# Resultados Recentes na Busca pelo Plasma de Quarks e Gluons

*Marcelo G. Munhoz*

DFN-IFUSP

2005

STAR

# Resultados Recentes na Busca pelo Plasma de Quarks e Gluons

- Anúncio feito por *Brookhaven National Laboratory* em 18/05/2005 na reunião da *American Physical Society* ;
- Afinal, o que é o Plasma de Quarks e Gluons (QGP) ?
- Principais evidências experimentais para a afirmação feita no anúncio;
- Perspectivas para o futuro.

# Anúncio de 18/05/2005

***RHIC Scientists Serve Up "Perfect" Liquid***

*New state of matter more remarkable than predicted -- raising many new questions*

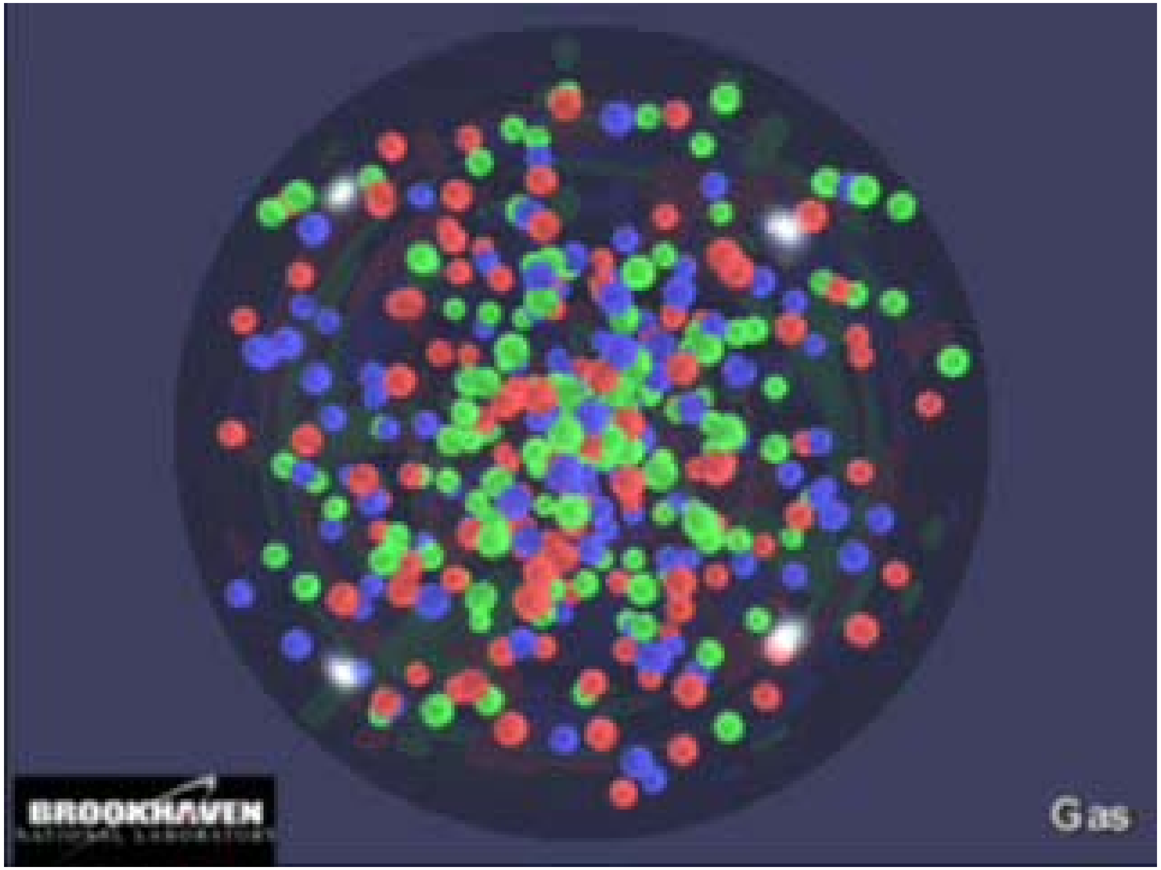
*April 18, 2005*

# Anúncio de 18/05/2005

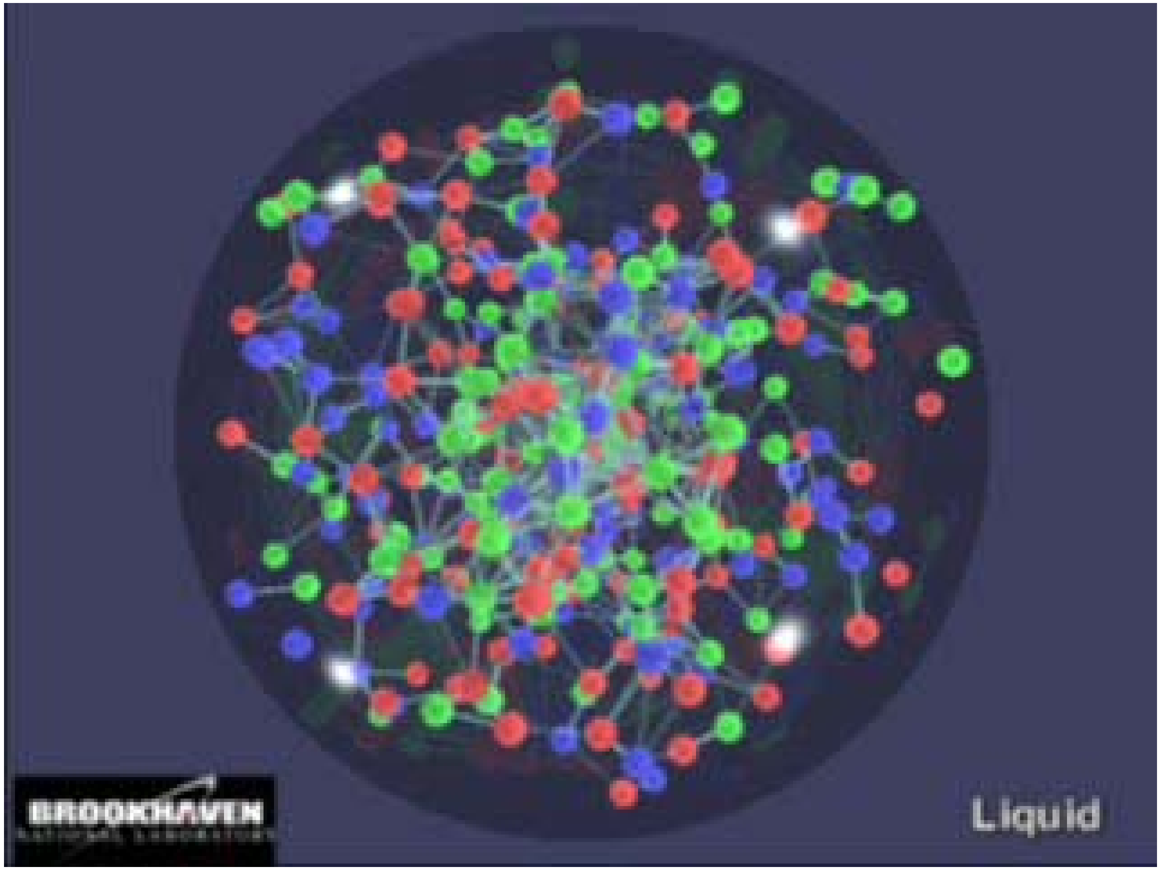
- "*… they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, **but it is a state quite different and even more remarkable than had been predicted**.*"

  "*…the scientists say that instead of behaving like **a gas of free quarks and gluons**, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like **a liquid**.*"

# O QGP como um “gás”



# O QGP como um "líquido"



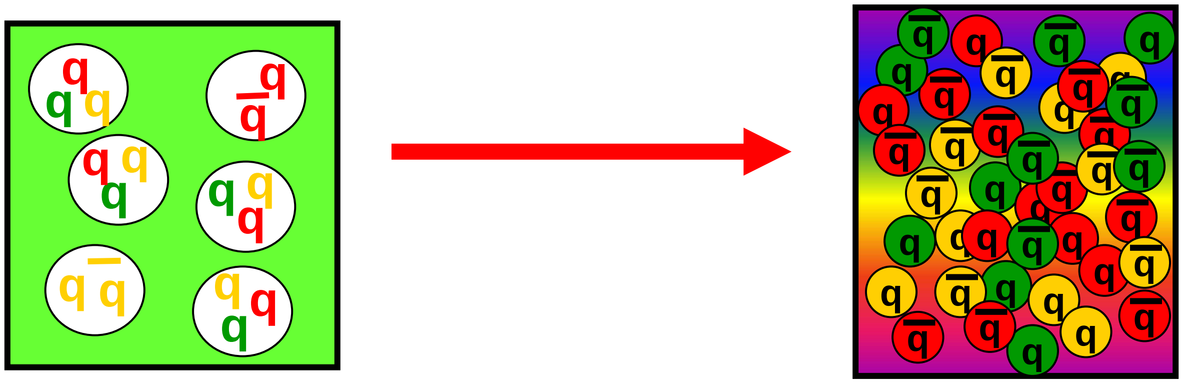
# Modelo Padrão

- A QCD (Quantum Chromo Dynamics) é **a** teoria usada para estudar e explicar as propriedades mais fundamentais do núcleo atômico – propriedades e interação entre quarks.
- Força entre quarks: troca de *gluons*
- Confinamento:
  - a interação quarks aumenta com a distância.

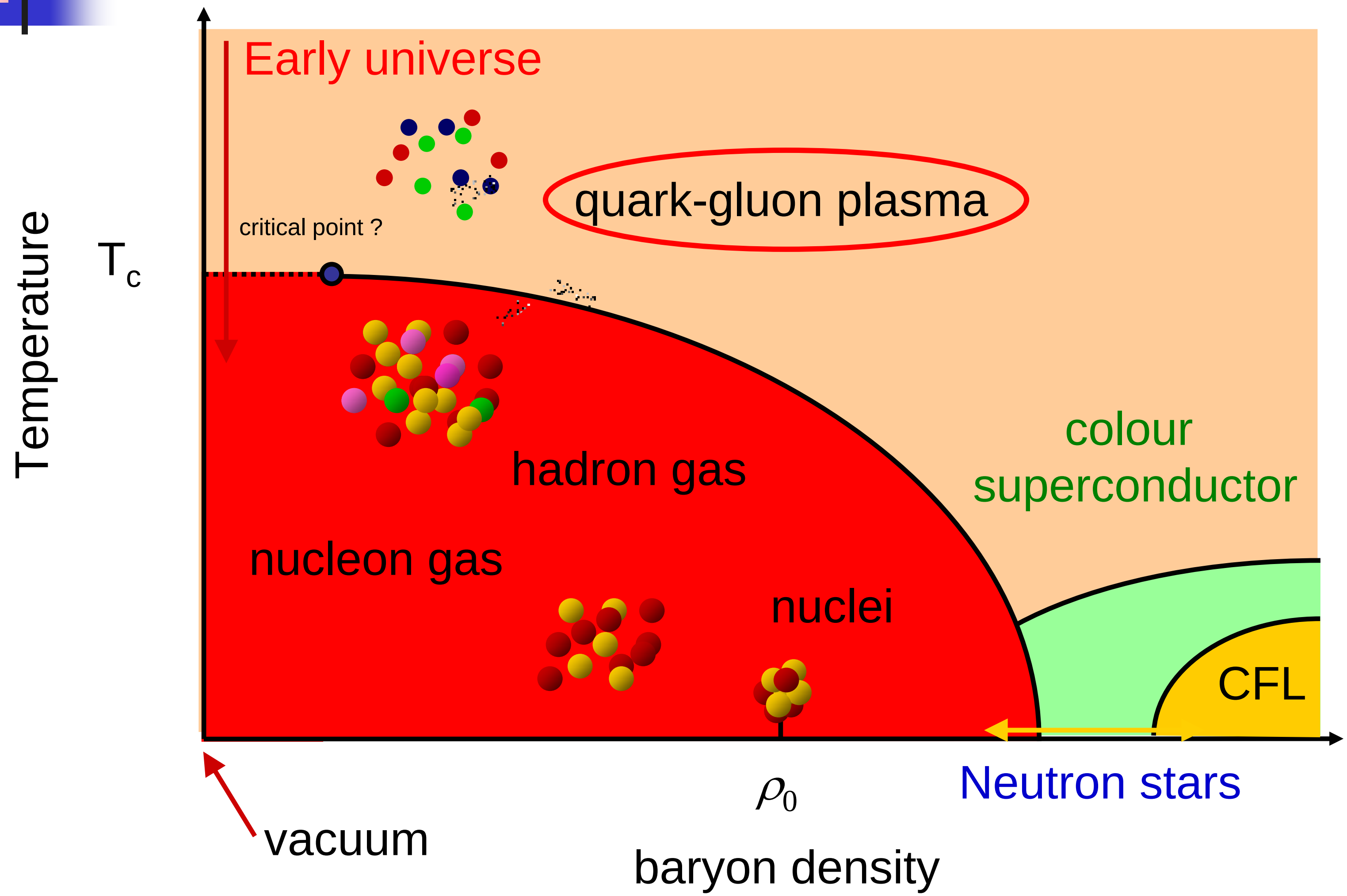
  ⇒ Quarks livres nunca foram observados
- Liberdade Assimptótica:
  - a interação entre quarks se torna fraca a pequenas distâncias.

# Modelo Padrão

- Ainda segundo a QCD, um sistema formado por hadrons, ao ser “aquecido” ou “comprimido”, deve passar por uma transição de fase, onde os constituintes desses hadrons estariam livres ou deconfinados.

