Neutron-Proton equilibration in dynamically-deformed nuclear systems

(at 35 MeV/nucleon)

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(on behalf of the SJY group)
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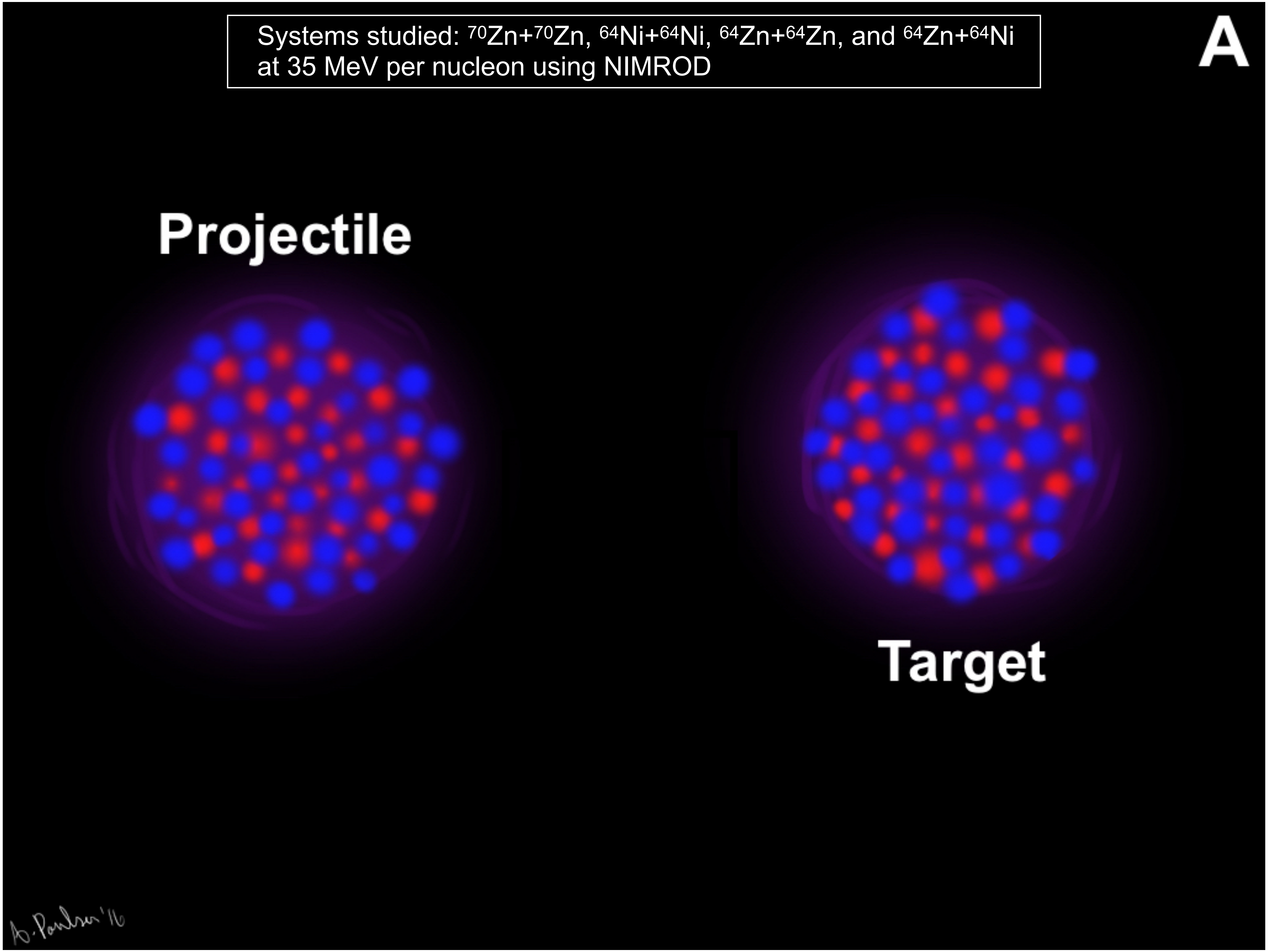
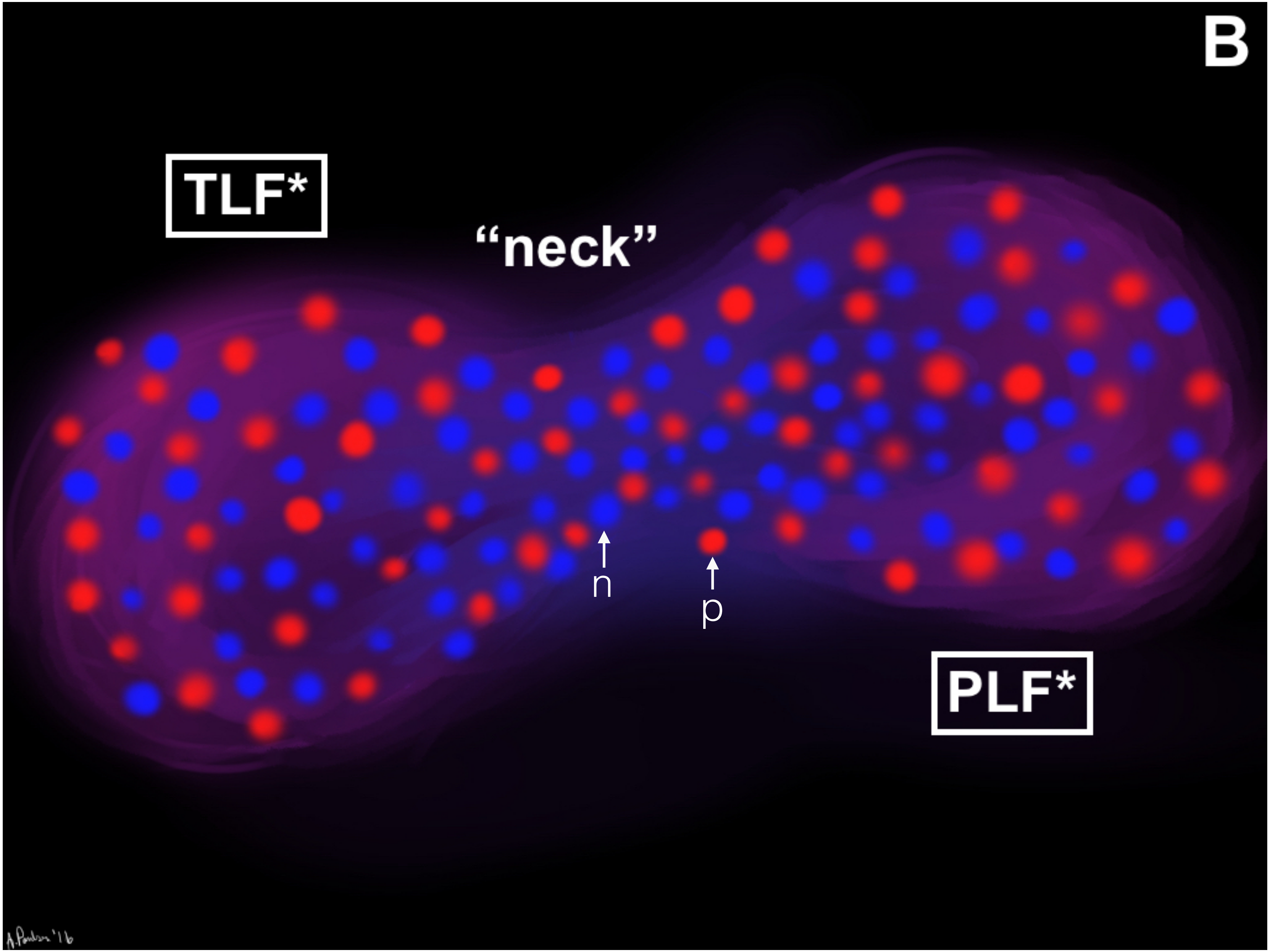
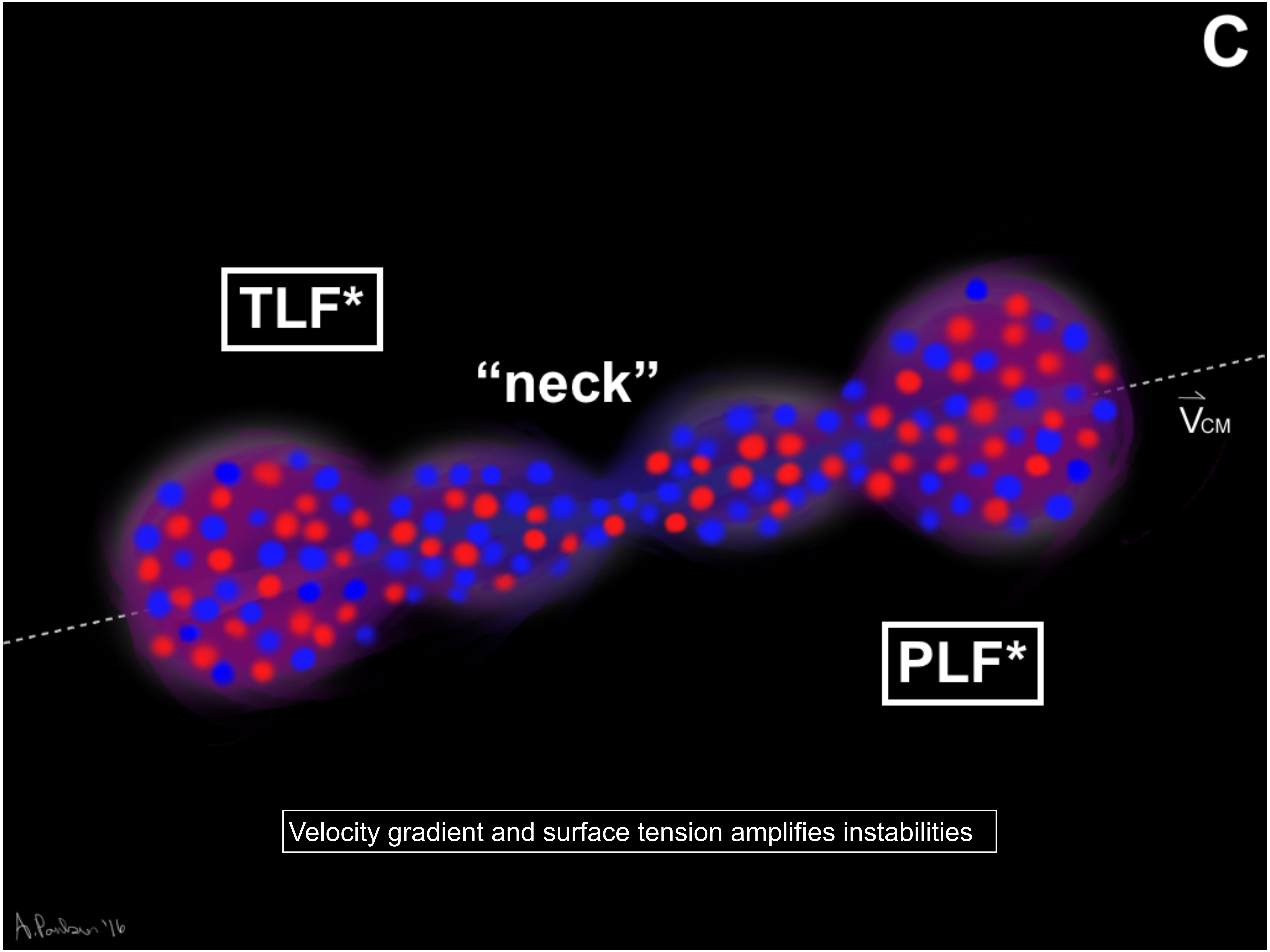
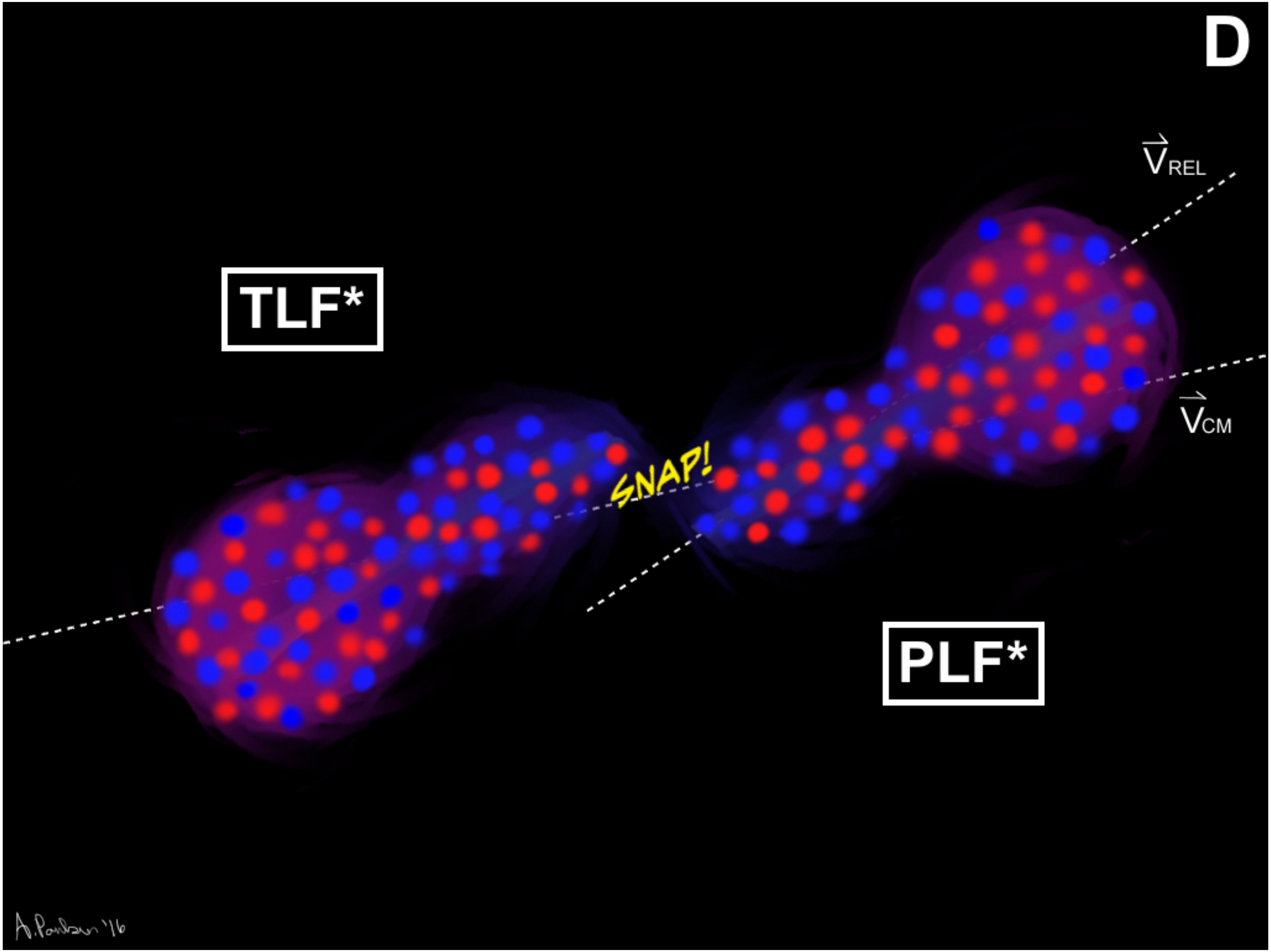
Systems studied: ^{70}Zn+^{70}Zn, ^{64}Ni+^{64}Ni, ^{64}Zn+^{64}Zn, and ^{64}Zn+^{64}Ni at 35 MeV per nucleon using NIMROD

