

# Introduction to Relativistic Heavy Ion Physics

## Lecture 1: How Did We Get Here ?

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# How Did We Get Here ?

- *Duality* has become an important theme in modern physics

- My title is deliberately dual :

    - A (brief) history of the universe

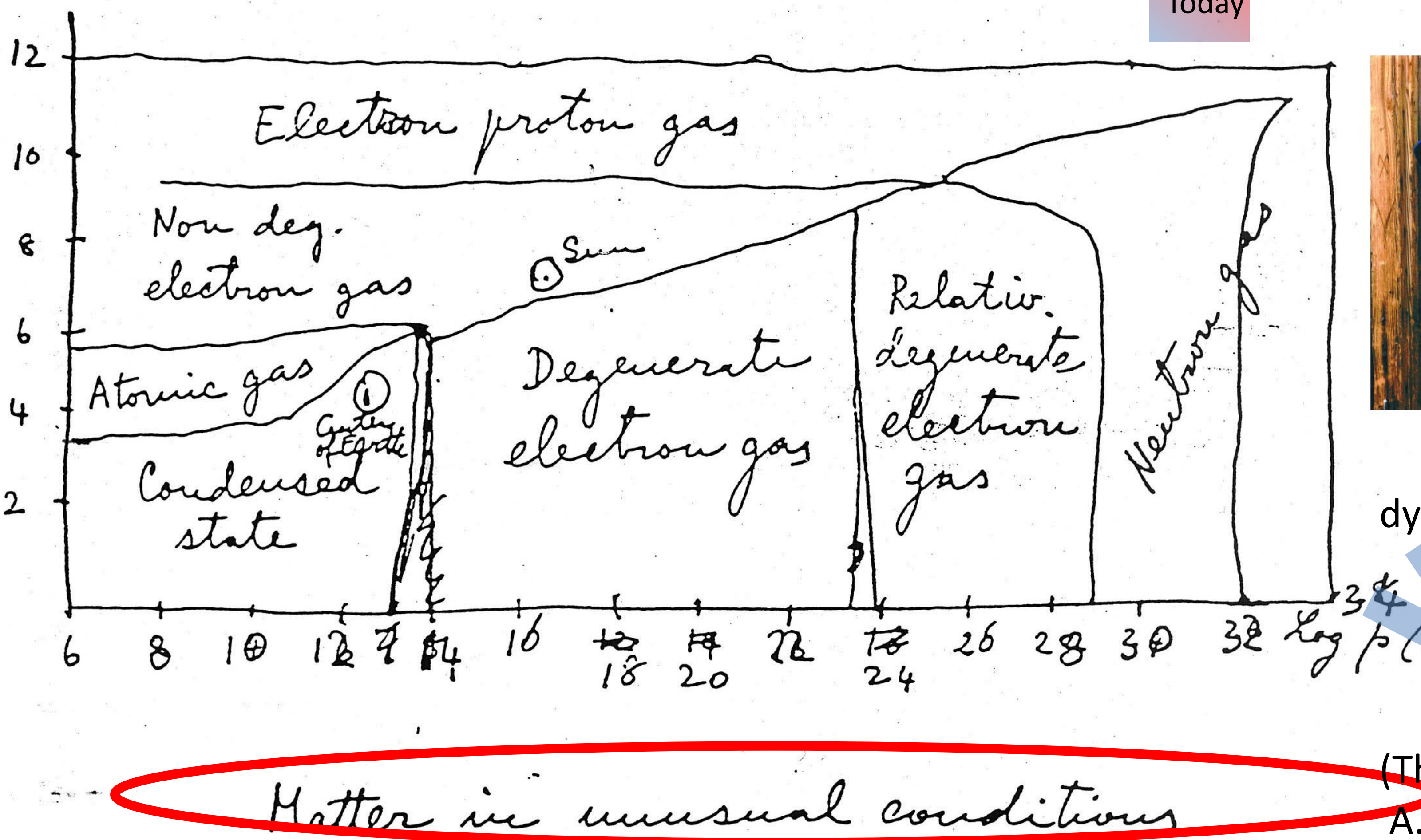
    - A (not so) brief history of heavy ion physics

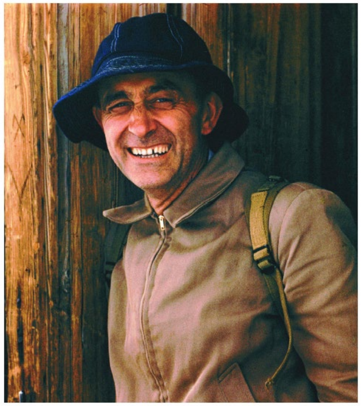
# Fermi's Vision

- ~1950: (Almost) included physics of 21st century
- See also remarks in his "statistical model" paper

**From Fermi *Notes on Thermodynamics and Statistics***

Today



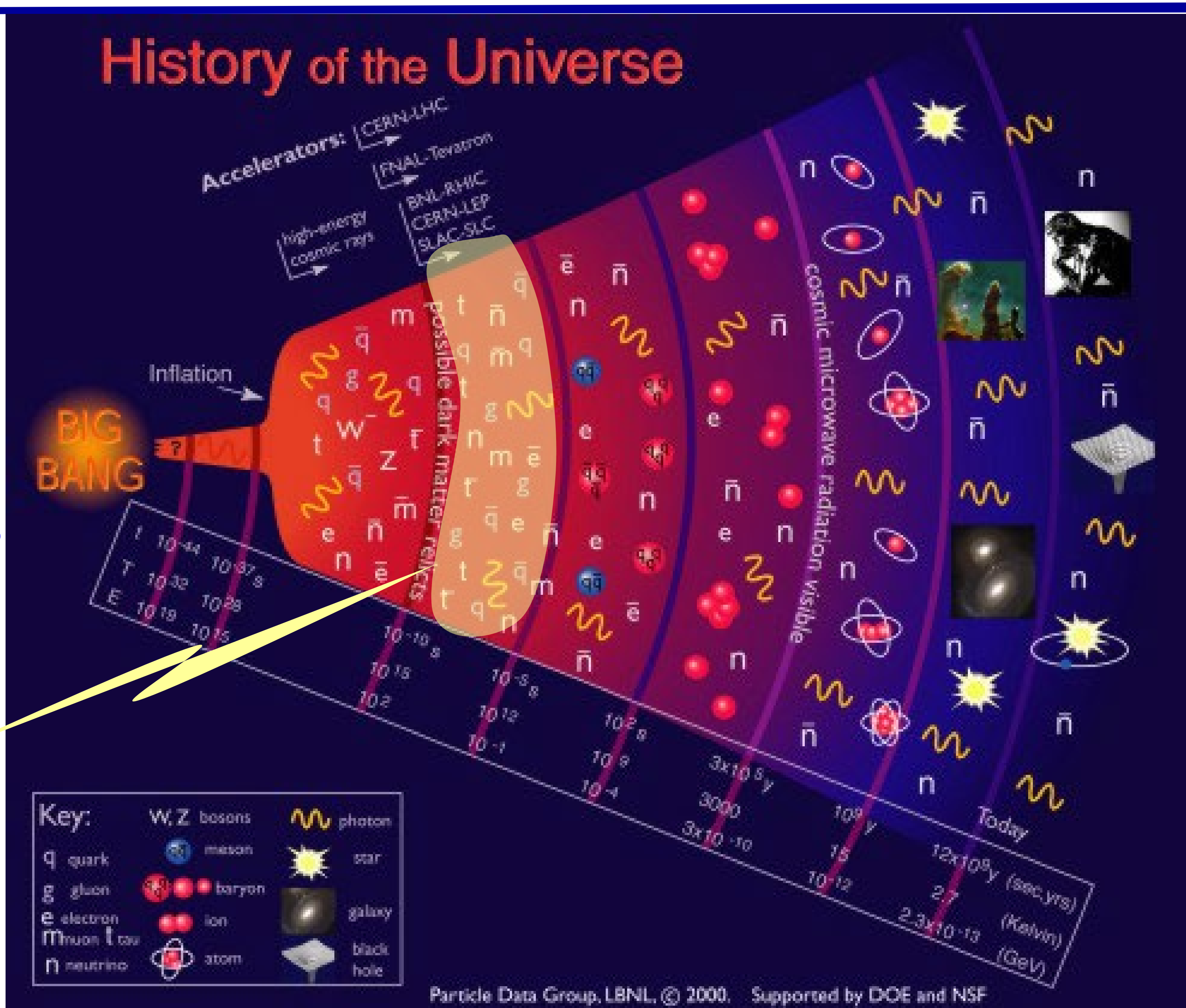



dyne/cm$^2$ !

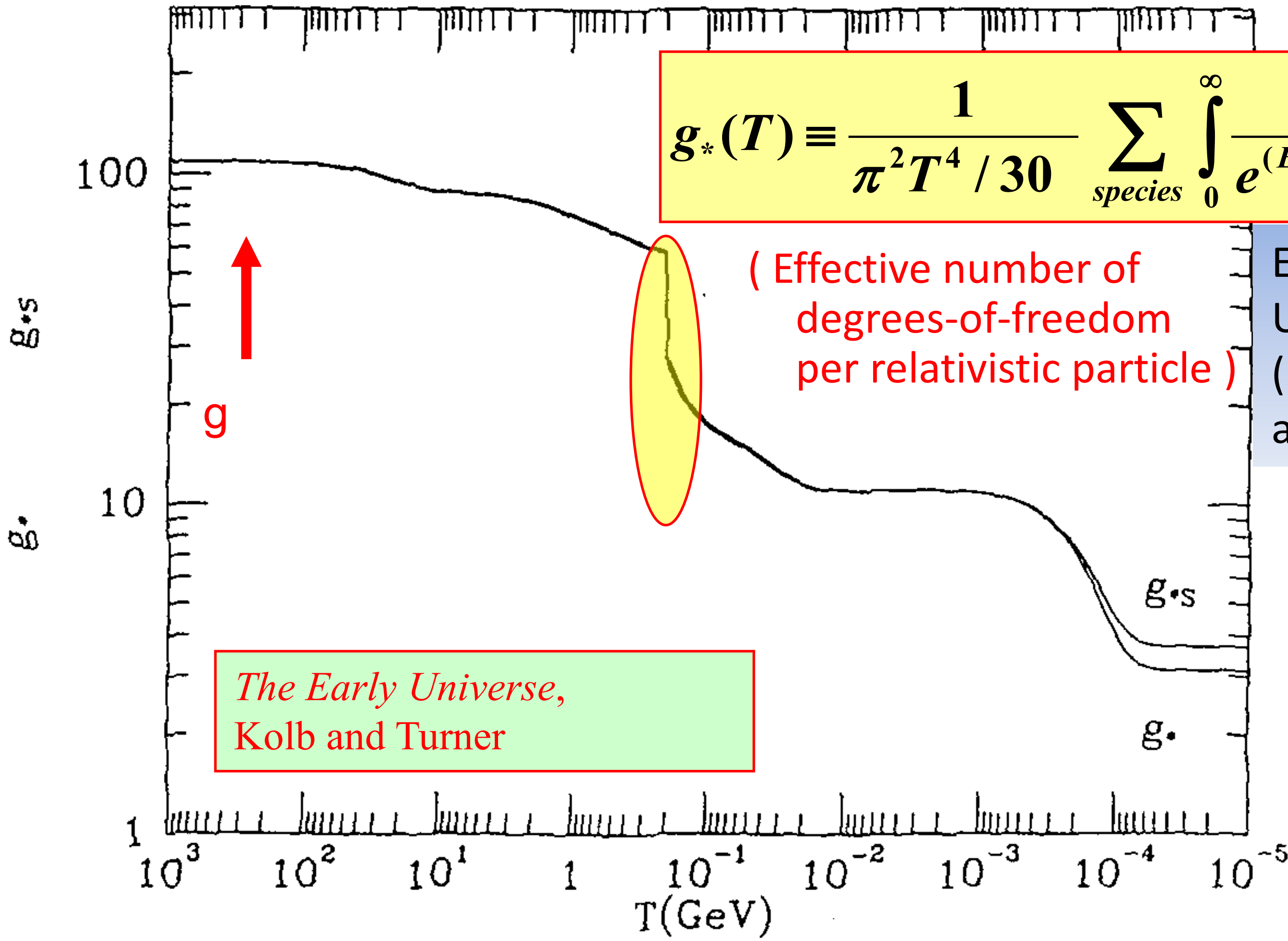
(Thanks to A. Melissinos)

# History of the Universe

- Density
  1 GeV / fm$^3$
  ~ $10^{15}$ gm/cm$^3$
- Temperature
  ~ 160 MeV
  ~ $10^{12}$ K
- Conditions that prevailed ~ 10 μs after the Big Bang



# History of the Massless Species




$$g_*(T) \equiv \frac{1}{\pi^2 T^4/30} \sum_{species} \int_0^\infty \frac{E_i(p)}{e^{(E_i-\mu_i)/T_i} \pm 1} \frac{d^3p}{(2\pi)^3}$$

( Effective number of degrees-of-freedom per relativistic particle )

Exercise 1: Understand this (may be easier after Lecture 2).

