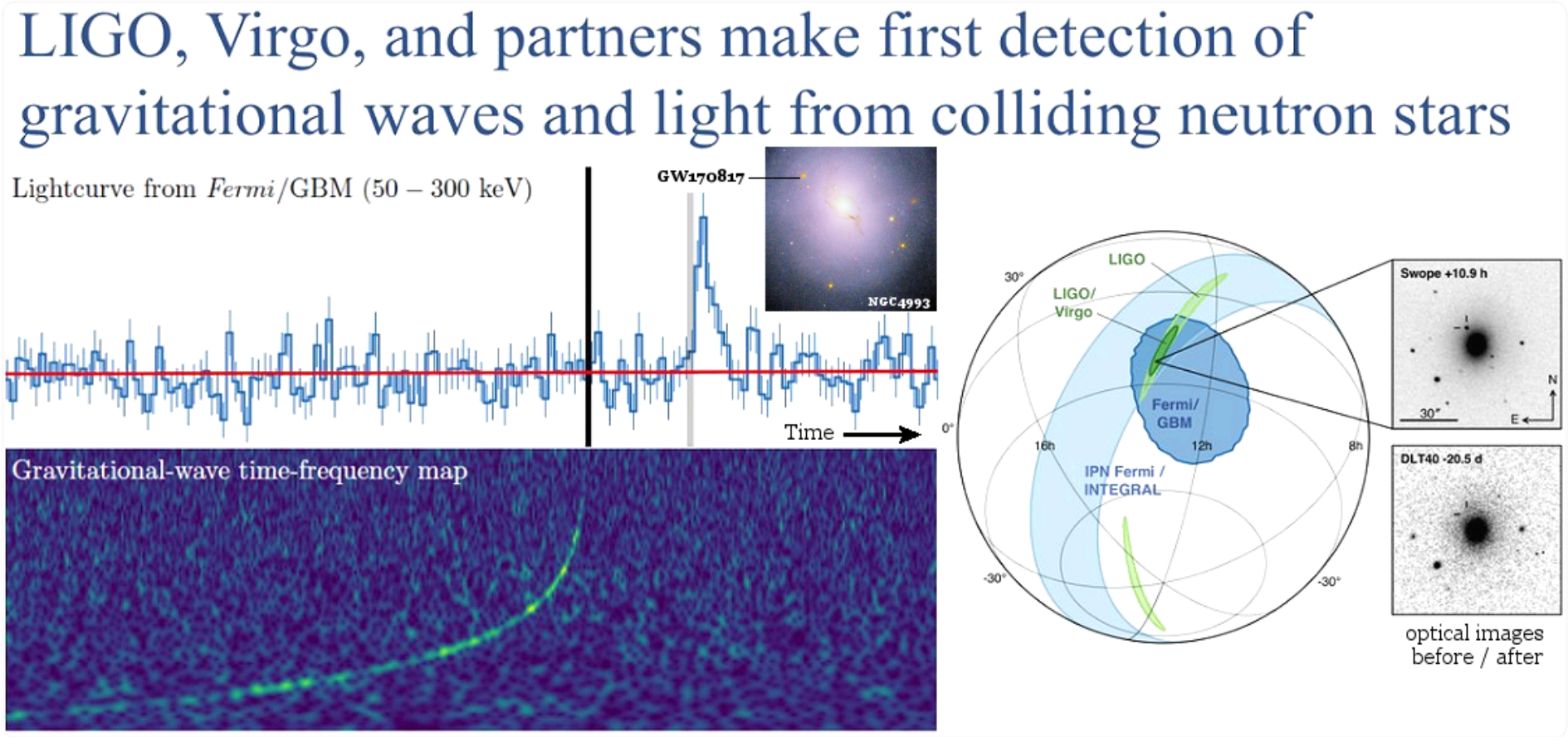
Experimental constraints on the nuclear equation-of-state from heavy-ion collisions

Sherry Yennello

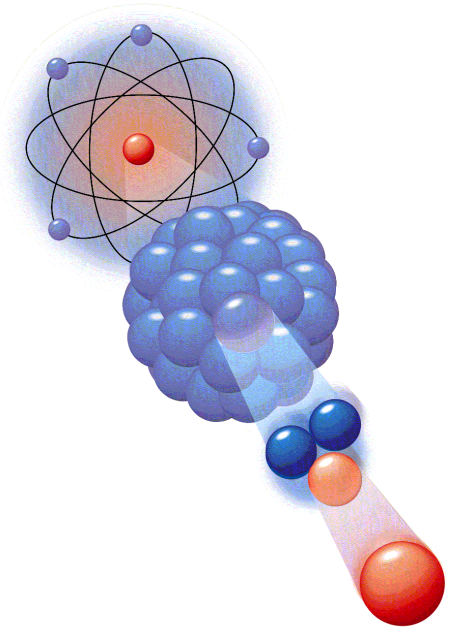
Texas A&M University

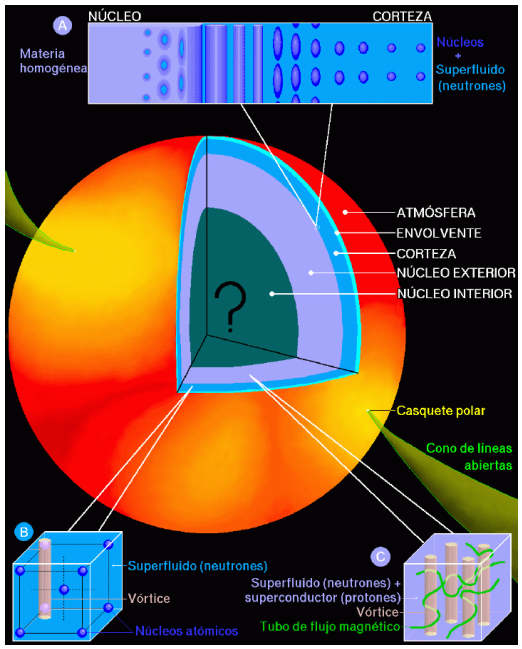
Science Magazine's Breakthrough of the Year 2017:



Atomic nuclei & Neutron star
(two vastly different systems)

A heavy nucleus (like ^{208}Pb) is 18 orders of magnitude smaller and 55 orders of magnitude lighter than a neutron star !





Yet bounded by a common entity, the nuclear Equation Of State (EOS) !

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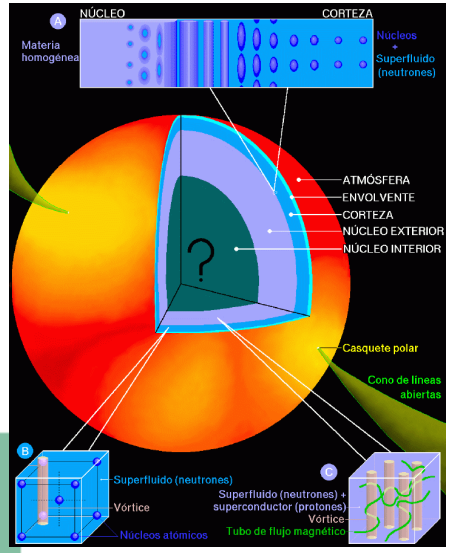
Nuclear Equation of State



Isospin Dependence of Strong Interactions

Nuclear Masses
Neutron Skin Thickness
Isovector Giant Dipole Resonances
Fission

Heavy Ion Flows
Multi-Fragmentation
Nuclei Far from Stability
Rare Isotope Beams

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

Supernovae
Weak Interactions
Early Rise of L_{ν_e}
Bounce Dynamics
Binding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational Properties

Binary Mergers
Decompression/Ejection of Neutron-Star Matter
r-Process

QPO's
Mass
Radius

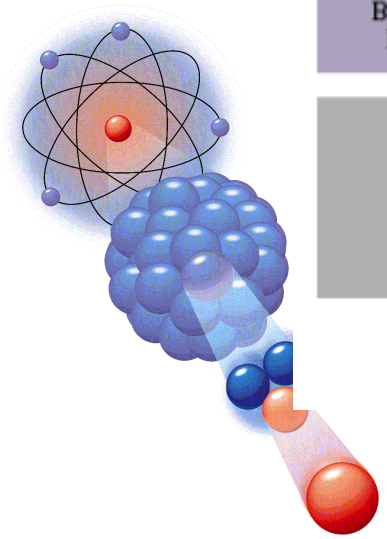
NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

Gravity Waves
Mass/Radius
dR/dM

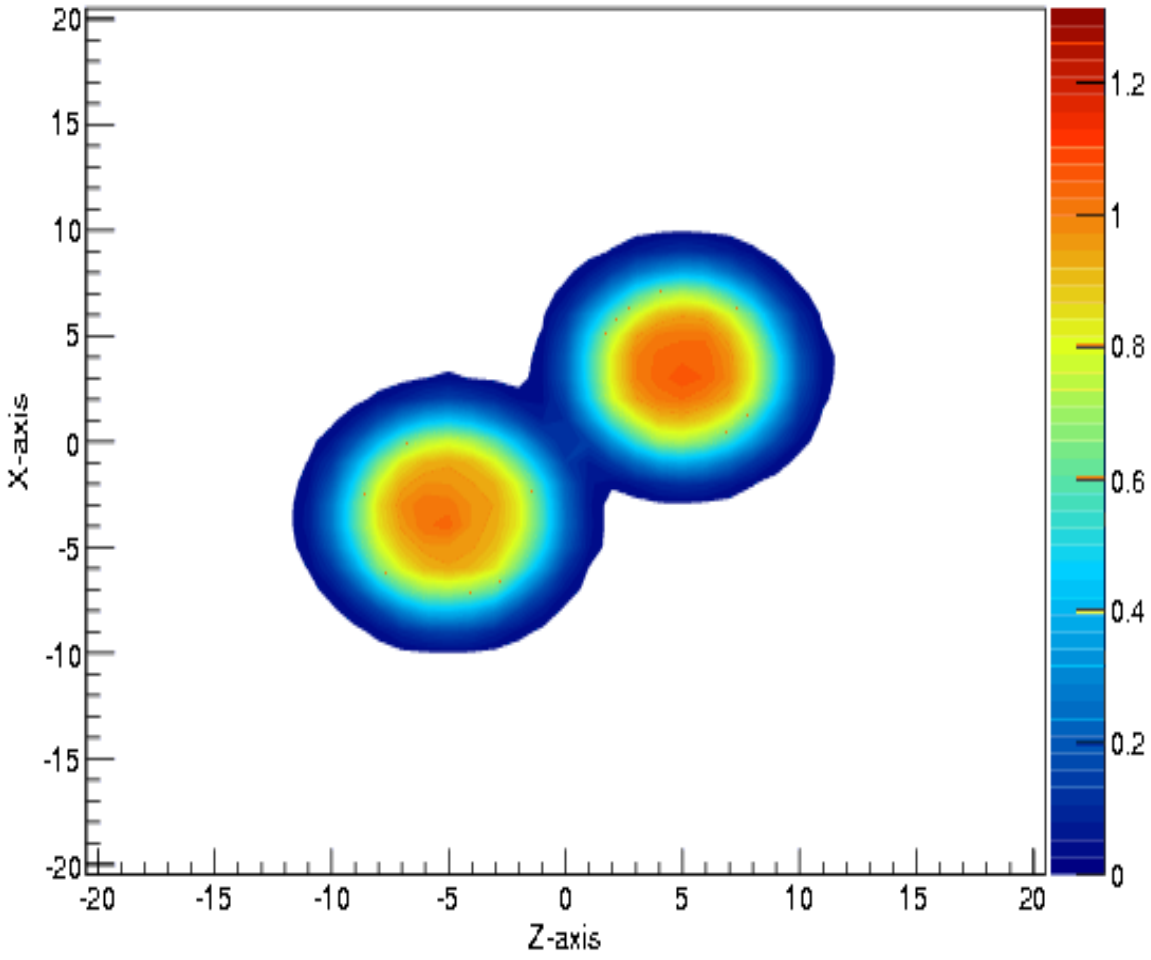
Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates



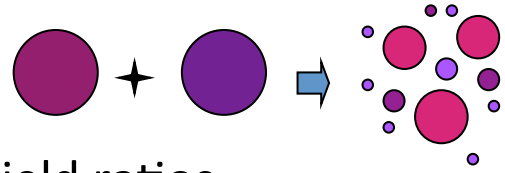
A. Steiner et al, Phys. Rept. 411 (2005) 325

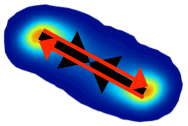
Experimental constraints on the nuclear equation-of-state from heavy-ion collisions

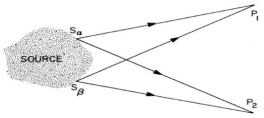


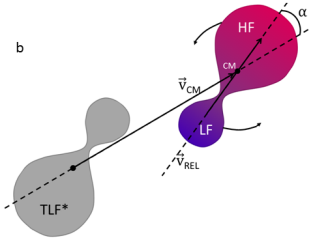
Observables sensitive to the EOS ?

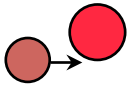
Neutron-skin thicknesses
Pygmy resonances
Fragment isotope distribution, isotopic & isobaric yield ratios
Isospin distillation/fractionation, relative n & p densities
Isospin transport / diffusion / migration
Nuclear stopping & NZ equilibration
Pre-equilibrium emission
Particle - particle correlation
Light cluster production
Collective Flow
Neck emission
Fusion vs Deep Inelastic reactions
Subthreshold particle production

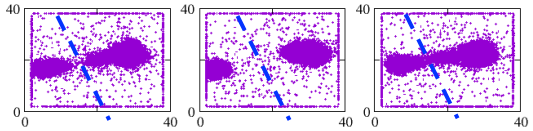












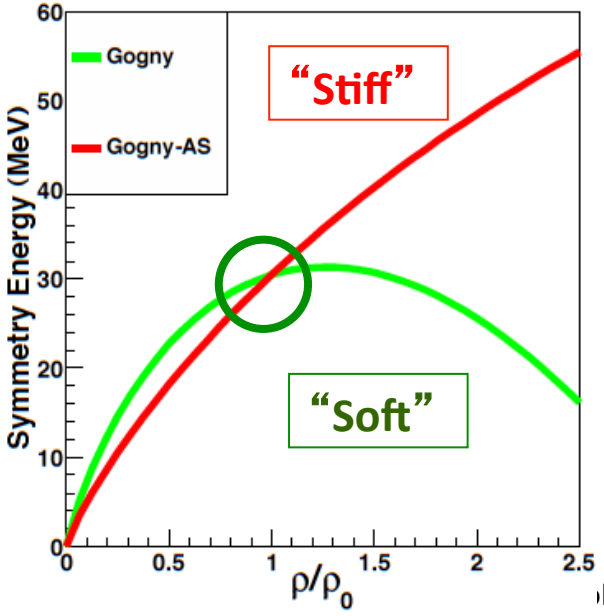
$$E_B = a_v A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} - \delta(A,Z)$$

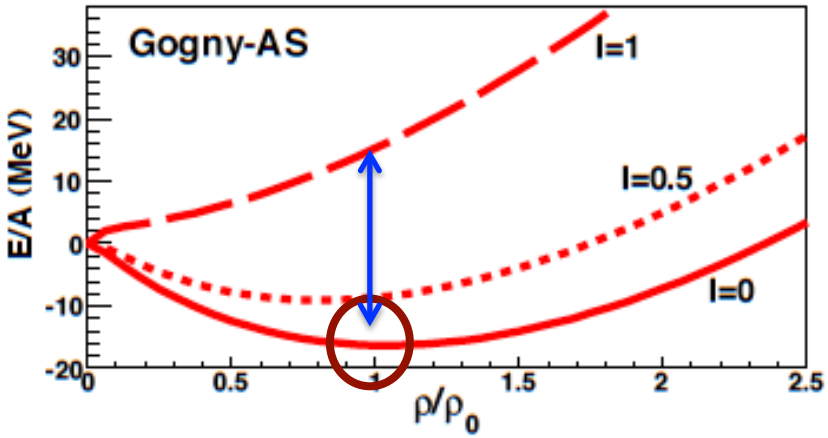
$$E(\rho, I) = E(\rho) + E_{sym}(\rho) I^2$$

$$with \quad I = \frac{\rho_n - \rho_p}{\rho_{Total}} \approx \frac{N-Z}{A}$$

Binding Energy of Symmetric Nuclear Matter

Symmetry Energy Term for Asymmetric Matter





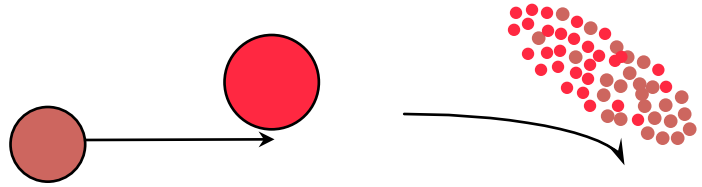
$$E_{sym}(\rho) = E(\rho,1) - E(\rho,0)$$

Transverse Collective Flow

Low beam energy

negative scattering
dominated by the attractive
mean field

High beam energy



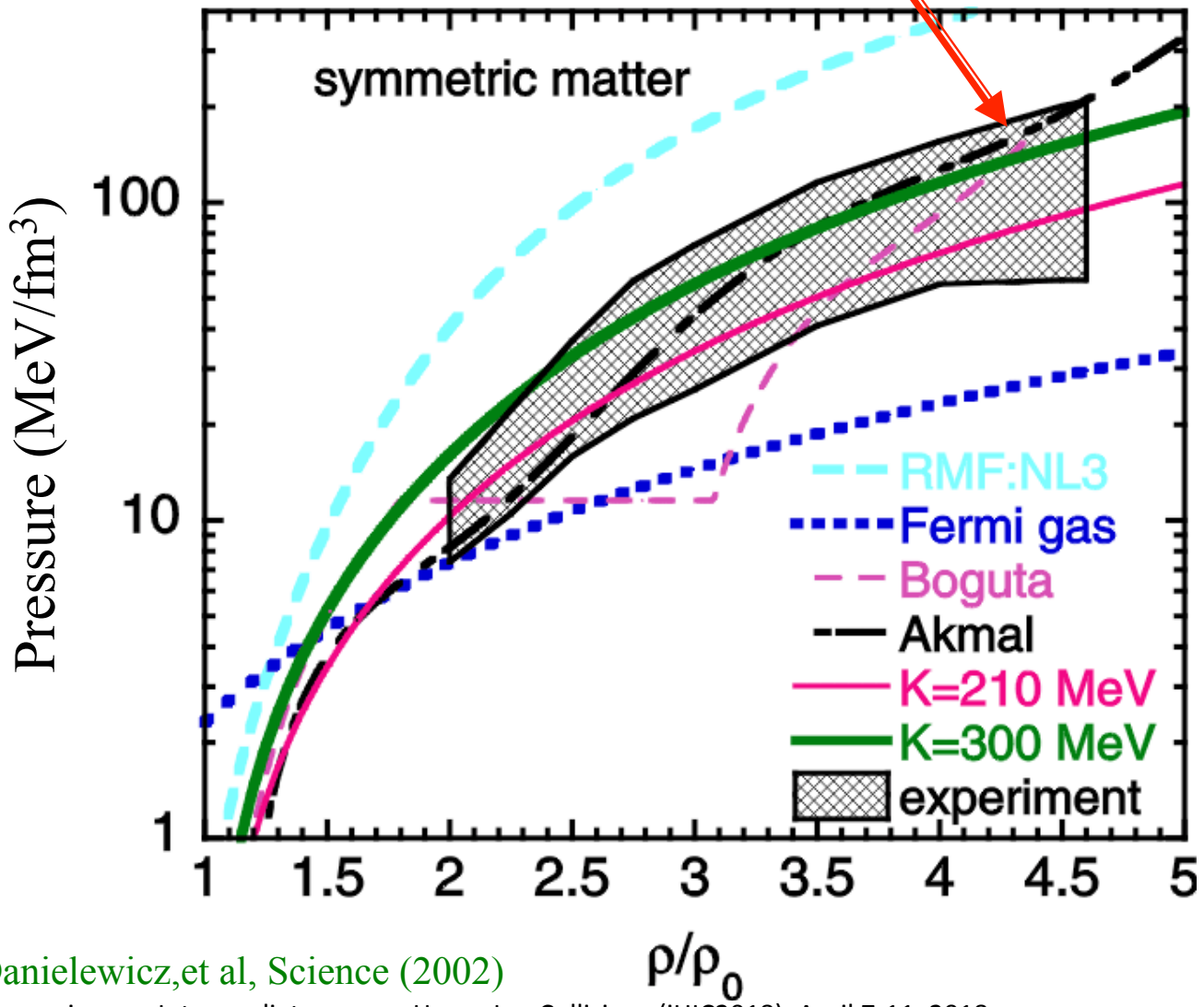
positive scattering
dominated by repulsive
nucleon-nucleon collisions

