



Intersection of nuclear structure and
high-energy nuclear collisions 2026 @ Kyoto Univ.

April 23, 2026

Azimuthal Asymmetric Flow

in Collisions of Deformed Nucleus

Shunji Nishimura

RIKEN

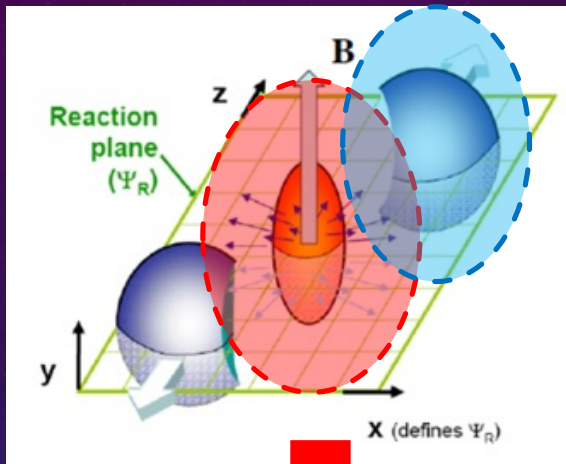
Keywords:

- High-Density Nuclear Matter
- Neutron Star
- Intersection of low & high energy nuclear physics

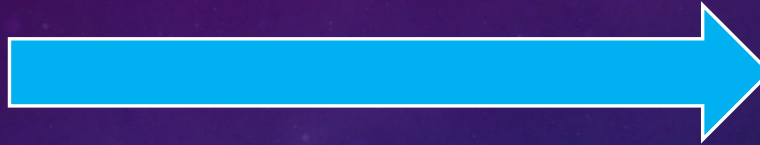


Heavy-Ion Collisions @ Bevalac at Lawrence Berkeley Lab.

RIBF, FRIB, FAIR, HIAF, ...



Research: Unstable Nuclei



Research: High-temp. High-density matter (QGP)

AGS, CERN-SPS, RHIC, LHC
FAIR, J-PARC-HI, NICA

Nuclear Deformation & Skin

H.H. Gutbrod, A.M. Poskanzer, H.G. Ritter
Pep. Prog. Phys. 52 (1989)

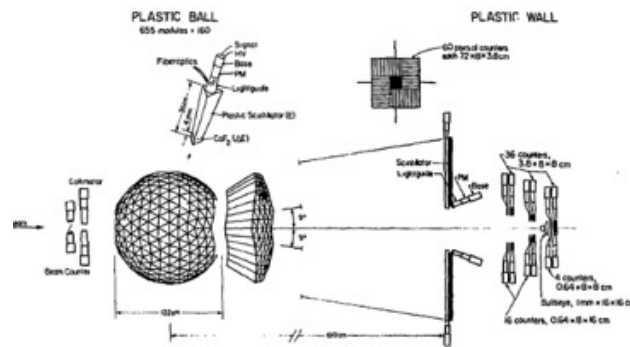
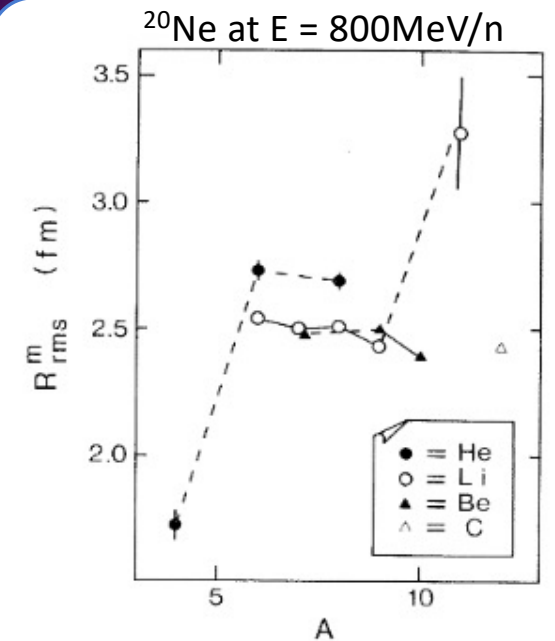


Fig. 1

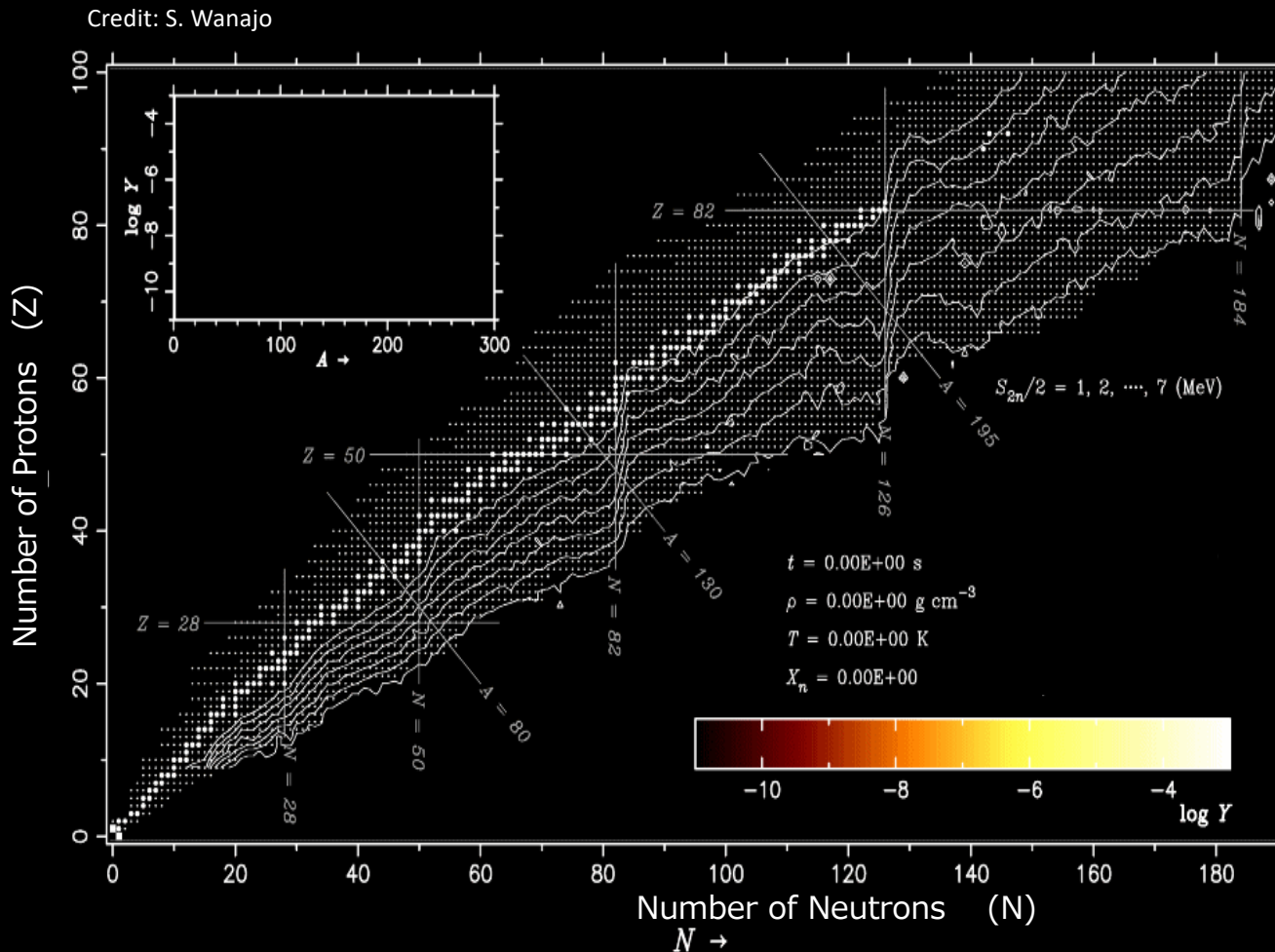


I. Tanihata, H. Hamagaki et al.,
PRL 55 (1985)

Nuclear Deformation, Neutron Halo
Neutron Skin

Mixture

Nuclear Physics: Bridging Discoveries with Astrophysics



r-Process Nucleosynthesis (rapid neutron capture process)

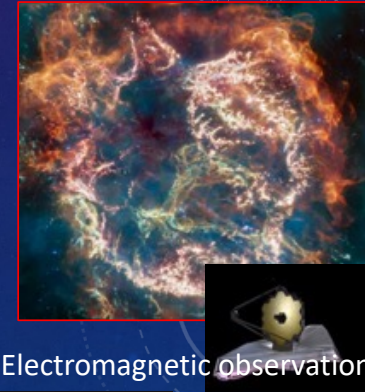
- Supernovae?
- Neutron star merger?
- When ?
- Dynamics in extreme conditions

Neutron Star Merger



Gravitational wave
observation

Supernovae



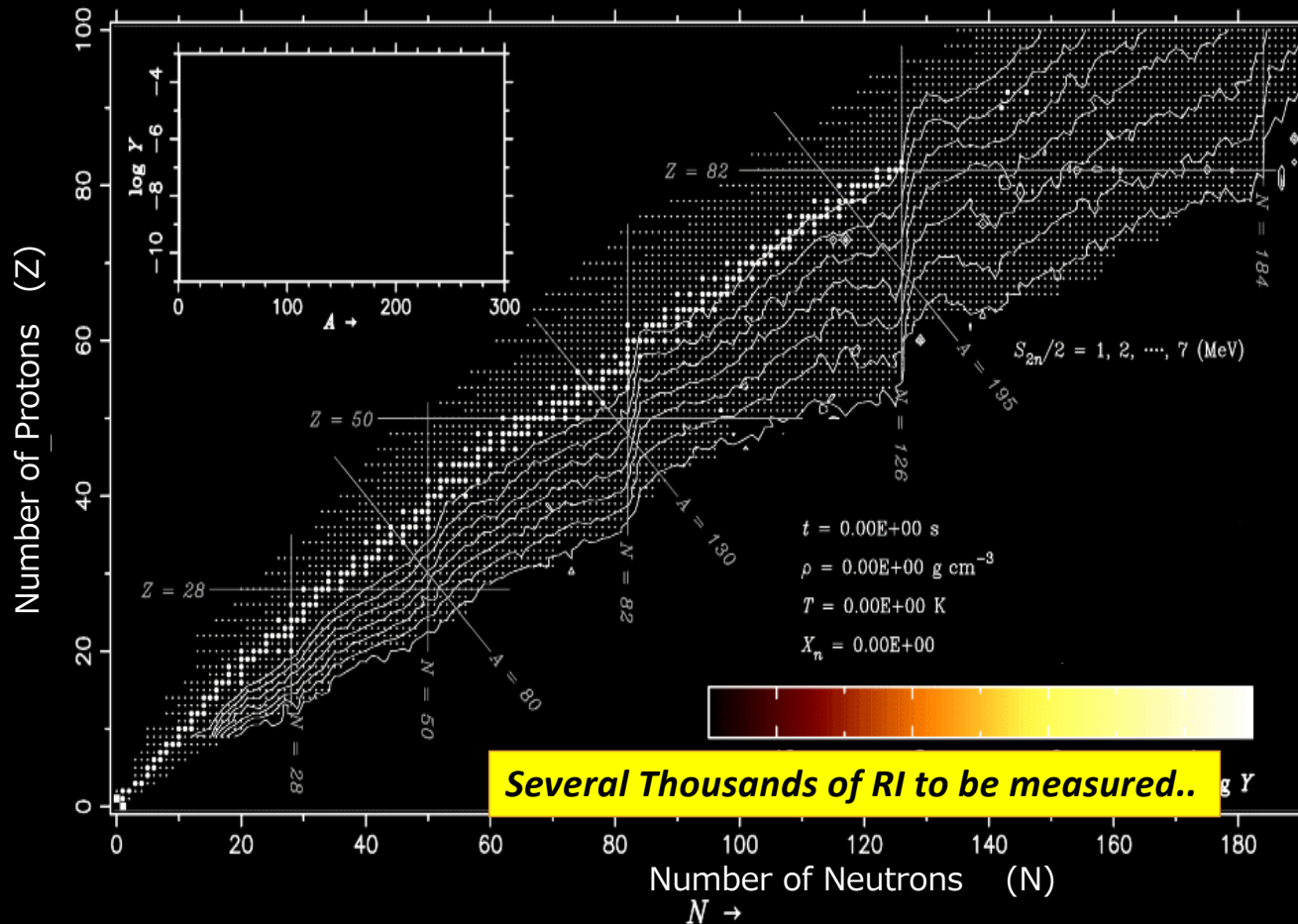
Electromagnetic observation



Connections with those observations

Required Inputs from Nuclear Physics for r-Process

Extreme Environments Achieved



☉ Masses:

- Determine the r-process path, global structure

☉ Beta-decays:

Half-lives:

- Speed of producing heavy elements

Beta-delayed neutron emissions:

- Determine the fine structure of r-elements
- Recapture of neutrons

☉ Nuclear reactions \leftrightarrow Masses

- Determine the r-process path

☉ Fission recycling:

- Production of heavy elements

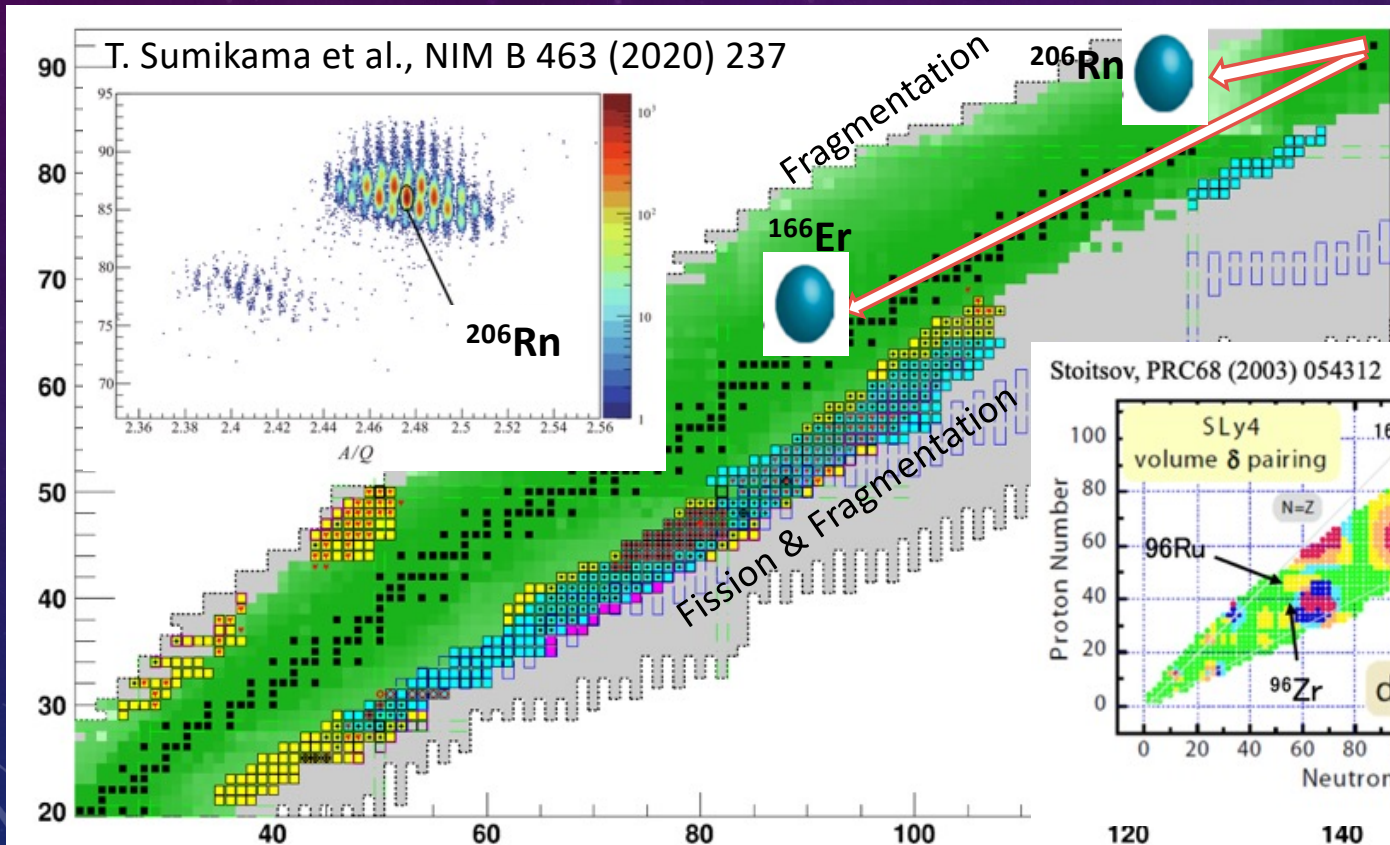
☉ Equation of State:

- Explosive conditions of NS-NS, SN

Production of Deformed Nuclei

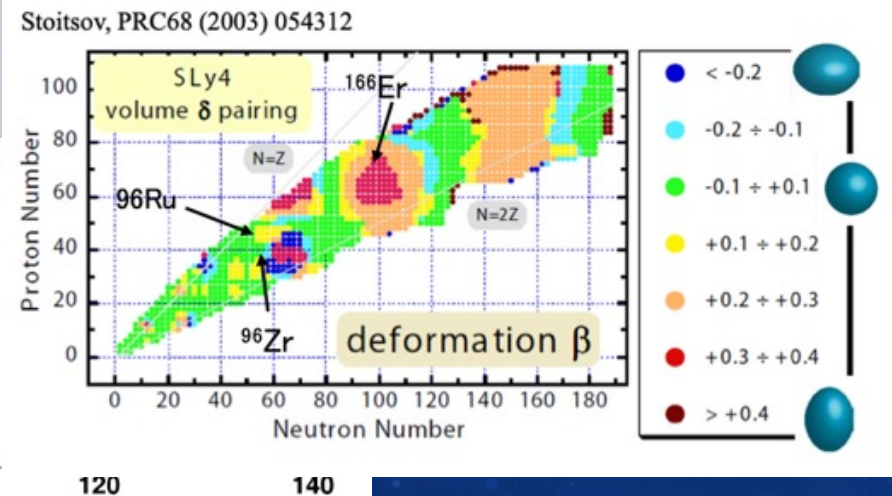
We are requesting 208Pb beam at RIBF..

