The HIC studies at RIKEN with the Spirit TPC and the quest for the symmetry energy

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on behalf of SpiRIT-TPC collaboration

Zimanyi Winter School 2025 : 1 Dec. to 6 Dec.

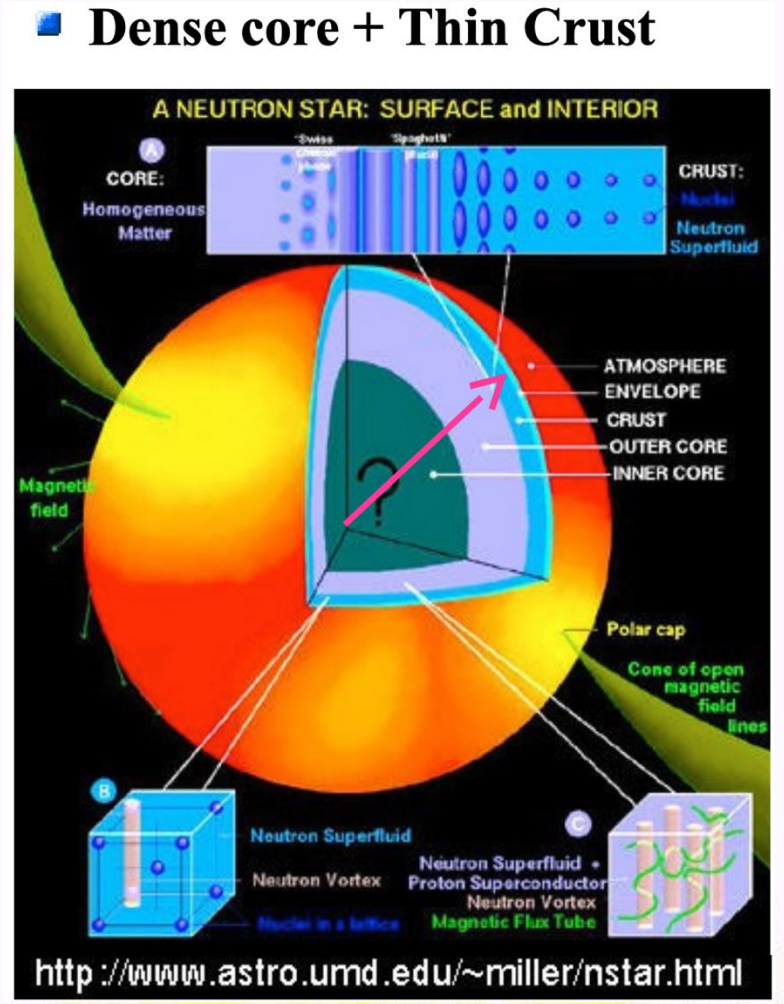
Contents

- Mysterious object Neutron star
- Constrain symmetry energy EOS at supra-saturation density using Heavy ion collision
- SpiRIT-TPC experiment at RIKEN-RIBF
- Multiple observables:
  - p/p ratio, flow, light charged particles production
- Constrain on EOS
- Day-two experiment above pion threshold
- Advertisement: 3D visualization –Deblurring analysis
- Summary

Internal structure of a Neutron star ?

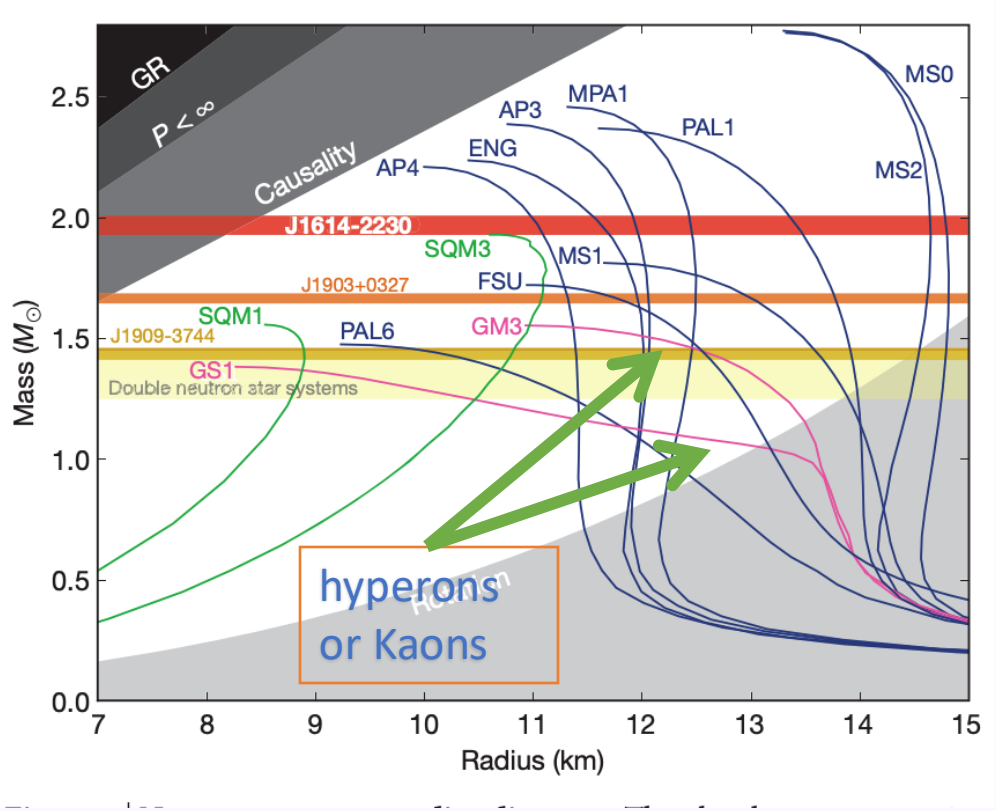
- It is about **10 km** in diameter and has a mass 1.4 times the solar mass.
- A neutron star can be viewed as one gigantic, densely packed nucleus.
- Two fundamental questions arise:
  - What is its internal structure?
  - Why doesn't it collapse under its own gravity?

- Knowing the internal Equation of State (EOS) is a common theme not only in nuclear physics research but also in astrophysics.



Various EOS prediction

Demorest et al., Nature 467 (2010) 1081

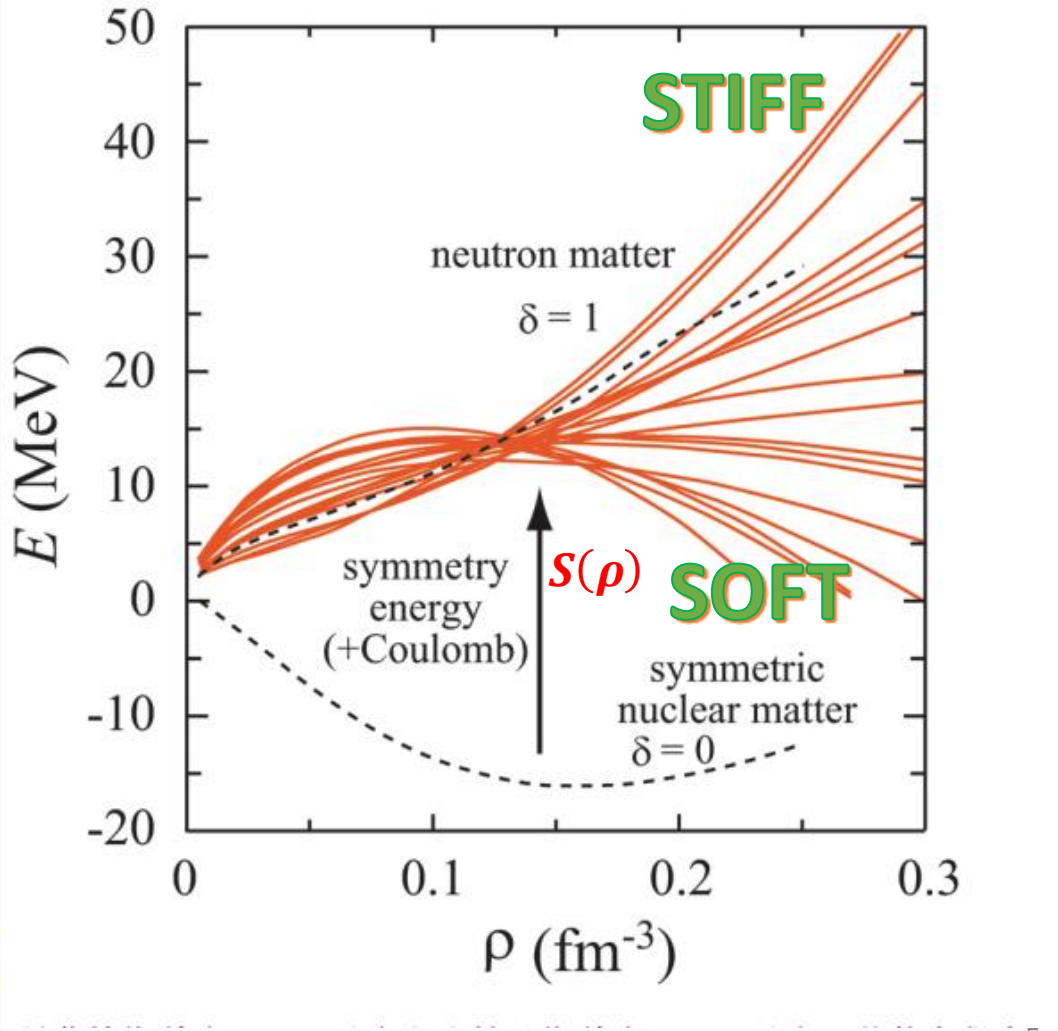


- **A neutron stars** (PSR J1614-2230) with twice the mass of the Sun was discovered **in 2010.**
- **Its existence ruled out internal structures containing hyperons or K-mesons (kaons) under conventional soft EOS assumptions.**
- Conventional theories must be modified to yield a significantly stiffer EOS.

EOS of Nuclear Symmetry Energy

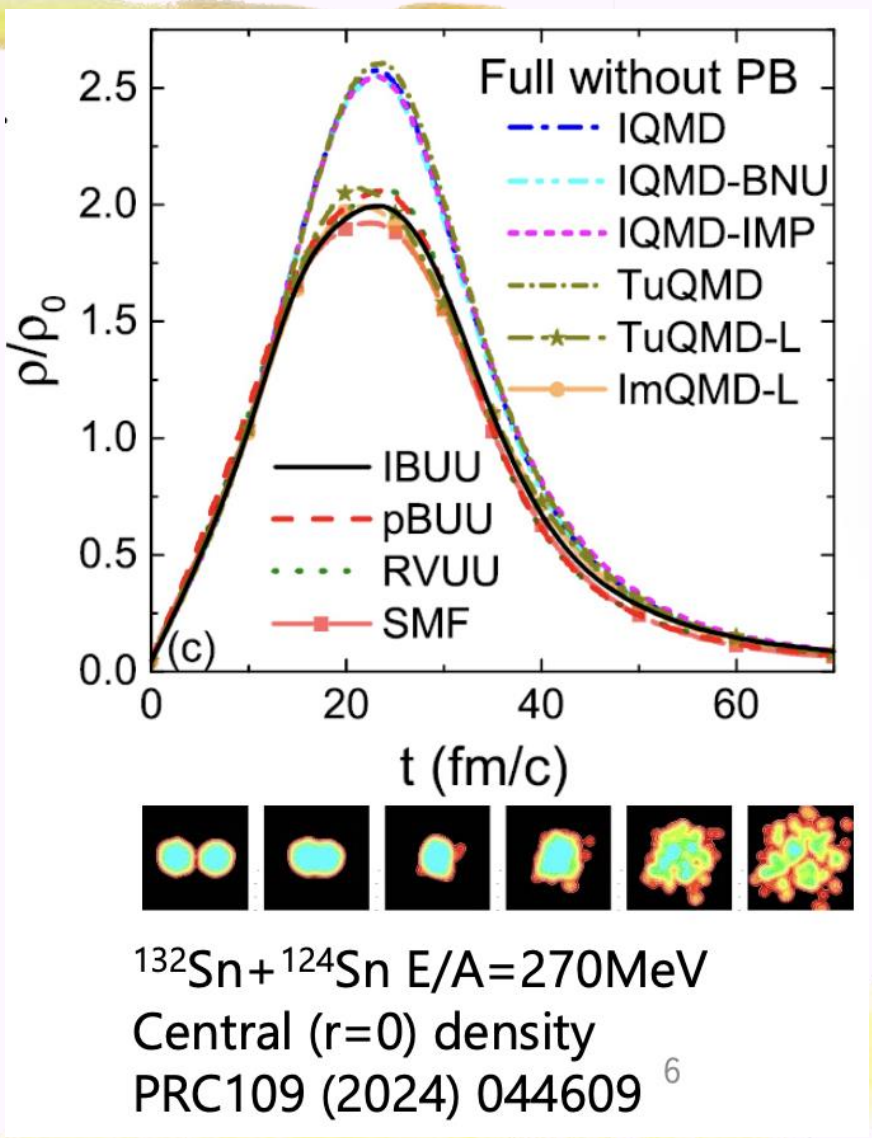
- Focus: Symmetry energy arising from neutron-proton density imbalance.
- In the equation of state:
  - $E(\rho,\delta) \approx E(\rho,0) + \boldsymbol{S(\rho)}\delta^2 + O(\delta^4)$, where $\delta = \frac{\rho_n - \rho_p}{\rho}$ (isospin asymmetry)
- Symmetry Energy:
  - $S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho}\right)^2$
- Constraining L and K_{sym} experimentally.

