Experimental Constraints on the EoS of Dense Matter

"Physics in *still* an Experimental Science"

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SπRIT Collaboration

HiRA Group

Nuclear Equation of State

- An equation that describes the relations among the pressure, energy, temperature, density and isospin asymmetry of nuclear systems.

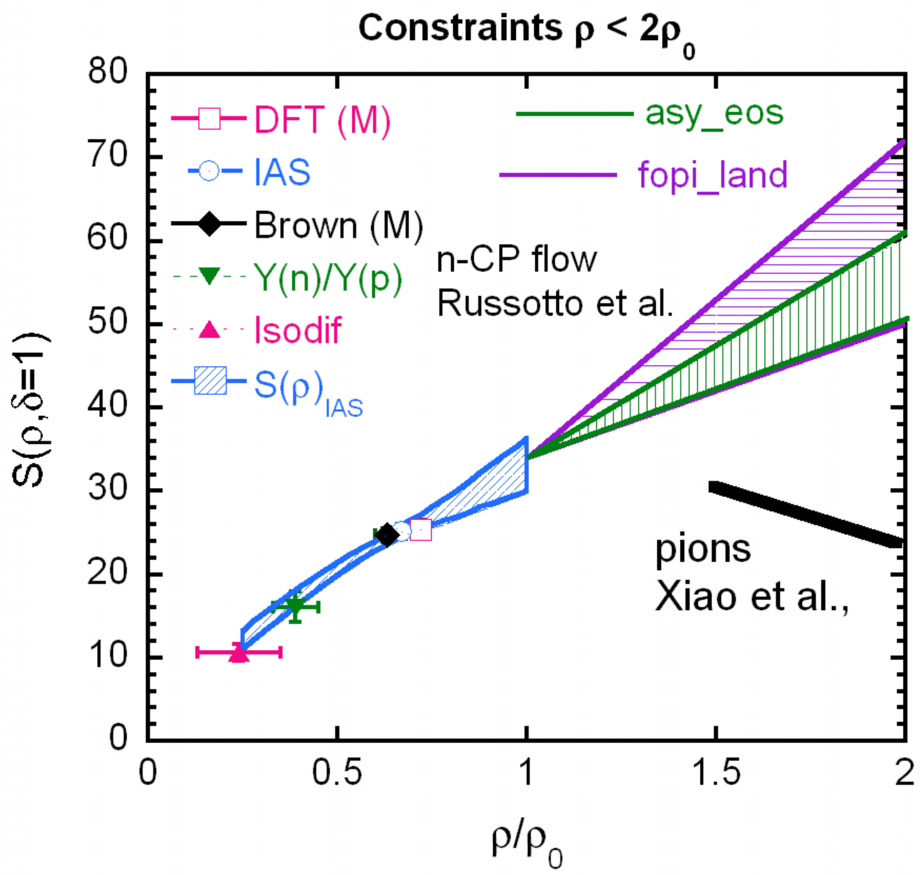
$$E/A \equiv \varepsilon(\rho,\delta,T=0) = \underline{\varepsilon(\rho,0,0)} + \underline{S(\rho,T}=0)\cdot\delta^2$$

EOS of symmetric nuclear matter

- Experimentally constrained in $0.5\rho_0 > \rho > 4.5\rho_0$
  - Collective flows
  - Isoscalar collective vibrations
  - Kaon production in HIC
- Behavior at $\rho=2\rho_0$ influences neutron star deformability and its mass radius relationship

Symmetry energy

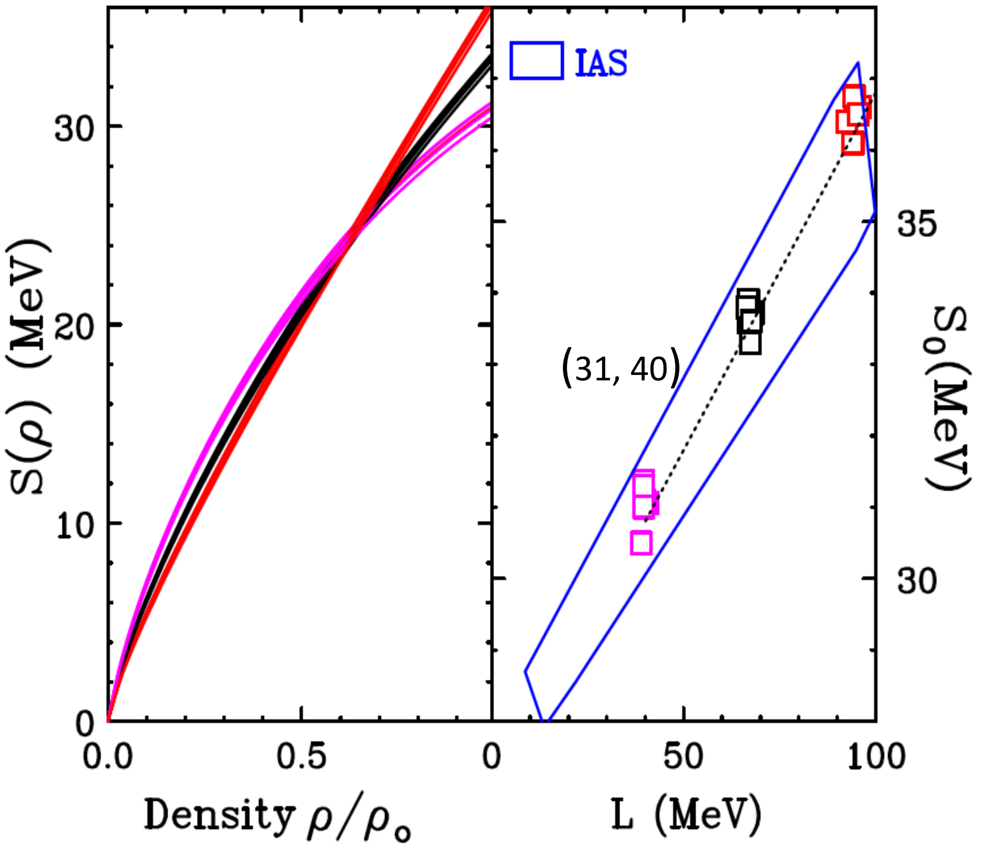
- Constrained at $0.25<\rho/\rho_0<0.75$
- Constrains crust/core transition density
- Relatively unconstrained at $\rho>\rho_0$
- Behavior at $\rho=2\rho_0$ influences neutron star deformability and its mass radius relationship



What density do nuclear masses constrain?

