Probing the nuclear symmetry energy with heavy ion collisions

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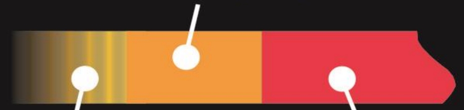
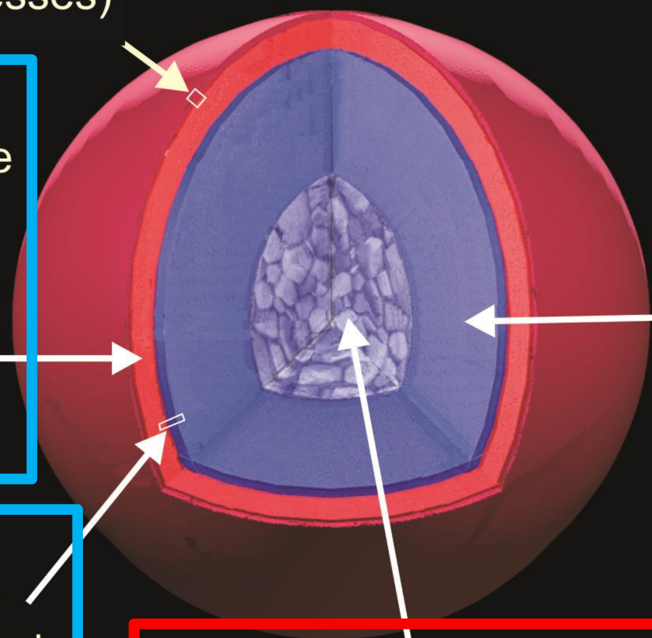
- Relevance to neutron stars
- Improving constraints at sub-saturation densities
- Improving constraints at supra-saturation densities
- Issues of momentum dependence
- Outlook and perspectives

To progress, you need the relevant Equations of State for matter in the star

Anatomy of a neutron star

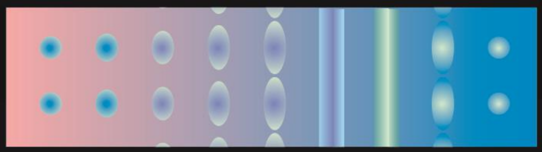




Inner crust: •To
Neutron gas in coexistence with "Coulomb lattice" of nuclei. Thickness governs observed frequencies in star quakes.

EoS at $\rho < \rho_0$

Inner boundary of inner crust: Transition to uniform "neutron matter"." Cylindrical and plate-like nuclear "pasta"



EoS at $\rho < \rho_0$

EoS at $\rho > \rho_0$

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

EoS at $\rho > \rho_0$

Inner core:
Composition
Could be nuc ... ter.
Governs max
cooling of proto-neutron star.

Strange or quark matter?

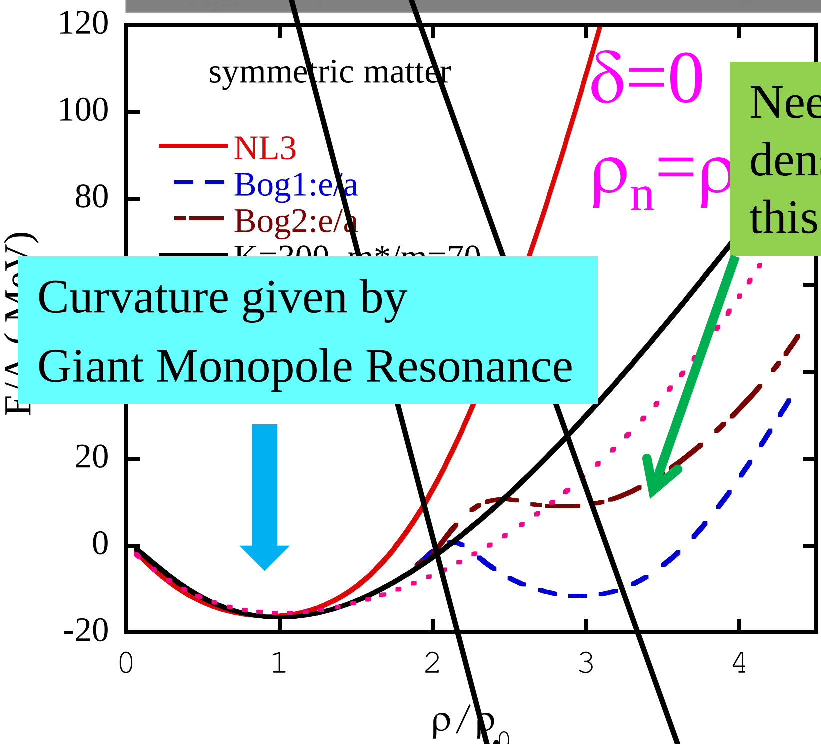
Key to understanding maximum N-star mass

momentum dependence

For N-stars T≈0 ⇒Can use energy/nucleon as EoS

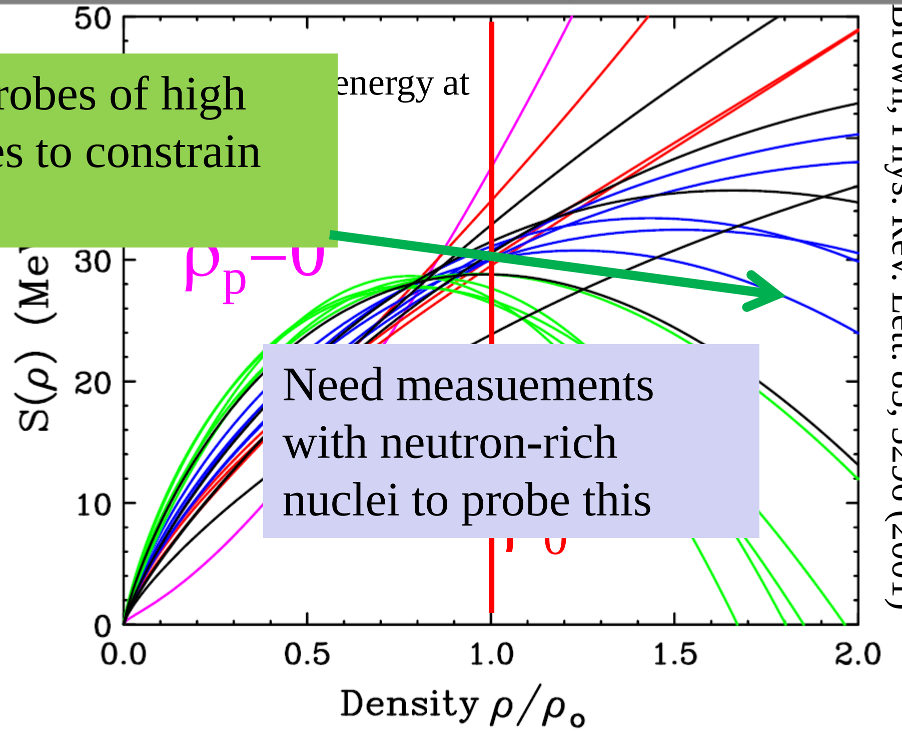
nuclear binding energy

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



Curvature given by Giant Monopole Resonance

Need probes of high densities to constrain this.



Need measuements with neutron-rich nuclei to probe this

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

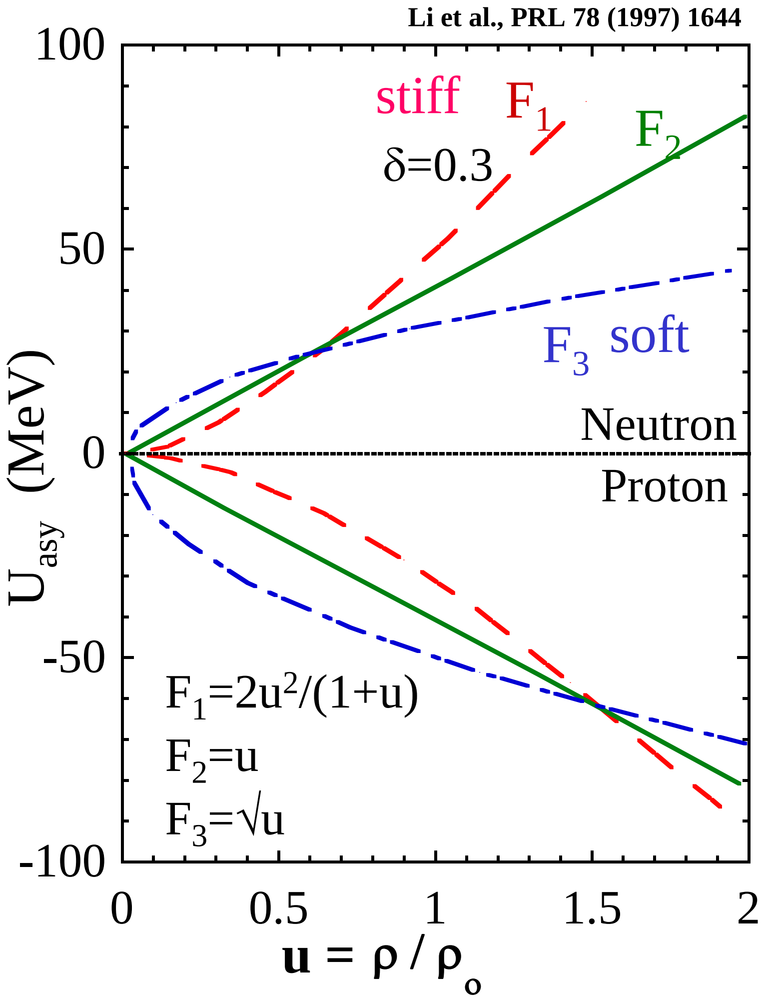
δ

∂ρ |s/a

- Symmetry energy calculated ... tions ... f S(ρ) ... of the EoS at $\rho < \rho_0$.

