Search for Nuclear Symmetry-Energy Observables in Heavy Ion Collisions to Understand the Properties of Neutron Stars

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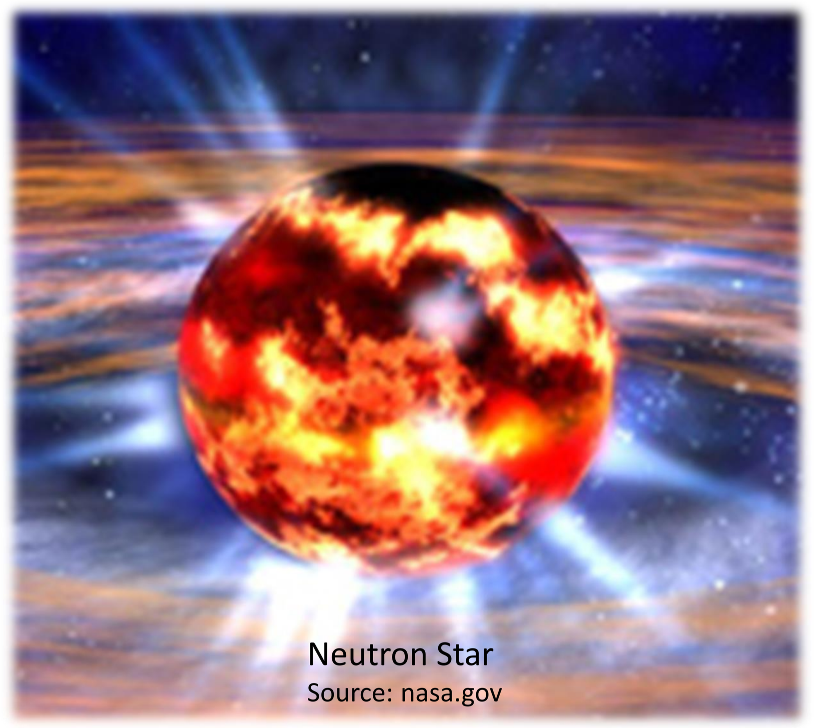
MOTIVATION

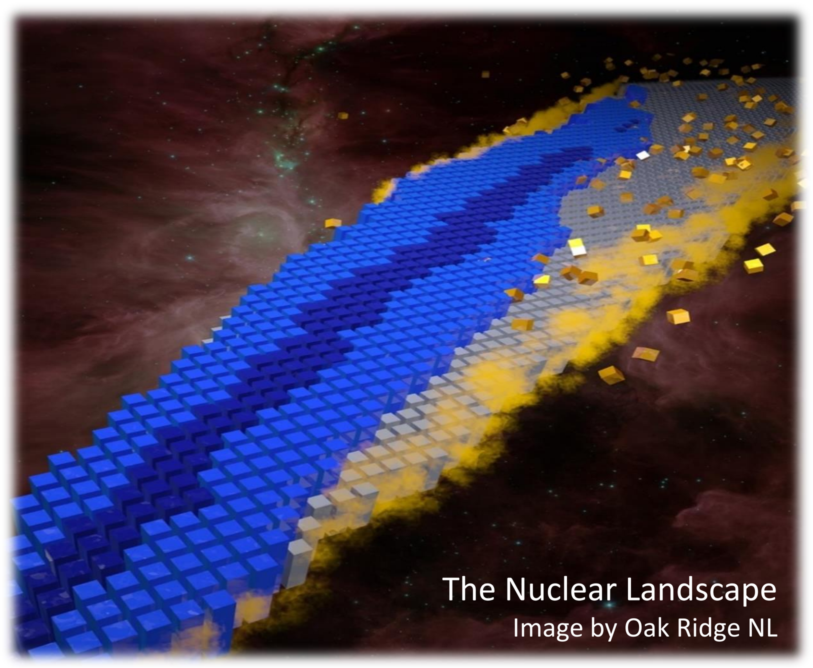
- **Neutron stars** are very dense astronomical objects



