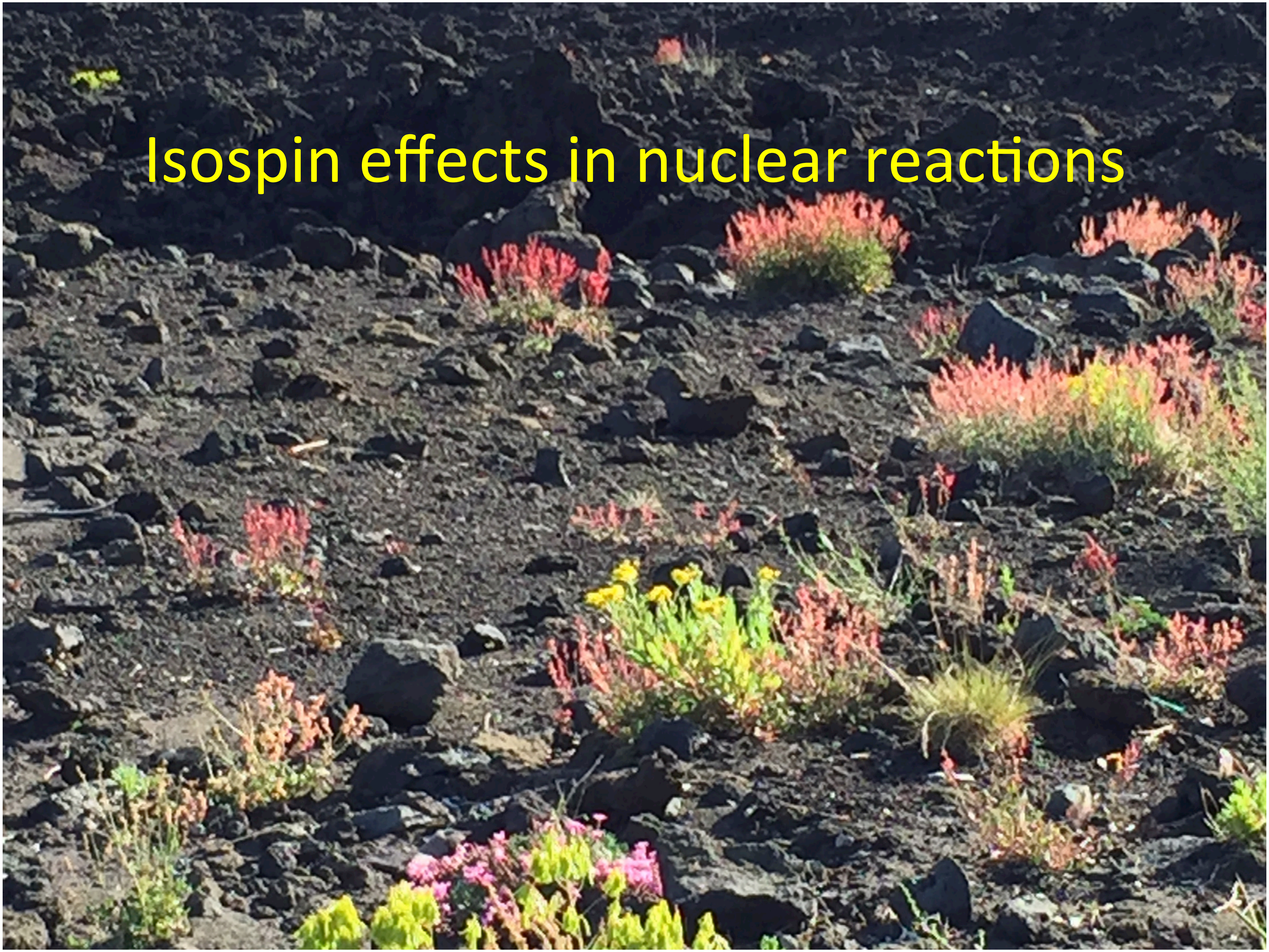
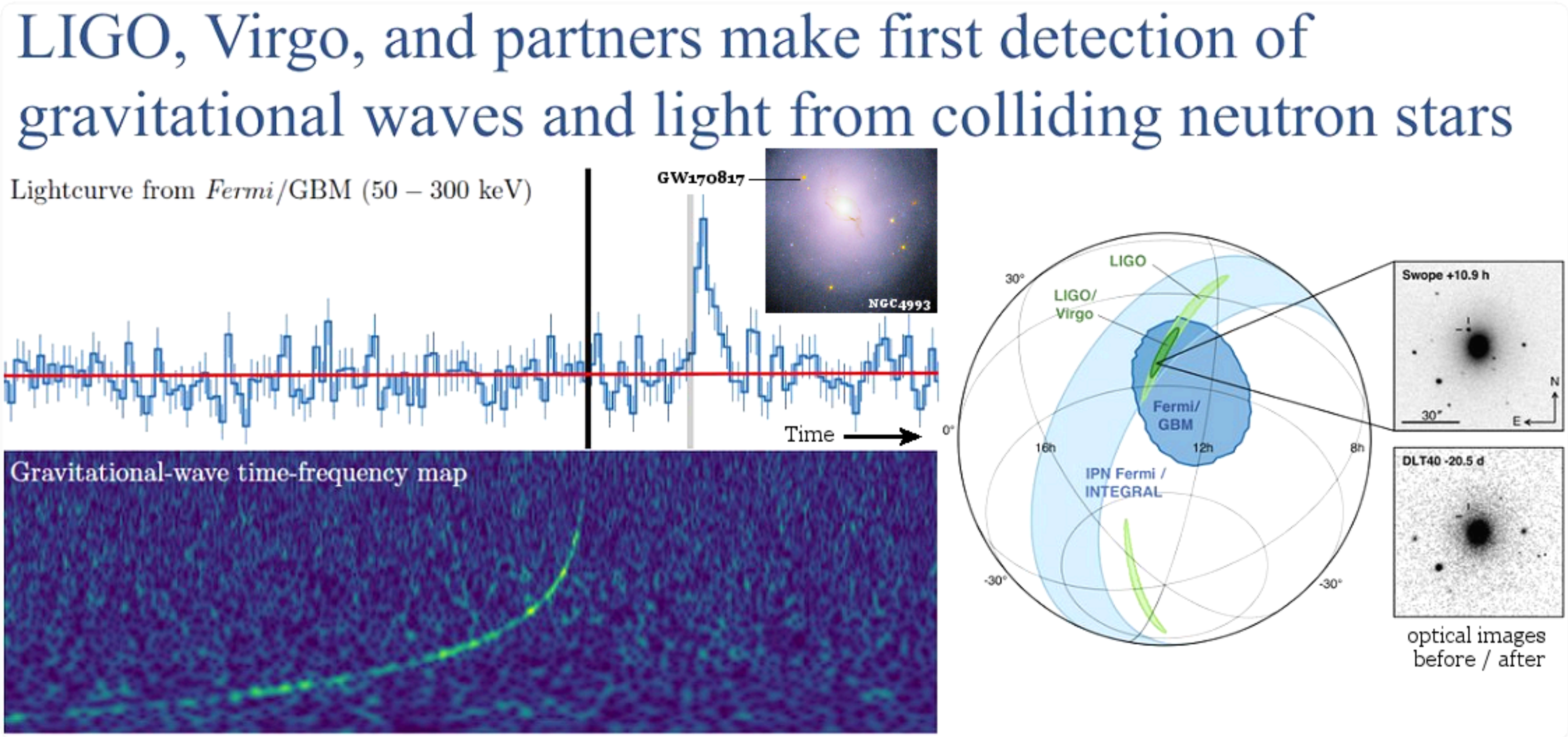

Isospin effects in nuclear reactions

Science Magazine's Breakthrough of the Year 2017:



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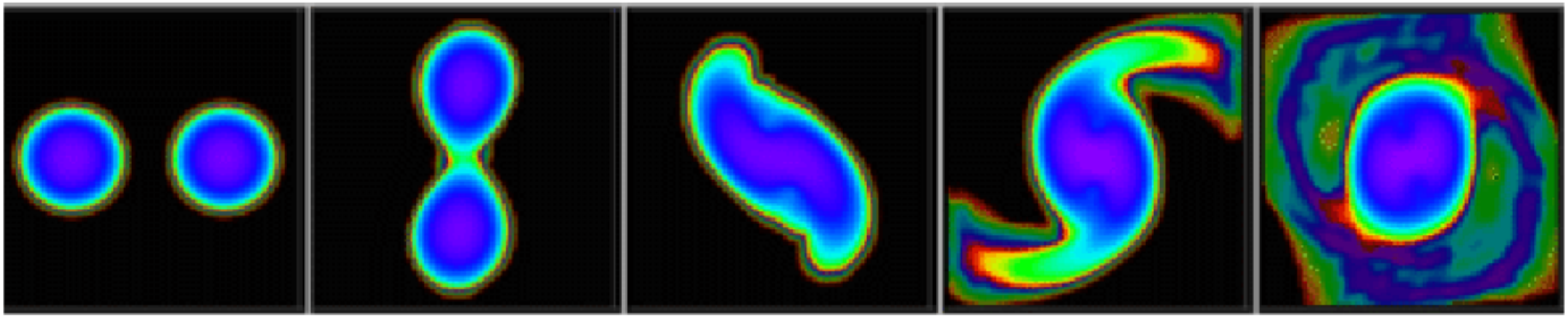

EOS – Asymmetry energy

- » Heat capacity
- » Partitioning of nuclear material - fragmentation
  - – Clustering – particularly at low density
  - – Inhomogeneous distribution of isospin
  - – Pasta
- » Equilibration
- » Deformation – tidal effects

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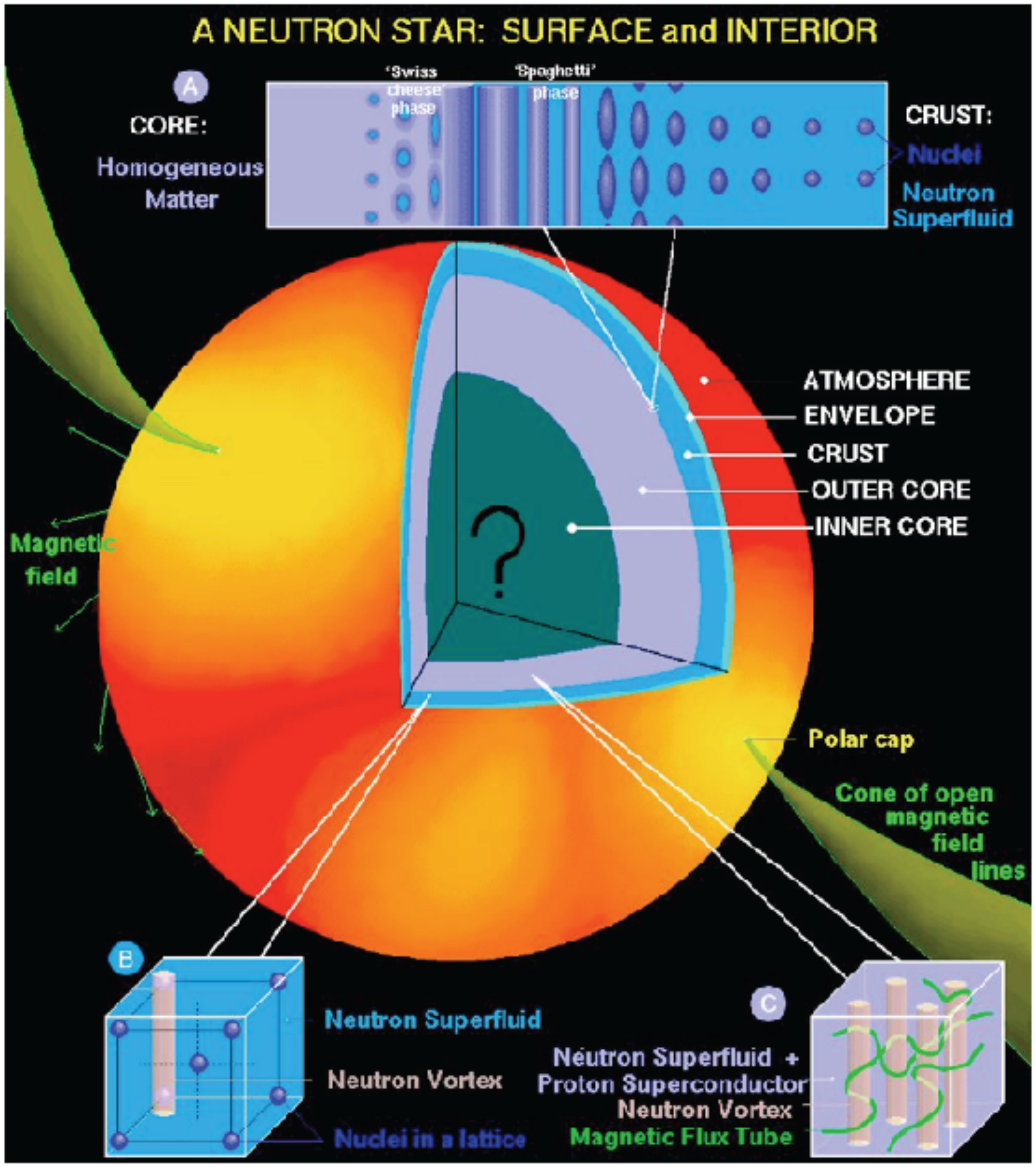
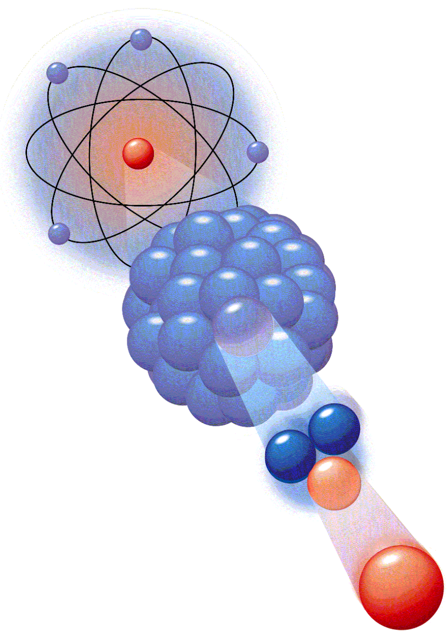
Neutron stars

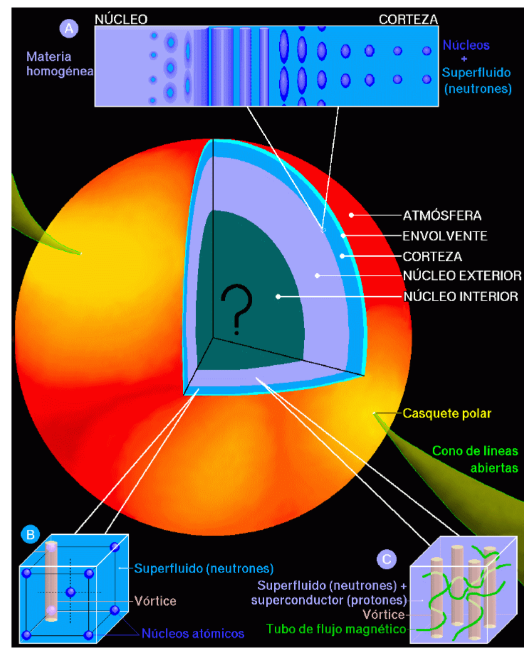
- Neutron stars are formed from the collapse of a massive star in a supernova explosion.
- Mass ~1.4 M_{sun}, Radius ~10 km
- Solid crust ~ 1km thick (~10^{12} g/cm^3) over liquid outer core of neutron rich matter(~10^{15} g/cm^3).
- Possible exotic phase in center: de-confined quark matter, strange matter, meson condensates, color superconductor...
- Structure determined by Equation of State (pressure vs density) of n rich matter.
- Figure: **Dany Page,** UNAM



Atomic nuclei & Neutron star
(two vastly different systems)

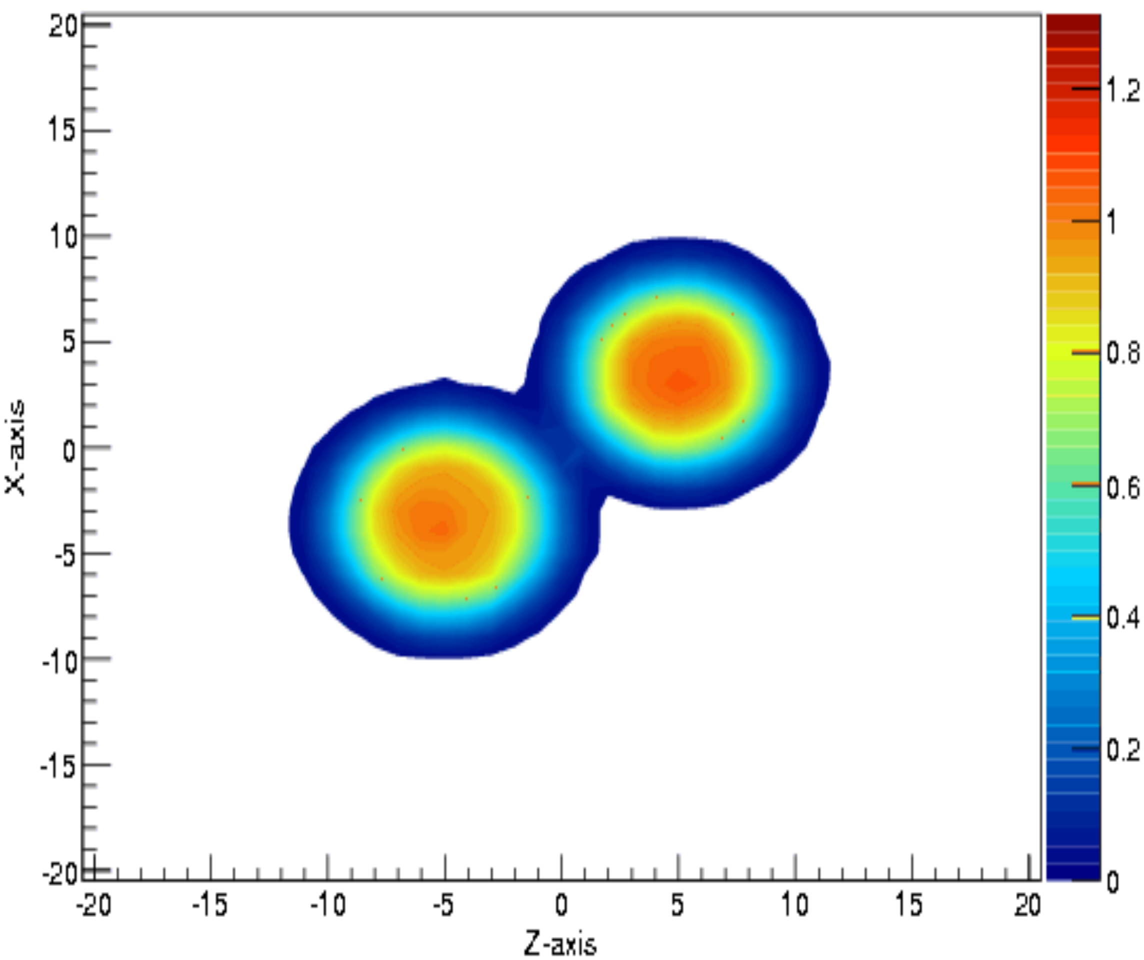
A heavy nucleus (like ^{208}Pb) is 18 orders of magnitude smaller and 55 orders of magnitude lighter than a neutron star !



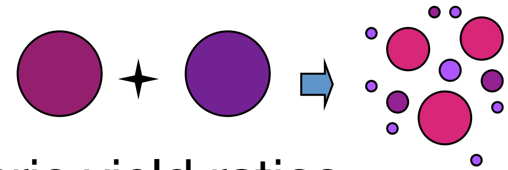


Yet bounded by a common entity, the nuclear Equation Of State (EOS) !

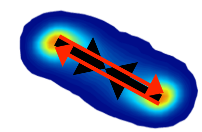
Experimental constraints on the nuclear equation-of-state from heavy-ion collisions



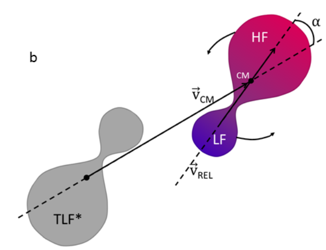
Observables sensitive to the EOS ?

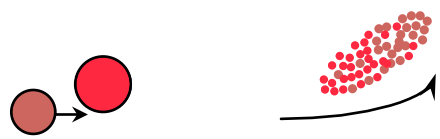


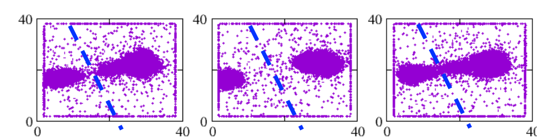
Neutron-skin thicknesses
Pygmy resonances
Fragment isotope distribution, isotopic & isobaric yield ratios
Isospin distillation/fractionation, relative n & p densities



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
…







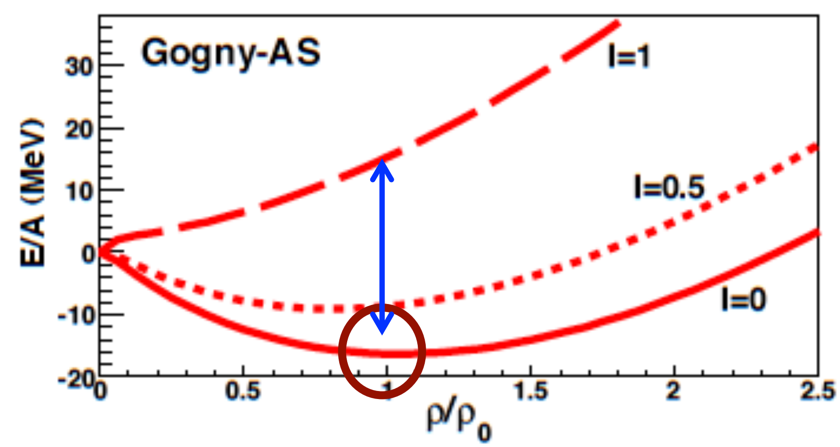
$$E_B = a_v A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} - \delta(A,Z)$$

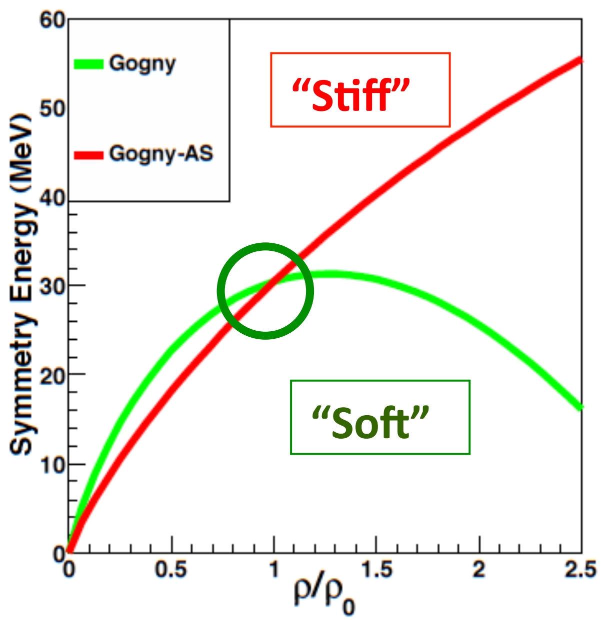
$$E(\rho, I) = E(\rho) + E_{sym}(\rho) I^2$$

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

Binding Energy of Symmetric Nuclear Matter

Symmetry Energy Term for Asymmetric Matter

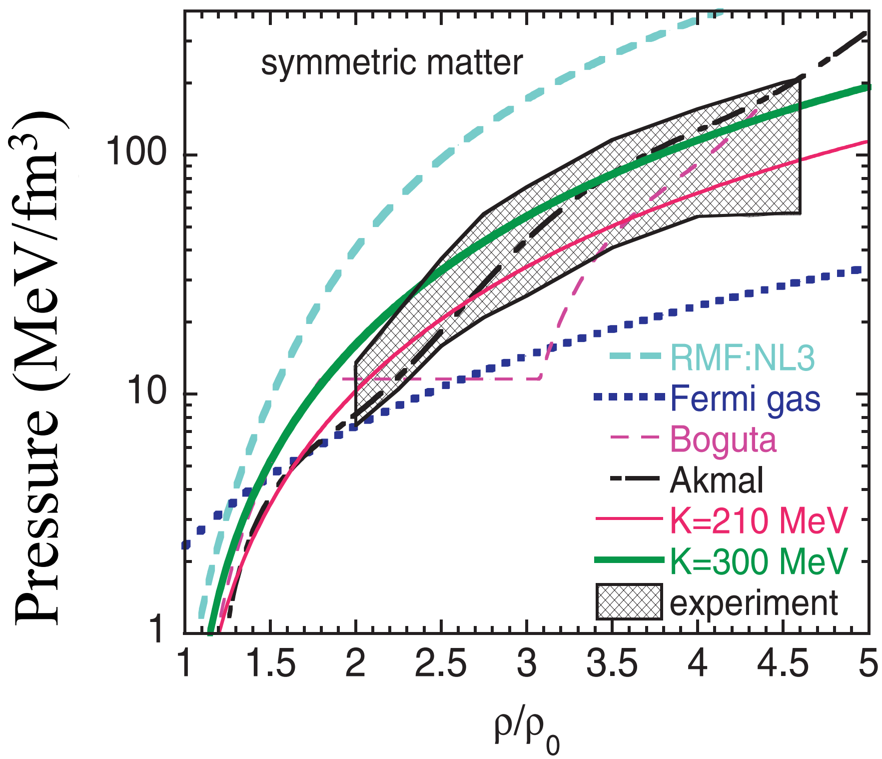


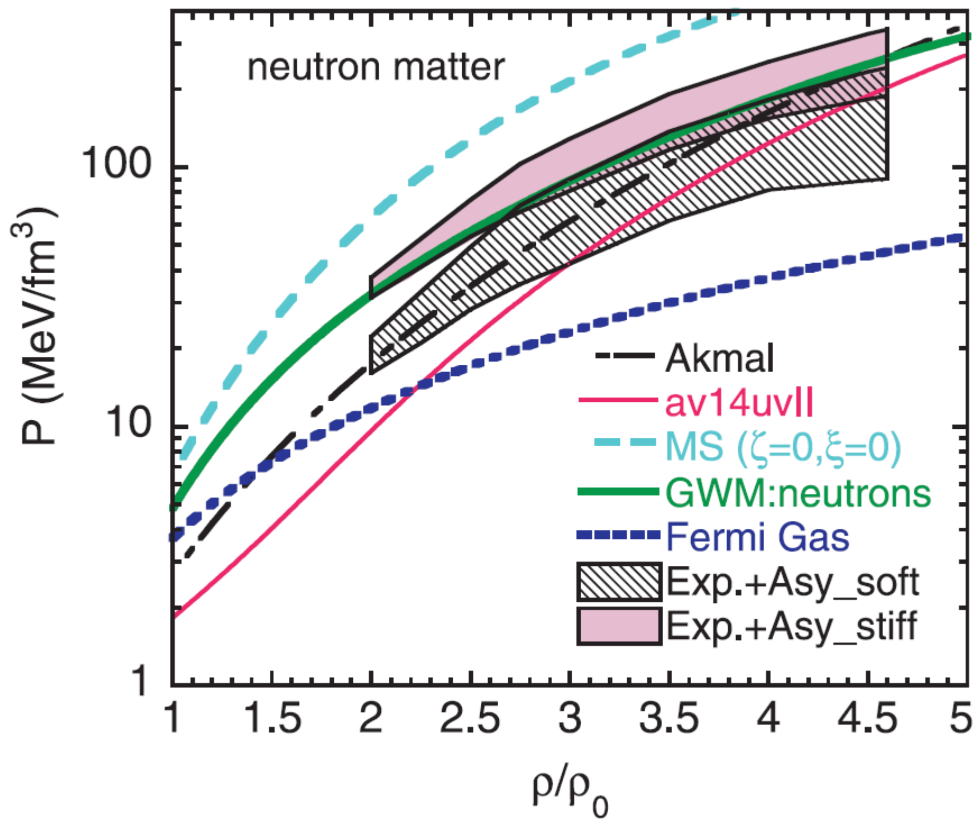


$$E_{sym}(\rho) = E(\rho,1) - E(\rho,0)$$

Constraining EOS from the flow measurements (Probing the high density dependence)

