Determination of the Equation of State of Asymmetric Matter in RIKEN

JUSTIPEN-JUSEIPEN Workshop, December 9-12, 2013

SAMURAI π-Reconstruction and Ion-tracker TPC

曾敏兒 Betty Tsang, NSCL/MSU

Participating institutes in the TPC construction

U.S. DEPARTMENT OF ENERGY
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MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

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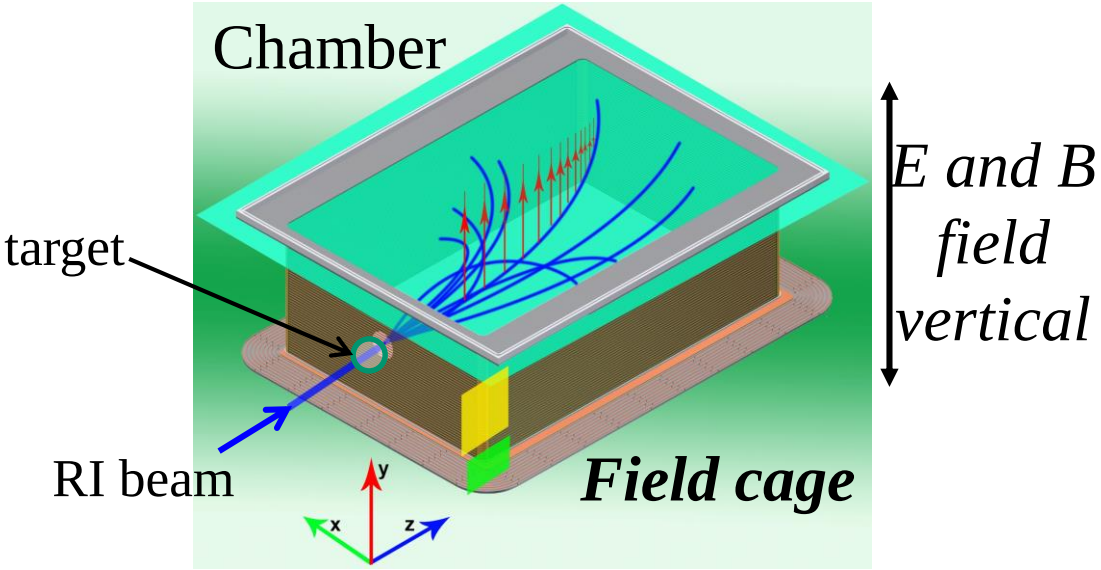
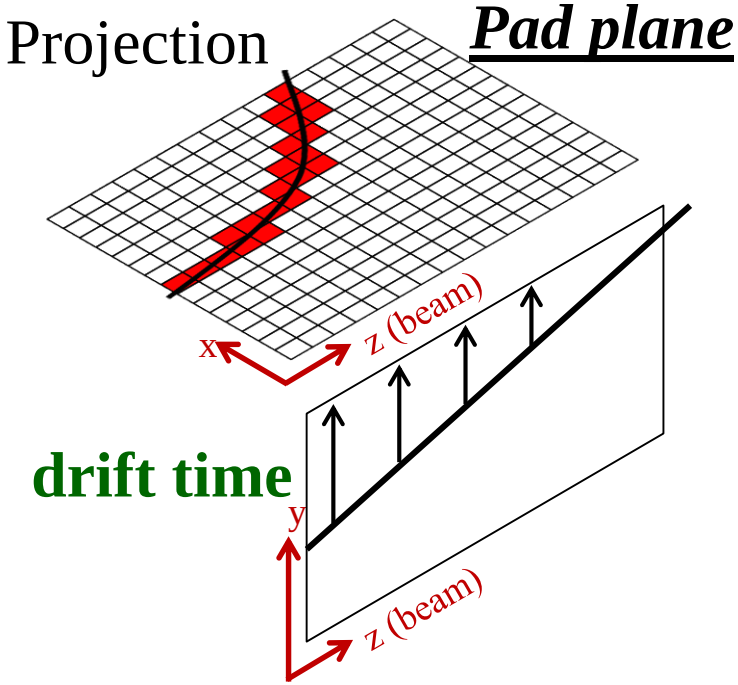
Time-projection chamber 时间投影室

particle tracker in a magnet





Charged fragments from nuclear collisions ionize detector gas

Electrons drift in E-field toward charge-sensing pads

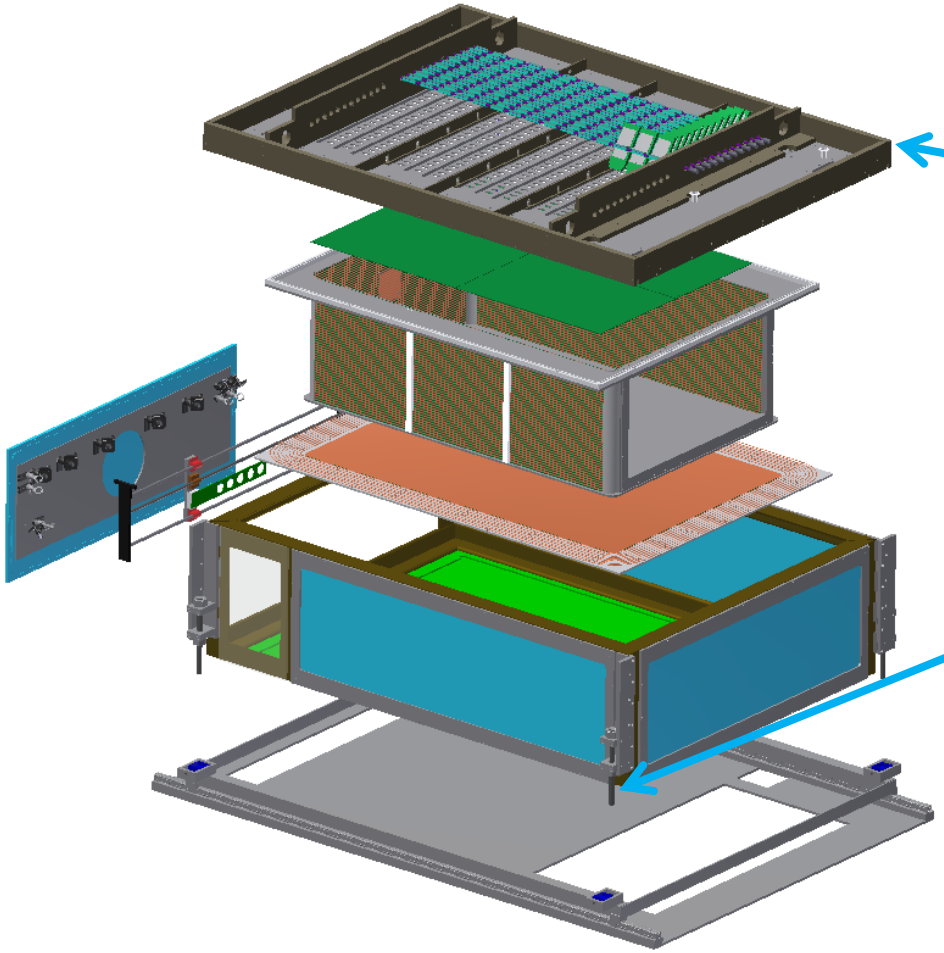
Positions and **time** of arrival → 3D path

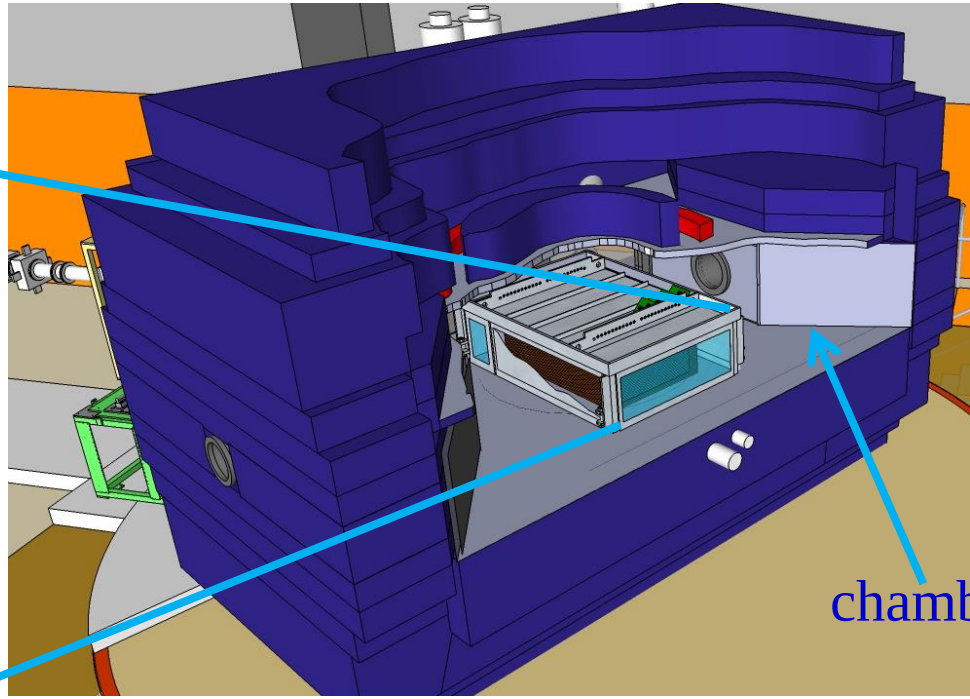
Momentum from curvature of path in B-field

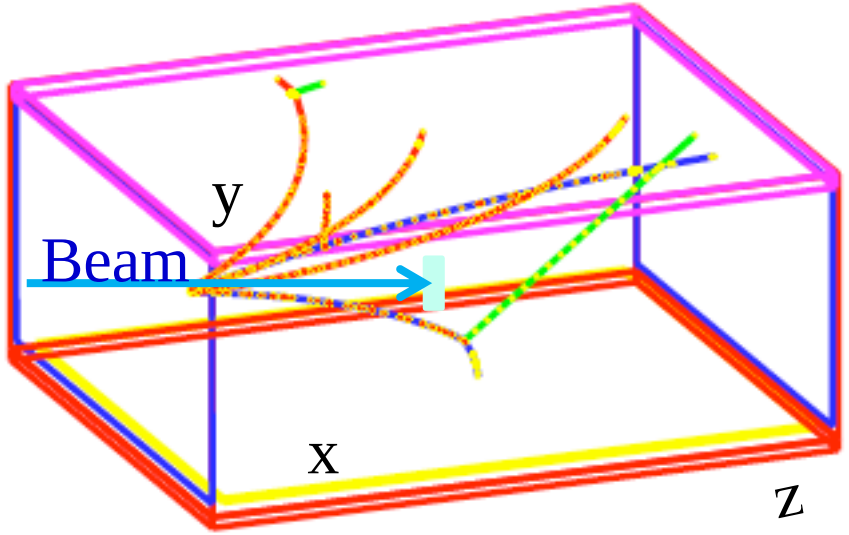
Particle type from energy loss and magnetic rigidity

Figure courtesy of J. Estee, J. Barney

S-TPC will be installed inside the SAMURAI dipole magnet in RIKEN







Determination of the Equation of State of Asymmetric Matter program in RIKEN

Introduction

Experimental Observables:

- ***Heavy Ion Collisions near Fermi energy E/A~50 MeV***
  - ***Isospin diffusions***
- ***Comparison of constraints to other observables from nuclear masses and structure***
- ***HIC is viable probe to study the properties nuclear matter.***

Experimental Observables:

- ***Challenges***
  - ***3n forces***
  - ***effective nucleon masses***
- ***Observations from Neutron Star***
- ***Heavy Ion Collisions in RIKEN; E/A>200 MeV***
  - ***pi-/pi+ ratios and flow; charge particles yield ratios and flow – new detectors***
- ***Status of SπRIT project***

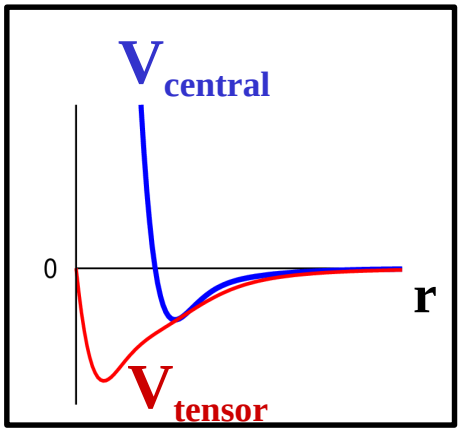
Summary and Outlook

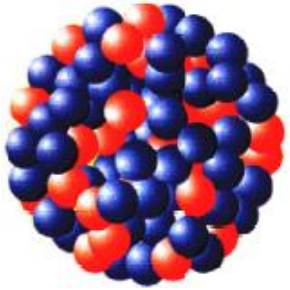
Nuclear Equation of State

Mathematical Relationship between energy, temperature, pressure, density in nuclear matter

