Explore QCD Phase Diagram in High-Energy Nuclear Collisions at RHIC

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Outline

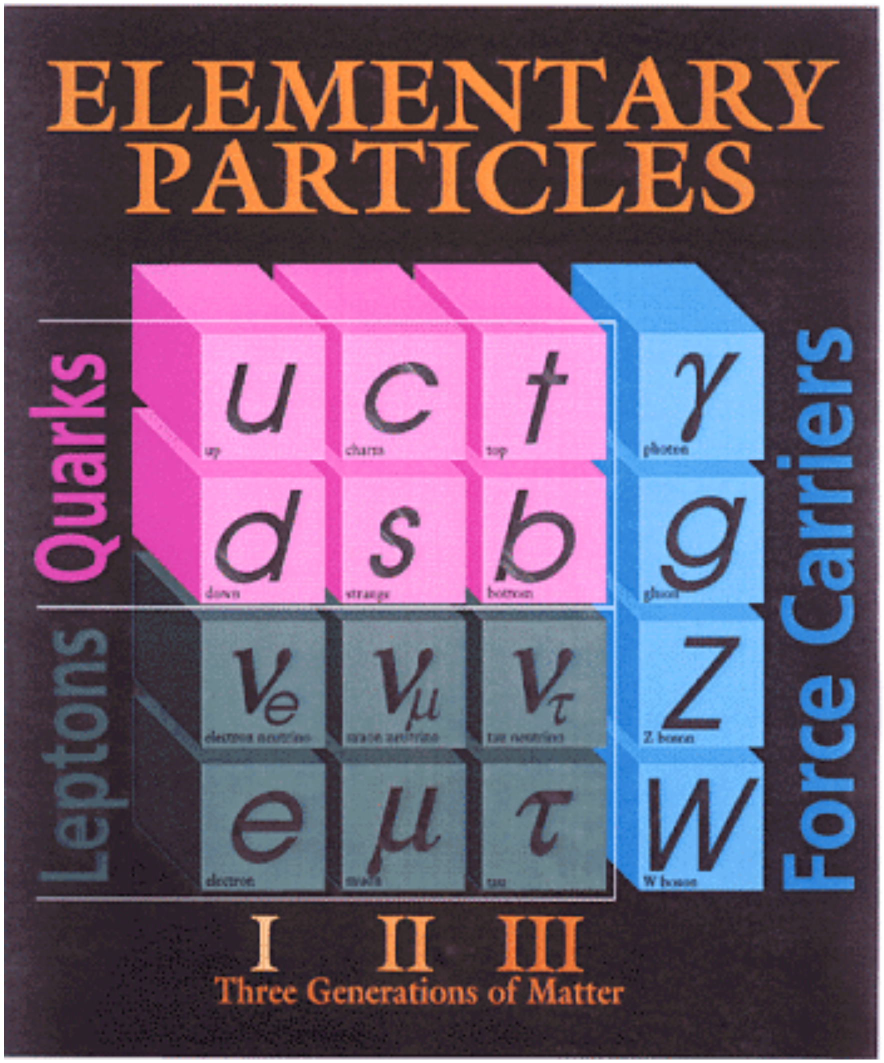
(1) Introduction

(2) Recent results from RHIC

(3) Future programs

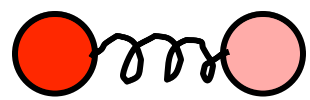
(4) Summary

Basics on Quantum Chromodynamics

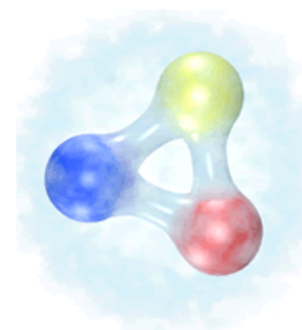


1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:

meson

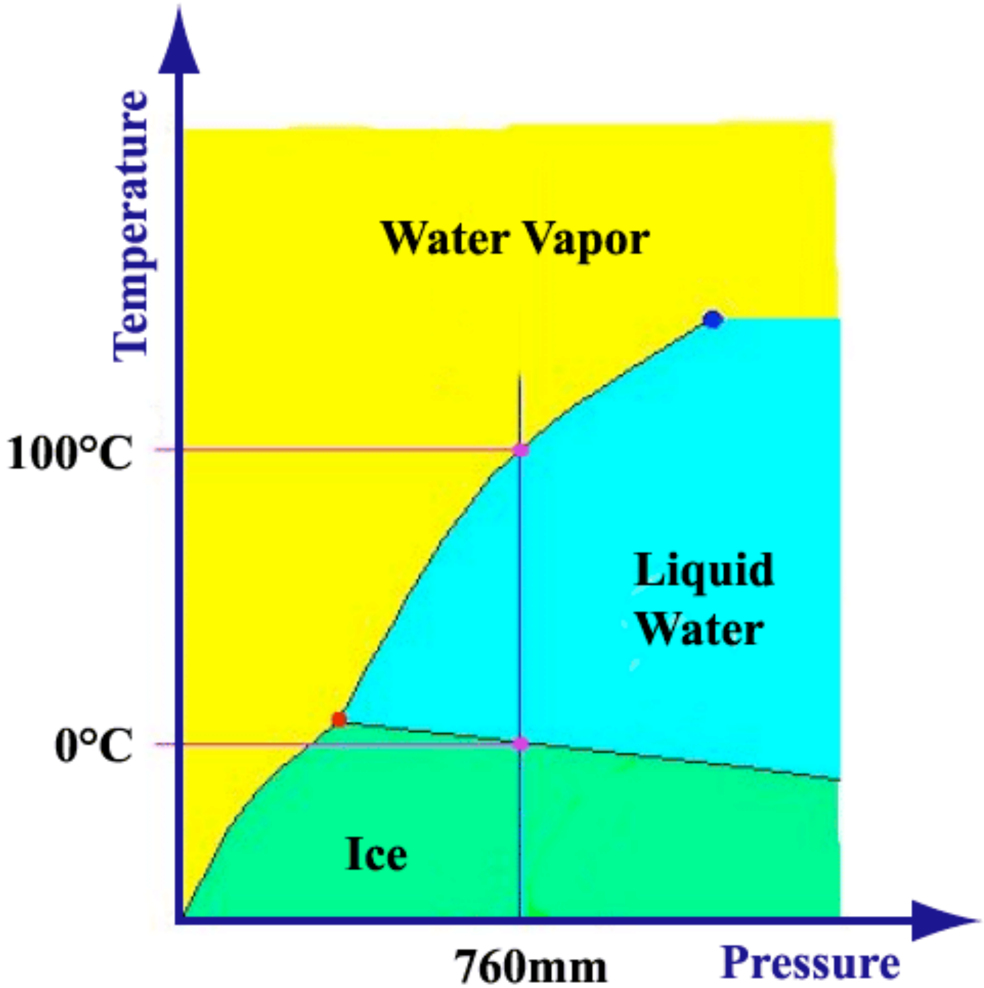


baryon



3) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

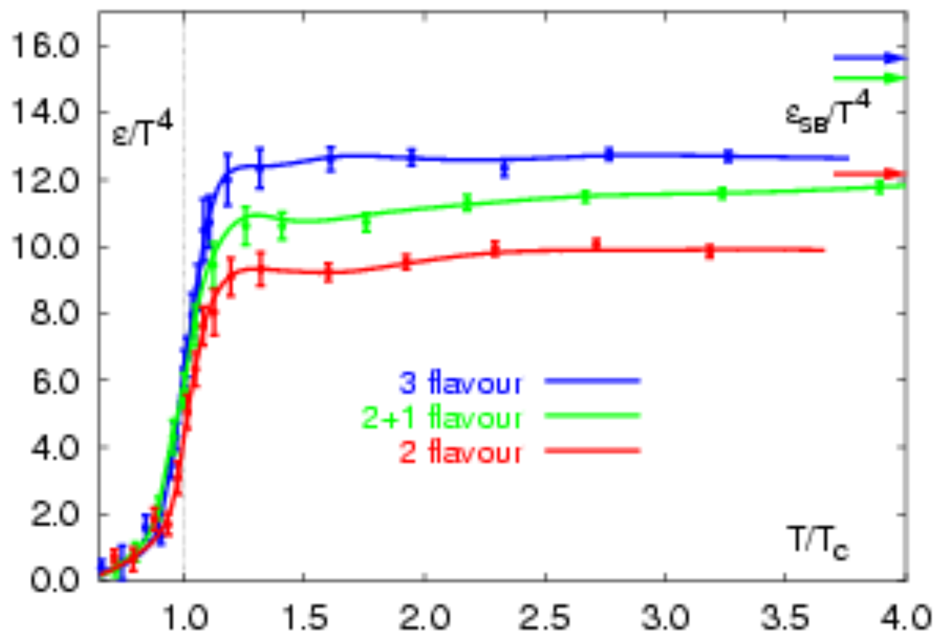
Phase Diagram: Water



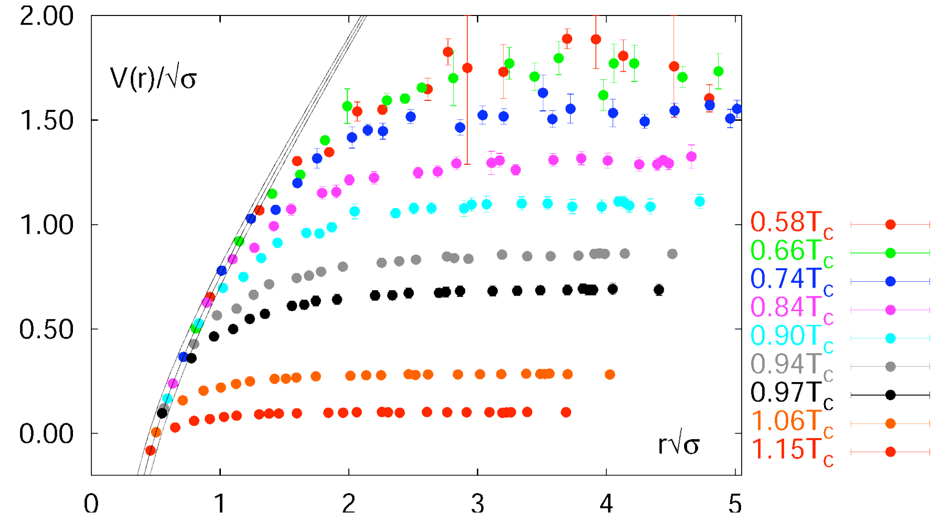
Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

Lattice QCD Predictions

Energy density



Heavy quark potential



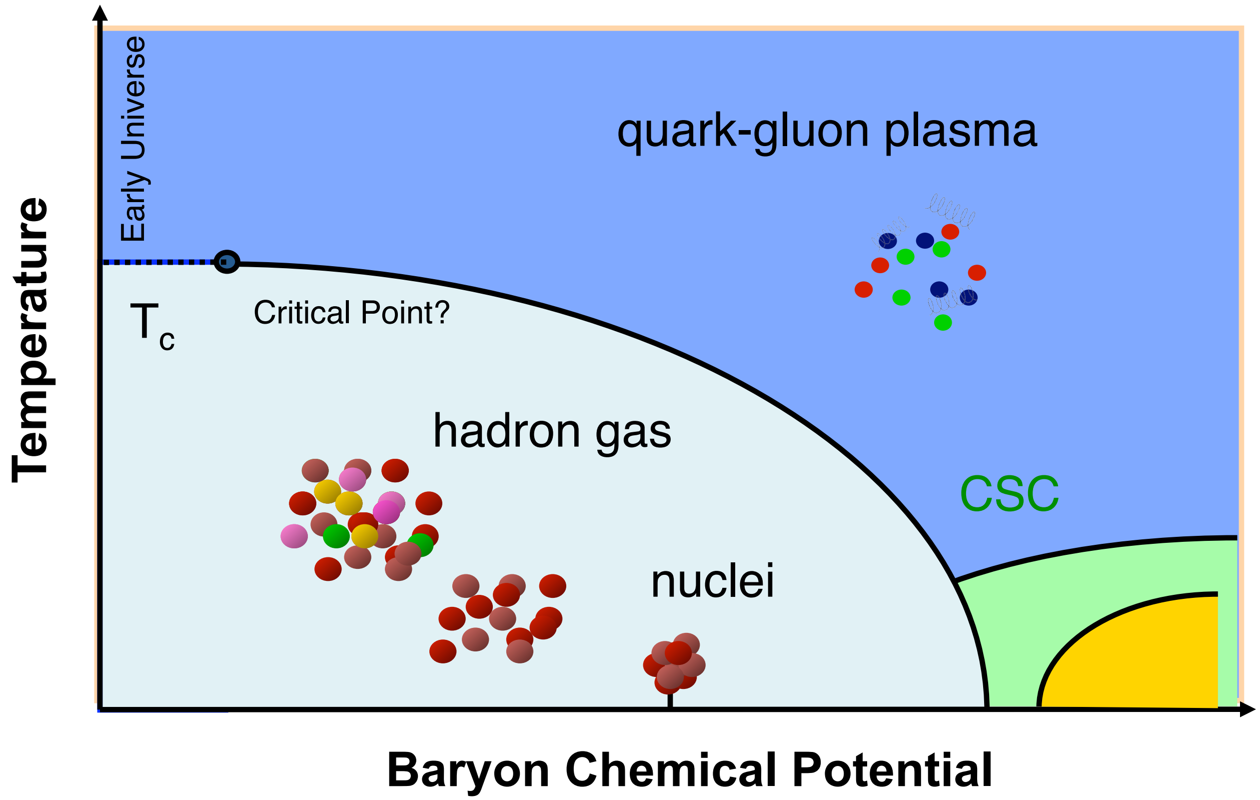
Temperature

Left: Large increase in energy density at **T_C ~ 170 MeV**.
Not reach the non-interacting S.B. limit.

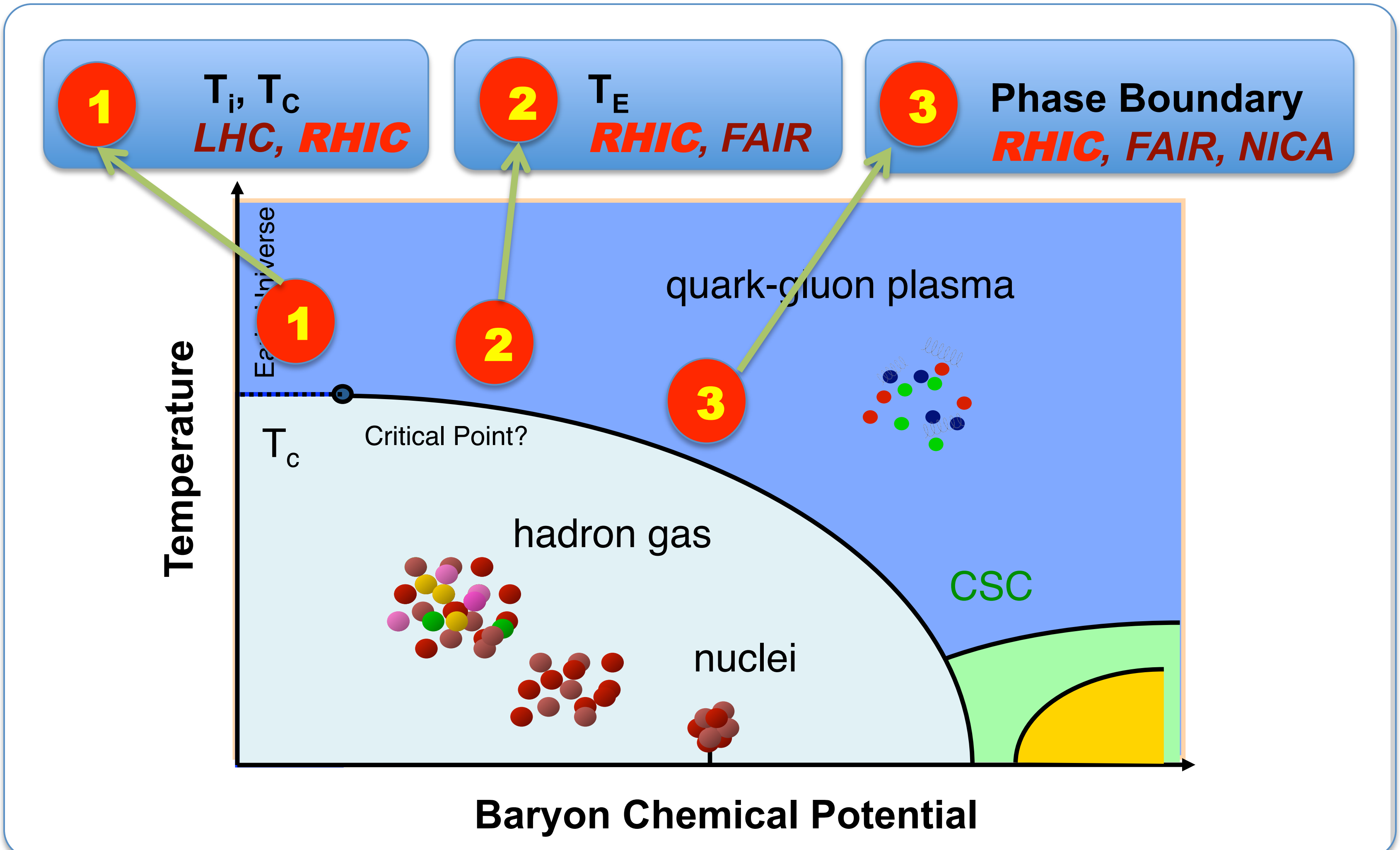
Right: Heavy quark potentials are melted at high temperature.

