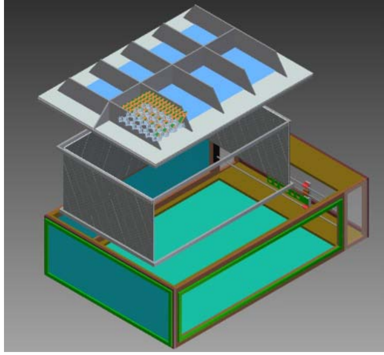
Symmetry Energy Project (SEP)

http://groups.nscl.msu.edu/hira/sep.htm

http://nscl.msu.edu/~tsang

Betty Tsang, NSCL, MSU



Determination of the Equation of State of Asymmetric Nuclear Matter

NSCL MSU, USA: B. Tsang & W. Lynch,
E. Brown, Zibi Chajecki, Pawel Danielewicz,
A. Steiner, Gary Westfall.
Texas A&M University, College Station:
Sherry Yennello, A. McIntosh
Western Michigan University: Michael Famiano
GSI,DE: Wolfgang Trautmann , Yvonne Leifels
Daresbury Laboratory, UK: Roy Lemmon
INFN LNS, Catania, IT: Giuseppe Verde, Angelo Pagano,
Paulo Russotto, Massimo di Toro, Maria Colonna,
Aldo Bonasera, Vincenzo Greco
SUBATECH, FR: Christoph Hartnack
GANIL, FR: Abdou Chbihi, John Frankland, Jean-Pierre Wieleczko
China Institute of Atomic Energy: Yingxun Zhang, Zhuxia Li, Fei Lu (Peking University), Y.G. Ma, Wendong Tian (Chinese Shanghai Academy of Sciences)
Brazil: Sergio Souza, Raul Donangelo, Brett Carlson

RIKEN, JP: Hiroshi Sakurai, Shunji Nishimura, Yoichi Nakai, Atsushi Taketani
Kyoto University: Tetsuya Murakami
Tohoku University: Akira Ono
Rikkyo University: Jiro Murata, K. Ieki

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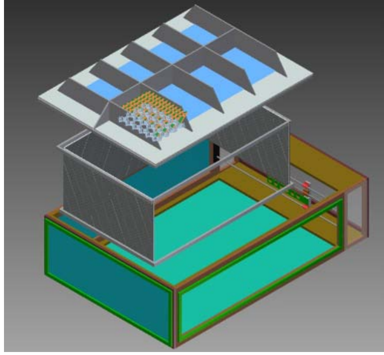


Outline

I. **Introduction of NSCL, FRIB**
II. **Equation of State of Symmetric Nuclear Matter**
III. **Symmetry energy in EoS of Asymmetric Matter**
   A. **Constraints from HIC**
      a) **n/p ratios**
      b) **Isospin diffusion**
   B. **Constraints from other observables from finite nuclei**
      a) **Nuclear masses → Isobaric Analog States**
      b) **Neutron skin thicknesses**
      c) **Pygmy Dipole Resonances**
      d) **Giant Dipole Resonances**
      e) **Current Status of the Symmetry Energy Project**
IV. **Current Status of the Symmetry Energy Project**
V. **Summary & Conclusion**

The National Superconducting Cyclotron Laboratory

Michigan State University

NSCL

Michigan State University

The National Superconducting Cyclotron Laboratory

Michigan State University

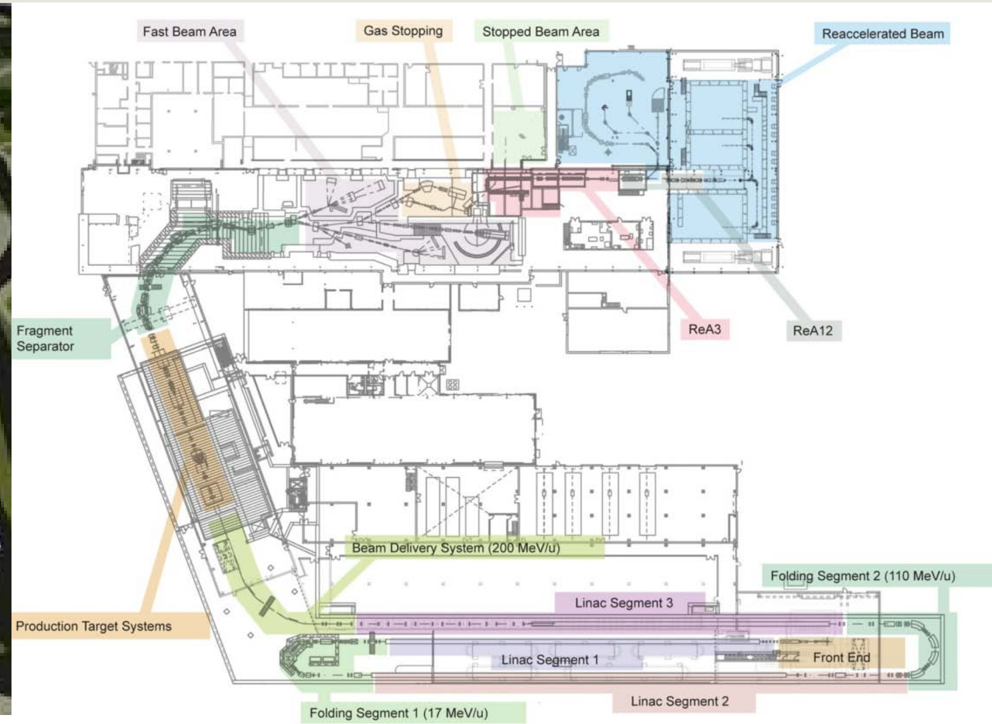
NSCL

A national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

431 employees, including 35 faculty, 70 graduate and 59 undergraduate students

as of December 7, 2010

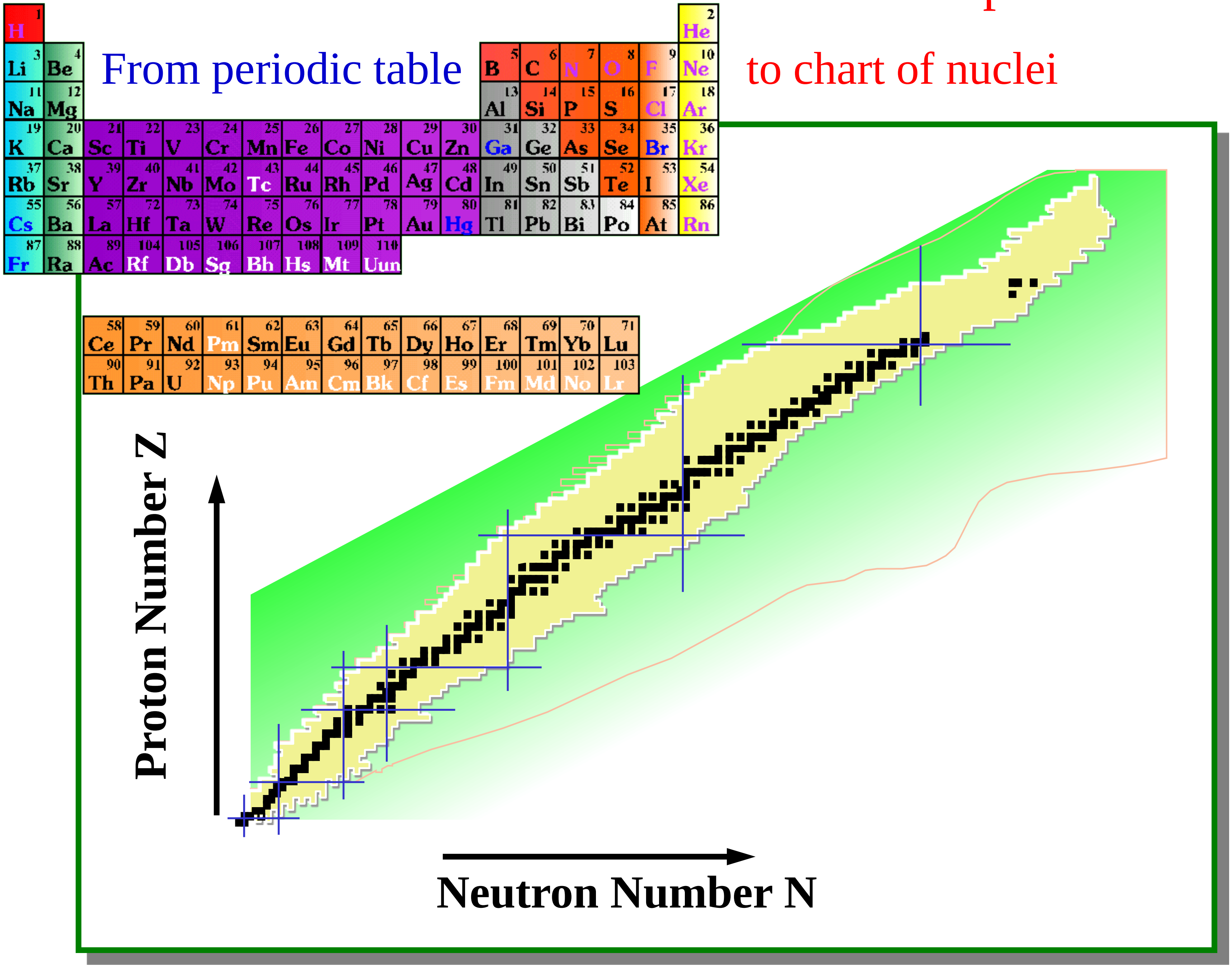
Facility for Rare Isotope Beams (FRIB)



FRIB will provide intense beams of rare isotopes (that is, short-lived nuclei not normally found on Earth). FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.

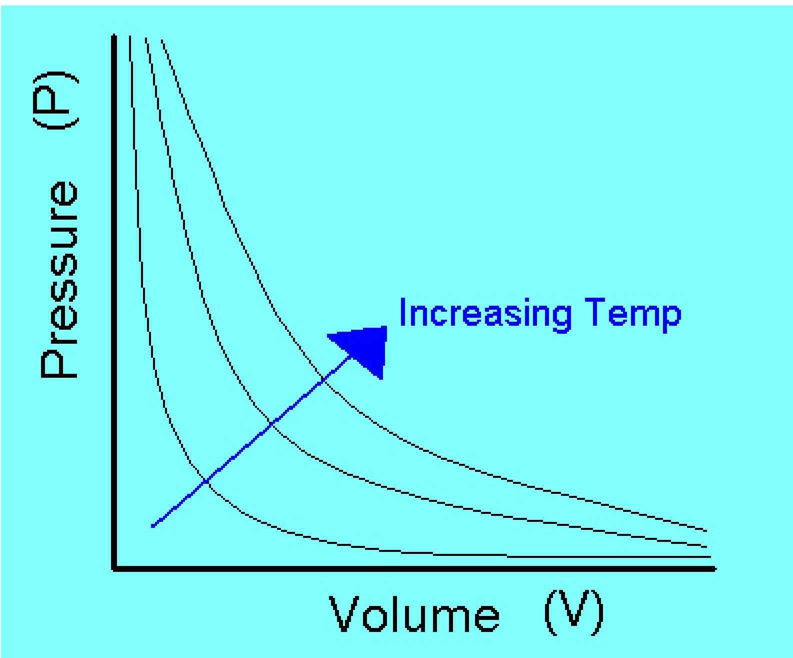
Cost: $640M; construction start: 2013; completion: 2020

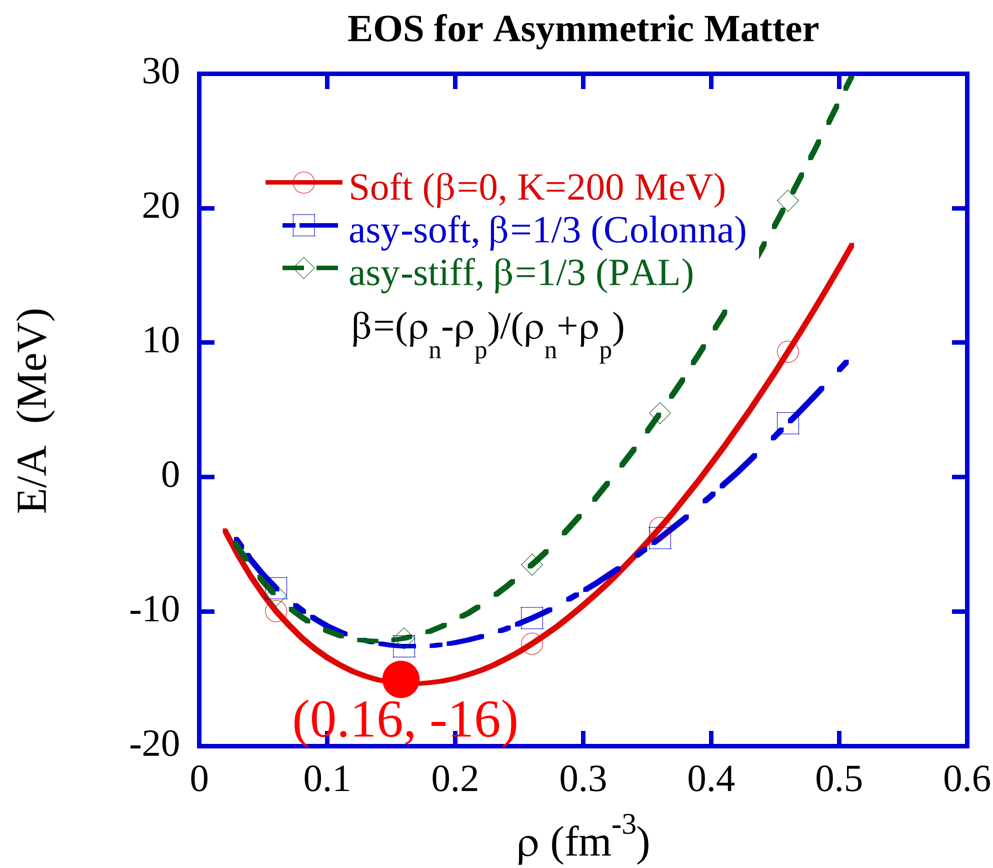
From Elements to Rare isotopes

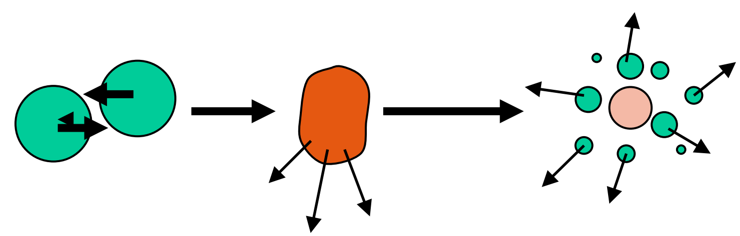


Equation of State (EoS)