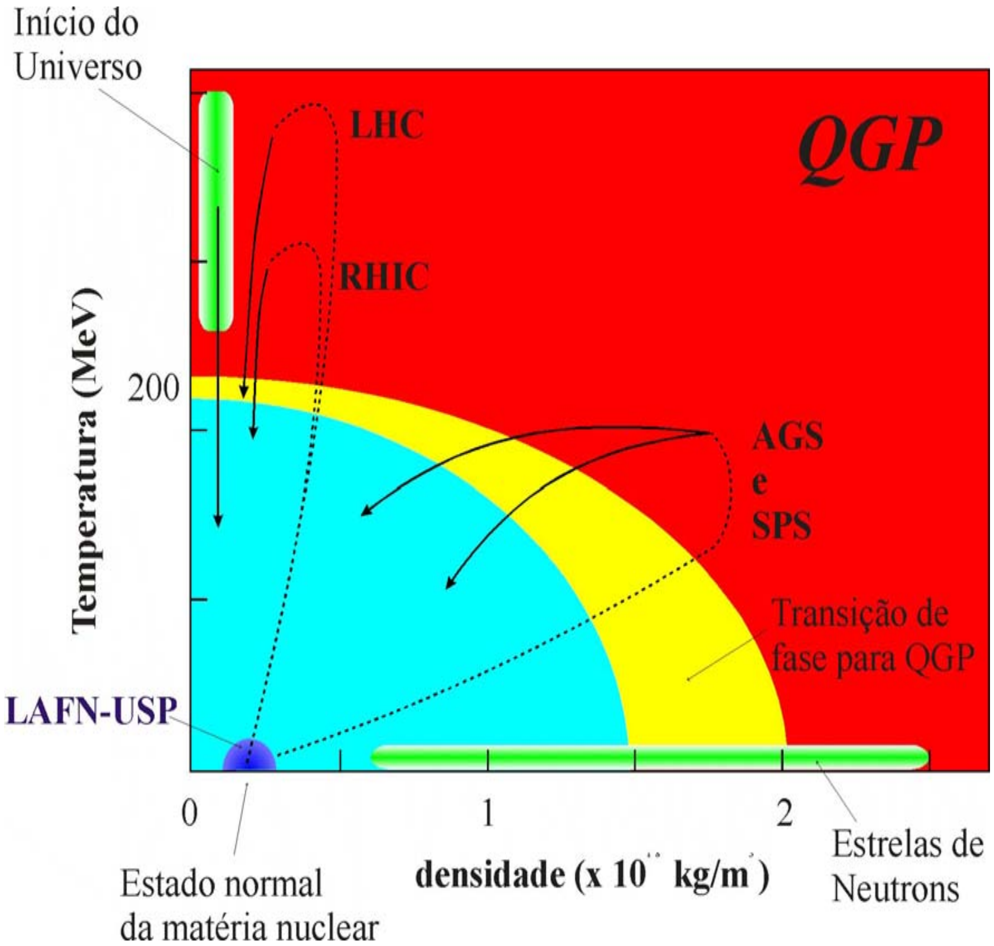


# O Diagrama de fase da QCD

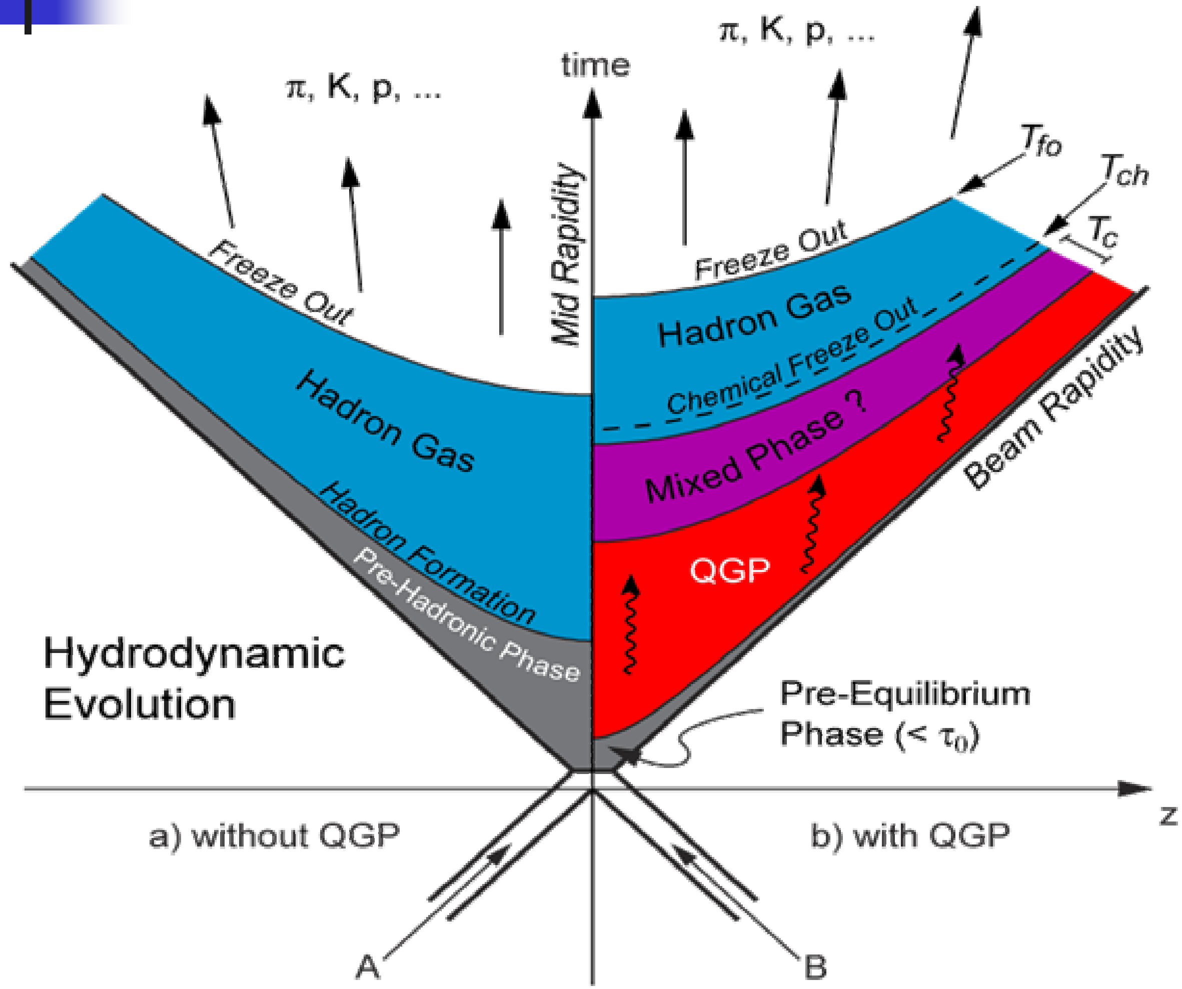


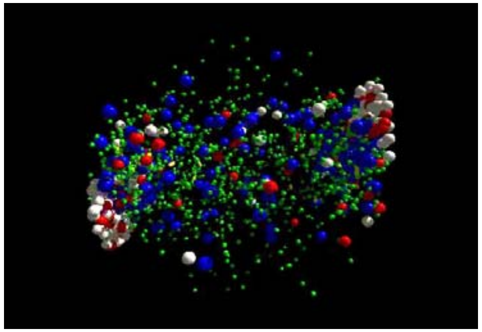
# O Diagrama de fase da QCD

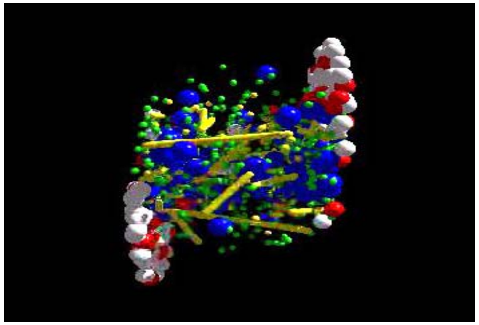
- O diagrama de fase pode ser estudado experimentalmente através de colisões entre íons pesados a energias relativísticas...

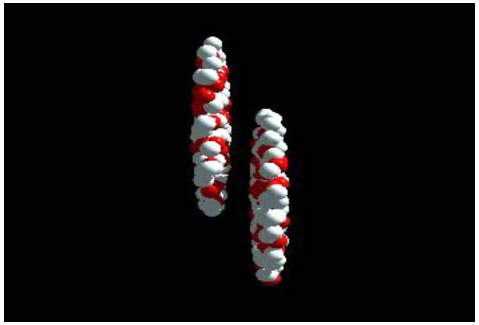


# Os vários estágios da colisão (?)







# Perguntas básicas

- Nas colisões entre íons pesados relativísticos formou-se um sistema em equilíbrio que podemos caracterizar seu estado?
- Em caso afirmativo, ele é o estado da matéria previsto pela QCD?

# Evolução da definição de QGP

- NSAC Long Range Plan (1983)
  - "*...under conditions of very elevated energy density, nuclear matter will exist in a wholly new phase in which there are no nucleons or hadrons composed of quarks in individual bags, but an extended quark-gluon plasma, within which* ***the quarks are deconfined and move independently****...*"

# Evolução da definição de QGP

- National Academy of Sciences Survey in Nuclear Physics (1984)
  - "*…that under conditions of sufficiently high temperature and density in nuclear matter, a transition will occur from excited hadronic matter to a quark-gluon plasma, in which the quarks, antiquarks and gluons of which hadrons are composed* ***become deconfined and are able to move about freely****…*"

# Evolução da definição de QGP

- NSAC Long Range Plan (1989)
  - "*...a transition from the confined phase of QCD, in which the degrees of freedom are the familiar nucleons and mesons and in which a quark is able to move around only inside its parent nucleon, to a new **deconfined** phase, called the quark-gluon plasma, in which hadrons dissolve into a plasma of quarks and gluons, which are then **free to move over a large volume**.*"

# Evolução da definição de QGP

- NSAC Assessment of Nuclear Science (1994)
  - "*When nuclear matter is heated to extremely high temperatures or compressed to very large densities we expect it to respond with a drastic transformation, in which the quarks and gluons, that are normally confined within individual neutrons and protons, are* ***able to move over large distances****. A new phase of matter, called Quark-Gluon Plasma, is formed.*"

# Evolução da definição de QGP

- NSAC Long Range Plan (1996)
  - "*...at temperatures in excess of $T_c$ nuclear matter is predicted to consist of* ***unconfined****, nearly massless quarks and gluons, a state called the quark-gluon plasma.*"

# Evolução da definição de QGP

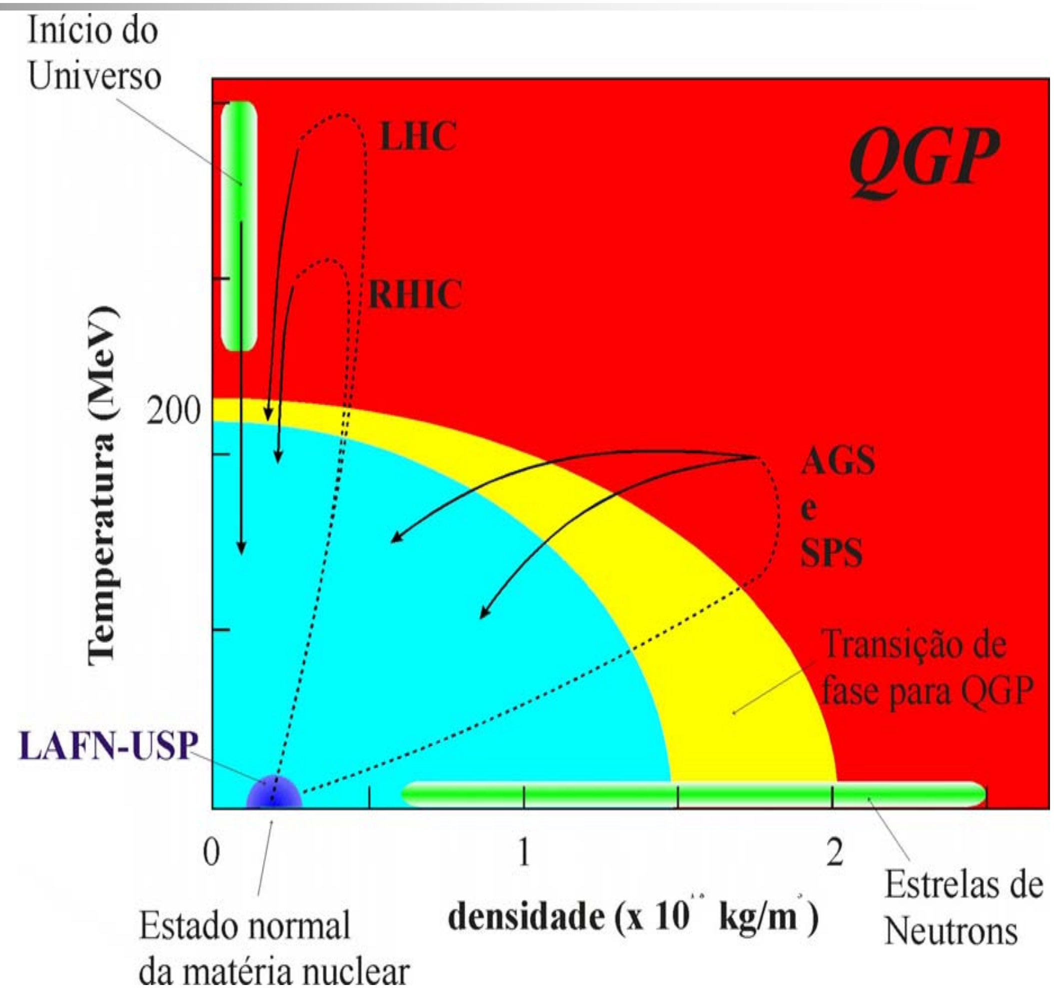
- National Academy of Sciences Survey in Nuclear Physics (1999)
  - "*…at RHIC such high energy densities will be created that quarks and gluons are expected to become* ***deconfined across a volume that is large compared to that of a hadron****.*"

# Evolução da definição de QGP

- The STAR Collaboration's Critical Assessment of the Evidence from RHIC Collisions (2005)
  - *"A locally thermally equilibrated state of matter in which quarks and gluons are* ***deconfined*** *from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes."*

# Programas Experimentais com Íons Pesados Relativísticos

| $\sqrt{s_{NN}}\,(GeV/c)$ | |
|---|---|
| 2000 | LHC |
| **200** | **RHIC** |
| 20 | SPS |
| 5 | AGS |
| 1 | SIS |

