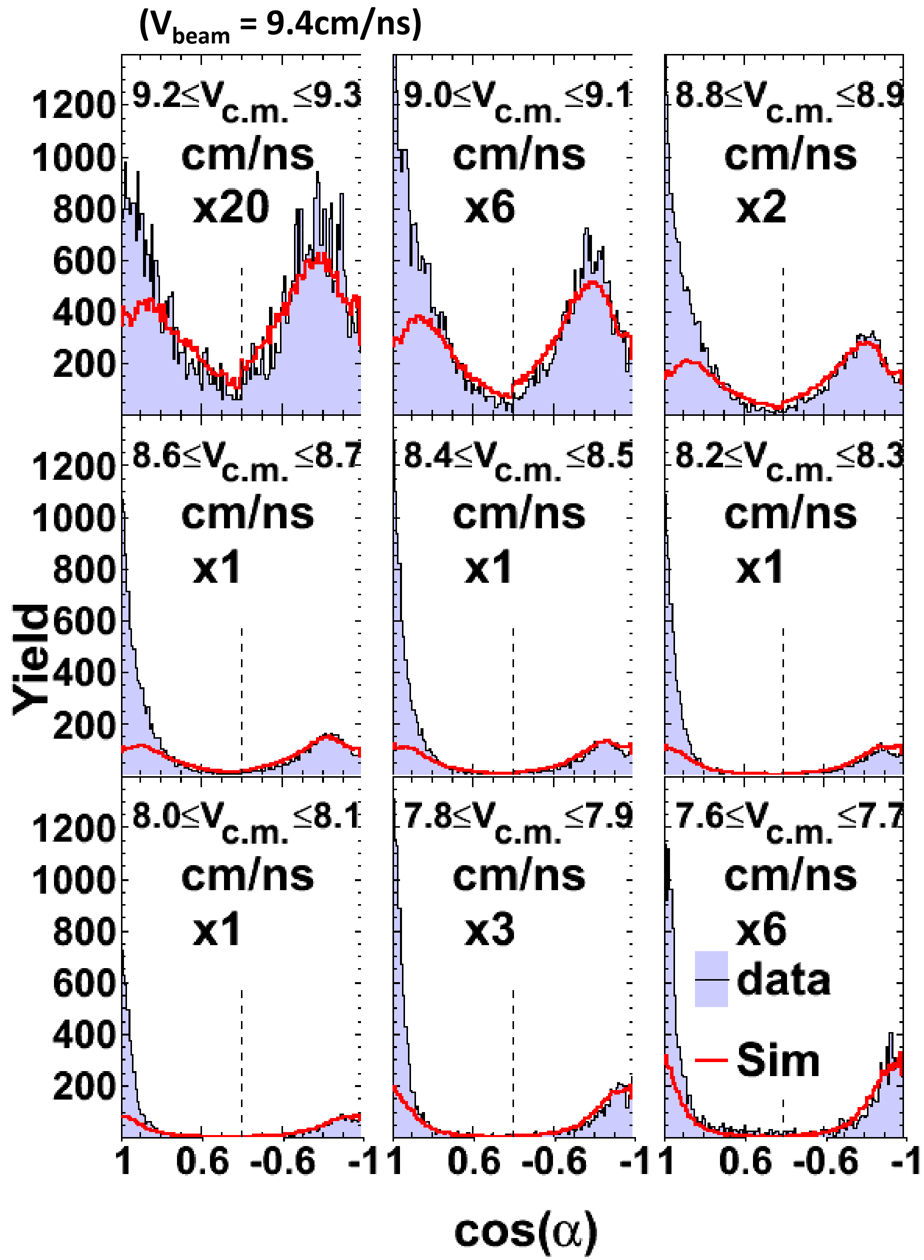




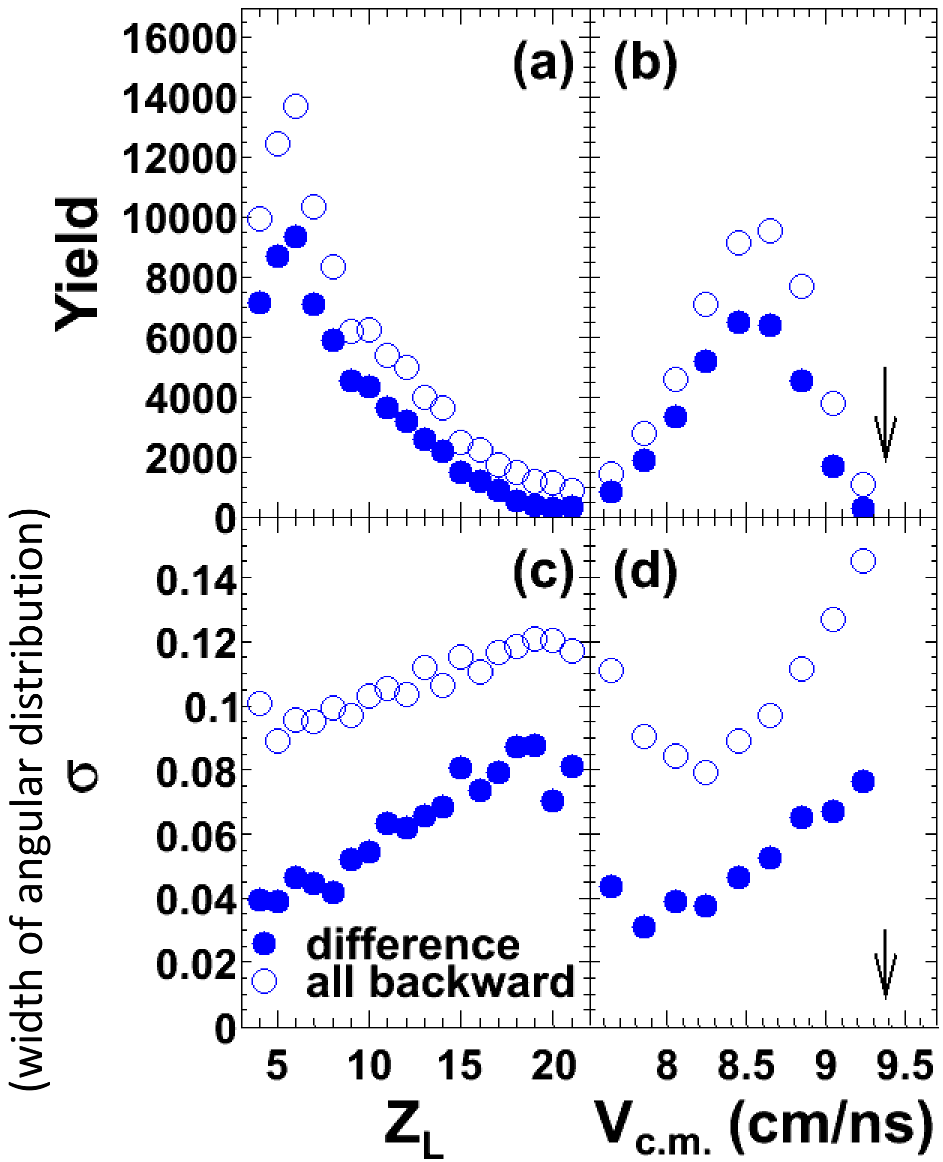
- Excess yield of IMF emitted toward Target-Like Fragment
- —— Isotropic emission cannot account for backward yield
- Strong alignment
- **Alignment decreases with Z_L**
- **Persists to near-symmetric splits**
- Mechanism…

