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

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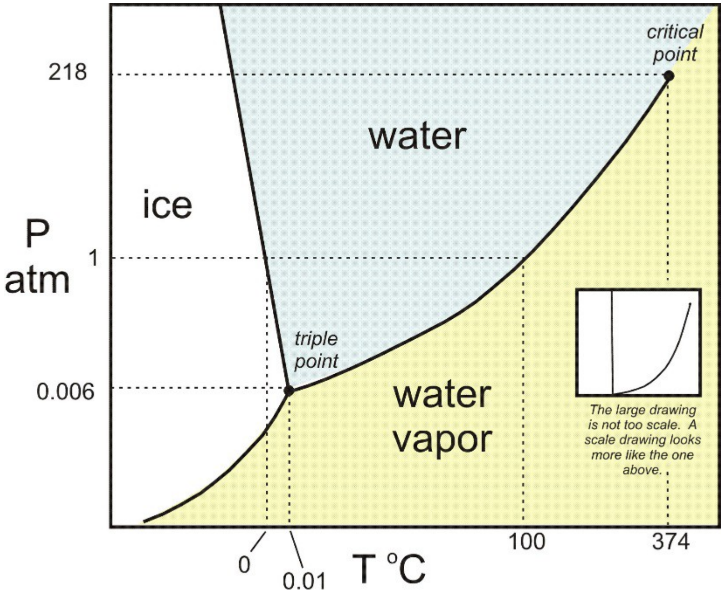
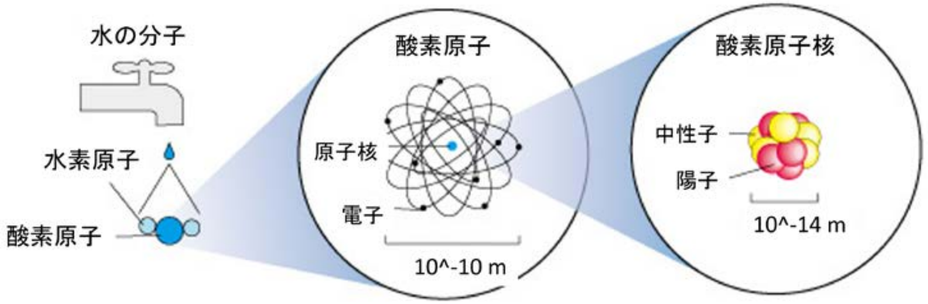
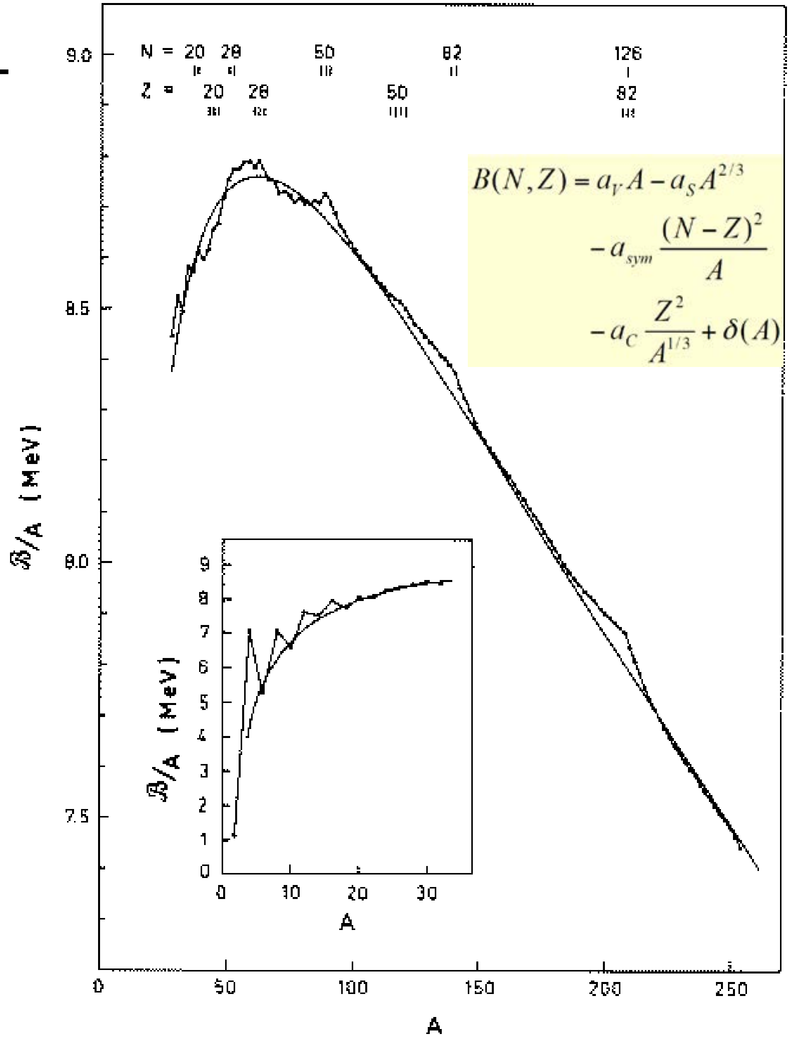
Nuclear matter : many body system of nucleon

Bohr & Mottelson
Nuclear Structure Vol.1

- Equation of State describes the relationship of thermodynamical quantity ←→ EoS of ideal gas:PV=nRT
- Phase of diagram because of interaction between the molecules.







$$B(N,Z) = a_V A - a_S A^{2/3} - a_{sym}\frac{(N-Z)^2}{A} - a_C\frac{Z^2}{A^{1/3}} + \delta(A)$$

- Nuclear liquid drop model
- 1st order description of nuclear mass is succeeded. (Bethe-Weizsäcker Mass formula)

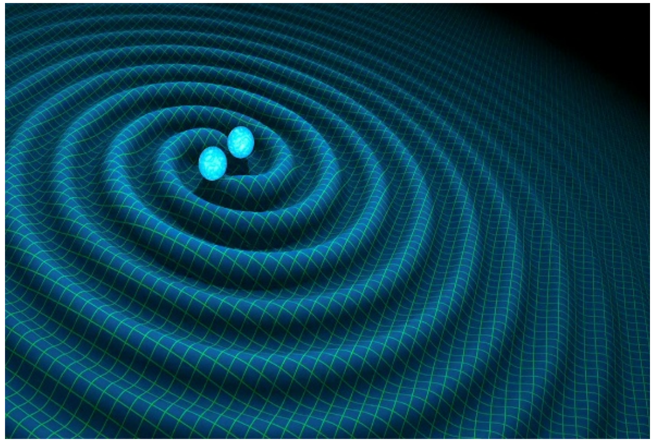
Asymmetric nuclear matter EOS: Symmetry Energy term of nuclear EOS

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

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

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

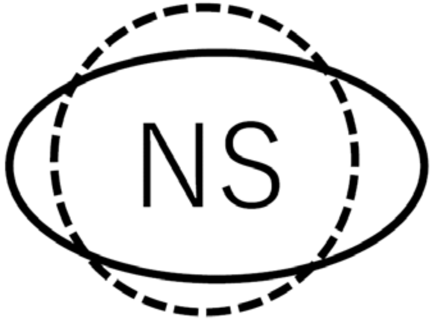
- The asymmetric term of nuclear EOS depends on δ
- Important term especially for astrophysics
  - Neutron star structure (T~0)
    - Solar mass star with the radius of ~10km.
  - Supernovae process (T~ O(10) MeV)
  - Neutron star merger/Gravitational wave



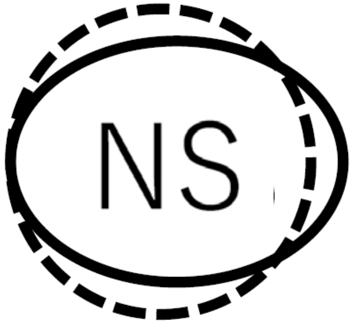
Visualization of a NS merger and the gravitational waves

Gravitational wave from neutron star merger
Tidal deformation depends on nuclear EoS

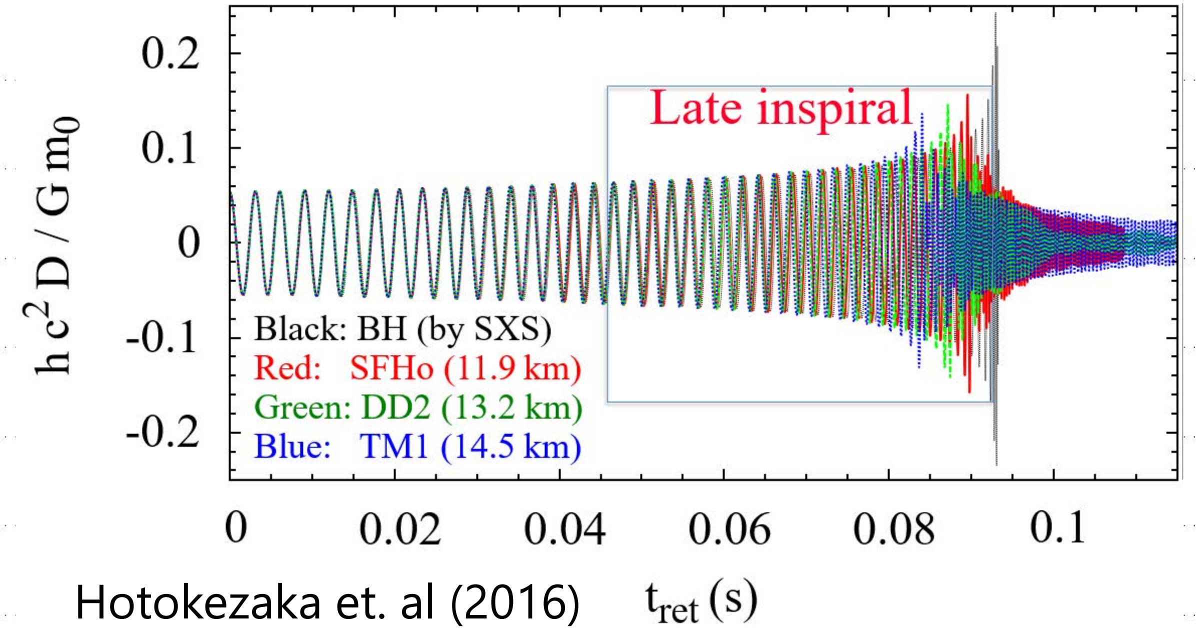
A. Bauswein, S. Goriely, and H.-T. Janka
APJ, 773, 21 (2013)