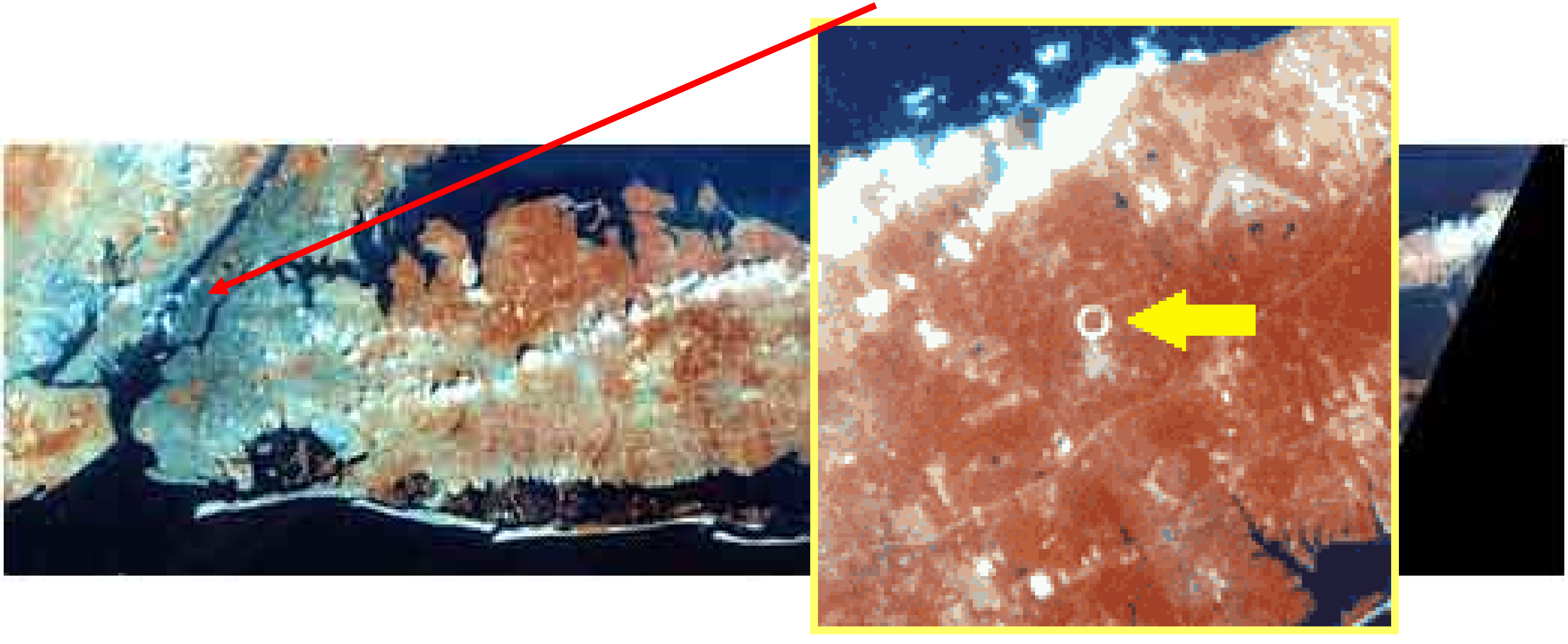


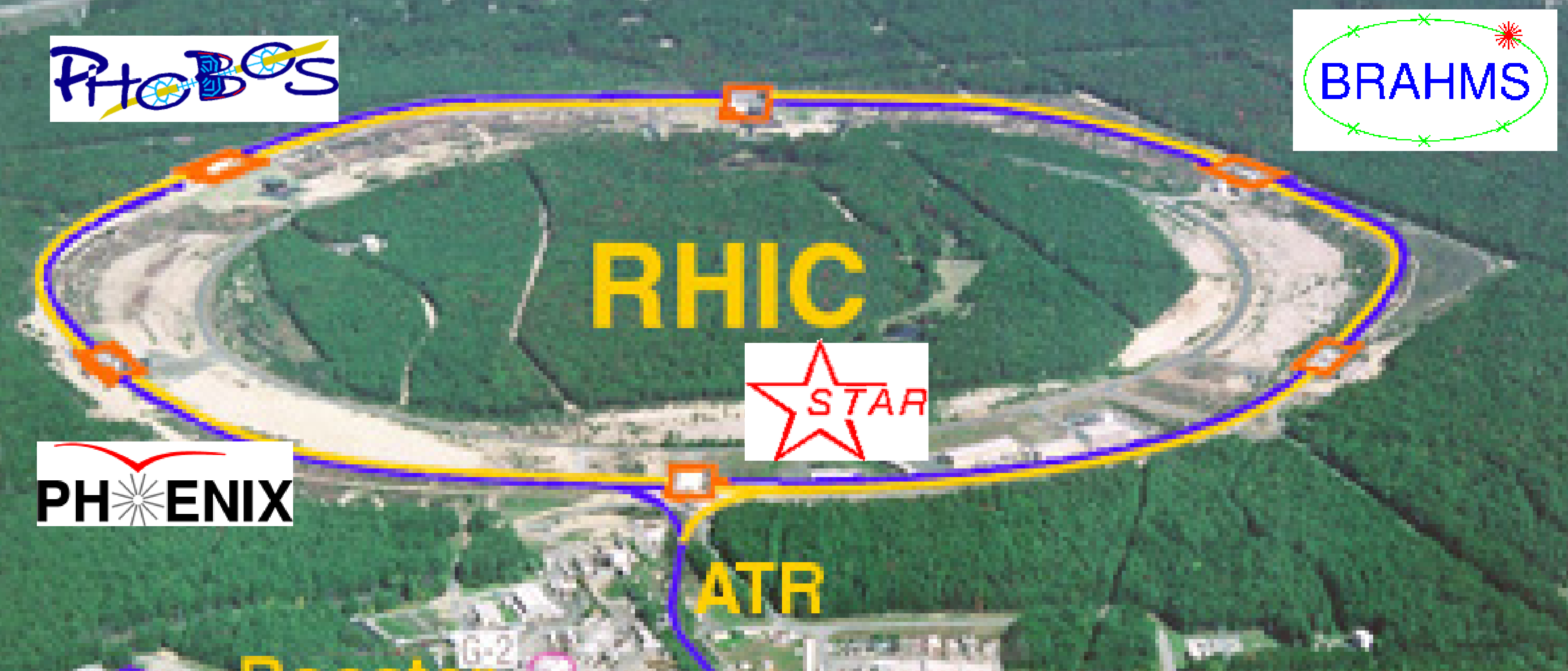
# RHIC

## Relativistic Heavy Ions Collider

Brookhaven National Laboratory

Long Island - NY - USA






- Beam energy up to 100 *GeV/A : 19.6*, *62.4*, *130*, *200 GeV/A*;
- Two independent rings (asymmetric beam collisions are possible);
- Beam species from proton to *Au*: *Au+Au*, *p+p*, *d+Au*,*Cu+Cu*;
- Six interaction points: STAR, PHENIX, PHOBOS and BRAHMS

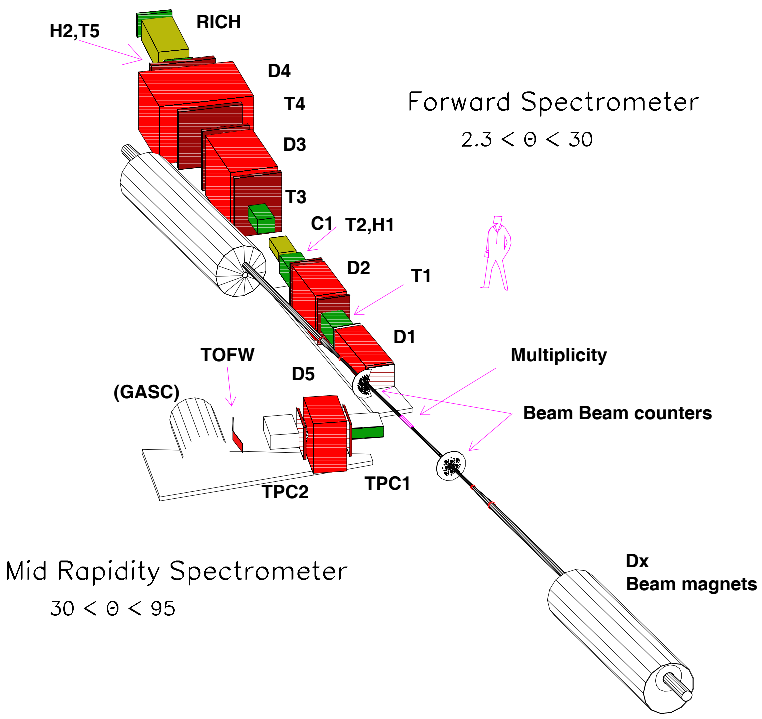
# The Two "Small" Experiments at RHIC

## BRAHMS

**2 "Conventional" Spectrometers**

**Magnets, Tracking Chambers, TOF, RICH**

**~40 Participants**



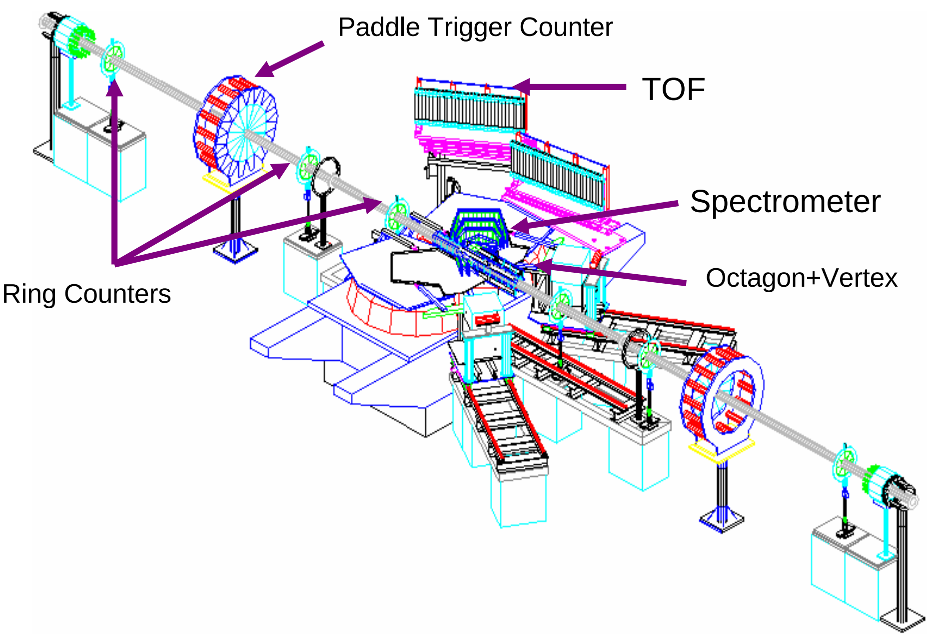

- **Inclusive Particle Production Over Large Rapidity Range**

## PHOBOS

**"Table-top" 2 Arm Spectrometer**

**Magnet, Si μ-Strips, Si Multiplicity Rings, TOF**

**~80 Participants**

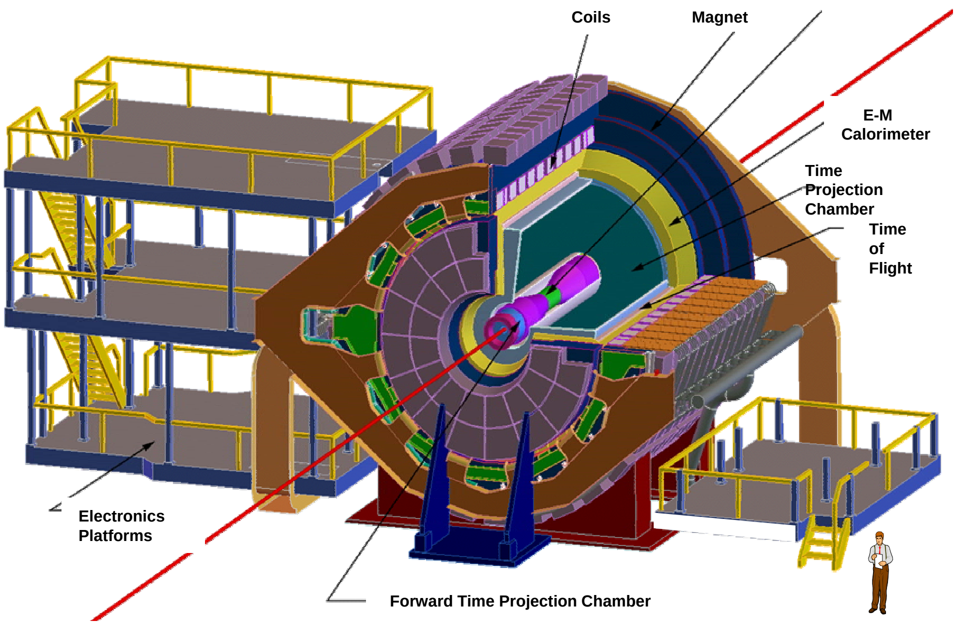



- **Charged Hadrons in Select Solid Angle**
- **Multiplicity in 4π**
- **Particle Correlations**

# The Two “Large” Detectors at RHIC

## STAR

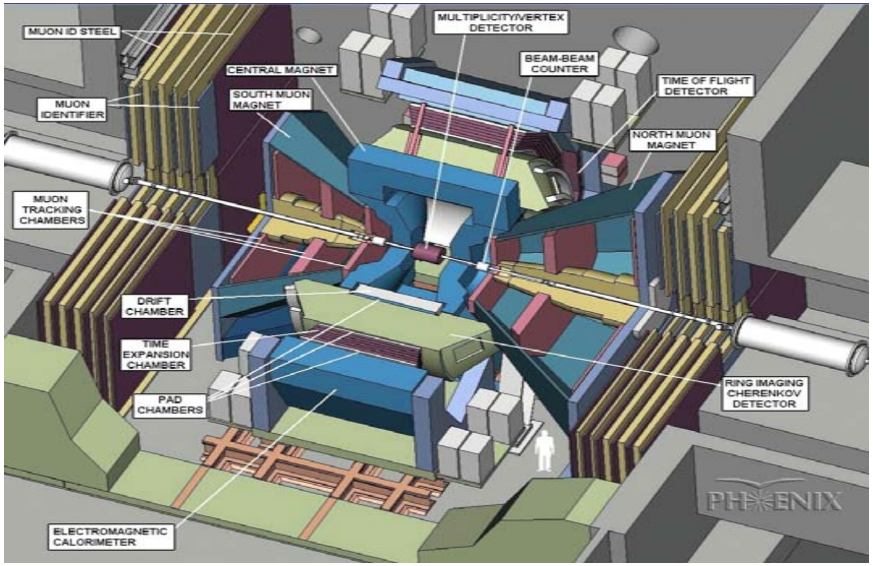
**Solenoidal field**
**Large-Ω Tracking**
**TPC’s, Si-Vertex Tracking**
**RICH, EM Cal, TOF**
**~420 Participants**




- **Measurements of Hadronic Observables using a Large Acceptance**
- **Event-by-Event Analyses of Hadrons and Jets**

## PHENIX

**Axial Field**
**High Resolution & Rates**
**2 Central Arms, 2 Forward Arms**
**TEC, RICH, EM Cal, Si, TOF, μ-ID**
**~450 Participants**




- **Leptons, Photons, and Hadrons in Selected Solid Angles**
- **Simultaneous Detection of Various Phase Transition Phenomena**

# Perguntas básicas

- Nas colisões entre íons pesados relativísticos formou-se um sistema em equilíbrio que podemos caracterizar seu estado?
- Em caso afirmativo, ele é o estado da matéria previsto pela QCD?

