Experimental study of asymmetric nuclear matter EOS from heavy-ion reactions with RIBF-SPiRIT

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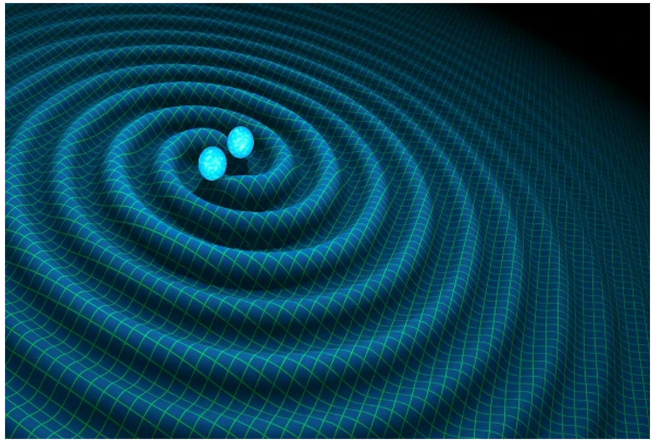
Asymmetric nuclear matter EOS: Symmetry Energy term of nuclear EOS

- Equation of state of nuclear matter can be reconstructed by using the differential thermodynamic identity:

$$E(T,\rho,\delta) = E(T,\rho,\delta=0) + E_{sym}(T,\rho)\delta^2 + O(\delta^4)$$

$$\delta = (\rho_n - \rho_p)/\rho$$

- The asymmetric term of nuclear EOS depends on δ
- Important term especially for astrophysics
  - Neutron star structure (T~0)
    - T ~ 10^6 K ~ 100 eV ←→ n Fermi-E ~ 10MeV
  - Supernovae process (T~ O(10) MeV)
  - Neutron star merger/Gravitational wave



Visualization of a NS merger and the gravitational waves

Asymmetric nuclear matter EOS: Symmetry Energy term of nuclear EOS

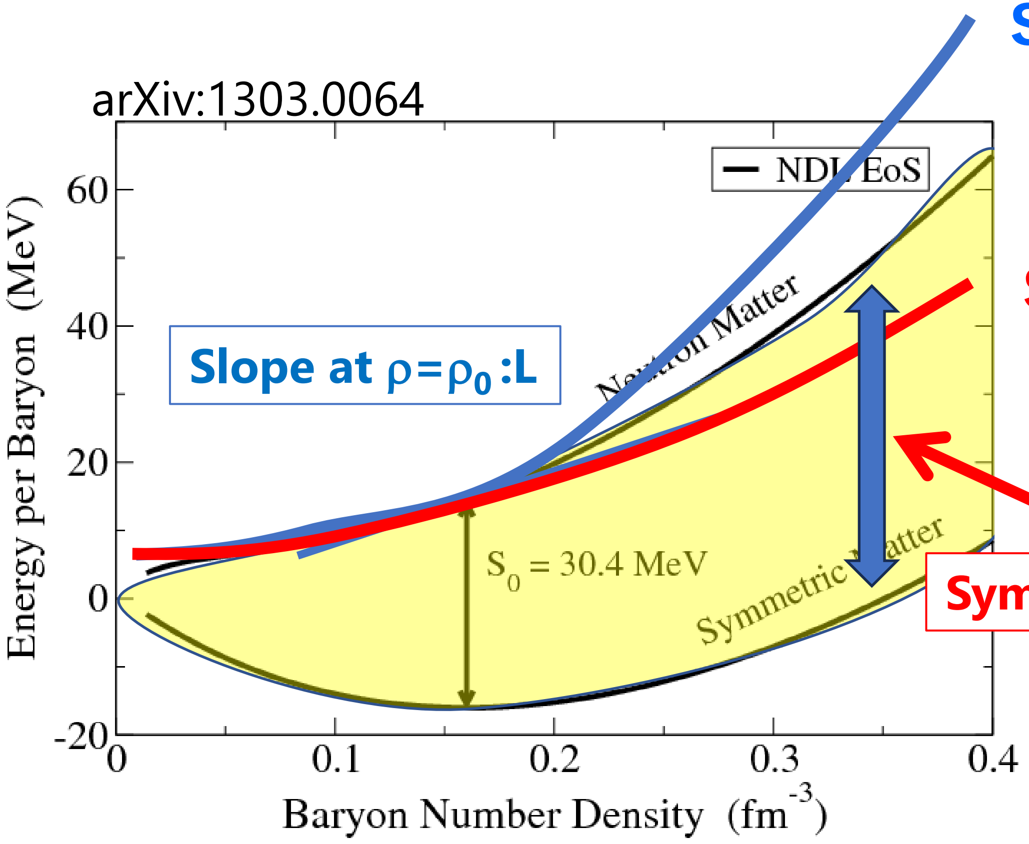
$$E(T,\rho,\delta) = E(T,\rho,\delta=0) + E_{sym}(T,\rho)\delta^2 + O(\delta^4)$$

$$\delta = (\rho_n - \rho_p)/\rho$$

stiff

soft

arXiv:1303.0064



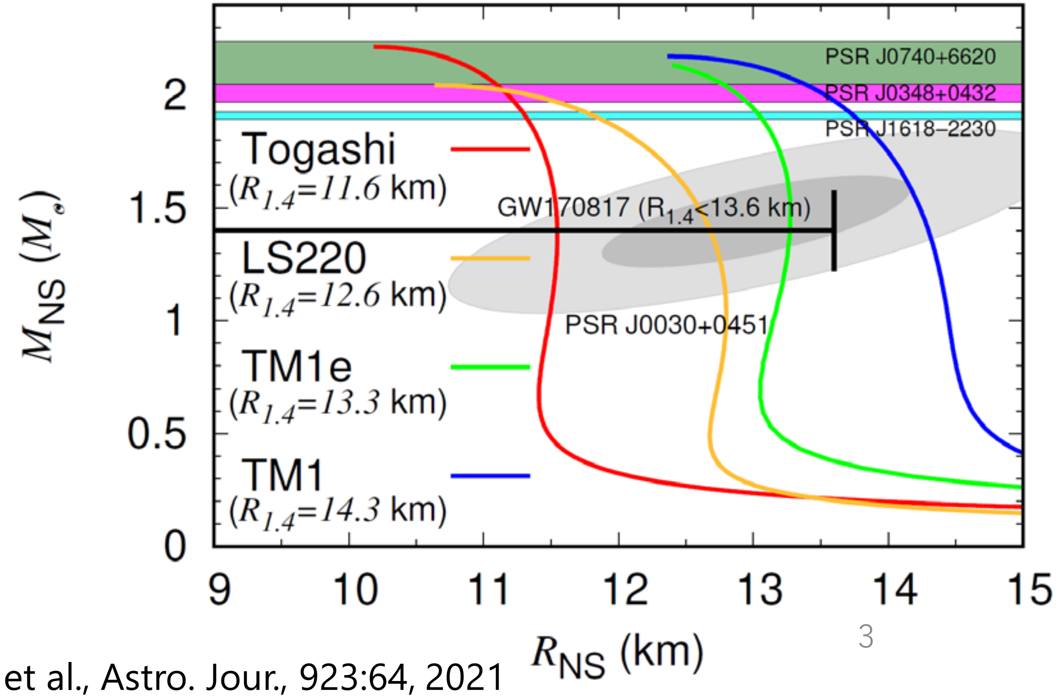
Slope at $\rho=\rho_0$: L

Symmetry Energy

Parameter L is often referred to compare the SE as it can be obtained both from Astrophysics and nuclear physics.

Soft
Easier to be compressed

Stiff
Harder to be compressed

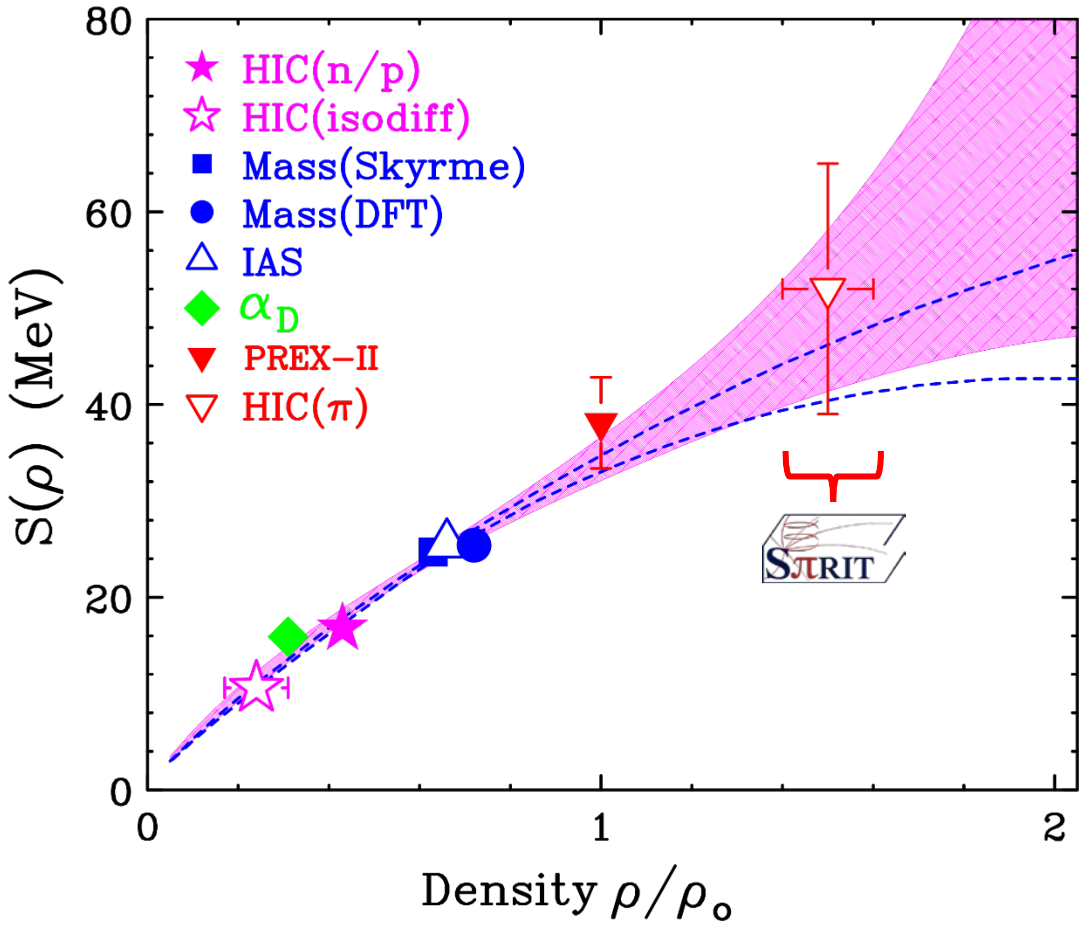


Dohi et al., Astro. Jour., 923:64, 2021

Density dependent Symmetry Energy (SE) constraints obtained from structure and HI collisions