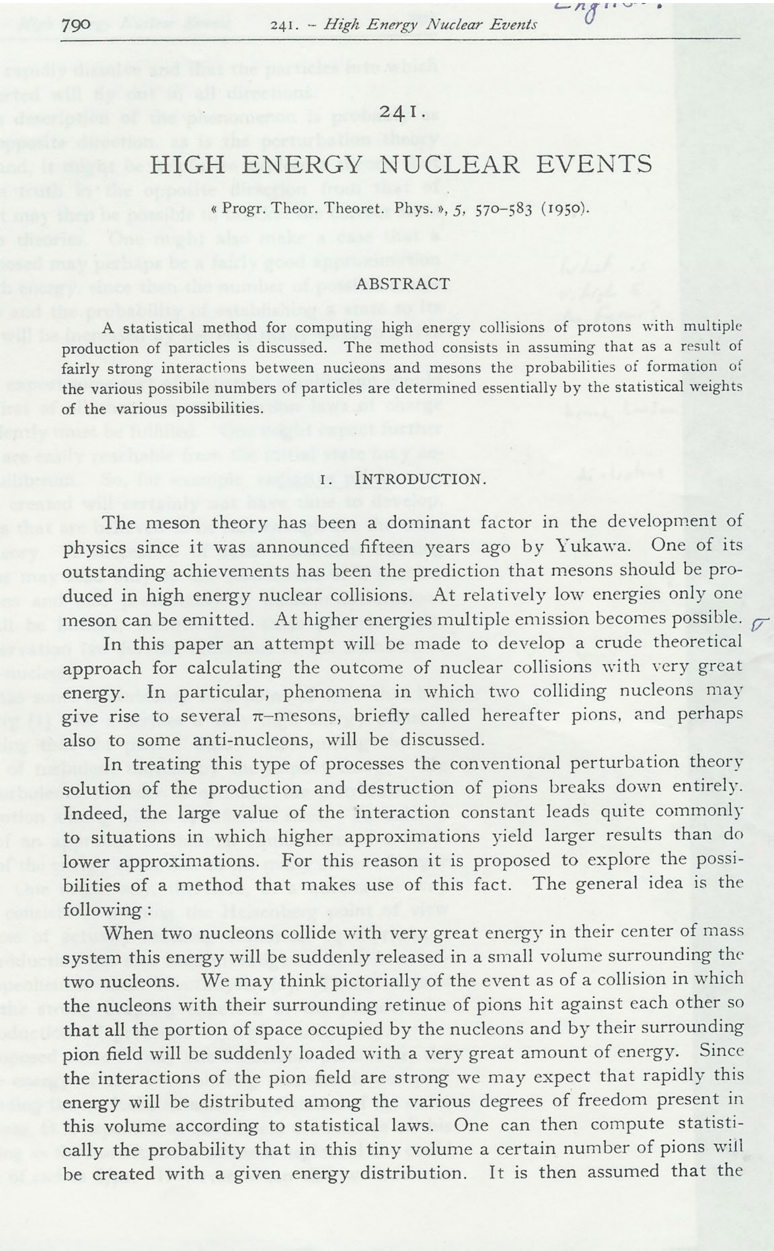
*The Early Universe,*
Kolb and Turner

Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory.

# First Application of Statistical Methods in "High Energy" Physics



- Fermi (1950)
  - "High Energy Nuclear Events", Prog. Theor. Phys. 5, 570 (1950)
  - Lays groundwork for statistical approach to particle production in strong interactions:
    - "Since the interactions of the pion field are *strong*, we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws."
  - (Emphasis added by WAZ)



790 241. – *High Energy Nuclear Events*

241.

HIGH ENERGY NUCLEAR EVENTS

« Progr. Theor. Theoret. Phys. », 5, 570–583 (1950).

ABSTRACT

A statistical method for computing high energy collisions of protons with multiple production of particles is discussed. The method consists in assuming that as a result of fairly strong interactions between nucleons and mesons the probabilities of formation of the various possibile numbers of particles are determined essentially by the statistical weights of the various possibilities.

1. INTRODUCTION.

The meson theory has been a dominant factor in the development of physics since it was announced fifteen years ago by Yukawa. One of its outstanding achievements has been the prediction that mesons should be produced in high energy nuclear collisions. At relatively low energies only one meson can be emitted. At higher energies multiple emission becomes possible.

In this paper an attempt will be made to develop a crude theoretical approach for calculating the outcome of nuclear collisions with very great energy. In particular, phenomena in which two colliding nucleons may give rise to several $\pi$–mesons, briefly called hereafter pions, and perhaps also to some anti-nucleons, will be discussed.

In treating this type of processes the conventional perturbation theory solution of the production and destruction of pions breaks down entirely. Indeed, the large value of the interaction constant leads quite commonly to situations in which higher approximations yield larger results than do lower approximations. For this reason it is proposed to explore the possibilities of a method that makes use of this fact. The general idea is the following:

When two nucleons collide with very great energy in their center of mass system this energy will be suddenly released in a small volume surrounding the two nucleons. We may think pictorially of the event as of a collision in which the nucleons with their surrounding retinue of pions hit against each other so that all the portion of space occupied by the nucleons and by their surrounding pion field will be suddenly loaded with a very great amount of energy. Since the interactions of the pion field are strong we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws. One can then compute statistically the probability that in this tiny volume a certain number of pions will be created with a given energy distribution. It is then assumed that the

# First Application of Statistical Methods in "High Energy" Physics



- Fermi (1950)
  - "High Energy Nuclear Events", Prog. Theor. Phys. 5, 570 (1950)
- Nothing more than phase space:

$$\frac{dN}{dE} = \left(\frac{V}{2\pi\hbar}\right)^n \frac{d(\text{momentum space})}{dE}$$

$$= \left(\frac{V}{2\pi\hbar}\right)^n \int \delta(E_1 + E_2 + \cdots E_n - E)\ d^3p_1 d^3p_2 \cdots d^3p_n$$

- Total number of produced particles $N \sim s^{1/4}$ where $s = (p_1 + p_2)^2$

# Fermi Statistical Model

- Was deliberately intended as an extreme assumption:
  - "*may then be possible to bracket the correct state of fact between the two theories*" (statistical model and perturbation theory)
- Later severely criticized by Landau
  - H.L. Anderson: "*In the later literature this made it appear the theory was always wrong, a point that Fermi didn't enjoy at all.*"

# Essential Role of Hydrodynamics



- Landau (1955)
  - Significant extension of Fermi's approach
  - Considers fundamental roles of
    - Hydrodynamic evolution
    - Entropy
  - "The defects of Fermi's theory arise mainly because the expansion of the compound system is not correctly taken into account…
    (The) expansion of the system can be considered on the basis of *relativistic hydrodynamics*."
  - (Emphasis added by WAZ)

## 88. A HYDRODYNAMIC THEORY OF MULTIPLE FORMATION OF PARTICLES

### 1. Introduction

Experiment shows that in collisions of very fast particles a large number of new particles are formed in multi-prong stars. The energy of the particles which produce such stars is of the order of $10^{12}$ eV or more. A characteristic feature is that such collisions occur not only between a nucleon and a nucleus but also between two nucleons. For example, the formation of two mesons in neutron–proton collisions has been observed at comparatively low energies, of the order of $10^9$ eV, in cosmotron experiments[1].

Fermi[2,3] originated the ingenious idea of considering the collision process at very high energies by the use of thermodynamic methos. The main points of his theory are as follows.

(1) It is assumed that, when two nucleons of very high energy collide, energy is released in a very small volume $V$ in their centre of mass system. Since the nuclear interaction is very strong and the volume is small, the distribution of energy will be determined by statistical laws. The collision of high-energy particles may therefore be treated without recourse to any specific theories of nuclear interaction.

(2) The volume $V$ in which energy is released is determined by the dimensions of the meson cloud around the nucleons, whose radius is $\hbar/\mu c$, $\mu$ being the mass of the pion. But since the nucleons are moving at very high speeds, the meson cloud surrounding them will undergo a Lorentz contraction in the direction of motion. Thus the volume $V$ will be, in order of magnitude,

$$V = \frac{4\pi}{3}\left(\frac{\hbar}{\mu c}\right)^3 \frac{2Mc^2}{E'}, \tag{1.1}$$

where $M$ is the mass of a nucleon and $E'$ the nucleon energy in the centre of mass system.

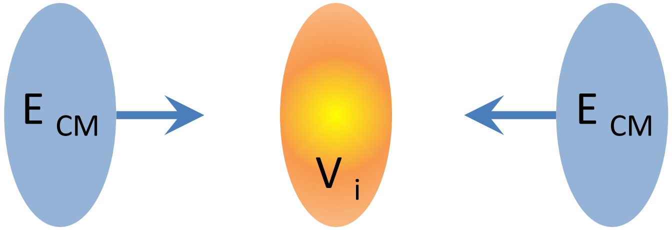
(3) Fermi assumes that particles are formed, in accordance with the laws of statistical equilibrium, in the volume $V$ at the instant of collision. The particles formed do not interact further with one another, but leave the volume in a "frozen" state.

С. З. Беленький и Л. Д. Ландау, Гидродинамическая теория множественного образования частиц, *Успехи Физических Наук*, 56, 309 (1955).
S. Z. Belenkij and L. D. Landau, Hydrodynamic theory of multiple production of particles, *Nuovo Cimento*, Supplement, 3, 15 (1956).



# Essential Role of Entropy

- Strongly interacting system
  - Particle number not conserved
  - Entropy is conserved
    - Compute initial entropy *density*




$$\text{Energy density} = \epsilon = \frac{2E_{CM}}{V_i} = \frac{2E_{CM}}{V_0/\gamma_{CM}} = \frac{2E_{CM}}{V_0}\frac{E_{CM}}{E_0} \sim n_{Dof}\,\frac{\pi^2}{30}T^4$$

See Lecture 2

$$\Rightarrow T \sim \sqrt{E_{CM}}$$

$$\text{Entropy density} = s \sim T^3 \sim E_{CM}^{3/2}$$

$$\Rightarrow \text{Total entropy } S \sim s\,V_i \sim E_{CM}^{3/2}\,\frac{V_0}{\gamma_{CM}} \sim E_{CM}^{3/2}\,V_0\,\frac{E_0}{E_{CM}} \sim E_{CM}^{1/2}$$

$$\text{Total number } N \sim S \sim E_{CM}^{1/2}$$

or $\boxed{N \sim s^{1/4}}$ , (Overloading symbol!) where now $s \equiv (p_1 + p_2)^2$

# Alternative History

- Circa 1955-1960:
  - The essential of
    - Statistical distribution of energy
    - Hydrodynamic expansion
  - in the strong interaction was widely recognized
  - This became the prevailing method for modeling the “bulk” in hadron+hadron collisions
- 1960 to present:
  - Deviations from the hydro expectations were recognized as new physics
- But that’s not what happened…

# Hydro Developments 1955-1975



- # Zero
- Above statement true to 0-th, $1^{st}$ (?) order
  - Hydro developed by a few workers
  - Statistical methods by Hagedorn and his collaborators
  - Both viewed as well outside mainstream
- Instead
  - Mesons: $\eta, \quad \rho, \quad \omega, \quad K_0^*(800), \quad K^*(892), \quad \eta', \quad f_0(980), \quad a_0(980), \quad \phi, \quad \ldots \; J/\Psi, \; \ldots$
  - Baryons: $\Delta^-, \quad \Delta^0, \quad \Delta^+, \quad \Delta^{++}, \quad \ldots, \quad \Sigma^\pm, \quad \Sigma^0, \quad \Sigma^\pm(1385), \quad \Sigma^0(1385), \quad \Xi^-, \; \Xi^0, \; \Xi^-(1530), \; \Xi^0(1530), \; \ldots, \; \Omega^-, \; \ldots$
  - 1955: anti-proton
  - 1957: Parity violation
  - 1961-64: Eightfold way
  - 1962: Two neutrinos
  - 1964: CP Violation
  - 1968: Electroweak unification (Theory)
  - 1968-73: Scaling in deep-inelastic scattering
  - 1973: QCD (Theory)

# 1970's: New Motivation



- T.D. Lee and G.C. Wick, ``Vacuum Stability And Vacuum Excitation In a Spin 0 Field Theory,'' Phys. Rev. **D9**, 2291 (1974).
- This also motivated the start of the experimental program in high energy nuclear collisions
- "Bear Mountain Workshop",1974
- Long interregnum:
  - LBNL Bevalac
  - (GSI-SIS, Dubna, CERN ISR)
  - BNL AGS
  - CERN SPS
  - ….
  - RHIC
  - LHC

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Report of the Workshop on

BEV/NUCLEON COLLISIONS OF HEAVY IONS - HOW AND WHY

NATIONAL SCIENCE FOUNDATION

AND

NEVIS LABORATORIES, COLUMBIA UNIVERSITY

NOVEMBER 29-DECEMBER 1, 1974

BEAR MOUNTAIN, NEW YORK

# New Motivation



- Simple argument:
  - HEP: Concentrate ever higher energies in (effectively) ever smaller volumes
  - NP: Create highest possible energies over an ‘extended’ volume
- Goal: Search for new, exotic forms of matter
  - Super-heavy nuclei
  - Stable strange nuclei
  - Nuclear shock-waves
  - Pion condensates

$$\gamma \leftrightarrow \vec{E}(\vec{x},t)$$
$$\pi \leftrightarrow \Pi(\vec{x},t)$$

