Pion Simulations for Symmetry Energy Studies

Search for Symmetry-Energy Observables to Understand the Properties of Neutron Stars

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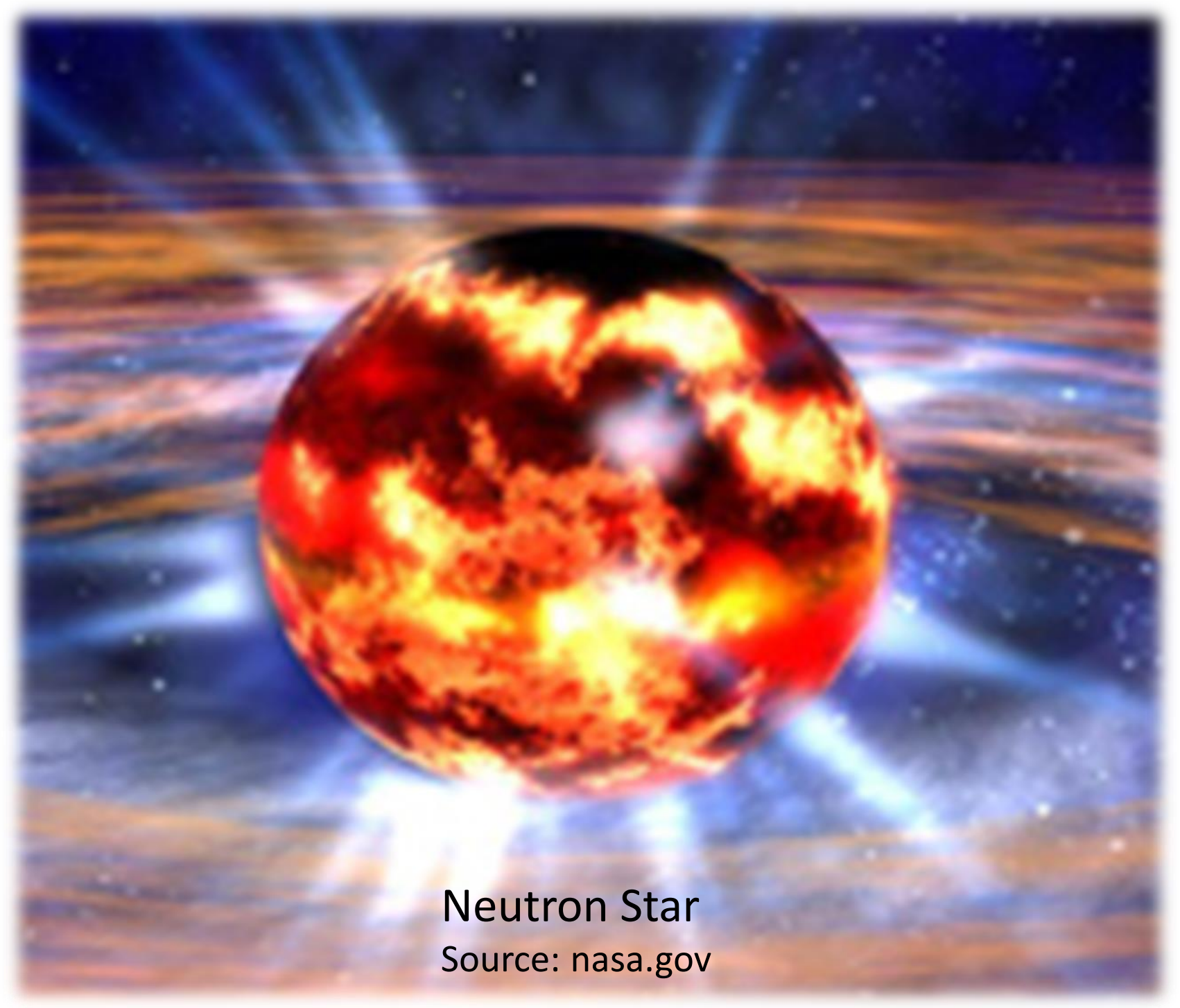
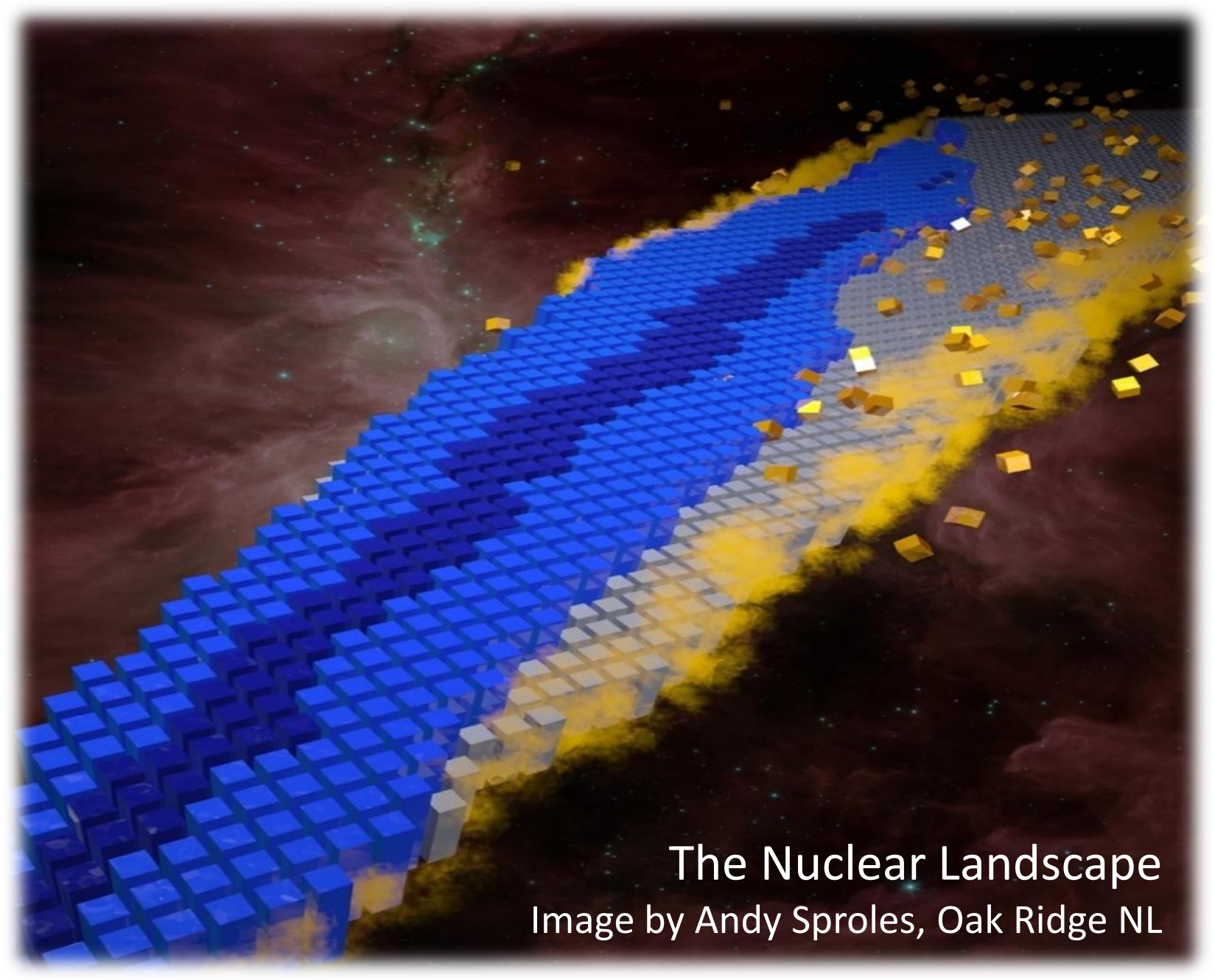
MOTIVATION