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

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





✓*Nuclear Force – What is the nature of the nuclear force?*

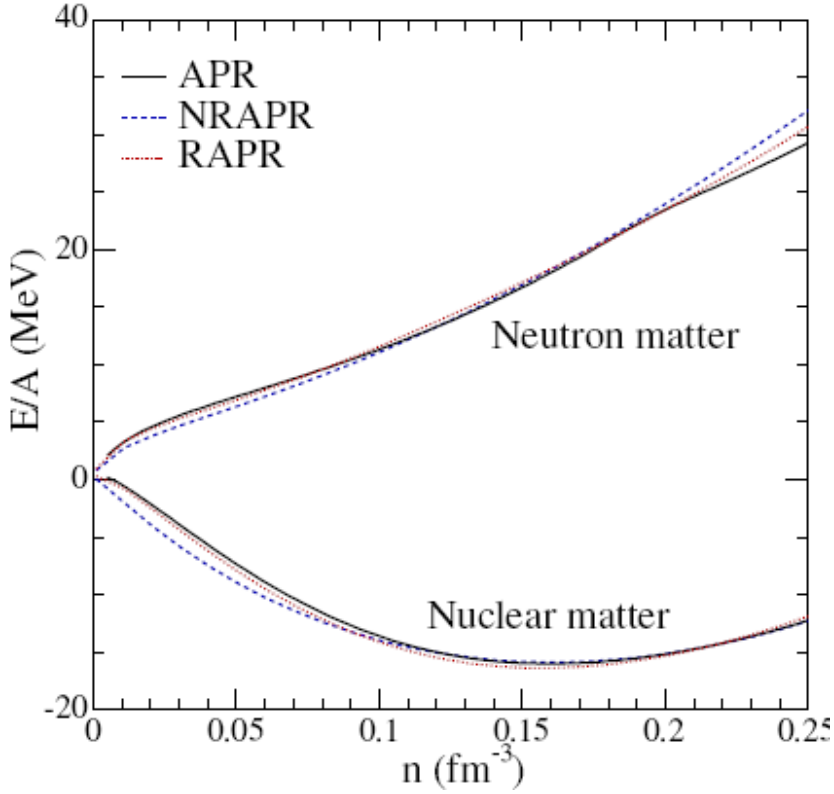
✓*Nuclear Structure – What binds protons and neutrons into stable nuclei and rare isotopes?*

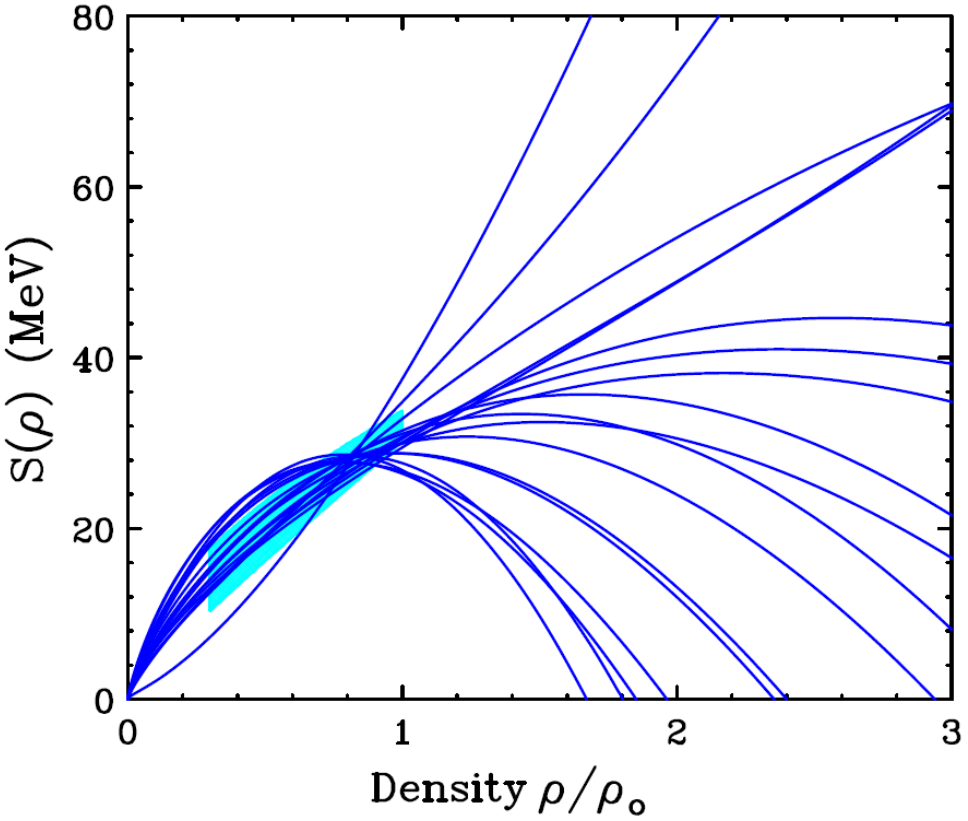
✓*Nuclear Astrophysics – What is the nature of neutron stars and dense nuclear matter?*

SπRIT

Equation of State of Asymmetric Nuclear Matter

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





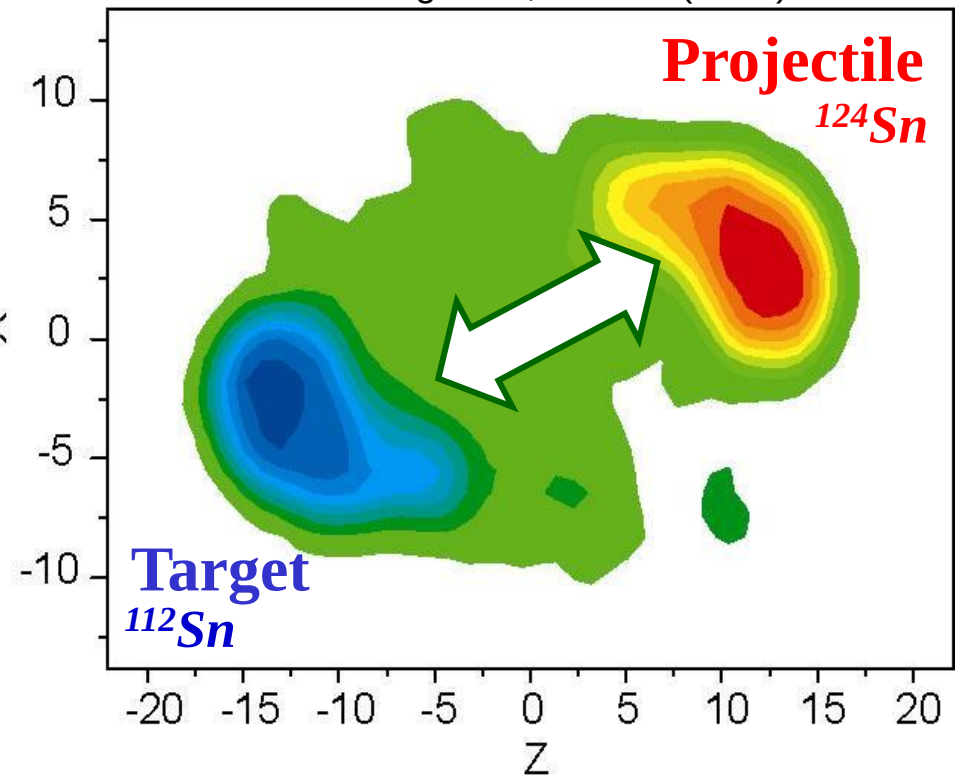
Density dependence of symmetry energy

SπRIT

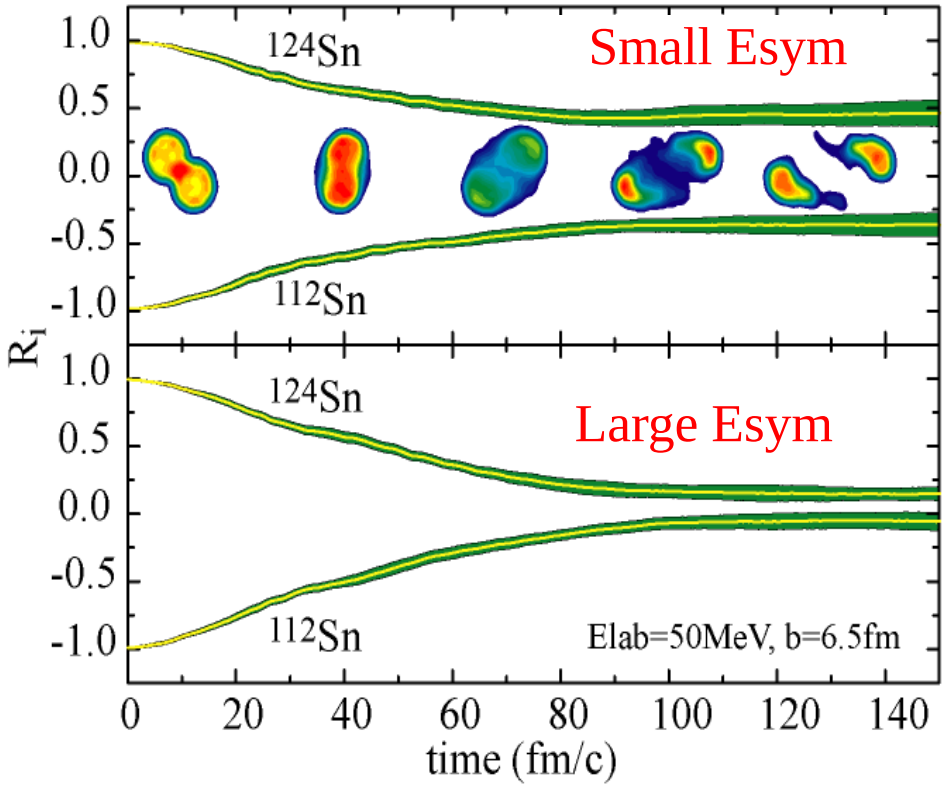
Isospin Diffusion observable to study E_{sym} with Heavy Ion Collisions

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

Tsang et al., PRL 92 (2004) 062701



Tsang, Shi et al., PRL92, 062701(2004)

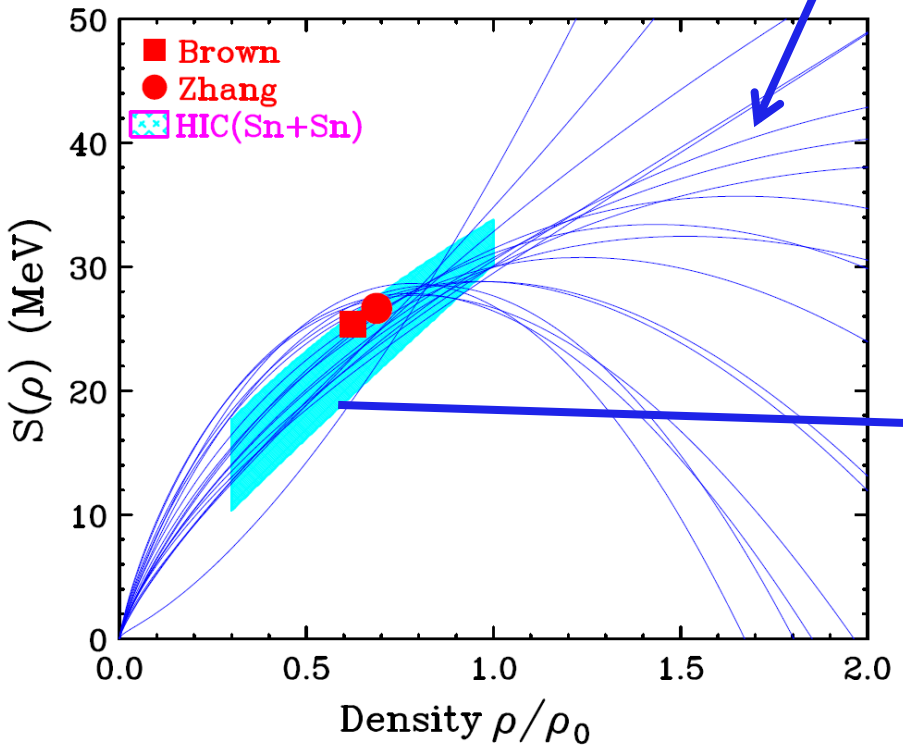


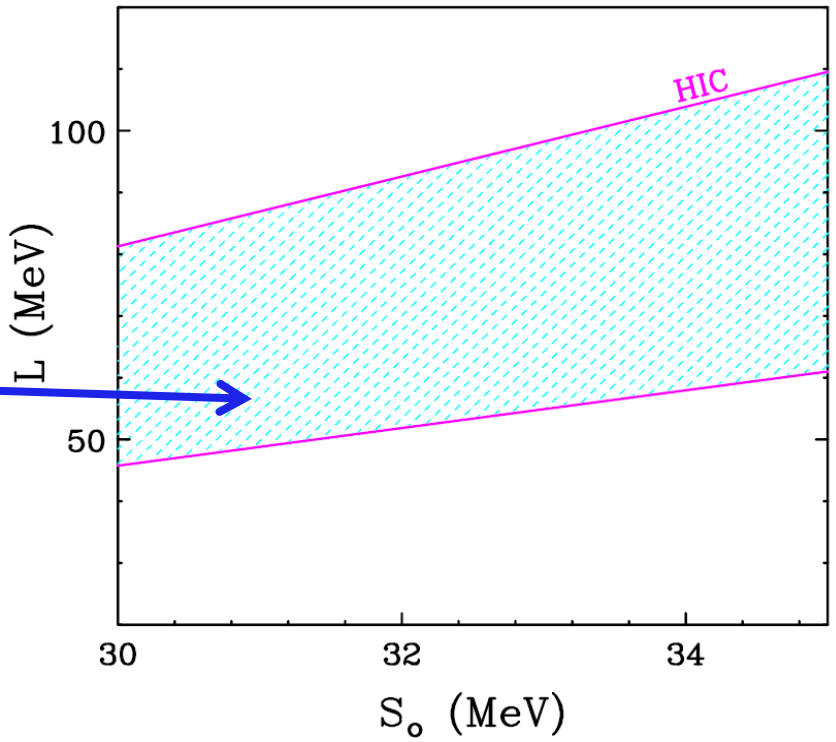
Isospin Diffusion; low ρ, E_{beam}

Bao-An Li et al., Phys. Rep. 464, 113 (2008)
Tsang, Zhang et al., PRL122, 122701(2009)