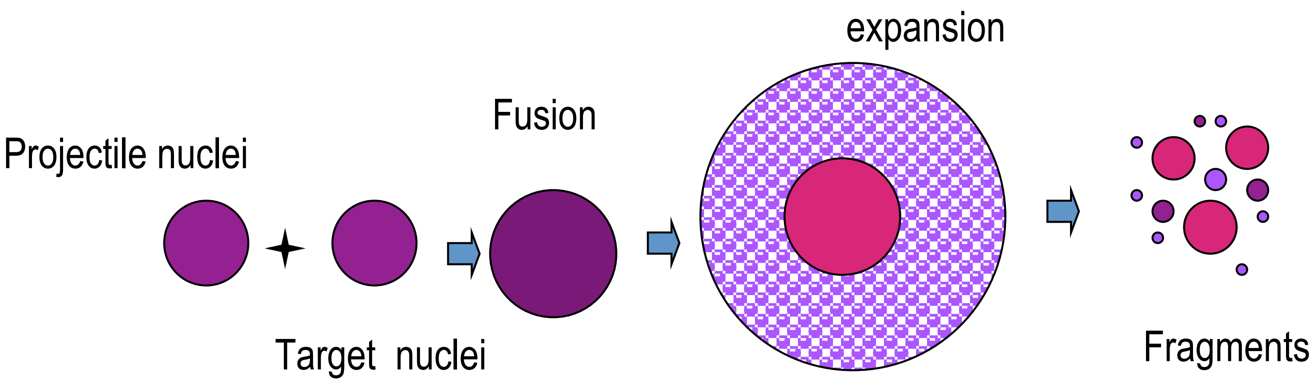
Au+Au flow (E/A~1-8 GeV)

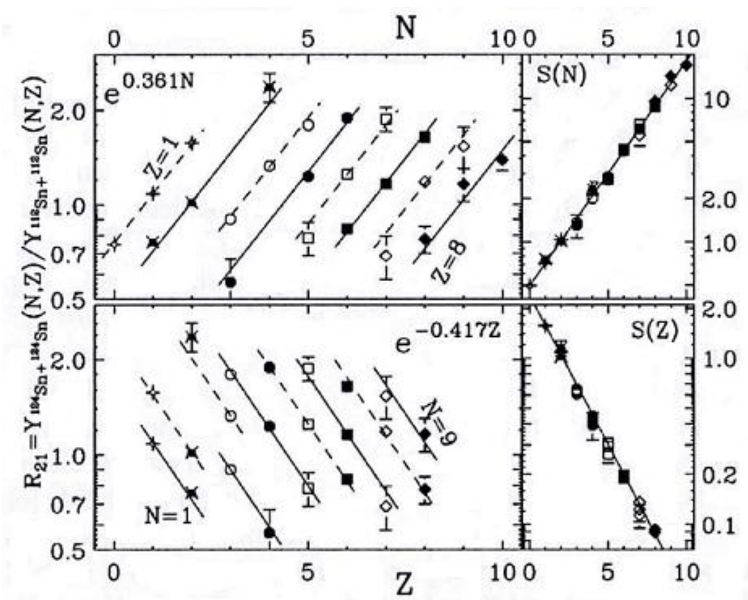




Danielewicz, Lacy, Lynch, Science 298,1592 (2002)

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

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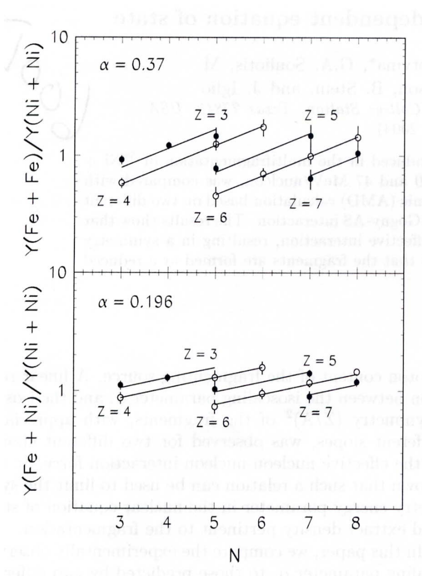
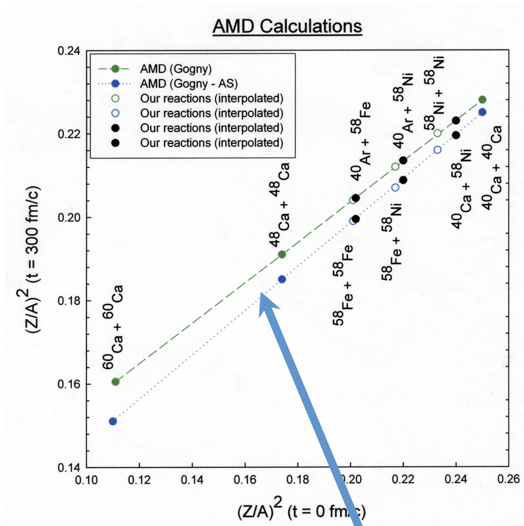
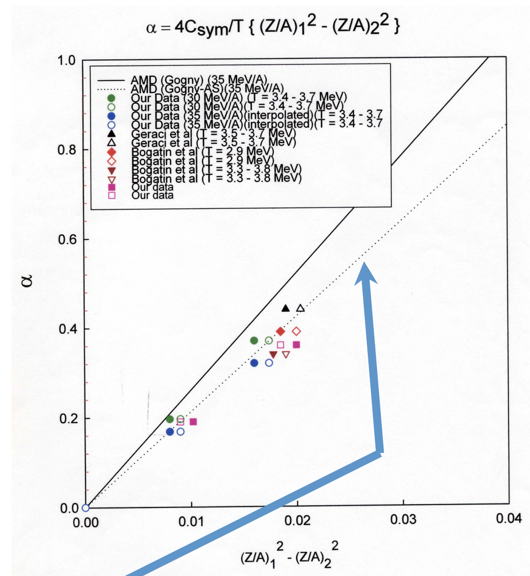
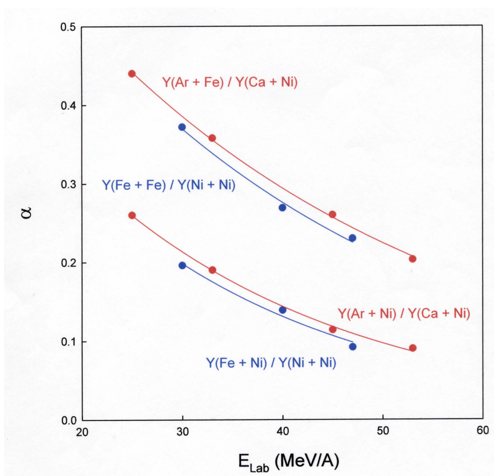
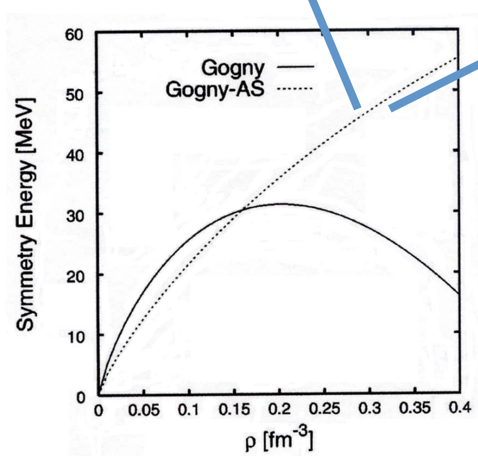
Symmetry energy and the scaling parameter α











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

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

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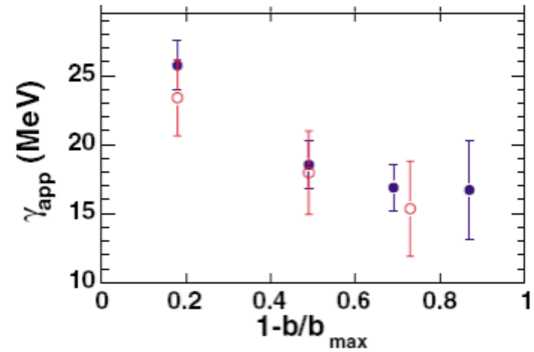
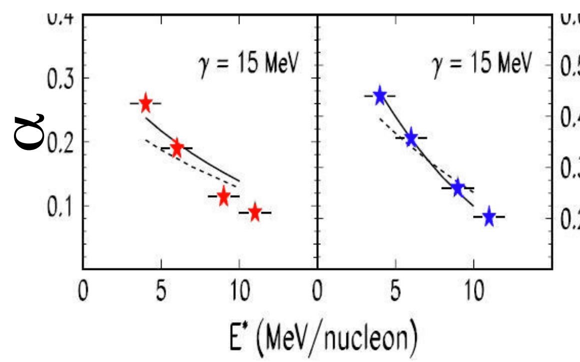
Decrease in Asymmetry energy (Expt. Observation)



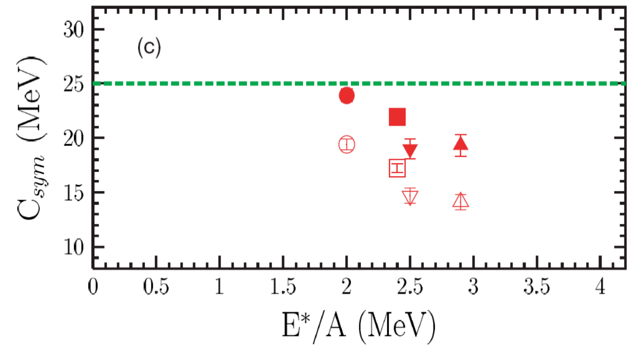
A. Le Fevre et al., PRL 94 (2005) 162701

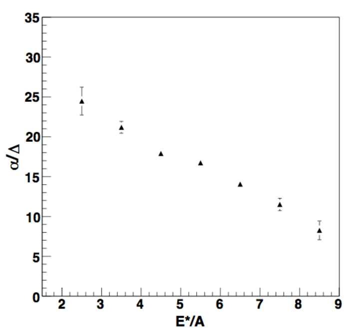


J. Iglio et al., PRC 74 (2006) 024605

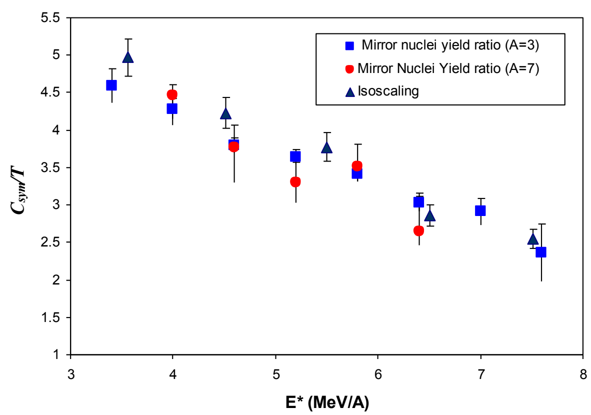
G.A. Souliotis et al., PRC 73 (2006) 024606

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

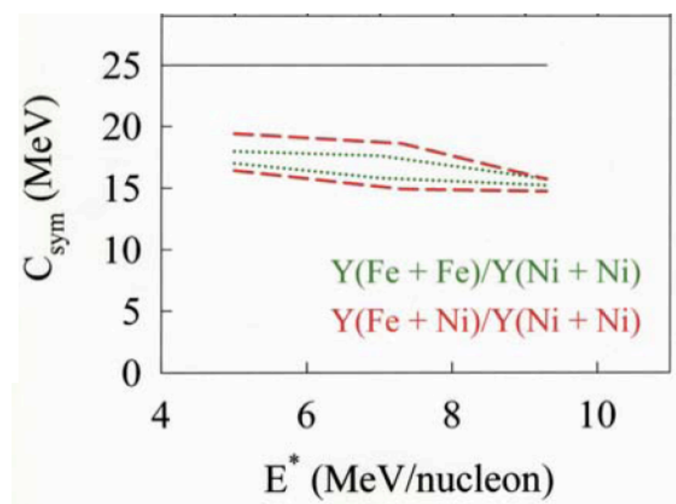




S. Wuenschel, Phys. Rev. C 79, 061602(R) (2009)



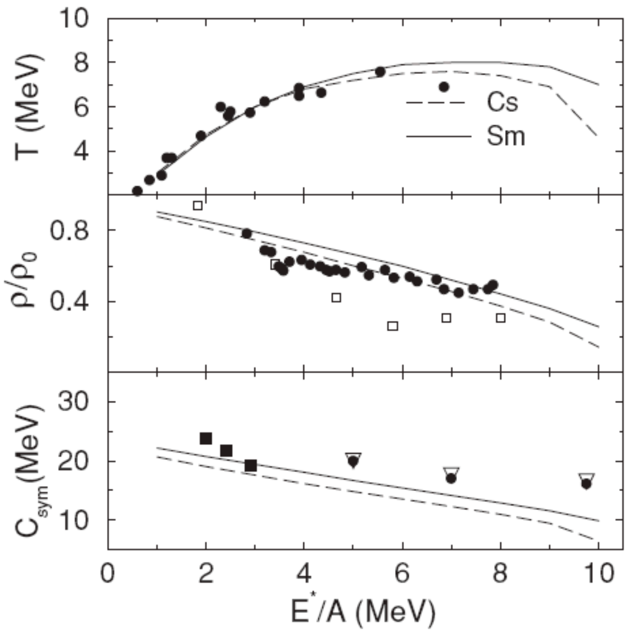
R. Tripathi, Phys. Rev. C **83**, 054609 (2011).
Int. J. Mod. Phys. E 21, 1250019 (2012)



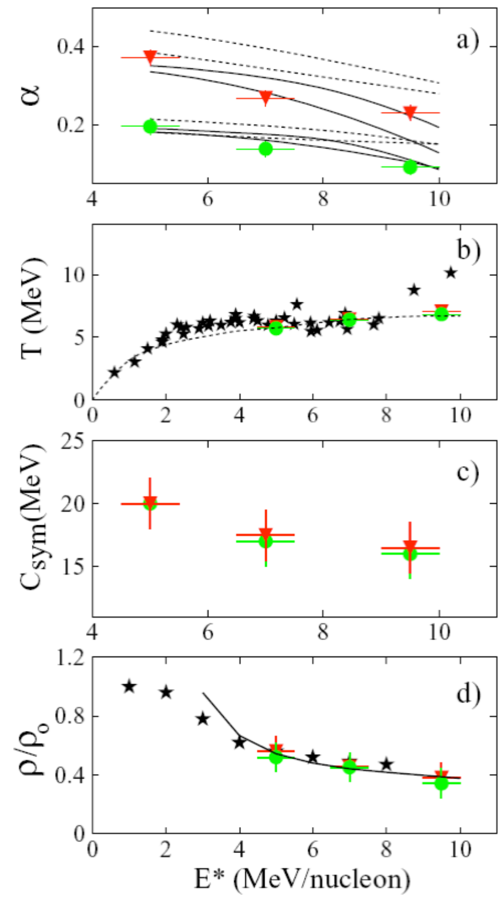
D.V. Shetty et al., PRC 74 (2005) 024602

Decrease in E_{sym} related to thermal expansion

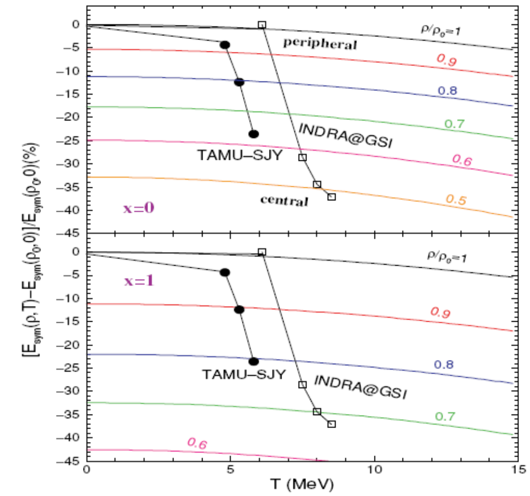
- Finite T Thomas-Fermi Seyler Blanchard interaction



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

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Determination of symmetry energy through dependence of fragment yield ratios on source isospin

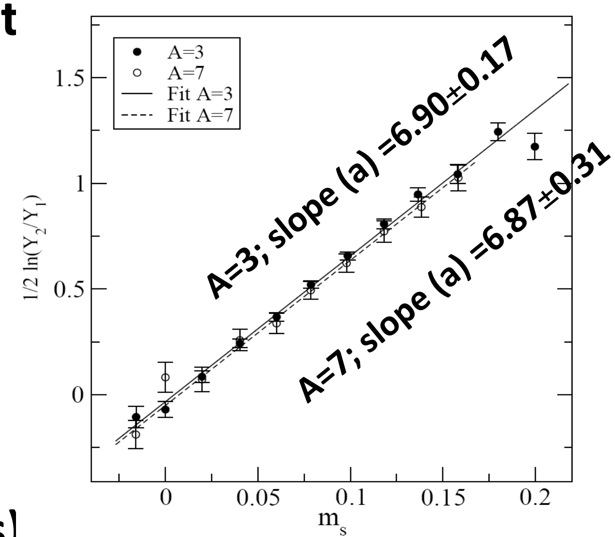
Landau expansion of free energy near the critical point

$$\frac{F}{T} = \frac{1}{2}am^2 + \frac{1}{4}bm^4 + \frac{1}{6}cm^6 - \frac{H}{T}m$$

m (=N-Z)/A: Order parameter

H : External field

$$\frac{H}{T} = am_S\left(1 + Higher\,order\,terms\,in\,'m'\,and\,'m_s'\right)$$

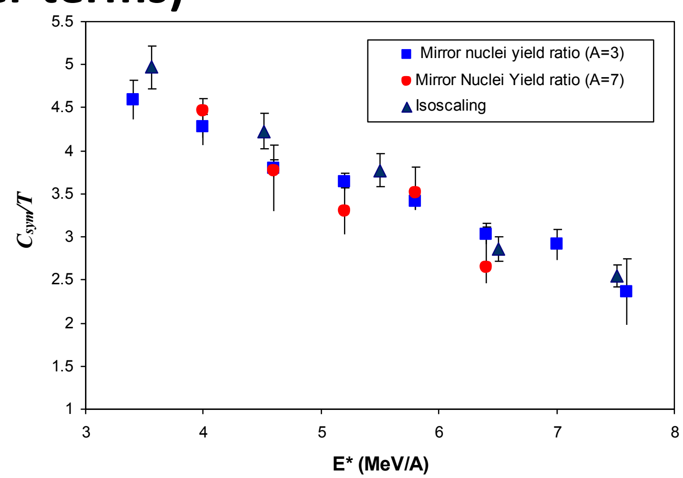


For mirror nuclei yield ratio (ignoring higher order terms)

$$\frac{1}{2}\ln\left(\frac{Y_2}{Y_1}\right) = am_S$$

Source Isospin

$$\frac{C_{Sym}}{T} \approx \frac{1}{2}a$$



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

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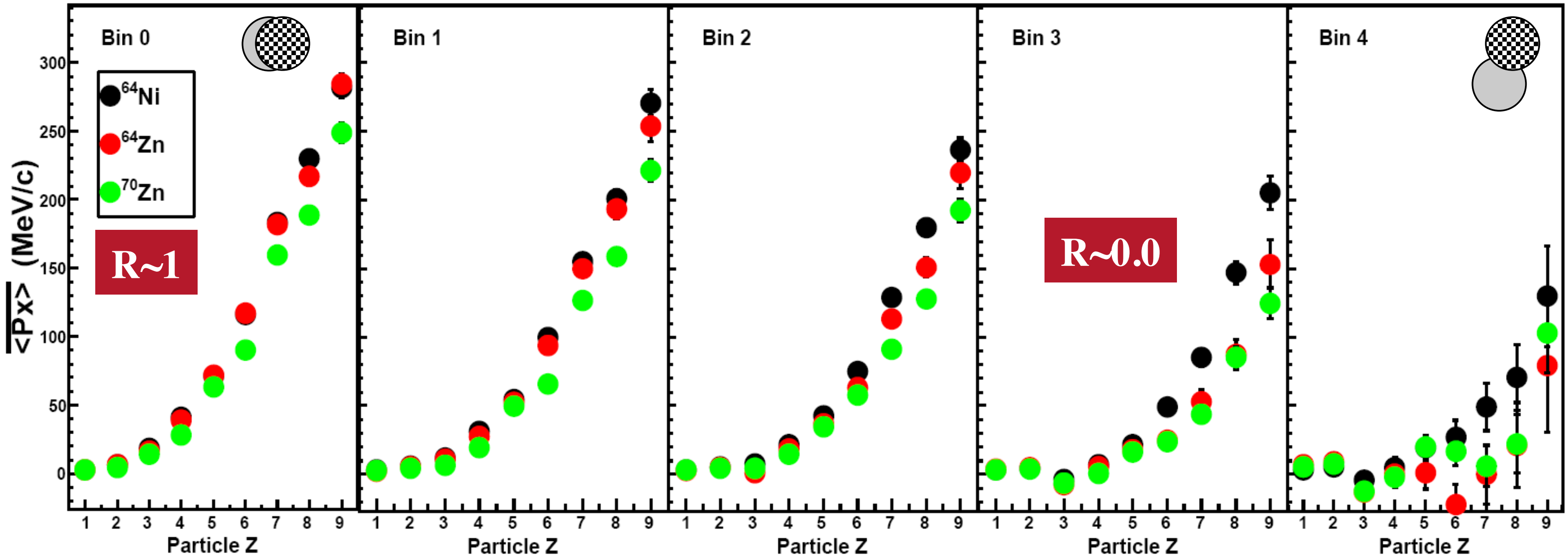
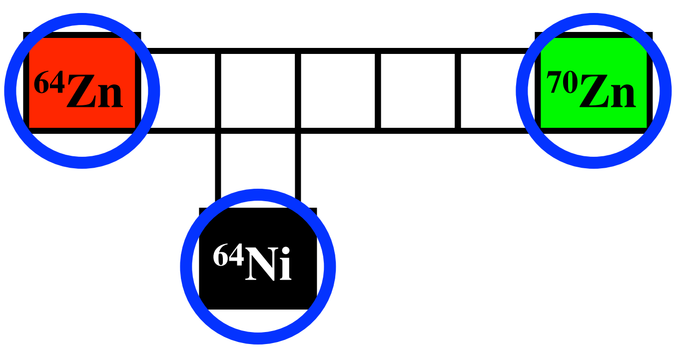
IMF Transverse Flow



Mass Dependence → *Charge Dependence*



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

Kohley, PRC85(2012)