- Crossover technique:
  - Alex Brown fit the masses of doubly closed shell nuclei, while setting different values neutron skin thicknesses of ΔR_{np}=0.16, 0.20 and 0.24 fm. All Brown fits provide S(ρ)=24.8±0.7 MeV at ρ/ρ_0=0.63±.03 as shown at left.
- Slope technique
  - The values for S_0 and L lie on a line in the S_0 and L plane along which $S(0.63\rho_0)$ remains constant. This line lies perpendicular to the gradient of $S(0.63\rho_0)$ in the the S_0 and L plane.
  - The slope, M, of the line and the form of the function is sufficient to determine ρ/ρ_0=0.63±.03 and S(ρ)=24.8 ±0.7 MeV.
- Pearson correlation technique
  - Stabdard statistical analysis technique that can correlate data or assumption with conclusion

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



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

M depends monotonically on ρ_s

Influence of S(ρ) on a neutron star

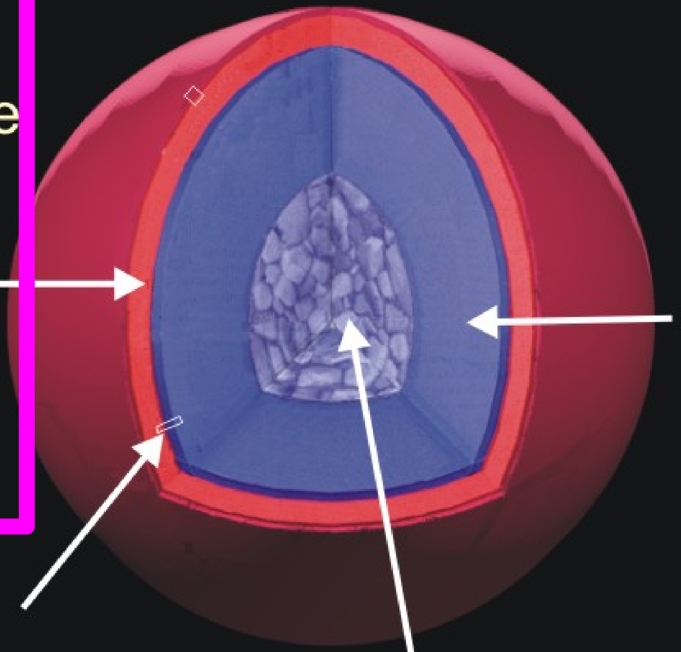
S(ρ): = density dep. of symmetry energy

$\rho < \rho_0$

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

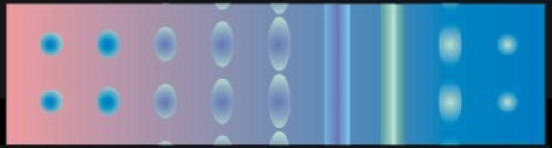
$\rho > \rho_0$

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: [redacted]



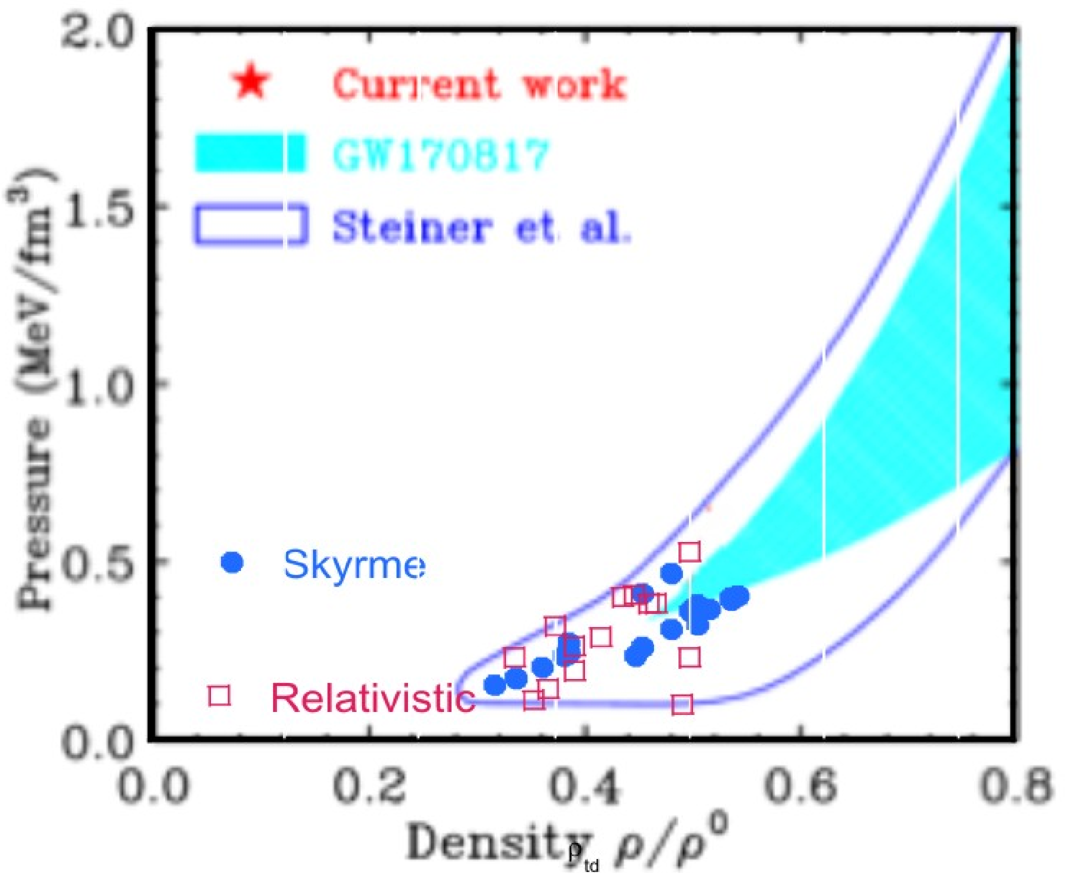
At the crust-core boundary uniform matter becomes adiabatically unstable to break into isolated liquid structures surrounded by neutron-rich gas.

What a constraint on masses provides.

- Ducoin et al., calculated the crust-core transition density, pressure and proton fraction for 21 Skyrme and 14 relativistic models. Ducoin et al, C 83, 045810 (2011)
- Observed that the transition density, pressure and proton fraction are strongly correlated with the first three terms of a Taylor expansion of the symmetry energy functional about $\rho_{01}=0.10\ fm^{-3}$.

$$S(\rho) = S_{0.1} + \frac{L_{0.1}}{3}\left(\frac{\rho}{\rho_{0.1}} - 1\right) + \frac{K_{sym,0.1}}{18}\left(\frac{\rho}{\rho_{0.1}} - 1\right)^2 + \dots$$

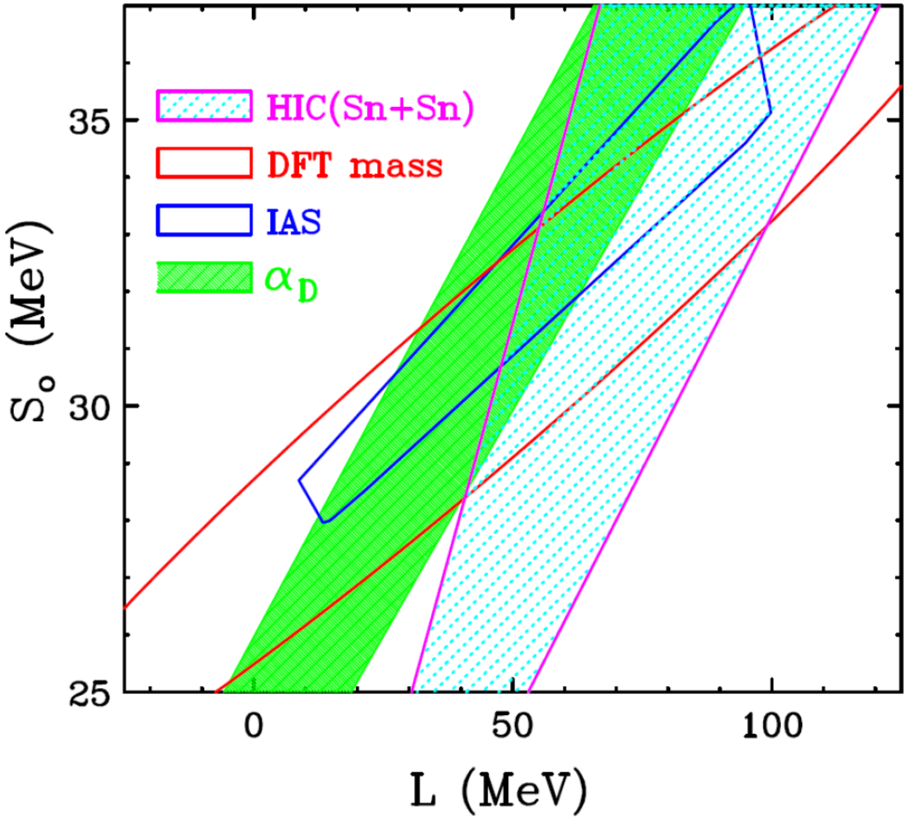
- They showed that these differences in the predictions for P_{cc} and ρ_{cc} stem from differences in L_{01} and K_{01}



$$L_{01} = 2\rho_{01}\,\partial S/\partial\rho\big|_{\rho_{01}} \qquad K_{01} = (2\rho_{01})^2\,\partial^2 S/\partial\rho^2\big|_{\rho_{01}}$$

