Experimental studies on isospin chronology and the asymmetric nuclear EOS in heavy ion collisions

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1. Introduction: Isospin transport in HIC and Isospin Chronology (5)

2. Hanbury-Brown and Twiss Method (5)

3. Isospin effect on HBT correlations in Heavy Ion Reactions (5)

4. Summary (2')

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Symmetry Energy

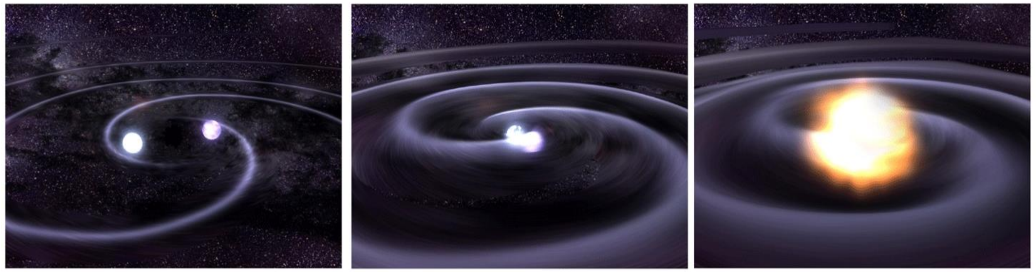
$$B(Z,A) = B_v + B_s + B_c + B_a + B_p$$
$$= a_v A - a_s A^{2/3} - a_c Z^2 A^{-1/3} - a_a (A/2 - Z)^2 A^{-1} + a_p \delta A^{-1/2}$$

Symmetry Term: $a_a (A/2 - Z)^2 A^{-1}$

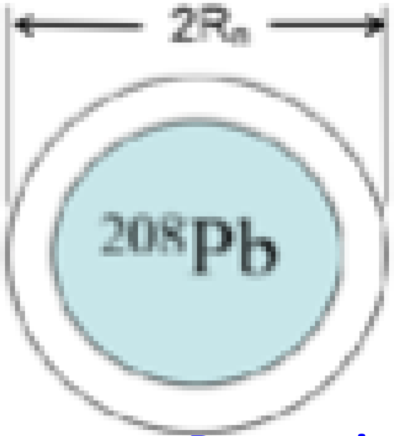
$$E(\rho,\delta) = E_0(\rho) + \delta^2 E_{sym}(\rho) = a_V + \frac{\kappa}{18}\varepsilon^2 + \frac{J}{162}\varepsilon^3 + \ldots + \delta^2\left(E_{sym} + \frac{L}{3}\varepsilon + \ldots\right)$$

κ:Compressibility

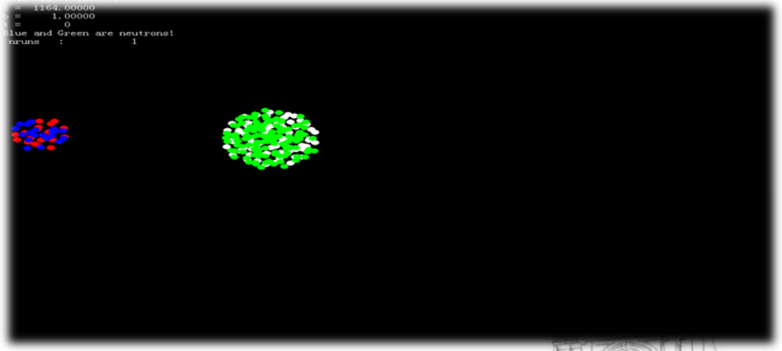
$E_{sym}(\rho)$



（Neutron Star and NS Merge）



（Static or Resonant Properties of Nuclei）



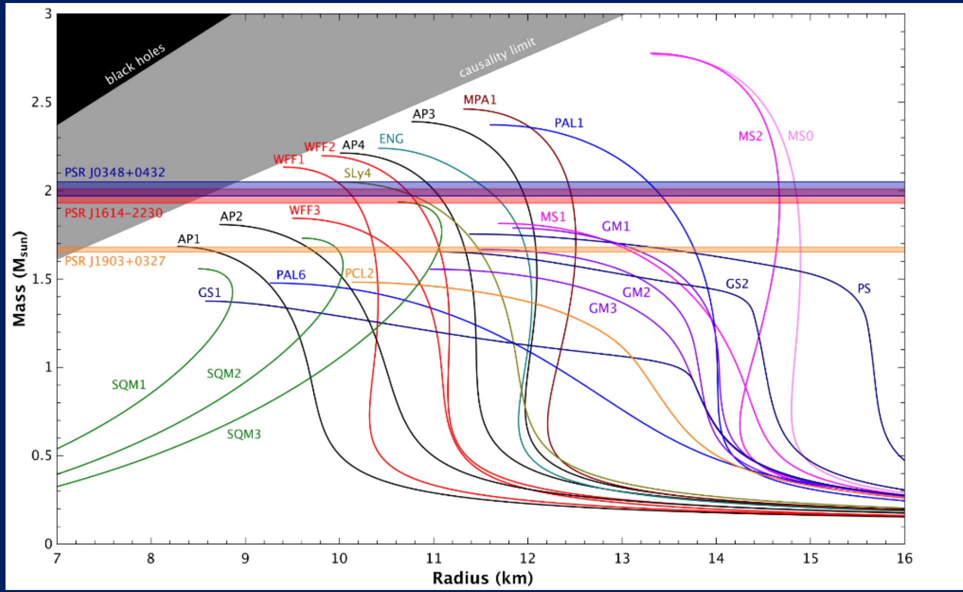
（Heavy Ion Collisions）

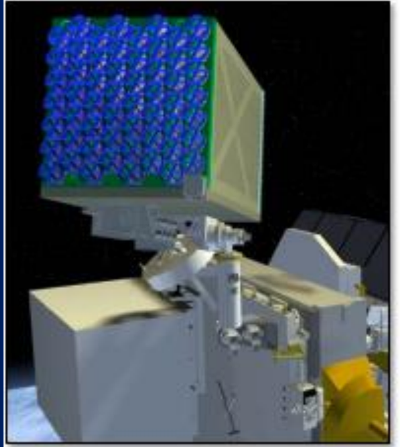
$E_{sym}(\rho)$ becomes a frontier in major Labs

Neutron Star Observatory:

The Neutron Star Interior Composition Explorer （NICER）

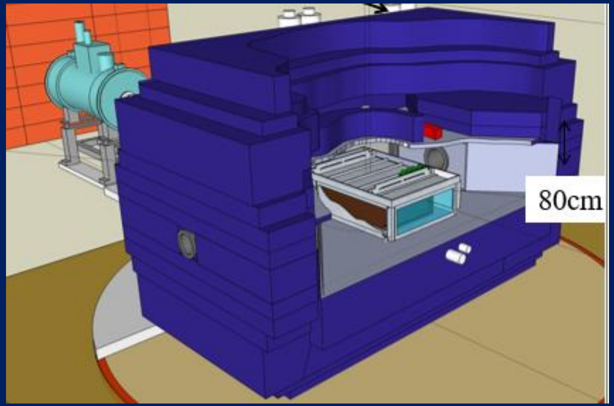
To Constrain EOS of nuclear matter through precise M and R measurements of several neutron stars.

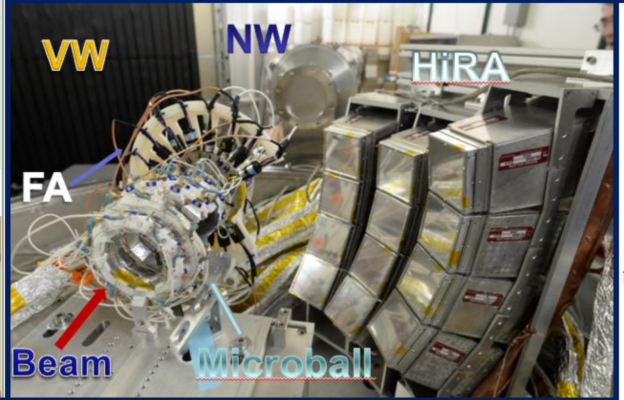


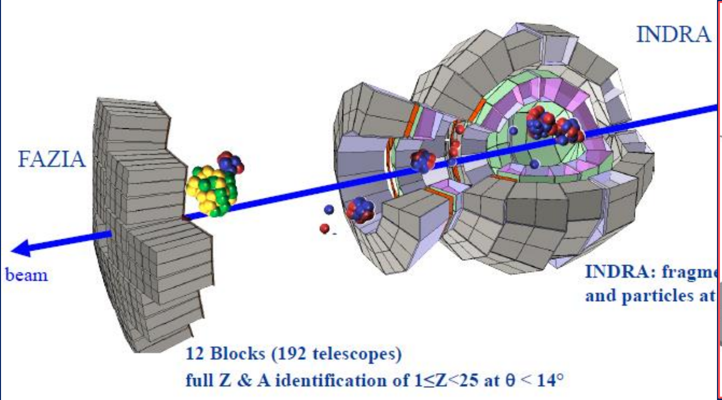


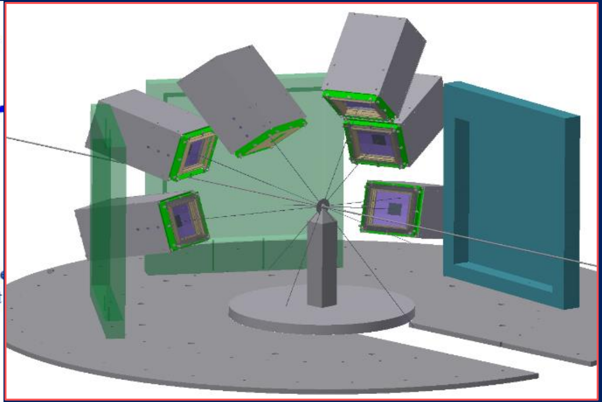
HI accelerator and RIB facilities:

SAMURAI-TPC@RIKEN HIRA@NSCL，MSU INDRA@GANIL RIBLL @ HIRFL







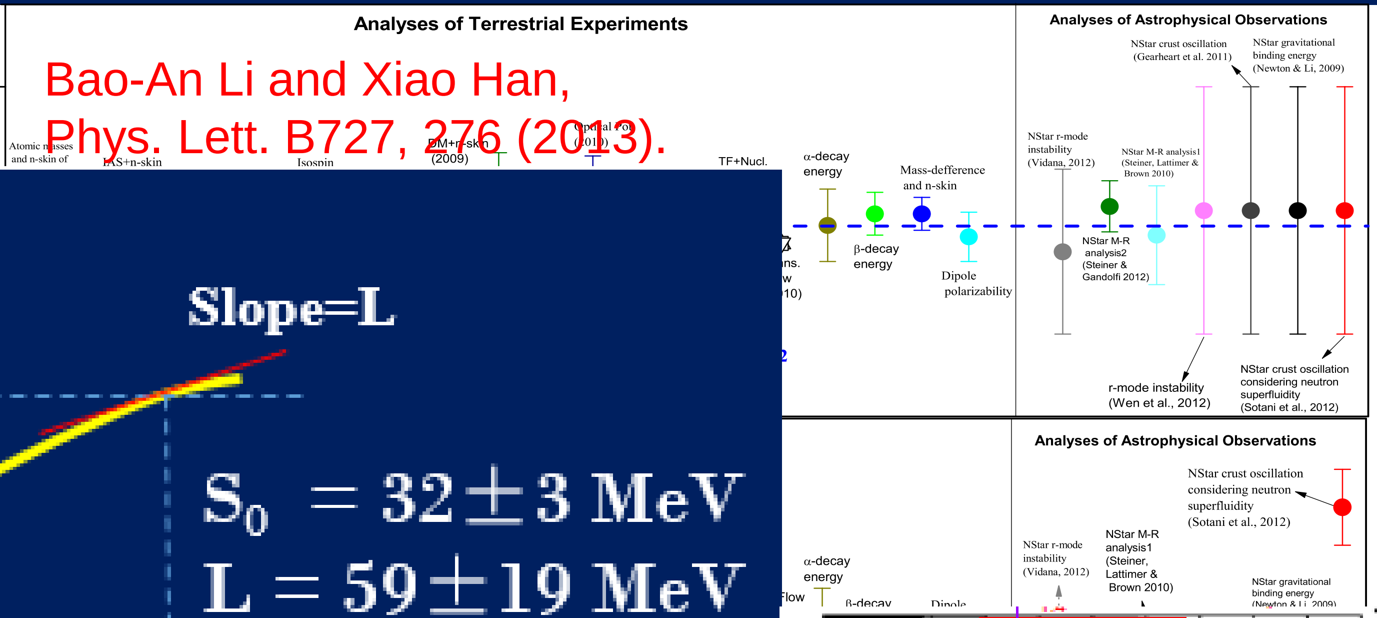


Isospin transport and the constraint of $E_{sym}(\rho)$

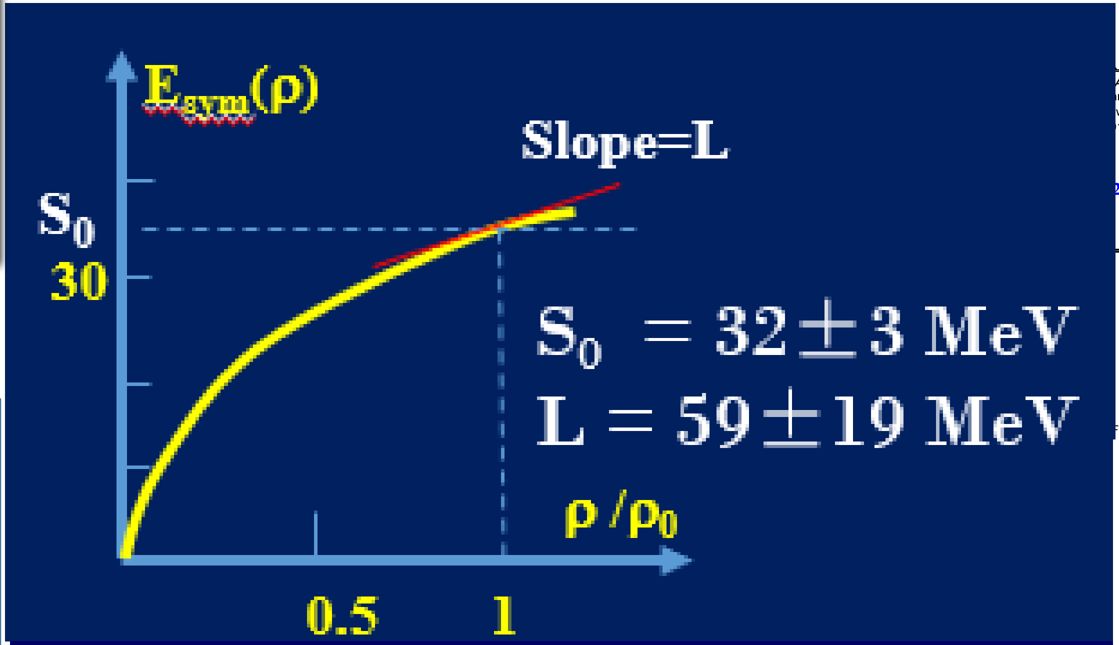
At sub-saturation densities

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 …)
- → …. ….