Soft → Easy to be deformed



Stiff → Small deformation



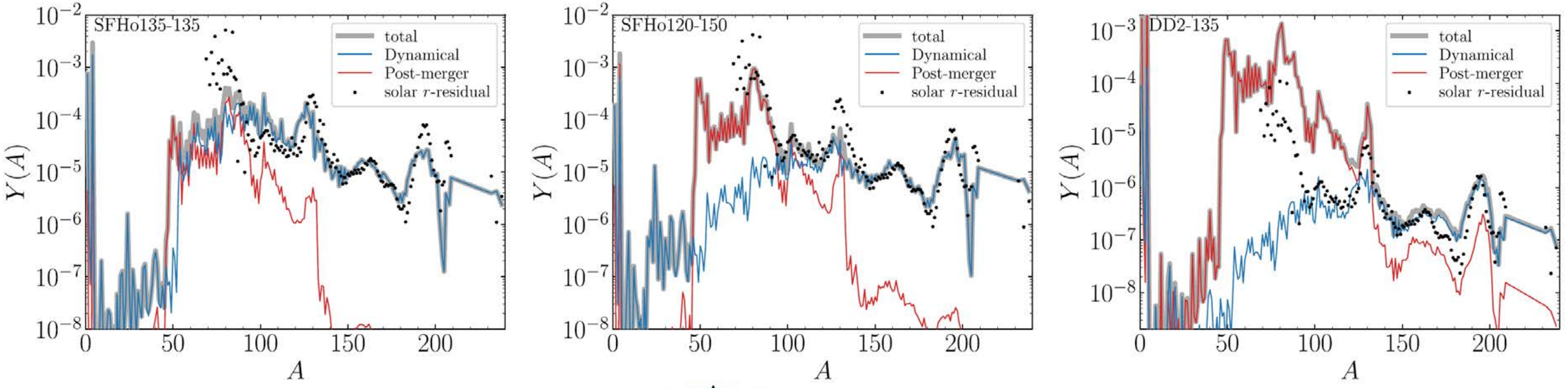
Hotokezaka et. al (2016)

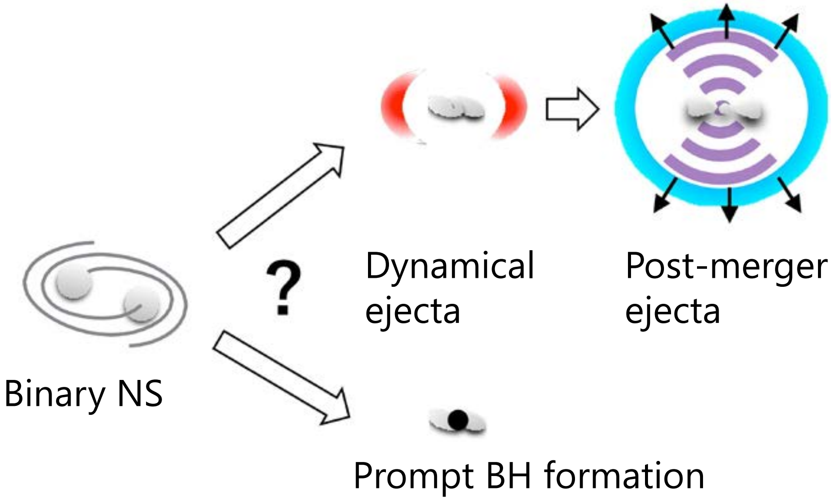
$$\Lambda = \frac{2}{3}k_2\left(\frac{c^2R}{GM}\right)^5 = \frac{64}{3}k_2\left(\frac{R}{R_s}\right)^5$$

$\Lambda<800$ (90% confidence)

GW170817 PRL 119 161101

Nuclear EoS is important also for the r-process nuclear synthesis in neutron star merger





Fujibayashi APJ 2023

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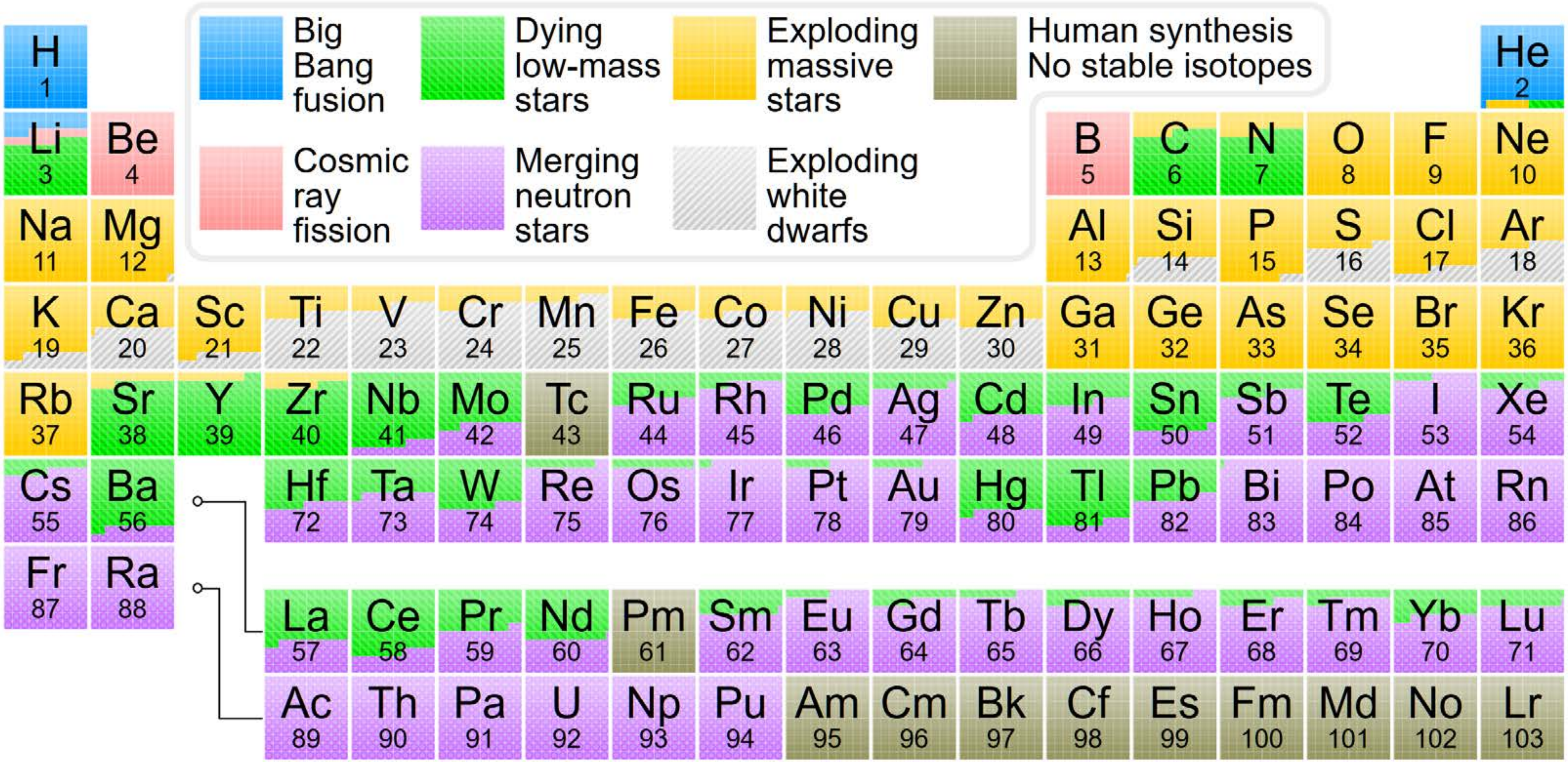
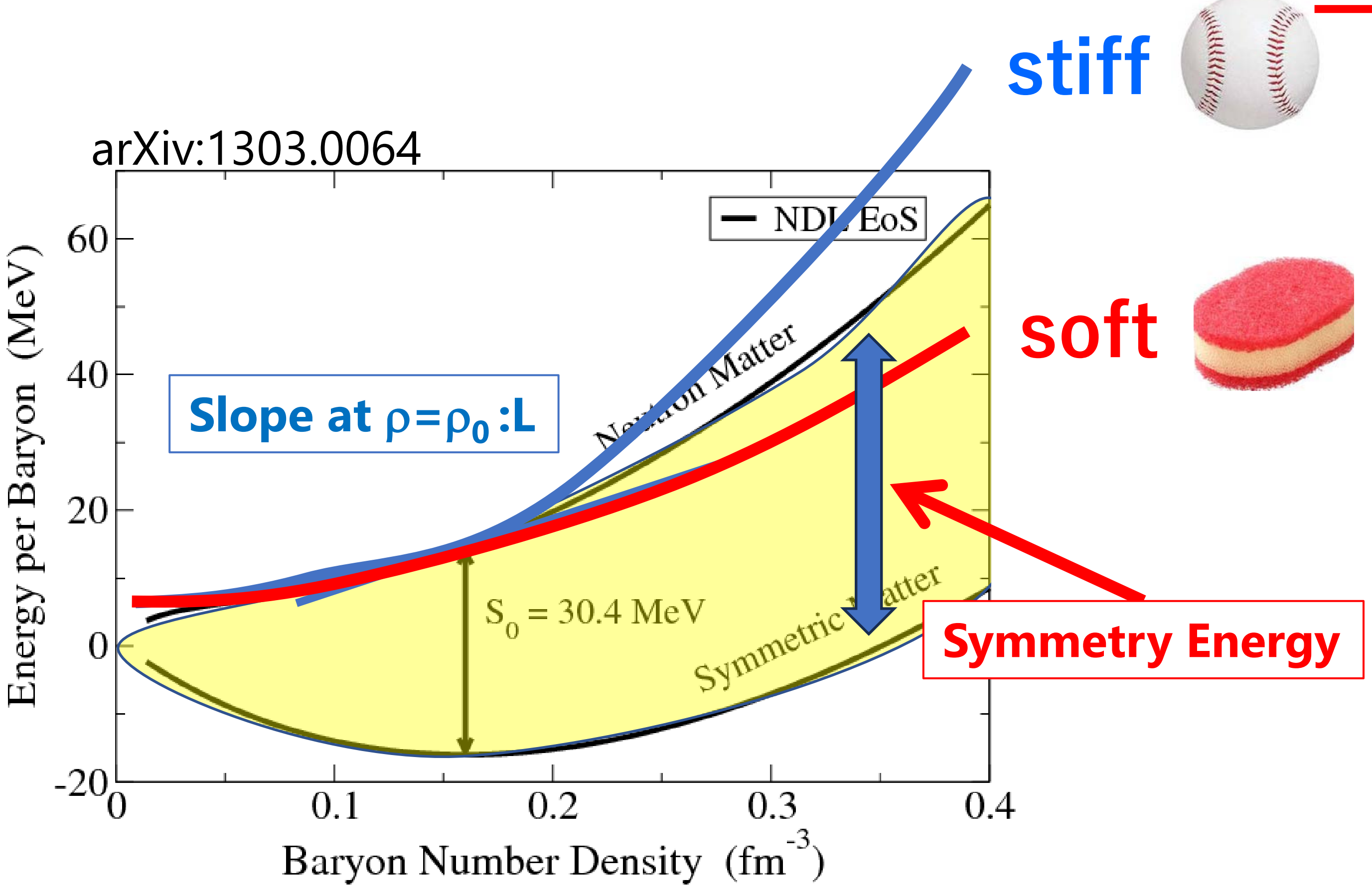


