Nuclear EOS, the bridge between mini-merger and giant-merger

Zhigang Xiao
Department of Physics， Tsinghua University

清華大学物理系
TSINGHUA UNIVERSITY DEPARTMENT OF PHYSICS

Shanghai Jiaotong University, China
September 26-28, 2018

Content

1 Introduction (4')

2 Isospin transport in HIC and Isospin Chronology

2.1 Isospin dependent particle emission hierarchy (3')

2.2 Long time isospin-drift process and $E_{sym}(\rho)$ (3')

2.3 Isospin Chronology with $HIRA^{TU}$: future plan (4')

3 Isovector orientation effect of deuteron: A new tool to constrain $E_{sym}(\rho)$ (2')

4. Summary (1')

清華大學物理系 TSINGHUA UNIVERSITY DEPARTMENT OF PHYSICS

Nuclear Symmetry Energy

Isospin Dependence of Strong Interactions

Nuclei Properties

- Nuclear Masses
- Neutron Skin Thickness
- Isovector Giant Dipole Resonances
- Fission

Nuclear reactions

- Heavy Ion Flows
- Multi-Fragmentation
- Nuclei Far from Stability
- Rare Isotope Beams

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

Supernovae
Weak Interactions
Early Rise of $L_{\nu e}$
Bounce Dynamics
Binding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational
Properties

Binary Mergers
Decompression/Ejection
of Neutron-Star Matter
r-Process

QPO's
Mass
Radius

NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

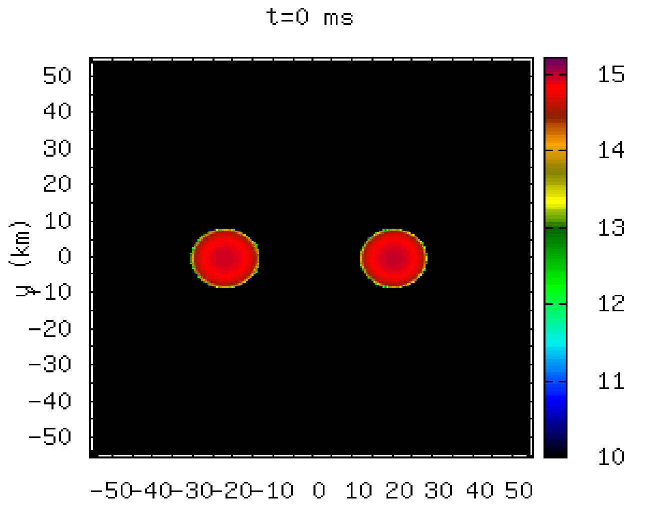
Gravity Waves
Mass/Radius
dR/dM

Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates

A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, *Phys. Rep. 411, 325 (2005).*

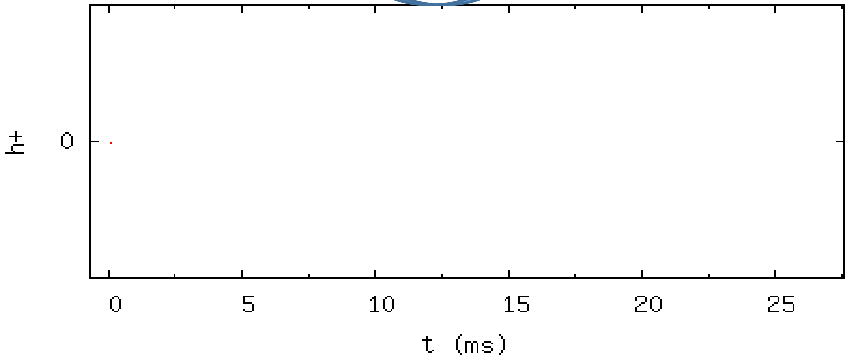
GW170817：Polarizability of neutron star （a giant nucleus）

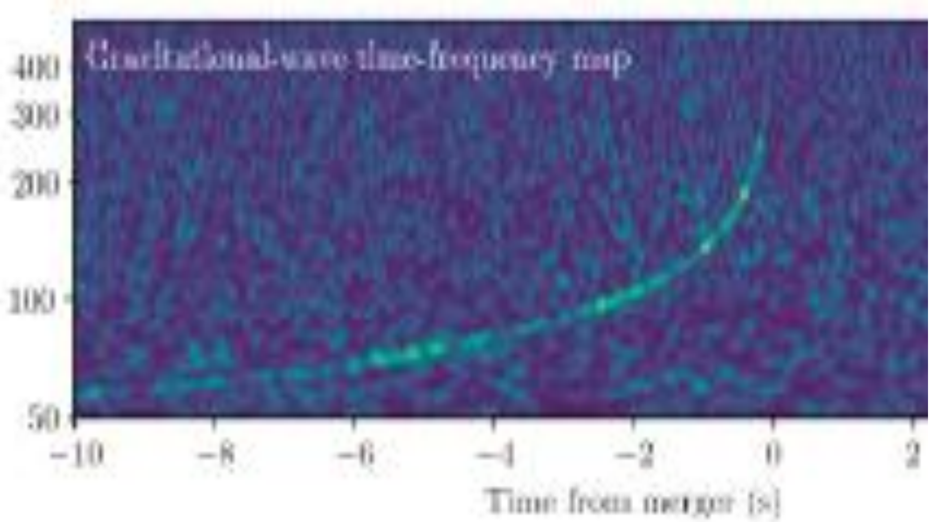


Dimensionless Tidal Deformability

$$\Lambda = \frac{2}{3} k_2 (R/M)^5$$

NS compactness

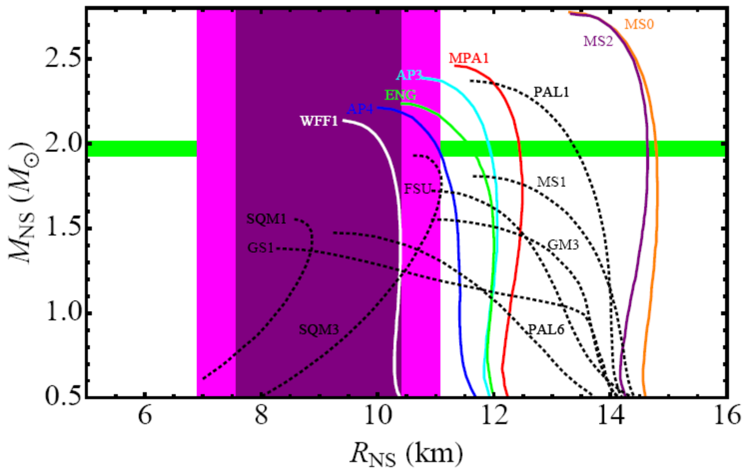




$$R_{NS} = 9.1^{+1.3}_{-1.5} \text{ km (90\%-confidence)}$$

Rutledge/Guillot, ApJ772 (2013)

GW ↔ Λ ↔ R/M ↔ EOS



- Mass quadrupole polarizability of a NS: $\Lambda \propto R^5$
- Ligo is sensitive to the increase in orbital frequency as the system loses energy to both GW and internal excitation of NS.
- GW170817 data place limits on polarizability of NS and hence up limits on NS radius.

●Consistent, but less strictive： arXiv:1801.04620

Very Brief Rev. of $E_{sym}(\rho)$ at $\rho<\rho_0$ in HIC

VOLUME 78, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1997

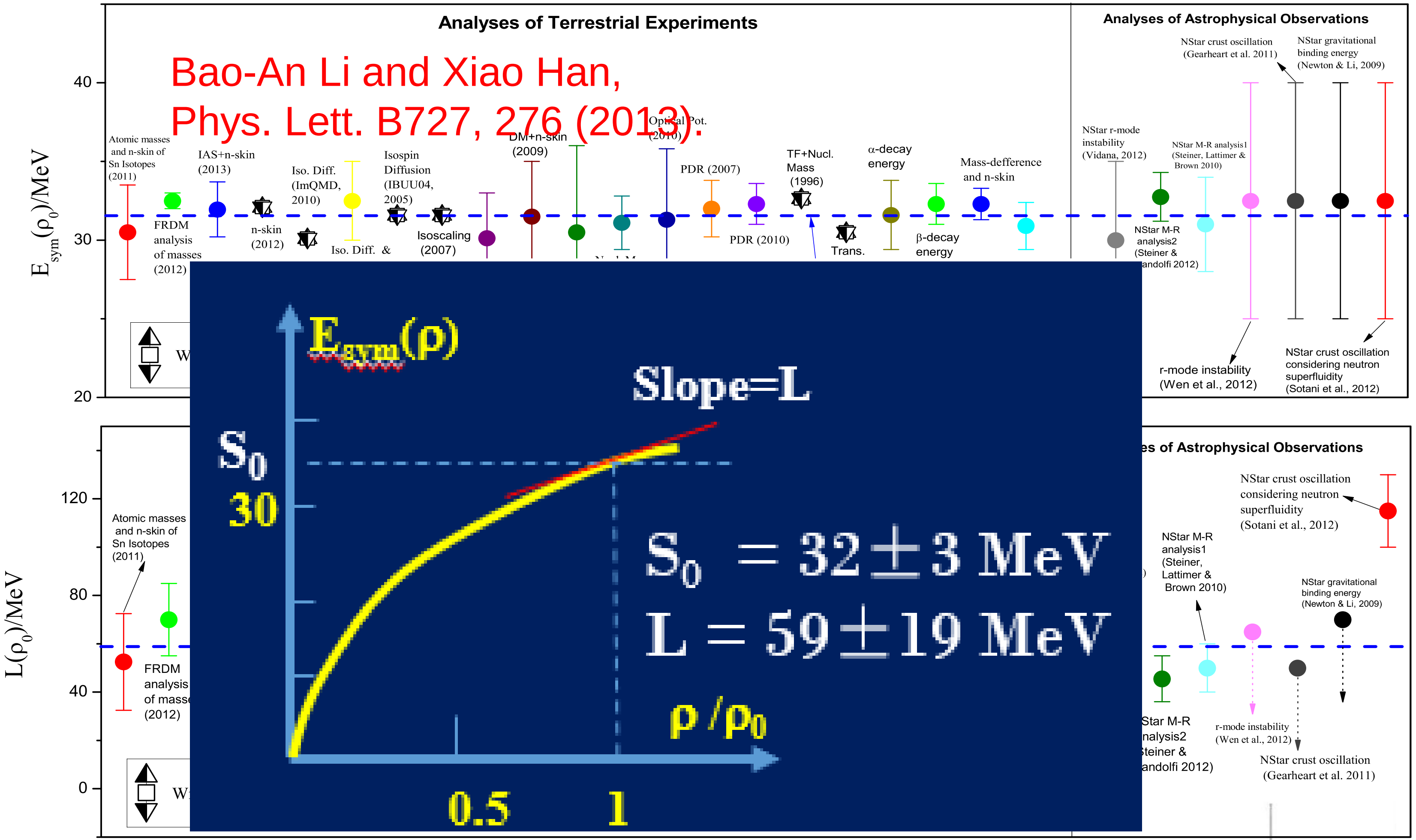
Equation of State of Asymmetric Nuclear Matter and Collisions of Neutron-Rich Nuclei

Bao-An Li,[1,*] C. M. Ko,[1,†] and Zhongzhou Ren[2,‡]

A. Jedele,[1,2,*] A. B. McIntosh,[1,†] K. Hagel,[1] M. Huang,[1] L. Heilborn,[1,2] Z. Kohley,[3,4] L. W. May,[1,2]

Isospin transport and the constraint of $E_{sym}(\rho)$

At sub-saturation densities



List extends:

→ Isospin diffusion (MSU …)

→ Isospin scalaring and isospin fractionaiton (MSU…)

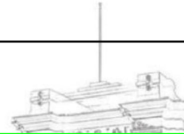
→ n/p ratio of fast and pre-equilibrium nucleons (MSU …)

→ N/Z of the emitted fragments (LNS, TAMU, MSU, HIRFL …)

→ GMR strength (ND …)

→ HBT correlation function (KVI, MSU, HIRFL …)

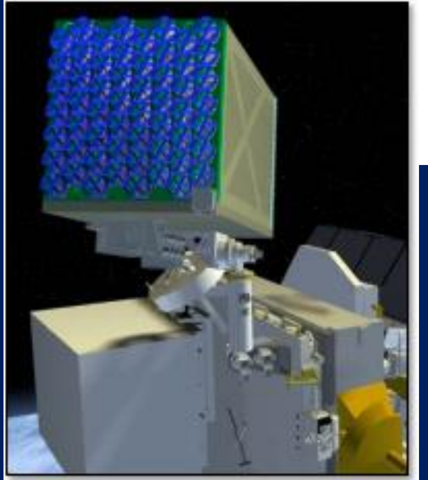
→ …. ….



Proton radioactivity: E_{sym}= 29.3 MeV L=51.8 MeV

N. Wan, C. Xu et al., Phys. Rev. C 94, 044322 (2016).

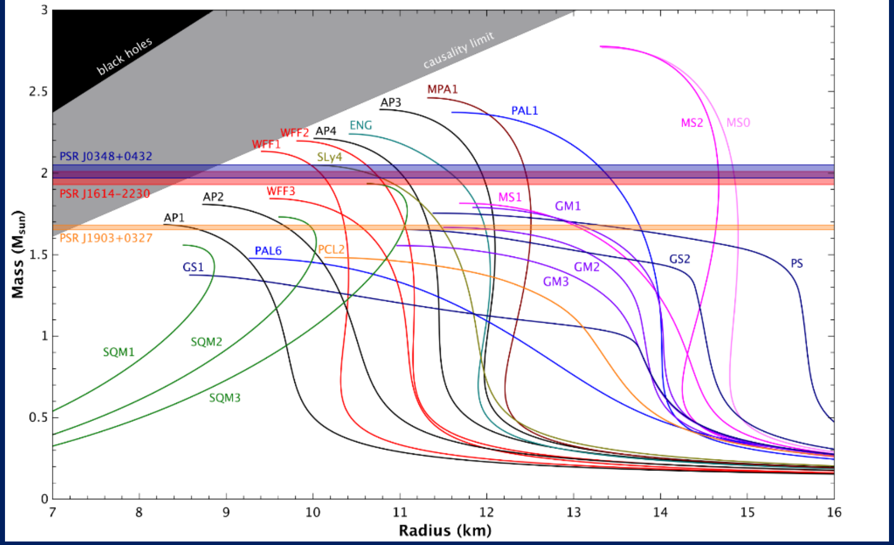
$E_{sym}(\rho)$ becomes a frontier in major Labs



Neutron Star Observatory:

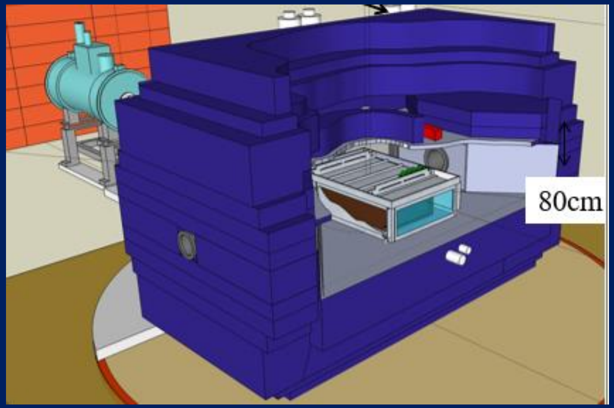
The Neutron Star Interior Composition Explorer （NICER）

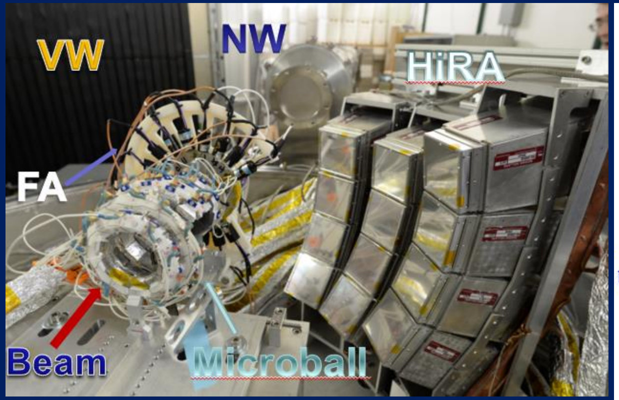
Key Objective： Constrain the equation of state of bulk nuclear matter through precise mass and radius measurements of several neutron stars.