Bao-An Li and Xiao Han, Phys. Lett. B727, 276 (2013).

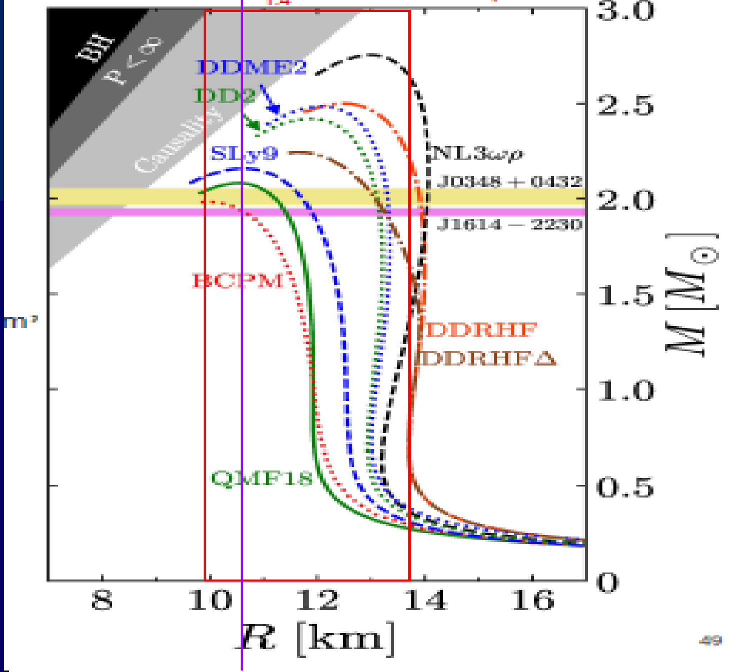


Globe Optical Potential Fit: L=53±23 MeV
C. Xu et al, PRC 82, 054607 (2010)

Proton Emission: L = 52 ± 7 MeV
N. Wan et al., PRC 94, 044322 (2016)

GW170817 QMF18: L= 40 MeV
Ang Li et al., **APJ, 862,98 (2018)**

H. Sagawa's talk: L= 42 ± 14



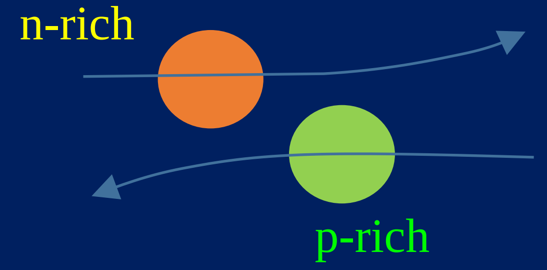
Symmetry Energy and isospin transport in HIC

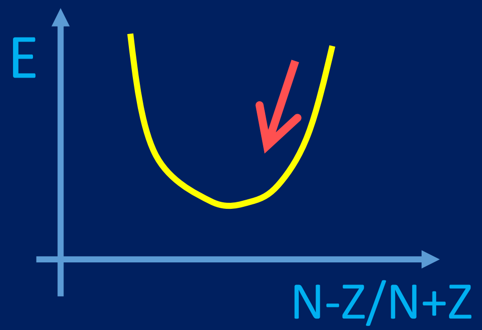
Two mechanisms governs the transport of IDOF in nuclear collisions:

1. Isospin Diffusion：

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

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



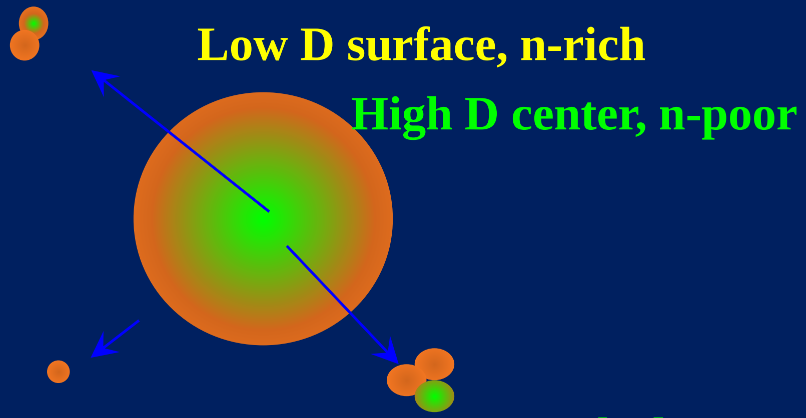


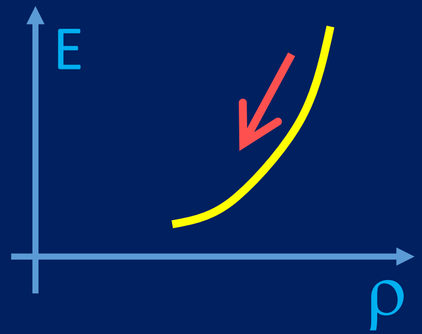
Likely terminated when P-T separated.

2. Isospin Drift：

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

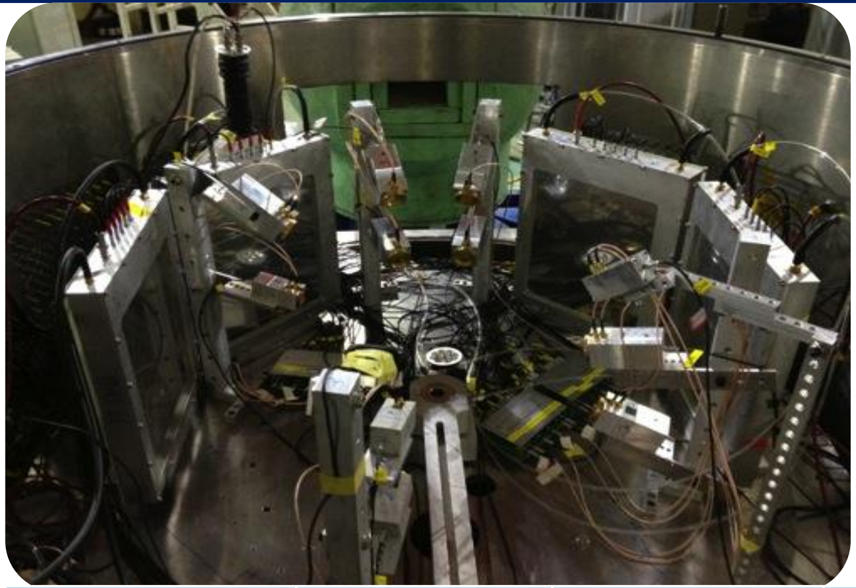
$$D_n^\rho - D_p^\rho \propto 4I\,\frac{\partial E_{sym}(\rho)}{\partial\rho}$$



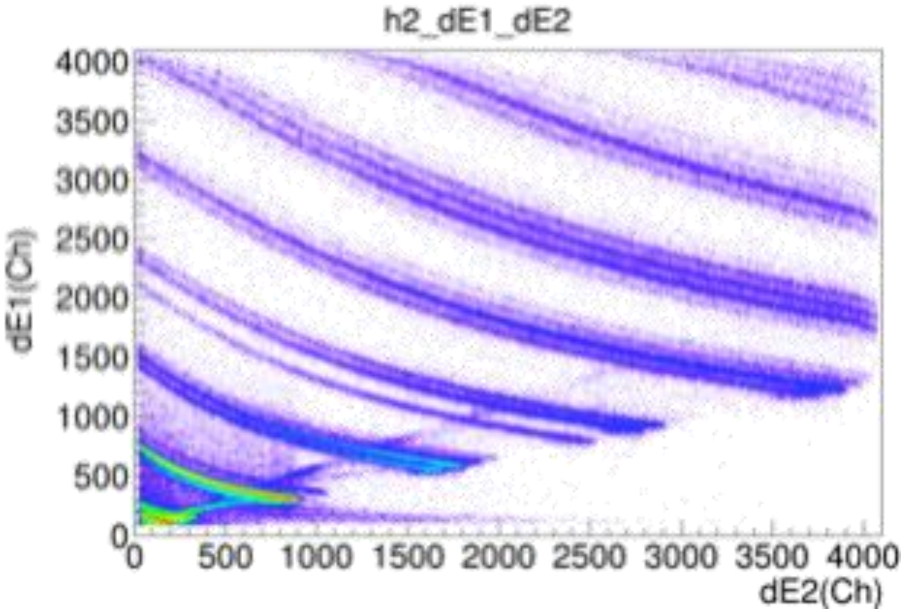


Likely persists for long time.

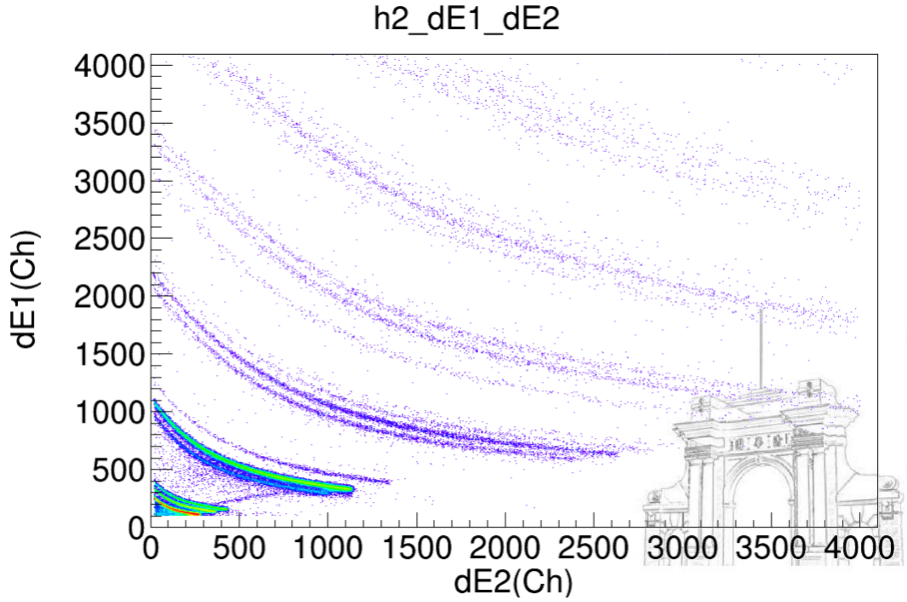
Long time isospin drift and the constraint of $E_{sym}(\rho)$



