Probing symmetry energy using SAMURAI

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Symmetry energy

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2$$

$$\delta \equiv (\rho_n - \rho_p)/\rho$$

$$E_{stm}(\rho) \equiv \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial\delta^2}\bigg|_{\delta=0} = E(\rho,1) - E(\rho,0)$$

Constraining the symmetry energy at supra-saturation densities $\rho \approx 2\rho_0$.

$$K_0 = 9\rho_{\rm sat} \frac{d^2 E(\rho, 0)}{d\rho^2}\bigg|_{\rho=\rho_{\rm sat}},$$

$$J = S(\rho_{\rm sat}), \quad = a_{sym}$$

$$L = 3\rho_{\rm sat} \frac{dS(\rho)}{d\rho}\bigg|_{\rho=\rho_{\rm sat}},$$

$$E(\rho, \delta) = E(\rho, 0) + S(\rho)\delta^2 + \mathcal{O}(\delta^4),$$

$$S(\rho) = S(\rho_{\rm sat}) + L\epsilon + \frac{K_{\rm sym}}{2}\epsilon^2 + \mathcal{O}(\epsilon^3),$$

Incompressibility of symmetric nuclear matter

Around saturation density ρ_0

231 ± 5 MeV ← TAMU GMR

Youngblood et al. PRL 82 (1999) 691.

Inclusion of recent RCNP ISGDR data

Uchida et al. P.L. B557 (2003) 12.

$$K_0 \approx 215 MeV$$

At $2\rho_0 < \rho < 5\rho_0$

210～300 MeV

←Flow analysis

see Danielewicz et al. Science 298 (2002) 1592.

Transverse flow F

From high energy

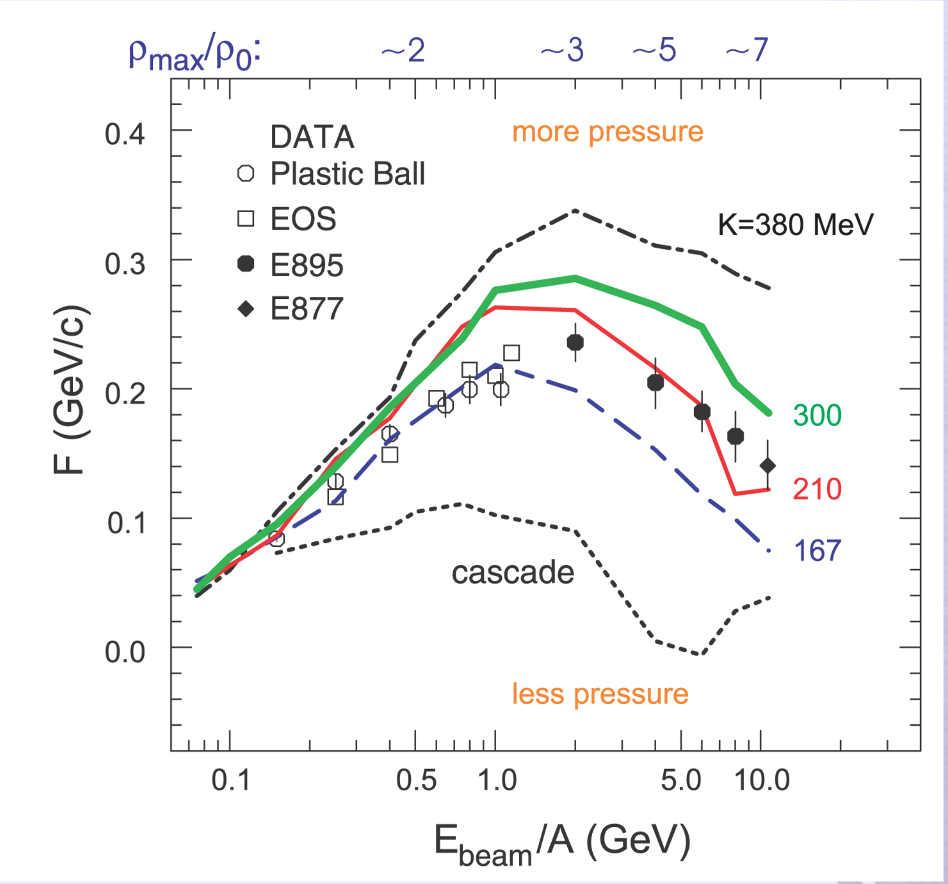
Au+Au collision

(b=5-7 fm)

$$F = \left. \frac{d\langle p_x / A \rangle}{d(y / y_{cm})} \right|_{y/y_{cm}=1}$$

Lines are transport theory

(without and with mean field)



Symmetry Energy around normal density

Through GMR

$$E_{ISGMR} = \left(K_A / m\langle r^2 \rangle\right)^{1/2}$$

$$E_{ISGDR} = \left((7/3)\left(K_A + 27/25\varepsilon_F\right)/m\langle r^2 \rangle\right)^{1/2}$$

