Time-resolved equilibration: How to measure the motion of protons and neutrons on a sub-zeptosecond timeframe

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Motivation:

Constrain the nuclear equation of state.

Background:

Mechanism: dynamical breakup.

We can prepare nuclear matter with an initial N-Z gradient.

Hypothesis:

Since N-Z equilibration and nuclear rotation take place on a similar timescale, the rotation can be used as a chronometer of the equilibration.

Methods:

NIMROD 4π array @ Texas A&M University.

First measurement of N-Z of both fragments in binary splits.

Fine time resolution from alignment angle.

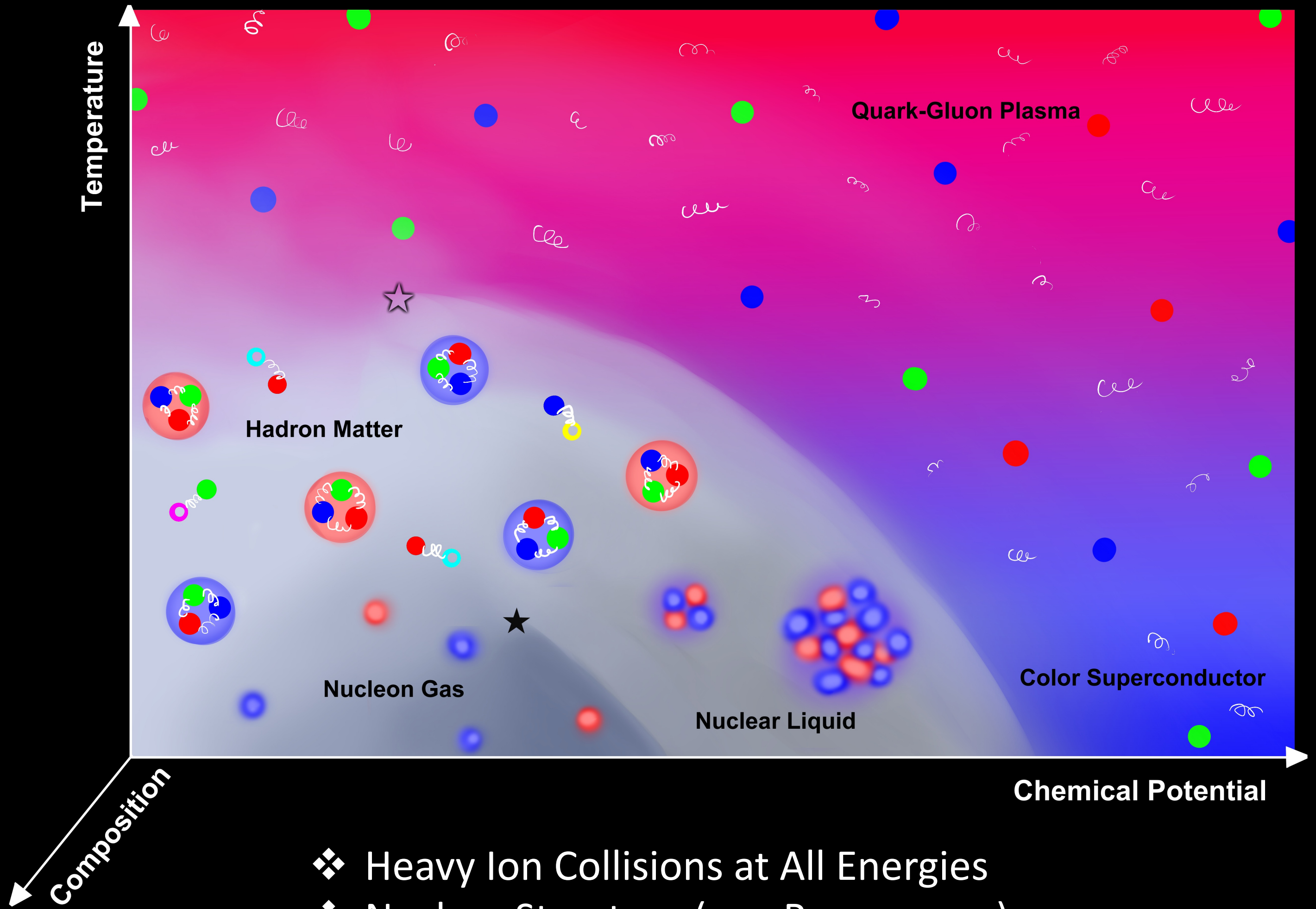
Results:

<u>We observe Neutron-Proton equilibration as a function of time.</u>

Equilibration curve is approximately exponential → First order kinetics.

Sub-Zeptosecond timescale.

Nuclear Equation of State: T,μ,ρ,P,E*,I



- ❖ Heavy Ion Collisions at All Energies
- ❖ Nuclear Structure (e.g. Resonances)
- ❖ Supernovae (nucleosynthesis)
- ❖ Neutron Stars (Crust to Core)
- ➢ n-p Asymmetry Crucial

Energy of Finite Nuclear Matter

Zero Temperature, fixed density:

$$E = c_v A - c_s A^{\frac{2}{3}} - c_c \frac{Z(Z-1)}{A^{\frac{1}{3}}} - c_a \frac{(N-Z)^2}{A} \pm c_p \delta$$

volume surface Coulomb asymmetry pairing

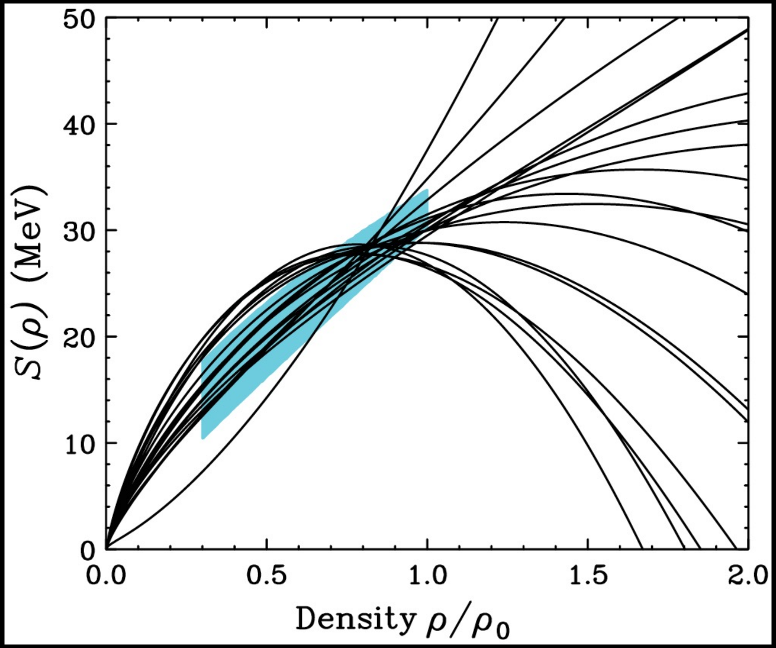
Finite Temperature, variable density:

$$E(\rho, I) = E(\rho, 0) + \left(\frac{N-Z}{A}\right)^2 E_{asym}(\rho)$$

<u>Asymmetry Energy</u>

- Energy penalty for having more neutrons than protons
- Depends on density.

Asymmetry Energy



Tsang et al. PRC 86, 015803 (2012)

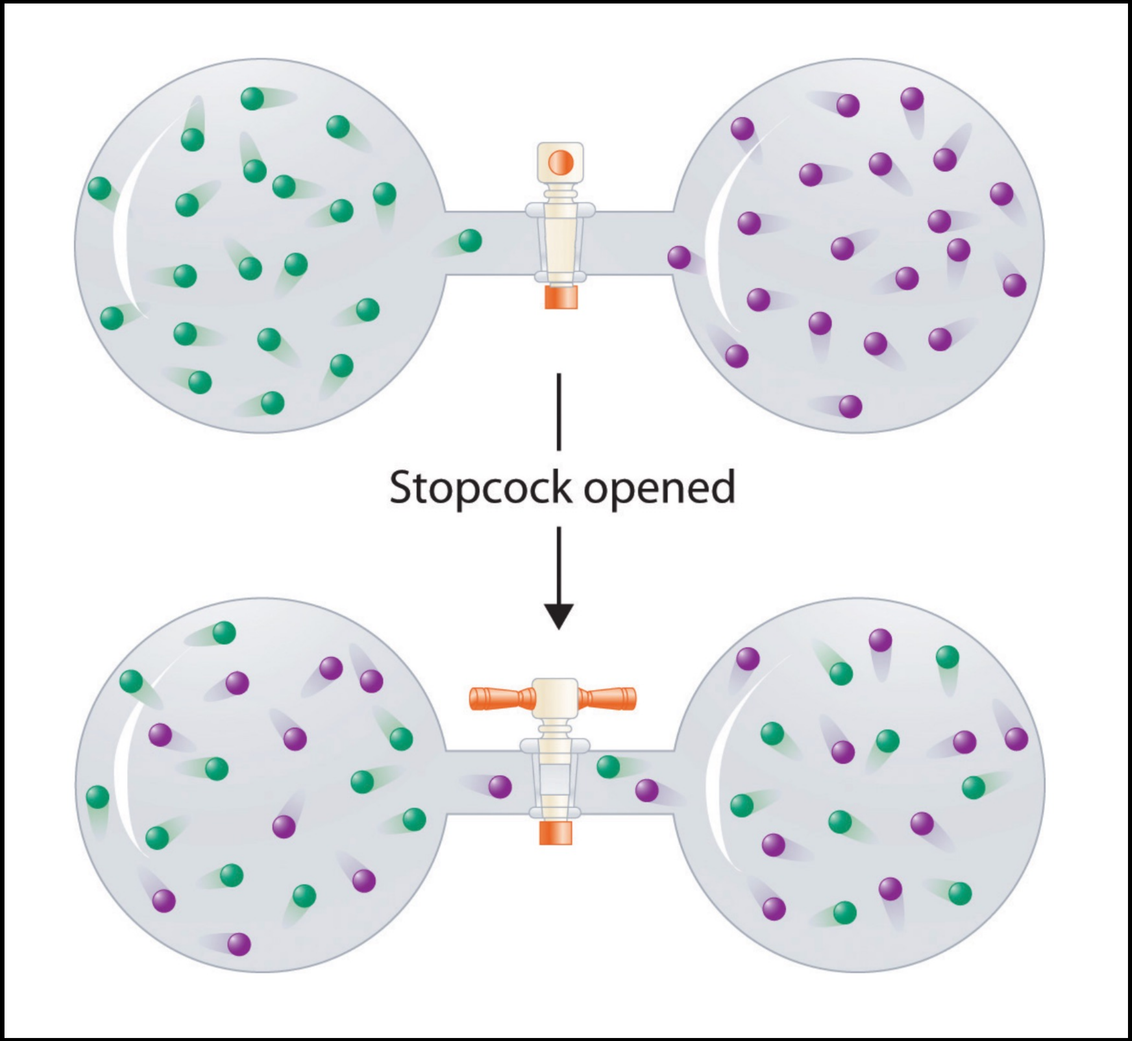
Energy penalty or having more neutron than protons