Constraining EOS from flow measurements

$$E(\rho, \delta) = E(\rho, \delta=0) + E_{sym}(\rho,\delta)\,\delta^2$$

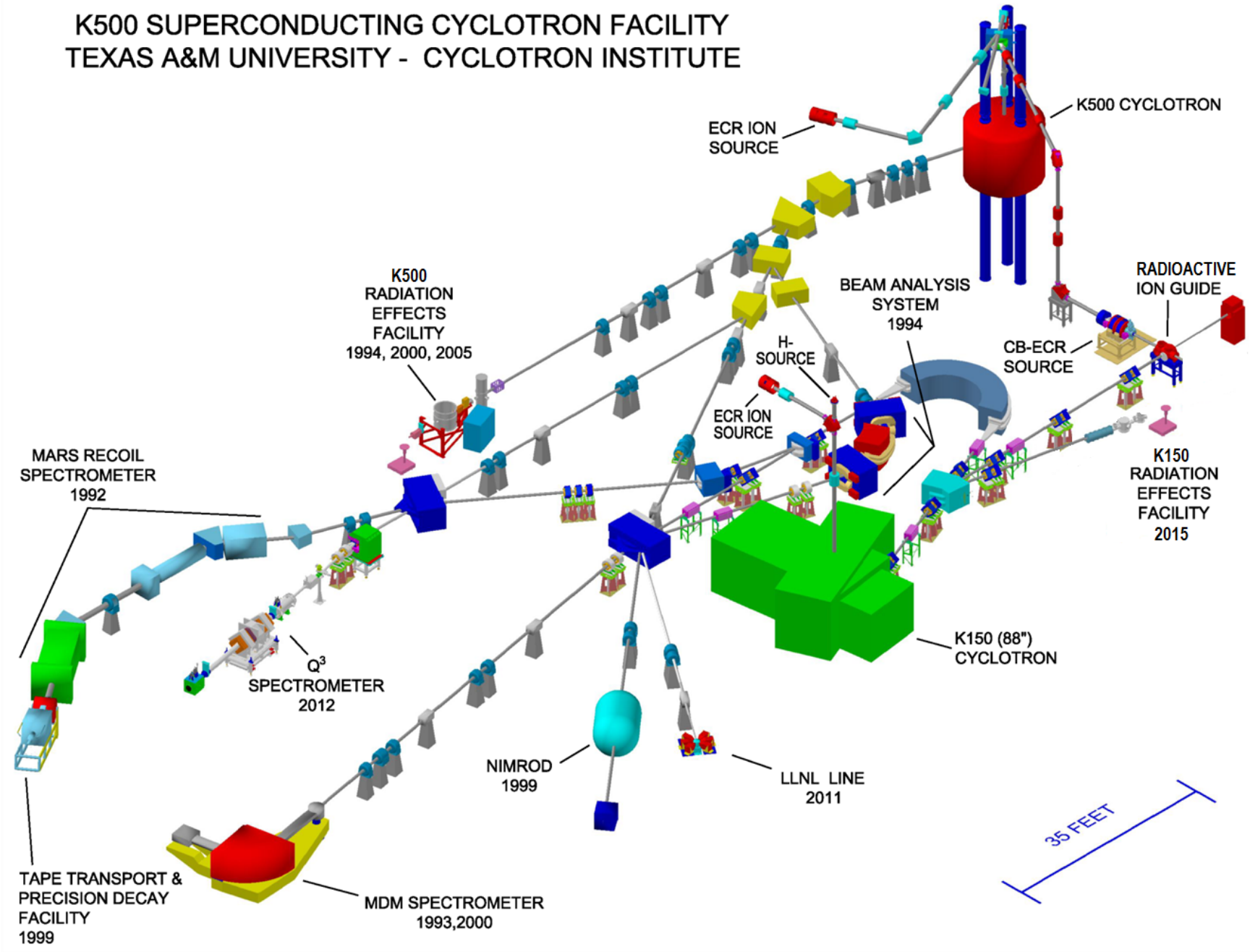
$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

Au+Au flow (E/A~1-8 GeV)



Not well constrained

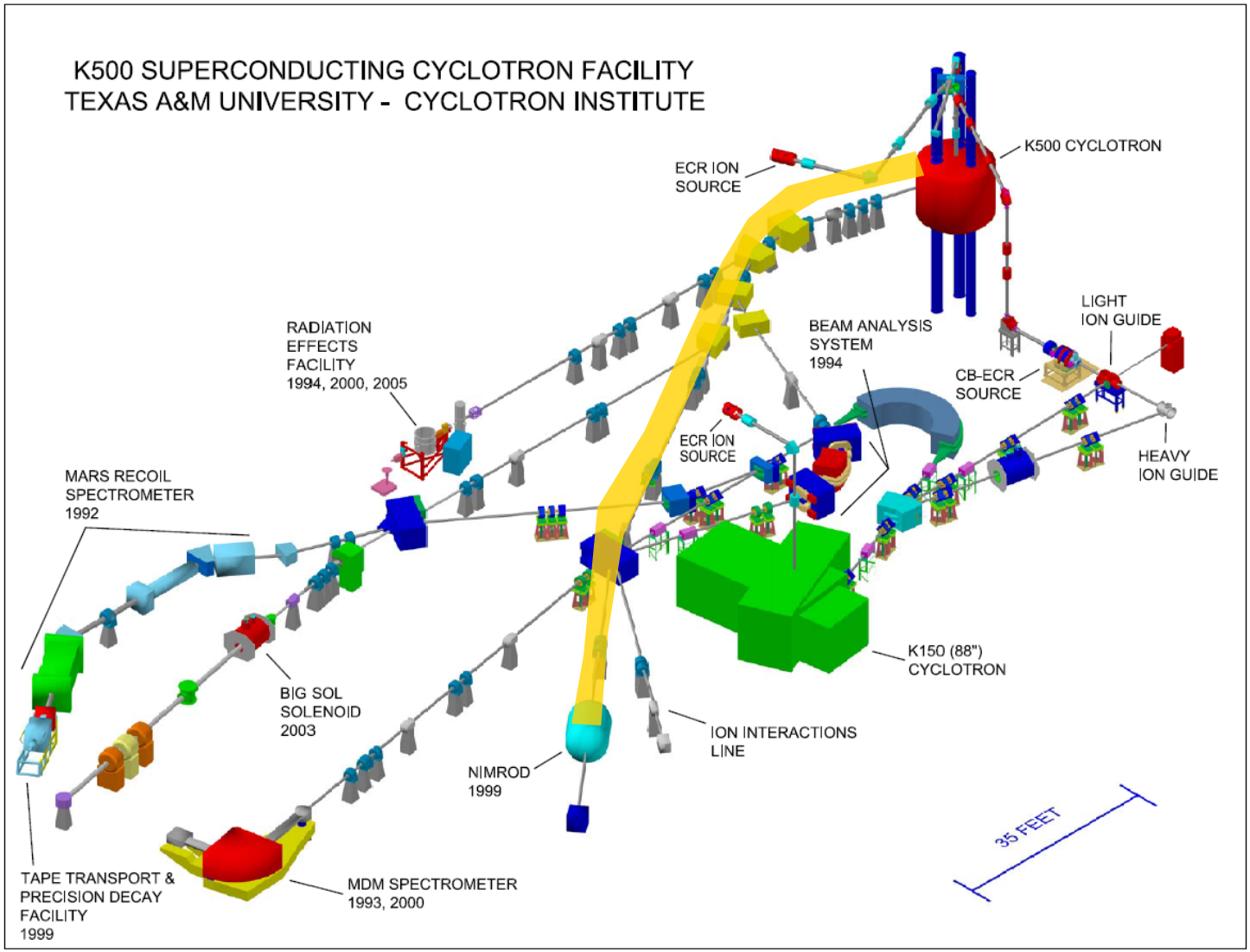
Danielewicz,et al, Science (2002)


K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE
ECR ION SOURCE
K500 CYCLOTRON
K500 RADIATION EFFECTS FACILITY 1994, 2000, 2005
BEAM ANALYSIS SYSTEM 1994
RADIOACTIVE ION GUIDE
H- SOURCE
CB-ECR SOURCE
ECR ION SOURCE
MARS RECOIL SPECTROMETER 1992
K150 RADIATION EFFECTS FACILITY 2015
Q3 SPECTROMETER 2012
K150 (88") CYCLOTRON
NIMROD 1999
LLNL LINE 2011
TAPE TRANSPORT & PRECISION DECAY FACILITY 1999
MDM SPECTROMETER 1993,2000
35 FEET

Experiment

Beam Energy: 35 MeV/nucleon
Reactions: $^{70}Zn+^{70}Zn$, $^{64}Zn+^{64}Zn$, & $^{64}Ni+^{64}Ni$

NIMROD-ISiS Array



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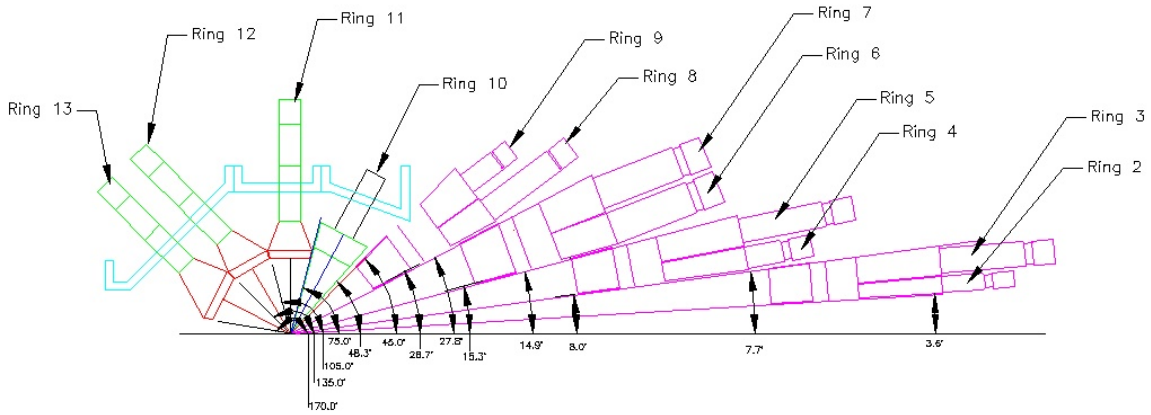
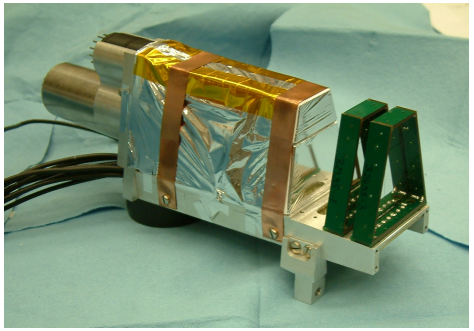
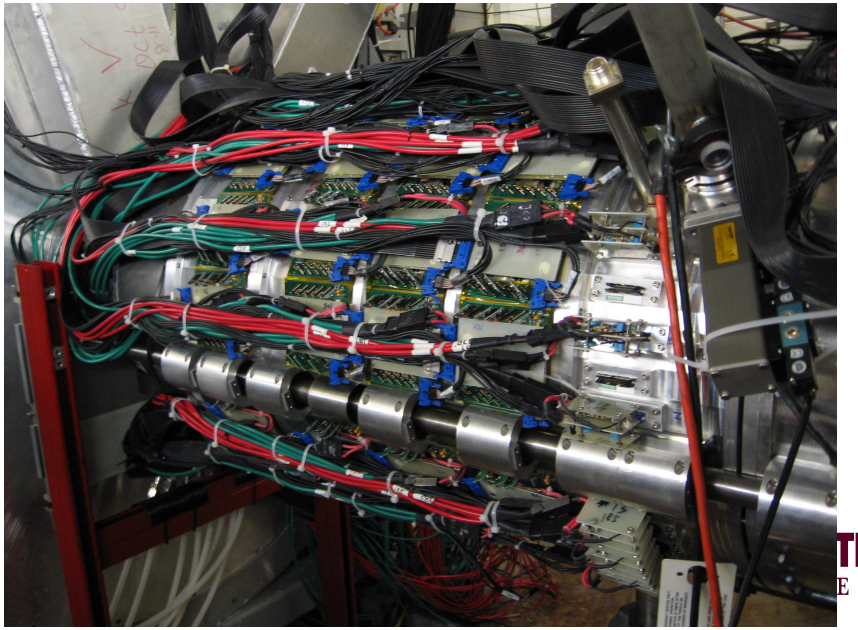
NIMROD - ISiS

- 228 modules
  - Si/CsI
  - Some Si/Si/CsI
  - Ion Chambers
- 14 rings
- 3.6^{o}-167^{o}
- Neutron Ball





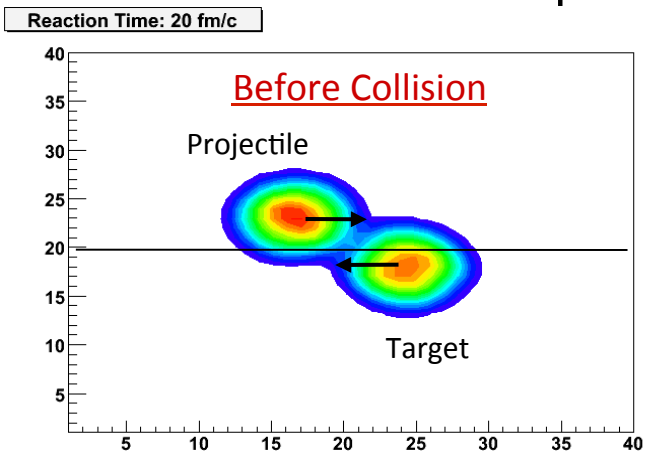


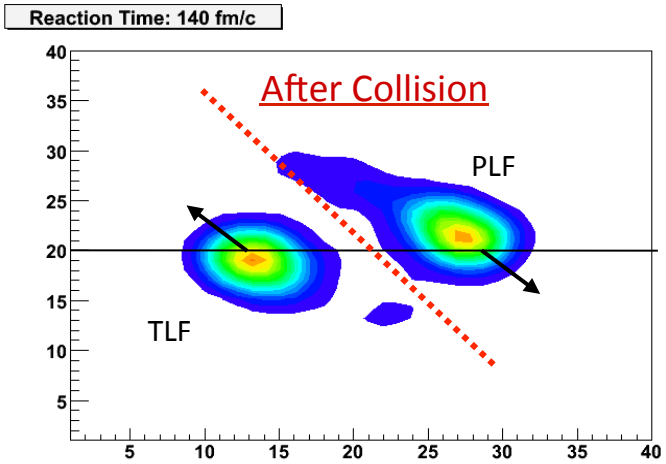
S. Wuenschel et al. NIMA doi:10.1016/j.nima.2009.03.187

Collective Transverse Flow

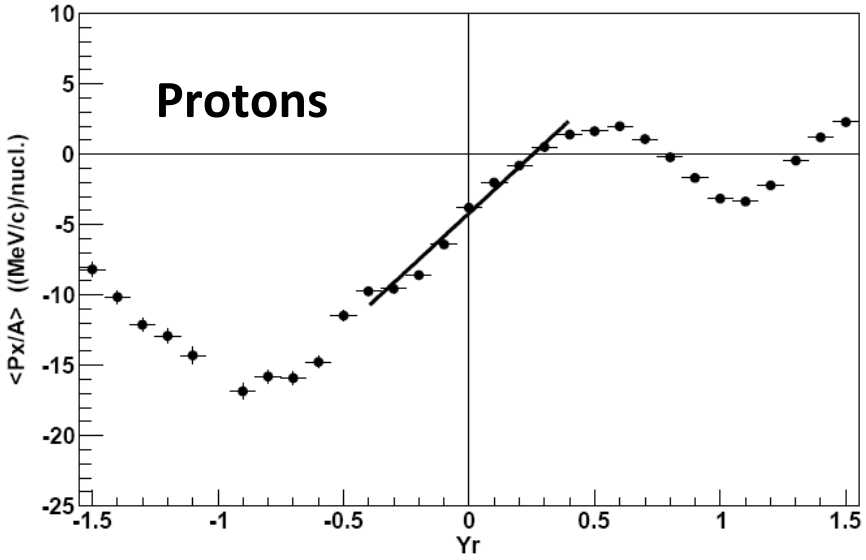
Directed/Transverse/Sideward Flow

Examination of space-momentum correlation of particle emission in the reaction plane.

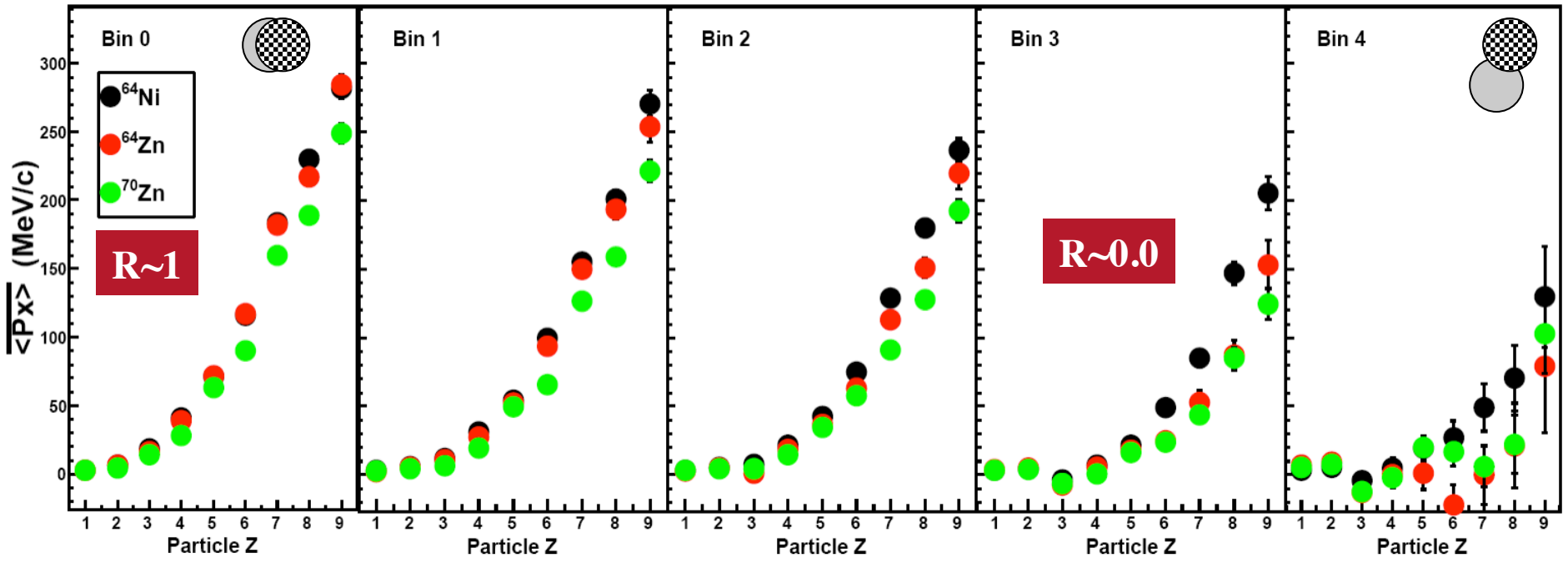




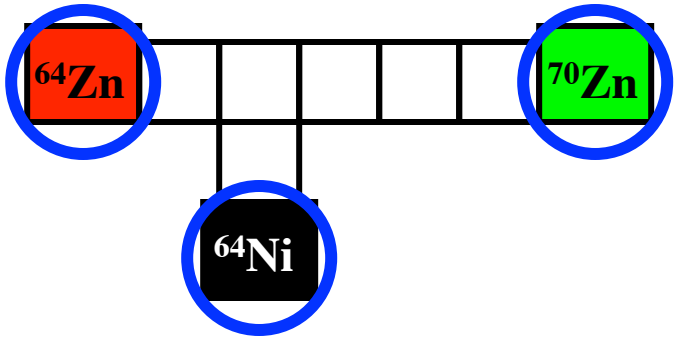
$$F(MeV/c) = \left.\frac{\partial \langle P_x \rangle}{\partial Y_{red}}\right|_{Y=mid-rapidity}$$



IMF Transverse Flow



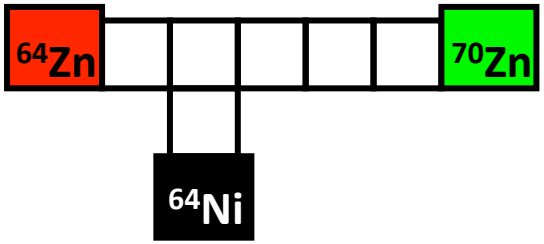
Mass Dependence → *Charge Dependence*

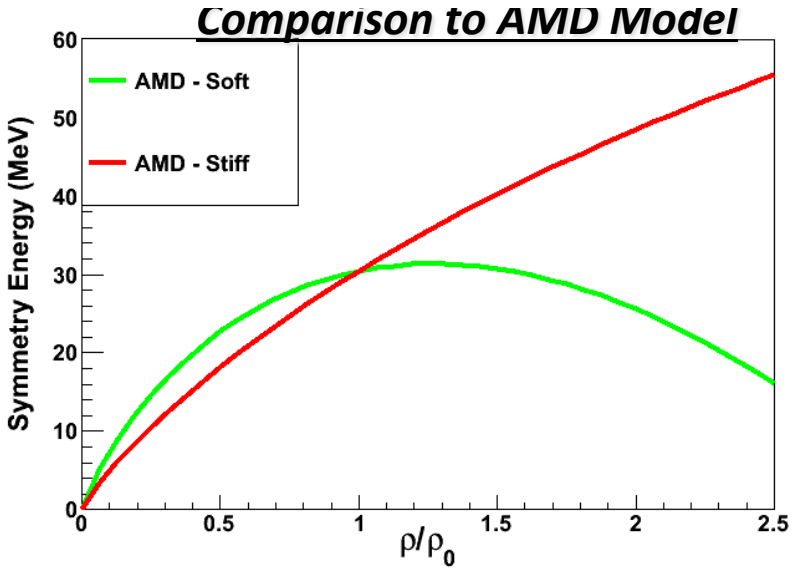


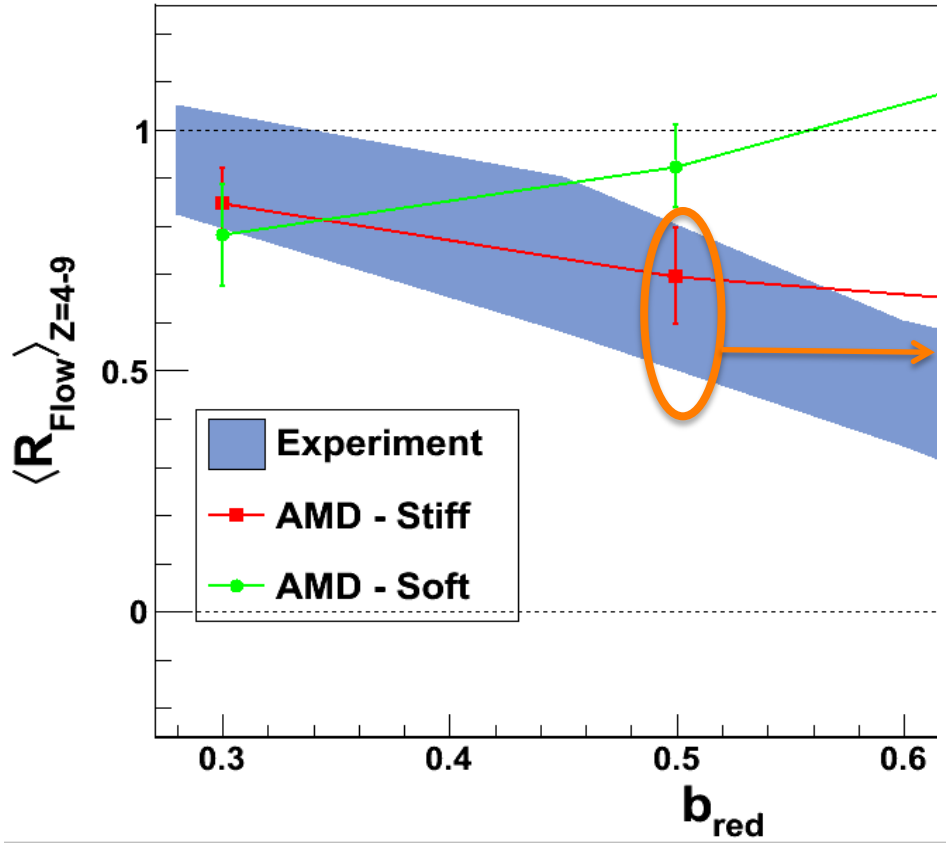
$$R_{Flow} = \frac{\overline{\langle Px/A \rangle}_{^{64}Zn} - \overline{\langle Px/A \rangle}_{^{70}Zn}}{\overline{\langle Px/A \rangle}_{^{64}Ni} - \overline{\langle Px/A \rangle}_{^{70}Zn}}$$