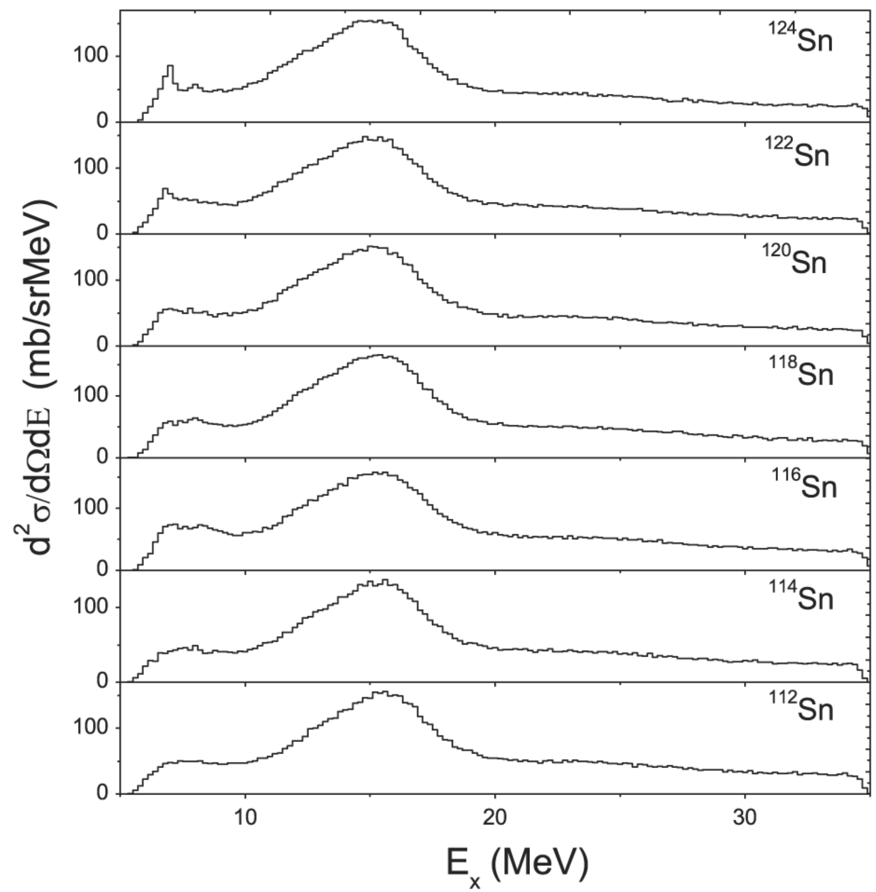


FIG. 1. Excitation-energy spectra for all even-*A* Sn isotopes, obtained from inelastic α scattering at $\theta_{\text{lab}} = 0.69°$.

T.Li et al., Phys. Rev. Lett. 99 162503 (2007)

$$K_A \sim K_{\text{vol}}(1 + cA^{-1/3}) + K_\tau[(N - Z)/A]^2 + K_{\text{Coul}} Z^2 A^{-4/3}.$$

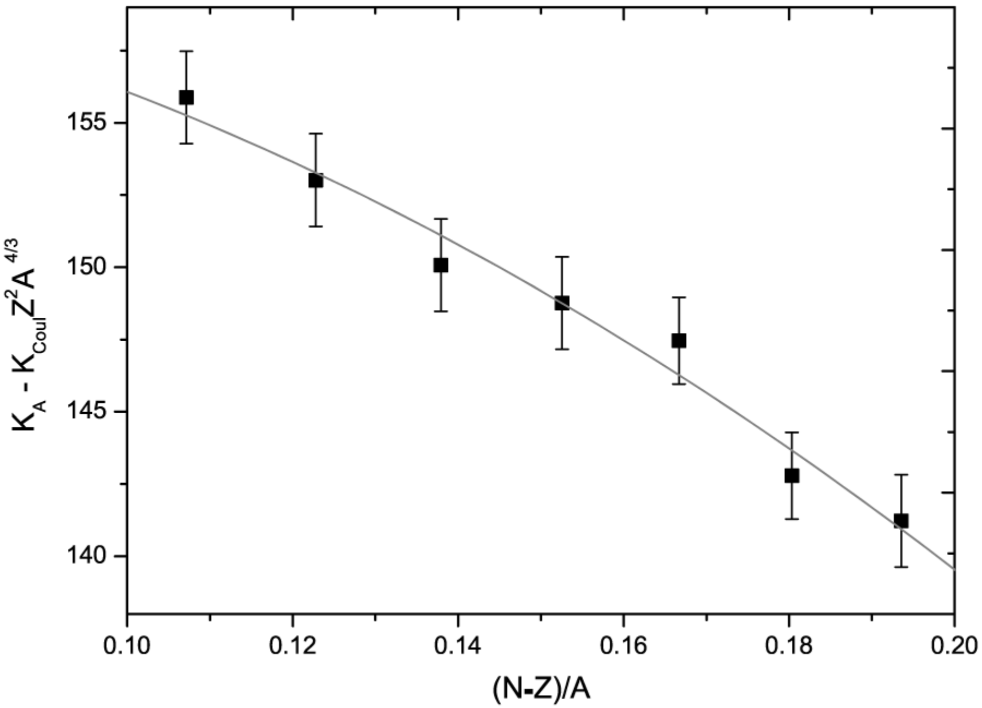
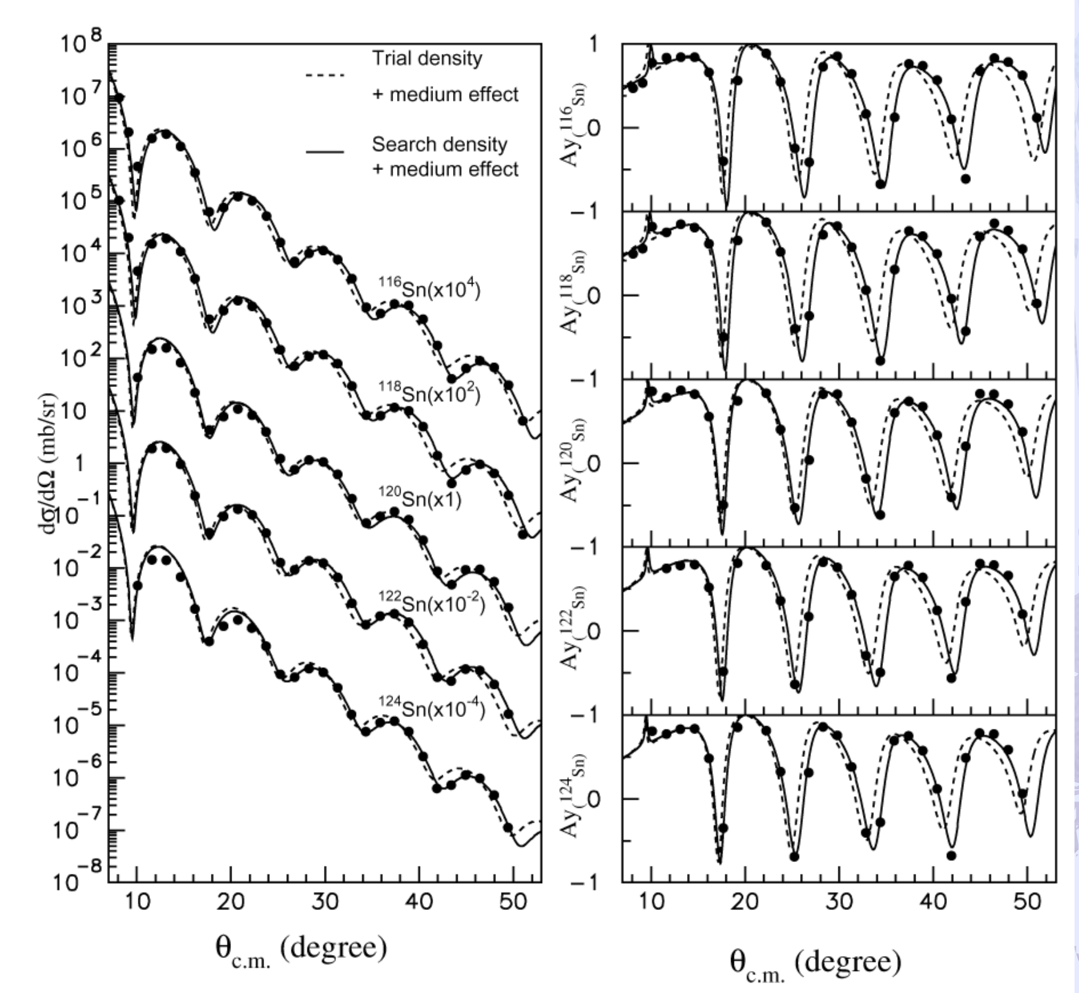


FIG. 4 (color online). Systematics of the difference $K_A - K_{\text{Coul}} Z^2 A^{-4/3}$ in the Sn isotopes as a function of the "asymmetry parameter" $[(N - Z)/A]$; $K_{\text{Coul}} = -5.2$ MeV [33]. The solid line represents a least-squares quadratic fit to the data.

