QCD Phase Structure at High-Baryon Density Region

CSR-External-target Experiment (CEE)

Zhigang Xiao[(1)] and Nu Xu[(2)]

[(1)] Department of Physics, Tsinghua University, Beijing

[(2)] College of Physical Science and Technology, Central China Normal University, Wuhan

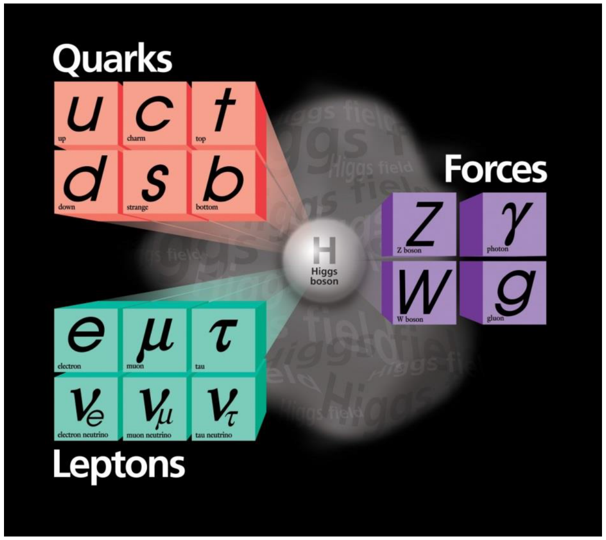
Outline

1 Introduction

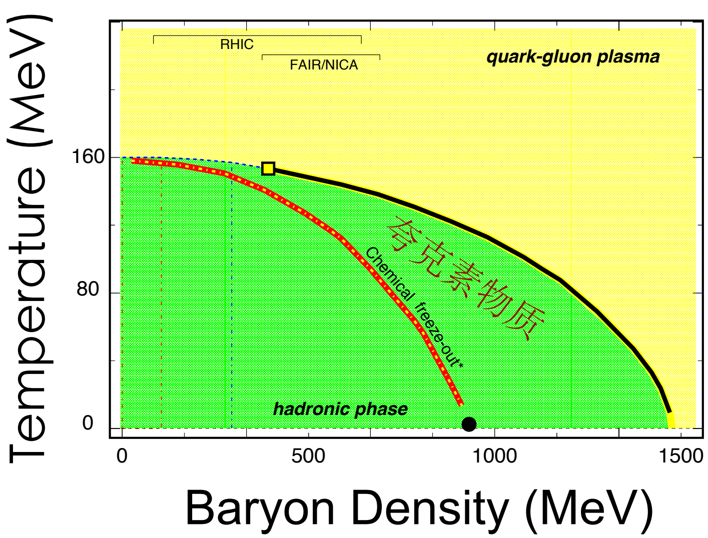
2 CEE Project
CSR External-target Experiment

3 HIAF

Study QCD Phase Structure



2013 Nobel Prize
In Physics

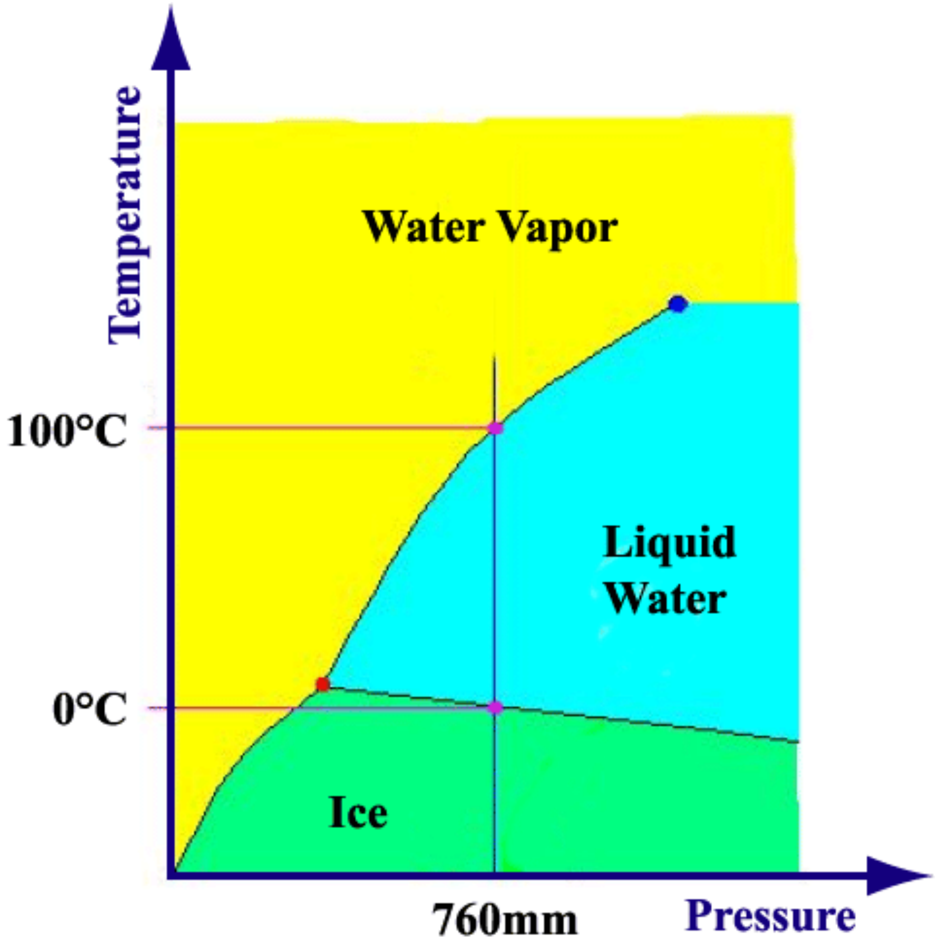


(1) The discovery of Higgs
- Origin of matter
- Standard Model ➔ Theory

(2) The QCD Phase-structure
- Confinement
- Hadron structure
- Spontaneous break of χ_C
- **QCD Phase boundary**
  Critical point …

Emergent Properties of the QCD

Phase Diagram



Phase diagram:

A ***map*** shows that at given degrees of freedom, how matter organize itself under external conditions. New orders, regularities, properties, … emerge.

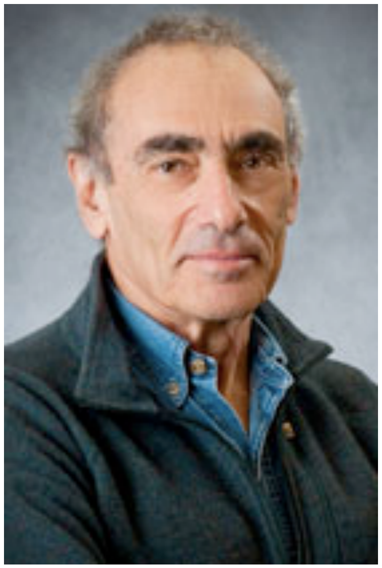
Water: H_2O

QCD Phase Diagram:

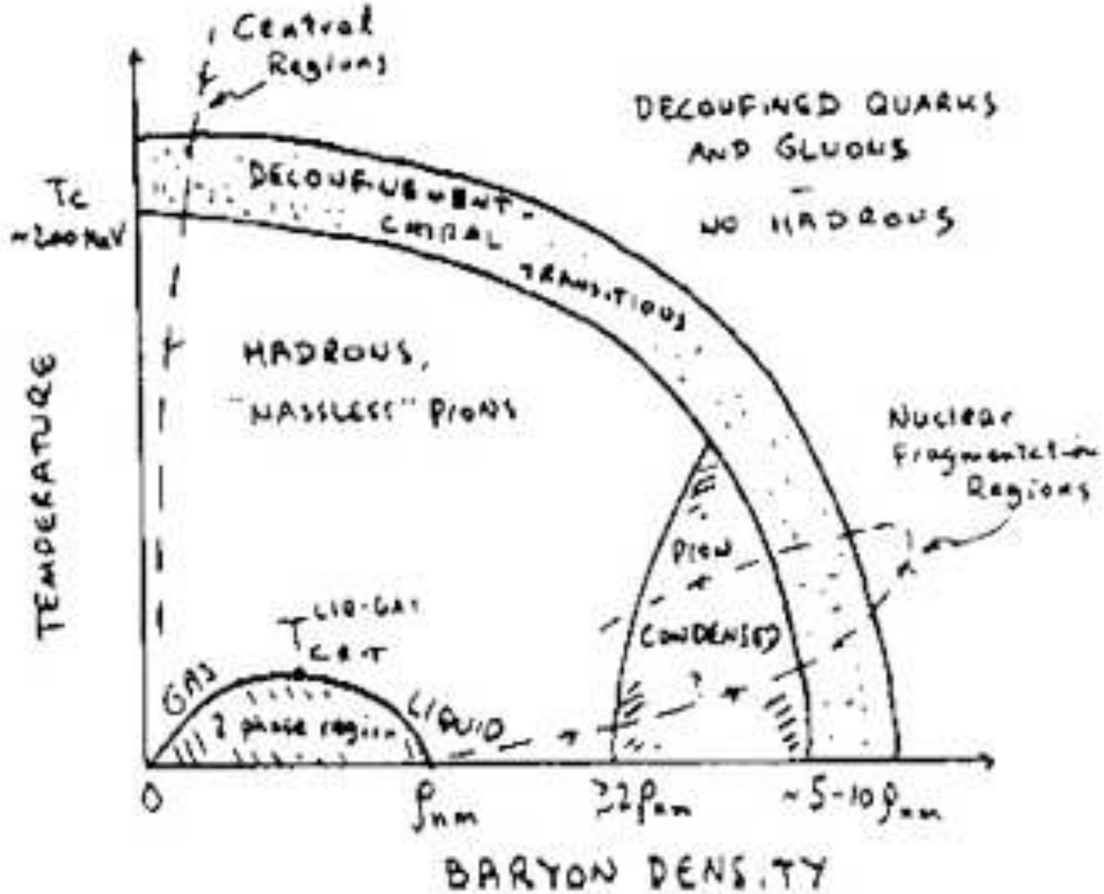
Structure of matter with color degrees of freedom, *quarks* and *gluons*.

QCD Phase Diagram (1983)

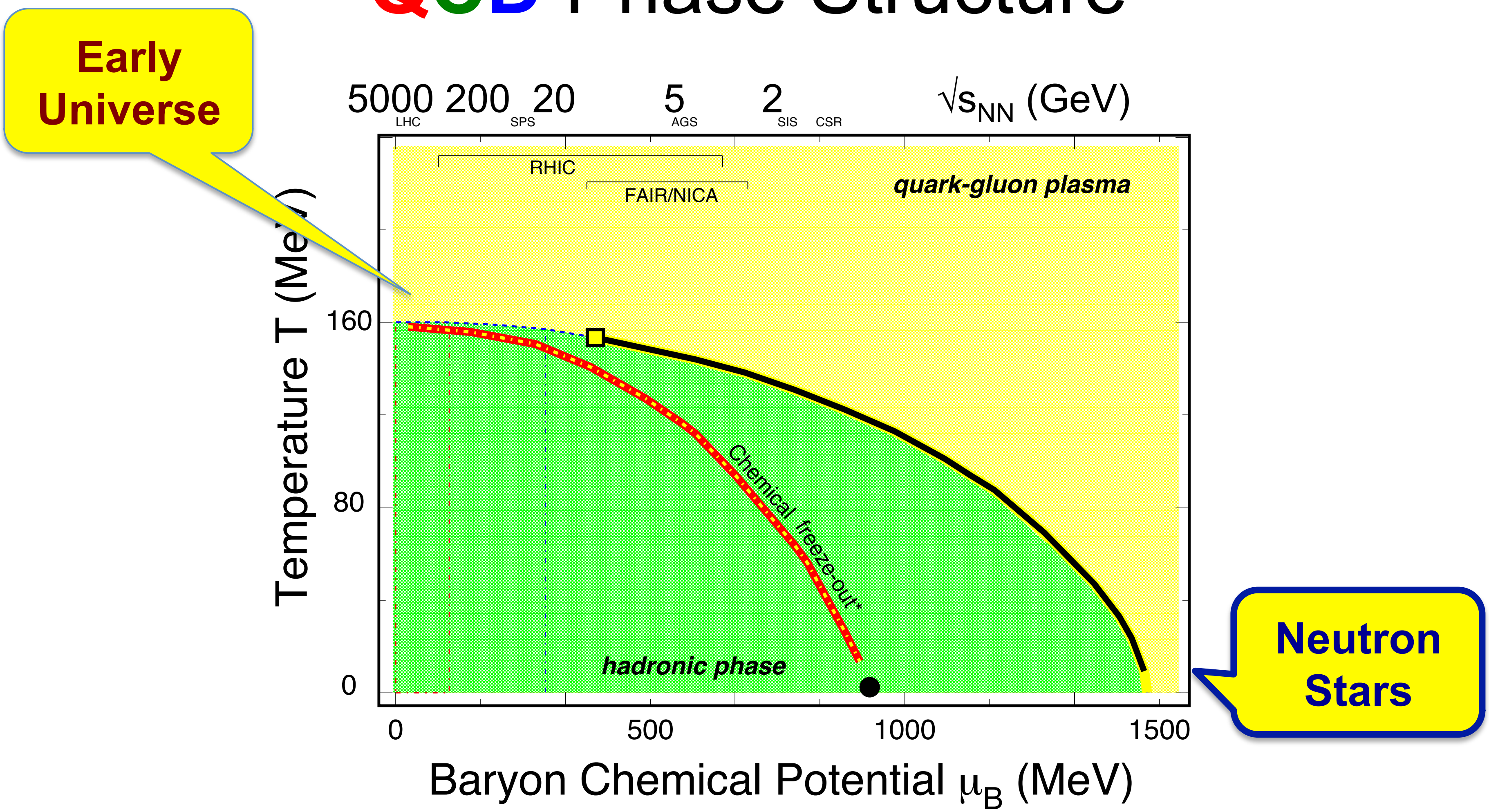
1983 US Long Range Plan *- by Gordon Baym*



