Measurement of spectral pion ratio in Sn+Sn collisions for the constraint of density dependent nuclear symmetry energy

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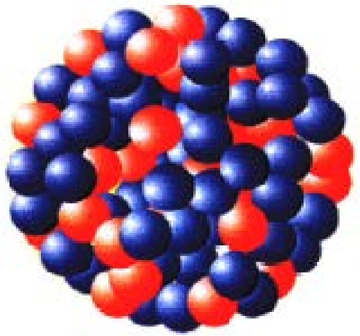
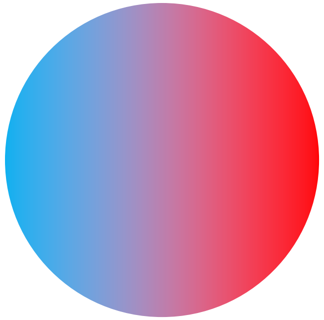
2021/09/28 RIBF Nuclear Physics Seminar

Nuclei: many body system composed of protons and neutrons

- Many-body quantum-system with spontaneous order and self organization
  - Shell structure without inner core
- Two aspects: microscopic and macroscopic
- Superposition of single state nucleon ←→ bulk matter (hydro, gas)





- Equation of State (EOS) is a thermodynamic equation relating state variables which describe the state of matter.
- There is a EOS to describe the state of nuclear matter.

Important term in nuclear Equation Of State (EOS): Symmetry energy

- Equation of State (EOS): Equation for the relation among pressure (p), temperature ($\tau = k_B T$), and volume(V) to describe the states of matter
- Equation of state of nuclear matter can be reconstructed by using the differential thermodynamic identity:

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

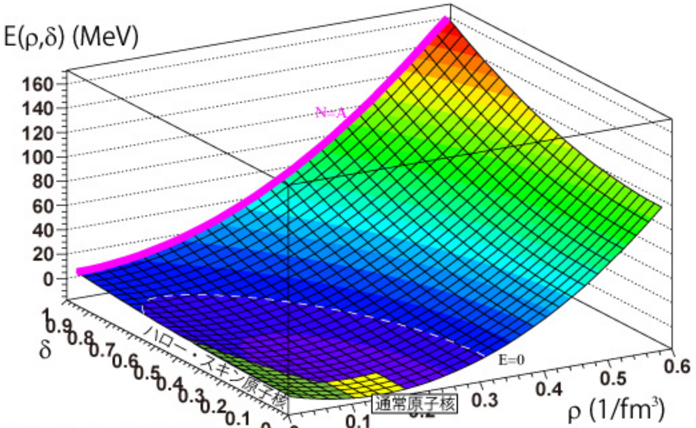
$$\delta = (\rho_n - \rho_p)/\rho$$

- The <u>asymmetric term</u> of nuclear EOS depending on δ
- Often temperature(T) is assumed to be about 0.
  - Because experimental constraint mainly give by nuclear structure information.
  - Neutron star is kind of cold matter where T can be assumed to be zero.: T ~ 10^6 K ~ 100 eV
    - Fermi-energy of neutron: O(10)MeV

Important term in nuclear EOS : Symmetry energy

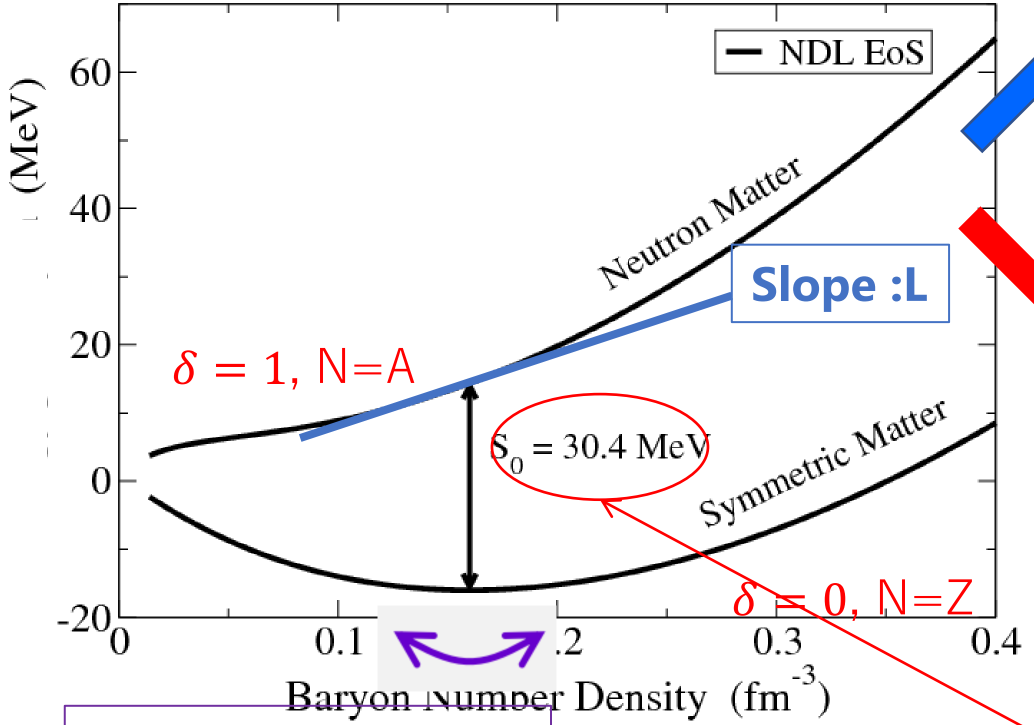
$$E(T,\rho,\delta) = E(T,\rho,\delta=0) + E_{sym}(T,\rho)\delta^2 + O(\delta^4)$$

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



FSU in PhysRevC.79.054311

arXiv:1303.0064



Incompressibility :K

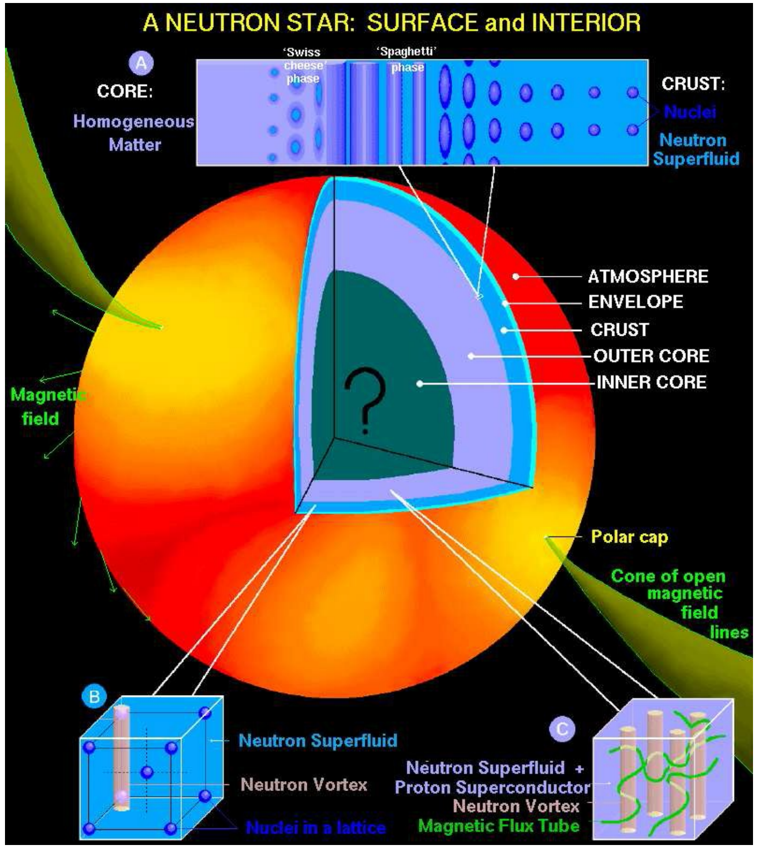
Symmetry Energy at $\rho=\rho_0$:S (or J)

stiff

soft

Motivation to study symmetry term of nuclear EOS: important for nuclear/astro-physics

- Nuclear structure
  - Sustain neutron rich matter of heavy ions/super heavy ions.
  - Information for beyond the super heavy elements.
- Supernovae process
  - Symmetry term affects supernovae explosion dynamics.
- Neutron star structure
  - Supreme asymmetry nuclear matter
  - Neutron star is formed with symmetry energy



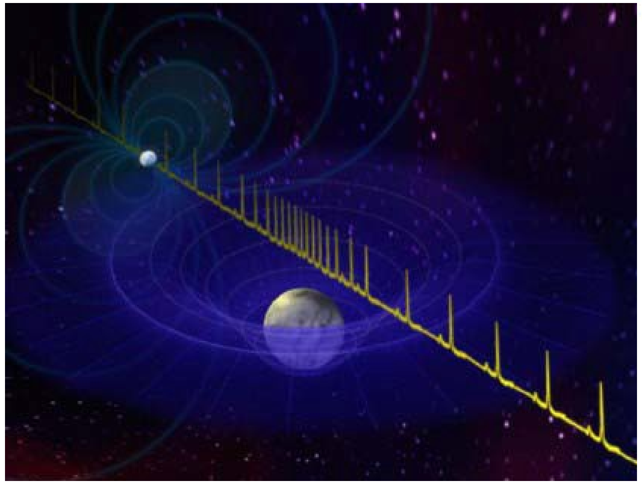
- Neutron star merger/Gravitational wave
  - Wave structure of gravitational wave made by neutron star merger depends on its equation of state

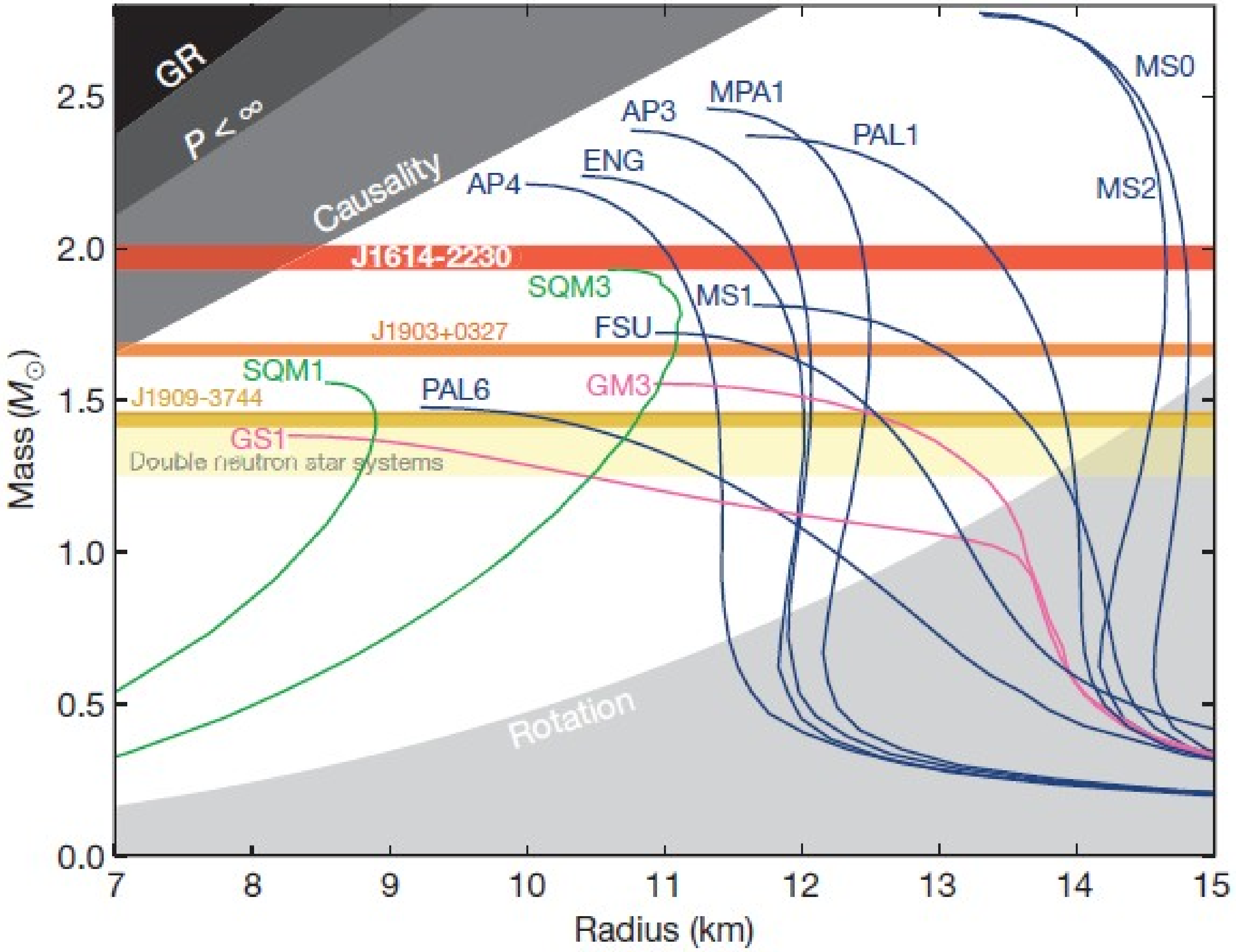
A lot of predicted EOS was ruled out by the observation of heavy neutron star