EoS of asymmetric matter -- Constraints from Heavy Ion Collisions (HIC)

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





B.A. Brown,PRL85(2000)5296
Tsang et al,PRL102,122701(2009)

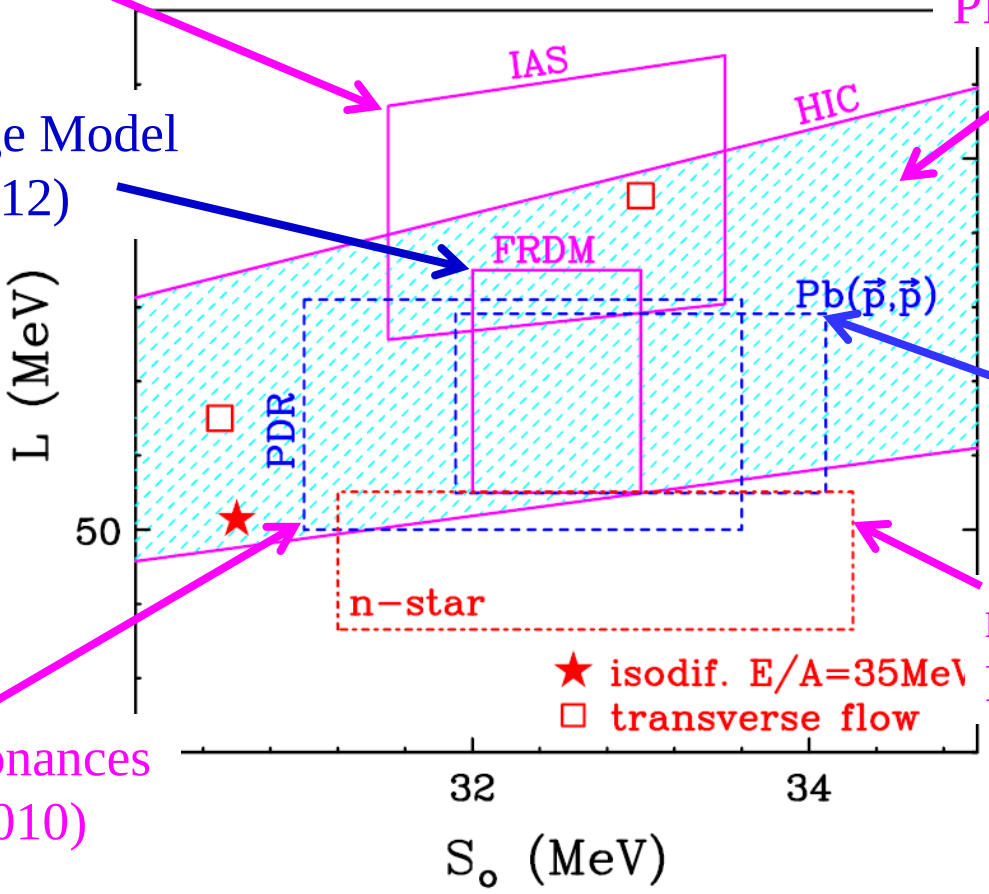
$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2 + \ldots$$

Consistent Constraints on Symmetry Energy from different experiments→ HIC is a viable probe

Isobaric Analogue States
NPA 818, 36 (2009)

heavy ion collisions
PRL 102,122701(2009)

Finite Droplet Range Model
PRL108,052501(2012)



p elastic scattering
PRC82,044611(2010)

neutron-star radius
PRL108,01102(2012)

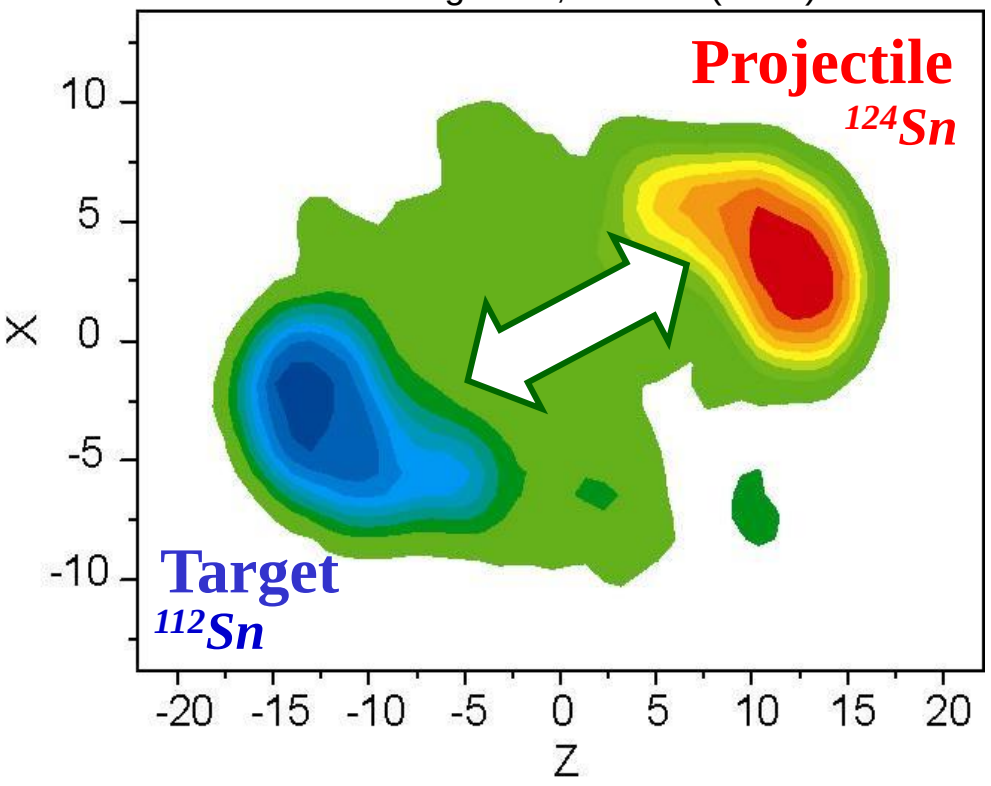
Pygmy Dipole Resonances
PRC 81, 041304 (2010)

Tsang et al. C 86, 015803 (2012)

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

Improve symmetry energy constraints with RIB

Tsang et al., PRL 92 (2004) 062701



$$ID = \vec{j}_n - \vec{j}_p = -\rho D_\delta \vec{\nabla}\delta$$

$\vec{\nabla}\delta$ increases with RIB

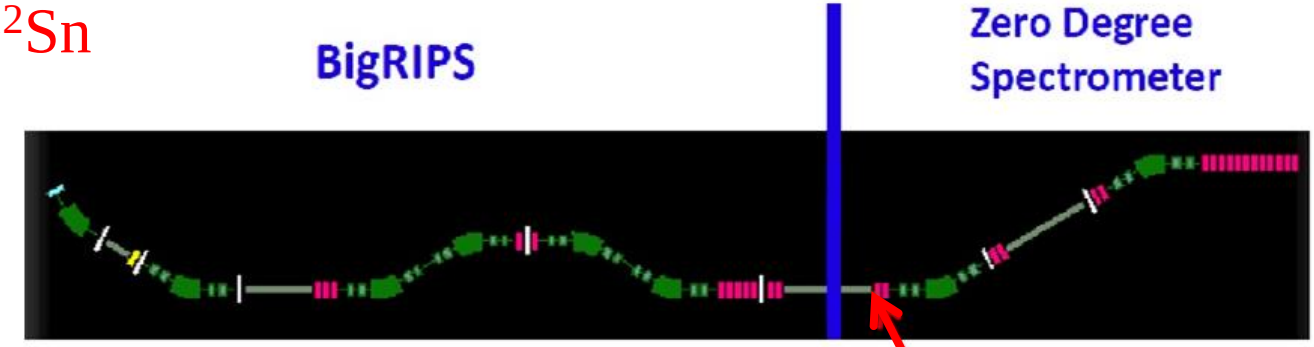
Use Projectile-like fragments as observables