https://en.wikipedia.org/wiki/Nucleosynthesis

Asymmetric nuclear matter EOS: Symmetry Energy term of nuclear EOS

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

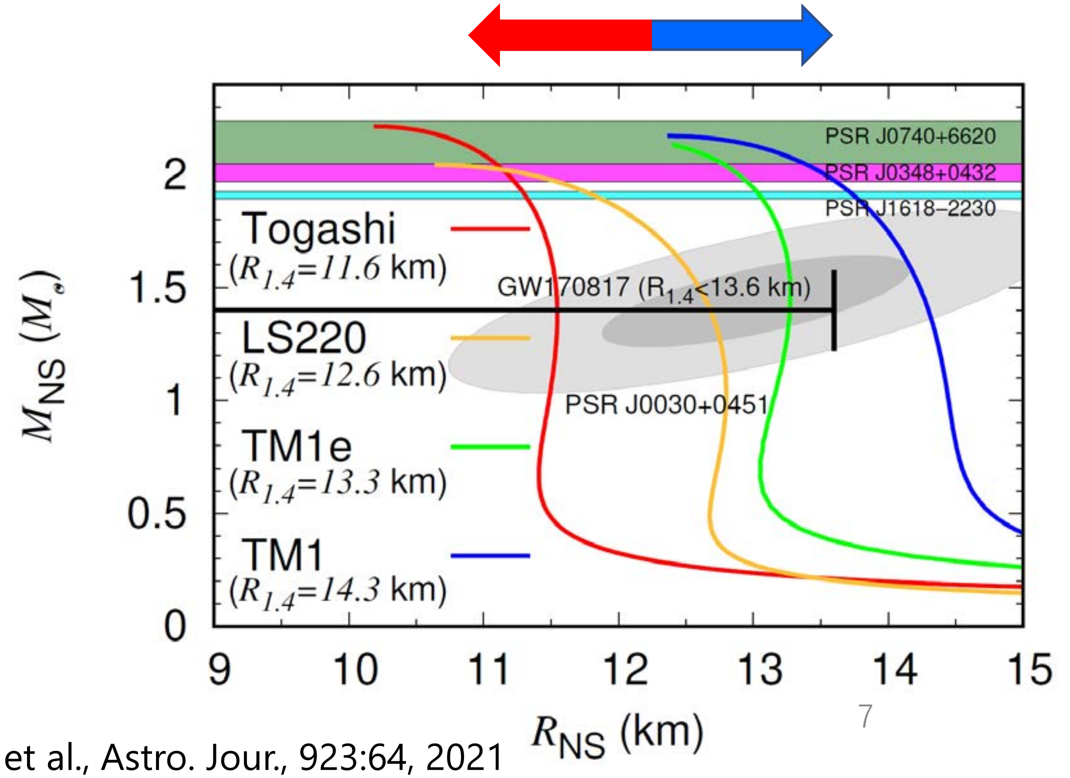
$$\delta = (\rho_n - \rho_p)/\rho$$



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

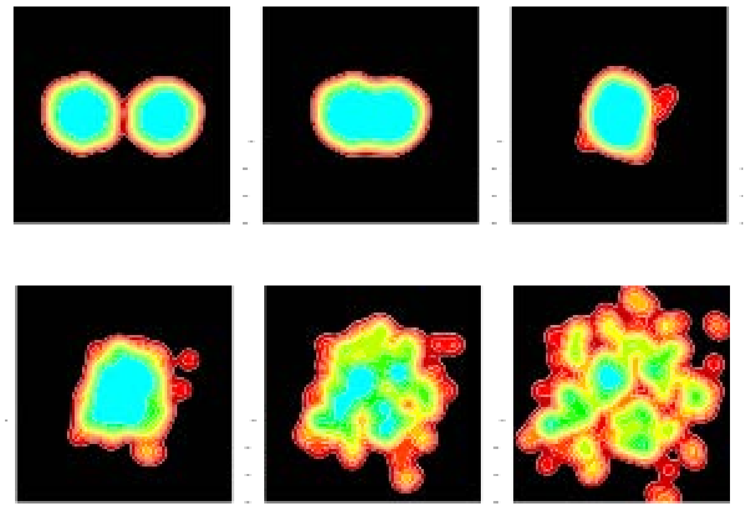
Stiff Harder to be compressed



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

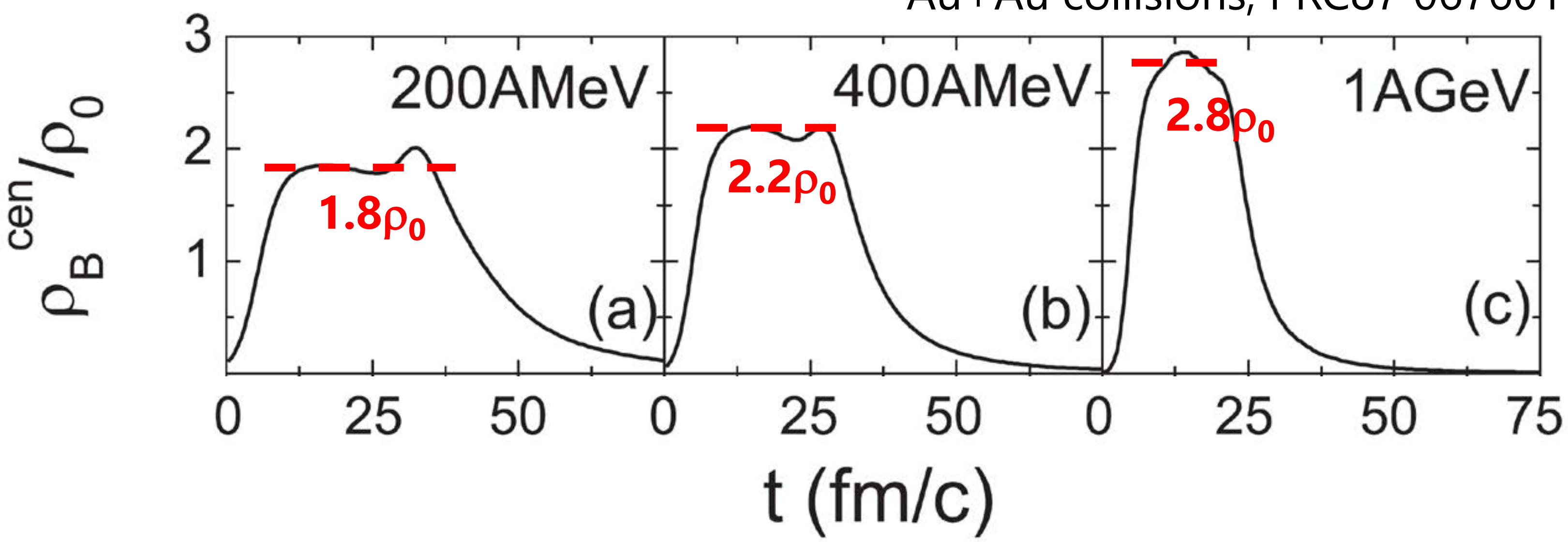
Terrestrial experimental study of high dense matter nuclear symmetry energy → Heavy Ion Collision (HIC)

Sn+Sn @300MeV/u



Central density as a function of time.

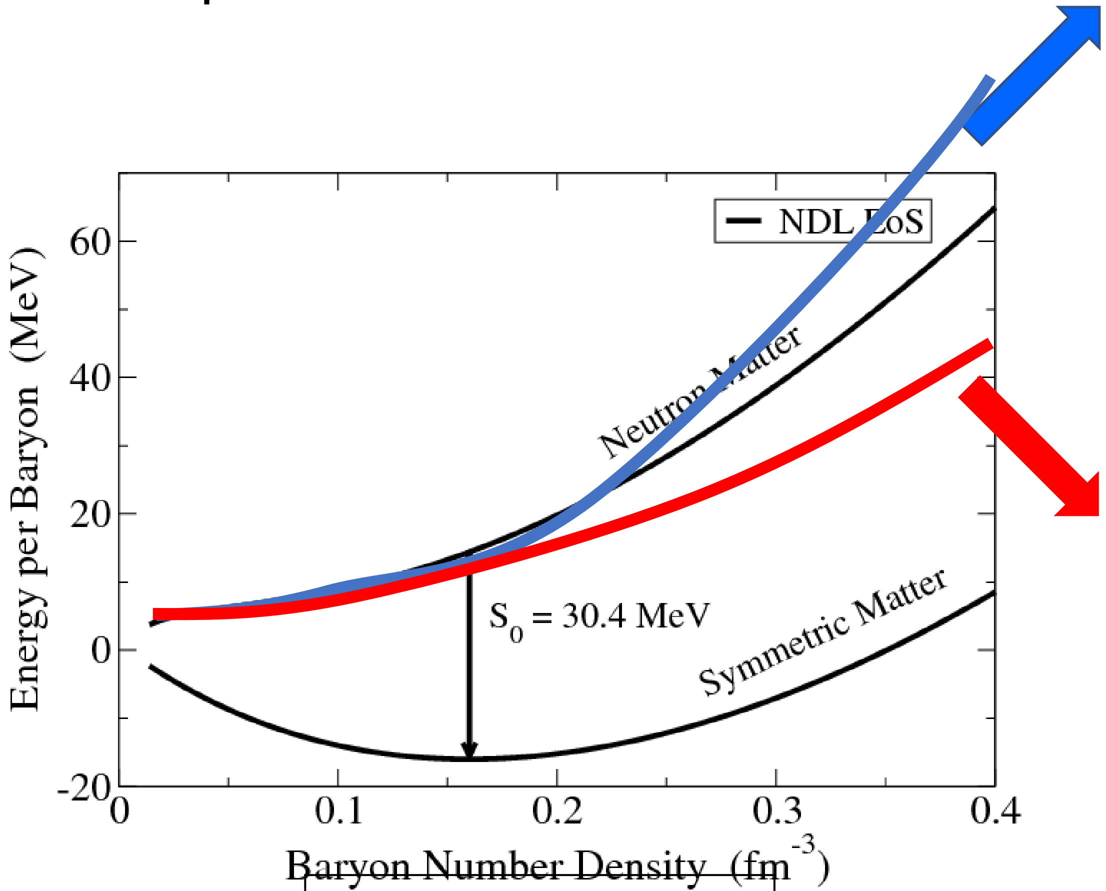
Au+Au collisions, PRC87 067601



- 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

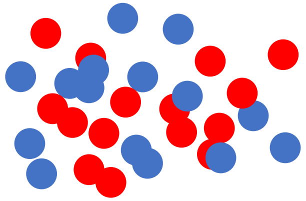


$\rho_0 = 2.5 \times 10^{14}$ g/cm^3

Stiff symmetry energy (large L)