This was the situation in 2001 ⇔ EoS is now much more constrained

Improvement ⇔ Improved constraints on the potential energy contributions to S(ρ) which provide the largest uncertainties



- In a neutron-rich system, the symmetry energy attracts protons and repels neutrons
- Observables that can probe sub-saturation densities:
  - Isospin diffusion:
  - Neutron-proton spectra and flows.
  - Difference between neutron and proton matter radii.
  - Giant and pygmy dipole resonances
  - El dipole polarizability α_D
  - Nuclear binding energies and isobaric analog resonance energies.

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

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

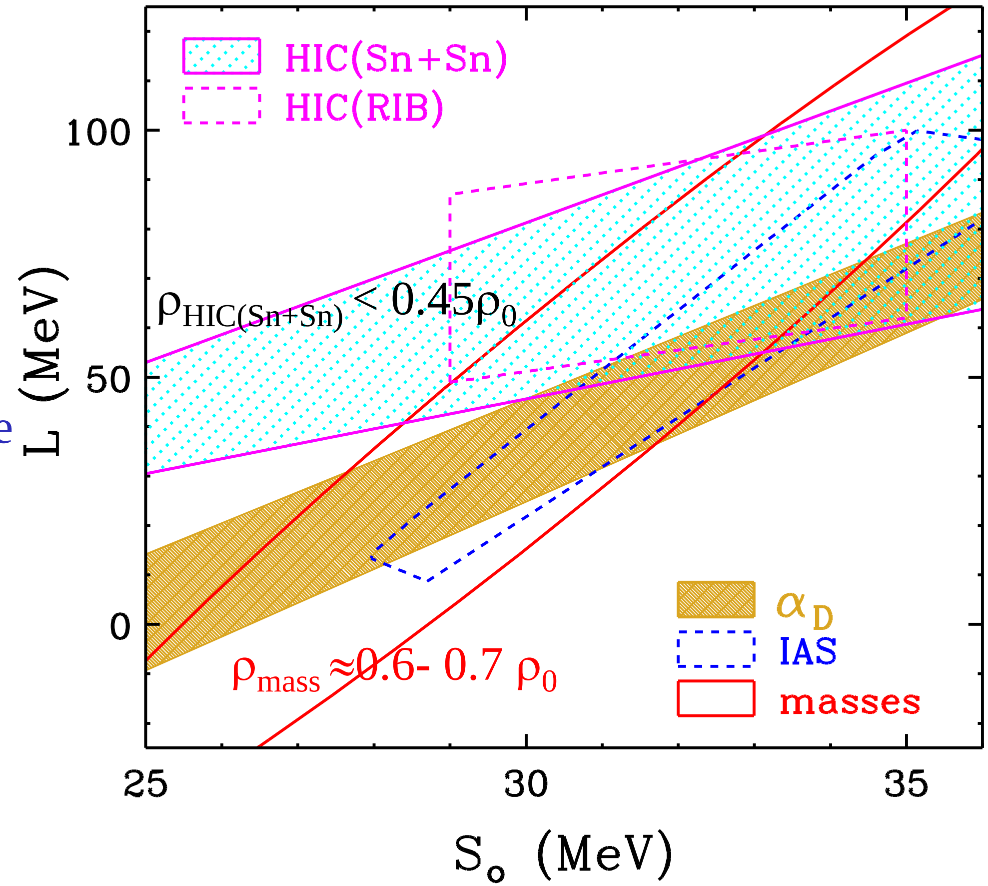
$$S(\rho) = S_o + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \ldots$$

- Taylor expand about ρ_0
- Experimental observables are mainly sensitive to $S_0=S(\rho_0)$ 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)
  - Transverse flow HIC (RIB)
- Slope of constraint indicates the sensitive density

$$\rho_{sens.} = \rho_0\left(1-3/M\right);\ \text{M is slope}$$

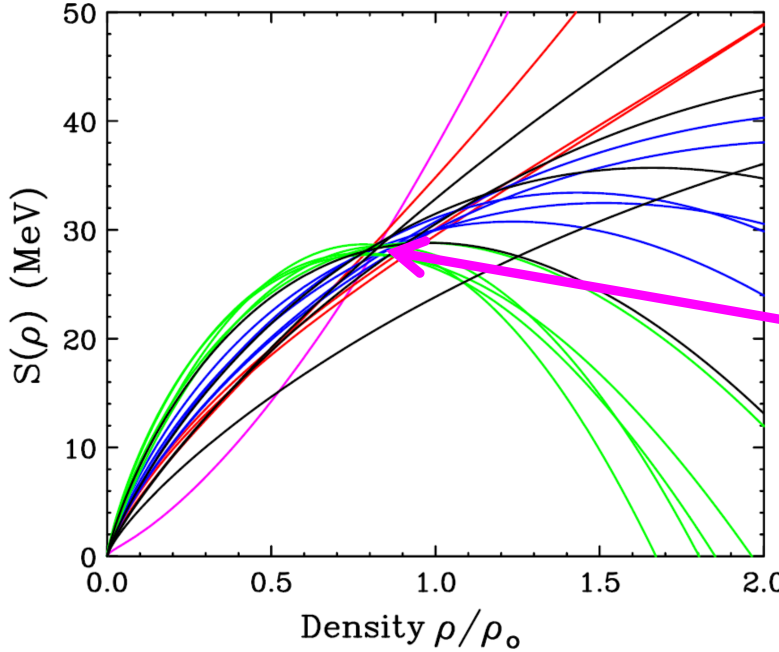
- Neutron skin $R_{np} = \langle r_n^2\rangle^{1/2} - \langle r_p^2\rangle^{1/2}$ is only sensitive to L.
- Realistic theoretical "Error bars" are key to combining constraints.

ICNT 2013 Summary report Horowitz, et al.,



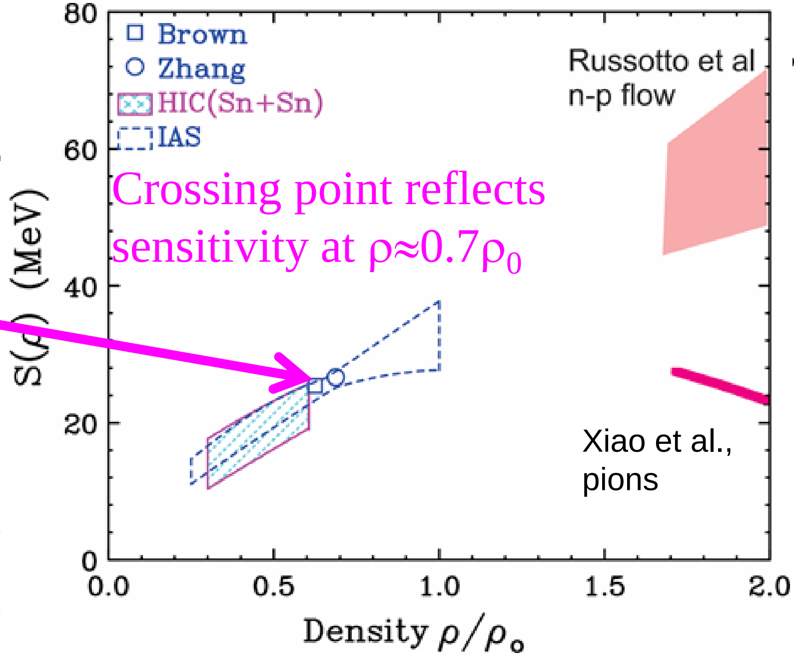
Past vs. Present status of S(ρ)

Brown 2001 obtained by fitting Sn masses



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

Constraints 2014 showing sensitive densities

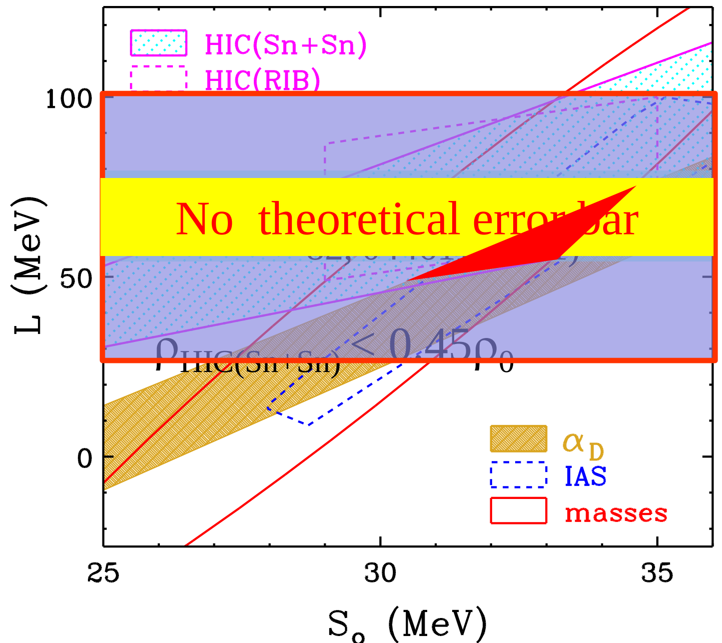


Adapted from ICNT 2013 Summary report Horowitz, et al.,

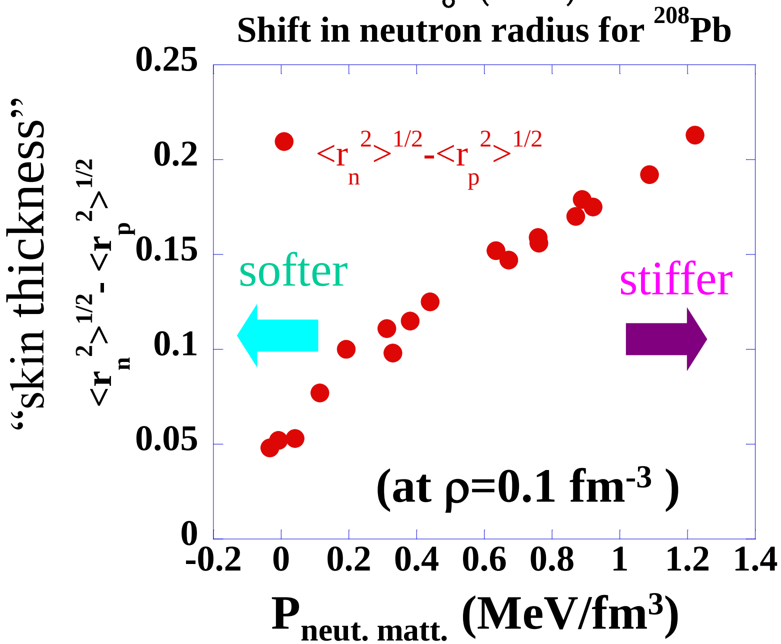
- Have initial constraints at sub and supra-saturation densities:
  - Contours reflect assessment of theoretical and experimental uncertainties
- Relevant questions:
  - How do we improve the constraints at $\rho<\rho_0$?
  - How do we improve the constraints at supra-saturation densities?
  - How do we deal with momentum dependencies of mean fields?
    - Important for non-zero temperatures and non-equilibrium systems

