CU Physics Department Colloquium

Monday, September 12, 2011 4:10 PM 428 Pupin Hall

Discovery of the Ω1-: 1964

Parity, Neutrinos, Heavy Ions, RBRC: T.D. Lee and Me

In 1964 the BBC made a video of the discovery of Ω1- . This included interviews with Richard Feynman, Murray Gell-Mann, and myself. An edited version (27 minutes) will be shown. I will then briefly comment on this video. As noted in the title of my talk, I will then proceed to discuss several exciting areas of Physics that T.D. Lee and I had the pleasure of actively participating in and contributing to from 1955 to the present. These include parity violations in weak interactions, use of high energy neutrinos as a probe of weak interactions, the utilization of relativistic heavy ion beams to create a new form of matter sQGP (strongly interacting quark gluon plasma) and the creation of a new center for the study of non-perturbative QCD.

Nicholas Samios, Brookhaven National Laboratory

Hosted by Miklos Gyulassy

Discovery of the Ω^- : 1964

Parity, Neutrinos, Heavy Ions, RBRC: T.D. Lee and Me

Nicholas P. Samios

September 12, 2011

Columbia University

Comments on Video:

CERN Conference – International 1962

Presented evidence for:

Ξ^* (1520)

ϕ (1020)

Gell-Mann

Eightfold Way – SU (3) Ω^-

AGS – 1960

Experimental Detector – 1958-1963

80" Bubble Chamber

Separated K^- beam 5 GeV/c

Strategy – Preponderance of Negative Strangeness

$$Q = I_3 + \frac{S+B}{2}$$

Consequence for Ω^- Proposal:

March 1962	Proposal
	$K^- p$ 3.5-5.0 GeV/c
June 1962	PAC Deferred
Sept. 1963	Proposal – updated to include Ω^- possibility
Oct. 1963	PAC Approved
Feb. 1964	Discovery

Ω^- event not typical $P(2\gamma) \approx 10^{-4}$

Aside

SU(3) → Quarks/Aces 1964

Gell-Mann

Eightfold Way:	Meson Baryons	$\left.\right\}$ 1, 8, 10, $\overline{10}$, 27
Quarks:	Meson Restricted to 1, 8 Baryons Restricted to 1, 8, 10	
Consequence:	Quarks have Fractional Charge as well as Baryon Number	

Zweig

$\phi \rightarrow \frac{\rho\pi}{K\bar{K}} = .35 \pm .20$ expect 3-4

Why such a small value?

Hidden Strangeness (aces)

T.D. Lee and N.P. Samios (1955-Present)

I. Parity

Experimental Group

Steinberger, Leitner, Schwartz, Samios

Search for Strange Particles, there Properties and Decay Modes

$\pi^- p \rightarrow \Lambda^o K^o; \Sigma^- K^+$

*Questions of Parity Conservation and Weak Interactions

Lee and Yang June 1956-October 1956

Measure a Pseudoscalar $\sigma \cdot p$

CO^{60}; μ decay; Λ^o decay

Experiments

Wu et. al.	CO^{60} decay	Jan 1957-Feb 1957
Garwin et. al.	μ^+ decay	Jan 1957-Feb 1957
Friedman et. al.	μ^+ decay	Jan 1957-Feb 1957
Eisler et. al.	Λ^o decay	Oct 1957-Dec 1957

Parity Violated in Weak Inductions

*Opened up a New Field of Research

Aside:

Parity non conservation in Hyeron Decay

$\pi^- p \rightarrow \Lambda^o + K^o$

$\Lambda^o \rightarrow p\pi^-$

$(p_\pi - x\, p_\Lambda) \cdot p_p$

		Asymmetry	Up/Down
Budde et. al.	22 Λ^os Sept. 1956	.55±.43	14/8
Samios (thesis)	41 Λ^os Jan. 1957	.34±.30	24/17
Eisler et. al.	263 Λ^os Dec. 1957	.40±.11	158/105

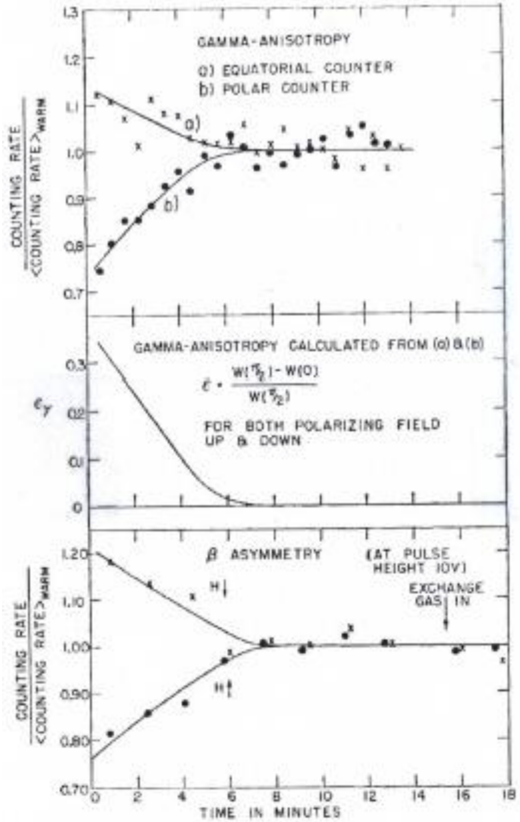


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

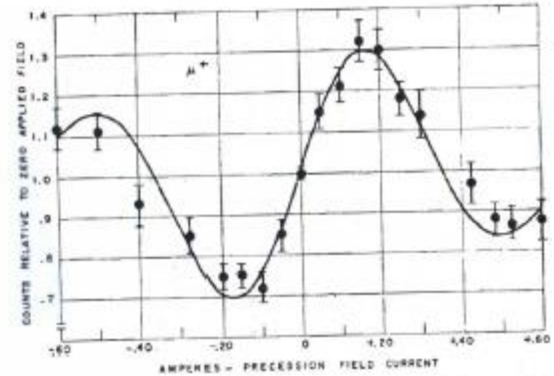


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

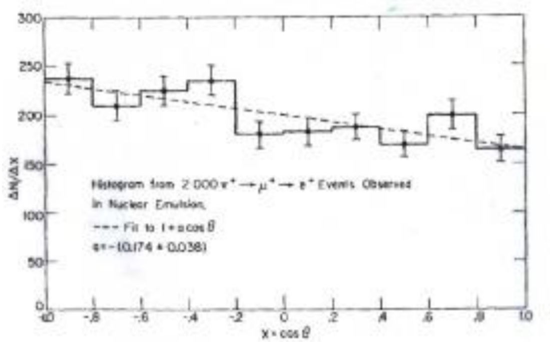


FIG. 1. Histogram from 2000 $\pi^+\to\mu^+\to e^+$ events observed in nuclear emulsion. Dashed curve is least-squares fit to $1+a\cos\theta$; $a=-(0.174\pm0.038)$. Indicated errors are statistical standard deviations.

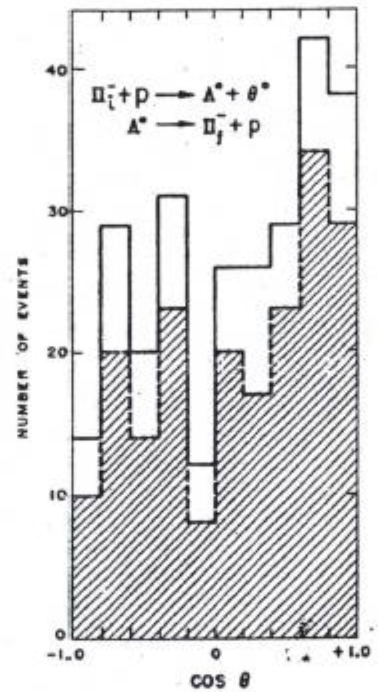


FIG. 1. Distribution in cosθ for process (1). The shaded area represents events for production angles in the center-of-mass

II. Neutrino Physics

*Theoretical Discussion on Feasible High Energy Neutrino Experiments

Lee and Yang Feb 1960-March 1960

a. Identity of neutrino

$$\nu_e = \nu_\mu \,?$$

b. Neutral currents

c. Possible existence of $W^\pm$

Mu - decay

$$G_F \approx \frac{g^2}{M_W^2}$$

1962 – Danby et. al. (Lederman, Schwartz, Steinberger)

$$\nu_\mu \neq \nu_e$$

1973 – Gargamelle $\nu_\mu e \rightarrow \nu_\mu e$ 3 events

Neutral Currents $\nu_\mu N \rightarrow \nu_\mu$ hadrons

*Opened up a whole new area of research

Samios et. al. (Baltay, Palmer…)

ν Program at BNL and Fermilab

7’ B.C. — 15’ B.C.

