The 2nd International Workshop on Physics at High Baryon Density
(PHD2025, 第二届高重子密度物理国际研讨会)

Oct. 17, 2026

A Possible Study of Collective Flows in Low-Energy Collisions of Deformed Nuclei

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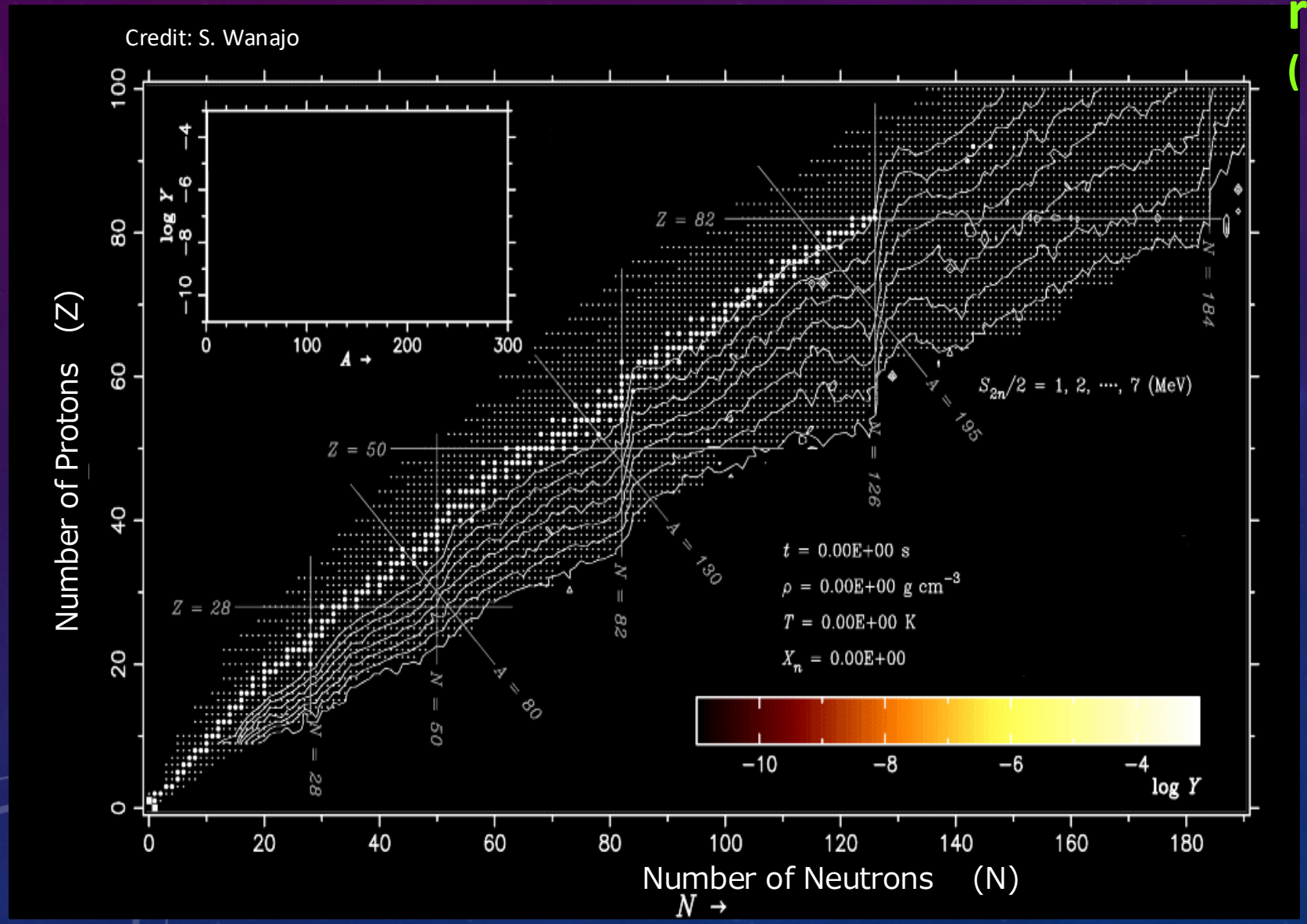
Keywords:
- High-Density Nuclear Matter
- Neutron Star
- Intersection of low & high energy nuclear physics

Nuclear Physics: Bridging Discoveries with Astrophysics



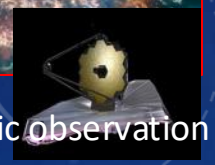
r-Process Nucleosynthesis

(rapid neutron capture process)

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

Neutron Star Merger

Supernovae

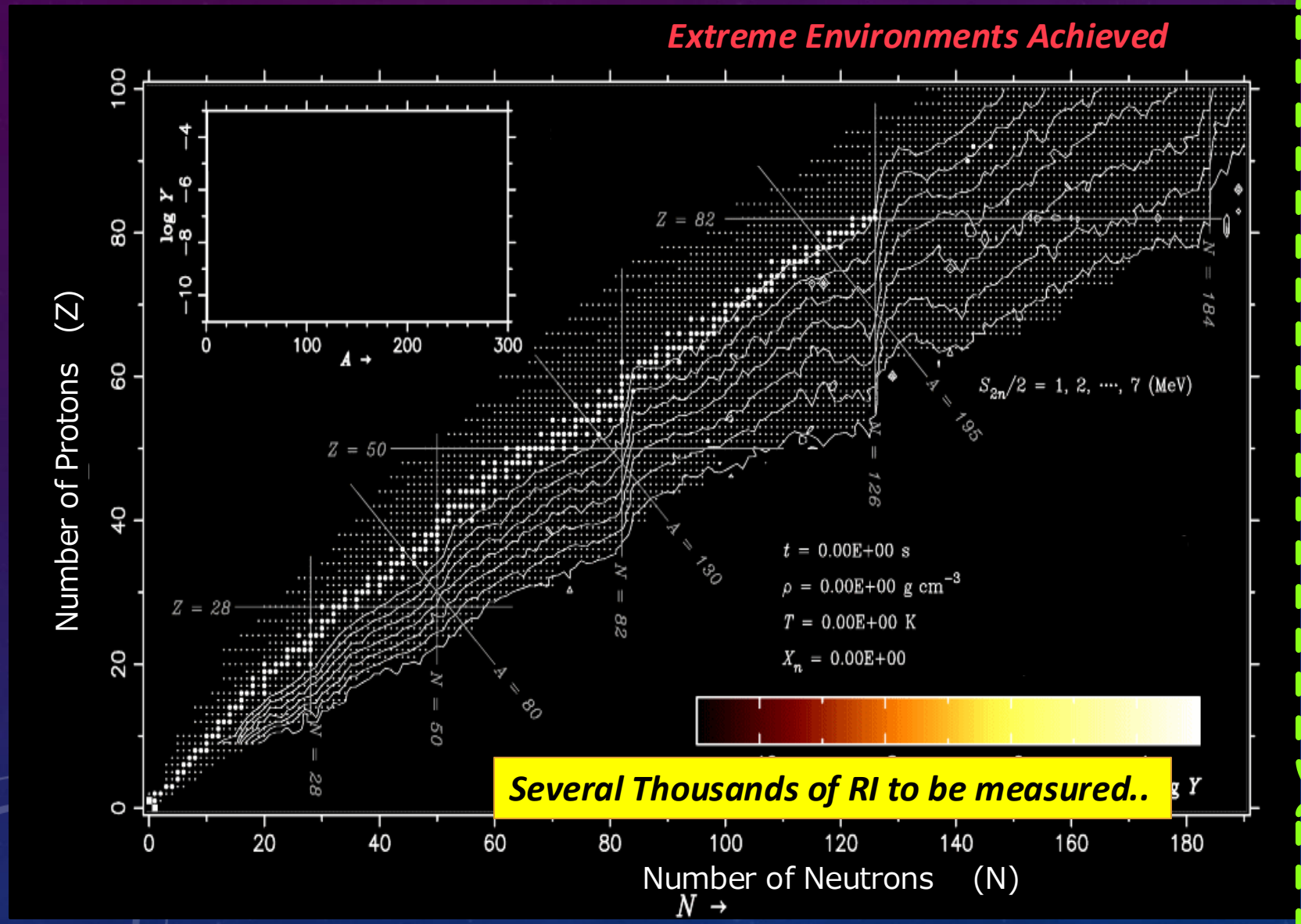


Gravitational wave observation

Electromagnetic observation

Connections with those observations

Required Inputs from Nuclear Physics for r-Process



◎ Masses:
- Determine the r-process path, global structure

◎ Beta-decays:
Half-lives:
- Speed of producing heavy elements

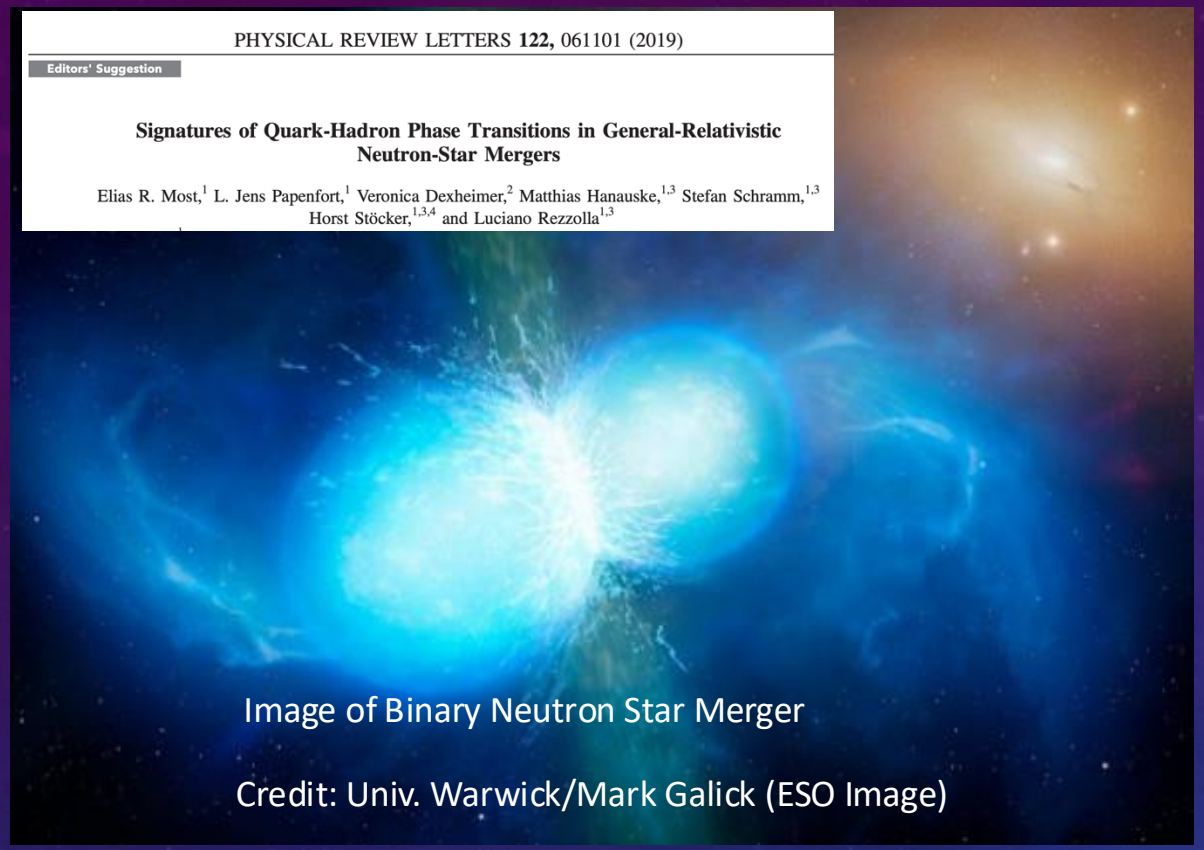
Beta-delayed neutron emissions:
- Determine the fine structure of r-elements
- Recapture of neutrons

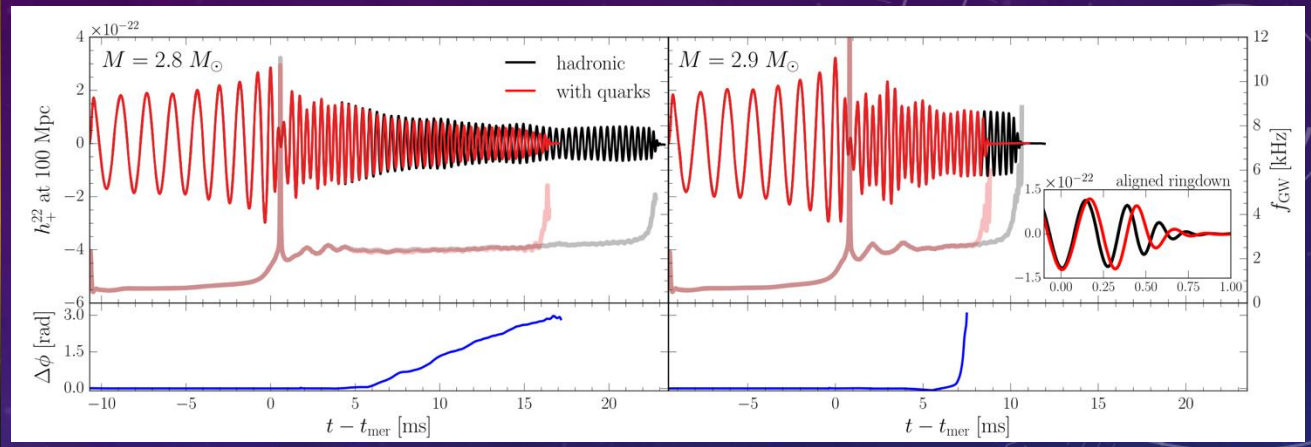
◎ Nuclear reactions ←→ Masses
- Determine the r-process path

