RIB induced reactions at NSCL and FRIB

Zach Kohley

National Superconducting Cyclotron Laboratory
Department of Chemistry
Michigan State University, E. Lansing, MI

NuSYM13, E. Lansing, MI
July 22, 2013

Outline

- Nuclear EoS
- NSCL and FRIB
- FRIB for exploring $E_{sym}(\rho)$
- A test case using RIBs at NSCL

Symmetry Energy

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

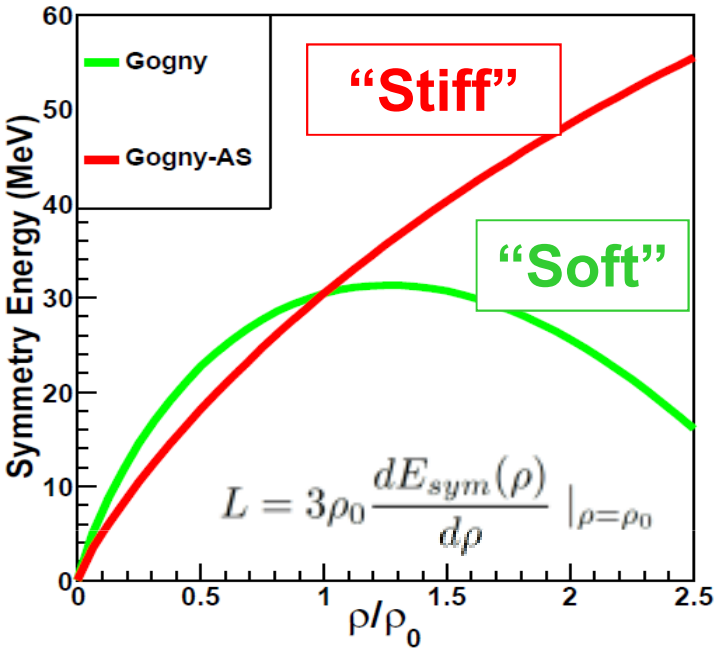
Nuclear Equation of State (EoS)

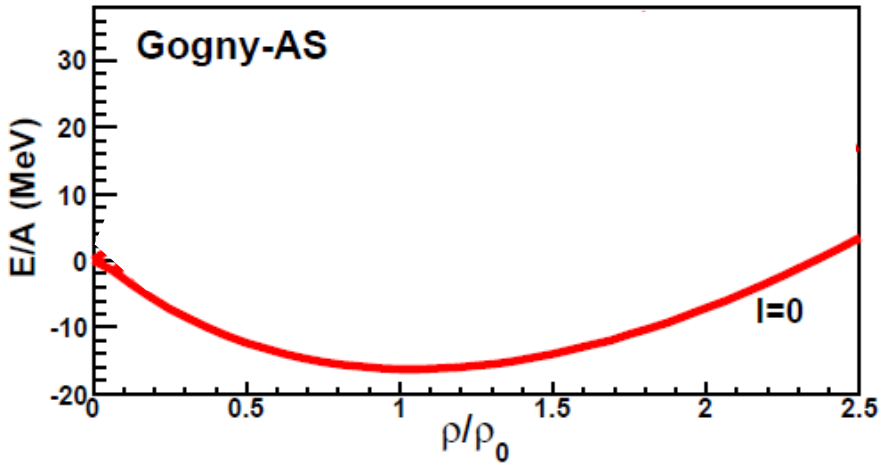
$$E(\rho,\delta) = E(\rho) + E_{sym}(\rho)\delta^2$$

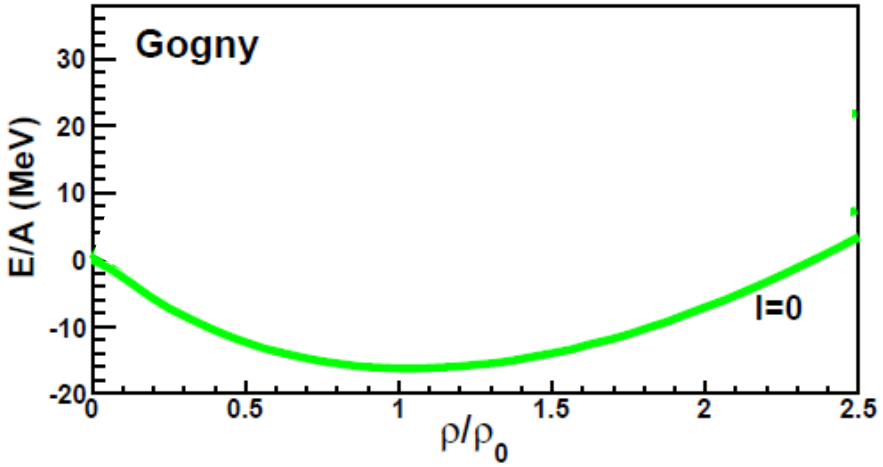
$$with \quad \delta = \frac{\rho_n - \rho_p}{\rho_{Total}} \approx \frac{N-Z}{A}$$

Binding Energy of Symmetric Nuclear Matter

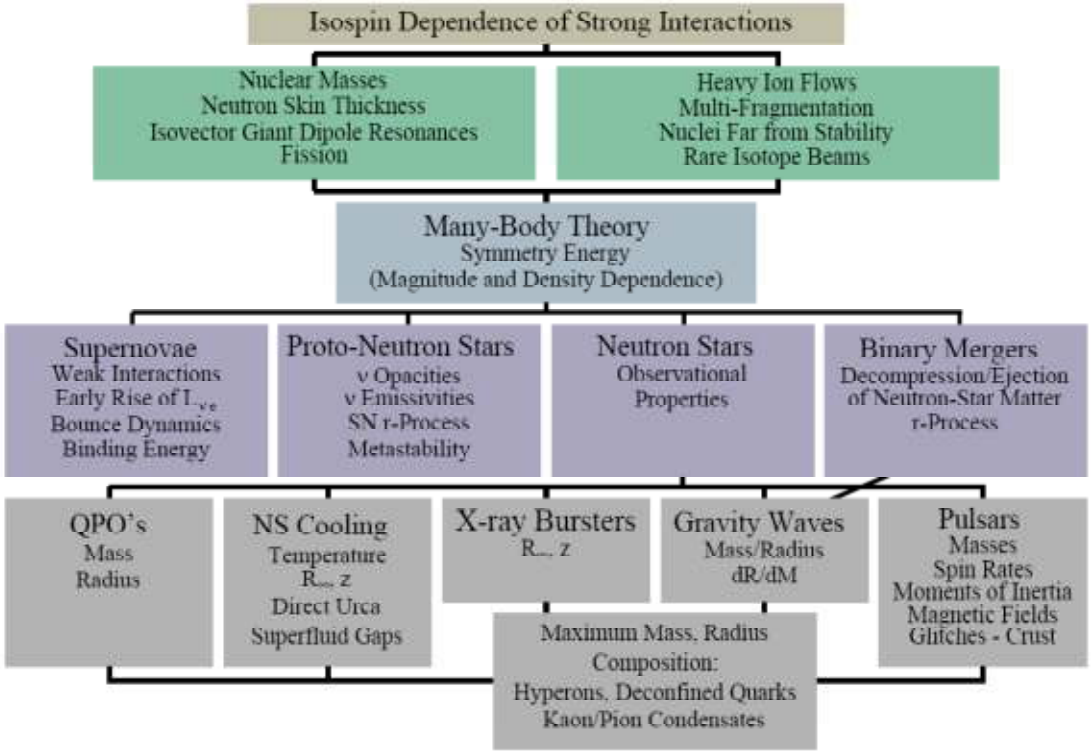
Symmetry Energy Term for Asymmetric Matter