- Mass of J1614-2230 pulser is 2 solar mass

Demorest et al., Nature 467 (2010) 1081

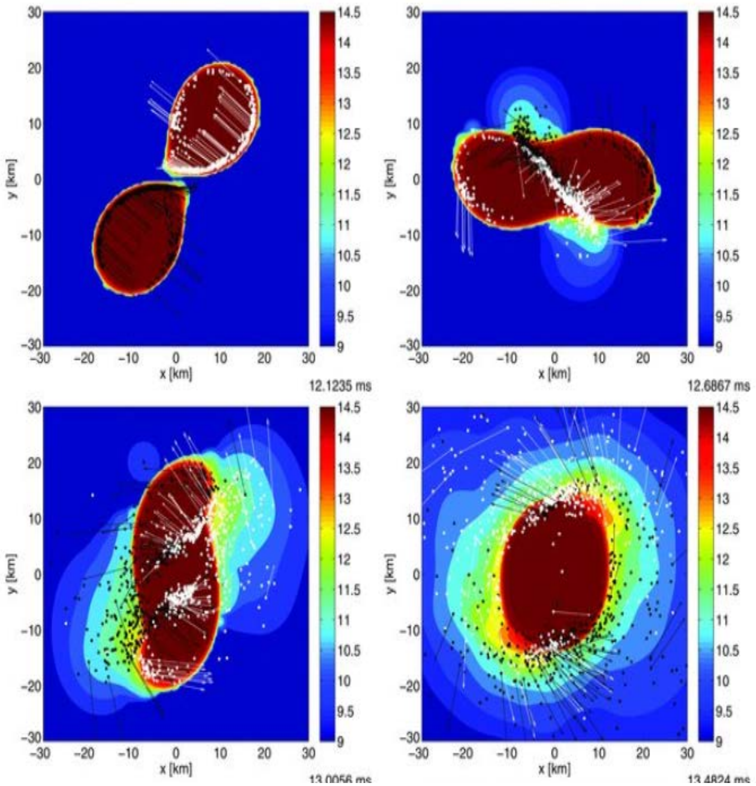
Shapiro delay

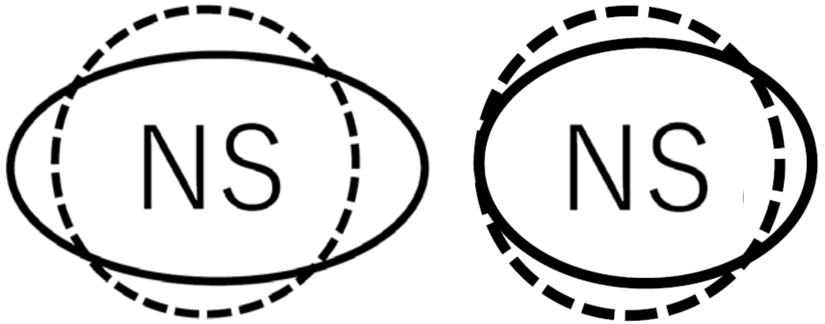




EoS and tidal deformation of the Neutron Star Merger

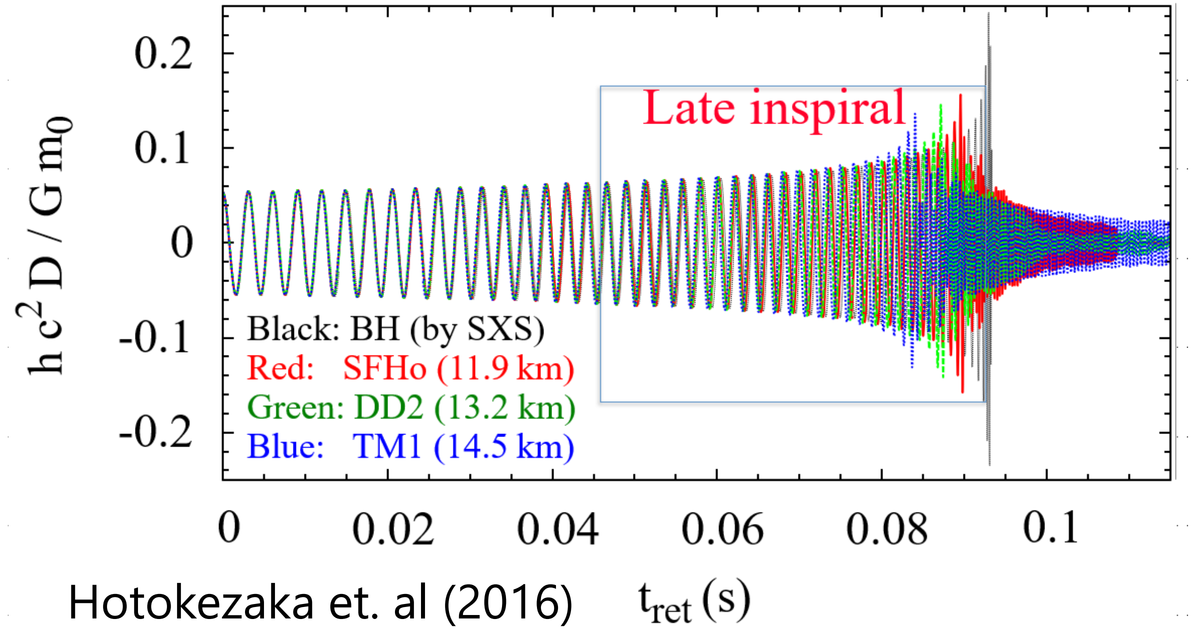
A. Bauswein, S. Goriely, and H.-T. Janka,
APJ, 773, 21 (2013)





Soft EoS → Large deformability

Stiff EoS → Small deformability



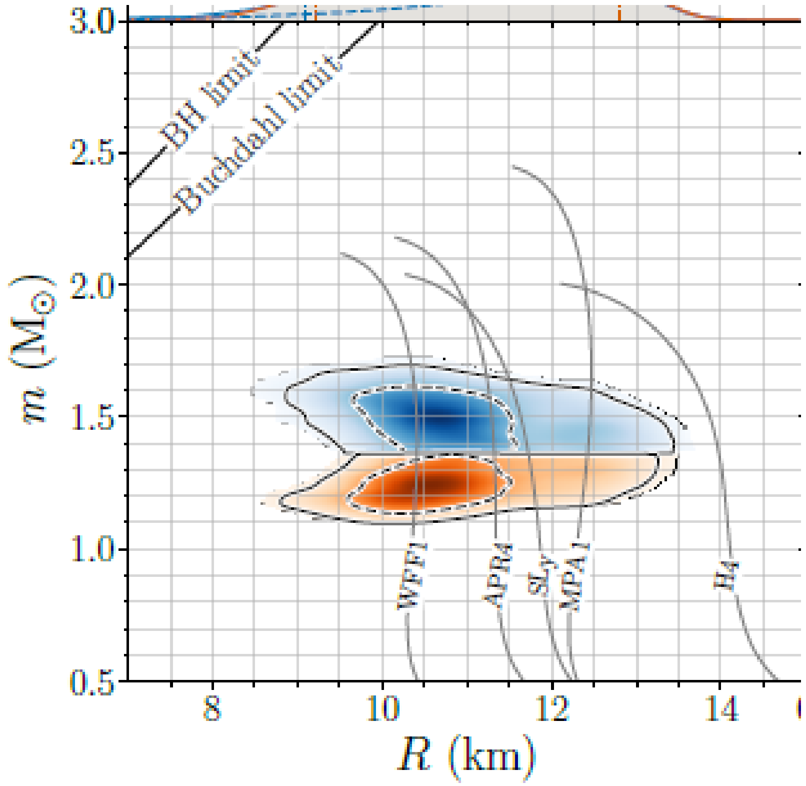
Hotokezaka et. al (2016)

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

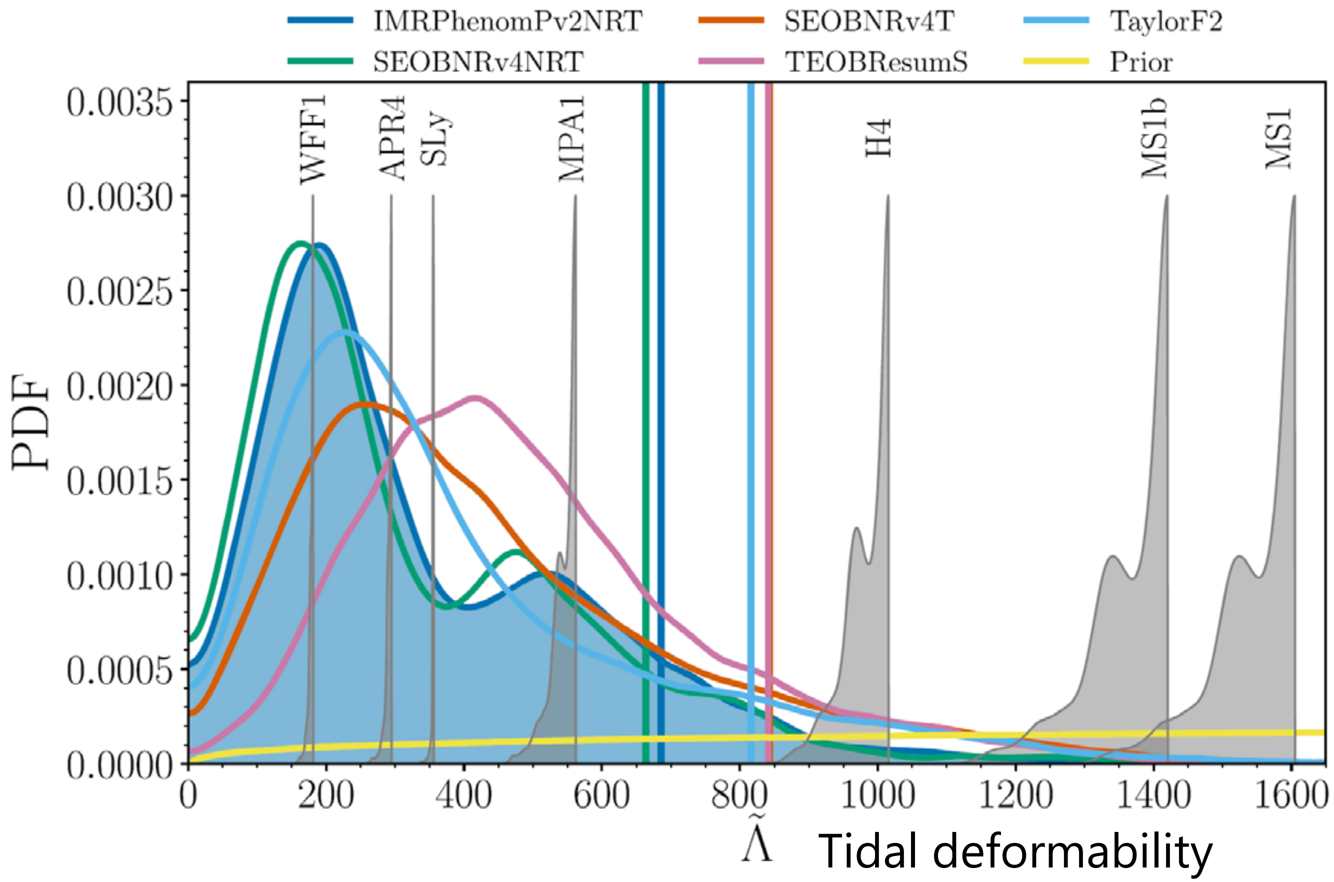
Λ<800 (90% confidence)

GW170817 PRL 119 161101

Constraint of nuclear EoS from tidal deformation of NS Merger



Posterior distributions for each waveform models

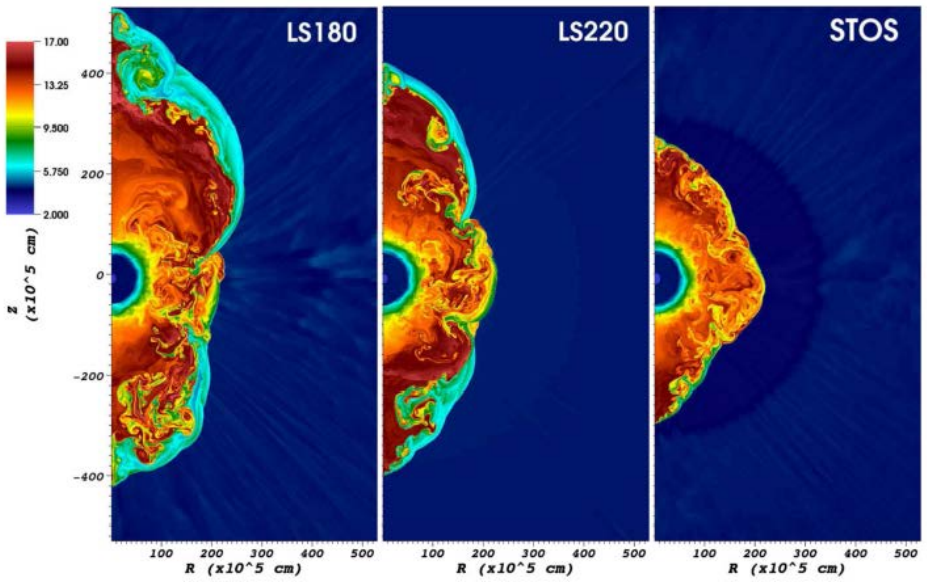


Tidal deformability

PHYSICAL REVIEW X 9, 031040 (2019)

Current issue on supernovae simulation related to EOS

- Around 2005~ it was succeeded to reproduce the explosion by employing 2D, 3D models.
- Still the released energy from explosion is not large enough to explain the observation.
  - 1~2 order smaller
- Prefer soft EOS to reproduce the explosion.
  - Softer EOS leads to a more compact proto neutron star, stronger instabilities, earlier explosions.
- EOS at $\rho=2\sim3\rho_0$, Z/A~0.3-0.35 is important for supernovae calculation.

