Study the QCD Phase Structure at the *High Baryon Density*

- Recent Results from RHIC Beam Energy Scan-I

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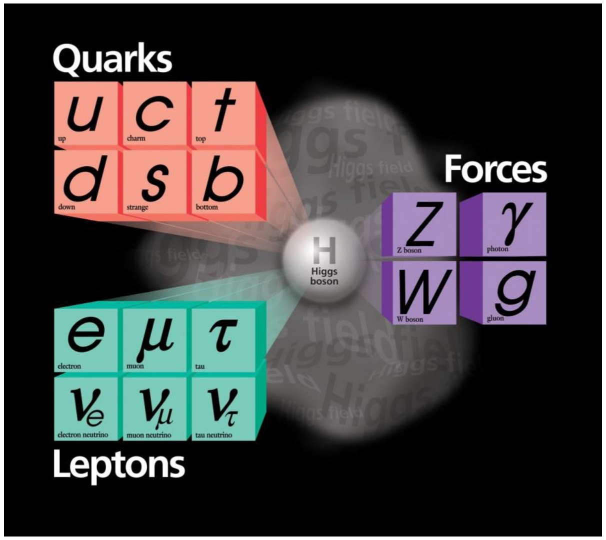
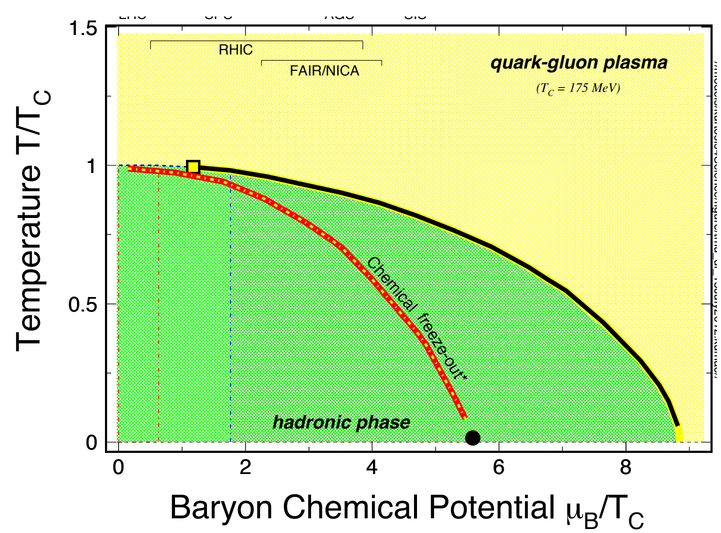
QCD in the Twenty-First Century



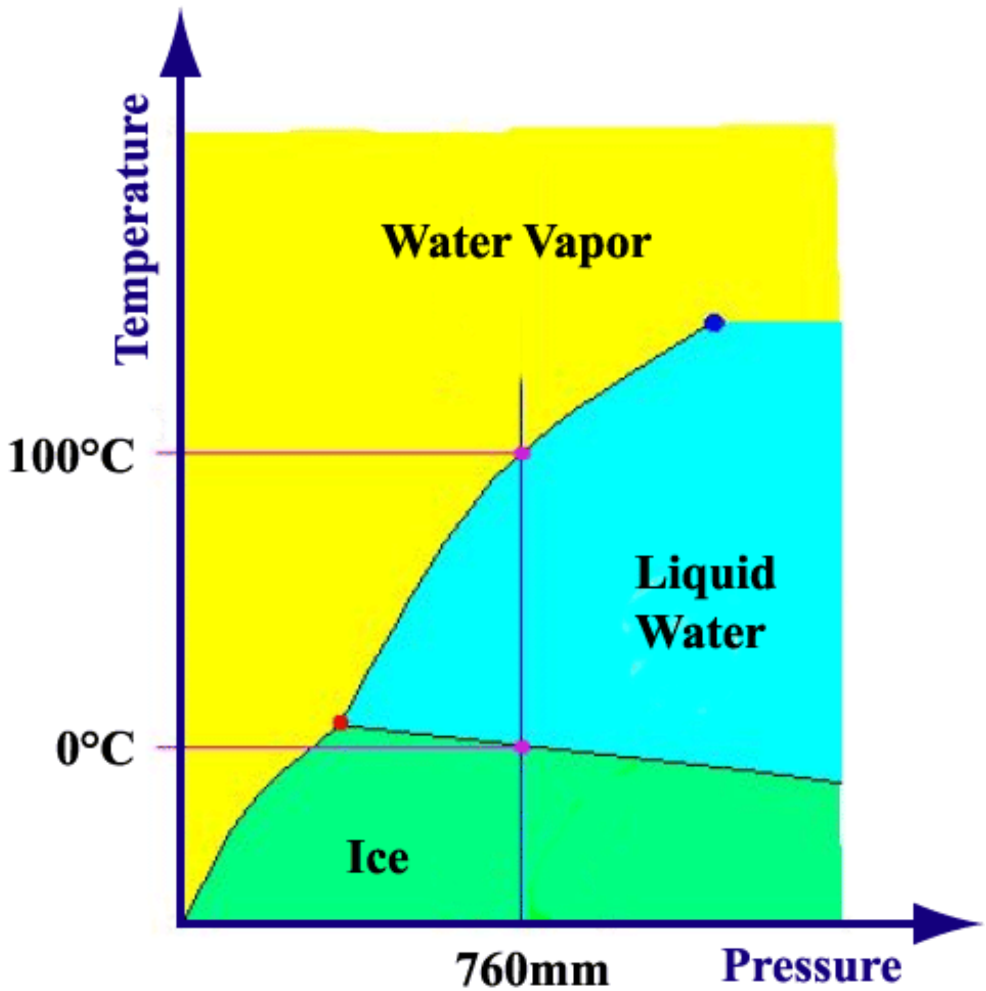
Emergent properties with QCD degrees of freedom!

(1) Higgs Particle –
- **Origin of Mass**, **QCD dof**
- Standard Model ➔ The *Theory*

(2) QCD Emergent Properties:
- Confinement
- χ_C symmetry
- QCD Phase Structure
- Nucleon helicity structure
- Non-linear QCD at small-x



Phase Diagram: Water

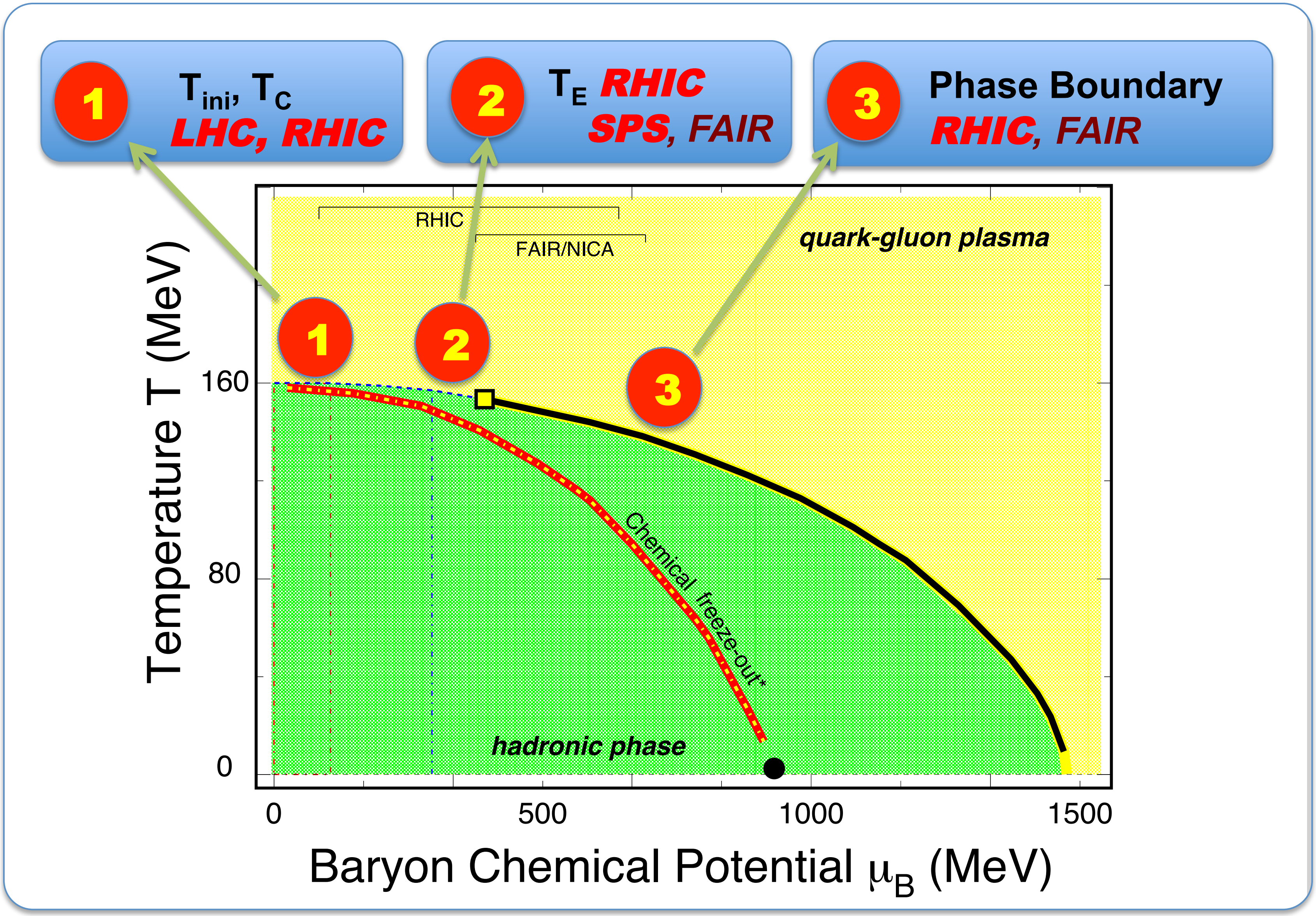


Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

Water: H_2O

The QCD phase diagram: structure of matter with quark-, gluon-degrees (color degrees) of freedom.

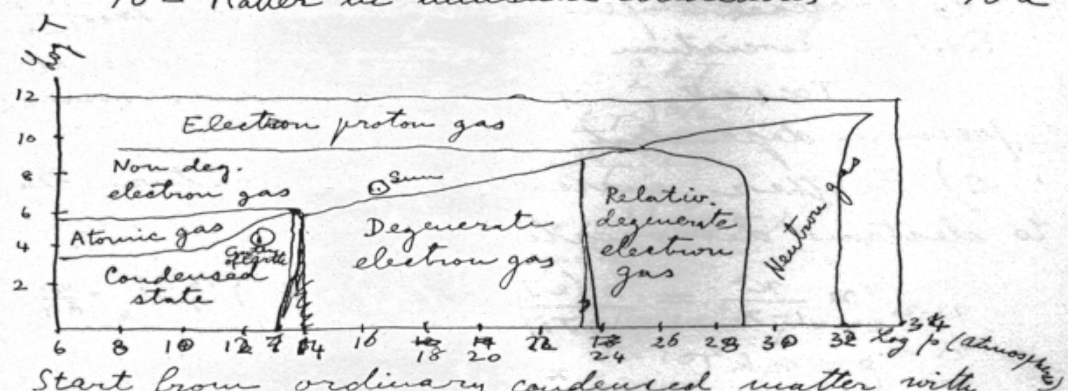
The QCD Phase Diagram and High-Energy Nuclear Collisions



E. Fermi

E. Fermi: *"Notes on Thermodynamics and Statistics" (1953)*

70 — Matter in unusual conditions 70 a



Start from ordinary condensed matter with ~~dominion~~ equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV —

Condition $\qquad \overline{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3} \frac{h^2 n^{2/3}}{2^{2/3} m} \qquad p = \frac{2}{3}\overline{w} n$

$$\overline{w} = 3.6 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$$

$$n \approx 10^{24} \qquad p = \frac{2}{3} 3.2 \times 10^{-11} \times 10^{24} \approx 2 \times 10^{13}$$

$$\approx 2 \times 10^{7} \text{ atm}$$

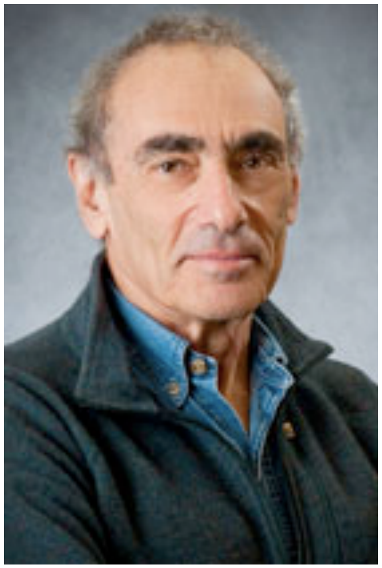
As pressure increases beyond this point

$$p = 3.6 \times 10^{-27} n^{2/3} n \times \frac{2}{3} = 2.4 \times 10^{-27} n^{5/3}$$

$$n = 6 \times 10^{23} \frac{\rho}{A} Z \qquad p = 10^{13.01} \left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2 \times 10^{12} \rho^{5/3}$$

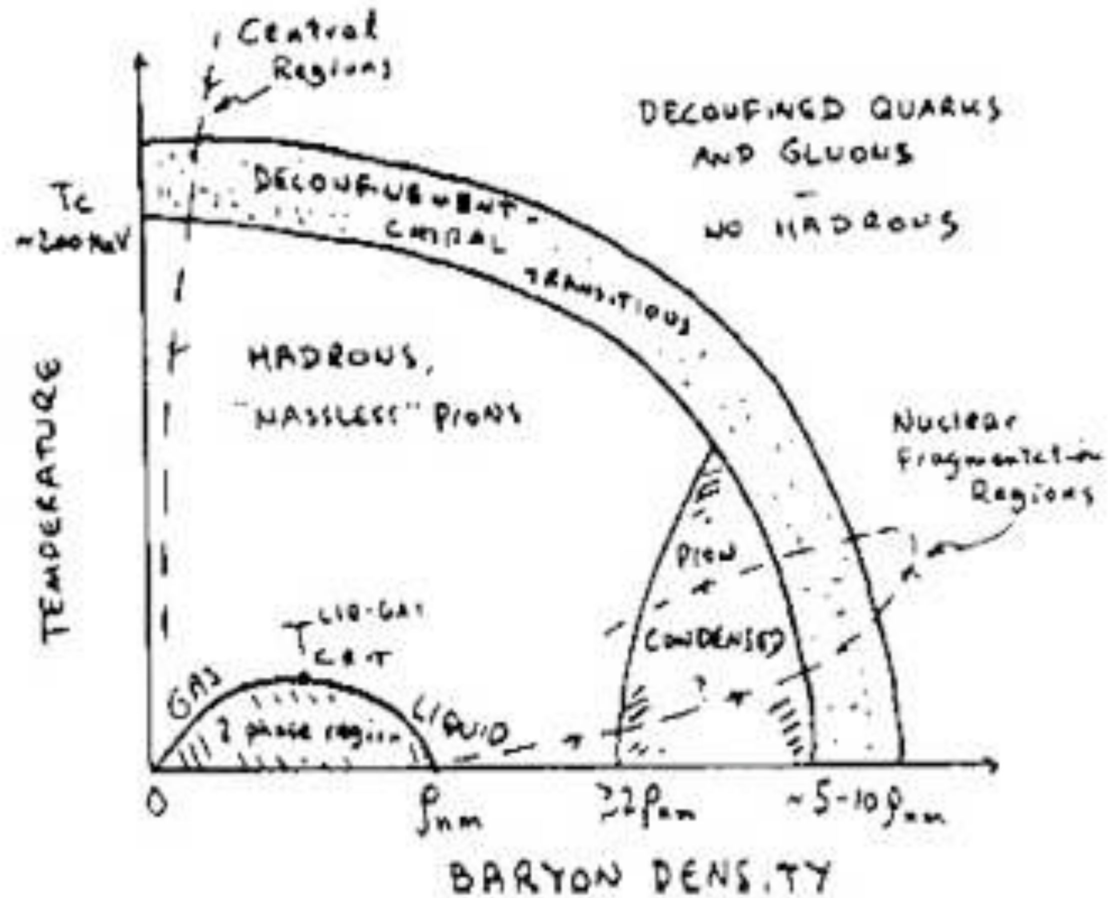
- 171 -

QCD Phase Diagram (1983)