10,000 liters liquid H_2 — 25,000 liters liquid N_c/H_2

Broad Program – Study of Neutrino Interactions at High Energy

0.5-10 GeV; 5-25 GeV

Cross Sections, Form Factors, Unusual Events…

Electro-weak Symmetry Breaking: Glashow 1961, Weinberg 1967, Salan 1968.

Neutral Currents – Weinberg Angle

$\nu_\mu + e^- \rightarrow \nu_\mu e^- \quad \sigma \approx 10^{-42}\ cm^2$

Alibron et. al. April 1978

$\sin^2\theta_w > 1$

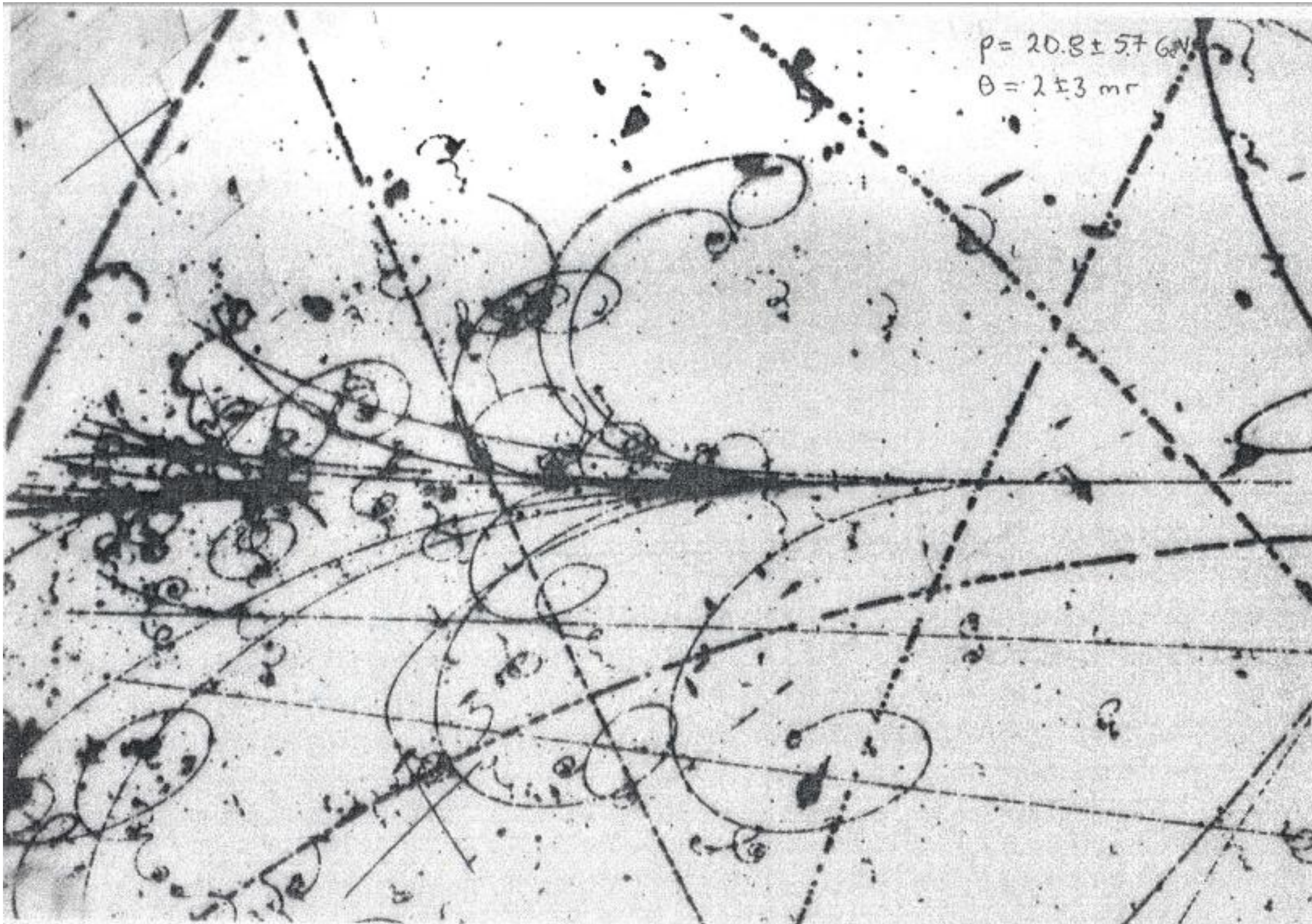
Baltay et. al. June 1978-August 1978

$\sin^2\theta_w = .23 \pm .12$

Prescott/Hughes et. al. July 1978-August 1978

$\sin^2\theta_w = .20 \pm .03$

Asymmetry = $(-9.5 \pm 1.6)\ 10^{-5}$


p = 20.8 ± 5.7 GeV
θ = 2 ± 3 mr

Charm

Ting/Richter $J/\psi \rightarrow e^+e^-$ Nov.-Dec. 1974

Narrow State Mass 3.1 GeV

What is it?

October 1970 G.I.M. Introduced 4th Quark to Suppress Flavor Changing Neutral Current: Glashow, Iliopoulos, Maiani

Such as $K_L \rightarrow \mu^+\mu^-$ $< 10^{-9}$

$\bar{u}$ (dcos θ + S Sin θ)

new $\bar{c}$ (- d Sin θ + S Cos θ)

Consequence

Produce Single Strange Particle in Neutrino Interactions

(ordinarily associated production)

