重イオン衝突におけるパイオン測定を通した対称エネルギー(Symmetry energy)の研究

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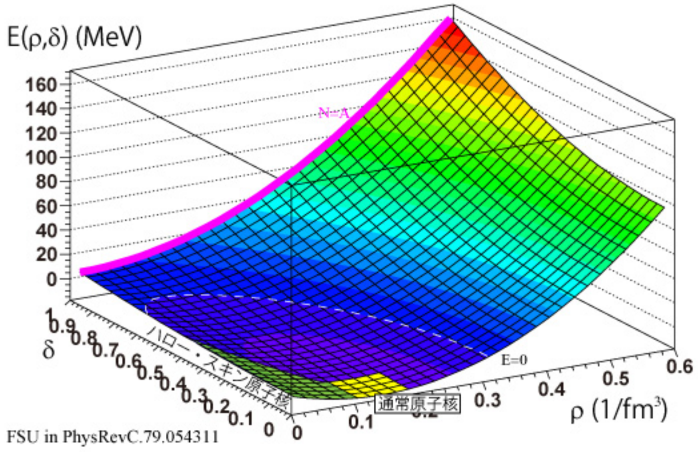
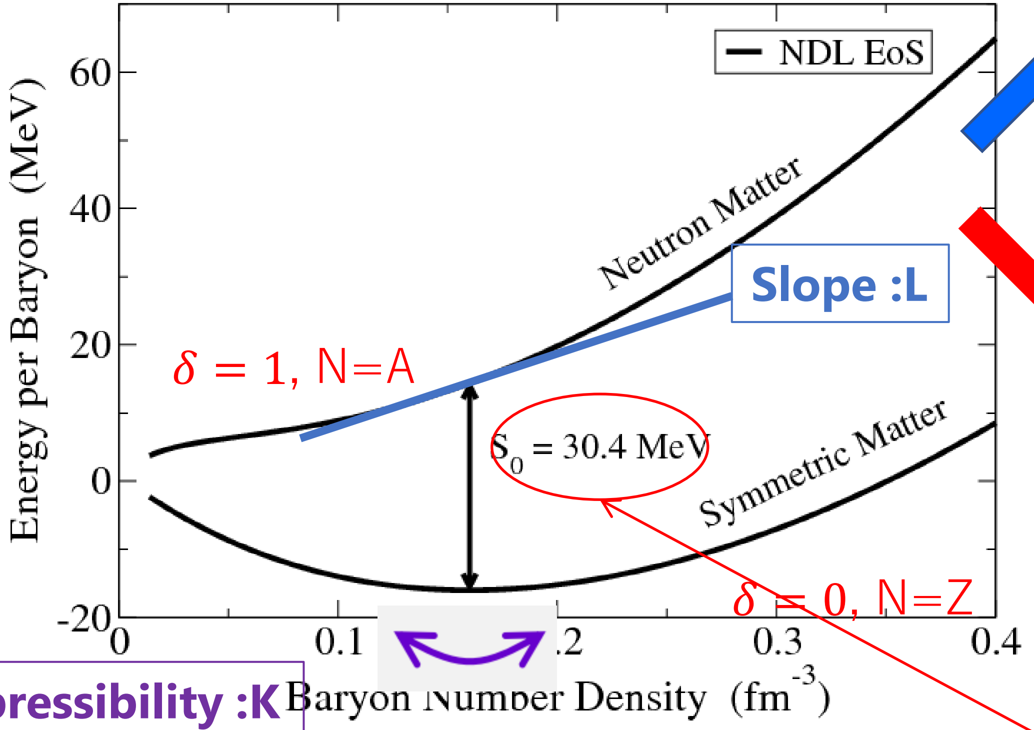
Important term in nuclear EOS : Symmetry energy term to govern neutron star structure

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

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



arXiv:1303.0064



stiff

soft

Incompressibility :K

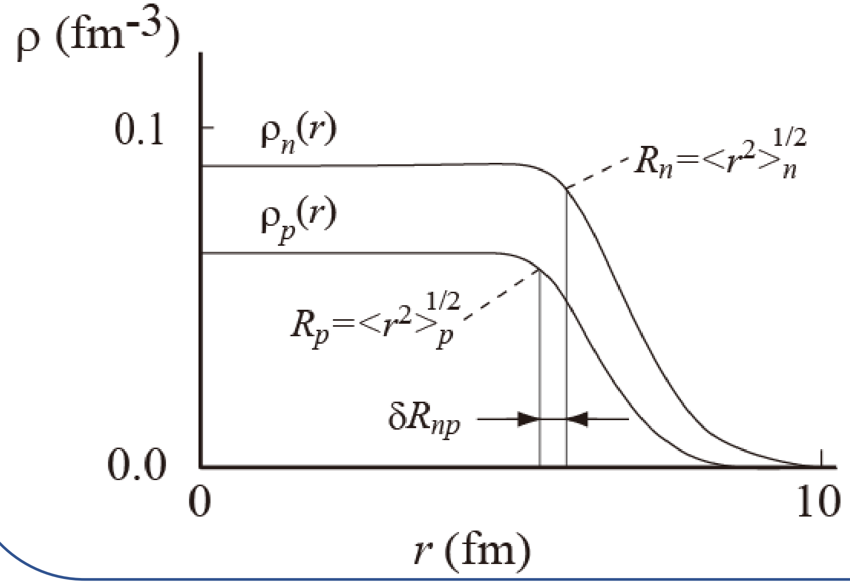
Symmetry Energy at $\rho=\rho_0$:S (or J)

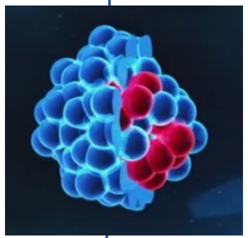
ρ_0: saturation density (~0.17fm^{-3})

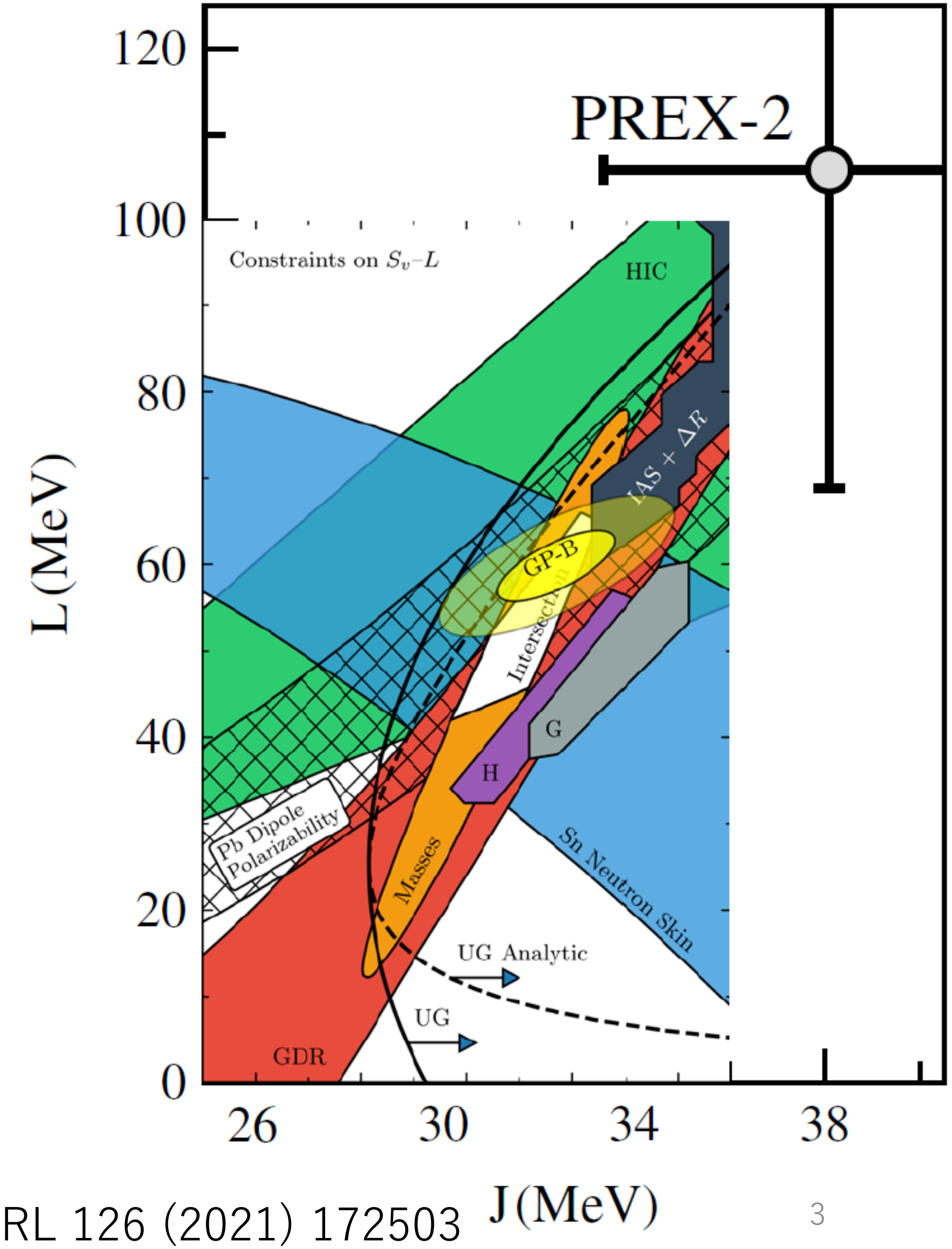
Experimental constraint of EoS e.g. neutron skin thickness

