Understanding the Properties of Neutron Stars through Heavy Ion Collisions Simulation and the Nuclear Symmetry Energy

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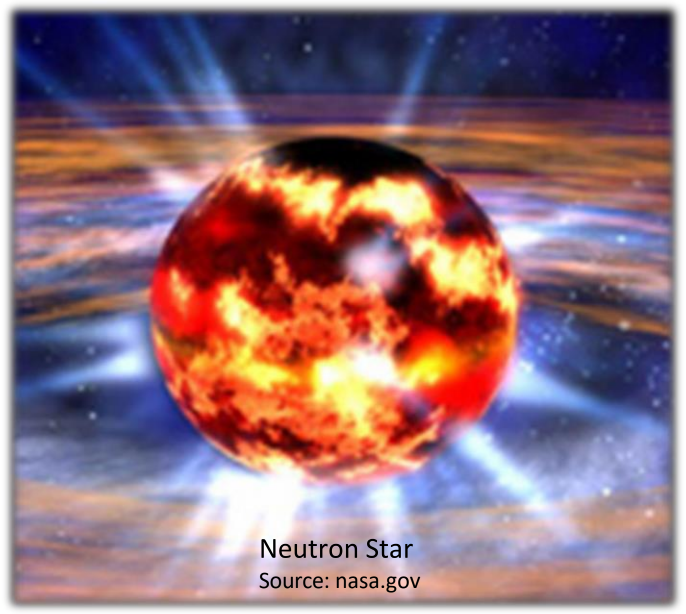
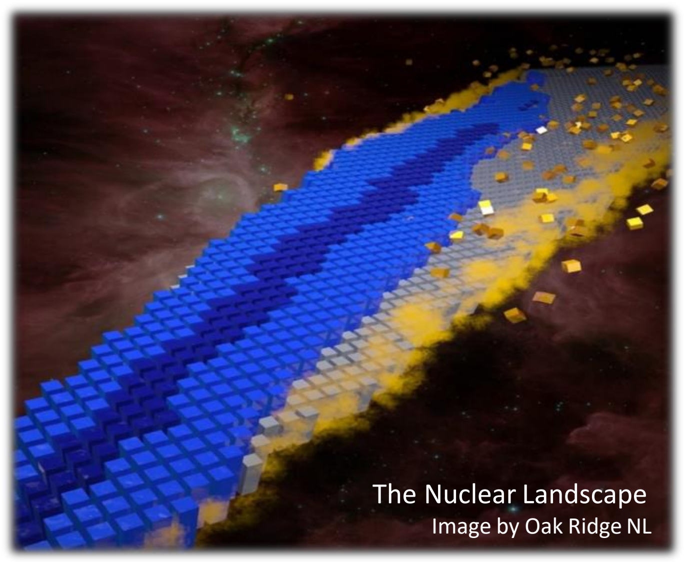
MOTIVATION

- **Neutron stars** are very dense astronomical objects



Why does a neutron star not collapse under its own weight? Pressure from symmetry-energy counters the gravity.

The **nuclear symmetry-energy,** a part of the **Nuclear Equation of State (EOS)**, is the price paid for having unequal numbers of neutrons and protons



Symmetry energy influences wide range of objects from *mass-radius relationship* of neutron stars to *halo nuclei* and *neutron skins.*

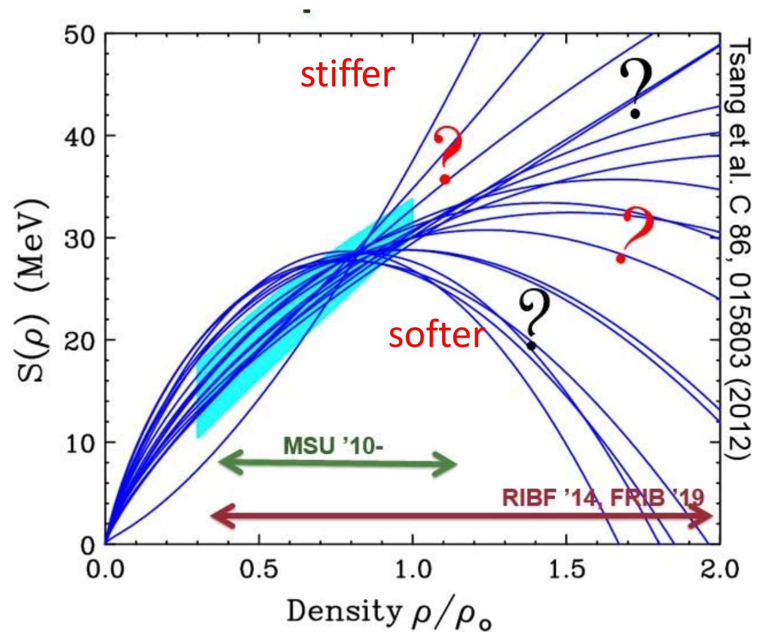
HEAVY ION COLLISIONS & pBUU TRANSPORT MODEL