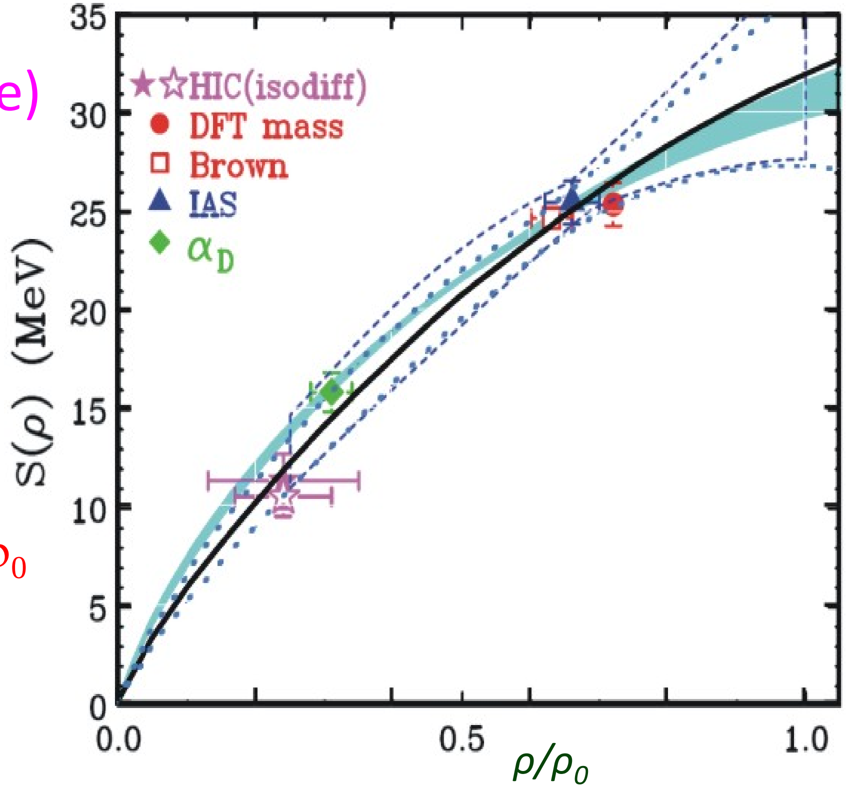
From S_0 – L correlations to $S(\rho)$

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



- HIC (cross-over, slope)
- IAS (Pearson, slope)
- α_D (Pearson)
- Dft (slope)_

The contours are the constraints extrapolated to ρ_0

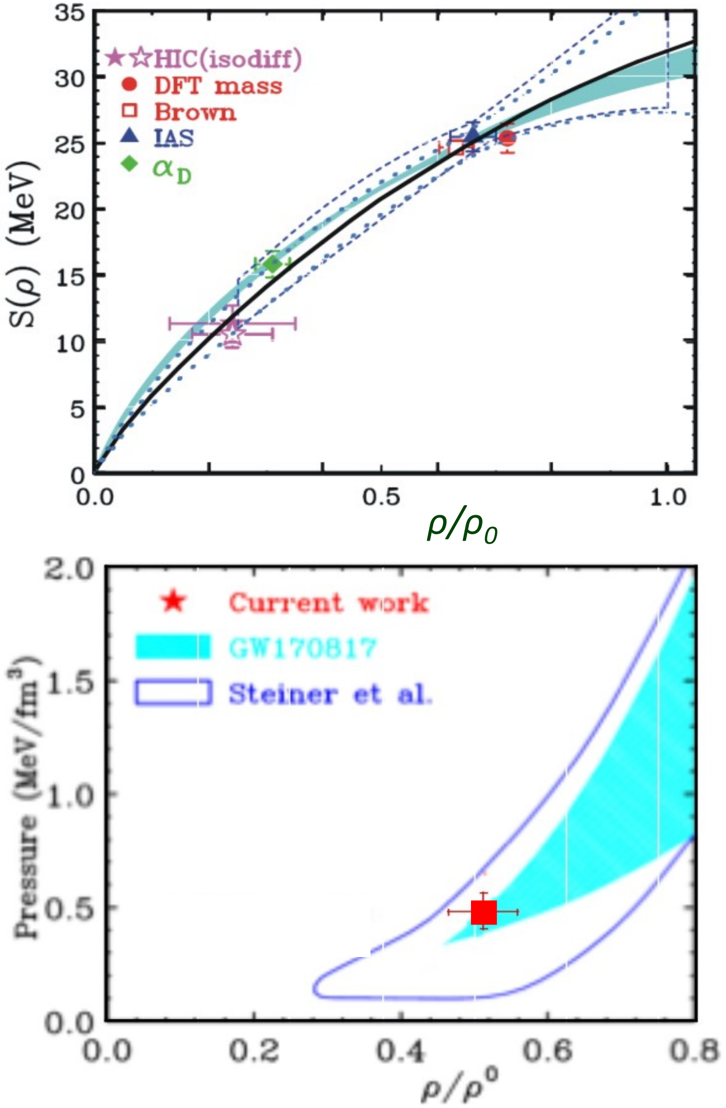


- Note the consistency of the results.
- If you want to measure $S(\rho)$ you need a observable that probes ρ at the density you need it.

Constraints on the crust-core transition density

- Constraints on $S(\rho_s)$ from structure and low energy reactions are shown by the points in the top figure. The solid line shows a constrained fit to these data.
- Following Ducoin et al., PRC, 83 (2011) 045810, this fit enables a good estimate of the NS crust-core transition density and pressure.
- The red point in the lower figure shows the cross-core transition density and pressure obtained from this fit. It implies that the crust core transition occurs at $\approx \rho_0/2$.
- Additional or more precise constraints on $S(\rho_s)$ will help. A tighter constraint on L would be especially helpful.

$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho}{\rho_0} - 1\right) + \frac{K_{sym}}{18}\left(\frac{\rho}{\rho_0} - 1\right)^2 + \dots$$



Lynch and Tsang, arXiv:1805.10757 5.10757 & 2019

What do we know to constrain EoS of symmetric nucleonic matter at $\rho>\rho_0$?