Gordon Baym

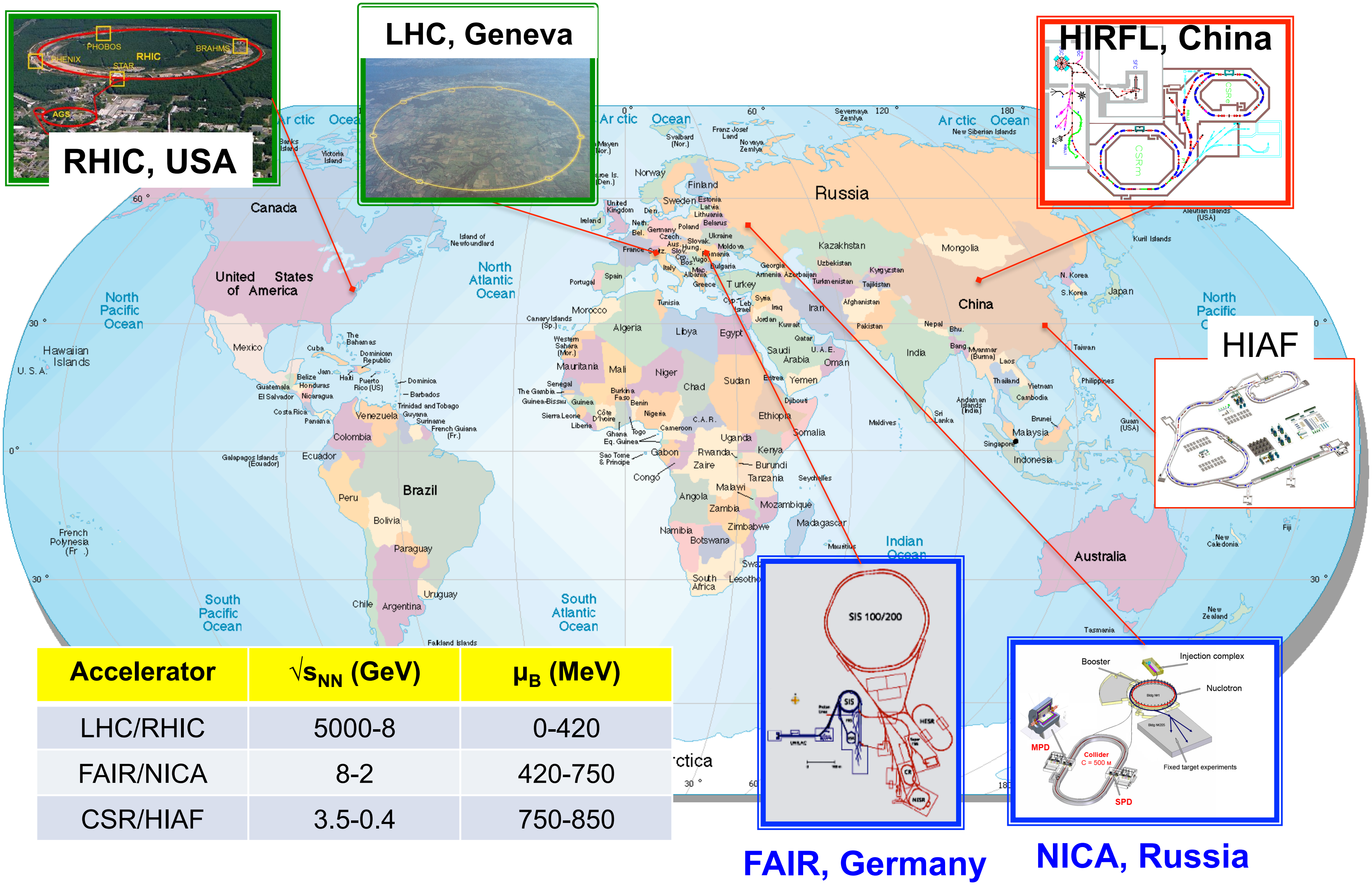


High-Energy Nuclear Collisions and the QCD Phase Structure



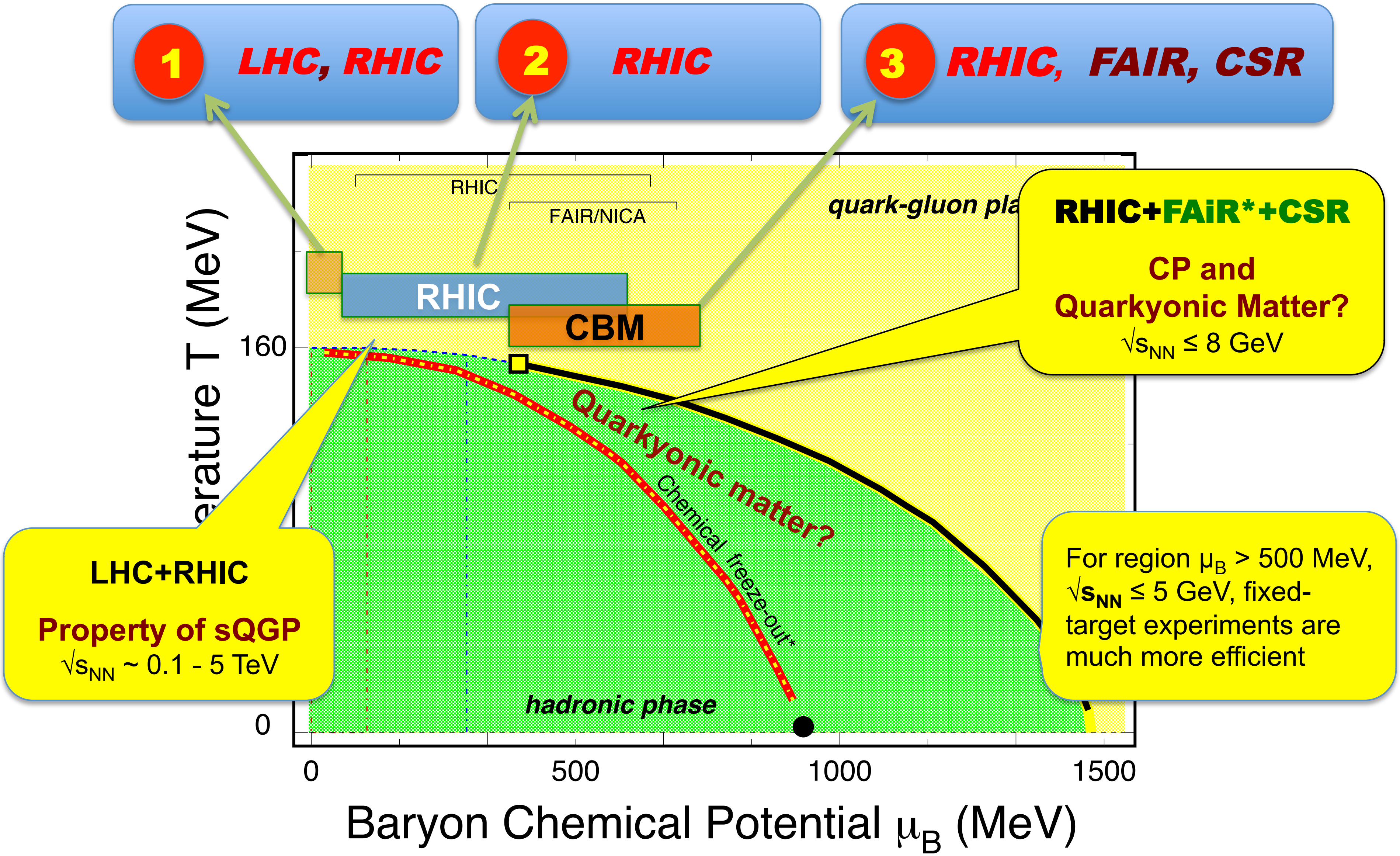
1) Baryon chemical potential μ_B is inversely proportional to the collision energy
2) $\mu_B \sim 0$: smooth-crossover from QGP to hadrons
3) $\mu_B >> 0$: models predicts a first-order phase transition
   ➔ QCD critical point at finite μ_B

High-Energy HI Accelerators

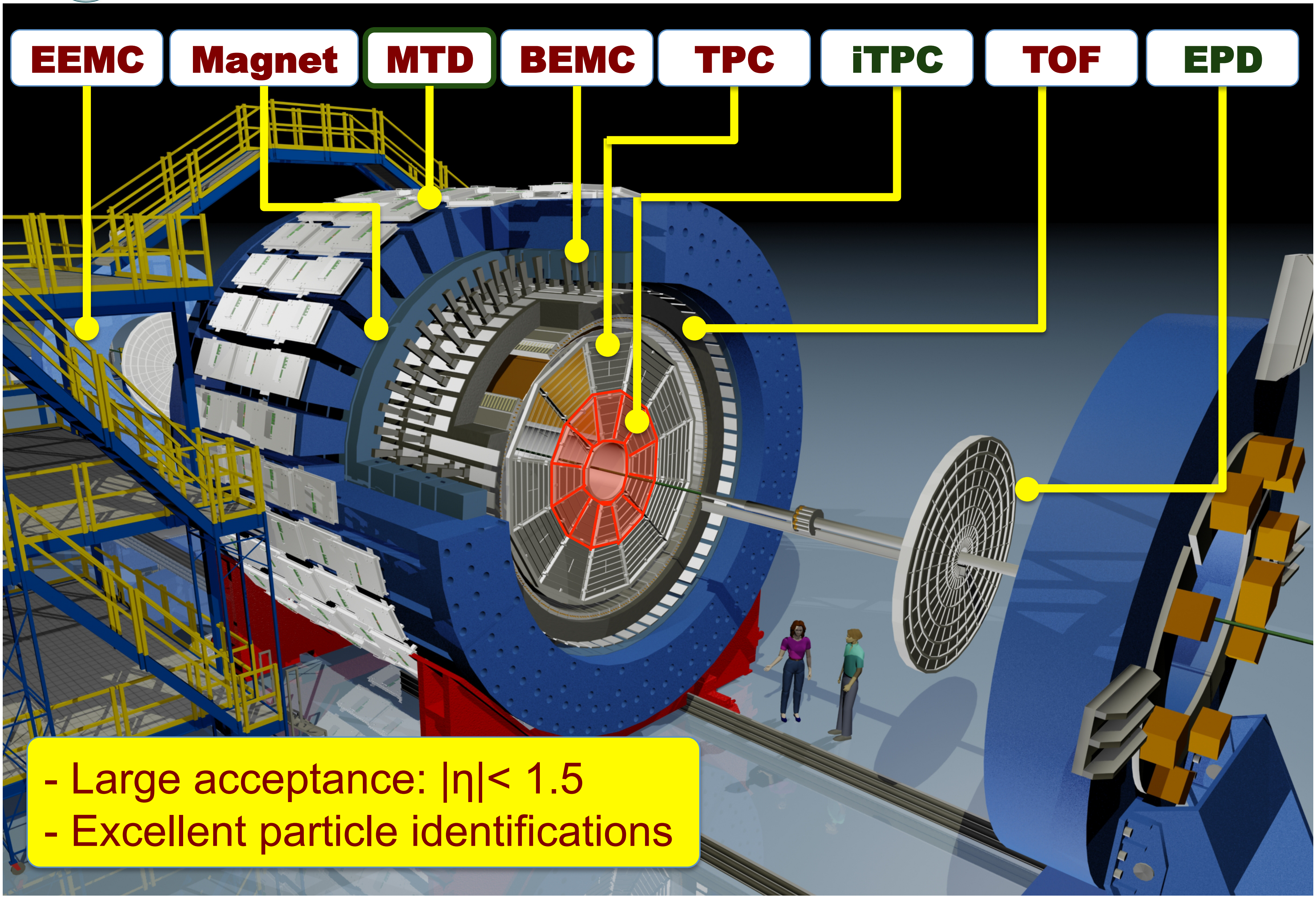


Accelerator	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)
LHC/RHIC	5000-8	0-420
FAIR/NICA	8-2	420-750
CSR/HIAF	3.5-0.4	750-850