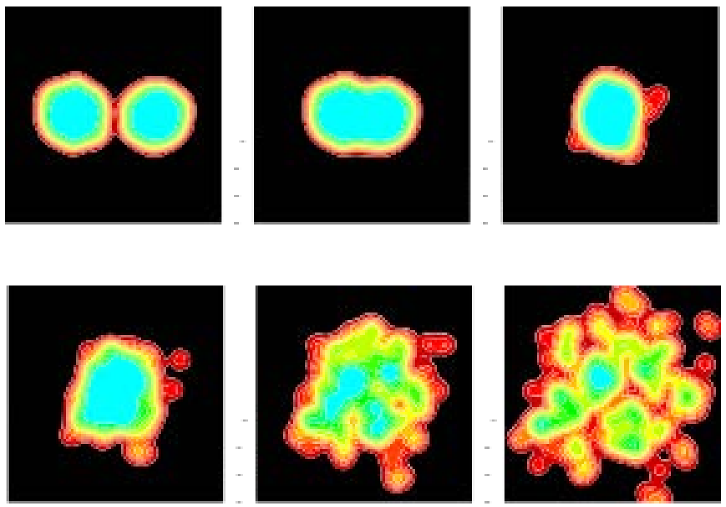
- Plotting constrain on SE at the sensitive density for each observables.
  - Skin thickness, nuclear mass, electric dipole polarizability.
- New data point at $\rho \sim 1.5\rho_0$
- The trend of fitted function is statistically consistent with the symmetry energy extracted by Danielewicz and Lee (DL3).

W.G. Lynch and M.B. Tsang PLB 830, 137098 (2022)



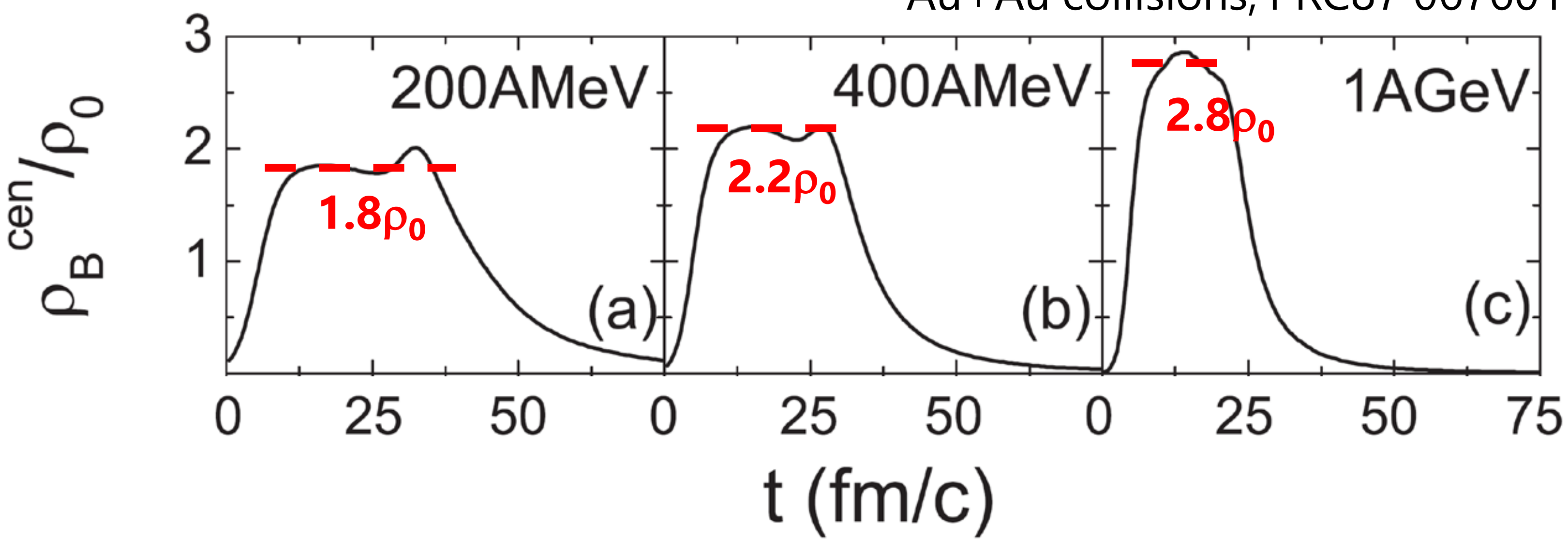
Terrestrial experimental study of high dense matter nuclear symmetry energy → Heavy Ion Collision (HIC)

Sn+Sn @300MeV/u



Central density as a function of time.

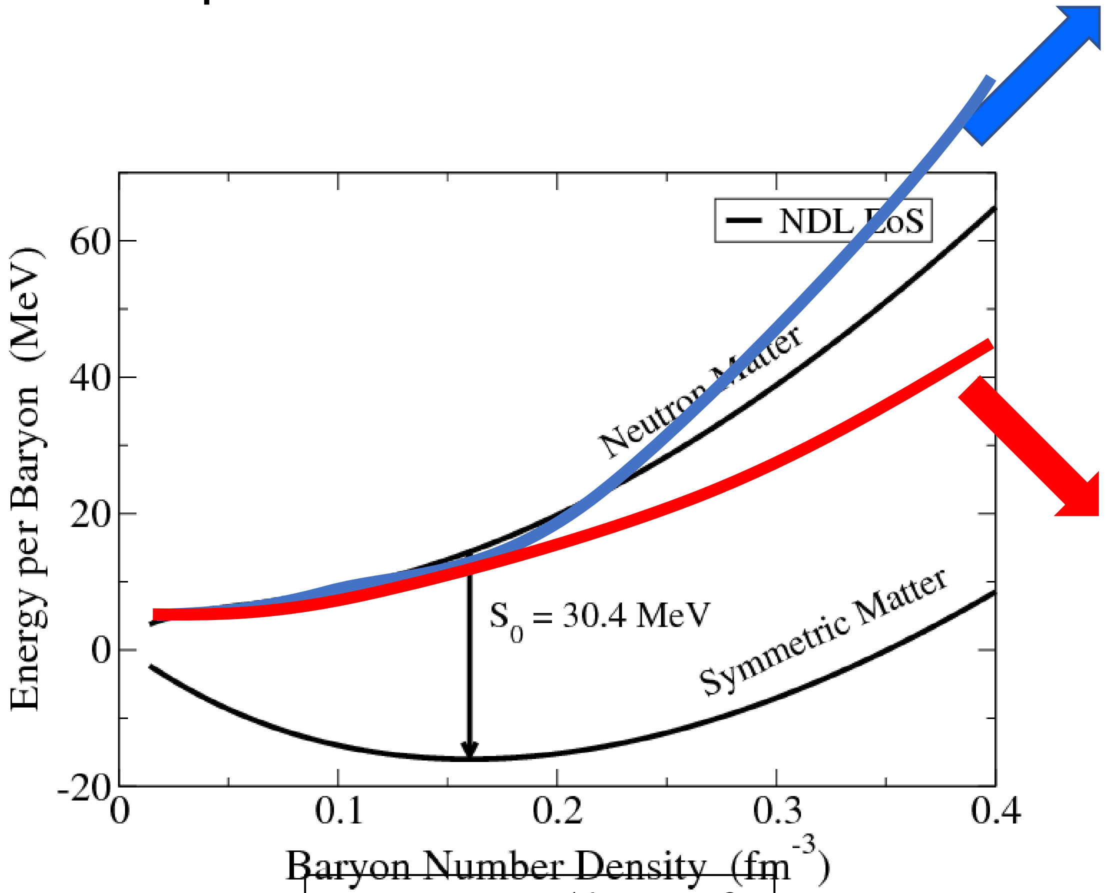
Au+Au collisions, PRC87 067601



- Unique way to realize high dense matter in laboratory.
- Quite challenging to extract the information of high dense matter symmetry energy since we need the help of transport model.
    - Mixture of equilibrium and non-equilibrium state.

Experimental observables from heavy ion collision to constrain the symmetry energy

- No direct observables, but contains the information of symmetry energy
- Symmetry energy → appeared as pressure difference between neutron and proton

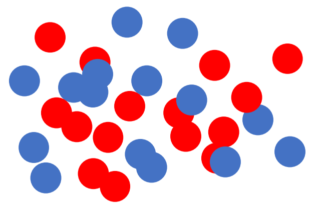


$\rho_0 = 2.5 \times 10^{14}$ g/cm^3

Stiff symmetry energy (large L)

→ lower ρ_n/ρ_p in higher dense region

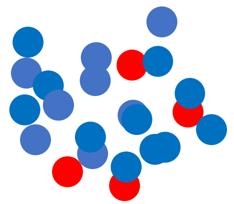
→ lower n/p in high ρ



Soft symmetry energy (small L)

→ larger ρ_n/ρ_p in higher dense region

→ larger n/p in high ρ



Experimental observables from heavy ion collision to constrain the symmetry energy

- No direct observables, but contains the information of symmetry energy
- Symmetry energy → appeared as pressure difference between neutron and proton