- To 0-th order: all predates QCD

CONTENTS

Session I. Chairman: R. Serber



Session II. Chairman: J. Weneser



Session III. Chairman: L.M. Lederman



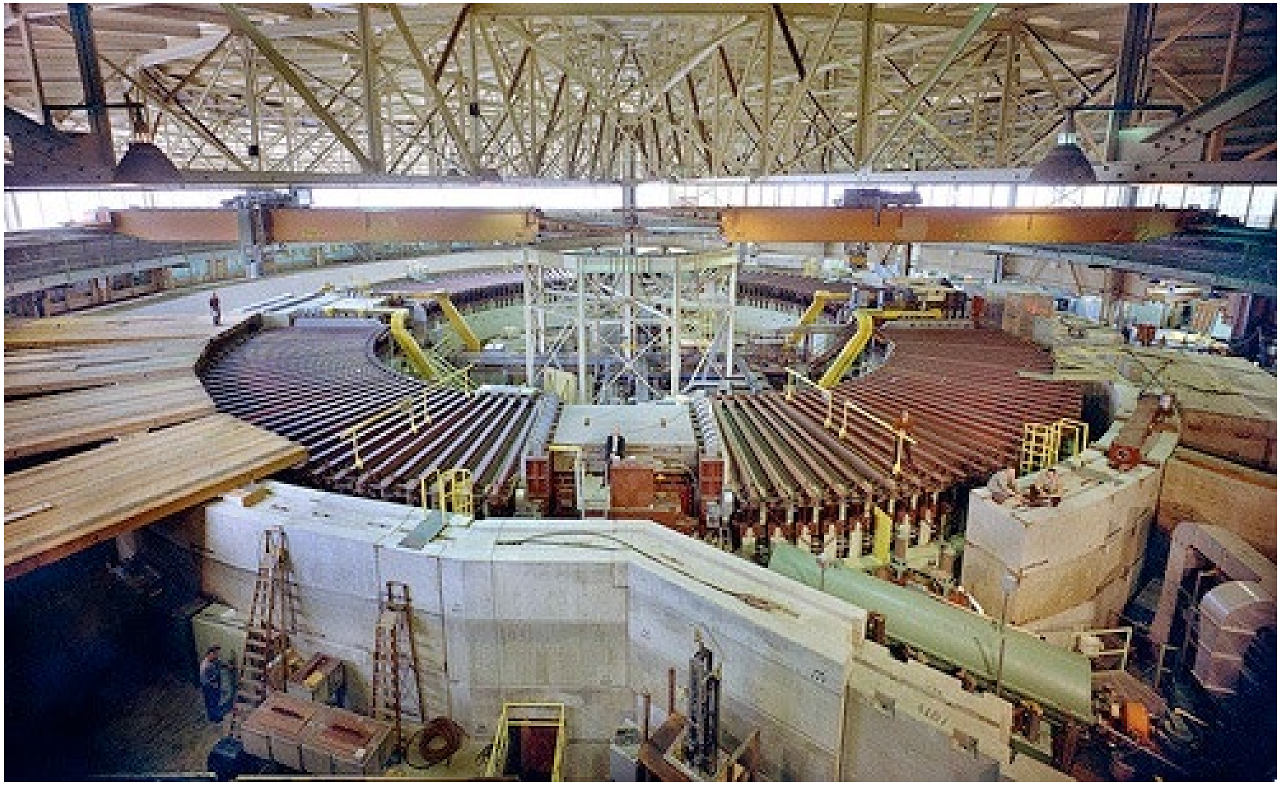
Session IV. Chairman: J.P. Schiffer



Session V. Chairman: H.G. Blosser

# It Began at the Bevalac

- ~1972-1984
- First machine capable of accelerating ~all nuclei to "relativistic" energies
  - Beam (kinetic) energies of 1.5-2.1 GeV per nucleon

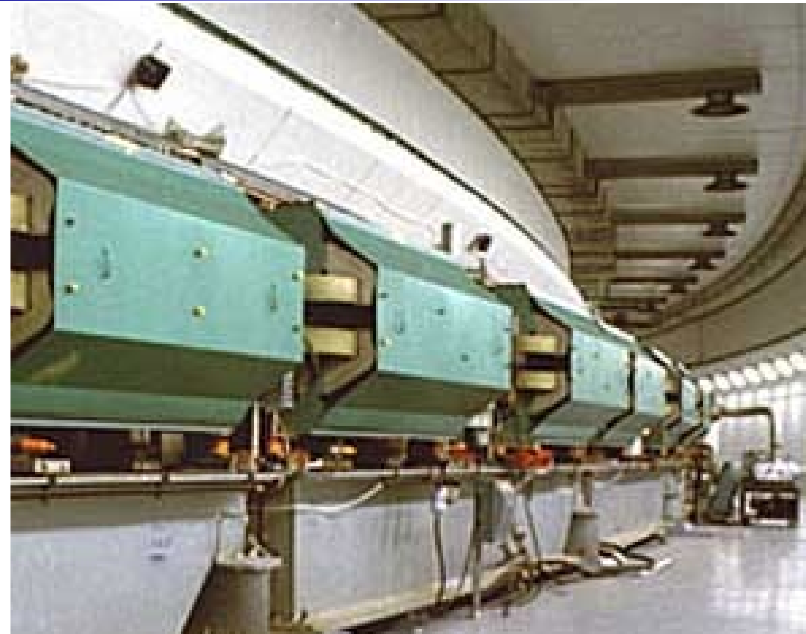


# Bevalac Physics

- Achievements:
  - Established basic terminology
  - Development of “new” techniques
    - Crude flow measures
    - “Hanbury Brown  Twiss” (HBT) interferometry
    - Hadrochemisty
- Review: *Relativistic Nucleus-Nucleus Collisions: from the BEVALAC to RHIC*, R. Stock, nucl-ex/0405007
- Liabilities
  - “Parasitic” program
  - Absence of underlying theory

# It Continued at the AGS and SPS

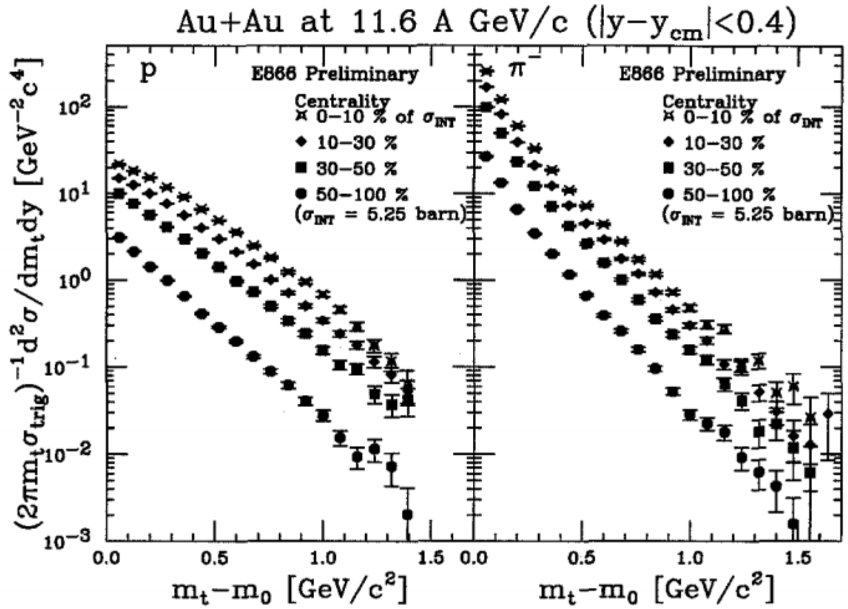
- Fixed-target programs
- AGS
  - Au beams up to 11.6 GeV/N ( aka 11.6 A·GeV )
- SPS
  - Pb beams up to 158 GeV/N ( aka 158 A·GeV )



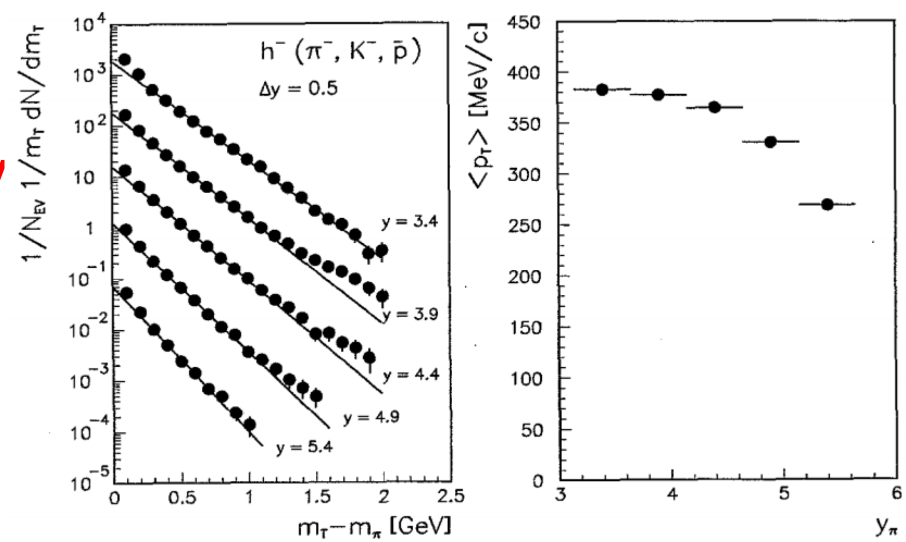


# AGS + SPS Program

- Extensive "spectral" measurements
- Described by "blast-wave" parameterizations
- Development of
  - HBT technology
  - Elliptic flow methodology
- Observation of "anomalous" J/ψ suppression (SPS)

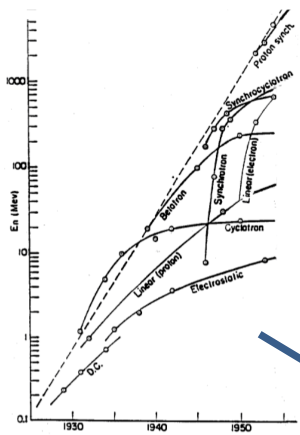


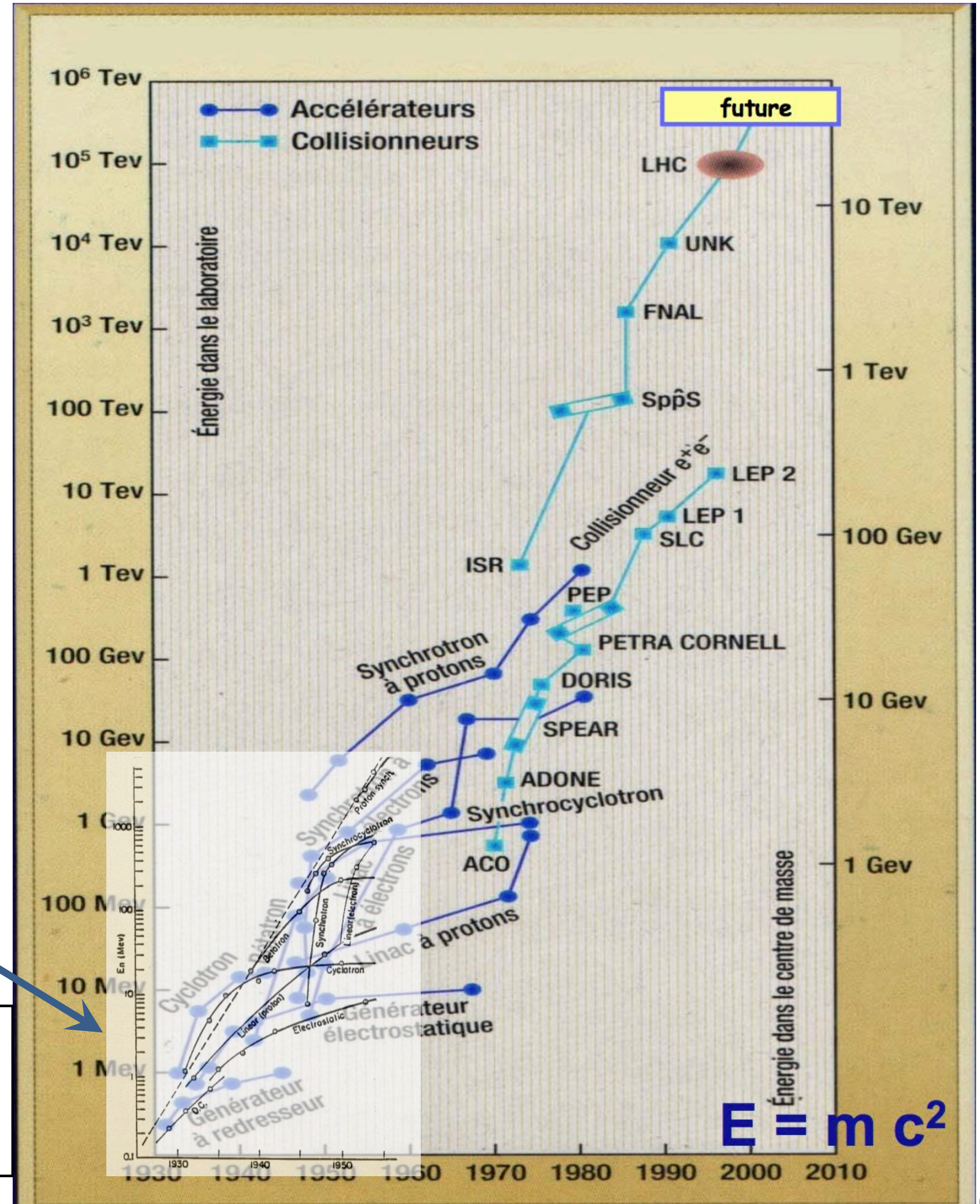

Pb+Pb, NA49 Preliminary



# HEP Livingston Plots

- M.S. Livingston c. 1960 (pre-Moore's Law) noted exponential growth of accelerator energies:




High Power Accelerators for Very Intense Neutron Sources, S. Barbanotti and C. Pagani, presented at the International Workshop on Accelerator based on Neutron Sources for Medical, Industrial and Scientific Applications in Torino, May 23, 2008

# HEP Livingston Plots Meet Reality



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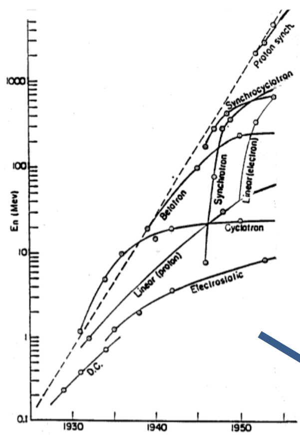