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



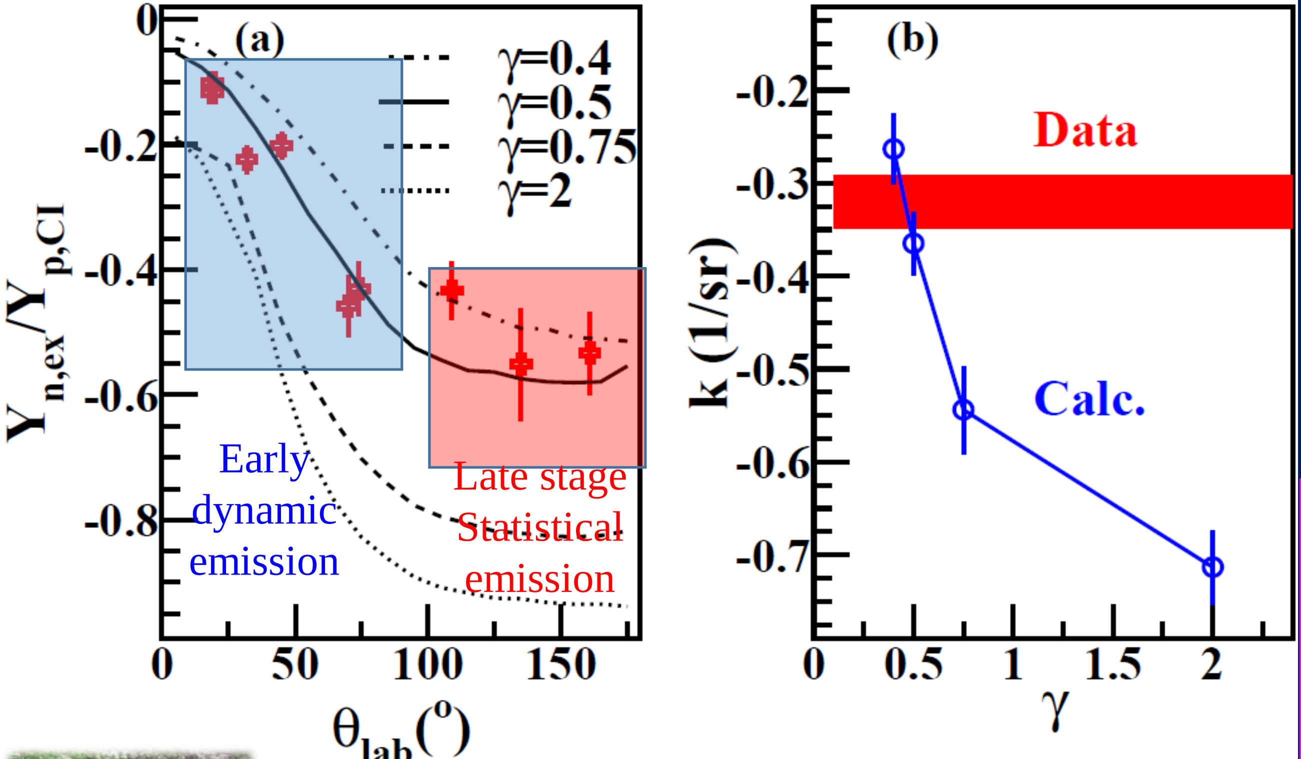
Telescope	Silicon1 (μm)	Silicon2 (μm)	CsI(cm)	Position (θ,φ)
Telescope1#	150	200	2*2*3	(37,69)
Telescope2#	75	200	2*2*3	(19,39)
Telescope3#	75	200	2*2*3	(19,39)
Telescope4#	50	200	2*2*3	(45,170)
Telescope5#	30	200	2*2*3	(74,39)
Telescope6#	50	300	1.5*1.5*2	(70,13)
Telescope7#	25	300	1.5*1.5*2	(161,37)
Telescope10#	30	200	2*2*3	(109,196)
Telescope11#	50	300	1.5*1.5*2	(135,110)



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.

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

2） $E_{sym}(\rho)$: γ=0.46±0.025（STDEV）

L=47±14 MeV （CL=95%）

with S_0 fixed at 28.3 MeV.

Globe Optical Potential Fit: L=52.7±22.5 MeV PRC (2010)
Proton Emission: L = 51.8 ± 7.2 MeV， PRC(2016)
GW170817 QMF18: L= 40 MeV **APJ，(2018)**
IAS-ΔR_{np}, L = 42 ±14 MeV H. Sagawa's talk

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]

- **How long is long?**
- **How short is short?**
- **How do we measure?**

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2. Hanbury-Brown and Twiss Method (5)

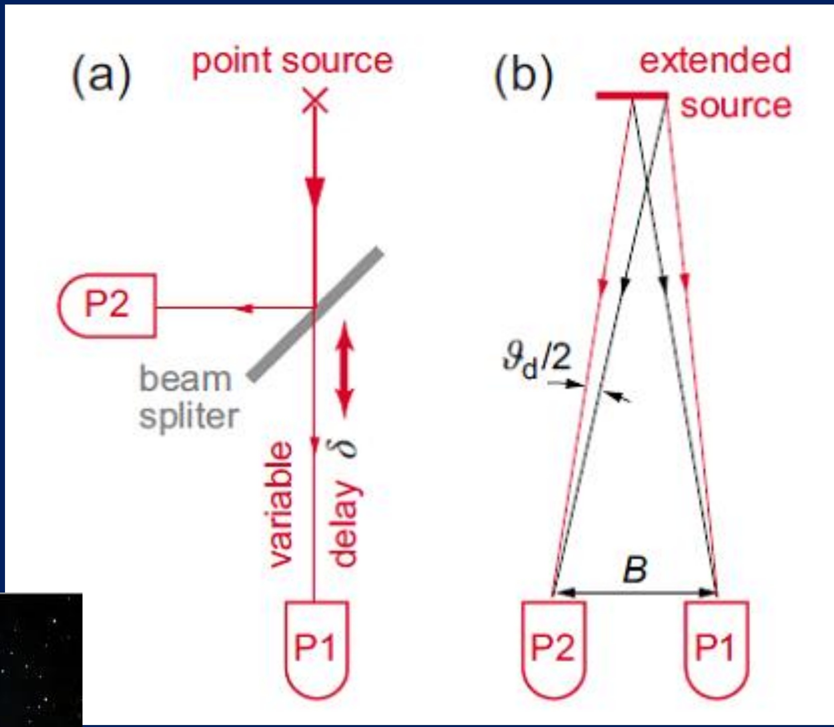
3. Isospin effect HBT correlations in Heavy Ion Reactions (5)

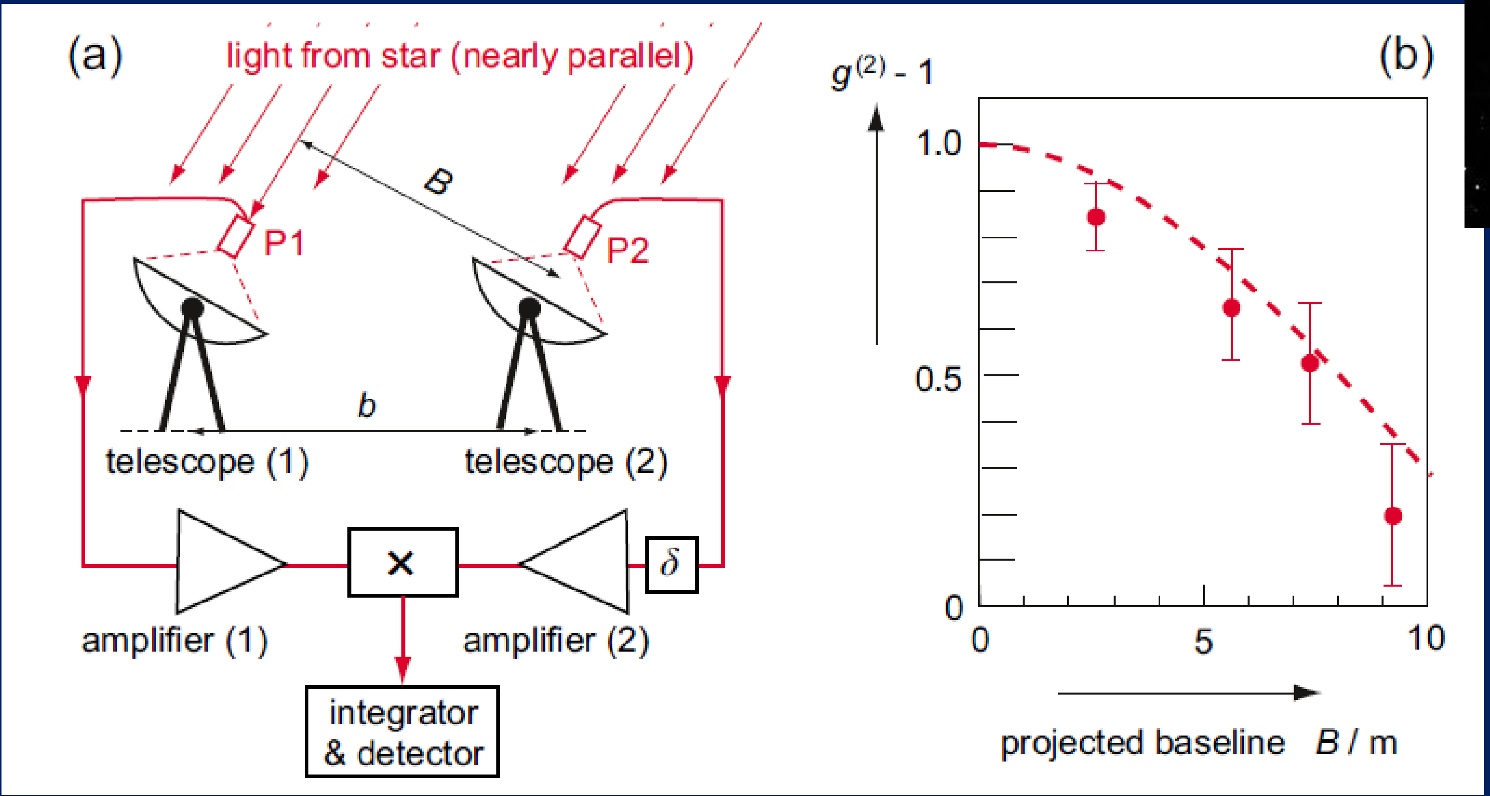
4. Summary (2')

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）





- **HBT is invented to measure the space information**

Hanbury Brown and Twiss，
Nature 178， 1046（1956）

HBT correlation

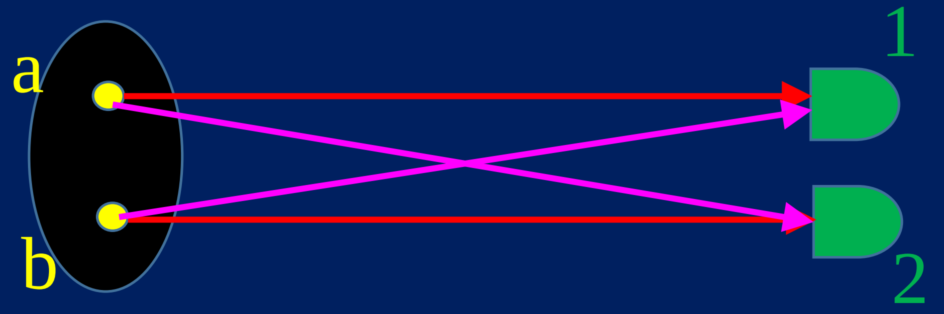
Unlike the amplitude interference! HBT correlation is intensity interferometry, referring the correlation of the two intensities. It is the second order interference.

In a classic picture: the spherical waves emitted from a and b are :

$$\alpha\, e^{ik|\vec{r}-\vec{r_a}|+i\varphi_a}/|\vec{r}-\vec{r_a}| \qquad\qquad \beta\, e^{ik|\vec{r}-\vec{r_b}|+i\varphi_b}/|\vec{r}-\vec{r_b}|$$

The amplitude of the signal seen in Detector 1:

$$A_1=\frac{1}{L}\left[\alpha e^{ikr_{1a}+i\varphi_a}+\beta e^{ikr_{1b}+i\varphi_b}\right]$$



Do the average over time, one has: $\left\langle e^{i(\varphi_b-\varphi_a)}\right\rangle=0$

One get the light intensity is:

$$\langle I_1\rangle=\langle I_2\rangle=\frac{1}{L^2}\left[\alpha^2+\beta^2\right]$$

HBT correlation

Finally， One arrive at : $\langle I_1 I_2\rangle = \frac{1}{L^4}\left[L^4\langle I_1\rangle\langle I_2\rangle + 2\alpha^2\beta^2 cos\left((\vec{k}_2-\vec{k}_1)\cdot\vec{R}\right)\right]$

The Correlation function is defined as :

$$C(\vec{d},k_1,k_2) = \frac{\langle I_1 I_2\rangle}{\langle I_1\rangle\langle I_2\rangle} = 1 + 2\frac{\langle\alpha^2\rangle\langle\beta^2\rangle}{(\alpha^2+\beta^2)^2} cos\left((\vec{k}_2-\vec{k}_1)\cdot\vec{R}\right)$$

Approximately, it reads :

$$C(\vec{d},k_1,k_2) \approx 1 + \frac{1}{2} cos\left((\vec{k}_2-\vec{k}_1)\cdot\vec{R}\right)$$

Considering a source with density distribution ρ(r), the correlation function is written as

$$C(\vec{d},k_1,k_2) - 1 = \left|\int \rho(r) e^{i(\vec{k}_1-\vec{k}_2)\cdot\vec{r}} d^3r\right|^2$$

Obviously, C is as a function of d via Δ***k***， d is the base line of the two detectors.

$C(\vec{d},k_1,k_2)$ is the Fourier transformation of the density distribution of the source.

