Neutron-Proton equilibration in dynamically-deformed nuclear systems

(at 35 MeV/nucleon)

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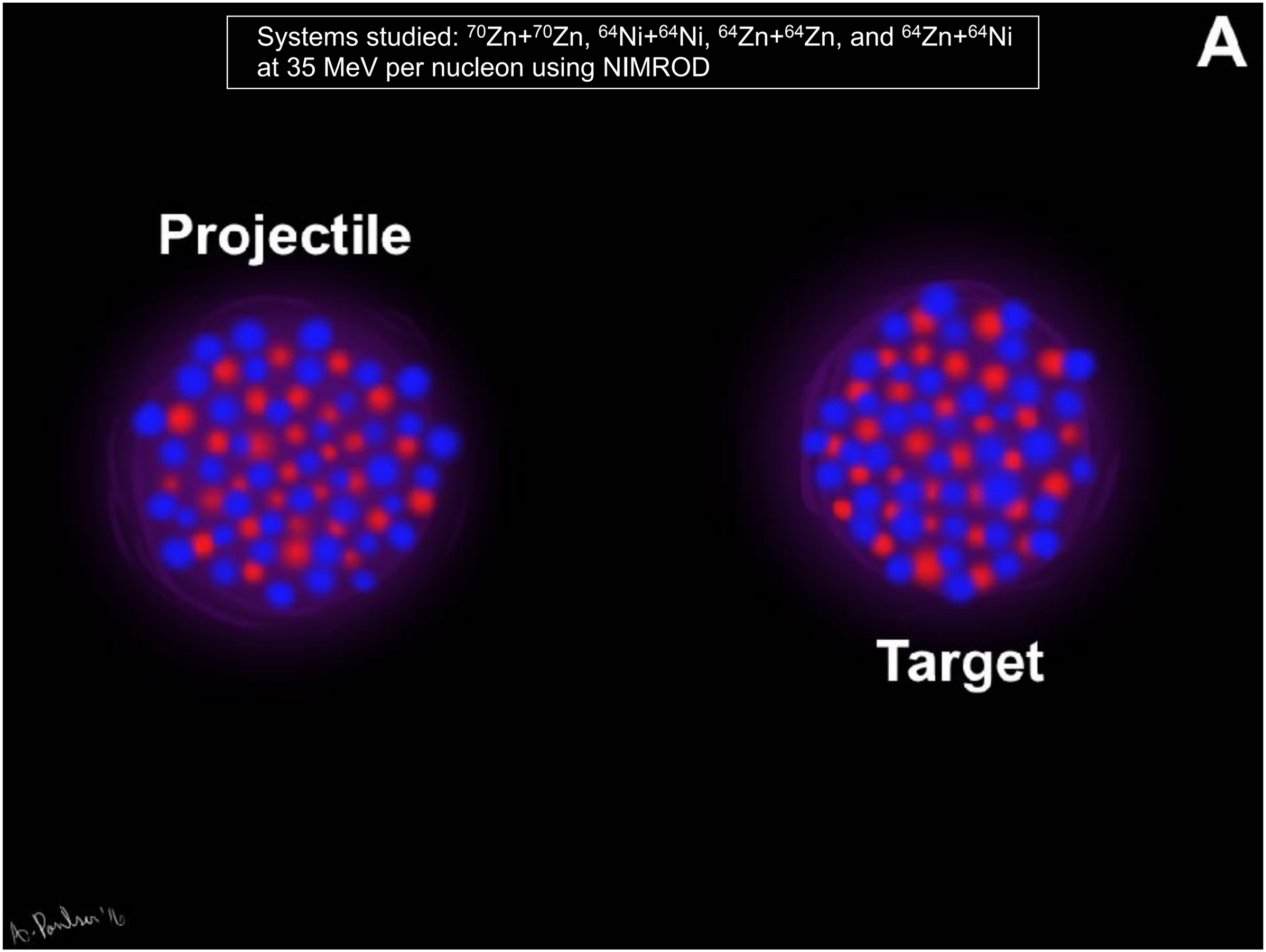
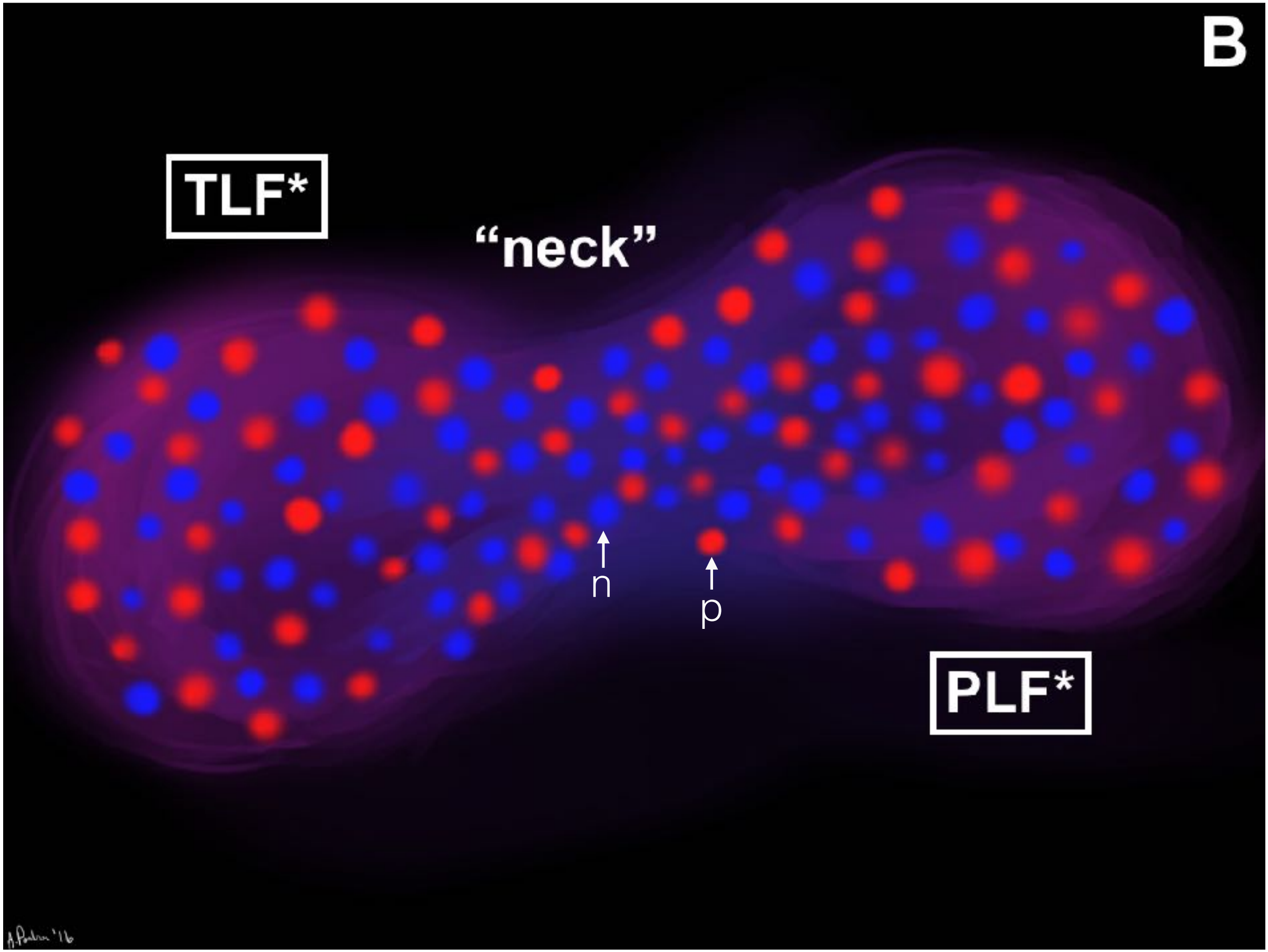
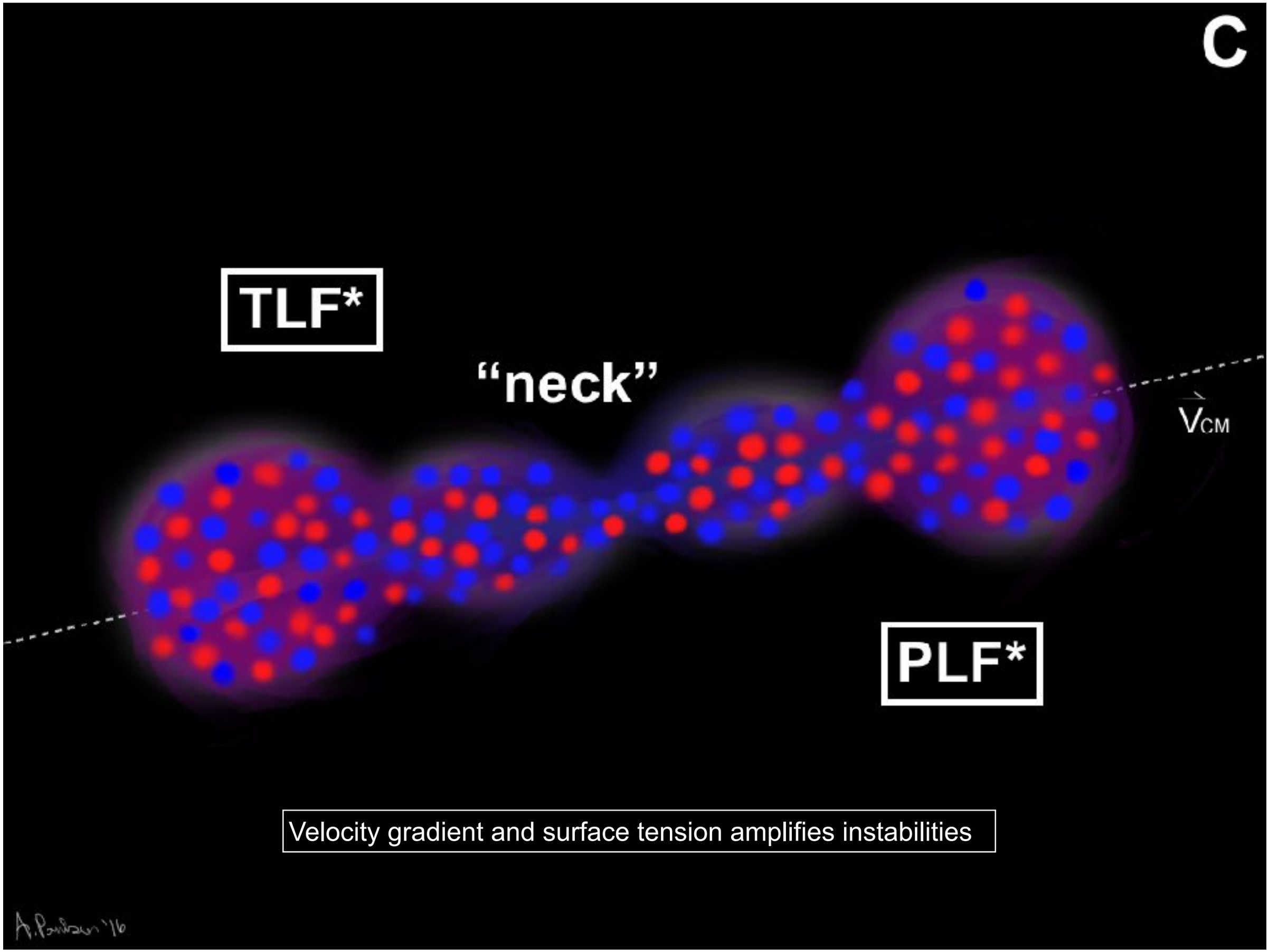
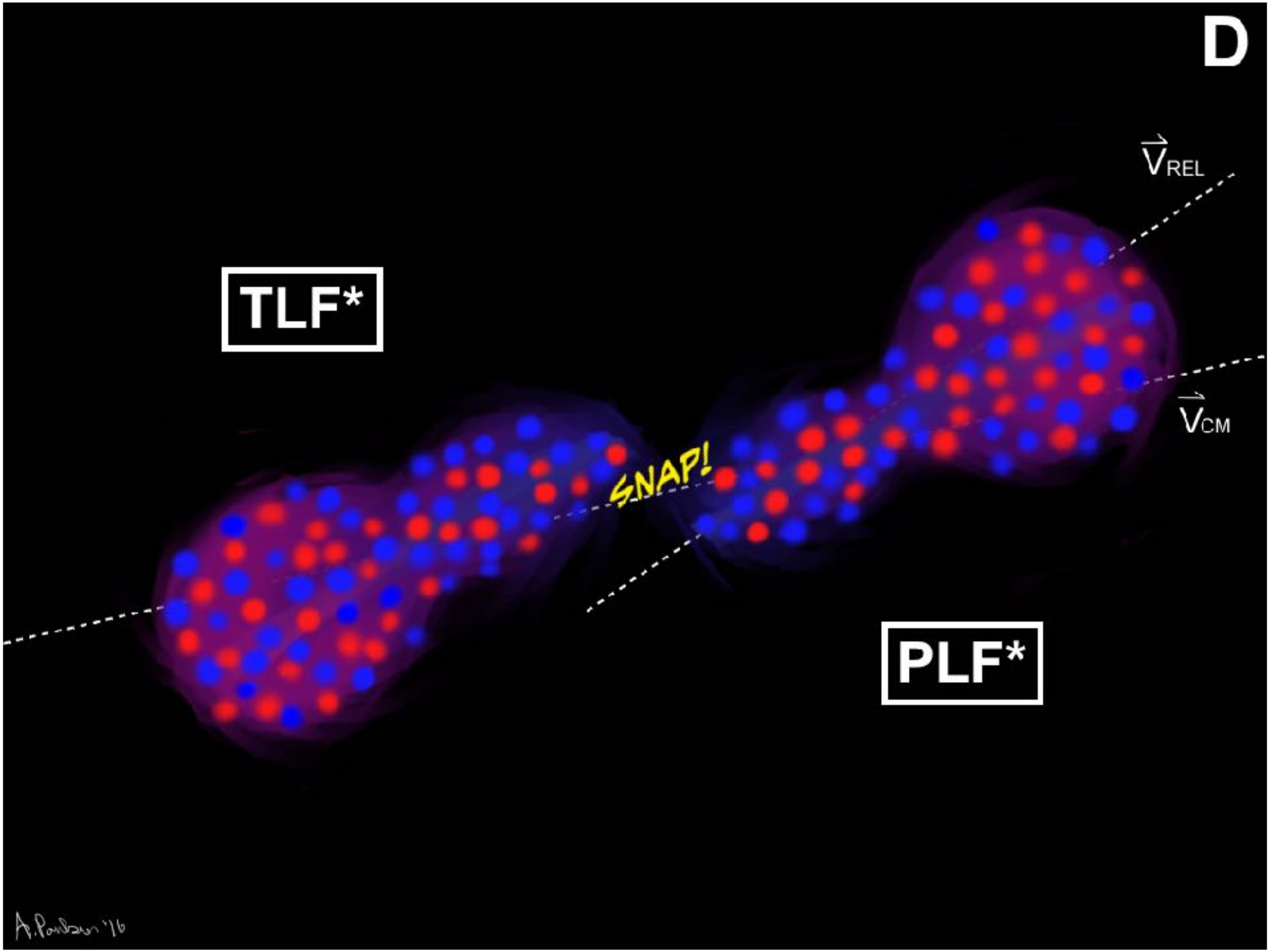