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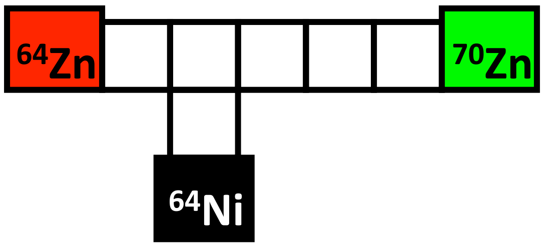
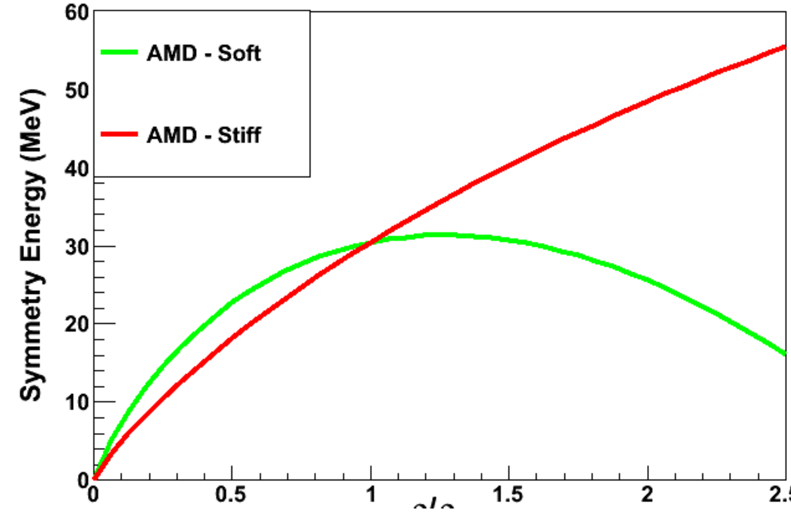
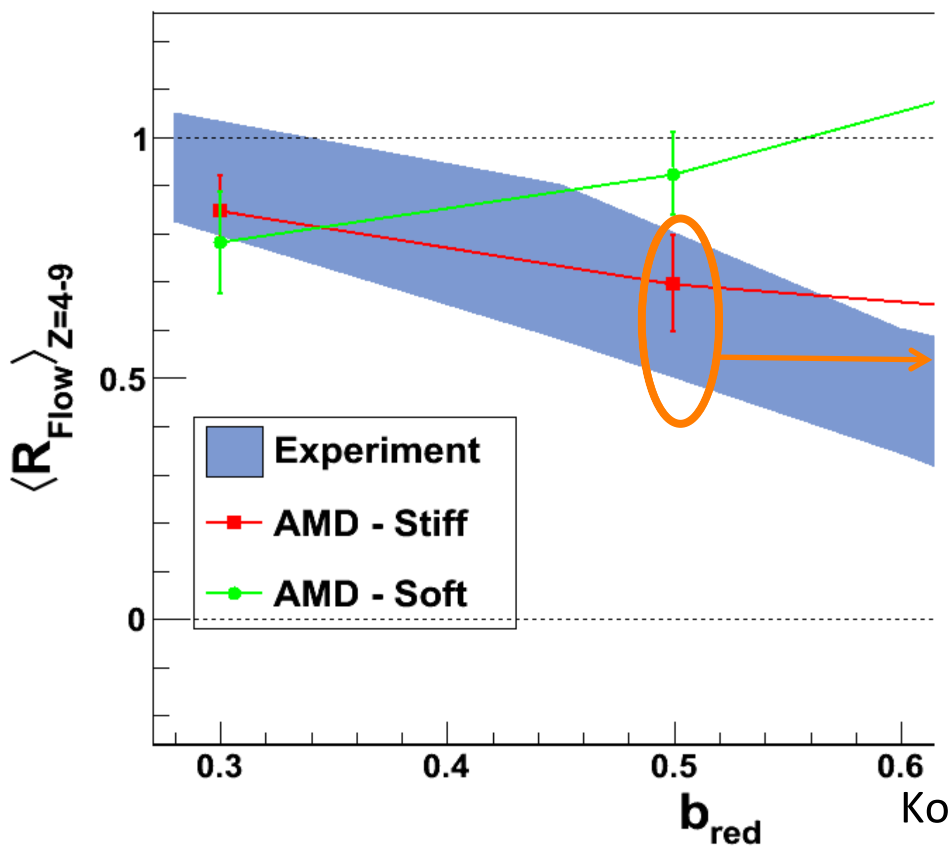
IMF Transverse Flow

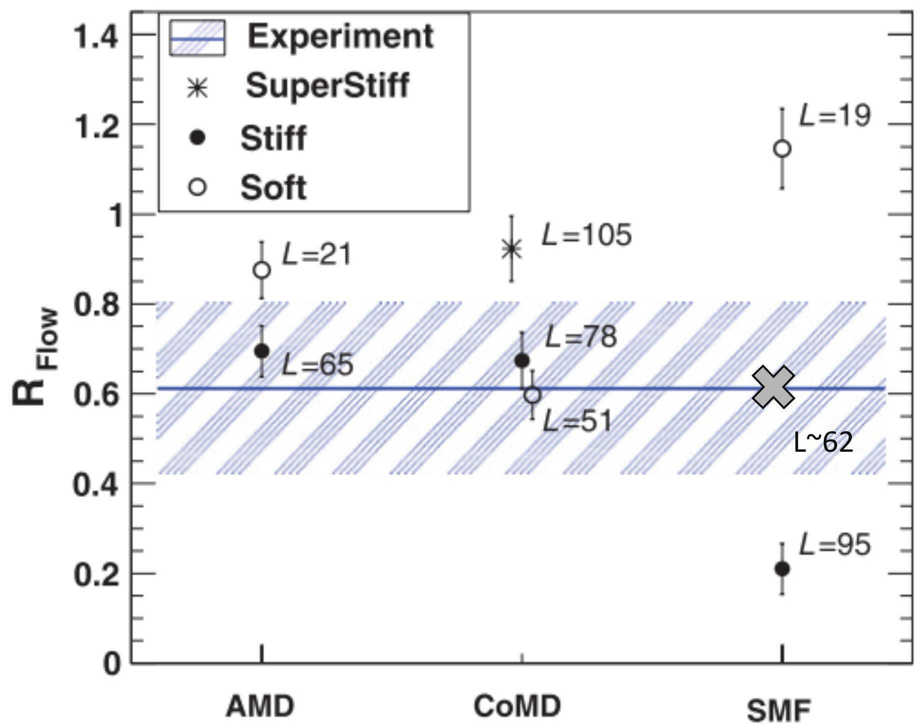
$$R_{Flow} = \frac{\overline{\langle Px/A \rangle}_{^{64}Zn} - \overline{\langle Px/A \rangle}_{^{70}Zn}}{\overline{\langle Px/A \rangle}_{^{64}Ni} - \overline{\langle Px/A \rangle}_{^{70}Zn}}$$



Comparison to AMD Model



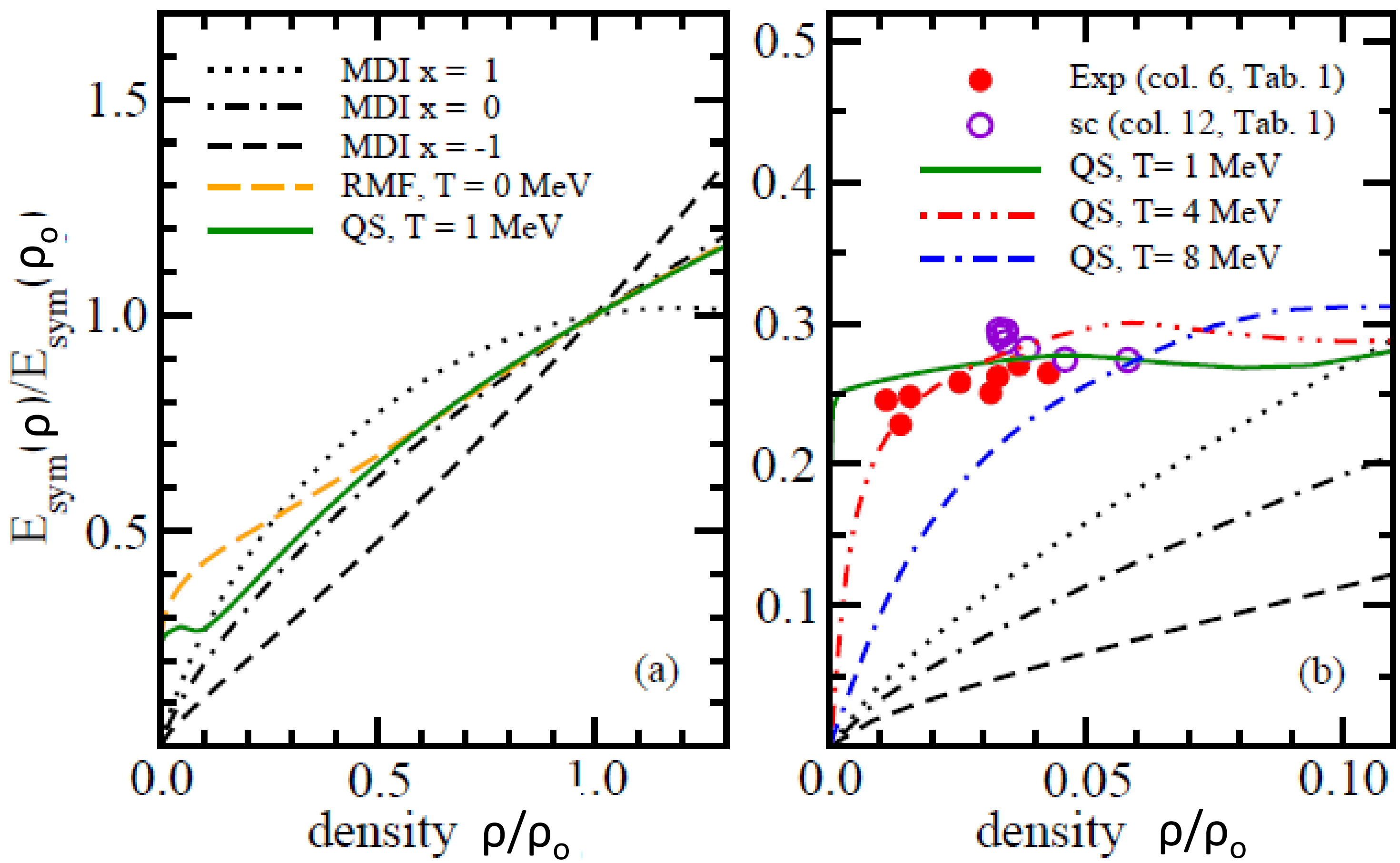




Kohley, PRC85(2012)

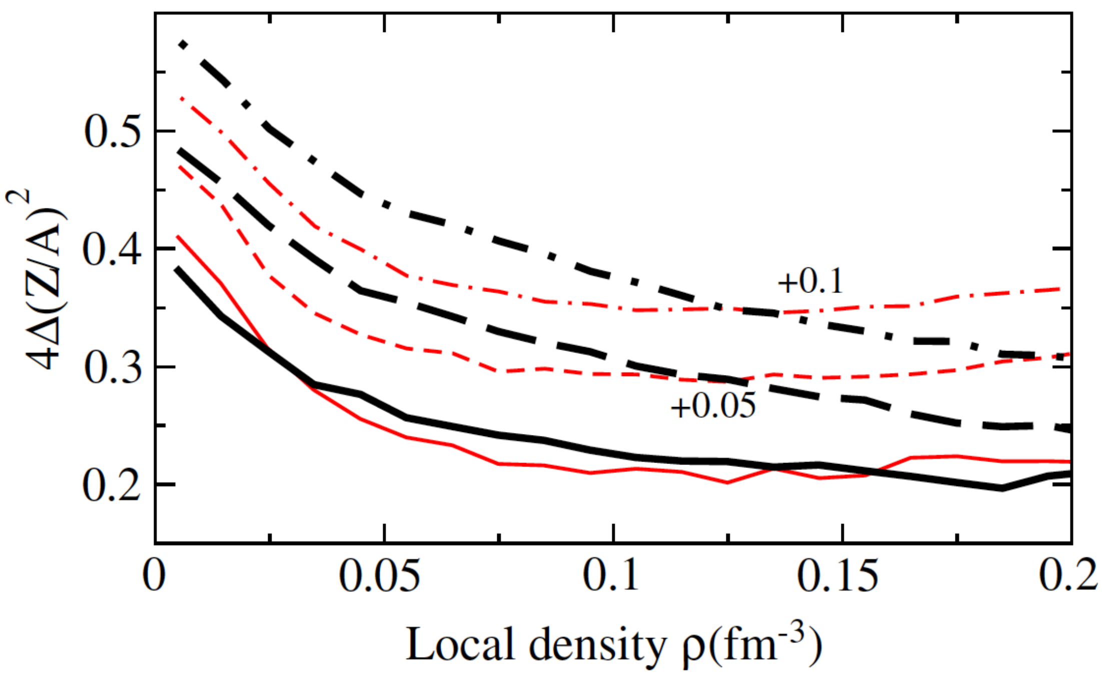
Symmetry energy of dilute warm nuclear matter

Clusters important for low density matter



Phys.Rev.Lett.104:202501,2010

Fluctuations and Symmetry Energy in Nuclear Fragmentation Dynamics



The amplitude of isovector fluctuations follows the evolution of the local density and approaches the corresponding local equilibrium value that is linked to the density-dependent symmetry free energy. Thus, fragment isospin fluctuations and isoscaling parameters are related to the symmetry energy at the fragment formation density.

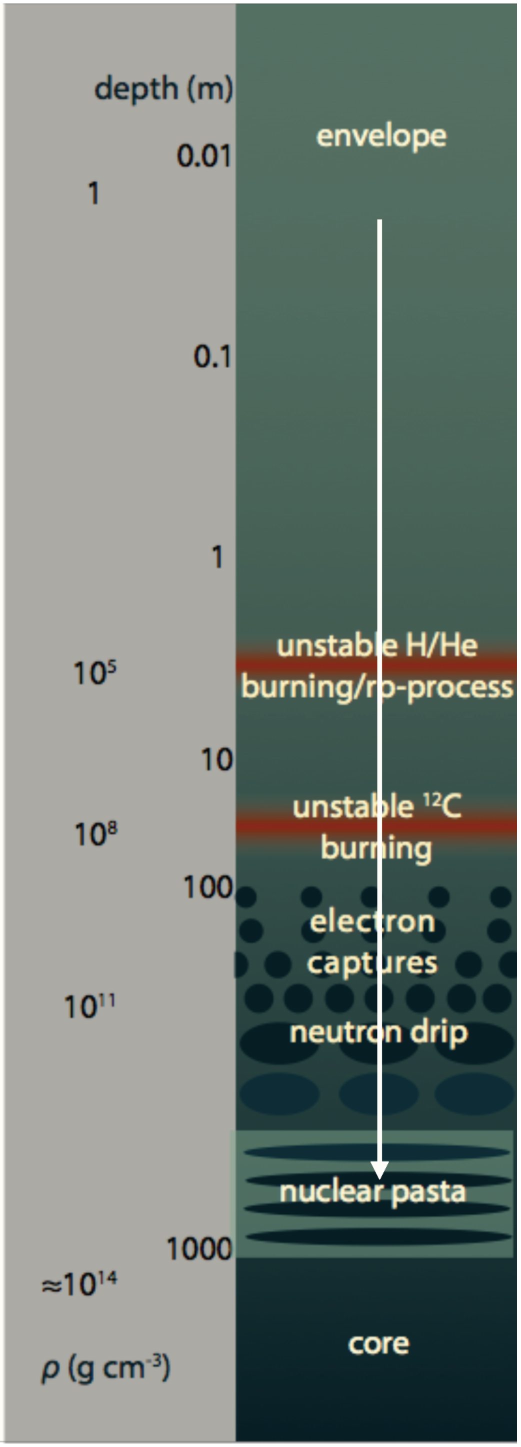
M. Colonna, PRL 110, 042701 (2013)

Why neutron star crusts?

A. Piro, Carnegie Obs.

Accretion pushes matter through the crust and induces reactions.

These reactions produce a wealth of observable phenomena over a wide range of timescales.



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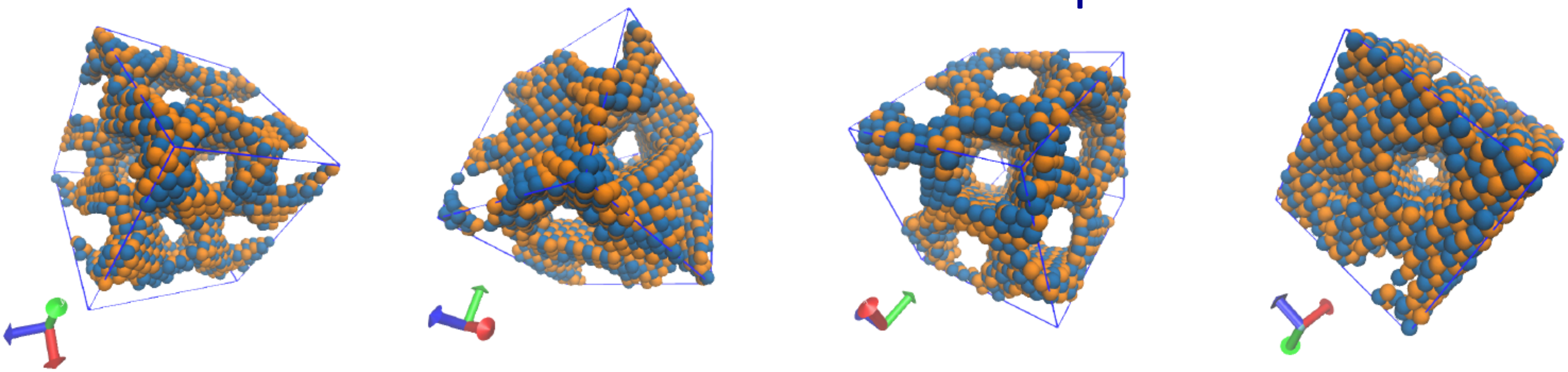
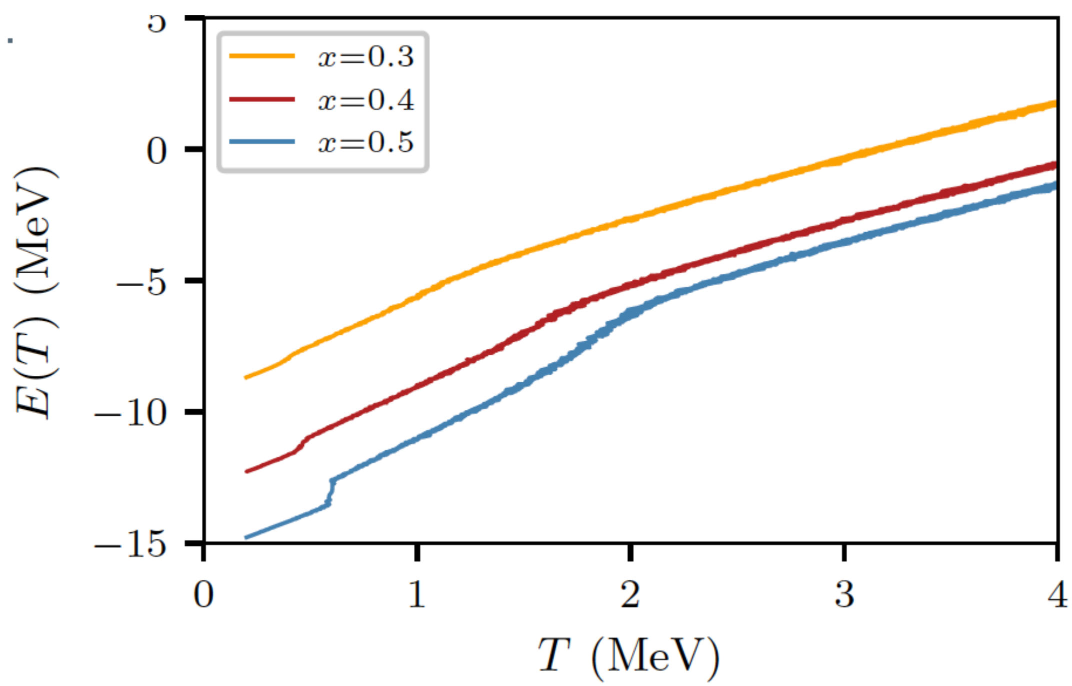
NSF Physics Frontier Center

Phase transitions in nuclear pasta



(a) $\rho = 0.05$ (b) $\rho = 0.06$ (c) $\rho = 0.07$ (d) $\rho = 0.085$



Dorso, 2018

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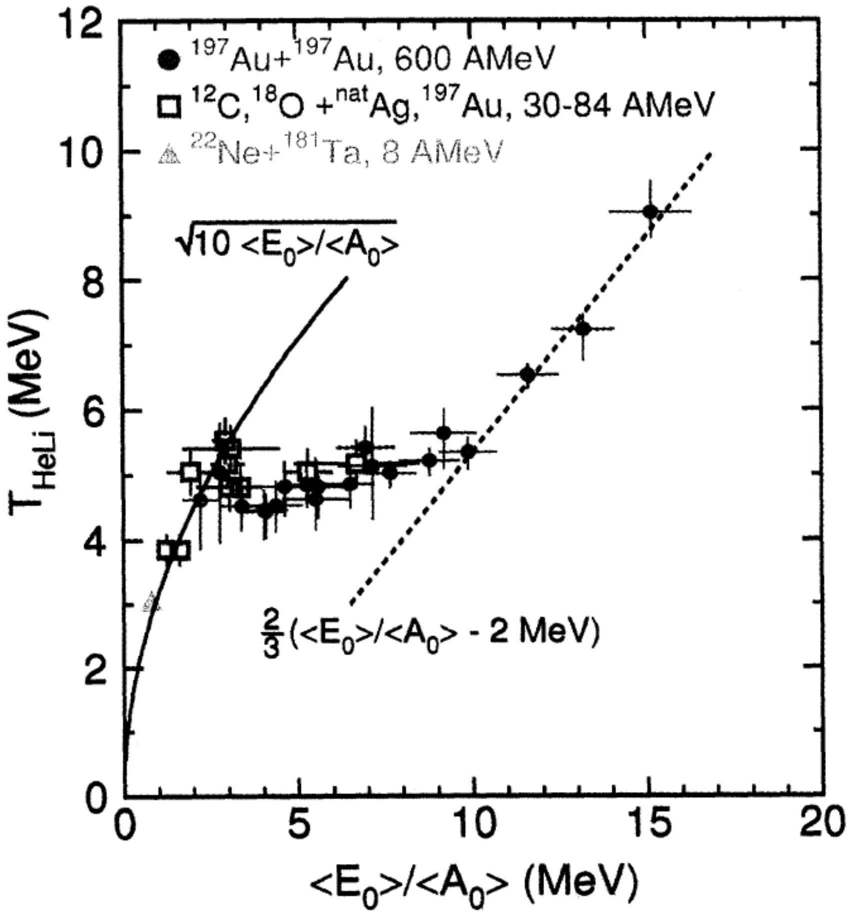
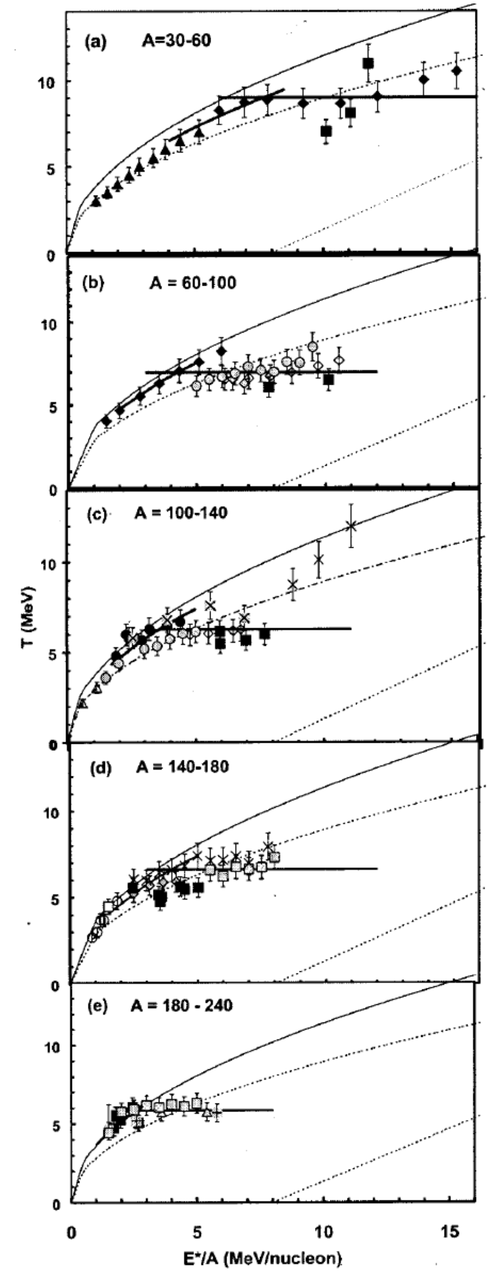
Nuclear Caloric Curve





Pochodzalla et al. PRL 75, 1040 (1995)

Natowitz et al. PRC, 034618 (2002)

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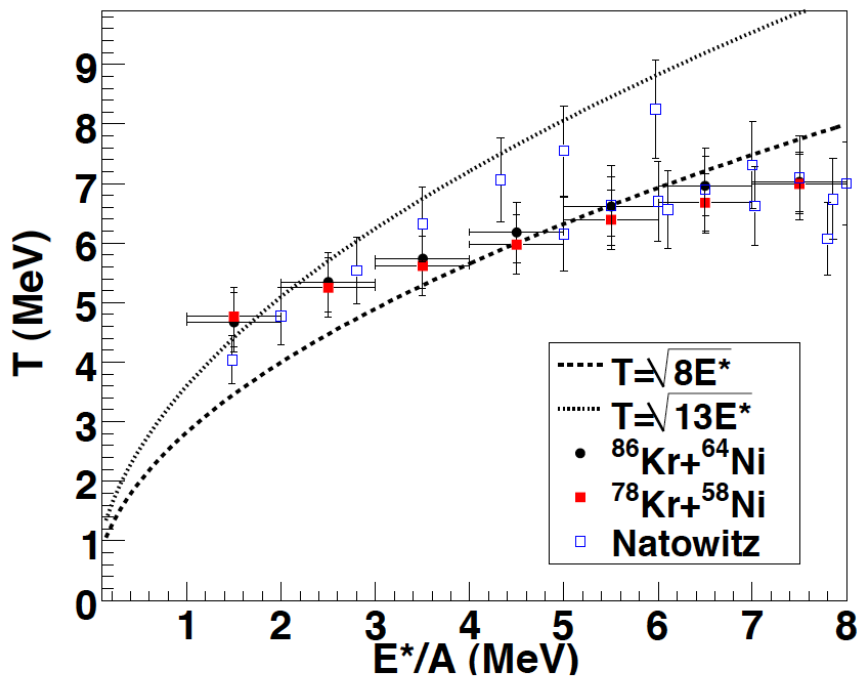
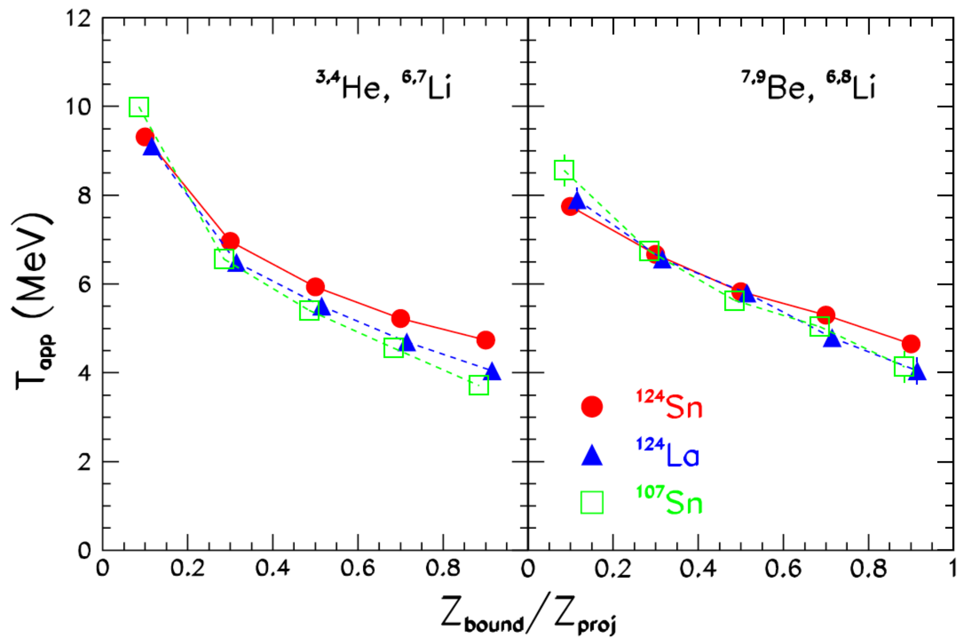
Caloric Curve: Asymmetry Dependence?

