Equilibration Chronometry

Alan McIntosh
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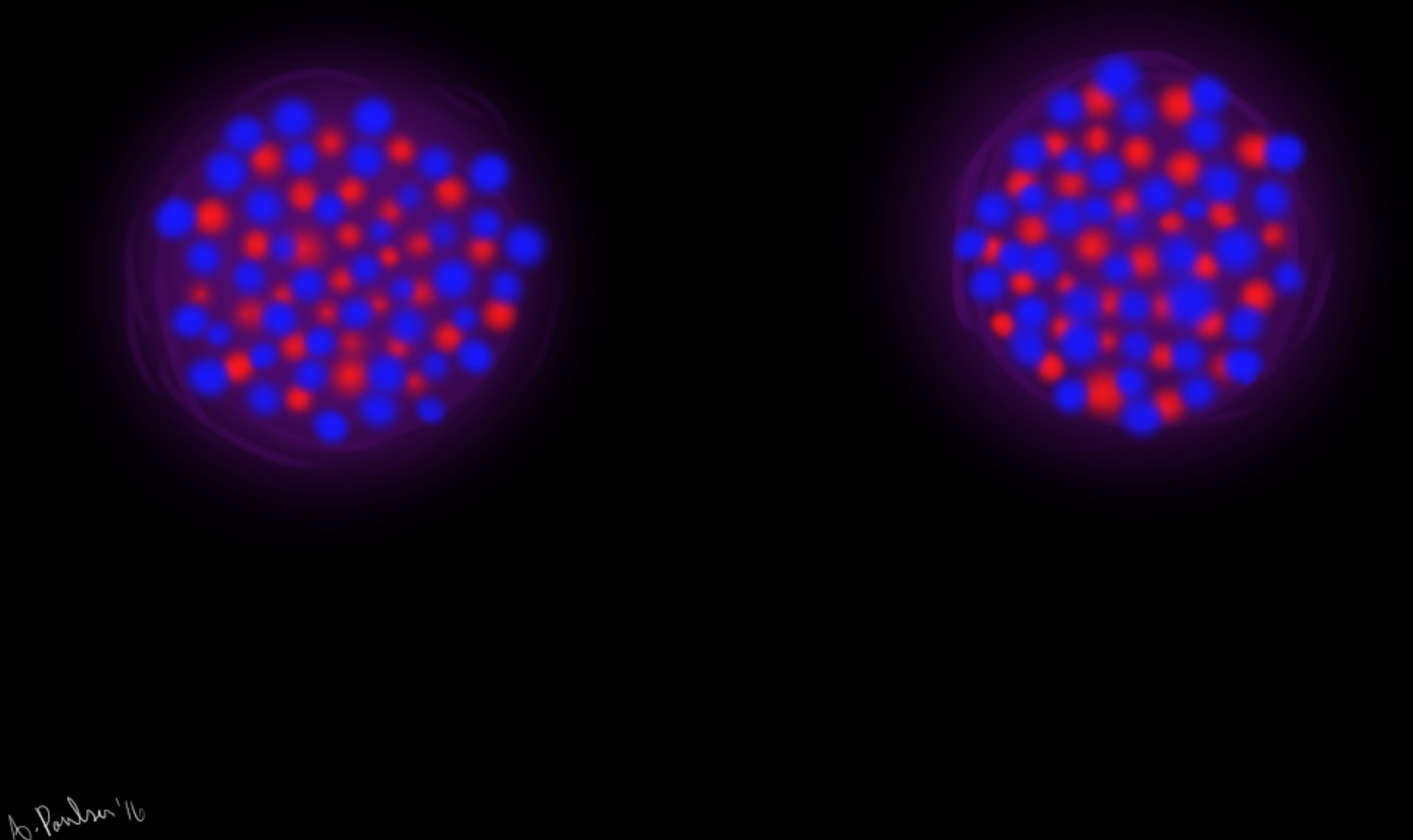
Projectile approaches target

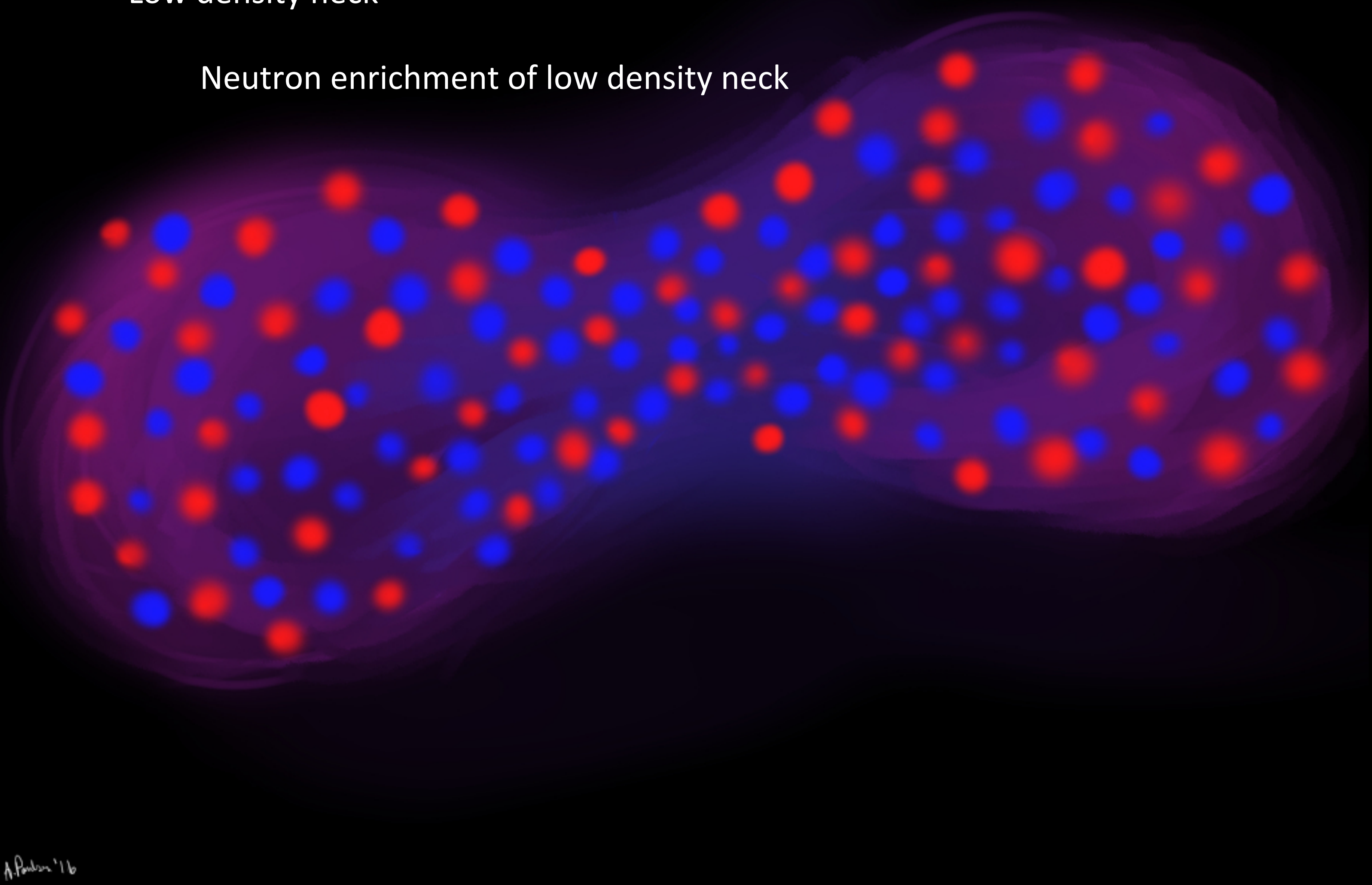
non-central collision near the Fermi Energy



