Equilibration Chronometry

Characterizing neutron-proton equilibration with sub-zeptosecond resolution

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INPC 2016

Motivation:

Constrain the nuclear equation of state.

Background:

NZ equilibration should be directly observable in heavy ion reactions.
One fragment from binary split evolves in time.

Hypothesis:

The composition of the two fragments from a binary split should evolve toward each other with time.

Methods:

NIMROD 4π array.
First measurement of NZ of both fragments.
Fine time resolution from alignment angle.

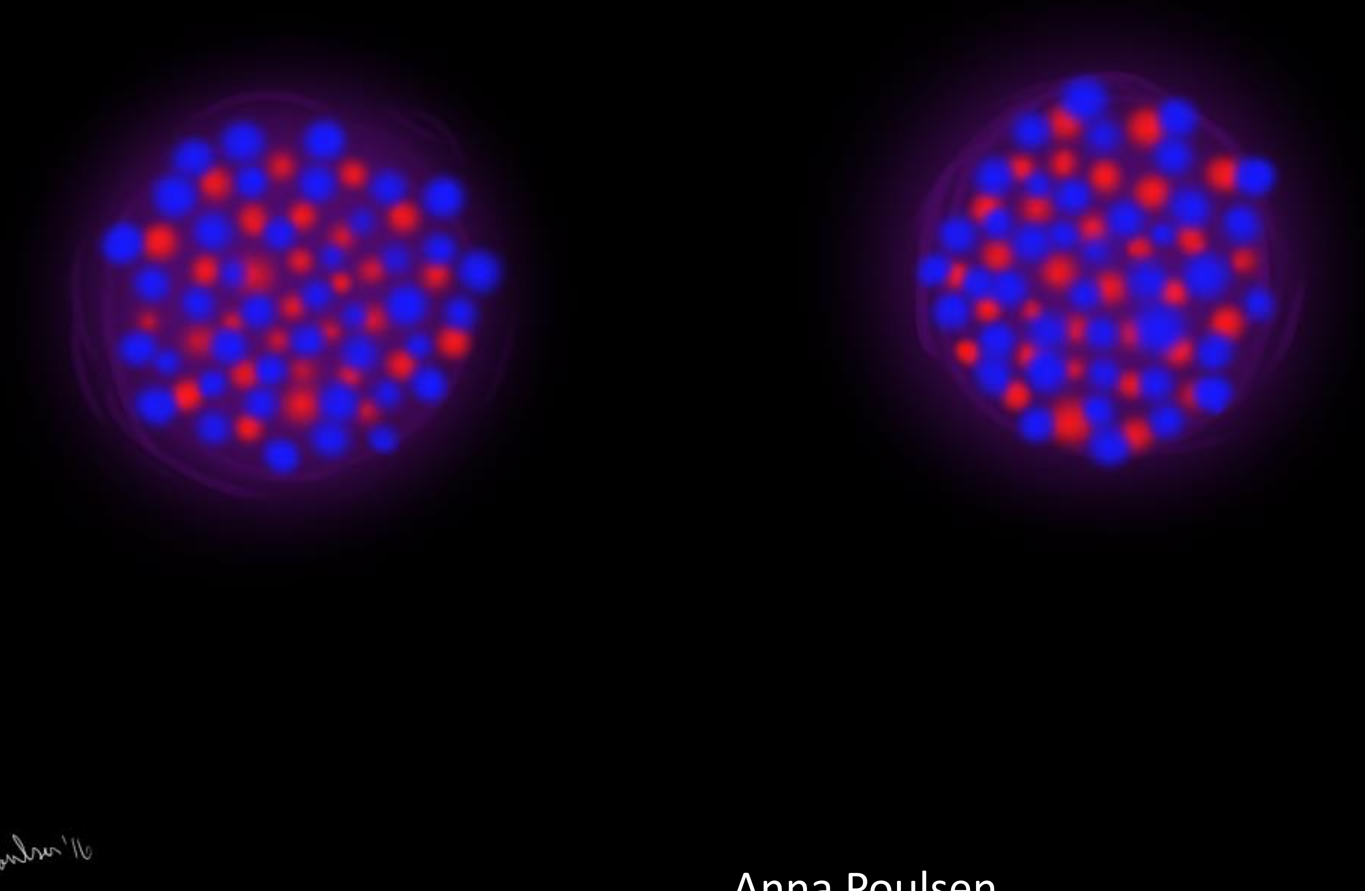
Results:

<u>We observe NZ equilibration as a function of time.</u>
Equilibration curve is approximately exponential → First order kinetics
Zeptosecond timescale.

Target

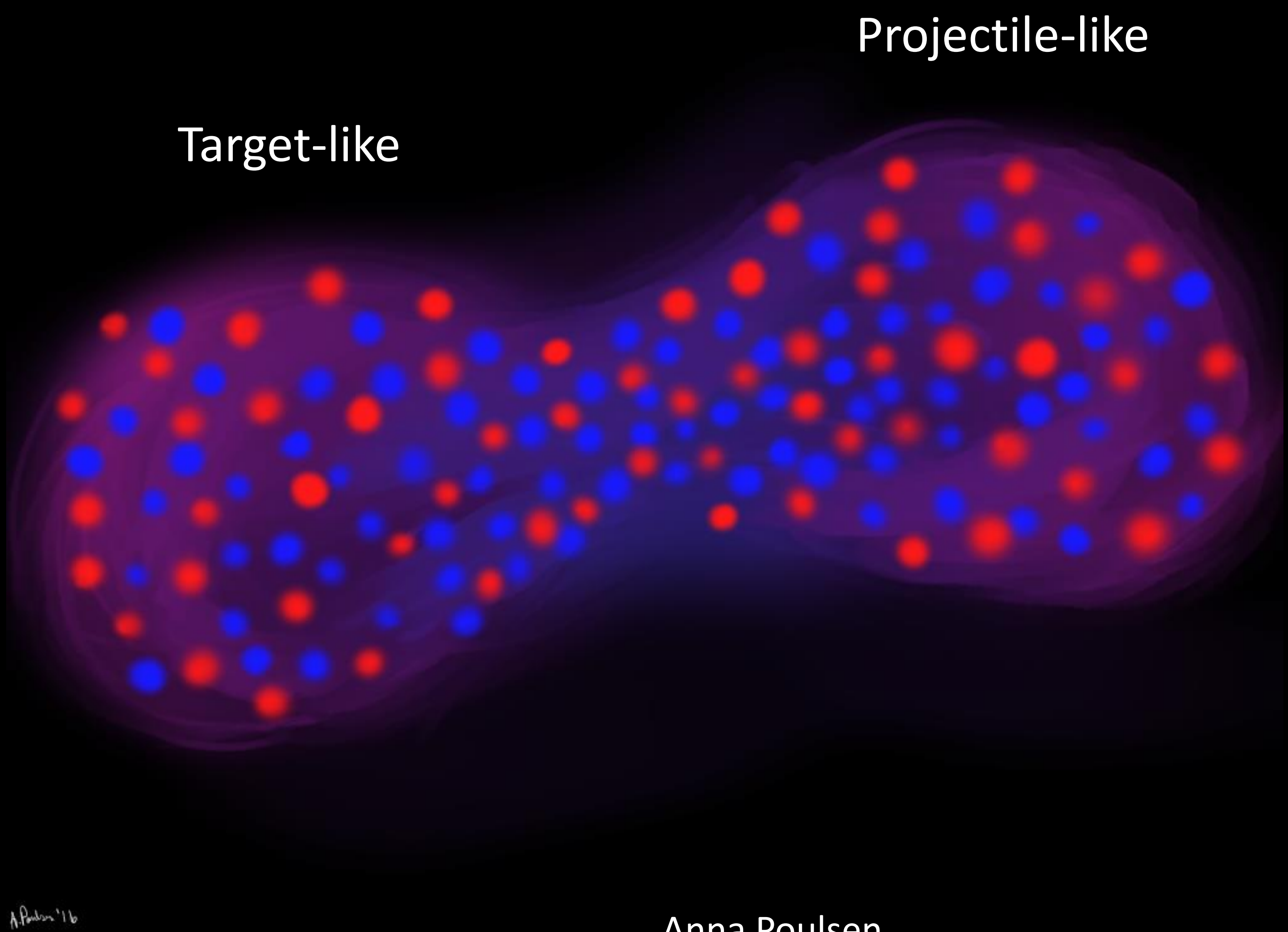
Projectile

Zn-70



Zn-70

Anna Poulsen
https://oxidantshappencomics.wordpress.com/



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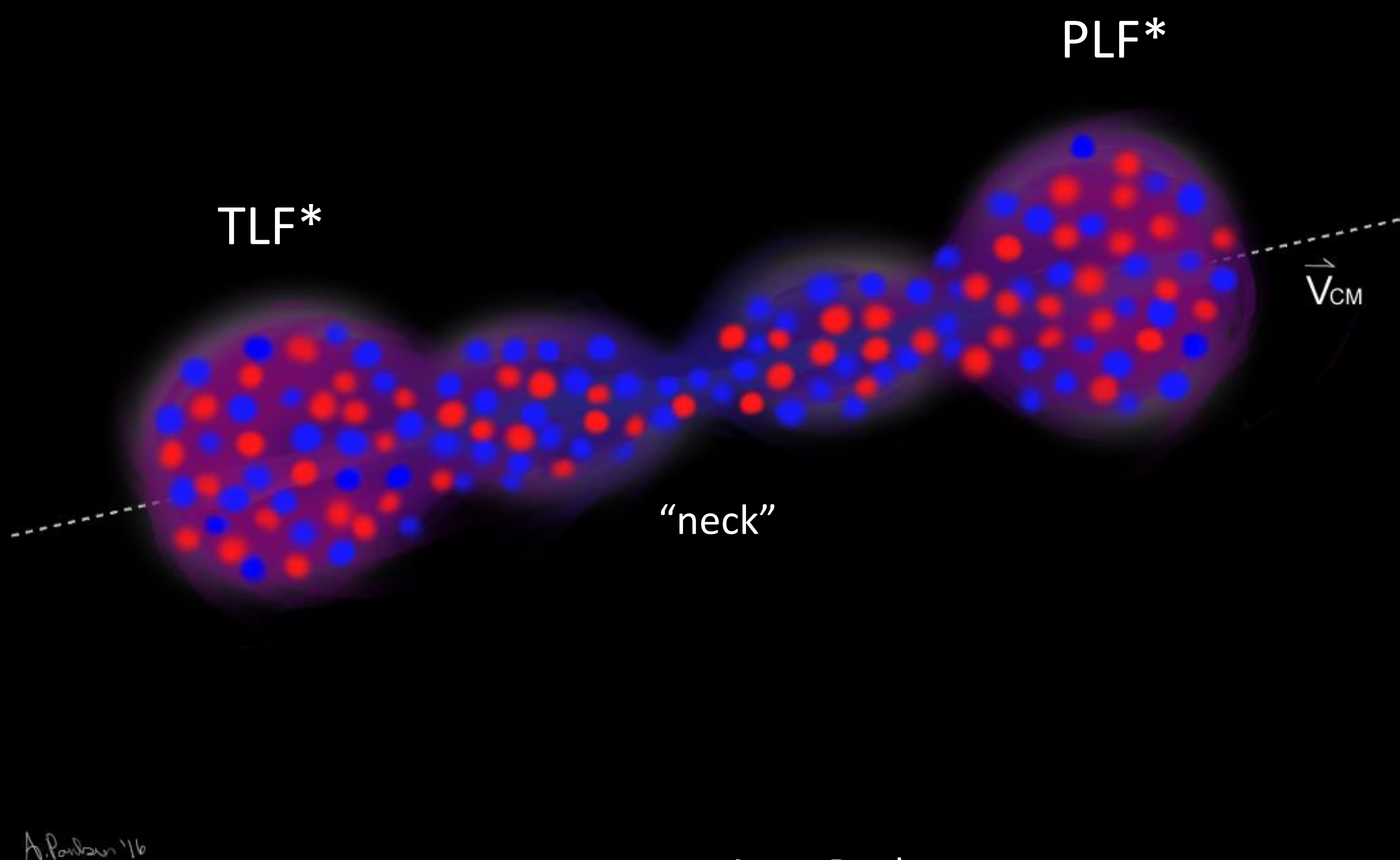

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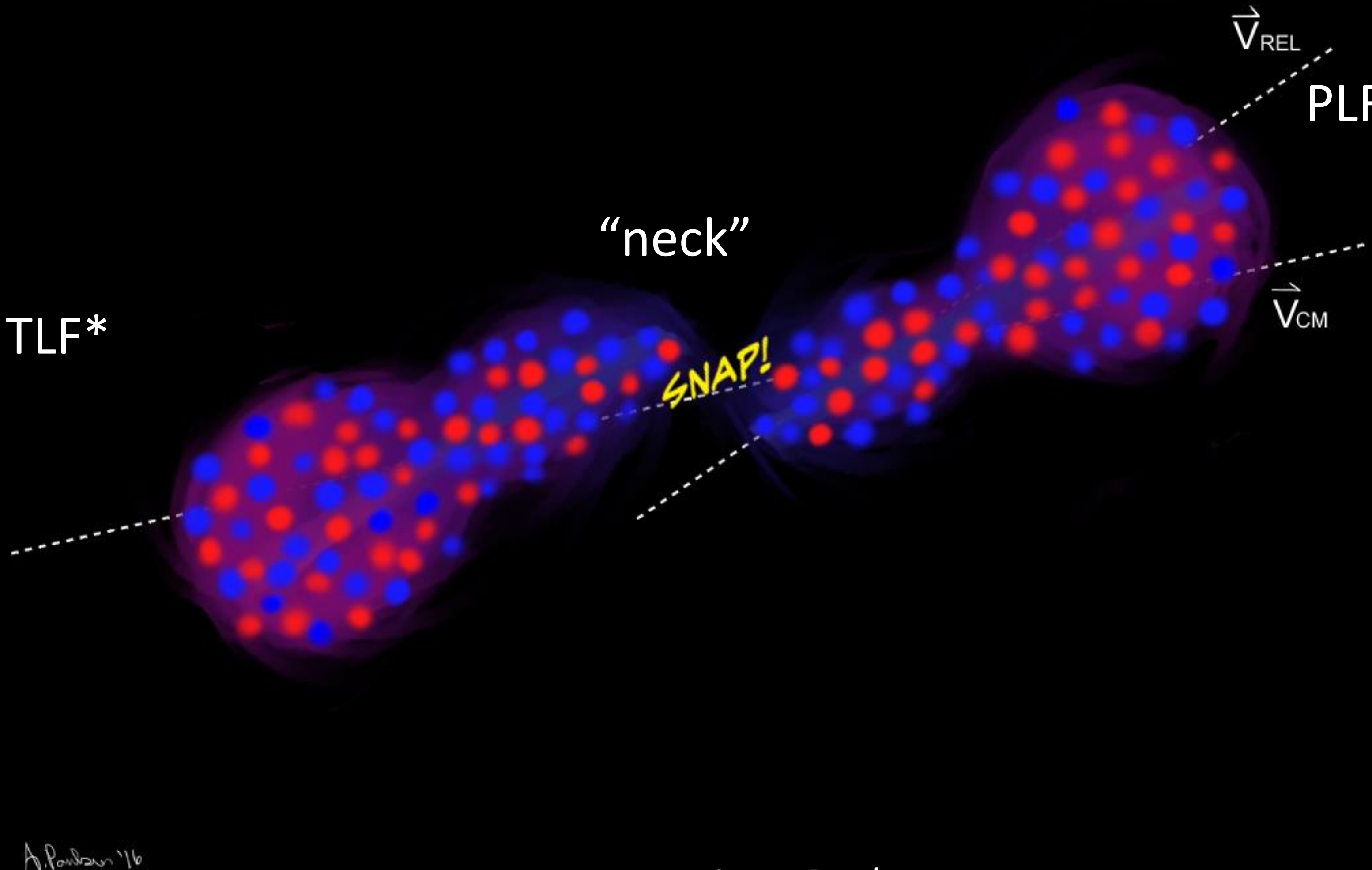