JPS vol69 No1(2014)



Heavy ion collision (HIC)

- Heavy ion collision is a unique tool to study high-density nuclear matter.
- About 2 times saturation density.



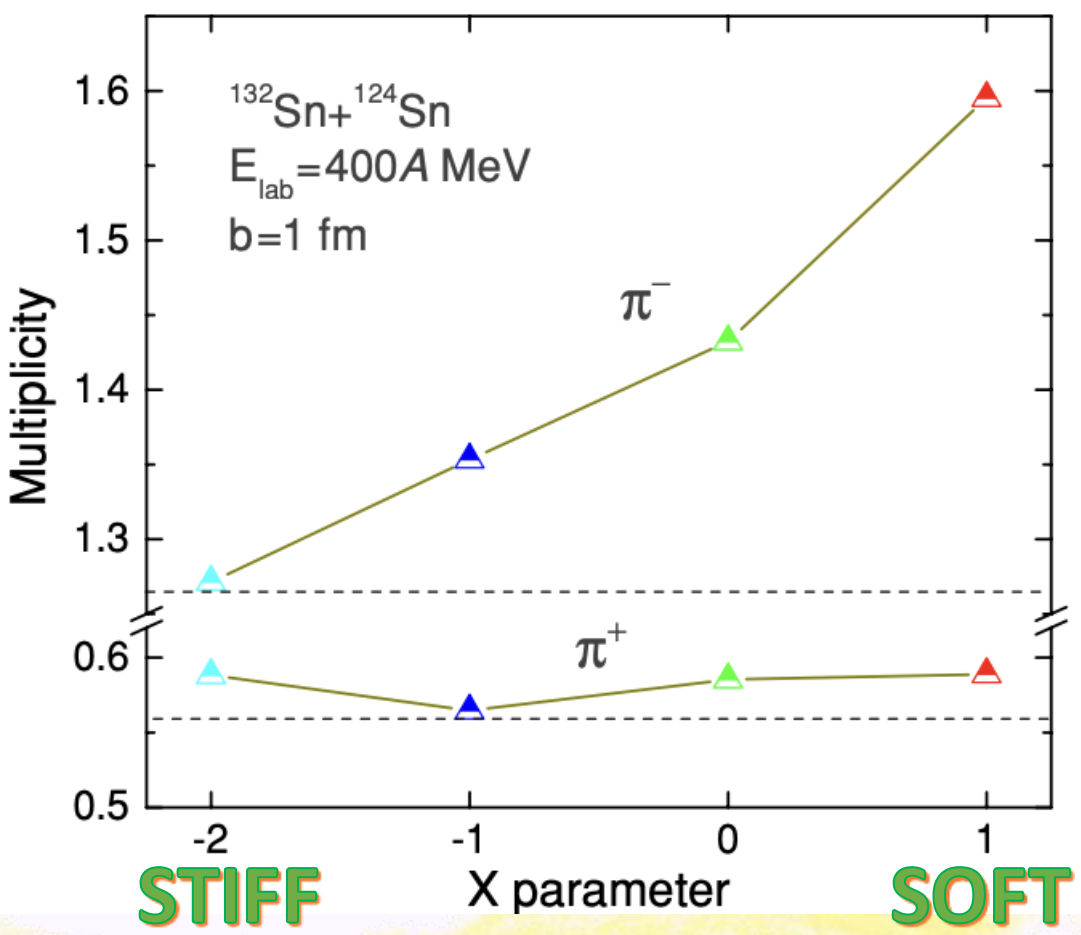
^{132}Sn+^{124}Sn E/A=270MeV
Central (r=0) density
PRC109 (2024) 044609

How do we measure it?

① Ratio of π^-/π^+

*B.-A. Li, et.al., Phys. Rev. C Nucl. Phys. **71**, 014608 (2005).*

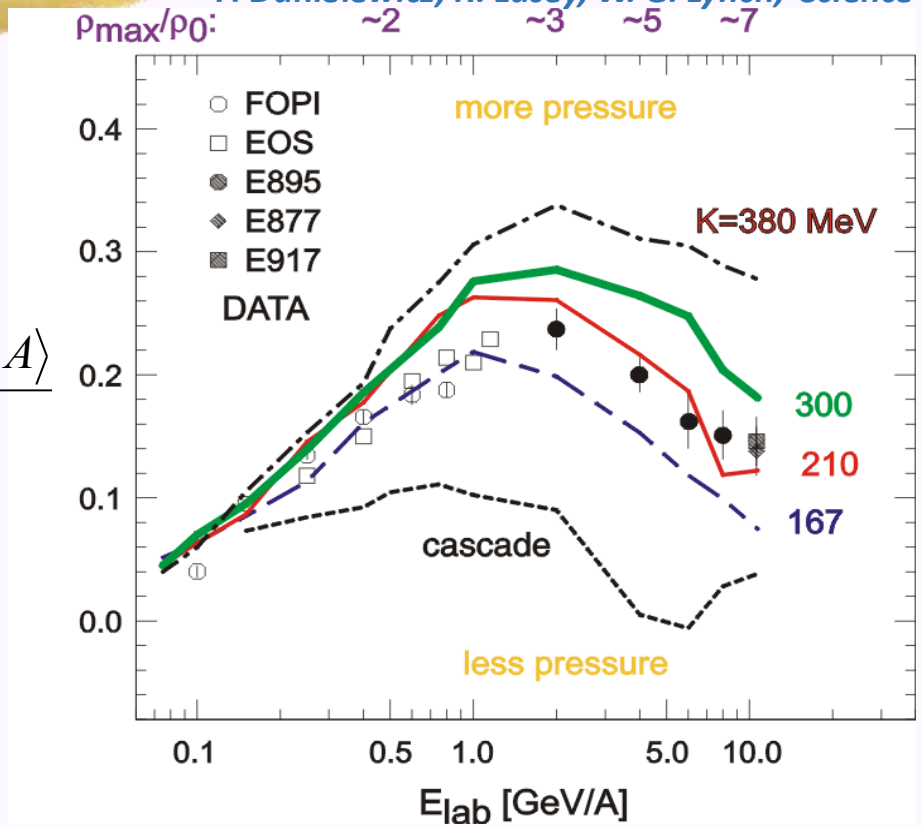
- Pions are produced through Δ resonances.
  - $n + n \rightarrow p + \Delta^- \rightarrow p + n + \pi^-$
  - $p + p \rightarrow n + \Delta^{++} \rightarrow n + p + \pi^+$
  - $(\pi^-/\pi^+)_{like} \equiv \frac{\pi^- + \Delta^- + \frac{1}{3}\Delta^0}{\pi^+ + \Delta^{++} + \frac{1}{3}\Delta^+}$
- Neutrons repulsive and protons attractive in asymmetric system.
- A soft EOS for the nuclear symmetry energy leads to an increase in the π^-/π^+ ratio.



② Directed and Elliptic Flow

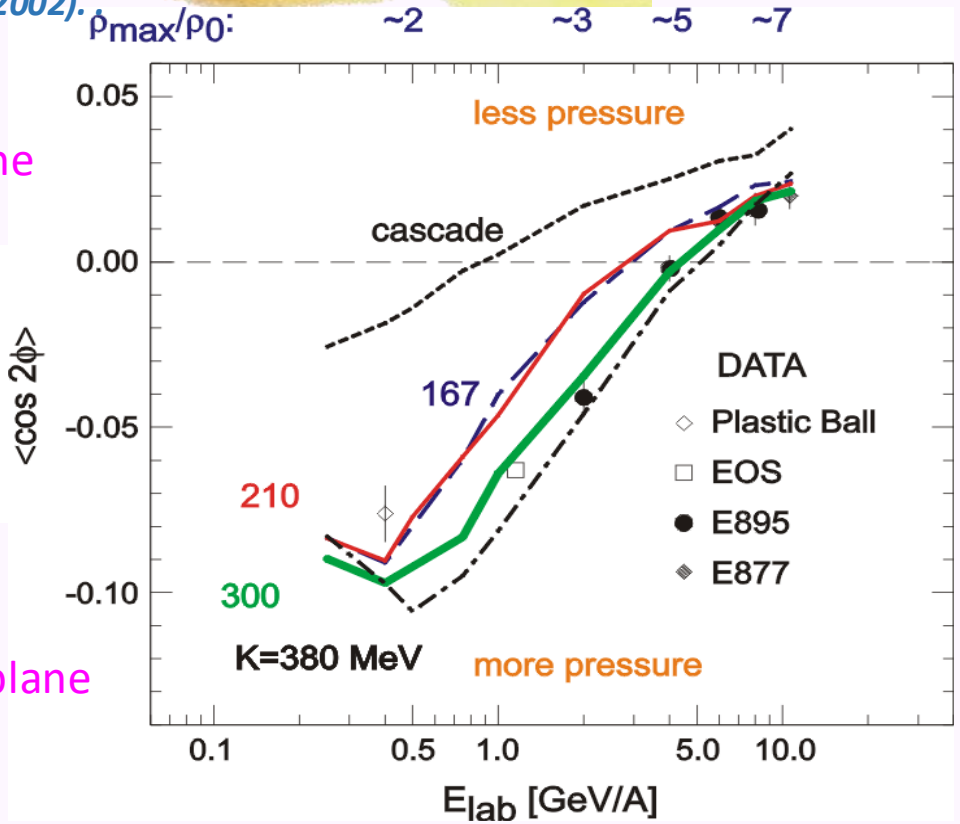
P. Danielewicz, R. Lacey, W. G. Lynch, Science 298, 1592–1596 (2002).