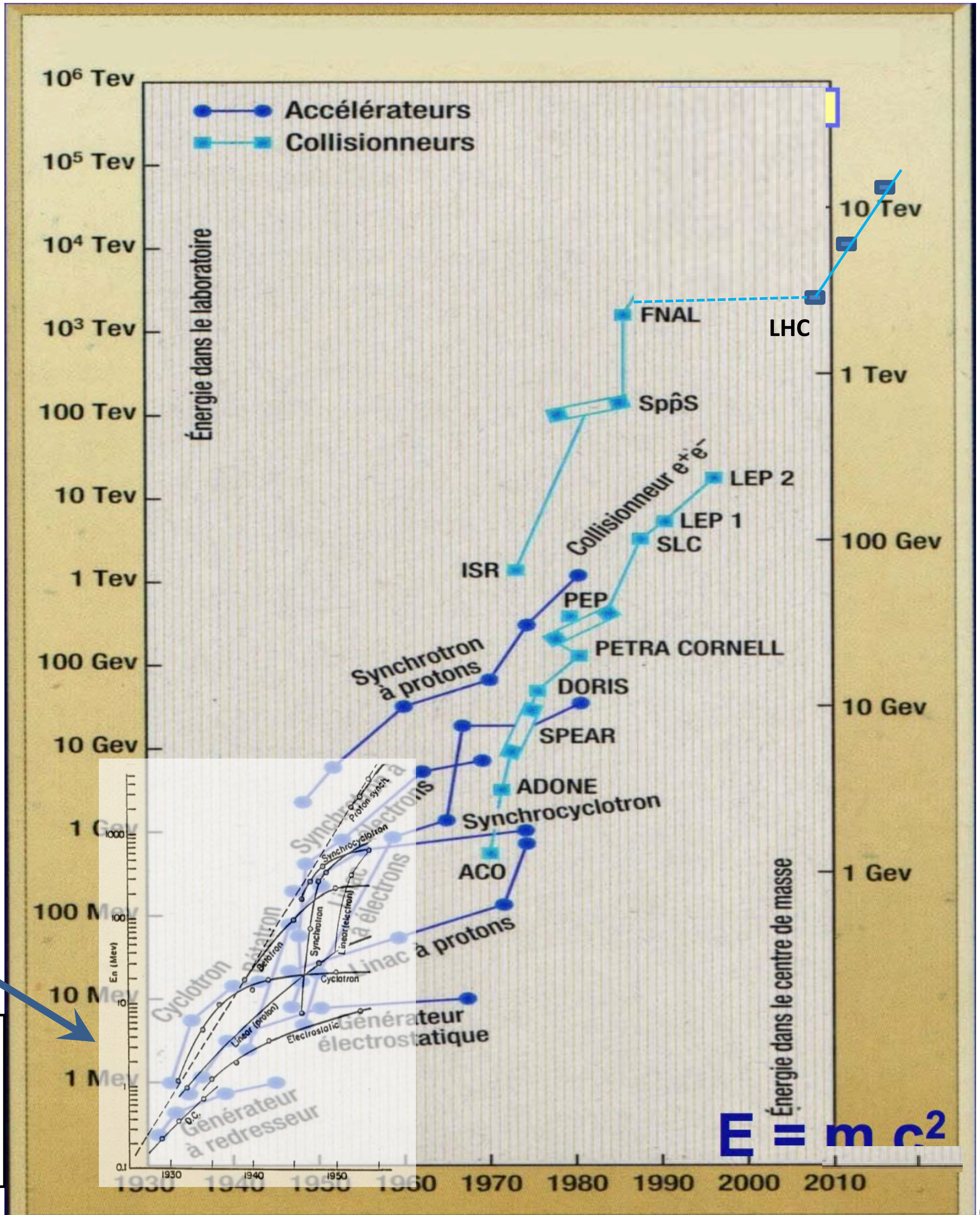


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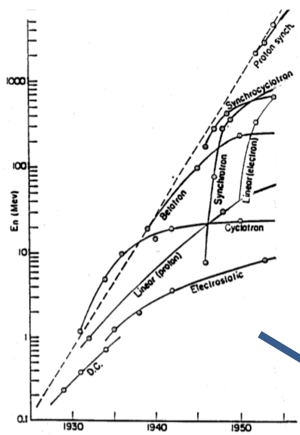


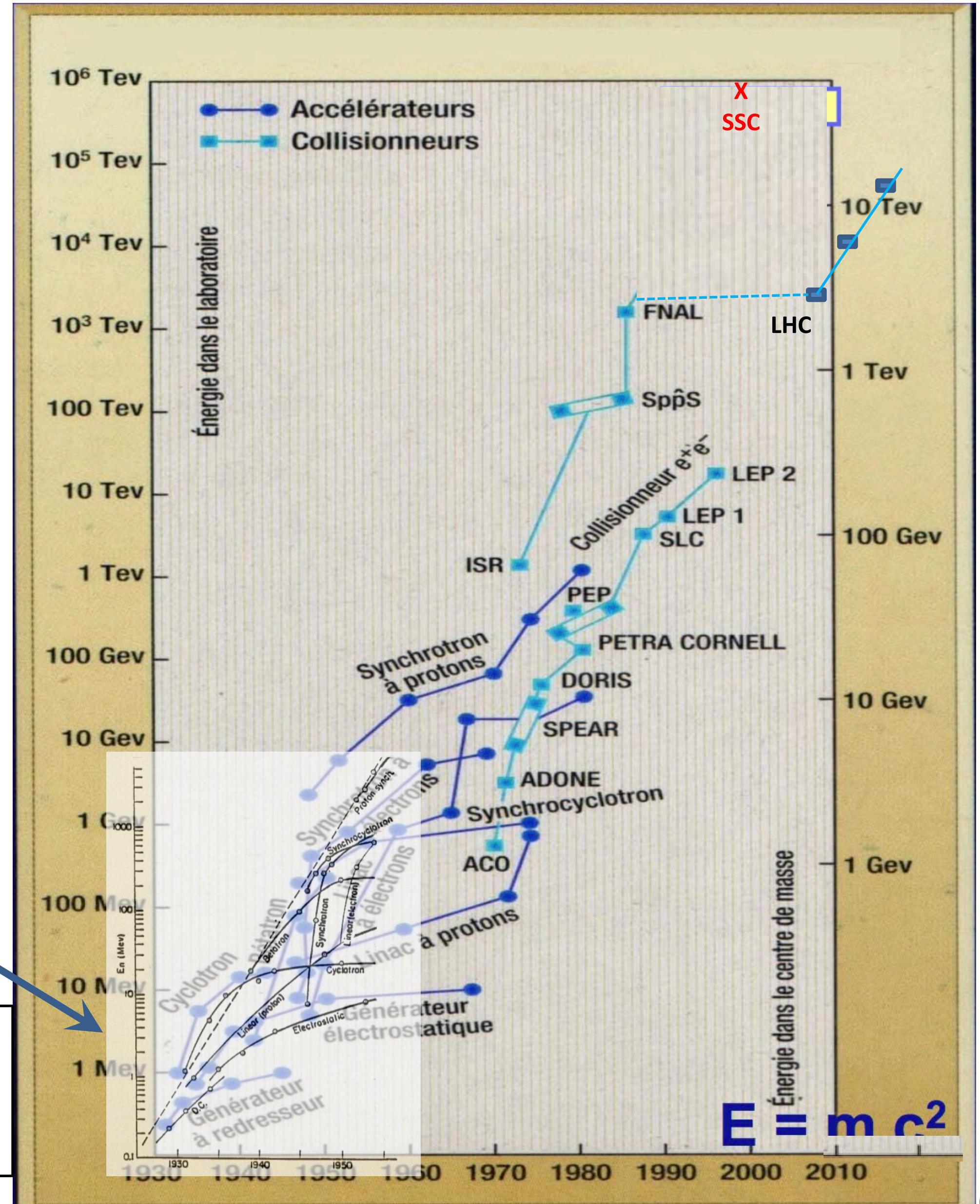


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# RHI Livingston Plot

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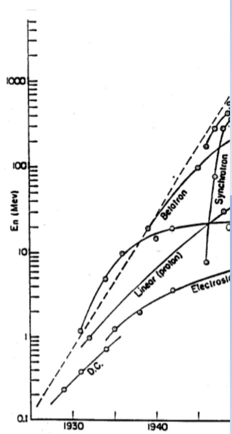
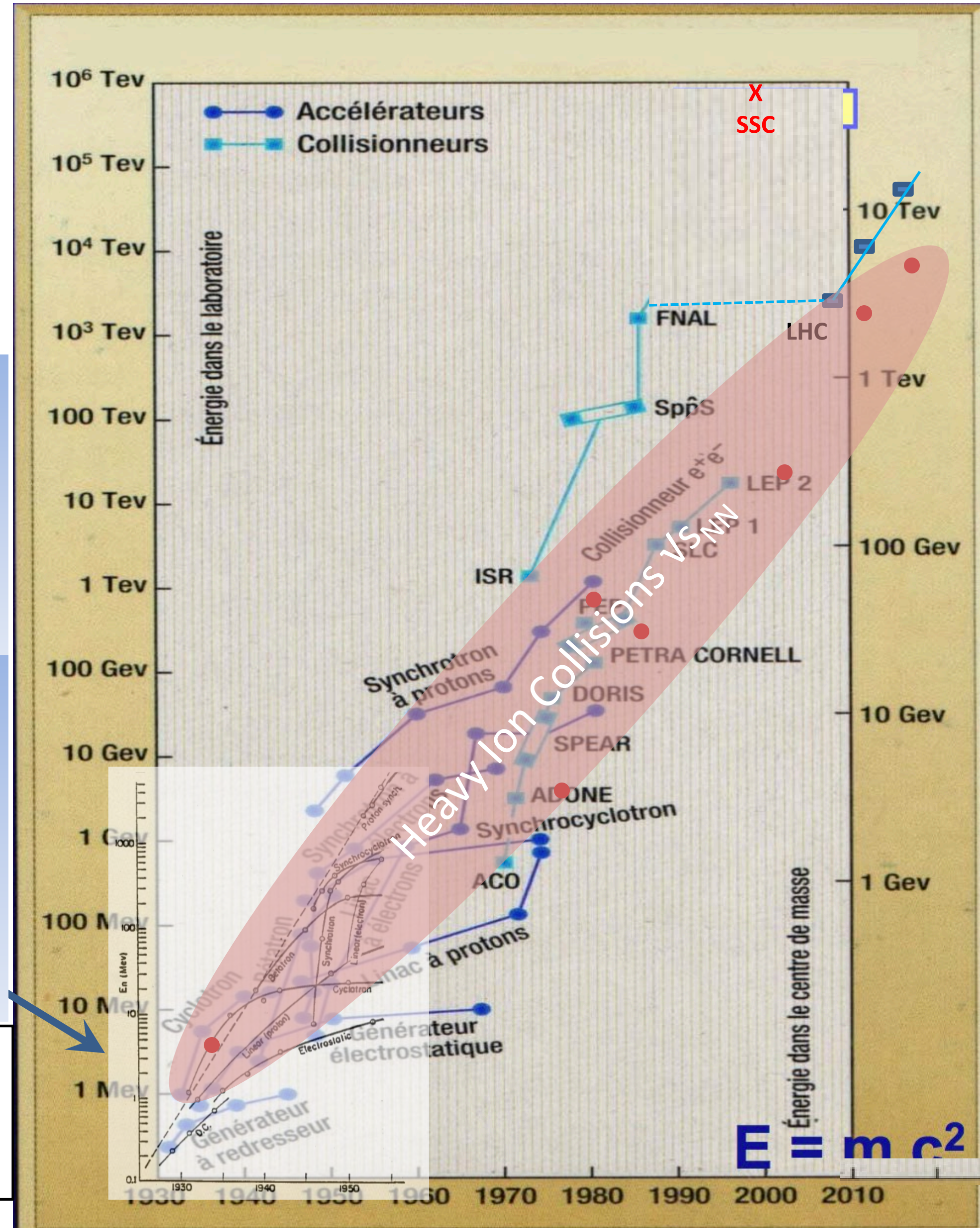



Exercise 2:
Make sure you can "effortlessly" convert between two vertical scales

Exercise 3:
Make sure you understand why heavy ion "line" is displaced from HEP line.

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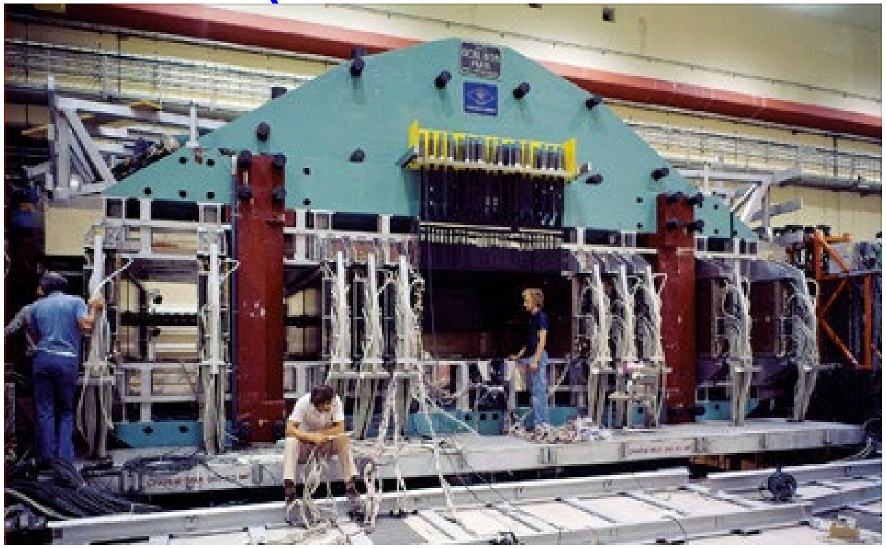
# The CERN ISR

