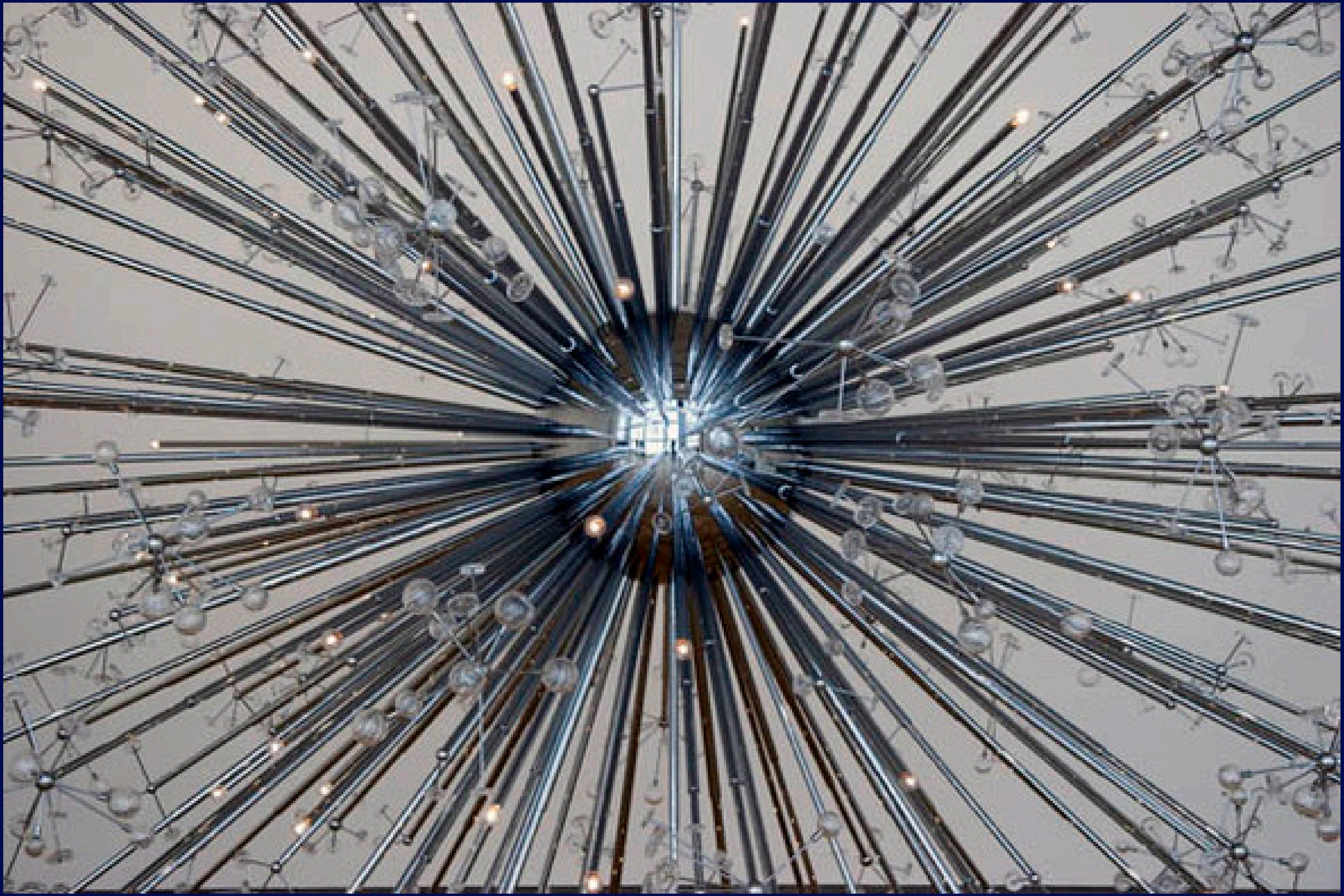


3 Lectures

- **Lecture 1**
  - Introduction to Heavy Ion Collisions
- **Lecture 2**
  - Hydrodynamics in Heavy Ion Collisions
- **Lecture 3**
  - Probing the Near-Perfect Fluid at RHIC