$$\frac{\partial\langle p_x / A\rangle}{\partial y}$$



in plane

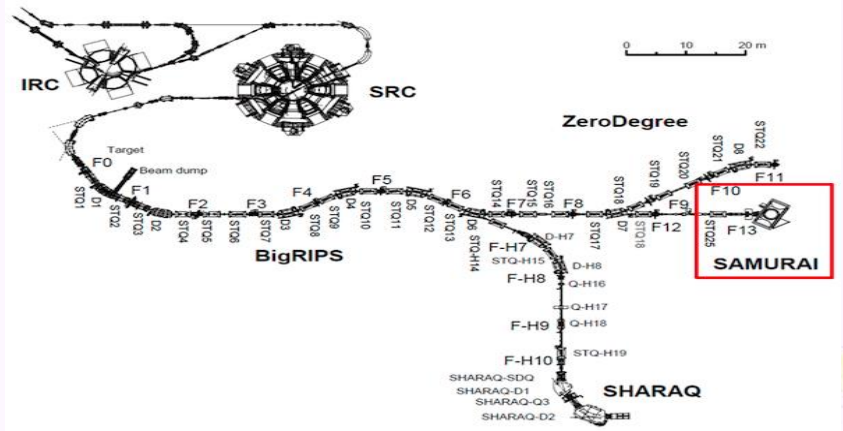
out of plane

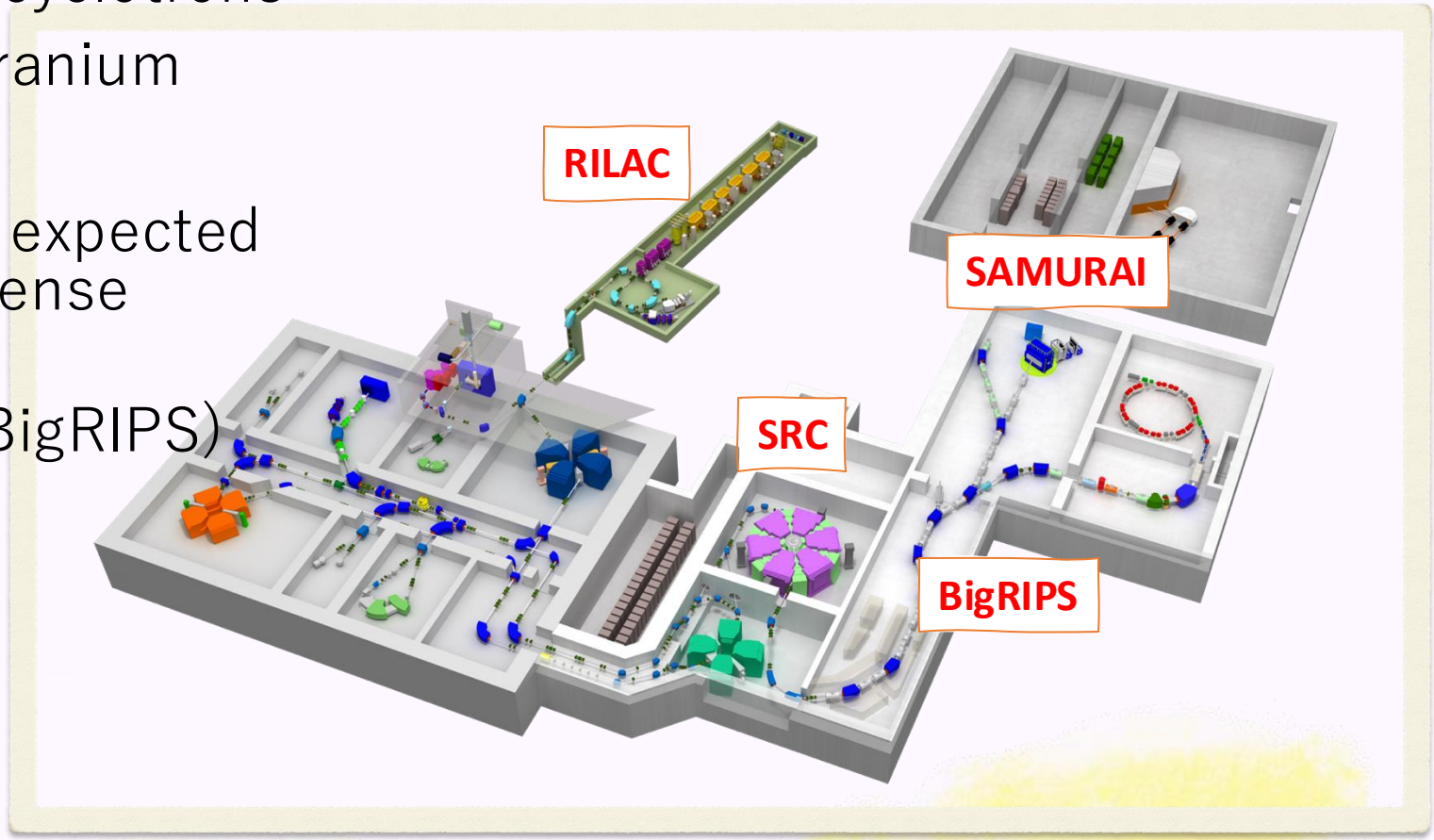


- The strength of flow dependence on the incident energy.
- The cascade model completely failed to produce experimental results.
- A model that includes a mean-field potential with specific compressibility is required.
- Contribute to constrain EOS.

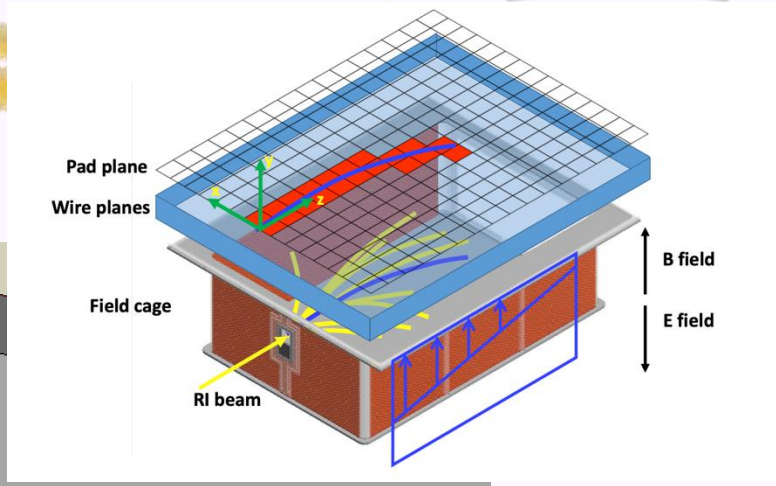
RIKEN RIBF (RI Beam Factory)

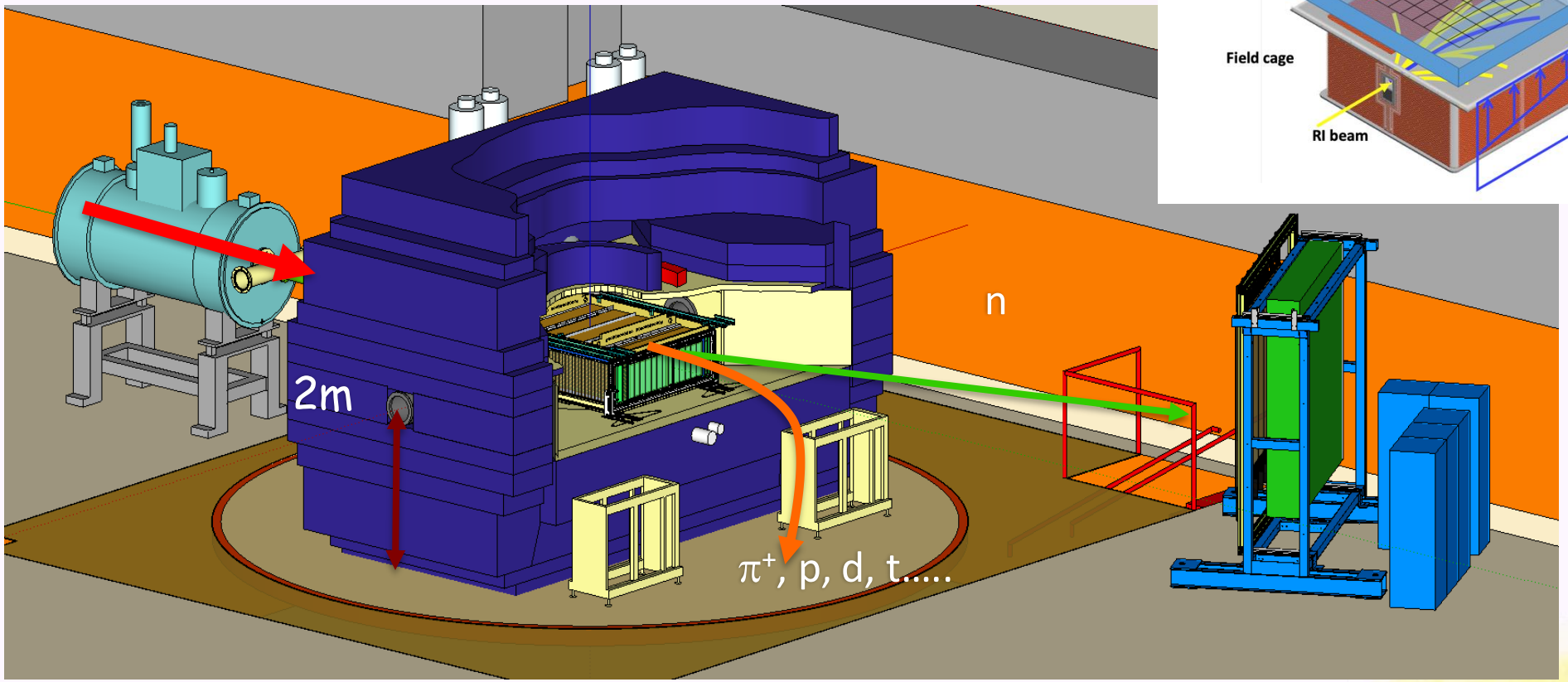
- Accelerator consisting of four cyclotrons
- Accelerating from proton to Uranium
- Maximum energy 340MeV/u
- High-density baryon matter is expected because spectators help condense matter.
- In-flight fragment separator (BigRIPS)





SpiRIT-TPC Experiment





- TPC is housed in the SAMURAI mag with 0.5T.

SpiRIT Experiment at RIKEN-RIBF

- An experiment was conducted by comparing systems with different asymmetries (neutron/proton ratios).
- The first EOS experiment of heavy-ion collisions (HIC) using unstable nuclear beams.

Primary	Beam	Target	E_{beam}/A	δ_{sys}	evt(M)	2016
^{124}Xe	^{108}Sn	^{112}Sn	269	0.09	8	4/30-5/4
	^{112}Sn	^{124}Sn	270	0.15	5	5/4-5/6
238 U	^{132}Sn	^{124}Sn	269	0.22	9	5/25-5/29
	^{124}Sn	^{112}Sn	270	0.15	5	5/30-6/1

π^-/π^+, light charged particles

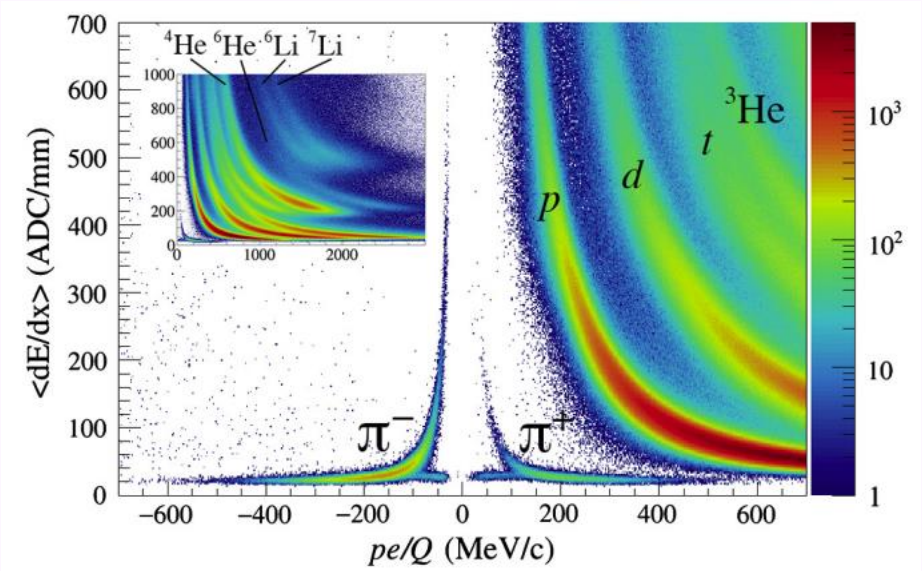
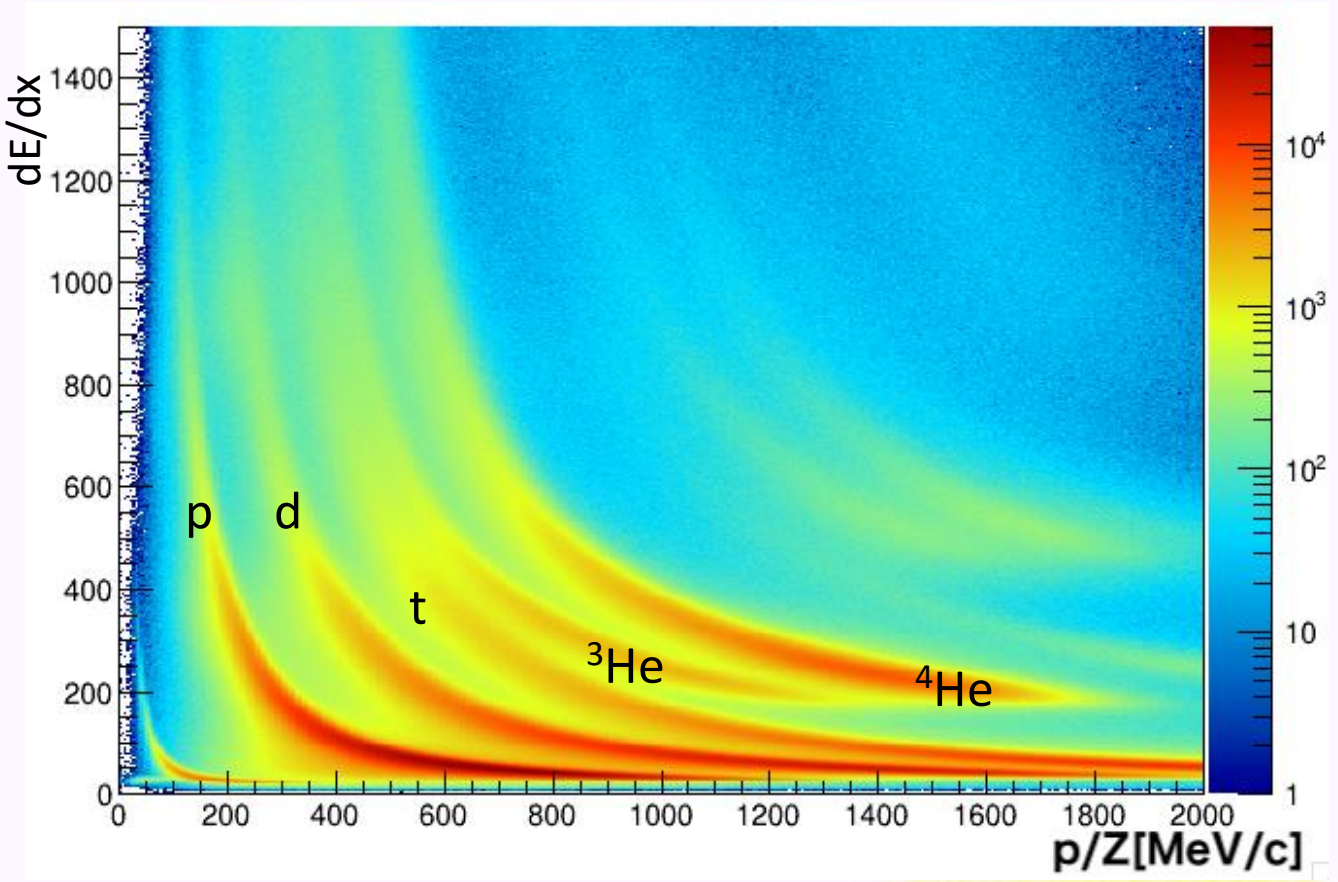


Fig. 2. Particle identification plot from the ^{132}Sn +^{124}Sn reactions, measured with the SπRIT TPC. The main plot focuses on the resolution of the pions; the broader spectrum of positively charged particles is shown in the inset.