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


Neutron Star
Source: nasa.gov

Why does not a neutron star 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 Andy Sproles, Oak Ridge NL

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

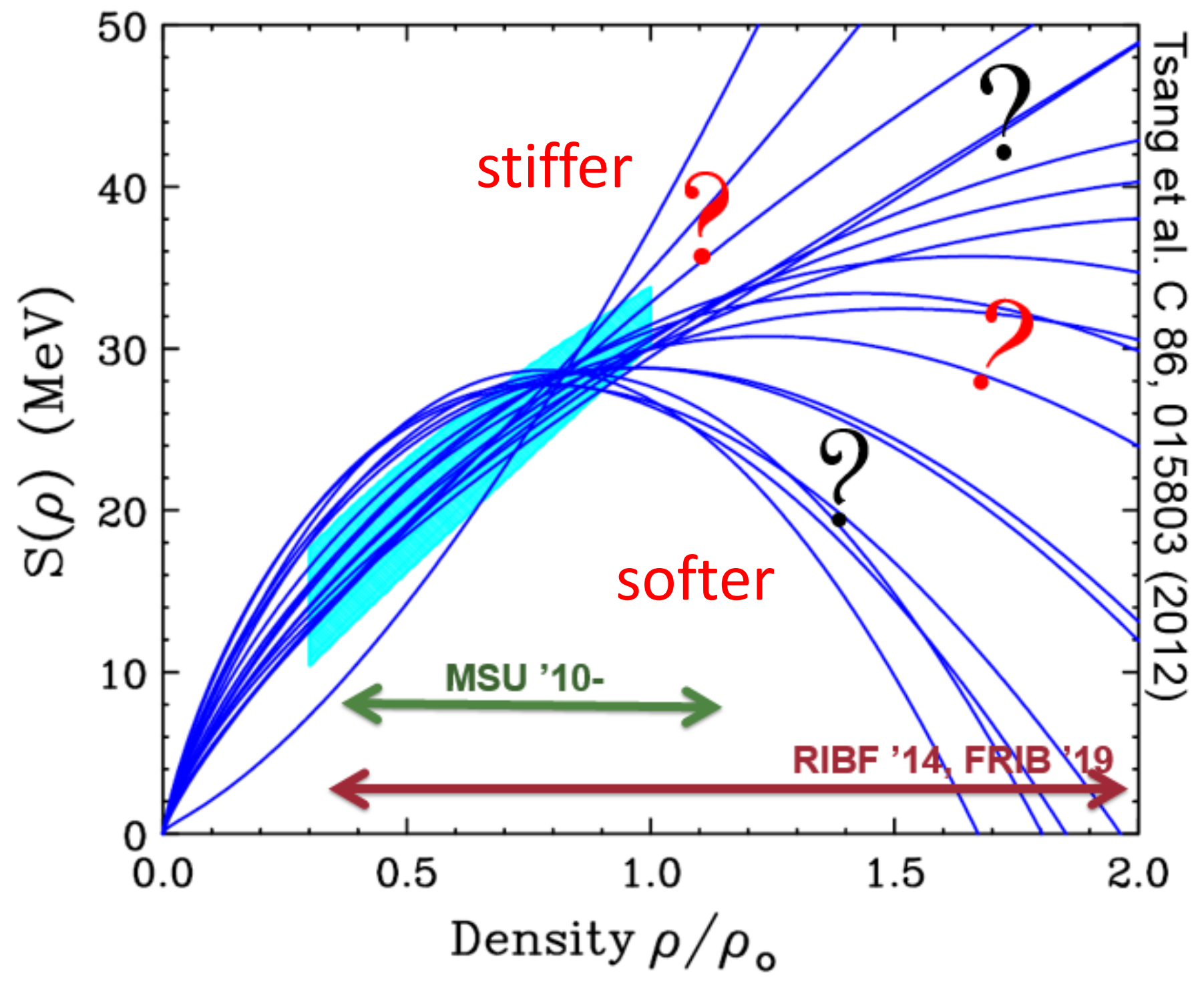
HEAVY ION COLLISIONS & pBUU TRANSPORT MODEL

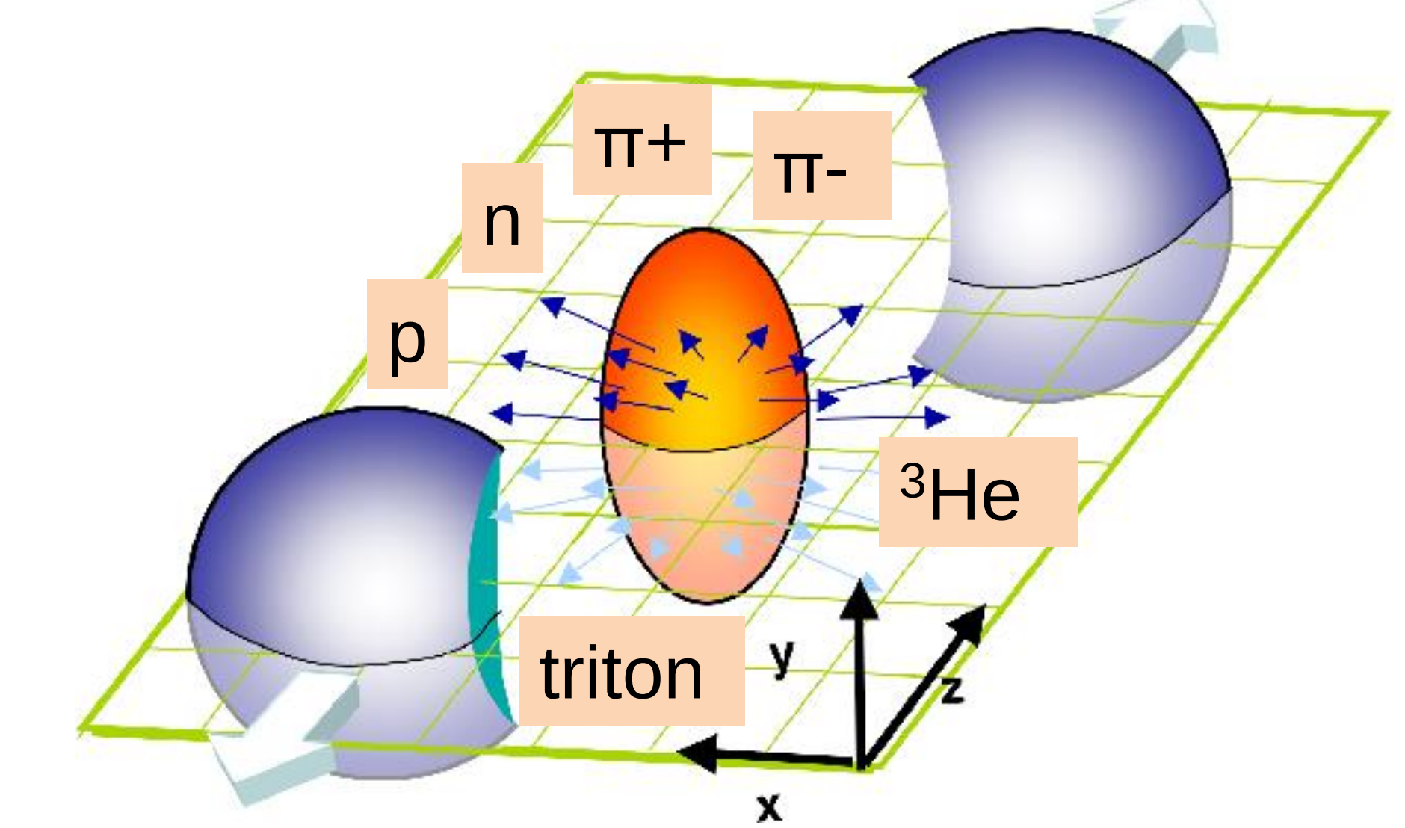
The Nuclear Equation of State (EOS)

