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Isospin Dynamics in Heavy Ion Reactions and Constraining of Nuclear Symmetry Energy

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Outline

1 Introduction： Nuclear Symmetry Energy from Heavy ion collisions

2 Transport of Isospin DOF in HIC

2.1 Isospin Dependent Hierarchy of Particle Emission

2.2 Extraction of $E_{sym}(\rho)$

2.3 HIRA^{TU}： Isospin chronology study

3 Future： Isovector orientation effect of deuteron-induced reaction

4 Summary

Symmetry Energy as a function of density

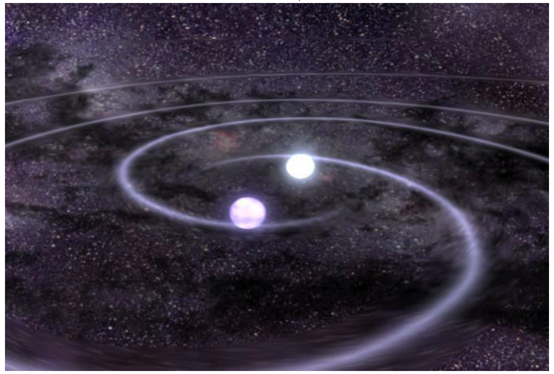
$$B(Z,A) = B_v + B_s + B_c + B_a + B_p$$
$$= a_v A - a_s A^{2/3} - a_c Z^2 A^{-1/3} - a_a (A/2 - Z)^2 A^{-1} + a_p \delta A^{-1/2}$$

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

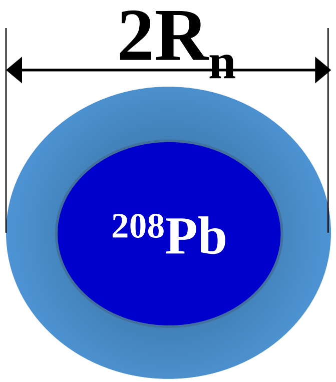
$$E(\rho,\delta) = E_0(\rho) + \delta^2 E_{sym}(\rho) = a_V + \frac{\kappa}{18}\varepsilon^2 + \frac{J}{162}\varepsilon^3 + \ldots + \delta^2\left(E_{sym} + \frac{L}{3}\varepsilon + \ldots\right)$$

κ:Compressibility

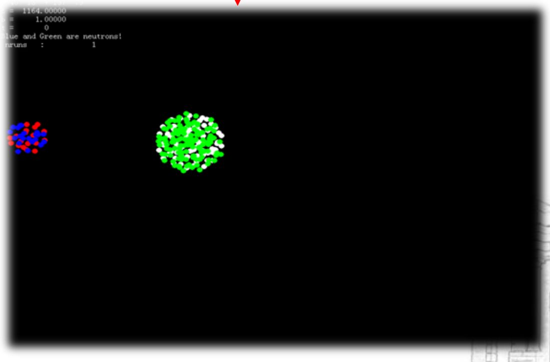
$E_{sym}(\rho)$



（Neutron Star and NS Merge）



（Static or Resonant Properties of Nuclei）

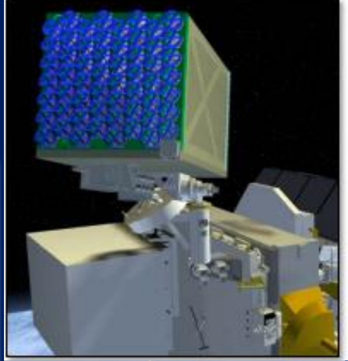


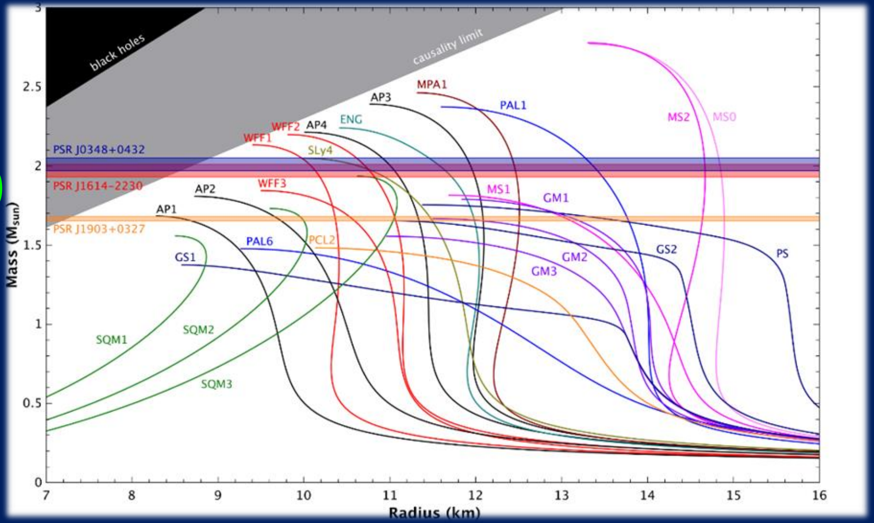
（Heavy Ion Collisions）

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

Neutron Star Observatory:

Neutron Star Interior Composition Explorer (NICER)

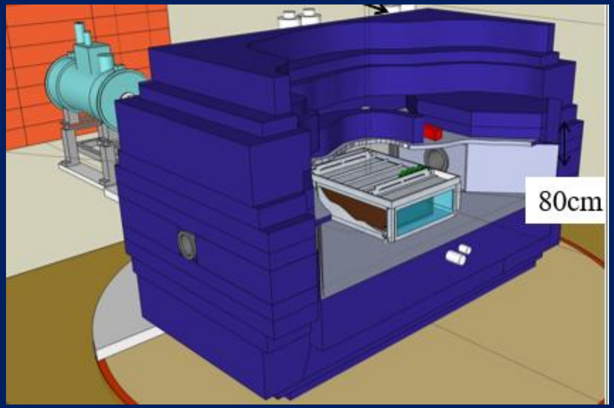


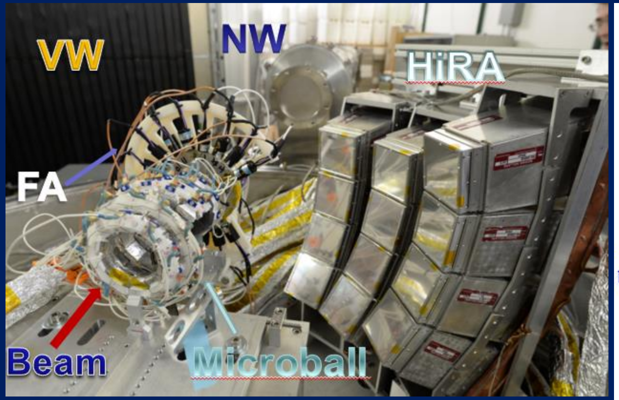


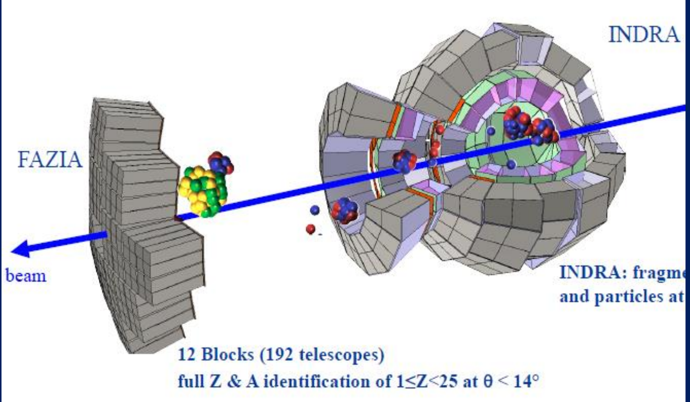
To Constrain EOS of nuclear matter through precise M and R measurements of several neutron stars.

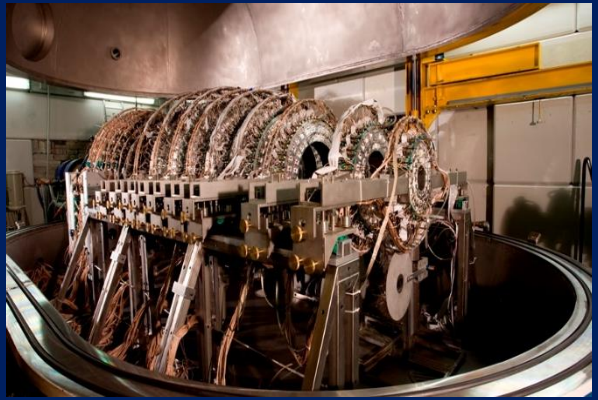
HI accelerator and RIB facilities:

SAMURAI-TPC@RIKEN **HIRA@NSCL，MSU** **INDRA@GANIL** **CHIMERA @ INFN**



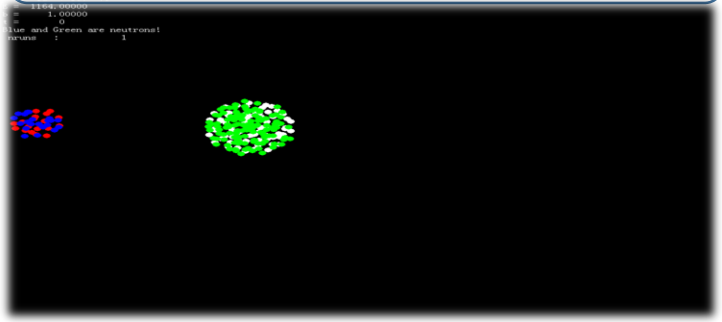


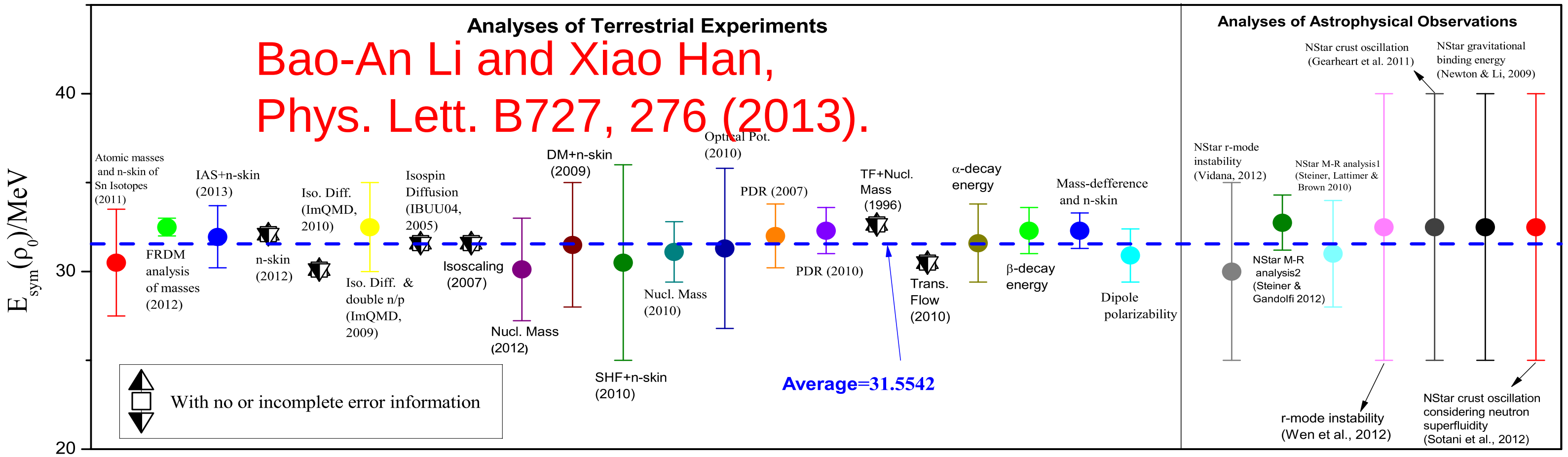


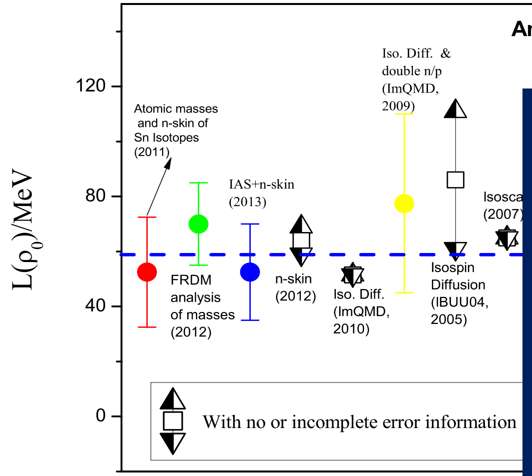


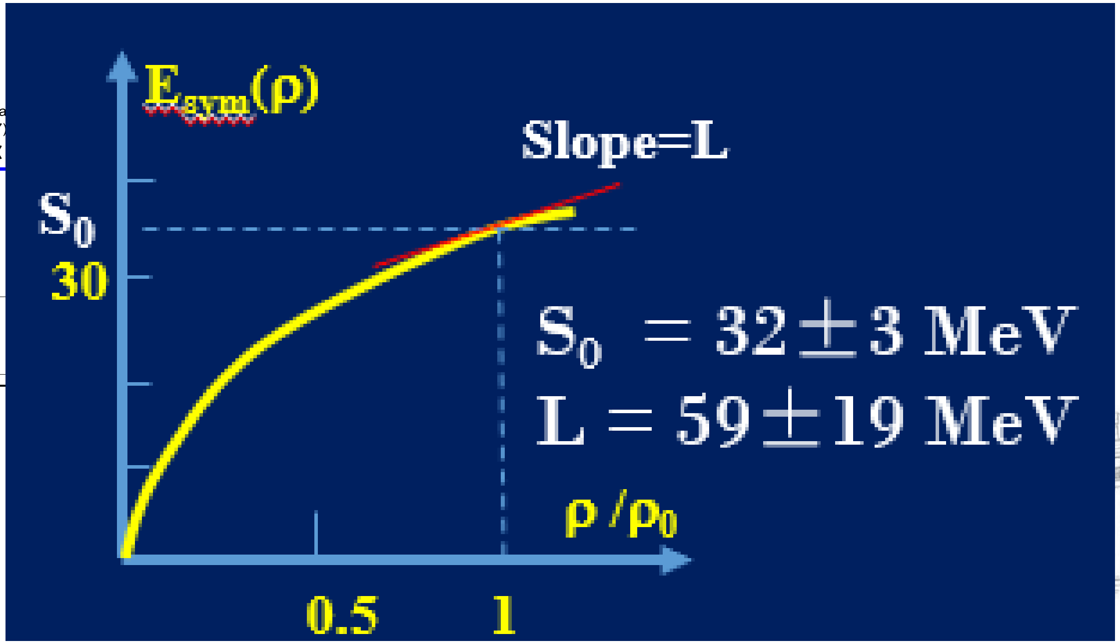
Isospin transport and the constraint of $E_{sym}(\rho)$

At sub-saturation densities









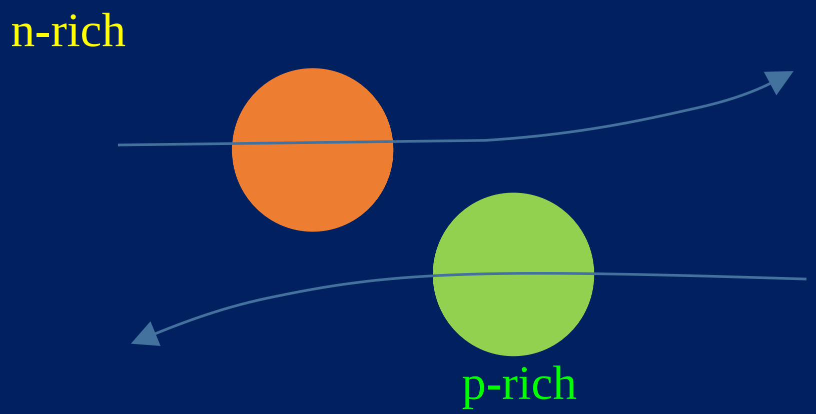
List extends:

- → 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 …)
- → …. ….

Symmetry Energy and isospin transport in HIC

Mechanisms governs the transport of IDOF in nuclear collisions:

1. Isospin Diffusion ：

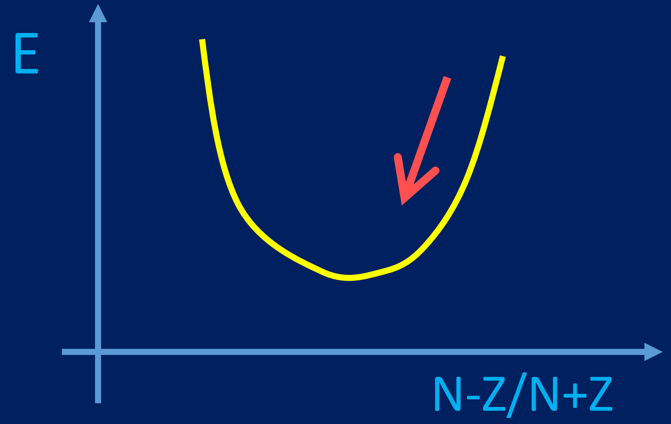


$$\boldsymbol{j}_{\mathrm{np}} = \boldsymbol{j}_n^I - \boldsymbol{j}_p^I = -\left(\boldsymbol{D}_n^I - \boldsymbol{D}_p^I\right)\nabla \boldsymbol{I}$$

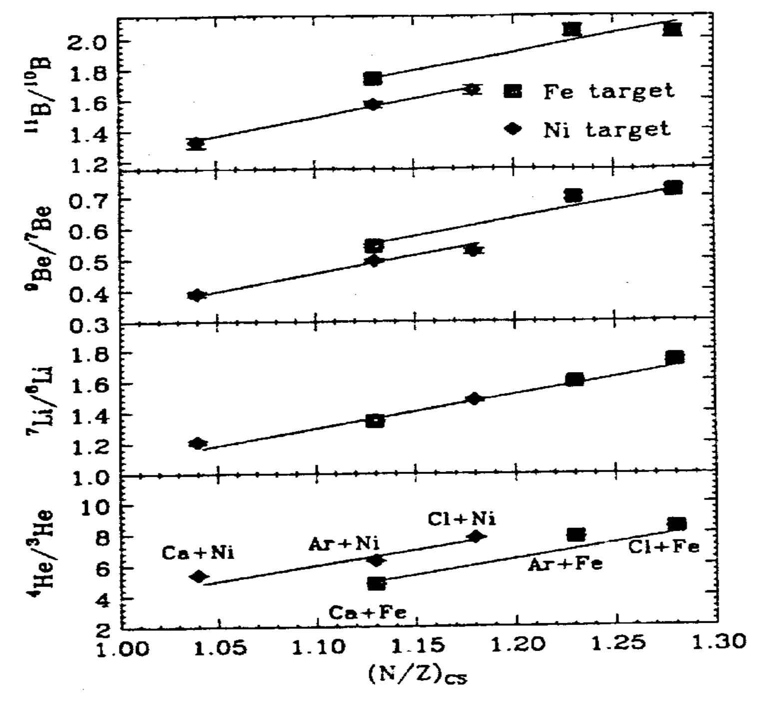
$$\boldsymbol{D}_n^I - \boldsymbol{D}_p^I \propto 4\boldsymbol{\rho}\boldsymbol{E}_{sym}(\boldsymbol{\rho})$$

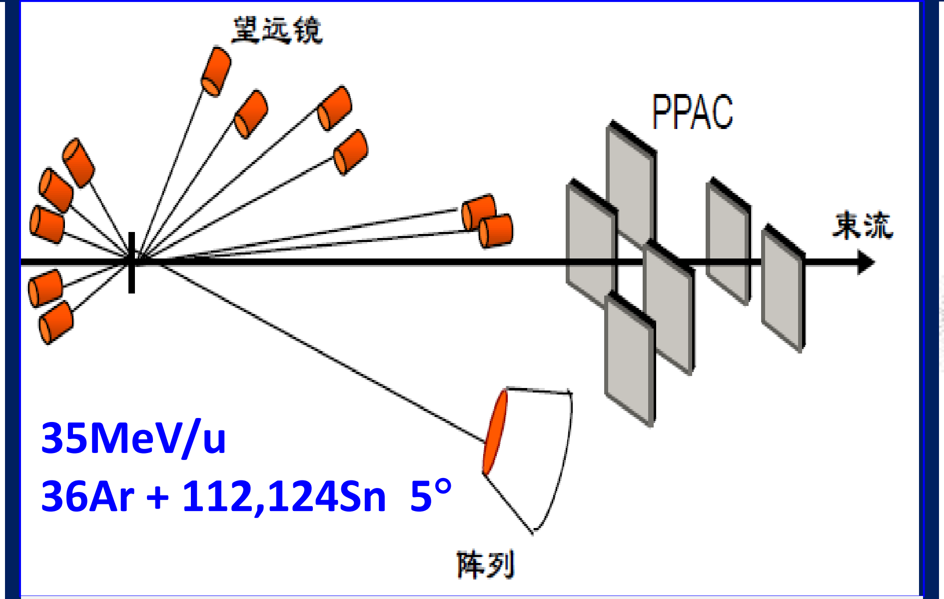
Likely terminated when P-T separated.

A everyday-life analog of isospin diffusion

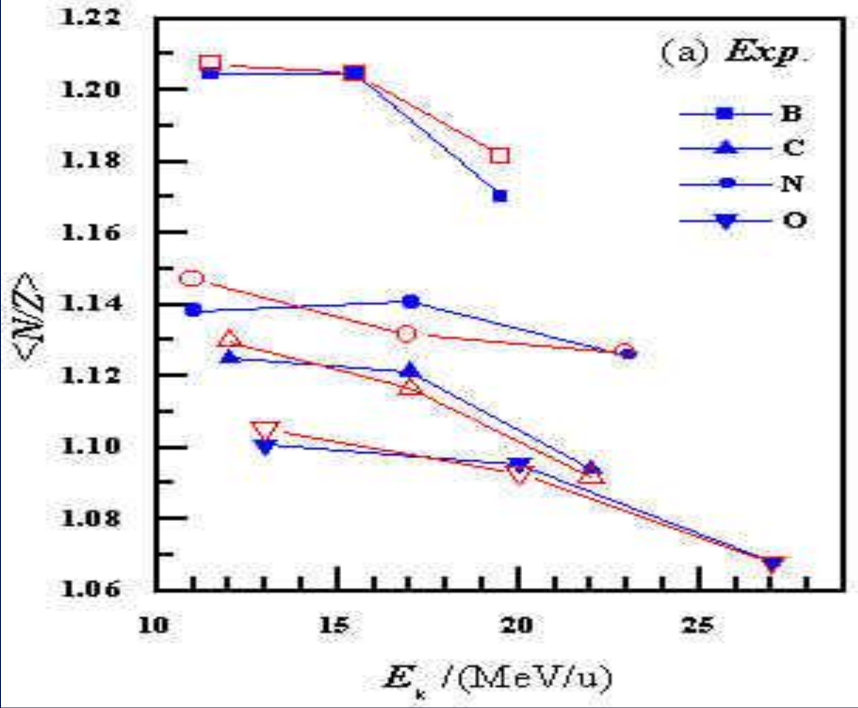


Isospin Diffusion





H. Y. Wu， ZGX, et al.**PLB 538** (2002) 39



→Bao-An Li et al., **PRC 57**, 2065 (1998).
→ S. Yennello et al., **PL B 321**, 15 (1994).
→ LW Chen et al., **JPG 23**, 211 (1997).
→ ZY Sun et al., **PRC 82**, 051603 (2010).

