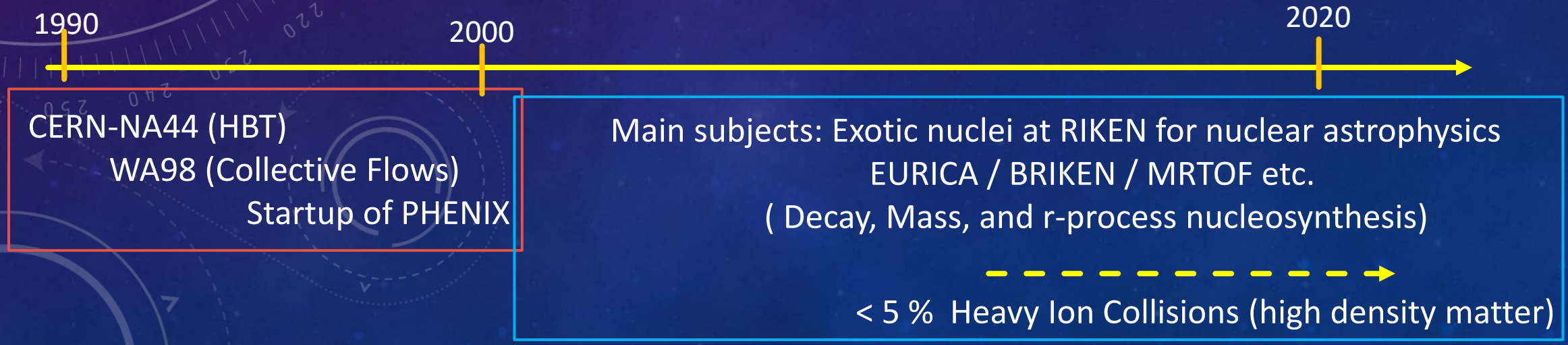
Dense matter from nuclear reactions in Astro- and heavy-ion physics

[Pioneering of "*Directed Spectator Beam Physics*" with Deformed Nuclei]

Shunji Nishimura (RIKEN)



Intersection of nuclear structure and high-energy nuclear collisions

Energy scale (and interests / language..) is quite different.

keV ~ MeV n, p, (pion) γ-rays, β-rays	←→	MeV ~ GeV ~ TeV pion, kaon, p, ϕ, p-bar, Λ, ...

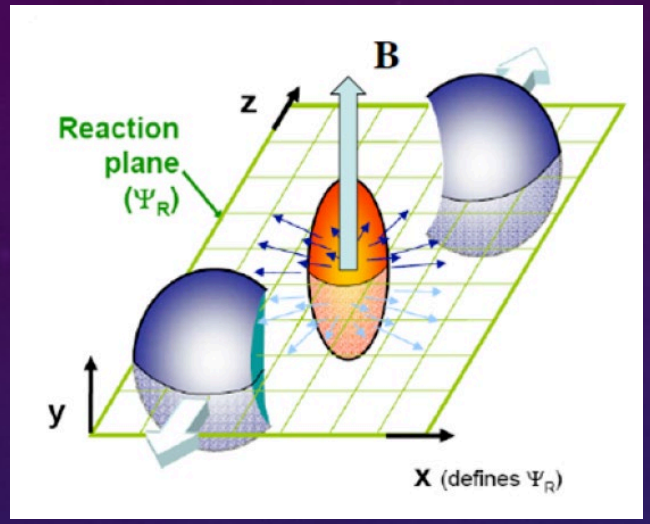
Different interests & heavy-ion reactions

Low energy nucl. structure

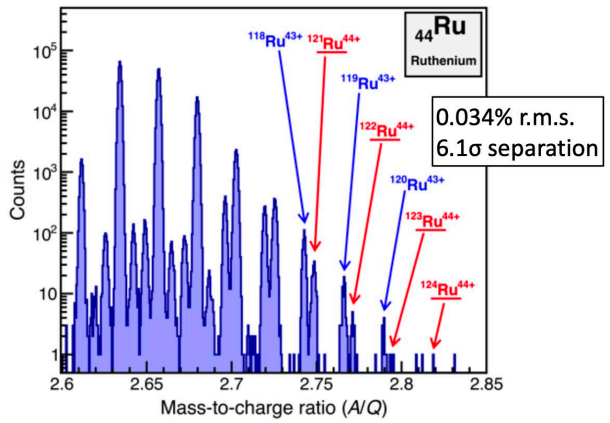
^{238}U + Be, ^{124,136}Xe + Be, ^{208}Pb + Be, ^{48}Ca + Be...

Heavy-ion collisions are used for production of neutron-rich and neutron-deficient nuclei at fast beam facilities.

(GANIL, MSU, RIKEN, GSI, ...)



BigRIPS superconducting RI beam separator



N. Fukuda et al., Nucl. Instrum. Meth. B 317, 323 ('13)

^{124}Ru

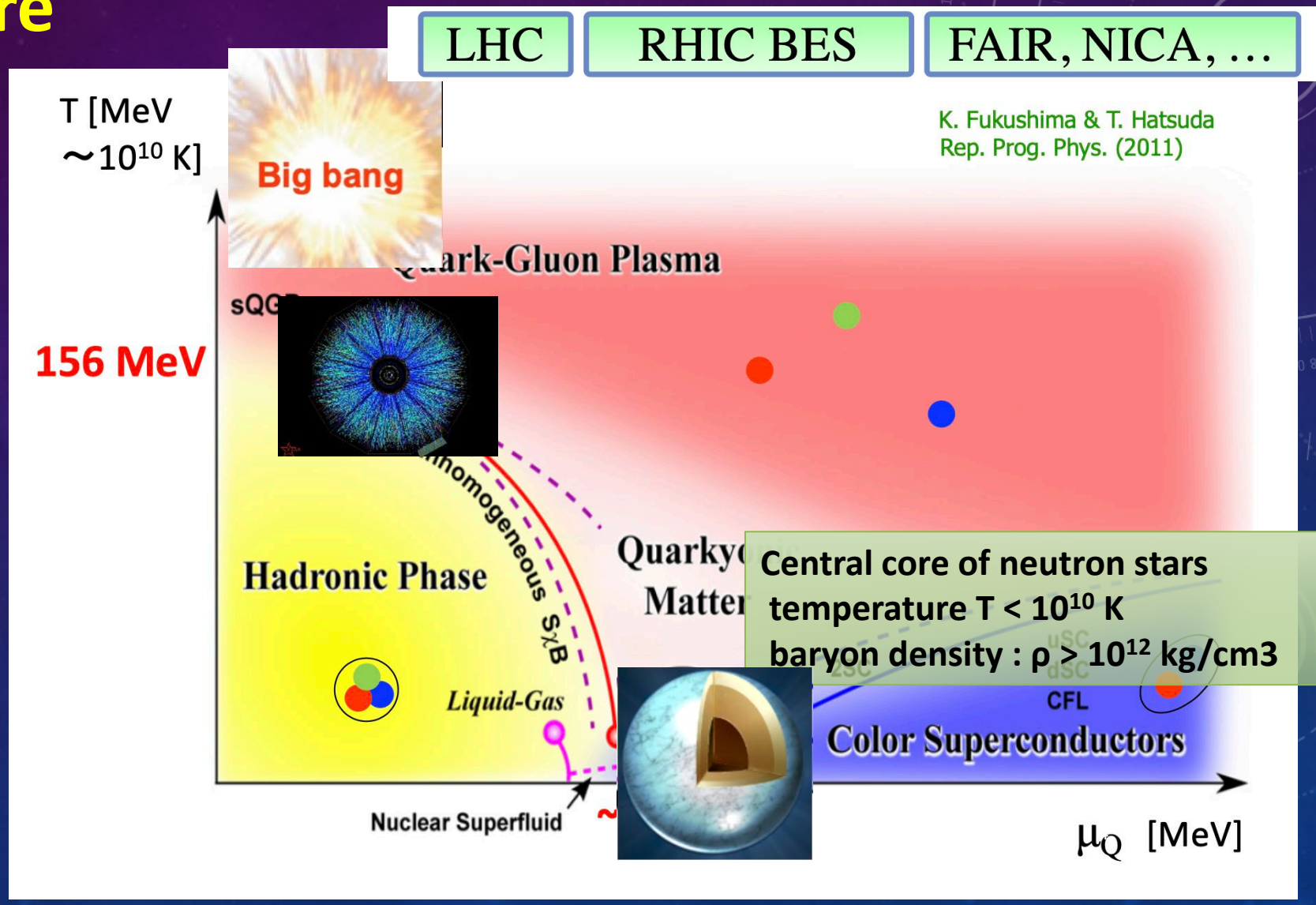
Z = 44, N = 52 + 28 neutrons

High energy nuclear collisions

QCD Phase Structure

Early Universe
time: t ~ 1—4 sec
temperature: T > 10^{12} K
baryon density: ρ ~ 0

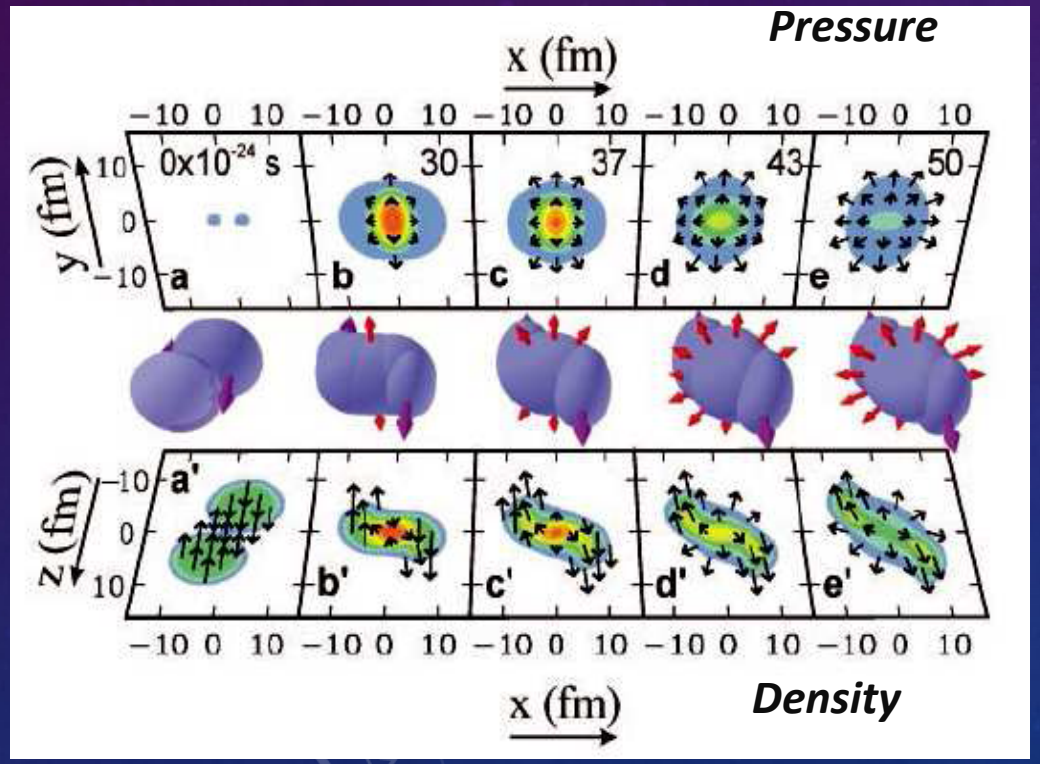
Relativistic heavy-ion collisions
time: t ~ 10^{-22} sec
temperature : T > 10^{12}K
baryon density : ρ ~ 0

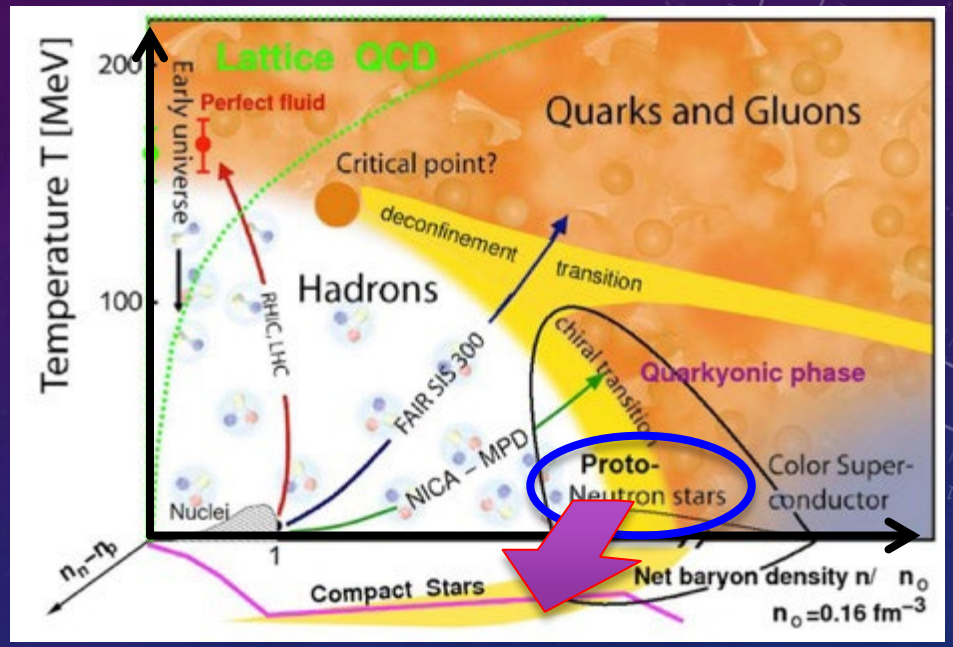


Central core of neutron stars
temperature T < 10^{10} K
baryon density : ρ > 10^{12} kg/cm3