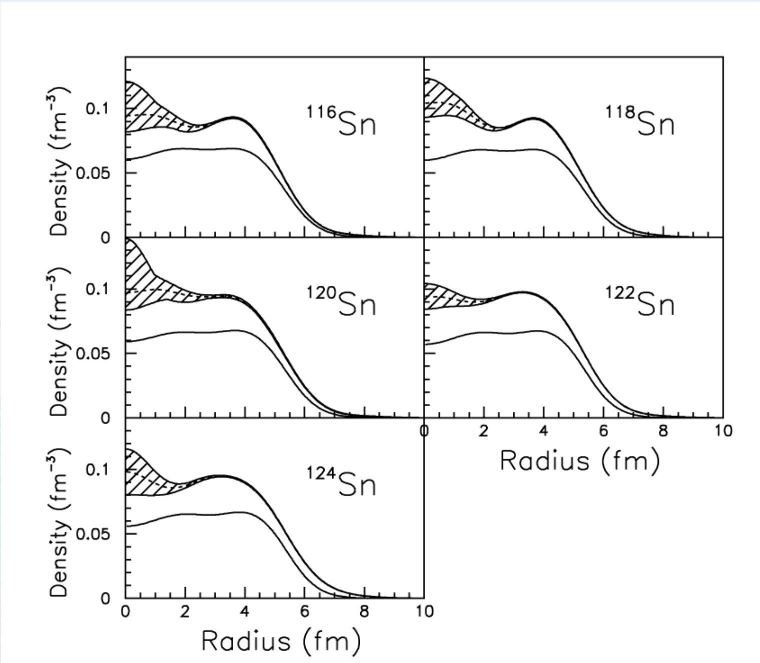
$$K_\tau = -550 \pm 100 \text{ MeV}$$

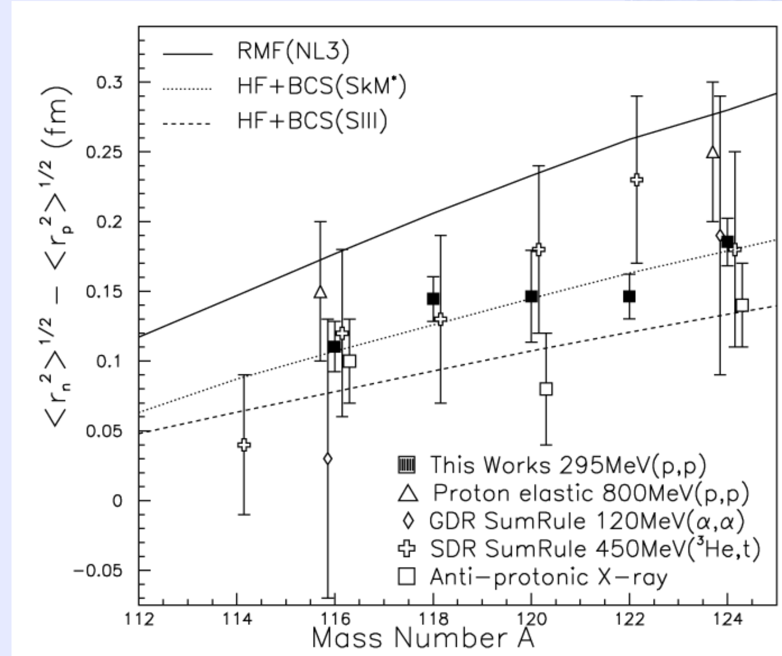
Symmetry Energy around normal density

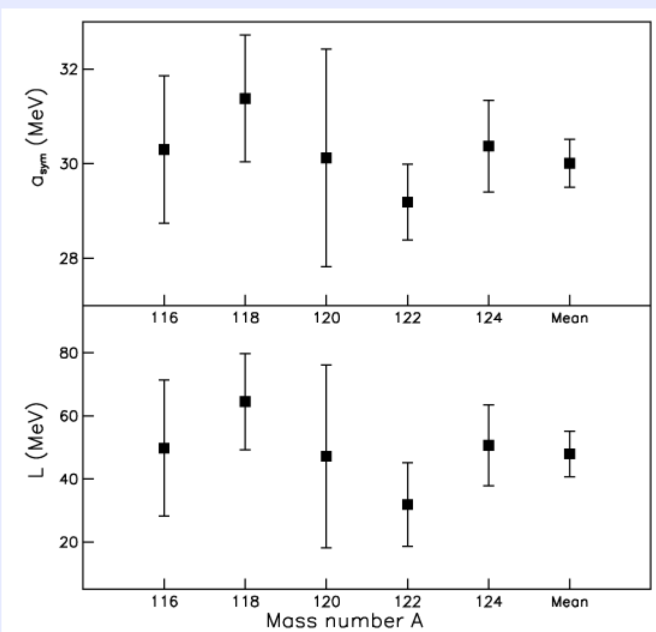
Through proton elastic scattering at 295MeV



S. Terashima , PhD. Thesis 2008







$$a_{\rm sym} = 30.0\,^{+0.5}_{-0.4} \pm 2.0_{\rm sys.}\ ({\rm MeV})$$

$$L = 47.9\,^{+7.2}_{-7.9} \pm 15.0_{\rm sys.}\ ({\rm MeV})$$

Do we know enough about EOS then?

- Asymmetric Nuclear Matter around saturation density

  We learnt some from structure of neutron-rich nucleus, but …..

  B.A. Brown,
  Phys. Rev. Lett. 85 (2000) 5296.

