Probing the EoS of asymmetric matter

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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 $\rho>\rho_0$
- Outlook

ε(ρ,δ) is the equation of state

ε (ρ,δ)=(E/A (ρ,δ) = E/A (ρ,0) + ™^{2}•S(ρ)

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

S(ρ) is the symmetry energy

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

P is the pressure

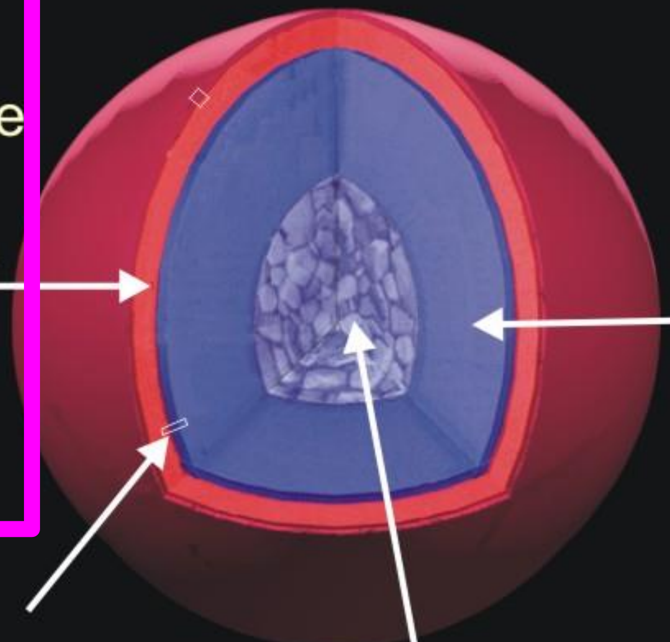
ρ is the number density

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 thick-ness of crust and the observed frequencies in star quakes.



- c

$\rho > \rho_0$

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.

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 in peripheral collisions HIC (Sn+Sn)
- Calculations often use Skyrme functionals for these observables of the form:

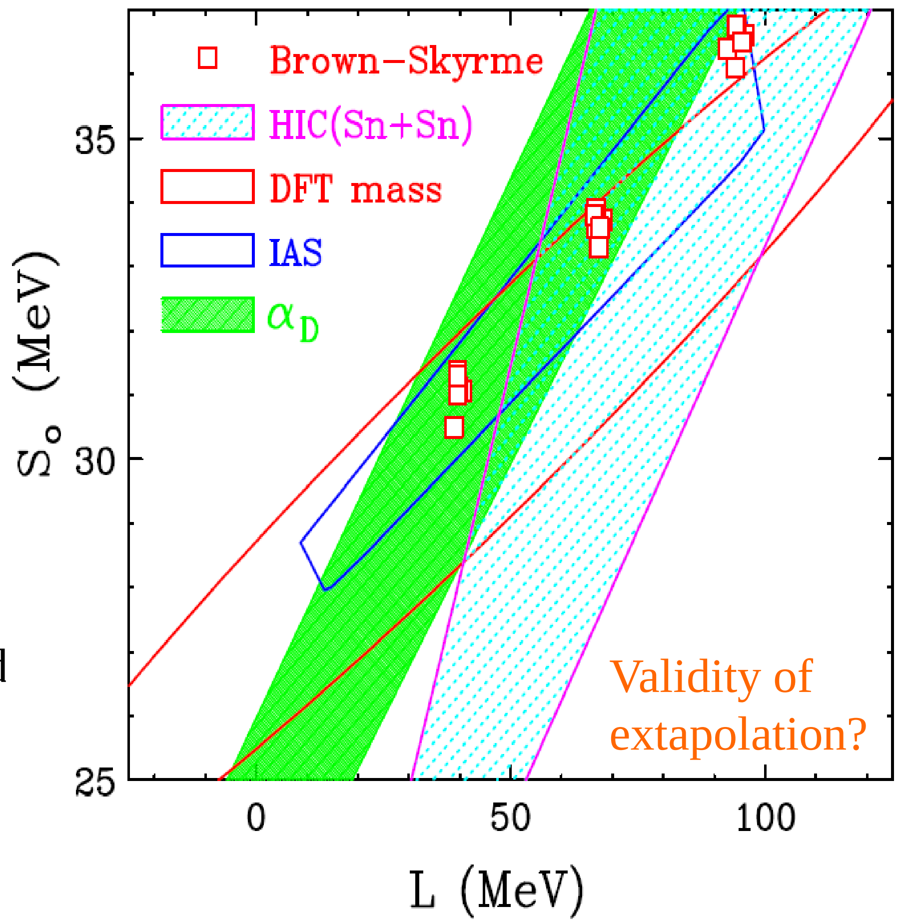
$$S(\rho)=a\rho+b\rho^{1+\sigma}+c\rho^{2/3}+d\rho^{5/3}$$

  - c and d provide kinetic energy and effective mass contributions to S(ρ) and are independent of S_0 and L.
  - Constraints on S_0 and L come from the fit values of a and b, where

$$a=S_0/\rho_0-b\rho_0^{\sigma}-c\rho_0^{-1/3}-d\rho_0^{2/3}$$

$$b=\left[L/3-S_0+c\rho_0^{2/3}+d\rho_0^{5/3}\right]/\left[\sigma\rho_0^{1+\sigma}\right]$$