Heavy Ion Collisions and Collective Flow

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





M. Chartier et al

EOS, Compressibility
→ Supernovae, Neutron-star

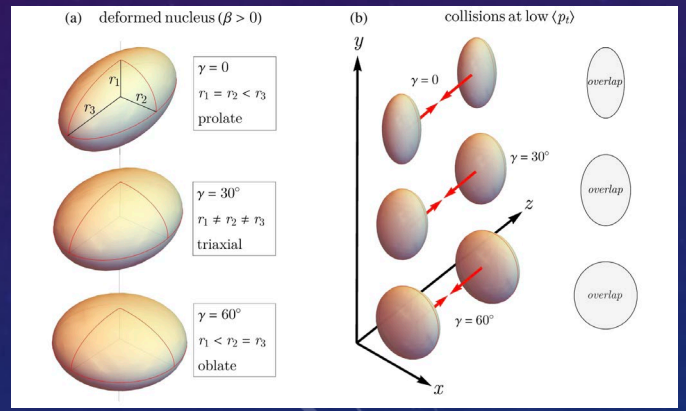
Feedback

Intersection of nuclear structure

Feedback

and high-energy nuclear collisions

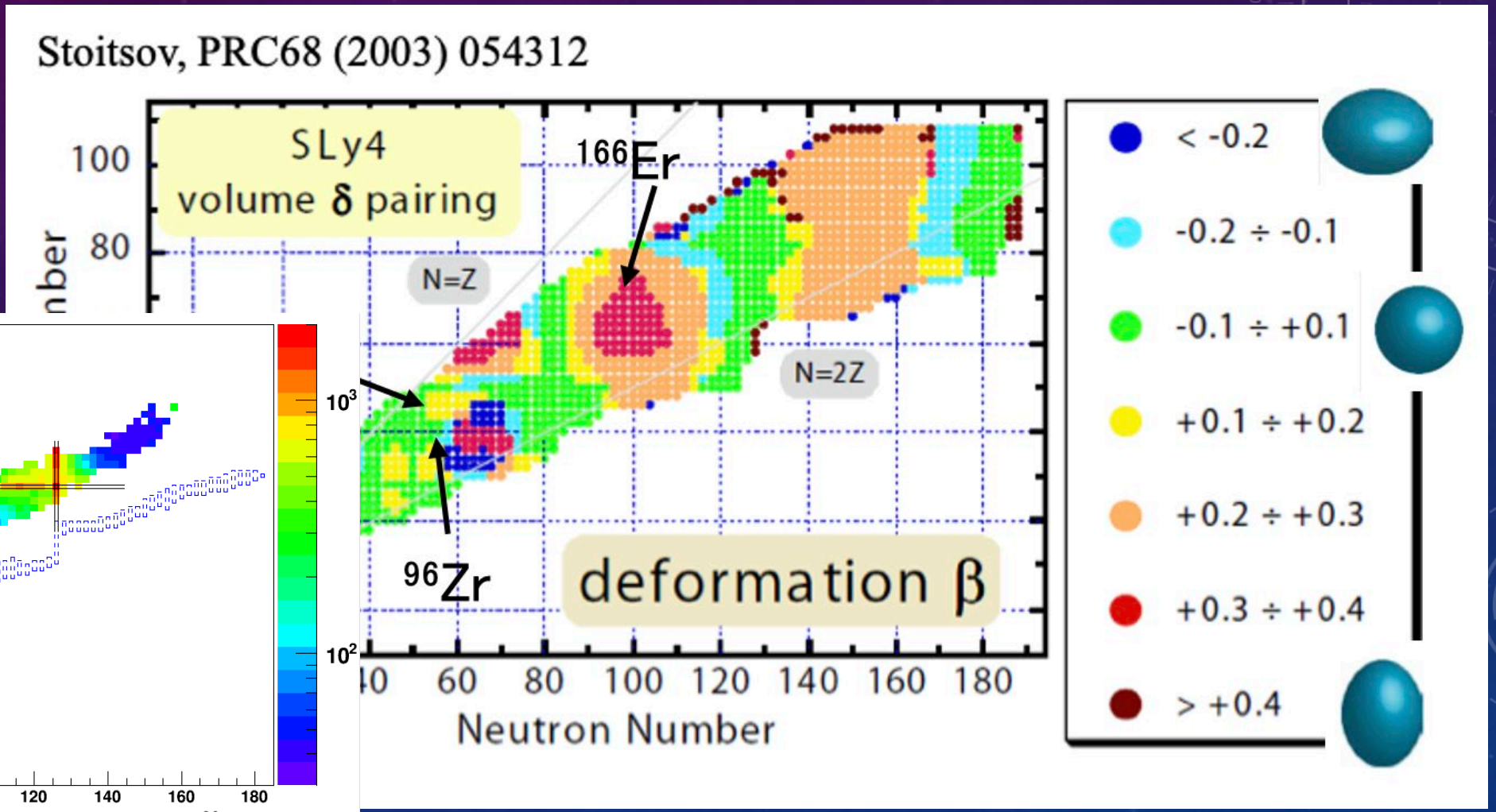
B. Bally et al., PRL128, 082301 (2022)

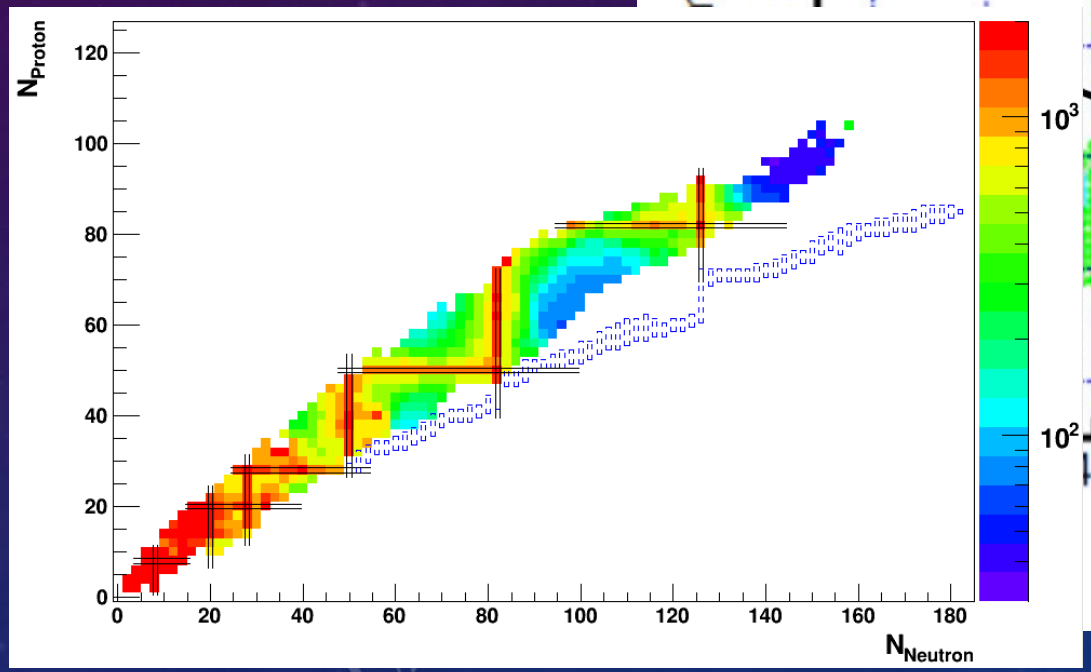


Keywords :
Deformed Nucleus & Collisions

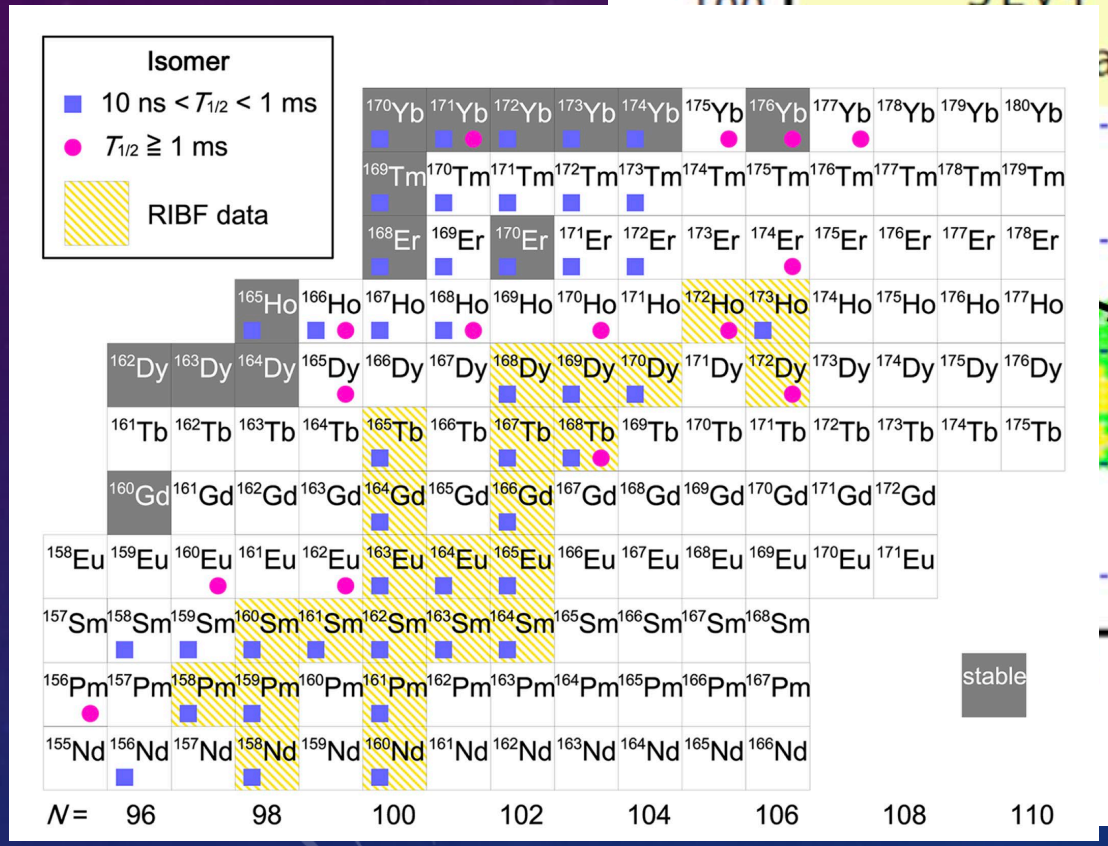
What is the next strategy for future experiments ?

Deformed Nuclei and Excited States

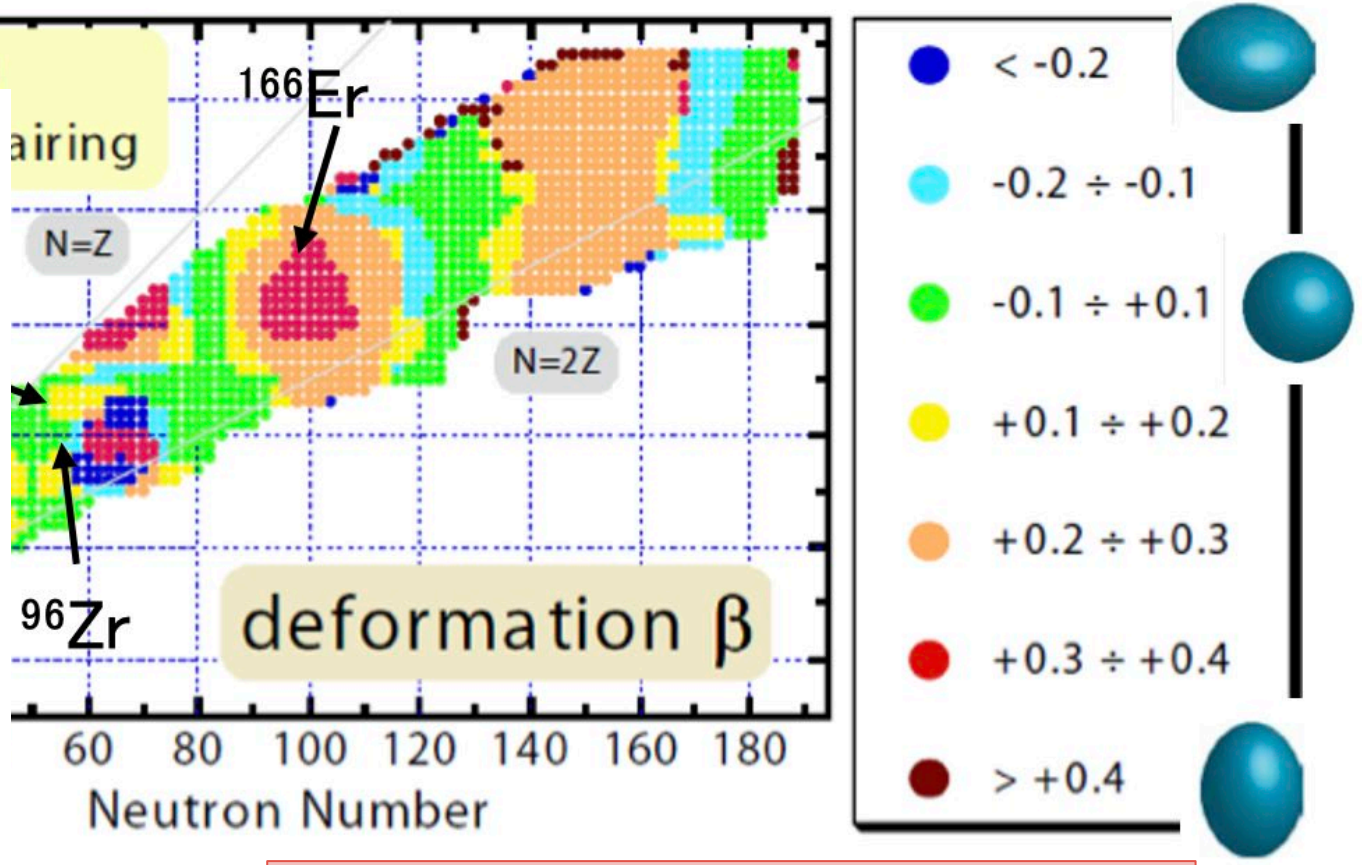




Deformed Nuclei and Excited States



Stoitsov, PRC68 (2003) 054312



Application to heavy-ion collisions

Future Experiments with Polarized Beams and Targets(1985)

Volume 159B, number 4,5,6 PHYSICS LETTERS 26 September 1985

FUTURE EXPERIMENTS WITH POLARIZED BEAMS AND TARGETS IN RELATIVISTIC HEAVY-ION COLLISIONS ☆

A. ROSENHAUER, J.A. MARUHN, H. STÖCKER[1] and W. GREINER
Institut für Theoretische Physik der Johann Wolfgang Goethe Universität, Frankfurt, Fed. Rep. Germany

Received 13 March 1985; revised manuscript received 30 May 1985

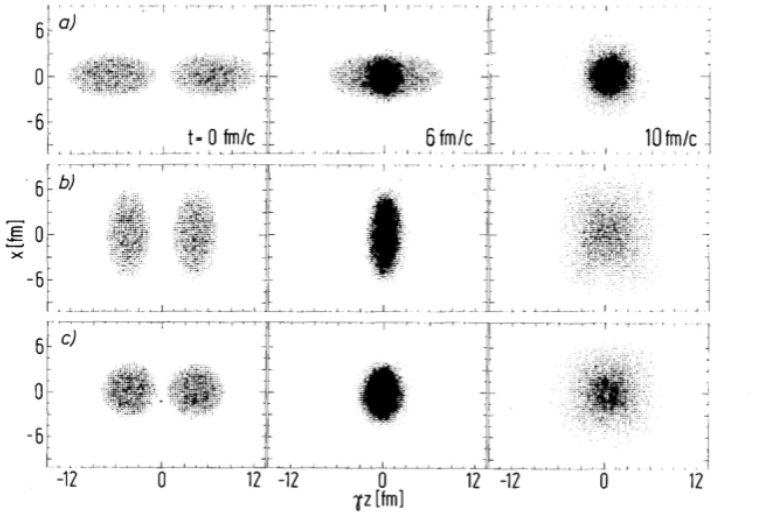


Fig. 1. Illustration of the compression and expansion stage in a central collision. The density at different reaction times as indicated is plotted for the three constellations. The "head on head" collision corresponds to (a), the "belly on belly" orientation to (b) and the reaction of two spherical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

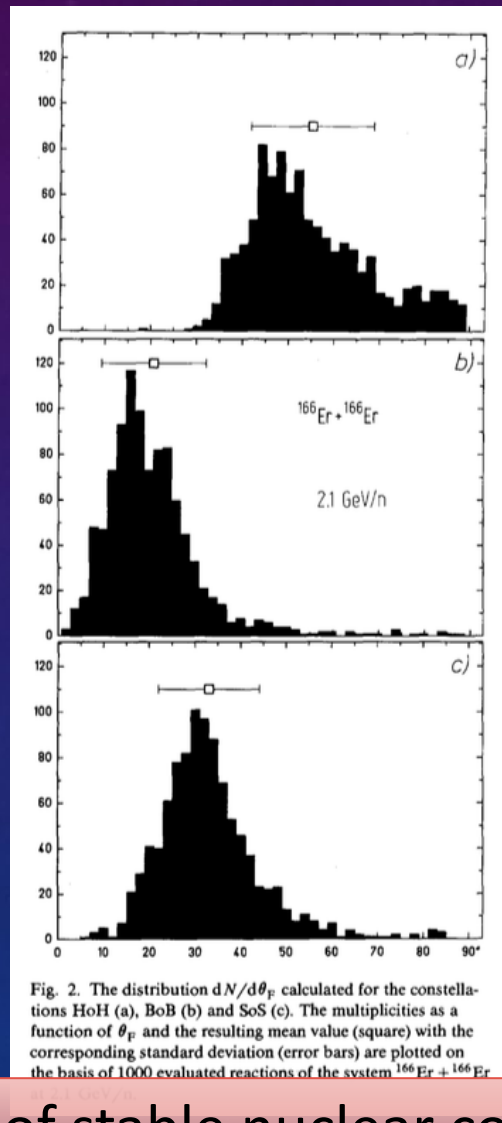


Fig. 2. The distribution $dN/d\theta_F$ calculated for the constellations HoH (a), BoB (b) and SoS (c). The multiplicities as a function of θ_F and the resulting mean value (square) with the corresponding standard deviation (error bars) are plotted on the basis of 1000 evaluated reactions of the system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