High-Energy Nuclear Collisions

Explore the QCD landscape and the structure of the matter with partonic degrees of freedom.



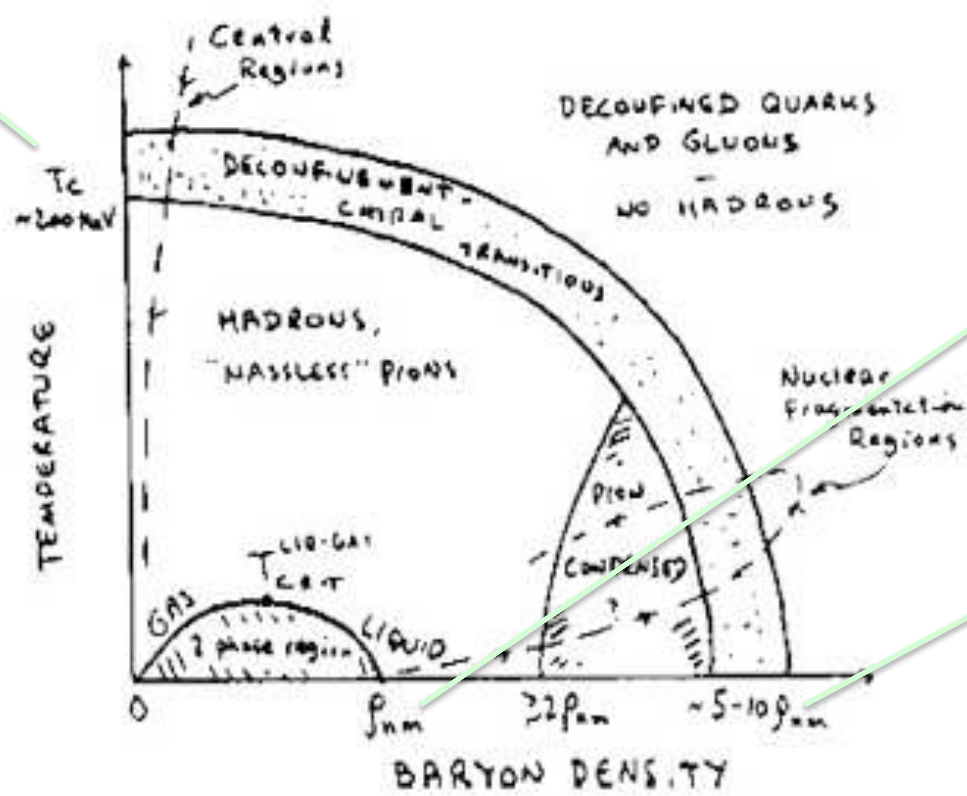
The QCD Phase Diagram and High-Energy Nuclear Collisions



QCD Phase Diagram 1983

1983 US Long Range Plan *- by Gordon Baym*

T_C ~ 200 MeV!



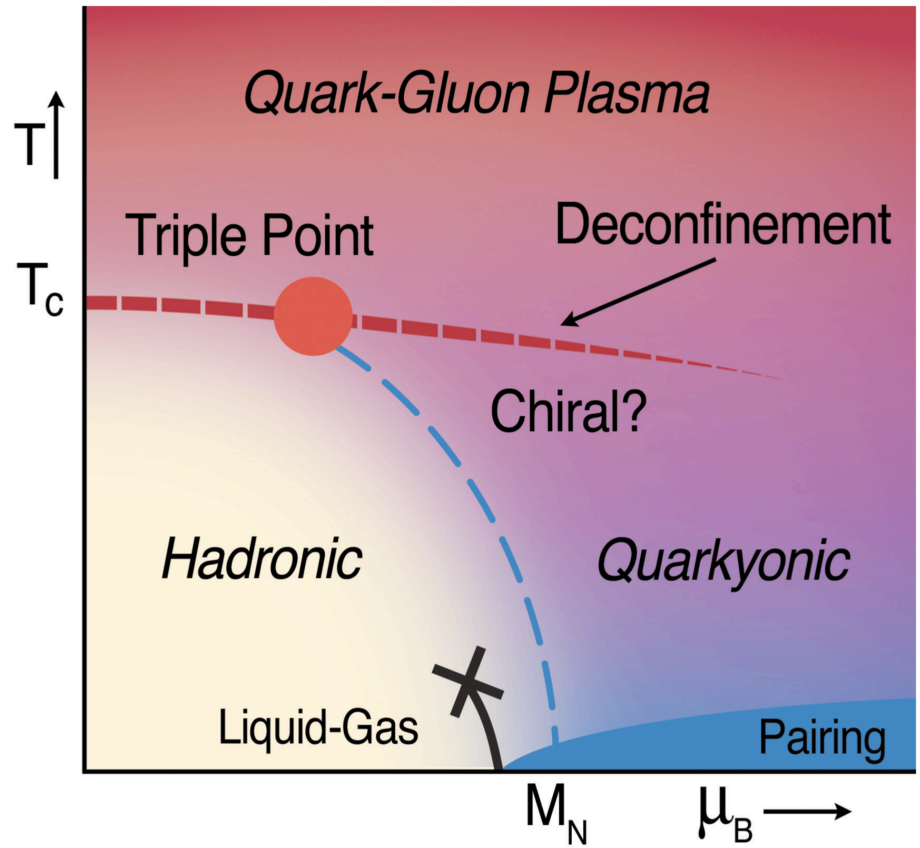
(1, 2, 5-10)ρ

QCD Phase Diagram 2009

nucl-th: 0907.4489, NPA830,709(09) *L. McLerran*

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*

???



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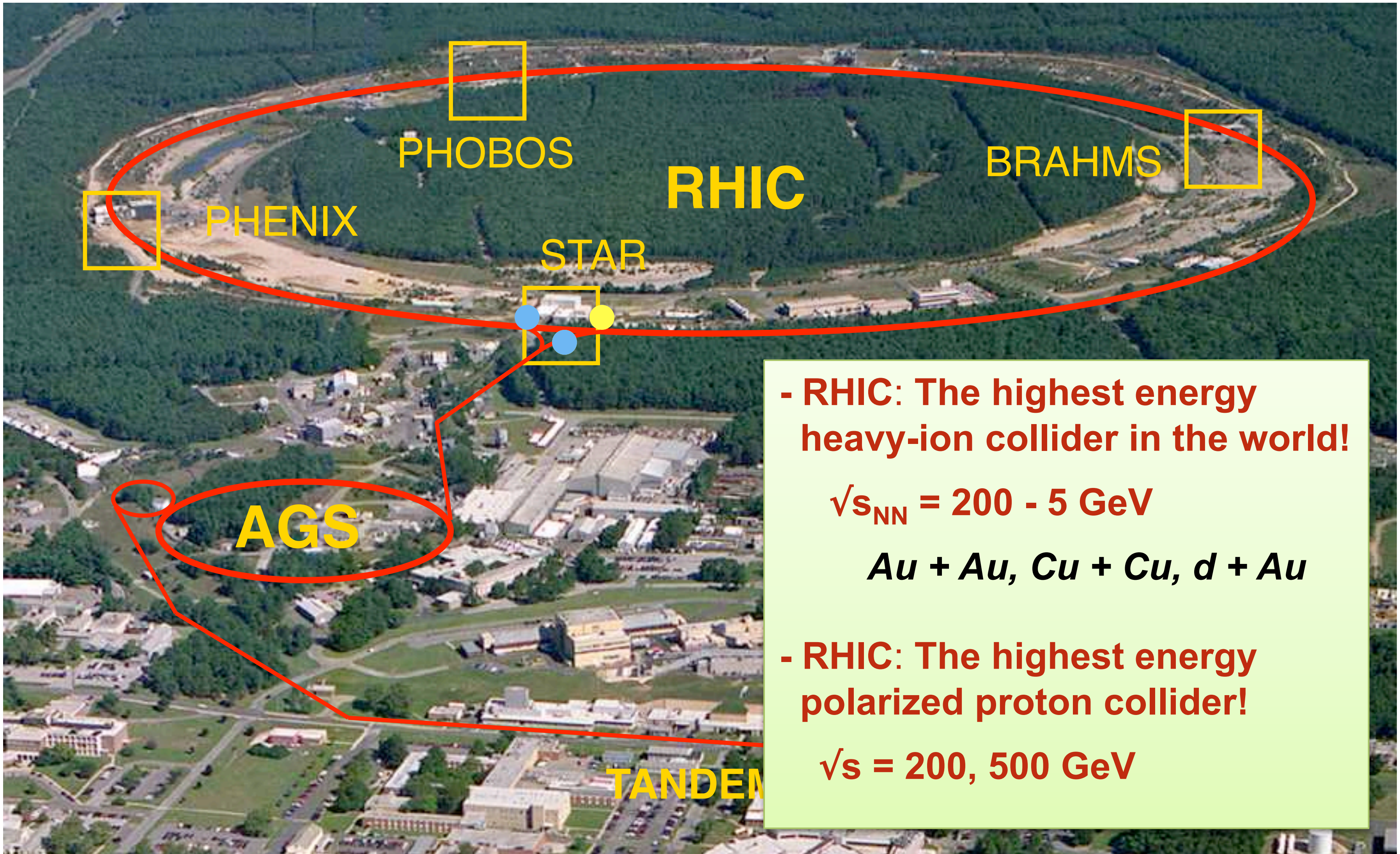
Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



- **RHIC: The highest energy heavy-ion collider in the world!**

  $\sqrt{s_{NN}}$ **= 200 - 5 GeV**

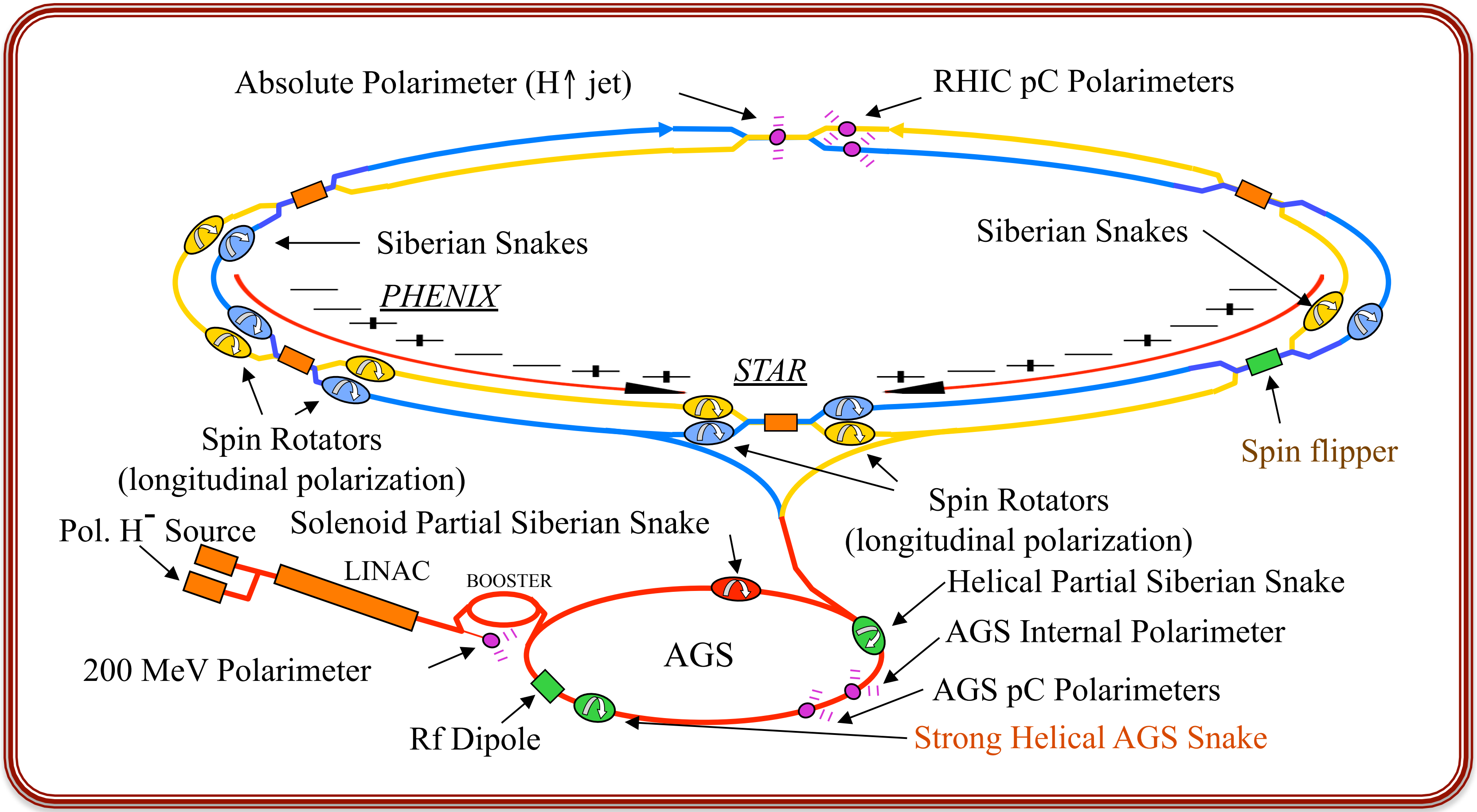
  Au + Au, Cu + Cu, d + Au

- **RHIC: The highest energy polarized proton collider!**

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

Animation M. Lisa

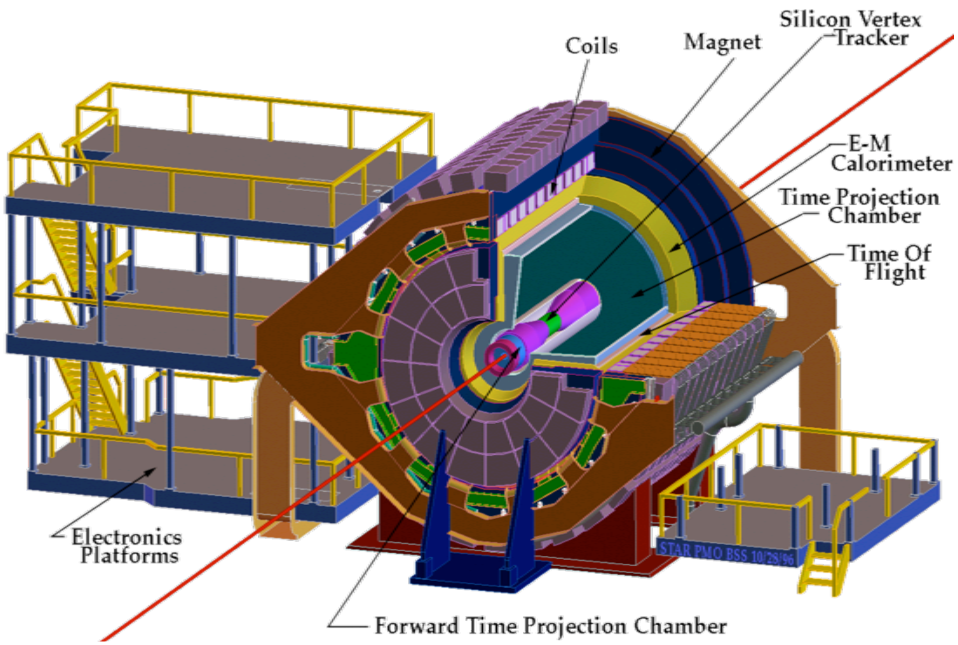
RHIC: Polarized Hadron Collider



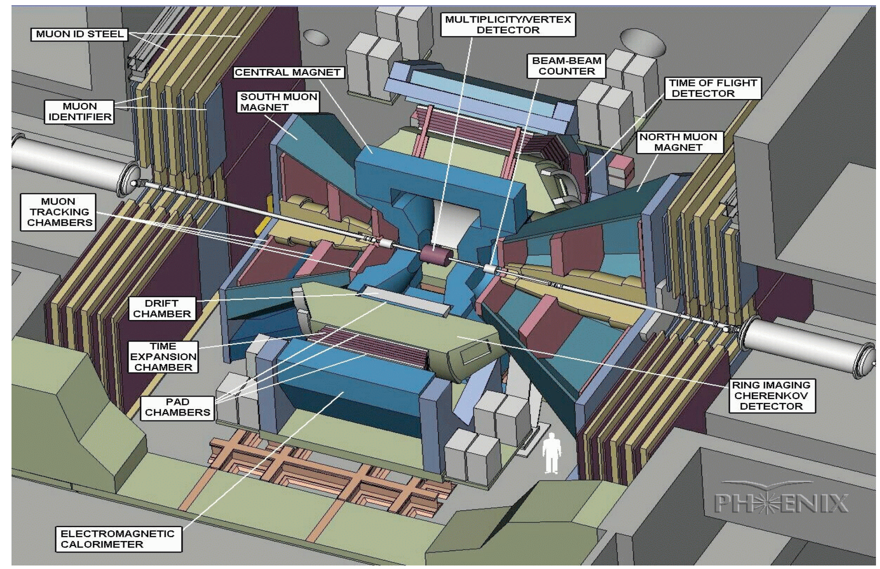
- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- “Billions” of spin reversals during a fill