Exploring QCD Phase Structure



STAR Detector System

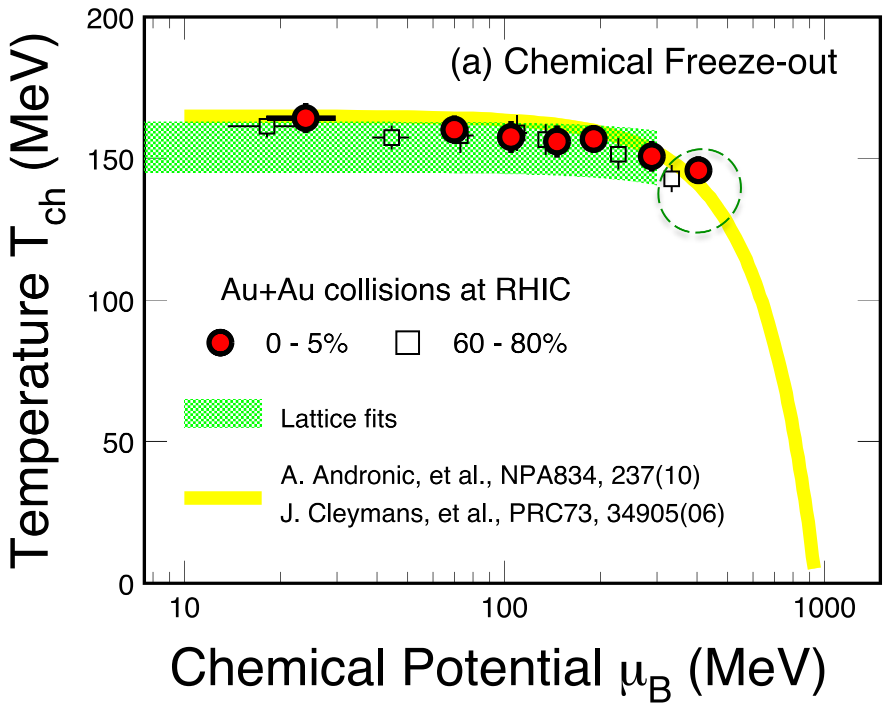


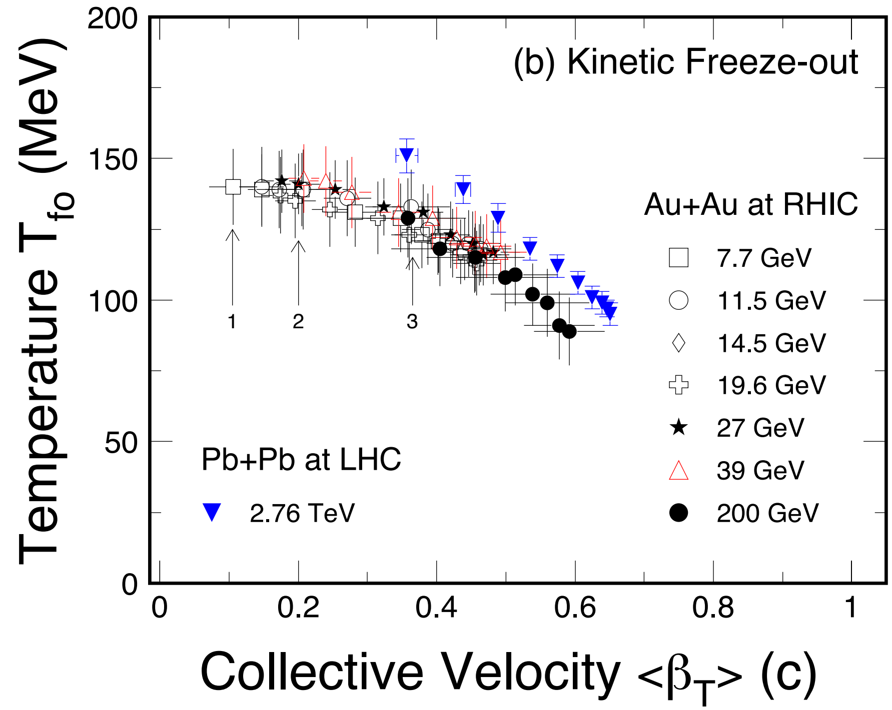
- Large acceptance: $|\eta| < 1.5$
- Excellent particle identifications

Collectivity
集体运动现象

$$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] = 0$$
$$\partial_\mu[s\, u^\mu] = 0$$

Bulk Properties at Freeze-outs





Chemical Freeze-out: (GCE)

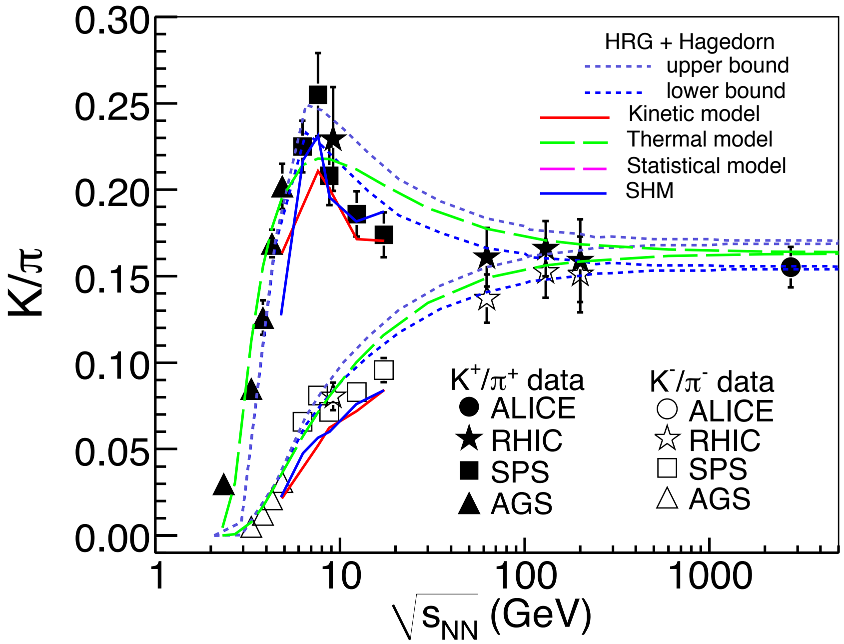
- Weak temperature dependence
- Centrality dependence μ_B!
- LGT calculations indicate the Critical Region around μ_B **~ 300 MeV?**

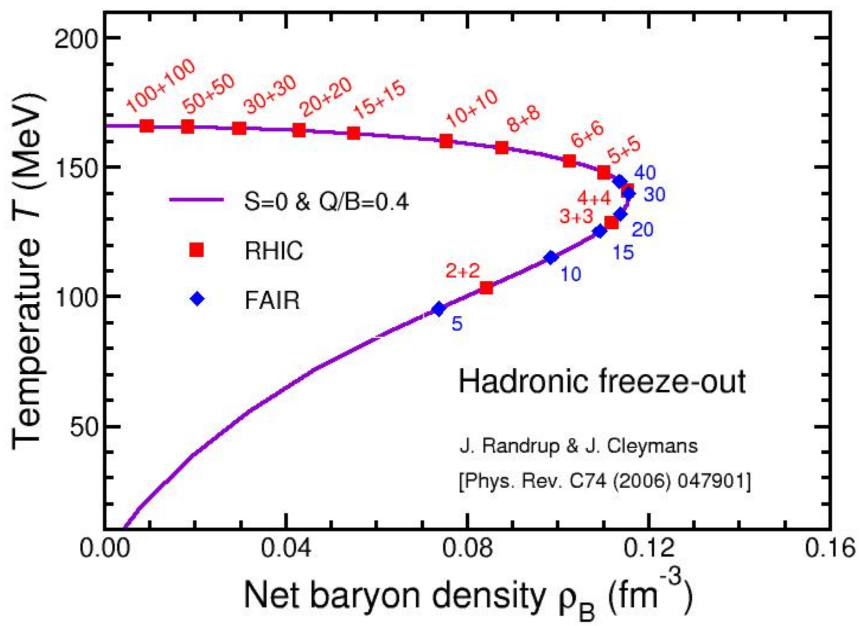
Kinetic Freeze-out:

- Central collisions => lower value of T_{fo} and larger collectivity β_T
- **Stronger collectivity at higher energy, even for peripheral collisions**

- ALICE: B.Abelev et al., PRL**109**, 252301(12); PRC**88**, 044910(2013).
- STAR: J. Adams, et al., NPA**757**, 102(05); **STAR**: 1701.07065
- S. Mukherjee: Private communications. August, 2012

K/π Ratios and Baryon Density

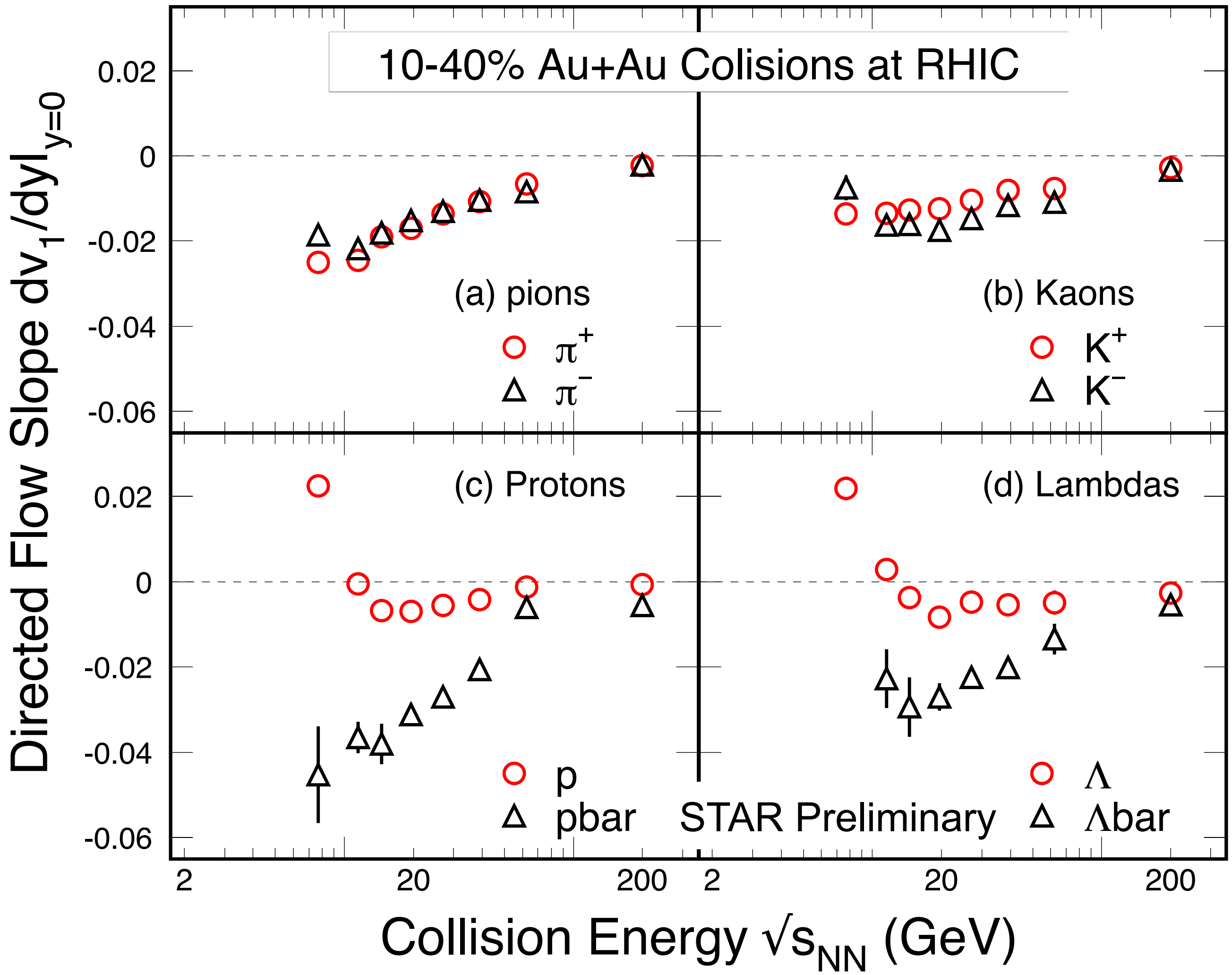




1) The **K^+/π** ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV,
   K^-/π ratio merges with **K^+/π** at higher collision energy
2) Model: **Baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV**
3) At **$\sqrt{s_{NN}}$ > 8 GeV, pair production becomes important**