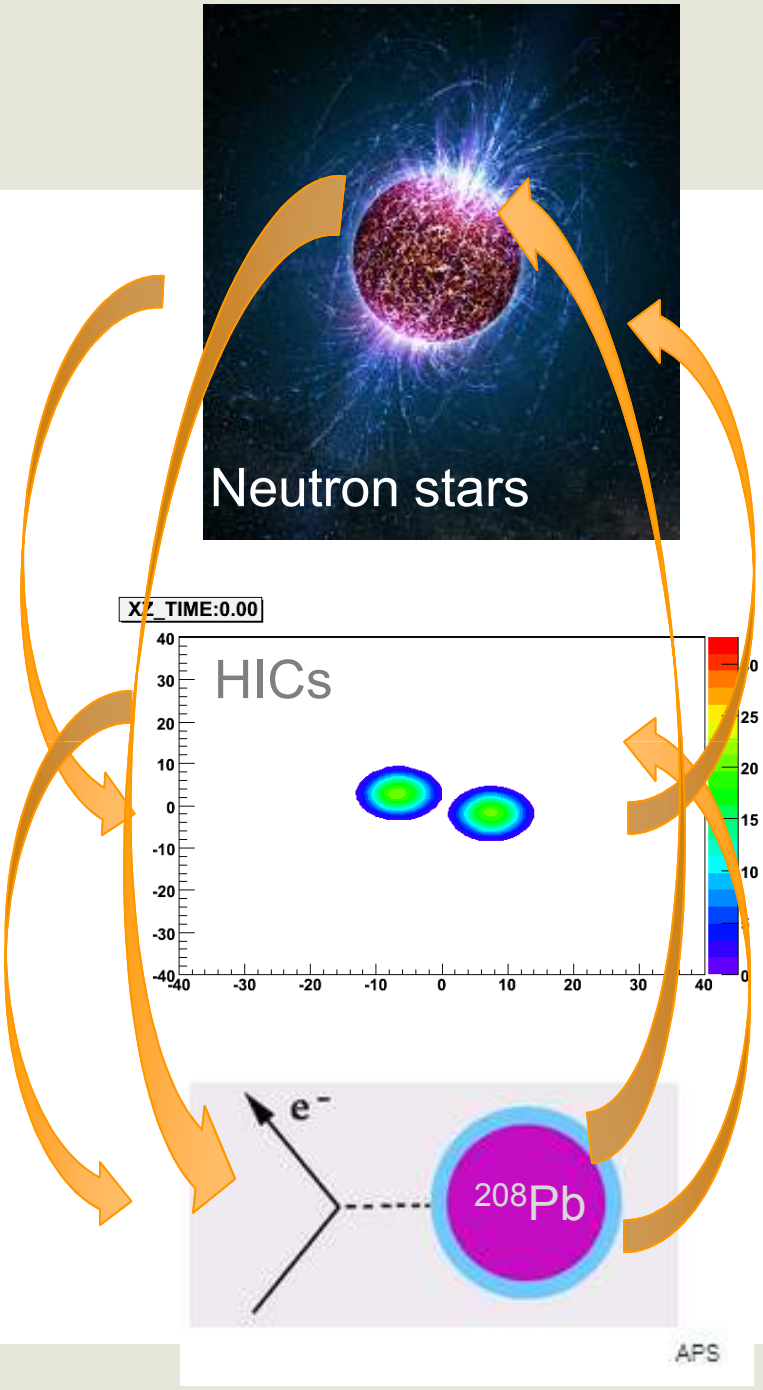




Symmetry Energy

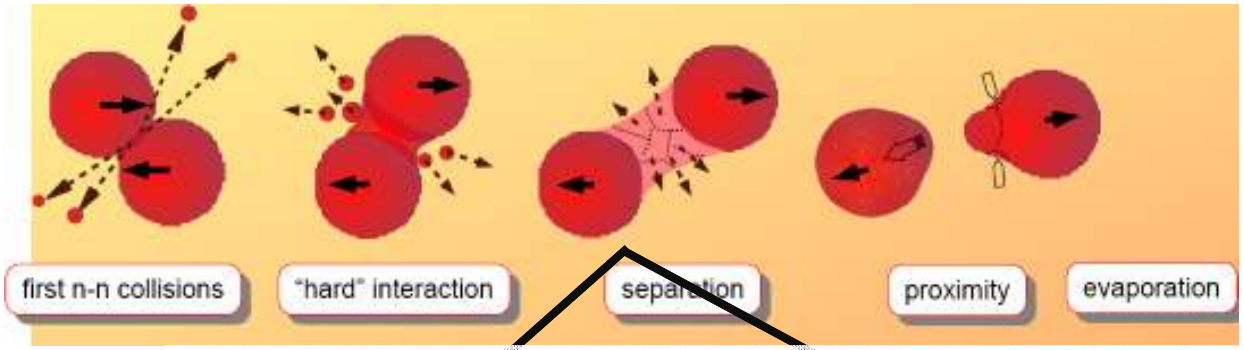


A.W. Steiner et al., Phys. Rep. **411,** 325 (2005).



Heavy-ion collisions

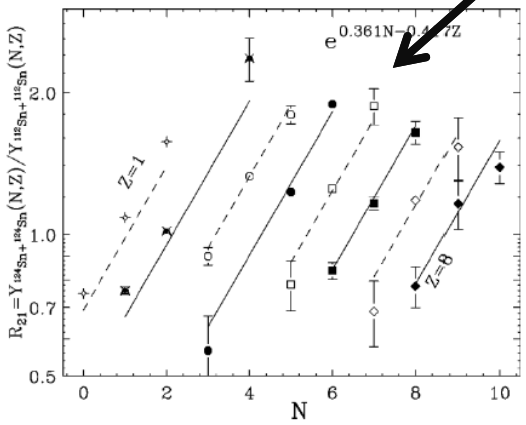
Powerful laboratory tool to explore EoS



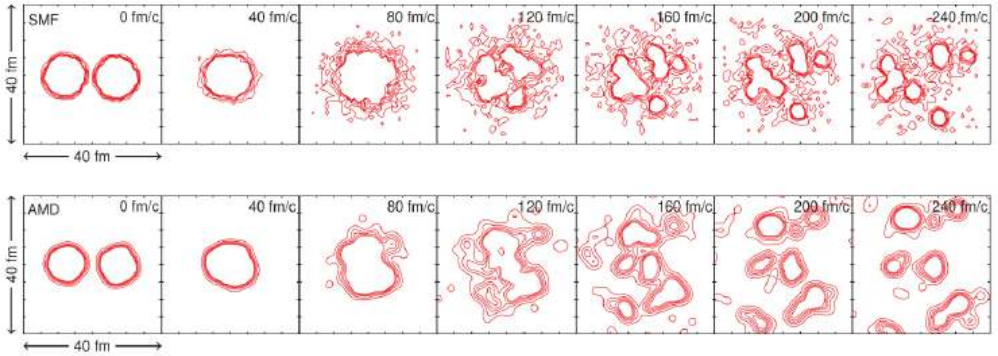
Need to make connections between experiment and EoS

