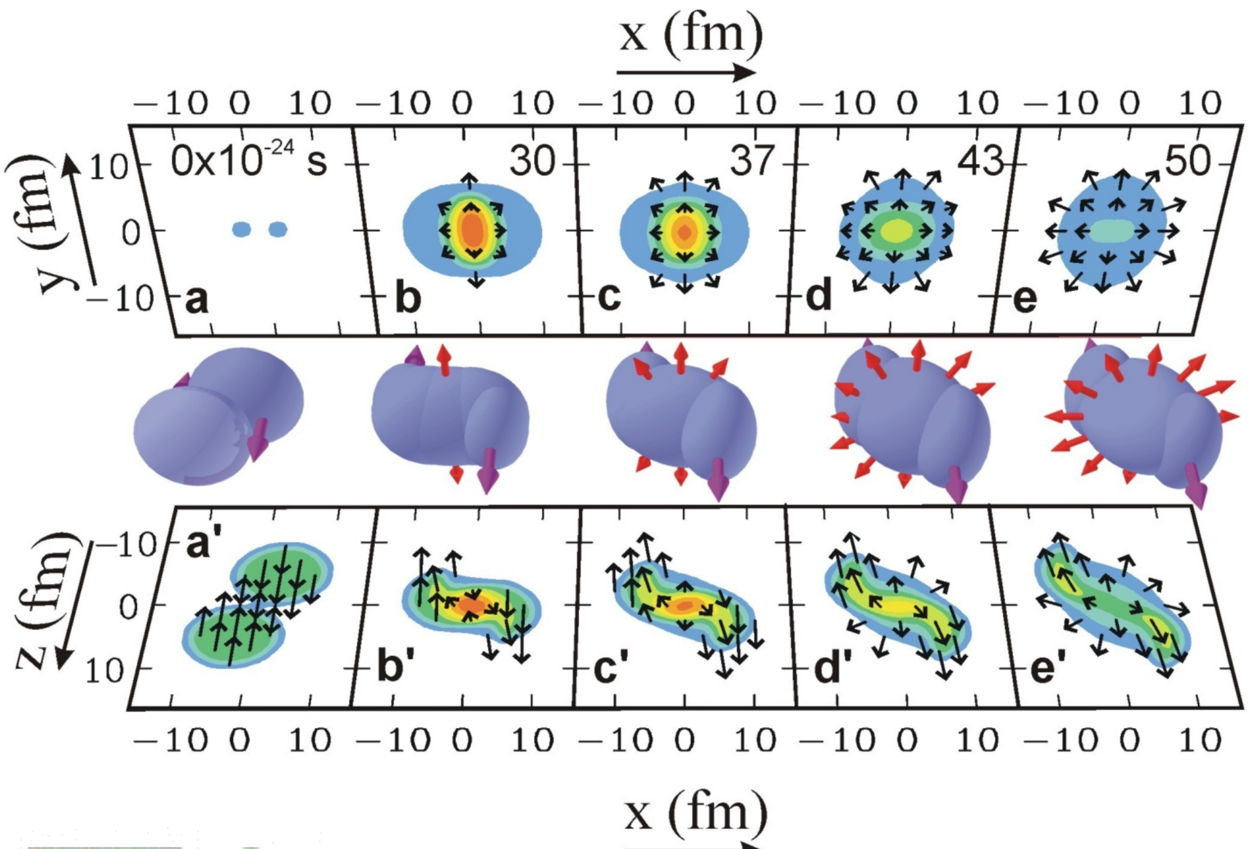
Experimental Observables to study the nuclear symmetry energy with Heavy Ion Collision



Heavy Ion Meeting

April 13, 2012

Pohang, Korea

Betty Tsang

The National Superconducting Cyclotron Laboratory
Michigan State University

NSCL

JINA

The National Superconducting Cyclotron Laboratory

Michigan State University

NSCL

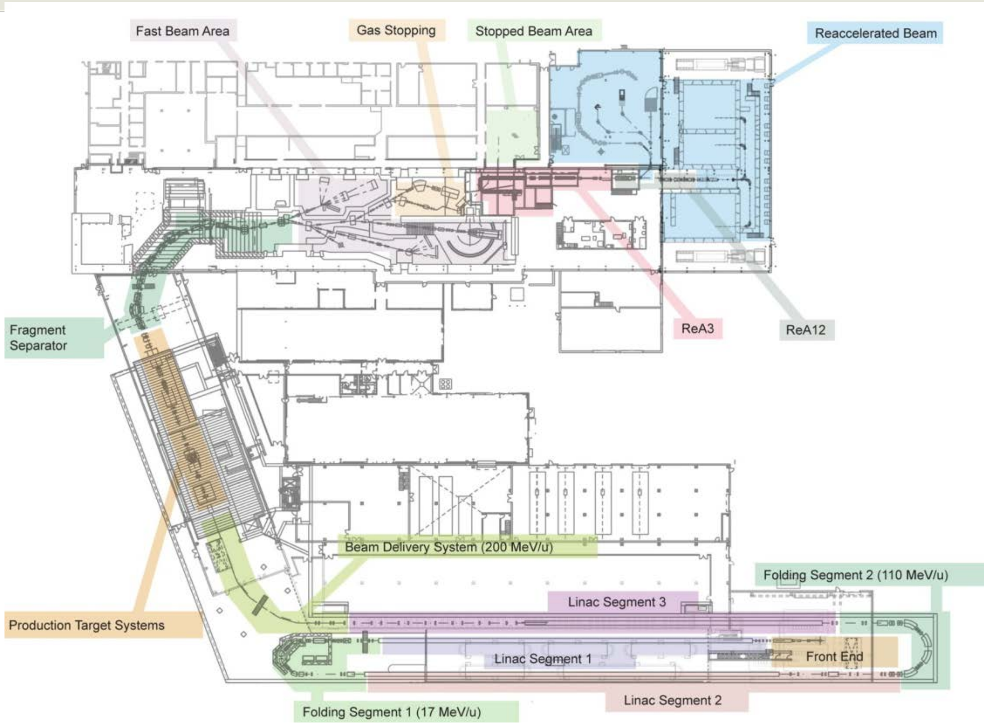
U.S. flagship user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

USA
State and Capital
N
C A N A D A
New York City
Chicago
San Francisco
Los Angeles
PACIFIC
OCEAN
MEXICO
CANADA
Pacific
Ocean
Pacific
Ocean

NSCL

Michigan State University

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.

282 employees, including 24 faculty, 46 graduate, and 51 undergraduate students.

(as of March 05)

489 employees, including 40 faculty, 64 graduate and 70 undergraduate students

as of August 16, 2011

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.

Nuclear Equation of State

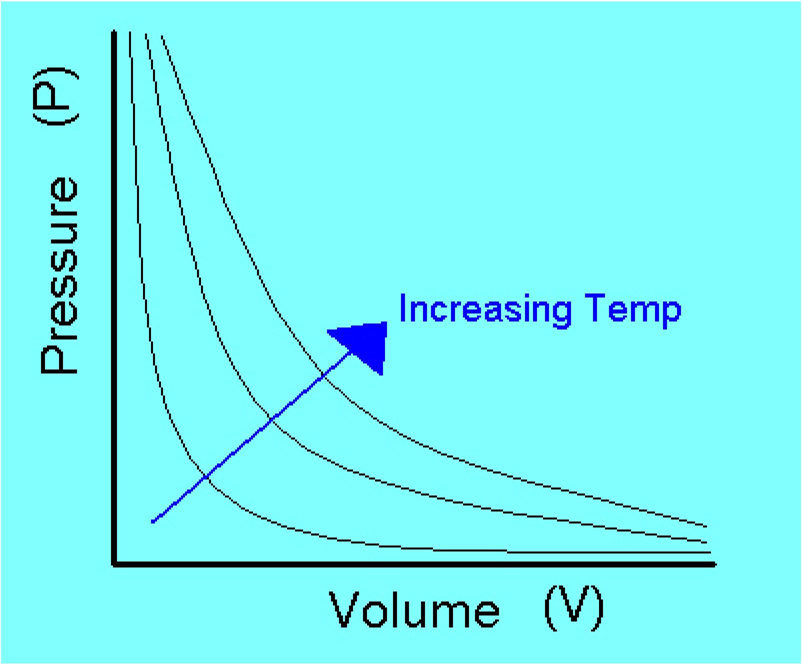
$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$
$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

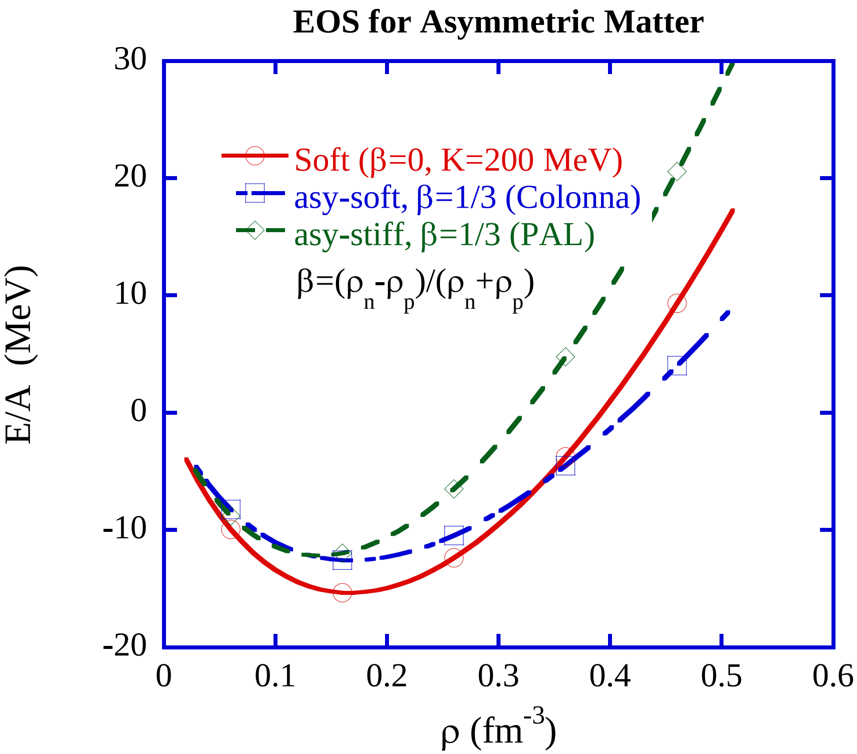
Research with rare isotope beams

- ✓*Nuclear Structure – What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?*
- ✓*Nuclear Astrophysics – What is the nature of neutron stars and dense nuclear matter? What is the origin of elements heavier than iron in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?*
- ✓*Tests of Fundamental Symmetries – Why is there now more matter than antimatter in the universe?*

Equation of State (EoS)

Ideal gas: PV=nRT



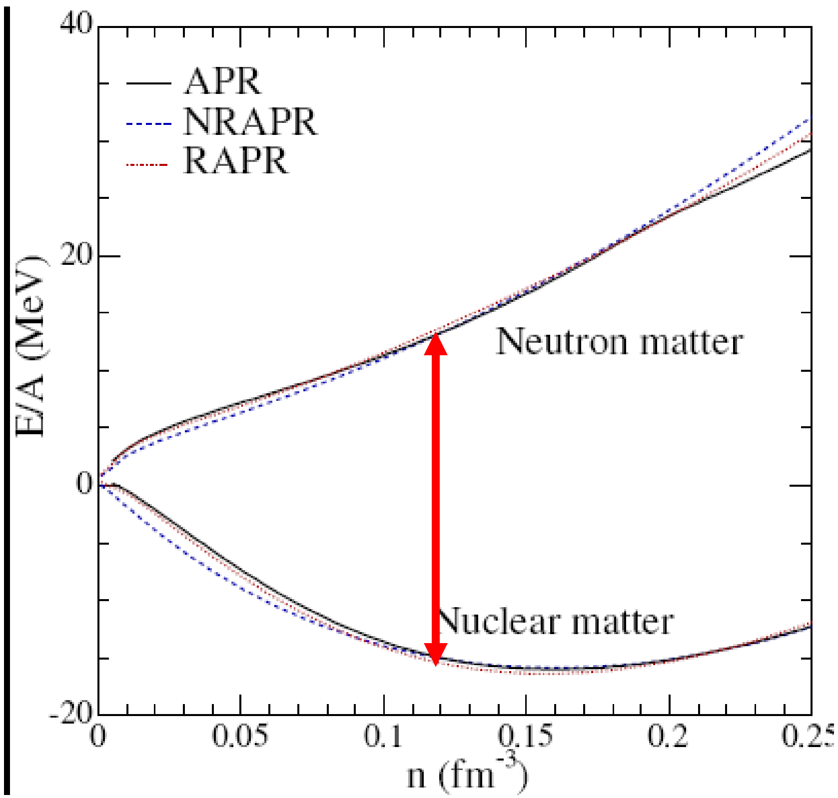


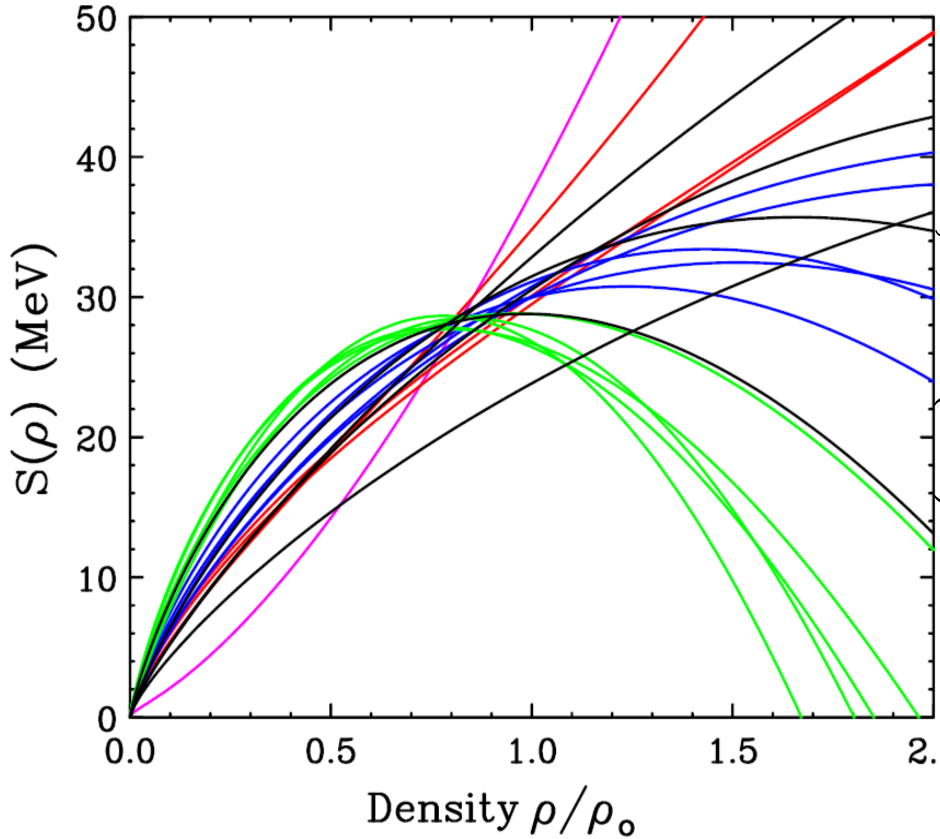
Definition of Symmetry Energy

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

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho);$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$





B.A. Brown, PRL 85 (2000) 5296

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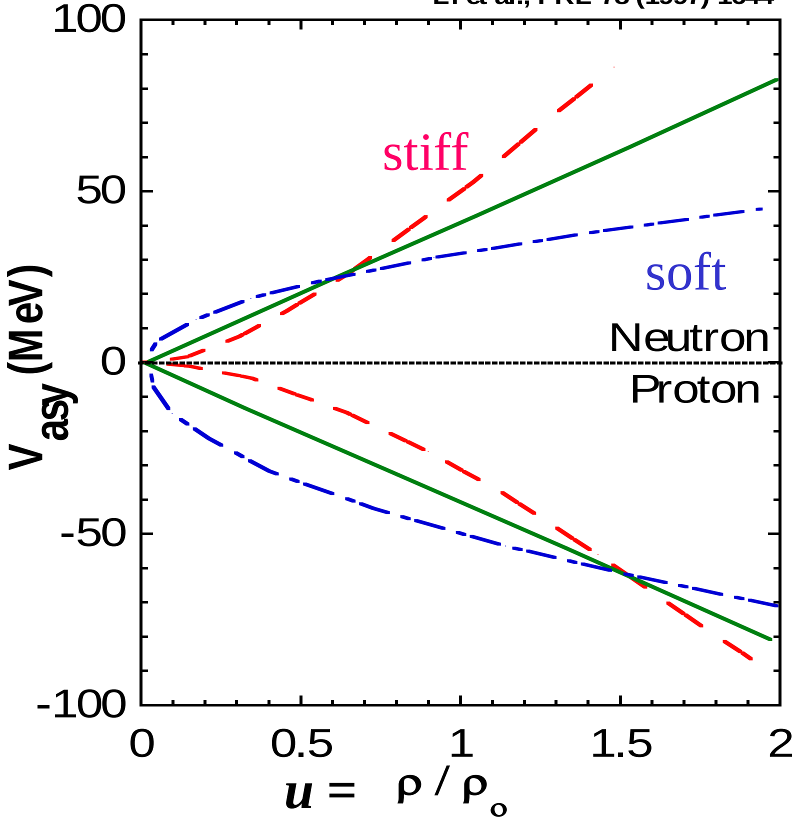
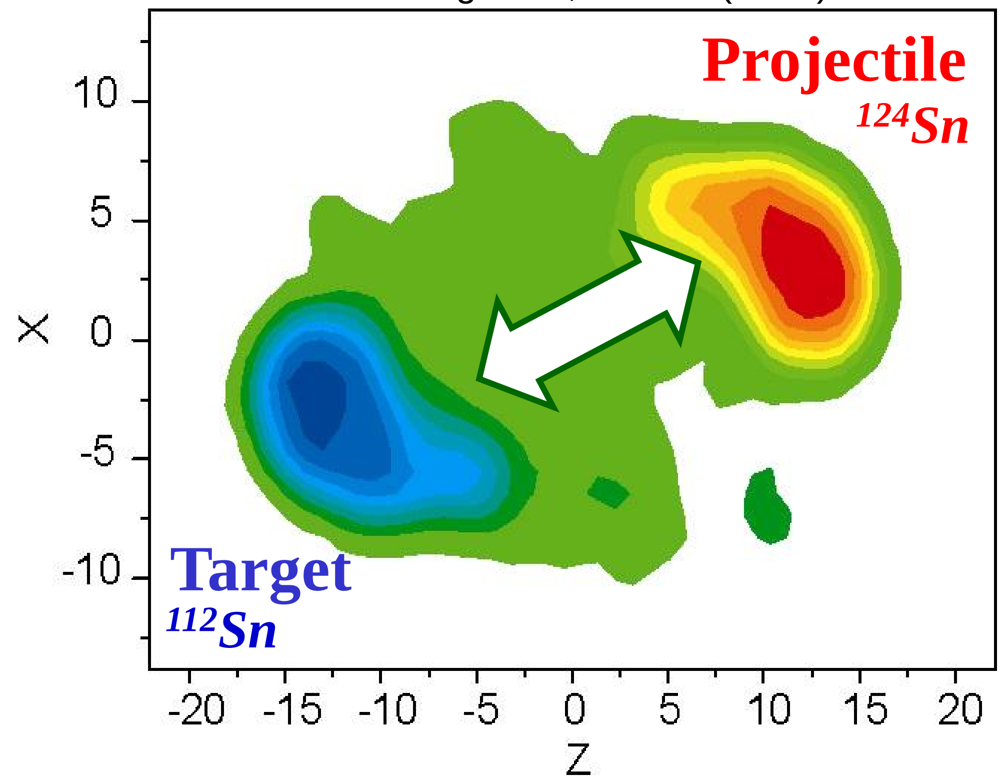
Two observables: n/p ratios and isospin diffusion