Overlap of target and projectile

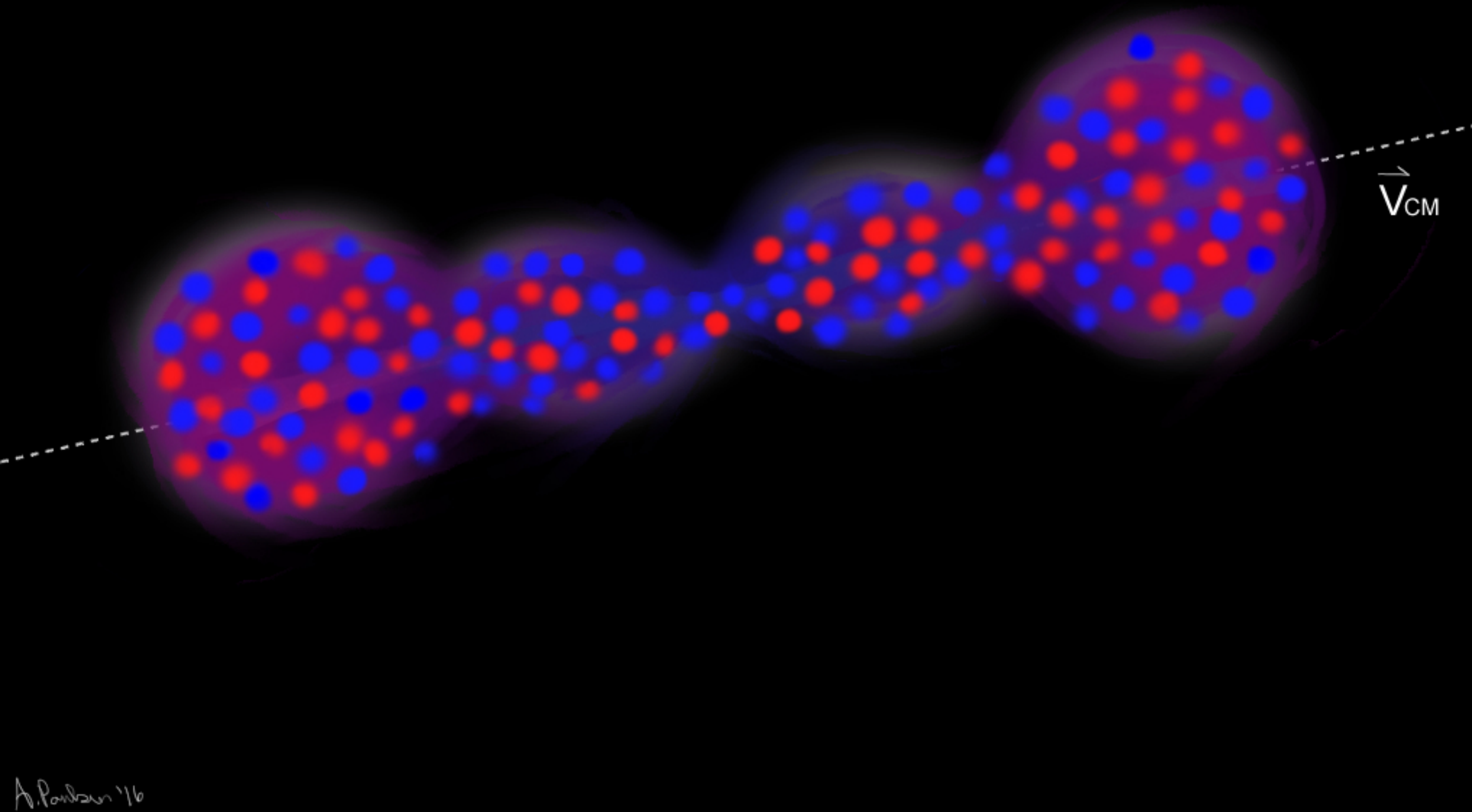
Low density neck

Neutron enrichment of low density neck



Velocity gradient, surface tension

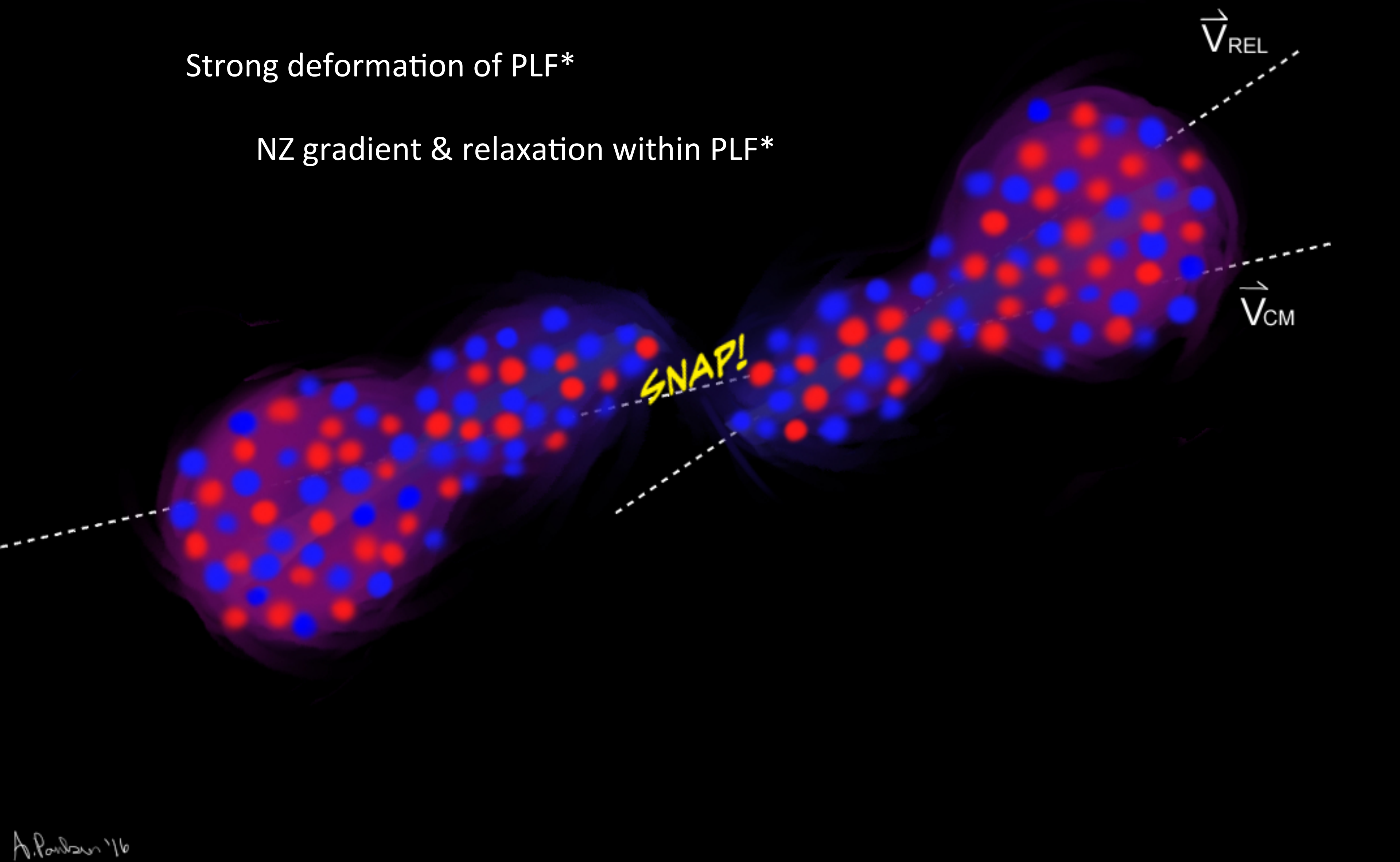
Instabilities develop (Rayleigh-like)



Rupture of neck

Strong deformation of PLF*

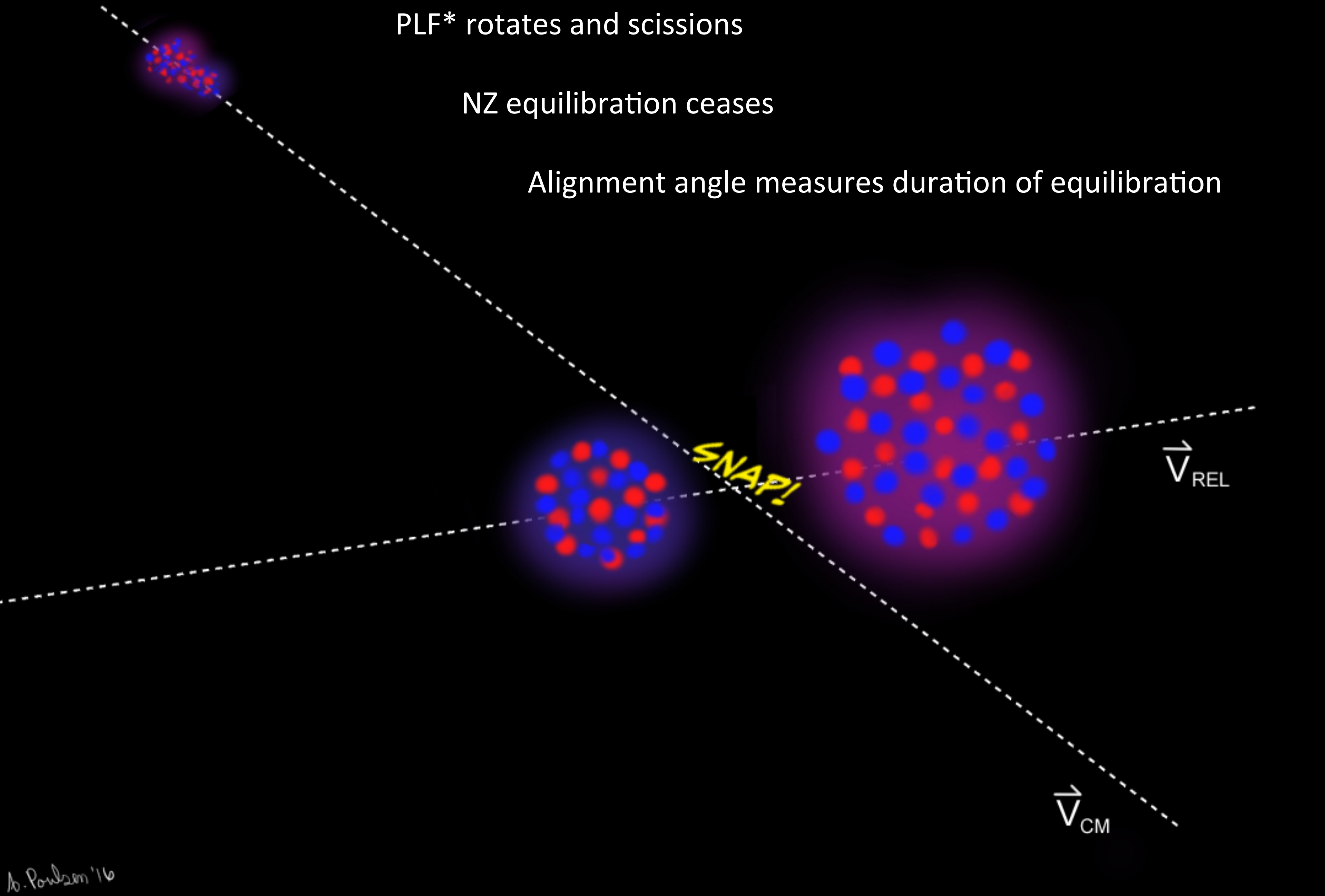
NZ gradient & relaxation within PLF*



PLF* rotates and scissions

NZ equilibration ceases

Alignment angle measures duration of equilibration



Dynamical Decay & Neutron Content

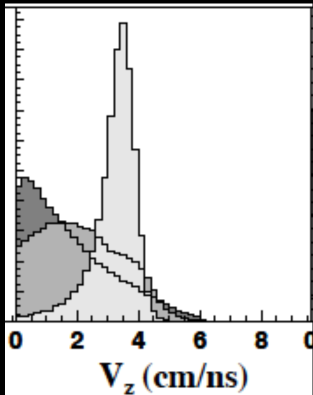
Correlation between fragment size and velocity.
Angular distribution shows strong alignment
Observed in many systems by many groups.

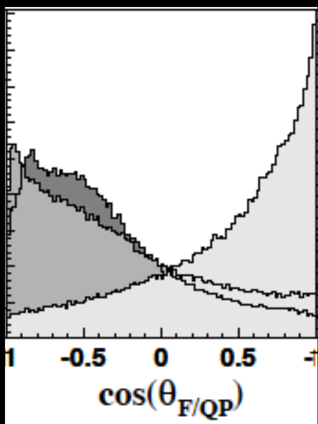
Not compatible with standard statistical decay.

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

...at the expense of the Quasi-Projectile

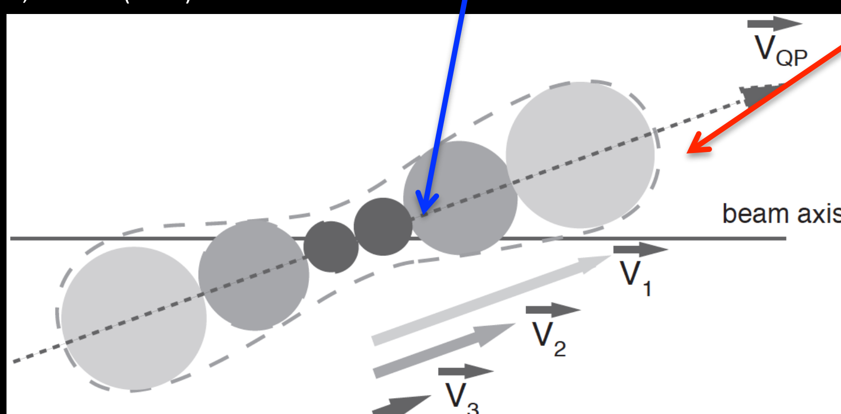
Mid-Rapidity Material (neck) is neutron rich

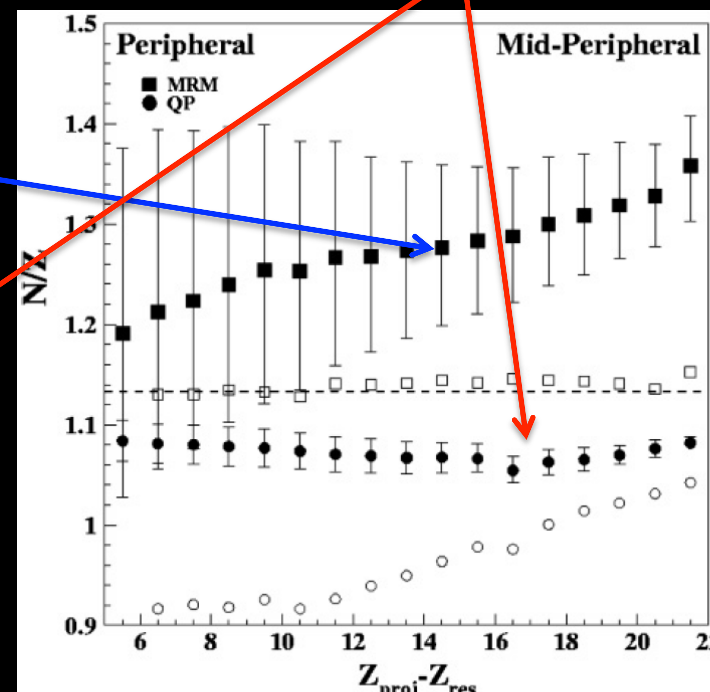




Ta+Au@33AMeV

Colin et al. PRC 67, 064603 (2003)