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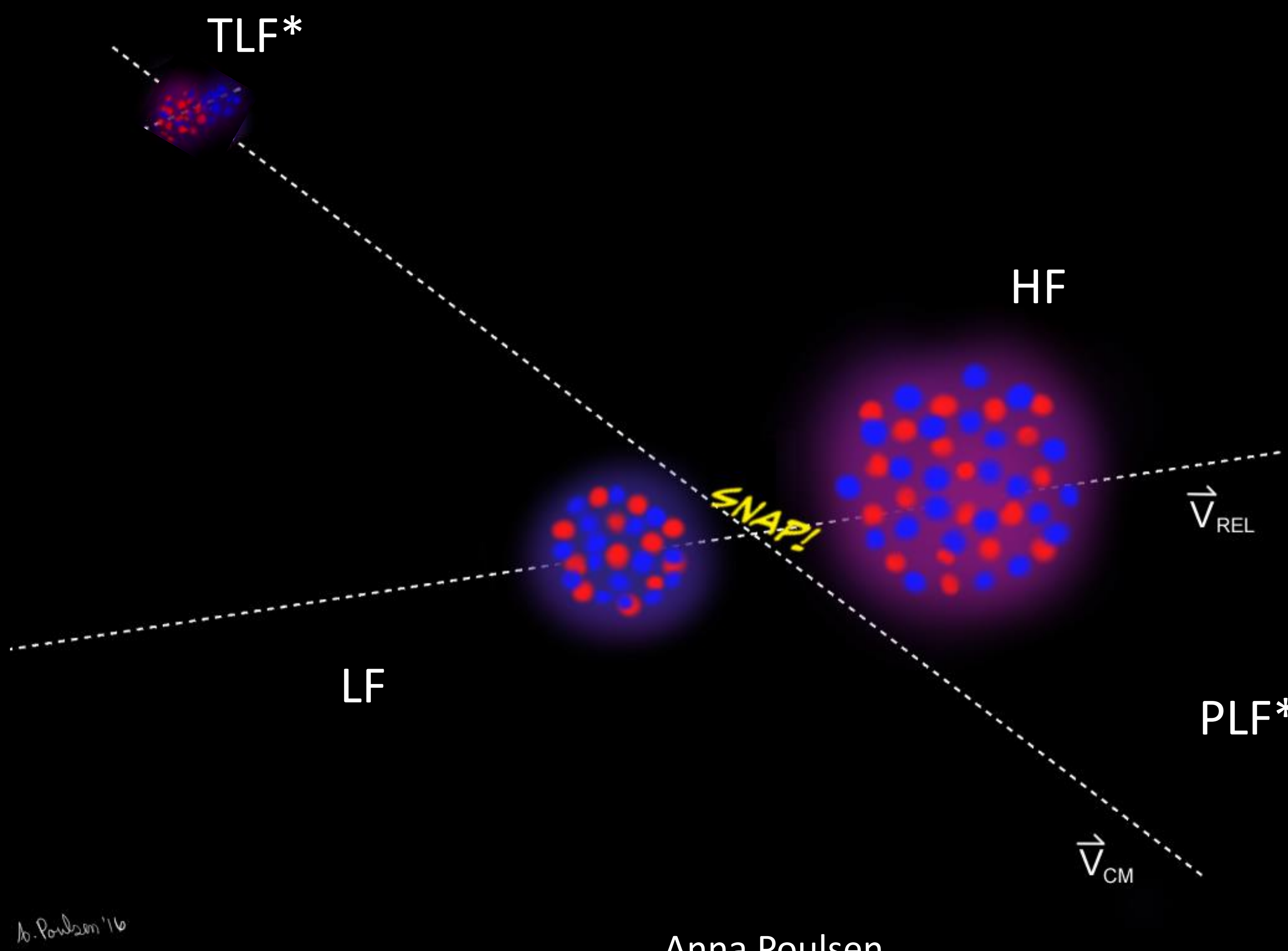

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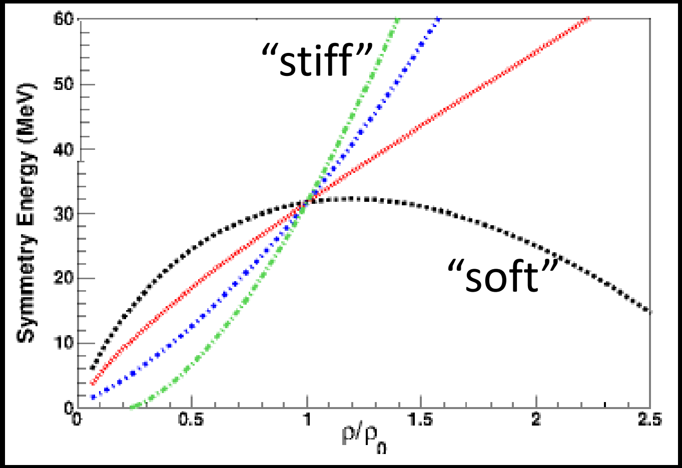
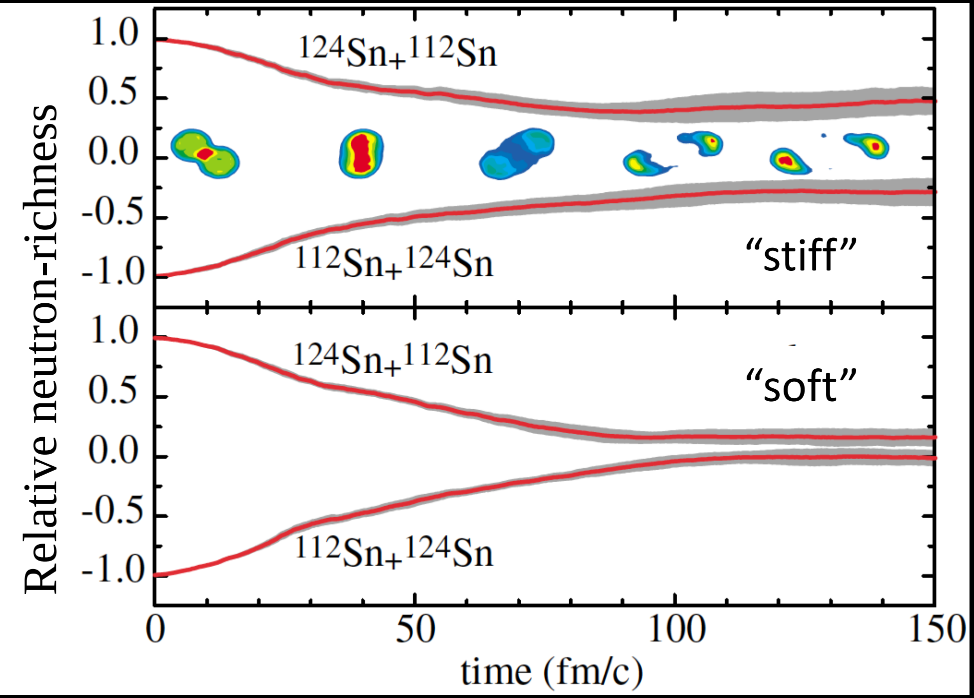
Probing the Equation of State with NZ Equilibration





Tsang et al. PRC 86, 015803 (2012)
Tsang et al, PRL 92, 06270 (2004)

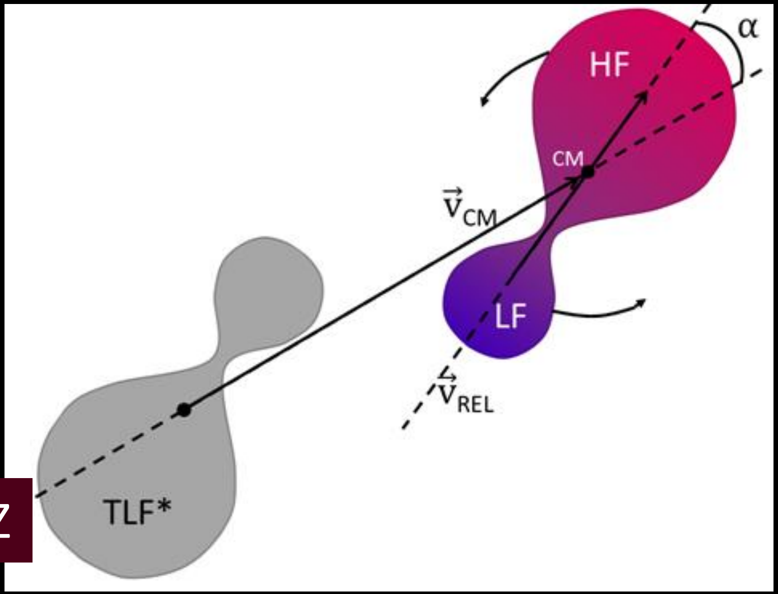
Degree of equilibration between projectile and target determined by

- contact time
- strength of the driving potential (EoS).

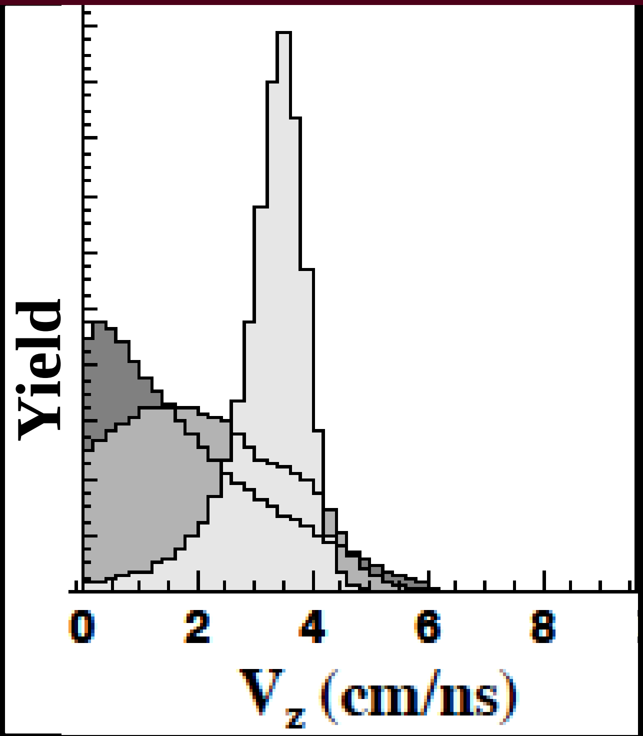
Measure as a function of time?

- *Why shouldn't we?*

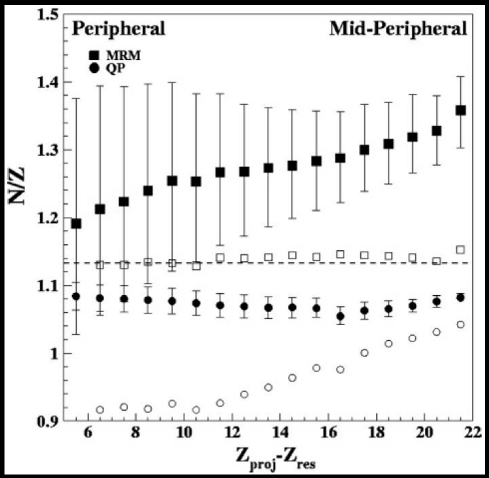
Asymptotic values provide information to the EoS



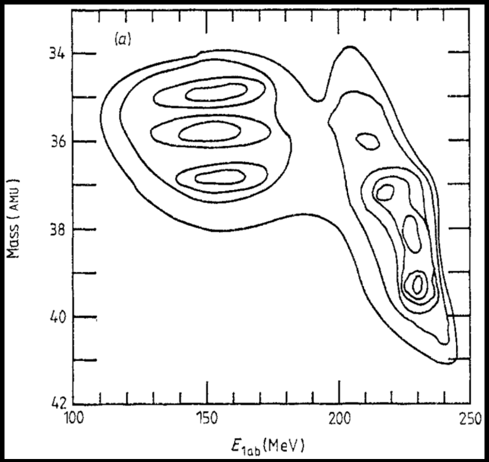
1. Ordered, aligned decay in Z



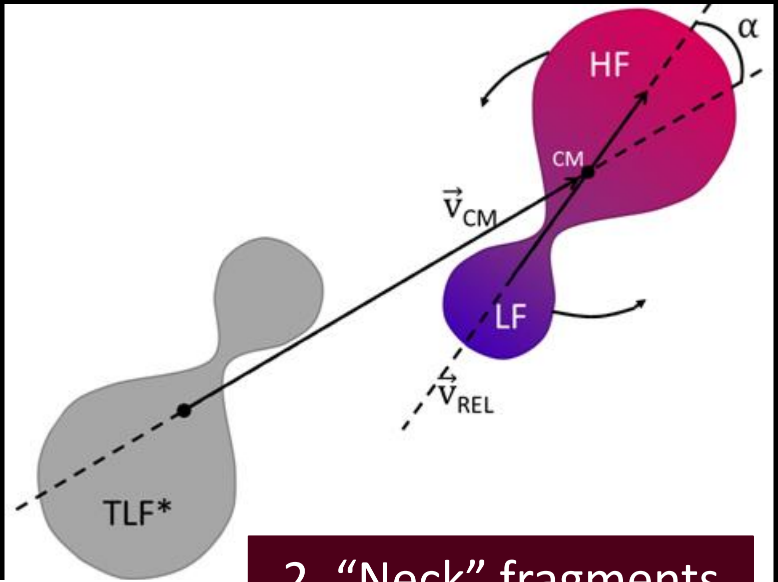
Colin et al, PRC 67, 064603 (2003)



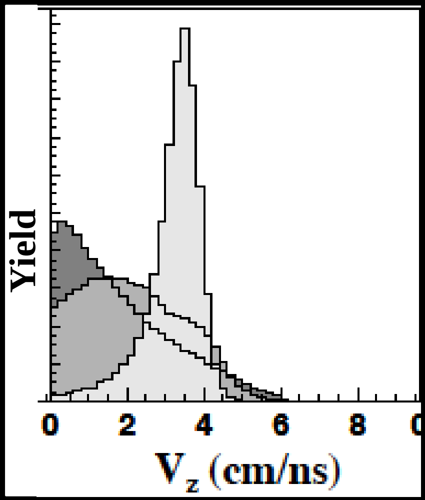
Theriault et al, PRC 74, 051602 (2006)



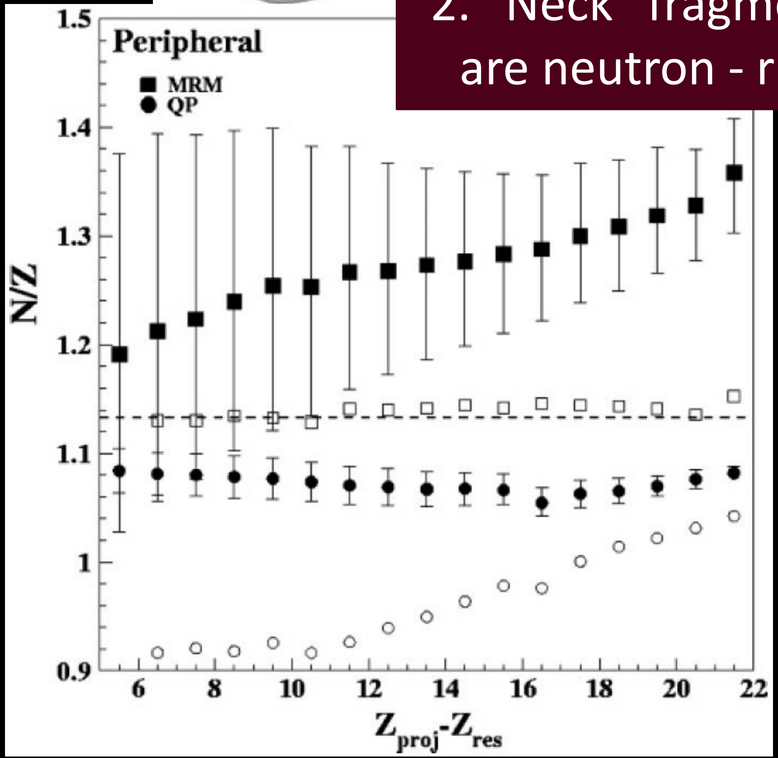
Galin et al, Z. Physik A. 278, 347-352 (1976)

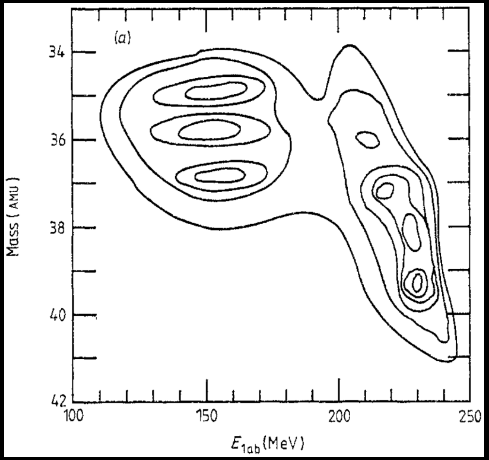


2. "Neck" fragments are neutron - rich



Colin et al, PRC 67, 064603 (2003)