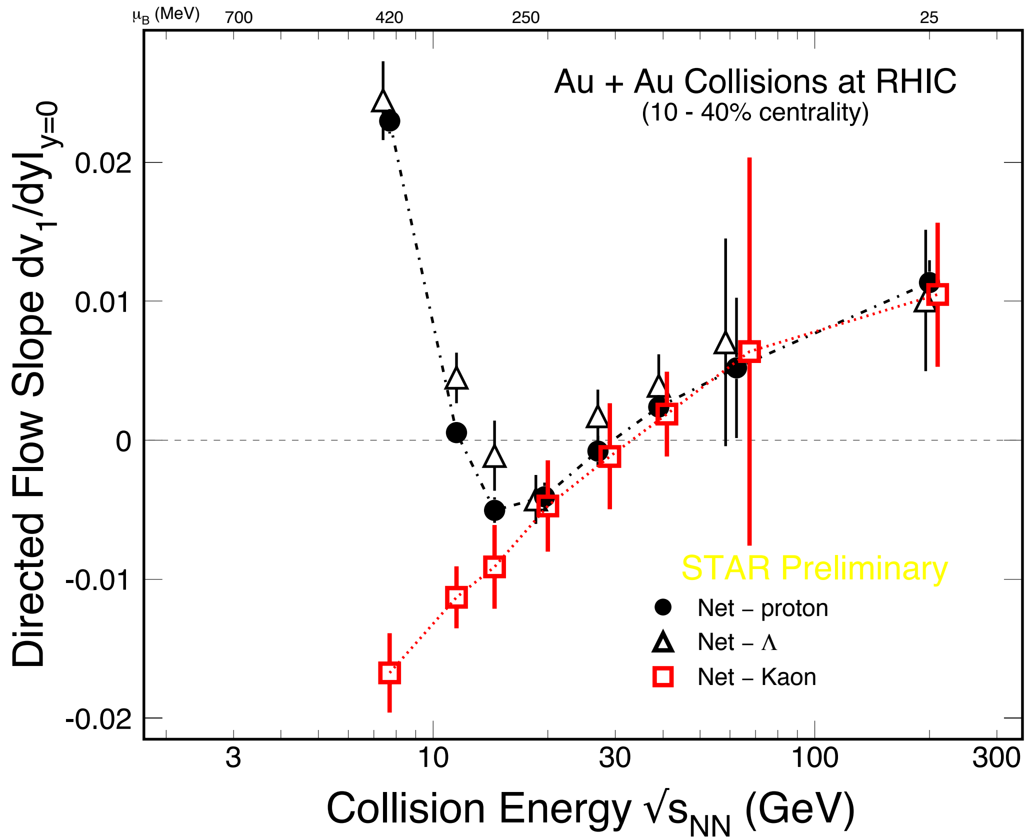
STAR: 1701.07065; J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(2006)

v_1 versus Energy



1) All produced hadrons mid-y v_1 slope < 0
2) At $\sqrt{s_{NN}}$ < 10 GeV, Baryons' v_1 becomes > 0

v_1 vs. Energy: Softest Point?



● STAR: PRL**112**, 162301(2014)

□ △ STAR: Preliminary

1) Minimum at $\sqrt{s_{NN}}$ = 10 GeV for net-proton and net-Λ, but net-Kaon data continue decreasing as energy decreases

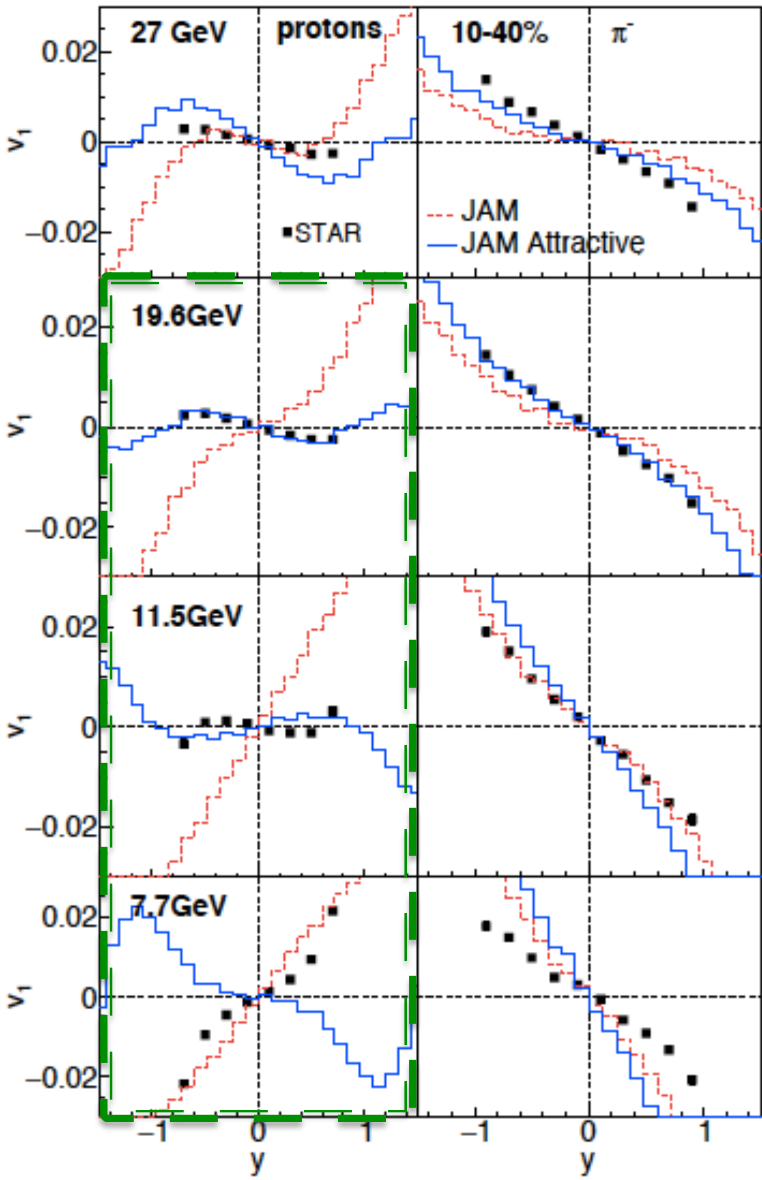
2) At low energy, or in the region where the net-baryon density is large, repulsive force is expected, v_1 slope is large and positive!

3) Softest point only for baryons?

4) Need model to explain!

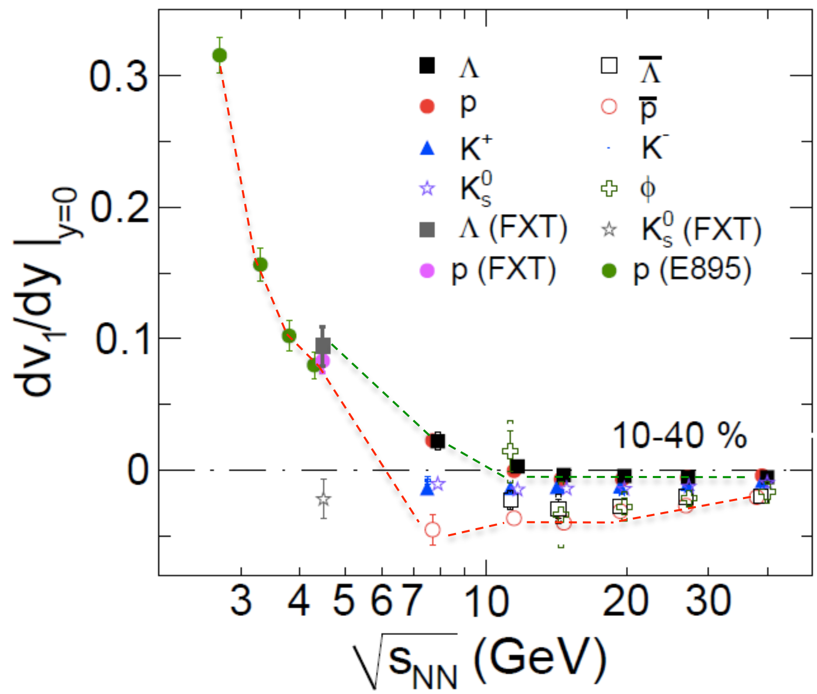
- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)
- Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16), arXiv: **1601.07692**

v_1 vs. Energy: Softest Point?



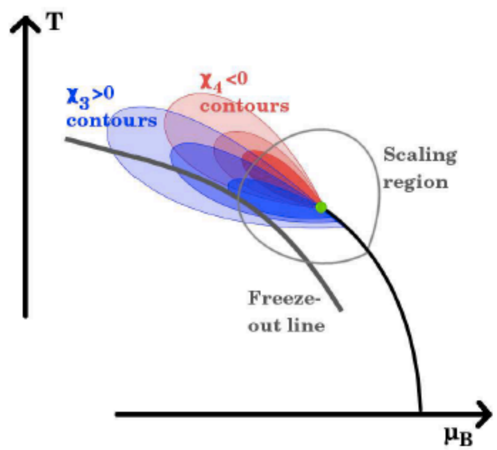
"Attractive force" → Change of the EOS ~ "softest point"

- Y. Nara, A. Ohnishi, H. Stoecker, arXiv: **1601.07692** ; PRC94, 034906(2016)

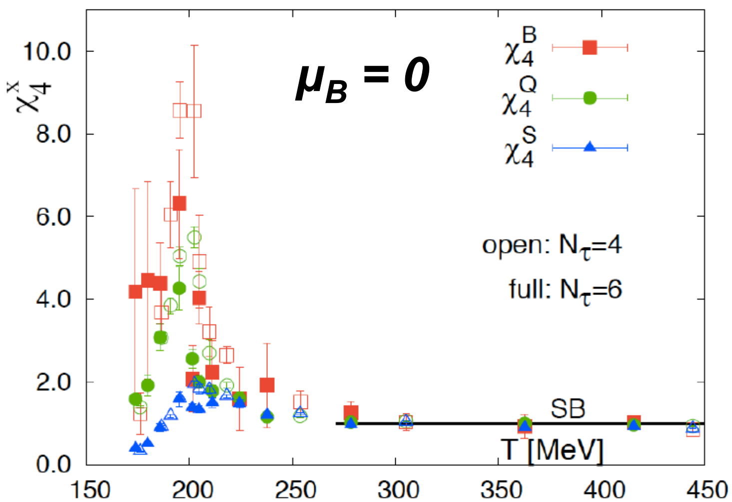


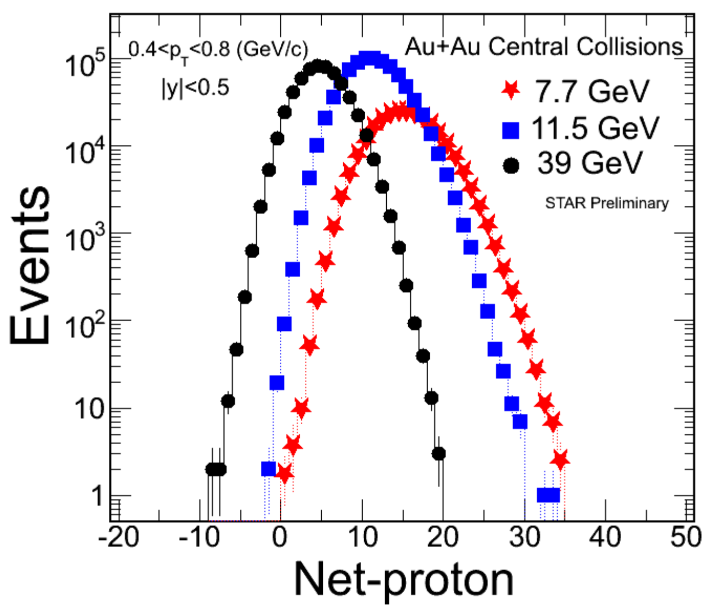
STAR data: Kathryn Meehan, QM2017

Criticality
临界现象



Higher Moments and Criticality





1) Higher moments of conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \;\; \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \;\; \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

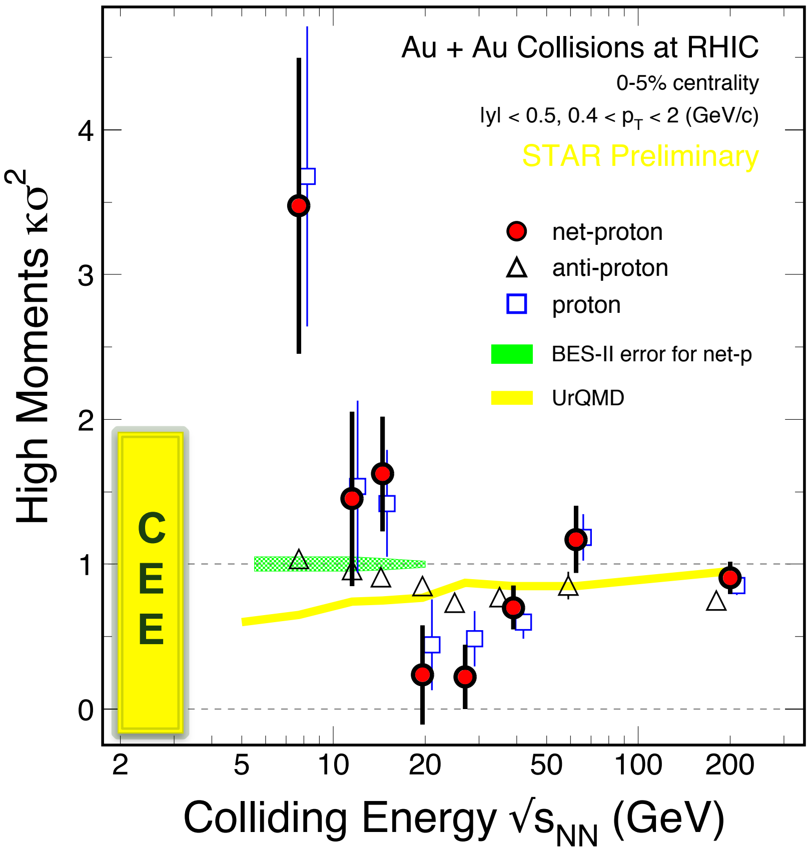
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