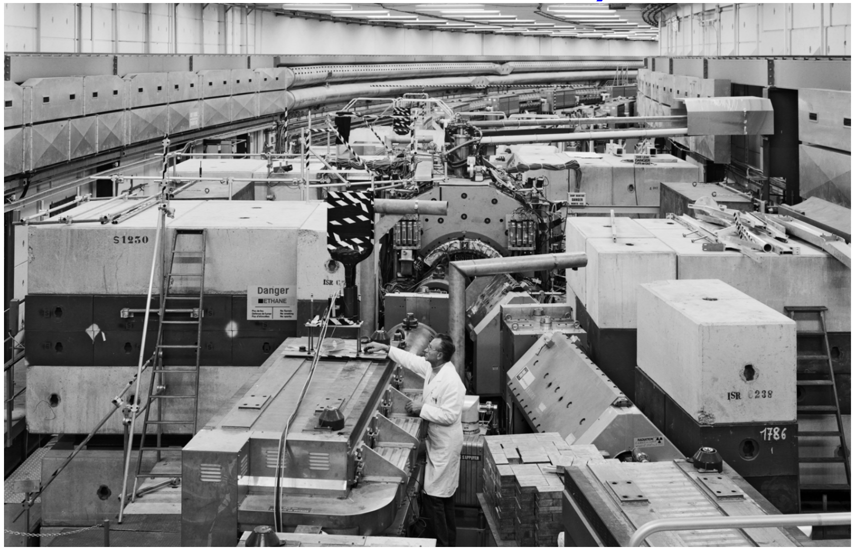
- The world's first *light* ion collider

# The CERN ISR



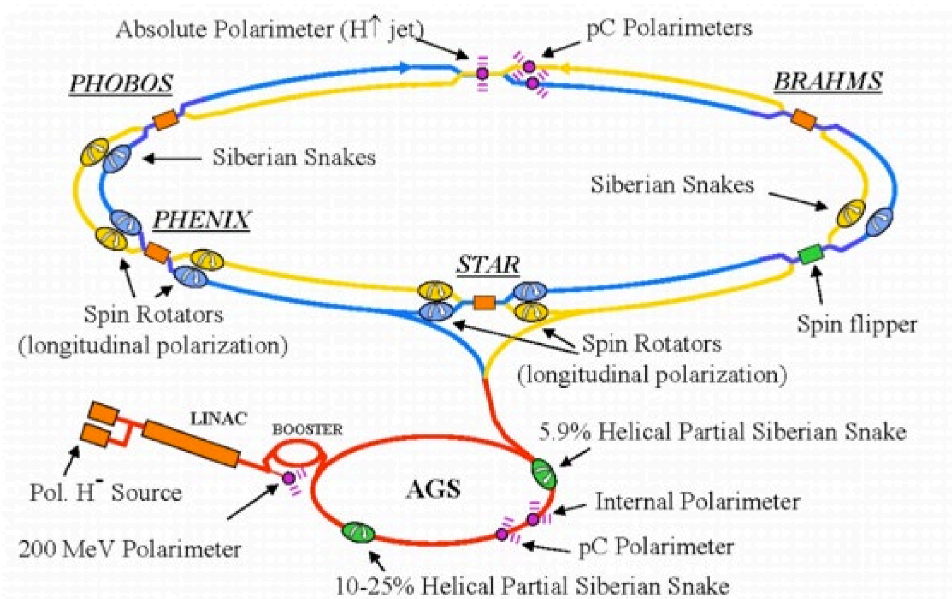
- The world's first *light* ion collider
  (and first hadron collider detectors)



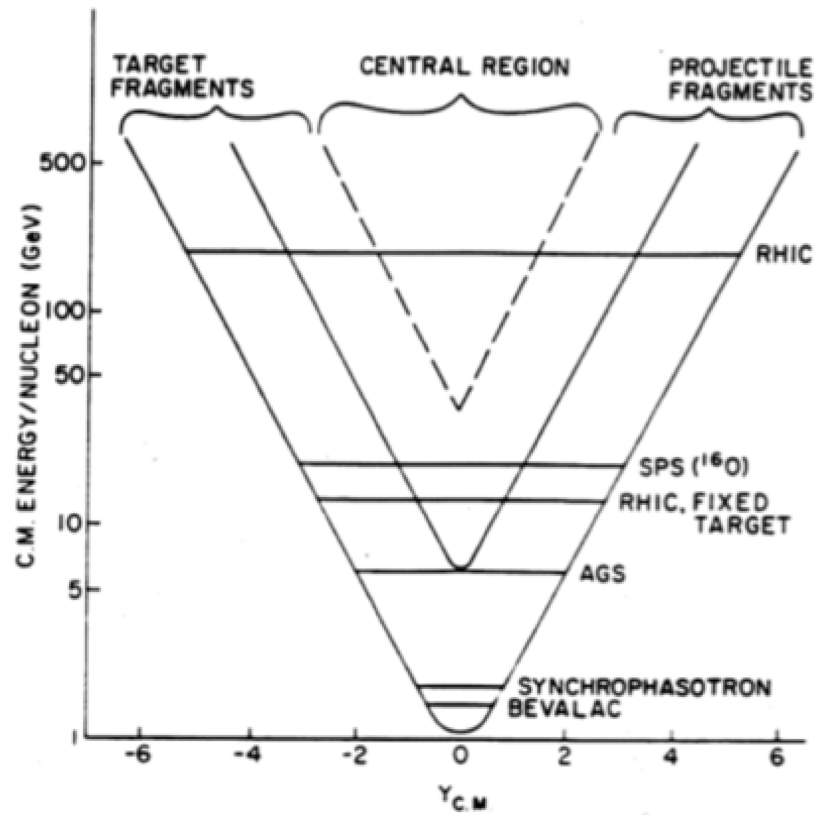



# RHIC Changed Everything

- The world's first *purpose-built heavy* ion collider




Exercise 4:
Map CM energies to indicated rapidity ranges.



# Purpose-Built for What?

## Physics goals of RHIC

- Achieve highest energy densities in extended matter for relatively long times
- Learn the dynamics of high density matter: energy deposition, stopping, formation of excitations, onset of equilibration, hadronization, freezeout
- Search for collective effects beyond individual pp scattering, or pA scattering
- Study role of new degrees of freedom
- Produce and study quark-gluon plasma with large A at E above a few GeV/fm$^3$
- Extract nuclear equation of state, application to astrophysics

G. Baym, 1/95

What are the properties of matter at extremely high energy, or baryon, density? From nuclear matter scales ($\rho_0$=0.16/fm$^3$, $E_0$=0.15GeV/fm$^3$) to orders of magnitude beyond?

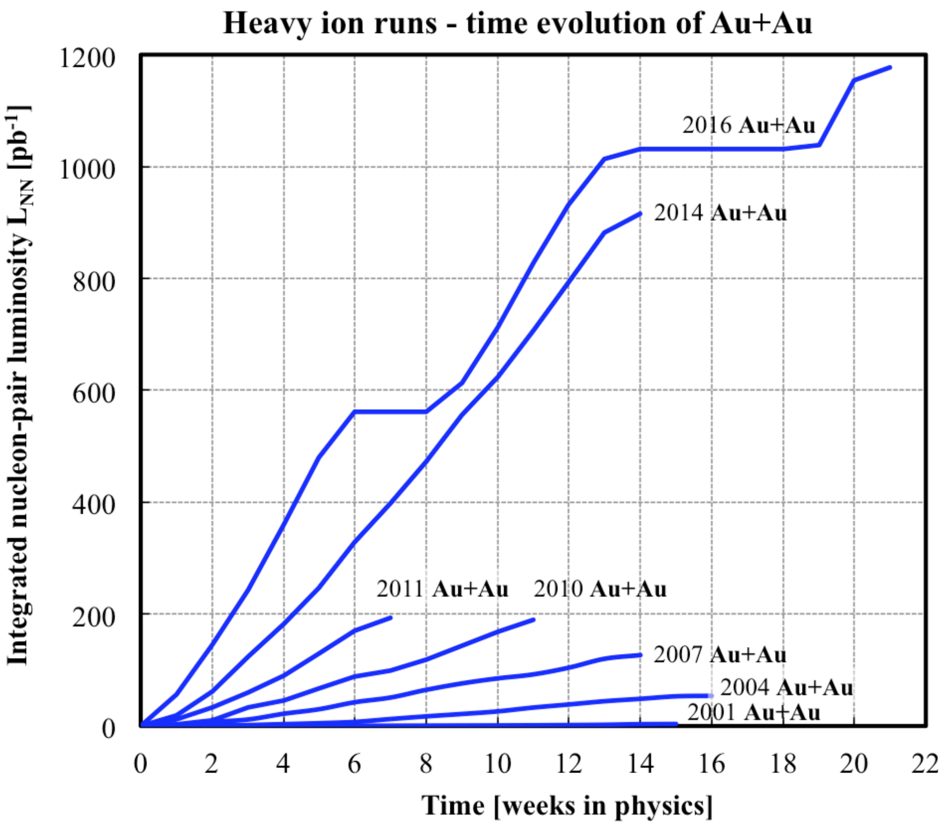
- What are its effective degrees of freedom? From nucleonic to hadronic to quark-gluon.
- What are the states of matter? Recognizable quark-gluon plasma? Strangelets? ...?
- What is the structure of qcd on large distance scales? Phase transitions? Monopoles?
- Surprises!

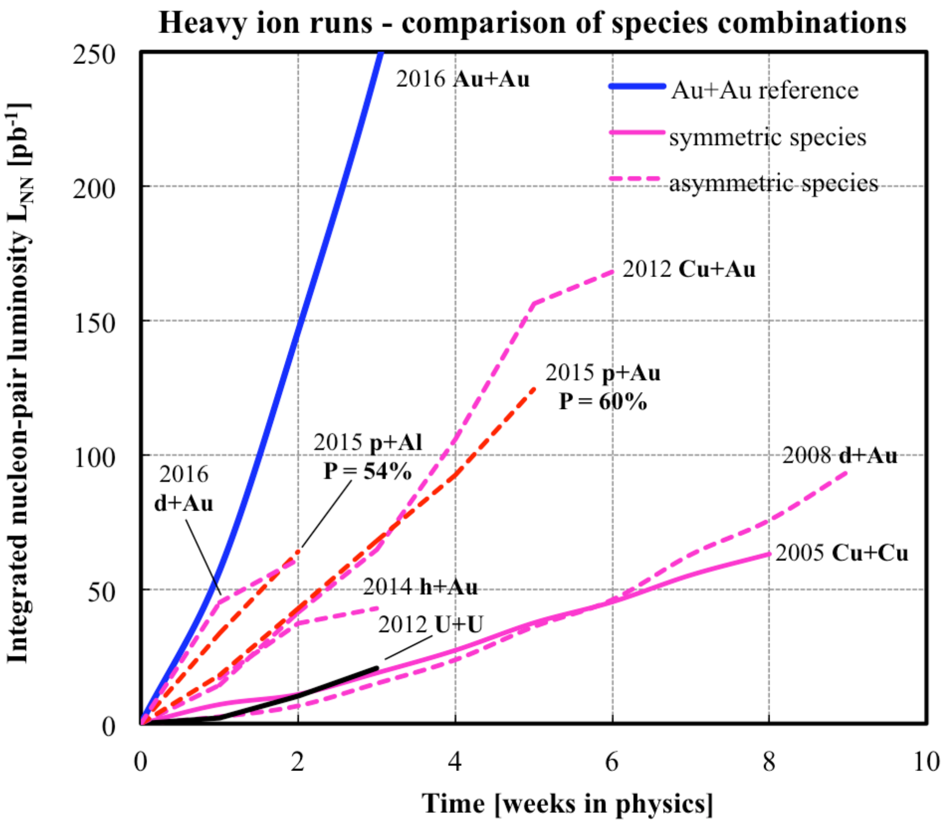
*Terra incognita*

G. Baym, 1/95

# RHIC

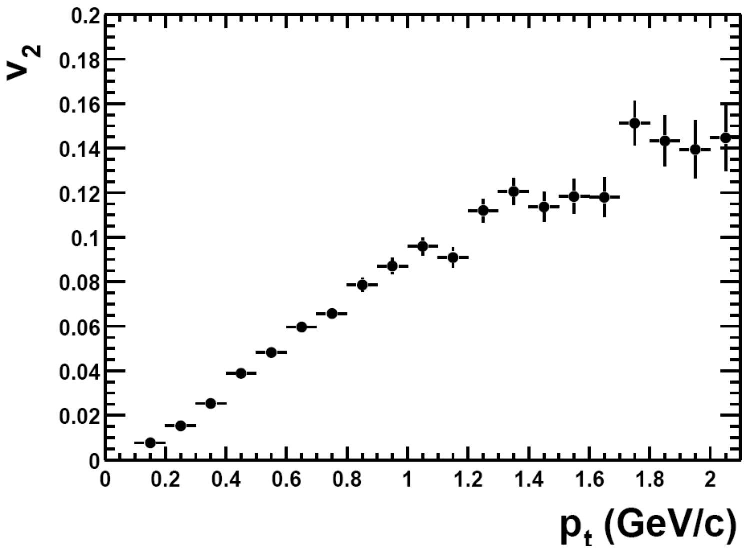
- The world's first *purpose-built* heavy ion collider
  - Has demonstrated its enormous flexibility
  - Has enabled a decade+ of fundamental discoveries



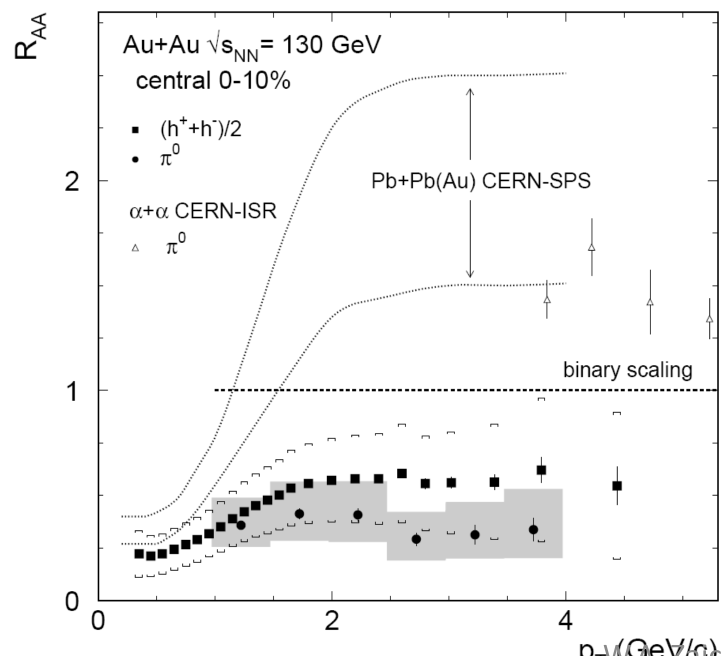



# RHIC's First Two Major Discoveries

- Discovery of strong "elliptic" flow:
  - Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}}$= 130 GeV, STAR Collaboration, Phys.Rev.Lett.86:402-407,2001
  - *654 citations*