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

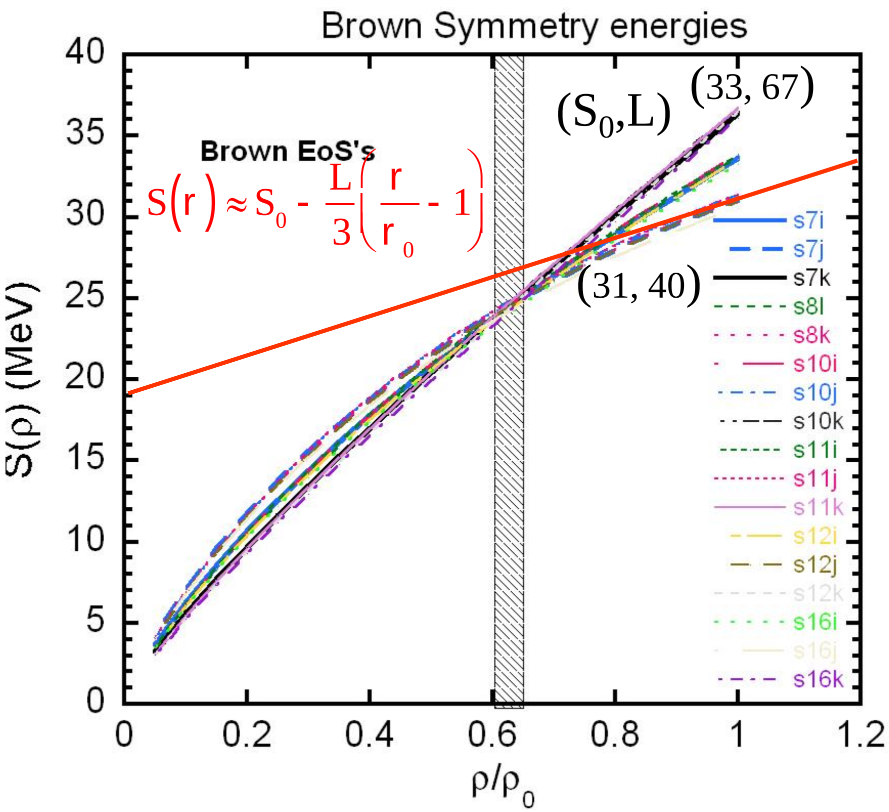


Horowitz, et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 093001

The values for S_0 and L are obtained at subsaturation densities, and are extrapolated to ρ_0.

What density does each observable actually probe? consider the fits of Alex Brown to masses.

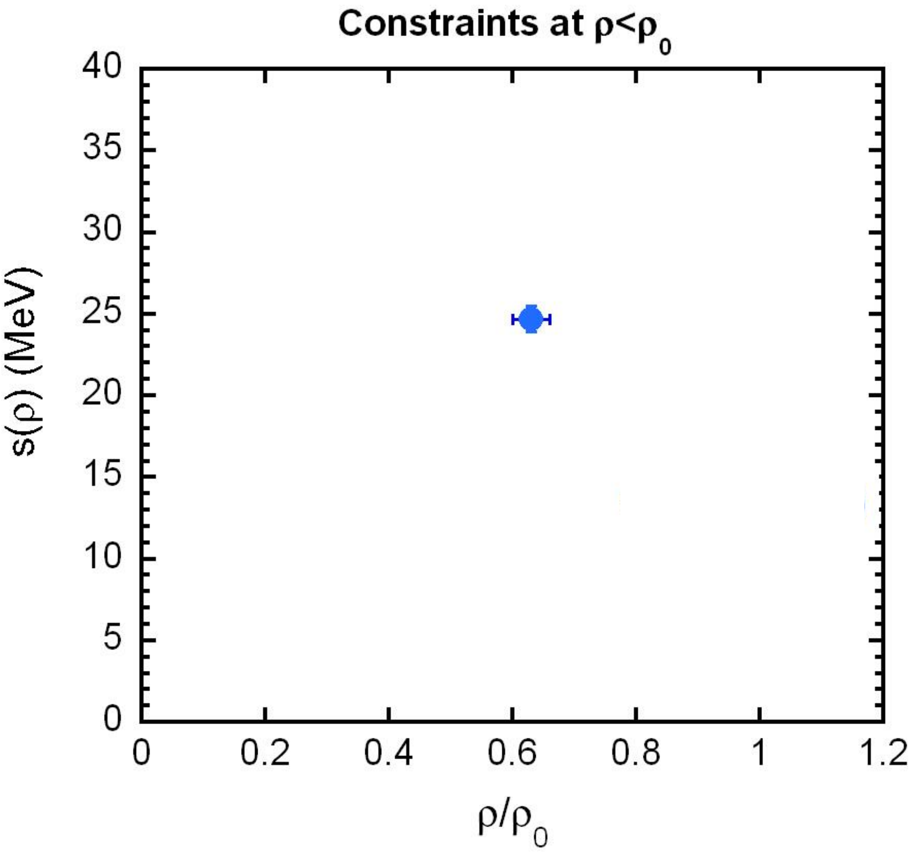
- Alex fit the masses of doubly closed shell nuclei well, but allowed different neutron skin thicknesses of ΔR_{np}=0.16, 0.20 and 24 fm. These correspond to the 3 different regions in the (S_0, L) plane.
- All Brown fits provide S(ρ)=24.8 MeV at ρ/ρ_0=0.63±.03. This is what the masses determine.
- Let’s test the linear extrapolation
- The symmetry energy functional is not linear between $0.6<\rho/\rho_0<1$.
- Extrapolation to ρ_0 depends on the non-linearity of S(ρ) at 0.63 <ρ <1, which is not constrained. Constraints on S_0 and L depend on this non-linear extrapolation.



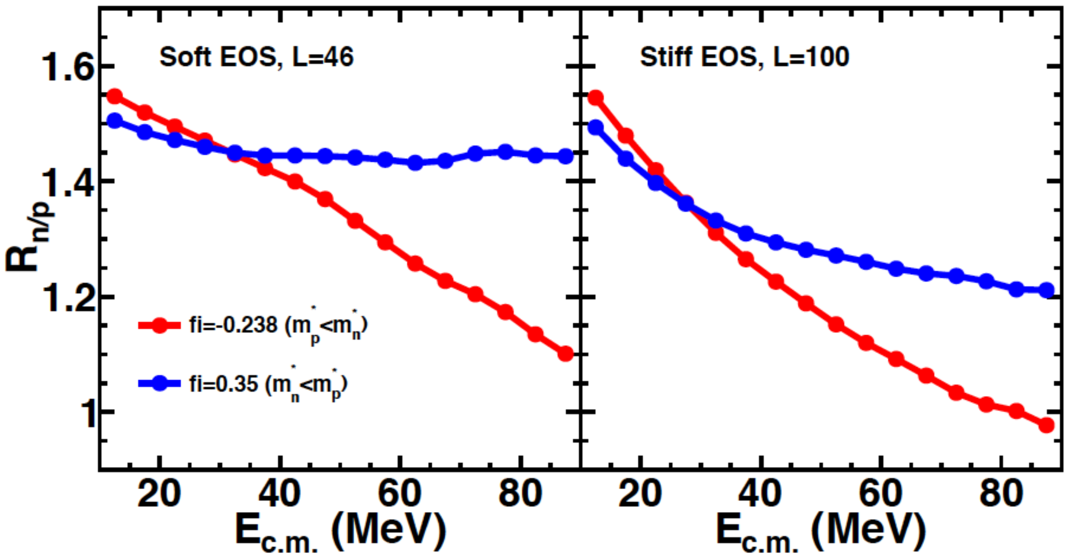
B.A. Brown, Phys. Rev. Lett. 111, 232502 (2013)

What does that tell us?