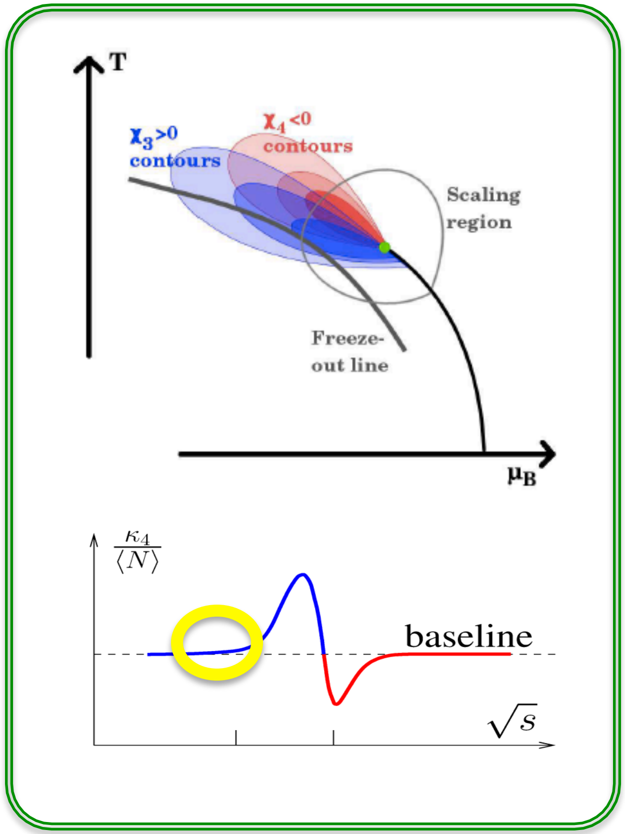
4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

References:

- STAR: *PRL* **105**, 22303(10); *ibid*, **112**, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06) // M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11),
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)
- PBM, A. Rustamov, J. Stachel, arXiv:1612.00702

Search for the QCD Critical Point





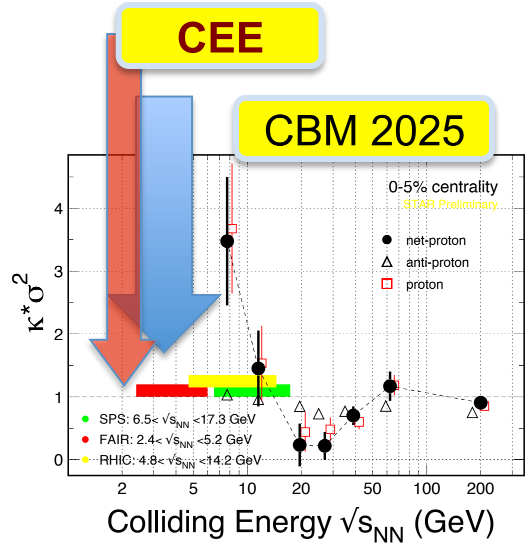
1) CEP=(μ_E=685, T_E=106)MeV => $\sqrt{s_{NN}}$ ~ 4 GeV

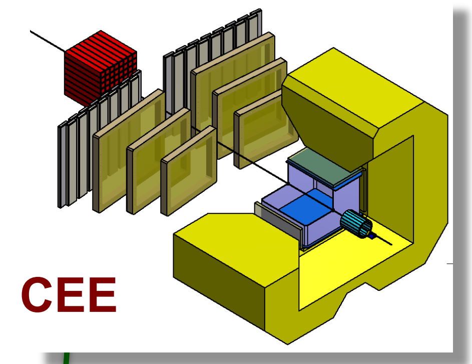
F. Gao, et al. PR**D93**, 094019(2016)

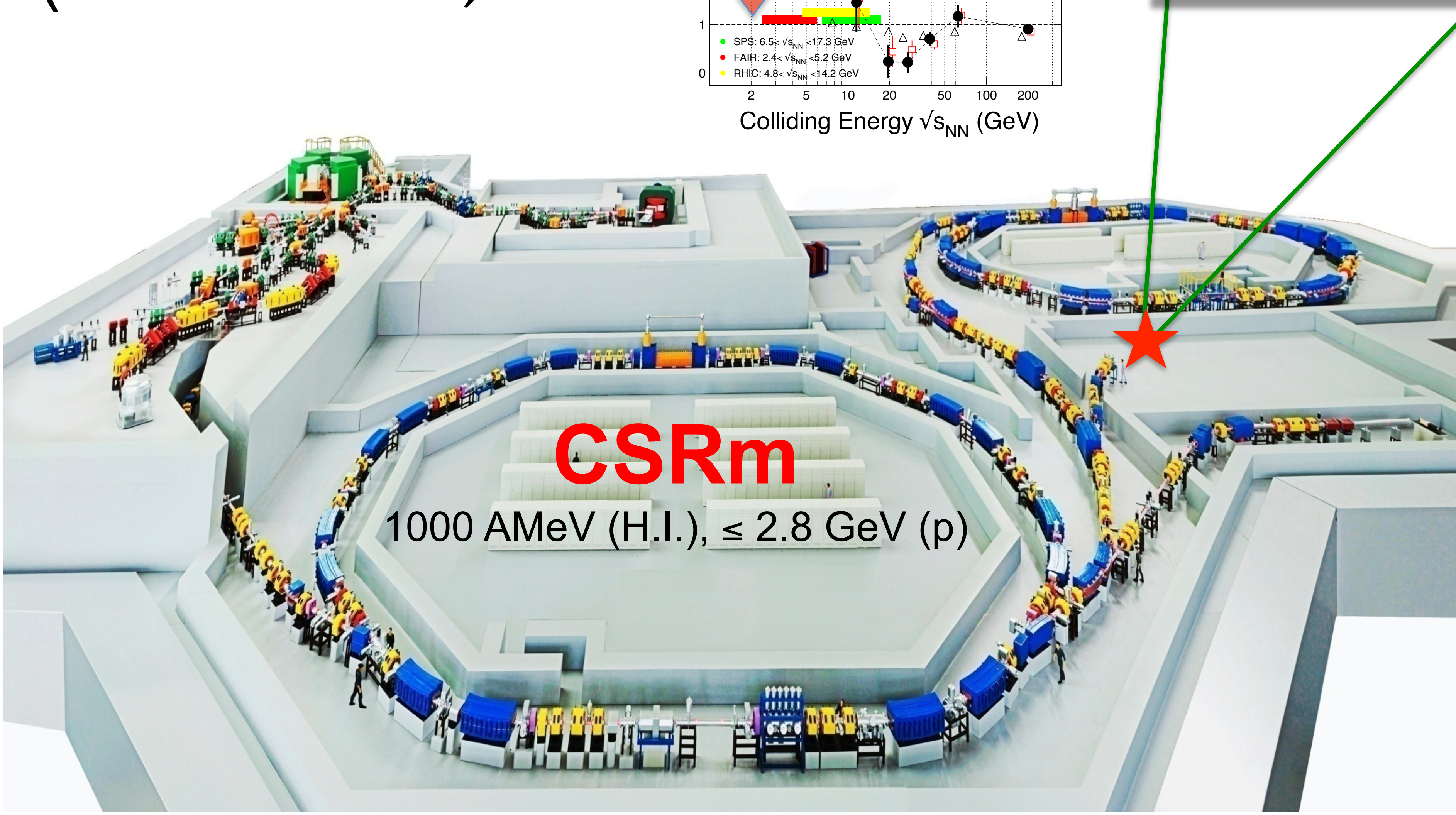
2) At CSR: $\sqrt{s_{NN}}$ ~ 2 GeV and at **HIAF: $\sqrt{s_{NN}}$ ~ 3.5 GeV**

➔ CEE is important to complete the 'CP oscillation'

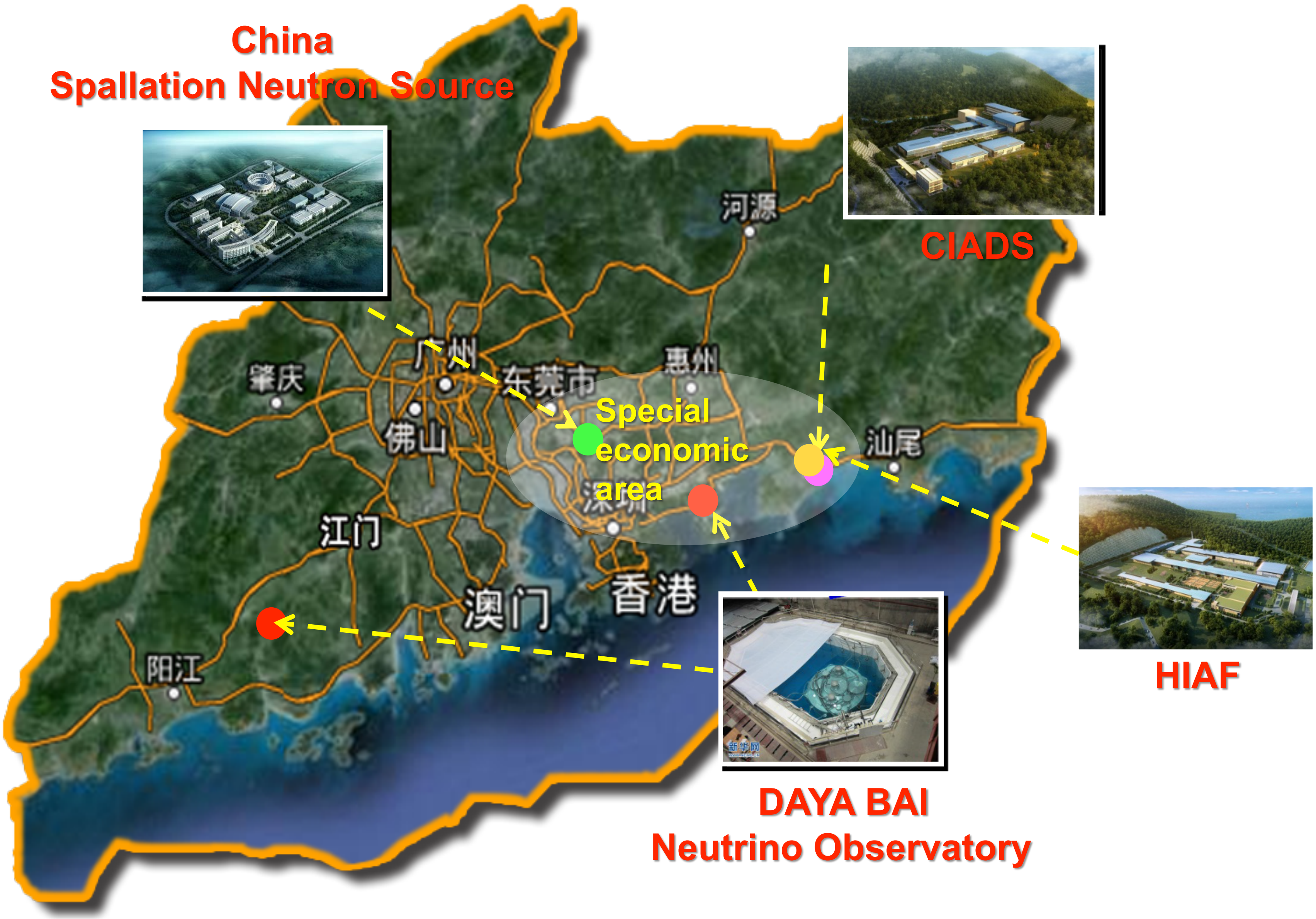
兰州重离子加速器
冷却储存环
(HIRFL-CSR)