Experiment



S. Wuenschel, Ph.D. Thesis, 2009



Sfienti et al., PRL 102, 152701 (2009)

Slight offset of neutron-rich system, but not statistically significant

Possible dependence on asymmetry, depends on impact parameter and thermometer.

Selection was on the system composition.
Should use **reconstructed-source composition**

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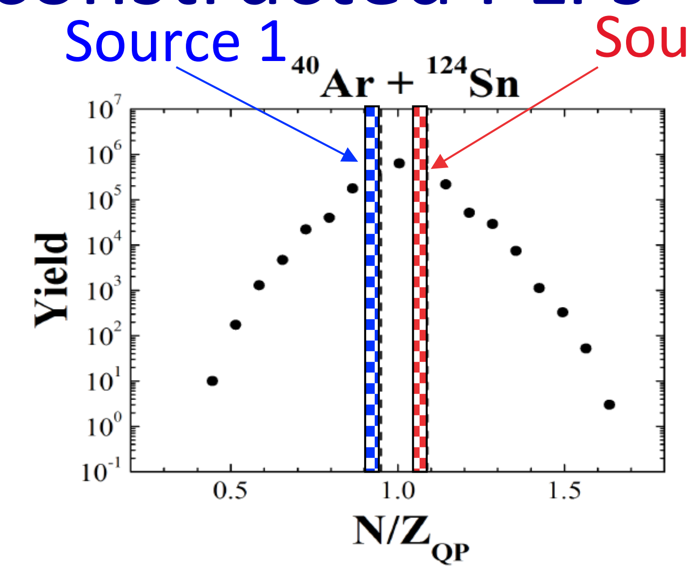
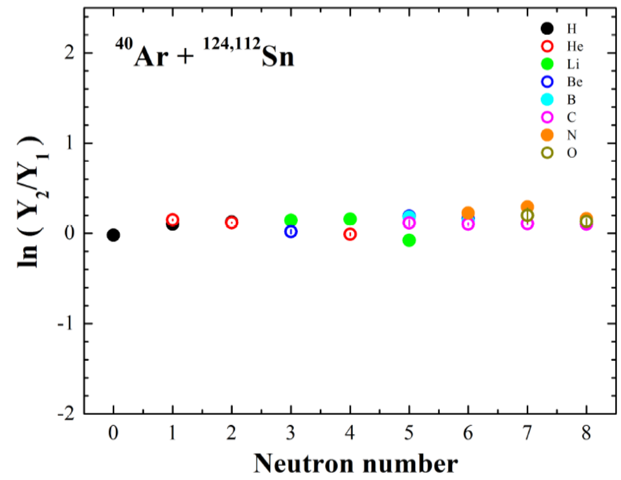
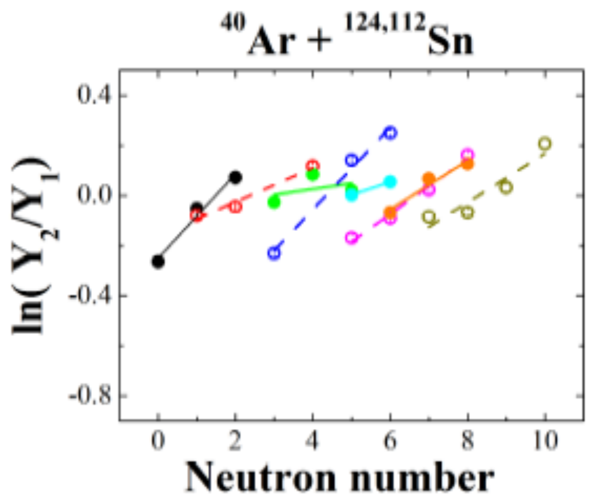
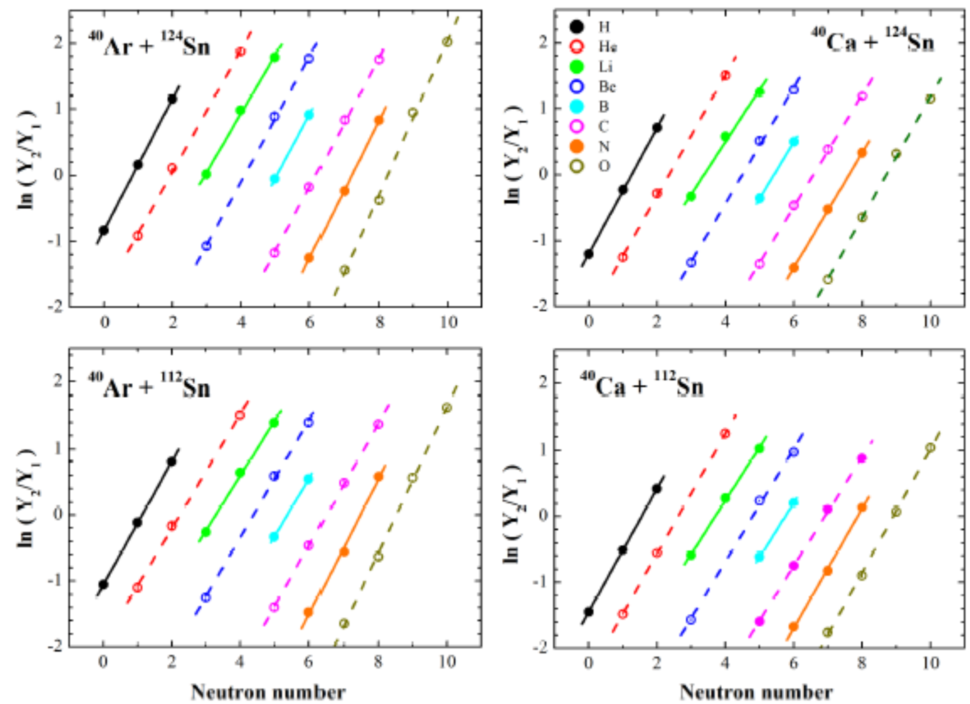
Reconstructed PLFs









Galanopolus, Nucl Phys A 837, 145 (2010)

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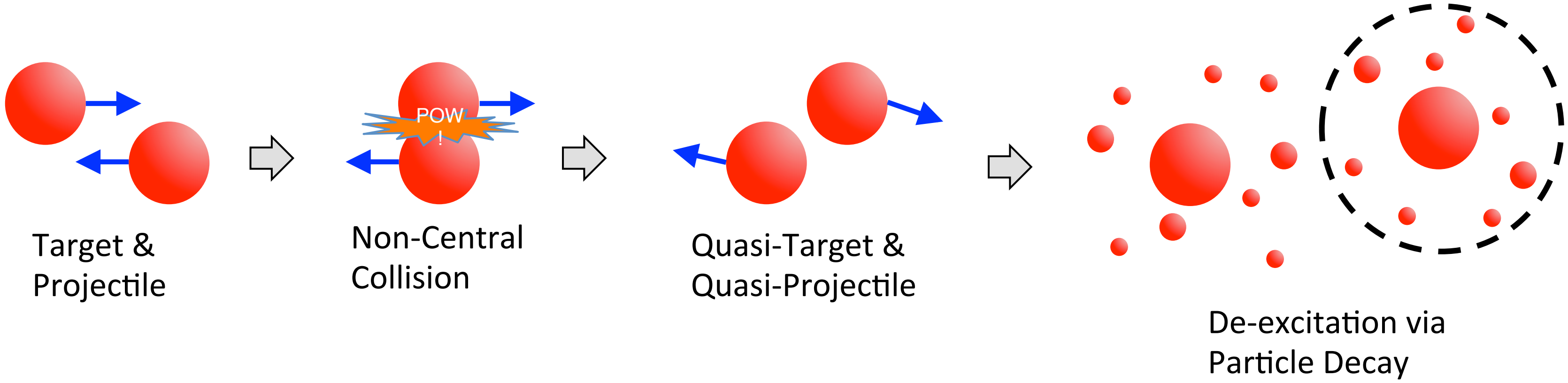
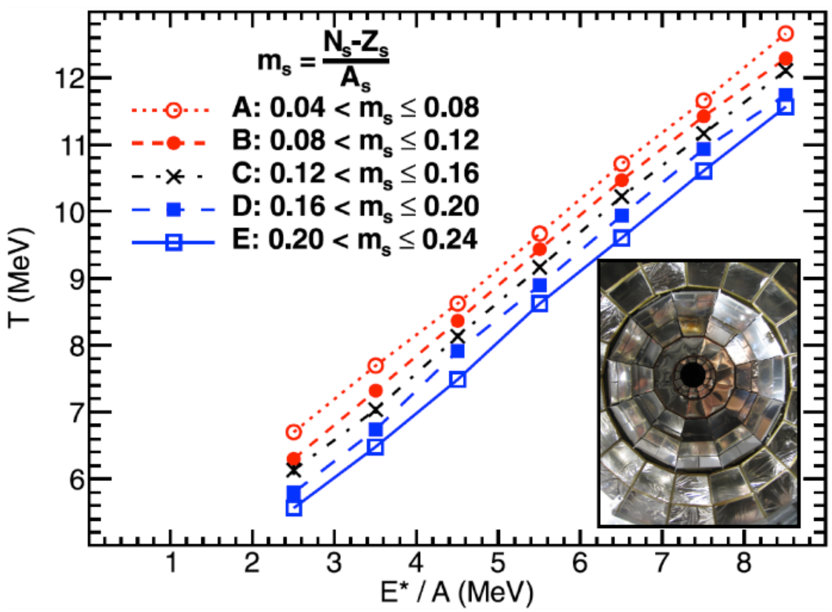
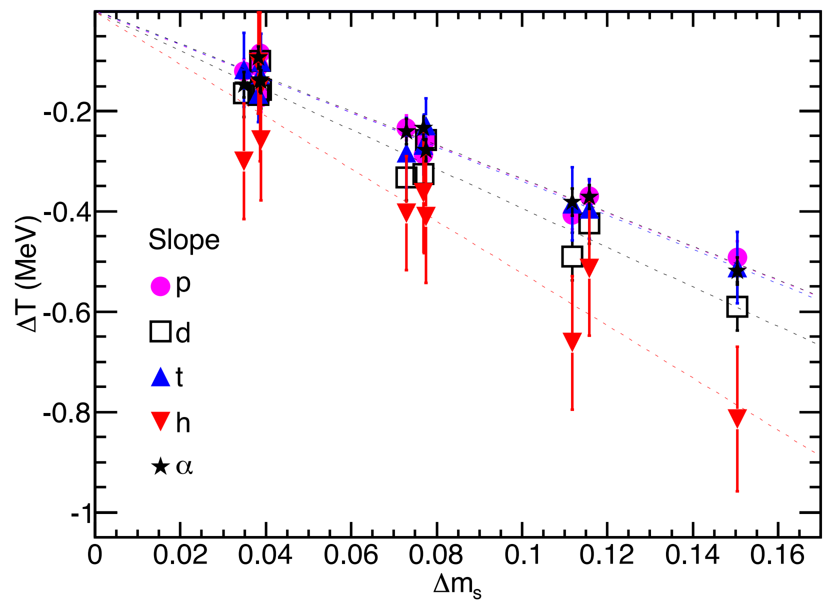
Asymmetry Dependence of the Nuclear Caloric Curve







McIntosh, PLB **719**, 337 - 340 (2013)

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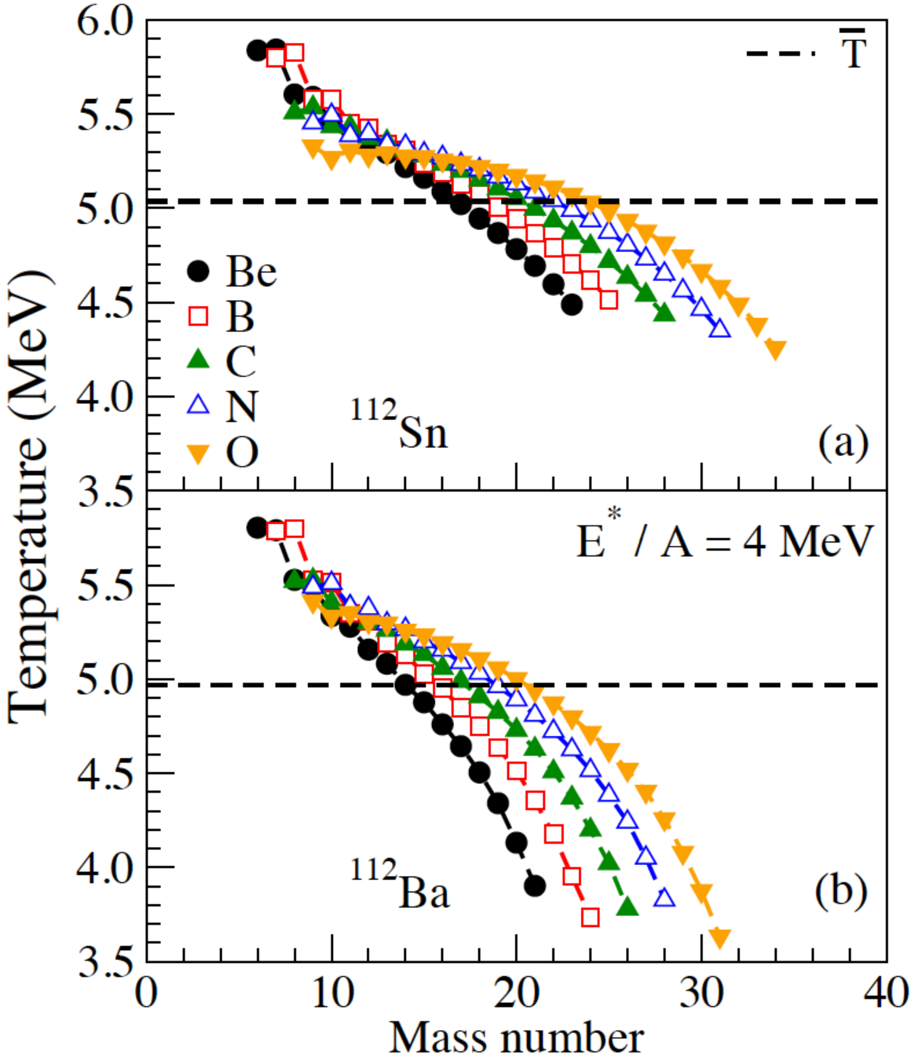
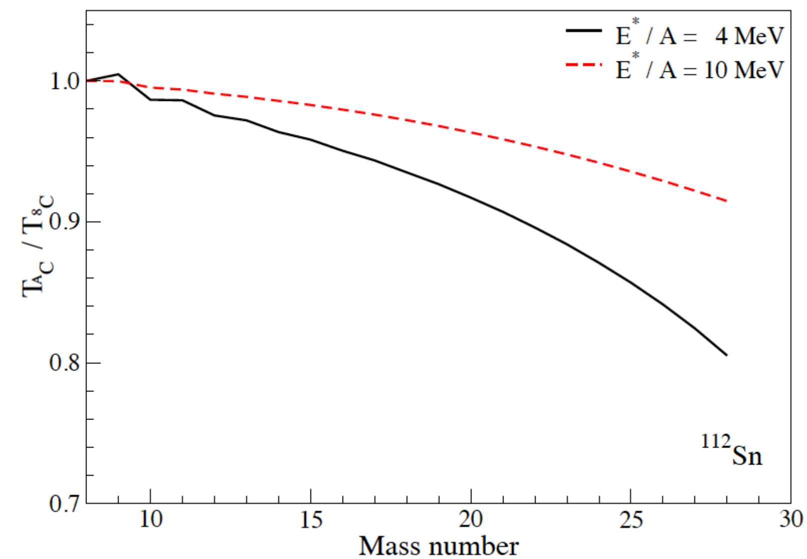
Isotopic dependence of the fragments' internal temperatures observed in multifragment emission





SMM-DE, emphasizing the discretization of the energy.

S.R. Souza, 2017

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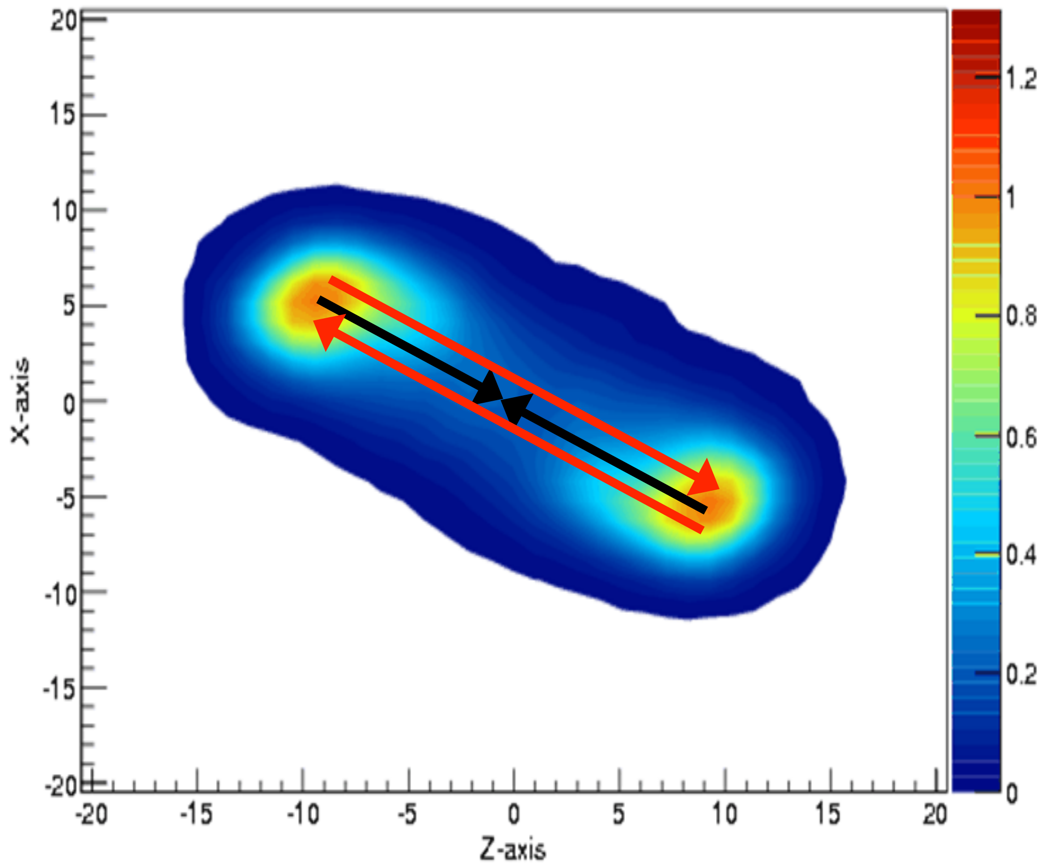
Isospin Transport

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)

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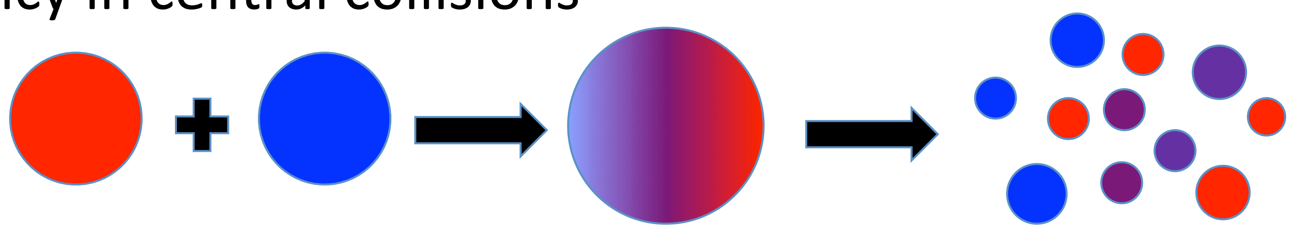
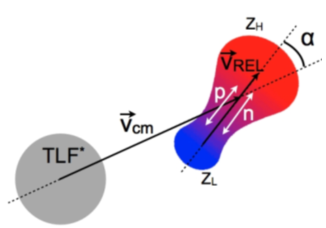
Isospin Equilibration can be studied in multiple ways

Translucency in central collisions



Diffusion between target and projectile in peripheral collisions

Transport in deformed nuclear systems



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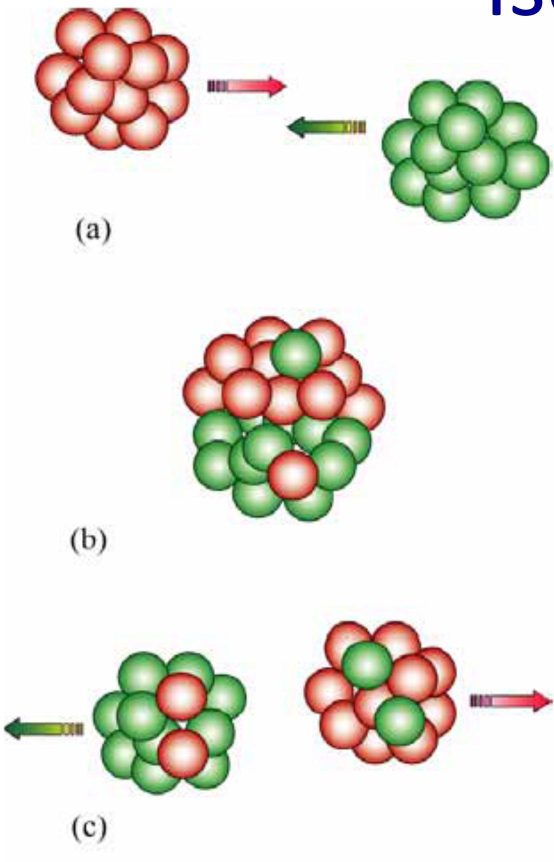
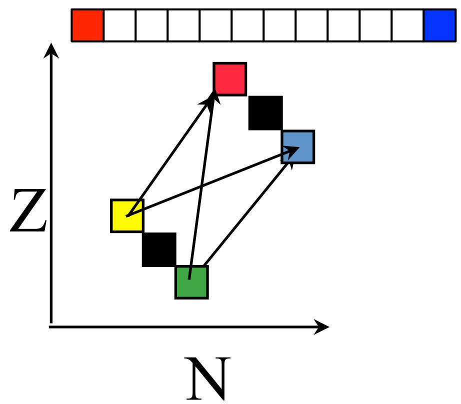
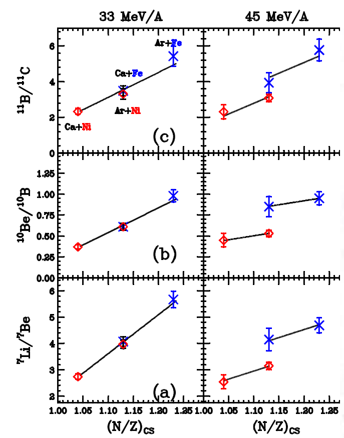
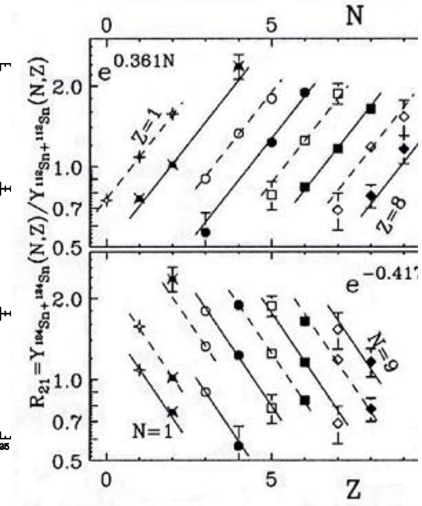
Isospin Equilibration / Diffusion









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)

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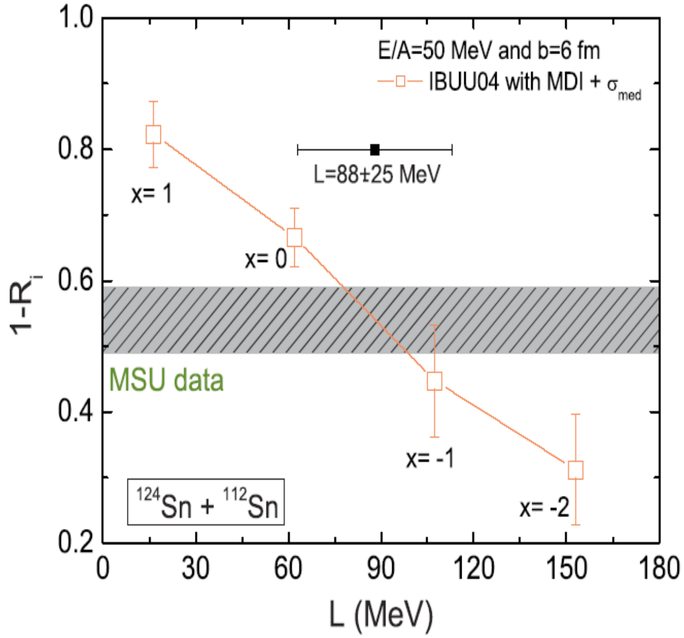
iBUU Isospin tracer results