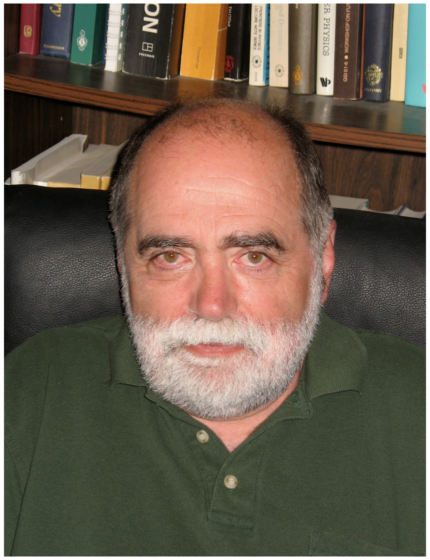


Gordon Baym

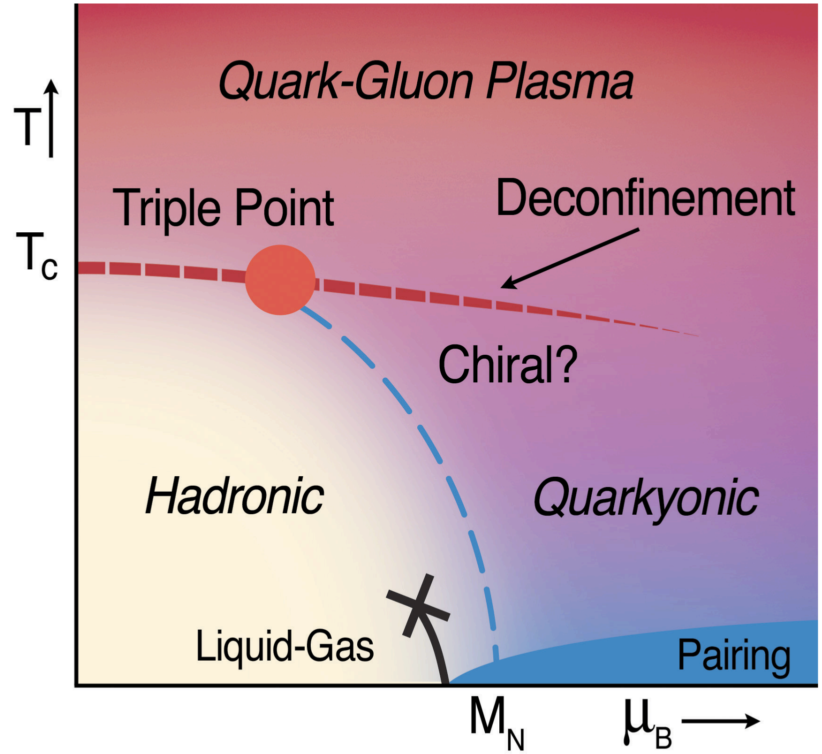
1983 US Long Range Plan *- by Gordon Baym*



QCD Phase Diagram (2009)



Larry McLerran



nucl-th: 0907.4489, NPA830,709(09) *L. McLerran*
NP**A837**, 65(2010) nucl-th 0911.4806: *A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel*

Experiments: Systematic measurements (E_{beam}, A_{size}) :

to extract **numbers** that are related to the ***phase diagram***!

Outline

(1) Introduction

(2) Experimental Setup

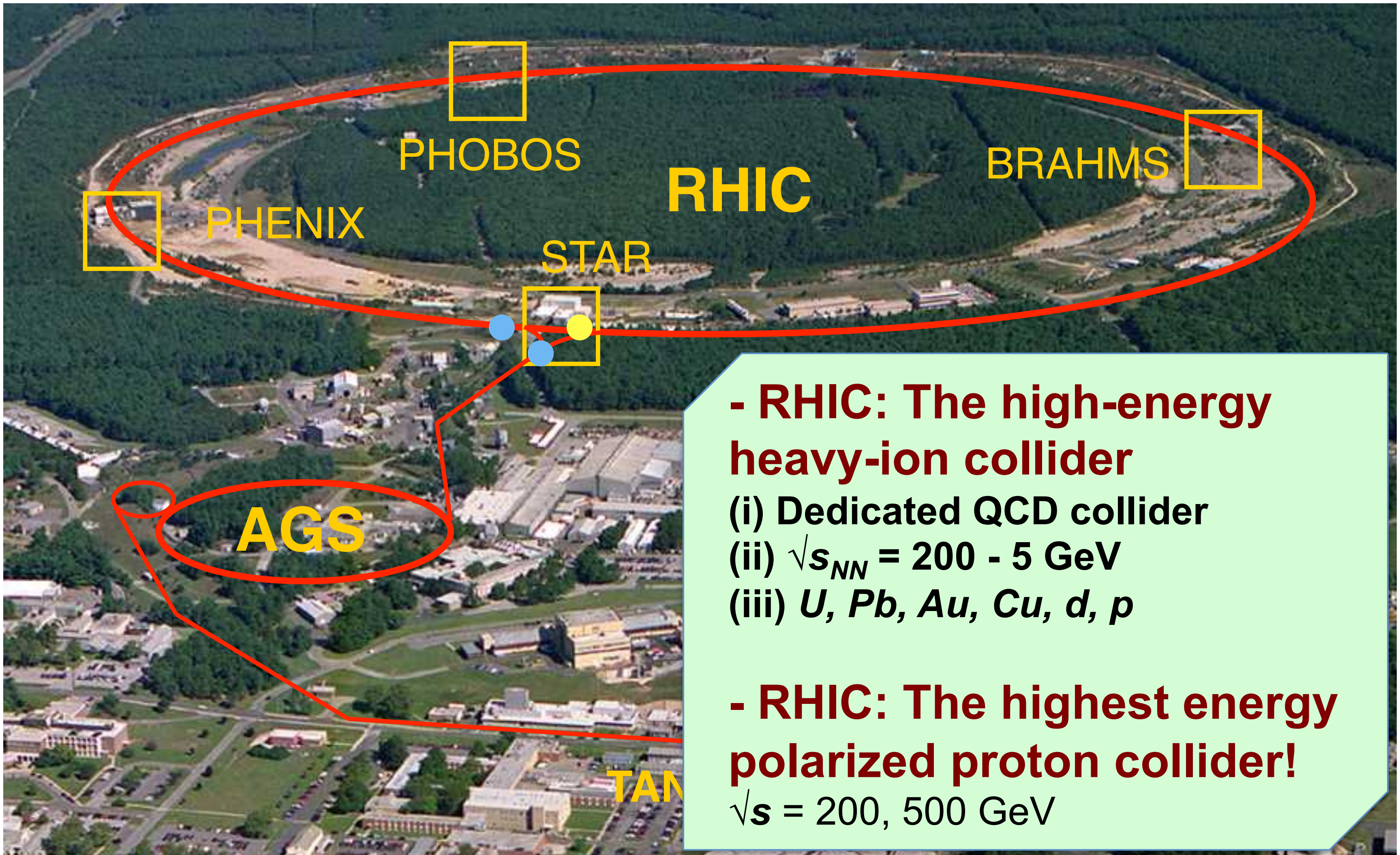
(3) Recent Results from RHIC

- Collectivity
- Criticality
- Chirality

(4) Summary and Outlook

Relativistic **H**eavy **I**on **C**ollider

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: The high-energy heavy-ion collider

(i) Dedicated QCD collider

(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV

(iii) *U, Pb, Au, Cu, d, p*

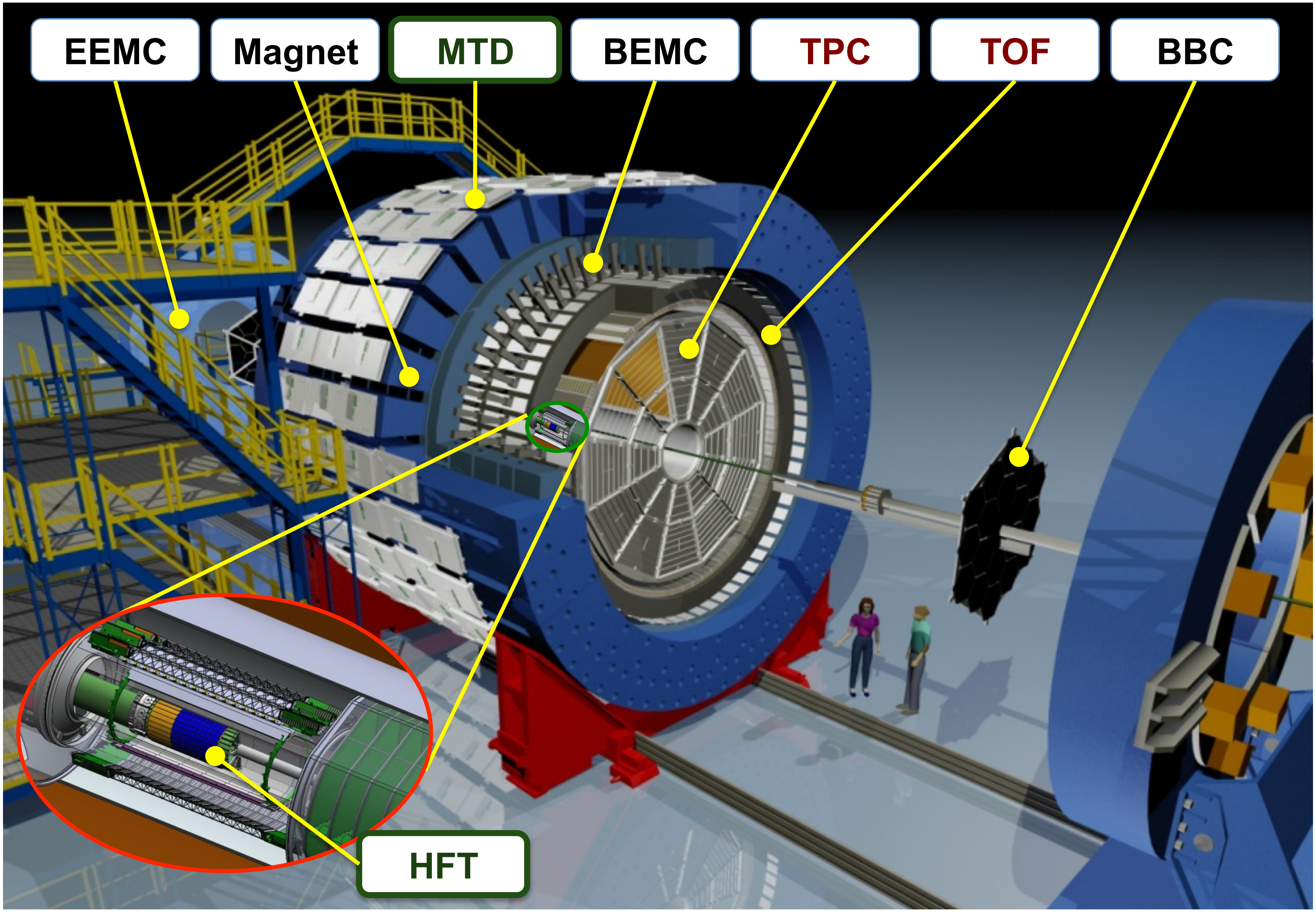
- RHIC: The highest energy polarized proton collider!