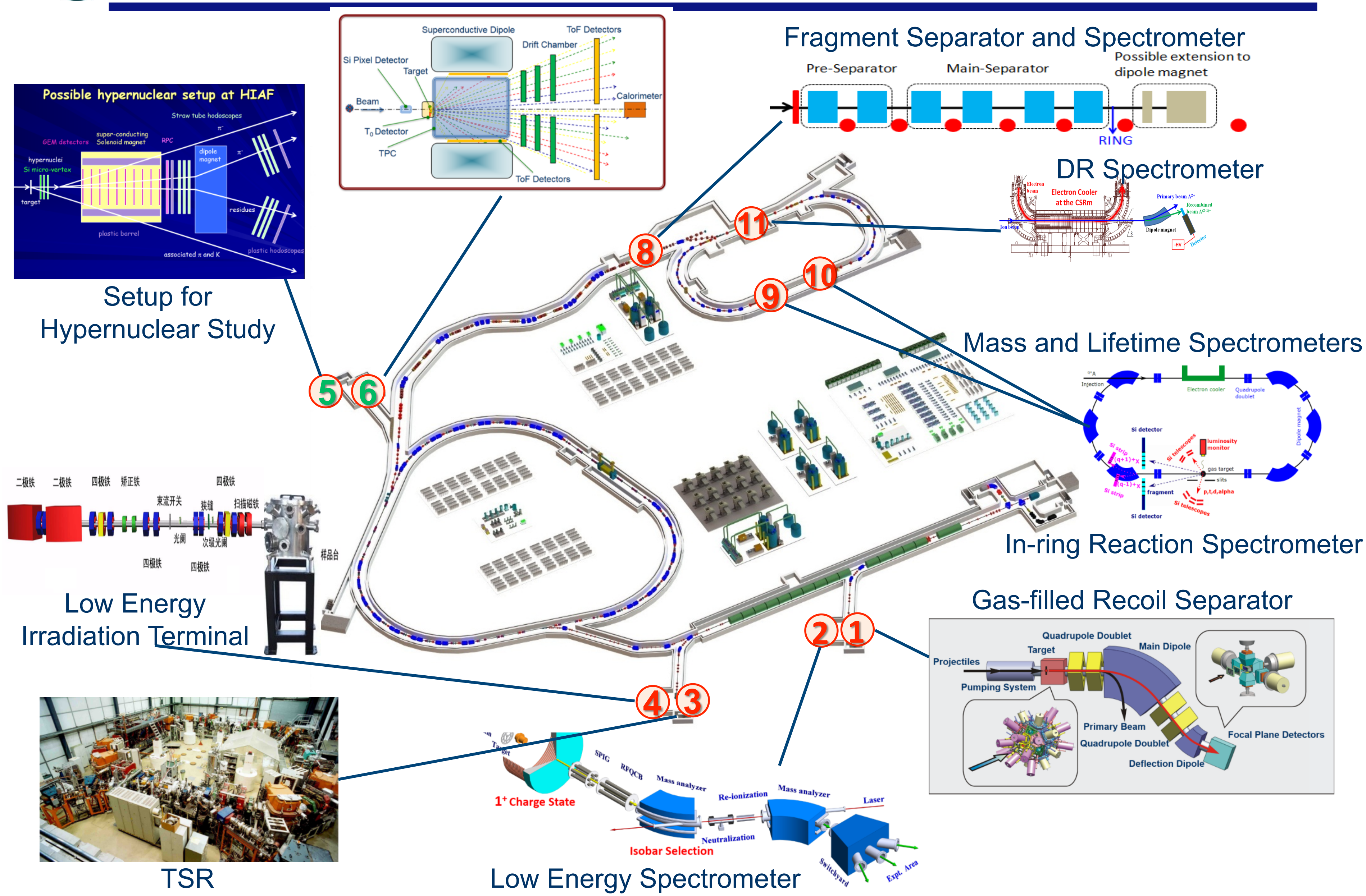

广 东 省 政 区
HIAF



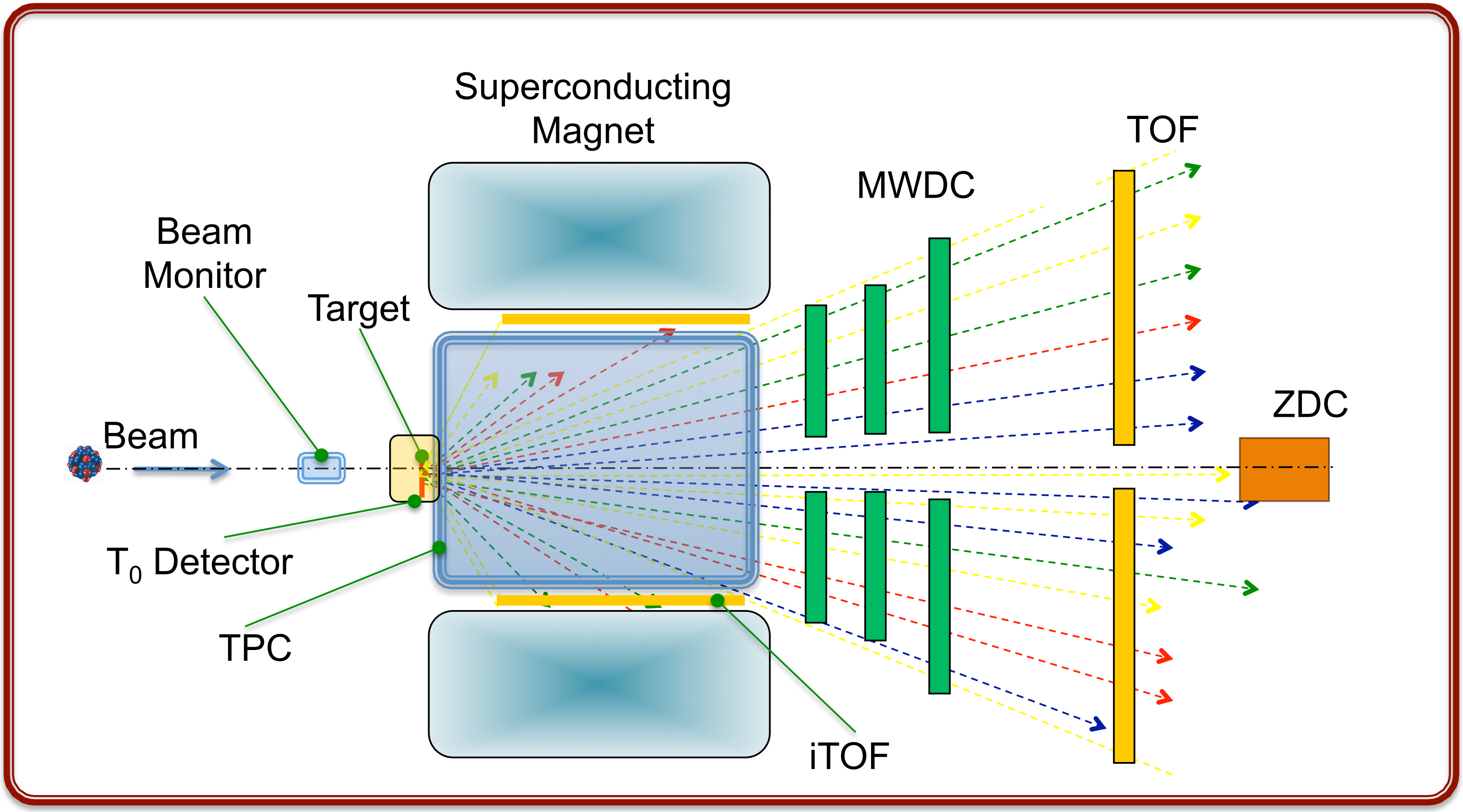
The establishment of the National Research Center at the Pearl River Delta is planned

Huizhou city and Guangdong province will cover the expenses for land, preparing land, constructing roads, electricity and water supply stations, …

Experimental Setups at HIAF



CEE Concept



技术亮点 1) Beam Monitor (CCNU)

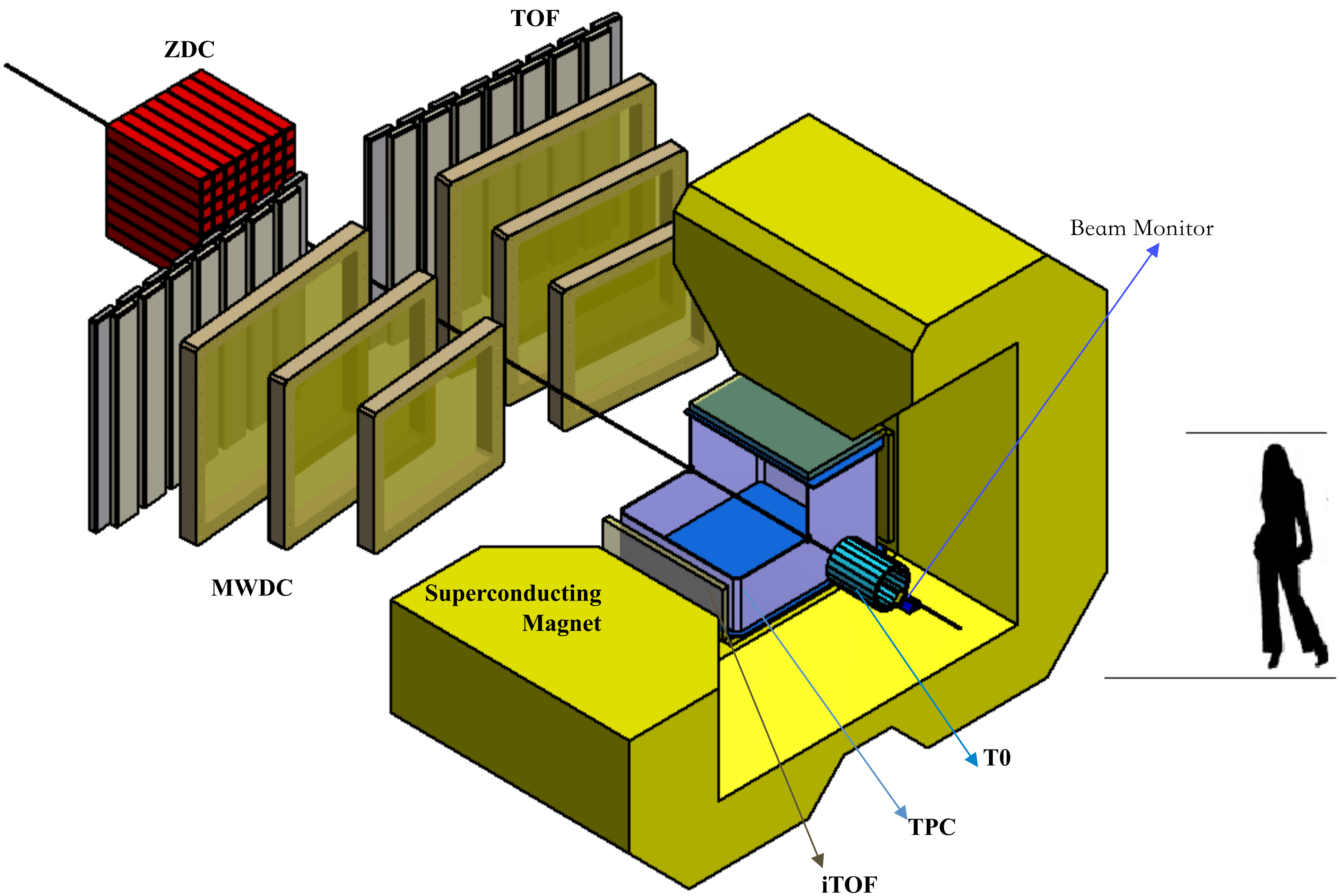
自主研制 2) Time of Flight Detector (MRPC) (THU、USTC)

3) Time Project Chamber (SINAP, CAS)

4) DAQ (USTC)

5) Superconducting Magnet (IMP, CAS)

CEE Concept

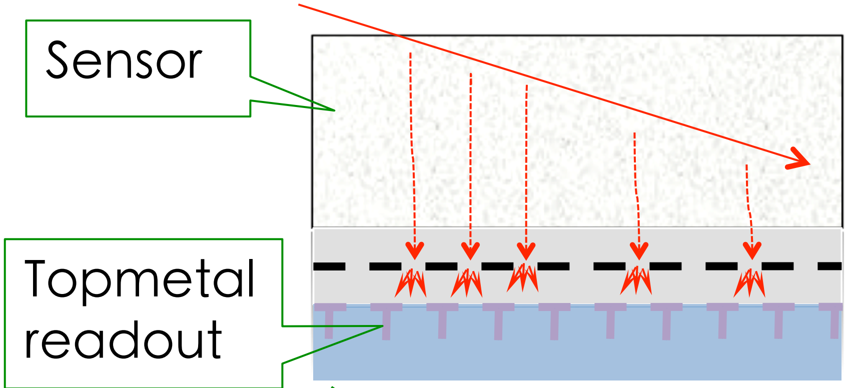

TOF
ZDC
Beam Monitor
MWDC
Superconducting
Magnet
T0
TPC
iTOF

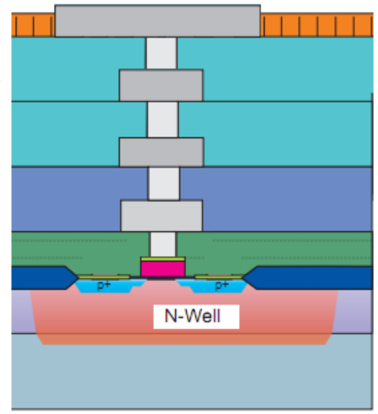
CEE: design parameters

零度角量能器 ZDC	
总体尺寸	1(长)×1.5(高)×1.5(宽) m^3
能量分辨	10%
通道数	400
超导磁铁	
总体尺寸	2.5 (长)×3 (高)×4 (宽) m^3
均匀场区尺寸	1(长)×0.8(高)×1.2(宽) m^3
中心场/均匀度	5kG / 1%
总体重量	200 吨
漂移室径迹探测器	
横向位置分辨	0.3 mm
漂移室层数	3
通道数	3000
总面积	12 m^2
相对动量分辨	5%