Lecture 1

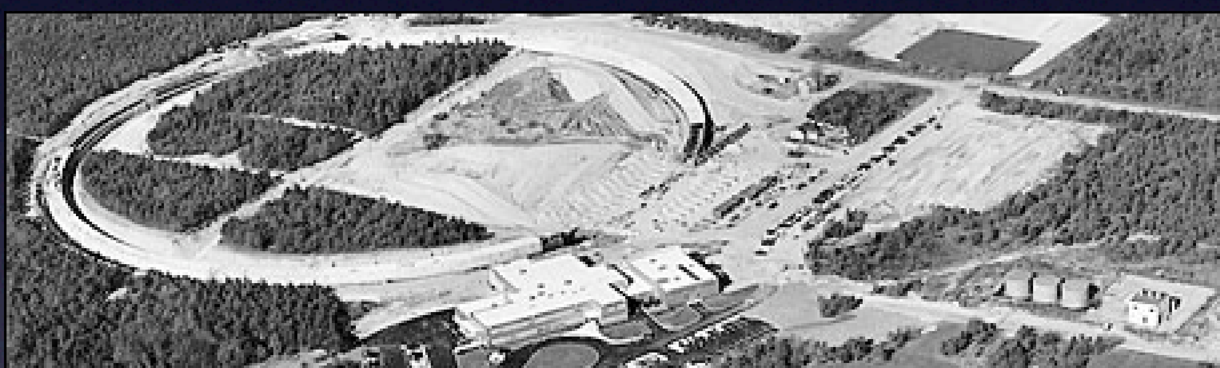
Introduction to the Study of Heavy Ion Collisions

Peter Steinberg
Brookhaven National Laboratory
National Nuclear Physics Summer School, July 2007

Hotter, Denser, Faster, Smaller... and Nearly-Perfect: What's the Matter at RHIC?

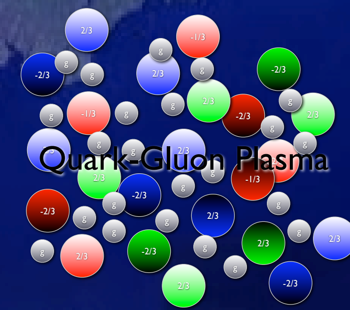
Peter Steinberg
Brookhaven National Laboratory
National Nuclear Physics Summer School, July 2007

Brookhaven @



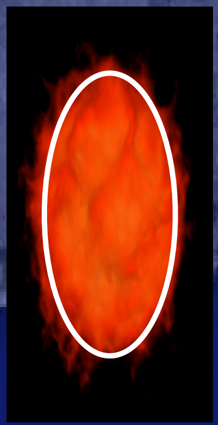
50+ years of accelerator physics: Cosmotron, AGS, RHIC