$^{238}\text{U} + \text{W}$ collisions \rightarrow Select deformed fragment using semi-central collisions



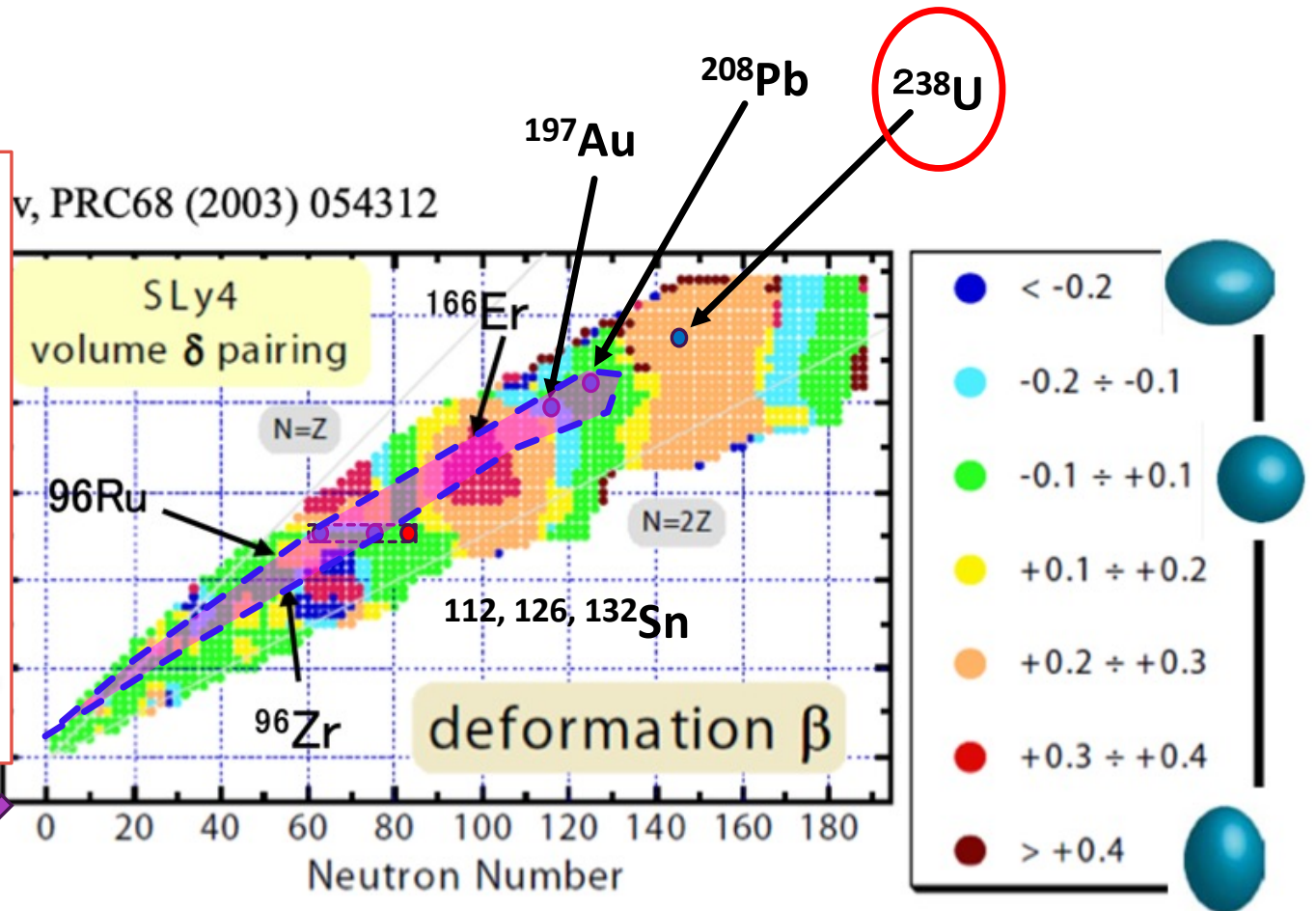
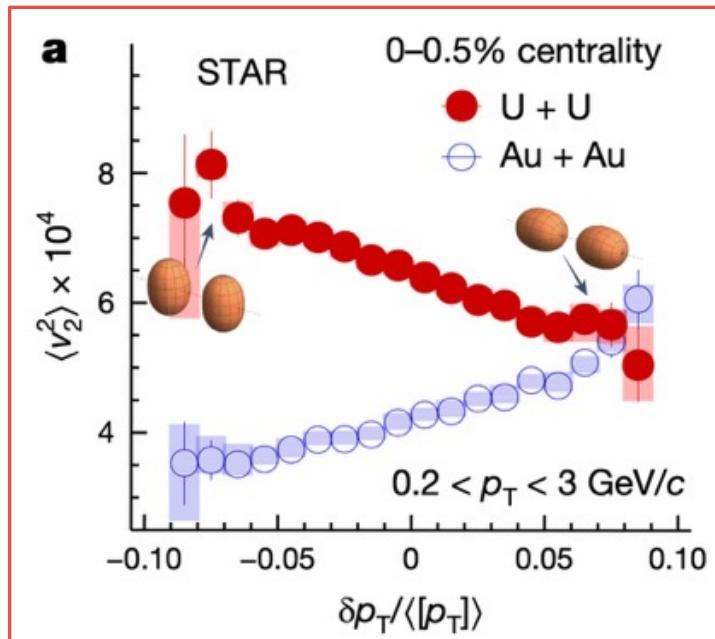
Beam int. of ^{238}U : 10^{11} cps

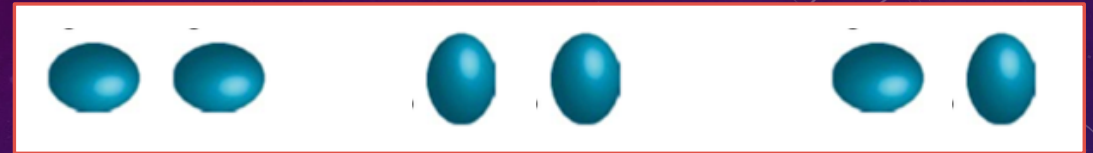
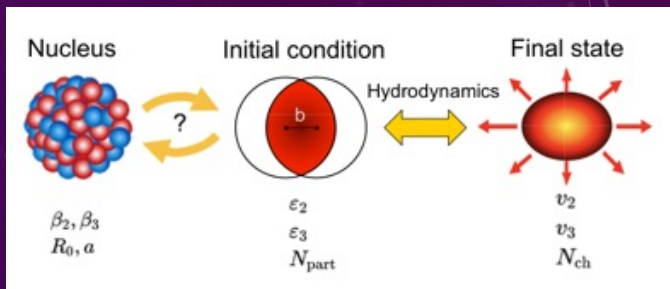
Deformed RI
For example...
 ^{208}Rn , ^{166}Er , etc..



$^{238}\text{U} + ^{238}\text{U}$ Collisions

Nature Vol 635, Nov. 2024
(STAR Collaboration)





Deformed Nucleus + Nucleus Collision

© Azimuthal asymmetric flow is sensitive probe of geometry of initial collision

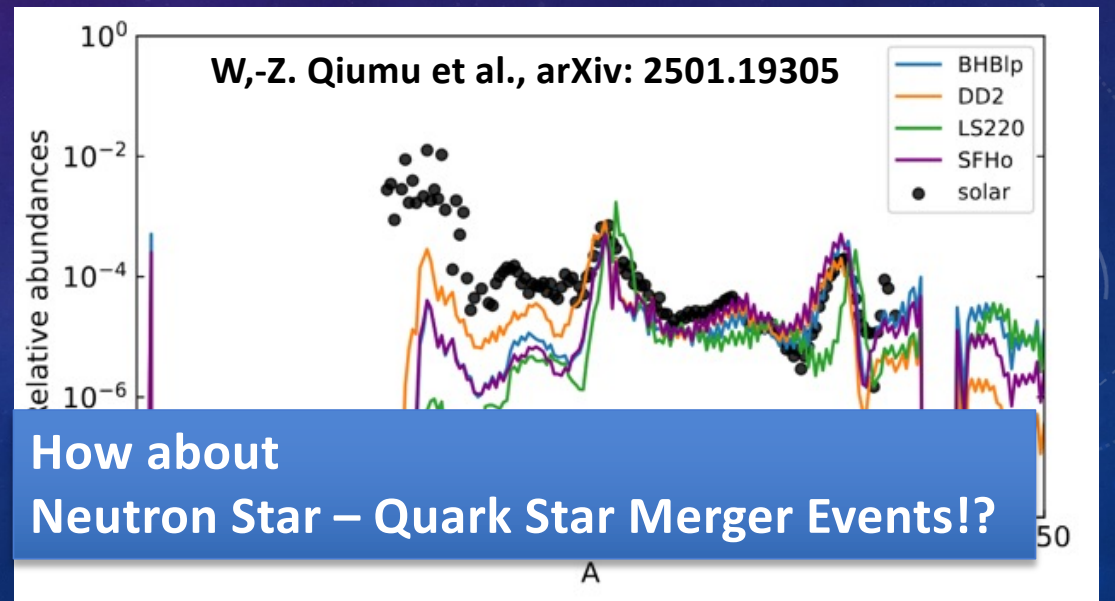
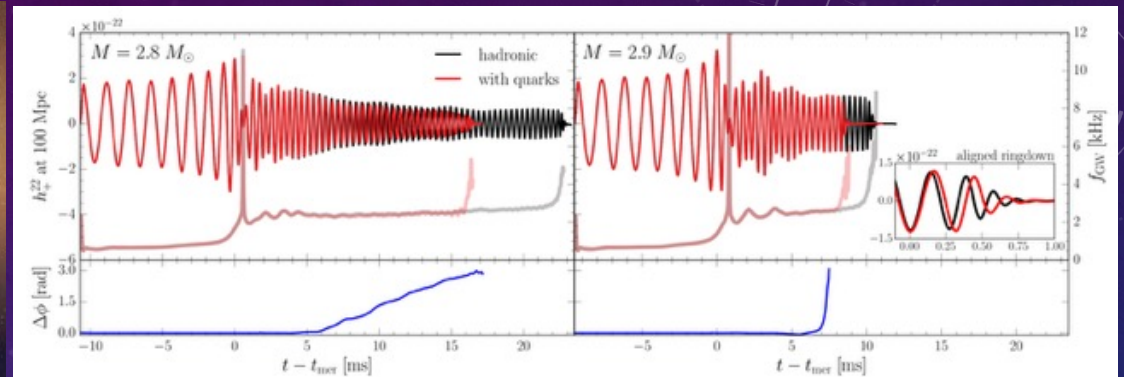
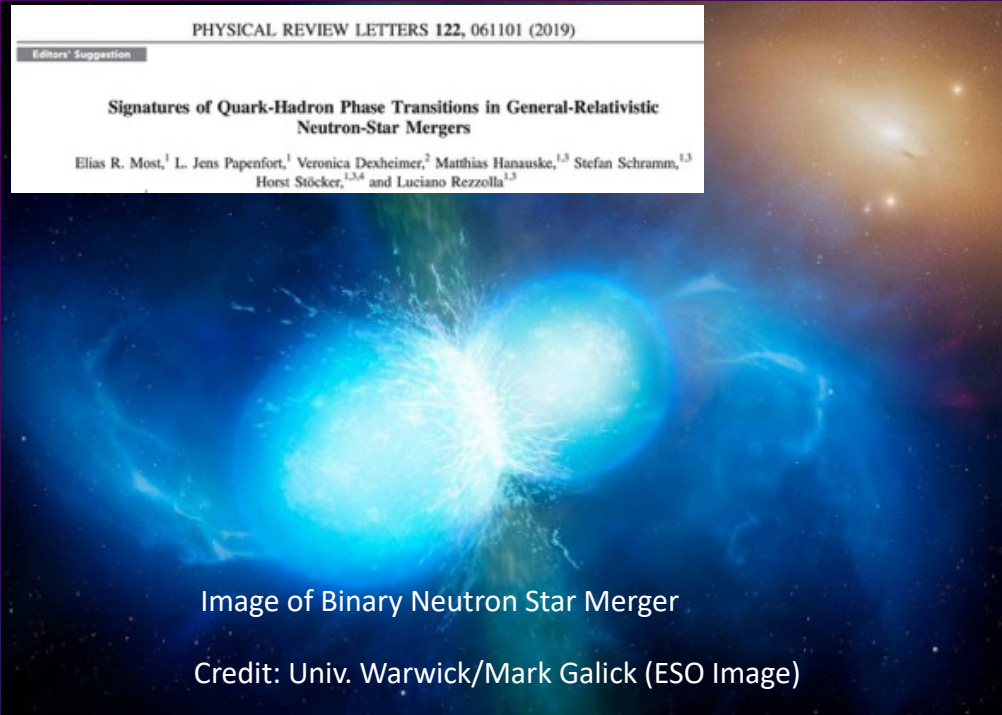
1) Identification of the nuclear deformation using heavy-ion collisions

2) Feedback to the observables in heavy-ion collisions

Application:

→ Study the high-density (high-temperature) matter inside neutron star

Signatures of Quark-Hadron Phase Transition in Neutron-Star Mergers

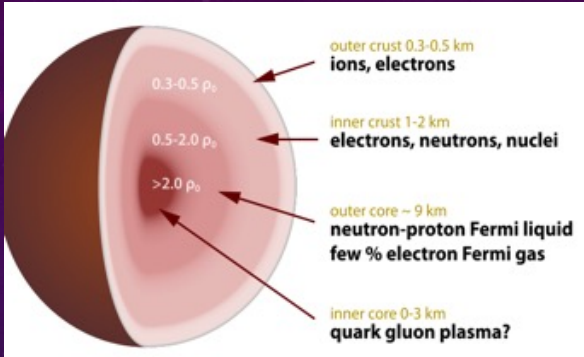


- EOS, Compressibility
- Supernovae, Neutron-star merger

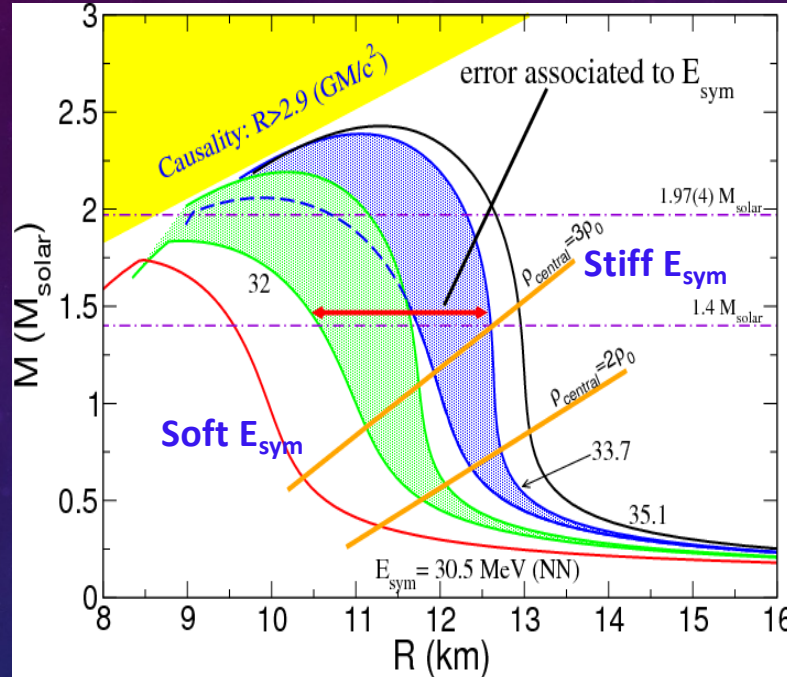
- r-process nucleosynthesis

How about
Neutron Star – Quark Star Merger Events!?