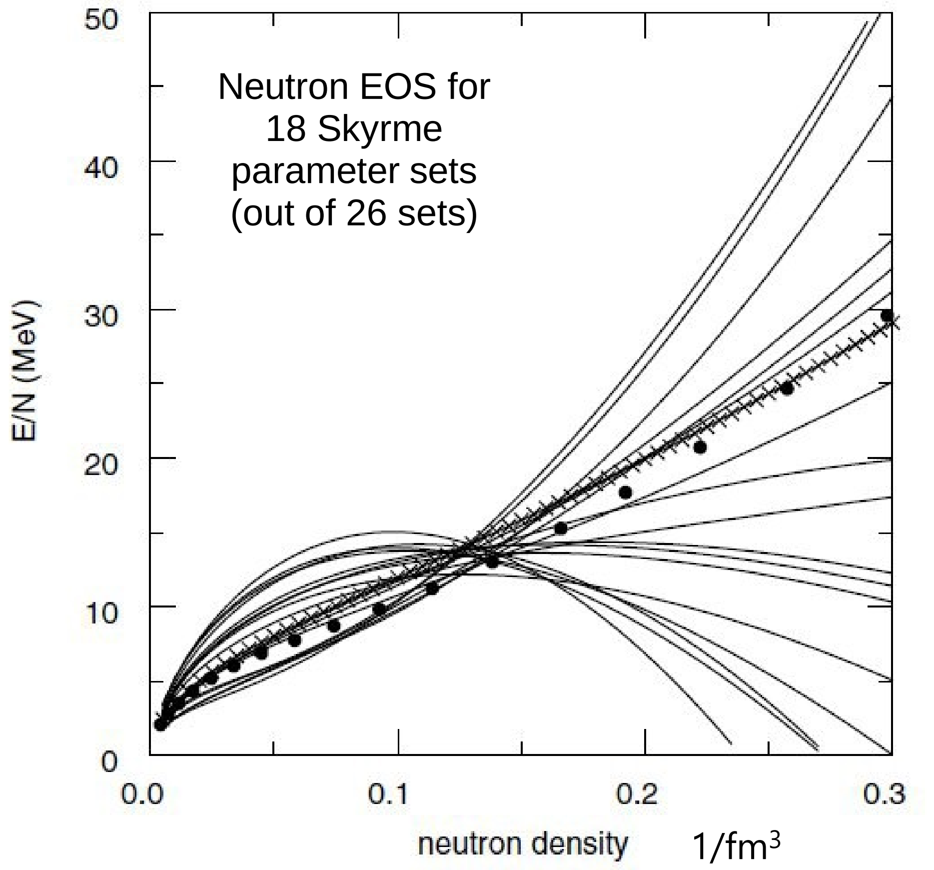


Couch 2012

Experimental study of symmetry energy as input for astrophysical researches

- 20 years ago, Brown showed that many different Skyrme effective interactions can fit the binding energies of Sn nuclei between ^{100}Sn and ^{132}Sn
- Yet predict very different density dependences for the symmetry energy term in the nuclear EoS.
- Well determined only around $\rho \sim \rho_0$ and Z~N
  - EOS for $\rho \sim \rho_0$, Z<<N by last decade study.
  - Higher order effect such as 3BF can not be neglected.

●: Friedman-Pandharipande EOS
×: SkX



B.A. Brown, Phys. Rev. Lett. 85, 5296 (2000).

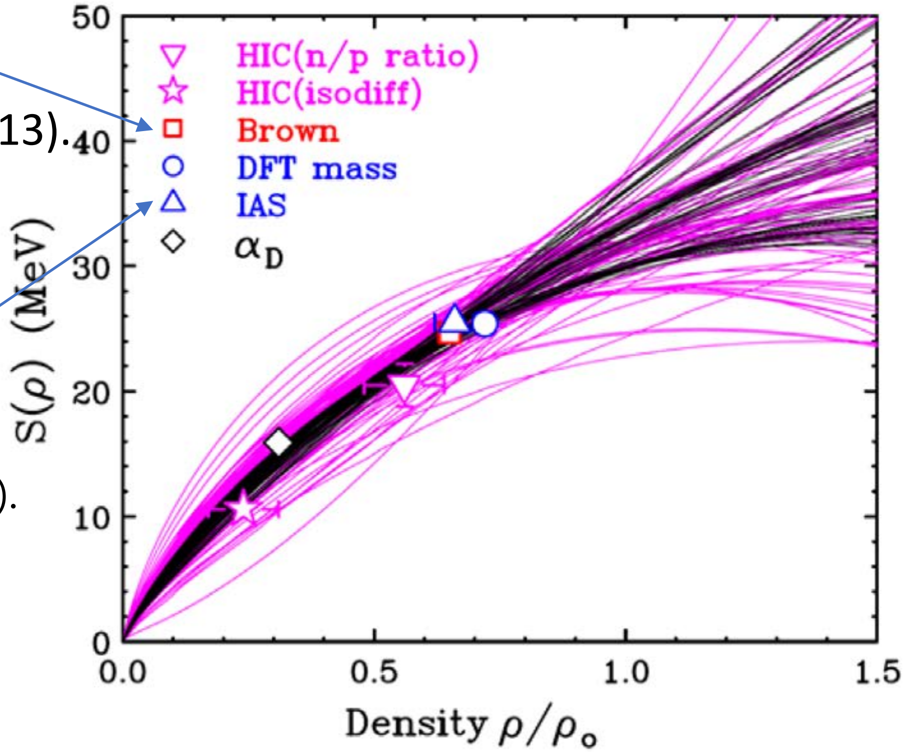
Constraint given by terrestrial nuclear experiments

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.
- No data point above saturation density.

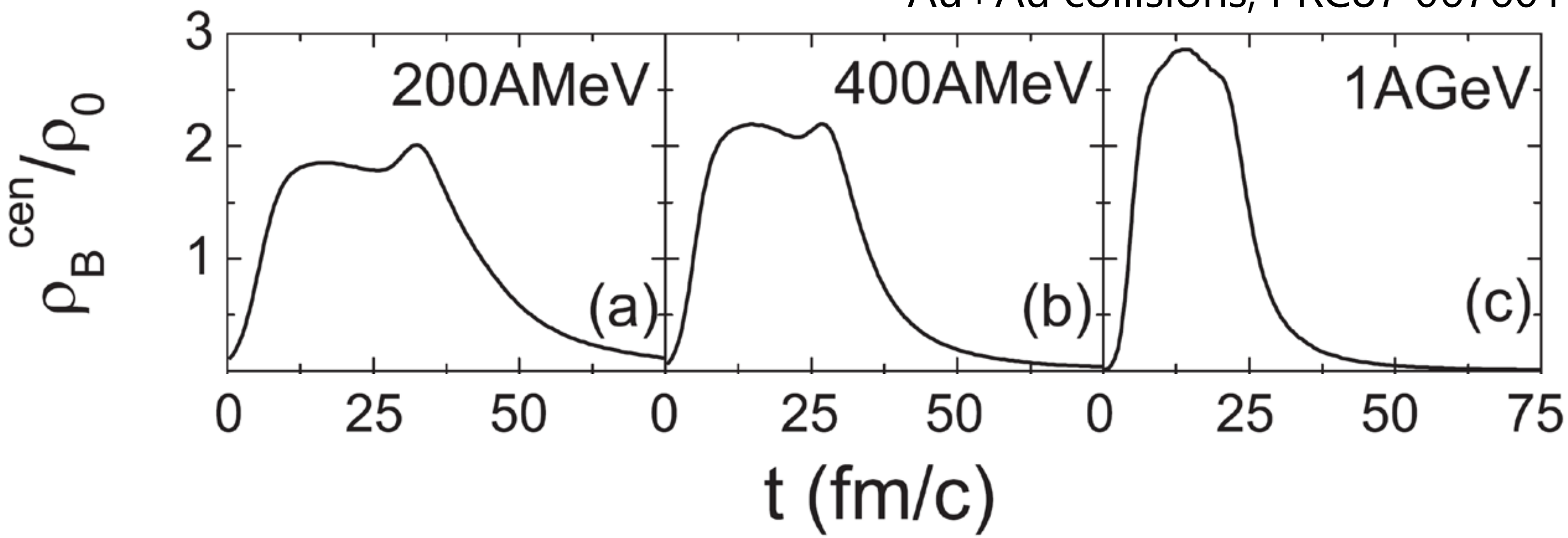
Heavy RI collision experiment for the study of high dense nuclear EOS

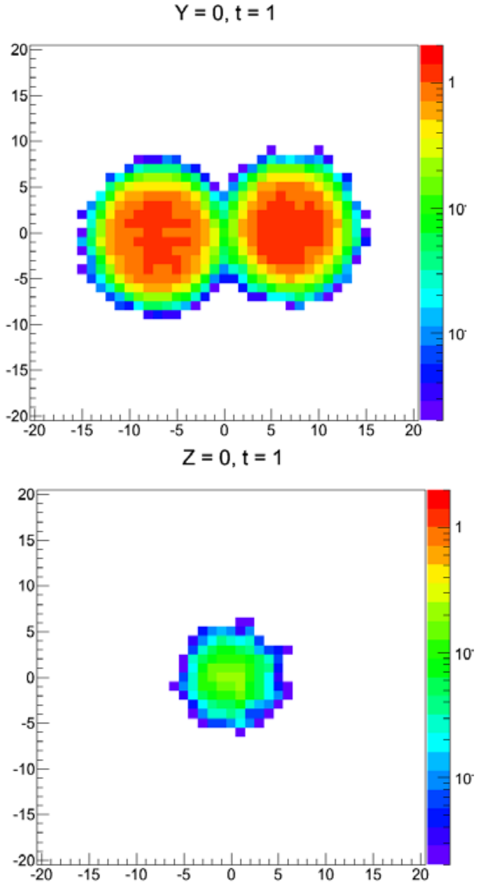
Introduction to SπRIT

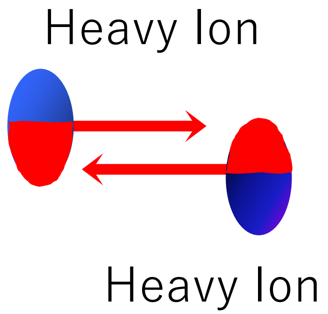
Terrestrial experimental study of high dense matter nuclear symmetry energy → heavy RI collision

Central density as a function of T.

Au+Au collisions, PRC87 067601







IBUU by Li

- Currently, heavy ion collision is the kind of 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.