- This analysis provides an unambiguous value for S(ρ)=24.8 ±0.8 MeV at ρ/ρ_0=.0.63±0.03
- This is the density where Brown's analyses constrain S(ρ) best.
- Additional information can be provided by separately analyzing the fits of masses over different mass ranges. (e.g. Danielewicz, et al, Nucl. Phys. A 922 (2014) 1.)



Constraints from ratios of neutron and proton spectra



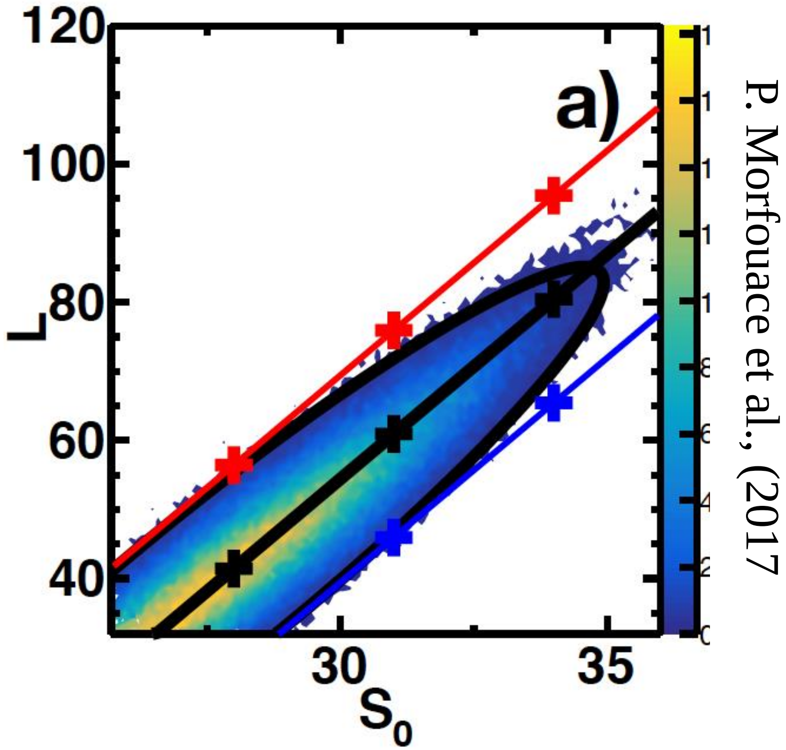
Y.X. Zhang, P. Morfouace et al., (2017

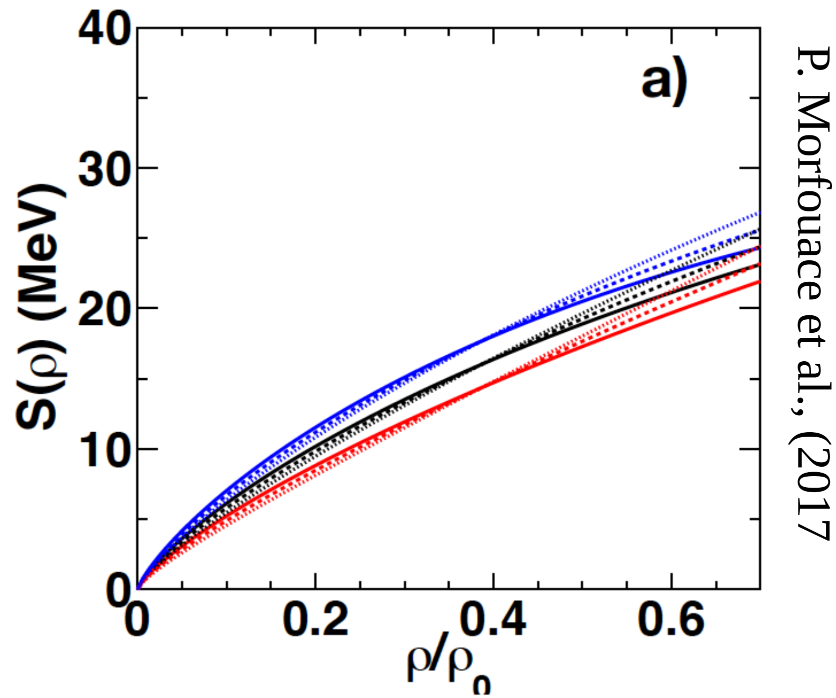
- Symmetry potential expels neutrons and attracts protons. Sensitive to L, S_0, and nucleon effective masses.
- Measured ratios spectra for neutrons and protons at 90^0 in the center of mass for central $^{124}Sn+^{124}Sn$ and $^{112}S+^{112}Sn$ collisions at E/A=120 MeV.

$$R_{n/p} = \frac{dM_n\left(q_{cm} = 90°\right) / dE_{cm}dW}{dM_p\left(q_{cm} = 90°\right) / dE_{cm}dW}$$

- Theory predicts that smaller L will result in larger $R_{n/p}$.
- Calculate the ratios with ImQMD transport theory varying S_0, L, m_n* and m_p*