- Large L ⇔ Small E_{sym} in low ρ ⇔ Thick neutron skin (neutron goes to outside (dilute side))
- Small L ⇔ Large E_{sym} in low ρ ⇔ Thin neutron skin
- PREX exp.: Phys. Rev. Lett. 126 (2021) 172502
  - Rn ~ Rw = 5.795 ± 0.082(exp) ± 0.013(theo) fm (1%)
  - Rn – Rp = 0.278 ± 0.078(exp) ± 0.012(theo) fm (25%)
  - δr_{np}→L: 106±37 MeV

Density distribution of protons and neutrons in a nucleus



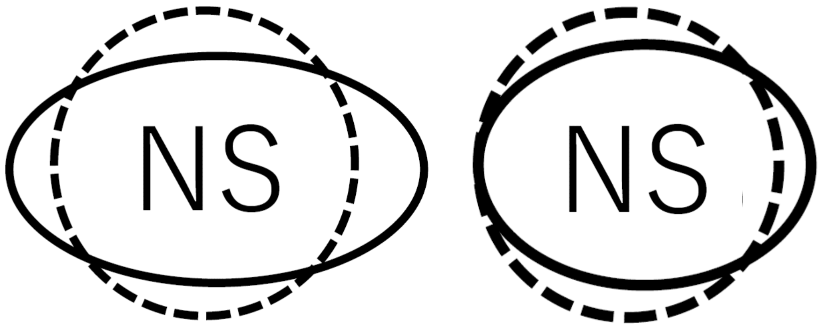




PRL 126 (2021) 172503

Constraint of nuclear EoS from tidal deformation of NS Merger

A. Bauswein, S. Goriely, and H.-T. Janka,
APJ, 773, 21 (2013)



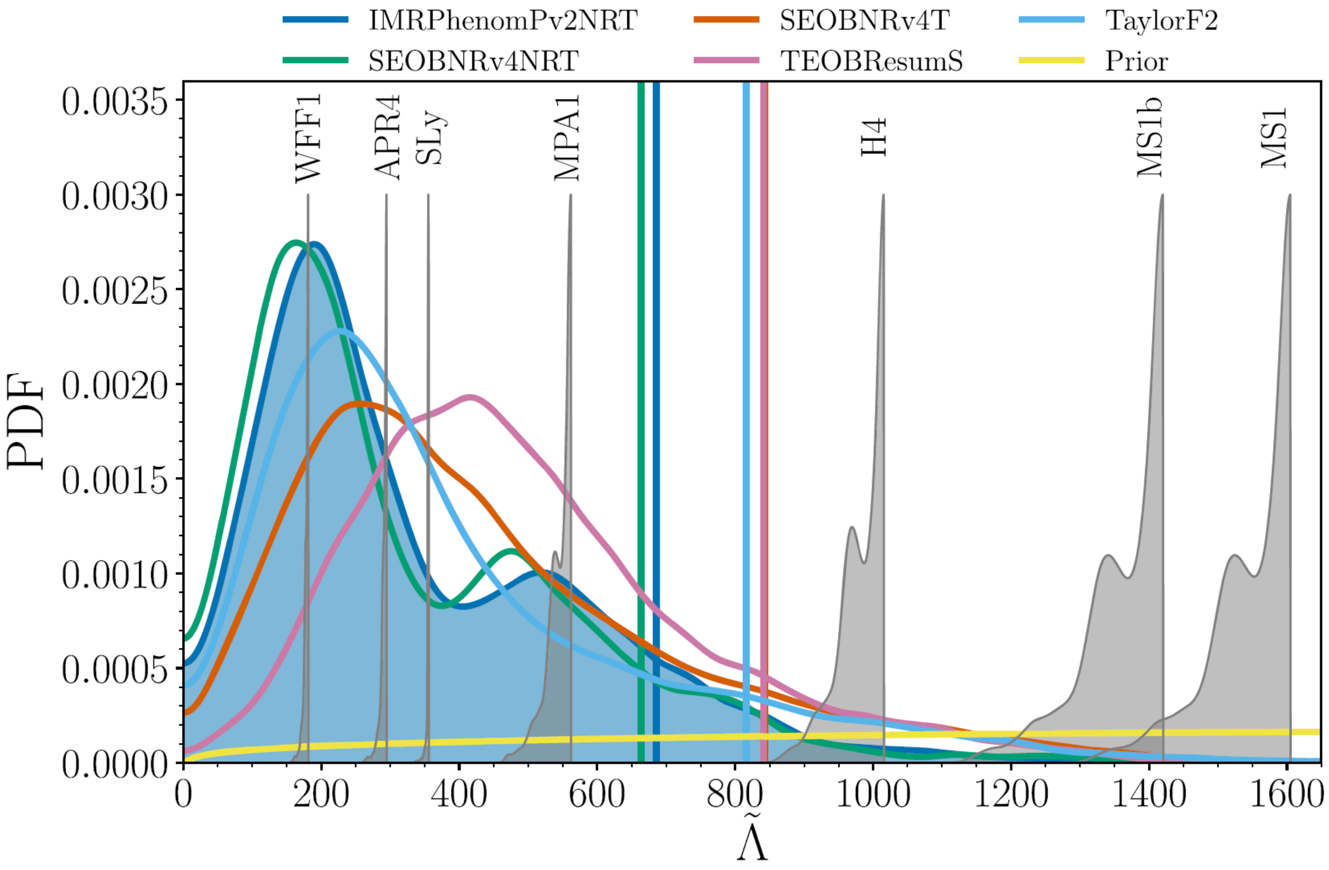
Soft EoS → Large deformability

Stiff EoS → Small deformability

$$\Lambda = \frac{2}{3}k_2\left(\frac{c^2 R}{GM}\right)^5 = \frac{64}{3}k_2\left(\frac{R}{R_s}\right)^5$$

Λ<800 (90% confidence)