Ideal gas: $PV=nRT$





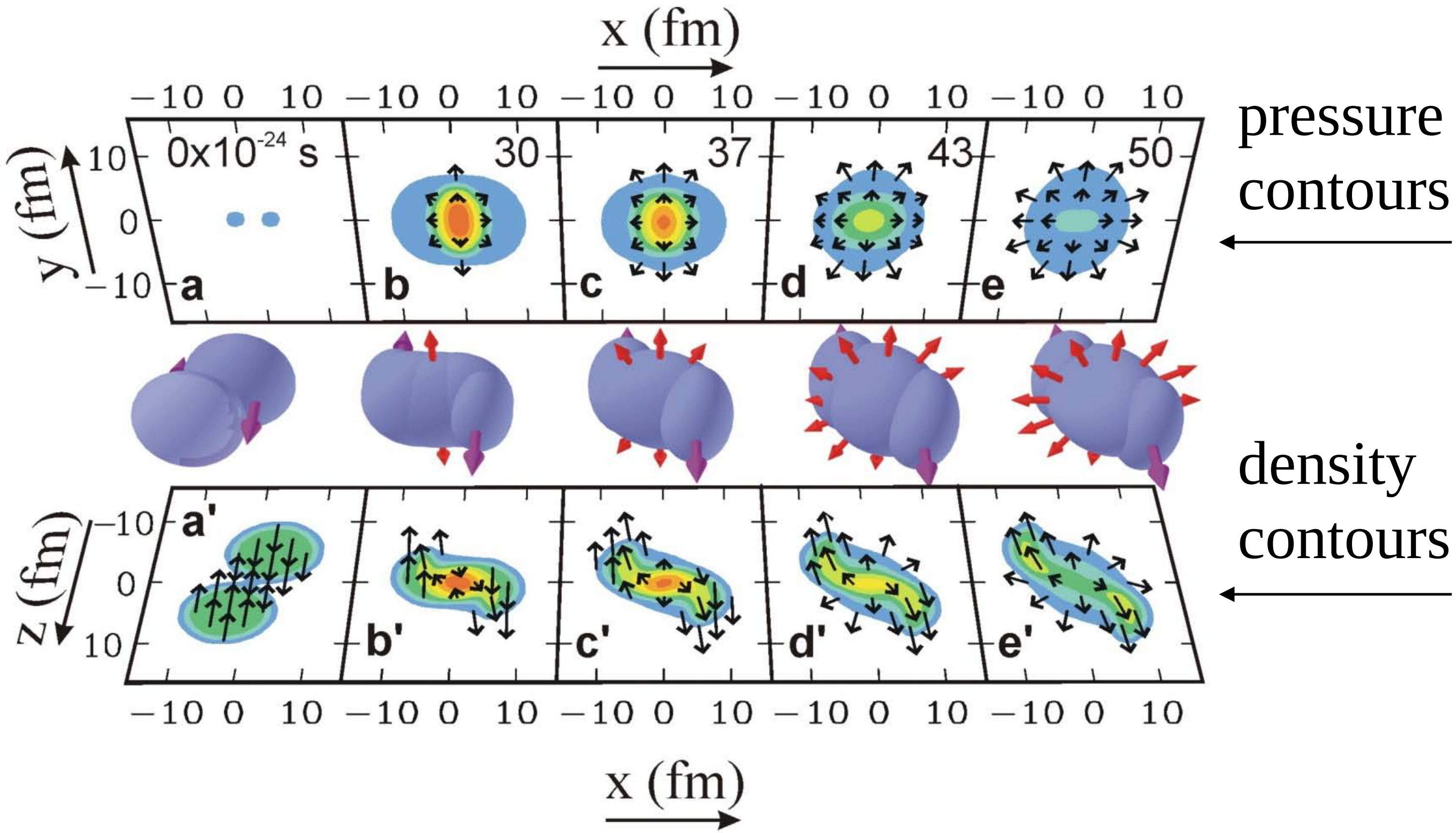


How to determine nuclear EOS

- Measure collisions
- Simulate collisions with transport theory (BUU)
- Identify observables that are sensitive to EOS
  - Directed transverse flow (in-plane)
  - “Elliptical flow” out of plane, e.g. “squeeze-out”
  - …
- Find the mean field(s) that describes the data.
- Constrain the relevant input variables in the transport models by additional data.
- Use the mean field potentials to calculate the EOS.

Constraining the EOS using Heavy Ion collisions

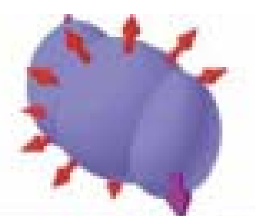
Au+Au collisions E/A = 1 GeV)



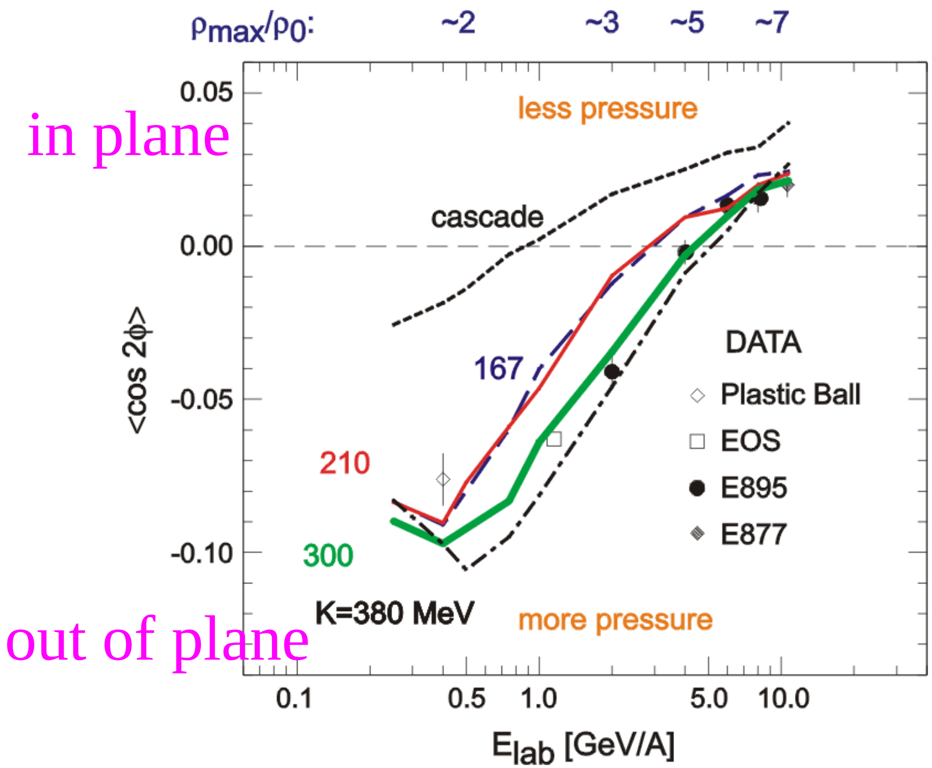
Two observable due to the high pressures formed in the overlap region:

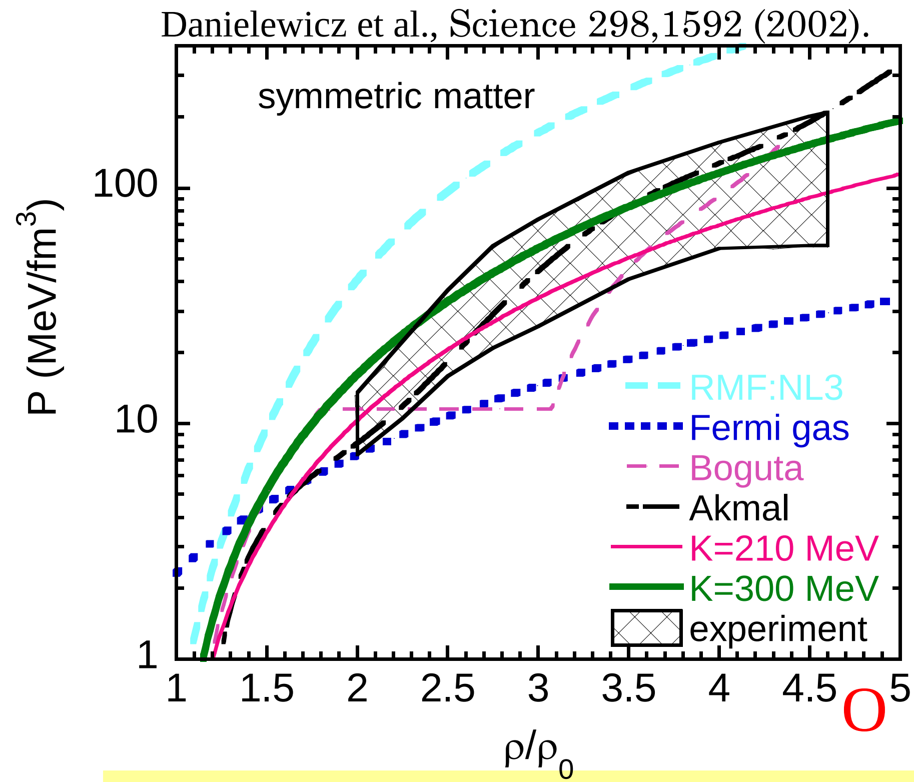
– Nucleons deflected sideways in the reaction plane.

– Nucleons are “squeezed out” above and below the reaction plane. .



Determination of symmetric matter EOS from nucleus-nucleus collisions





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The curves represent calculations with parameterized Skyrme mean fields

They are adjusted to find the pressure that replicates the observed flow.

The boundaries represent the range of pressures obtained for the mean fields that reproduce the data.

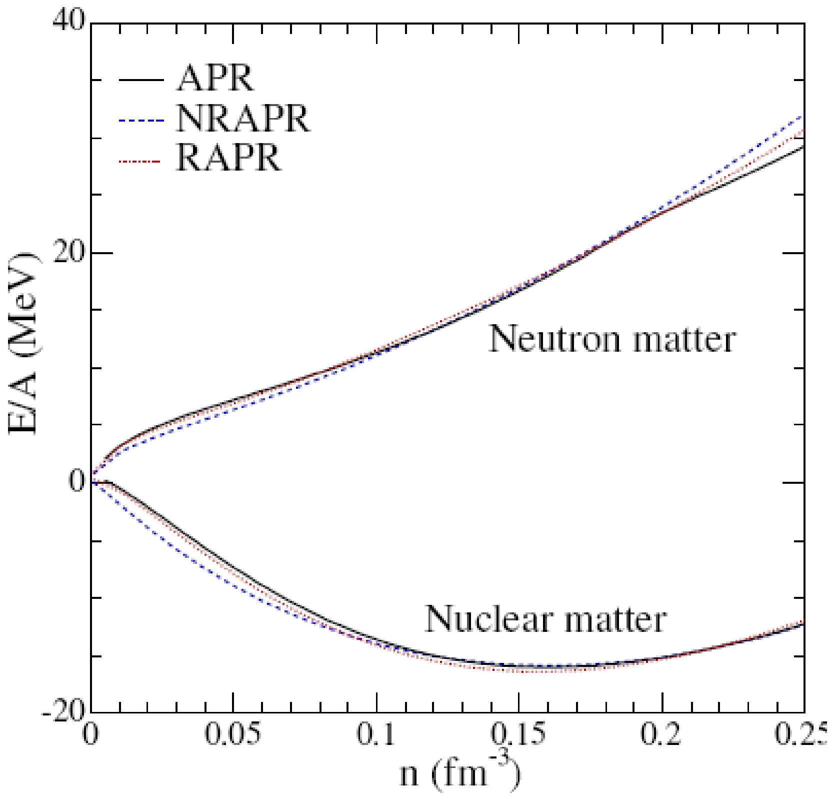
They also reflect the uncertainties from the input parameters in the model.

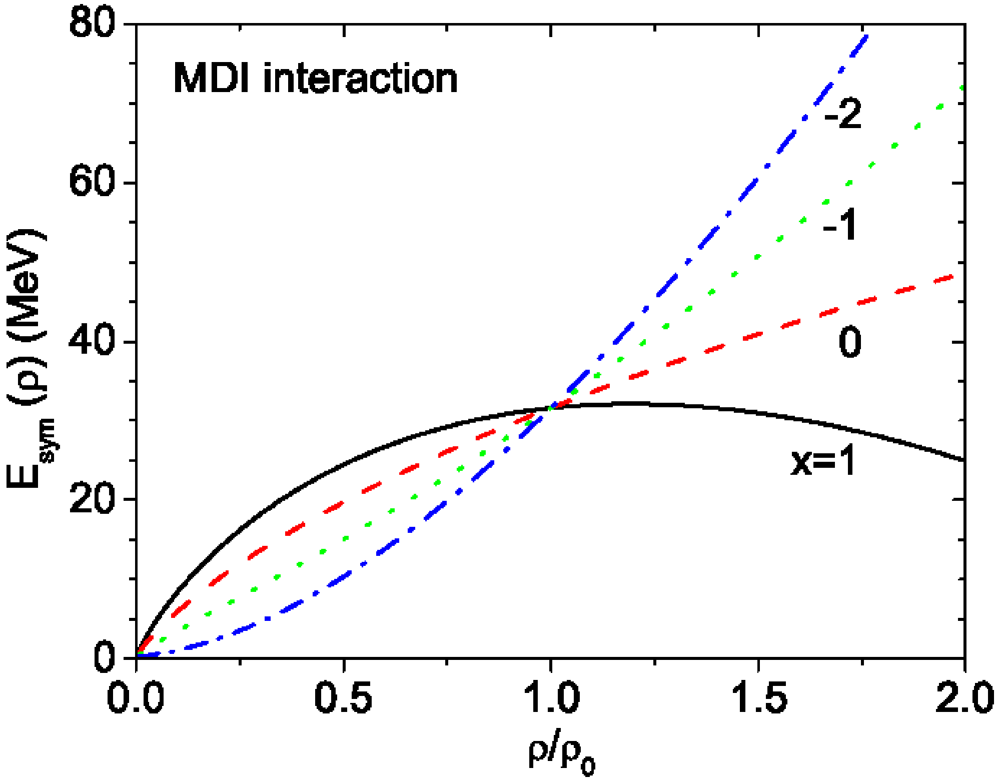
Nuclear Equation of State of asymmetric matter

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$
$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

$$S(\rho) = S_o + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho_B}\bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}$$





Density dependence of symmetry energy

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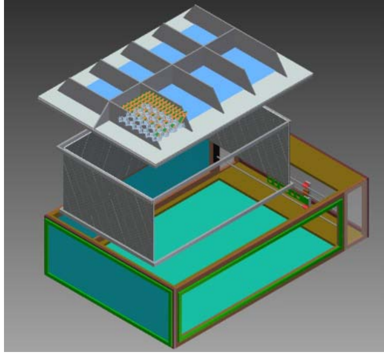