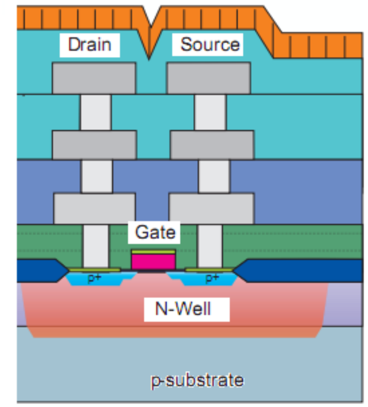
时间投影室探测器（TPC）	
灵敏区体积	1.(长)×0.8(高)×1.(宽) m^3
读出片大小	～80 mm^2
通道数	12k
工作气体	90% Ar + 10% CH_4
相对动量分辨	π、p典型值5%，总≤10%。
粒子种类量程	Z <= 2, π, p, d, t, He
双径迹区分	< 3 cm
径迹多重性限制	200
1级触发事件率	1000 Hz
微像素定位探测器	
位置分辨	< 50 μm
时间分辨	1μs
探测器层数	2
像素数	360k
总面积	18cm^2
飞行时间探测器	
时间分辨	eTOF < 80 ps， iTOF < 50 ps T_0 < 50ps
占有度	10%~15%
总面积	12m^2
通道数	3000

Topmetal Concept



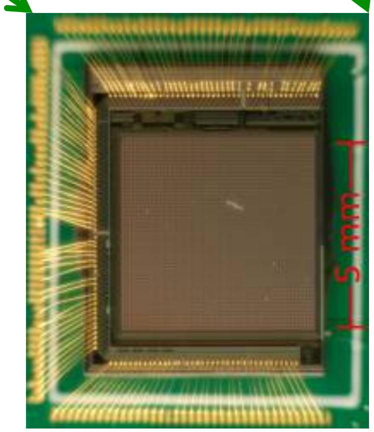


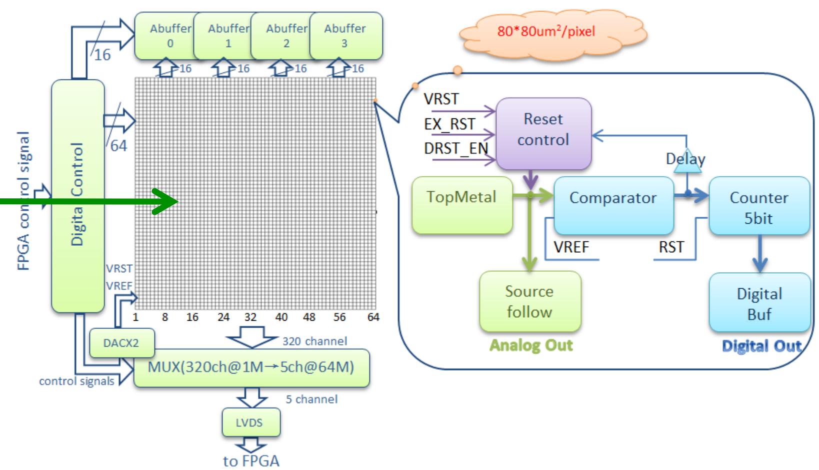
Topmetal



CMOS

Beam Monitor



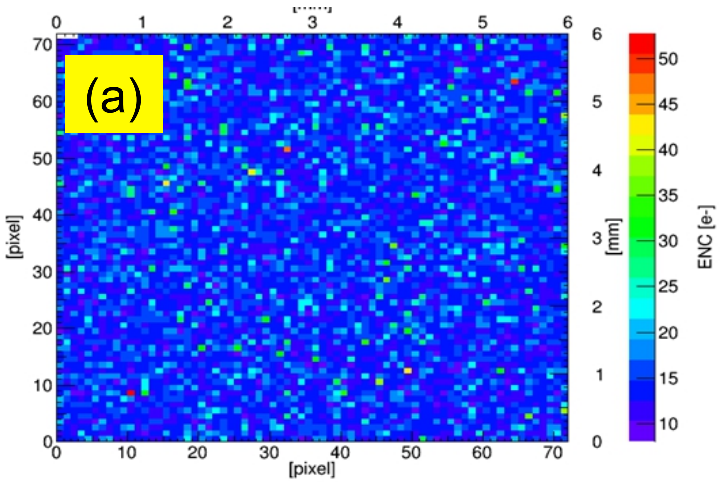


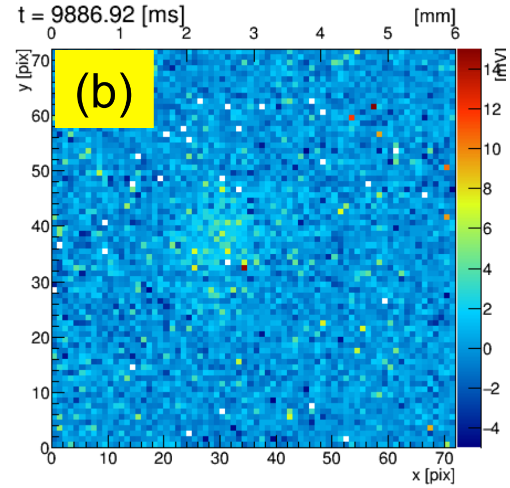
Position and charge sensitivity

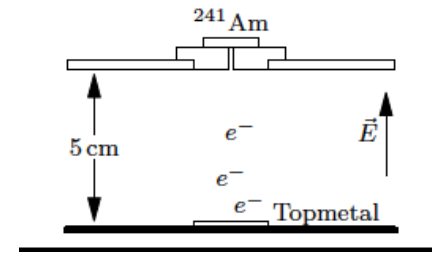
Topmetal Test Results

NIMA, 849, 20-24 (2017)

中国发明专利 申请（专利）号：201210039357.1

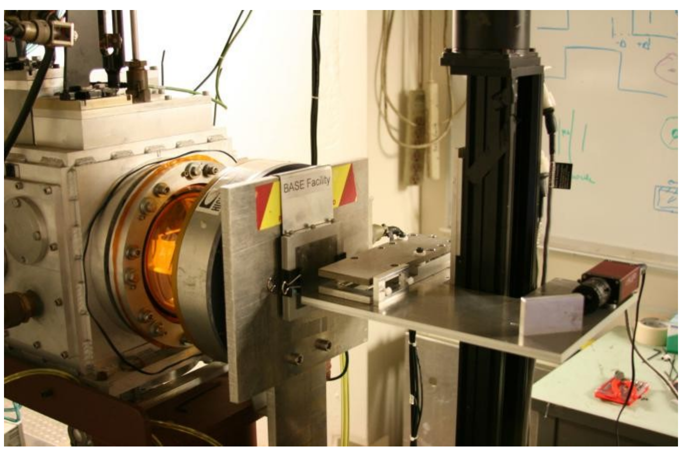


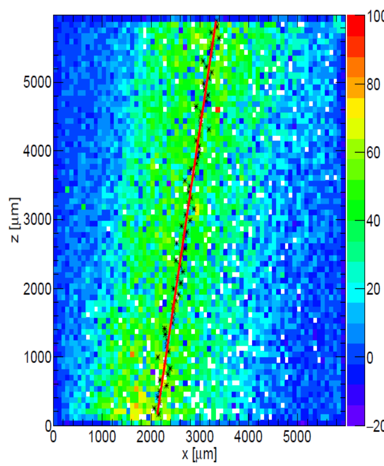




2015: (a) **<ENC> ≤ 13e**

(b) sensitive to single charge particle

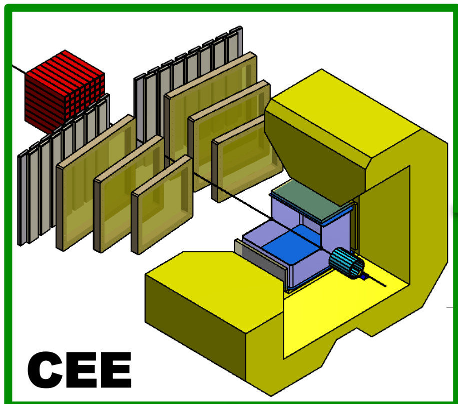


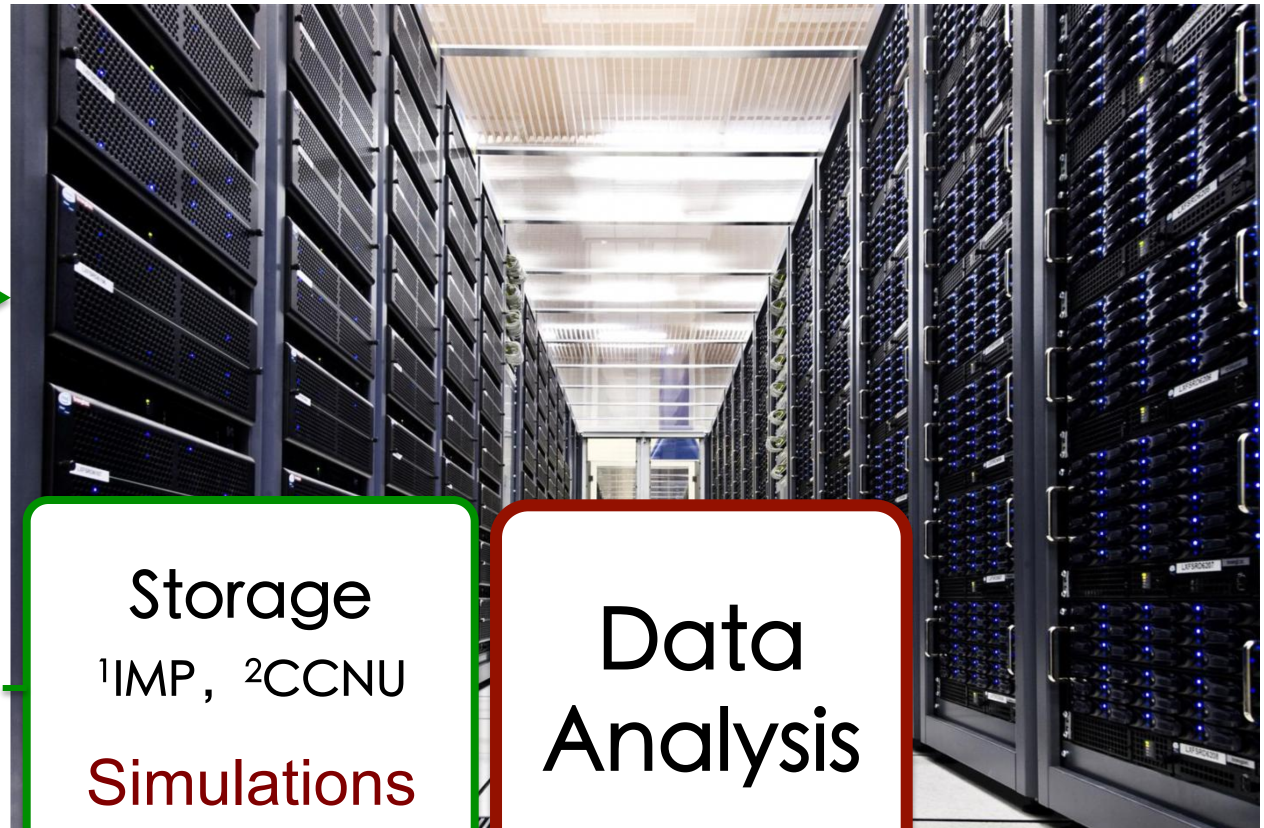


2016 results:

- position resolution < 17 μm
- NIMA, 849, 20-24 (17)

Computing Centers for Data Storage and Analysis





Storage

[1]IMP, [2]CCNU

Simulations

Data Analysis

1) Institute of Physics: Computing + Storage
2) CCNU: New Computing Center (**NSC^3**)