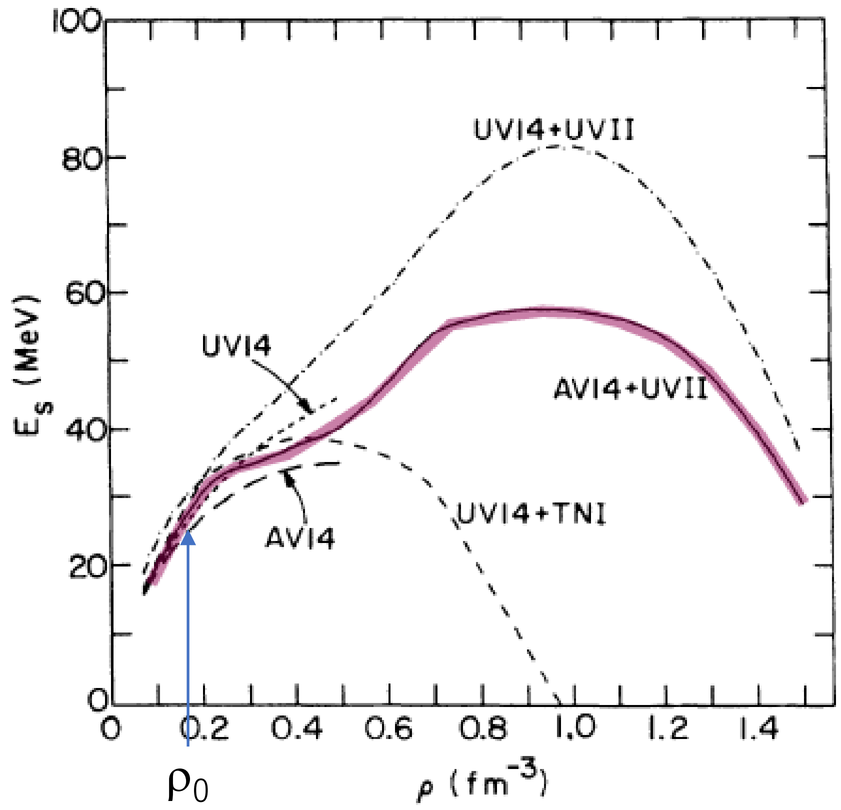
GW170817 PRL 119 161101

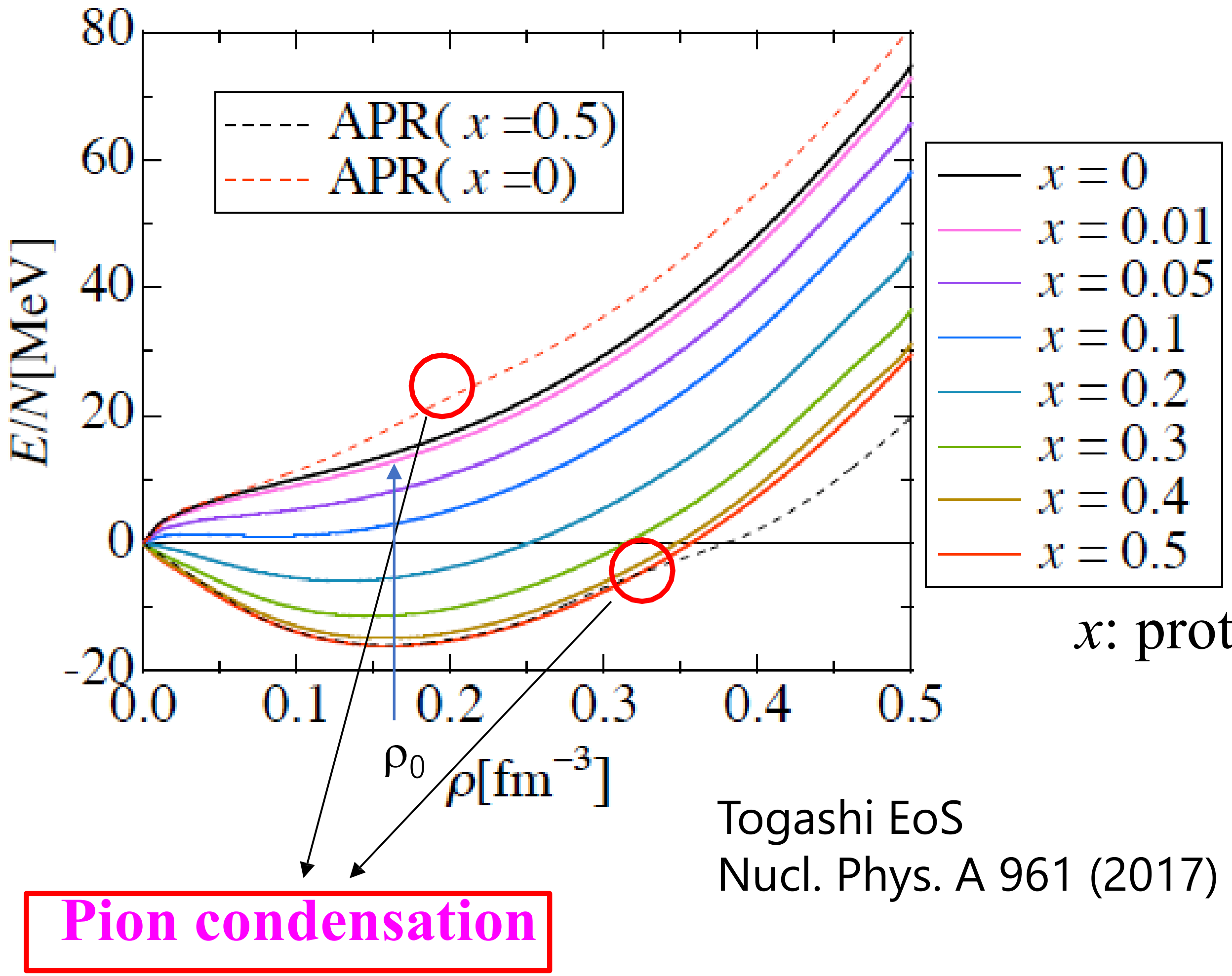


PHYSICAL REVIEW X 9, 031040 (2019)

Determination of L and J is not essential to see high dense neutron matter EoS

Wiringa, Fiks, & Fabrocini 1988





x: proton fraction

Togashi EoS
Nucl. Phys. A 961 (2017) 78

- Above saturation density, the symmetry energy density dependence may have a different energy dependence

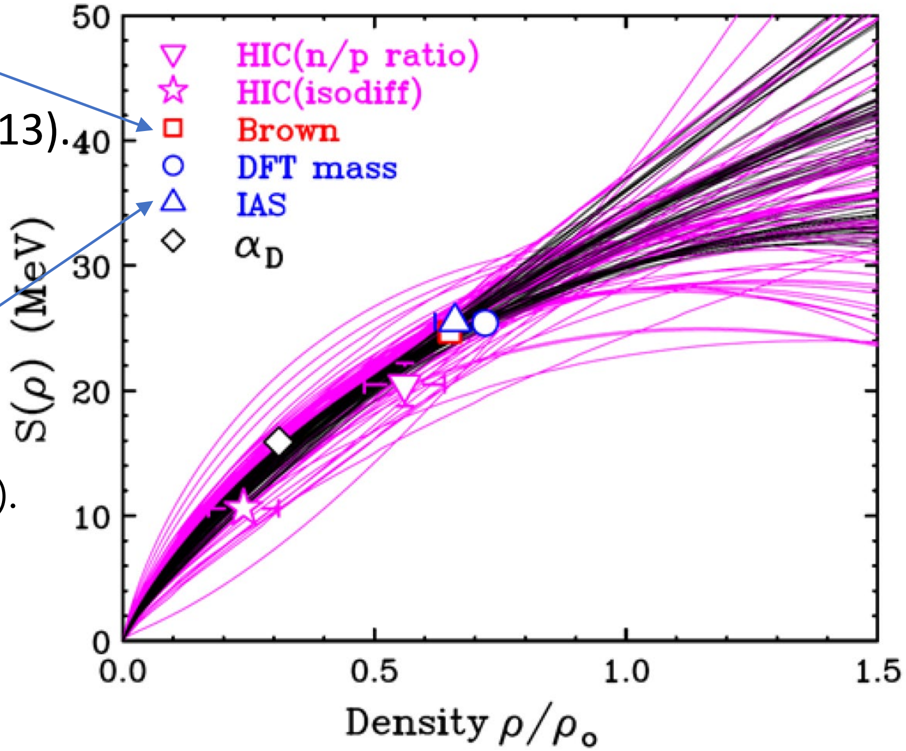
δr_{np} probes the symmetry energy at $\rho\sim0.1\text{fm}^{-3}$

from δr_{np}

Phys. Rev. Lett. 111, 232502 (2013).

σ of (n,p) reaction

Nucl. Phys. A 958, 147-186 (2017).



DFT mass: Analysis of nuclear masses using DFT PRC 87, 015806 (2013).

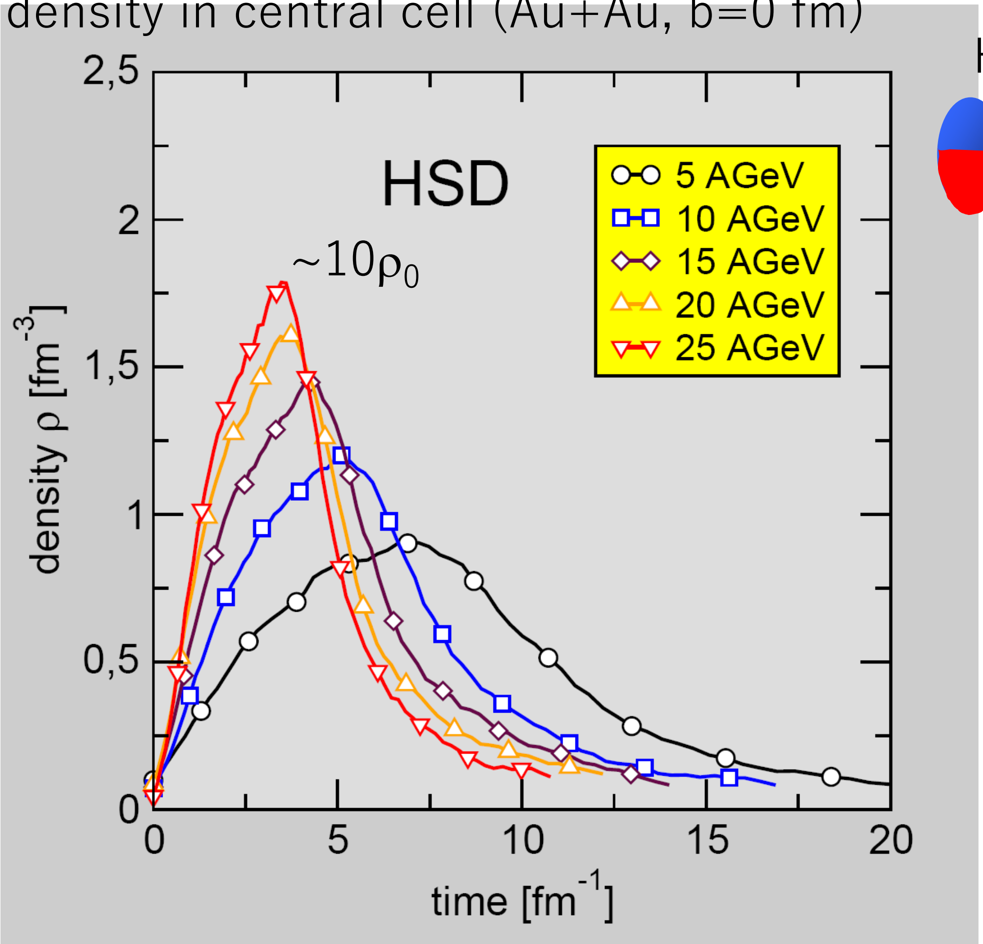
α_D: ^{208}Pb electric dipole polarizability PRL 107, 062502 (2011).