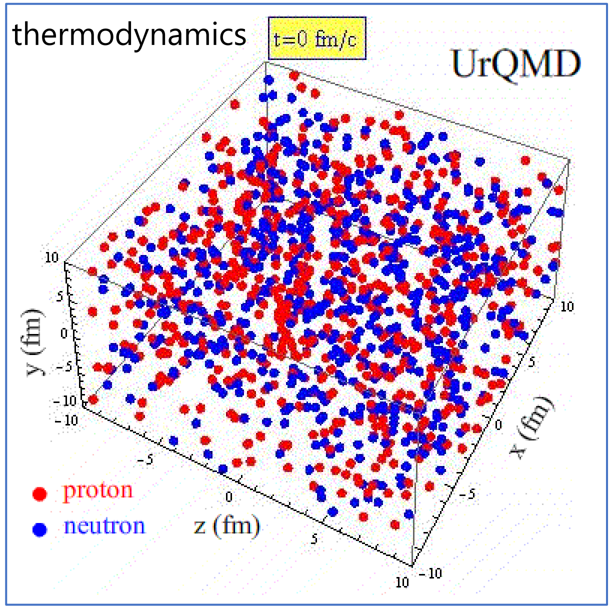
We need to rely on transport theory to reproduce heavy ion collisions

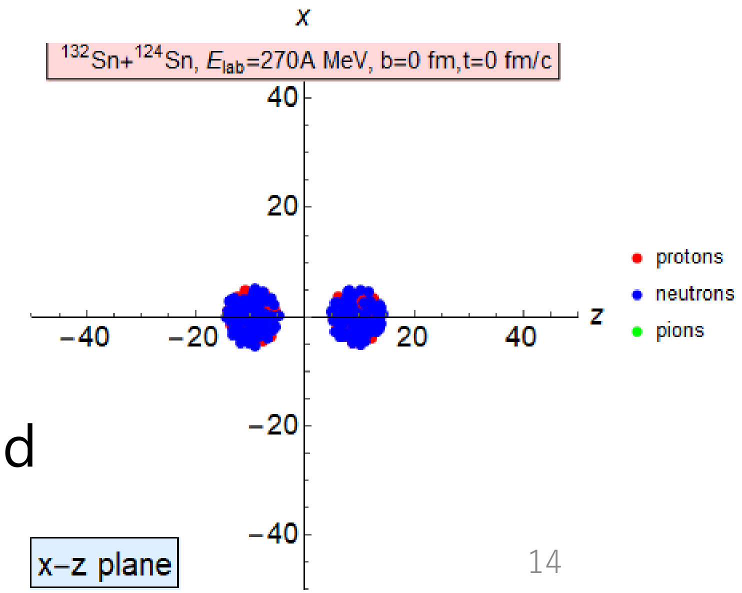
Observables In HIC ⟷ **Simulate HIC** ⟷ **Transport theory** ⟷ **Mean field U** ⟷ **EOS**

- Theoretical tool to describe HIC dynamics: transport theory:
  - QMD: Quantum Molecular Dynamics
  - BUU: Boltzmann-Uehling-Uhlenbeck eq. (Bertsch Phys. Rep. 160, 189 (1988).).
- Each nucleon is represented by ~1000 test particles that propagate classically under the influence of the self-consistent mean field U and subject to collisions due to the residual interaction.

- They are supposed to describe
- Mixture of equilibrium and non-equilibrium state
- Final state particles nucleon flows, the nucleation of weakly bound light particles and the production of nucleon resonances.

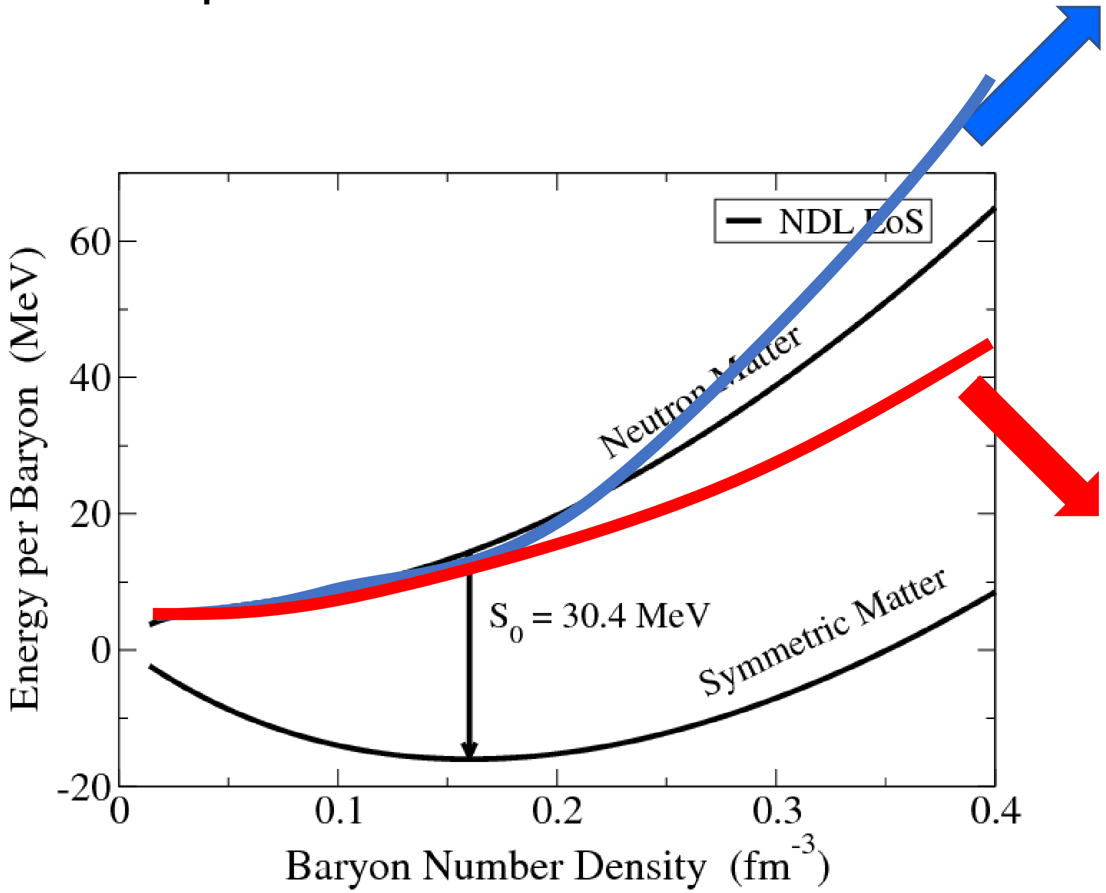
→What we can observe experimentally





Experimental observables from heavy ion collision to constrain the symmetry energy

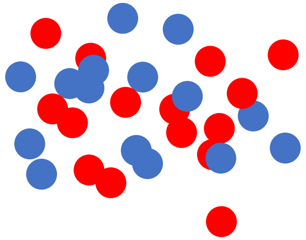
- No direct observables, but contains the information of symmetry energy
- Symmetry energy → appeared as pressure difference between neutron and proton



Stiff symmetry energy

→ lower ρ_n/ρ_p in higher dense region

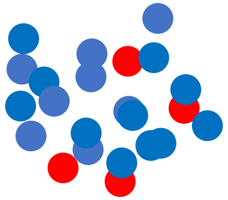
→ lower n/p, less triton



Soft symmetry energy

→ larger ρ_n/ρ_p in higher dense region

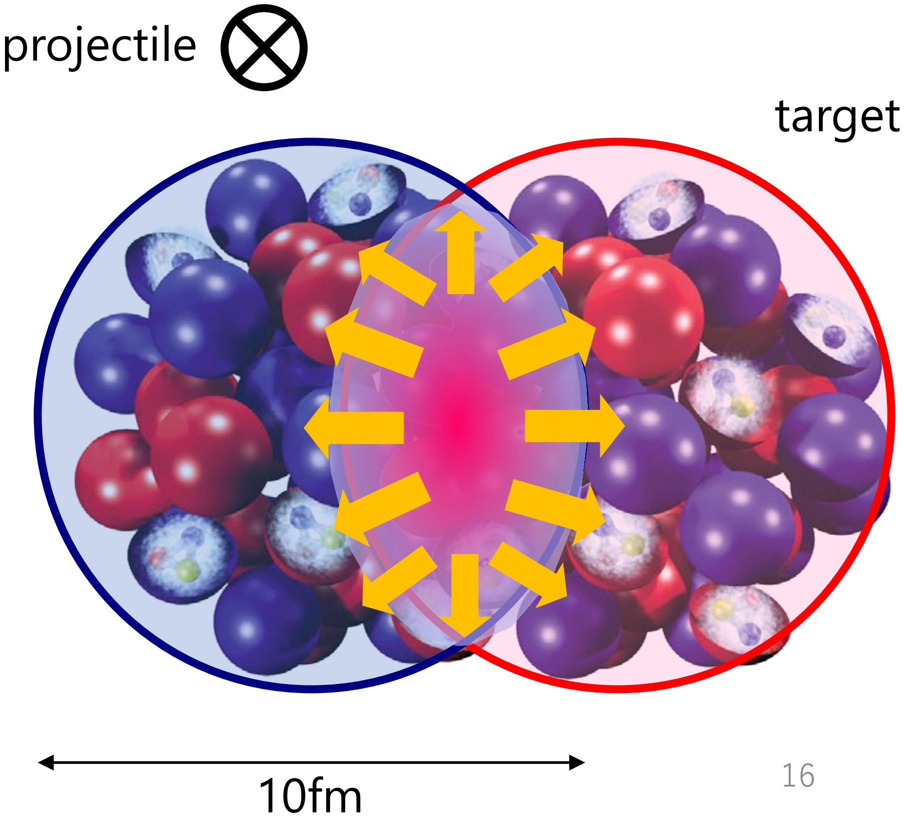
→ larger n/p, more triton



Experimental observables from heavy ion collision to constrain the symmetry energy

- Many type of probes are proposed to study symmetry energy from HIC
  - Prefer less dependent on the models
  - Mainly ratio of isospin opposite particles to maximize the dependence on symmetry energy: ~O(10%) difference

- Proton-to-neutron ratio
- π+ to π- ratio
- Triton to helium-3 ratio
  - expected comparable to proton-to-neutron ratio
  - t: d+p, ^{3}He: d+n
- Particle production anisotropy
  - Reflect pressure difference in bulk matter
  - so-called "flow"



Charged pion ratio as a probe to constrain symmetry energy

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

π^- production (main reaction)

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

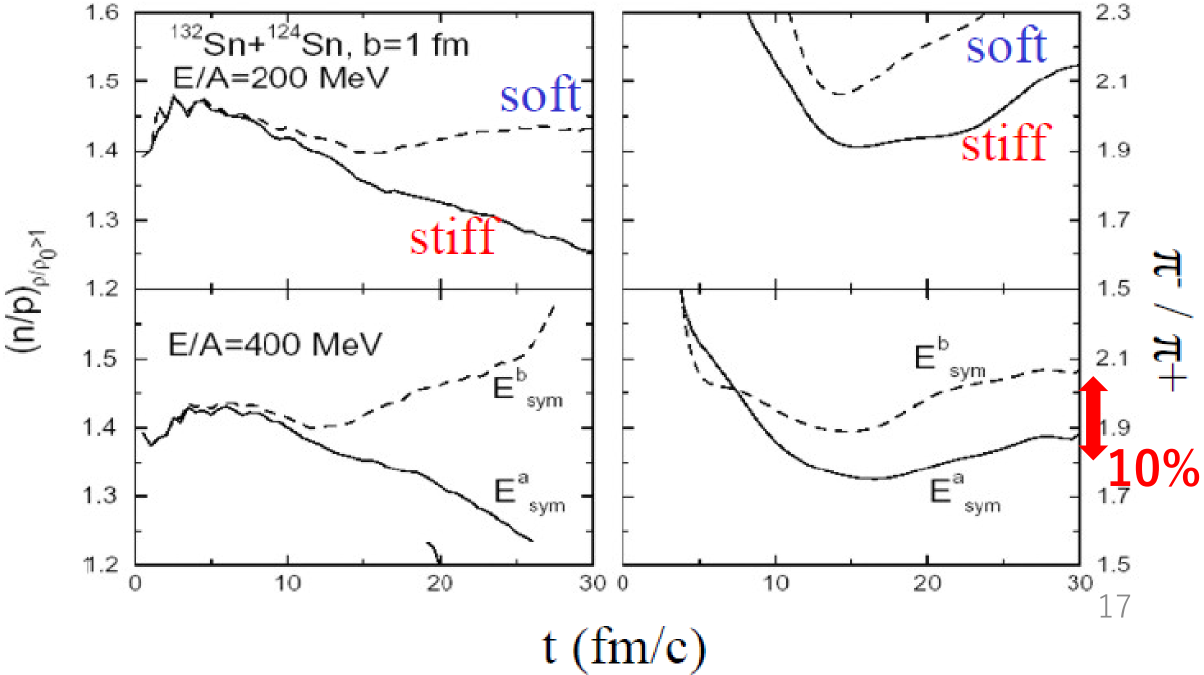
π^+ production (main)