Application of HBT in nuclear physics

- 1960s， Goldhaber Analyzed the ππ correlation in p̄p anilation
- 1977， S. Koonin extended the HBT to pp correlation in heavy ion reactions

Distribution of proton in the fireball

$$\frac{1}{\sigma}\frac{d\sigma}{d\mathbf{p}_1\, d\mathbf{p}_2} = \int_{-\infty}^{\infty} dt_1\, dt_2 \int d\mathbf{r}_1\, d\mathbf{r}_2\, D(\mathbf{r}_1 t_1, \mathbf{p})\, D(\mathbf{r}_2 t_2, \mathbf{p}) \times \left\{\tfrac{1}{4}\left|{}^1\Psi_{\mathbf{p}_1\mathbf{p}_2}(\mathbf{r}_1', \mathbf{r}_2)\right|^2 + \tfrac{3}{4}\left|{}^3\Psi_{\mathbf{p}_1\mathbf{p}_2}(\mathbf{r}_1', \mathbf{r}_2)\right|^2\right\} . \quad (1)$$

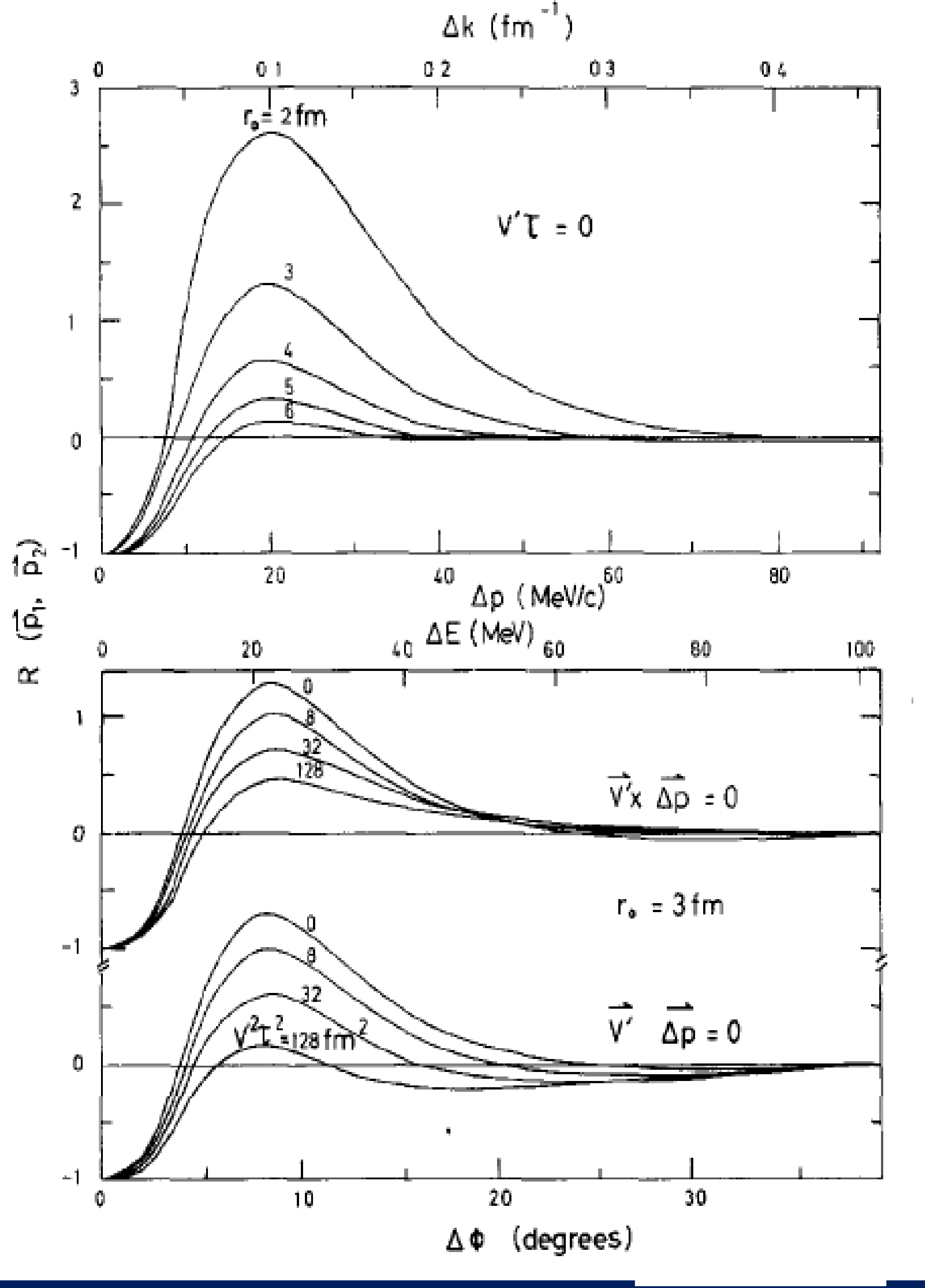
Plane wave multiplying the pp relative motion wave function。

$$D(\mathbf{r}t, \mathbf{p}) = \frac{1}{\sigma}\frac{d\sigma}{d\mathbf{p}} \left(\frac{1}{\pi^{3/2} r_0^3}\, e^{-(\mathbf{r}-\mathbf{V}_0 t)^2/r_0^2}\right)\left(\frac{1}{\pi^{1/2}\tau}\, e^{-t^2/\tau^2}\right) \quad (2)$$

PROTON PICTURES OF HIGH-ENERGY NUCLEAR COLLISIONS

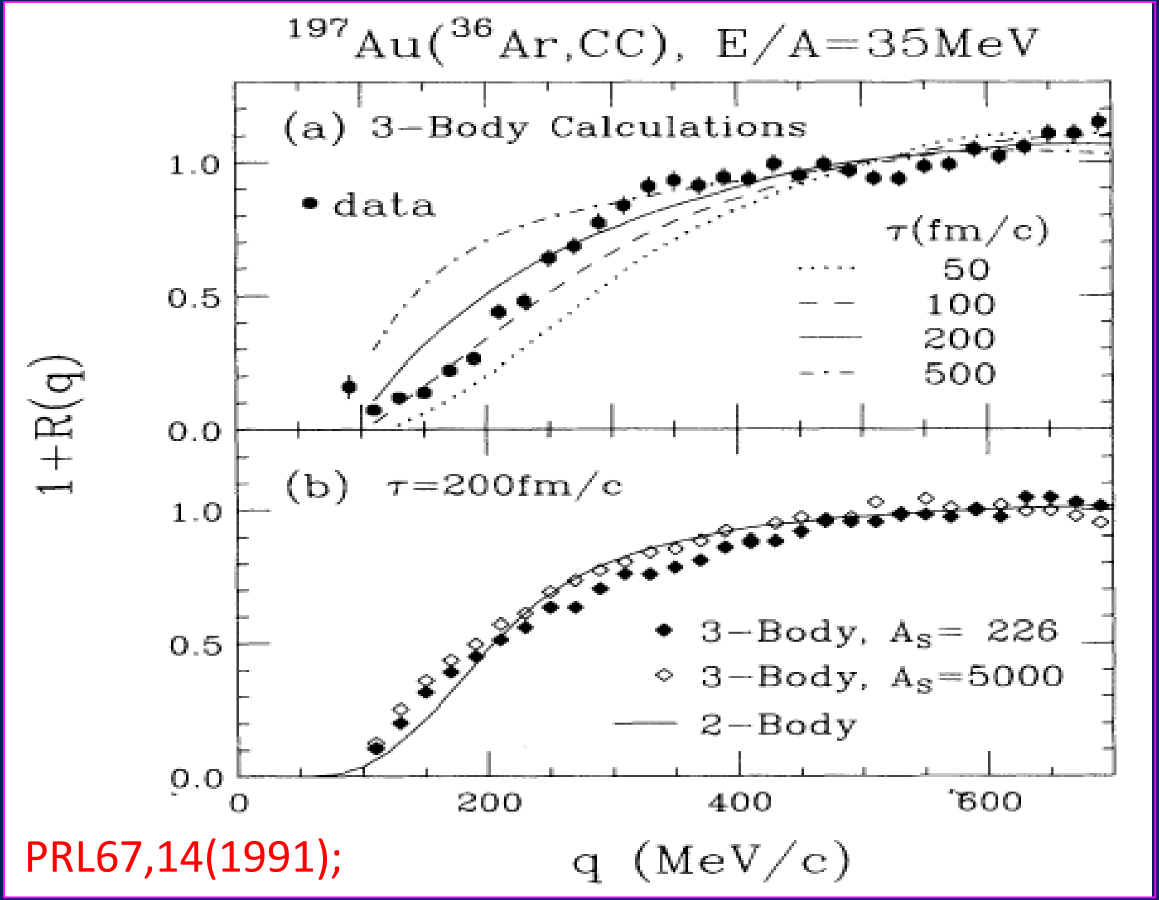
Steven E. KOONIN[1]
The Niels Borh Institute, Copenhagen, Denmark

PLB70,43(1977)

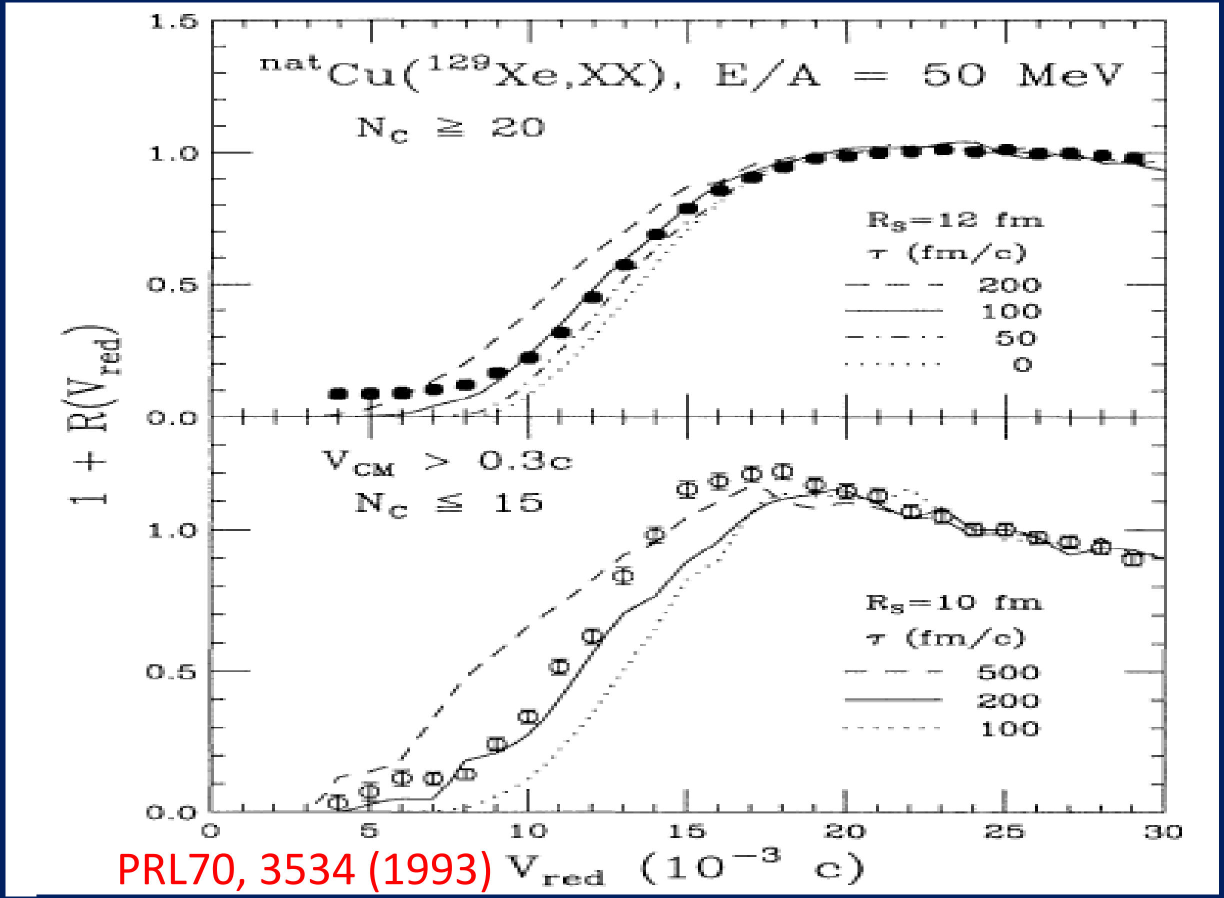


HBT extensively used in HIC since 1990s

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



PRL67,14(1991);



PRL70, 3534 (1993)

Y. D. Kim , IMF correlation function in 35 MeV/u Ar+Au ,

IMF emission time scale: 100-200 fm/c.