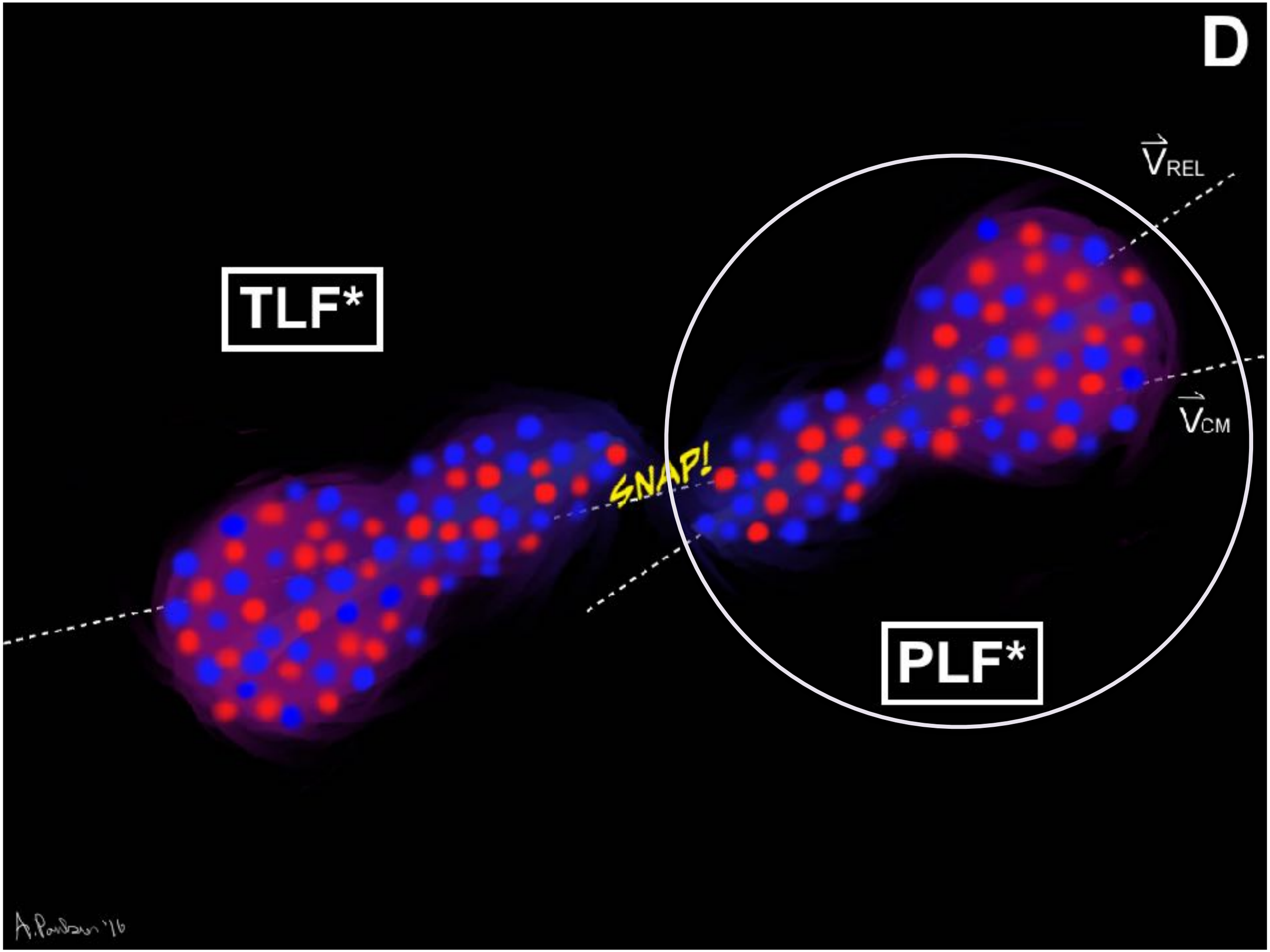
Systems studied: $^{70}Zn+^{70}Zn$, $^{64}Ni+^{64}Ni$, $^{64}Zn+^{64}Zn$, and $^{64}Zn+^{64}Ni$ at 35 MeV per nucleon using NIMROD