1. Transport Theory: e.g. BUU Time dependent Thomas Fermi
2. Density dependent momentum independent mean field potentials (Direct term HF).

$$U_n\left(\rho_n,\rho_p\right) \qquad U_p\left(\rho_n,\rho_p\right)$$

   - Must bind nuclei properly at correct density and nuclear radius.
   - Extrapolate reasonably to high density

3. Density dependent momentum dependent mean field potentials (Exchange term. Finite range)

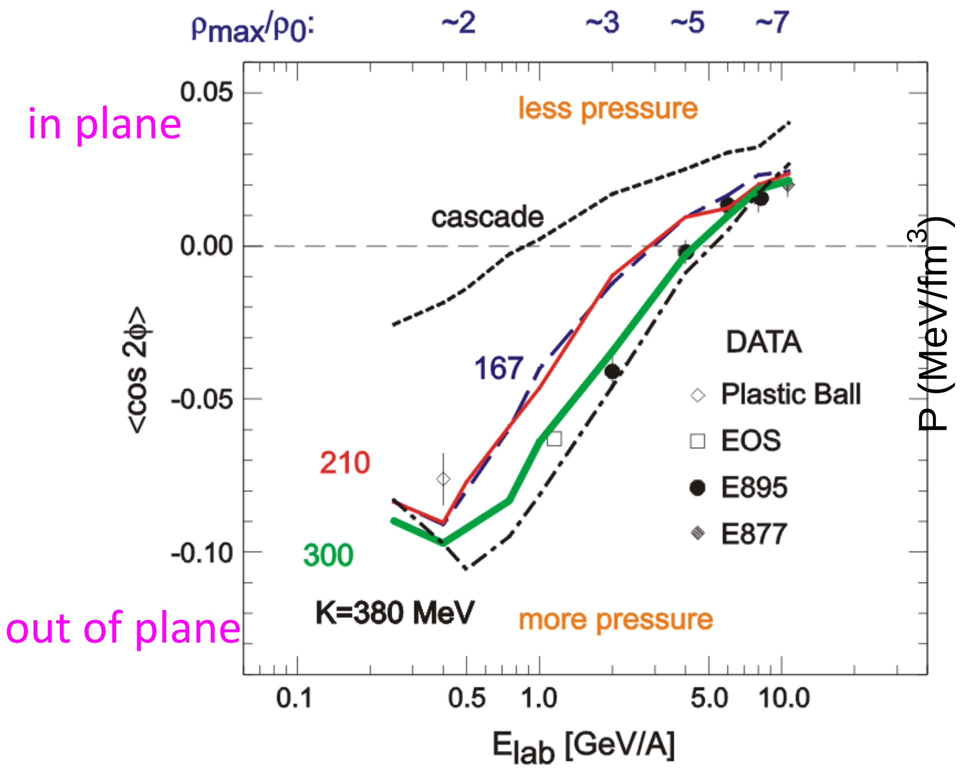
$$U_{n,k}\left(\rho_n,\rho_p,p_n^2,f_n\left(p_n\right),f_p\left(p_n\right)\right) \qquad U_{p,k}\left(\rho_n,\rho_p,p_n^2,f_n\left(p_n\right),f_p\left(p_n\right)\right)$$

   - Governs the thermal and non-equilibrium behavior and momentum dependence of optical potentials.

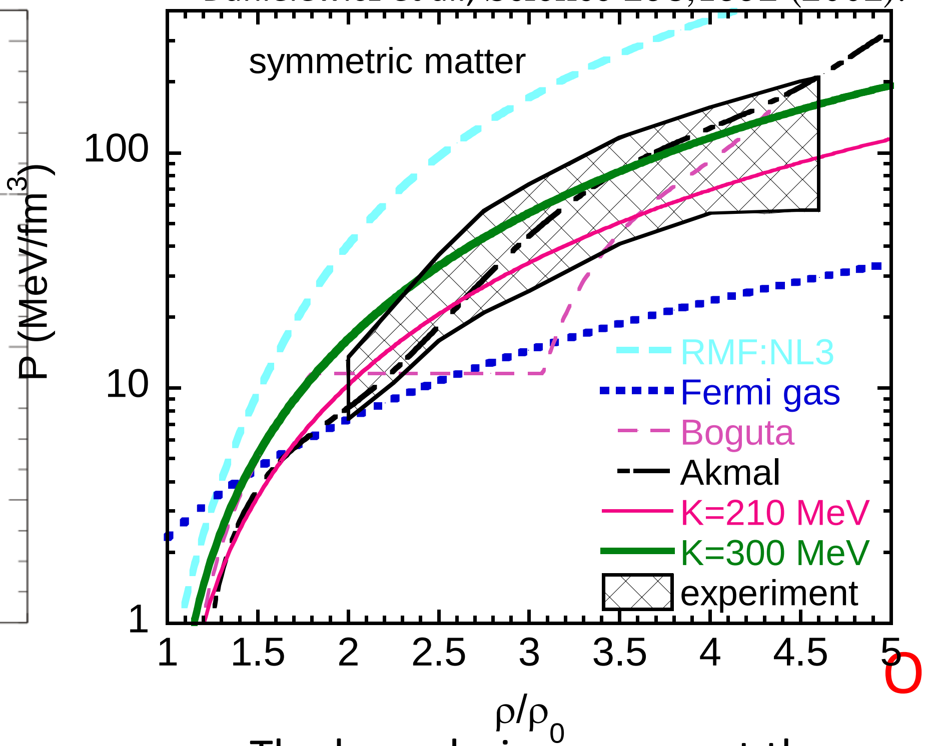
4. Cross sections induced by the residual interactions+ Pauli blocking

- All of these quantities must be fixed by Experimental Data!