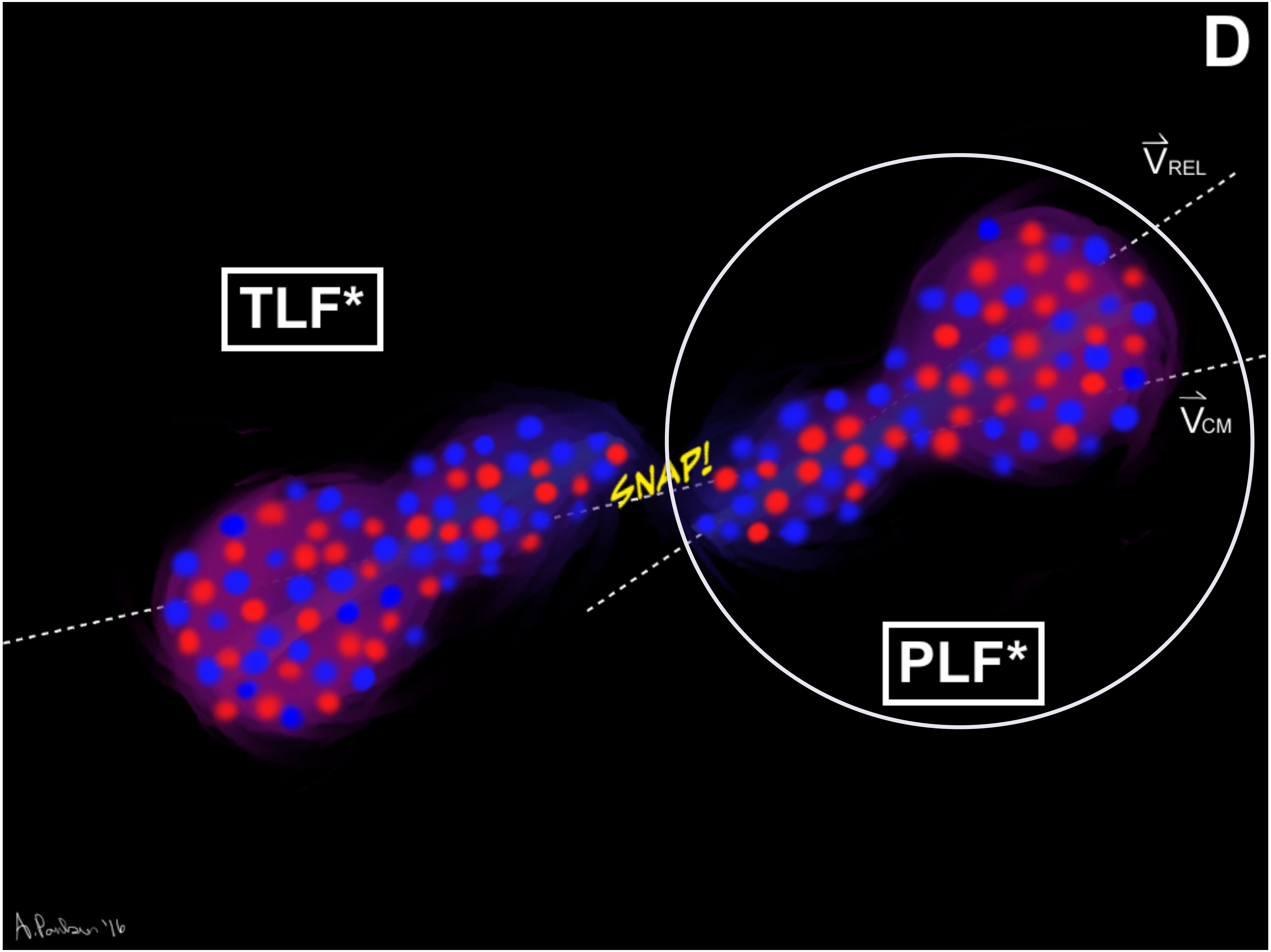


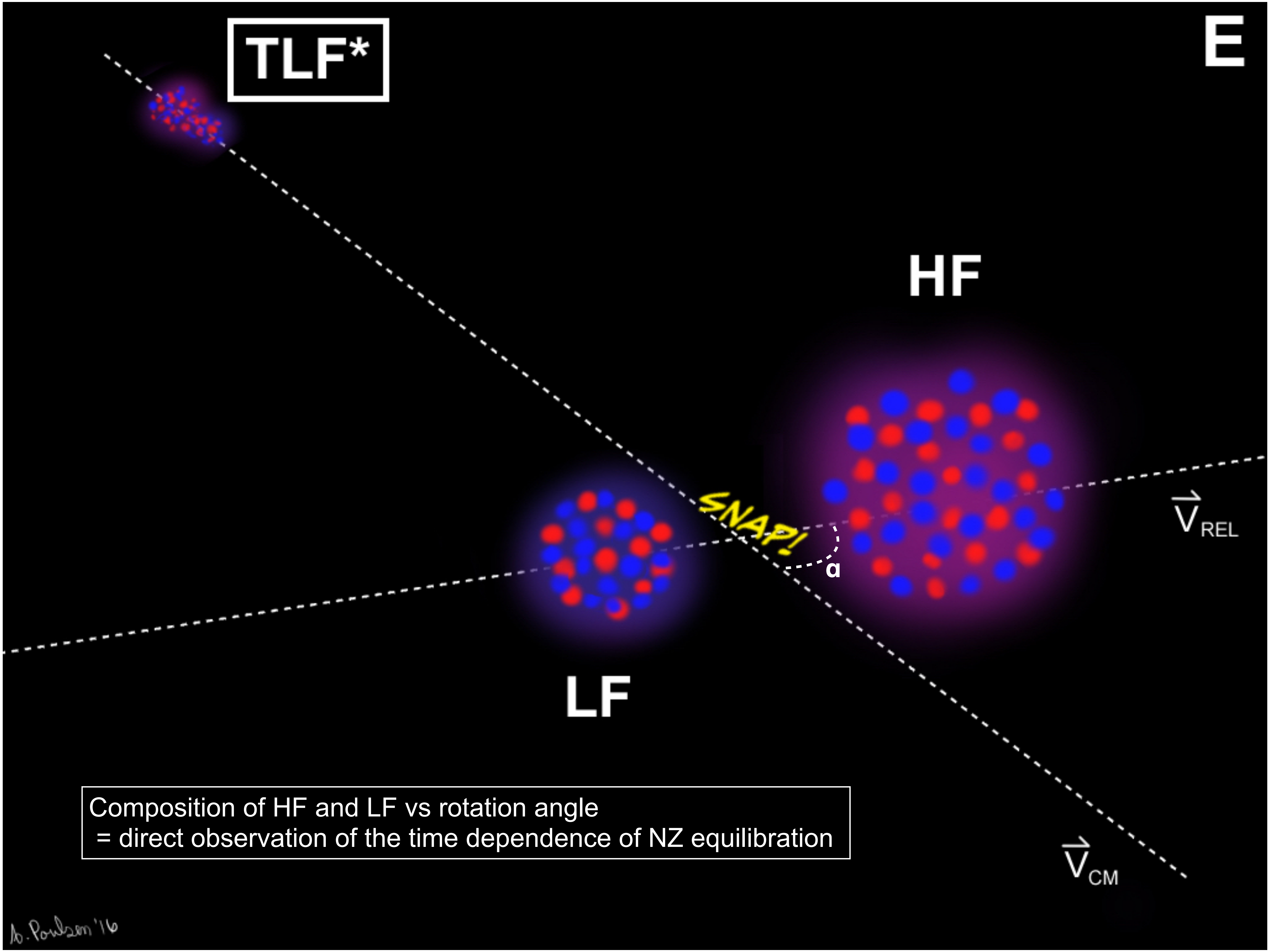

B
TLF*
"neck"
n
p
PLF*
A.Paulsen '16



Velocity gradient and surface tension amplifies instabilities


D
TLF*
PLF*
SNAP!
$\vec{V}_{REL}$
$\vec{V}_{CM}$
A.Paulsen '16

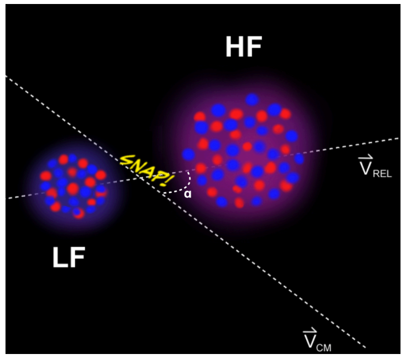

D
TLF*
PLF*
$\vec{V}_{REL}$
$\vec{V}_{CM}$
SNAP!
A.Ponbon '16



Composition of HF and LF vs rotation angle
= direct observation of the time dependence of NZ equilibration

Angular (α) distributions:

- Lifetime of PLF* correlated with rotation angle:



$$\alpha = \mathrm{acos}\left(\frac{\vec{v}_{cm}\cdot\vec{v}_{rel}}{|\vec{v}_{cm}||\vec{v}_{rel}|}\right)$$

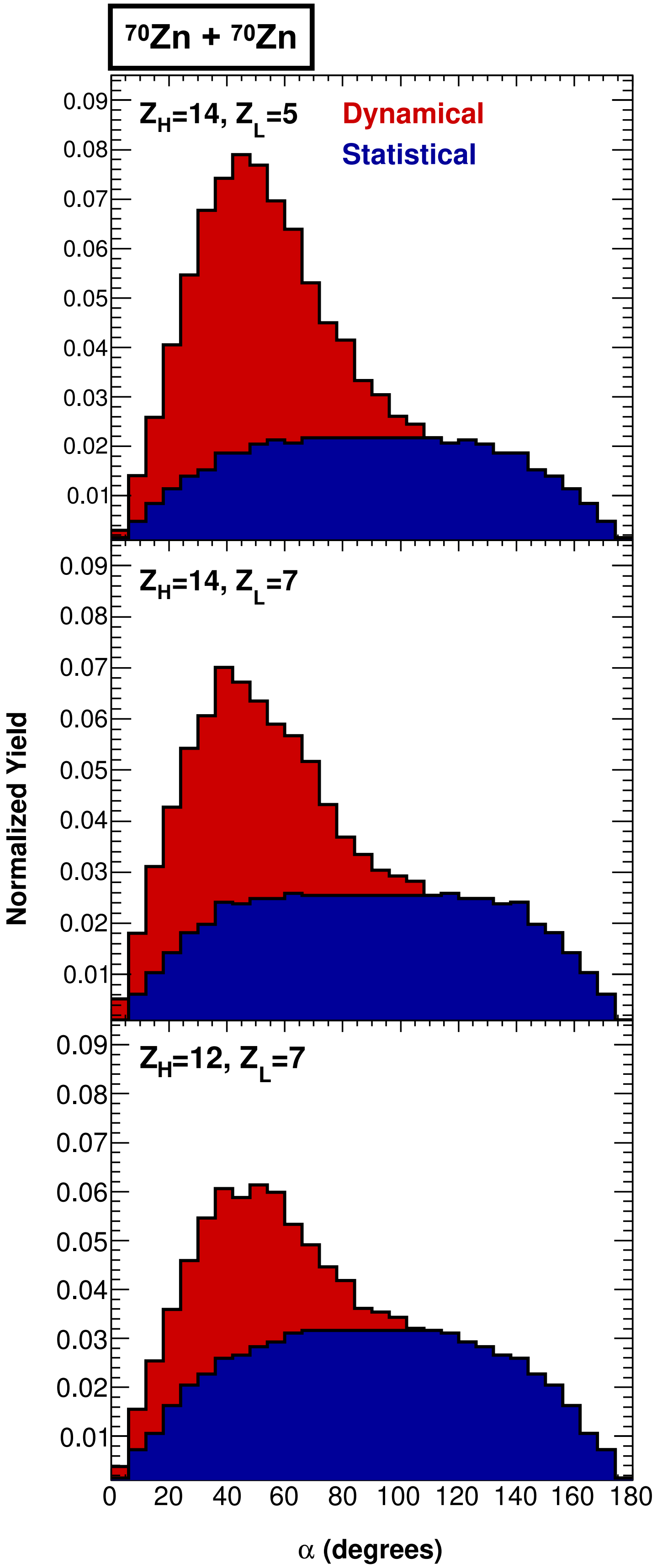