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

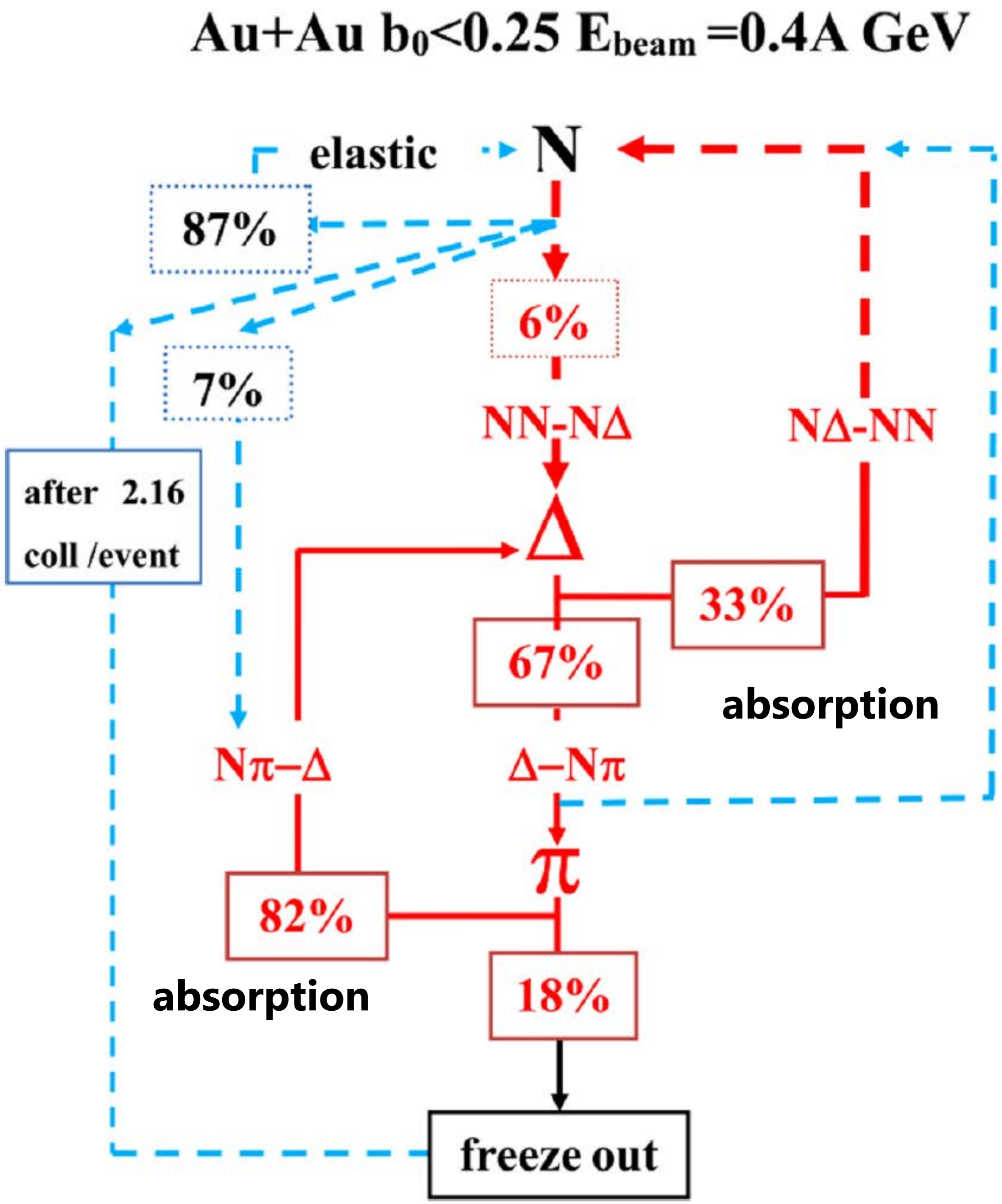
Simple expectation :

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

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

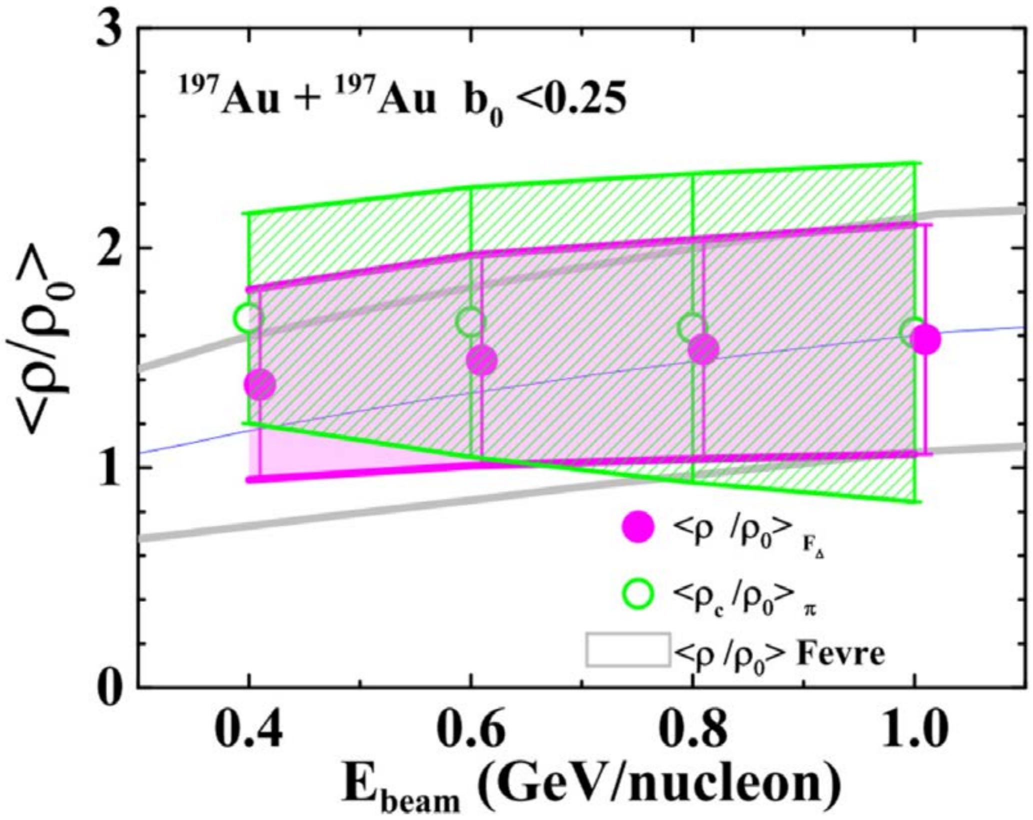


pion ratio probes the symmetry energy at $\rho \sim 1.5\rho_0$



Pion weighted density

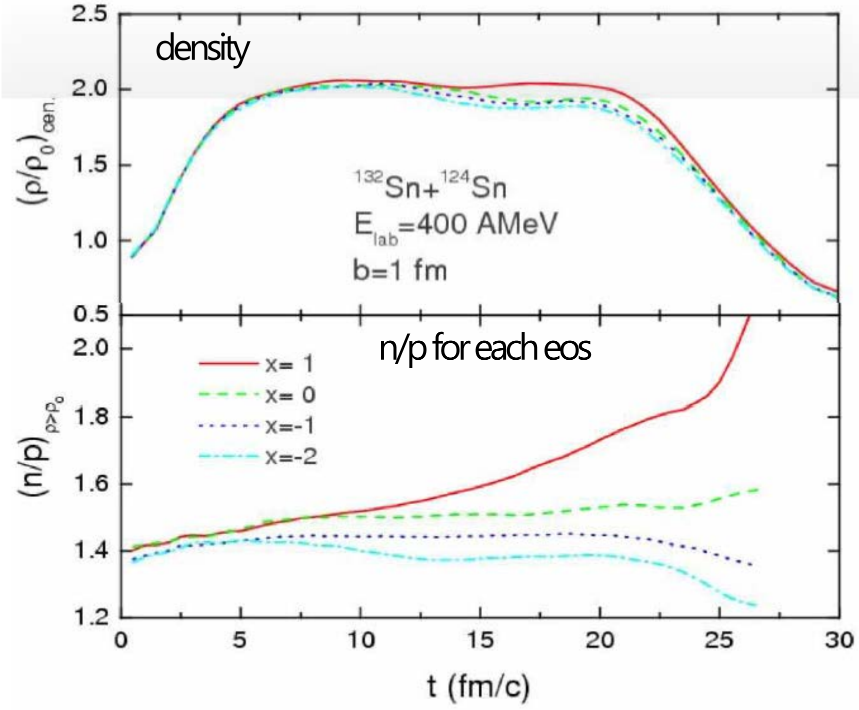
Phys. Rev. C 103, 014616 (2021).



Heavy RI Collision program @RIKEN-RIBF: SPiRIT project

- Experimental project to give a constrain on the density dependent symmetry energy main for higher dense region.
- Systematic measurement in same *Z* but different *N* system realized with heavy RI beam.
  - Control nuclear effect.
  - <u>$\rho \sim 2\rho_0$ nuclear matter at RIBF energy.</u>
- 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 finished successfully.
  - 2016 Apr. – Jun.
  - Measurements were performed for 4 systems.

Yong, PRC **73**, 034603 (2006)



- $^{132}Sn + ^{124}Sn$ @E_{beam}/A = 270 MeV, δ_{system} = 0.22
- $^{124}Sn + ^{112}Sn$ @E_{beam}/A = 270 MeV, δ_{system} = 0.15
- $^{112}Sn + ^{124}Sn$ @E_{beam}/A = 270 MeV, δ_{system} = 0.15
- $^{108}Sn + ^{112}Sn$ @E_{beam}/A = 270 MeV, δ_{system} = 0.09

SPiRIT Collaboration for HIC Exp. at RIBF

SAMURAI Pion Reconstruction and Ion Tracker

International Collaboration aiming to study density dependent symmetry energy through **Heavy RI Collision** experiments.

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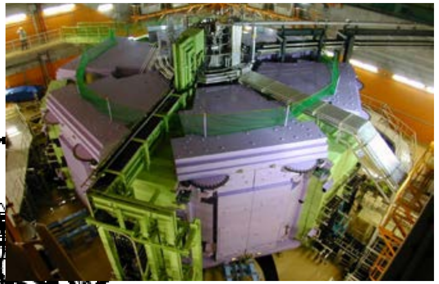
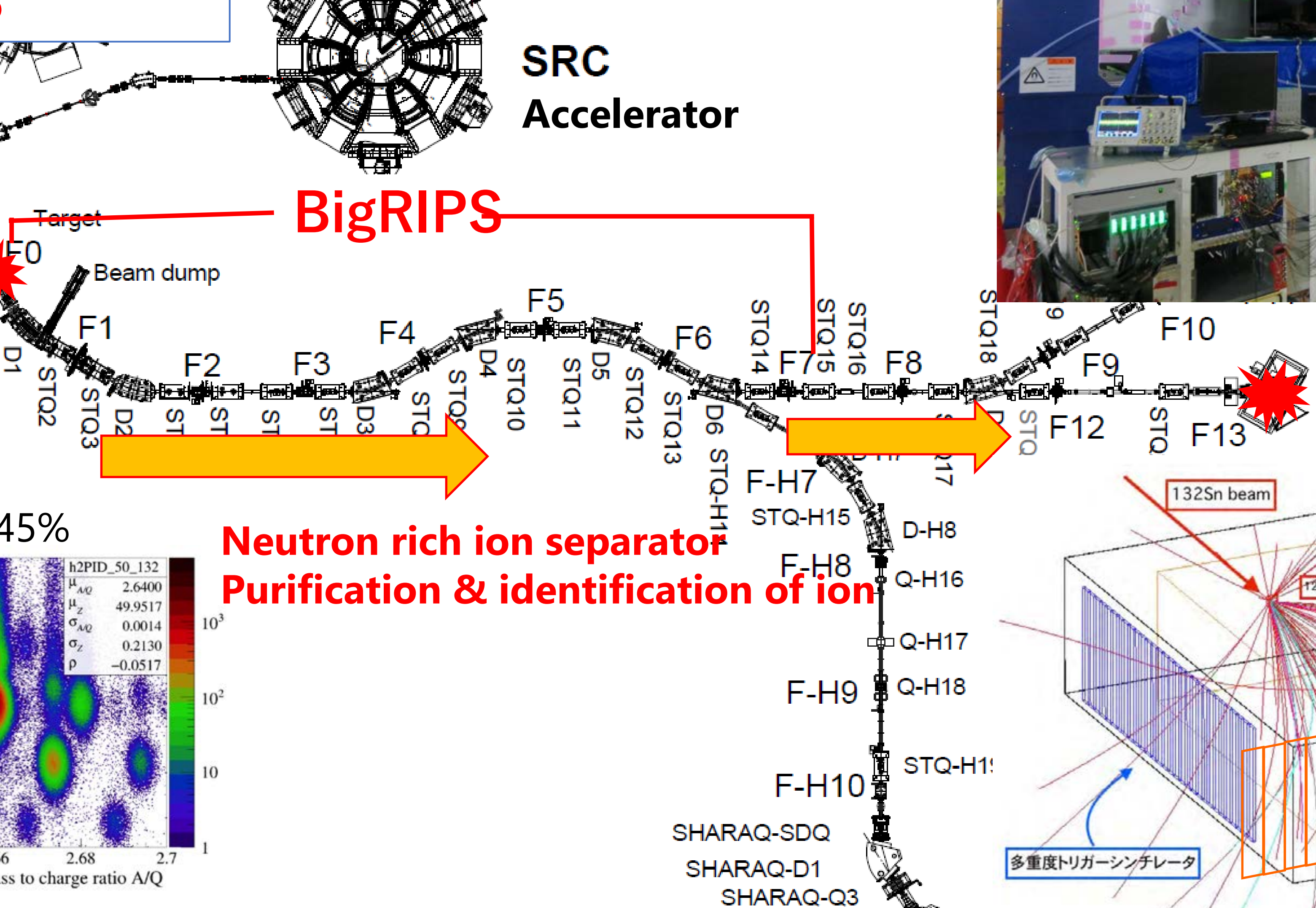
MEXT
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