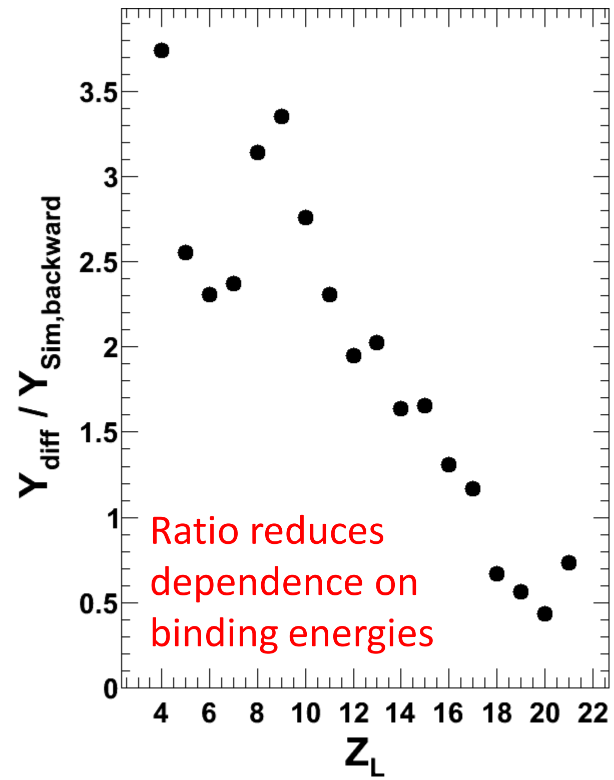
Velocity Damping and Alignment

- Detector acceptance accounted for
- Isotropic emission describes forward emission, but not backward emission
- **Correlation: Alignment increases with damping**



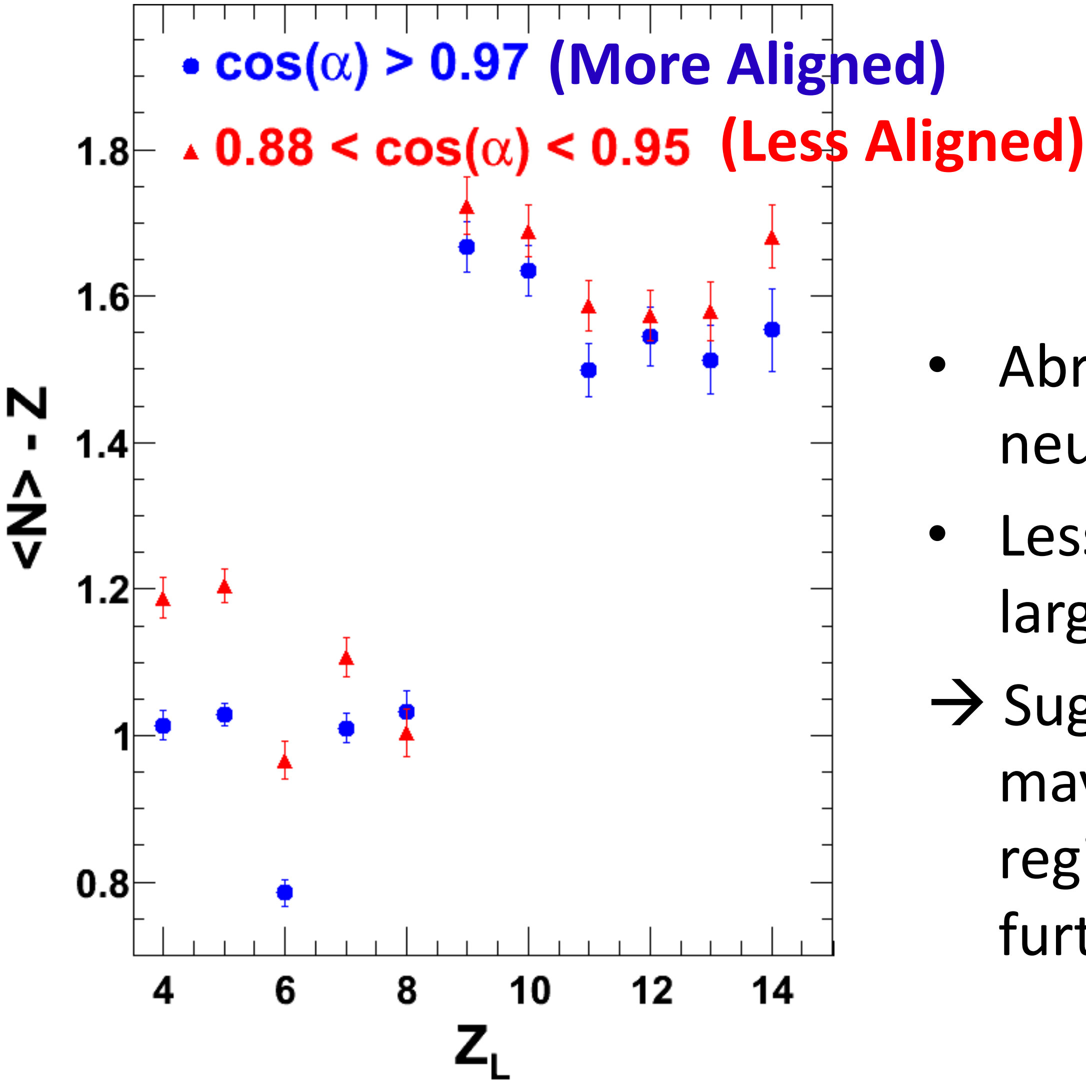
- Smooth evolution in both the yield and width
  - Asymmetric ←→ Symmetric
  - Small damping ←→ Large damping

