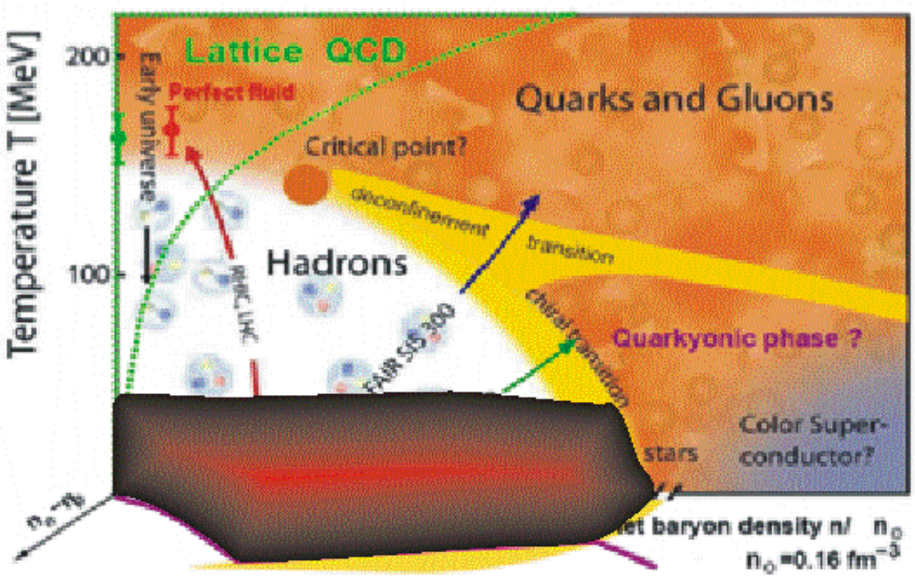
Probing the EoS of Asymmetric matter

W. Lynch: NSCL and Department of Physics and Astronomy
Michigan State University and the HiRA and SπRIT collaborations



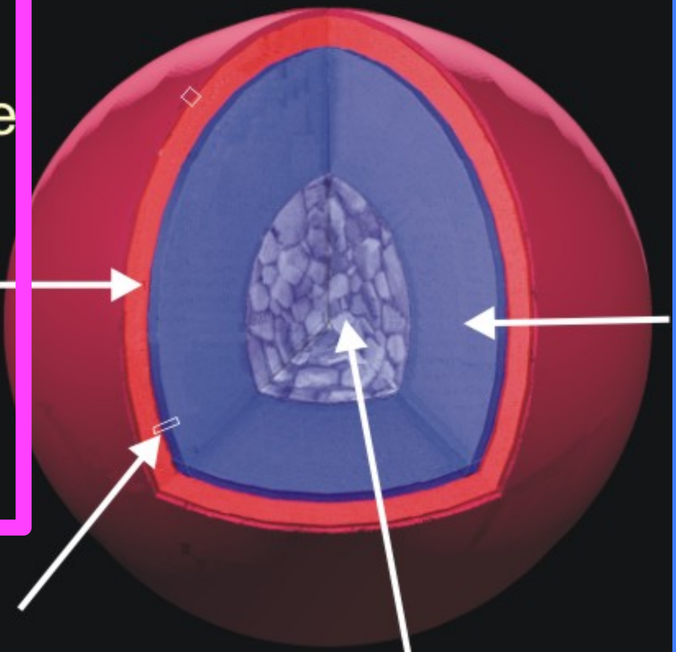
- Symmetry energy, EoS and neutron stars.
- Laboratory constraints on the symmetry energy at $\rho<\rho_0$
- Extension of constraints to $\rho>\rho_0$
- New experiment with the SπRIT TPC at RIBF

Influence of S(ρ) on a neutron star

S(ρ): = density dep. of symmetry energy

$\rho < \rho_0$

Inner crust:
Neutron gas in coexistence with "Coulomb lattice" of nuclei. S(ρ) governs thickness of crust and the observed frequencies in star quakes.



$\rho > \rho_0$

Outer core:
Composed of neutron-rich nuclear matter. S(ρ) Governs stellar radii, and moments of inertia.

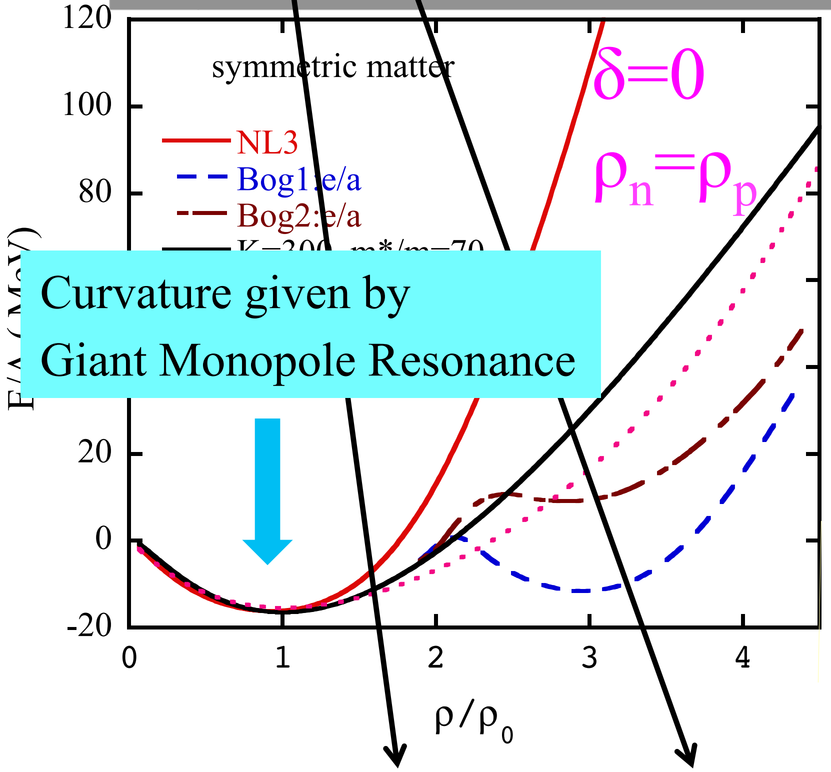
Inner boundary of inner crust: Cylindrical and plate-like nuclear "pasta"

Inner core:
Composition is unknown. Could be nuclear, quark or strange matter.

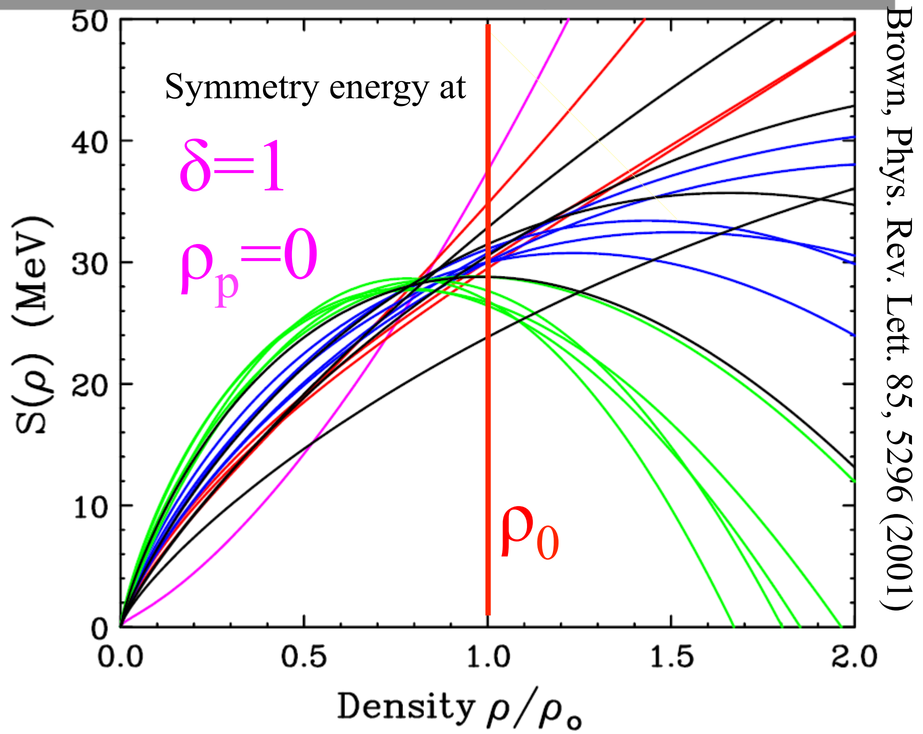
$\varepsilon(\rho,0,\delta)$= E/A: How does it depend on ρ and δ?