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

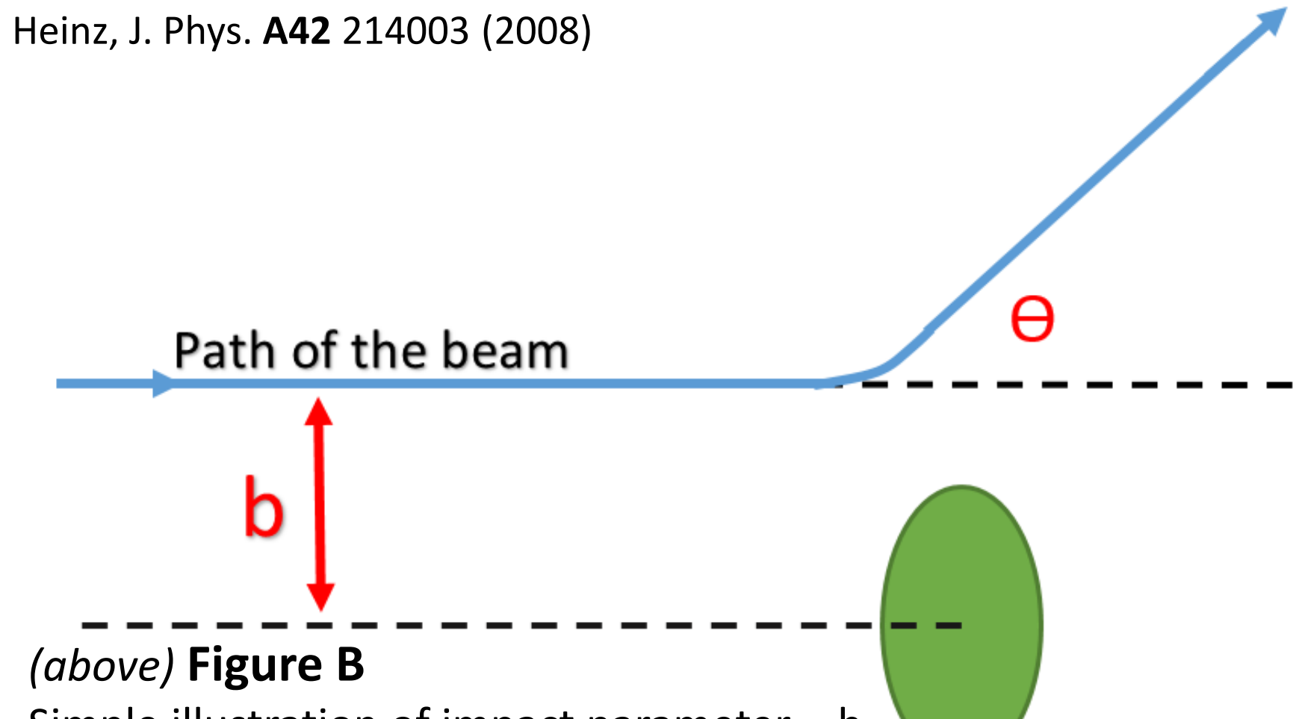
$$S(\rho) = S_{kin0}\left(\frac{\rho}{\rho_0}\right)^{\frac{2}{3}} + S_{int0}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

- Symmetry energy is not well understood, especially at **high density.**
- We can use **Colliding heavy ions 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)