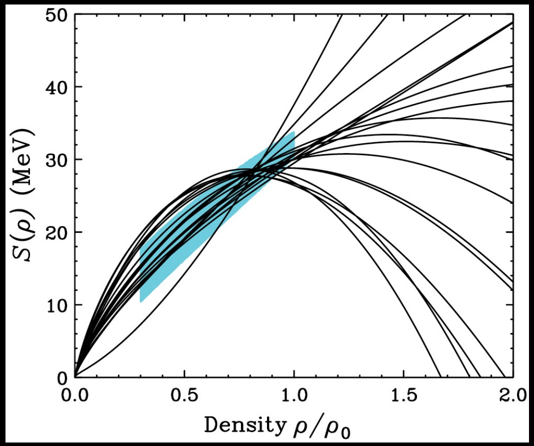
Depends on Density

Largest uncertainty in the nuclear Equation of State

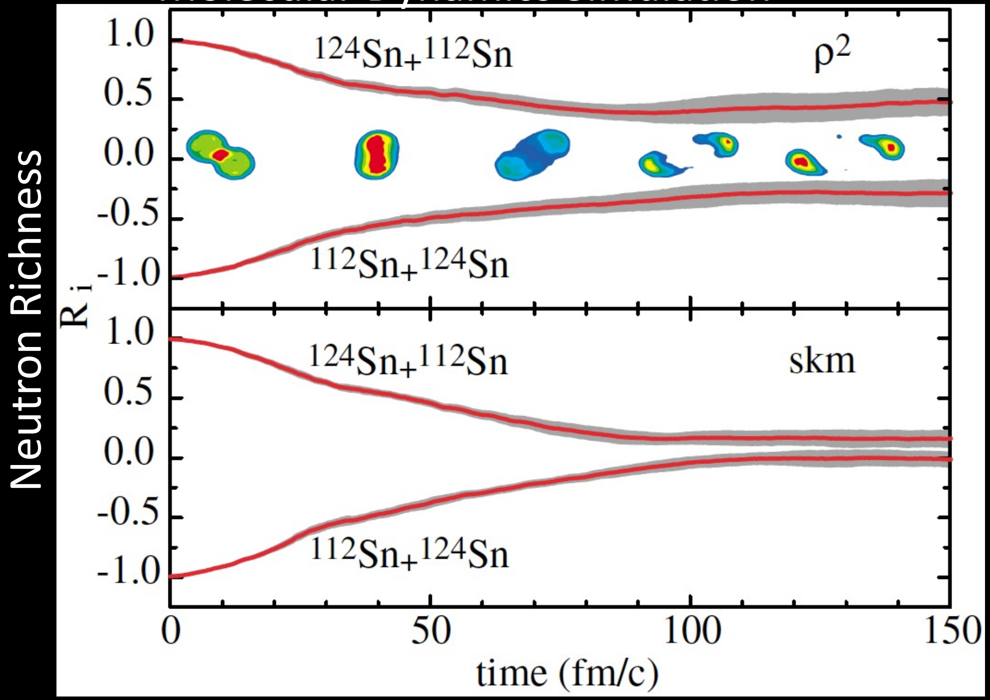
Energy penalty is reduced by putting the excess neutrons at low density

Mixing of Gases





Molecular Dynamics Simulation



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

Probing the Equation of State with N-Z Equilibration

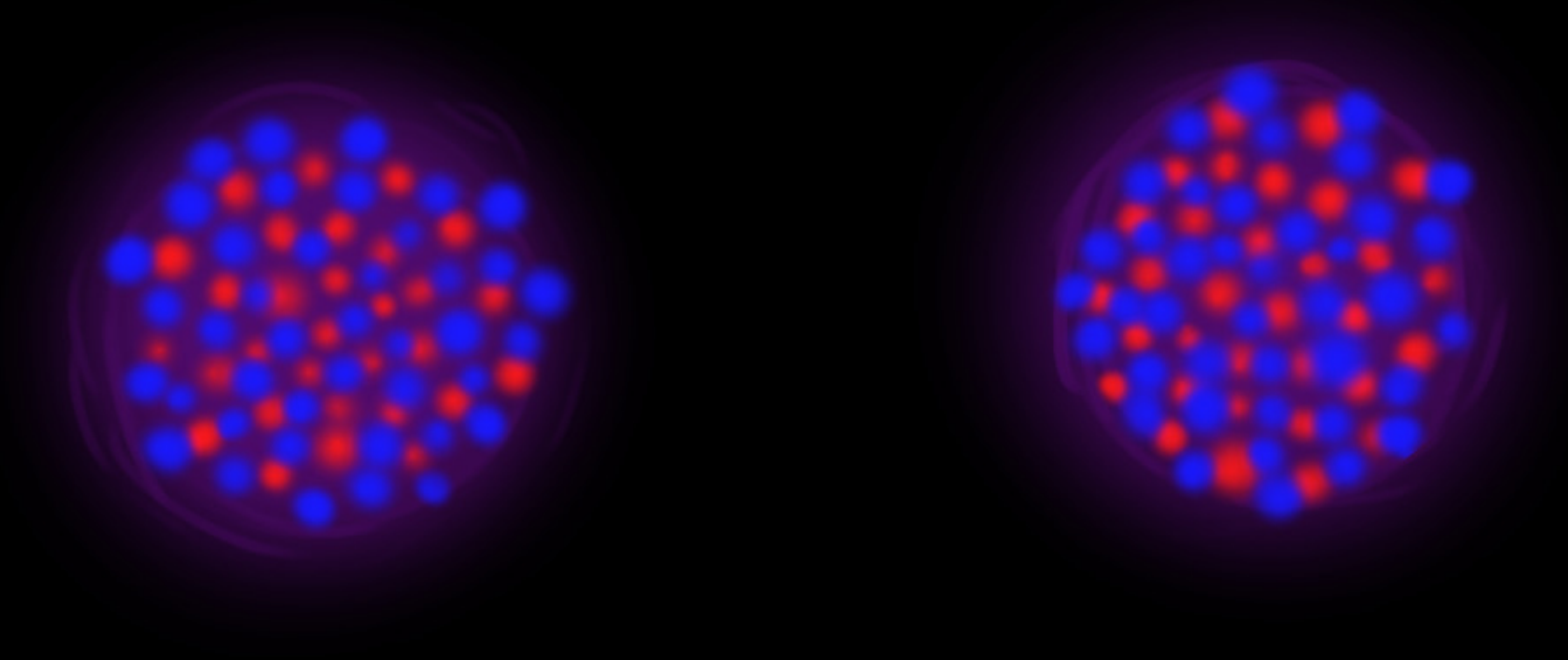
Degree of equilibration between Proj & Targ determined by contact time and strength of the driving potential (EoS).

Measure as a function of time?
Why shouldn't we?

Asymptotic values provide information to the EoS, modified by secondary decay.

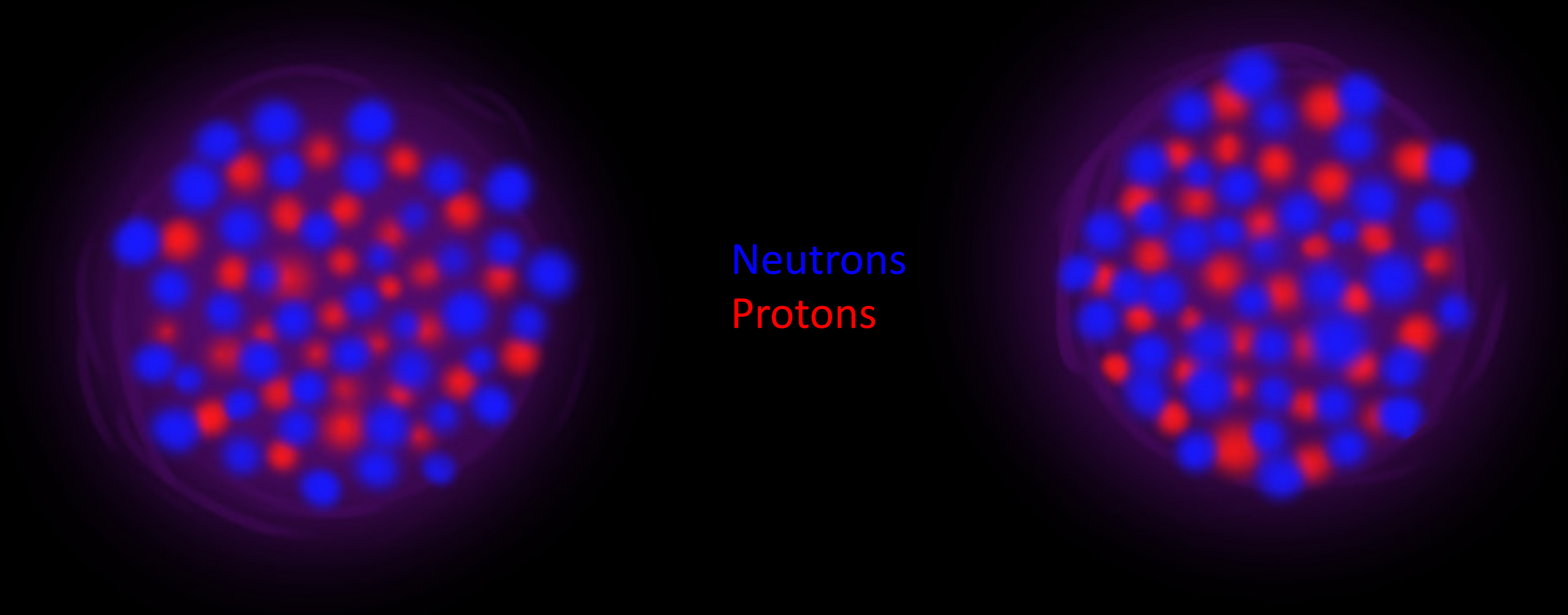
Surrogates for N-Z of primary fragment (e.g. isoscaling, yield ratios) can be used.