→ lower ρ_n/ρ_p in higher dense region

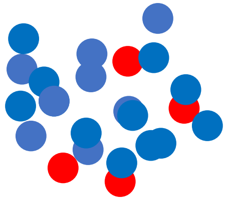
→ lower n/p in high ρ



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

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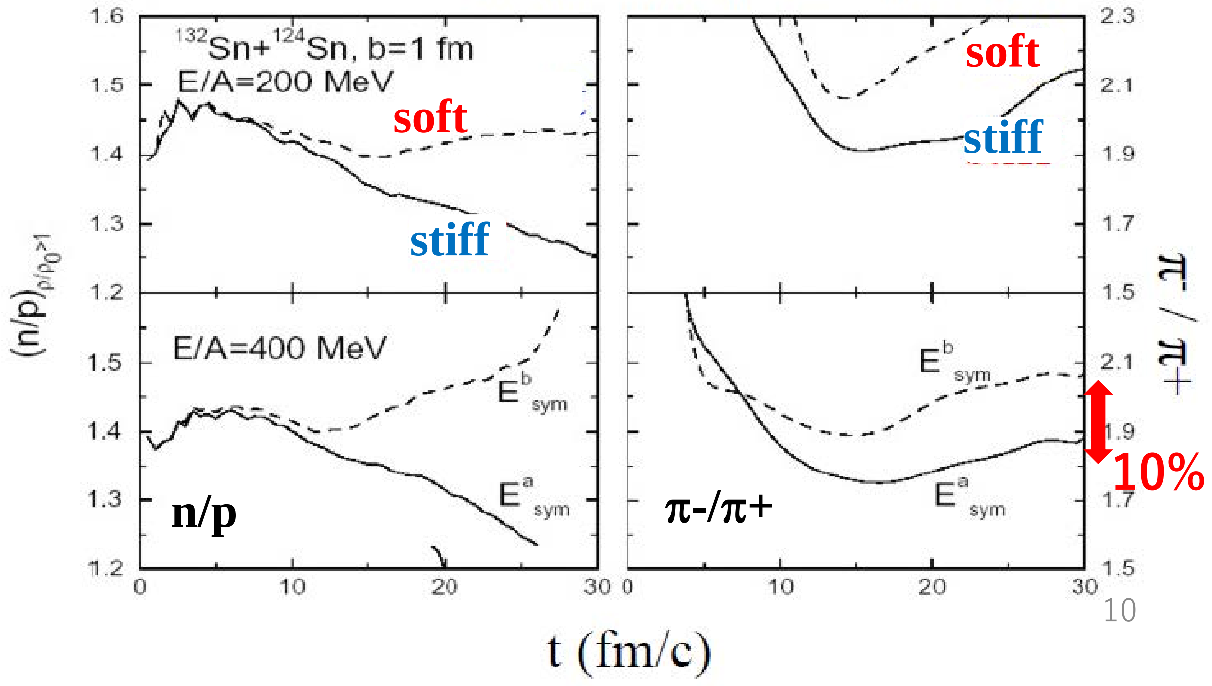
π^- production (main reaction)

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

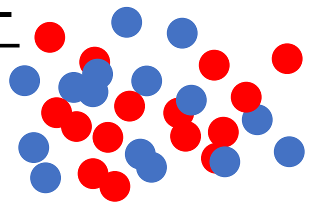
π^+ production (main)

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

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+



Soft symmetry energy (small L)
→ larger ρ_n/ρ_p in higher dense region
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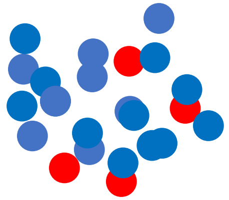
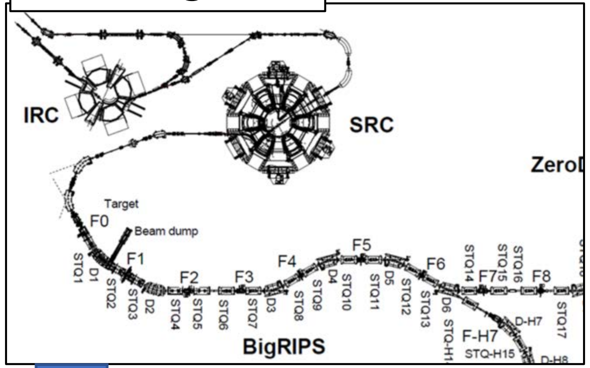
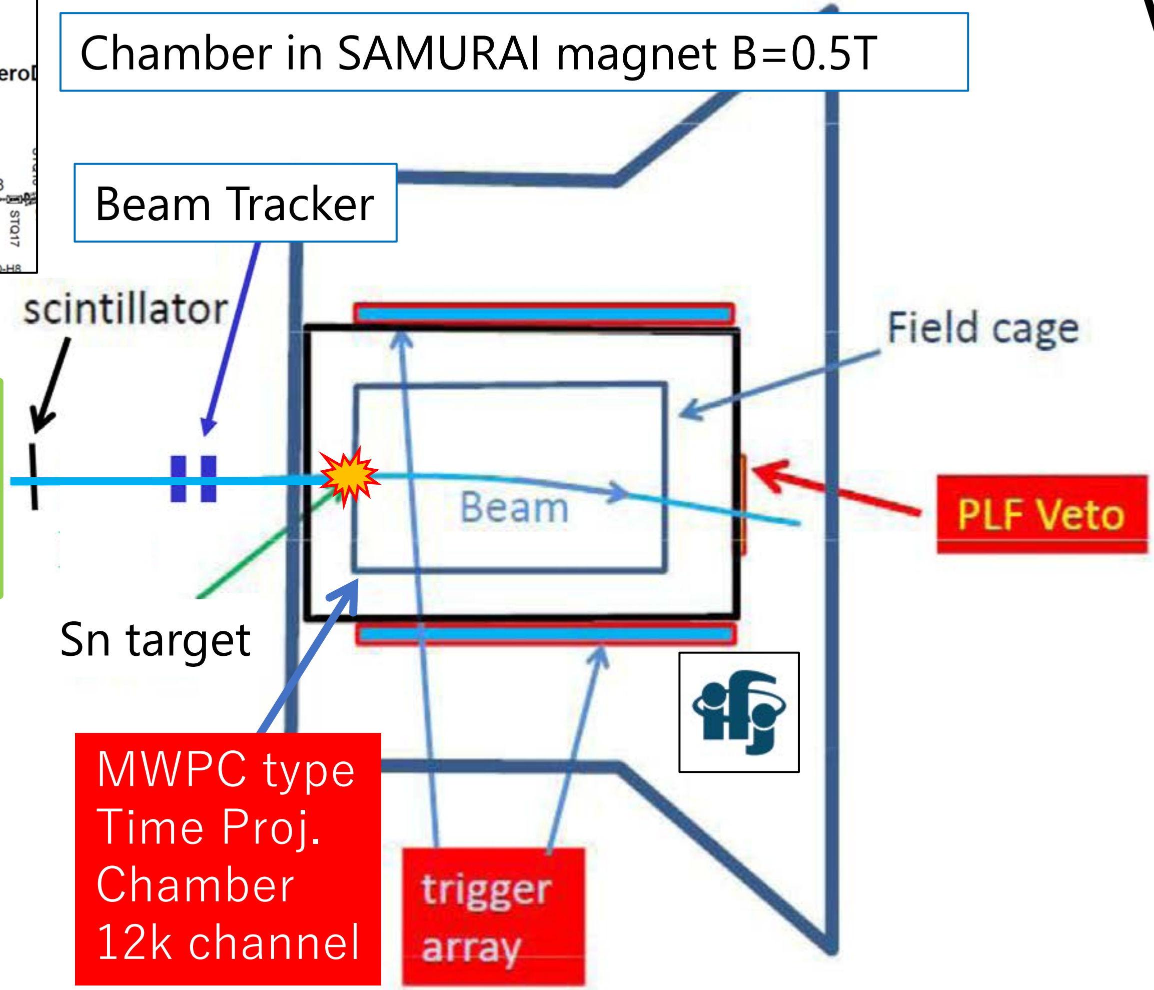


SPiRIT experiment: neutron rich Sn+Sn collision
beam line+TPC+trigger+neutron detector