D. Bowman , 50 MeV/u Xe+Cu， IMF correlation function at different centrality, time scale confirmed at 100 fm/c.

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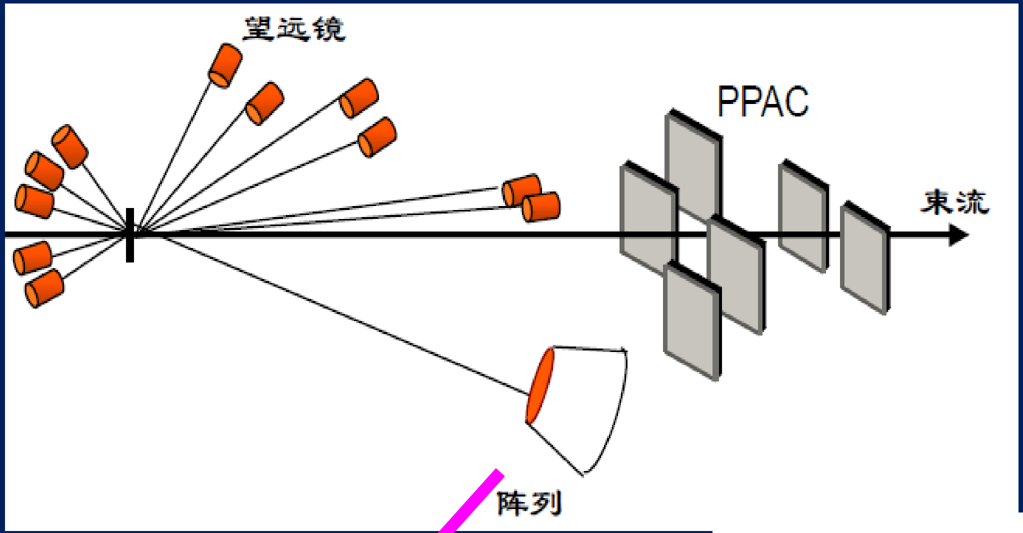
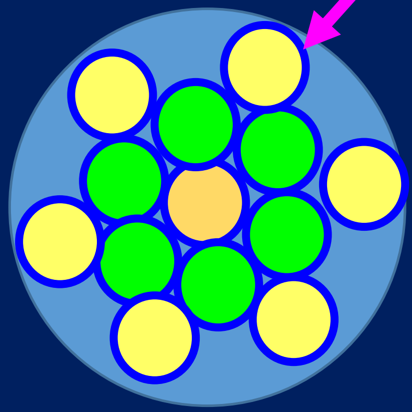
Experimental measurement of Isospin effect on IMF HBT correlation

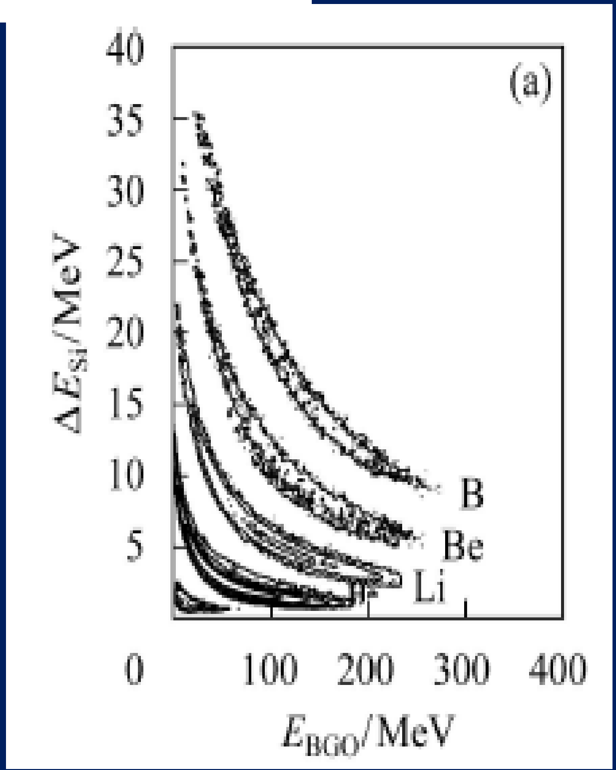


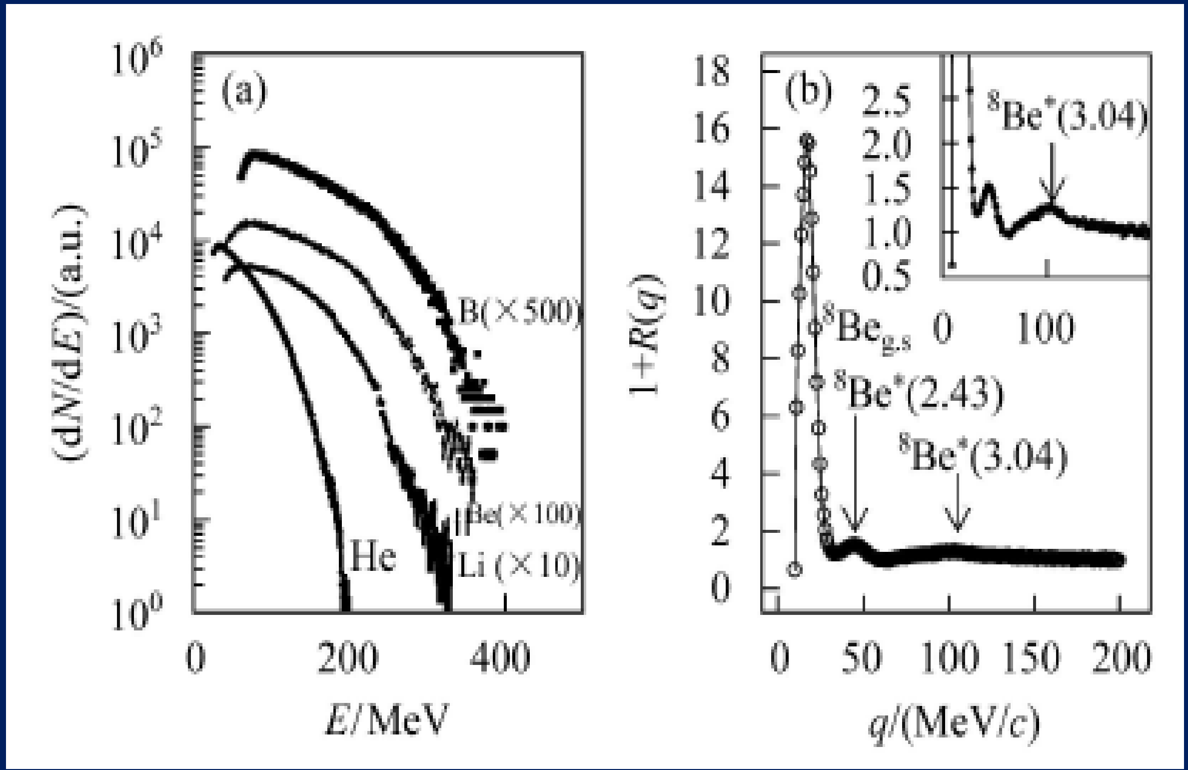
- **Reaction: 35MeV $^{36}Ar+^{112,124}Sn$**
- **Isospin effect on IMF HBT correlation**



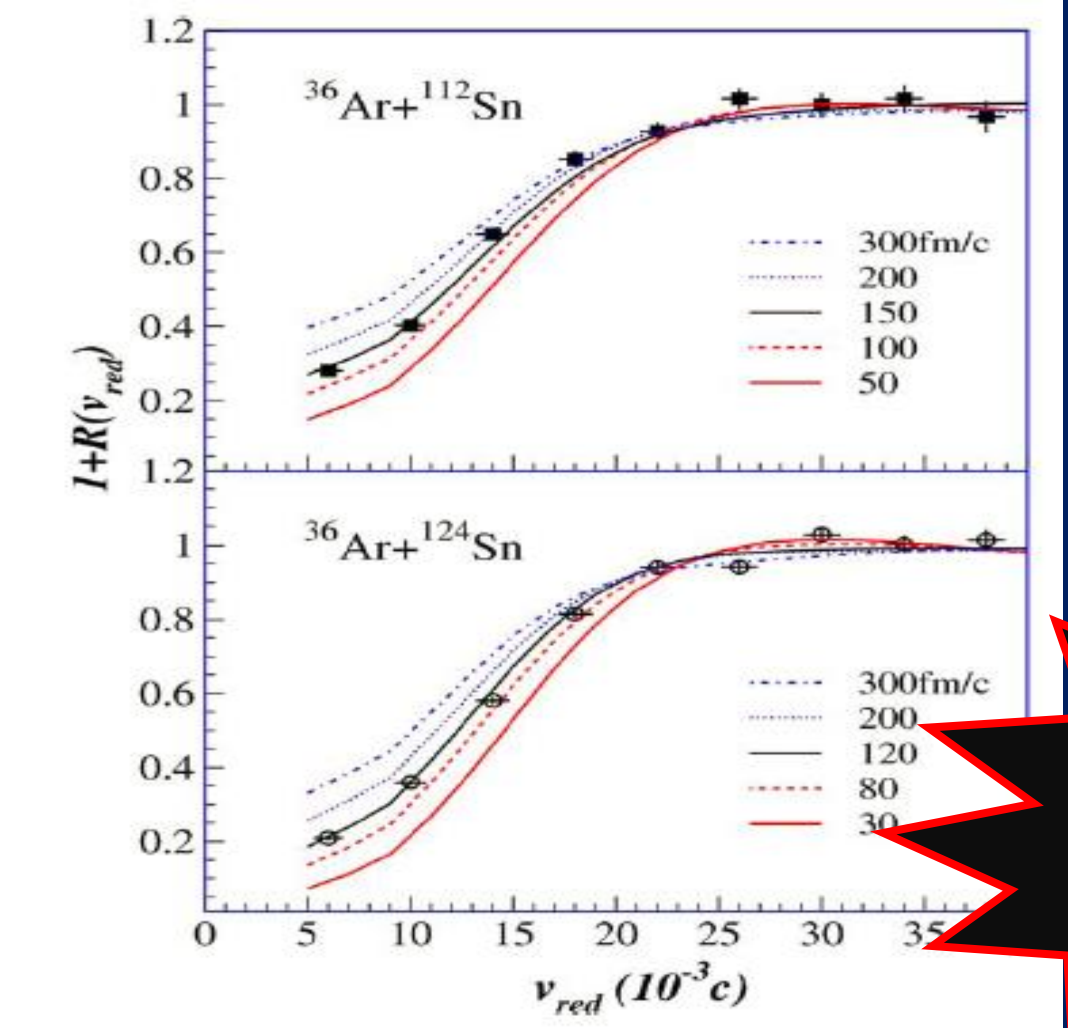
Hodoscope： 13-unit closely packed Si-BGO array