1.The Femtoworld

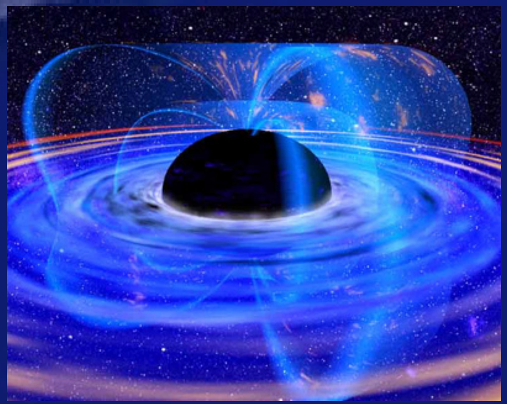


2. Quarks, Gluons, States of Matter

3. What we do at RHIC



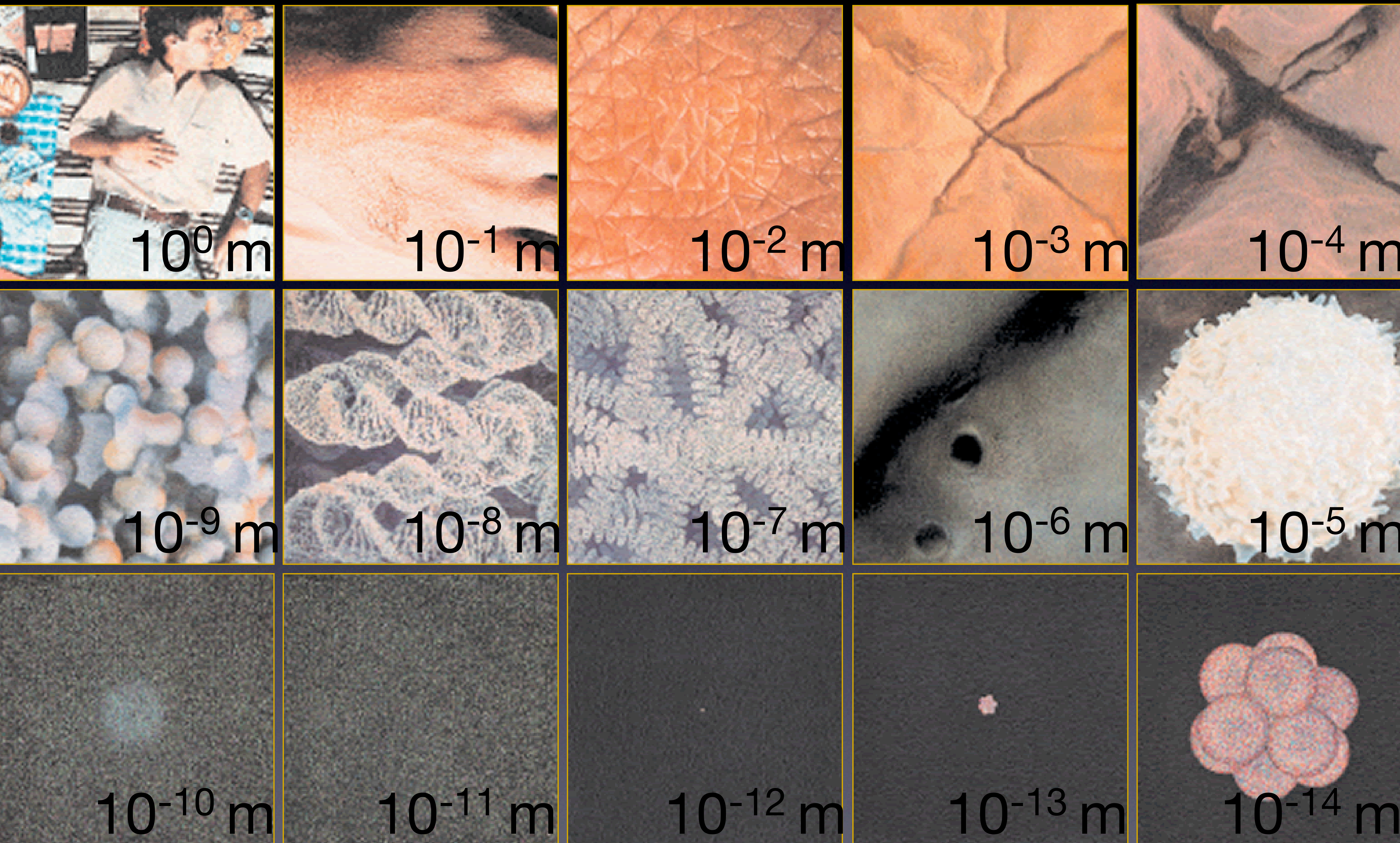
4. Creating matter at RHIC



5. The Future

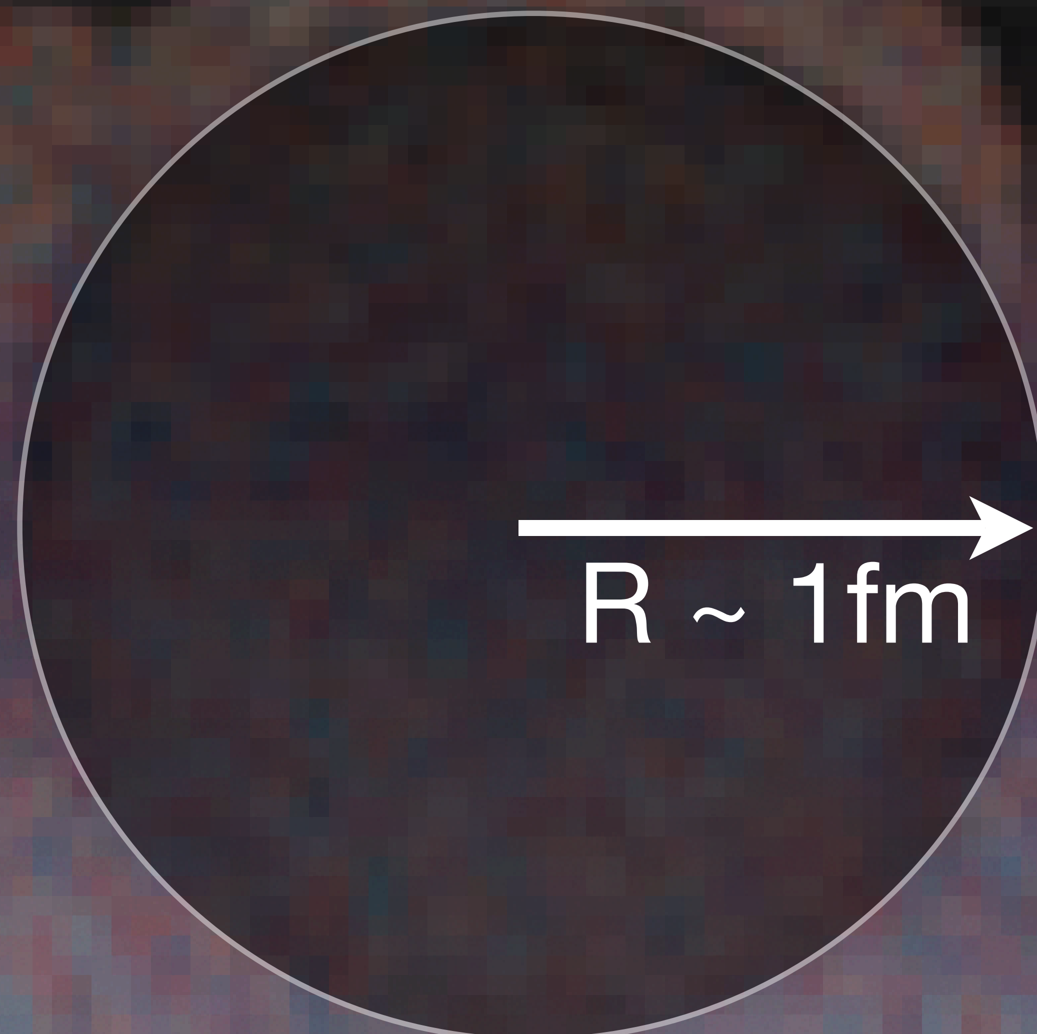
A Brief Roadmap

Powers of 10



10^{0} m
10^{-1} m
10^{-2} m
10^{-3} m
10^{-4} m
10^{-9} m
10^{-8} m
10^{-7} m