Li et al., PRL 78 (1997) 1644



$Y(n)/Y(p)$; $t/^3He$, π^+/π^-

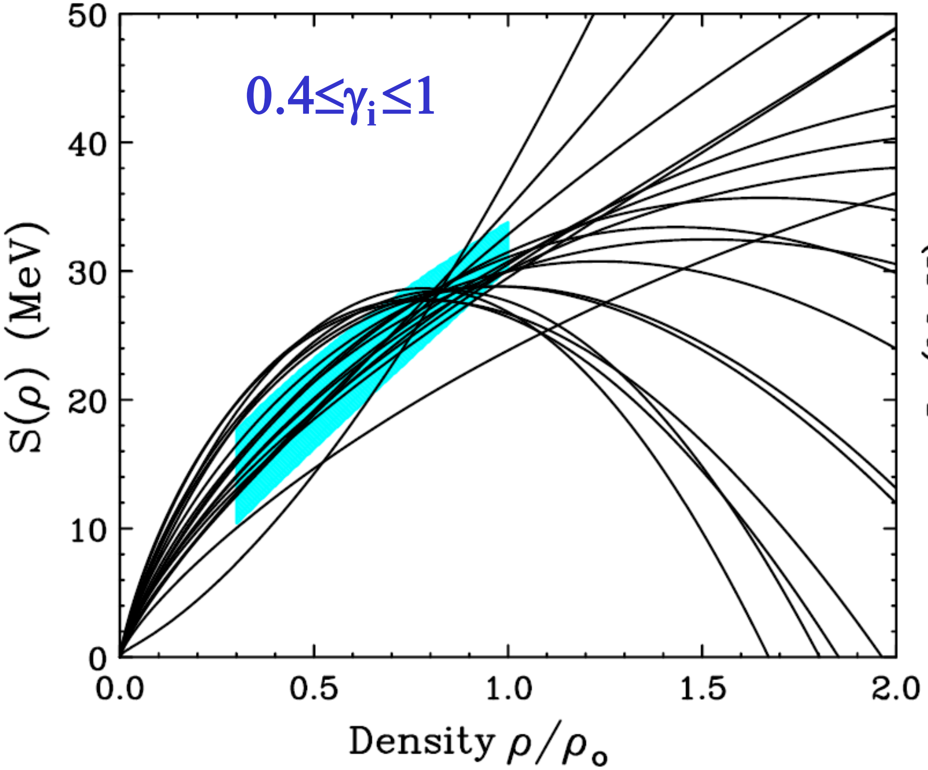
Tsang et al., PRL 92 (2004) 062701

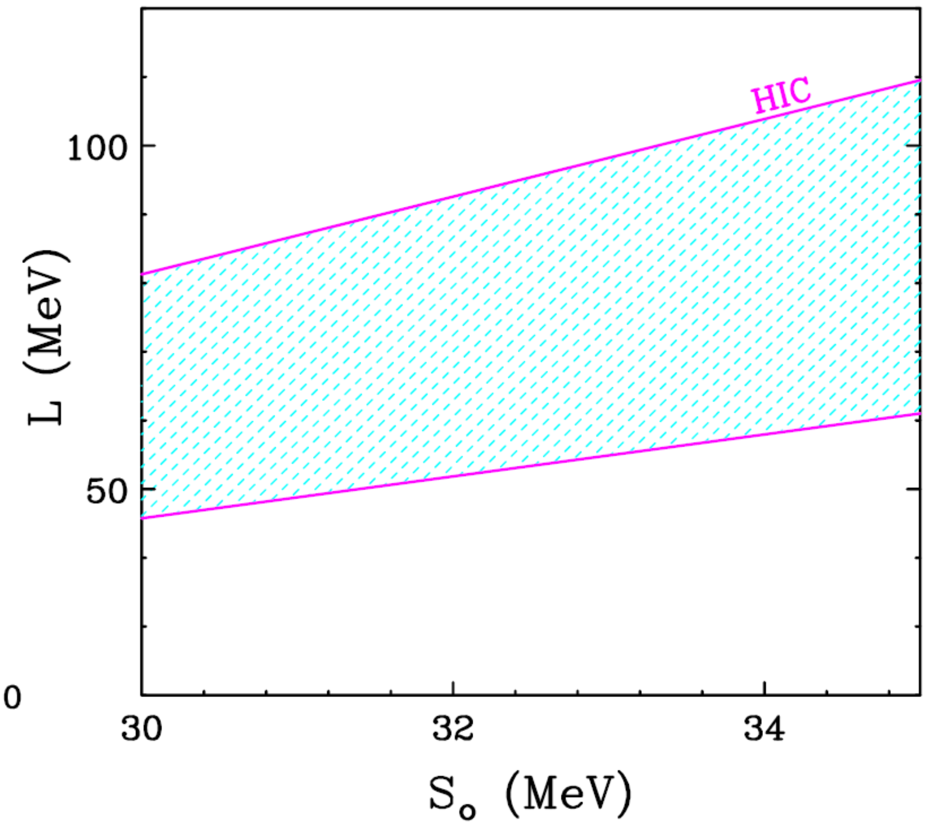


Isospin Diffusion; low ρ, E_{beam}

Symmetry energy constraints from HIC

arXiv:1204.0466





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

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

Symmetry energy constraints from HIC

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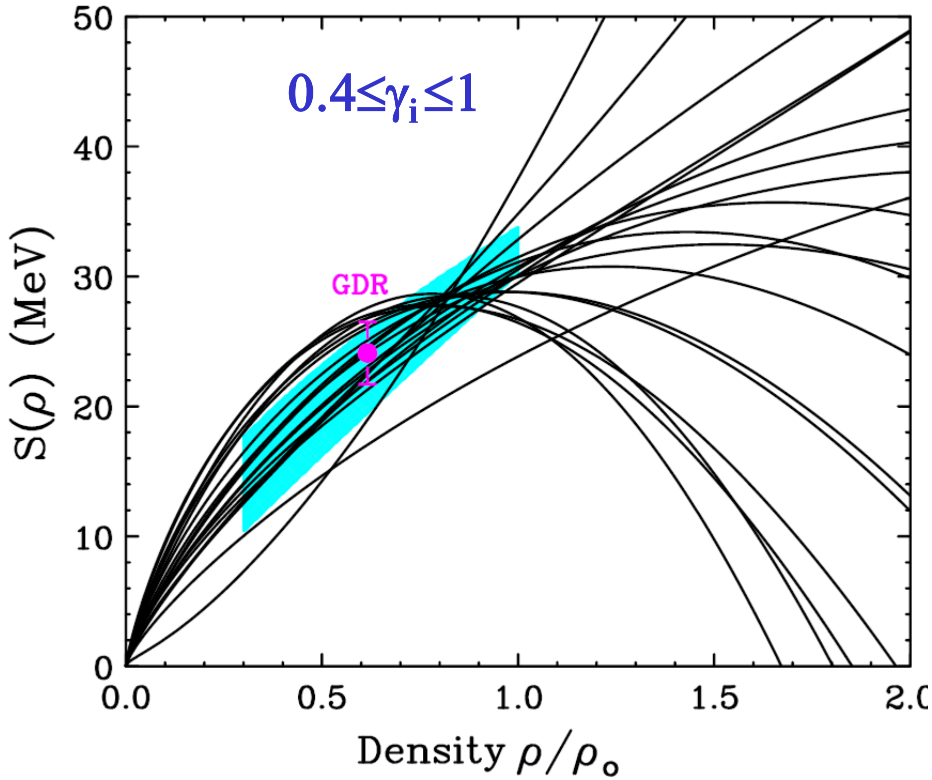

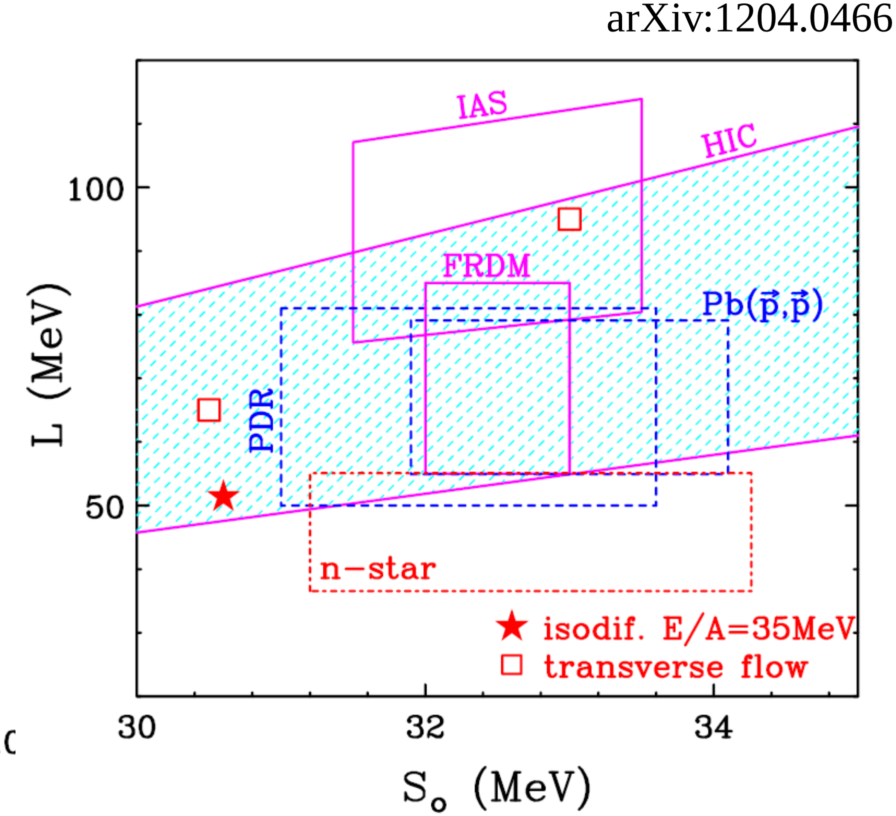

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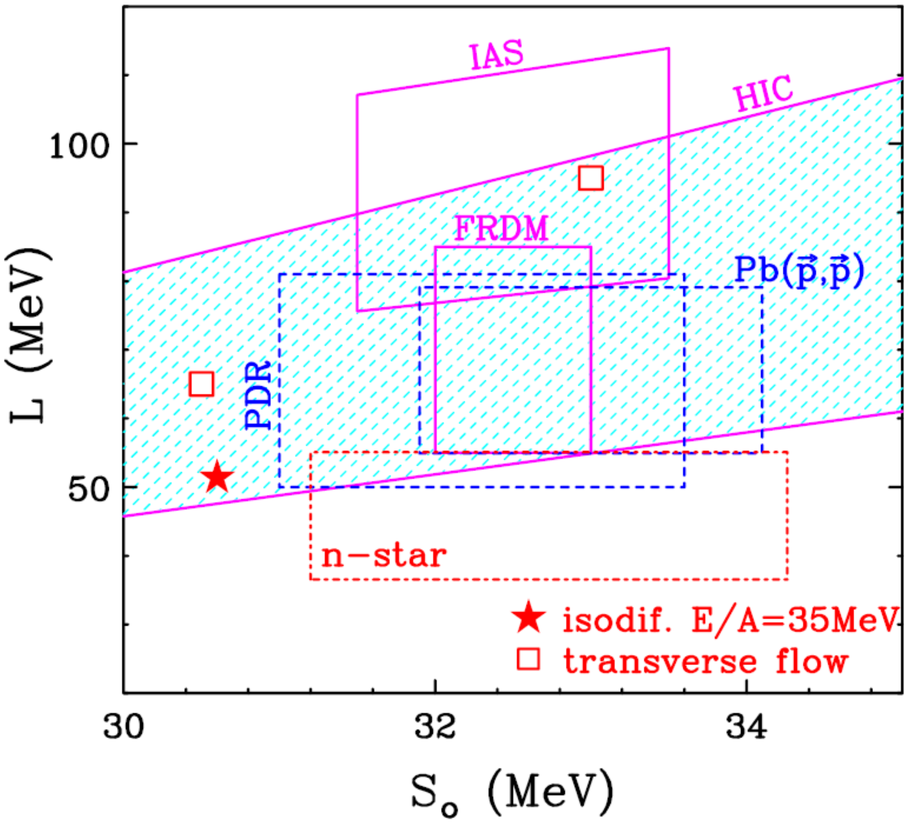
$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho_B}\bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}$$

HIC has been successful in obtaining constraints on the symmetry energy at $0.3<\rho/\rho_O<1$

Summary



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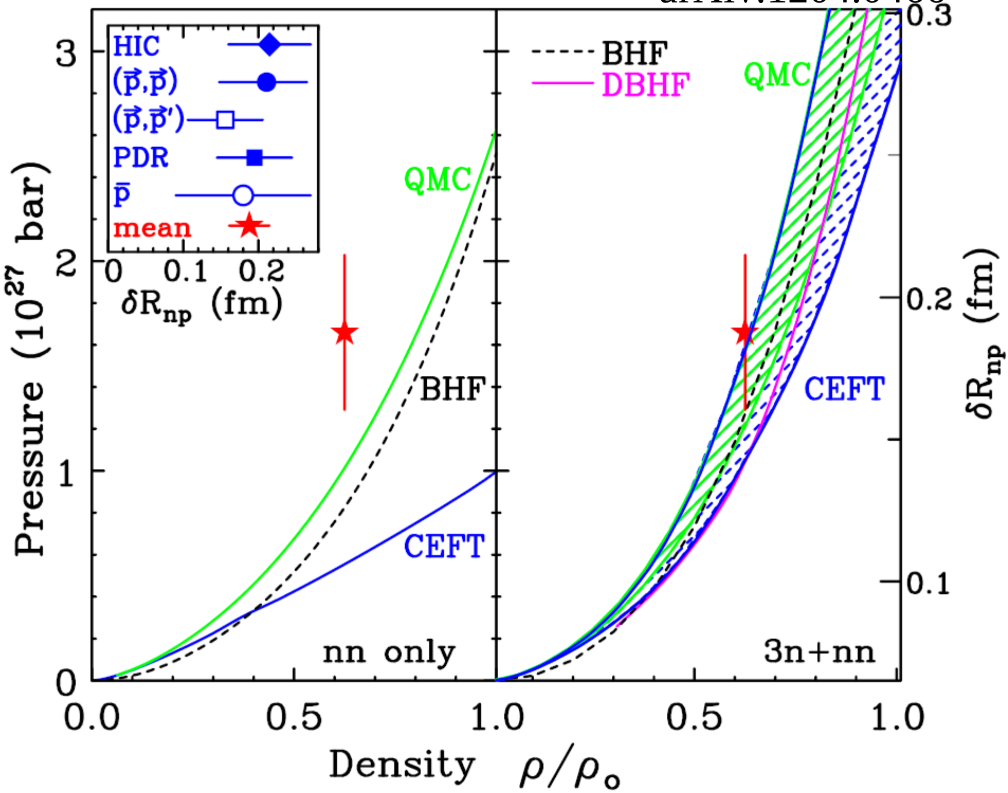