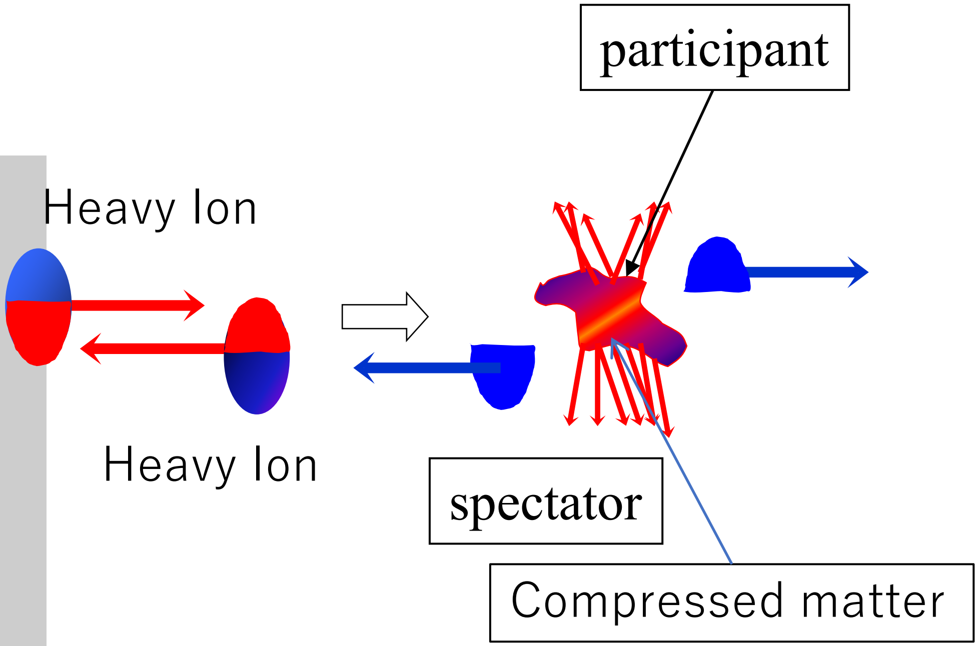
- The region where the experimental constraint on EoS depends on the type of experimental constraint.
- Constraints based on nuclear structure information → $\rho\sim\rho_0$ or more dilute matter.

Heavy ion collision (HIC) to probe high dense symmetry energy → small (O(10fm)) but unique way to realize high dense matter in laboratory

W. Cassing et al., Giessen: Hadron-String Dynamics (HSD): mean field, hadrons + resonances + strings

Baryon density in central cell (Au+Au, b=0 fm)

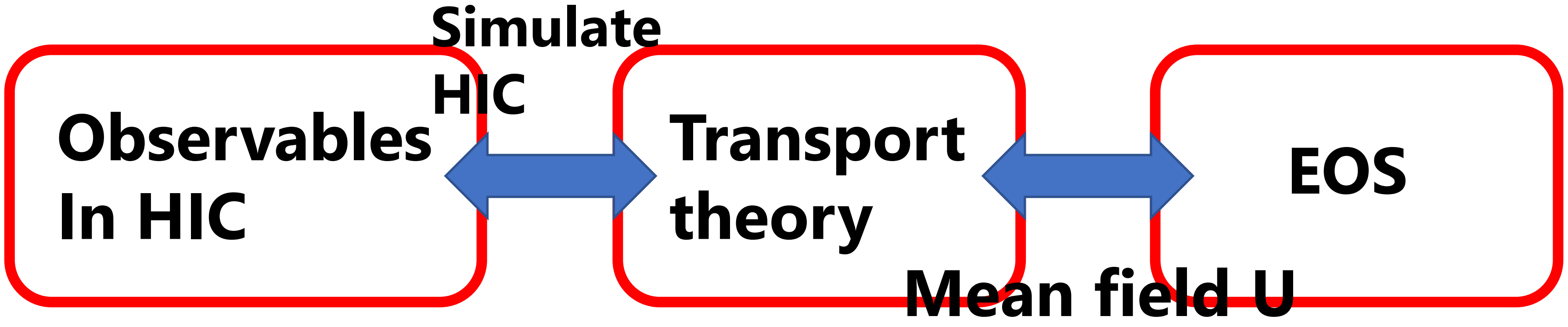




- Plenty of heavy ion collision experiments were performed with stable nucleus, such as Au and Pb.

^{197}Au: $N/Z = 1.49$, $\delta = 0.197$

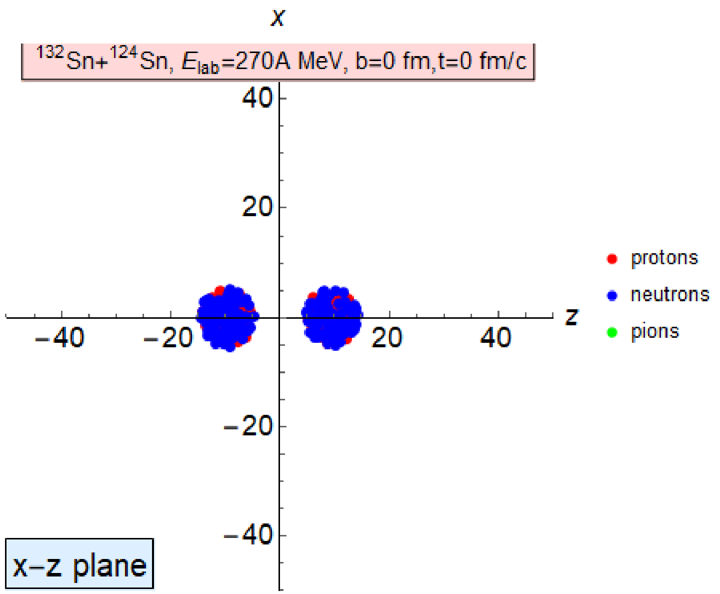
We need to rely on transport theory to reproduce heavy ion collisions → crucial issue to the study of EoS



- Transport theory: theoretical tool to describe the dynamics of heavy ion collision
  - Quite difficult to reproduce the system of collision: mixture of equilibrium and non-equilibrium

- What we can observe experimentally from heavy ion collision is final state particles after freezing out of the system.

- Need to account for nuclear effect which cannot be reproduce with superposition of nucleon-nucleon collisions



pion production in heavy ion collison: probing nuclear symmetry energy

- Soft EOS→large ρ_n/ρ_p in high dense region→large π^- production
- If all of pions are produced through Δ production, $Y(\pi^-)/Y(\pi^+)\approx(\rho_n/\rho_p)^2$
  - In equilibrium state, $\mu(\pi^+)-\mu(\pi^-)=2(\mu_p-\mu_n)$
- Y(π⁻)/Y(π⁺) as well as Y(n)/Y(p) → good probe for nuclear EOS

π^- production (main reaction)

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

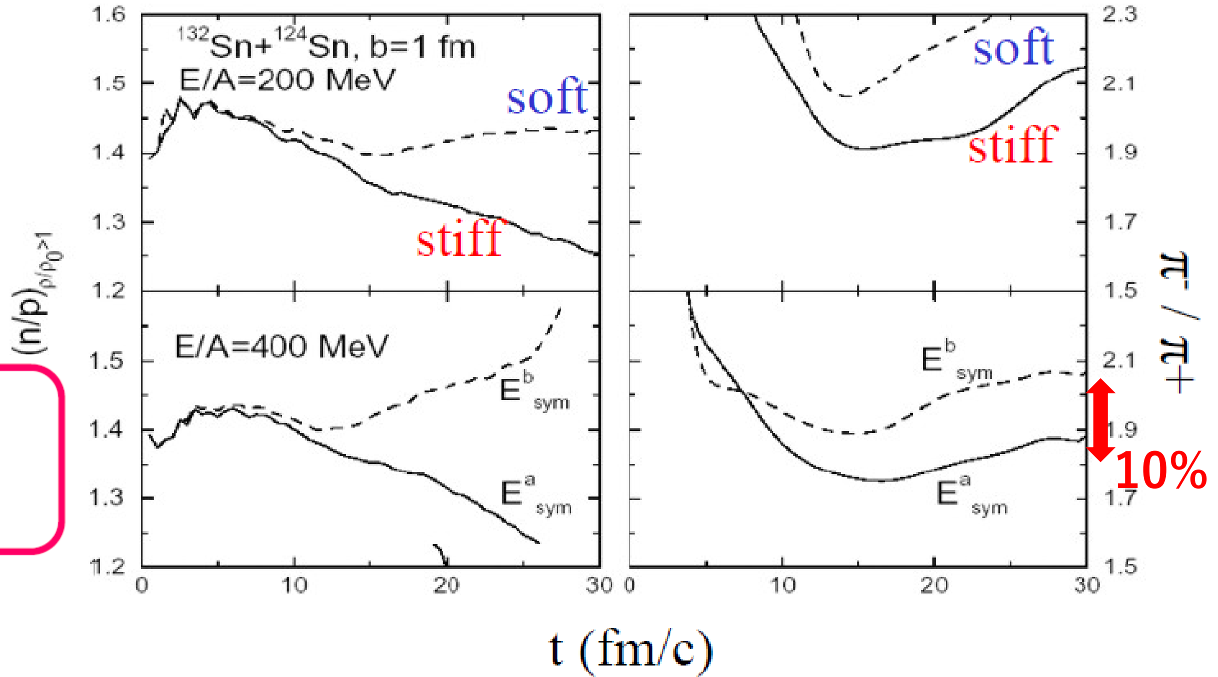
π^+ production (main)