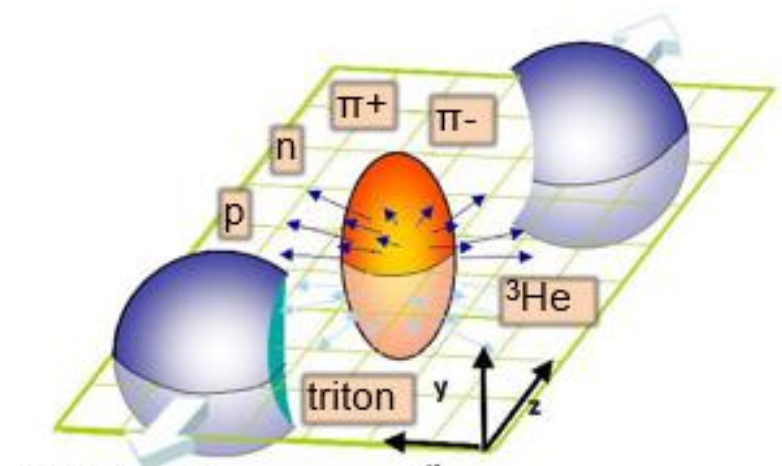
The Nuclear Equation of State (EOS)

$$\frac{E(\rho,\alpha)}{A} = \frac{E(\rho,\alpha=0)}{A} + S(\rho)\alpha^2 \text{ where } \alpha = \frac{N-Z}{A}$$

$$S(\rho) \propto \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

- Symmetry-energy is not well understood, especially at **high density.**
- We can use **Heavy Ion Collisions at high energy** to produce high-density region to study symmetry energy.
- Our goal is to **find the most sensitive observable** constructed from particles produced during the collisions.
- Heavy Ion Collision **simulations** were done using **pBUU** (*Boltzmann-Uehling-Uhlenbeck*) transport model [1]:
  - ^{132}Sn + ^{124}Sn and ^{108}Sn + ^{112}Sn
  - Beam energy: 200 & 300 MeV/u
  - 2 E_{sym} parametrizations:
    - *Soft* (γ=0.5, $E_{sym} \propto \sqrt{\rho}$)
    - *Stiff* (γ=1.75, $E_{sym} \propto \rho$)



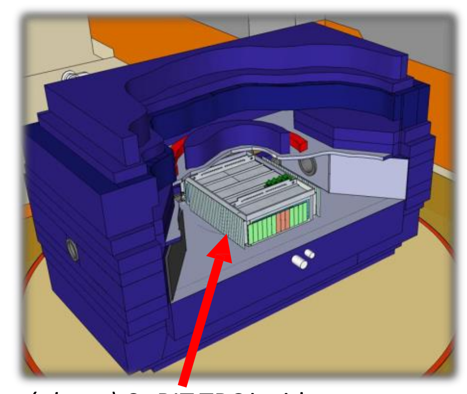


(above) Figure A
A schematic view of a heavy ion collision and particles produced
U. W. Heinz, J. Phys. A42 214003 (2008)

References
[1] J. Hong and P. Danielewicz, Phys. Rev. C **90**, 024605 (2014)