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



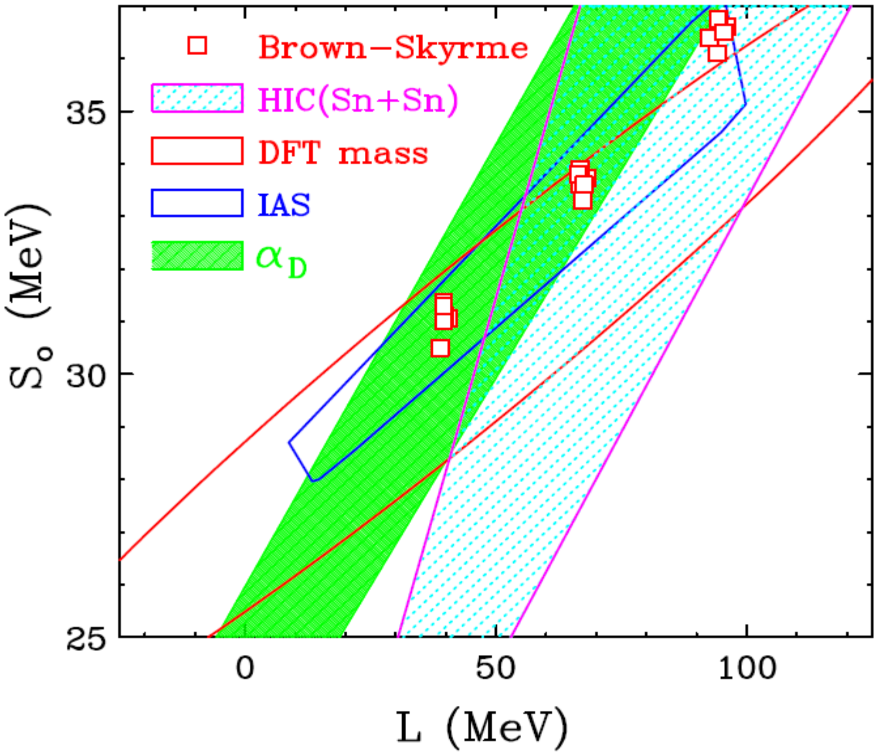


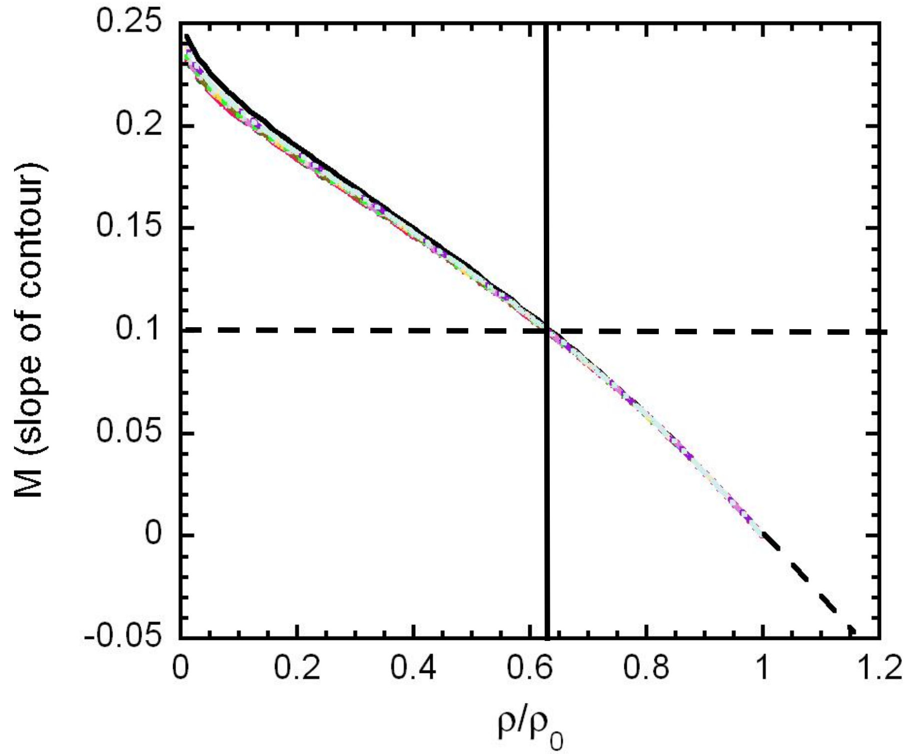
- Four dimensional Bayesian analyses of spectral ratios using Madai:
- Parameters: S_0, L, m_n^* and m_p^*

- We obtain ρ_S/ρ_0= 0.39⊕0.6 and $S(\rho_S)$ = 16.1±1.8 MeV.
- The effective masses are very important for neutron-star cooling, and will be measured more precisely next spring.
- Best fit : m_s^* / m_N=0.77±0.11 and

$$\left(m_n / m_n^* - m_p / m_p^*\right) / \left(2d\right) = 0.5 \pm 0.6$$

What density do the constraint contours imply?





- Major axis of contour is in the direction of $\vec{u}$ and has slope M

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

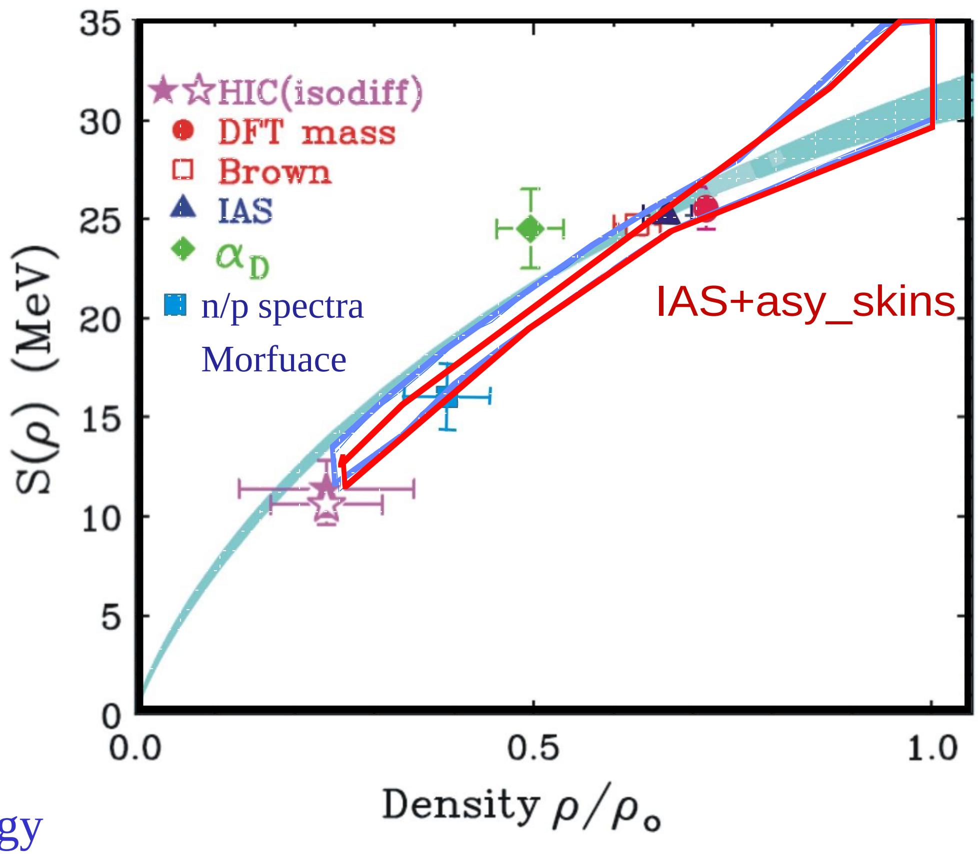
M depends monotonically on ρ_s

- Best point to evaluate M and determine ρ_s and $S(\rho)$ is at the center of the ellipse.
- ρ_s is not very model dependent, however.
- For Brown M_{exp}= -0.100± 0.008 ρ_S/ρ_0= 0.63$\oplus$0.3 and $S(\rho_S)$ = 24.7±0.8 MeV, same as before.