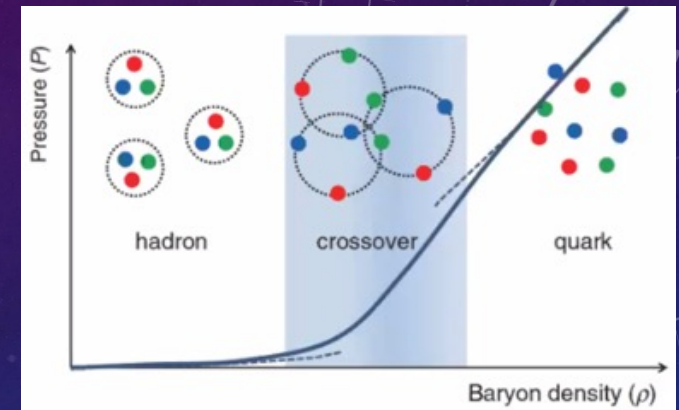
Neutron Star and Equation of State (EOS)



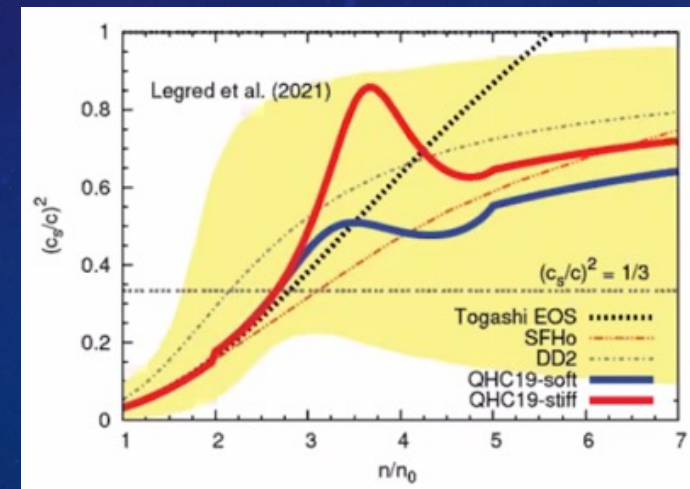
M vs R



T. Kojo, G. Baym, and T. Hatsuda, *Astrophys. Jour* 934, 46 (2022)



speed of sound: $c_s^2 = dP/d\epsilon < 1$ (causality)



Heavy Neutron Star
($\sim 2 M_{\odot}$!)

Radius-Mass \leftrightarrow EOS of High Density Neutron Matter

FAIR, HIAF, J-PARC-HI can provide high density nuclear matter !
 $3 \sim 7 \rho_0$

High Density Baryonic Matter & Heavy-Ion Collisions

LHC

RHIC BES

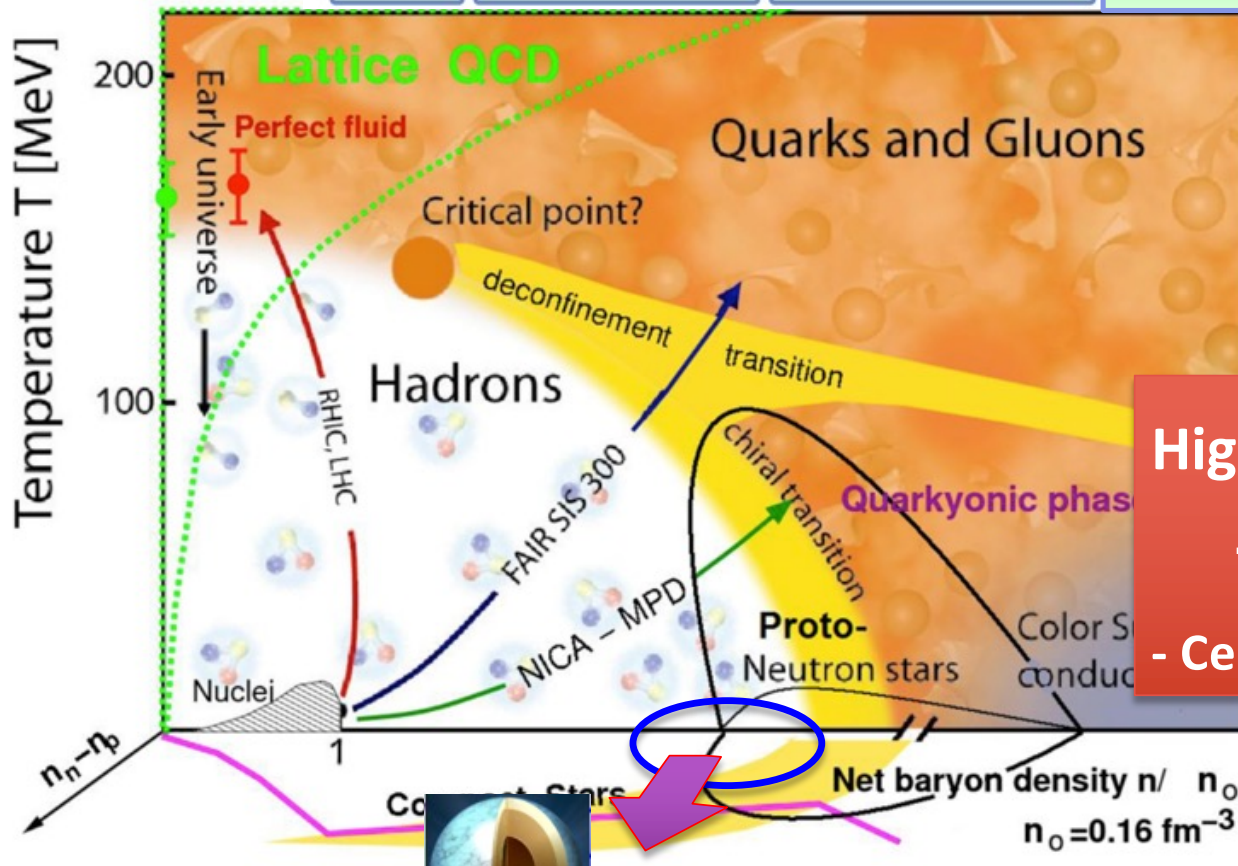
FAIR, NICA, ...

J-PARC-HI

IMP/HIAF

HIMAC

RIBF / FRIB



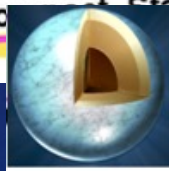
M. Chartier et al

High density neutron matter

→ $^{238}\text{U} + ^{238}\text{U}$ Collisions

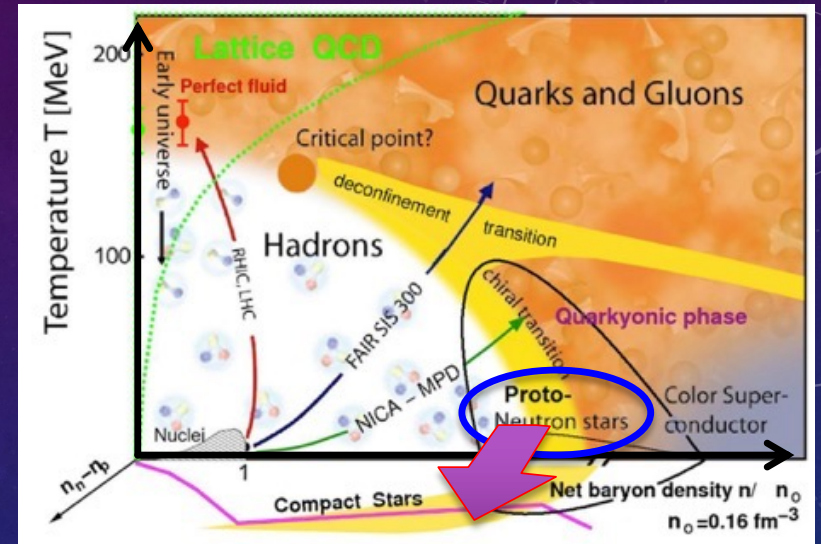
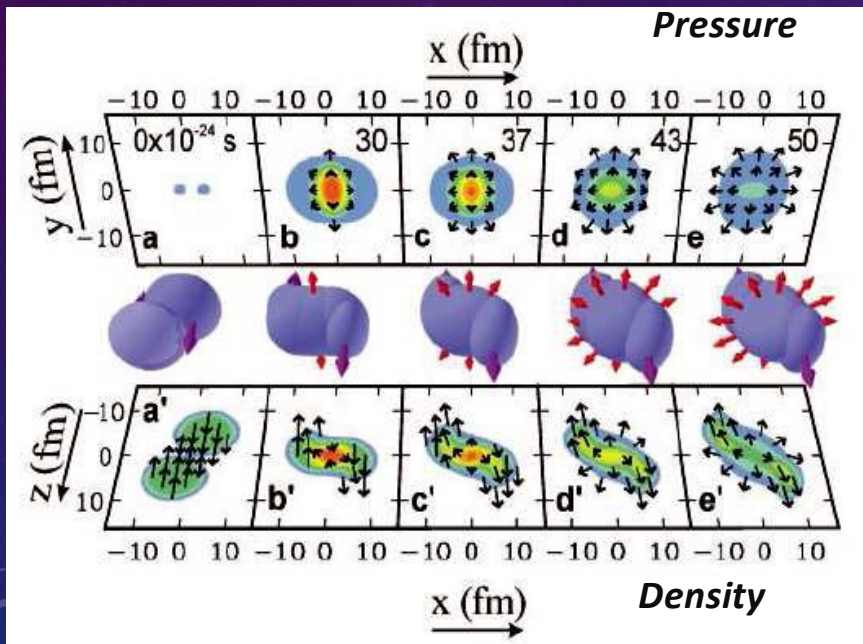
- Central Collisions ↔ Collective Flow

neutron-proton asymmetry



Heavy Ion Collisions and Collective Flow

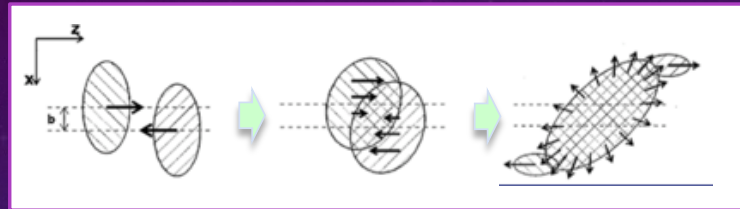
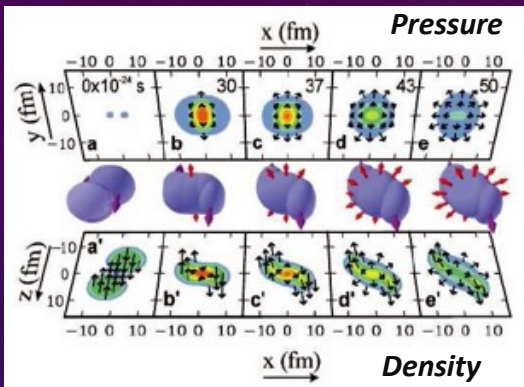
Danielewicz et al., Science 298(2002)1592.



EOS, Compressibility
 → Supernovae, Neutron-star

Equation of State and Azimuthal Asymmetric Flow ($\rho / \rho_0 \sim 2$)

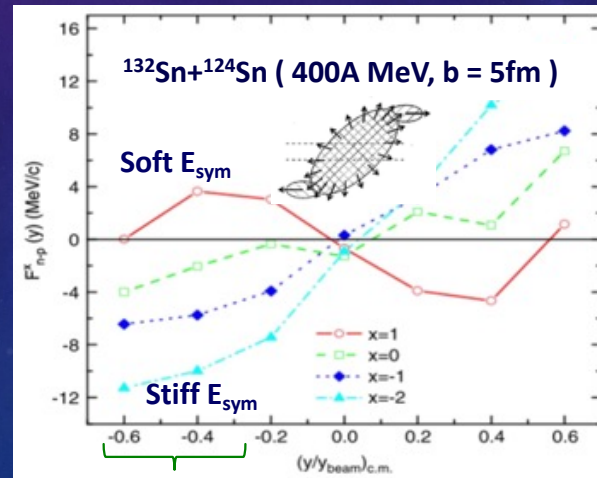
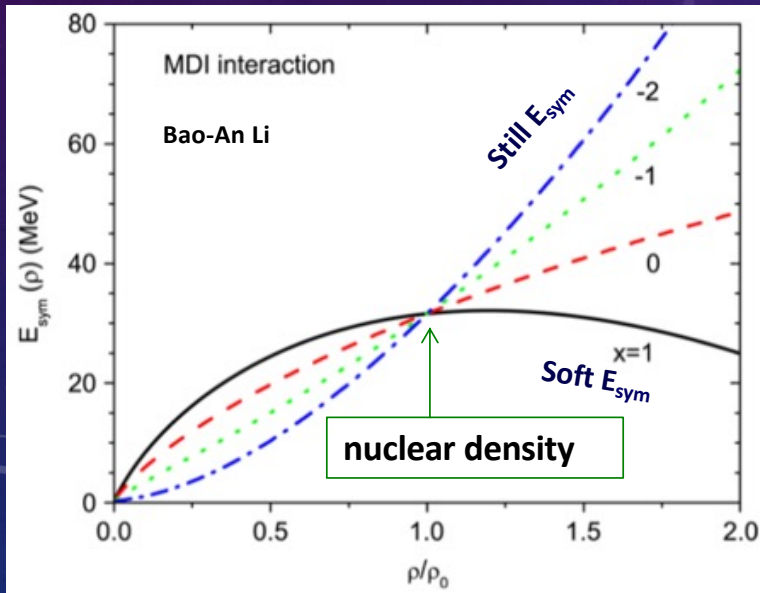
Danielewicz et al., Science 298(2002)1592.



$$F_{n-p}^x(y) \equiv \frac{1}{N(y)} \sum_{i=1}^{N(y)} p_i^x(y) w_i$$

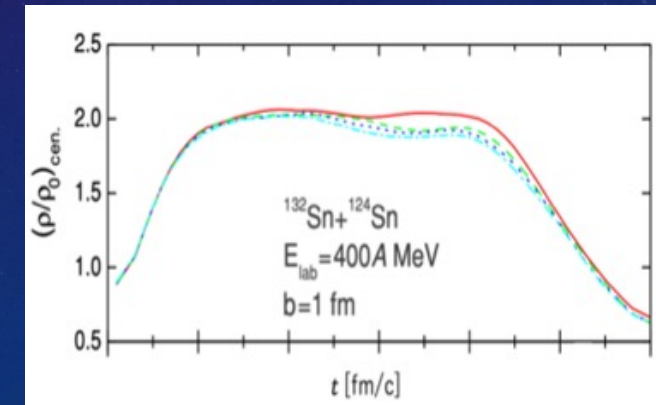
$$= \frac{N_n(y)}{N(y)} \langle p_n^x(y) \rangle - \frac{N_p(y)}{N(y)} \langle p_p^x(y) \rangle$$

High density matter
 - central collisions
 - non-central collisions



Target Rapidity

Bao-An Li etc.



Issue and Test

Can we measure directed & elliptic flow of proton, neutron and pions at lower energies (0.3 GeV – 10 GeV/u)?

Can we study the EOS at high density matter ?