Determination of symmetric matter EOS from nucleus-nucleus collisions



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

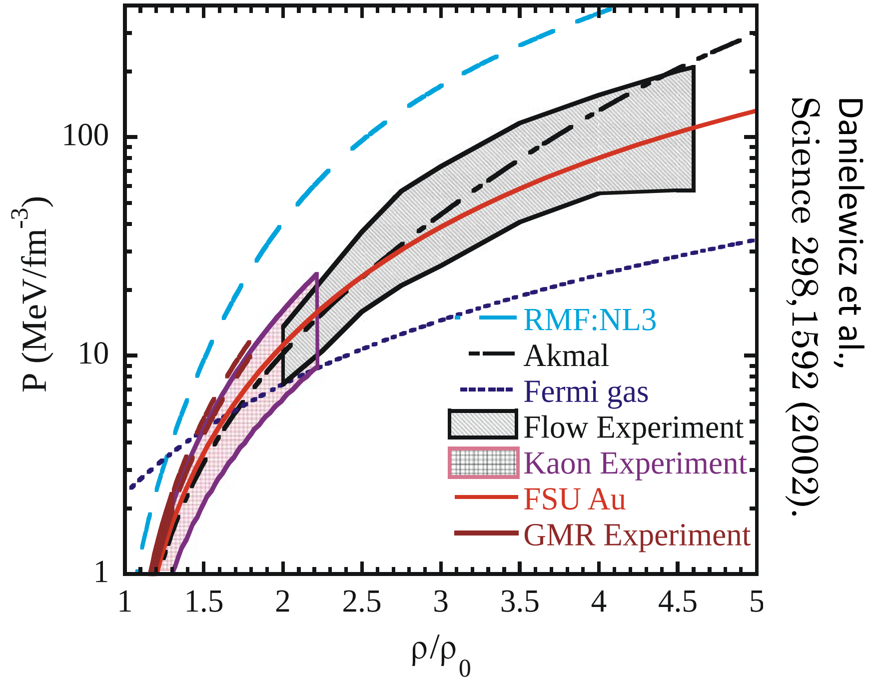


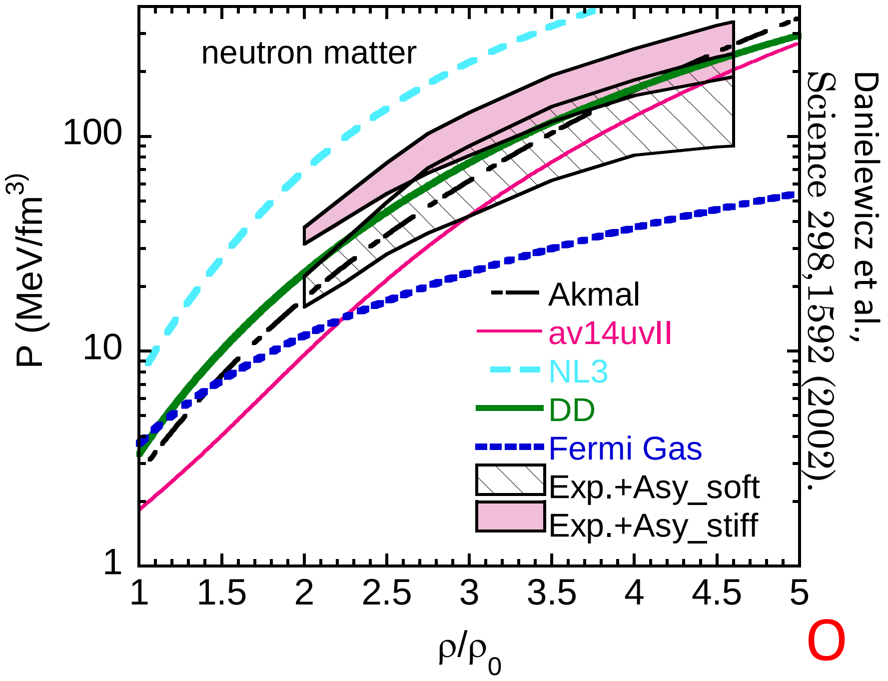
- The curves labeled by K_{nm} represent calculations with parameterized Skyrme mean fields
  - They are adjusted to find the pressure that replicates the observed transverse flow.

- The boundaries represent the range of pressures obtained for the mean fields that reproduce the data.
- They also reflect the uncertainties from the effective mass and in-medium cross sections.

Constraints from collective flow on EOS at $\rho > 2\rho_0$.

$E/A(\rho, \delta) = E/A(\rho, 0) + \delta^2 \cdot S(\rho)$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$





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- Note: analysis required additional constraints on m* and σ_{NN}.
- 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.

- The symmetry energy dominates the uncertainty in the n-matter EOS.
- Both laboratory and astronomical constraints on the density dependence of the symmetry energy are urgently needed.

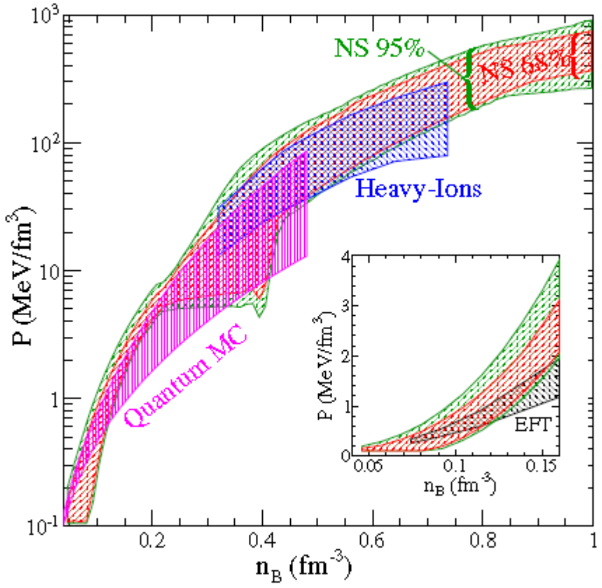
How does this match to various neutron star observations?

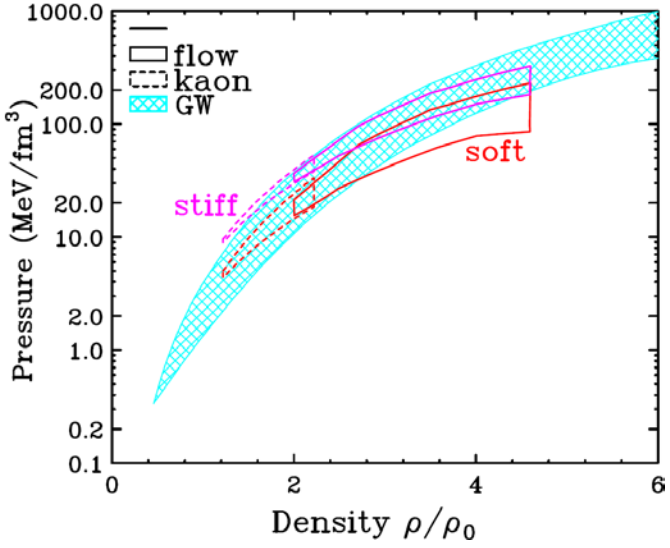
$$EoS \Leftrightarrow \varepsilon(\rho,\delta) \approx \varepsilon(\rho,0) + S(\rho)\delta^2; \delta = (\rho_n - \rho_p)/\rho$$

- Symmetric matter ε(ρ,0) at ρ>ρ
  - Flow with EoS TPC at LBL (2002)
  - GSI Kaon constraint (2009)
  - GSI Flow constraint (2016)
  - Essential to constrain
    - local isoscaler mean field: $\varepsilon(\rho, 0)$
    - Non-local isoscaler mean field: $m_S^*(\rho)$
- Extrapolation to neutron matter:
  - Using parameterization by Prakash & Latimer

    $S(\rho)_{stiff}=12.7\times(\rho/\rho_0)^{2/3}+38\times(\rho/\rho_0)^2/(1+\rho/\rho_0)$

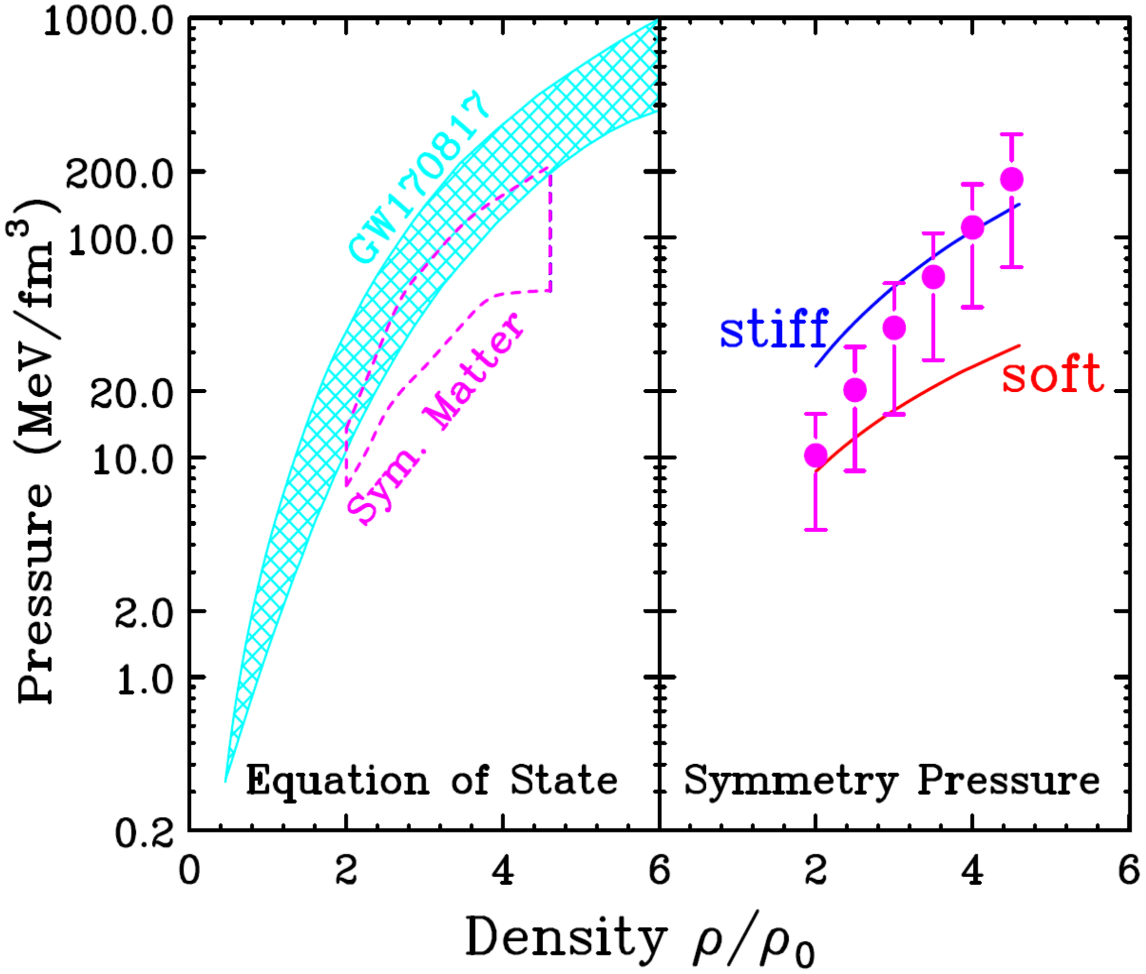
    $S(\rho)_{soft}=12.7\times(\rho/\rho_0)^{2/3}+19\times(\rho/\rho_0)^{1/2}$
  - This a reasonable bracketing assumption.
  - Matches NS radii from x-ray bursters
  - Matches GW17081 constraints amazingly well.