Signature for Charm Production

Baryon Charm

Extraordinary Event

5 Charged Particles

1 strongly interacts

1 decays

2 scatter off electrons

1 Λ° decay

Two Charm Baryons Σ_c^{++}, Λ_c^{+} Produced by 13 GeV Neutrino in Hydrogen

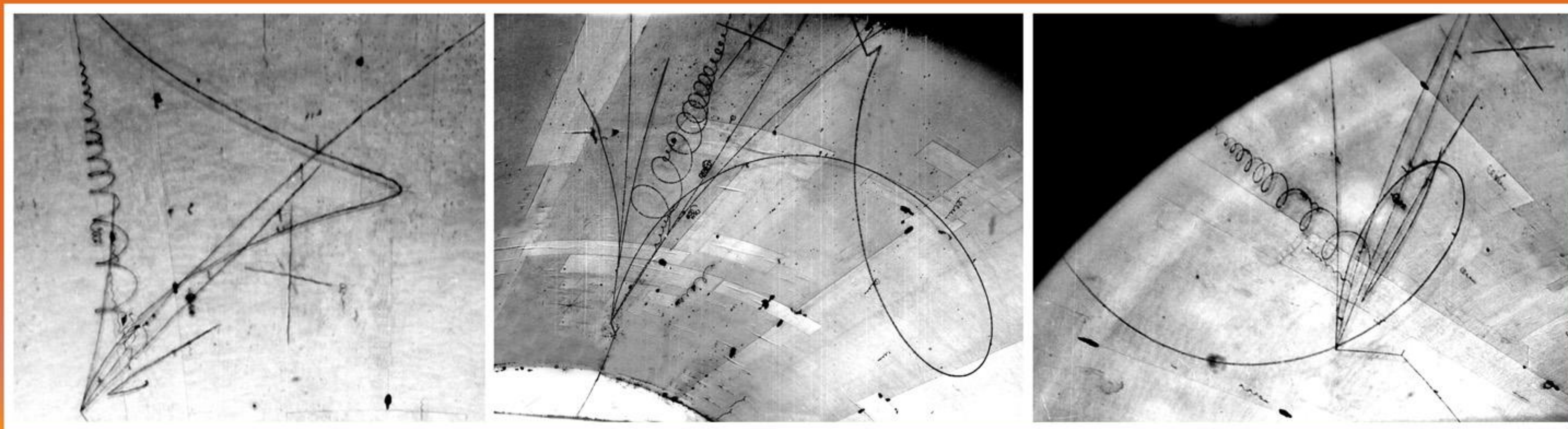
$M(\Sigma_c^{++}) = 2426 \pm 12$ MeV

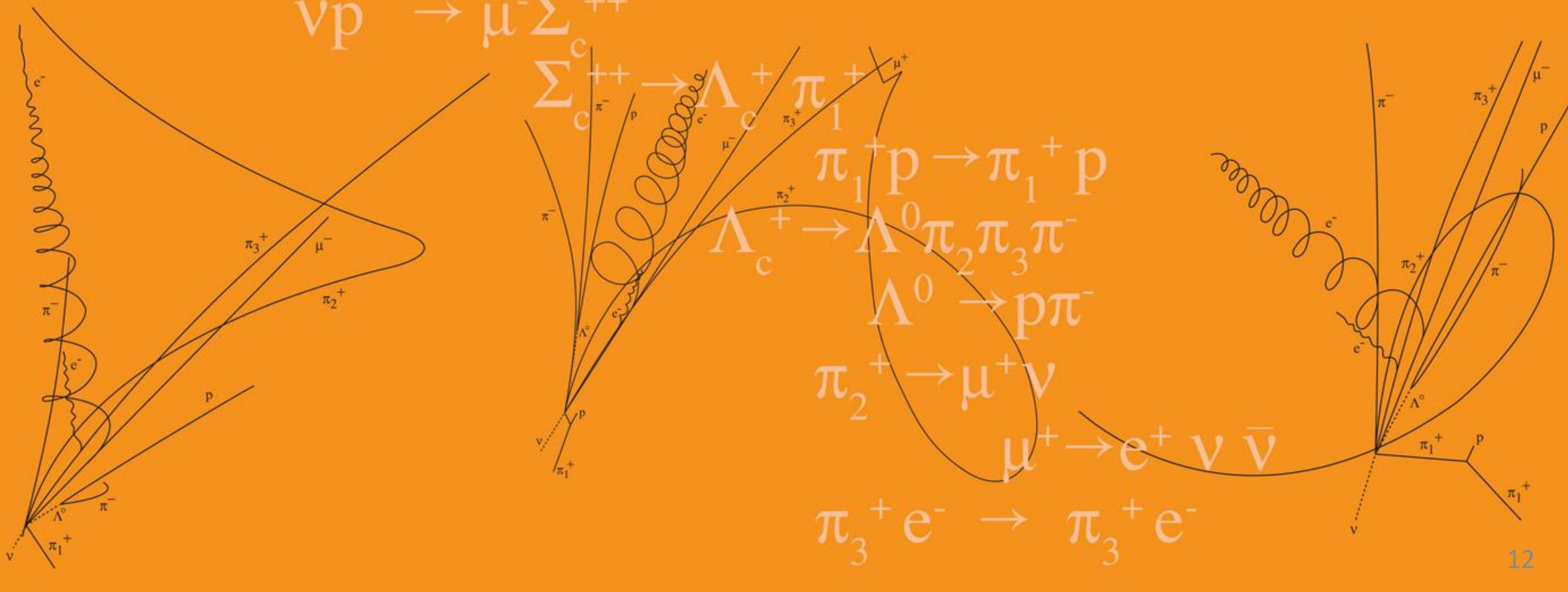
$\Delta M(\Sigma_c^{++} - \Lambda_c^{+}) = 166 \pm 15$ MeV

$M(\Lambda_c^{+}) = 2260$ MeV

Cazzoli et. al.	March 1975-April 1975	Discovery & Introduced Notation: Λ_c, Σ_c, Ξ_c, etc. (Confirmed Baltay et. al. 1979)
De Rujula, Georgi & Glashow	February 1975-July 1975 $M\,\Lambda_c^{+} \approx 2200$ MeV $\Delta M(\Sigma_c^{++} - \Lambda_c^{+}) = 160$ MeV	
Goldhaber et. al.	June 1975-August 1976 Meson Charm D°	

DISCOVERY OF CHARM BARYONS





$\nu p \rightarrow \mu^- \Sigma_c^{++}$

$\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi_1^+$

$\pi_1^+ p \rightarrow \pi_1^+ p$

$\Lambda_c^+ \rightarrow \Lambda^0 \pi_2 \pi_3 \pi^-$

$\Lambda^0 \rightarrow p \pi^-$

$\pi_2^+ \rightarrow \mu^+ \nu$

$\mu^+ \rightarrow e^+ \nu \bar{\nu}$

$\pi_3^+ e^- \rightarrow \pi_3^+ e^-$

Involvement:

Particles

Mesons				
J^P				
0^-	$\pi^{\pm}\pi^{\circ}$	K	η	η'
1^-	ρ	K^*	ω	ϕ
2^+	A_2	K^{**}	f^o	f'
Baryons				
$1/2^+$	$\Sigma^{\pm}$ Σ°	Ξ	Λ	
$3/2^+$	Δ	Y_1^*	Ξ^*	Ω^-
$1/2^+$	Λ_c^+	Σ_c^{++}		

Discovery

↑ Properties

*III. Excited Vacuum and Relativistic Heavy Ion Physics

Vacuum Stability and Vacuum Excitation in a Spin O Field Theory

T.D. Lee and G.C. Wick — Jan. 1974-April 1974

Abnormal Nuclear States of Vacuum Excitation

T.D. Lee — April 1975

Workshop on Heavy Ions: Bear Mountain, N.Y. Nov. 29-Dec. 1, 1974

"Hitherto, in high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of "vacuum," we must turn to a different direction; we should investigate some "bulk" phenomena by distributing high energy over a relatively large volume. *The fact that this direction has never been explored should*, by itself, *serve as an incentive for doing such experiments."*

Heavy Ion Collisions

In this way one could temporarily restore broken symmetries of the physical vacuum and possibly create abnormal state of nuclear matter.

Bielefeld University 1980

Subsequent Quark Matter Meetings

*Opened up a whole new area of Physics

Letter to James Leiss - Associate Director
Office of High Energy and Nuclear Physics
DOE

April 22, 1983
From – N.P. Samios – Director of BNL
Proposal for CBA Construction
Primary PP.

"The scope of this project outlined in the early part of this letter encompasses a dedicated pp facility. This however naturally lends itself to the addition of both a relativistic colliding heavy-ion capability and to the polarization of the protons, at small additional cost. This is due to the fact that CBA is composed of two separate rings with long straight sections, the availability of a heavy-ion injector at BNL (the Tandem Van de Graff) and an on-going project at the AGS for producing polarized protons by the end of 1984. The implementation of both or either of these possibilities would provide unique and exciting new physics opportunities."

Heavy ions and spin considered to be an exciting physics opportunity for CBA.

A few words concerning RHIC

The preamble to the RHIC Conceptual Design Report of 1989 is especially Prophetic: I quote,

The essential motivation for colliding nuclei at ultrarelativistic energies is the production of matter at extreme conditions of temperature and density: extended volumes of hadronic matter with energy densities greater than 10 times that of the nuclear ground state should be realizable. There is little direct knowledge about what to expect under such conditions. They have not been detected anywhere in the natural universe, and are just beginning to be approached through experiments with ion beams in experiments at Brookhaven and CERN. Thus the proposed facility represents a venture into an almost completely unknown regime for the study of basic properties of matter.

While this leap into the unknown is by itself compelling attraction for both experimenters and theorists, it is also true that very specific goals for discovery and exploration can be defined within the present understanding of Quantum Chromodynamics (QCD) – as developed from high energy collisions of elementary particles – and the low energy behavior of bulk nuclear matter. The parameters of the proposed machine complex will allow the experimenter to make contact with both regimes in the systematic study of new phenomenon.

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 an extended confined plasma of quarks and gluons.

I would say that this dream envisioned for RHIC has been fulfilled

RHIC – Proposal for Construction

1987 BNL for Project Start in 1989 – Declined by DOE

1988 BNL for Project Start in 1990 – DOE Agrees

Declined by OMB

1989 Nuclear Science Advisory Committee

Reasserted RHIC Highest Priority

BNL, DOE, OMB all agree

1990 RHIC included in Congressional Budget

for Construction Start in 1991.