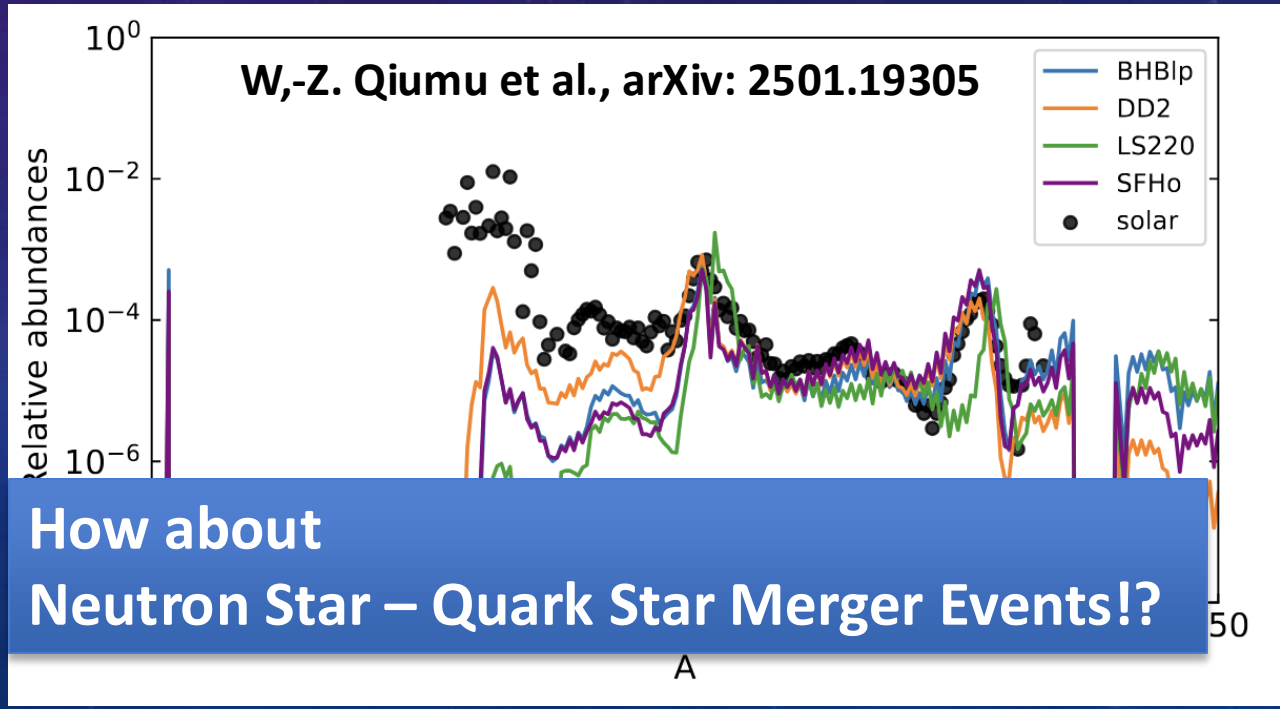
◎Fission recycling:
- Production of heavy elements

◎Equation of State:
- Explosive conditions of NS-NS, SN

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



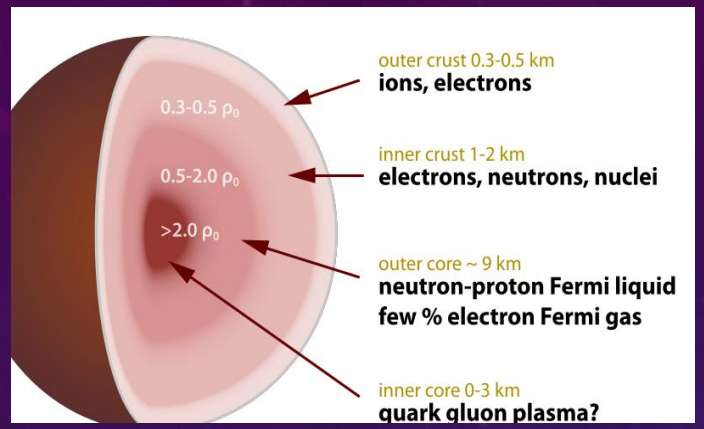




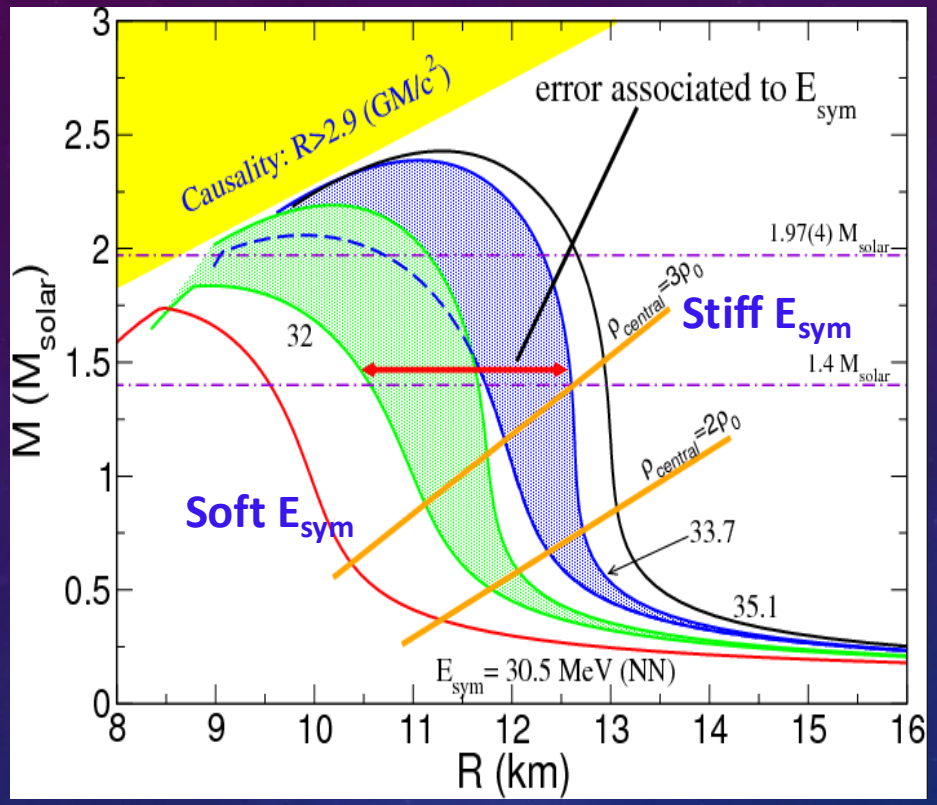
- EOS, Compressibility
  → Supernovae, Neutron-star merger
- r-process nucleosynthesis

How about
Neutron Star – Quark Star Merger Events!?

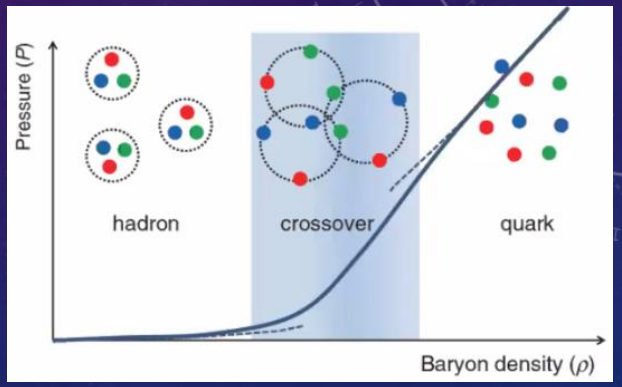
Neutron Star and Equation of State (EOS)

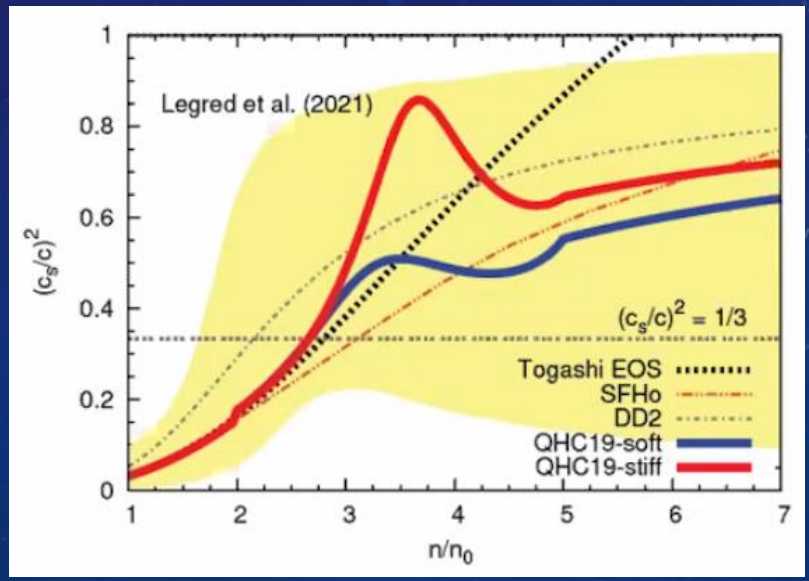


M vs R



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





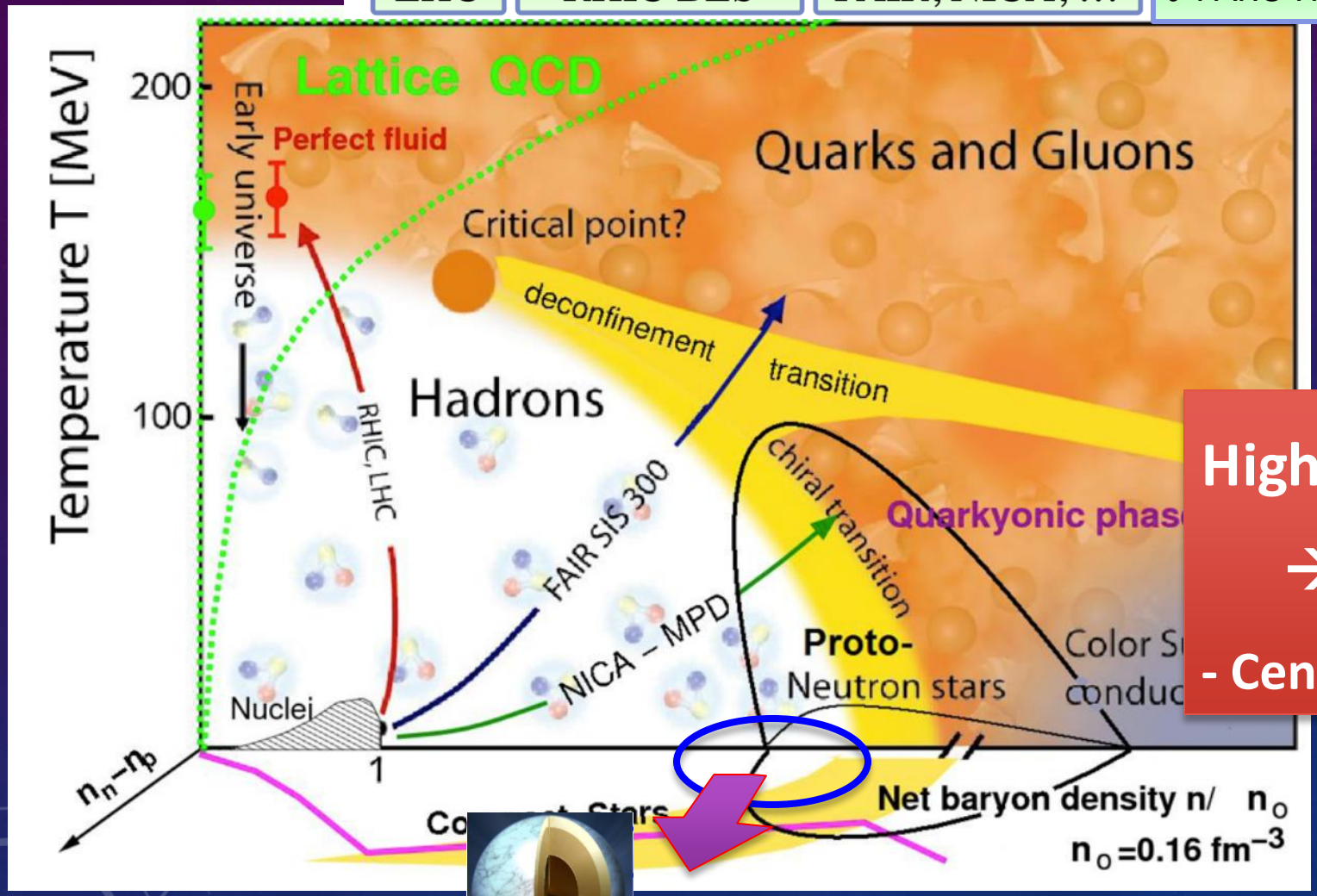
Heavy Neutron Star
(~ 2 $M_\odot$!)

Radius-Mass ←→ EOS of High Density Neutron Matter

FAIR/J-PARC-HI can provide high density nuclear matter !
~ 7 ρ_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