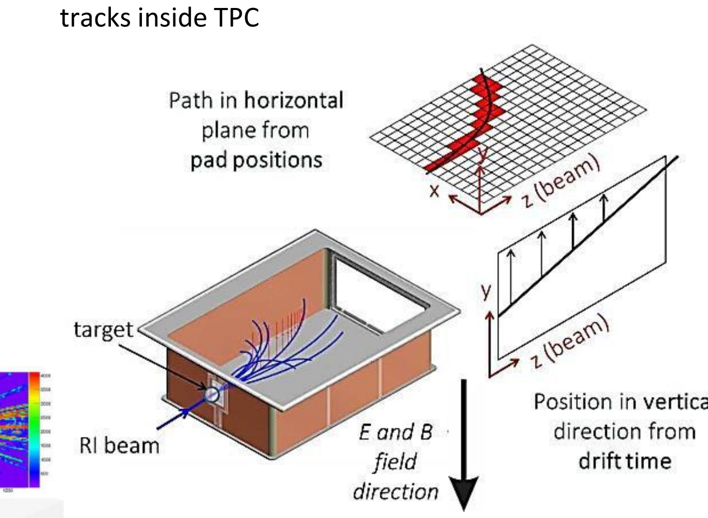
EXPERIMENTAL PLANS

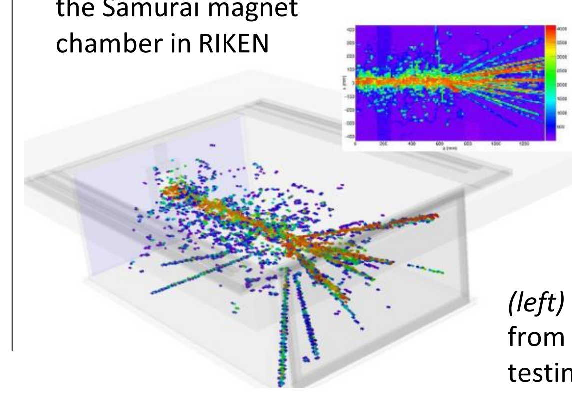
- We need 300 MeV/u with reasonable-intensity **^{132}Sn** & **^{108}Sn** secondary beams, available at RIBF (RIKEN), Japan & FRIB (2020)
- We need a **time-projection chamber** (TPC) inside a strong magnet to detect particles.
- In 2010, MSU received a $1.2m grant from DOE to construct *SπRIT (SAMURAI Pion-Reconstruction and Ion-Tracker)* TPC
  - Two experiments in Japan have been approved: **^{132}Sn + ^{124}Sn** and **^{108}Sn + ^{112}Sn** (2016).
- Data from these experiments will be compared to the simulations to extract the value of *gamma* (γ)



(above) SπRIT TPC inside the Samurai magnet chamber in RIKEN

(below) Interpretation of possible particle tracks inside TPC





(left) An actual event from the commissioning testing run (Oct 2015)

R. Shane, et al., Nucl. Instrum. Meth. A **784**, 513-517(2015).

RESULTS

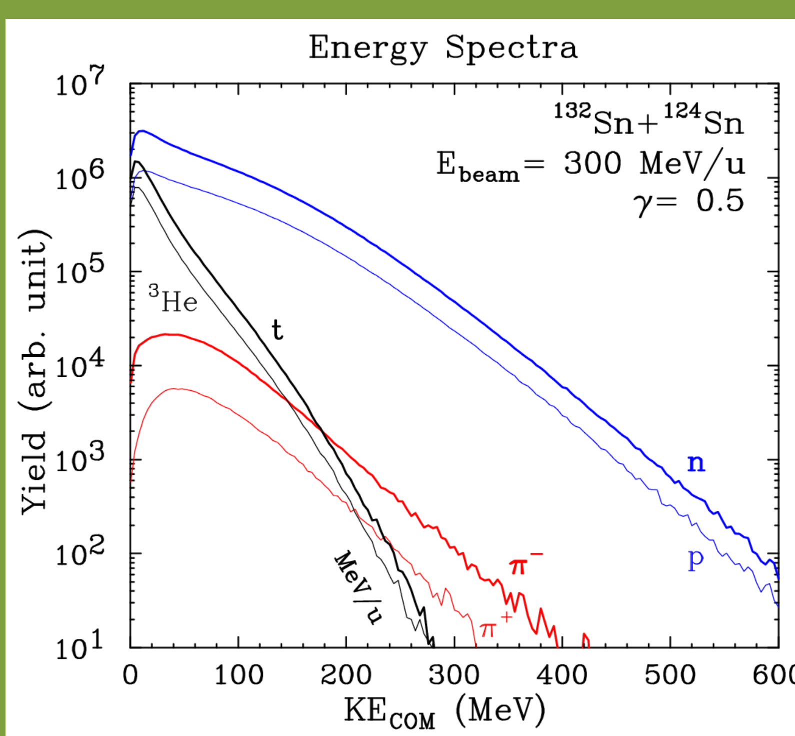


Figure 1
Relative yield for neutron, proton, triton, ^{3}He, and pions.