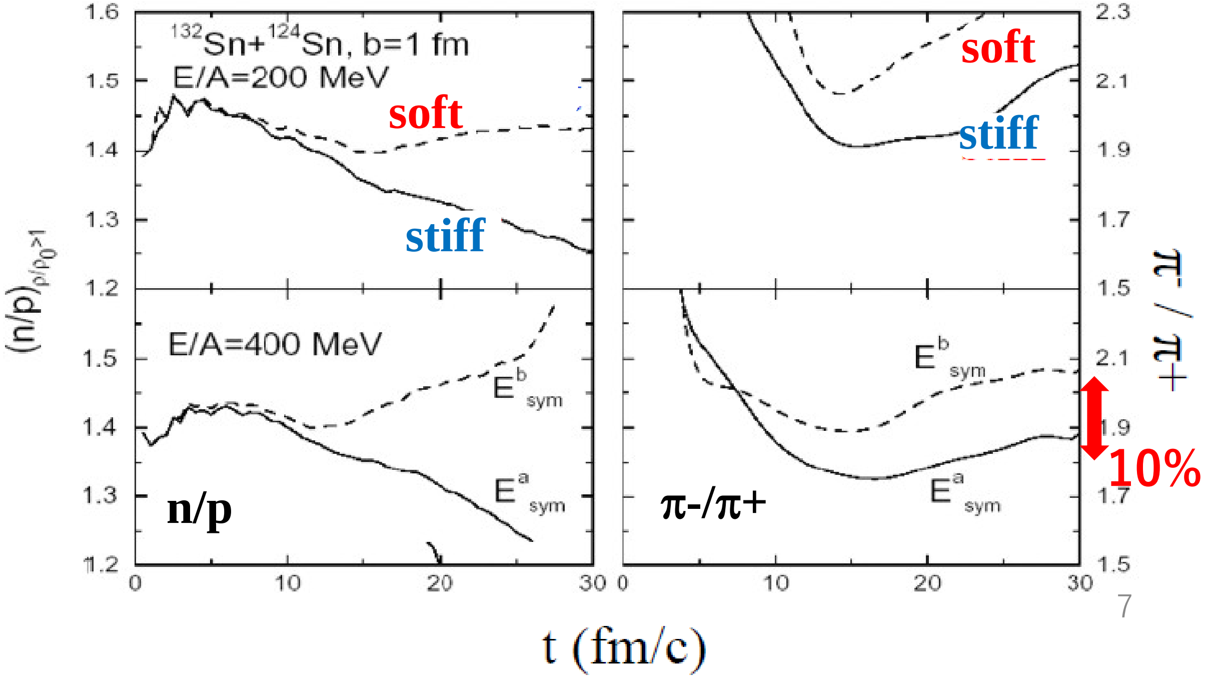
π^- production (main reaction)

$$nn \to p\Delta^-$$
$$\Delta^- \to n\pi^-$$

π^+ production (main)

$$pp \to n\Delta^{++}$$
$$\Delta^{++} \to p\pi^+$$

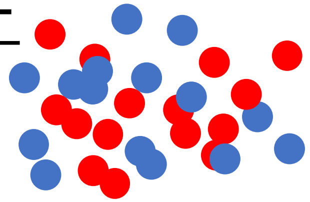
Li et al., Nucl.Phys. A734 (2004) 593.



Stiff symmetry energy (large L)

→ lower ρ_n/ρ_p in higher dense region

→ lower n/p, lower π-/π+



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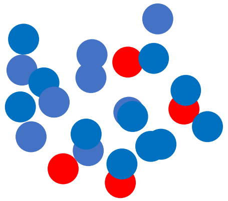
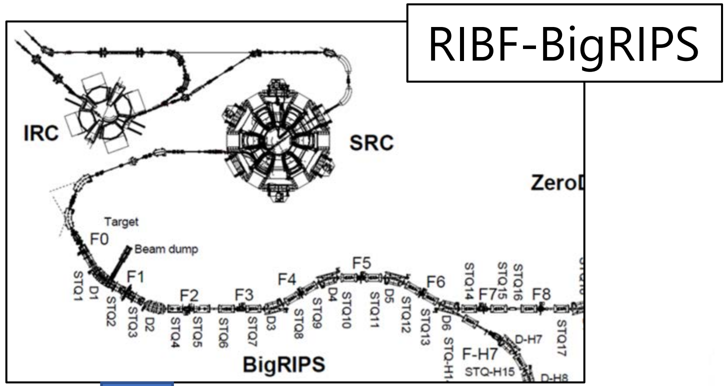


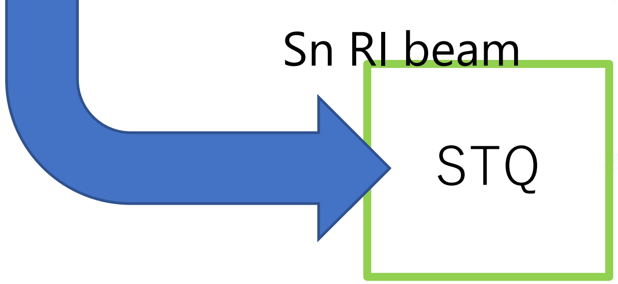
Heavy RI Collision program @RIBF

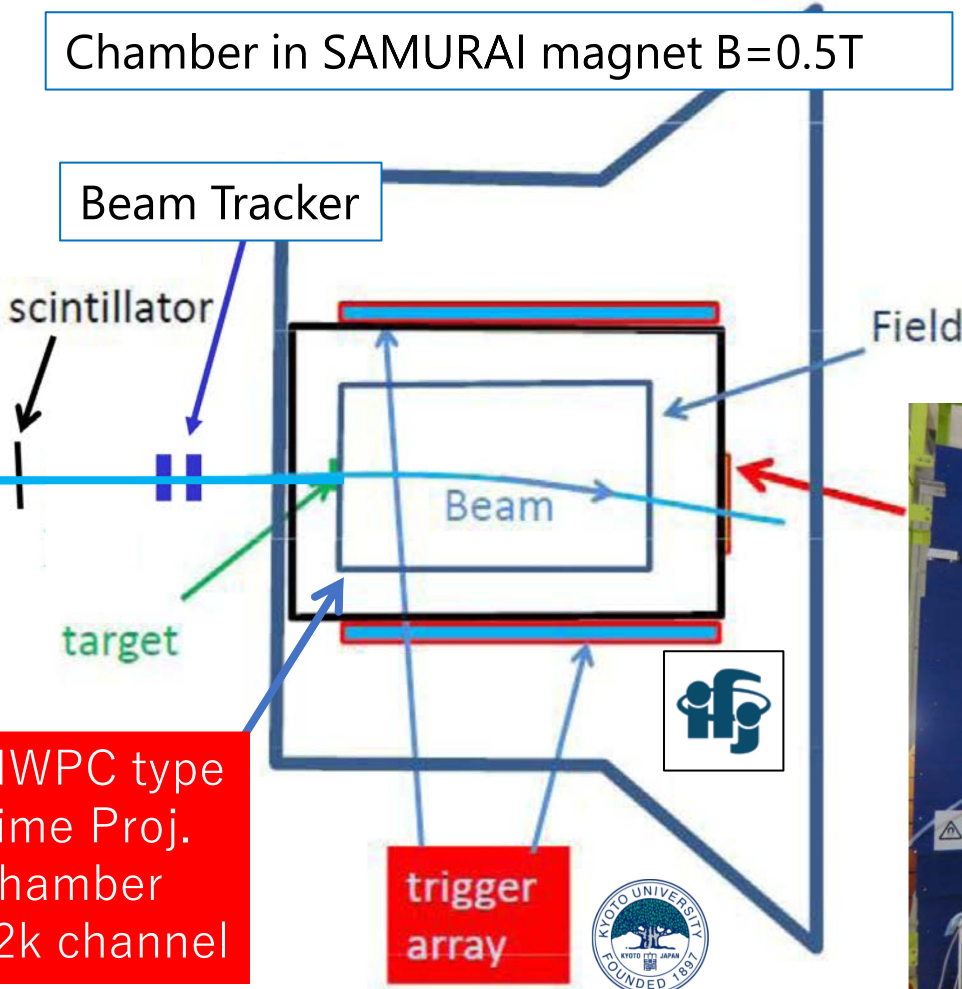
- Experimental project to give a constrain on the density dependent symmetry energy mainly for higher dense region.
- Systematic measurements in same *Z* but different *N* systems realized with heavy RI beam.
  - Additional parameter we can control. (Control nuclear effect.)
  - **$\rho\sim2\rho_0$** nuclear matter at RIBF energy.
- Effect of symmetry energy on each observables is expected to be largest around this energy region. (especially pion emission)
- 1st experimental campaign using Sn (Z=50) isotopes in 2016 spring.
  - Data taken for 4 systems.

  - ^{132}Sn + ^{124}Sn @E_{beam}/A = 270 MeV, Yp=0.39
  - ^{124}Sn + ^{112}Sn @E_{beam}/A = 270 MeV, Yp=0.42
  - ^{112}Sn + ^{124}Sn @E_{beam}/A = 270 MeV, Yp=0.42
  - ^{108}Sn + ^{112}Sn @E_{beam}/A = 270 MeV, Yp=0.45

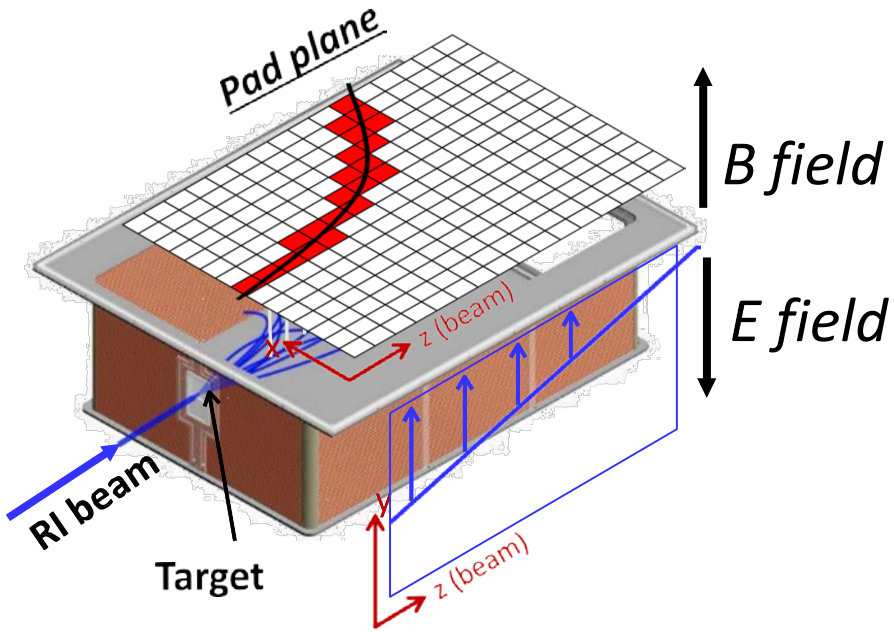
SPiRIT experimental setup top view: beam line+TPC+trigger+neutron detector