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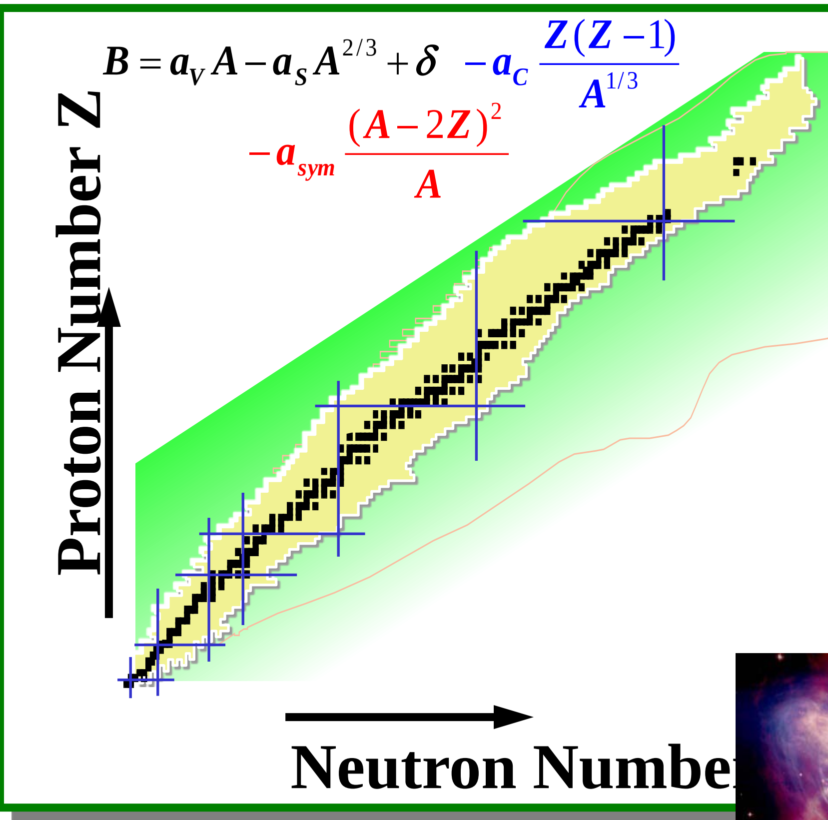
Strategies used to study the symmetry energy with Heavy Ion collisions

Isospin degree of freedom



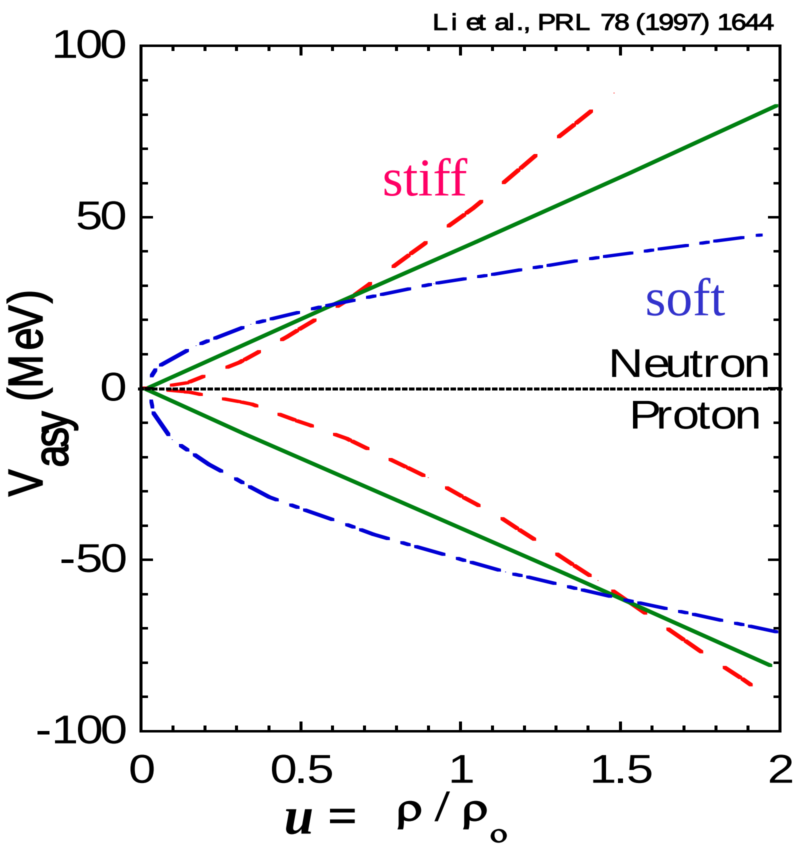
Crab Pulsar

Hubble ST

- Vary the N/Z compositions of projectile and targets
  ^{124}Sn+^{124}Sn, ^{124}Sn+^{112}Sn, ^{112}Sn+^{124}Sn, ^{112}Sn+^{112}Sn
- Measure N/Z compositions of emitted particles
  - n & p yields
  - isotopes yields – isospin diffusion
  - Results interpreted with transport models that simulate the collisions.

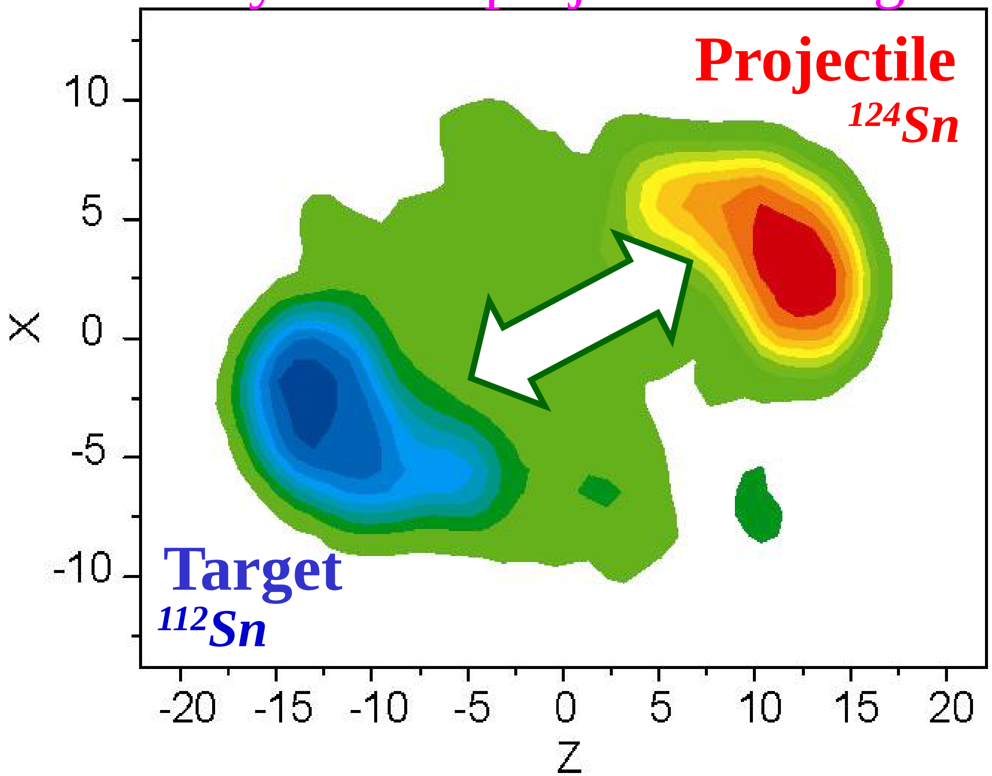
Two observables: n/p ratios and isospin diffusion

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$
$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$