Using the kinetic of the p-like residues as a clock, We found that,
→in Peripheral collision, N/Z of the projectile increases with lowering the kinetic energy， showing the transport process of IDOF.

Confirmed in later experiments：
G. A. Souliotis et al., **PRC90**, 064612 (2014).
G. A. Souliotis et al., **PLB588**, 35 (2004).

VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

Isospin Diffusion and th

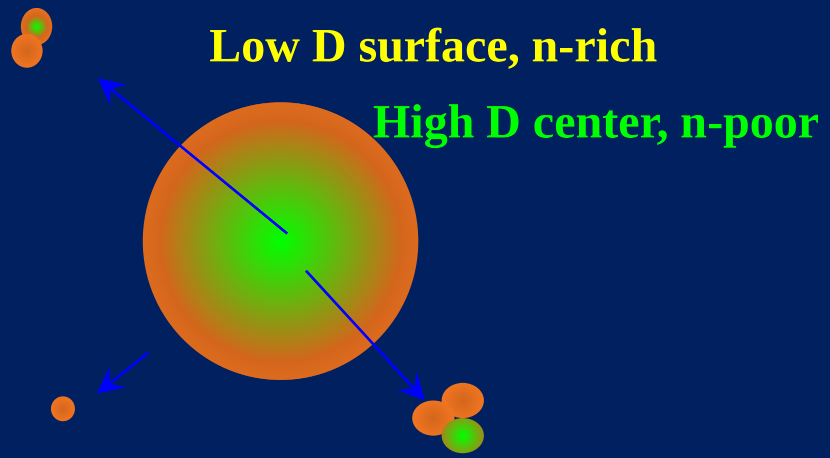
M. B. Tsang, T. X. Liu, L. Shi, P. D

B. Tsang et al., PRL 2004,
Report of isospin diffusion and $E_{sym}(\rho)$

Symmetry Energy and isospin transport in HIC

Mechanisms governs the transport of IDOF in nuclear collisions (II)

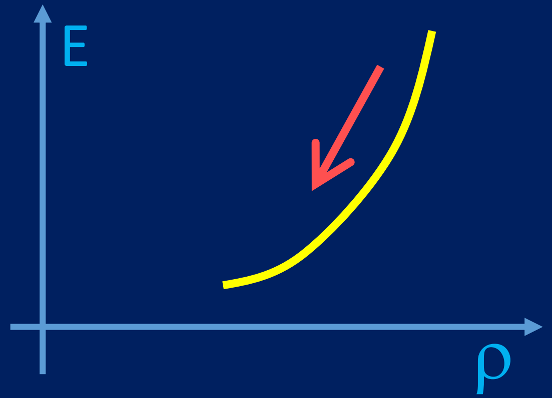
2. Isospin Drift：



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

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

Likely persists for longer time.



A everyday-life analog of isospin drift

What is our Motivations with HIC?

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

→ Neck Emission in Fission reactions is characterized by low density and neutron-richness.

→ Transport of isospin degree of freedom (IDOF) involving the neck emission helps to identify a probe.

2) To measure quantitatively the time scale of the transport of IDOF.

3) To develop new method to pin down the $E_{sym}(\rho)$ （$\rho<\rho_0$）.

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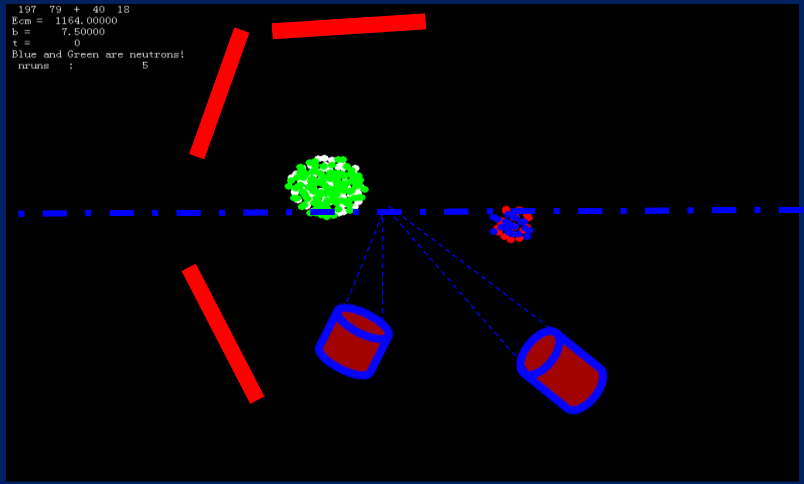
4 Summary

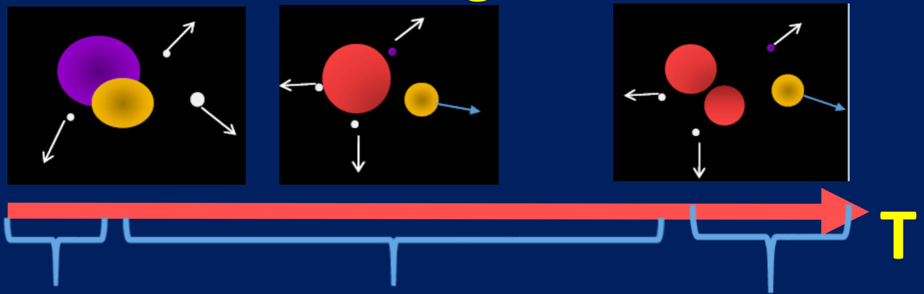
2.1 Isospin Dependent Hierarchy of Particle Emission

35 MeV/u Ar+ Au.

Trigger: 2 fission fragments .AND. 1 LCP

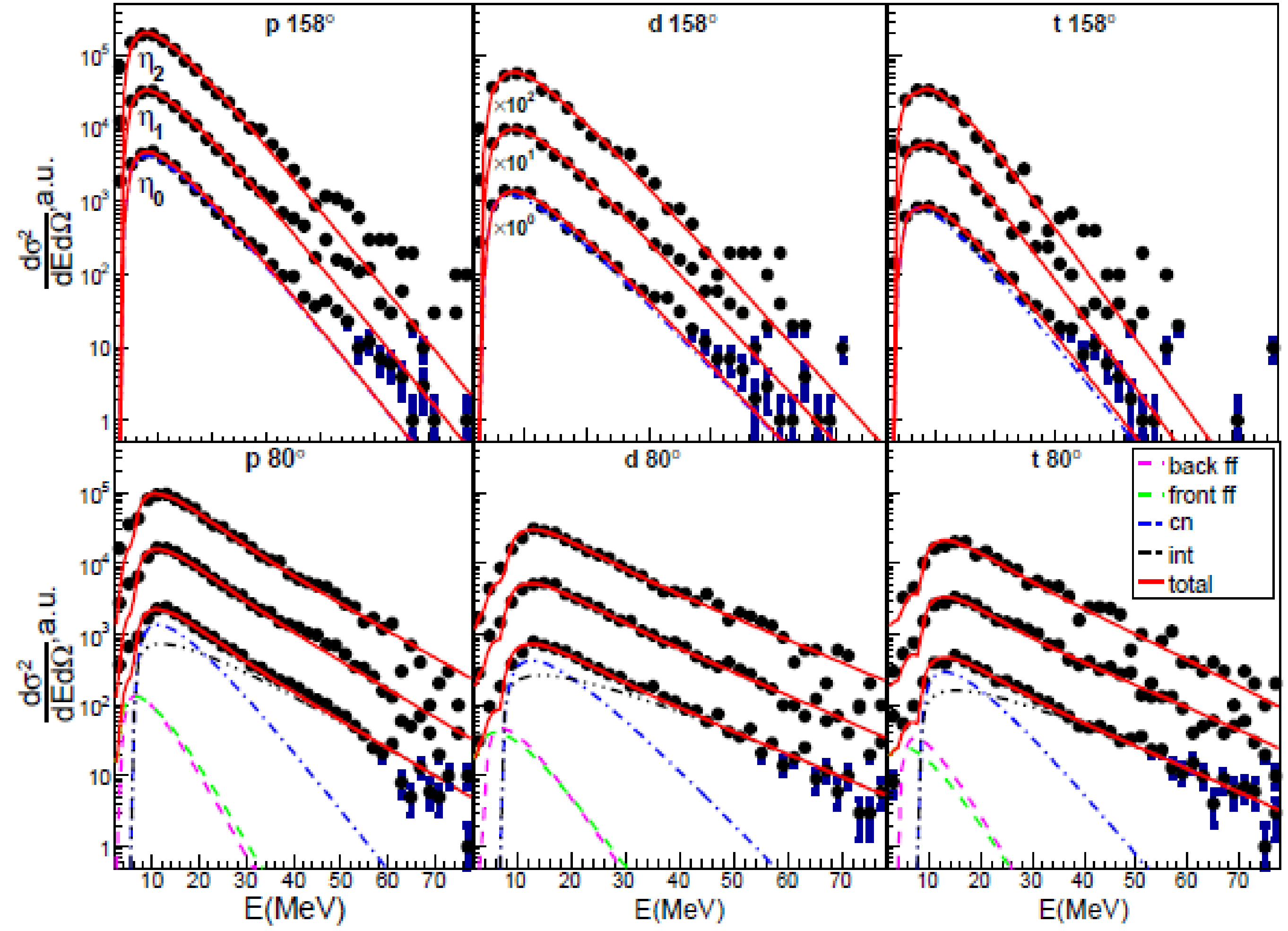


- Three Moving source:

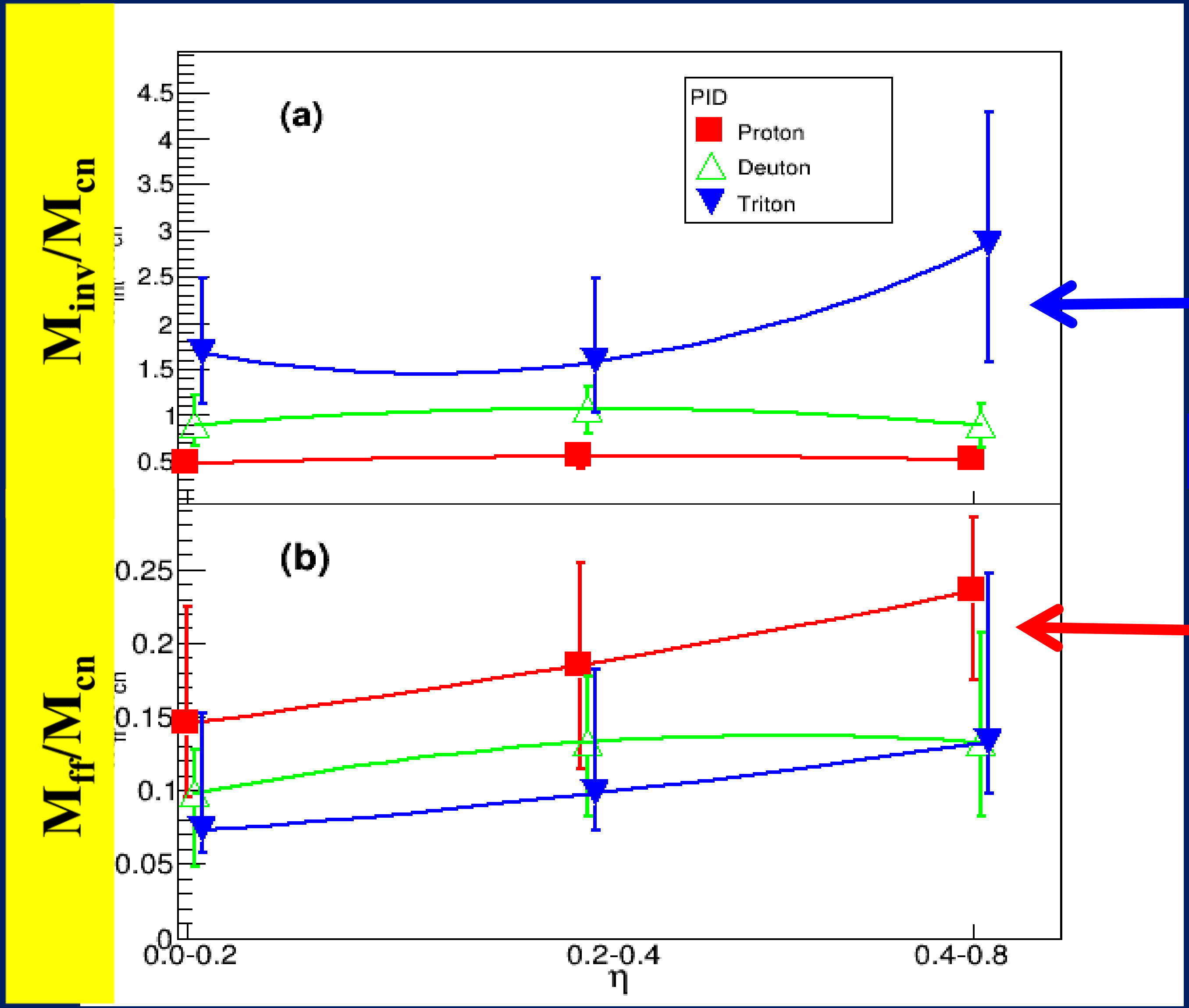


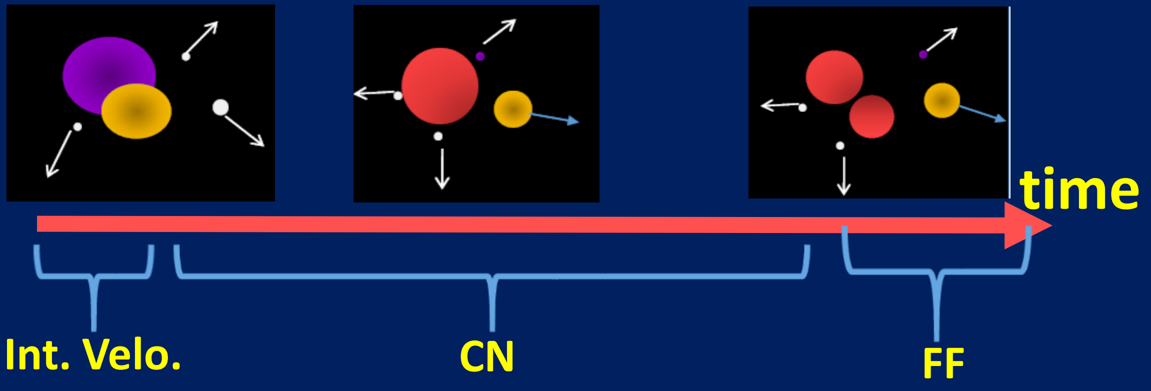
Inter. Velocity **CN** **Fiss. Frag.**

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



Multi moving source analysis





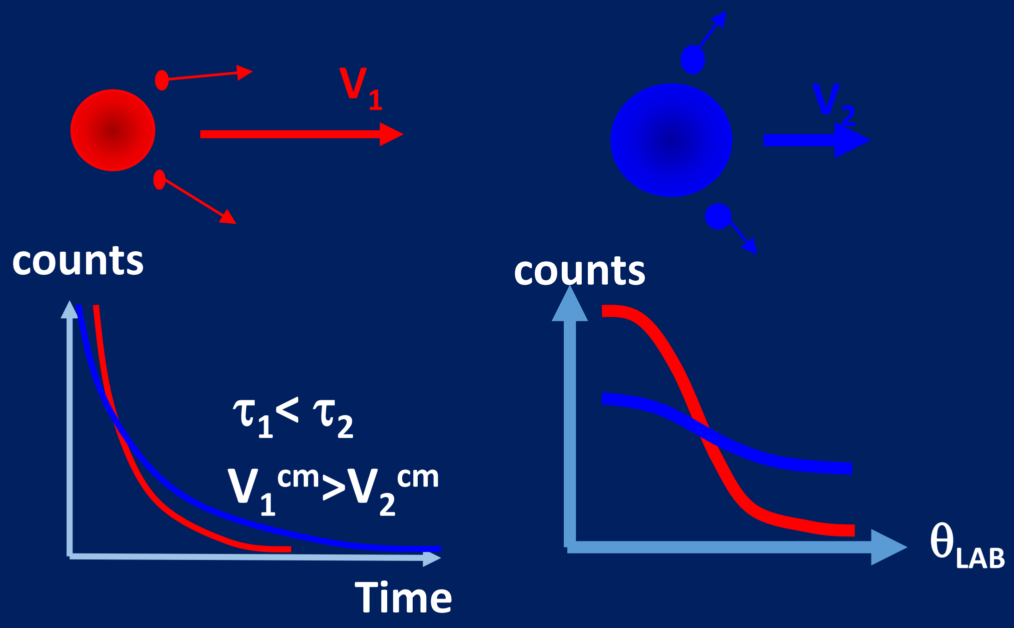
More triton emission

More proton emission

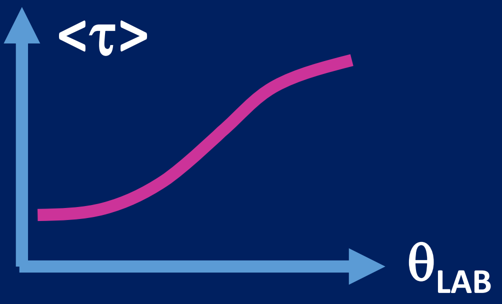
A isospin-dependent hierarchy of particle emission is observed.

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

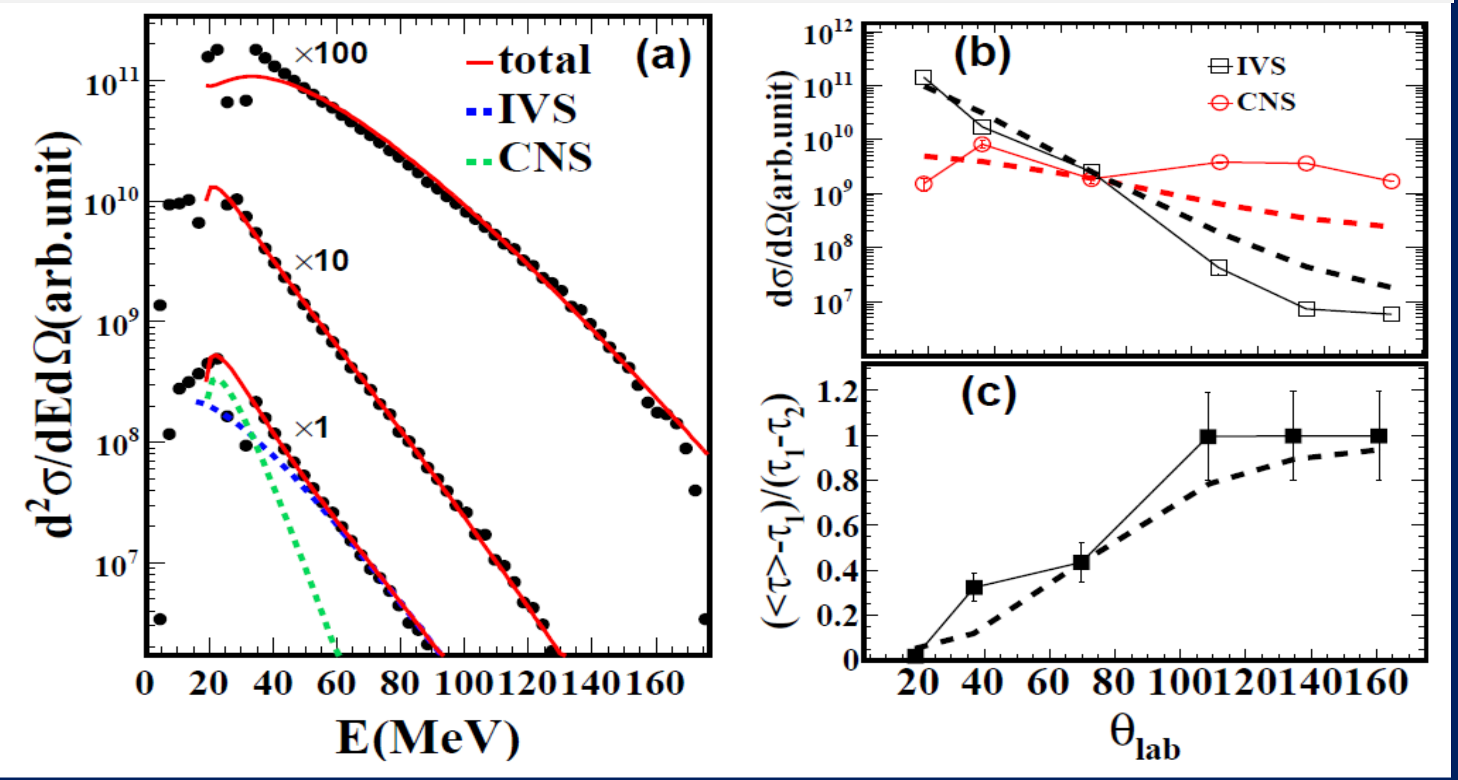
2.2 Long-time feature of isospin drift



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



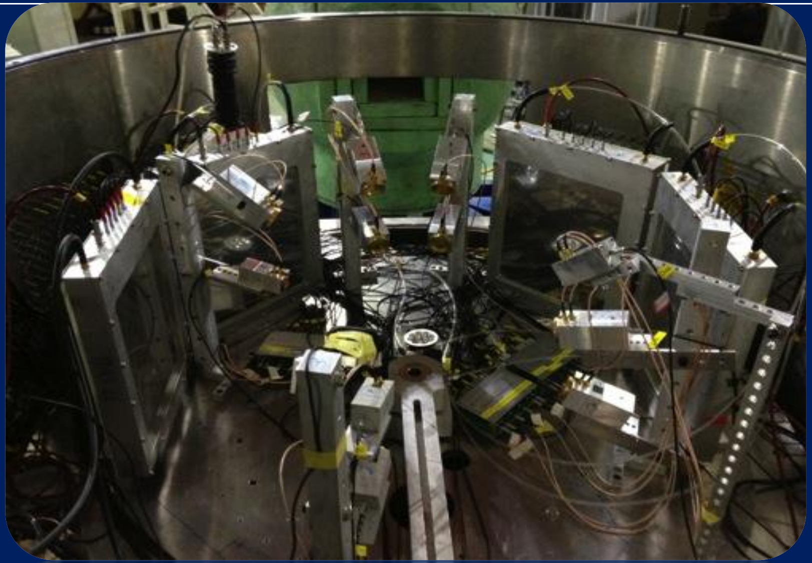
30 MeV/u Ar+Au @ RIBLL, HIRFL, Lanzhou



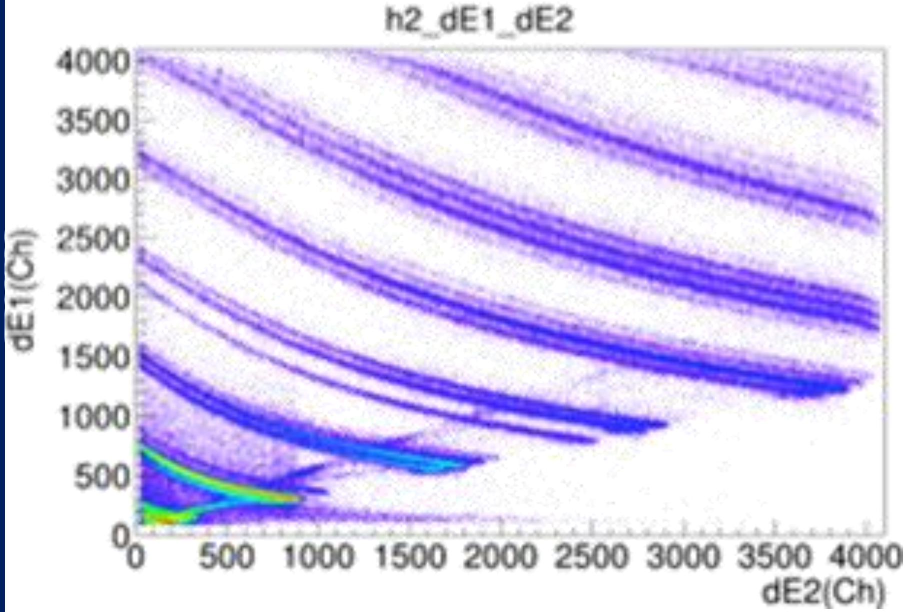
→ moving-source analysis indicates that a qualitative relation between angular distribution and the average emission time exists