Equilibration and Nuclear Dynamics



Projectile approaches target

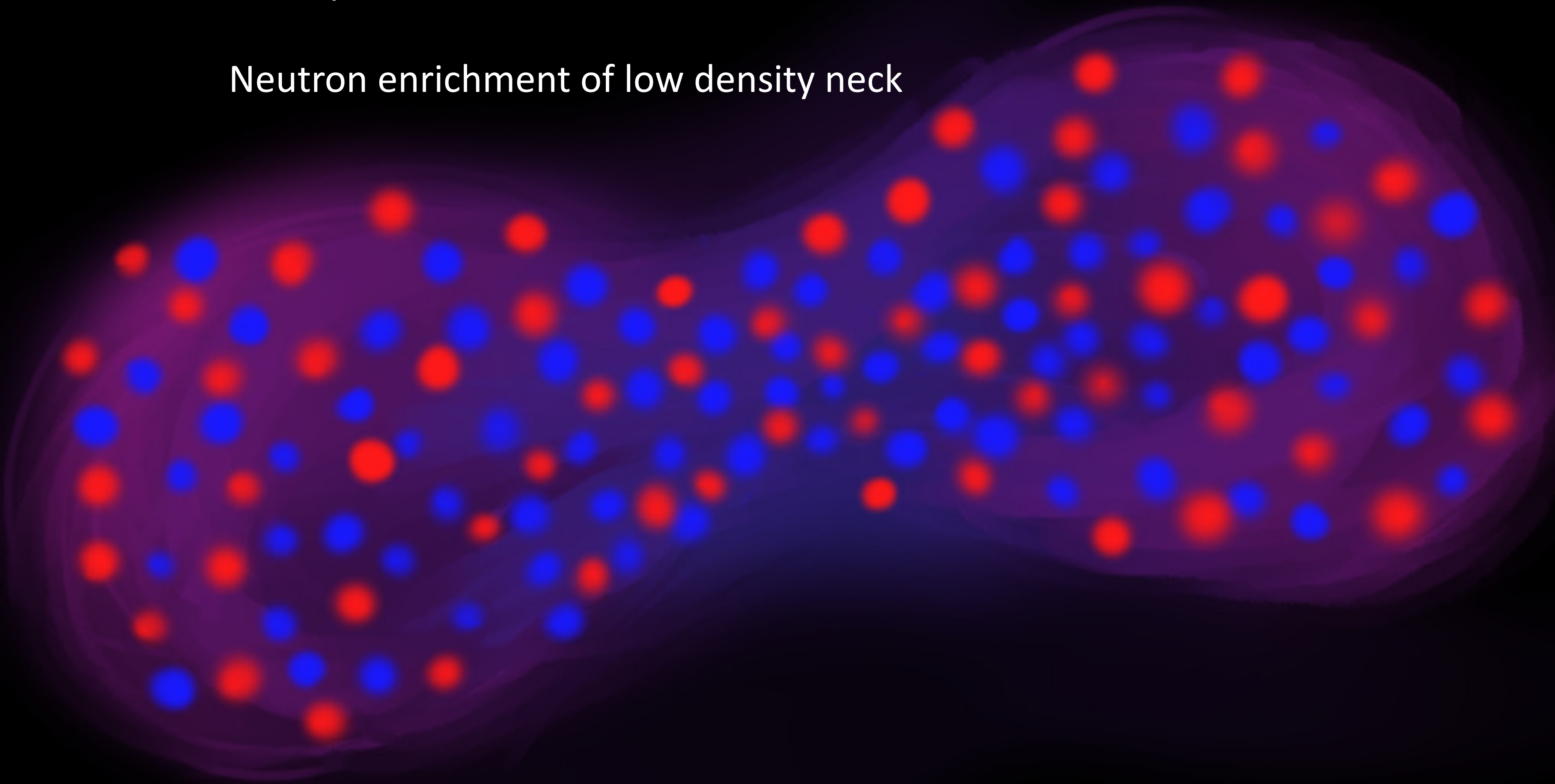
non-central collision near the Fermi Energy