nuclear binding energy

$$B_{A,Z} = a_v[1-b_1((N-Z)/A)^2]A - a_s[1-b_2((N-Z)/A)^2]A^{2/3} - a_c Z^2/A^{1/3} + \delta_{A,Z}A^{-1/2} + C_d Z^2/A$$



Curvature given by Giant Monopole Resonance



Brown, Phys. Rev. Lett. 85, 5296 (2001)

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

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

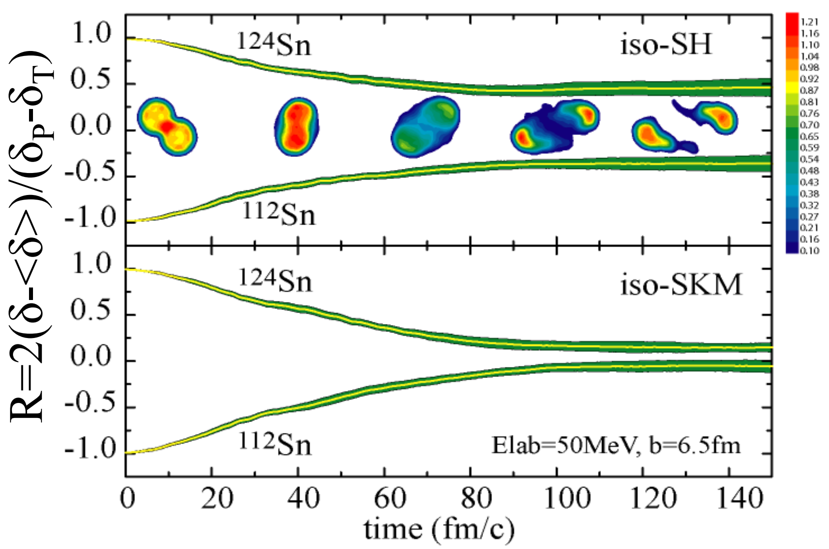
$$P = \rho^2 \left.\frac{\partial(E/A)}{\partial\rho}\right|_{s/a}$$

- Symmetry energy calculated here with effective interactions constrained by Sn masses
- This does not adequately constrain the symmetry energy at higher or lower densities

Observables to constrain low density EoS

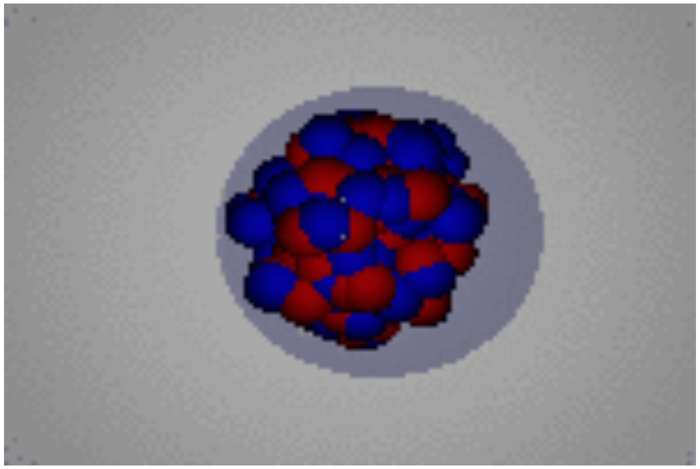
$$B_{A,Z} = a_v[1-b_1((N-Z)/A)^2]A - a_s[1-b_2((N-Z)/A)^2]A^{2/3}+....$$

- Binding energies of nuclei, Isobaric analog states.

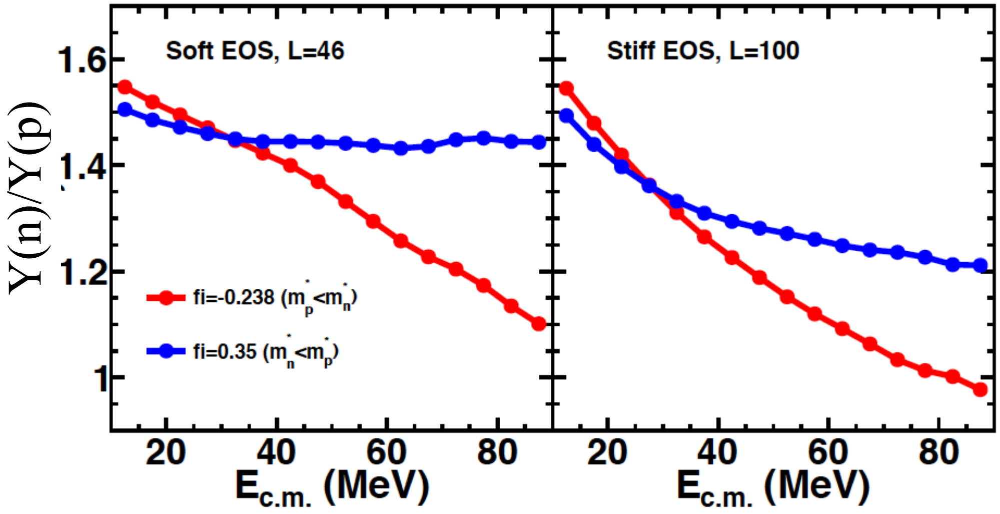


L. Shi, P. thesis, (2003)

- diffusion between nuclei of different δ



- Asymmetry and dynamics of nuclear surfaces: E1 excitations



P. Mrofouace, (2017)

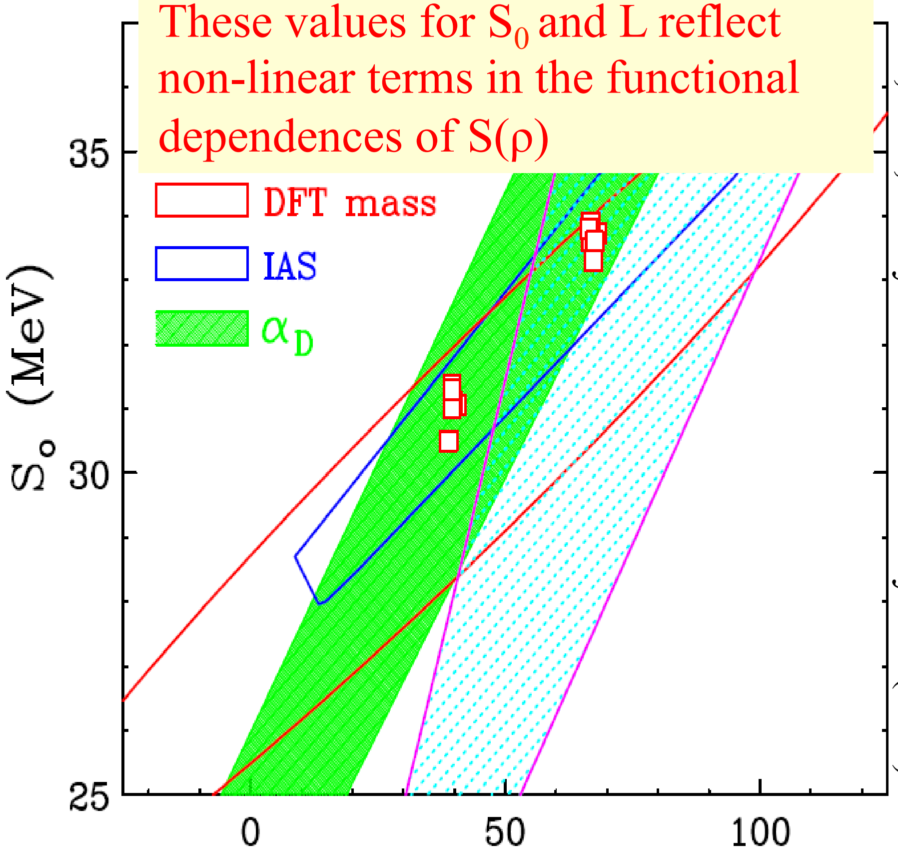
- Ratios of neutron/proton spectra in central ^{124}Sn+^{124}Sn collisions (δ dep. of radial flow)