$\sqrt{s}$ = 200, 500 GeV

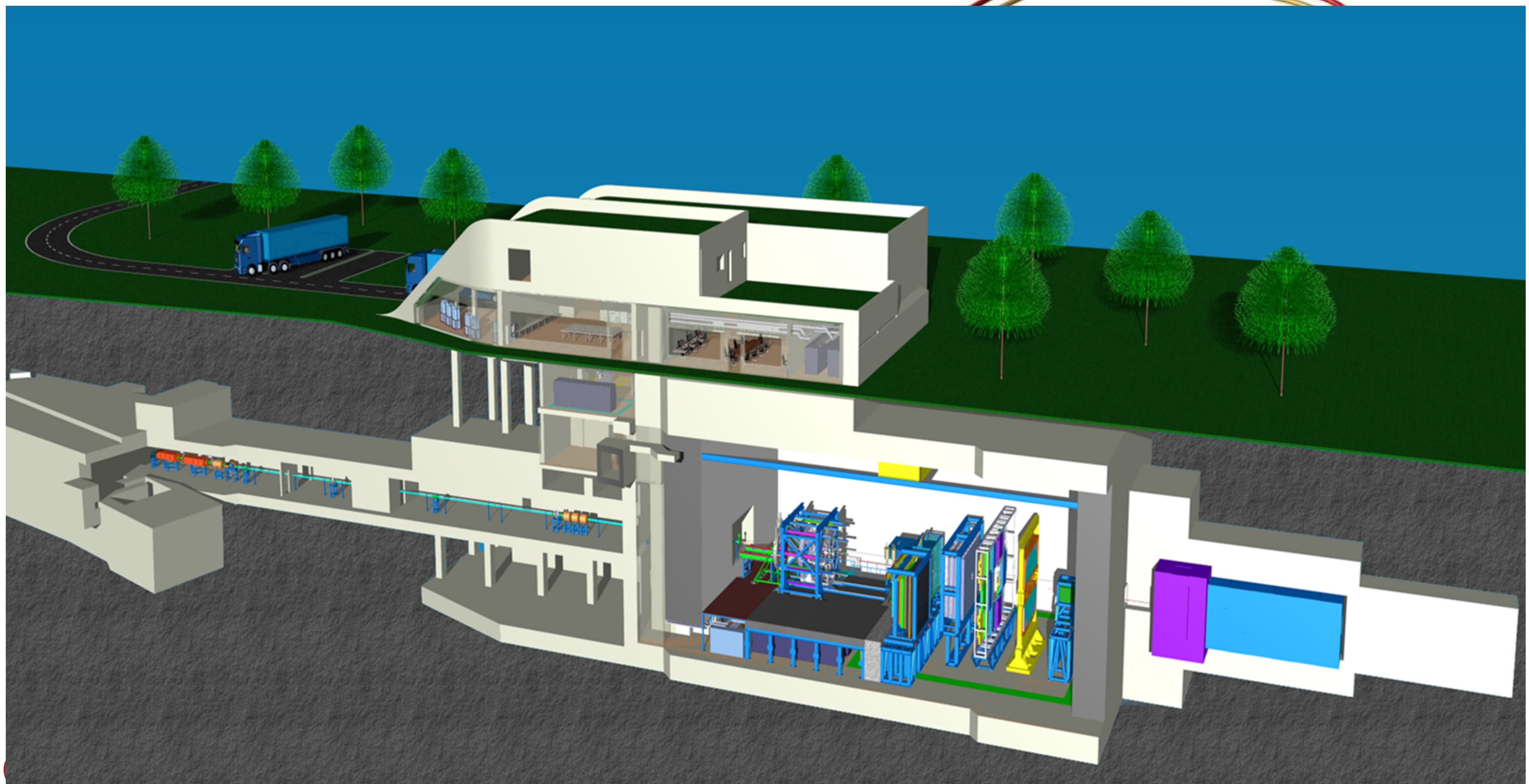
Animation M. Lisa


STAR Collaboration

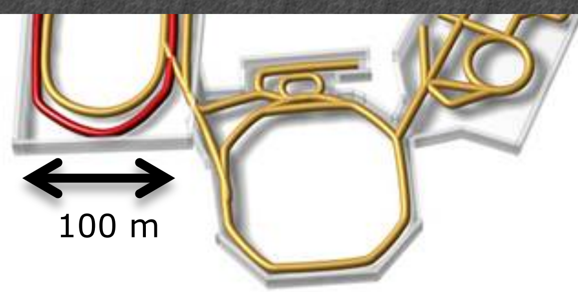
STAR Detector System



Facility for Antiproton & Ion Research

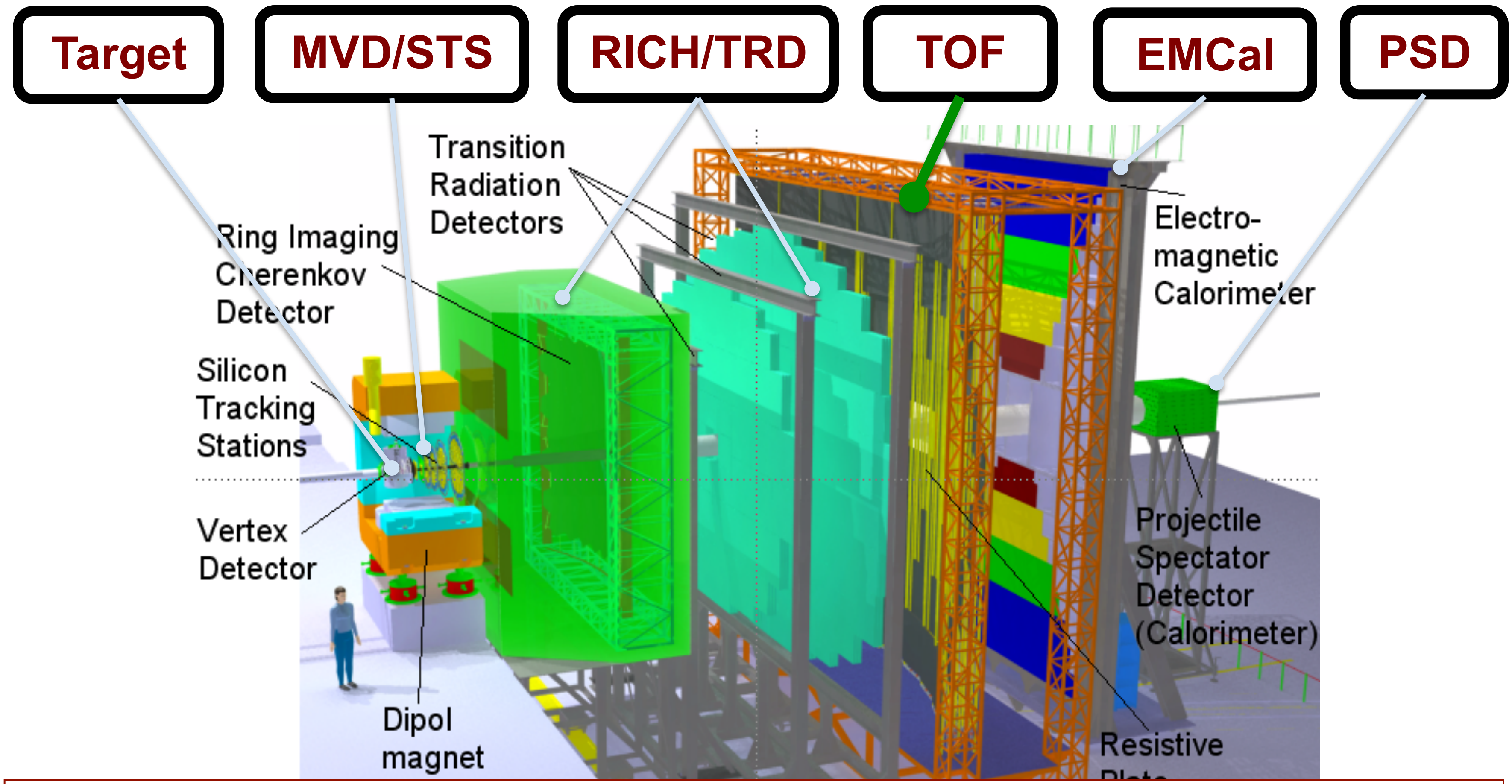


- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV



FAIR phase 1
FAIR phase 2

The CBM Experiment at FAIR

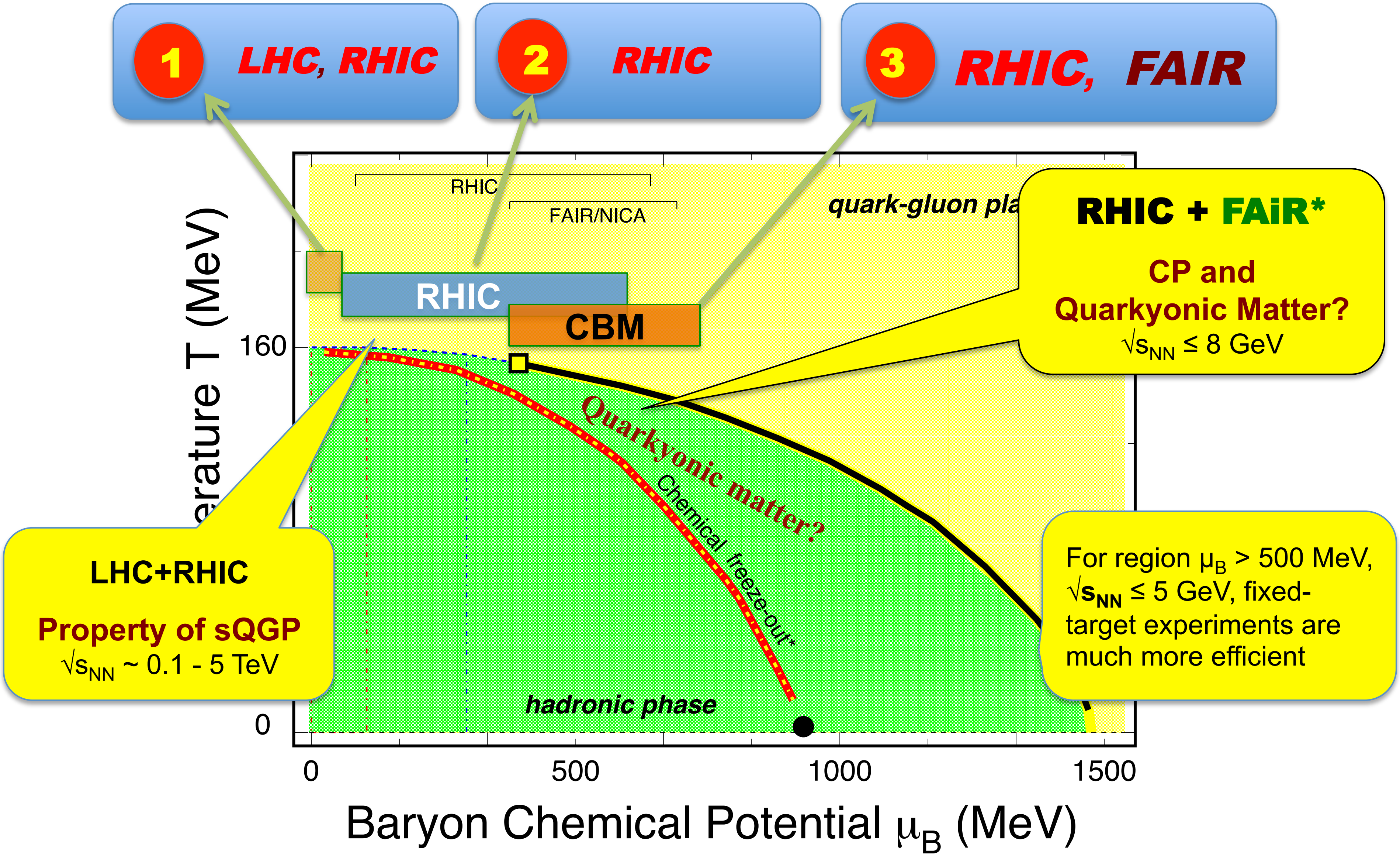


FAIR: the highest intensity accelerator complex in the 21st century

Precision measurements at high baryon density region for:

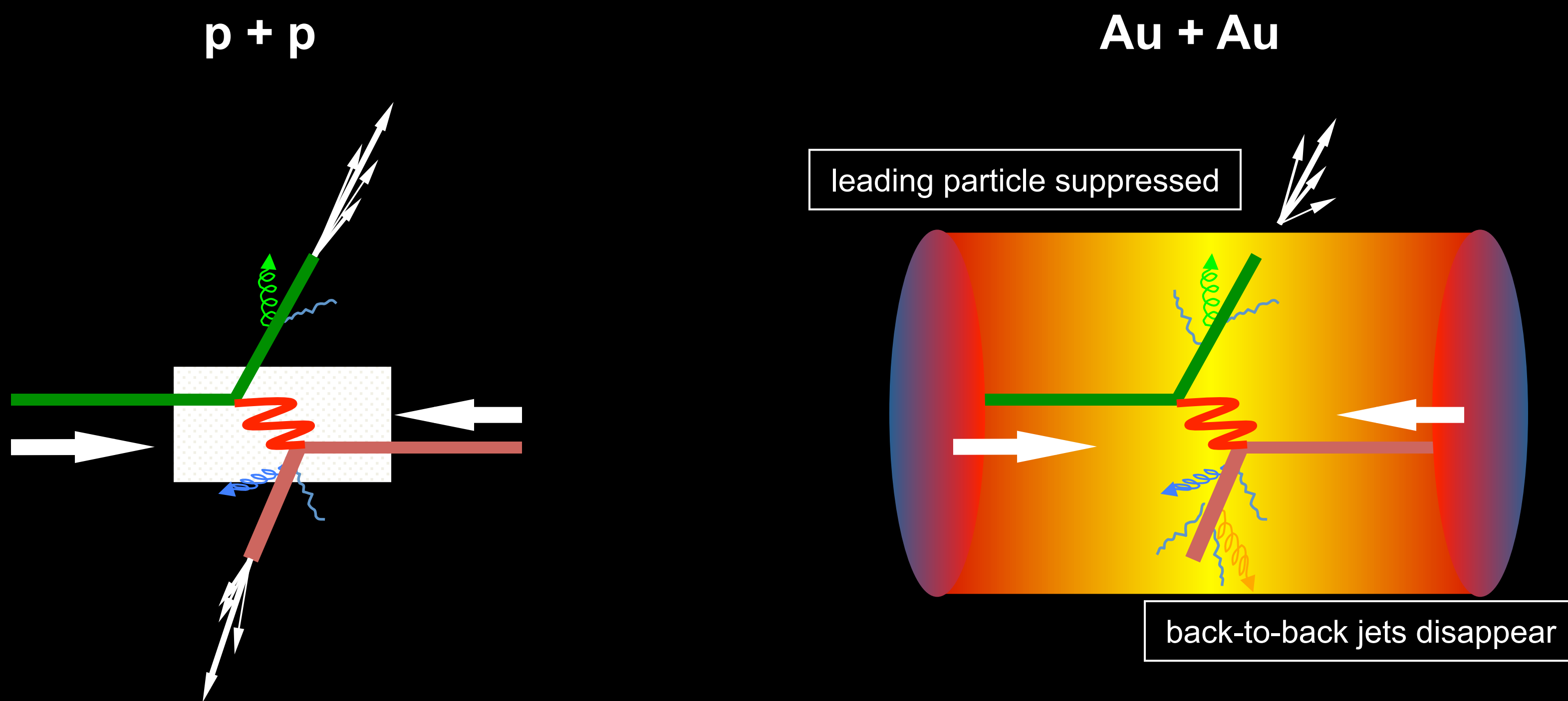
(i) Dileptons (***e, μ***); (ii) High order correlations; (iii) Flavor productions (***s, c***)