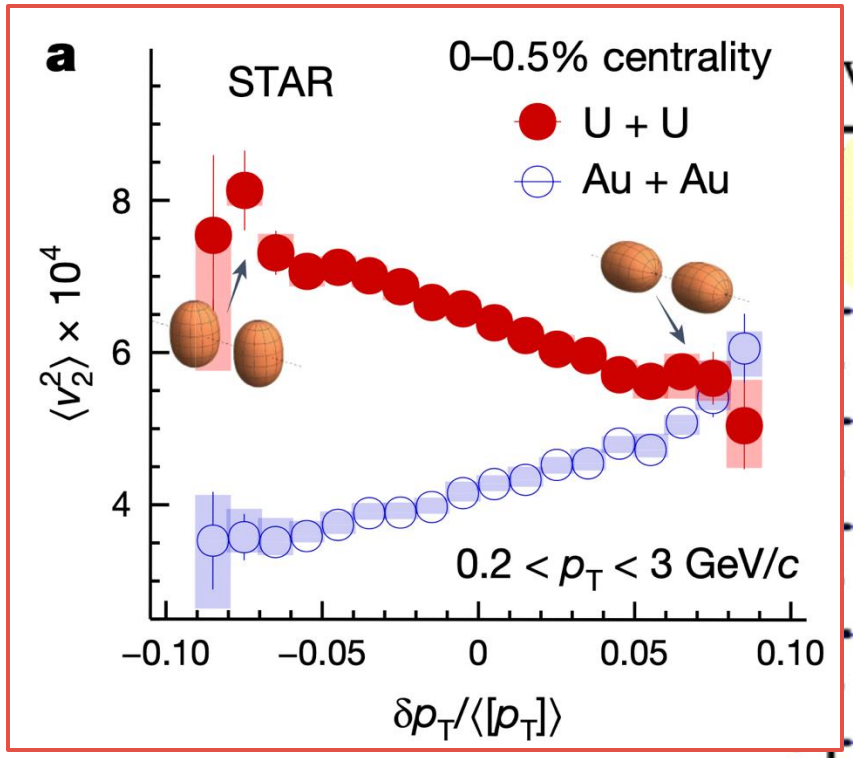
→ ^{238}U + ^{238}U Collisions

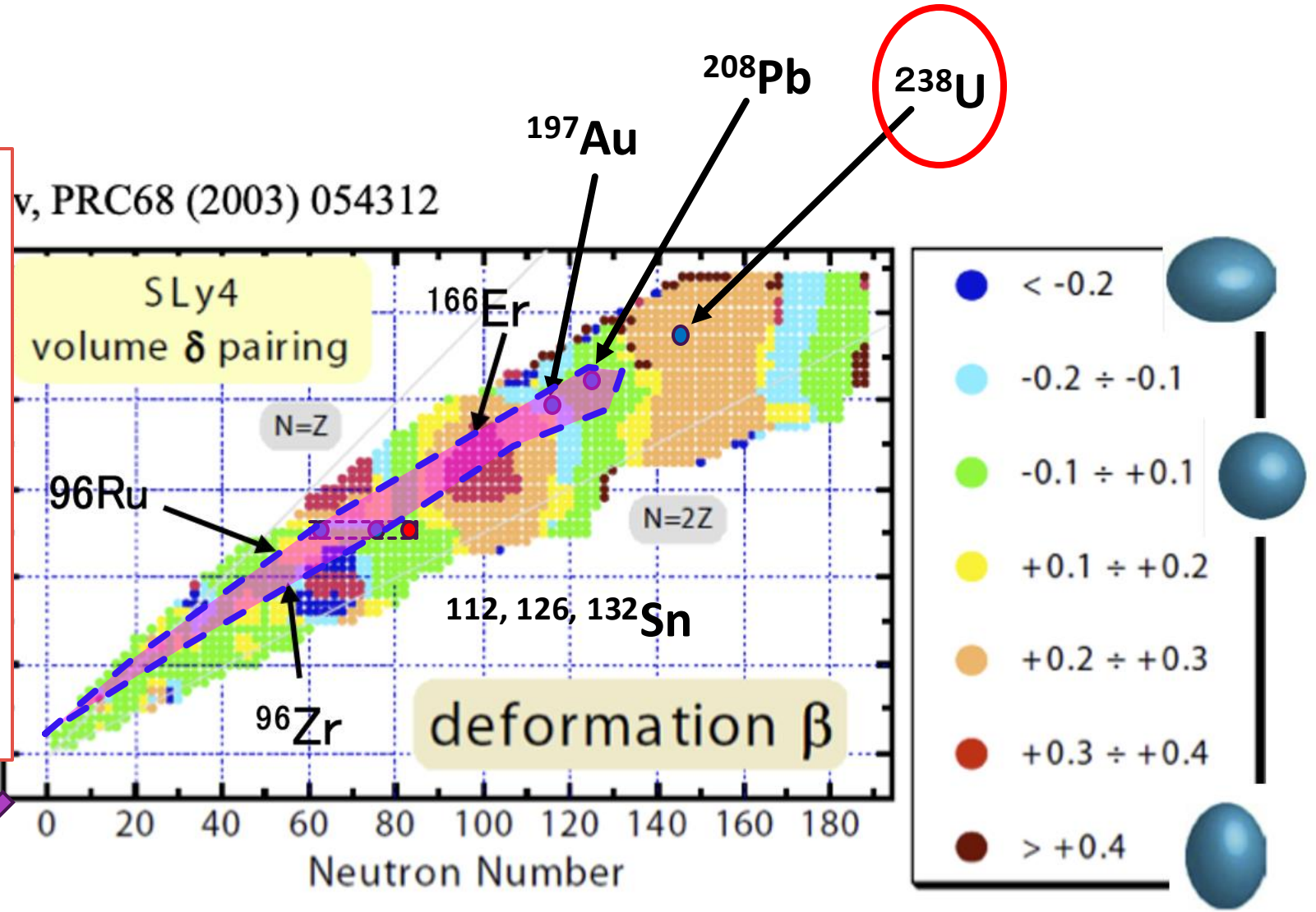
- Central Collisions ←→ Collective Flow

neutron-proton asymmetry

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

Nature Vol 635, Nov. 2024
(STAR Collaboration)





励起状態

Idea of Deformed Nucleus + Nucleus Collisions

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

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

Tip-Tip

Body-Body

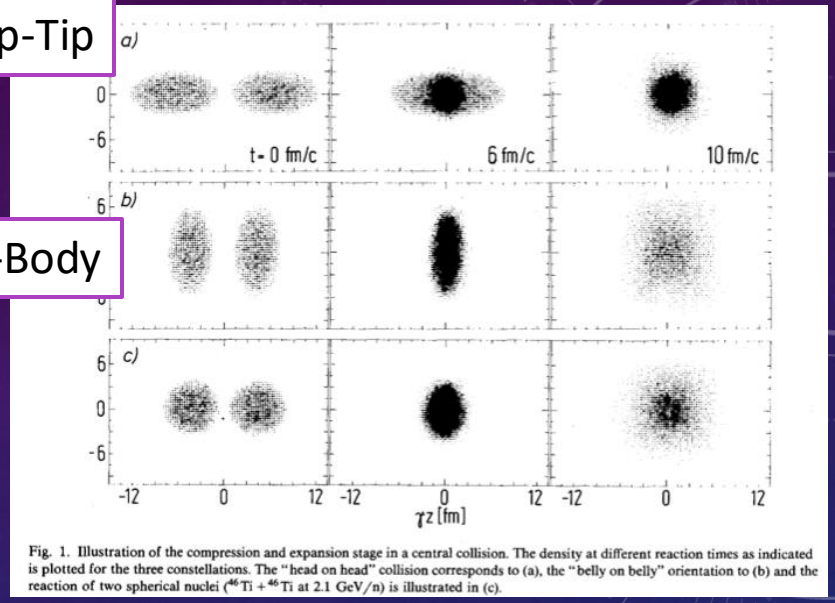
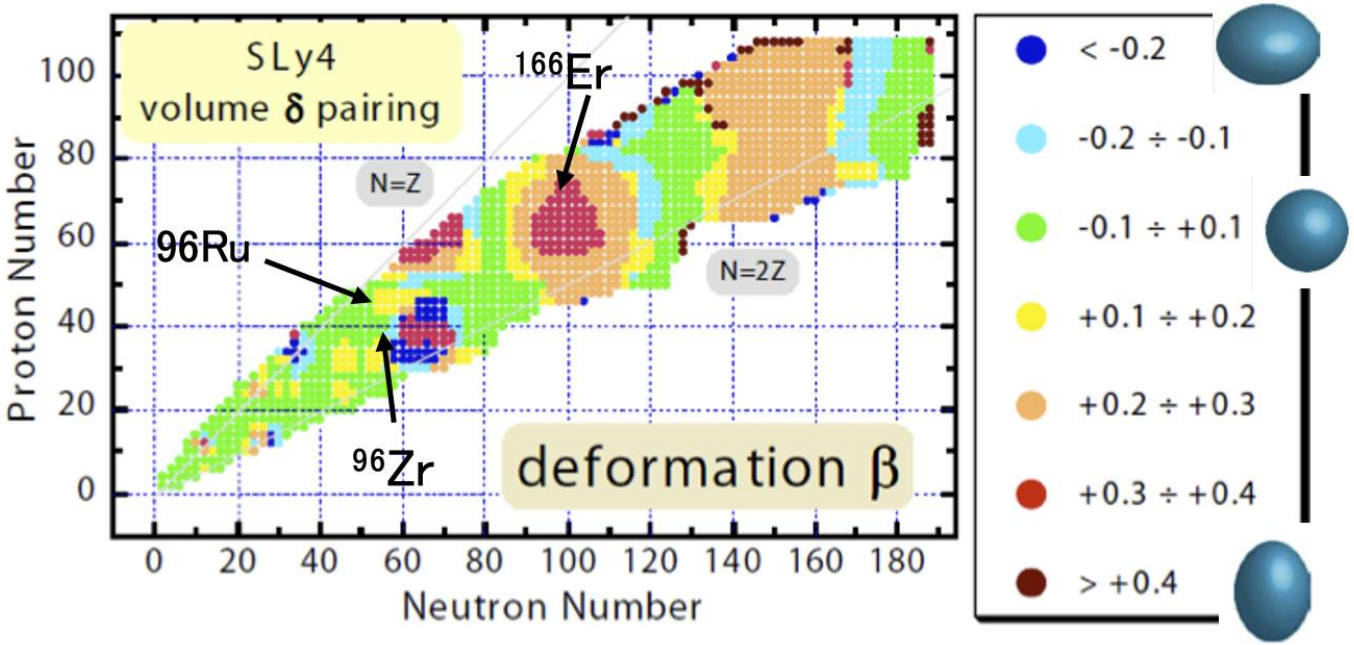


Fig. 1. Illustration of the compression and expansion stage in a central collision. The density at different reaction times as indicated is plotted for the three constellations. The "head on head" collision corresponds to (a), the "belly on belly" orientation to (b) and the reaction of two spherical nuclei (^{46}Ti + ^{46}Ti at 2.1 GeV/n) is illustrated in (c).

Stoitsov, PRC68 (2003) 054312



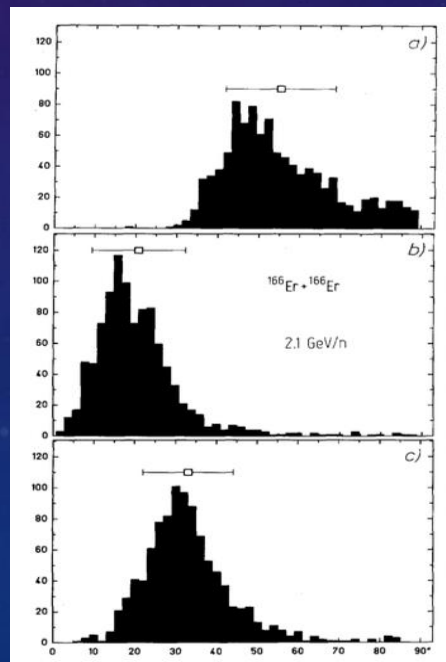


Fig. 2. The distribution $dN/d\theta_F$ calculated for the constellations HoH (a), BoB (b) and SoS (c). The multiplicities as a function of θ_F and the resulting mean value (square) with the corresponding standard deviation (error bars) are plotted on the basis of 1000 evaluated reactions of the system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

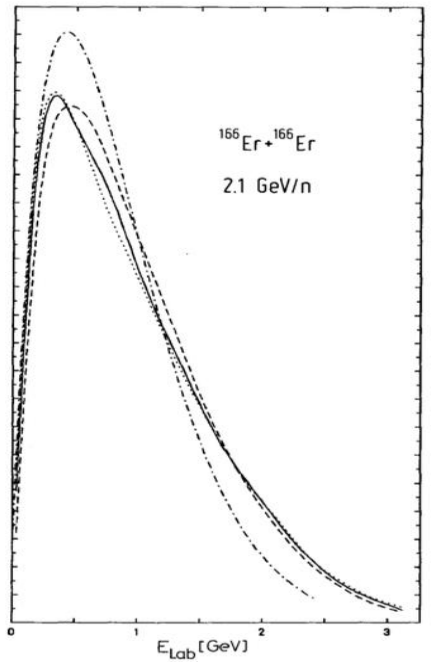
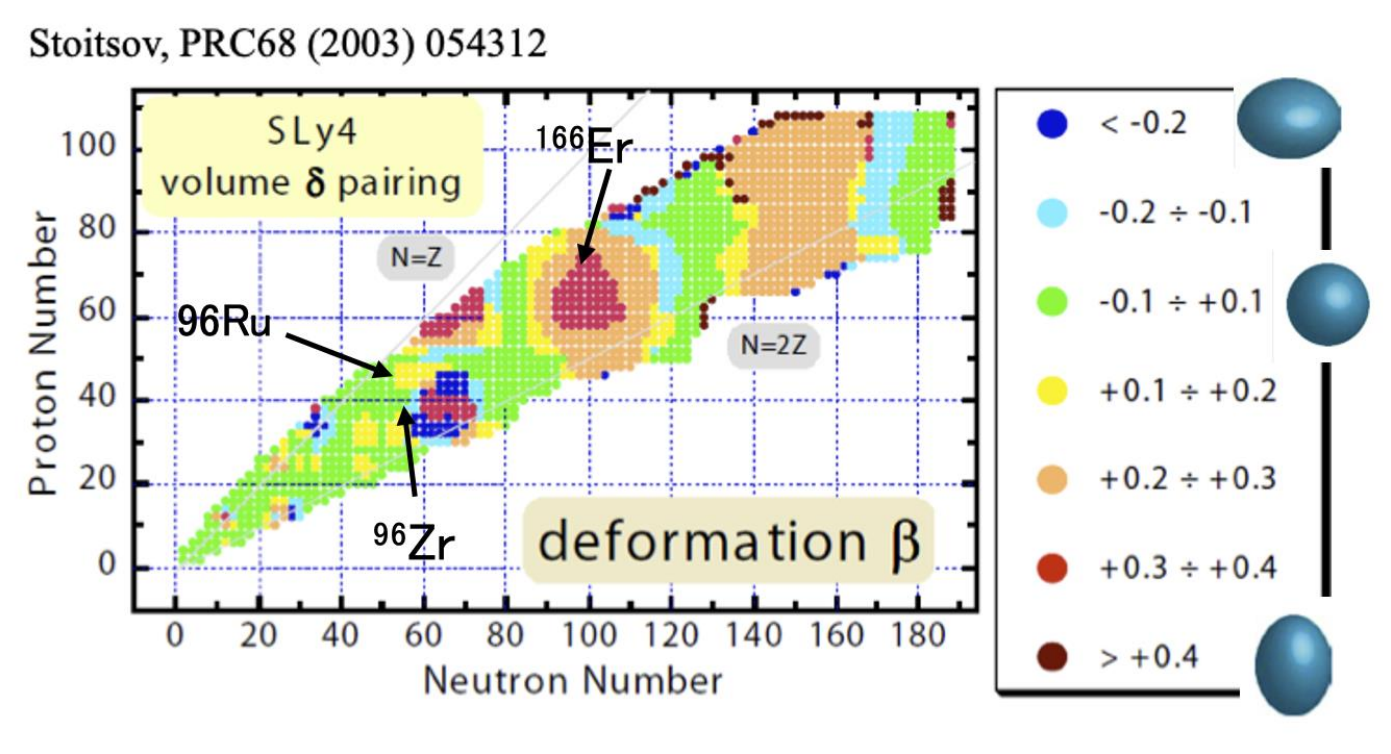


Fig. 3. Energy distribution dN/dE of all participant particles detected by the plastic ball. The spectrum obtained in the lab-system has been plotted for the cases HoH (dashed line), BoB (dotted line) and SoS (full line). The dash–dotted line shows the energy spectrum of a fireball.