  Precise measurement of neutron Radius in ^{208}Pb

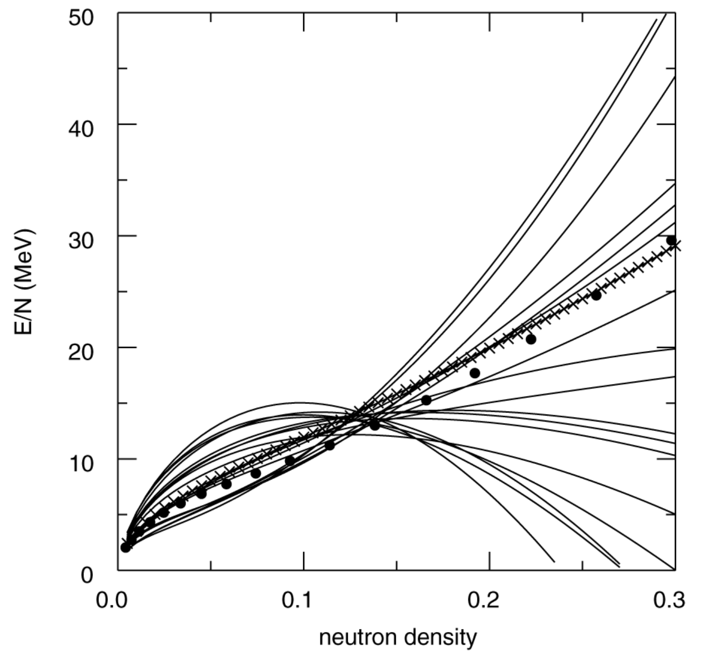


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Why do we have to know symmetry energy?

Density, radius and proton fraction of neutron stars strongly depends on it!!!!

Lattimer and Prakash,
APJ 550 (2001) 426.

$$e_{sym}(\rho) = (2^{2/3}-1)\frac{3}{5}E_F^0\left[u^{2/3}-F(u)\right]+e_{sym}(\rho_0)F(u)$$

$$F(u)=\frac{2u^2}{1+u}$$

$$F(u)=u$$

$$F(u)=u^{1/2}$$

$$u \equiv \rho/\rho_0$$

soft

E^0_F: Fermi energy

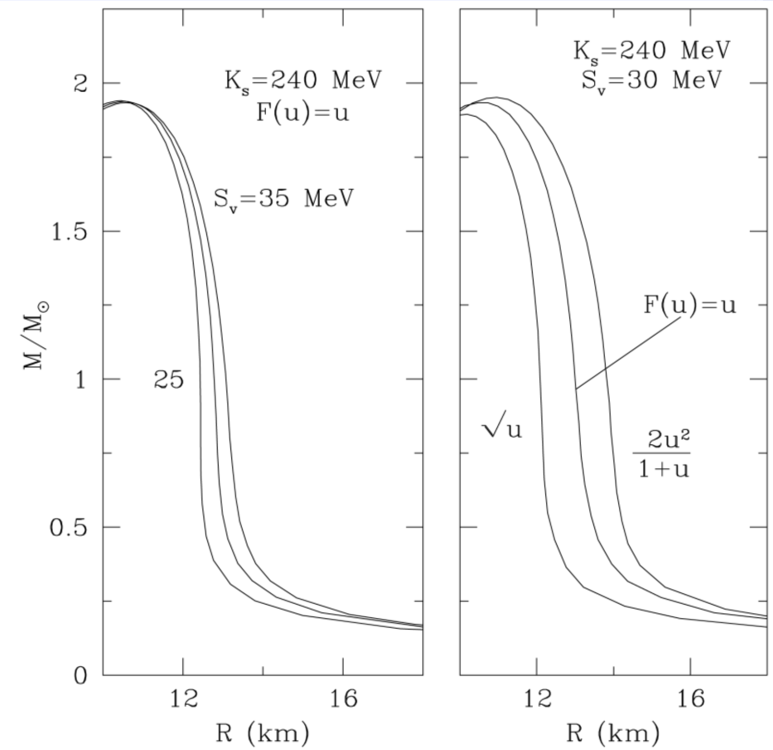
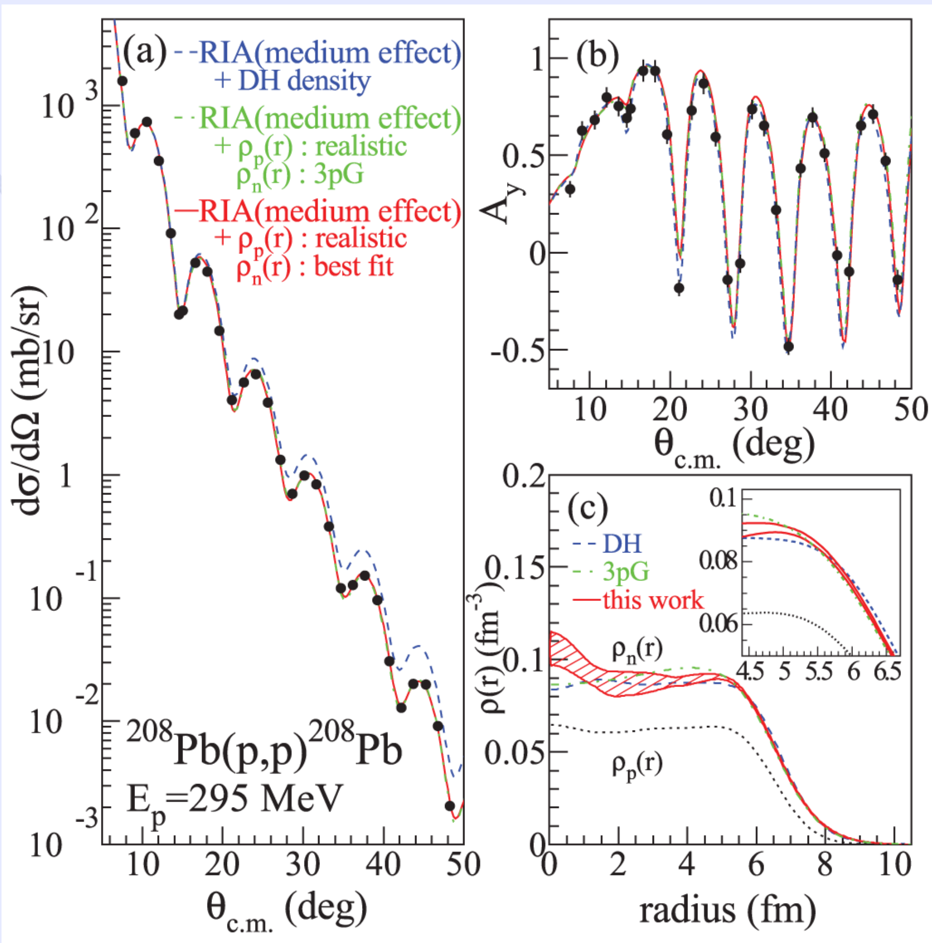
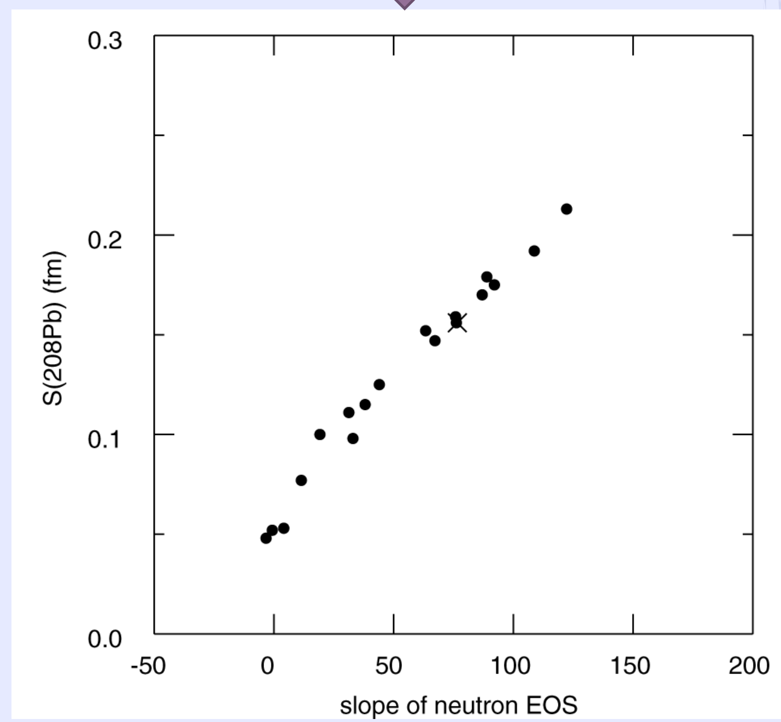