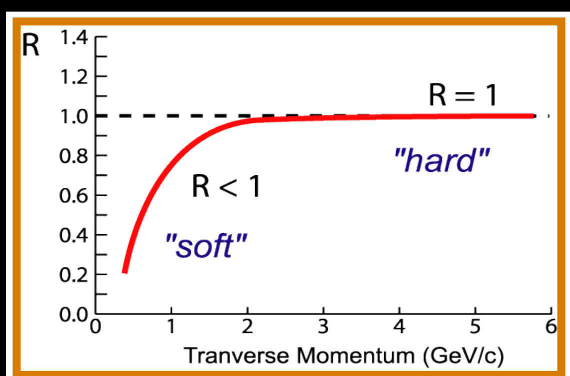
Exploring QCD Phase Structure



Results from the Top Energy 200GeV Au+Au Collisions

Jet Quenching at RHIC

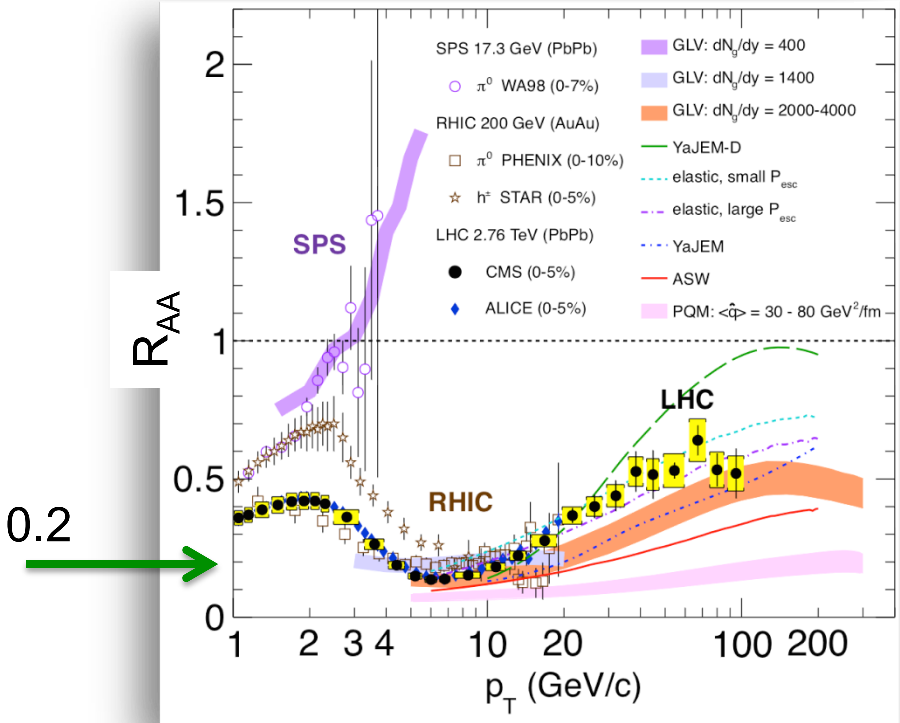


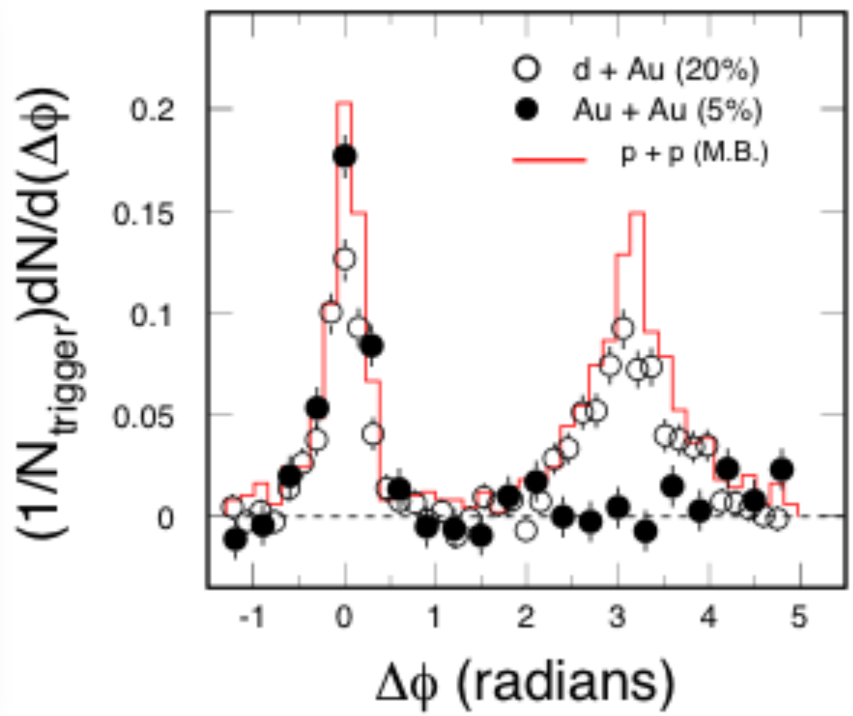


Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

Suppression and Correlation



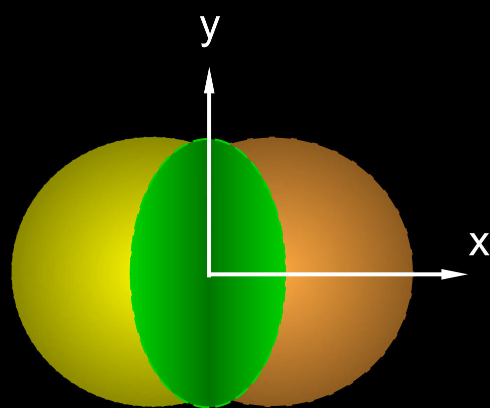


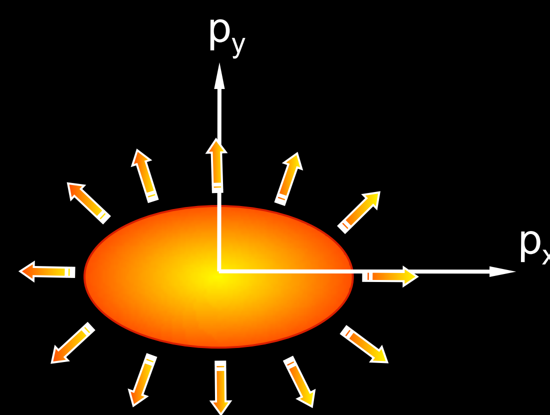
High momentum light quark hadrons and away-side jets are suppressed

Energy density at high-energy nuclear collisions:
ε > 5 GeV/fm^3 ~ 30ε_0

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

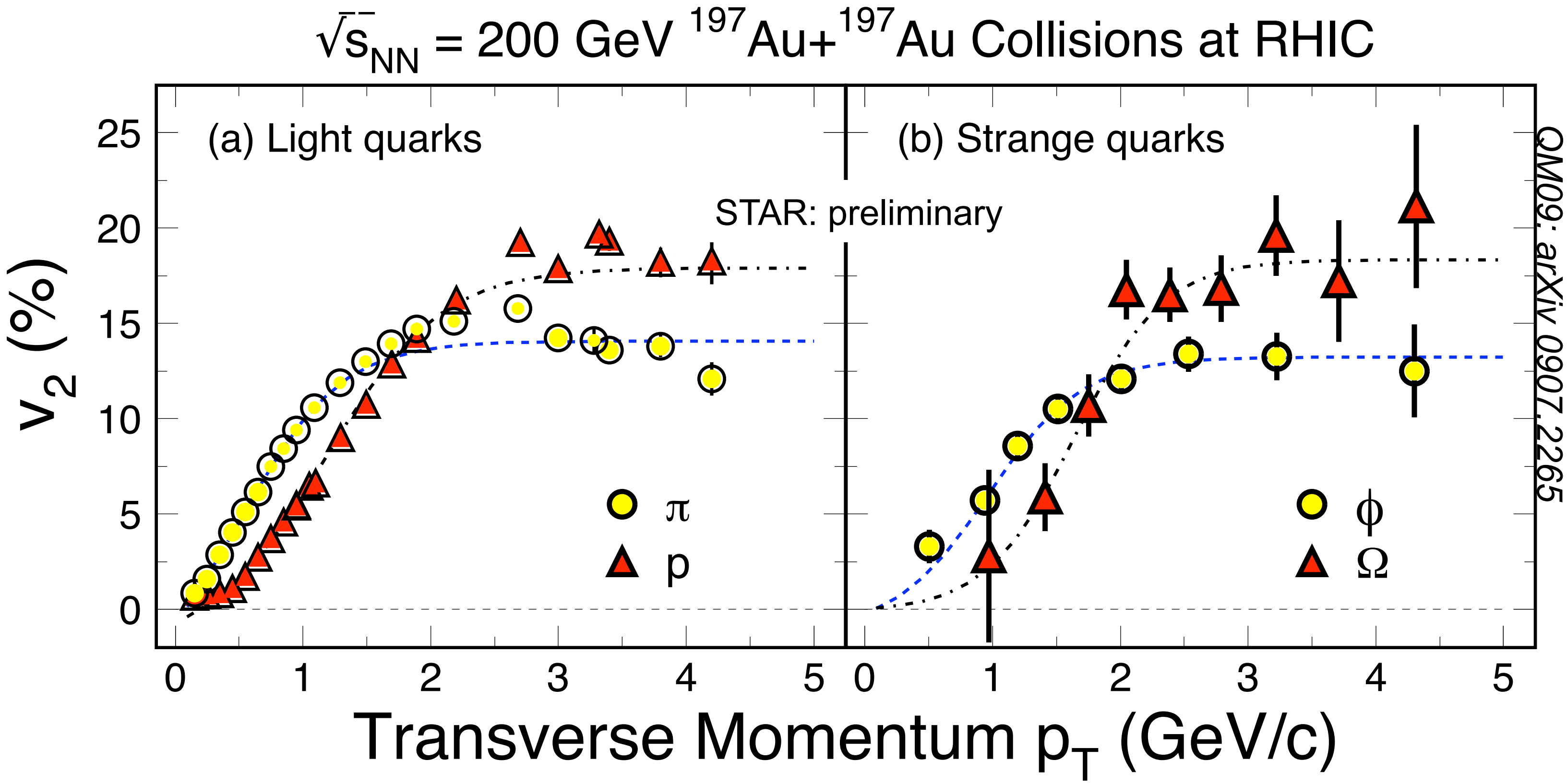




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

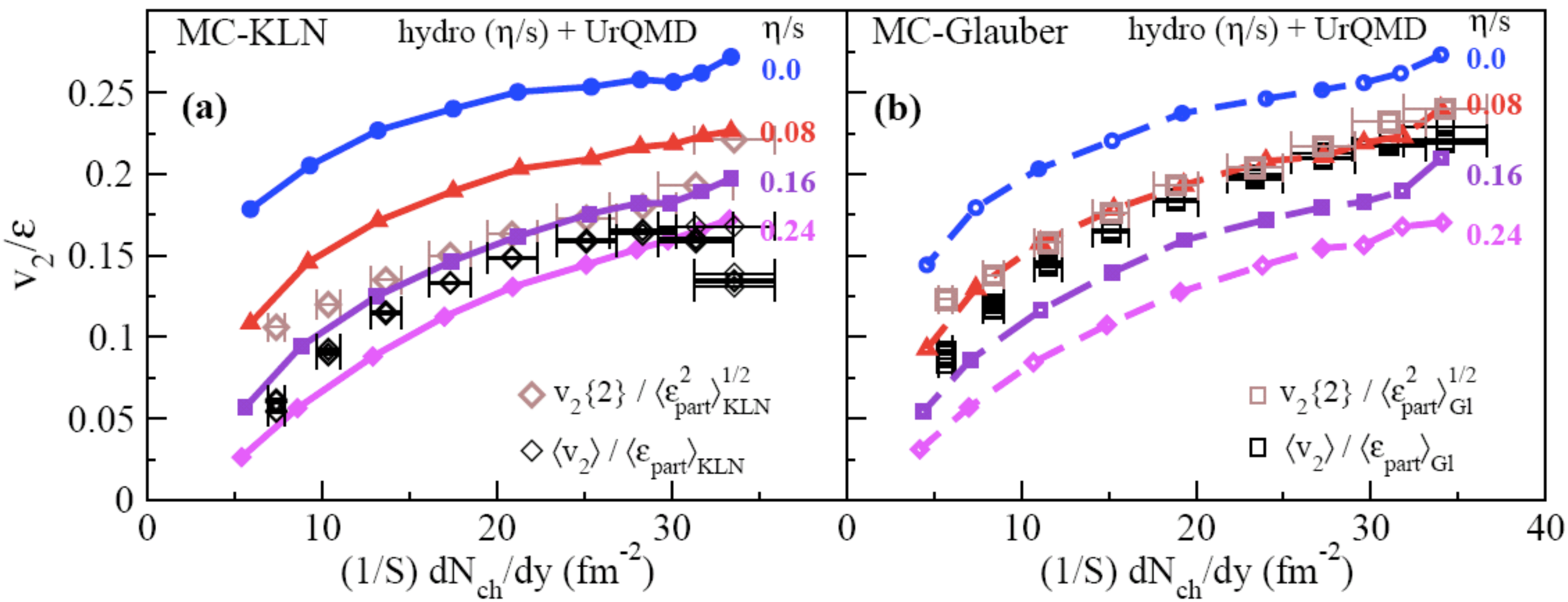
Partonic Collectivity at RHIC



Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

➔ ***Partonic Collectivity, necessary for QGP!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