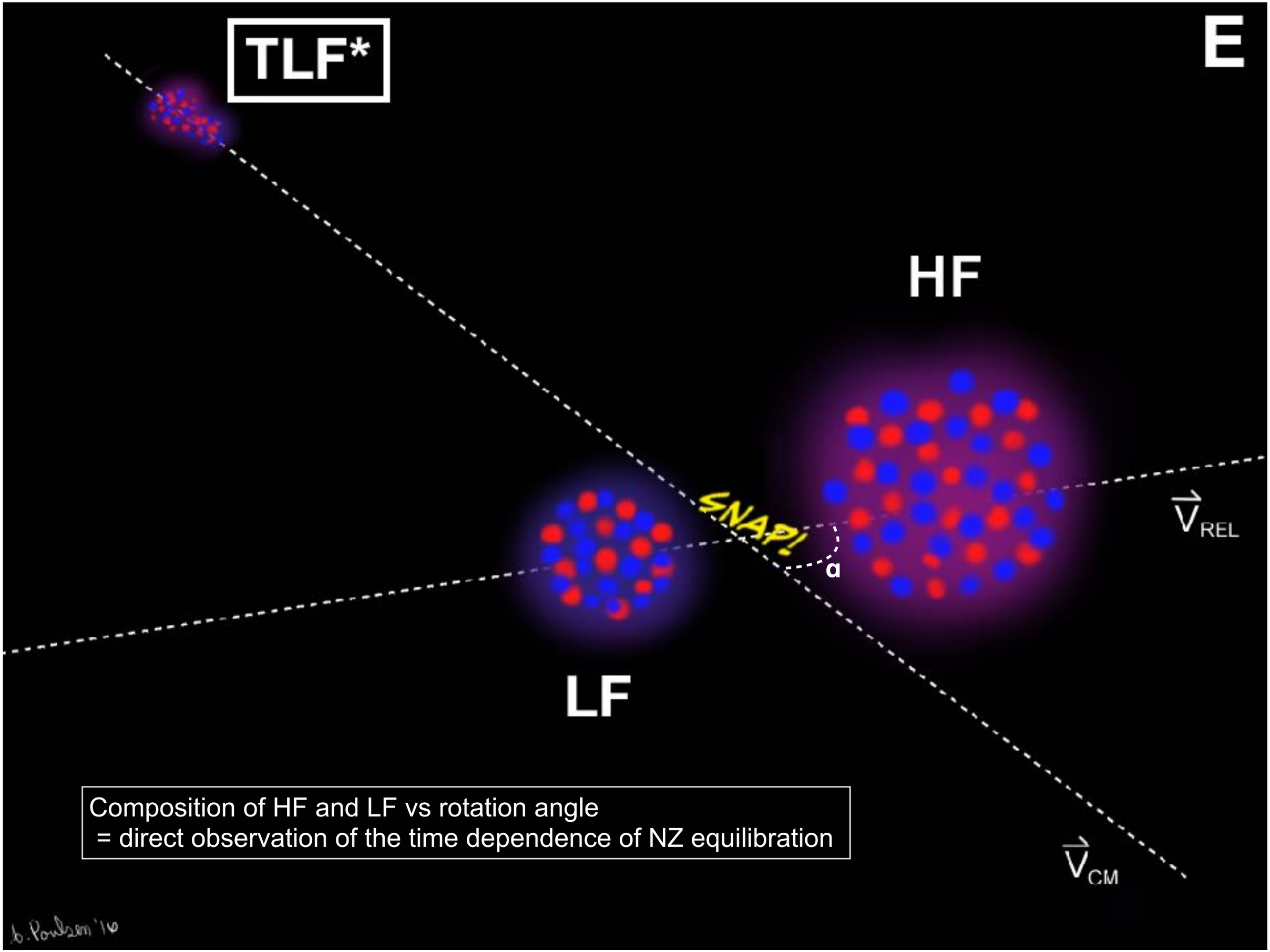



B
TLF*
“neck”
n
p
PLF*


C
TLF*
"neck"
$\vec{V}_{CM}$
PLF*
Velocity gradient and surface tension amplifies instabilities

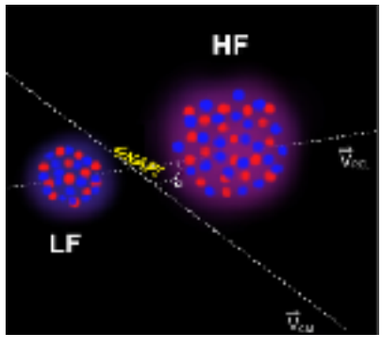

D
$\vec{V}_{REL}$
TLF*
$\vec{V}_{CM}$
SNAP!
PLF*
A. Poudou '16


D
$\vec{V}_{REL}$
TLF*
$\vec{V}_{CM}$
SNAP!
PLF*


TLF*
E
HF
SNAP!
α
$\vec{V}_{REL}$
LF
$\vec{V}_{CM}$
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:



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

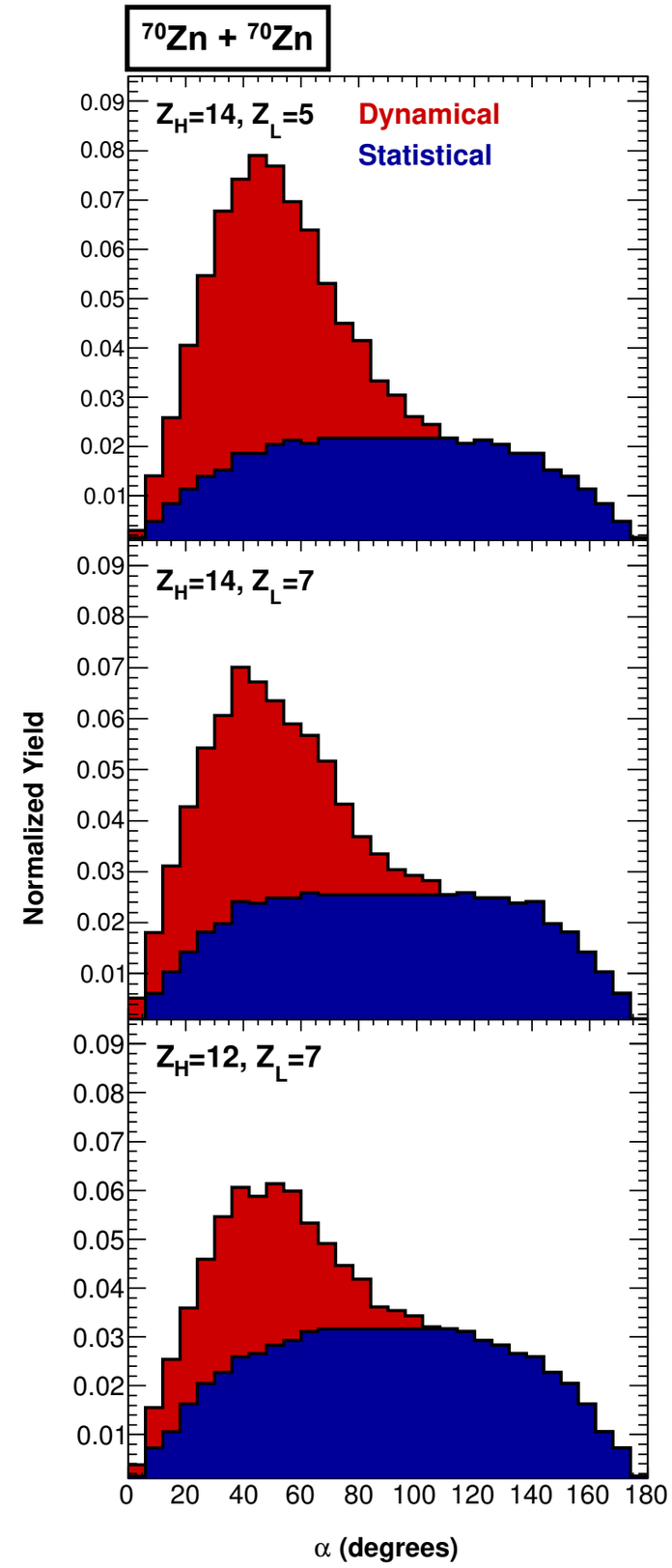
- Angular distribution peaked for most aligned configuration. Decreases in yield with decreasing alignment.

- 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.

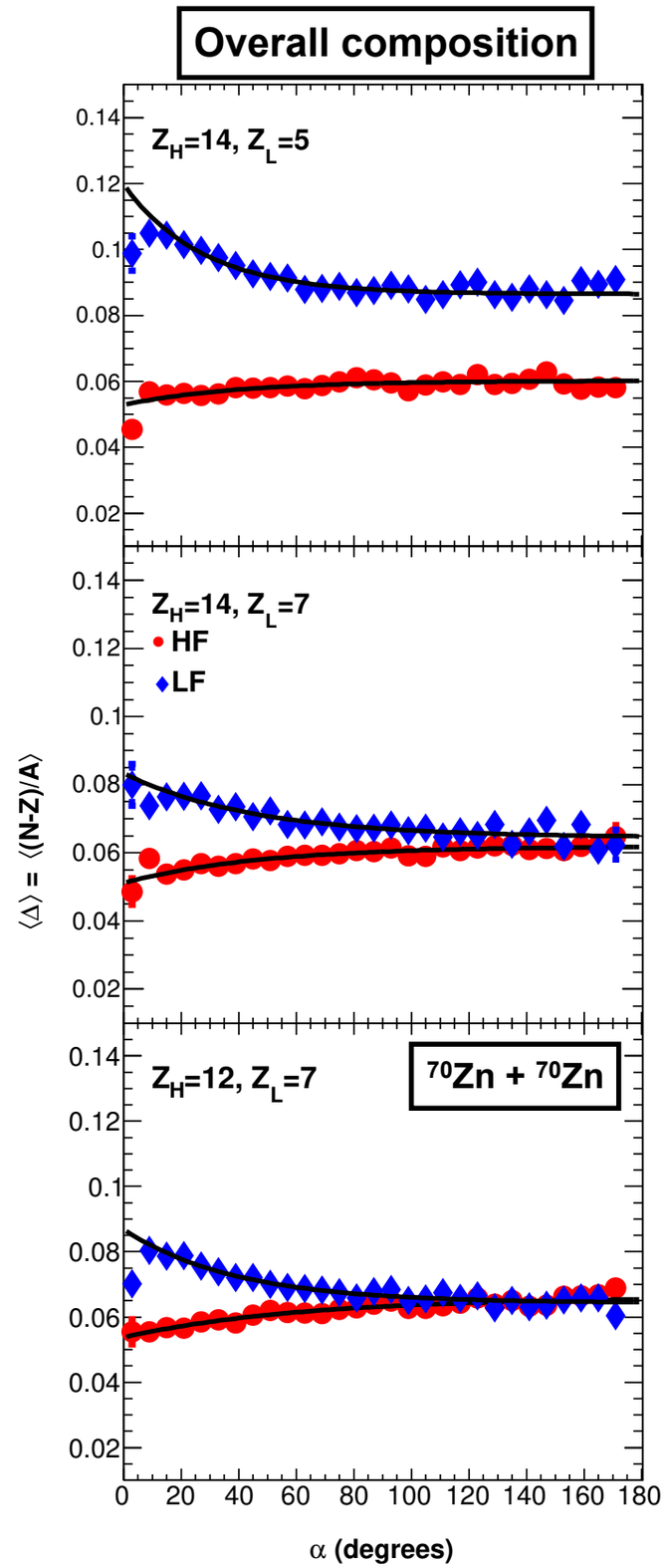


Composition vs decay alignment:

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

- 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.