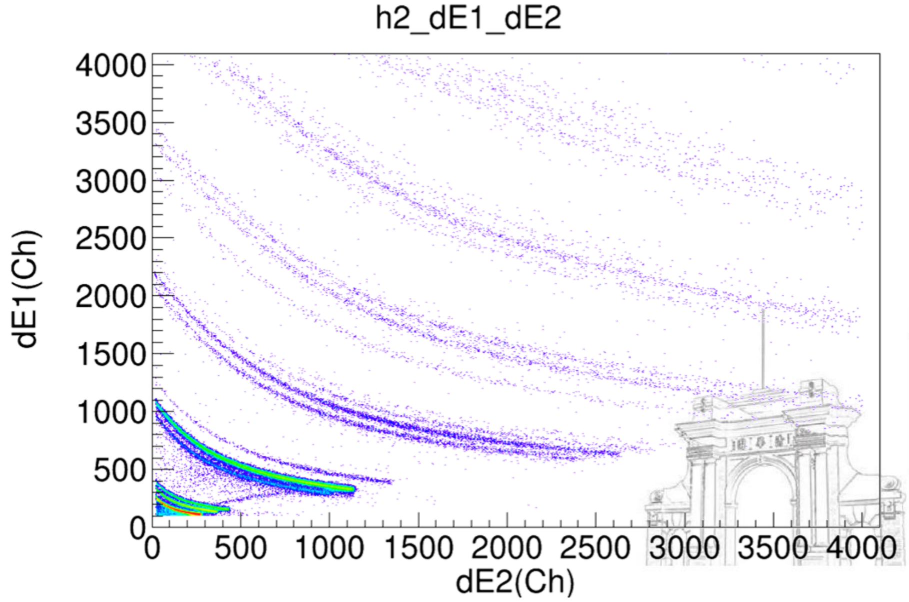
→ The relationship shall holds, even though the real process is more complex.

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



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





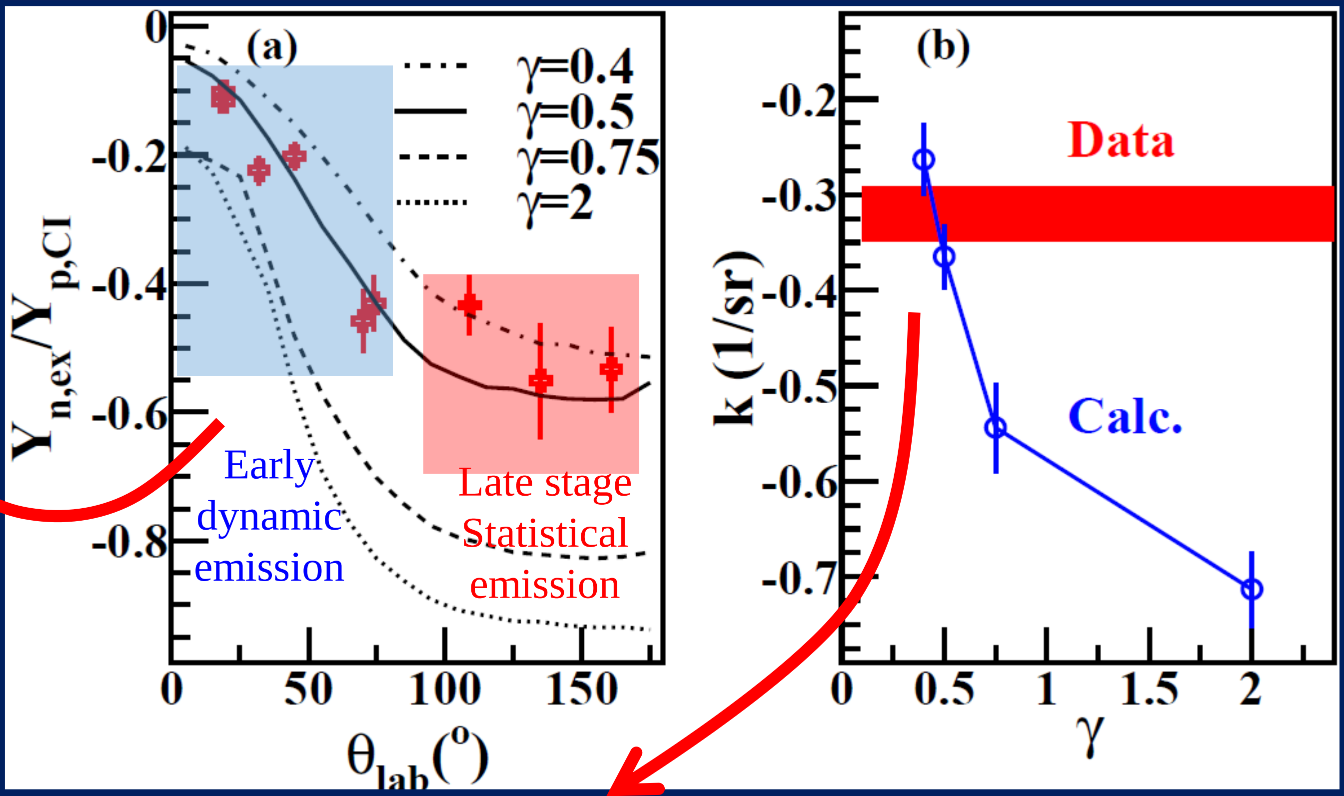
Telescope	Silicon1 (μm)	Silicon2 (μm)	CsI(cm)	Position (θ,φ)
Telescope1#	150	200	2*2*3	(37,69)
Telescope2#	75	200	2*2*3	(19,39)
Telescope3#	75	200	2*2*3	(19,39)
Telescope4#	50	200	2*2*3	(45,170)
Telescope5#	30	200	2*2*3	(74,39)
Telescope6#	50	300	1.5*1.5*2	(70,13)
Telescope7#	25	300	1.5*1.5*2	(161,37)
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） Isospin drift is long time process, persisting from early dynamic emission to late statistical emission



GO Potential Fit:
L=53±23 MeV
PRC 82, 054607 (2010)
Proton Emission:
L = 52 ± 7 MeV
PRC 94, 044322 (2016)
GW170817 QMF18:
L= 40 MeV
APJ, 862,98 (2018)
H. Sagawa et al., :
L= 42 ± 14
Custipen 2019
H. Shen et al., TM1e
L=40 MeV

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

2）$E_{sym}(\rho)$： γ=0.46±0.025（STDEV）
L=47±14 MeV （CL=95%）
with S_0 fixed at 28.3 MeV.

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

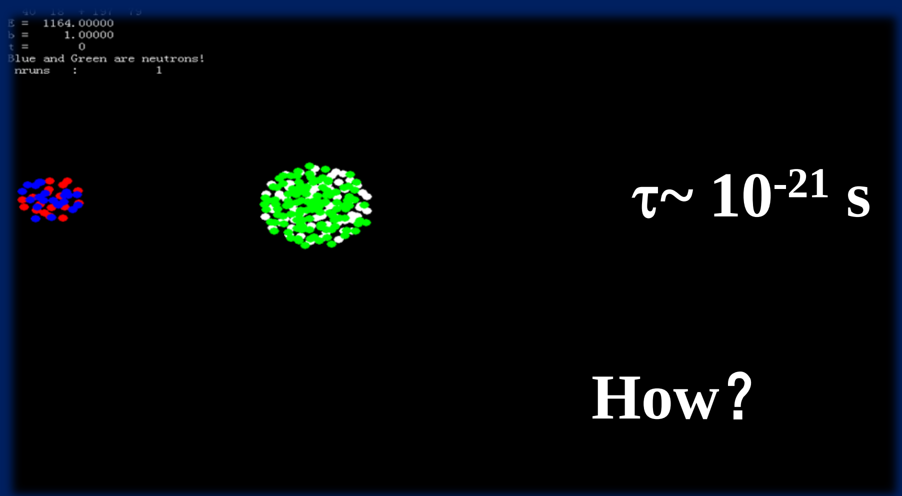
2.3 HIRA^{TU} : Isospin Chronology

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

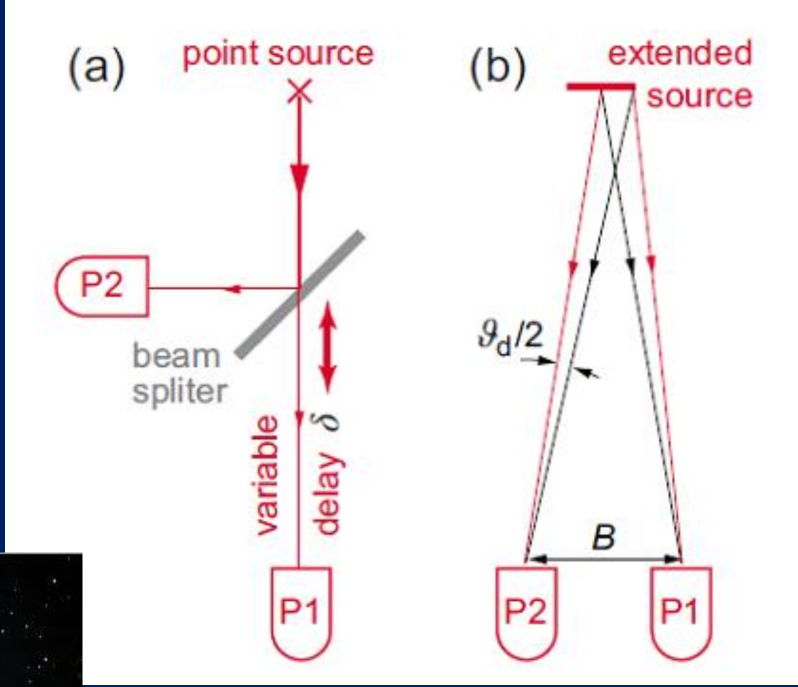
- **Isospin Chronology:** A chronology is an account or record of the times and the order in which a series of past events took place.

10^{-2} s

10^{-21} s

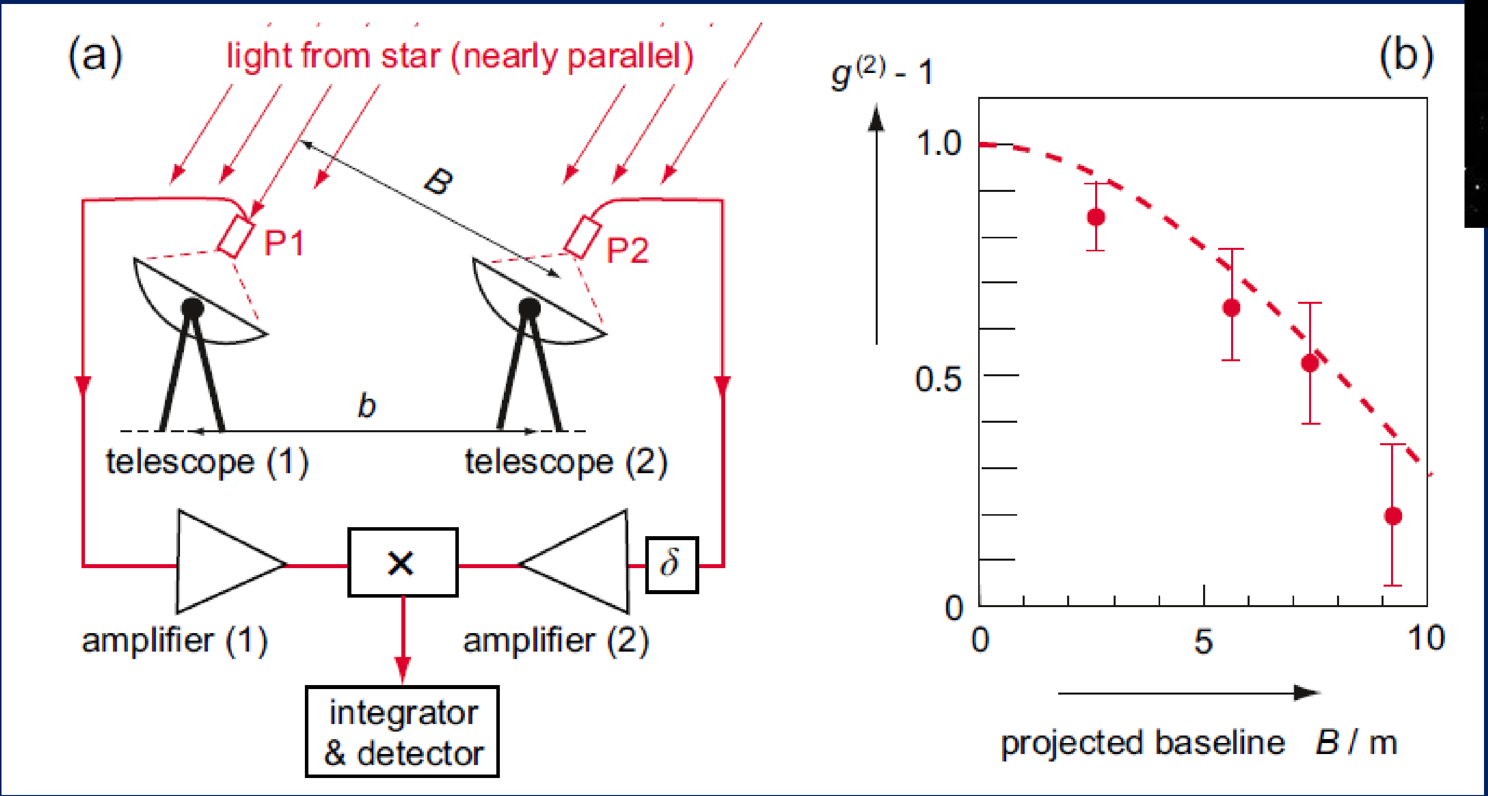


Hanbury Brown-Twiss Method



- 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）



- **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.

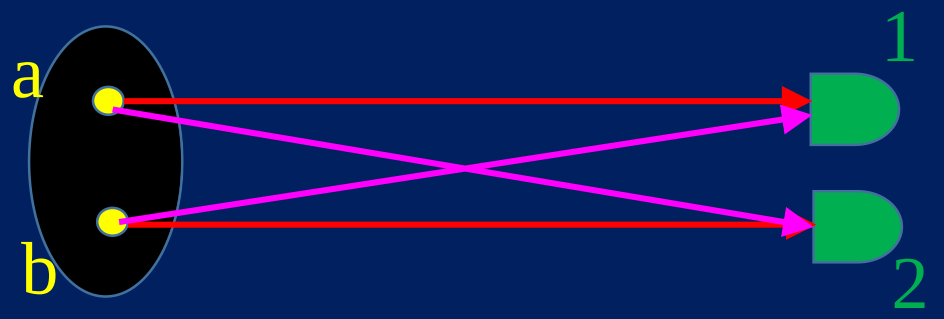
In a classic picture: the spherical waves emitted from a and b are :

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

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: $\langle e^{i(\varphi_b-\varphi_a)} \rangle = 0$



One get the light intensity is:

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

HBT correlation

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

The Correlation function is defined as :

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

Approximately, it reads :

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

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

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

Obviously, C is as a function of d via $\Delta \boldsymbol{k}$, d is the base line of the two detectors.

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

HBT in nuclear physics

- 1960s, Goldhaber Analyzed the ππ correlation in $\bar{p}p$ anilation
- 1977, S. Koonin extended the HBT to pp correlation in heavy ion reactions

Distribution of proton in the fireball

$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{p}_1 d\boldsymbol{p}_2} = \int_{-\infty}^{\infty} dt_1 dt_2 \int d\boldsymbol{r}_1 d\boldsymbol{r}_2 D(\boldsymbol{r}_1 t_1, \boldsymbol{p}) D(\boldsymbol{r}_2 t_2, \boldsymbol{p})$$

$$\times \{\tfrac{1}{4}|{}^1\Psi_{\boldsymbol{p}_1\boldsymbol{p}_2}(\boldsymbol{r}_1', \boldsymbol{r}_2)|^2 + \tfrac{3}{4}|{}^3\Psi_{\boldsymbol{p}_1\boldsymbol{p}_2}(\boldsymbol{r}_1', \boldsymbol{r}_2)|^2\} . \quad (1)$$

Plane wave multiplying the pp relative motion wave function。

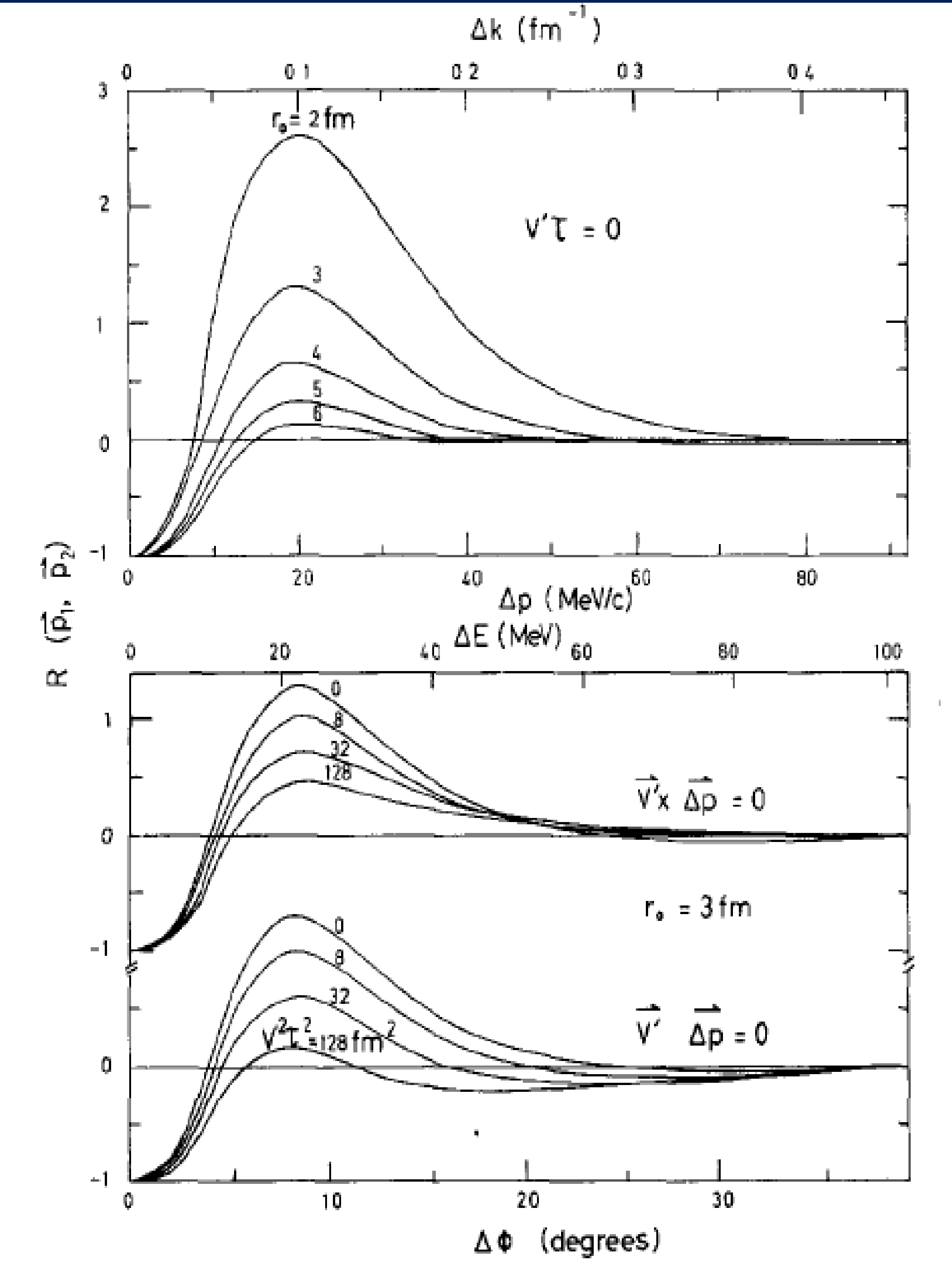
$$D(\boldsymbol{r}t, \boldsymbol{p}) = \frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{p}}\left(\frac{1}{\pi^{3/2} r_0^3} e^{-(\boldsymbol{r}-\boldsymbol{V}_0 t)^2/r_0^2}\right)\left(\frac{1}{\pi^{1/2}\tau} e^{-t^2/\tau^2}\right) \quad (2)$$

PROTON PICTURES OF HIGH-ENERGY NUCLEAR COLLISIONS

Steven E. KOONIN[1]