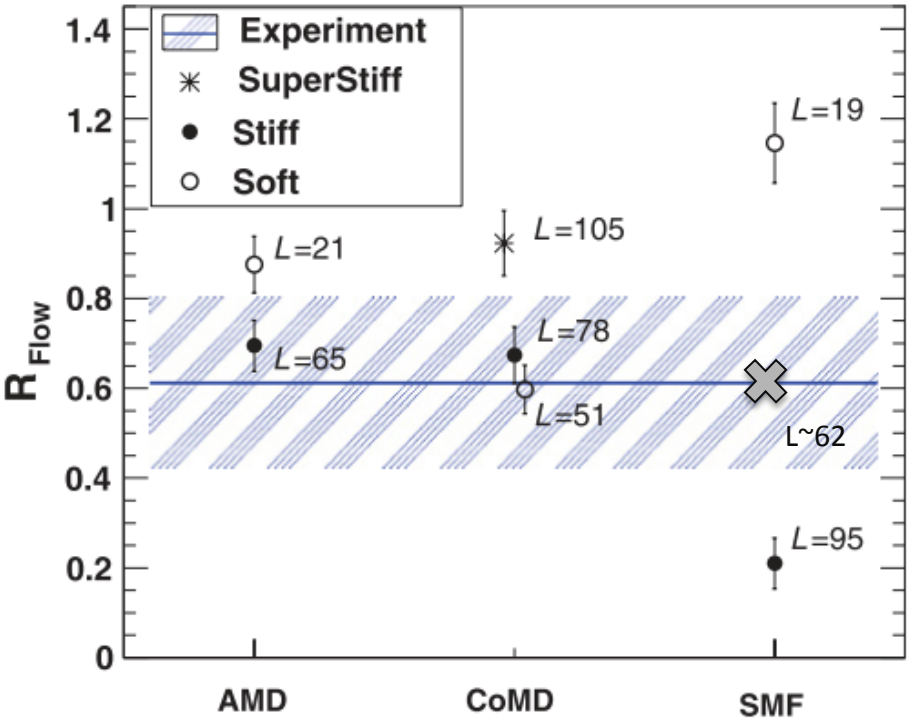
IMF Transverse Flow

$$R_{Flow} = \frac{\overline{\langle Px/A \rangle_{^{64}Zn}} - \overline{\langle Px/A \rangle_{^{70}Zn}}}{\overline{\langle Px/A \rangle_{^{64}Ni}} - \overline{\langle Px/A \rangle_{^{70}Zn}}}$$



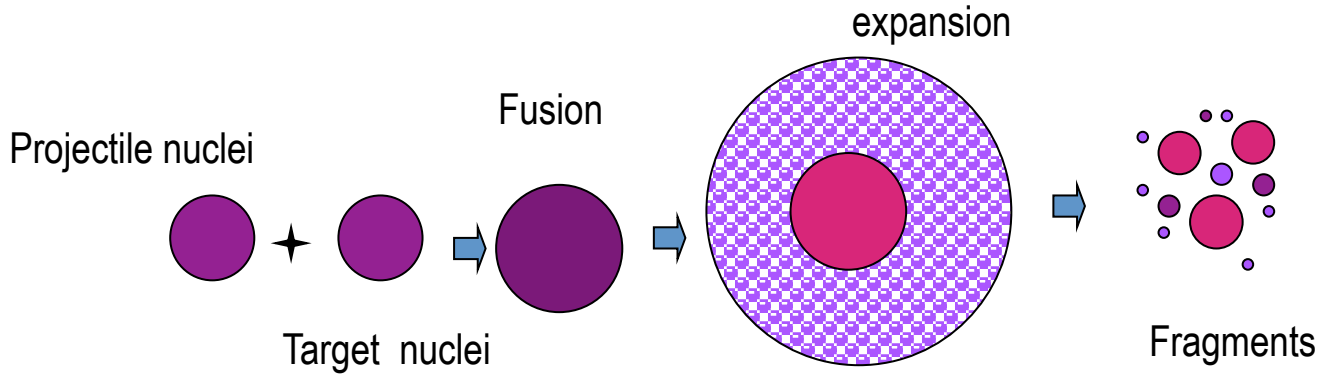


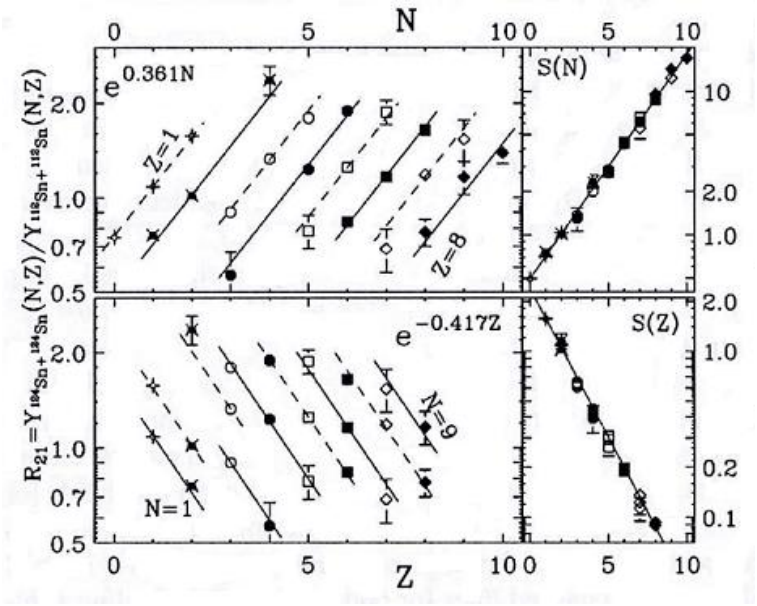




Kohley, PRC85(2012)

Studying density dependence of symmetry energy : Multifragmentation





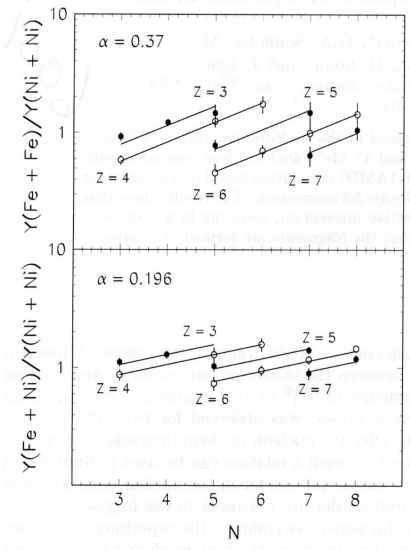
$$\alpha = \frac{4C_{sym}}{T}\left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right)$$

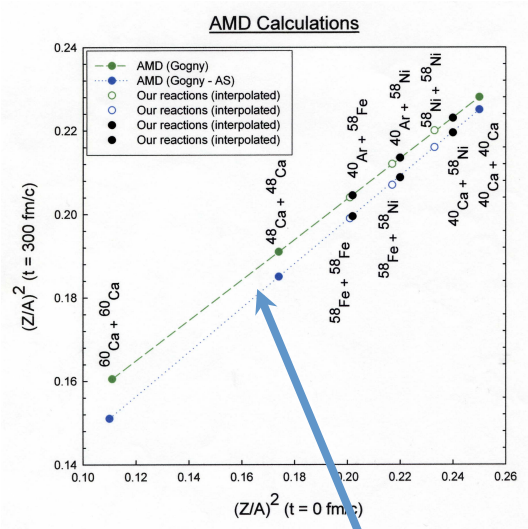
α – *Scaling parameter*

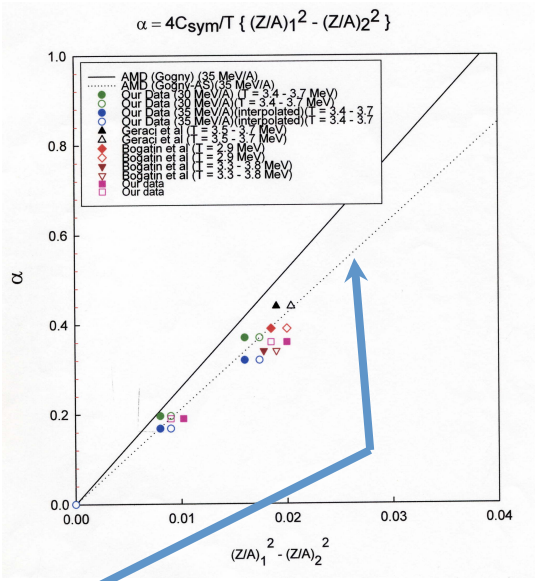
C_{sym} – *Symmetry energy*

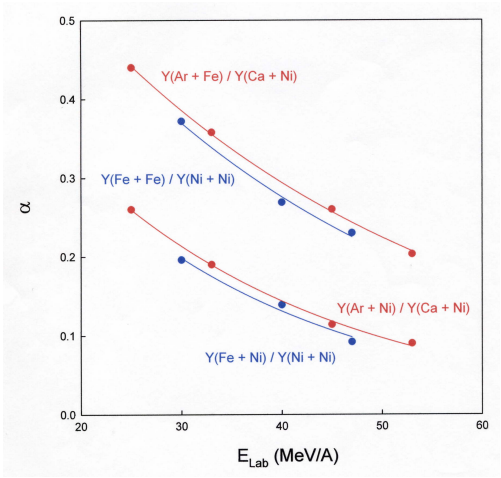
M.B. Tsang et al, Phys. Rev. Lett 68 (2001) 5023

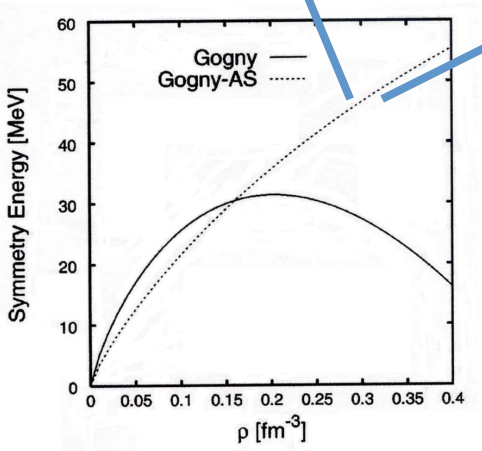
Symmetry energy and the scaling parameter α







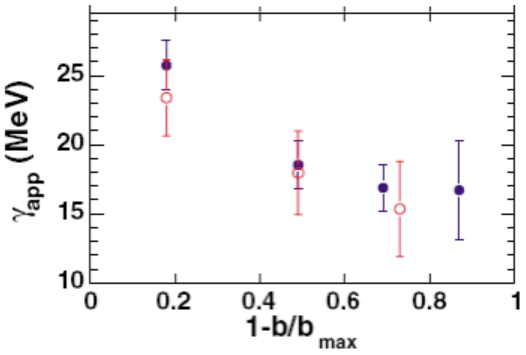




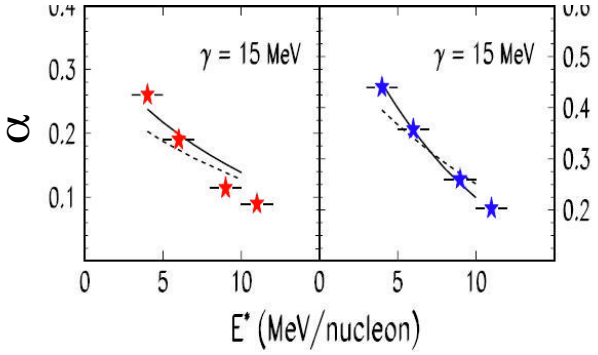
$$\alpha T = 4C_{sym}\left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right)$$

D. V. Shetty et al, Phys. Rev. C 70 (2004) 011601(R)

Decrease in Asymmetry energy (Expt. Observation)



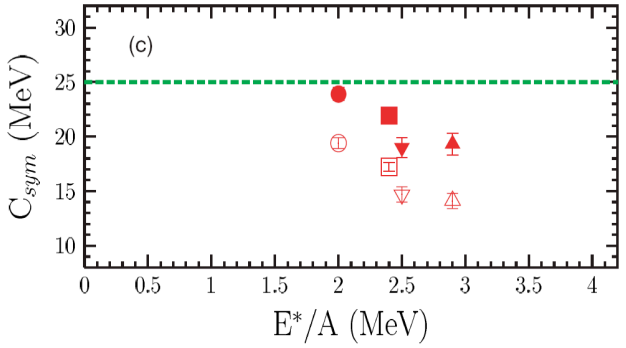
A. Le Fevre et al., PRL 94 (2005) 162701

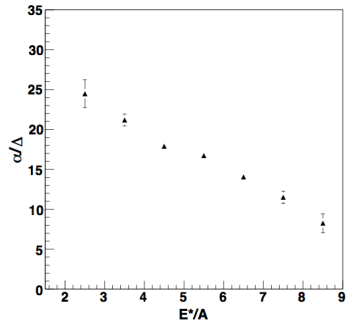


J. Iglio et al., PRC 74 (2006) 024605

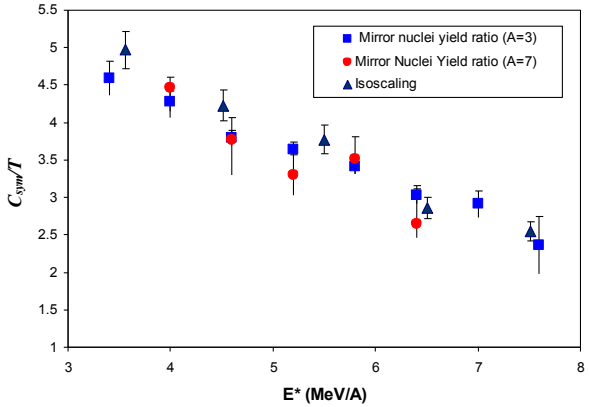
G.A. Souliotis et al., PRC 73 (2006) 024606

G.A. Souliotis et al., PRC 75 (2007) 011601

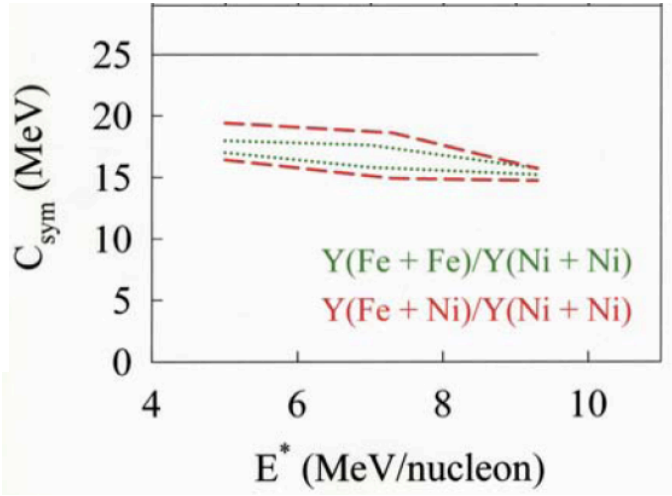




S. Wuenschel, Phys. Rev. C 79, 061602(R) (2009)



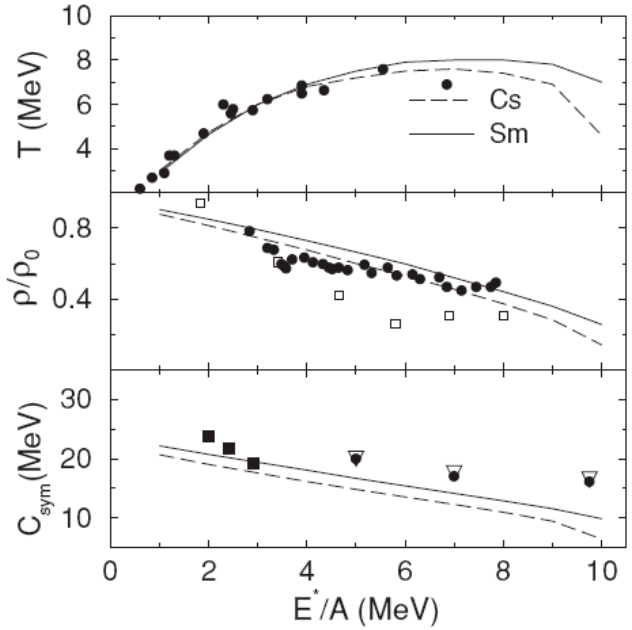
R. Tripathi, Phys. Rev. C **83**, 054609 (2011).
Int. J. Mod. Phys. E 21, 1250019 (2012)



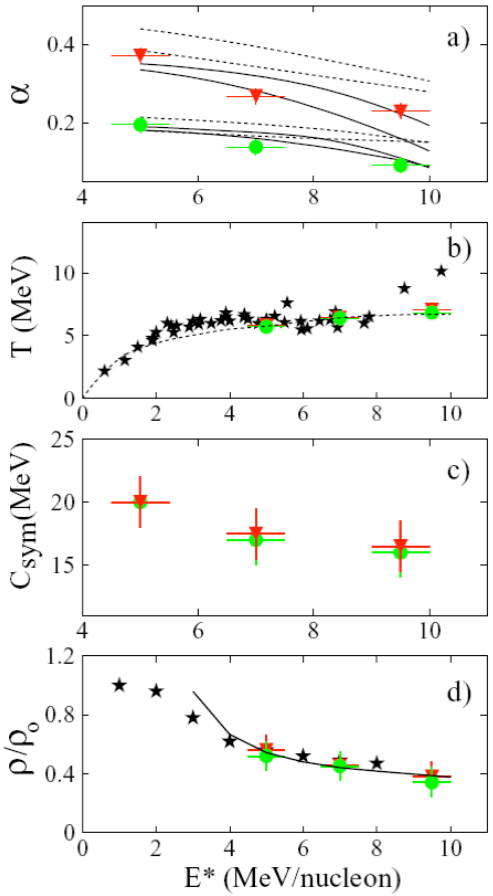
D.V. Shetty et al., PRC 74 (2005) 024602

Decrease in E_{sym} related to thermal expansion

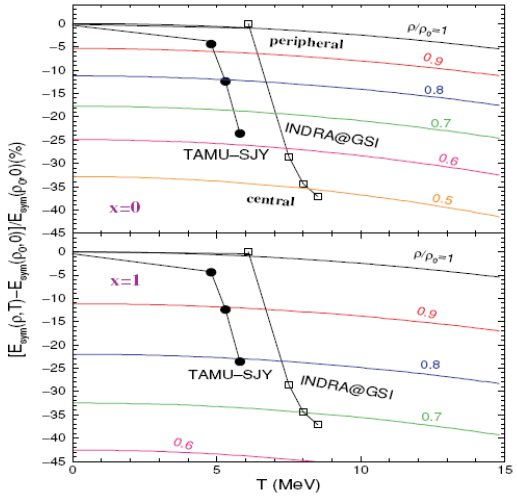
- Finite T Thomas-Fermi
  Seyler Blanchard interaction



S.K. Samaddar et al., PRC 76 (2007) 041602



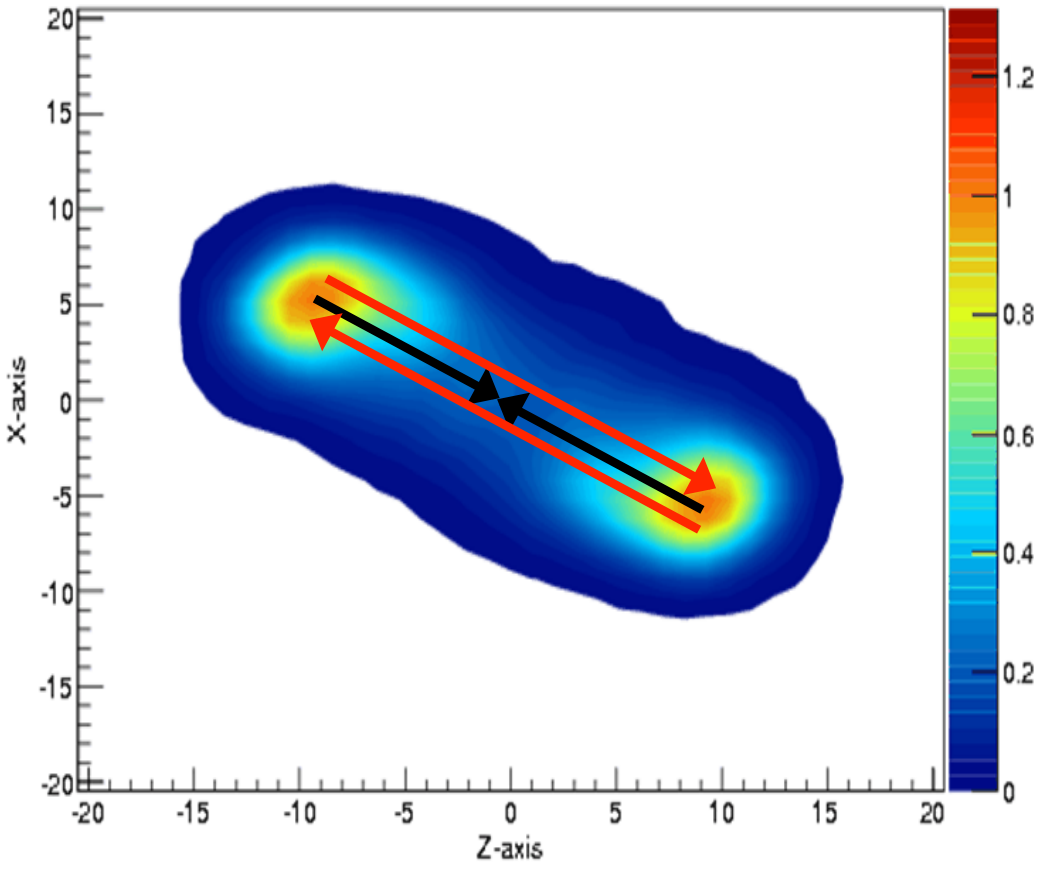
D.V. Shetty et al., PRC 76 (2007) 024606