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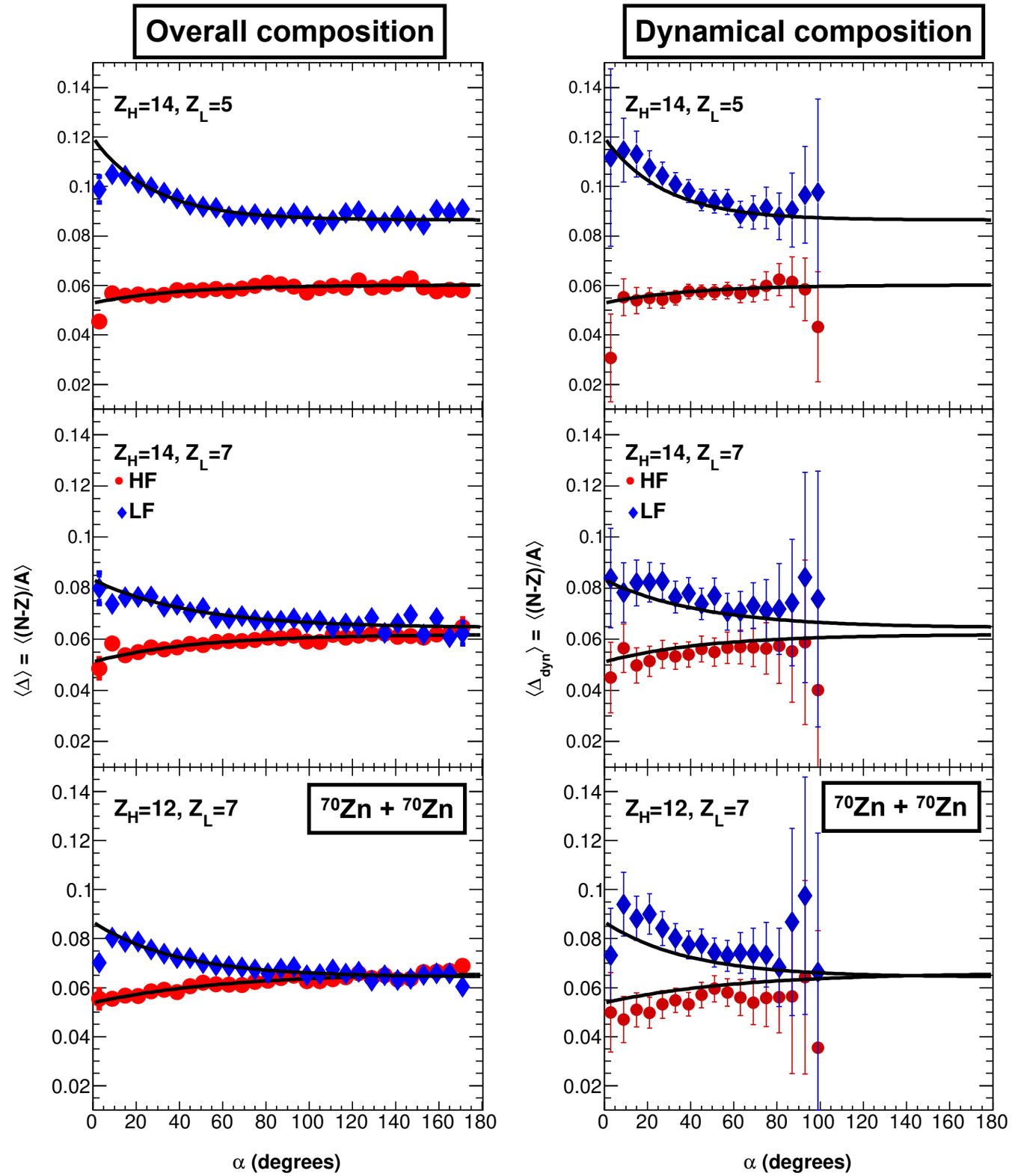
- Dynamical composition generally follows the same trend as the overall composition (more extreme).