Laboratory constraints on Symmetry energy at $\rho<\rho_0$

- Such Experimental observables have been analyzed to provide constraints on $S_0=S(\rho_0)$ and L.
- Some sensitive observables:
  - masses
  - Isobaric Analog States (IAS)
  - Electric dipole polarizability (α_0)
  - Diffusion of neutrons and protons between nuclei of different N/Z in peripheral collisions HIC (Sn+Sn)

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

These values for S_0 and L reflect non-linear terms in the functional dependences of $S(\rho)$



Horowitz, et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 093001

- Slope of constraint indicates the sensitive density

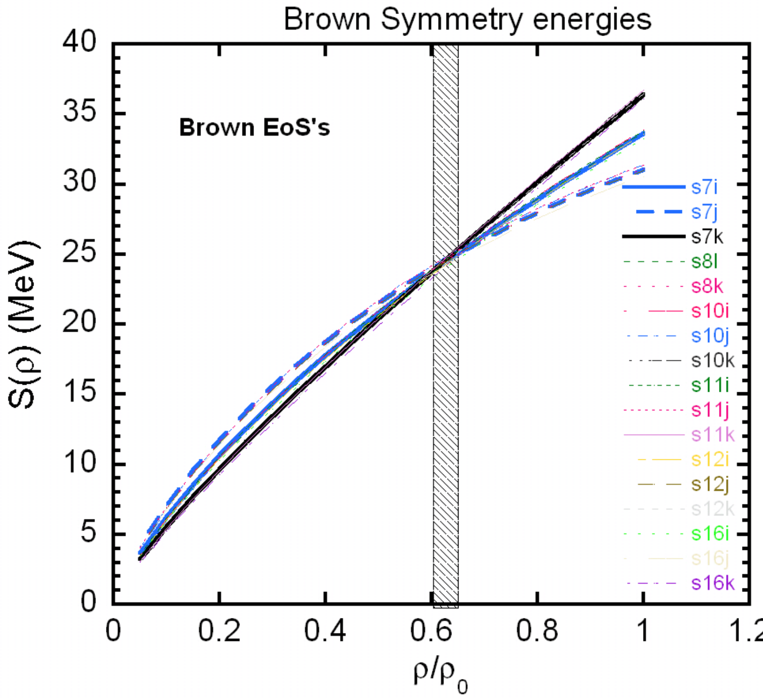
$$M=-\left(\partial S(\rho_s)/\partial L\right)/\left(\partial S(\rho_s)/\partial S_0\right);$$

M is slope

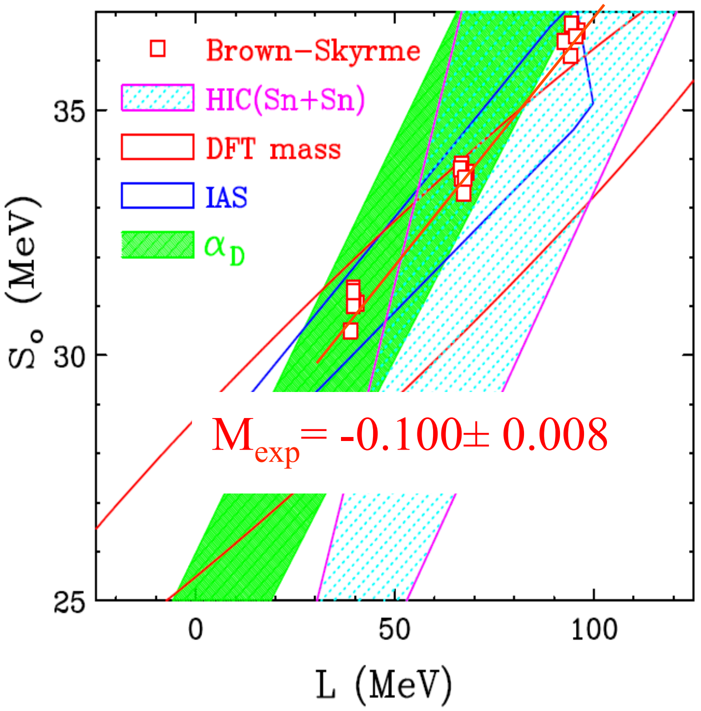
- M is monotonic function of density ➔ Can determine density ρ_s from slope and then get $S(\rho_s)$

➔ use each contour to obtain $S(\rho_s)$ at the density ρ_s probed by that measurement

Demonstration for Mass analyses of Brown



BA Brown PRL 111, 232502 (2013)



Adapted from Horowitz, et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 093001

- Brown directly examined the functions S(ρ) that fit masses of closed shell nuclei. These functions agreed at
- $\rho_S/\rho_0 = 0.63\pm0.3$ where they had the value $S(\rho_S) = 25.4\pm0.8$ MeV
- Now we redo this analysis with the slope technique.

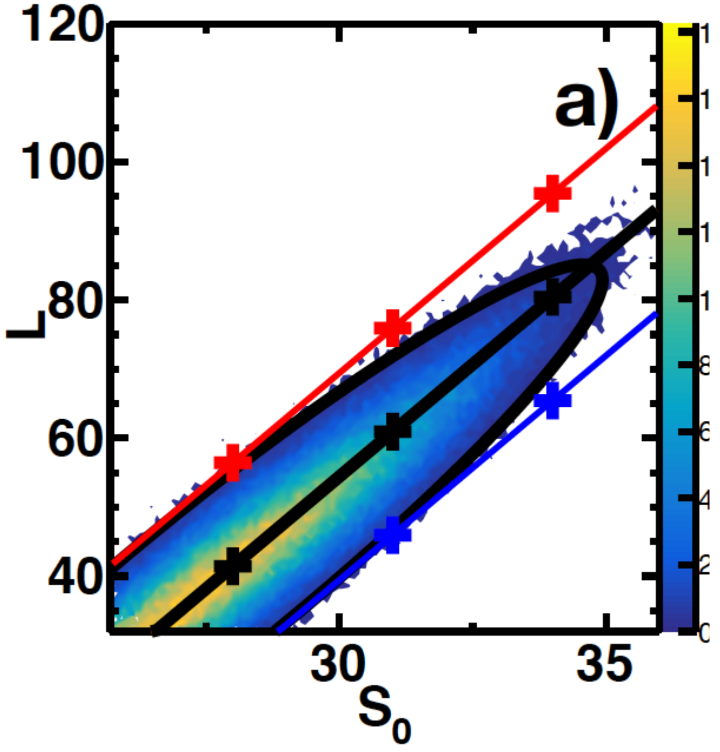
$$M(\rho_s) = -\left(\partial S(\rho_s)/\partial L\right)/\left(\partial S(\rho_s)/\partial S_0\right);$$