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

- Sensitive observables that are or will be more extensively explored :
  - masses:
    - Penning traps, TOF
  - Isobaric Analog States (IAS)
    - Reaccelerated RIB's ReA3 and CARABU: AT-TPC collab.
  - Isospin diffusion between nuclei of different N/Z in peripheral HIC
    - Sn+Sn NSCL: new results soon
  - Neutron skins:
    - PREX, CREX at JLAB
  - Isoscalar GMR
    - RCNP-ND, MAYA, AT-TPC collaborations
  - Neutron and proton transverse and elliptical flow
  - Fragmentation of hot nuclei:
    - TAMU



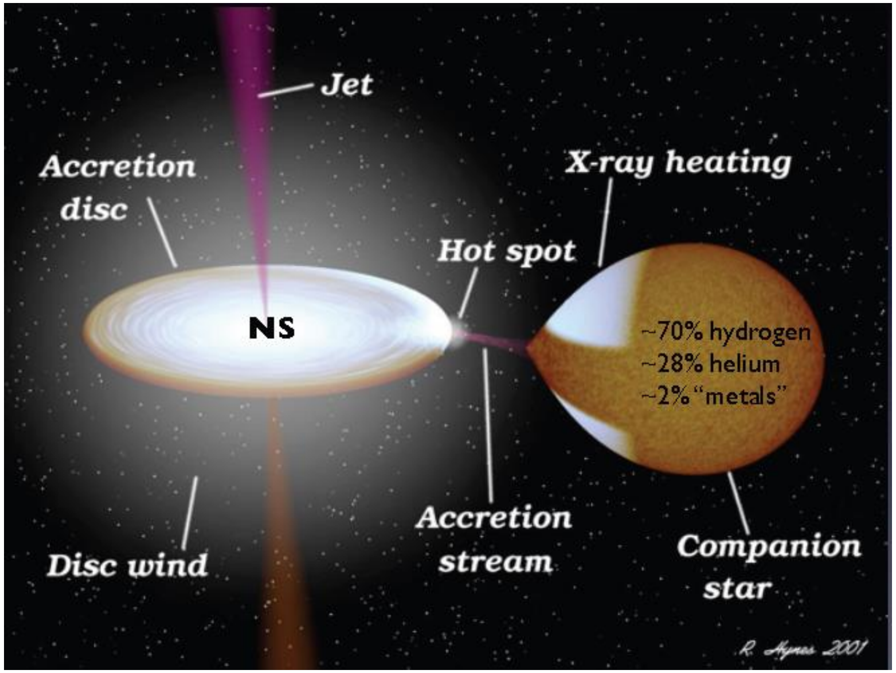
Horowitz, et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 093001



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

New challenge: probing supra-saturation densities $\rho \approx 2\rho_0$

- EoS & Symmetry energy influence:
  - Neutron star stability against gravitational collapse
  - Stellar density profile
  - Internal structure: occurrence of various phases.
- Observational consequences:
  - Cooling rates of proto-neutron stars: D. Yakovlev et al, Phys.Rep 354, 1 (2001)
  - Correlation between stellar masses and radii–two sites:
    - X-ray bursters
    - Quiescent x-ray binary systems



- Steiner et al., ApJ 722, 33 extract R=12.5±1.5 km from both x-ray bursters and quiescent x-ray binaries consistent with a soft neutron matter EoS.

New challenge: probing supra-saturation densities $\rho\approx2\rho_0$

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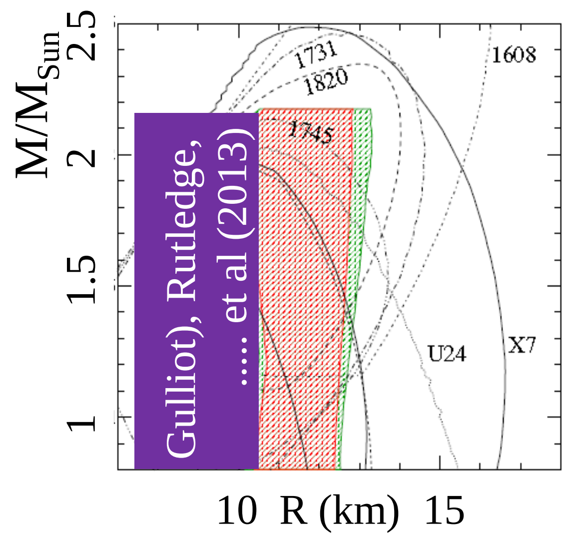
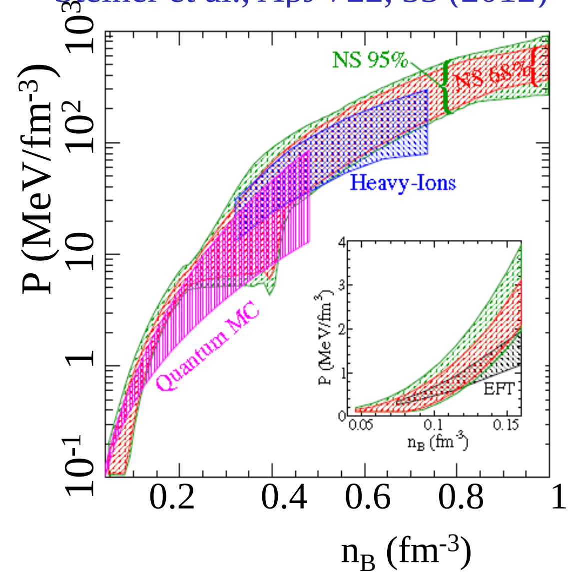


Steiner et al., ApJ 722, 33 (2012)

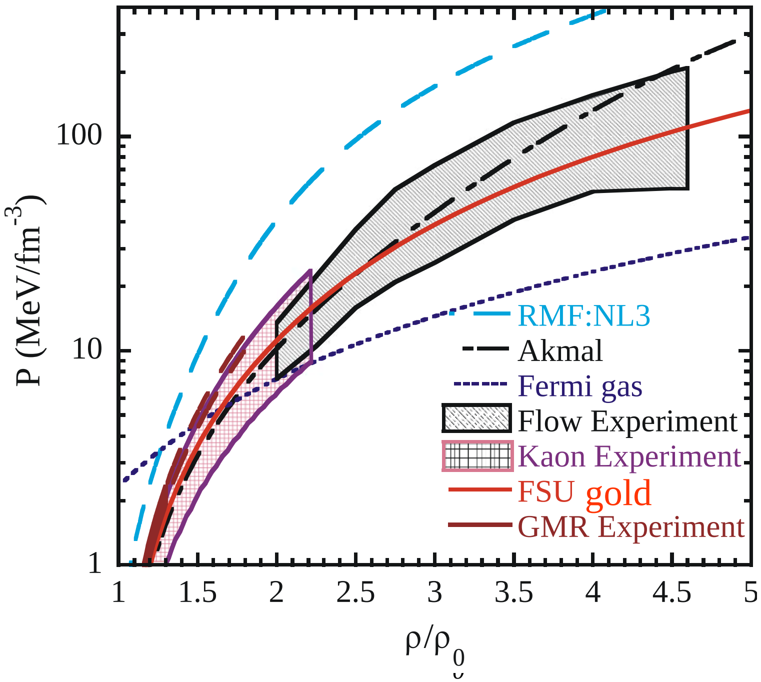


- Steiner et al., ApJ 722, 33 extract R=12.5±1.5 km, larger than Ozel (R=10±2 km) arXiv:1210.0916v1.
- Sensitive to modeling of radiation transport – see Suleimanov et al, ApJ 742, 122 who extract ~ 2 km larger radii.
- Rutledge studied quiesent only x-ray binary systems and extracts ~ 3km smaller radii.

⇒ It is important to obtain laboratory constraints. For high densities, one needs heavy-ion collisions.

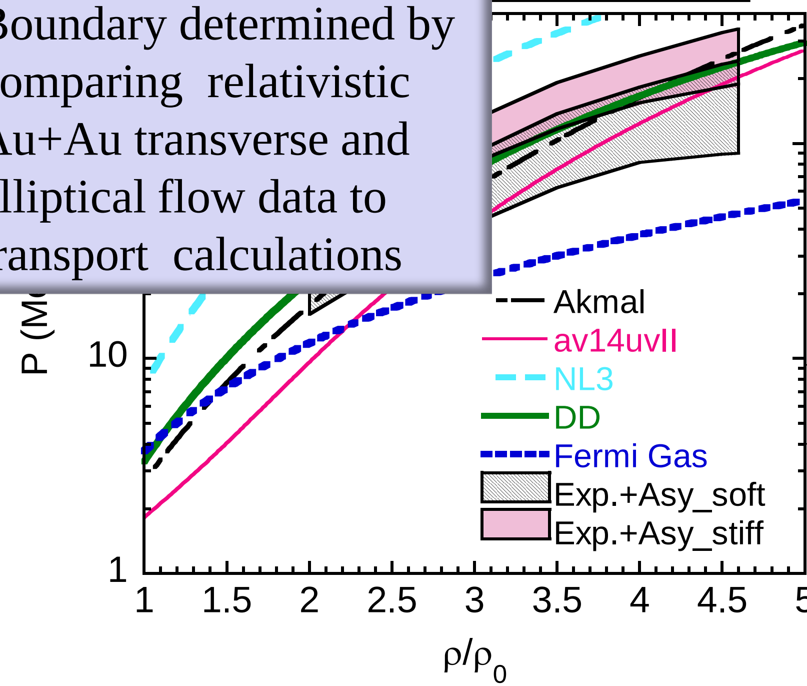
Laboratory Constraints on symmetric matter EOS at $\rho > 2\rho_0$.