# Modelos Térmicos

Temperature — Chemical Potential

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3}\int \mathrm{d}^3\mathrm{p}\, \left[\mathrm{e}^{\sqrt{\mathrm{p}^2+m_j^2}/T+\boldsymbol{\mu}\cdot\mathbf{q}_j/T} \pm 1\right]^{-1}$$

Yield — Mass — Quantum Numbers

**Hagedorn, Becattini, Braun-Munzinger, Cleymans, Letessier, Mekijan,Rafelski, Redlich,Stachel, Tounsi**

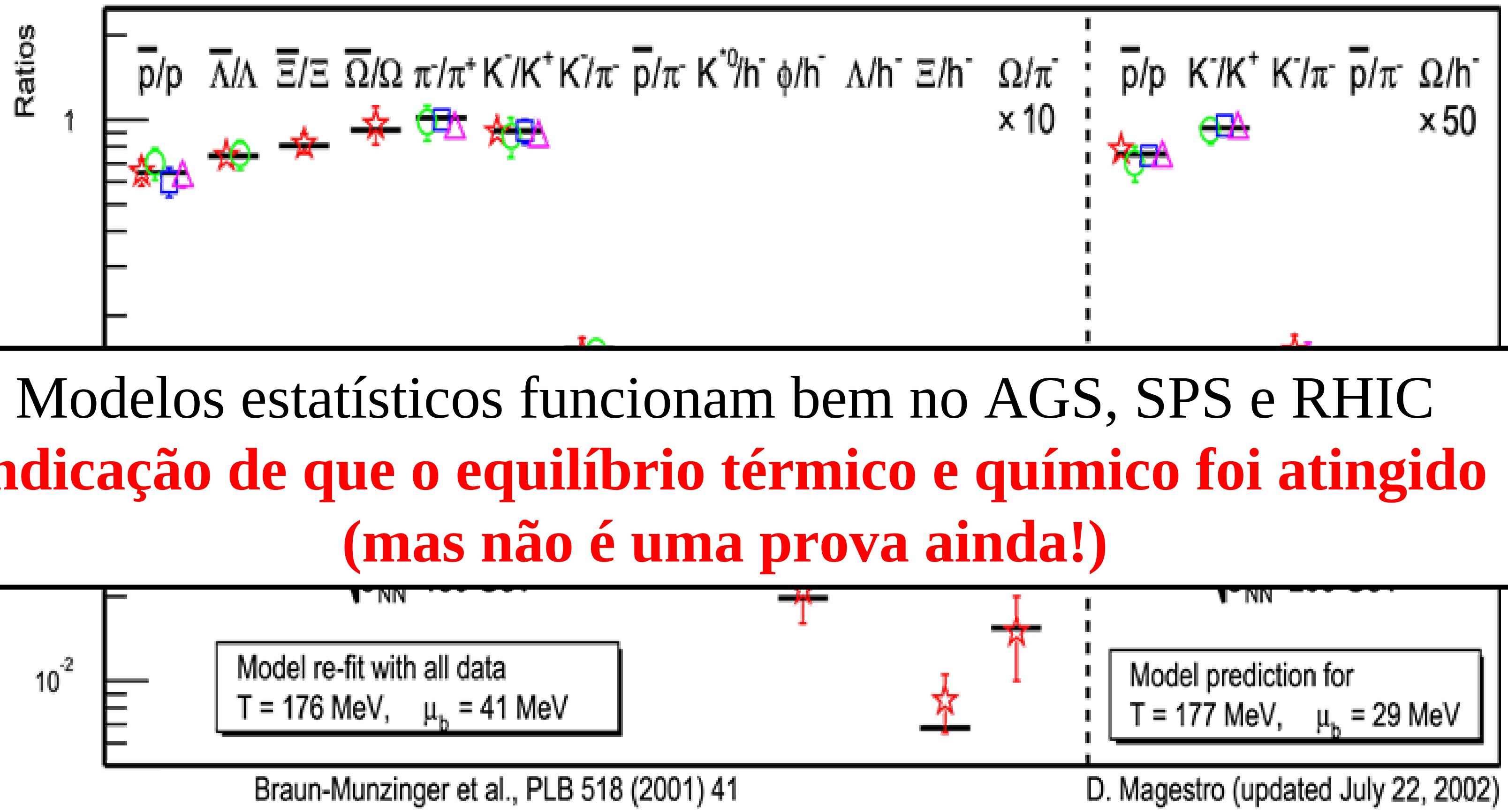
*Assume:* Ideal hadron resonance gas thermally and chemically equilibrated

*Recipe:* grand canonical ⇒ partition function ⇒ density of particles of species *j*

*Input:* measured particle ratios

*Output:* temperature T and baryo-chemical potential $\mu_B$

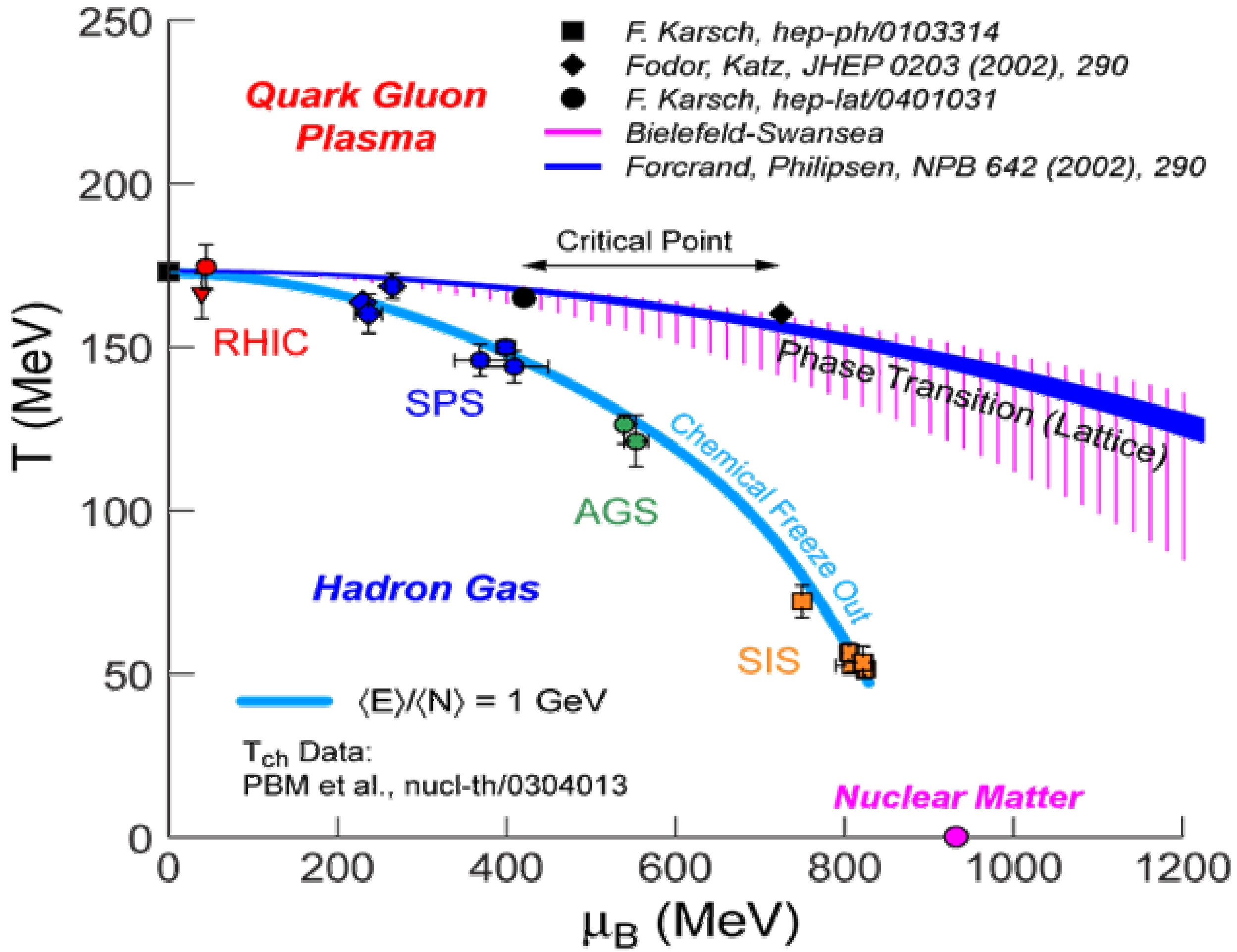
# Modelos Térmicos




Modelos estatísticos funcionam bem no AGS, SPS e RHIC

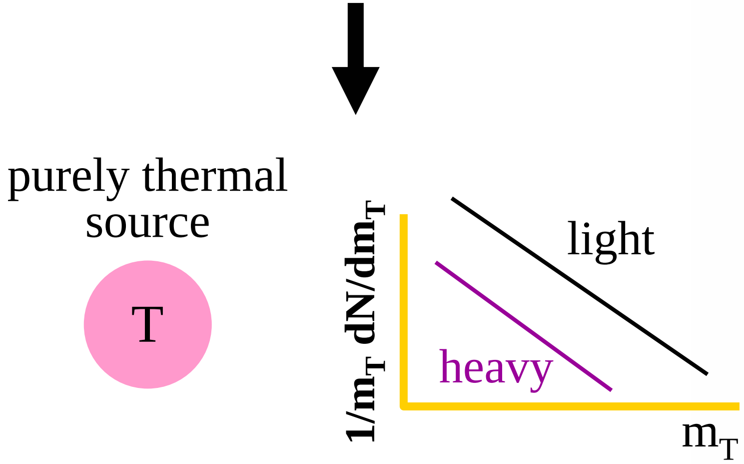
**Indicação de que o equilíbrio térmico e químico foi atingido (mas não é uma prova ainda!)**

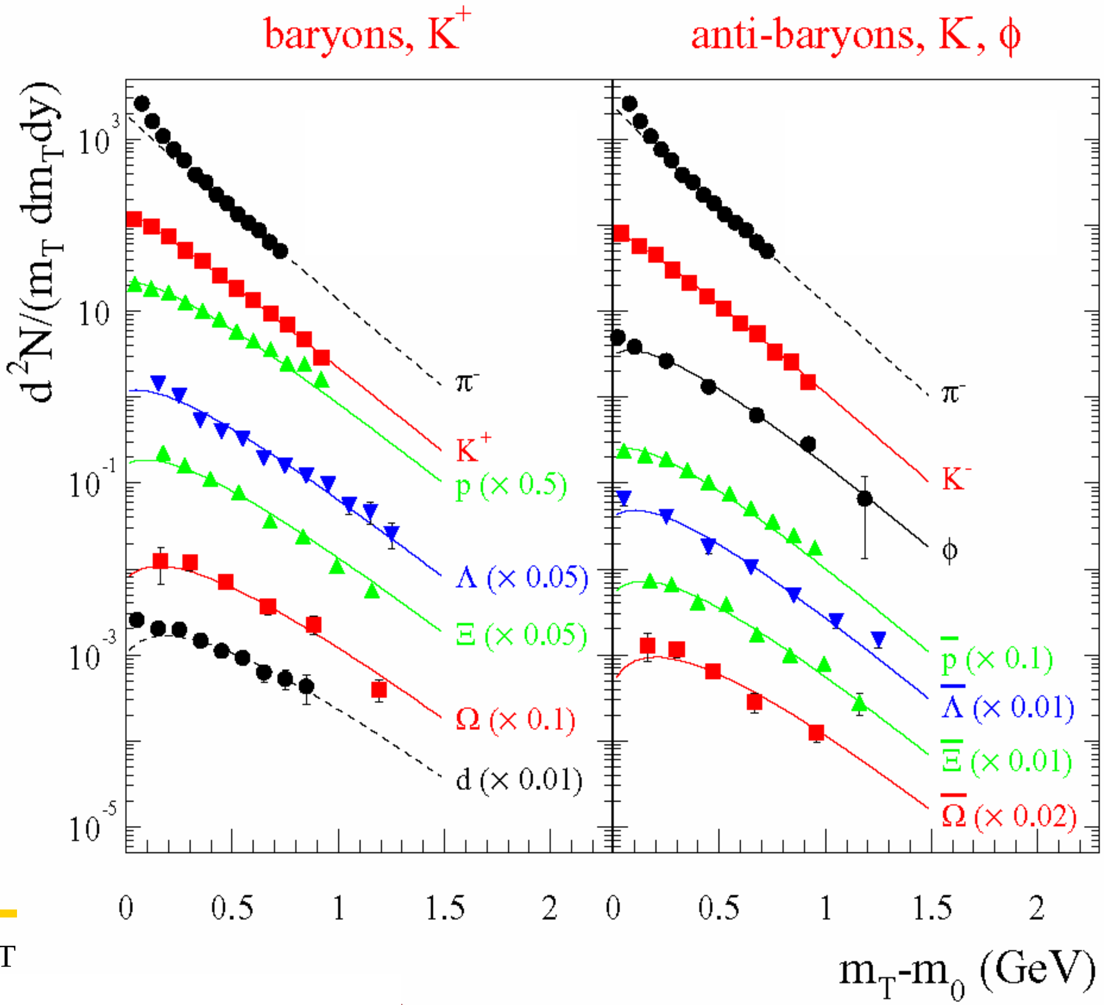
# O Diagrama de fase



# Espectro de momento transversal

- O número de partículas diminui exponencialmente com o momento transversal.
- Equilíbrio térmico?