M depends monotonically on ρ_s

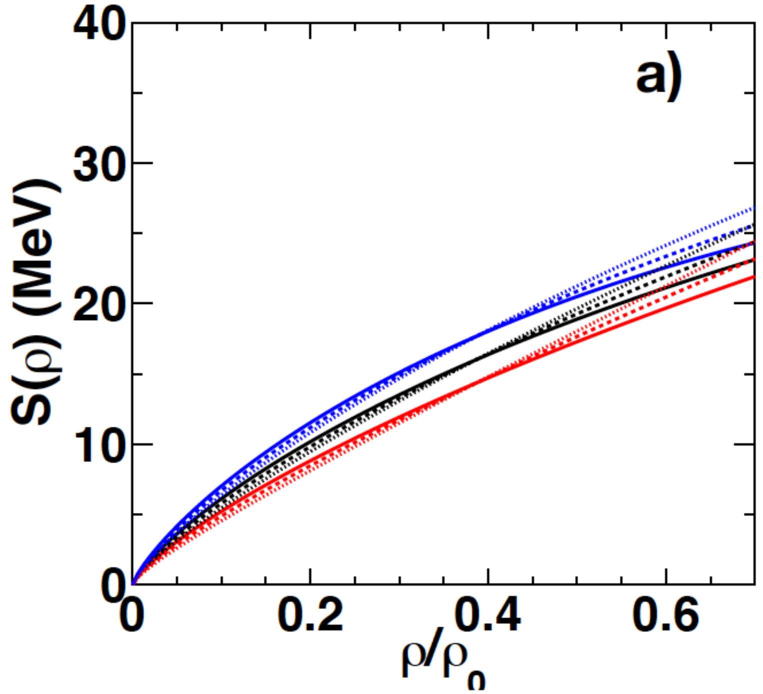
- Using $M_{exp} = -0.100\pm 0.008$ and the functional dependence of $S(\rho_S)$ provides: $\rho_S/\rho_0 = 0.65\pm0.3$ and $S(\rho_S) = 25.1\pm0.8$ MeV.

- We used the slope technique to obtain $\rho_S/\rho_0 = 0.76\pm0.2$ and $S(\rho_S) = 27.1\pm1.1$ MeV for the DFT constraint. Similarly, we obtain $\rho_S/\rho_0 = 0.74\pm0.3$ and $S(\rho_S) = 27.3\pm0.9$ MeV for the IAS constraint.

Constraints from ratios of neutron/proton spectra in central ^{124}Sn+^{124}Sn and ^{112}Sn+^{112}Sn collsions



P. Morfouace et al., (2017



P. Morfouace et al., (2017

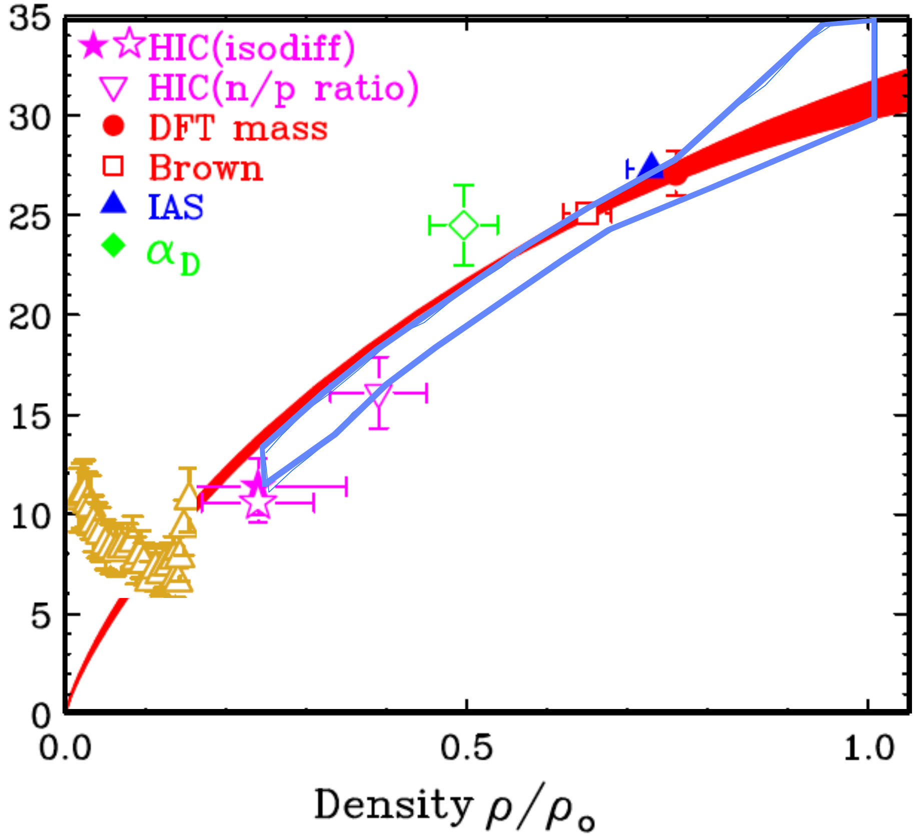
- Four dimensional Bayesian analyses of spectral ratios using Madai:
- Parameters: S$_0$, L, m_n^* and m_p^*

- We obtain ρ_S/ρ_0= 0.39±0.6 and $S(\rho_S)$ = 16.1±1.8 MeV.
- Best fit : S$_0$= 16.1±1.8 MeV, L= 16.1±1.8 , m_s^* / m_N=0.77±0.11 and $m_n / m_n^* - m_p / m_p^* = 0.5 \pm 0.6$
- The effective masses are very important for neutron-star cooling.

Density dependence of symmetry energy

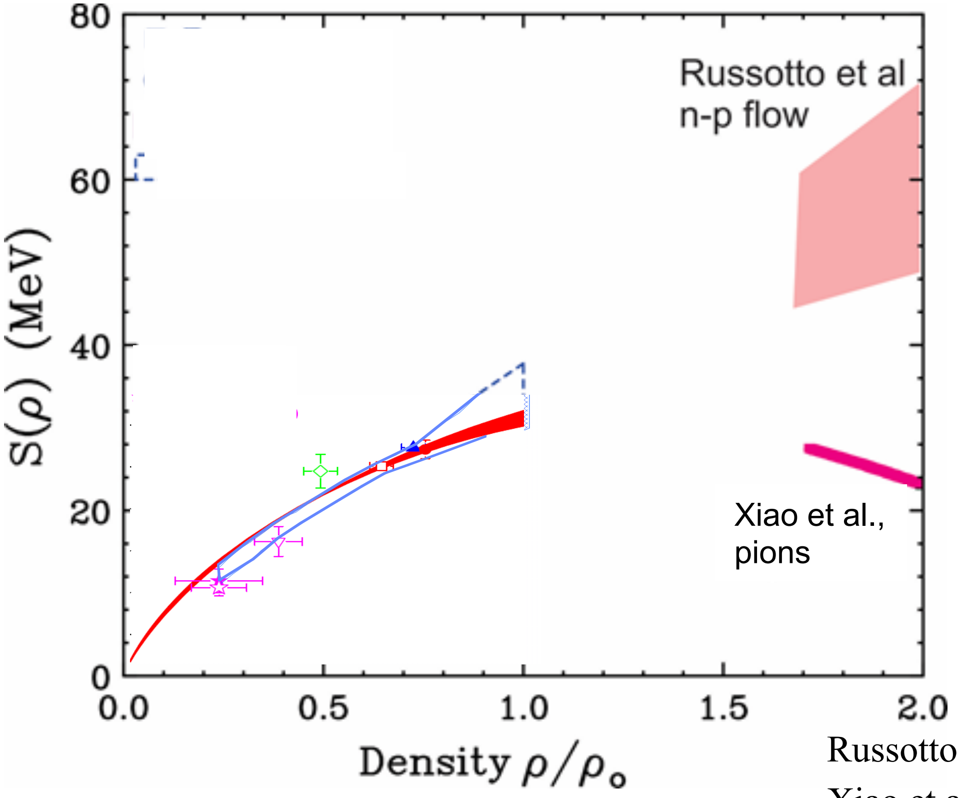
- Figure shows the values for S(ρ) obtained by these analyses.
- The best constrained values are at $0.6<\rho/\rho_0<0.80$. Little or no constraints above $\rho/\rho_0 \approx 0.8$.
- Red curve is the ab-initio calculation by C. Drischler et al. (2014)
- Constraints are similar to the dessity dependence from IAS recently published by Danielewicz and Lee (2017) shown by blue contour.