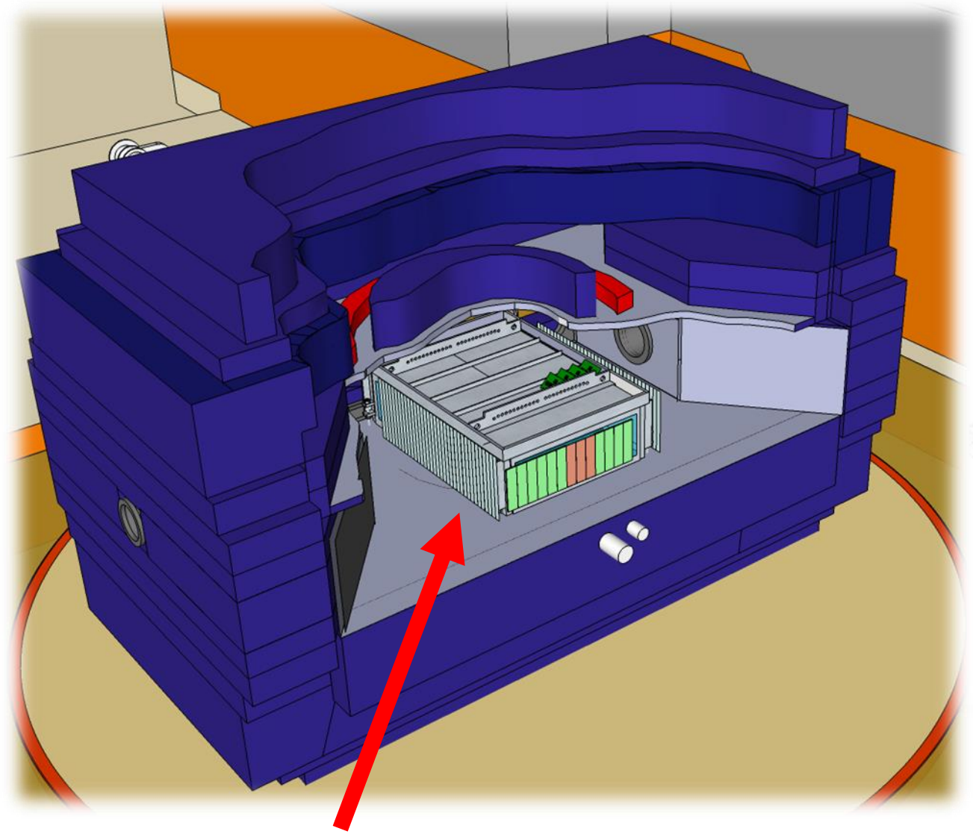


(above) **Figure B**
Simple illustration of impact parameter – b.
Image by Hananiel Setiawan