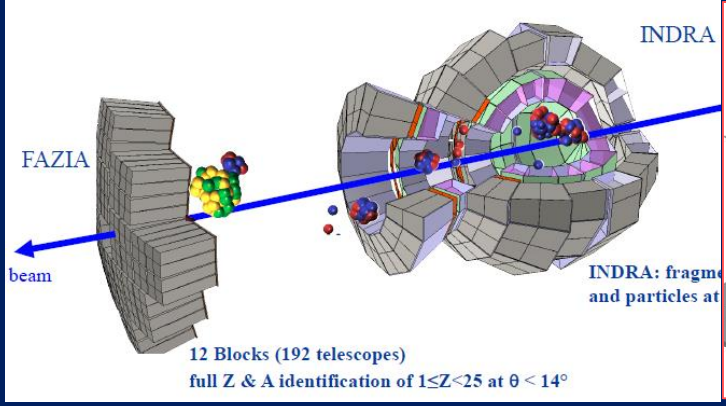


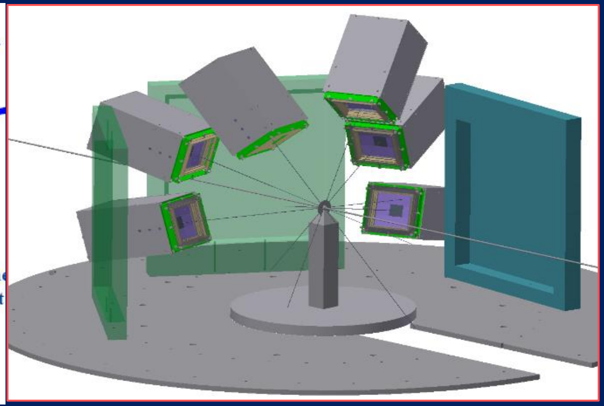
HI accelerator and RIB facilities:

SAMURAI-TPC@RIKEN **HIRA@FRIB** **INDRA@GANIL** **RIBLL @ HIRFL**









What is our Motivations ?

1) Look for new $E_{sym}(\rho)$ （$\rho<\rho_0$） probes in slow process for the enhanced sensitivity.

Neck Emission in Fission reactions: Low density neutron-rich neck, possibly a long time process.

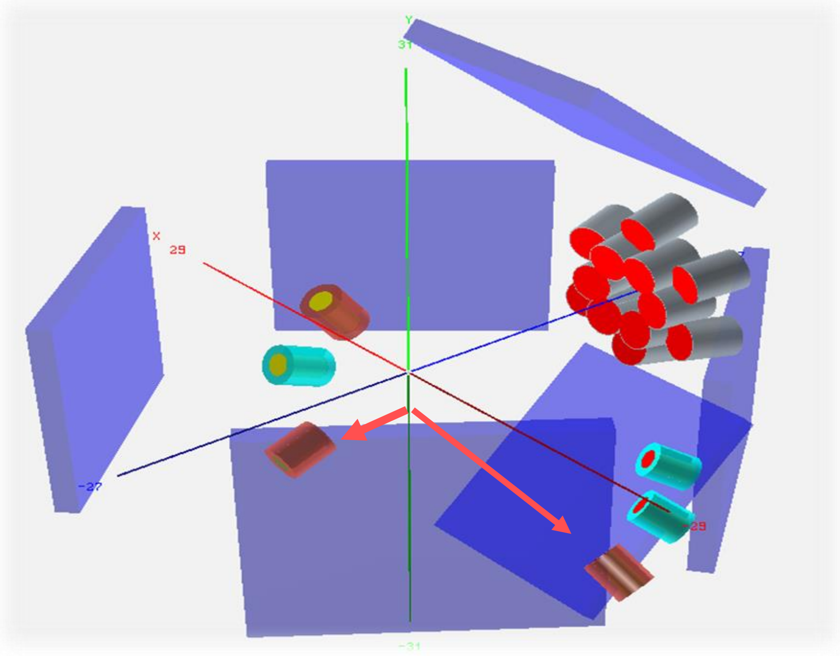
(First presented on 8th China-Japan joint nuclear physics symposium, Oct. 2012)

2) To develop a method to measure quantitatively the time scale of the transport of IDOF.

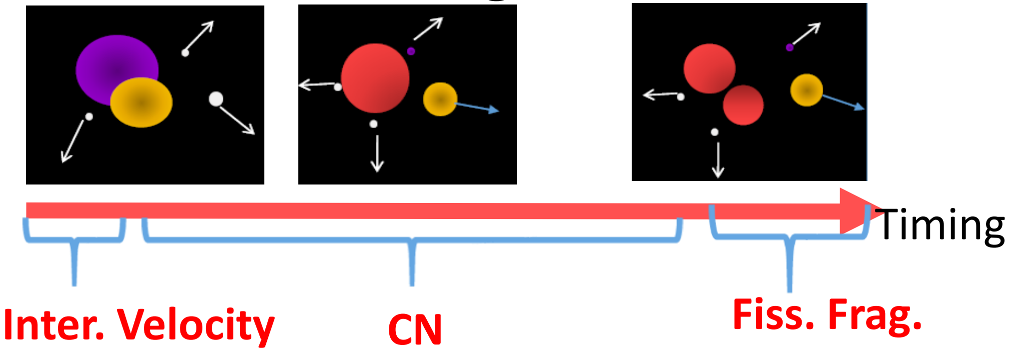
Content

2.1 Isopsin dependent hierarchy of particle emission

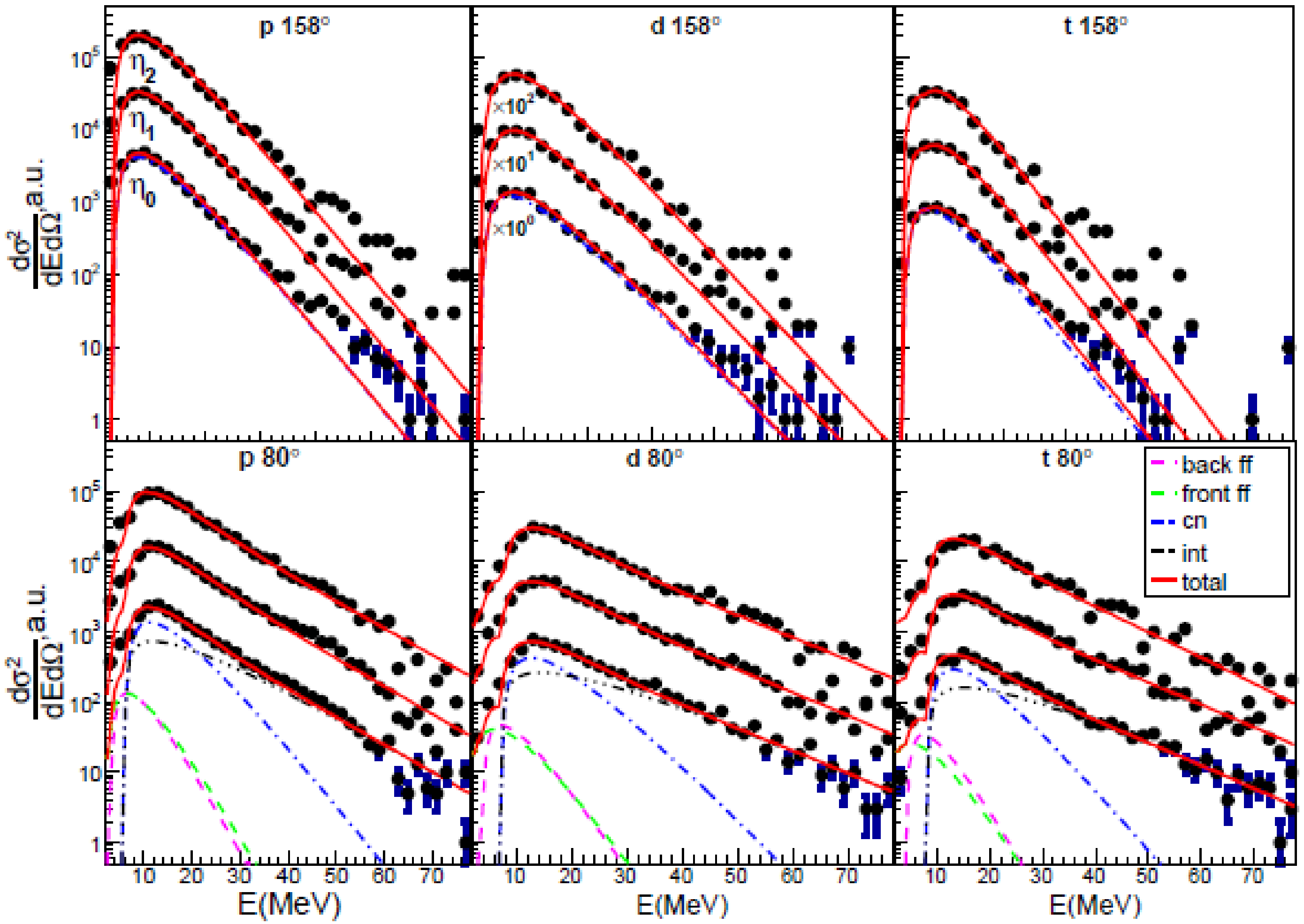
35 MeV/u Ar+ Au.
Trigger: 2 fold fragments .AND. 1 LCP



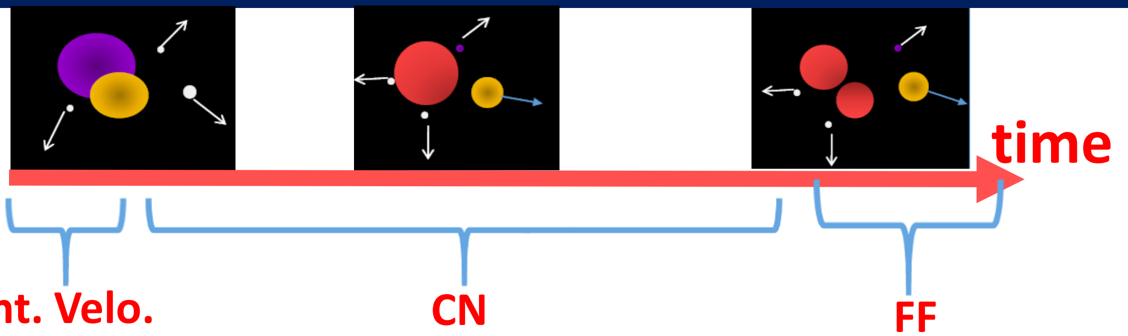
- Three Moving source:



$$\frac{d^2\sigma}{d\Omega dE} = \frac{N}{2(\pi T)^{3/2}}(E-E_c)^{1/2}\exp[-(E-E_c)/T]$$