10^{-6} m
10^{-5} m
10^{-10} m
10^{-11} m
10^{-12} m
10^{-13} m
10^{-14} m

“The Femtoworld”

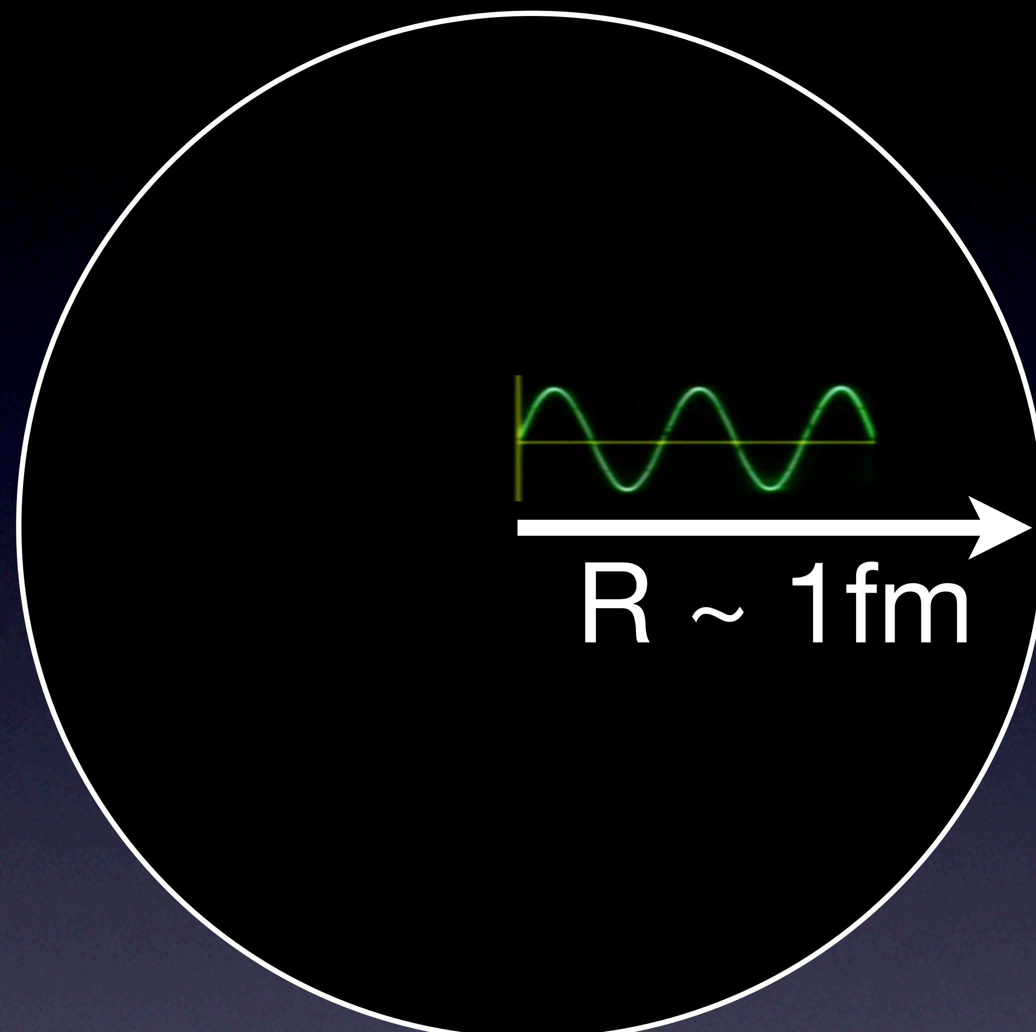


In 2007, “Nuclear Physics” is the study of the Particles and Forces active at the “femtometer” scale

1 femtometer = 1fm = 0.000000000000001m

Adopted in 1964, it comes from the Danish or Norwegian *femten*, meaning *fifteen*.