W.G. Lynch and M.B. Tsang, (2017



- Probing $\rho/\rho_0<0.25$ is the domain of correlation studies because matter in this region is mechanically unstable with respect to the formation of clusters. That is why the symmetry energy in nature does not go to zero. .

Status of symmetry energy

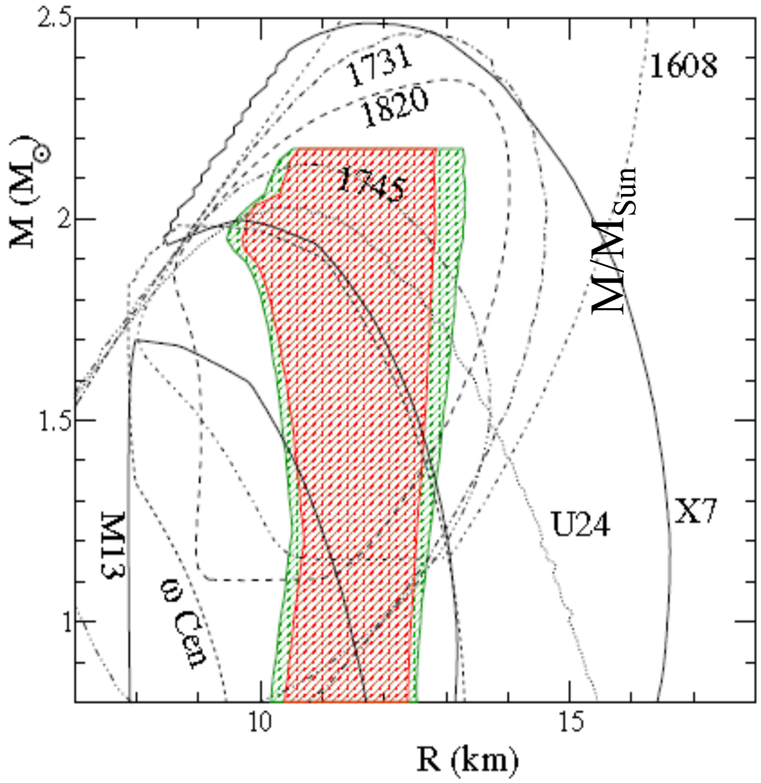


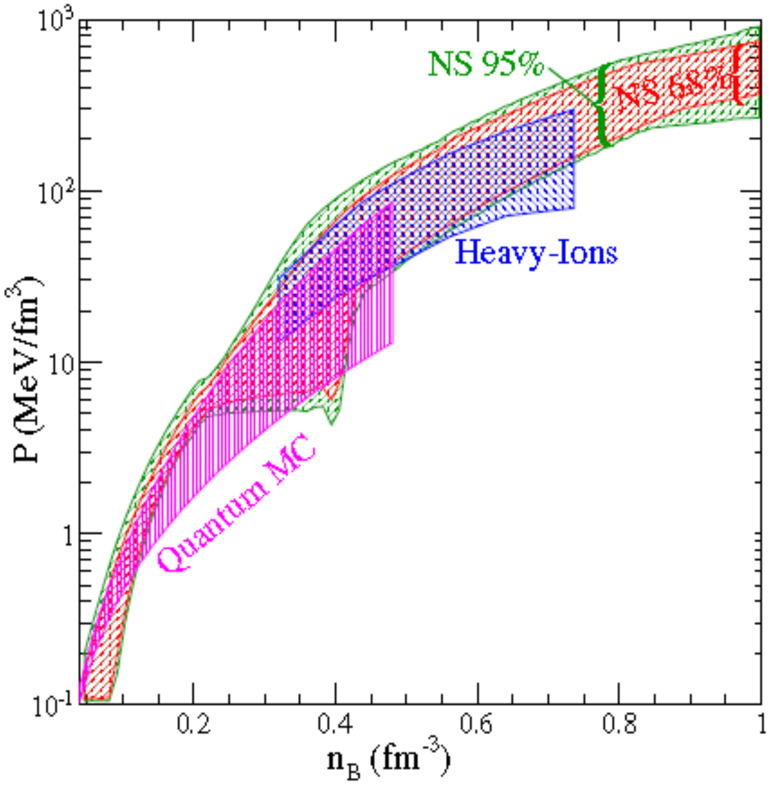
Russotto et al., PLB, 697, 471 (2011)

Xiao et al., PRL 102, 062502 (2009).

- Many nuclear stucture and reactions have constrained the symmetry energy at $\rho<\rho_0$, as I have discussed.
  - At $\rho<\rho_0$, situation improving rapidly.
- At $\rho>\rho_0$, work just beginning.
  - Important to constrain all theoretical unknowns and reconcile discrepancies.

Constraining the EoS and Symmetry Energy at $\rho>\rho_0$



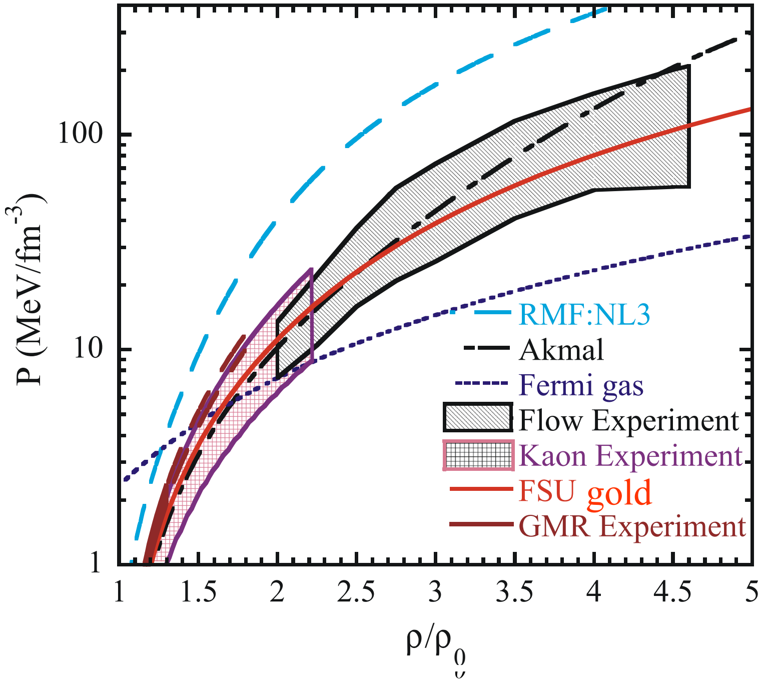


Steiner et al., ApJ 722, 33 (2012)

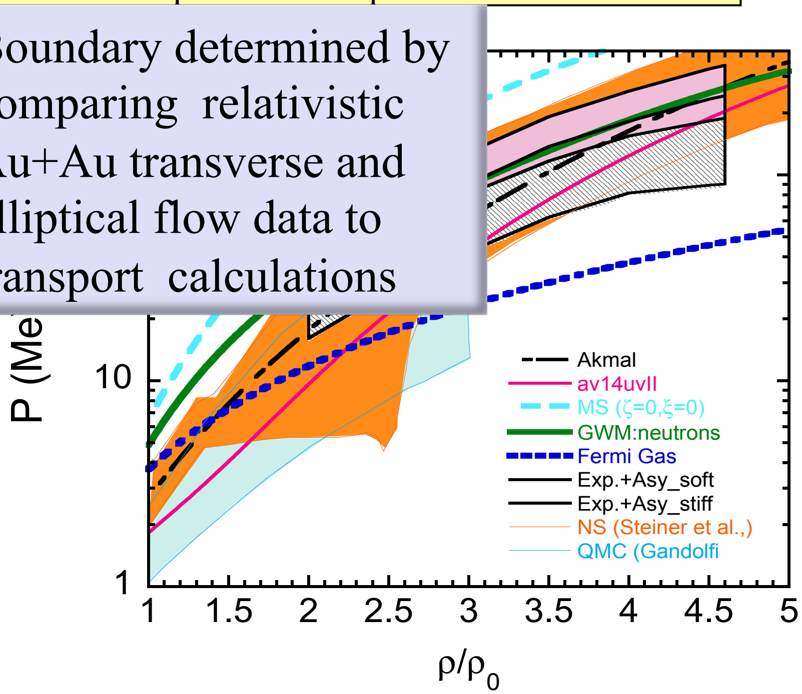
- Steiner et al., ApJ 722, 33 extract R=11.5±1.5 km from X-ray bursters and quiescent binary systems. Other radius measurements have differed by the order of 2 km.
- Comparable constraints on pressure of $30\ \mathrm{MeV/fm}^3 < P < 86\ \mathrm{MeV/fm}^3$ at n_B =0.43 /fm^3 from neutron star R vs. M correlation and Heavy ion collisions. (Factor of 3). Uncertainties are large, yet constraints are useful. Heavy ion “constraints” appear much tighter at $0.3<n_B<0.4$ /fm^3