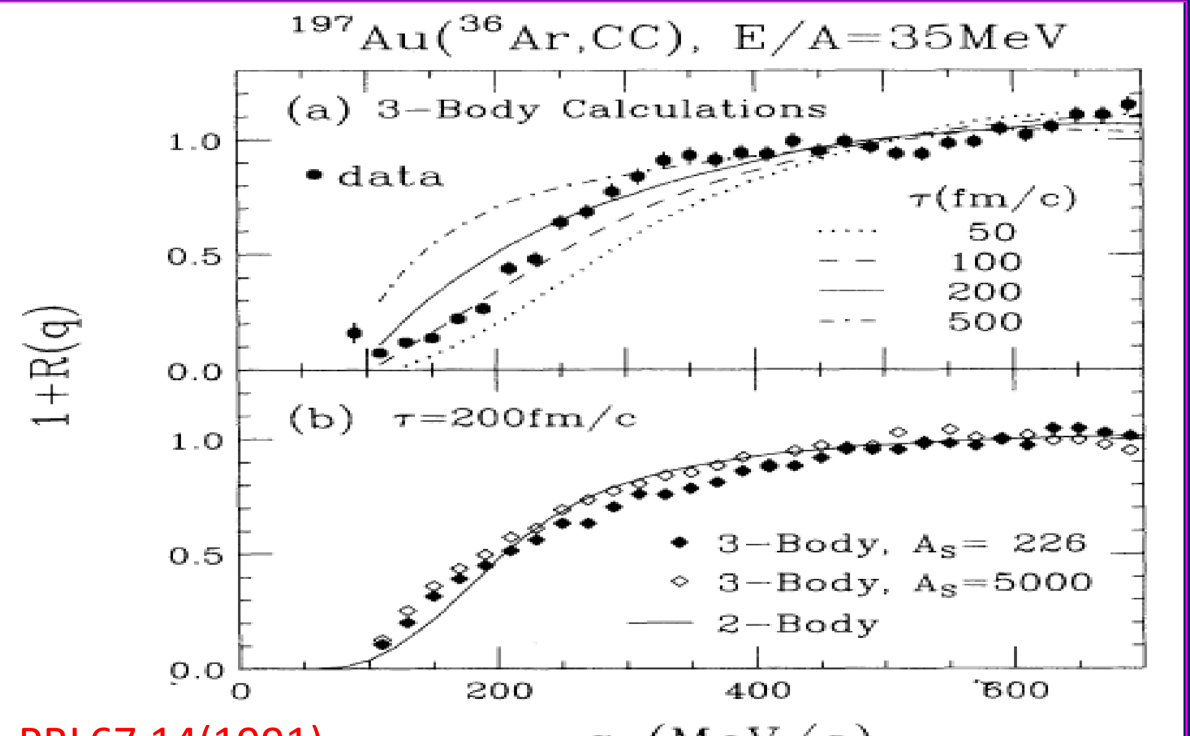
The Niels Borh Institute, Copenhagen, Denmark

PLB70,43(1977)

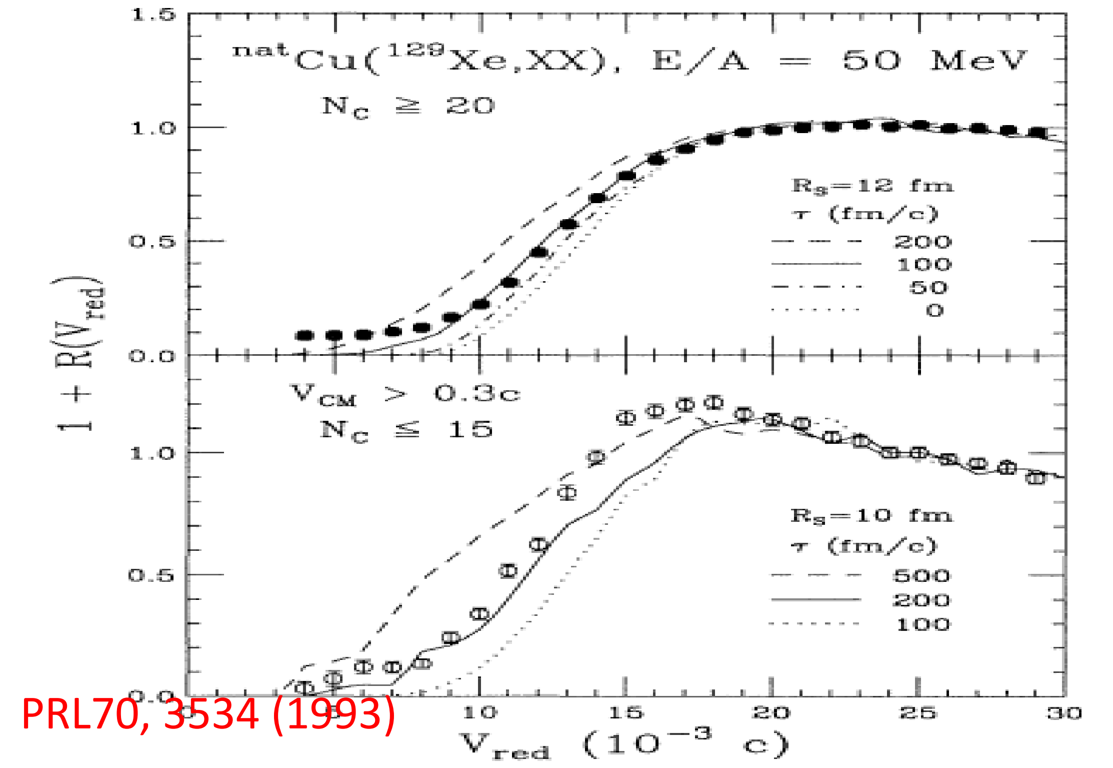


Since 1990s HBT widely applied in nuclear reactions

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



PRL67,14(1991);



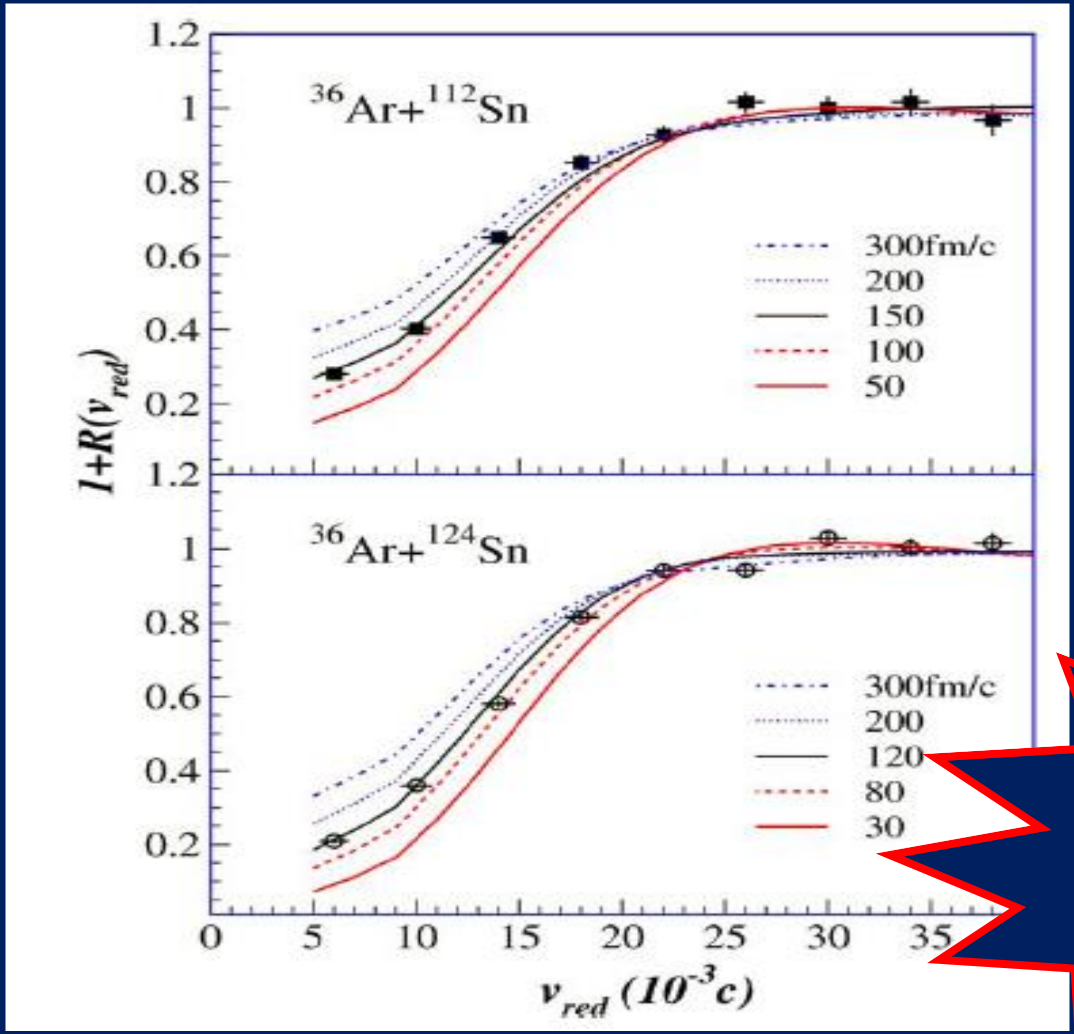
PRL70, 3534 (1993)

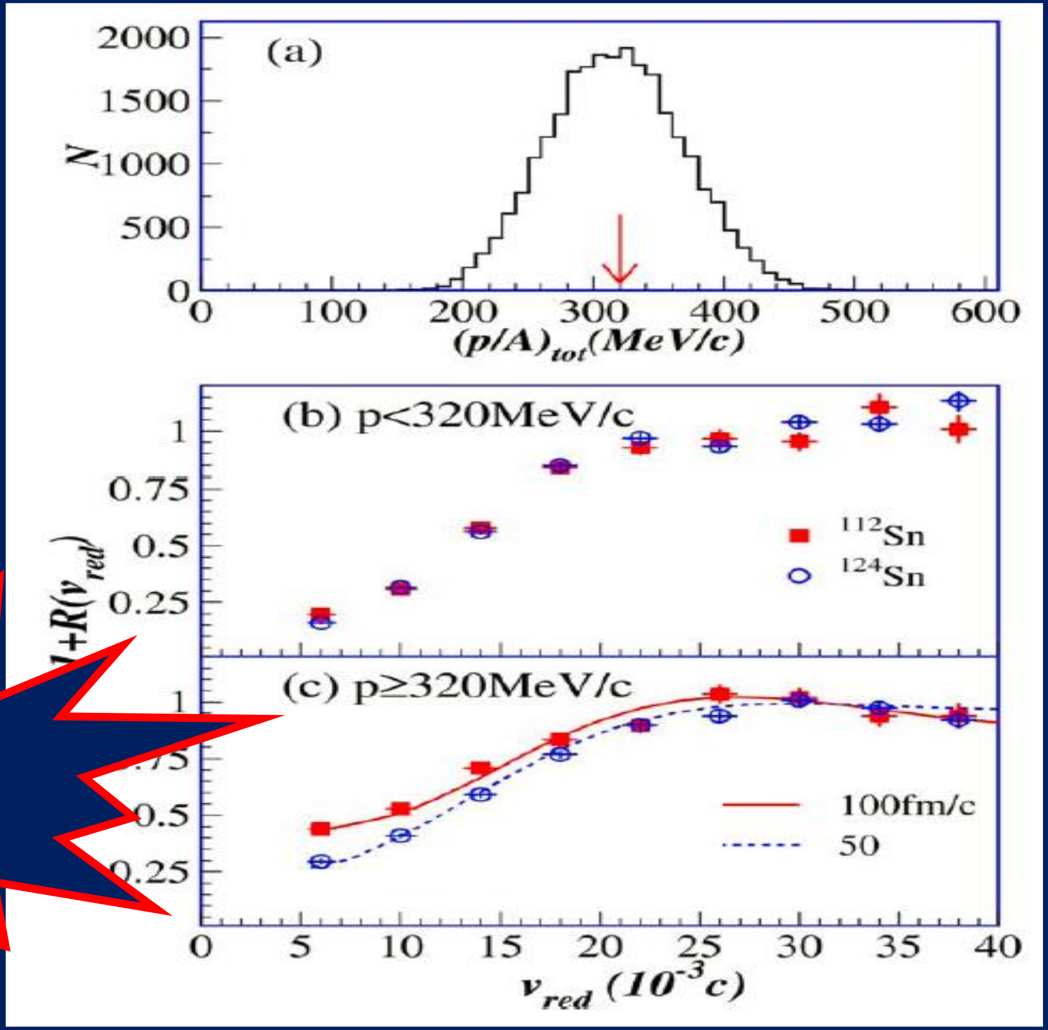
Y. D. Kim , IMF correlation function in 35 MeV/u Ar+Au，

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.

Isospin Effect in HBT Correlation Function





~50 fm/c time resolution achievable

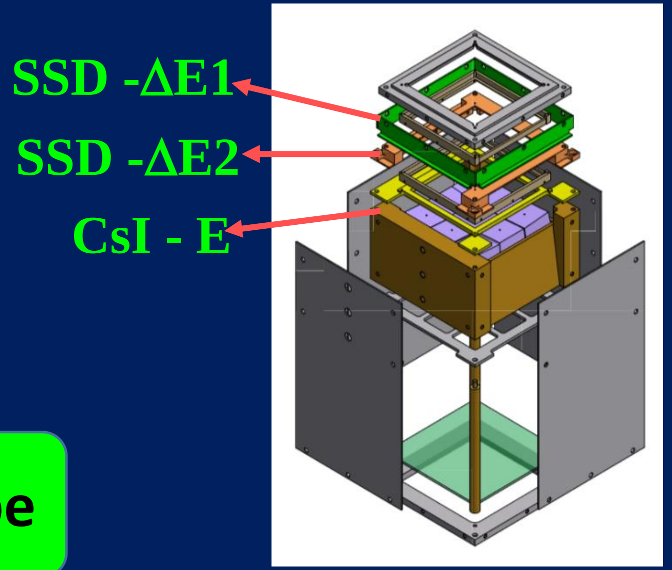
ZGX, R. J. Hu, H. Y. Wu et al., **PLB 639**,436 (2006) ; R. J. Hu, ZGX et al., **HEPNP 31**, 350 (2007)

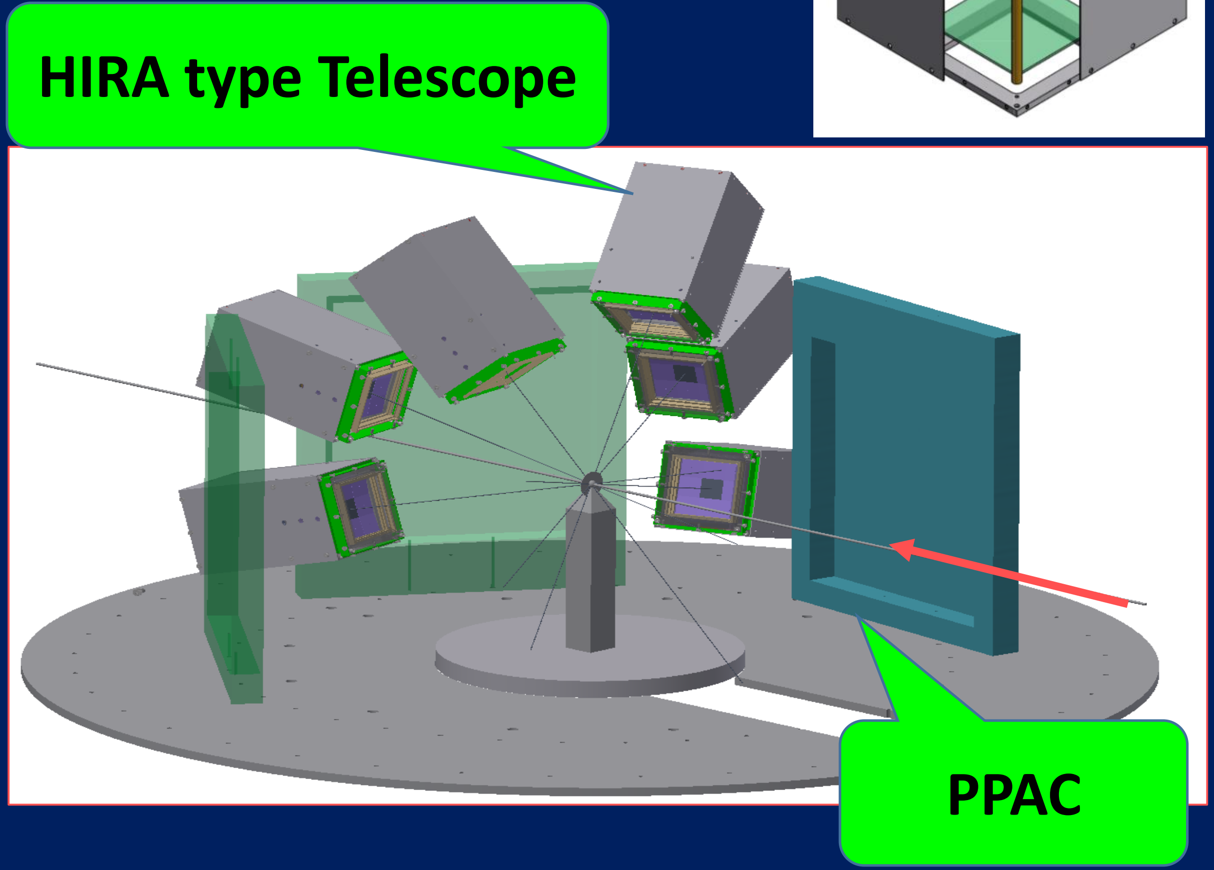
- Stronger Coulomb anti-correlation is observed in Ar+^{124}Sn , this difference arises from the isospin difference of the two system.

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

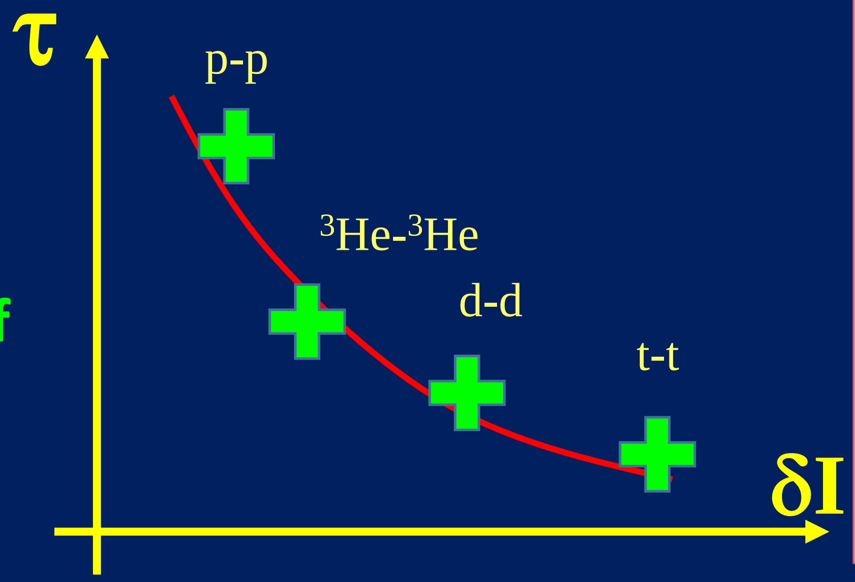
- **H**eavy **I**on **R**esearch **A**rray at **T**singhua **U**niversity **(HIRA^{TU})**

Technique Features：
  Fission Fragments： PPAC
  LCP in coincidence： SSD-SSD-CsI Telescope
  Total Channels： 700
  Position/Energy Resolution： 2mm / 1%

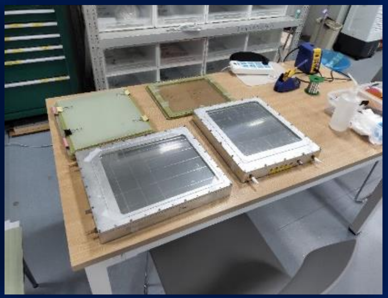
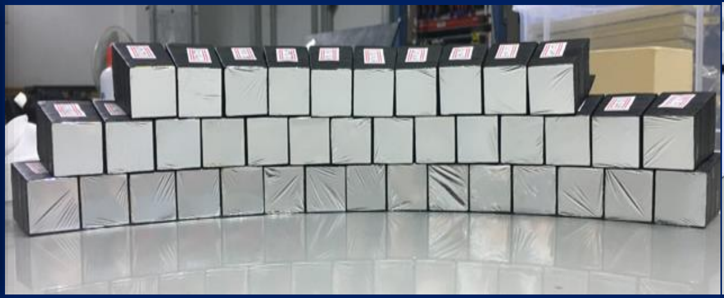
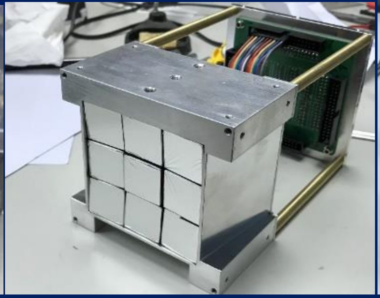
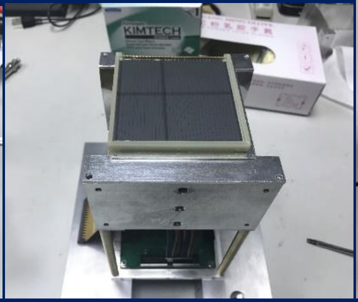
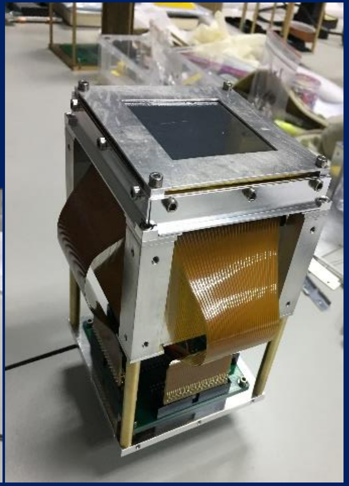




Capable of measuring the HBT correlation of isospin-resolved particle pair

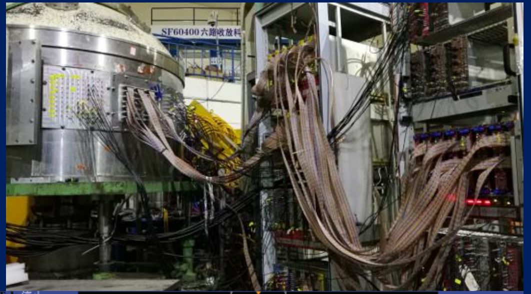
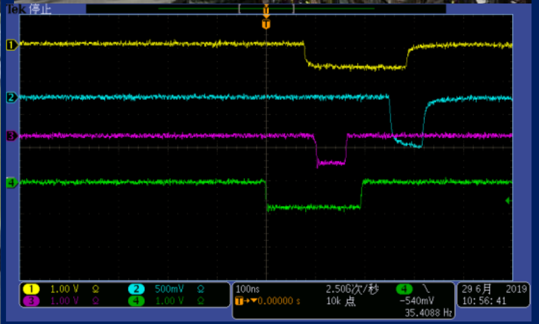