Time in the Femtoworld

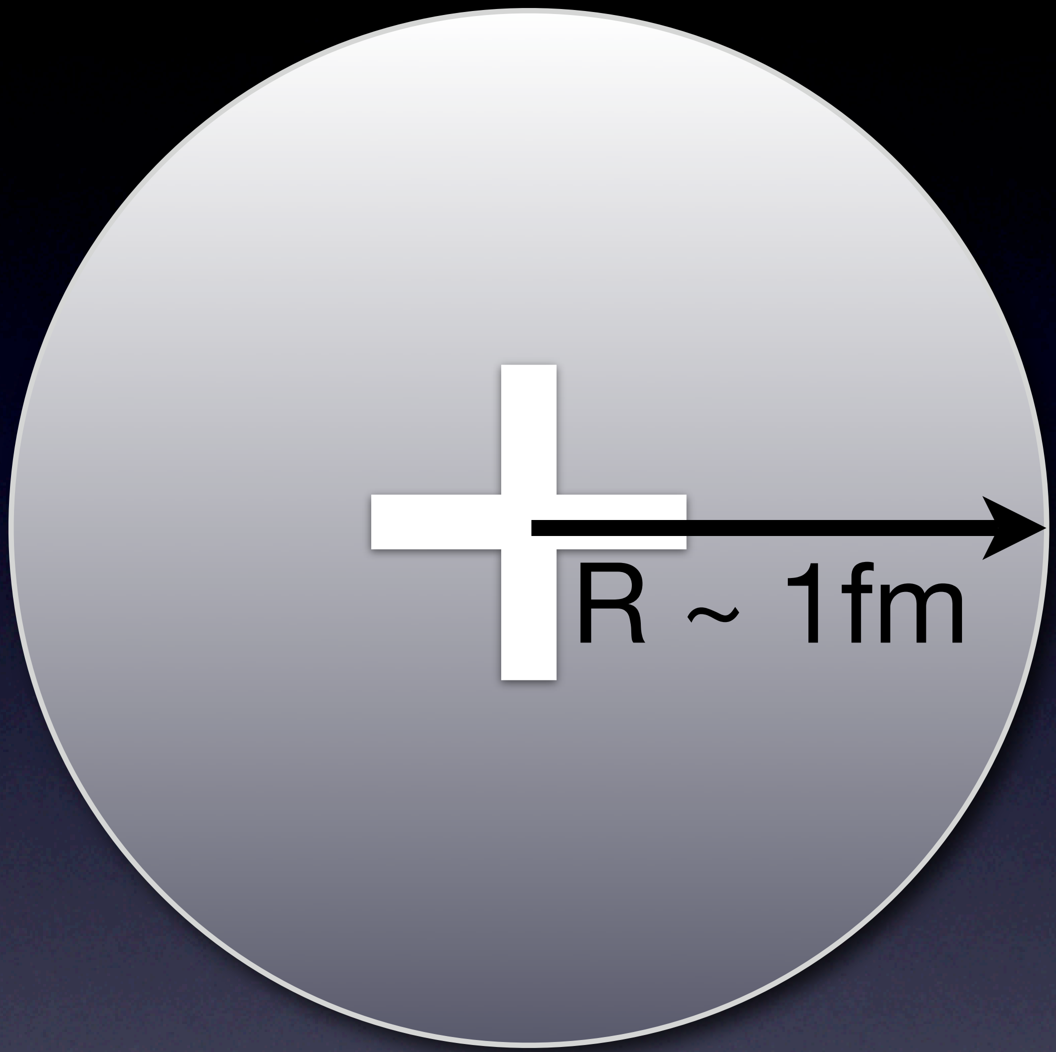


It takes light $3x10^{-24}$ seconds (3 “yoctoseconds”)
to travel 1 femtometer in vacuum.

1 ys = 0.000000000000000000000001 sec

1 fm/c is the basic “time scale” of strong interaction physics

What's in a proton?