- Angular distribution peaked for most aligned configuration. Decreases in yield with decreasing alignment.

- Excess yield largest and most strongly aligned for most asymmetric splits.

- Less aligned decays represent longer decay times.

$$Y_T = Y_d + Y_s$$

- Dynamical yield dominates at small angles and decreases as α increases.



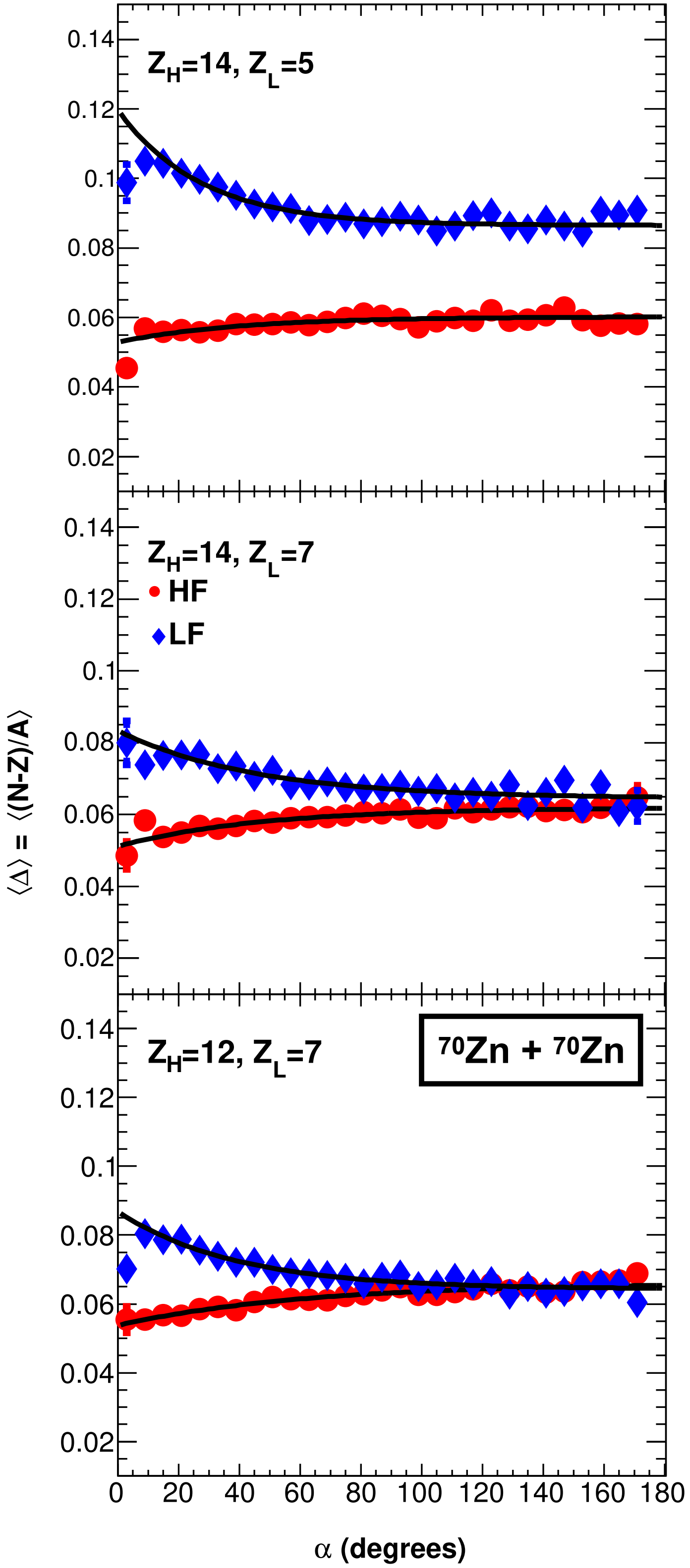
Composition vs decay alignment:

$$\Delta_{Observable} = f_s\Delta_S + f_d\Delta_d$$

- As angle of rotation increases, Δ_{HF} (Δ_{LF}) start off very n-poor (n-rich), then evolve towards each other.

- Exponential fit: ***a* + *b* e**$^{-c(\alpha)}$
  - ***a*** = equilibrium value
  - ***c*** = rate constant for equilibration
- First-order kinetics (for all the systems studied).