HIRA^{TU}: Phase-1 Experiments

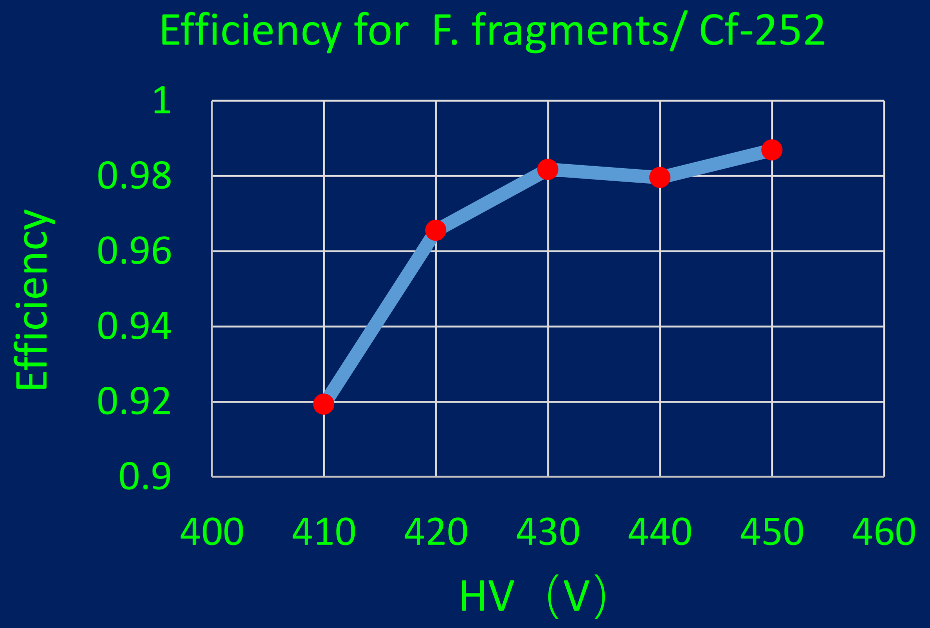







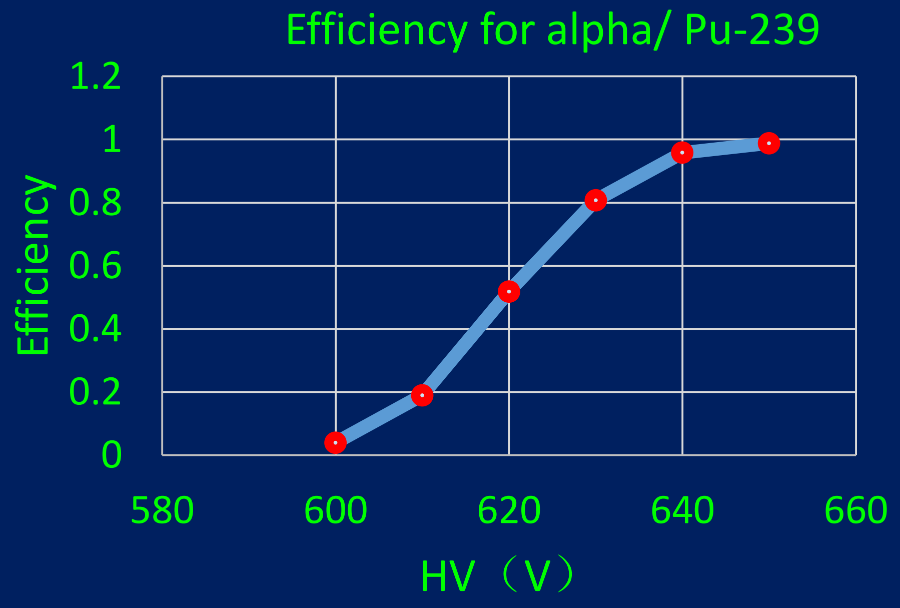

Beam time: 6-13 Feb., 2018;
Reaction: Ar+Au at 30 MeV/u;
1/3 SSD telescopes

Beam time: 5-12 July., 2019;
Reaction: Kr+Au at 25 MeV/u;
2/3 SSD telescopes with cooling

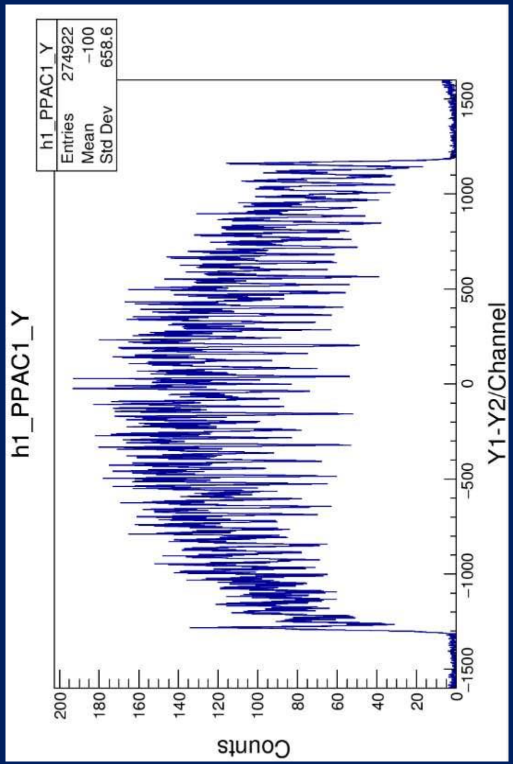



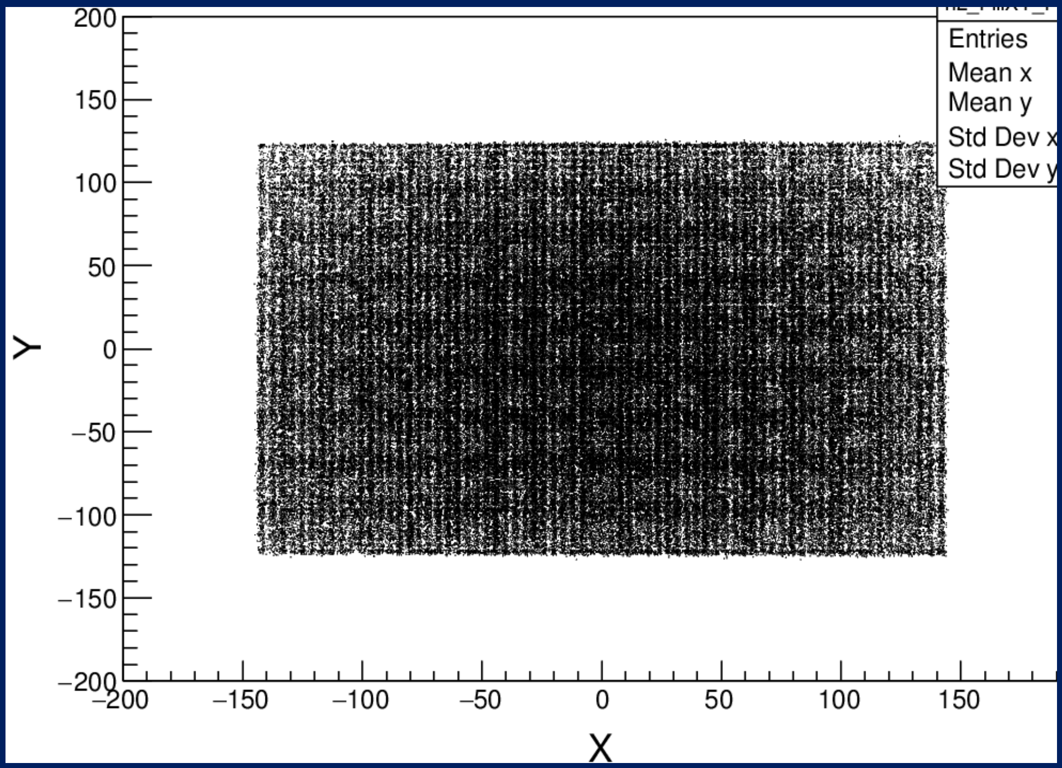

PPAC Performance for fission fragments（30 MeV/u Ar+Au）

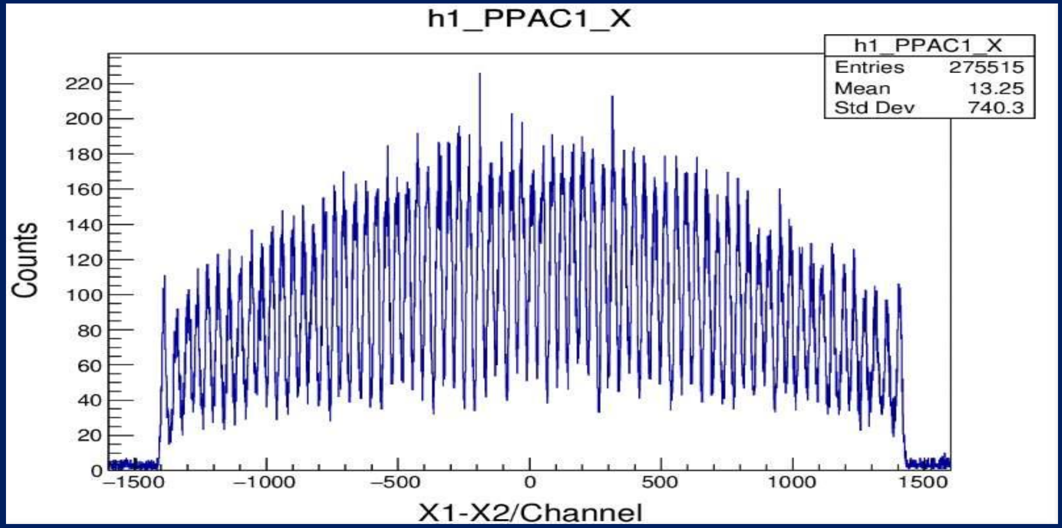




X. L Wei. Et al., Nucl. Engin. Tech. 2019



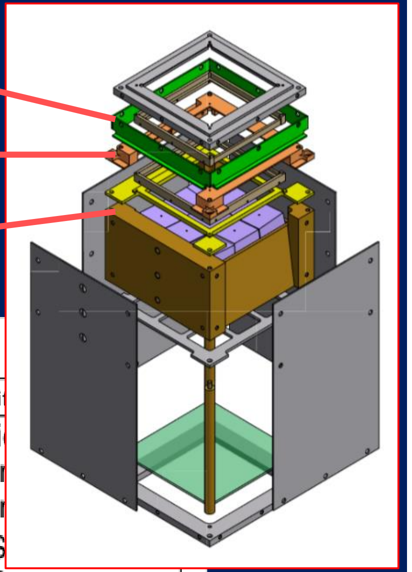


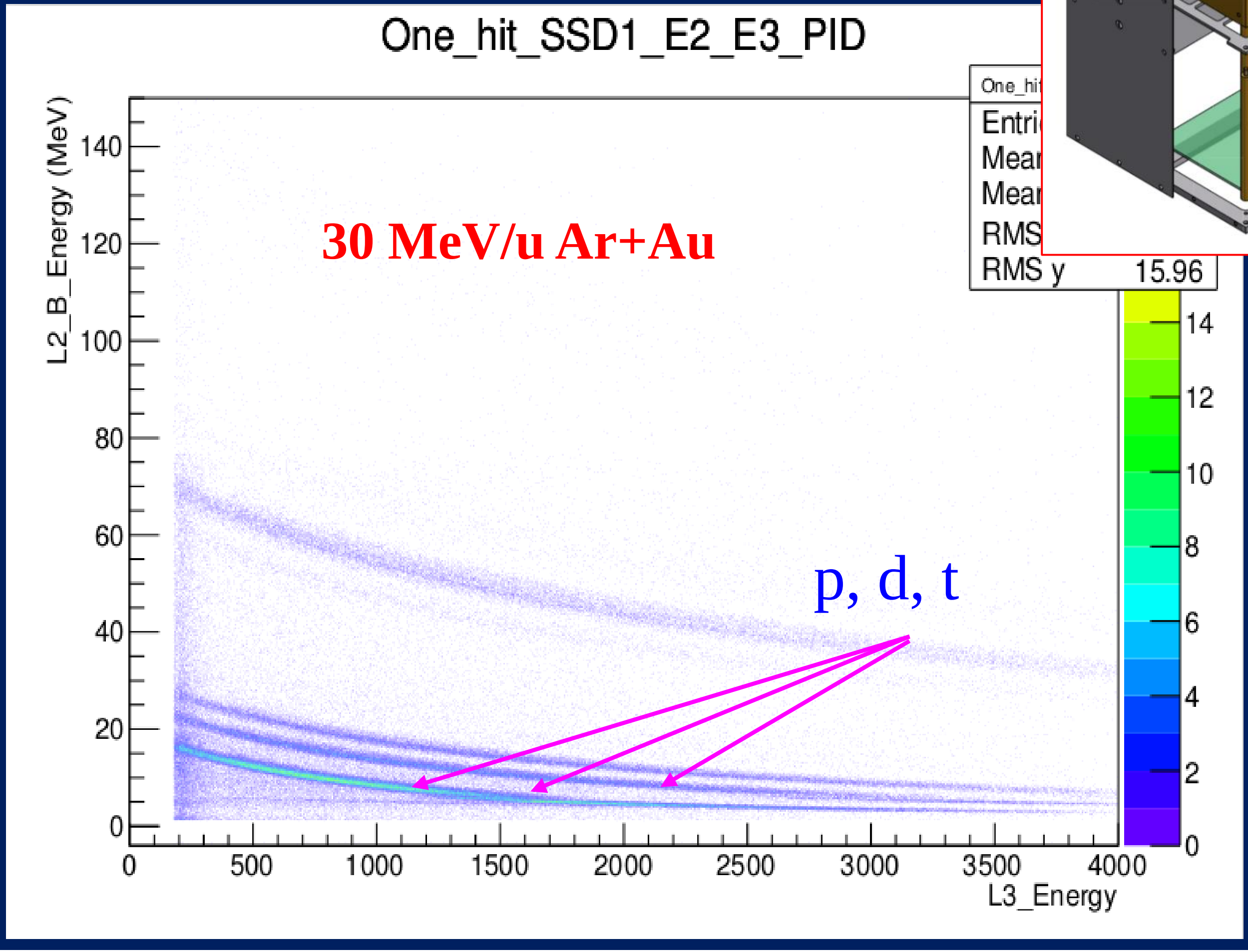


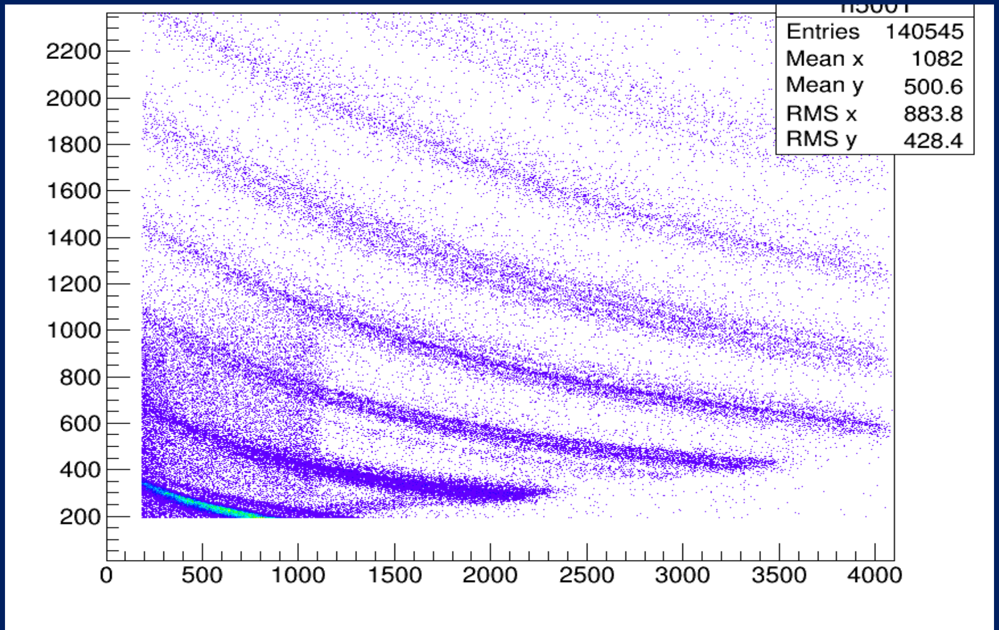
Performance of the Silicon Strip Telescopes

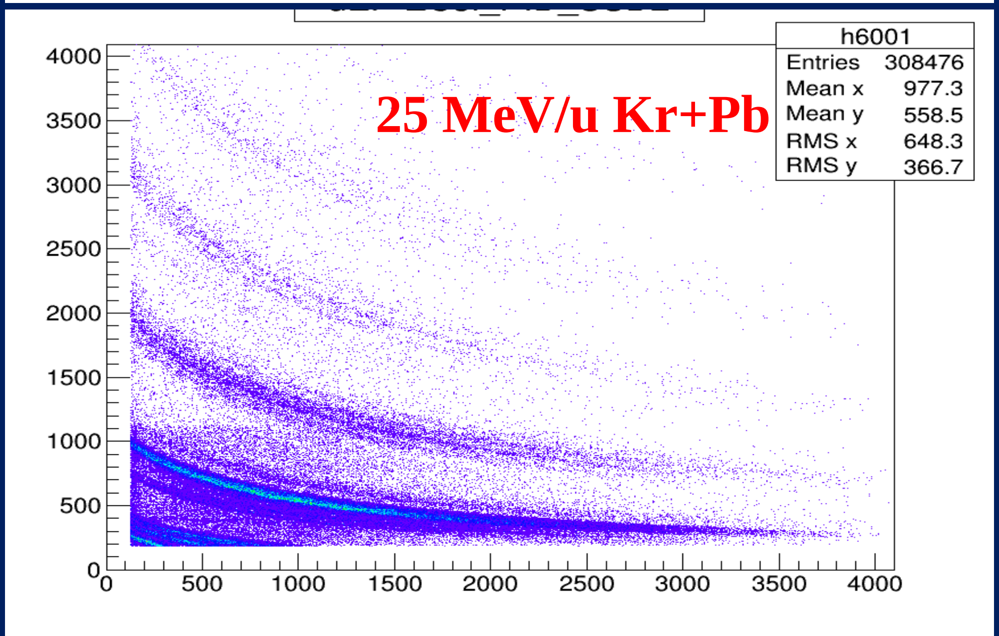
Telescope： SSD+SSD+CsI

- Sensitive area: 64 ×64 mm^3
- Stripe width: 2mm
- CsI granularity： 23 ×23 ×50 mm^3

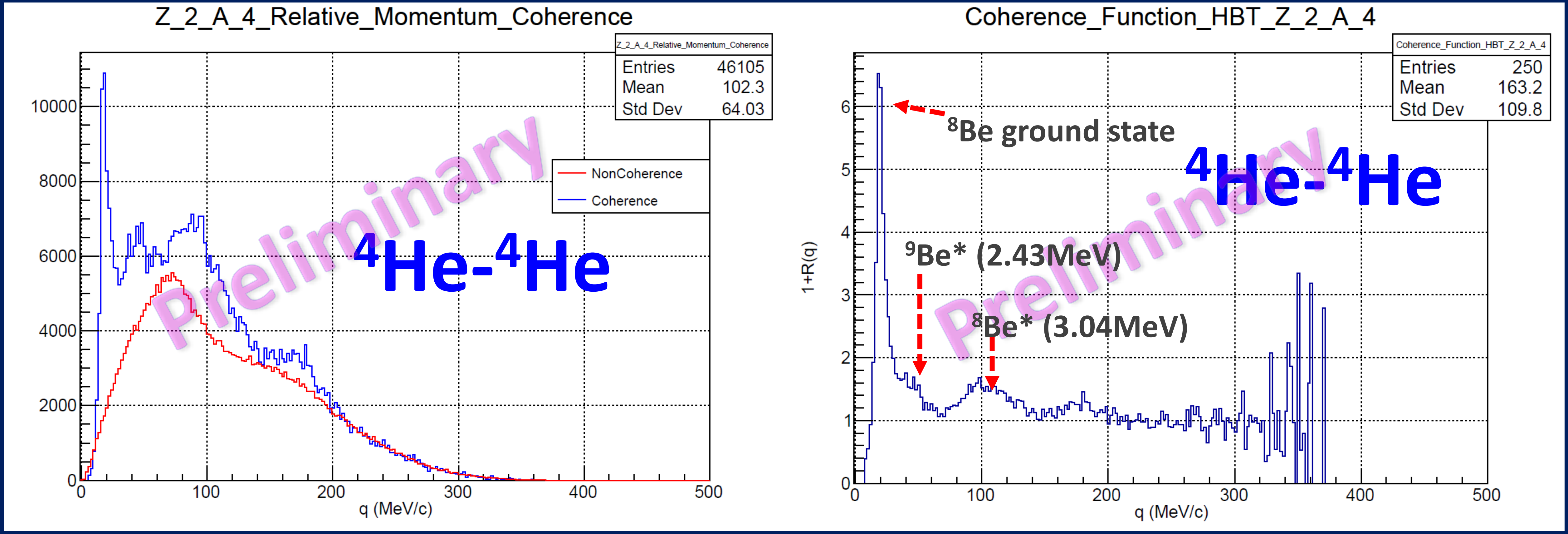








Preliminary Correlation function for α-α pair



Physical output of phase 1 experiment is expected in near future!

Outline

1 Introduction： Nuclear Symmetry Energy from HIC

2 Transport of Isospin DOF in HIC

2.1 Isospin Dependent Hierarchy of Particle Emission

2.2 Extraction of $E_{sym}(\rho)$

2.3 HIRA^{TU}： Isospin chronology study

3 Future： Isovector orientation effect of deuteron-induced reaction

4 Summary

4. Summary

Wealthy information of the transport of **isospin** degree of freedom and **$E_{sym}(\rho)$** 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 of d-induced scattering provides a novel method to constrain **$E_{sym}(\rho)$**.