Large Detectors at RHIC

STAR



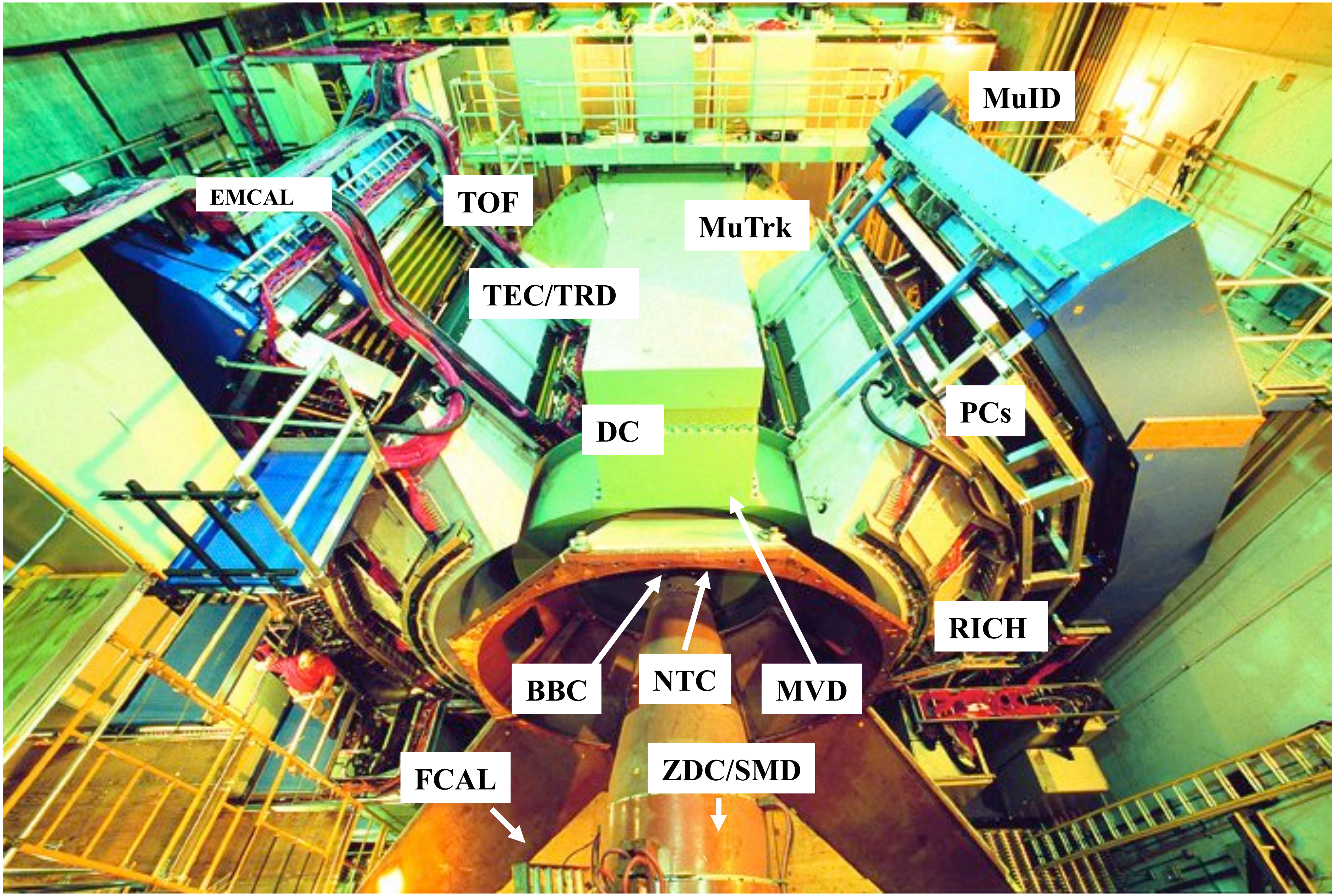
PHENIX

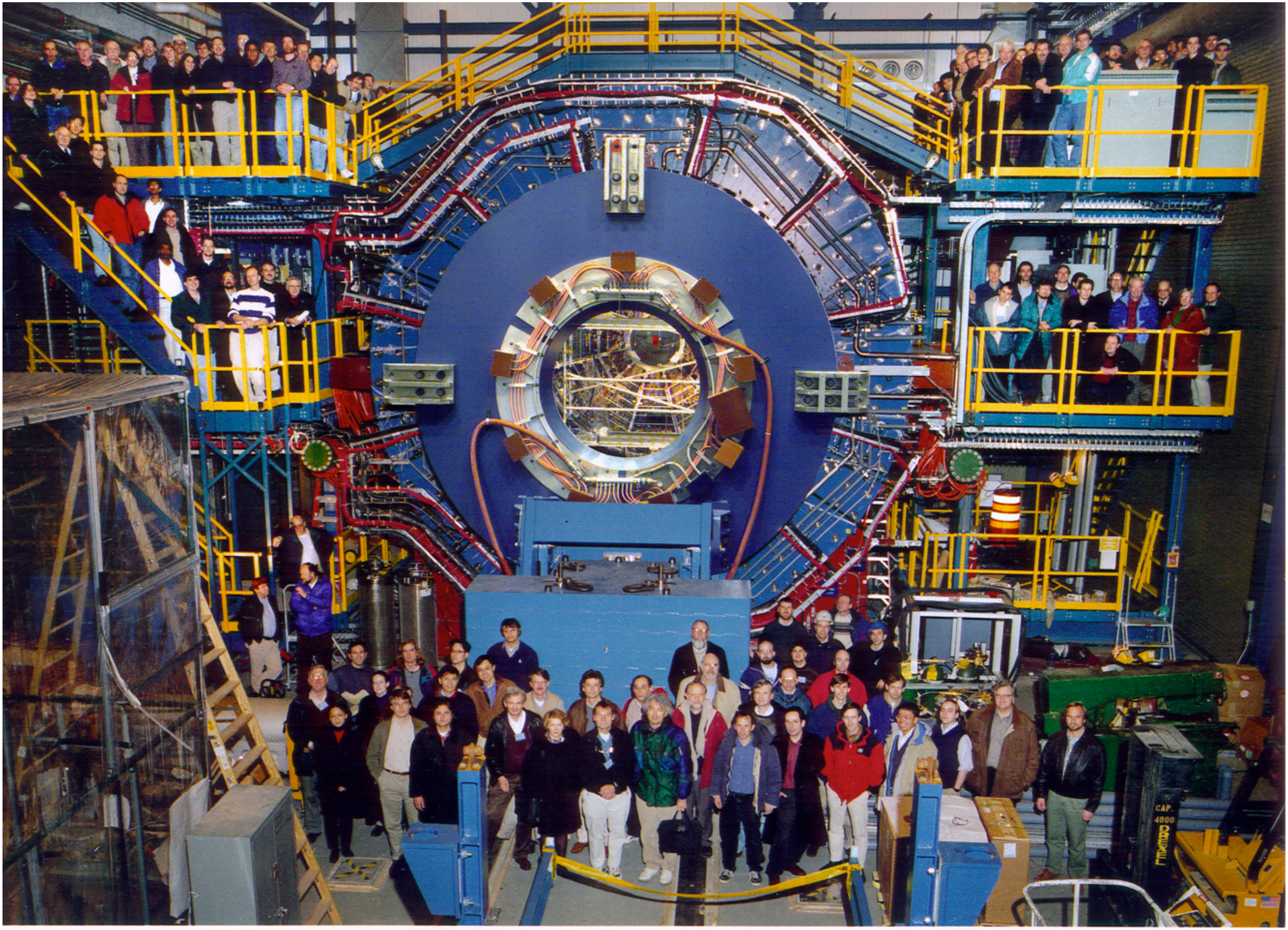


STAR
Large acceptance
Full azimuthal coverage

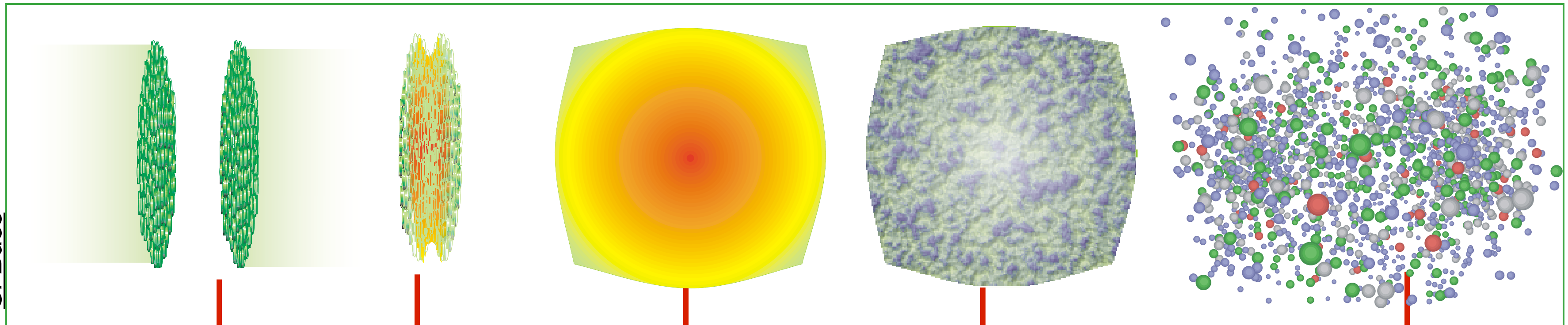
PHENIX
Small acceptance
Good particle identification for leptons e, μ

Bird's View of PHENIX




CAP.
4000
DREXEL

High-energy Nuclear Collisions


S. Bass

Initial conditions

Initial high Q^2 interactions

Partonic matter - QGP - The hot-QCD

Hadronization and Freeze-out

(1) Hard scattering production - QCD prediction
(2) Interactions with medium - deconfinement/thermalization
(3) Initial parton density

(1) Initial condition in high-energy nuclear collisions - Color Glass Condensation
(2) Cold-QCD-matter, small-x, high-parton density
- parton structures in nucleon / nucleus

Physics Goals at RHIC

RHIC

Au+Au, Cu+Cu, d+Au, p+p collisions at 200 – 5 GeV

- **Identify and study the property of matter (EOS) with partonic degrees of freedom.**

- **Explore the QCD phase diagram.**

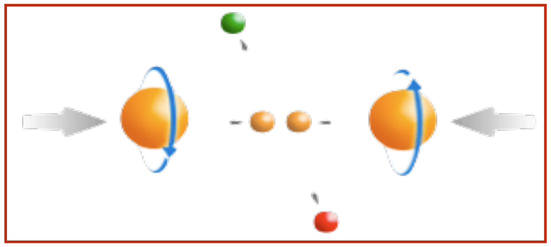
Polarized p+p collisions at 200 & 500 GeV

- **Study the origin of spin in *p*.**

p+p, d+Au pp2pp

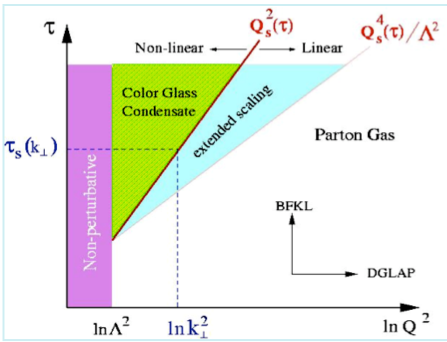
- **Investigate the physics at small-*x*, gluon-rich region.**

STAR Physics Focus



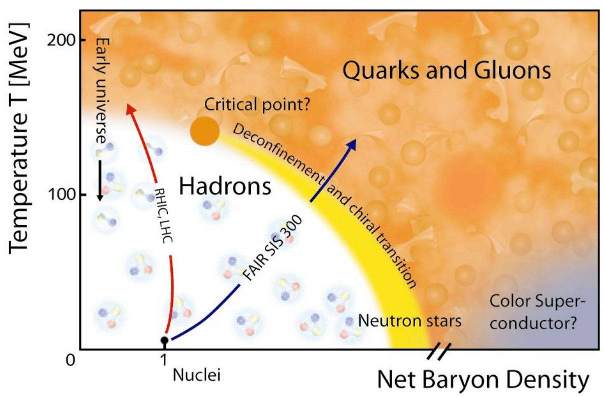
Polarized *p+p* program

- Study ***proton intrinsic properties***



Forward program

- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***



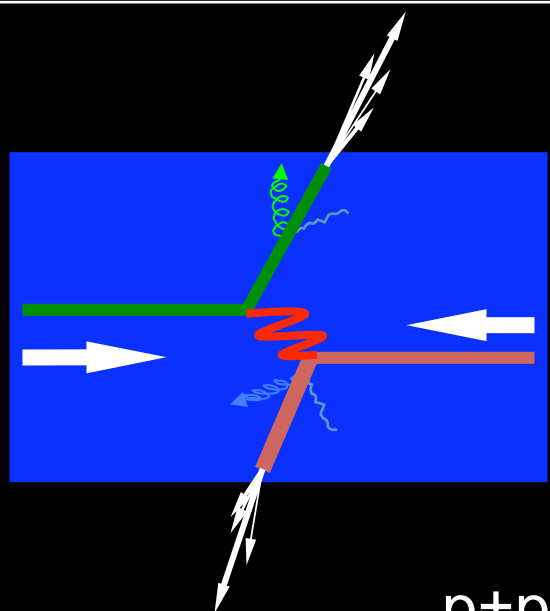
1) At 200 GeV top energy

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

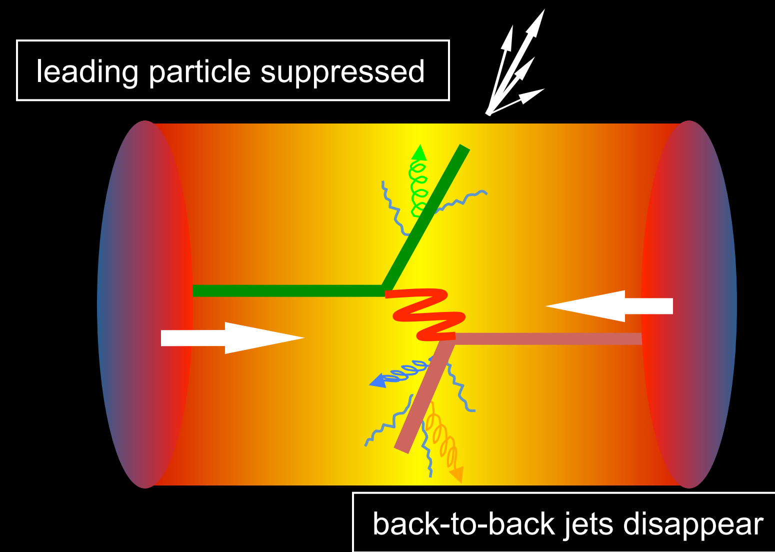
2) RHIC beam energy scan

- Search for the ***QCD critical point***
- Chiral symmetry restoration

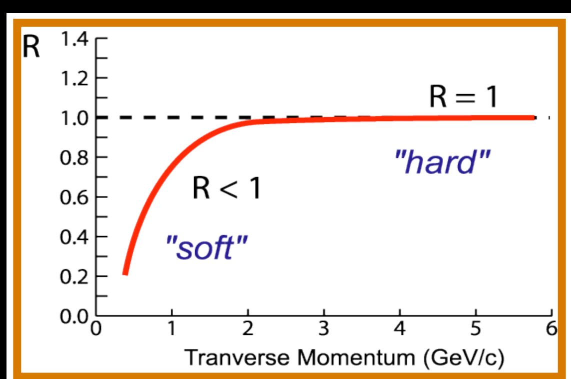
Energy Loss in A+A Collisions



p+p



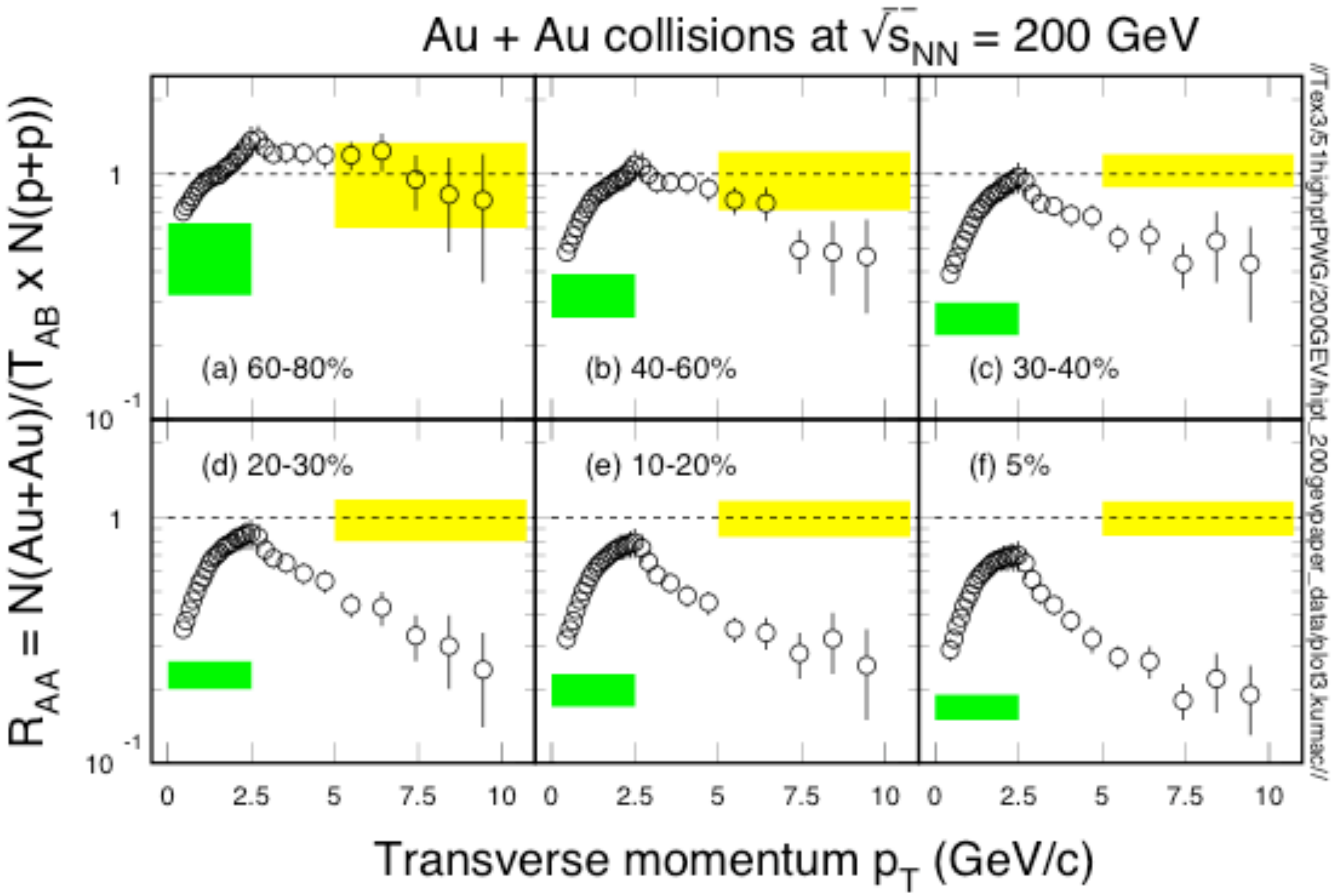
Au + Au

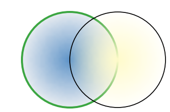


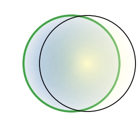
Nuclear Modification Factor:

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

Hadron Suppression at RHIC

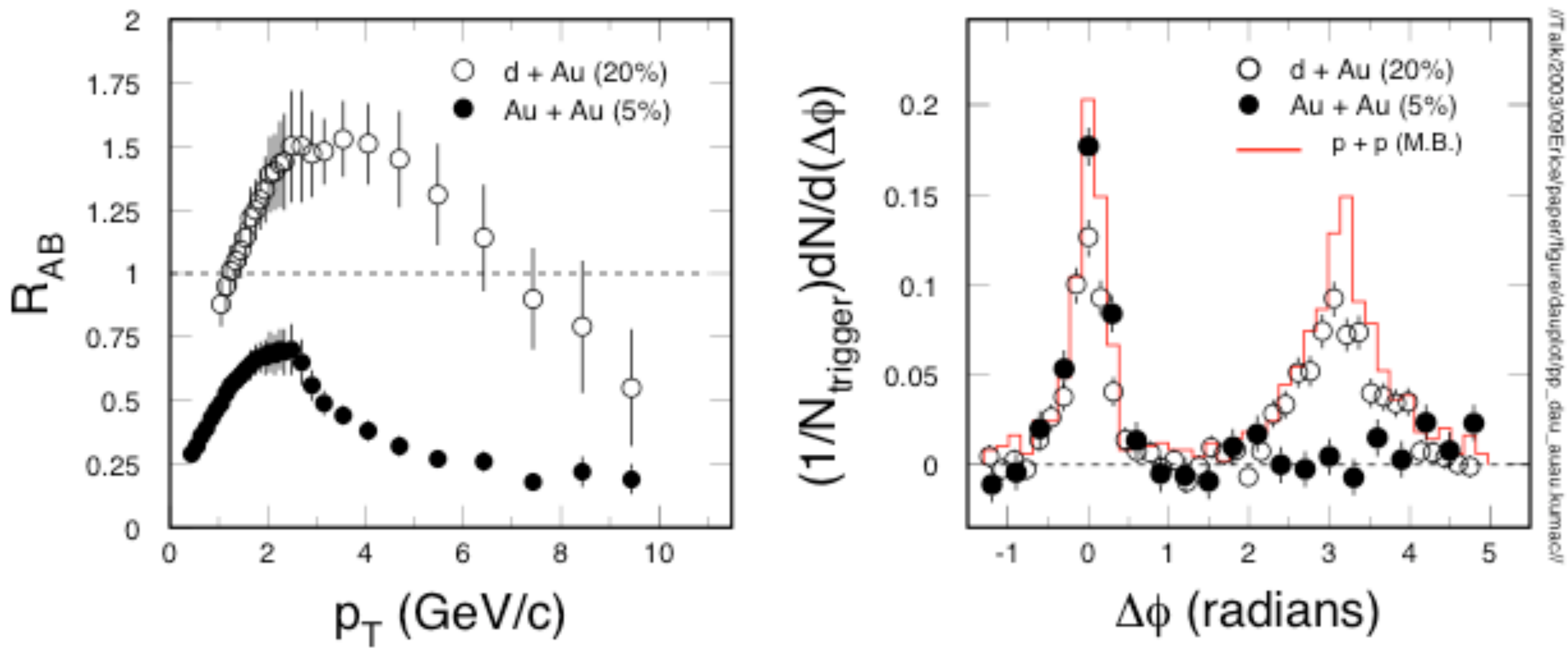






Hadron suppression in more central Au+Au collisions!

Suppression and Correlations



In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: **ε** > 5 GeV/fm^3 ~ 30**ε_0**

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

…

Pressure, Flow, …

$$\tau d\sigma = dU + pdV$$

σ– entropy; p – pressure; U – internal energy; V – volume
$\tau = k_B T$, thermal energy per dof

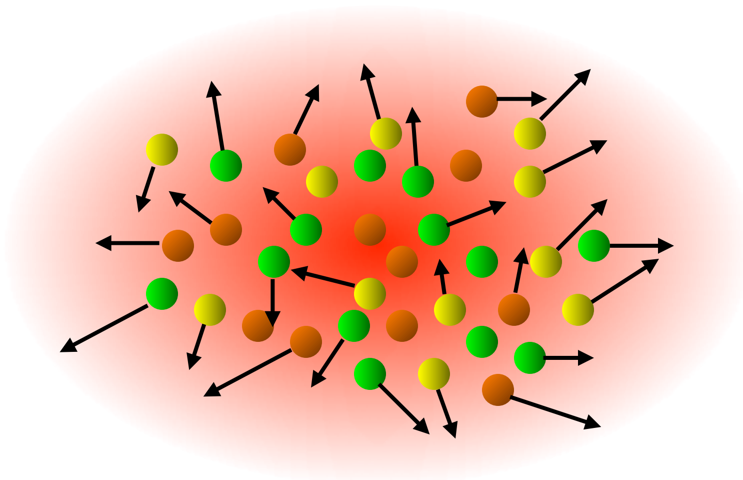
In high-energy nuclear collisions, *interaction* among *constituents* and *density distribution* will lead to:

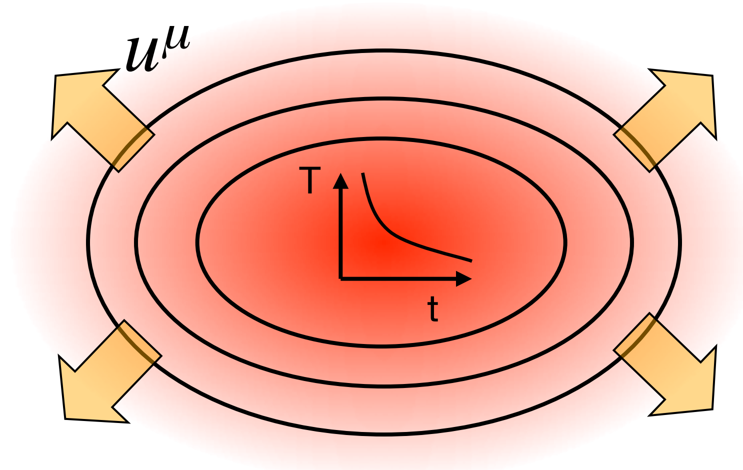
pressure gradient ⇔ collective flow

⇔ number of degrees of freedom (dof)
⇔ Equation of State (EOS)
⇔ No thermalization is needed – pressure gradient only depends on the ***density gradient and interactions***.
⇒ Space-time-momentum correlations!

Timescales of Expansion Dynamics

microscopic view vs **macroscopic view**





scattering rate $\nu_{ab} \sim$

$$\int \frac{d^3 p_a}{(2\pi)^3} \frac{d^3 p_b}{(2\pi)^3} f_a(p_a) f_b(p_b) \sigma_{ab}(s) \left| \vec{v}_a - \vec{v}_b \right|$$

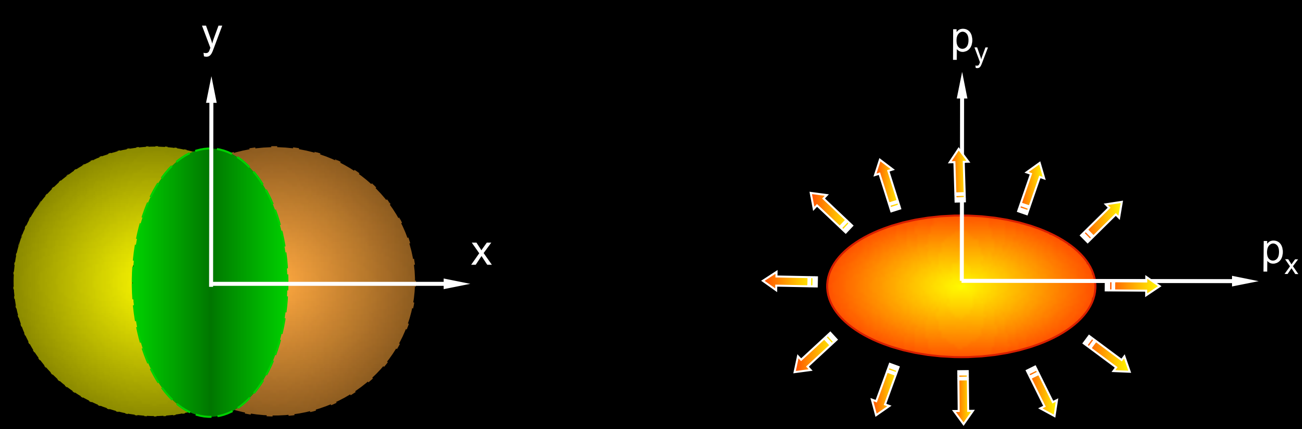
expansion rate $\partial_\mu u^\mu$

dilution rate $\partial_\tau s$

A macroscopic treatment requires that the scattering rate is larger than macroscopic rates

Anisotropy Parameter v_2

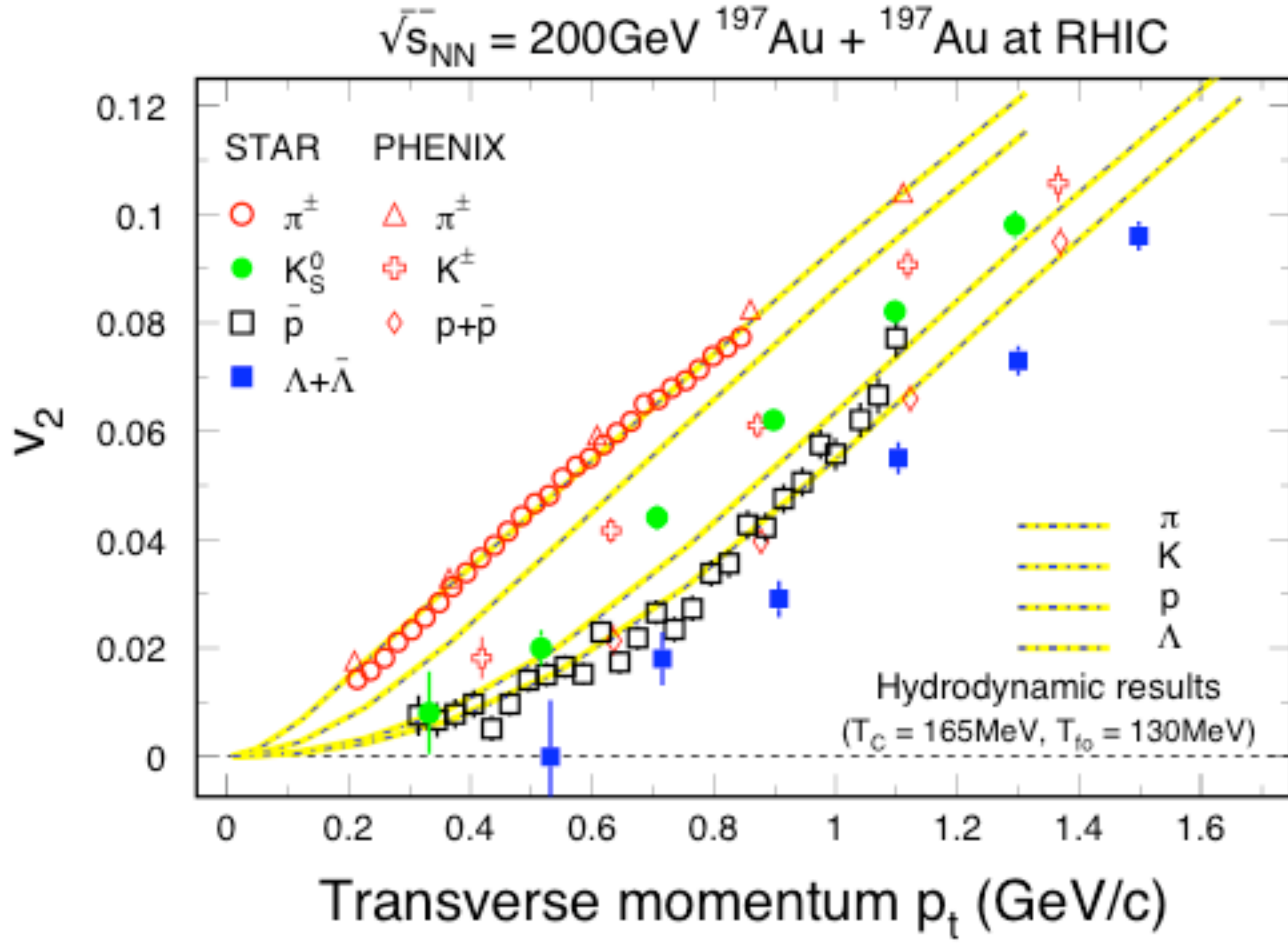
coordinate-space-anisotropy ➪ momentum-space-anisotropy



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

Initial/final conditions, EoS, degrees of freedom

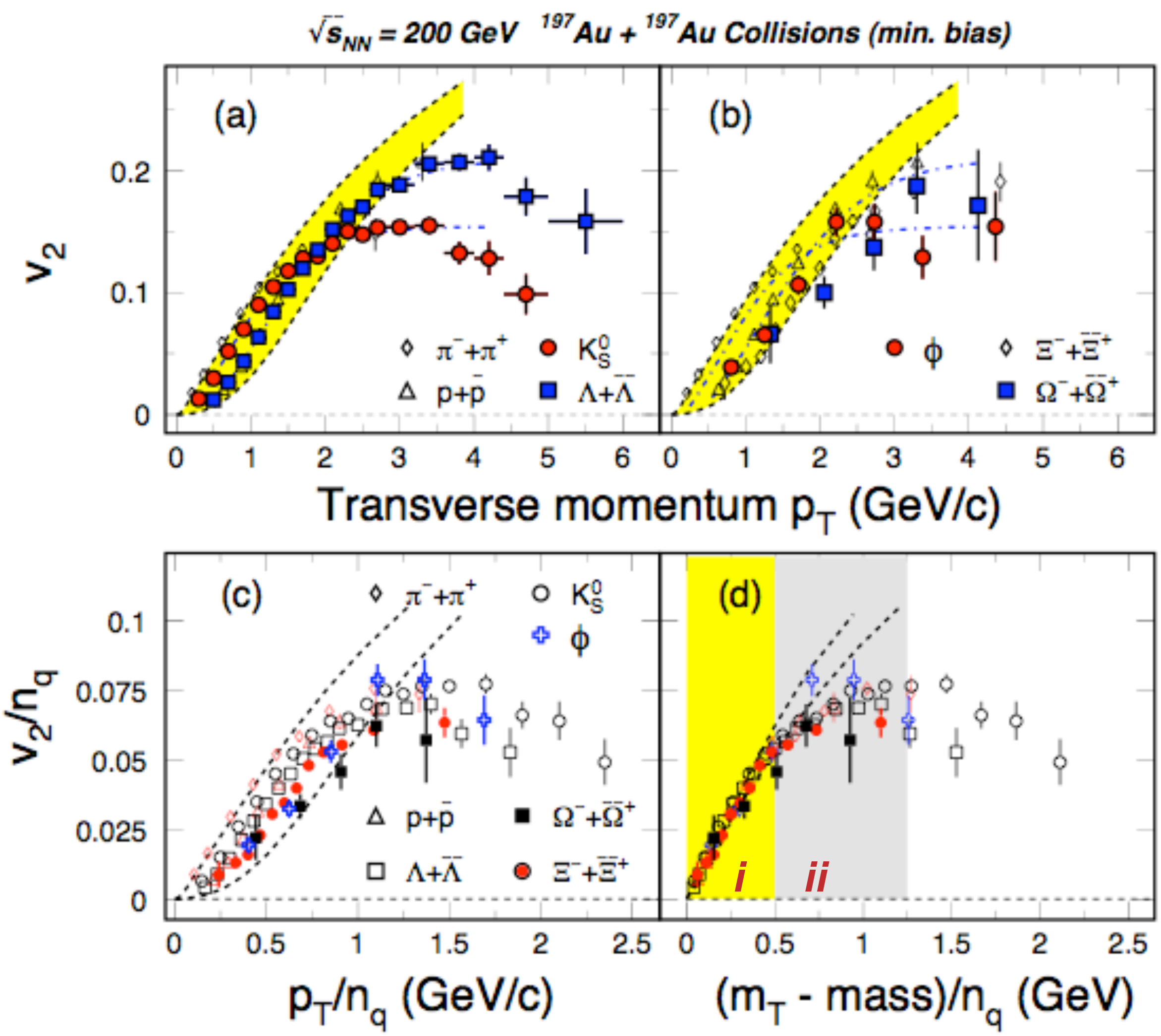
v_2 at Low p_T Region



P. Huovinen, private communications, 2004

- Minimum bias data!
- At low p_T, model result fits mass hierarchy well - *Collective motion at RHIC*
- More work needed to fix the details in the model calculations.