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

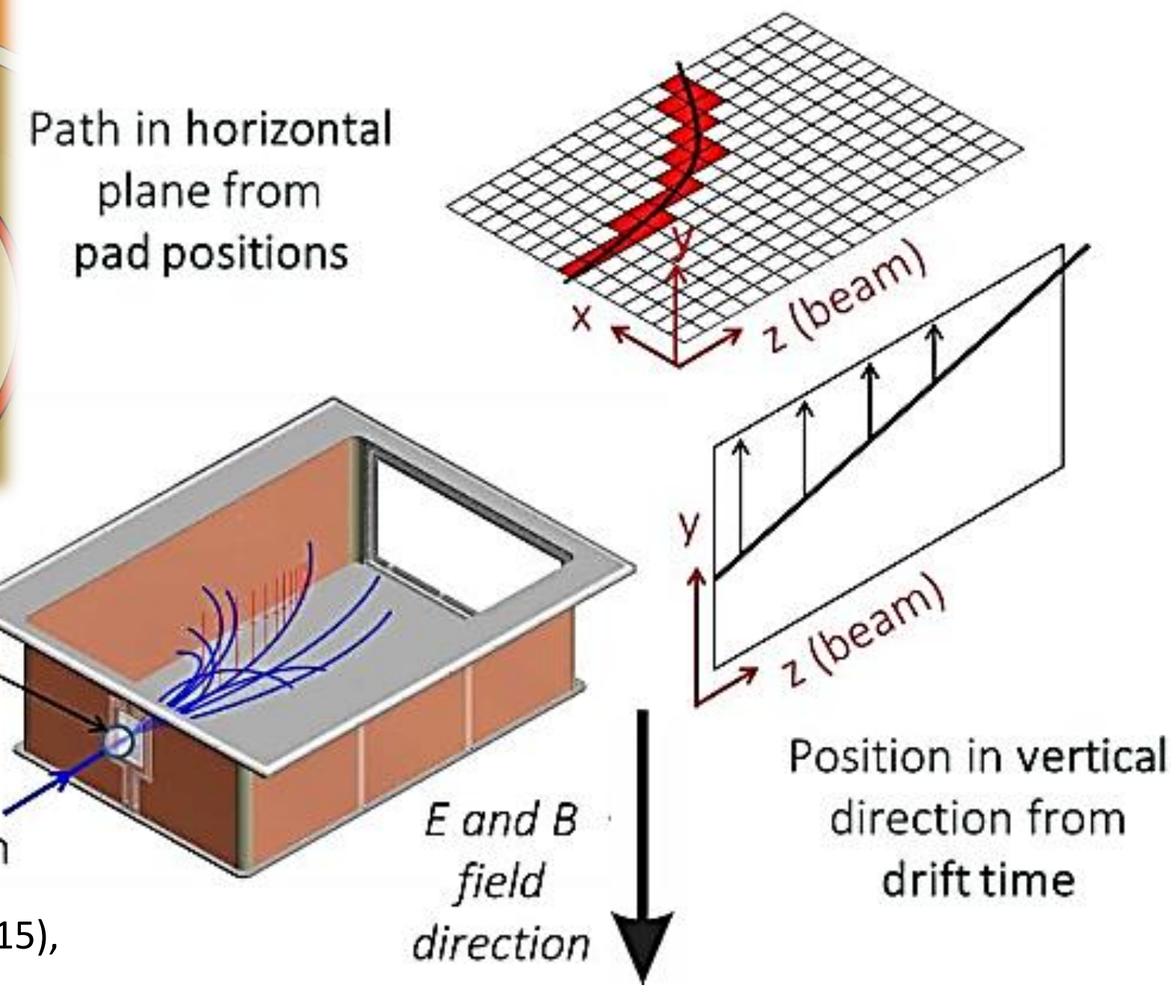
EXPERIMENTAL PLANS

- 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** (2015) 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) **Figure C**
Interpretation of possible particle tracks inside TPC