FIG. 4.—Mass-radius curves for selected PAL (Prakash et al. 1988) forces showing the sensitivity to symmetry energy. The left-hand panel shows variations arising from different choices of S_v, the symmetry energy evaluated at n_s; the right-hand panel shows variations arising from different choices of the density dependence of the potential contributions to the symmetry energy, $F(u)$, where $u = n/n_s$.

Zenihiro et al. PRC82（2010）044611



$$\Delta r_{np} = 0.211^{+0.054}_{-0.063}\, fm$$



Vary S_0 to obtain allowed values for different S_0 and compare to other probes and analyses

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

GDR: Trippa, PRC77, 061304

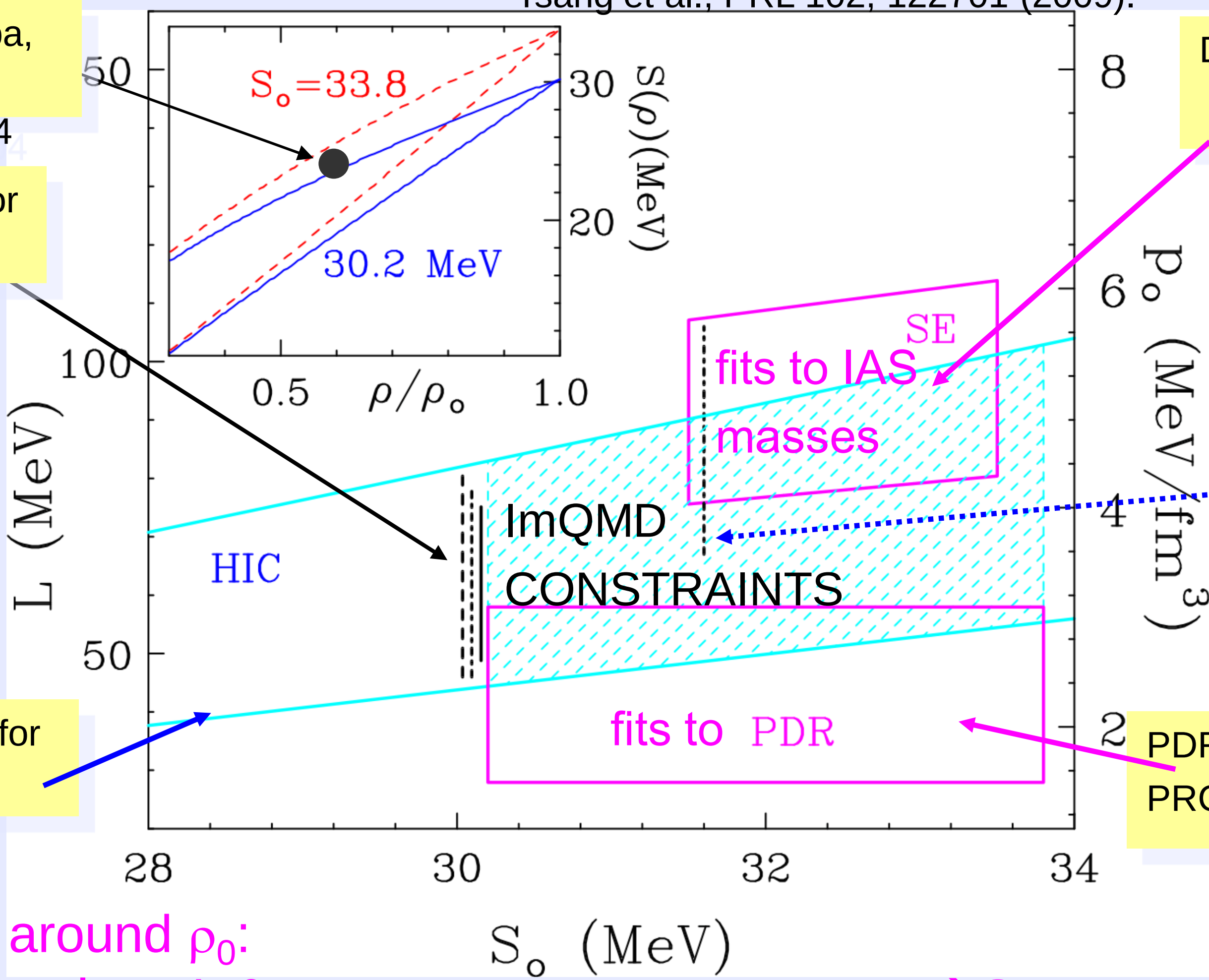
ImQMD fits for S_0=30.1 MeV

ImQMD fits for variable S_0

Danielewicz, Lee, NPA 818, 36 (2009)

Bao-An Li et al., Phys. Rep. 464, 113 (2008).