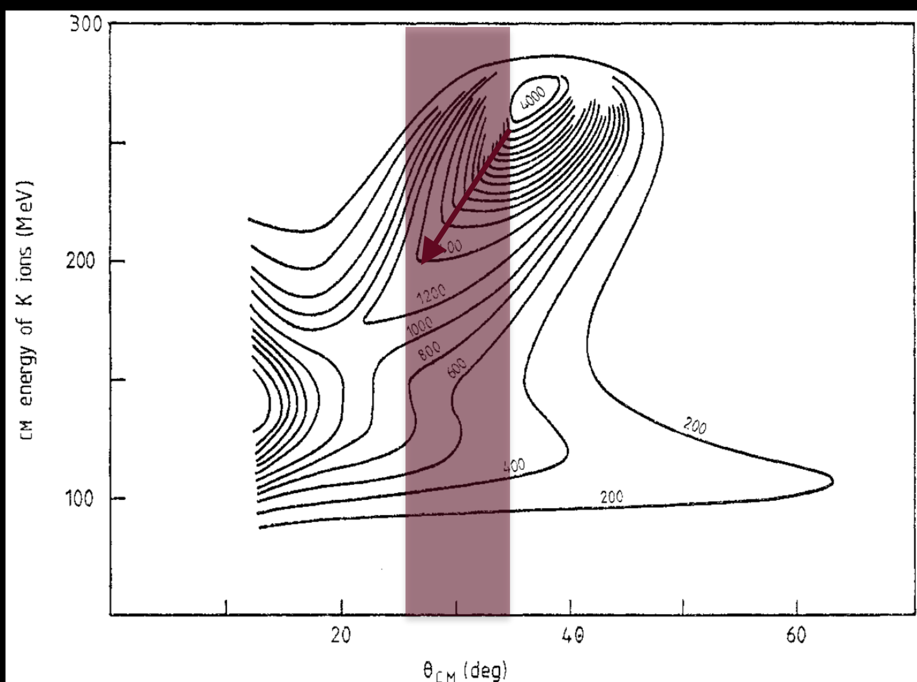


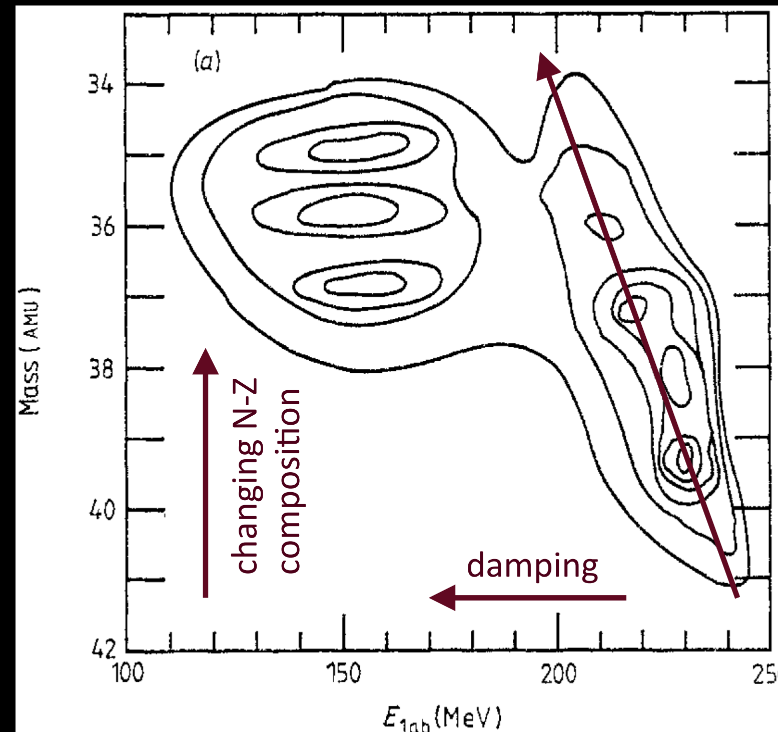


Early work on N-Z equilibration:

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

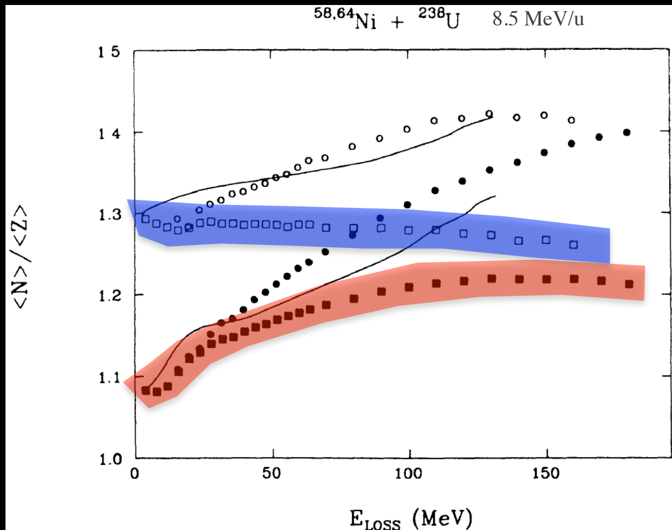
"In order to follow the time evolution of the collective degrees of freedom excited in heavy reactions one needs a clock. Nature has provided one which, although not very accurate, can span incredibly short times. This clock is the angular deflection of the fragments."



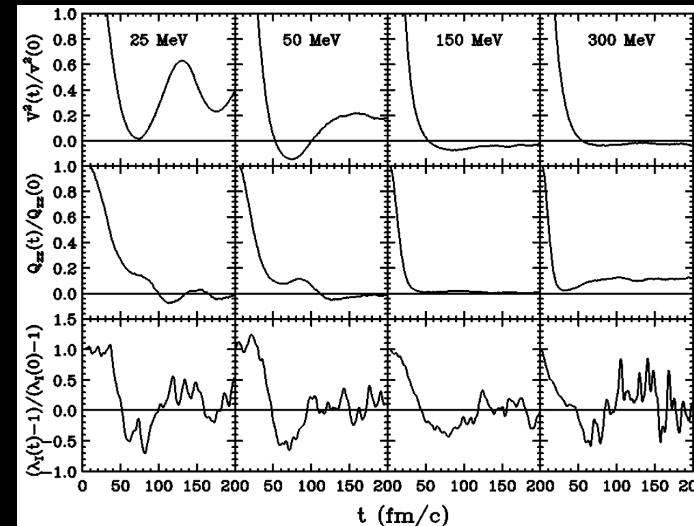


Longer contact time
→ more energy damping
→ more N-Z equilibration

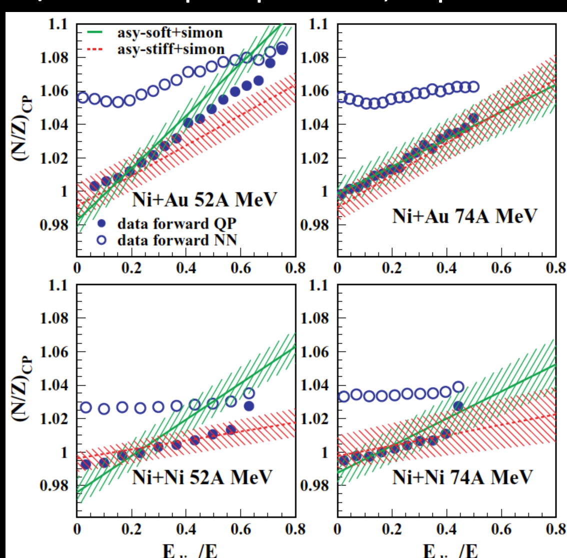
Planeta et al, PRC 35, 195 (1988)
Different projectiles tend toward the same $(N/Z)_{eq}$



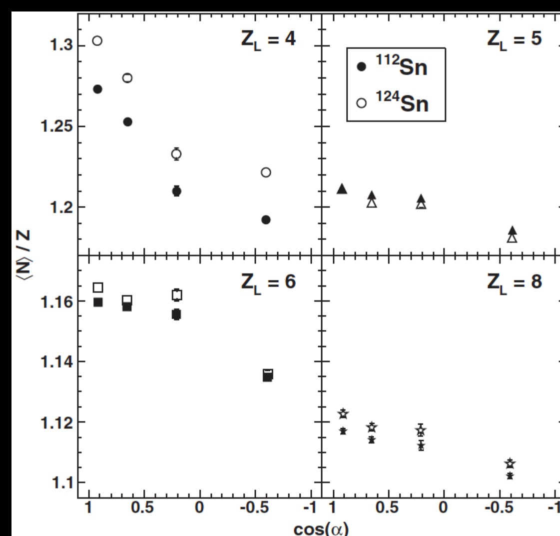
Li and Ko PRC 57 2065 (1998)
N/Z equilibration timescale in BUU



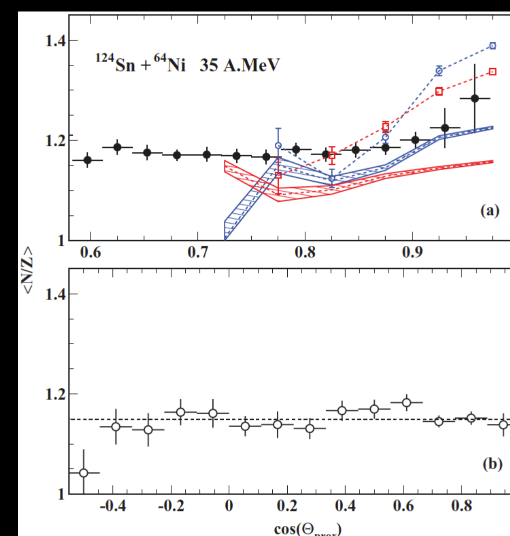
Galichet et al., PRC 79, 064615 (2009)
N/Z of complex particles, exp & BNV



Hudan et al. PRC 86, 921603(R) (2012)
Xe+Sn@50AMeV



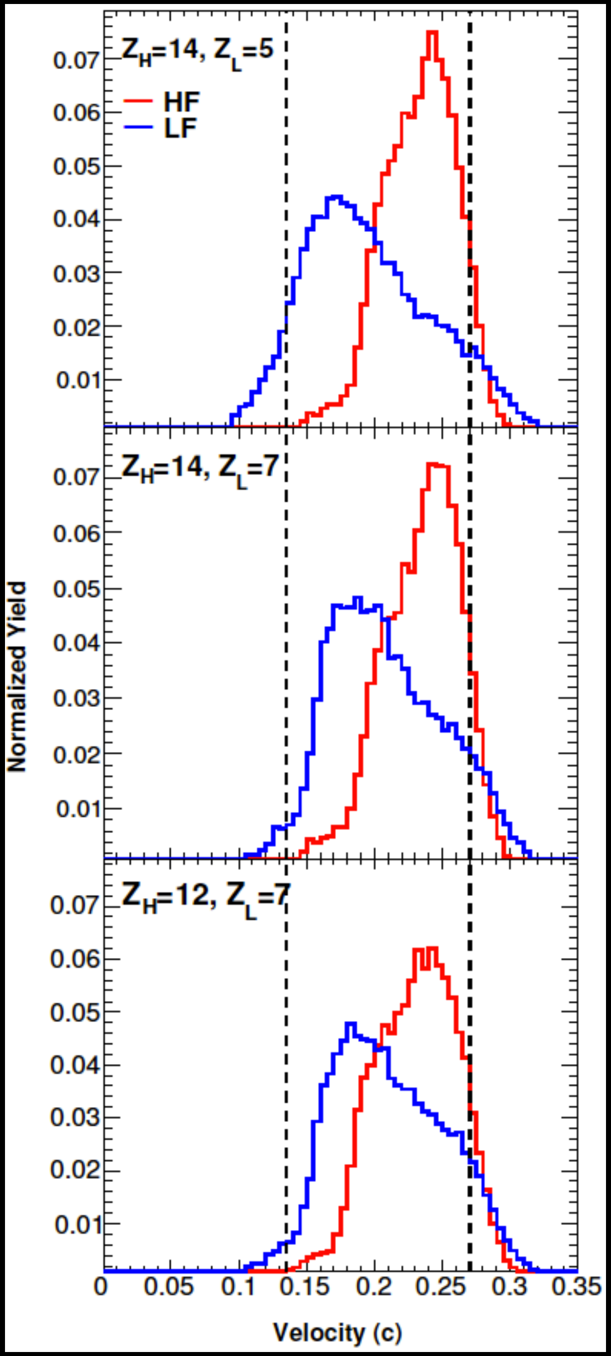
E. DeFilippo et al., PRC 86, 014610 (2012)
Observation of dependence