B.A. Li et al., PRC 74 (2006) 034610

Isospin Transport

iBUU ^{70}Zn + ^{64}Zn b = 7 fm collision: density contour plots in XZ plane



$$D_q^\rho = ct\left(\frac{\partial \mu_q}{\partial \rho}\right)_{I,T}$$

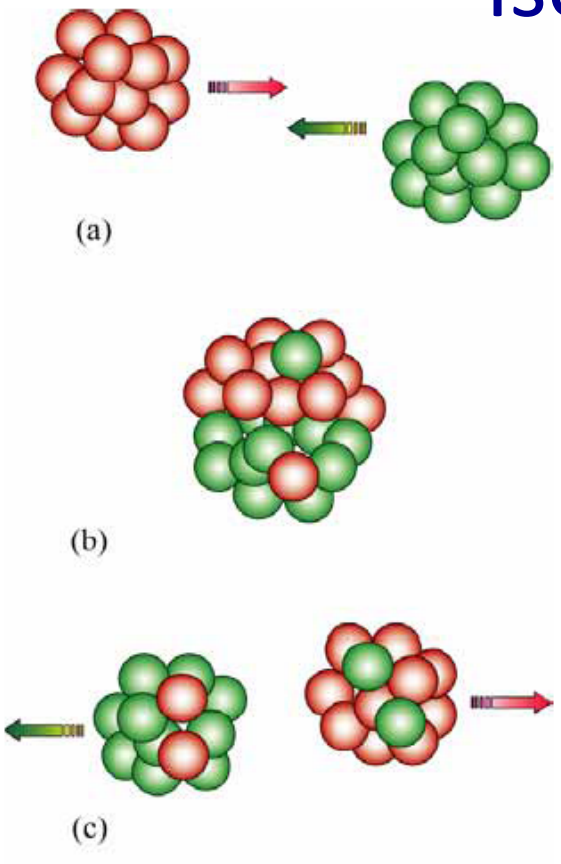
$$D_q^I = -ct\left(\frac{\partial \mu_q}{\partial I}\right)_{\rho,T}$$

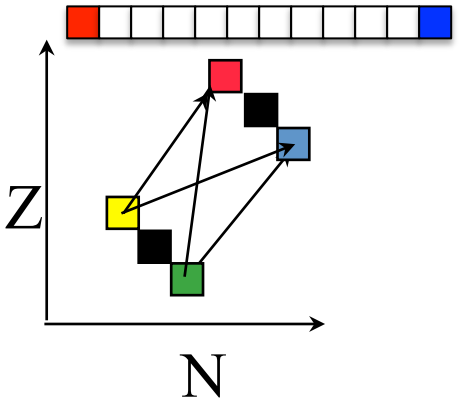
$$(q = n,\ p)$$

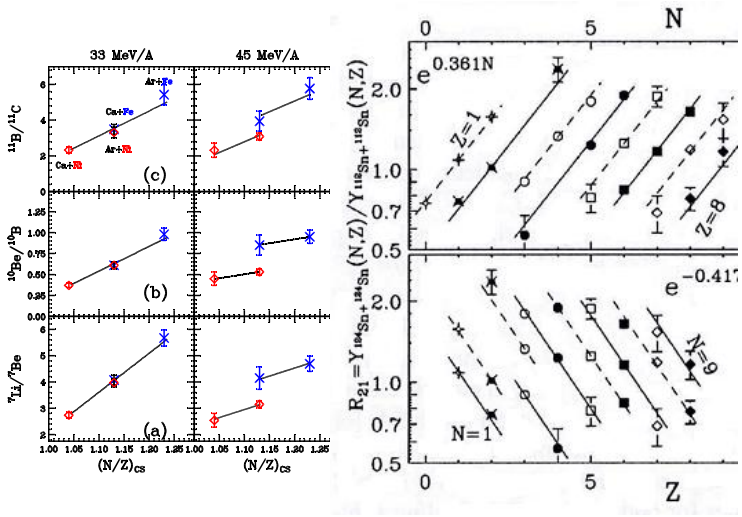
Drift (total nucleon density dependent)

Diffusion (isospin concentration dependent)

Isospin Equilibration / Diffusion







Non equilibration with Isotopically resolved fragments / ratios: Yennello, PLB321(94), Johnston, PLB 371 (1996),B.A. Li, PRC52(1995)

Isospin Tracer Method
Rami, et al, PRL84 (2000)

$$R_i = \frac{2\delta_i - \delta_{NR} - \delta_{NP}}{\delta_{NR} - \delta_{NP}}$$

where $\delta_i = I_i = \frac{(N_i - Z_i)}{(N_i + Z_i)}$

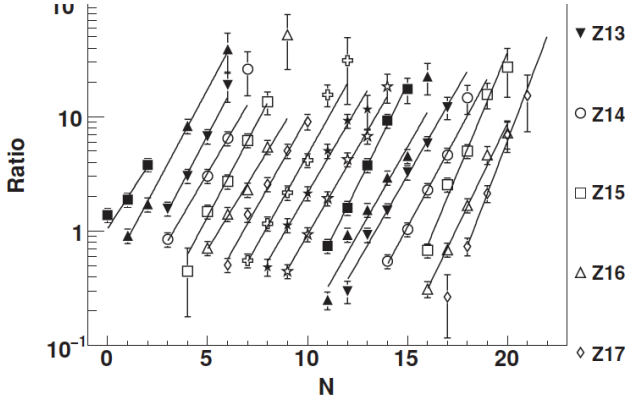
Diffusion coefficient connected to symmetry potential
L Shi & P Danielewicz, PRC68 (2003)

Measured isospin diffusion in Sn+Sn
Tsang, PRL92 (2004)

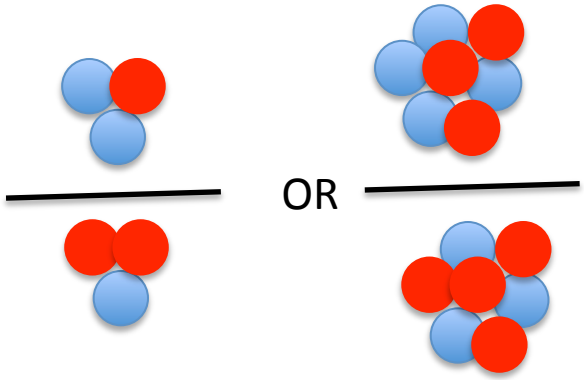
Multiple systems / multiple observables

System Pairs	Systems
Zn systems	$^{70}Zn+^{70}Zn$ $^{70}Zn+^{64}Zn$ $^{64}Zn+^{70}Zn$ $^{64}Zn+^{64}Zn$
A=64 systems	$^{64}Zn+^{64}Zn$ $^{64}Zn+^{64}Ni$ $^{64}Ni+^{64}Zn$ $^{64}Ni+^{64}Ni$

Isoscaling

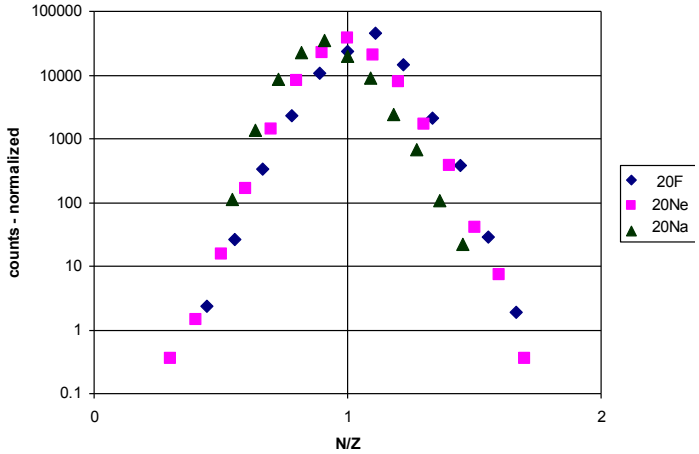


Isobaric ratios

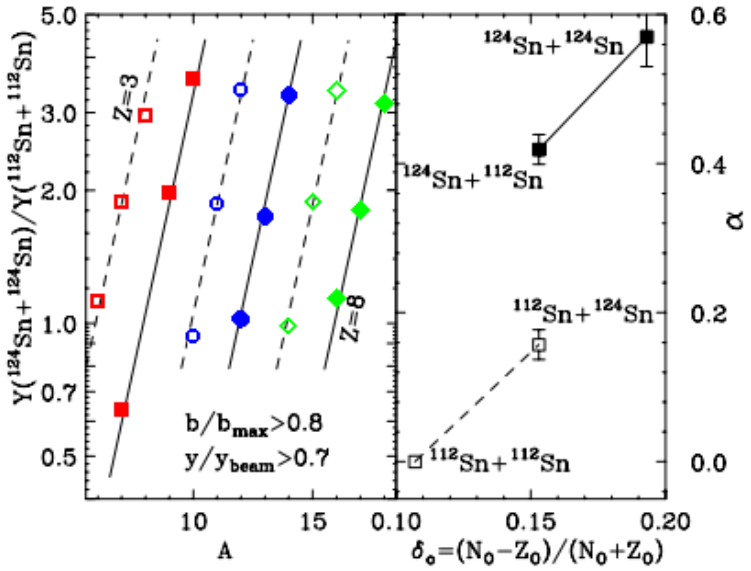


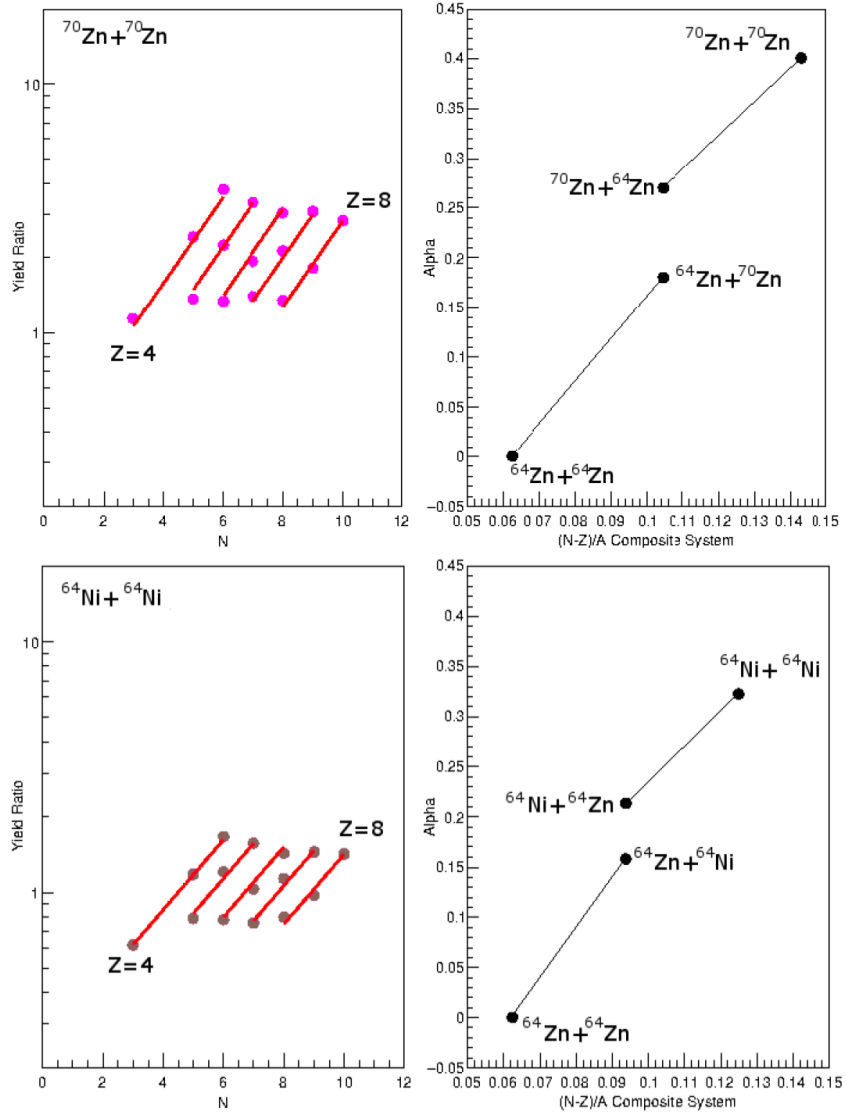
QP_{ms}

$m_s = (N-Z)/A$



Partial Equliibration





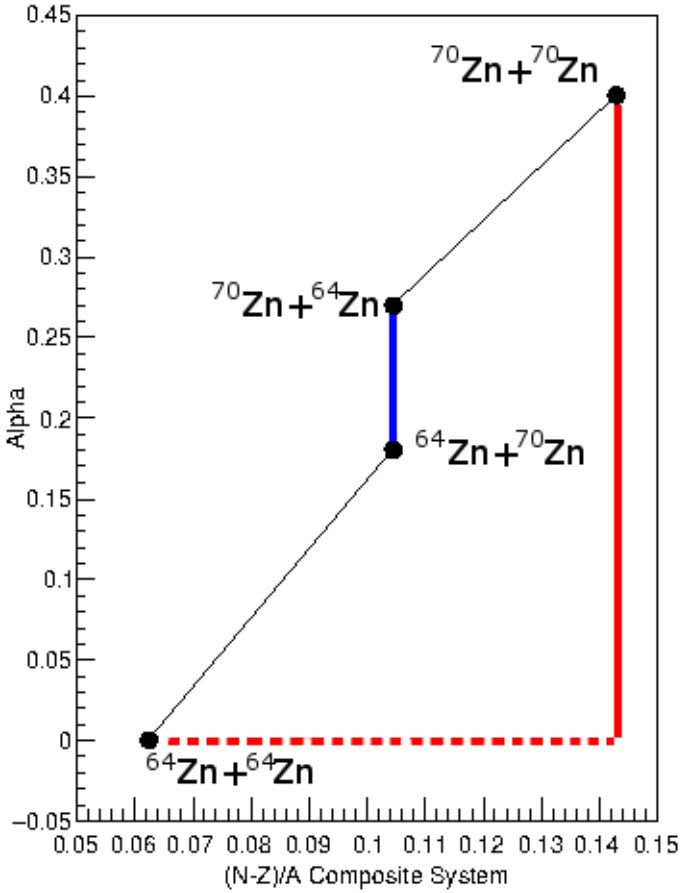
Consistent with the work of Tsang (PRL92 (2004)) in seeing partial equilibration and Johnston (PLB 371 (1996)) and Li (PRC52(1995)) in the effect of beam energy on equilibration

Equlibration calculation

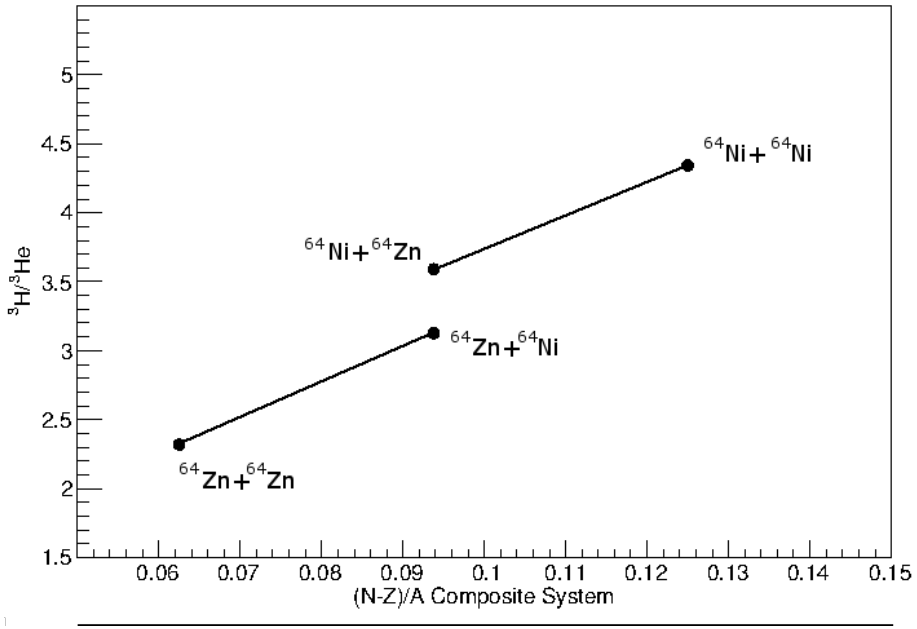
$$\text{Percent Equilibration} = \frac{(x_{NR} - x_{NP}) - (x_{xS1} - x_{xS2})}{x_{NR} - x_{NP}} * 100\%$$

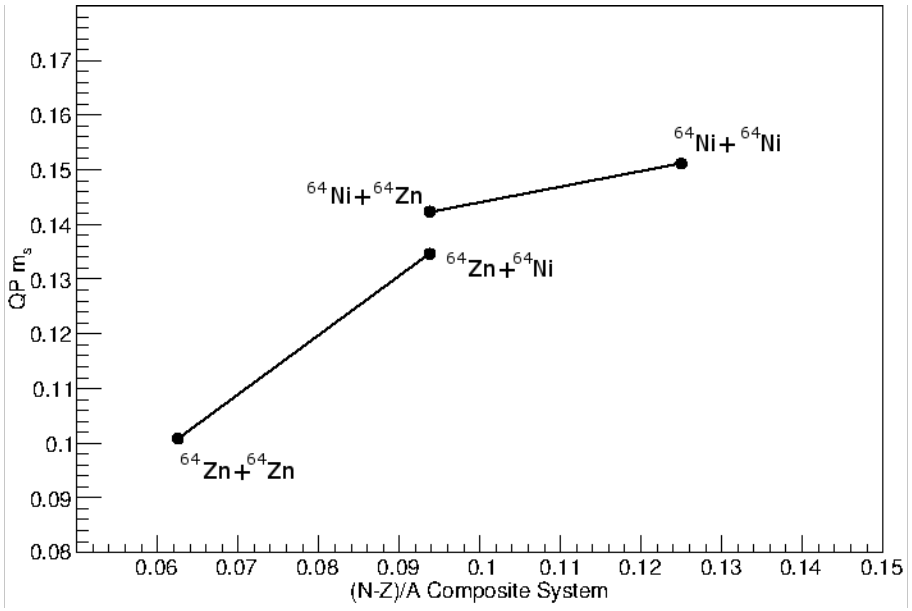
» Measures separation between cross systems relative to separation between symmetric systems

77 ± 5 % equilibration



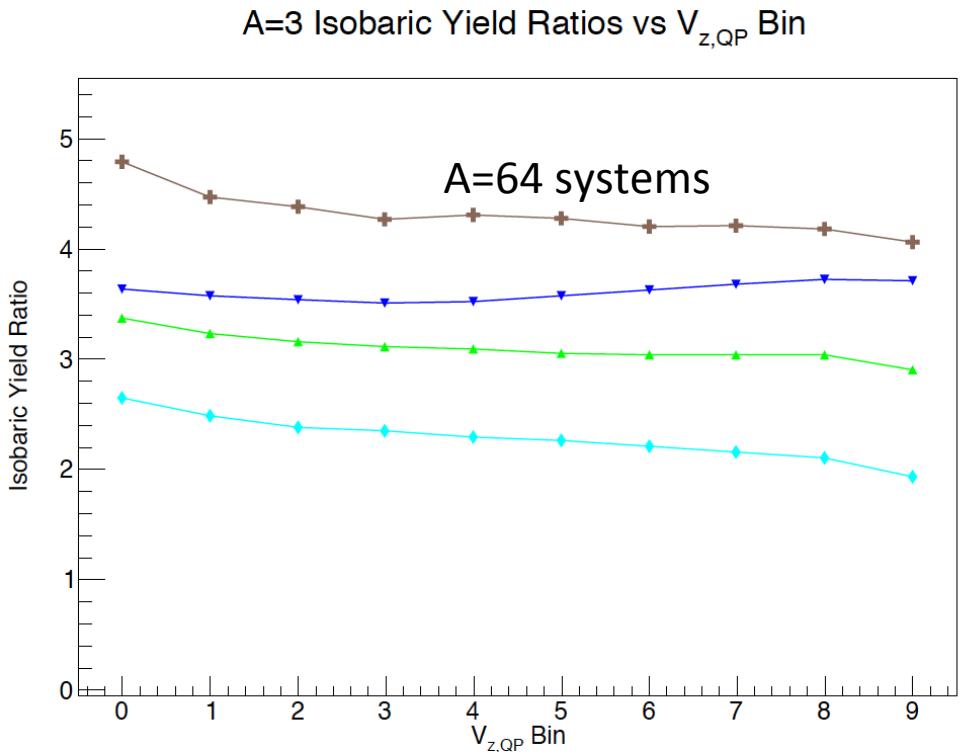
Method from Keksis, *Phys. Rev. C* ***81****, 054602 (2010).*

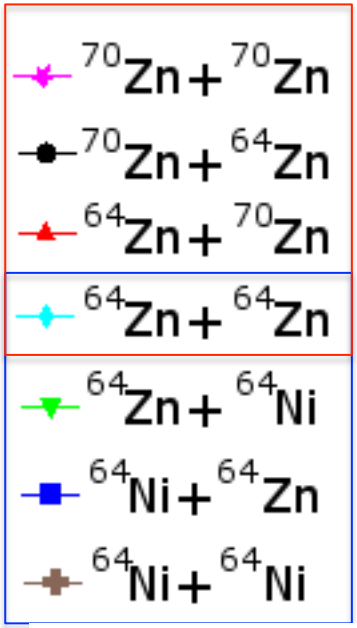


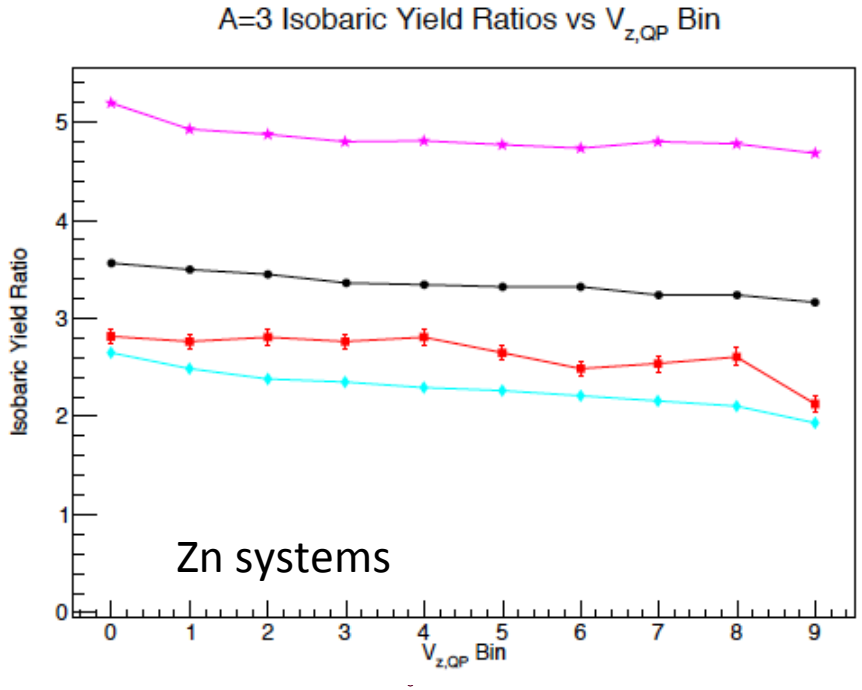


Equilibration observable	35 MeV/nucleon $^{70,64}Zn+^{70,64}Zn$	35 MeV/nucleon $^{64}Zn,Ni+^{64}Zn,Ni$	50 MeV/nucleon $^{124,112}Sn+^{124,112}Sn$ [20]
Isoscaling α (Z=4-8)		83±5%	
Isoscaling α (Z=4-14)		85±7%	
$^{3}H/^{3}He$ ratio		77±4%	
QP m_s		85±5%	