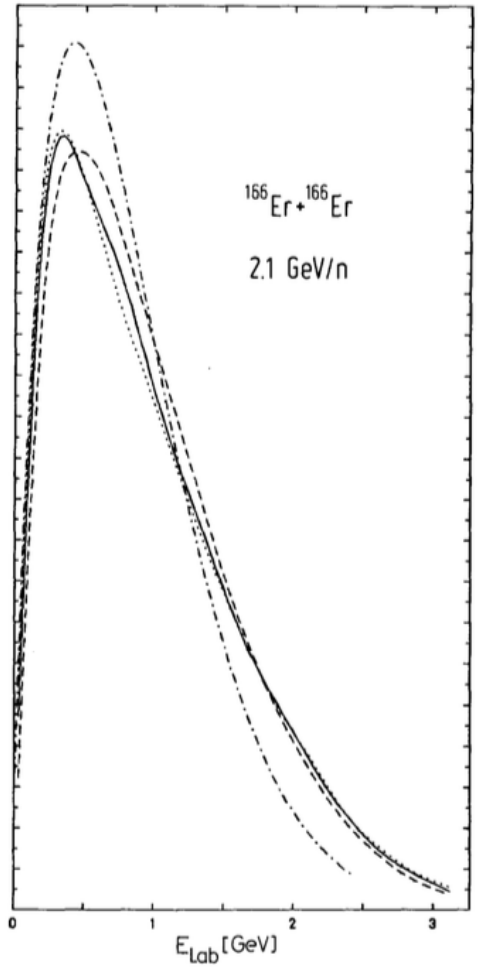


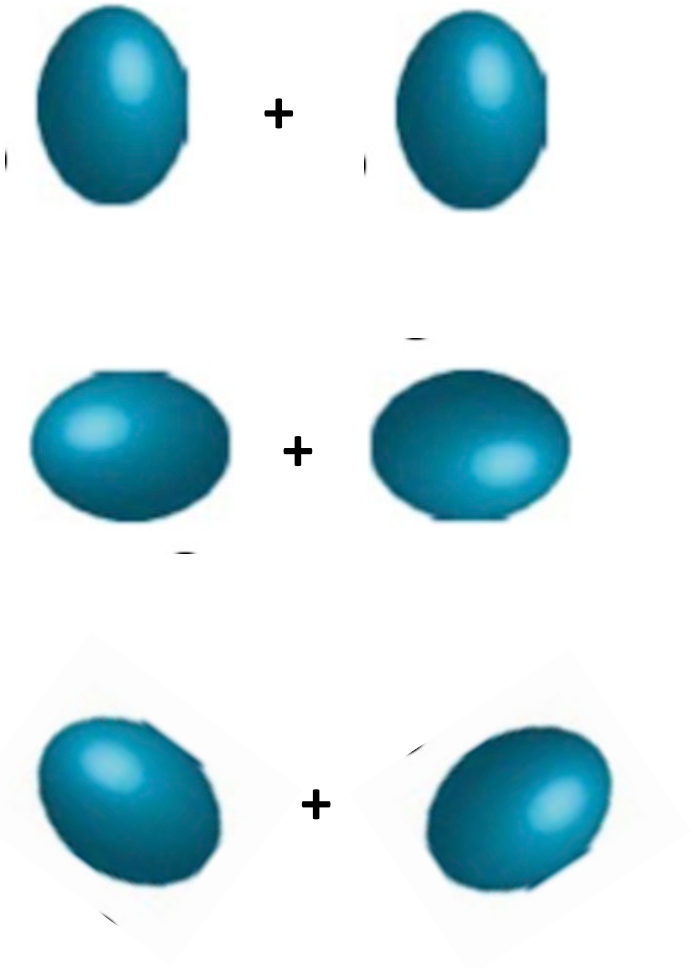
Fig. 3. Energy distribution dN/dE of all participant particles detected by the plastic ball. The spectrum obtained in the lab-system has been plotted for the cases HoH (dashed line), (full line). The dash–dotted line of a fireball.

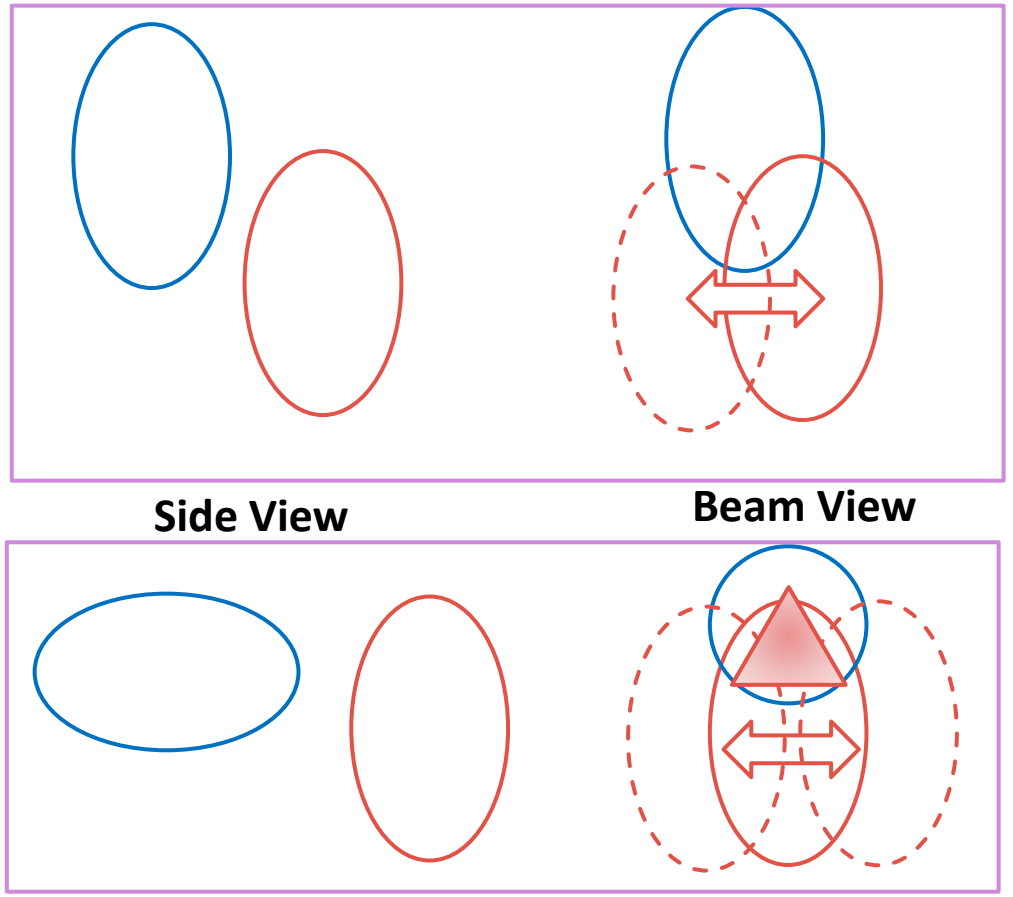
This is a case of stable nuclear collisions.

Deformed Nuclear Collisions

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

Variety type of collision patterns





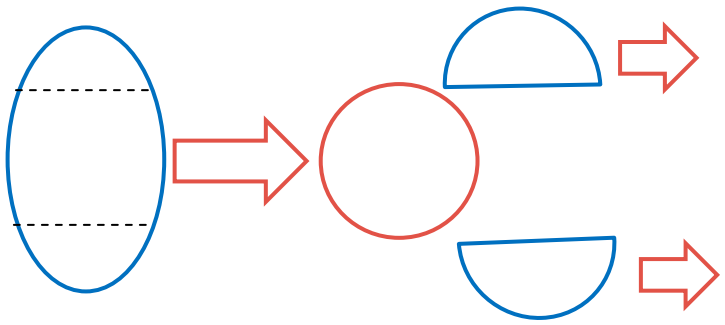
Triangular shape of overlapping region?

→ Events with larger V3 component?

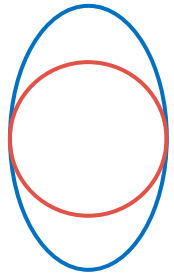
Centrality / $N_{Participants}$ vs Multiplicity

S. Bhatta, V. Barirathi,
EPJ C (2022) 82, 855

Deformed nuclei + spherical nuclear collisions



Side View



Egg shape overlap

Beam View

- **Collider can see both spectators forward and backward.**
  Choose asymmetric spectators !?
- **Fixed target exp. can see only beam spectator.**
  But, easy to identify spectators (N, Z)

Open Questions related

to Deformed Nucleus Collisions

Open Questions

① Is there any possibility to measure stable + Isomer collisions ?

- Any possible events of isomer collisions in high energy HI data (collider)?

② Is there any possibility to control deformed nuclei?

- Related research topics in lower energy experiments
- Any possible technique for fixed target experiments (collider exp.?)

③ Is there any common interests in high- and low-energy field ?

- High density neutron-rich matter and neutron stars
- Nuclear shape study using heavy-ion collisions ?

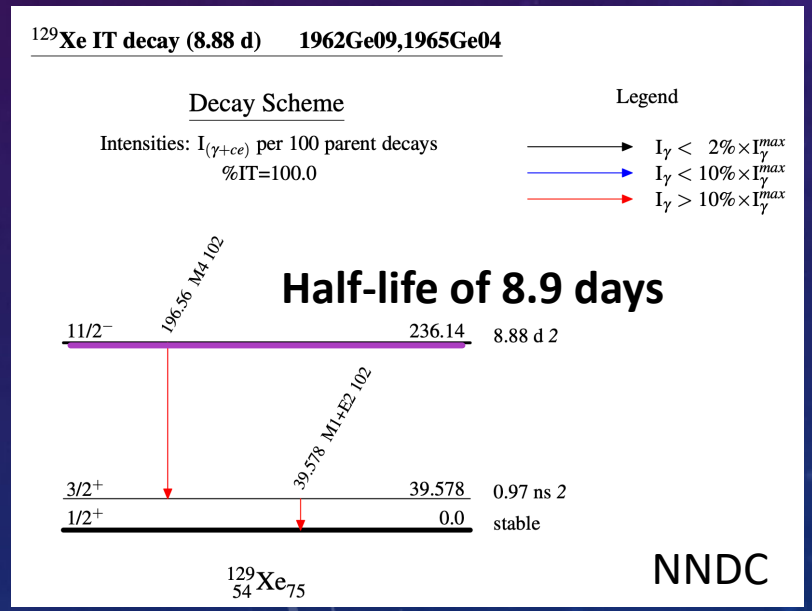
Stable + Isomer collisions ? ... Very low event rate

^{129}Xe + ^{129}Xe Collisions

Z = 54

Z = 54

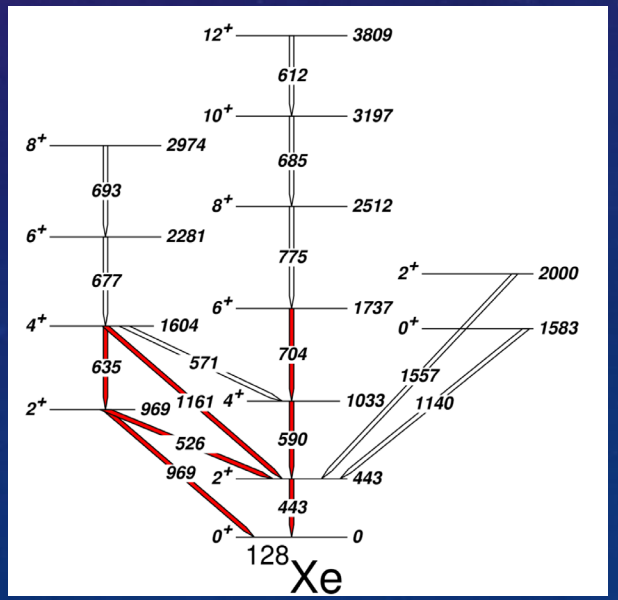
Jiangyoung's question about beam excited by Coulomb excitation during Monday's discussion time.



10^{13} ions

1 MHz collisions

Any localization of isomers in beam bunch?



LHC

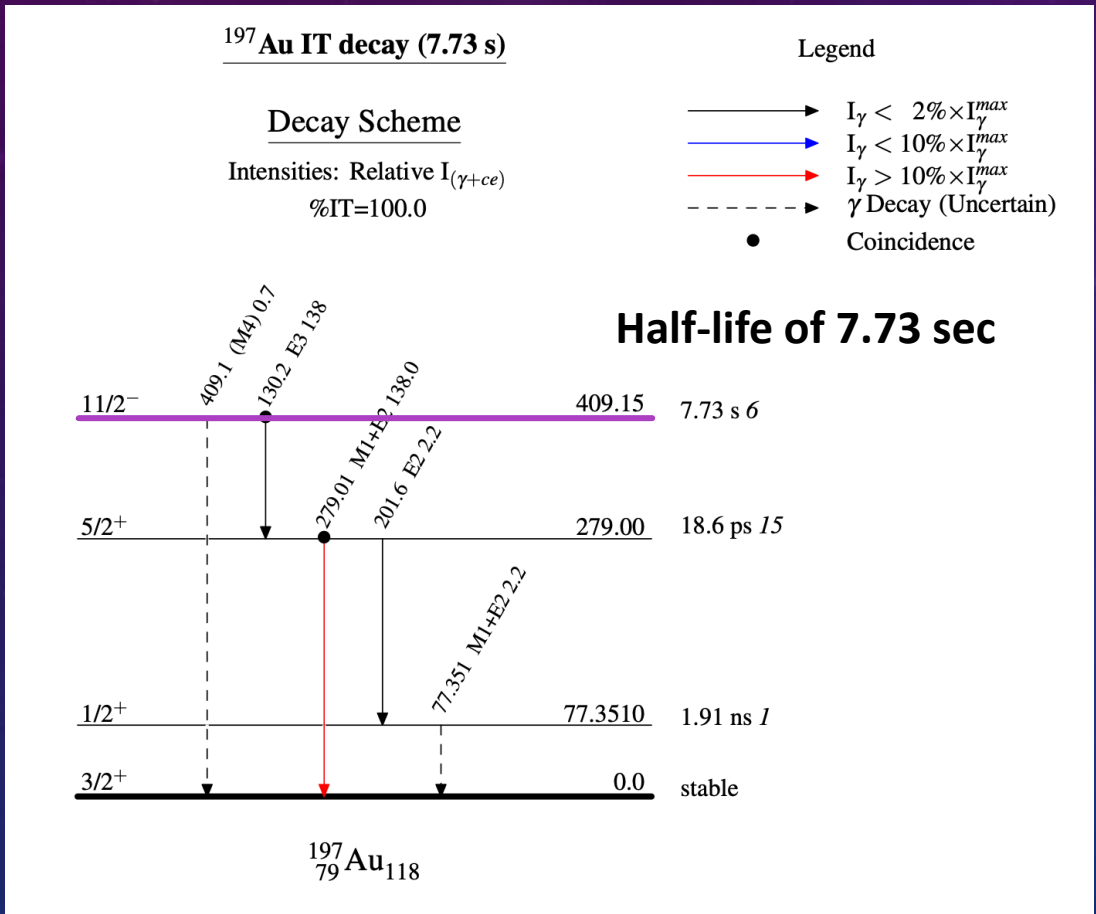
accumulation of isomers as function of time ?

Coulomb excitation of ^{126,128}Xe
Phys. Rev. C 106, 034311 (2022)
S. Kisyov et al., ReA3 @MSU

Stable + Isomer collisions ? … Very low event rate

How about ^{197}Au + ^{197}Au Collisions

NNDC



Lorentz factor γ = 108 at 100GeV/n

→ 7.73 x 108 = 834s

~ 14 mins

Excited energy : 409 keV

Shape of 197Au and 197Au*

Possible gate of timing, trajectory in

Inject long-lived isomer of 129Xe just before injection to LHC ring ? (Coulomb excitation by Pb / W plate ?