Overall composition



Composition vs decay alignment:

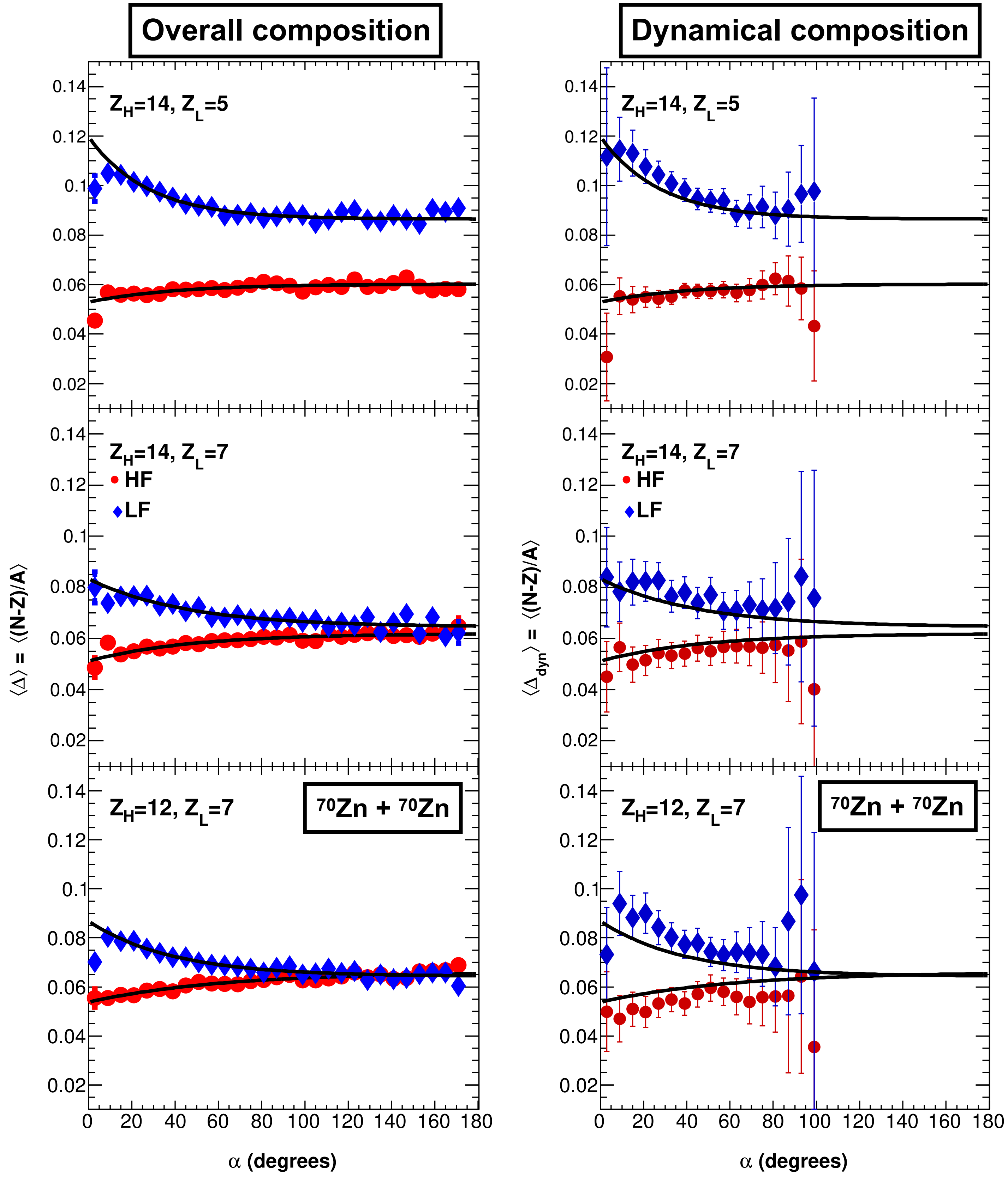
$$\Delta_{\text{Observable}} = f_S\Delta_S + f_d\Delta_d$$

- As angle of rotation increases, Δ_{HF} (Δ_{LF}) start off very n-poor (n-rich), then evolve towards each other.

- Exponential fit: ***a* + *b* e$^{-c(\alpha)}$**
  - ***a*** = equilibrium value
  - ***c*** = rate constant for equilibration
- First-order kinetics.

- Dynamical composition generally follows the same trend as the overall composition (more extreme).

- Rate of change of the composition unaffected by correction



Secondary decay (SD):

using GEMINI++

full markers: <Δ>/α correlation prior to SD

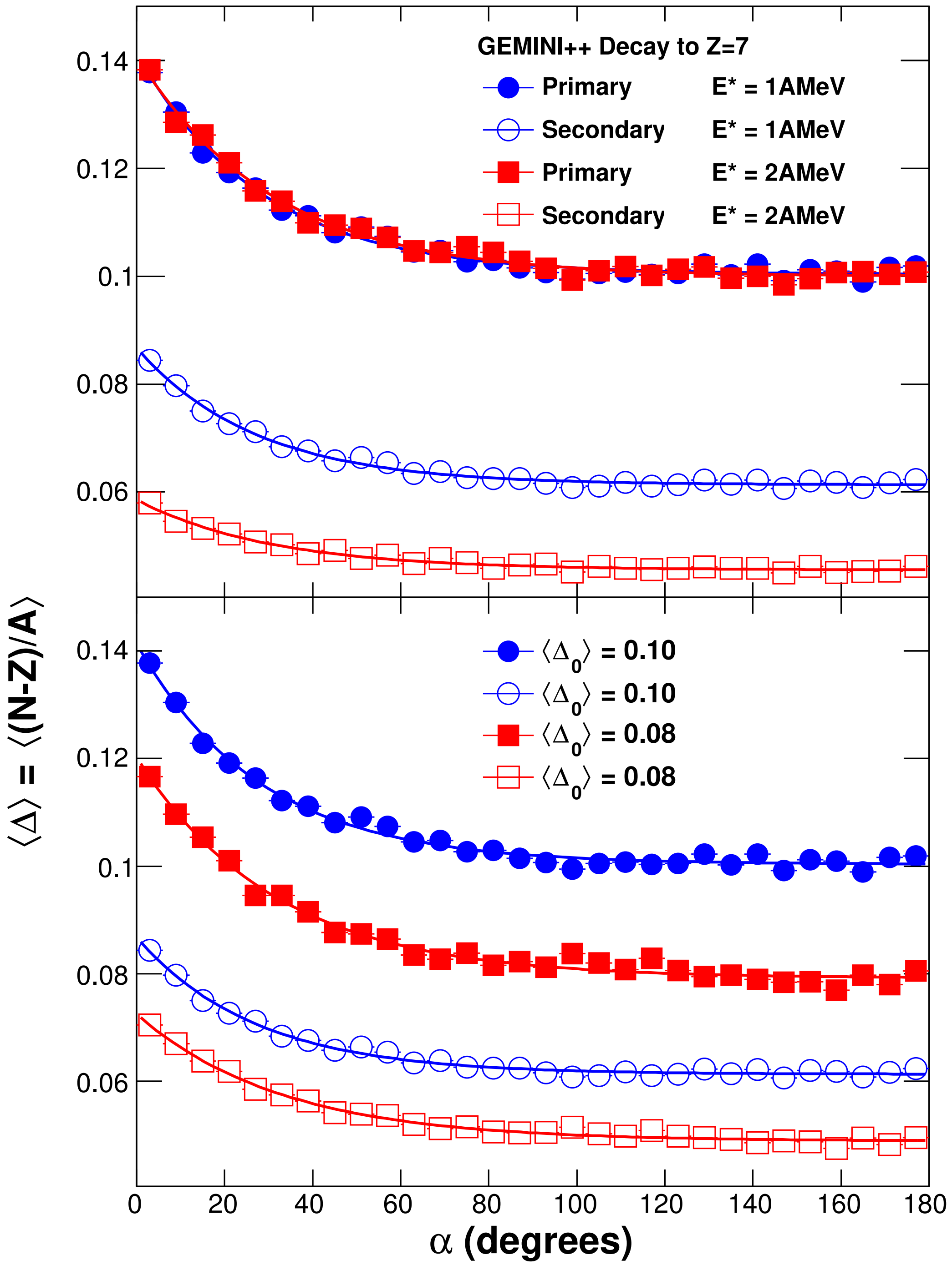
open markers: <Δ>/α correlation of the final state fragments

Varying the initial excitation energy:

- In both cases (🔵 🟥), exponential dependence maintained.
- Shift to lower composition and muting of the amplitude (stronger for higher excitation energy)

Varying the starting <Δ>:

- System with initially larger asymmetry shifted down strongly by SD. (System farther from valley of stability feels a stronger force driving it back toward the valley)
- After SD, the more n-rich system remains more n-rich.



The trend is not destroyed or created, and the characteristic rate of the exponential is retained.

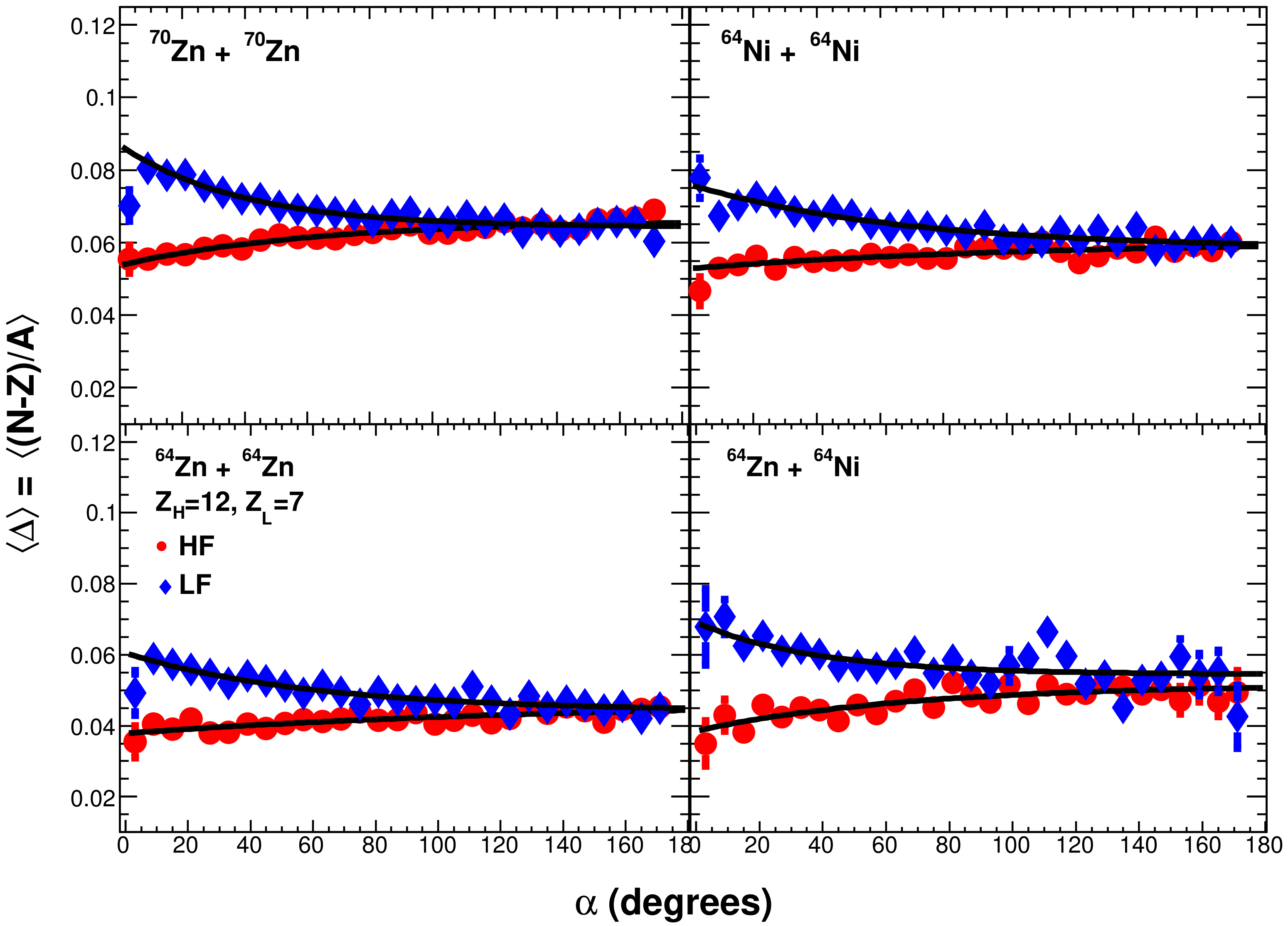
Composition vs decay alignment: for different systems

- Δ/α (^{70}Zn, ^{64}Ni) correlations essentially the same.