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

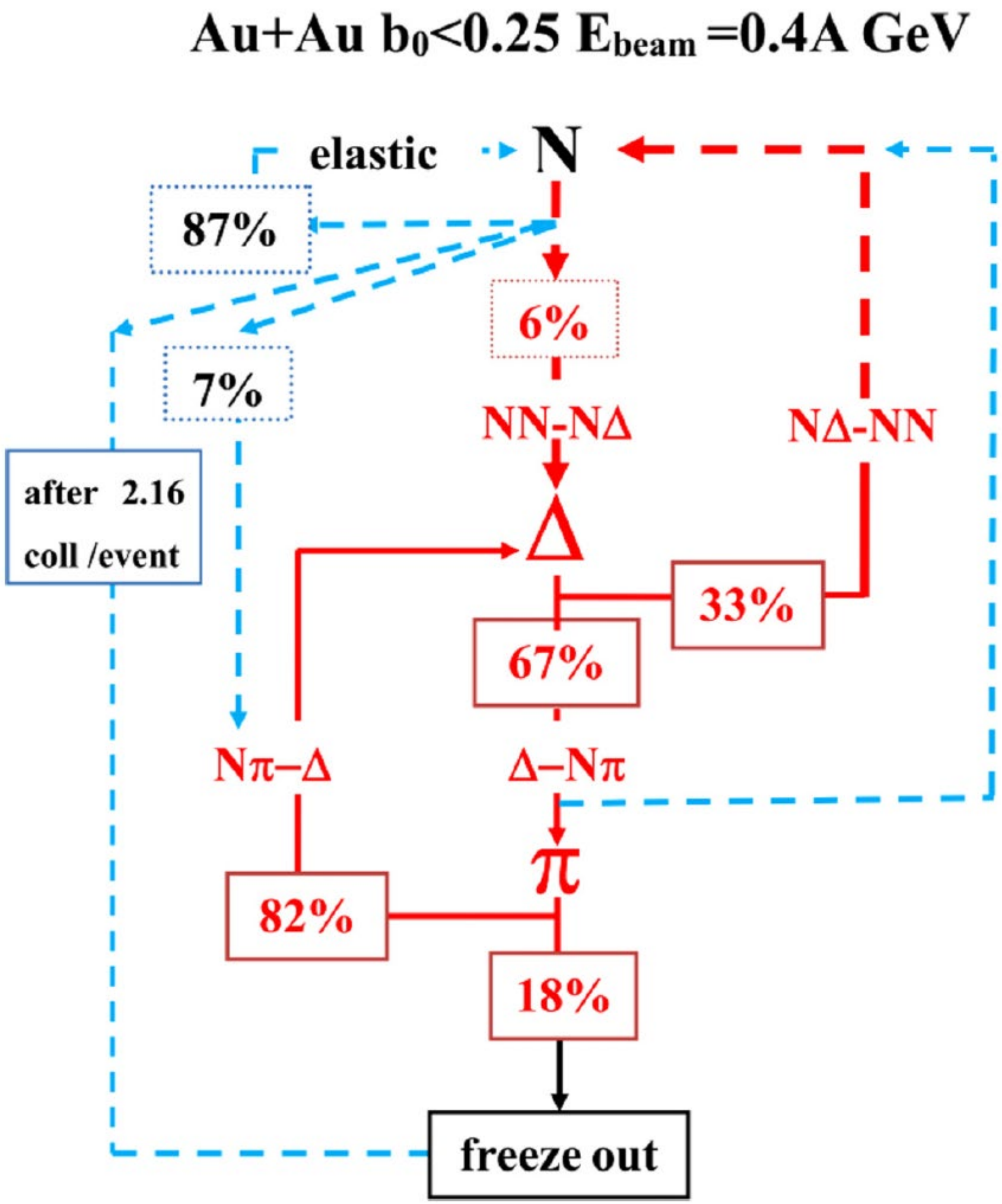
Simple expectation :

$$\left(\frac{\pi^-}{\pi^+}\right) \simeq \frac{5N^2+NZ}{5Z^2+NZ} \simeq \left(\frac{N}{Z}\right)^2$$

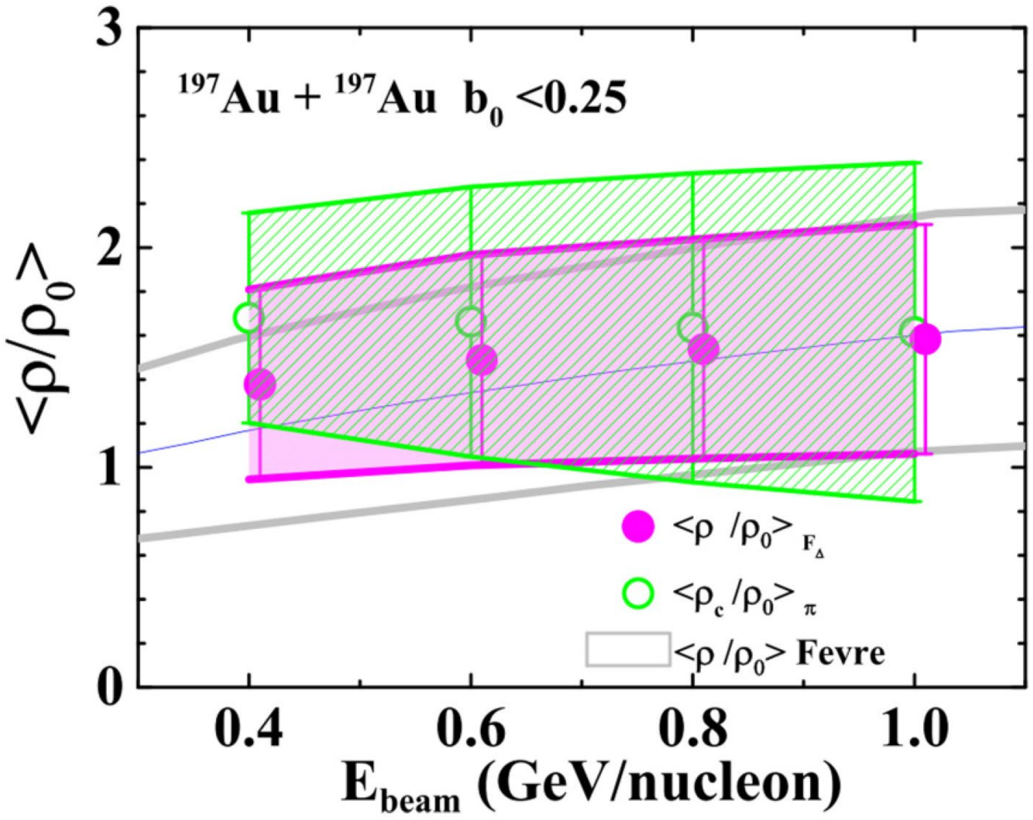
Li et al., Nucl.Phys. A734 (2004) 593.



pion ratio probes the symmetry energy at $\rho \sim 1.5\rho_0$



Pion weighted density
Phys. Rev. C 103, 014616 (2021).