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



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

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



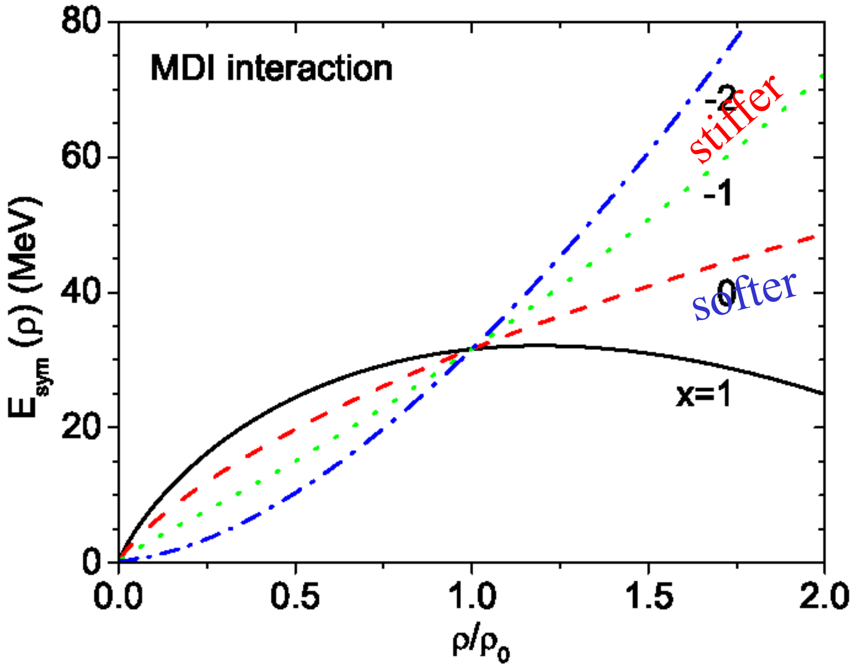
Danielewicz et al., Science 298,1592 (2002).

- 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}.

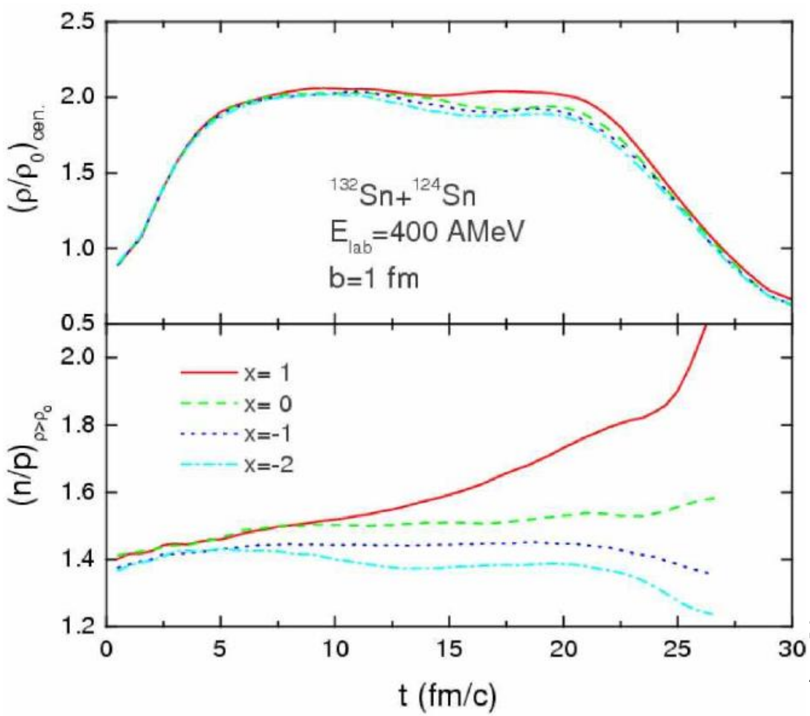
- The symmetry energy dominates the uncertainty in the n-matter EOS.
- Improved laboratory constraints on the density dependence of the symmetry energy are needed to tighten the constraints.

Symmetry energy studies at $\rho \approx 2\rho_0$

- Densities of $\rho \approx 2\rho_0$ can be achieved at E/A ≈400 MeV.
  - Provides information relevant to the mass-radius relation of neutron stars and possibly about direct URCA cooling in proto-neutron stars.
  - Stronger (stiffer) density dependence of symmetry energy expels more neutrons from densest region. Since π^- originates from n-n collisions and π^+ originates from p-p collisions, this reduces the π^-/π^+ spectral ratio



B-A Li



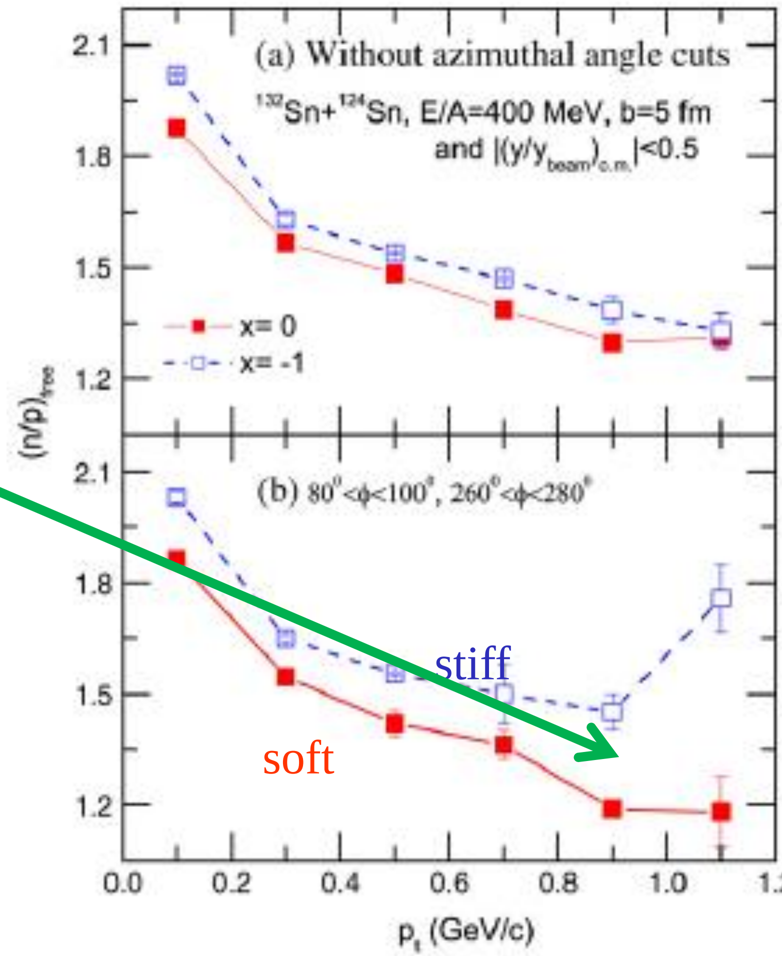
larger π^-/π^+

smaller π^-/π^+

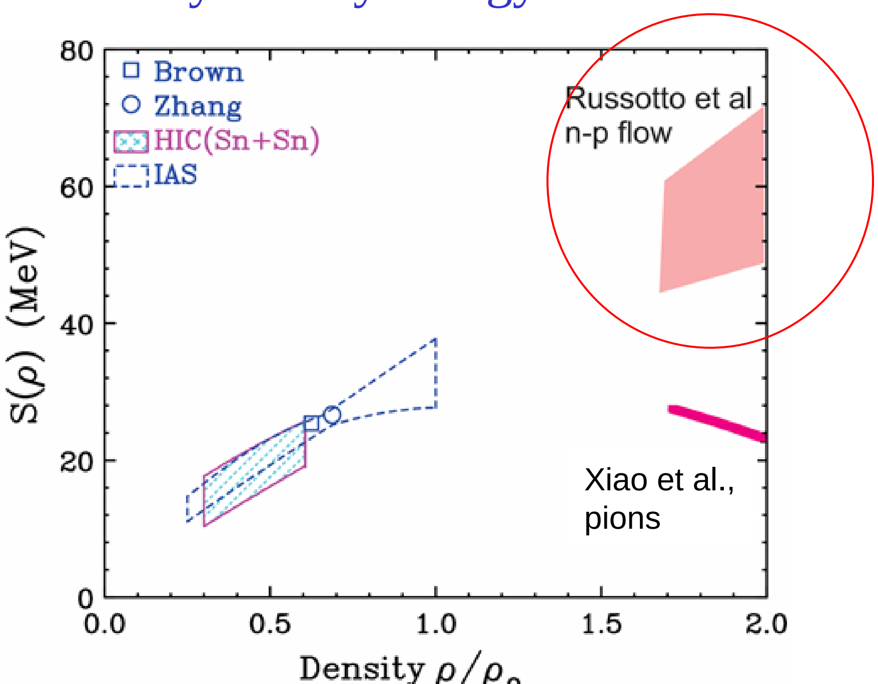
R

Comparisons of neutron and proton observables :

- Most models predict the differences between neutron and proton flows and t and ^{3}He flows to be sensitive to the symmetry energy and the n and p effective mass difference.
- At this energy, the ratio of neutron over proton spectra out of the reaction plane displays a significant sensitivity the symmetry energy.