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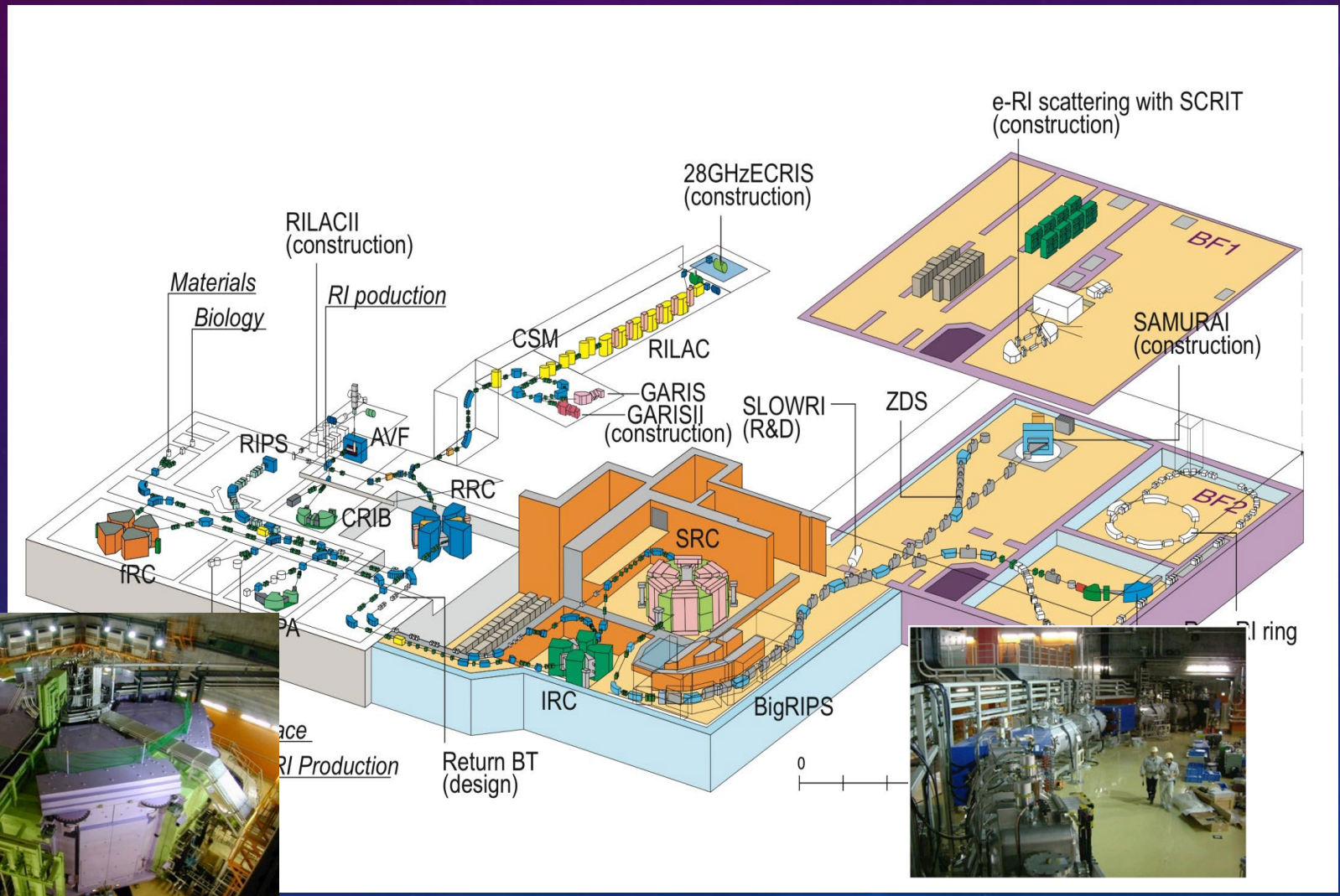
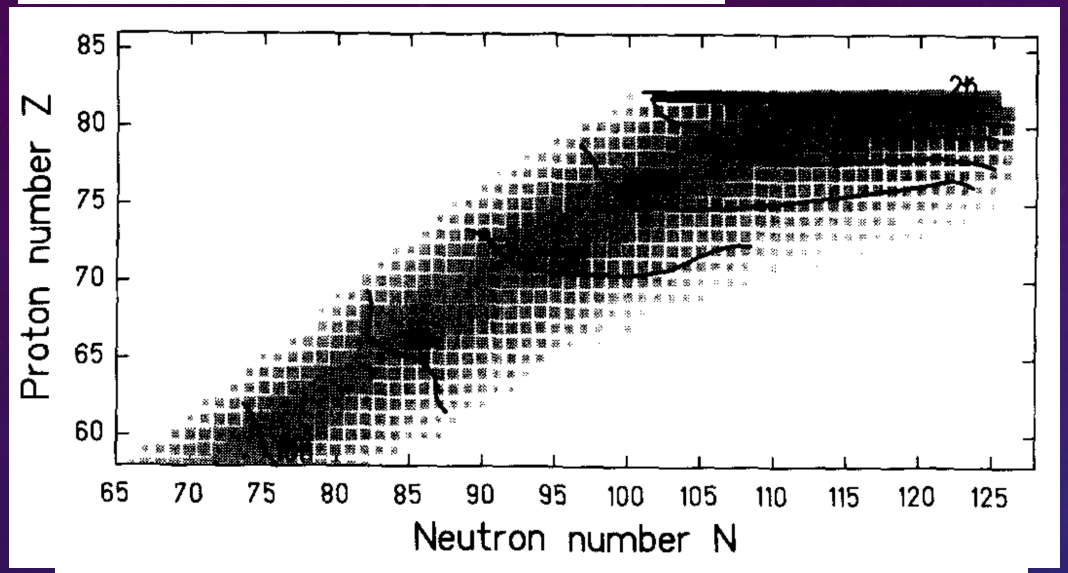
Radioactive Isotope Beam Facility RIBF



Fragments (Spectators)

M. de Jong et al., Nucl. Phys. A **613** (1997) 435.



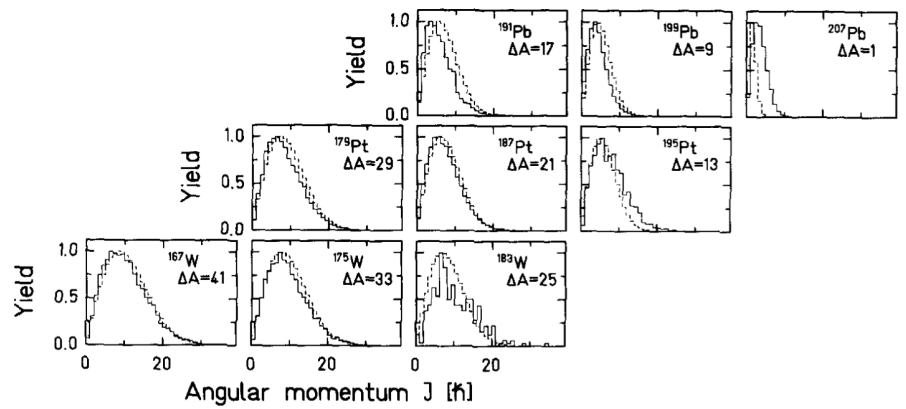
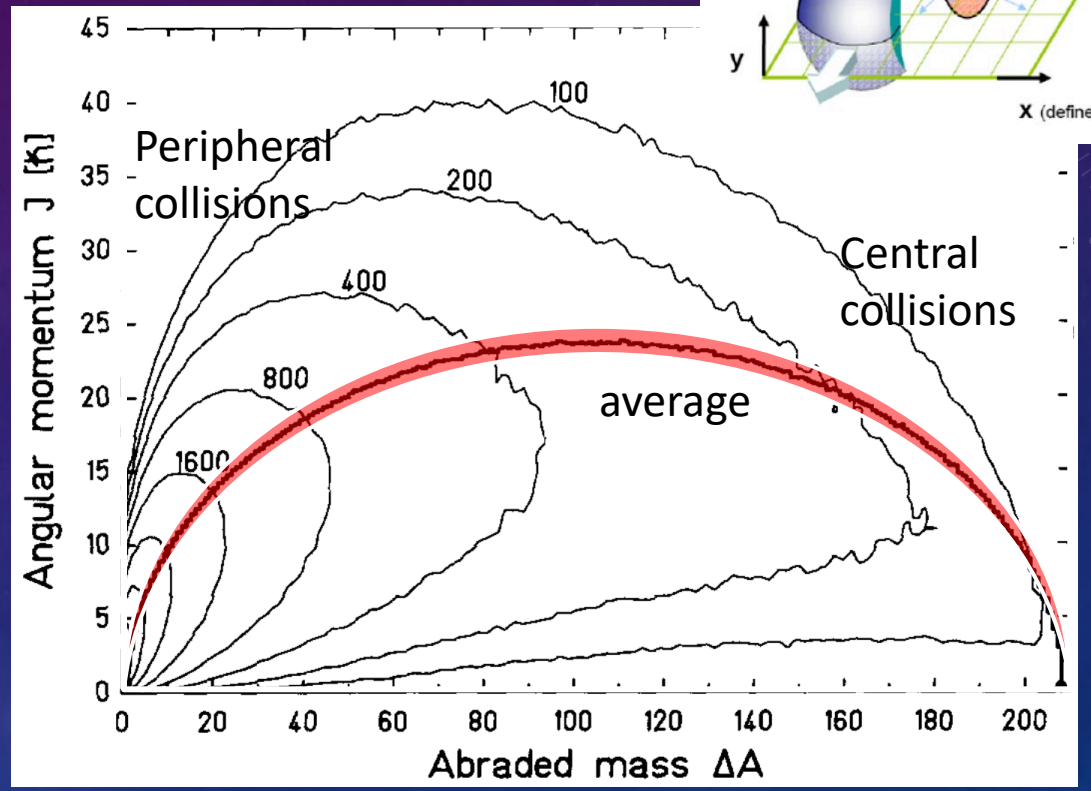
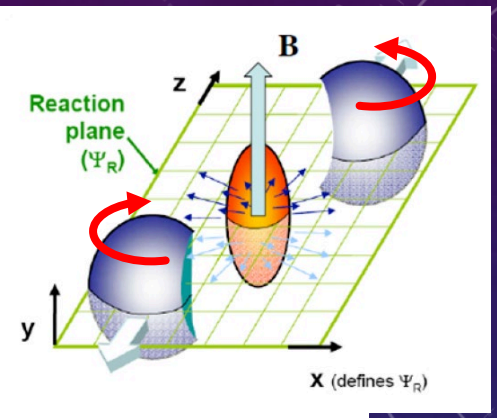


Fig. 5. The angular-momentum distribution for various isotopes of lead, platinum and tungsten. Each distribution is normalized to its maximum value. The dashed lines are approximations using the spin-cutoff parameter according to Eq. (16) with $\bar{\nu} = 2.0$.

Statistical abrasion-ablation model



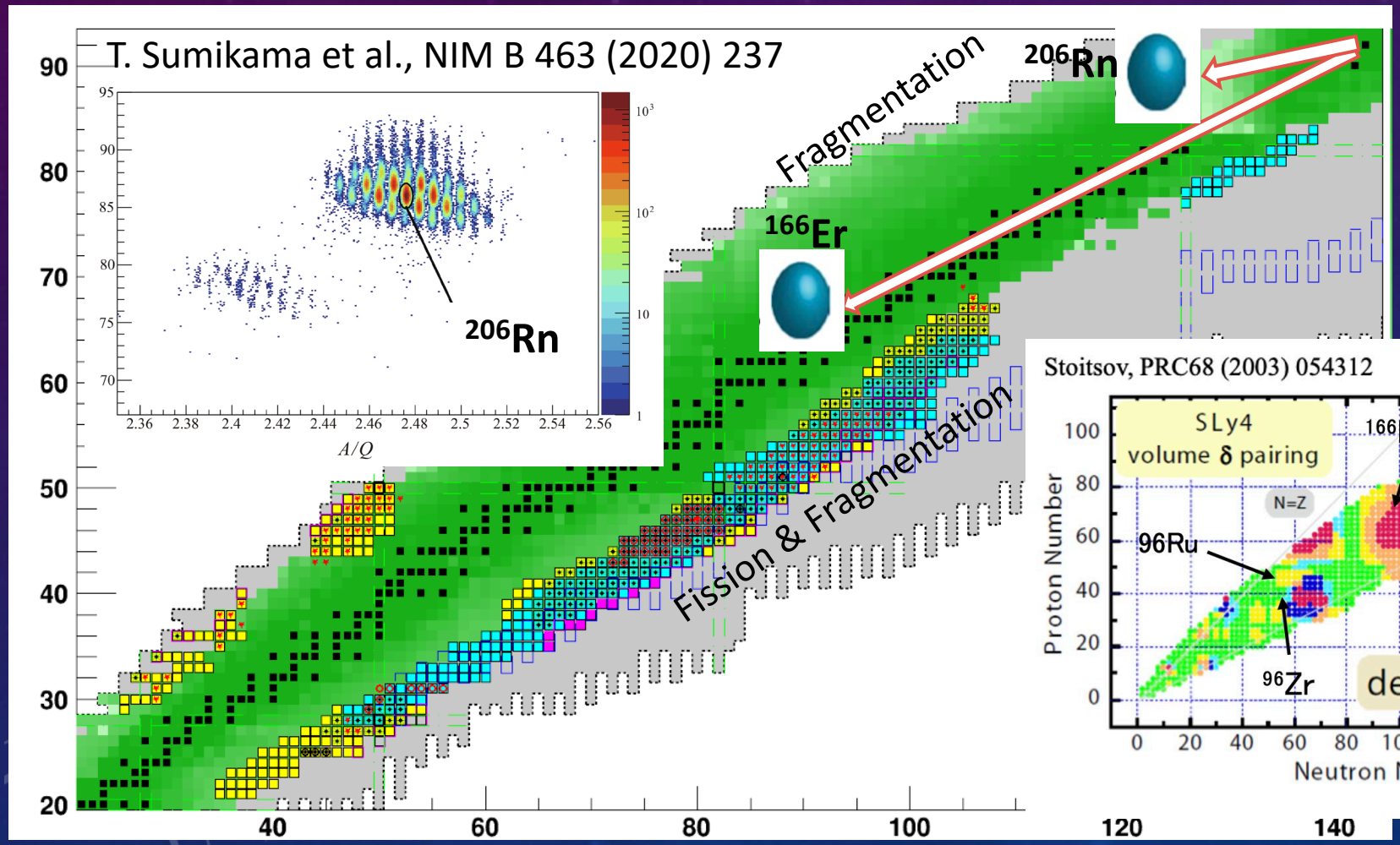


① Angular Momentum,
② Azimuthal Asymmetric Flow, and
③ Deformed Nuclei

Production of Deformed Nuclei

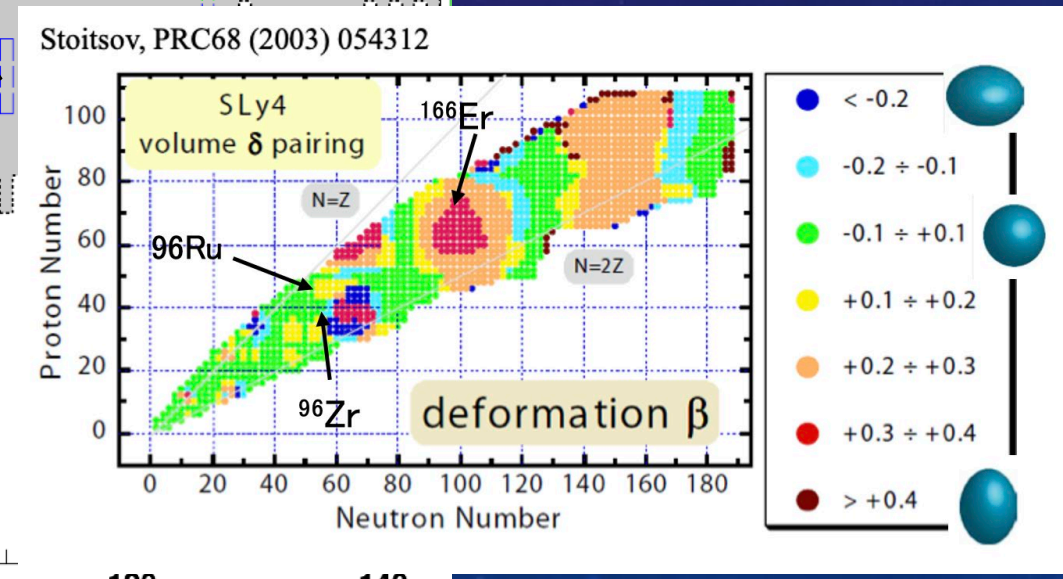
We are requesting 208Pb beam at RIBF..