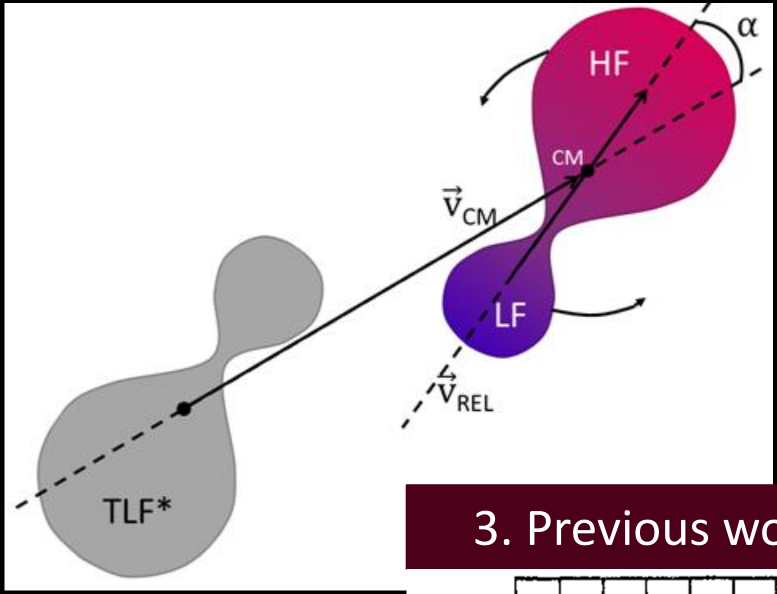


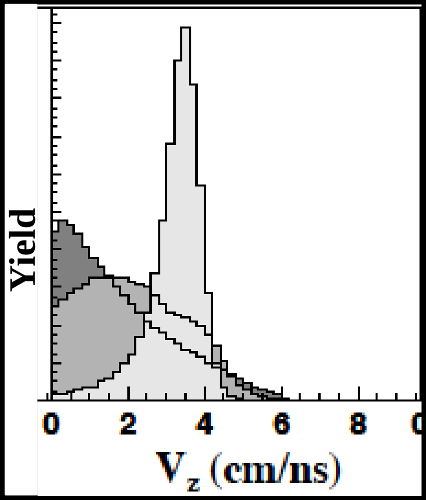


Galin et al, Z. Physik A. 278, 347-352 (1976)

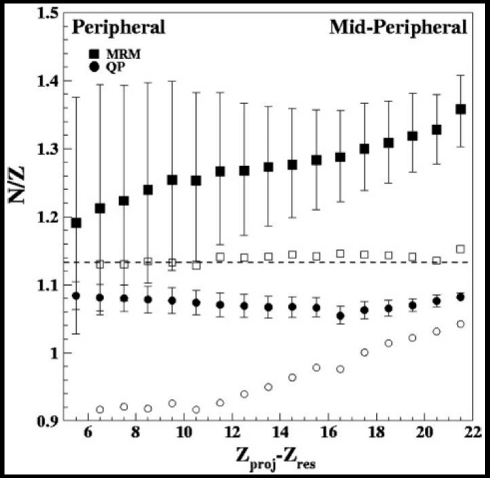
Theriault et al, PRC 74, 051602 (2006)

3. Previous work on timescale

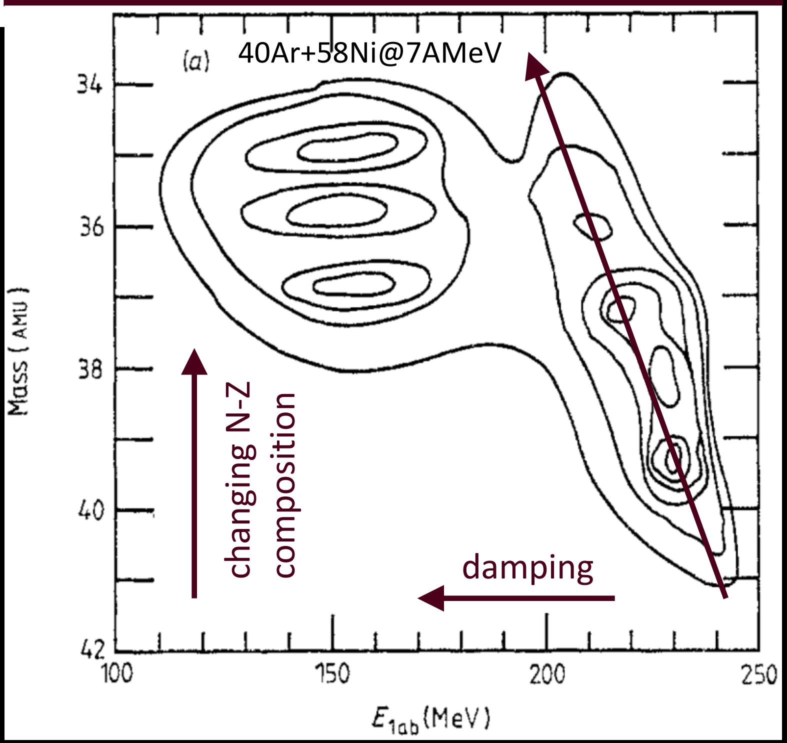




Colin et al, PRC 67, 064603 (2003)



Theriault et al, PRC 74, 051602 (2006)

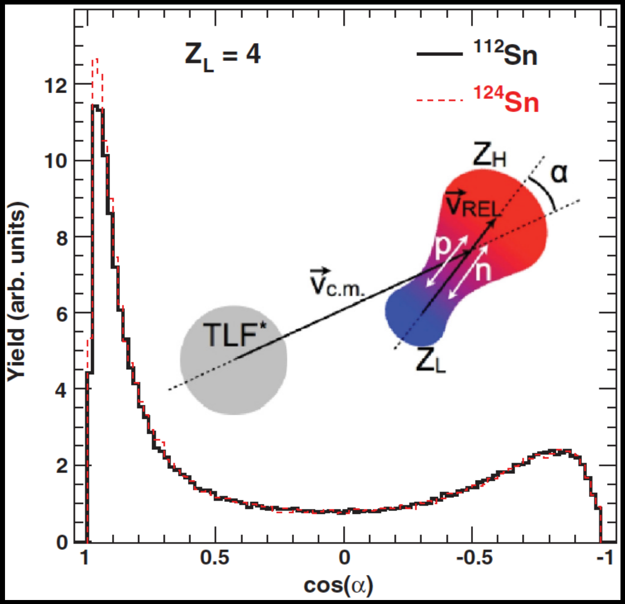


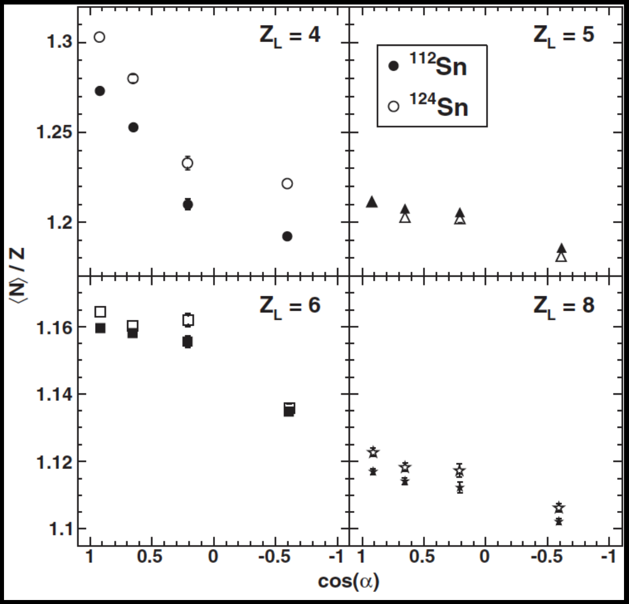
Galin et al, Z. Physik A. 278, 347-352 (1976)

Connecting NZ equilibration to angle

Hudan et al. PRC 86, 921603(R) (2012)

Xe + Sn @ 50A MeV





Angular distribution strongly aligned

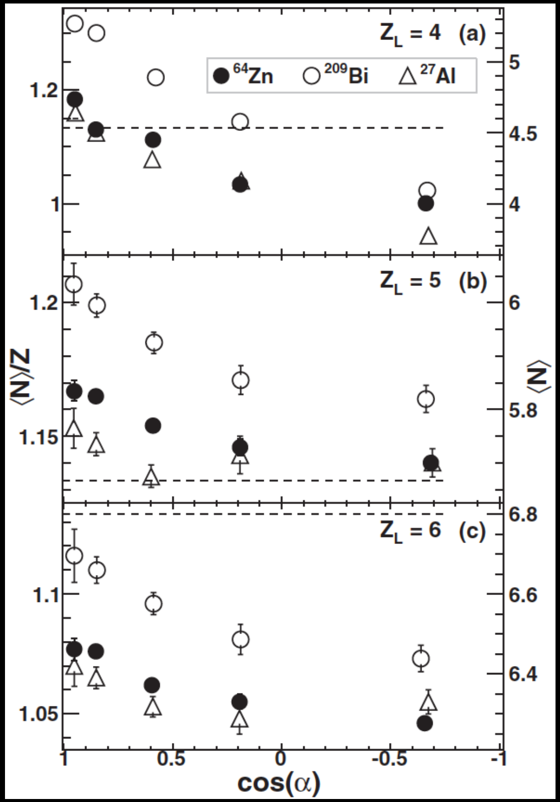
- Indicates dynamical decay

Time scale shorter than rotational period

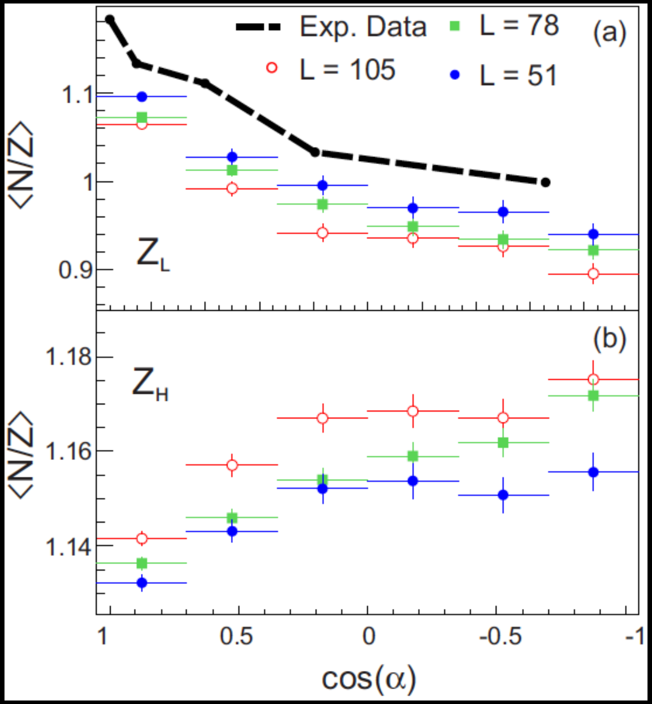
Composition (N/Z) of lighter fragment decreases monotonically with decay orientation

Target effects and simulations

Brown et al. PRC 87, 061601(R) (2013)
Stiefel et al. PRC 90, 061605(R) (2014)
Zn + Al, Zn, Bi @ 45A MeV



- Consistent with Hudan
- NZ composition depends on NZ target composition

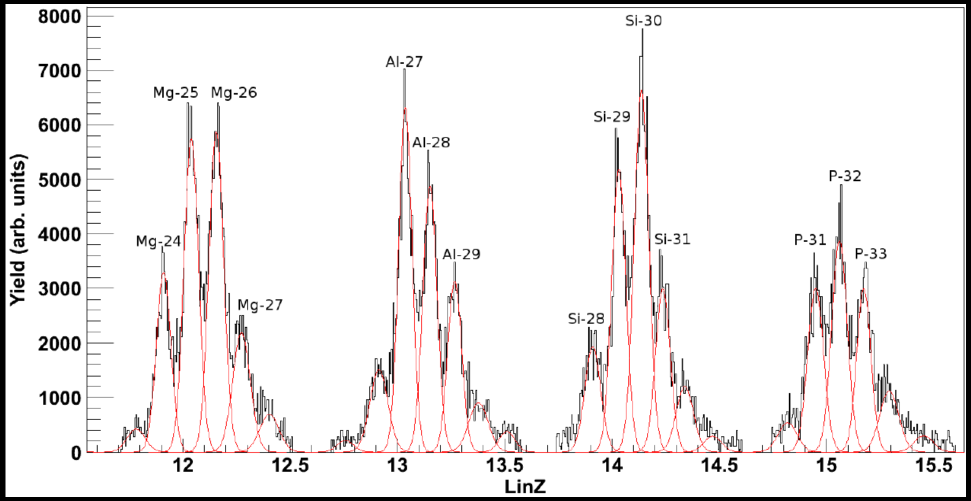


- Agrees with data
- Dependent on density dependence

OUR NEW MEASUREMENT

NIMROD 4π Array
$^{70}Zn + ^{70}Zn$ @ 35A MeV

- High-statistics, large angular acceptance and measurement of NZ composition of **HF** and **LF**.
- First-class isotopic resolution
  - Z=17 in many detectors
  - beyond Z=20 in high-performing detectors



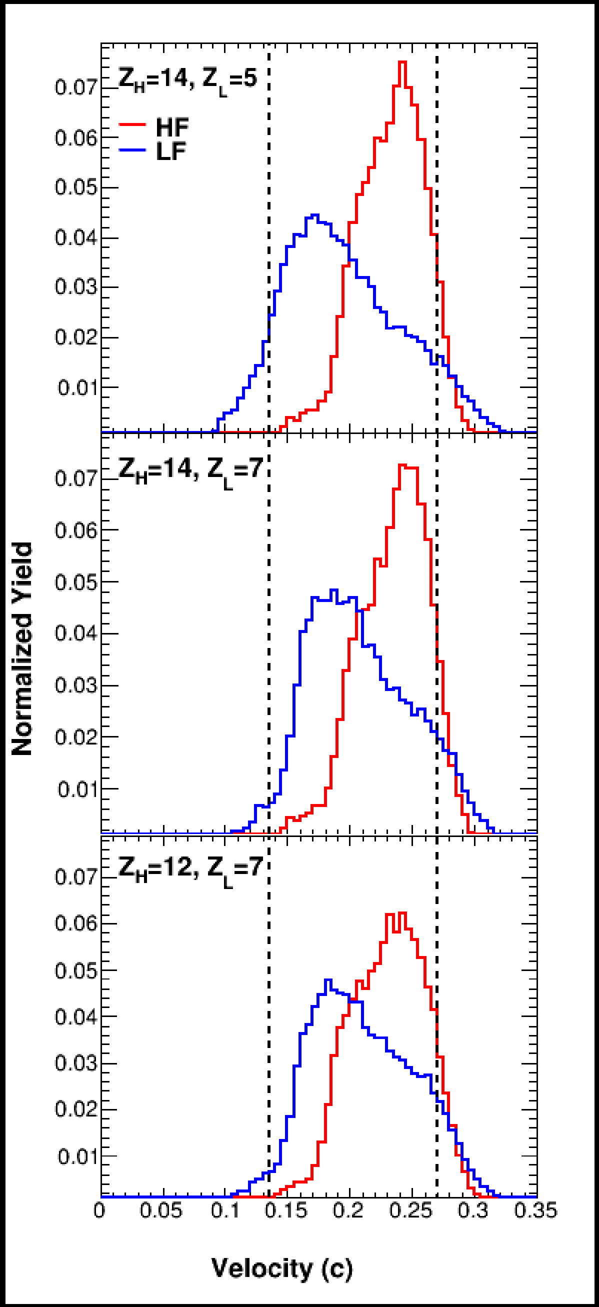
Cuts in analysis:

$Z_H \geq 12$

$Z_L \geq 3$

$Z_H + Z_L + \Sigma Z_{other} \geq 21$

Origin of Fragments

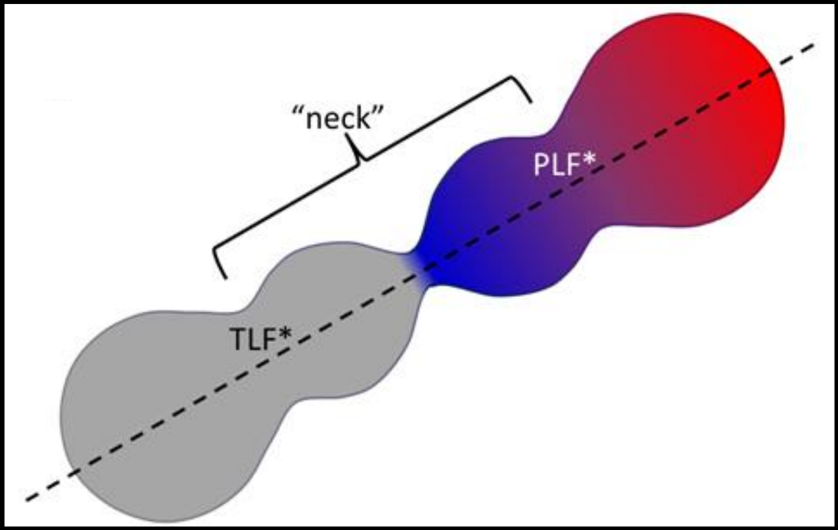


Both fragments predominantly forward of mid-velocity

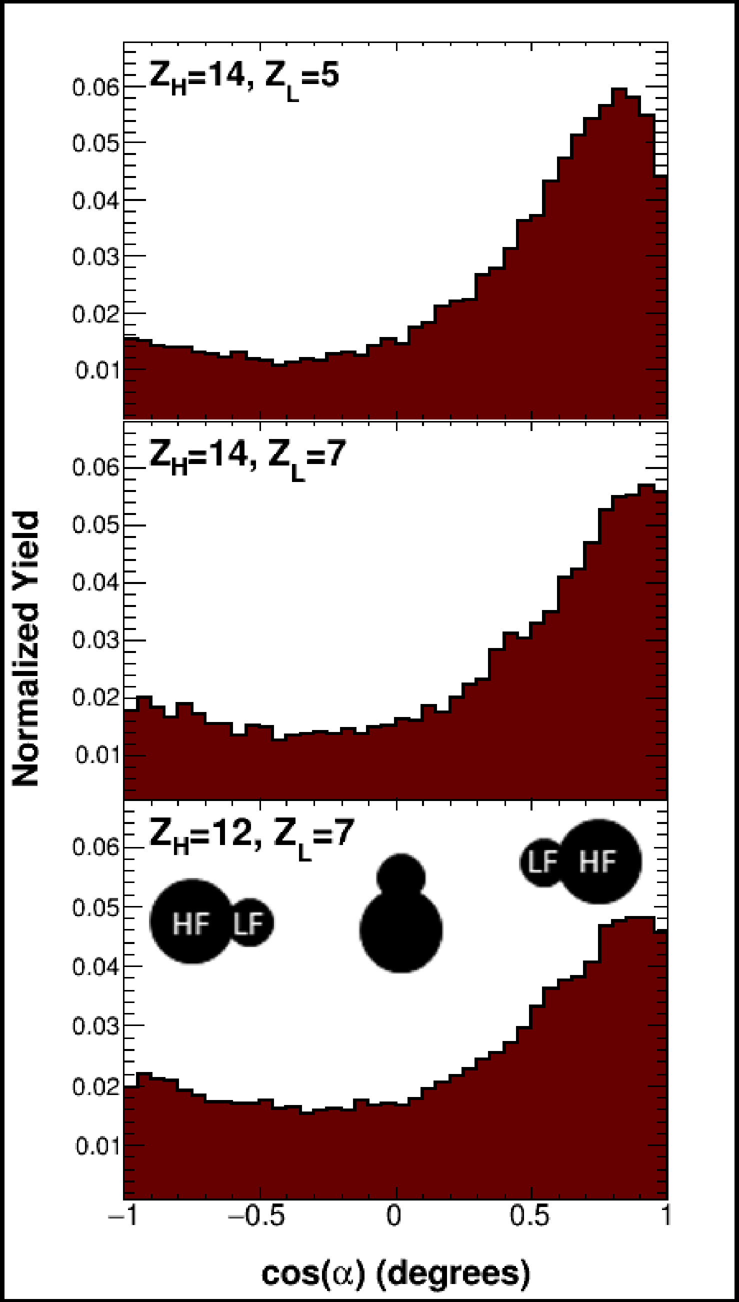
→They may both be from PLF*, not TLF*

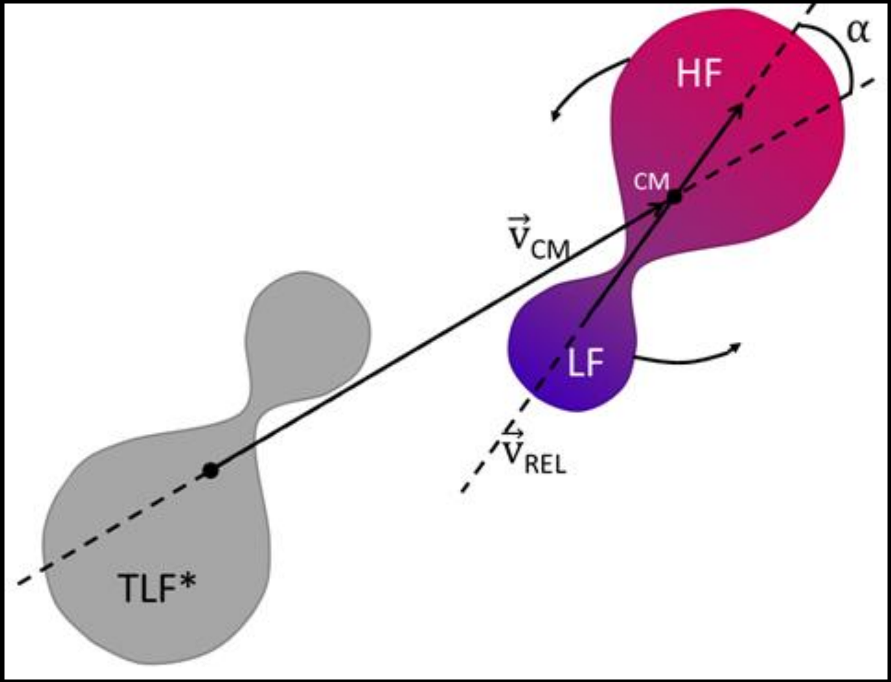
Heavier fragment is on average faster

→Consistent with dynamical decay



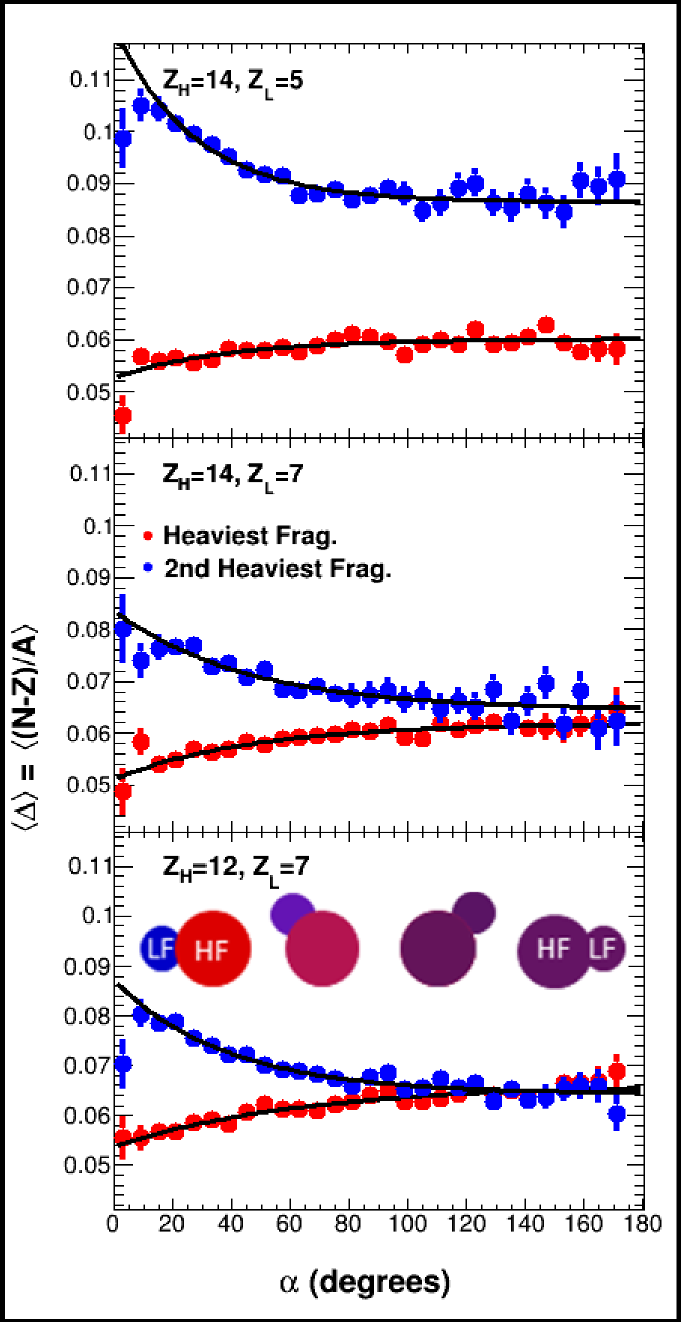
Angular Distributions





Strong alignment
→Consistent with dynamical decay
→Decay timescale is faster than rotational period

Composition of both fragments



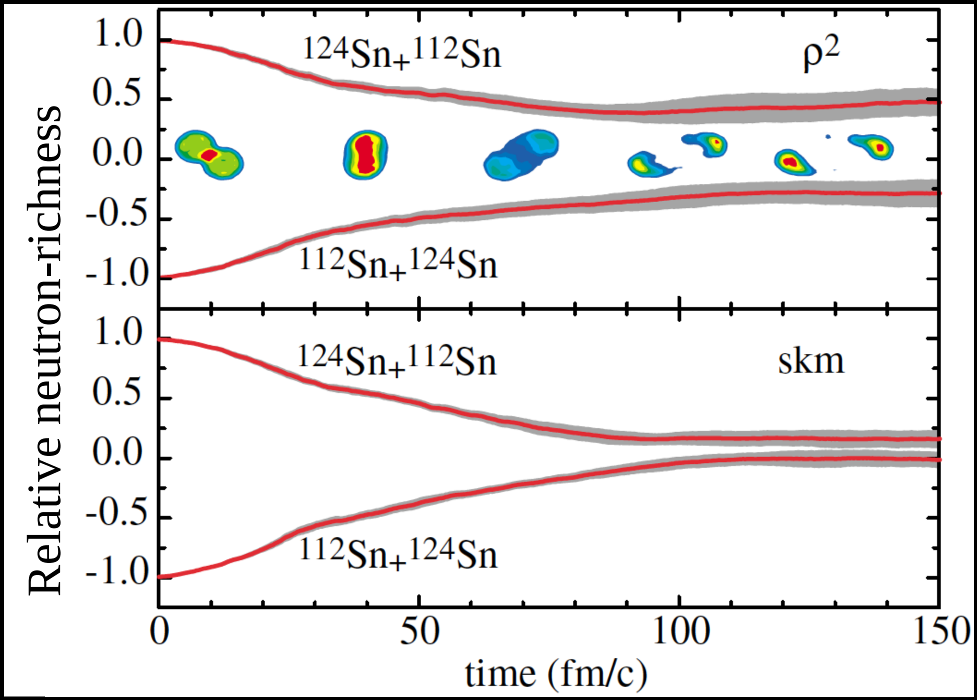
The lighter fragment becomes less neutron rich as the PLF* rotates

The heavier fragment becomes more neutron rich as the PLF* rotates

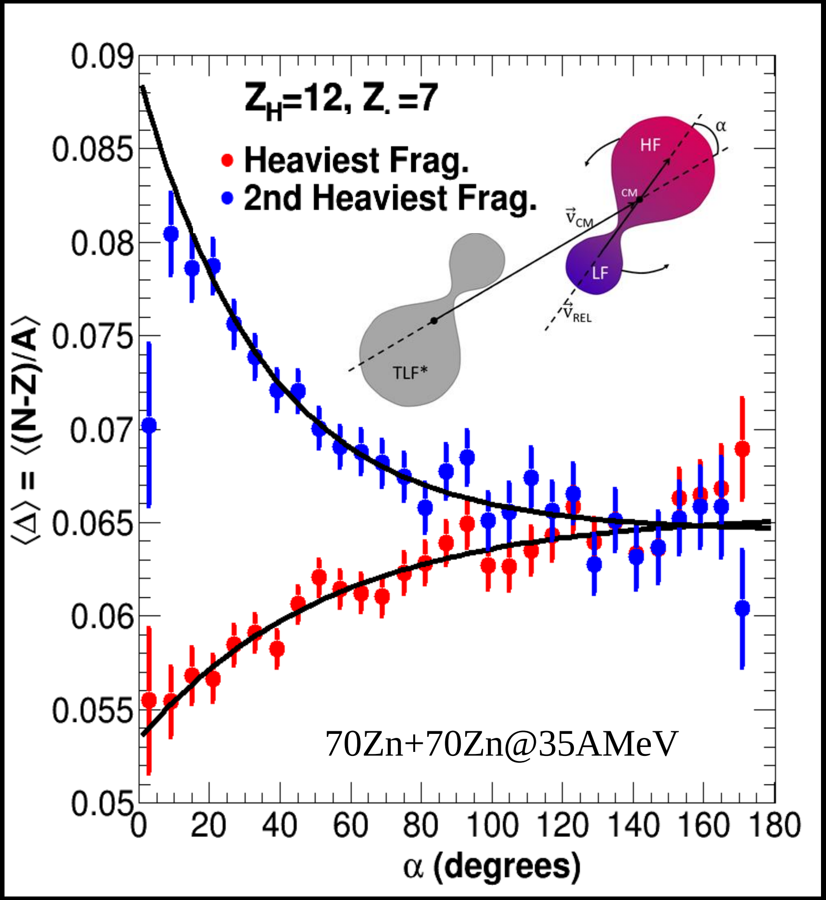
Observe the evolution is approx. exponential
→ Consistent with first-order kinetics

The timescale for **HF** and **LF** are approximately equal
→ Most equilibration occurring within 60°

We observe equilibration as a function of time

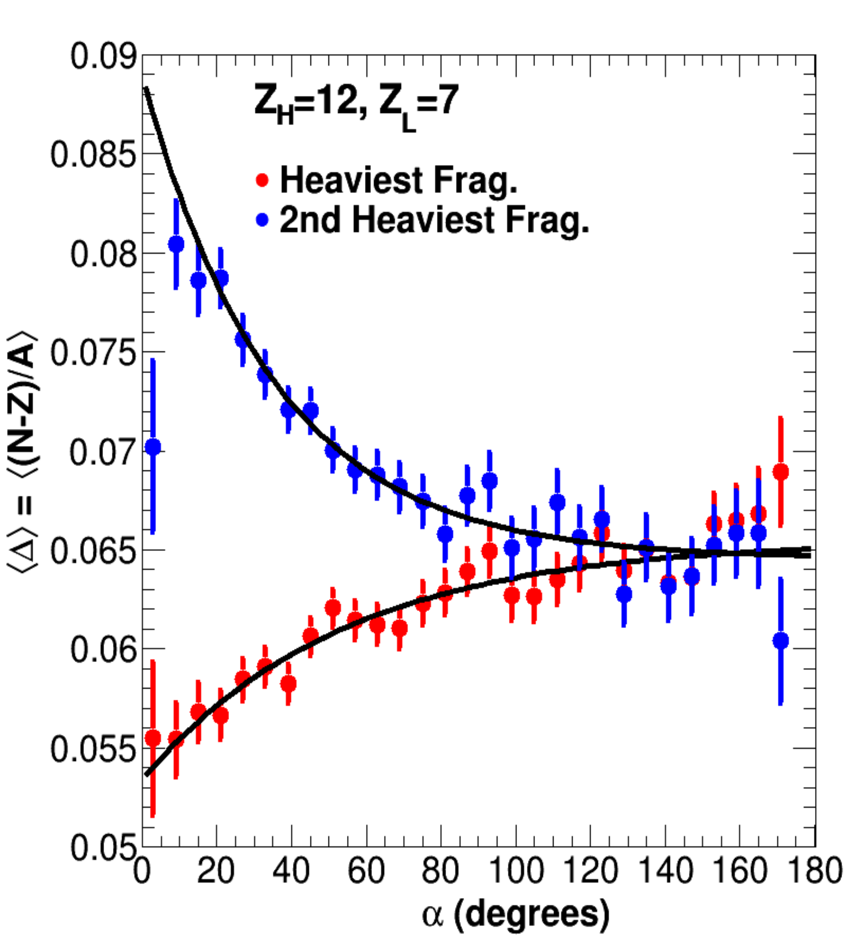


2004 simulation
Tsang et al



2015 data analysis
Jedele et al

Rate of Equilibration



Fit:

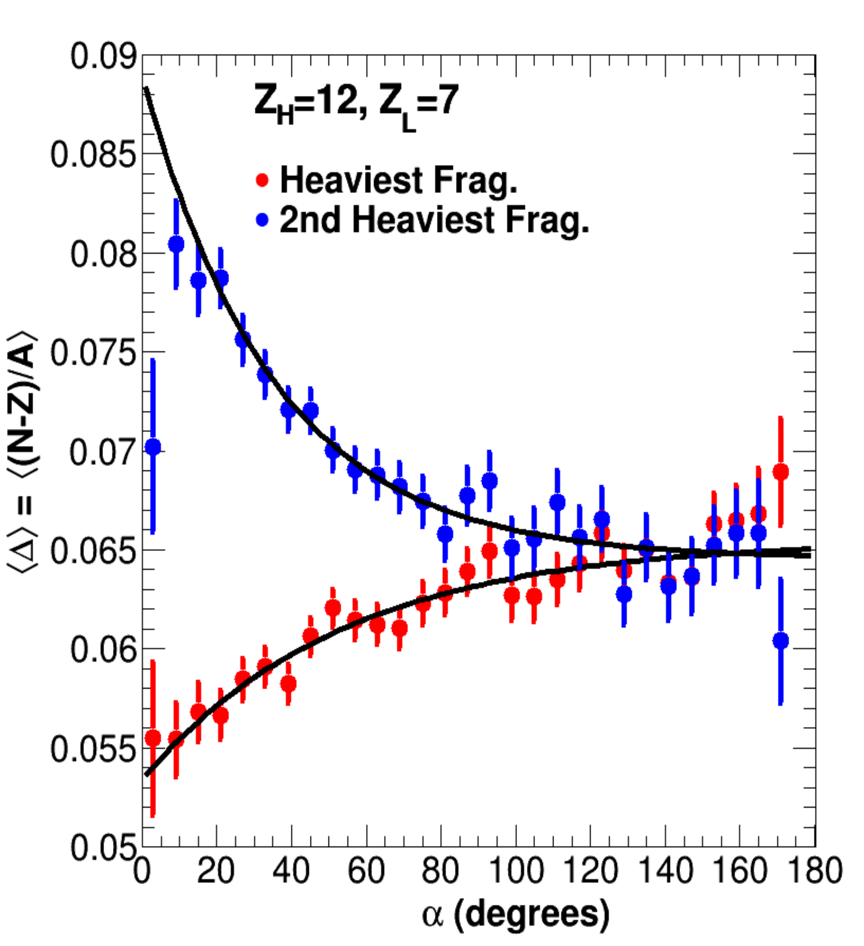
$\Delta = a + b \exp[-c\alpha]$

a: equilibrium value

b: distance from equilibrium at t=0

c: NZ equilibration rate constant

Angle to Time



$$t = \alpha / \omega$$

$$\omega = J \hbar / I_{eff}$$

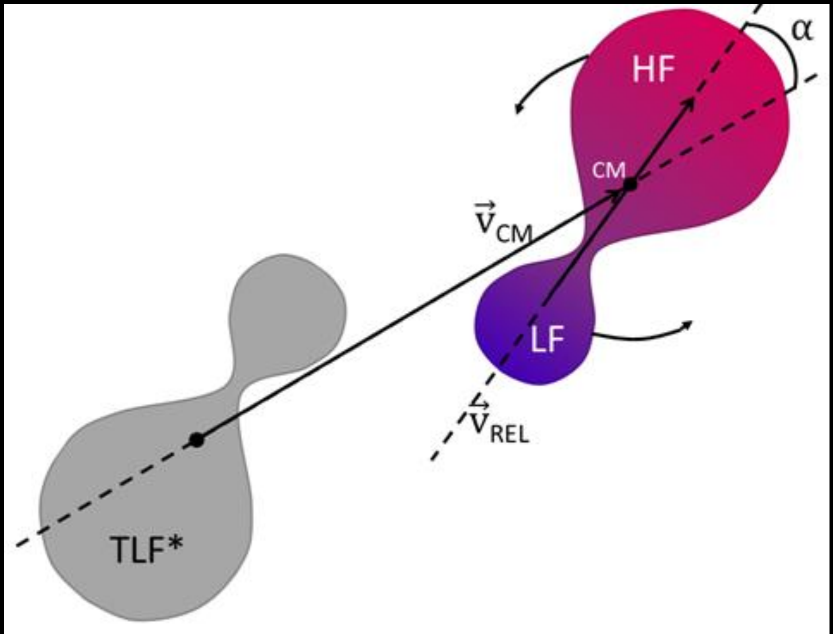
The moment of inertia calculated for 2 touching spheres

- radii from masses of 2 fragments

Angular Momentum

Angular momentum information from evaporative emission of light, charged particles

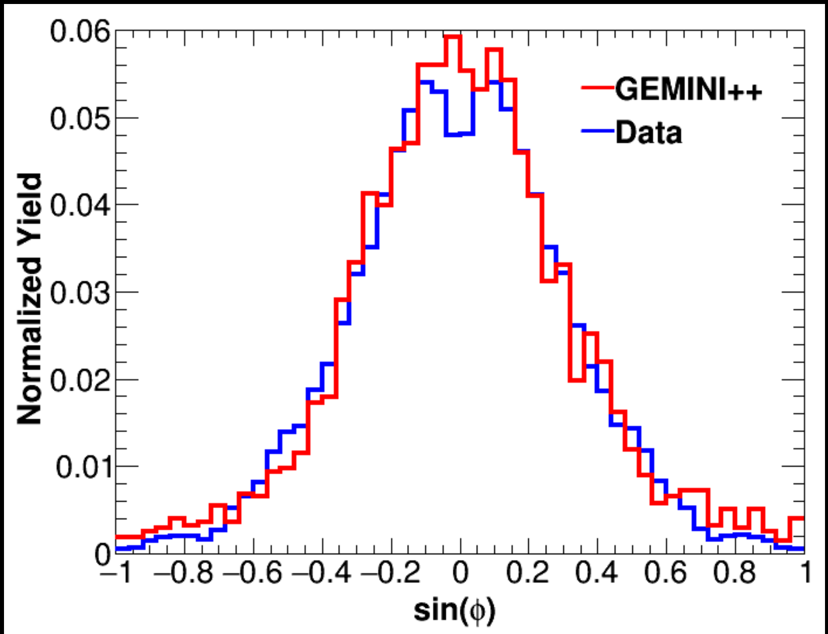
No spin: emission probability equal in all directions
High spin: equatorial emission preferred



GEMINI simulations:

J = 10ħ at E*/A=0.8 MeV
J = 50ħ at E*/A=1.2 MeV

J=22ħ (geometric mean) used



Time Scale

		rate constants		mean equilibration times	
Z_H,Z_L Pairing	Rotational Period (zs)	k_H (zs^{-1})	k_L (zs^{-1})	τ_H (zs)	τ_L (zs)
14,5	$2\pm^{5}_{1}$	$4\pm^{5}_{3}$	$6\pm^{7}_{3}$	$0.3\pm^{0.6}_{0.1}$	$0.2\pm^{0.4}_{0.1}$
14,7	$3\pm^{7}_{1}$	$3\pm^{3}_{2}$	$3\pm^{3}_{2}$	$0.4\pm^{0.9}_{0.2}$	$0.4\pm^{0.8}_{0.2}$
12,7	$3\pm^{6}_{1}$	$2\pm^{3}_{1}$	$4\pm^{4}_{2}$	$0.5\pm^{1}_{0.2}$	$0.3\pm^{0.6}_{0.1}$

Combining results from 43 pairing:

Average	$3\pm^{6}_{1}$	$3\pm^{4}_{2}$	$4\pm^{4}_{2}$	$0.3\pm^{0.7}_{0.2}$	$0.3\pm^{0.6}_{0.1}$

→ mean equilibration time is ~100 fm/c

Summary

- First measurement of composition of the 2 largest fragments as a function of time from a dynamically decaying PLF*
- Large solid-angle coverage and high statistics allow very fine selection of decay angle → high time resolution
- NZ of regions of the deformed PLF* are observed to be initially dissimilar, and evolve toward each other
- NZ evolution is exponential, occurs over approx. 0.3 zeptosecond timescale

Yennello Research Group & Collaborators

A. Jedele, A.B. McIntosh, K. Hagel, L. Heilborn, M. Huang, Z.W. Kohley, L.W. May, E. McCleskey, M. Youngs, A. Zarrella, S.J. Yennello

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

Department of Energy
DE-FG02-93ER40773

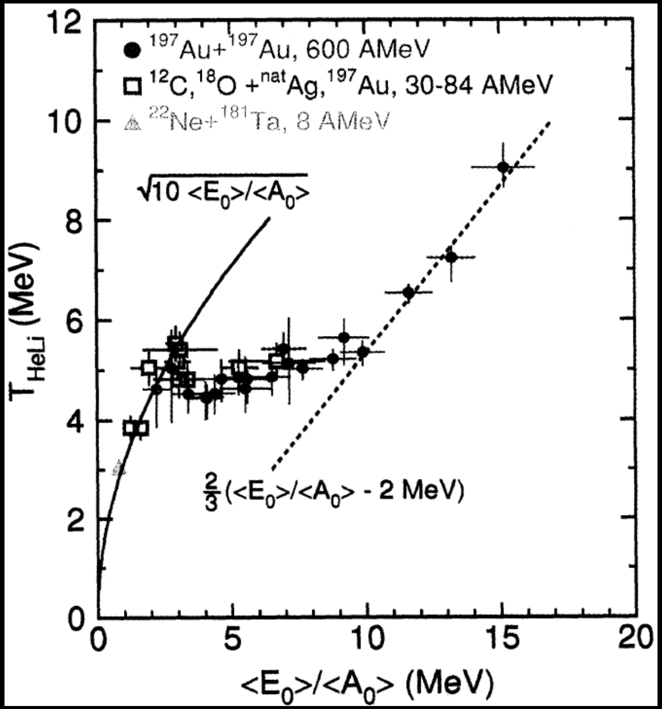
Welch Foundation
A-1266

QUESTIONS?

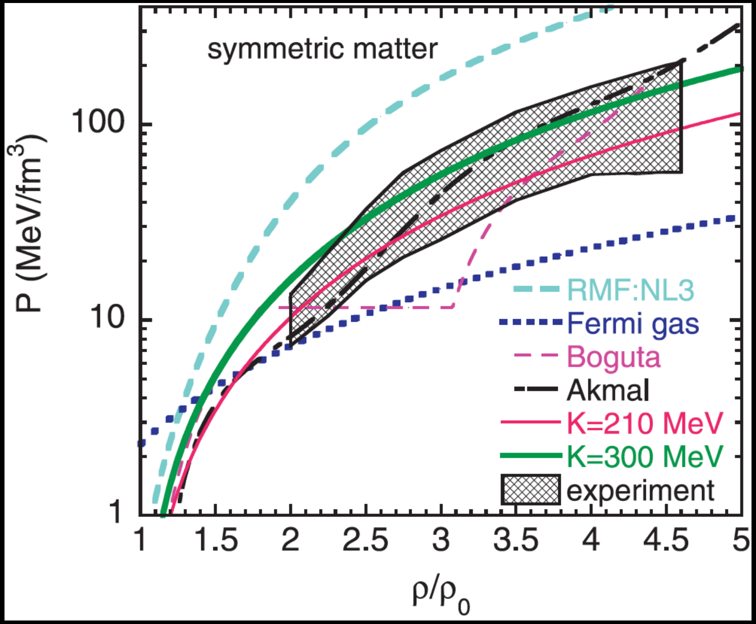
Supplementary Material

Nuclear Equation of State

Relates:
Energy, Temperature, Density, Pressure, Chemical Potential

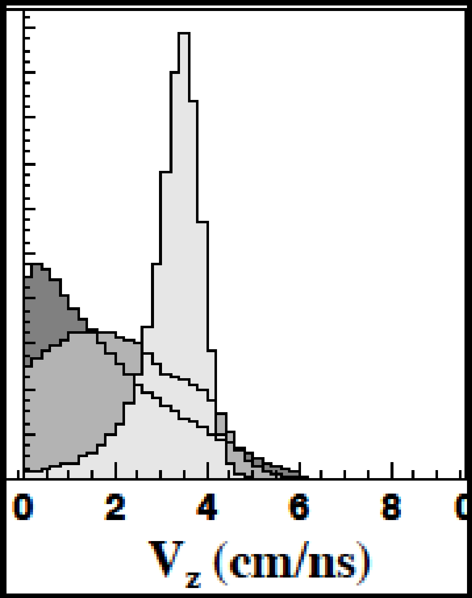


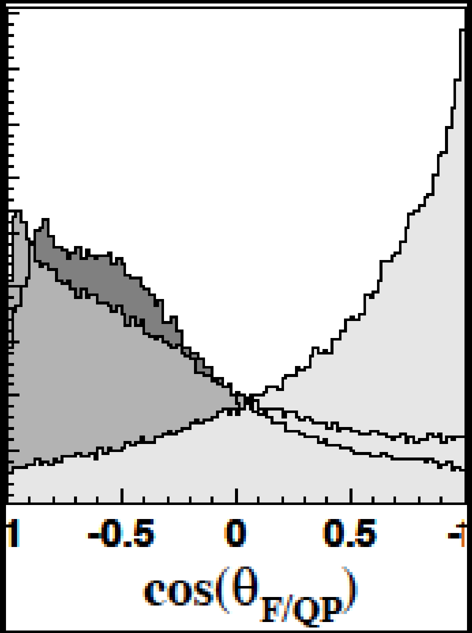
Pochodzalla et al. PRL 75, 1040 (1995)



Danielewicz, Lacey and Lynch. Science 298, 1592 (2002)

Ta+Au@33AMeV



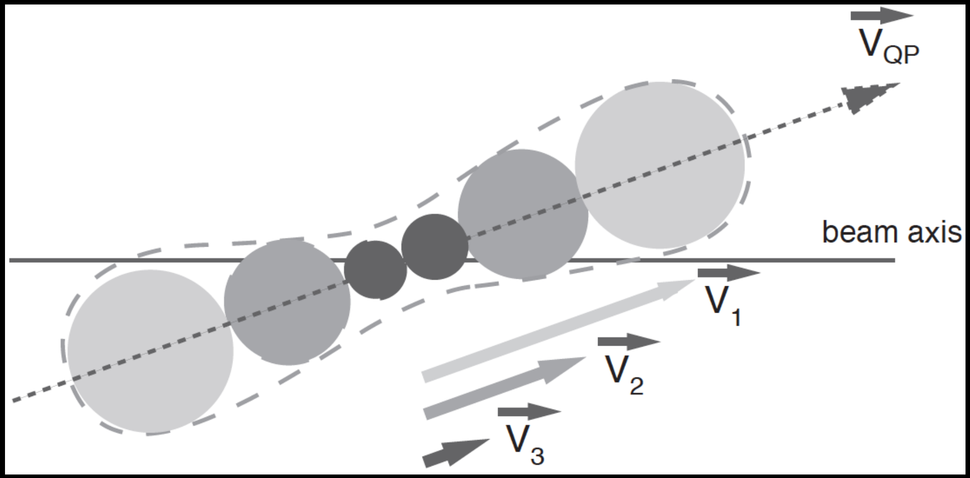


Dynamical Decay (a.k.a. Aligned Decay)

Correlation between fragment size and velocity.
Angular distribution shows strong alignment
Observed in many systems by many groups.

Not compatible with standard statistical decay.