- Δ/α (^{64}Zn) correlation shifted to lower values (i.e. lower equilibrium composition). Same rate constants and change from initial to final value.

Comparing the symmetric and the asymmetric systems:

- Δ/α correlations for the symmetric system are systematically lower
  → **target effects.**

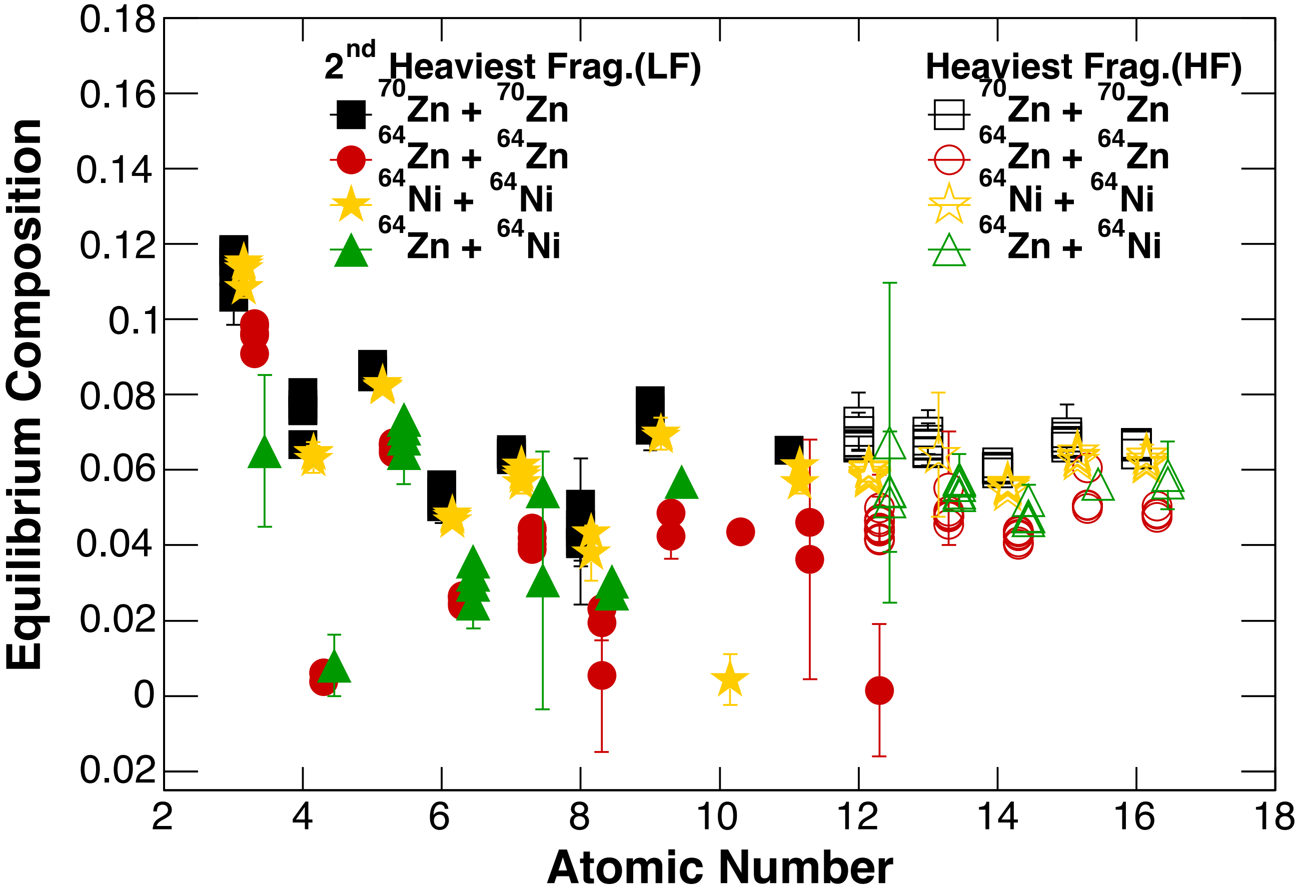


Equilibrium composition

$$\langle\Delta\rangle = a + b\, e^{-c(\alpha)}$$

- Z_{L}, Z_{H} values fairly clustered ➔ equilibrium value for LF (HF) depends on Z_{L} (Z_{H}) but not on Z_{H} (Z_{L}).
- Comparing ^{70}Zn (■) and ^{64}Ni (★) systems (similar n-rich system composition): ~ same equilibrium composition.
- ^{64}Zn (●): consistently less n-rich equilibrium compositions
- The asymmetric ^{64}Zn + ^{64}Ni system (▲): slightly + n-rich daughters than the n-poor syst. slightly - n-rich daughters than the n-rich systs.

➔ **target effect**



Rate constant for equilibration:

$$\langle\Delta\rangle = a + b\, e^{-c(\alpha)}$$

- Exponential slope

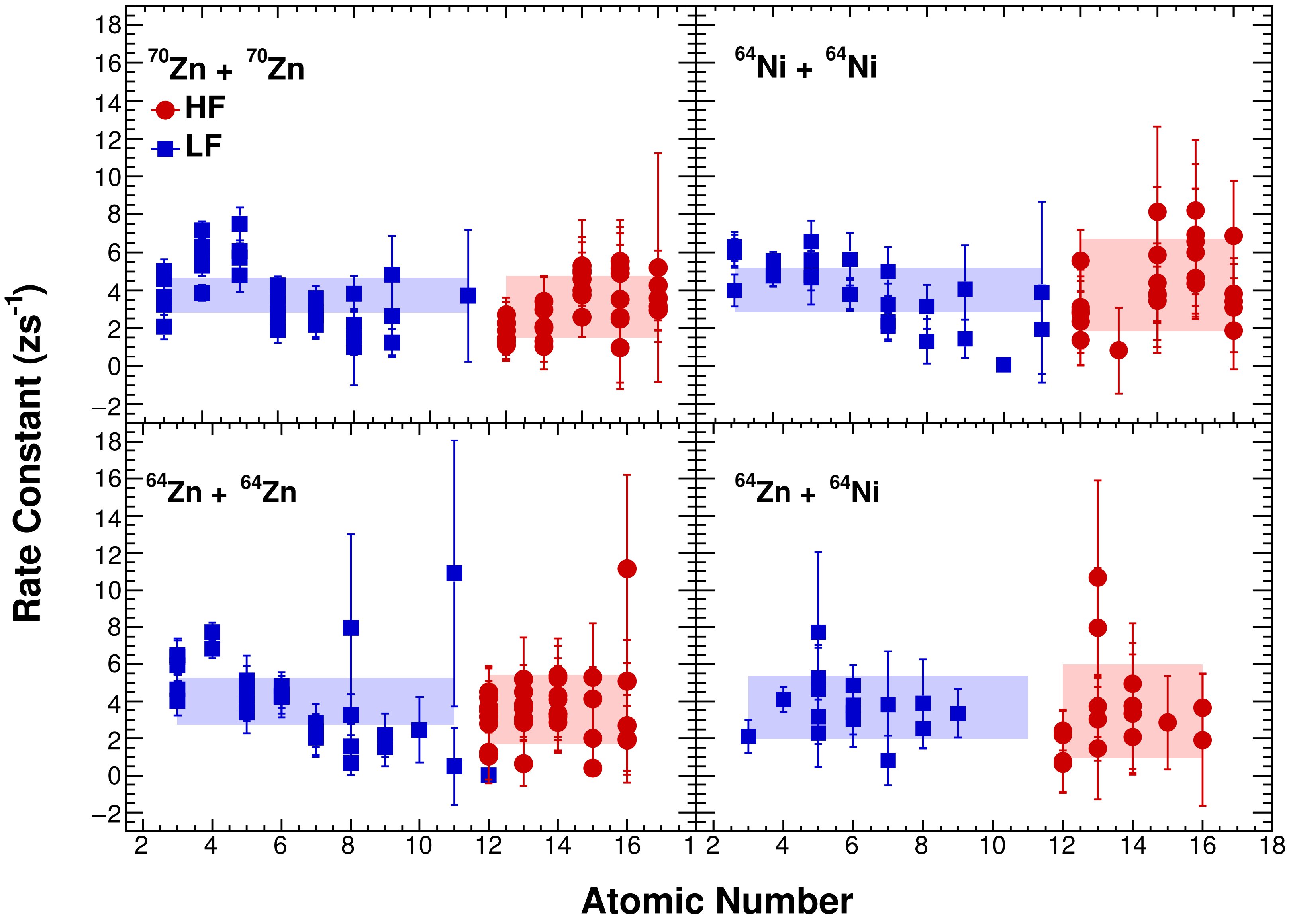
- Average rate constant zs^{-1}:

  LF 4 ± 1

  HF 4 ± 2

- Relevant parameter to calculate the equilibration times.