Isoscaling

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

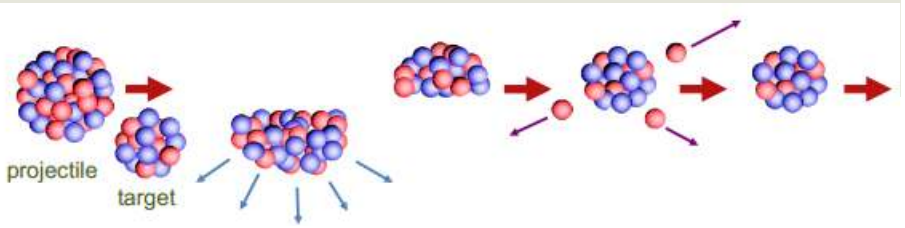


Transport models

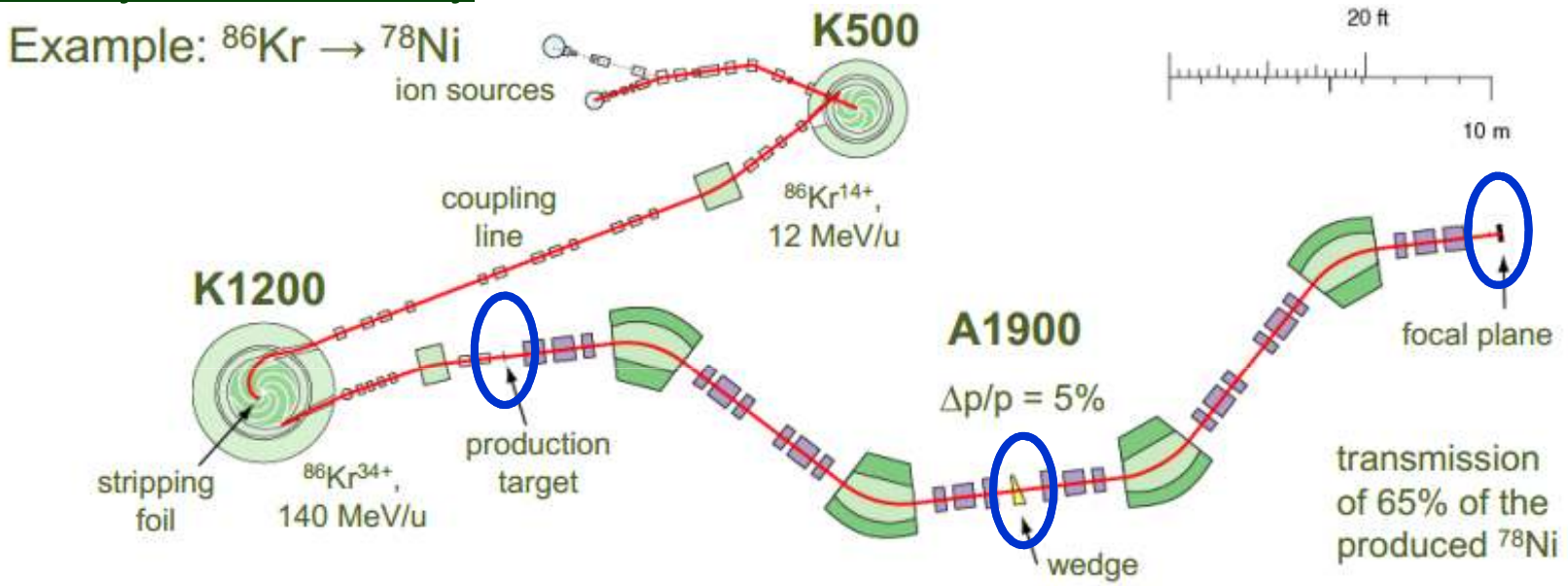


NSCL

In the heavy-ion business



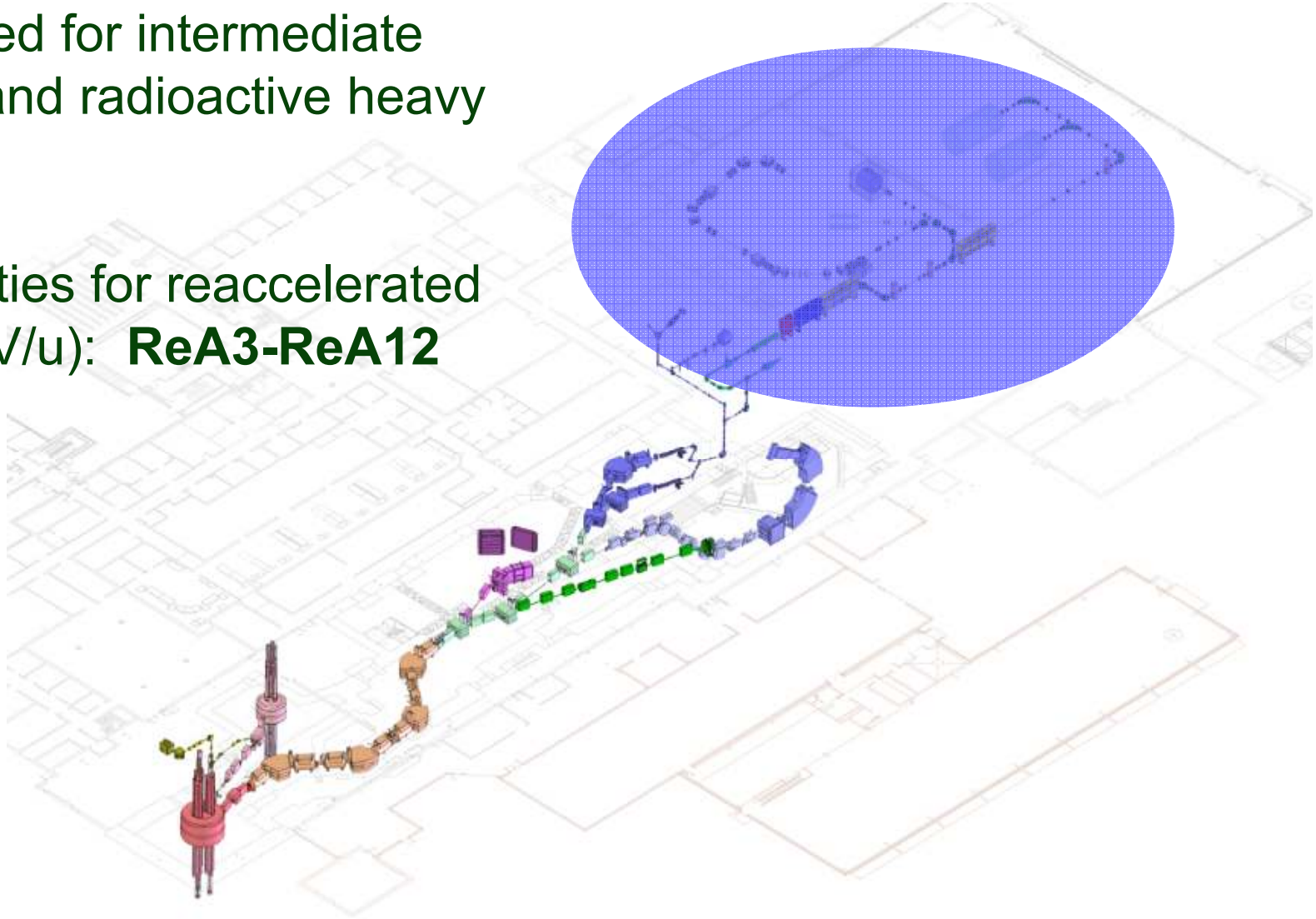
Coupled Cyclotron Facility



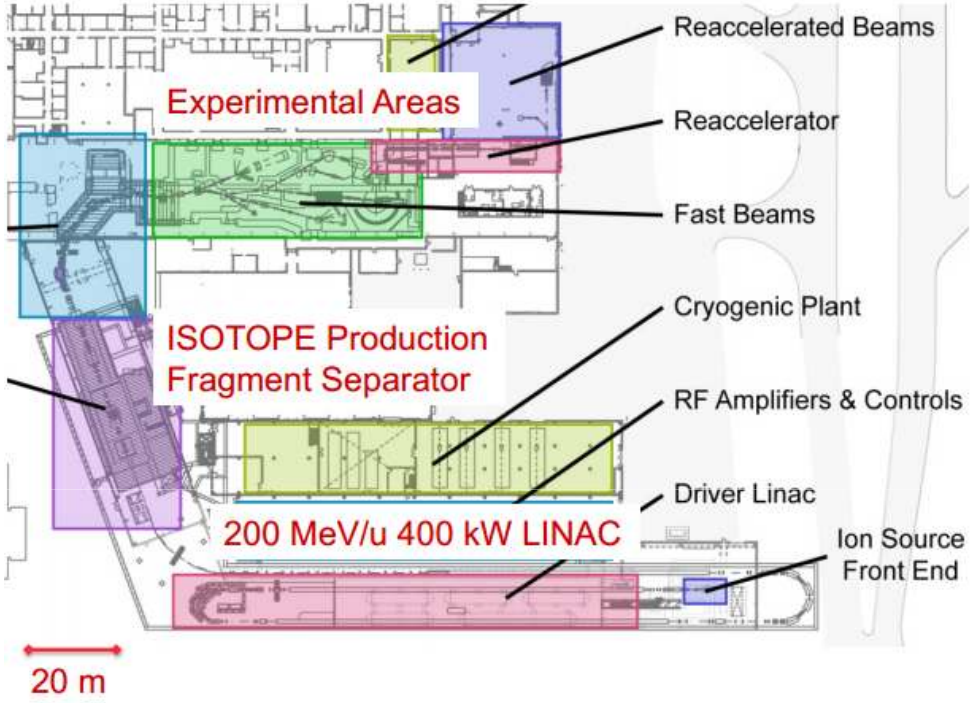
NSCL

-Well established for intermediate energy stable and radioactive heavy ion beams.

- NEW capabilities for reaccelerated RIBs (~3-5 MeV/u): **ReA3-ReA12**



FRIB

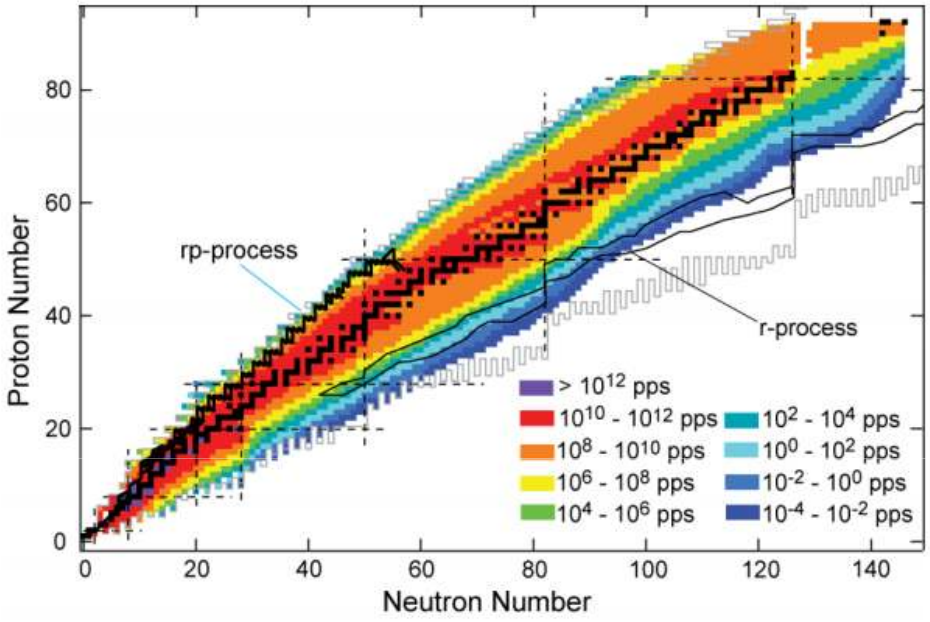


U.S. Flagship Facility for Rare Isotope Beams

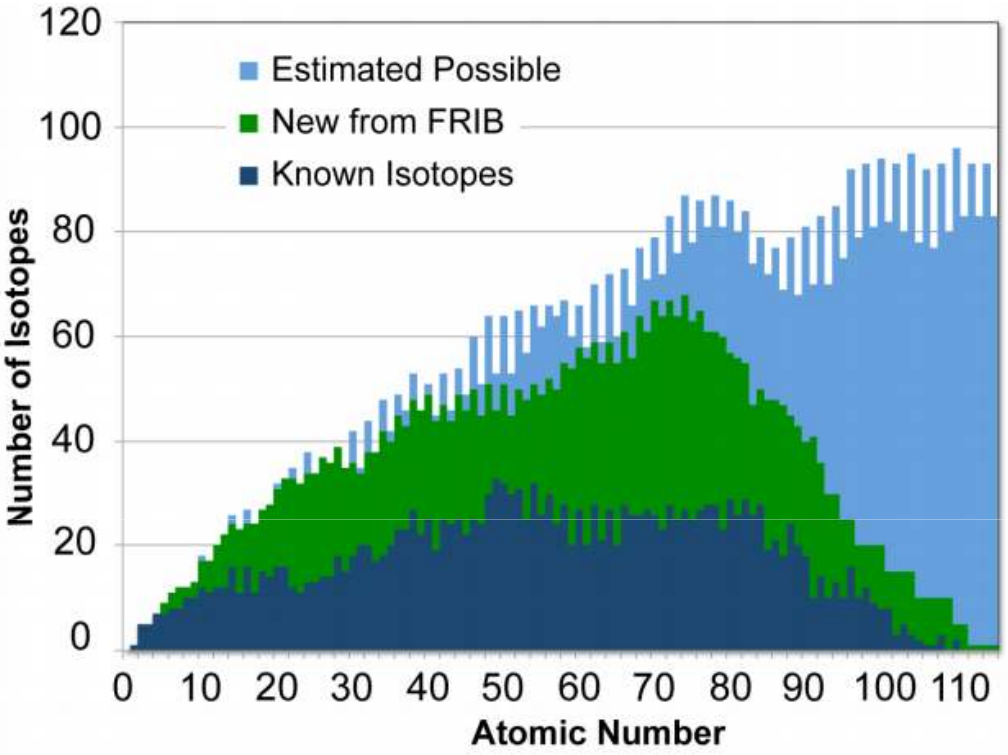
400 kW heavy-ion beams; 200 MeV/u rare isotope beams