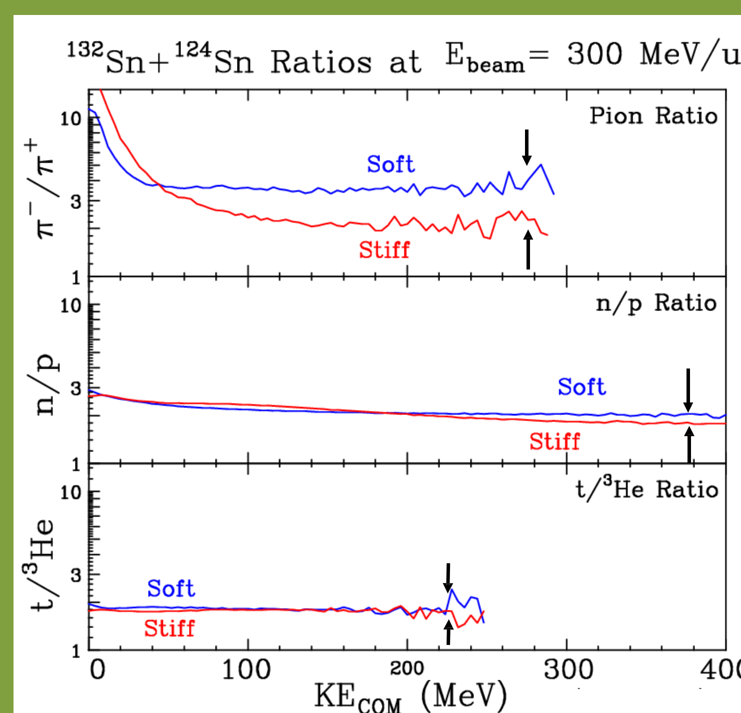


Figure 2
Comparison of pion ratio (π-/π+), n/p ratio, and t/^{3}He ratio.

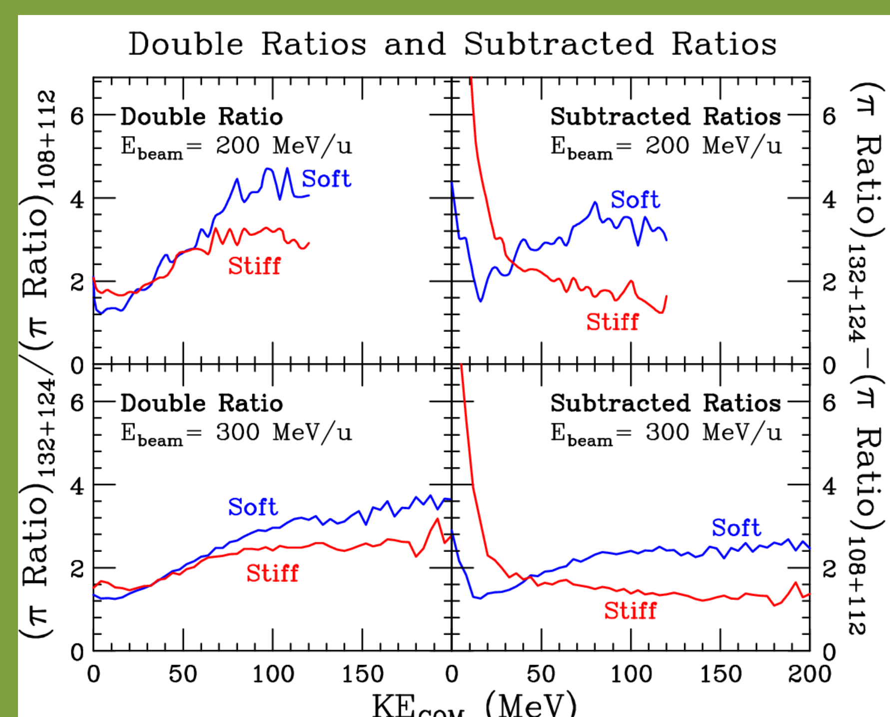


Figure 3
Enhanced pion ratios of **^{132}Sn + ^{124}Sn** & **^{108}Sn + ^{112}Sn** using double & subtracted ratios methods.

SUMMARY | NEXT STEP

- Simulations show that pion ratio is the most sensitive observable, compared to n/p and triton/^{3}He.
- Experiments of (Sn+Sn) collisions will be carried out in RIKEN, Japan in 2016.
- We plan to do more simulations with asymmetric system of ^{48}Ca+^{124}Sn and ^{40}Ca+^{112}Sn for planning future experiments.

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