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



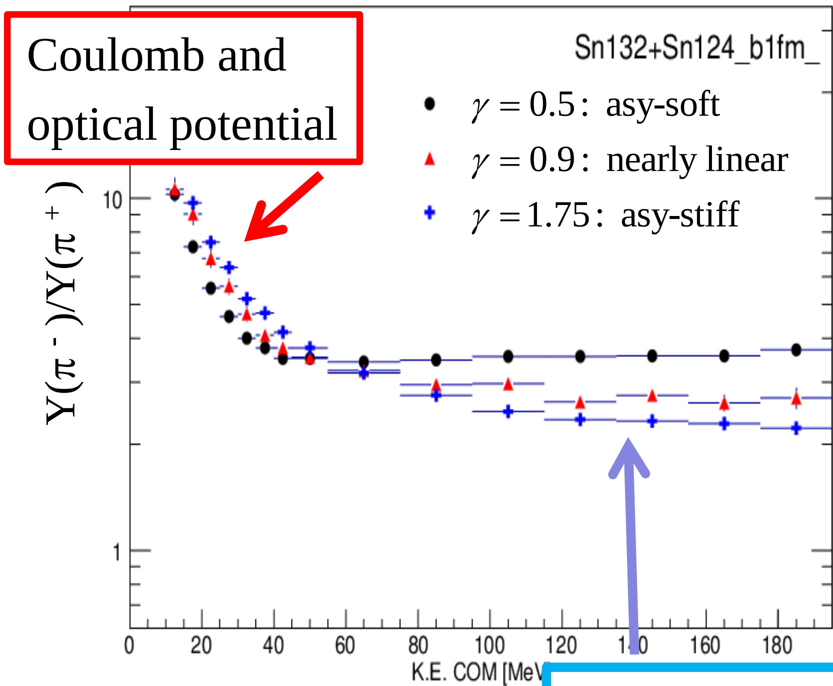
- A new experiment was performed at GSI and new results may be expected:
  - Asyeos exp.

Probing $\rho > \rho_0$ via pion production

- 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, $Y(\pi^-)/Y(\pi^+) \approx (\rho_n/\rho_p)^2$
  - In equilibrium, $\mu(\pi^+) - \mu(\pi^-) = 2(\mu_p - \mu_n)$

E/A = 300 MeV

Coulomb and optical potential



more n-n than p-p collisions for soft Symmetry energy

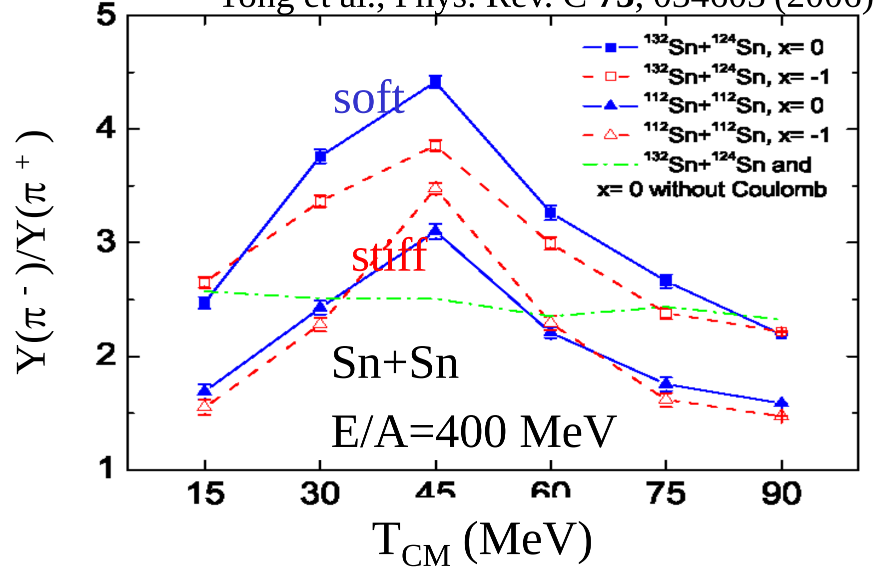
J. Estee, J. Hong, P. Danielewicz, priv. com. (2015)

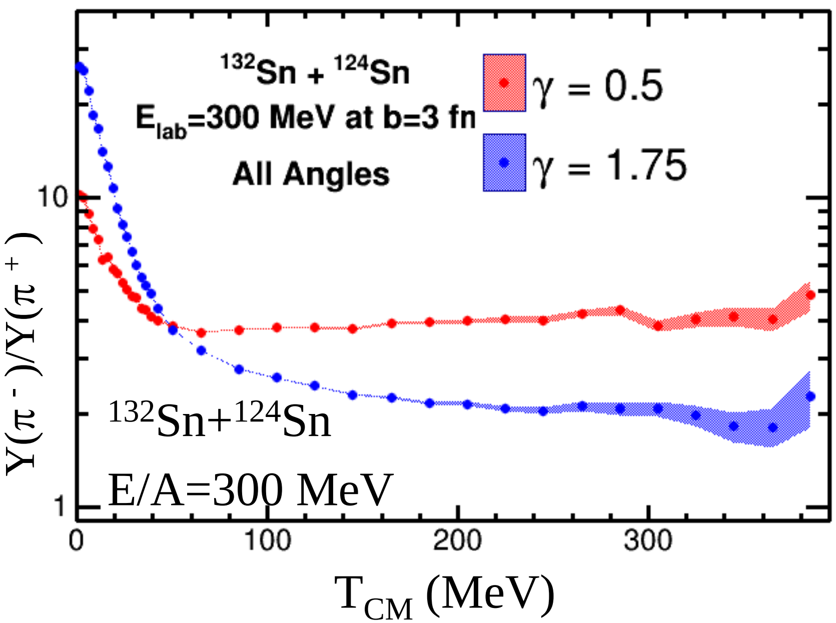
- Most calculations and measurements have focused on total pion yields, effect – difficult to measure and calculate. Ratios of spectra are more sen integrated yields.
  - Most clear sensitivity is for early pion emission at higher energies.
  - The integrated yields are difficult to measure because they require measuring the full pion spectrum down to very low energies in the CM. system.
  - Low energy pions strongly reflect pion charge exchange, and pion optical potentials.

Comparison to other calculated pion spectra

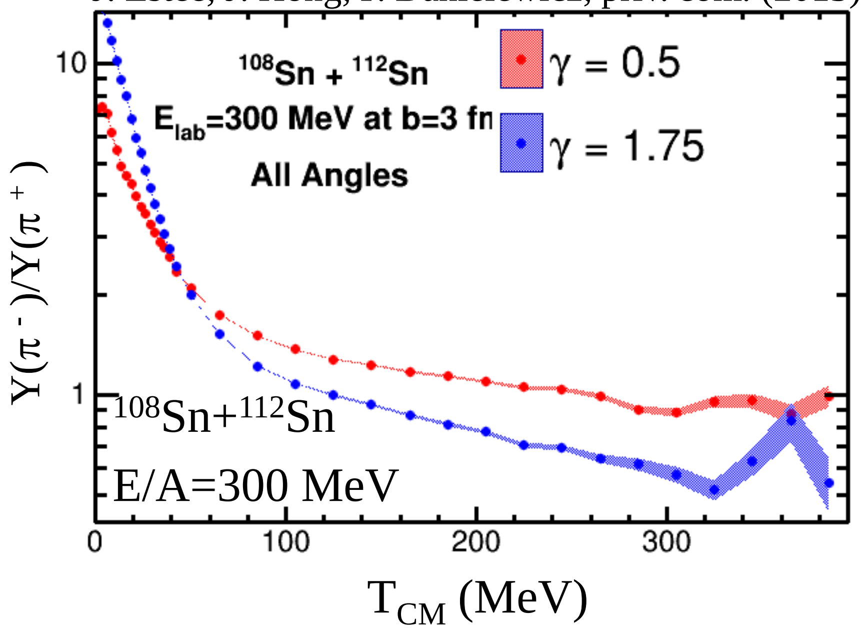
- Calculations of $^{132}Sn+^{124}Sn$ and $^{112}S+^{112}Sn$ spectral ratios were performed by Yong et al.,
- Behavior at low T_{CM} are very different. (no pion optical potential)
- Why does the latest calc. increase at low T_{CM}?

Yong et al., Phys. Rev. C **73**, 034603 (2006)



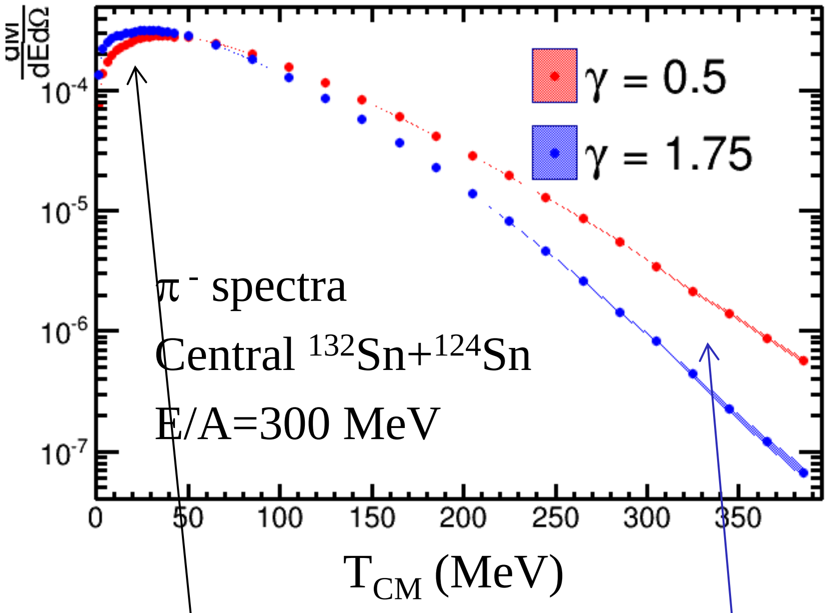


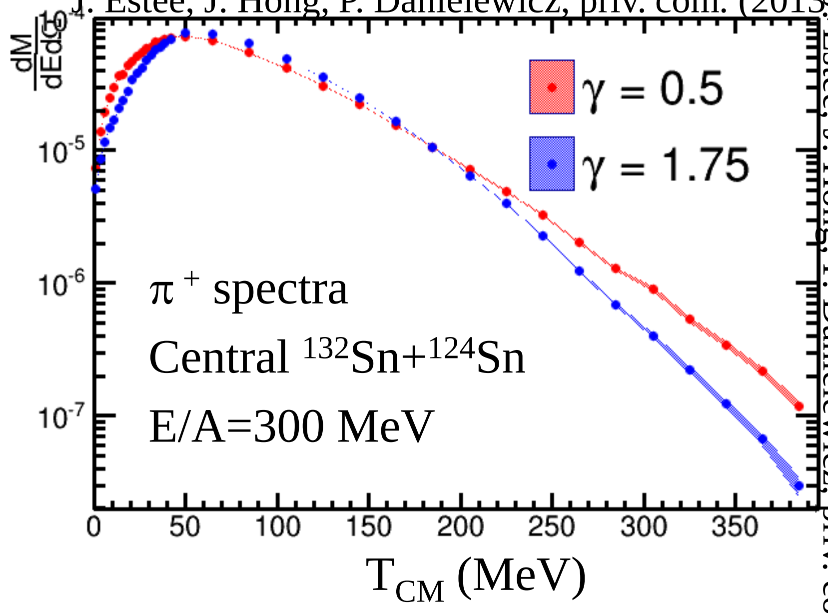
J. Estee, J. Hong, P. Danielewicz, priv. com. (2013)