R. Shane, et al., Nucl. Instrum. Meth. A (2015), doi:10.1016/j.nima.2015.01.26

RESULTS

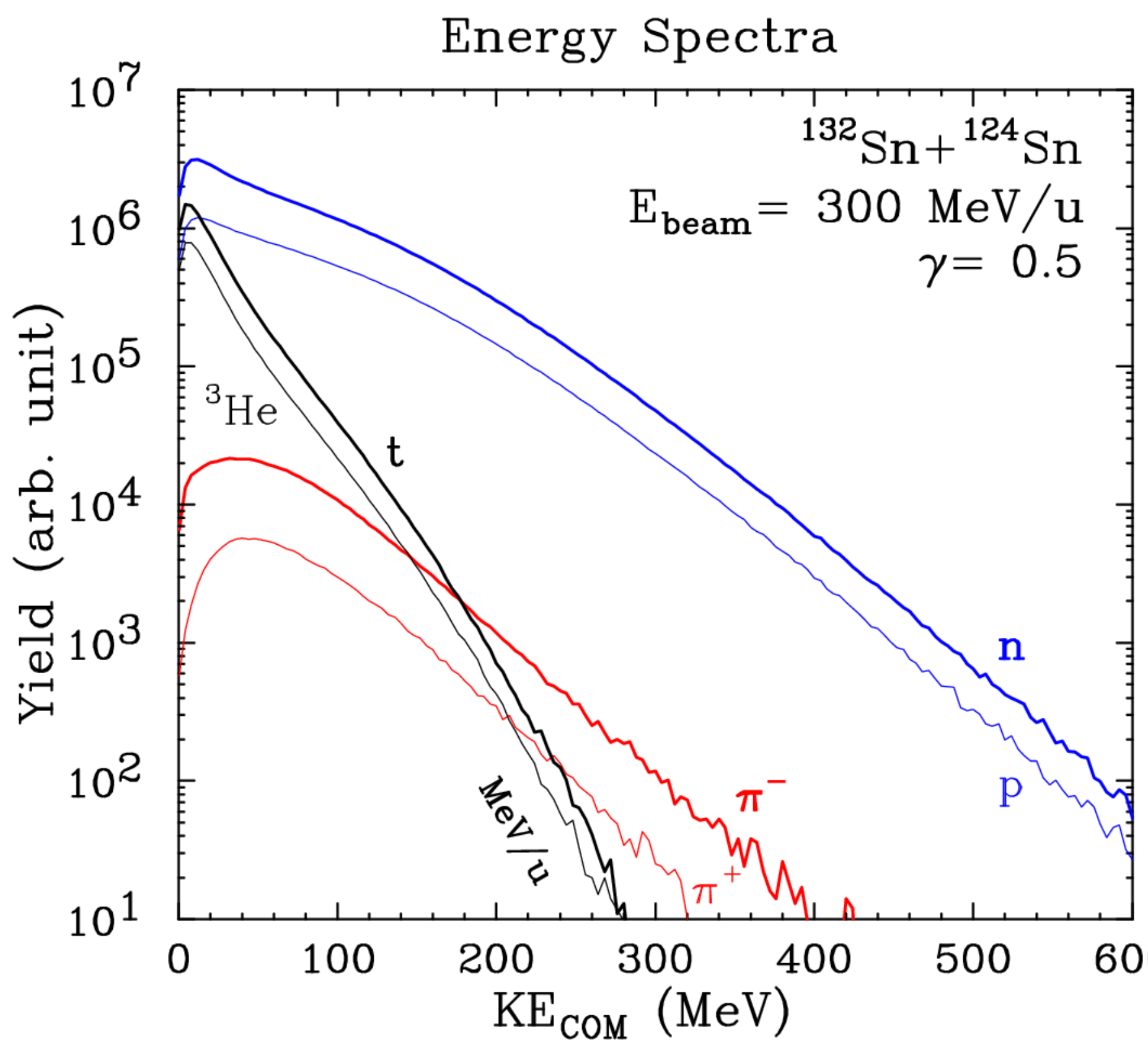


Figure 1