RHIC: High luminosity (polarized) hadron collider

Discovery and study of the Quark-Gluon Plasma (QGP)

- 2 independent 3.8 km SC rings accelerating and colliding up to 250 GeV pol. protons and up to 100 GeV/n HI beams at 6 IPs
- High level of flexibility:
  - Center-of-mass energy range: 7 – 500 GeV
  - Collision of unequal species including p-A
  - 6 independent collision points
- Accelerator innovations/challenges:
  - Transition energy crossing with SC ring
  - Polarized proton acceleration using Siberian snakes
  - High energy stochastic cooling of HI beams

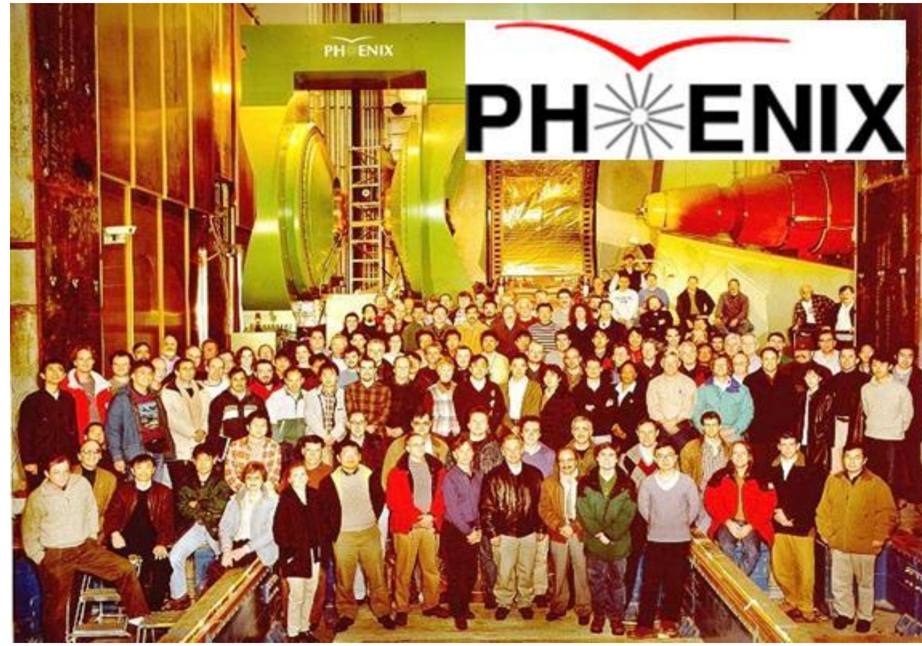
Achieved average store luminosities:	
Au–Au (100 GeV/n)	30×10^{26} cm^{-2} s^{-1}
p↑–p↑ (250 GeV) (<P> = 46%)	90×10^{30} cm^{-2} s^{-1}
Goal with additional luminosity upgrades:	
Au–Au (100 GeV/n)	40×10^{26} cm^{-2} s^{-1}
p↑–p↑ (250 GeV) (<P> = 70%)	300×10^{30} cm^{-2} s^{-1}

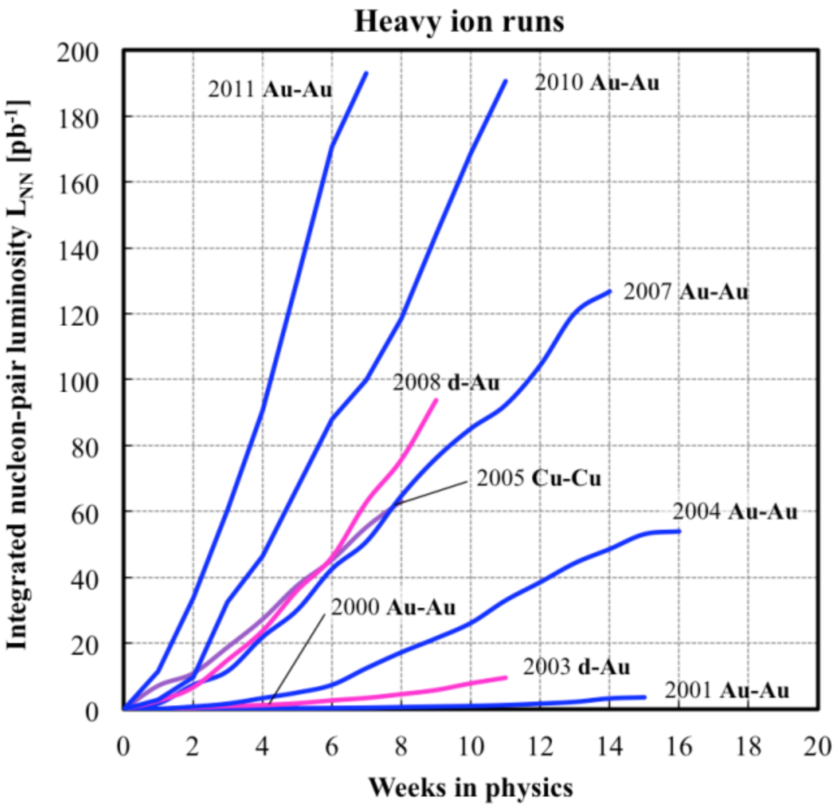
Four Detectors

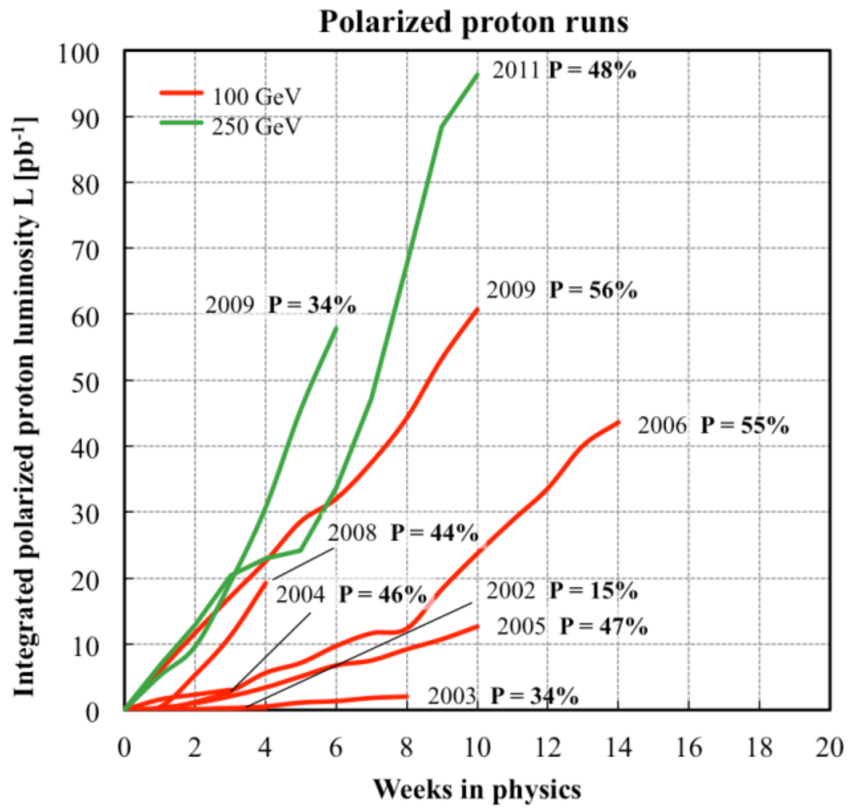
1200 Physicists

50 Countries

2000 Publications







Note: The nucleon-pair luminosity is defined as $L_{NN} = A_1 A_2 L$, where L is the luminosity, and A_1 and A_2 are the number of nucleons of the ions in the two beam respectively.