U.S. DEPARTMENT OF ENERGY
Office of Science

RIKEN-RIBF: RI production at world leading RI facility

U-238 345 MeV/u beam
Z=92、N=146

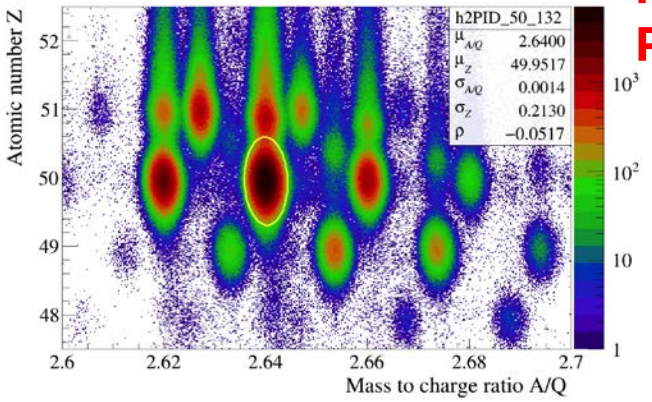


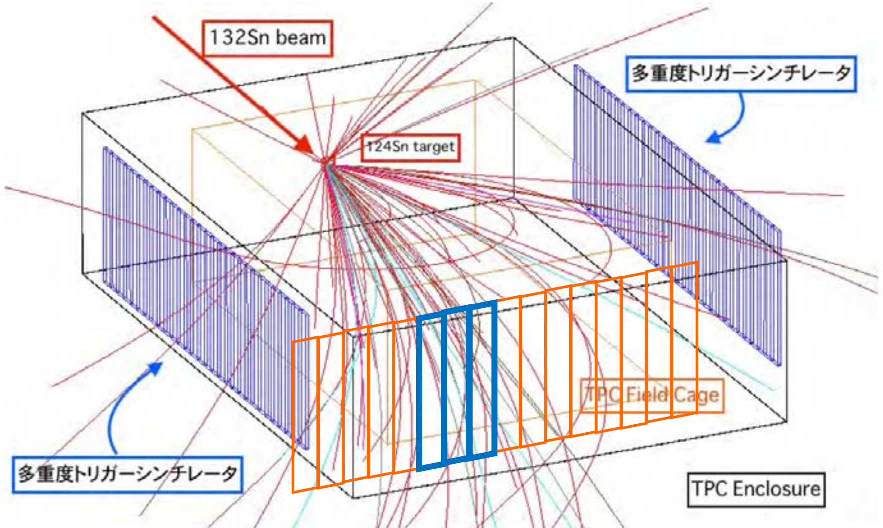


BigRIPS

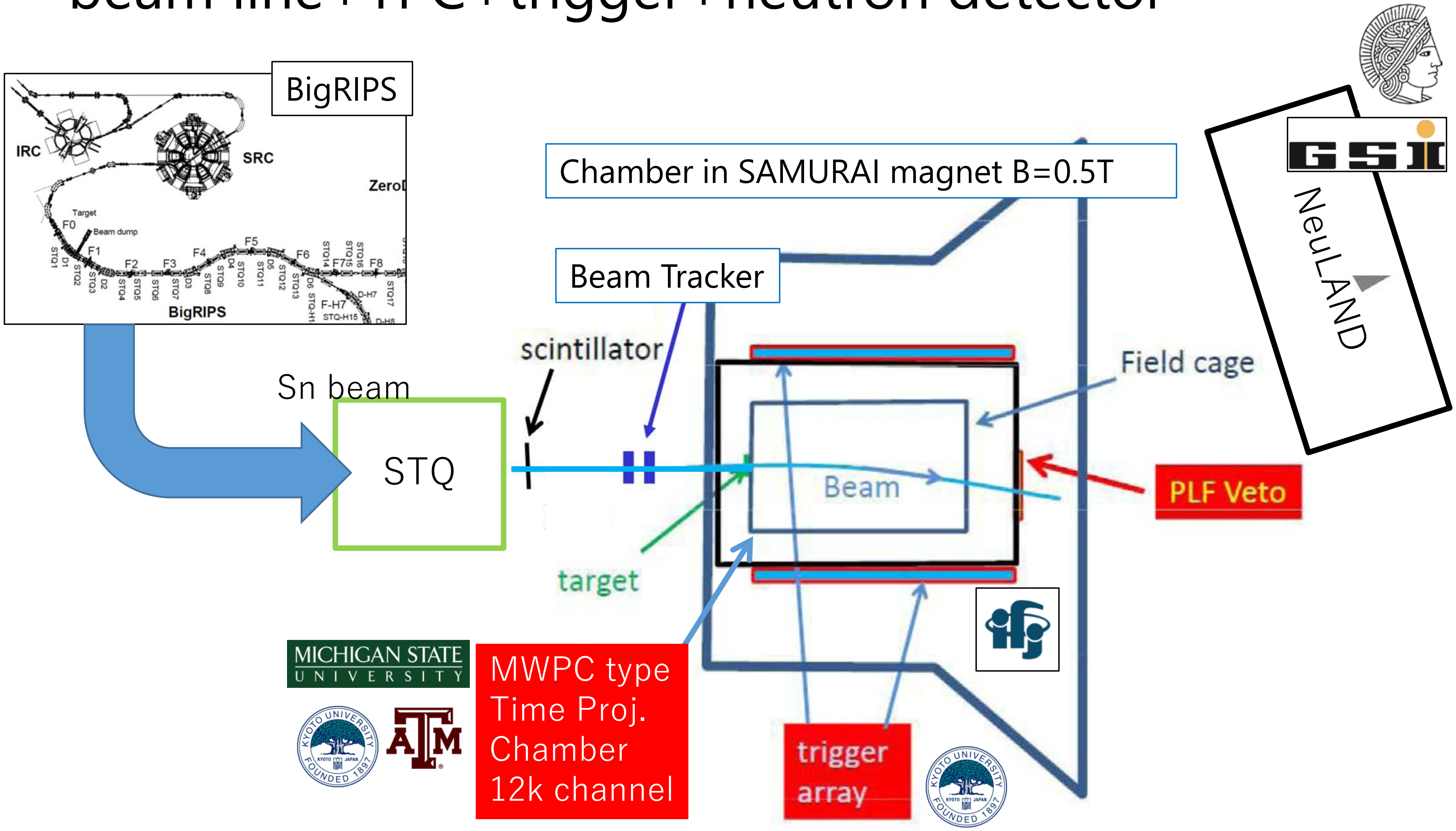
Neutron rich ion separator
Purification & identification of ion

^{132}Sn: purity 45%



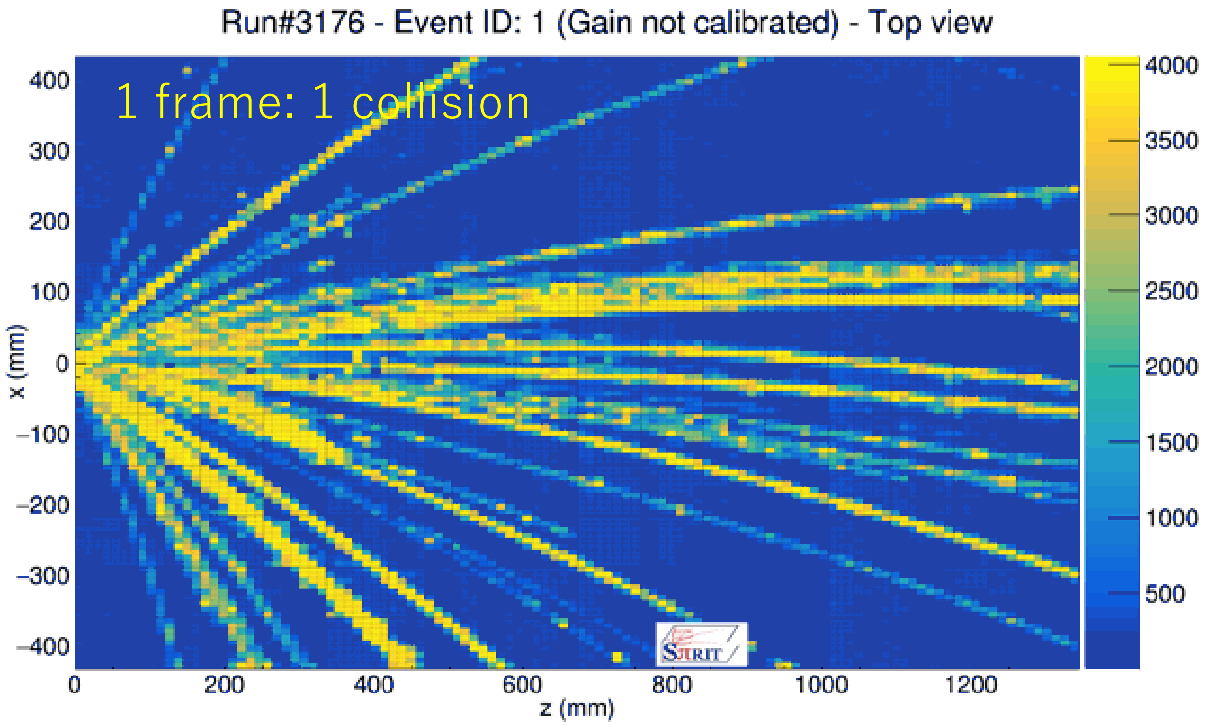


SPiRIT experimental setup top view: beam line+TPC+trigger+neutron detector

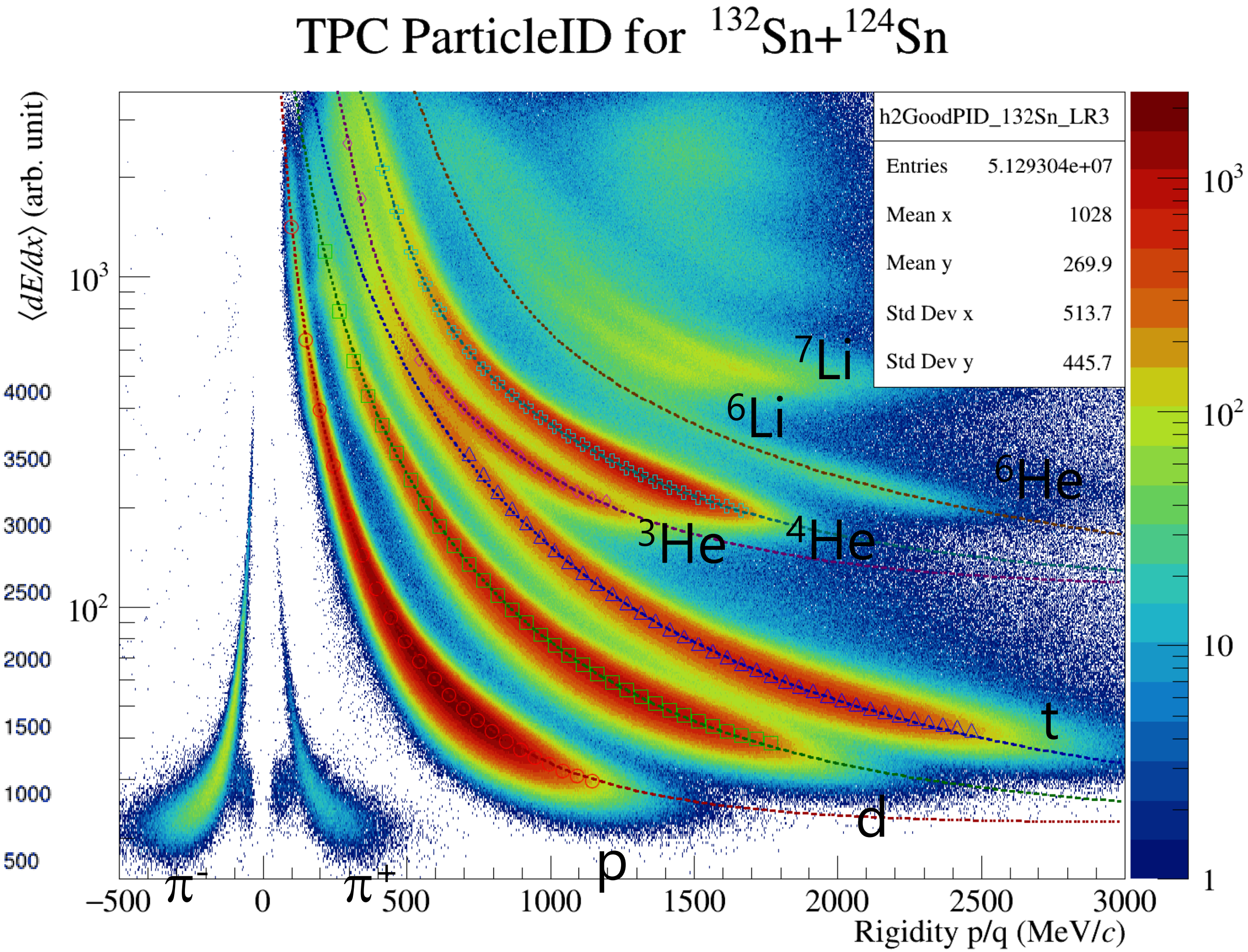


Particle ID and reconstruction with Time Projection Chamber

- Detect most of particles produced in a collision.
  - Optimize gain for pion measurement.
- Particle identification from dE/dx – rigidity correlation
- Rigidity → reconstruction of particle momentum