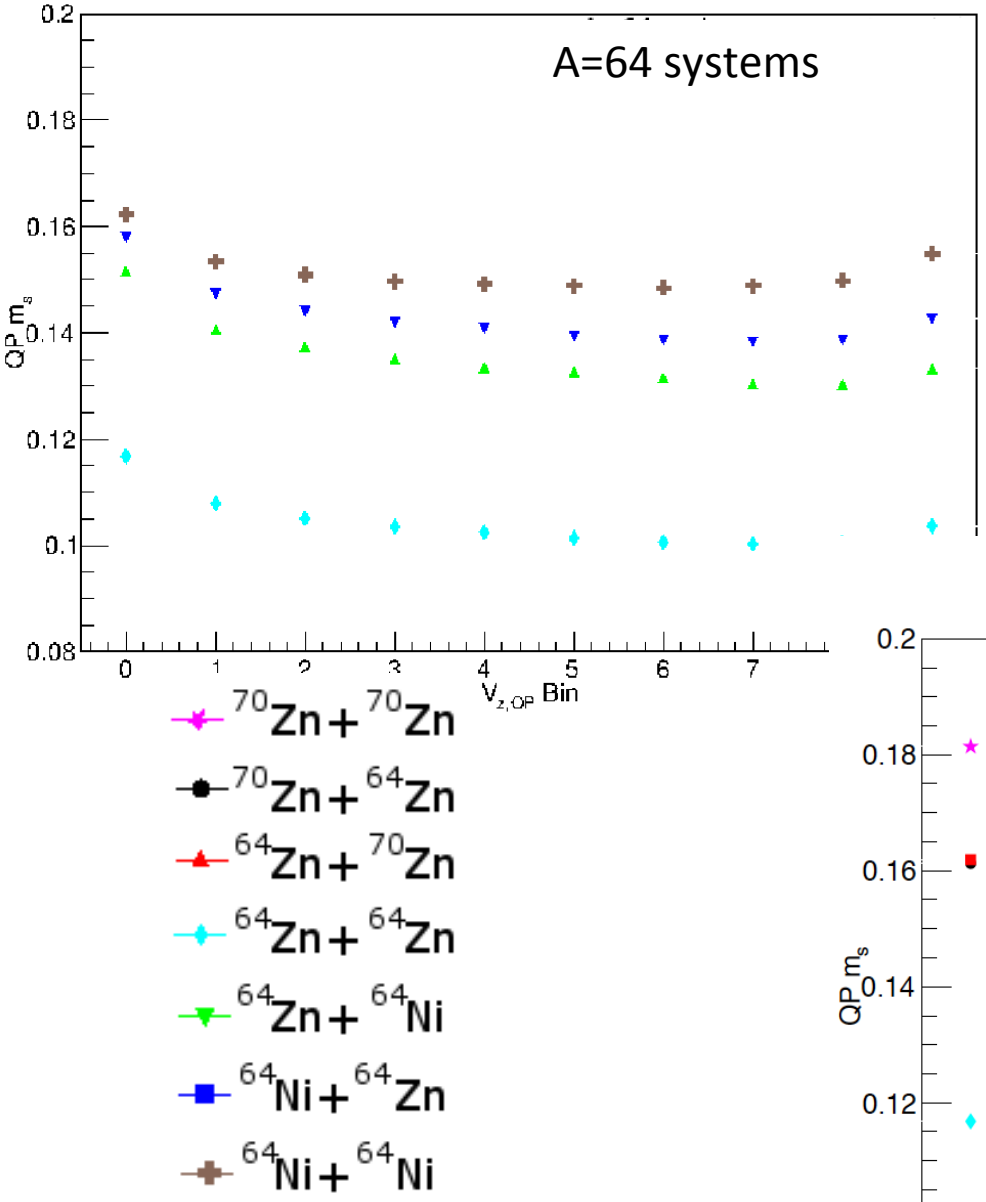
Impact parameter dependence in the data



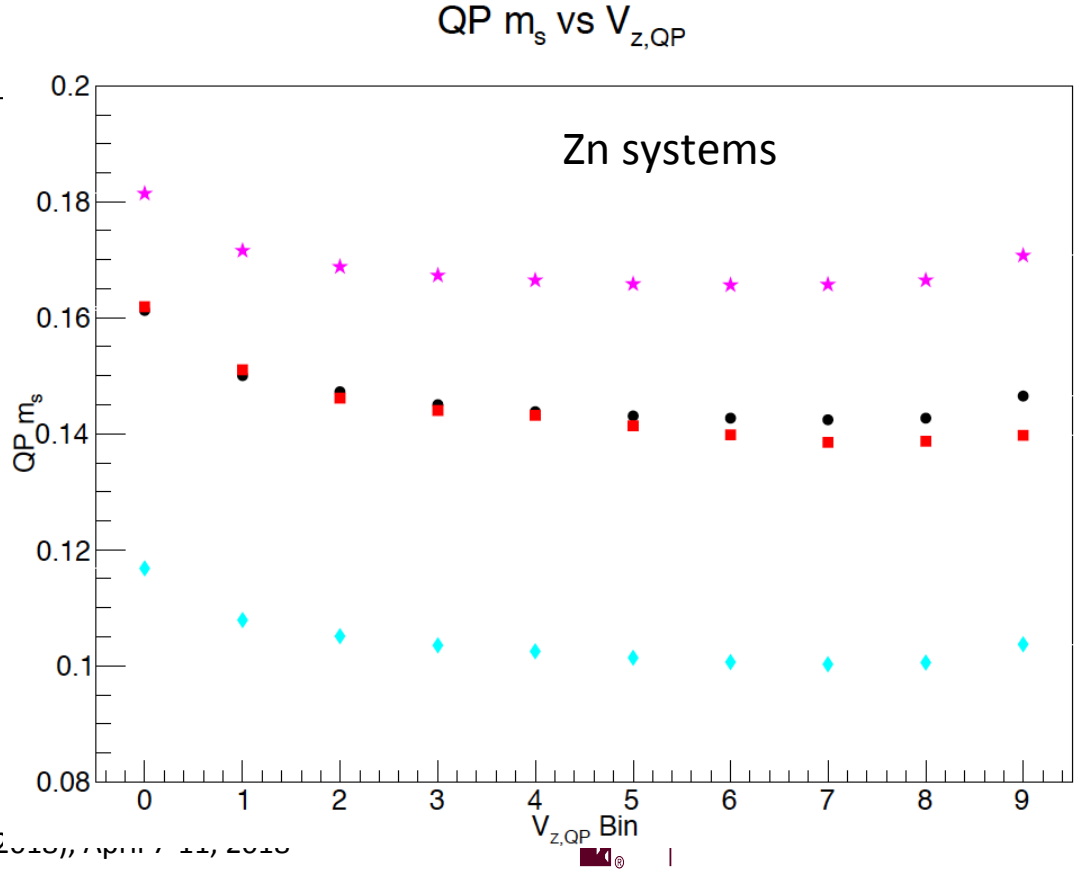




QP_{ms}

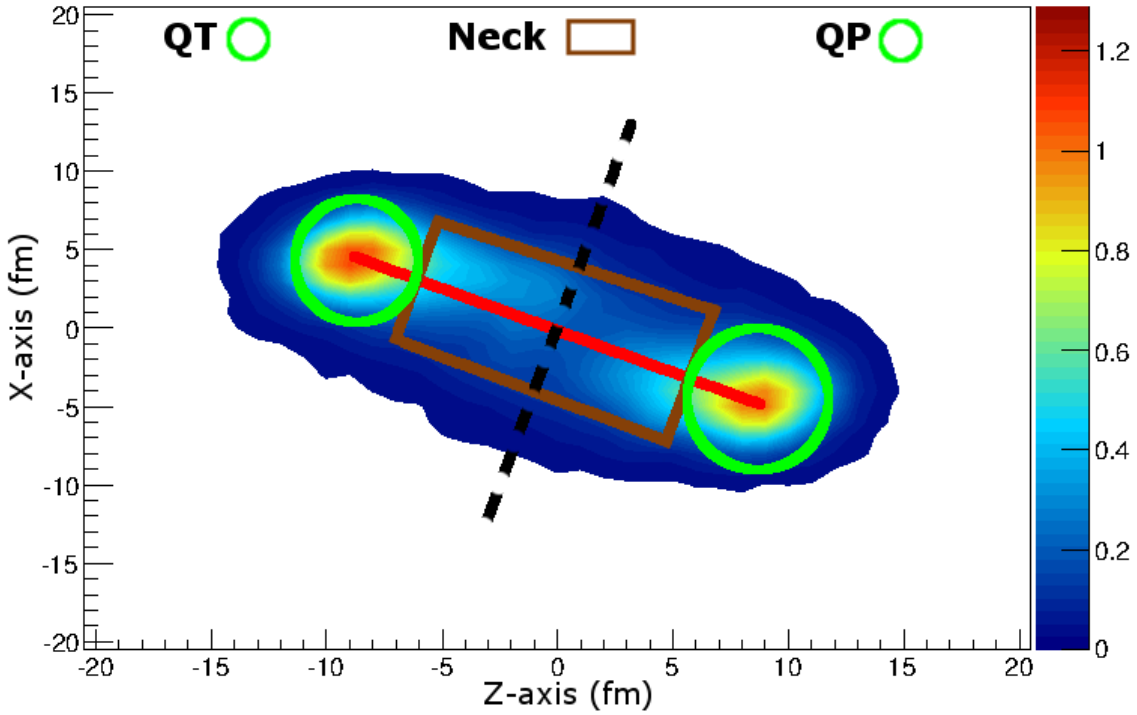


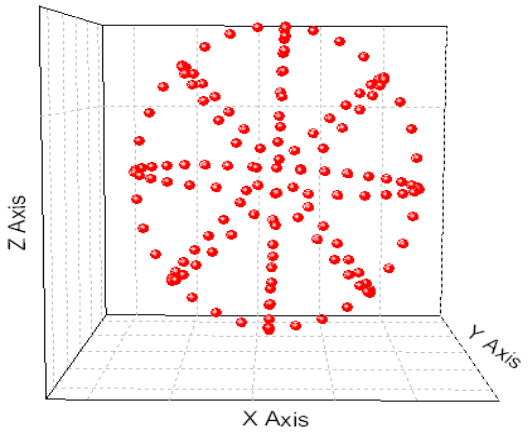
Zn systems show much more equilibration then A=64 systems



Theoretical calculations

- Isospin-dependent Boltzmann-Uehling-Uhlenbeck (iBUU) transport code
  - Momentum dependent interaction
  - Mean-field model using test-particles
  - Developed method of looking at properties of the hot QP
    - » This allows us access to conditions and effects right after transport occurs



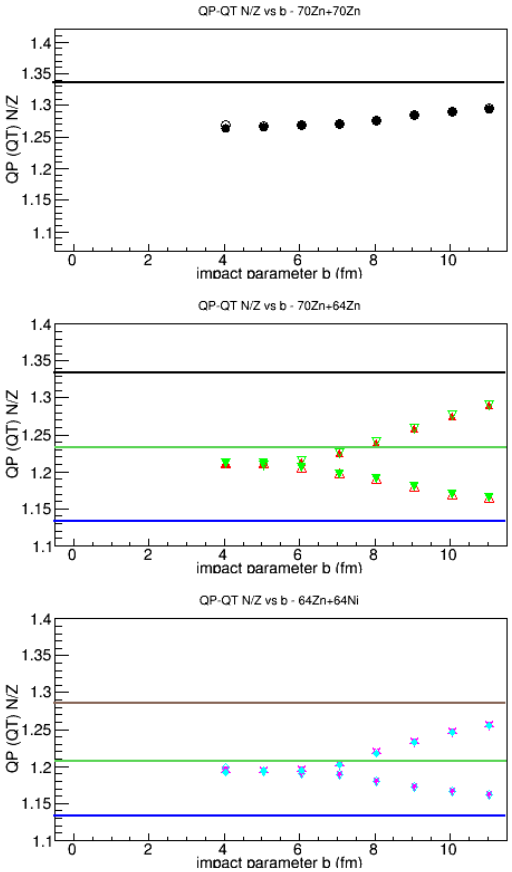


The N/Z of the QP and the amount of equilibration depends on the symmetry energy

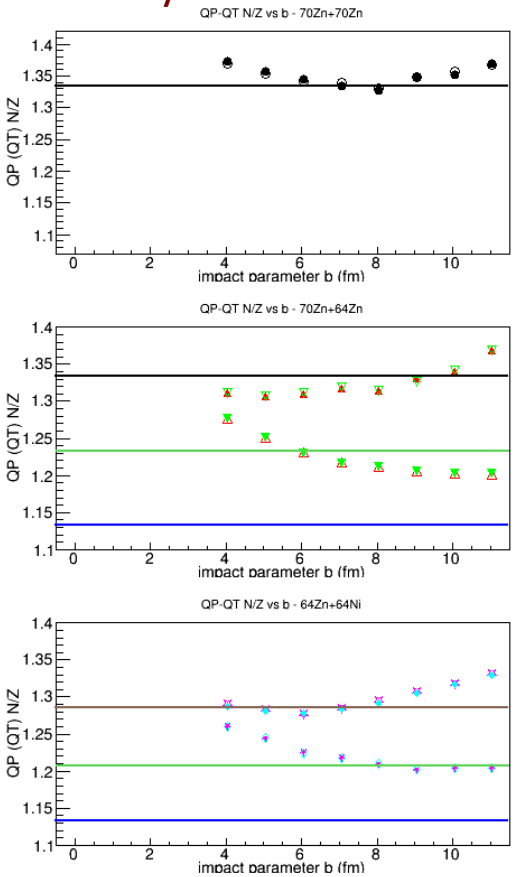
$^{70}Zn + {}^{70}Zn$
$^{70}Zn + {}^{64}Zn$
$^{64}Zn + {}^{70}Zn$
$^{64}Zn + {}^{64}Zn$
$^{64}Zn + {}^{64}Ni$
$^{64}Ni + {}^{64}Zn$
$^{64}Ni + {}^{64}Ni$

Lines are N/Z for the Proj, Tgt and composite system

"asy-soft" x=1



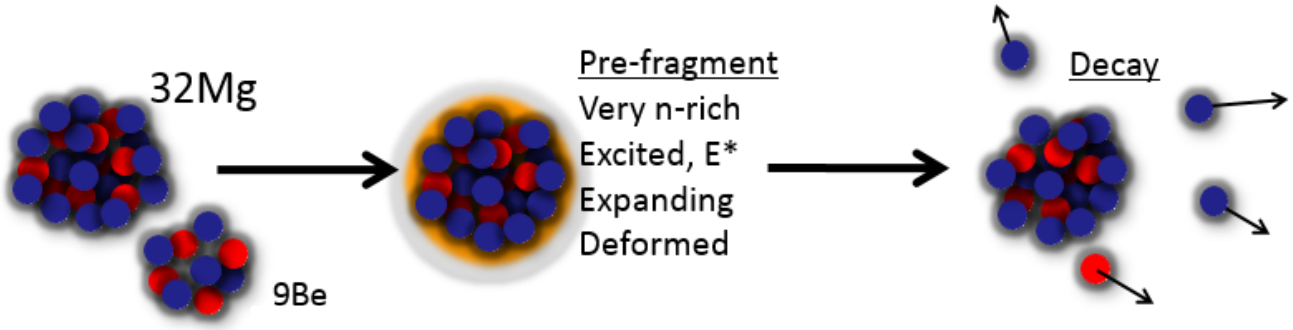
"asy-stiff" x=-2



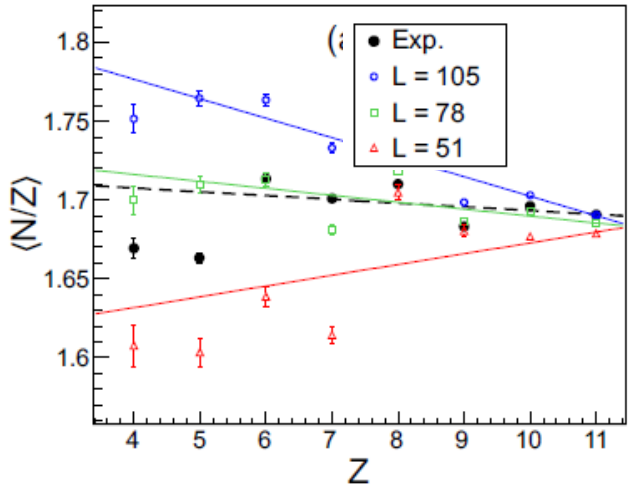
L. May , PhD 2015

Detect PLF directly

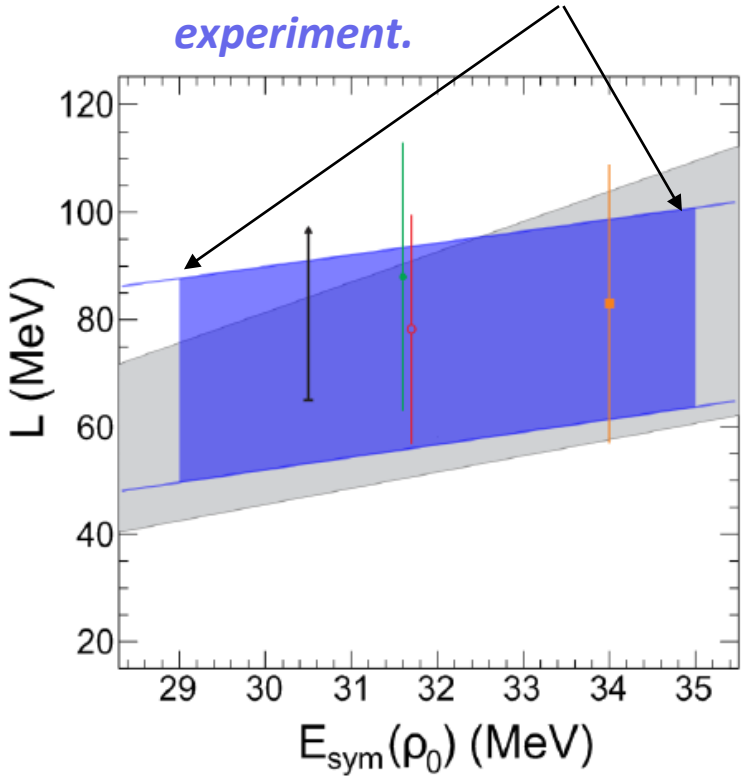
Measure neutrons and N/Z of PLF using MoNA-LISA-Sweeper setup



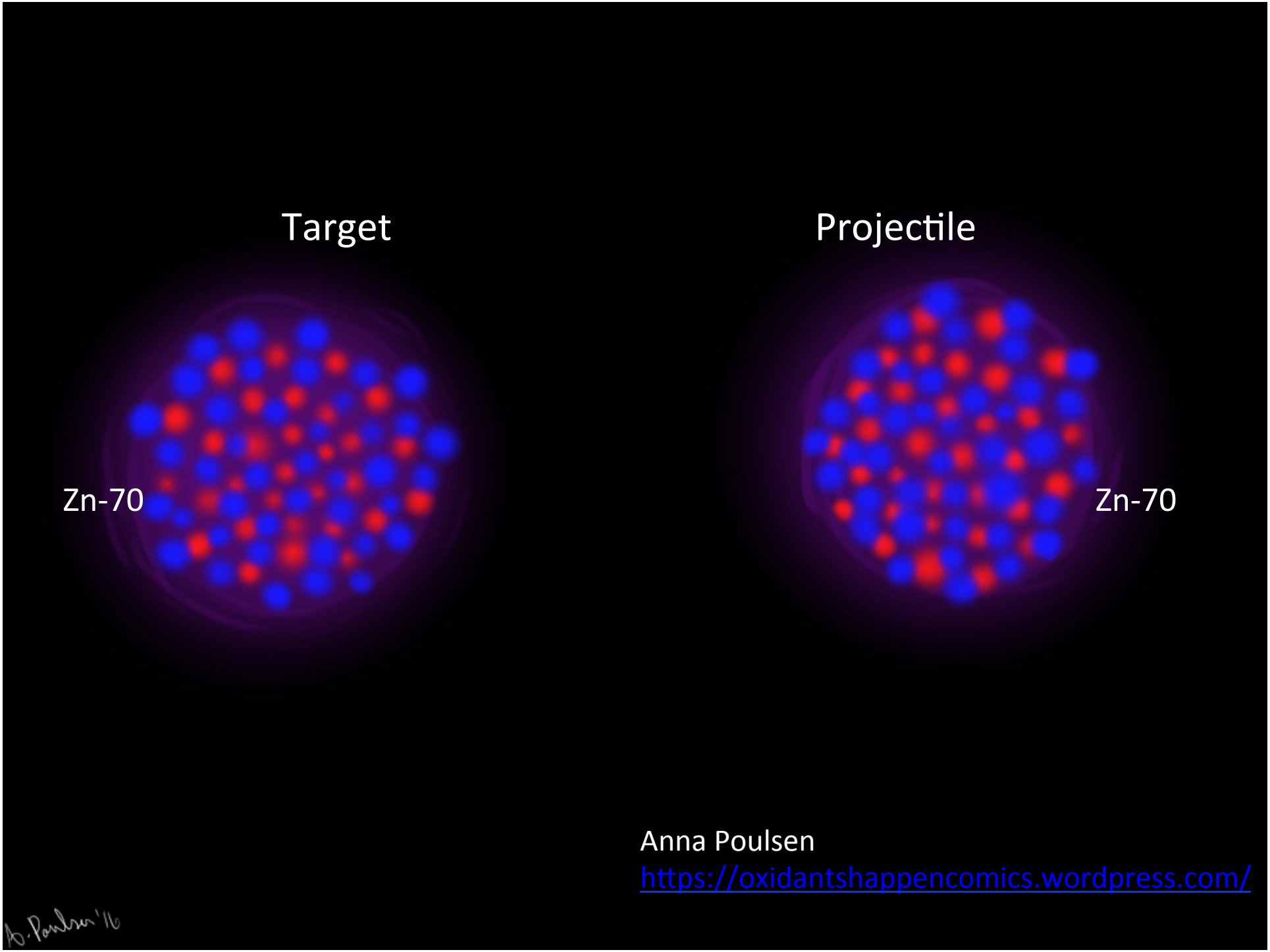
Compared to Constrained Molecular Dynamics (CoMD-II) model: *M. Papa et al. PRC* ***64,*** *24612, (2001).*