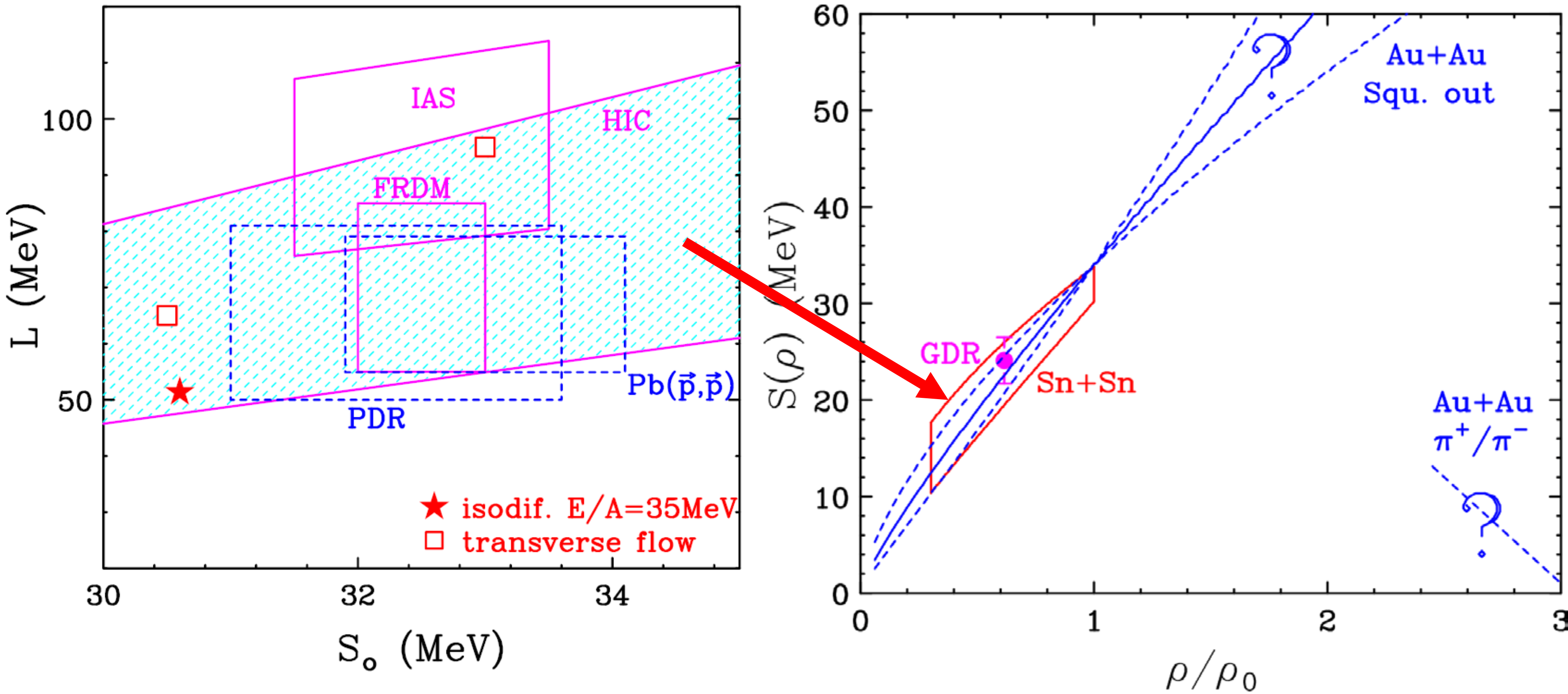
Symmetry Energy constraints for $0.3<\rho/\rho_o<1$ are consistent even though different experimental techniques and theories are involved.

3n force is needed in the description of EoS of pure n-matter.

arXiv:1204.0466

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

arXiv:1204.0466



Xiao et al., PRL102, 062502 (2009)
Russotto et al., PL B697 (2011) 471

HIC has been successful in obtaining constraints on the symmetry energy at $0.3<\rho/\rho_O<1$

Lessons learned from LE measurements:

1. HI collision dynamics are complex but prove to be sensitive to density dependence of symmetry energy.
2. Need multiple observables to verify results and to add credibility to the constraints
3. Problems still remain, e.g.
   - How to extract results to T=0;
   - Control of input parameters in transport models.
4. Provide guidance to the experiments at high energy

Talk Outline

1. Review of LE experimental observables
2. Discussions of HE experimental observables and experiments at RIKEN, KoRIA & FRIB

How to obtain the information about EoS?

Both astrophysical and laboratory observables can constrain the EoS, $\varepsilon(\rho,T,\delta)$ or $P(\rho,T,\delta)$ indirectly.

Experiments:

Accelerator: Projectile, target, energy

Detectors: Information of emitted particles – identity, spatial info, energy, yields →construct observables

Models

Input: Projectile, target, energy.

Simulate the collisions with the appropriate physics

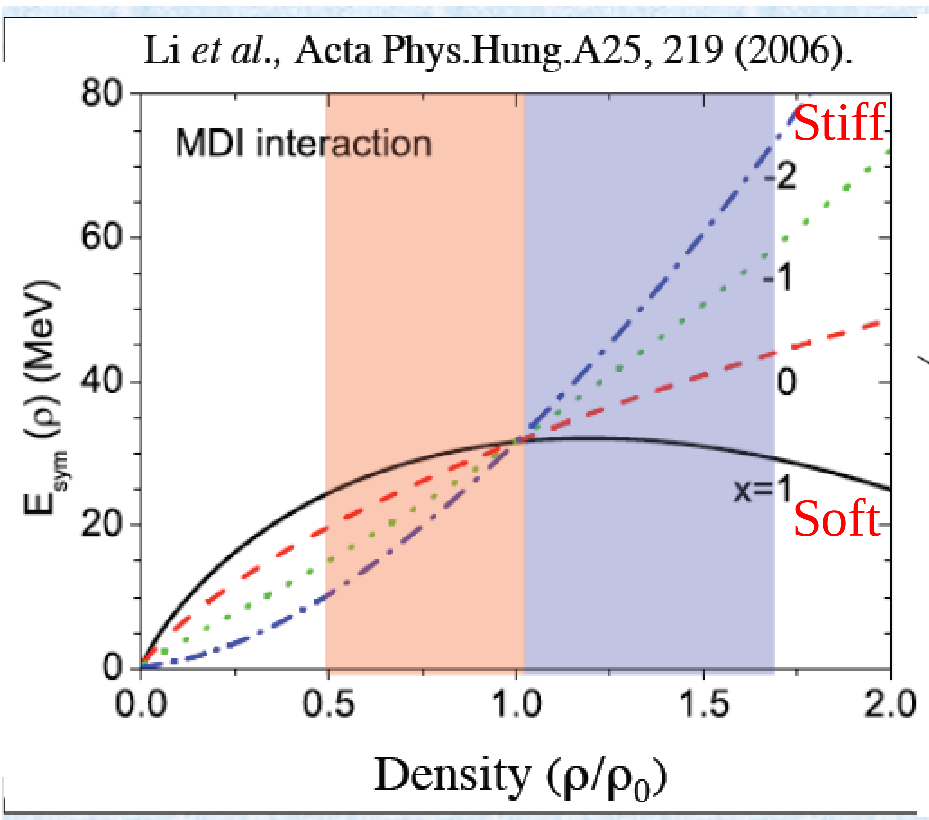
Success depends on the comparisons of observables.

What are the experimental challenges?

What are the theory challenges?

Density Dependence of Symmetry Energy

Density region sampled depends on reaction mechanisms (impact parameter) & beam energy



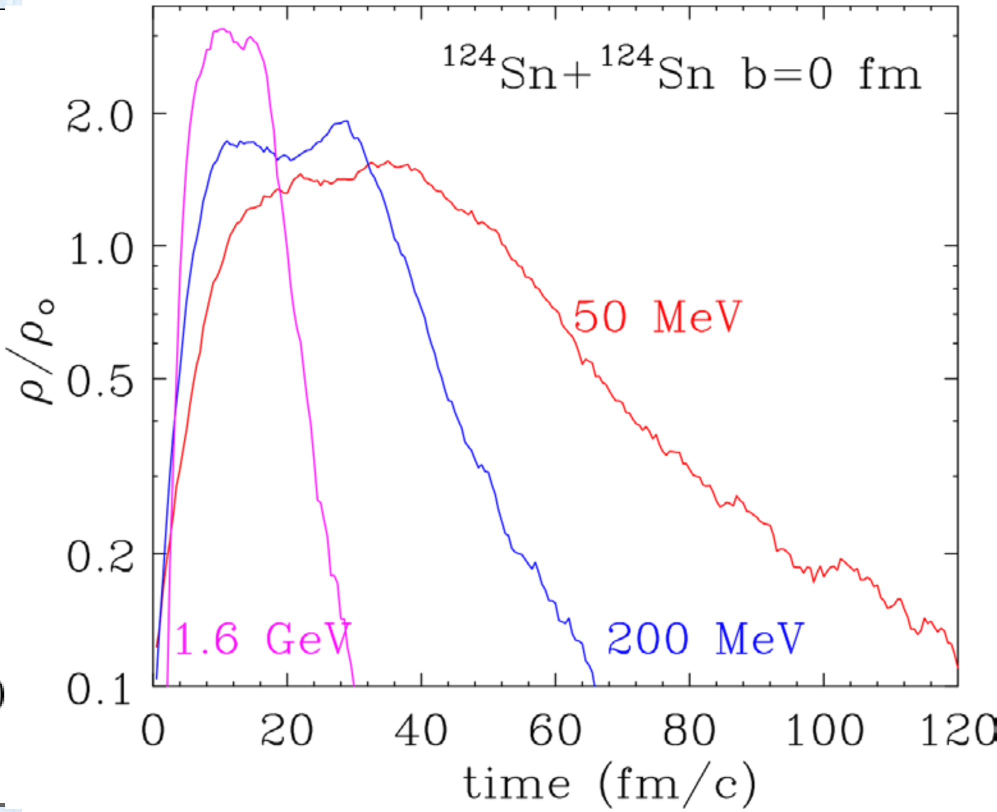
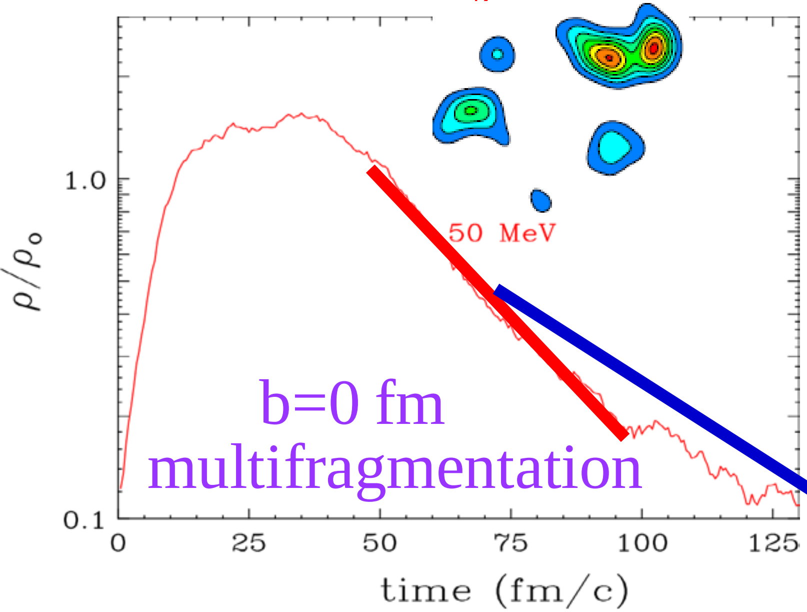


Figure credit : A. Bickley

Observab les:

- *$\rho<\rho_o$: Isospin diffusion, n/p ratios. flow and observables from NS.*
- *$\rho>\rho_o$: HIC the only game in town: n/p, t/^{3}He, flow, p^+/p^- ratio*

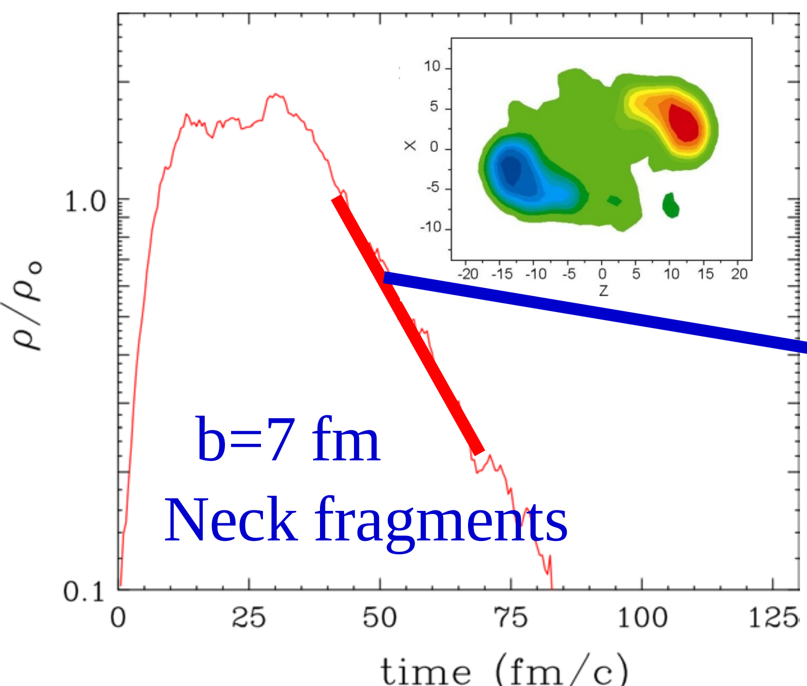
Heavy Ion collision: $^{124}Sn+^{124}Sn$, E/A=50 MeV

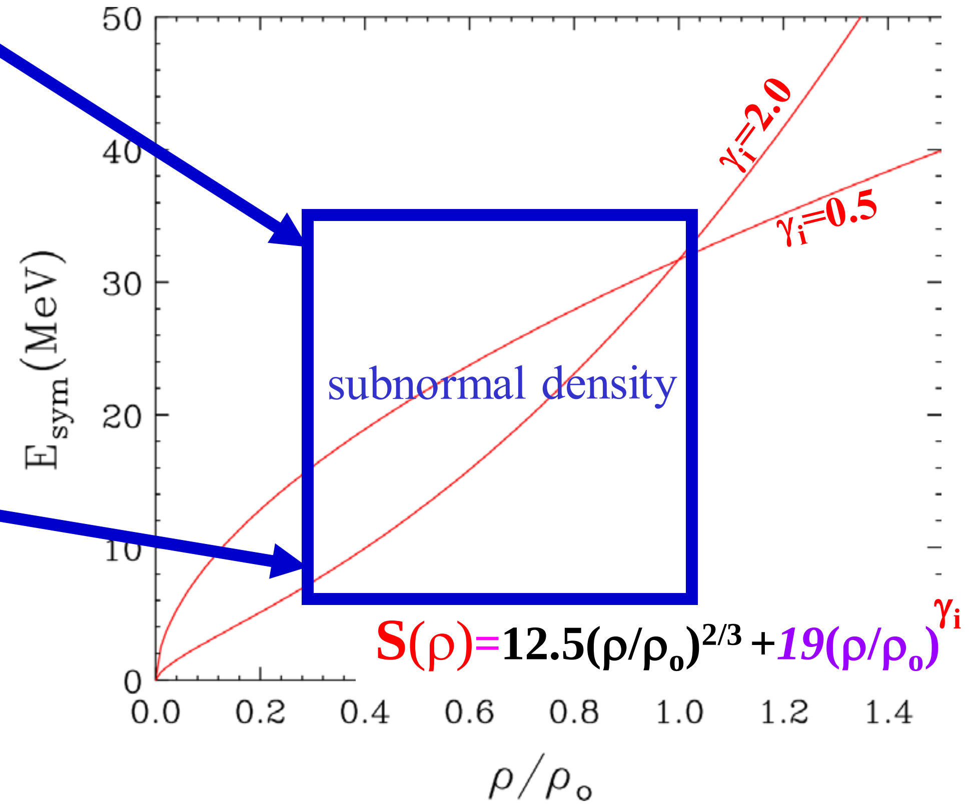


Reaction mechanism of fragment productions depends on impact parameters

Charged fragments (Z=3-20) are formed at subnormal density

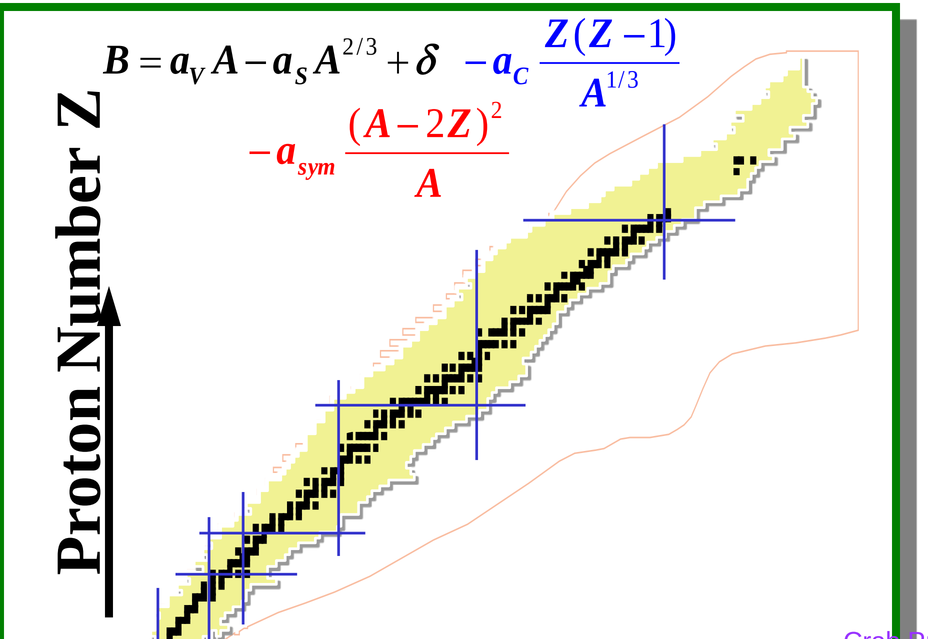
Impact parameter selection is a must!