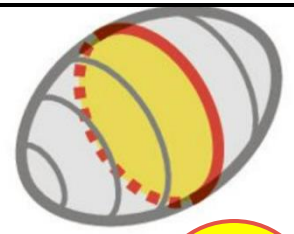
Deformed Nucleus-Nucleus Collisions : $^{166}Er + ^{166}Er$

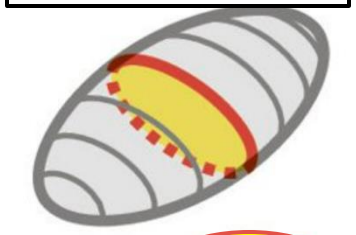
A. Rosenhauer, J.A. Maruhn, H. Stocker, and W. Greiner
Phys. Lett. 159B, (1985)



Nuclear Shape of ^{166}Er

Before	*This Work*
Rugby Ball Shape	**Almond Shape**





cross section **Circle**

cross section **Ellipse**

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"

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 (v1, v2)
→ Asymmetric Collision Geometry

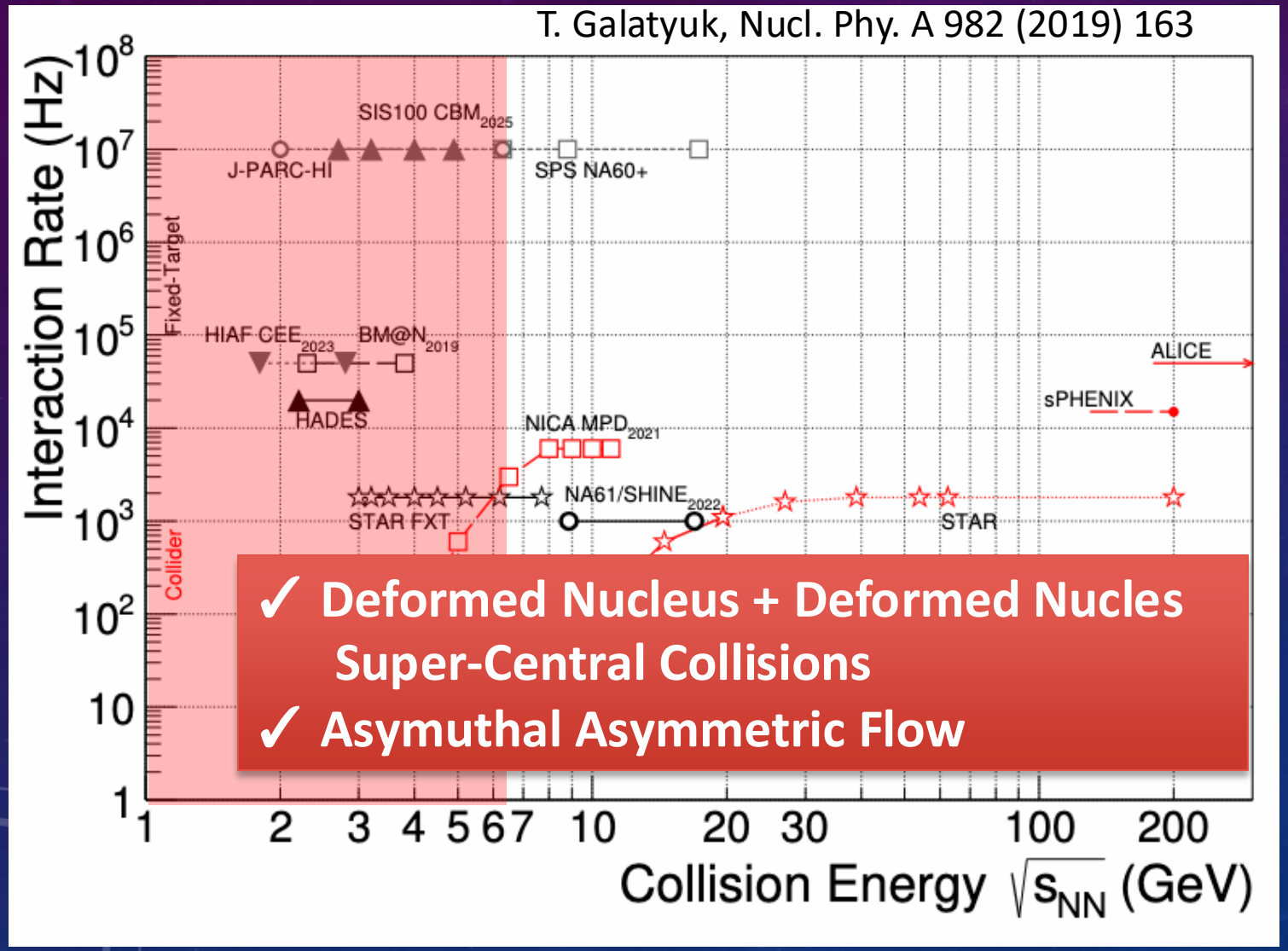
Centrality: Non-Central Collisions
→ "Super-Central Deformed Nucleus + Nucleus Collisions" is ideal to create high density matter. (Tip-Tip & Body-Body Collisions)
→ Lower Energy Heavy-Ion Collisions → "Spectator Free" in v2 observable.

Issues & Questions:
Complex Collision Condition: $(\text{Deformation Axis})^2$ & Impact parameter
→ Can we identify the collision type? → Spectator, Multiplicity information.
→ Can we proof the nuclear shape via heavy-ion collisions?

Equation of State (EOS)

High Density Nuclear Matter vs Beam Energies

Neutron detection



1） High Density Nuclear Matter
⟷ Neutron Star

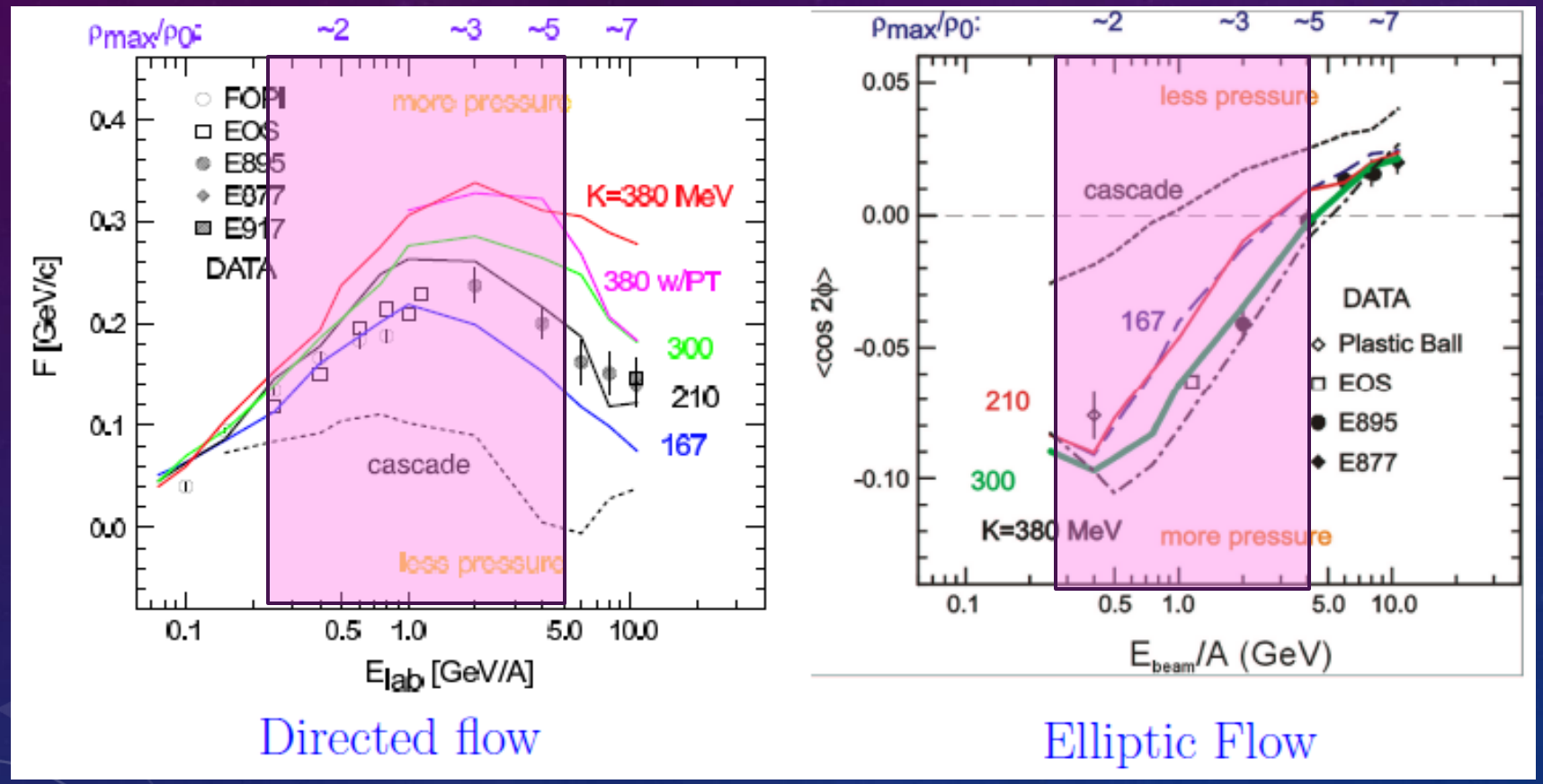
2） Search for Rare Collisions
Super Central Collisions (b=0)

✓ Spherical Shape Nuclei
✓ Deformed Shape Nuclei

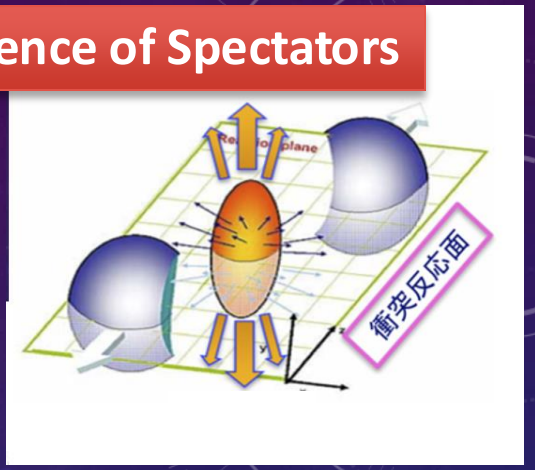
3） Collective Flow
✓ Radial Flow
✓ v1 (directed flow)
✓ v2 (elliptic flow)

High Density Matter and Collective Flow

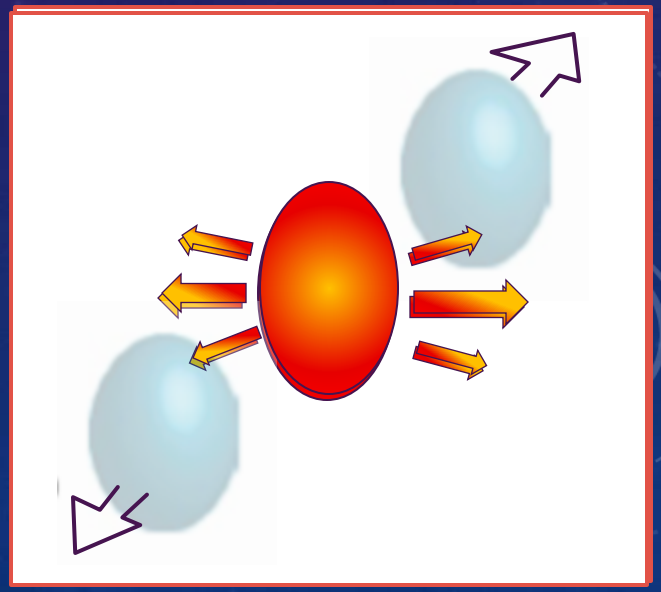
$$\frac{dN}{d\phi}(y, p_t) = N_0[1 + 2V_1(y, p_t)\cos(\phi) + 2V_2(y, p_t)\cos(2\phi)]$$



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.

Directed and Elliptic Flow

proton, neutron, π+, d, ...

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

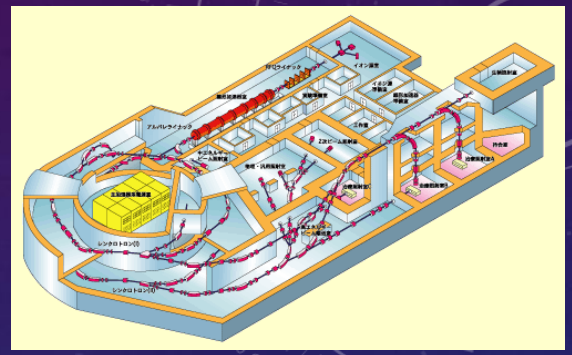
RIKEN ... T. Isobe, Y. Nakai, S. Nishimura,

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

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

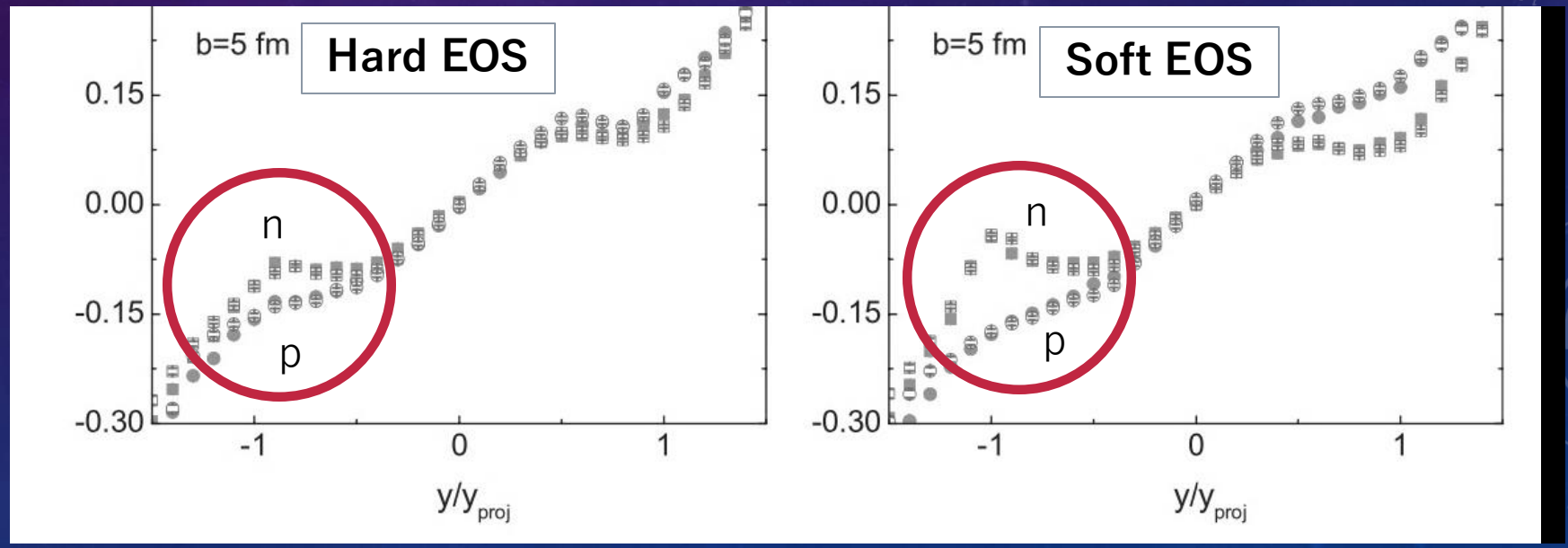
Kyoto U. ... Y. Hijikata

NIRS ... E. Takada



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

Theoretical calc. (LQMD) $^{124}Sn+^{124}Sn$ (400 AMeV)

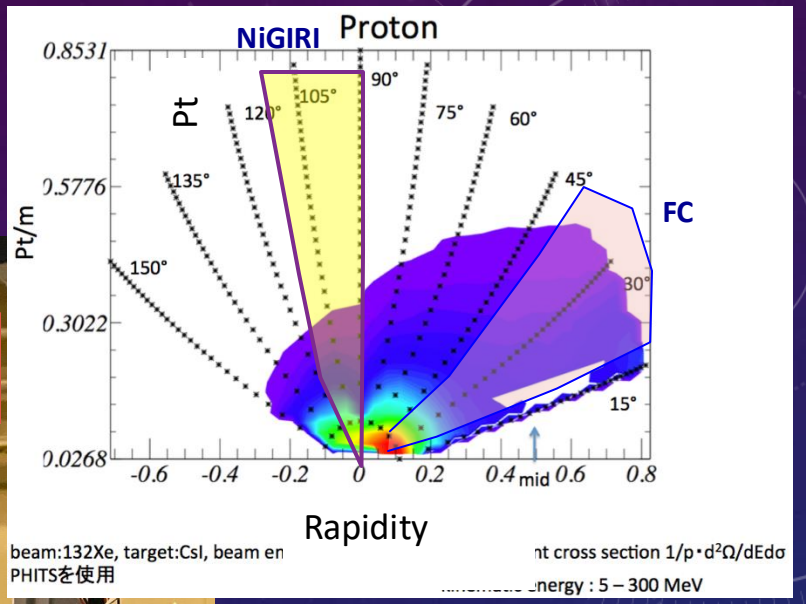


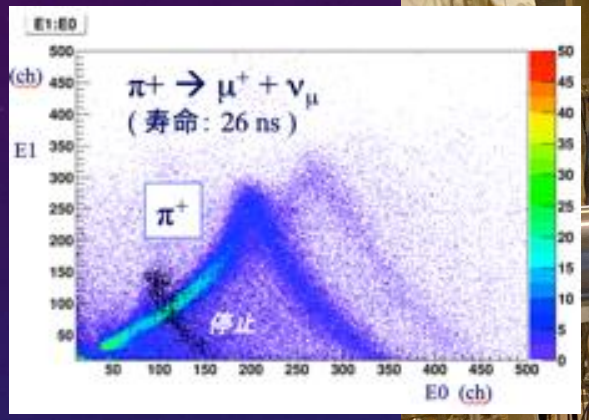
Goal: Direct Comparison of Directed Flow V_1 at Target Rapidity