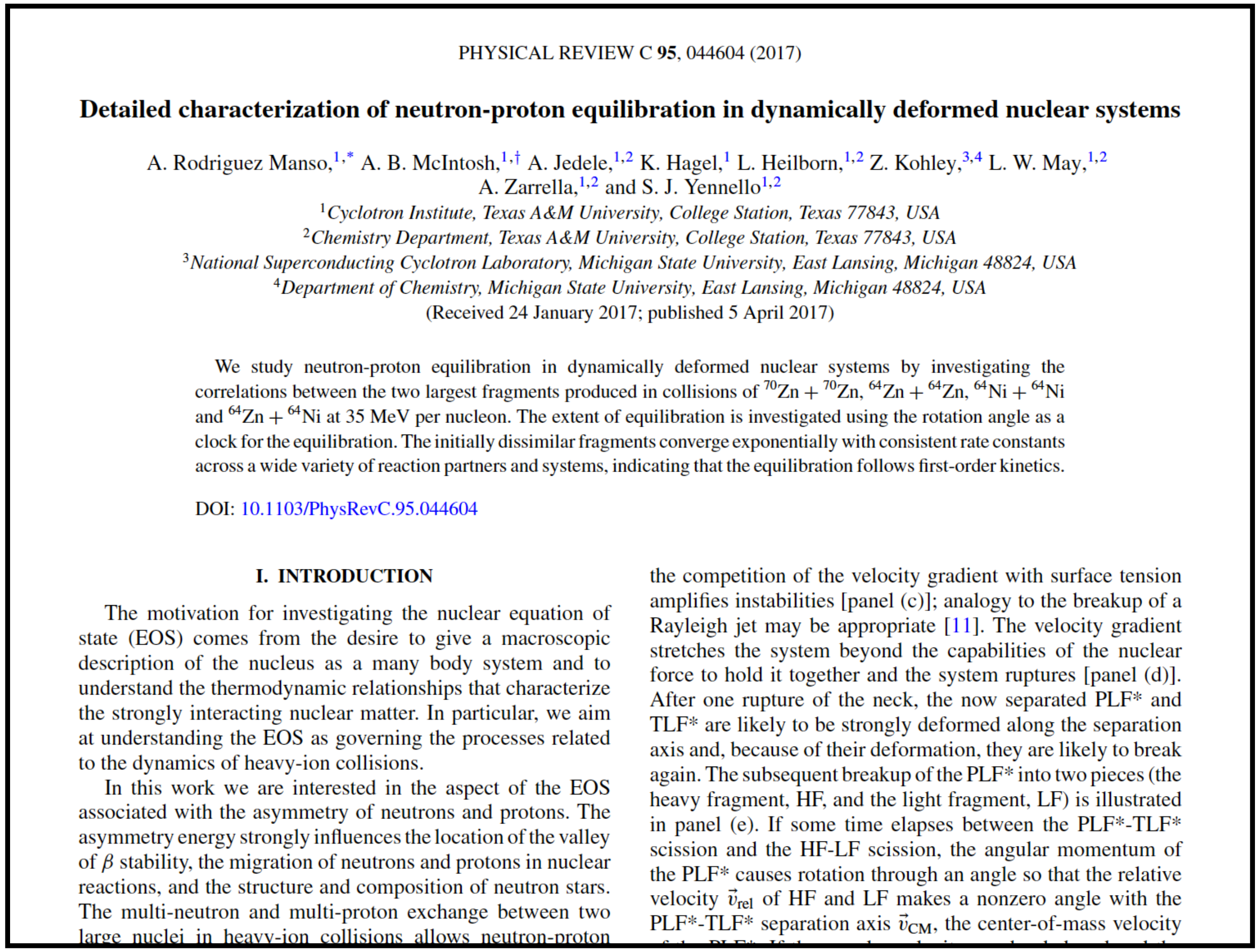
- Describes how fast the equilibration occurs within the PLF*.



- Agreement of rates → force driving the equilibration is independent of the size of both partners only depends on the difference in asymmetry

Summary:

- Study the time-dependence of **n-p equilibration** in dynamically deformed nuclear systems by examining the **composition of fragments** produced by a system out of equilibrium.
- Method to measure the equilibration's time evolution by studying the **fragments** emitted from the PLF* as a function of the **breakup alignment angle**.
- The alignment angle serves efficiently as an effective **clock for equilibration**.
- The variation of the composition as a function of the alignment angle shows an **exponential** behavior for both LF and HF, suggesting **first-order kinetics**, for all the systems studied.
- The yield and measured composition are used to extract an estimate for the purely **dynamical component**.
- Small systematic effect in the composition for reactions of a relatively n-poor projectile with a n-rich **target**.
- **No significant differences in the rate constants** between systems of different initial composition.



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

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We study neutron-proton equilibration in dynamically deformed nuclear systems by investigating the correlations between the two largest fragments produced in collisions of ^{70}Zn + ^{70}Zn, ^{64}Zn + ^{64}Zn, ^{64}Ni + ^{64}Ni and ^{64}Zn + ^{64}Ni at 35 MeV per nucleon. The extent of equilibration is investigated using the rotation angle as a clock for the equilibration. The initially dissimilar fragments converge exponentially with consistent rate constants across a wide variety of reaction partners and systems, indicating that the equilibration follows first-order kinetics.

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I. INTRODUCTION

The motivation for investigating the nuclear equation of state (EOS) comes from the desire to give a macroscopic description of the nucleus as a many body system and to understand the thermodynamic relationships that characterize the strongly interacting nuclear matter. In particular, we aim at understanding the EOS as governing the processes related to the dynamics of heavy-ion collisions.

In this work we are interested in the aspect of the EOS associated with the asymmetry of neutrons and protons. The asymmetry energy strongly influences the location of the valley of β stability, the migration of neutrons and protons in nuclear reactions, and the structure and composition of neutron stars. The multi-neutron and multi-proton exchange between two large nuclei in heavy-ion collisions allows neutron-proton

the competition of the velocity gradient with surface tension amplifies instabilities [panel (c)]; analogy to the breakup of a Rayleigh jet may be appropriate [11]. The velocity gradient stretches the system beyond the capabilities of the nuclear force to hold it together and the system ruptures [panel (d)]. After one rupture of the neck, the now separated PLF* and TLF* are likely to be strongly deformed along the separation axis and, because of their deformation, they are likely to break again. The subsequent breakup of the PLF* into two pieces (the heavy fragment, HF, and the light fragment, LF) is illustrated in panel (e). If some time elapses between the PLF*-TLF* scission and the HF-LF scission, the angular momentum of the PLF* causes rotation through an angle so that the relative velocity $\vec{v}_{\mathrm{rel}}$ of HF and LF makes a nonzero angle with the PLF*-TLF* separation axis $\vec{v}_{\mathrm{CM}}$, the center-of-mass velocity

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Next:

- **Comparison to** Boltzmann-Langevin One Body **(BLOB)**

Dynamical transport model

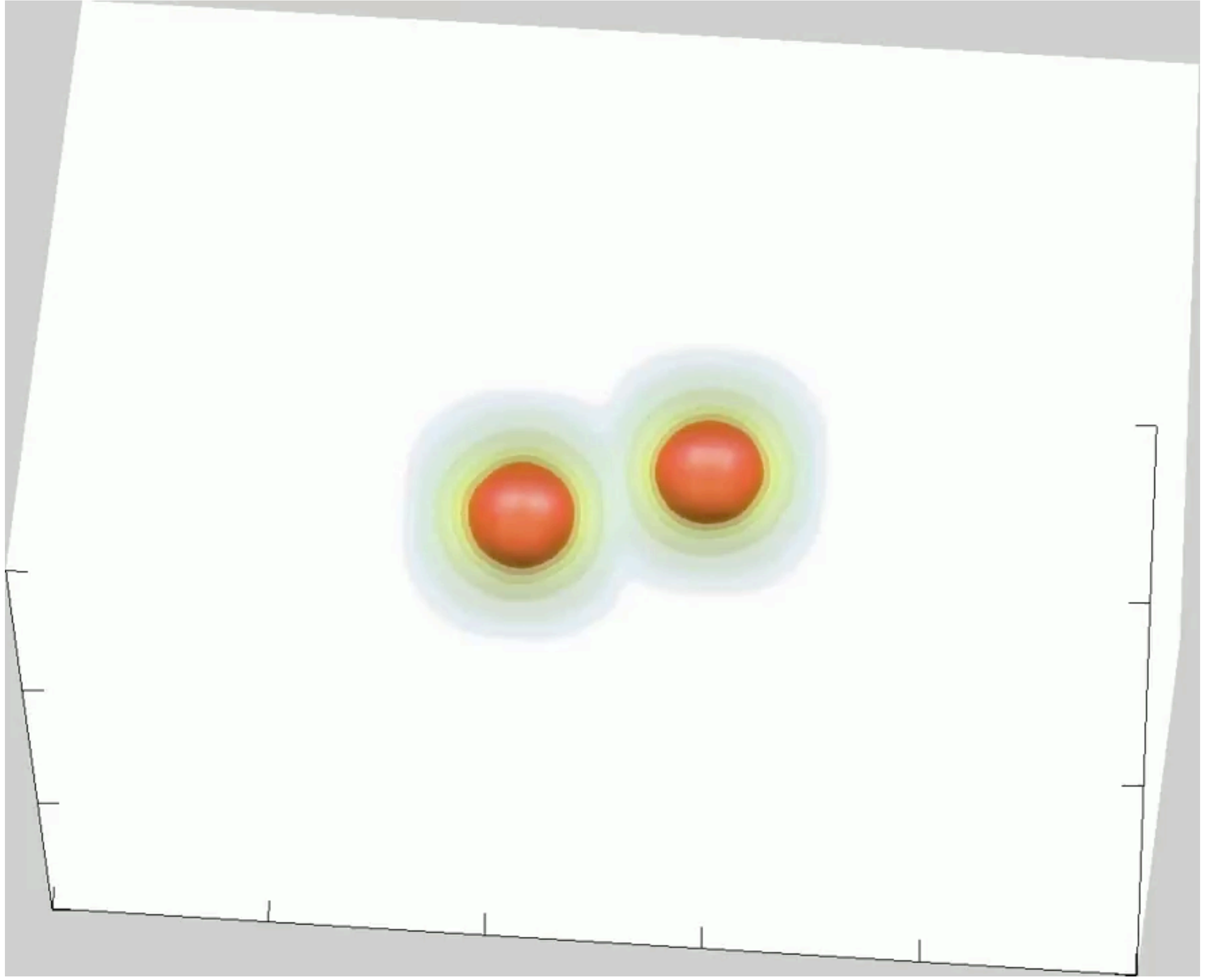
Relatively fast running theory/experiment comparison tool.

Characterize the very fast early stages of the collision process which are out of equilibrium.

Sizable neck fragments.

Unifies in a common approach the description of fluctuations in nuclear matter, and a predictive description of the disintegration of nuclei into nuclear fragments.