Strategies used to study the symmetry energy with Heavy Ion collisions below E/A=100 MeV

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

Strategies used to study the symmetry energy with Heavy Ion collisions below E/A=100 MeV

At E/A>100 MeV, $\rho>\rho_o$
Strategies should be similar but observables maybe different

- 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
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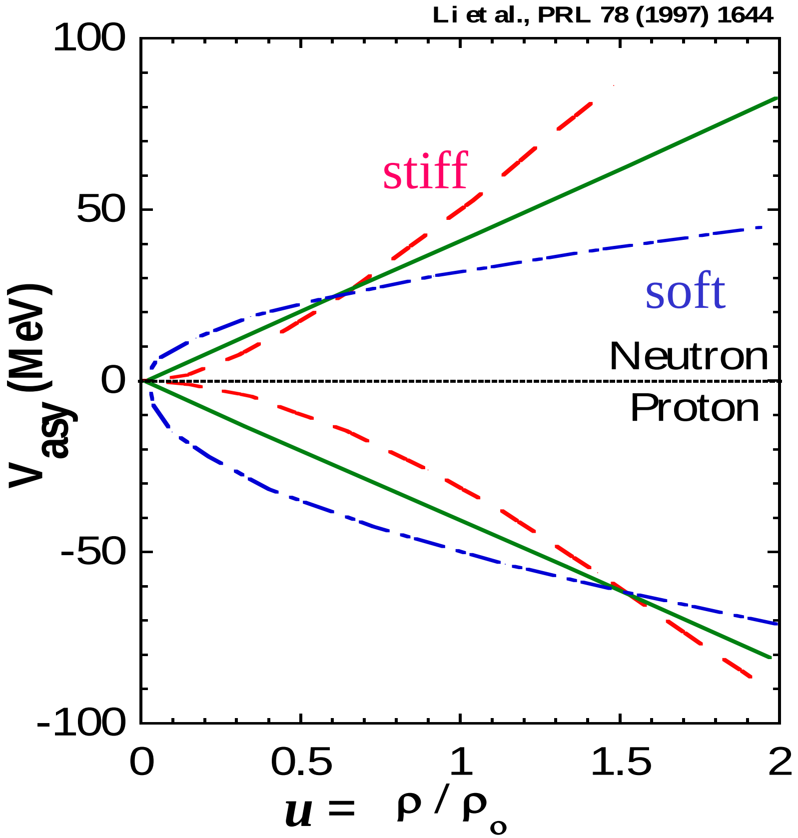
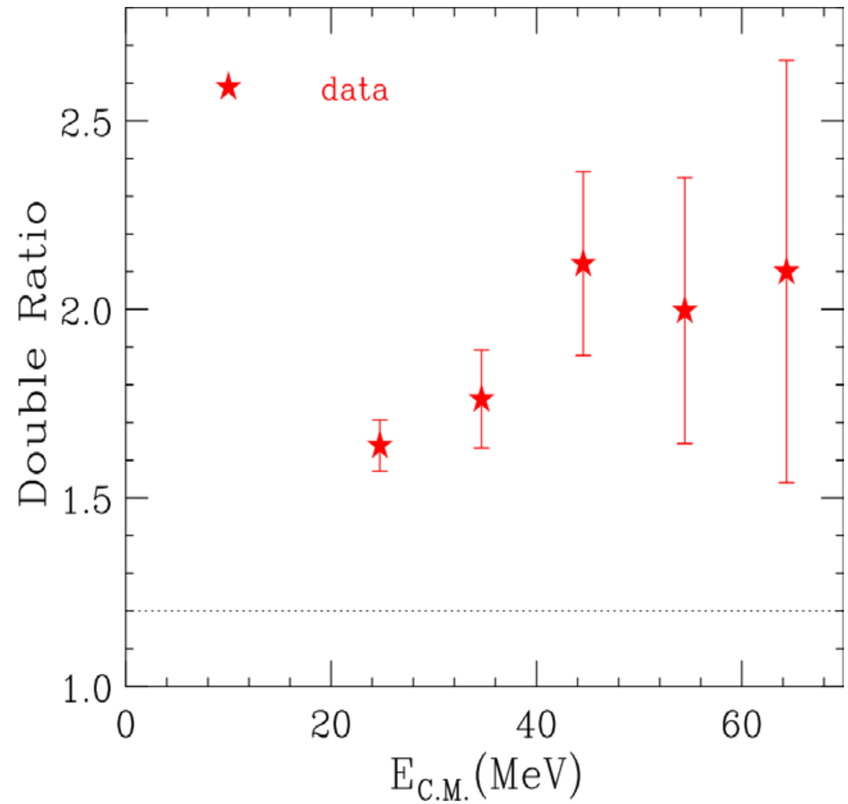
Two observables: n/p ratios and isospin diffusion





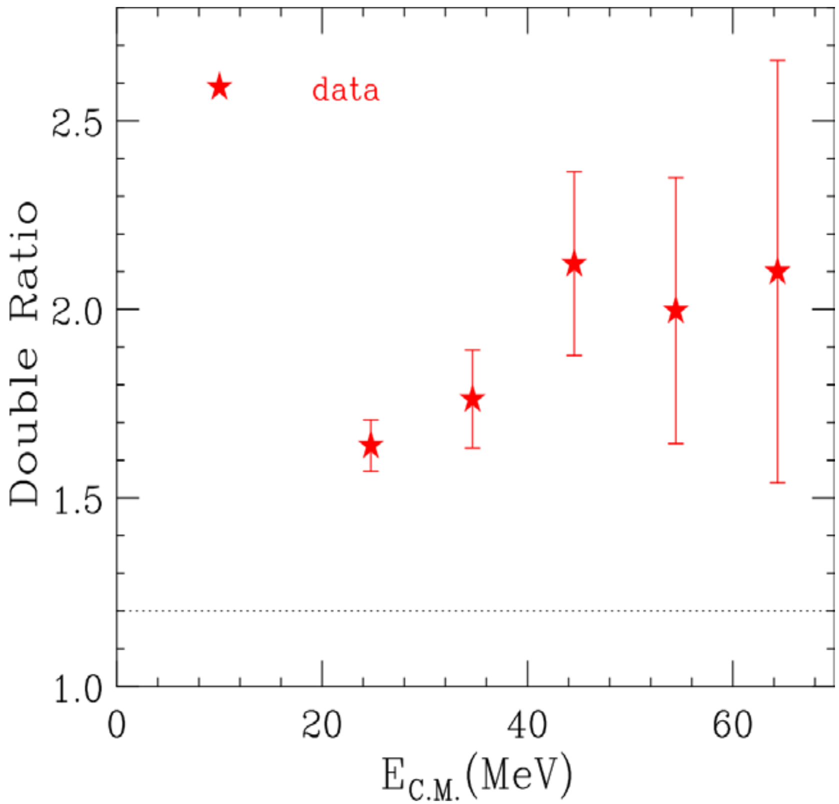
Data : Famiano et al. PRL 97 (2006) 052701

Double Ratio ⇨ $\dfrac{^{124}Sn+^{124}Sn; Y(n)/Y(p)}{^{112}Sn+^{112}Sn; Y(n)/Y(p)}$ ⇨ minimize systematic errors

n/p double yield ratios and flow ratios

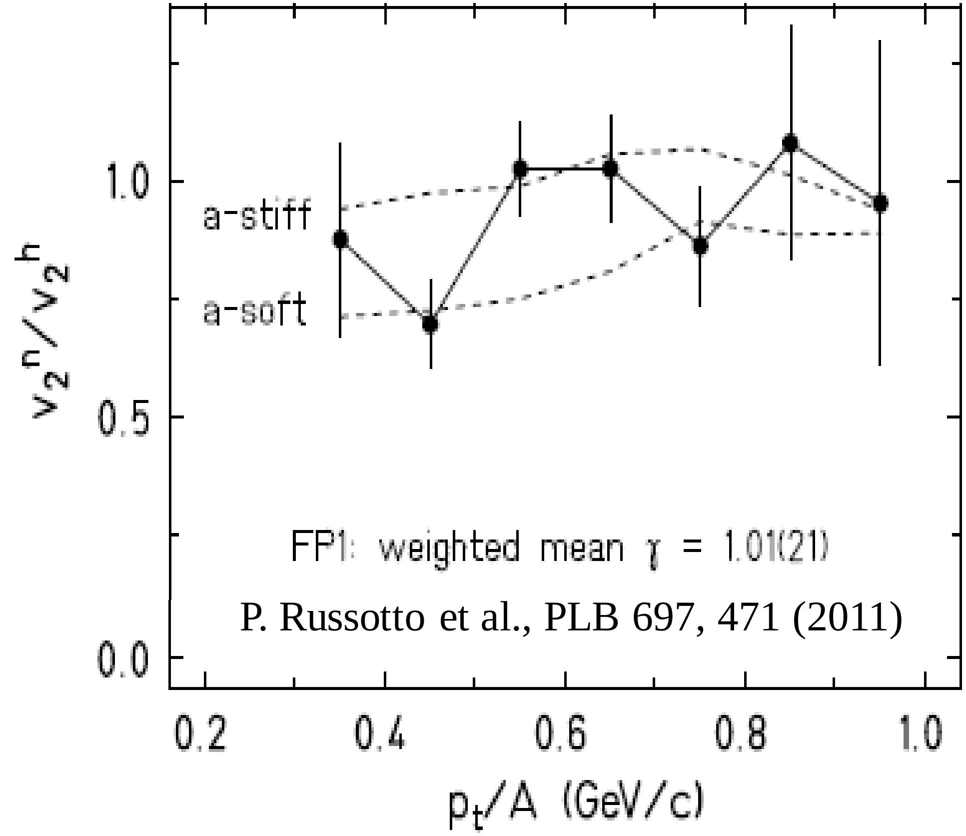
Data : Famiano et al. PRL 97 (2006) 052701

50 A.MeV Sn+Sn



Russotto et al., PL B697 (2011) 471

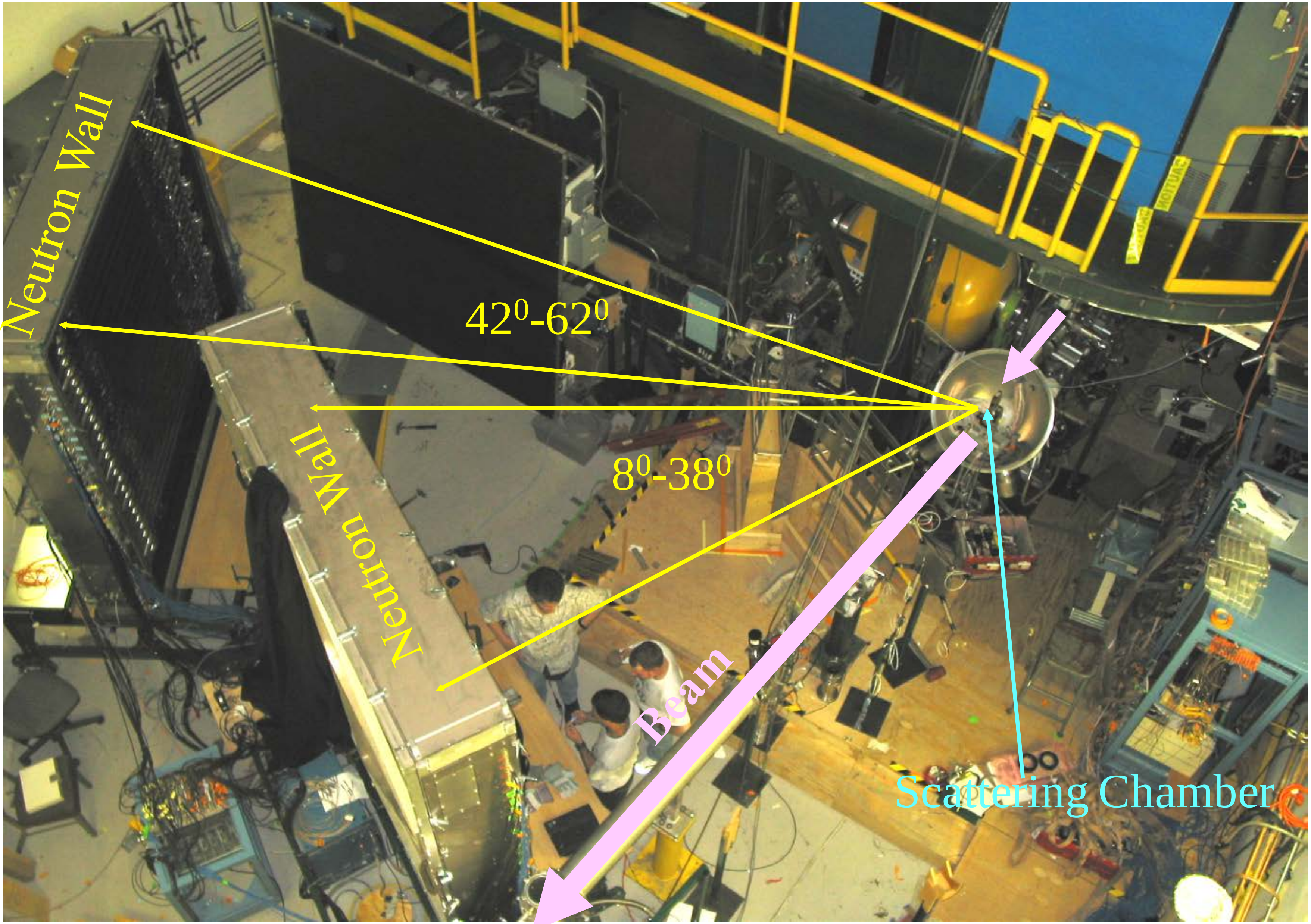
400 A.MeV Au + Au



Theorists frustration: large experimental uncertainties!

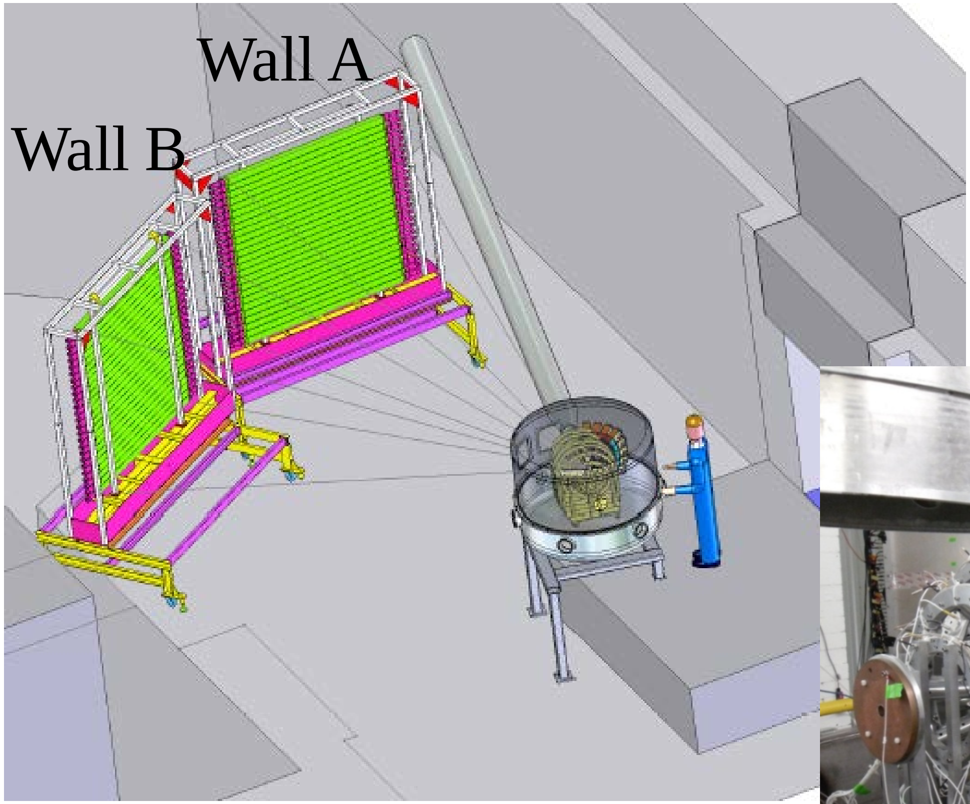
Results from better designed experiments are coming!