Comparison with Model Results

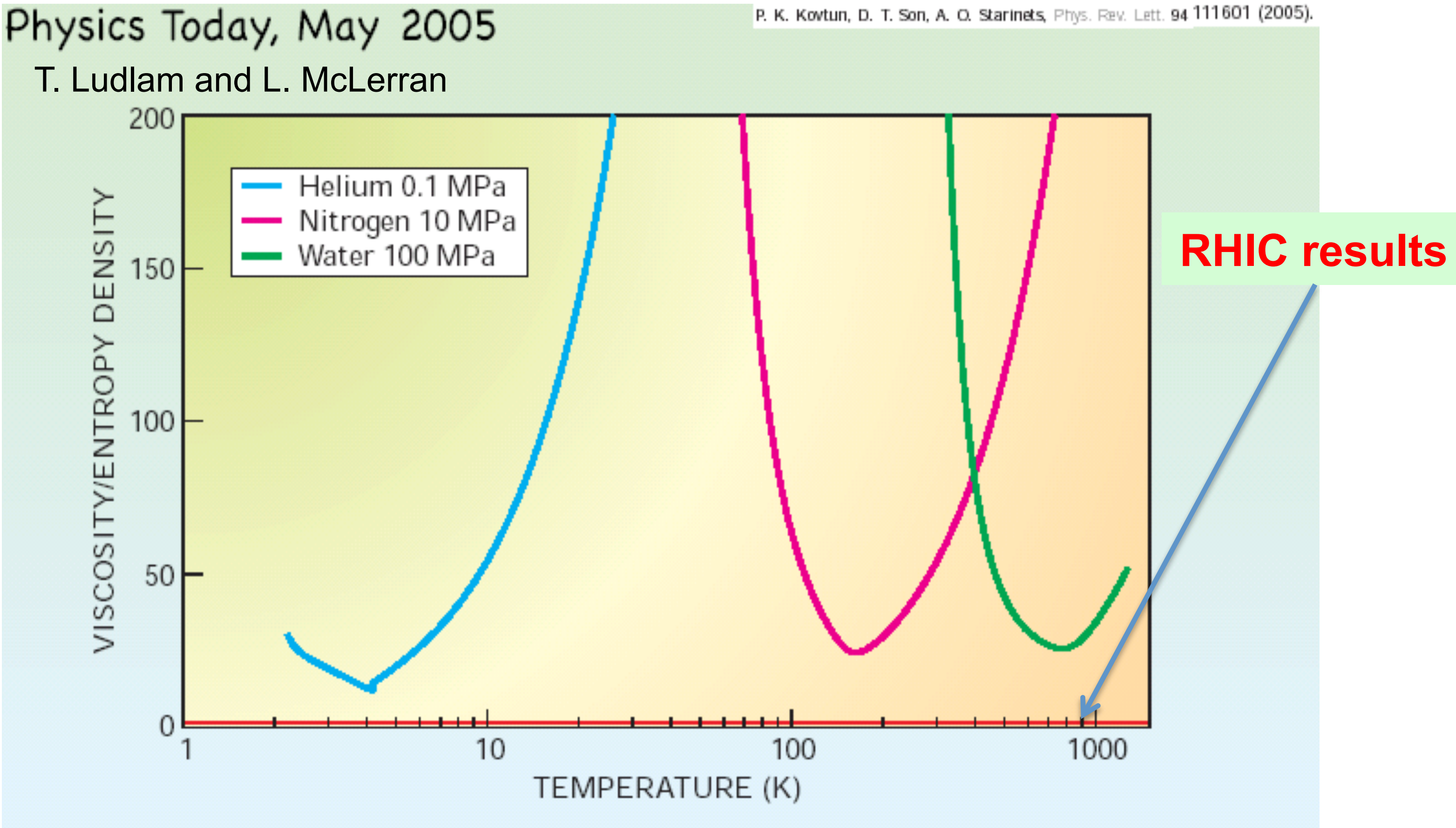


➔ ***Small value*** of specific viscosity over entropy ***η/s***

➔ Model uncertainty dominated by ***initial eccentricity ε***

Model: Song *et al.* ***PRL106****, 192301(2011), arXiv:1011.2783*

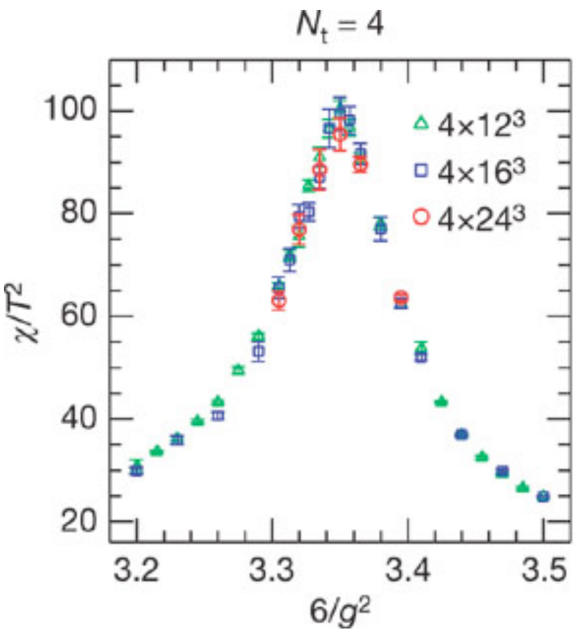
Low *η/s* for QCD Matter at RHIC

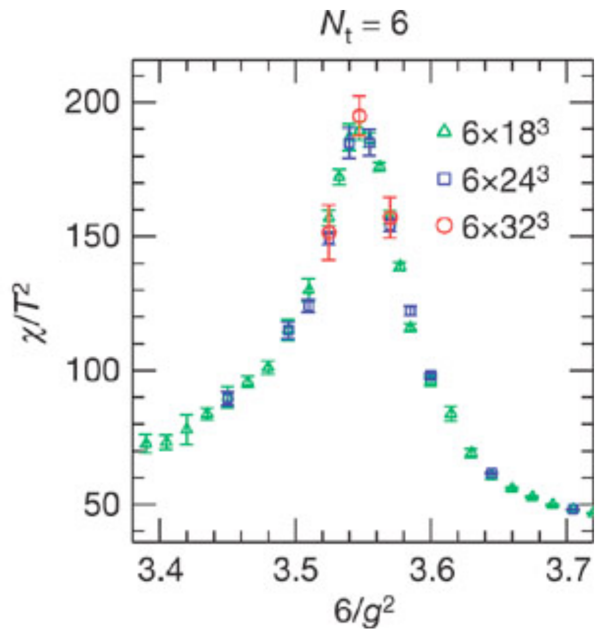


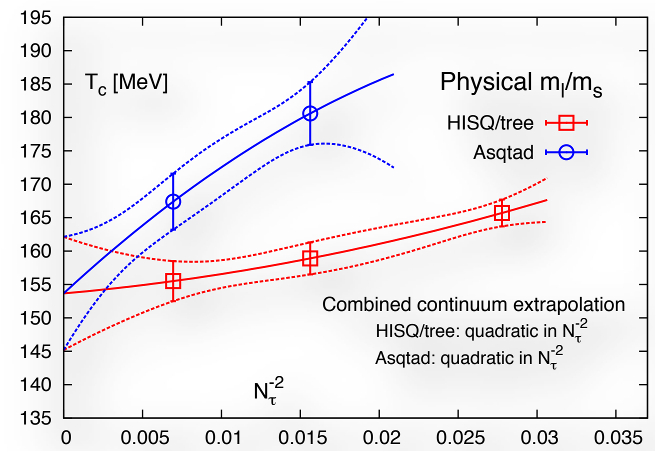
1) ***η/s* ≥ 1/4π, 'perfect liquid'**

2) ***η/s*(QCD matter) << *η/s*(QED matter)**

Phase Transition at $\mu_B \sim 0$







State of art lattice calculations show that for nuclear collisions at high energy, $\mu_B \sim 0$, the phase transition from hadronic matter to quark-gluon plasma is a ***smooth crossover*** at $\boldsymbol{T_{PC} \cong 154 \pm 9}$***** MeV.

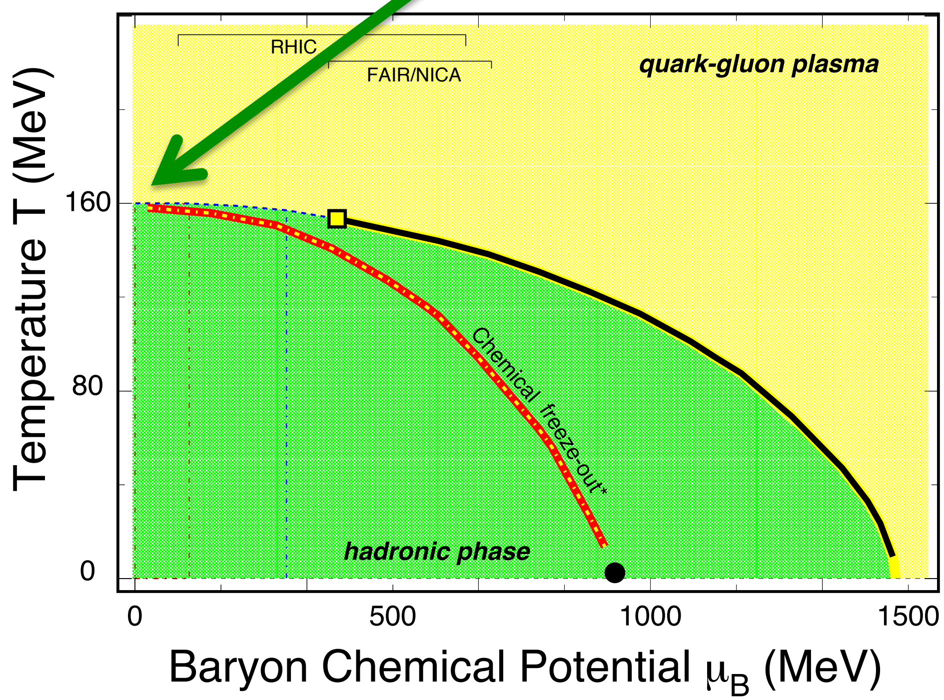
* Chiral condensates

Y. Aoki et al., *Nature* ***443***, 675(2006), Nucl. Phys. ***A830***, 805c(2009)

A. Bazavov et al., PRD85, 054503(2012).

Beam Energy Scan-I at RHIC

At $\mu_B \sim 0$: sQGP is formed & the transition is ***crossover***



Study QCD Phase Structure

- Onset of sQGP
- Phase boundary and critical point
- Chrial symmetry restoration

Observables:

1st order phase transition

(1) Azimuthally sensitive HBT

(2) Directed flow v_1

Partonic vs. hadronic dof

(3) R_{AA}: Nucl. Mod. Fact.

(4) Charge separation

(5) v_2 - NCQ scaling

Critical point, correl. length

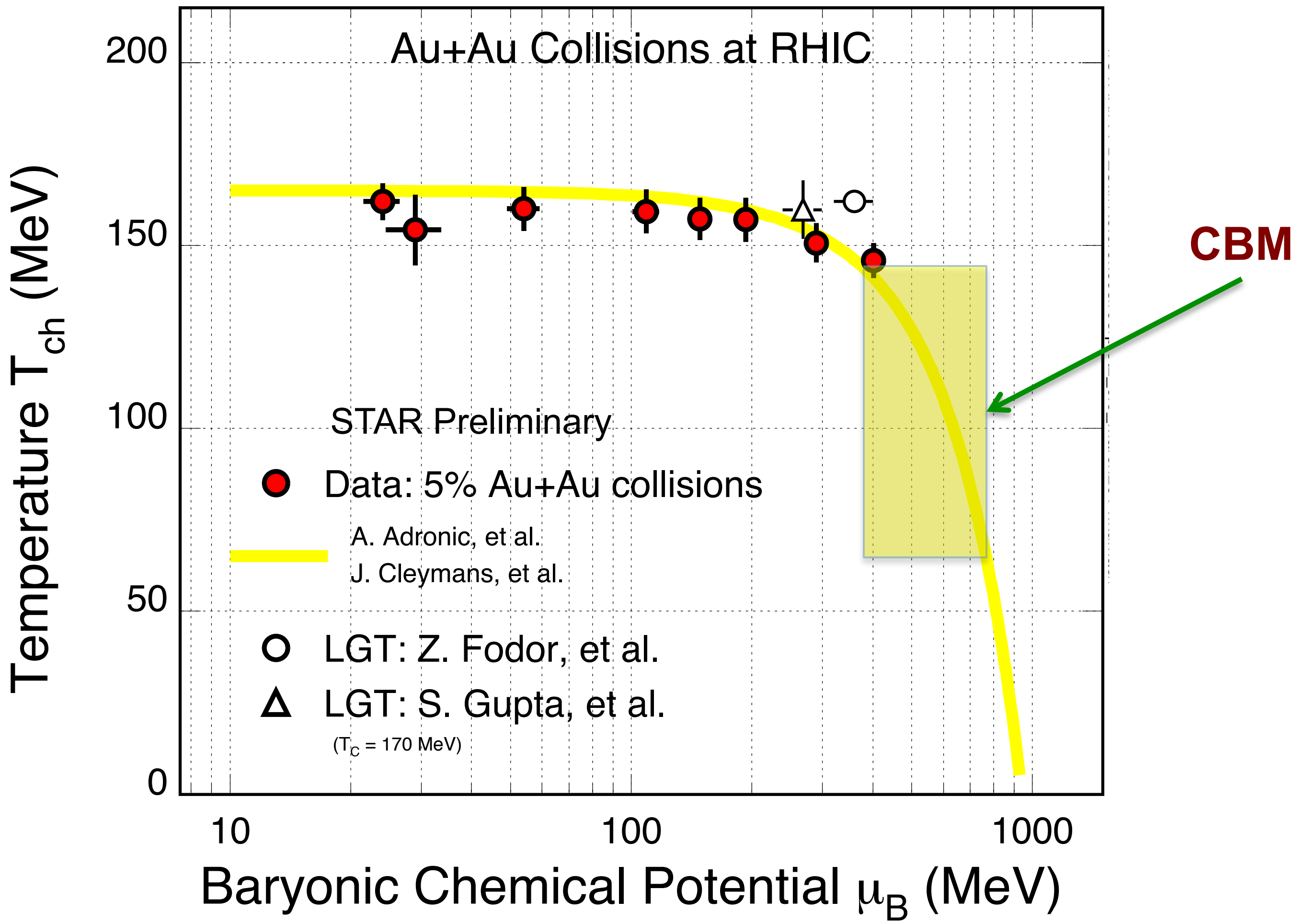
(6) Fluctuations

Chiral symmetry restoration

(7) Di-lepton production

BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39 GeV

Bulk Properties at Freeze-out



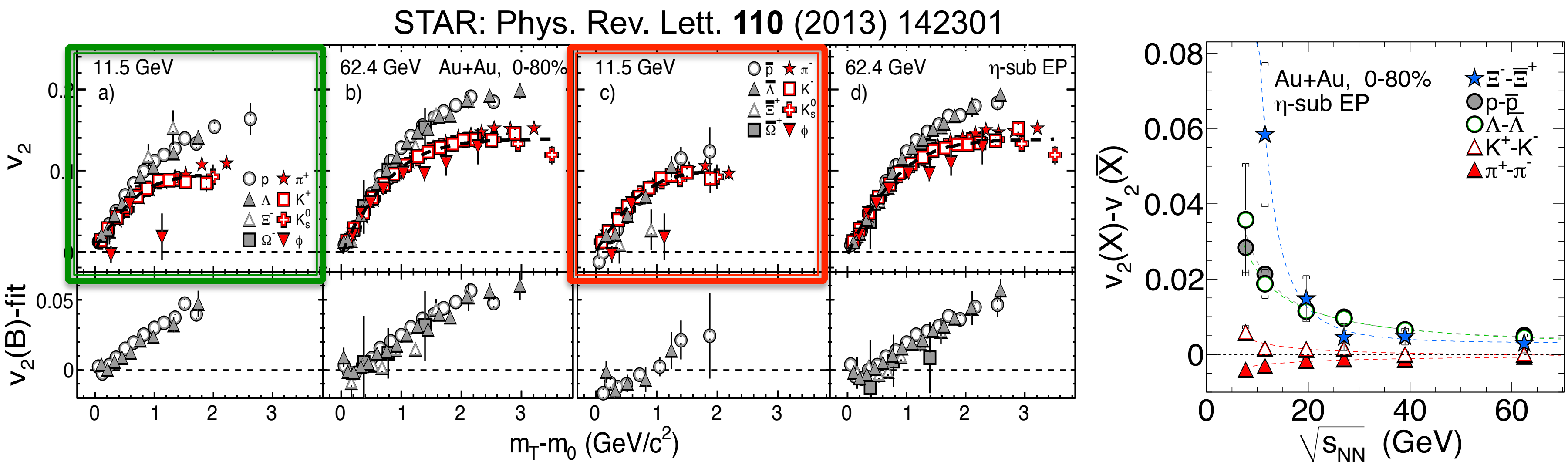
Chemical Freeze-out: (GCE)

- RHIC (20 ≤ μ_B ≤ 420 MeV): small temperature variation
- CBM (400 ≤ μ_B ≤ 750 MeV): temperature changes dramatically!

Recent results from RHIC BES-I

Collectivity

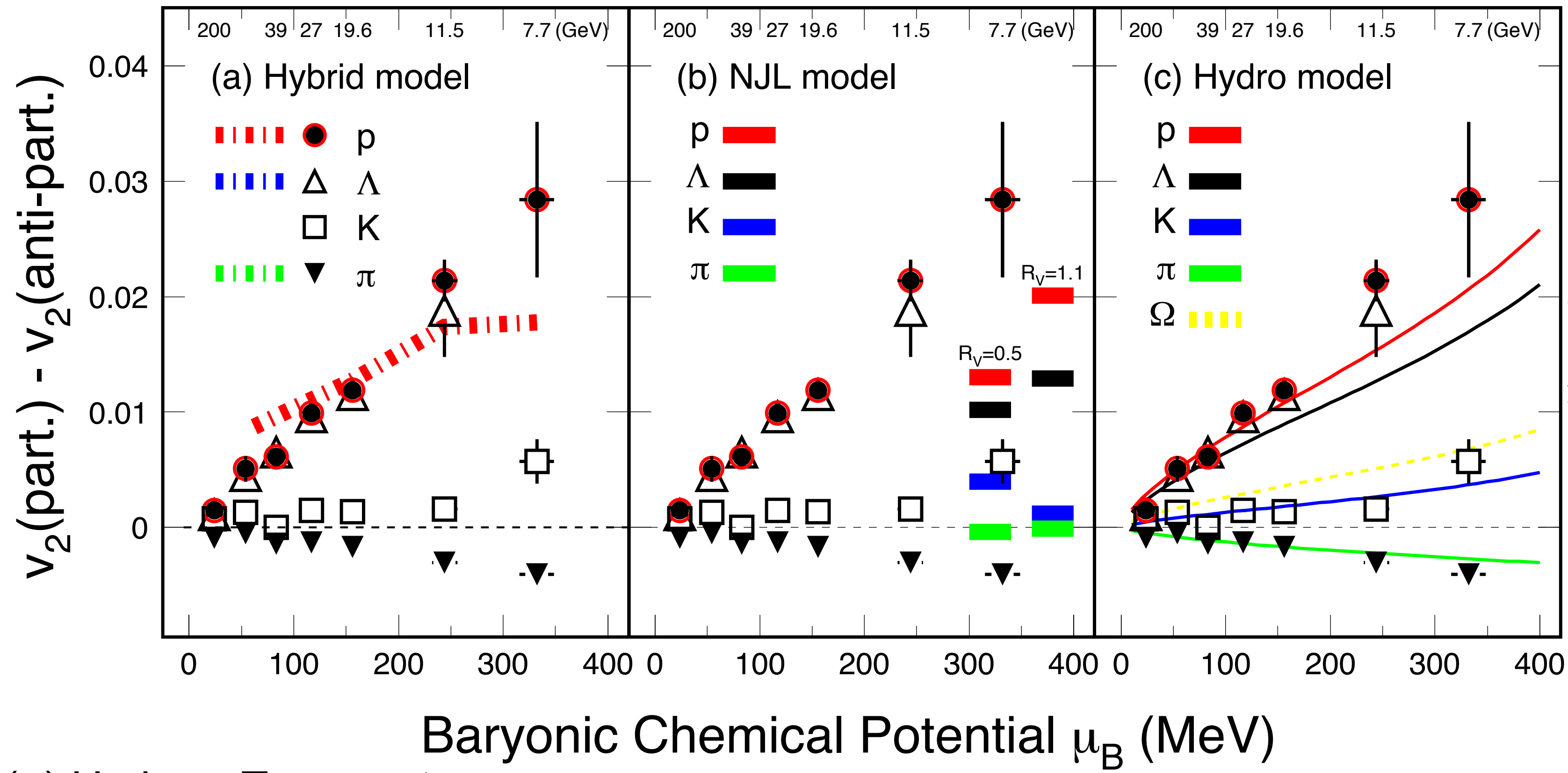
Collectivity v_2 Measurements



1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

2) At $\sqrt{s_{NN}}$ < 11.5 GeV, the universal v_2 **NCQ scaling is broken,** consistent with hadronic interactions becoming dominant.