BLOB calculation:
Violent nuclear reaction dynamics, neck fragmentation



^{70}Zn+^{70}Zn 35AMeV (b=5.7) producing ^{45}Ca,^{40}Cl,^{6}Li,d (at 400fm/c)

https://www.youtube.com/watch?v=l5ul-iux1ik
Paolo Napolitani

Next:

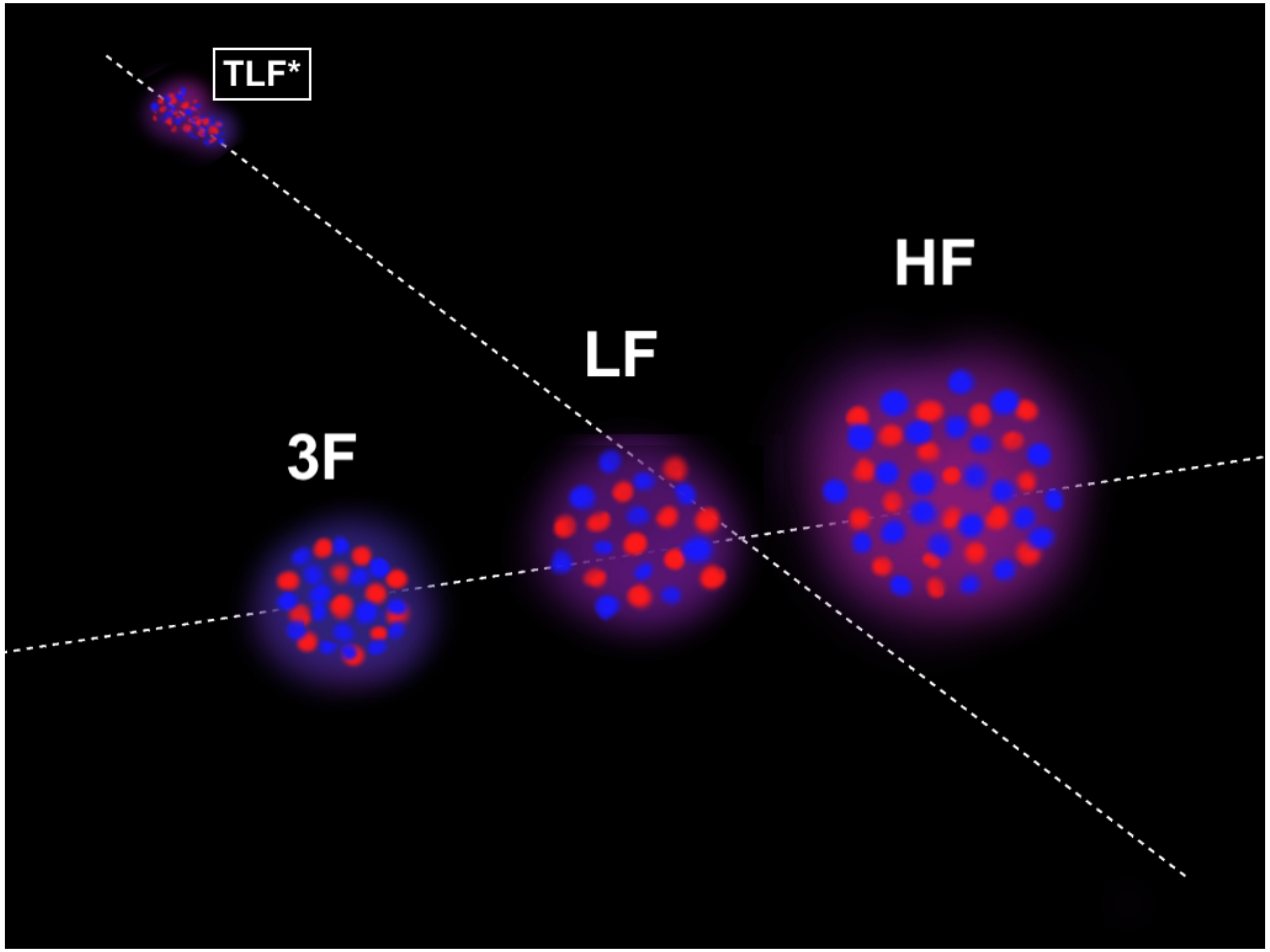
- **3 Fragments analysis**

How did the breaking happened?
Was it simultaneously or in a double rupture?

Did the 3rd fragment separated first or maybe not?

Are the 3 fragments aligned with each other? Are they in a string of pearls?

Are they aligned with the Vcm vector?

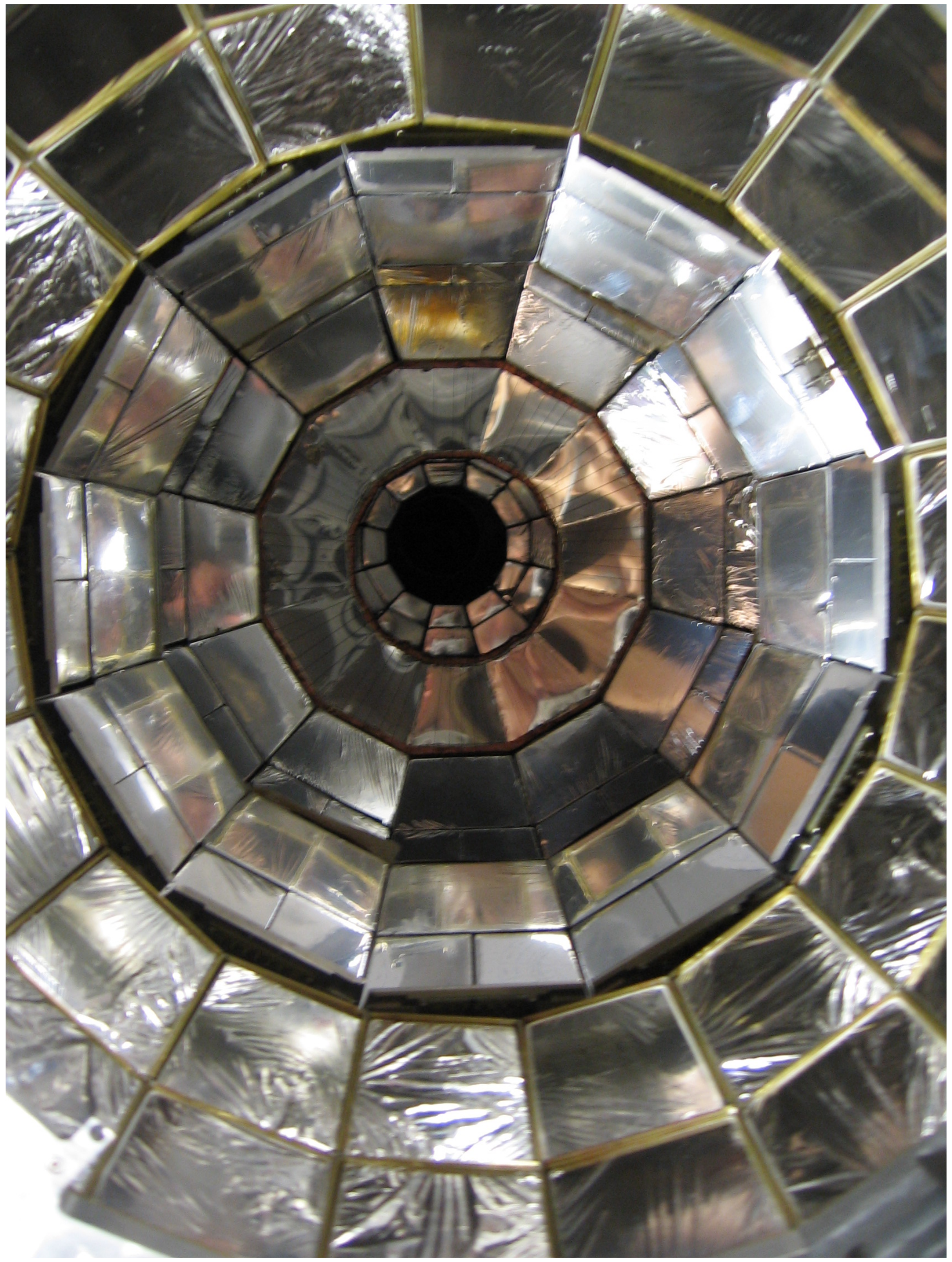


Next:

- **Follow up experiment**

How does the beam energy affects the reaction mechanism?

How does this affect the NZ equilibration?



NIMROD 4π array

Thank you!

SJY group and collaborators:

A. Rodriguez Manso, A.B. McIntosh, A. Jedele, K. Hagel, L. Heilborn, Z.W. Kohley, L.W. May, A. Zarrella, S.J. Yennello

Department of Energy
DE-FG02-93ER40773

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A-1266

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Backup Slides

Neutron **I**on **M**ultidetector **for** **R**eaction **O**riented **D**ynamics **(NIMROD)**

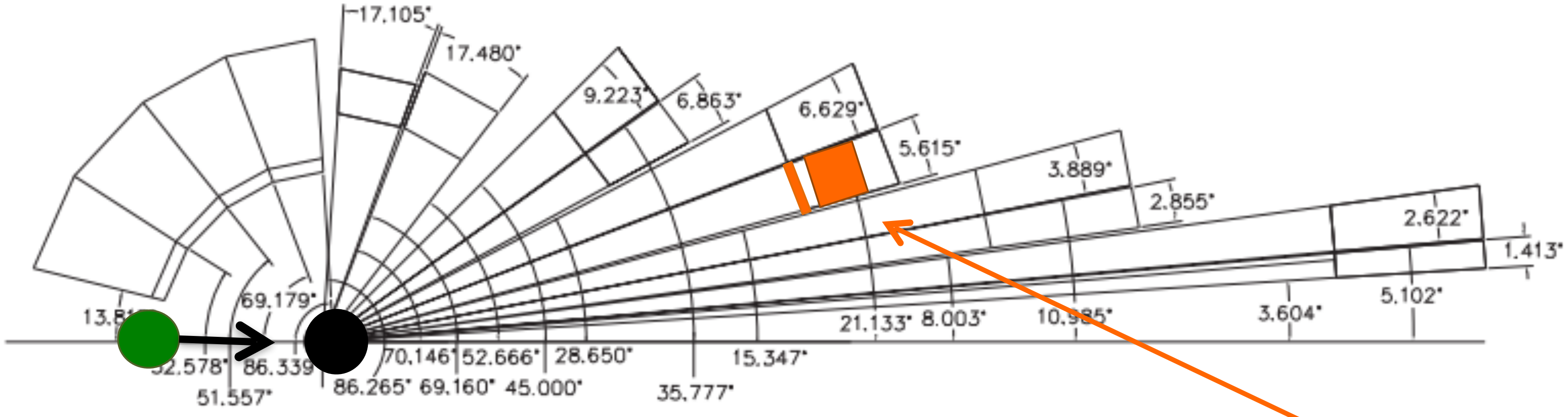
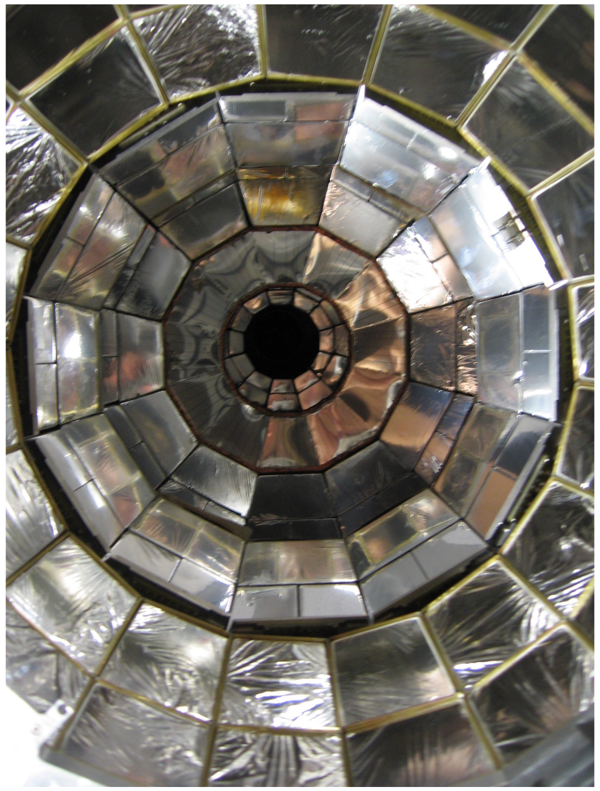