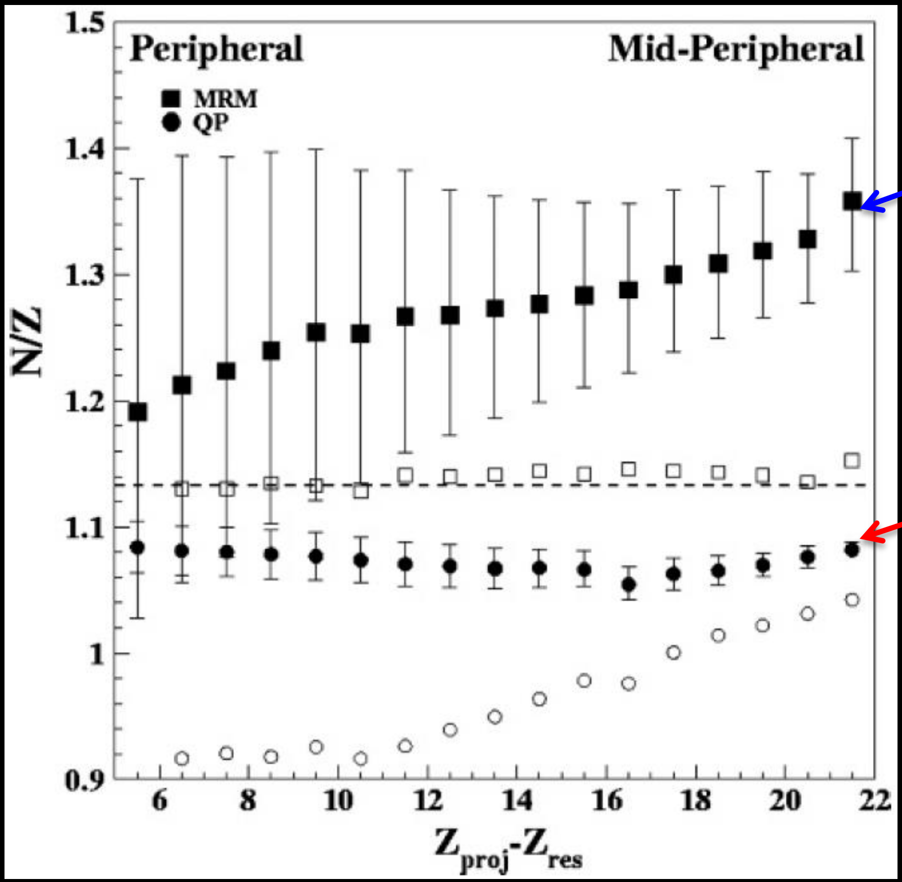
Mechanism: production of low density neck, followed by multiple neck rupture



Colin et al. PRC 67, 064603 (2003)

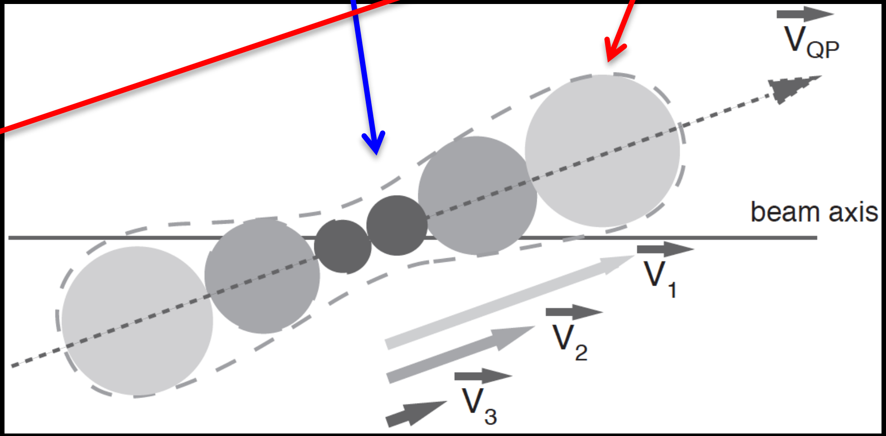
Neutron Content of the Dynamically Deformed System

^{64}Zn+^{64}Zn@45AMeV



Mid-Rapidity Material (neck) is neutron rich

...at the expense of the Quasi-Projectile

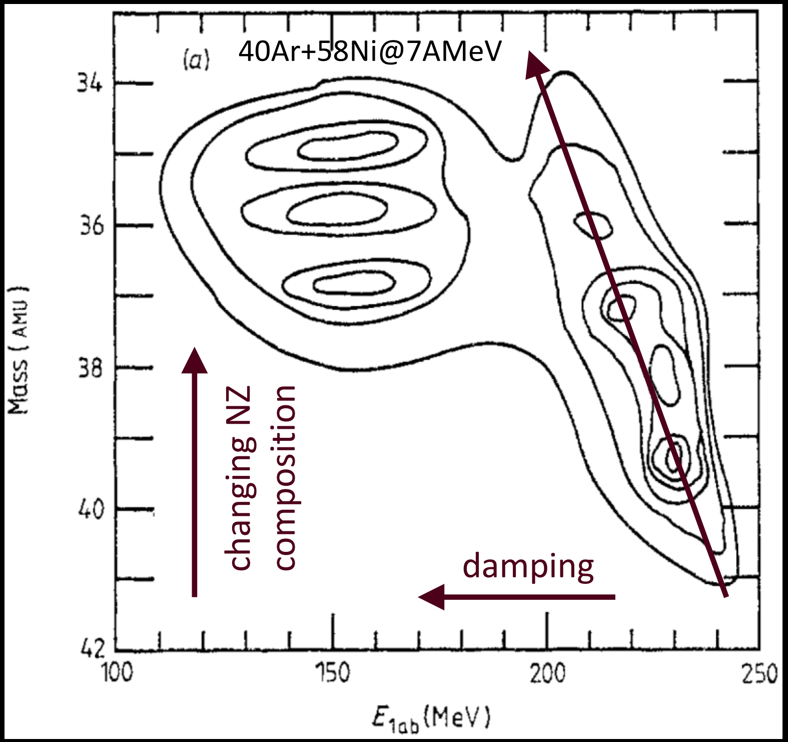


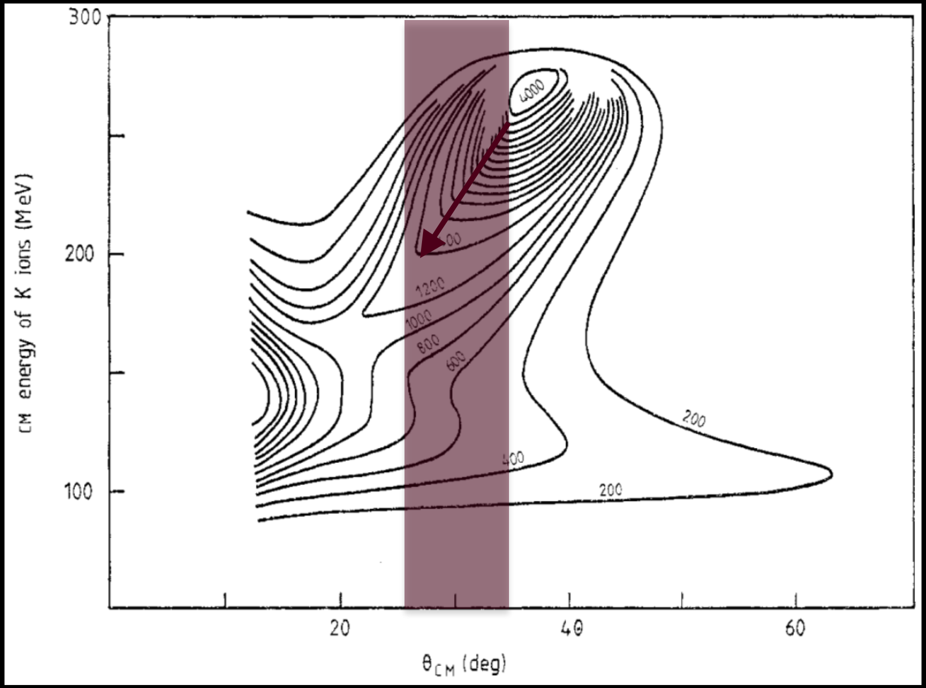
Theriault et al. PRC 74, 051602(R) (2006)

Getting Time from Rotation

Moretto & Schmitt. Rep. Prog. Phys. 44, 533 (1981)

"In order to follow the time evolution of the collective degrees of freedom excited in heavy reactions one needs a clock. Nature has provided one which, although not very accurate, can span incredibly short times. This clock is the angular deflection of the fragments."

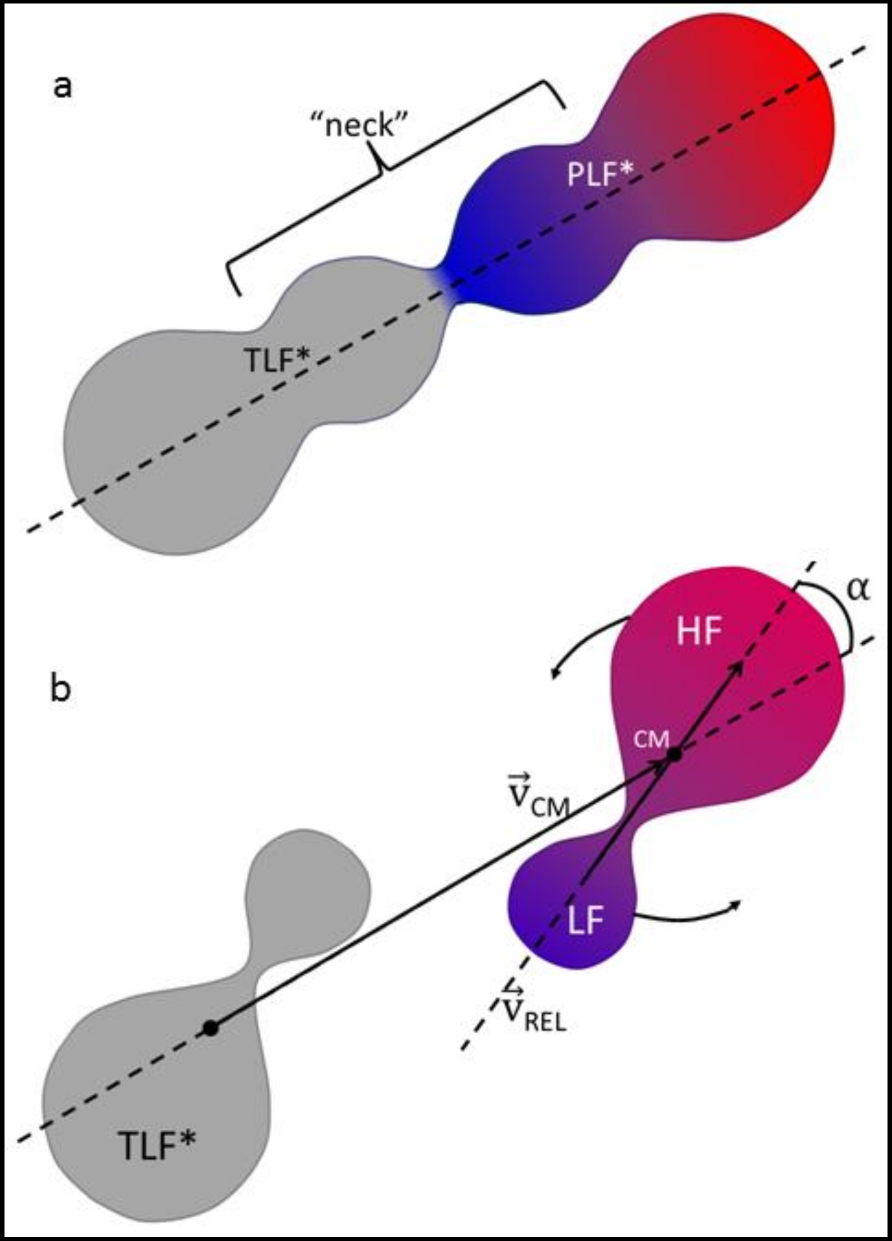




Longer contact time

→ more energy damping

→ more NZ equilibration



The Key Insight

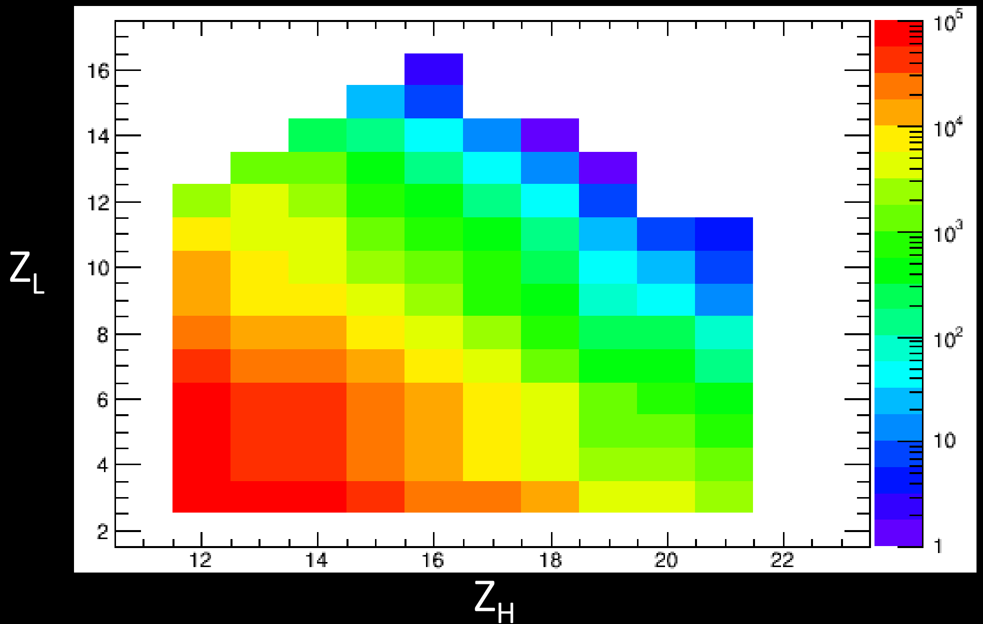
The system has angular momentum.

After the first neck rupture, and before the second rupture, two things are happening:

1. the Quasi-Projectile is spinning
2. the two regions of the deformed PLF* can transfer n,p toward equilibrium

Therefore, we can use the rotation angle like a clock and observe n,p transfer as a function of time!

Select a PLF*



$Z_H \geq 12$
$Z_L \geq 3$
$Z_H + Z_L + \mathbf{\Sigma}\, Z_{other} \geq 21$

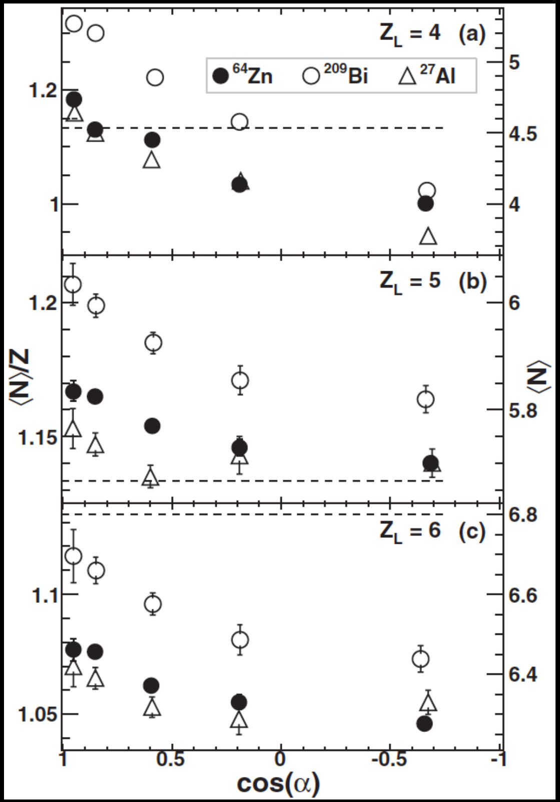
I'll show results for ZH,ZL pairs:
(12,7)
(14,7)
(14,5)

Smoother trends with higher statistics, but generally representative of the entire set.