Laboratory Constraints on symmetric matter EOS at $\rho > 2\rho_0$.

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



Lynch Prog. Part. Nucl. Phys. 62,427 (2009)



Boundary determined by comparing relativistic Au+Au transverse and elliptical flow data to transport calculations

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

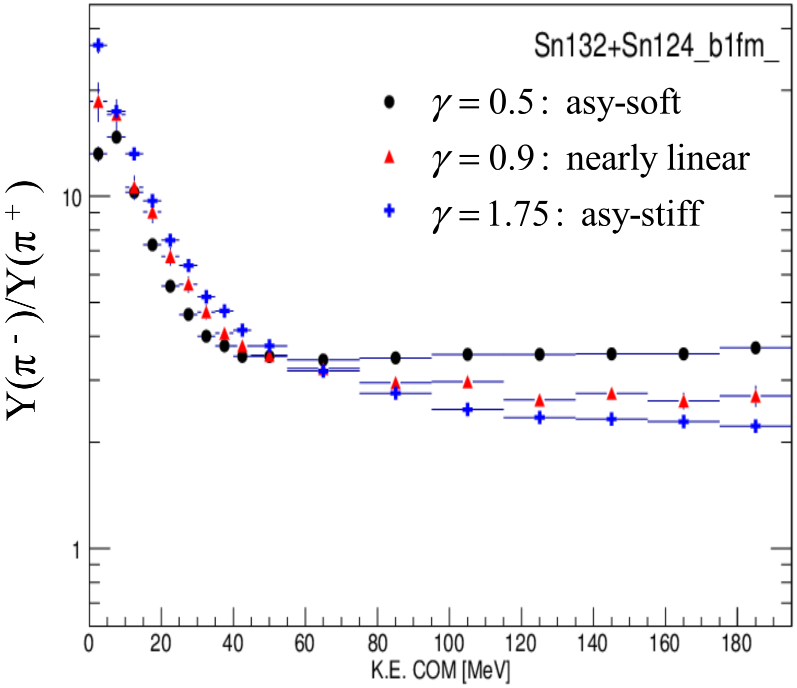
- Flow confirms the softening of the EOS at high density.
- Constraints from kaon production are consistent with the flow constraints and bridge gap to GMR constraints.
- Note: analysis requires additional constraints on m* and σ_{NN}.

- The symmetry energy dominates the uncertainty in the n-matter EOS.
- Neutron star matter “constraint” includes symmetry energy uncertainties
- Improved laboratory constraints on the density dependence of the symmetry energy are needed to verify and tighten the constraints.

Probing $\rho>\rho_0$ via pion production

- Stiff S(ρ) drives neutrons out and pulls protons into dense neutron-rich matter. Effect less for soft S(ρ) . Can be probed by comparing n to p emission .
- Larger values for ρ_n/ρ_p at high density for the soft asymmetry term (x=0) causes stronger emission of negative pions for the soft asymmetry term (x=0) than for the stiff one (x=-1).
- Expectations for $Y(\pi^-)/Y(\pi^+)$
  - In delta resonance model, $Y(\pi^-)/Y^+)\sim(\rho_{n,}/\rho_p)^2$
  - In equilibrium, $\mu(\pi^-)-\mu(\pi^+)=2(\mu_n-\mu_p)$

E/A = 300 MeV

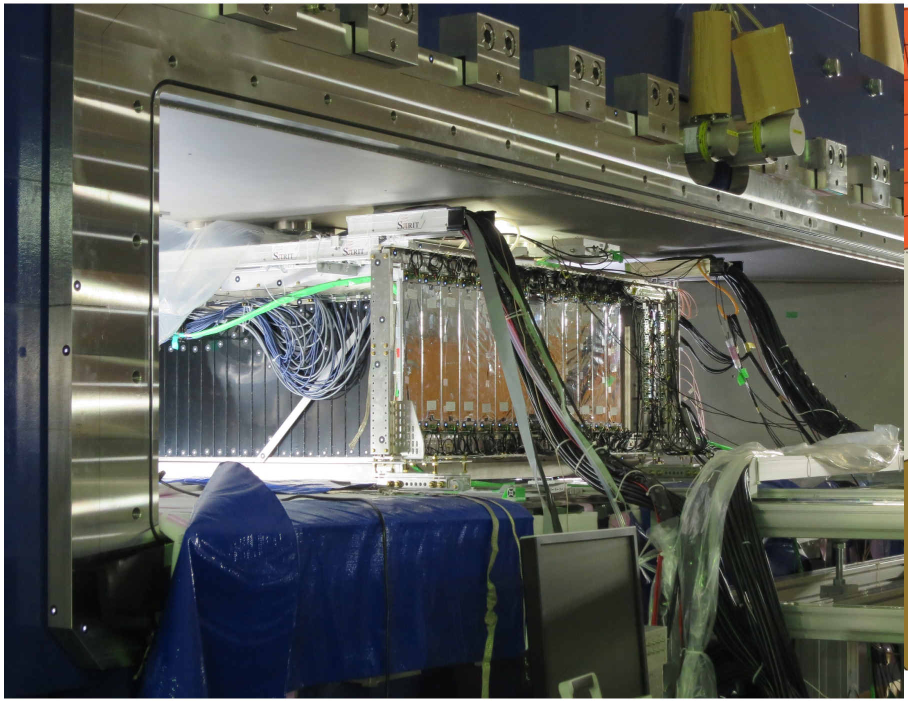


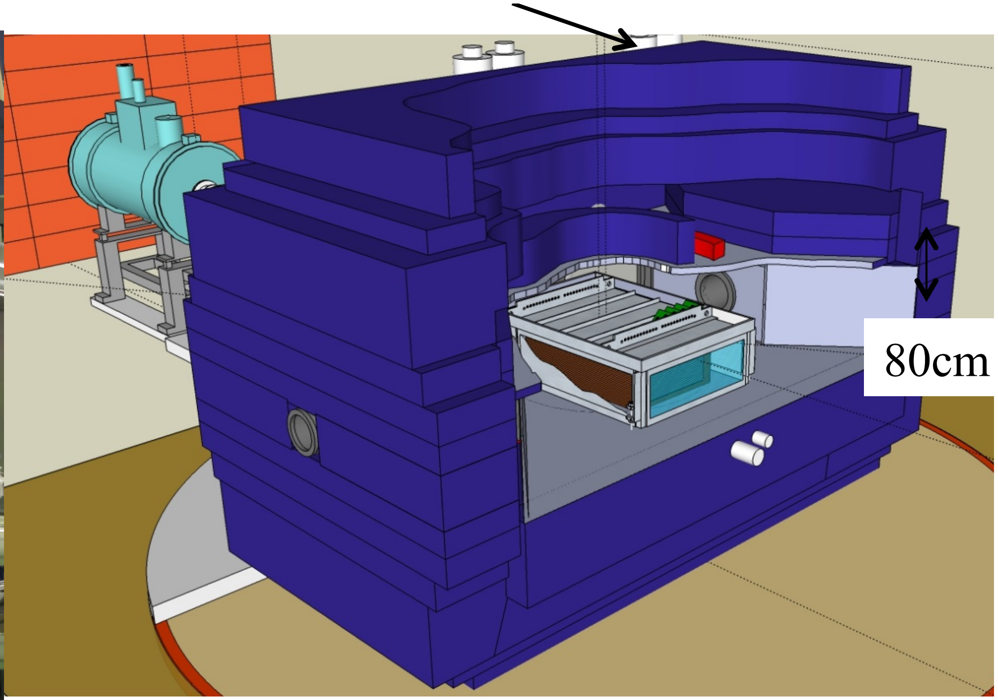
M.B. Tsang et al., PRC (2017).