^{238}U + W collisions → Select deformed fragment using semi-central collisions

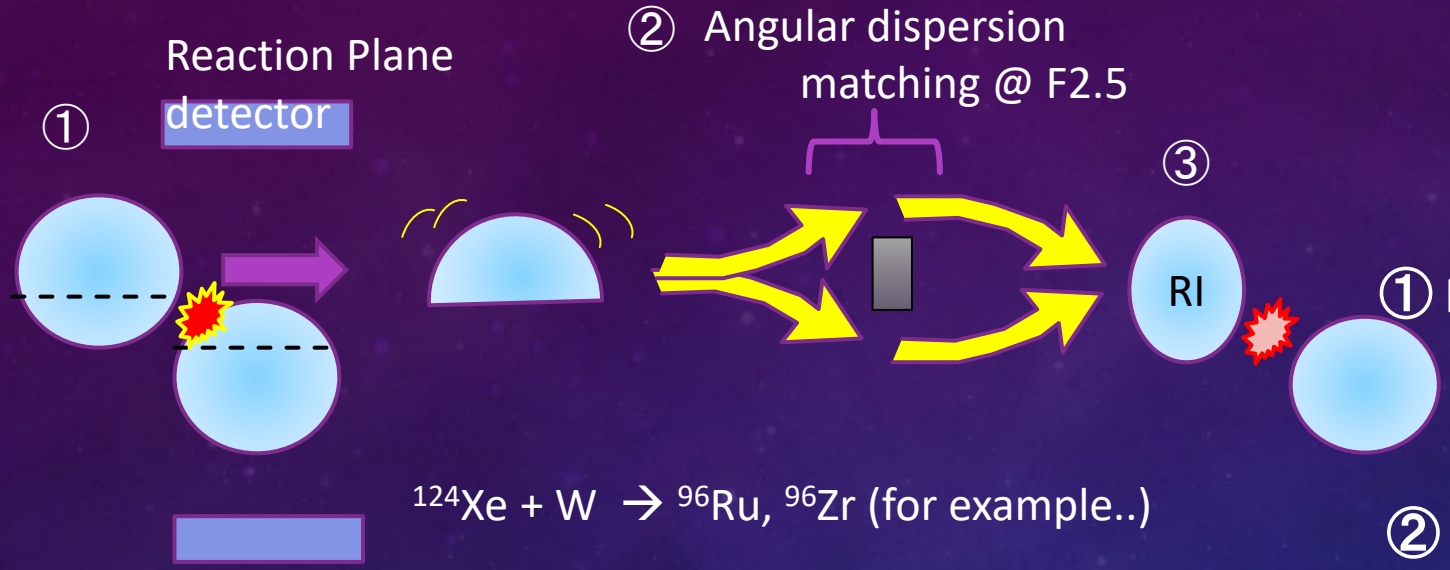


Beam int. of 238U : 10^{11} cps

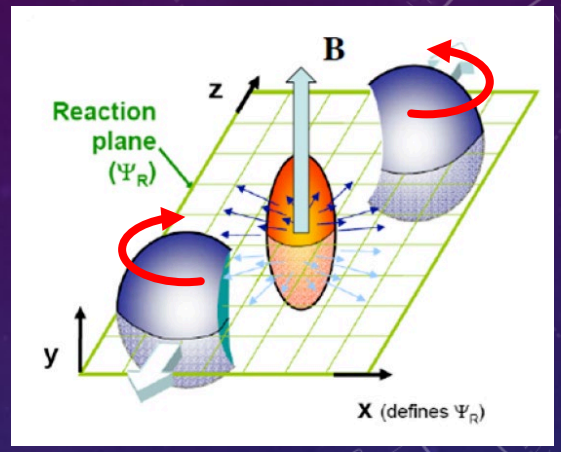
Deformed RI
For example...
^{208}Rn, ^{166}Er, etc..



Directed Spectator Beam for Deformed RI + Nuclear Collisions



^{124}Xe + W → ^{96}Ru, ^{96}Zr (for example..)

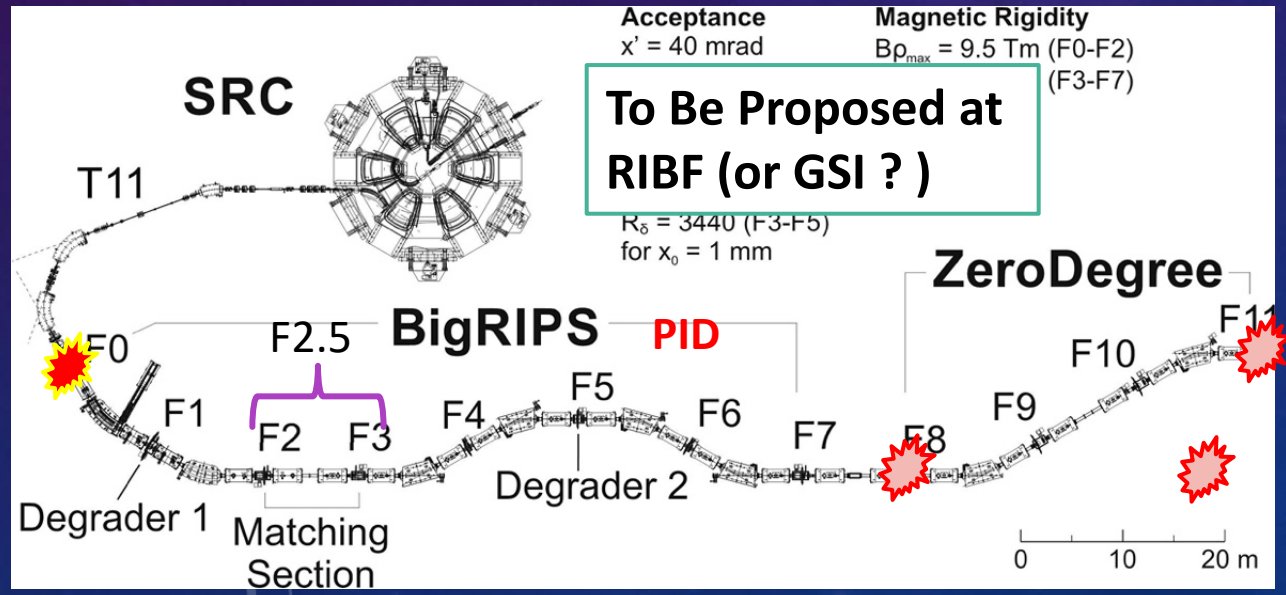


① Non-central collisions @ F0
for production of fragments

② Position ←→ Direction of bounce off
for fragments

③ Particle Identification (PID)
of fragments : RI (Z, N)
... polarized RI and its axis
←→. Position at ② F2.5

④ Deformed RI + Nucleus collisions
→ Study on asymmetric flow
(Double-differential reaction study
ϕ1 (b-vector) – ϕ2 (Particles)



Isomers in ESR

Mass measurement & Isomers

M.W. Reed et al., Phys. Rev. C 86, 054321 (2012)

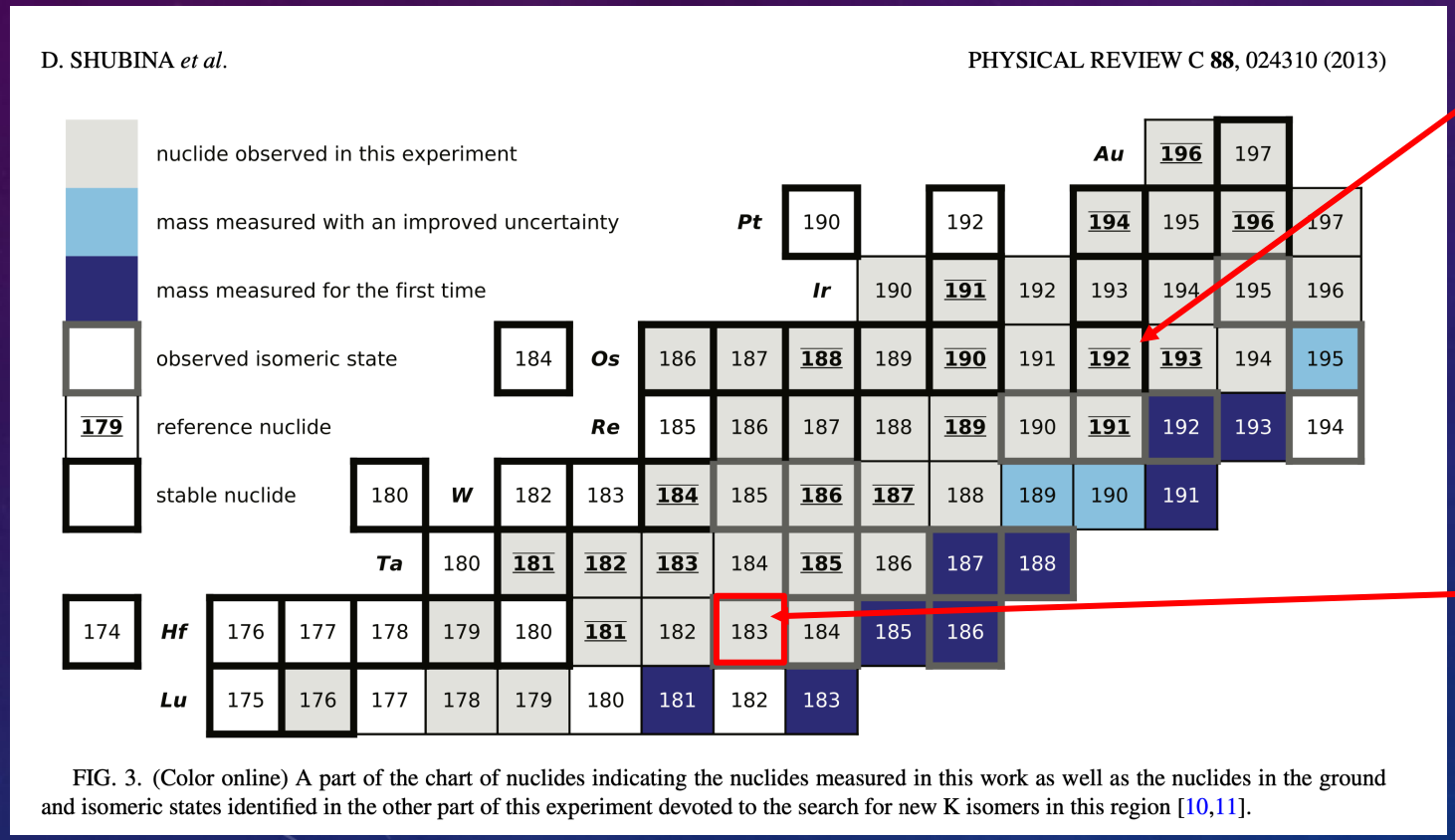
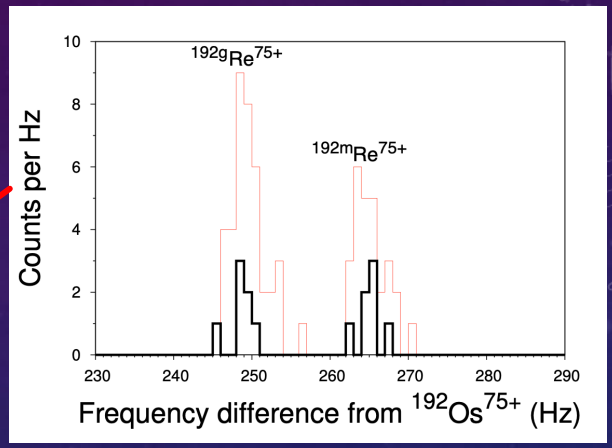
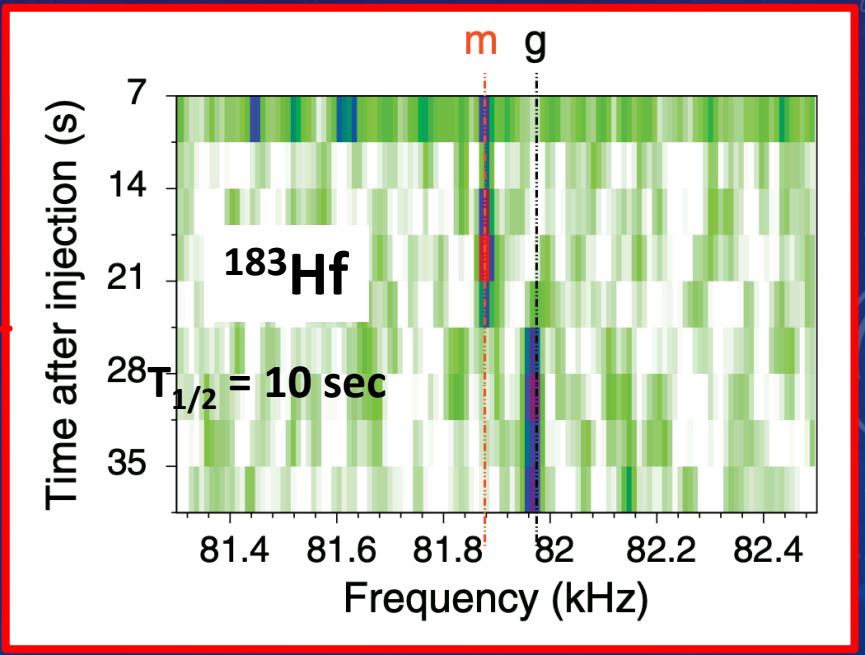


FIG. 3. (Color online) A part of the chart of nuclides indicating the nuclides measured in this work as well as the nuclides in the ground and isomeric states identified in the other part of this experiment devoted to the search for new K isomers in this region [10,11].