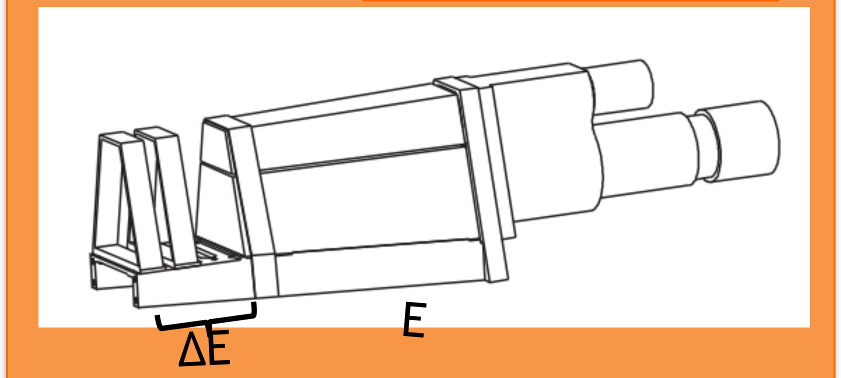
Fig. 1. Angular configuration of the NIMROD–ISiS detector.

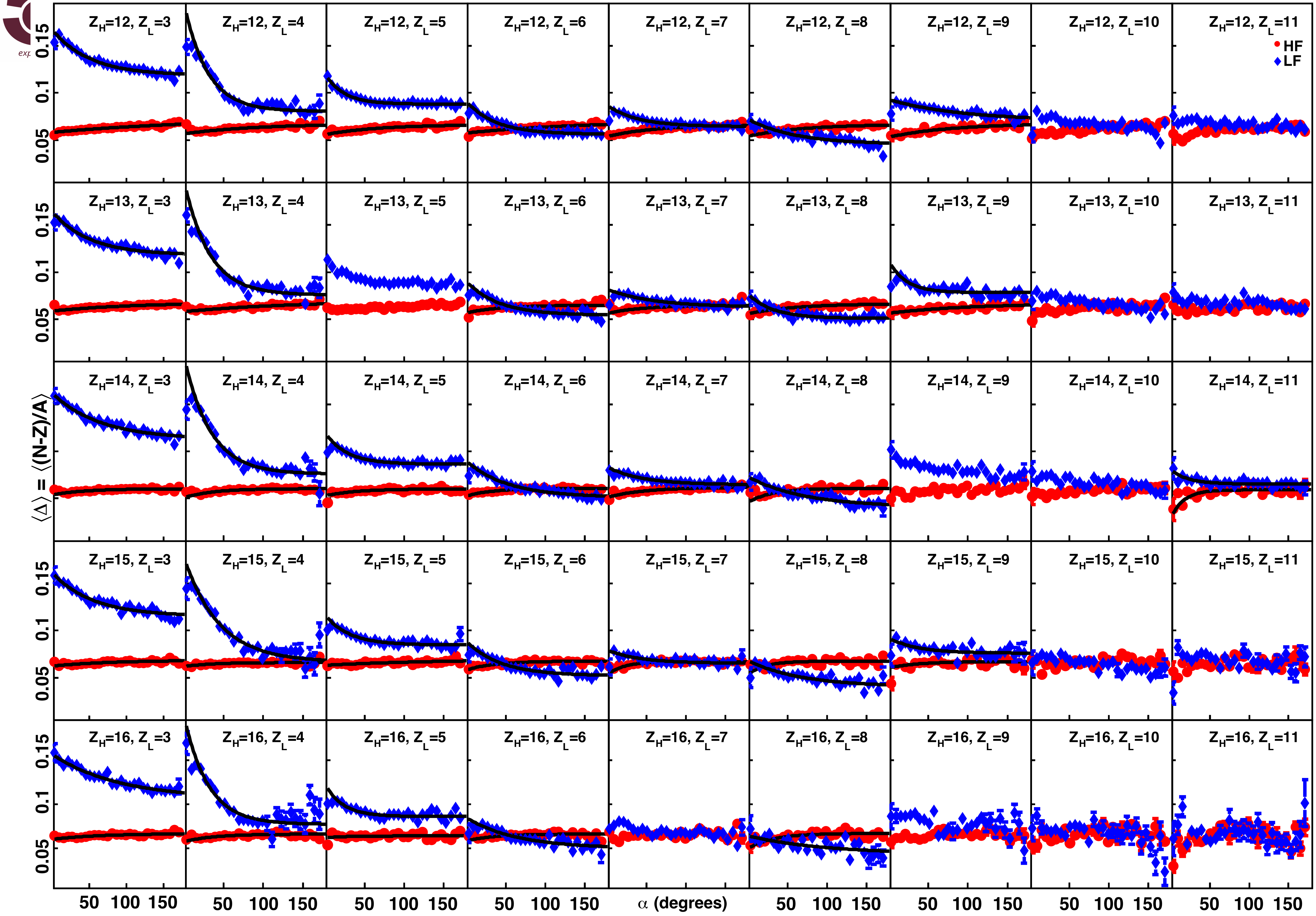


Multidetector array for reactions between massive target and projectiles:

- Total of 228 detector modules arranged in 14 annular rings (2-3 detectors/module)
- Projectile energies go from 20MeV to 4GeV
- 4π coverage (3.6° to 167.0°) = nearly complete geometrical coverage
- excellent isotopic ID

Detector Module




⟨Δ⟩ = ⟨(N-Z)/A⟩
0.05
0.1
0.15
α (degrees)
50
100
150
● HF
◆ LF
Z_H=12, Z_L=3
Z_H=12, Z_L=4
Z_H=12, Z_L=5
Z_H=12, Z_L=6
Z_H=12, Z_L=7
Z_H=12, Z_L=8
Z_H=12, Z_L=9
Z_H=12, Z_L=10
Z_H=12, Z_L=11
Z_H=13, Z_L=3
Z_H=13, Z_L=4
Z_H=13, Z_L=5
Z_H=13, Z_L=6
Z_H=13, Z_L=7
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Z_H=14, Z_L=7
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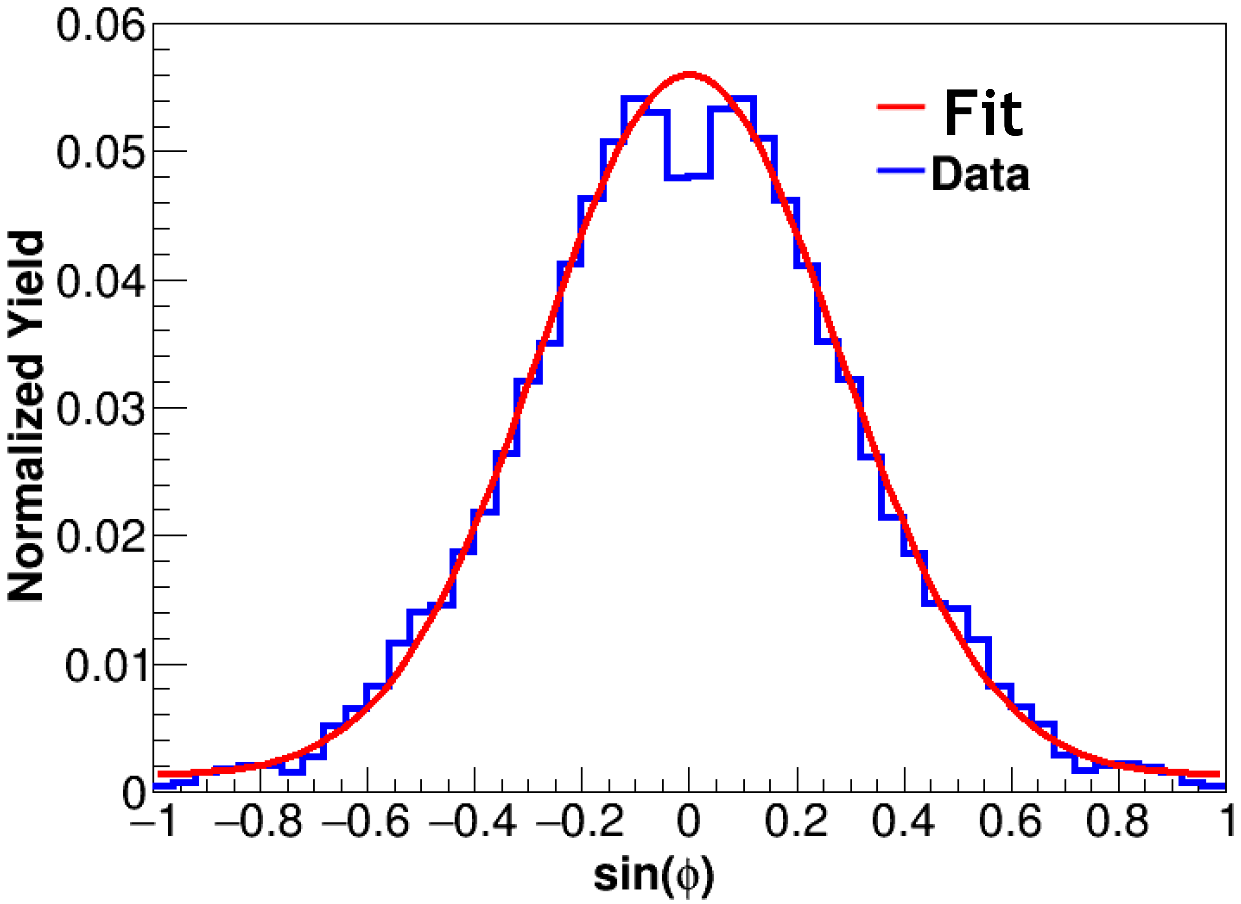
Z_H=16, Z_L=6
Z_H=16, Z_L=7
Z_H=16, Z_L=8
Z_H=16, Z_L=9
Z_H=16, Z_L=10
Z_H=16, Z_L=11

Time-Scale

$t = \alpha/\omega$ where $\omega = J\hbar/I_{eff}$

ω(angular frequency),
J (angular momentum)



- The **J** is determined using the width of the out-of-plane α particle distribution
- 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.
- Moment of inertia is calculated using a 2 touching spheres model:

$$I_{eff} = m_{ZH}r_{CM,ZH}^2 + \tfrac{2}{5}m_{ZH}r_{ZH}^2 + m_{ZL}r_{CM,ZL}^2 + \tfrac{2}{5}m_{ZL}r_{ZL}^2$$

- Using a complete rotational period:

$$t = (1\text{-}4)\ \text{zs}$$