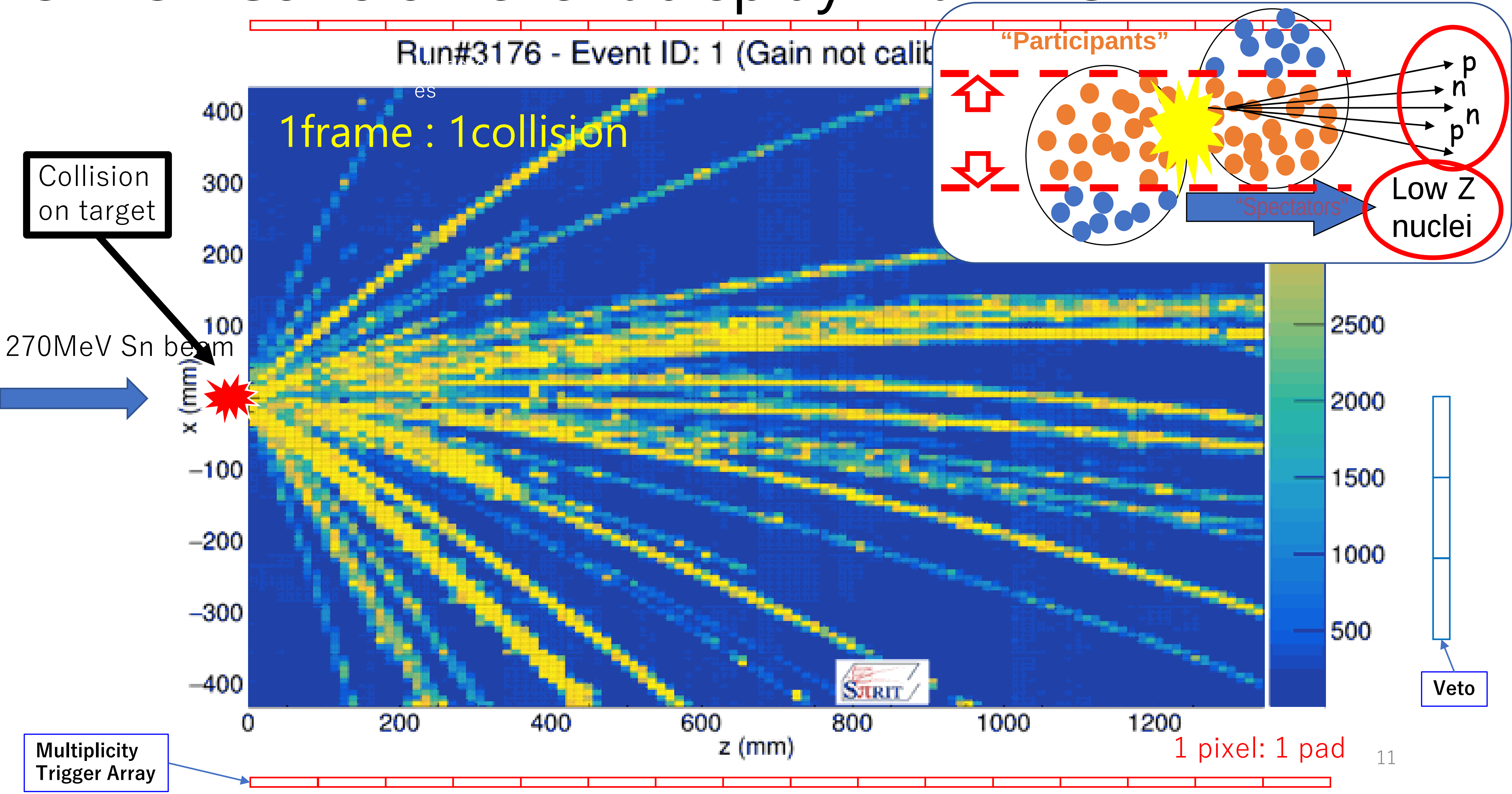


Our device for heavy RI collosion experiment: Time Projection Chamber (TPC)



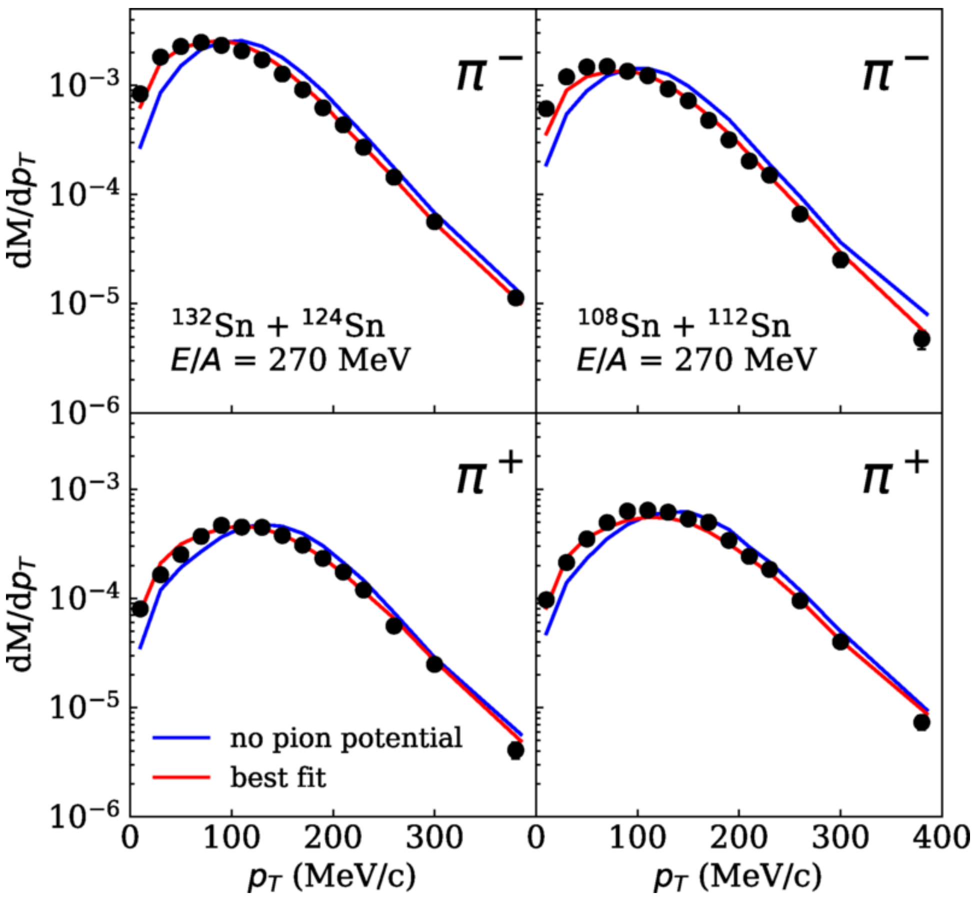
- Large 3D tracking detector in magnet (B=0.5T).
  - Energetic charged particle make electron-ion pair in gas (P10).
  - Electrons are drifted along with E-field.
  - Energy loss – residual → particle identification.
    - $B\rho = \frac{A}{Z}\frac{p_{nucl}}{e}$
    - dE/dX←BetheBroth(Z,v)

Sn+Sn Collision event display with TPC



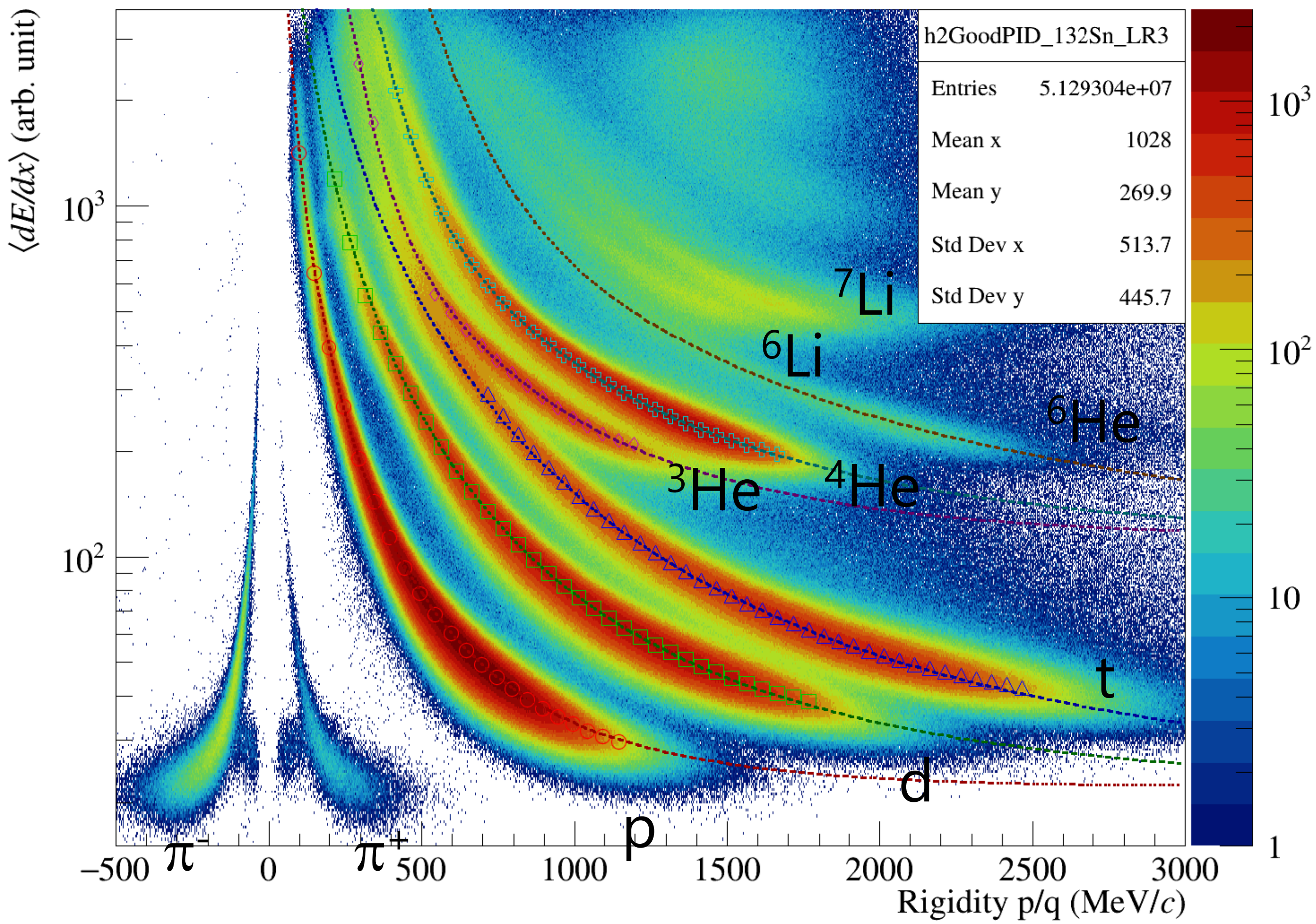
Charged particle measurement with Time Projection Chamber