Isomer ... M.Pfutzner et al., PRC 65, 064604

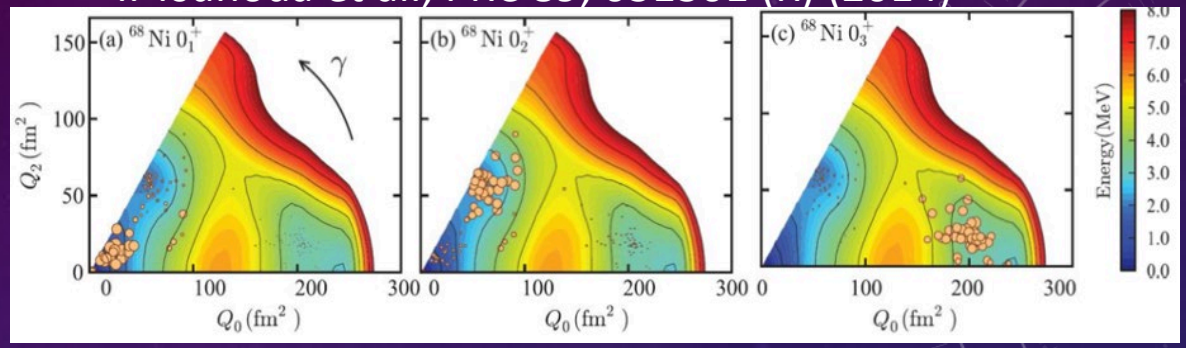


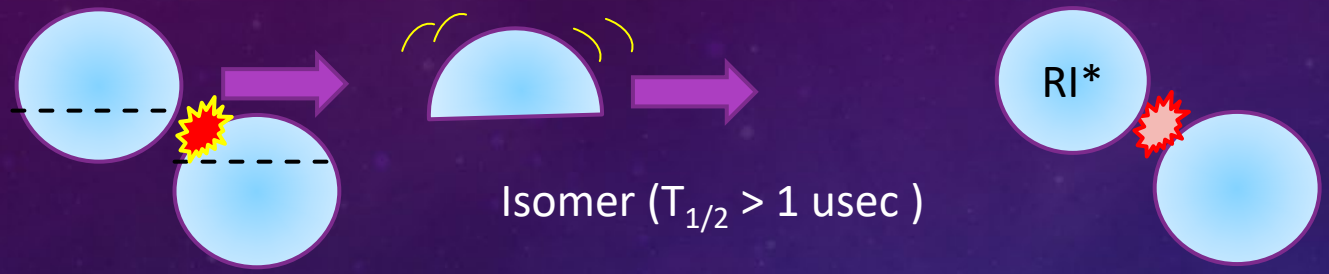
^{192}Re



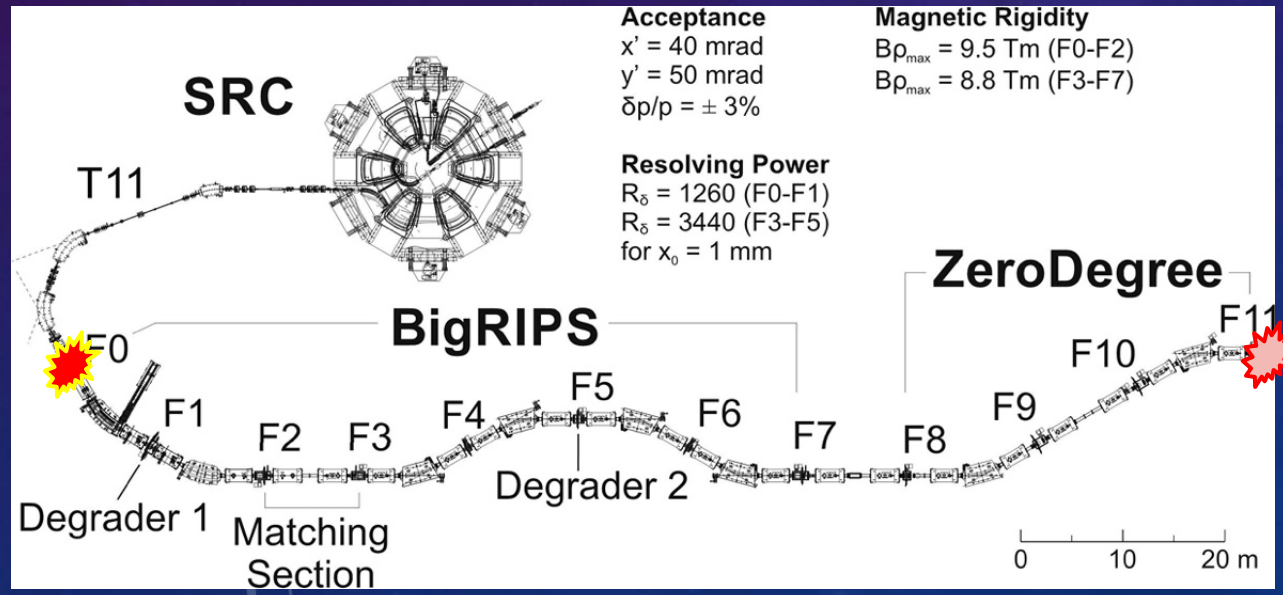
Stable + Isomer collisions ?

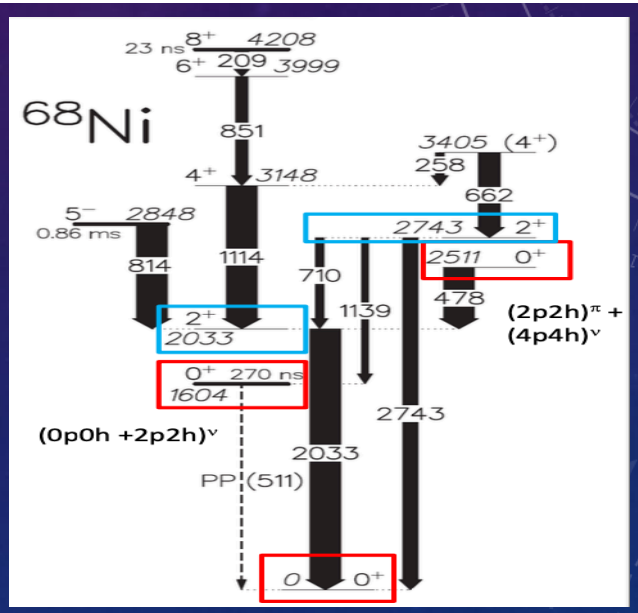
Y. Tsunoda et al., PRC 89, 031301 (R) (2014)





Some possibility to perform experiments (fixed target)?





In-flight mass measurement with good timing detectors

We may identify isomeric state on an event by event basis reaction plane vs emission angle of gamma..

Open Questions

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- High density neutron-rich matter and neutron stars
- Nuclear shape study using heavy-ion collisions ?

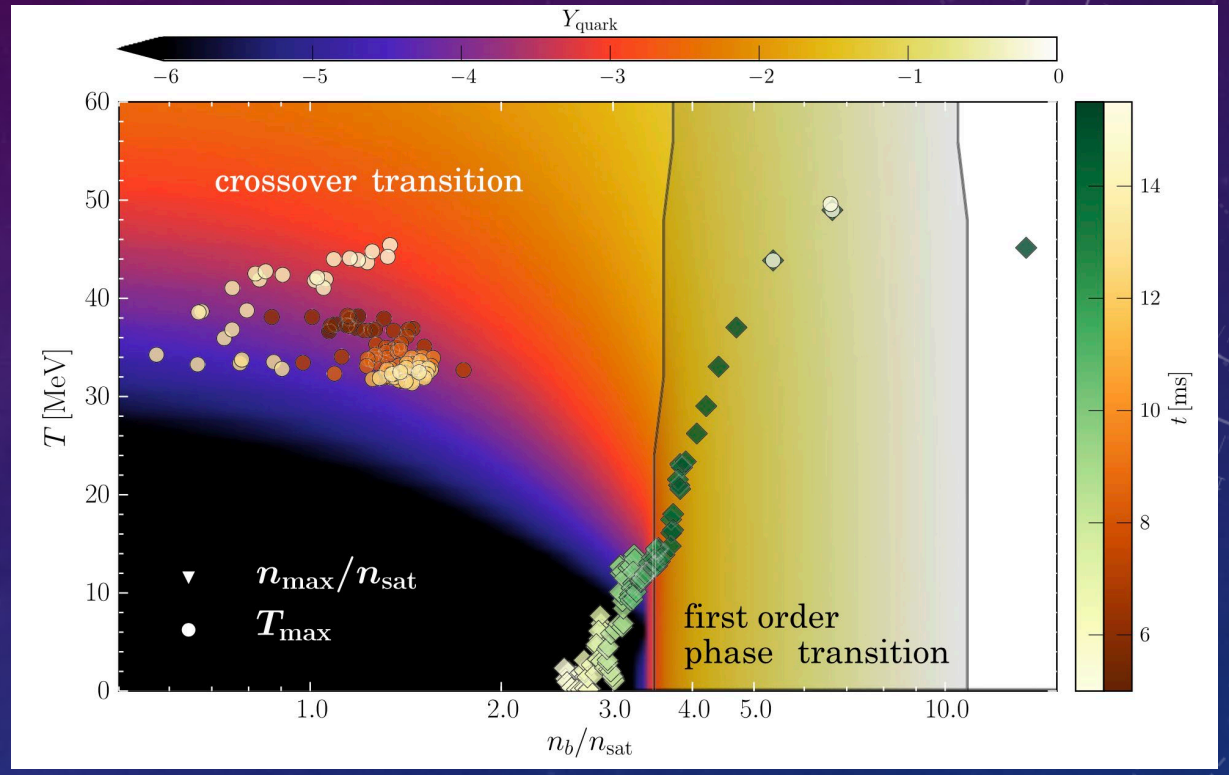
High Density

(Neutron-rich) Nuclear Matter

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

Image of Binary Neutron Star Merger

Credit: Univ. Warwick/Mark Galick (ESO Image)

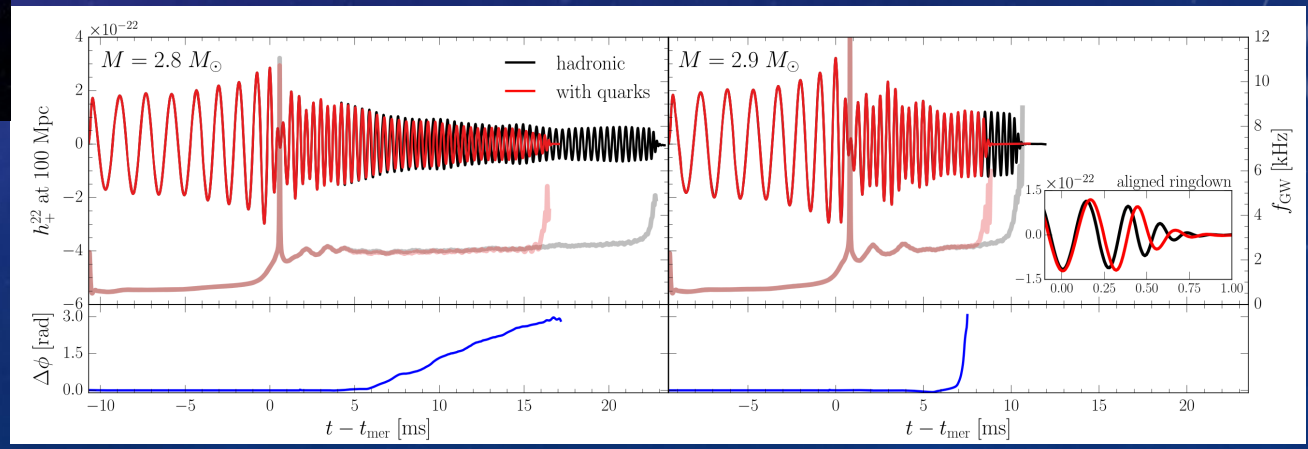


PHYSICAL REVIEW LETTERS **122,** 061101 (2019)

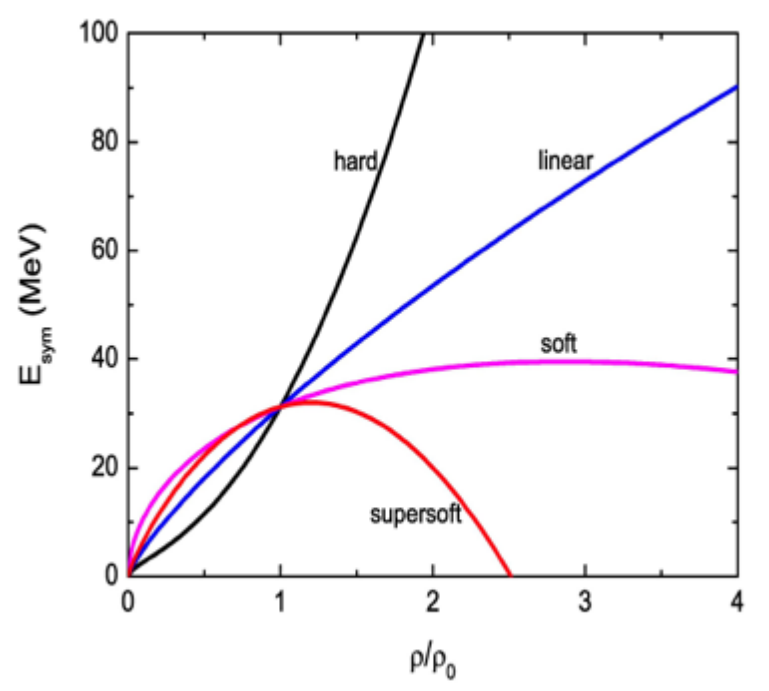
Editors' Suggestion

Signatures of Quark-Hadron Phase Transitions in General-Relativistic Neutron-Star Mergers

Elias R. Most,[1] L. Jens Papenfort,[1] Veronica Dexheimer,[2] Matthias Hanauske,[1,3] Stefan Schramm,[1,3] Horst Stöcker,[1,3,4] and Luciano Rezzolla[1,3]



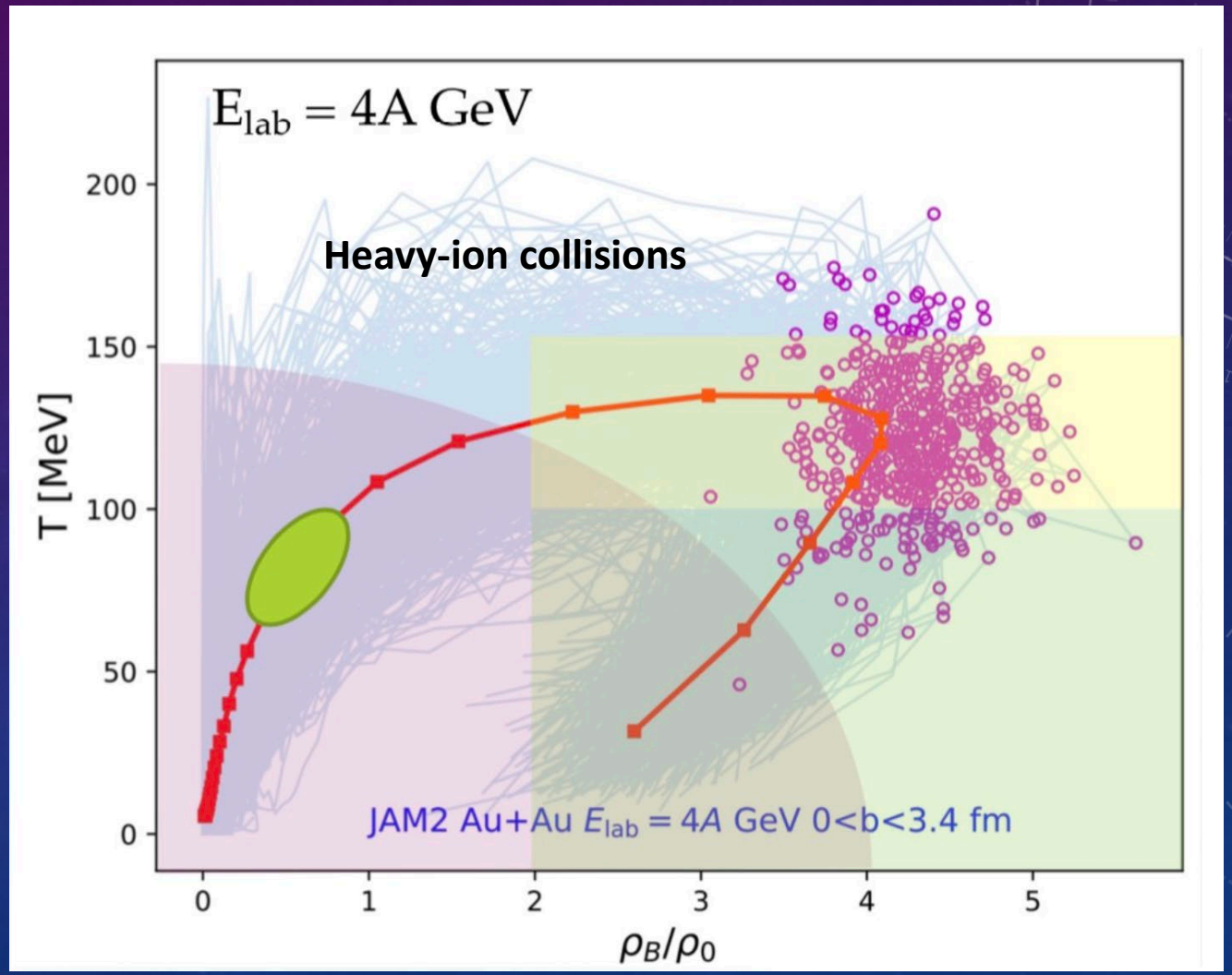
High Density Matter using Heavy-Ion Collisions



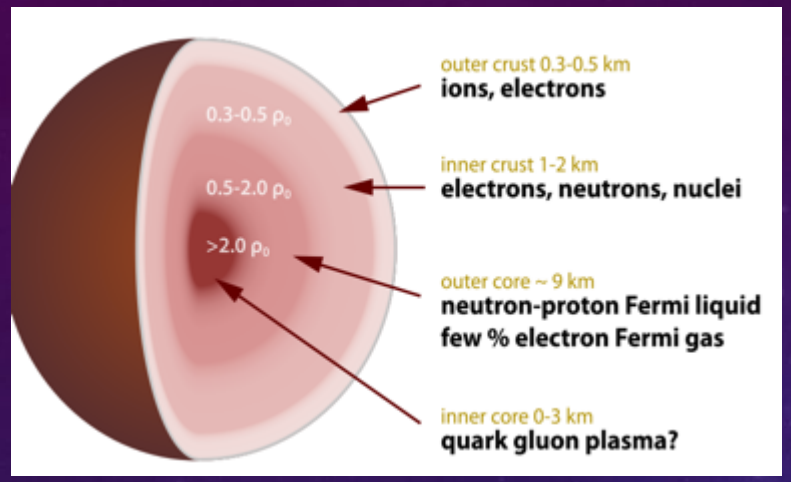
$$E(\rho, \delta) = E(\rho, \delta = 0) + E_{\text{sym}}(\rho)\delta^2 + \mathcal{O}(\delta^4).$$