↔ Influence of spectators in flow measurements

Keywords: Deformed Nucleus – Nucleus Collisions

Pilot Experiment for Collective Flow at HIMAC H447 Collaboration (Following up Experiment of H355)



RIKEN ... T. Isobe, Y. Nakai, S. Nishimura,

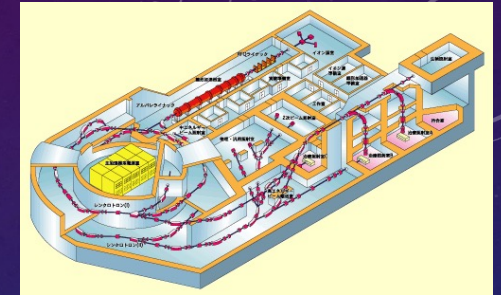
U. Tokyo ... K. Kokubun, R. Mizuno, M. Niikura, S. Yamamura, Y.Y. Tsun

U. Tsukuba ... S. Esumi, H. Tanabe

Kyoto U. ... Y. Hijikata

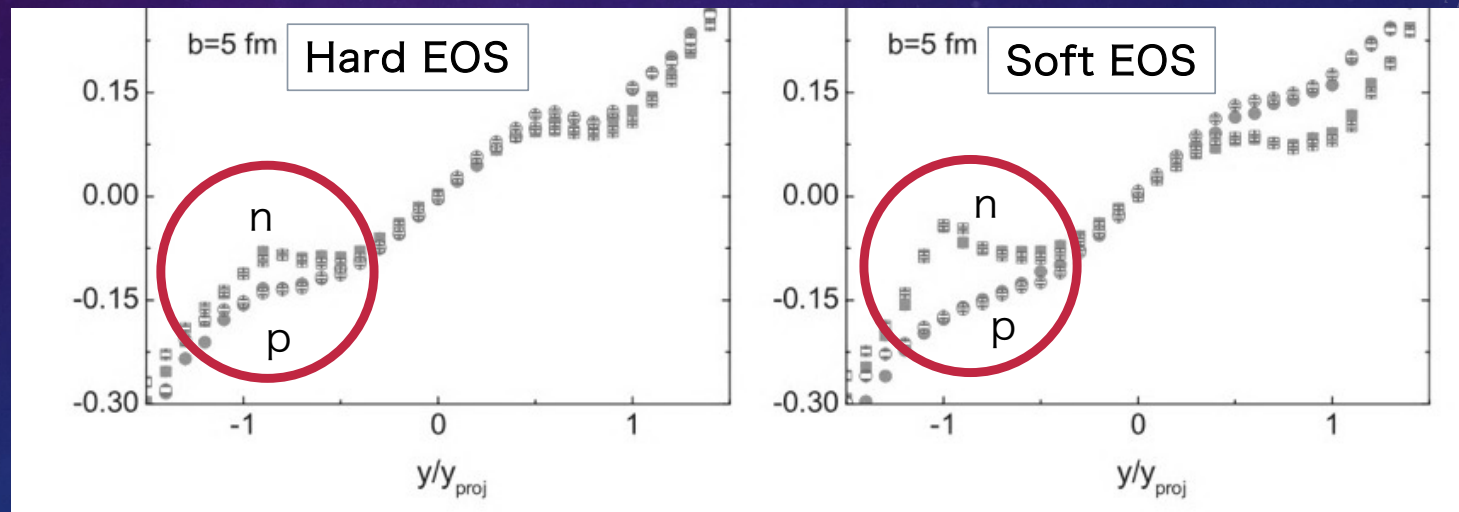
NIRS ... E. Takada

Z.-Q. Feng, Phys. Rev. C 85, 014604 (2012)



Theoretical calc. (LQMD)

$^{124}\text{Sn}+^{124}\text{Sn}$ (400 A MeV)



Goal: Direct Comparison of Directed Flow V_1 at Target Rapidity

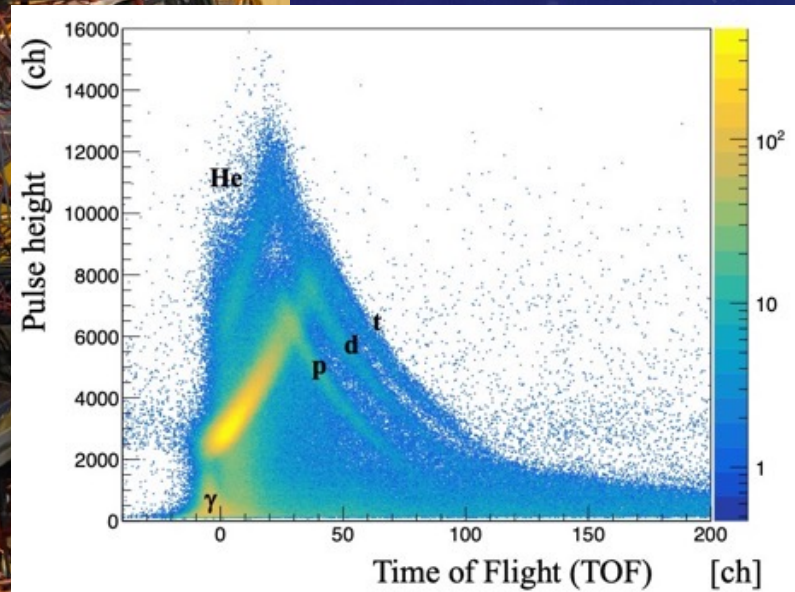
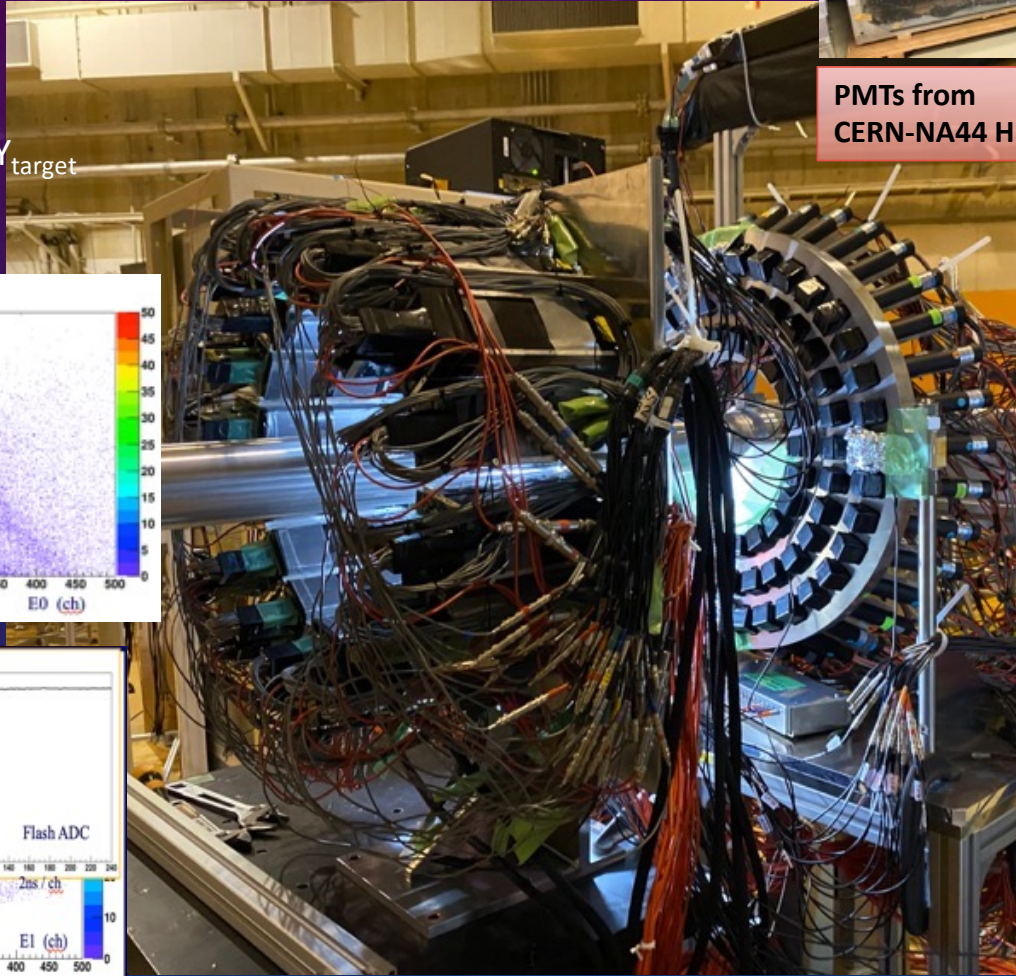
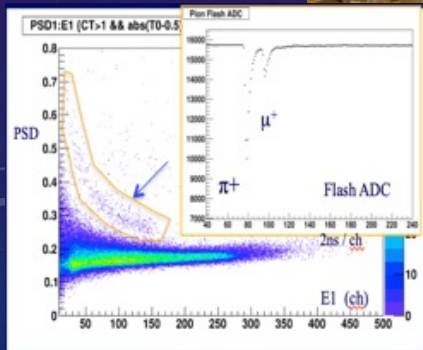
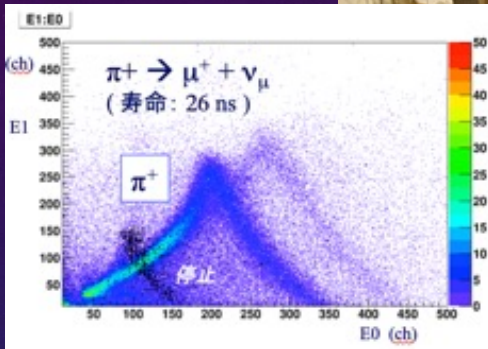
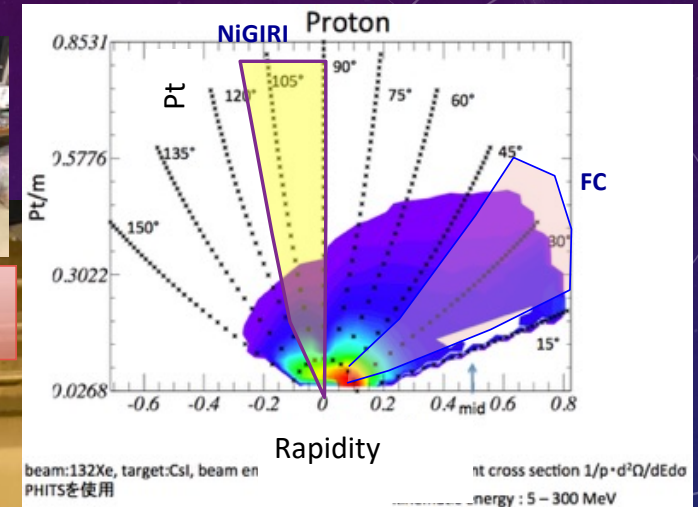
Pilot Flow Experiment at HIMAC H447

$^{132}\text{Xe} + \text{CsI}$ Collisions at 400 AMeV

NiGIRI detector@ γ target



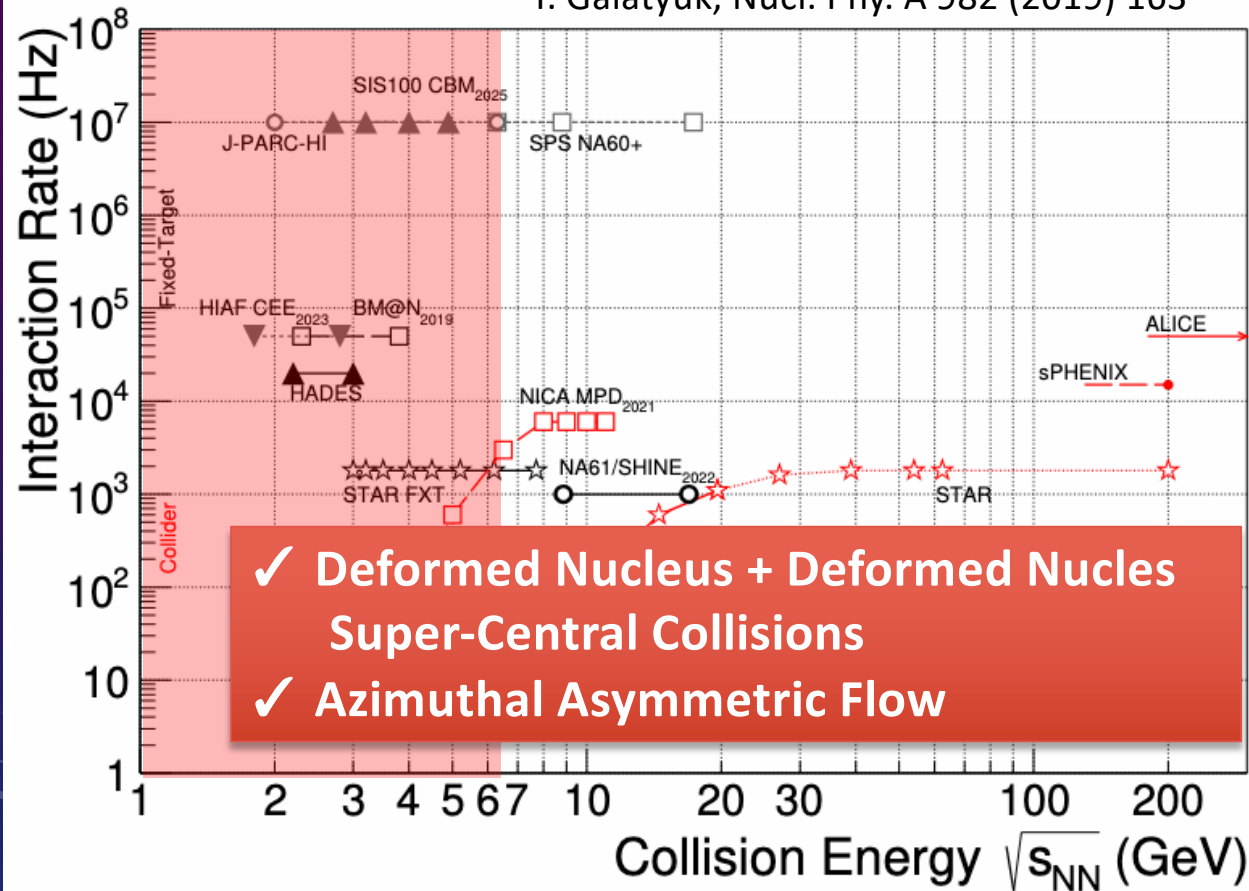
PMTs from CERN-NA44 H1 Hod.



Equation of State (EOS)

High Density Nuclear Matter vs Beam Energies

T. Galatyuk, Nucl. Phys. A 982 (2019) 163



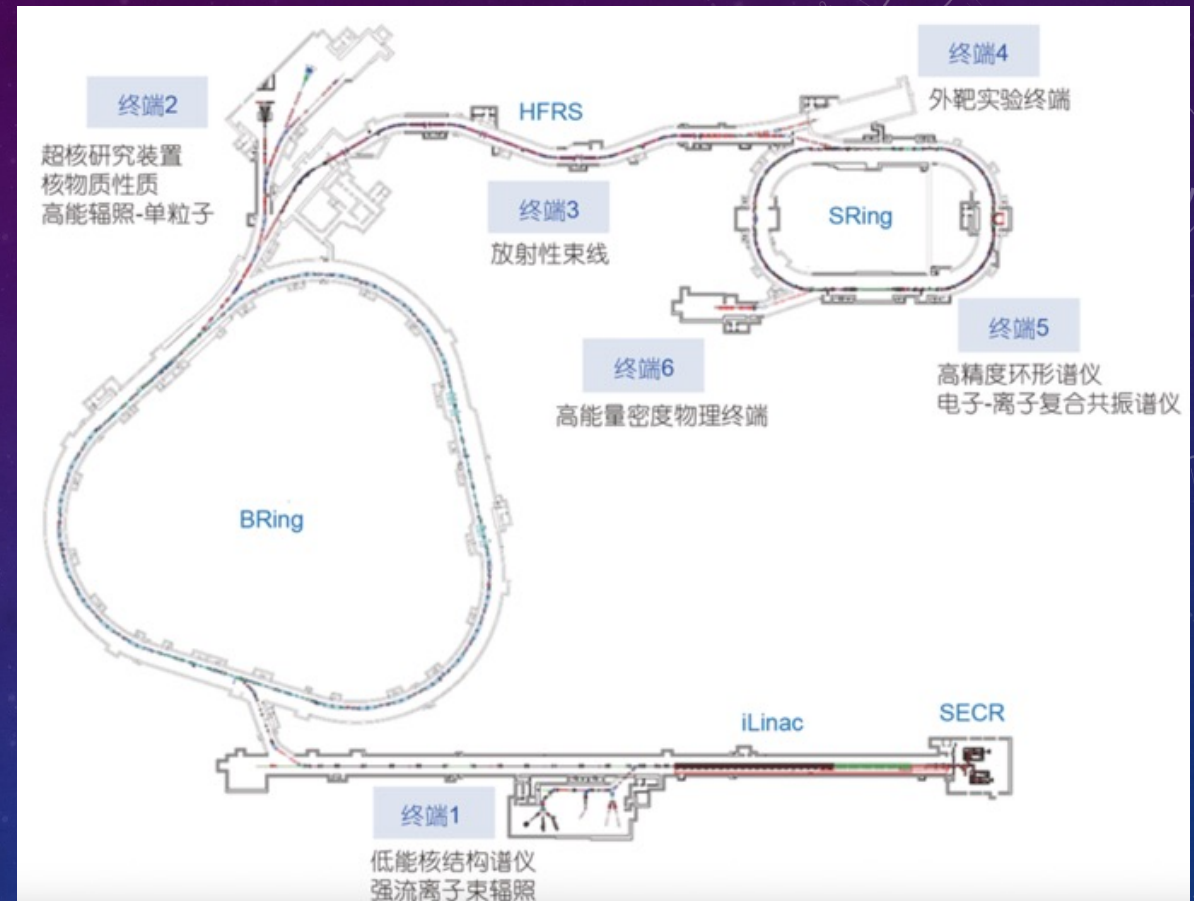
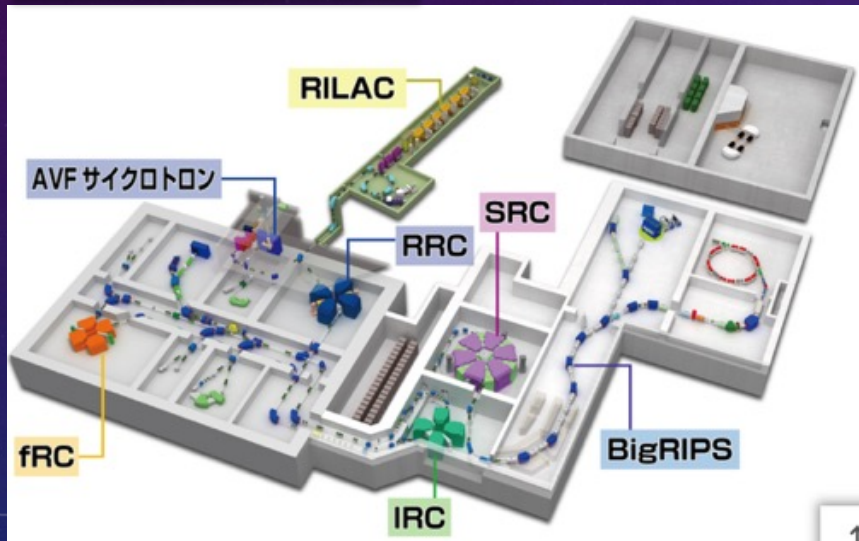
Neutron detection

- 1) High Density Nuclear Matter
 ↔ Neutron Star
- 2) Search for Rare Collisions
 Super Central Collisions ($b=0$)
 - ✓ Spherical Shape Nuclei
 - ✓ Deformed Shape Nuclei
- 3) Collective Flow
 - ✓ Radial Flow
 - ✓ v_1 (directed flow)
 - ✓ v_2 (elliptic flow)

Power of RI Production

FRIB
GSI FAIR

RIBF: ~ 345 MeV/u

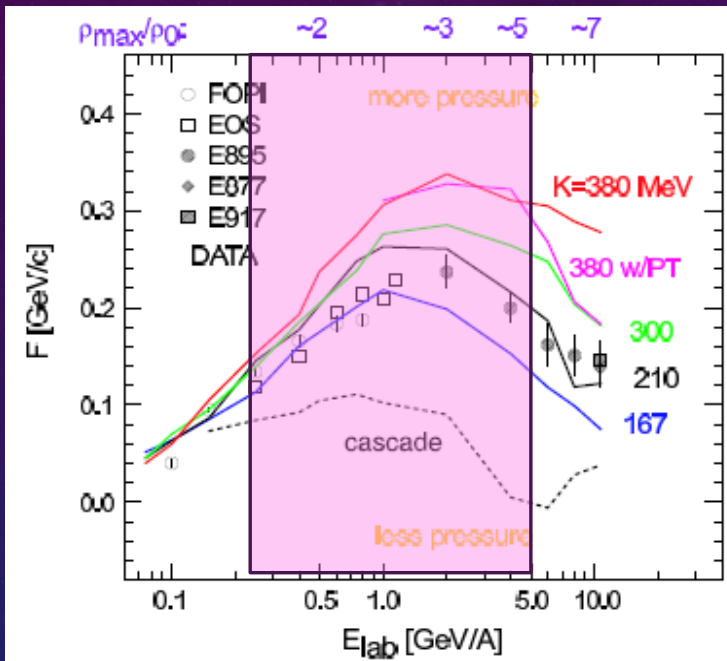


Experimental program has been started at HIAF!