- There are two key observables
  - Comparing the spectra multiplicities and flows of π^- to π^+.
  - Comparing the spectra and flows of neutrons to protons. Effects are opposite to pions and are predicted to be smaller.
  - Both are measured in the SπRIT experiment at RIKEN.

SPπRIT-Time Projection Chamber exp. at RIBF

Shane et al., NIMA 784 (2015) 513



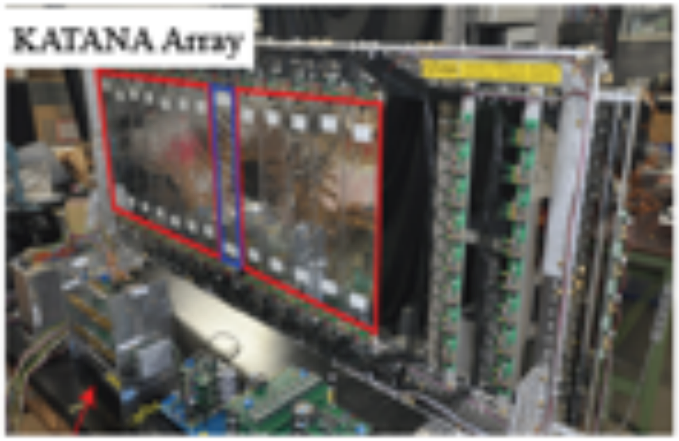


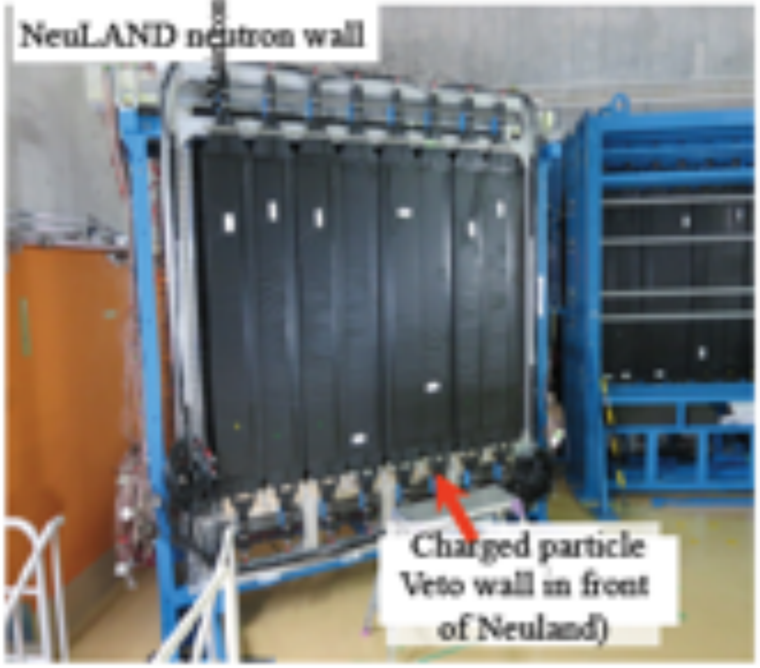
- 134 x 86 x 53 cm^3 effective volume
- dE/dX – Bρ particle identification.
- Target at the entrance of chamber.
- Readout with ~12000 pads.
- Neutrons 15°<θ<30° meas. by NeuLAND
- Experiment completed 6/1/2016

E/A MeV	**Reaction**	$\frac{N-Z}{A}$	**focus**
280	^{132}Sn+^{124}Sn	.22	S(ρ), $m^*_n - m^*_p$
280	^{108}Sn+^{112}Sn	.08	S(ρ), $m^*_n - m^*_p$
280	^{124}Sn+^{112}Sn	.15	σ_{nn}, σ_{np}, σ_{pp}
280	^{112}Sn+^{124}Sn	.15	σ_{nn}, σ_{np}, σ_{pp}

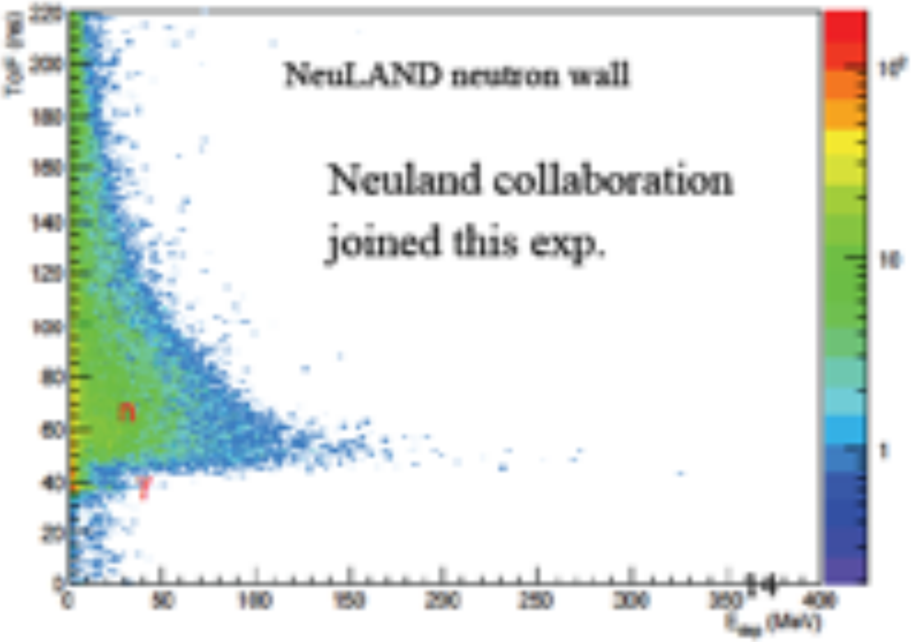
Ancillary detectors: trigger scintillators and Neuland neutron wall.