How spectra influence these ratios

J. Estee, J. Hong, P. Danielewicz, priv. com. (2013)

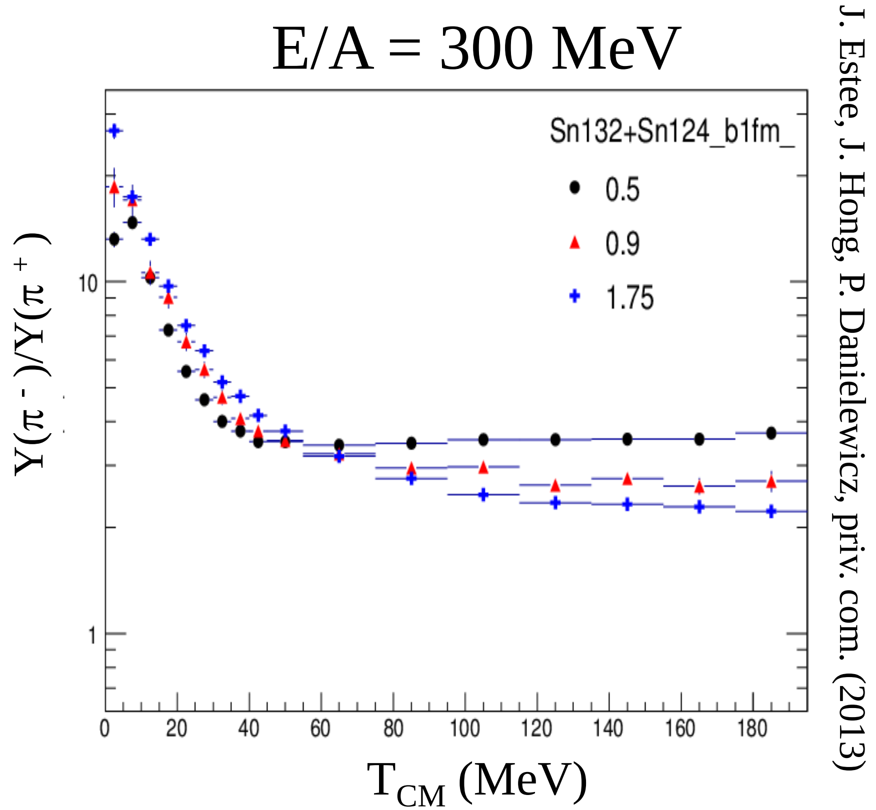


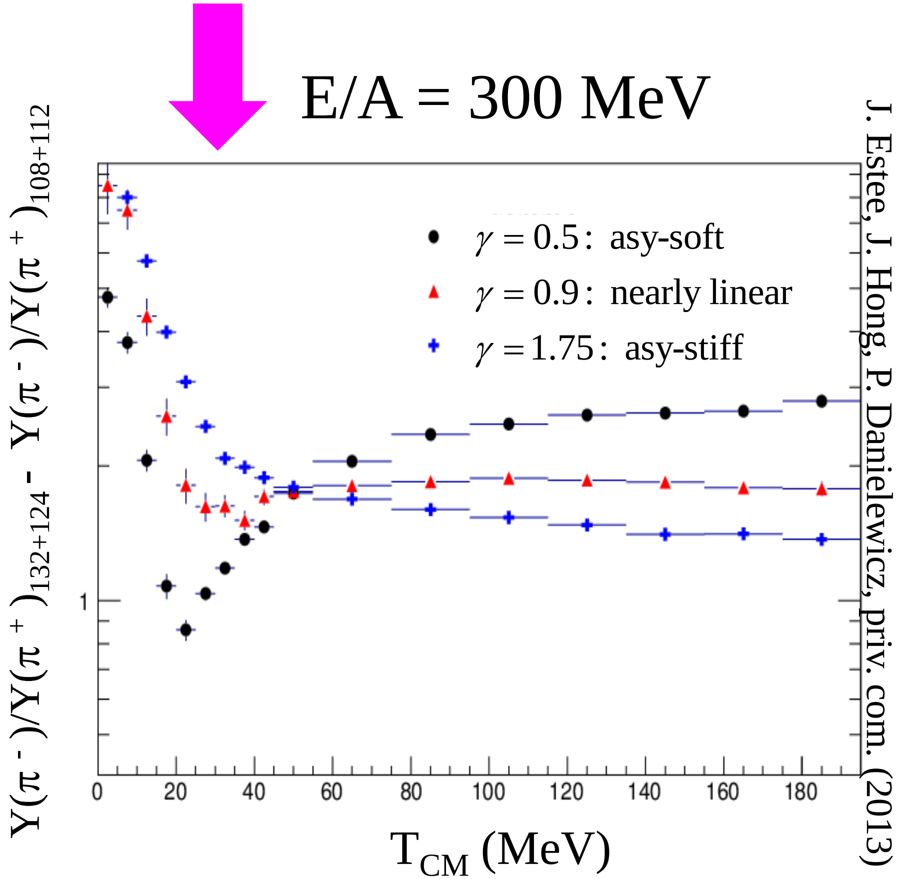


J. Estee, J. Hong, P. Danielewicz, priv. com. (2013)

- Higher energy emissions reflect the asymmetry dependence predicted by the delta resonance model.
  - $Y(\pi^-)/Y(\pi^+) \approx (\rho_{n,}/\rho_p)^2$
- Low energy emission reflect the combined influence of the Coulomb and optical potentials.

Difference between ^{132}Sn+ ^{124}Sn and ^{108}Sn+ ^{112}Sn collisions



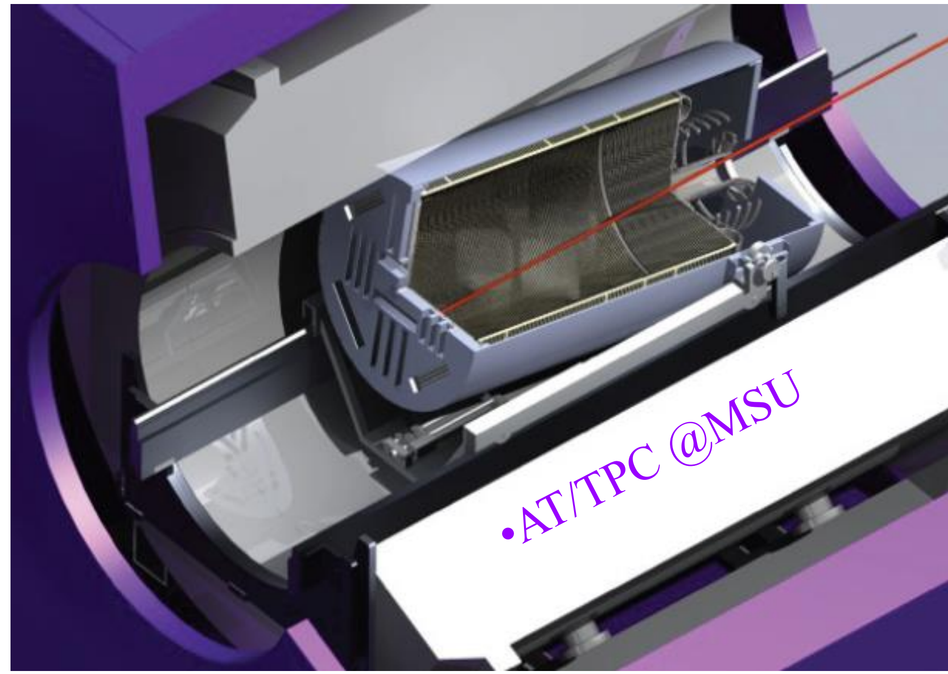


- Comparing two systems with different asymmetries enhances the sensitivity to the symmetry energy.
- Experiment has been approved for 13.5 days of running at the RIBF facility at RIKEN.

Devices: SAMURAI TPC and AT-TPC

SπRIT TPC

Active Target -TPC



- U.S./Japan collaboration
  - Uses SAMURAI dipole
  - Recently completed (2013)
  - Measure π^+, π^-, t, ^{3}He, n, p next year, hopefully.