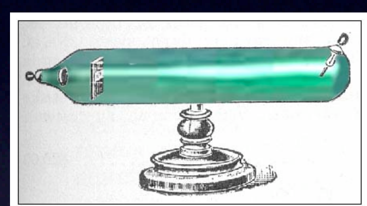


We have long known that a proton has a charge, mass, size and spin, but none of these properties point to what's “inside”

The Particle “Zoo”

1890 1900 1910 1920 1930 1940 1950 1960 1970

e^- (1897) — Thomson’s “electron”



p (1919)

n e^+ (1932)

$\mu^\pm$ (1937)

$\pi^\pm$ $K^\pm$ π^o $\Sigma^\pm$ $\bar{p}$ $\bar{\Lambda}^o$ ρ

K^o Ξ^- ν_e Ξ^o ω

Λ^o $\bar{n}$ η

Δ Σ^o K^*

ν_μ

ϕ

f

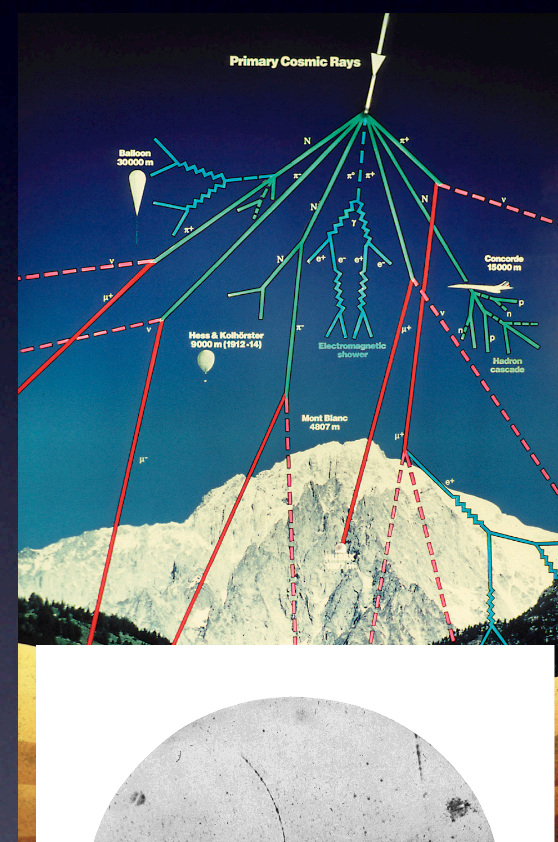
a_2

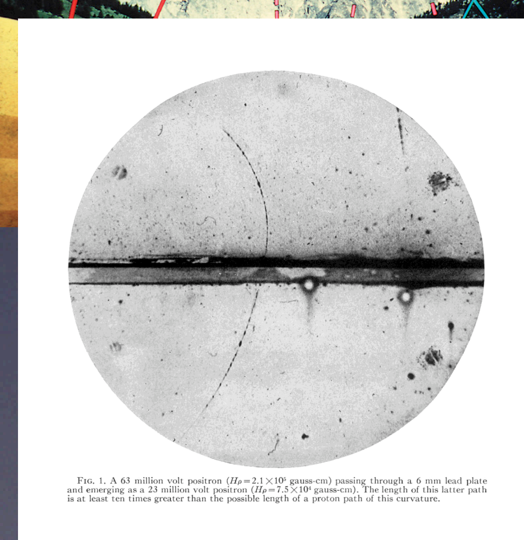
η^*

Ω^-

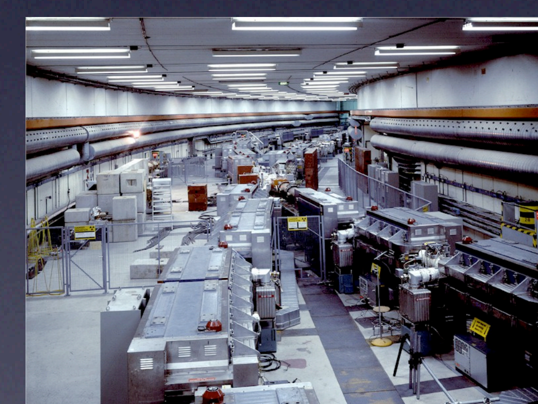
BNL

Berkeley



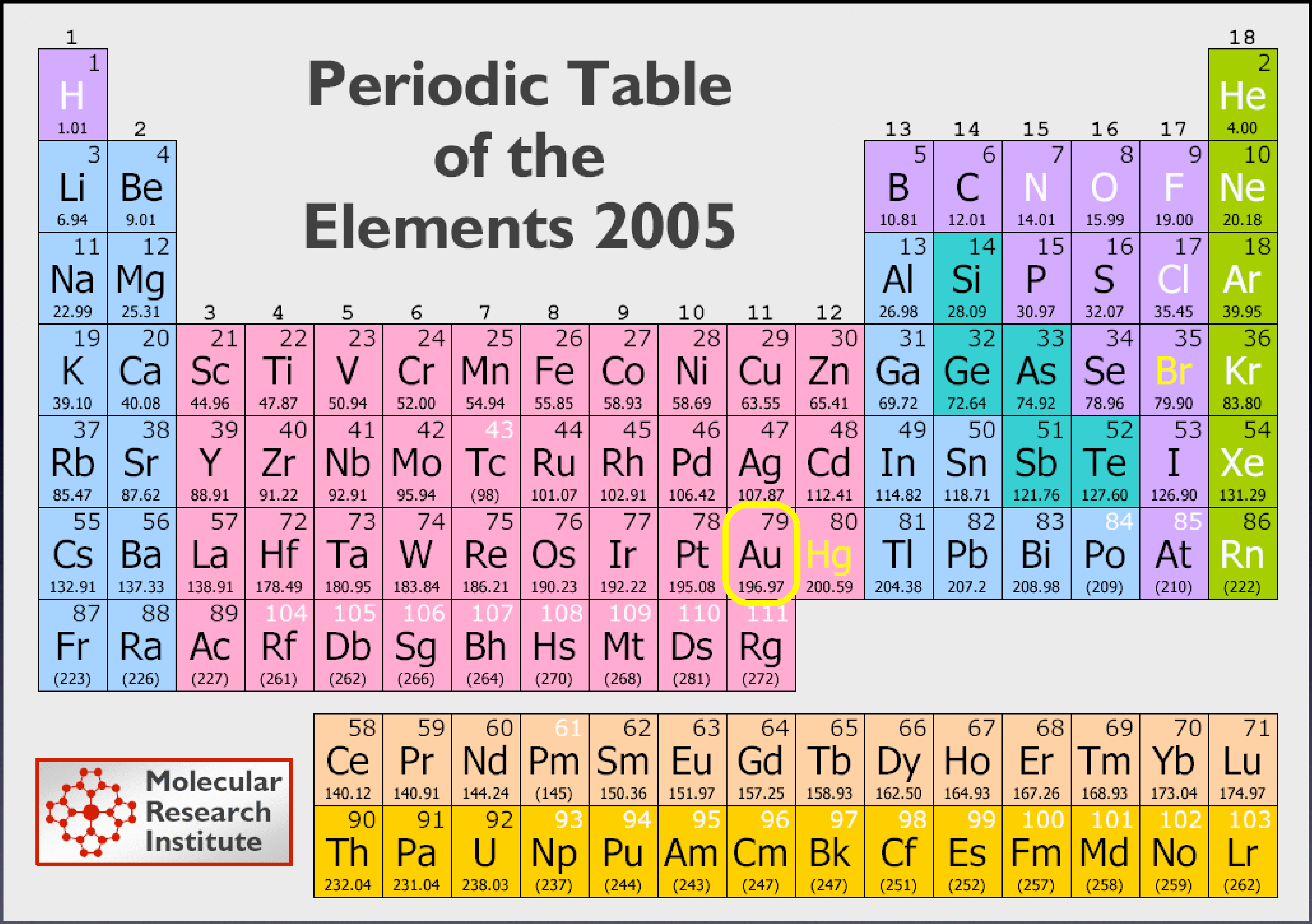


Antimatter!