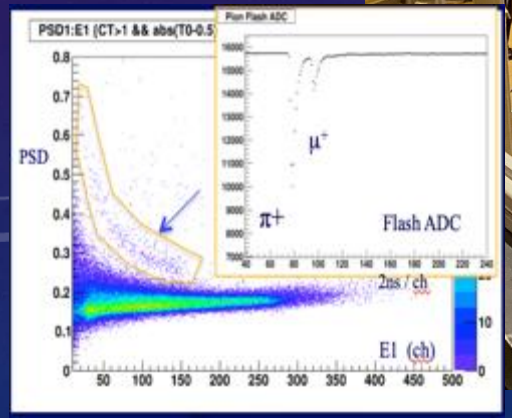
Pilot Flow Experiment at HIMAC H447
^{132}Xe + CsI Collisions at 400 AMeV

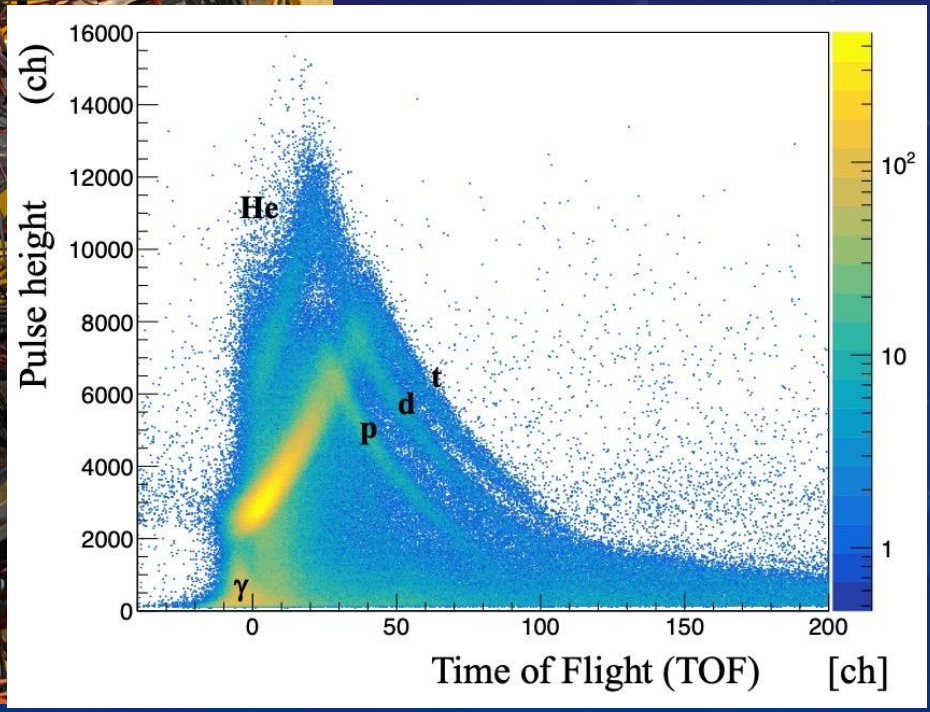
NiGIRI detector@Y_{target}

PMTs from
CERN-NA44 H1 Hod.



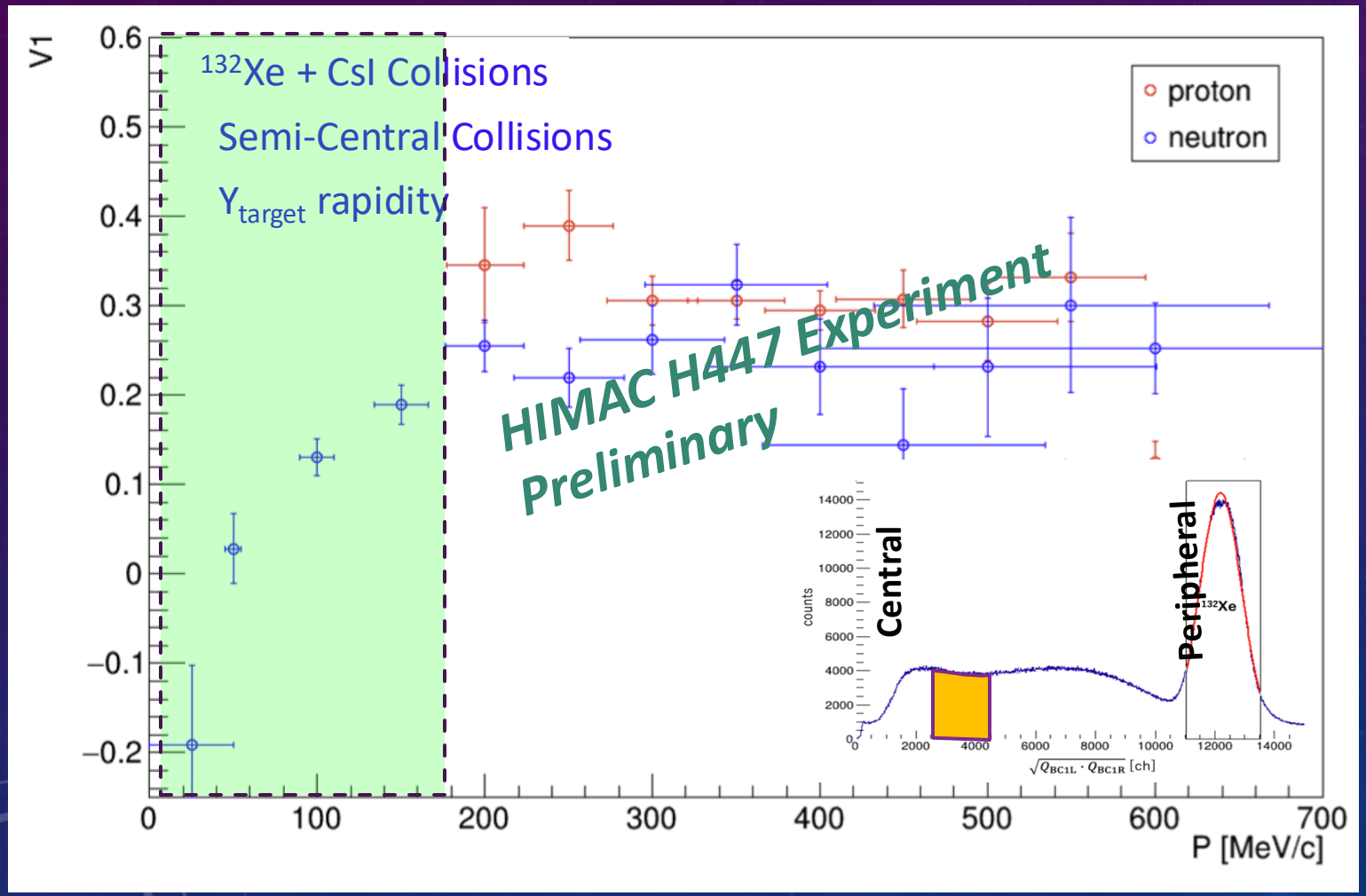


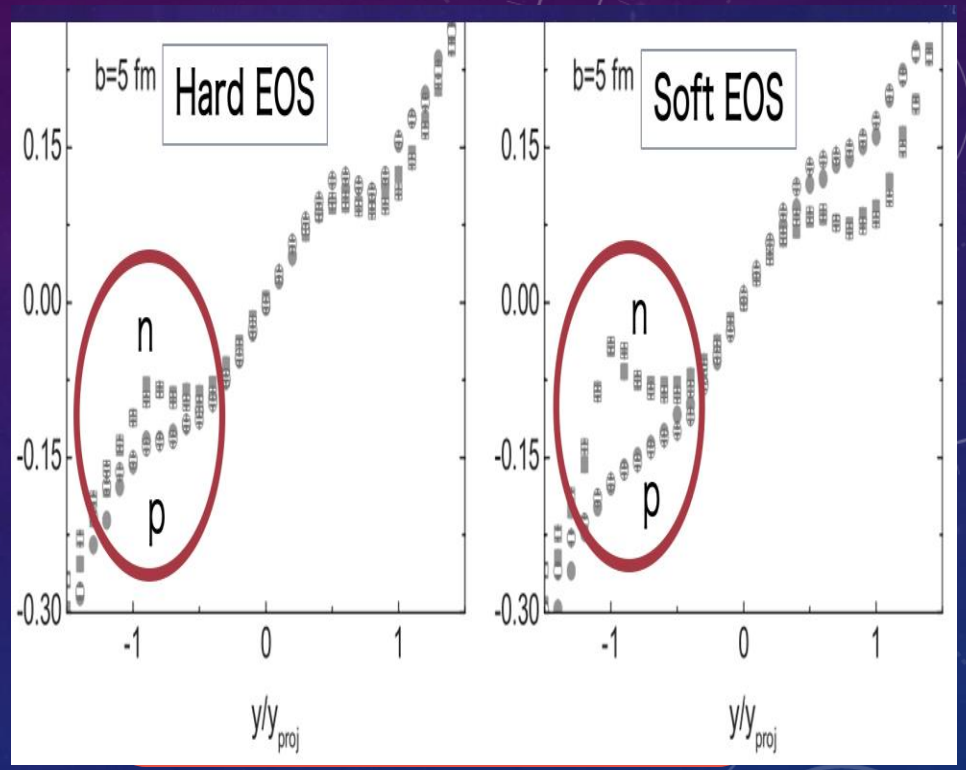




Direct Comparison of Directed Flow V_1 at Target Rapidity
proton vs neutron

S. Yamamura, H. Tanabe Master Thesis (2022)



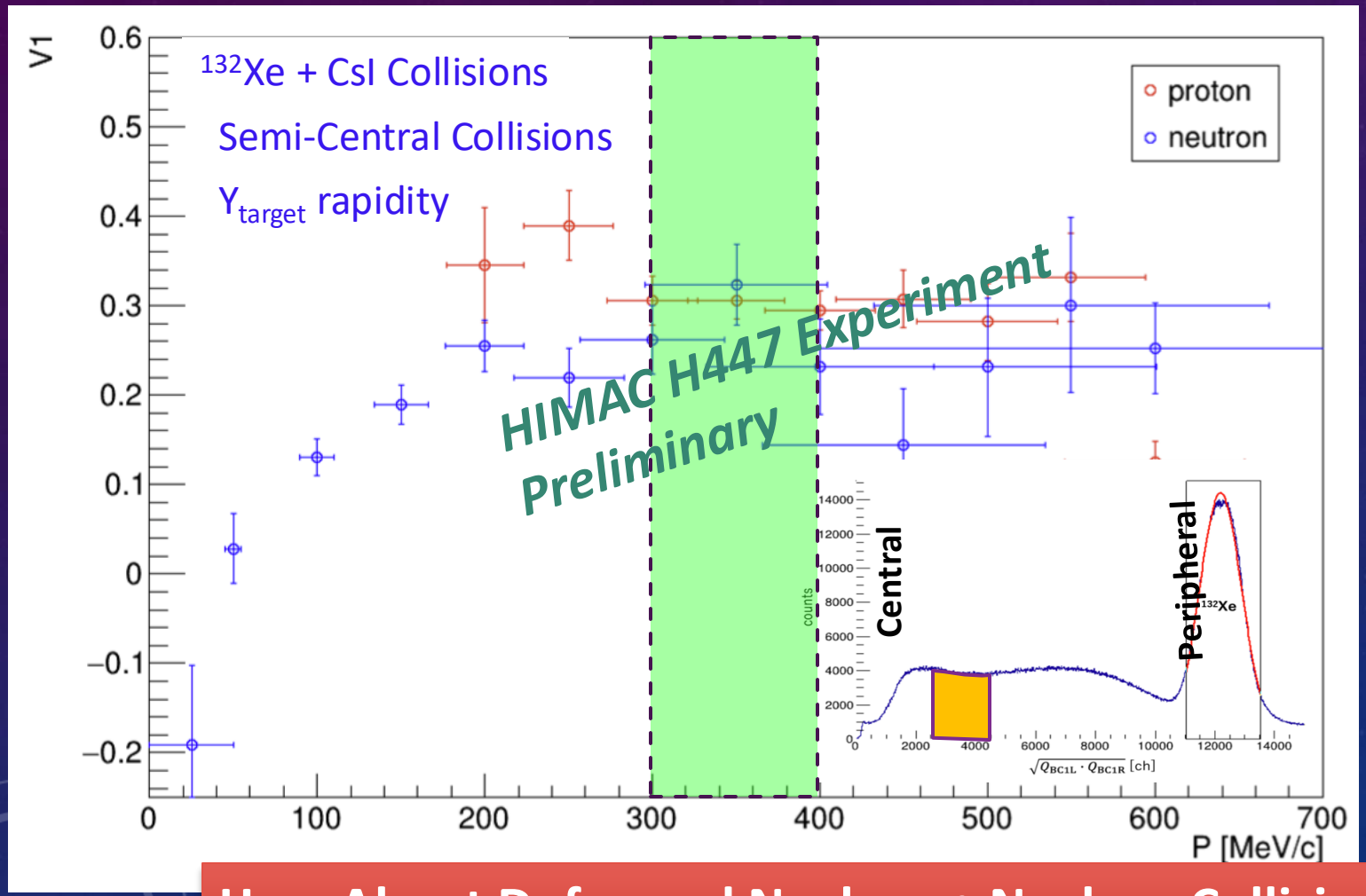


Consistent V_1 for proton ←→ GSI Exp.