PDR: A. Klimkiewicz, PRC 76, 051603 (2007).



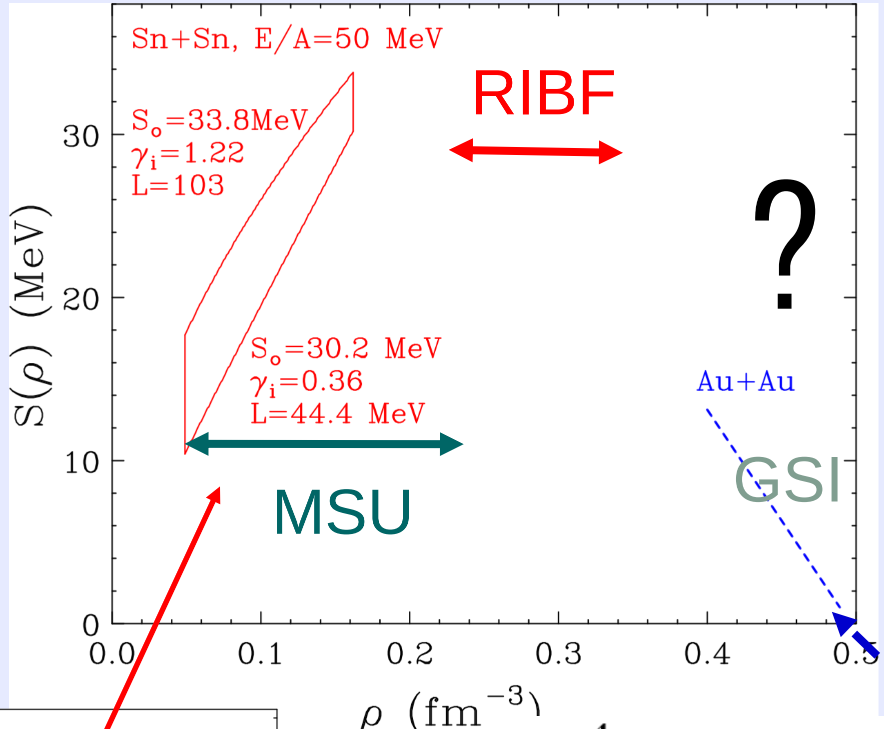
Expansion around ρ_0:

→Symmetry slope L & curvature K

→Symmetry pressure P_{sym}

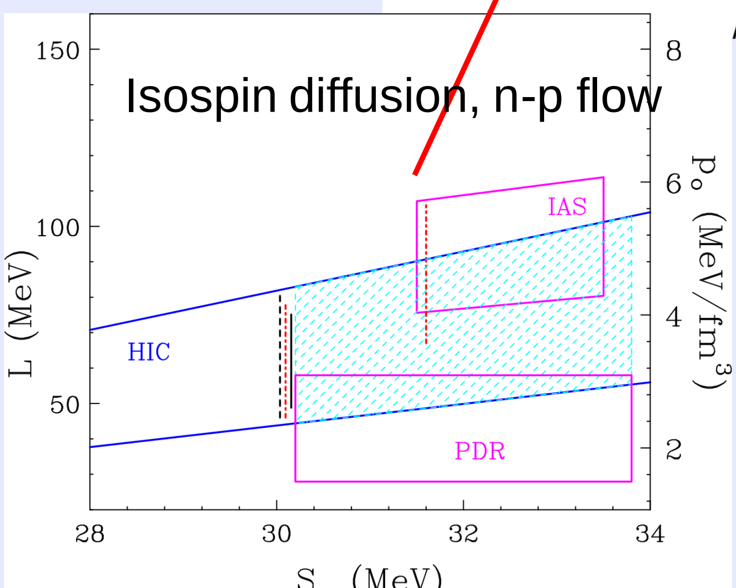
$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B-\rho_0}{\rho_0}\right)^2 + \dots$$

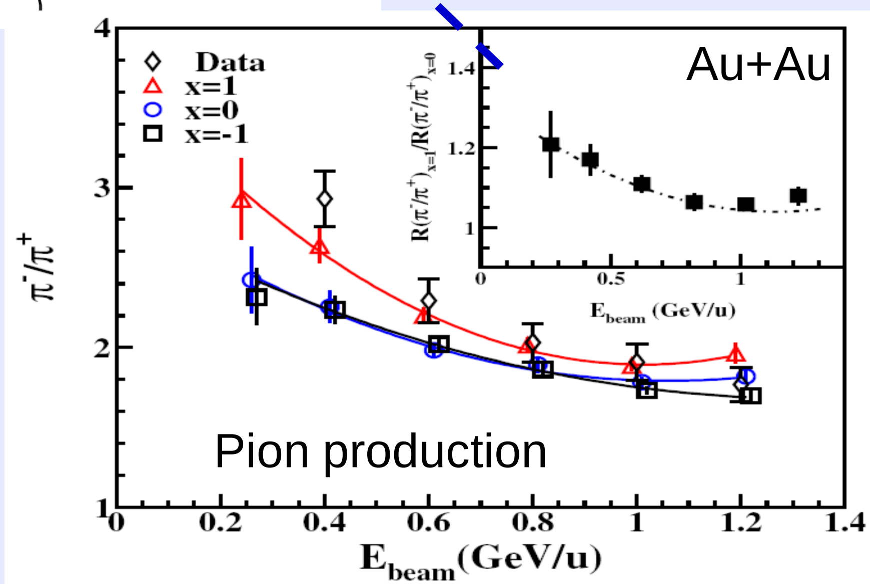
$$L = 3\rho_0 \left.\frac{\partial E_{sym}}{\partial \rho_B}\right|_{\rho_B=\rho_0} = \frac{3}{\rho_0}P_{sym}$$



RIBF can constrain the symmetry energy at ~ 2ρ_0.

Requires data with controlled variations in system asymmetry





Xiao, et al., arXiv:0808.0186 (2008)
Reisdorf, et al., NPA 781 (2007) 459.