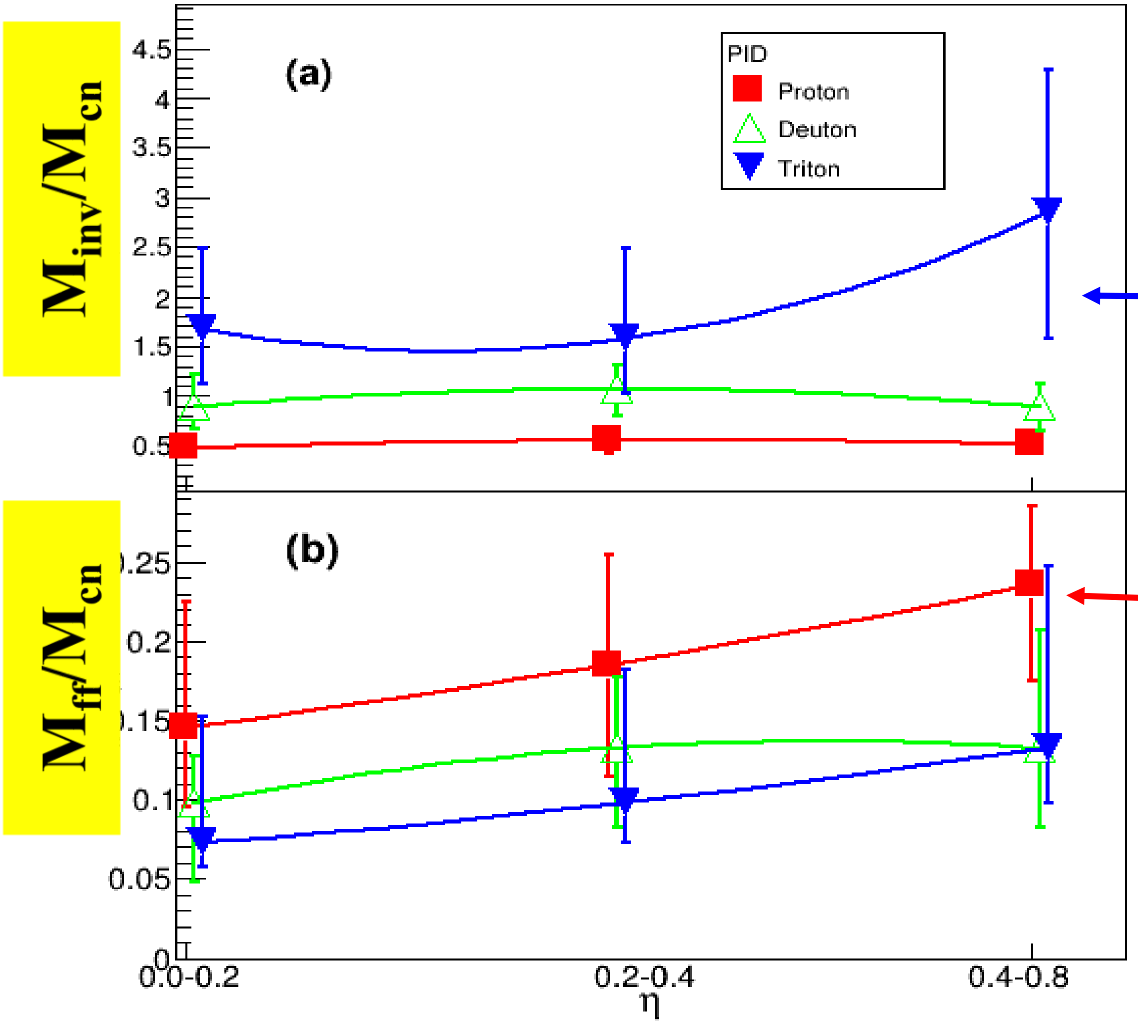


Minimum χ2 analysis and particle emission hierarchy



More triton emission

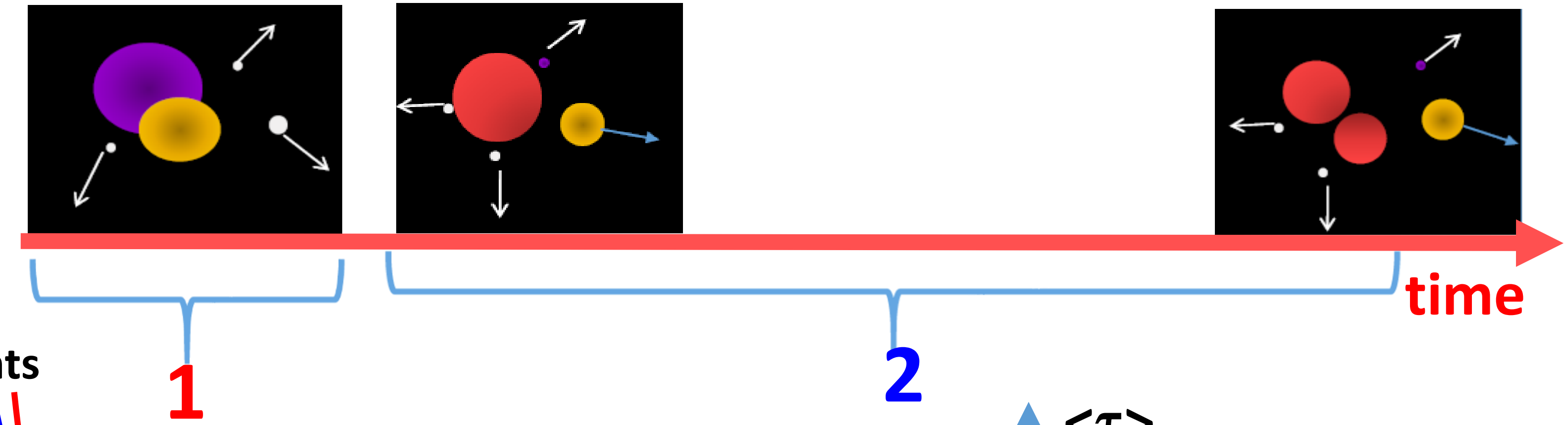
More proton emission

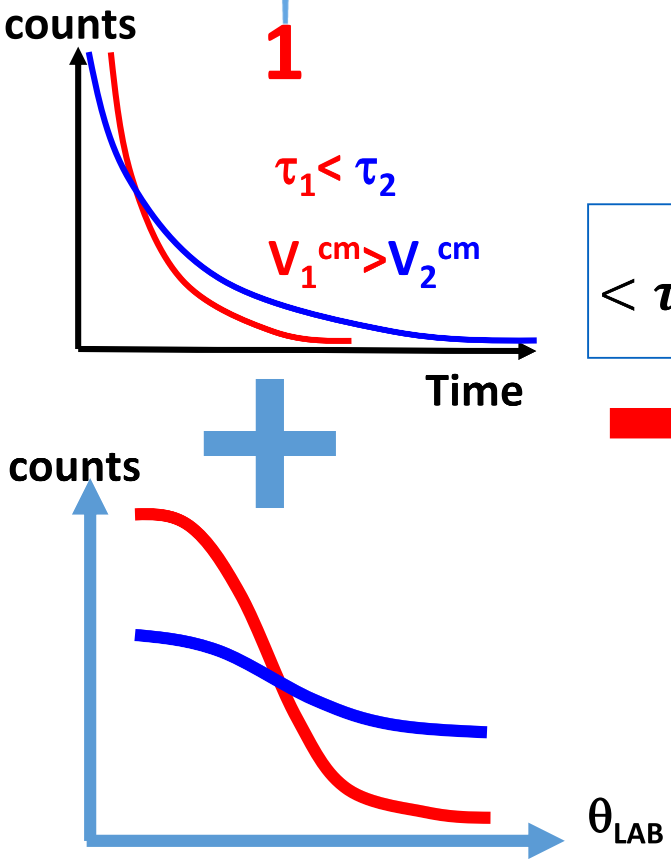


A isospin-dependent hierarchy of particle emission is observed.

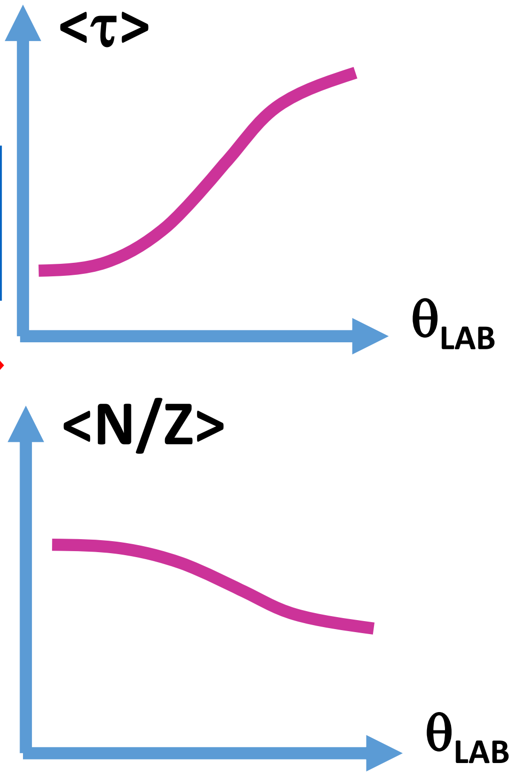
R. S. Wang, Y. Zhang, XZG… et al.,
PRC89 (2014) 064613

Build a qualitative relation between the angle in lab and the emission time





$$< \tau > = \frac{n_1 \tau_1 + n_2 \tau_2}{n_1 + n_2}$$



1 Angular distribution in large angular range reflects the time evolution of isospin transport；

2 A stiffer symmetry energy leads to faster isospin drift, thus to more rapidly changing in angular distribution.

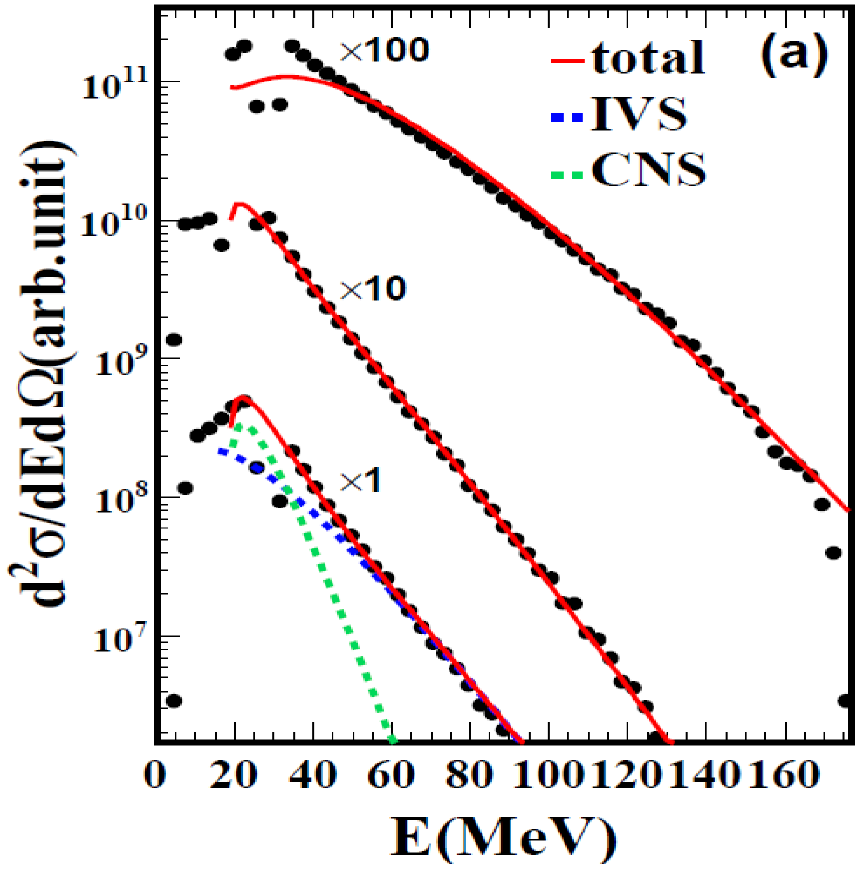
$$j_{\mathrm{np}} = j_n - j_p$$
$$= \left(D_n^\rho - D_p^\rho\right)\nabla\rho - \left(D_n^I - D_p^I\right)\nabla I$$

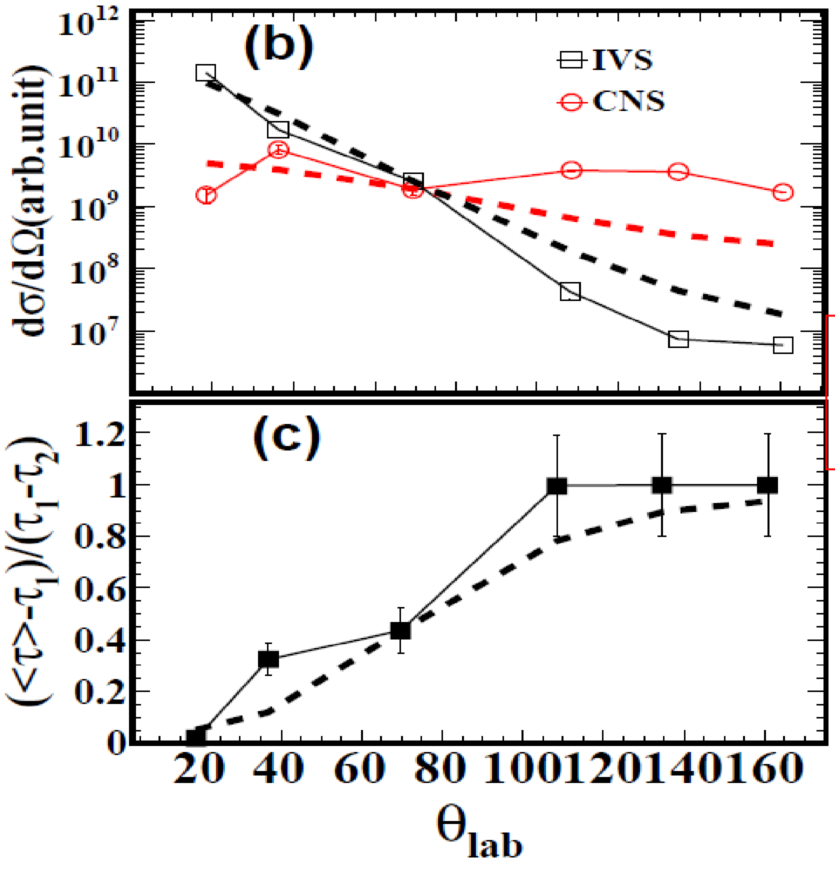
$$D_n^\rho - D_p^\rho \propto 4I \frac{\partial E_{sym}(\rho)}{\partial \rho}$$

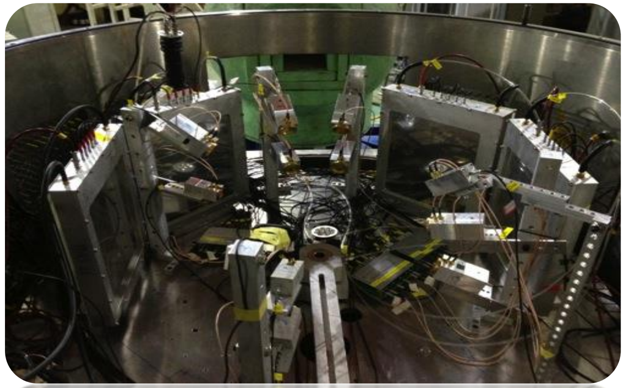
Q. H. Wu, Y. X. Zhang, ZGX, et al., **PRC 91**, 014617(2015)

2.2 Long time isospin drift and the constraint of $E_{sym}(\rho)$

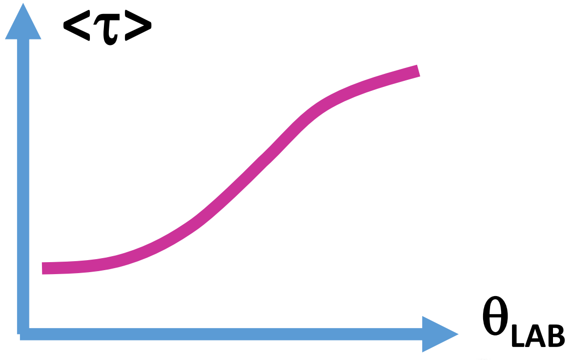
30 MeV/u Ar+Au @ RIBLL, HIRFL, Lanzhou







$$<\tau> = \frac{n_1\tau_1 + n_2\tau_2}{n_1 + n_2}$$



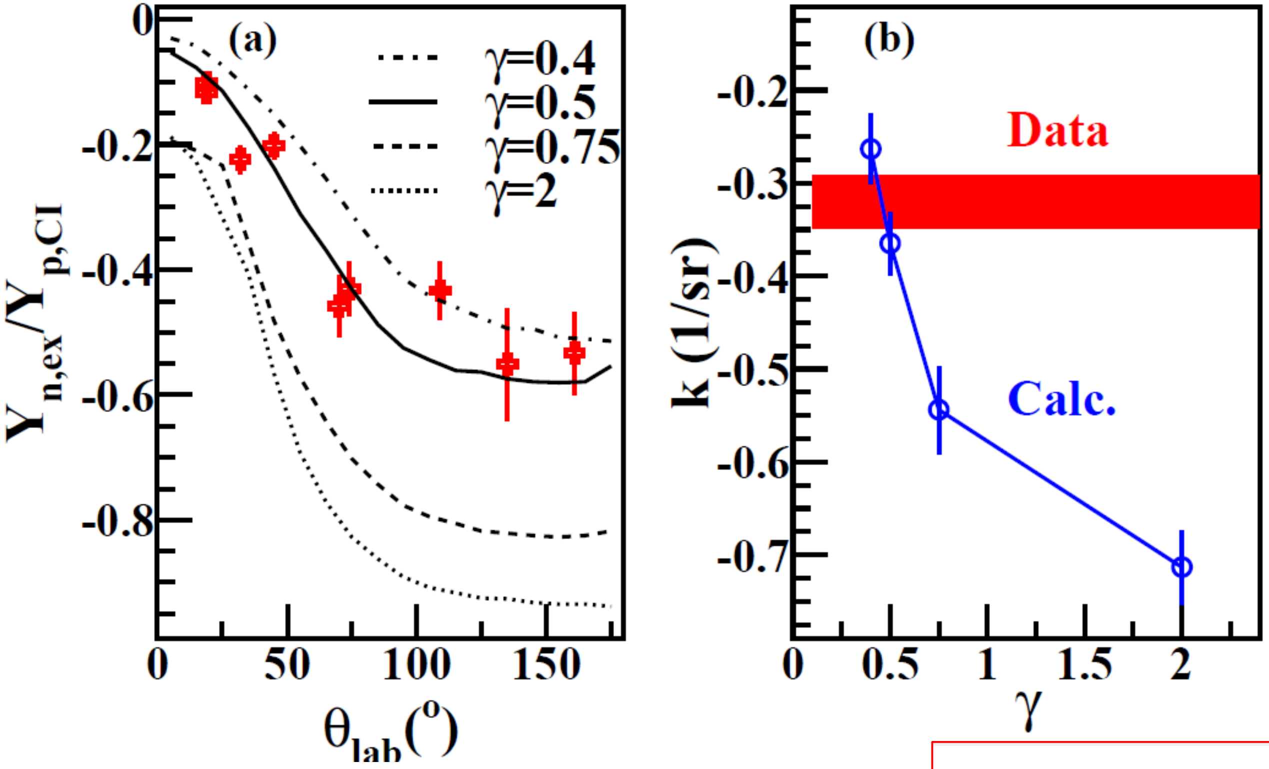
→ moving-source analysis indicates that a qualitative relation between angular distribution and the average emission time exists

→ The relationship shall holds, even though the real process is more complex.

Constraint of the $E_{sym}(\rho)$ with IMQMD+GEMINI

$$\frac{Y_{n,ex}}{Y_{p,CI}} = \frac{\sum y_i (N_i - Z_i)}{\sum y_i Z_i}$$

$$\frac{Y_{n,ex}}{Y_{p,CI}} = k\theta_{lab} + b$$



1）In the wide angular range, the neutron richness decreases with angle in lab. The rapidness depends on the stiffness of $E_{sym}(\rho)$

→ Isospin drift is long time process, persisting from early dynamic emission to late statistical emission

2）$E_{sym}(\rho)$: $\gamma=0.46\pm0.025$（STDEV）

L=47±14 MeV （CL=95%）

with S_0 fixed at 28.3 MeV.