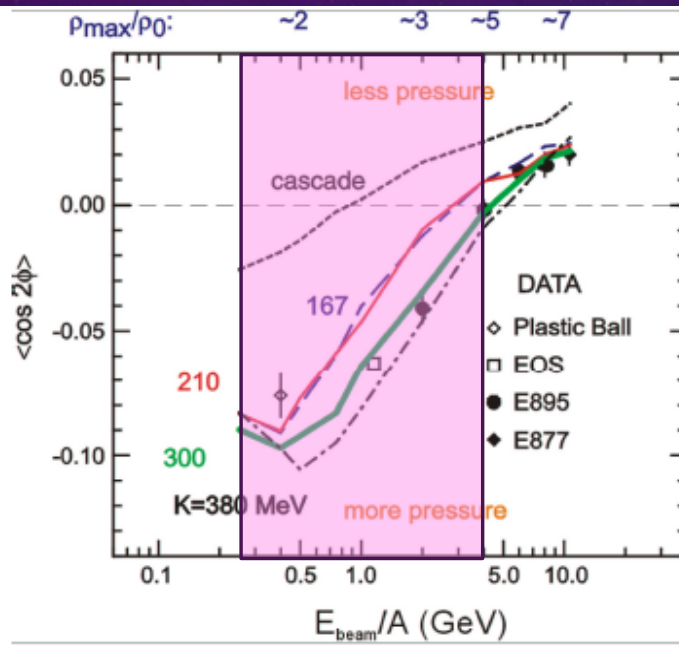
For example: ^{209}Bi ... 3×10^{10} particles / pulse, at $E = 800 \text{ MeV/u}$

High Density Matter and Collective Flow

$$\frac{dN}{d\phi}(y, p_t) = N_0[1 + 2V_1(y, p_t) \cos(\phi) + 2V_2(y, p_t) \cos(2\phi)]$$

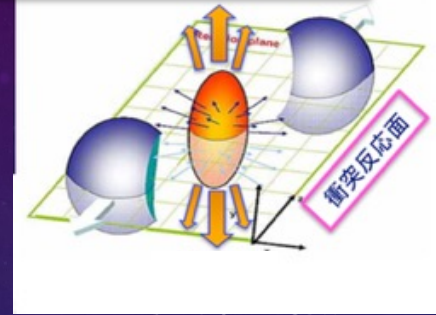


Directed flow

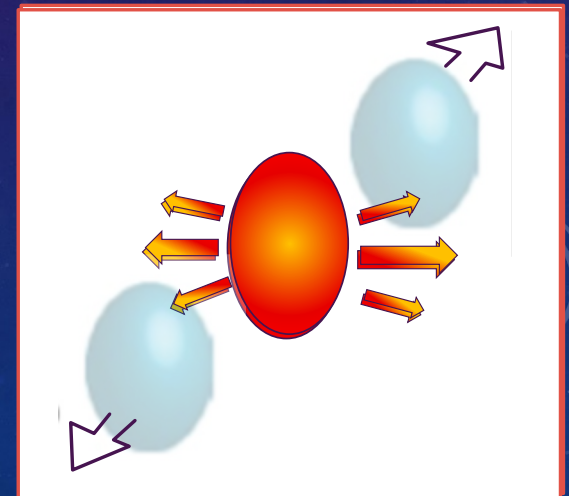


Elliptic Flow

Influence of Spectators



Super-Central Body-Body Collisions



P. Danielewicz, R. Lacey and W. G. Lynch, Science, 298 (2002), 1592A.
 Andronic et al., Phys. Lett. B612 (2005) 173.



<http://www.nucl.phys.tohoku.ac.jp/old/opencampus/articles/article1.html>

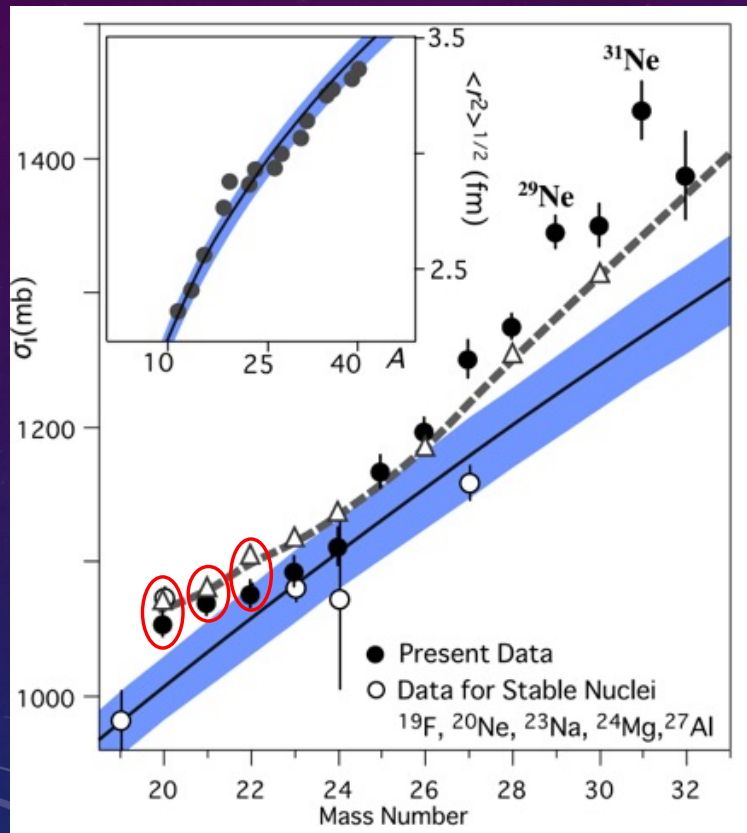
Deformed Nucleus-Nucleus Collisions

Most Deformed Nucleus

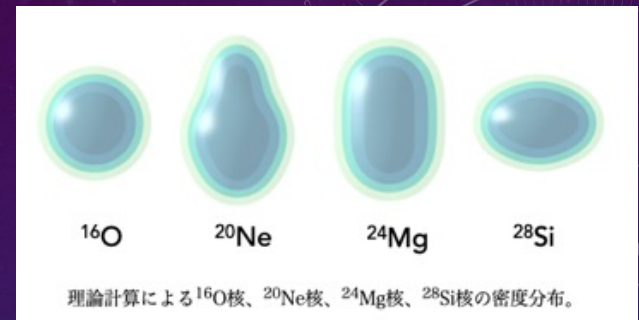
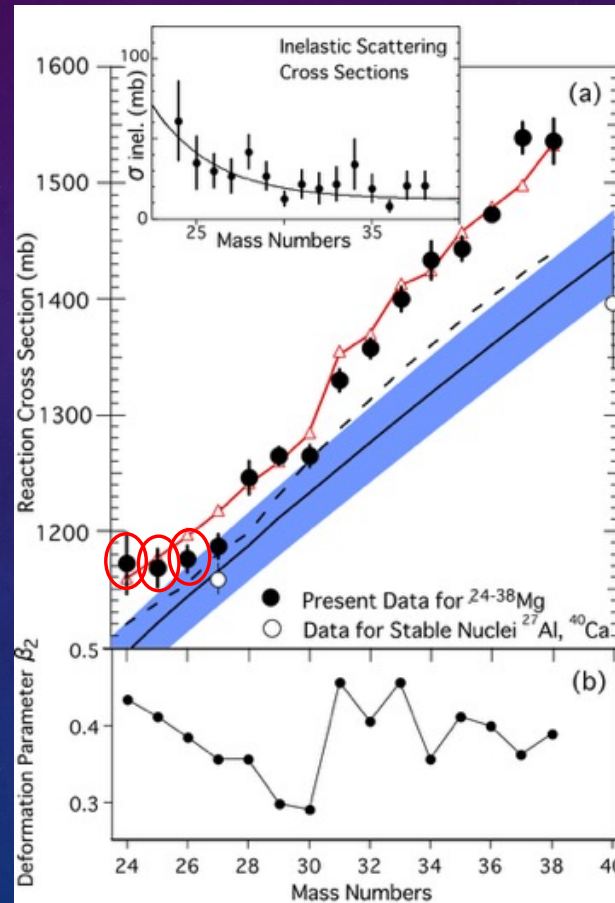
Deformed Nucleus-Nucleus Collisions Interaction Cross-Section Exp.

M. Takechi PLB 707 (2012) 357

M. Takechi PRC90, 061305 (R) 2014



Stable $^{20,21,22}\text{Ne}$



σ_i Integrated values

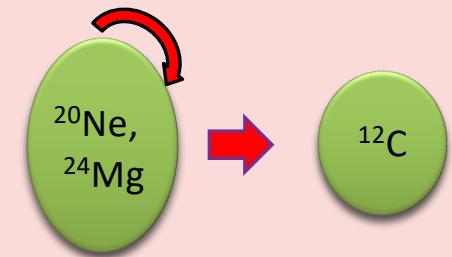


Variation of Deformation Parameter among Theory

^{20}Ne , ^{23}Na , ^{24}Mg , and ^{27}Al

S. Watanabe et al.,
PRC 89, 044610 (2014)

σ_1 Integrated values

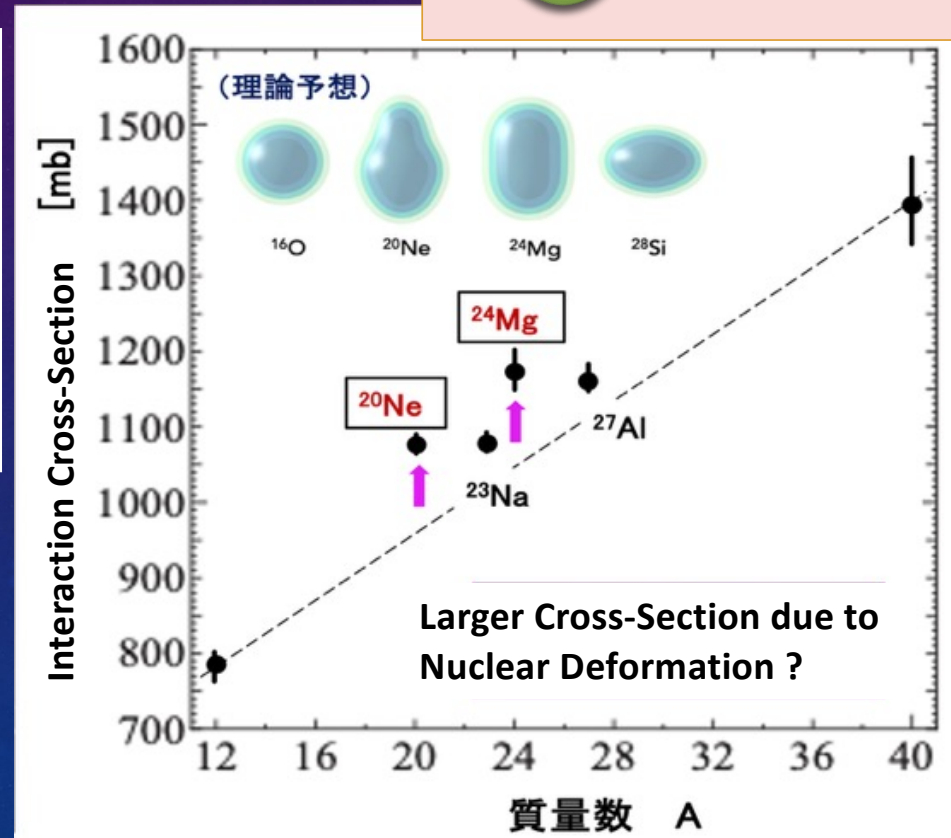


Theory β_2	NNDC	FRDM	CEA(p)	CEA(n)	AMD	KTUY α_2
^{16}O	0.353	-0.010	0	0		
^{20}Ne	0.72	0.364	0.68	0.662		0.164
^{23}Na		0.386	0.738	0.738		0.174
^{24}Mg	0.613	0.393	0.747	0.729	0.42	0.147
^{27}Al		-0.392	-0.464	-0.469		0.022

Nuclear Structure & Deformation of Nuclei

- (1) Excited States (In-beam gamma, decay)
- (2) Interaction cross-section
- (3) ::

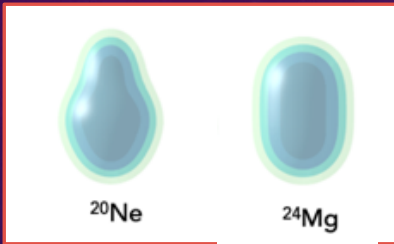
Experimental results suggest large deformation
for ^{20}Ne and ^{24}Mg



Azimuthal Asymmetry in Deformed Nucleus: Flow V_1 , V_2 , & V_3 in Central Collisions

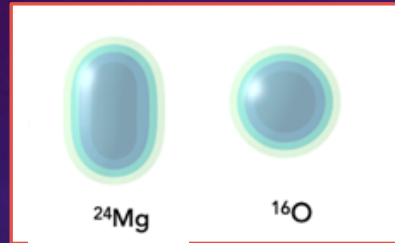
Beam

$^{20-22}\text{Ne}$, $^{24-26}\text{Mg}$



Target

$^{24-26}\text{Mg}$, ^{16}O



+

Theoretical calculation before experiment at HIMAC..