Some of the Major Findings at RHIC

sQGP: Strongly Interacting Quark Gluon Plasma
Perfect Fluid
Jets and Flow

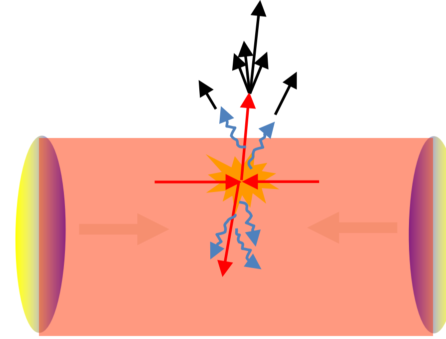
Gluon Contribution to Proton Spin
Very Small

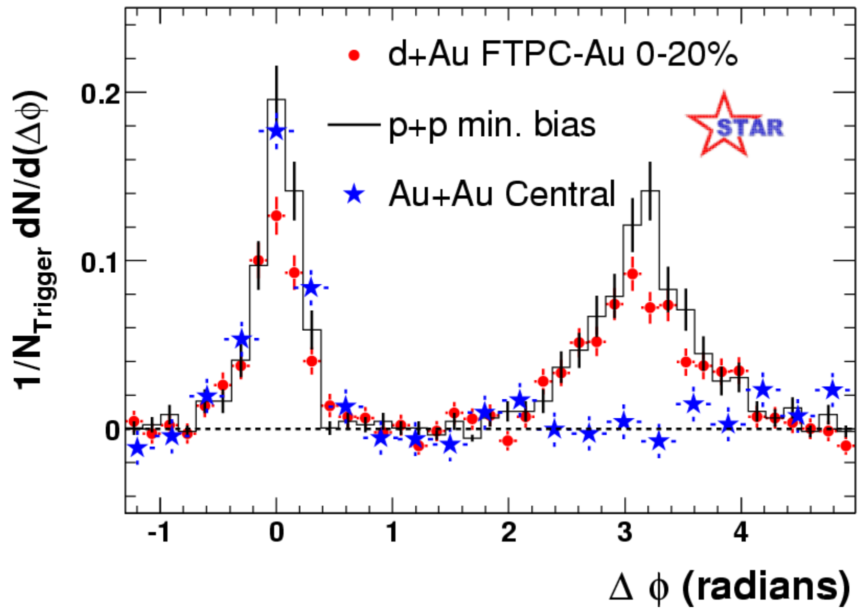
Un-Envisioned Forms of High Energy Dense Matter in the Initial State
Anisotropies, Long Range Correlations

Initial “Temperature” (higher than Λ_{QCD})
Direct photon and di-leptons

Anti Matter
Discovery of $^{4}\overline{He}$, $^{3}_{\Lambda}\overline{H}$

Jets Modified by the Medium

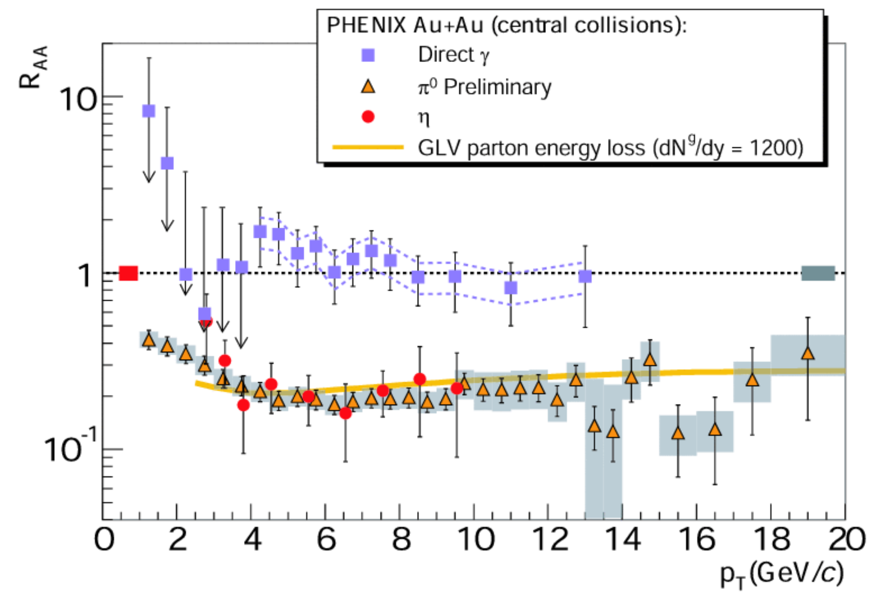




Away side suppression

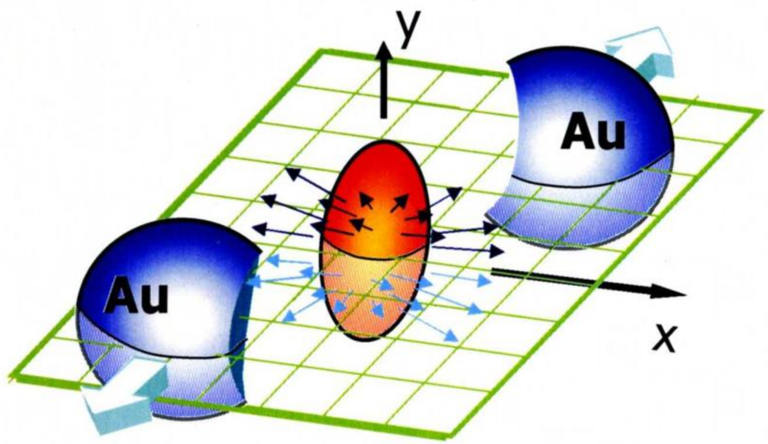
4 < p_T(trig) < 6 GeV/c

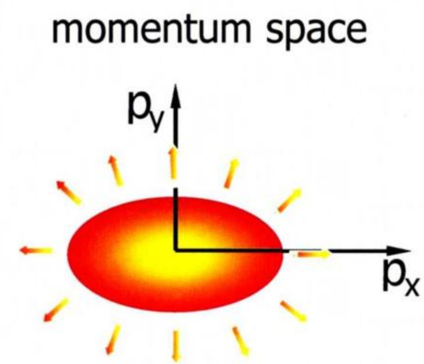
p_T(assoc) > 2 GeV/c



PHENIX

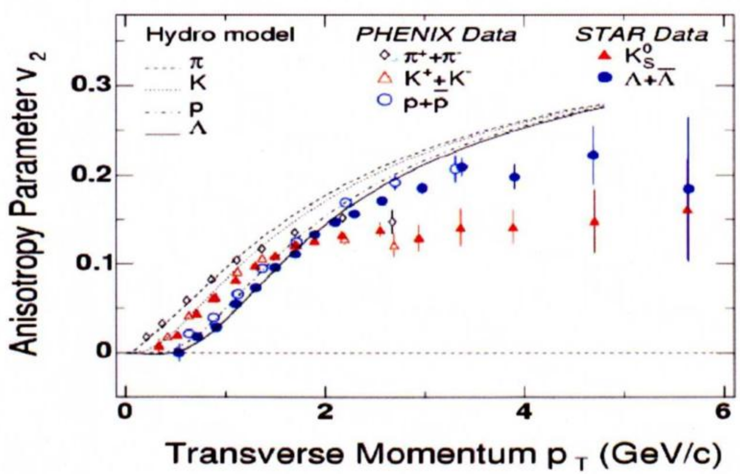
Elliptic Flow (V2)

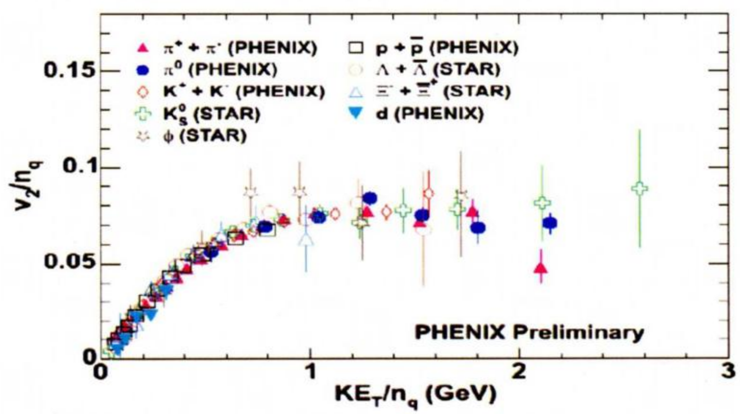




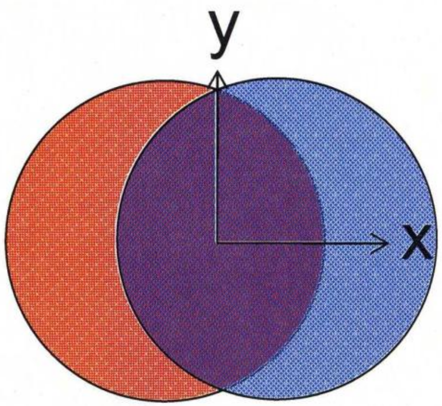
$$dN/d\phi = 1 + 2\,V_2 \cos 2\,(\phi - \psi) + \dots$$