Measure all of particles produced in a HIC
Particle ID based on rigidity-dE/dx (dE/dx ∝ Z^2)
Rigidity → particle momentum

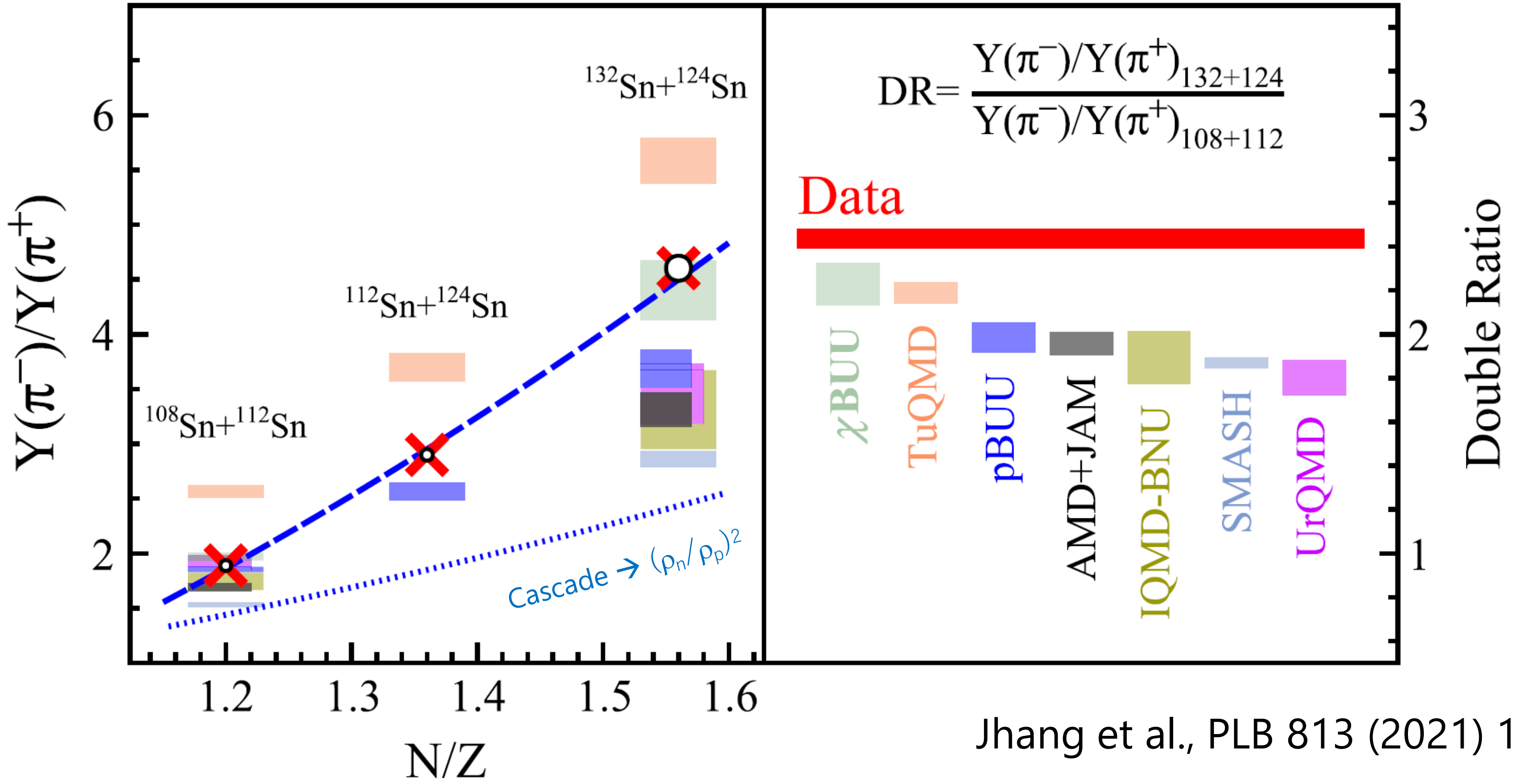


Estee et al., PRL 126 (2021) 162701

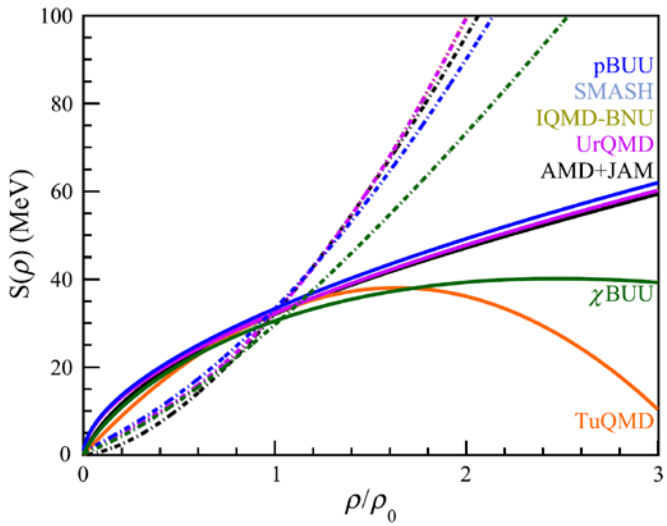
TPC ParticleID for ^{132}Sn+^{124}Sn



Result on pion multiplicity: pion ratio
→Large discrepancy among theoretical models



E_{sym} in each model



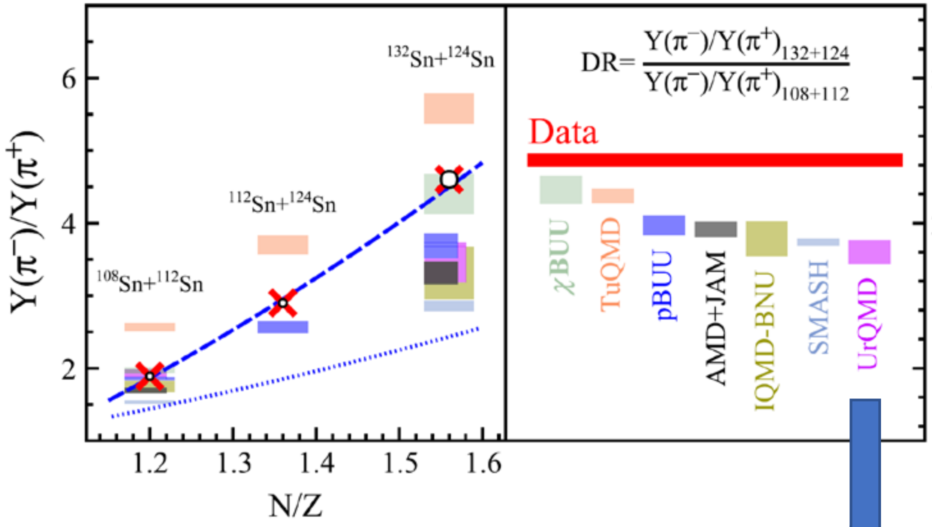
Jhang et al., PLB 813 (2021) 136016

- Numerical calculation of HIC dynamics by using transport theory.
- Predictions with same EoS are supposed to be same →Larger discrepancy than experimental result.
- Different assumptions regarding the mean field potentials for Δ baryons and pions can influence the pion multiplicities.

Need to understand the discrepancy among the model or use the observables which do not depend on model

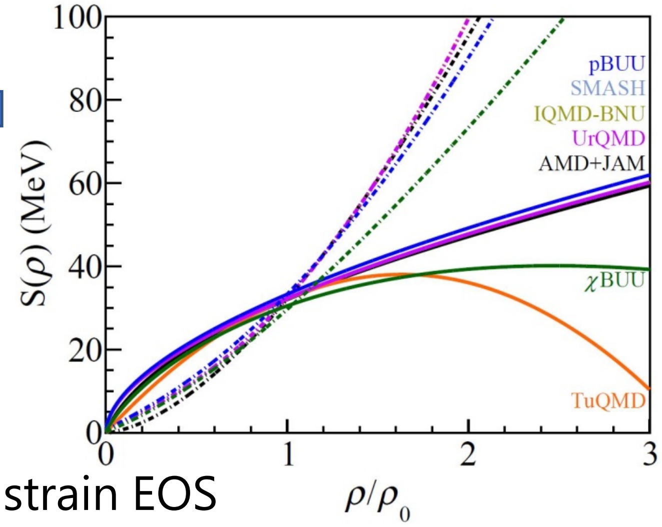
Observables In HIC ⟷ **Transport theory** ⟷ **EOS**