Overlap of target and projectile

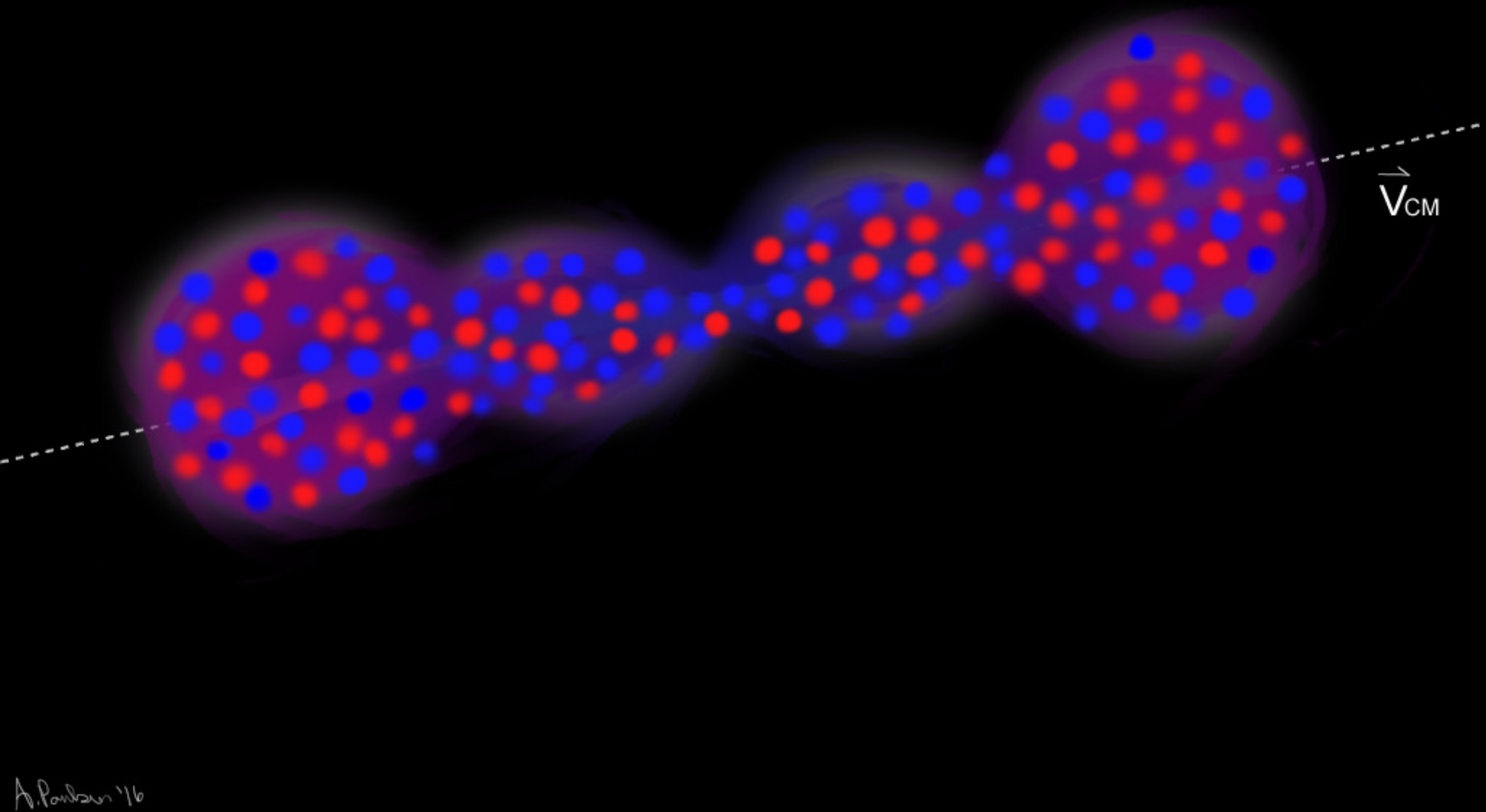
Low density neck

Neutron enrichment of low density neck



Velocity gradient, surface tension

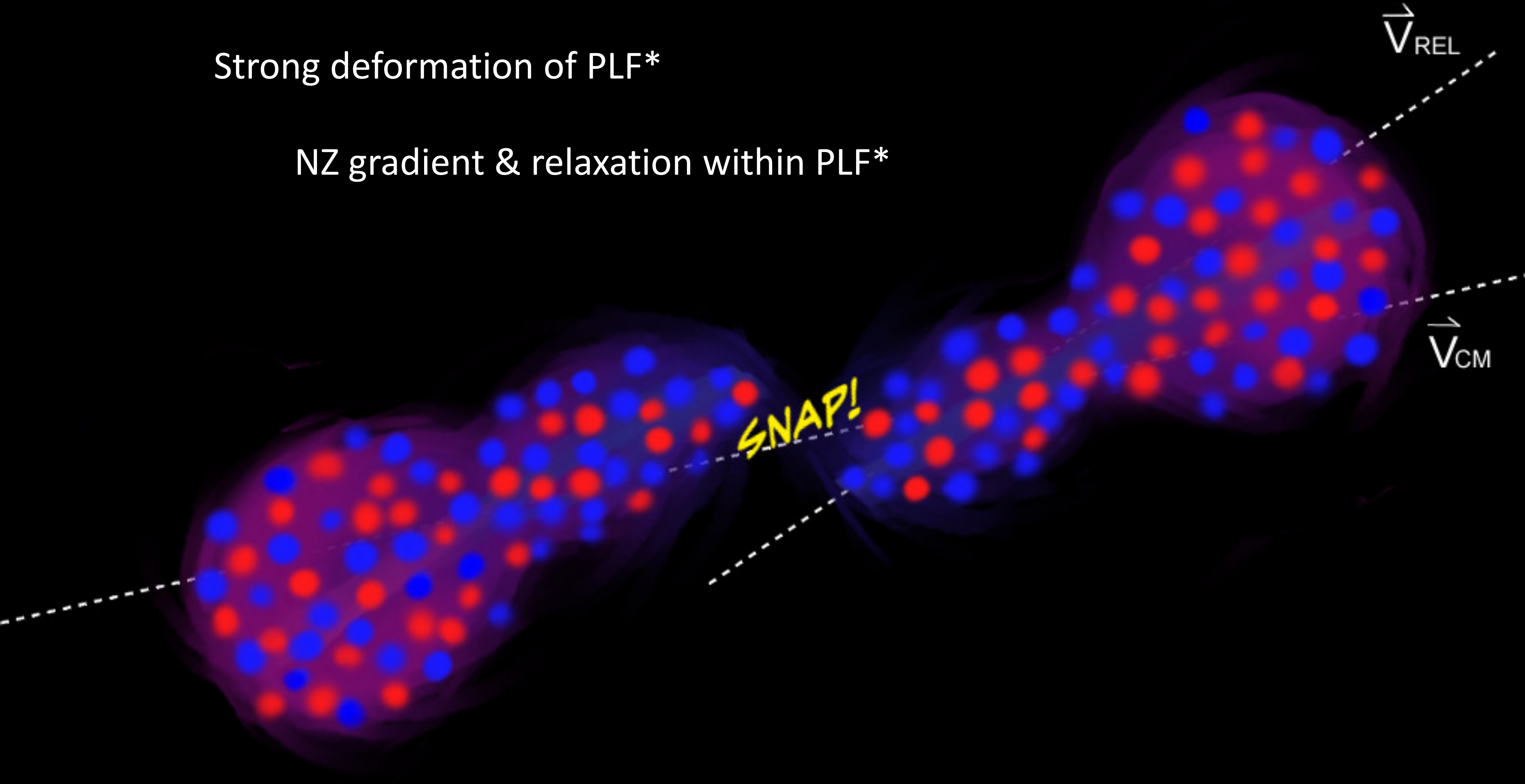
Instabilities develop



Rupture of neck

Strong deformation of PLF*

NZ gradient & relaxation within PLF*

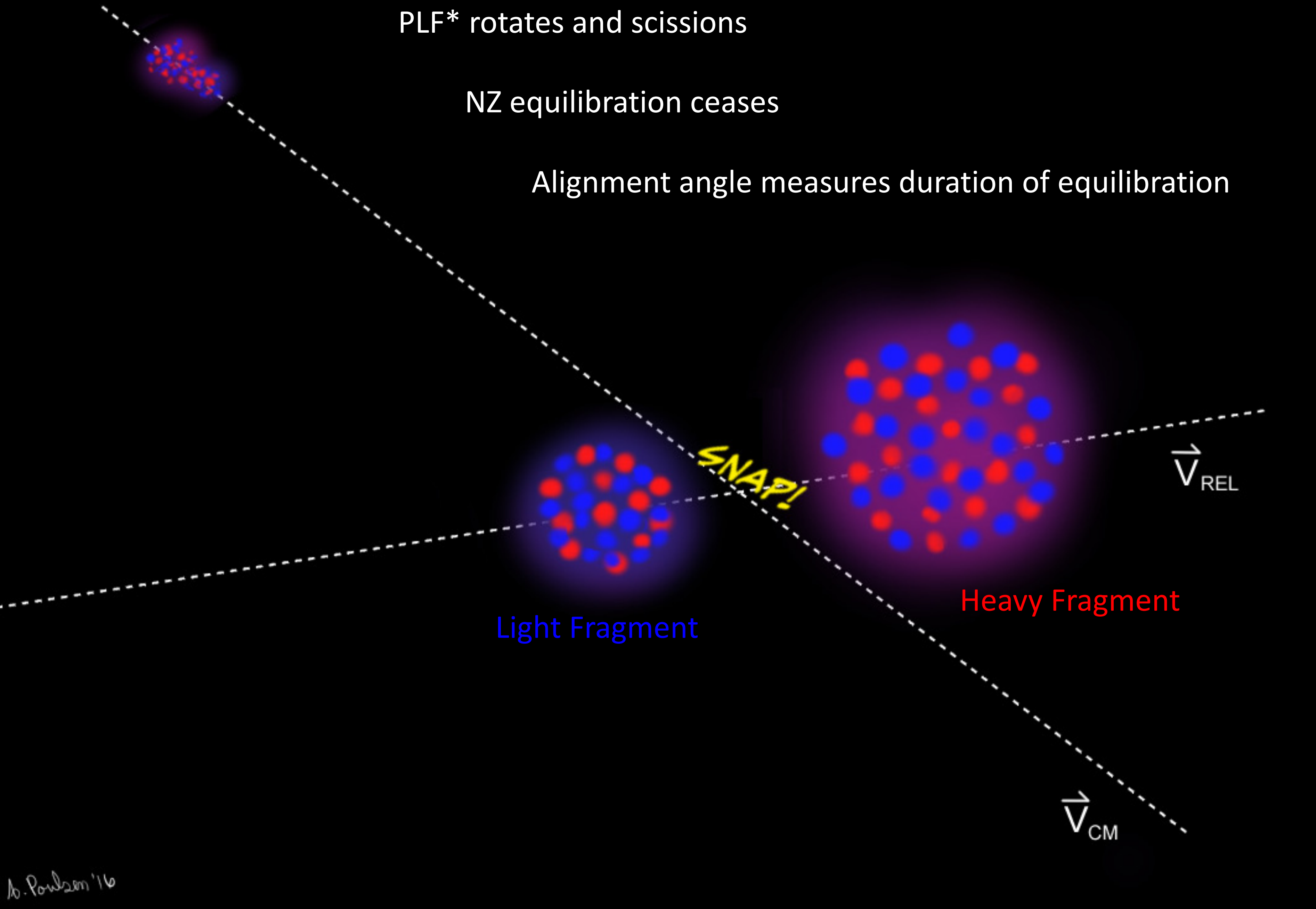


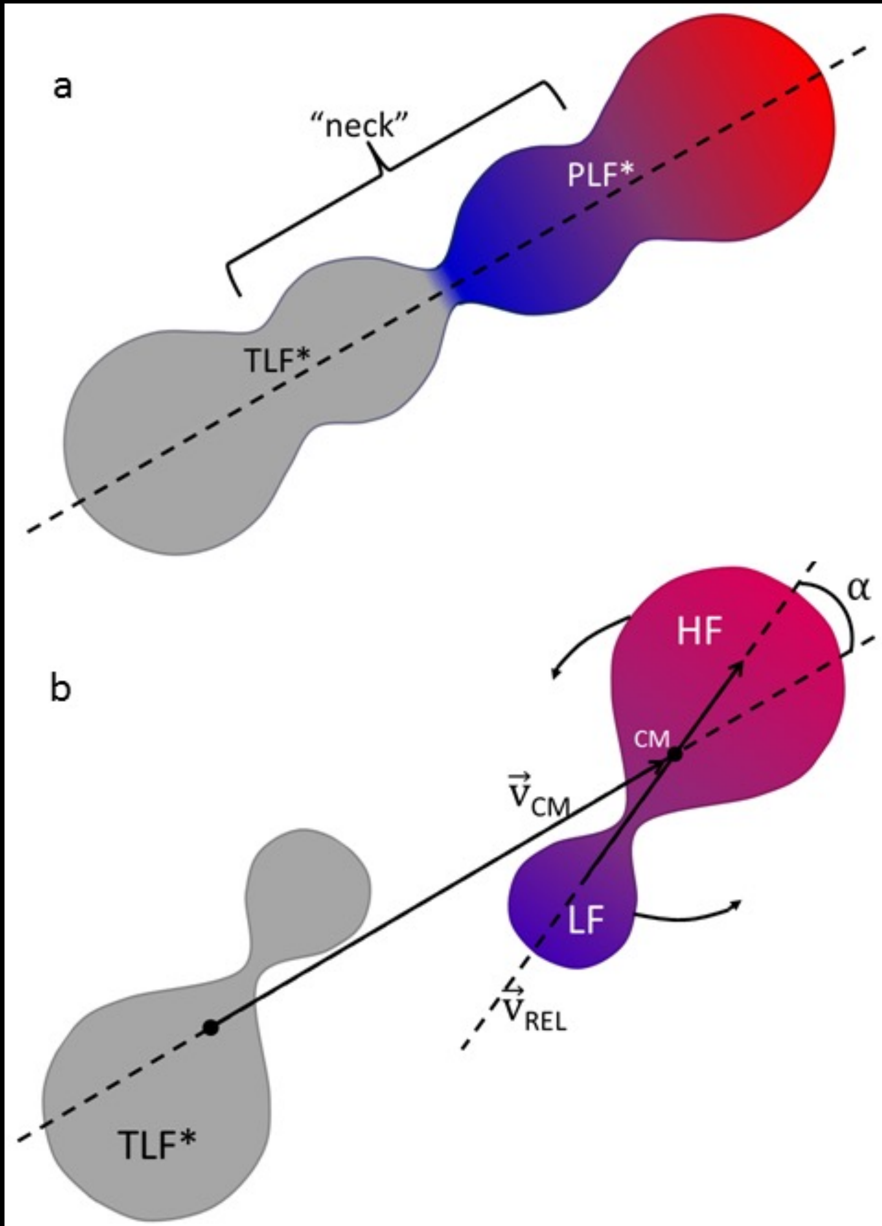
A.Pandaru '16

PLF* rotates and scissions

NZ equilibration ceases

Alignment angle measures duration of 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 PLF* is spinning
2. the two regions of the deformed QP 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!