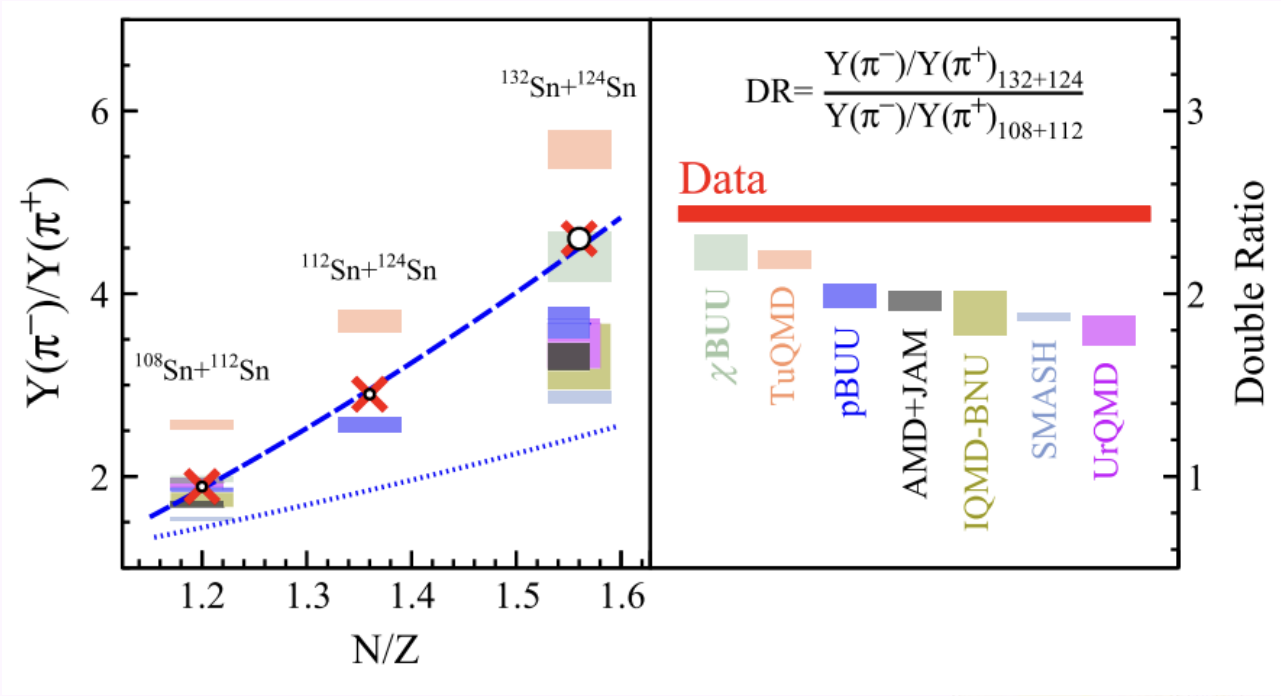


- Light charged particles as well as pions were identified.

Results: ① Ratio of π^-/π^+

Jhang G, *Phys Lett B*. 2021;813:136016.

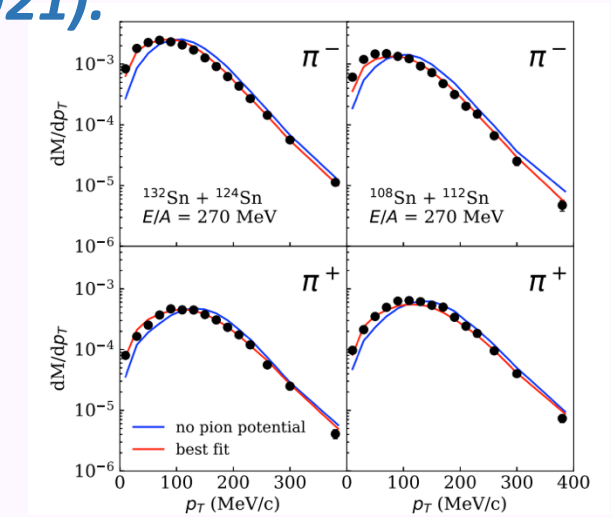
- Compared data with many transport models.
- Models underestimated our data.

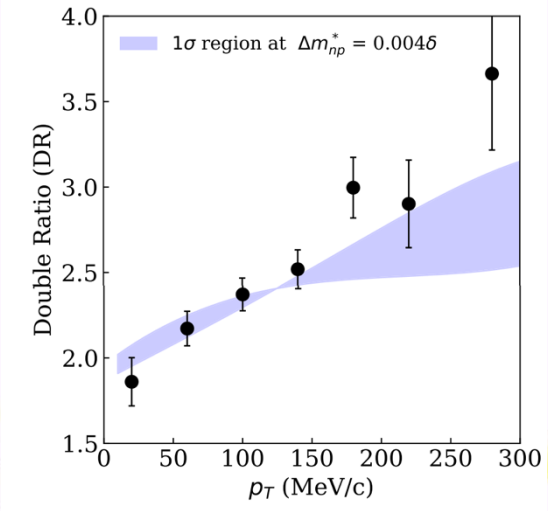


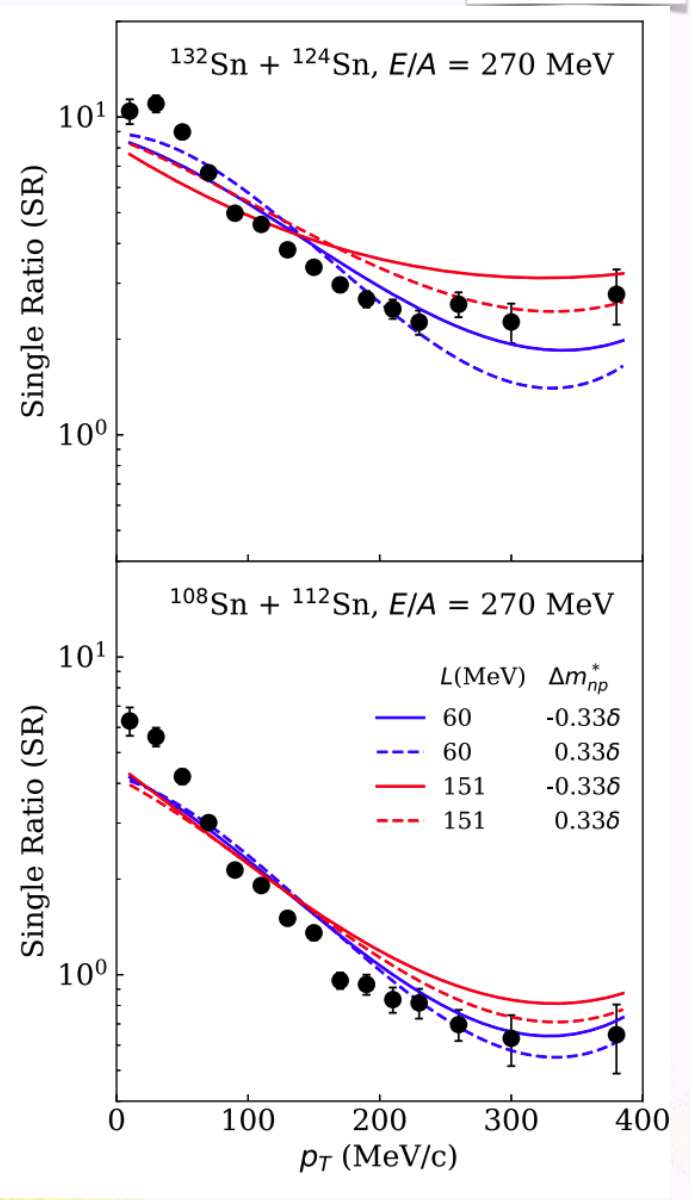
Results: ① Ratio of π^-/π^+

J. Estee, Phys. Rev. Lett. 126, 162701 (2021).

- The Pt spectrums were compared to dcQMD.
- Differences in EOS become evident in the high-momentum region of the single-ratio.
- Double ratio, L=77 ± 28 MeV, indicating a soft EOS.



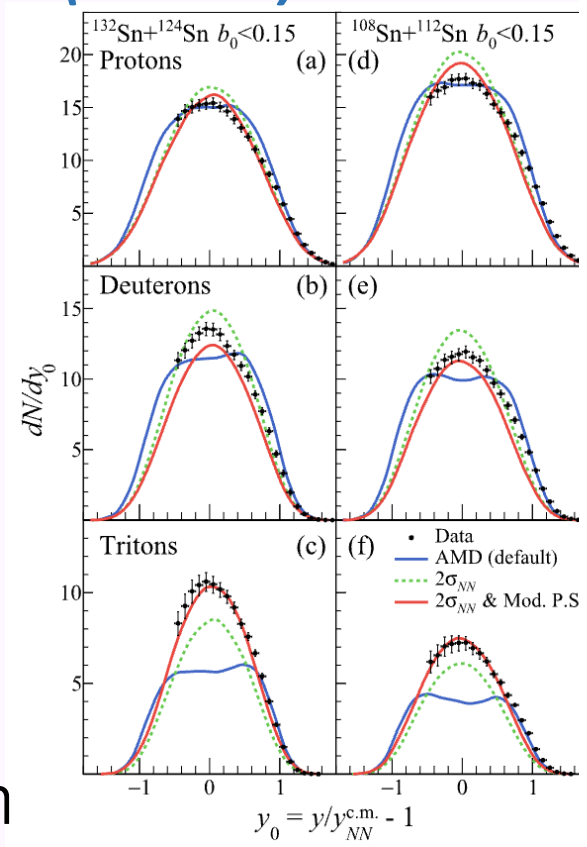


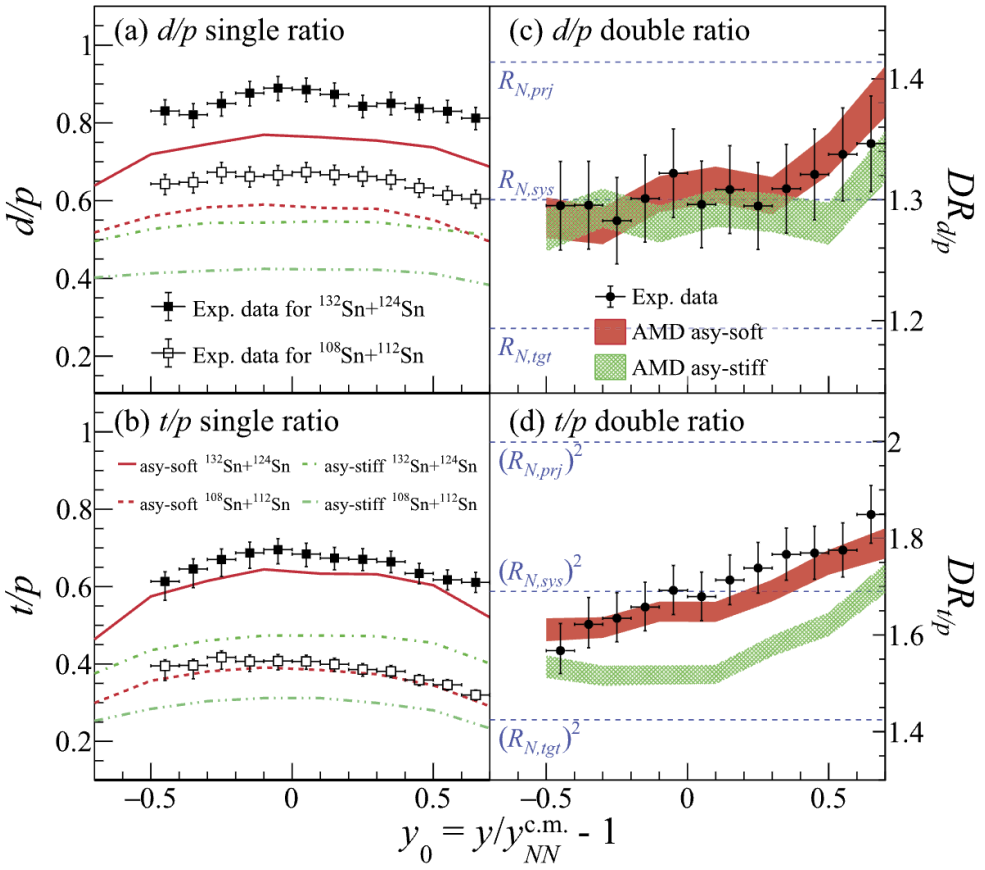


Production ratio of hydrogen clusters

Kaneko M, Phys Lett B. 2021;822(136681):136681.