Hit position Resolution ~ 1cm

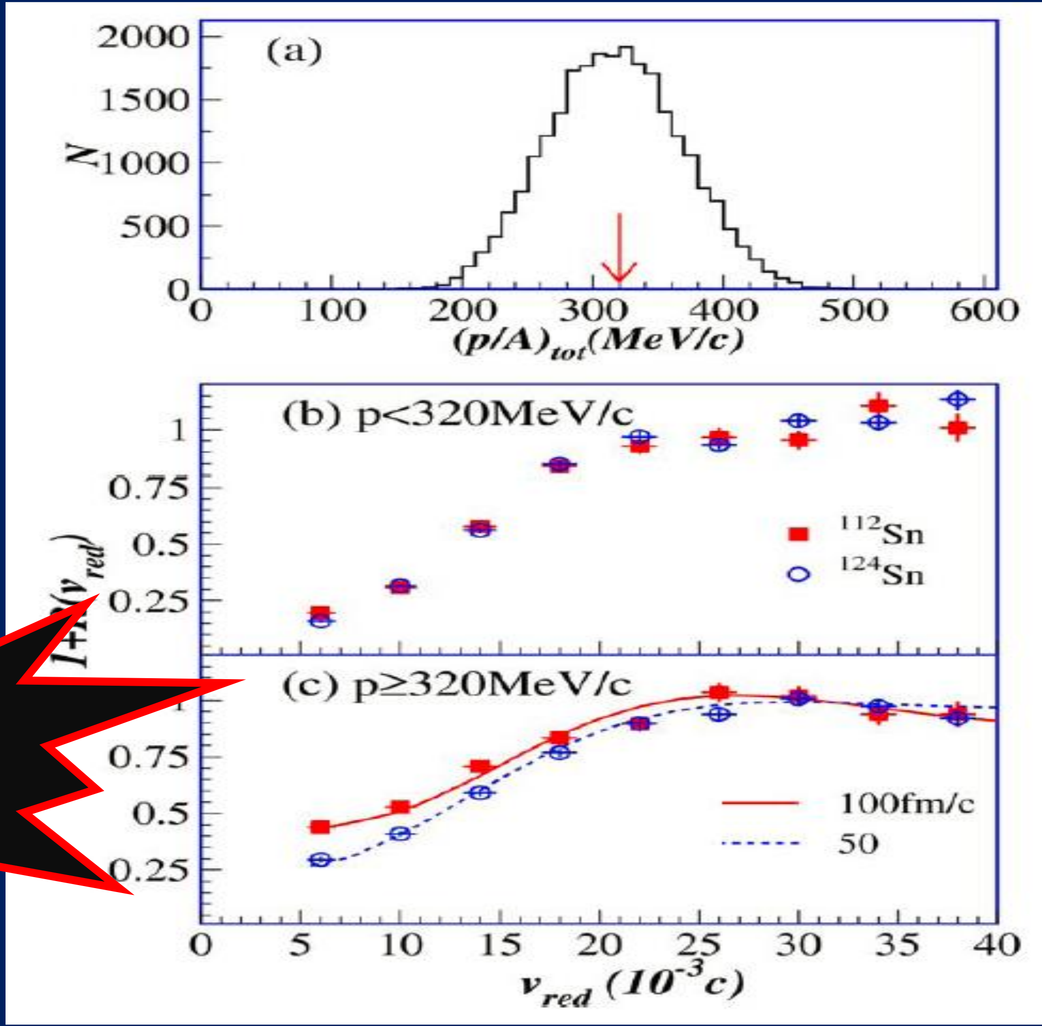




Experimental measurement of isospin dependent HBT correlation of IMF



~50 fm/c time resolution achievable



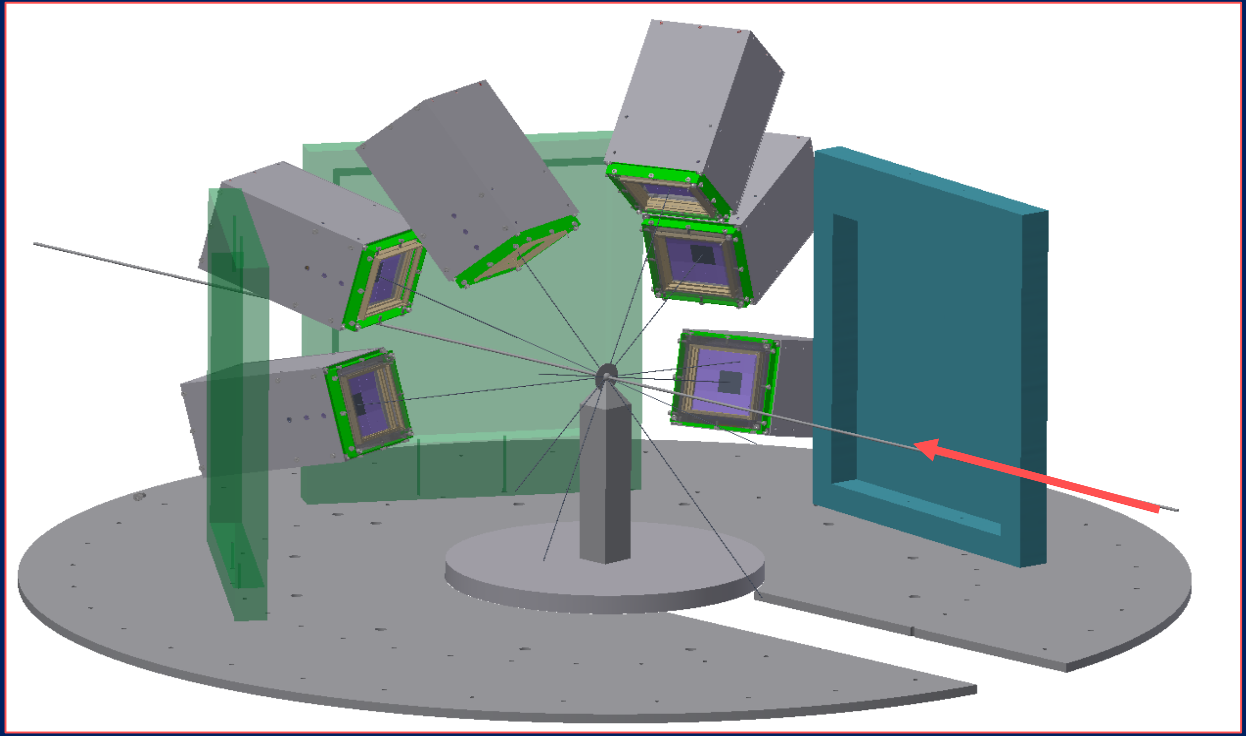
ZGX, R. J. Hu, H. Y. Wu et al., **PLB 639**,436 (2006) ; R. J. Hu, ZGX et al., **HEPNP 31**, 350 (2007)

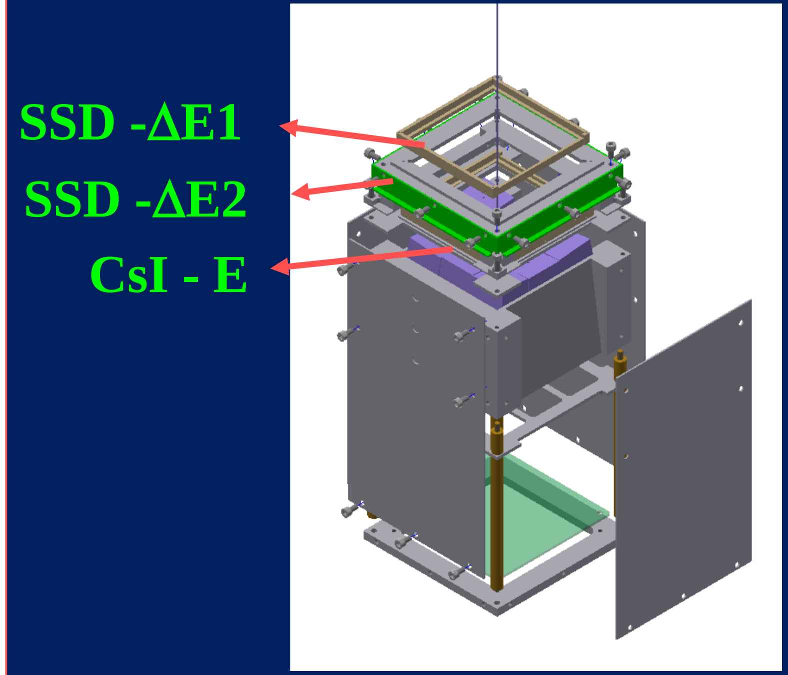
- Stronger Coulomb anti-correlation is observed in Ar+^{124}Sn , this difference arises from the isospin difference of the two system.

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

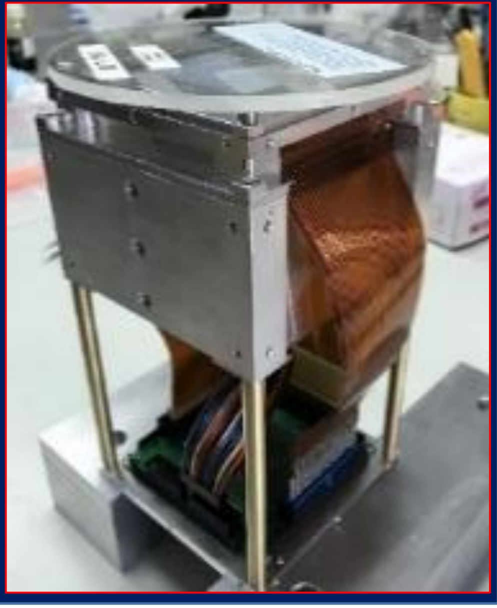
- **H**eavy **I**on **R**esearch **A**rray at **T**singhua **U**niversity **(HIRA^{TU})**

Build HIRA-type arrays + PPACs



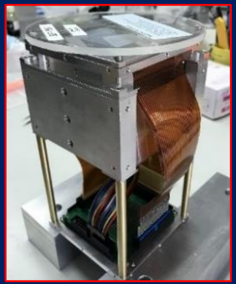
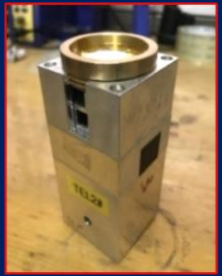
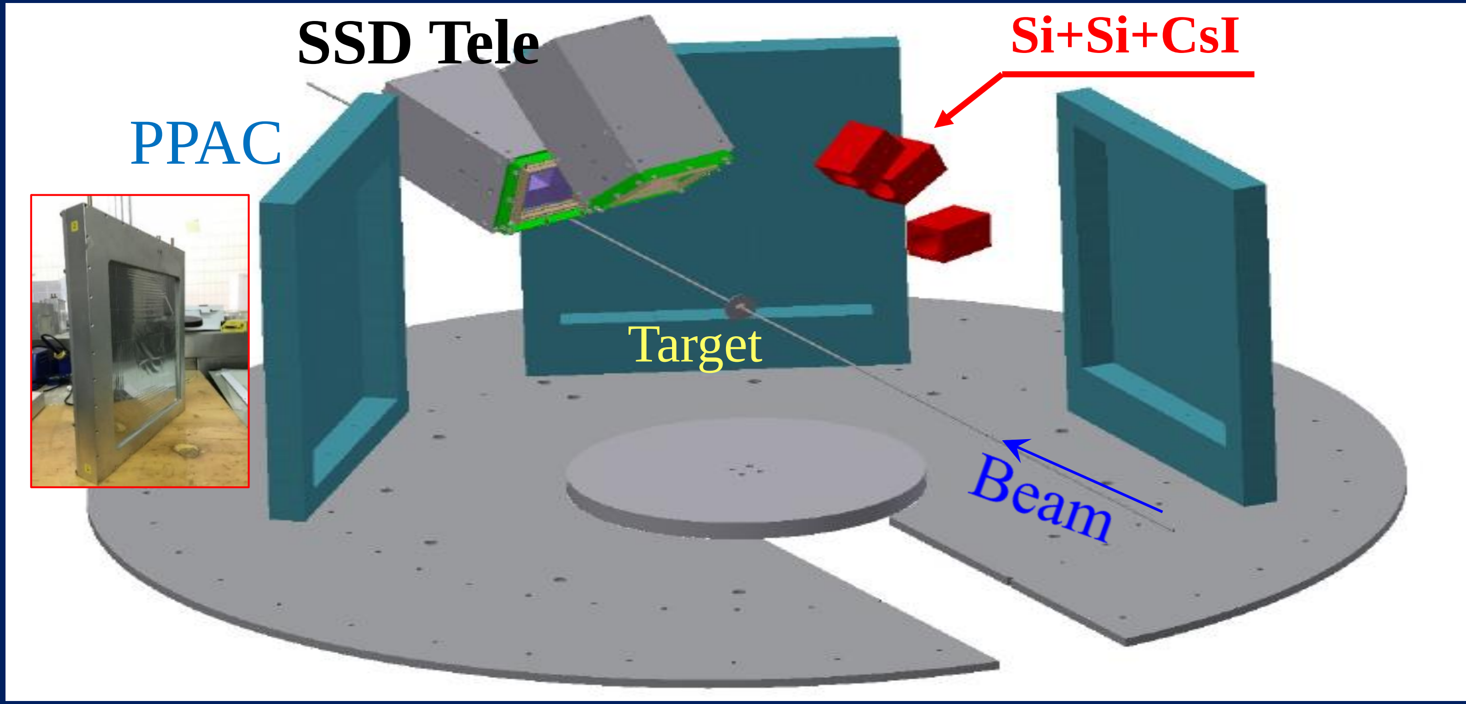


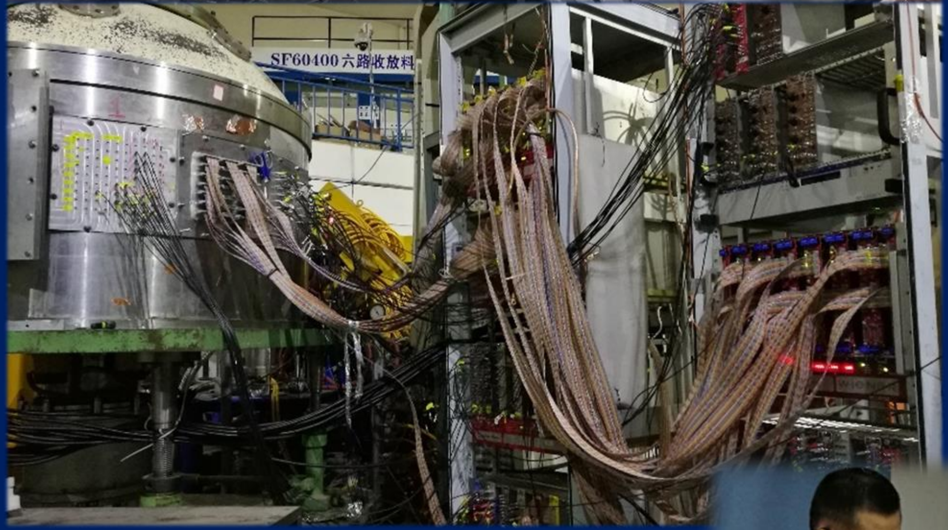
Hit position Resolution ~ 2mm



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) ✓

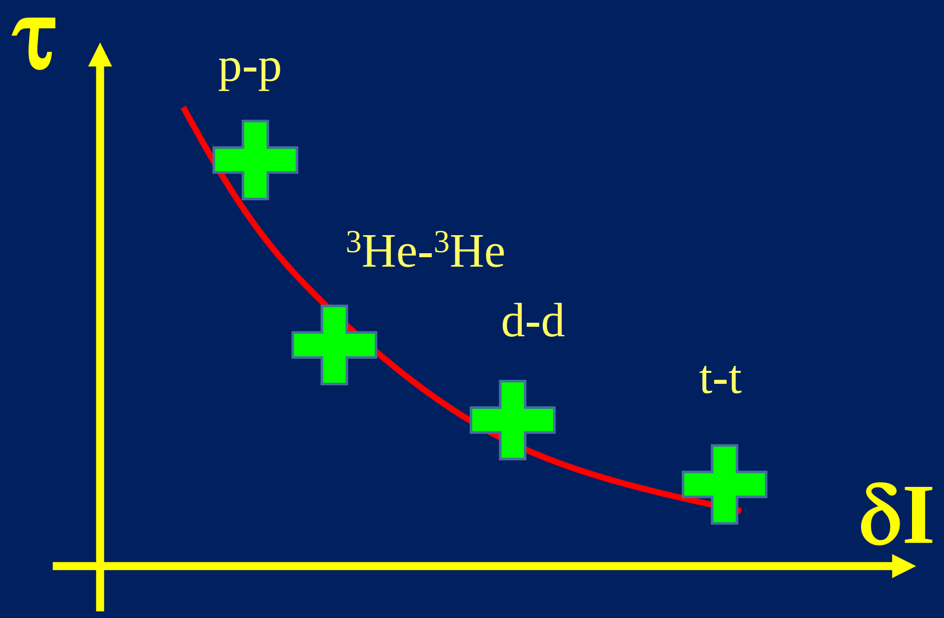



Beam time: 6-13 Feb., 2018;
Reaction: Ar+Au at 30 MeV/u;
Experiment at: RIBLL HIRFL