Neutron Star
Source: nasa.gov

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



The Nuclear Landscape
Image by Oak Ridge NL

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

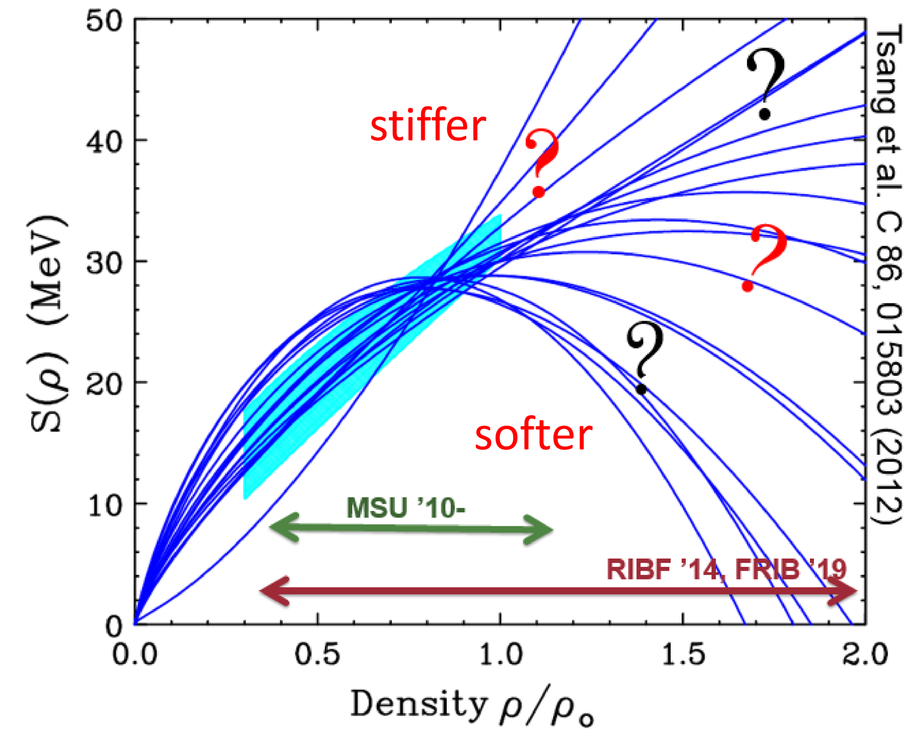
HEAVY ION COLLISIONS & pBUU TRANSPORT MODEL

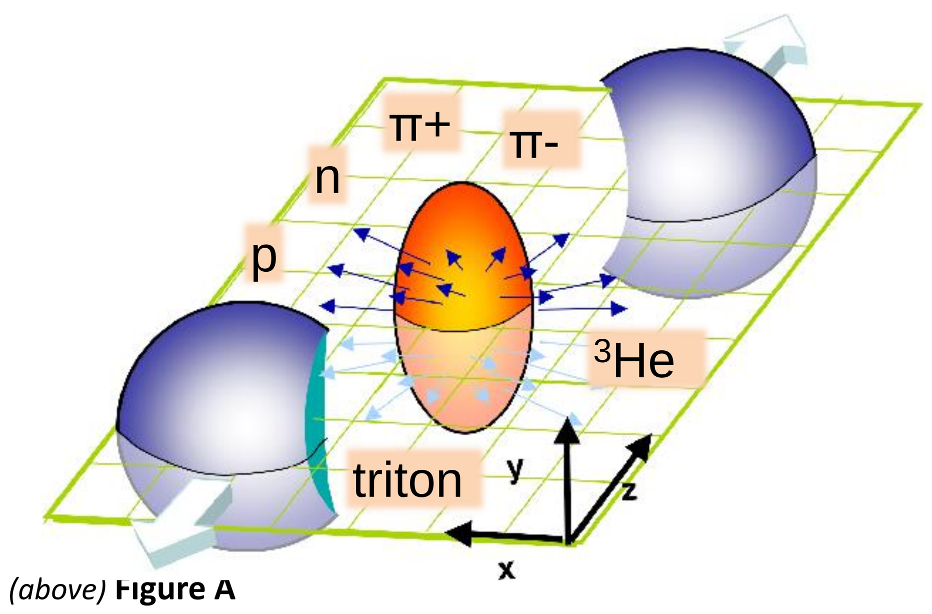
The Nuclear Equation of State (EOS)