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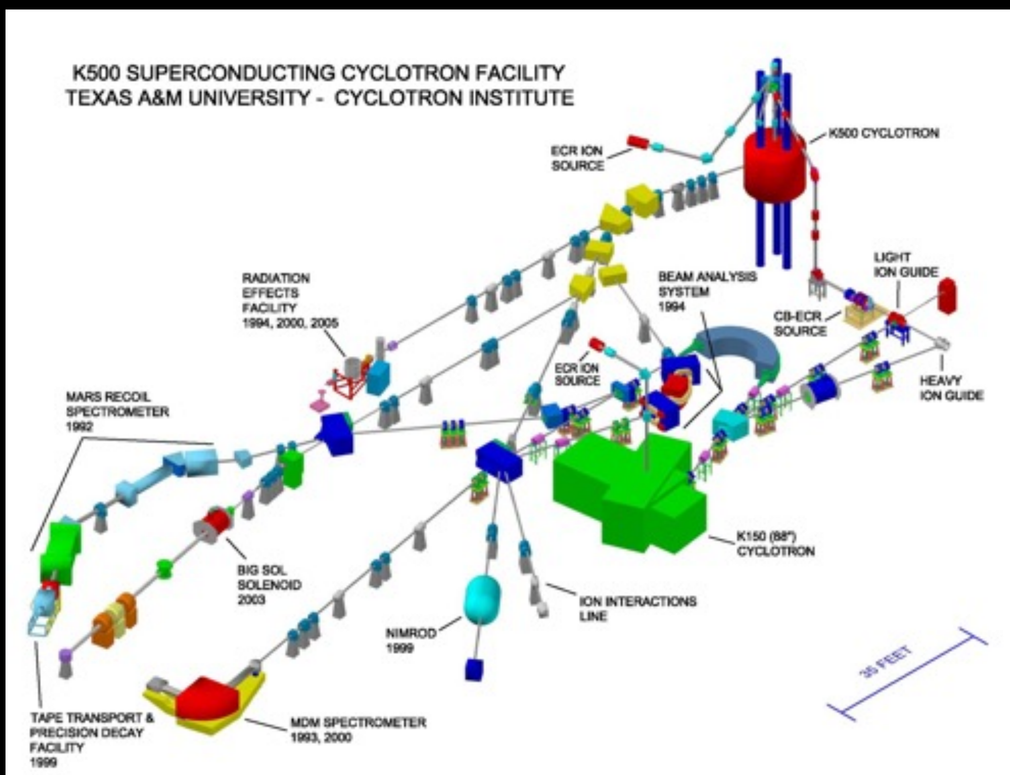
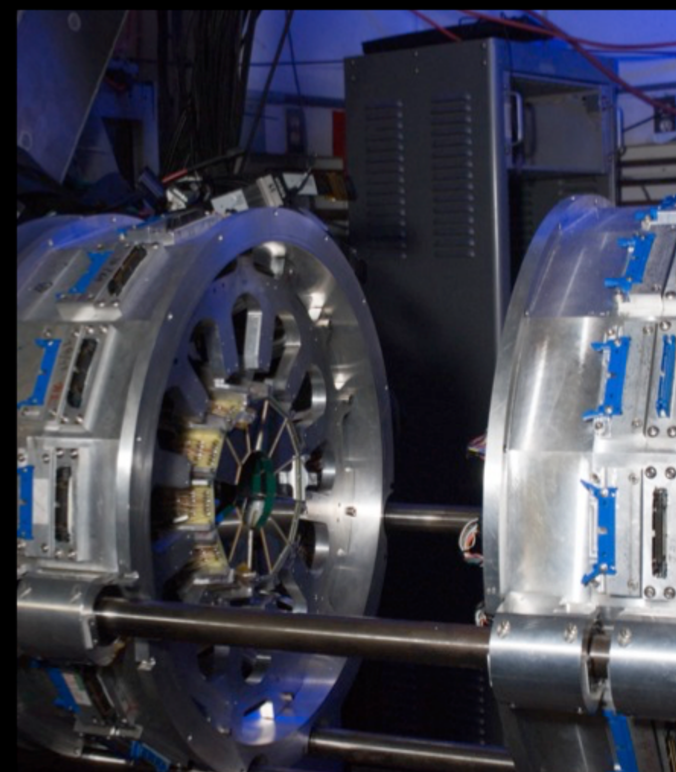
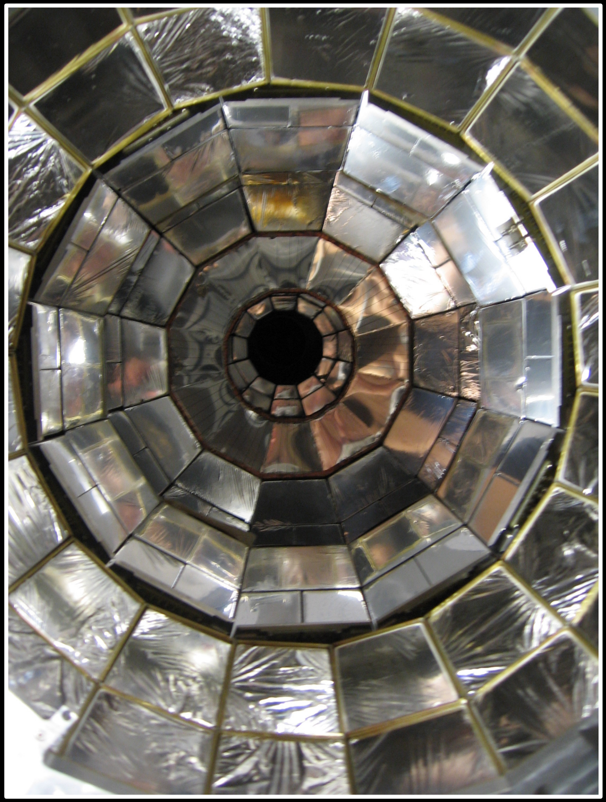
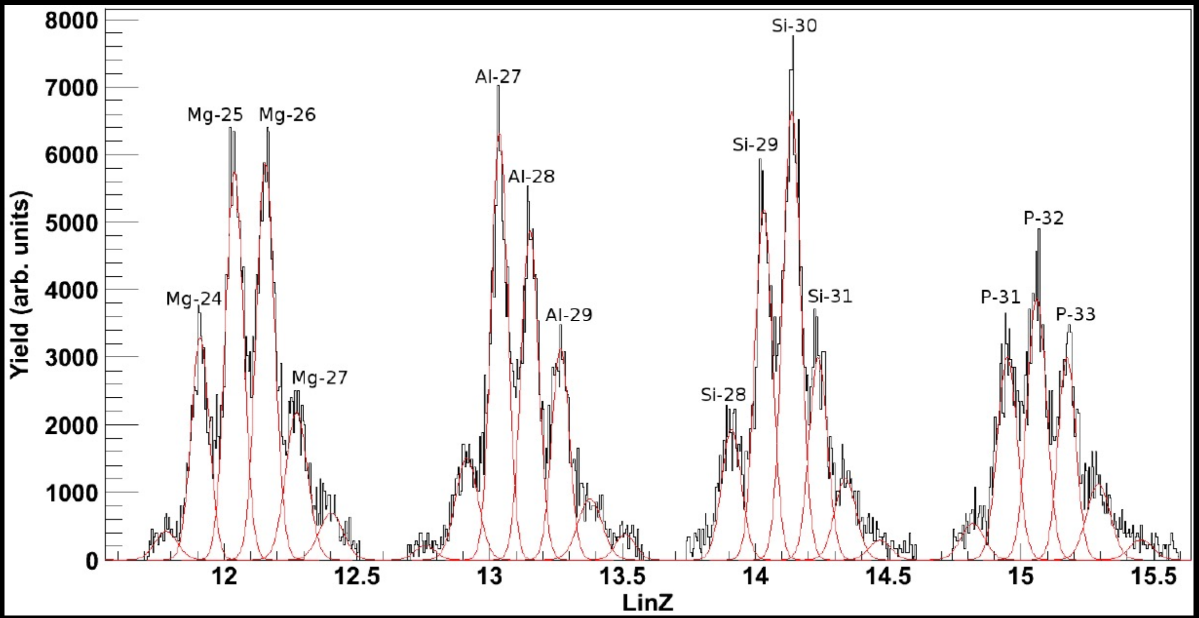




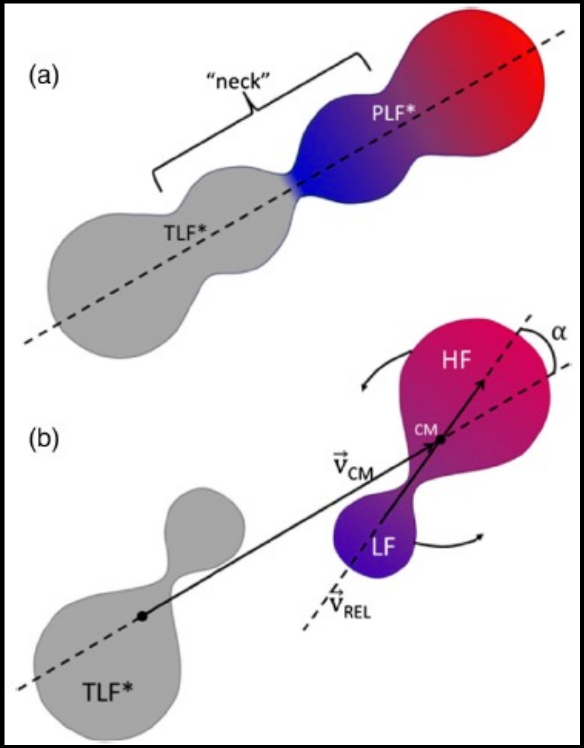
NIMROD 4π Array
$^{70}Zn + ^{70}Zn$ @ 35A MeV

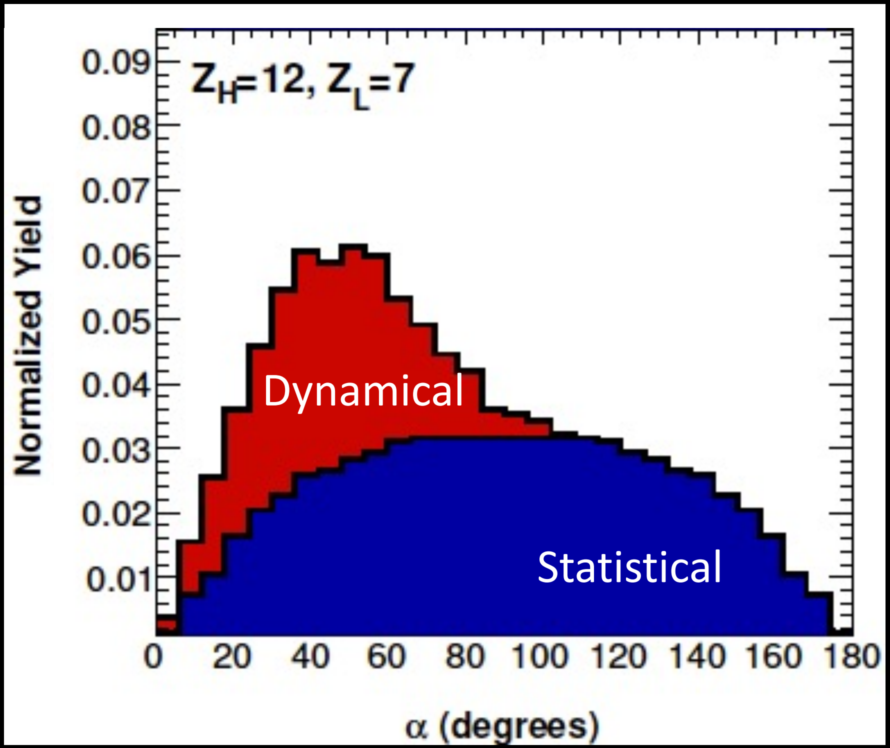




- Full geometrical coverage
- First-class isotopic resolution
- ➢ High-statistics, large acceptance and measurement of N-Z composition of both major fragments participating in the equilibration.