Upgradable to 400 MeV/u

FRIB



Rates are available at http://groups.nscl.msu.edu/frib/rates/



Erler *et al. Nature* **486**, 509 (2012)

FRIB

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

Increase asymmetry,
Increase sensitivity

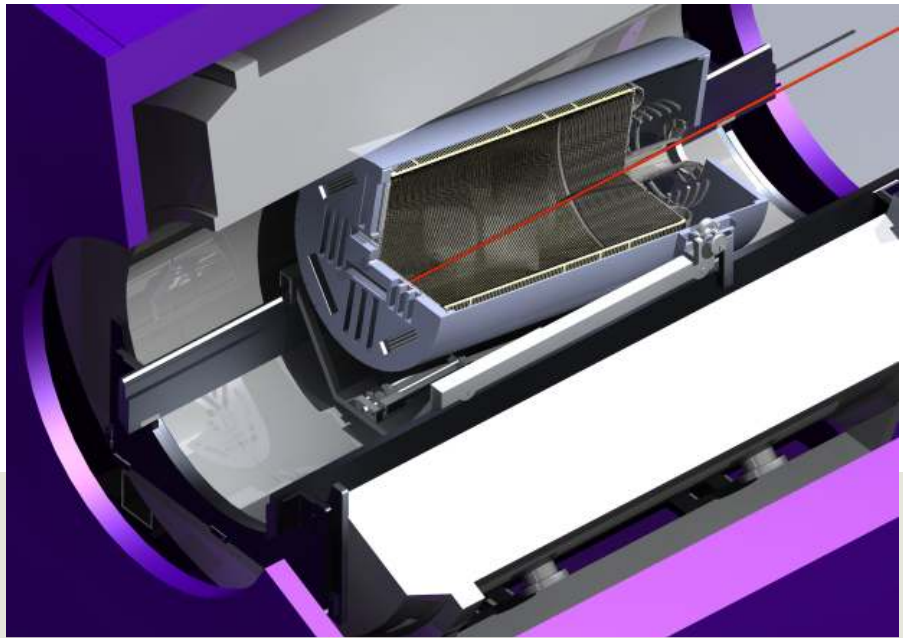
2) Increase energy access to $\rho > \rho_0$

Lynch and Tsang:

Program using Sn RIBs

- Isospin diffusion
- N/P, t/3He ratios
- Flow

AT-TPC under construction
$\pi+/\pi-$ measurements



FRIB

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

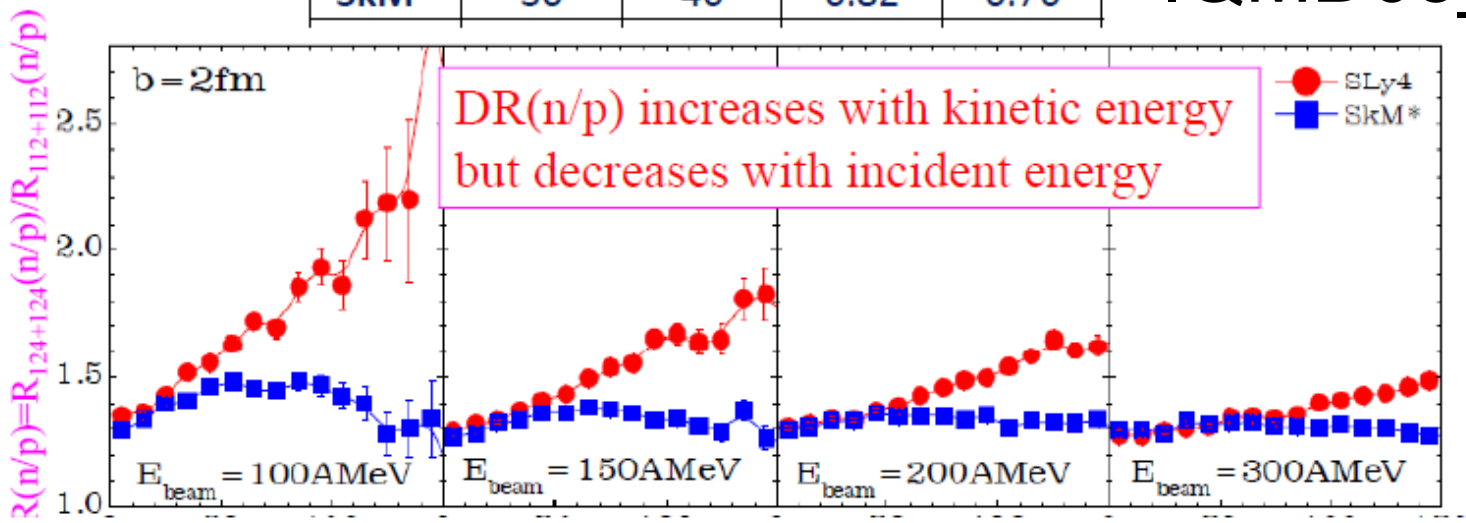
Increase asymmetry,
Increase sensitivity

2) Increase energy access to $\rho > \rho_0$

FRIB will provide access to region sensitive to effective mass

Skyrme	S0(MeV)	L (MeV)	m_n^*/m_n	m_p^*/m_p
SLy4	32	46	0.68	0.71
SkM*	30	46	0.82	0.76

IQMD05_sky

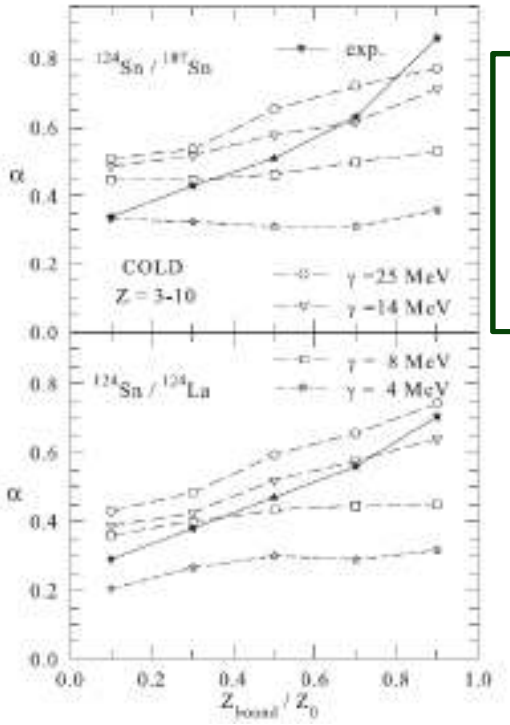


Using RIBs to explore EoS

Very few experiments using RIBs for EoS studies.

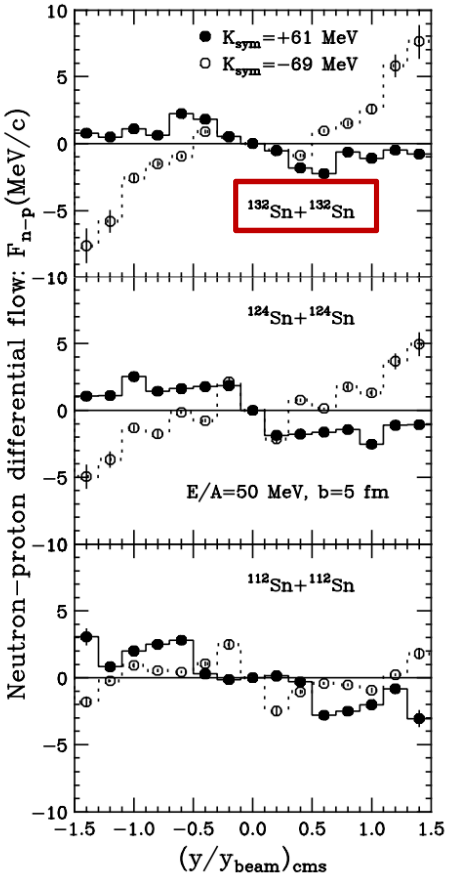
Theorists seem to have access to more intense RIBs and radioactive targets.

ALADIN

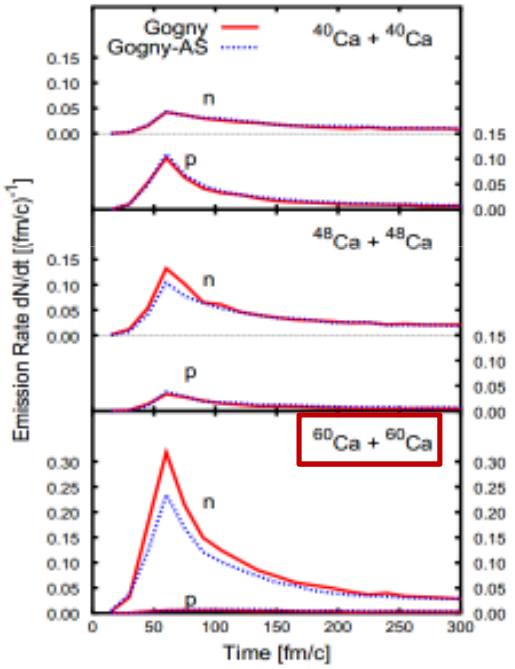


Ogul, PRC **83,** 024608 (2011)