RIKEN experiment NP0709

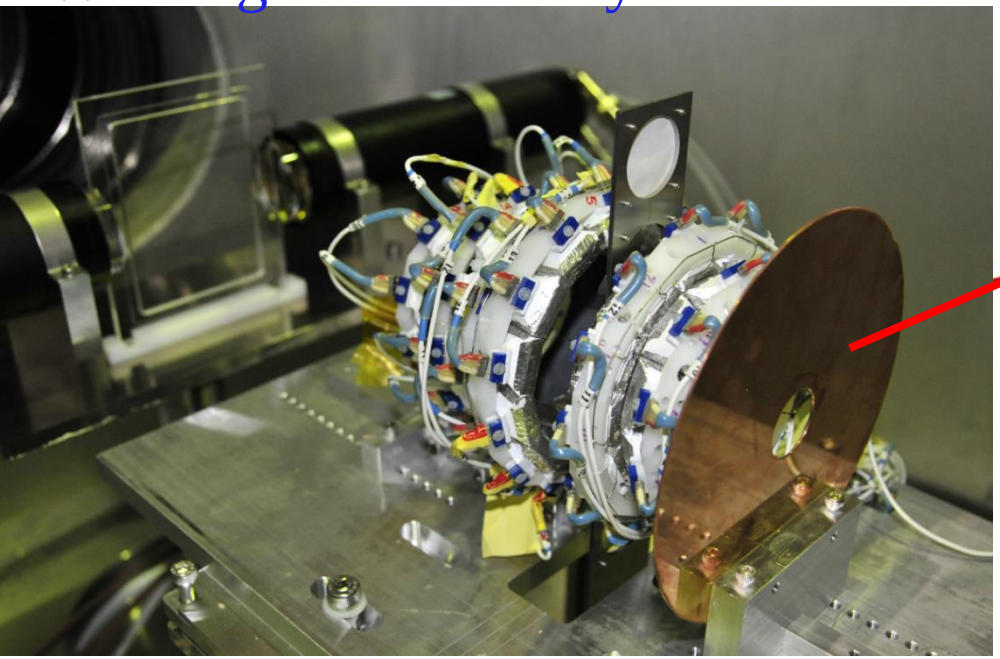
Experiment set up for NP0709

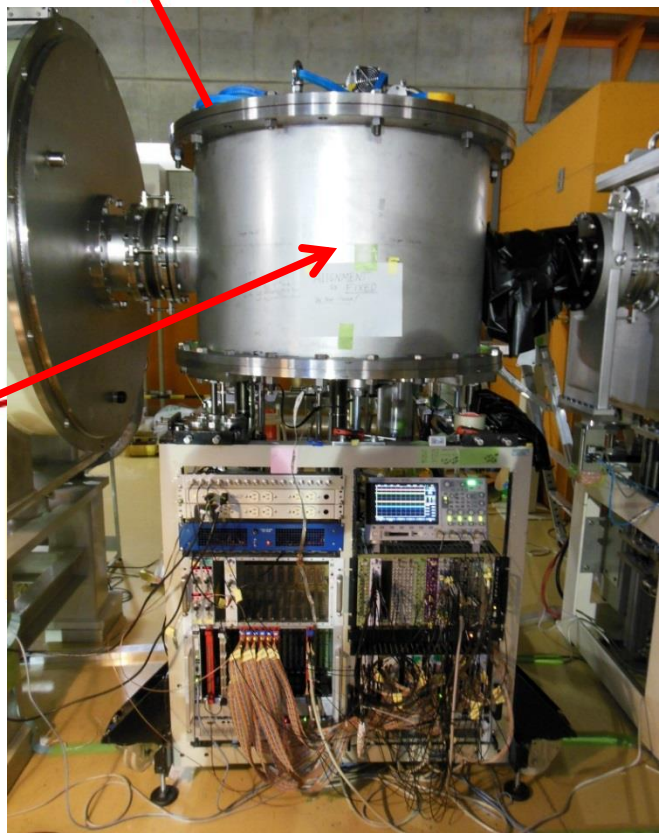
June 11-15, 2013

$^{107}In + ^{124}Sn$
$^{112}Sn + ^{112}Sn$



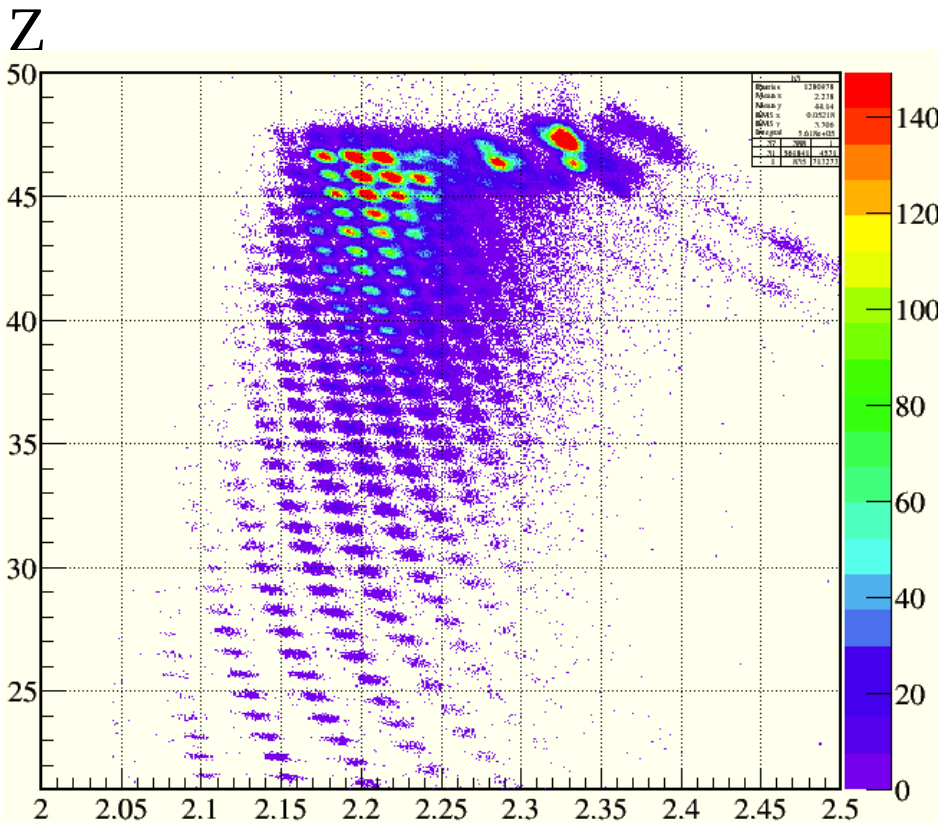
Washington University microball



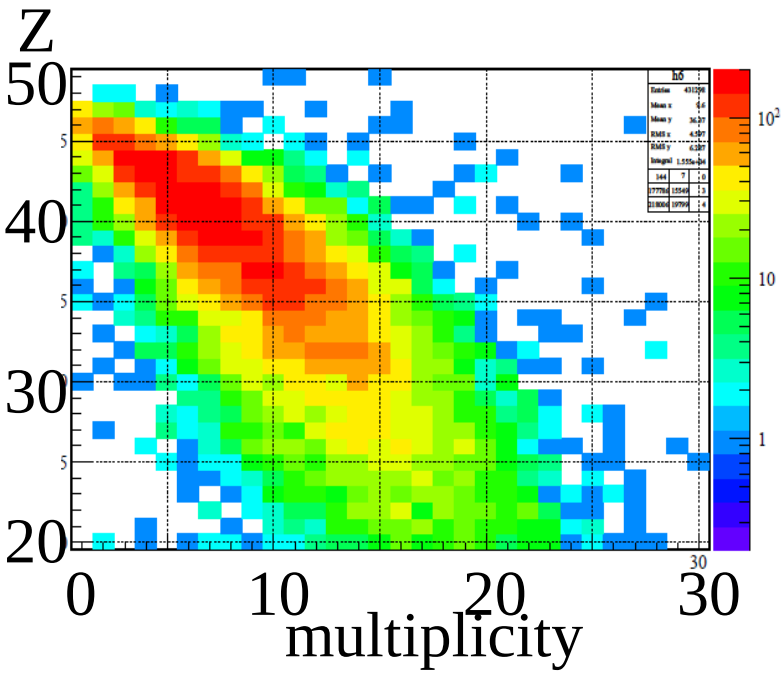


Online Analysis NP0709

June 11-15, 2013



^{107}In + ^{124}Sn (new reaction)
^{112}Sn+^{112}Sn (reference to MSU)

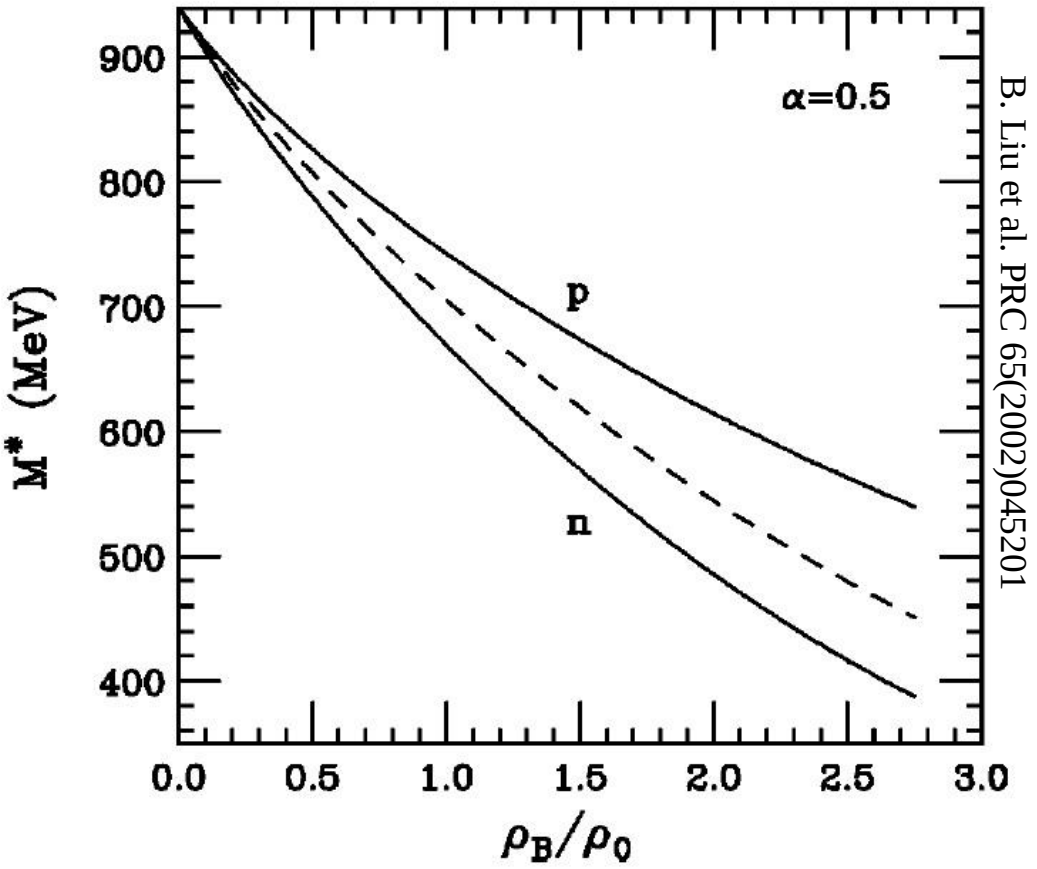


$$R_i(\delta) = 2 \cdot \frac{X - (X^{MSU}_{124+124} + X^{MSU}_{112+112})/2}{X^{MSU}_{124+124} - X^{MSU}_{112+112}}$$

To reduce systematic errors, we must do two reactions (one MSU reference) with exact same set up.

Symmetry energy and effective nucleon mass

$$\frac{m_\tau^*}{m_\tau} = [1 + \frac{m_\tau}{|\mathbf{p}|}\frac{dU_\tau}{d|\mathbf{p}|}]^{-1}_{\mathbf{p}=\mathbf{p}_F^\tau}$$

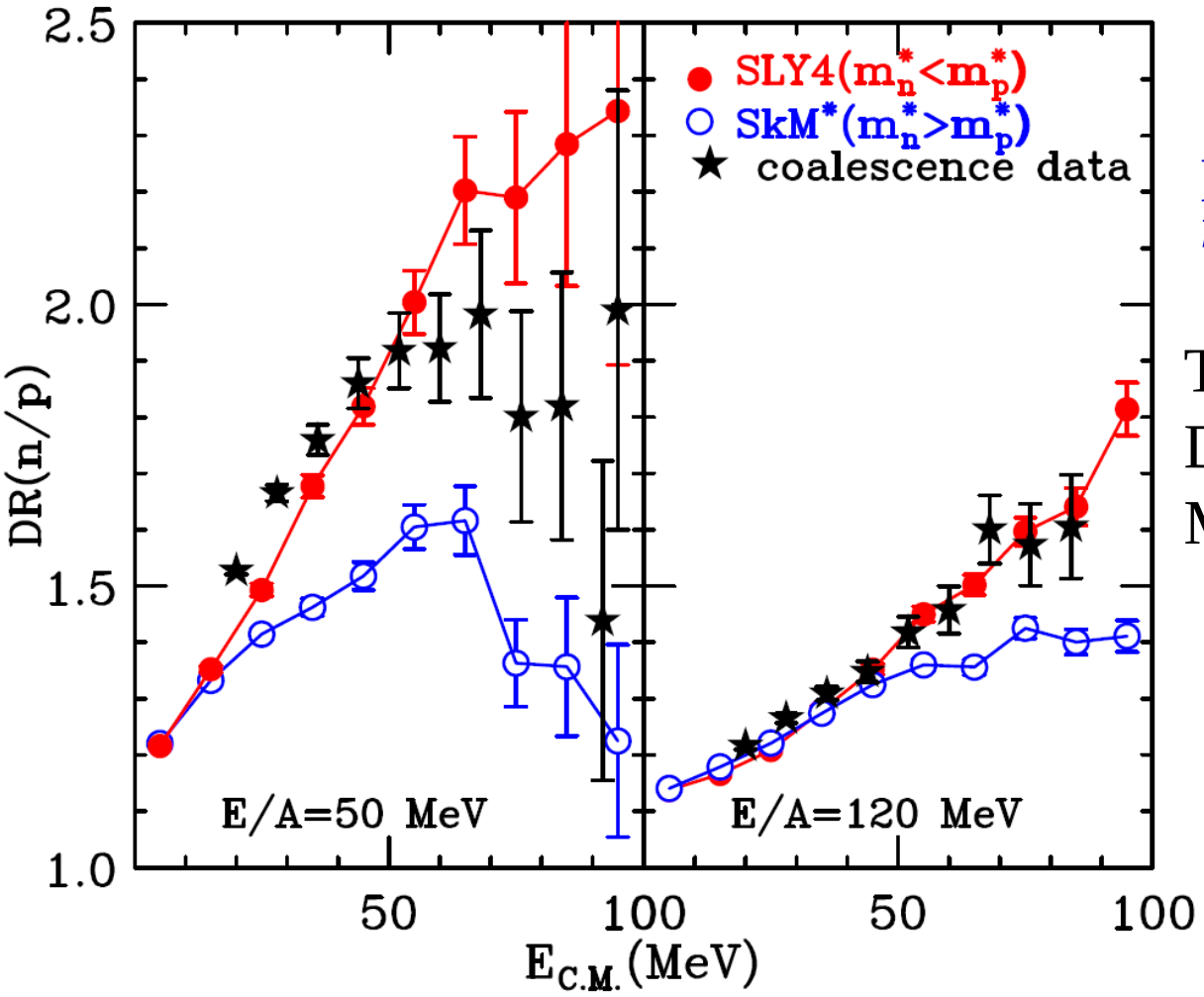


B. Liu et al. PRC 65(2002)045201

Mass splitting increases with density and asymmetry.

Larger effect at high energy?