BES v_2 and Model Comparison



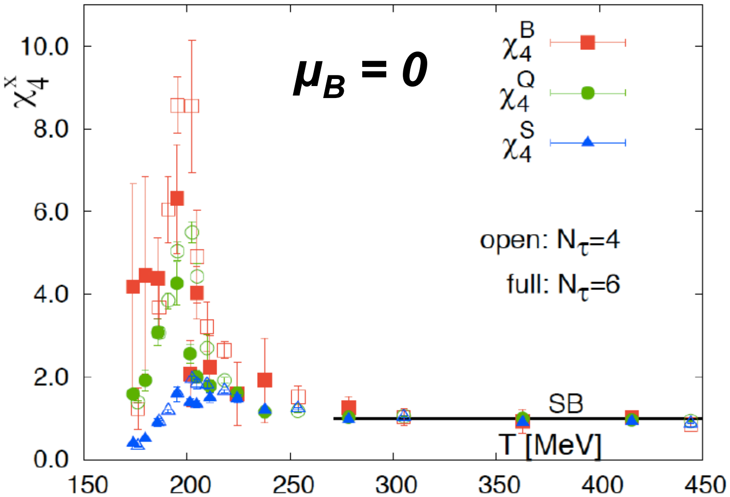
(a) Hydro + Transport: [J. Steinheimer, et al. PRC86, 44902(13).]

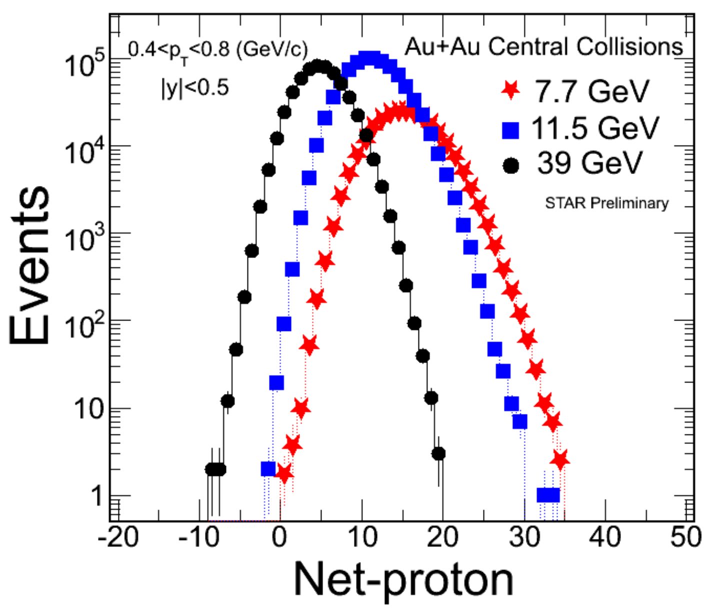
(b) NJL model: Hadron splitting consistent. Sensitive to vector-coupling, **CME, net-baryon density dependent.** [J. Xu, et al., arXiv:1308.1753/PRL112.012301]

(c) Pure Hydro solution with μ_B, viscosity: [Hatta et al. arXiv:1502.05894//1505.04226// 1507.04690 //]. **Chemical potential driven!**

Criticality

Higher Moments





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

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

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

3) Direct comparison with calculations at any order:

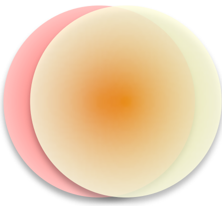
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

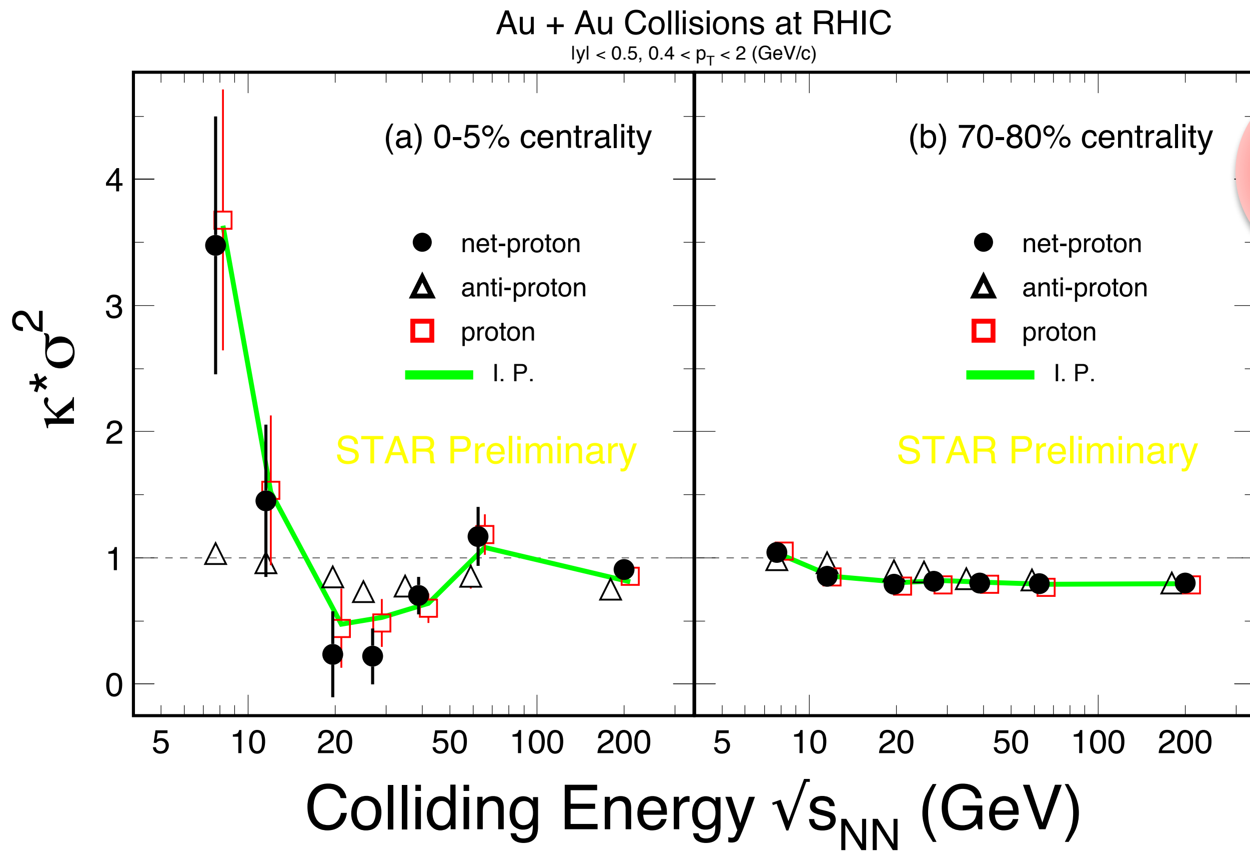
References:

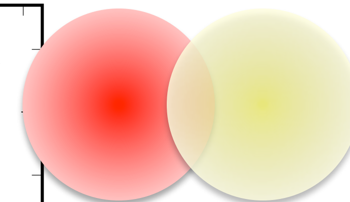
- STAR: *PRL*105, 22303(10); *ibid*, 032302(14)
- M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11) // S.Ejiri et al, PLB633, 275(06)
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et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

Net-proton Higher Moment



central





peripheral

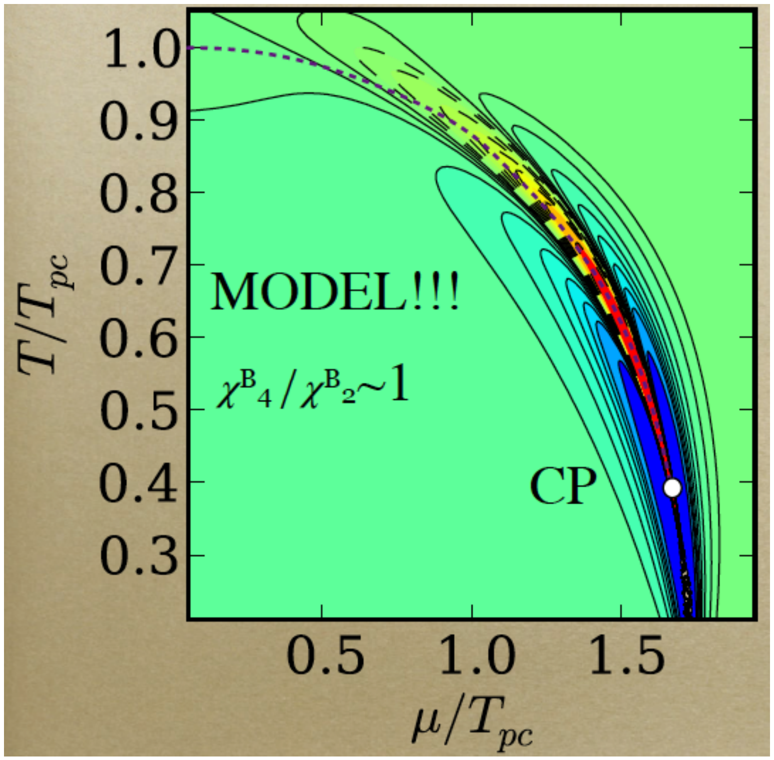
Net-proton results: All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$ ~ 20 GeV.

Non-monotonic behavior in central collision! *X.F. Luo, CPOD2014*

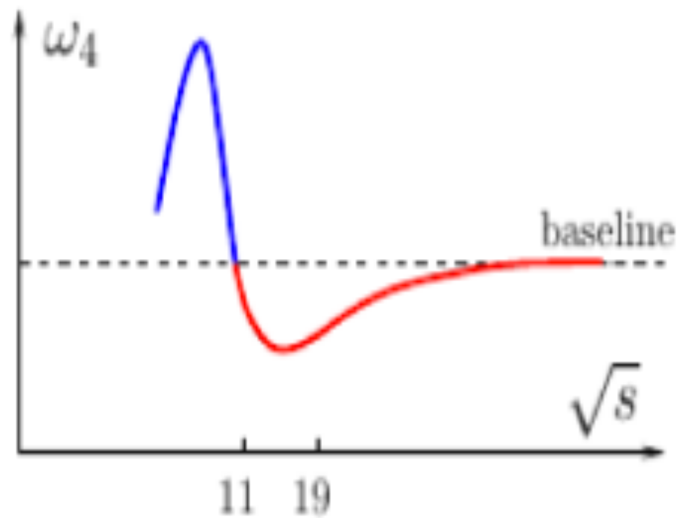
Question: What will happen at even lower collision energy?

Expectation from Calculations

V. Skokov, Quark Matter 2012

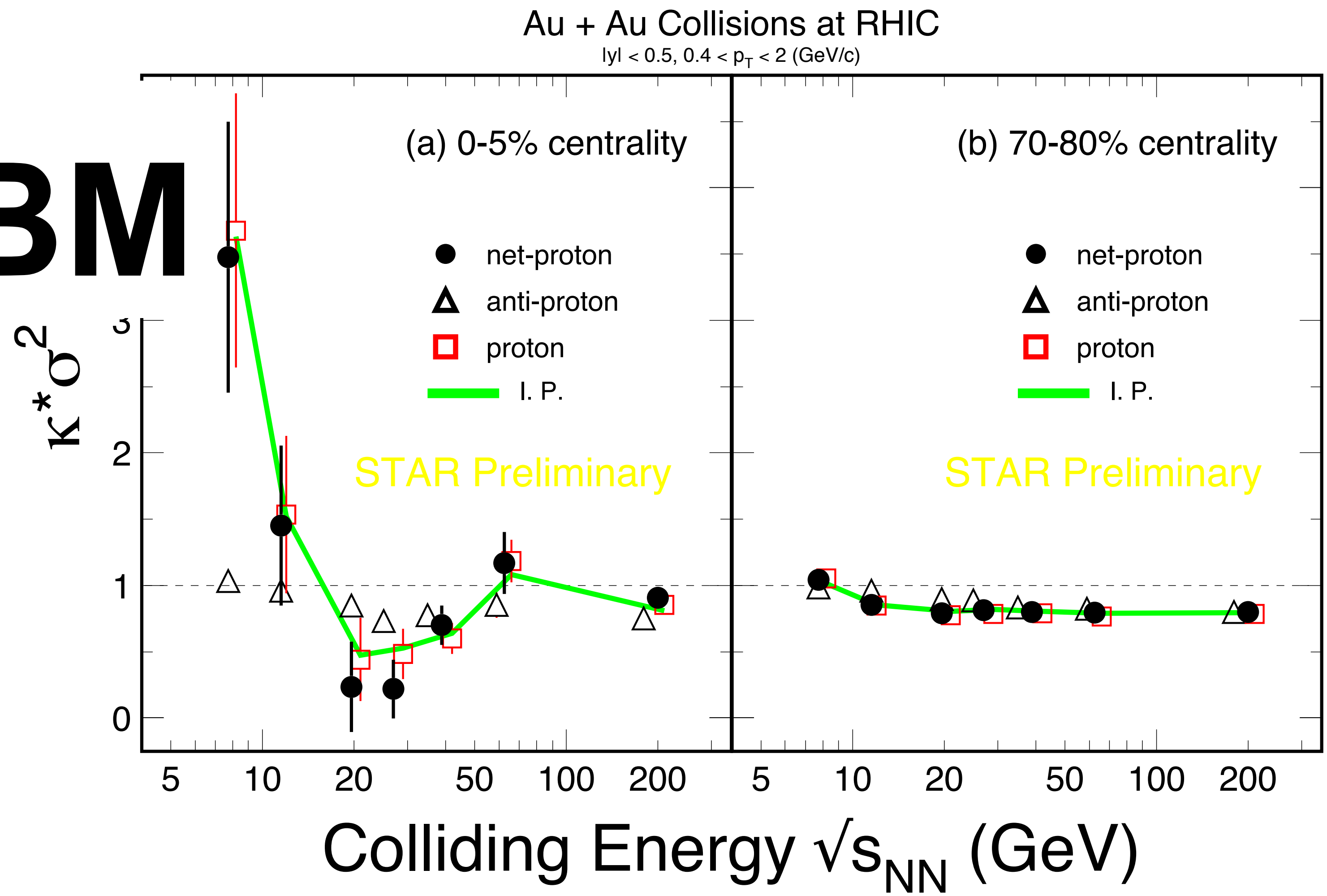


M. Stephanoc, ***PRL107***, 052301(2011)



"Oscillating pattern" around the reference is expected.

Net-proton Higher Moment



Question: What will happen at even lower collision energy?