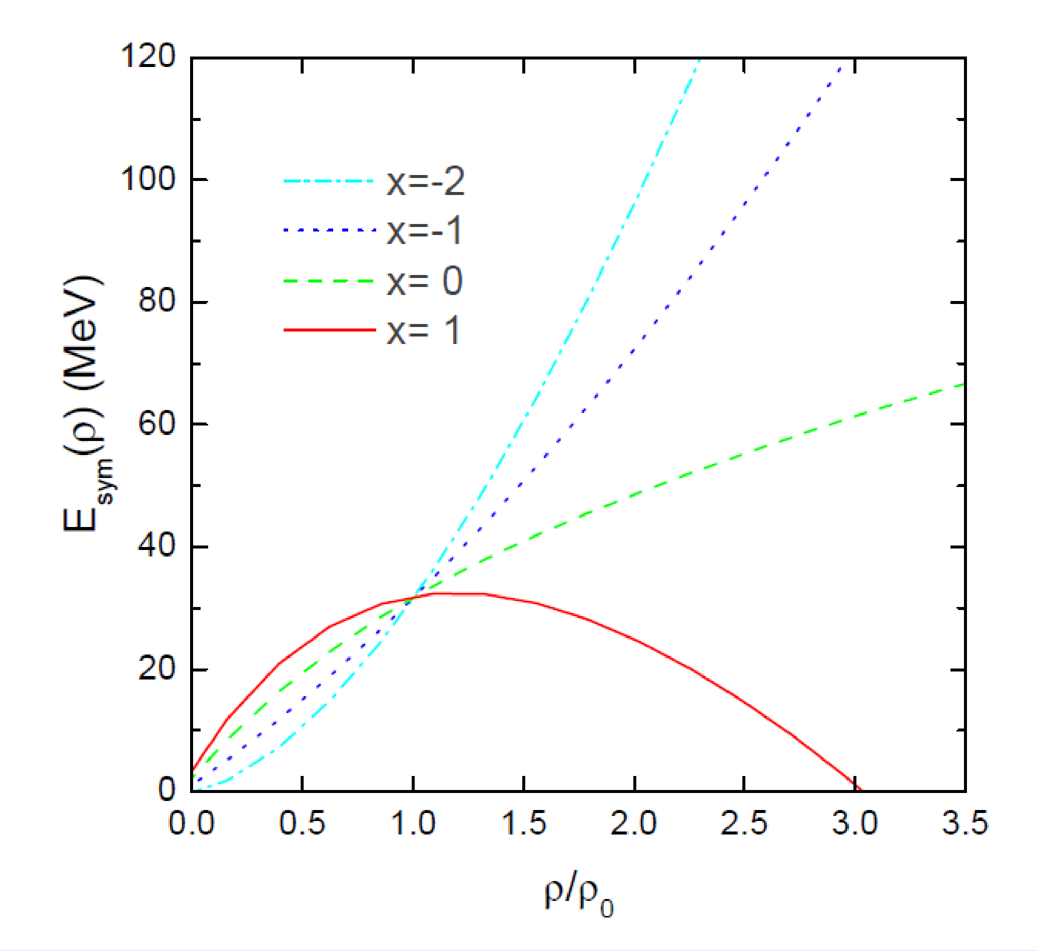
How to probe asymmetry energy at supra-saturation densities?

According to Bao-An Li's predictions using VUU

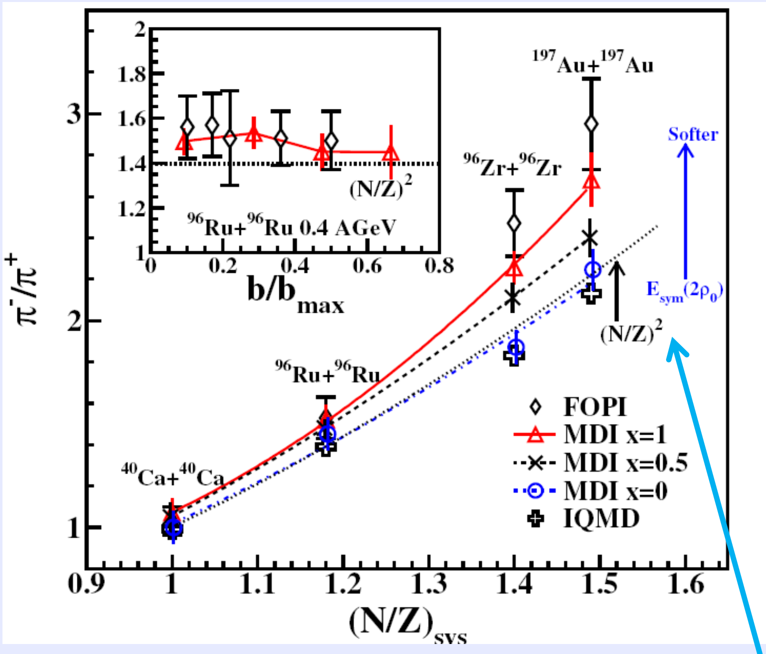
Should know n/p ratio in HD nuclear matter

1. Pre-equilibrium neutron and proton spectra
2. Fragment isotopic distribution in central collision
3. Transverse collective flow
4. Neutron-proton differential flow
5. π^-/π^+ ratio

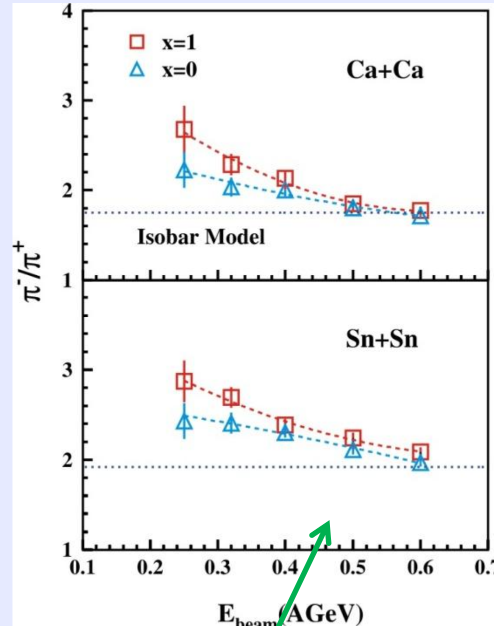
Definition of x-parameter



Consideration for pion ratios



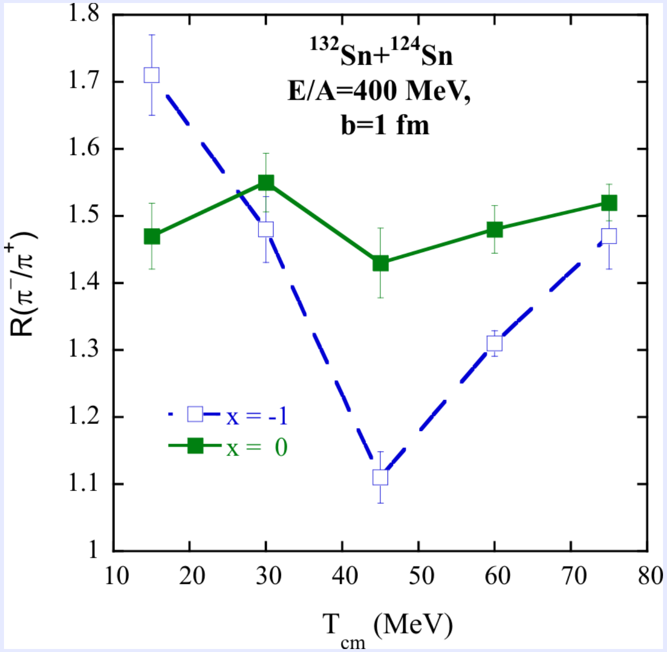
Xiao, et al., arXiv:0808.0186 (2008)
Reisdorf, et al., NPA 781 (2007) 459.