谢谢

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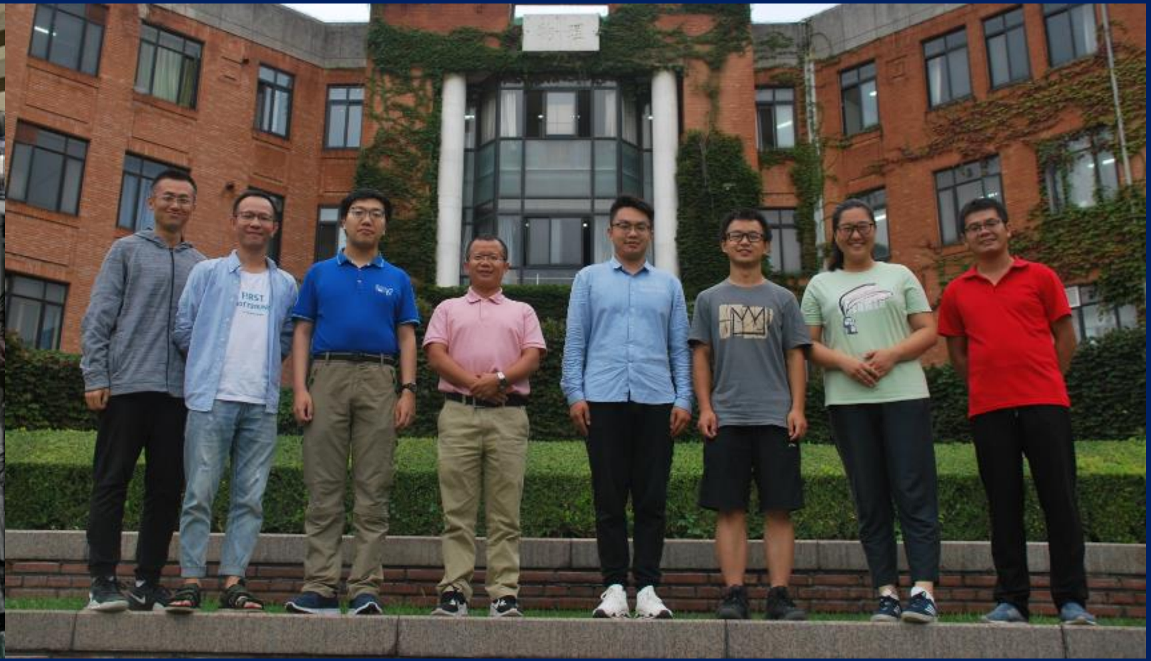


Backup Slides

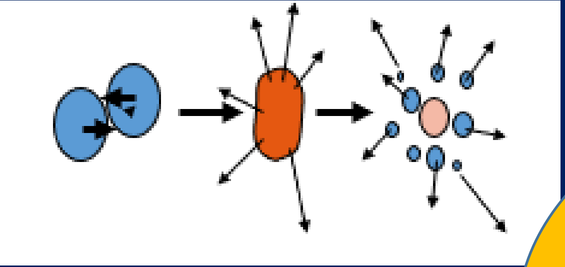
3 Future: Isovector orientation of d-induced reaction as a probe of $E_{sym}(\rho)$?

Caution: $E_{sym}(\rho)$ is not the only unknown factor!

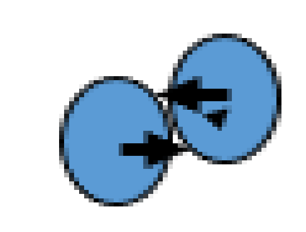
- → **Isospin diffusion (MSU …)**
- → **Isospin scaling and isospin fractionation (MSU…)**
- → **n/p ratio (MSU …)**
- → **N/Z of the emitted fragments (LNS, TAMU, MSU, HIRFL …)**
- → **GMR strength (ND …)**
- → **…. ….**

EOS, σ, clustering …

Transport Model +Statistic Decay model



What you can measure is the event-wise particle yields and phase space distribution



The initial state of two colliding nuclei

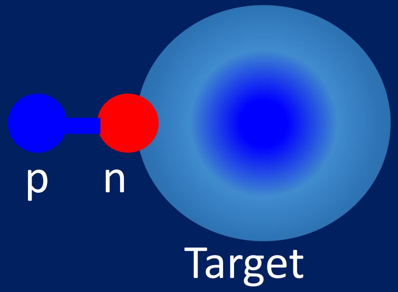
Can we find a sensitive and clean probe in direct reaction: deuteron scattering

Polarization Effect in d-induced reaction

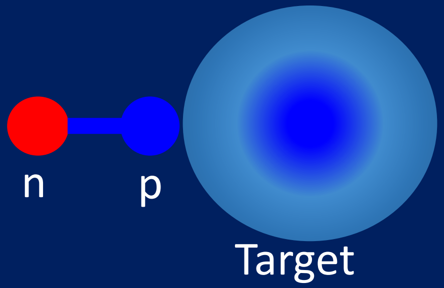
- Oppenheimer proposed first

- J. R. Oppenheimer et al., Phys. Rev. 48, 500 (1935)
- E. O. Lawrence et al., Phys. Rev. 48, 493(1935)

Favored



Un-favored



Coulomb polarization

(Reorientation)

The Transmutation Functions for Some Cases of Deuteron-Induced Radioactivity[1]

Ernest O. Lawrence, Edwin McMillan and R. L. Thornton, *Radiation Laboratory, Department of Physics, University of California, Berkeley*

(Received July 1, 1935)

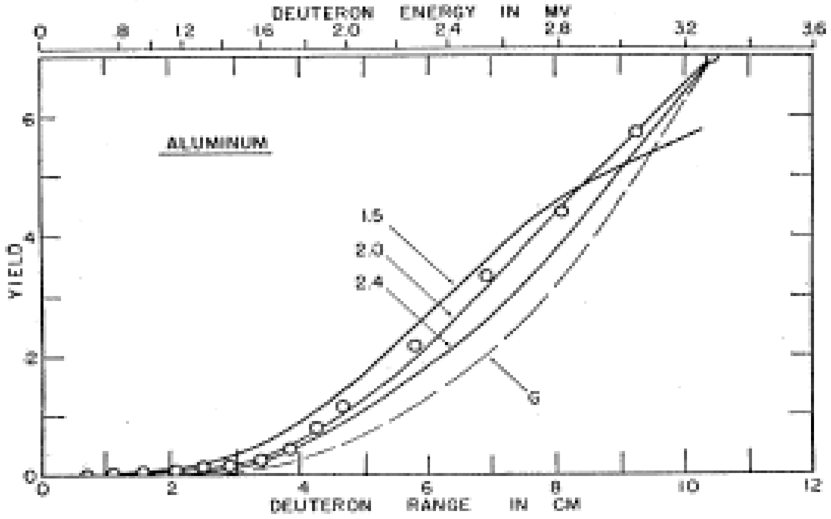


Fig. 2. Differential excitation curve of the radioactivity induced in aluminum ($Z=13$) by deuteron bombardment. Circles, experimental points. Solid lines, Oppenheimer-Phillips functions with the values of I given by the numbers, in MV. Dashed line, Gamow function.

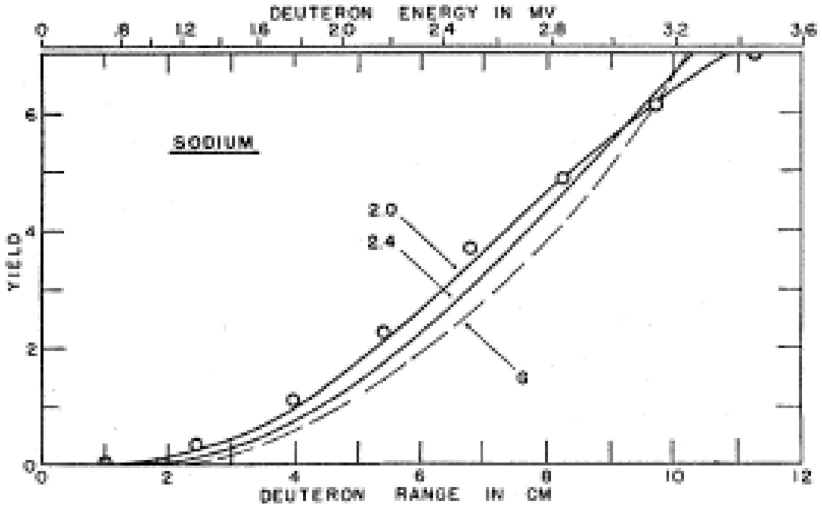
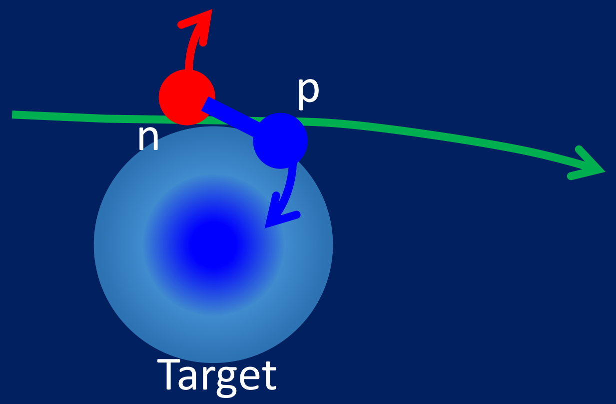


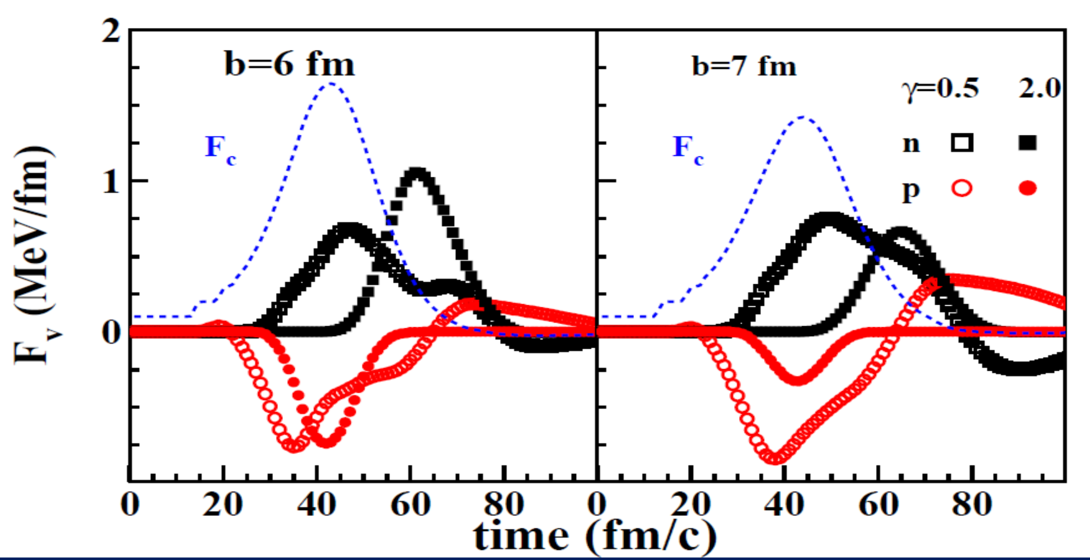
Fig. 3. Differential excitation curve of the sodium radioactivity ($Z=11$). Notation same as in Fig. 2. The ordinate of the highest energy experimental point is probably too low.

A nature question arises now……

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

- **Isovector force**, attractive for proton and repulsive for neutron, shall leads to ***isovector reorientation***, characterized by **the modification of the direction of the relative motion.**



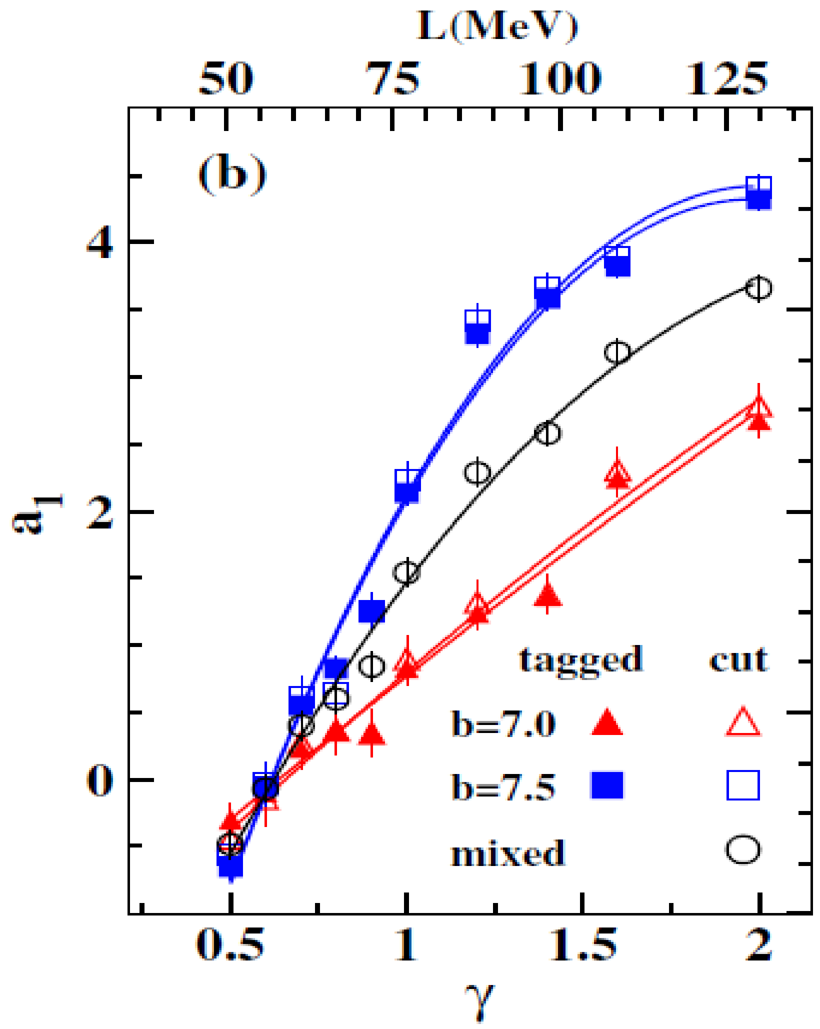


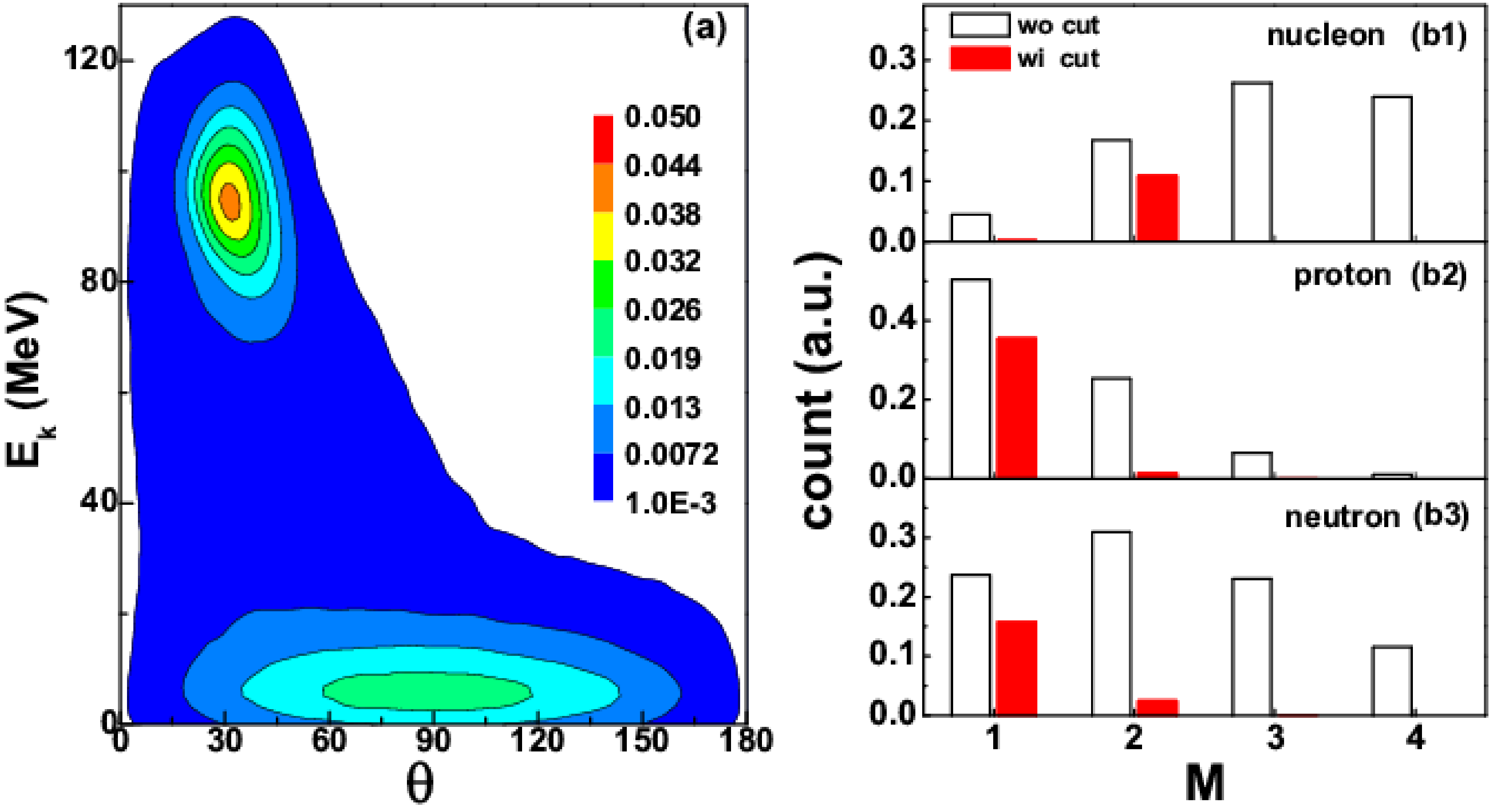
Isovector force act on p and n like a torque

→ Reorientation effect

- If this effect is detectable, it should be sensitive to the isovector potential **(→ symmetry energy!) at low densities** (< 0.5 ρ0)

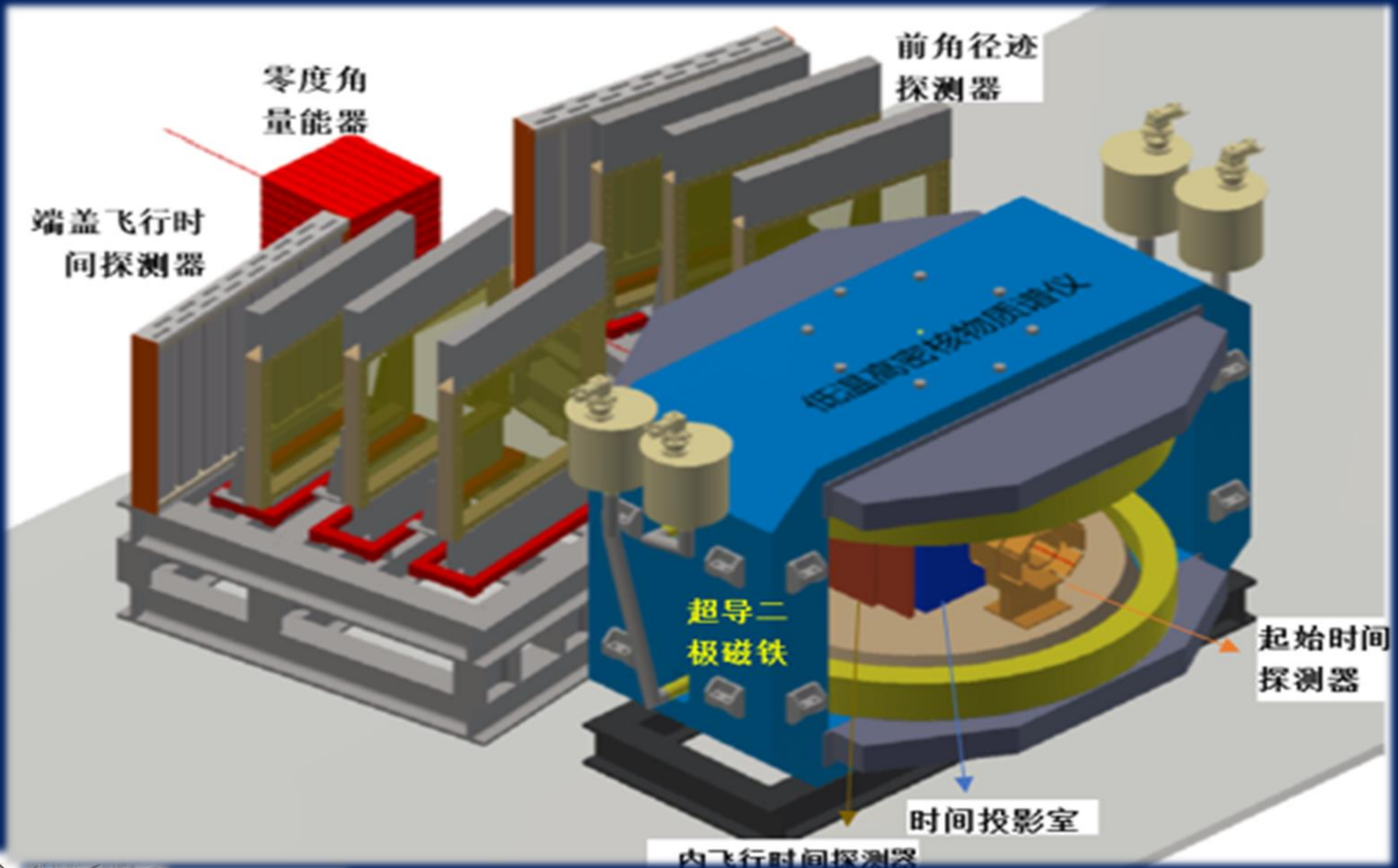
Sensitivity of the dependence of the angular distribution on $E_{sym}(\rho)$

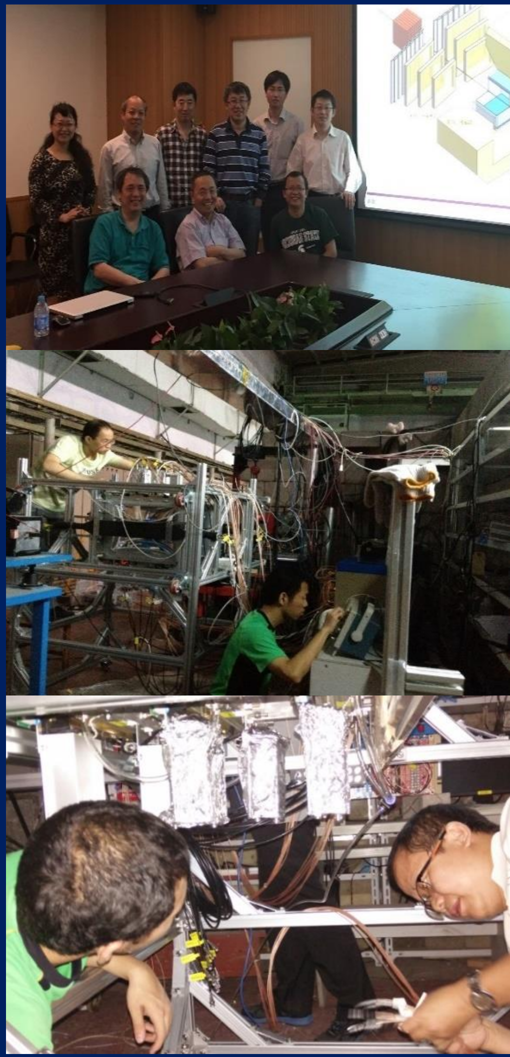




- A new way to study the $E_{sym}(\rho)$: Direct reaction may be used as a new method. It is equivalent to measuring the n/p global optic potential difference.