RIBF-BigRIPS Making neutron rich beam



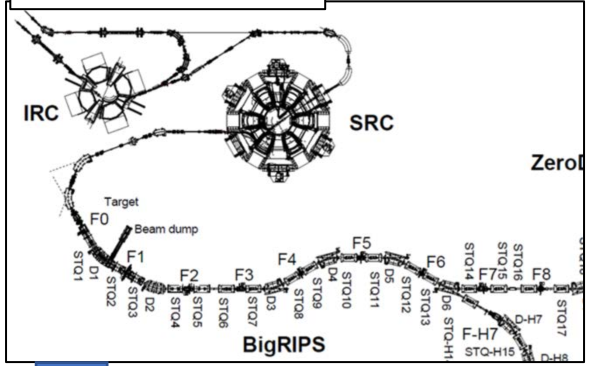


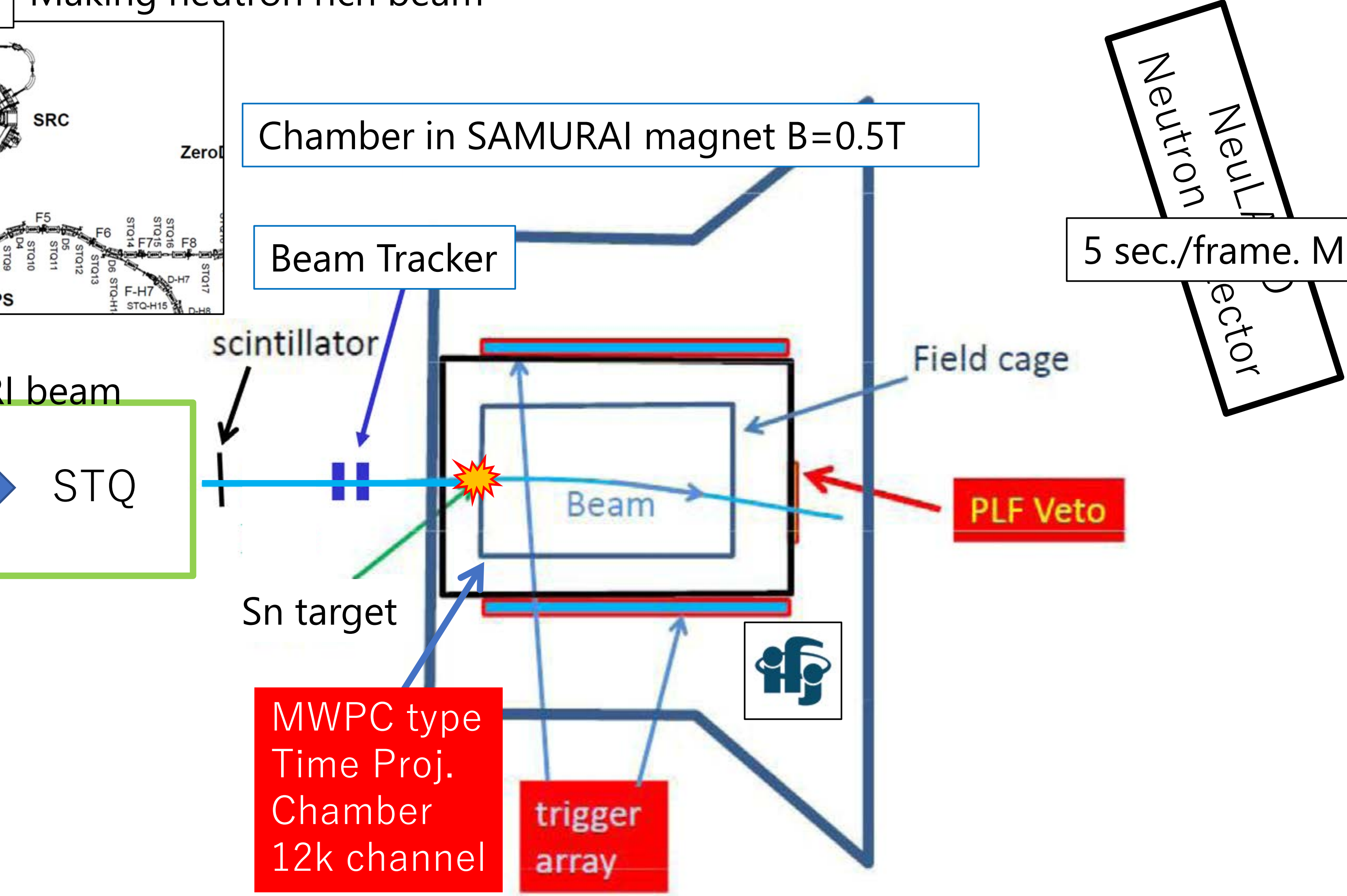
NeuLAND
Neutron detector

SPiRIT experiment: neutron rich Sn+Sn collision beam line+TPC+trigger+neutron detector

RIBF-BigRIPS

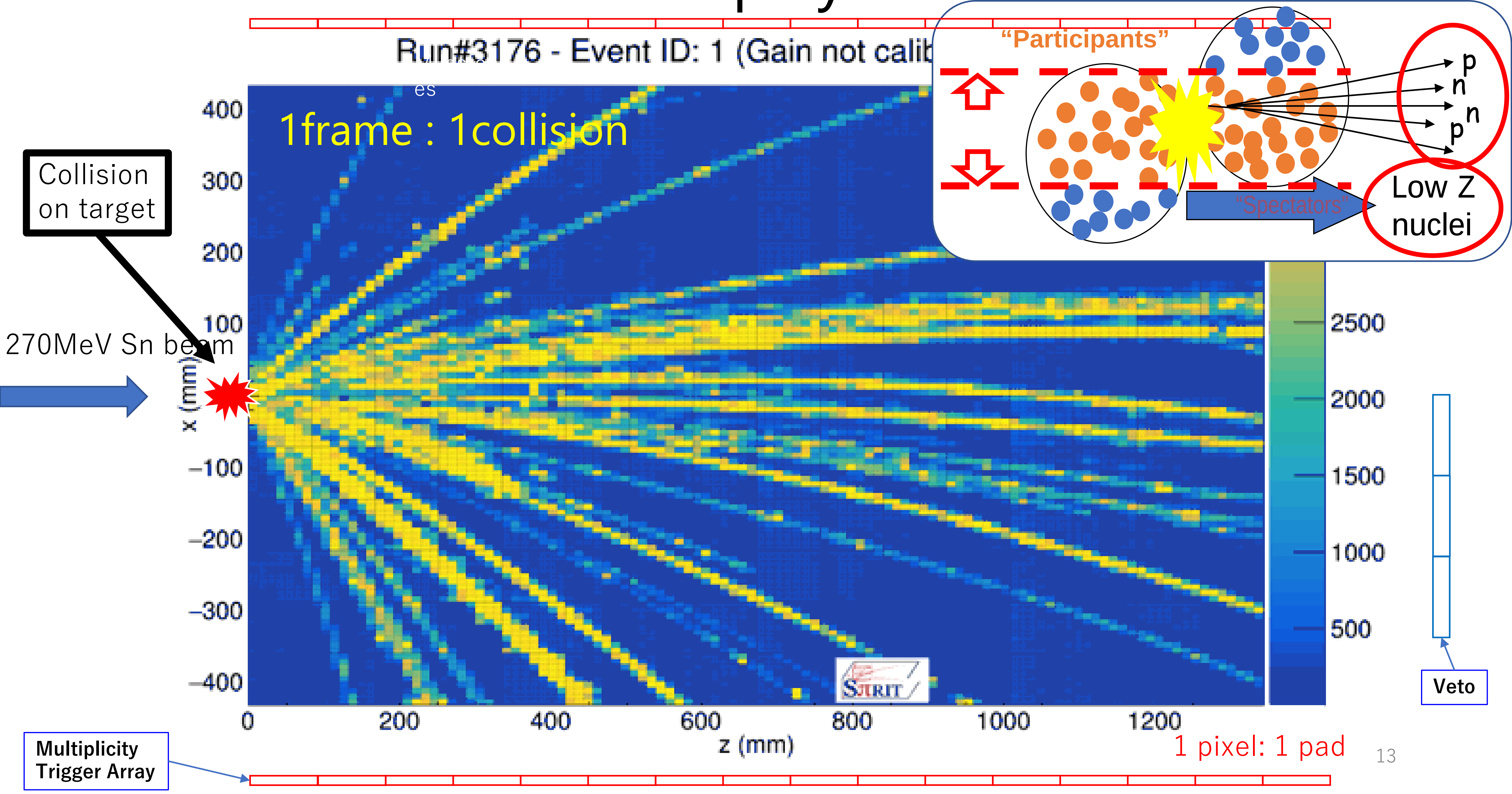
Making neutron rich beam





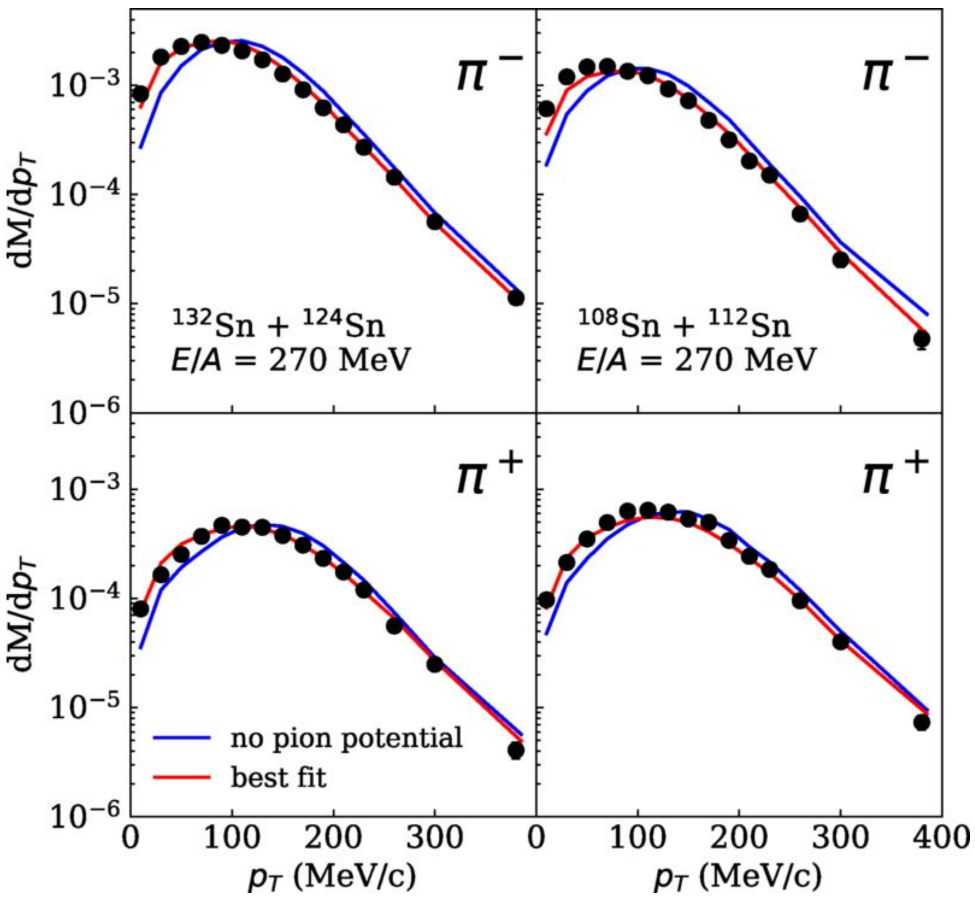
5 sec./frame. Movie for ~2.5 hour.