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

➩ **N_q scaling** novel hadronization process

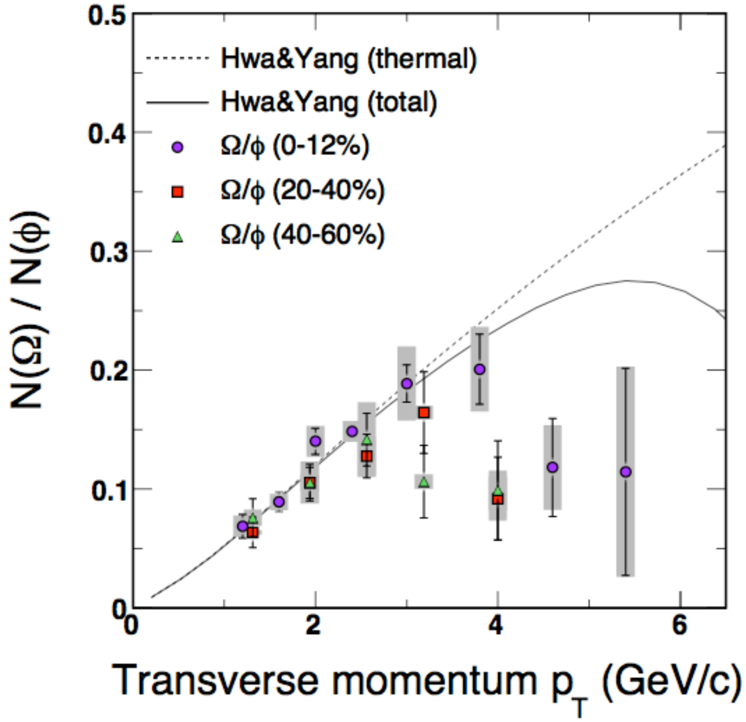
➩ **Parton flow** De-confinement

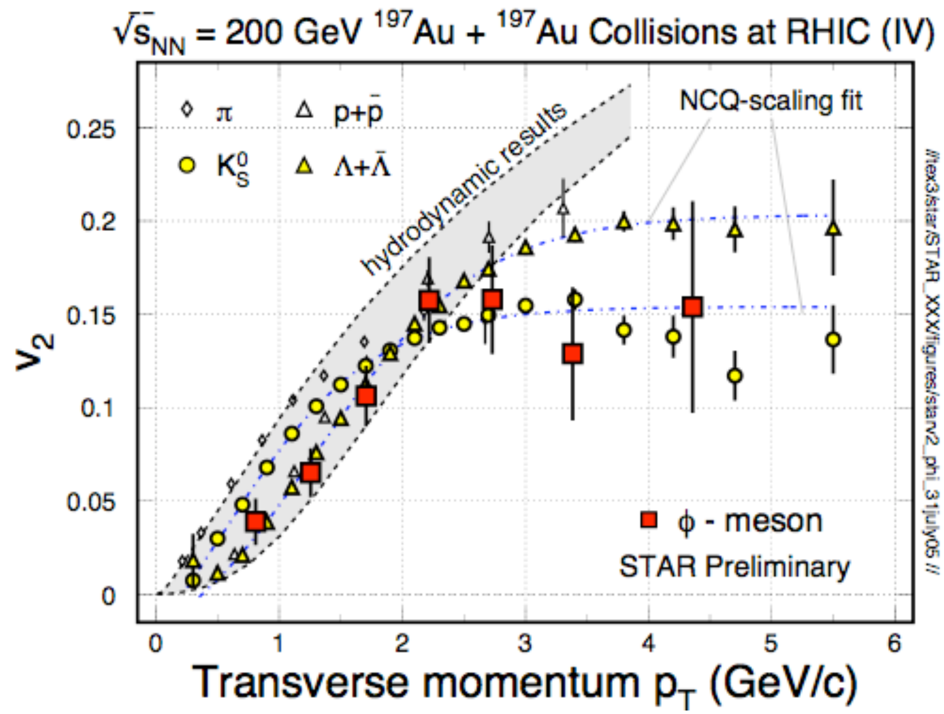
*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

φ-meson Flow: Partonic Flow

STAR: Phys. Rev. Lett. ***99***, 112301(2007).

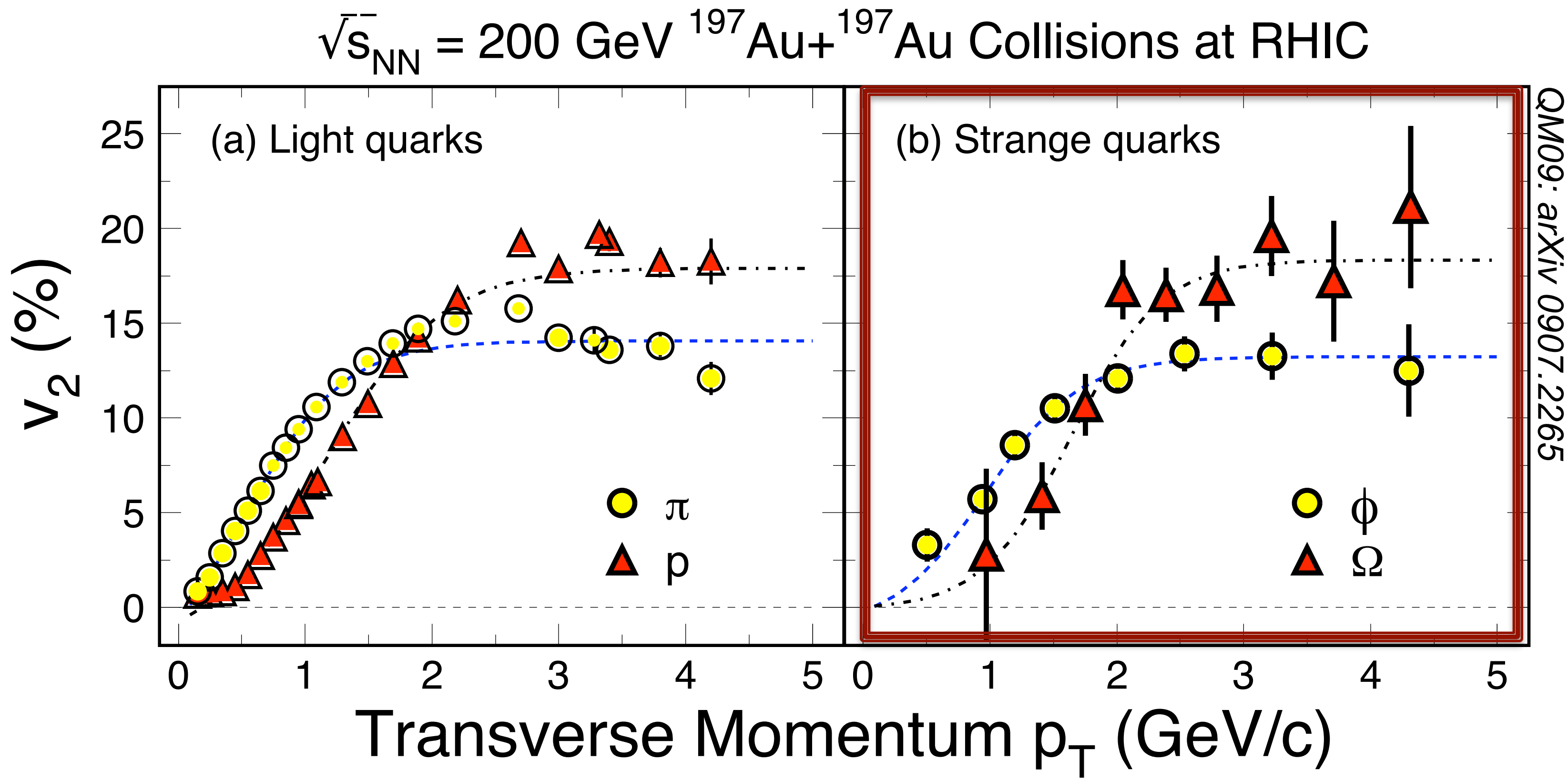




"**φ-mesons (and other hadrons) are produced via coalescence of seemingly thermalized quarks in central Au+Au collisions. This observation implies *hot and dense matter with partonic collectivity* has been formed at RHIC**"

*STAR: Phys. Rev. Lett. **99**, 112301(2007)*

Partonic Collectivity at RHIC



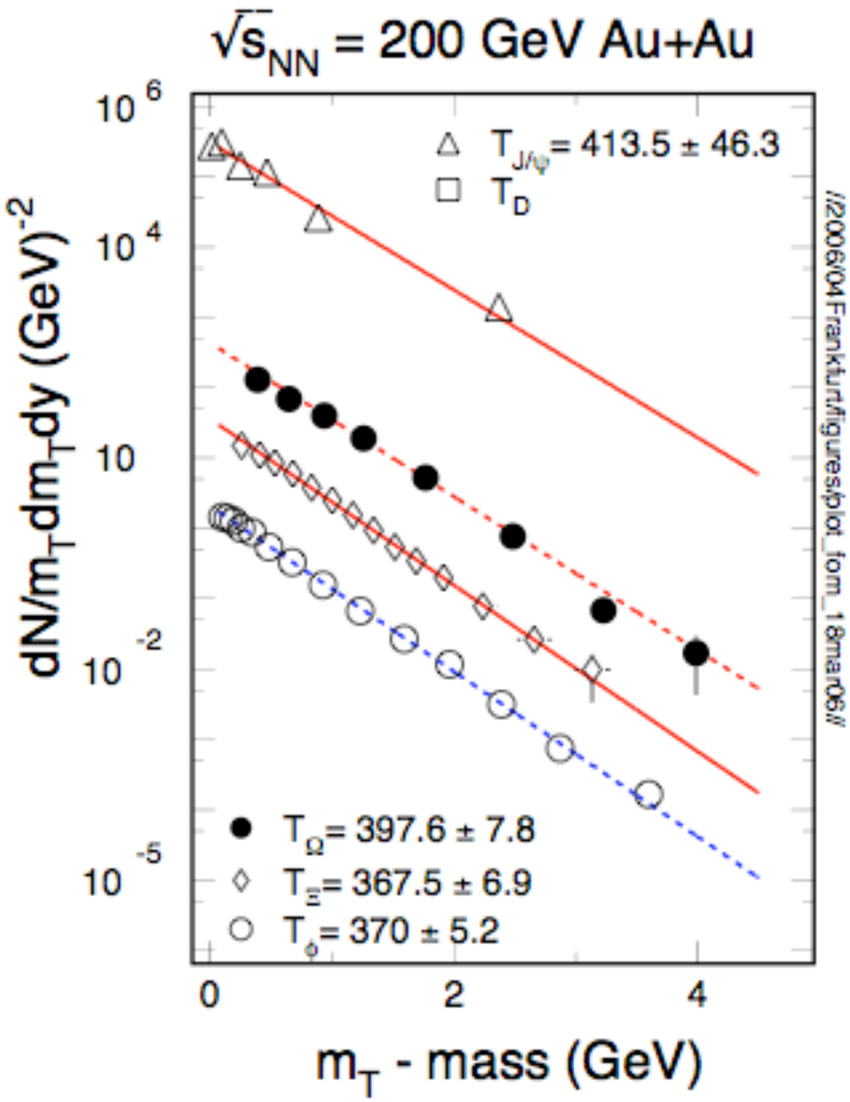
Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): number of quarks ordering
s-quark hadron: smaller interaction strength in hadronic medium
light- and s-quark hadrons: similar v_2 pattern

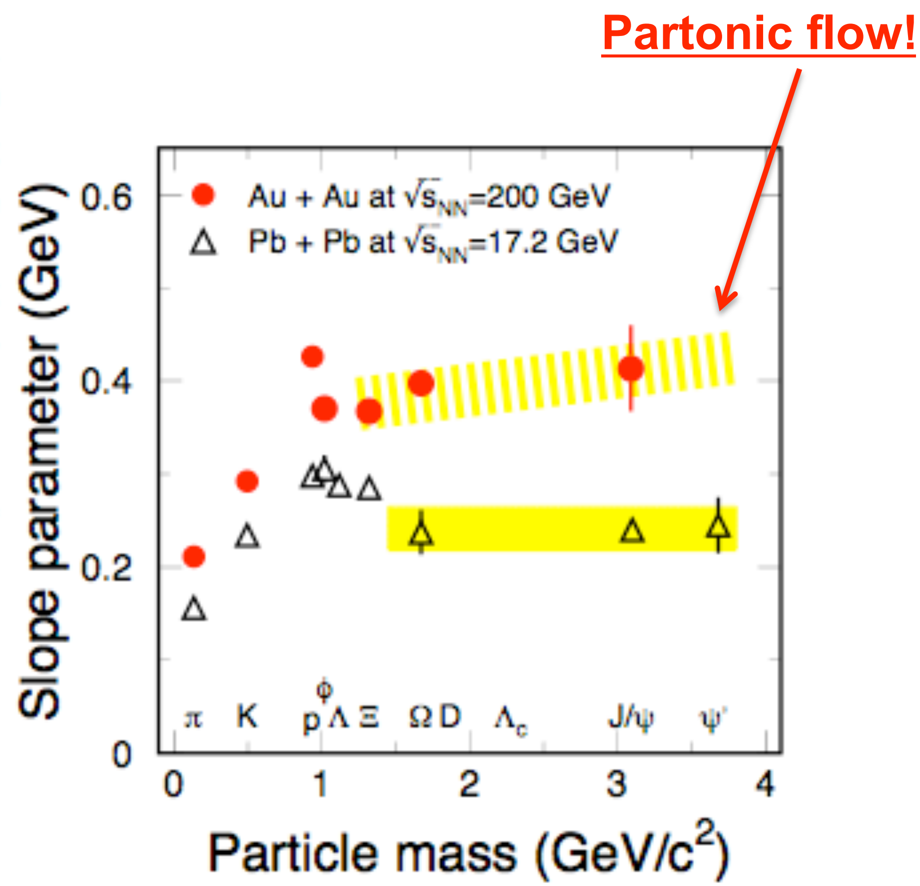
=> Collectivity developed at partonic stage!

Slope Parameter Systematics

$$m_T = \sqrt{p_T^2 + m^2}$$

$$f \propto exp(-m_T / T_{slope})$$





EoS Parameters at RHIC

In central Au+Au collisions at RHIC

- **partonic freeze-out:**

  $^*T_{pfo} = 165 \pm 10$ MeV weak centrality dependence

  $v_{pfo} \geq 0.2$ (c)

- **hadronic freeze-out:**

  $^*T_{fo} = 100 \pm 5$ (MeV) strong centrality dependence

  $v_{fo} = 0.6 \pm 0.05$ (c)

Systematic study, understand the centrality dependence of the EoS parameters

* *Thermalization assumed*

sQGP and the QCD Phase Diagram

200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

Jet energy loss: R_{AA}
Strong collectivity: v_0, v_1, v_2
Hadronization via coalescence: n_q-scaling

Questions:

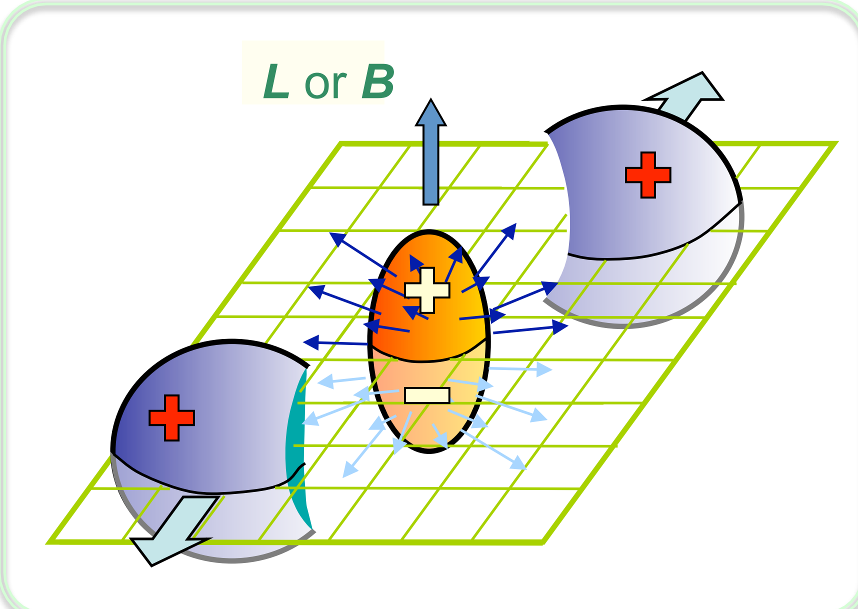
Has the thermalization reached at RHIC?