Relative yield for neutron, proton, triton, ³He, and pions.

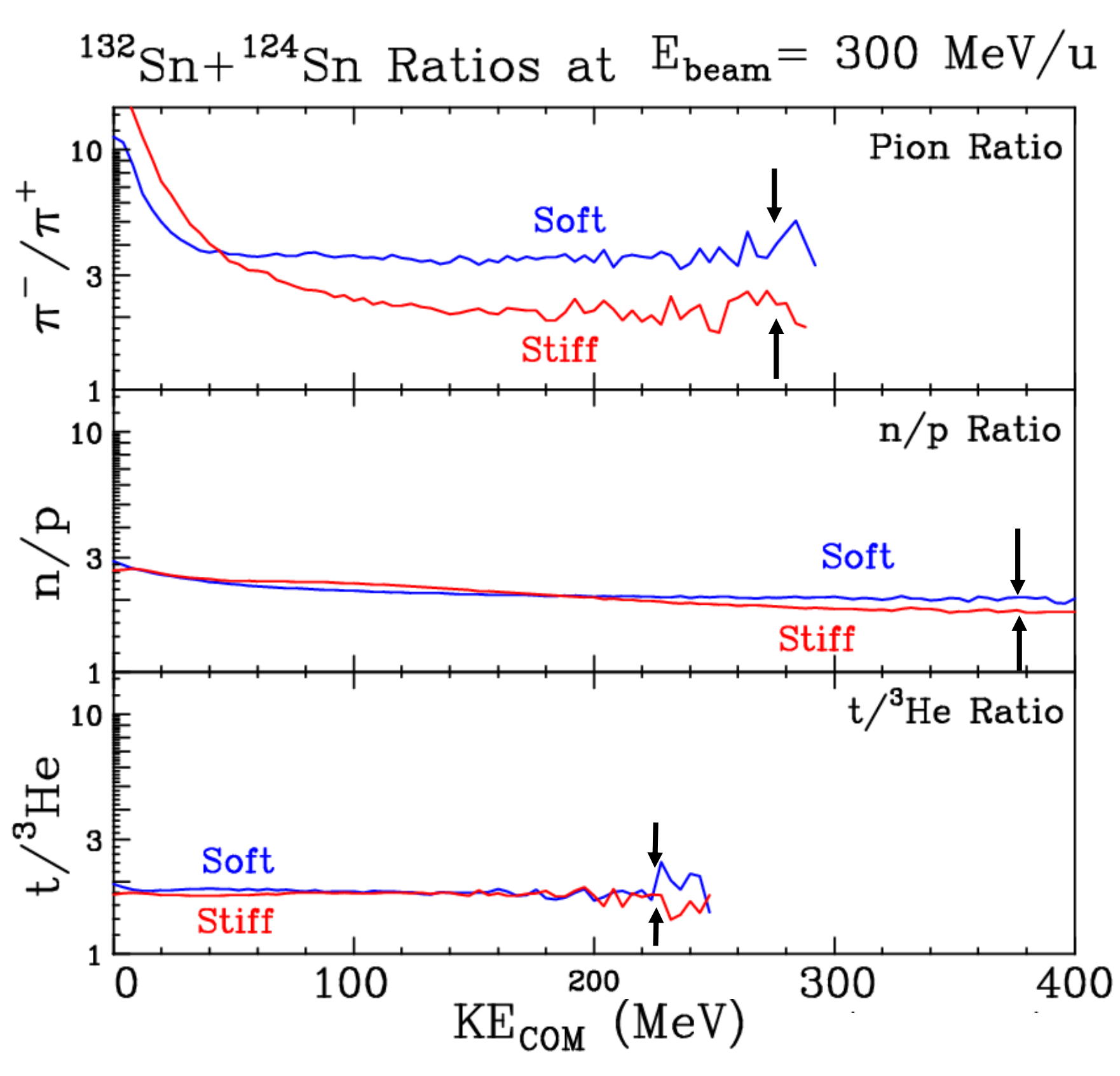


Figure 2
Comparison of pion ratio (π-/π+), n/p ratio, and t/³He ratio.