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



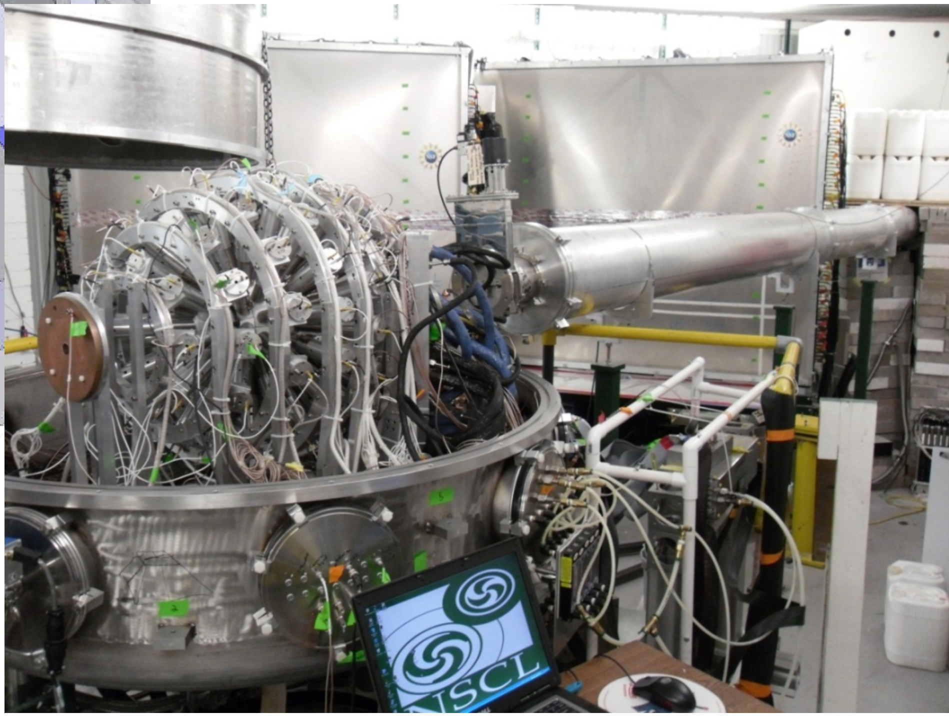
Famiano et al

Complicated Experimental Layout



Courtesy Mike Famiano

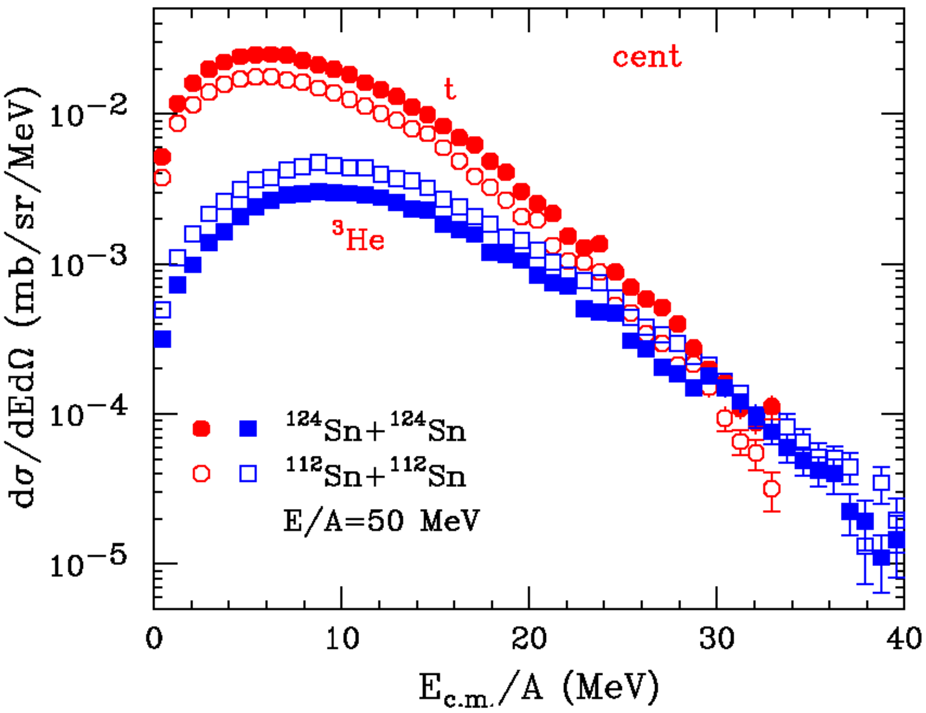
LASSA – charged particles
Miniball – impact parameter

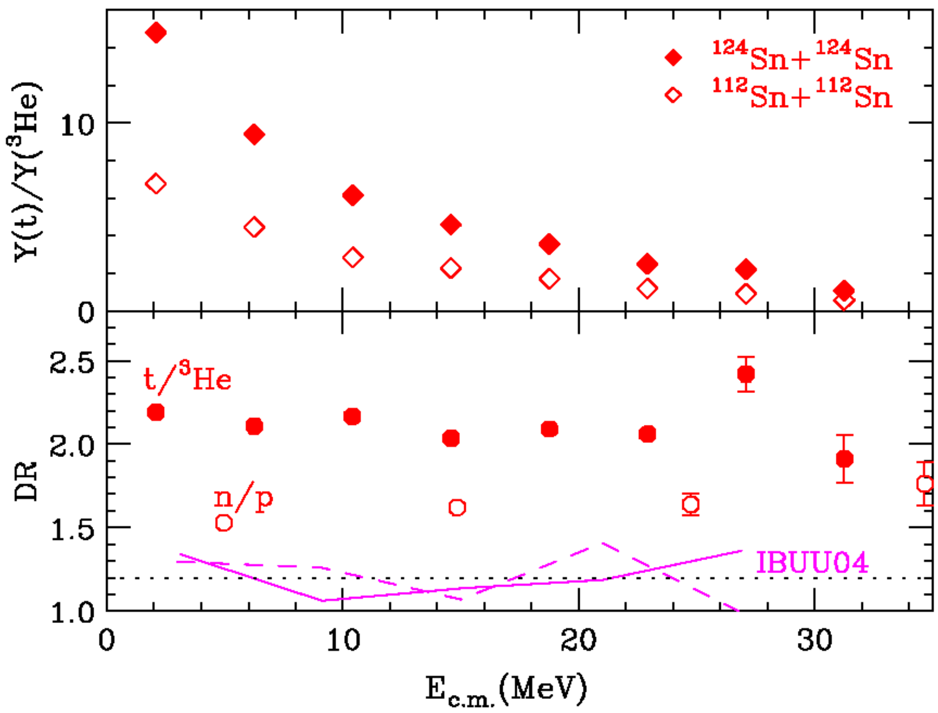


Neutron walls – neutrons
Forward Array – time start
Proton Veto scintillators

Dan Coupland, PhD thesis (2013)

$t/^3He$ Double Ratios (central collisions)





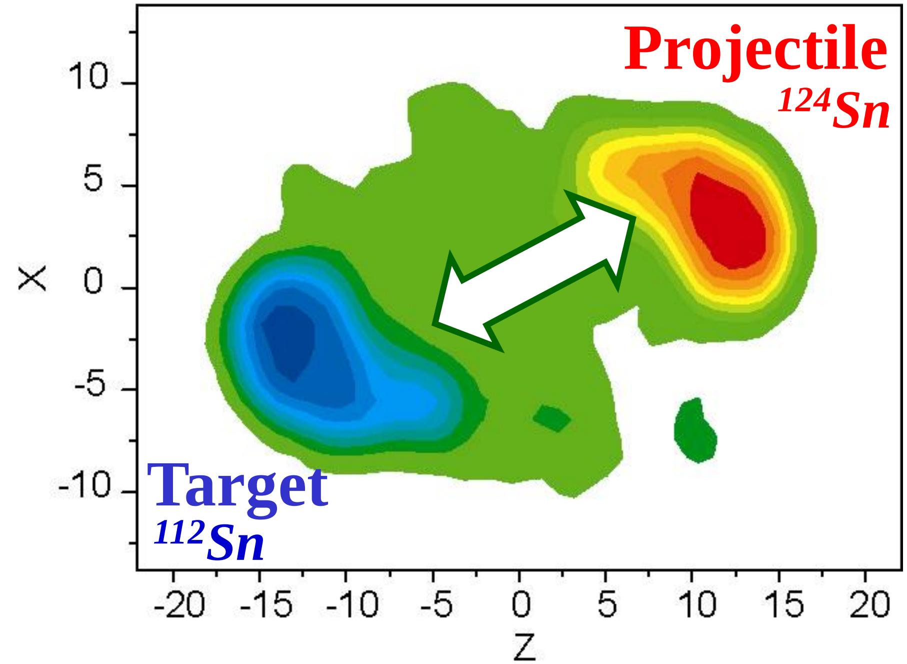
Detection of $t/^3He$ are better controlled but still have cut off problems at high energy due to statistics and detector limitations.

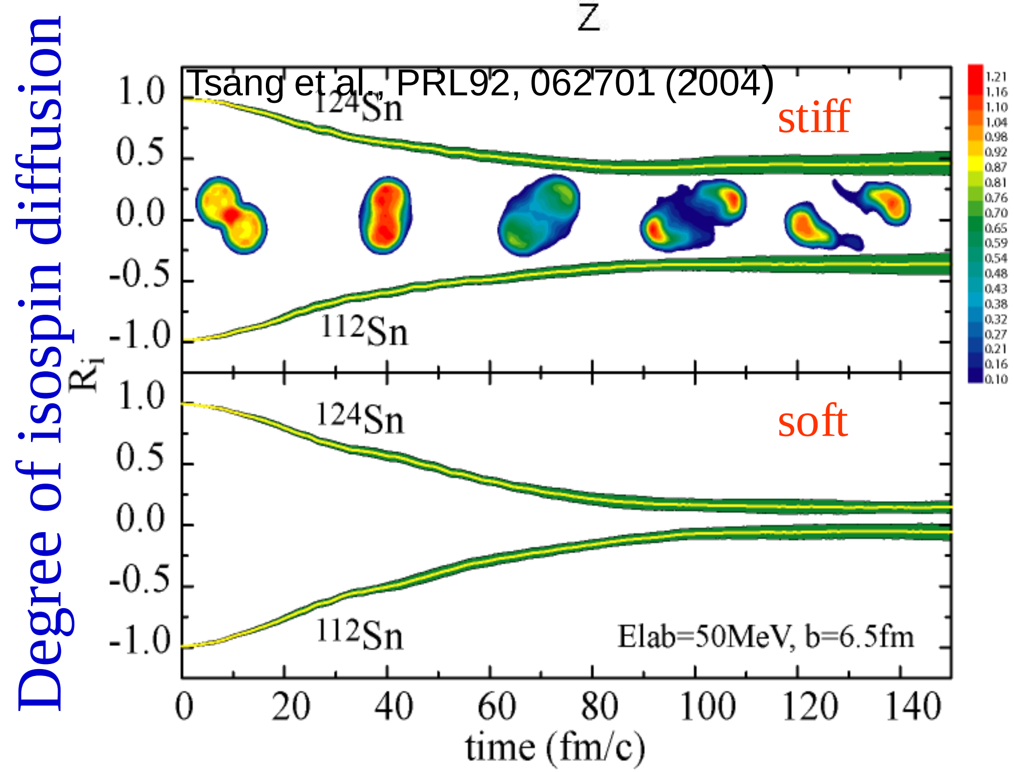
More suitable for experiments at higher beam energy

Experimental Observable :
Isospin Diffusion

- ***Isospin "diffuse" through low-density neck region***
- ***Symmetry energy drives system towards equilibrium.***
  - ***stiff EOS → small diffusion; $|R_i|>>0$***
  - ***soft EOS → fast equilibrium; $R_i \to 0$***
- ***Advantages***
  - ***Sequential decays and non diffusion effects normalized by the symmetric systems***

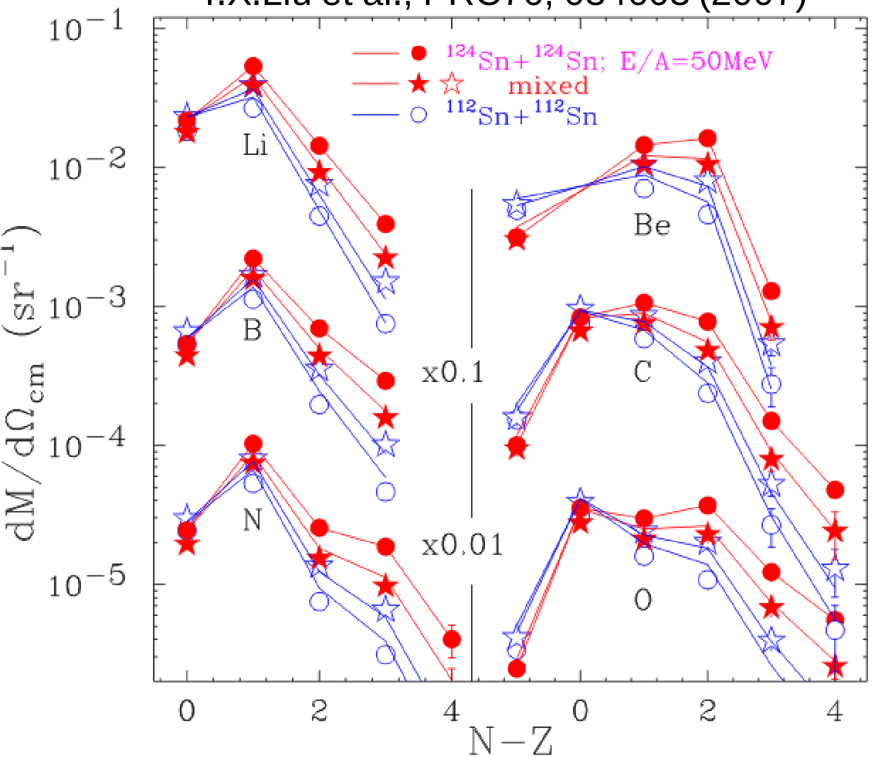
$$R_i = 2\frac{x_{AB} - (x_{AA} + x_{BB})/2}{x_{AA} - x_{BB}}$$





Isotope distributions and isospin diffusions

T.X.Liu et al., PRC76, 034603 (2007)

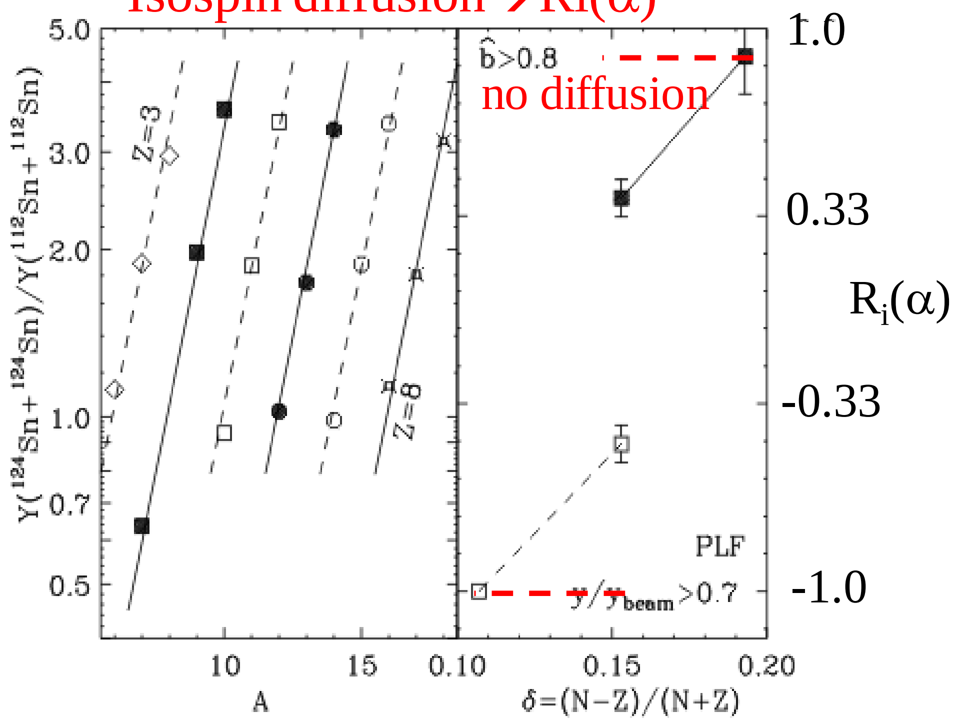


This can be described by the isoscaling parameters α and β:

$$\frac{Y_2(N,Z)}{Y_1(N,Z)} = C\exp(\alpha N + \beta Z)$$

α and β are related to the nucleon chemical potentials

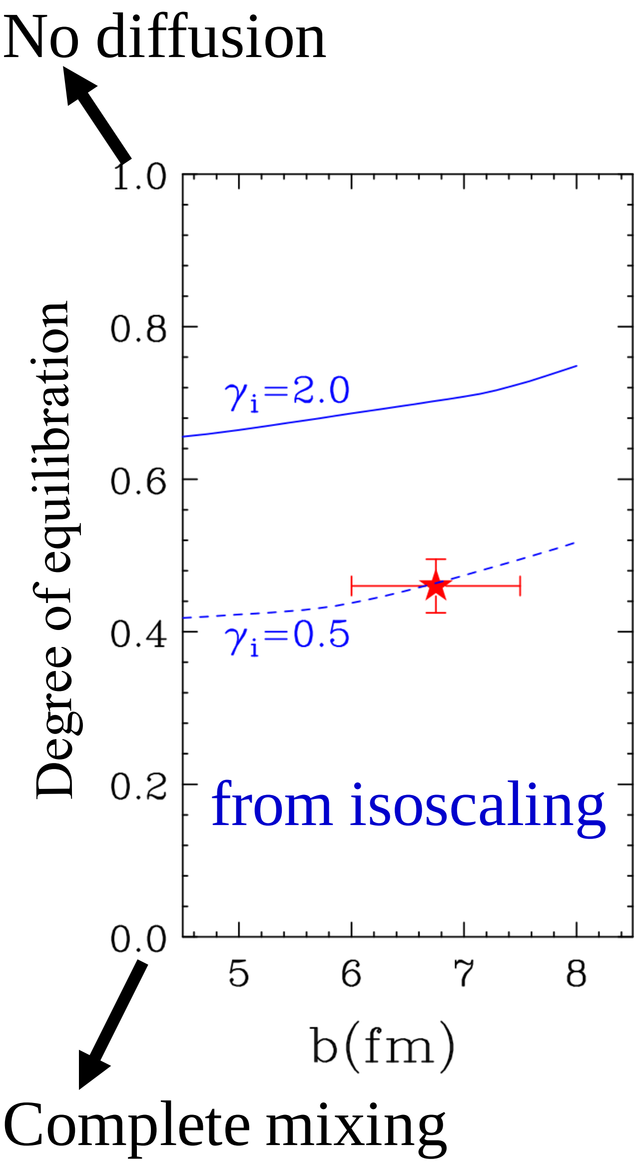
Isospin diffusion→Ri(α)