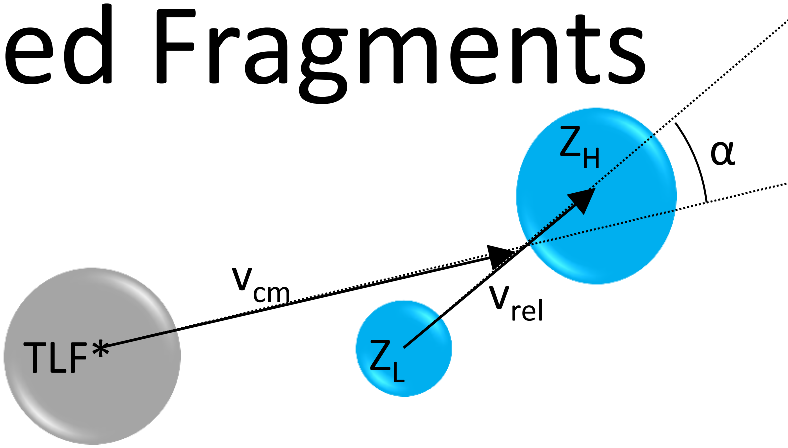




Relative yield is peaked at Z_L=9

Composition of Aligned Fragments





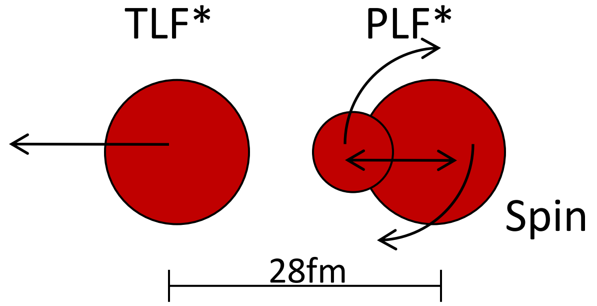
- Abrupt change in average neutron excess at Z_L=9
- Less aligned fragments have larger neutron excess