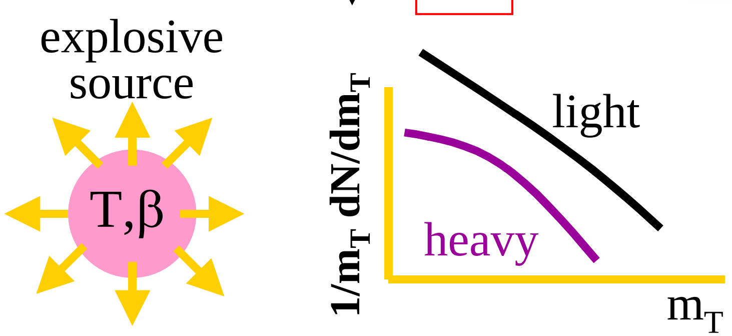



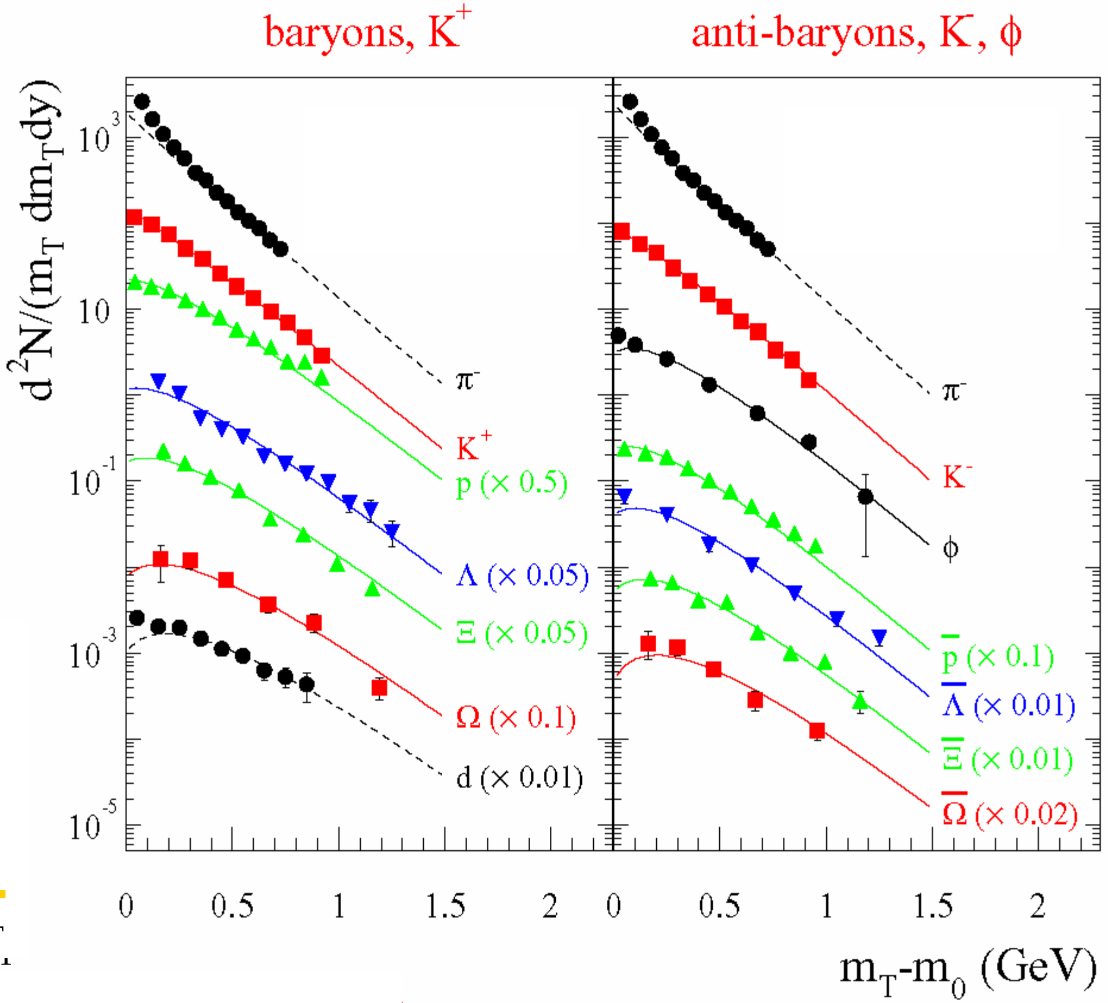
# Espectro de momento transversal

- Dependência exponencial:

$$\frac{d^2N}{dy\,dm_t} \propto e^{-m_t/kT}$$

?



# Espectro de momento transversal

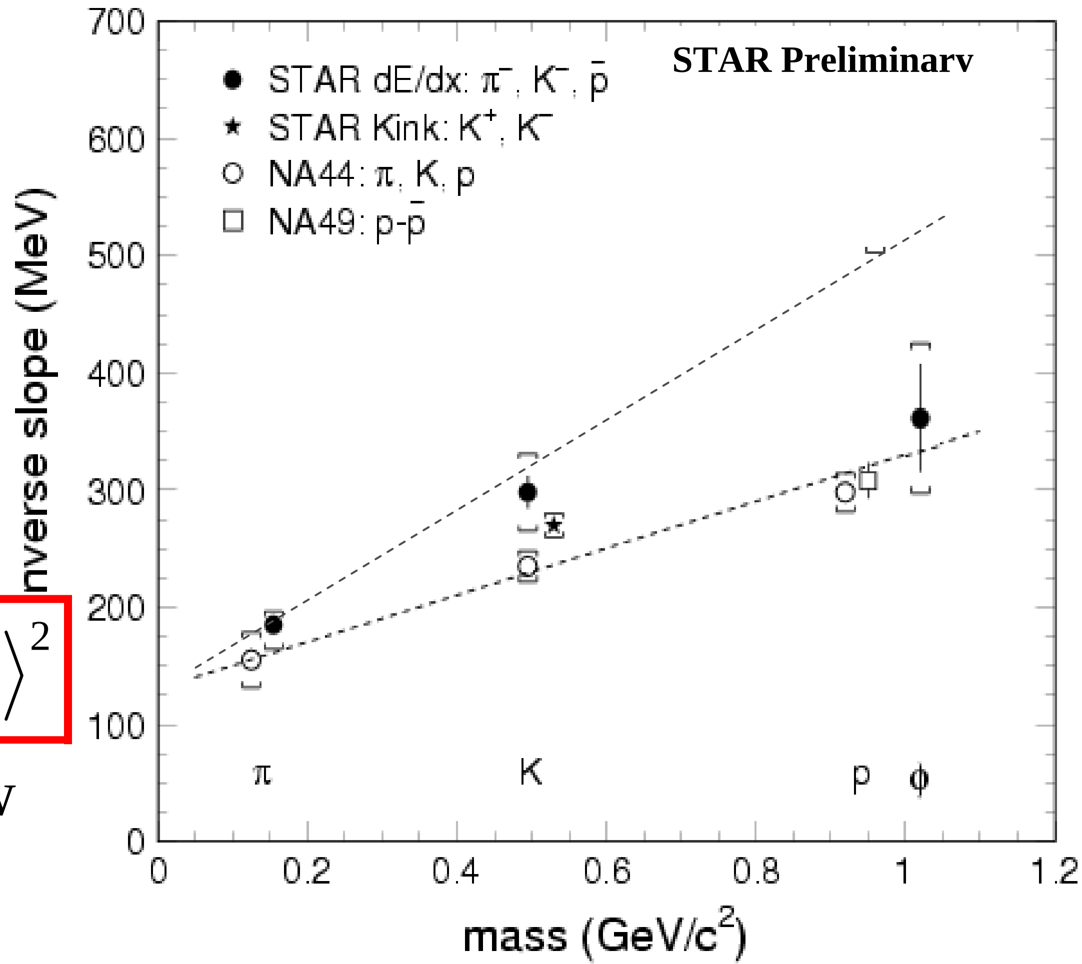
- Dependência exponencial:

$$\frac{d^2N}{dy\,dm_t} \propto e^{-m_t/kT}$$

↓

$$T = T_{freeze-out} + 1/2 \cdot m \cdot \langle \beta_r \rangle^2$$

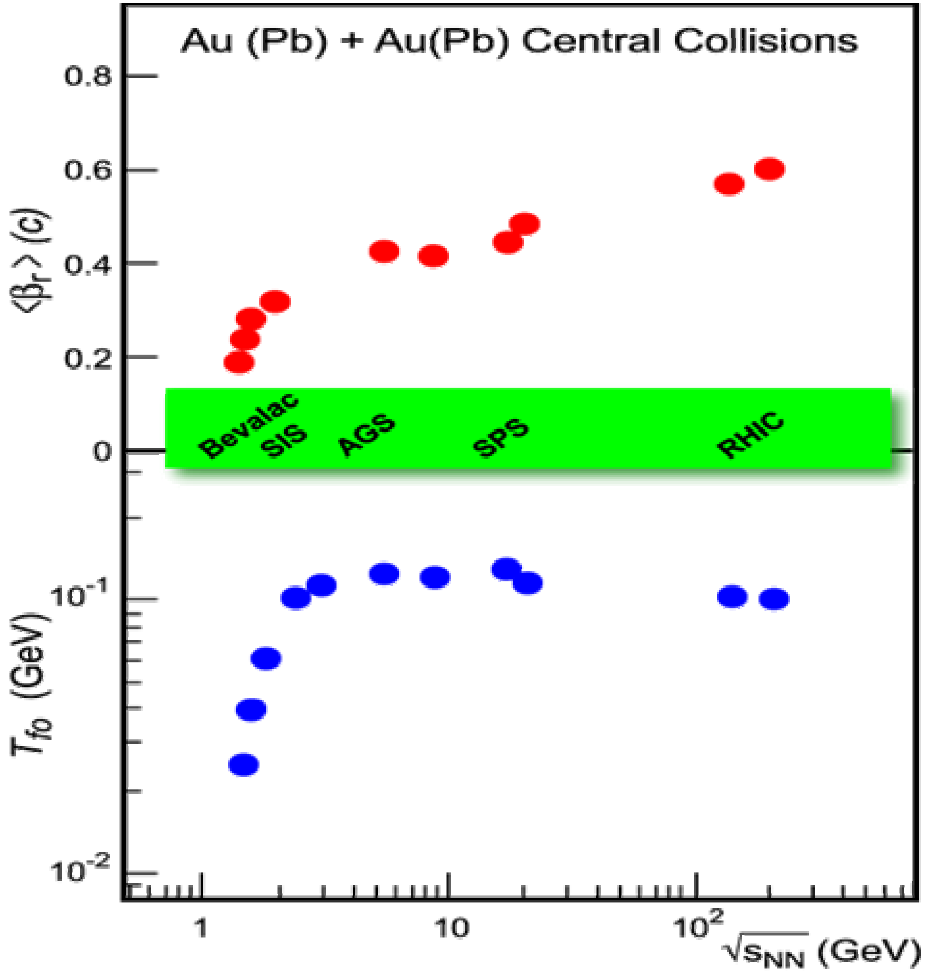
where $\langle \beta_r \rangle^2$ = averaged flow velocity