PHYSICAL REVIEW C **108**, 034607 (2023)

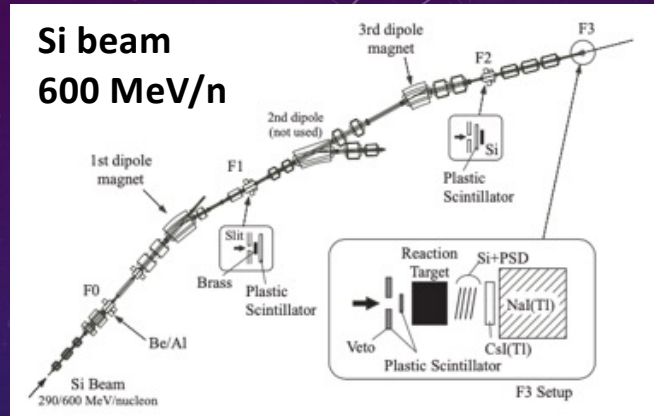
Impact of quadrupole deformation on intermediate-energy heavy-ion collisions

Xiao-Hua Fan,^{1,2} Zu-Xing Yang^{2,1,*}, Peng-Hui Chen,³ Shunji Nishimura² and Zhi-Pan Li¹

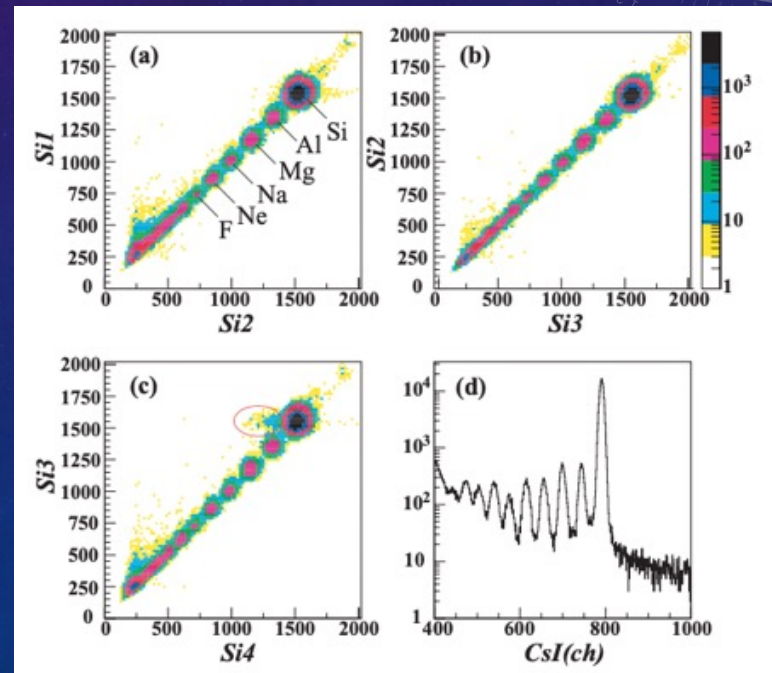
¹School of Physical Science and Technology, Southwest University, Chongqing 400715, China

²RIKEN Nishina Center, Wako, Saitama 351-0198, Japan

³College of Physics Science and Technology, Yangzhou University, Yangzhou, Jiangsu 225002, China

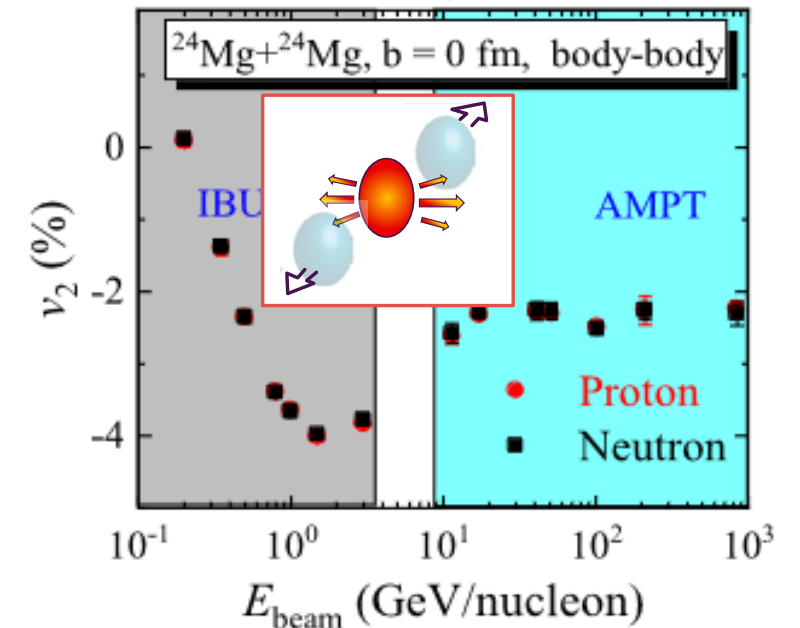
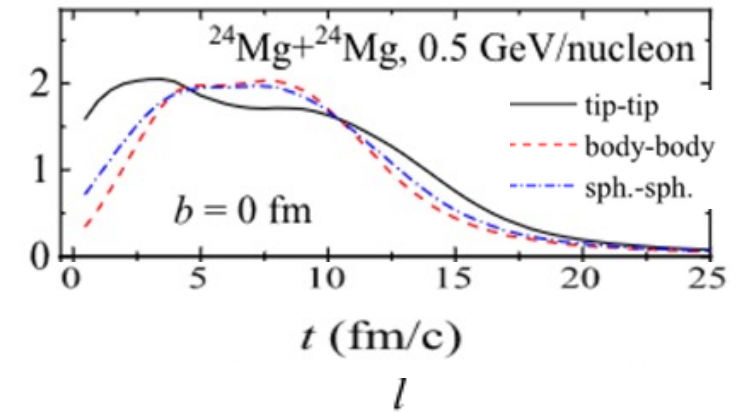
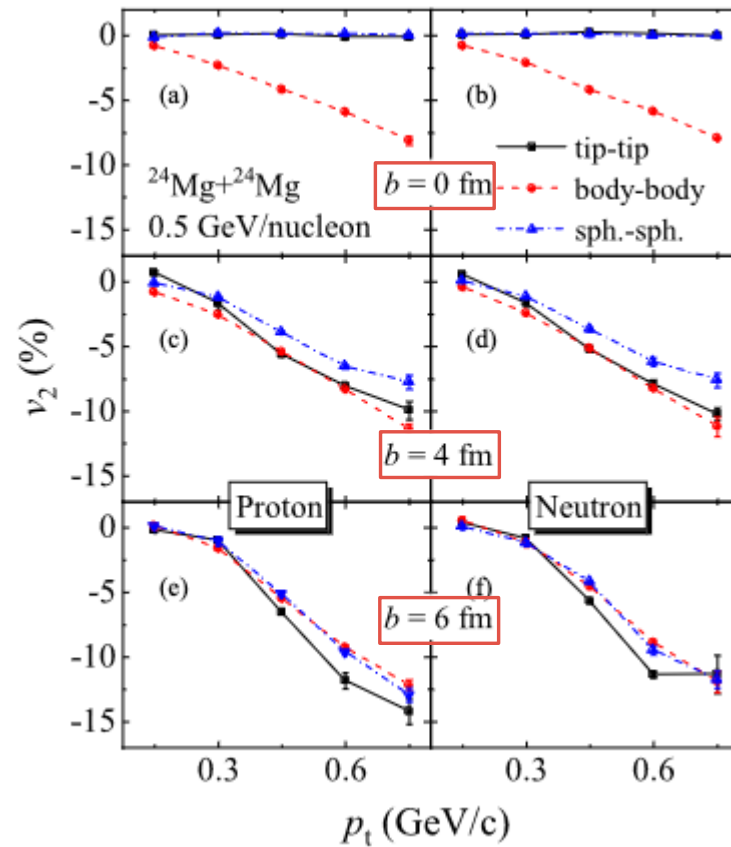
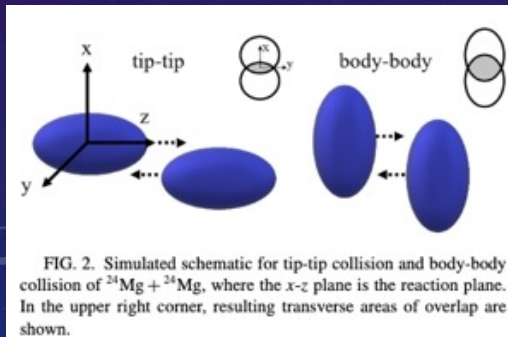
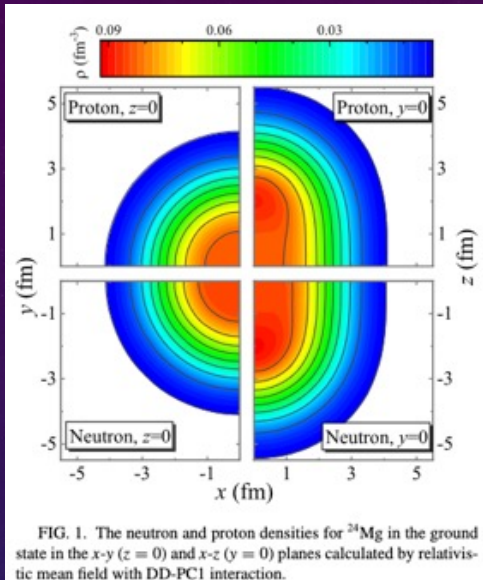


T. Yamaguchi et al., PRC 82, 014609



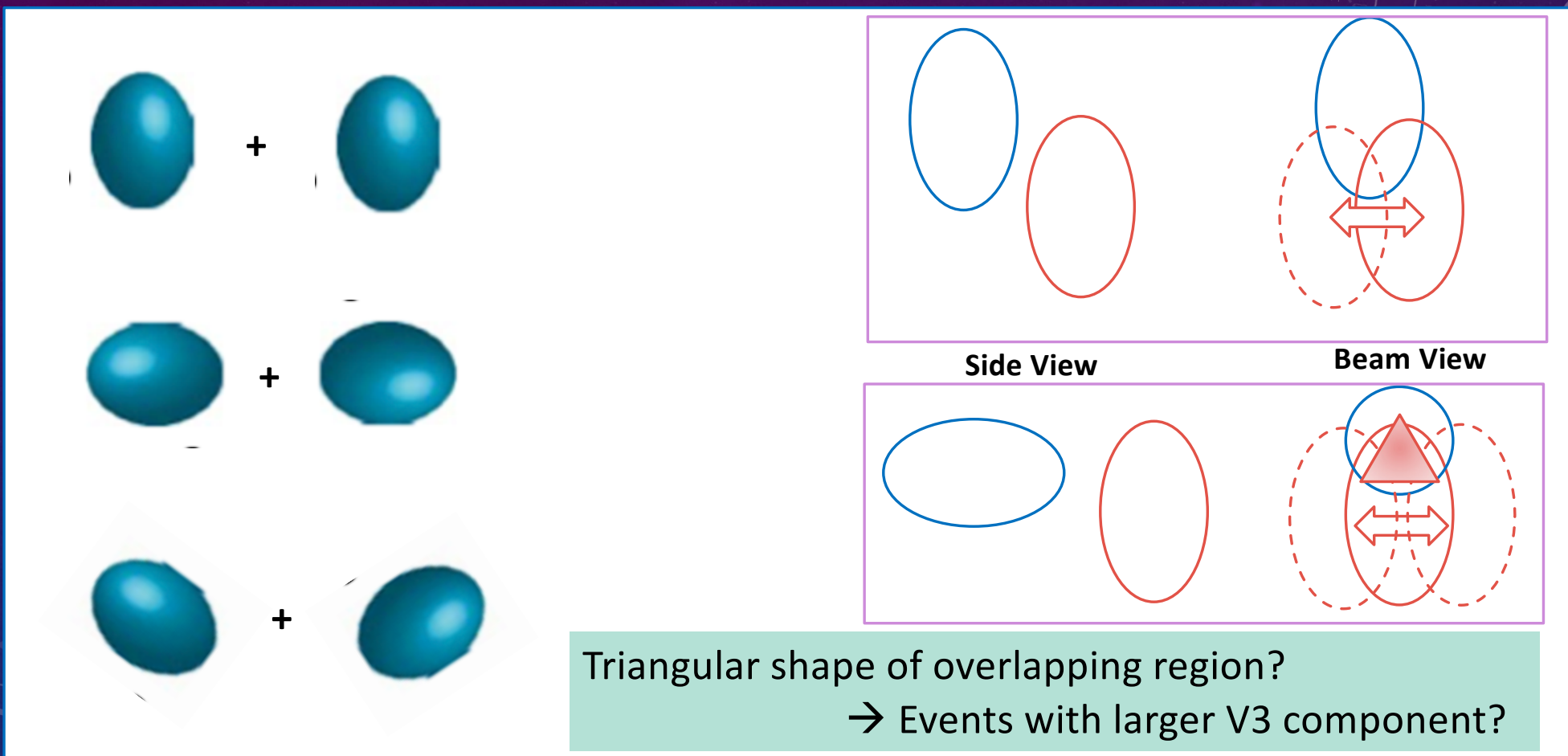
$^{24}\text{Mg} + ^{24}\text{Mg}$ Collision (0.5 GeV/n)

X-H. Fan, Z-X. Yang, P-H. Chen, SN, Z-P. Li,
PRC 108, 034607 (2023)



No Shadowing / Compression Effects
by the Spectators

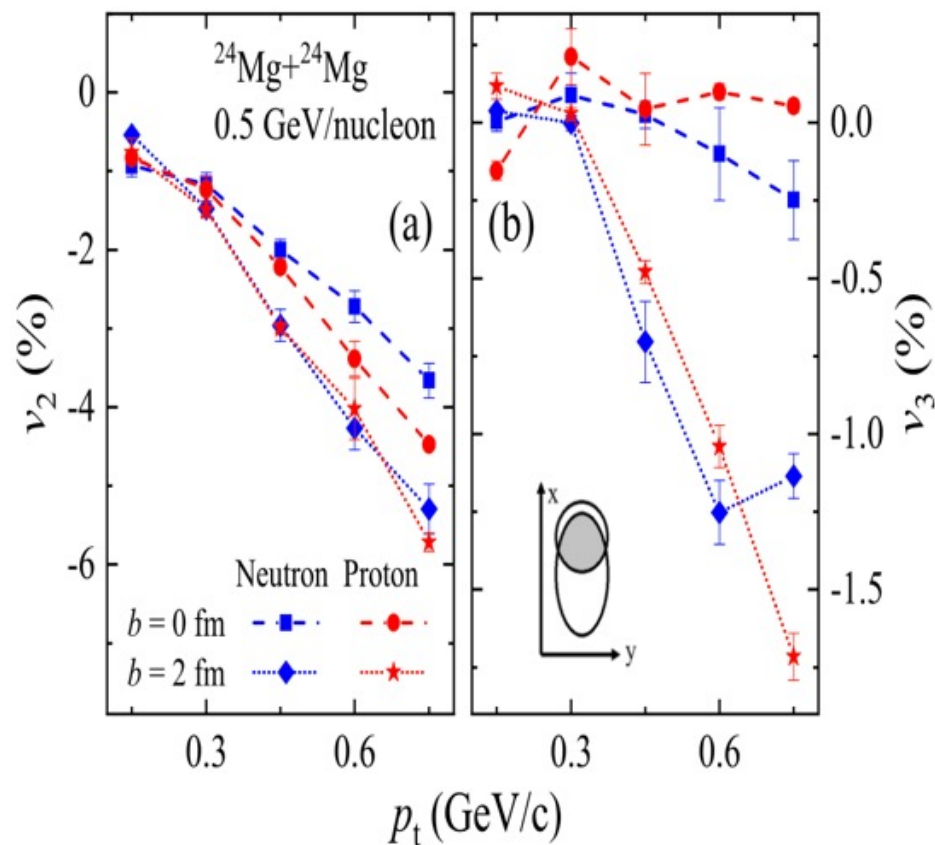
Deformed Nuclear Collisions



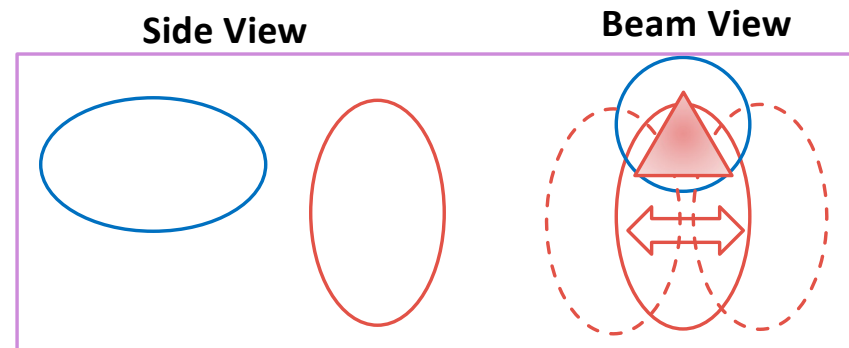
Various Type of Collisions → High intensity beam & fast data taking system / trigger Needed.

Deformed Nucleus + Nucleus Collisions

Initial geometrical collisions vs Flows (V_1, V_2, V_3, \dots)



Various types of collision pattern



Triangular shape of overlapping region?
→ V_3 component appears.

HIMAC stopped delivering high energy heavy-ion beam...