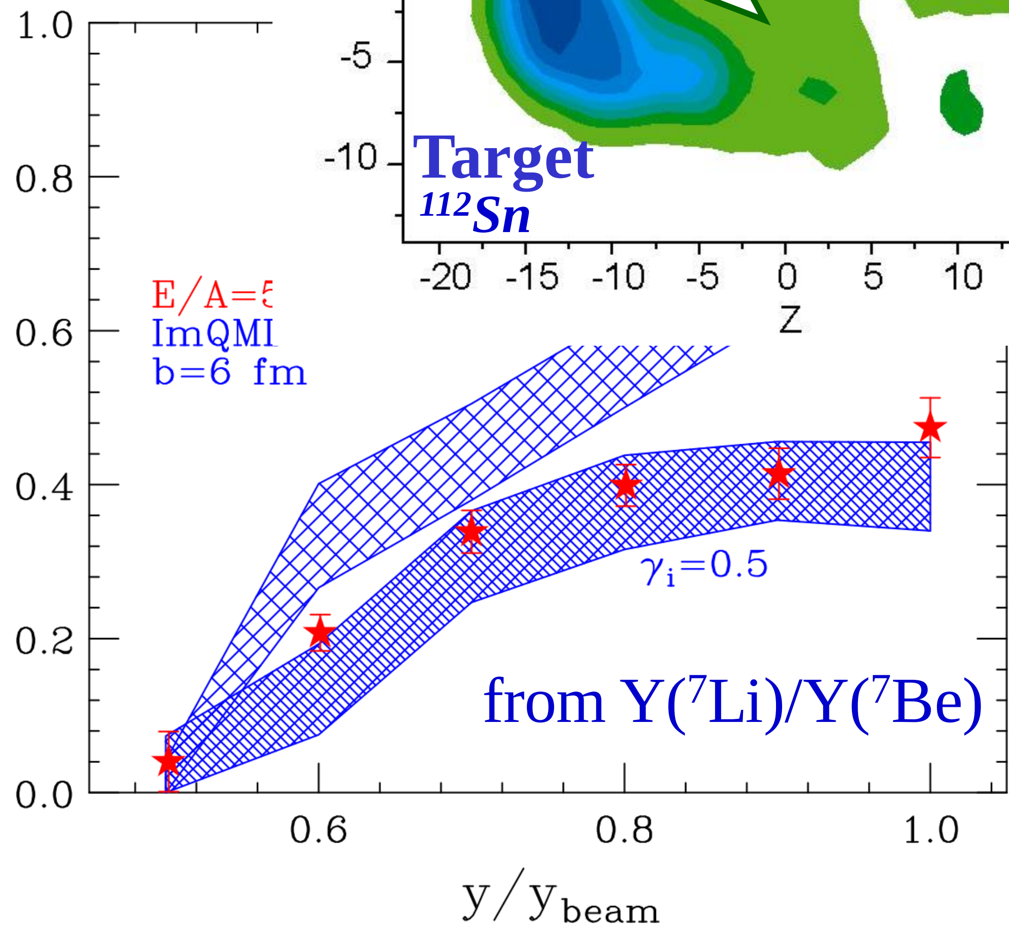


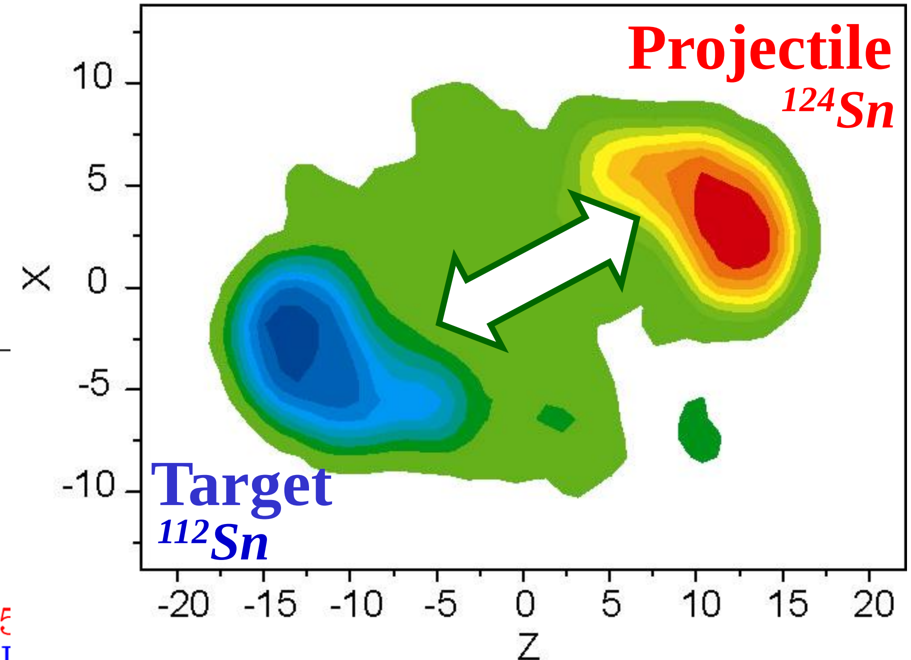
Tsang et al., PRL92, 062701 (2004)

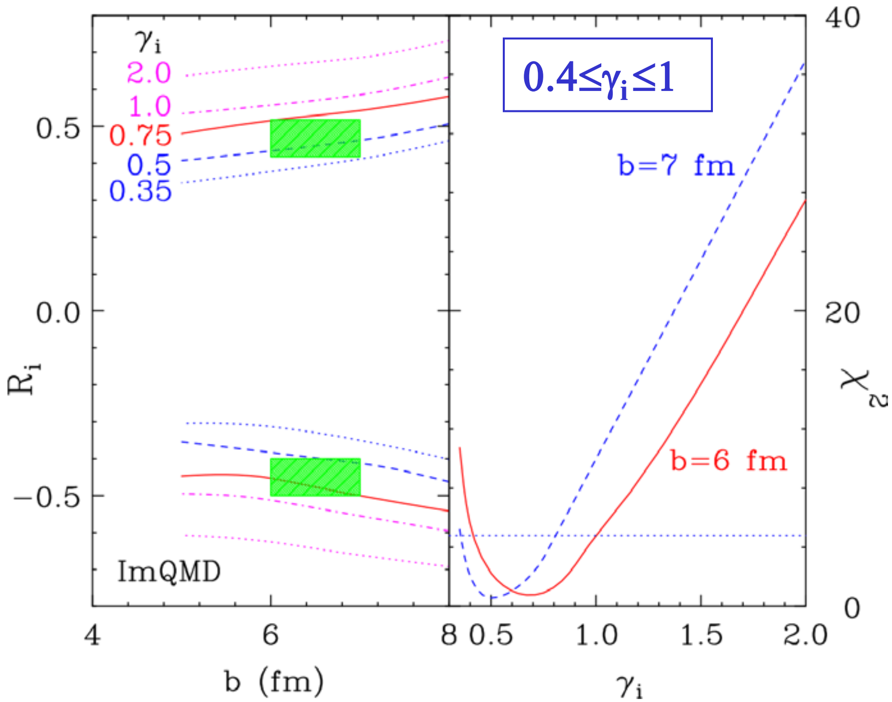
The main effect of changing the asymmetry of the projectile spectator remnant is to shift the isotopic distributions of the products of its decay

Isospin Diffusion





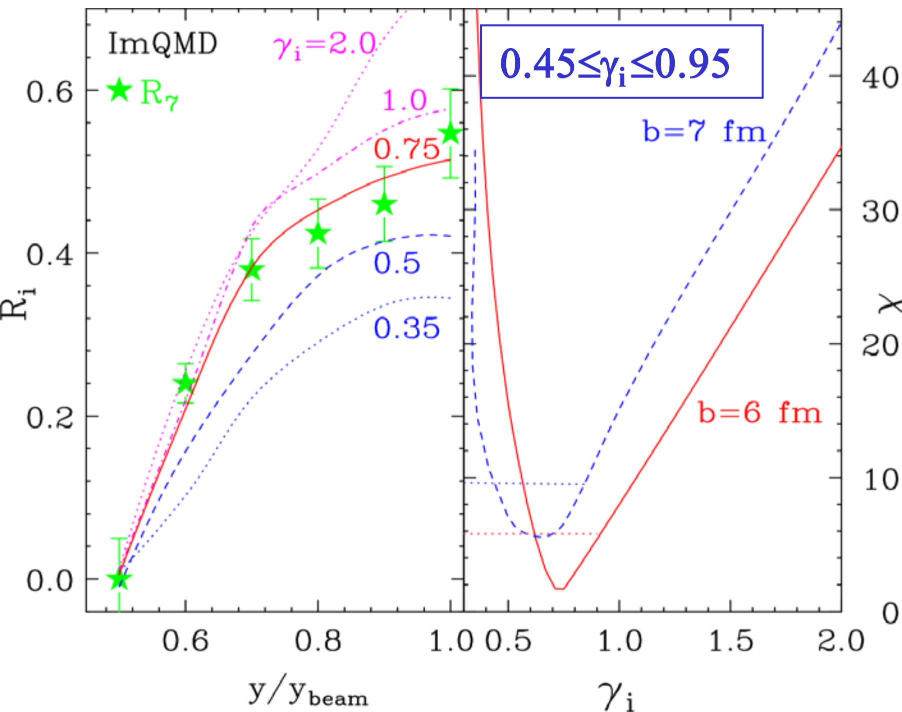




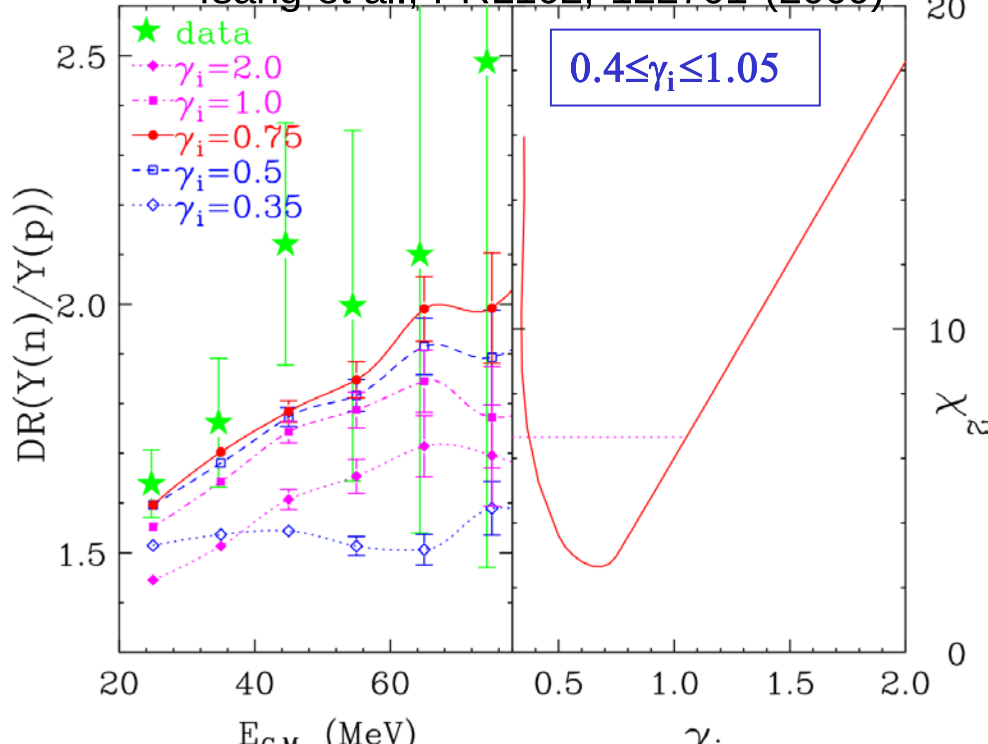
ImQMD model describes np ratios and two isospin diffusion measurements:

$$S(\rho)=12.5(\rho/\rho_o)^{2/3}+17.6\,(\rho/\rho_o)^{\gamma_i}$$

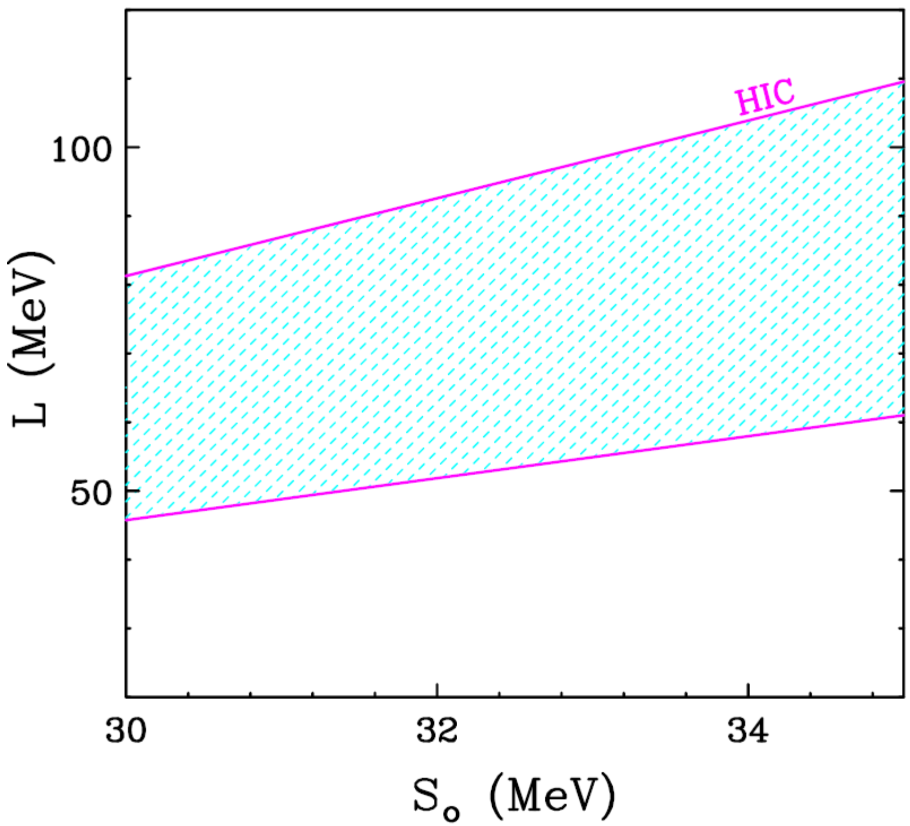
Consistent constraints from the χ^2 analysis of three observables $0.4\leq\gamma_i\leq1$

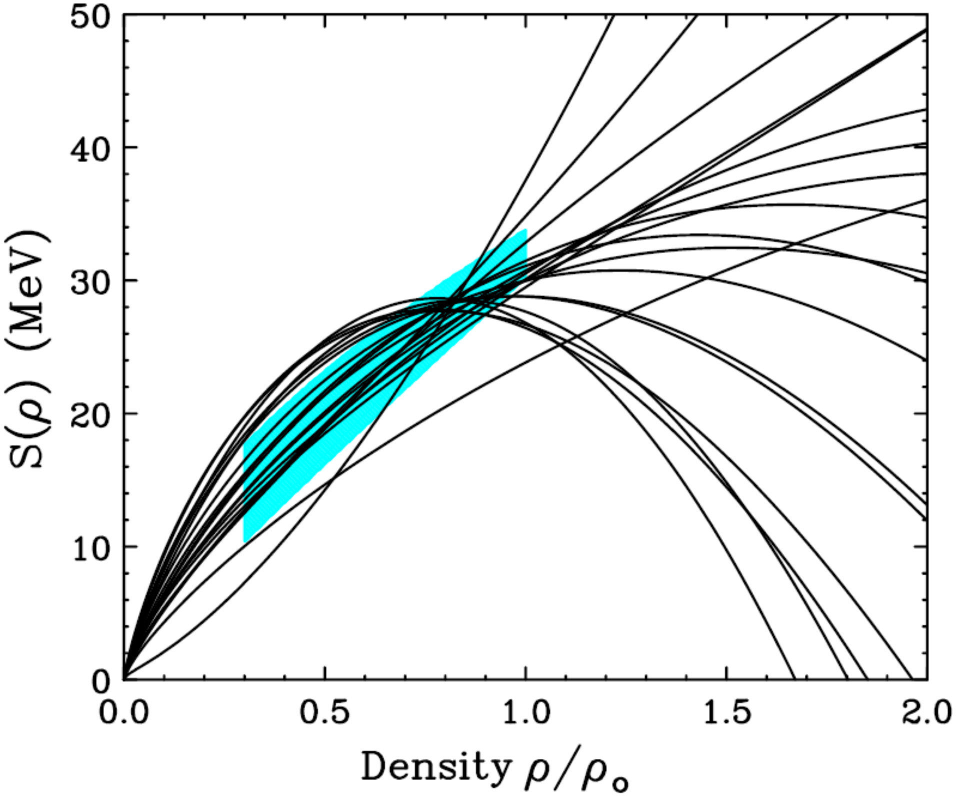


Tsang et al., PRL102, 122701 (2009)



HIC constraints at sub-saturation densities





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

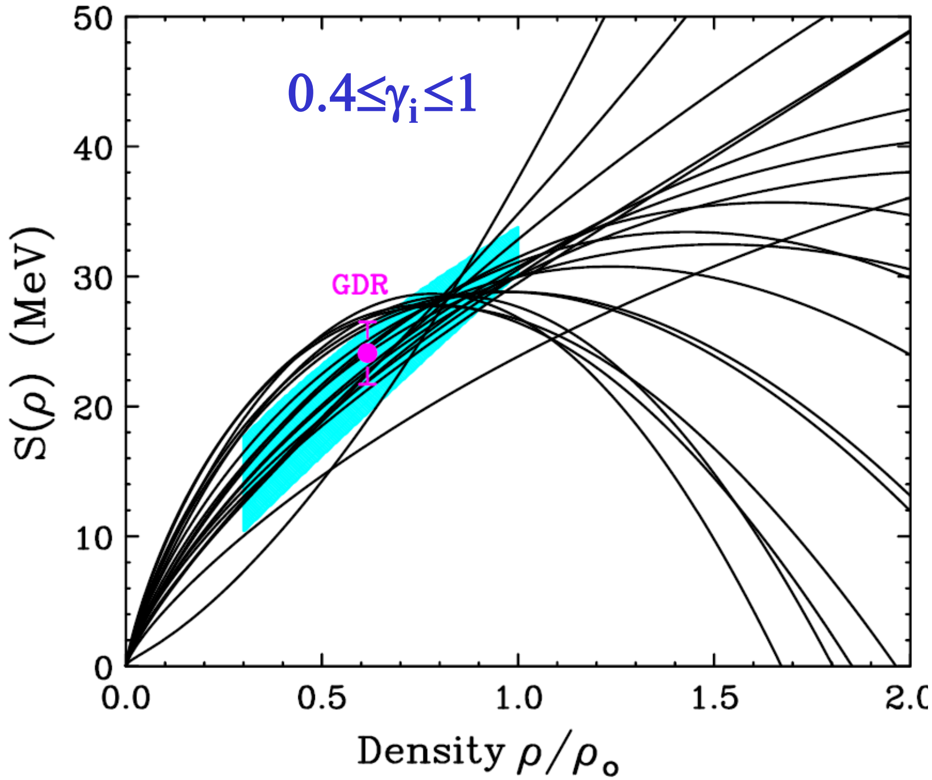
$$S(\rho) = 12.5(\rho/\rho_o)^{2/3} + 17.6(\rho/\rho_o)^{\gamma_i}$$