Aligned Decay

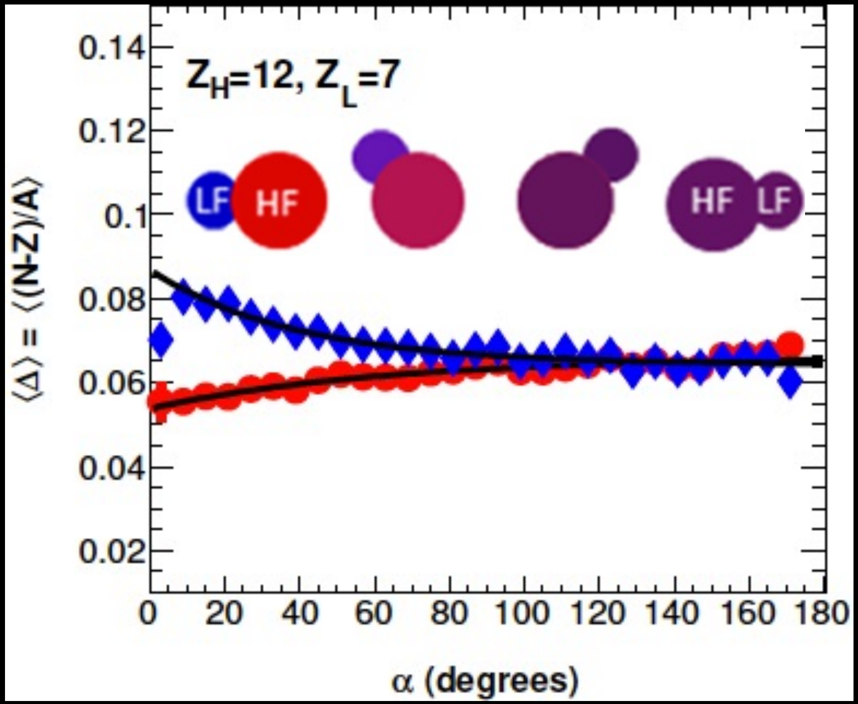




The angle α is a surrogate for time.

A. Jedele et al. PRL 118 (2017) 062501

Equilibration



Composition vs alignment

Δ = (N-Z)/A

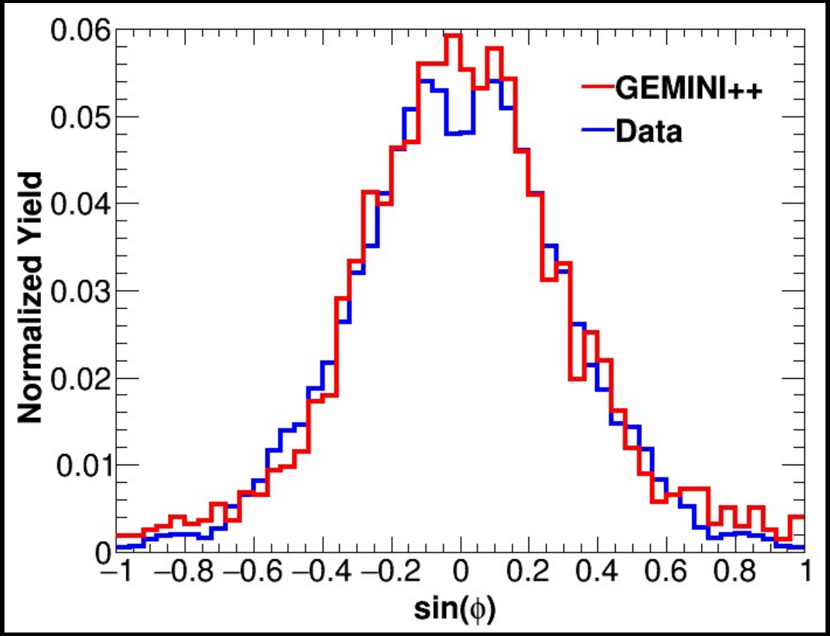
As LF loses neutrons, HF gains neutrons

Exponential dependence
→ First Order Kinetics
→ i.e. The rate of change of the neutron excess is proportional to the relative neutron excess

A. Jedele et al. PRL 118 (2017) 062501

Assessing the Equilibration Time Scale

Evaporative emission → angular momentum
No spin → Isotropic
Increasing spin → In-plane emission



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.

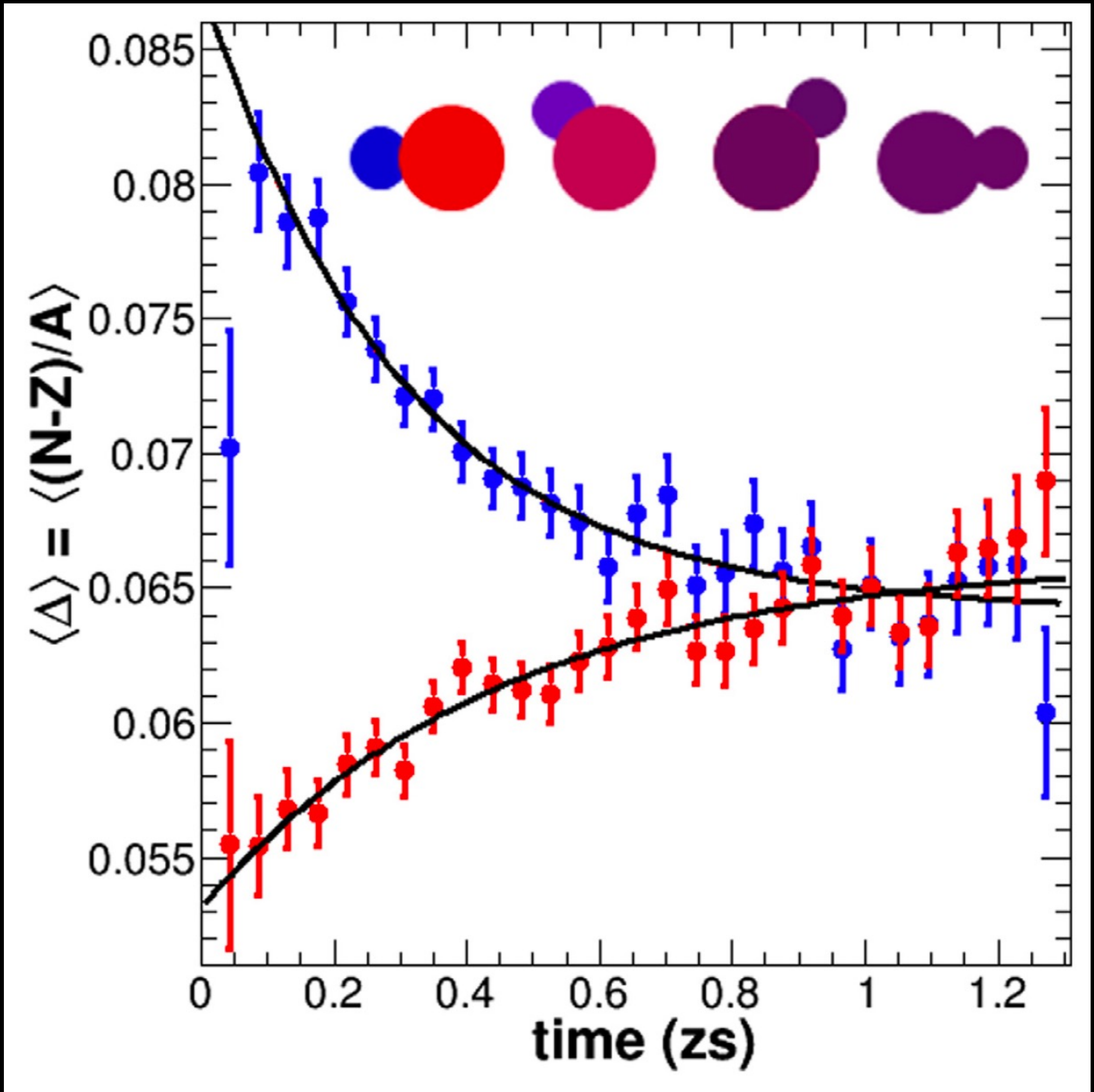
$$\omega = J\hbar / I_{eff}$$

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.

$$t = \alpha / \omega$$

A. Jedele et al. PRL 118 (2017) 062501

Equilibration Chronometry



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

A. Jedele et al. PRL 118 (2017) 062501
A.B. McIntosh and S.J. Yennello PPNP 108 (2019) 103707

What about the effect of…

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

A. Rodriguez Manso PRC 95 (2017) 044604

How does varying
the **beam and target composition**
affect the equilibration signature?

A. Rodriguez Manso PRC 95 (2017) 044604

Are there other observables
for equilibration chronometry?

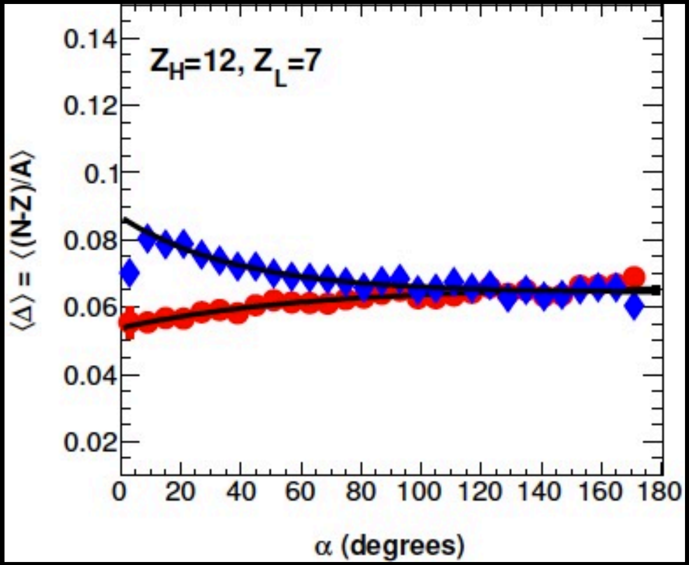
A. Hannaman et al PRC 101 (2020) 034605

Can we verify the time scale?