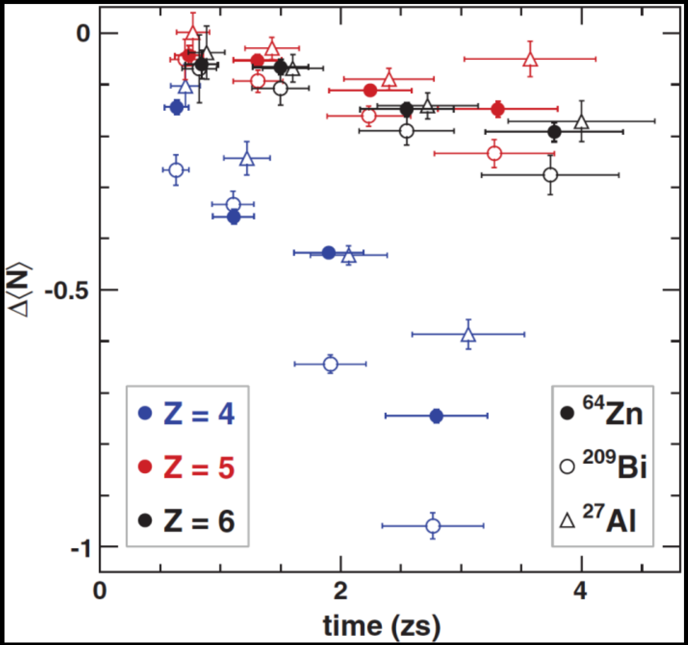
The second observation:

Brown et al. PRC 87, 061601(R) (2013)

Zn+Al,Zn,Bi@45AMeV



Composition (N/Z) of the lighter of the two fragments decreases monotonically with decay orientation

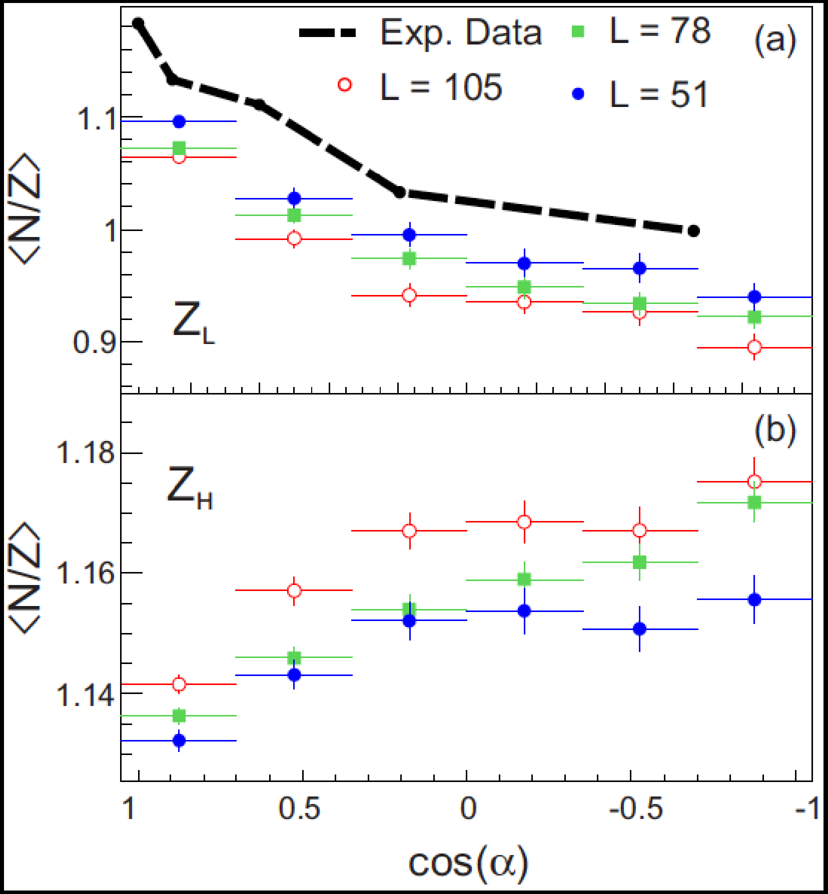


Using out-of-plane angular distributions, the time scale is deduced to be in the zeptoseconds

The first simulation:

Stiefel et al. PRC 90, 061605(R) (2014)

Zn+Zn@45AMeV



The composition of the light fragment decreases monotonically by nearly the same amount as the data

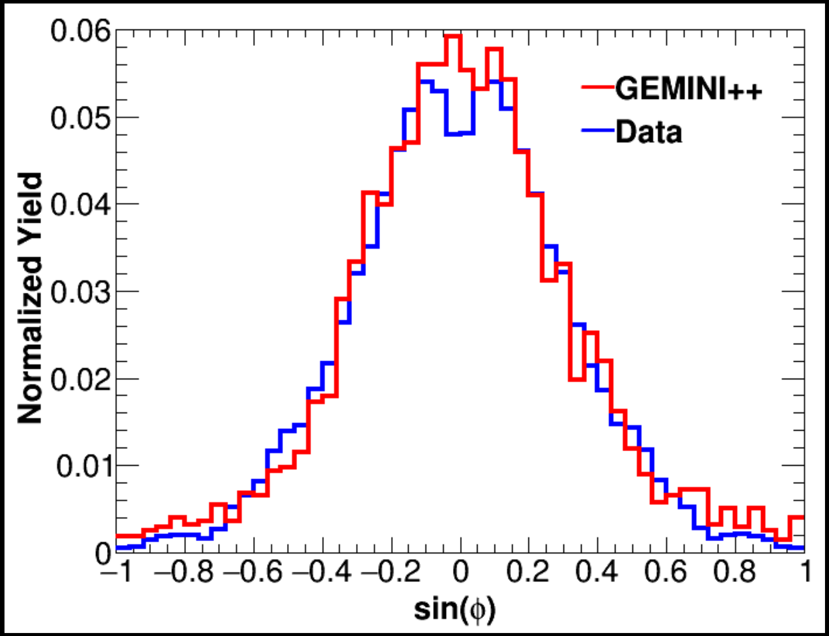
The composition of the heavy fragment increases, mirroring the light fragment

Consistent with the proposed mechanism

Sensitivity to the Asymmetry Energy in the Equation of State (L param) is observed

Systematic differences between the experiment and simulation must be explored

Assessing the Time Scale



GEMINI simulations: reproducing this width can be done with spin from 10ħ (E*/A=0.8MeV) to 50ħ (E*/A=1.2MeV). We can take J=22ħ with a factor of 2.2 uncertainty.

$$\omega = J\hbar / I_{eff}$$

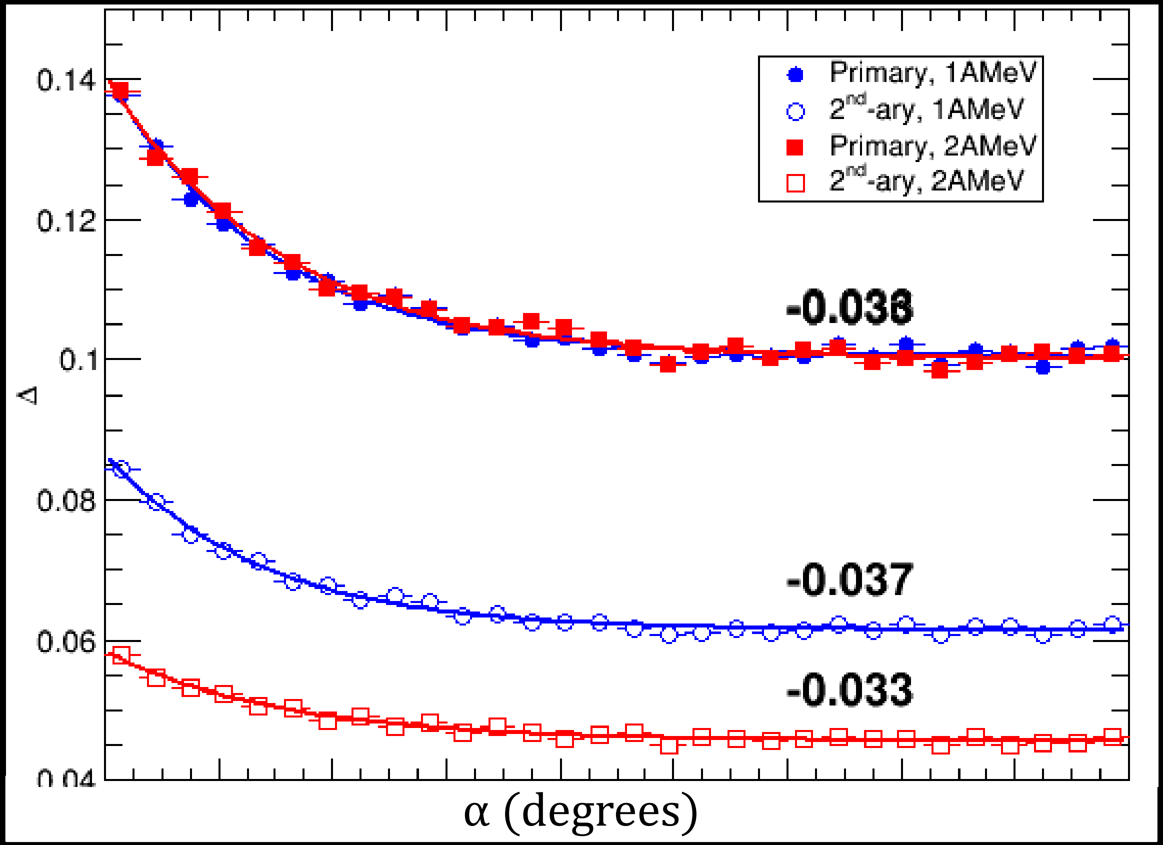
The moment of inertia, I, is calculated for two touching spheres with radii given by the masses of the two fragments.
I : from 2.8E42MeVs^2 to 9.9E42MeVs^2 depending on fragment masses.

$$t = \alpha / \omega$$

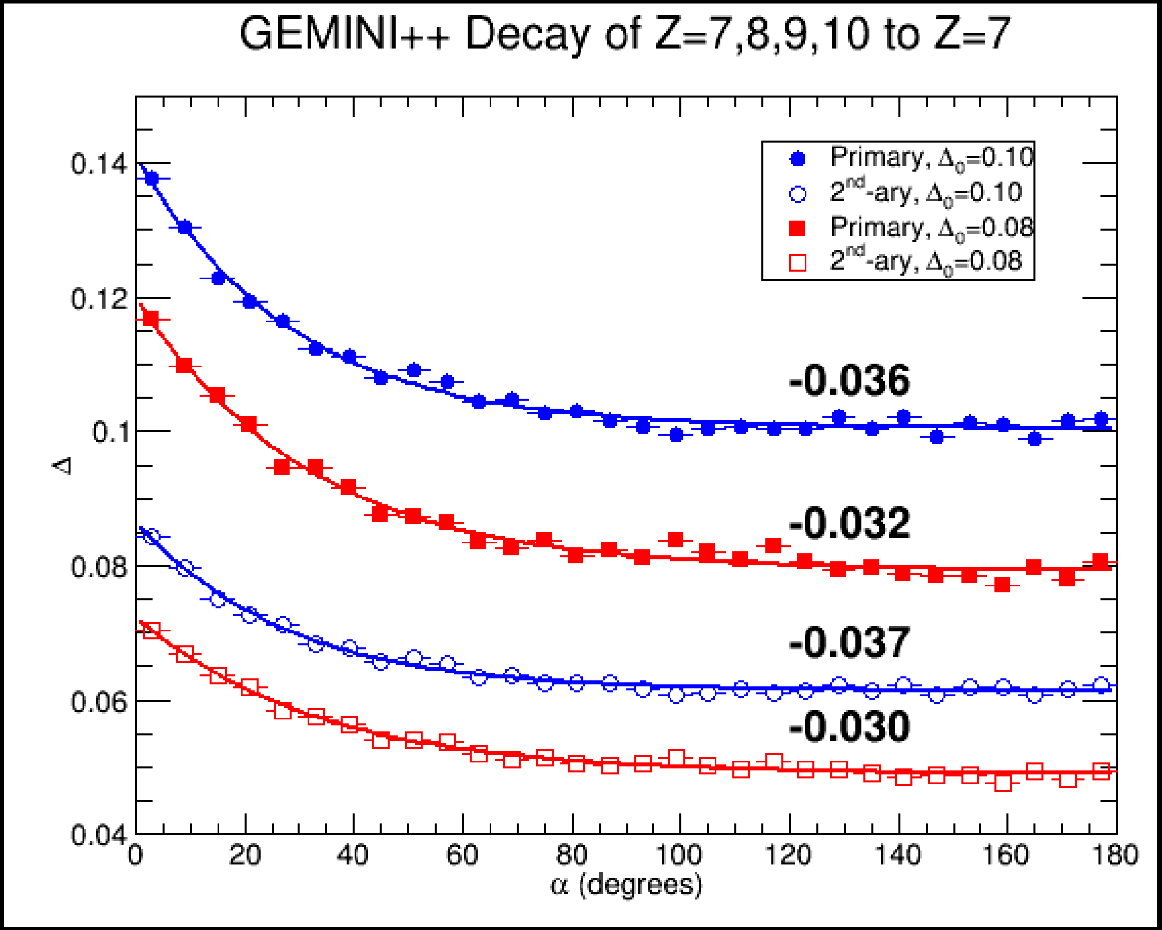
Secondary Decay

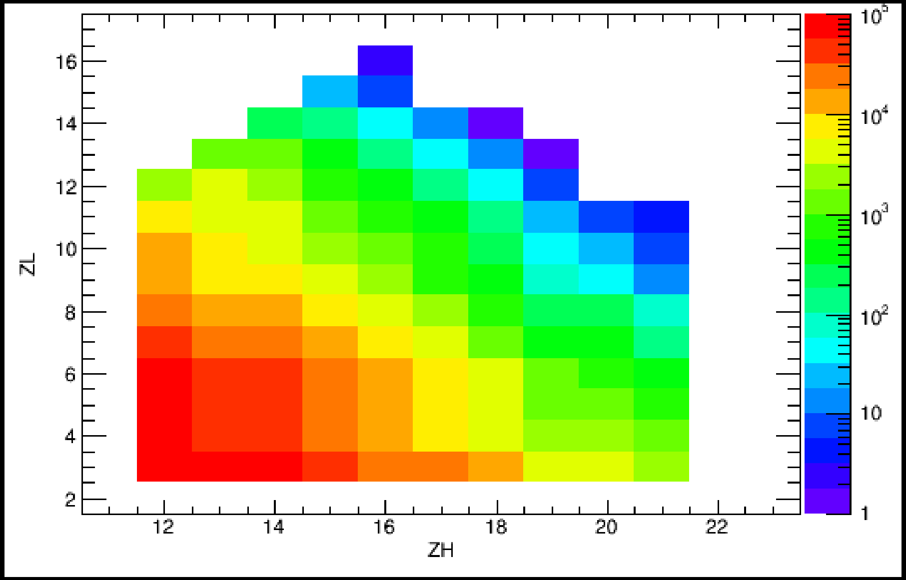
- GEMINI++
- I choose:
  - alpha (random on flat distribution 0-180°)
  - initial Δ (from Gaussian)
    - mean of Gaussian follows some exponential with alpha
    - width is large and constant
  - Z=7,8,9,10
  - A is calculated directly from Δ and Z
  - E*/A = is fixed at 1 or 2 MeV/nucleon
  - $J=5\hbar$

Secondary Decay

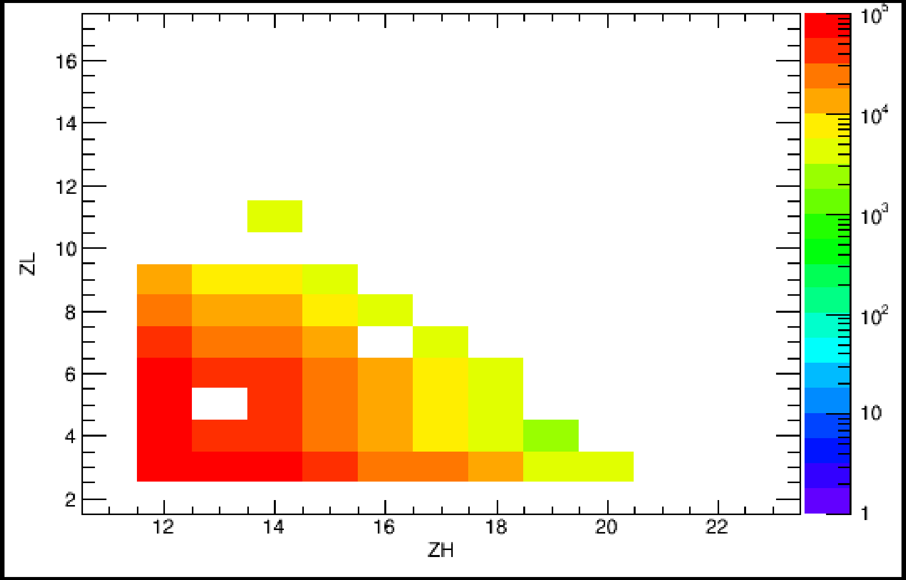


Secondary Decay





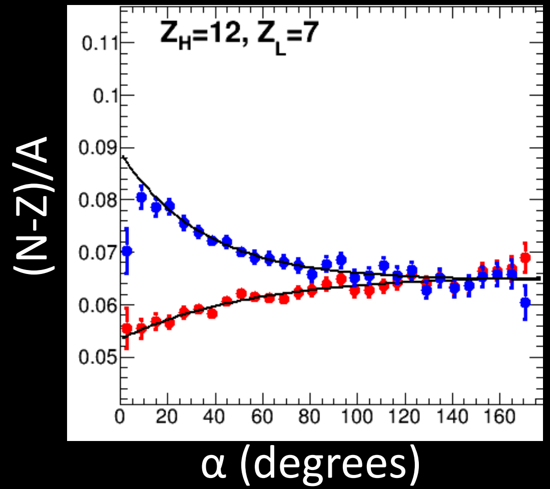
All ZH,ZL pairs that pass PLF* selection.