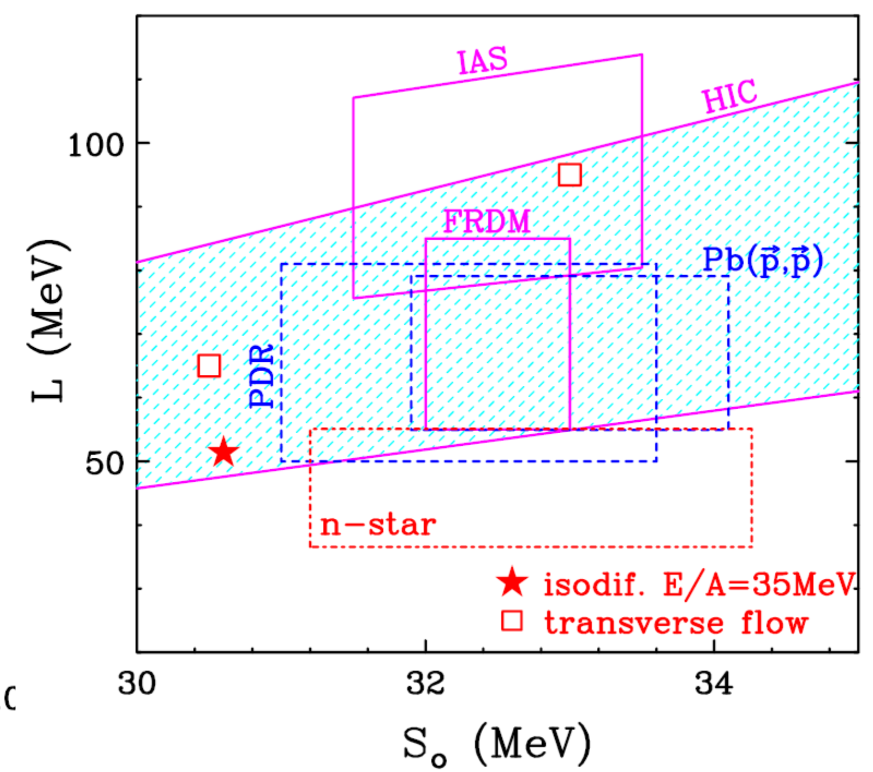
$$0.4 \le \gamma_i \le 1$$

Typel & Brown, PRC 64, 027302 (2001)

Symmetry energy constraints from HIC

arXiv:1204.0466



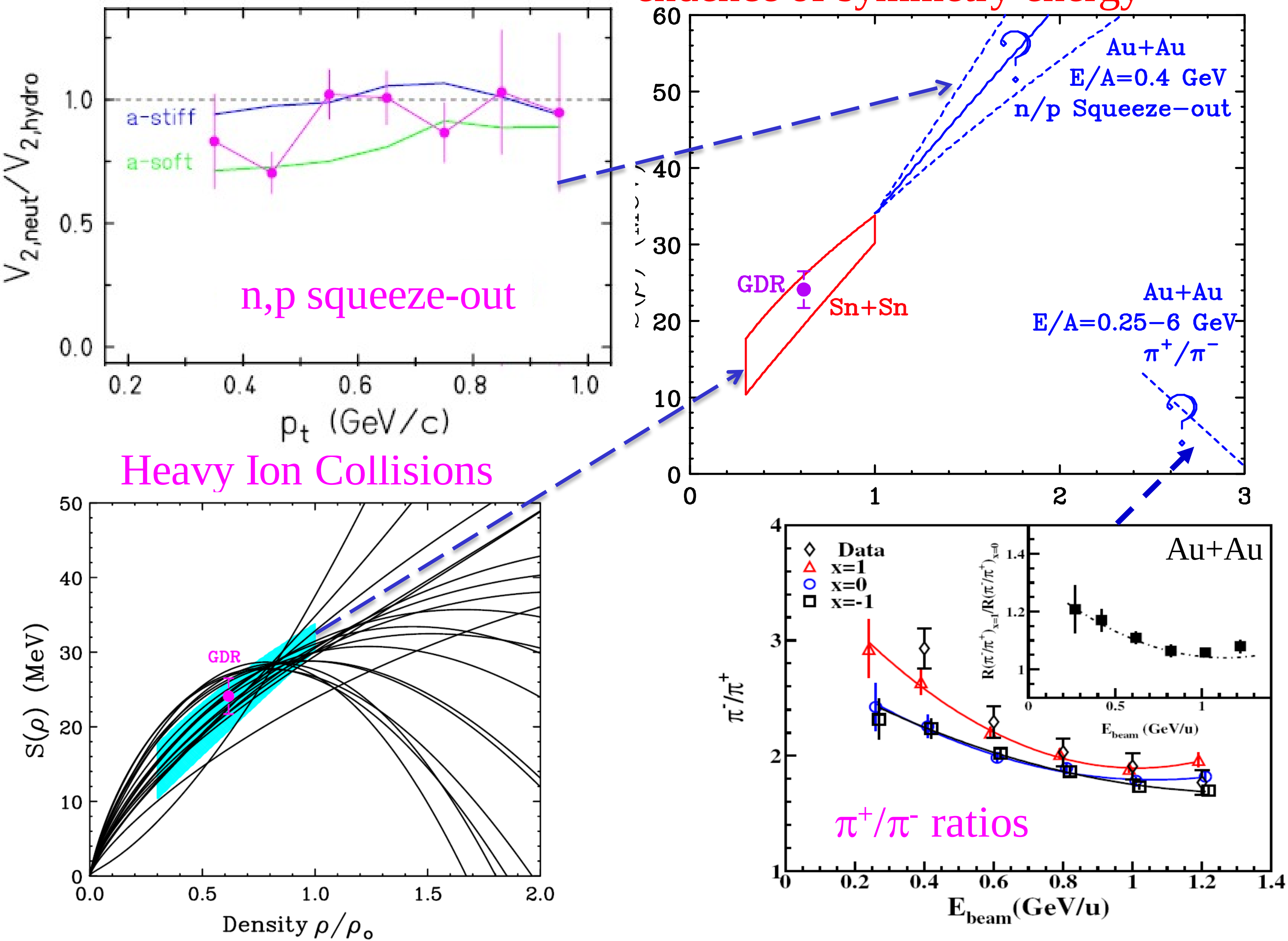


$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2 + \dots$$

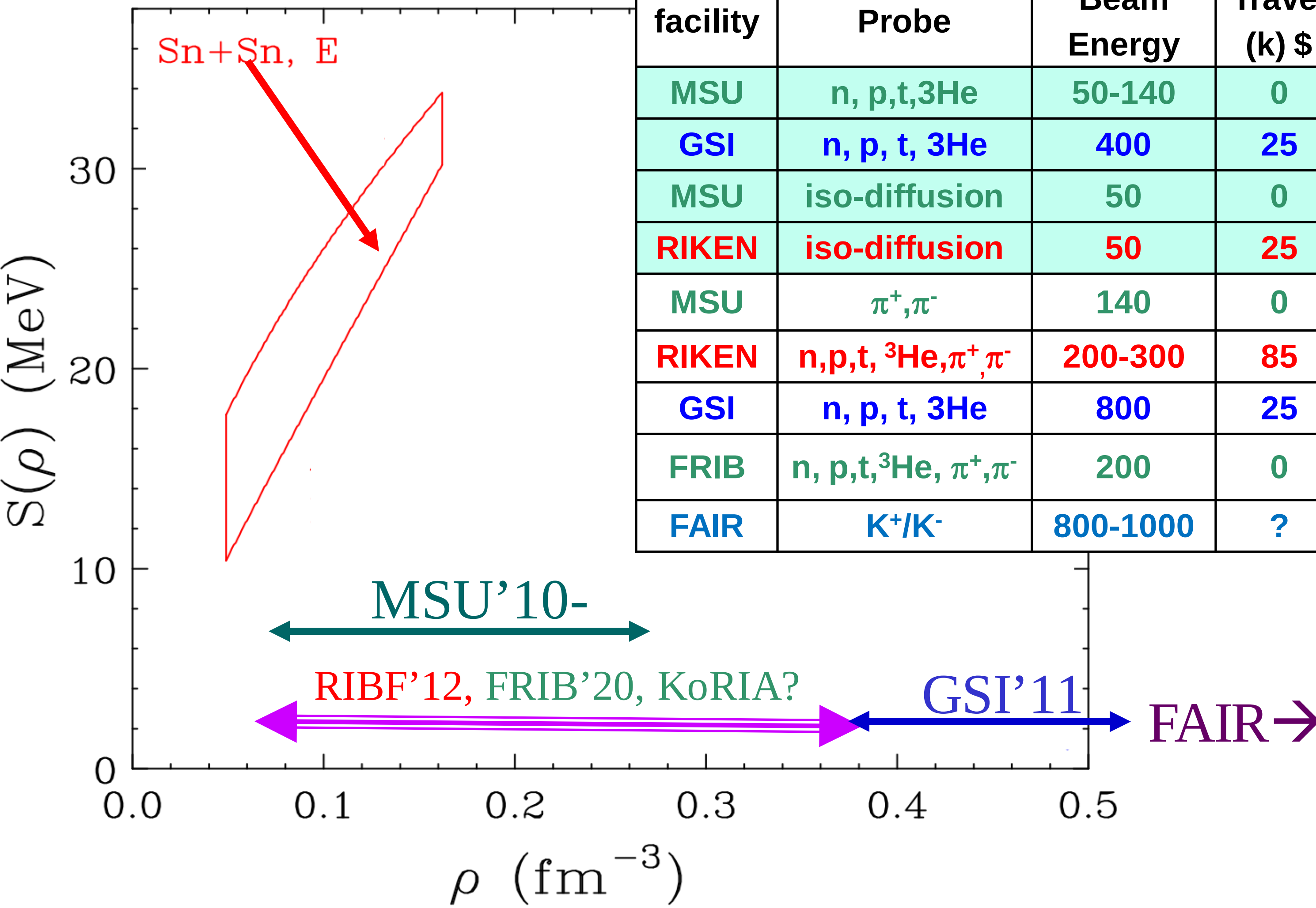
$$L = 3\rho_0 \left.\frac{\partial E_{sym}}{\partial \rho_B}\right|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}$$

HIC has been successful in obtaining constraints on the symmetry energy at $0.3<\rho/\rho_O<1$

Constraints on the density dependence of symmetry energy



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	2010/2011	$<\rho_o$
RIKEN	iso-diffusion	50	25	2010	$<\rho_o$
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	$3\rho_o$



Symmetry Energy Project → International collaboration to determine the symmetry energy over a range of density

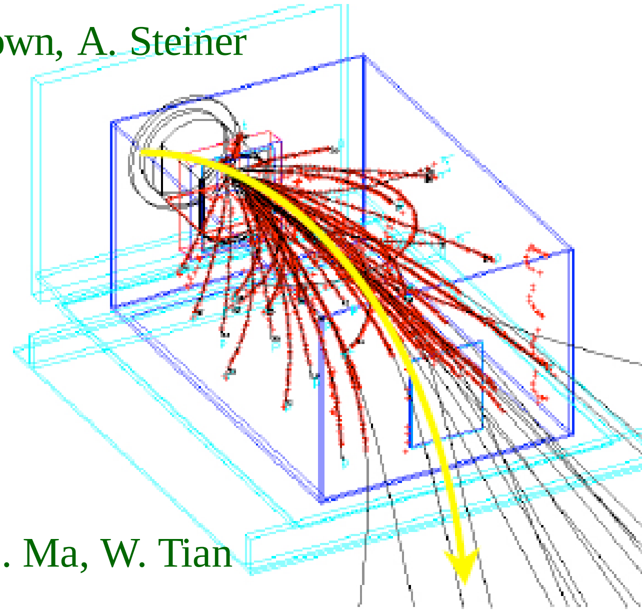
Require: New Detectors (TPC), & theory support

Nuclear Symmetry Energy (NuSym) 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
Korea University, Korea: Byungsik Hong



The Time projection chamber is being built in the US to measure π+/ π- & light charge particles in RIKEN

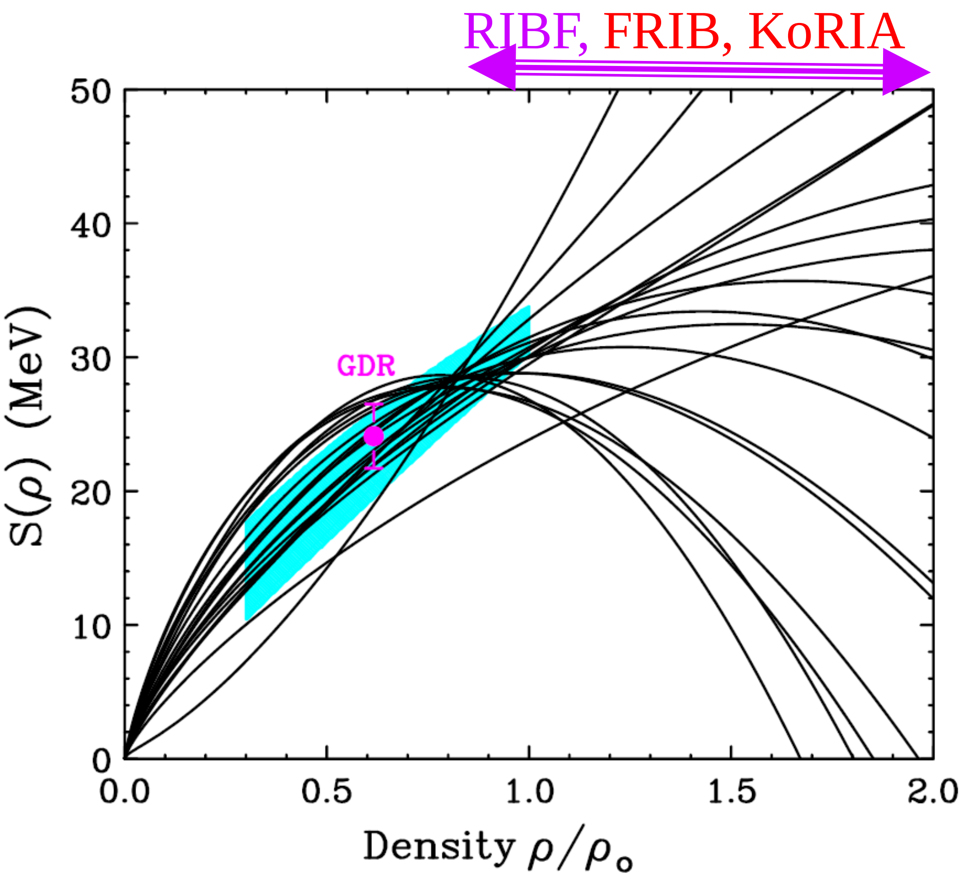
Isospin Observables in HIC at supra-normal densities

E/A=50-100 MeV
Neutron/proton and t/^{3}He and light isotopes energy spectra & flow

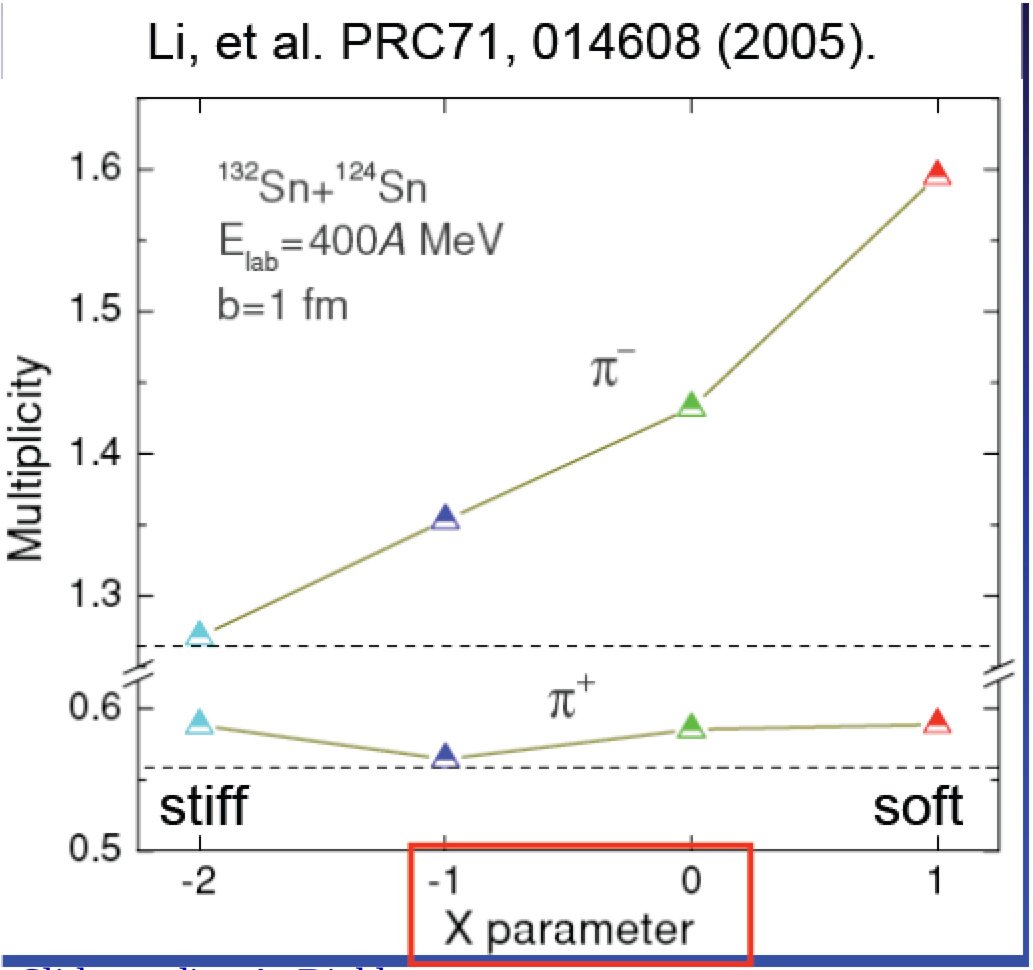
E/A>150 MeV
- π^+/π^- spectra
- π^+/π^- flow

$$\frac{\pi^-}{\pi^+} \propto e^{(\mu_n-\mu_p)/T}$$

Preliminary data shows:
n/p remains robust at E/A=120 MeV. May be able to extend measurements to E/A~200 MeV



A new isospin observable



Slide credit : A. Bickley

$$\frac{\pi^-}{\pi^+} \propto e^{(\mu_n - \mu_p)/T}$$

- π- generated from n+n collisions
- π+ generated from p+p
- Collisions of neutron rich nuclei: N(π-)>N(π+)
- π- multiplicity dependent on density dependence of EOS

Different transport codes make different predictions!