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

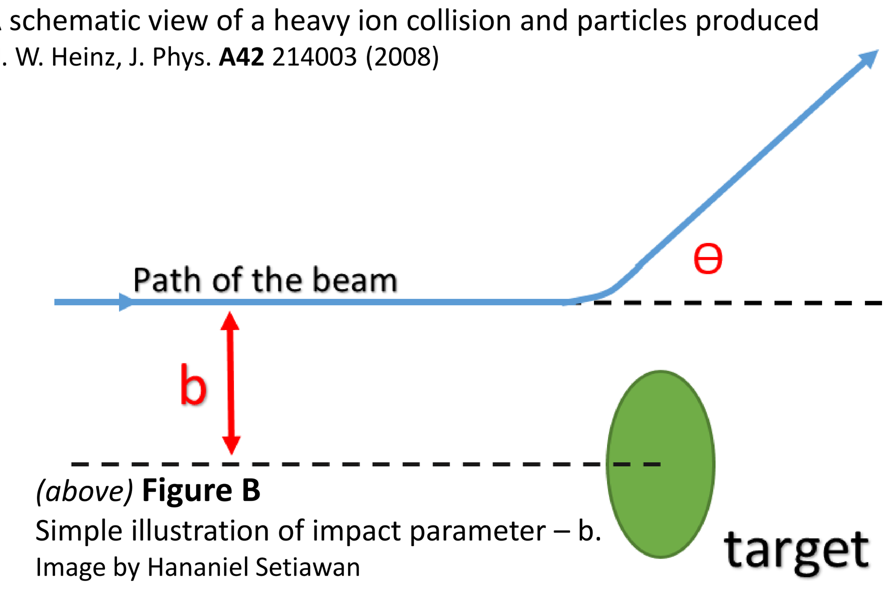
$$S(\rho) = S_{kin0}\left(\frac{\rho}{\rho_0}\right)^{\frac{2}{3}} + S_{int0}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

- 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 best & 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)

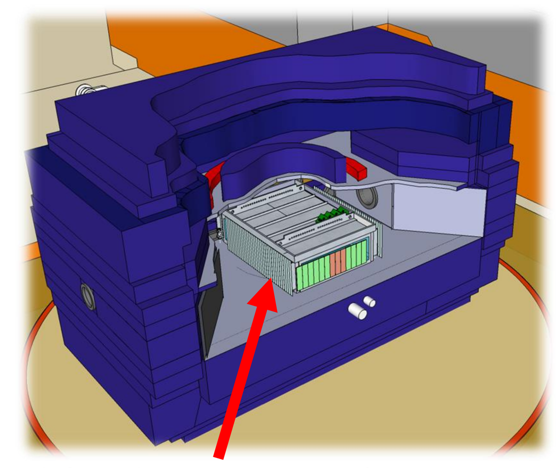


(above) **Figure B**
Simple illustration of impact parameter – b.
Image by Hananiel Setiawan