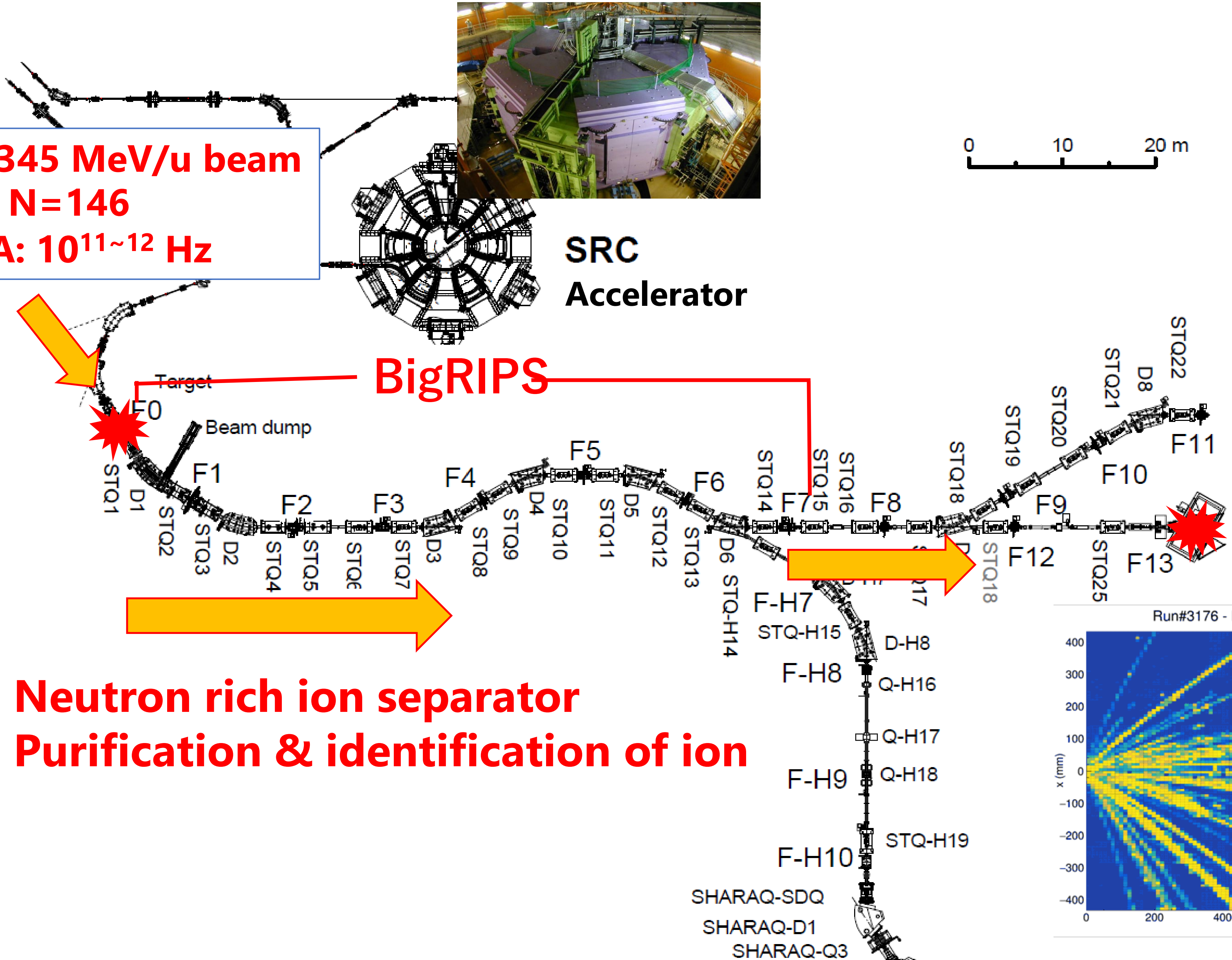
Heavy RI Collision program @RIKEN-RIBF

- 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.
  - Control nuclear effect.
  - $\rho \sim 2\rho_0$ nuclear matter at RIBF energy.
- Effect of symmetry energy on each observables is expected to be largest around this energy region. (especially pion emission)
- 1^{st} experimental campaign using Sn (Z=50) isotopes finished successfully.
  - 2016 Apr. – Jun.
  - Measurements were performed for 4 systems.

  - ^{132}Sn + ^{124}Sn @E_{beam}/A = 270 MeV(v/*c*~0.6), Yp=0.39
  - ^{124}Sn + ^{112}Sn @E_{beam}/A = 270 MeV(v/*c*~0.6), Yp=0.42
  - ^{112}Sn + ^{124}Sn @E_{beam}/A = 270 MeV(v/*c*~0.6), Yp=0.42
  - ^{108}Sn + ^{112}Sn @E_{beam}/A = 270 MeV(v/*c*~0.6), Yp=0.45

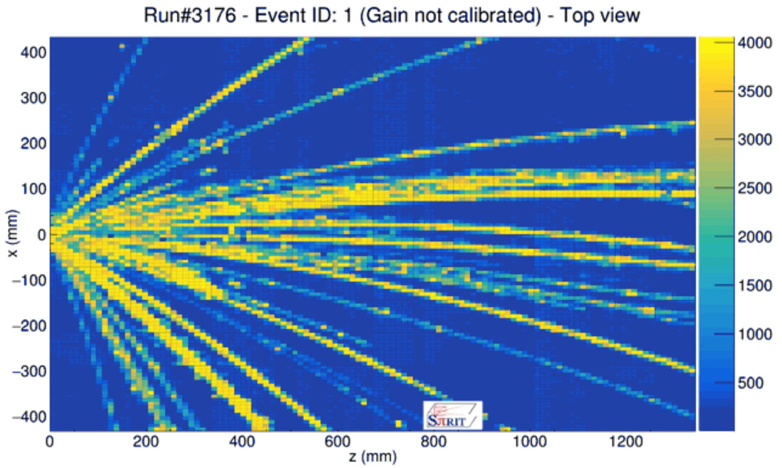
RIKEN-RIBF: RI production at world leading RI facility