CEE: A spectrometer for studies on cold and dense nuclear matter





Conceptual Design： Liming Lü, Han Yi, <u>ZGX, </u>Ming Shao, Song Zhang, Guoqing Xiao and Nu Xu., **Science China， Phys. Mech. & Astro. 60**, 012021 (2017)

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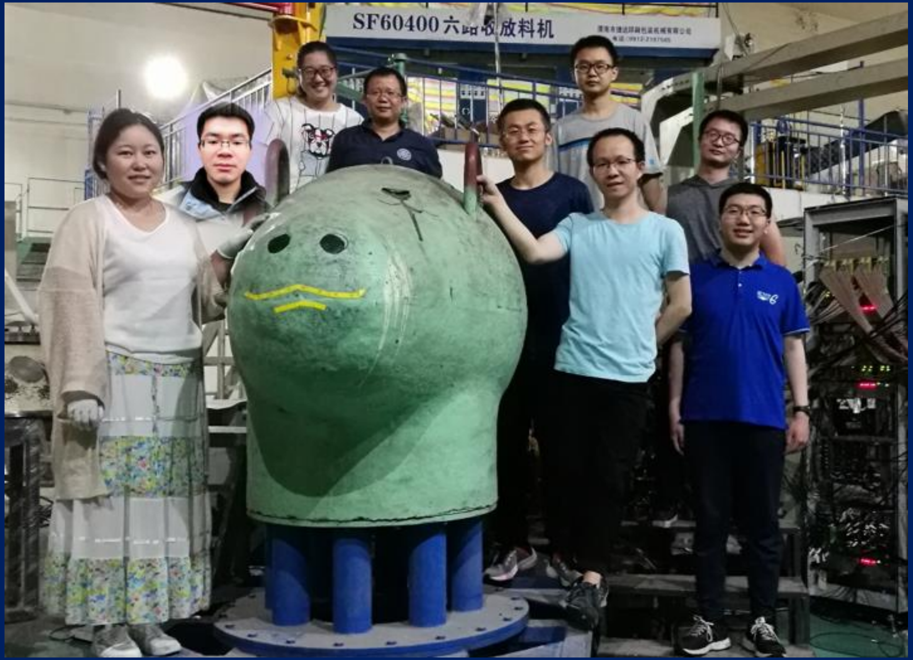
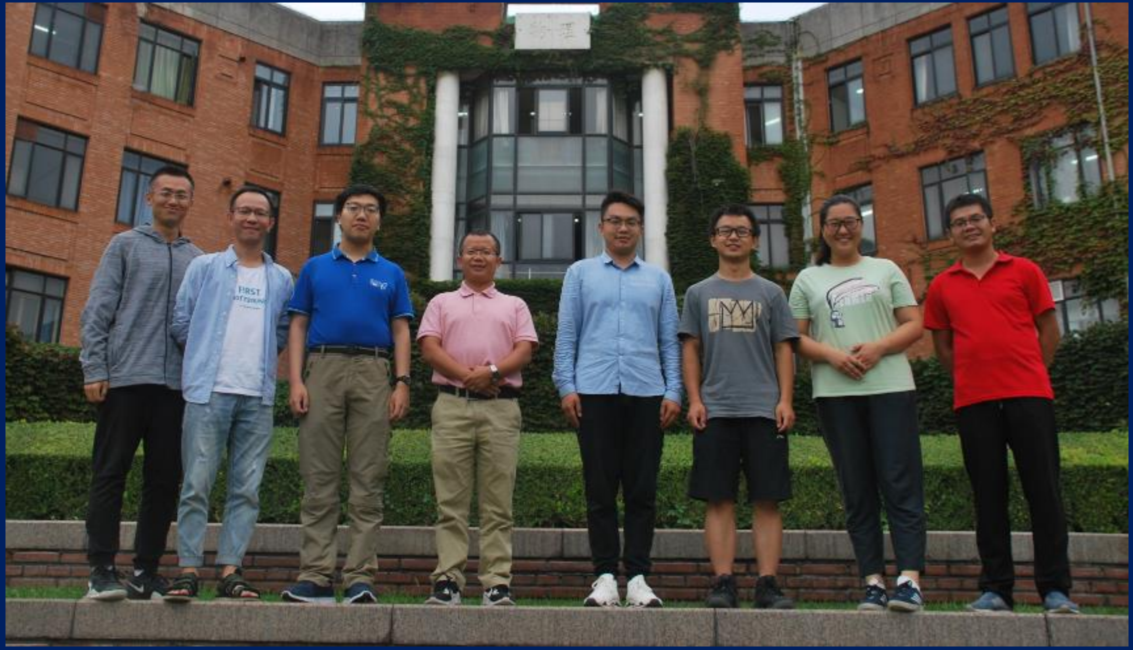




Very Brief Rev. of $E_{sym}(\rho)$ at $\rho<\rho_0$ in HIC

VOLUME 78, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1997

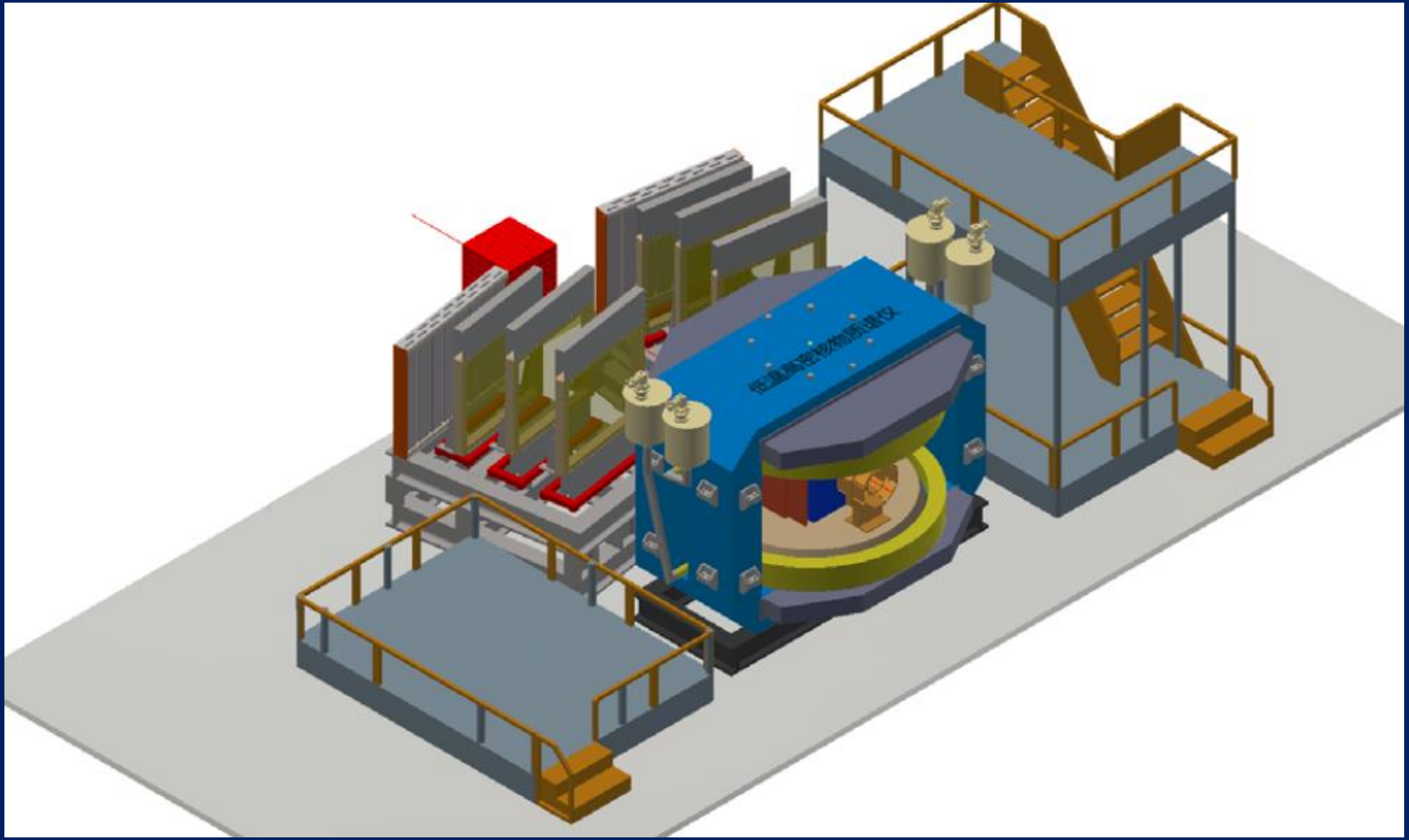
Equation of State of Asymmetric Nuclear Matter and Collisions of Neutron-Rich Nuclei

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]

未来计划 1： CEE的立项建造 --- HIAF 和 HIRFL 能区重离子反应

主要研究目标：2~3 倍饱和密度处核物质性质研究



1）TPC+MWDC 径迹重建模拟和探测器硬件研发

2）该能区新物理/探针寻找

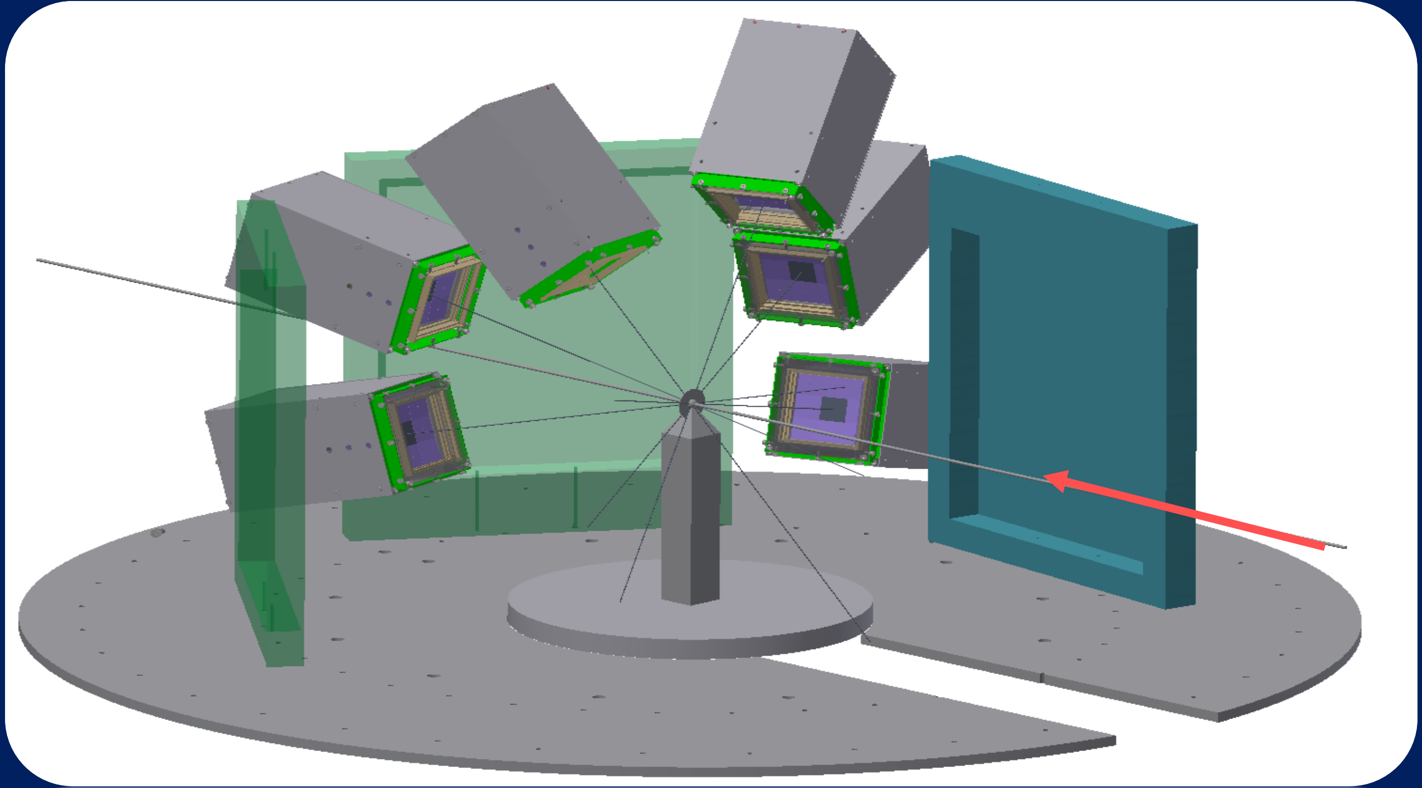
→Λ 产额与核物质状态方程

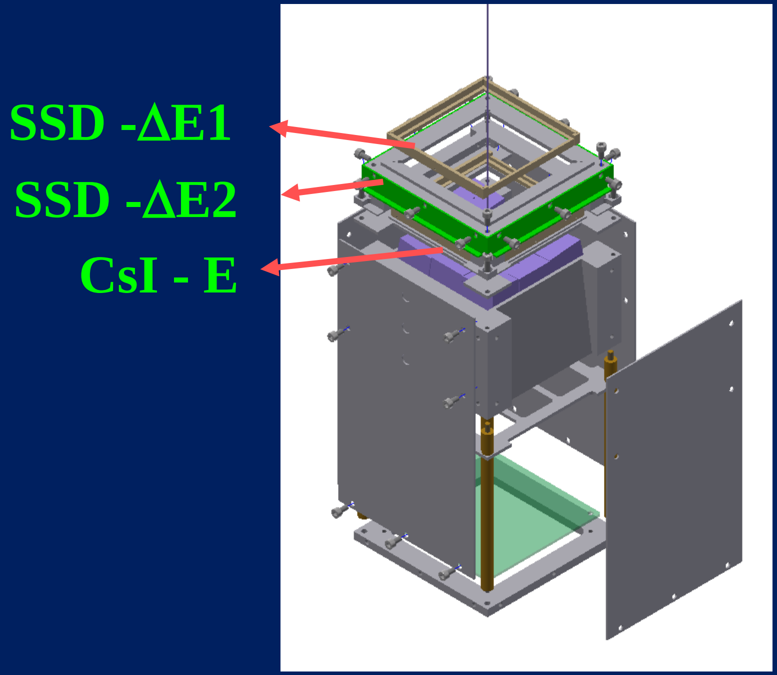
→K^0/K^+ 比值与3ρ0处对称能

未来计划2： HIRA^{TU}：重离子研究阵列 ---- 清华

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

主要研究目标：
颈部发射的同位旋效应；快裂变动力学性质研究
→ 低密区丰中子物质性质研究



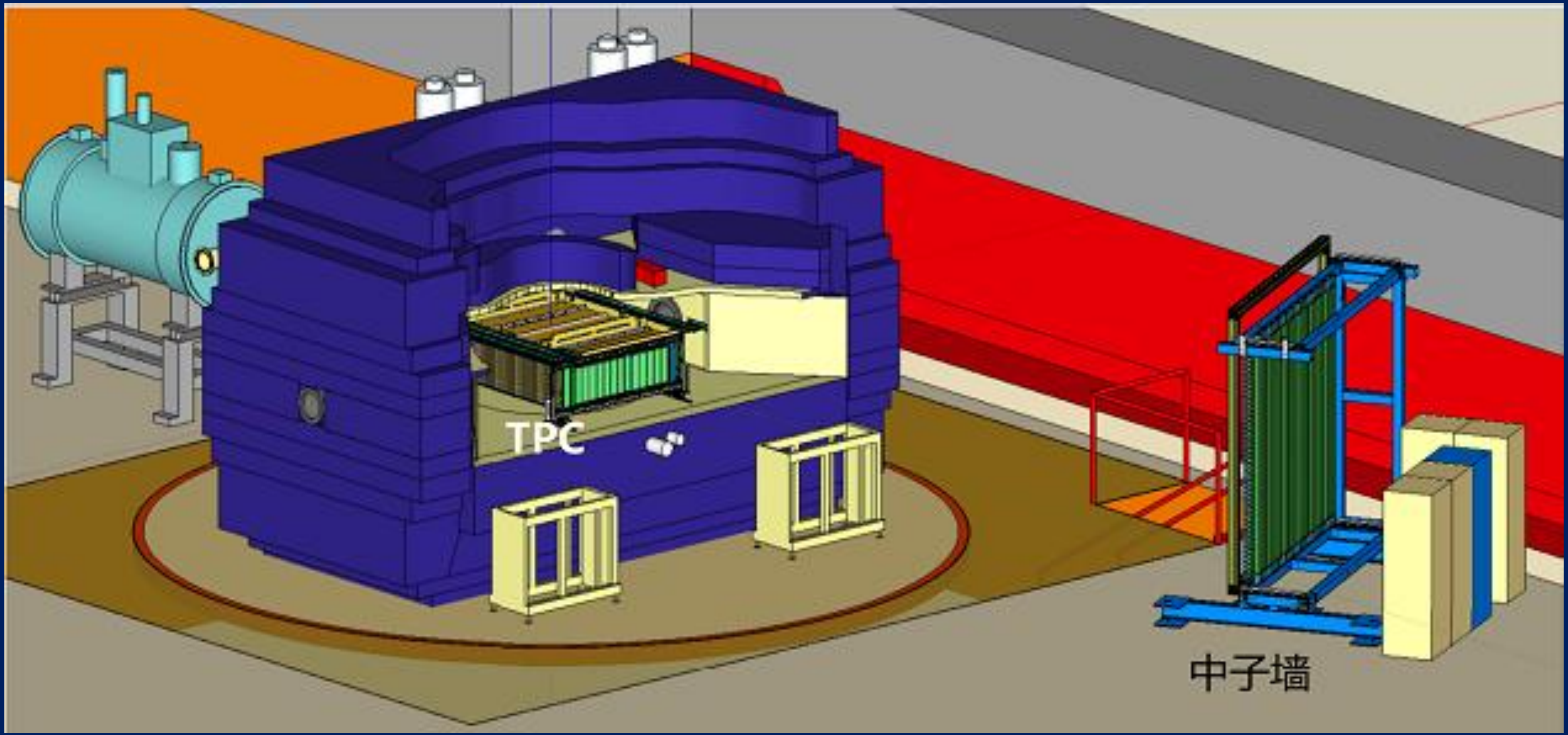


HIRA型的望远镜阵列和PPAC阵列构成

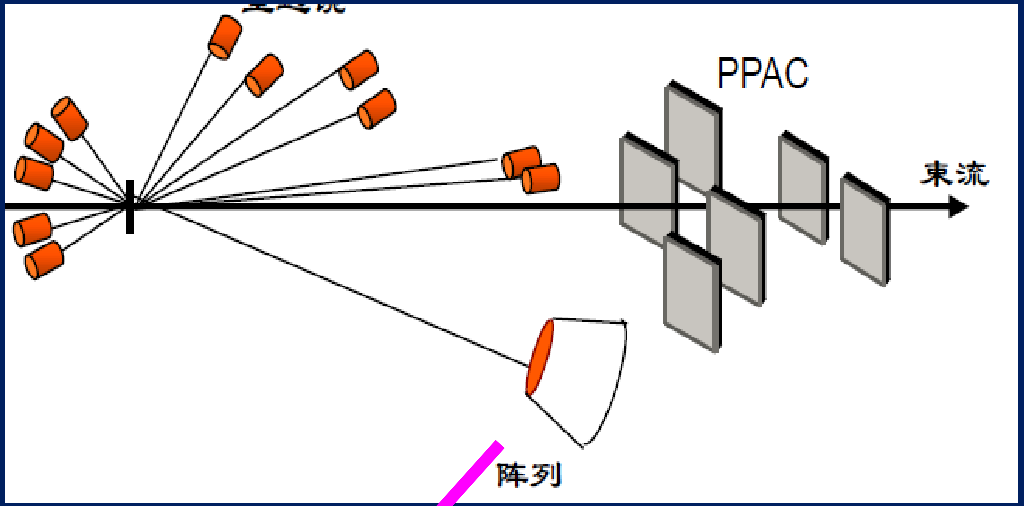
未来计划 3：　极化氘核的破裂反应精确测量

主要研究目标：

测量极化氘核的破裂反应，除了约束对称能（中子、质子与靶核光学势）以外，研究氘核散射中的各类精细效应（与质子关联）。

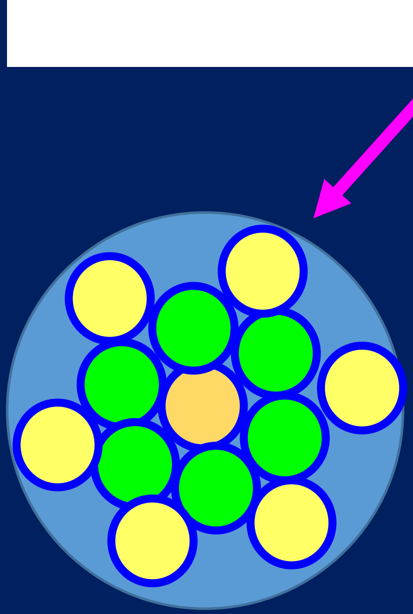


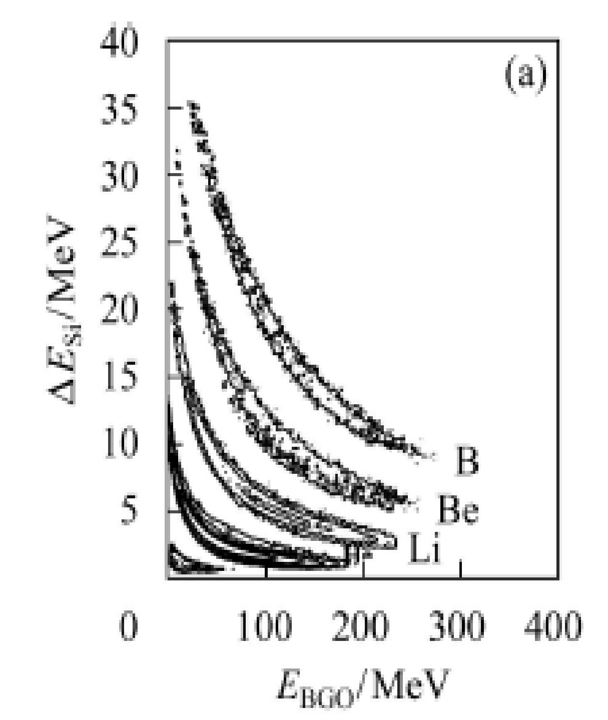
Experimental measurement of Isospin effect on IMF HBT correlation