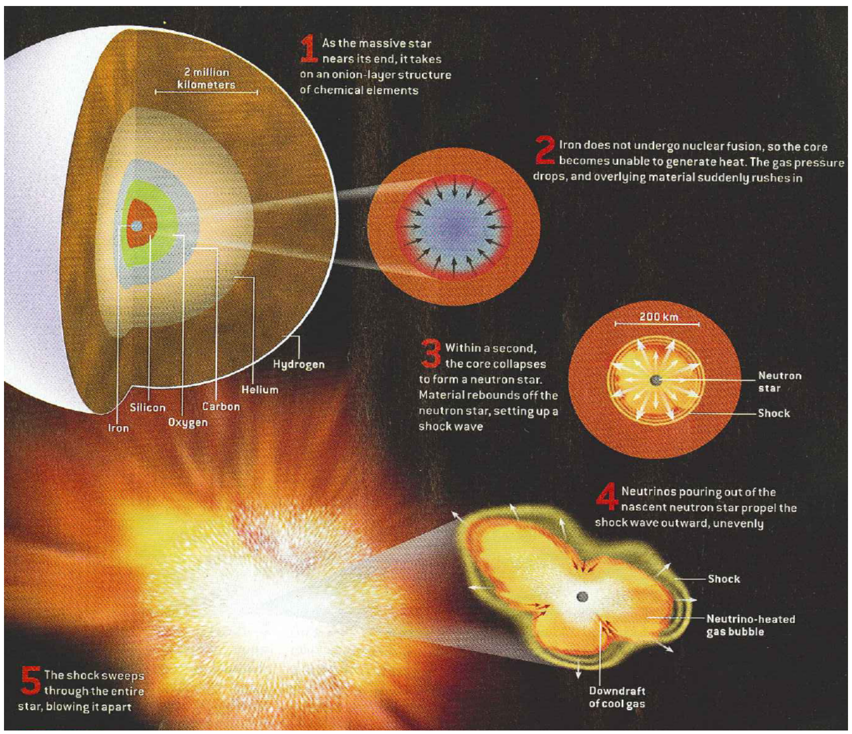
CEE Team

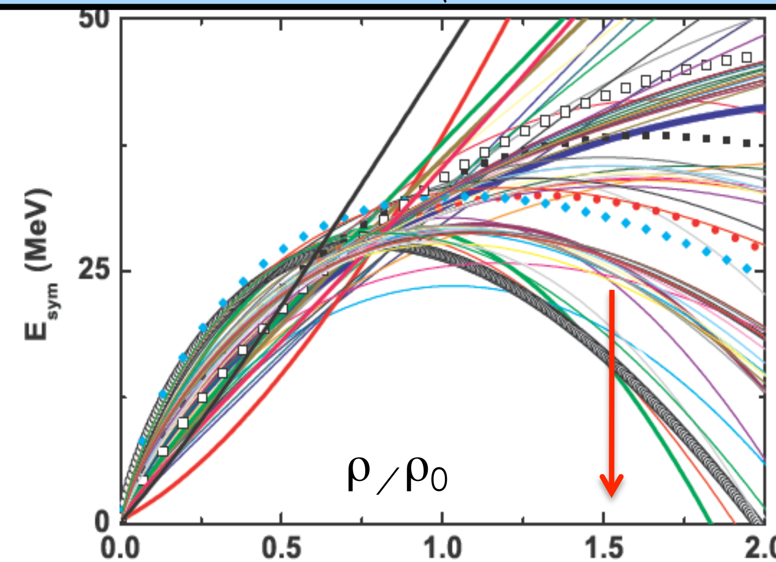
CCNU, IMP, SINAP, Tsinghua Univ., USTC, PKU, Fudan Univ. HIT, Lanzhou Univ., ...

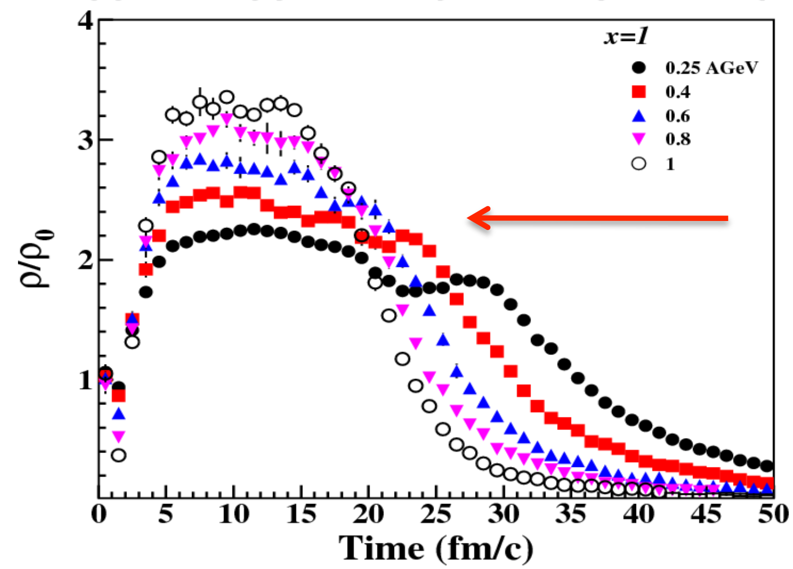
北京大学，复旦大学，湖州师范学院，哈尔滨工业大学、兰州大学，三峡大学, 中国地质大学

(I) Symmetry Energy and EOS

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

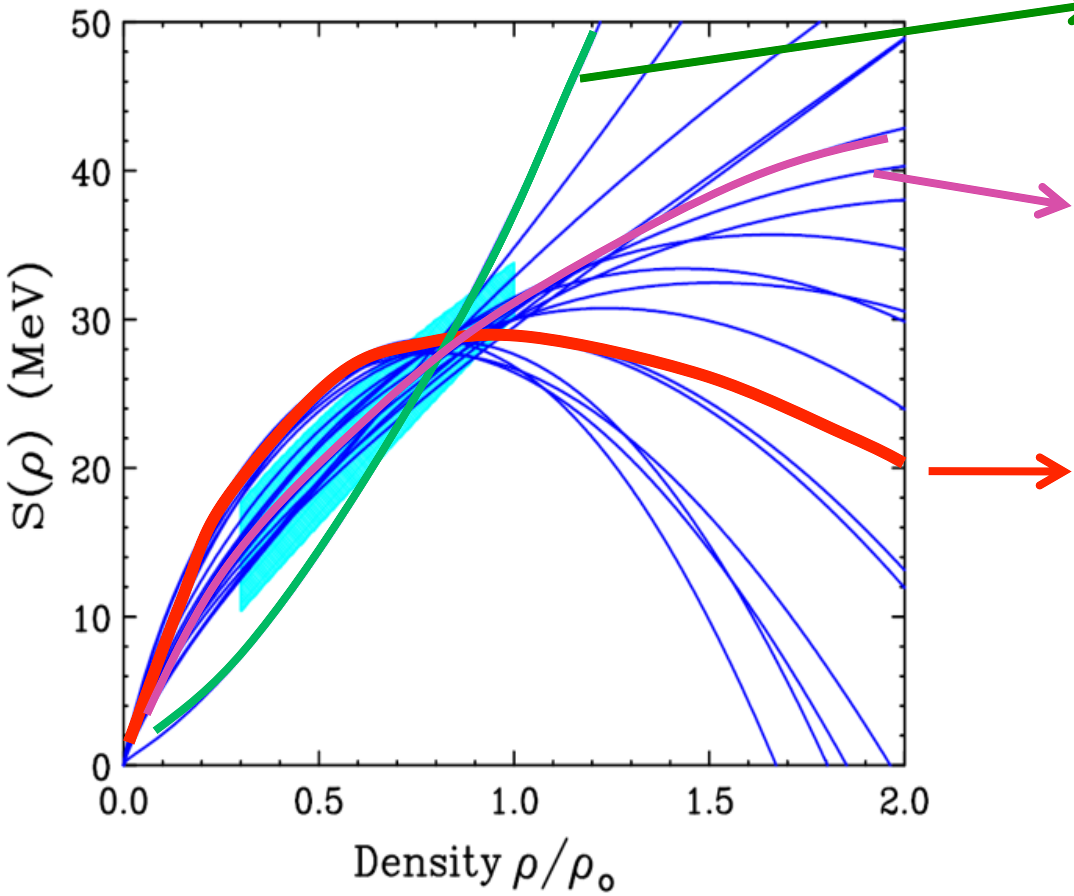






HIRFL-CSR and HIAF are ideal energy region for study symmetry energy at high baryon density

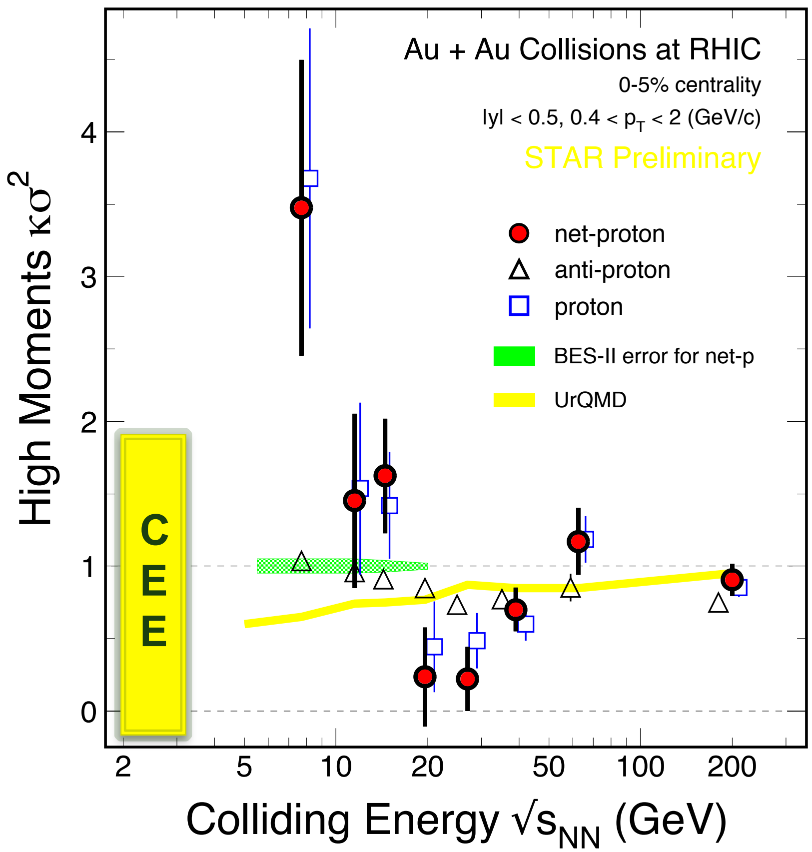
$E_{sym}(\rho)$ Above Saturation Density

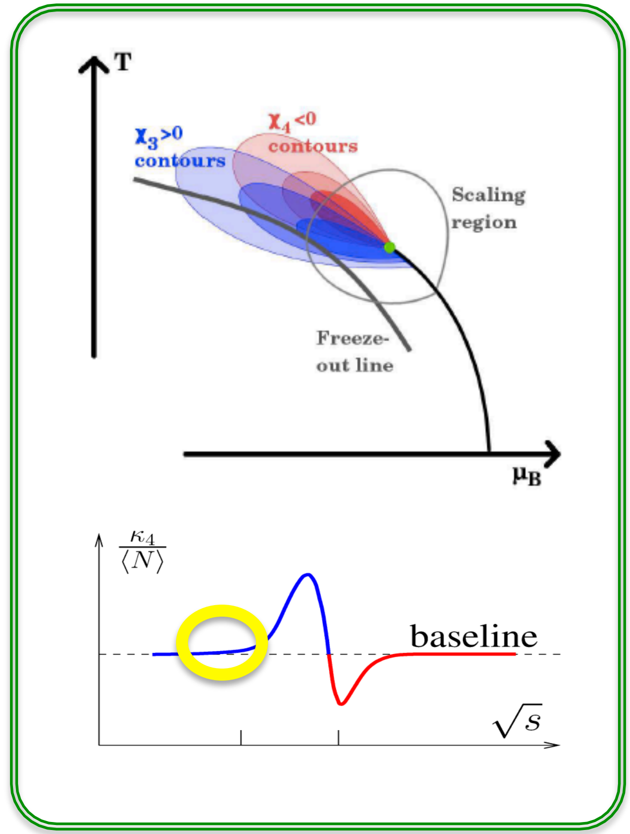


- **Stiff** π^-/π^+
  Phys. Lett. B683, 140(2010)
- **Moderate nucleon flow**
  Phys. Lett. B697, 471 (2011)
  Phys. Lett. B700, 139 (2011)
- **Soft** π^-/π^+
  Phys. Rev. Lett. 102, 062502(2009)
  Phys. Lett. B718, 1510(2013)
- **No sensitivity in peon ratios**
  J. Hong et al. ArXiv: 1307.7654

- Medium effect are important by J. Xu et al.
- More experimental data at $\rho/\rho_0 > 1$ are needed

(II) Search for the QCD Critical Point





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F. Gao, et al. PR**D93**, 094019(2016)

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➔ CEE is important to complete the 'CP oscillation'

Summary

1) HIAF is scheduled to be online in 2024. CEE is important for exploring the QCD phase structure in the high baryon density region

2) Physics focus:
   1) QCD critical point — proton PID
   2) **V_1** of (π, K, p, Λ) — pion PID
   3) Symmetry energy
   4) Polarized target

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Thanks for your attention!