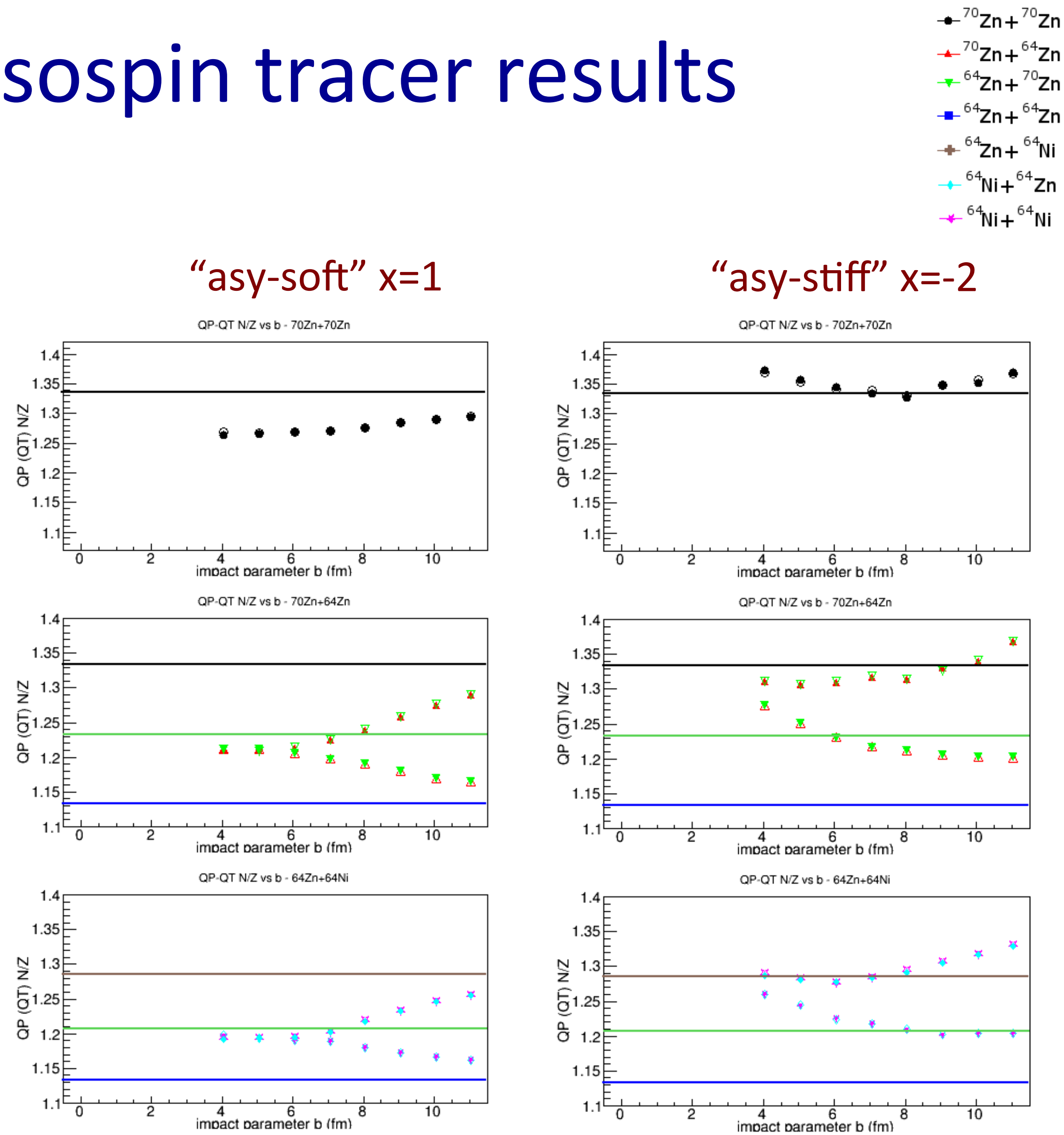
$^{112,124}Sn+^{112,124}Sn$

Tsang, PRL 92 (2004)



Chen/Ko/Li, PRC72,064309 (2005)

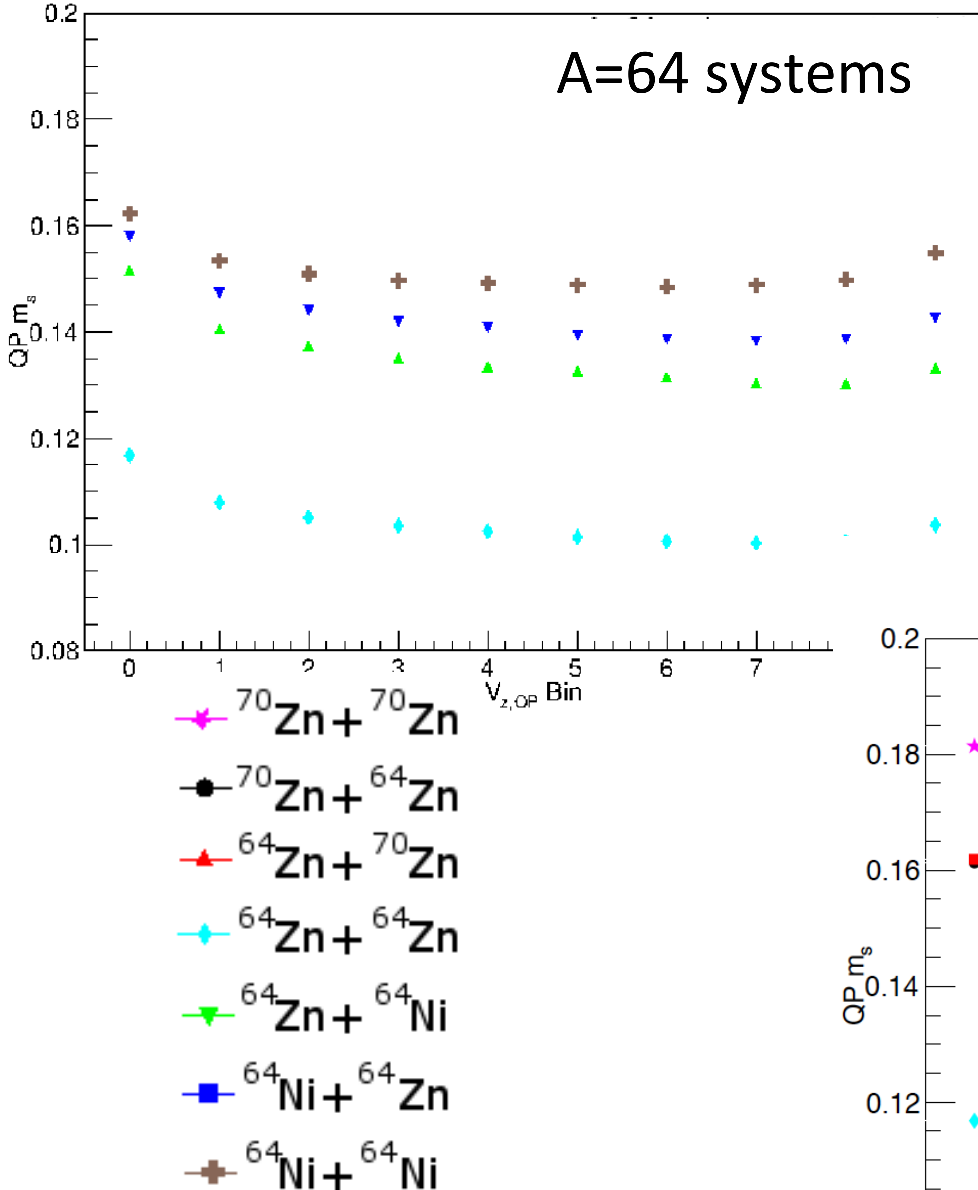
"asy-soft" x=1 "asy-stiff" x=-2



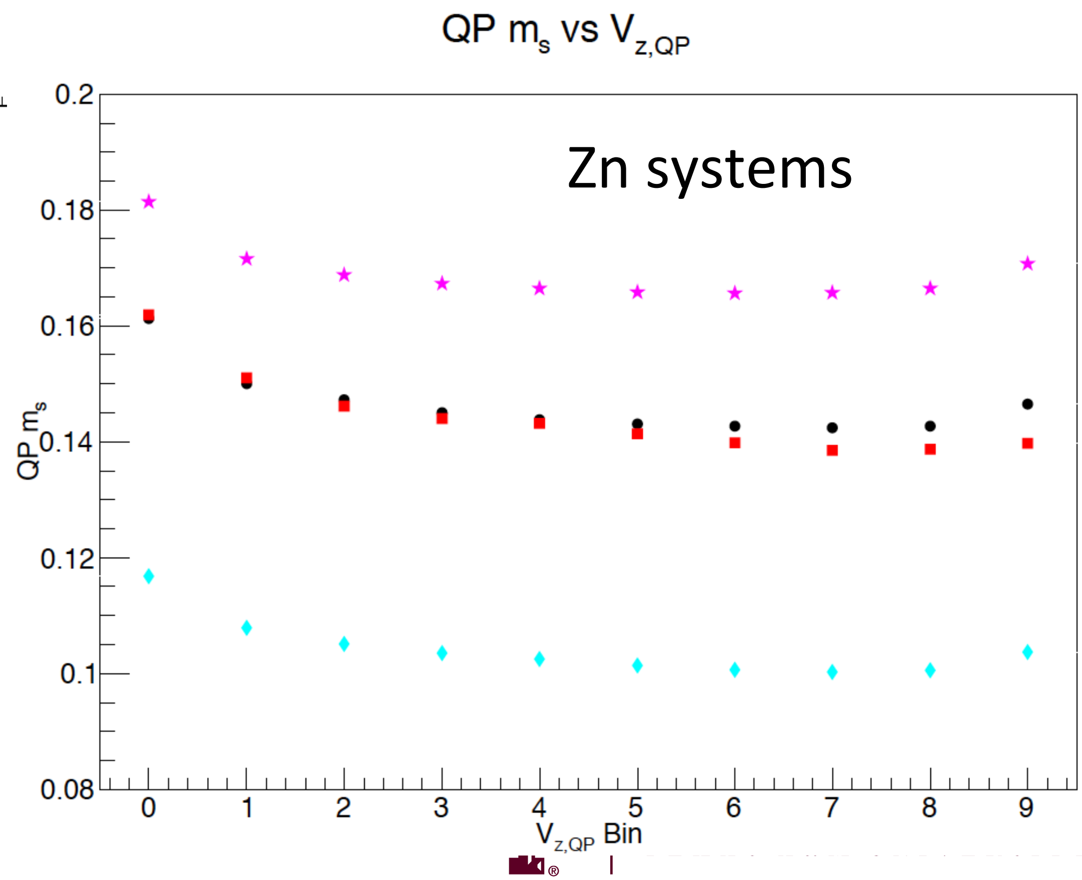
Lines are values for the composite system N/Z

L. May , PhD 2015

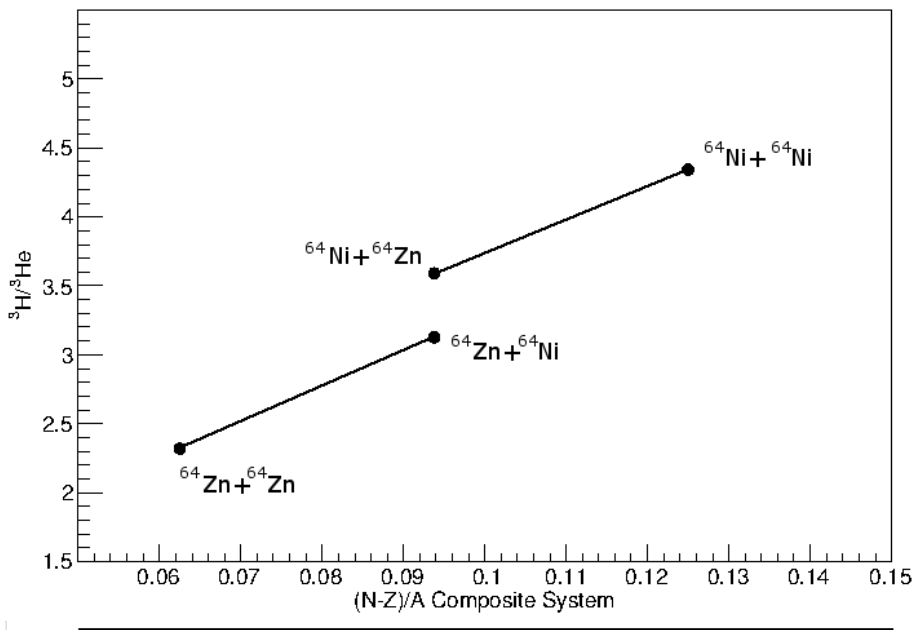
QP_{ms}

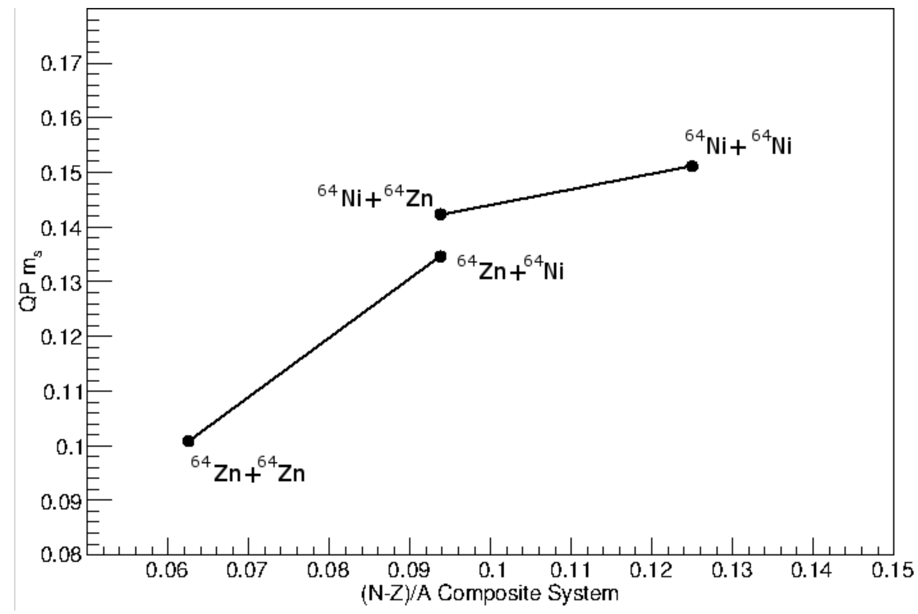


Zn systems show much more equilibration then A=64 systems



L. May 2018

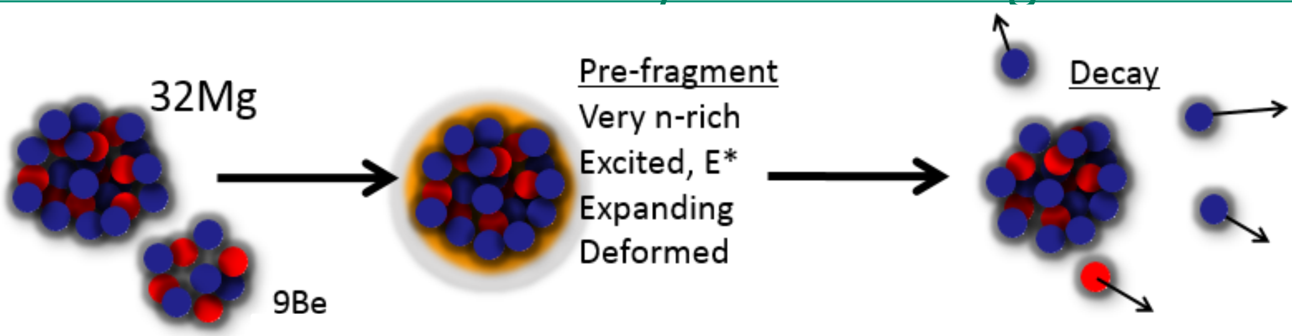




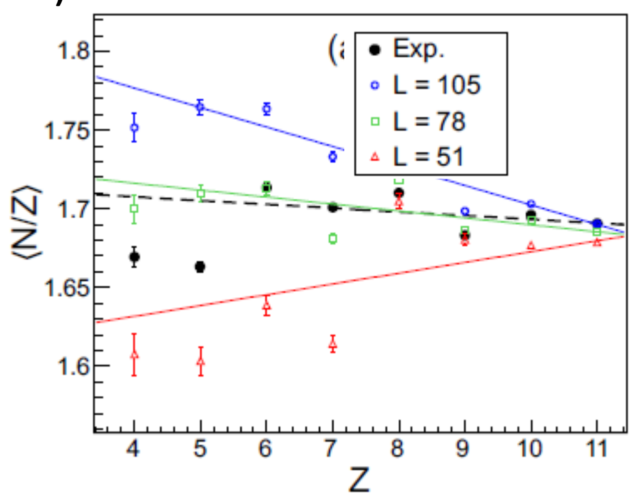
Equilibration observable	35 MeV/nucleon ^{70,64}Zn+^{70,64}Zn	35 MeV/nucleon ^{64}Zn,Ni+^{64}Zn,Ni	50 MeV/nucleon ^{124,112}Sn+^{124,112}Sn [20]
Isoscaling α (Z=4-8)	77±5%	83±5%	54%
Isoscaling α (Z=4-14)	76±7%	85±7%	-
^{3}H/^{3}He ratio	72±4%	77±4%	-
QP m_s	96±5%	85±5%	-

Detect PLF directly

Measure neutrons and N/Z of PLF using MoNA-

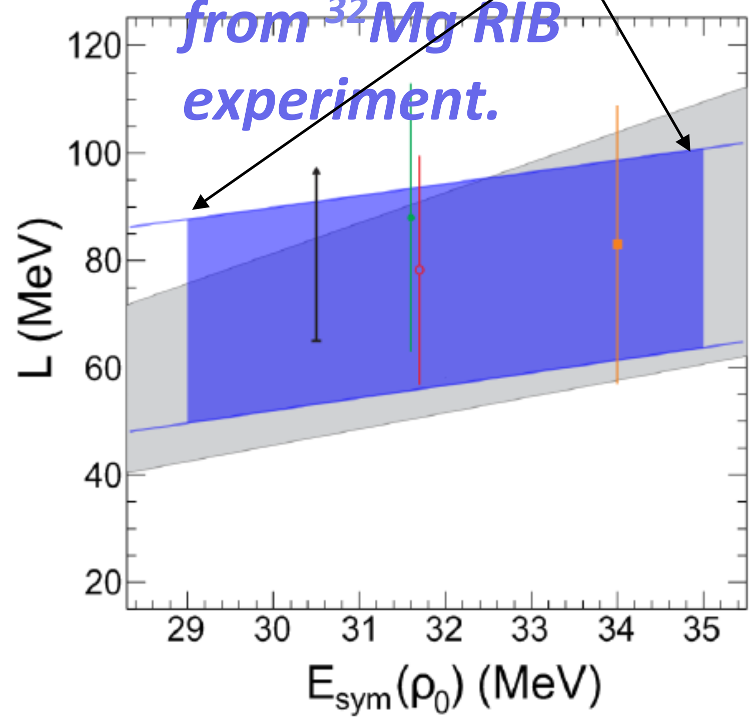


Compared to Constrained Molecular Dynamics (CoMD-II) model: *M. Papa et al. PRC **64,** 24612, (2001).*

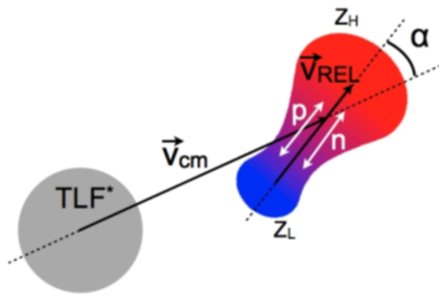


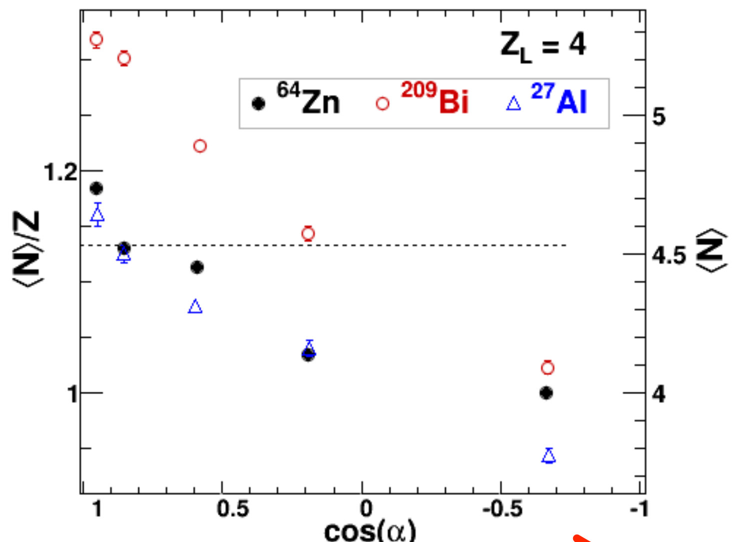
Kohley et al. PRC 88, 041601(R) (2013).

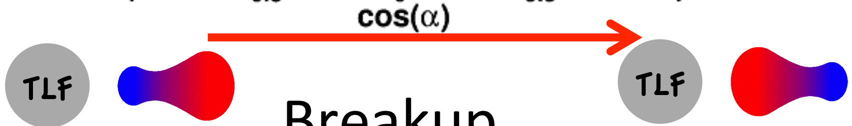
Purple area new constraints extracted from ^{32}Mg RIB experiment.



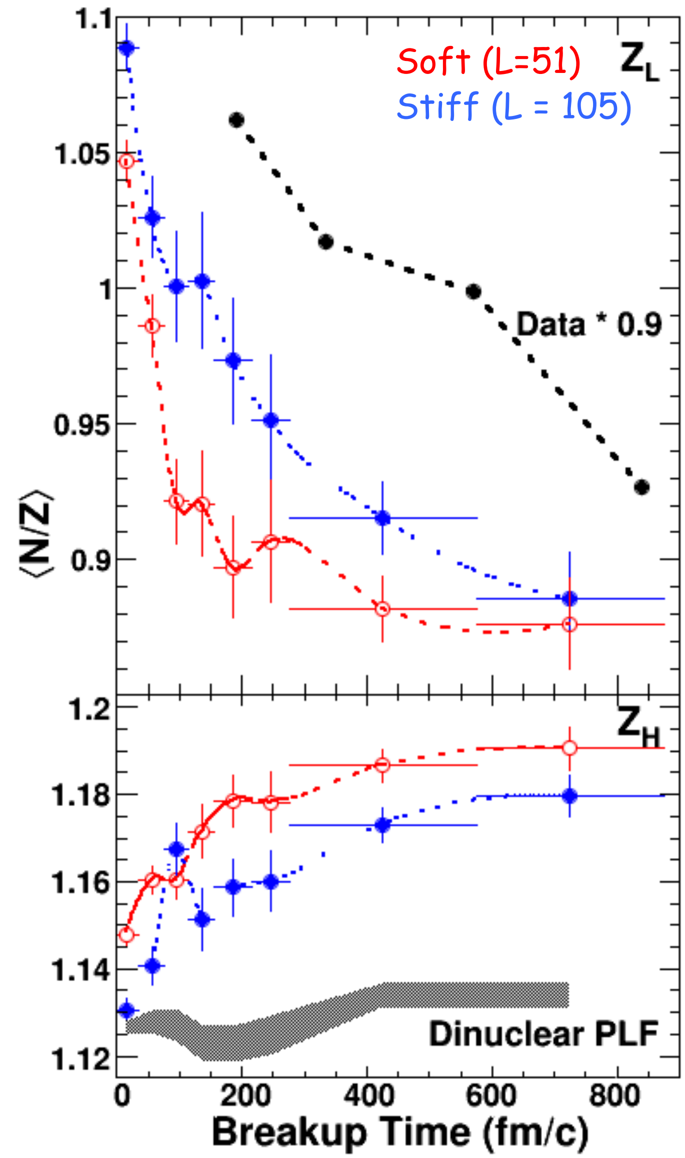
N/Z transport within a deformed nuclear system







Breakup
time



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

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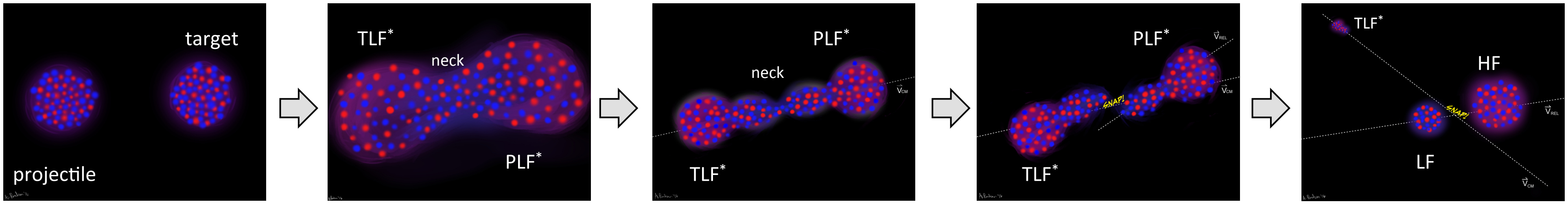
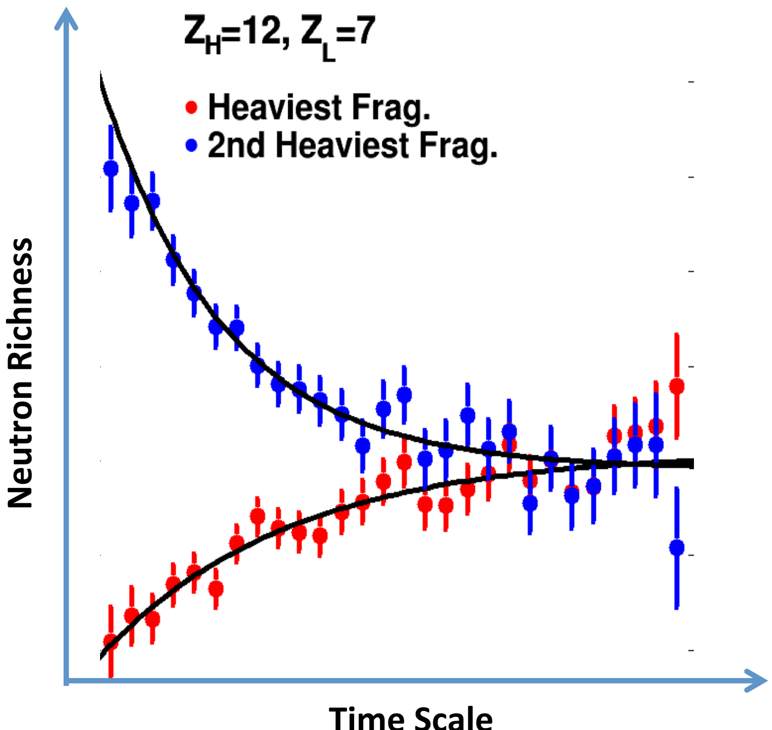
Equilibration Chronometry

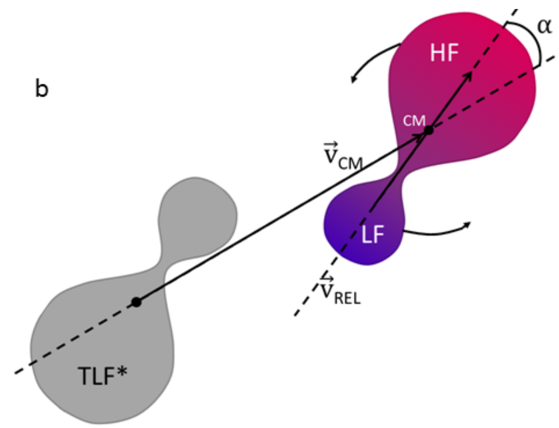
Characterizing neutron-proton equilibration with sub-zeptosecond resolution





t=0

t ≈ 1.5z
(450fm/c)



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

Equilibration curve is approximately exponential

→ First order kinetics

Zeptosecond timescale.