When (at which energy) does this transition happen?

How does the QCD phase diagram look like?

Search for Local Parity Violation

in High Energy Nuclear Collisions

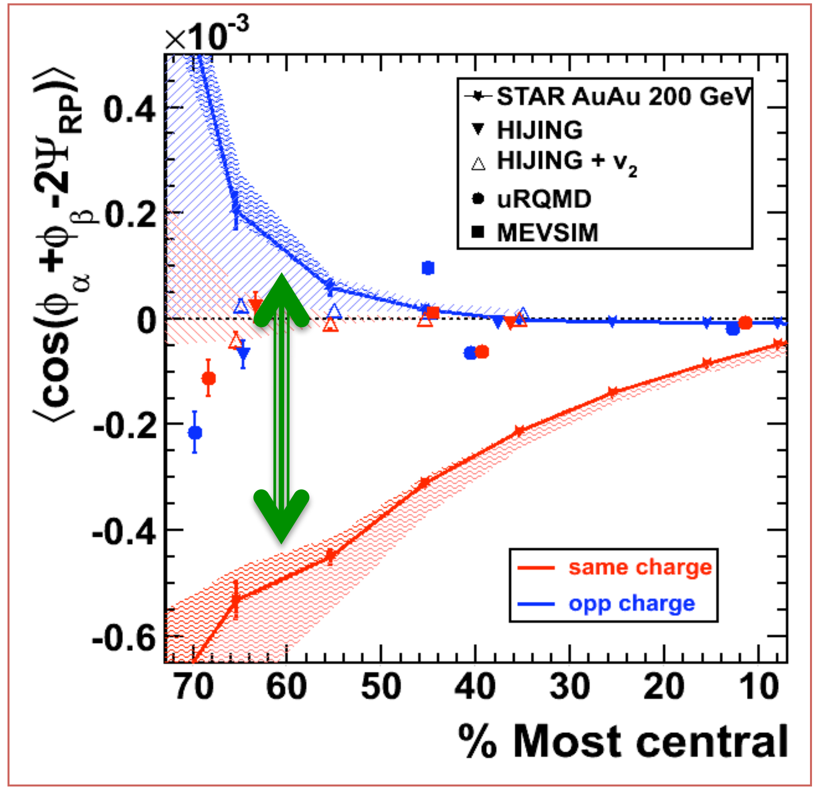


$$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$$

Parity even observable

Voloshin, PR C62, 044901(00).

STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).



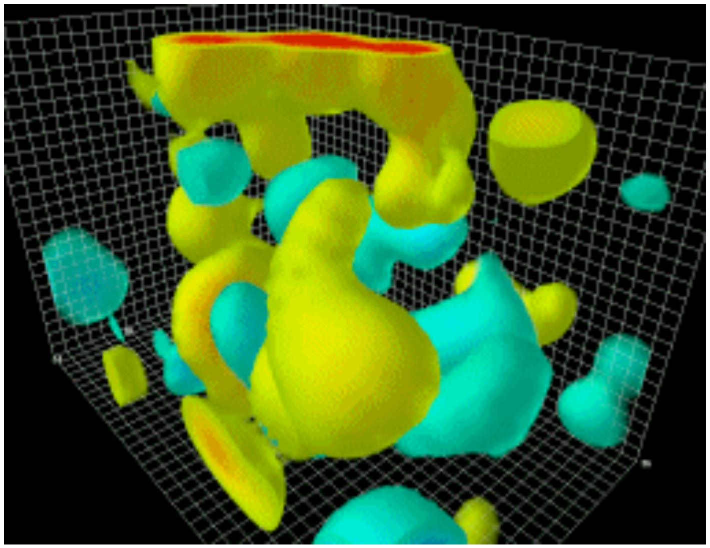
The separation between the same-charge and opposite-charge correlations.

- **Strong external EM field**
- ***De-confinement*** **and** ***Chiral symmetry restoration***

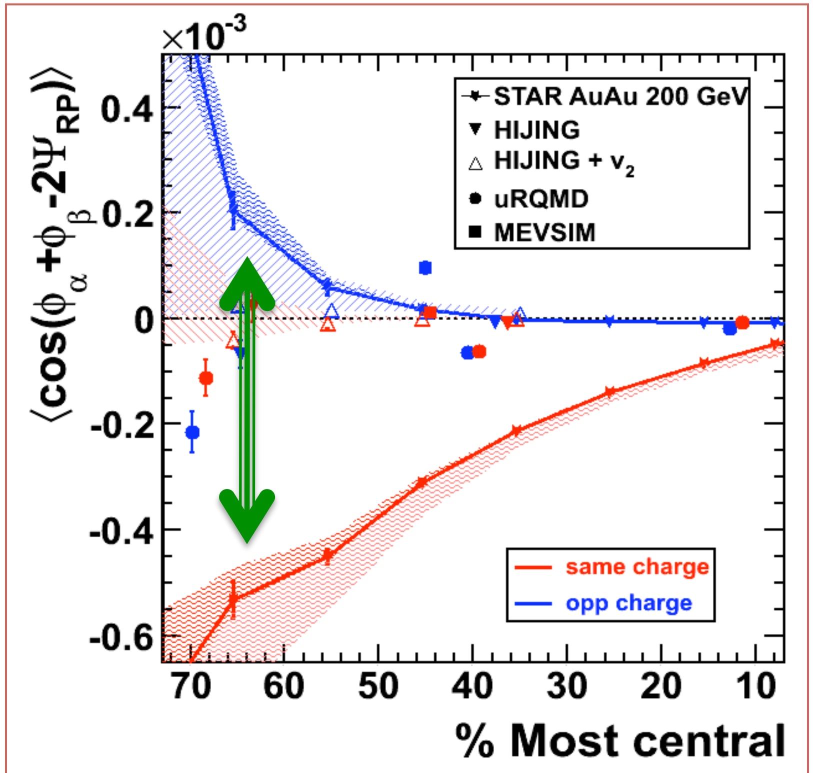
Search for Local Parity Violation

in High Energy Nuclear Collisions

Animation by *Derek Leinweber*



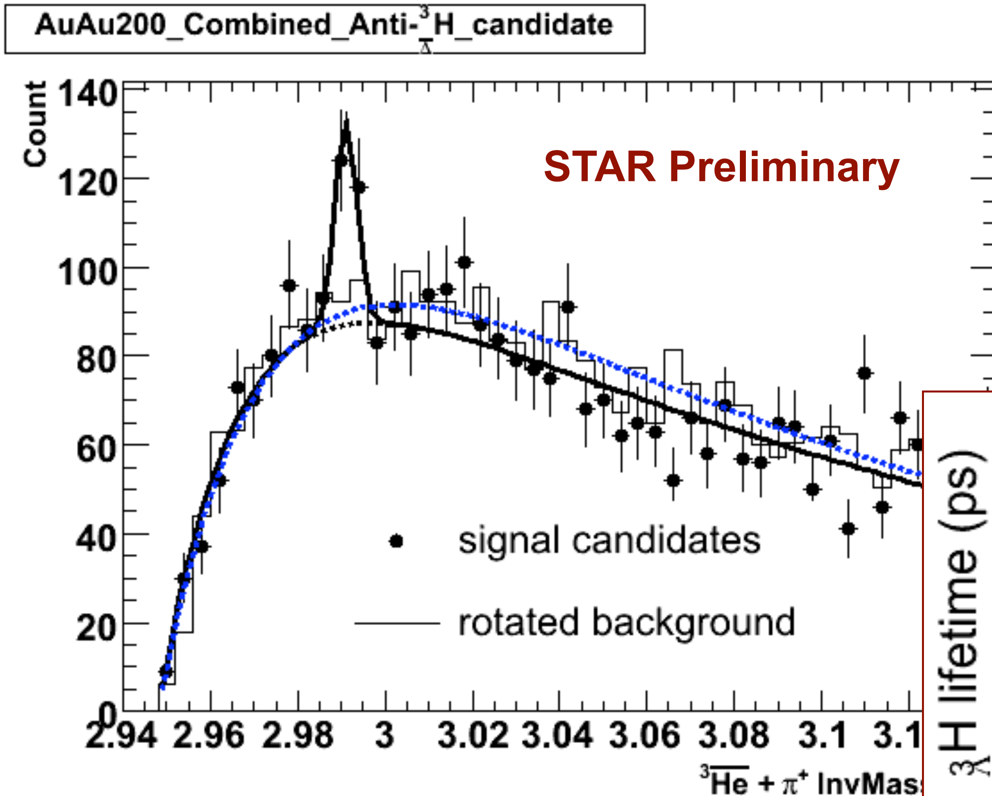
Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS). An observation of the *spontaneous strong* parity violation would be a clear proof for the existence of such physics.



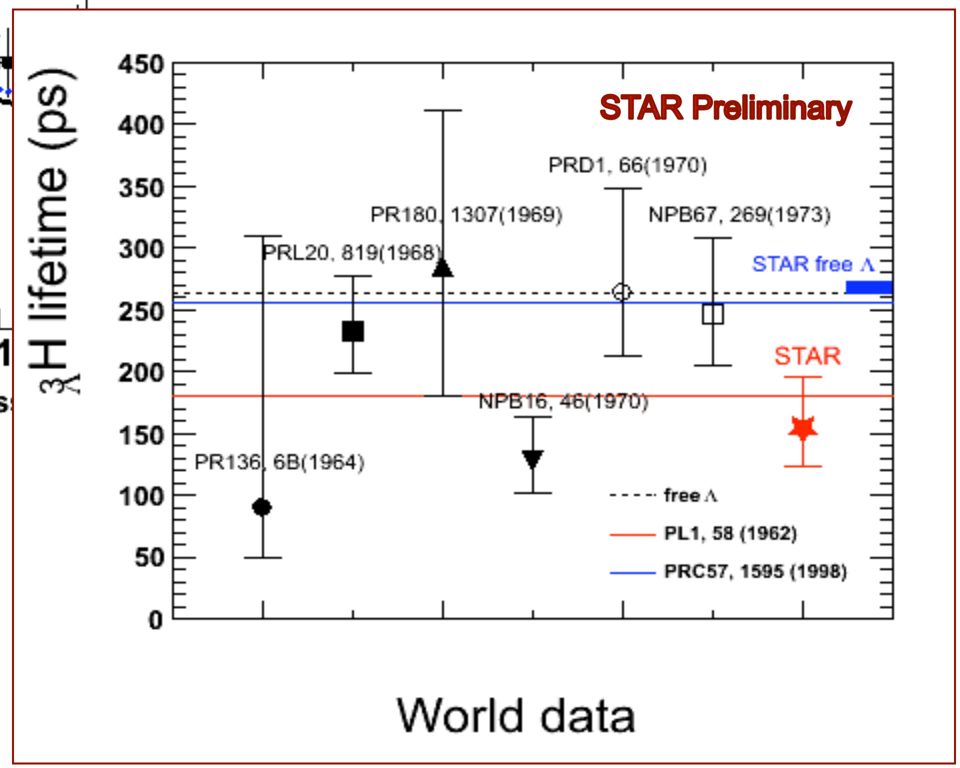
Chiral Magnetic Effect:

Kharzeev, PL B633 260 (2006).
Kharzeev, Zhitnitsky, NP A797 67(07).
Kharzeev, McLerran, Warringa, NP A803 227(08).
Fukushima, Kharzeev, Warringa, PR D78, 074033(08).

First Observation of $^{3}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \bar{\pi}^{-}$



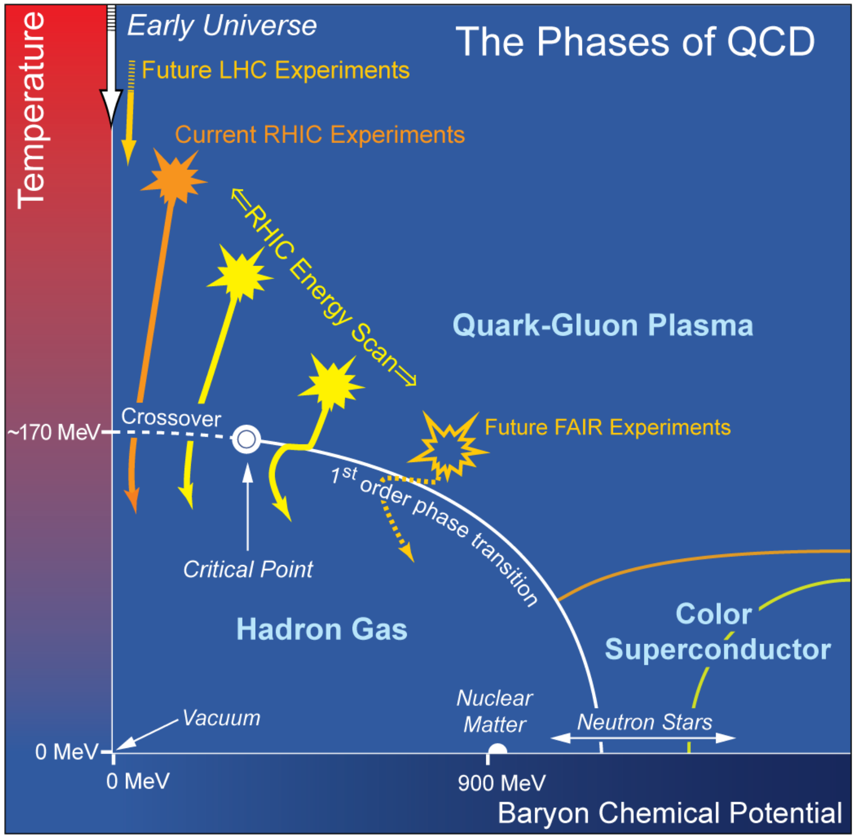
200 GeV Au+Au collisions at RHIC



First observation of
an anti-hypernucleus

Submitted to ***Science*** *Magazine*

The QCD Critical Point



RHIC (200) & LHC: Determine the temperature ***T_{ini}, T_C***

BES: Explore the QCD phase diagram ***T_E*** **and the location** ***phase boundary***

- LGT prediction on the transition temperature T_C is robust.