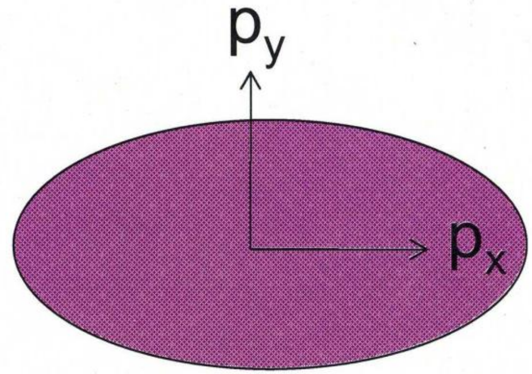
Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

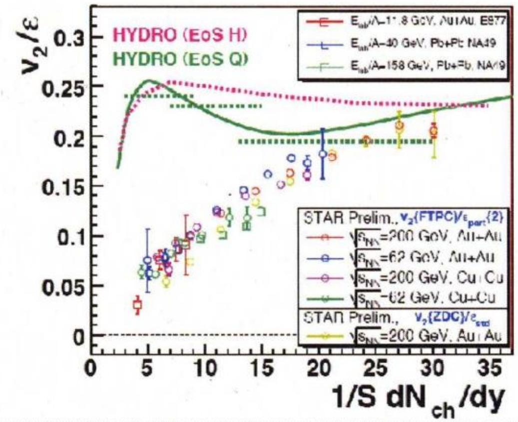




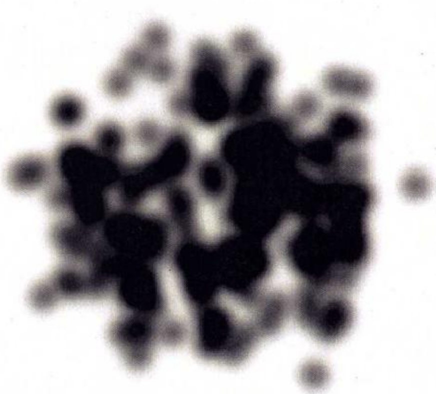
From v_2 to v_n: and what we learn



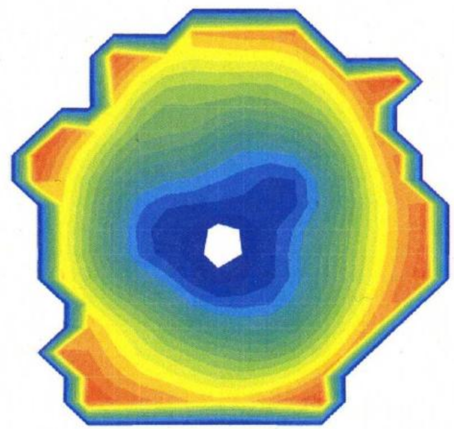




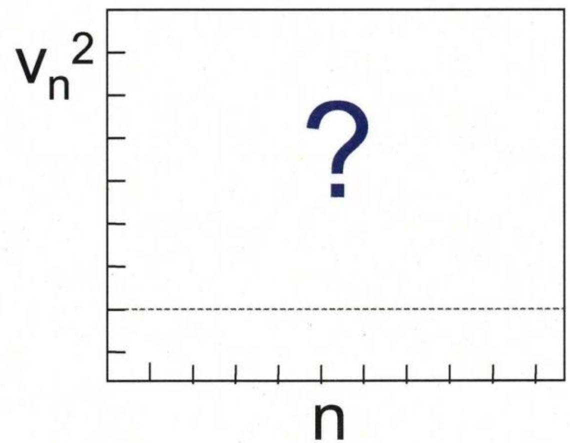
$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$



Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100:022303



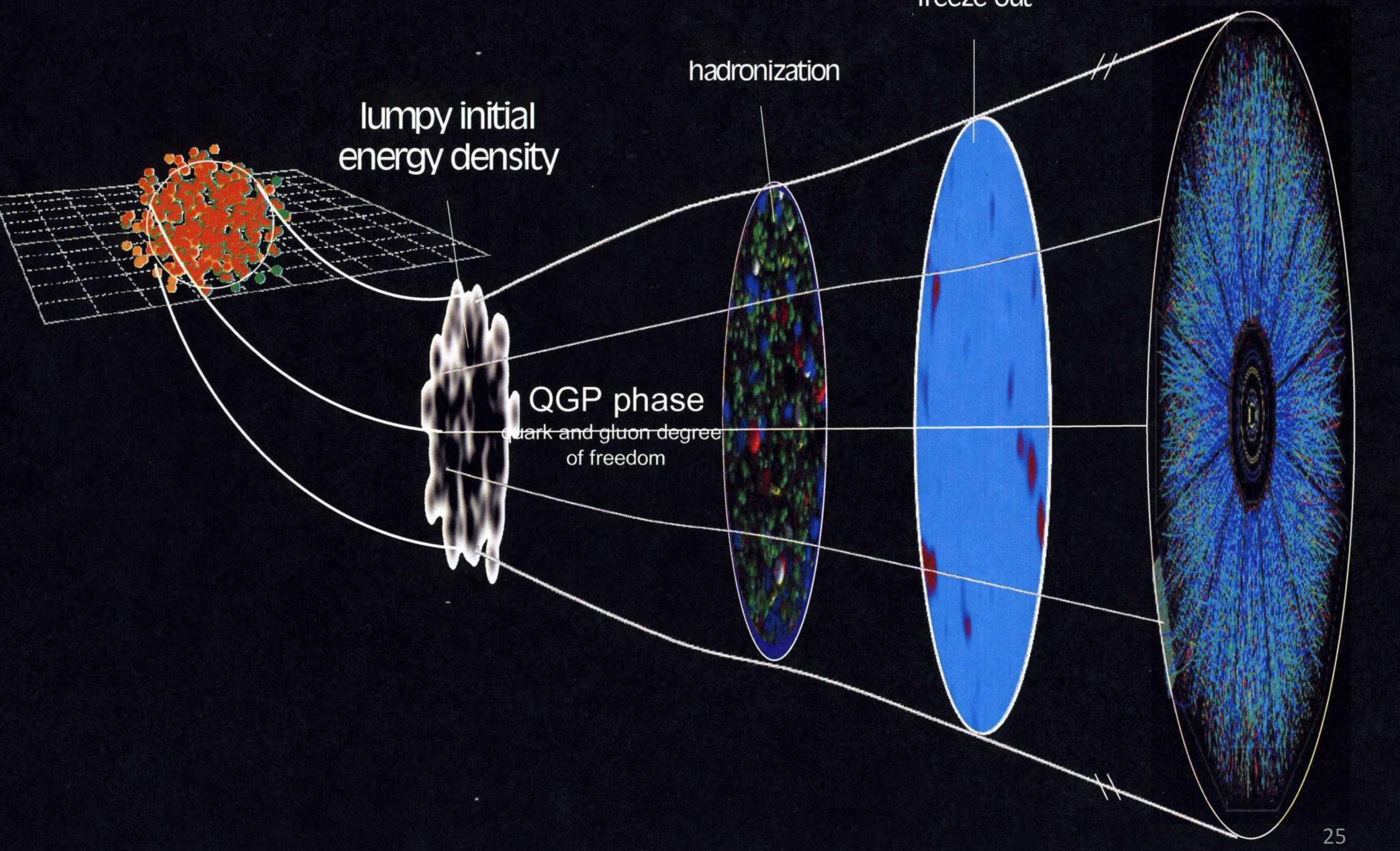
K. Werner, Iu. Karpenko, K. Mikhailov, T. Pierog, arXiv:11043269



Fluctuations imply odd terms aren't necessarily zero and v_n^2 vs. n will provide information about the system like lifetime, viscosity, etc.