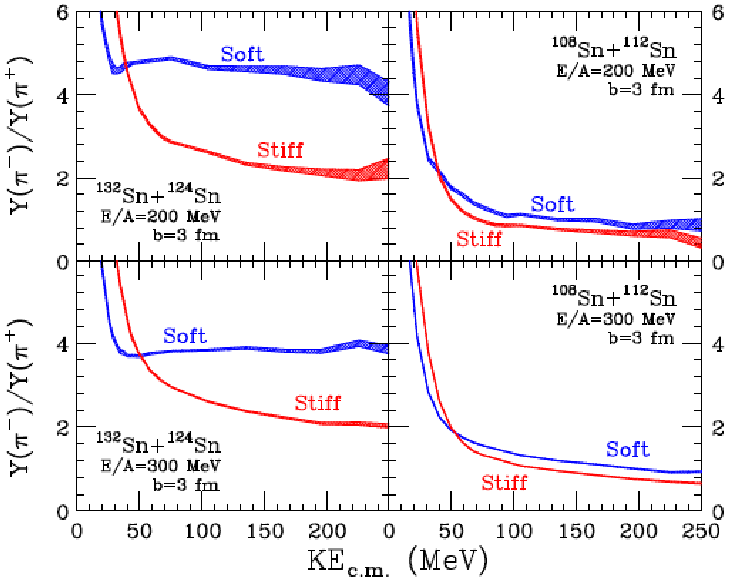
What have we learned about the symmetry energy or symmetry pressure?

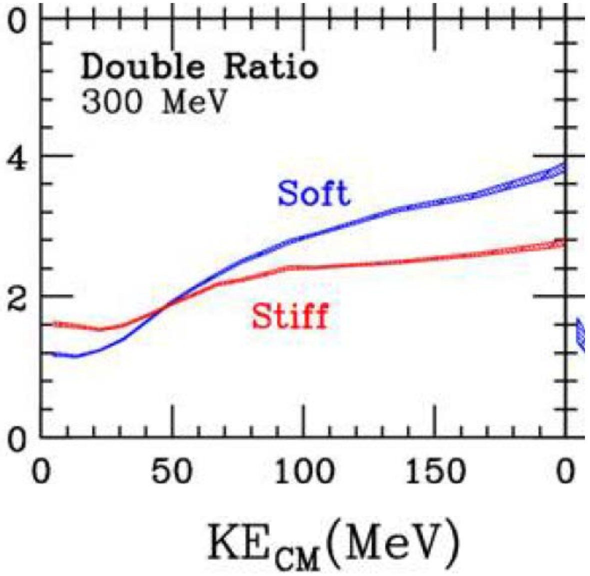
- GW neutron matter pressure exceeds pymmetric matter pressure.
- Most probable symmetry pressure can be obtained by subtraction.
- “Error bars” are 50% confidence limits.
- At 90% confidence level a negative symmetry pressure, corresponding to decreasing symmetry energy cannot be precluded.
- Need laboratory constraint on symmetry energy



The Symmetry energy is key to determining where the phase transitions occur within neutron stars (crust-core, delta, strange or quark matter).

- No astronomical observation *currently constrains the symmetry energy in the NS core*.
- Goal of experiments is to probe *Symmetry energy in HIC at energies where densities approach* 2▯0
  - $For\ {}^{132}Sn + {}^{124}Sn, symmetry\ energy\ repels\ n's\ from\ and\ p's\ to\ dense\ neutron\ rich\ region.$
  - $For\ 108Xe + 112Sn\ symmetry\ \ plays\ almost\ no\ role \rightarrow$ both reactions are important.
  - $1^{st}\ observable$: $Y(n, KE)/Y(p, KE)$: (radial, transverse, ellliptcal flows): sensitive to S(ρ), $m_v^*(\rho)$
    - Nucleonic probes improve with incident energy.
    - Gave reasonable positive pressure in Au+Au collisions
    - See talk by A. Le Fevre





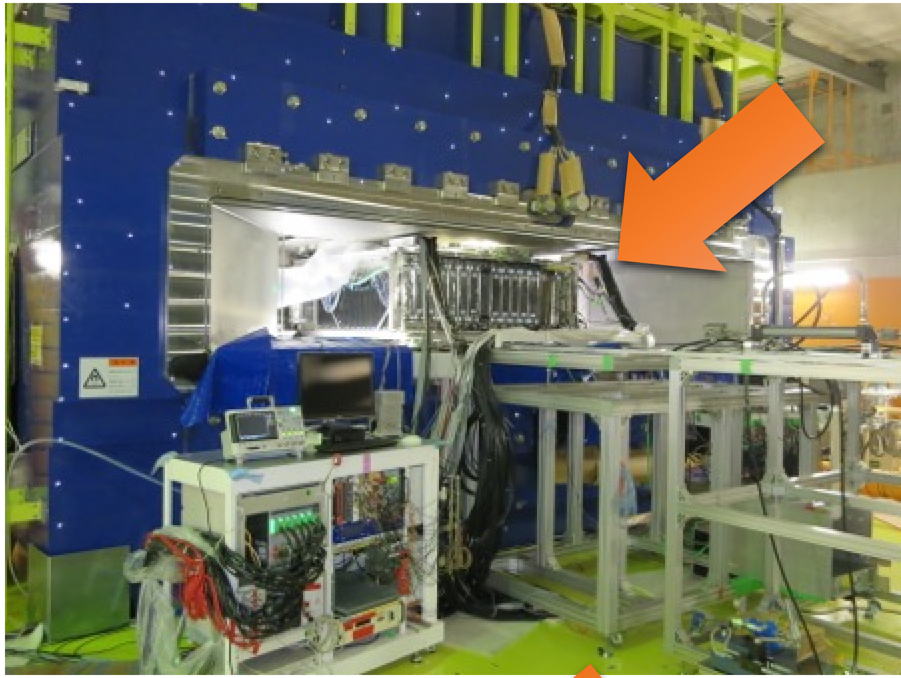
- $2^{nd}\ obs.: Y(\pi^-, KE)/Y(\pi^+, KE)$
  - Probe more sensitive at lower incident energy.
  - Potentially large effects
  - No published data