Sligly weaker V_1 for neutron observed around P_t ~ 200 MeV/c

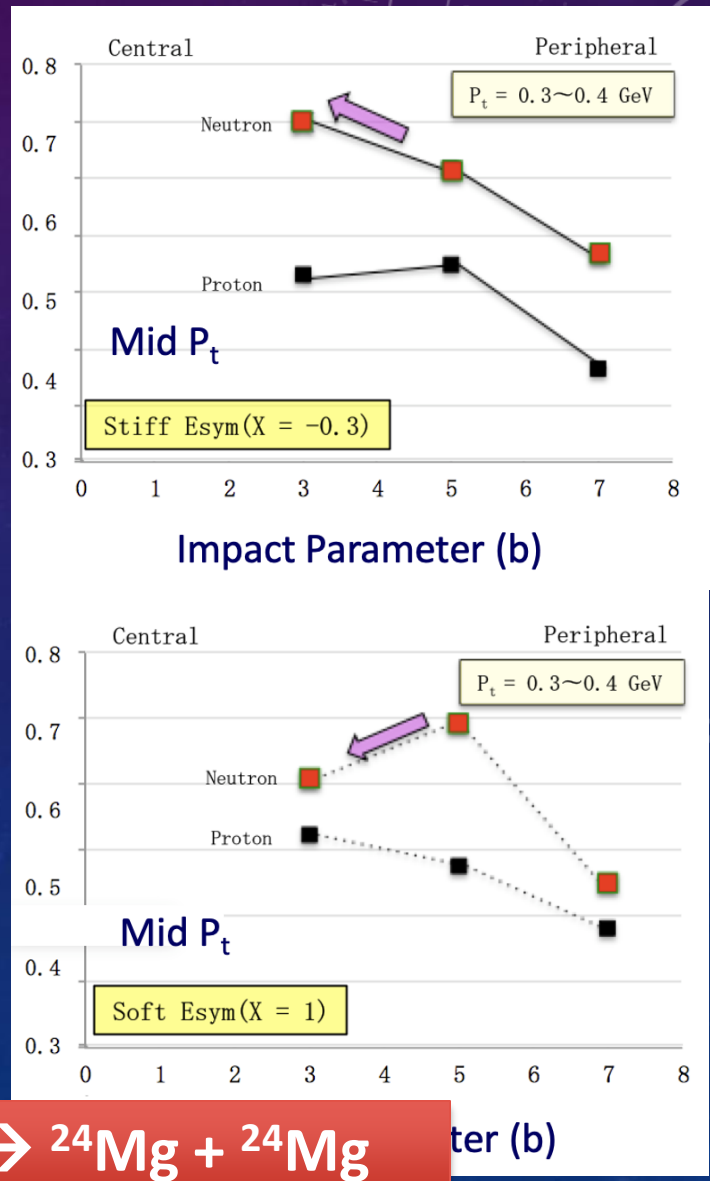
Direct Comparison of Directed Flow V_1 at Target Rapidity
proton vs neutron

S. Yamamura, H. Tanabe Master Thesis (2022)



by B.A. Li

400 MeV/u ^{132}Xe+CsI (−0.70 < Ycm < −0.25)

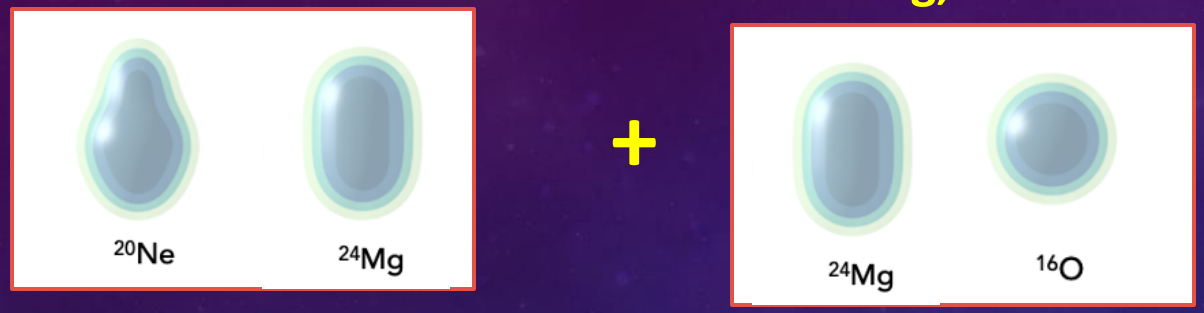


How About Deformed Nucleus + Nucleus Collisions!? → ^{24}Mg + ^{24}Mg

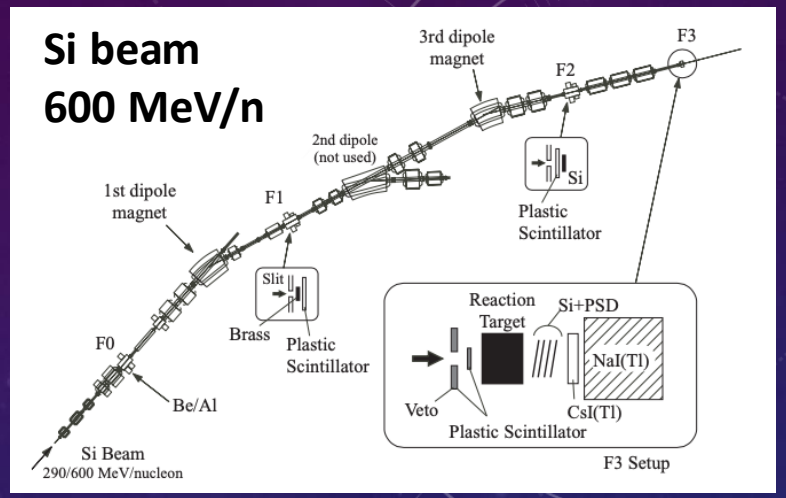
Azimuthal Asymmetry in Deformed Nucleus: Flow V1, V2, & V3 in Central Collisions

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

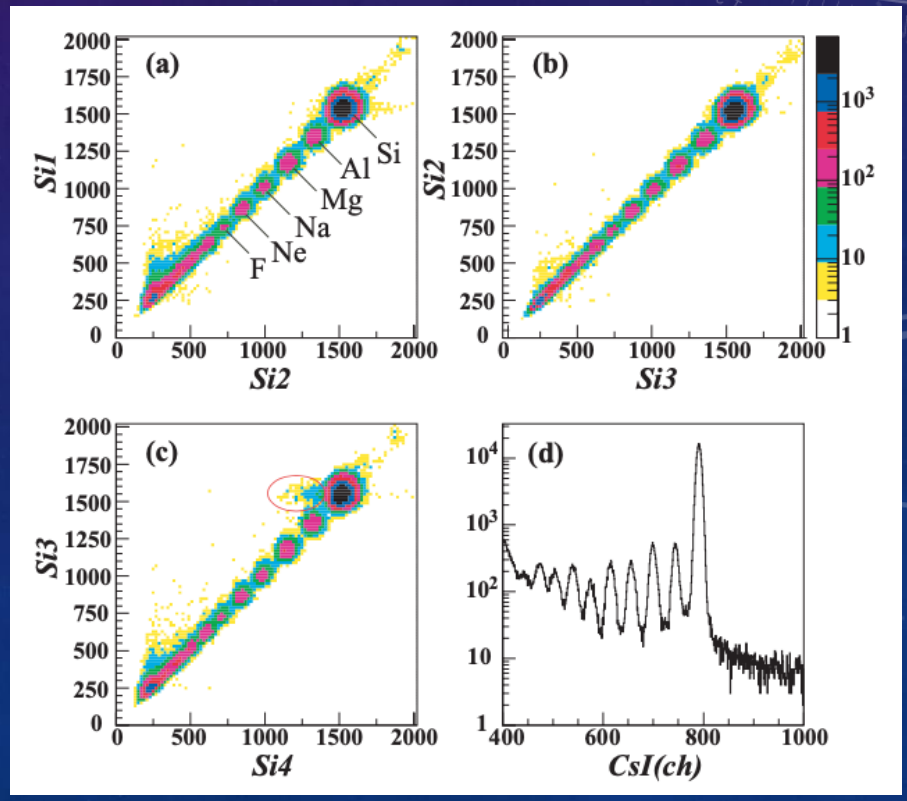
Target $^{24\text{-}26}$Mg, ^{16}O



Theoretical calculation before experiment at HIMAC..



T. Yamaguchi et al., PRC 82, 014609



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 Nishimura,[2] and Zhi-Pan Li[1]

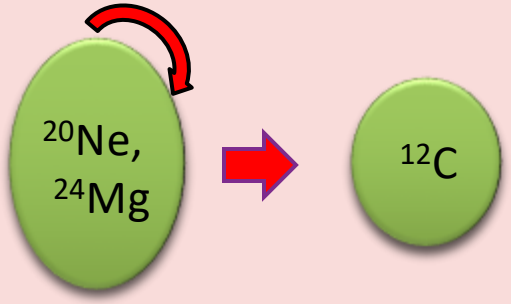
[1]*School of Physical Science and Technology, Southwest University, Chongqing 400715, China*

[2]*RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*

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

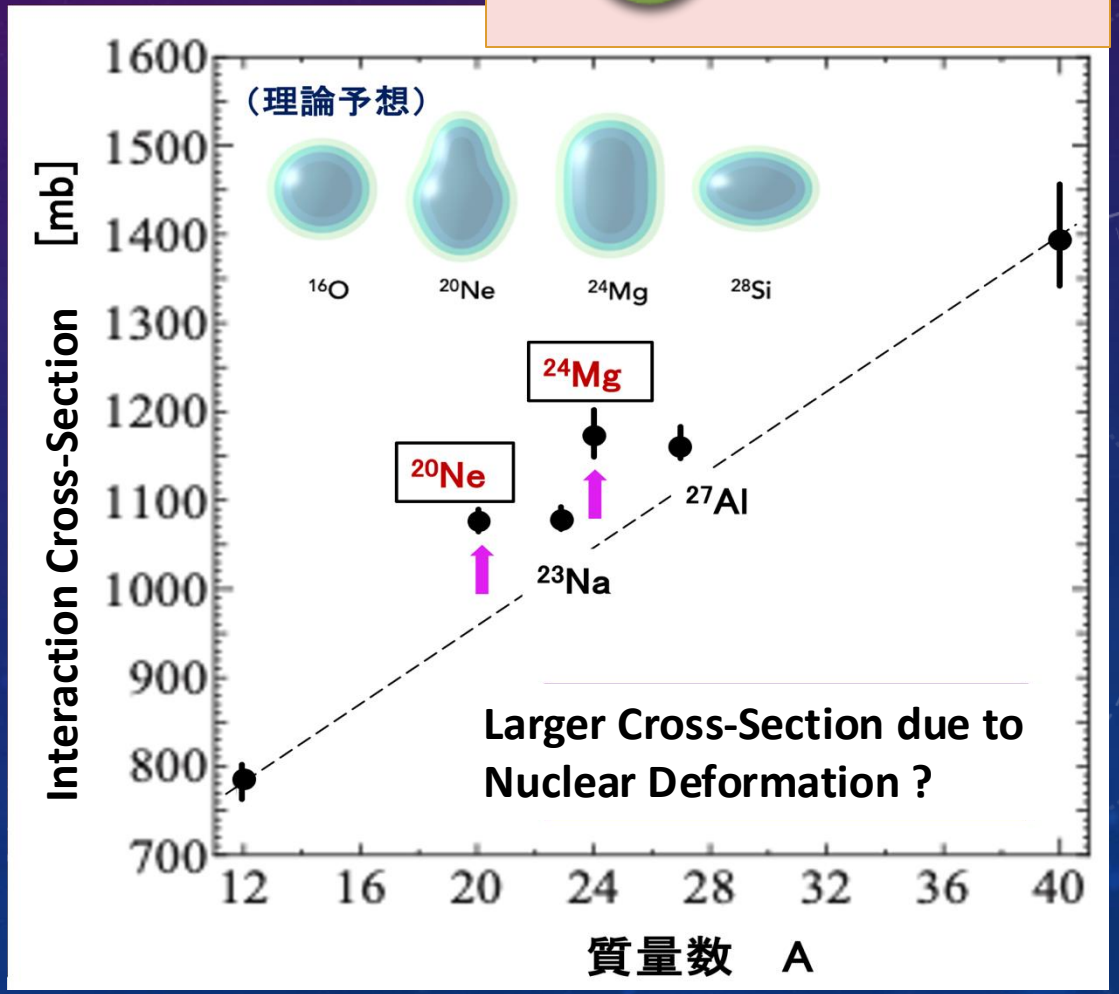
Variation of Deformation Parameter among Theory
^{20}Ne, ^{23}Na, ^{24}Mg, and ^{27}Al

σ_I .... Integrated values



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

Theory β2	NNDC	FRDM	CEA(p)	CEA(n)	AMD	KTUY α2
^{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

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

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

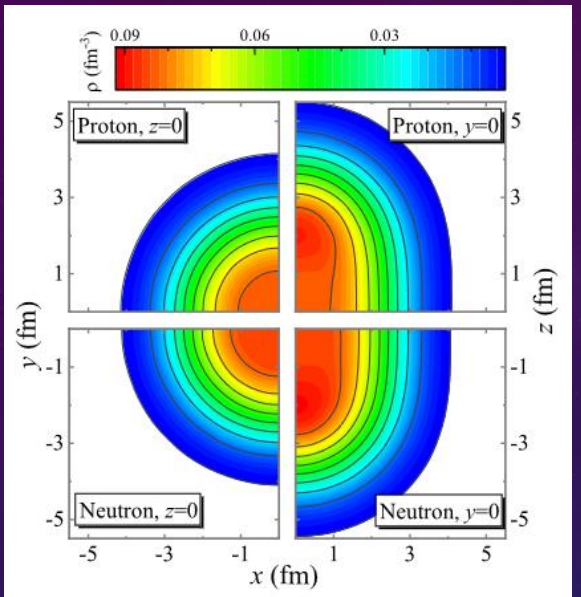


FIG. 1. The neutron and proton densities for ^{24}Mg in the ground state in the x-y ($z = 0$) and x-z ($y = 0$) planes calculated by relativistic mean field with DD-PC1 interaction.