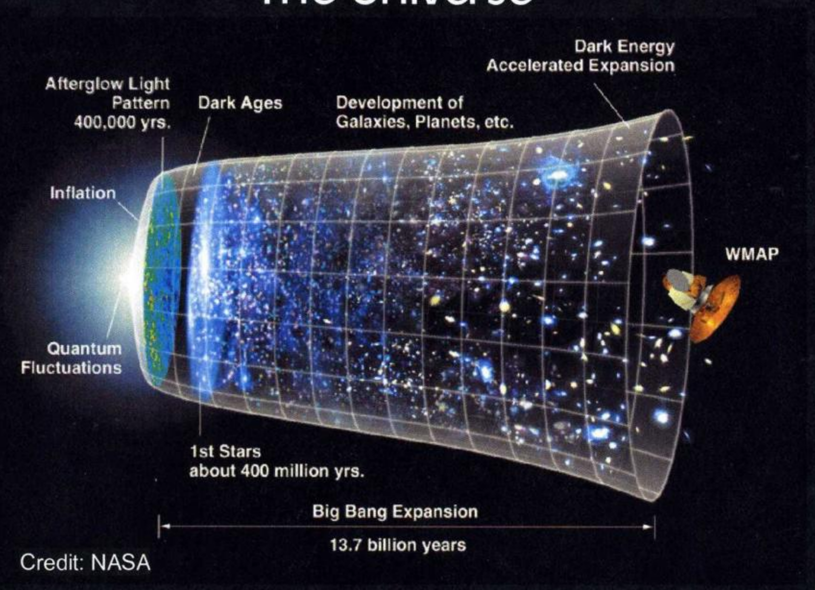
A.P. Mishra, R. K. Mohapatra, P. S. Saumia, A. M. Srivastava, Phys. Rev. C77: 064902, 2008
P. Sorensen, WWND, arXiv:0808.0503 (2008); J. Phys. G37: 094011, 2010

Expansion of the little bang



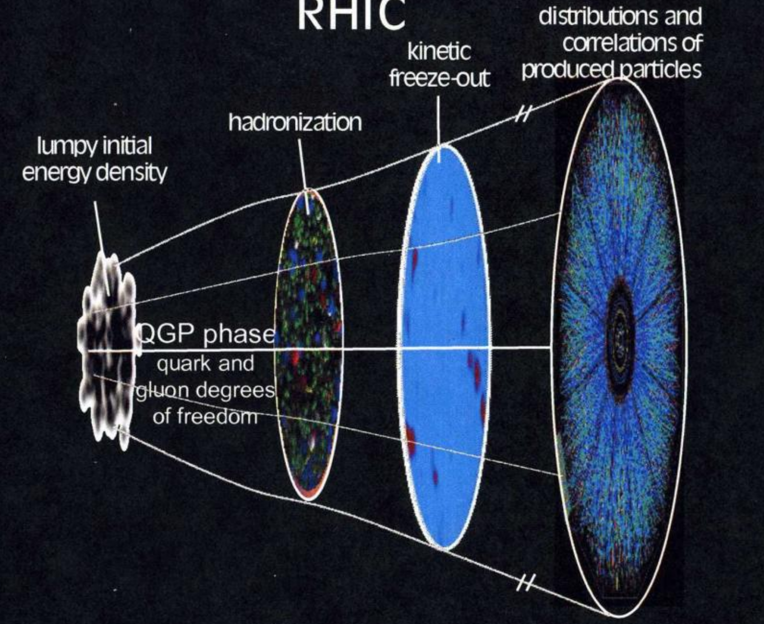
The Evidence Validates this Analogy

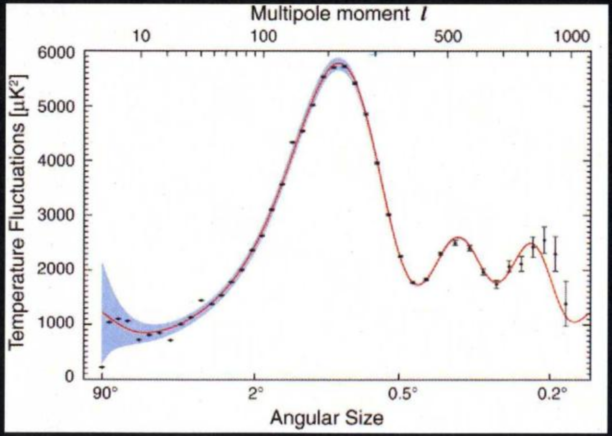
The Universe



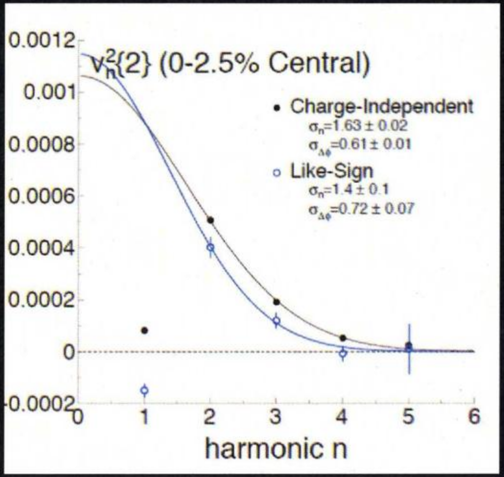
Credit: NASA

RHIC



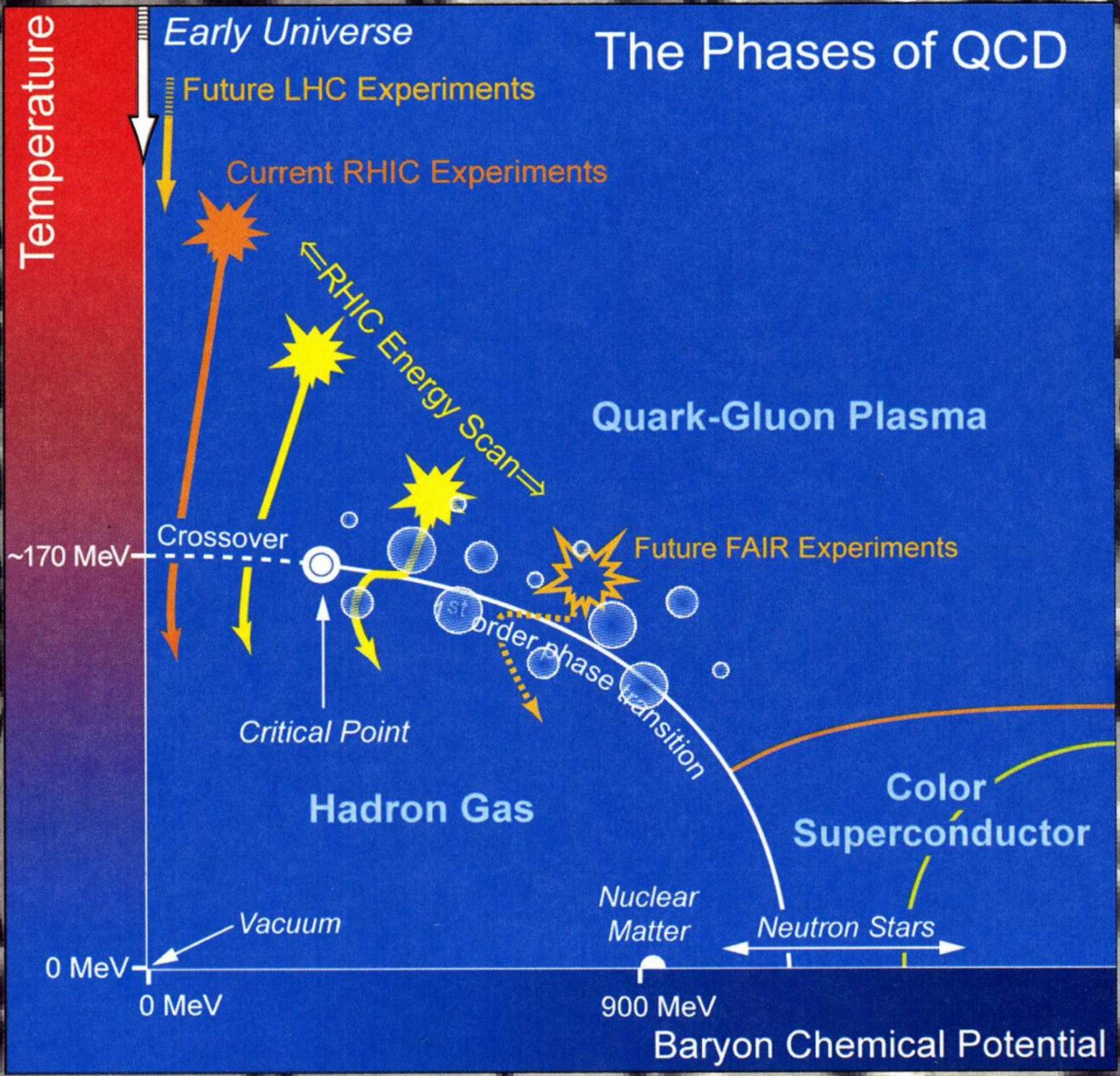


WMAP



RHIC

Phase Transitions: 1st order or smooth
Do the little bangs boil?