New Detector(s)

At beam energy > 100 A.MeV, fragment production decreases.
Observables are:
n/p ratios, flow, t/3He ratios, flow, π+/ π- ratios

Properties of the Time projection chamber (TPC)

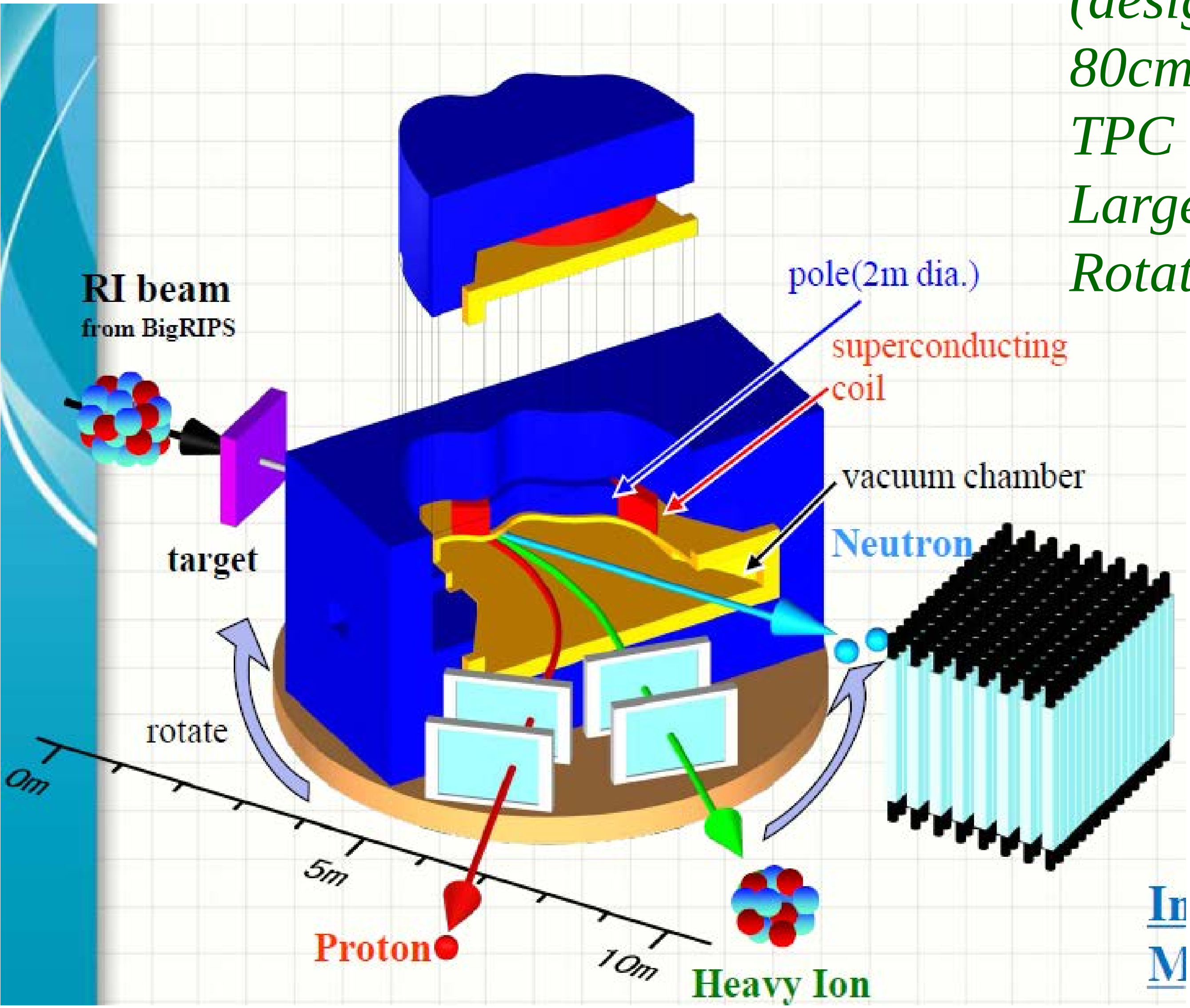
Particle identification (dE/dX–track rigidity)
Charged pions, Proton, Light ions (t, 3He)

Centrality Determination (b):
momentum measurement

Reaction plane determination
Ability to measure large number of multiple particles

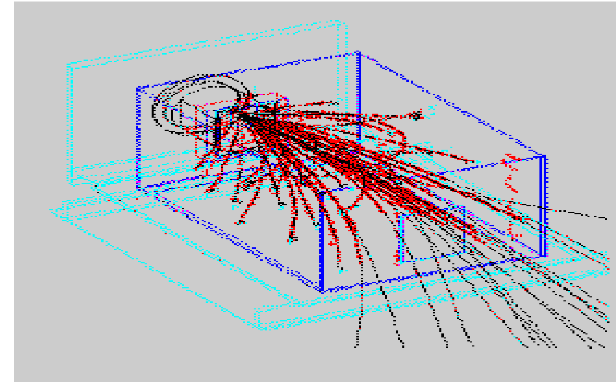
SAMURAI @ RIKEN

Superconducting Magnet
3T with 2m dia. pole
(designed resolution 1/700)
80cm gap (vertical)
TPC
Large Vacuum Chamber
Rotational Stage



SAMURAI-TPC

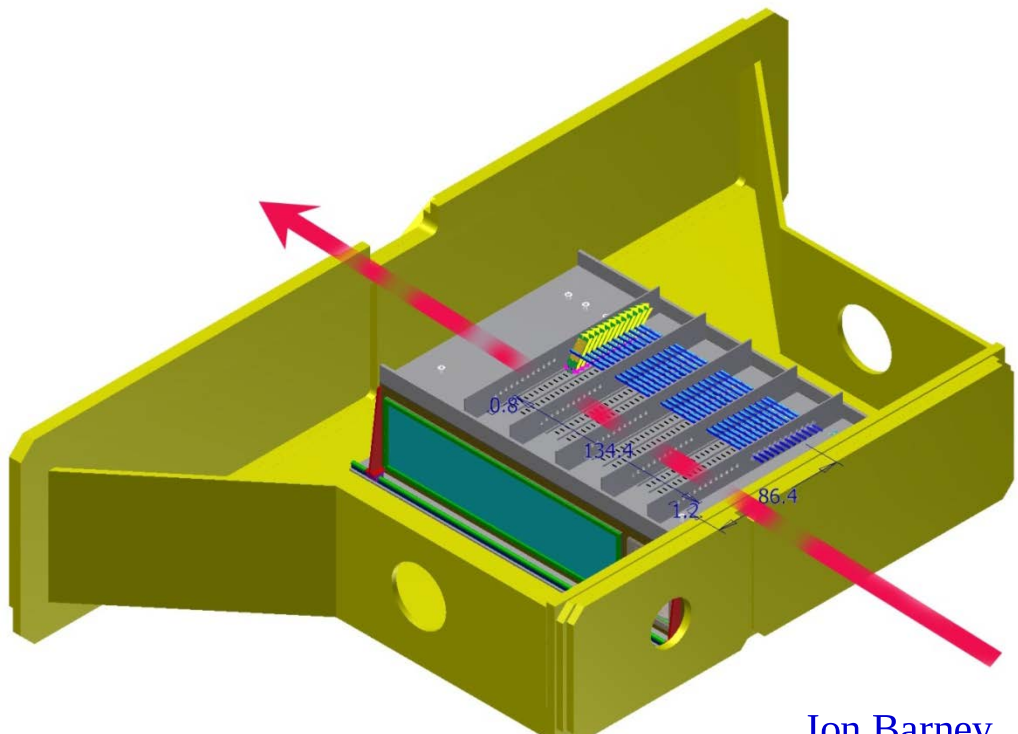
The SAMURAI Time Projection Chamber (TPC) tracks the light charged particles and pions after the heavy ion collisions.



SAMURAI Dipole Magnet

Slide credit : A. Bickley

TPC in the Vacuum Chamber

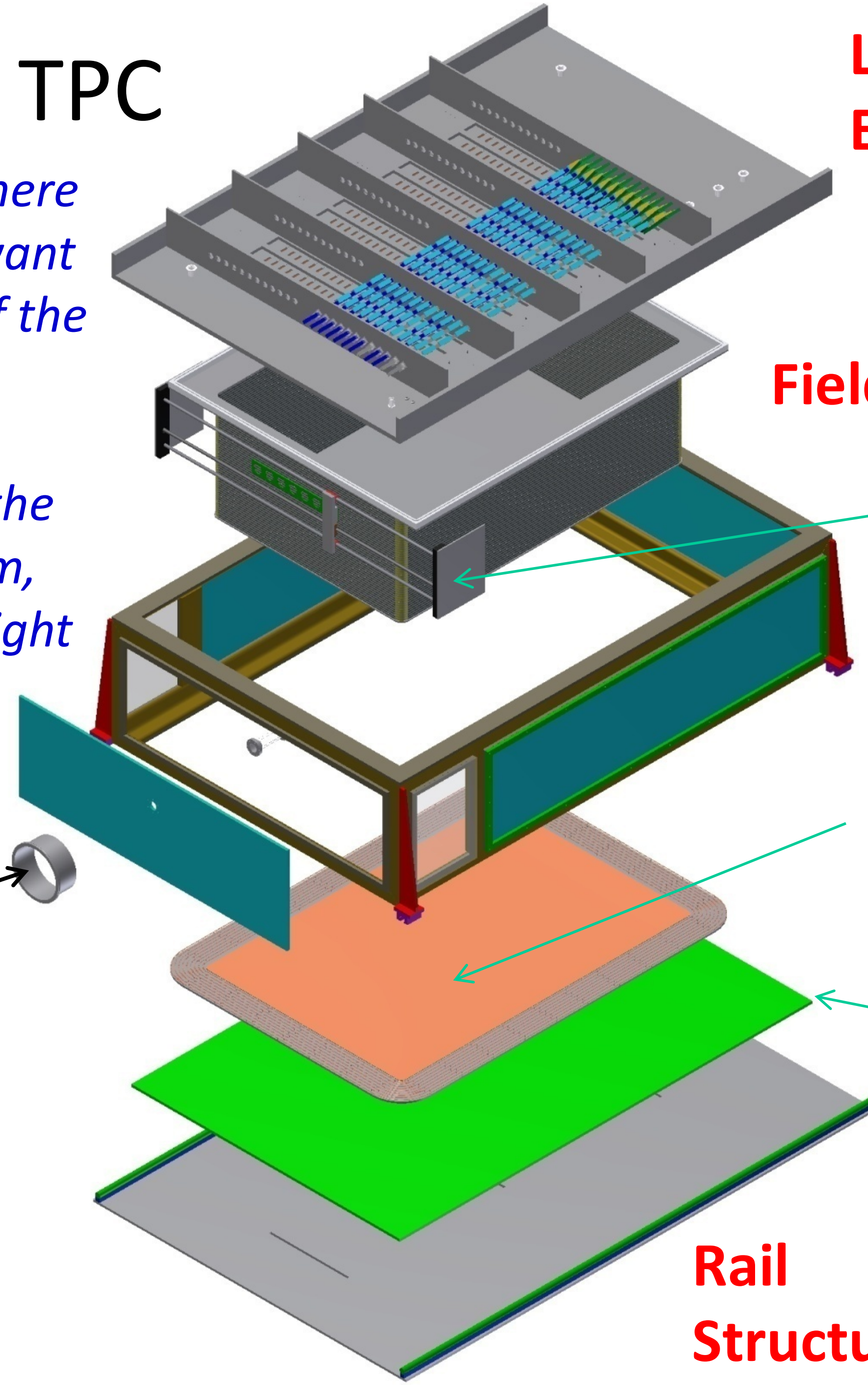


Jon Barney

The SAMURAI TPC

- *Since the field cage is where the magic happens, we want to maximize the height of the field cage.*

- *The height is limited by the magnet chamber to 80 cm, but by minimizing the height of other parts we can maximize the field cage height*



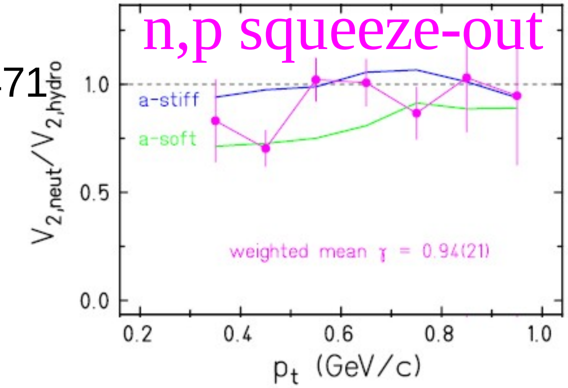
Jon Barney

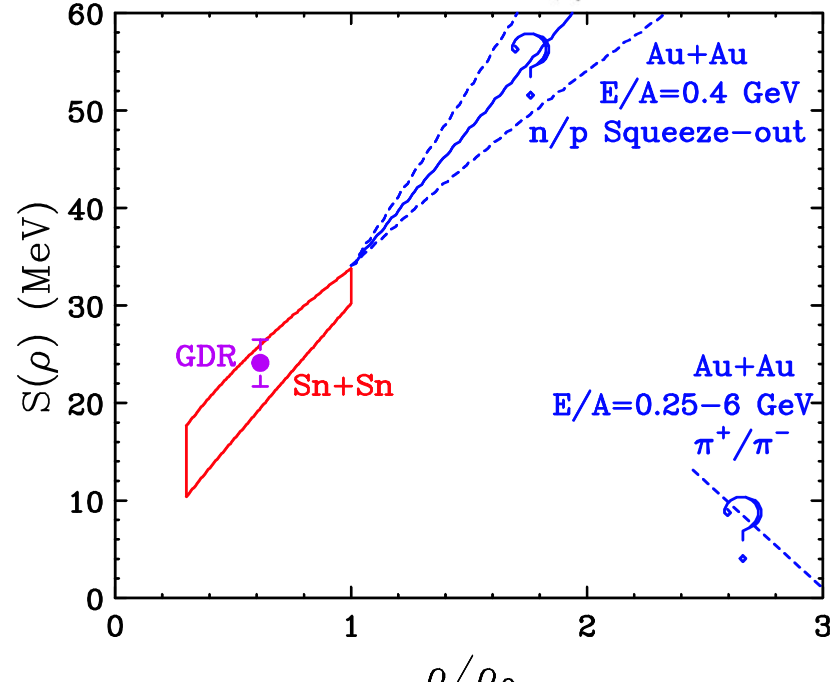
Summary

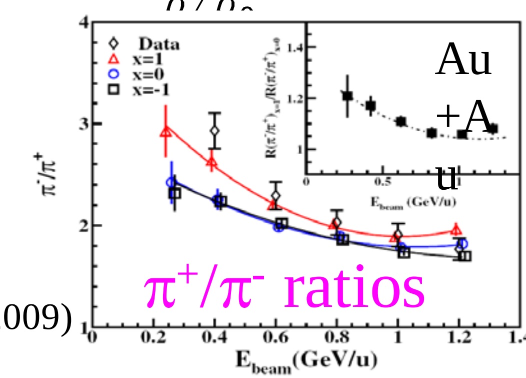
- *Success at low energy HIC program suggests paths forward to higher energy program to determine the density dependence of symmetry energy at high density – important program in any nuclear science LR plans.*
- *HIC is the only way on earth to create nuclear matter with $\rho>\rho_o$.*
- *Challenges remains:*
- *New detectors to measure new observables. TPC to detect p's.*
- *Extension of current observables to high energy (n,/p, t/3He…)*
- *HIC experiments are complicated, need advance planning and "floor place/footprint" in new facilities.*

Much work remains – exciting time to join the international effort!

Russotto et al.,
PL B697 (2011) 471







Xiao et al., PRL102, 062502 (2009)