Deformed Nucleus + Nucleus Collisions

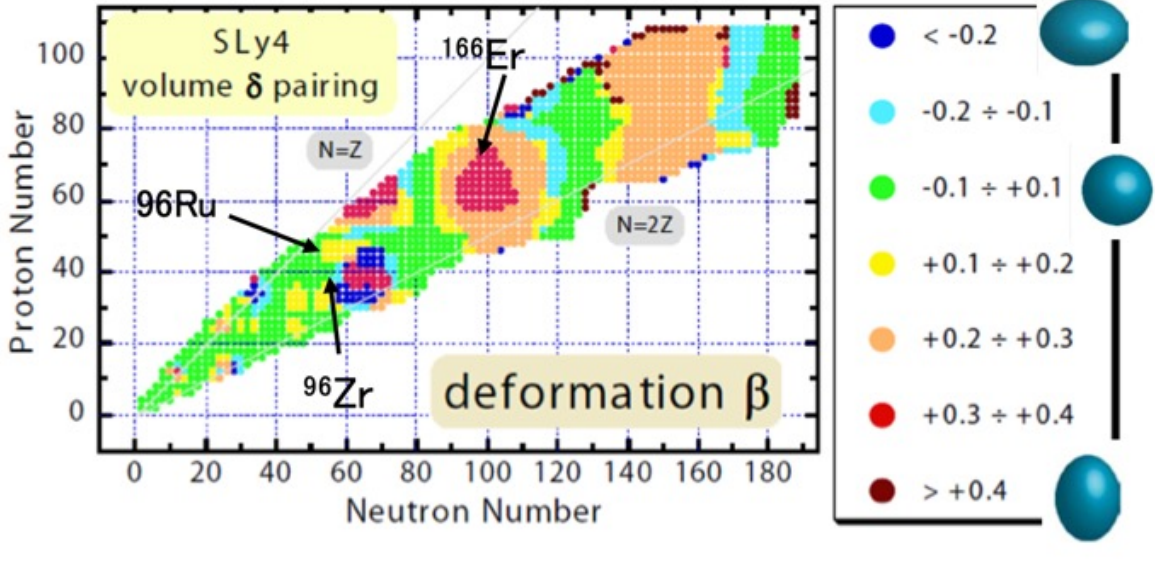
Heavier Nucleus

Idea of Deformed Nucleus + Nucleus Collisions

$^{166}\text{Er} + ^{166}\text{Er}$ Collisions (2.1 GeV/n)

A. Rosenhauer, J.A. Maruhn, H. Stocker, and W. Greiner
 Phys. Lett. 159B, (1985)

Stoitsov, PRC68 (2003) 054312



Tip-Tip

Body-Body

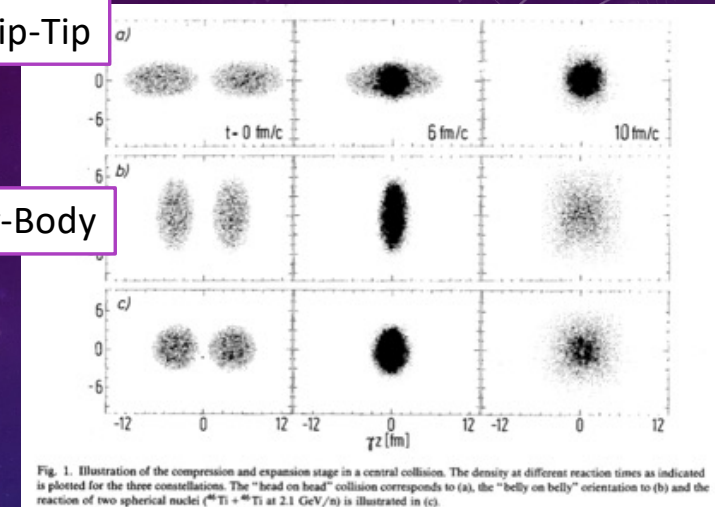


Fig. 1. Illustration of the compression and expansion stage in a central collision. The density at different reaction times as indicated is plotted for the three constellations. The "head on head" collision corresponds to (a), the "belly on belly" orientation to (b) and the reaction of two spherical nuclei ($^{48}\text{Ti} + ^{48}\text{Ti}$) at 2.1 GeV/n is illustrated in (c).

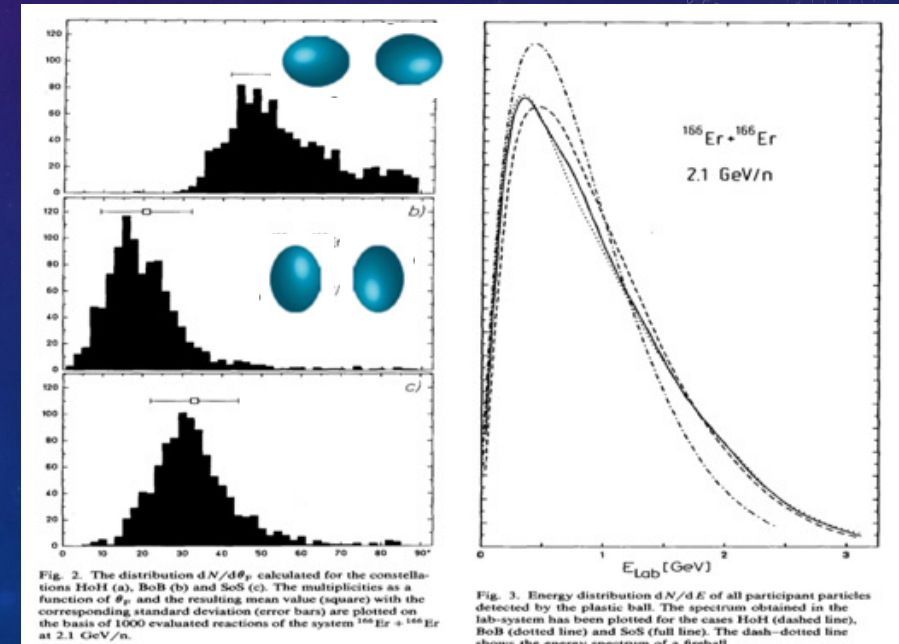


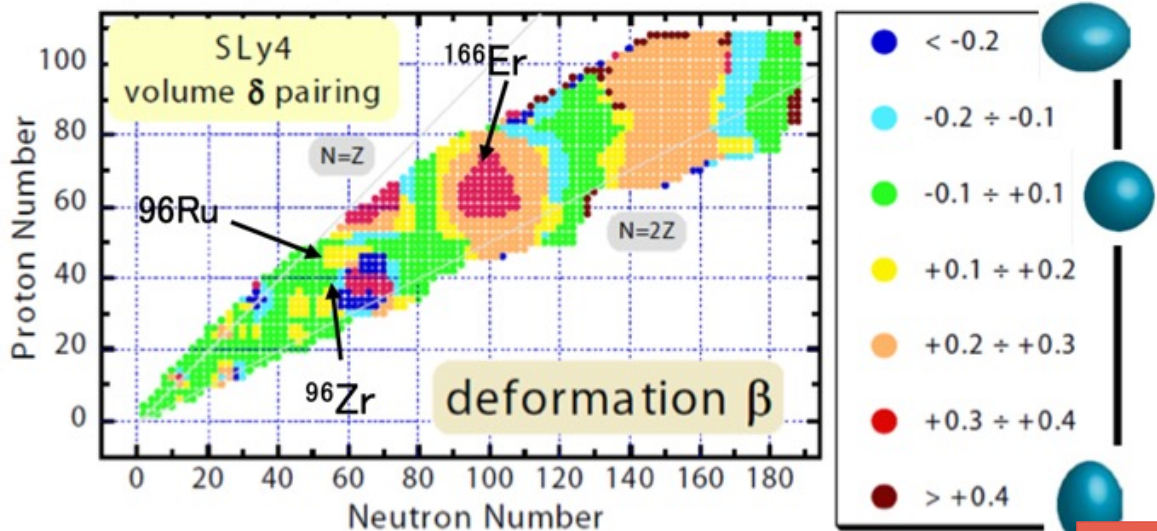
Fig. 2. The distribution $dN/d\theta_p$ calculated for the constellations HoH (a), BoB (b) and SoS (c). The multiplicities as a function of θ_p and the resulting mean value (square) with the corresponding standard deviation (error bars) are plotted on the basis of 1000 evaluated reactions of the system $^{166}\text{Er} + ^{166}\text{Er}$ at 2.1 GeV/n.

Fig. 3. Energy distribution dN/dE of all participant particles detected by the plastic ball. The spectrum obtained in the lab-system has been plotted for the cases HoH (dashed line), BoB (dotted line) and SoS (full line). The dash-dotted line shows the energy spectrum of a fireball.

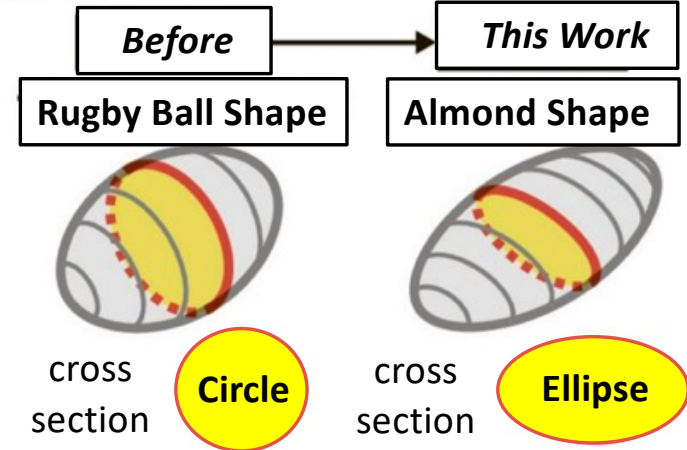
Deformed Nucleus-Nucleus Collisions : $^{166}\text{Er} + ^{166}\text{Er}$

A. Rosenhauer, J.A. Maruhn, H. Stocker, and W. Greiner
 Phys. Lett. 159B, (1985)

Stoitsov, PRC68 (2003) 054312



Nuclear Shape of ^{166}Er



T. Otsuka, Y. Tsunoda et al.,
 Eur. Phys. J. A (2025) 61:126
 "Prevailing triaxial shapes in atomic nuclei and
 a quantum theory of rotation of composite objects"

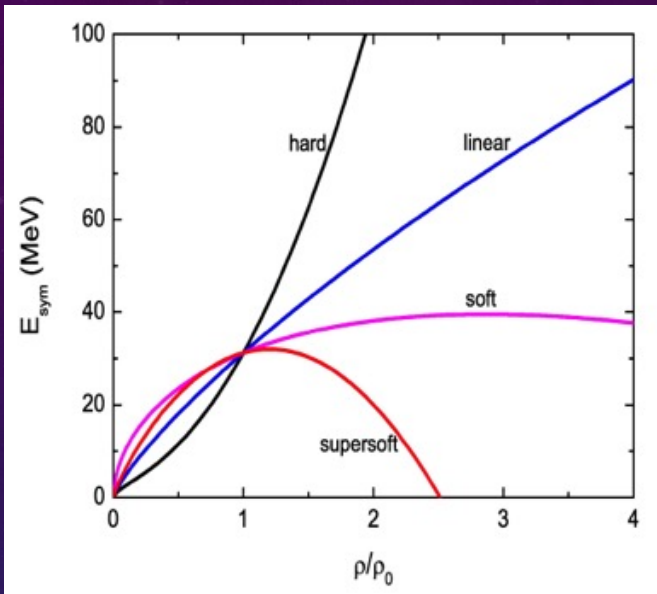
Super-Central Head-Head Collisions

- Highest density, multiplicities
- Azimuthal asymmetric collision geom.
- Spectator free



High Density Matter using Heavy-Ion Collisions

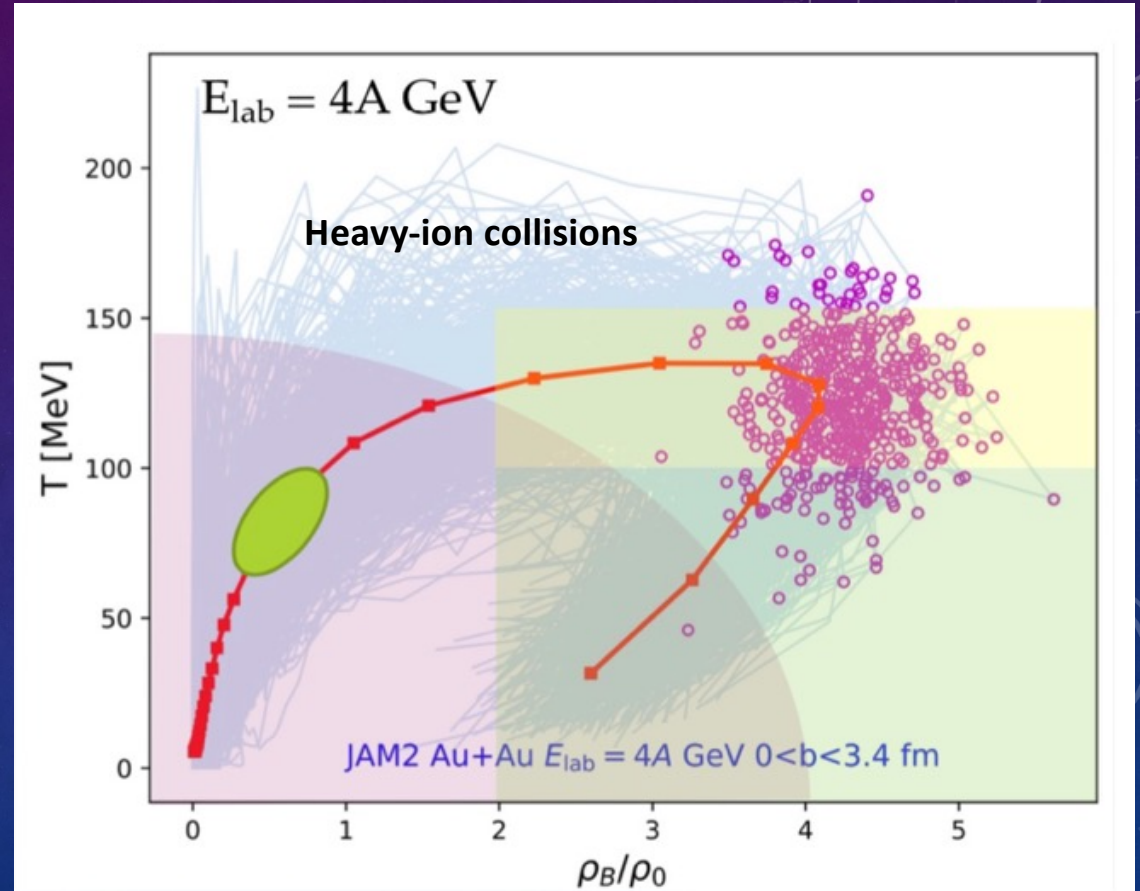
Nara, Ohnishi, Jinno, Murase...



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

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

(100 % neutron $\rightarrow \delta = 1$)



Equation of State of High-Density (Neutron-Rich) Matter

Stable Nucleus + Nucleus Collisions or Unstable Nucleus + Nucleus Collisions
(High intensity beam is required.)

Experimental observables: Collective Flows (v_1 , v_2)

→ Asymmetric Collision Geometry

Centrality: Non-Central Collisions

→ “Super-Central Deformed Nucleus + Nucleus Collisions” is ideal to create high density matter. (Tip-Tip & Body-Body Collisions)

→ Lower Energy Heavy-Ion Collisions → “Spectator Free” in v_2 observable.

Issues & Questions:

Complex Collision Condition: (Deformation Axis)² & Impact parameter

→ Can we identify the collision type? → Spectator, Multiplicity information.

→ Can we proof the nuclear shape via heavy-ion collisions?

$^{238}\text{U} + ^{238}\text{U}$ Collisions

The background features a gradient from dark purple to blue, overlaid with a field of small white stars. On the right side, there are several technical diagrams: a large circular scale with numerical markings from 80 to 210, concentric circles with arrows indicating rotation, and dashed lines with arrows pointing in various directions.