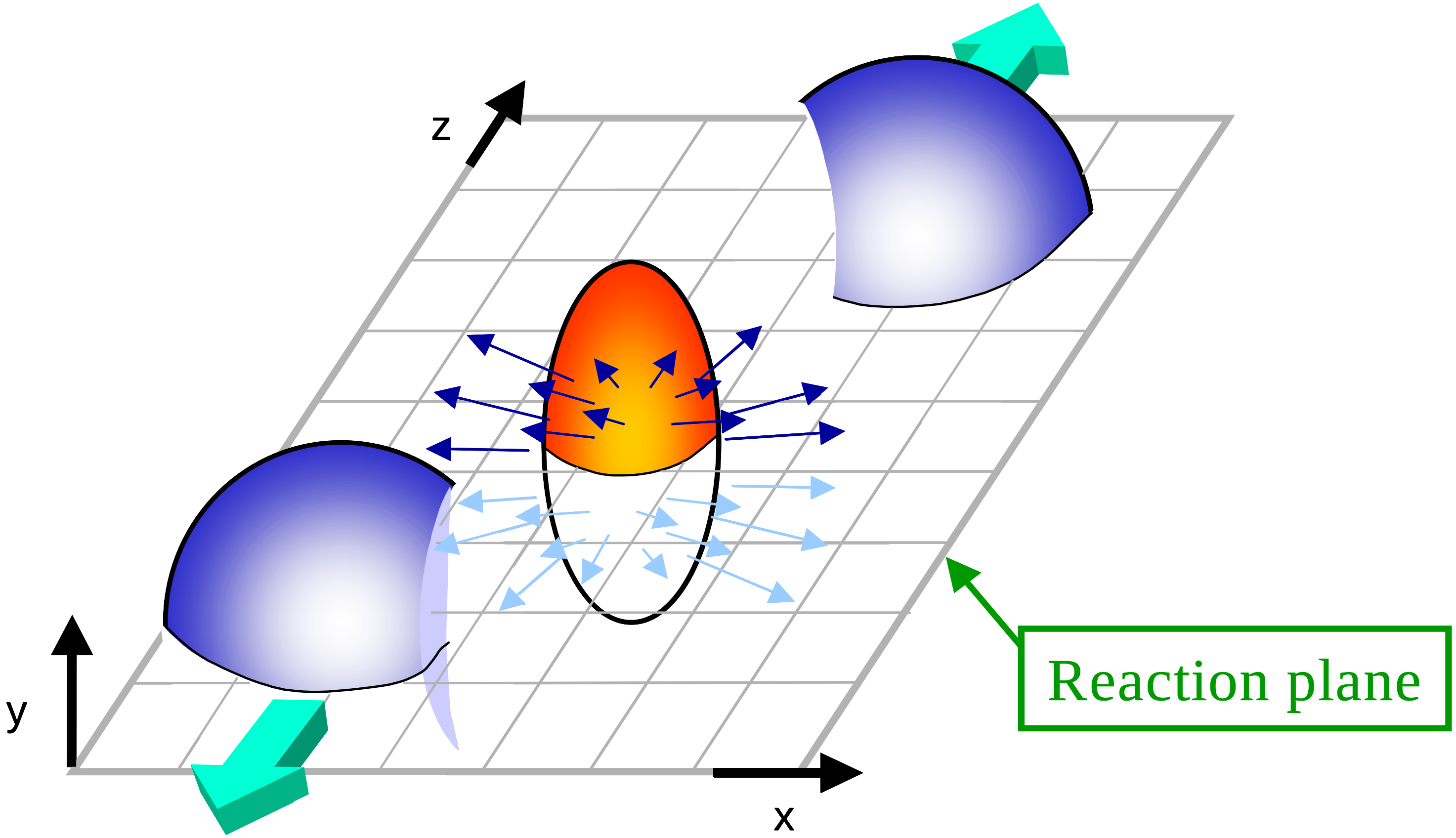
# Espectro de momento transversal

- $\chi^2$ map of $T_{freeze\text{-}out}$ and $\beta_r$ (contour plot are 95% C.L.);
- Minimum $\chi^2$ for different energies

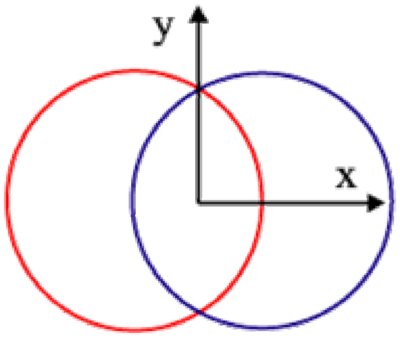
Strong collective radial expansion at RHIC
⇒ high pressure
⇒ high rescattering rate
⇒ Thermalization *likely*

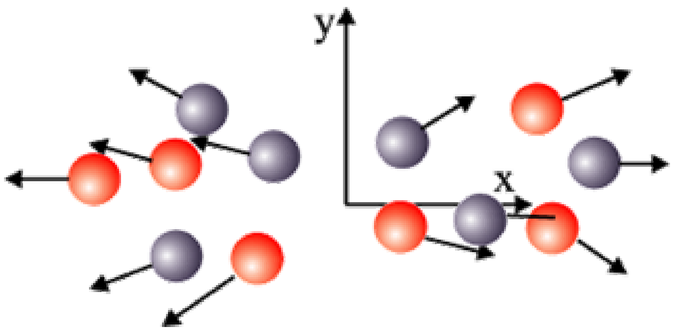


# Azimuthal Anisotropy of Emission: Elliptic Flow

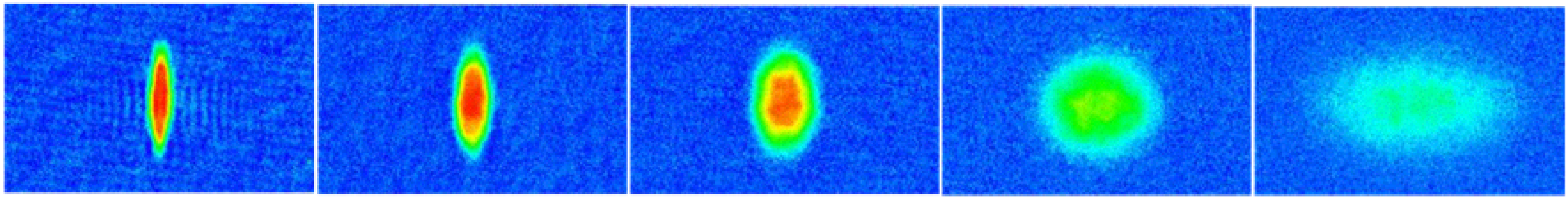


# Azimuthal Anisotropy of Emission: Elliptic Flow

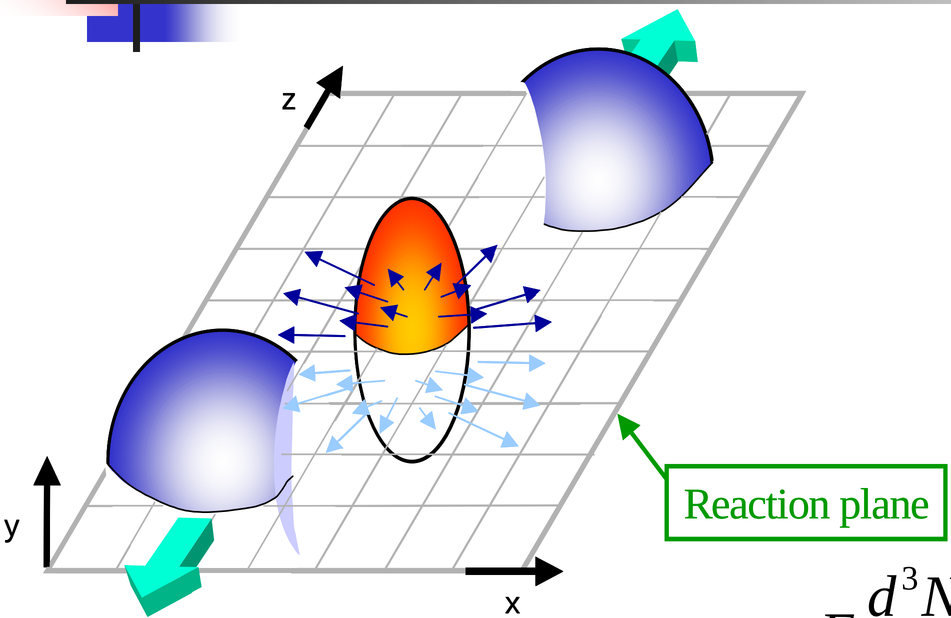


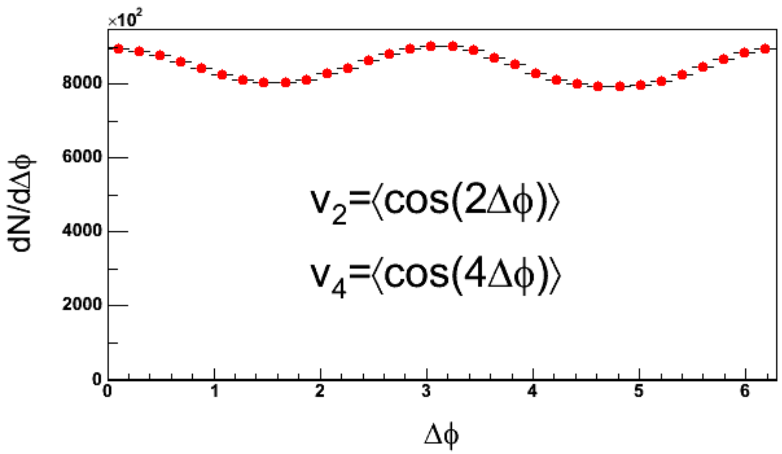




Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space



# Azimuthal Anisotropy of Emission: Elliptic Flow



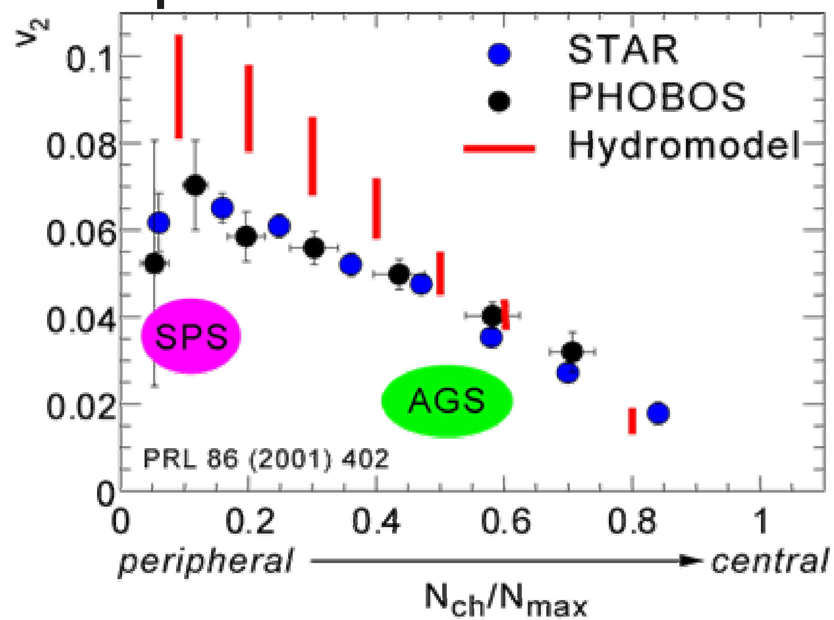



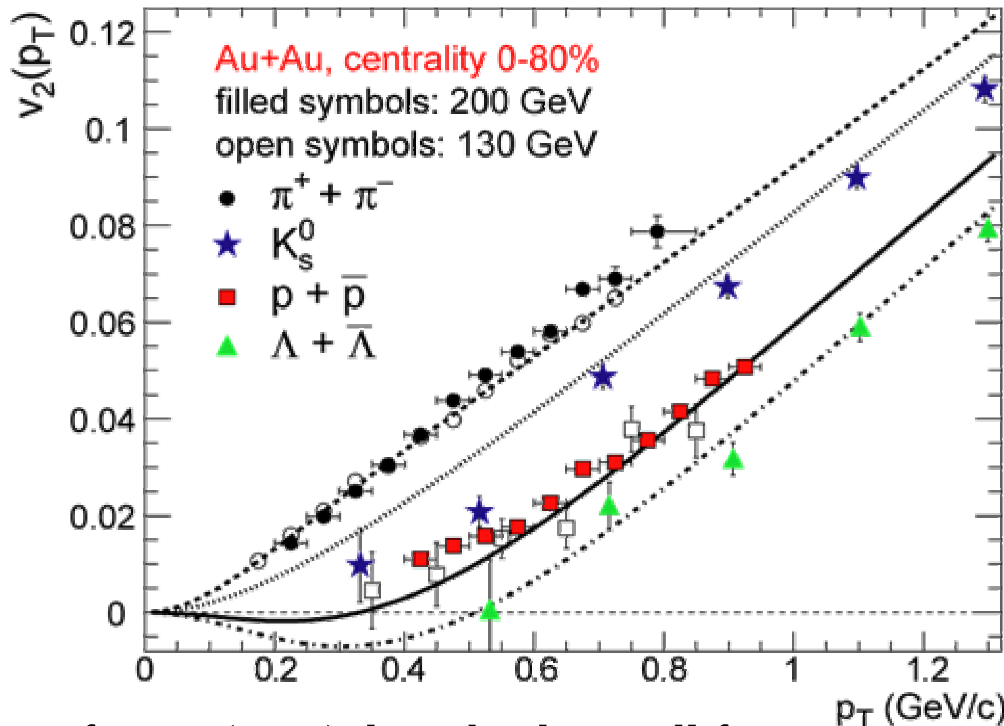

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\phi-\Psi_r\right)\right)\right)$$

Quantifying this effect $\Rightarrow$

$v_2$: $2^{nd}$ harmonic Fourier coefficient in dN/dϕ with respect to the reaction plane

# Large $v_2$: Strong internal pressure that builds up early



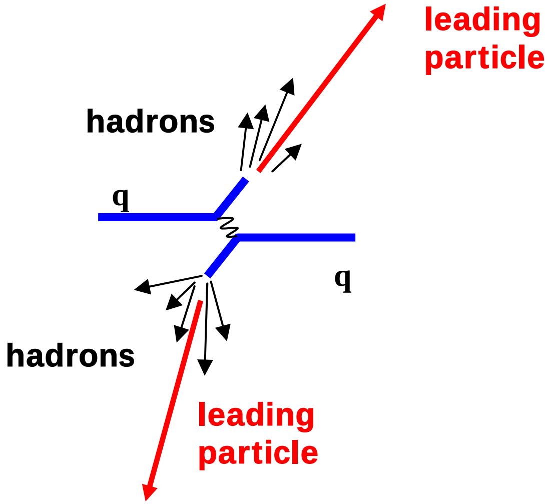



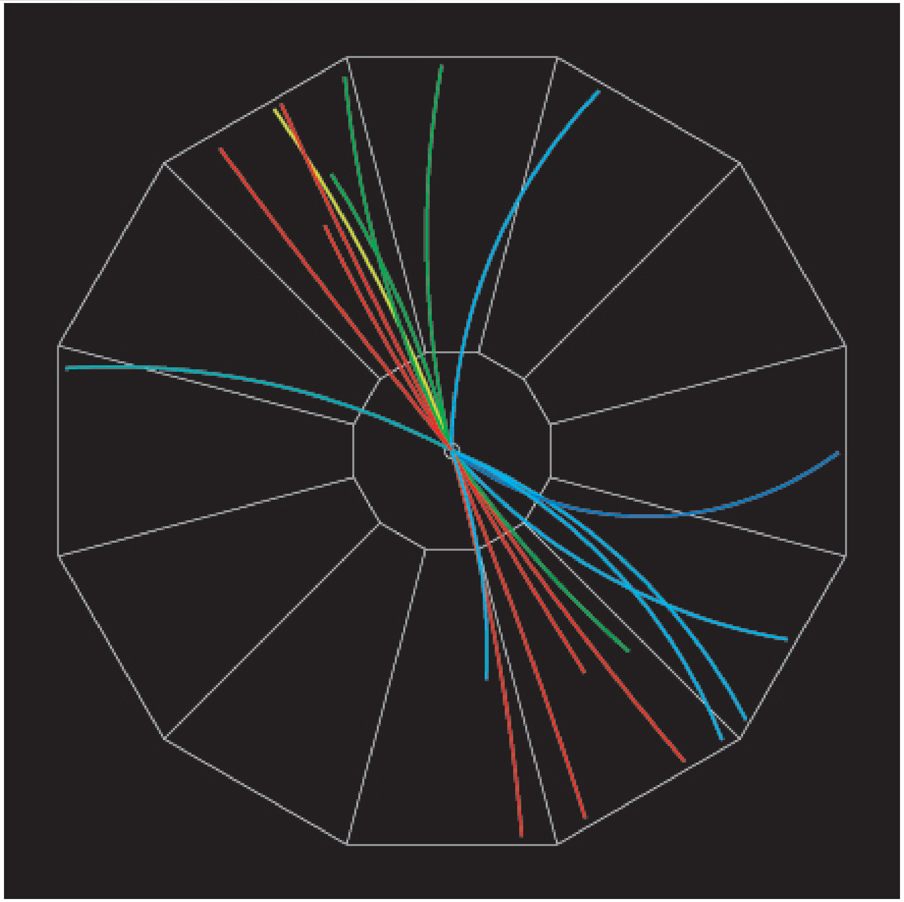

- Hydrodynamical models with soft Equation-of-State (EOS) describe data well for $p_T < 2.5$ GeV/c;
- Contrast to lower collision energies where hydro overpredicts elliptical flow;
- $v_2(\pi) > v_2(K) > v_2(p) > v_2(\Lambda)$
- **Compatible with early equilibration**