U-238 345 MeV/u beam
Z=92、N=146
100pnA: $10^{11\sim12}$ Hz

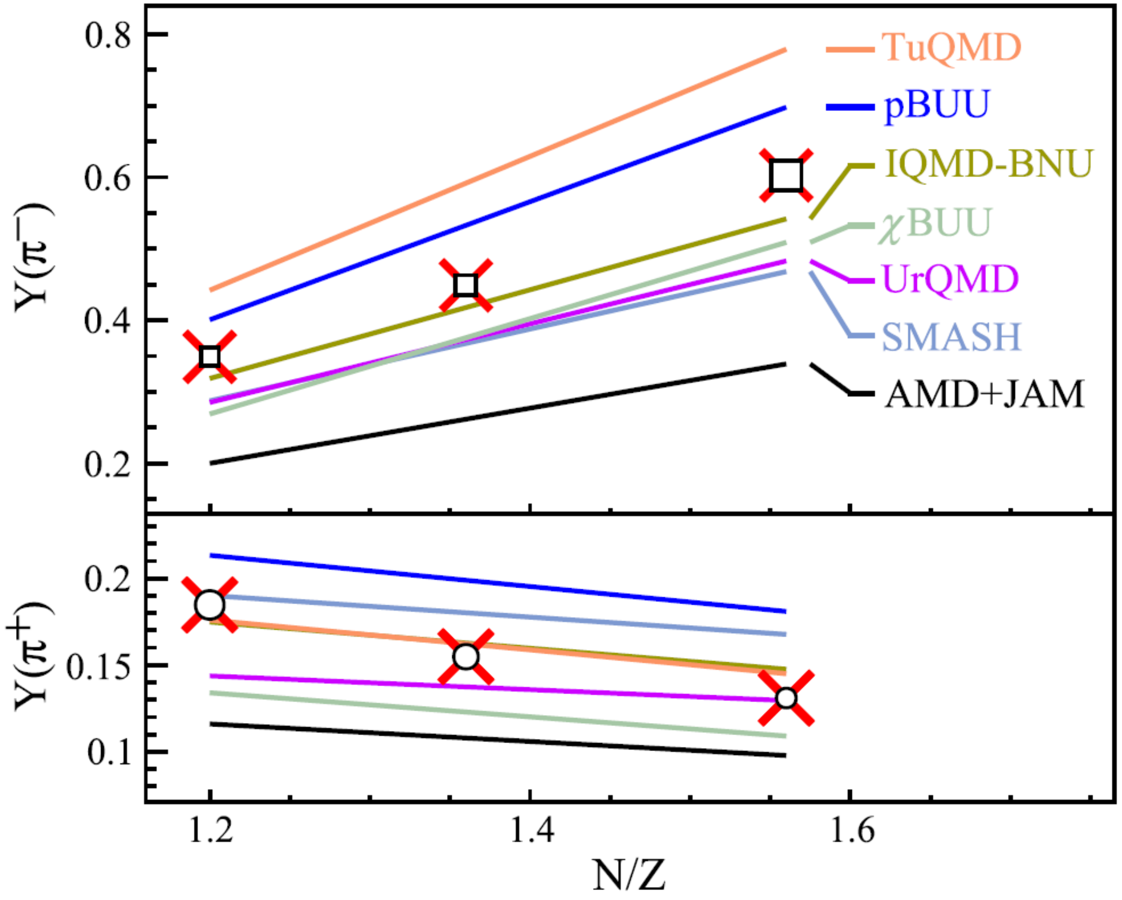


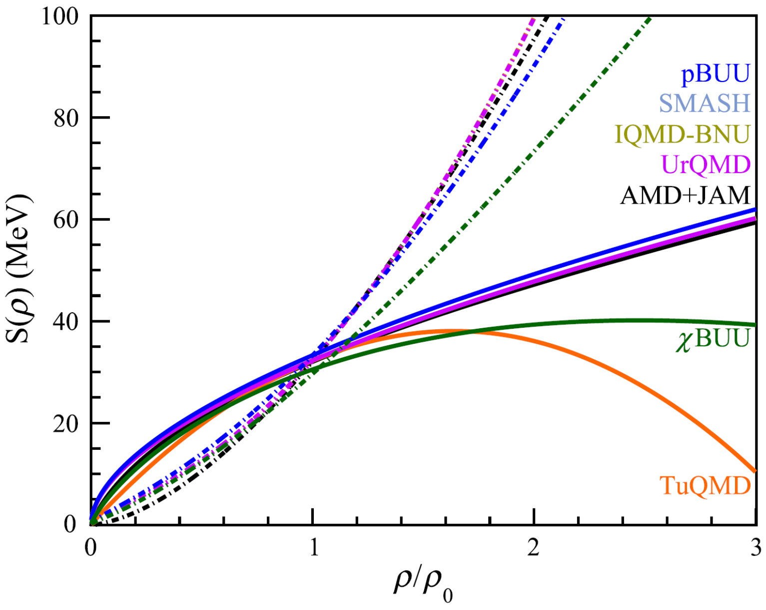
Neutron rich ion separator
Purification & identification of ion

1 frame: 1 collision

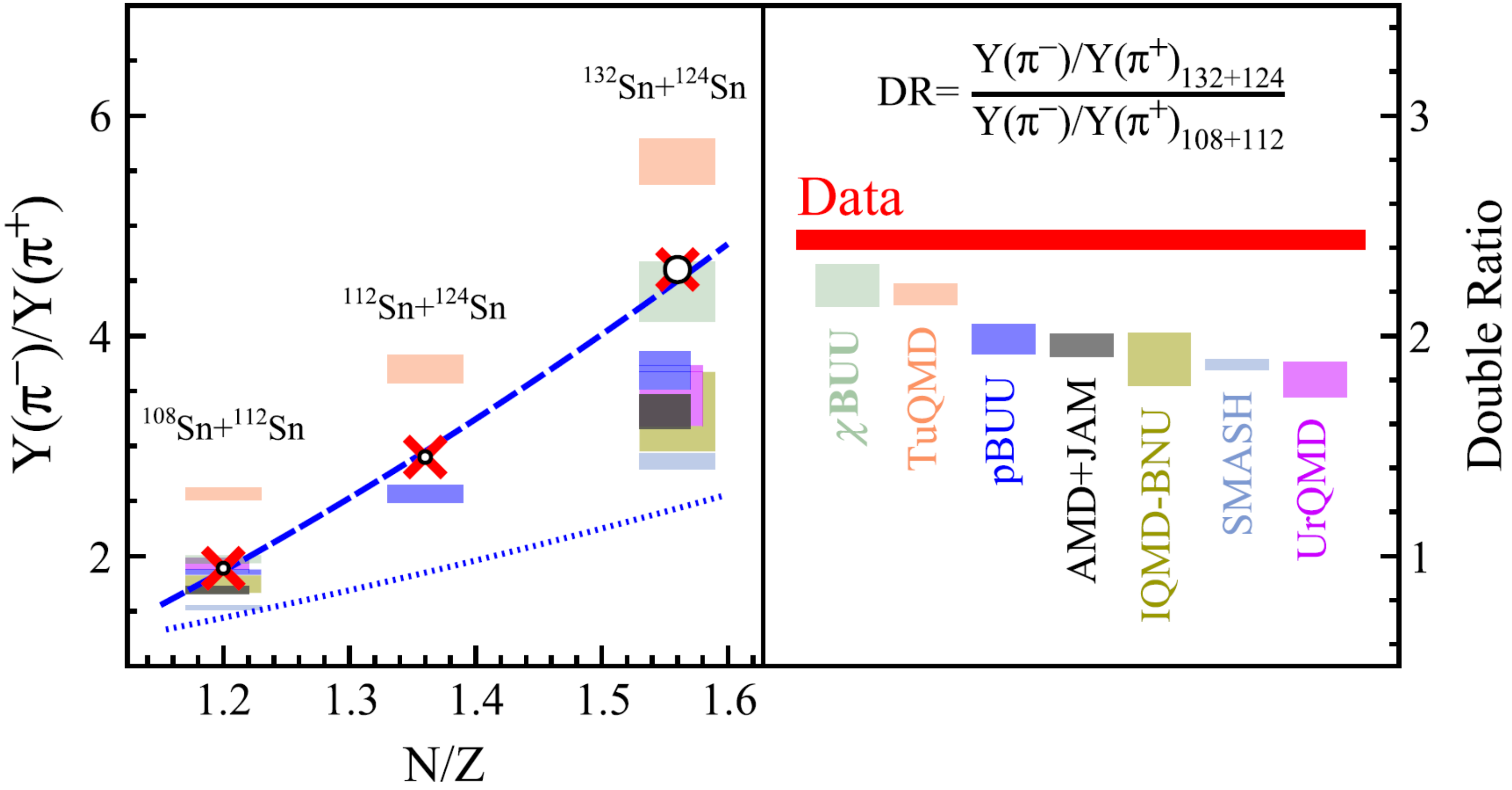


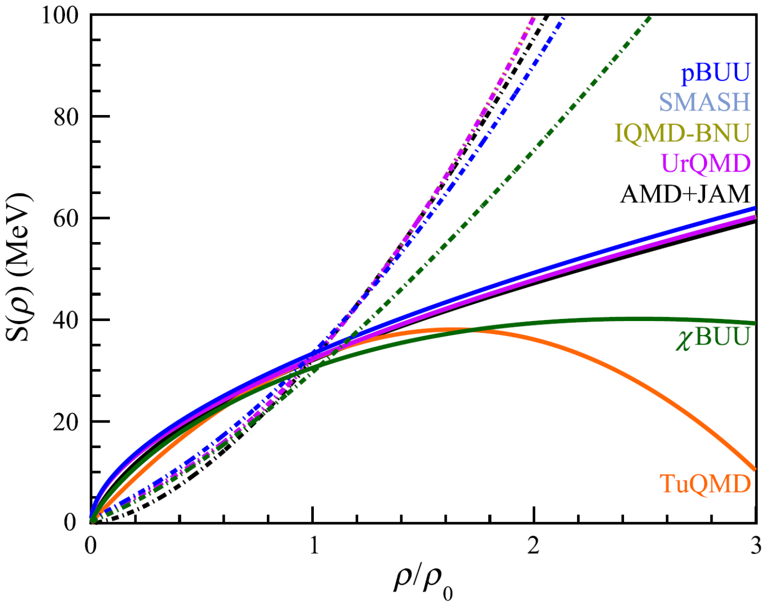
Result on pion multiplicity: number of pions generated collision by collision





Result on pion multiplicity: pion ratio





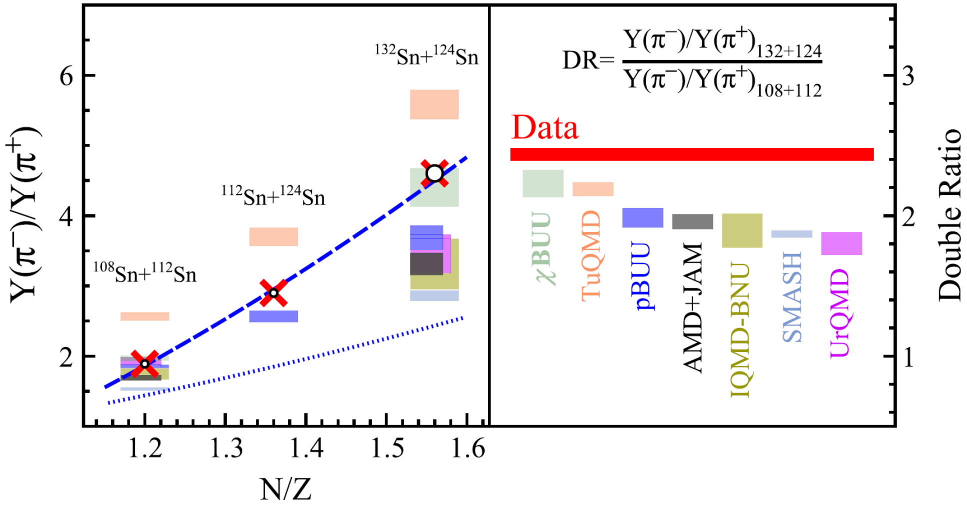
- Different assumptions regarding the mean field potentials for Δ baryons and pions can influence the pion multiplicities.

Need feedback to transport theory to reduce the discrepancy among models.