C. Xu et al, PRC 82, 054607 (2010).
N. Wan et al., PRC 94, 044322 (2016).

Y. Zhang， … ZGX , **PRC 95**， 041602(R) (2017)

RAPID COMMUNICATIONS

PHYSICAL REVIEW C 95, 041602(R) (2017)

Long-time drift of the isospin degree of freedom in heavy ion collisions

Yan Zhang (张嫣),[1] Junlong Tian (田俊龙),[2,*] Wenjing Cheng (程文静),[1] Fenhai Guan (关分海),[1] Yan Huang (黄彦),[1]

2.3 Isospin Chronology

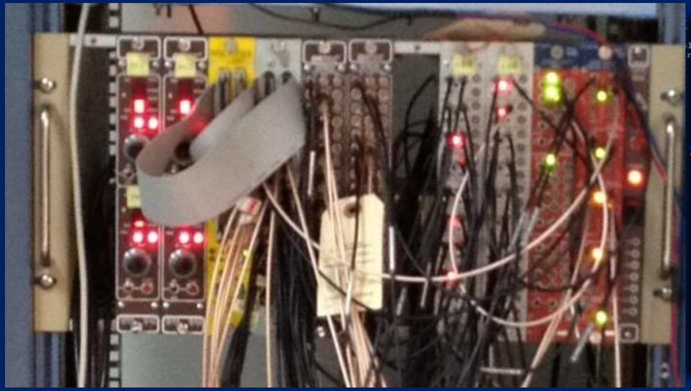
- **How long is long? How short is short?**

- A chronology is an account or record of the times and the order in which a series of past events took place.

In Physics: Dynamics describes how a system/quantity evolves with time, thus time information is a basic parameter for any physical process.

10^{-2} s

10^{-8} s

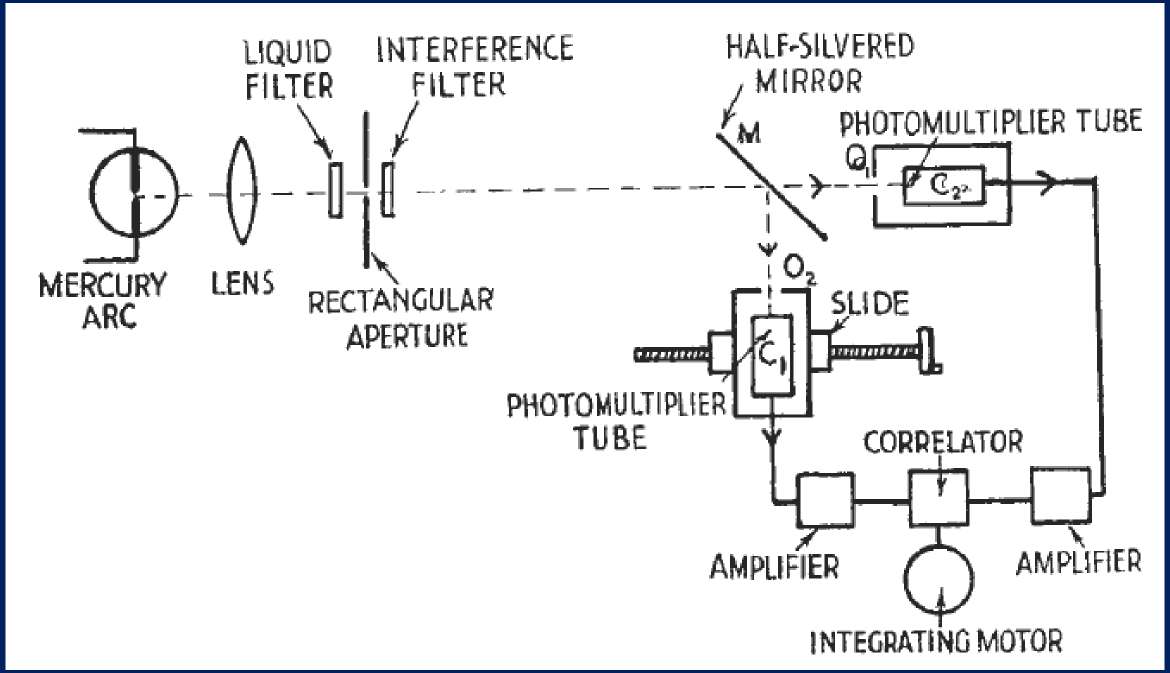


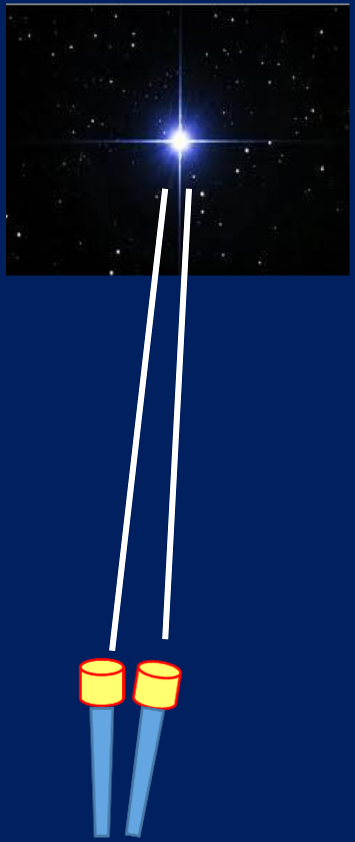
10^{-21} s

Hanbury Brown-Twiss Method

- 1950s, Hanbury Brown and Twiss propose a intensity interferometry to measure the size information of the stellar object.

Hanbury Brown and Twiss, **Nature 177**, 27 (1956)
Hanbury Brown and Twiss, **Nature 178**, 1046 (1956)





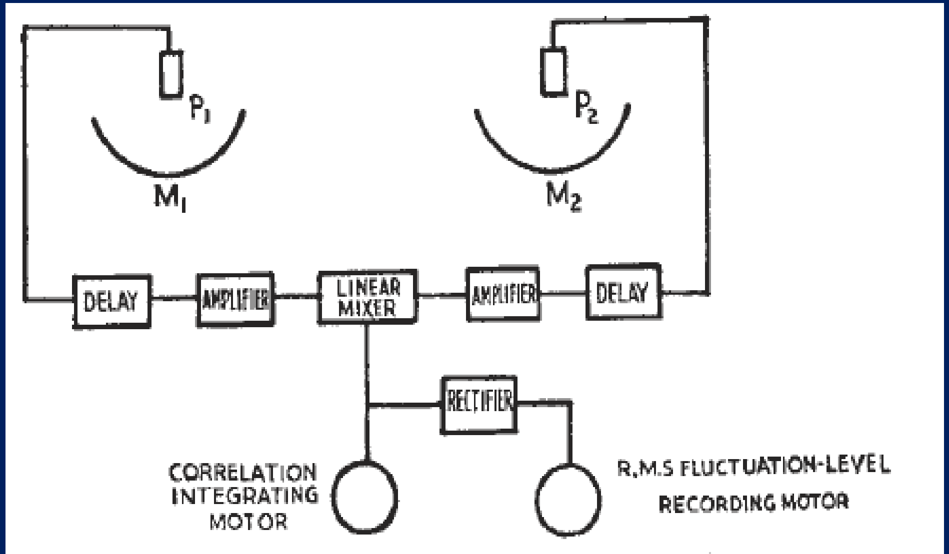
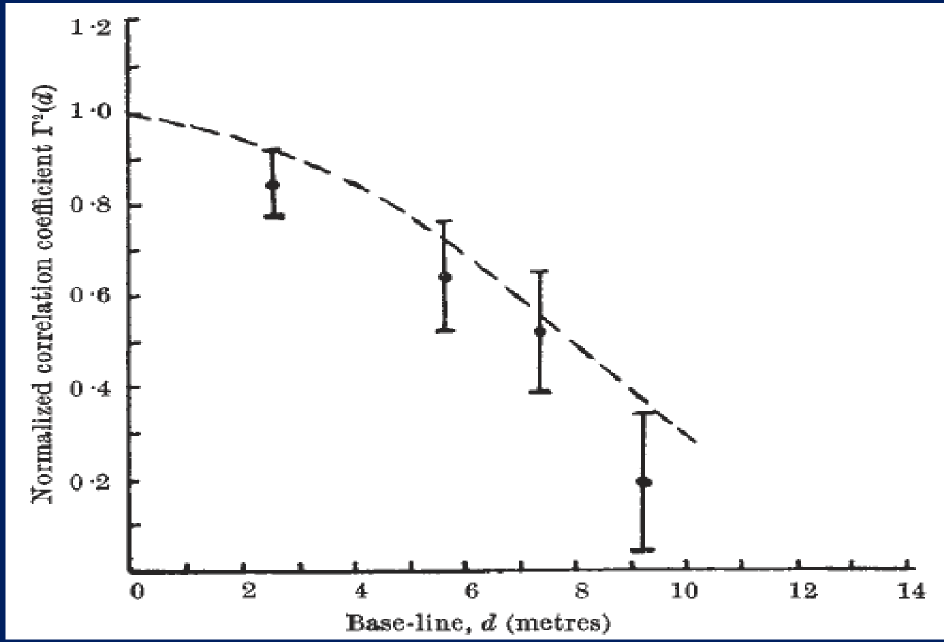


Fig. 1. Simplified diagram of the apparatus

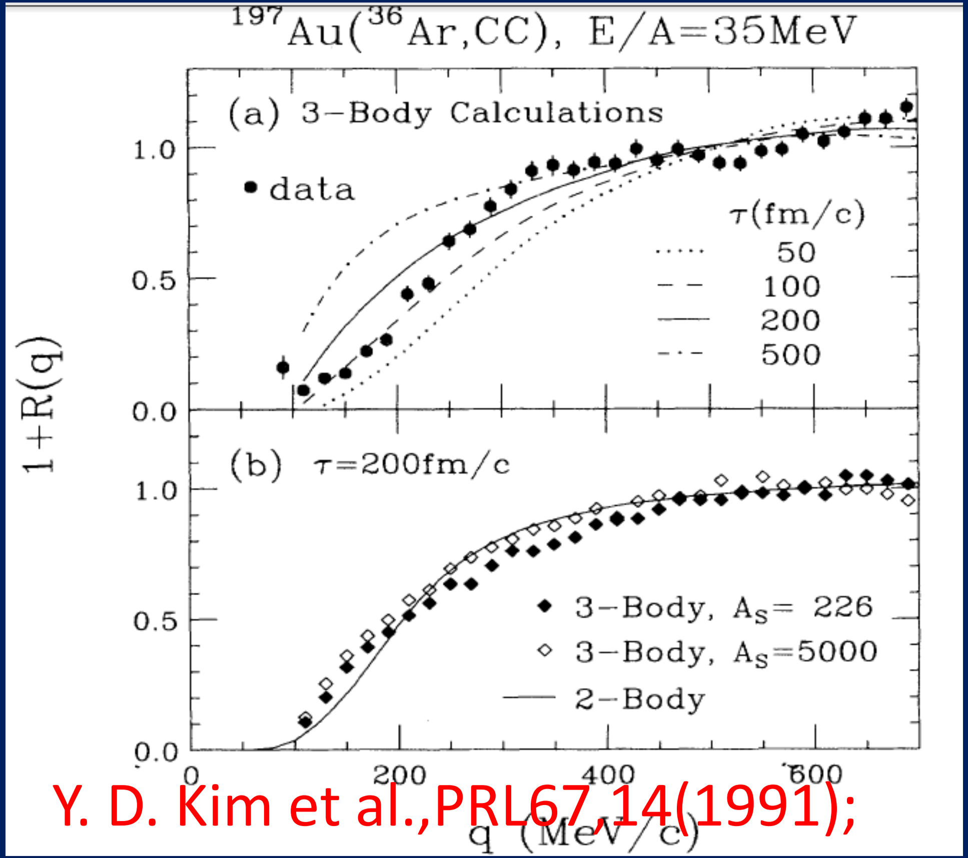


- **HBT is invented to measure the space information. It turns that both space and time information are incorporated.**

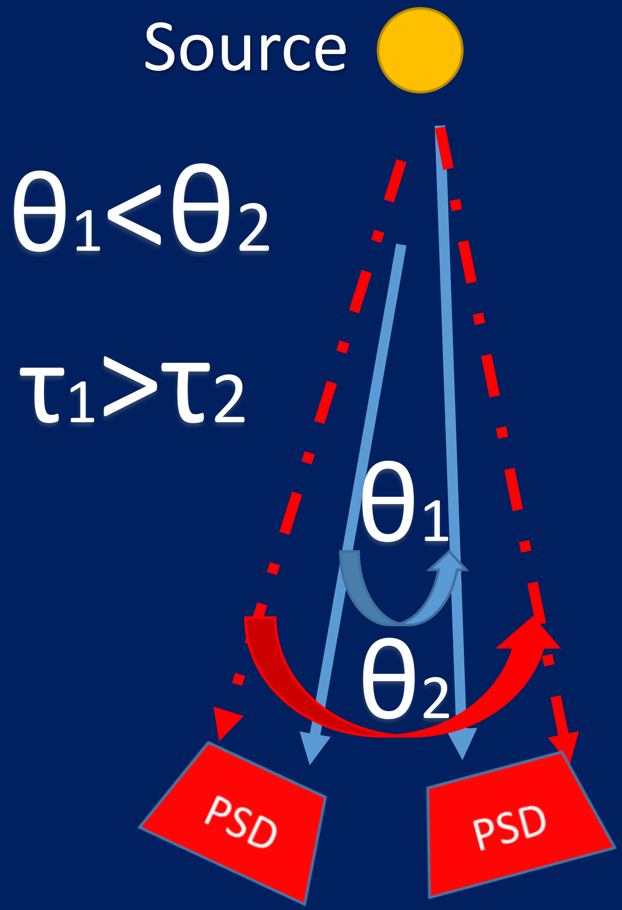
HBT in nuclear reactions

PLB70,43(1977), PRL67,14(1991); PRC51,1280(1995); PRC,69,031605R(2004); NPA620,214(1997); PRL 77,4508(1997) ; PRL70, 3534 (1993)……

$$1+\mathrm{R}(\vec{q})=C\,\frac{P(\vec{v}_1,\vec{v}_2)}{P(\vec{v}_1)P(\vec{v}_2)}$$



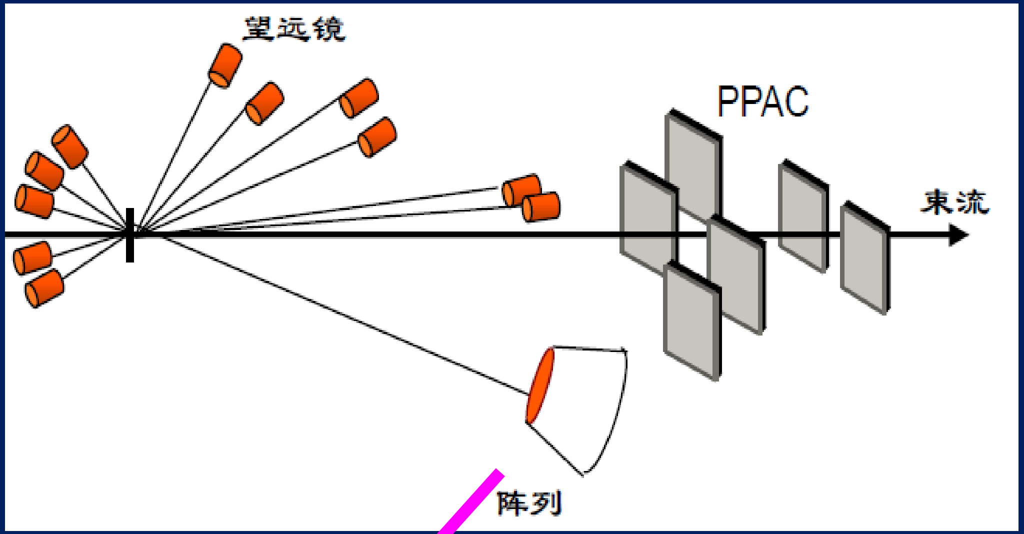
Y. D. Kim et al.,PRL67,14(1991);