Our measurement

$^{70}Zn+^{70}Zn$
$^{64}Ni+^{64}Ni$
$^{64}Zn+^{64}Zn$
$^{64}Zn+^{64}Ni$
@ 35 MeV/nucleon

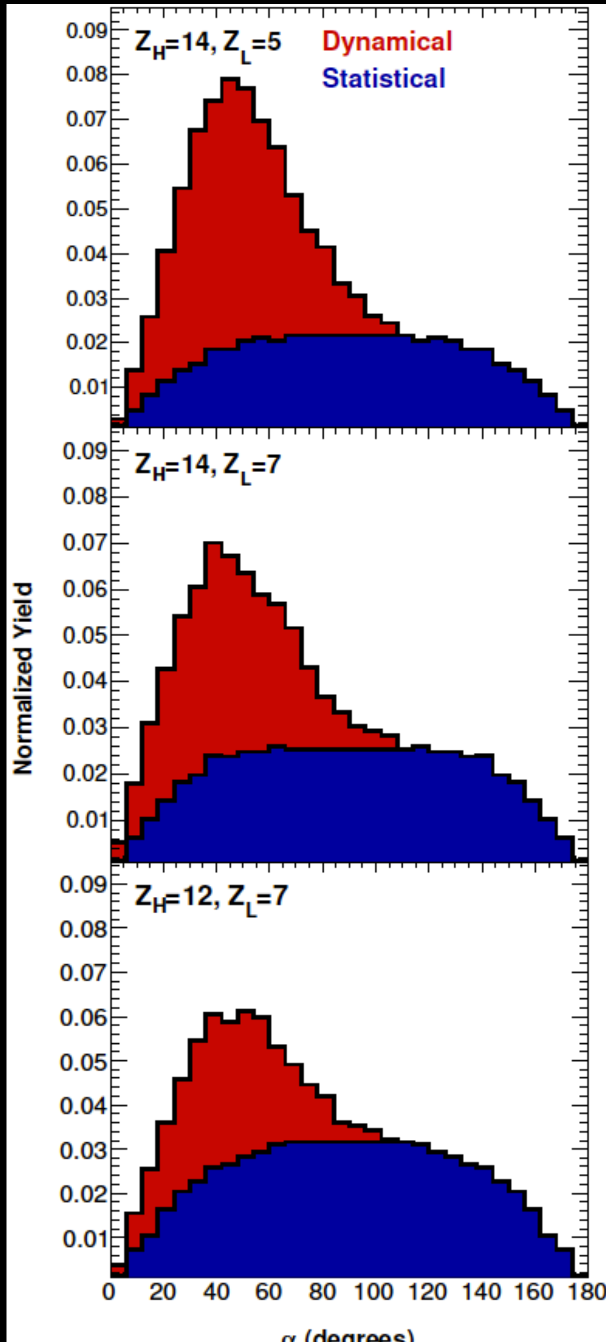
NIMROD 4π array
excellent isotopic resolution

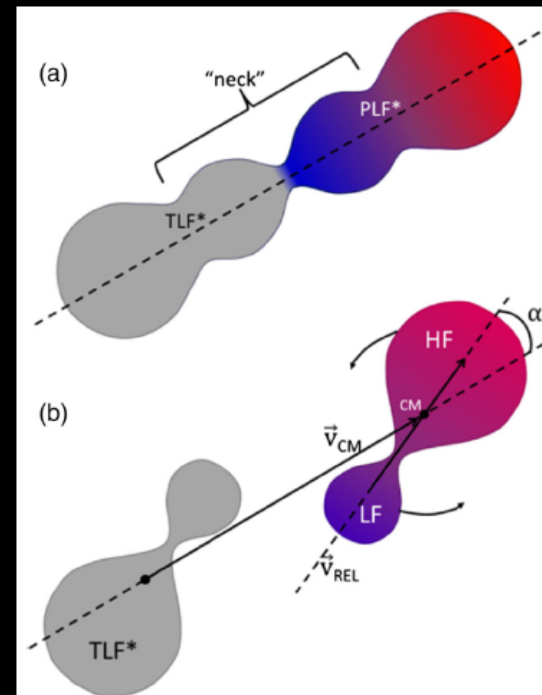


Velocity Distributions

These particles are daughters of the PLF*

Angular Distributions

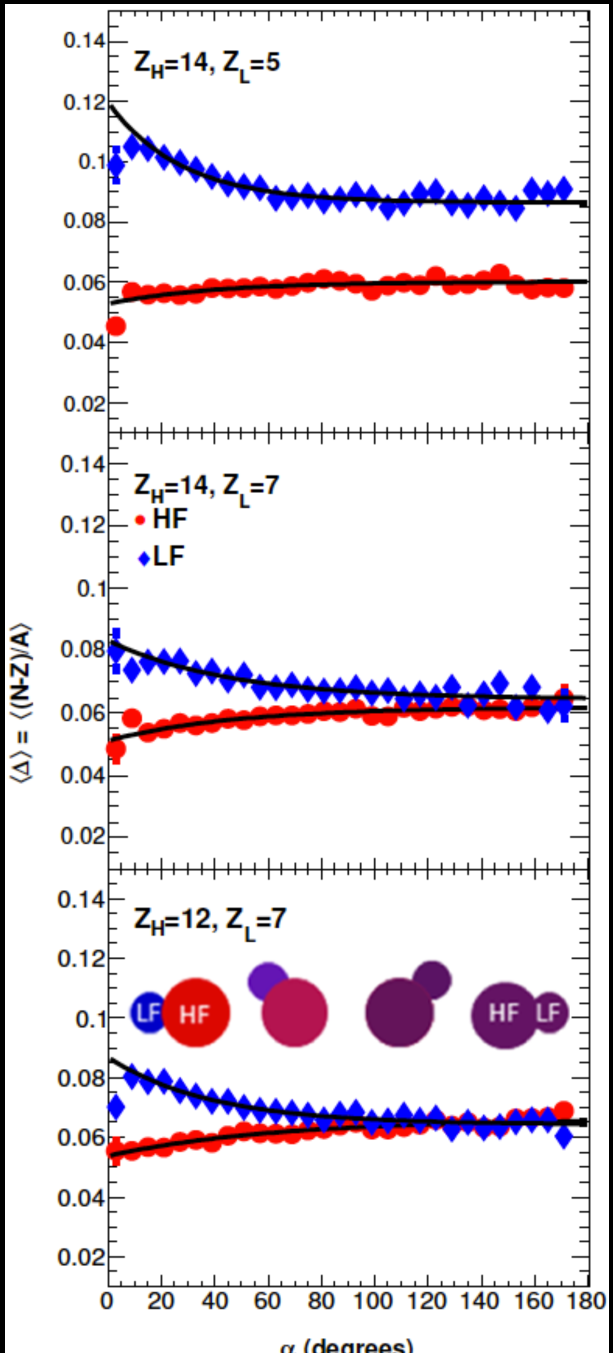




Separating Statistical and Dynamical

Assume yield α>100° is statistical
Reflect around 90°.
Interpolate smoothly 80°<α<100°

What remains is non-standard statistical
i.e. what remains is dynamical



Equilibration Chronometry

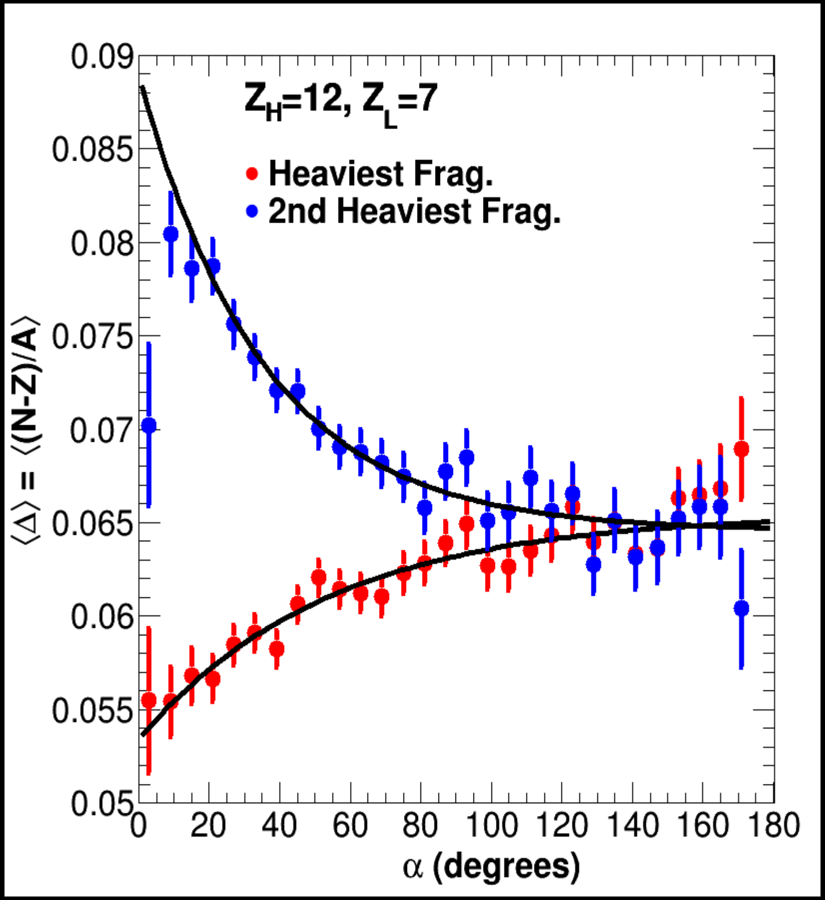
Composition vs alignment

$\Delta = (N-Z)/A$

As LF loses neutrons, HF gains neutrons

Exponential dependence → First Order Kinetics

Rate of Equilibration



Fit:

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

a: equilibrium value

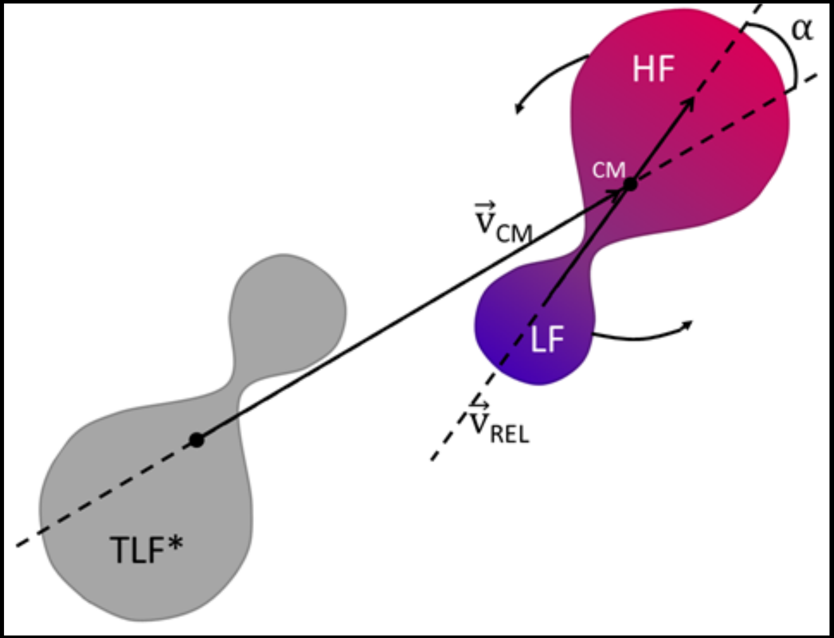
b: distance from equilibrium at t=0

c: N-Z equilibration rate constant

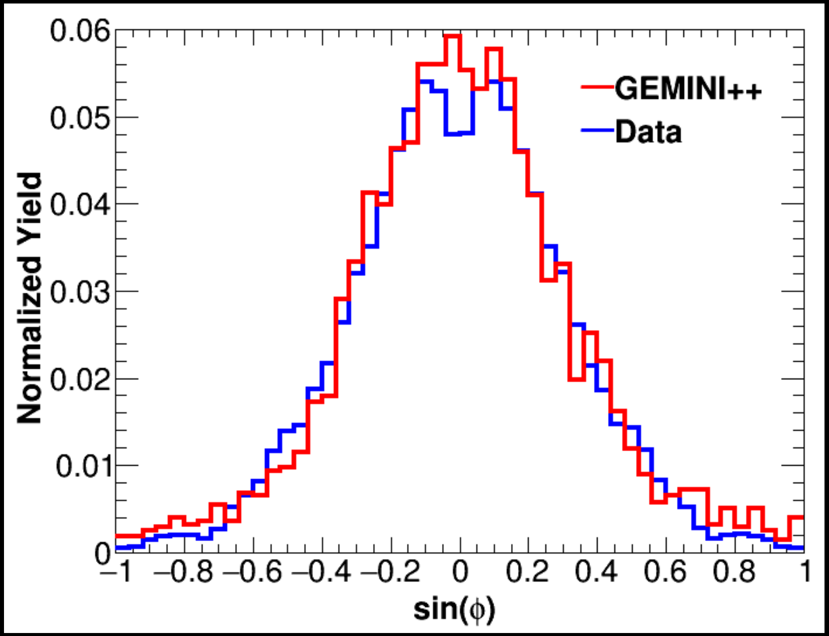
Assessing the Time Scale

Evaporative emission of light, charged particles contains information on the angular momentum