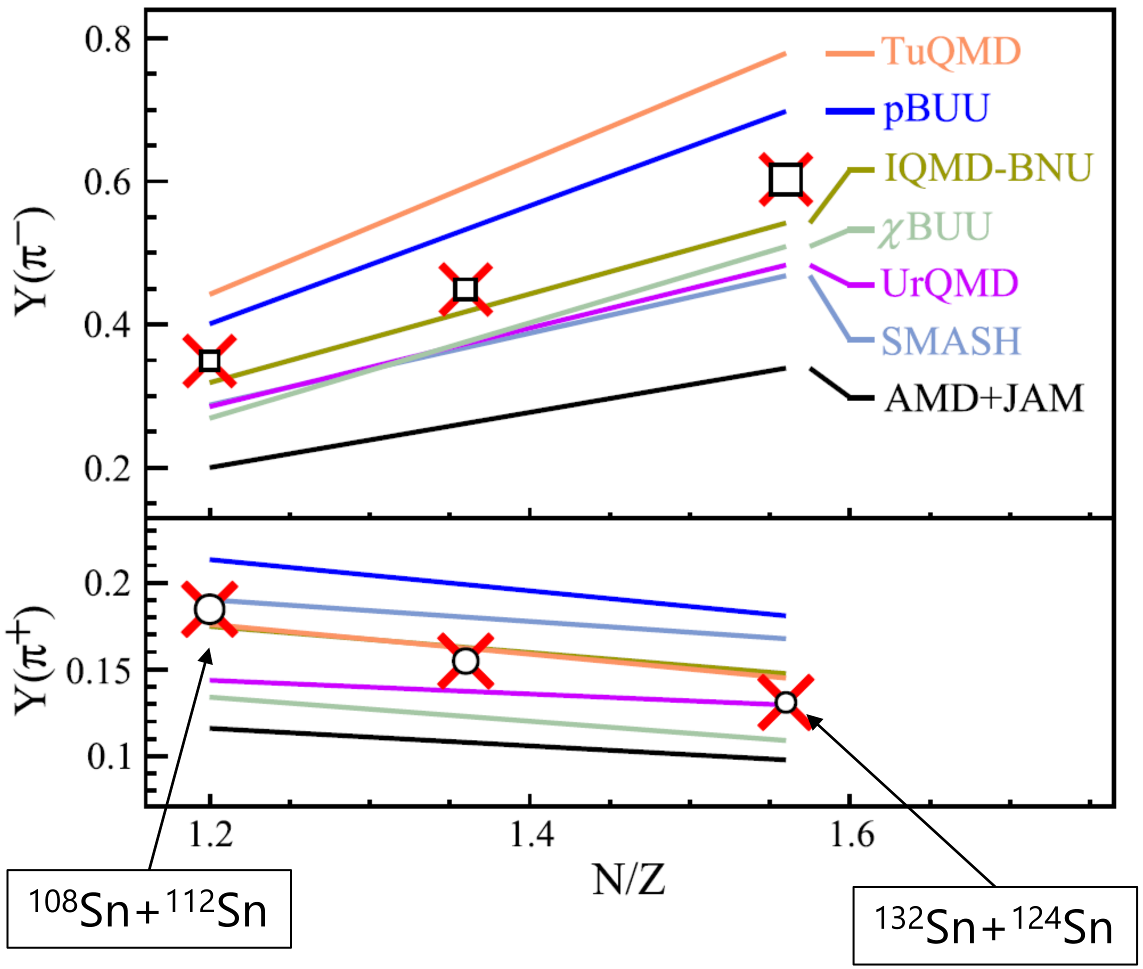


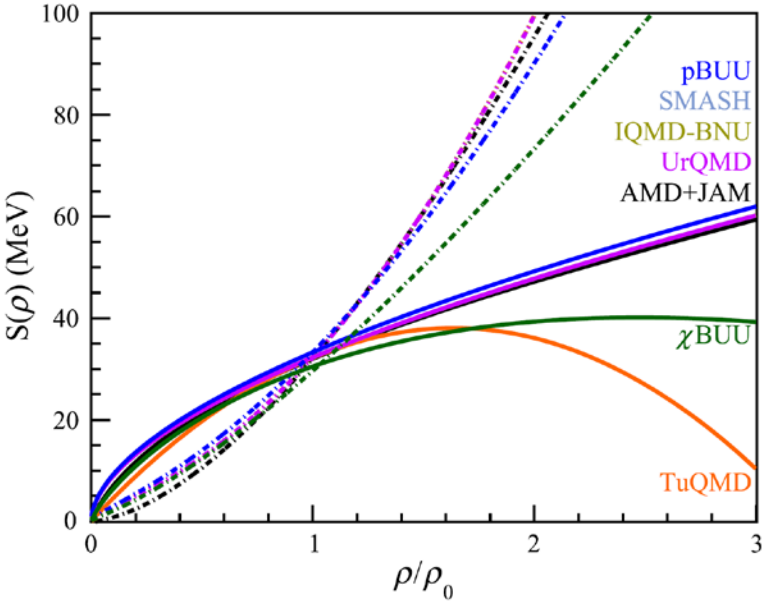
B=0.5T



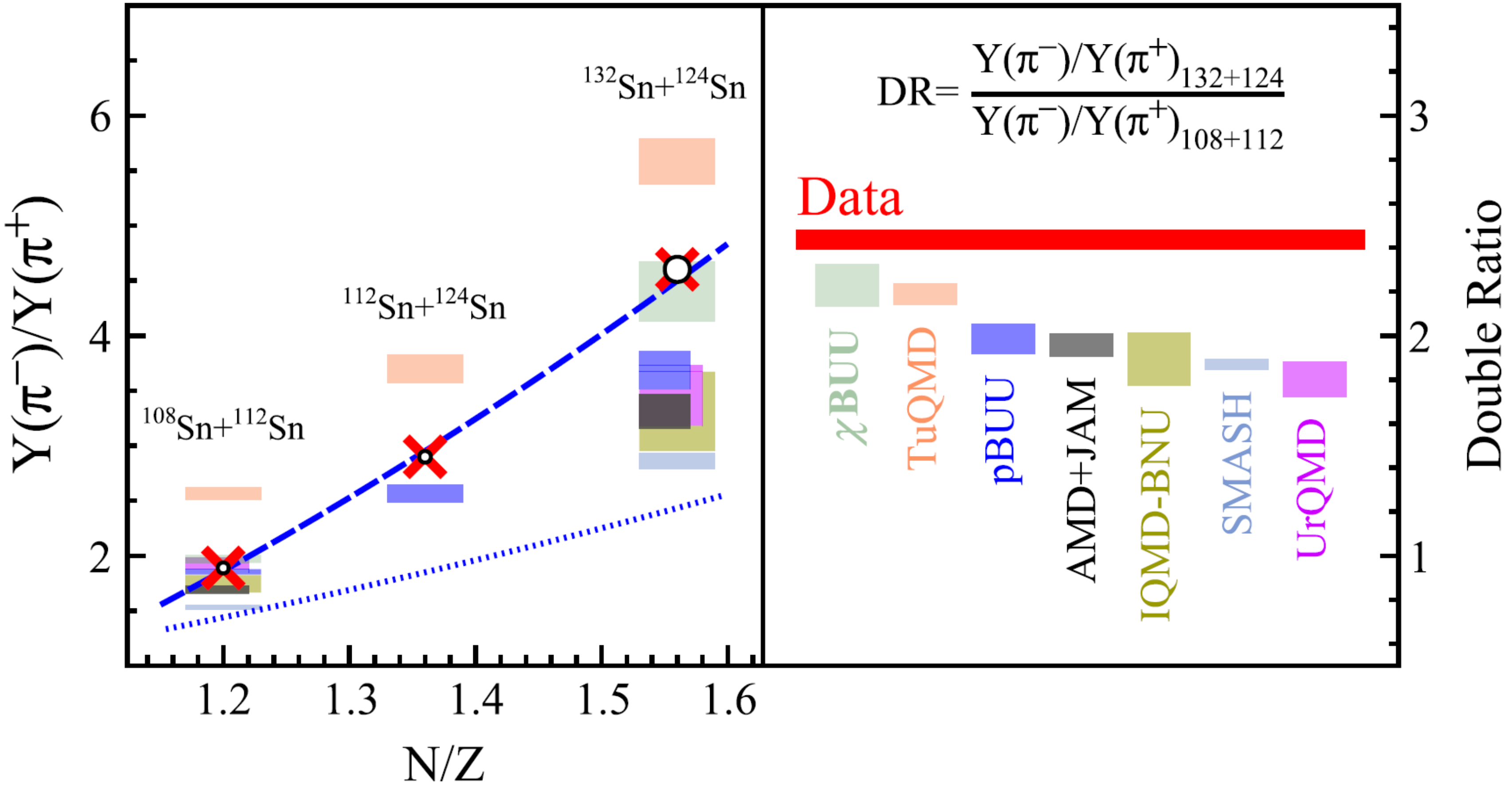
Result on pion multiplicity: number of pions generated collision by collision

PLB 813 (2021) 136016

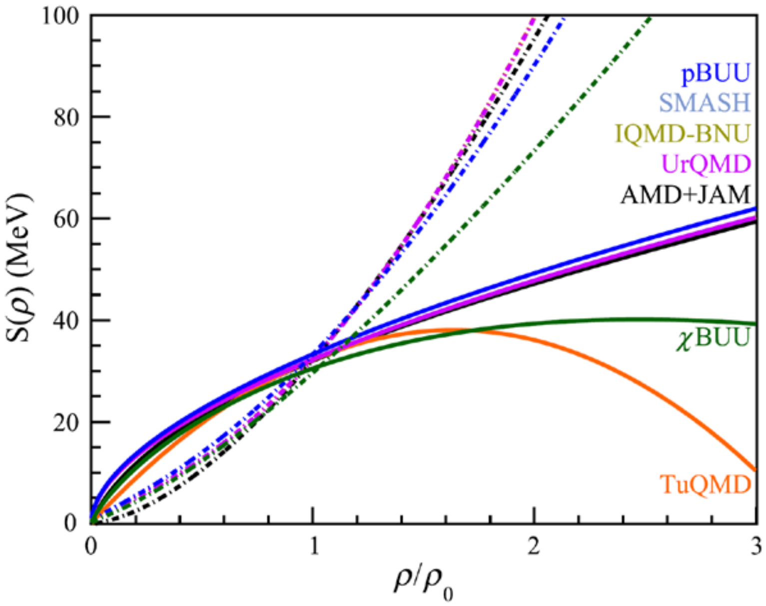




Result on pion multiplicity: pion ratio



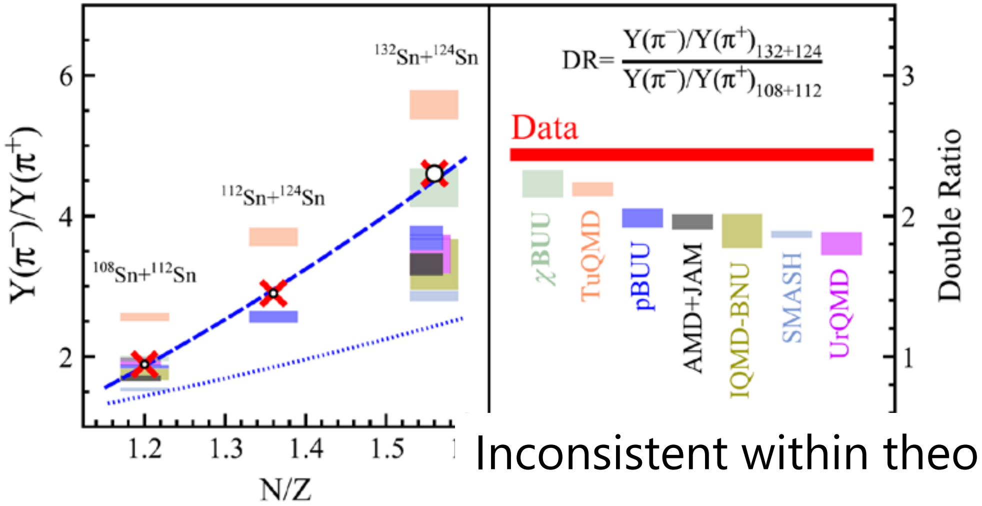
PLB 813 (2021) 136016



- The height of the boxes is given by the difference of predictions for the soft and stiff symmetry energies.
- Deviation among transport models is larger than sensitivity on symmetry energy.
- Different assumptions regarding the mean field potentials for Δ baryons and pions can influence the pion multiplicities.