Recent results from RHIC BES-I

Chirality

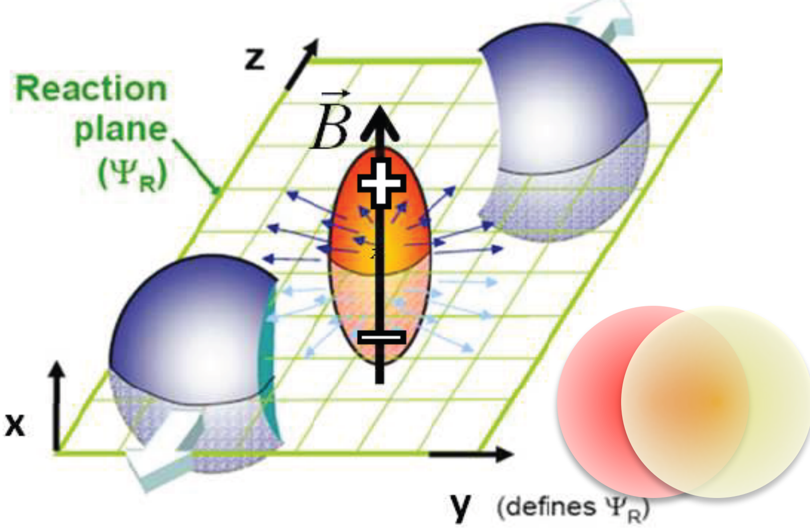
Chirality is life *– All DNAs are left-handed!*

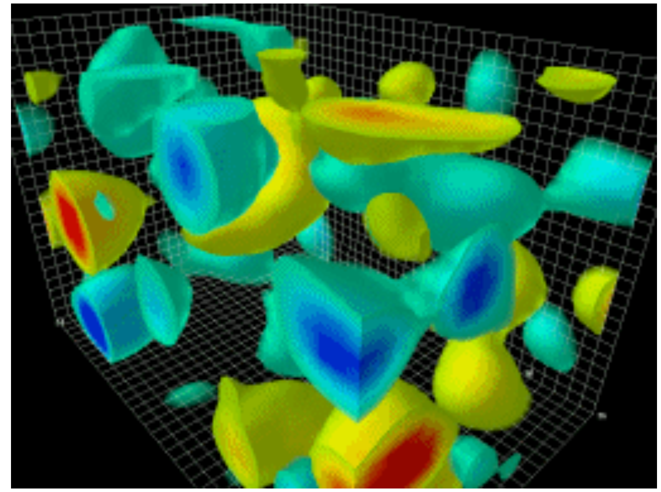
Study QCD Topological Structure

Hot/dense QCD Medium
Parity odd domains form

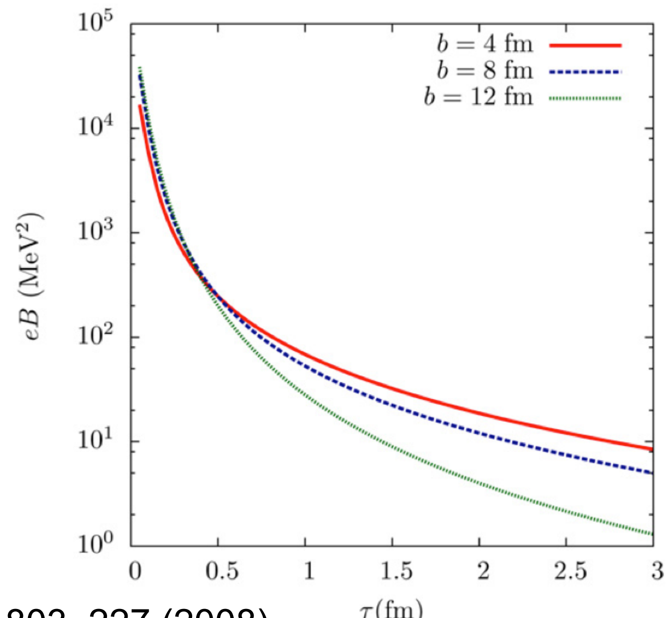
External Magnetic Field → Chiral magnetic effect (**CME**) (electric charge)

External Angular Momentum → Fluid Vorticity → Chiral vortical effect (**CVE**) (baryonic charge)



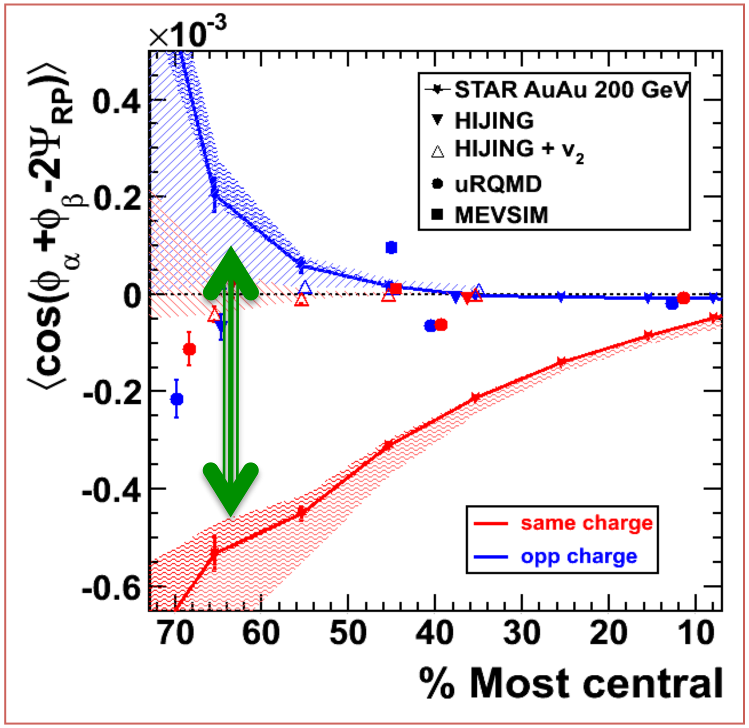


Animation by *Derek Leinweber*

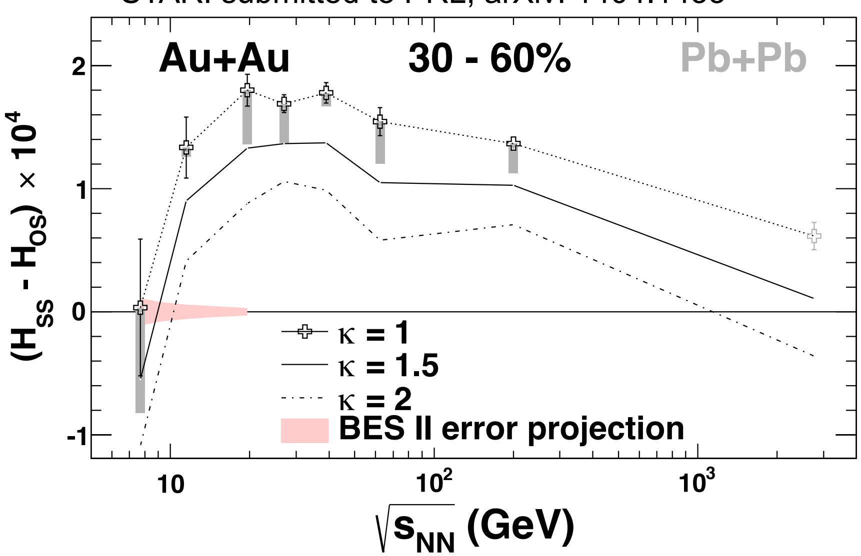


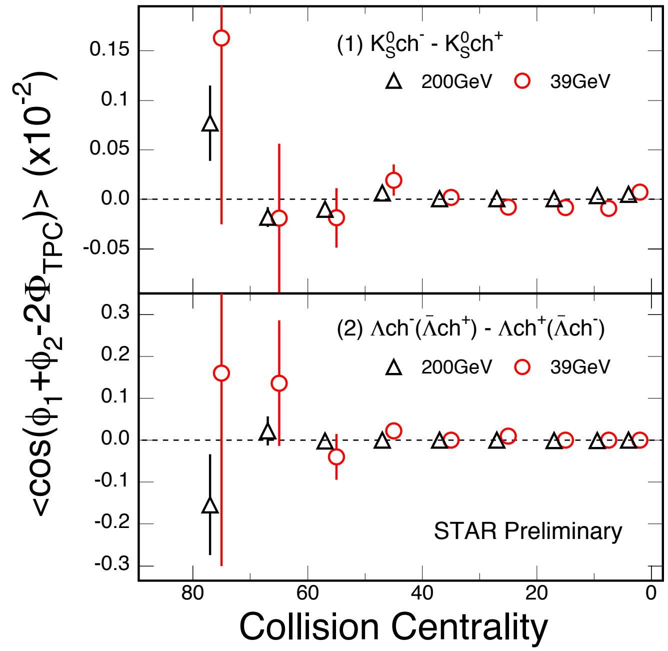
NPA 803, 227 (2008).

Charge Separation wrt Event Plane (CME)



STAR: submitted to PRL, arXiv: 1404.1433





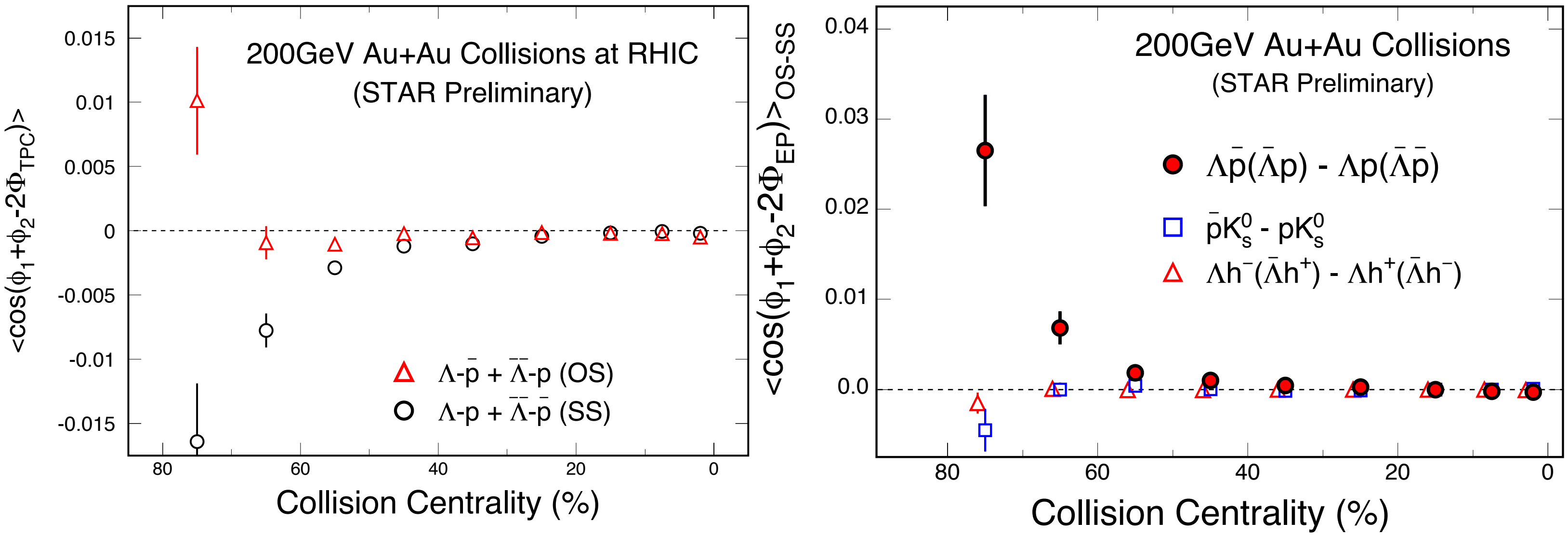
LPV(CME) disappears: with neutral hadrons:

LPV(CME) disappears at low energy:
➔hadronic interactions become dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: PRL. 103, 251601(09)
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

Baryon Separation wrt Event Plane (CVE)

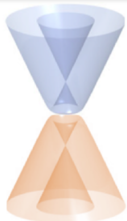
Λ-proton correlation: Λ contains the same B-charge as p but no e-charge

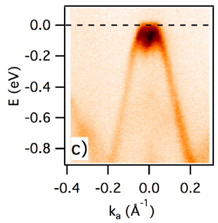


1) The opposite baryon-charge correlations (OS) are similar, ~ zero. But the same baryon-charge correlations (SS) are lower than that of the OS. The difference OS-SS is non-zero, ***baryon-charge separation***, as expected from the CVE
2) Neither p-K_0 nor Λ-charge hadron correlations show any separation effect, consistent with CVE

STAR: F. Zhao, QM2014 Proceedings
Kharzeev, D.T. Son, PRL106, 062301(11); D. Kharzeev. PLB633, 260 (06); D. Kharzeev, et al. NPA803, 227(08)

Chiral Symmetry is Life





"Observation of the chiral magnetic effect in $ZrTe_5$"

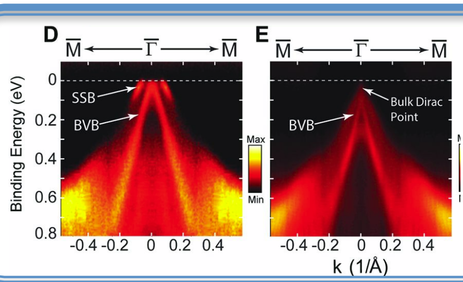
Q. Li et al., arXiv: 1412.6543 [cond-mat.str-el]

"Force of nature gave life its asymmetry"

'Left-handed' electrons destroy certain organic molecules faster than their mirror versions.

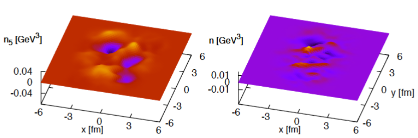
E. Gibney, ***Nature***, 25 September 2014

J.M. Dreiling and T.J. Gay, ***PRL113***, 118103(2014)



"Discovery of a Three-Dimensional Topological Dirac Semimetal, Na_3Bi"

Z.K. Liu et al., ***Science***, 343, 864(2014)

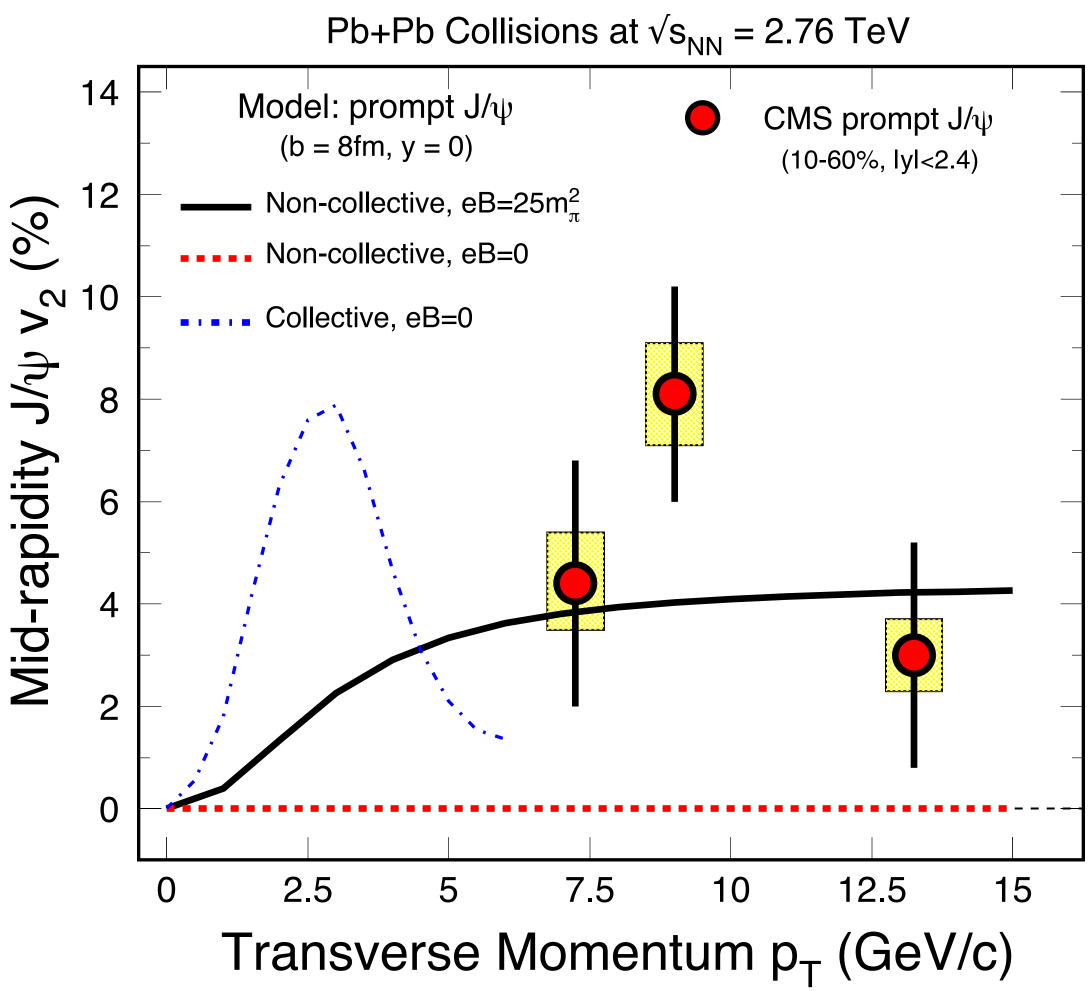


"The Chiral magnetic effect in heavy-ion collisions from event-by-event anomalous hydrodynamics"