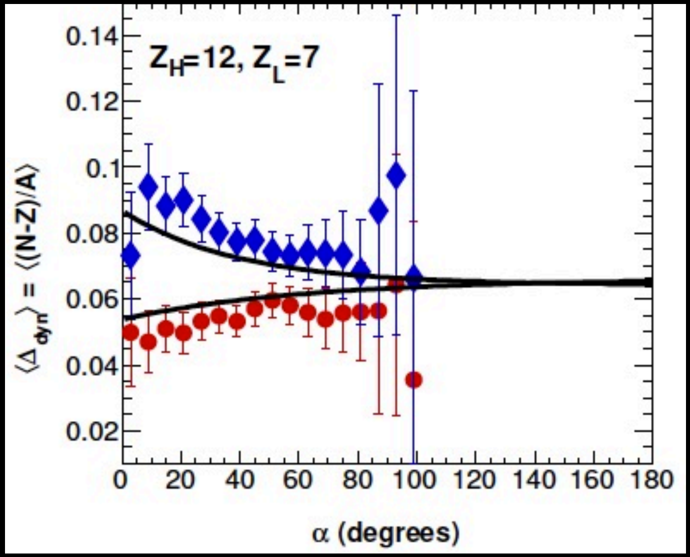
B. Harvey et al. PRC 102 (2020) 064625

Effect of Statistical Decay

Raw (Inclusive)



Isolated Dynamical Component
General trend maintained



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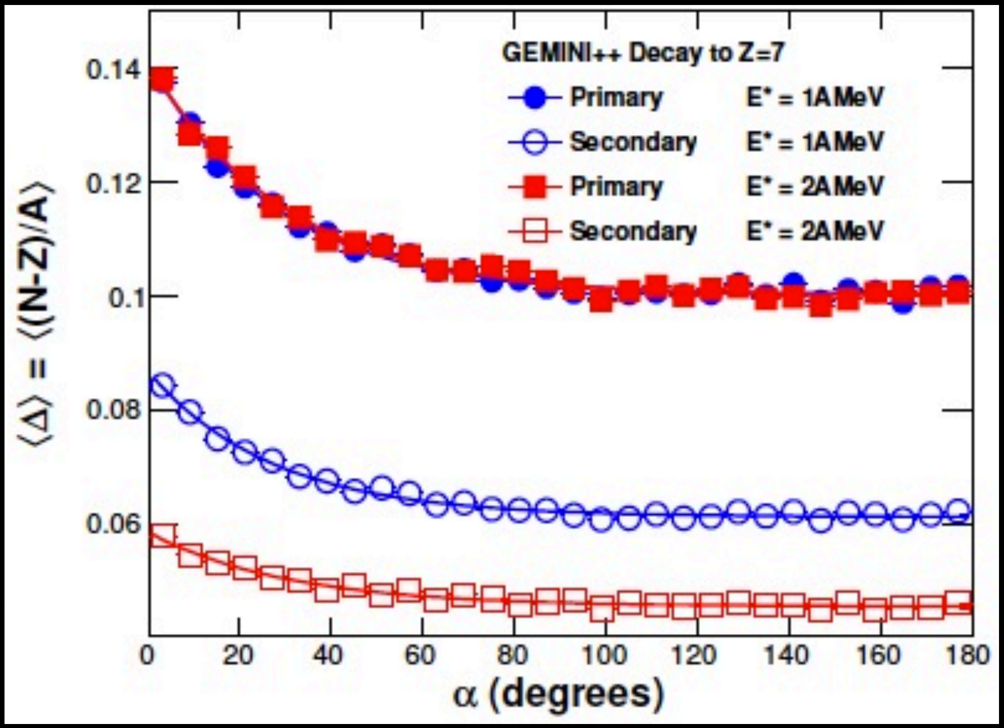
Effect of Secondary Decay



Secondary Decay mutes the effect
Does not create
Does not destroy

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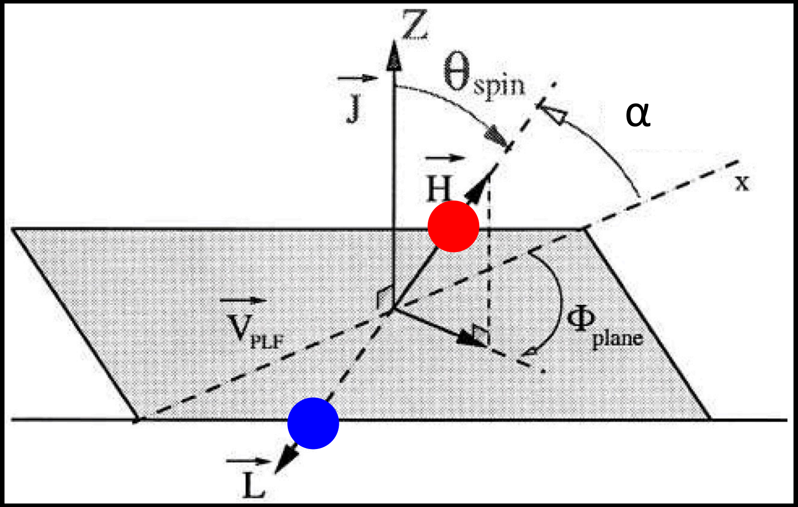
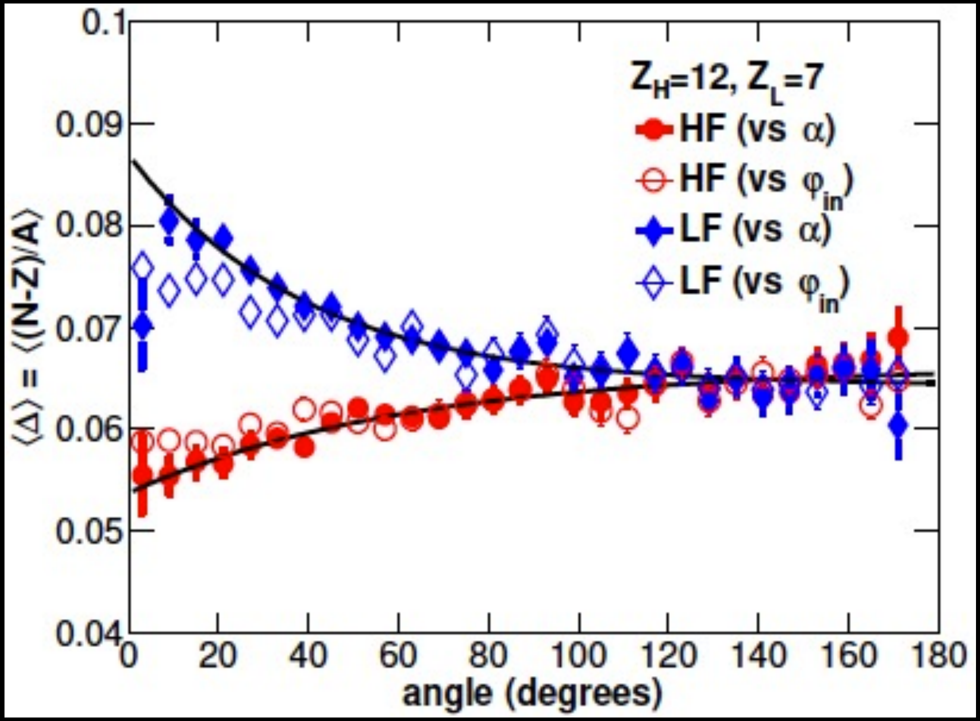
Equilibration and Choice of Alignment Angles





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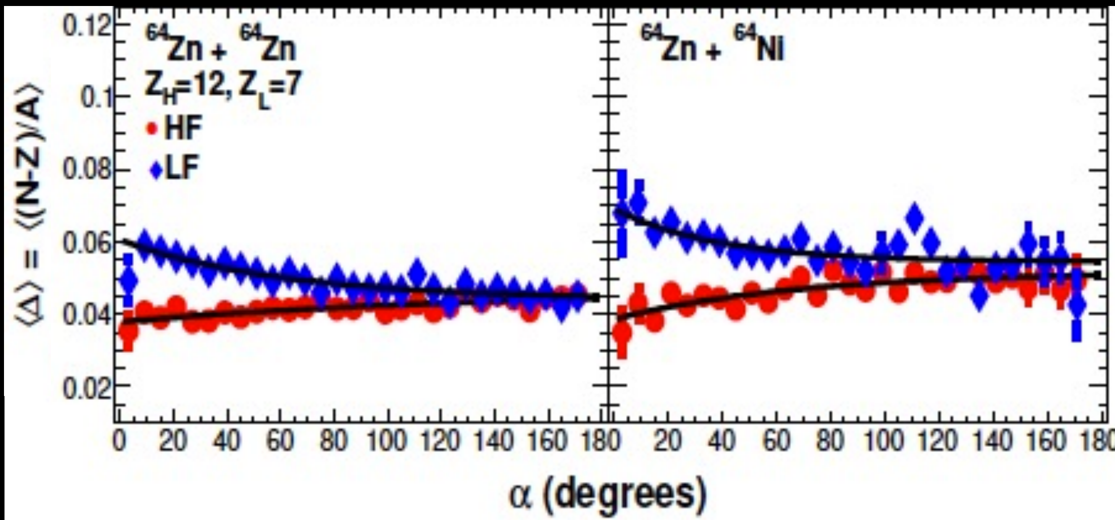
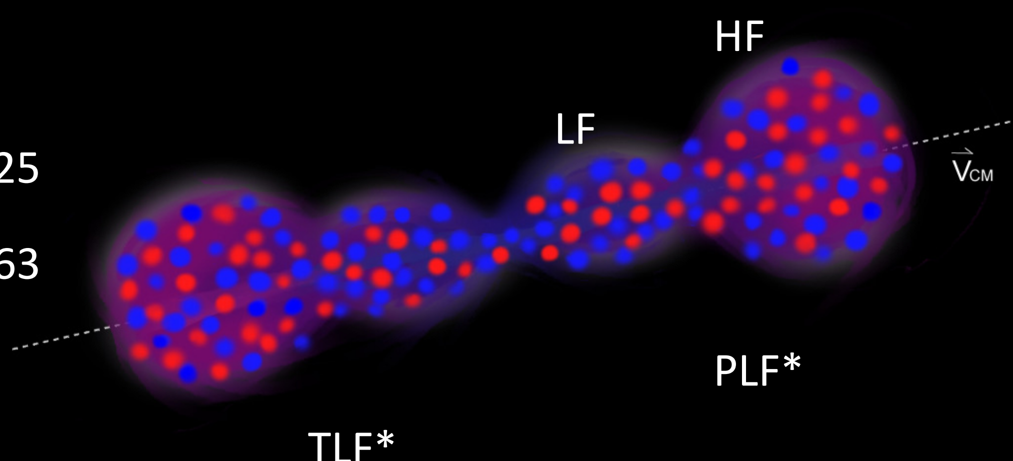
Effect of Target Composition



64Zn+64Zn vs 64Zn+70Zn
Increase only target asymmetry

→ Higher initial asymmetry in LF
→ Same initial asymmetry in HF
→ Higher equilibrium asymmetry