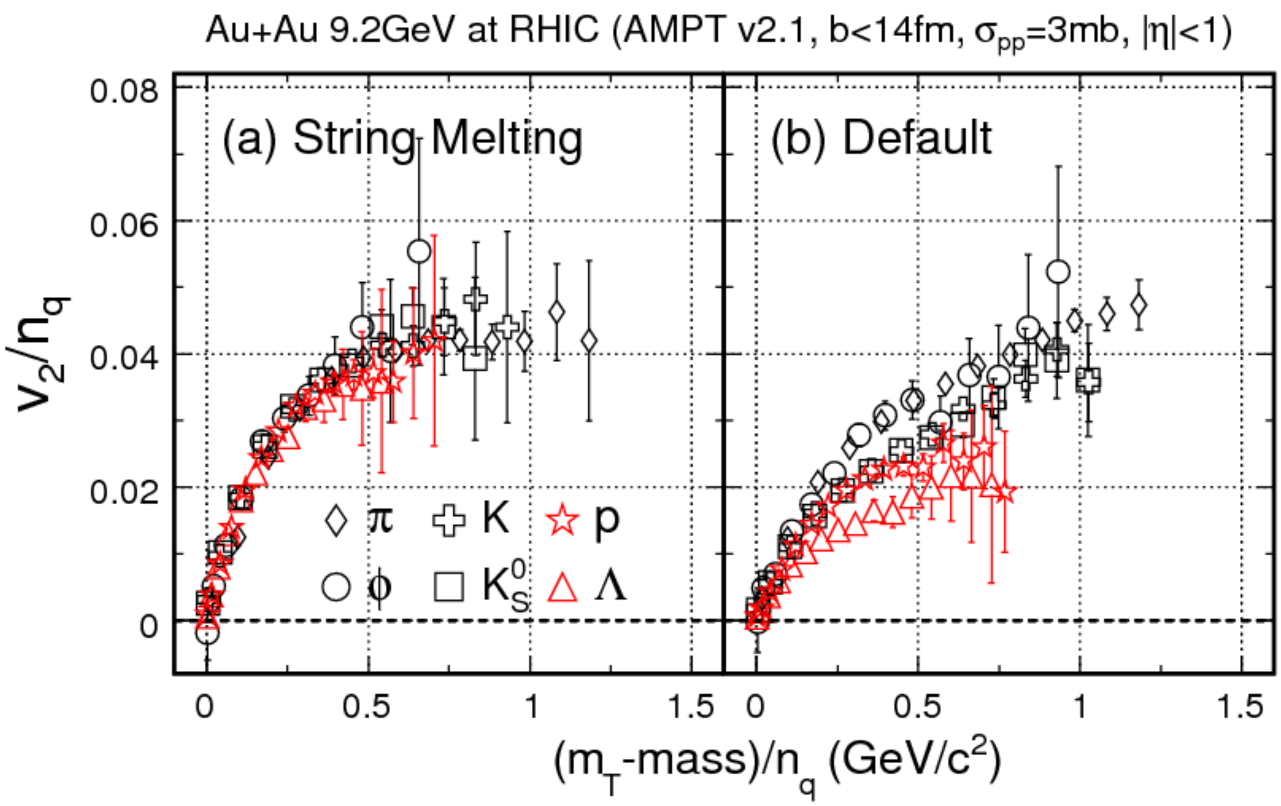
- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

** Thermalization has been assumed*

http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

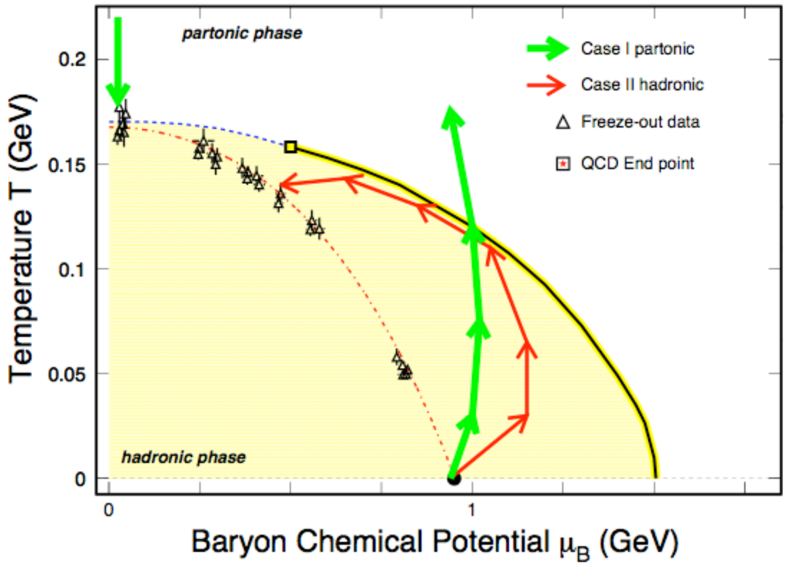
Au+Au Collisions at 9.2 GeV AMPT (v2.1)

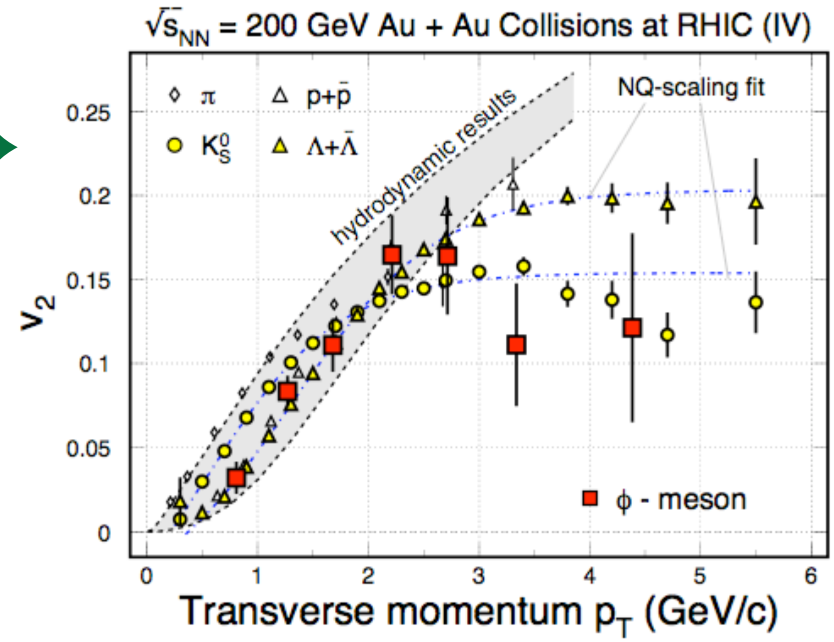


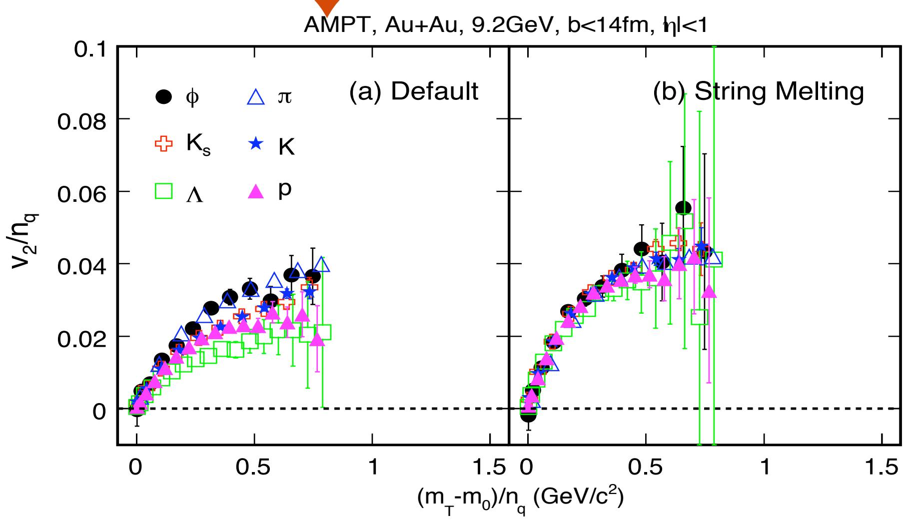
J. Tian *et al*, Phys. Rev. **C79**, 067901(2009).

(a) Patonic matter: coalescence of massive quarks for hadronization ➔ Clear NQ scaling in v_2 !	***(b) Hadronic matter:*** rescatterings amongst hadrons ➔ No NQ scaling in v_2 !

Observable*: Quark Scaling in v_2





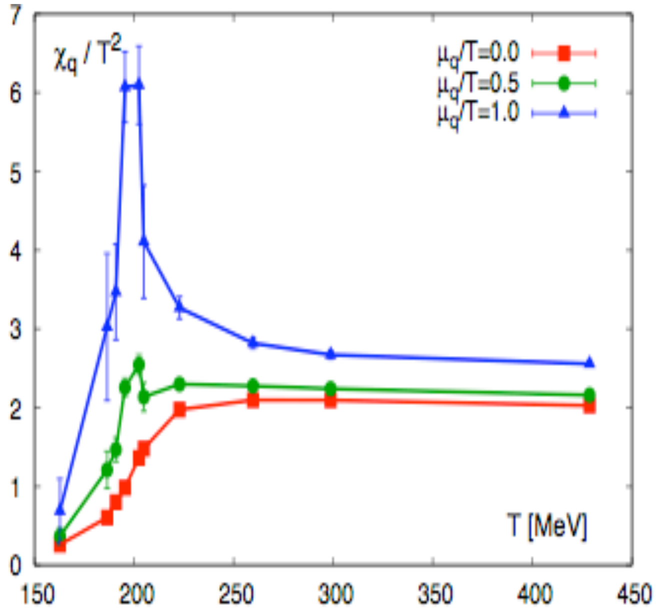


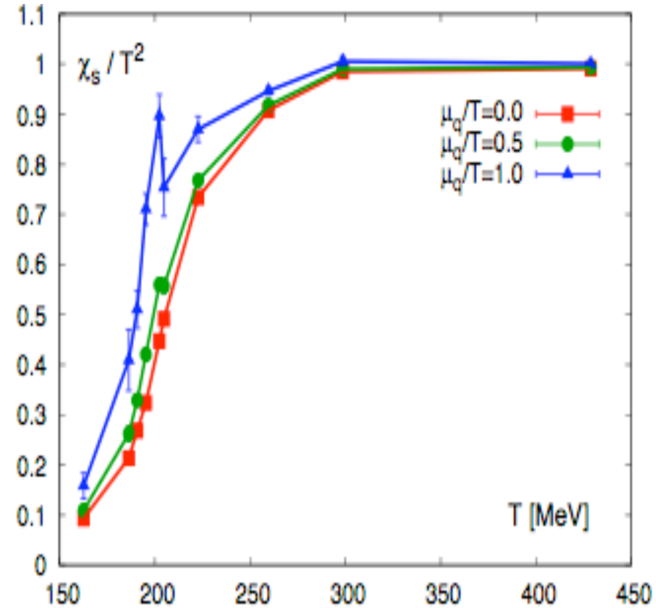
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Observables: χ_q, χ_S





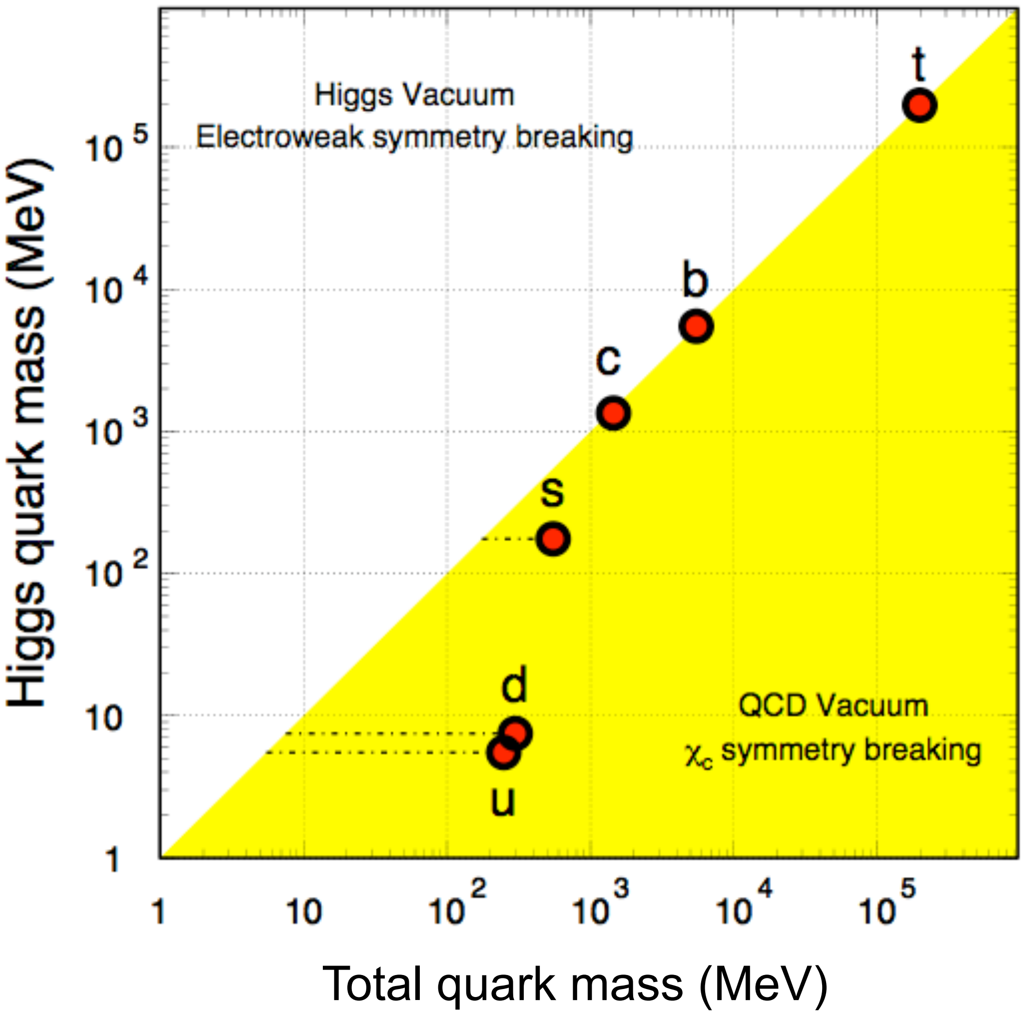
Event by event:

1. net-proton Kurtosis $K_p(E)$*
2. two proton correlation functions $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

* *Gavai and Gupta, 03, 05; Gupta 0909.4630*
M. Cheng et al. 08
Gupta, Karsch, Stephanov, INT, 08

Quark Masses



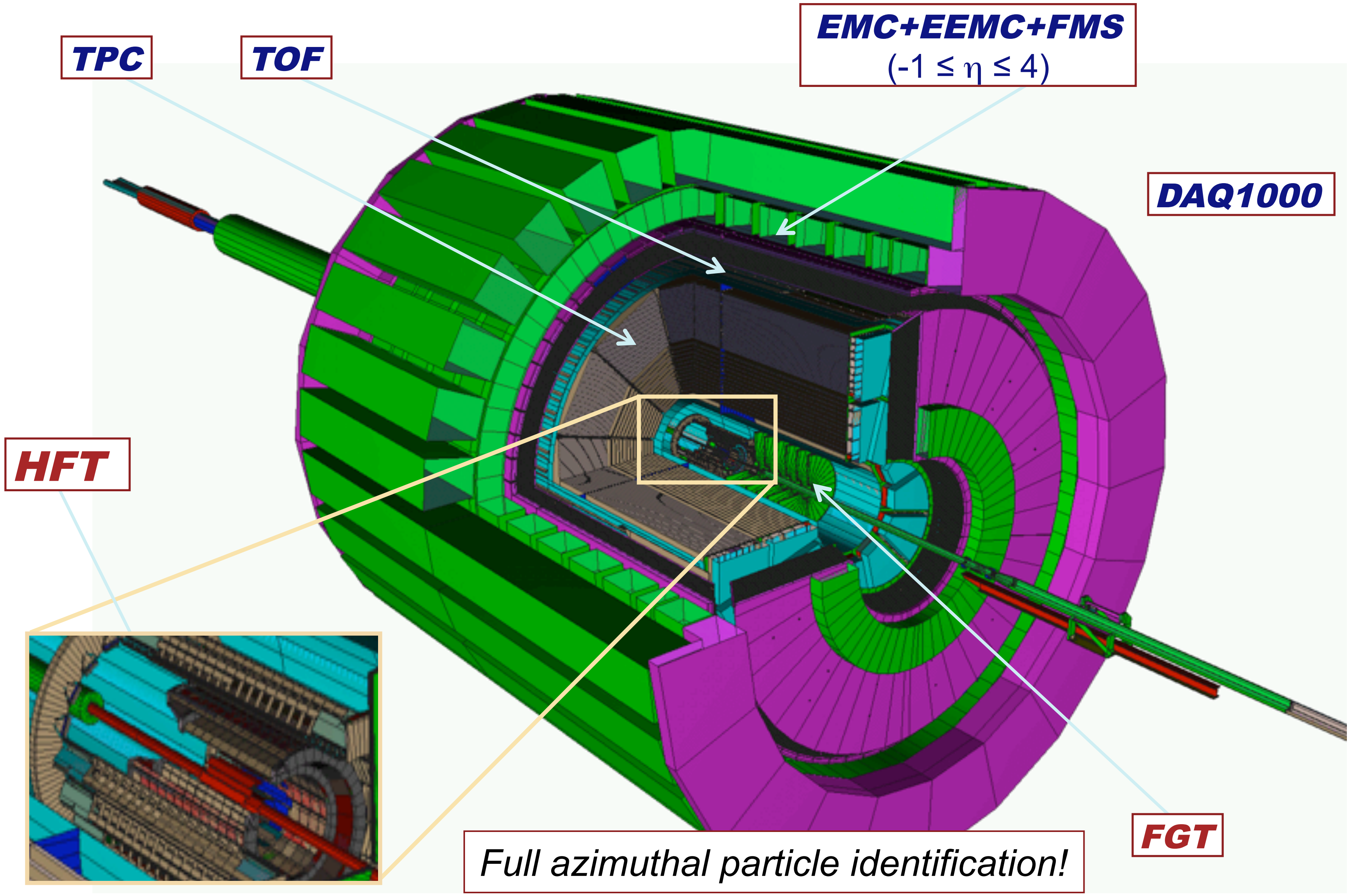
1) Higgs mass: electro-weak symmetry breaking. (current quark mass)
2) QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇨ New mass scale compared to the excitation of the system.

⇨ Important tool for studying properties of the hot/dense medium at RHIC.

⇨ Test pQCD predictions at RHIC.

STAR Detectors



Full azimuthal particle identification!