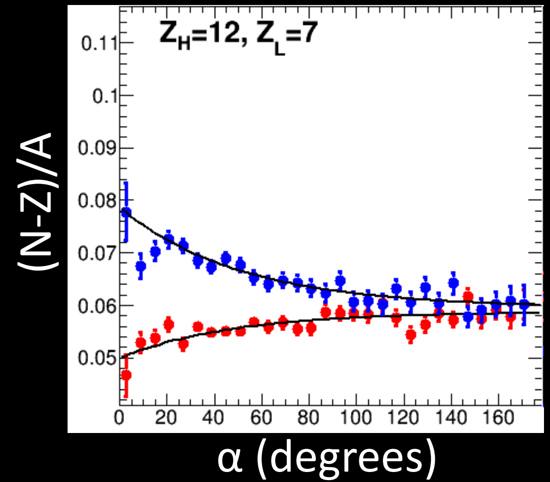


All ZH,ZL pairs that for which equilibration rate constants can be extracted.

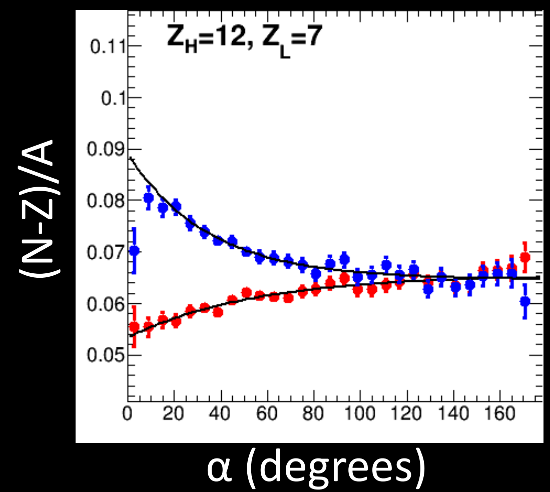
- Limited by statistics in most cases.
- The very small change in the composition of the heavy fragment limits other cases.

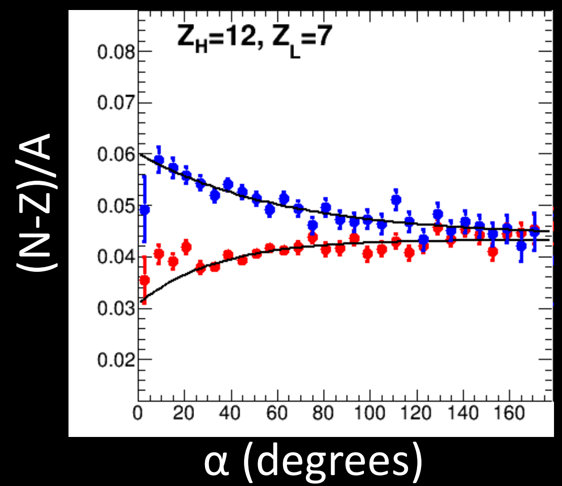
^{70}Zn-^{70}Zn vs. ^{64}Ni-^{64}Ni systems





^{70}Zn-^{70}Zn vs. ^{64}Zn-^{64}Zn systems

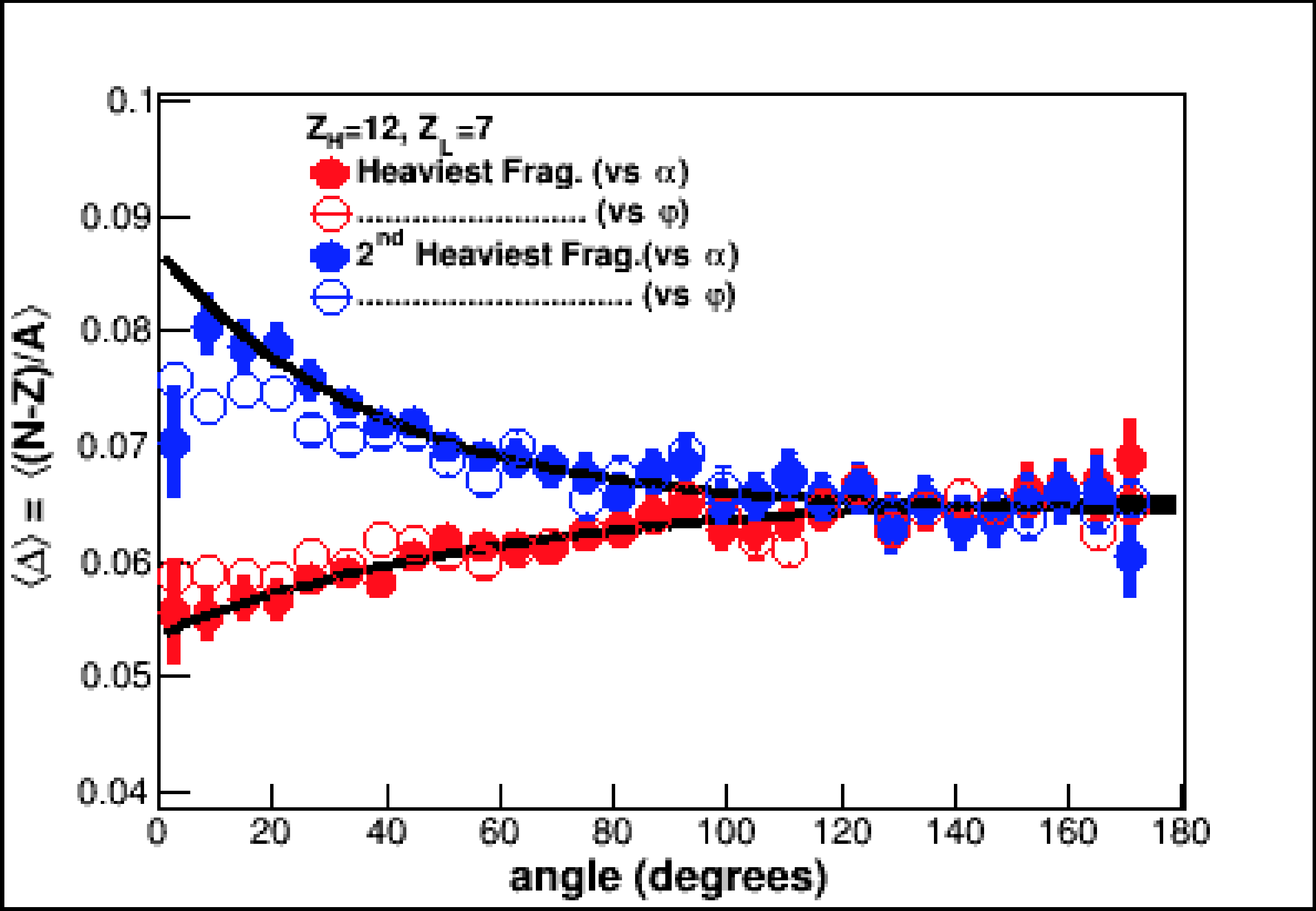




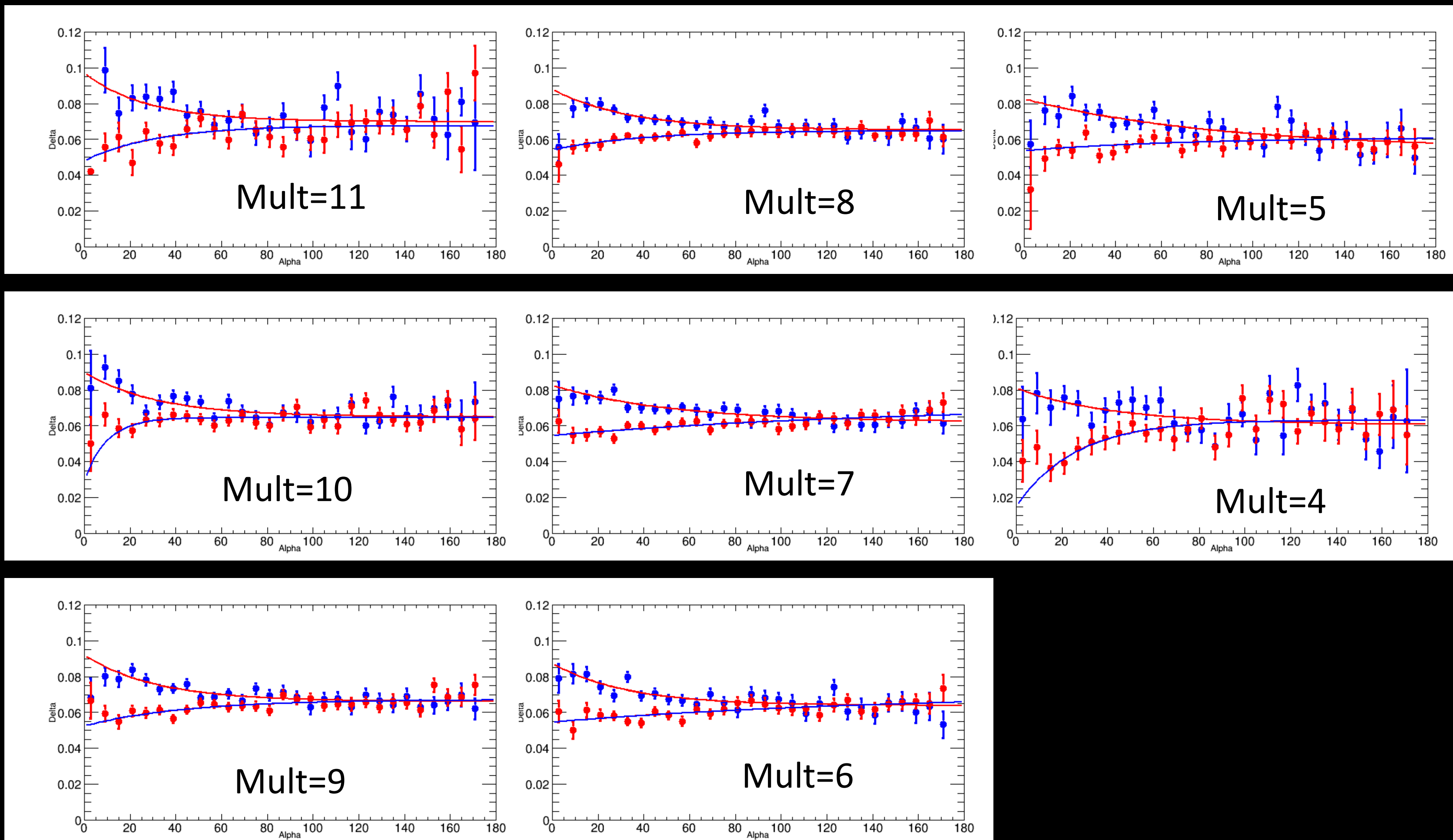
First – order kinematics

- $\frac{d\triangle}{dt} = -c\ \triangle$
  - c is a constant
- Visually:
  - Rate of equilibration only linearly dependent on the composition of the two fragments
  - No contribution from other variables

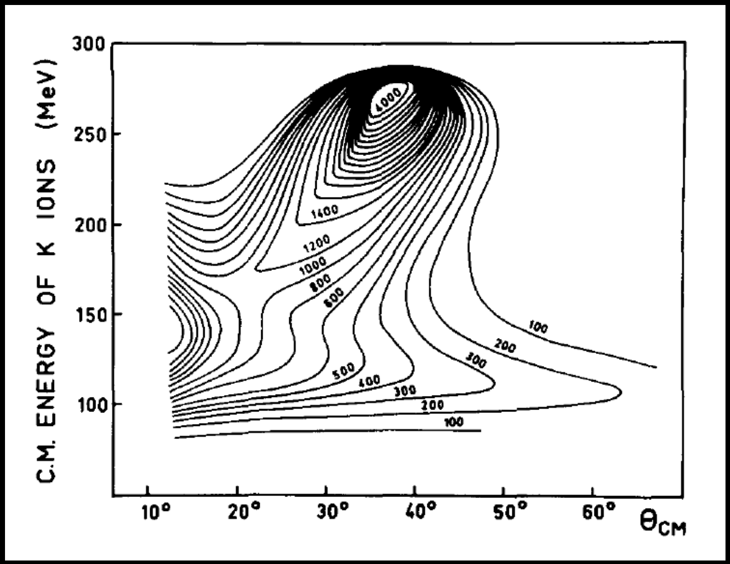
Out-of-plane distribution

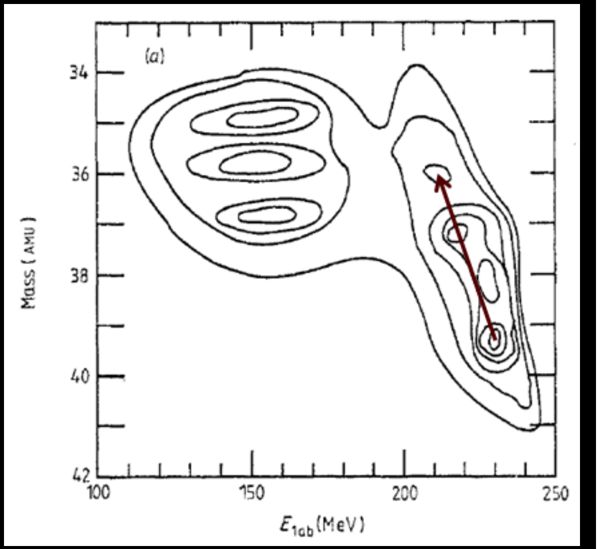


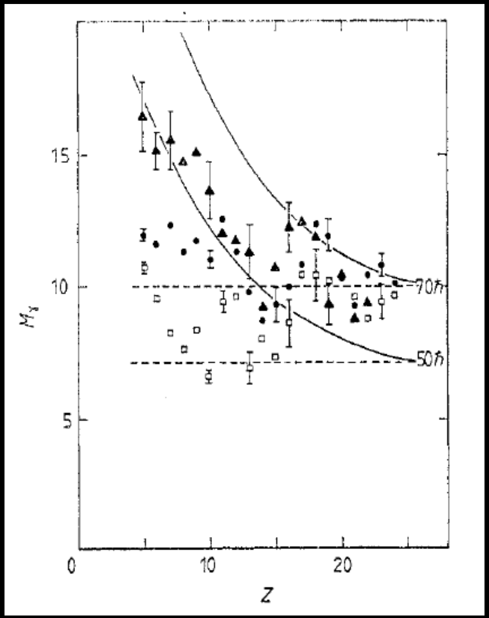
Filtered by impact parameter (Multiplicity)

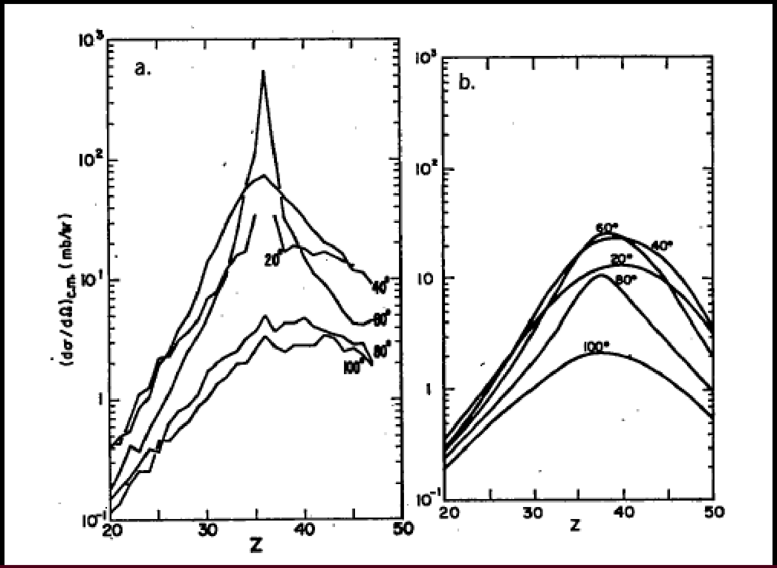


First probes of timescale









Future Work

- Measure time-dependence of N-Z equilibration for total system (PLF + TLF)
  - $^{64,70}Zn + ^{64,70}Zn$ at 10A MeV
  - MDM spectrometer at Texas A&M University
  - Measure Z,A of PLF as a function of angle
    - Angular momentum of system better understood (more research – for example Natowitz 1978)

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