Recent application of HBT on two-proton emission mechanism

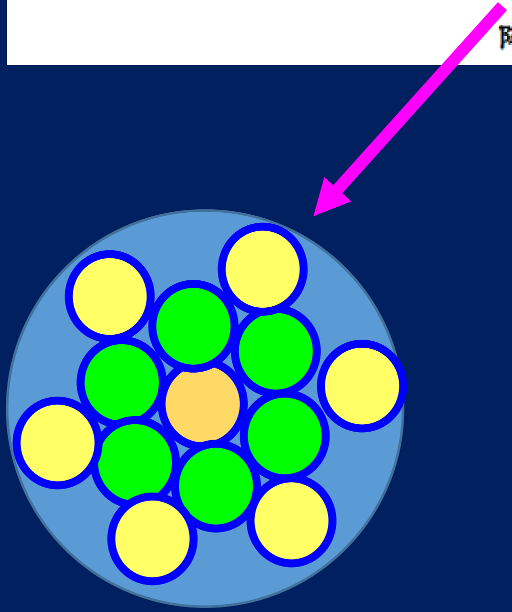
Cf YG Ma's talk

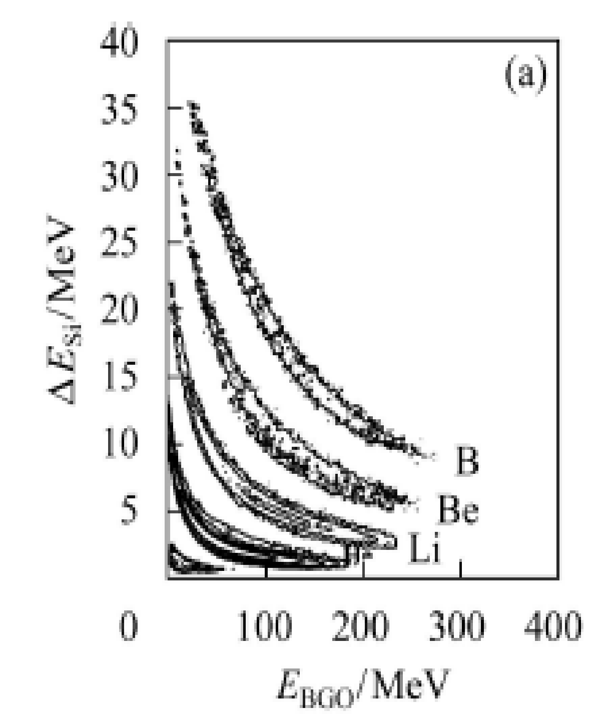
Experimental measurement of Isospin effect on IMF HBT correlation

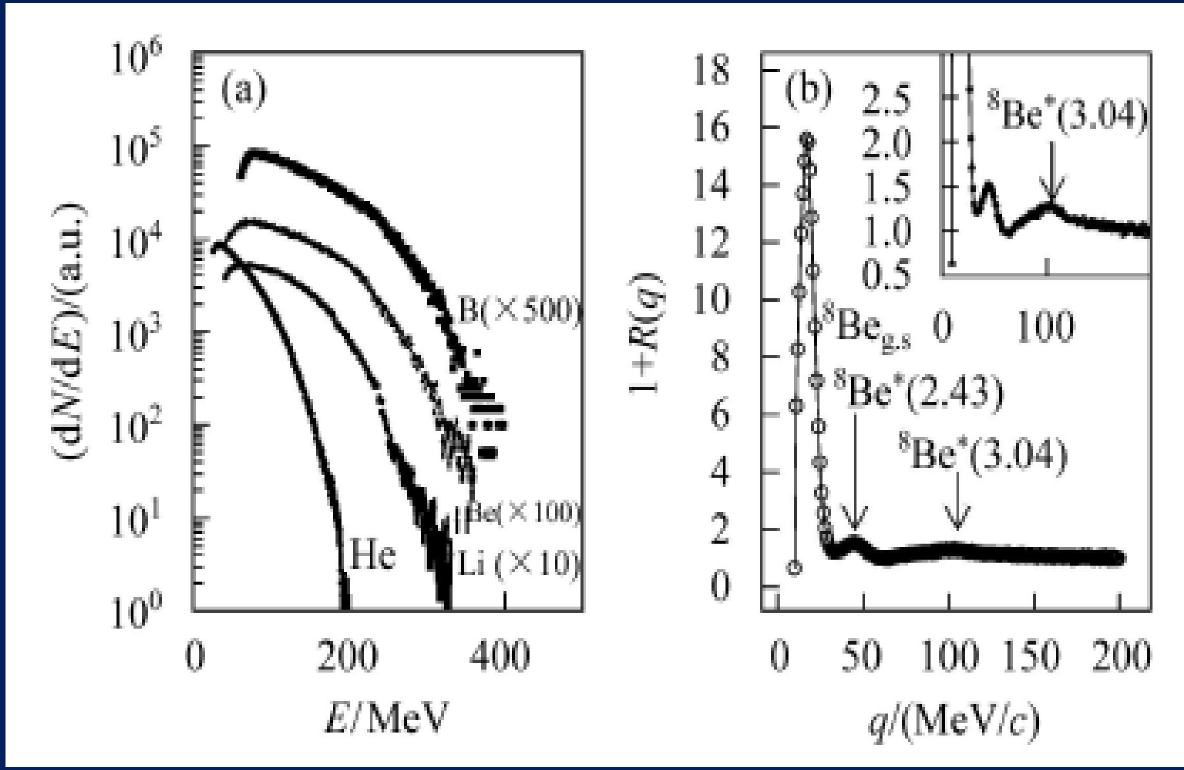


- **Reaction： 35MeV $^{36}Ar+^{112,124}Sn$**
- **Isospin effect on IMF HBT correlation**
- **Hodoscope： 13-unit closely packed Si-BGO array**

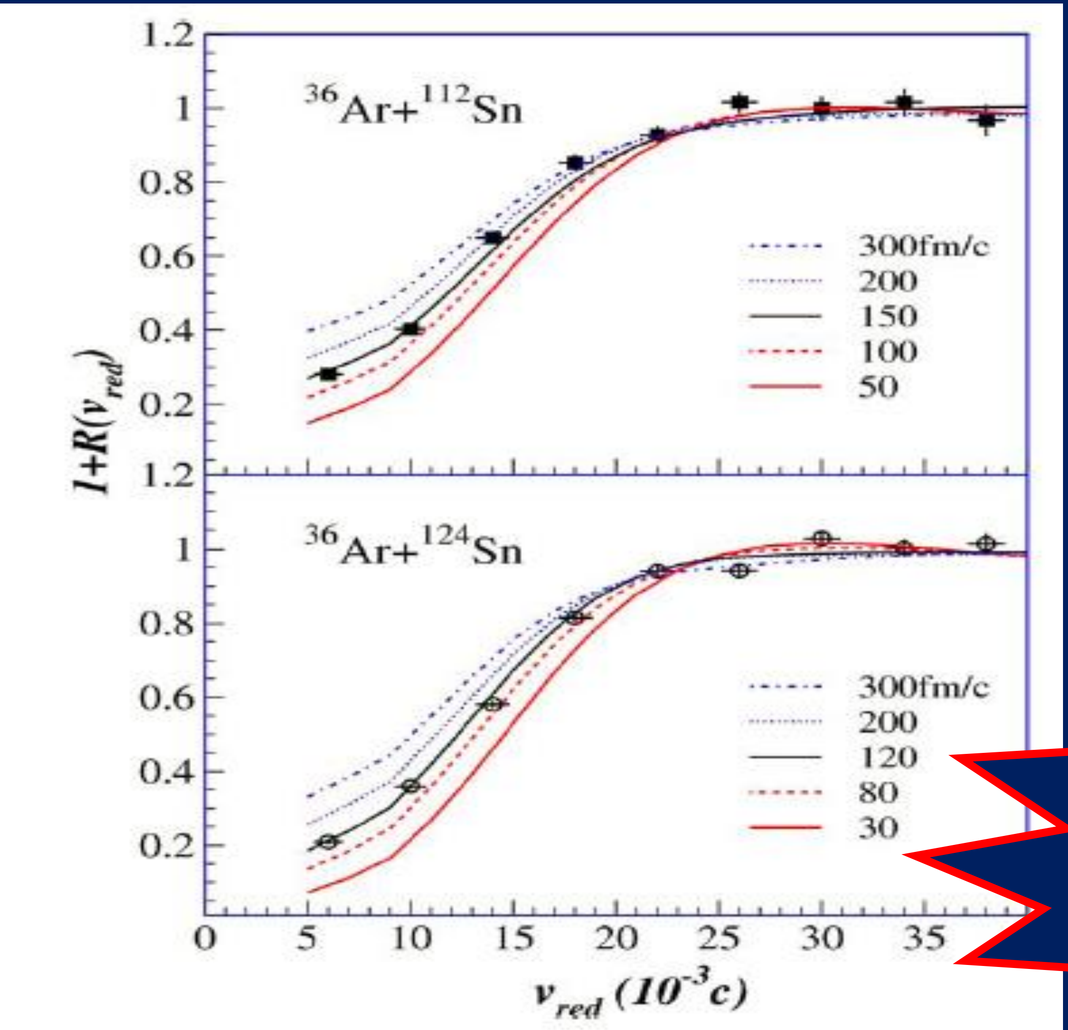
Hit position Resolution ~ 1cm



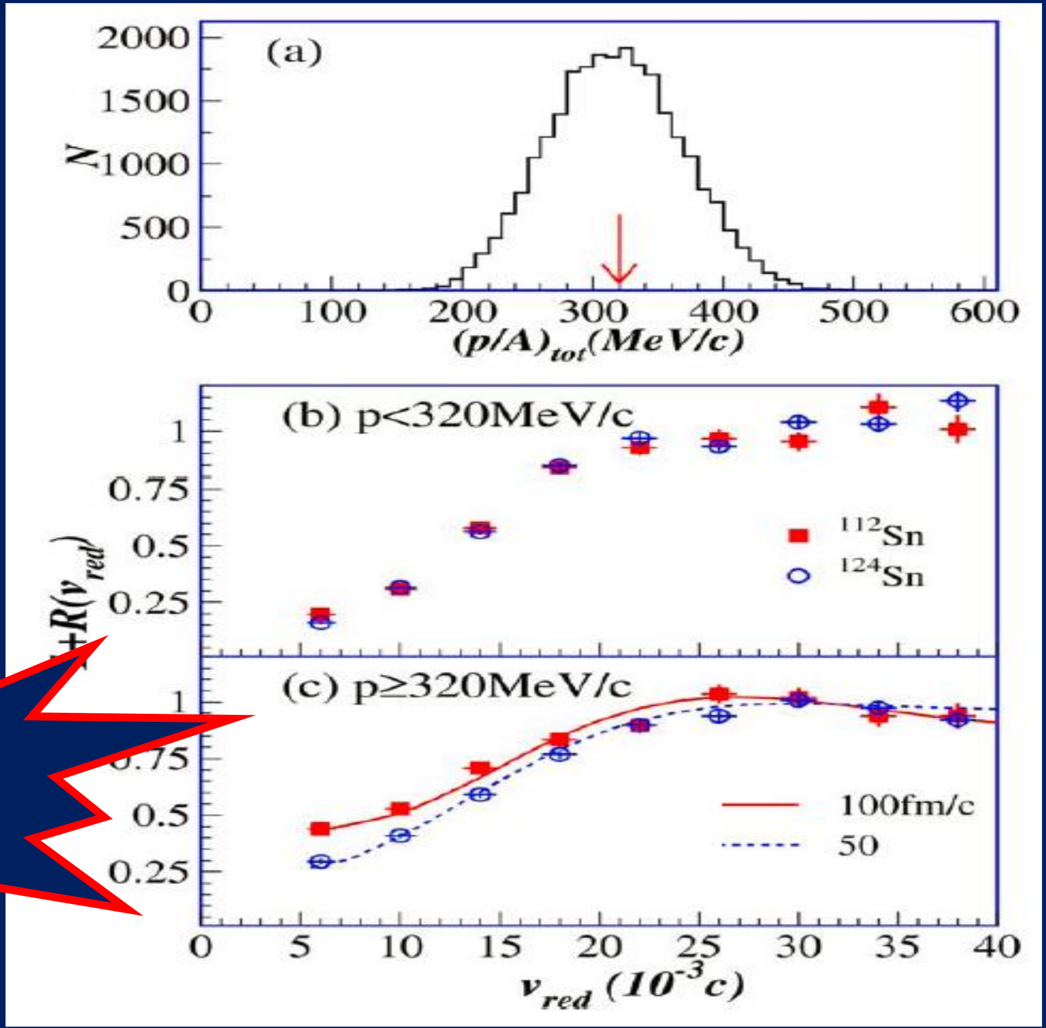




Experimental measurement of isospin dependent HBT correlation of IMF



~50 fm/c time resolution achievable



ZGX， R. J. Hu, H. Y. Wu et al., **PLB 639**,436 (2006)； R. J. Hu, ZGX et al., **HEPNP 31**, 350 (2007)

- Stronger Coulomb anti-correlation is observed in Ar+^{124}Sn , this difference arises from the isospin difference of the two system.

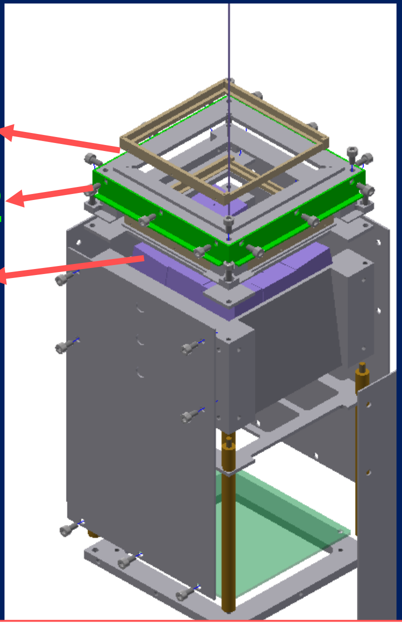
HIRA^{TU} : A future array for Isospin chronology in HIC

- **H**eavy **I**on **R**esearch **A**rray at **T**singhua **U**niversity **(HIRA^{TU})**
- Next Step: Isospin dependent of the particle emission time scale with HBT method.