- Rate of change of the composition unaffected by correction

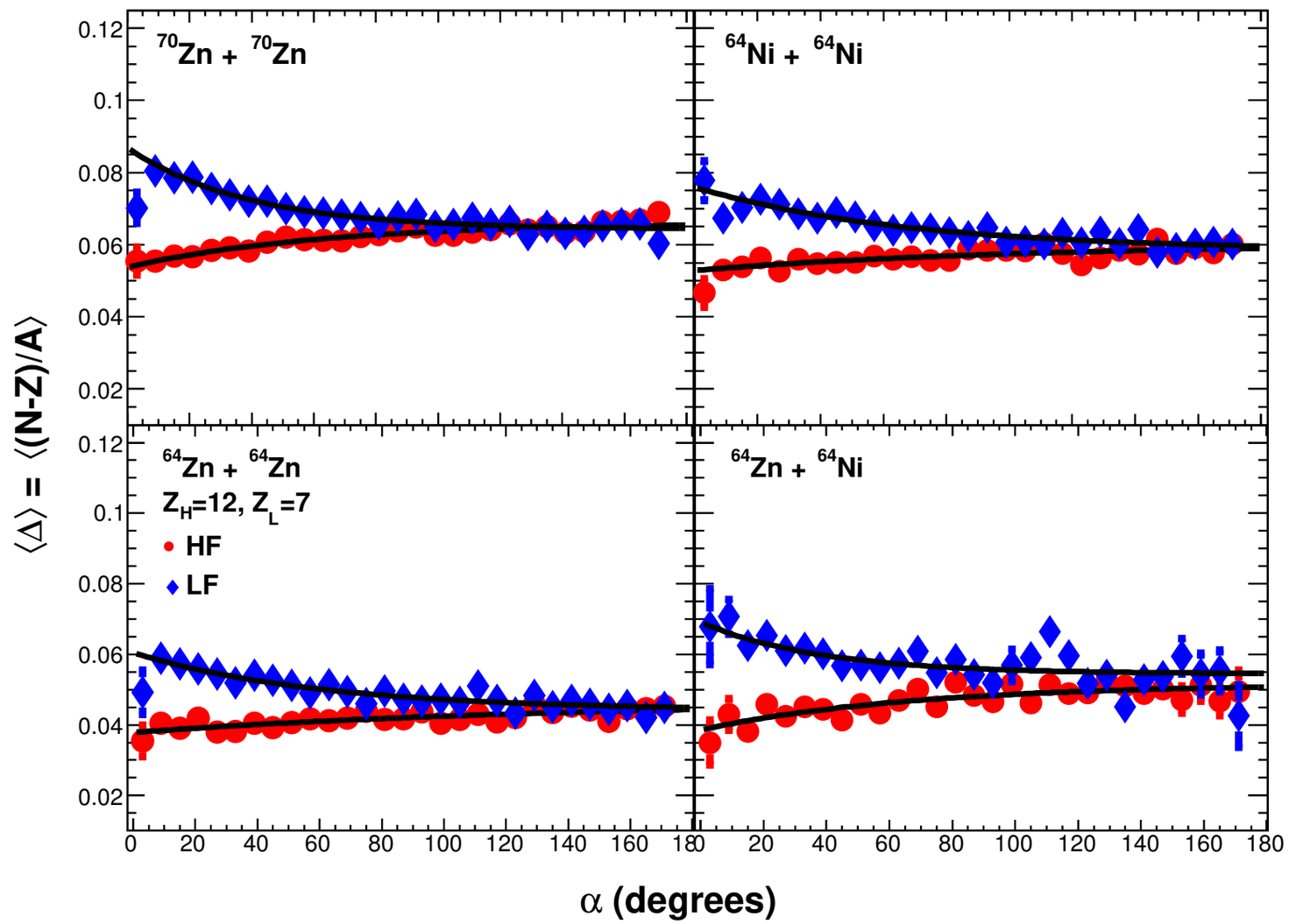


Composition vs decay alignment: for different systems

- 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.**

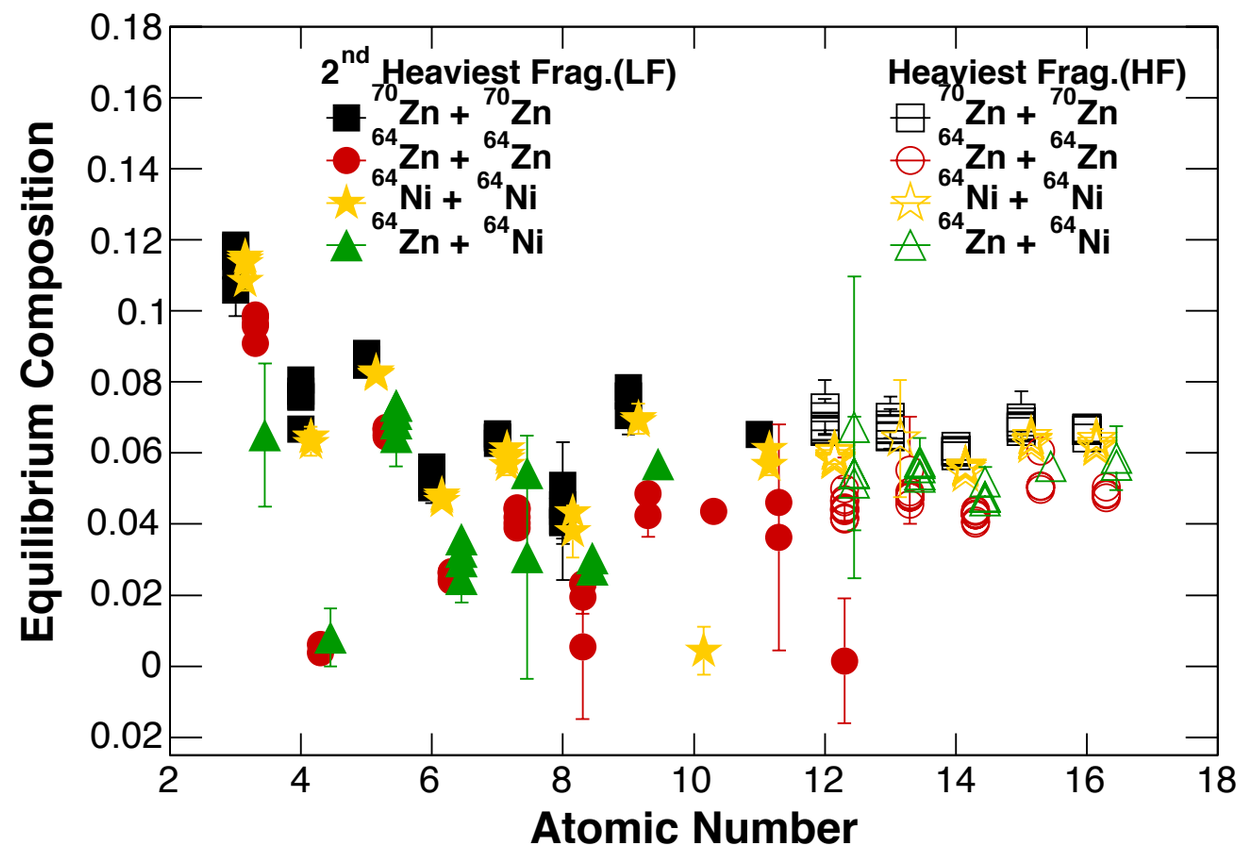


Equilibrium composition

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

- 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 syst.