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

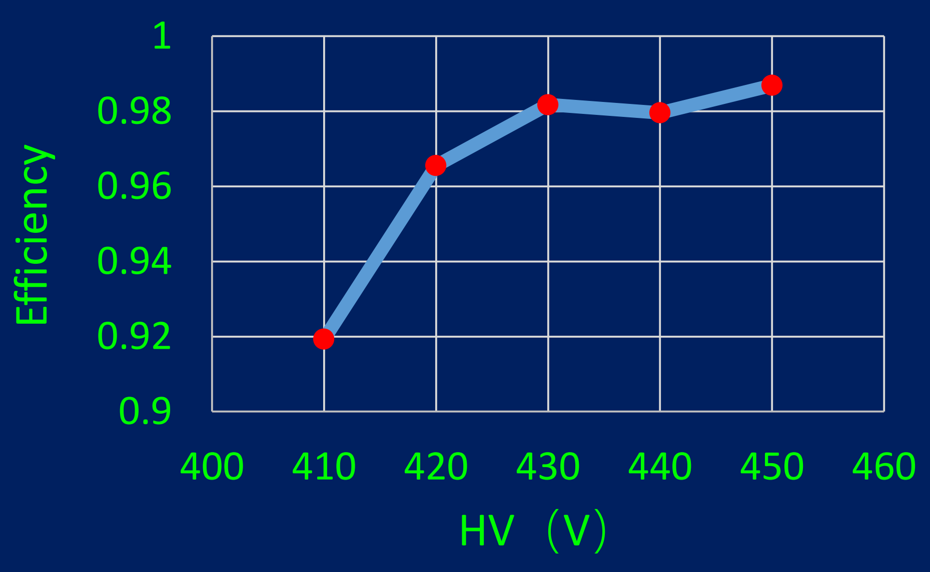
- Phase I Experiment: Isospin dependent of the particle emission time scale with HBT method.

First Physical goal: Isospin-resolved HBT

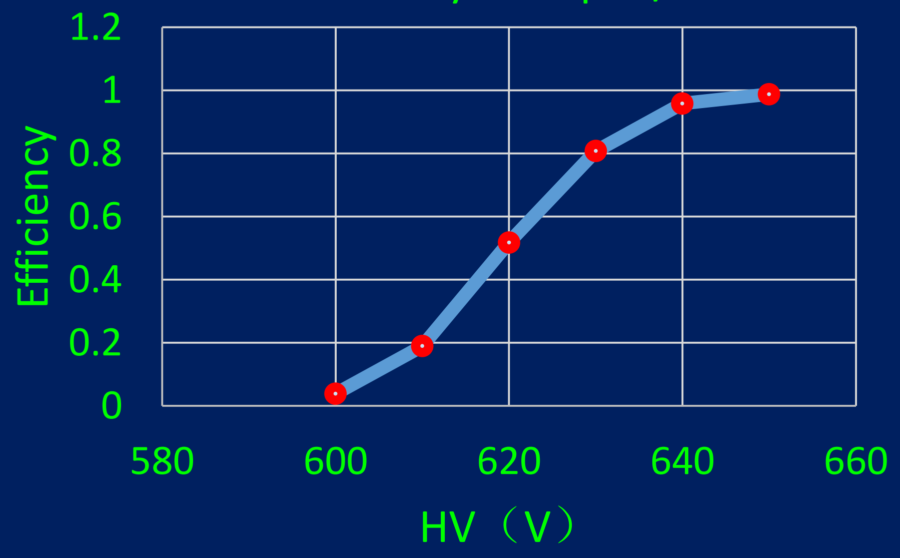


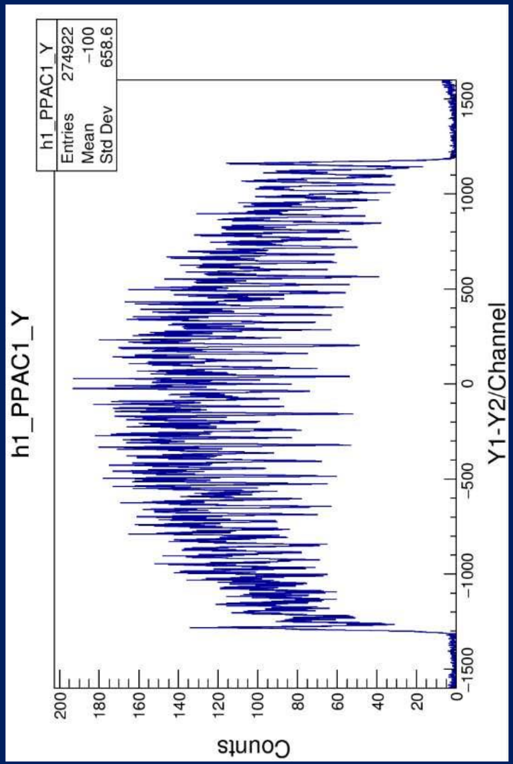
Performance of PPACs in beam experiment （30 MeV/u Ar+Au）