- U.S. Collaboration (NSF MRI)
  - Solenoidal (MRI) magnet
  - Recently completed (2013)
  - Will enable future measurements of π^+, π^-, t, ^{3}He, n, p








MSU, Texas A&M, WMU,
Kyoto U., Riken, Seoul U.,
Tsinghua U., Liverpool




SπRIT





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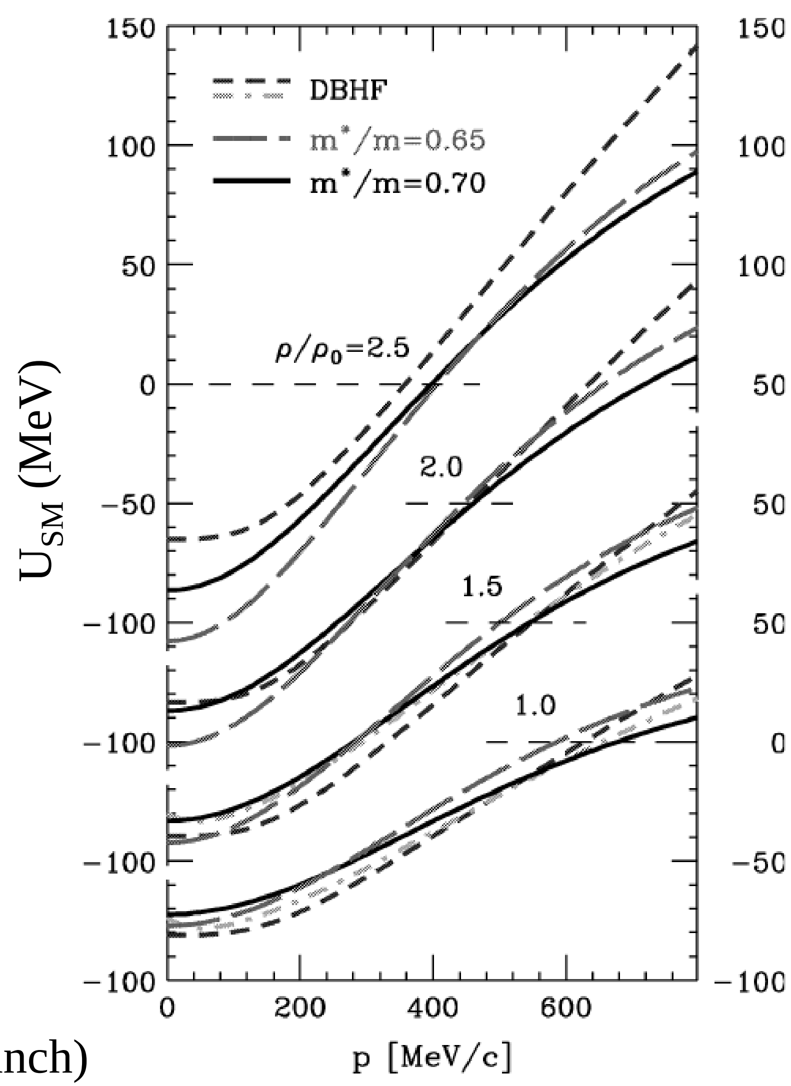
Another issue: momentum dependence of mean fields

- Momentum dependence of the mean field (real part of optical potential) is well established for symmetric matter.
  - At low energies, it can be described by effective mass, m*:
    $$p^2\left(\frac{1}{2m^*}-\frac{1}{2m}\right)=p^2\left.\frac{\partial U}{\partial p^2}\right|_{p^2=0}$$
  - Momentum dependence increases with ρ, is maximal at $p=p_F$ and vanishes as $p\to\infty$.
- Symmetry potential mom. dependence?
- This uncertainty influences m^*_n, and m^*_p and has an significant influence on the excitation energy – temperature relationship for neutron stars. $T^2 \propto E^*/A \cdot \left(m_n/m^*_n\right)$
- It also influences the neutrino flux from neutron stars: (Baldo etal PRC 89, 048801 (2014)).

P. Danielewicz / Nuclear Physics A 673 (2000) 375–410



$$Q^{(DU)} \propto \frac{m^*_n}{m_n}\cdot\frac{m^*_p}{m_p}T^6 \qquad Q^{(Mn)} \propto \left(\frac{m^*_n}{m_n}\right)^3\cdot\frac{m^*_p}{m_p}\cdot T^8$$

direct Urca modified Urca (neutron branch)

Emission of neutrons and protons from a neutron-rich system

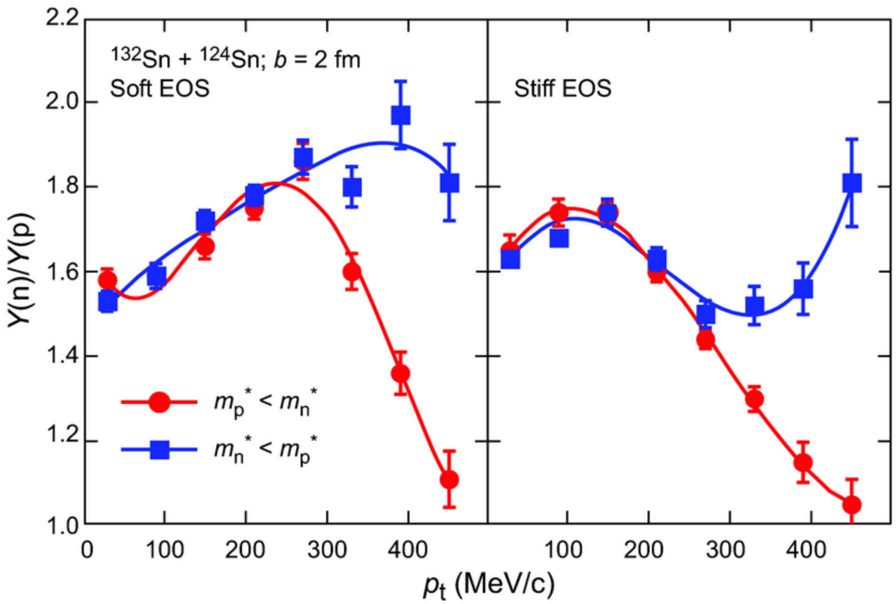
Kinetic Esym + Mom. Dep.

- For an expanding and statistically emitting source, it is easy to show that that the n/p ratio depends on μ_n and μ_p, at low T (in the effective mass approx. and neglecting V_{Coul}).

$$\left.\frac{dN_n(t_n)}{dN_p(t_p)}\right|_{t_n=t_p=t} \propto \exp\left(\left[\mu_n - \mu_p\right]/T\right) \approx \exp\left(\left[\frac{p_{F,n}^2}{2m_{n,eff}} - \frac{p_{F,p}^2}{2m_{p,eff}} + c2\delta\rho^{\gamma}\right]/T\right)$$

  - The effective mass effects dominate at early higher energies, corresponding to early emission times when density is higher.
- Trend is well supported by transport theory and by simple dynamical arguments.

Ratios of center of mass spectra at 90^0



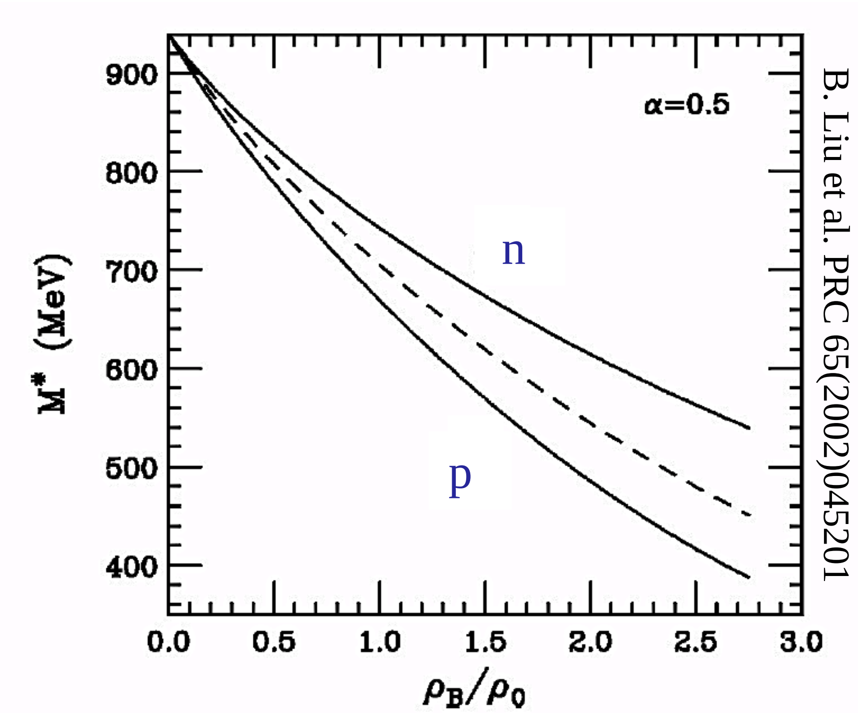
Rizzo et al., PRC 72, 064609 (2005)

Symmetry potential contribution: neutron expelled and protons attracted by symmetry potential

From dynamical point of view (e.g. in transport theory)

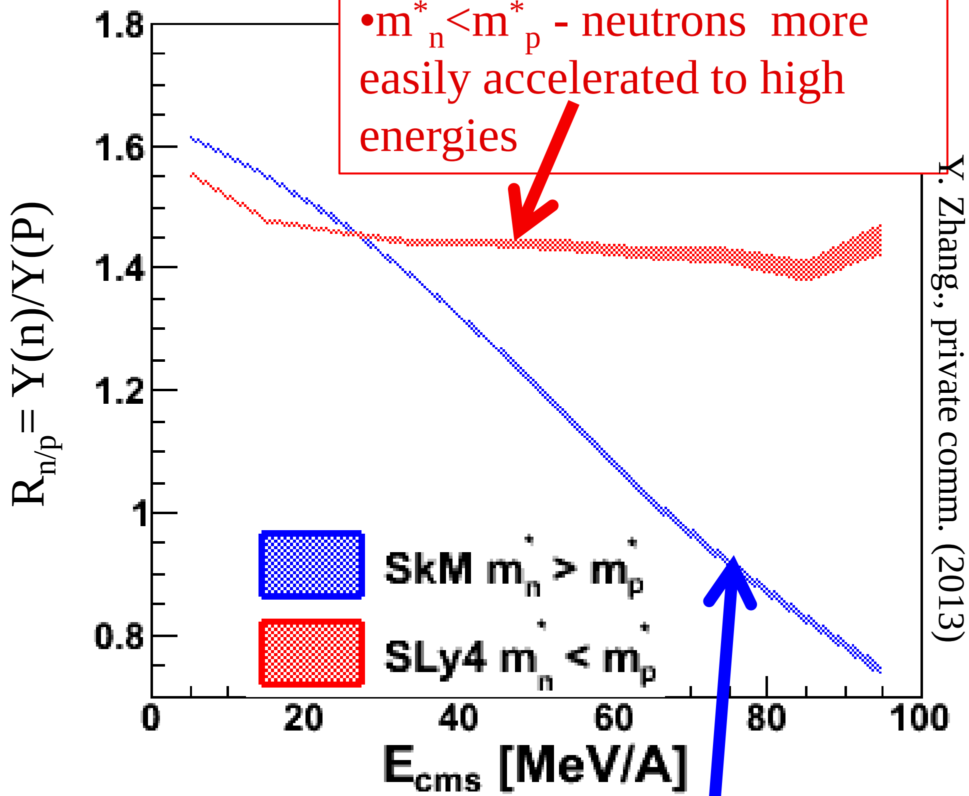
$$\text{if } U_{sym} = U_{sym}\left(\rho, p^2\right)$$