Mean field U



Pion, LCP, Flow Data

Prediction with Theory
Assume σ_{NN} and m^*_{np}

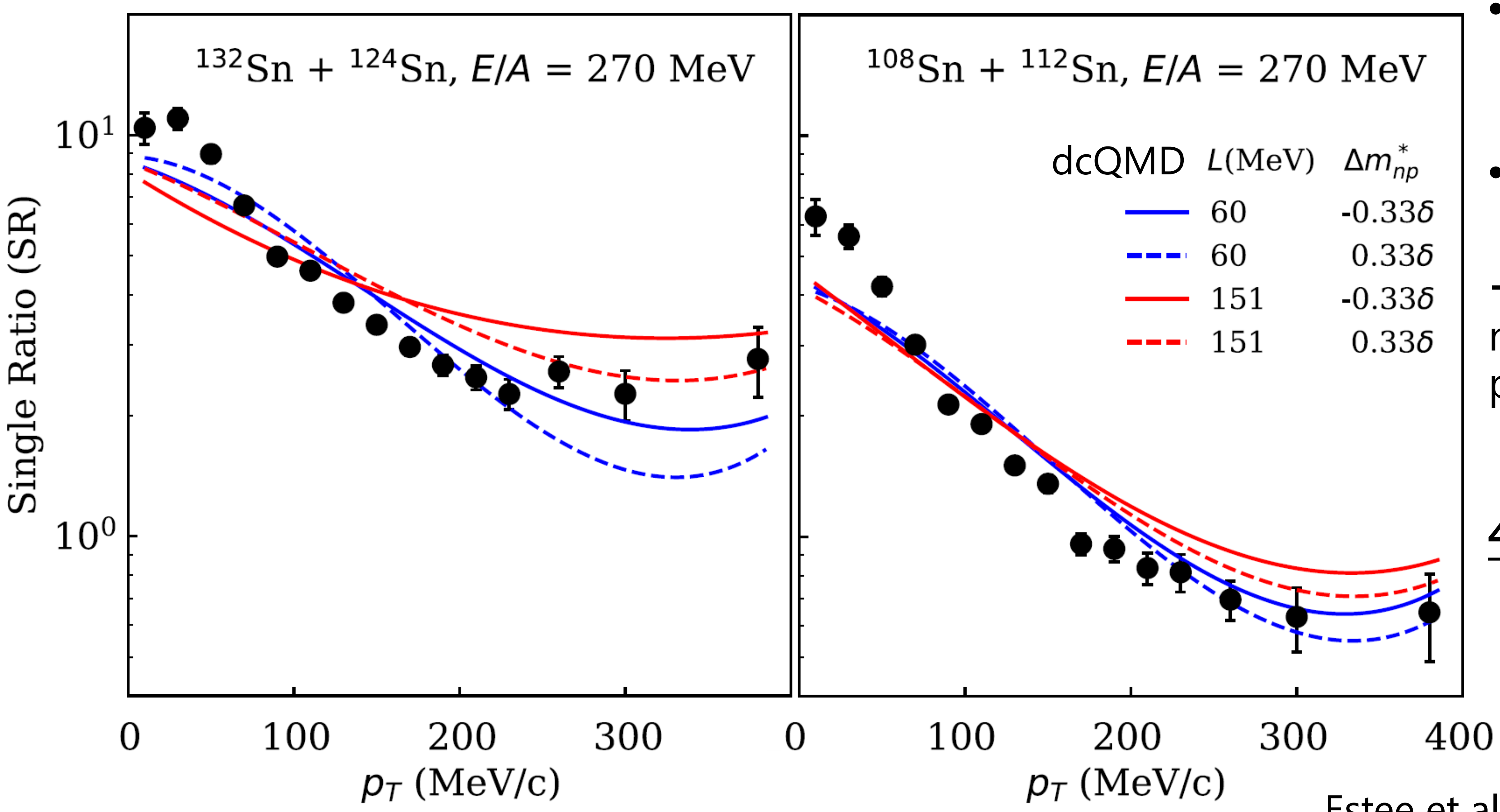


Constrain EOS

Feedback to Theory w/ exp. data
determine σ_{NN} and m^*_{np}

High-momentum pion data: reduce the influence from the assumption for Δ/pion mean field potential

- Sensitivity to the isospin dependence of mean field dominates at high-pT.



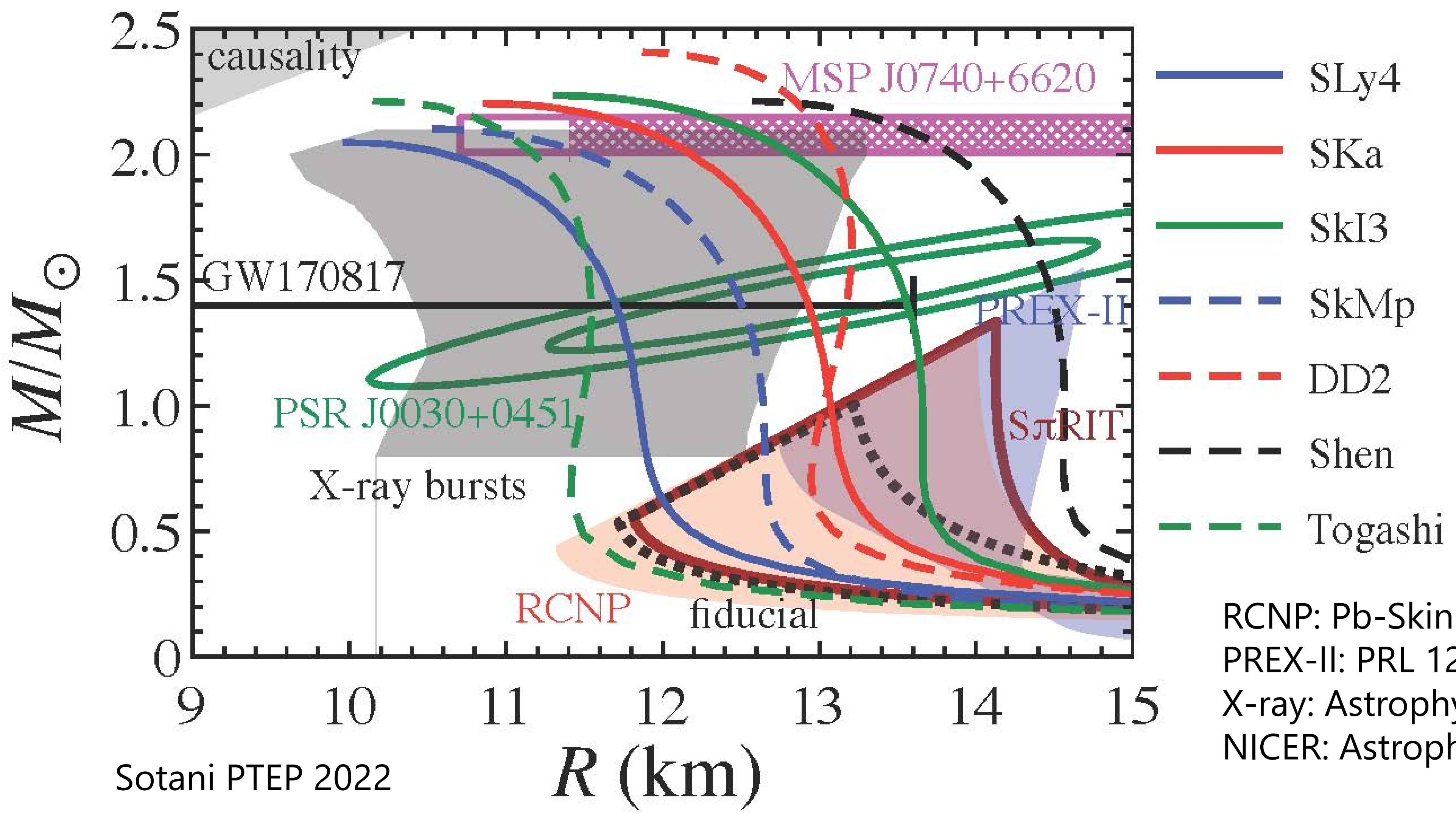
- Neutron rich system shows more sensitivity at high-pT.
- Calculation underestimate at low-pT.

→Coulomb effect and/or non-resonant pion production.

<u>42<L<117</u>

Estee et al., PRL 126 (2021) 162701

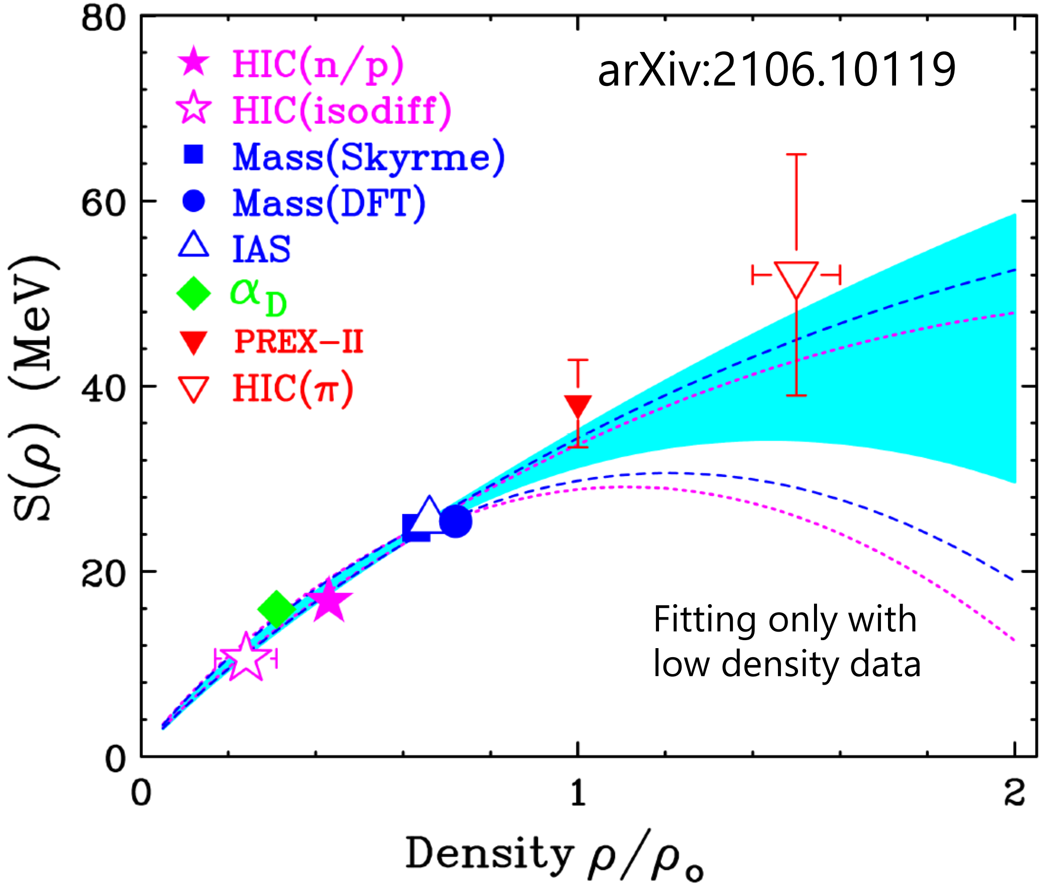
Constrain given by HIC shows consistency with other constrains