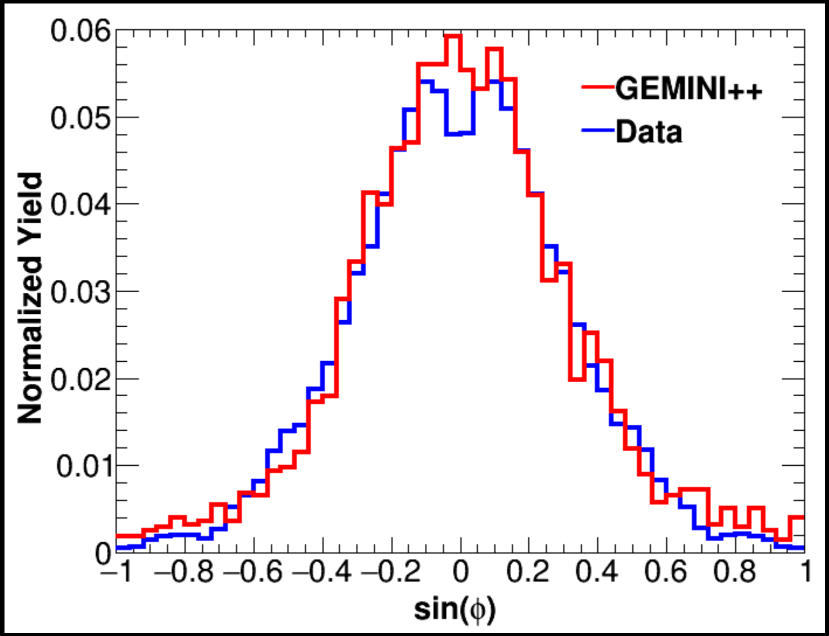
For no spin, the emission probability is equal in all directions. For high spin, equatorial emission is preferred.



The equatorial plane is defined by v_{CM} and the beam axis. The angular distribution of alpha particles relative to this plane is examined.



Assessing the Time Scale



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

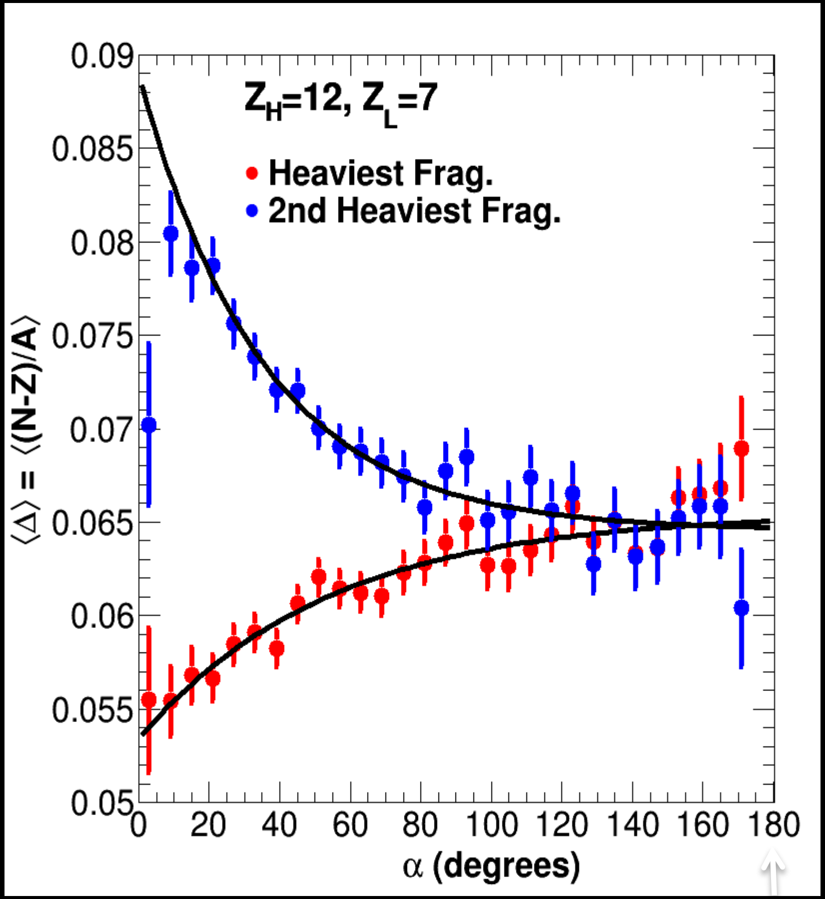
$$\omega = J \hbar / I_{eff}$$

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.

$$t = \alpha / \omega$$

Time Scale



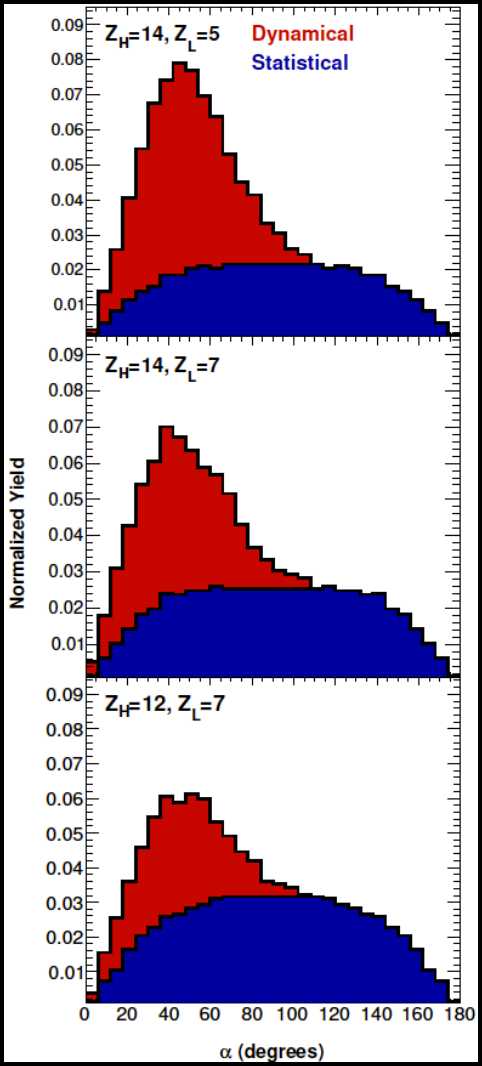
t=0

1/e time
~0.3zs
(100fm/c)

t ≈ 1.5zs
(450fm/c)

What about the effect of…

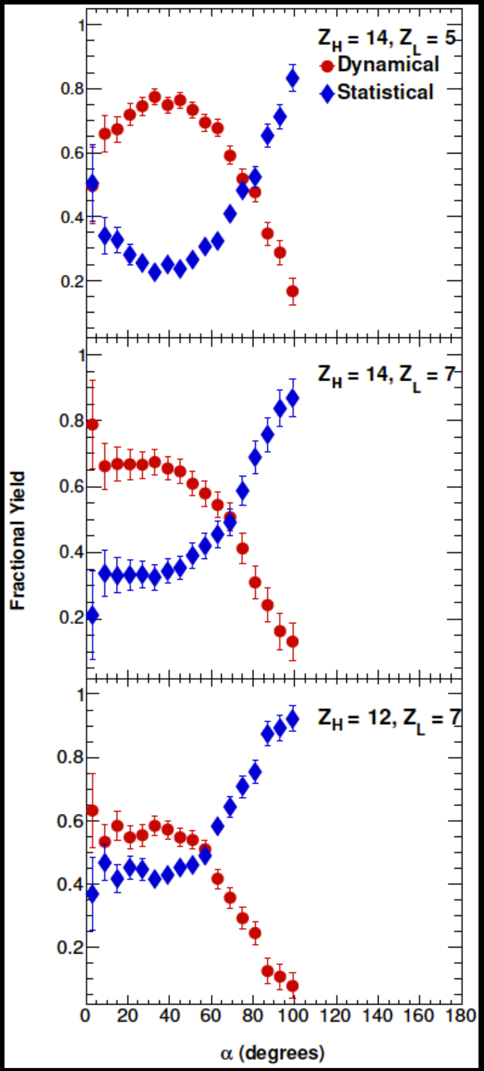
- Statistical decay
- Effect of secondary decay
- Choice of alignment angle



Separating Stat & Dynam

Fractional Yield

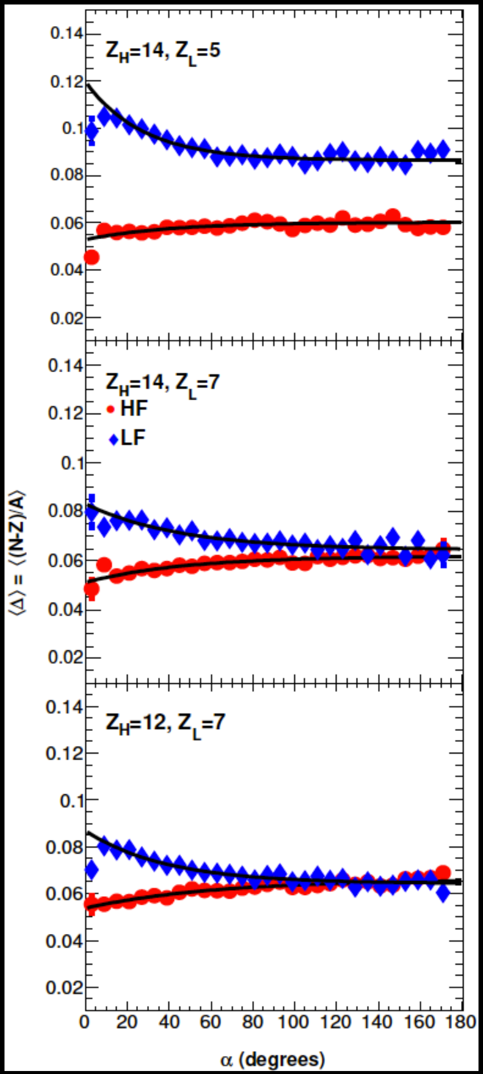
$f_{stat} = Y_{stat} / (Y_{stat}+Y_{dyn})$
$f_{dyn} = Y_{dyn} / (Y_{stat}+Y_{dyn})$