SSD -ΔE1

SSD -ΔE2

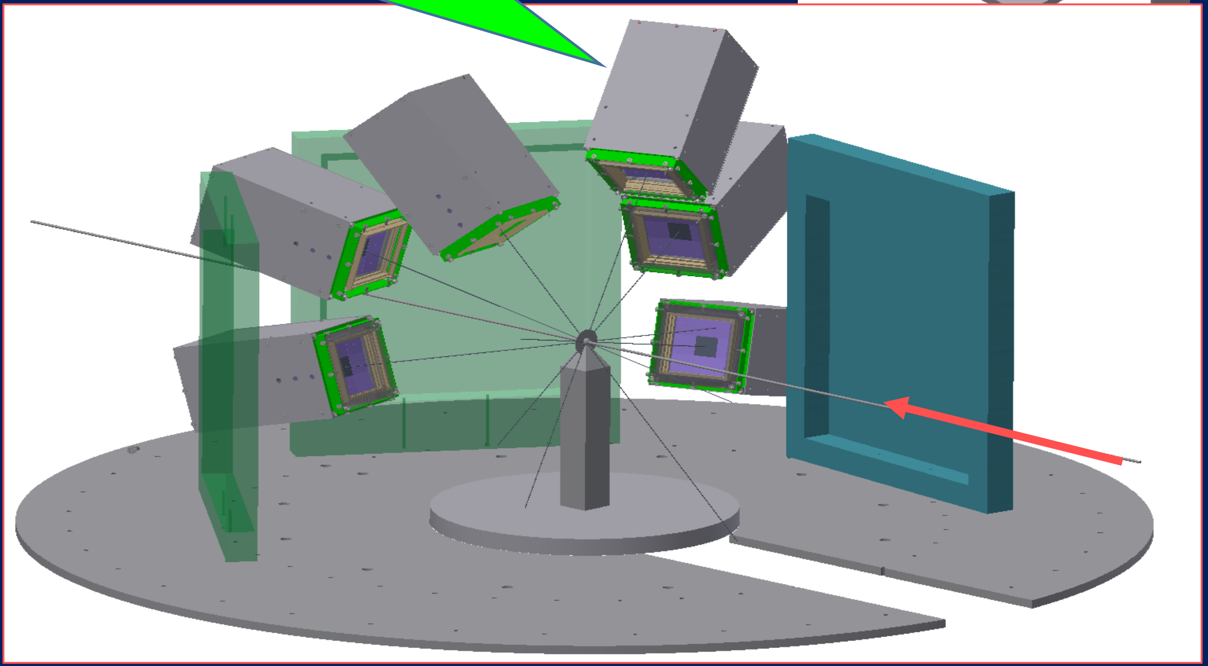
CsI - E



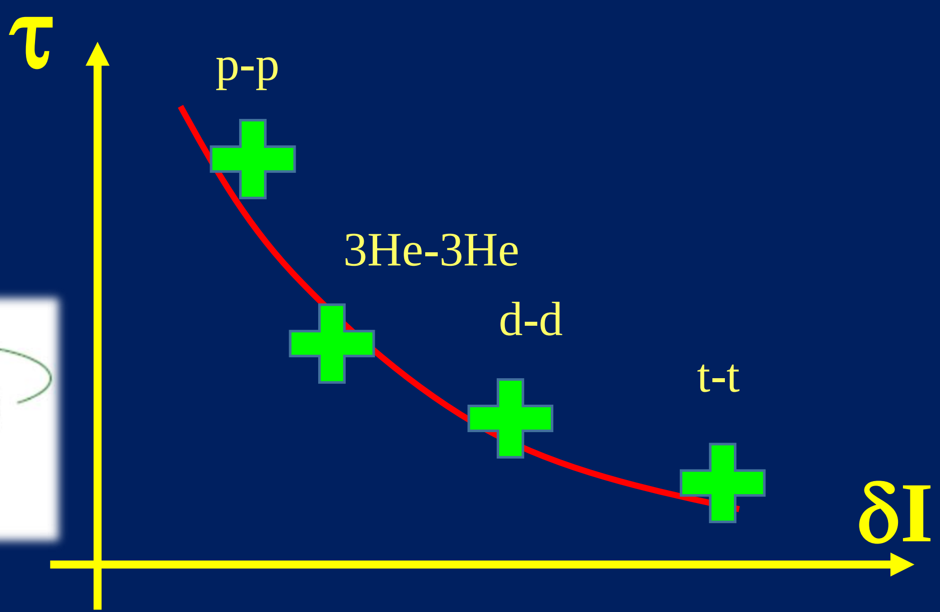
Hit position Resolution ~ 2mm

Build a HIRA-type arrays + PPACs

HIRA type Telescope



First Physical goal: Isospin-resolved HBT

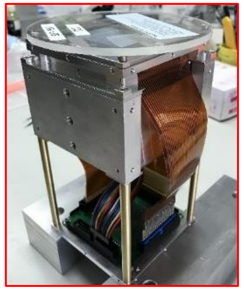


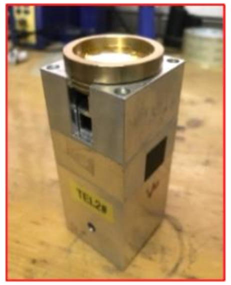
HIRA^{TU}: Phase-1 Experiment

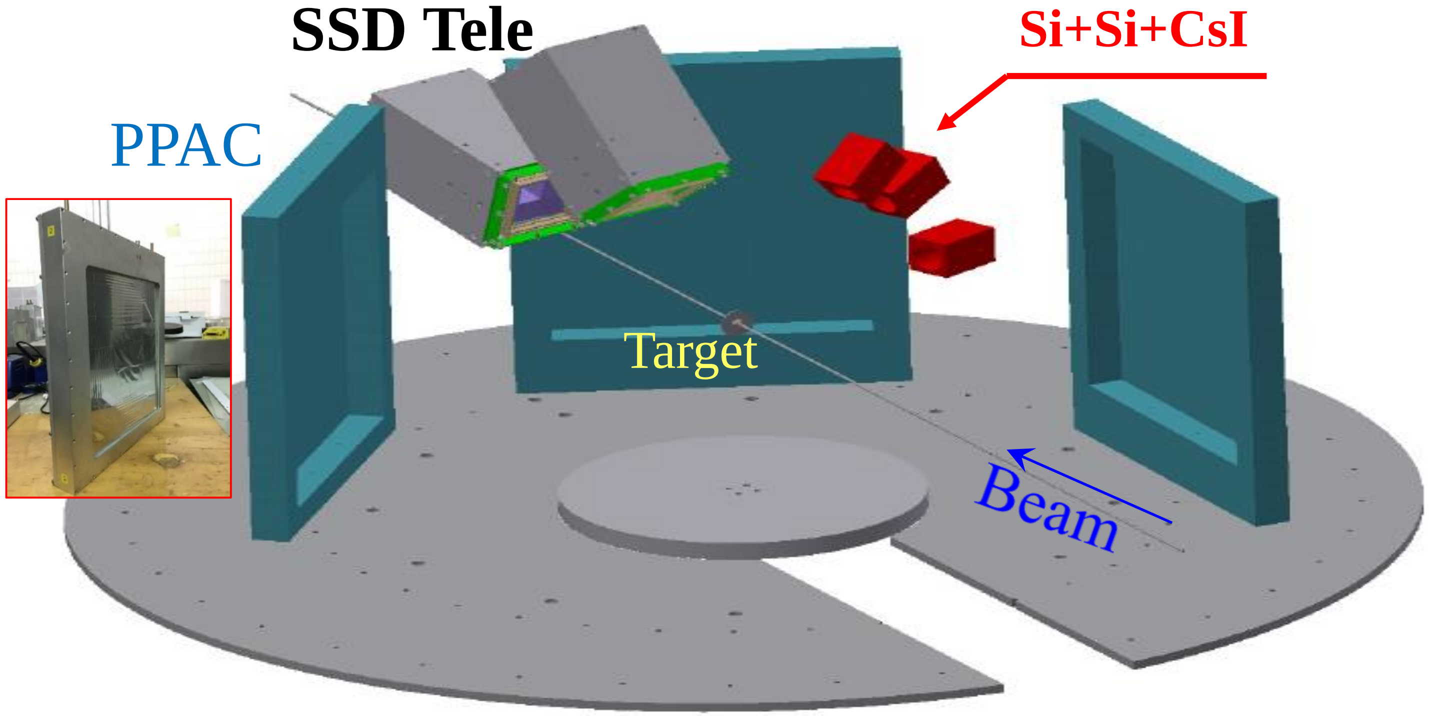
→ 3 PPAC (250 mm ×350 mm) ✓

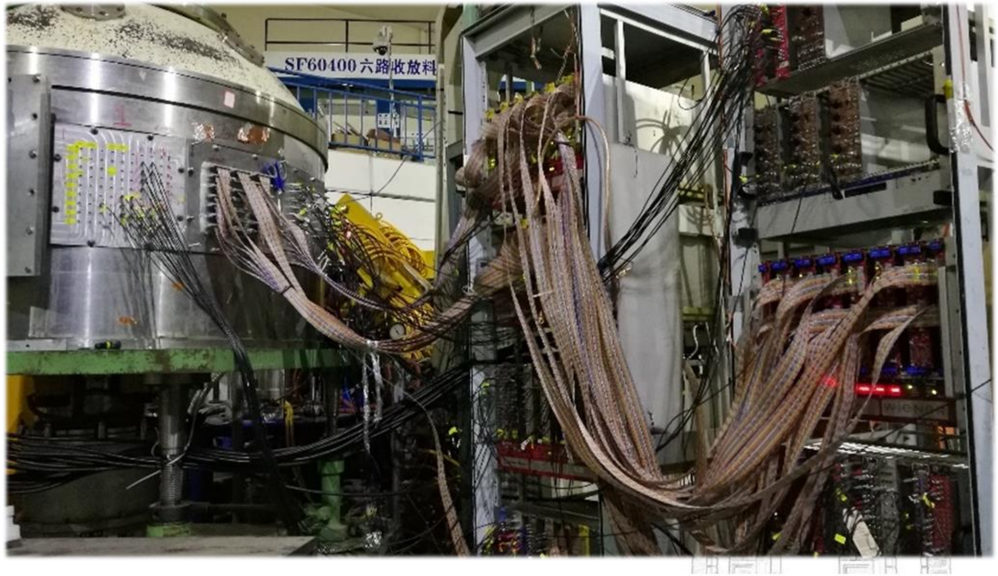
→ 2 SSD-telescopes (65μm+1500 μm + CsI) ✓