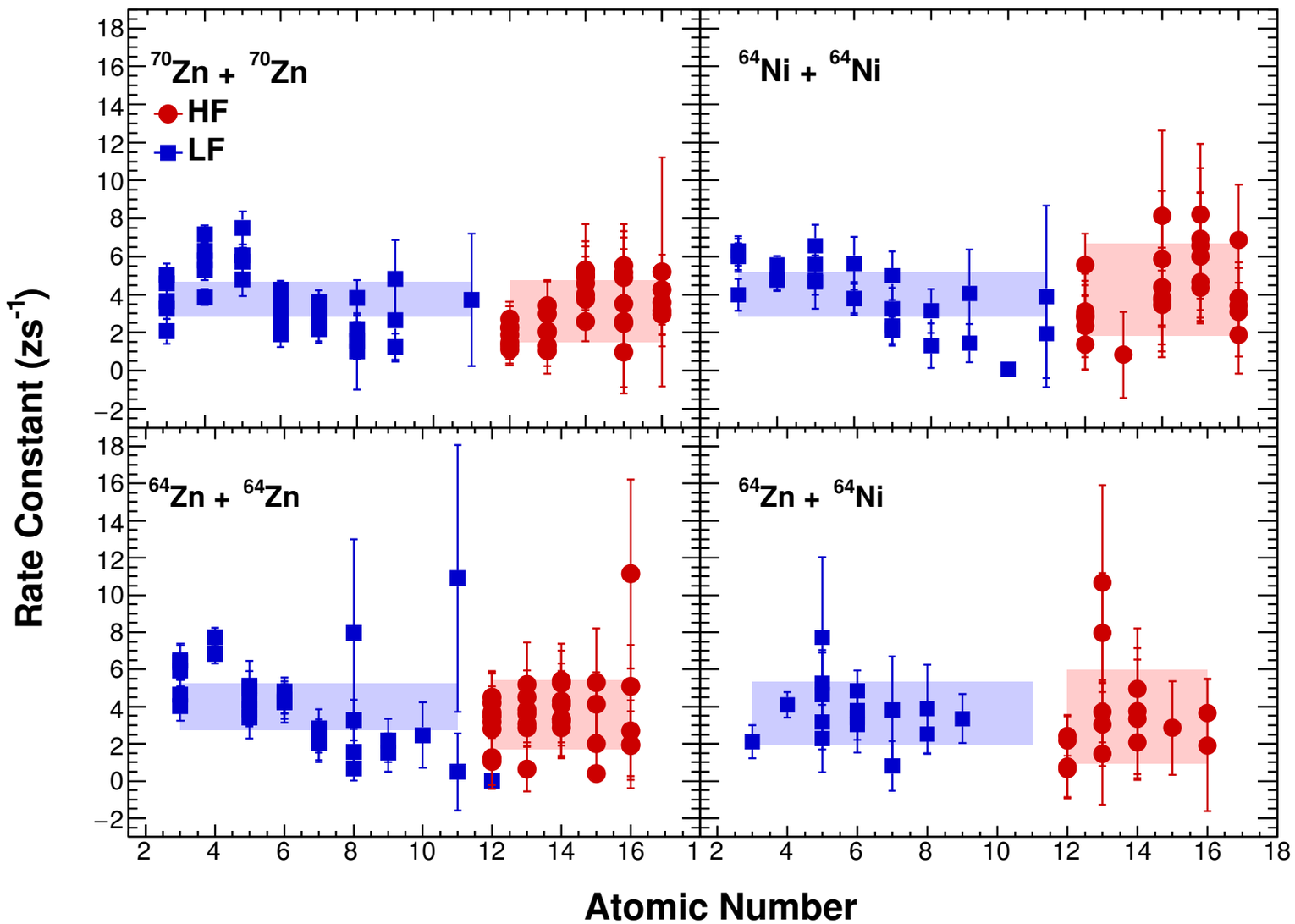
→ **target effect**



Rate constant for equilibration:

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

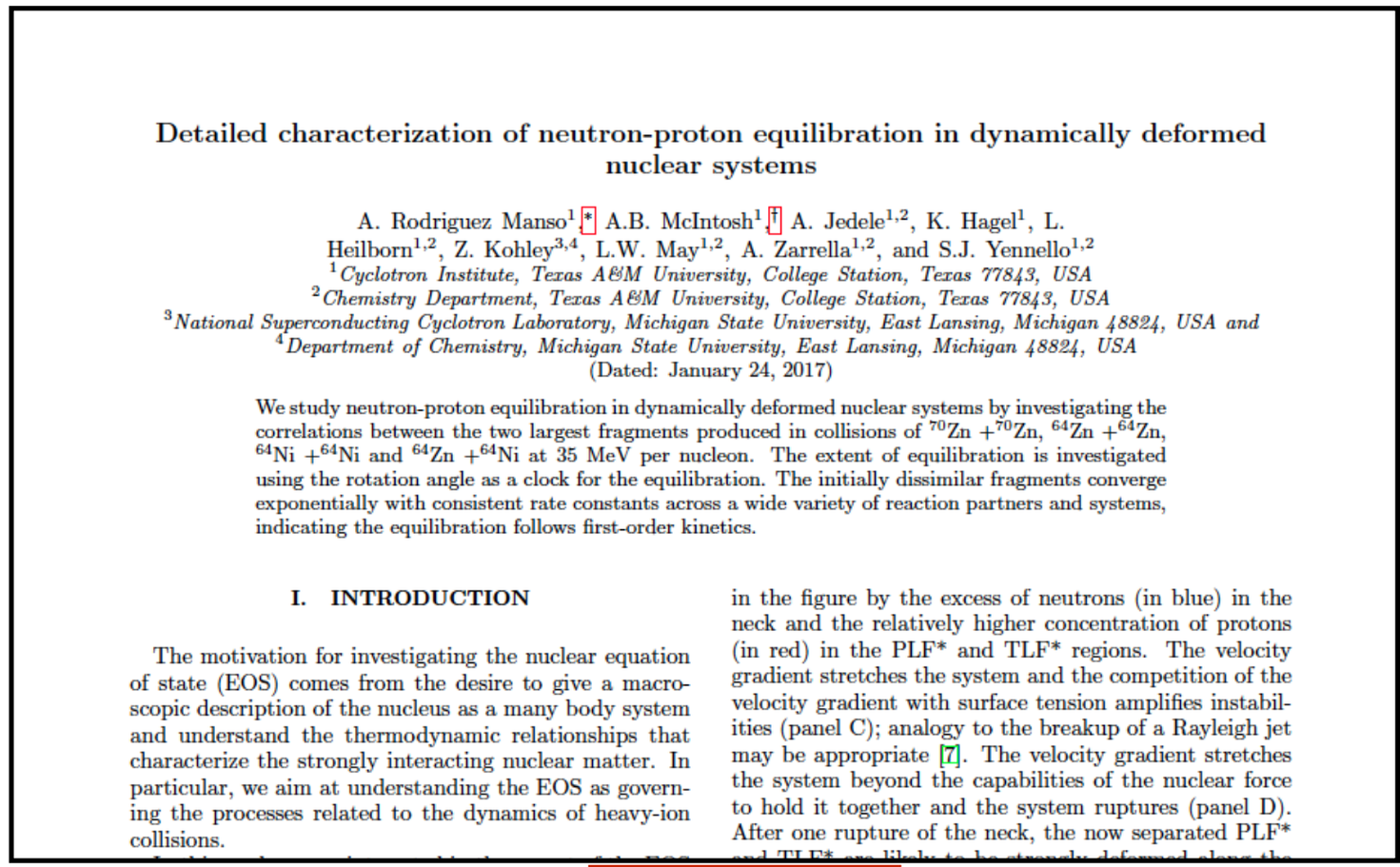
- Exponential slope
- Average rate constant zs^{-1}:
  LF 4 ± 1
  HF 4 ± 2
- Relevant parameter to calculate the equilibration times.
- Describes how fast the equilibration occurs within the PLF*.



- 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.



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

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[4]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
(Dated: January 24, 2017)

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 the equilibration follows first-order kinetics.

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 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 the figure by the excess of neutrons (in blue) in the neck and the relatively higher concentration of protons (in red) in the PLF* and TLF* regions. The velocity gradient stretches the system and the competition of the velocity gradient with surface tension amplifies instabilities (panel C); analogy to the breakup of a Rayleigh jet may be appropriate [7]. 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*

Submitted to PRC

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

Welch Foundation
A-1266