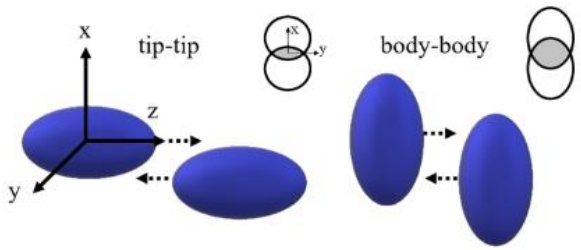
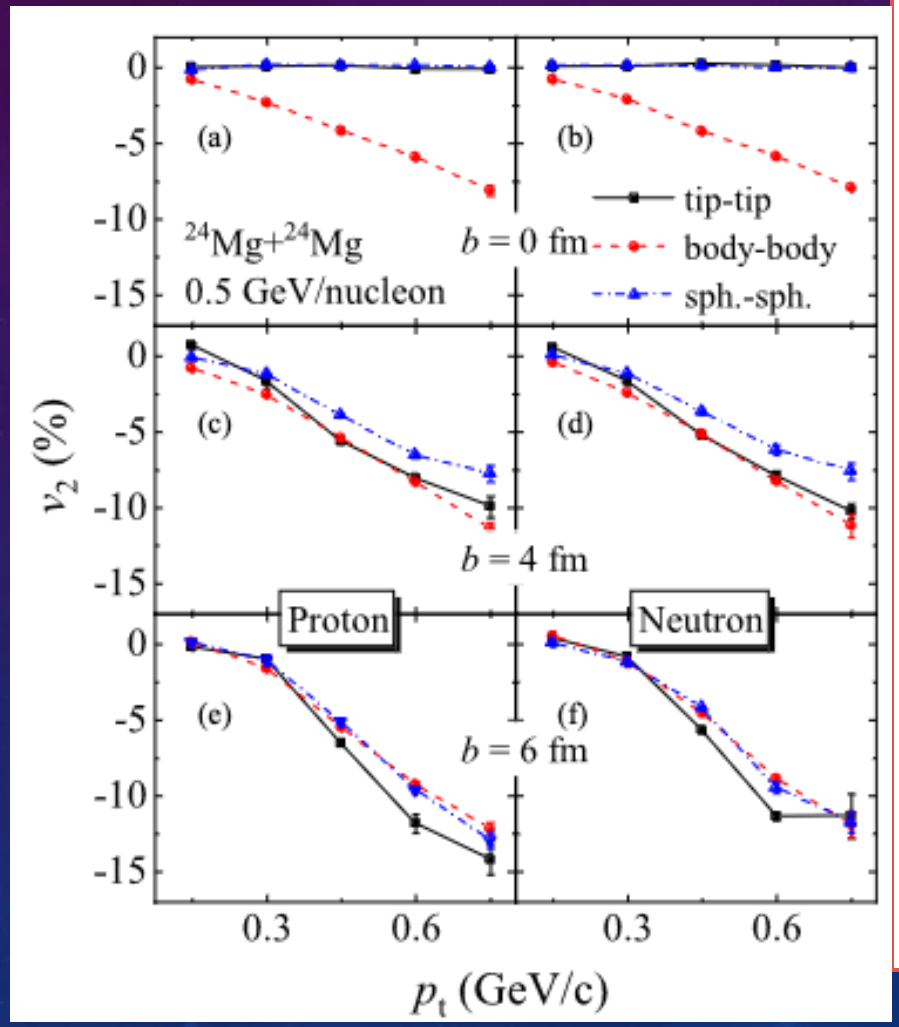
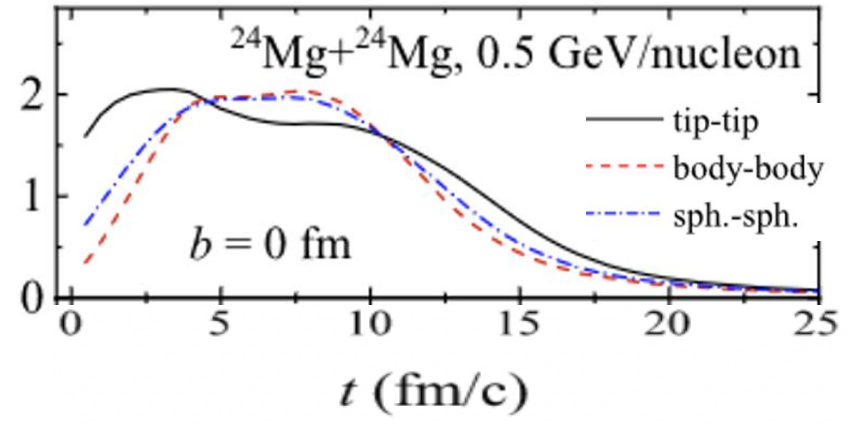
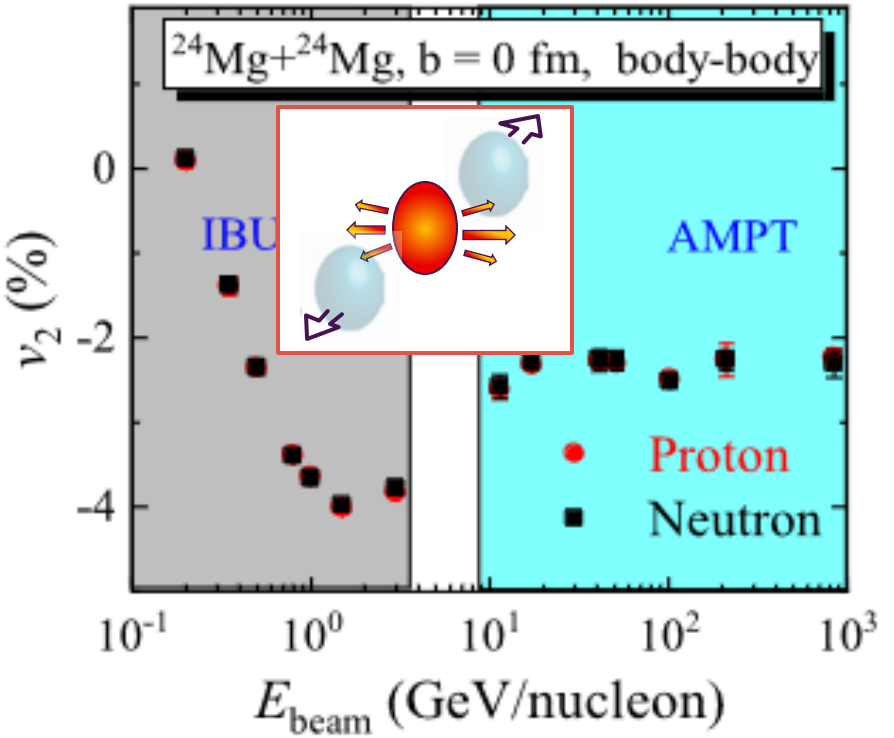


FIG. 2. Simulated schematic for tip-tip collision and body-body collision of ^{24}Mg + ^{24}Mg, where the x-z plane is the reaction plane. In the upper right corner, resulting transverse areas of overlap are shown.



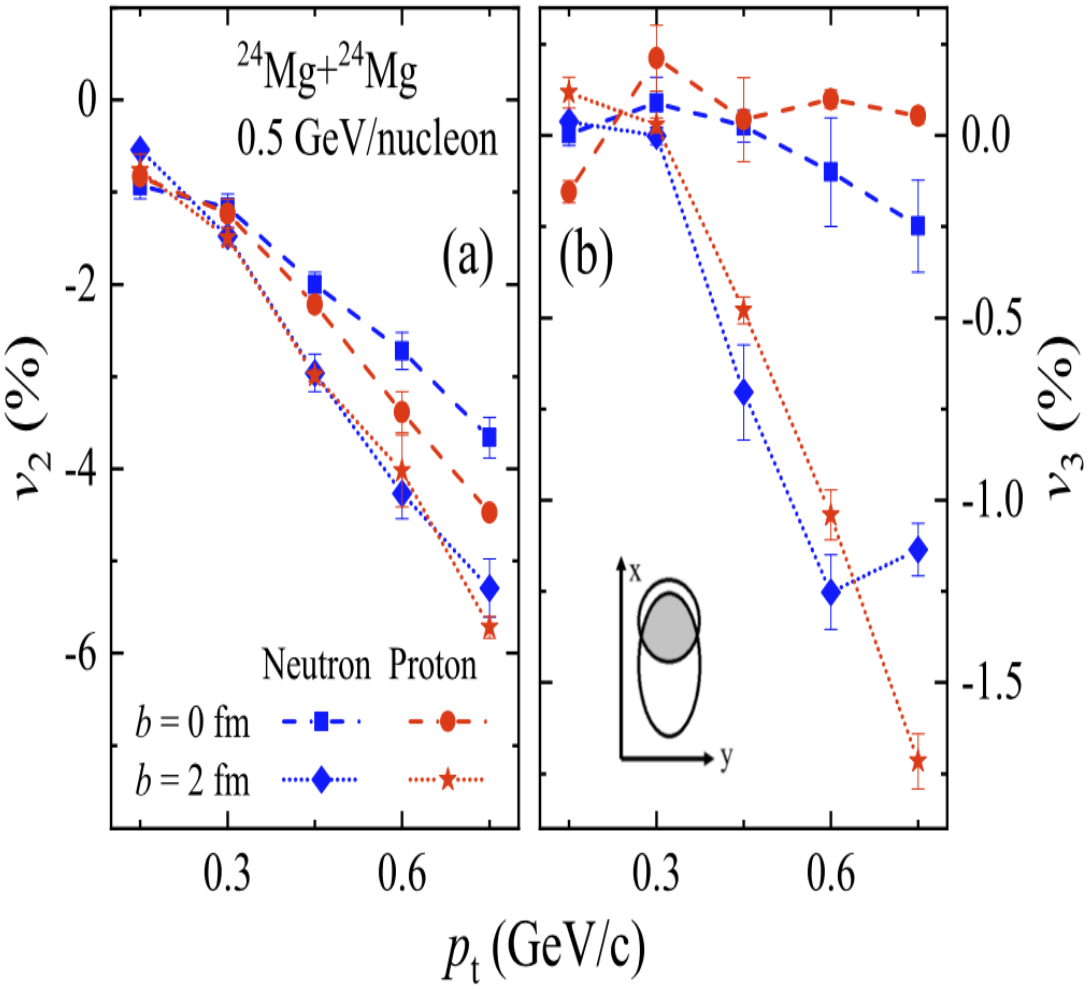




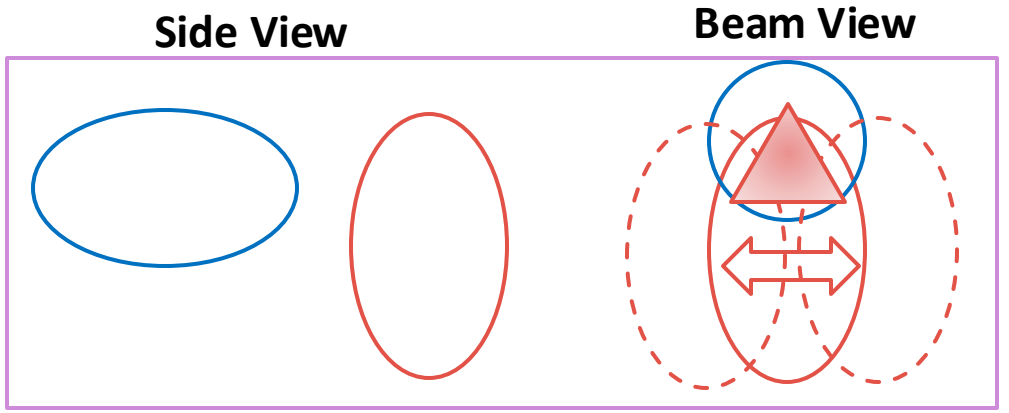
No Shadowing / Compression Effects by the Spectators

Deformed Nucleus + Nucleus Collisions

Initial geometrical collisions vs Flows (V1, V2, V3, …)



Various types of collision pattern



Triangular shape of overlapping region?
→ V3 component appears.

HIMAC stoped delivering high energy heavy-ion beam…

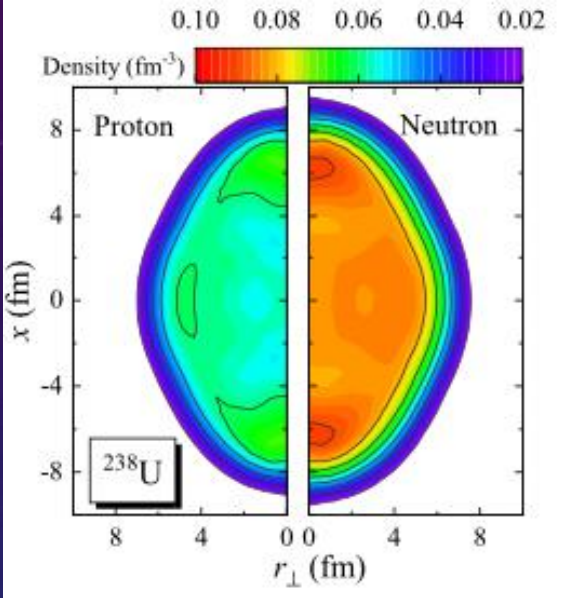
Deformed Nucleus-Nucleus Collisions (^{238}U + ^{238}U) at 1 GeV/n

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



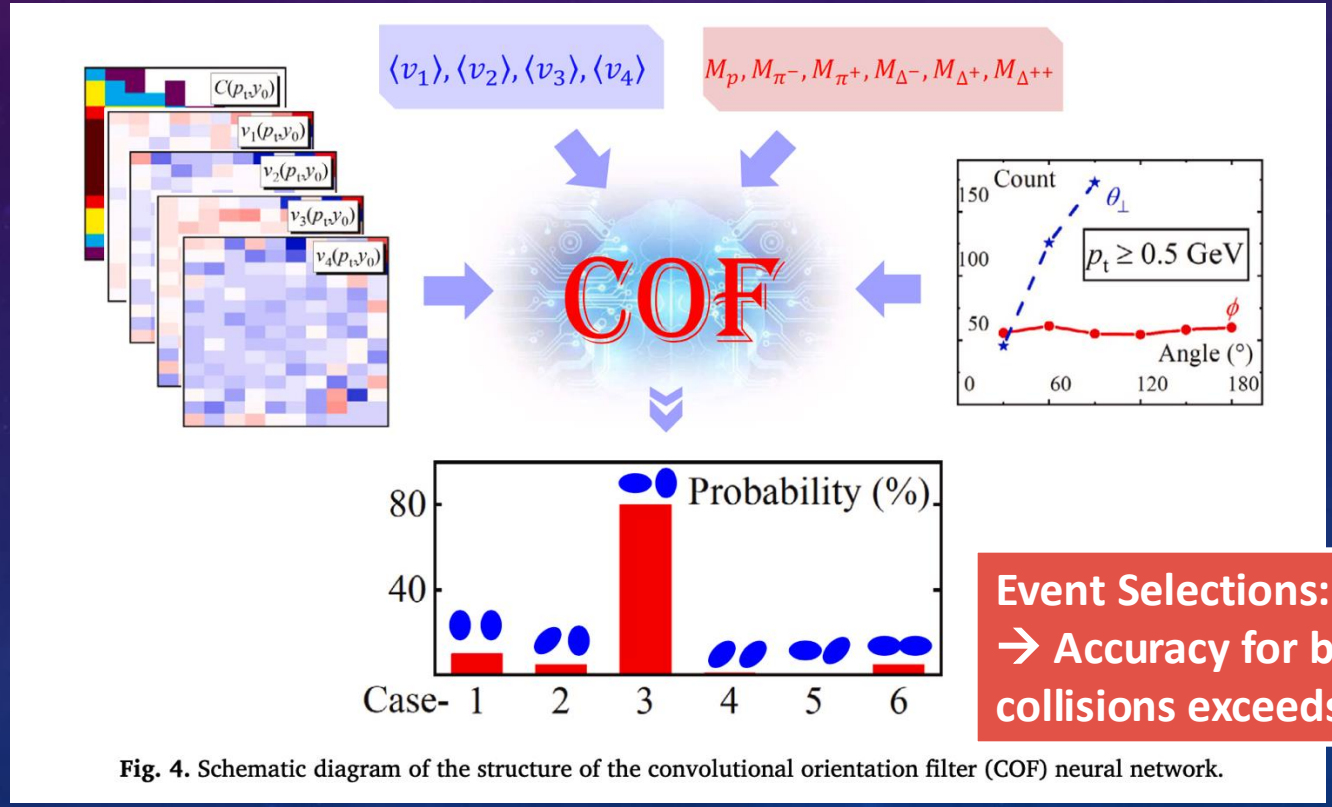
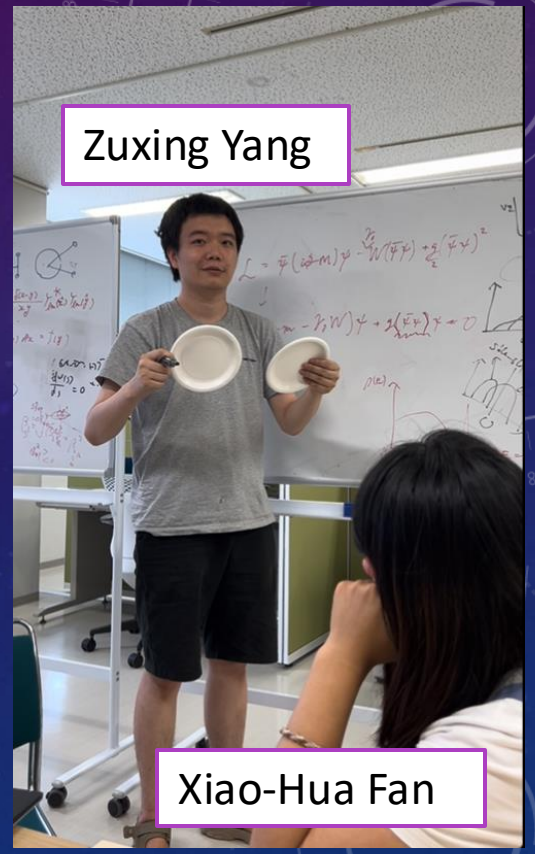


Fig. 4. Schematic diagram of the structure of the convolutional orientation filter (COF) neural network.