Density dependence of symmetry energy

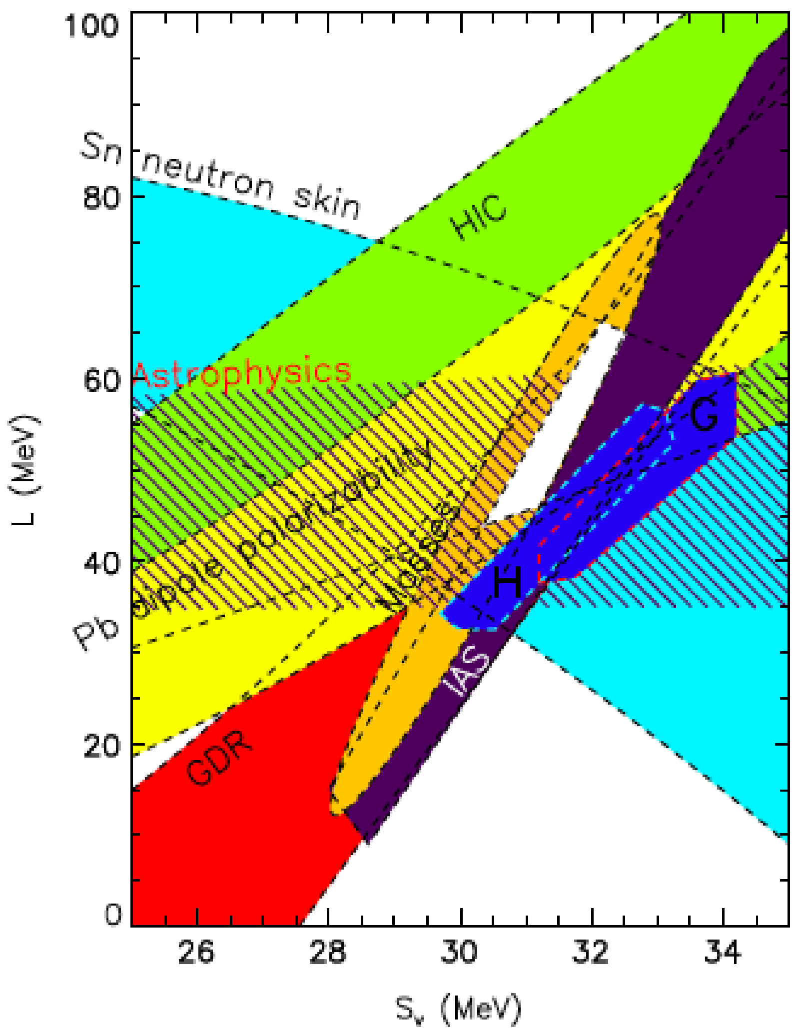
W.G. Lynch and M.B. Tsang, (2017)

- 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. PRC (2014)
- Constraints are similar to the density dependence from IAS recently published by Danielewicz et al., NPA (2017) shown by blue contour.
- Constraints from IAS and asymmetry skins by by Danielewicz et al., NPA (2017) shown by red contour.
- The polarizability constraint is not directly a constraint on symmetry energy and can not be analyzed as the others. I refer you to Zhang PRC 92, (20150.



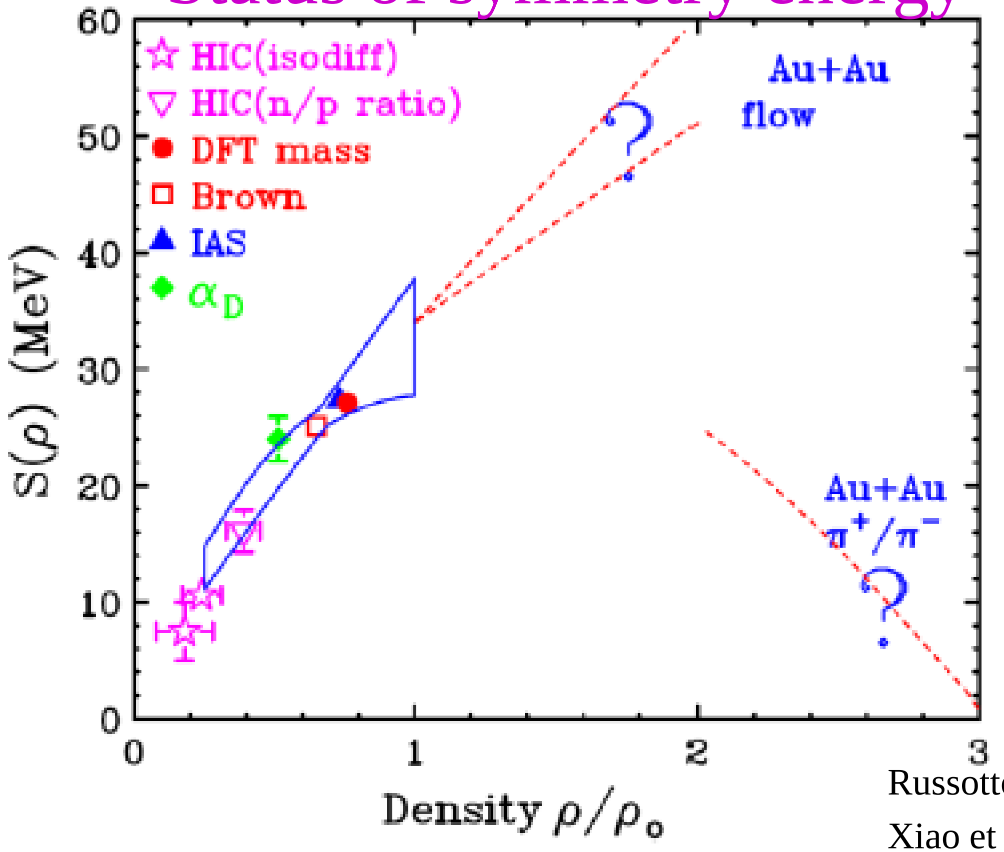
Intermediate Summary

Latimer and Prakash Phys. Rep. 92014)



- Constraint contours, as shown on the right, are inherently misleading.
  - To obtain the values for L and S_0 shown by these contours, one must do an unconstrained non-linear extrapolation from the sensitive density ρ_s to ρ_0.
  - We know little about $S(\rho)$ near ρ_0 ➔ this extrapolation is rather uncertain.
- It is much better to provide the symmetry energy at the sensitive density of each observable.