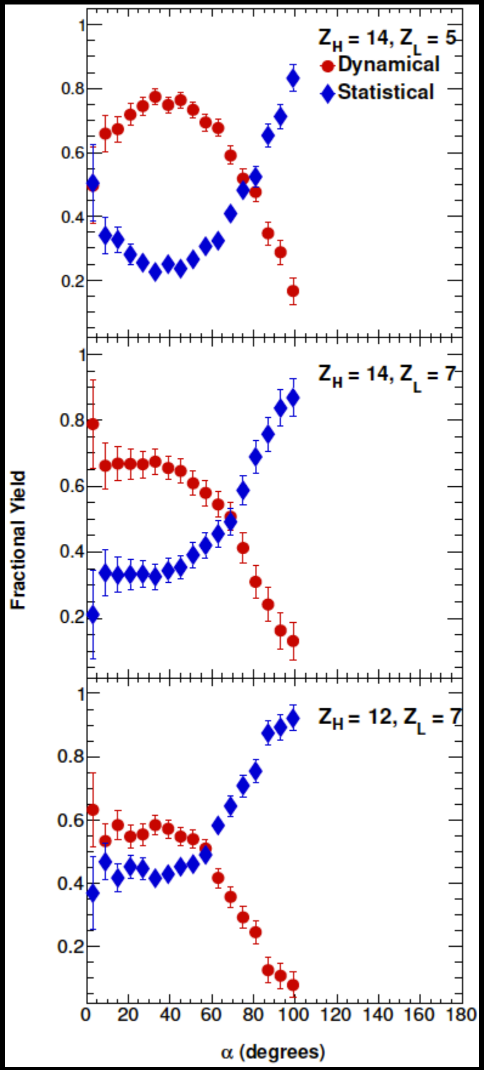


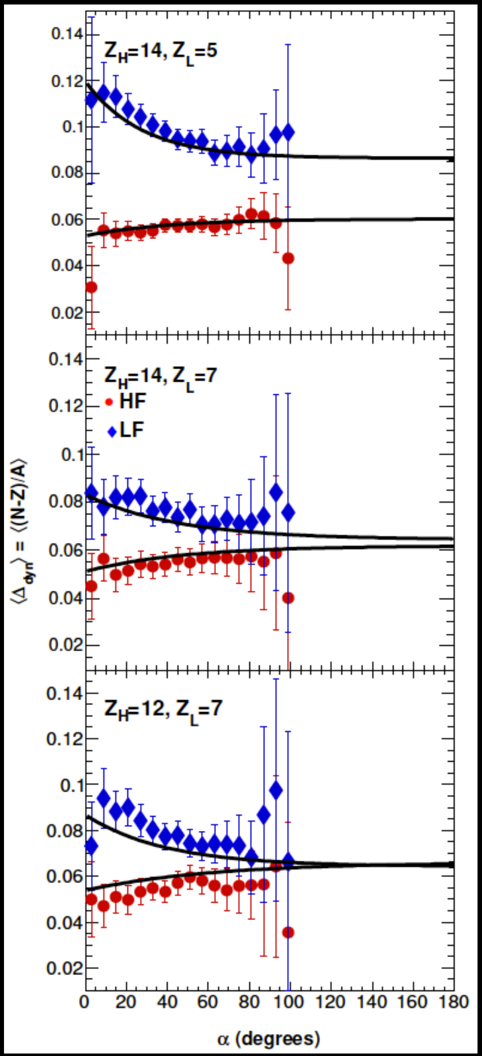
Effect of Statistical Decay

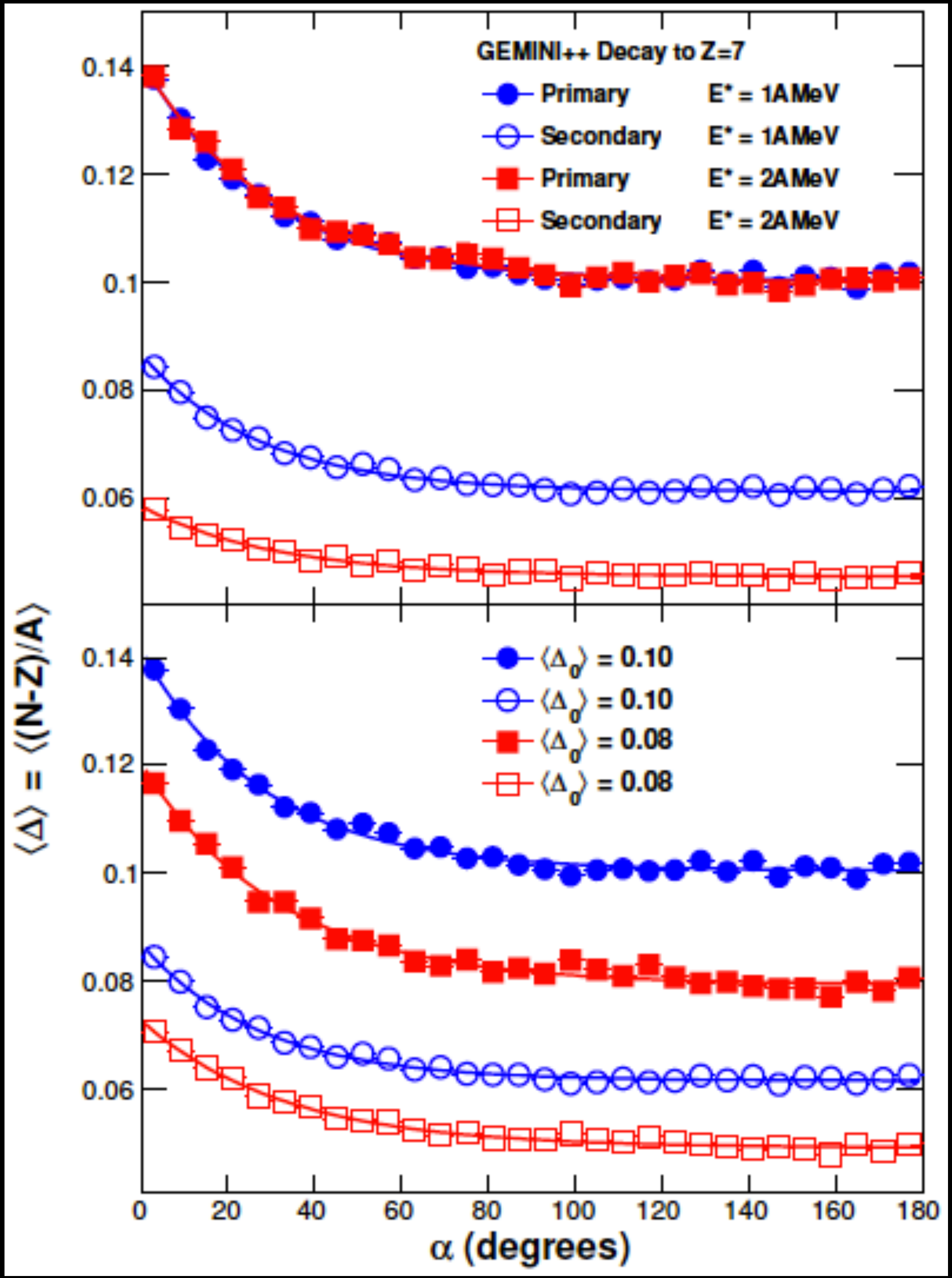
$$\Delta = \Delta_{stat} f_{stat} + \Delta_{dyn} f_{dyn}$$

Isolated Dynamical Component
General trend maintained







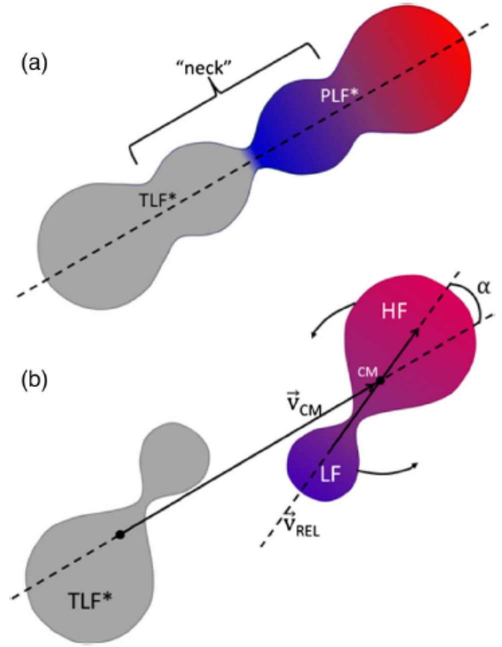


Effect of Secondary Decay

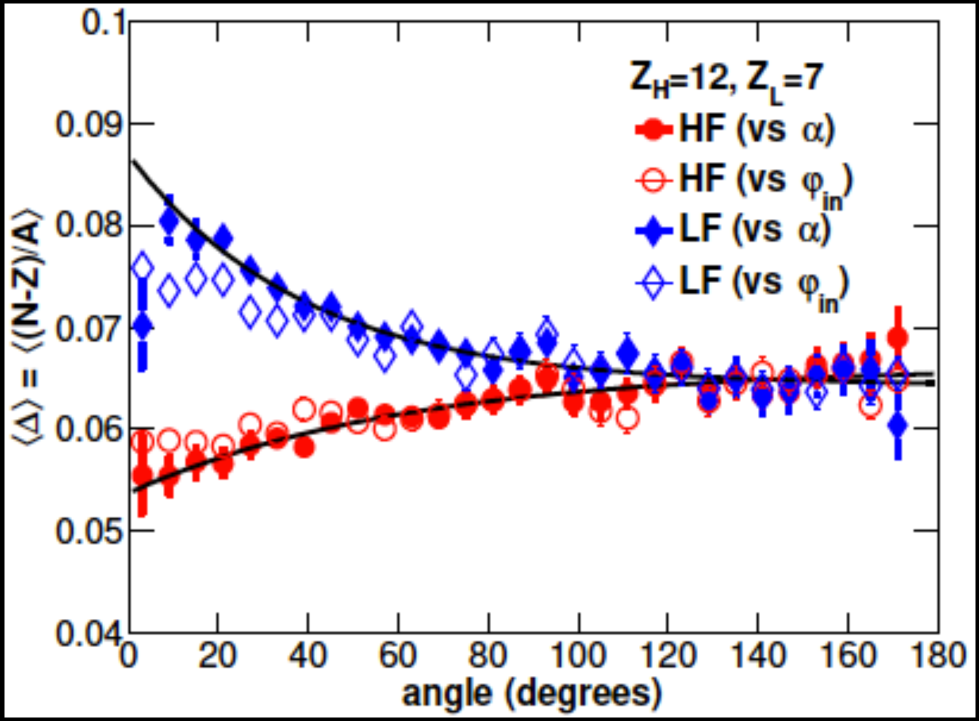
Shift toward β-stability
Decreases amplitude
Larger effect for larger E*
Dependence of final value on initial value

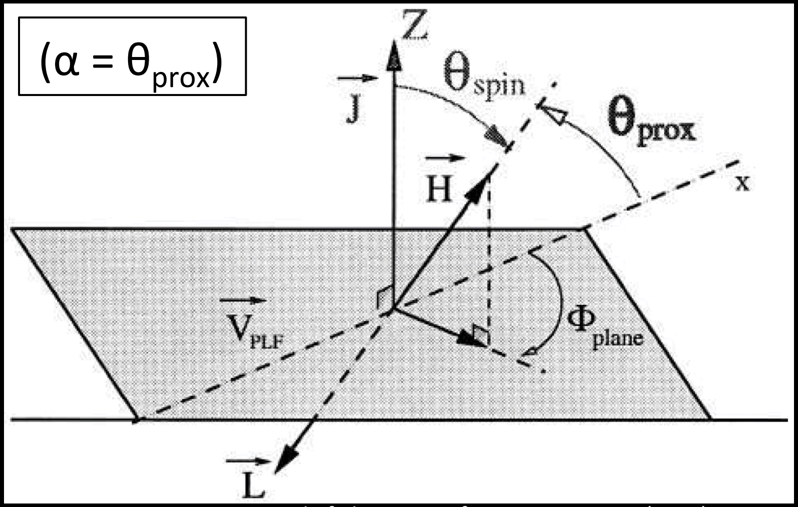
Secondary Decay mutes the effect
Does not create
Does not destroy