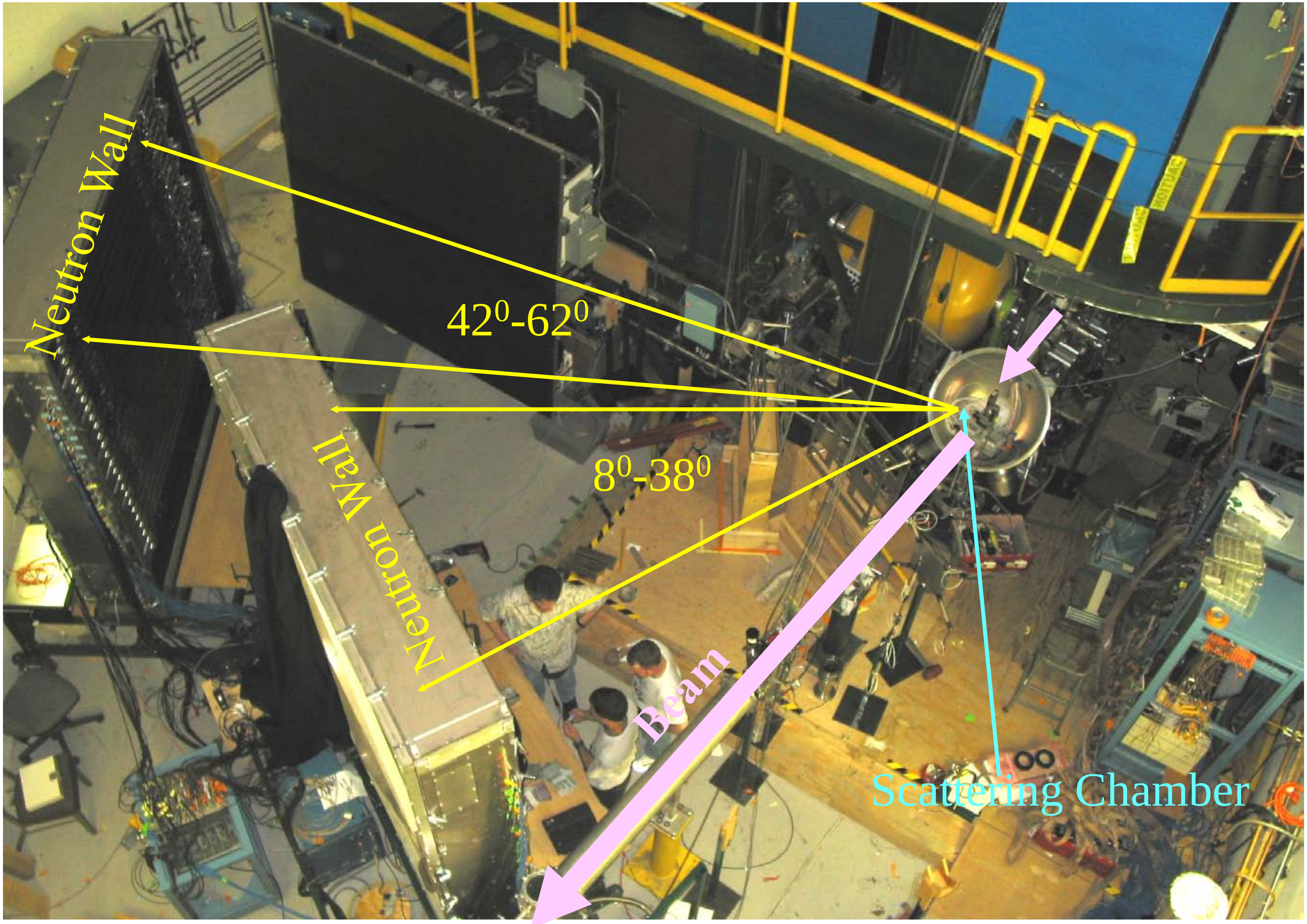
$Y(n)/Y(p)$; $t/^3He$, π^+/π^-

Vary N/Z of projectile & target



Isospin Diffusion; low ρ, E_{beam}

n/p Experiment $^{124}Sn+^{124}Sn$; $^{112}Sn+^{112}Sn$; E/A=50 MeV

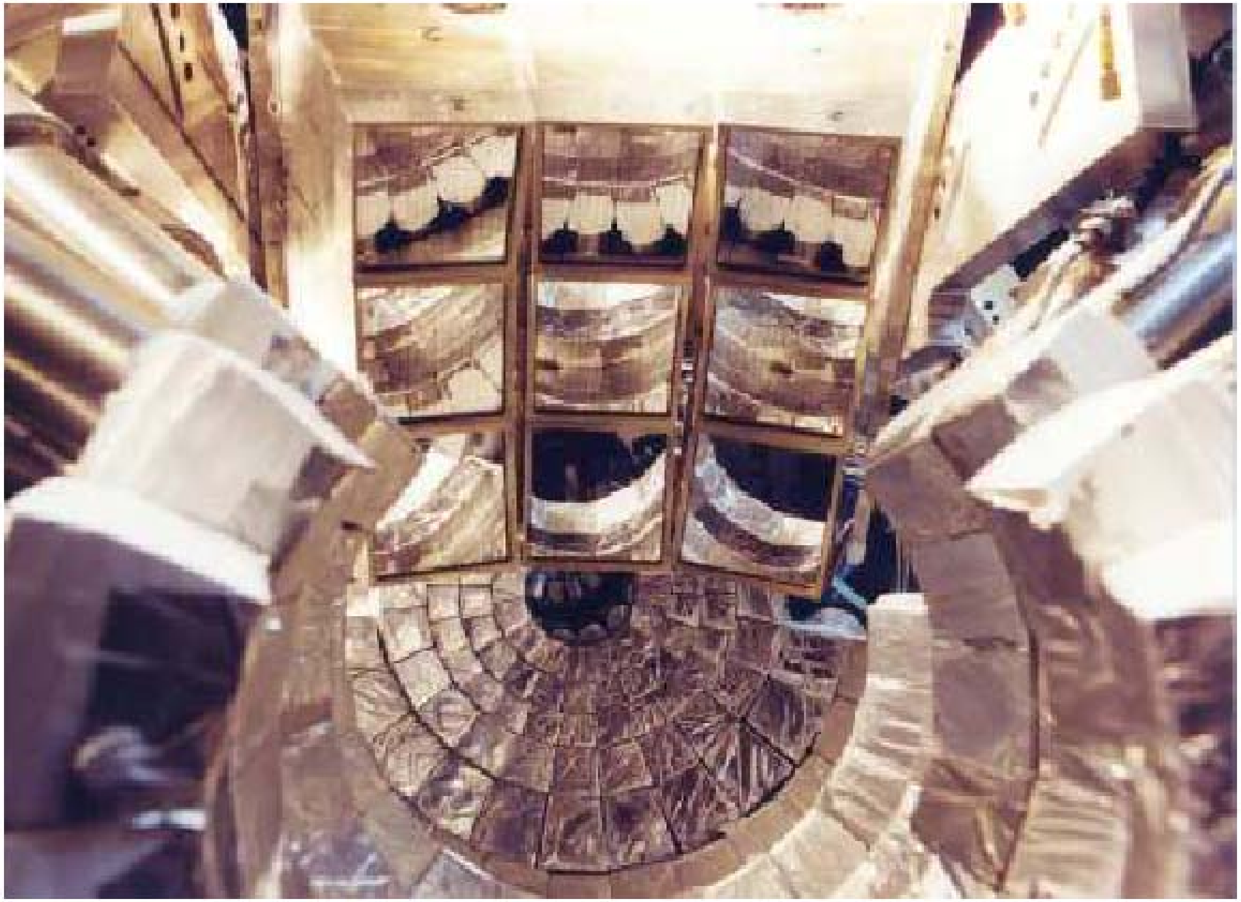


Famiano et al

Isotope Distribution Experiment

MSU, IUCF, WU collaboration

Sn+Sn collisions involving ^{124}Sn, ^{112}Sn at E/A=50 MeV

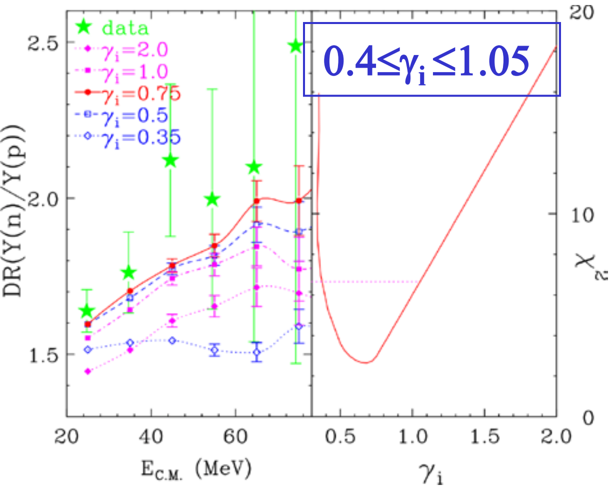


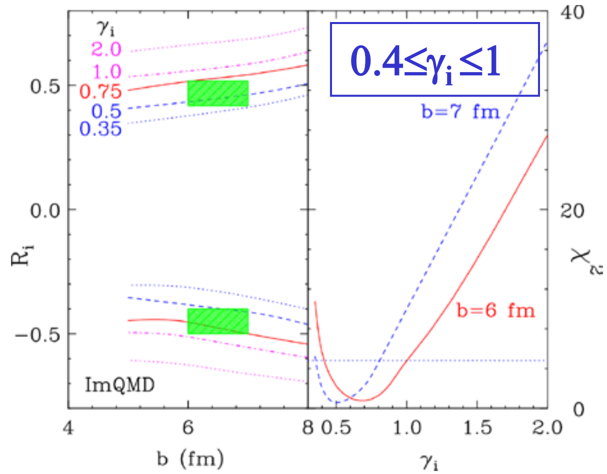
Miniball + Miniwall
4 π multiplicity array
Z identification, A<4

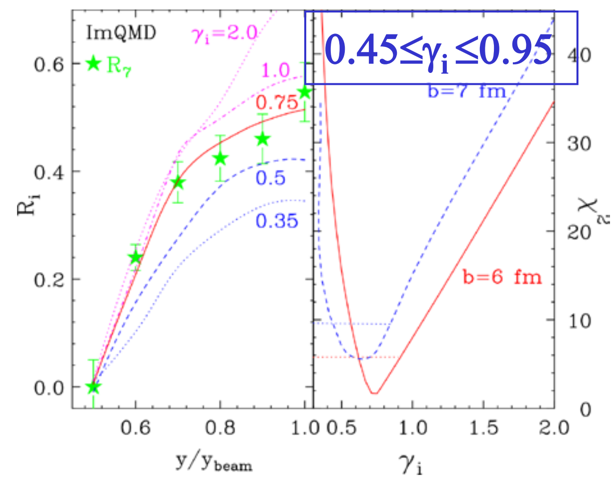
LASSA
Si strip +CsI array
Good E, position,
isotope resolutions

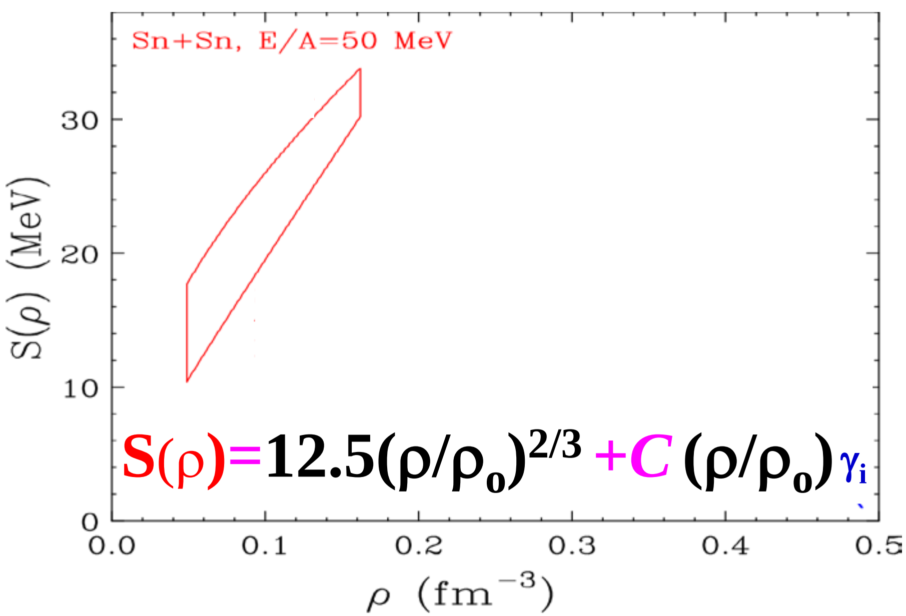
Xu et al, PRL, 85, 716 (2000)

Constraints from np ratios and two isospin diffusion measurements



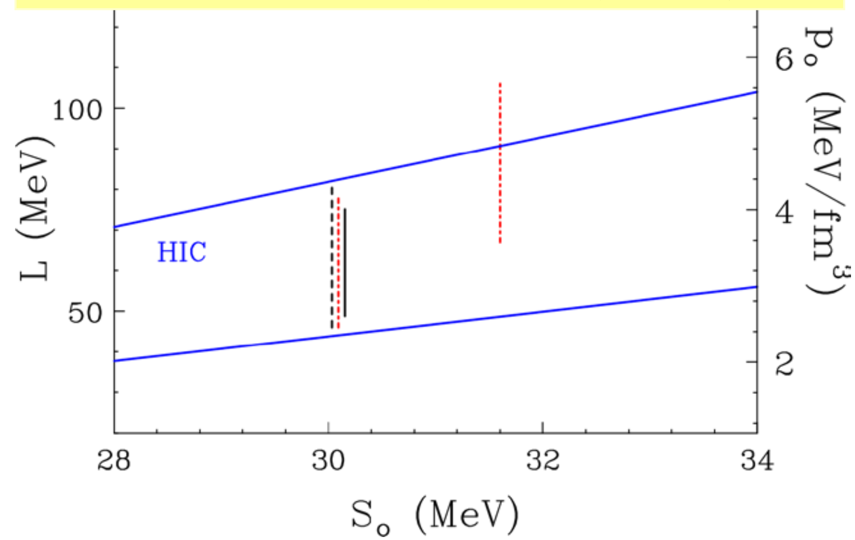






$S(\rho)=12.5(\rho/\rho_o)^{2/3}+C(\rho/\rho_o)^{\gamma_i}$

$$S(\rho)=S_o+\frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right)+\frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2+\ldots$$



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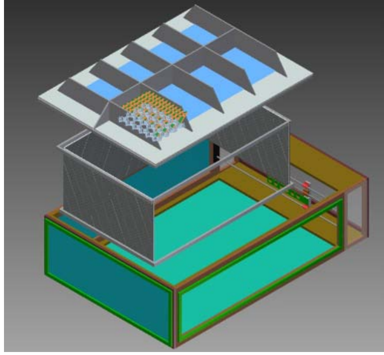

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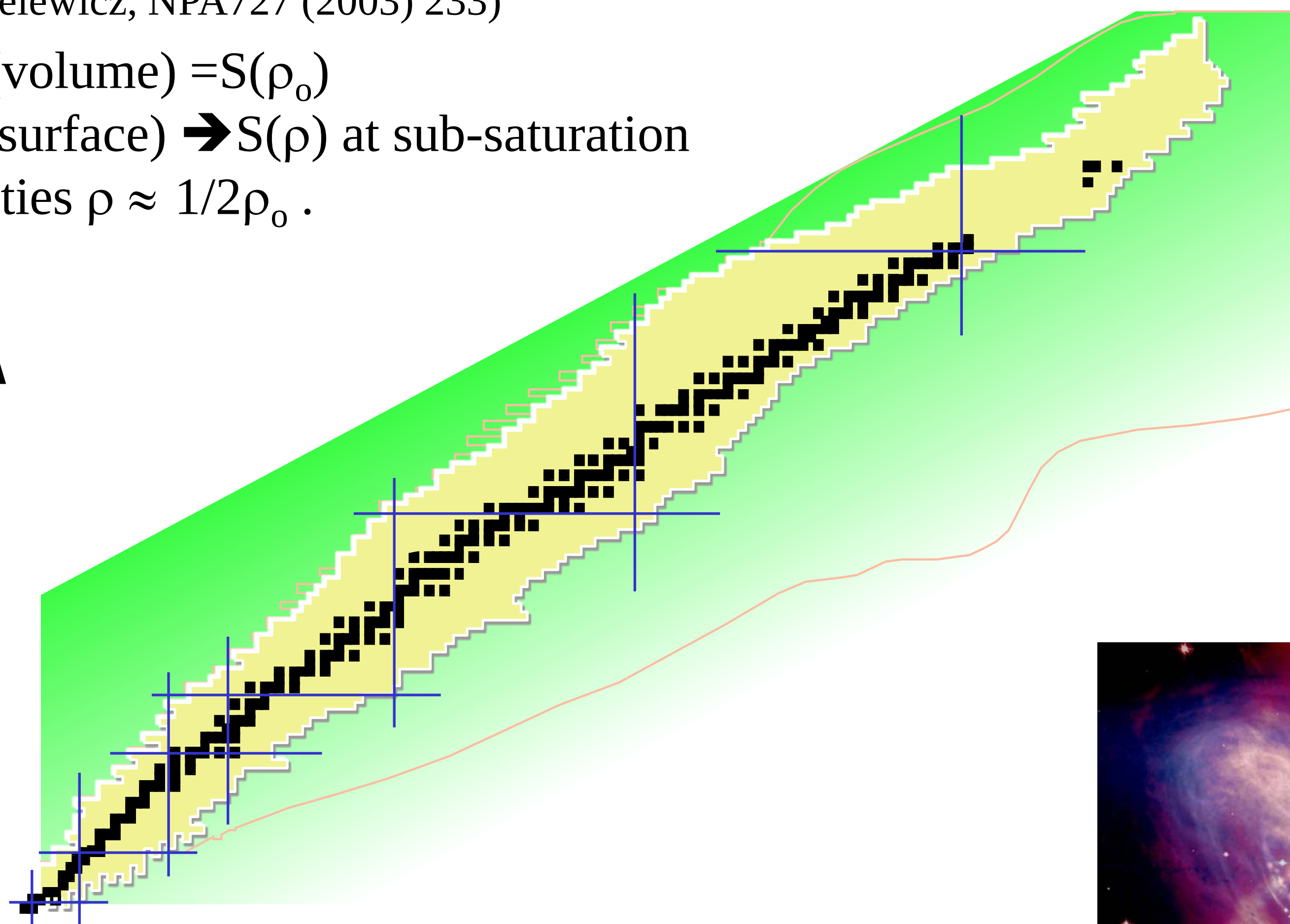
Symmetry Energy in Nuclei

$$B = a_V A - a_s A^{2/3} + \delta \quad - a_C \frac{Z(Z-1)}{A^{1/3}} \quad - \boxed{a_{sym} \frac{(A-2Z)^2}{A}}$$

(Danielewicz, NPA727 (2003) 233)

a_{sym} (volume) $= S(\rho_o)$
a_{sym} (surface) ➔ $S(\rho)$ at sub-saturation densities $\rho \approx 1/2\rho_o$.



Proton Number Z

Neutron Number N

Crab Pulsar

Hubble ST

Nuclear masses and the EoS

$$M_{A,Z}c^2 = Zm_pc^2 + (A-Z)m_nc^2 - B_{A,Z}$$

$$B = a_V A - a_S A^{2/3} + \delta \quad - a_C \frac{Z(Z-1)}{A^{1/3}} \quad - a_{sym} \frac{(A-2Z)^2}{A}$$

- Fits of the binding energy formula to experimental masses to provide values for a_v, a_s, a_c, a_{sym} and δ using AME2003, NPA 729, (2003) 129, 337.
- Problems: The binding energy formula is not unique

$$a_{sym} A \frac{(N-Z)^2}{A^2} \quad \text{OR} \quad \left(-a_V b_1 + a_S b_2 A^{2/3}\right)\frac{(N-Z)^2}{A^2} \quad \text{OR} \quad \frac{\alpha A}{1+(\alpha/\beta)A^{-1/3}} \frac{(N-Z)^2}{A^2}$$

- Problems: a_{sym} *is small compared to other terms*. a_c, a_{sym} are strongly correlated & shell effects are large.
- The best fits may not give reasonable parameters.
- Can we isolate a_{sym} from the rest of formula?