Sn+Sn Collision event display with TPC

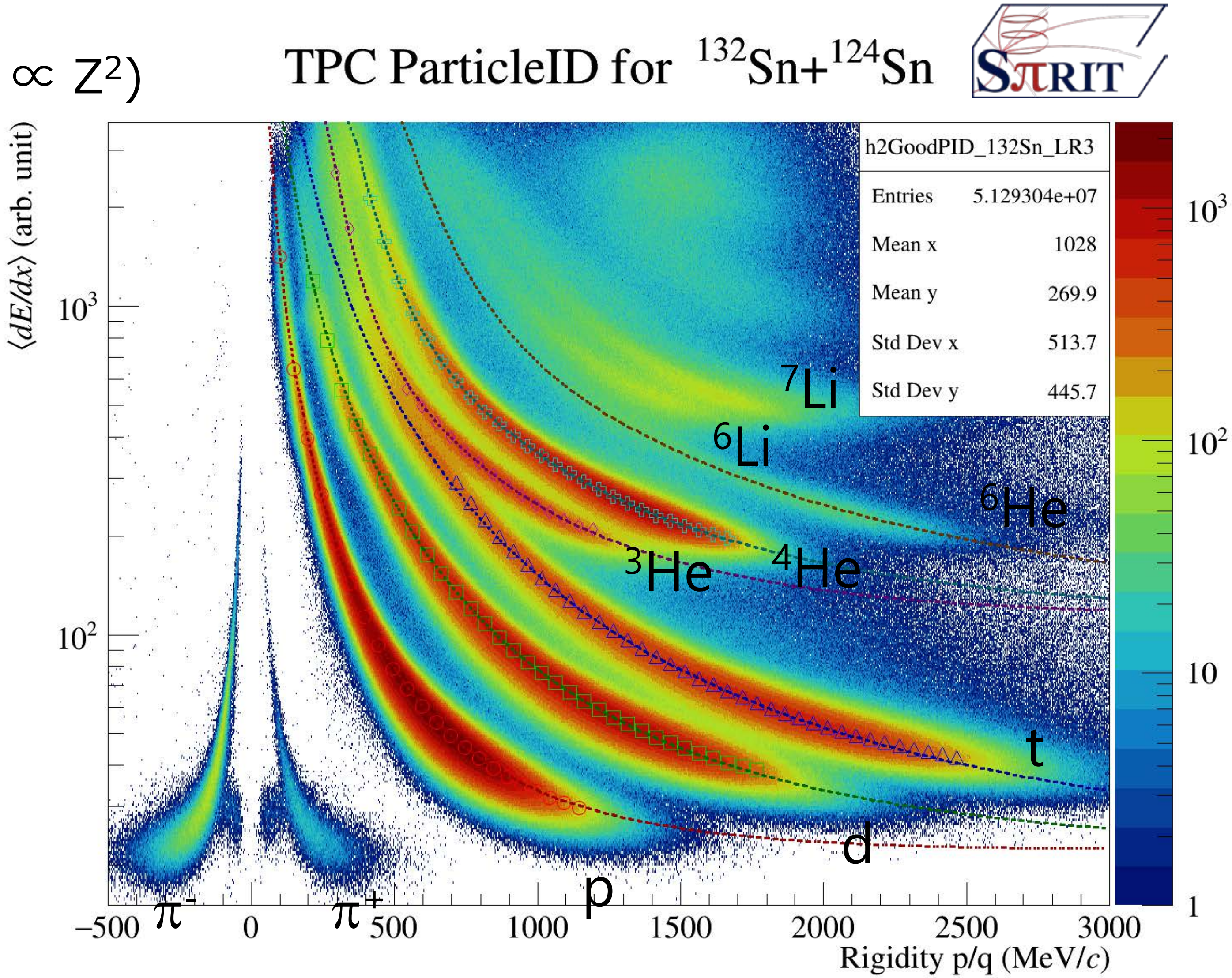


Charged particle measurement with Time Projection Chamber

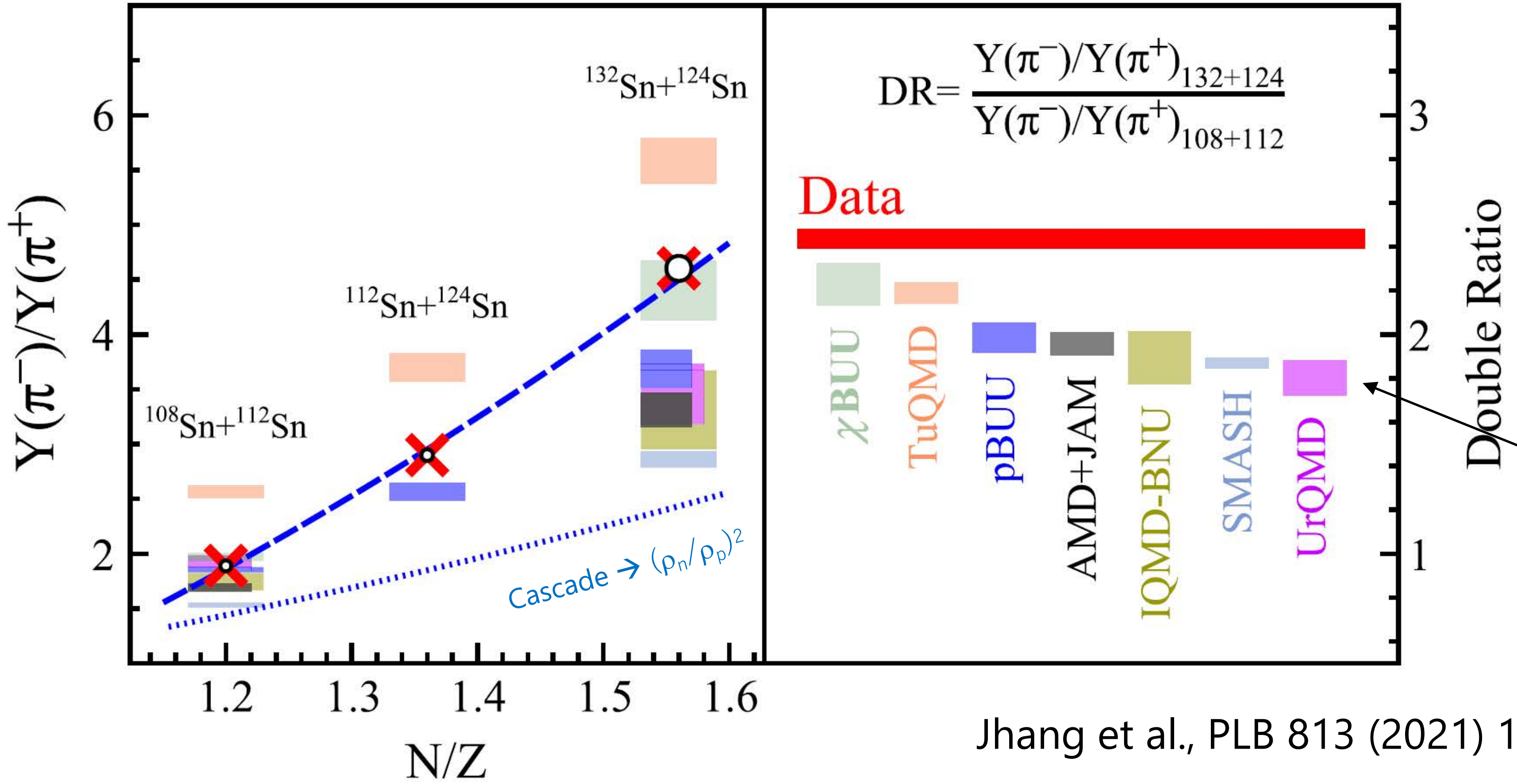
Measure all of particles produced in a HIC
Particle ID based on rigidity-dE/dx ($dE/dx \propto Z^2$)
Rigidity → particle momentum



Estee et al., PRL 126 (2021) 162701



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



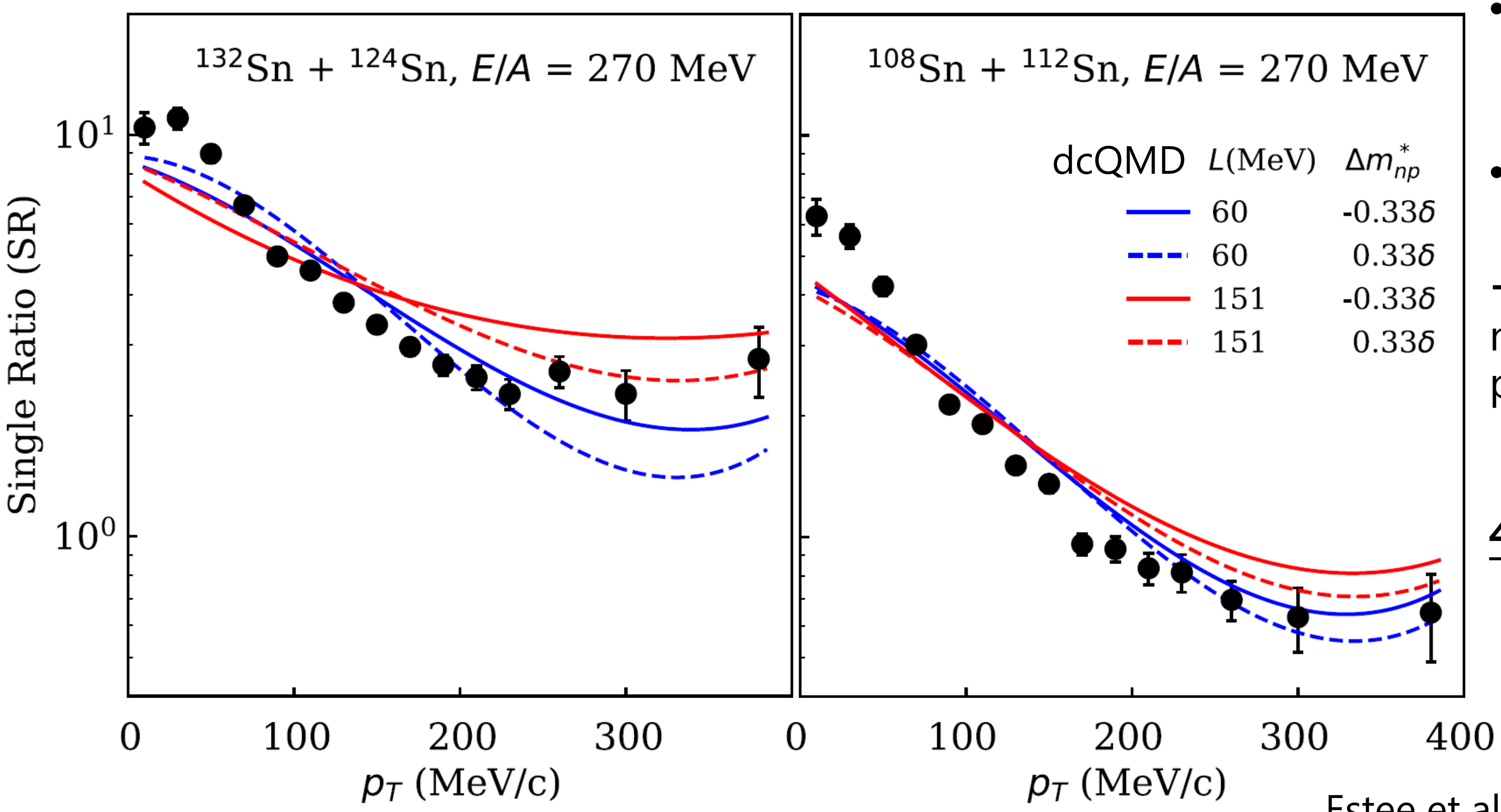
Size of error bar corresponds to the difference between Soft and stiff EoS.