→ 3 Si(Au)-CsI Telescopes (50 μm + 300 μm + CsI) ✓

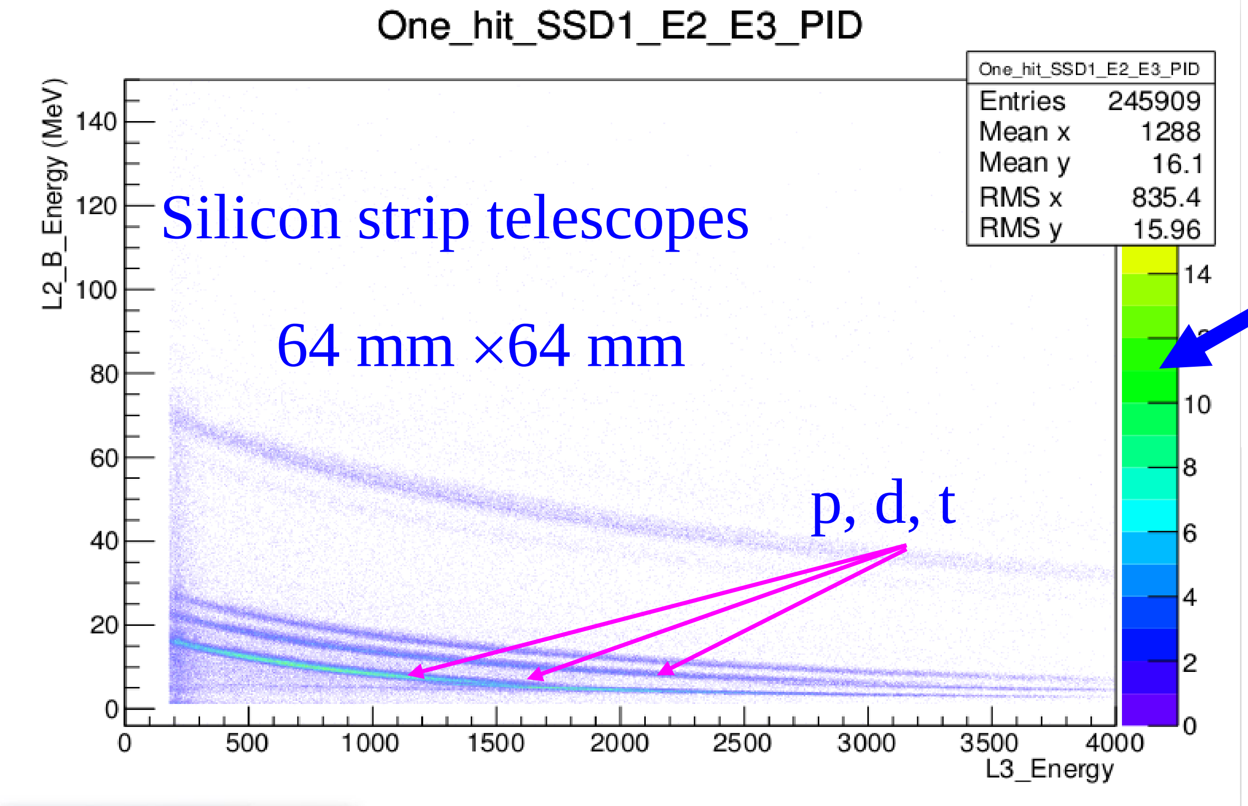


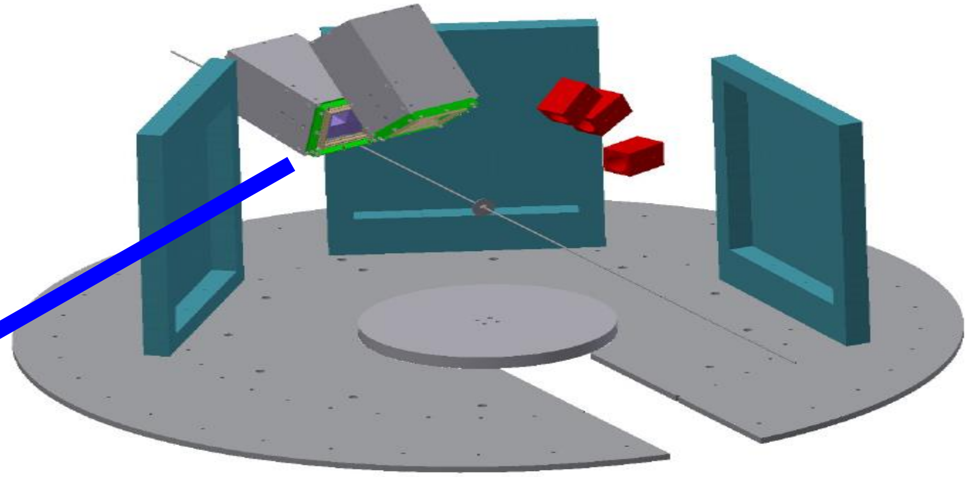


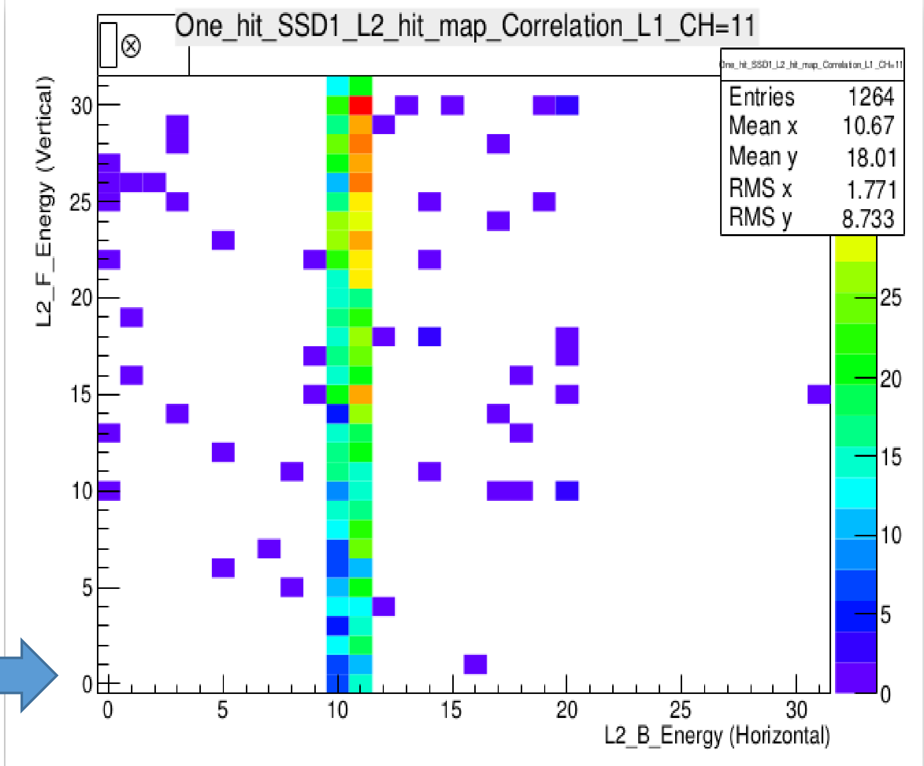




one LCP in coincidence with Fission

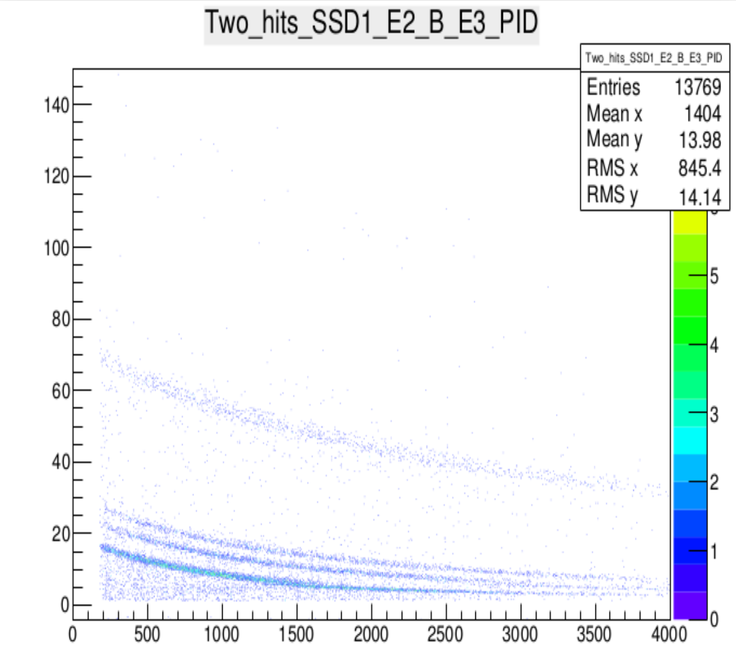


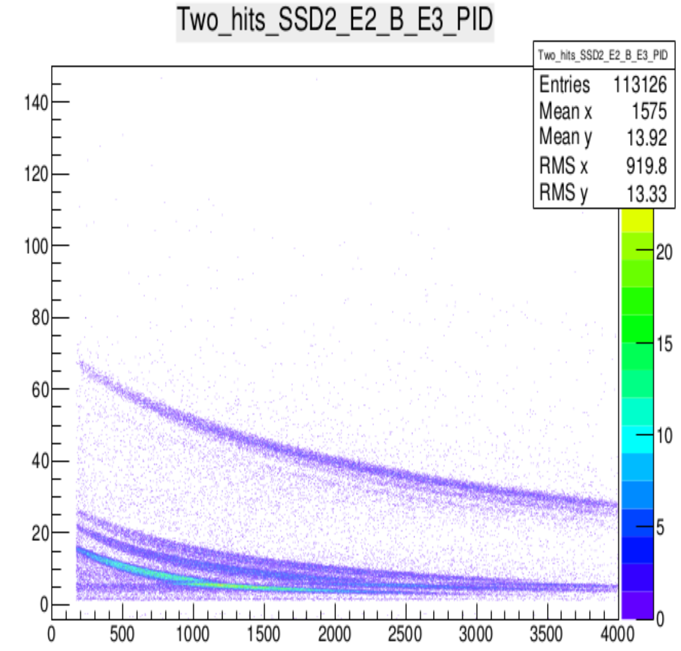


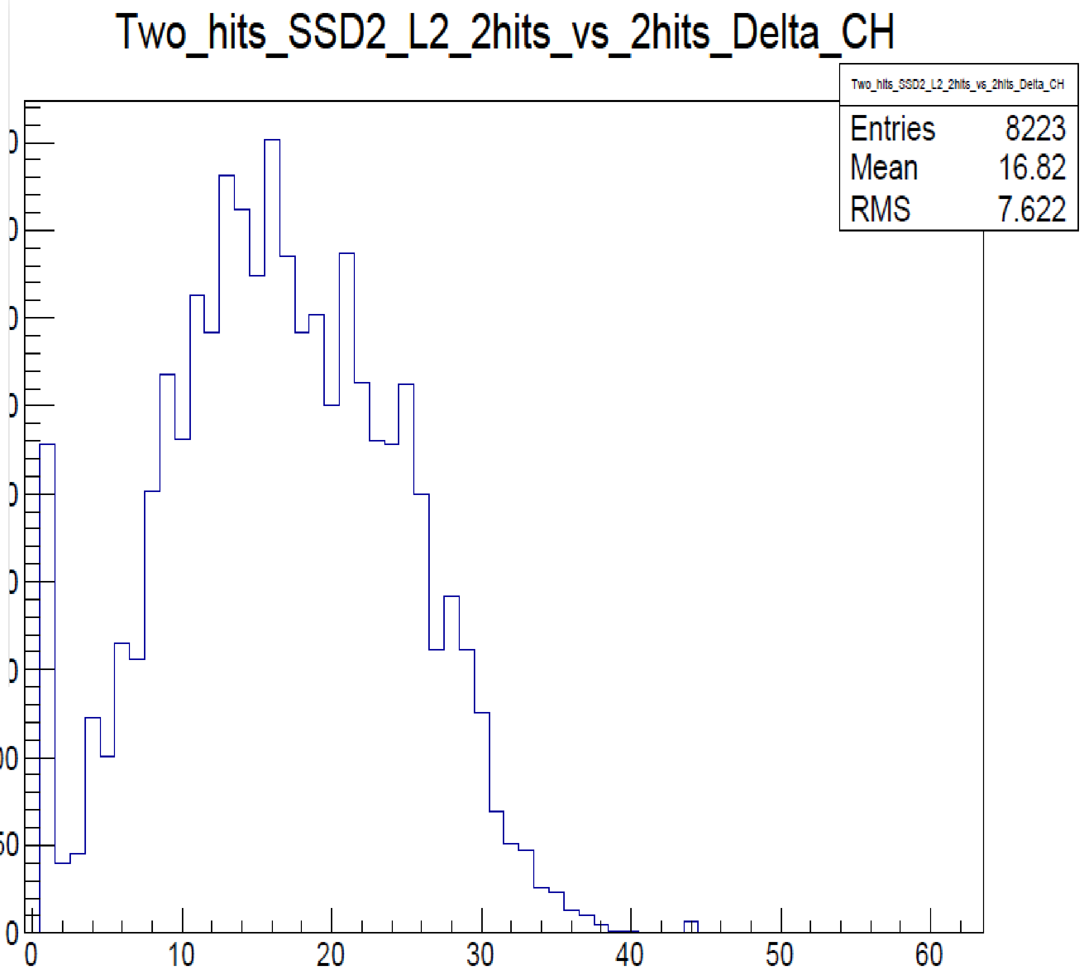


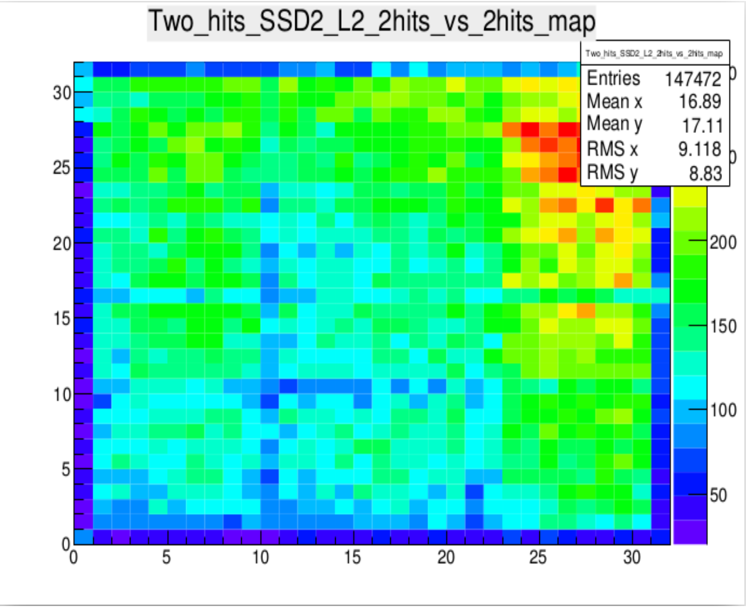
>98% matching efficiency of Layer 1 and Layer 2 of the SSD

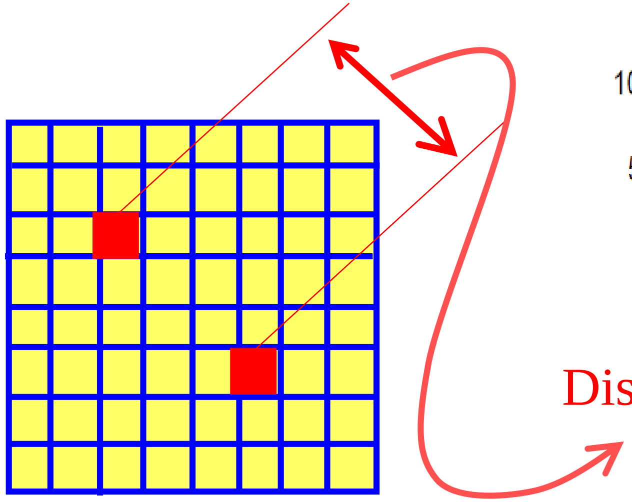
LCP-LCP correlation identified







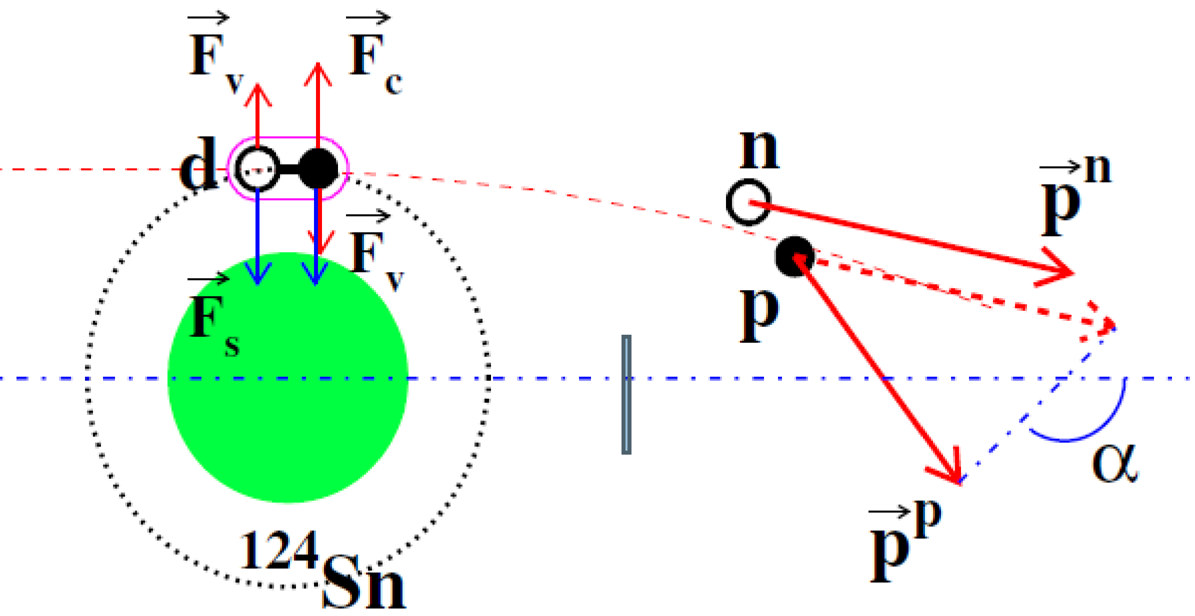




Distance between two correlated particles Pixels

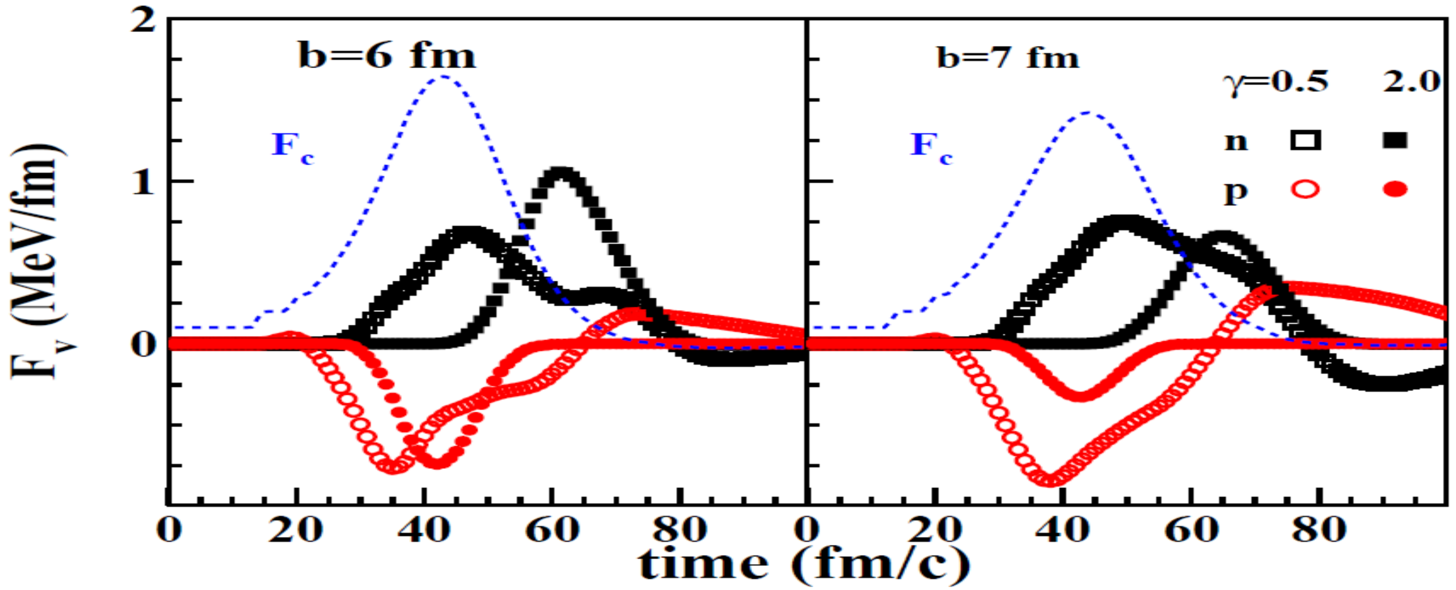
Physical output is expected in near future!