Data at high energy is consistent with $m_n^* < m_p^*$

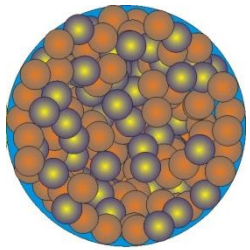


ImQMD05_sky
张英逊 (Y. Zhang)

Thesis data :
Daniel Coupland
Michael Youngs

Double Ratio ⇨ $\frac{^{124}Sn+^{124}Sn;Y(n_c)/Y(p_c)}{^{112}Sn+^{112}Sn;Y(n_c)/Y(p_c)}$ ⇨ minimize systematic errors

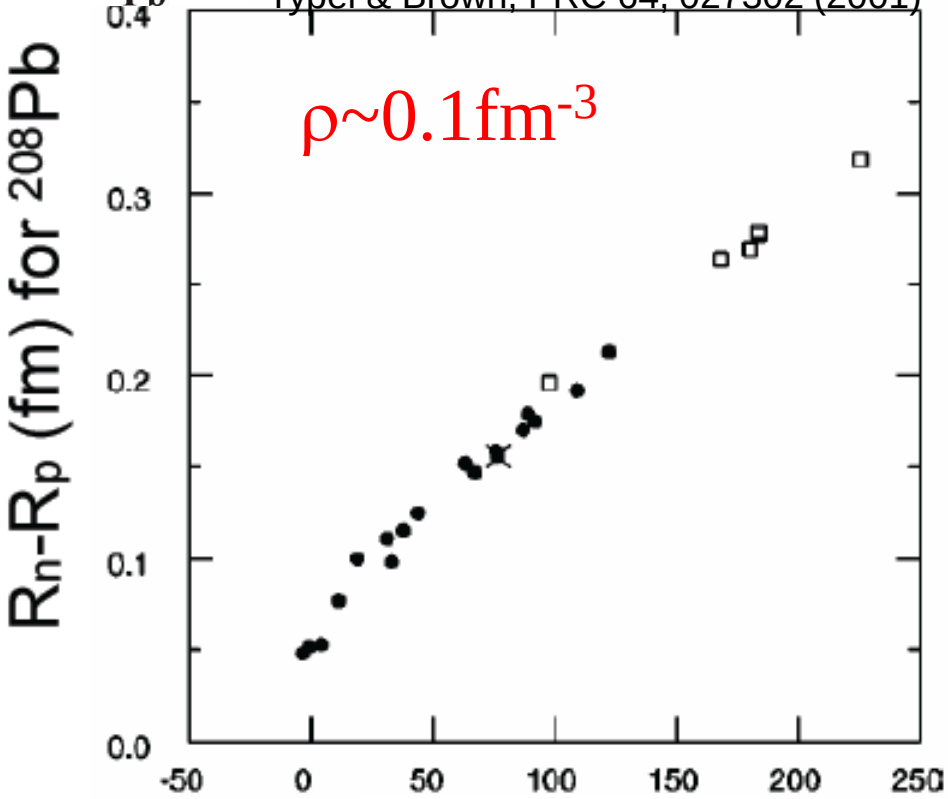
SπRIT

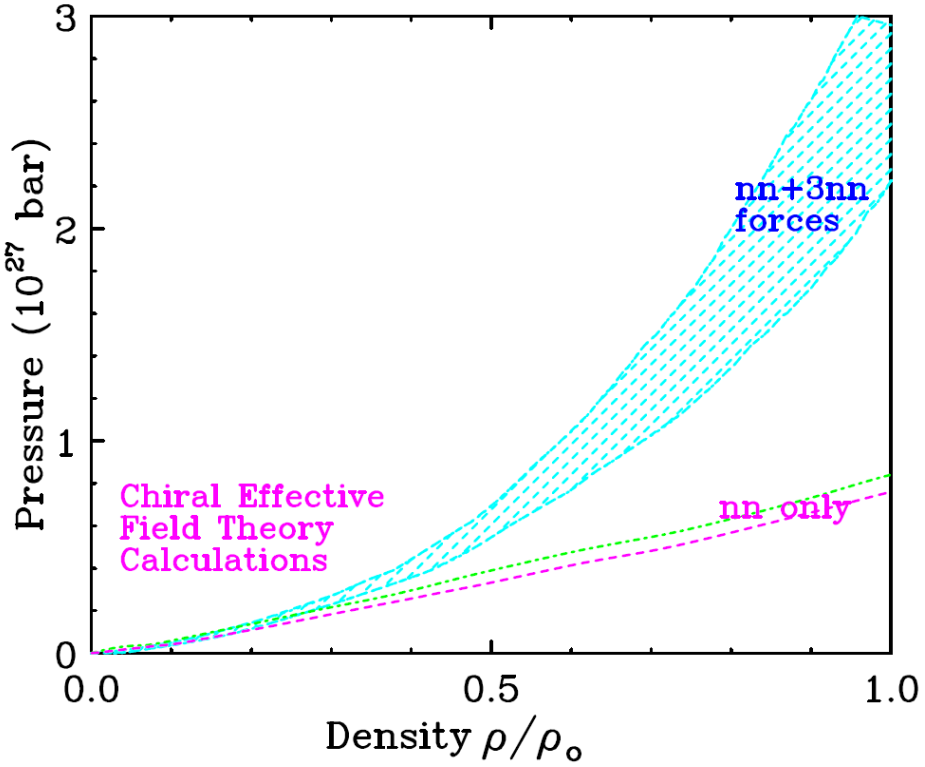


Importance of 3-body neutron-neutron force in the Equation of State of pure neutron matter

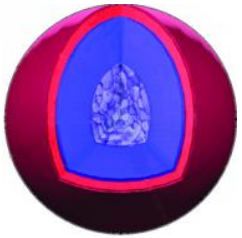
Typel & Brown, PRC 64, 027302 (2001)

$\rho \sim 0.1 fm^{-3}$





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



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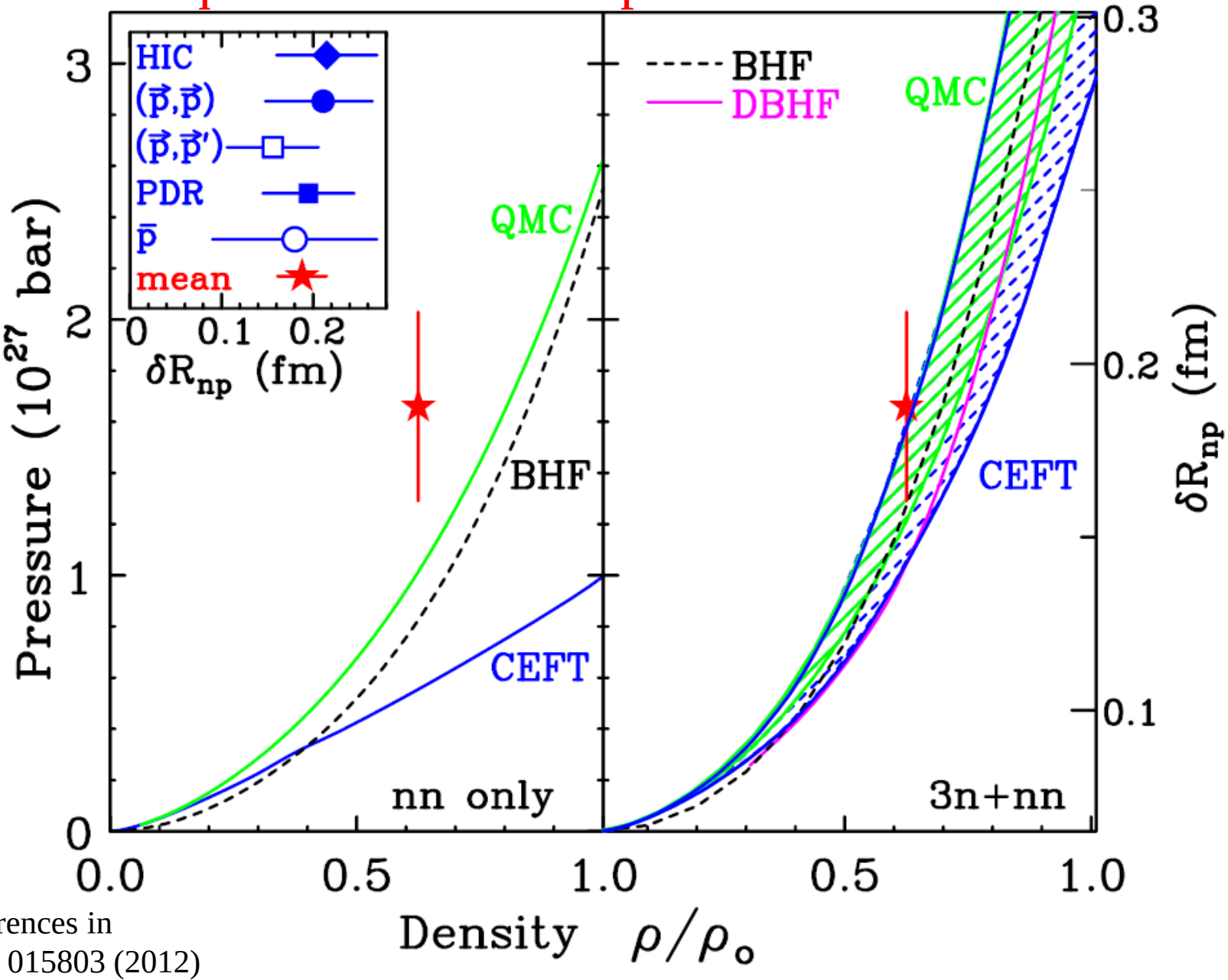
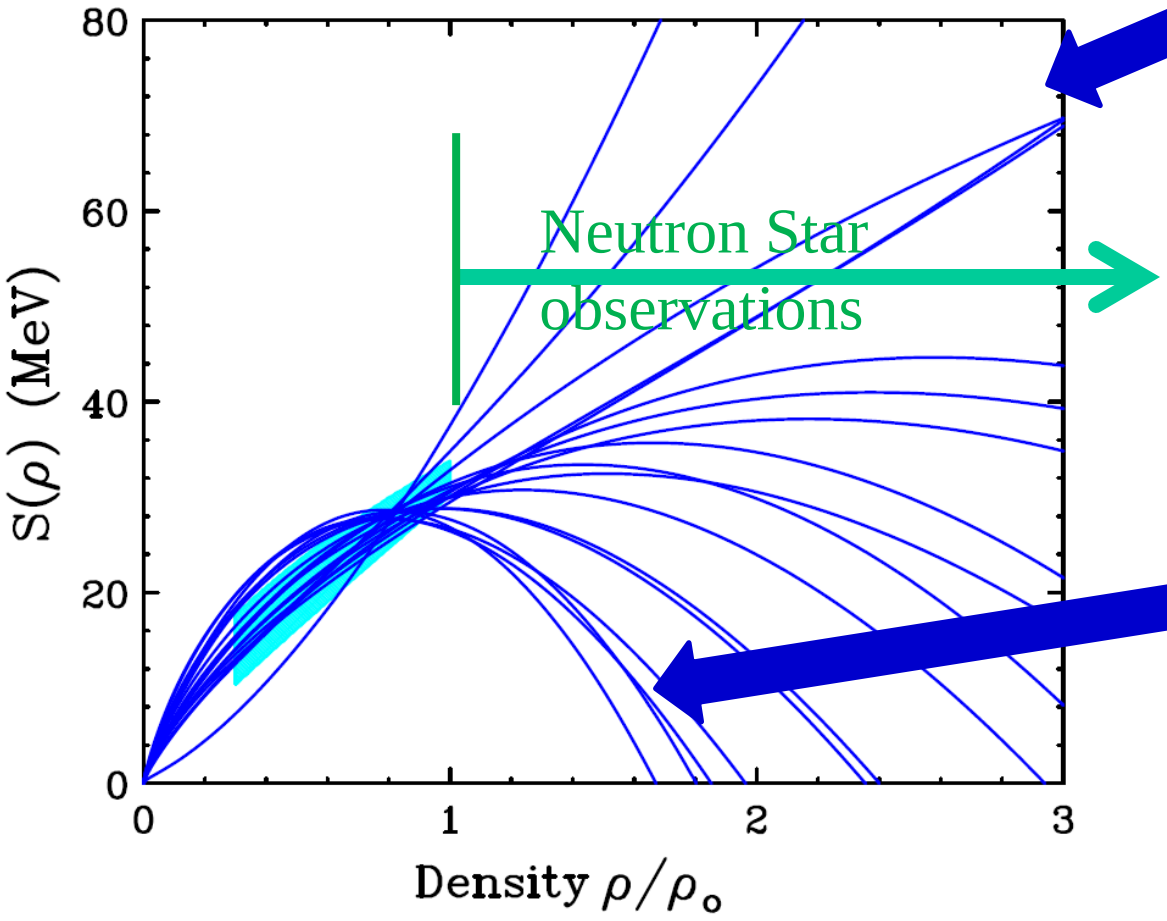
Importance of 3-body neutron-neutron force in the Equation of State of pure neutron matter