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

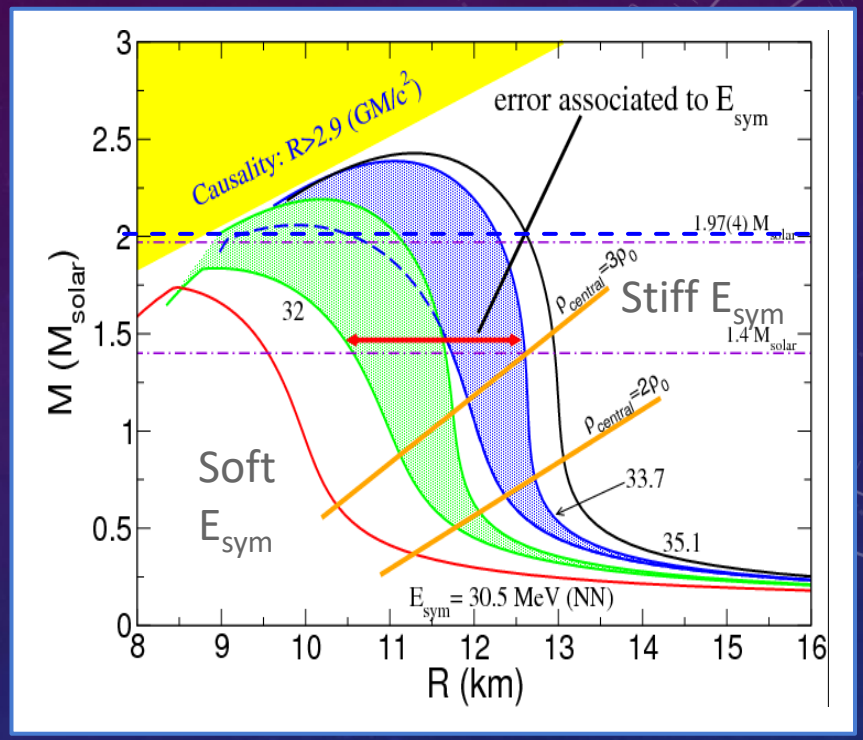
（ 100 % neutron → $\delta = 1$ ）

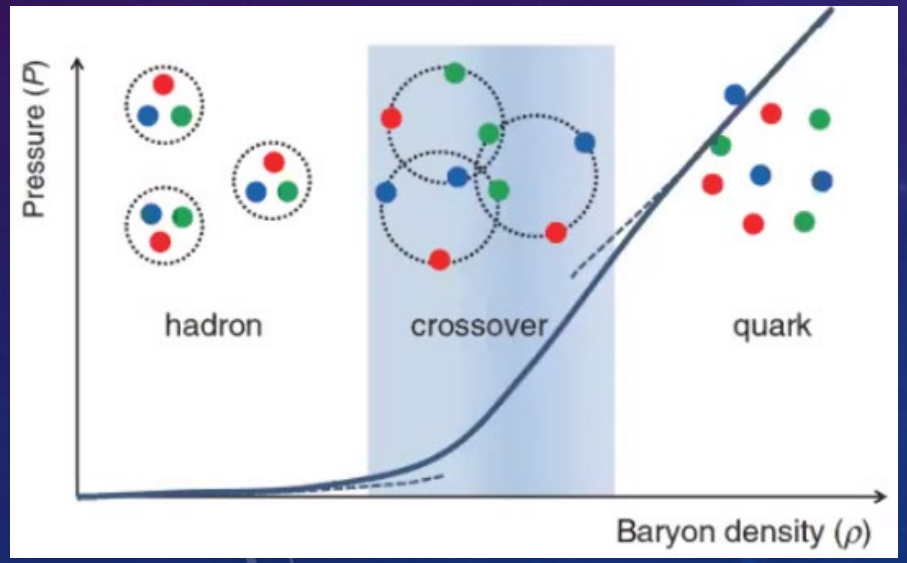


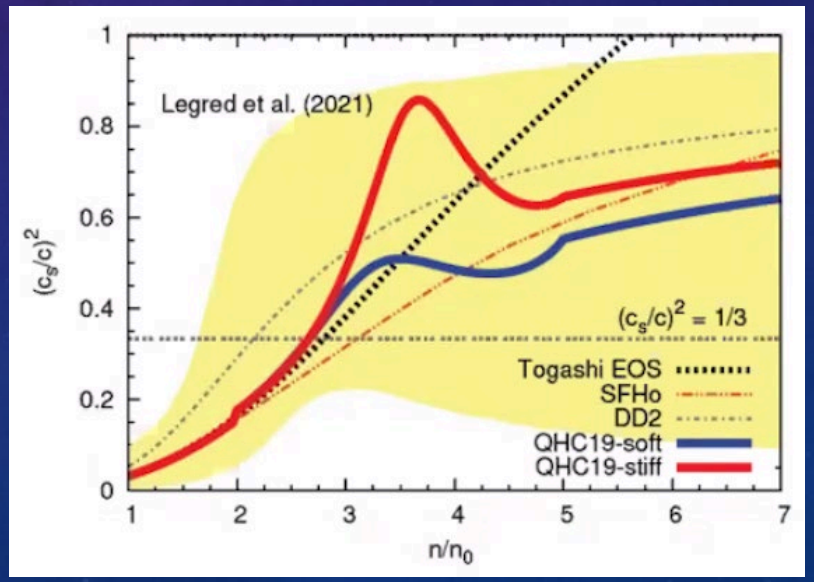
Neutron Star : M vs R



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







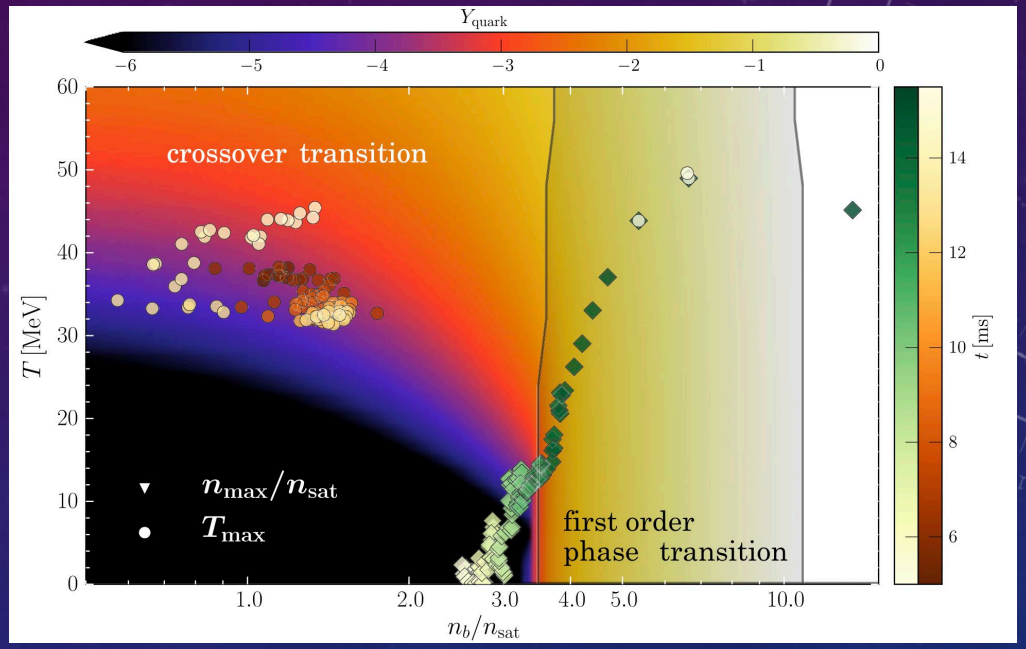
Quark-Hadron Phase Transitions in Neutron-Star Mergers

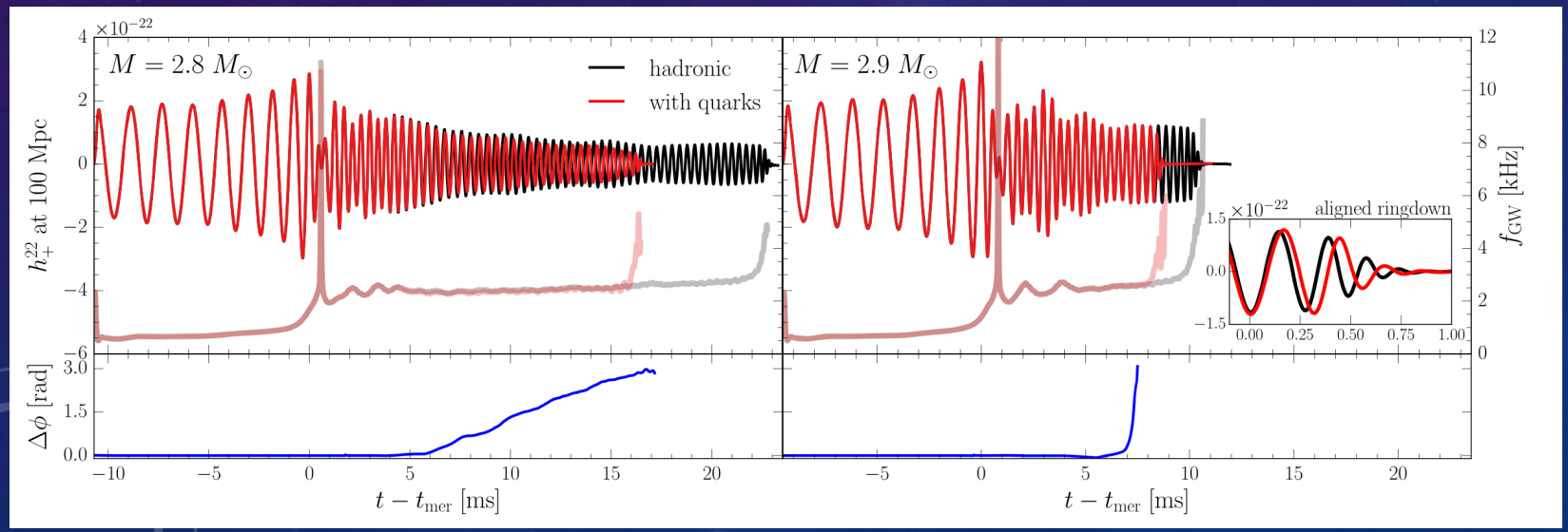
PHYSICAL REVIEW LETTERS **122,** 061101 (2019)

Editors' Suggestion

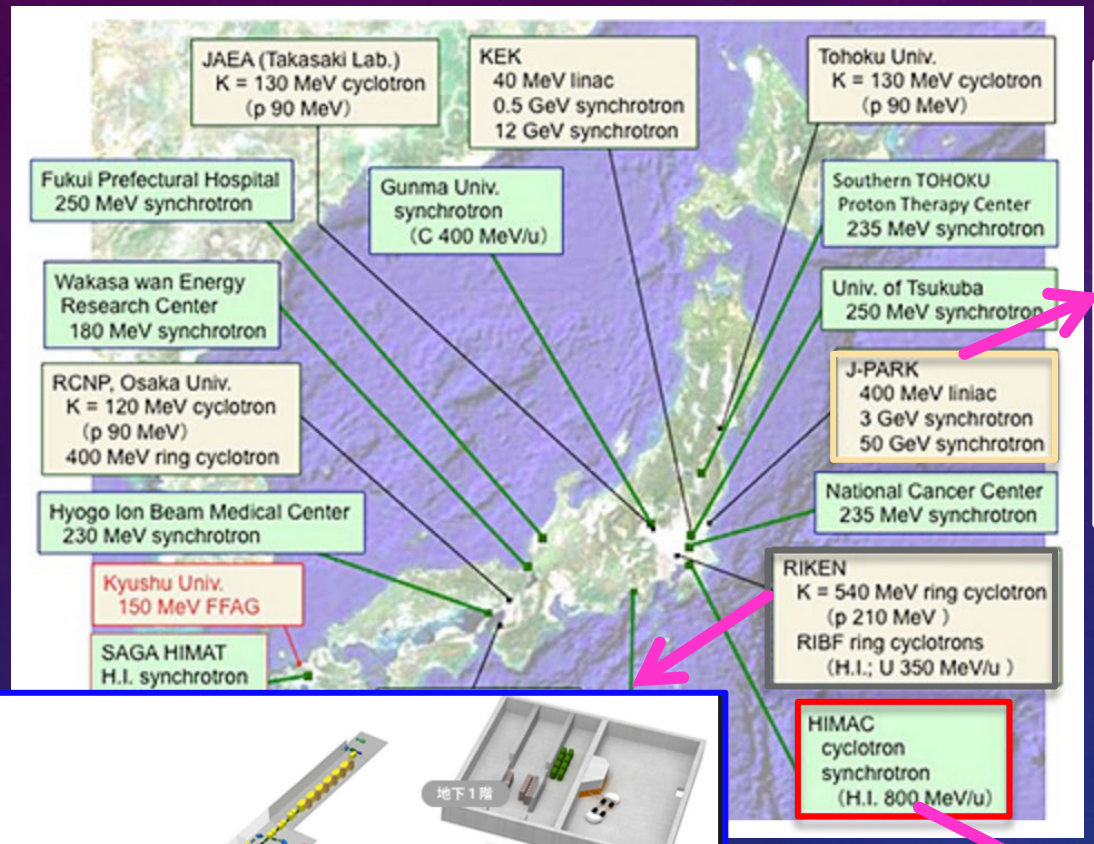
Signatures of Quark-Hadron Phase Transitions in General-Relativistic Neutron-Star Mergers

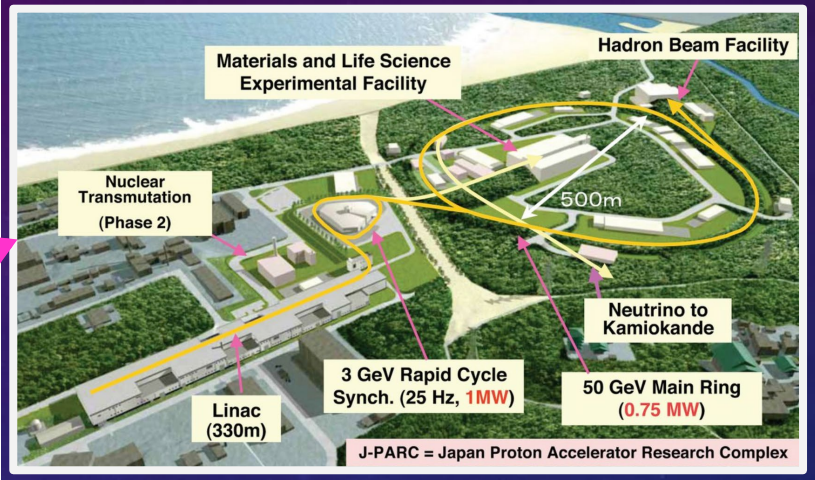
Elias R. Most,[1] L. Jens Papenfort,[1] Veronica Dexheimer,[2] Matthias Hanauske,[1,3] Stefan Schramm,[1,3] Horst Stöcker,[1,3,4] and Luciano Rezzolla[1,3]

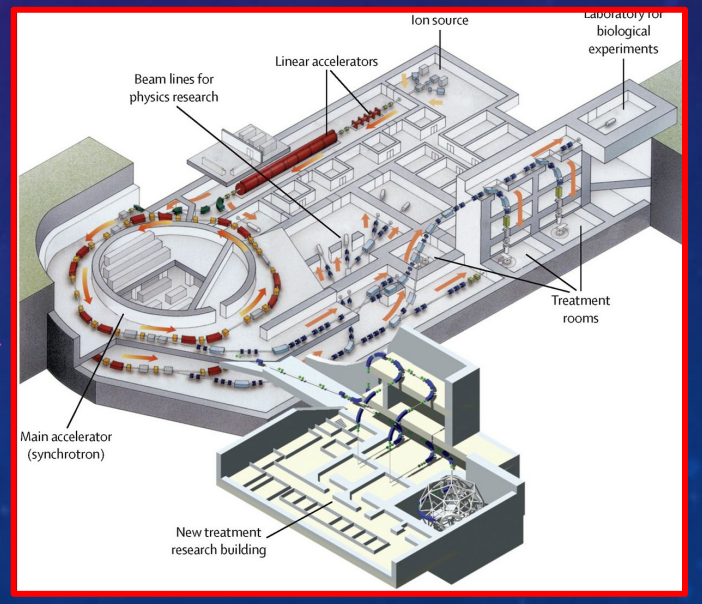




High Density Nuclear Matter using Heavy-Ion Collisions (Japan)