Effect of Choice of Alignment Angle



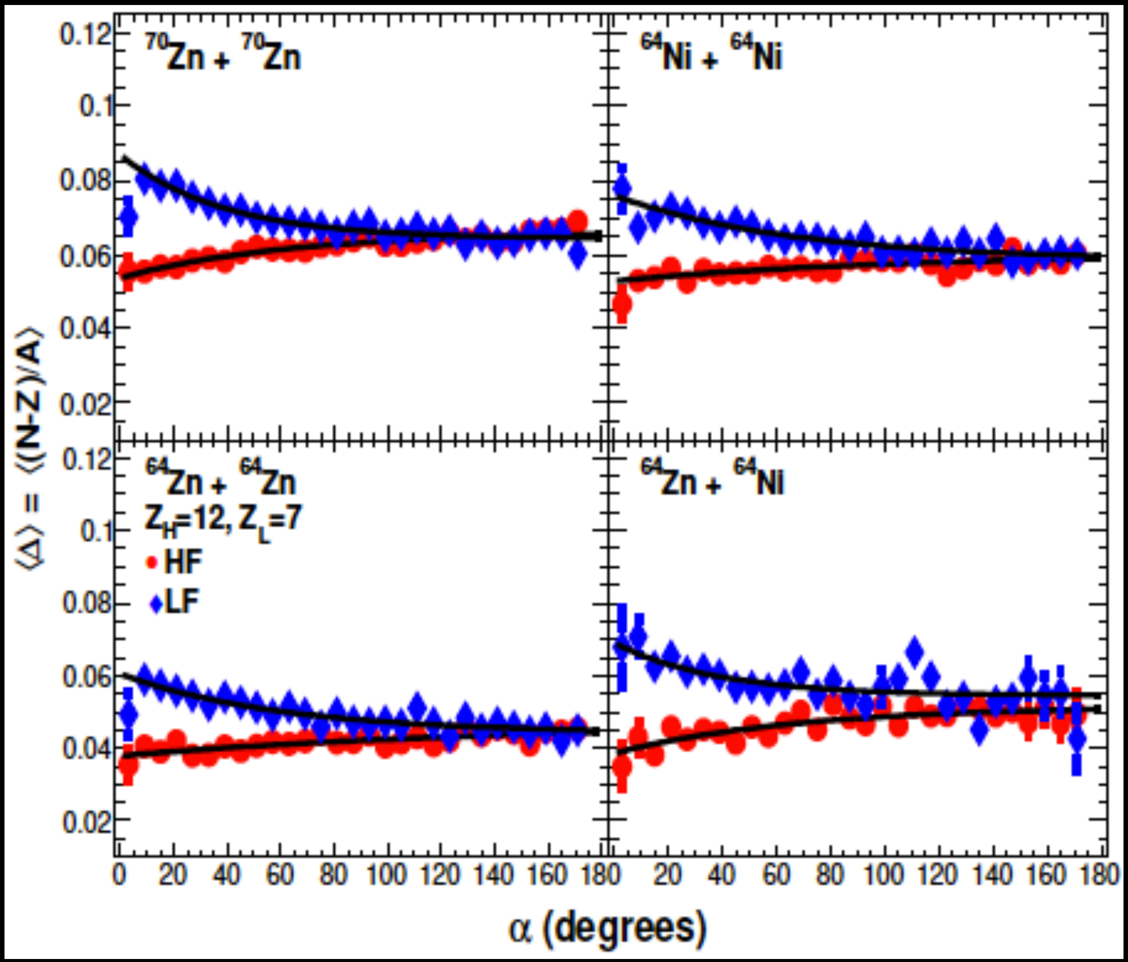
α is somewhat more sensitive





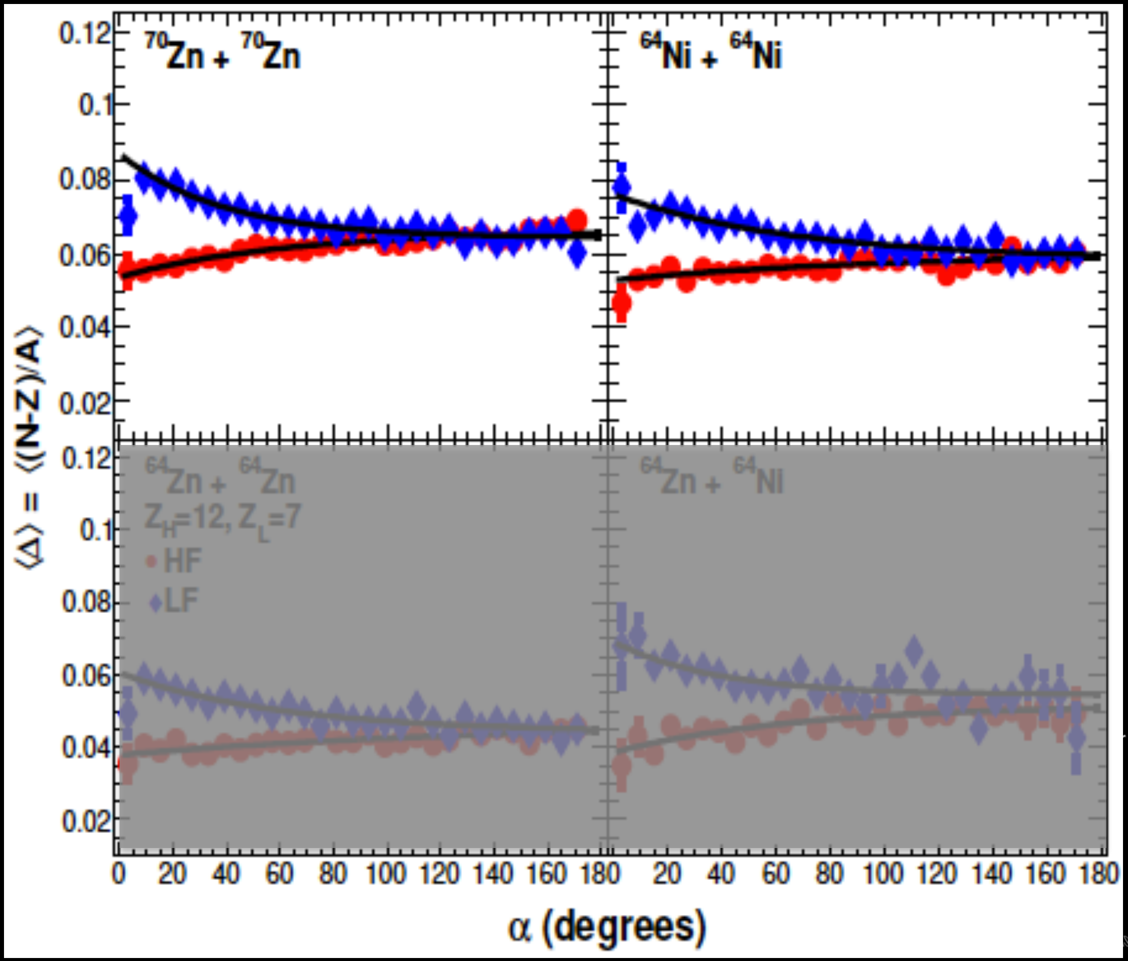
S Pirrone, Journal of Physics: Conference Series 527 (2014) 012030

Effect of Beam and Target Composition

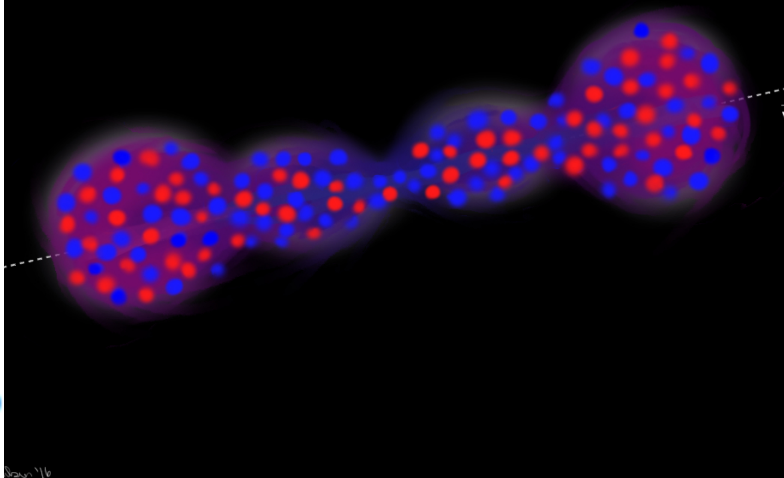


- Similar equilibration rates
- Notable differences in composition

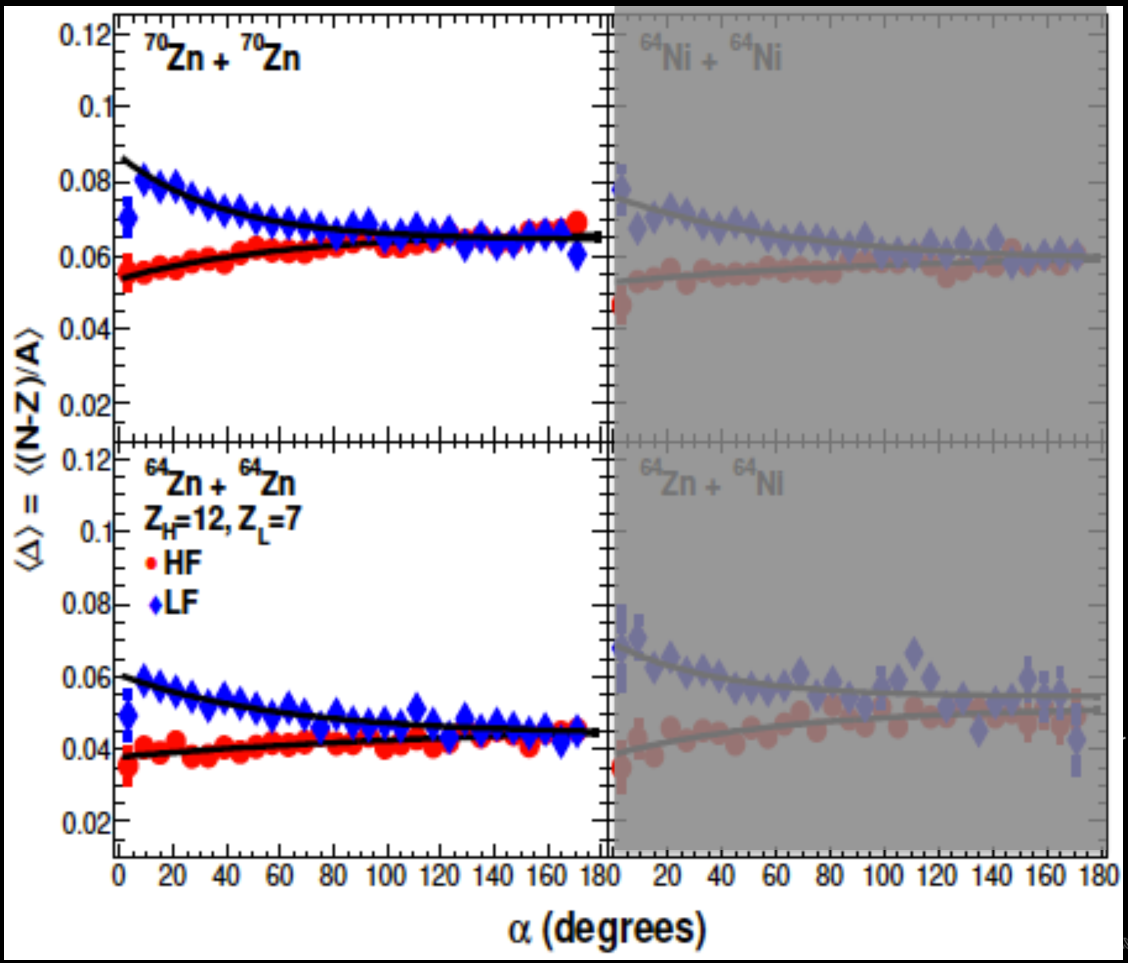
Effect of Beam and Target Composition



70Zn+70Zn vs 64Ni+64Ni
Slightly lower system asymmetry
→ Slightly lower composition