Status of symmetry energy

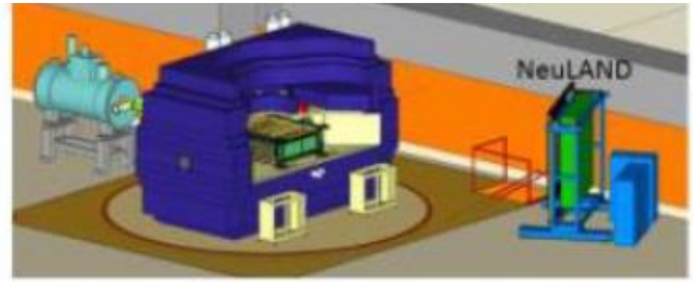


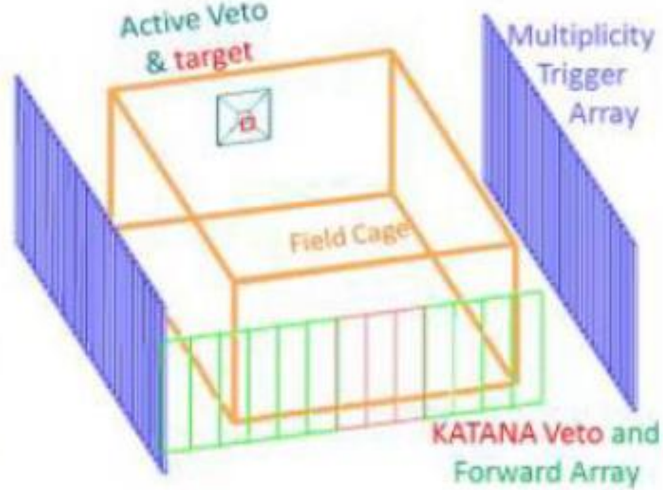
Russotto et al., PLB, 697, 471 (2011)
Xiao et al., PRL 102, 062502 (2009).

- 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.

SPπRIT-Time Projection Chamber exp. at RIBF

Experimental Setup



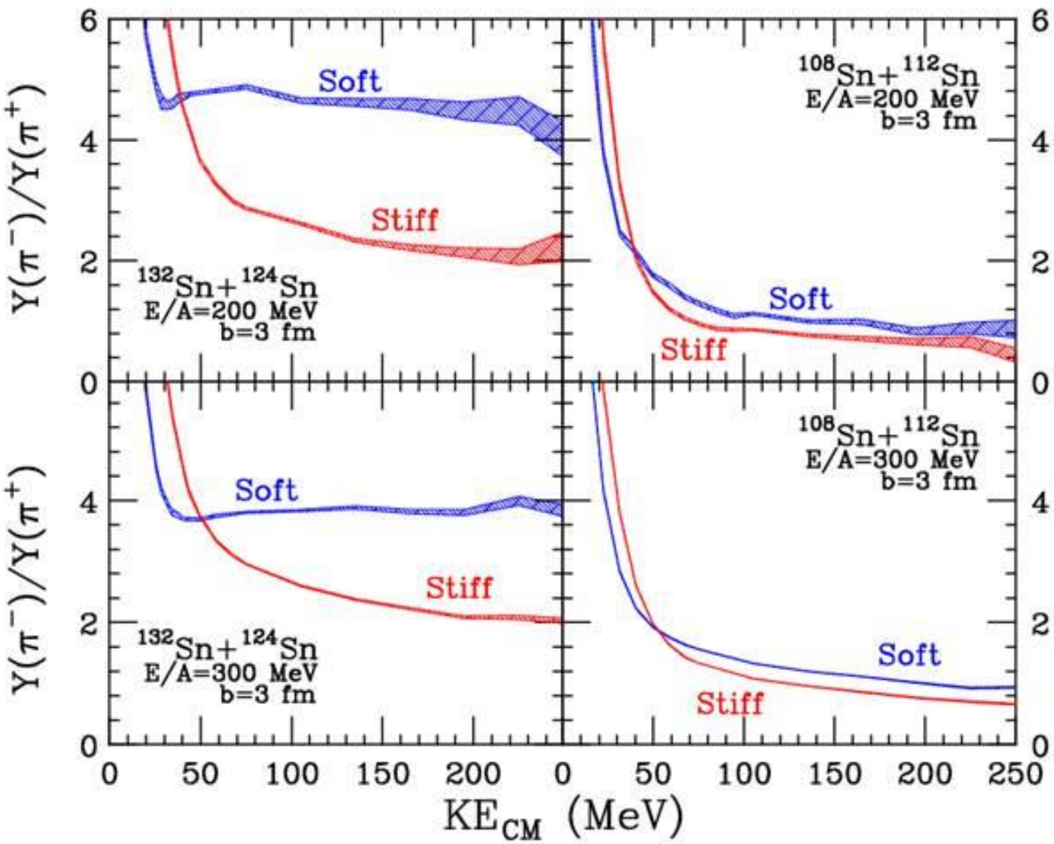


- 134 x 86 x 53 cm^3 effective volume
- dE/dX – B⟩ particle identification.
- Target at the entrance of chamber.
- Readout with ~12000 pads.
- Neutrons 15°<θ<30° meas. by NeuLAND
- Experiment completed 6/1/2016