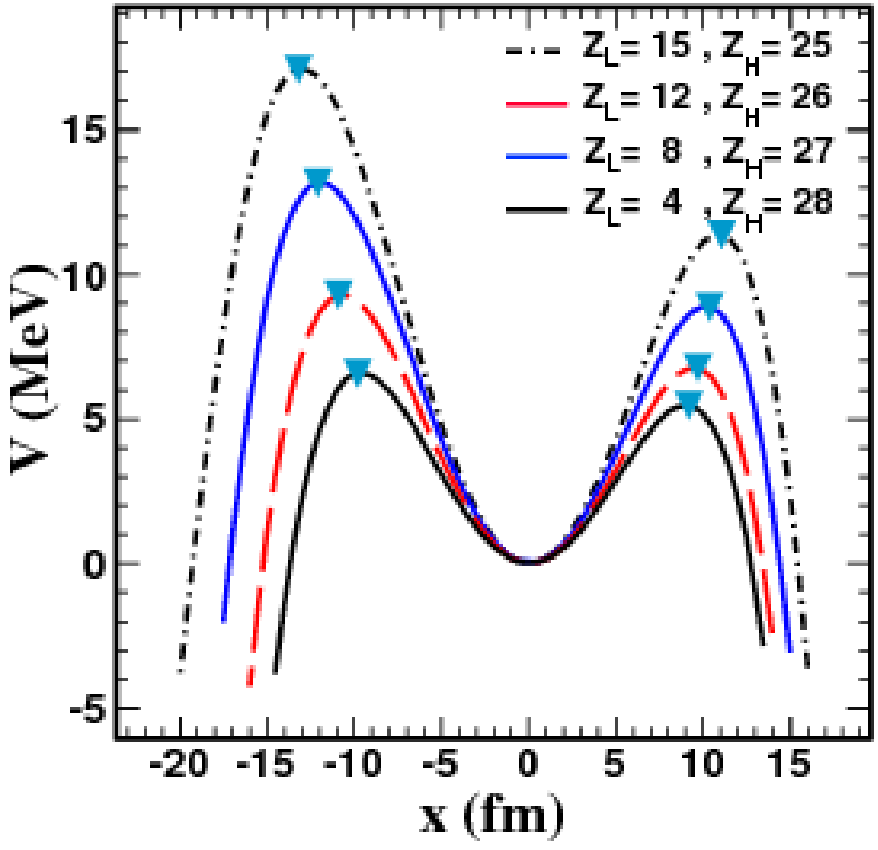
→ Suggests isospin equilibration may not reached between regions of the decaying PLF*, further investigation needed

^{124}Xe + ^{124}Sn @ E/A = 50 MeV
McIntosh et al., PRC 81, 034603 (2010)

Langevin Model

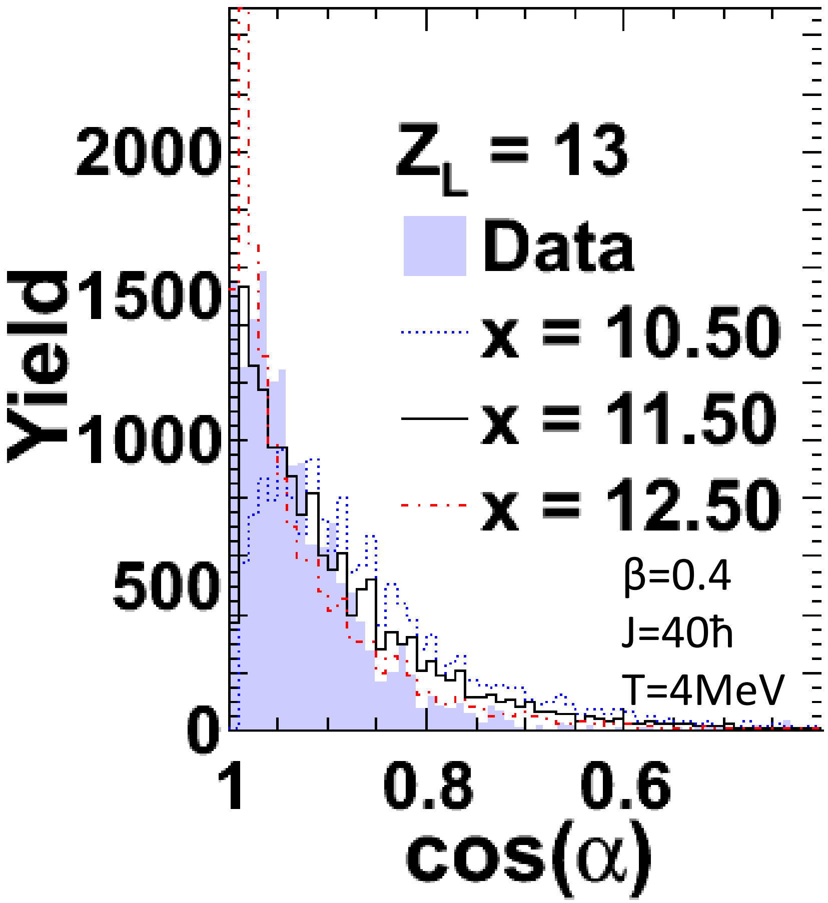
- Separation of PLF* into Z_L and Z_H evolves on a potential energy surface
- Nuclear between Z_H and Z_L
- Coulomb between Z_H, Z_L and the target-like fragment
- High-fraction Limit: Motion is over-damped
- Motion along the potential energy surface is stochastic (thermal)