Symmetry coefficient *from Isobaric Analog States*

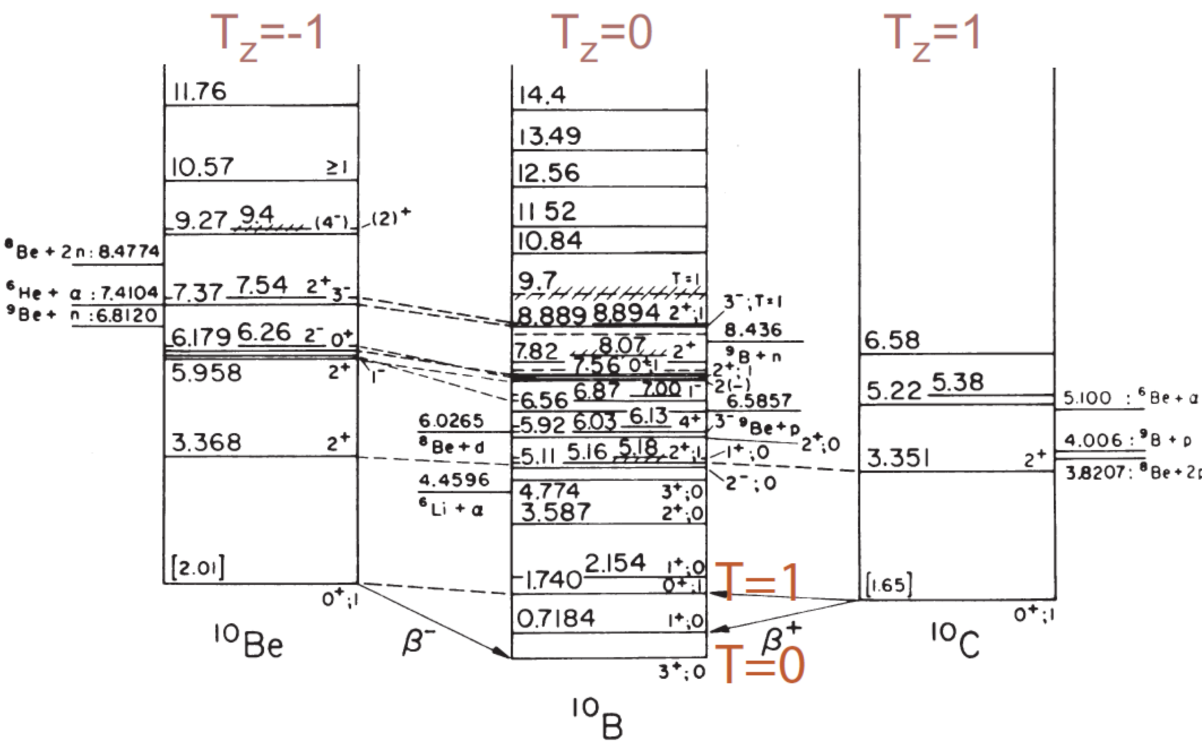
$$E = -a_V A + a_S A^{2/3} + a_C \frac{Z^2}{A^{1/3}} + a_a \frac{(N-Z)^2}{A} + E_{mic}$$

Charge invariance: invariance of nuclear interactions under rotations in n-p space

$$E_a = a_a(A)\,\frac{(N-Z)^2}{A} = 4\,a_a(A)\,\frac{T_z^2}{A}$$

$$T_z = (Z-N)/2$$

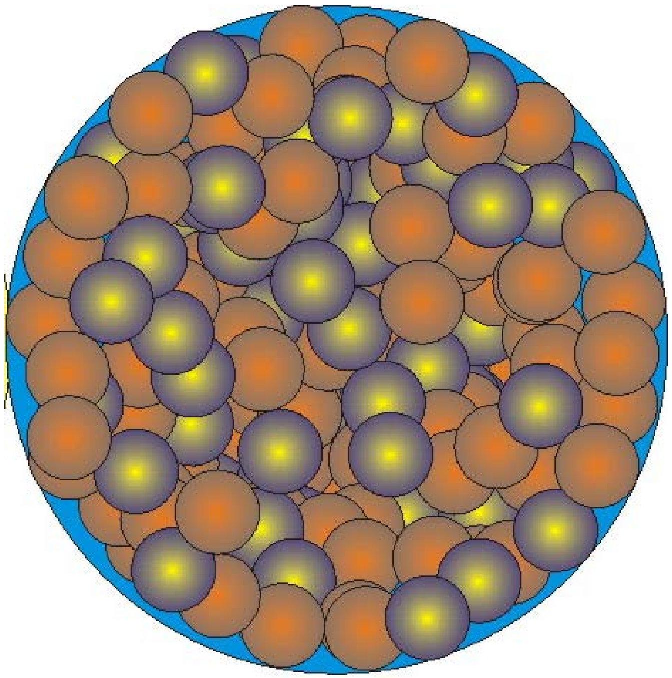
$$E_a = 4\,a_a(A)\,\frac{T^2}{A} = 4\,a_a(A)\,\frac{T(T+1)}{A}$$



P. Danielewicz & J. Lee, NPA 818, 36 (2009)

Symmetry energy on vastly differing length scales

$\sim 10^{-15}$ m ⟷ $\sim 10^{4}$ m



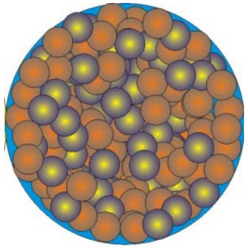
^{208}Pb

Neutron Star

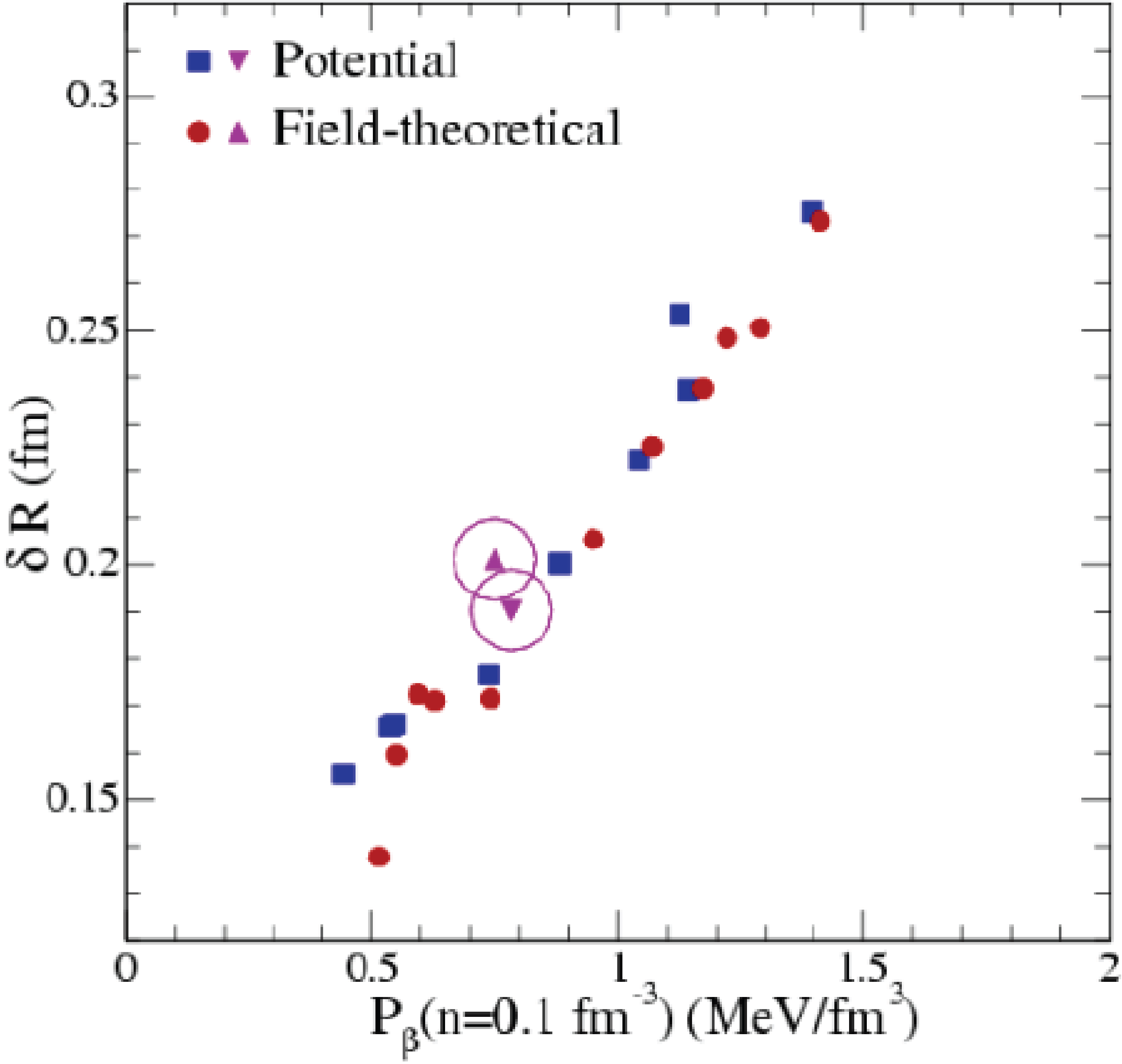
extrapolation from ^{208}Pb radius to n-star radius

C.J. Horowitz, J. Piekarewicz, Phys. Rev. Lett. 86 (2001) 5647

Extrapolation from ^{208}Pb radius to n-star radius

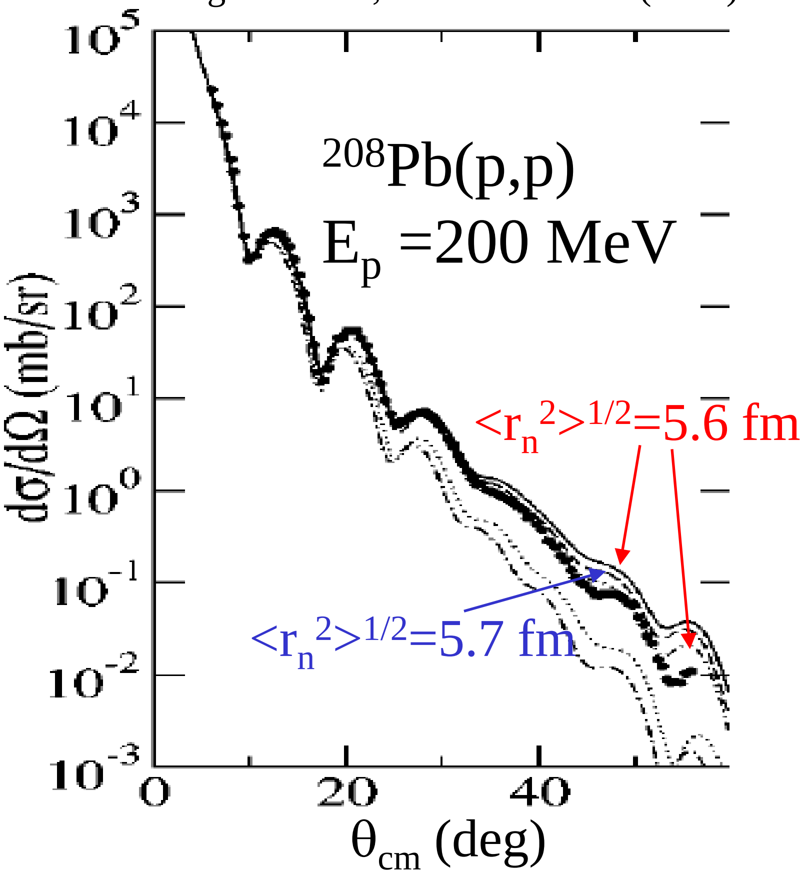


^{208}Pb



Measurements of radii

Karataglidis et al., PRC **65** 044306 (2002)



- Proton elastic scattering is sensitive to the neutron density, but the results can be ambiguous.
- Parity violating electron scattering may provide strong constraints on $\langle r_n^2\rangle^{1/2} - \langle r_p^2\rangle^{1/2}$ and on $S(\rho)$ for $\rho < \rho_s$. Expected uncertainties are of order 0.06 fm. (Horowitz et al., Phys. Rev. 63, 025501(2001).)

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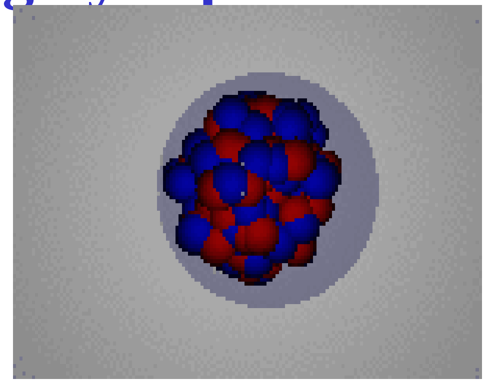
Symmetry Energy from Nuclear collective motion

Pygmy Dipole Resonance

Giant Dipole Resonance

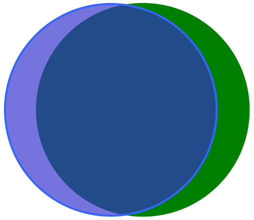
Symmetry Energy from Nuclear collective motion