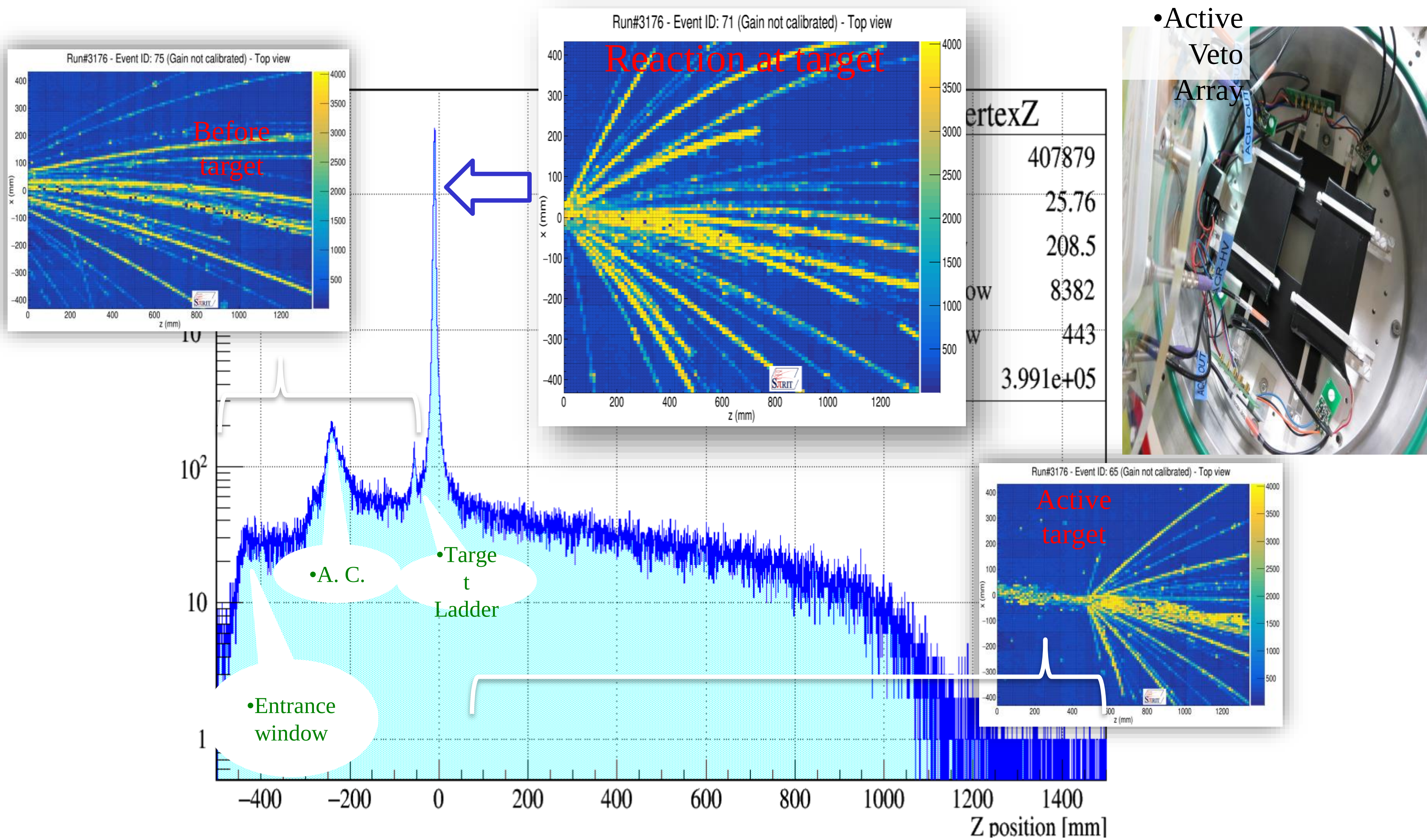
E/A MeV	Reaction	$\frac{N-Z}{A}$	focus
270	$^{132}Sn+^{124}Sn$	.22	$S(\rho)$, $m^*_n - m^*_p$
270	$^{108}Sn+^{112}Sn$	.08	$S(\rho)$, $m^*_n - m^*_p$
270	$^{124}Sn+^{112}Sn$	.15	σ_{nn}, σ_{np}, σ_{pp}
270	$^{112}Sn+^{124}Sn$	.15	σ_{nn}, σ_{np}, σ_{pp}

Studies with SπRIT TPC at $\rho >> \rho_0$

- Measure the energy dependence of pion production.
- Have measured at E/A=270 MeV.
- Spectra are sensitive to the symmetry energy.
- Most theories predict an enhanced sensitivity to the symmetry energy at lower incident energies.
- We plan to also measure at E/A=200 MeV.
  - Useful test of the transport theory description of pion production near threshold
- Similar information can be obtained by comparing neutron and proton emission.



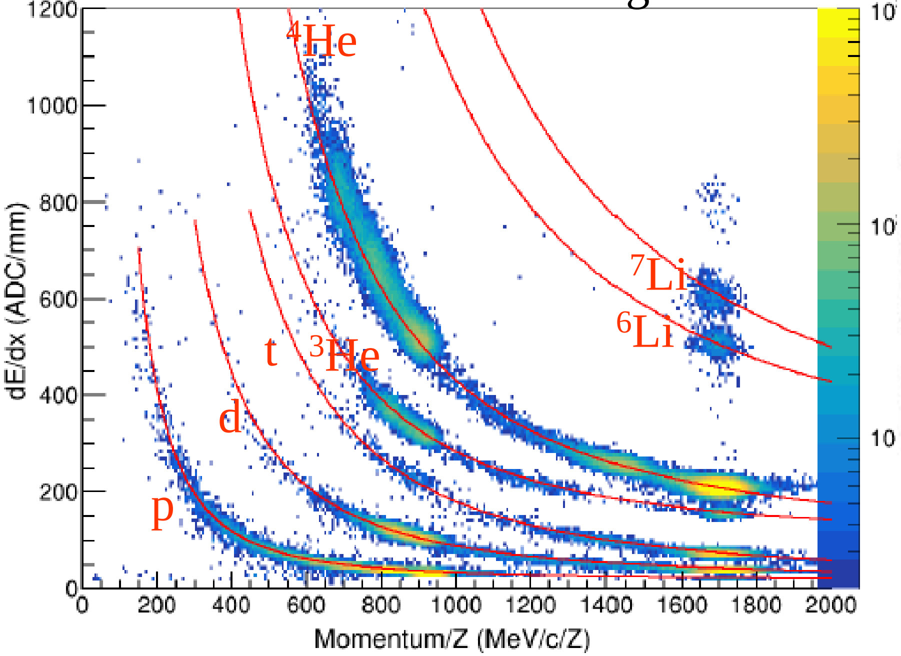
Some data: use of vertex reconstruction to separate reactions on target from reactions on counter gas.