Nature Vol 635, Nov. 2024
(STAR Collaboration)

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

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

$^{24}Mg + {}^{24}Mg$ 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 Nishimura,[2] and Zhi-Pan Li[1]
[1]*School of Physical Science and Technology, Southwest University, Chongqing 400715, China*
[2]*RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*
[3]*College of Physics Science and Technology, Yangzhou University, Yangzhou, Jiangsu 225002, China*

$^{238}U + {}^{238}U$ 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]
[a] *RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*
[b] *School 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]

Physics Letters B
Volume 866, July 2025, 139503

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 Li [2], and Shunji Nishimura [1]

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

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

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

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

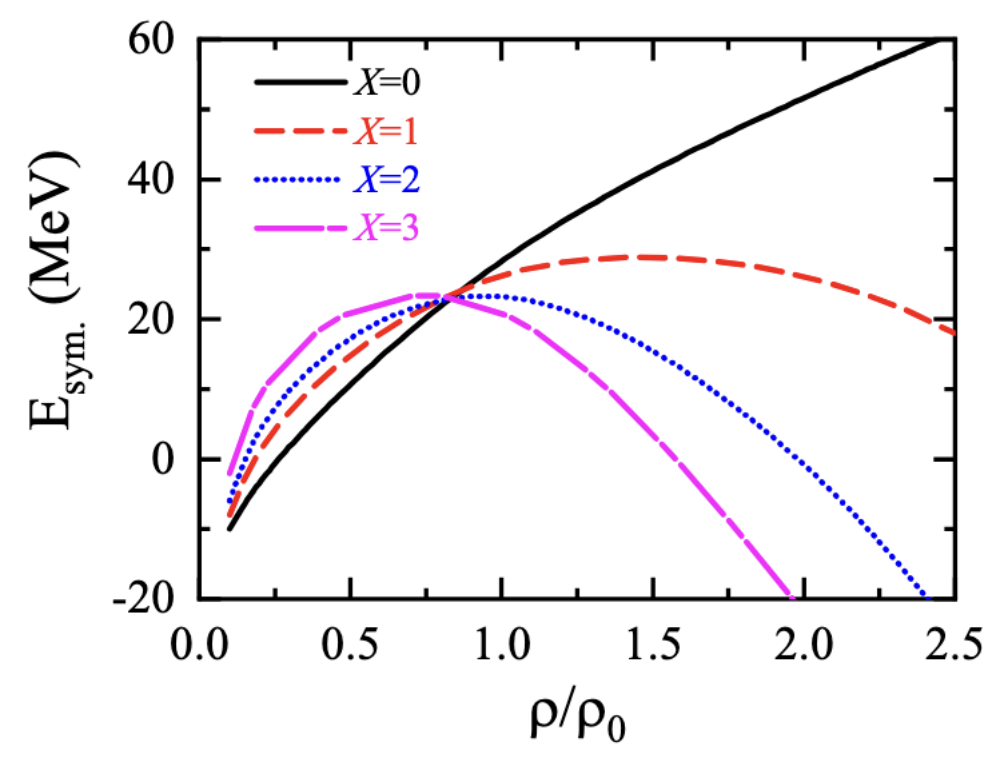


FIG. 4. Density-dependent symmetry energy $E_{sym.}$ with different symmetry energy parameters X.

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

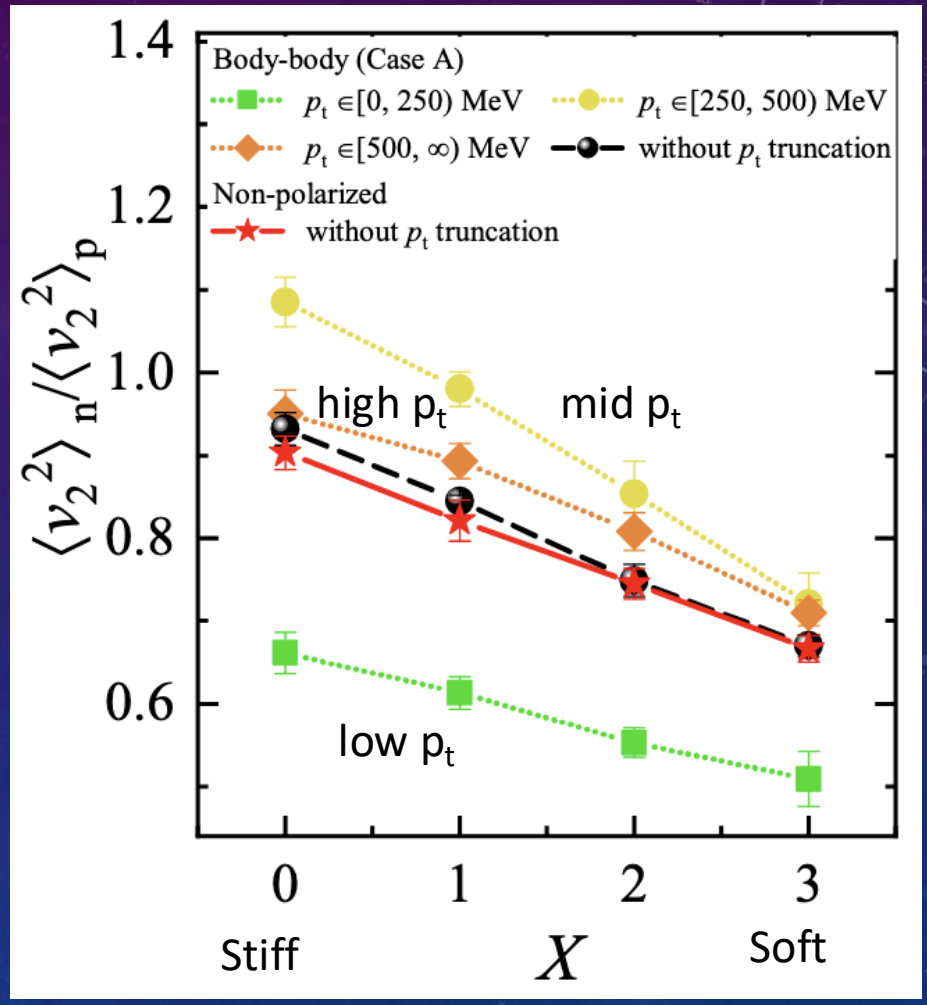


FIG. 7. The $\langle v_2^2\rangle_n/\langle v_2^2\rangle_p$ ratio as a function of the symmetry energy parameter with body-body (case A) and nonpolarized collisions. Different colors represent the truncation of transverse momentum over different intervals.

Summary

1）High Density Matter

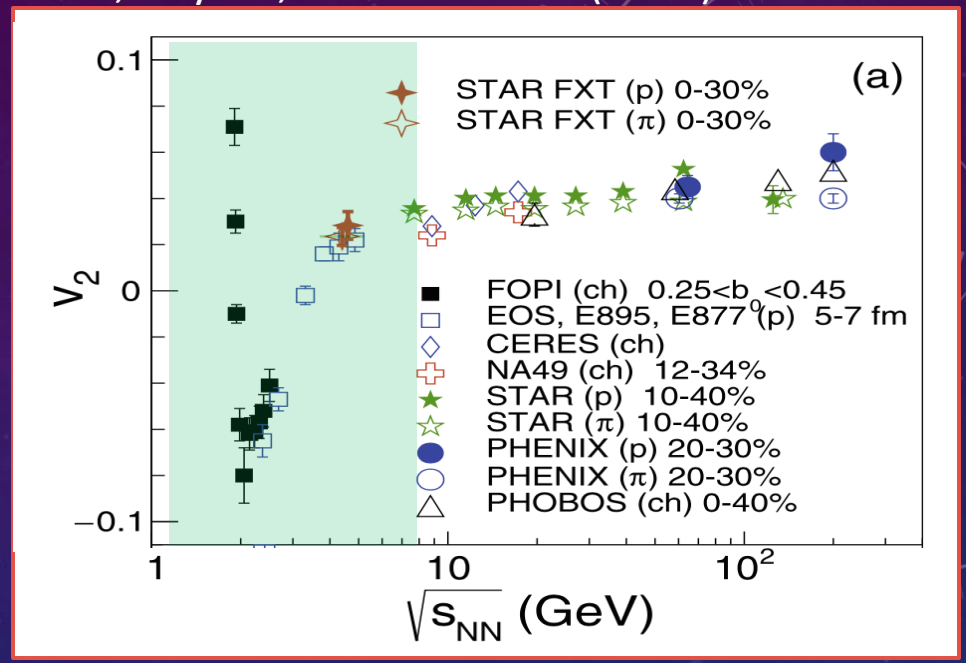
- Observation of Neutron Stars via Gravitational Wave / EM
- Importance of Nuclear Physics, especially Heavy-Ion Collisions

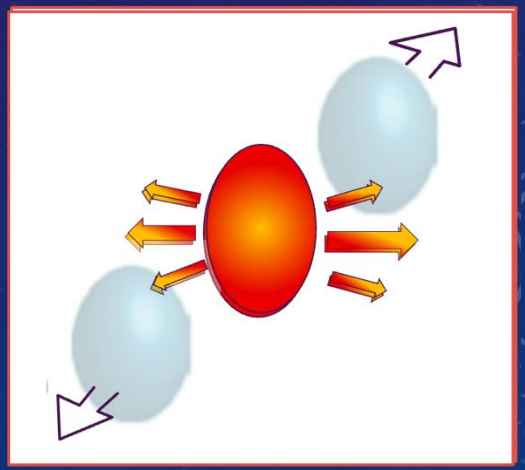
2）Study of EOS via Heavy-Ion Collisions

- Impact Parameter（b）and vector
- Acceptance of Detectors (pt, rapidity, particles)
  - → Energy Dependence vs Systematics and Bias
  - → Super High Density Matter ... Super-Central Collisions !
- Sensitive Probes of Initial Conditions

  Collective Flow, Especially v1 and v2 (and v3)
- Event by Event Analysis
  - → Multiplicity, Average Momentum, Flow, Spectator
- Deformed Nucleus-Nucleus Collisions Provide Unique Information.
  - Spectator Free of v2 below $\sqrt{s_{NN}}$ < 6 GeV
  - Possible Feedback to Nuclear Structure.

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

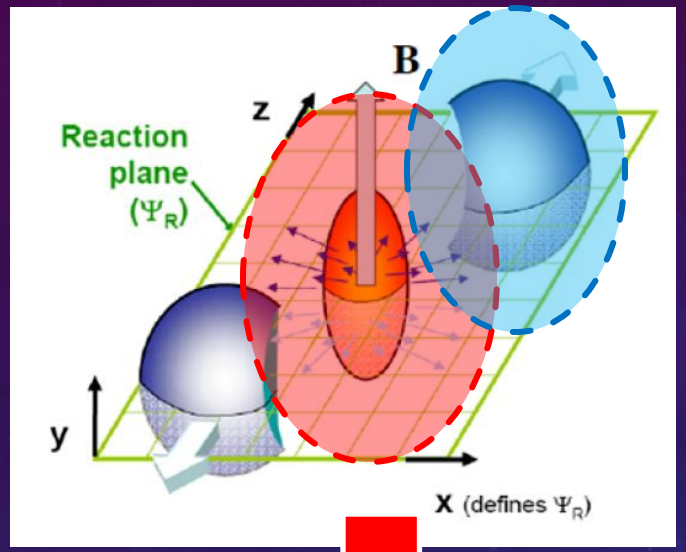




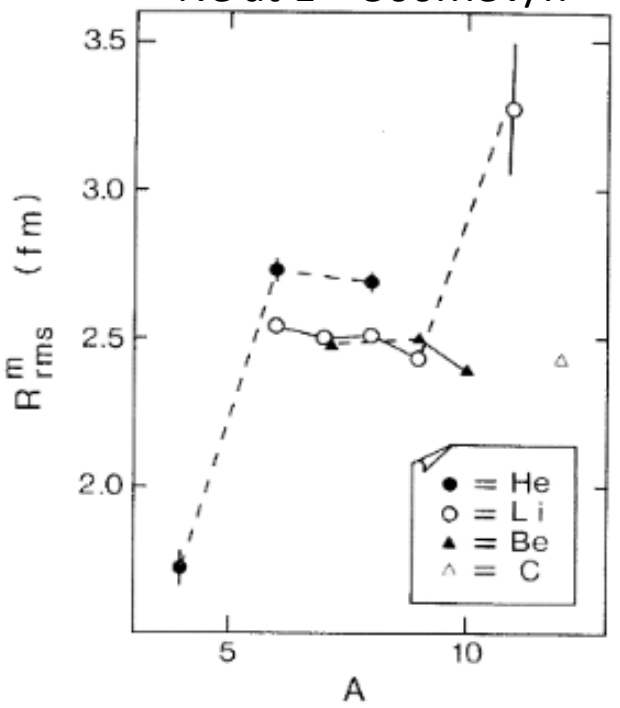
Super-Central Body-Body Collisions

Heavy-Ion Collisions @ Bevalac at Lawrence Berkeley Lab.

RIBF, FRIB, FAIR, HIAF, ...



Research : Unstable Nuclei



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

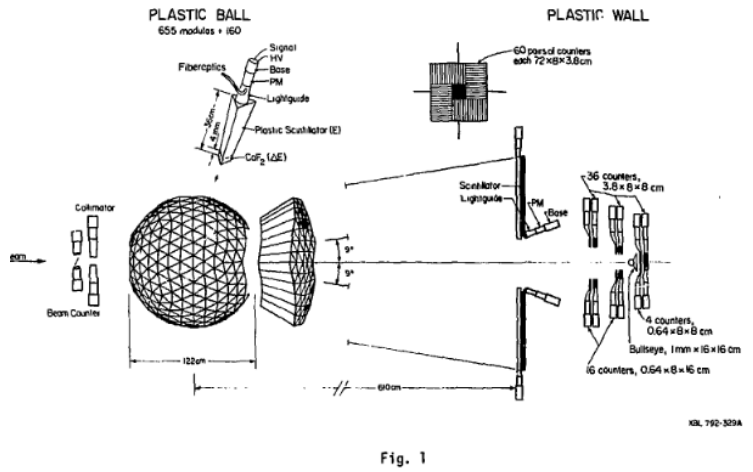
Nuclear Deformation、Neutron Halo
Neutron Skin

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

AGS, CENR-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)



Mixture