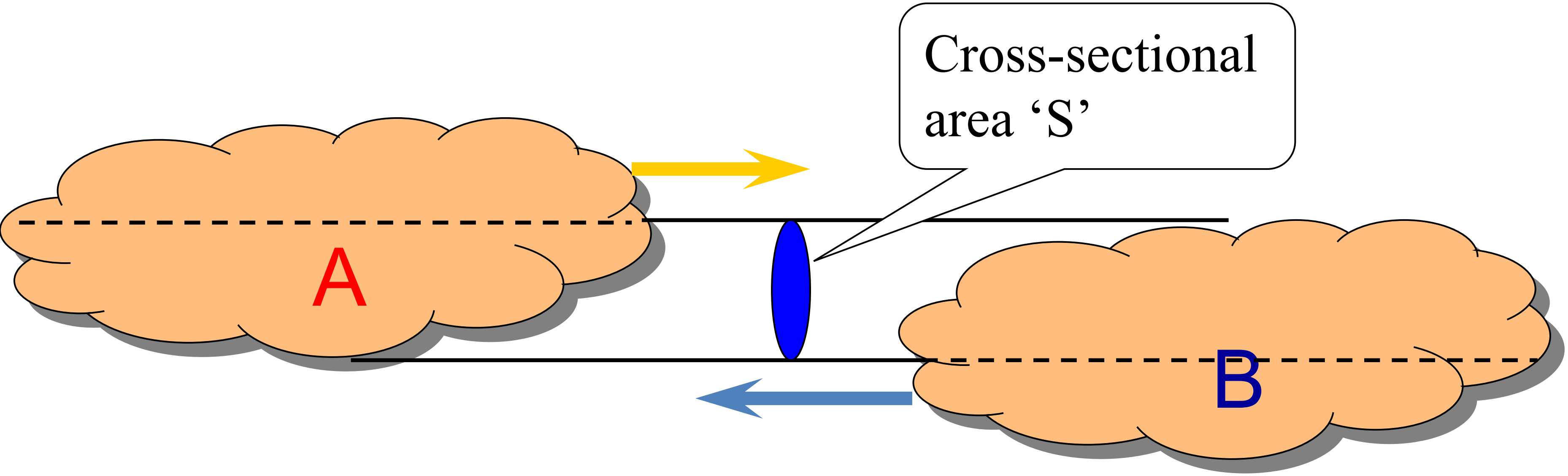

- Discovery of "jet quenching"
  - Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, PHENIX Collaboration, Phys.Rev.Lett.88:022301,2002
  - *967 citations*



# Luminosity



- Consider collision of ‘A’ ions per bunch
  with ‘B’ ions per bunch:

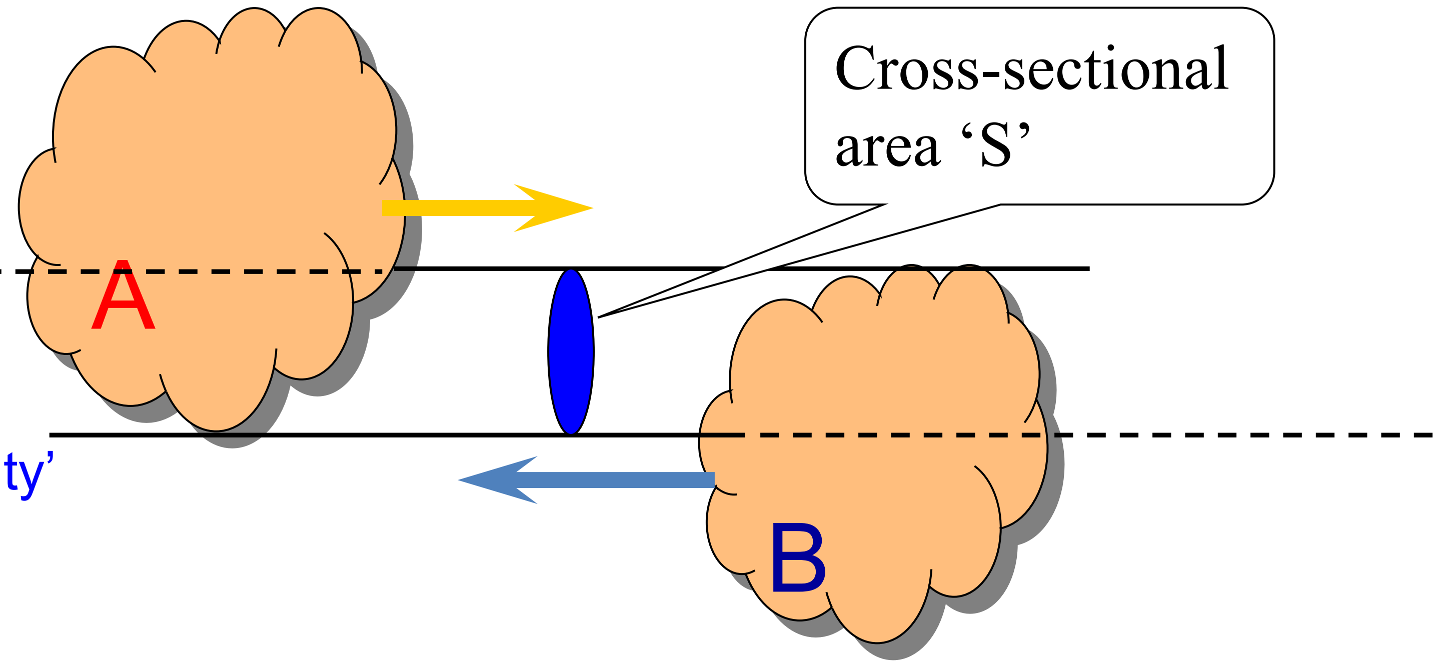



$$L \sim \frac{A \cdot B}{S}$$

# Change scale by ~ $10^9$



- Consider collision of 'A' nucleons per nucleus
  with 'B' nucleons per nucleus:




- 'Luminosity'

$$L \sim \frac{A \cdot B}{S} \sim N_{Coll} \propto A \cdot B$$

$$not \quad N_{Part} \propto A + B$$

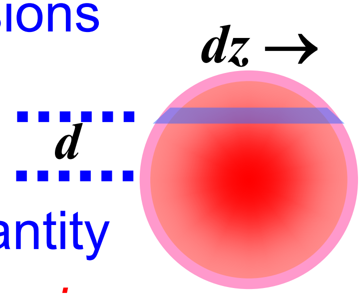
*Provided:*

No shadowing
□Small
cross-sections



# Rare Processes

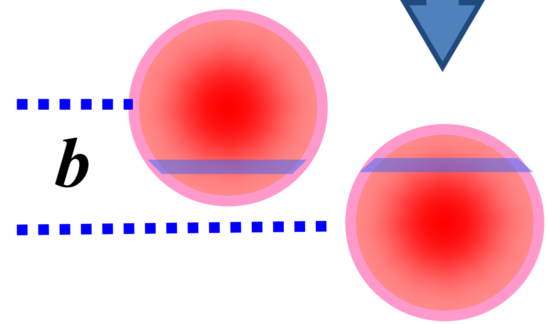
- Particle production via *rare processes* should scale with $N_{coll}$, the number of underlying binary nucleon-nucleon collisions




$$T_A(d) = \int \rho(d, z)\, dz$$

**Thickness Function**

- Roughly: Small $\sigma$  no shadowing
   *per nucleon* luminosity is relevant quantity
- Take scaling with $N_{coll}$ as our *null hypothesis* for hard processes




$$T_{AB}(b) = \int T_A(\vec{s} + \frac{\vec{b}}{2}) T_B(\vec{s} - \frac{\vec{b}}{2})\, d\vec{s}$$

**Overlap Function**

**If Nucleus "A" has A constituents**
**and Nucleus "B" has B constituents**
**which interact with cross section $\sigma_{\mathrm{INT}}$**
**the TOTAL cross section $\sigma_{\mathrm{AB}}$ is then**

$$\sigma_{\mathrm{AB}} = \int d^2b \left[1 - e^{-\sigma_{INT} T_{AB}(b)}\right]$$

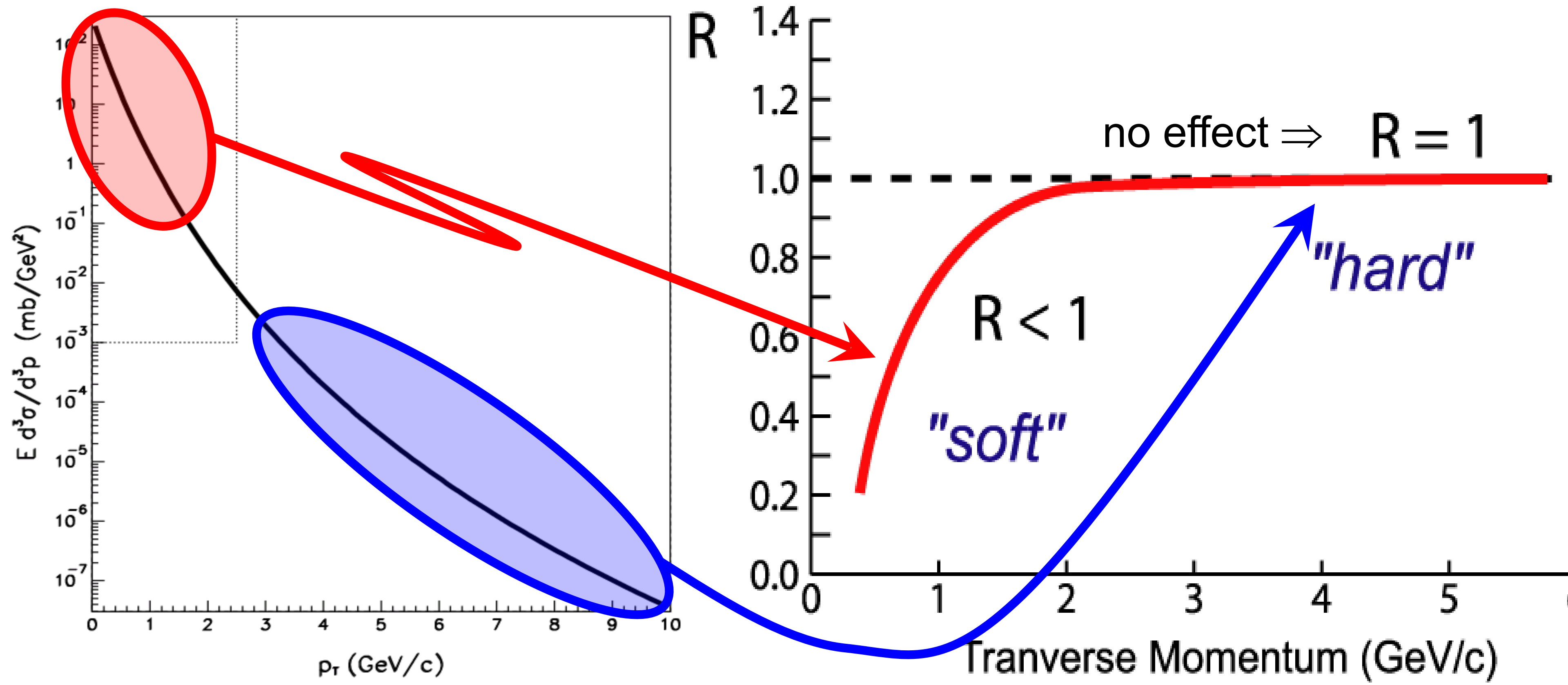
$$\rightarrow \approx A \cdot B \times \sigma_{\mathrm{INT}} \text{ for "small" } \sigma_{\mathrm{INT}}$$

Exercise 5: Show this.