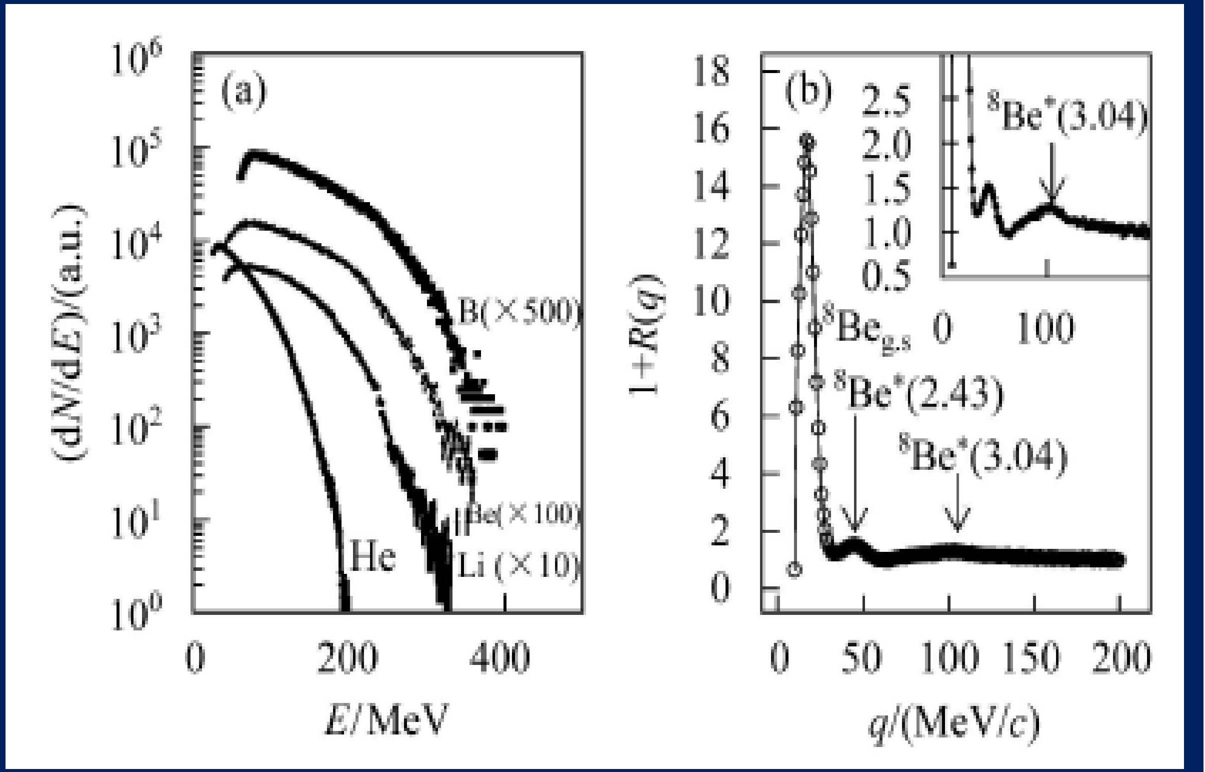


- **Reaction： 35MeV $^{36}Ar+^{112,124}Sn$**
- **Isospin effect on IMF HBT correlation**
- **Hodoscope： 13-unit closely packed Si-BGO array**

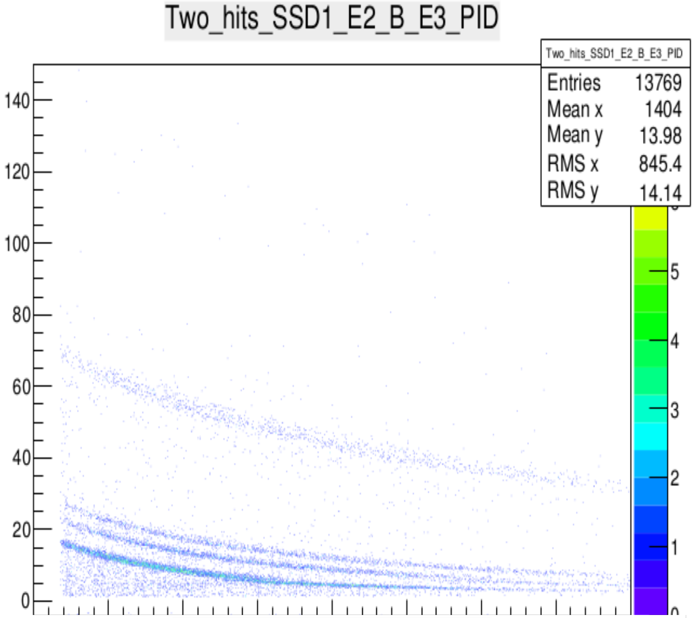
Hit position Resolution ~ 1cm

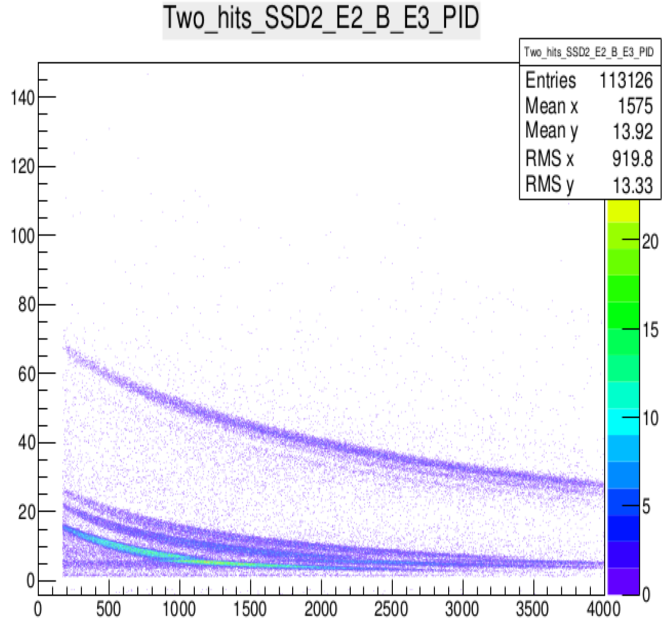


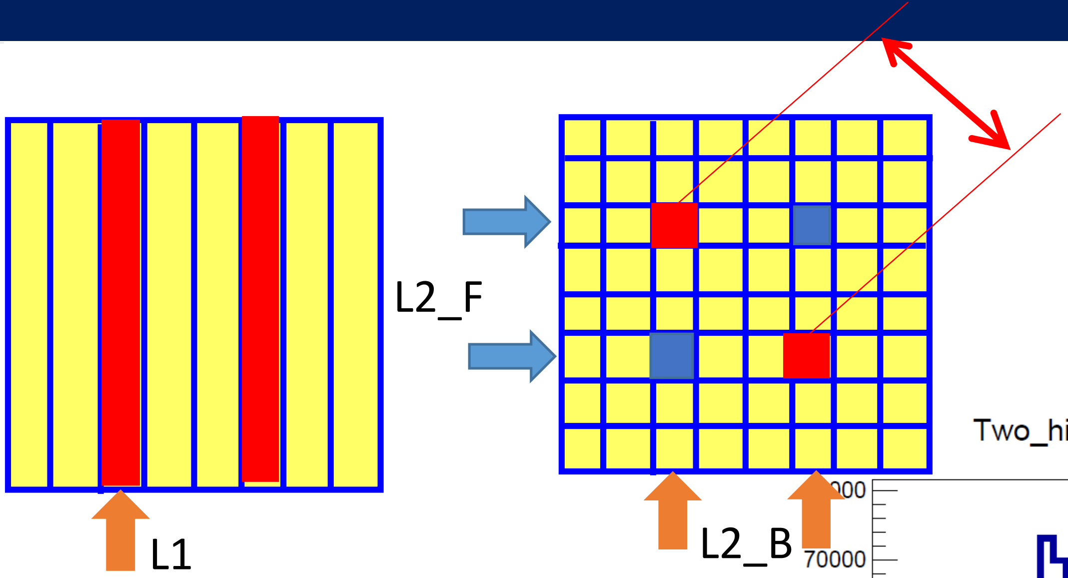


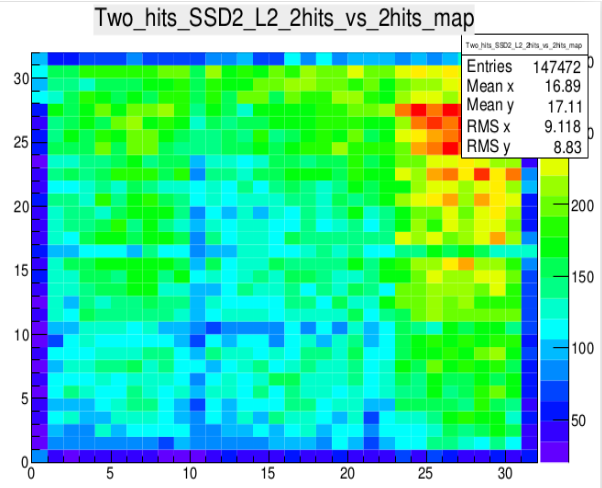


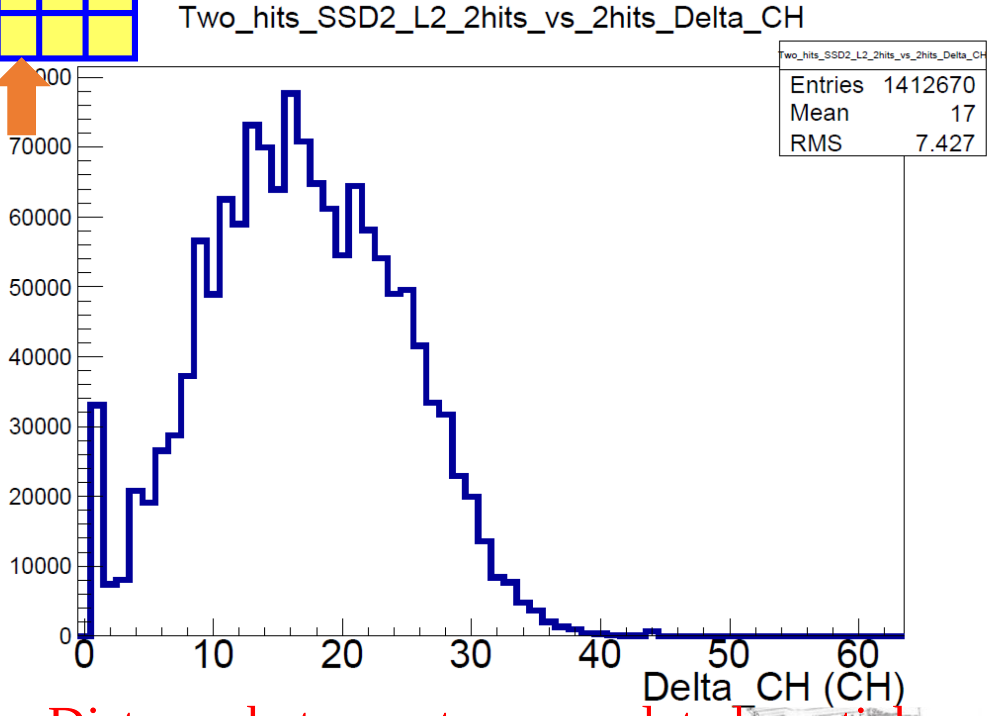
LCP-LCP correlation identified







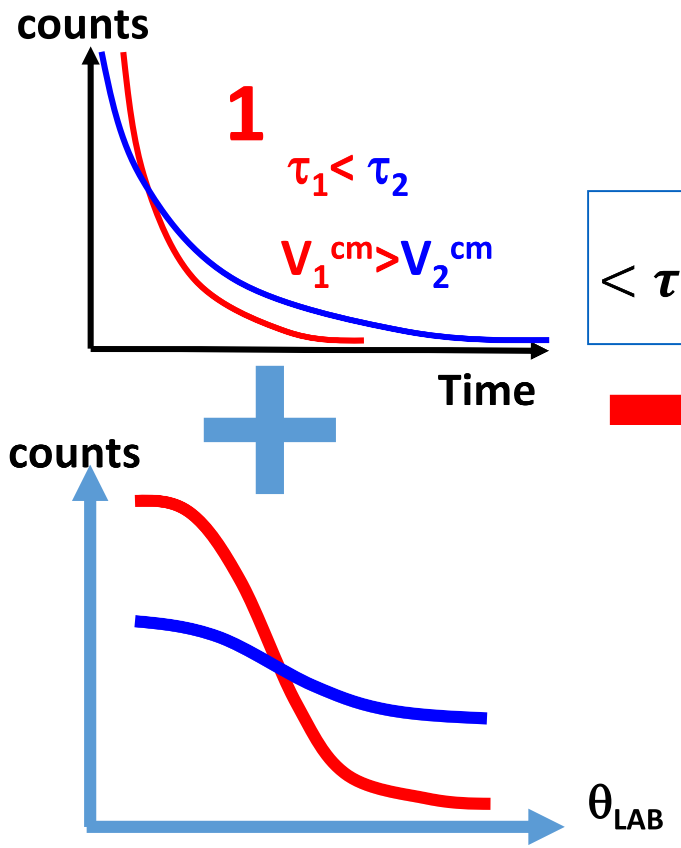




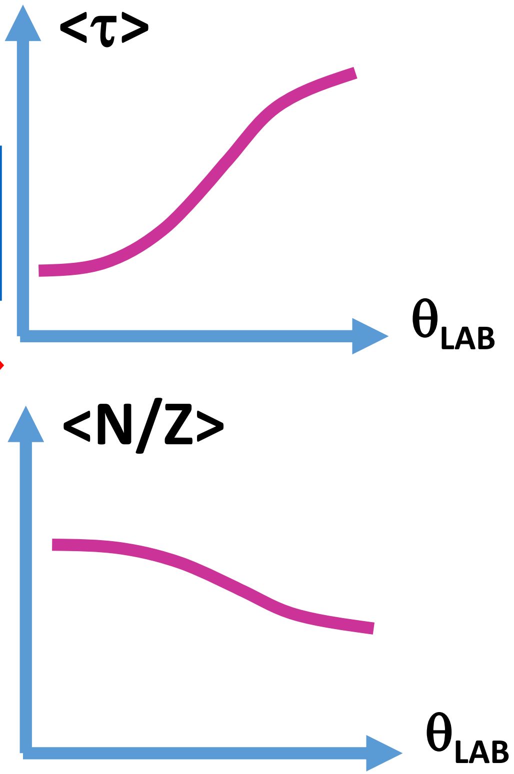
Distance between two correlated particles

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

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)

What is our Motivations with HIC?

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

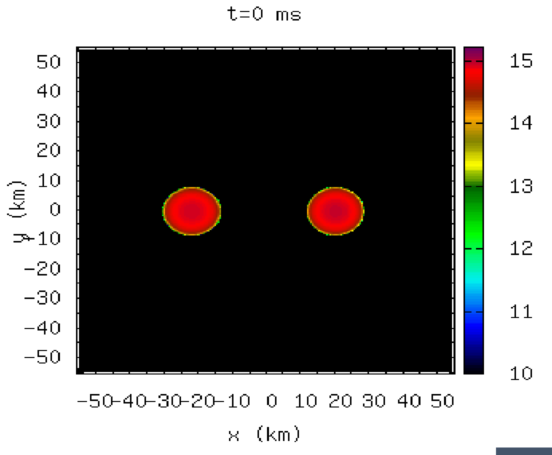
→ Neck Emission in Fission reactions is characterized by low density and neutron-richness.

→ Transport of isospin degree of freedom (IDOF) involving the neck emission helps to identify a probe.

2) To measure quantitatively the time scale of the transport of IDOF.

3) To develop new method to pin down the $E_{sym}(\rho)$ （$\rho<\rho_0$）.

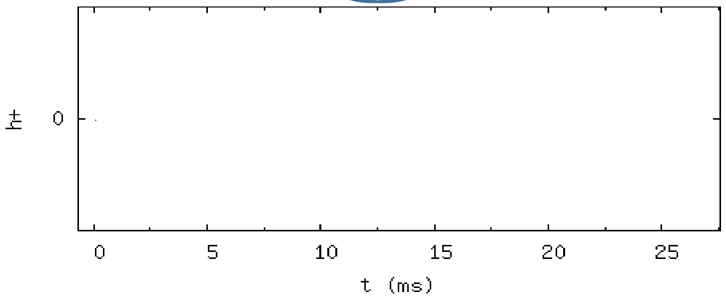
GW170817 与核物质压缩性质（核物态方程）的联系



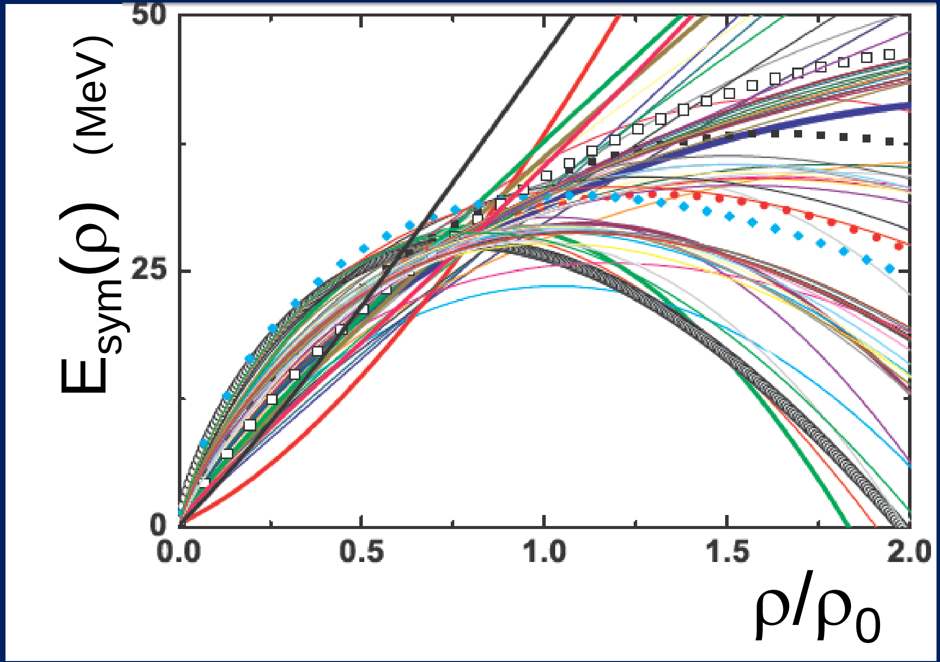
Dimensionless Tidal Deformability

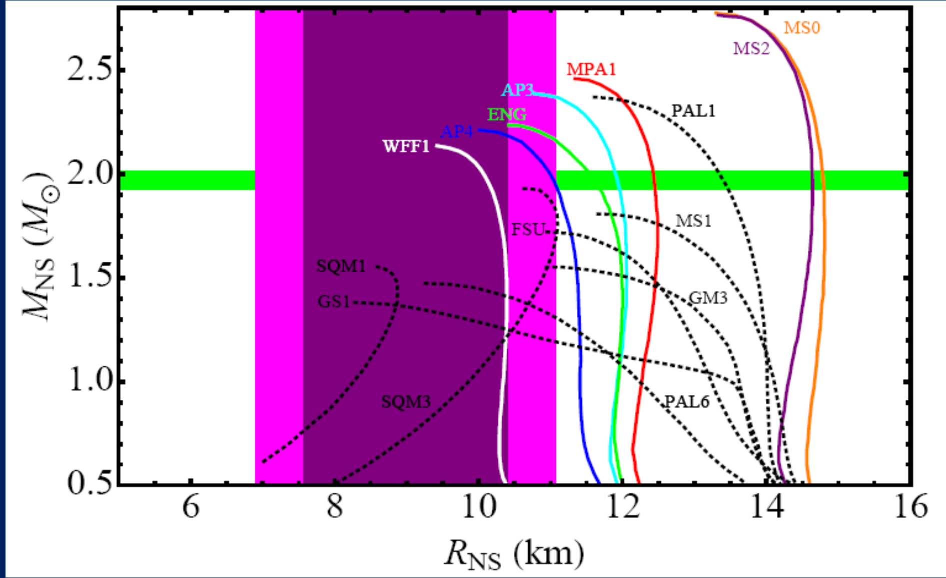
$$\Lambda = \frac{2}{3} k_2 (R/M)^5$$

NS compactness



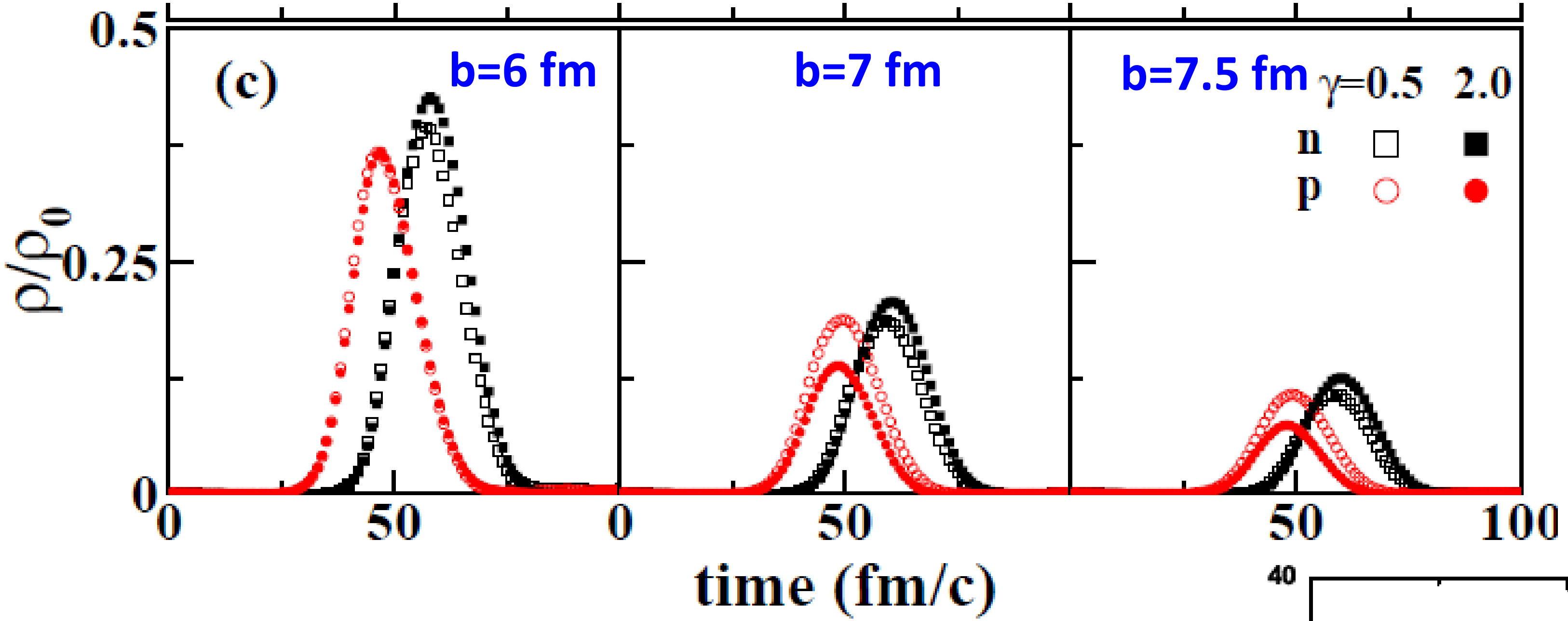
GW ↔ Λ ↔ R/M ↔ EOS





- 原子的电偶极矩和原子半径的三次方成比例：$\kappa \propto R^3$
- 中子星的四极质量极化度和中子星的半径5次方成比例 $\Lambda \propto R^5$
- Ligo对双中子星的轨道频率变化敏感，轨道半径取决于并和过程中引力波导致能量损失的和中子星内部激发过程。
- GW170817 的引力波探测，给出中子星的潮汐极化度限制，故能给出中子星的半径限制。

Density range of sensitivity



- What density region is this observable sensitive on?

  Density range < 0.5 ρ0