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

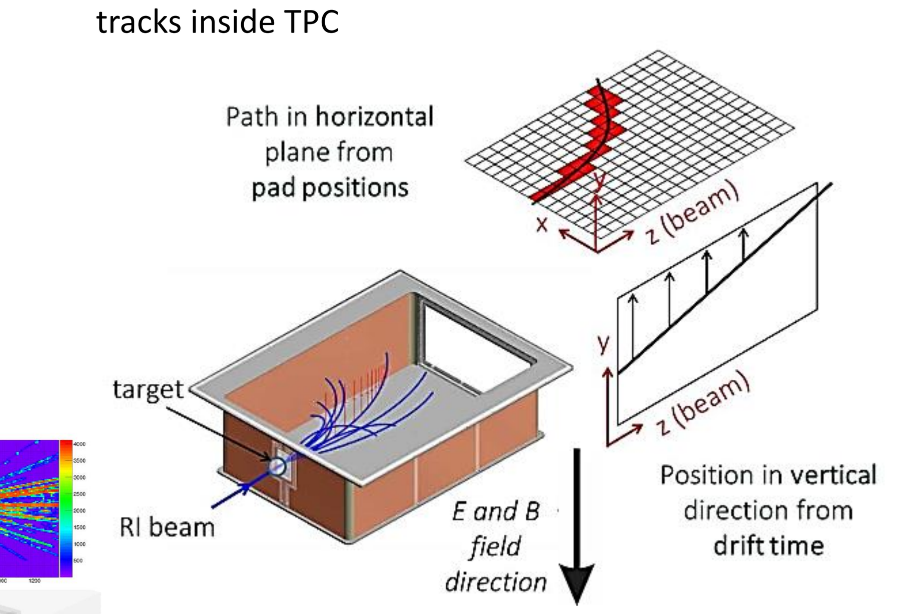
EXPERIMENTAL PLANS

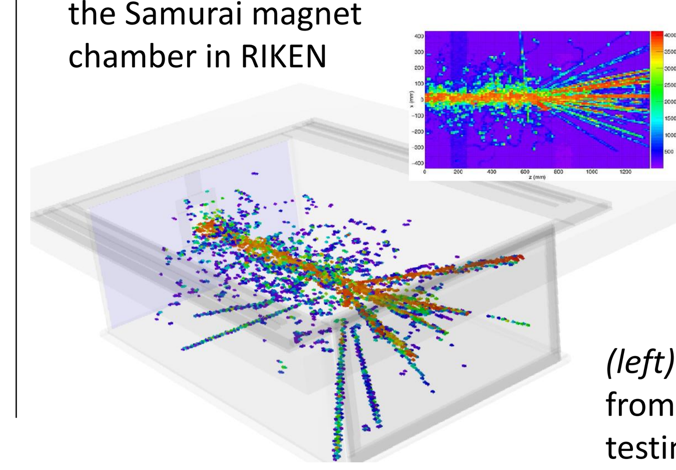
- We need 300 MeV/u with reasonable-intensity ^{132}**Sn** & ^{108}**Sn** secondary beams, available at RIBF (RIKEN), Japan & FRIB (2020)
- We need a **time-projection chamber** (TPC) inside a strong magnet to detect pions and other particles.
- In 2010, MSU received a $1.2 million grant from DOE to construct *SπRIT (SAMURAI Pion-Reconstruction and Ion-Tracker)*
  - Completed in 2013 & shipped to RIKEN in 2014
  - Two experiments 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