Physics Issues:

- **What are the properties of this newly discovered form of QCD matter?**
  sQGP

Temperature, thermalization, energy density, equation of state, viscosity, chiral symmetry

- **What are the initial state and early form of matter in heavy ion collisions?**

Gluon saturation
Color Glass Condensate?
Glasma?

- **How does the nucleon get its spin?**

Gluon contribution to nucleon spin.
Angular Momentum?

- **Is there a critical point and new phases of high density matter?**

Systematic search of QCD phase diagram

IV. RIKEN Brookhaven Research Center
T.D. Lee Crucial Role in its Establishment

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding (MOU) between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

RHIC Advisory Committee 1985-1997

Bromley	Chair	1985-1990
Feshback	Chair	1991-1997
T.D. Lee	"Member"	1985-1997

1995 MOU BNL-RIKEN

Spin Physics:	Accelerator	Snakes
		Rotators
		Polarimeters
	Detector	PHENIX Muon Arm

1997 MOU BNL-RIKEN

Established RBRC

T.D. Lee First Director

Inauguration of RBRC

Sep 22,1997

RBRC – Organization

T.D. Lee	Director	1997-2002
T.D. Lee	Director Emeritus	2003-present
N.P. Samios	Director	2003-present

Fellows (5 years), Post Docs (2 years)

No Permanent Members

Three Sections

Theory –	QCD, Spin	Lee, McLerran
Experiment –	QCD, Spin, PHENIX	Enyo, Bunce, Akiba
Computing –	Lattice Gauge Theory	Lee, Christ

Personnel

Total Number of RBRC Fellows and Post Docs

Past and Present: approx. 100

63 Theory 37 Experimental

Past Fellows

20 Theory → 19 Tenure 1 Other Fields

12 Experimental → 8 Tenure 2 Other Fields 2 Not Yet

Success Ratio: 27/30 = 90%

Past Post Docs

26 Theory → 10 Tenure 16 Not Yet

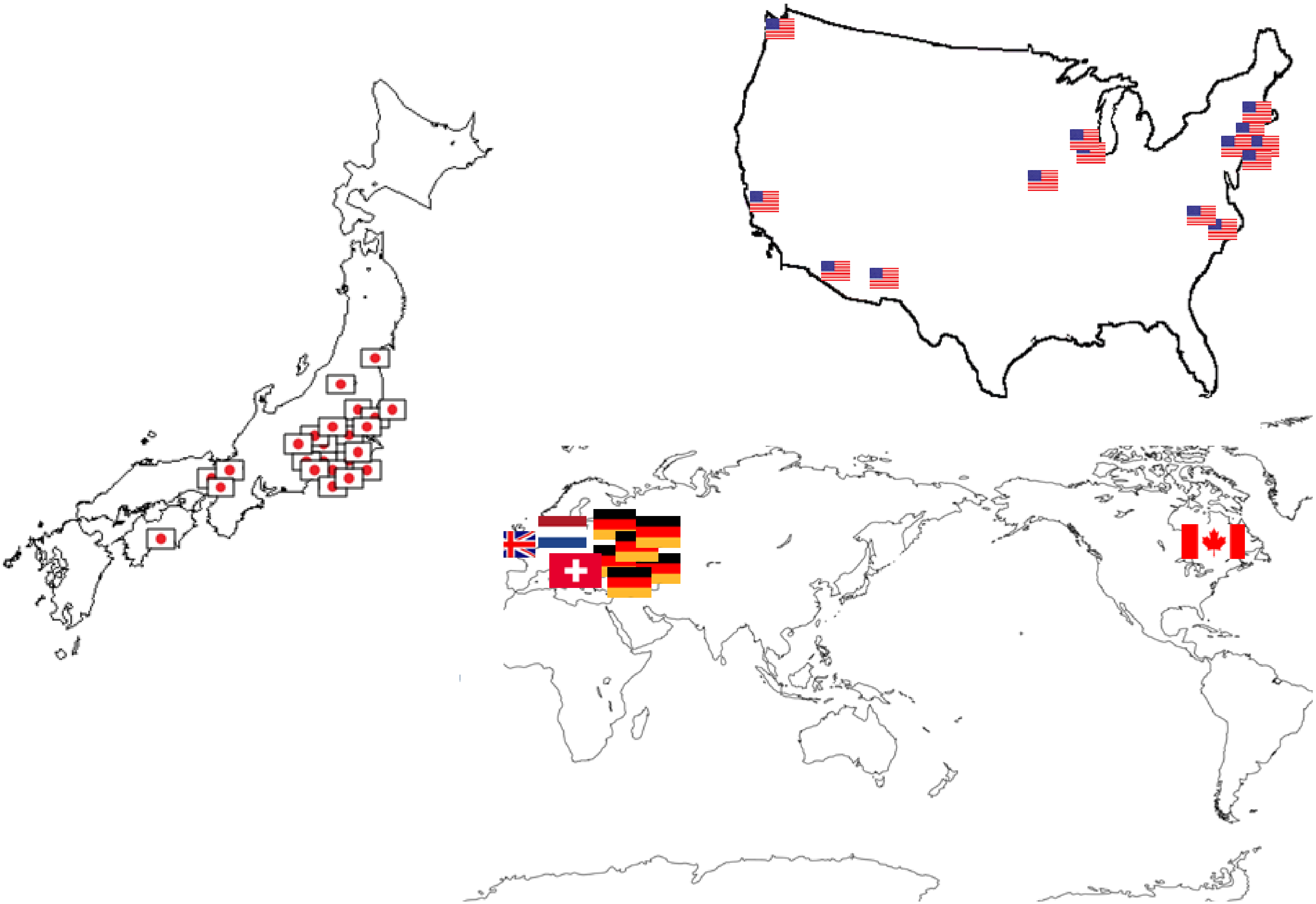
13 Experimental → 7 Tenure 6 Not Yet

Total Tenure to date: 27+17 = 44

International – Tenure

Theory:	10 U.S.	10 Japan	9 Western Europe
Experimental:	4 U.S.	11 Japan	----------

Geographic Distribution of Tenured RIKEN Graduates



Workshops

91 Total

41 Spin

10 Lattice Gauge Theory

40 Heavy ion, QGP

Publications

900+ Theory → 60% Journals; 40% Conferences

272+ Experimental → Approx. 100 PHENIX Publications

75 Major RBRC Contributions

PRL, PRC, PRD, Physics Letters

RBRC Proceedings

100+ Volumes

QCDSP .6 Tflop

QCDOC 2x10 Tflop

RBRC and DOE

Father of the IBM Blue-Gene

QCDCQ 600 Tflop

Hadron Spectroscopy

QCD at Finite T

CKM matrix elements

Precision QCD

Gordon Bell Prize for Computing Performance 1998

Oscillations: 3 Flavors

Quark Sector CKM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} .97 & .23 & (2-3i)10^{-3} \\ -.23 & .97 & .04 \\ (7-3i)10^{-3} & -.04 & .99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$J = 3.1 \times 10^{-5} \qquad \delta = 57^{\circ}$$

Lepton Sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} .81 & .51 & s_{13}e^{-i\delta} \\ -.4 - .6\, s_{13}e^{i\delta} & .6 - .4\, s_{13}e^{i\delta} & .7 \\ .4 - .6\, s_{13}e^{i\delta} & -.6 - .4\, s_{13}e^{i\delta} & .7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$s_{13} \equiv \sin\theta_{13} \quad \leq 0.2$$

$$J = .11 \sin 2\theta_{13} \sin\delta$$

Nick

Long Baseline Neutrino Experiment (LBNE)

Investigate Neutrino Matrix in Detail

θ_{13}, sign of Δm^2_{32}

Δm^2_{32}, Δm^2_{21}, θ_{23}, θ_{12}

Neutrino Mass Hierarchy

$\nu_3 > \nu_{1,2}$ or $\nu_{1,2} > \nu_3$

CP Violation

Proton Decay

Supernova

Requires

Large Detectors	> 200 kton Water Cerenkov
	> 20 kton Liquid Argon
Long Baseline	> 1,000 km
Intense Proton Beams	Power > 1 Mwatt
Wide Band ν Beam	0.5 -5 GeV
Reactions	ν_μ disappearance
	$\nu_\mu \rightarrow \nu_e$ appearance