$$\text{accel.} = \frac{d\upsilon}{dt} = \frac{\nabla U}{m^*}$$



Central $^{124}Sn + ^{124}Sn$ Collision

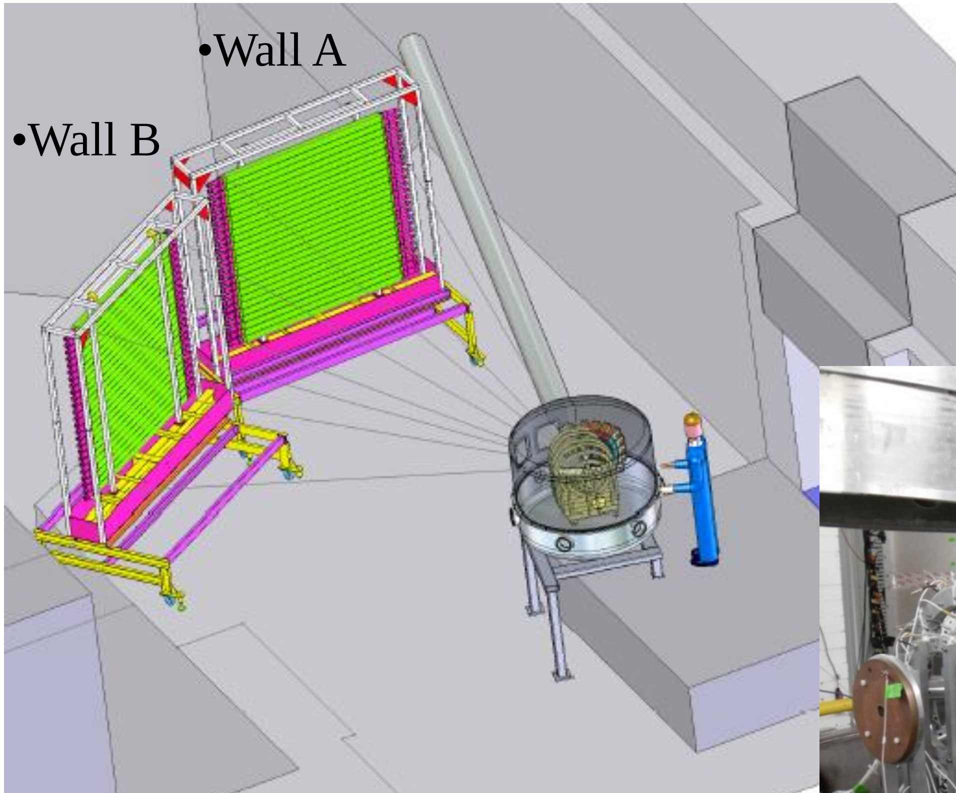
E/A = 120 MeV/A



• $m^*_n < m^*_p$ - neutrons more easily accelerated to high energies

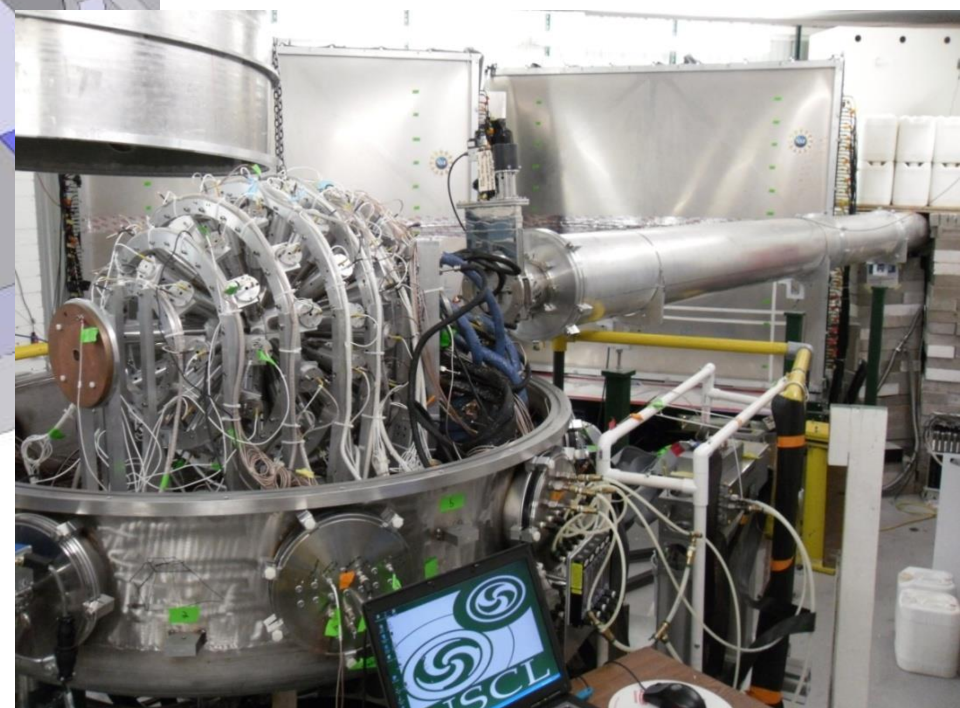
• $m^*_p < m^*_n$ – protons more easily accelerated to high energies

Experimental Layout
PhD theses: Daniel Coupland & Michael Youngs



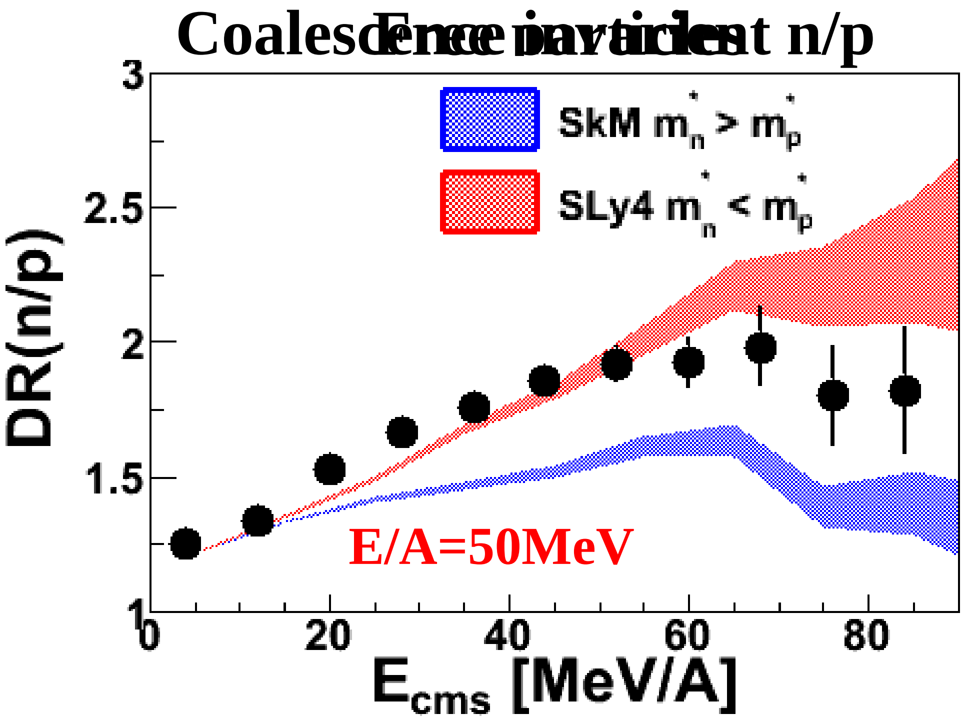
•Courtesy Mike Famiano

- LASSA – charged particles
- Miniball – impact parameter



- Neutron walls – neutrons
- Forward Array – time start
- Proton Veto scintillators

Comparisons with transport theory: n,p



$$DR_{n/p} = \frac{R_{n/p}\left({}^{124}Sn + {}^{124}Sn\right)}{R_{n/p}\left({}^{112}Sn + {}^{112}Sn\right)}$$

ImQMD05_sky: incorporate Skyrme interactions
Y. Zhang (2013) Private Communication
Tsang (2013) Private Communication
D. Coupland, M. Youngs (2013)

ImQMD:

- Cluster production does not have the correct binding energies for light fragments⇒too few fragments.
- Test semi-classical dynamics by constructing "coalescence invariant" nucleon spectra, which represent flows prior to clusterization.

Coalescence invariance:

- Coalescence protons or neutrons spectra include both free neutrons and protons and those within clusters. This is done for both experiment data and theoretical calculations.

The data suggest only a weak momentum dependence of the symmetry mean field potential

Summary and Outlook

- Experiment is beginning to provide constraints on the EoS.
  - Isospin diffusion, n/p spectral ratios, mass, IAS's, GMR, Pigmy and Giant Dipole resonances, E1 polarizabilities and neutron skin thicknesses already provide some constraints at $\rho \leq \rho_0$. These constraints should become more stringent.
  - These constraints $\rho < \rho_0$ may be helpful to understand phenomena occurring in the inner crust of neutrons stars.
  - New results for π^- , π^+, n, p , t, and ^{3}He spectra and flows will provide sensitivity to the symmetry energy at supra-saturation densities of $\rho \approx 2\rho_0$.
- Neutron star observations provide complimentary information.
  - Comparisons of laboratory and astronomical constraints on EoS at $\rho \approx 2\rho_0$ should prove to be very interesting.
- The importance of strange and quark matter in the inner core is an open question.
  - How can laboratory experiments contribute?