# Perguntas básicas

- Nas colisões entre íons pesados relativísticos formou-se um sistema em equilíbrio que podemos caracterizar seu estado?
  - Fortes indicações que um estado de equilíbrio foi atingido...
- Em caso afirmativo, ele é o estado da matéria previsto pela QCD?

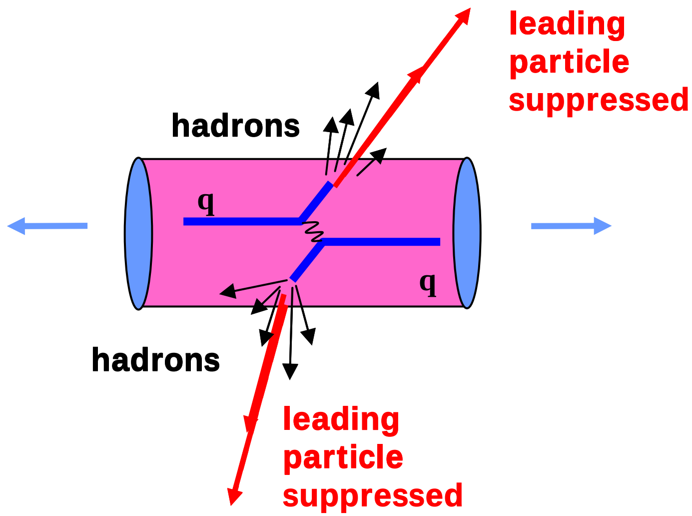
# Jets in p+p collisions

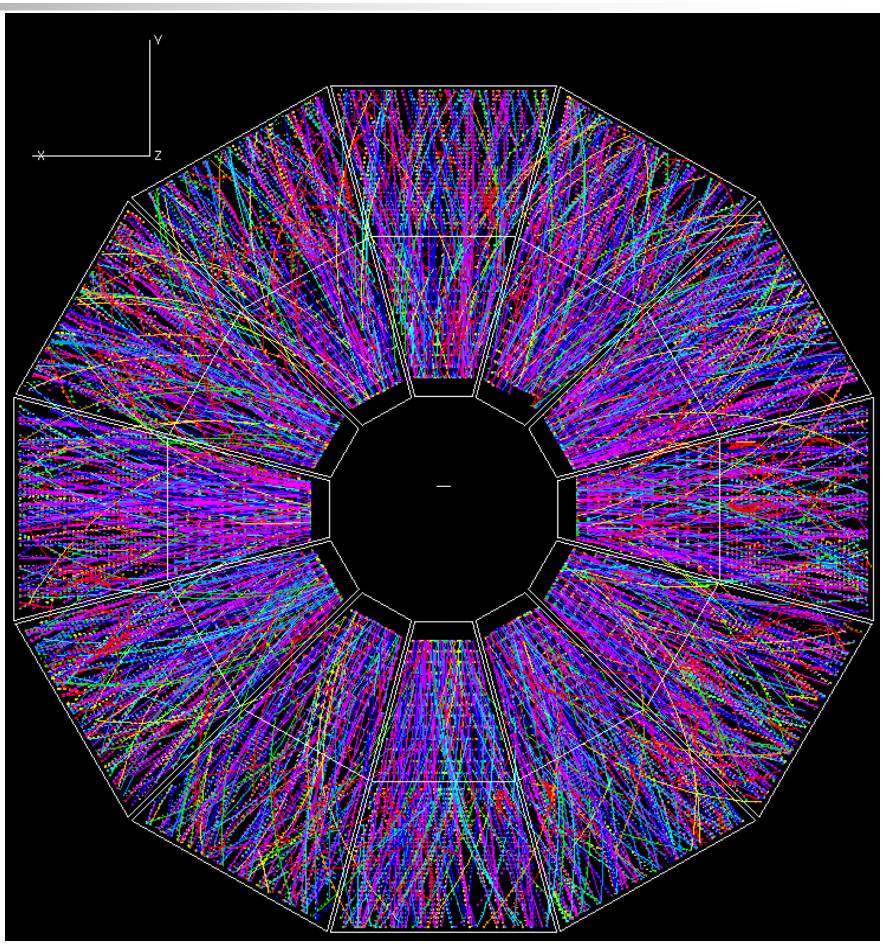


p+p →jet+jet
(STAR@RHIC)

# Jets in Au+Au collisions (??)

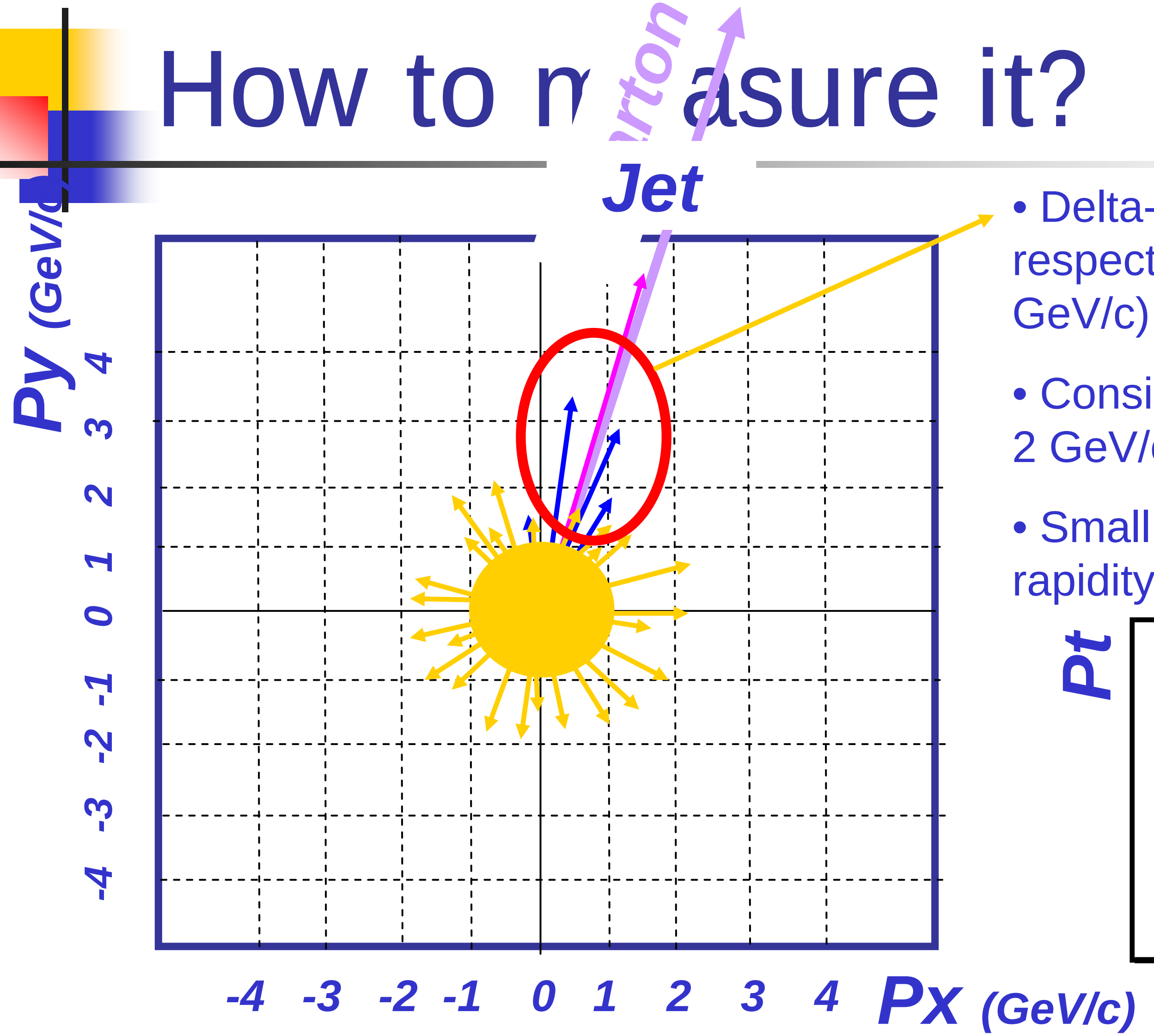


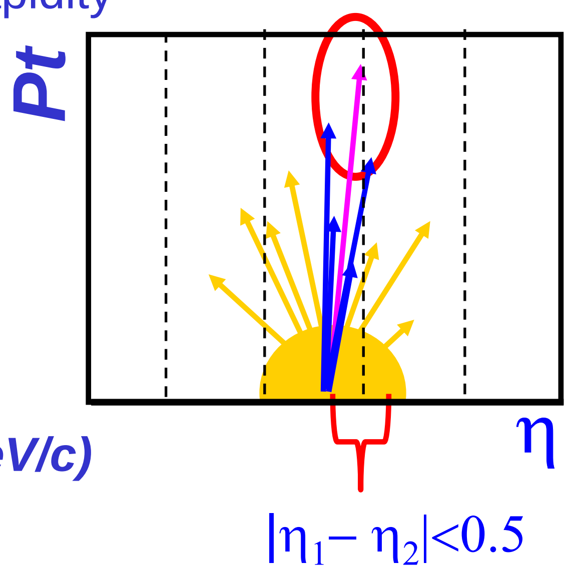
Is there a suppression of leading particles?

Au+Au →???
(STAR@RHIC)

# How to measure it?

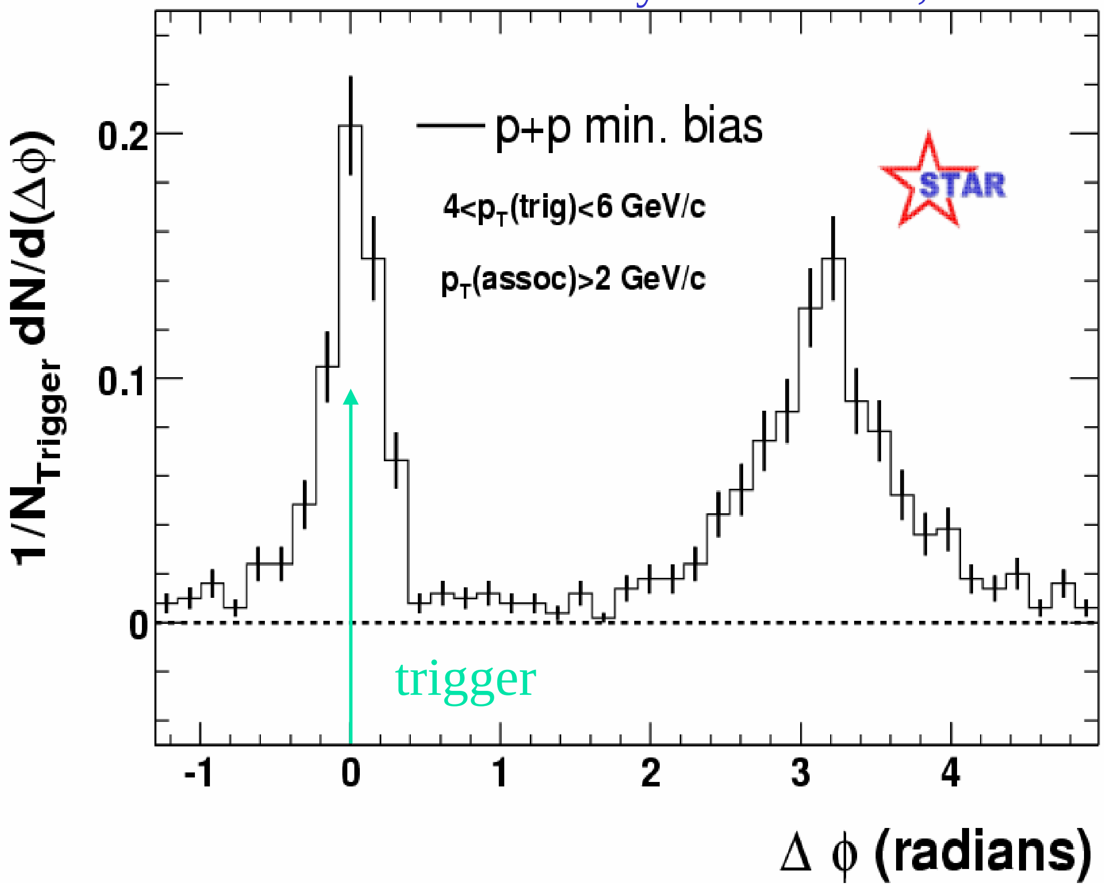



- Delta-Phi Correlation with respect to leading particle (>4 GeV/c)
- Consider only particles above 2 GeV/c
- Small difference in pseudo rapidity