- The comparison with the AMD model is because AMD explicitly treats cluster+cluster correlation
- Hydrogen clusters indicate that production yields are consistent with a softer EOS.

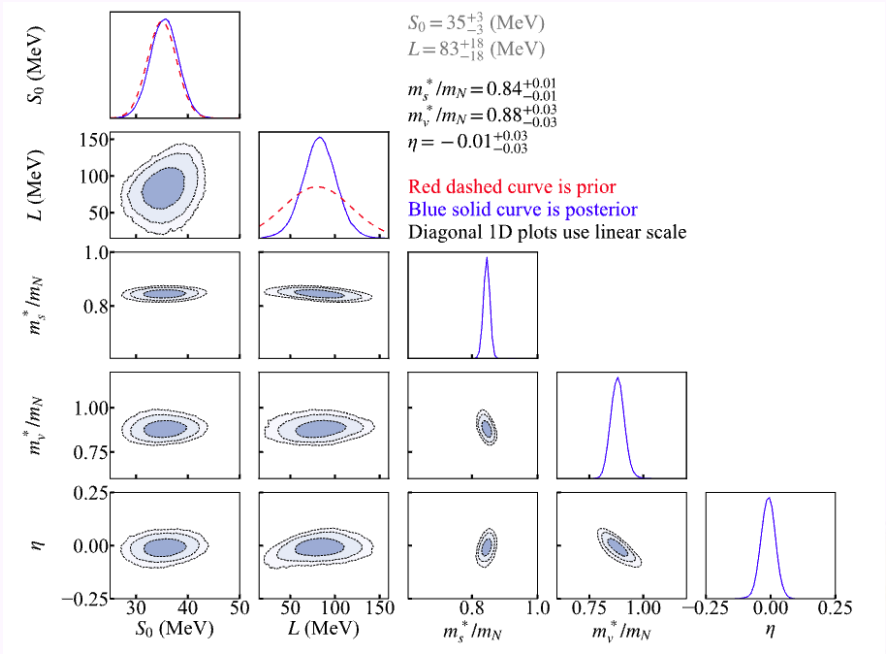


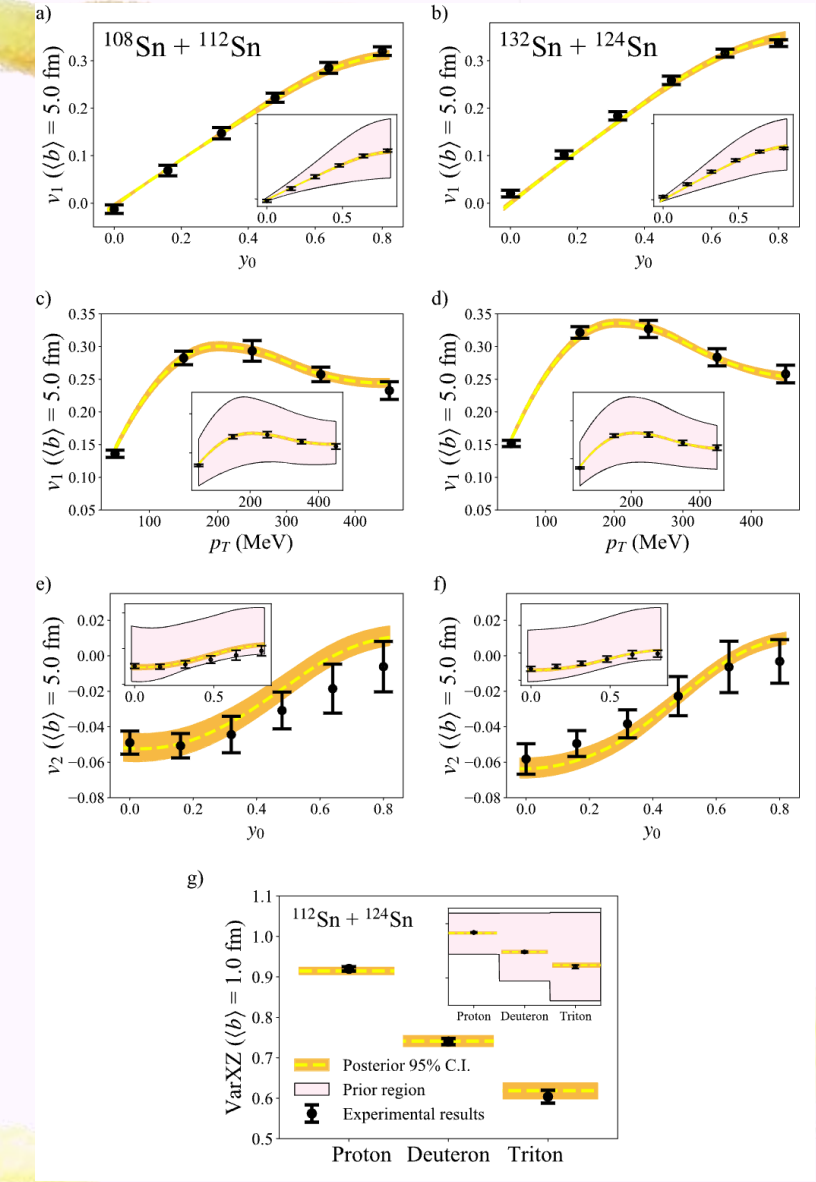


Bayesian Analysis

Tsang CY, Phys Lett B. 2024;853(138661):138661.

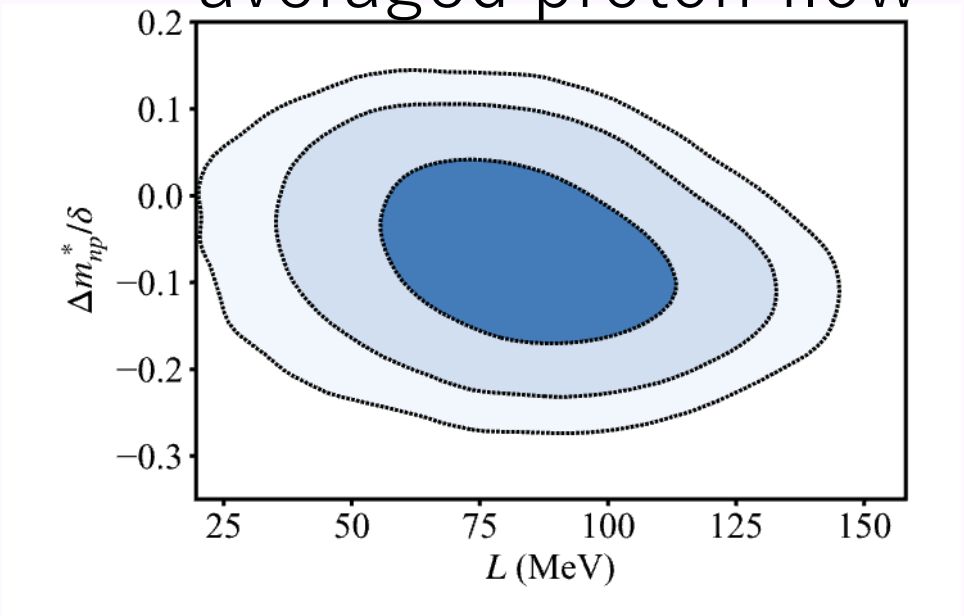
- Input: flow and stopping for protons in H and He.
- Model: ImQMD-Skm
- Taking into account the mass shift



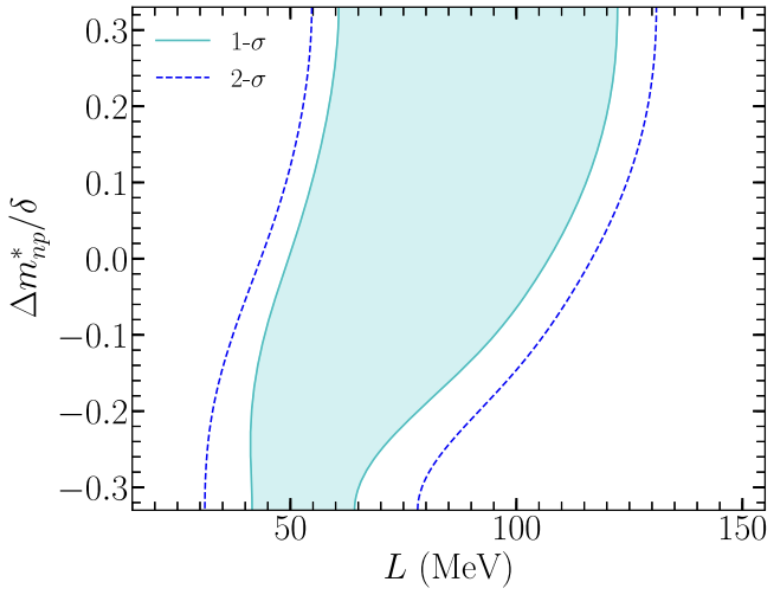


Constrained from two observables

averaged proton flow

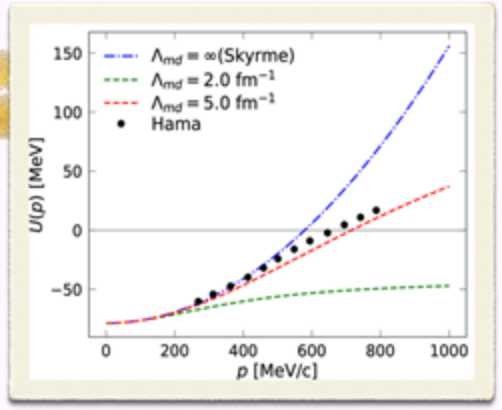


pion ratio



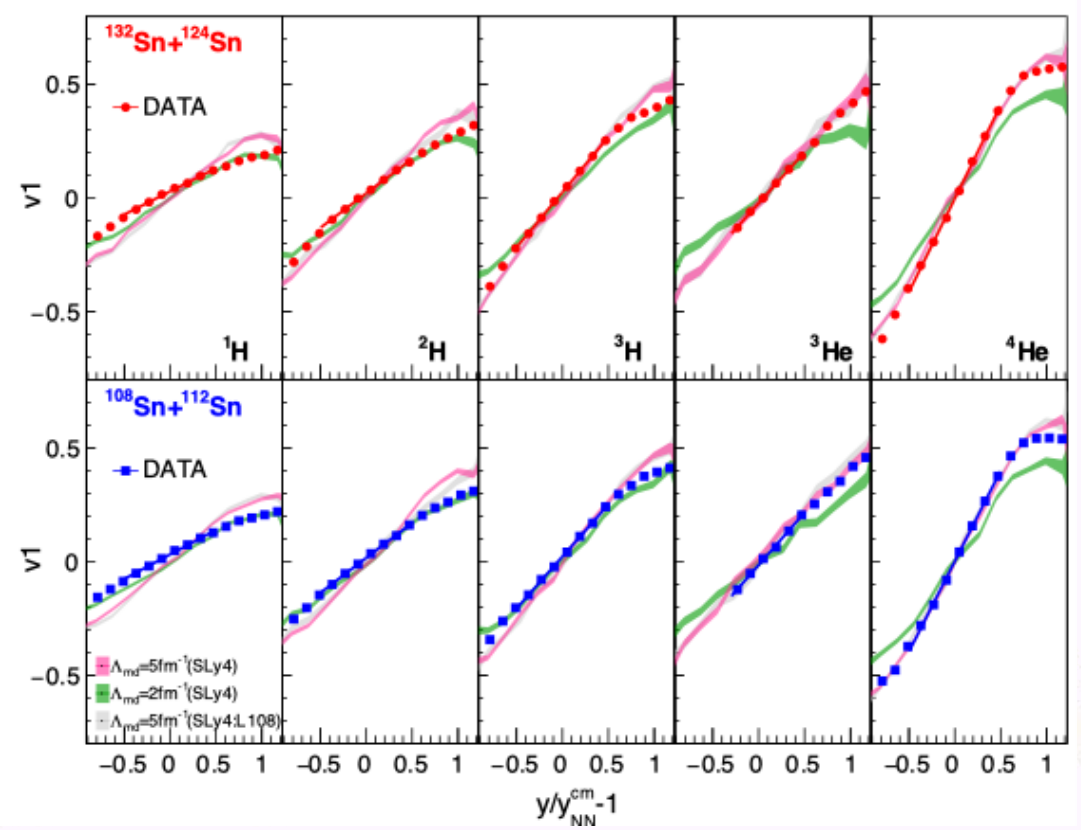
- They provide a different correlation between constraints on L and Δm^*_{np}.
- Adding more information on the model is required.