Deformed Nucleus-Nucleus Collisions ($^{238}\text{U} + ^{238}\text{U}$) at 1 GeV/n

Z.X. Yang, X.H. Fan, Z.P. Li, S.Nishimura, PLB 848 (2024) L38359

Mar. 5, 2024

Research Highlight

Physics / Astronomy

AI tool reveals the orientation of nuclei in heavy-ion collisions

The orientation of deformed atomic nuclei in particle collisions can be determined using a newly developed neural network

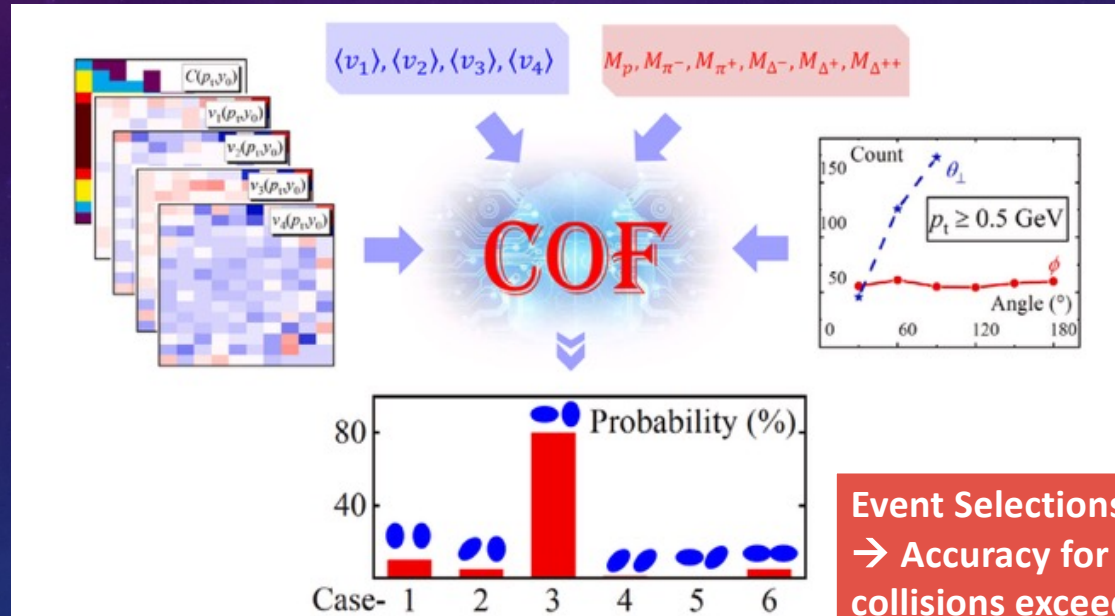
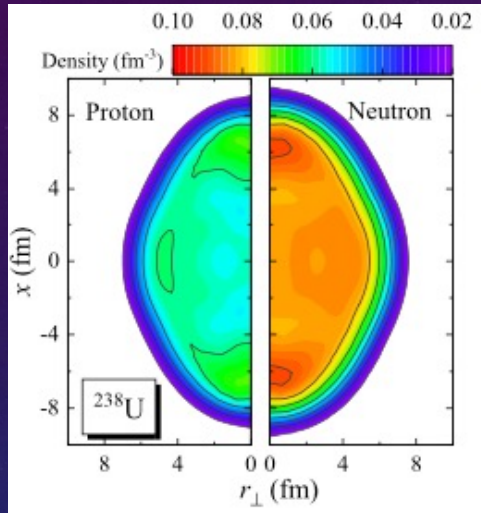
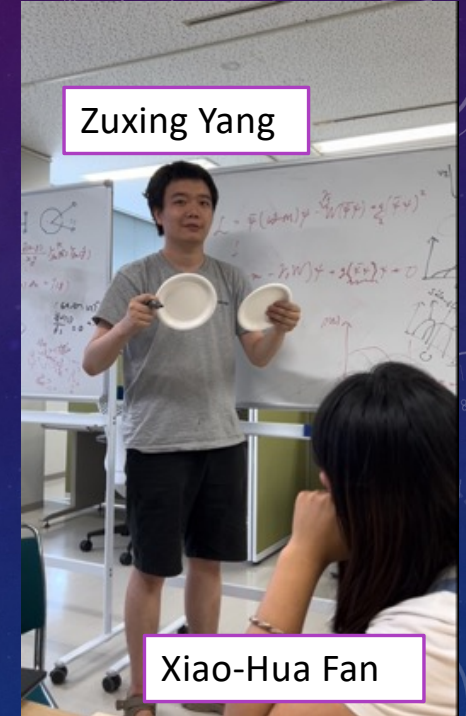
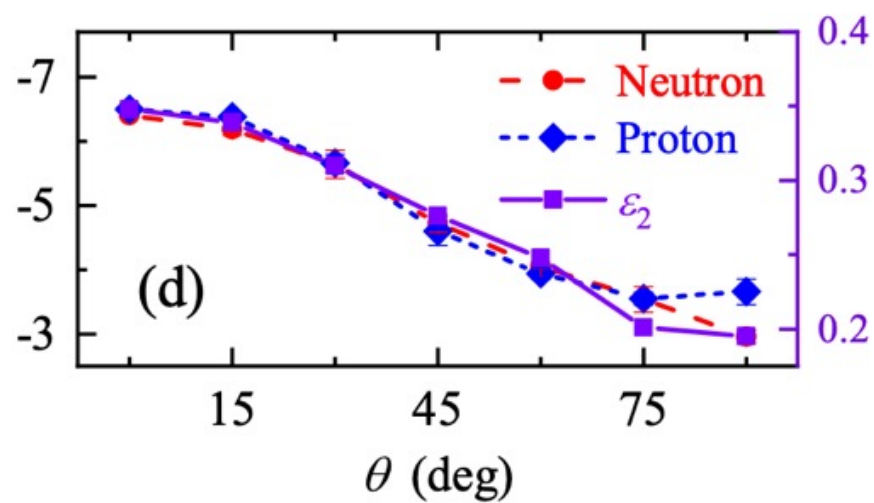
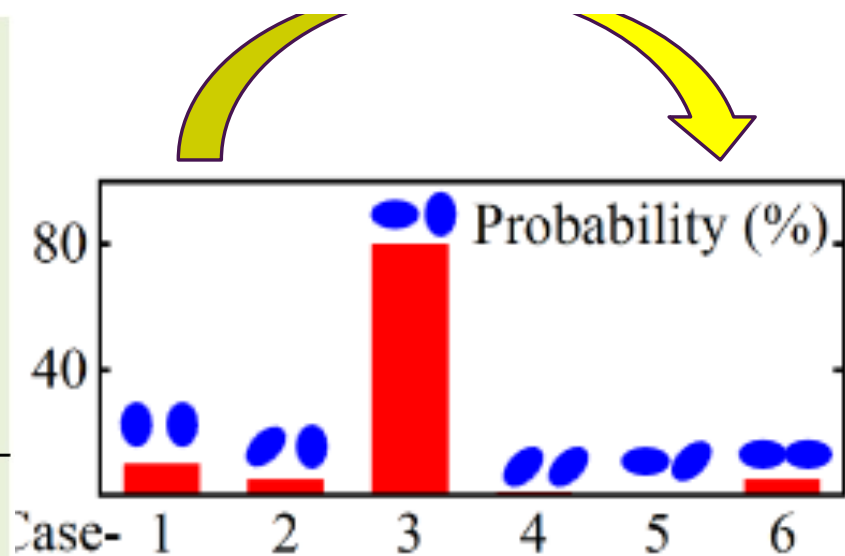
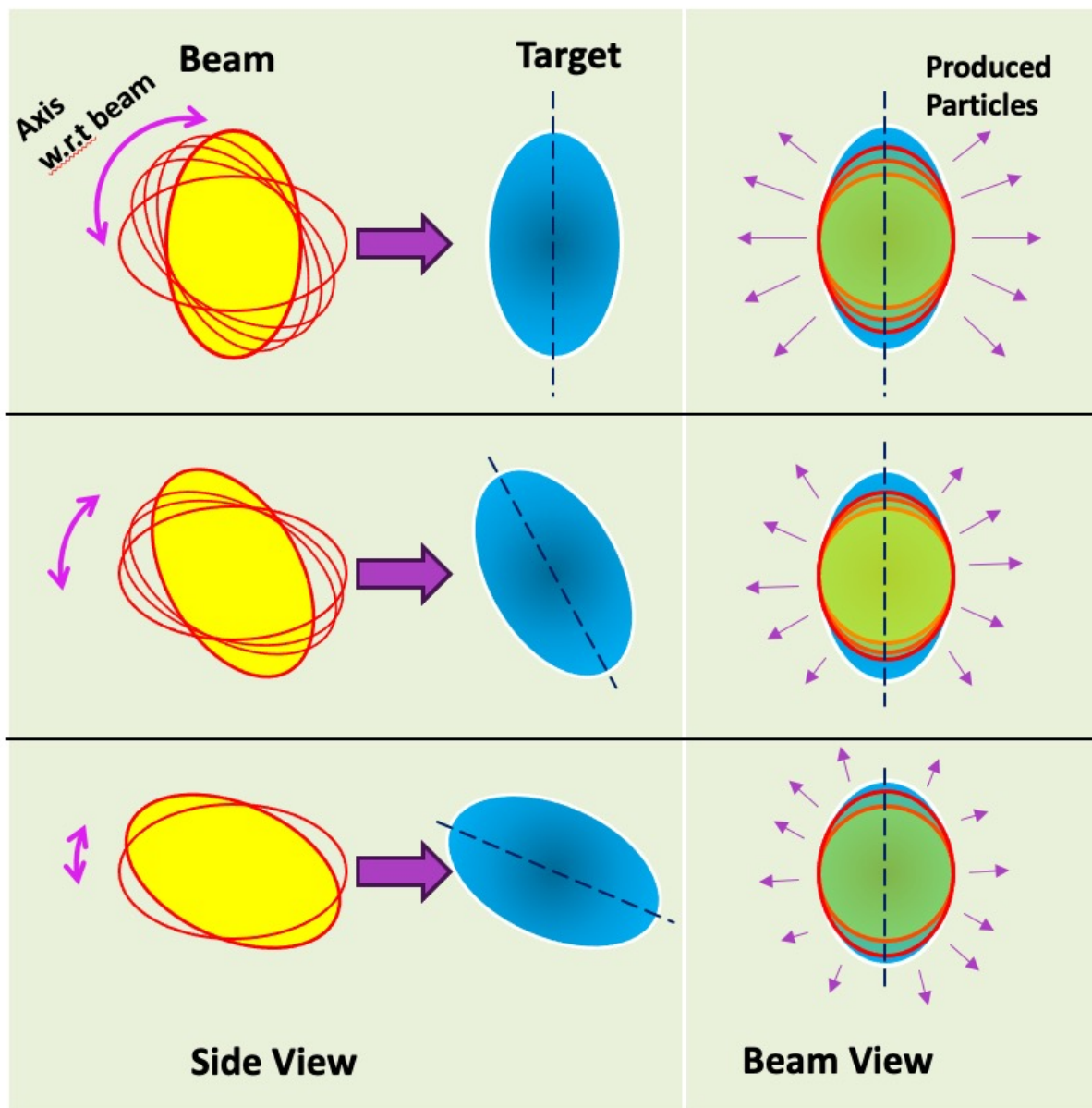


Fig. 4. Schematic diagram of the structure of the convolutional orientation filter (COF) neural network.



Event Selections: Beam Spectator Suppressed.
 → Accuracy for both tip-tip and body-body collisions exceeds 80%. (Demonstration)

Nature Vol 635, Nov. 2024
 (STAR Collaboration)



The background is a dark blue gradient with faint technical diagrams. On the right side, there are circular diagrams with concentric circles and radial lines, resembling a scale or a gauge, with numbers like 100, 120, 140, 160, 180, 190, and 200. There are also dashed lines and arrows indicating directions. In the bottom right, there are more circular diagrams with arrows. The overall theme is scientific or technical.

Directed and Elliptic Flow

proton, neutron, π^+ , d, ...

EOS & Elliptic Flow in $^{238}\text{U} + ^{238}\text{U}$ Collisions at 500 MeV/n

Z-X. Yang, X-H. Fan, Z.P. Li, S. Nishimura
 Phys. Rev. C 112, 024606 (2025)

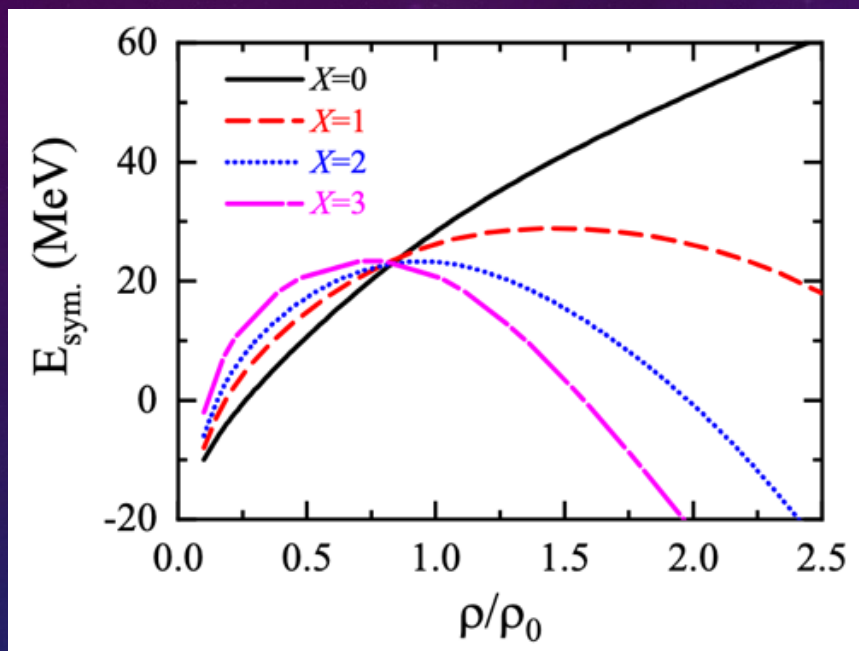


FIG. 4. Density-dependent symmetry energy $E_{\text{sym.}}$ with different symmetry energy parameters X .

V2 for $\pi^{+/-}$, $K^{+/-}$ might be more interesting..

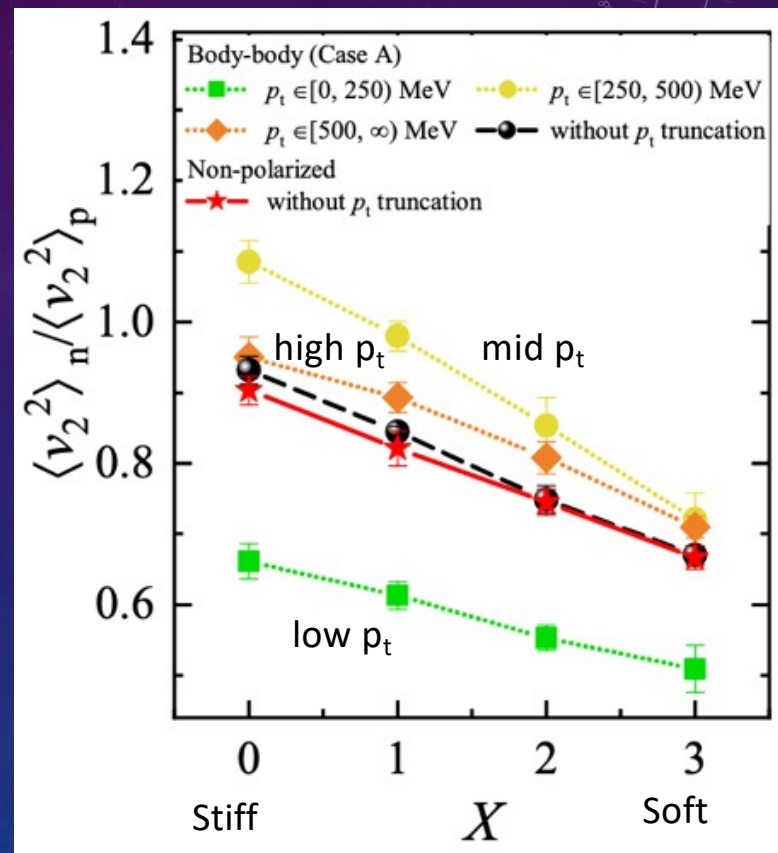


FIG. 7. The $\langle v_2^2 \rangle_n / \langle v_2^2 \rangle_p$ ratio as a function of the symmetry energy parameter with body-body (case A) and nonpolarized collisions. Different colors represent the truncation of transverse momentum over different intervals.

Study on Heavy-Ion Collisions at HIAF (Simulation & AI)

$^{24}\text{Mg} + ^{24}\text{Mg}$ Collisions

PHYSICAL REVIEW C **108**, 034607 (2023)

Impact of quadrupole deformation on intermediate-energy heavy-ion collisions

Xiao-Hua Fan,^{1,2} Zu-Xing Yang^{2,1,*}, Peng-Hui Chen,³ Shunji Nishimura² and Zhi-Pan Li¹

¹School of Physical Science and Technology, Southwest University, Chongqing 400715, China

²RIKEN Nishina Center, Wako, Saitama 351-0198, Japan

³College of Physics Science and Technology, Yangzhou University, Yangzhou, Jiangsu 225002, China

$^{238}\text{U} + ^{238}\text{U}$ Collisions

Phys. Lett. B **848** (2024) 138359



A neural network approach for orienting heavy-ion collision events

Zu-Xing Yang^{a,b,}, Xiao-Hua Fan^{b,a,}, Zhi-Pan Li^b, Shunji Nishimura^a

^aRIKEN Nishina Center, Wako, Saitama 351-0198, Japan

^bSchool of Physical Science and Technology, Southwest University, Chongqing 400715, China

Exploring the nuclear momentum anisotropy based on intermediate-energy heavy-ion collisions

Xiao-Hua Fan^{a,b,c}, Zu-Xing Yang^{b,a}  , Peng-Hui Chen^d, Zhi-Pan Li^a, Wei Zuo^{e,f}, Masaaki Kimura^b, Shunji Nishimura^b

Cross-checking the geometric effects in heavy-ion collisions at 500 MeV/nucleon

Zu-Xing Yang^{1,2,} Xiao-Hua Fan^{2,3,1,*}, Zhi-Pan Li², and Shunji Nishimura¹

Phys. Rev. C **112**, 024606 – Published 8 August, 2025

DOI: <https://doi.org/10.1103/fnzz-vxgq>

Physics Letters B

Volume 866, July 2025, 139503

Summary

© Study on EOS of high density (neutron-rich) matter is interesting topics.
→ Understanding the inside of neutron star (NS) and NS-NS merger

© Pilot experiment was conducted to study on directed flow of proton and neutron using $^{132}\text{Xe} + \text{CsI}$ collisions at 400A MeV

- Consistent result with FOPI experiment (proton)
- First case of direct comparison of neutron V_1 at target rapidity
- Smaller V_1 for neutron w.r.t. proton ? (to be confirmed).

© Future program for heavy-ion collisions

- V_1 and V_2 (& V_3) in deformed nucleus + nucleus collisions
- “sunny weather” below $E_{\text{lab}} < 10 \text{ AGeV}$
- Feedback to the nuclear structure physics
 - nuclear shape, super-heavy exp., transmutation, medical, ...

Niida, Miyake, AAPS Bulletin (2021) 31:12