Pygmy Dipole Resonance

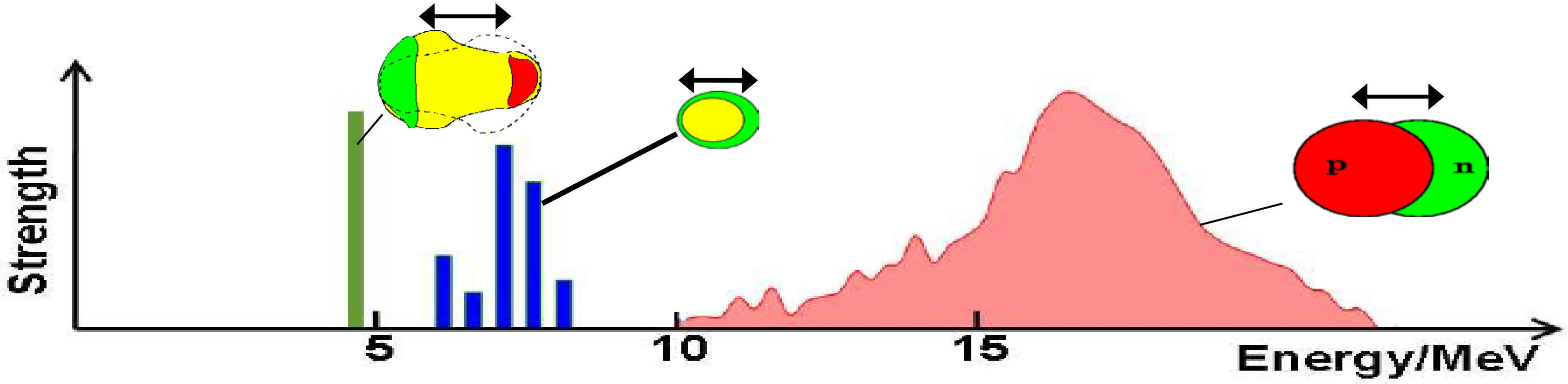


Collective oscillation of neutron skin against the Core → n-skin thickness

Giant Dipole Resonance



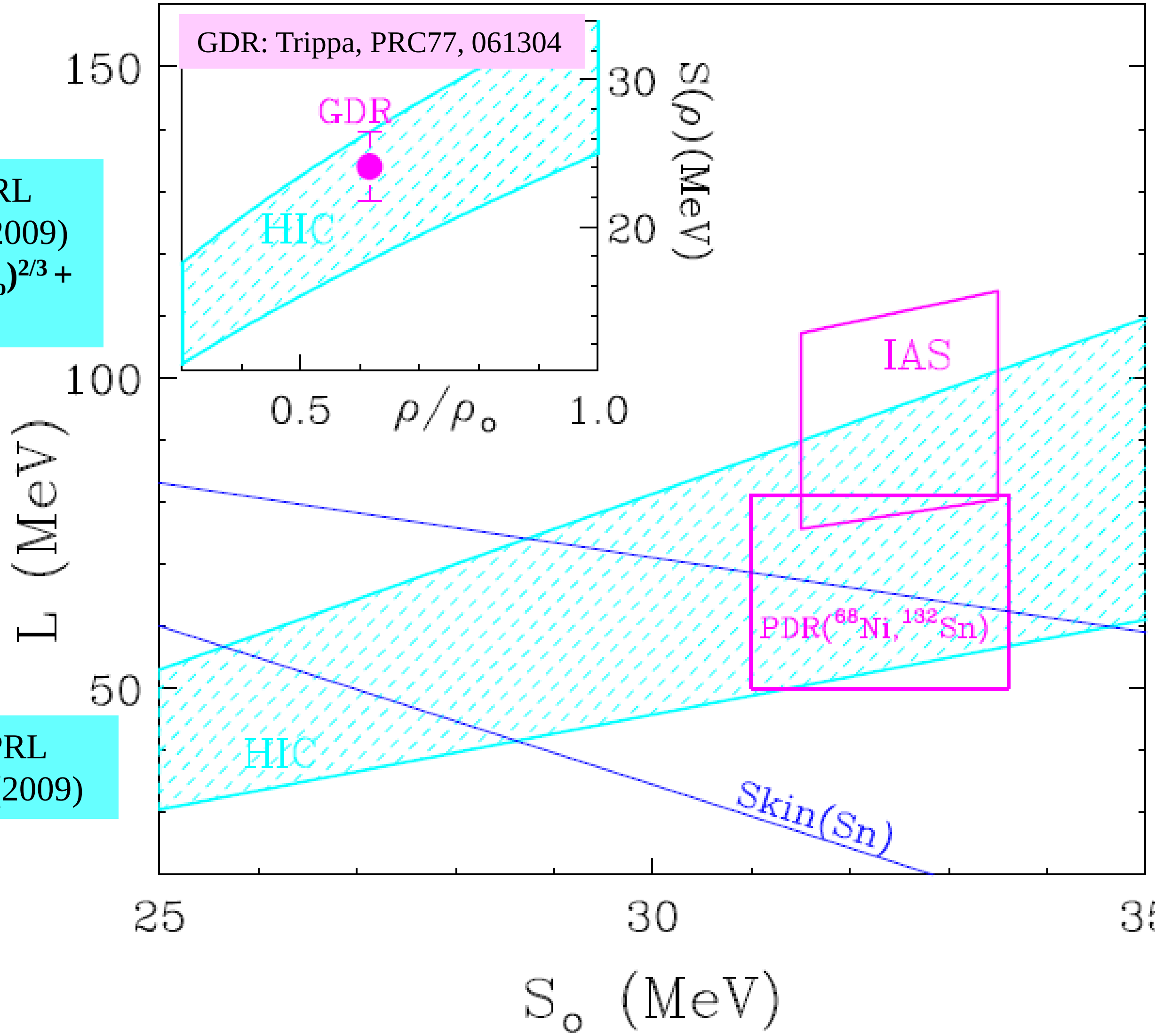
Collective oscillation of neutrons against protons



From Angela Bracco

Constraints on symmetry energy at subnormal density from existing data

Tsang et al., PRL 102, 122701 (2009)
$S(\rho)=12.5(\rho/\rho_o)^{2/3}$ + *17.6* $(\rho/\rho_o)^{\gamma}$



IAS : Danielewicz, Lee, NPA 818, 36 (2009)

PDR: A. Klimkiewicz, PRC 76, 051603 (2007)
A.Carbone, O.Wieland PRC81,041301(2010)

Tsang et al., PRL 102, 122701 (2009)

Skin(Sn): Chen et al., arXiv:1004/4672 (2009)

$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B-\rho_0}{\rho_0}\right)^2 + \ldots$$

$$L = 3\rho_0 \left.\frac{\partial E_{sym}}{\partial \rho_B}\right|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}$$

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L.G. Sobotka, R.J. Charity (WU)

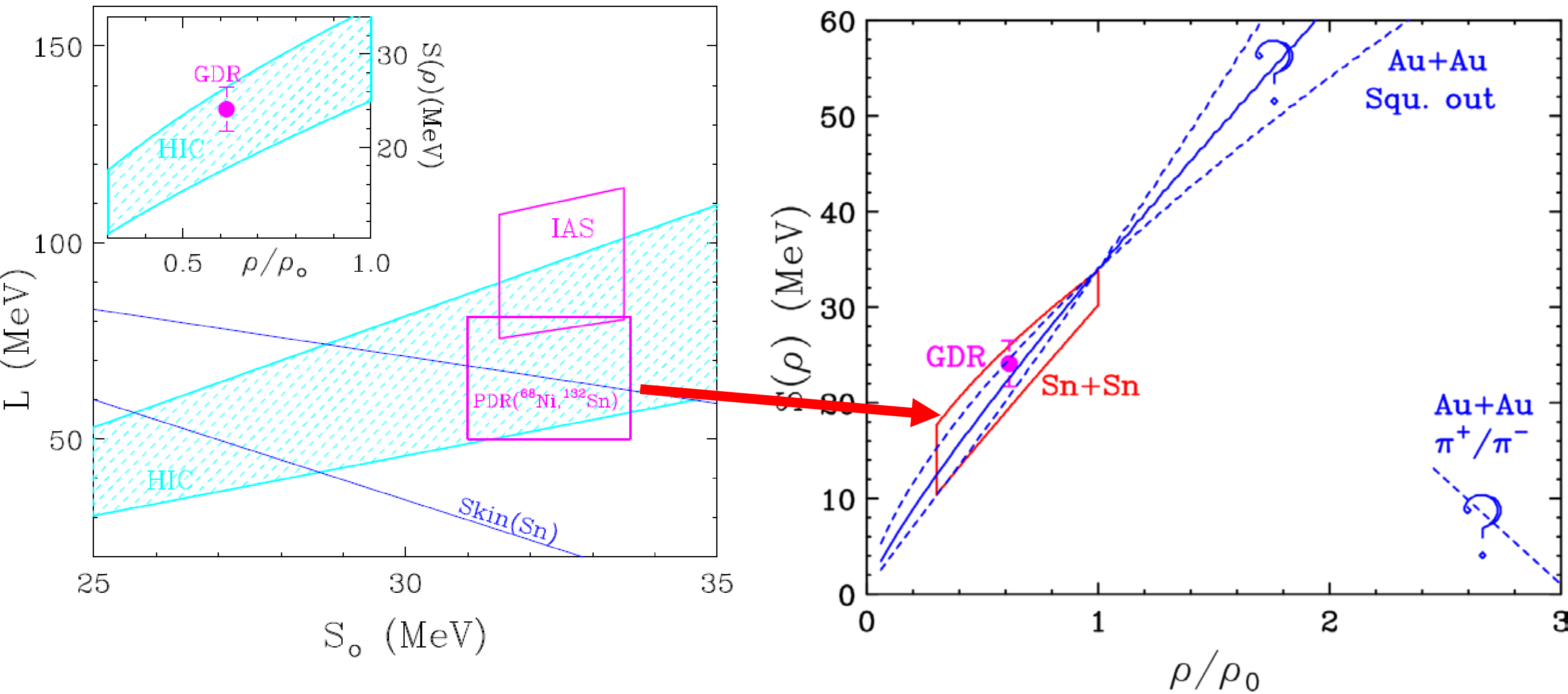
R. deSouza, V. E. Viola (IU)

M. Famiano: (Western Michigan U)

NSCL SEP journal Club

Zibi Chajecki, Dan Coupland, Rachel Hodges, Micha Kilburn, Fei Lu, Mike Youngs, Jack Winkelbauer

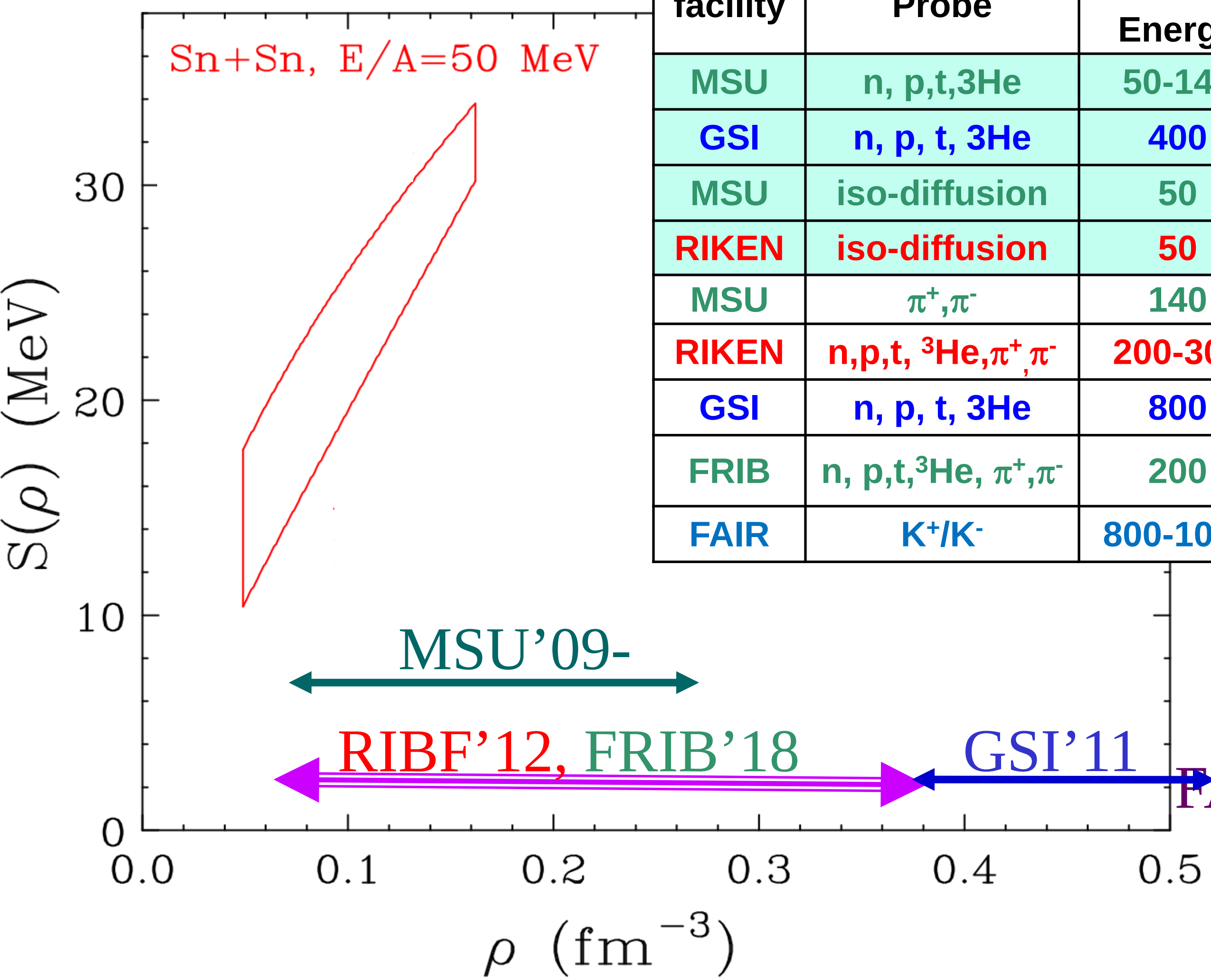
Constraints on the density dependence of symmetry energy at supra normal density



Au+Au experiments in high energy are not designed to measure symmetry energy

Need better experiments

Comprehensive Experimental Programs by SEP (international collaboration)



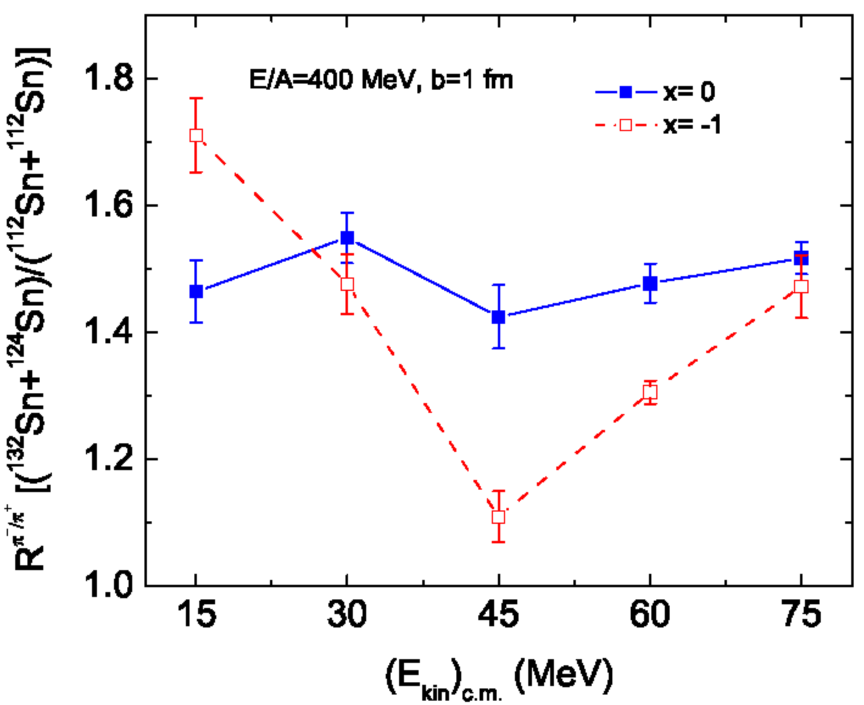
facility	Probe	Beam Energy	Travel (k) $	year	density
MSU	n, p,t,3He	50-140	0	2009	$<\rho_o$
GSI	n, p, t, 3He	400	25	2010/2011	2.5 ρ_o
MSU	iso-diffusion	50	0	2011	$<\rho_o$
RIKEN	iso-diffusion	50	25	2011	$<\rho_o$
MSU	π^+,π^-	140	0	2012-2014	1-1.5 ρ_o
RIKEN	n,p,t, ^{3}He,π^+,π^-	200-300	85	2012-2014	2ρ_o
GSI	n, p, t, 3He	800	25	2014	2-3ρ_o
FRIB	n, p,t,^{3}He, π^+,π^-	200	0	2018-	2-2.5 ρ_o
FAIR	K^+/K^-	800-1000	?	2018	3ρ_o

scientific program spans density range from 0.3 to 3 ρ_o at different facilities

SE Observables at High Energy (density)