See references in
PRC 86, 015803 (2012)

New observations of Neutron Stars



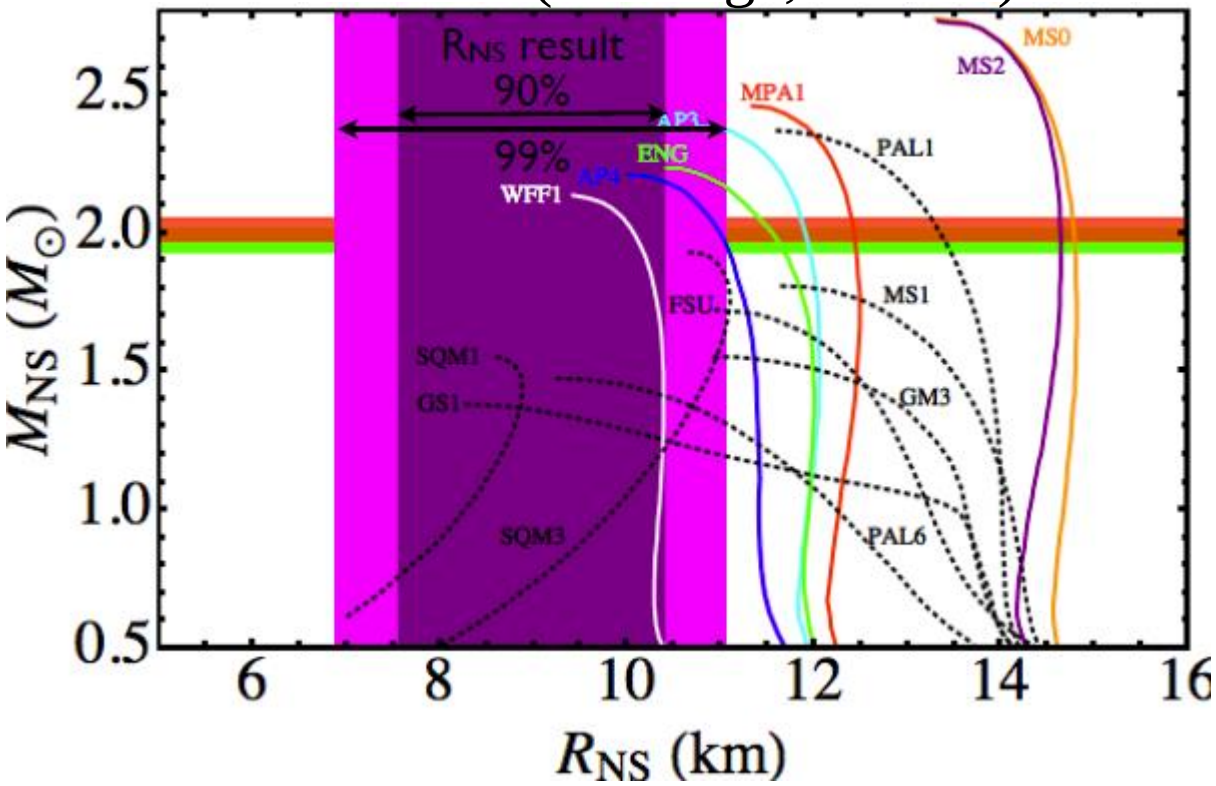
$M_{NS} \sim 2M_{sun}$ →
Large E_{sym} or
stiff EoS at high ρ
→ large radius

$R_{NS} \sim 9$ km →
Small E_{sym} or
Soft EoS at ~$2\rho_0$
→ Small mass

Above saturation density, the symmetry energy density dependence has a different energy dependence than Skyrme interactions.

New NS radius and mass observation suggests exotic form of density dependence of Symmetry energy

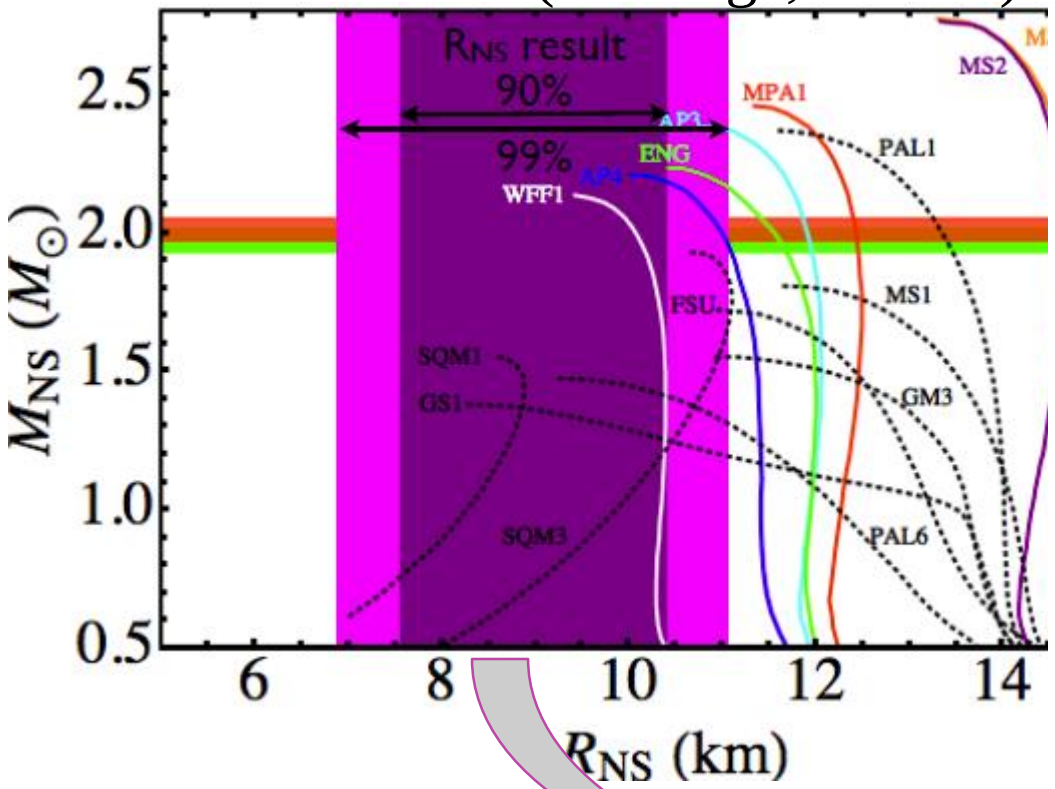
Neutron star radius (Rutledge, Gulliot)



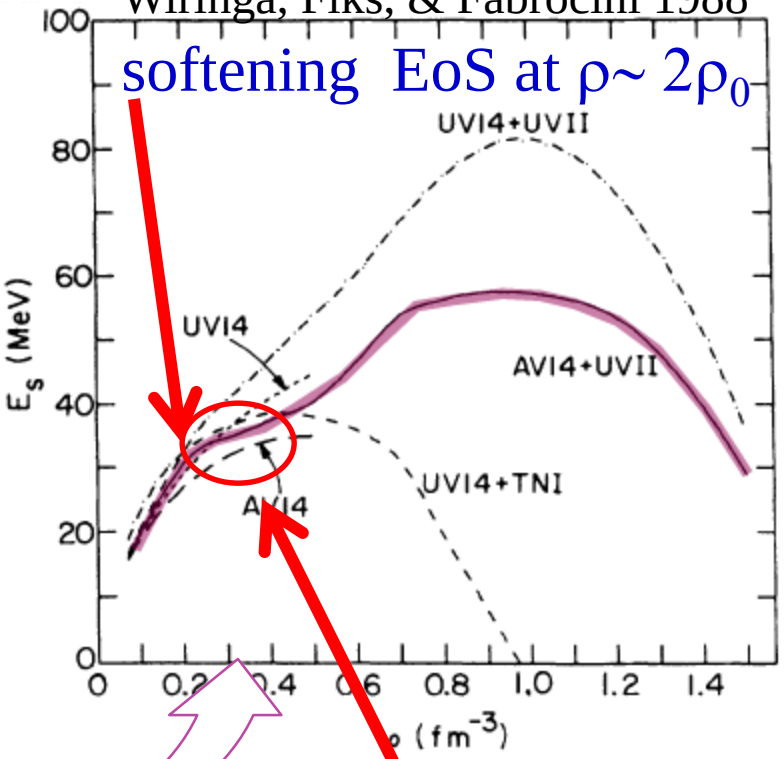
qLMXB

New NS radius and mass observation suggests exotic form of density dependence of Symmetry energy

Neutron star radius (Rutledge, Gulliot)



AV14+UVII
Wiringa, Fiks, & Fabrocini 1988



qLMXB

HIC@$2\rho_0$

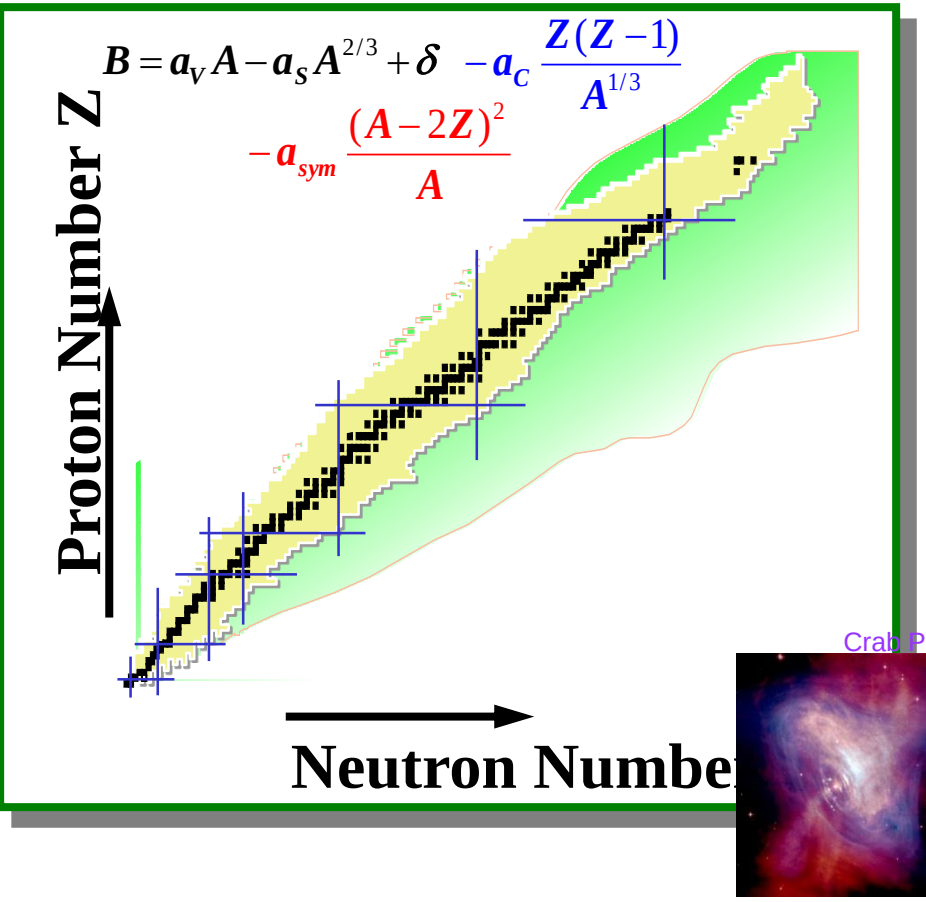
S. Guillot, M. Servillat, N. A. Webb, and R. E. Rutledge, Astrophys. J. 772, 7 (2013), 1302.0023