② Flow results “v1”

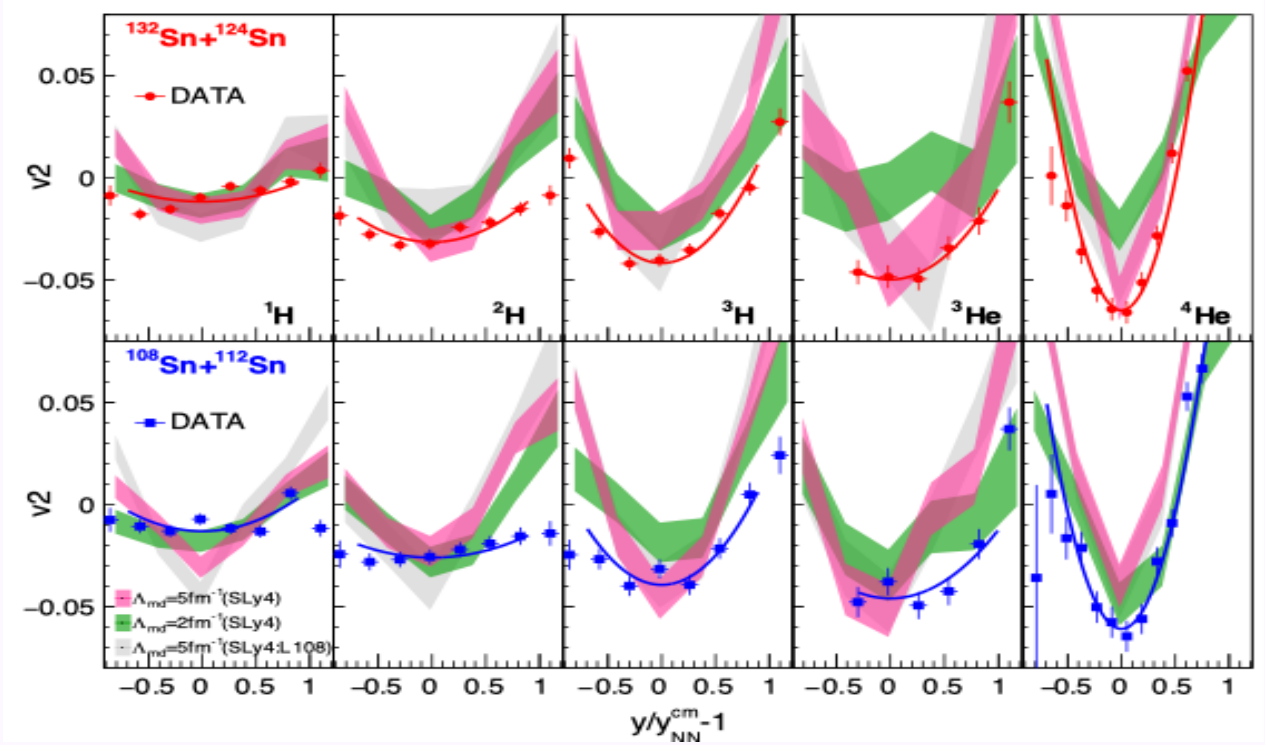


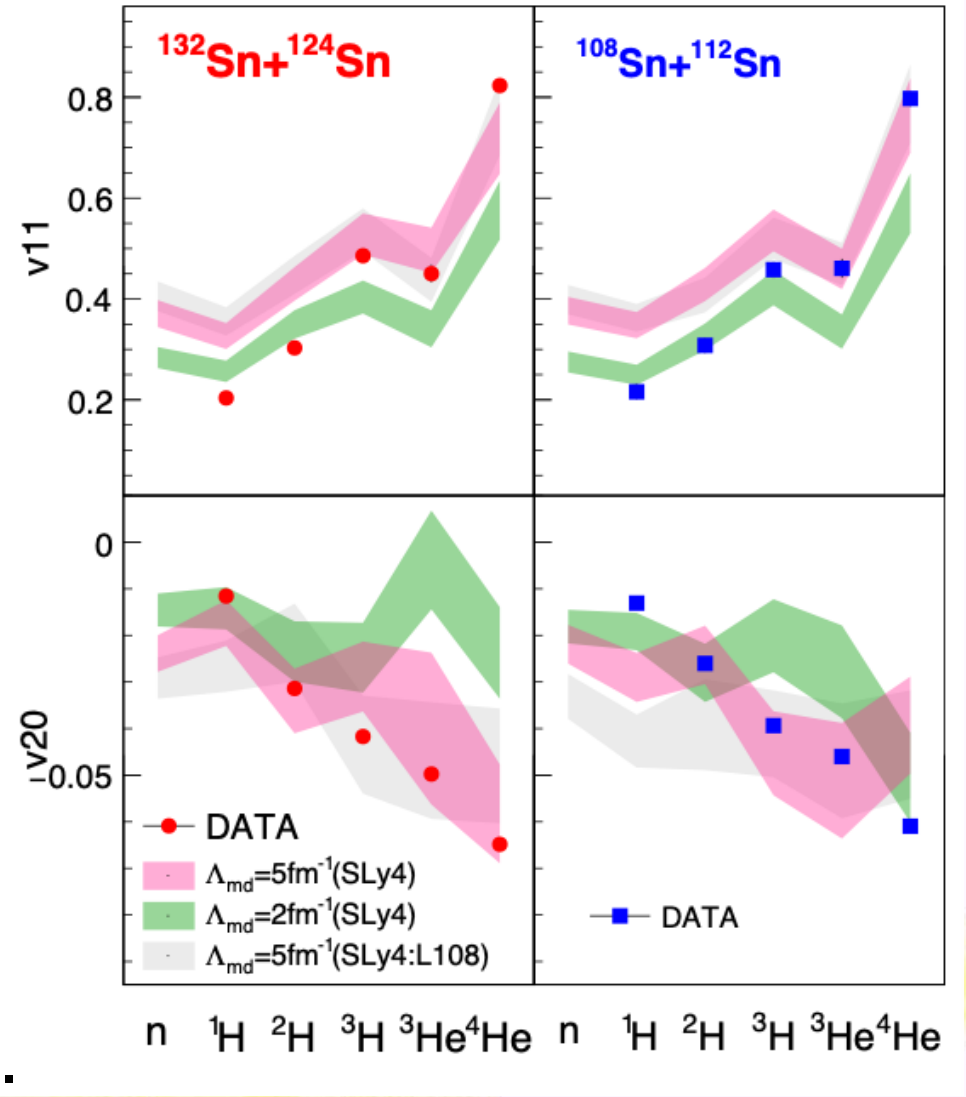
M. Kurata-Nishimura, Phys Lett B. 2025;871(139970):139970.

- Directed and Elliptic flow for p, d, t, 3He, and 4He.
- SLy4 momentum-dependent potential is weakened.
- Modestly weakened potential reproduces directed flow better.



② Flow results “v2”



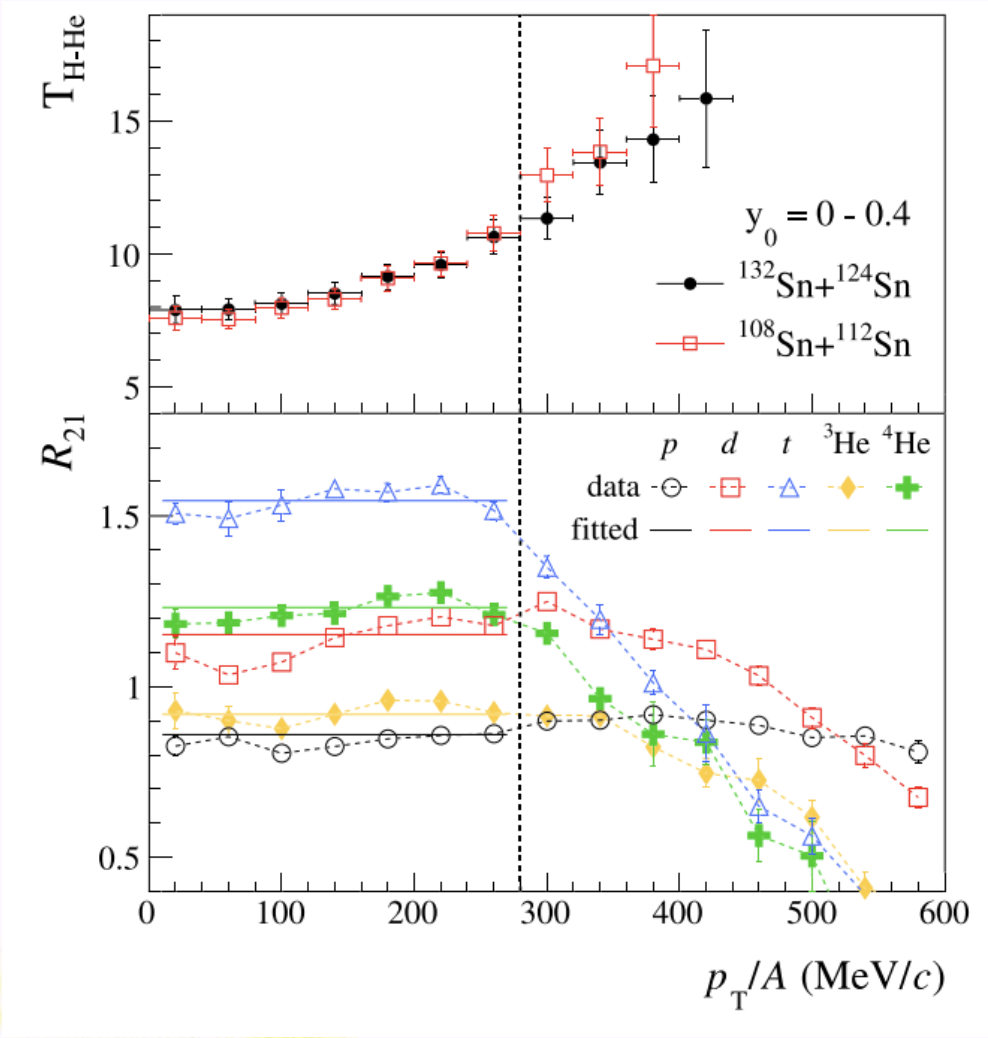


- One parameter set is not sufficient to explain the data.
- Elliptic flow is somewhat sensitive to EOS.