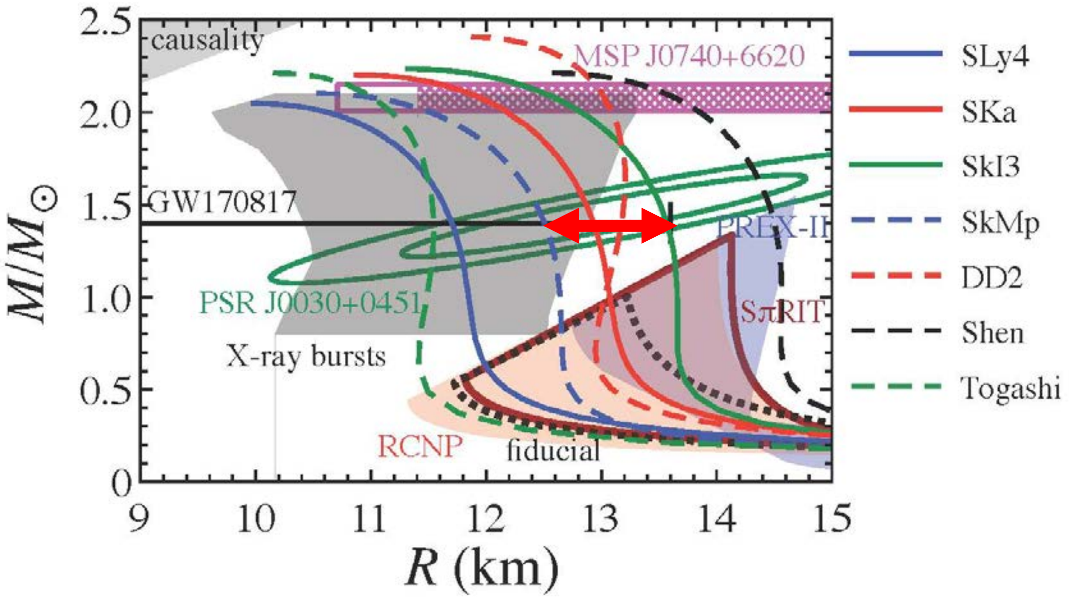


Sotani PTEP 2022

RCNP: Pb-Skin PRC 82 (2010) 044611
PREX-II: PRL 126 (2021) 172502
X-ray: Astrophys. J. Lett. 765 (2013) L5
NICER: Astrophys. J. Lett. 887 (2019) L24

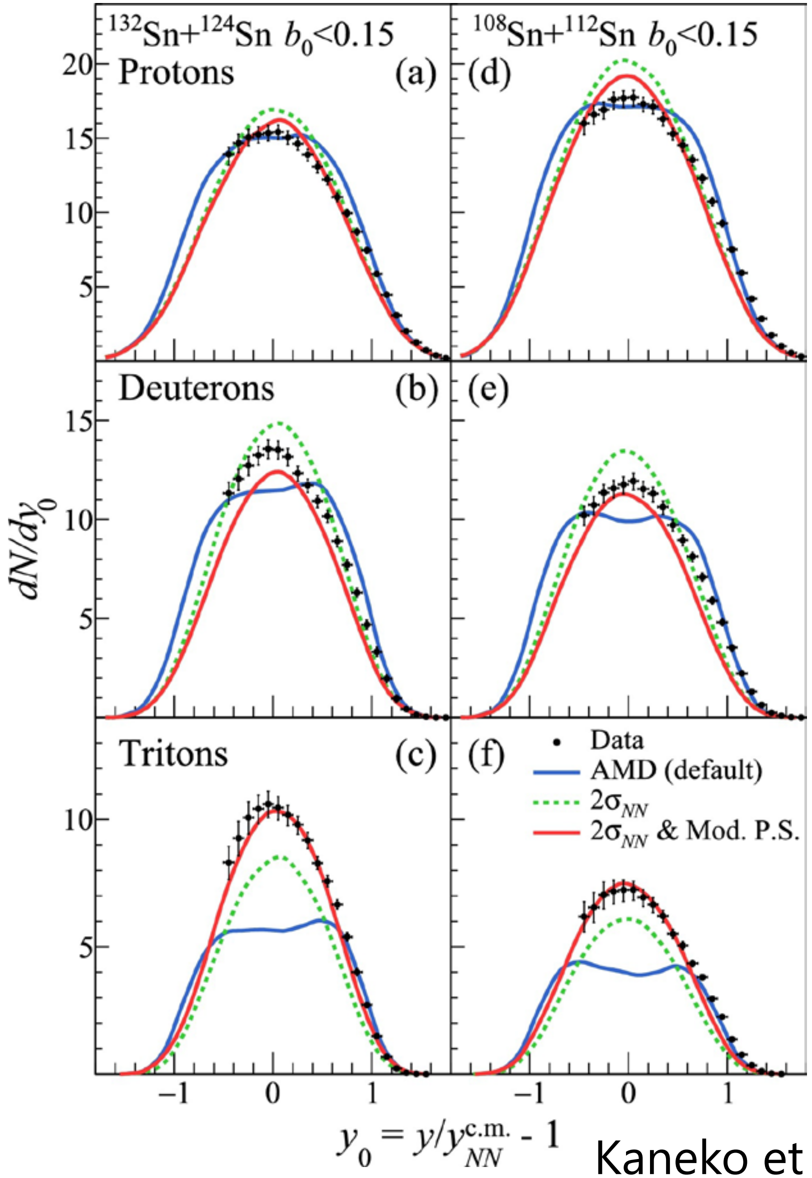
Compilation of experimentally determined symmetry energy



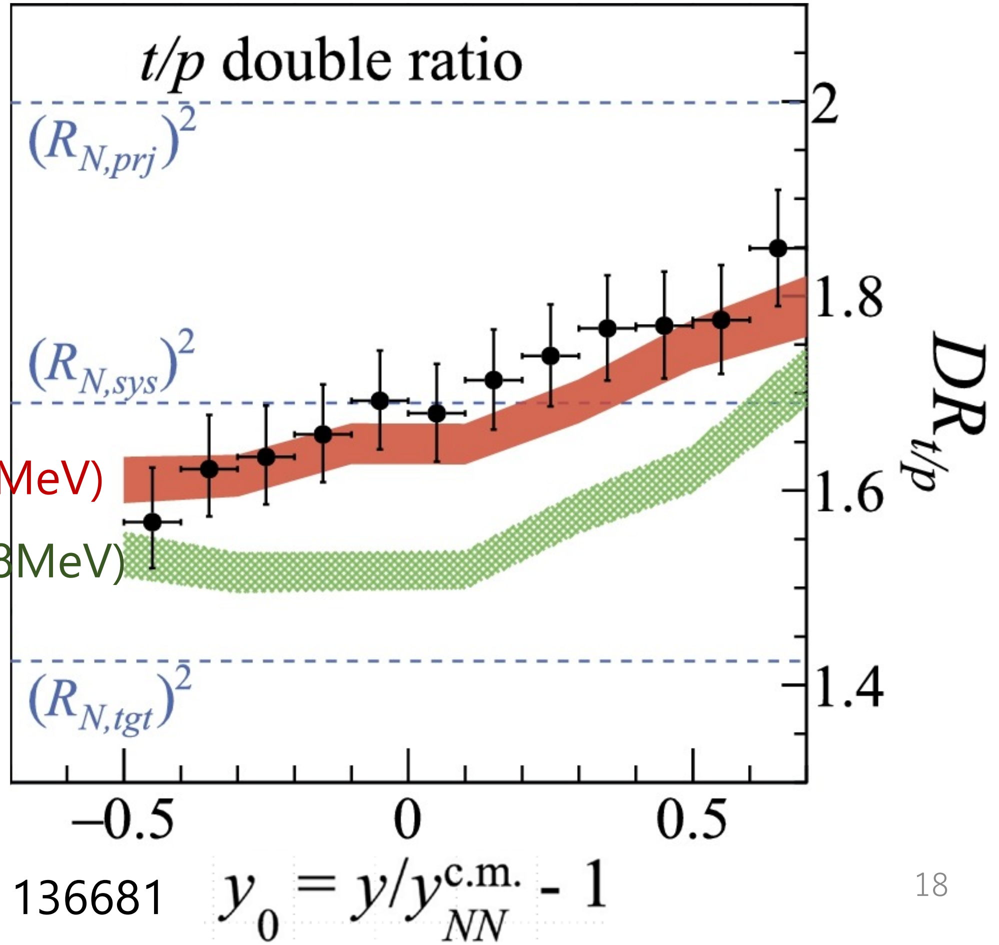


- Fitting with phenomenological formula: S_0=(33.3 ± 1.3) MeV, L= (59.6 ± 22.1) MeV
  - suggests a radius for a 1.4 solar mass neutron star of 13.1 ± 0.6 km

Extra observable: p/d/t dN/dy



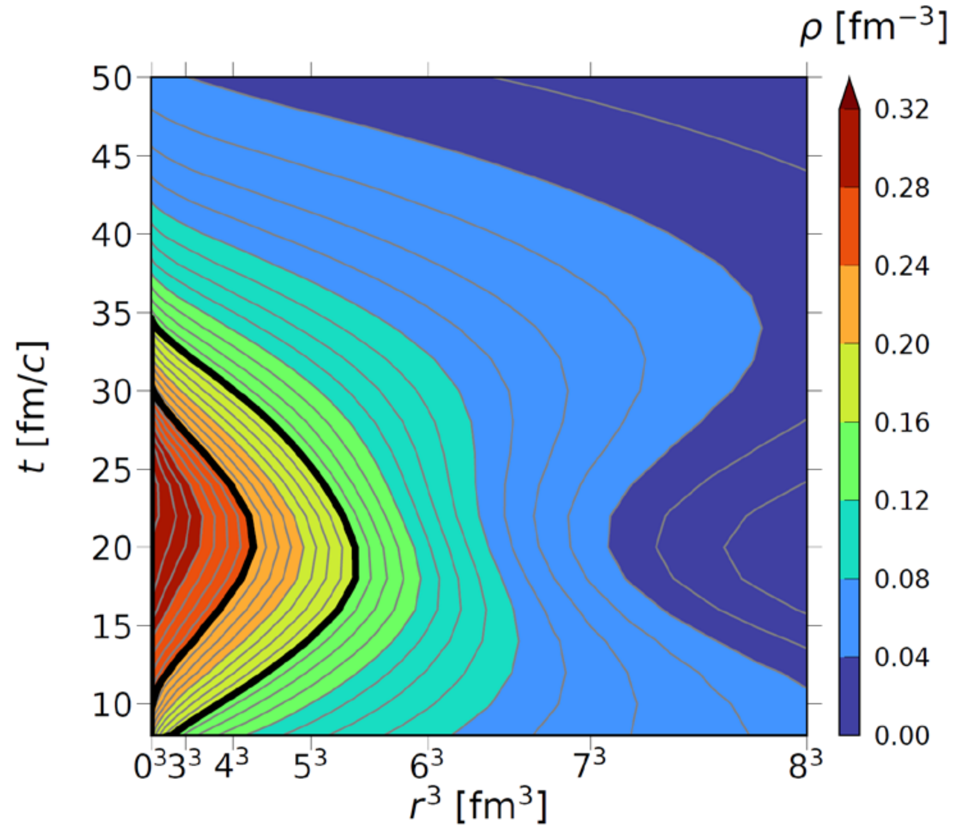
- Fundamental spectra to check the transport model.
  - Nucleon and clustering dynamics in HIC.
  - AMD is most reliable model to describe multiplicity.
- SE dependence appears in t/p ratio.
- **Data favor L =46MeV** rather than L =108MeV.