3 Isovector orientation of deuteron scattering off a target

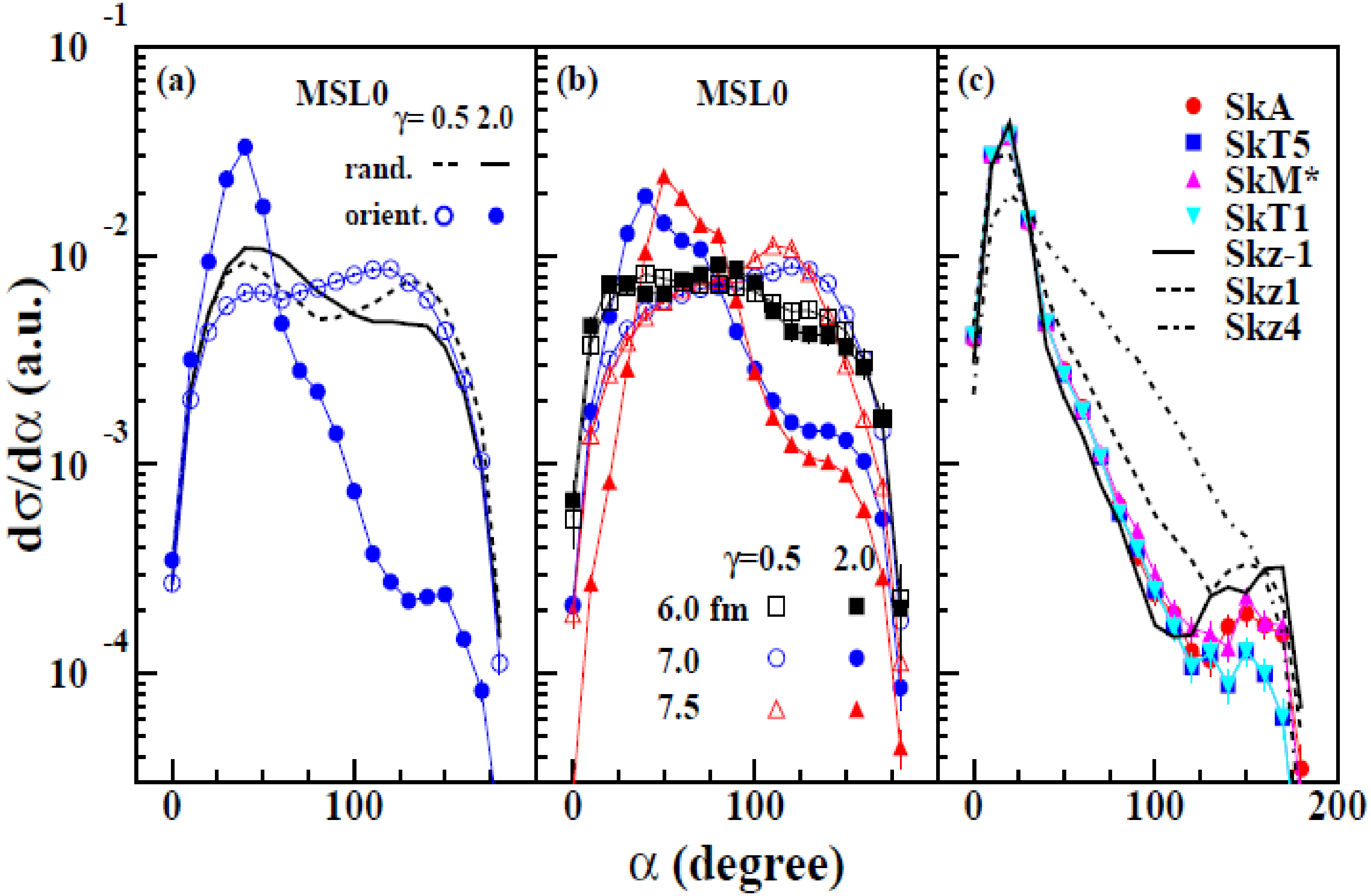


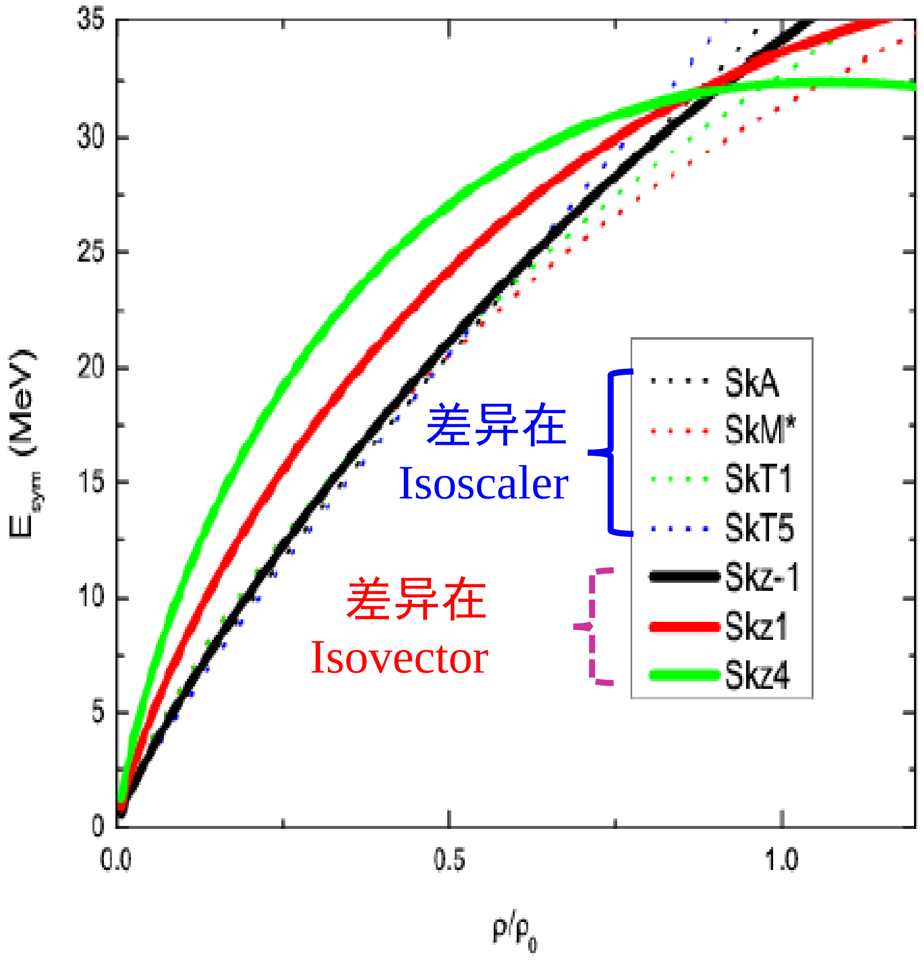
<u>Coulomb force</u> ,1 for proton and 0 for neutron, leads to ***Coulomb polarization*** (reorientation), characterized by **the moving away of proton**.

<u>Isovector force</u>, attractive for proton and repulsive for neutron, leads to ***isovector reorientation***, characterized by **the <u>modification</u> of the direction of the relative motion.**



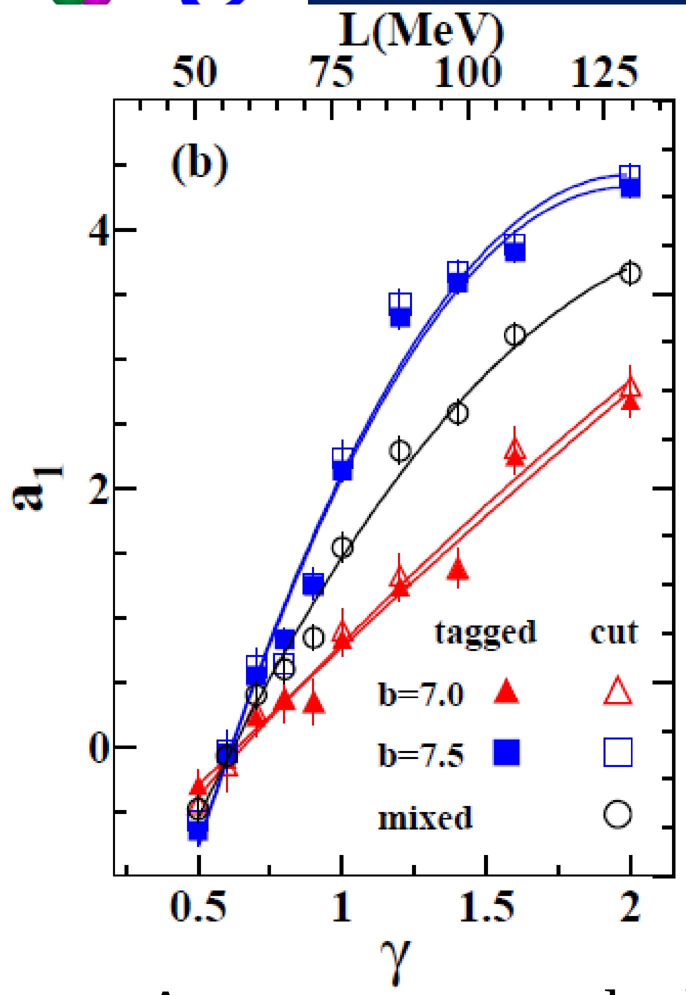
Angular distribution of neutron-proton relative momentum

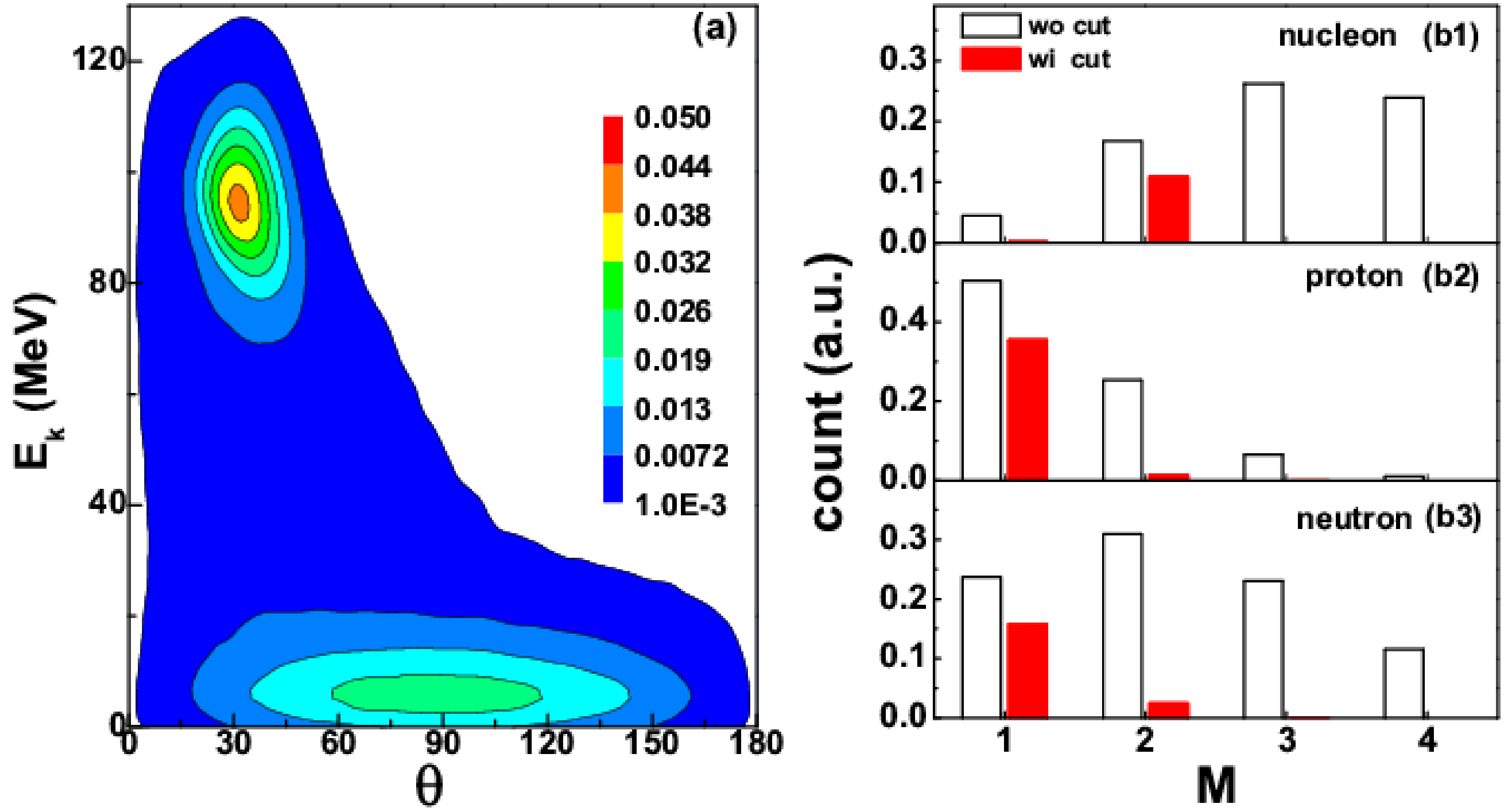




- Li Ou, <u>ZGX</u>, Han Yi, Ning Wang, Min Liu and Junlong Tian, **PRL 115**, 212501, (2015)

Extraction from the slope of the angular distribution





- A new way to study the symmetry energy!
- It is equivalent to measure the proton- and neutron- nucleus optic potential.

Global optical potential analysis L = 52.7 ± 22.5 MeV
Chang Xu et al., Phys. Rev. C 82, 054607 (2010)

清華大学物理系
TSINGHUA UNIVERSITY DEPARTMENT OF PHYSICS

4. Summary

Wealthy information of the transport of **isospin** degree of freedom and **nEOS** is contained in **heavy ion collisions**.

1）The isospin-dependent **emission hierarchy** of light charged particles has been observed， showing neutron-rich LCPs are emitted earlier.

2) Angular distribution of the relative neutron richness of the LCPs imply the **long time feature of isospin drift**, and set a constraint on $E_{sym}(\rho)$ with L=33-61 MeV at S_0=28.3 MeV（CL=95% ）

3) HBT function of LCPs shows dependence on the system N/Z. Isospin **chronology** using HBT method is expected with **HIRA**^{TU}.

4) Isovector orientation effect may serve as a novel tool to study the nuclear EOS.

Happy Birthday to Prof. Akito Arima
Much peace, happiness and good health to you

谢
谢

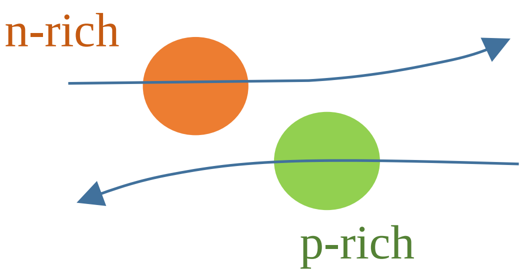
Asymmetric nuclear EOS and isospin transport

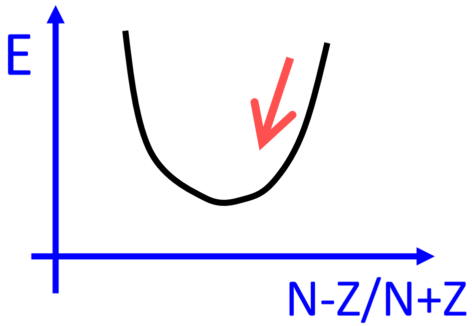
Two mechanisms governs the transport of IDOF in nuclear collisions:

1. Isospin Diffusion：

$$j_{\mathrm{np}} = j_n^I - j_p^I = -\left(D_n^I - D_p^I\right)\nabla I$$

$$D_n^I - D_p^I \propto 4\rho E_{sym}(\rho)$$



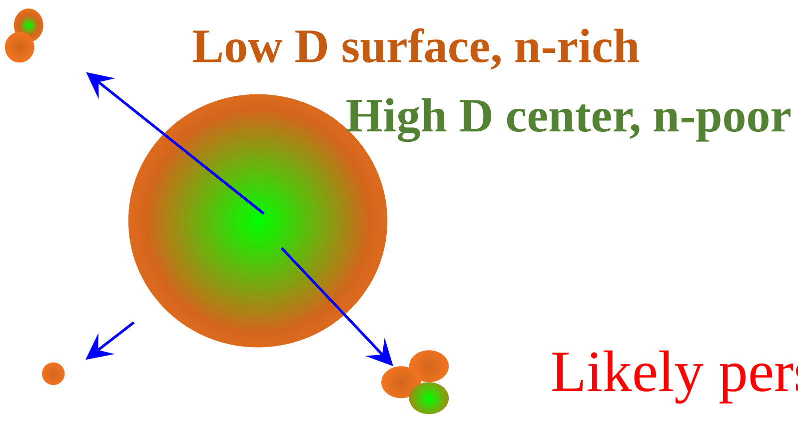


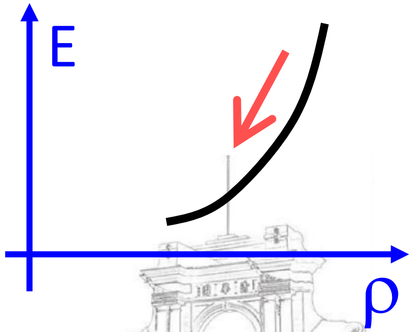
Likely terminated when P-T separated.

2. Isospin Drift：

$$j_{\mathrm{np}} = j_n^\rho - j_p^\rho = \left(D_n^\rho - D_p^\rho\right)\nabla\rho$$

$$D_n^\rho - D_p^\rho \propto 4I\,\frac{\partial E_{sym}(\rho)}{\partial\rho}$$





Likely persists for long time.

Beam time: 6-13 Feb., 2018;   Reaction: Ar+Au at 30 MeV/u;
Experimental site: RIBLL @ HIRFL

Collaboration groups:

Jiansong Wang's
IMP， CAS

Limin Duan's
IMP， CAS

Hongwei Wang's
SINAP， CAS