Central Multiplicity Trigger Array


KATANA Array

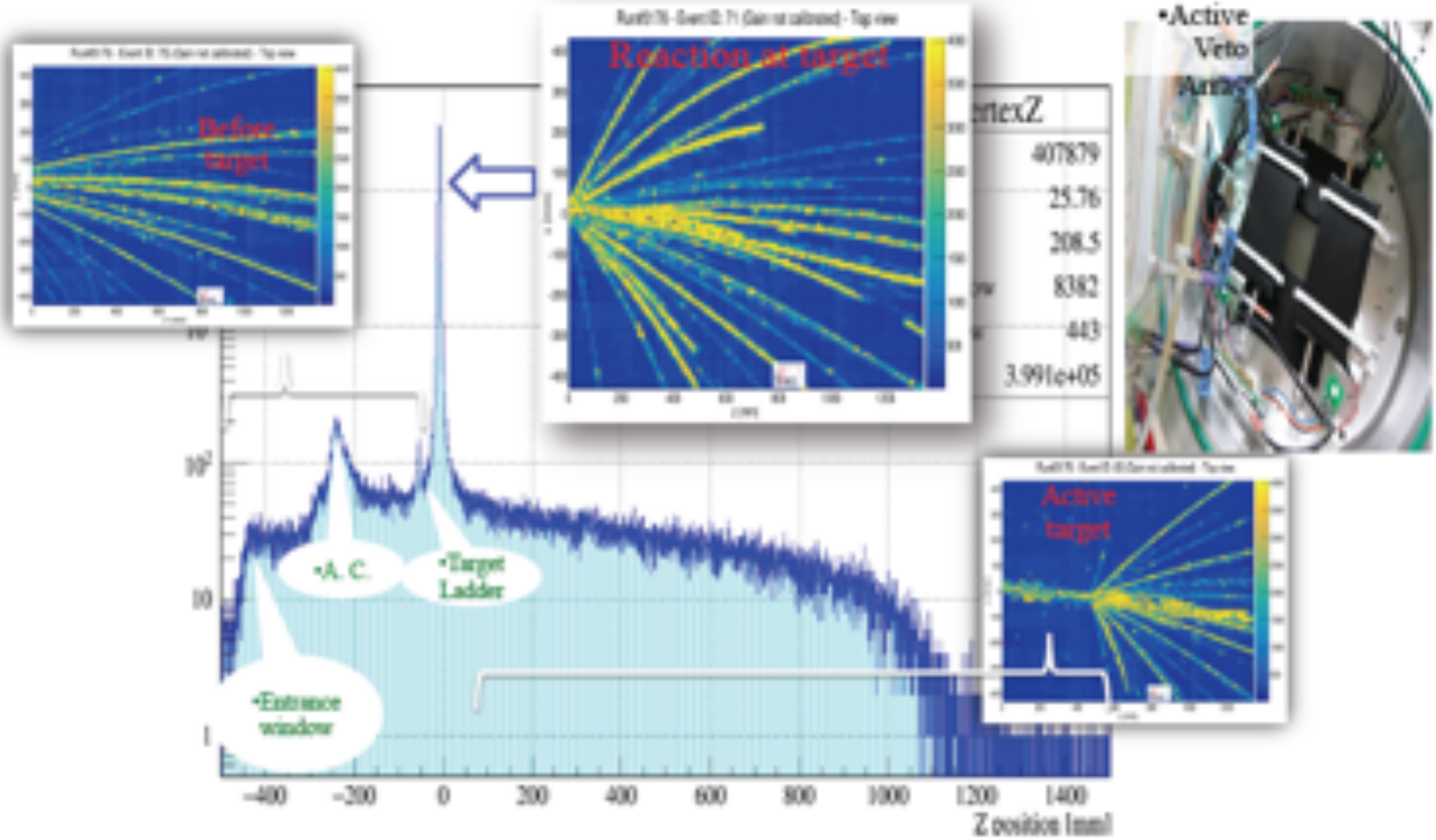

NeuLAND neutron wall

Charged particle Veto wall in front of Neuland)


NeuLAND neutron wall

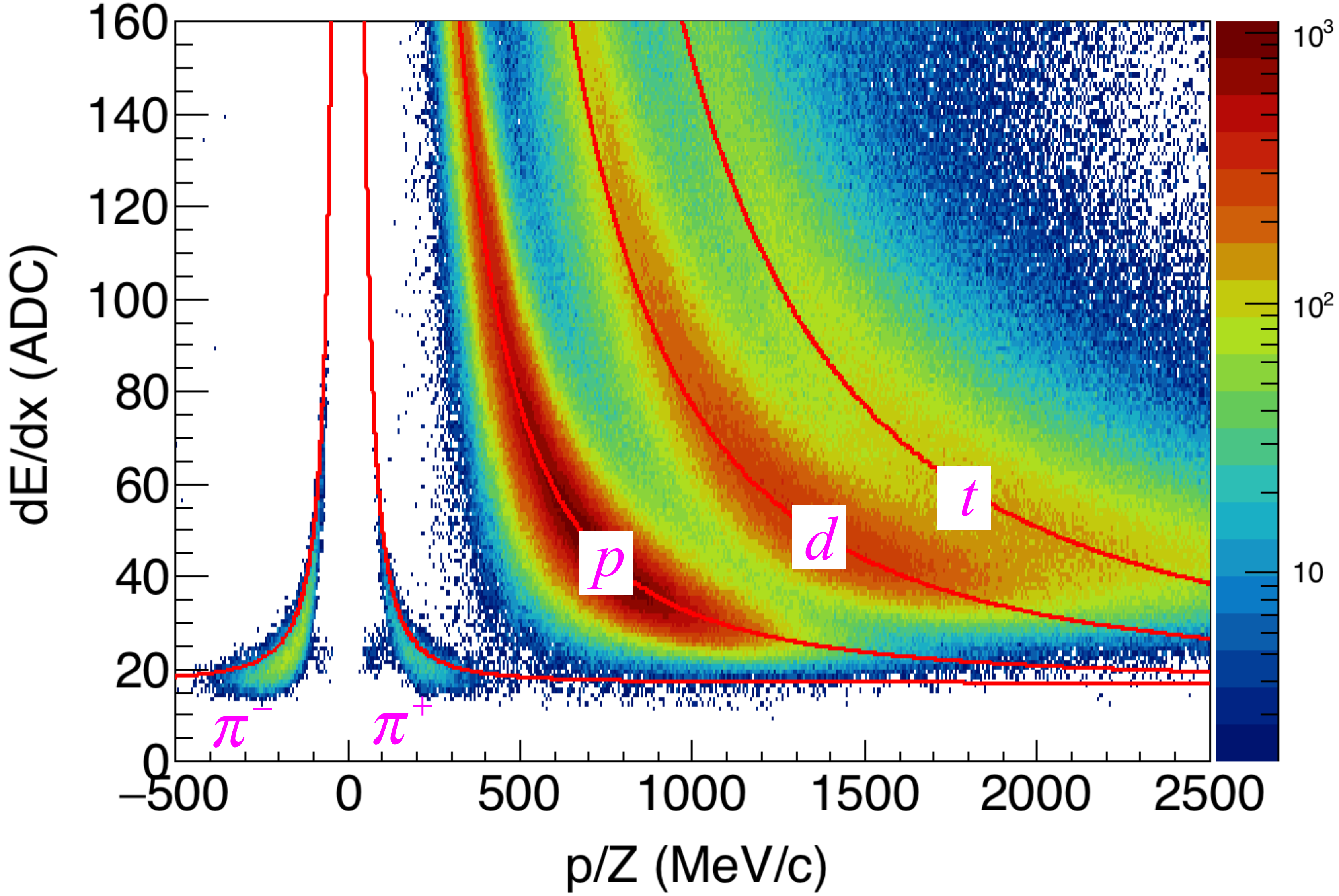
Neuland collaboration joined this exp.

Vertex reconstruction can separate reactions on target from reactions on counter gas.



- **Background can be eliminated**

PID for minimum ionizing particles (pions) is good.



Summary and outlook

- Significant constraints on the symmetry energy are emerging for $\rho<\rho_0$.
- Key issue is to determine the sensitive density probed by each observable and then extract the symmetry energy at that density.
  - Have constraints on $S(\rho)$ at $0.25<\rho/\rho_0<0.75$.
- Key issues are to constrain the symmetry energy at $0.80<\rho/\rho_0<2.0$.
  - There is an inconsistency between the conclusions from previous measurements of π^-/π^+ spectral ratios and the conclusions drawn from the comparison of n vs. p elliptical flows.
  - Additional experimental and theoretical work is needed to address this discrepancy.
- New SπRiT TPC experiment should be able to explore both observables and provide new constraints on $S(\rho)$ in the region of at $0.80<\rho/\rho_0<2.0$.

SπRIT

SAMURAI Pion Reconstruction and Ion Tracker

Collaboration of 50+ scientists from China, Japan, Korea, Poland and U.S.

SπRIT TPC is designed to probe the symmetry energy at $\rho > \rho_0$ at the RIBF facility in Wakoshi, Japan.

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