Jedele, 118, 062501 (2017)
Rodriguez Manso, PRC 95, 044604, 2017

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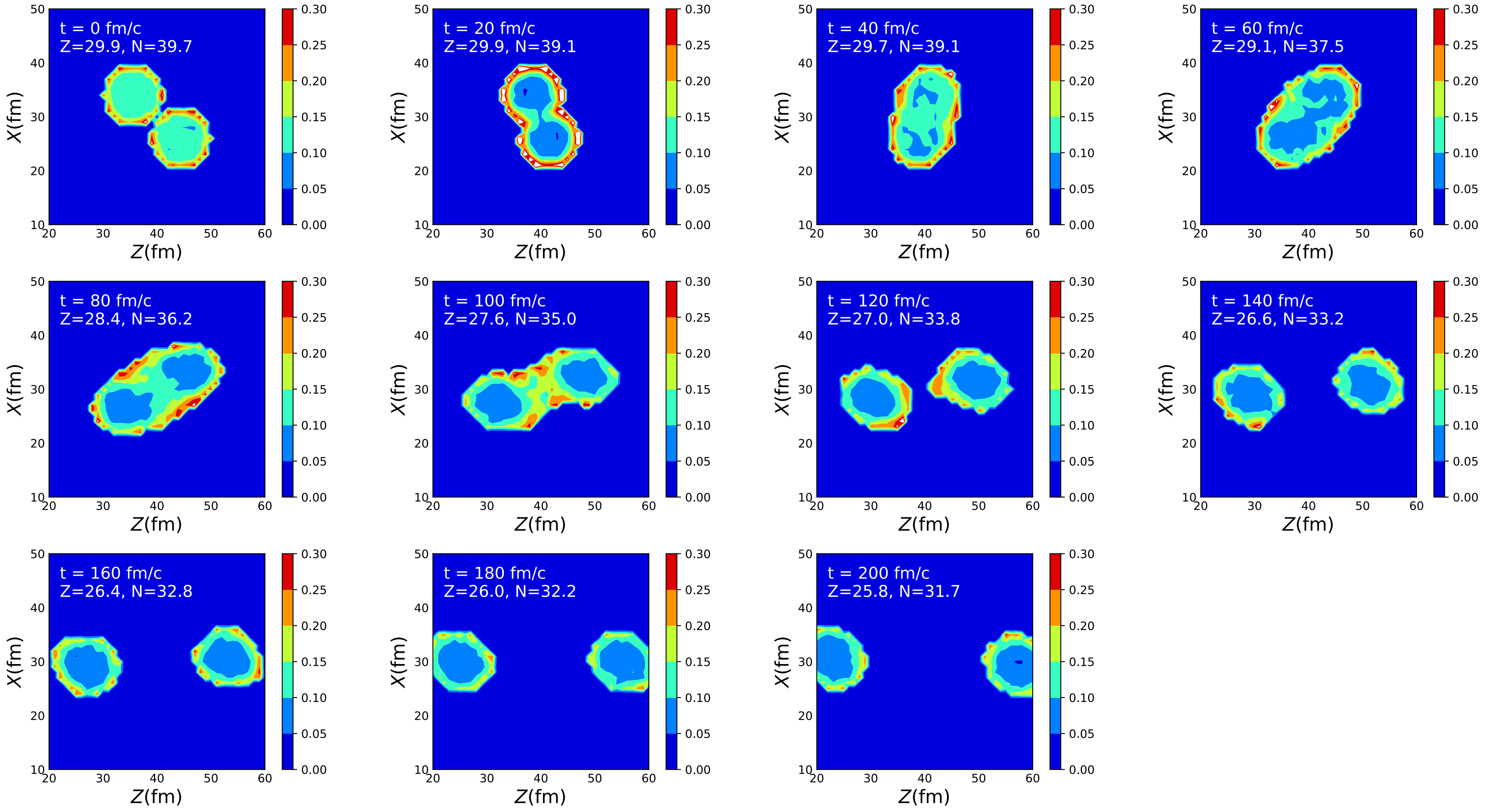
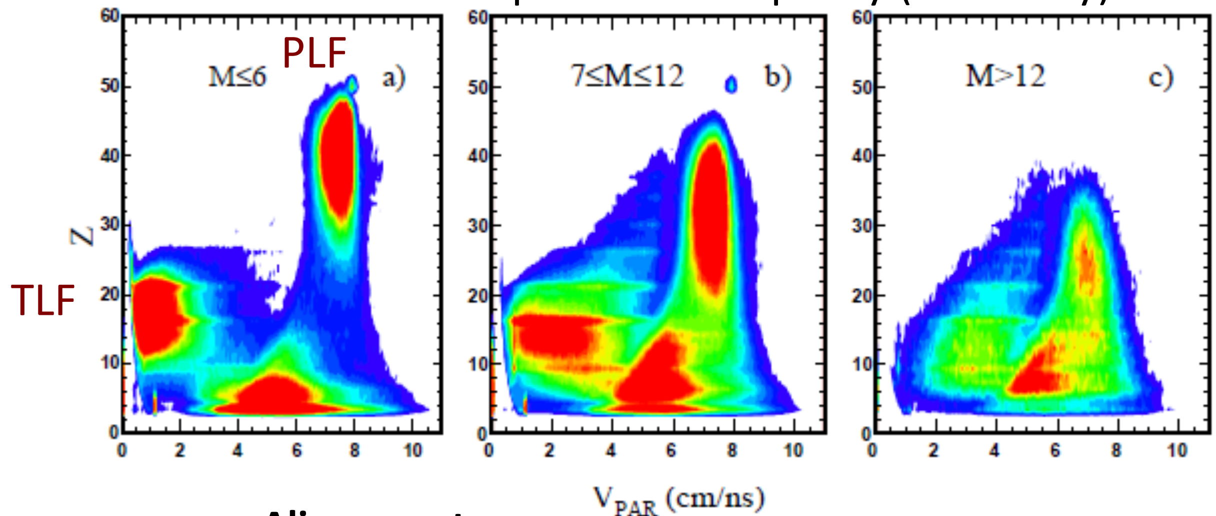


Private communication, Zhang & Ko

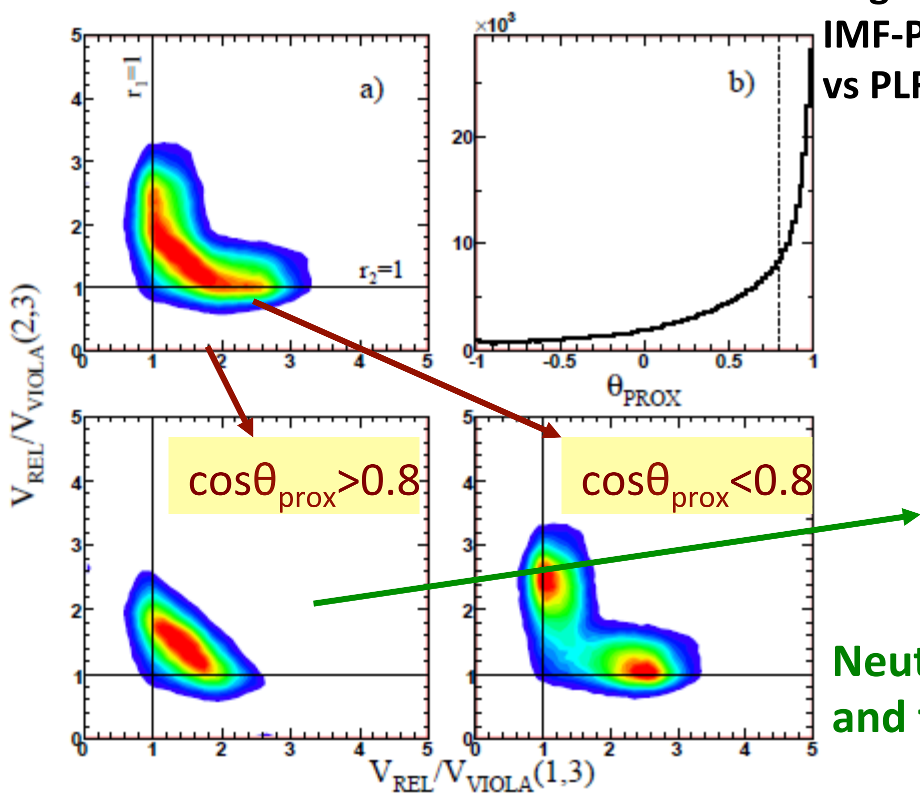
^{124}Sn + ^{64}Ni 35 AMeV: CHIMERA data

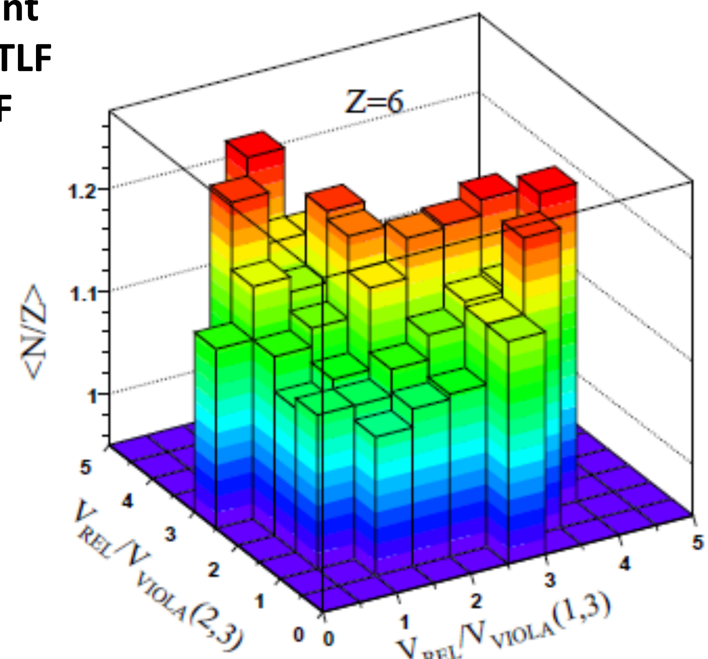
Semicentral (M=7)
v// selection of the 3 highest Z fragments:
1: PLF
2: TLF
3: Neck source

vs. particle multiplicity (centrality)



Alignement IMF-PLF/TLF vs PLF-TLF





Neutron enrichment for the largest Viola deviations and the highest degree of alignment :

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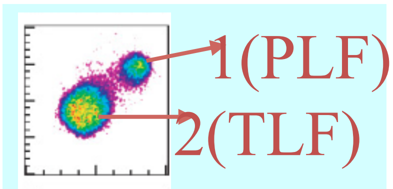
Comparison with data: Isospin equilibration ?

GANIL Experiment: Ni + Au @ 52 MeV/A
Simulations: SMF + decay

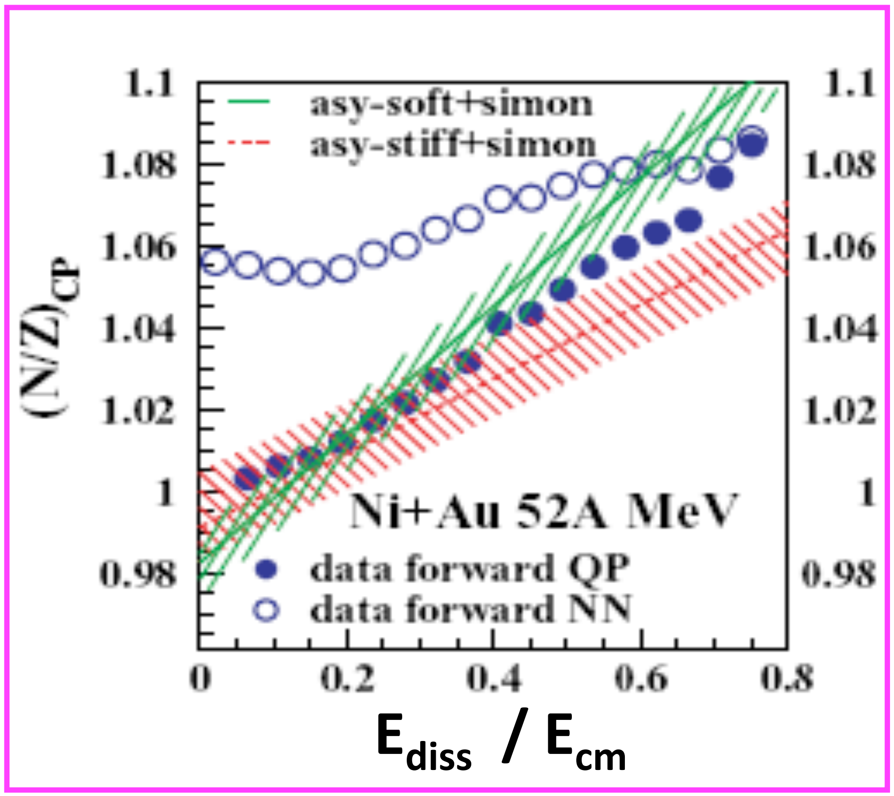


Isospin observables:
$(N/Z)_{CP}$ = N/Z of light charge particles

as a function of

Dissipated energy:
(contact time)

$$E_{diss} \quad E_{cm} - \frac{E_{kin} + E_{pot}^{Coul}}{A_{PLF} + A_{TLF}}$$



Galichet et al., PRC (2010)

Data:

- ● forward PLF
- ○ forward n-n c.m.
  (include emission from neck region)

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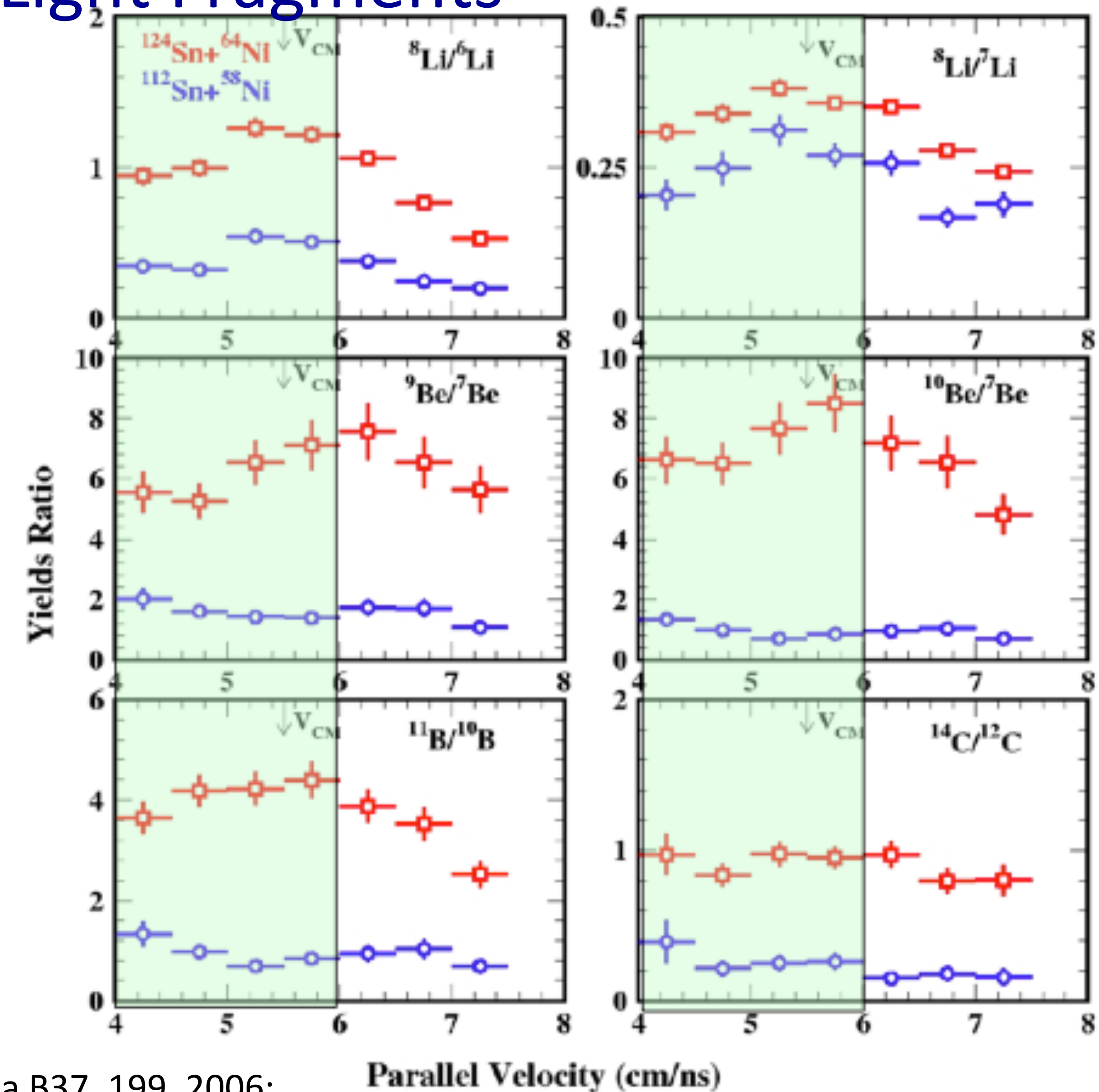
Isotopic Ratios For Light Fragments

(Z=3-6) IN THE 35/A.MeV
NEUTRON RICH $^{124}Sn+^{64}Ni$ AND
NEUTRON POOR $^{112}Sn + ^{58}Ni$
REACTIONS



Enhancement
In n-rich fragments
for mid velocity

E. De Filippo et al., Acta Physica Polonica B37, 199, 2006;
P. Russotto, Procs of IWM 05, pp. 13, ed. SIF, 2006.

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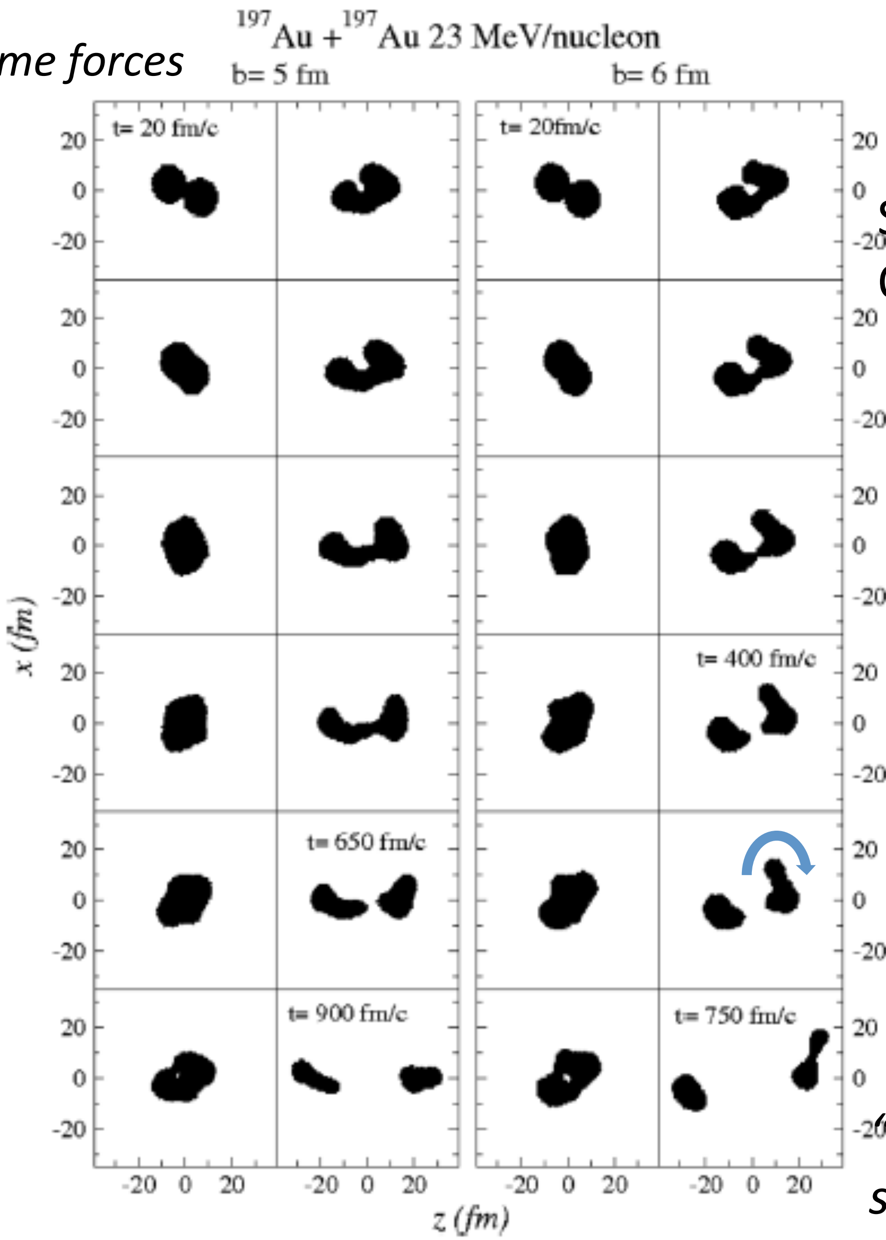
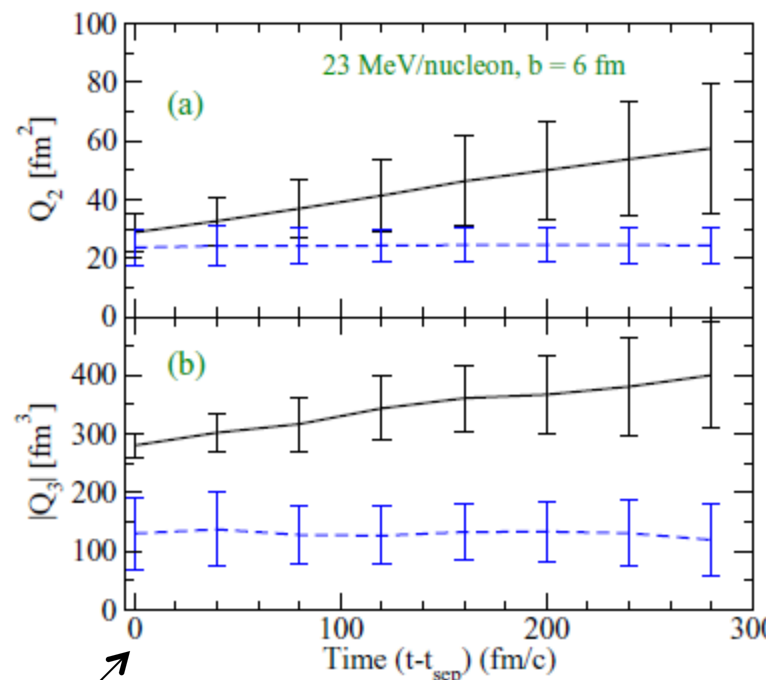
PLF-TLF shape properties

SMF
Skyrme forces



^{197}Au + ^{197}Au collisions - 23 MeV/A

Shape Observables:
Quadrupole and Octupole moments



D F

S F

D F

S F

"PLF-TLF separation time"

D F: deformed fragment

S F: "spherical" fragment

C.Rizzo et al., PRC 90 (2014)

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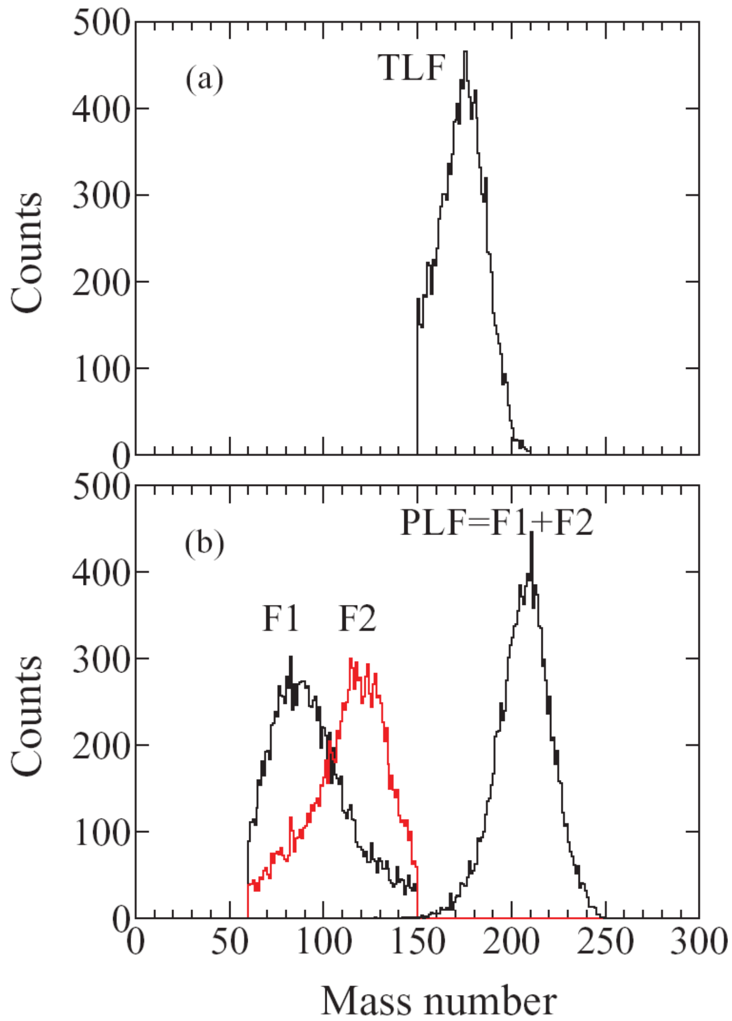
Ternary break-up