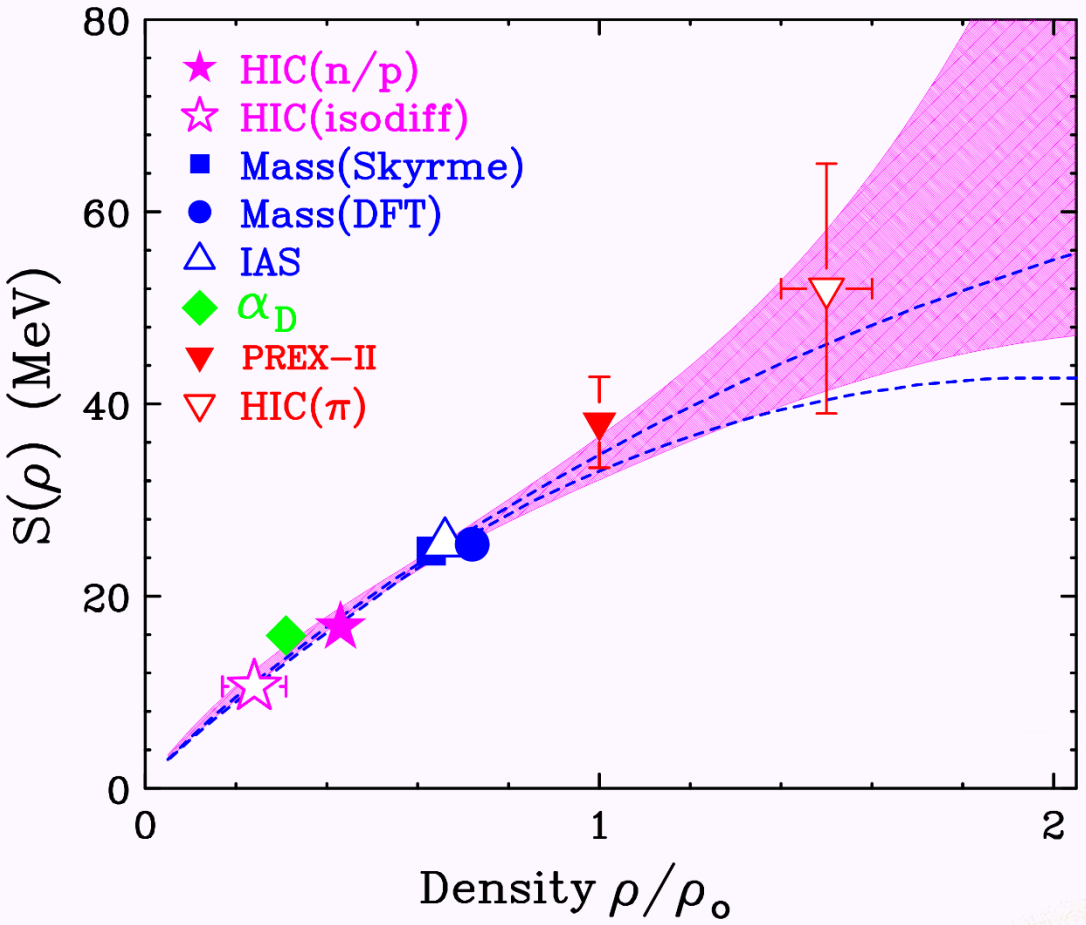
Isoscaling with light charged particles

Lee JW, Eur Phys J A. 2022;58(10).

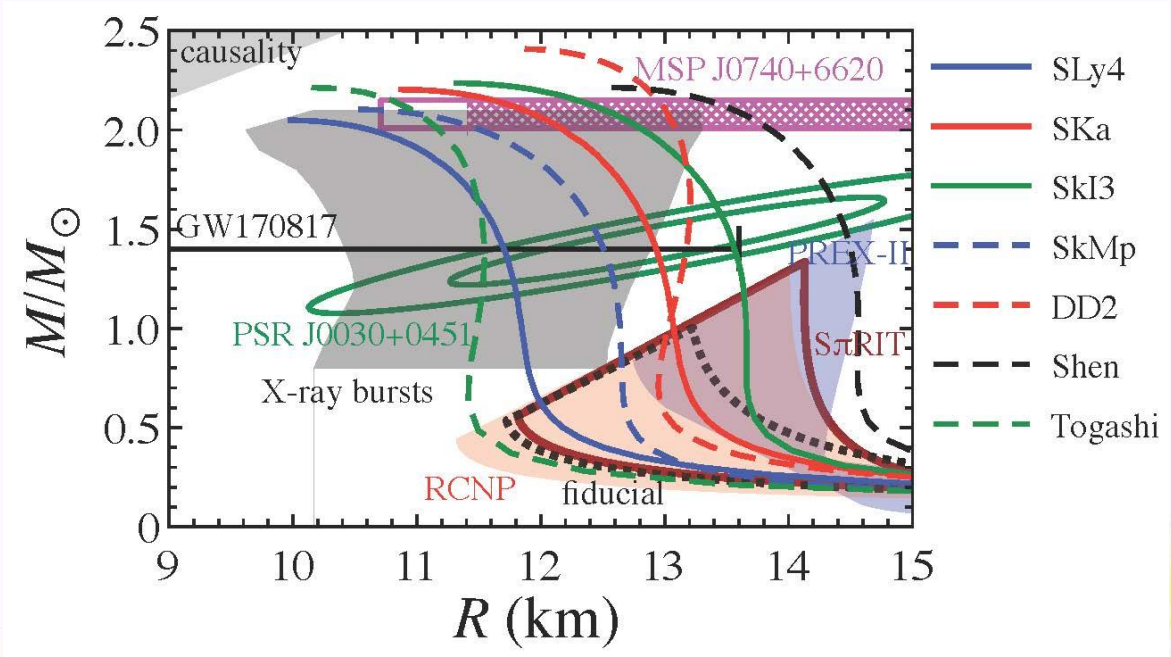
- Isoscaling does not hold when Pt > 280.
- It suggests partial thermal equilibrium.
- The AMD model doesn't display it.



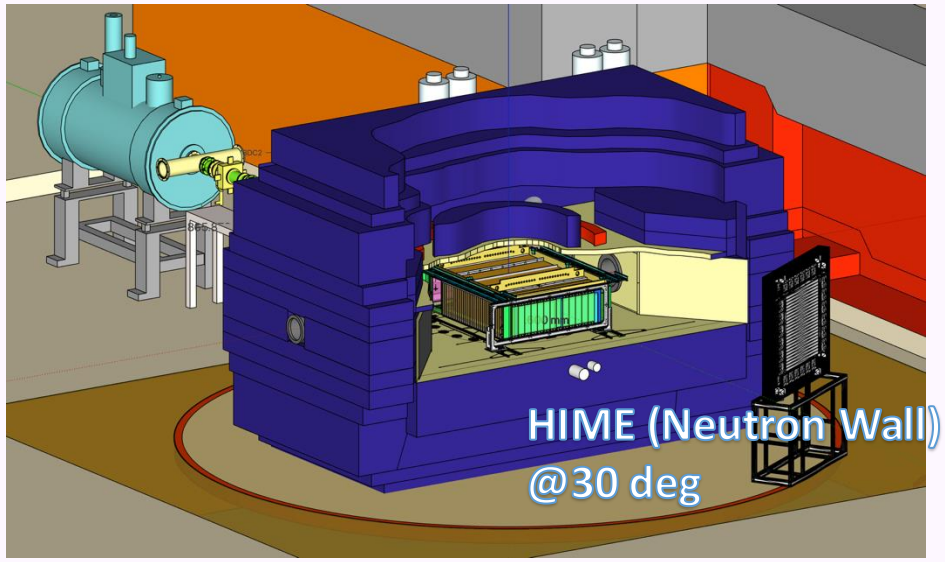
Constraining EOS



- Our data points are $S=52\pm13\text{MeV}@1.45\rho_0$.
- Consistent results.
- Indicating this region of the M–R relation.

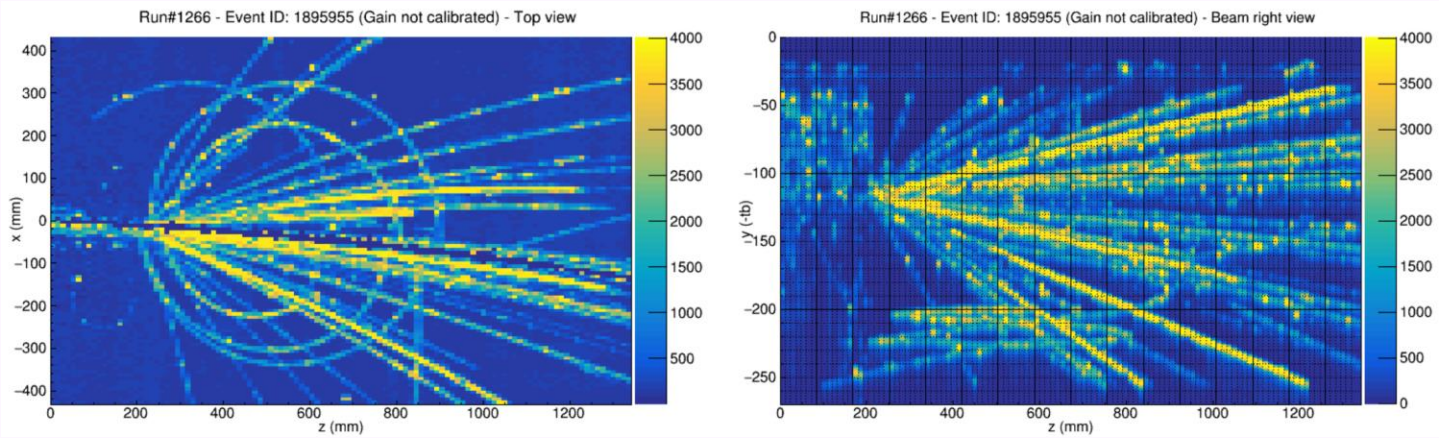


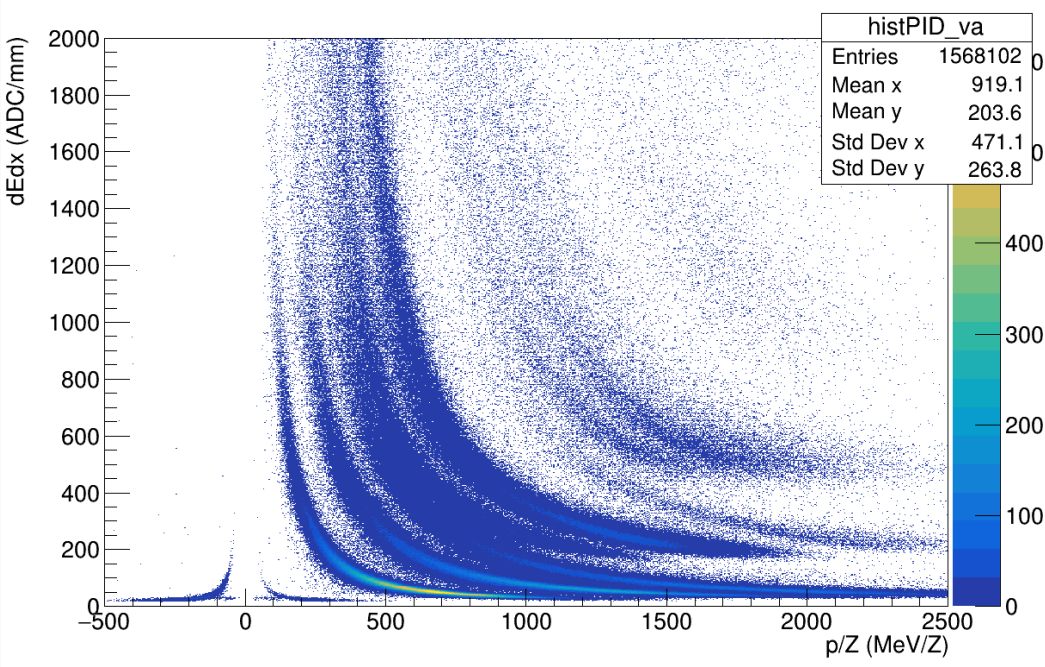
Day-two SpiRIT experiment in 2024



- $^{124}Xe + ^{112}Sn$ (320MeV/u)
- Above pion threshold
- HIME (a neutron wall from GSI/Darmstadt) was installed for neutron measurements.