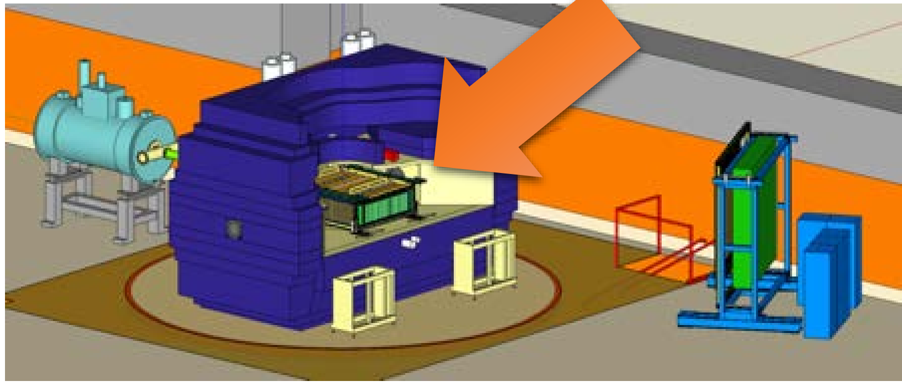
Proposed pion measurements of ratios and double ratios

Double ratio depends only on symmetry energy

SπRIT 2016 Campaign

- SAMURAI Pion Reconstruction and Ion Tracker Time Projection Chamber was installed within the SAMURAI superconducting magnet at RIBF/RIKEN.
- NueLAND was located at ~30^0





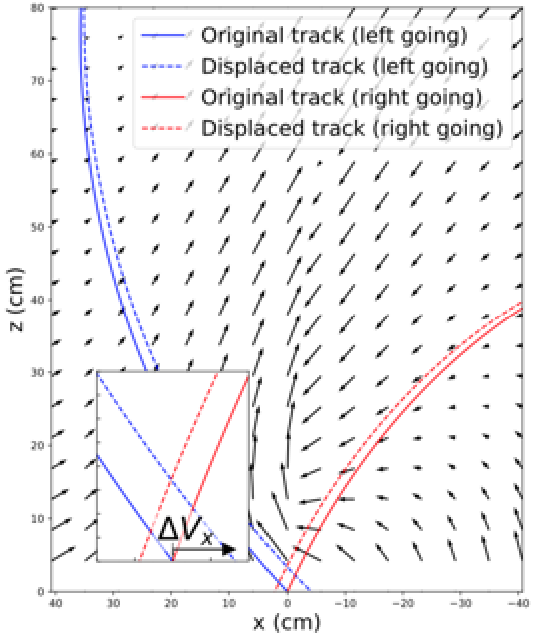
- E_{beam}=270 AMeV

System	δ=(N-Z)/A	#events
$^{132}Sn+^{124}Sn$	0.22	$3.8x10^6$
$^{108}Sn+^{112}Sn$	0.09	$2.4x10^6$
$^{112}Sn+^{124}Sn$	0.15	$1.8x10^6$
$^{124}Sn+^{112}Sn$	0.15	$2.5x10^5$

Cocktail (Z=1~3) with E=100, 300 MeV

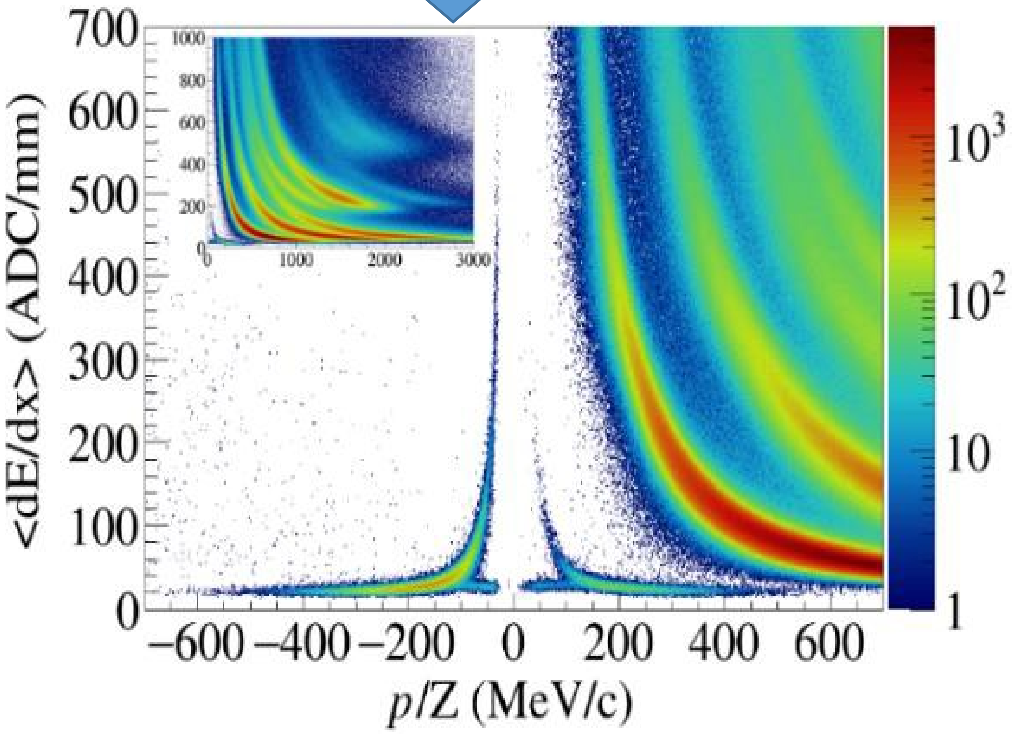
Technical results from previous experiment

- Eight technical papers published. One patent.
- Two more under review and two more in preparation.
- Illustrative examples:
  1. Algorithm for space charge corrections in a TPC.
  2. Dynamic range extended by factor 5, effectively 4000 to 1 maximum signal to noise.
  3. Efficiency by embedding test tracks in real data.



Uncorrected track misses vertex

PID from pions beyond Lithium



Scientific Results: 4 papers in preparation

- Seven groups of transport theorists have working to together for three years to make transport theory more quantitative.
- Published 3 theoretical articles on Transport model evaluation project. One focus was on transport model comparisons with analytically known solutions.
- First focus was on the total pion ratio $Y(\pi-)/Y(\pi^+)$.
- Error in data is size of points and mostly systematic:4% for multiplicity and 2% for ratios.
- Theory underpredicts data for many models.
- Normalizing pion production mechanism on Au+Au at E/A=400 MeV may have been problematic. → Normalize on Xe+Sn reactions and check the energy dependence carefully.

1^{st} paper

G. Jhang et al

Unpublished work.

Please do not distribute!