Tsang/Lynch
RIKEN, TAMU
Isospin Diffusion
Radioactive Sn



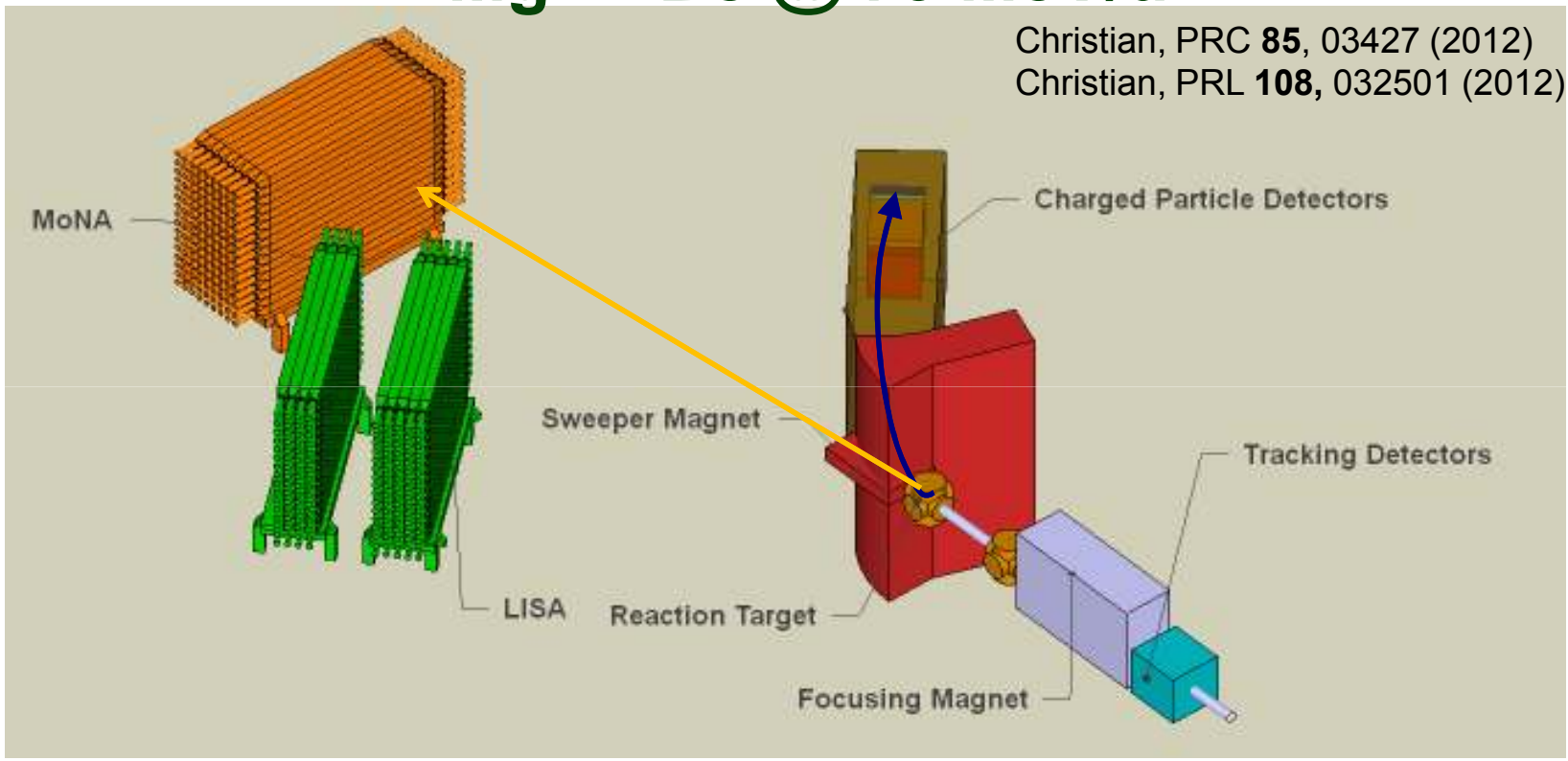
Li, PRL **85,** 4221 (2000)



Ono, AIP **791,** 83 (2005)

Test case at the NSCL

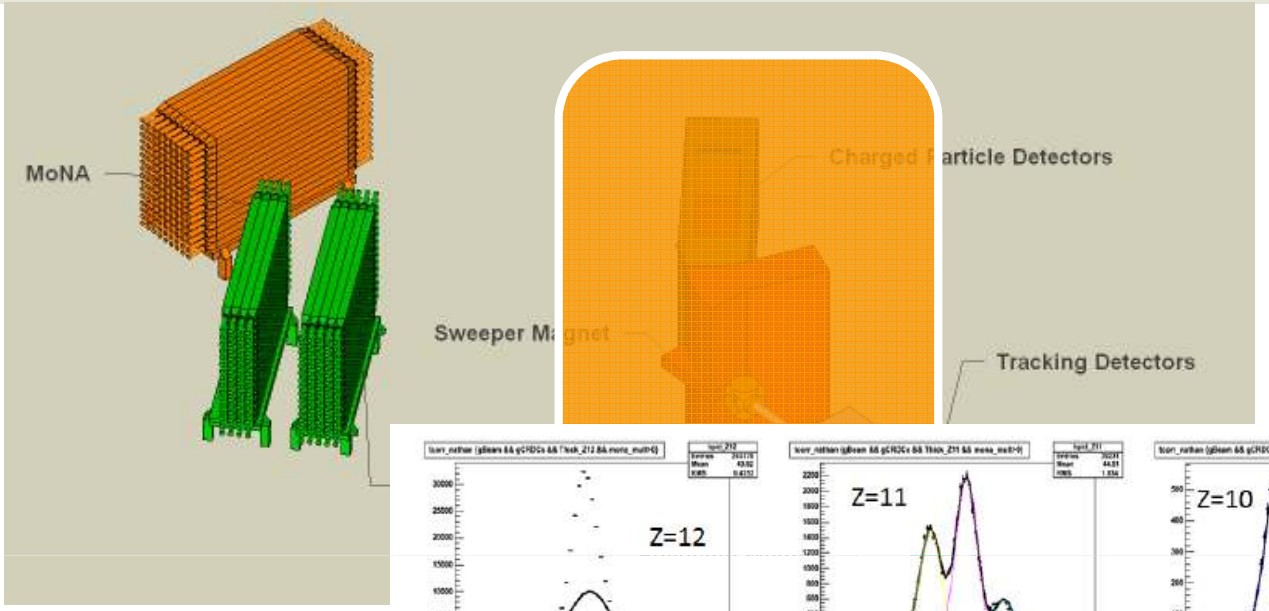
MoNA-LISA Experiment
^{32}Mg + ^{9}Be @ 73 MeV/u

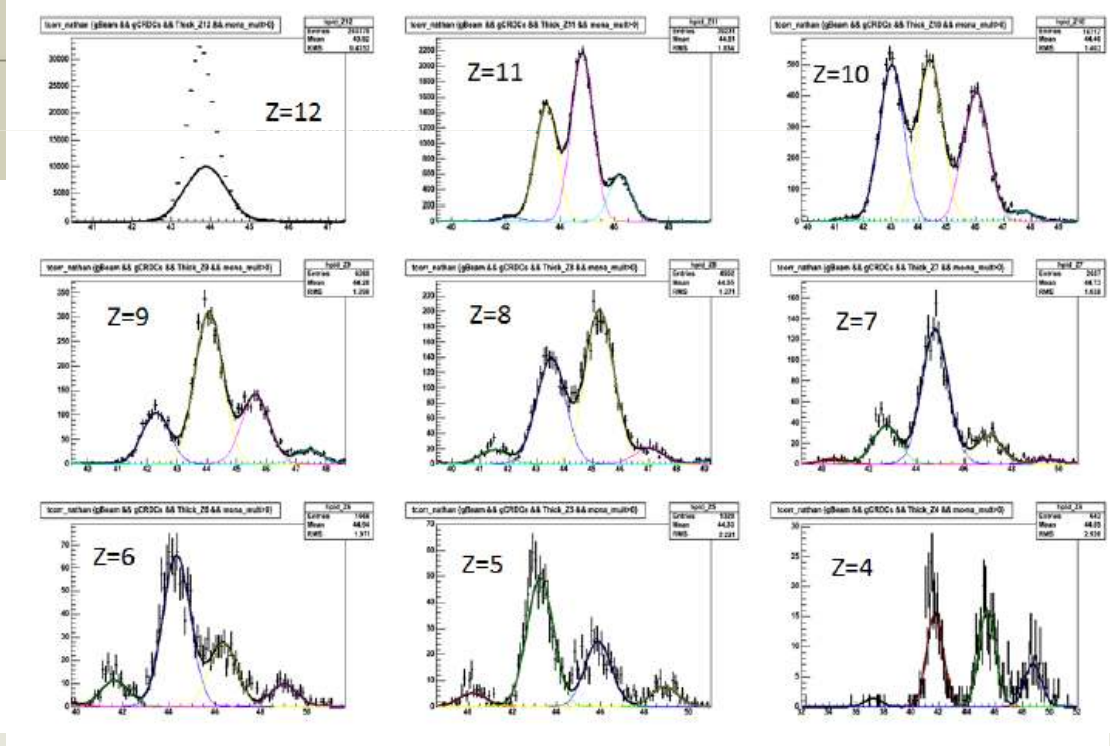


^{32}Mg, δ = 0.667
^{132}Sn, δ = 0.64

Measuring projectile-like fragments (PLFs) in coincidence with neutrons.