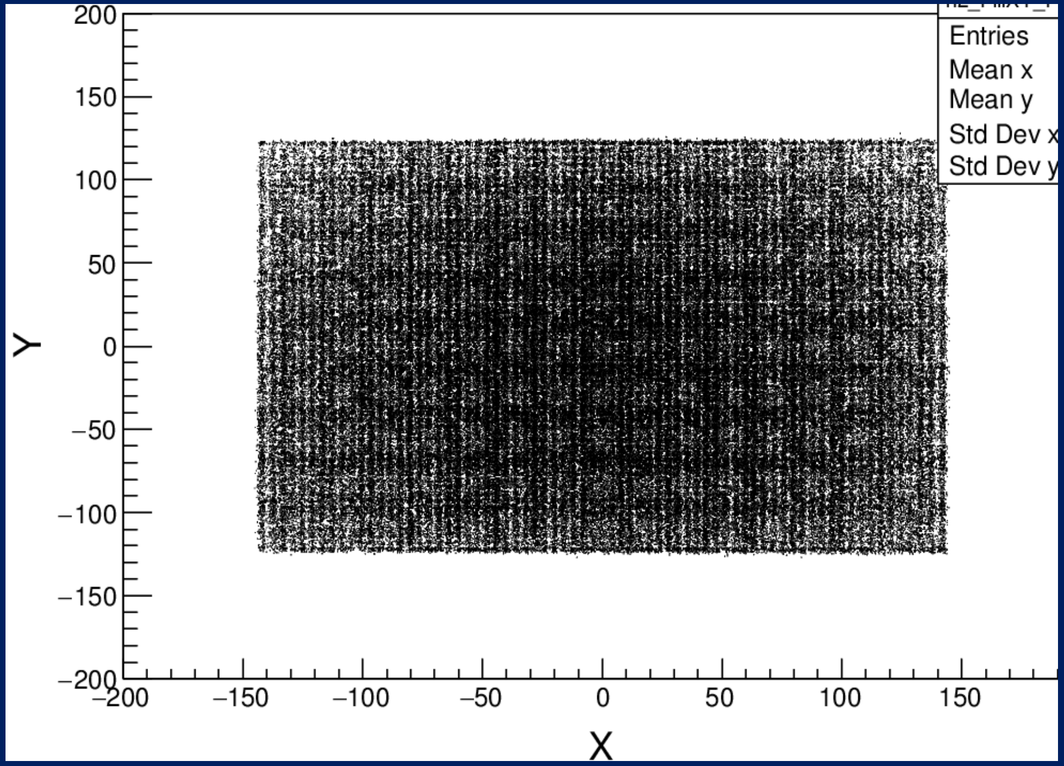
Efficiency for F. fragments/ Cf-252

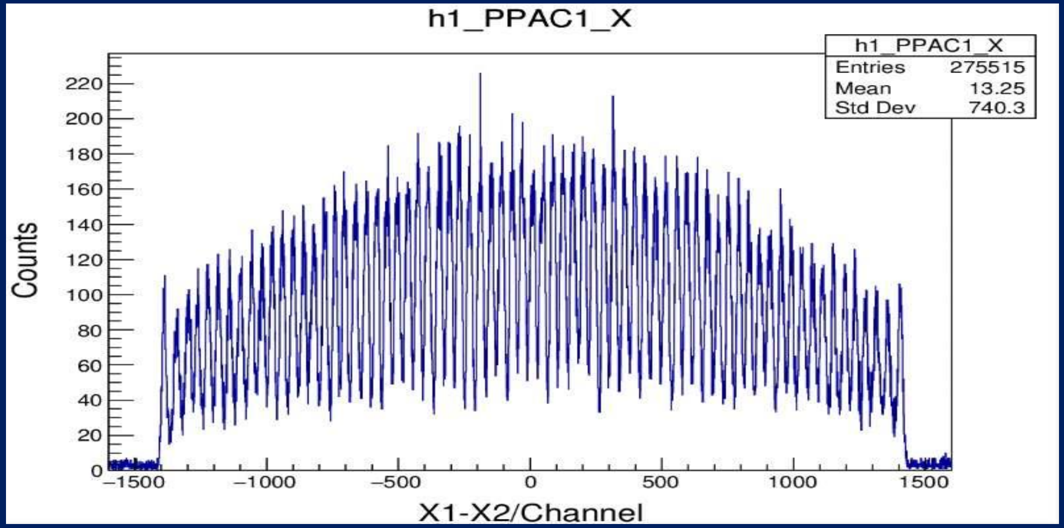


Efficiency for alpha/ Pu-239

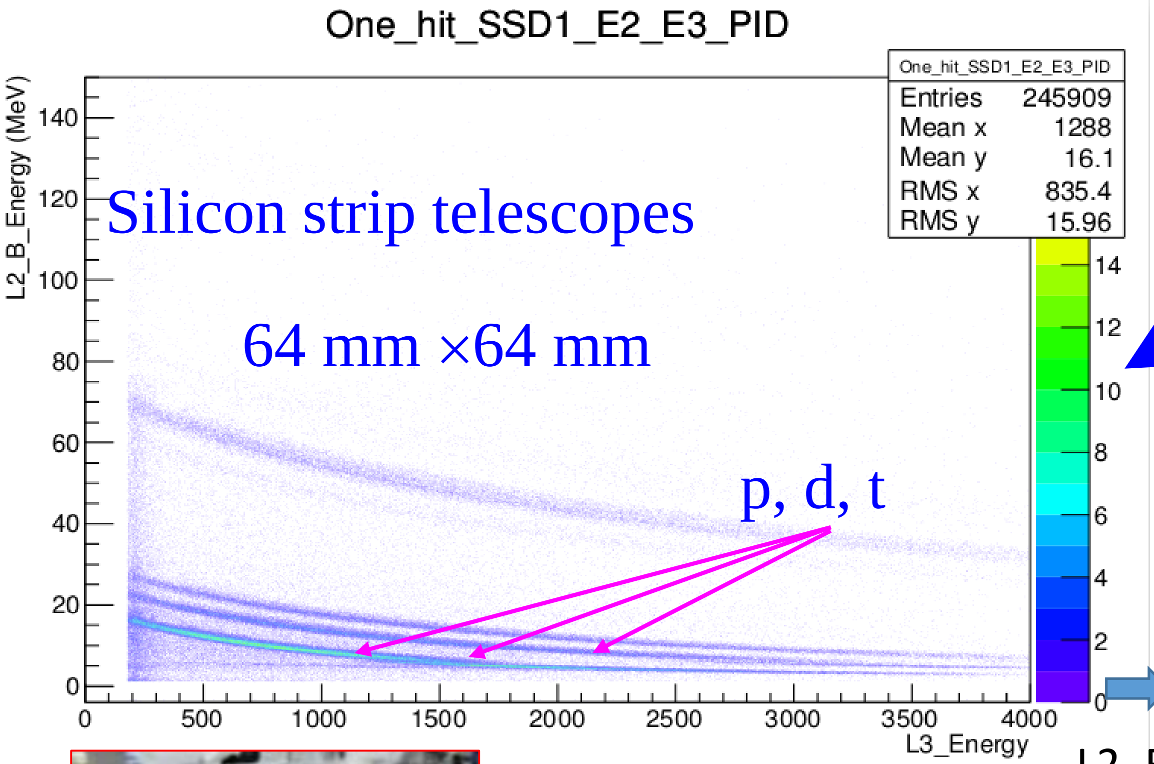


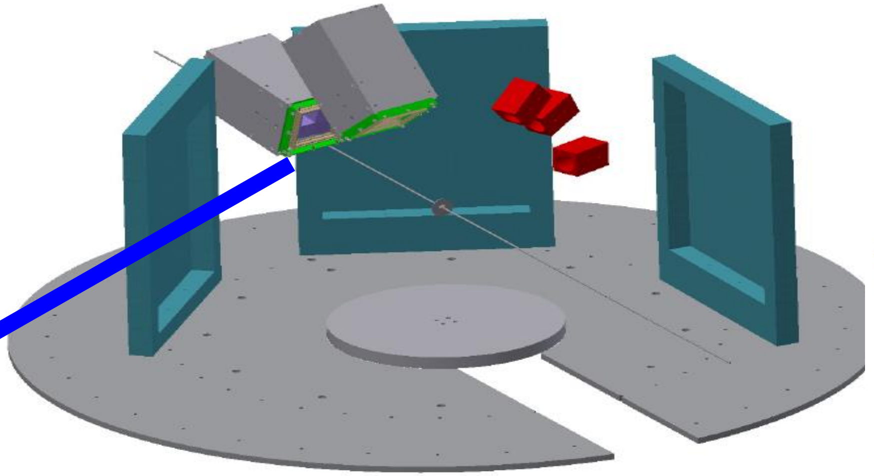


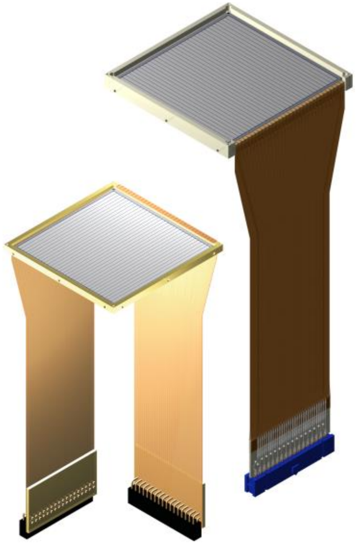


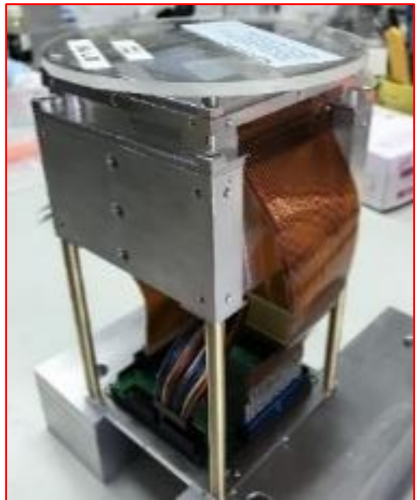


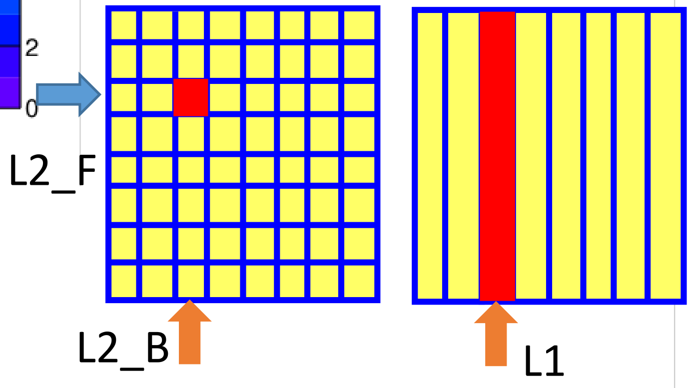
one LCP in coincidence with Fission

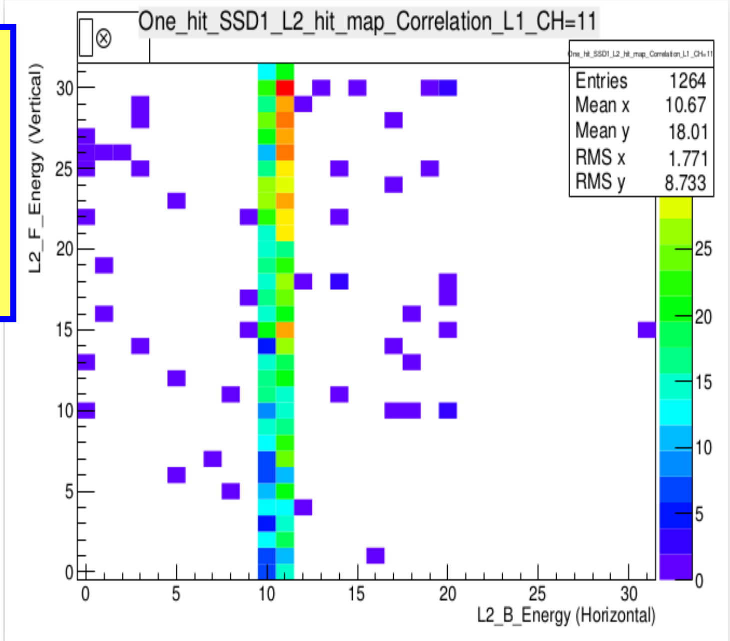






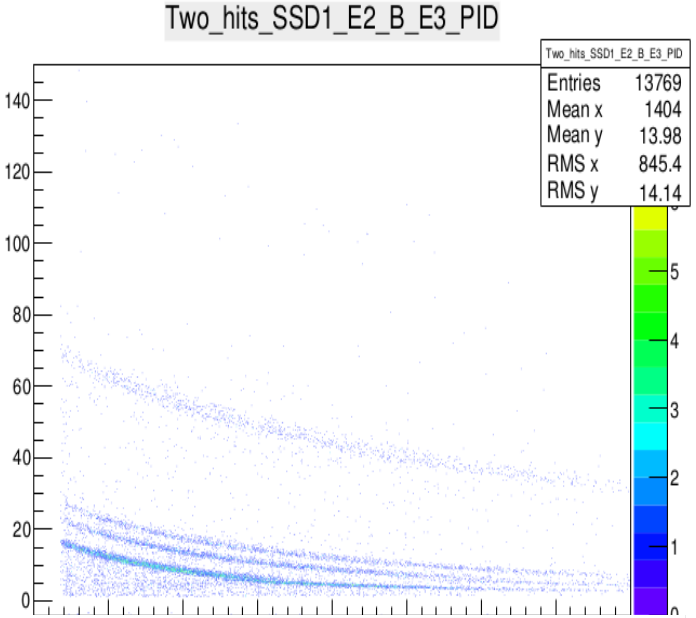


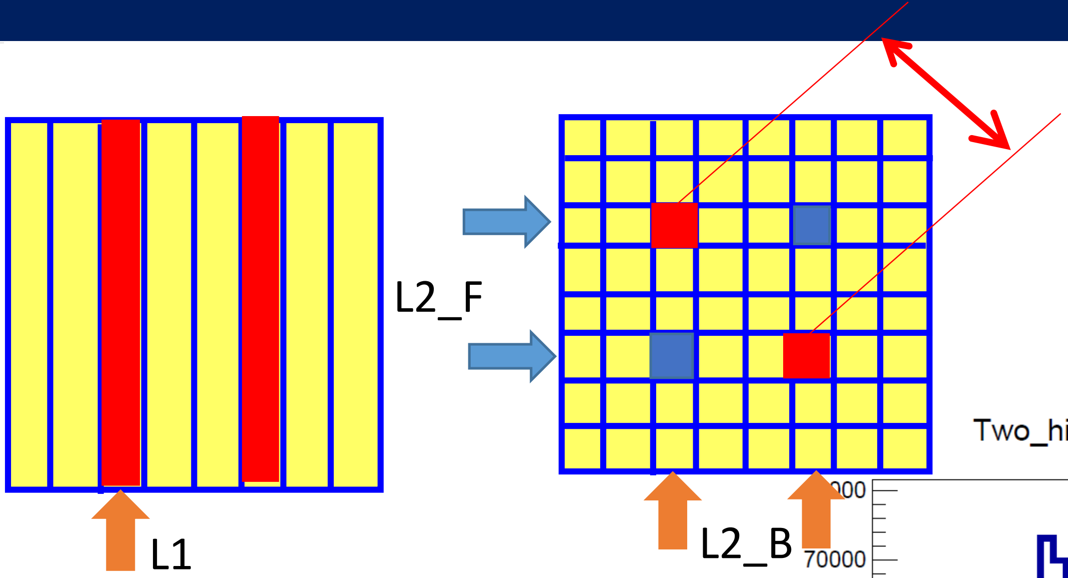


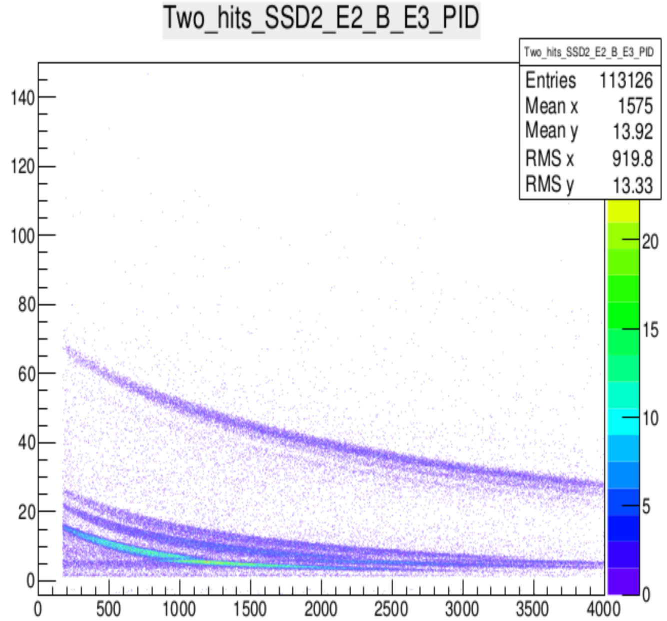


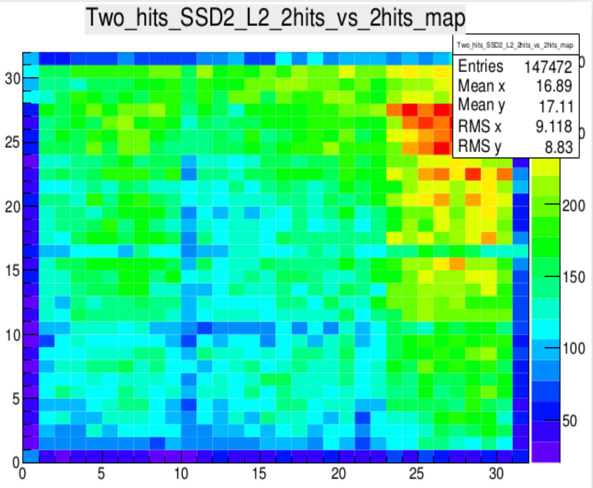
>98% matching efficiency of Layer 1 and Layer 2 of the SSD

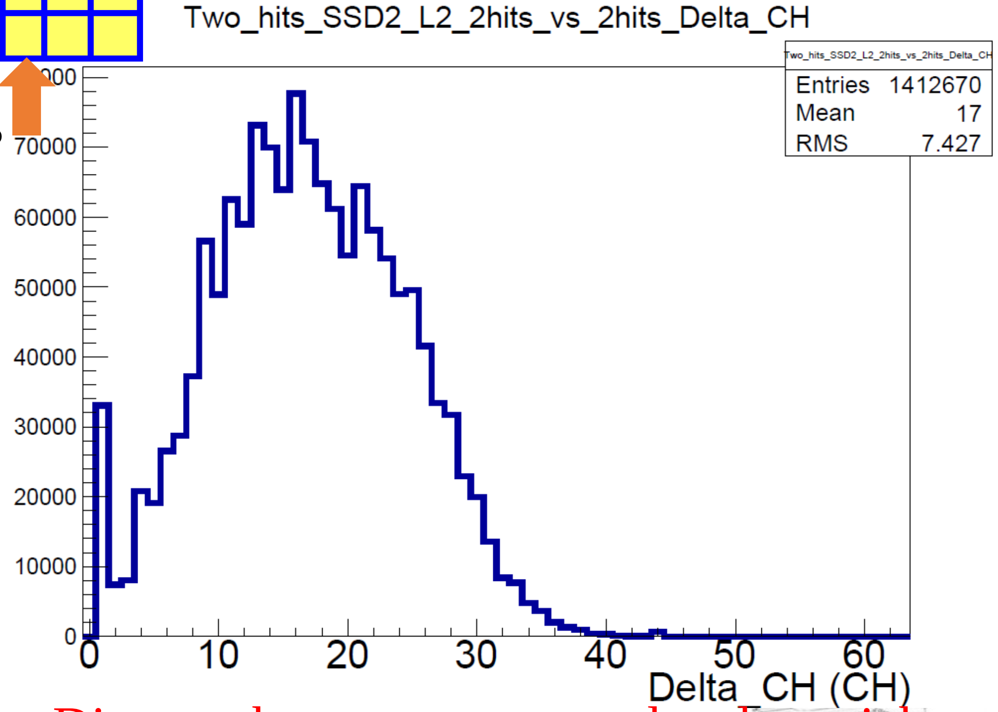
LCP-LCP correlation identified











Distance between two correlated particles

Physical output of phase 1 exp. is expected in near future!

清華大学物理系
TSINGHUA UNIVERSITY DEPARTMENT OF PHYSICS

4. Summary

Wealthy information of the transport of **isospin** DOF and **$E_{sym}(\rho)$** is contained in **HIC**.

The isospin-dependent **emission hierarchy** of light charged particles has been observed， showing neutron-rich LCPs are emitted earlier. Wide-range angular distribution of the relative neutron richness of the set a constraint on **$E_{sym}(\rho)$** with L=33-61 MeV at S_0=28.3 MeV （CL=95% ）

HBT method can be used for the quantitative assessment of the emission time and isospin dependent hierarchy of particle emission. HBT correlation function dependence on the system N/Z has been observed. With improving the detector performance, the Isospin **chronology** studies using HBT method is expected with **HIRA^{TU}**.

Thank you!

谢谢