FRIB

RIKEN NISHINA CENTER

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

Isospin degree of freedom

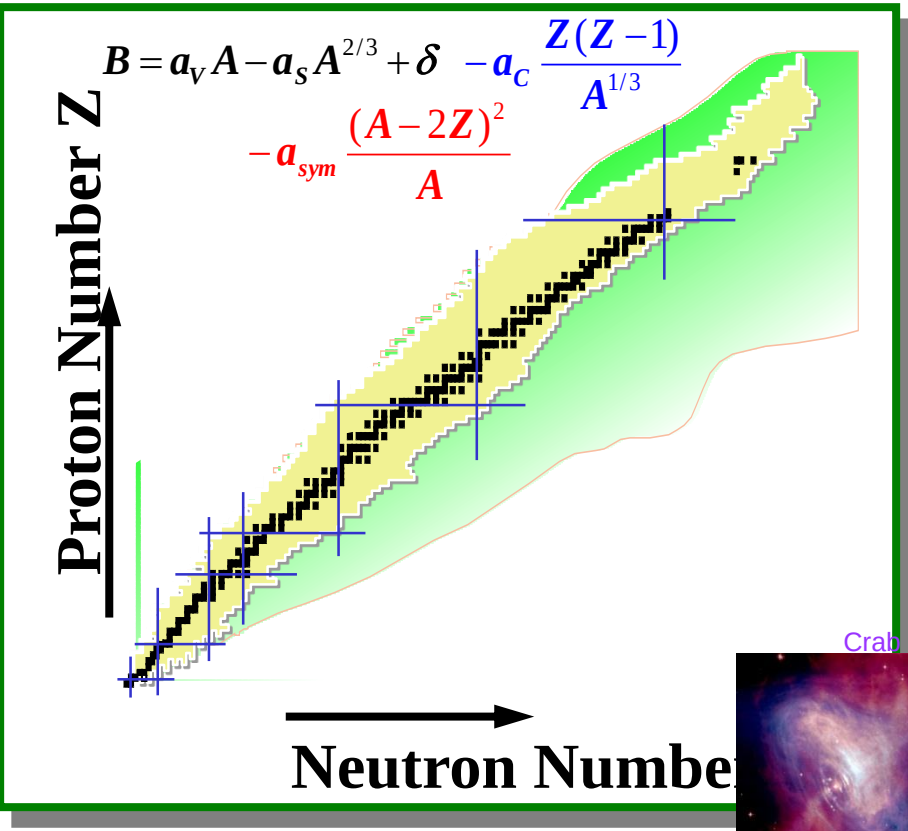


- Vary the N/Z compositions of projectile and targets
  - ^{124}Sn+^{124}Sn, ^{124}Sn+^{112}Sn, ^{112}Sn+^{124}Sn, ^{112}Sn+^{112}Sn
- Measure isospin sensitive observables such as isotope distributinos (isospin diffusion), n/p, t/^{3}He ratios, flow
- Simulate collisions with transport theory
  - *Find the symmetry energy density dependence that describes the data.*
  - *Constrain the relevant input transport variables.*

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

Successful Strategies used to study the symmetry energy with Heavy Ion collisions with RIB

Isospin degree of freedom



- Vary the N/Z compositions of projectile and targets e.g.
  - $^{132}Sn+^{124}Sn$, $^{132}Sn+^{112}Sn$, $^{108}Sn+^{124}Sn$, $^{108}Sn+^{112}Sn$
- Measure isospin sensitive observables such as isotope distributions (isospin diffusion), n/p, t/^{3}He ratios, flow
- Simulate collisions with transport theory
  - *Find the symmetry energy density dependence that describes the data.*
  - *Constrain the relevant input transport variables.*

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

Heavy Ion Collisions at high density with RIB

Old data: Au+Au, E/A=150 to 1500 MeV

Proposed New Experiments at RIB facilities

pi-/pi+		300 MeV & 200 MeV			
Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
132Sn	124Sn	1.64	1.48	1.56	0.16
132Sn	112Sn	1.64	1.24	1.44	0.40
108Sn	124Sn	1.16	1.48	1.32	-0.32
108Sn	112Sn	1.16	1.24	1.20	-0.08
124Sn	124Sn	1.48	1.48	1.48	0.00
112Sn	112Sn	1.24	1.24	1.24	0.00
112Ru	112Sn	1.55	1.24	1.38	0.31
126Sn	112Sn	1.52	1.24	1.38	0.28

Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
132Sn	64Ni	1.64	1.29	1.51	0.35
108Sn	58Ni	1.16	1.07	1.13	0.09

Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
56Ni	58Ni	1.00	1.07	1.04	-0.07
68Ni	64Ni	1.43	1.29	1.36	0.14

6.5 days approved by 2013 June RIKEN PAC
7 days approved by 2013 Dec RIKEN PAC

Similar RIB reactions can be used to study isospin diffusions.

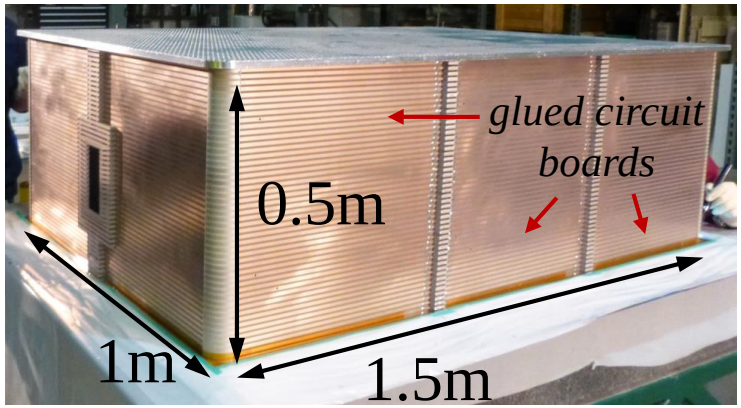
$$ID = \vec{j}_n - \vec{j}_p = -\rho D_\delta \vec{\nabla}\delta$$

ID Increase with $\vec{\nabla}\delta$

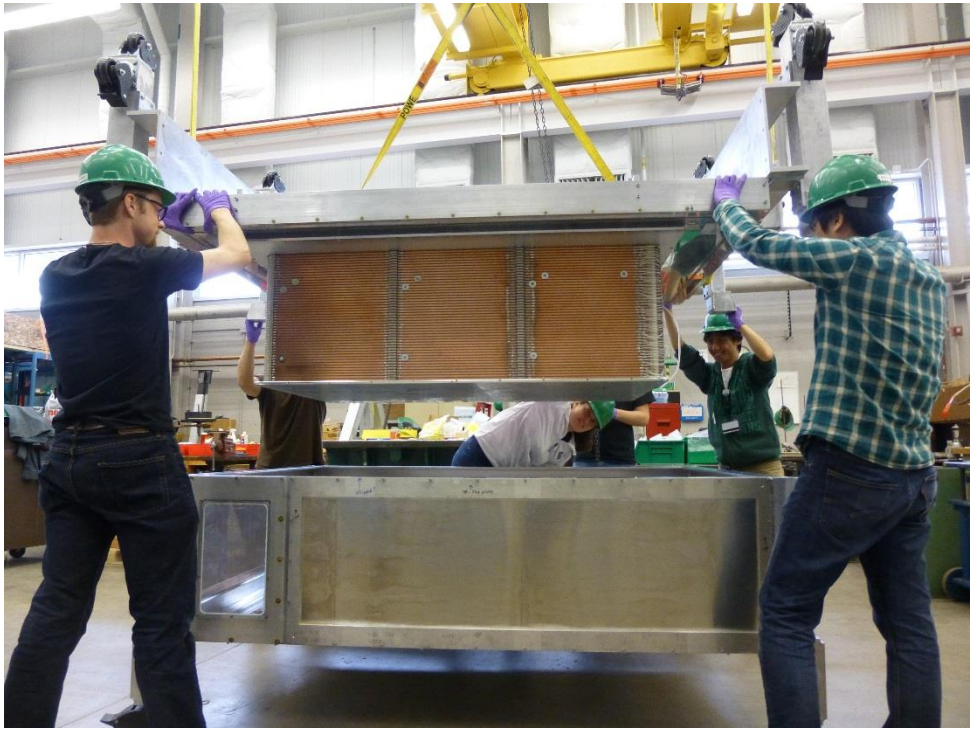
asymmetry gradient

Construction status

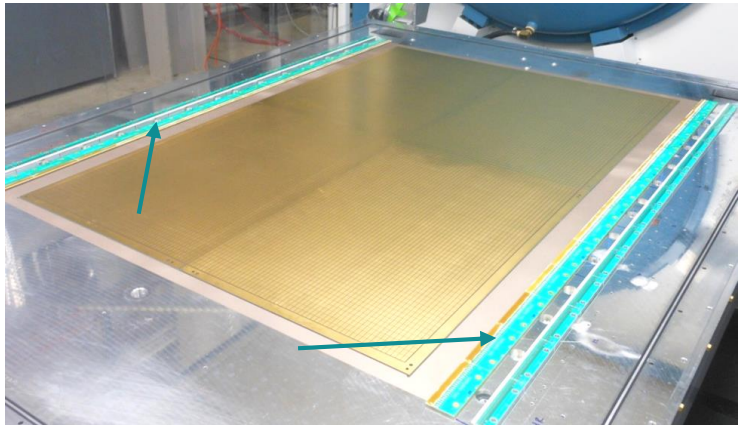
Gluing field cage together, Feb 2013



Assembled for initial testing, May 2013



Pad and wire planes, March 2013



12000 pads (8mm x12mm)
3500 wires

Go! SπRIT Go!

Ship to RIKEN, Japan in early 2014

Testing with state of the art -- GET prototypes (General Electronics for TPC)

10.5 bit dynamic range
1KHz – 10Gb/s

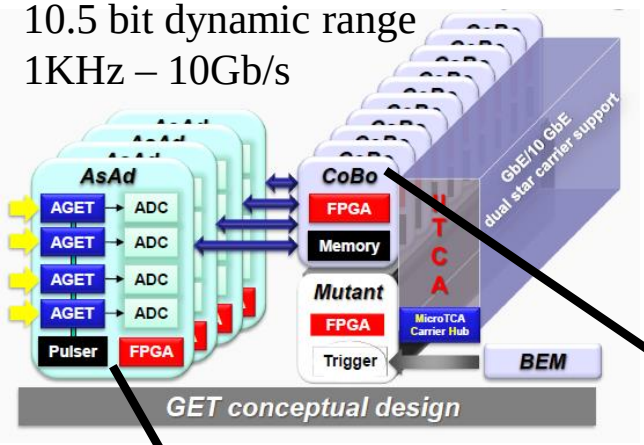
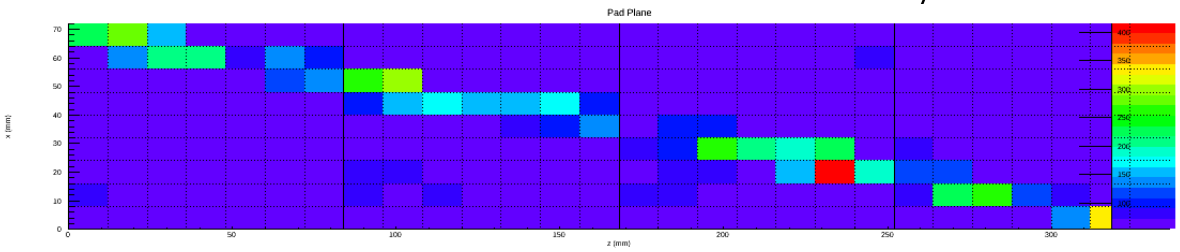
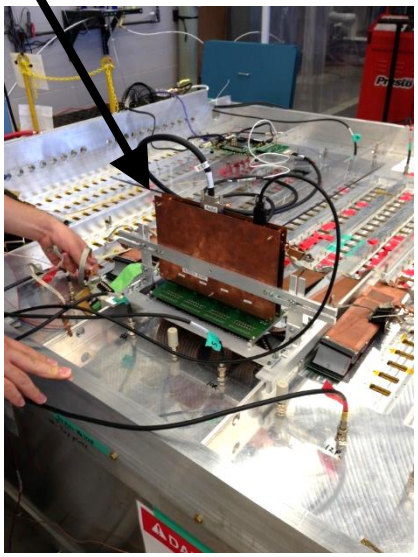
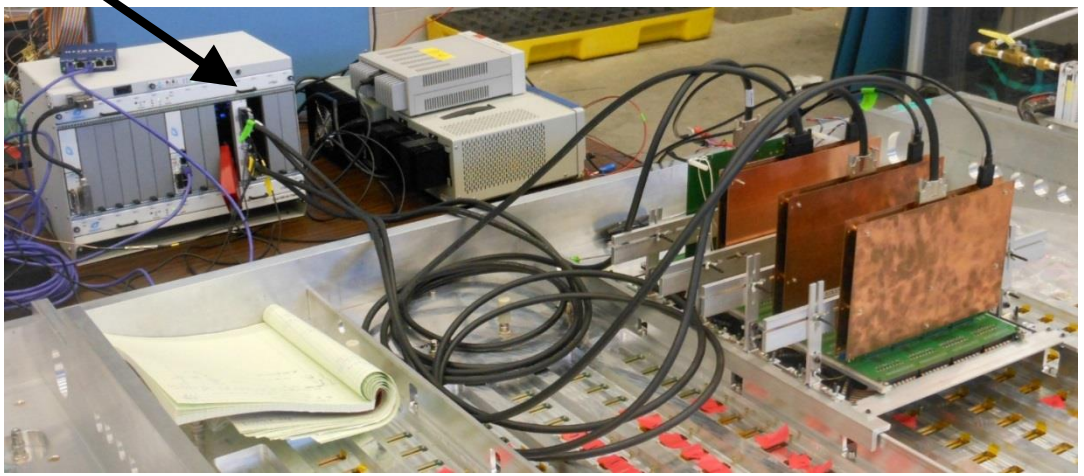


Figure courtesy of GET collaboration.

Pads that "see" cosmic ray







Testing with 1024 channel GET (1 CoBo (Concentration Board)+4AsAd (ASIC &ADC) at 1.2 GB/s ➔ taking 1000 four Magapixel digital photos per second.