$\Delta_0 = 0.125$
or
$\Delta_0 = 0.063$



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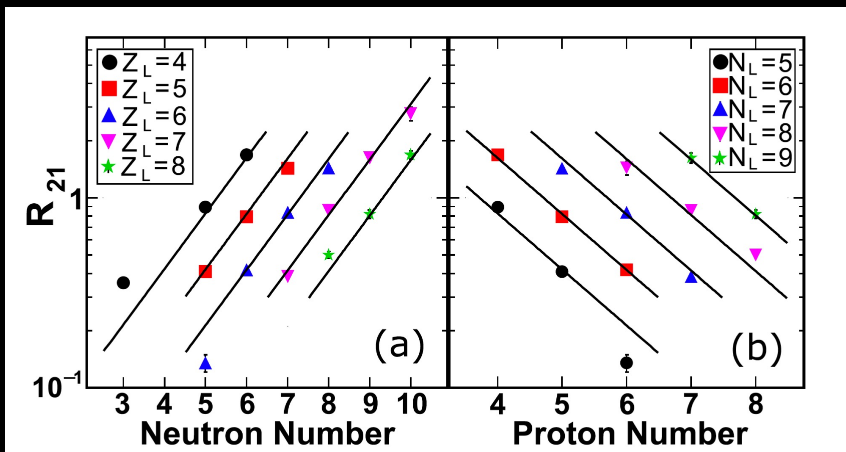
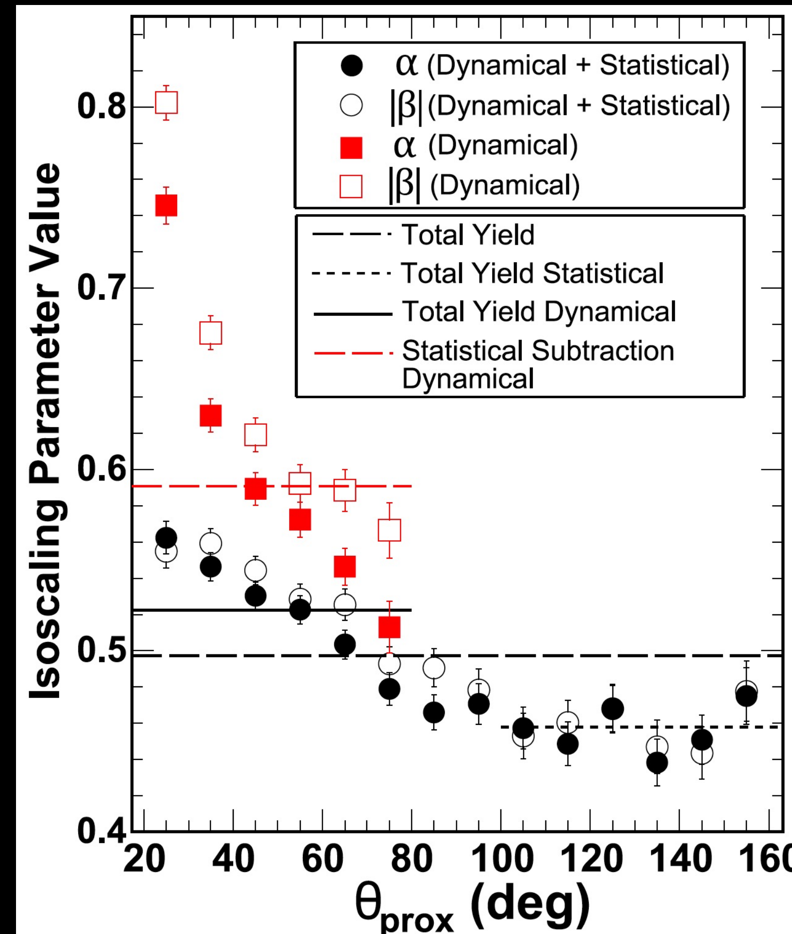
Isoscaling as Signature of Equilibration



$$R_{21} = Y_{70Zn}(Z,N) \,/\, Y_{64Zn}(Z,N)$$

More neutron-rich

Less neutron-rich



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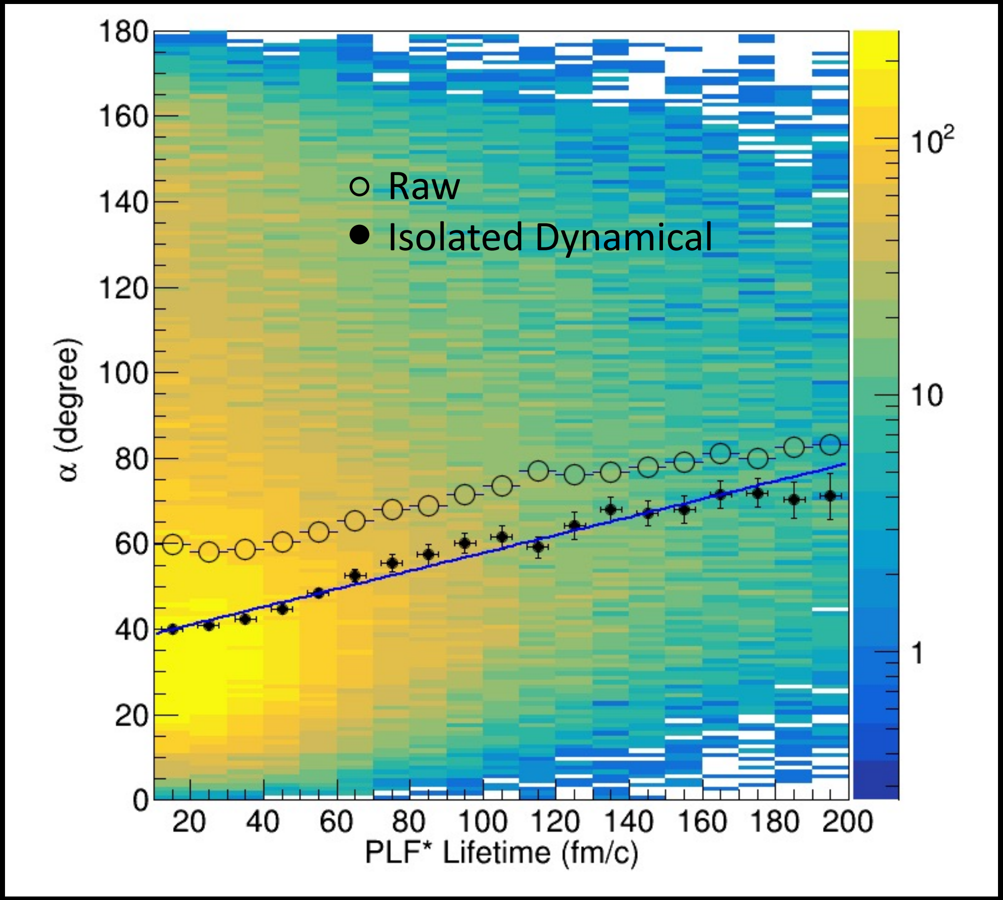
Timescale from Dynamical Simulations



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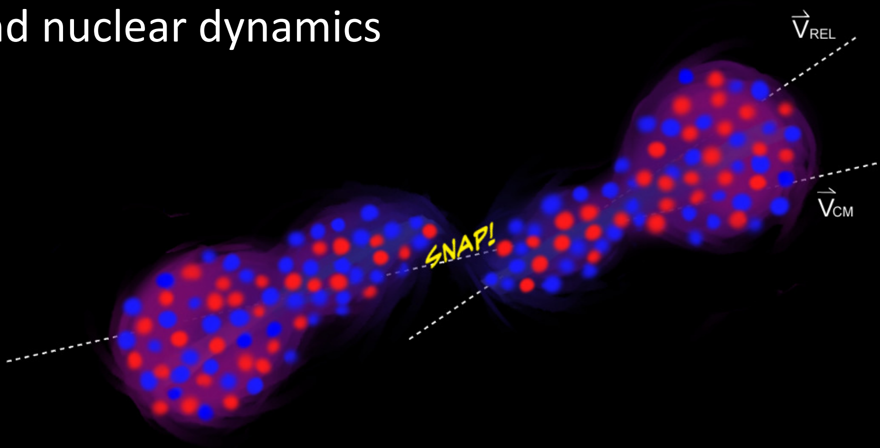
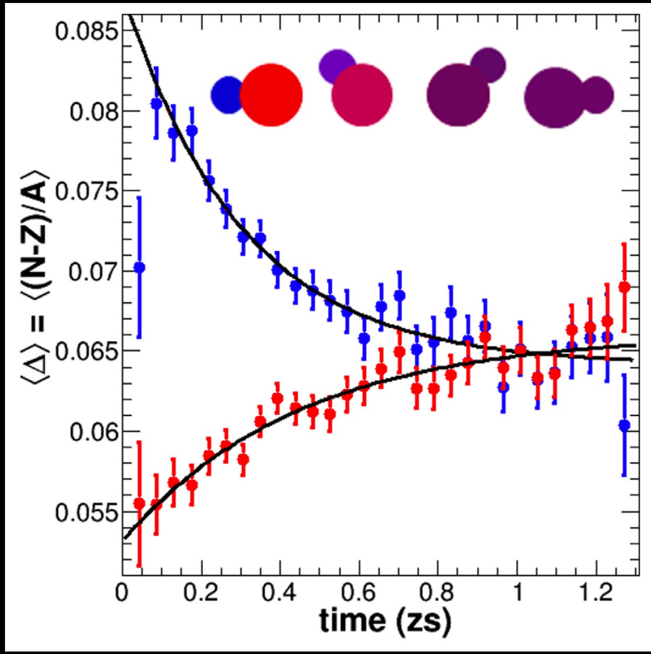
Equilibration Chronometry

Interplay of neutron-proton equilibration and nuclear dynamics

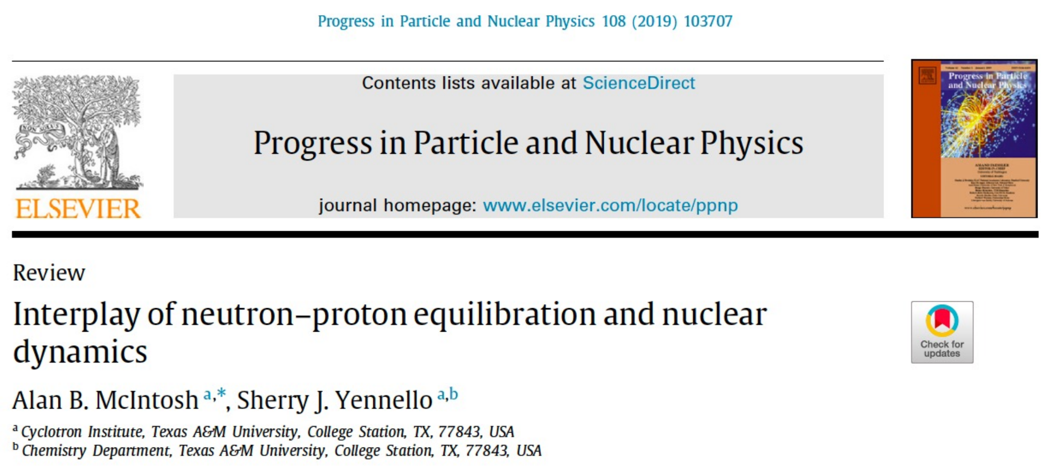




- Equilibration continues after PLF*/TLF* separation
- Composition Varies with Alignment

→ First Order Kinetics

- Robust
- Isoscaling Probe
- Verified time scale (MD simulation)



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Review

Interplay of neutron–proton equilibration and nuclear dynamics

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