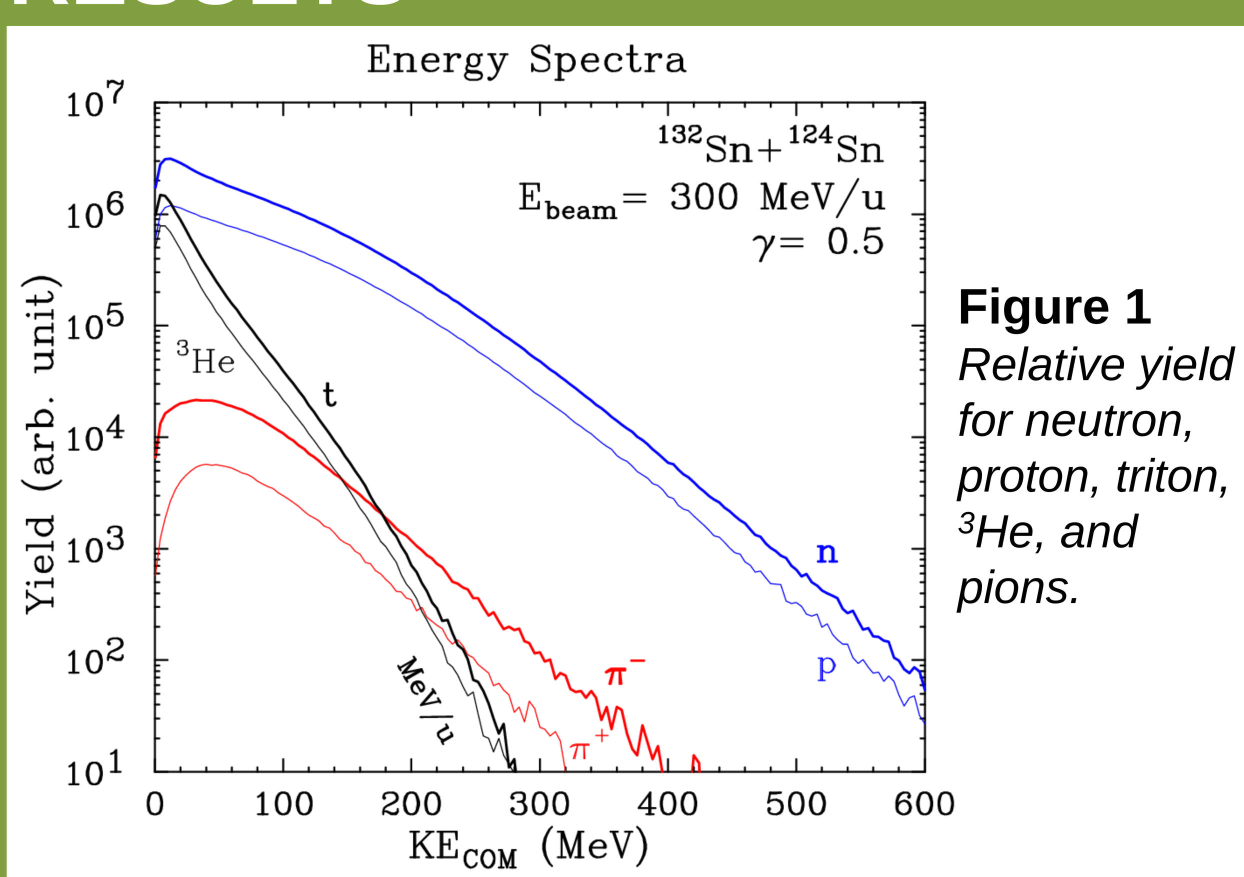


Figure 1
Relative yield for neutron, proton, triton, ³He, and pions.