Schedule

January 2014	Shipment of TPC to RIKEN
Spring 2014	Setup and testing of TPC/electronics
Summer 2014	Installation into SAMURAI magnet
Spring 2015?	Commissioning and first experiments (6.5 + 7 days Sn+Sn approved)

Collaboration members

United States: J. Barney, Z. Chajecki, P. Danielewicz, J. Estee, M. Famiano, U. Garg, W. Lynch, A. McIntosh, R. Shane, M. B. Tsang, S. Tangwancharoen, G. Westfall, S. Yennello, M. Youngs

Japan: K. Ieki, T. Isobe, T. Murakami, J. Murata, Y. Nakai, N. Nakatsuka, S. Nishimura, A. Ono, H. Sakurai, A. Taketani

China: F. Lu, R. Wang, Z. Xiao, Y. Zhang

United Kingdom: M. Chartier, R. Lemmon, W. Powell

France: E. Pollacco

Italy: G. Verde

Korea: B. Hong, G. Jhang

Poland: J. Lukasik

Special thanks

NSCL staff: J. Yurkon, D. Bazin, J. Pline, and many others

HiRA group students: R. H. Showalter, J. Winkelbauer

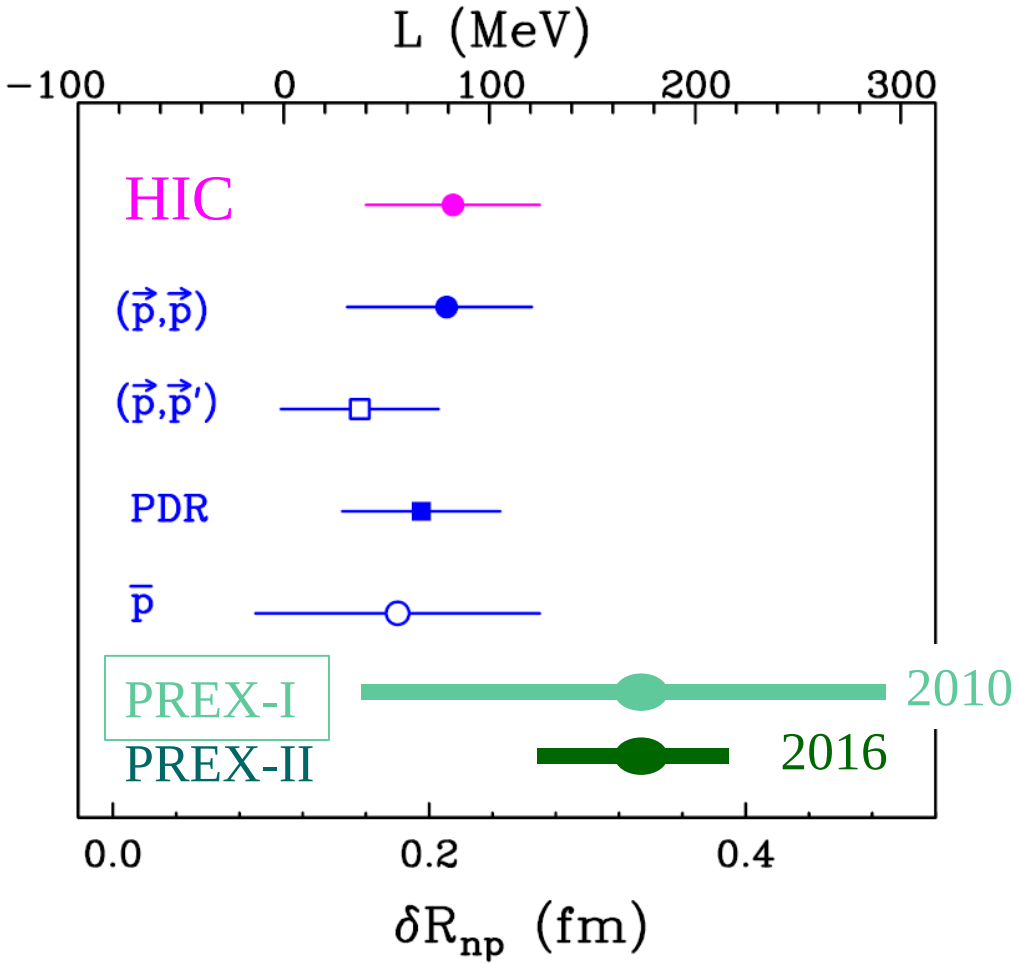
TAMU staff: R. Olsen

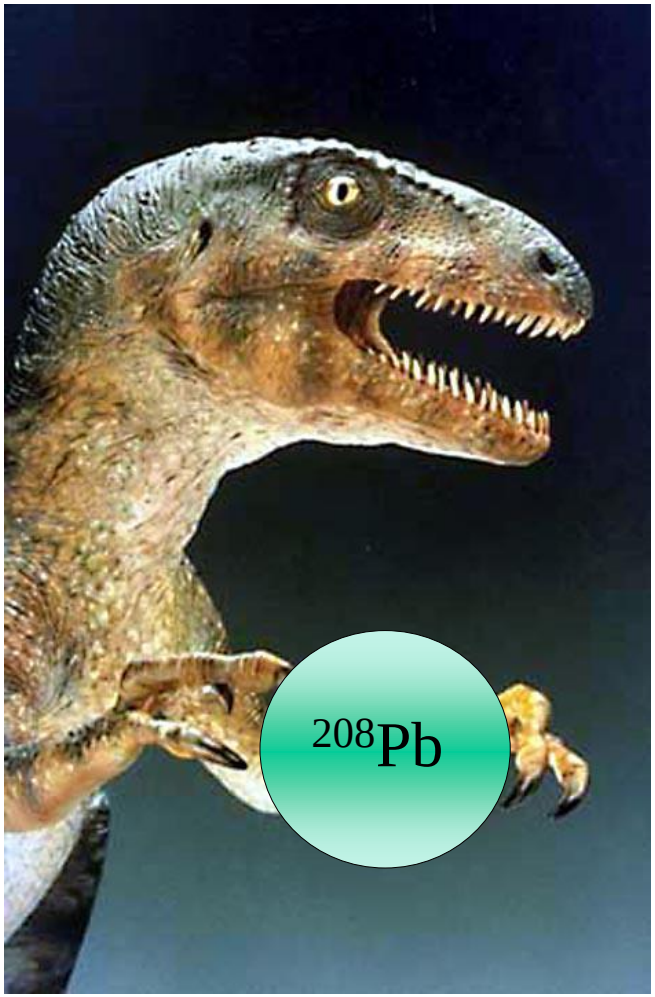
Summary

- The Equation of State is critical to our understanding on
  - Nuclear force;
  - Nuclear structure;
  - Neutron star properties
- Consistent constraints on the symmetry energy obtained at sub-saturation densities implies that
  - Same strategies to use collisions of RIB to study the EoS of asymmetric matter can be applied to high density.
- New observations of neutron star radius (~9Km) and masses (2solar) suggest a softening of EoS ~$2\rho_0$
  - Unique opportunity at RIKEN

Go East!

PREX vs. HIC experiments



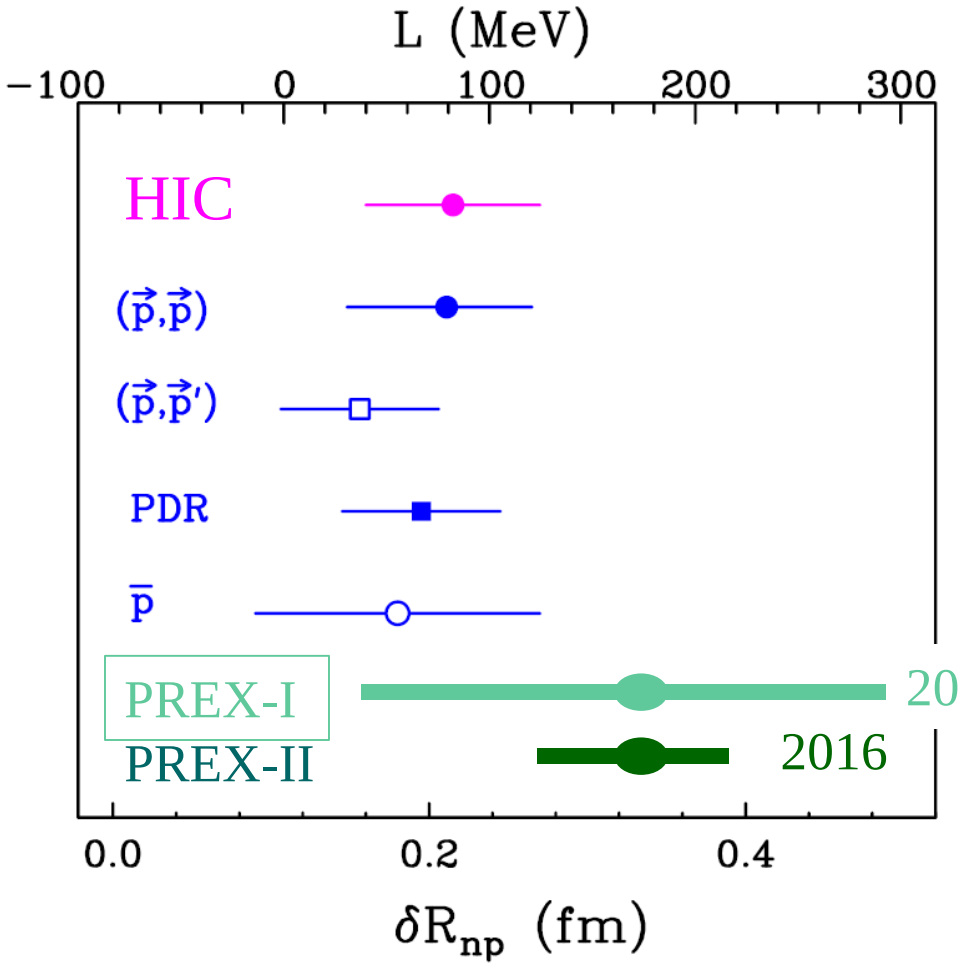


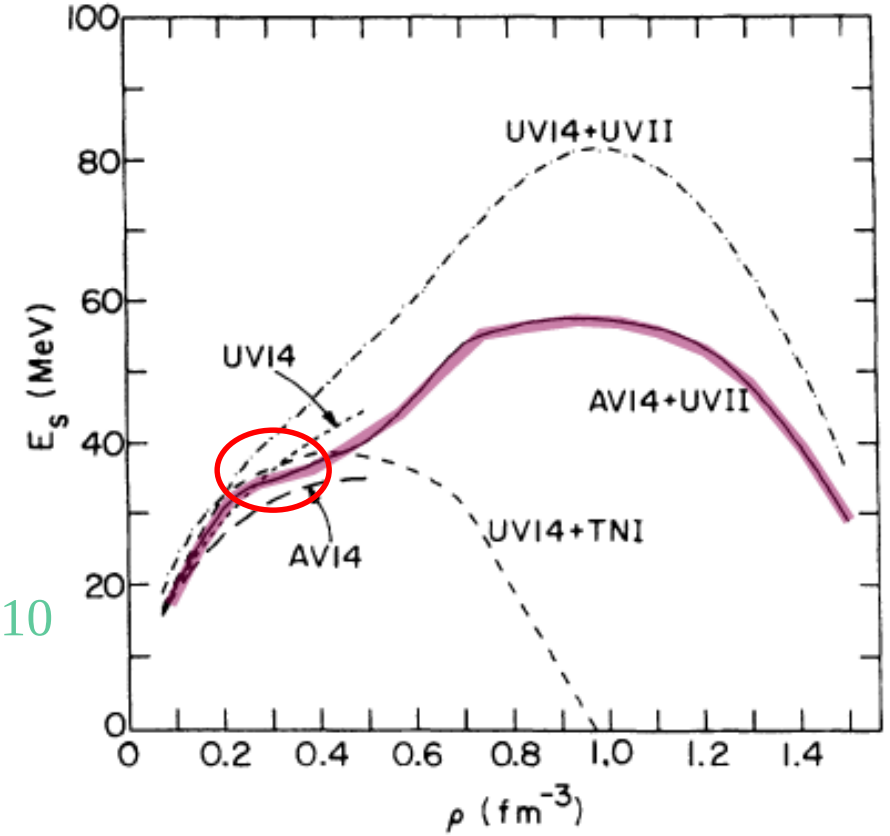
PREX-I: 0.33 + 0.16 - 0.18 fm

PREX-II: 0.33+0.06-0.06 fm (2016)

2 months Jlab beam time

PREX vs. HIC experiments

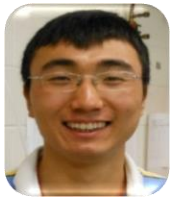




PREX-I: 0.33 + 0.16 - 0.18 fm
PREX-II: 0.33+0.06-0.06 fm (2016)
2 months Jlab beam time

SE@$2\rho_0$ will require strong support from RIKEN community

Thank you, JUSEIPEN



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