SpiRIT experiment in 2024

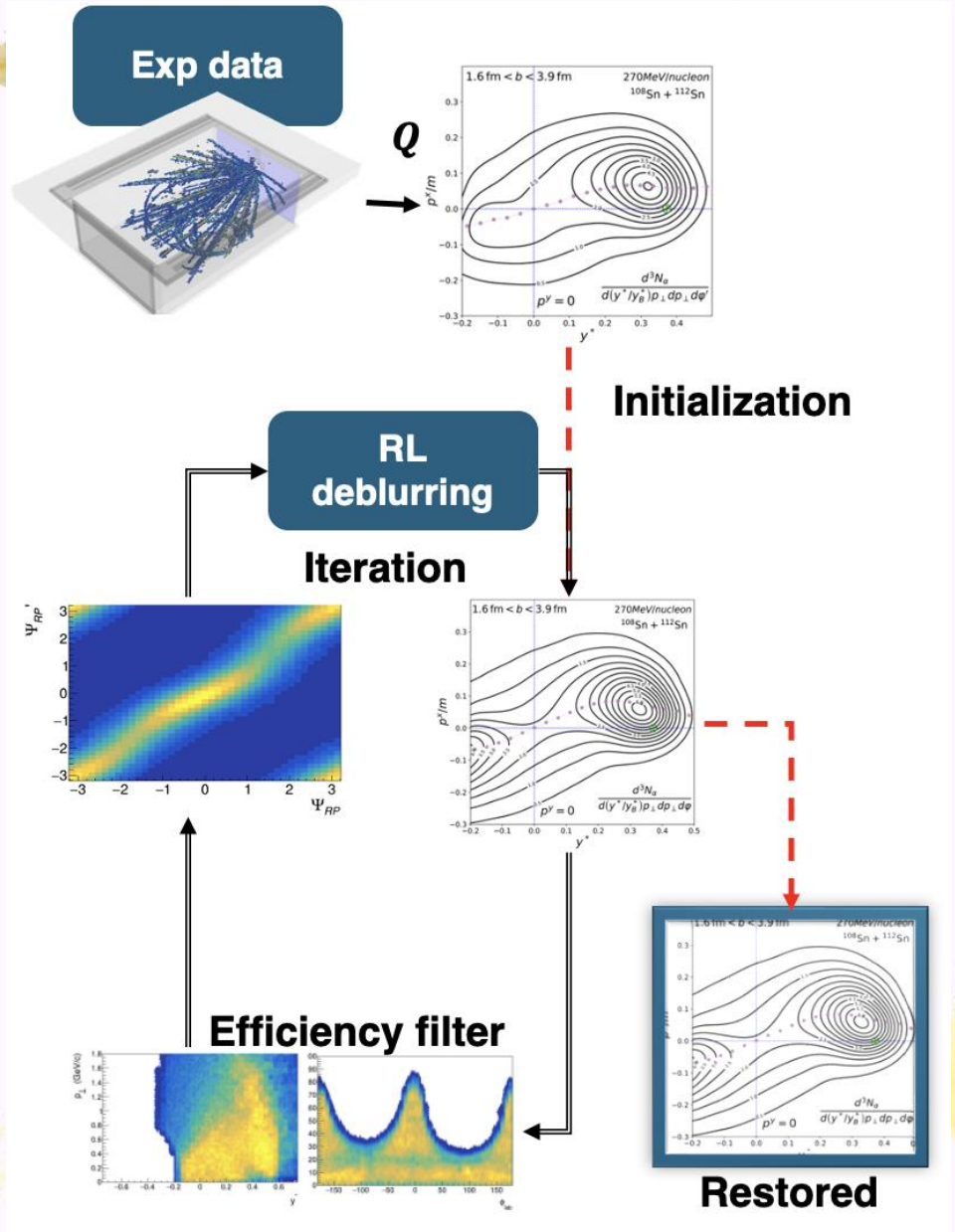




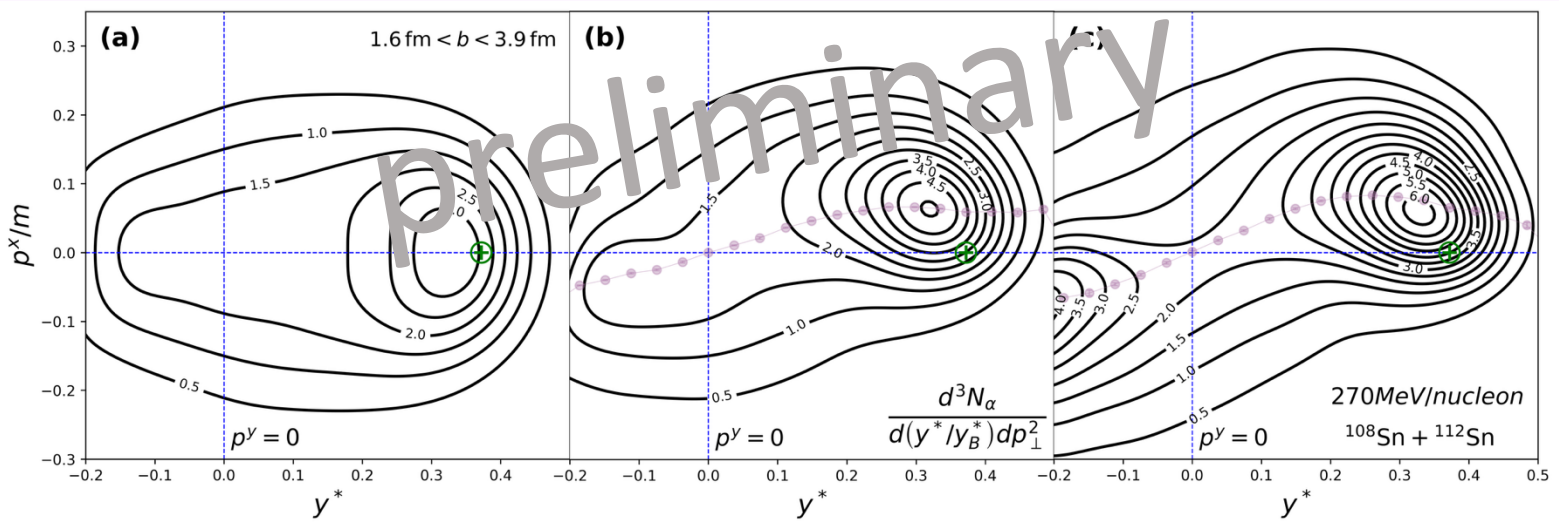
- PID is clear, and more pions were detected.
- Promising results are emerging.

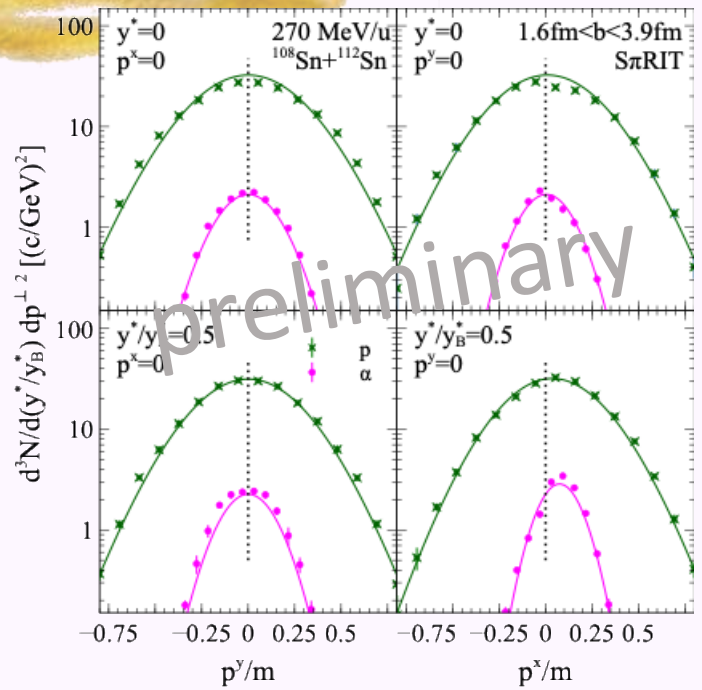
Deblurring analysis

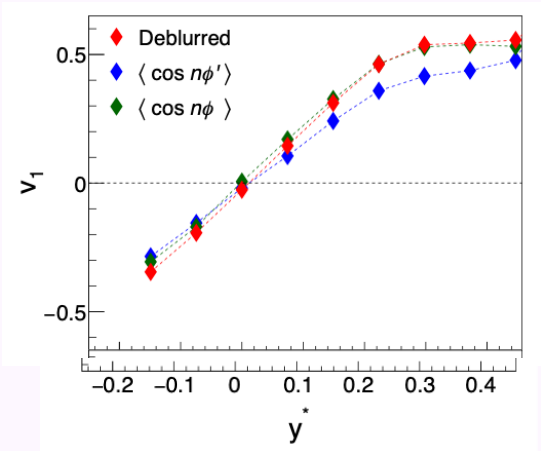
- Apply image processing techniques
- Triple differential distribution on the reaction plane.
- The reaction plane angle is restored iterative way.



3D visualization







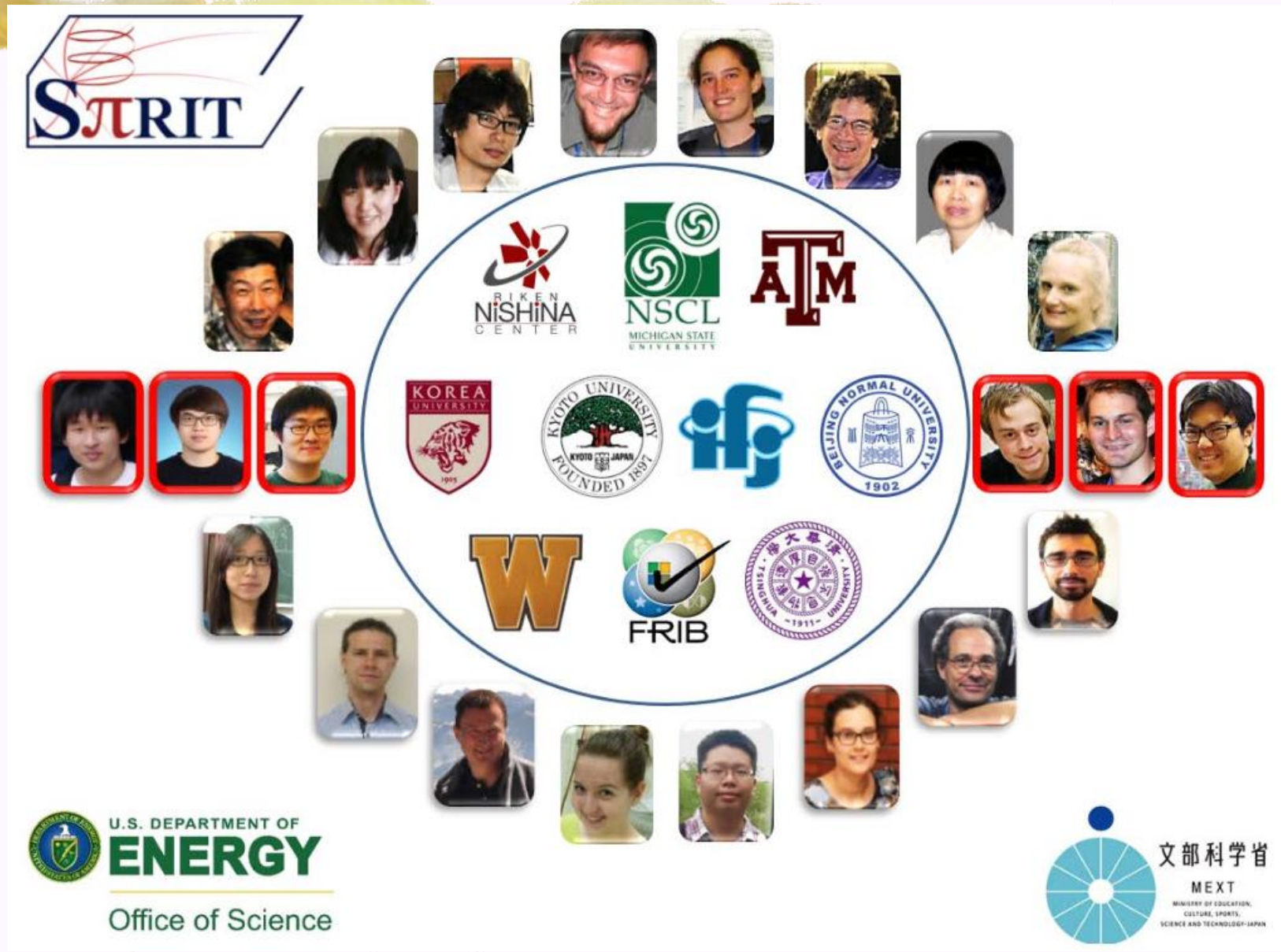
- Triple differential distribution is realized on the reaction plane.
- px/m and py/m distribution is visualized.

Summary

- The SpiRIT-TPC experiment at RIKEN-RIBF was reviewed.
- Multiple observables have been published.
  - π^-/π^+, flow, hydrogen isotopes, Bayesian analysis, isoscaling
- More information is necessary for improving models

- Day-two experiments in 2024.
- 3D analysis (Deblurring analysis)

Thank you


SπRIT
RIKEN NISHINA CENTER
NSCL
MICHIGAN STATE UNIVERSITY
KOREA UNIVERSITY
KYOTO UNIVERSITY FOUNDED 1897
BEIJING NORMAL UNIVERSITY 1902
FRIB
U.S. DEPARTMENT OF ENERGY
Office of Science
文部科学省
MEXT