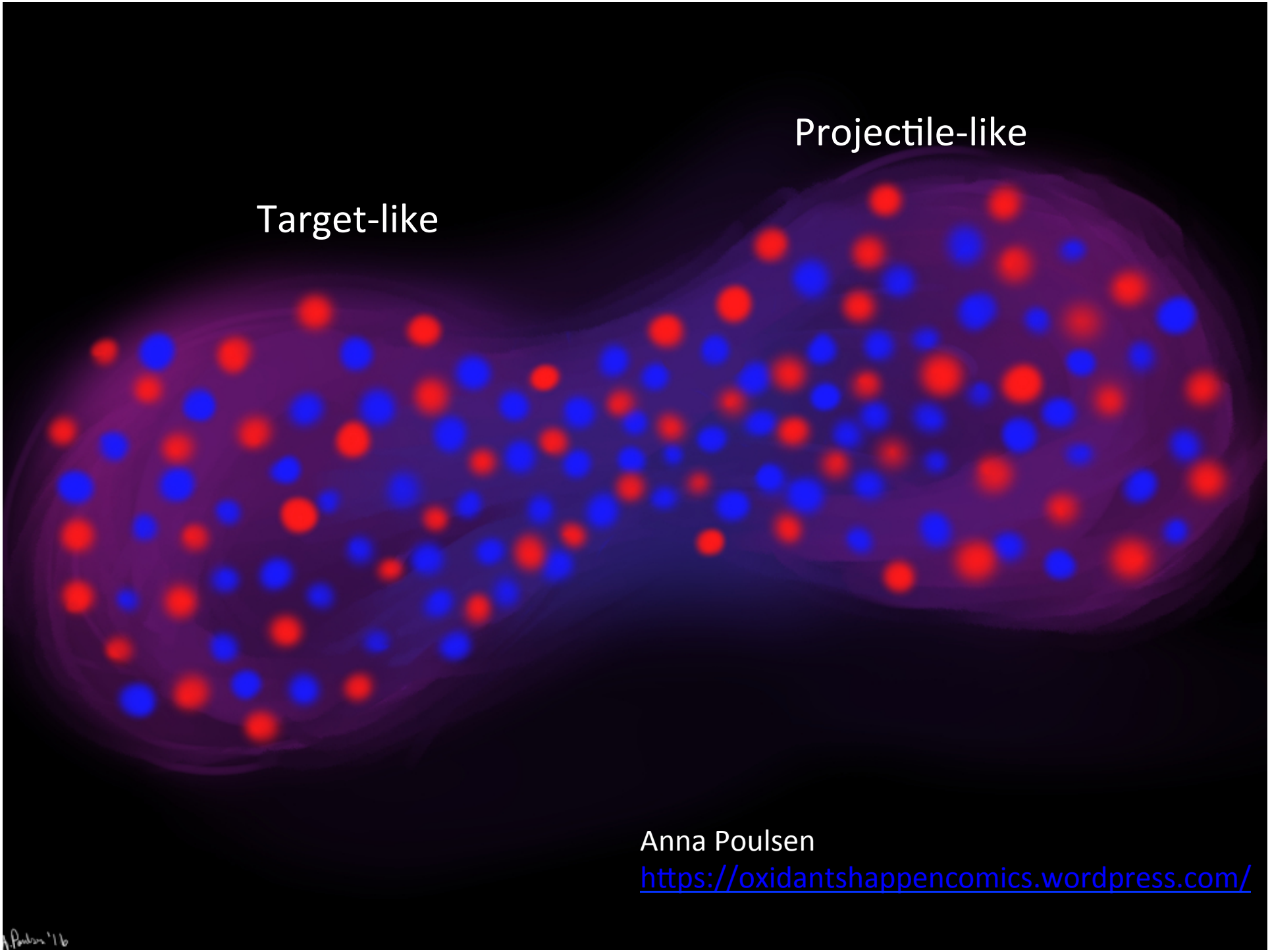


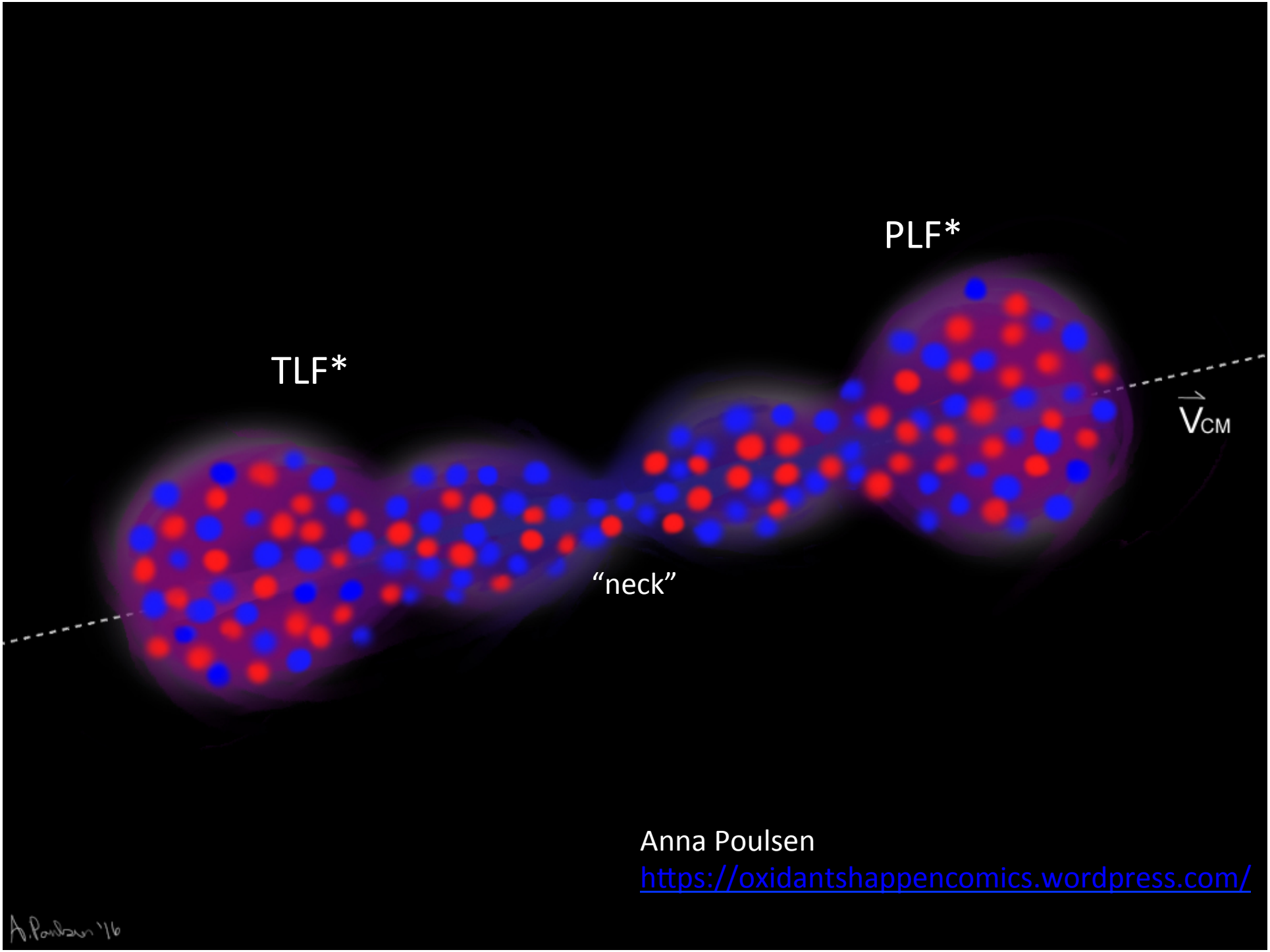
Purple area new constraints extracted from ^{32}Mg RIB experiment.

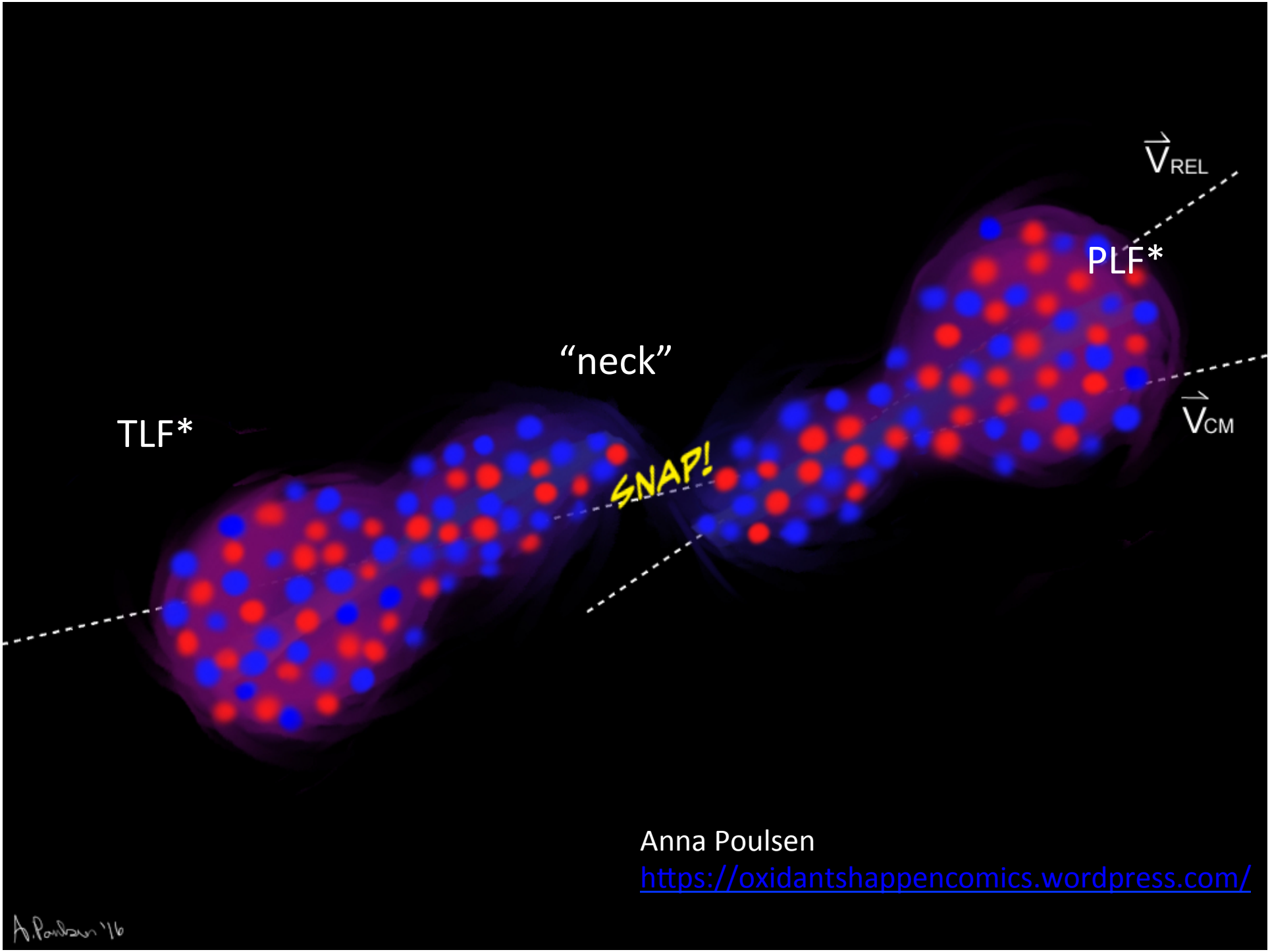


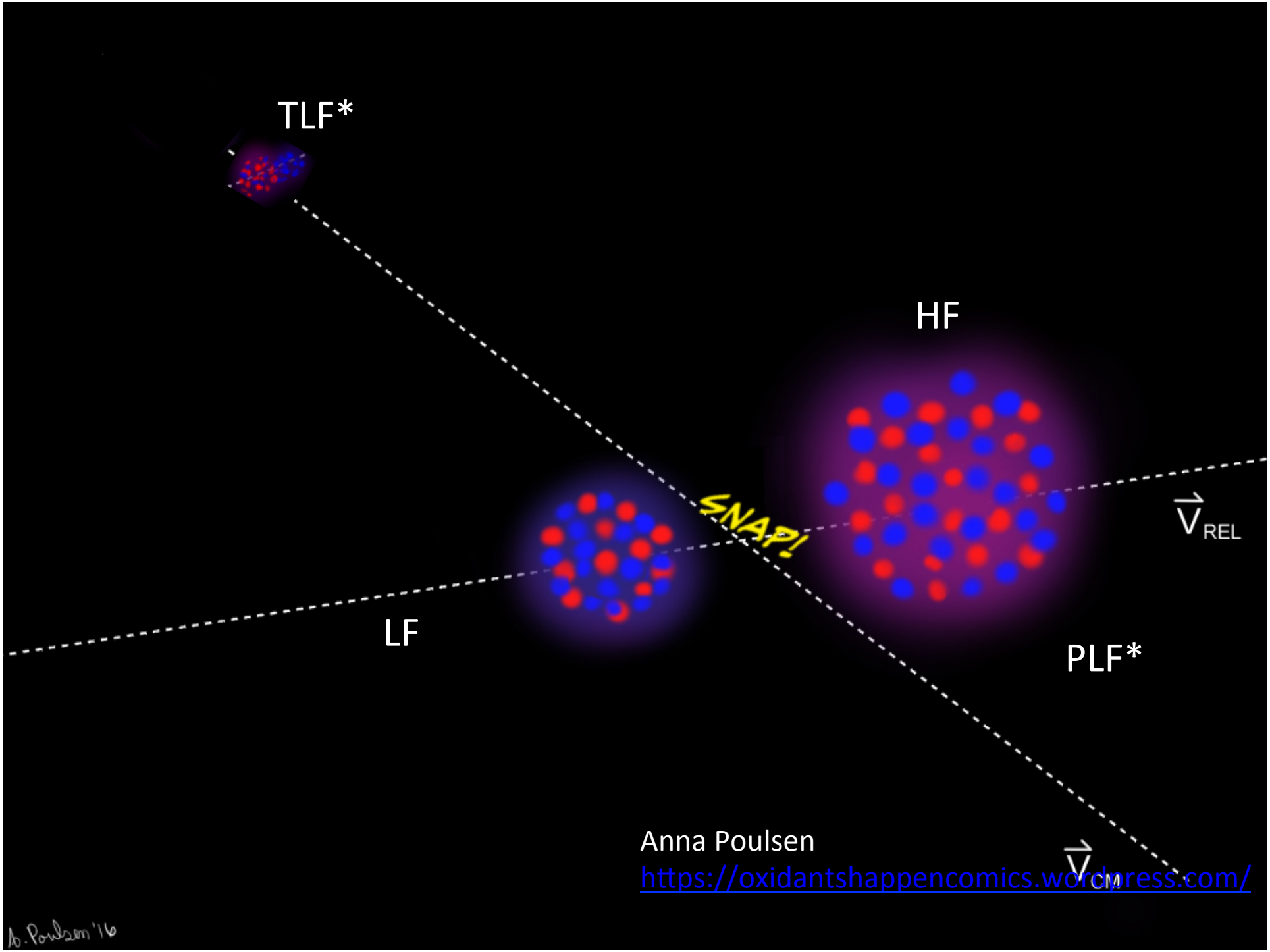
Kohley et al. PRC 88, 041601(R) (2013).


Target
Projectile
Zn-70
Zn-70
Anna Poulsen
https://oxidantshappencomics.wordpress.com/


Projectile-like
Target-like
Anna Poulsen
https://oxidantshappencomics.wordpress.com/


PLF*
TLF*
$\vec{V}_{CM}$
“neck”
Anna Poulsen
https://oxidantshappencomics.wordpress.com/
A. Poulsen '16

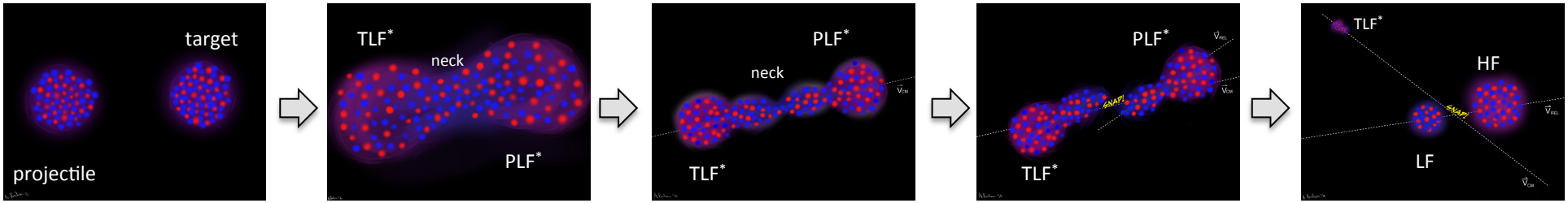

$\vec{V}_{REL}$
PLF*
"neck"
TLF*
SNAP!
$\vec{V}_{CM}$
Anna Poulsen
https://oxidantshappencomics.wordpress.com/

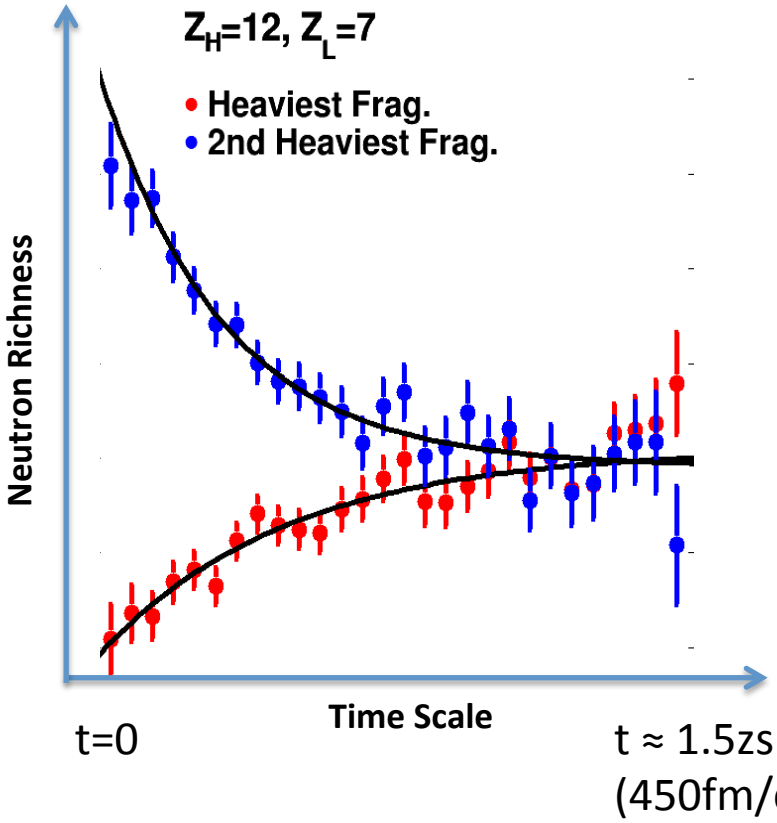


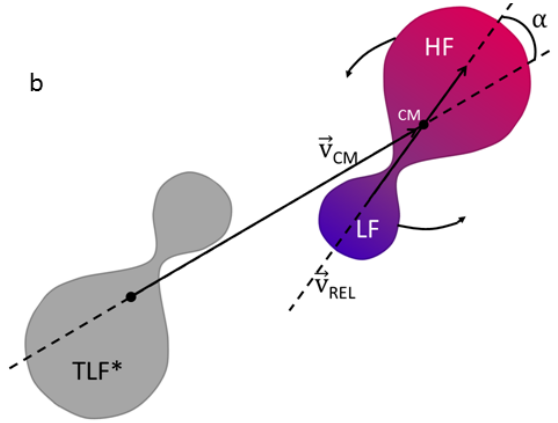
Anna Poulsen
https://oxidantshappencomics.wordpress.com/

Equilibration Chronometry

Characterizing neutron-proton equilibration with sub-zeptosecond resolution







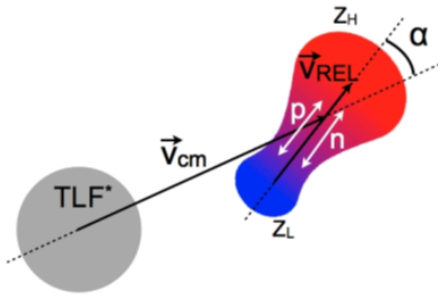
We observe N-Z equilibration as a function of time.