MoNA-LISA Experiment

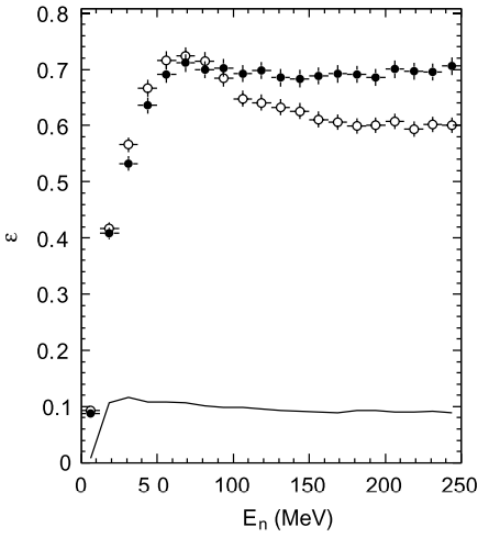


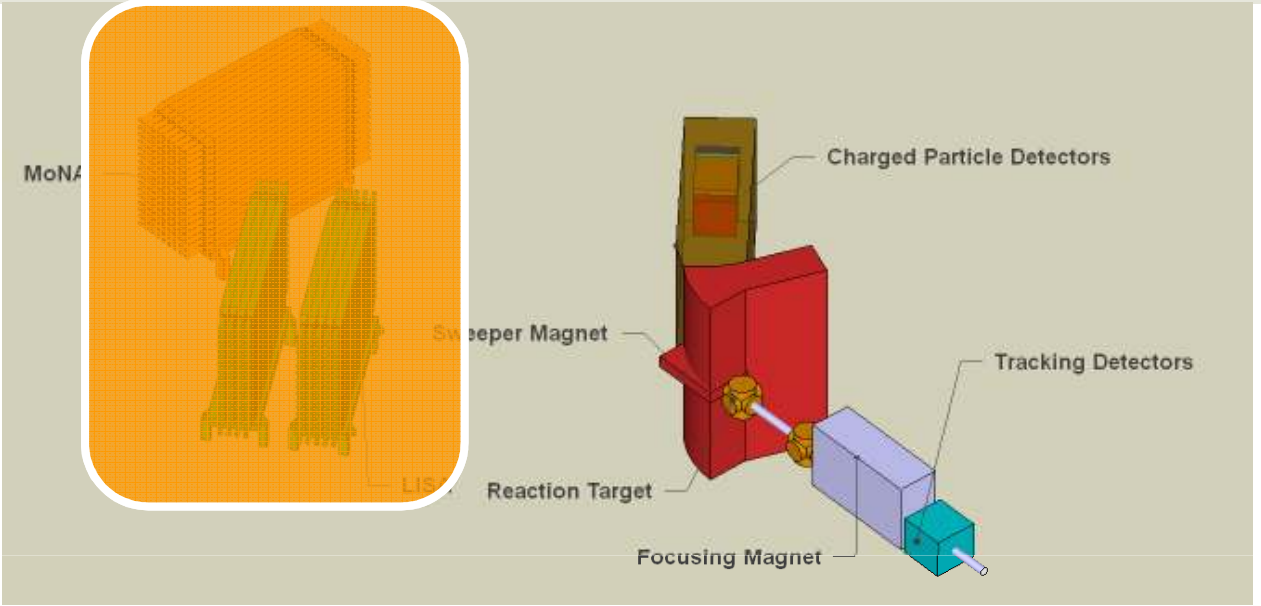


Sweeper Magnet:

- 4 Tm, bends fragments ~43°
- Large acceptance; +/- 8% Bρ
- CRDCs for tracking (Mass, Energy)
- CsI Hodoscope

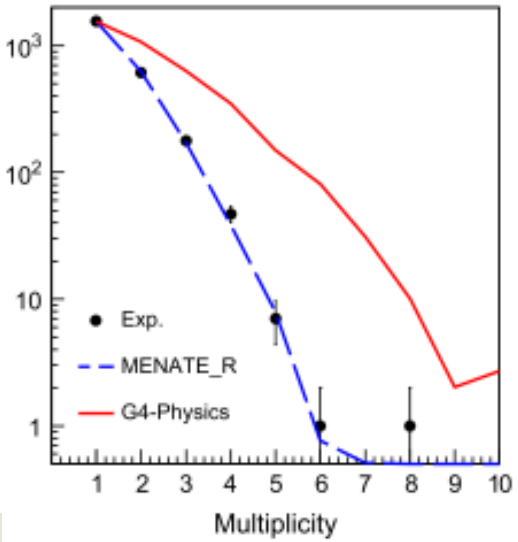
MoNA-LISA Experiment

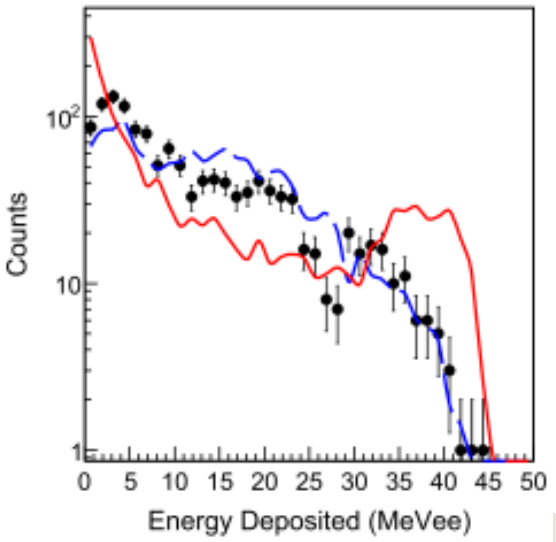




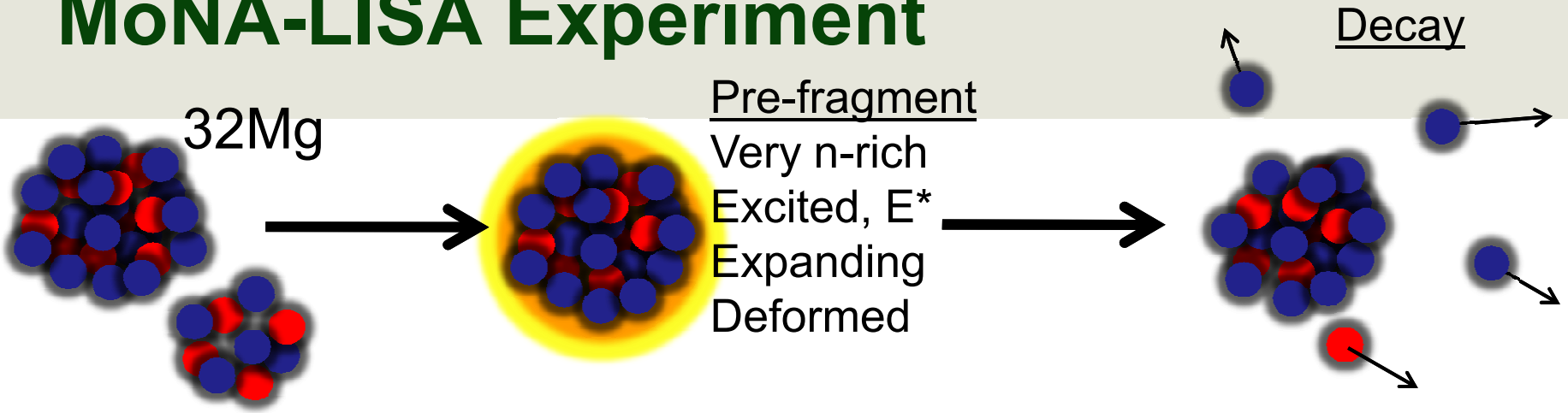
$^{17}C(-p)\rightarrow{}^{16}B\rightarrow{}^{15}B+n$

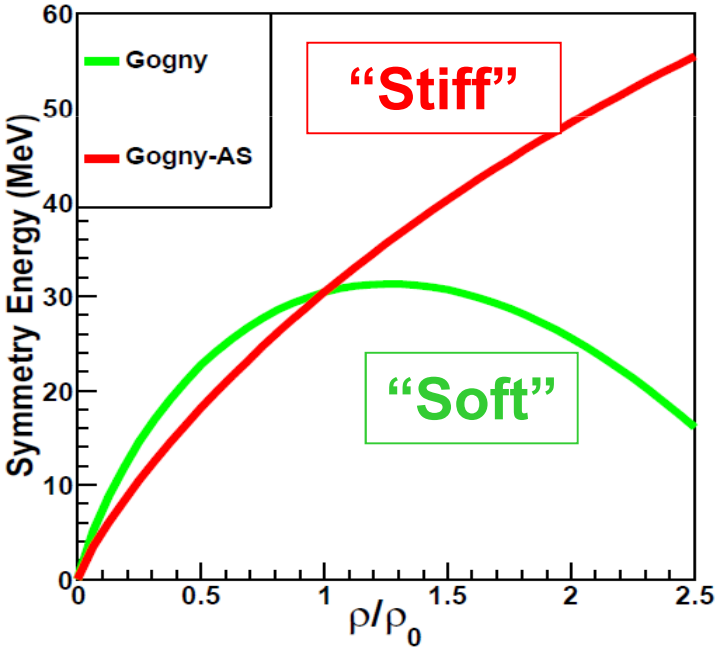
Kohley *et al.*, NIMA **682**, 59 (2012)