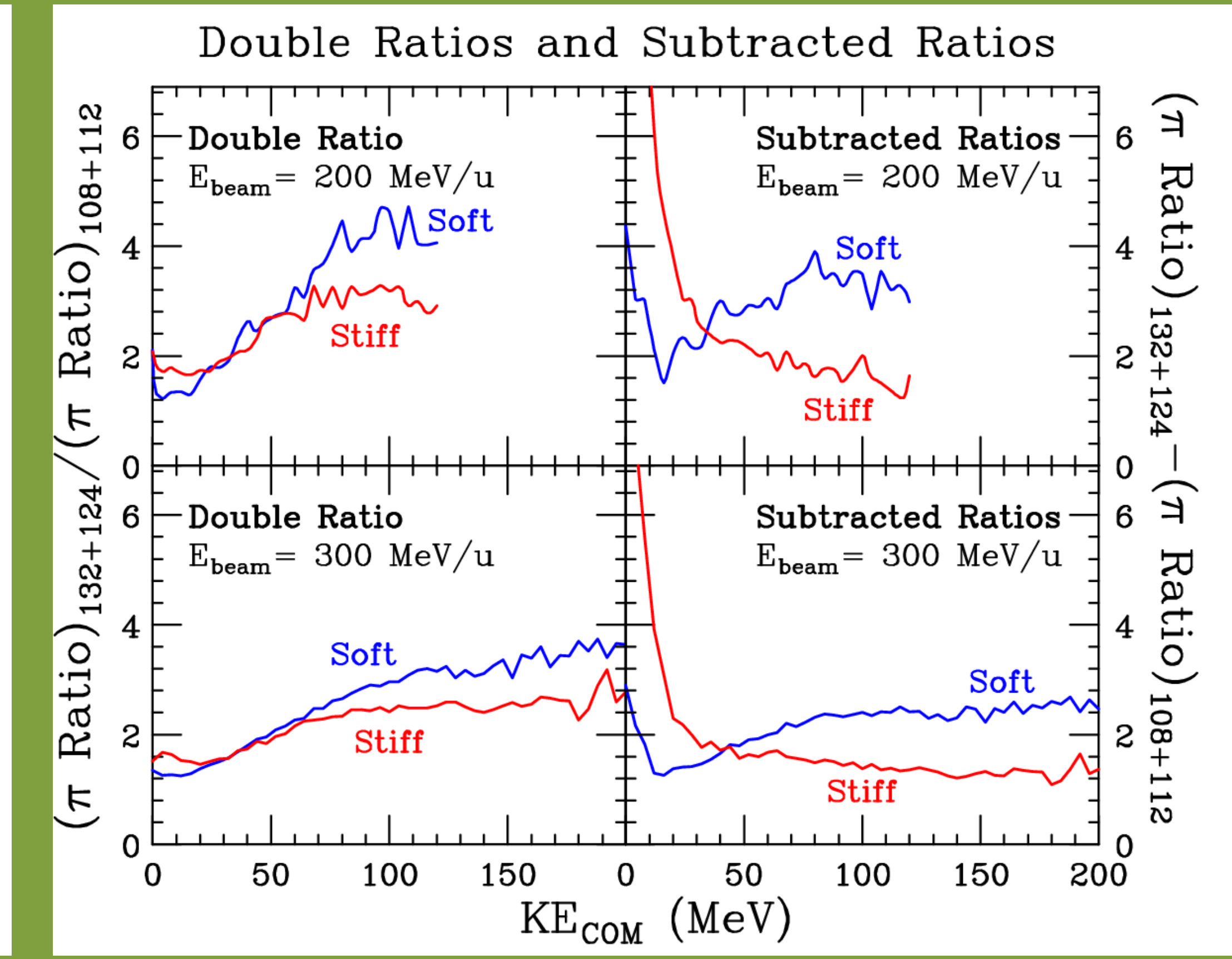


Figure 3
Enhanced pion ratios of ^{132}**Sn** + ^{124}**Sn** & ^{108}**Sn** + ^{112}**Sn** using double & subtracted ratios methods.

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 2015-16.
- We plan to do more simulations with asymmetric system of ^{48}Ca+^{124}Sn and ^{40}Ca+^{112}Sn for planning future experiments.

ACKNOWLEDGEMENTS:

US Department of Energy Grant No. DE-SC0004835

MSU NSCL/FRIB and *HiRA/SEP* group

J. Estee, J. Barney, Z. Chajecki, P. Danielewicz, J. Hong , W.G. Lynch, R. Shane, S. Tangwancharoen, M.B. Tsang, R. Showalter, S. Sweany, J. Winkelbauer, J. Manfredi

The NSCL is funded in part by Michigan State University and the National Science Foundation.