Y. Hirono et al., arXiv: 1412.0311 [hep-ph]

Assess the Initial Field

X.Y. Guo, P.F. Zhuang, *et al,* 1502.04407



1) Very strong external magnetic filed at the beginning of the heavy-ion collisions

2) Early production of the high p_T quarkonia are sensitive to the initial field

3) Measurements of the large p_T, non-collective v_2 of J/ψ, from Pb+ Pb collisions at LHC, seems consistent

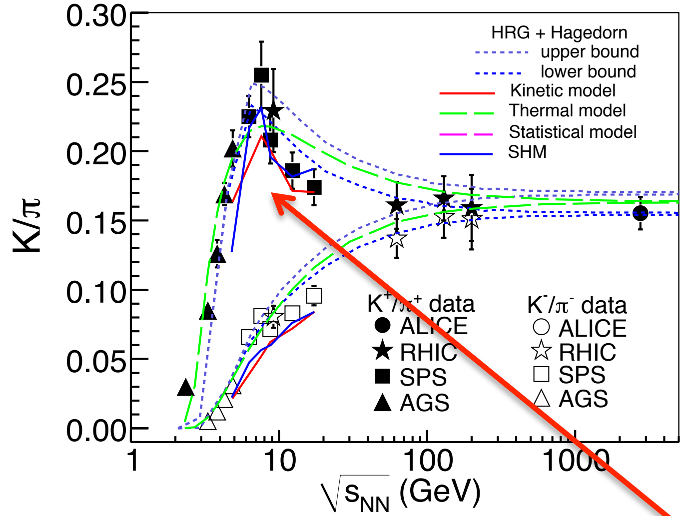
4) Future tests:
   - Upsilon v_2 from LHC
   - Collectivity of J/ψ
   - J/ψ v_2 from RHIC

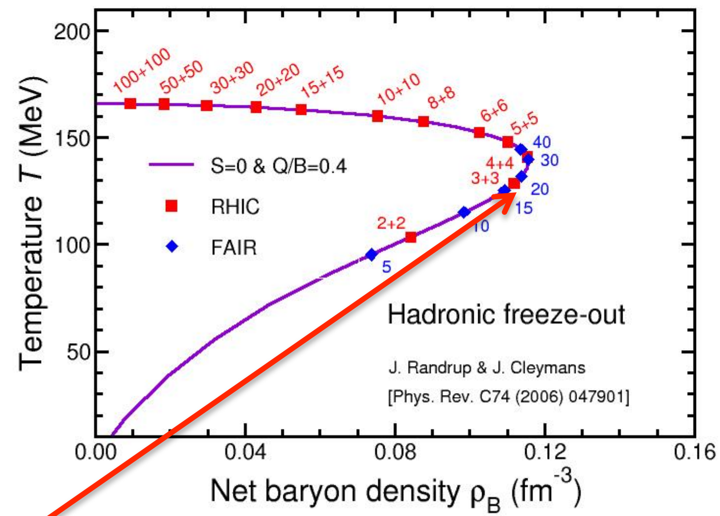
W.T. Deng and X.G. Huang, Phys. Rev. **C85**, 044907 (2012)
U. Gursoy, D. Kharzeev, K. Rajagopal, Phys. Rev. **C89**, 054905 (2014)

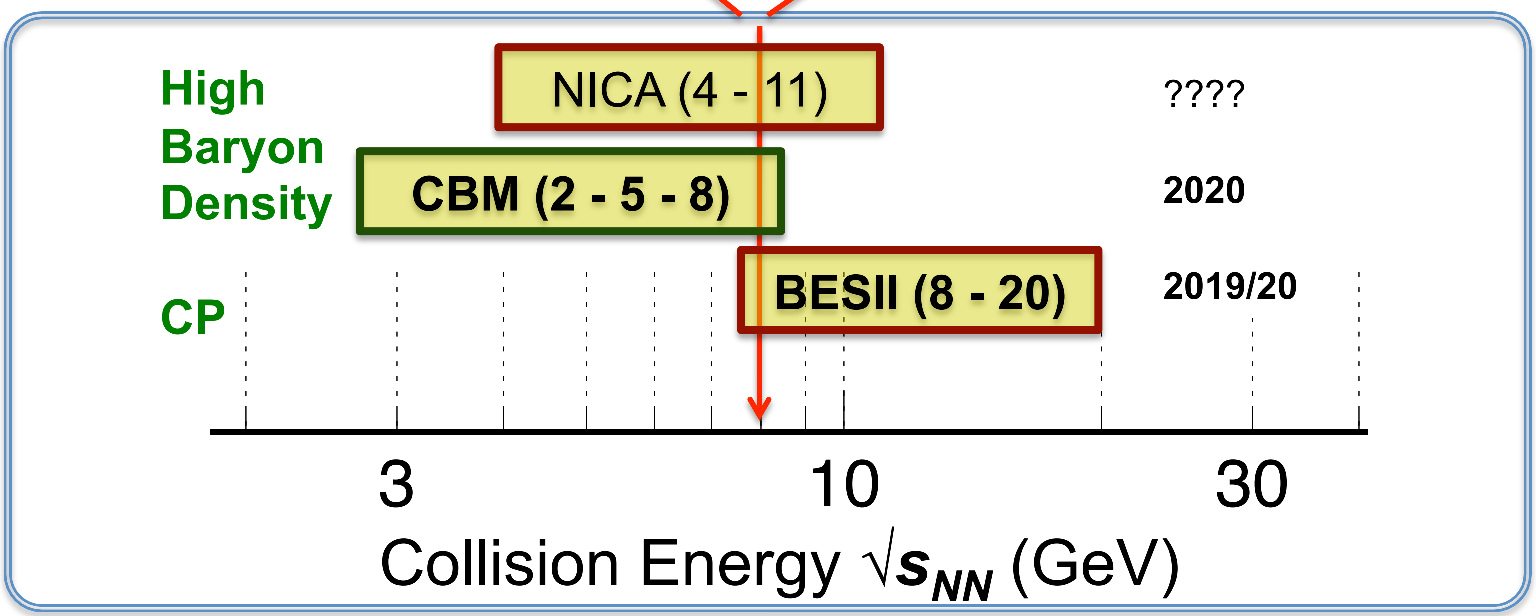
Outlook

Baryon Density Peaks at ~ $\sqrt{s_{NN}}$ = 8 GeV

1304.2969



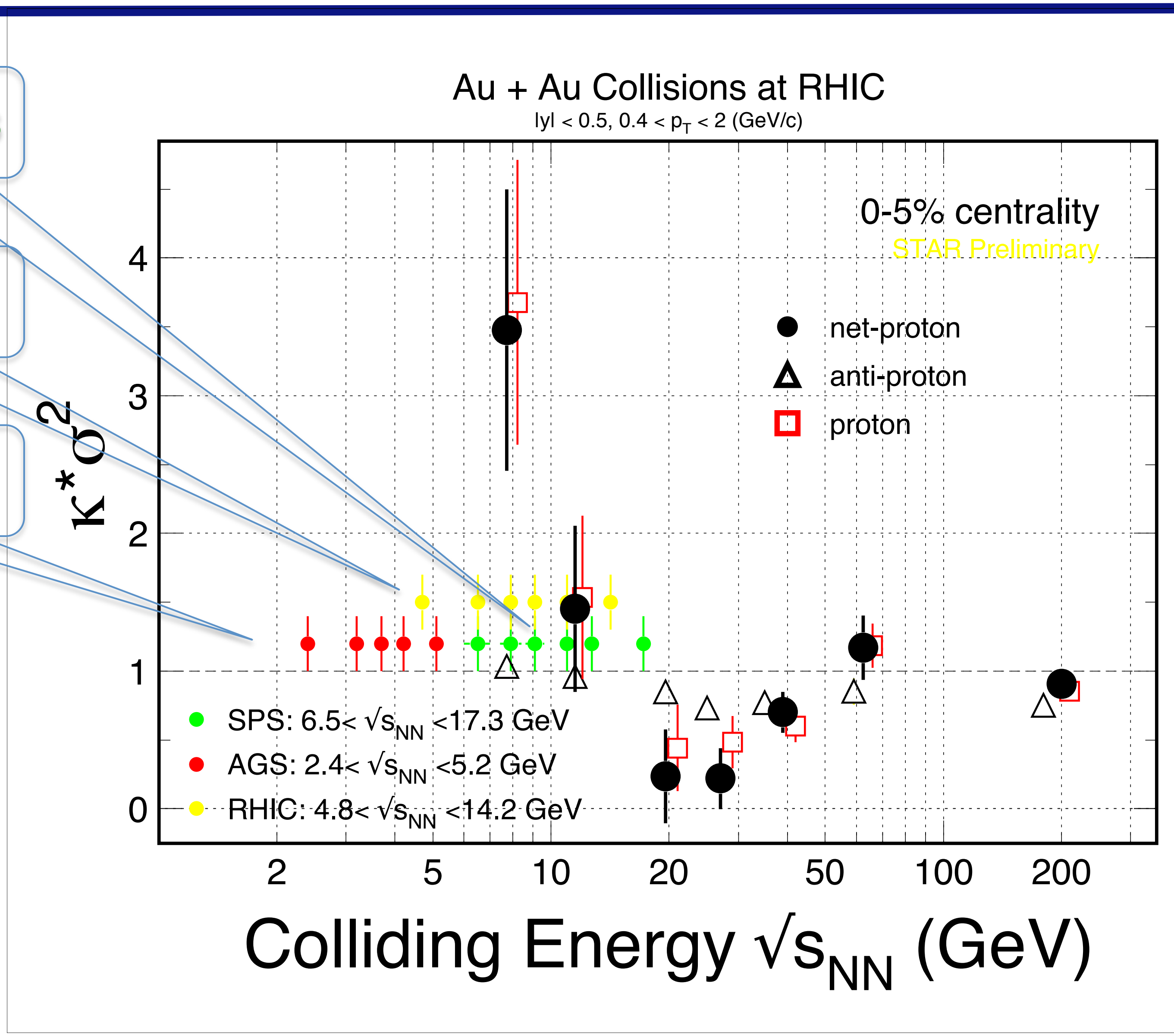




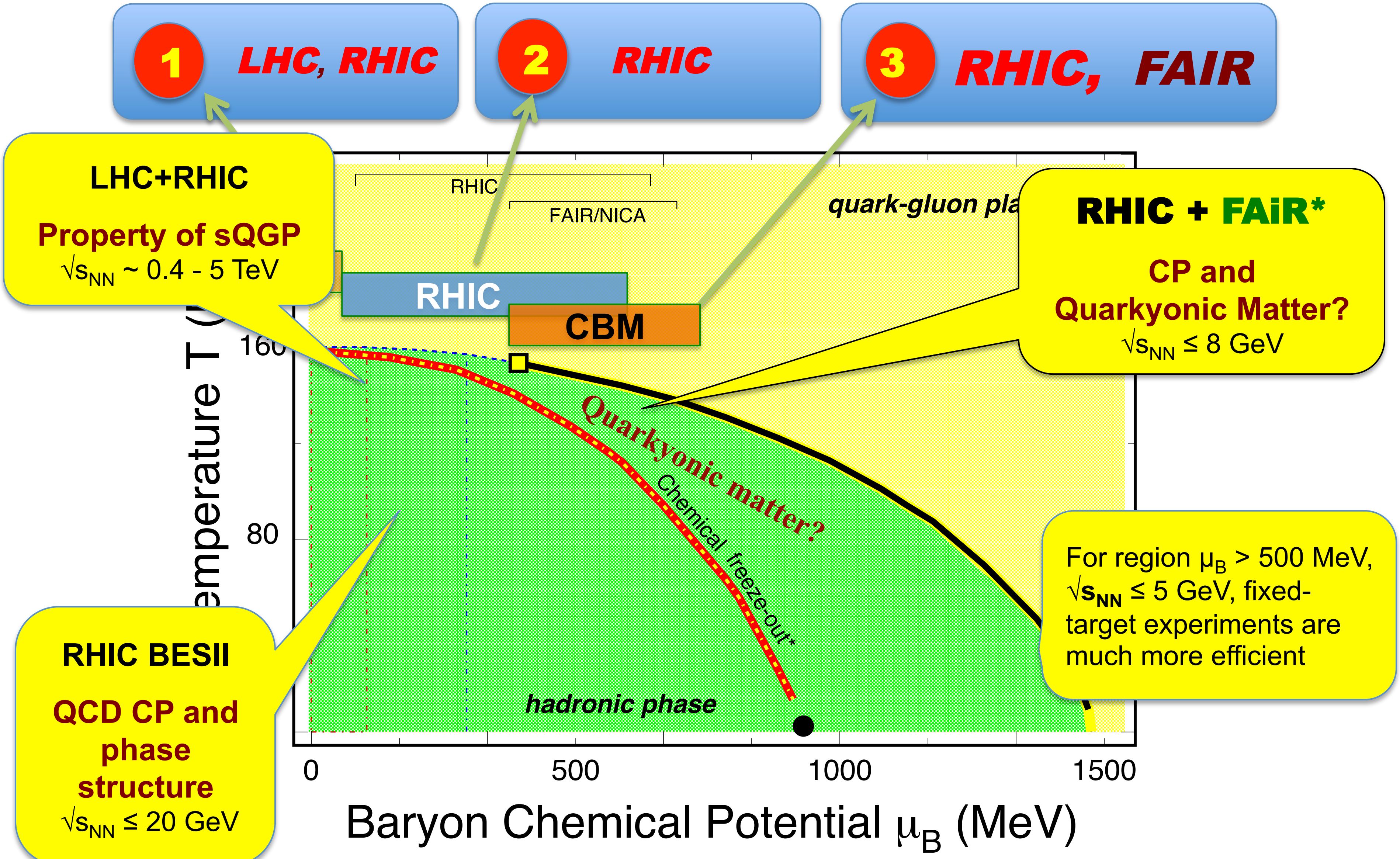
CBM@SPS

CBM@RHIC

CBM



Exploring QCD Phase Structure



Summary

Emergent properties of QCD

At large baryon density region

Go CBM!

2000 – 2015: QGP at $\mu_B \sim 0$ discovered
2015 – 2025: 1st order phase boundary
QCD Critical Point at large μ_B