# Systematizing Our Expectations

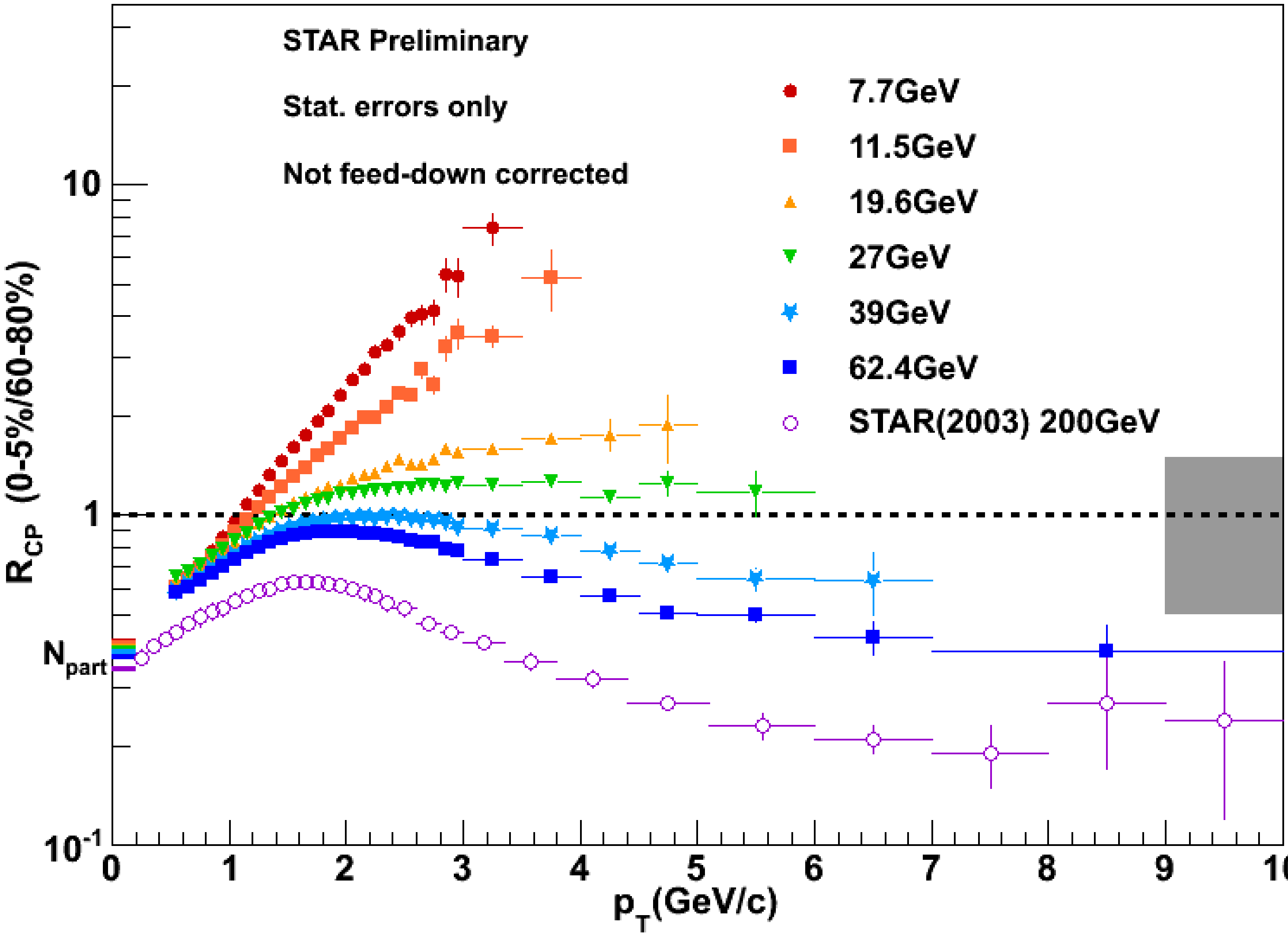
Describe in terms of *scaled ratio* $R_{AA}$ $\equiv \dfrac{\text{Yield in Au + Au Events}}{(A \bullet B)(\text{Yield in p + p Events})}$

= 1 for "baseline expectations"
> 1 "Cronin" enhancements (as in proton-nucleus)
< 1 (at high $p_T$) "anomalous" suppression



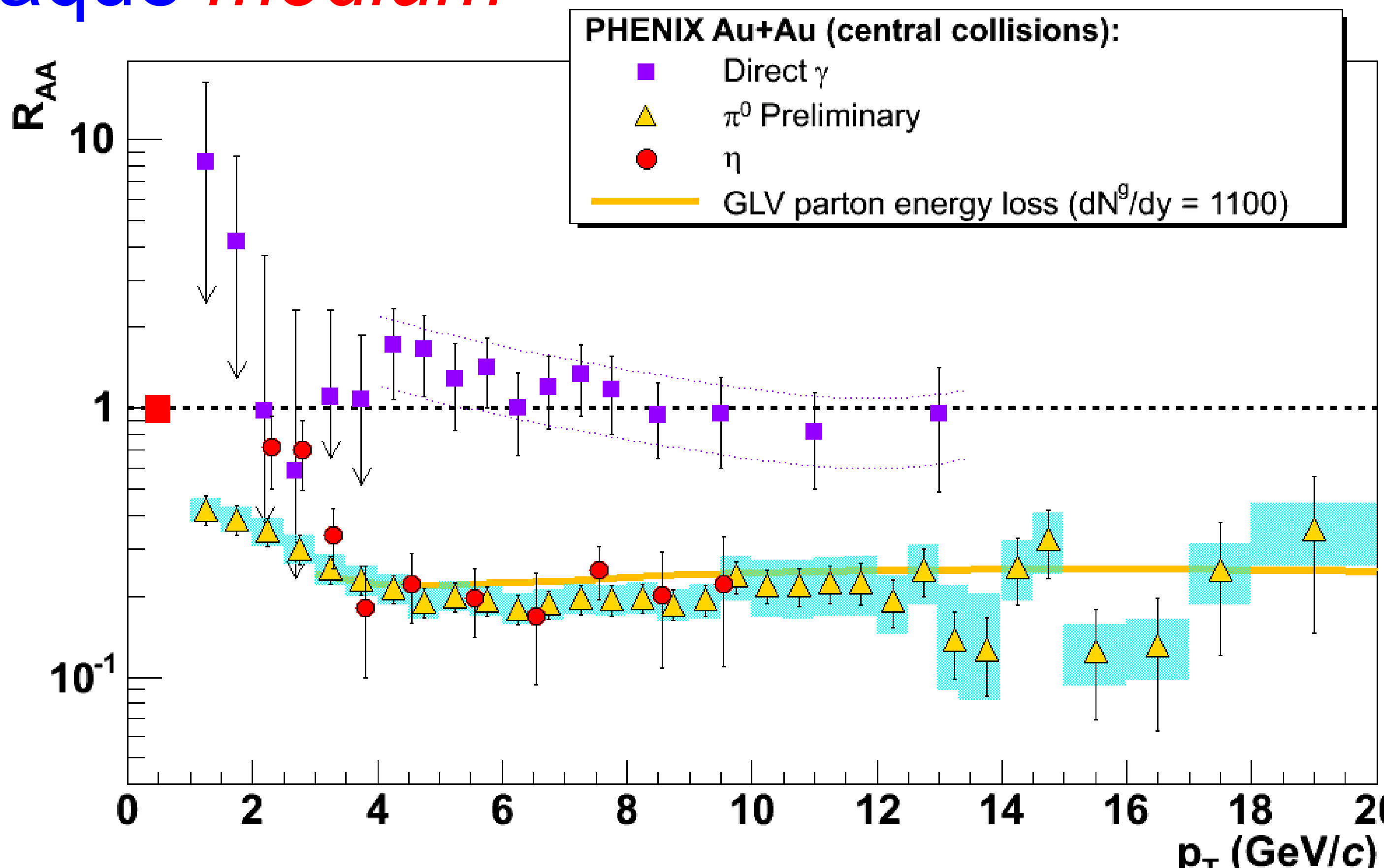
# Consistency Checks

- Suppression effect not present at lower √s ’s



# Consistency Checks

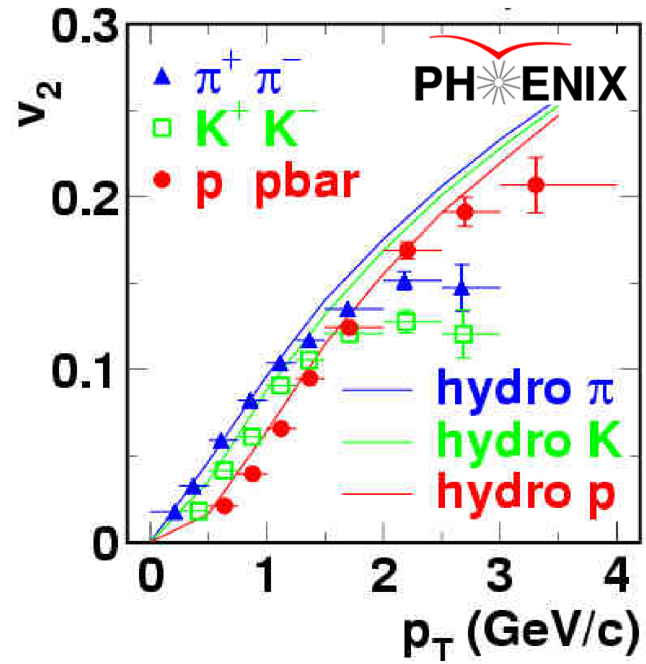
⇒Perturbative primordial yields in Au+Au collisions *absorbed* in *strongly*-coupled dense, opaque *medium*



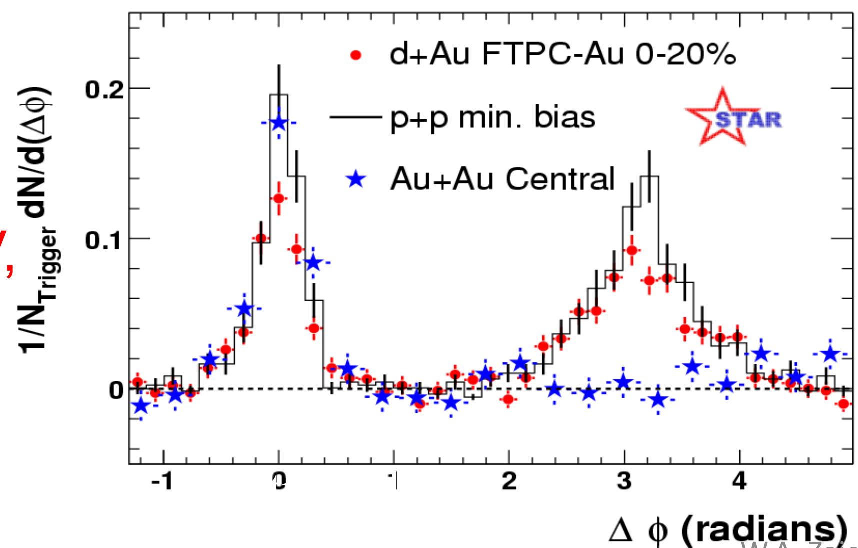
# Extending Those Major Discoveries

- "Fine structure" in elliptic flow:
  - Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV, PHENIX Collaboration, Phys.Rev.Lett.91:182301,2003
  - *711 citations*

Hydro from P. Huovinen et al., Phys. Lett. **B503**, 58 (2001)




- Disappearance of away-side "jet"
  - Disappearance of back-to-back high $p_T$ correlations in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, STAR Collaboration, Phys.Rev.Lett.90:082302,2003
  - *742 citations*



# Critical *in situ* Control Measurement

- 2000 – first collisions
- 2001 – major results from all 4 collaborations
- 2002 – first full-energy Au+Au run
- 2003 – d+Au control run

Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174 PRINT

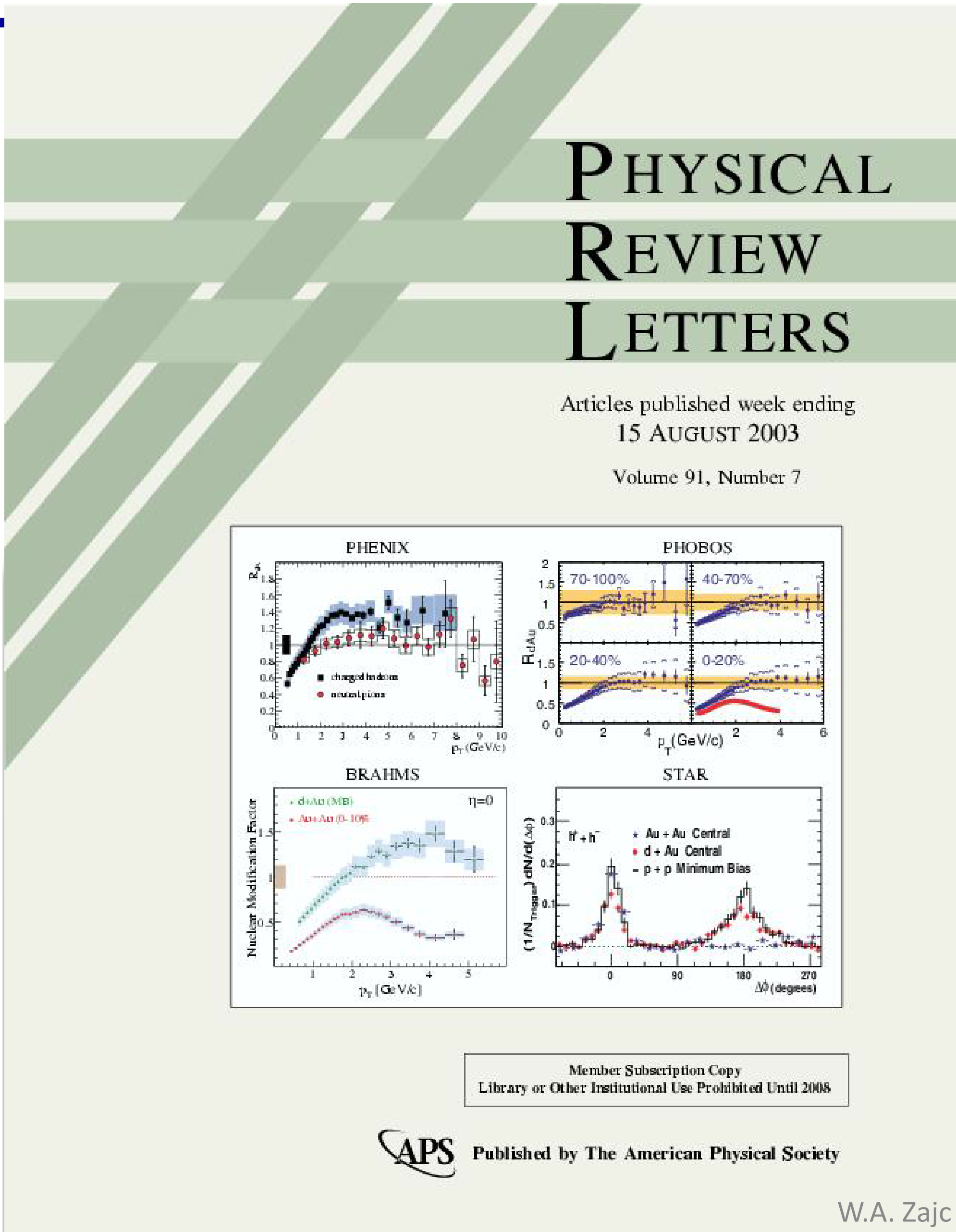
## Exciting First Results from Deuteron-Gold Collisions at Brookhaven

### Findings intensify search for new form of matter

June 11, 2003

UPTON, NY — The latest results from the Relativistic Heavy Ion Collider (RHIC), the world's most powerful facility for nuclear physics research, strengthen scientists' confidence that RHIC collisions of gold ions have created unusual conditions and that they are on the right path to discover a form of matter called the quark-gluon plasma, believed to have existed in the first microseconds after the birth of the universe. The results will be presented at a special colloquium at the U.S. Department of Energy's Brookhaven National Laboratory on June 18 at 11 a.m., to coincide with the submission of scientific papers on the results to Physical Review Letters by three of RHIC's international collaborations.