Effect of Beam and Target Composition



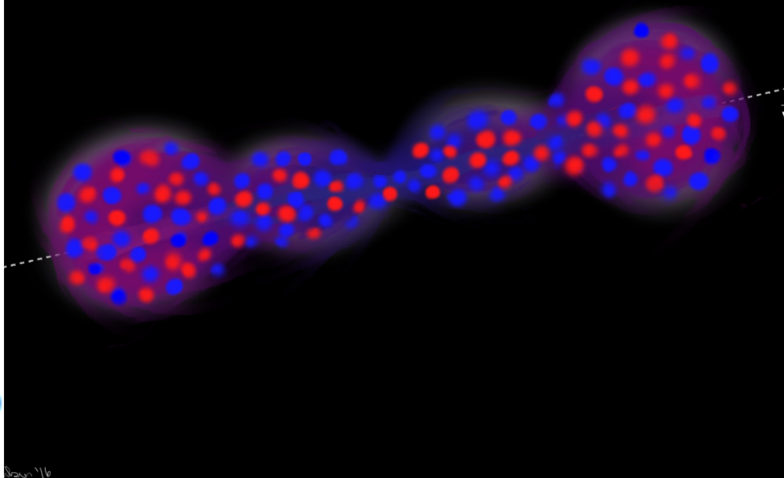
70Zn+70Zn vs 64Zn+64Zn

Lower proj. & targ. asymmetry

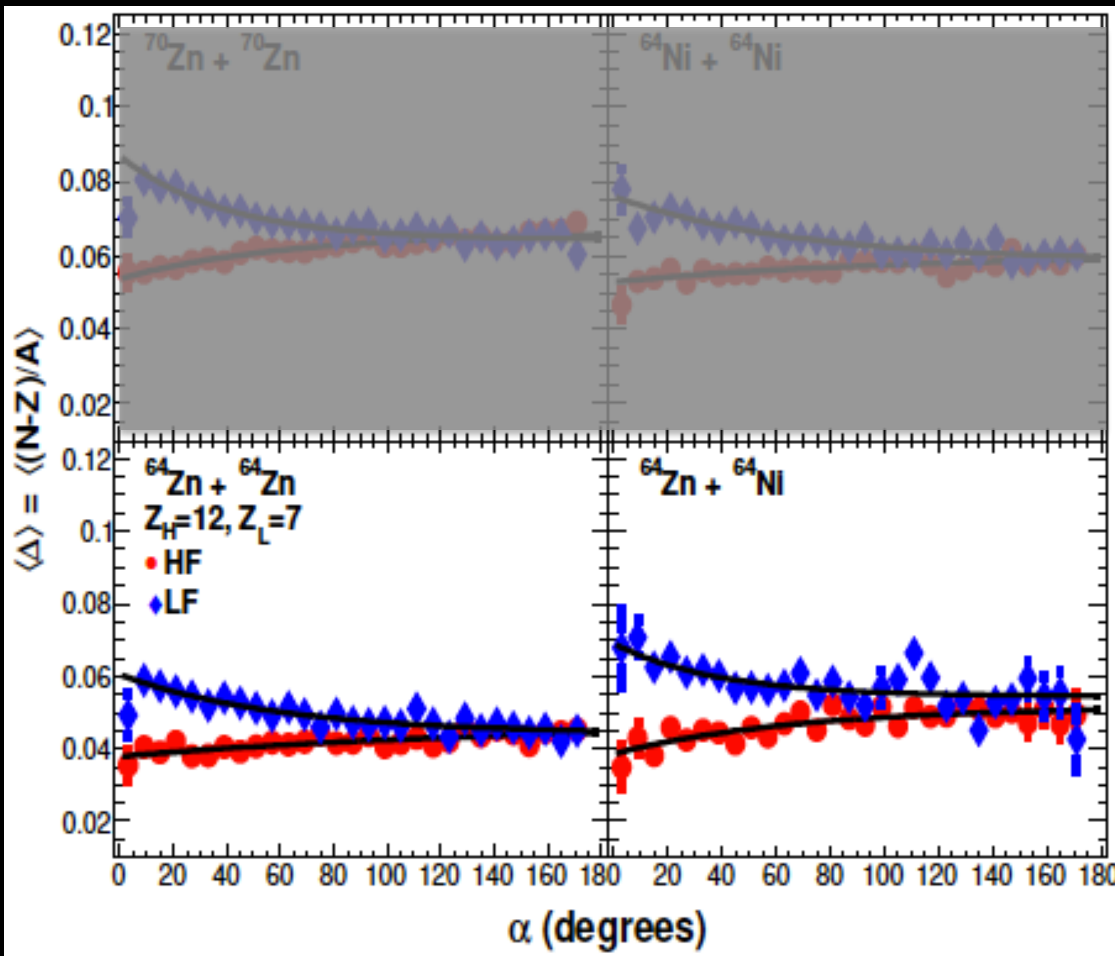
→ Lower initial asymmetry

→ Lower equilibrium asymmetry

→ Smaller change in asymmetry



Effect of Beam and Target Composition



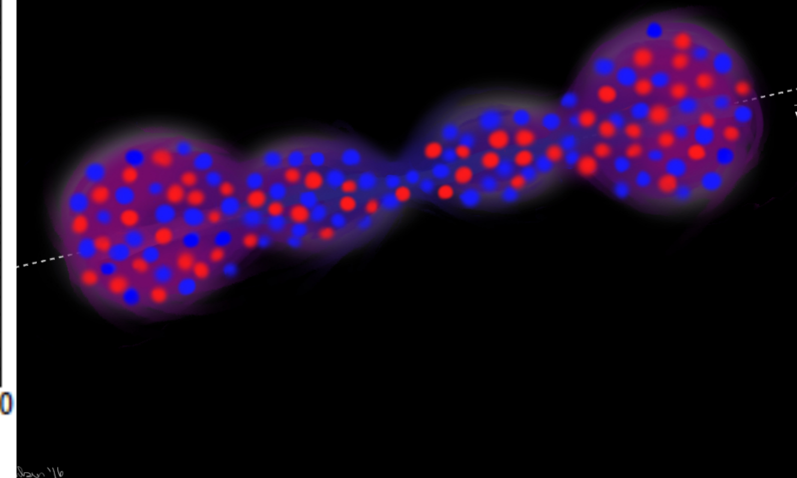
64Zn+64Zn vs 64Zn+70Zn

Increase only target asymmetry

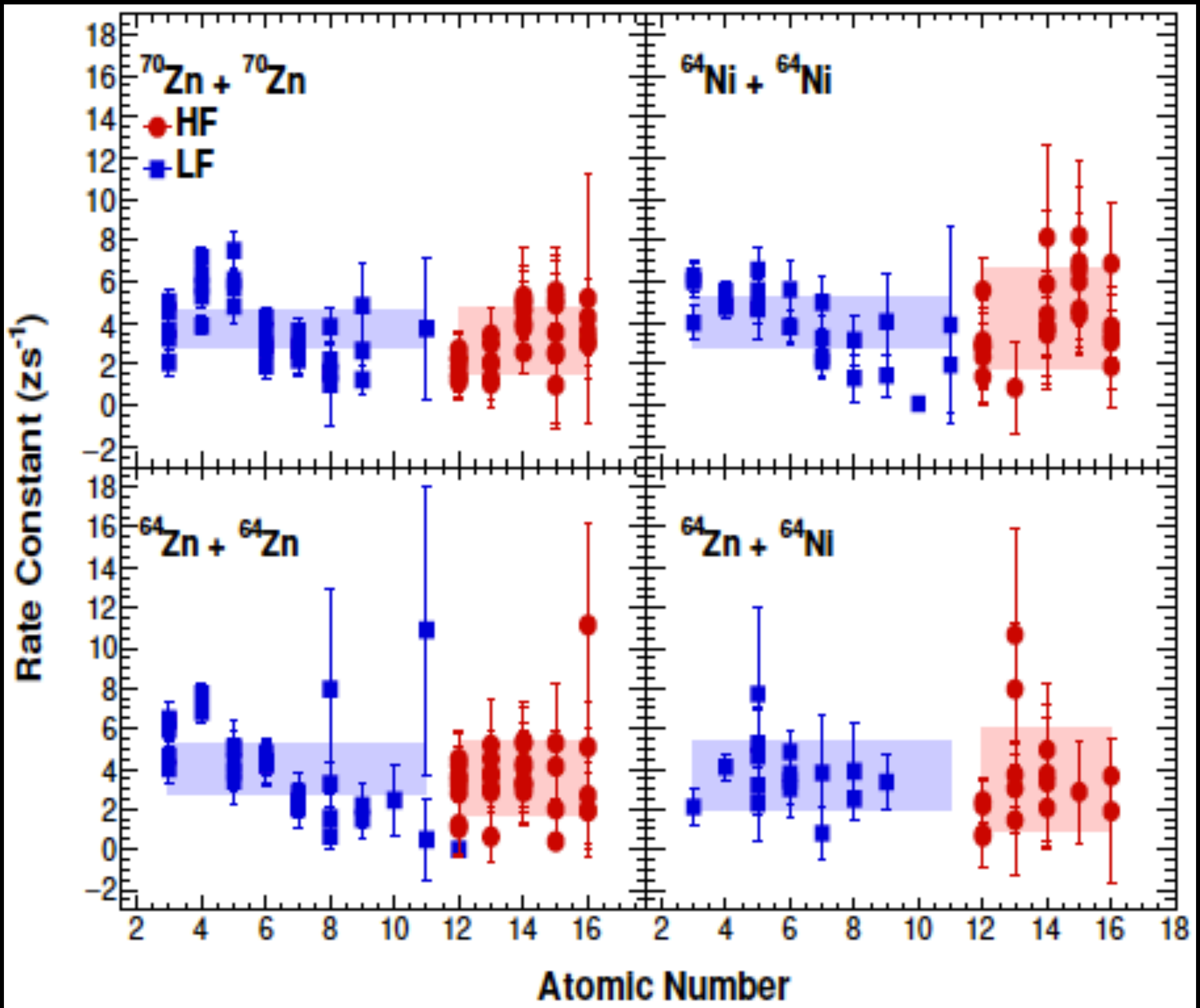
→ Higher initial asymmetry in LF

→ Same initial asymmetry in HF

→ Higher equilibrium asymmetry



Equilibration rate constants



Timescale is 0.3zs (100fm/c).

This is not only a measurement of the timescale.

We observe exponential change in the composition, infer the effect of first order kinetics, and extract a rate constant.

Yennello Research Group & Collaborators

PRL **118**, 062501 (2017) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2017

Characterizing Neutron-Proton Equilibration in Nuclear Reactions with Subzeptosecond Resolution

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PHYSICAL REVIEW C **00**, 004600 (2017)

Detailed characterization of neutron-proton equilibration in dynamically deformed nuclear systems

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Welch Foundation
A-1266

Upcoming Experiment

How does the equilibration depend on bombarding energy?

- More extreme densities probed at higher bombarding energy
- Evolution of shape deformation with bombarding energy
- Evolution of the break-up mechanism with beam energy

Ca+Ni @ 15, 25, 35, 45 MeV/nucleon
NIMROD 4π charged particle and 4π neutron array
Frags. of PLF*: isotopic resolution

Dear Colleagues,

Reaction dynamics around the Fermi energy is rich with new things for us to learn.

Equilibration chronometry can be a powerful tool. It shows time-dependence! I suggest this can be used to **refine the microscopic interactions** used in transport models and thereby constrain the EOS.

We can provide isotopic distributions of dynamically produced fragments as a function of alignment angle, and relate the alignment to time.

Together, I would like to explore:

- time dependence of NZ equilibration (actual time)
- time dependence of NZ equilibration (time from angle)
- the evolution of the total density and asymmetry density
- sensitivity to the microscopic interaction (e.g. Asy-Stiff vs -Soft)

Cheers,

-Alan