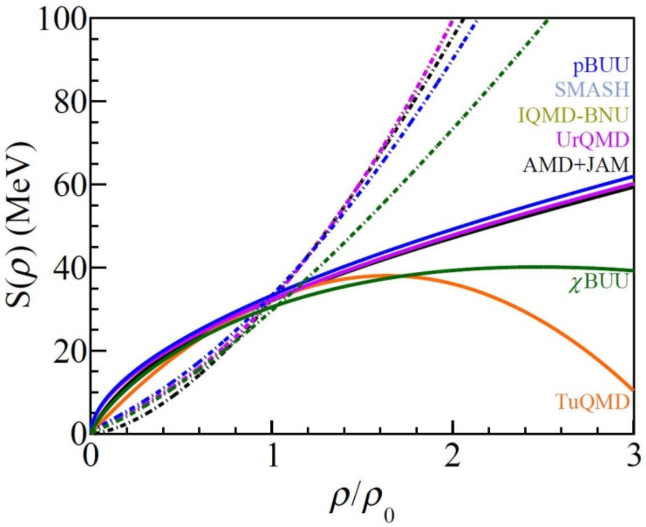
Giving feedback to transport theory to reduce the discrepancy among models. → to be updated!

Observables In HIC ⟷ **Simulate HIC** ⟷ **Transport theory** ⟷ **Mean field U** ⟷ **EOS**



Inconsistent within theories

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



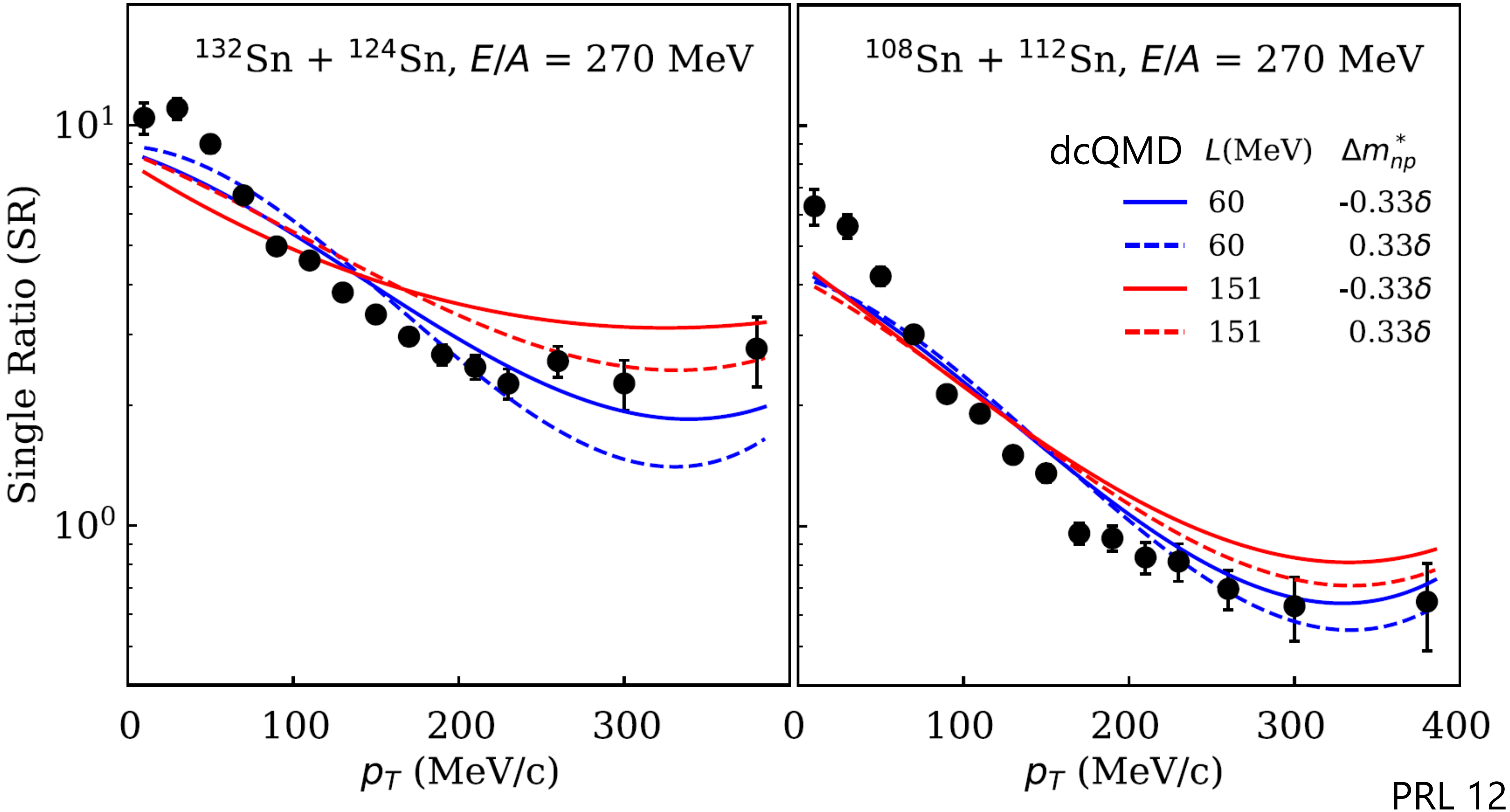
Constrain EOS

Transport Model Evaluation Project

Feedback to Theory w/ exp. data
(e.g. 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.



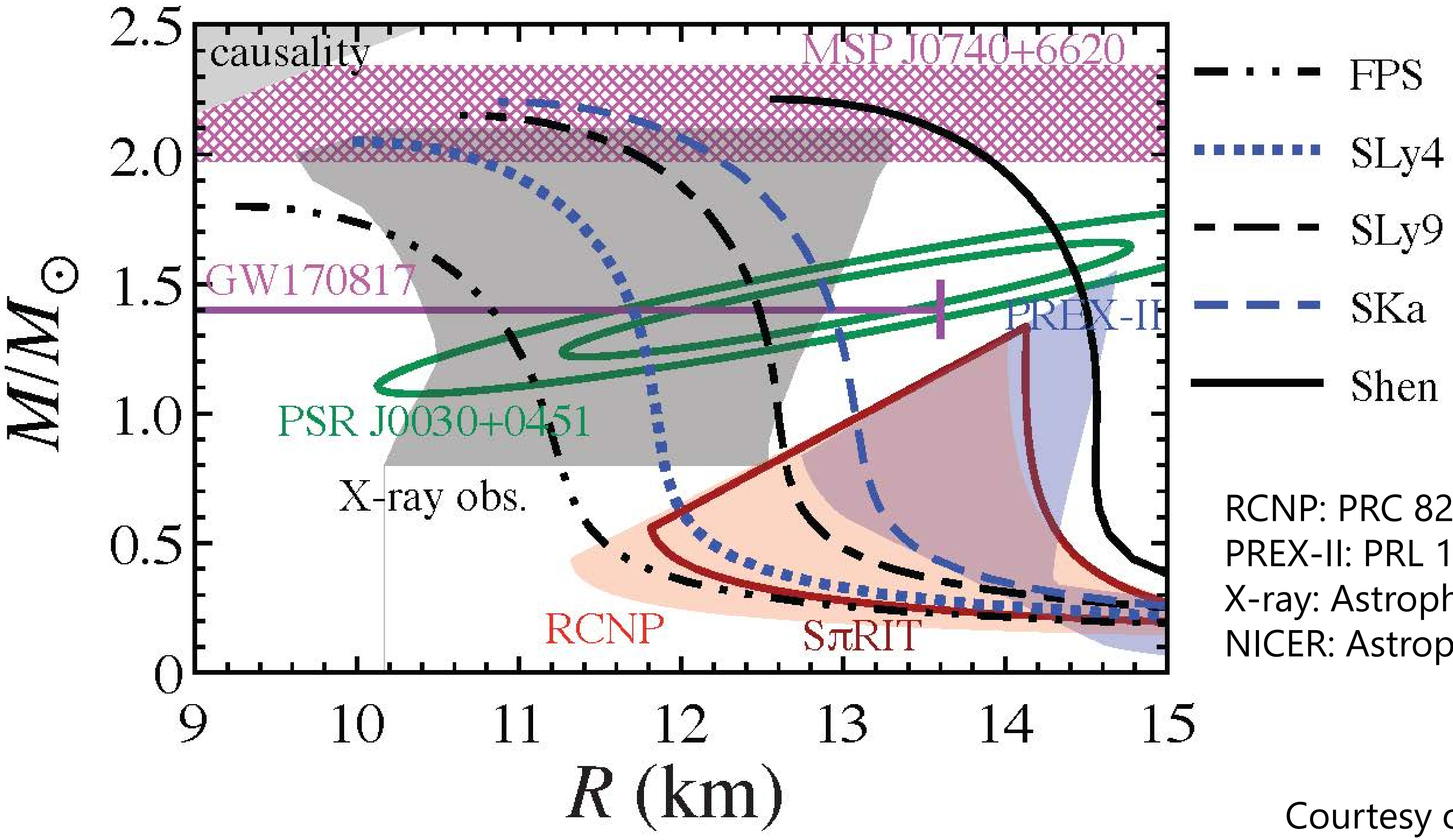
- Neutron rich system shows more sensitivity at high-pT.
- Calculation underestimate at low-pT.

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

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

PRL 126 (2021) 162701

Constrain given by SPiRIT shows consistency with other constrains



RCNP: 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

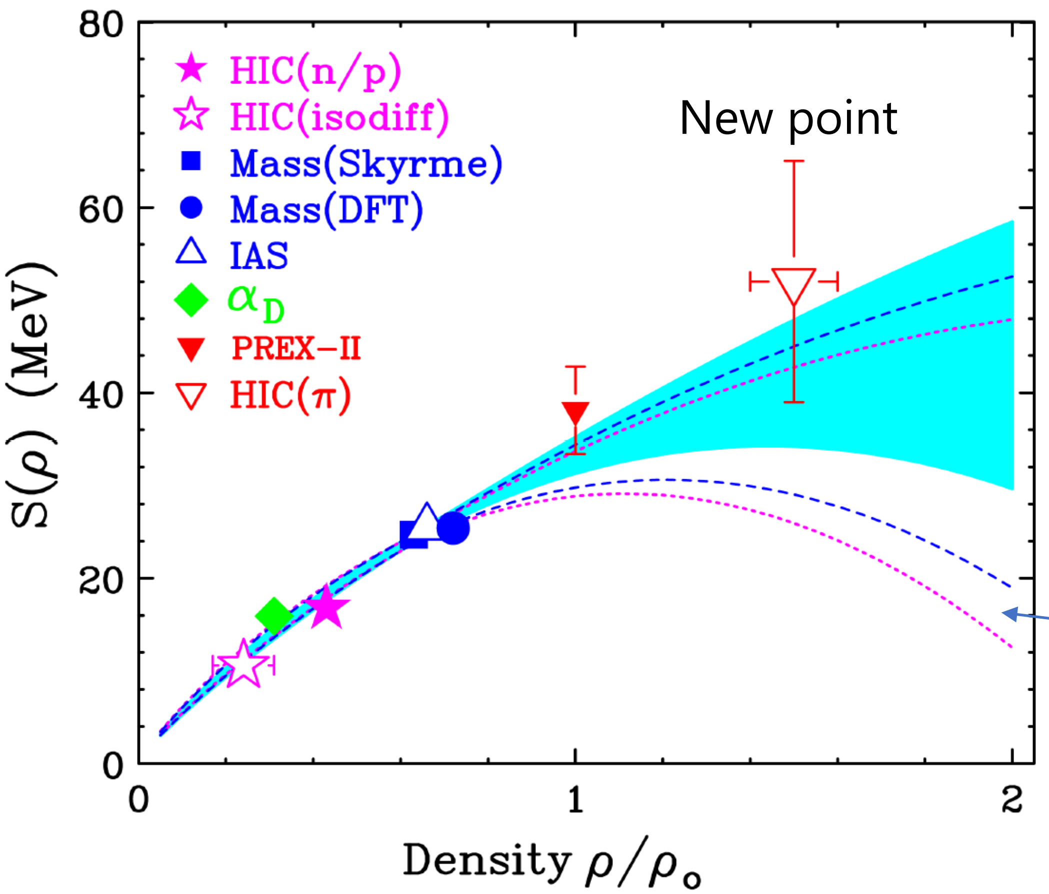
Courtesy of Sotani

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 result 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.