Kaneko et al., PLB 822 (2021) 136681

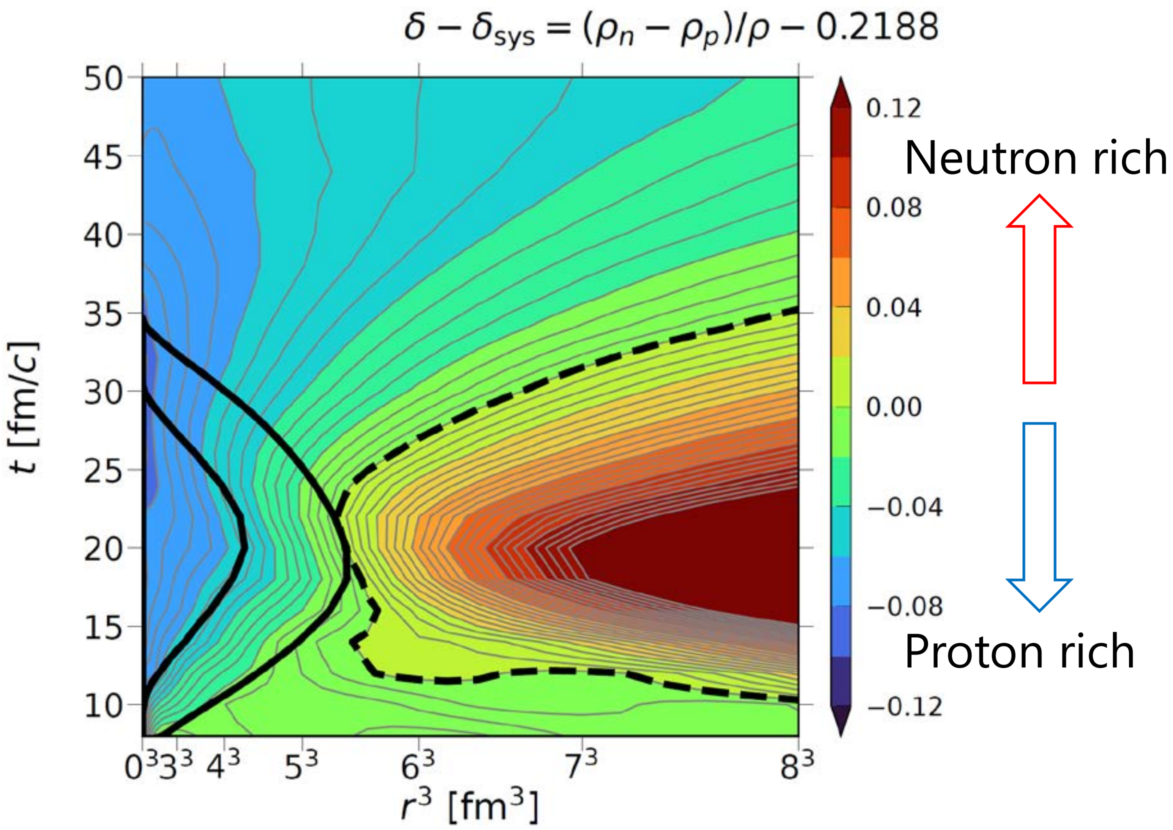
Cluster production in HIC: which density is probed?

Density profile as a function of T



AMD Calculation
$^{132}Sn+^{124}Sn$ E/A=270MeV
Courtesy of A. Ono

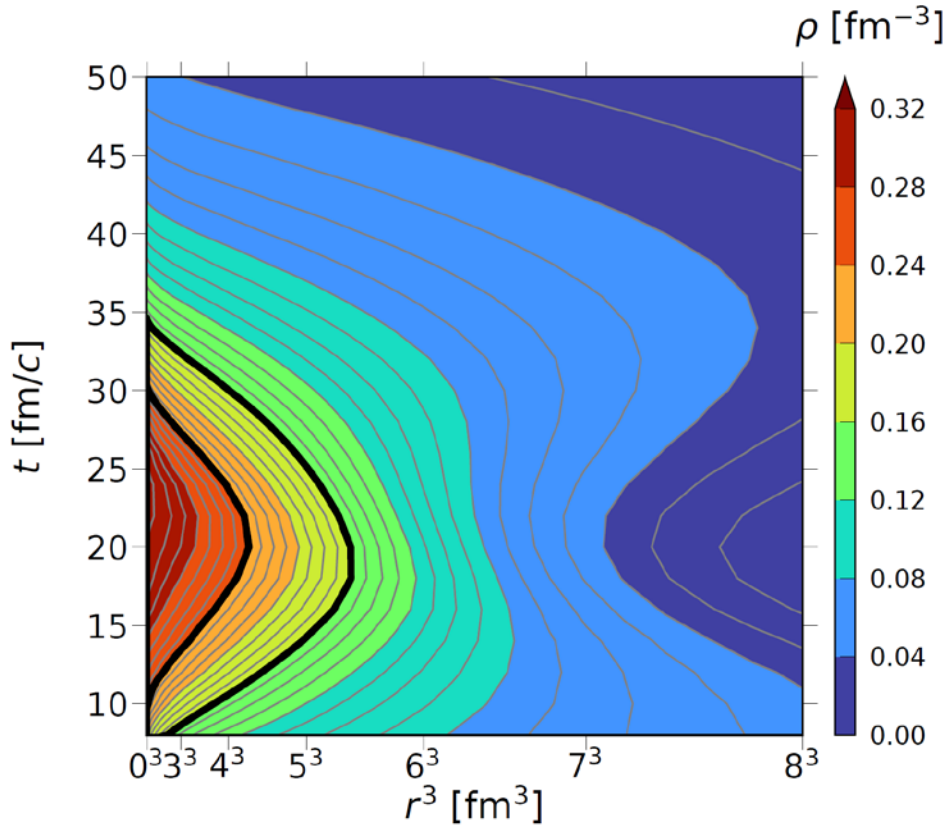
Nuclear asymmetry w.r.t. collision system



During collision (High dense):
Inside → less neutron
Outside → more neutron

Cluster production in HIC: which density is probed?

Density profile as a function of T



AMD Calculation
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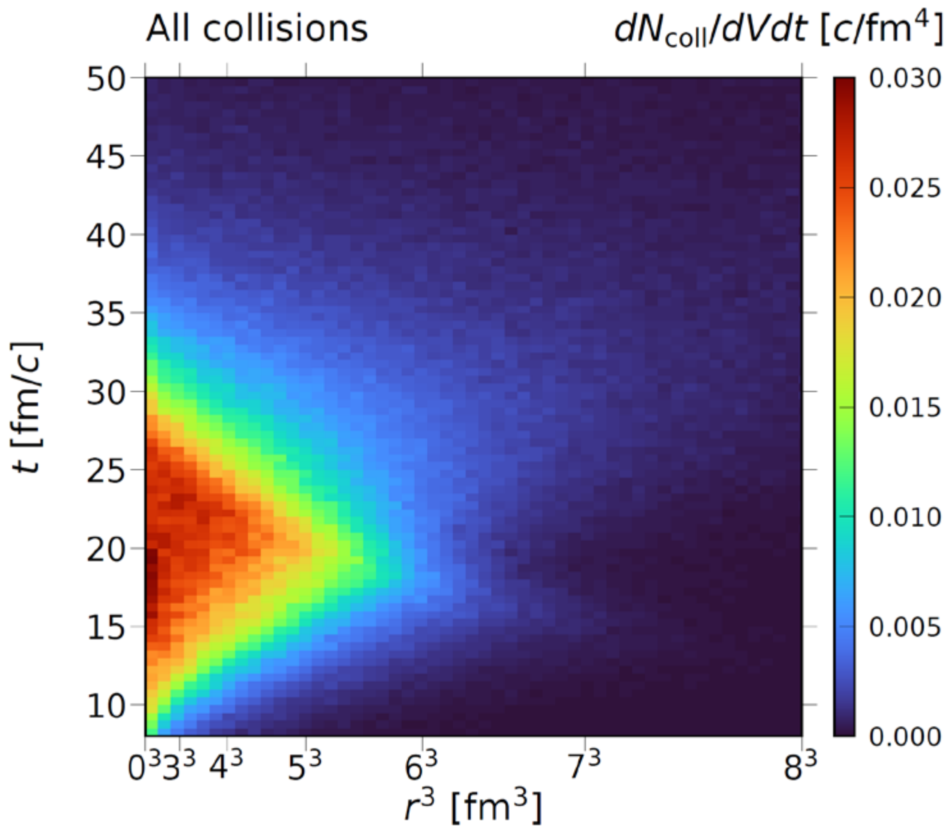
Distribution where a cluster is formed



Distribution of $N1 + N2 + B1 + B2 \rightarrow C1 + C2$ collisions (forming cluster).
Clusters are created mainly in the central part of the system. → probing high dense matter

Summary

- Symmetry energy term of nuclear EoS is essential to understand the property of neutron star.

- Heavy RI collision experiment was conducted at RIKEN-RIBF to give constraint on EoS for high dense regime.
  - Spirit experiment
  - Charged pion and hydrogen production was measured.

- Constrains for high dense ($\rho > \rho_0$) regime.
- Pion (SPiRIT) → L = 79.5±38 MeV with dcQMD
- t/p (SPiRIT) → L = 46±?? MeV with AMD
- n/p flow (AsyEOS@GSI) → L = 85±32 MeV with UrQMD