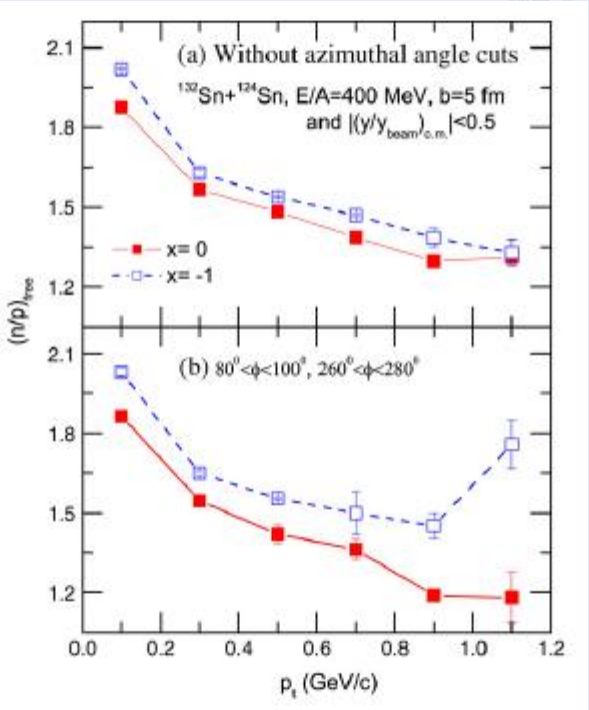
Zhang et al., arXiv:0904.0447v2 (2009)

- Sensitivity to symmetry energy is larger for neutron-rich beams
  - Largest sensitivity requires rare isotope beams such as ^{132}Sn and ^{108}Sn.
- Sensitivity increases with decreasing incident energy.
- Most sensitive measurements of π^-/π^+ ratios would be with beams available at RIBF or FAIR.

Available Observables :



Yong et al., PRC 73, 034603 (2006)



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

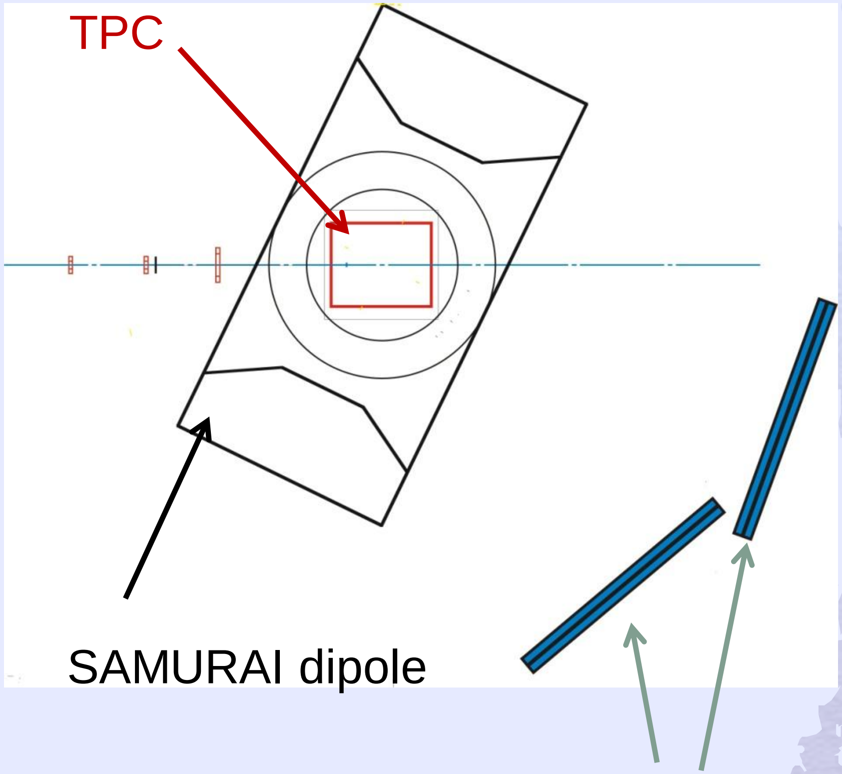
- Most model predict pion spectral ratios to be sensitive to symmetry.
- Double ratio removes sensitivty to differences between π^- and π^+ acceptances

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

- Most models predict the differences between neutron and proton flows and t and ^{3}He flows to be sensitive to the symmetry energy.
- The flows out of plane show a significant sensitivity.

Experimental setup

- The SAMURAI TPC would be used to constrain the density dependence of the symmetry energy through measurements of:
  - Pion production
  - Flow, including neutron flow measurments with the NEBULA array.



Research program as described in construction proposal

Probe	Devices	E_{lab}/A (MeV)	Part./s	Main Foci	Possible Reactions	FY
$\pi^+\pi^-$,p, n,t,^{3}He	TPC Nebula	200-300 350	10^4-10^5	E_{sym} m_n^*, m_p^*	^{132}Sn+^{124}Sn, ^{105}Sn+^{112}Sn, ^{52}Ca+^{48}Ca, ^{36}Ca+^{40}Ca ^{124}Sn+^{124}Sn, ^{112}Sn+^{112}Sn	2013 - 2014
$\pi^+\pi^-$ p, n,t,^{3}He	TPC Nebula	200-300	10^4-10^5	σ_{nn},σ_{pp} σ_{np}	^{100}Zr+^{40}Ca, ^{100}Ag+^{40}Ca, ^{107}Sn+^{40}Ca, ^{127}Sn+^{40}Ca	2015 - 2017

- Typical rates at 10^4/s are 3-4 pions/s of each charge and about 5 n's/s

  Goal is to run up to 10^5 /s
- Ideal would be to run 3-4 weeks/y. This corresponds to two experiments that each measure two pairs of systems: e.g. ^{132}Sn+^{124}Sn, ^{105}Sn+^{112}Sn at one incident energy.