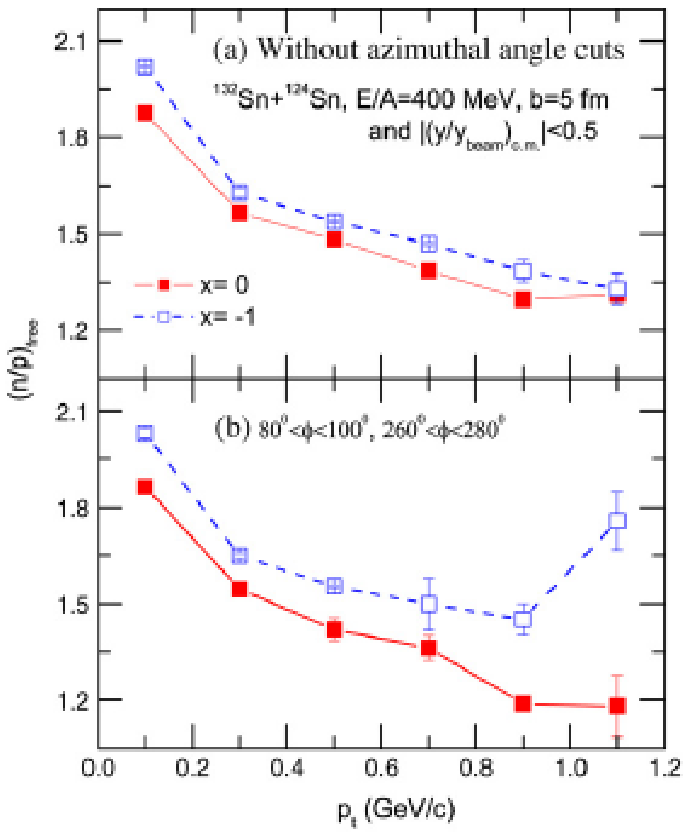
I. Double ratio: pion production

$$R^{\pi^-/\pi^+}\left({}^{132}\mathrm{Sn}+{}^{124}\mathrm{Sn}\right)/\left({}^{112}\mathrm{Sn}+{}^{112}\mathrm{Sn}\right)$$
$$=\frac{\left[Y\left(\pi^-\right)_{132+124}/Y\left(\pi^+\right)_{132+124}\right]}{\left[Y\left(\pi^-\right)_{112+112}/Y\left(\pi^+\right)_{112+112}\right]}$$



Yong et al., Phys. Rev. C **73**, 034603 (2006)

II. n/p or t/3He flows.



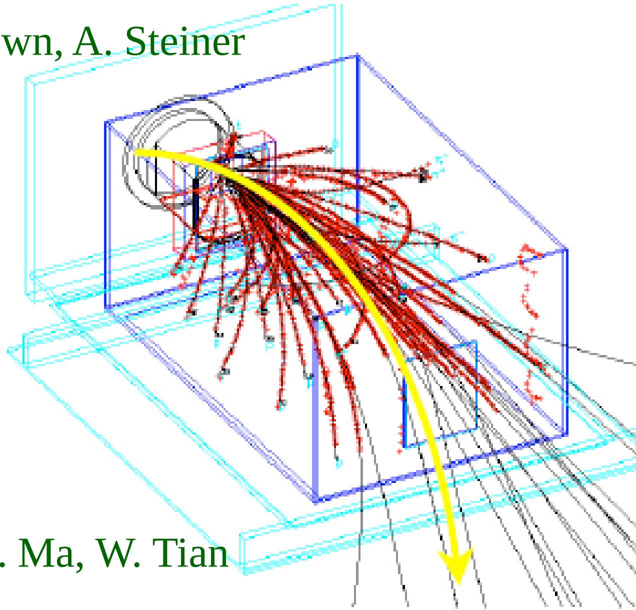
B.-A. Li et al., Phys. Rep. 464 (2008) 113.

Symmetry Energy Project (SEP) collaboration

http://groups.nscl.msu.edu/hira/sep.htm

Determination of the Equation of State of Asymmetric Nuclear Matter

MSU: B. Tsang & W. Lynch, G. Westfall, P. Danielewicz, E. Brown, A. Steiner
Texas A&M University : Sherry Yennello, Alan McIntosh
Western Michigan University : Michael Famiano
RIKEN, JP: TadaAki Isobe, Atsushi Taketani, Hiroshi Sakurai
Kyoto University: Tetsuya Murakami
Tohoku University: Akira Ono
GSI, Germany: Wolfgang Trautmann , Yvonne Leifels
Daresbury Laboratory, UK: Roy Lemmon
INFN LNS, Italy: Giuseppe Verde, Paulo Russotto
GANIL, France: Abdou Chbihi
CIAE, PU, CAS, China: Yingxun Zhang, Zhuxia Li, Fei Lu, Y.G. Ma, W. Tian



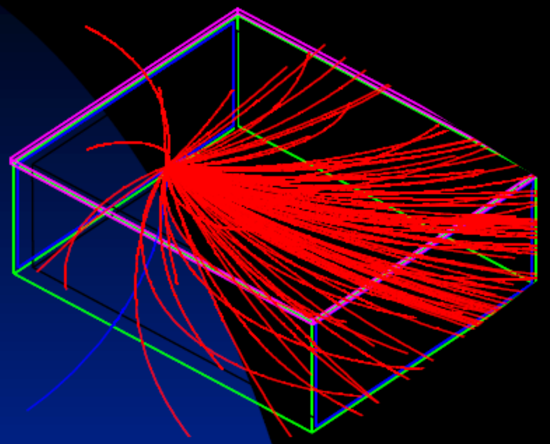
5th RIKEN PAC recommends completion of TPC in 2013

DOE FOA award

$1.2 M includes US contributions to SAMARAI TPC

10/1/2010 – 9/30/2015

TPC properties



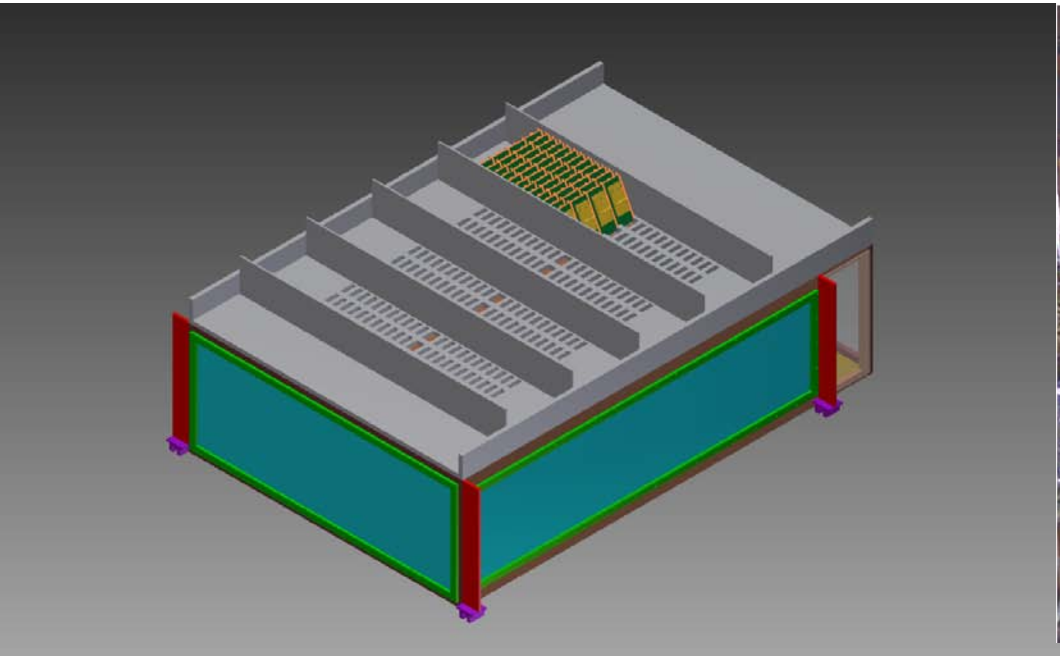
GEANT simulation
$^{132}Sn+^{124}Sn$ collisions at E/A=300 MeV

- **Good efficiency for pion track reconstruction is essential.**
- **Initial design is based upon EOS TPC, whose properties are well documented.**

SAMURAI TPC parameters	
Pad plane area	1.3m x 0.9 m
Number of pads	11664 (108 x 108)
Pad size	12 mm x 8 mm
Drift distance	55 cm
Pressure	1 atmosphere
dE/dx range	Z=1-3 (Star El.), 1-8 (Get El.)
Two track resolution	2.5 cm
Multiplicity limit	200 (large systems absolute pion eff.)

Texas A&M + MSU+WMU

RIKEN+ Kyoto University

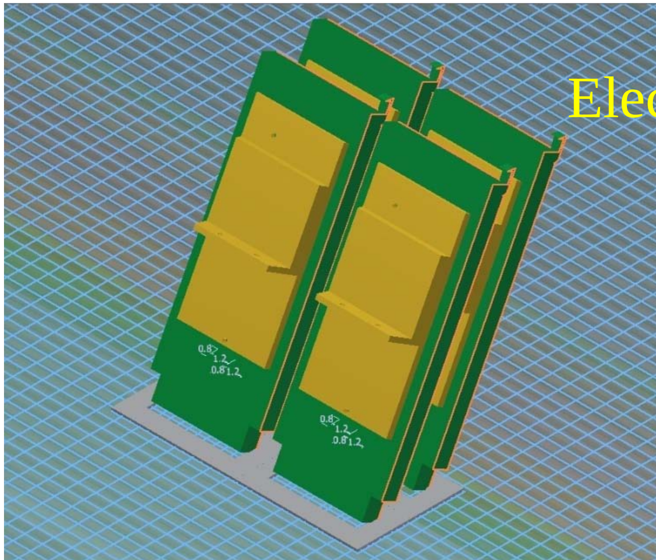


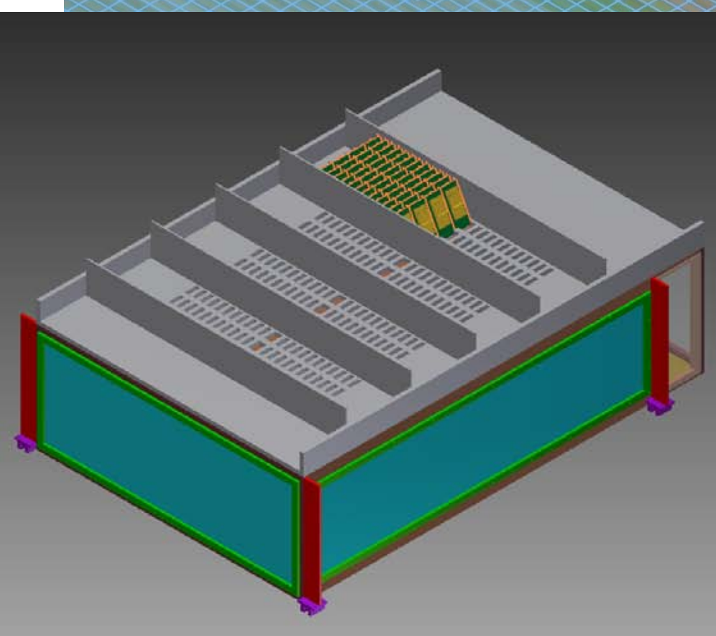
Alan McIntosh
Bill Lynch
Fei Lu
Jimmy Dunn (UG)
Jon Gilbert (UG)
Jon Barney (UG)
Michael Famiano

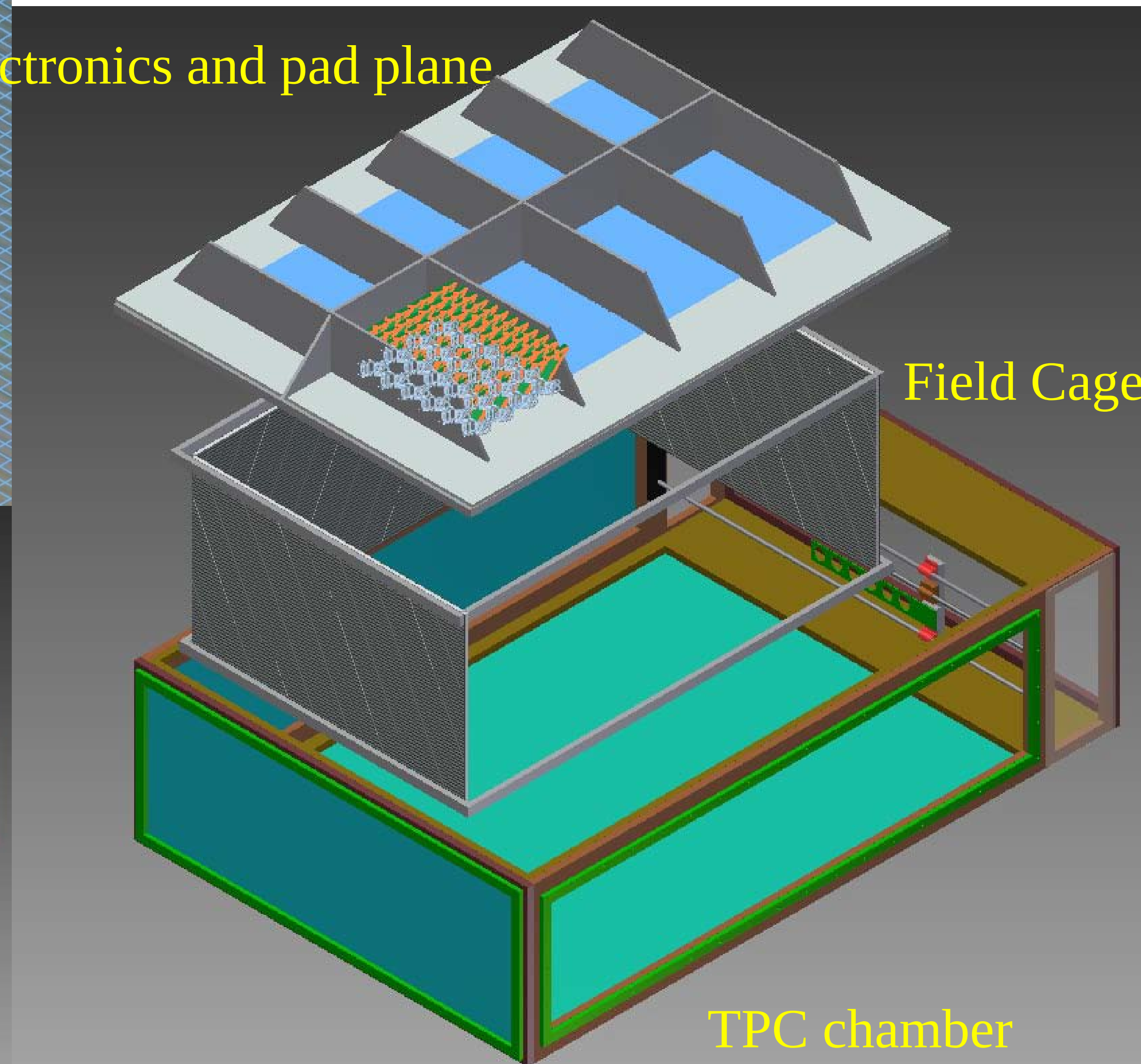
TadaAki Isobe
Atsushi Taketani
Hiro Sakurai
Tetsuya Murakami

Conceptual Design of the TPC detector

Alan McIntosh, Bill Lynch, Jimmy Dunn (UG), Jon Gilbert (UG), Jon Barney (UG)