MoNA-LISA Experiment



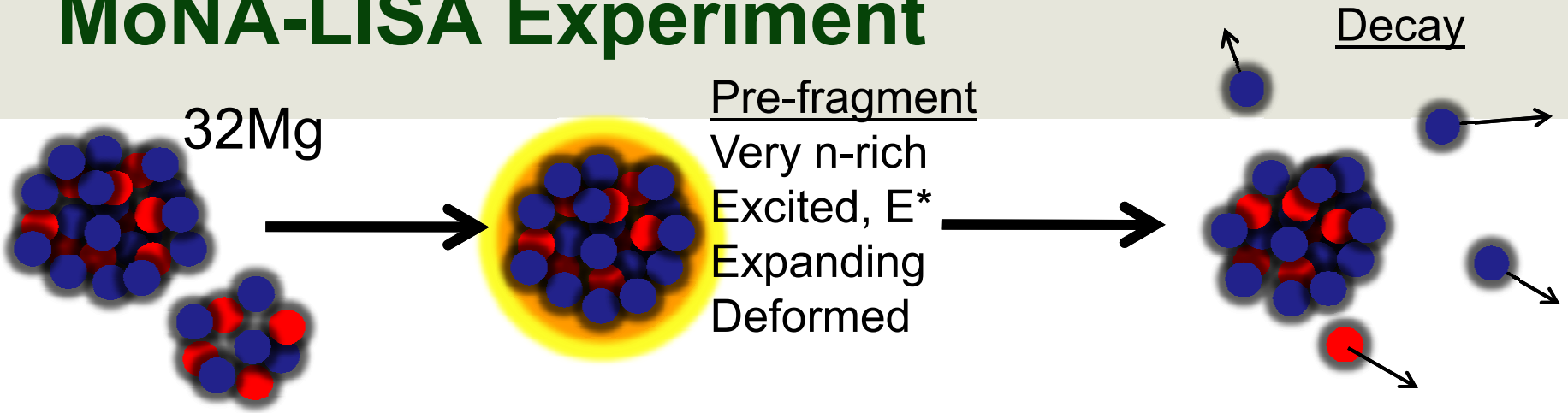


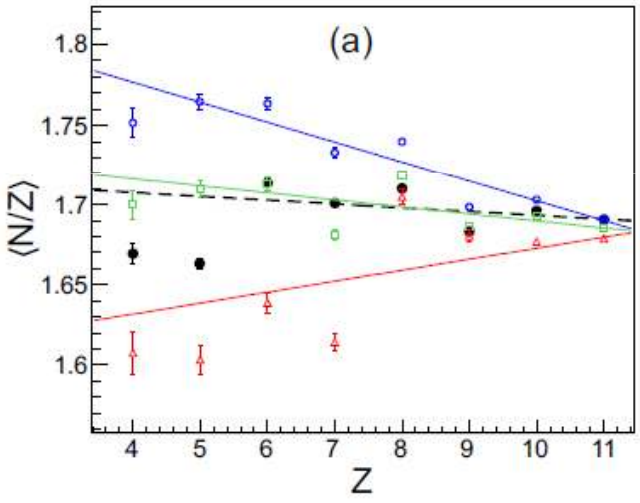
At $\rho/\rho_0 < 1$:

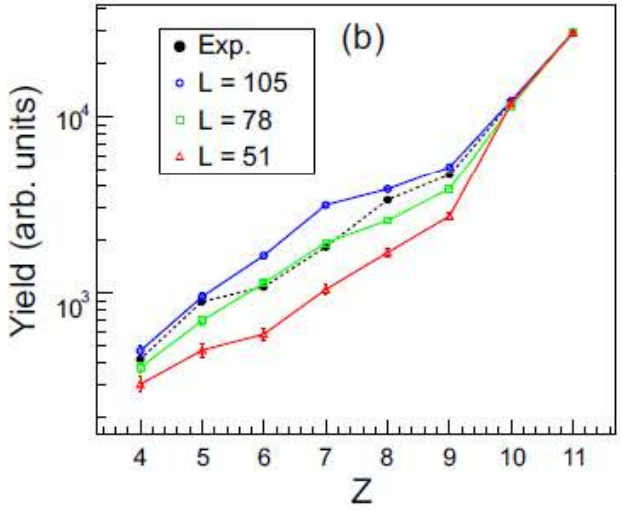
Soft is more repulsive = emit more neutrons

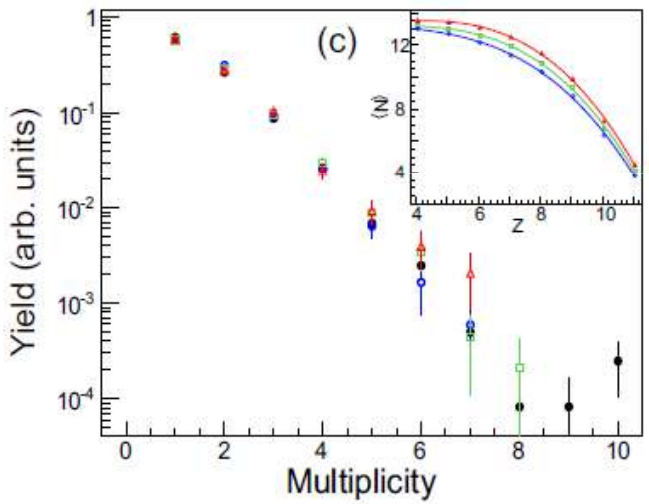
Stiff is less repulsive = emit less neutrons

MoNA-LISA Experiment









Constrained Molecular Dynamics (CoMD) model:

- 3 forms of $E_{sym}(\rho)$

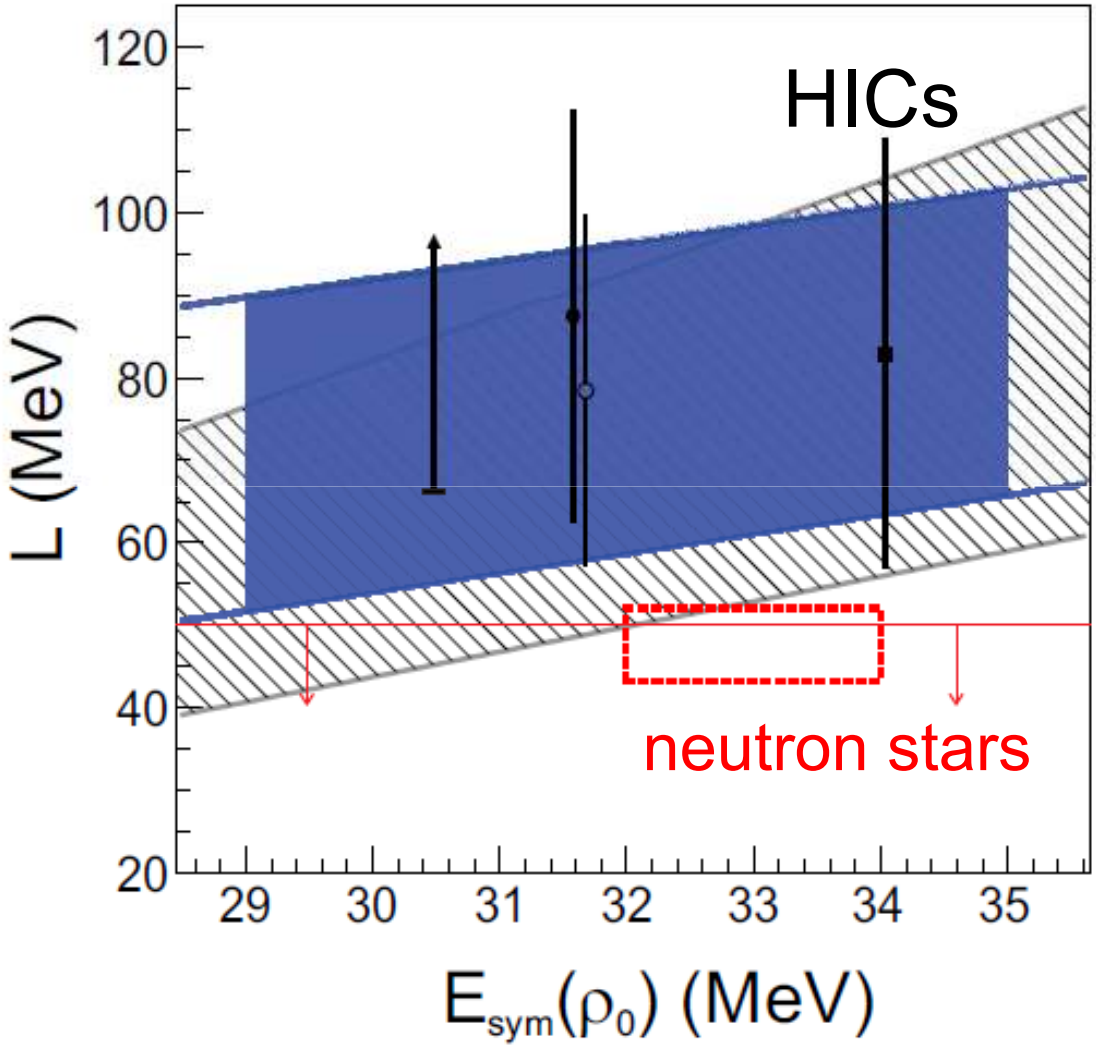
M. Papa, T. Maruyama, and A. Bonasera. PRC **64,** 24612, (2001).

- Consistent model of dynamics and decay (time = 1500 fm/c)

MoNA-LISA Experiment

$$L = 3\rho_0 \frac{dE_{sym}(\rho)}{d\rho}\Big|_{\rho=\rho_0}$$

Blue area constraints extracted from 32Mg RIB experiment.