# Jets and two-particle azimuthal distributions in p+p

Phys Rev Lett 90, 082302

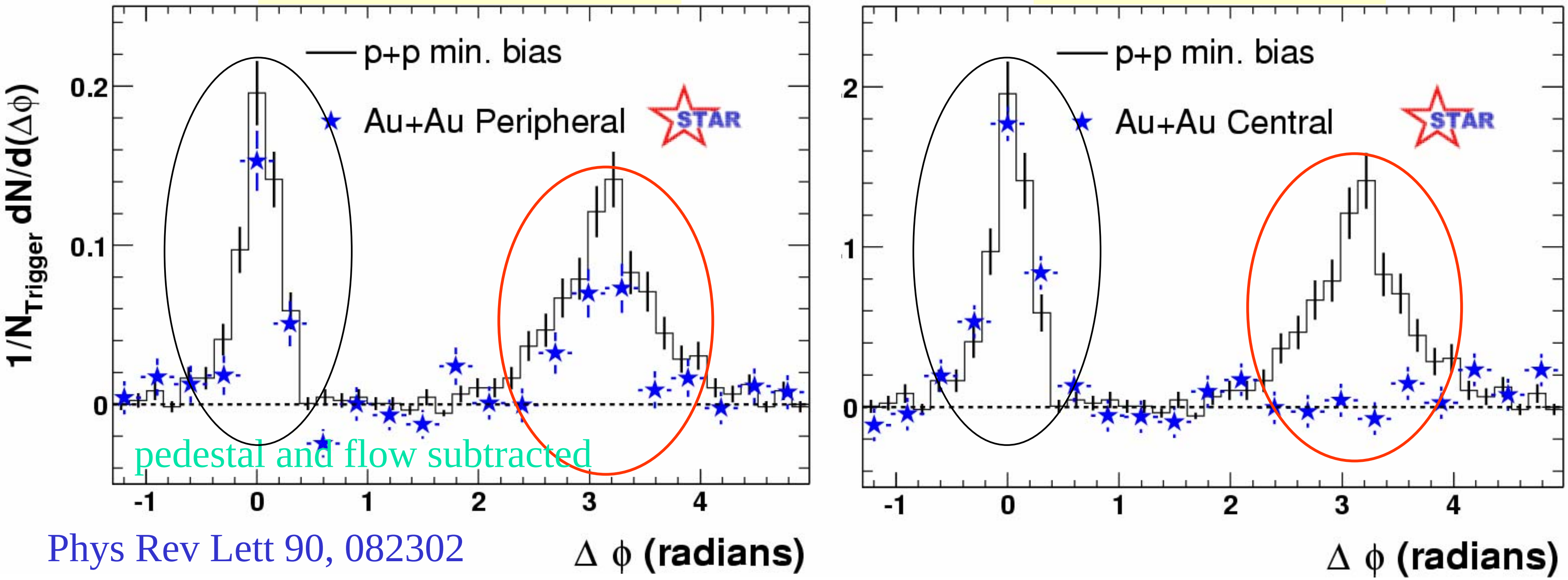



- **trigger**: highest $p_T$ track, $p_T$>4 GeV/c
- **Δφ distribution**: 2 GeV/c<$p_T$<$p_T^{trigger}$
- normalize to number of triggers

# Azimuthal distributions in Au+Au

Au+Au peripheral

Au+Au central



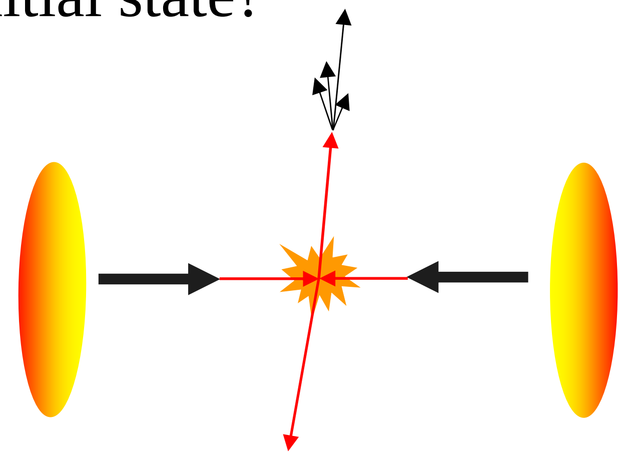

Phys Rev Lett 90, 082302

Near-side: peripheral and central Au+Au similar to p+p

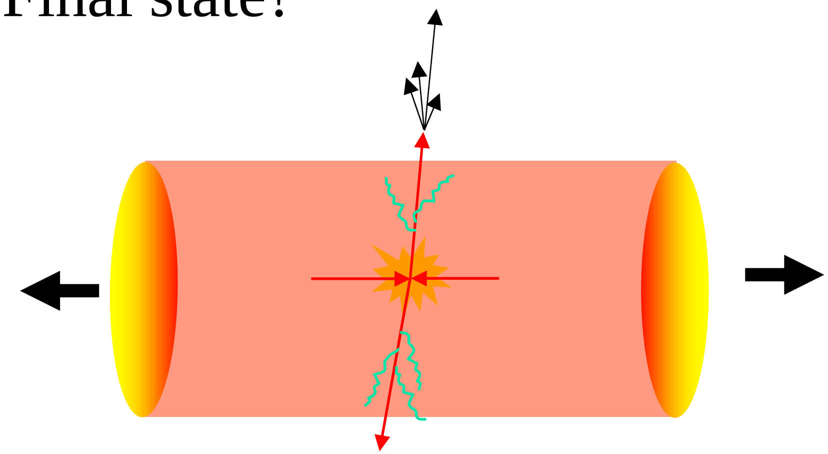
Strong suppression of back-to-back correlations in central Au+Au

# Is suppression an initial or final state effect?

Initial state?



Final state?

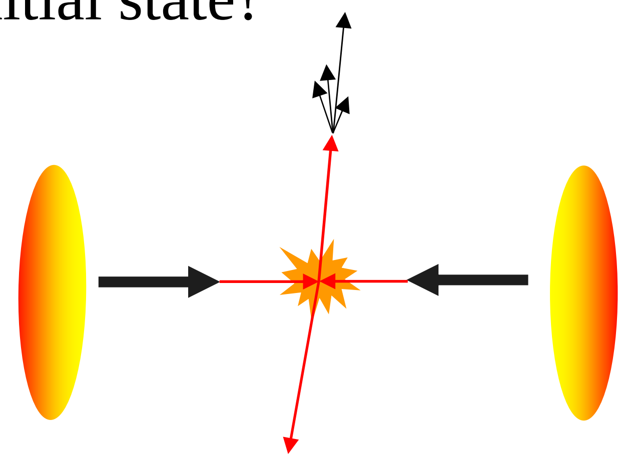


Strong modification of Au wavefunction (gluon saturation)

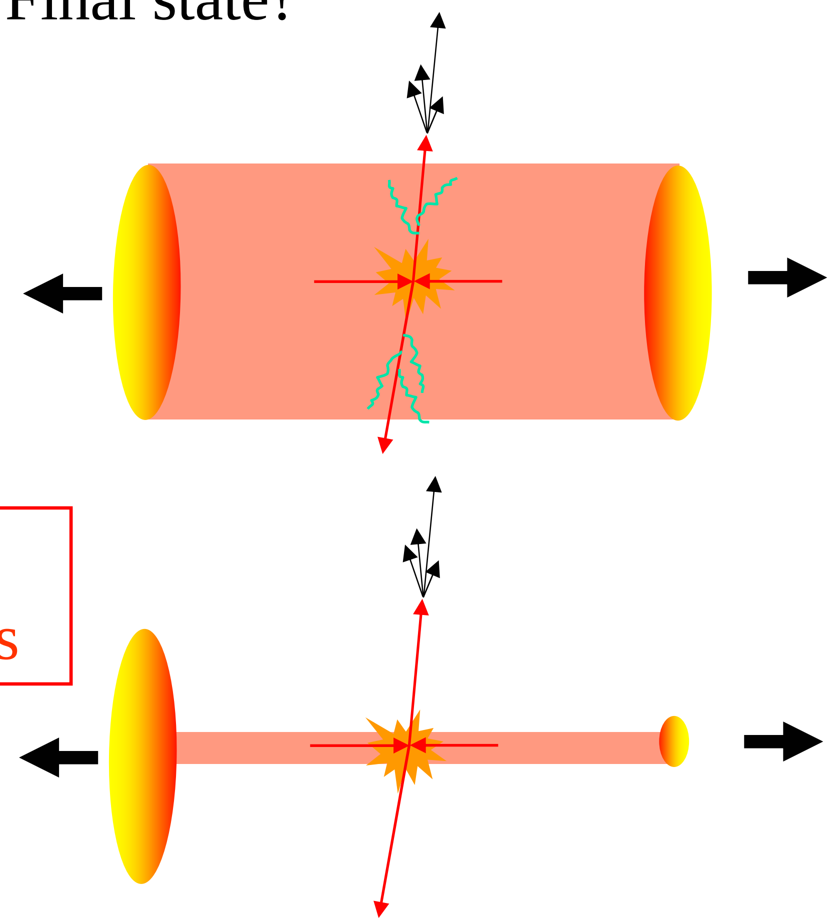
Partonic energy loss in dense medium generated in collision

# Is suppression an initial or final state effect?

Initial state?



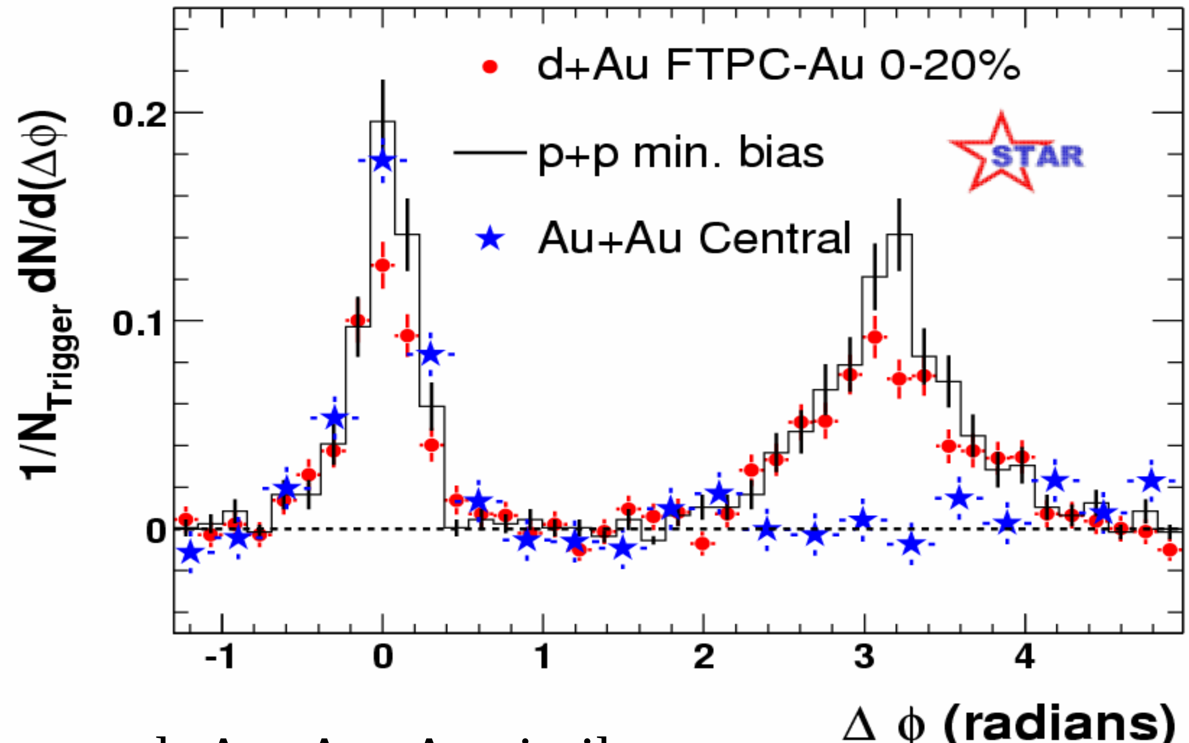
Final state?



How to discriminate?

Turn off final state ⇒ d+Au collisions

# Azimuthal distributions in d+Au




Near-side: p+p, d+Au, Au+Au similar

Back-to-back: Au+Au strongly suppressed relative to p+p and d+Au

Suppression of the back-to-back correlation in central Au+Au is a final-state effect

# Perguntas básicas

- Nas colisões entre íons pesados relativísticos formou-se um sistema em equilíbrio que podemos caracterizar seu estado?
  - Fortes indicações que um estado de equilíbrio foi atingido...
- Em caso afirmativo, ele é o estado da matéria previsto pela QCD?
  - O estado formado é denso e bastante dissipativo.

# Afinal, o QGP foi medido no RHIC?

Na verdade, a resposta depende da pessoa para quem você pergunta...

A resposta dos experimentais é:

Sabemos que colisões Au+Au geram um meio que

- é denso (muitas vezes a densidade da matéria nuclear “fria”)
- é dissipativo
- apresenta forte comportamento coletivo

Isto representa um progresso significativo no entendimento da matéria nuclear

Ainda é preciso mostrar que:

- A dissipação e o comportamento coletivo ocorrem entre quarks e gluons ao invés de hádrons
- O sistema está de fato termalizado

Desafio MUITO INTERESSANTE que o futuro nos promete...

# Evolução da definição de QGP

- Proposal for RHIC from BNL (1984)
  - "*The specific motivation from QCD is the belief that we can assemble macroscopic volumes of nuclear matter at such extreme thermodynamic conditions as to overcome the forces that confine constituents in normal hadrons, creating a new form of matter in a extended confined plasma of quarks and gluons.*"