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.

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.



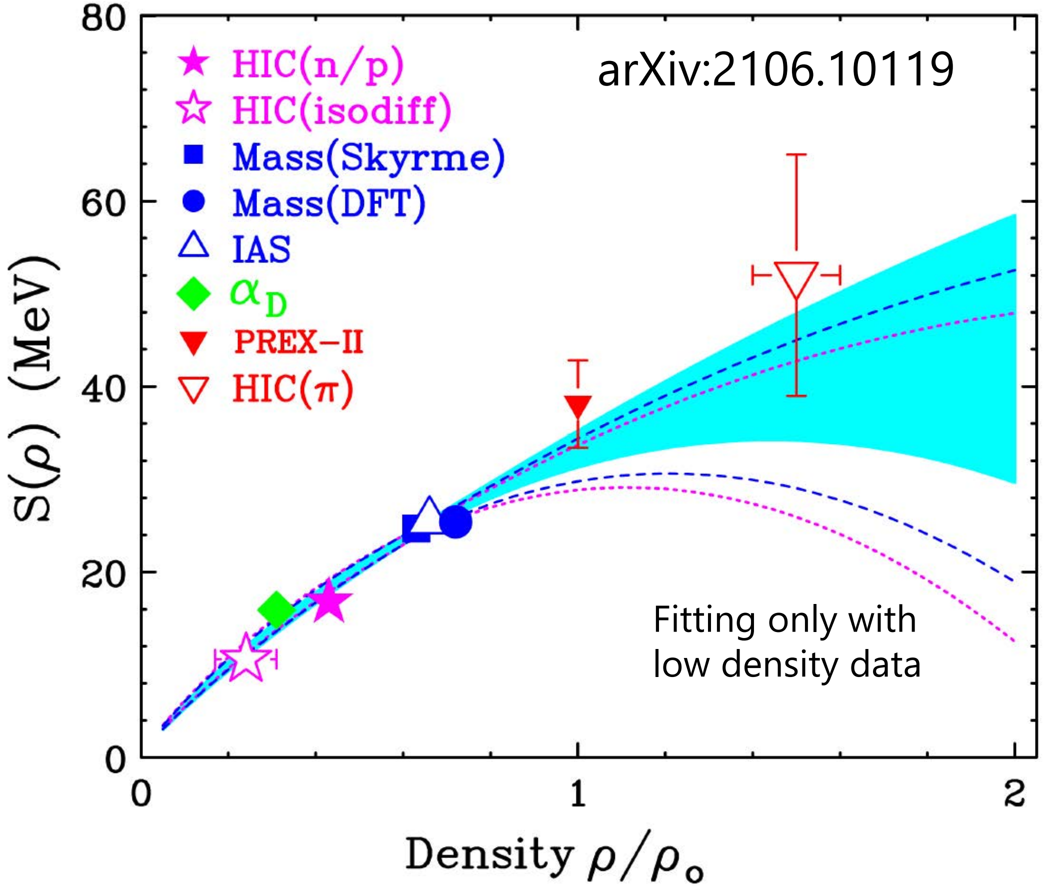
- Neutron rich system shows more sensitivity at high-pT.
- Calculation underestimate at low-pT.

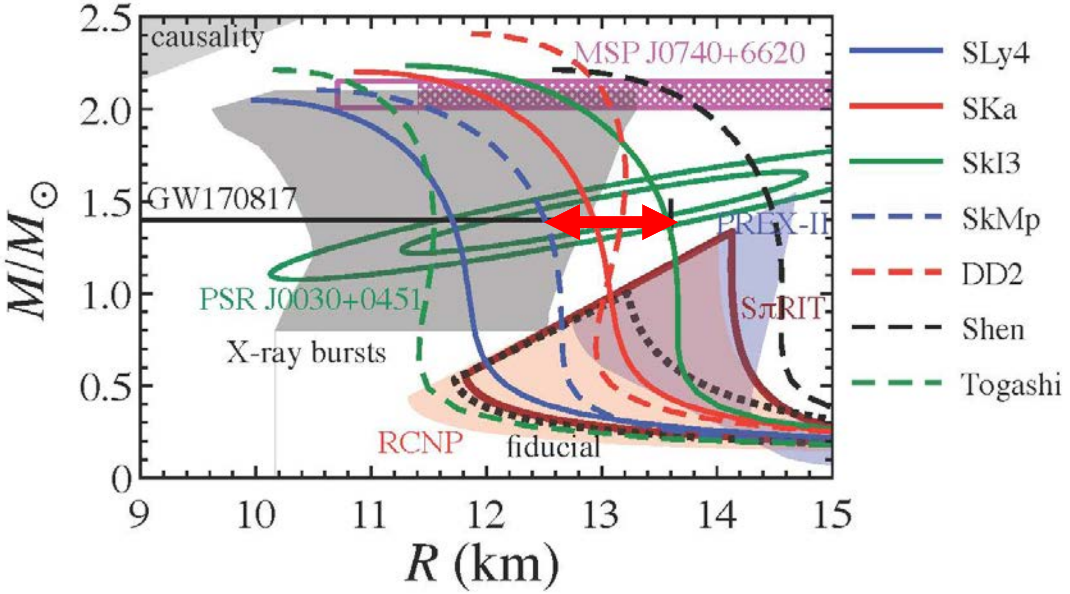
→Coulomb effect and/or non-resonant pion production.

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

Estee et al., PRL 126 (2021) 162701

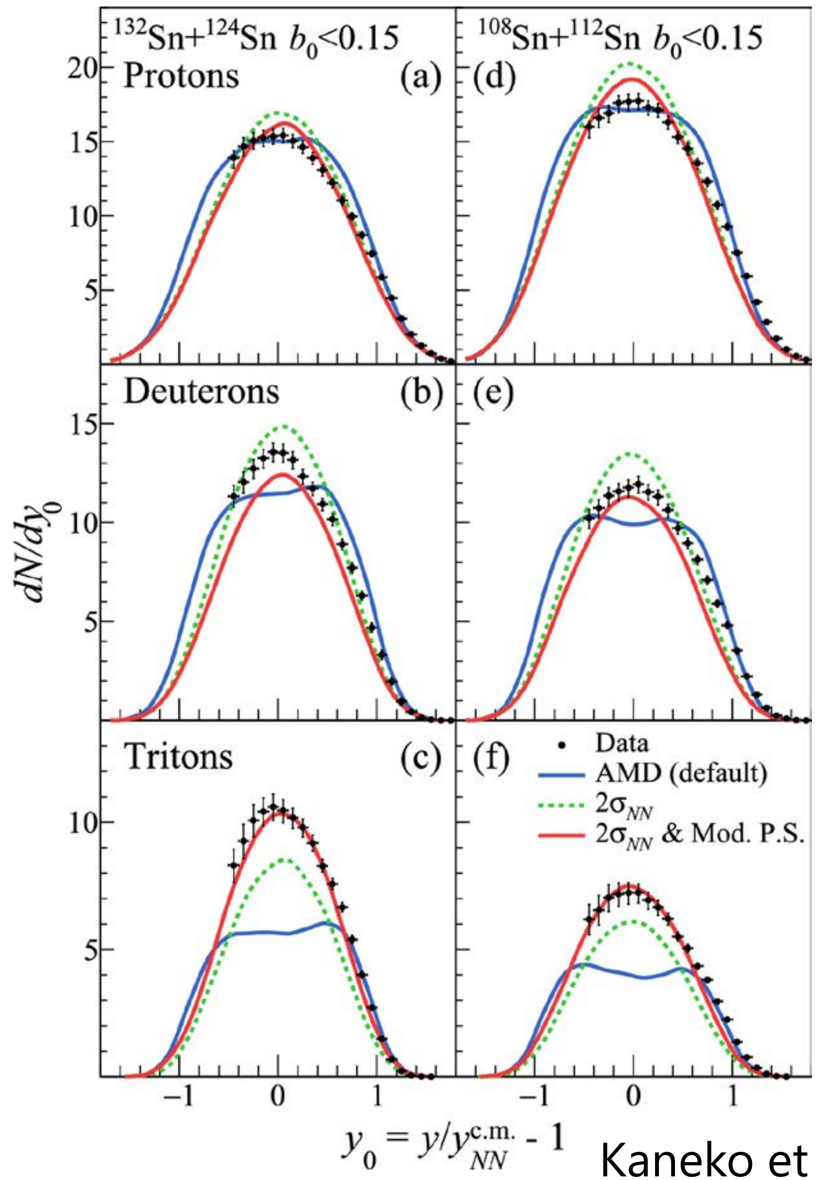
Compilation of experimentally determined symmetry energy