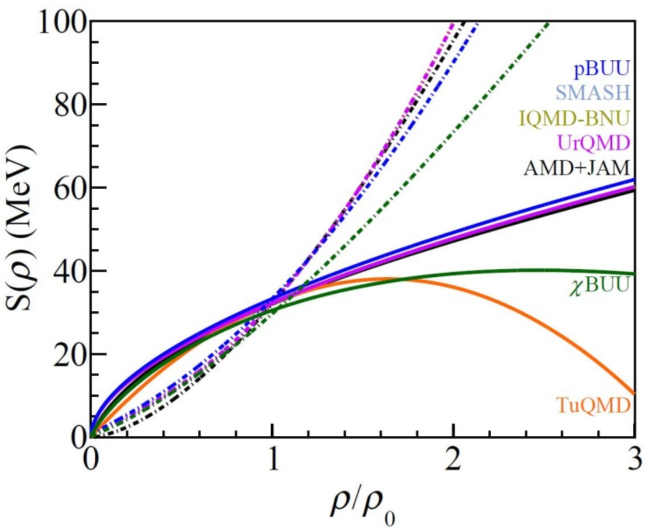
Simulate HIC

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

Mean field U



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



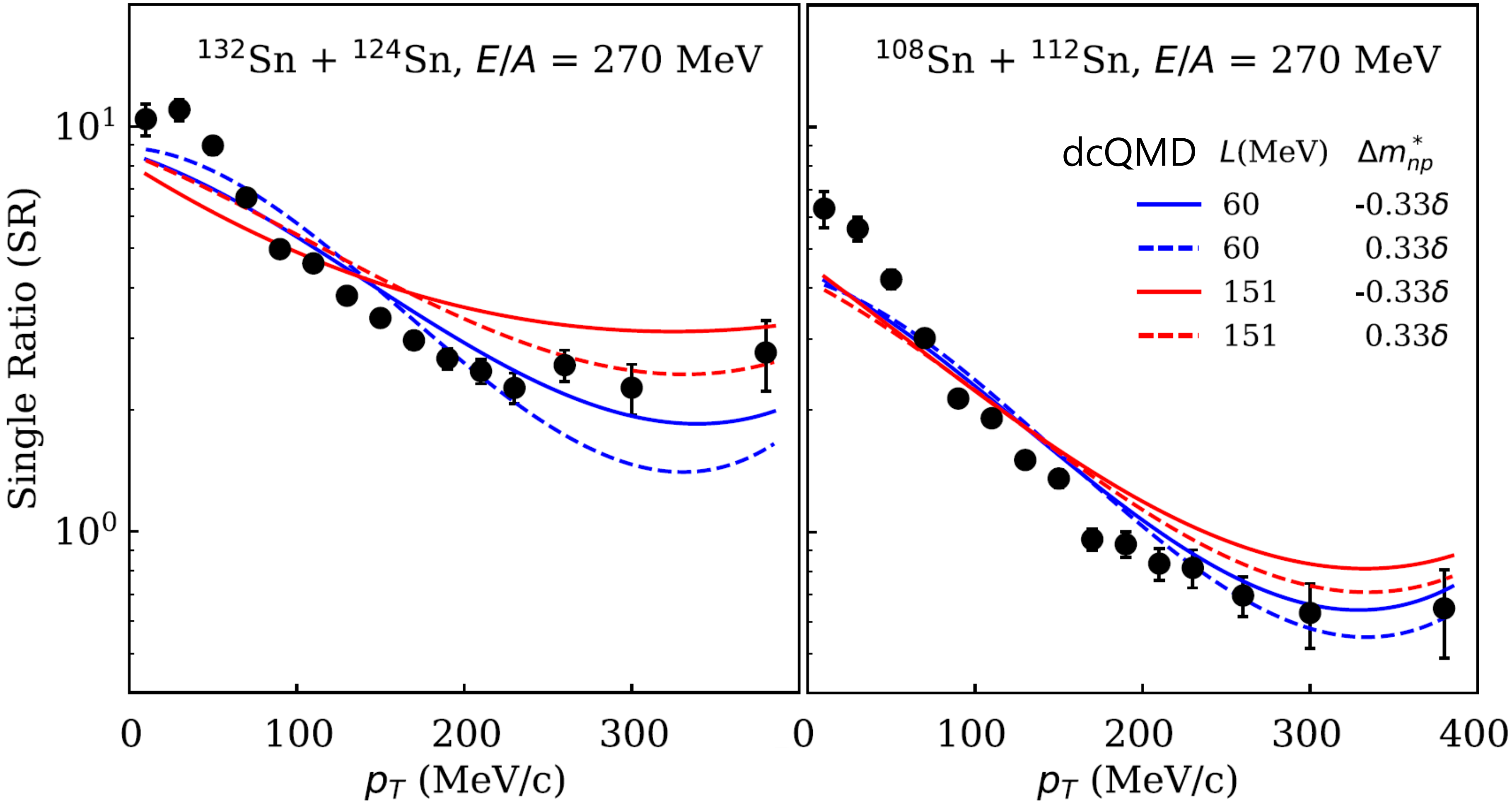
Inconsistent within theories

Constrain EOS

Feedback to Theory w/ exp. data
Determine nuclear effect (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.

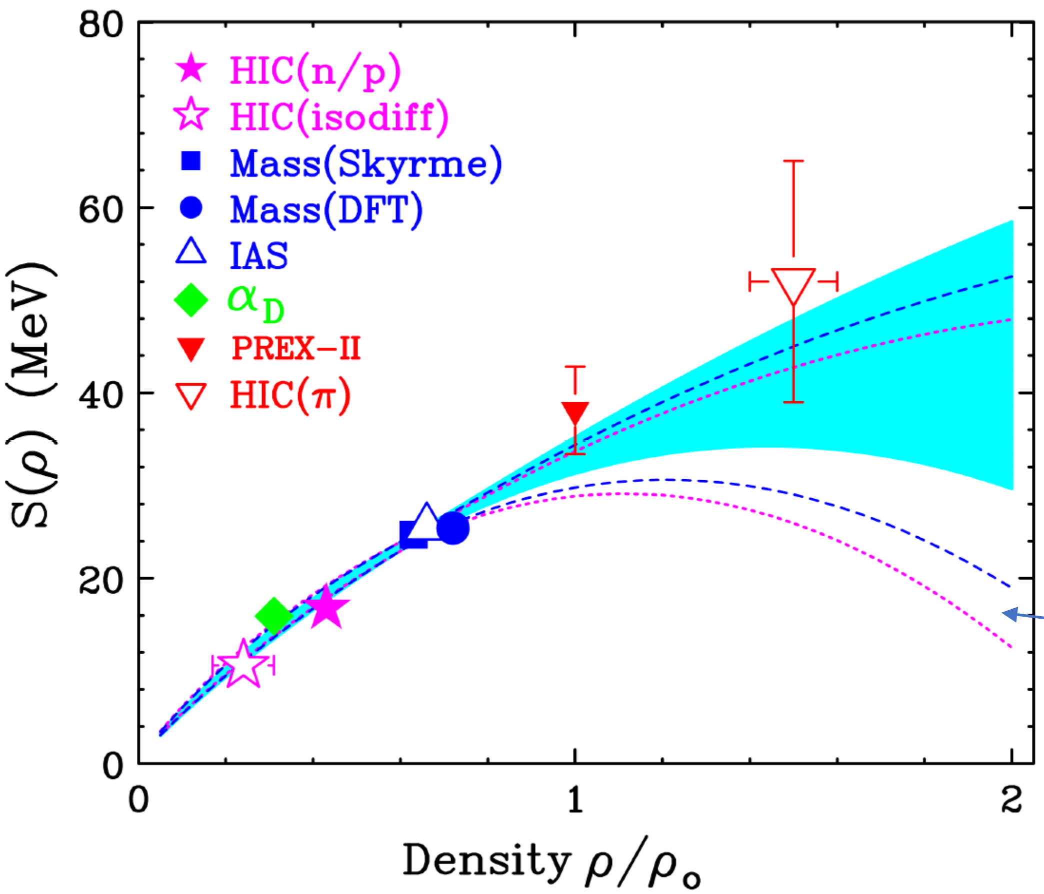
<u>42<L<117</u>

Compilation of experimentally determined symmetry energy

DFT mass: Analysis of nuclear masses using DFT
PRC 87, 015806 (2013).

IAS: σ of (n,p) reaction
NPA 958, 147-186 (2017).

α_D: ^{208}Pb electric dipole polarizability
PRL 107, 062502 (2011).



arXiv:2106.10119v1

Fitting only with low density data

- 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

Conclusion

- To give constraint on nuclear symmetry energy, pion production in neutron rich heavy ion collision was measured at RIKEN-RIBF.
- Pion production is expected to probe the symmetry energy at $\rho \sim 1.5 * \rho_0$.

- According to the comparison of data with transport model: $42 < L < 117$.
- We need to establish the sophisticated transport model to understand the collision dynamics and constrain the nuclear symmetry energy more precisely.

- Nuclear symmetry energy driven from the compilation of experimental data gives consistent result with the radius obtained with NICER.