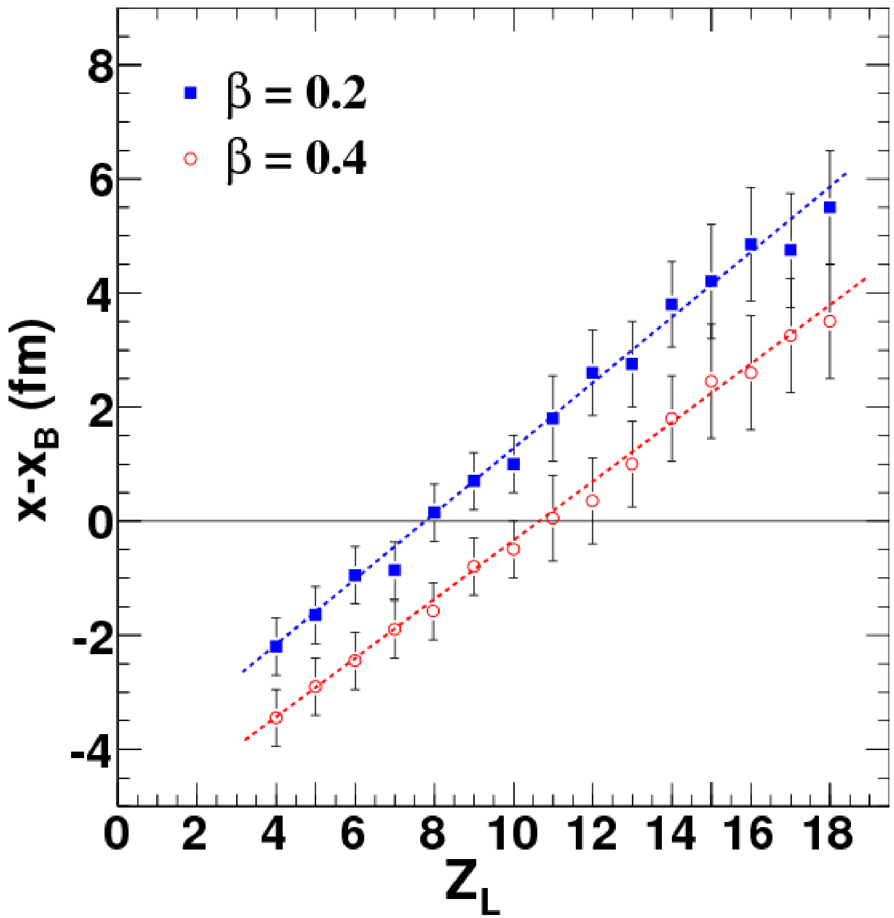




Langevin model courtesy of R. Charity

Langevin Model

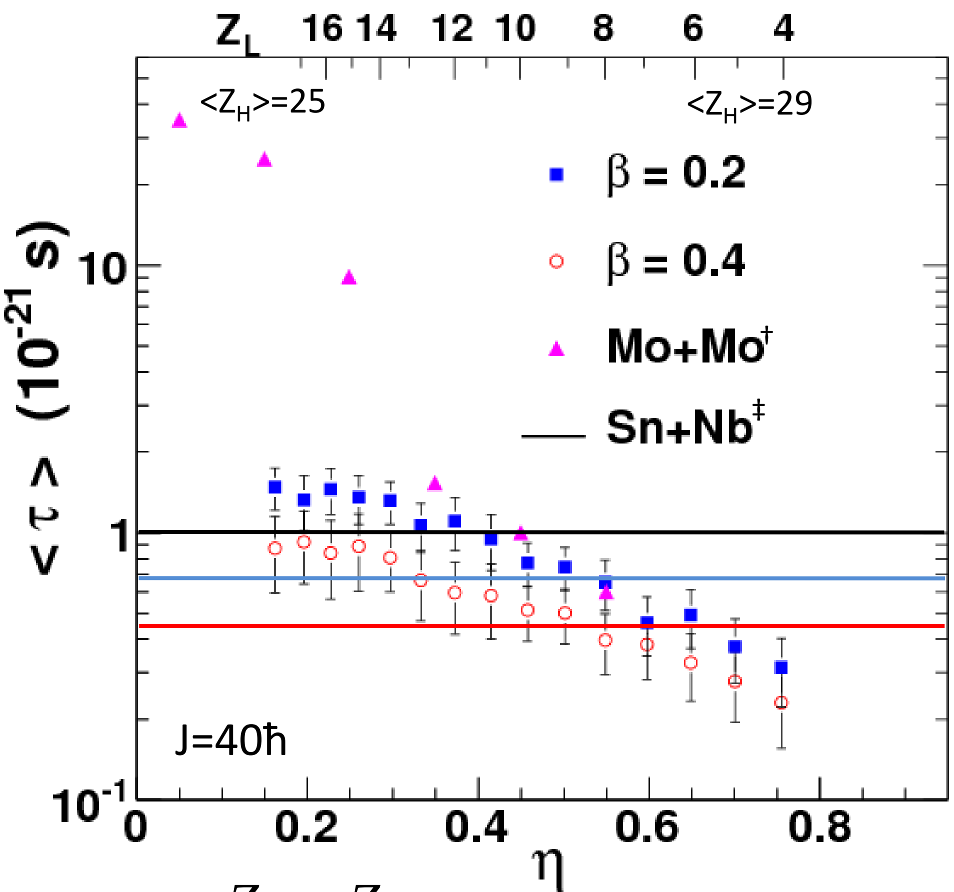




Account for detector acceptance & granularity.
Vary the initial deformation (x) to reproduce the experimental angular distributions.
→ Sensitivity <1.0fm

Within the context of the model, the lightest fragments are produced from systems already deformed beyond the barrier

Timescale of Aligned Decay



$$\eta = \frac{Z_H - Z_L}{Z_H + Z_L}$$

124Xe + 124Sn @ E/A = 50 MeV
McIntosh et al., PRC 81, 034603 (2010)

Z_L=4:
$\langle\tau\rangle$ = 0.25 - 0.35x10^{-21}s
(75-100fm/c)

Z_L=18:
$\langle\tau\rangle$ = 0.90 - 1.5x10^{-21}s
(270-450fm/c)

For J=30ħ → increase τ by 25%

† Mo + Mo at E/A = 20MeV
Casini et al., PRL **71**, 2567 (1993)

‡ ^{116}Sn + ^{93}Nb at E/A = 29MeV
Piantelli et al., PRL **88**, 052701 (2002)

Correlations Summary

- Smooth evolution of aligned component with size (Z_L)
  - Stronger alignment for small Z_L
  - Alignment persists for near-symmetric splits
- Smooth evolution of aligned component with damping
  - Alignment increases with damping
- Decay time-scale ($0.25\text{-}1.5\text{x}10^{-21}$s) evolves with Z_L (or η)
- Transition around Z_L=9 observed in:
  - Composition (N/Z), Relative Yield, Distance from the Barrier
- Observed dependence of composition on decay orientation
  - Suggests sensitivity to N/Z transport *within* an excited transiently-deformed nucleus – further investigation is needed.

McIntosh et al., PRC 81, 034603 (2010)

Final Remarks

- Dynamical transport models and molecular dynamics models are used to extract information on $E_{sym}(\rho)$.
- These models are successful in describing some aspects of fragment production – but a more complete description of the reaction is necessary to constrain $E_{sym}(\rho)$
- Single description of the reaction needed – respect both dynamical & statistical nature
- Cluster production in the dynamical evolution
- Correlations between observables for dynamically produced fragments → Further constraints for models