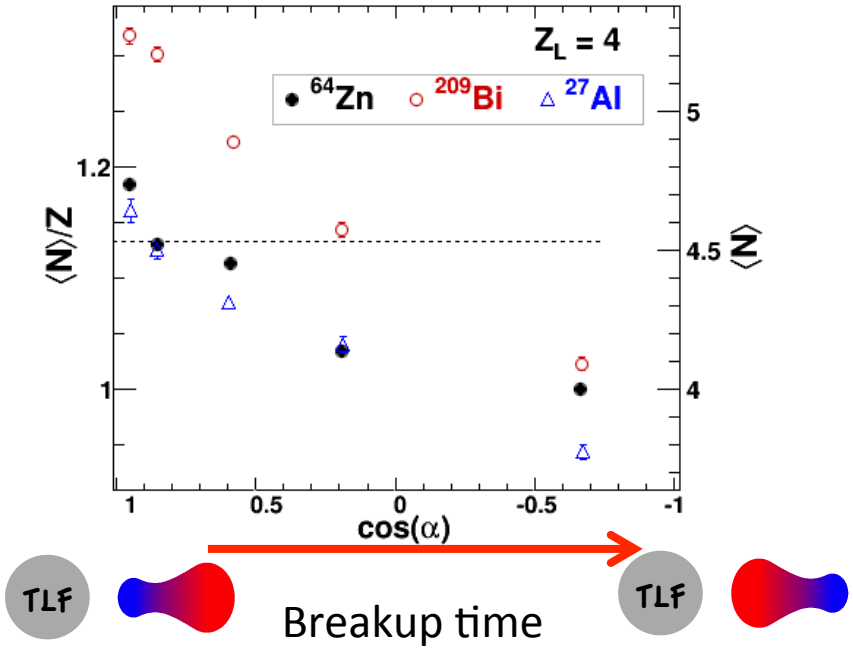
Equilibration curve is approximately exponential

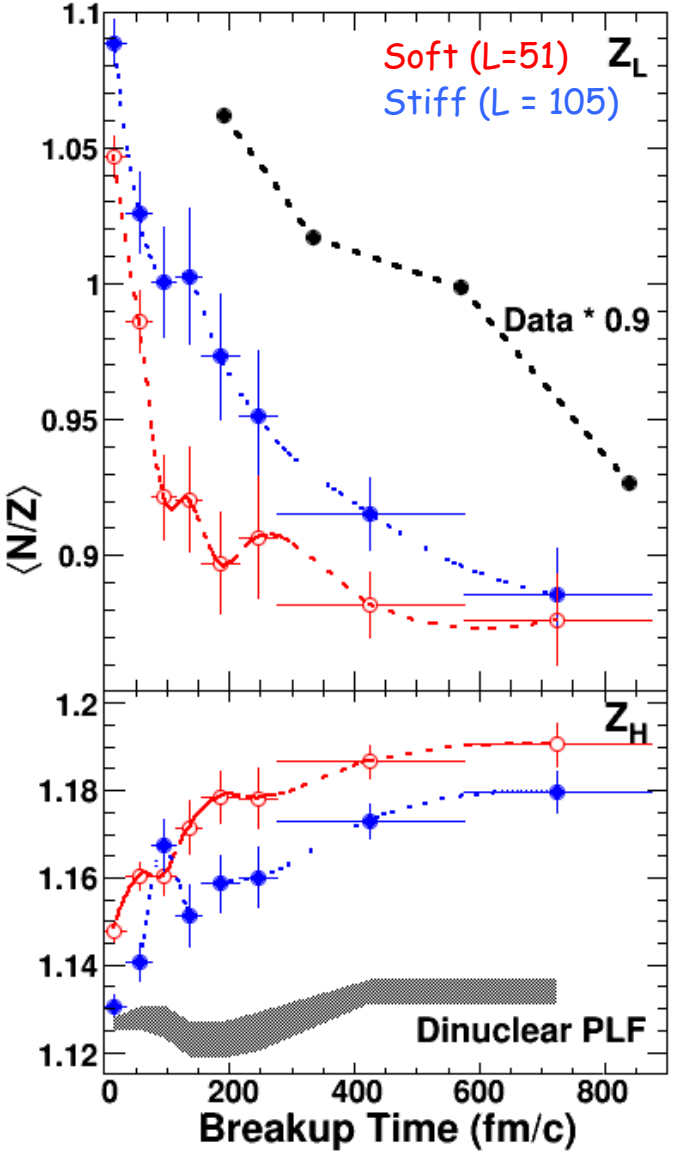
→ First order kinetics

Zeptosecond timescale.

Binary breakup of a projectile







K. Brown *et al.*, PRC**87**, 061601(R) (2013)
K. Stiefel *et al.*, PRC**90**, 061605(R) (2014)

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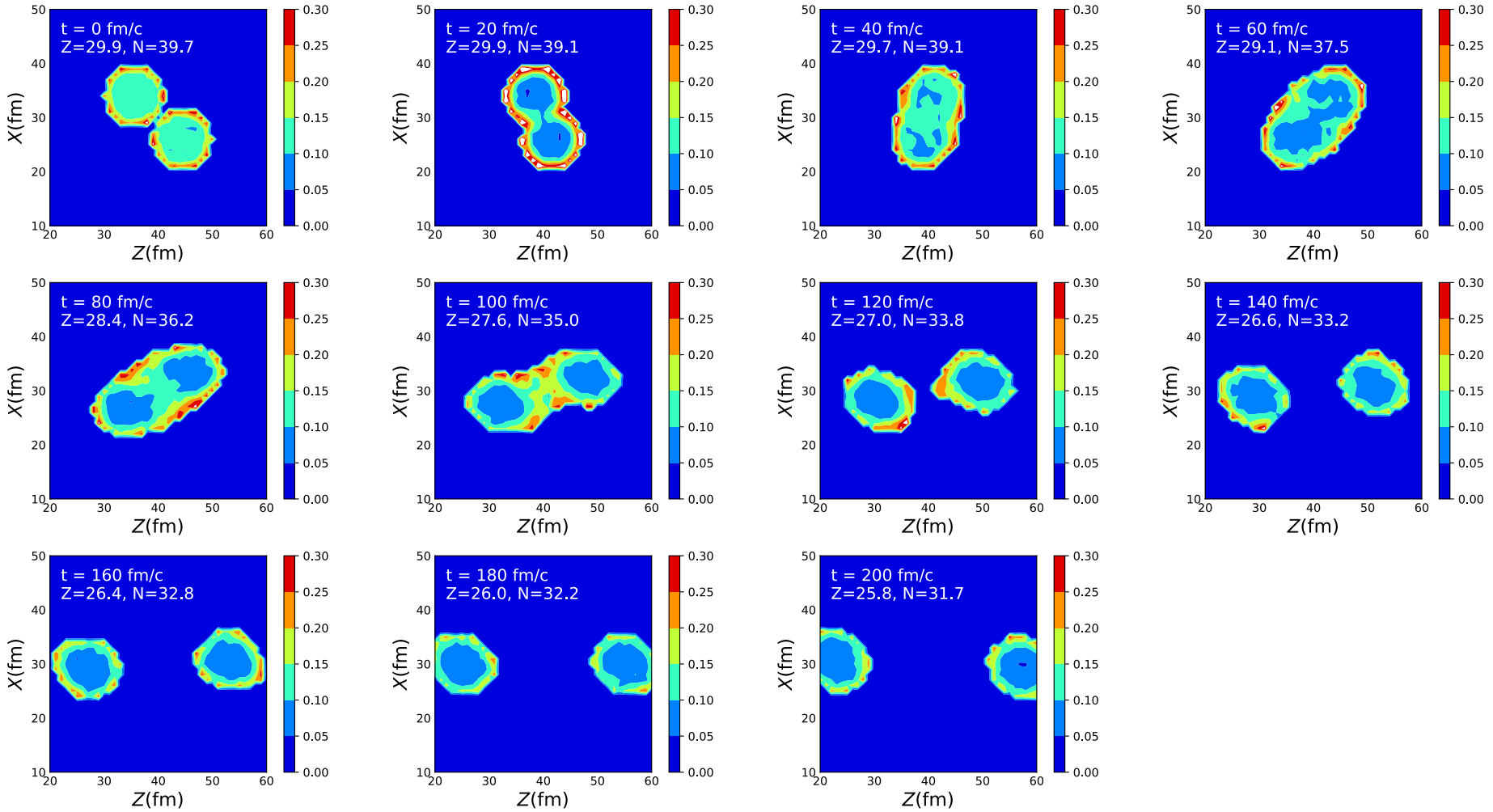
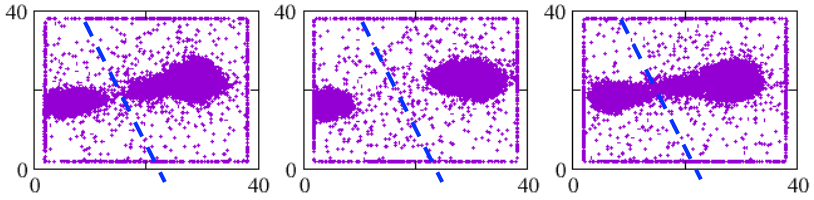


Private communication , Zhang & Ko

Ternary breakup in n-rich systems: Sensitivity to Esym

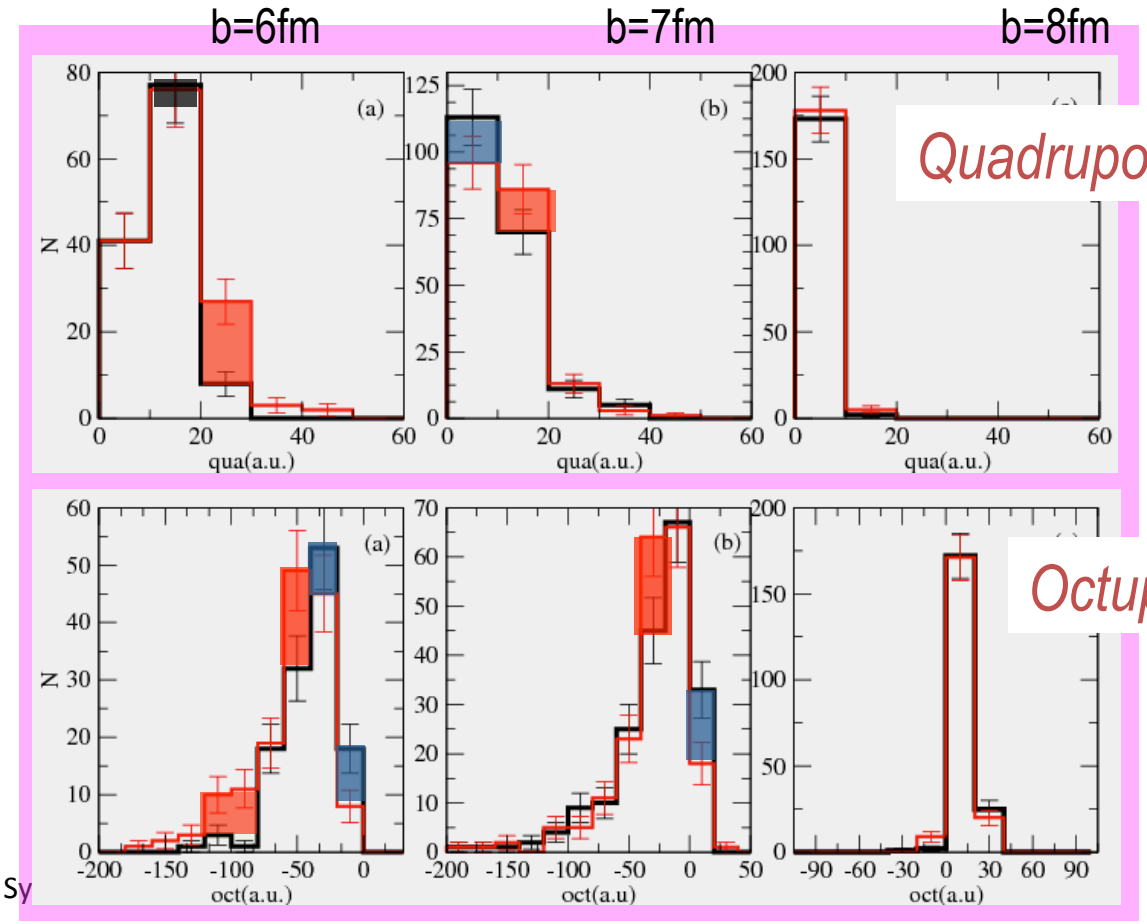


$^{132}Sn + ^{64}Ni$, E/A = 10 MeV, b = 7 fm
3 events, t = 500 fm/c

- Analysis of the deformation of the residues

200 runs each
per impact parameter

— *Asysoft*
— *Asystiff*



- Larger residue deformations
→ more ternary events
with Asystiff

Di Toro et al., NPA 787 (2007) 585c

Sy

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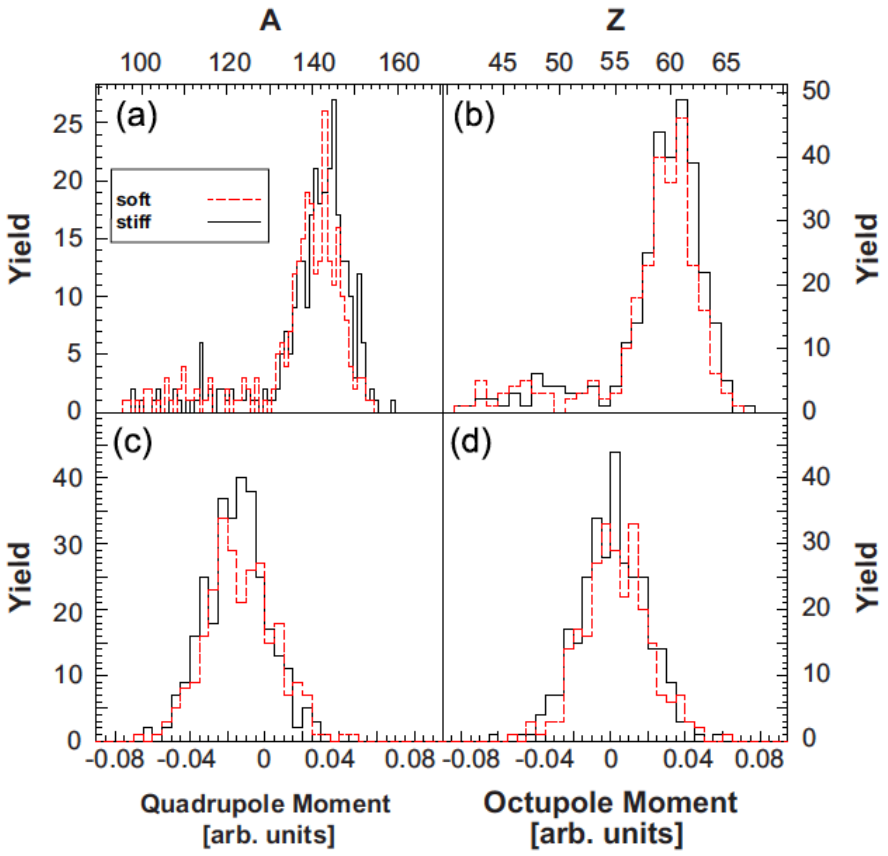
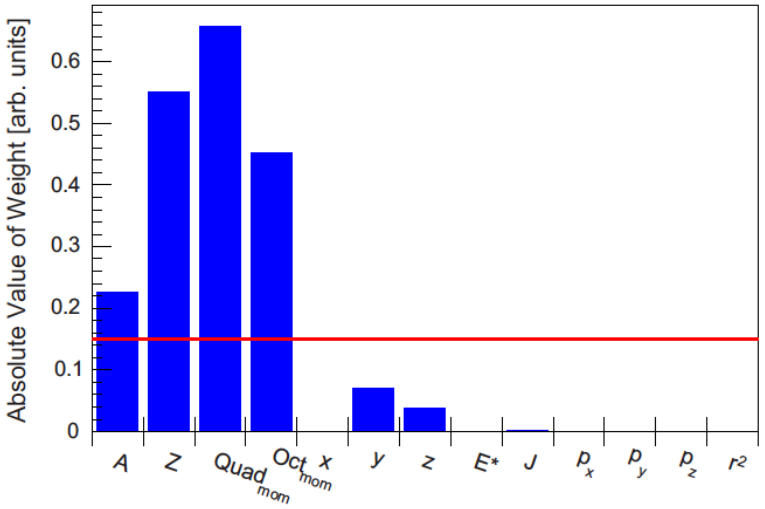
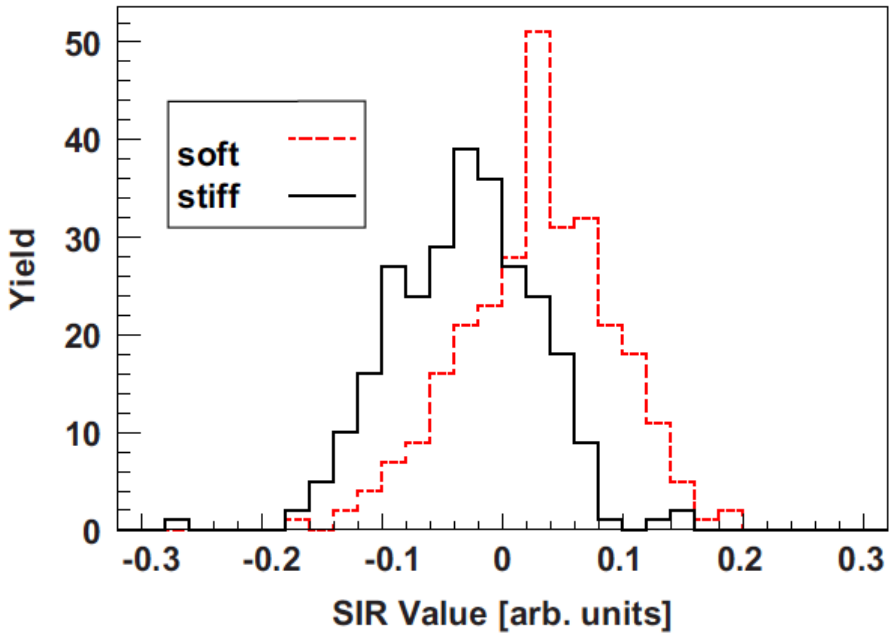
Sifting through the remnants







P. Cammarata, et al, NIMA 761 (2014) 1–6

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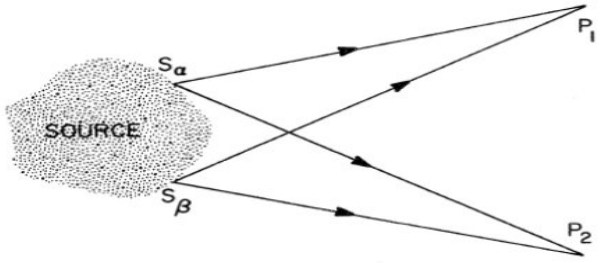
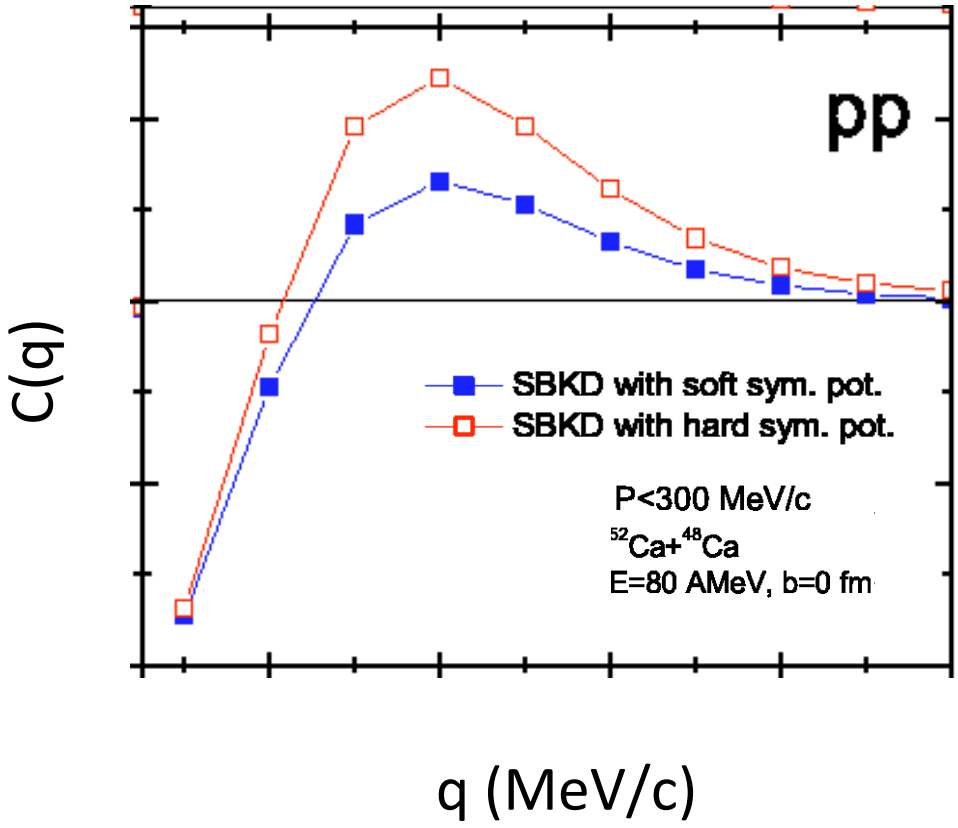
pp correlation function



$$C(q_{Rel}) = N\frac{Y_c(q_{Rel})}{Y_{nc}(q_{Rel})}$$

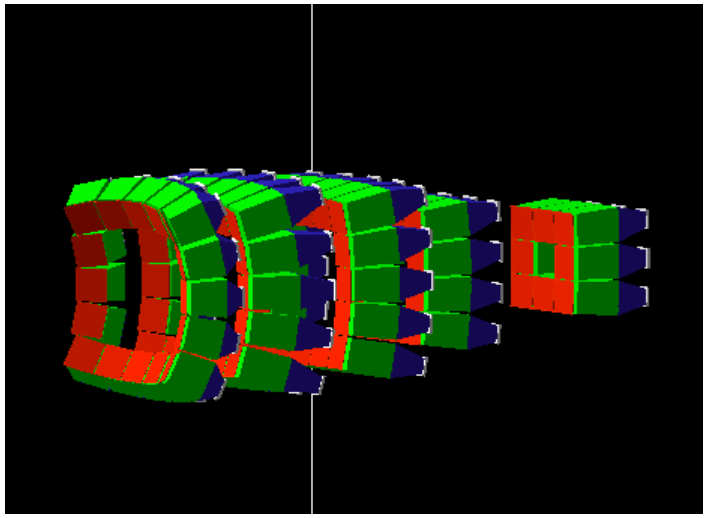
$$|\vec{q}_{Rel}| = \frac{1}{2}|\vec{p}_1 - \vec{p}_2|.$$