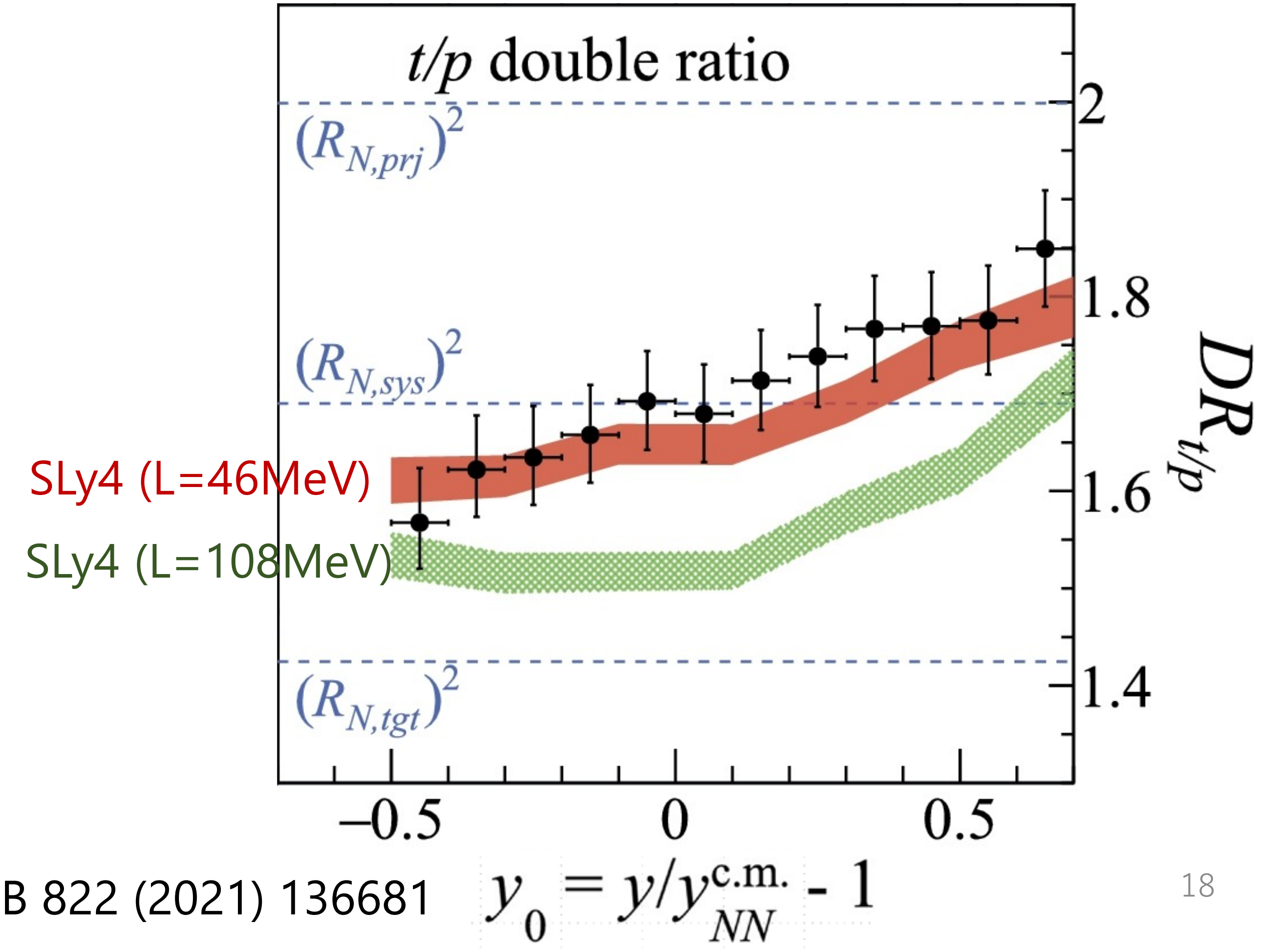


- Fitting with phenomenological formula: S_0=(33.3 ± 1.3) MeV, L= (59.6 ± 22.1) MeV
  - suggests a radius for a 1.4 solar mass neutron star of 13.1 ± 0.6 km

Extra observable: p/d/t dN/dy



- Fundamental spectra to check the transport model.
- EoS dependence appears in triton production.
  - Triton easily produced in neutron rich matter.
- **Data favor L =46MeV** rather than L =108MeV.



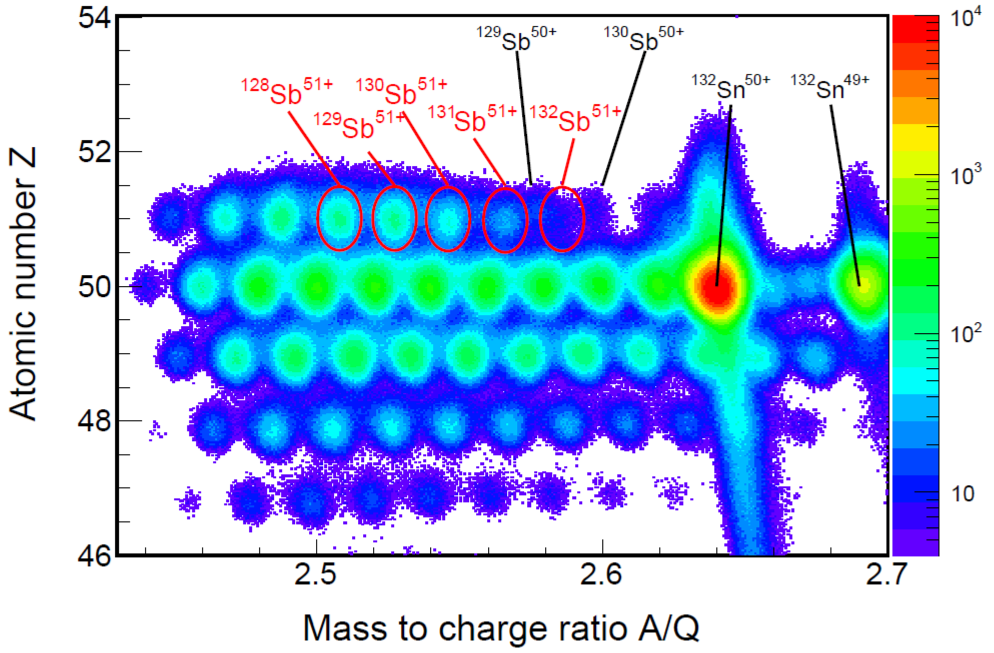
Kaneko et al., PLB 822 (2021) 136681

Difference from Relativistic HIC

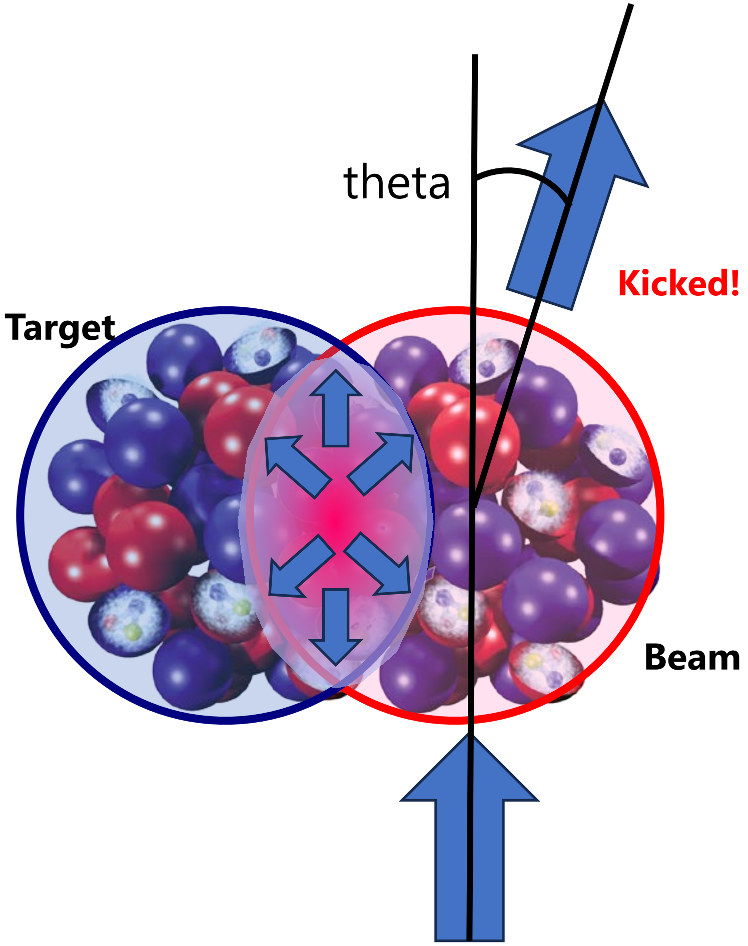
- Many body system composed of nucleons.
- Cluster state such as deuterium and alpha exists.
- x100 Longer collision time of ~O(10fm).
- Less charged particles.
    - Track finding is simpler.
    - Worse reaction plane resolution.

- Possible to measure neutron production and its flow.
- Possible to identify spectator and to measure its kinematics.

Sn132 + p reaction

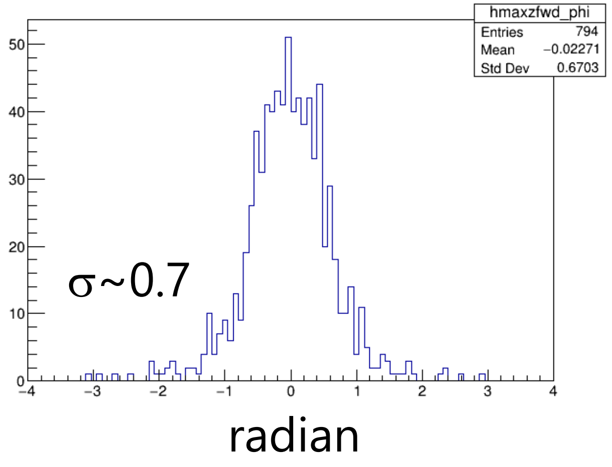


Measurement of spectator for event characterization

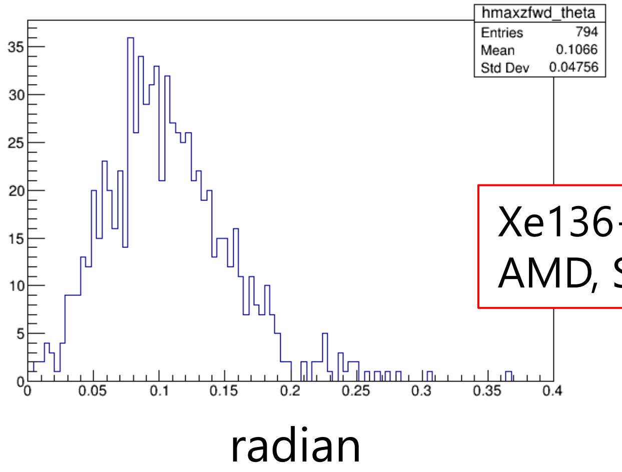


- Spectator would be useful for event characterization.
- According to AMD calculation:
  - It looks difficult to measure impact parameter through the measurement of spectator fragment.
  - Spectator information may deduce the reaction plane angle more preciously.
    - $\sigma(\Delta\varphi)$ w/ participants: 1rad
    - $\sigma(\Delta\varphi)$ w/ **spectator: 0.7 rad**

Δphi: phi(RP) – phi(spectator) of largest Z particle



theta of largest Z particle



Xe136+Sn124
AMD, SLy4, b=8fm

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.
- Delta baryon potential in dense matter is necessary to study pion production in HIC. → next step
- Proton/neutron measurement → next step for momentum dependence of U in matter.

- I am curious the universality of physics among the different hierarchy: nuclear matter and quark matter.
- Exiotic hadron ←→ Exiotic nuclei
- Halo state, Borromean, Strong E/B field …