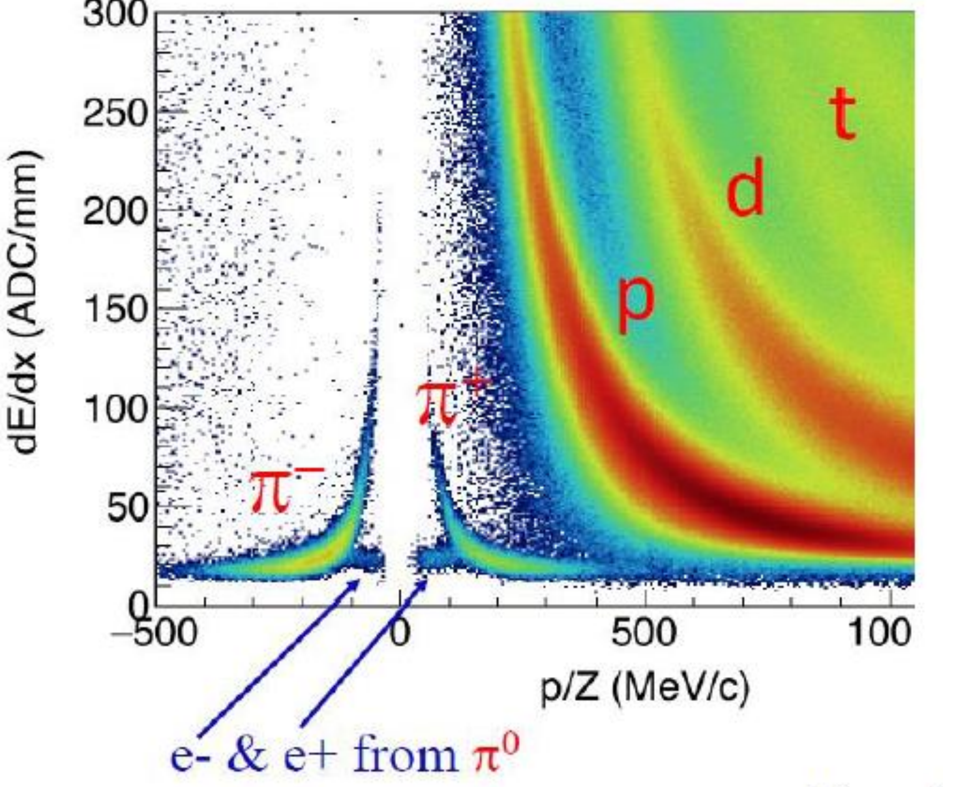
•**Background can be eliminated**

Everything worked, data looks excellent

Calibration beams at two rigidities

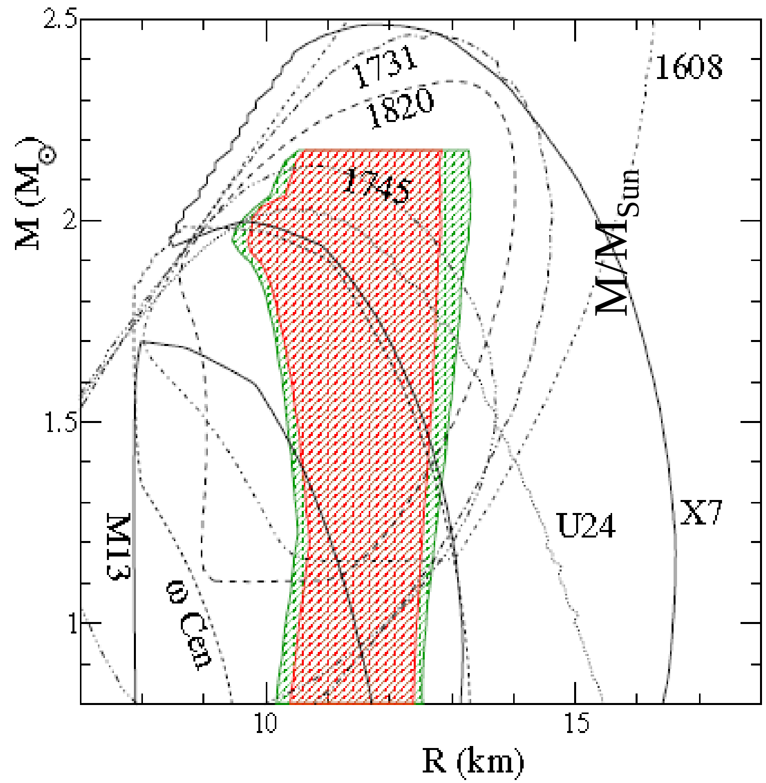


Central $^{132}Sn+^{124}Sn$ collisions

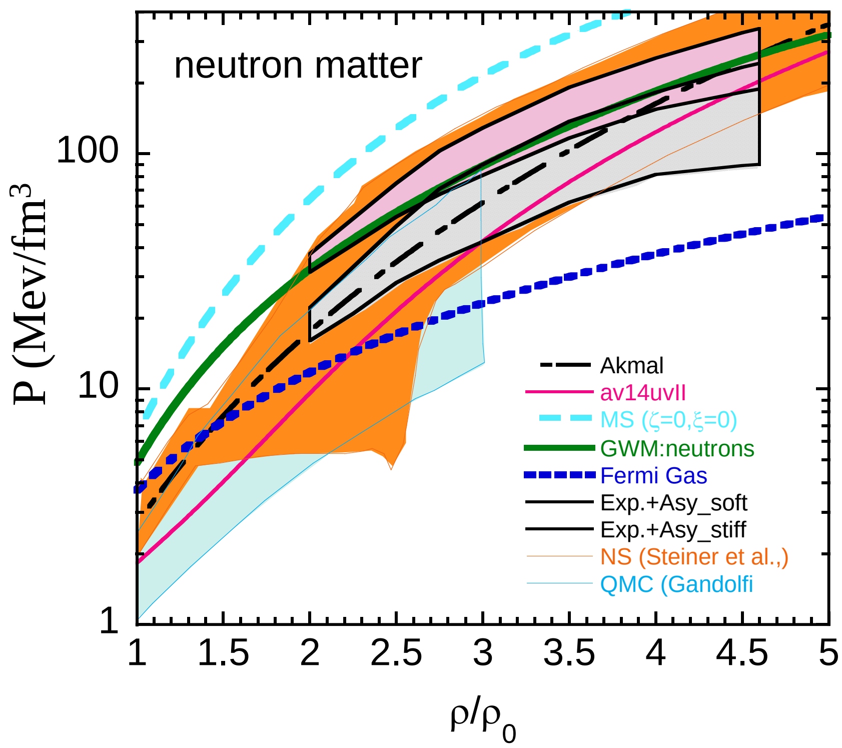


- We are able to identify cleanly pions through ions beyond ^{7}Li.
- Right now we are finalizing our calibrations for heavier ions.
- We also determining the experimental efficiencies in regions of high track density.
- First results for next year.

Relevance to the EoS at $\rho>\rho_0$



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



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

- 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 MeV/fm^3 < P < 86 MeV/fm^3 at n_B =0.43 /fm^3 from neutron star R vs. M correlation and Heavy ion collisions. (Factor of 3). Heavy ion “constraints” appear much tighter at $0.3<n_B<0.4$ /fm^3 and would be considerably improved by constraining S(ρ) at $\rho>\rho_0$.

Summary and outlook

- Significant constraints on the symmetry energy at well defined densities are emerging for $\rho<\rho_0$.
- It is important 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 $0.80<\rho/\rho_0<2.0$.
  - SπRiT TPC experimental program should be able to explore pion and nucleon observables and provide new constraints on $S(\rho)$ in the region of at $0.80<\rho/\rho_0<2.0$. This density region is highly relevant to the mass-radius relationship of neutron stars.
- This also probes the density region where there are contradictory constraints from previous measurements of π^-/π^+ spectral ratios and from the comparison of n vs. p elliptical flows.

SπRIT

SAMURAI Pion Reconstruction and Ion Tracker

50+ scientists from China, Japan, Korea, Poland, France, Germany 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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