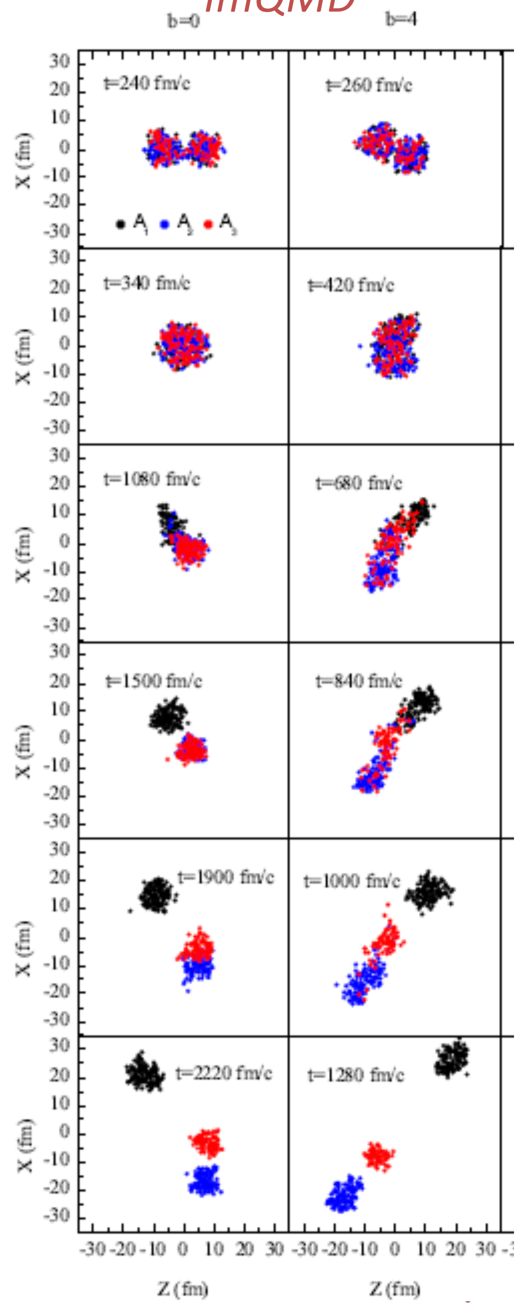
^{197}Au + ^{197}Au collisions - 15 MeV/A

(Chimera@LNS data) *PRC 81, 024605 (2010)*



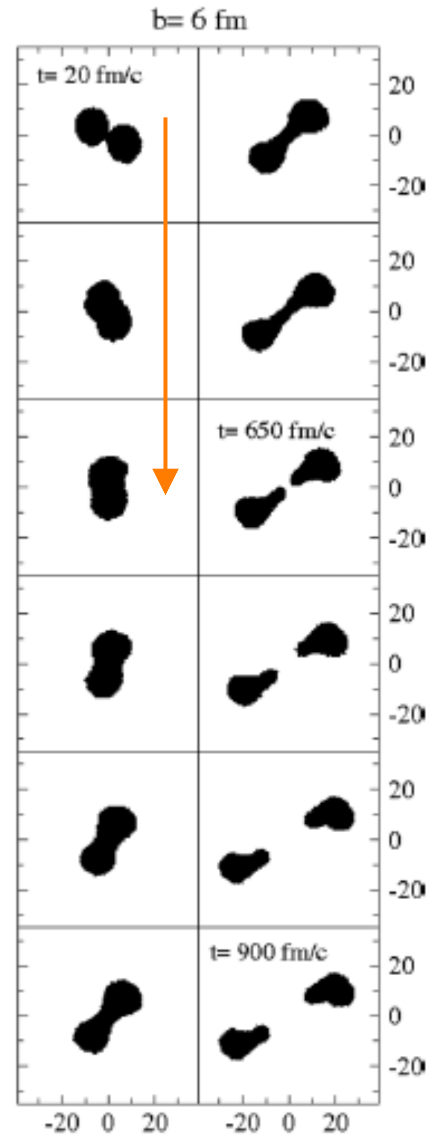
Y.Li et al., NPA 902 (2013)

ImQMD



C.Rizzo et al., PRC (2014)

SMF



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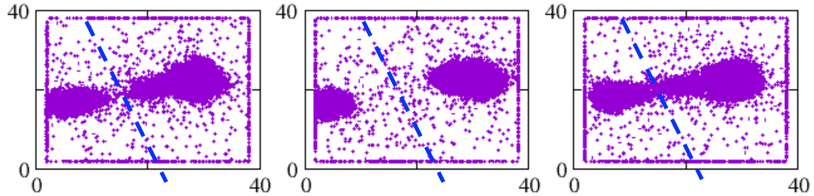
Ternary breakup in n-rich systems: Sensitivity to Esym

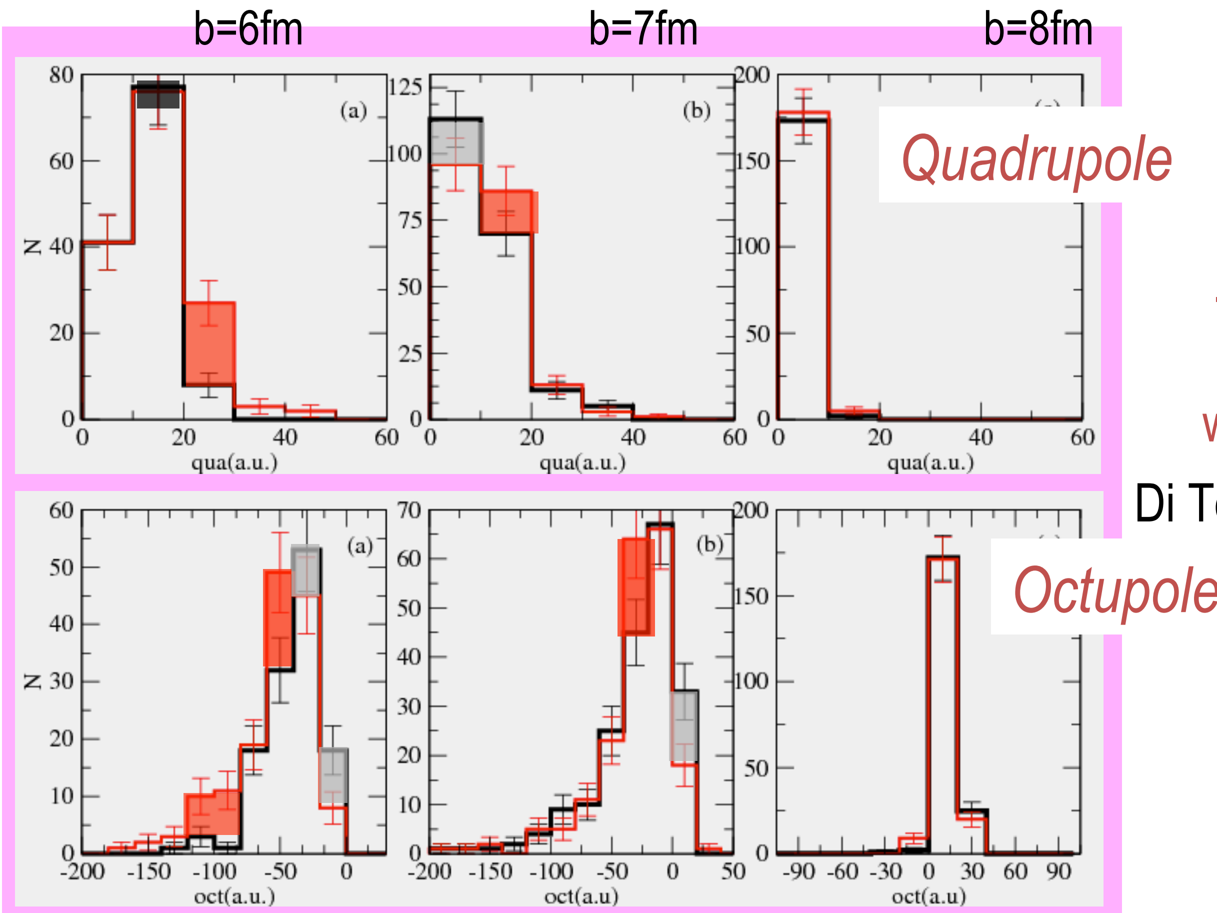


^{132}Sn + ^{64}Ni , E/A = 10 MeV, b = 7 fm

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

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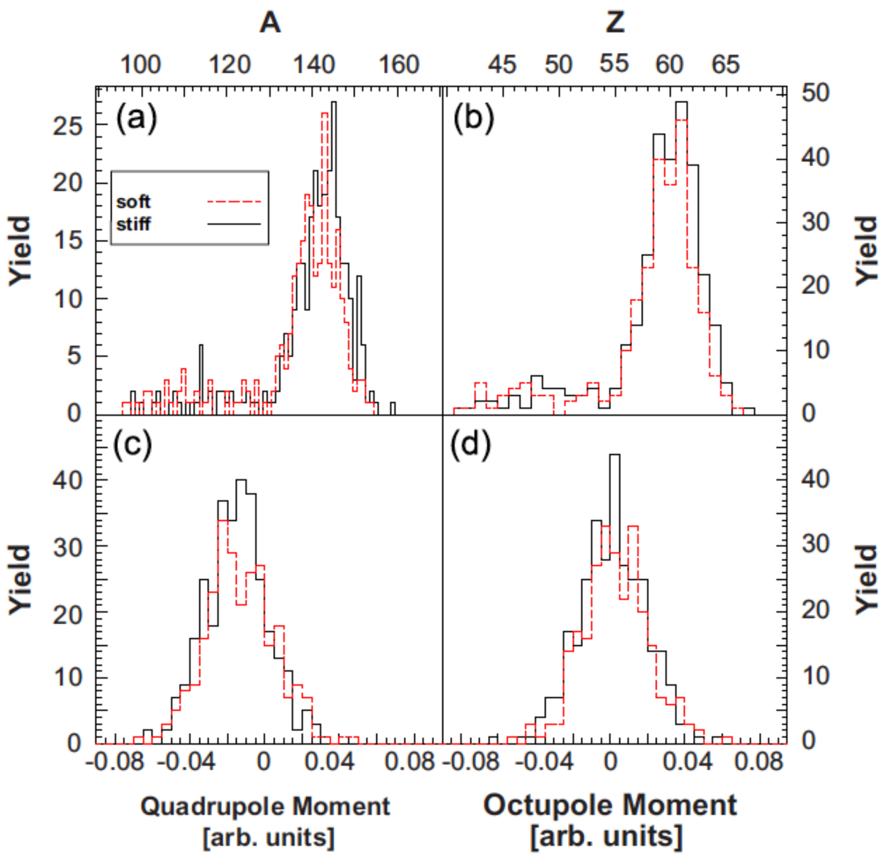
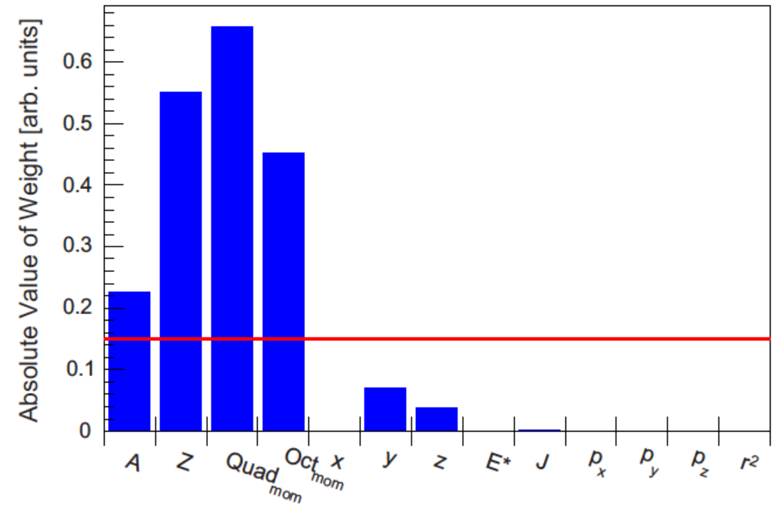
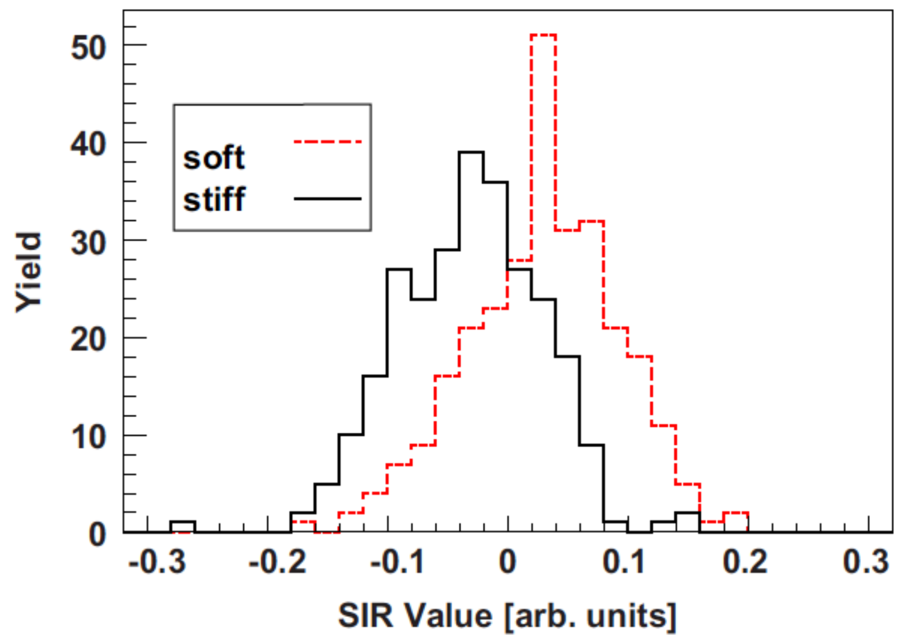
sifting through the remnants







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

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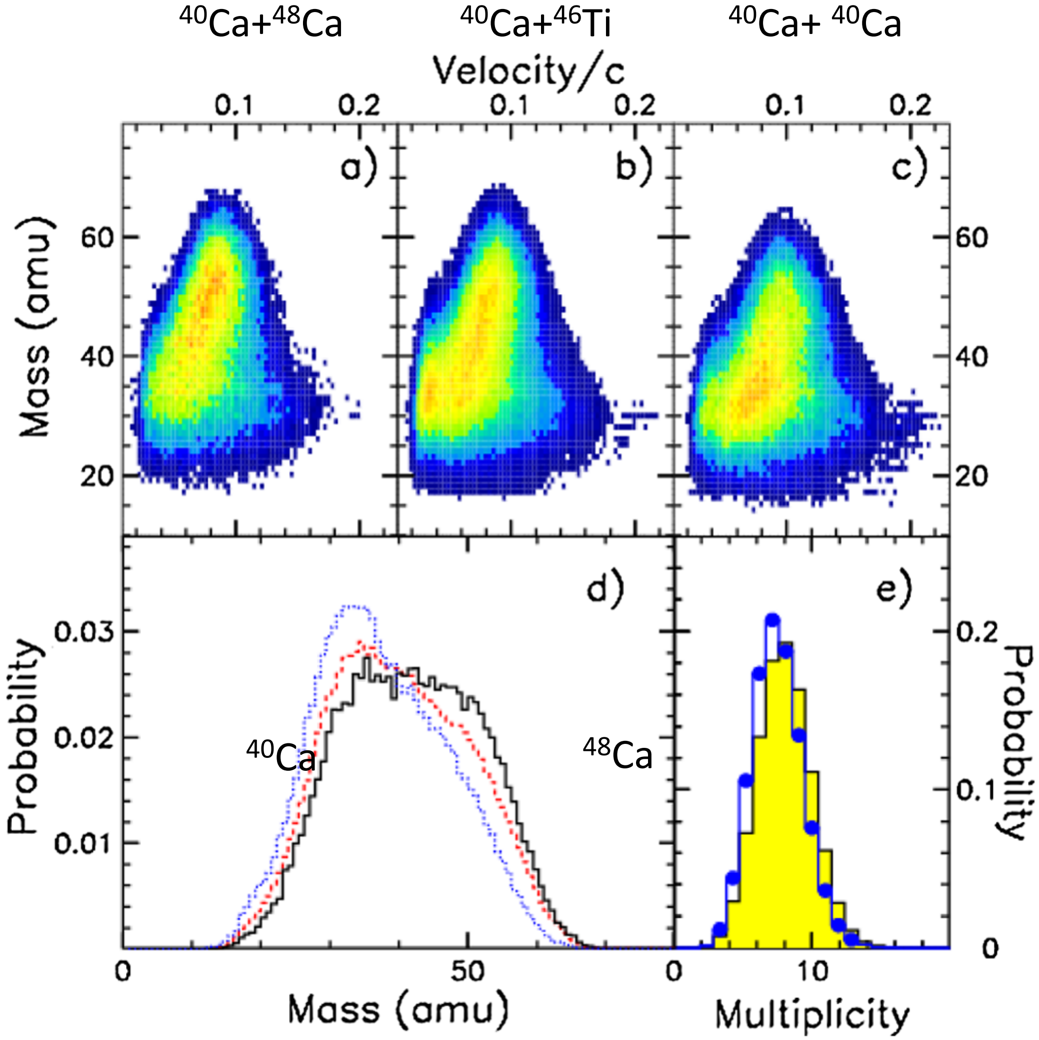
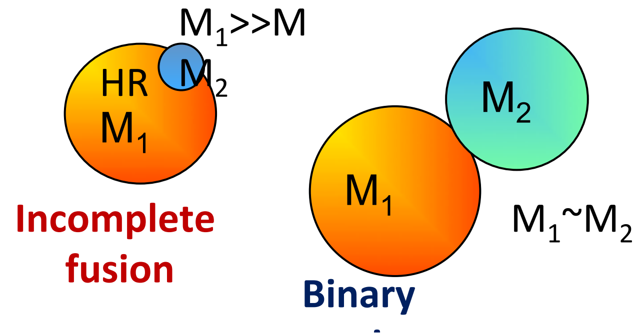
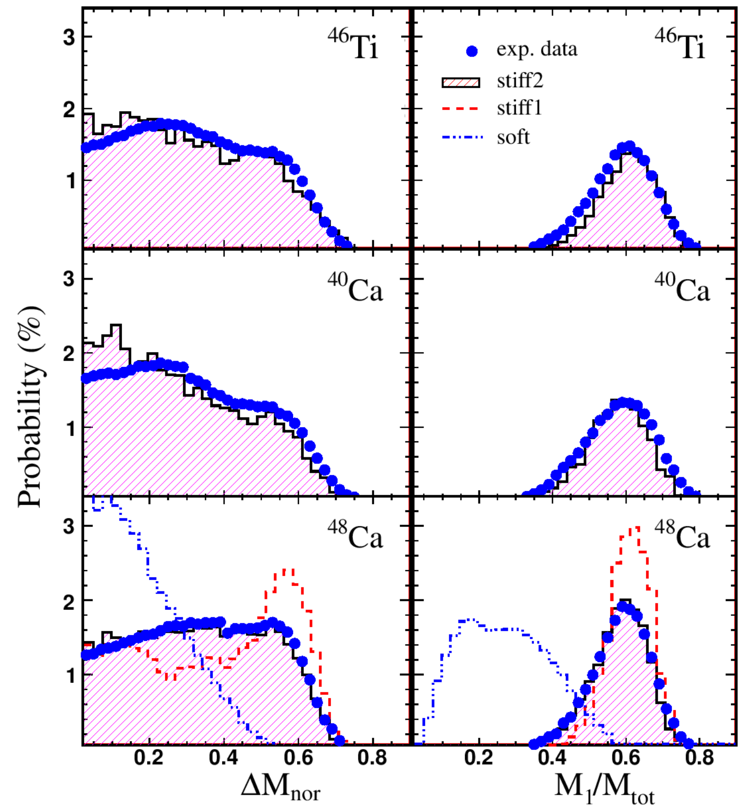
Isospin Dependence of Incomplete Fusion Reactions at 25 MeV/Nucleon







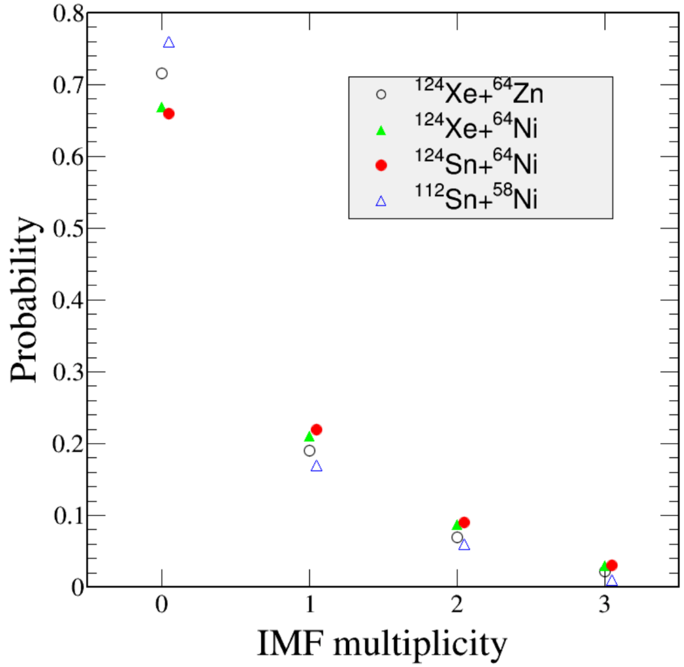
Higher probability for fusion using neutron rich systems

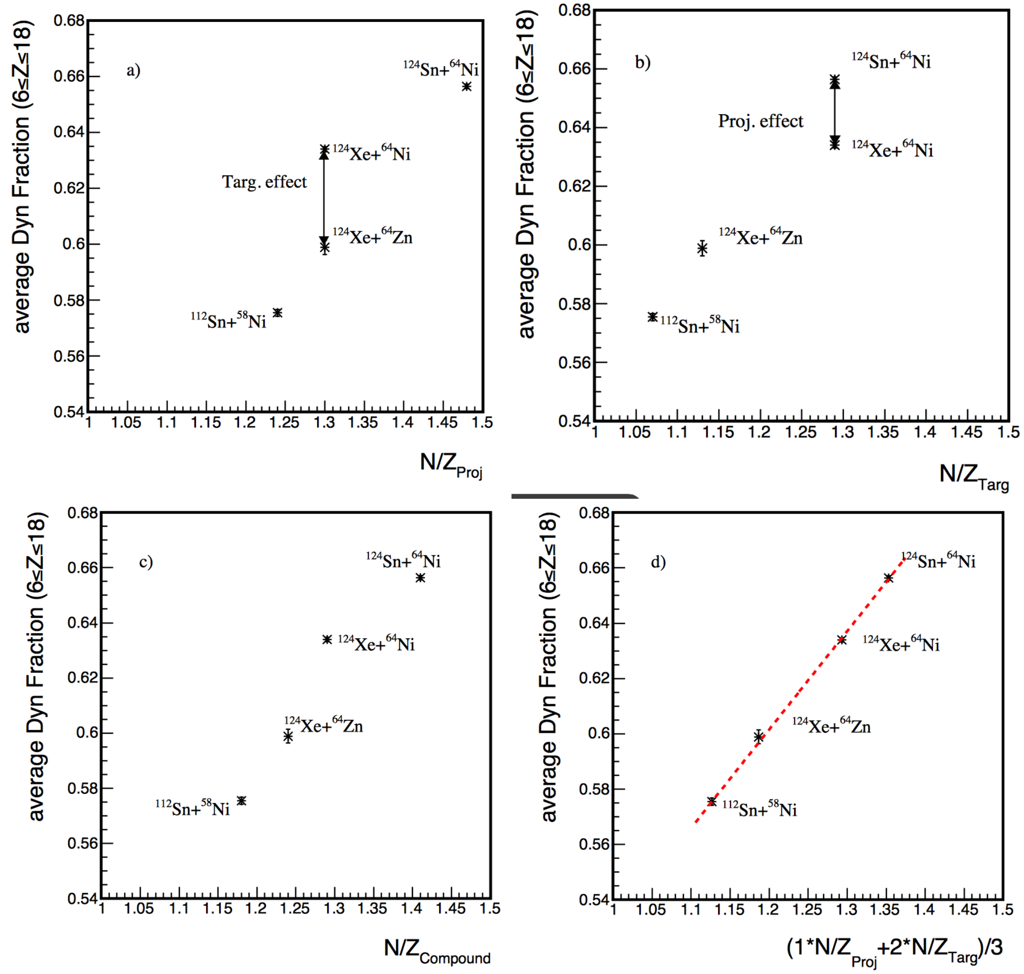
F. Amorini, G. Verde, PRL 102, 112701 (2009)
G. Cardella et al., PRC 85 084609 (2012)

Isospin influence on dynamical production of Intermediate Mass Fragments at Fermi Energies