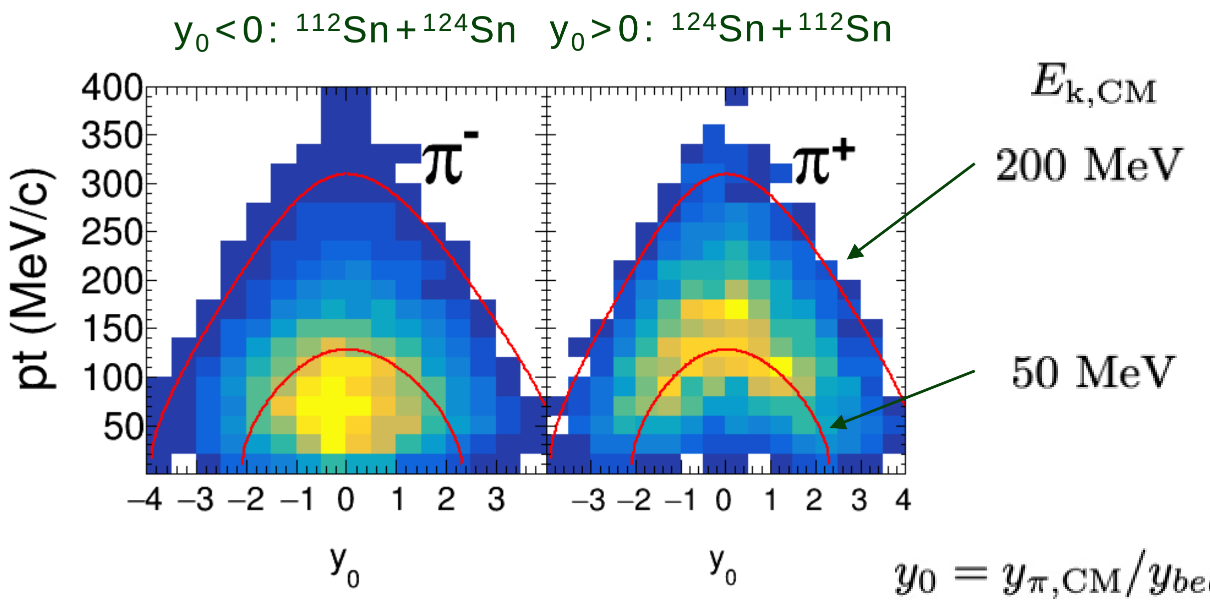
Effect of stiff of $S(\rho)$
Is known to be small.
Our uncertainties are small enough, but our focus is on spectra

Analysis of mirror systems   from J. Barney

2nd paper

- p_T-y_0 plot for π- shows Coulomb attraction towards the collision center resulting in low emission energy. Opposite phenomenon is observed for π+ by Coulomb repulsion.
- π-/π+ ratio shows symmetric in forward and backward rapidity regions as expected.

Unpublished work. Please do not distribute!

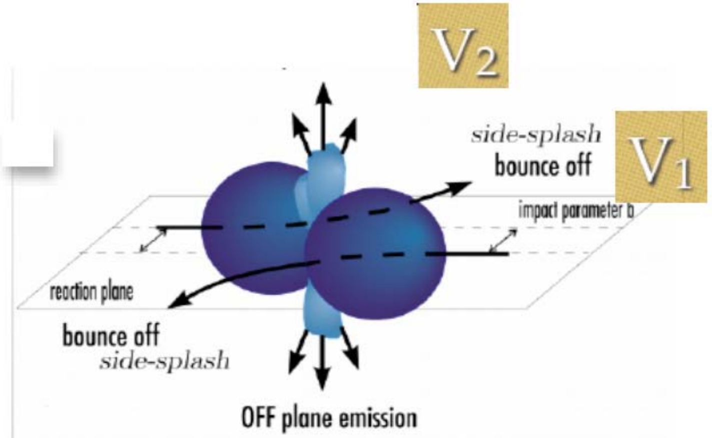


$y_0 = y_{\pi,\mathrm{CM}}/y_{beam,\mathrm{CM}}$

y_0

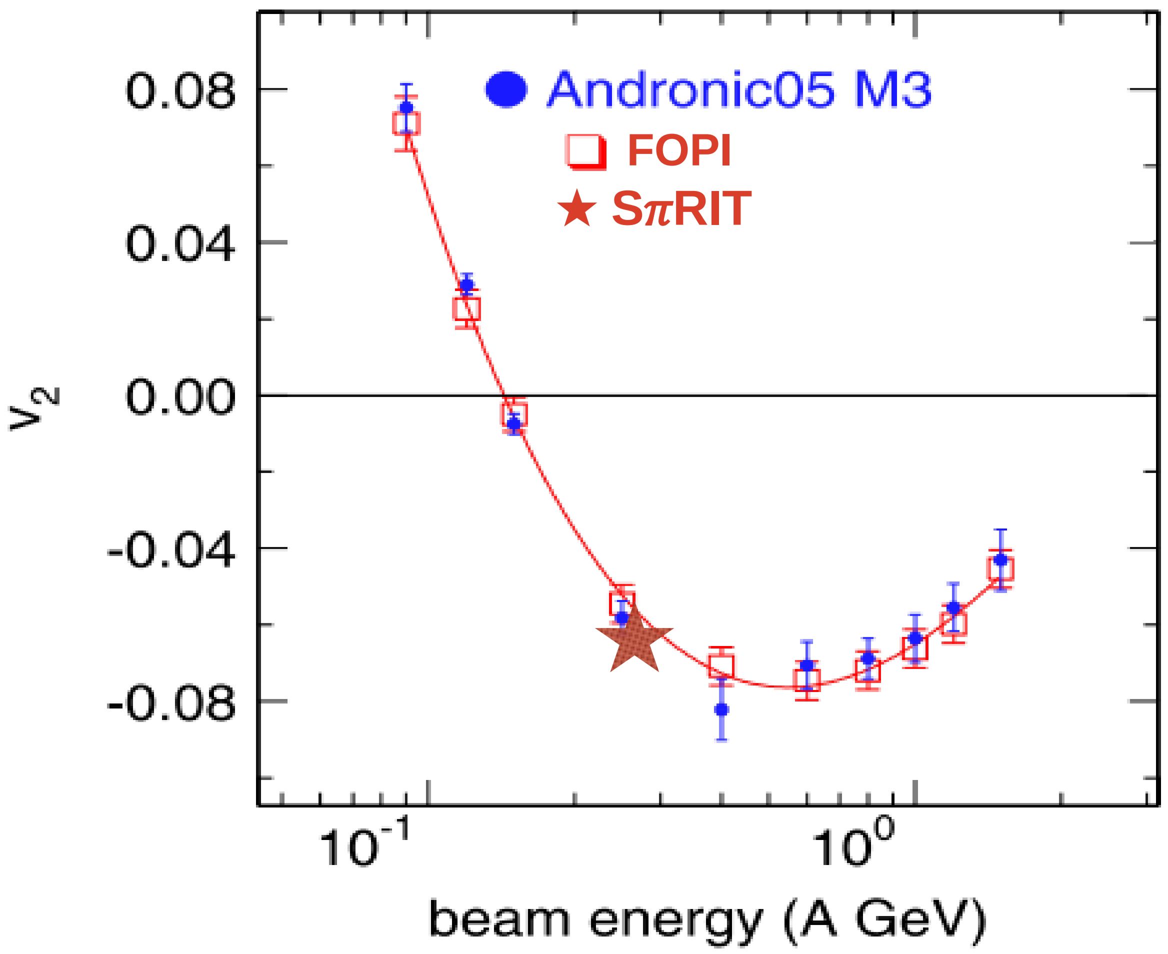
Isospin dependence of Elliptical Flow

from M. Kurata-Nishimura



- Comparison of $^{132}Sn+^{124}Sn$ and $^{108}Sn+^{112}Sn$ collisions

- Comparison of $^{132}Sn+^{124}Sn$ to systematics



Summary

- Experiment can be useful if the observables are carefully chosen so that the unknowns are constrained.
  - Example: crust-core transition density, you need to go beyond masses!!
- You need to know what density your observable probes!
  - Please do quantitative sensitivity tests.
- For HIC you need to constrain all unknowns in your theory.
  - Density dependent, momentum independent mean field potential
  - Density dependent momentum dependent mean field potential
  - In medium cross sections.
- Until that is done, all constraints will be preliminary.
- Right now the pressures in neutron stars are known to about factor of four.
- If you can constraint the pressure to less than a factor of two, it is progress,