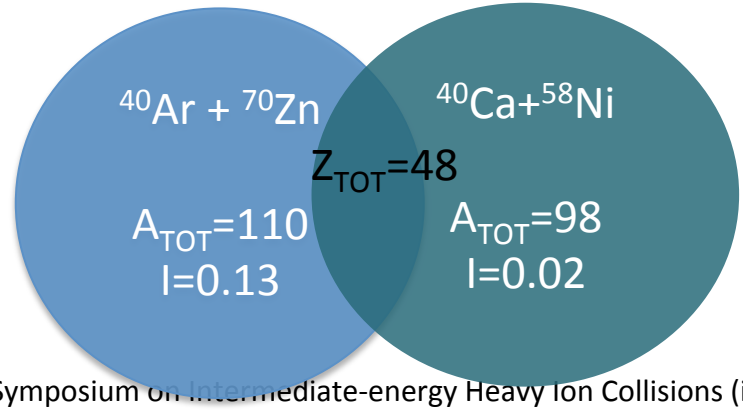


L. W. CHEN, C. M. KO, B. A. LI, *Phys. Rev. C*, **69,** 054606, (2004).

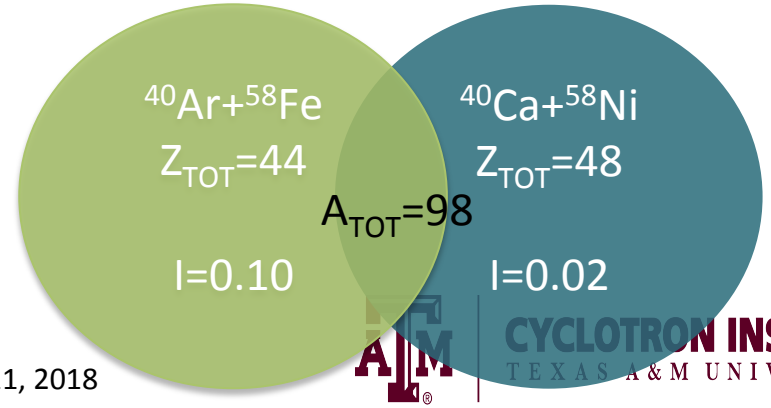
Experiment

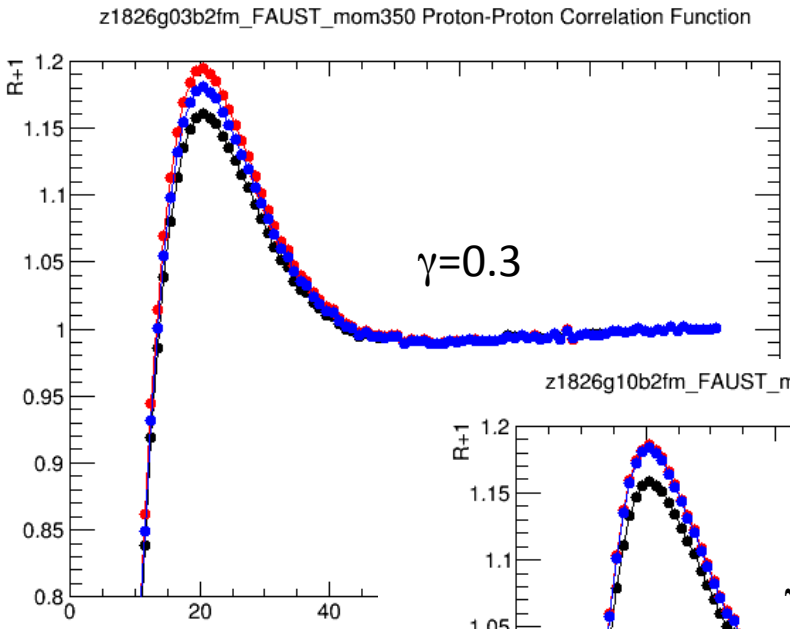
- Forward Array Using Silicon Technology (FAUST)
- 68 Si-CsI(Tl) Telescopes
- LCP Detection
- Systems: Asymmetry



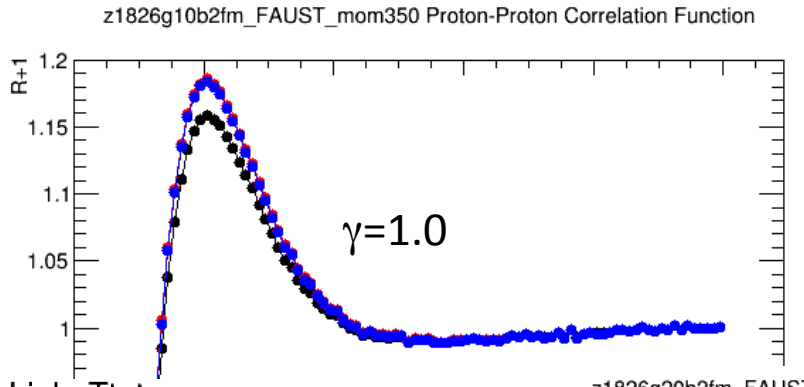


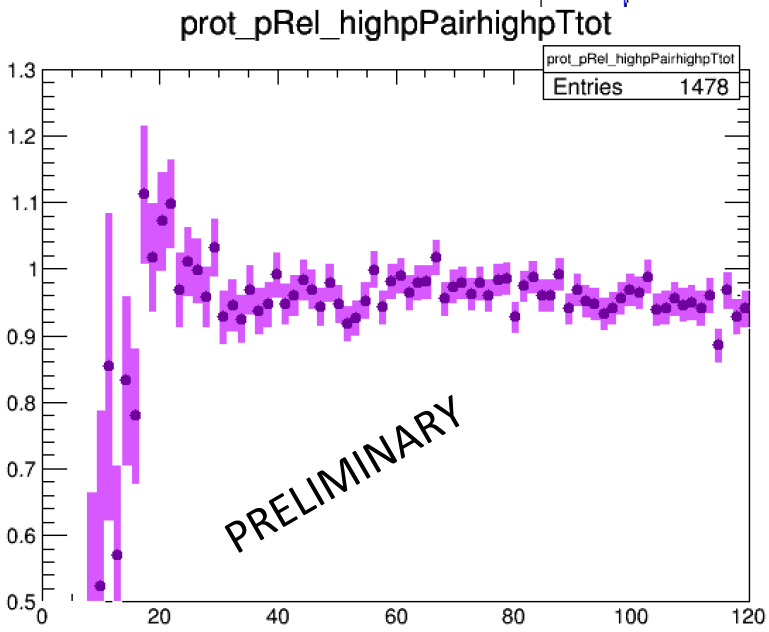
$$I = \frac{N - Z}{A}$$

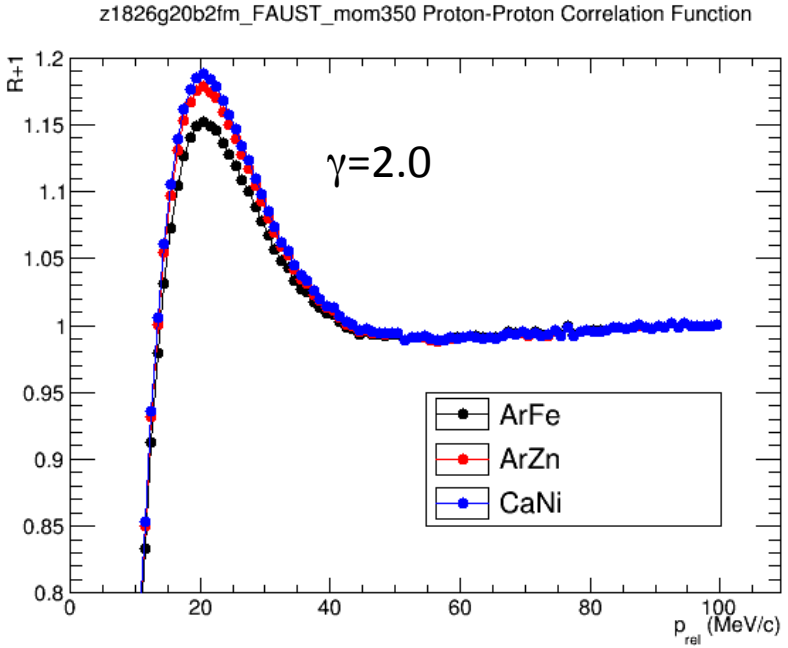



z1826g03b2fm_FAUST_mom350 Proton-Proton Correlation Function
R+1
γ=0.3

b=2fm

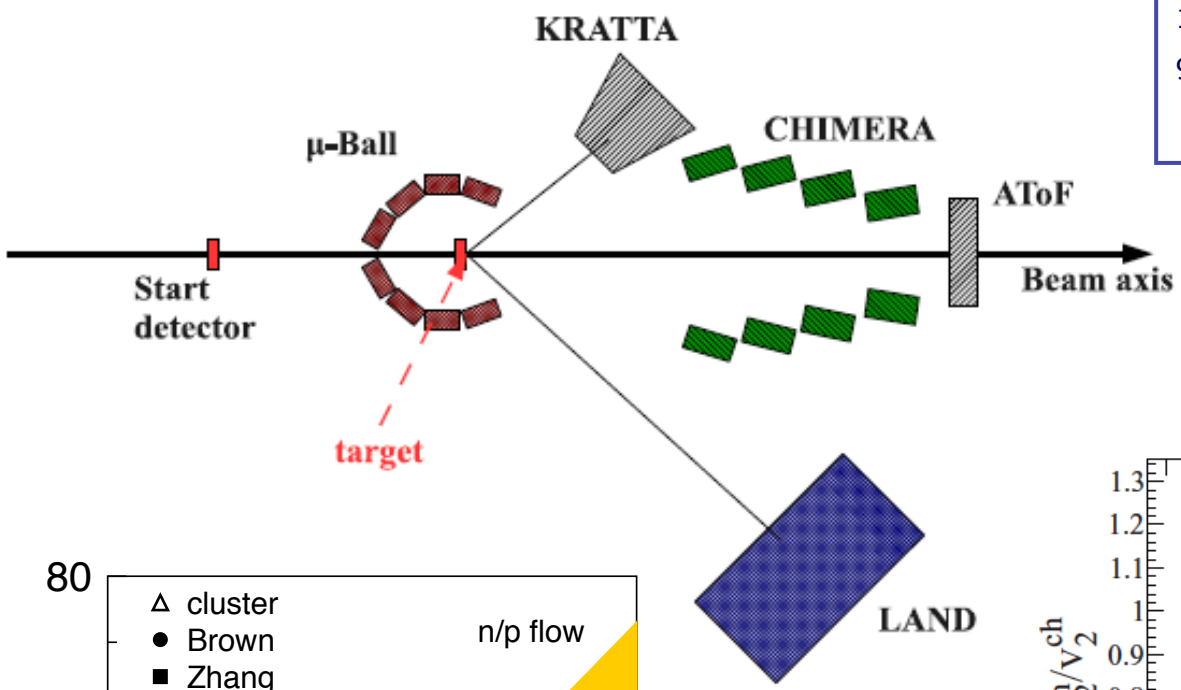

z1826g10b2fm_FAUST_mom350 Proton-Proton Correlation Function
R+1
γ=1.0

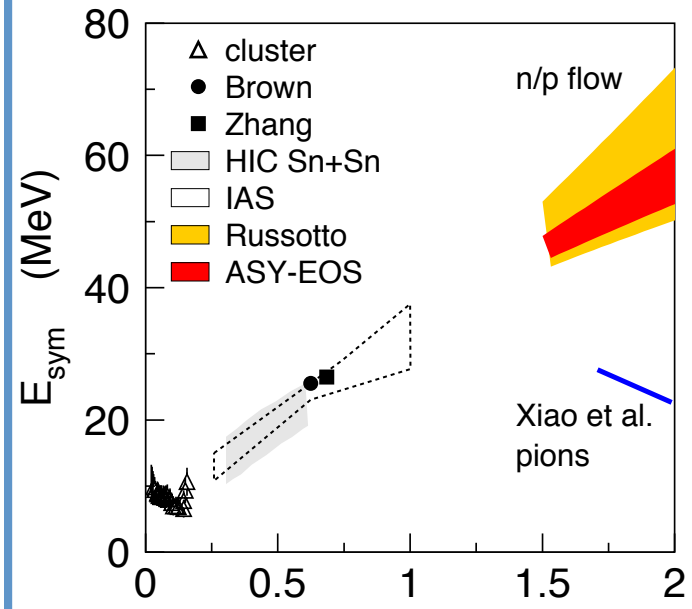

prot_pRel_highpPairhighpTtot
prot_pRel_highpPairhighpTtot
Entries 1478
PRELIMINARY

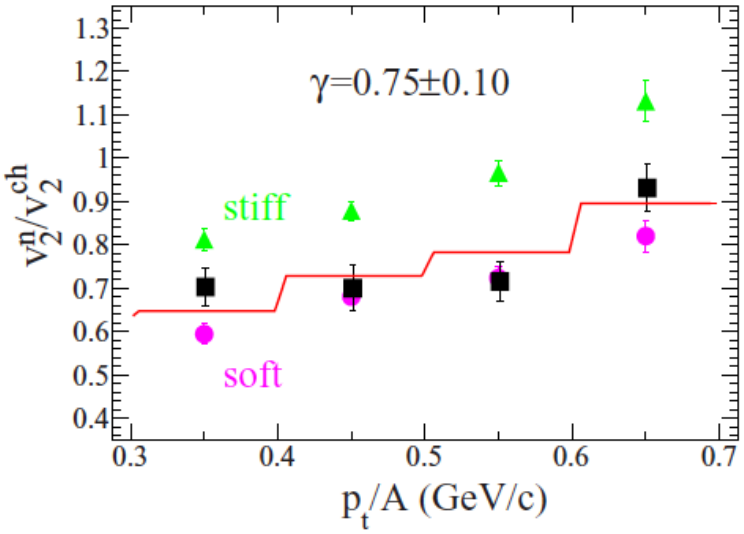

z1826g20b2fm_FAUST_mom350 Proton-Proton Correlation Function
R+1
γ=2.0
ArFe
ArZn
CaNi
p_rel (MeV/c)

Constraining the Symmetry Energy at Supra-Saturation Densities with Measurements of Neutron and Proton Elliptic Flows

^{197}Au + ^{197}Au @ 400 A MeV
^{96}Ru + ^{96}Ru @ 400 A MeV
^{96}Zr + ^{96}Zr @ 400 A MeV

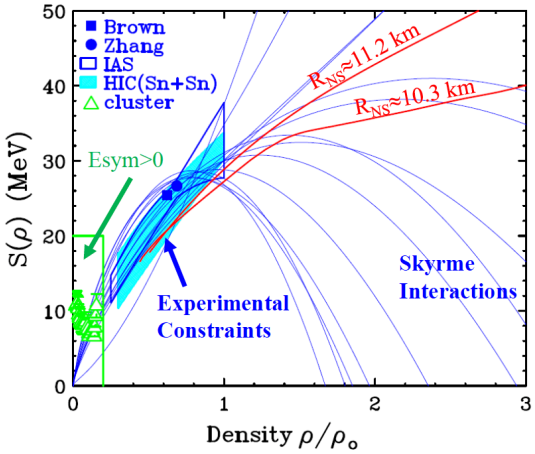






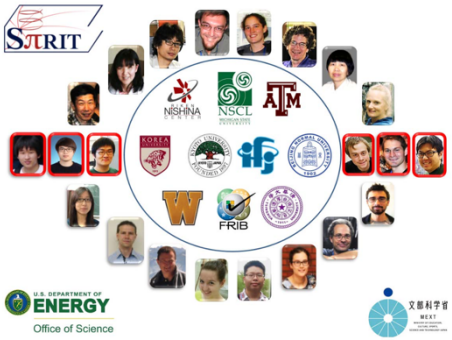
P. RUSSOTTO et al. PRC 94, 034608 (2016)

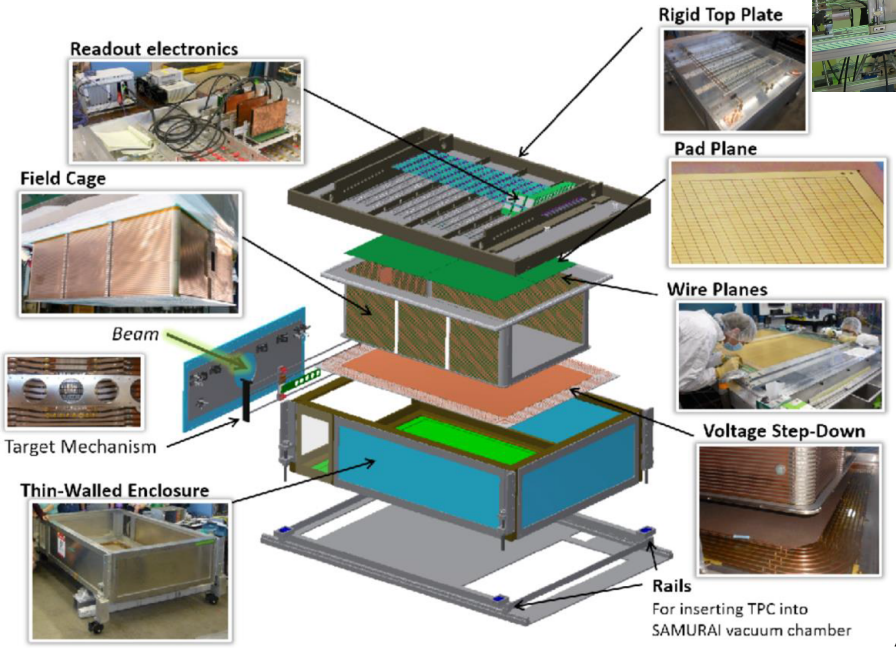
SPiRIT TPC @ SAMURAI

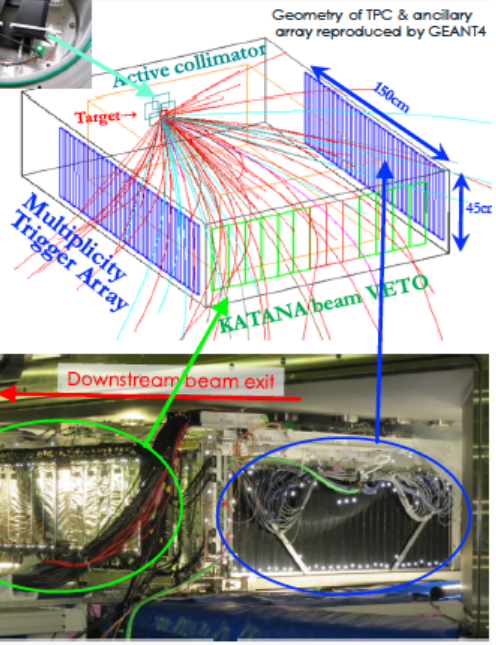


Constrain the Asymmetry Energy at **high density** through measurement of

- π-/π+, n/p, 3H/3He
- Differential Flow and Particle Yield Ratios
- ^{108}Sn+^{112}Sn, ^{130}Sn+^{124}Sn @ E/A ≥ 200 MeV



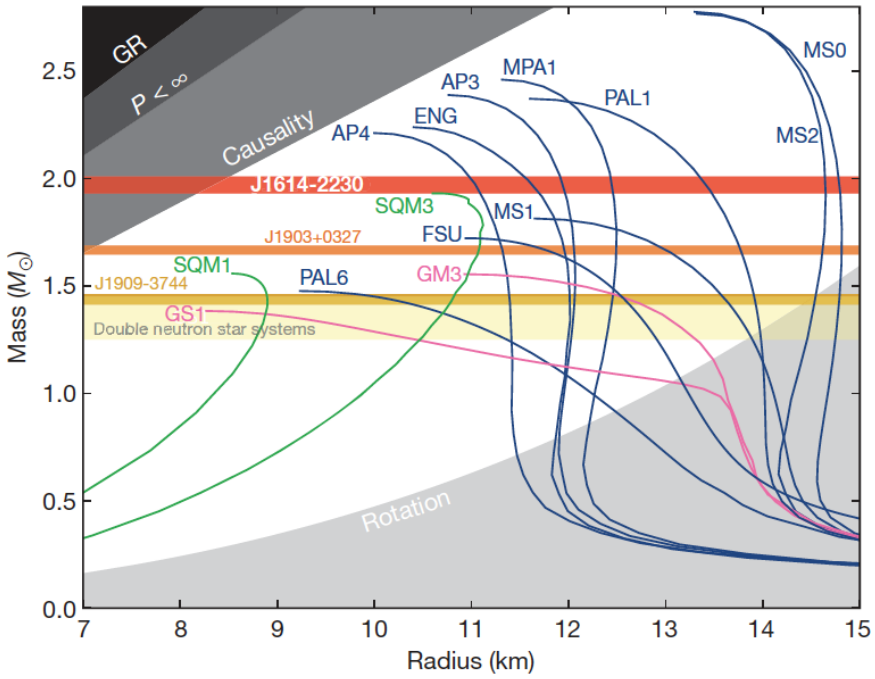




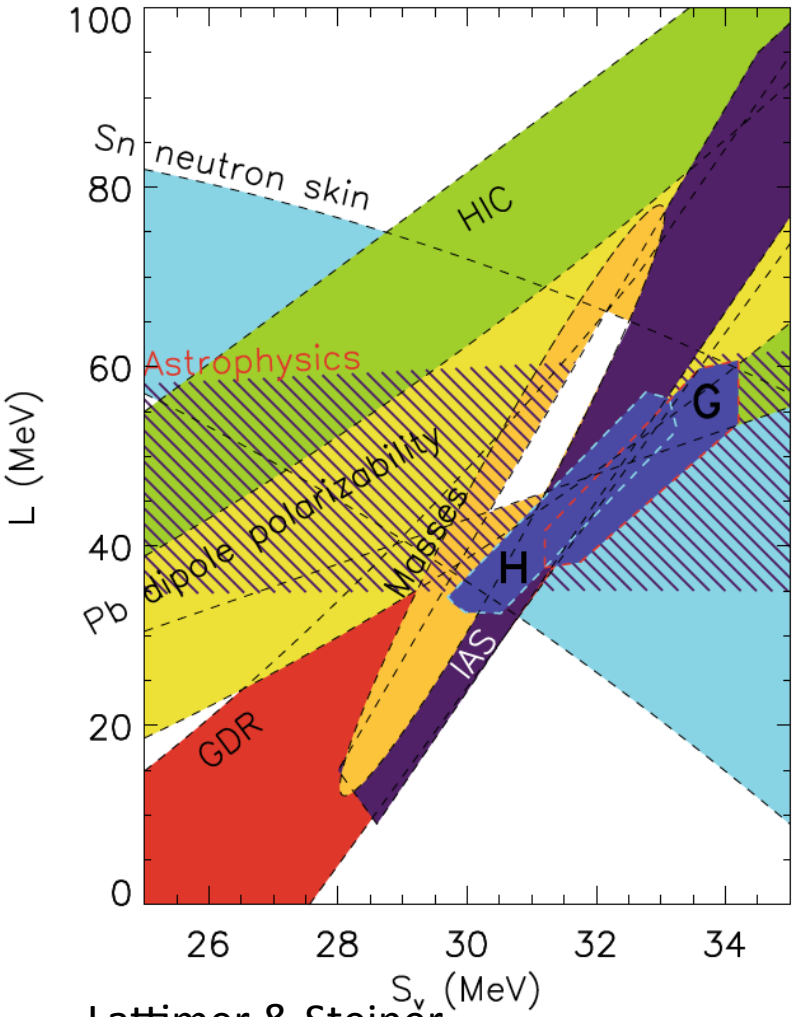
, April 7-11, 2018

Summary

- Many proposed observables
- Various data sets
- Need to understand differences in model predictions
- New observables with increased power to discriminate welcome



Demorest, Nature 2010



Lattimer & Steiner
Eur. Phys. J. A (2014)c

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