The di-Lepton Program at STAR

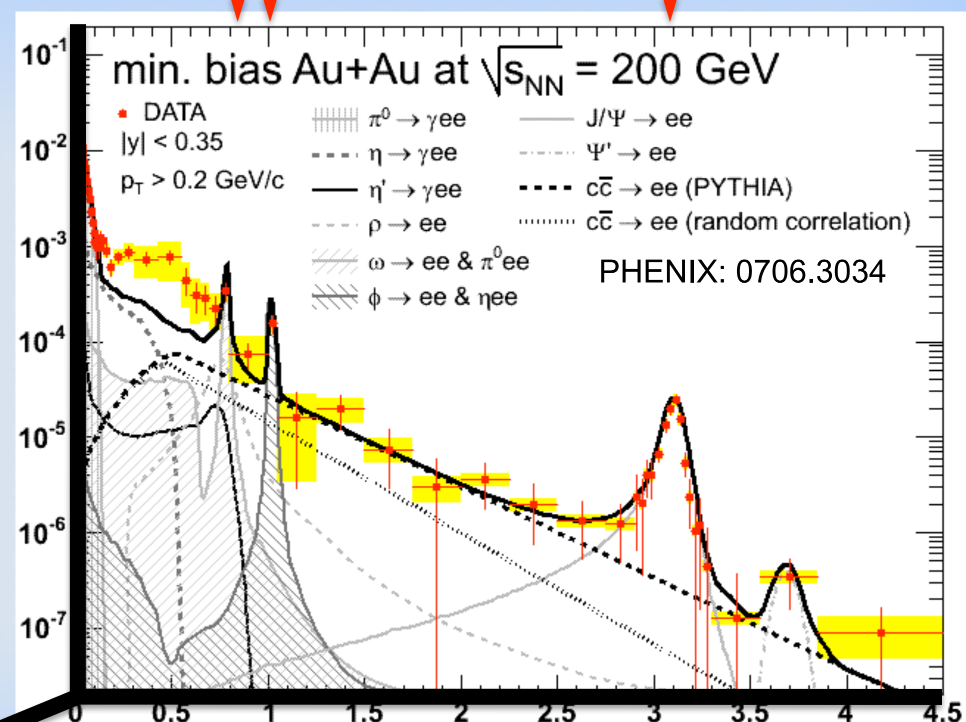
TOF + TPC + ***HFT***

(1) *σ, mass*

(2) v_2

(3) R_{AA}

ρ ϕ — ***DY, charm Bk*** — J/ψ



***Mass* (GeV/c²)**

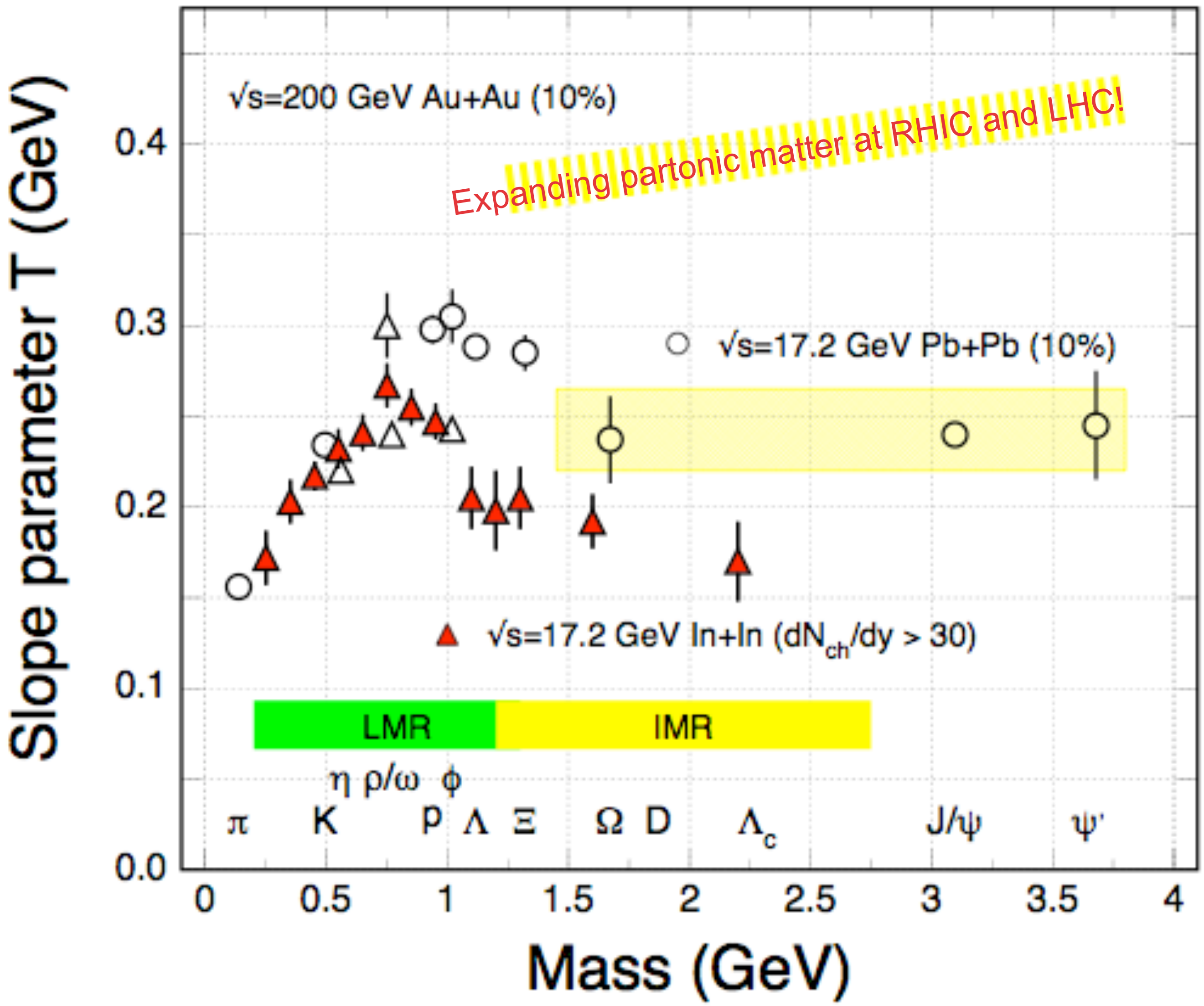
p_T (GeV/c)

- ✓ **Direct radiation from the Hot/Dense Medium**
- ✓ **Chiral symmetry Restoration**

⇨ ***A robust di-lepton physics program extending STAR scientific reach***

HFT: removing irreducible correlated charm background!

Direct Radiation



Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

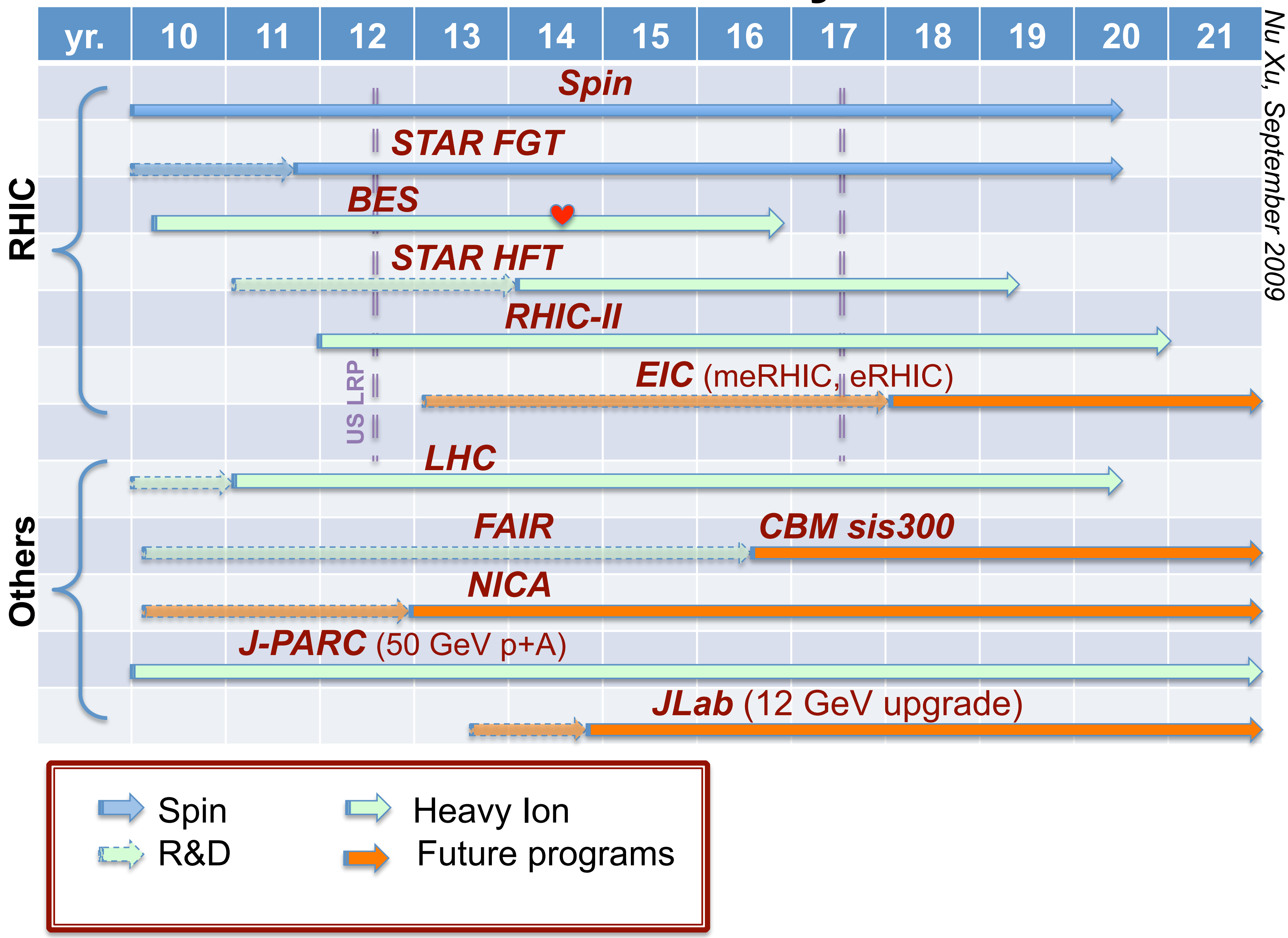
- Low mass region:
  ρ, ω, ϕ $\Rightarrow$ e^-e^+
  m_{inv} $\Rightarrow$ e^-e^+

  medium effect
  Chiral symmetry

- High mass region:
  J/ψ $\Rightarrow$ e^-e^+
  m_{inv} $\Rightarrow$ e^-e^+

  Direct radiation

Timeline of QCD and Heavy Ion Facilities



Summary

1) **At top energy, 200 GeV Au+Au collisions at RHIC, strongly interacting matter formed**

2) **Future i: heavy quark measurements:**
   - heavy quark collectivity, light quark thermalization

3) **Future ii: Beam energy scan:**
   - search for critical point and phase boundary

4) **RHIC has a strong and interesting physics program till 2020**

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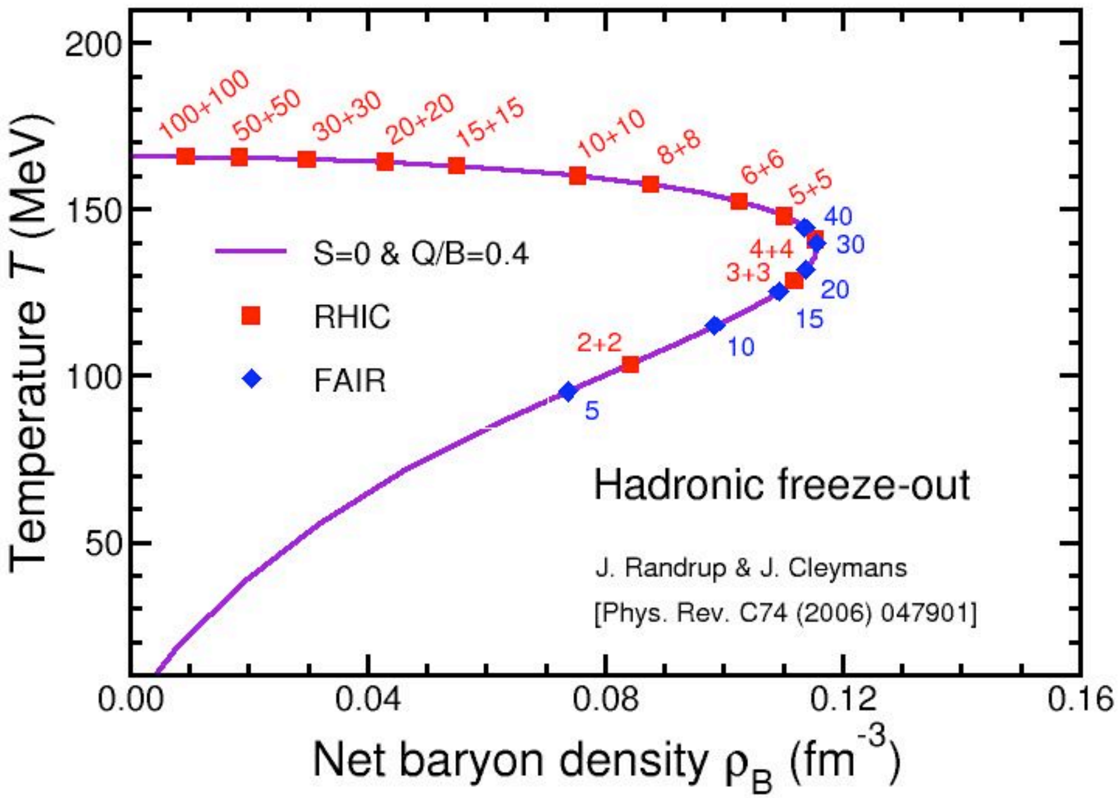
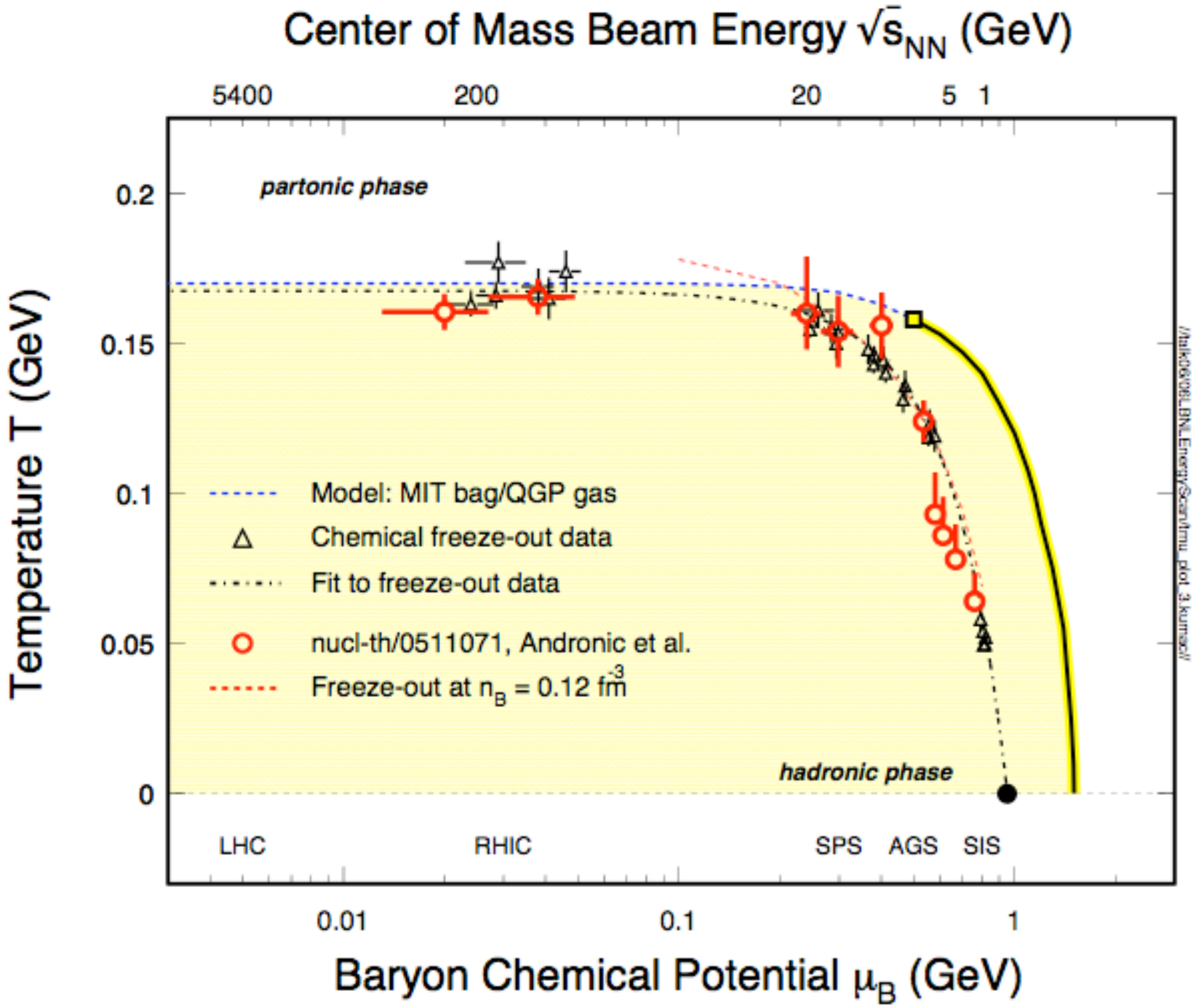


Temperature T (MeV)
Net baryon density ρB (fm-3)
S=0 & Q/B=0.4
RHIC
FAIR
Hadronic freeze-out
J. Randrup & J. Cleymans
[Phys. Rev. C74 (2006) 047901]
100+100
50+50
30+30
20+20
15+15
10+10
8+8
6+6
5+5
4+4
3+3
2+2
40
30
20
15
10
5

The QCD Phase Diagram



$T_{ch} \sim T_C$ (LGT) at RHIC

*Thermalization is assumed!

Recent review:

A. Andronic, et al, NP ***A772**,* *B. 167(06)*