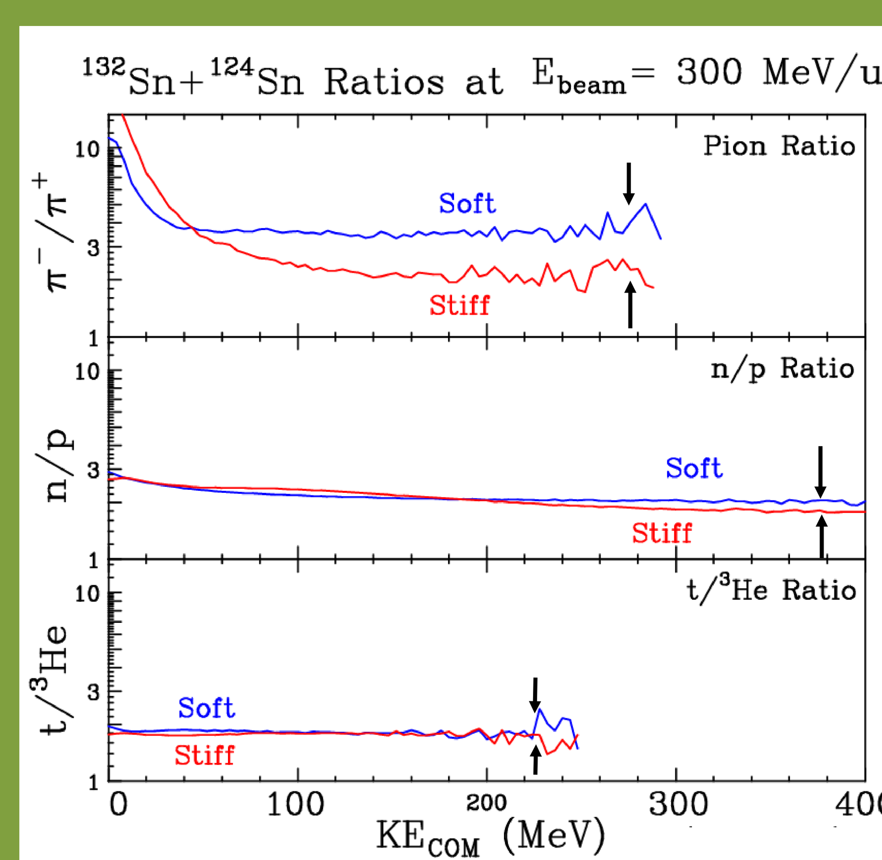


Figure 2
Comparison of pion ratio (π-/π+), n/p ratio, and t/³He ratio.

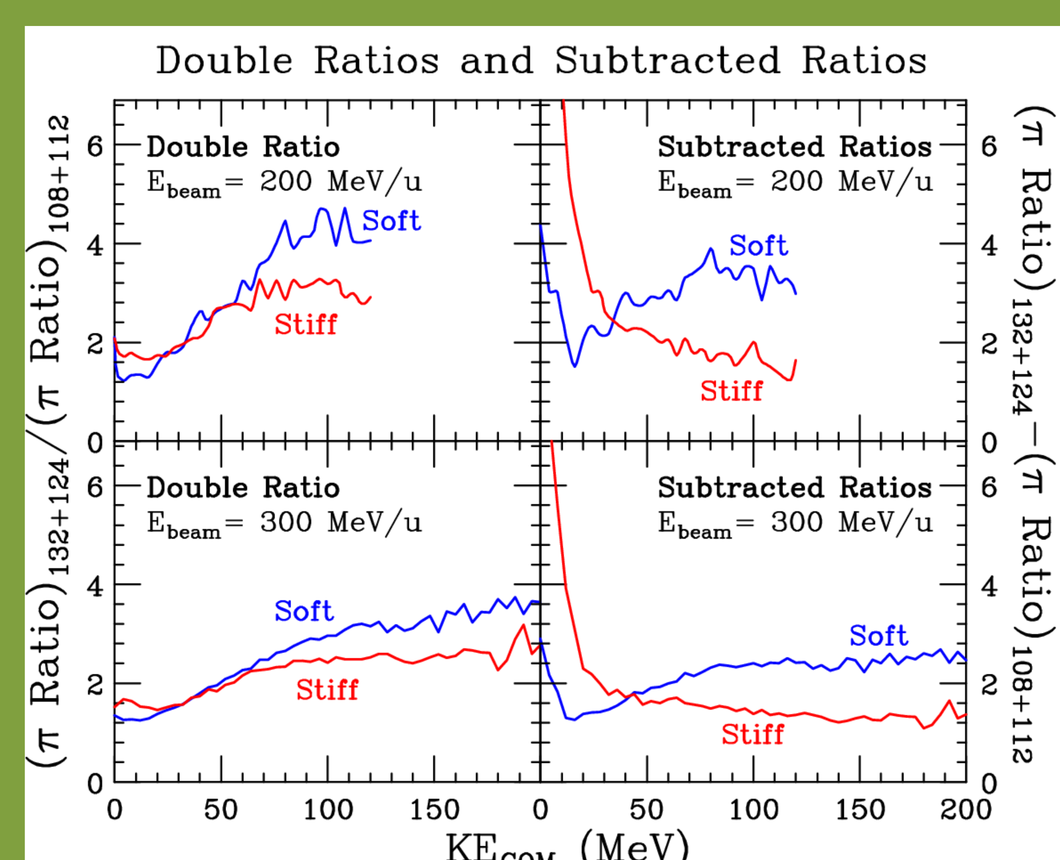


Figure 3
Enhanced pion ratios of ^{132}**Sn** + ^{124}**Sn** & ^{108}**Sn** + ^{112}**Sn** using double & subtracted ratios methods.

SUMMARY | NEXT STEP

- Simulations show that pion ratio is the most sensitive observable, compared to n/p and triton/³He.
- 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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