The scientists are not yet ready to claim the discovery of the quark-gluon plasma, however. That must await corroborating experiments, now under way at RHIC, that seek other signatures of quark-gluon plasma and explore alternative ideas for the kind of matter produced in these violent collisions.



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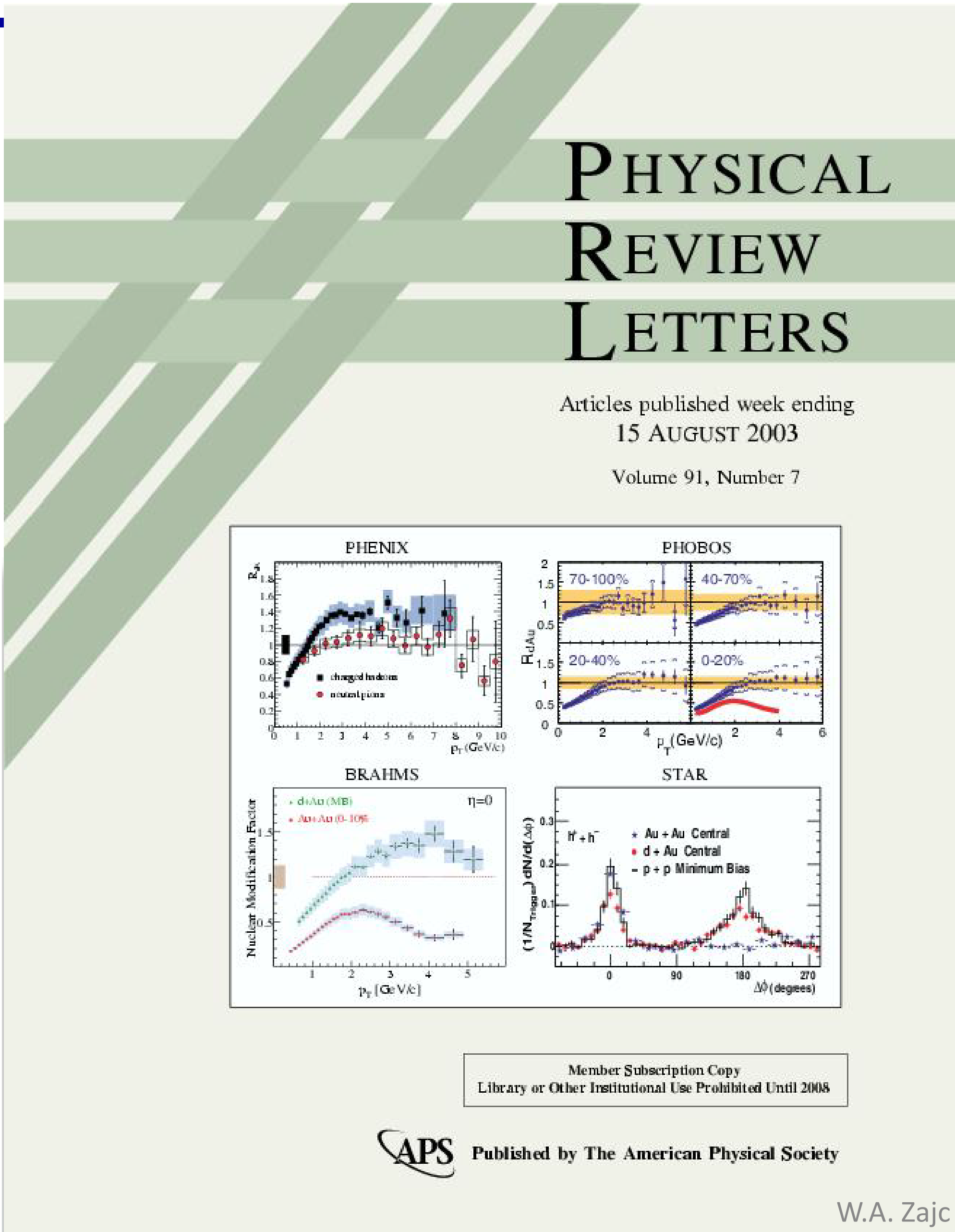

# Theoretical Guidance



- 1983: "an extended ***quark-gluon plasma*** within which the quarks are deconfined and move independently"

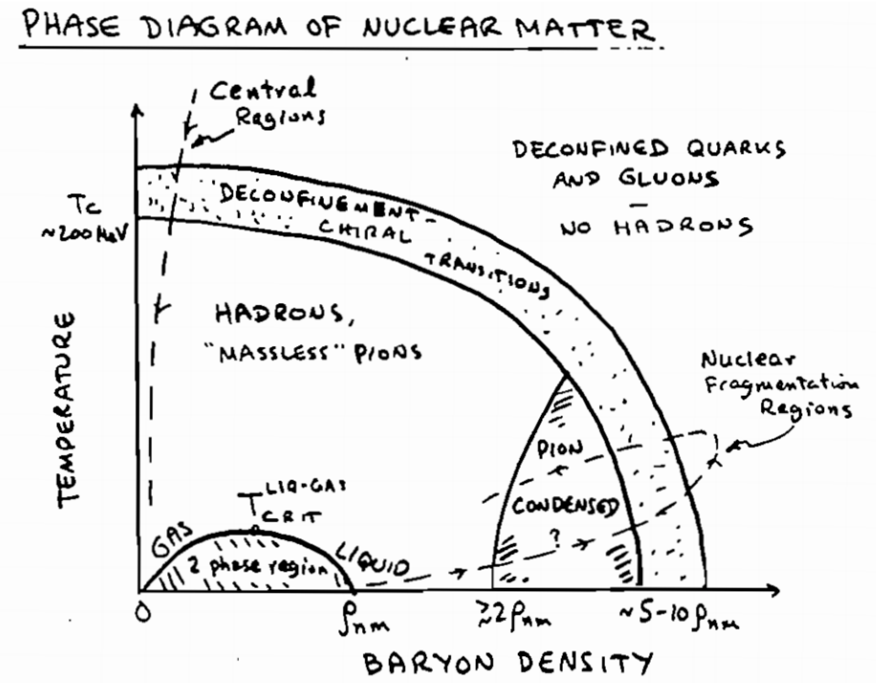


Fig. II.9-A. Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase" including a gas-liquid phase transition region, and *the transition region to deconfined quarks and gluons. The dashed* lines illustrate trajectories in this phase diagram that can be explored in ultra-relativistic heavy ion collisions.

# Theoretical Guidance

- 1983: “an extended ***quark-gluon plasma*** within which the quarks are deconfined and move independently”

- 1989: “quark-gluon plasma, in which hadrons dissolve into a plasma of quarks and gluons, which are then free to move over a large volume.”

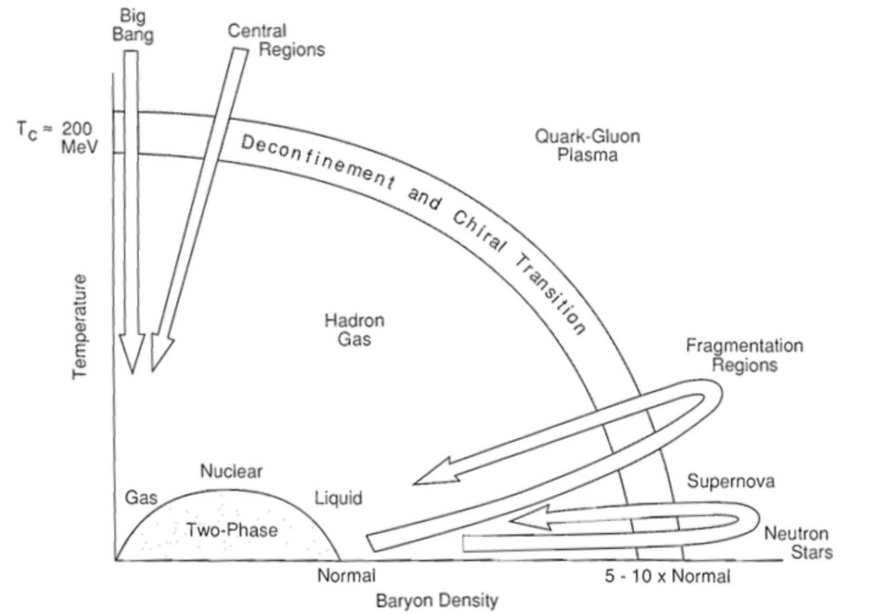


Figure 24: Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the “hadronic phase,” including a gas-liquid phase-transition region, and the transition region to deconfined quarks and gluons. The dashed lines illustrate trajectories in this phase diagram that can be explored in ultrarelativistic heavy-ion collisions.

# Theoretical Guidance

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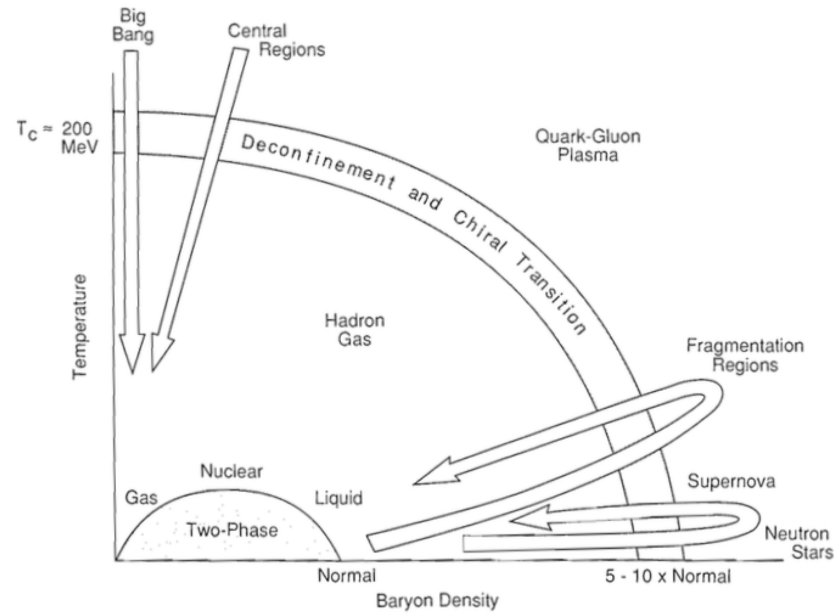


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- 1989: "quark-gluon plasma, in which hadrons dissolve into a plasma of quarks and gluons, which are then free to move over a large volume."
- 2000: "Quarks and gluons would then freely roam within the volume of the fireball created by the collision."

# The (Famous) RHIC "White Papers"



- *Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment*, Nucl.Phys. **A757** (2005) 1-27, nucl-ex/0410020
- *Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration*, Nucl.Phys. **A757** (2005) 184-283, nucl-ex/0410003
- *The PHOBOS perspective on discoveries at RHIC*, Nucl.Phys. **A757** (2005) 28-101, nucl-ex/0410022
- *Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions*, Nucl.Phys. **A757** (2005) 102-183, nucl-ex/0501009

# Addressing the nature of QGP discovery

- From the PHENIX "White Paper"
- [nucl-ex/0410003]()
- (2363 citations)

Q: What is the most relevant "experimentally observed property"?

A. Viscosity (suitably normalized)

so that concepts such as temperature, chemical potential and flow velocity apply and the system can be characterized by an experimentally determined equation of state. Additionally, experiments eventually should be able to determine the physical characteristics of the transition, for example the critical temperature, the order of the phase transition, and the speed of sound along with the nature of the underlying quasi-particles. While at (currently unobtainable) very high temperatures $T \gg T_c$ the quark-gluon plasma may act as a weakly interacting gas of quarks and gluons, in the transition region near $T_c$ the fundamental degrees of freedom may be considerably more complex. It is therefore appropriate to argue that the quark-gluon plasma must be defined in terms of its unique properties *at a given temperature*. To date the definition is provided by lattice QCD calculations. Ultimately we would expect to validate this by characterizing the quark-gluon plasma in terms of its experimentally observed properties. However, the real discoveries will be of the fascinating properties of high temperature nuclear matter, and not the naming of that matter.

### *1.2 Experimental Program*

The theoretical discussion of the nature of hadronic matter at extreme densities has been greatly stimulated by the realization that such conditions could be studied via relativistic heavy ion collisions [32]. Early investigations at the Berkeley Bevalac (c. 1975–1985), the BNL AGS (c. 1987–1995) and the CERN SPS (c. 1987–present) have reached their culmination with the commissioning of BNL's Relativistic Heavy Ion Collider (RHIC), a dedicated facility for the study of nuclear collisions at ultra-relativistic energies [33].

# Viscosity – “Suitably Normalized”?

- First, this is the *shear* viscosity η

- It is a dimensionful quantity: $\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$

- The ratio η/*s* , where *s* is entropy density, has units of $\hbar / k_B$

  Exercise 6: Show this.

  $\Rightarrow$ Dimensionless in natural units $\hbar = c = k_B = 1$

- It may satisfy a fundamental bound $\frac{\eta}{s} \geq \frac{1}{4\pi}$

(re)-discovered using black holes in 5-d space-time (!)