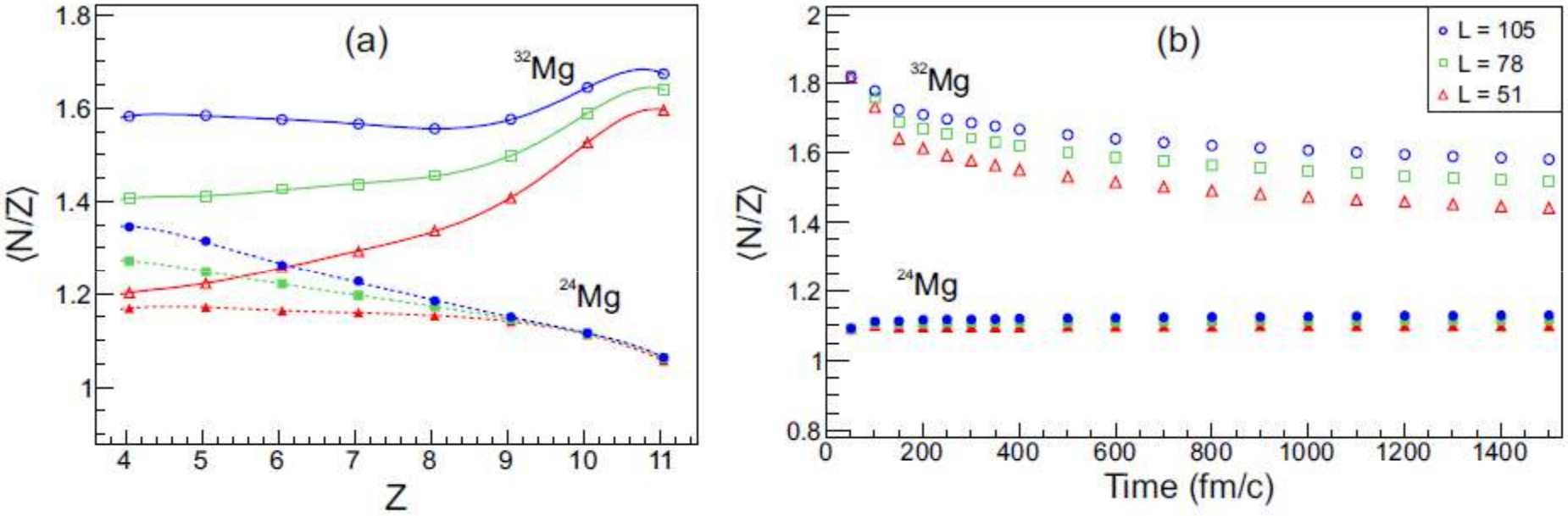


HICs Refs:
Tsang et al, PRL (2009)
Kohley et al, PRC (2010).
Russotto et al, PLB (2011)
Li, Chen, and Ko, Phys. Rep. (2008).
Shetty et al. PRC (2007)

NStar Refs:
Steiner and Gandolfi, PRL (2012)
Sotani, Nakazato, and Oyamastsu, PRL (2012)

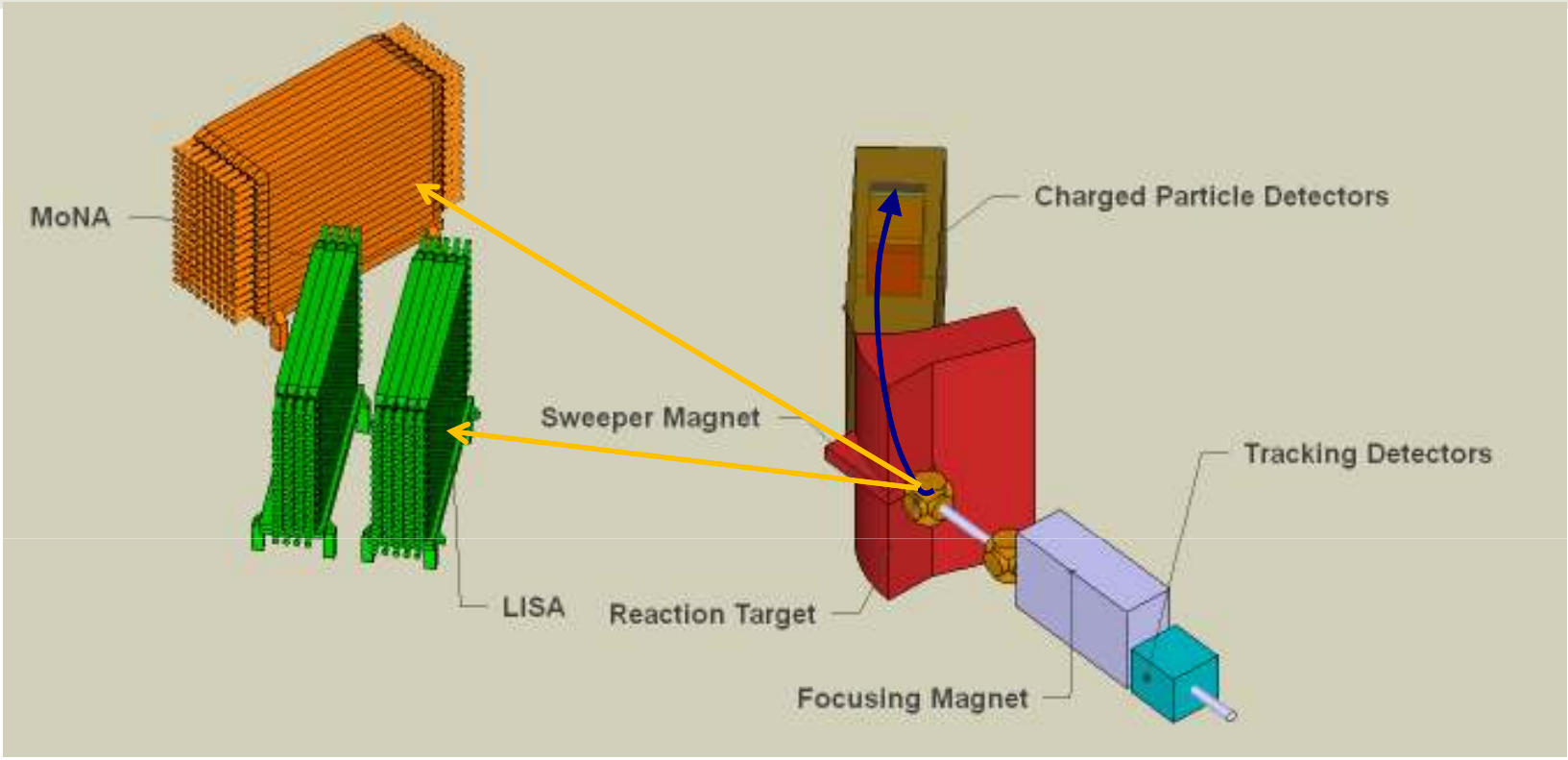
MoNA-LISA Experiment

How would the analysis have faired with a stable beam?



Increase sensitivity to E_{sym} by factor of 3

Future MoNA-LISA Program



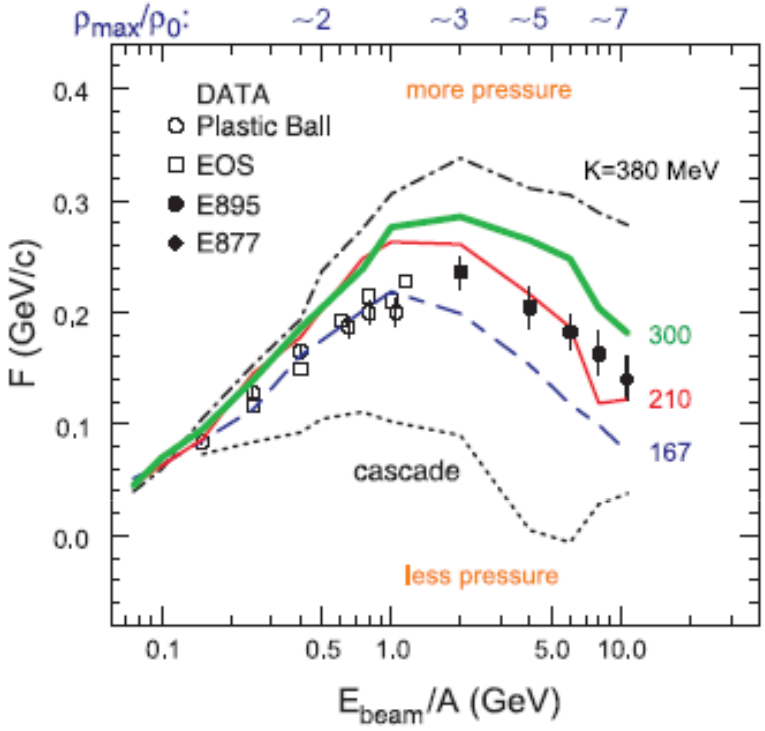
Thoennessen

Yennello
McIntosh
Bonasera

Tsang
Lynch

Approved PAC experiment to make further measurements with n-rich and p-rich RIBs.

Future ideas with FRIB



Danielewicz, Lynch, Lacey. Science (2002)

Systematic flow measurements allowed for critical constraints to be placed on the EoS for symmetric matter.

Develop a similar data set (sensitive to E_{sym}) over the energies and RIBs offered by FRIB…

RHIC-type energy scans

Summary

Huge opportunities for new experiments at the NSCL and FRIB.

RIB provide a new path forward in constraining E_{sym}

Working on a program using the unique capabilities of the MoNA-Sweeper setup to explore E_{sym} with RIBs.

Acknowledgments

NSCL

Thomas Baumann
Greg Christian
Mike Jones
Jenna Smith
Jesse Snyder
Artemis Spyrou
Michael Strongman
Michael Thoennessen

NSF

MICHIGAN STATE UNIVERSITY

CoMD
A. Bonasera
H. Zheng

Sponsors


Agilent Technologies


15 YEARS OF
EPJ.org
your physics journal


MICRON
SEMICONDUCTOR
LIMITED


A Phoenix Mecano Company
wiener
Plein & Baus, Corp.


XIA
Instruments That Advance The Art


VACUUM ONE


CANBERRA


CAEN
Tools for Discovery


MEWASA
SWISS MADE