Pilot Experiment related to Collective Flow using ^{132}Xe + CsI Collisions at 400 A MeV/u

Keywords:

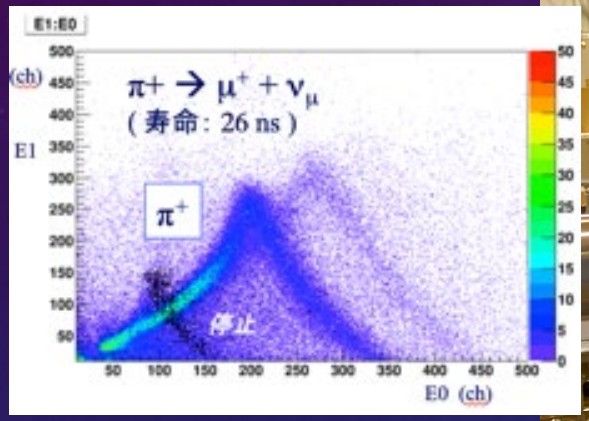
Heavy-Ion Collisions at Lower Energy Region (200 AMeV ~ 10 AGeV)

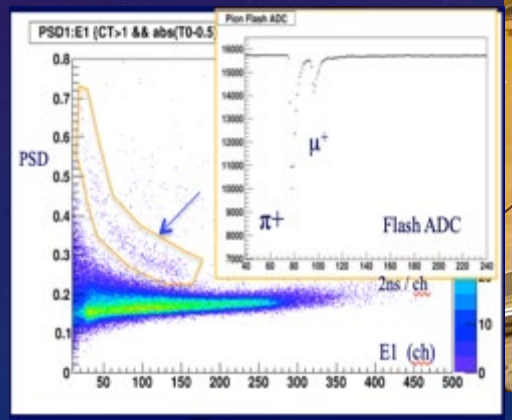
Collective Flow of Proton & Neutron

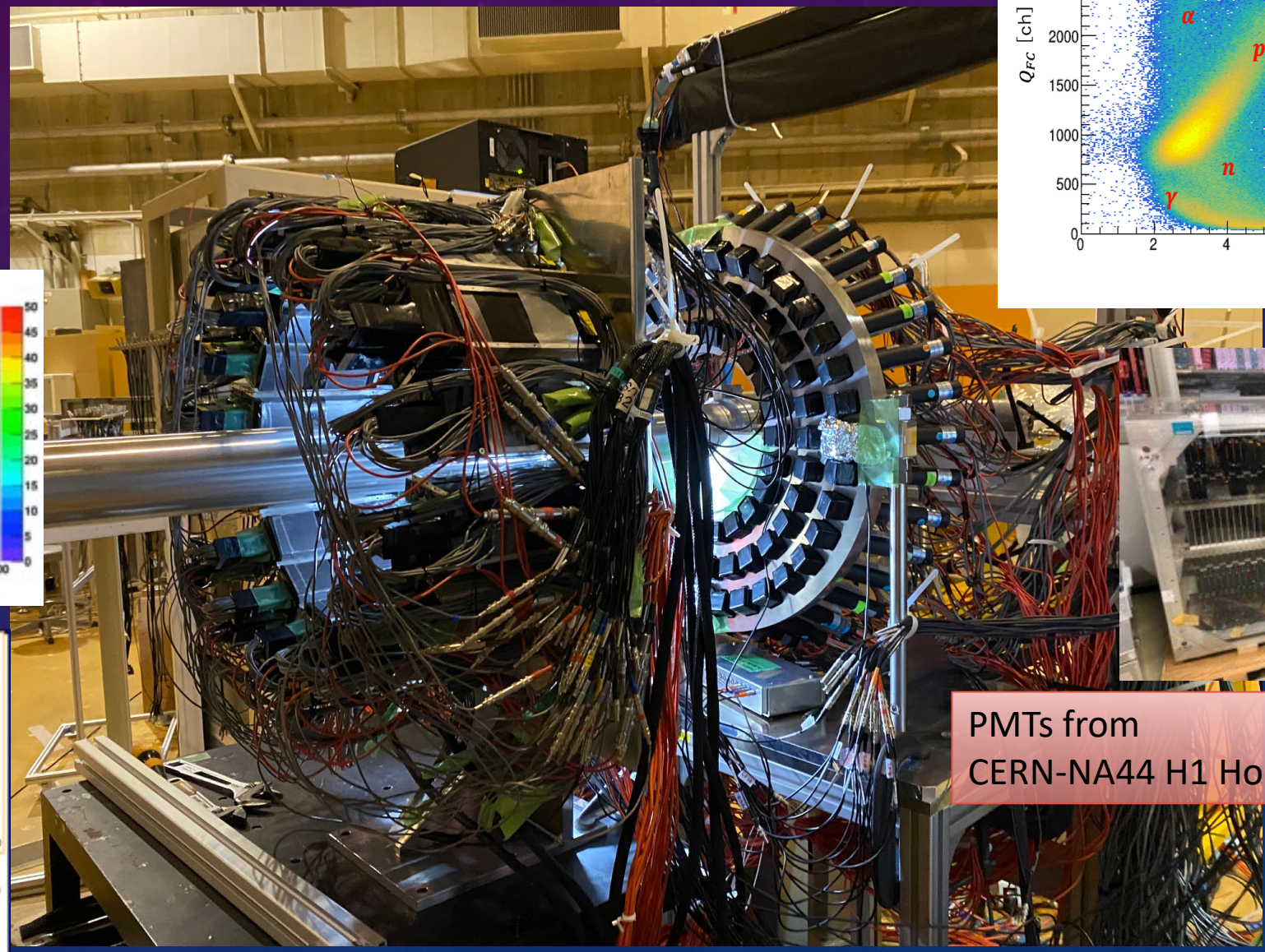
Systematic Study of Directed/Elliptic Flow

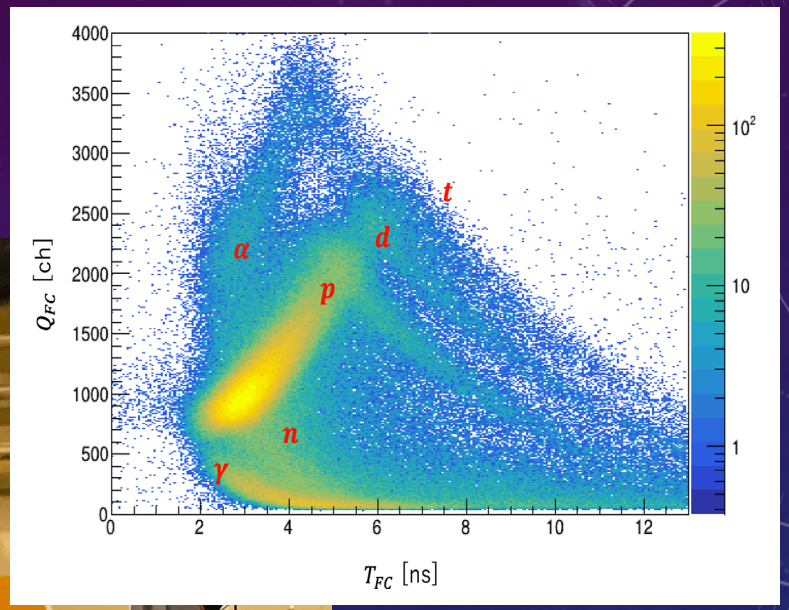
Neutron-Rich Heavy-Ion Collisions

Pilot Flow Experiment at HIMAC
132Xe + CsI Collisions at 400 AMeV/u





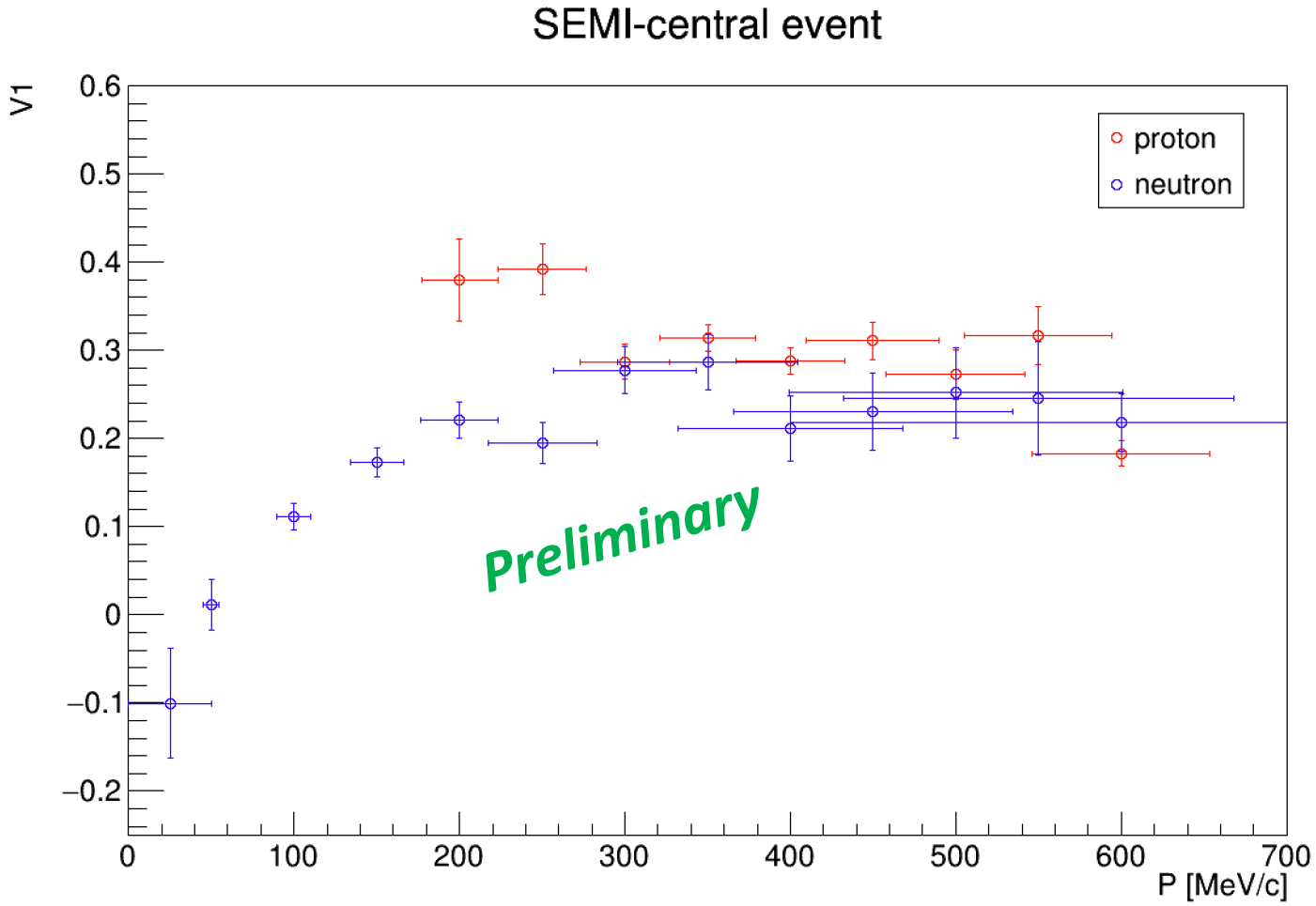


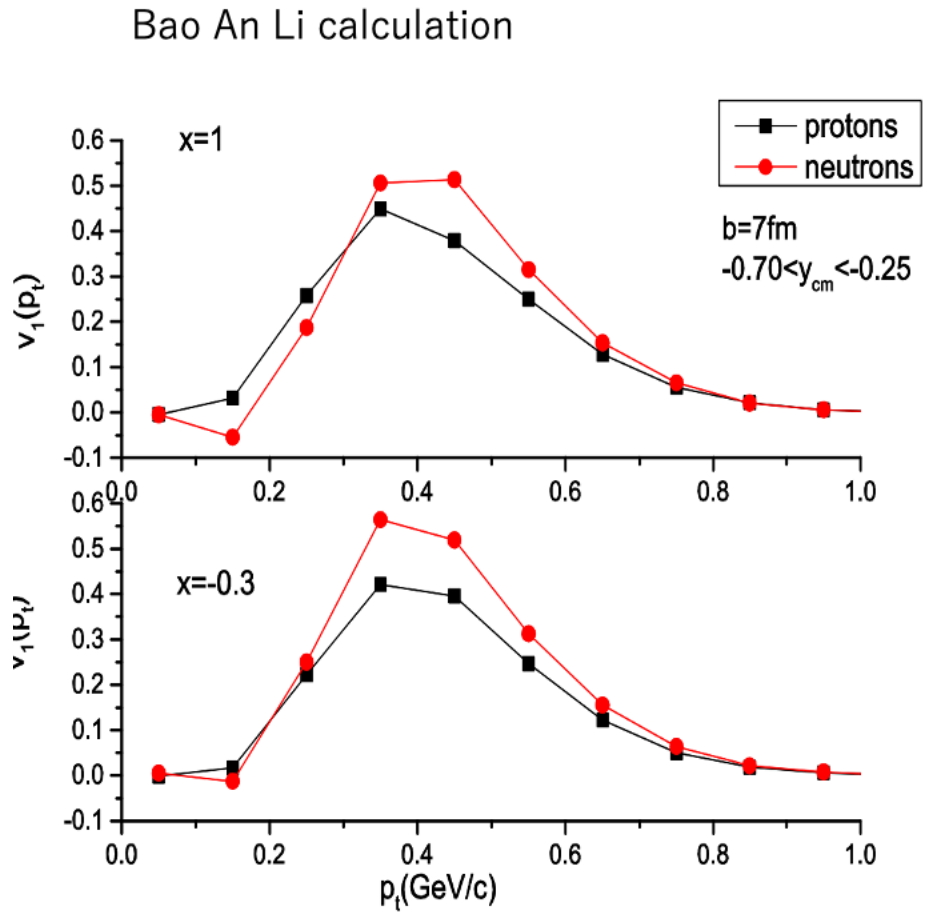


PMTs from
CERN-NA44 H1 Hodoscope

Directed Flows of proton and neutron at target rapidity

Ytarget

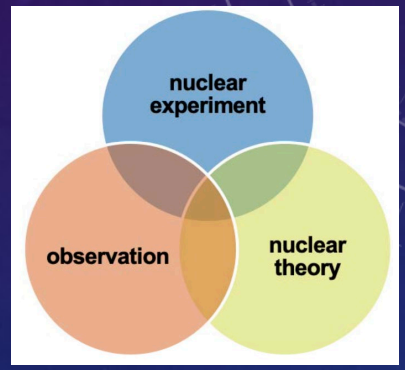




Summary

Mickey Mouse (MM) + MM Collisions

1) Deformed Nucleus-Nucleus Collisions :
   - Initial condition vs Flow are very interesting topics !
      - various collision types (Tip-Tip, Body-Body, etc.)
      - Selectivity of event types with multiplicity, Pt, rapidity
      - Backward and forward spectators are very important probe.
      - Search for events with anomaly. (Large V_3?) & fluctuations



2) Production of exotic nuclei in non-central collisions & reaction plane
   - Directed Spectator Beam using bounce-off of heavy-ion collisions
   - Possible application for nuclear size (interaction cross-section), isomers, fusion reactions, and double-differential flow in secondary heavy-ion collisions ..

3) Study on high density matter will be interesting topics for both nuclear structure and heavy-ion collisions.
   - Interdisciplinary collaboration among nuclear theory, experiment, and observation (neutron star (NS), supernova, NS-NS merger, r-process)