^{124}Xe + ^{64}Ni and ^{64}Zn

35 Mev/nuc





P. Russotto, 2018

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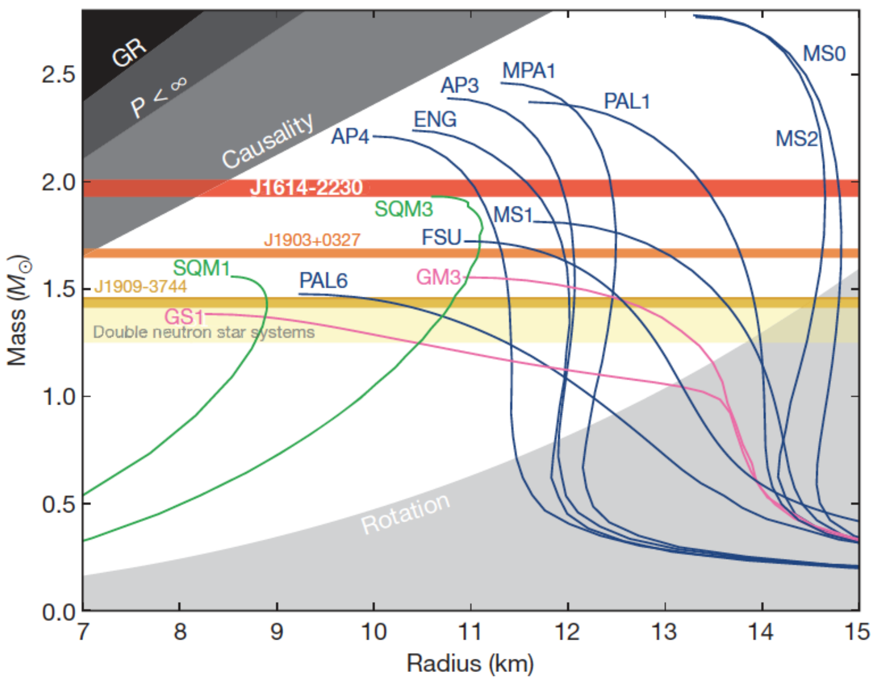
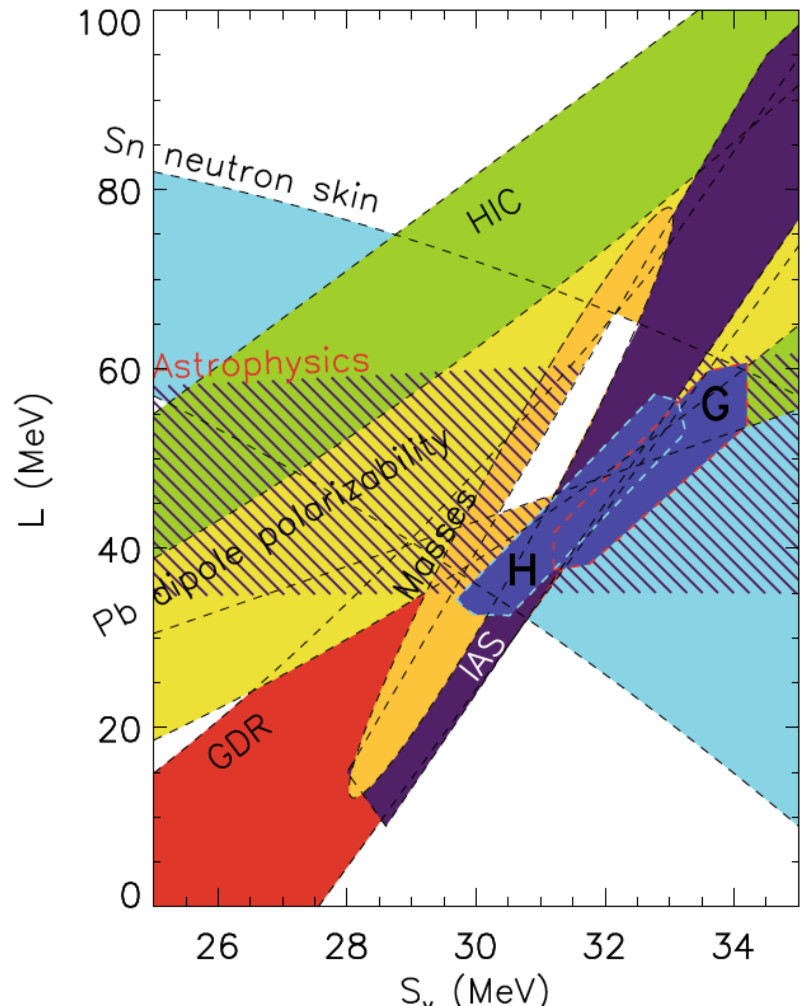
EOS comparison

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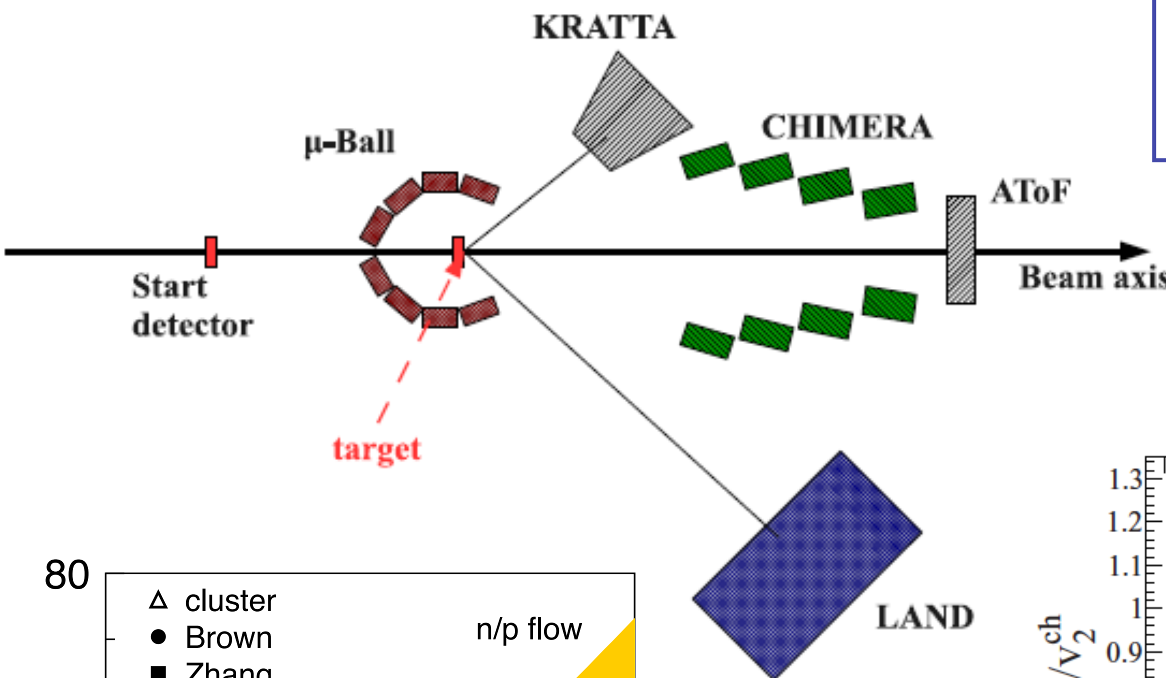
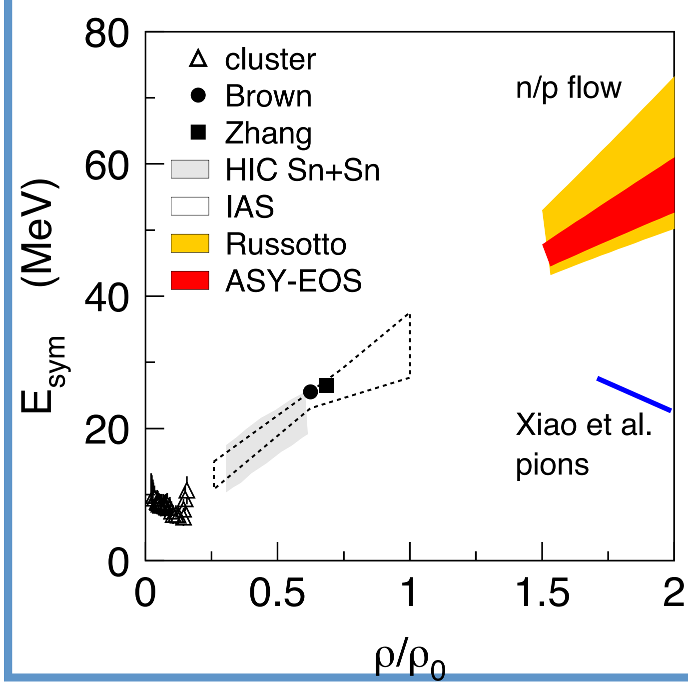
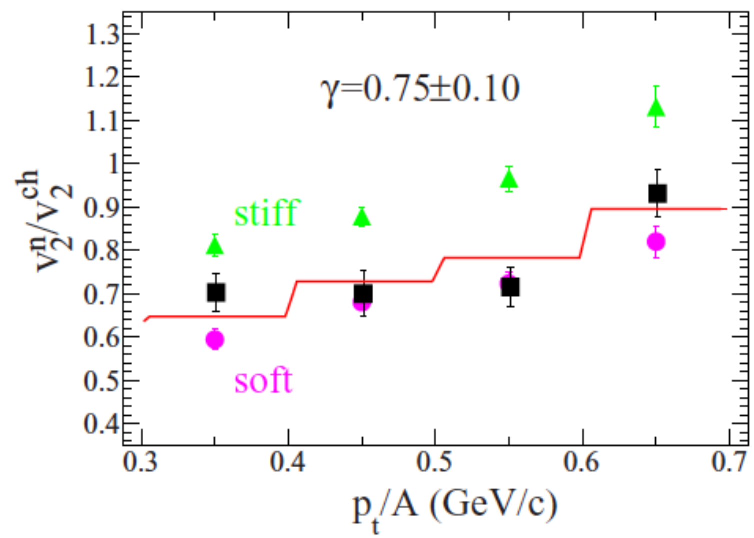
Constraining the Symmetry Energy at Supra-Saturation Densities with Measurements of Neutron and Proton Elliptic Flows

$^{197}Au + ^{197}Au$ @ 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)

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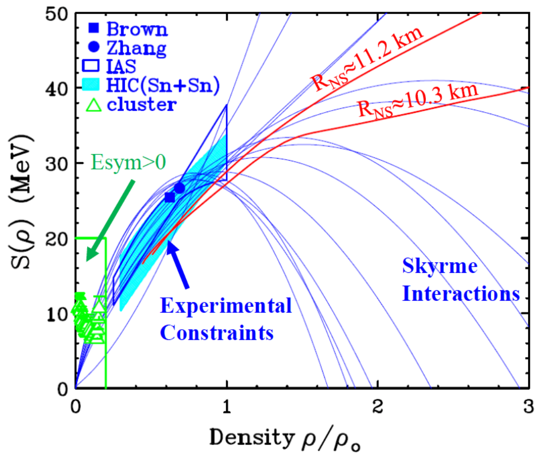
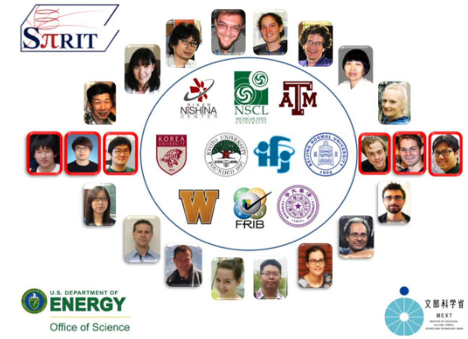
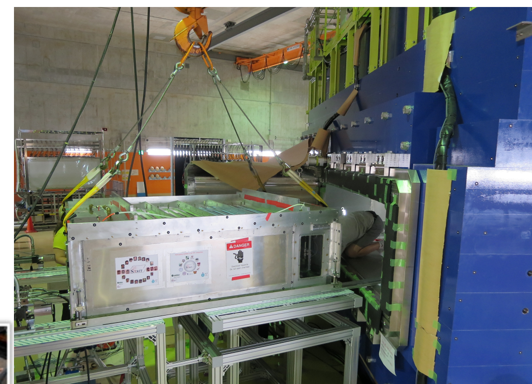
SPiRIT TPC @ SAMURAI



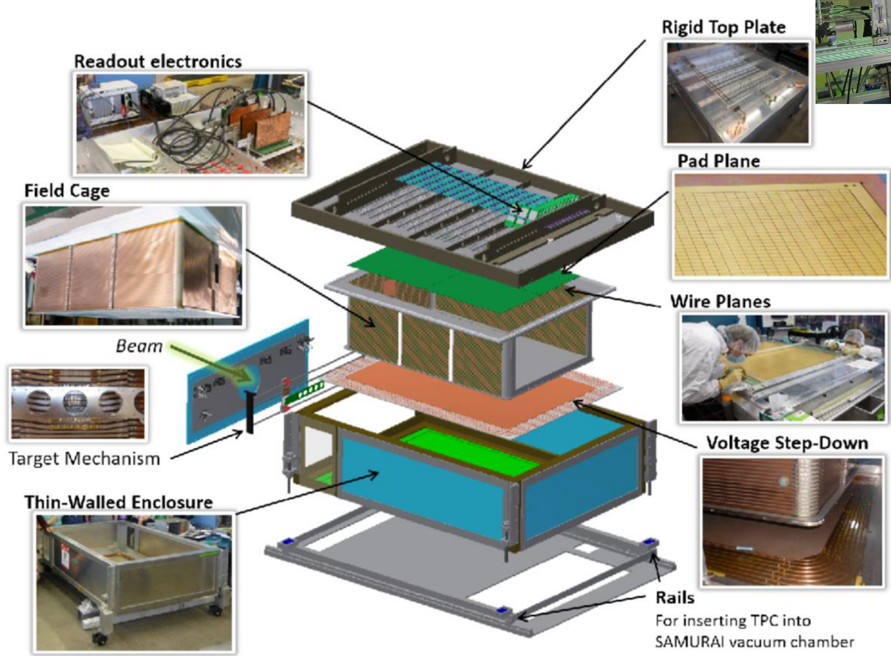
Constrain the Asymmetry Energy at **high density** through measurement of

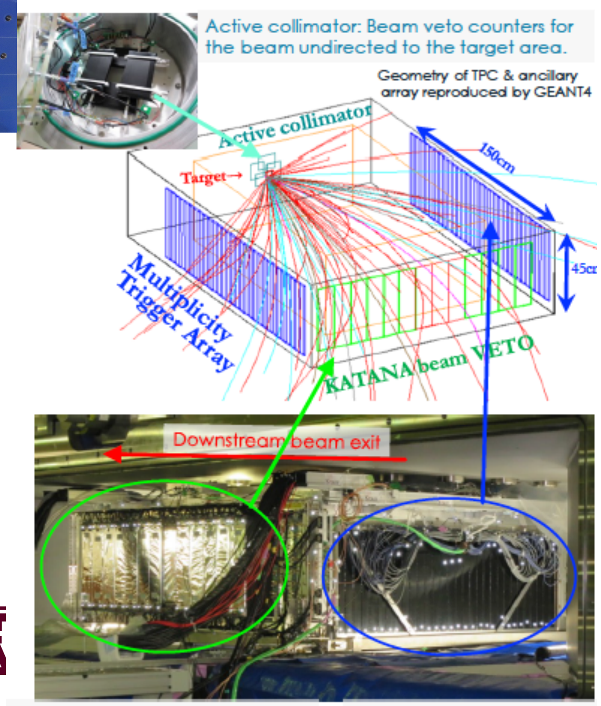
- π-/π+, n/p, 3H/3He
- Differential Flow and Particle Yield Ratios
- ^{108}Sn+^{112}Sn, ^{130}Sn+^{124}Sn @ E/A ≥ 200 MeV





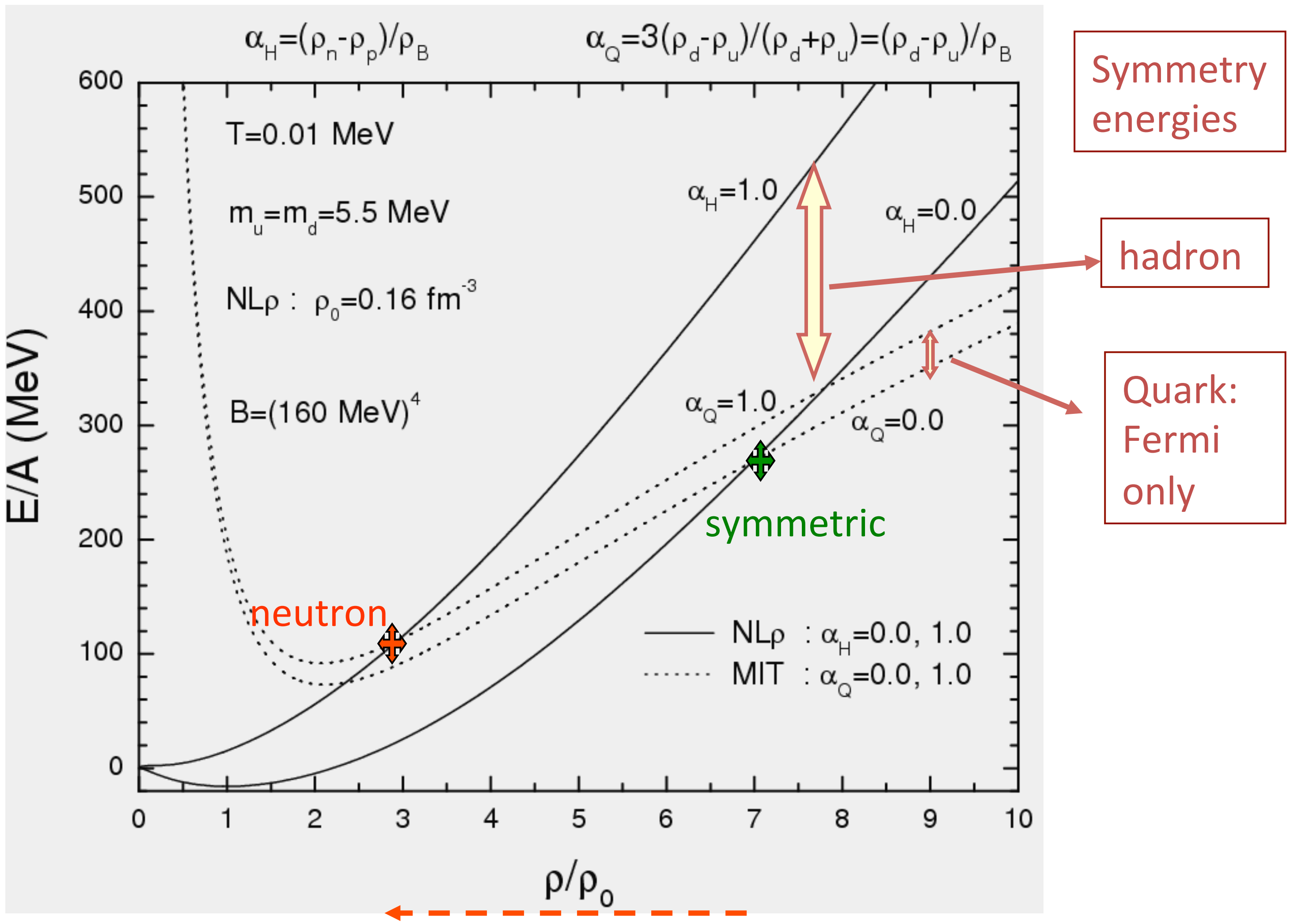
led





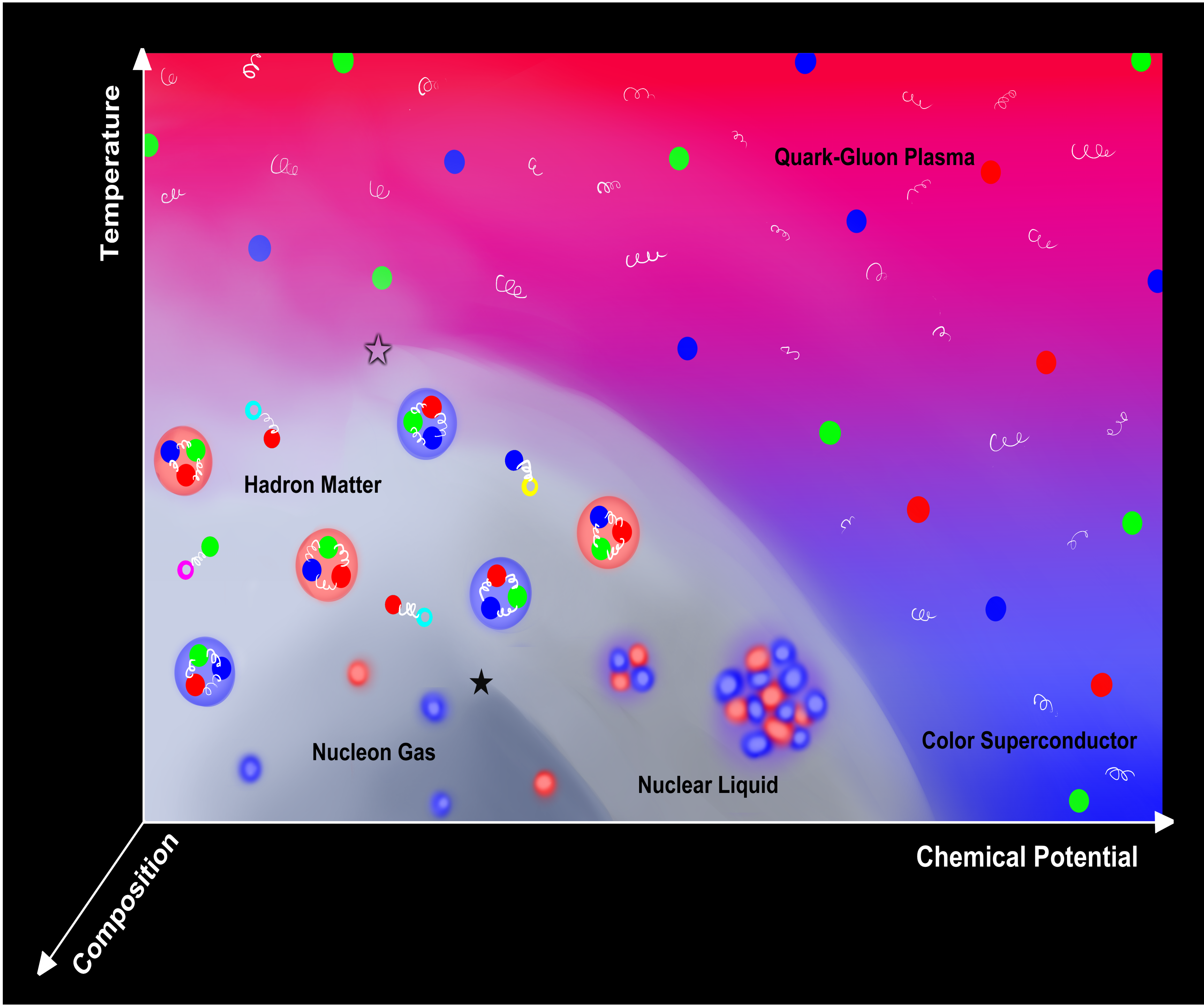
Symmetry energy at high density and the transition to quark matter

MIT-Bag
Energy density:
ε(free gas) + B



For very isospin asymmetric matter we can expect a much earlier transition to the quark phase

M.DiToro, B.Liu et al., PRC83 (2011)

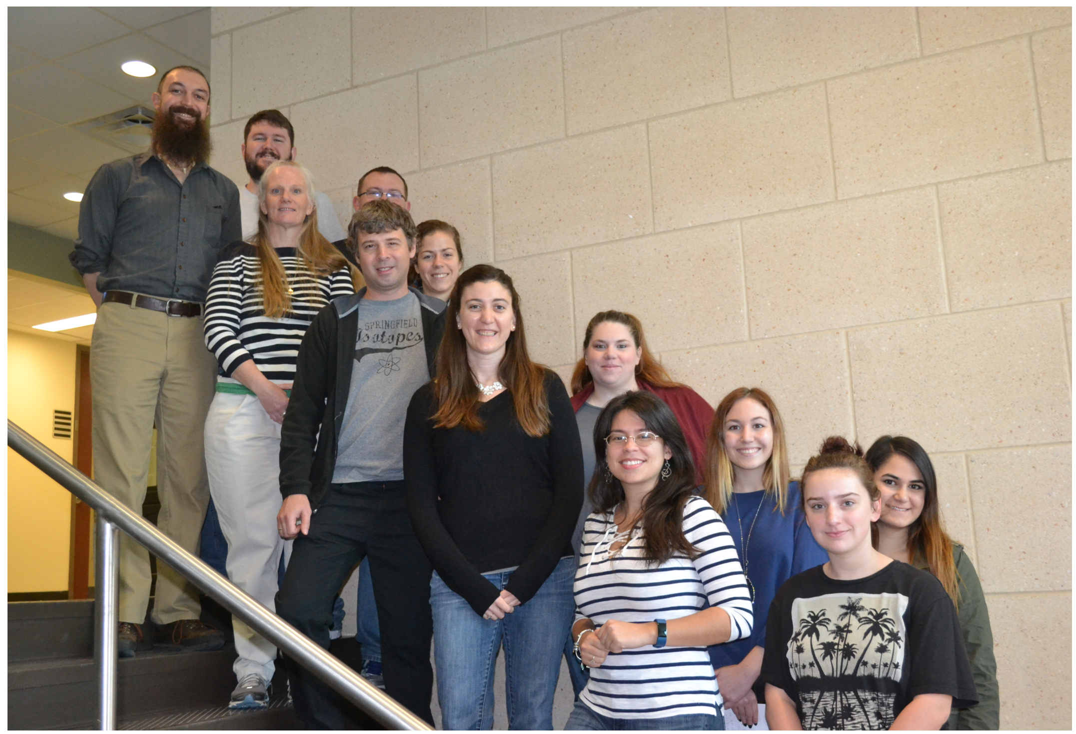

Temperature
Quark-Gluon Plasma
Hadron Matter
Nucleon Gas
Nuclear Liquid
Color Superconductor
Chemical Potential
Composition

Many Thanks

All the members of SJYGroup

The operations staff at the Texas A&M Cyclotron Institute

DOE, Welch Foundation & State of Texas



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