Electronics on the move: Zibi Chajecki, Jack Winkelbauer





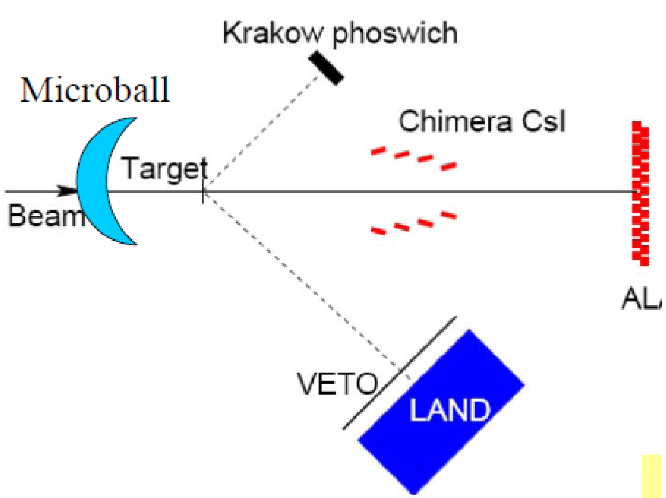
Current Status

NSCL experiments 05049 & 09042
Density dependence of the symmetry energy with emitted neutrons and protons
& Investigation of transport model parameters
(May & October, 2009)

facility	Probe	Beam Energy	Travel (k) $	year	density
MSU	n, p,t,3He	50-140	0	2009	$<\rho_o$
GSI	n, p, t, 3He	400	25	2010/2011	$2.5\ \rho_o$
MSU	iso-diffusion	50	0	2011	$<\rho_o$
RIKEN	iso-diffusion	50	25	2012	$<\rho_o$
MSU	π^+,π^-	140	0	2012-2014	$1\text{-}1.5\ \rho_o$
RIKEN	n,p,t, ^{3}He,π^+,π^-	200-300	85	2012-2014	$2\rho_o$
GSI	n, p, t, 3He	800	25	2014	$2\text{-}3\rho_o$
FRIB	n, p,t,^{3}He, π^+,π^-	200	0	2018-	$2\text{-}2.5\ \rho_o$
FAIR	K^+/K^-	800-1000	?	2018	$3\rho_o$

GSI S394, May 2011

Reaction	Energy (AMeV)	
^{197}Au+^{197}Au	400	N/Z=1.50
^{96}Zr+^{96}Zr	400	N/Z=1.40
^{96}Ru+^{96}Ru	400	N/Z=1.18

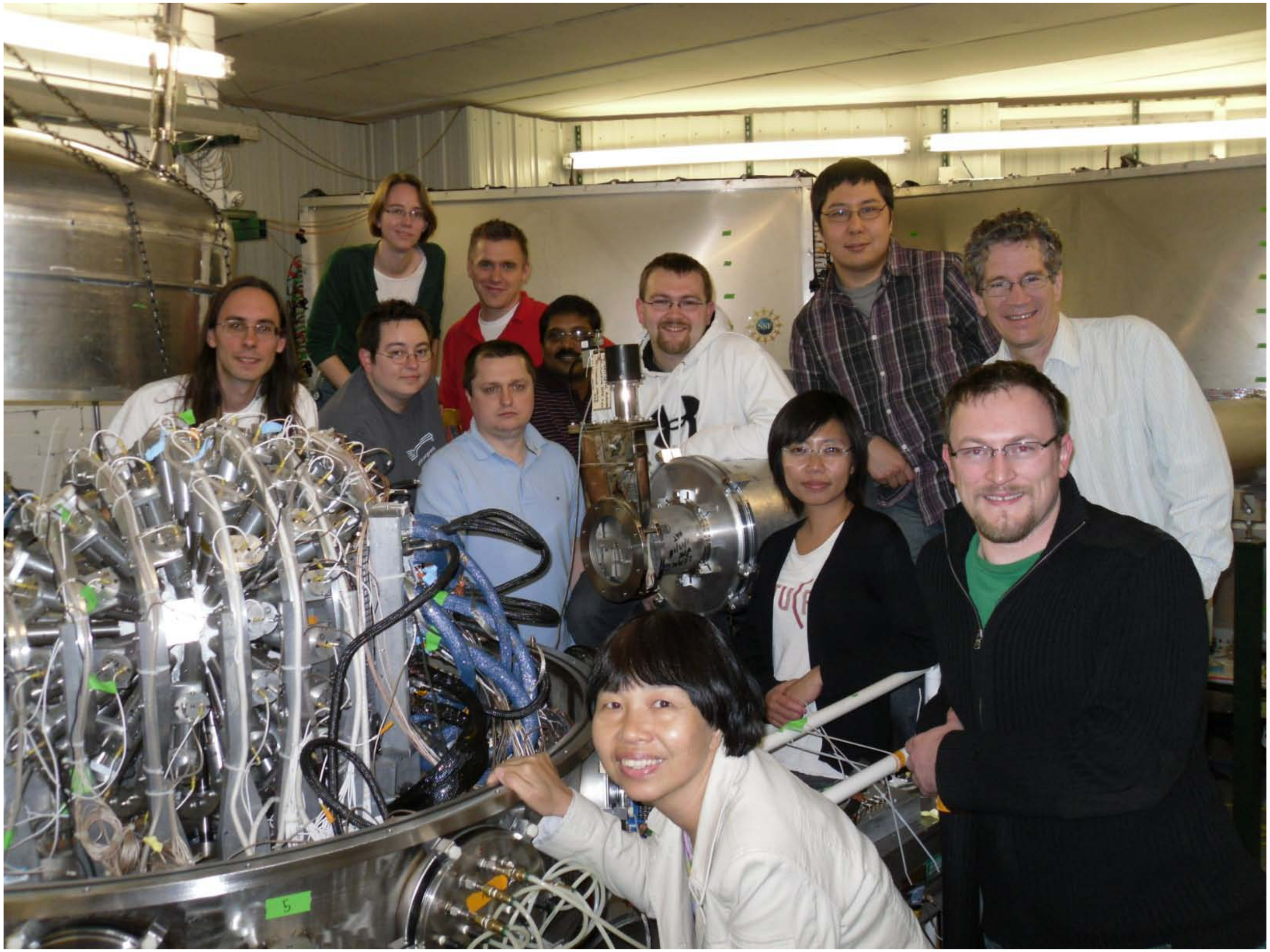


NSCL experiment 07038
Precision Measurements of Isospin Diffusion, June 2011)

n/p Experiment $^{124}Sn+^{124}Sn$; $^{112}Sn+^{112}Sn$; E/A=50 MeV

Famiano et al

Mike Youngs & Dan Coupland thesis expts

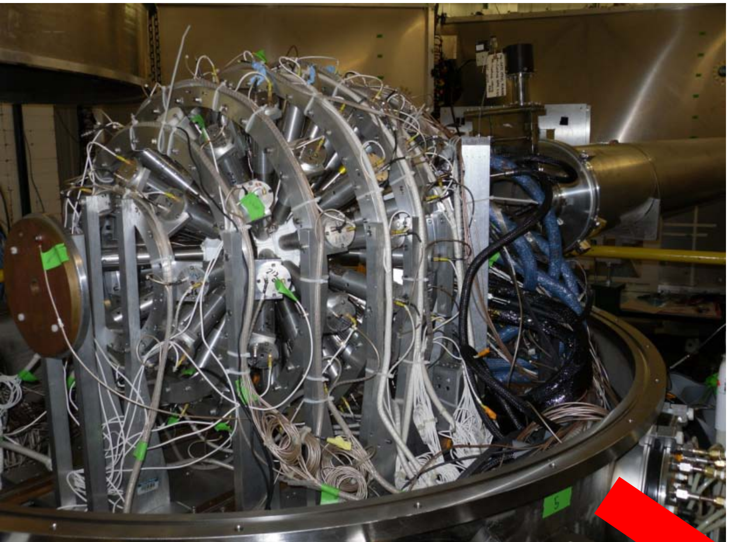


$^{124}Sn+^{124}Sn$; $^{112}Sn+^{112}Sn$; E/A=120 MeV

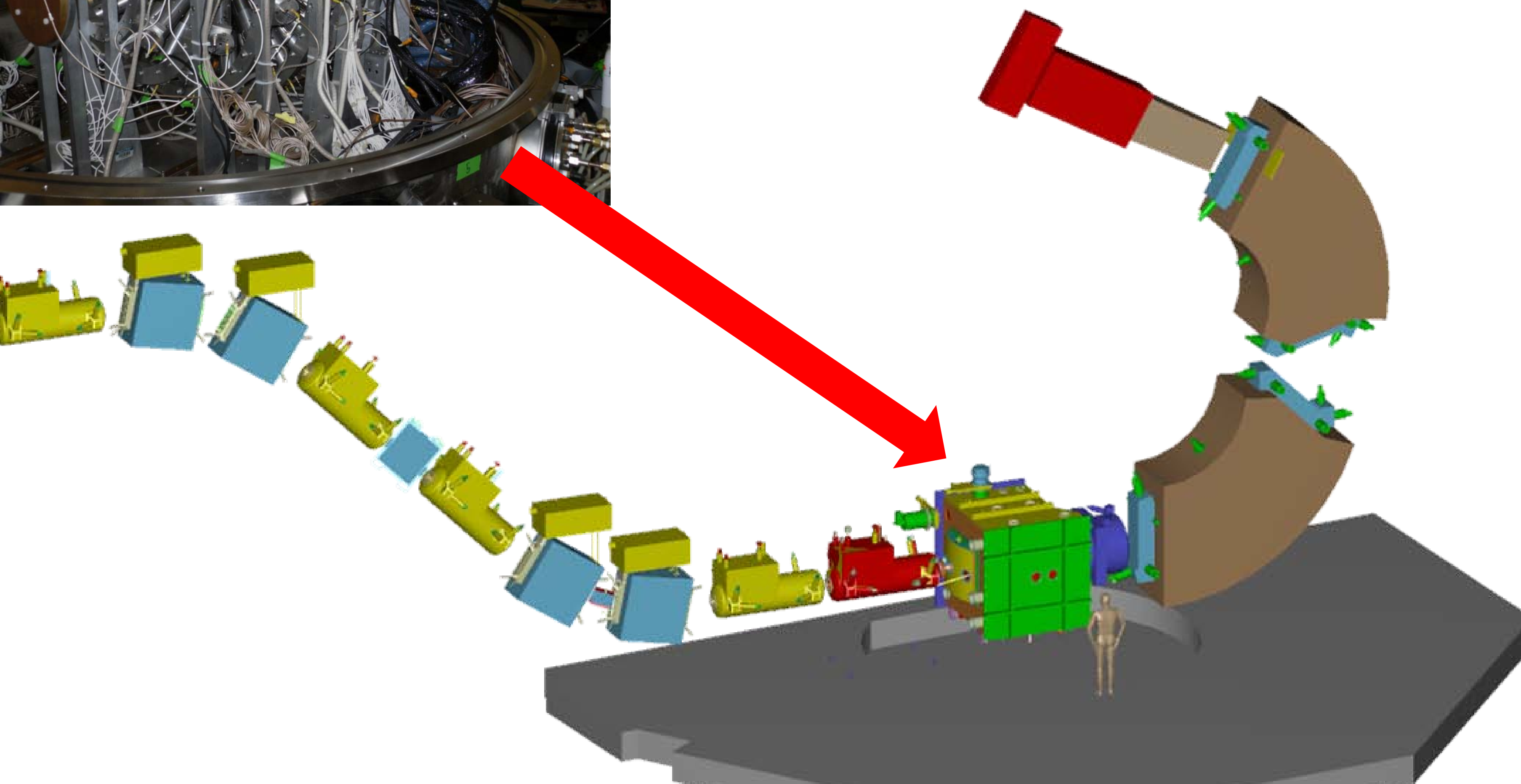
$^{48,40}Ca+^{112,124}Sn$; $^{48,40}Ca+^{112,124}Sn$

NSCL experiment 07038 & RIKEN (2012)

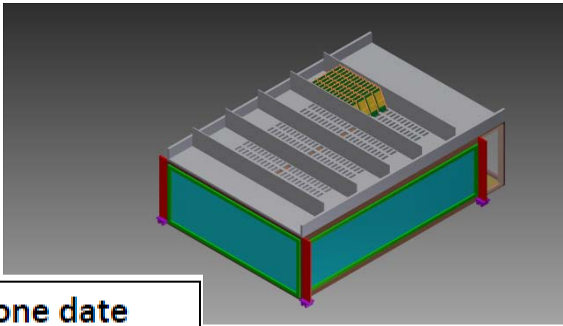
Precision Measurements of Isospin Diffusion (Jack Winkelbauer, June 2011)



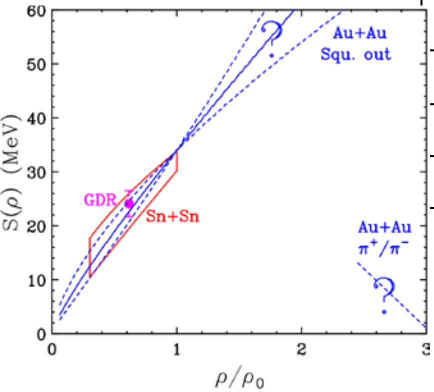
Projectile	Target	E/A	lab
124,118,112Sn	124,118,112Sn	50	NSCL
124,112,108Sn	124,112Sn	50	RIKEN



Milestone in Management Plan



Milestone		location	Milestone date (FY and quarter)	
Conceptual Design	Chamber	NSCL+TAMU	3/15	2011
Detailed Design	Chamber	NSCL+TAMU	8/15	2011
Construction	Chamber	NSCL/subcontract	Q3	2012
Conceptual Design	Detector	NSCL	3/15	2011
Detailed Design	Detector	NSCL	Q4	2011
Construction and Assembly	TPC	NSCL	Q4	2012
Test	TPC	NSCL	Q2	2013
contingency	TPC	NSCL	Q3	2013
Ship	TPC	NSCL	Q4	2013
Install & Test	TPC	RIKEN	Q1	2014
Commissioning	TPC	RIKEN	Q2	2014
Reconfigure new electronics		RIKEN	Q2	2015
π+/π- experiment		RIKEN	Q3	2014
n/p experiment		GSI	Q2	2011



Summary

The density dependence of the symmetry energy is of fundamental importance to nuclear physics and neutron star physics.

Observables in HI collisions provide constraints to the symmetry energy over a range of density.

Observables in HI collisions provide unique opportunities to probe the symmetry energy over a range of density especially for dense asymmetric matter.

The availability of intense fast rare isotope beams at a variety of energies at RIKEN, FRIB & FAIR allows increased precisions in probing the symmetry energy at a range of densities – Symmetry Energy Project (SEP); international collaboration of a global program.

http://www.nscl.msu.edu/~tsang/
tsang@nscl.msu.edu

S.E.P.
Symmetry Energy Project

Involvement of undergraduate students

NSF

MICHIGAN STATE UNIVERSITY

Department of Physics and Astronomy

Research Experience for Undergraduates Internships, Summer 2011