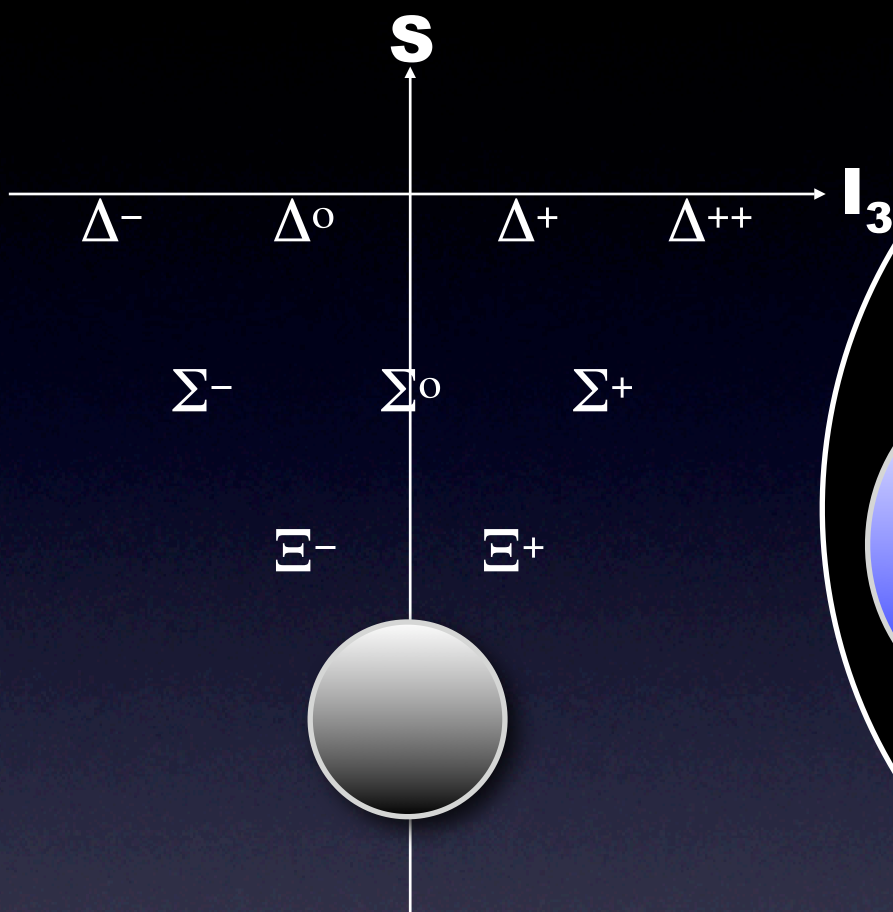
BNL AGS

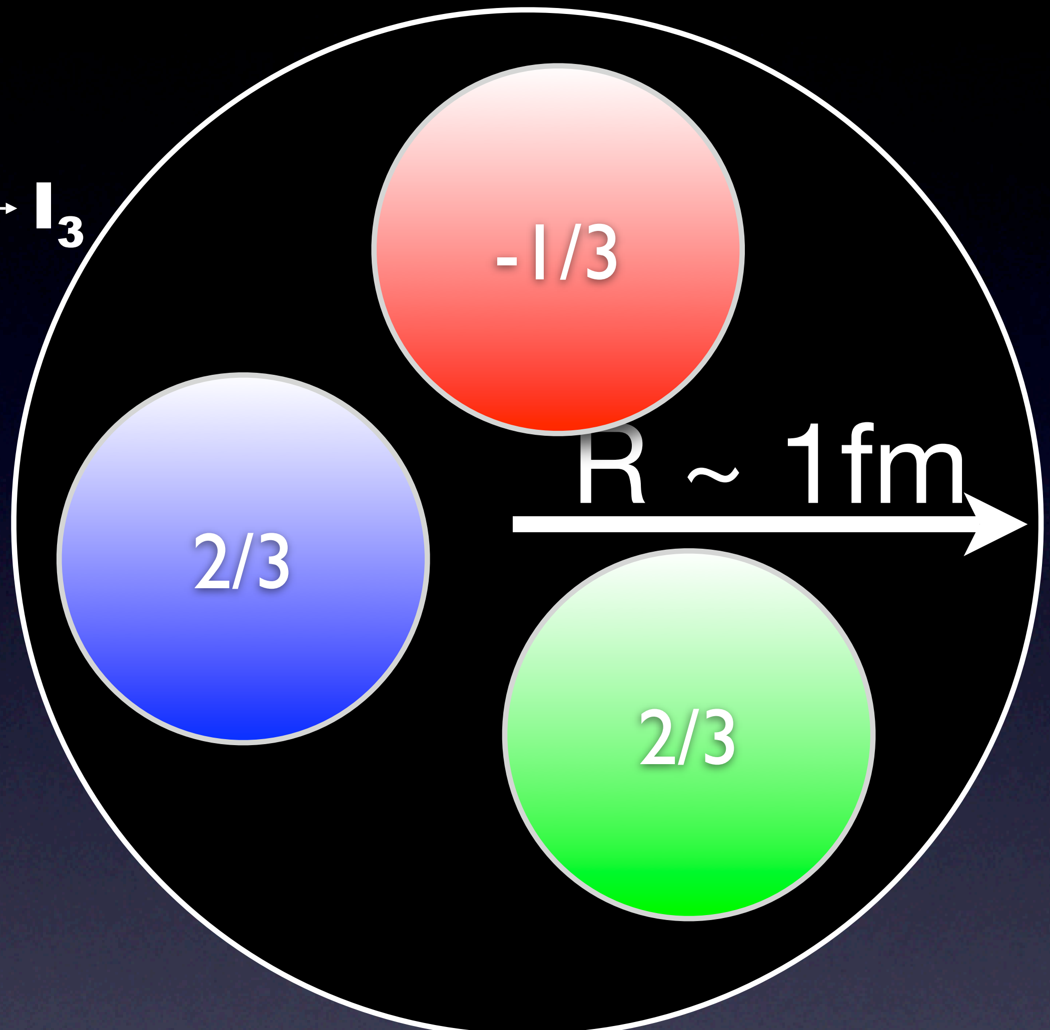
With new detectors and machines, many new particles were discovered!



The periodic table is a testament to the composition of atomic species (even without knowing their "insides"!)

Making Sense of the Zoo

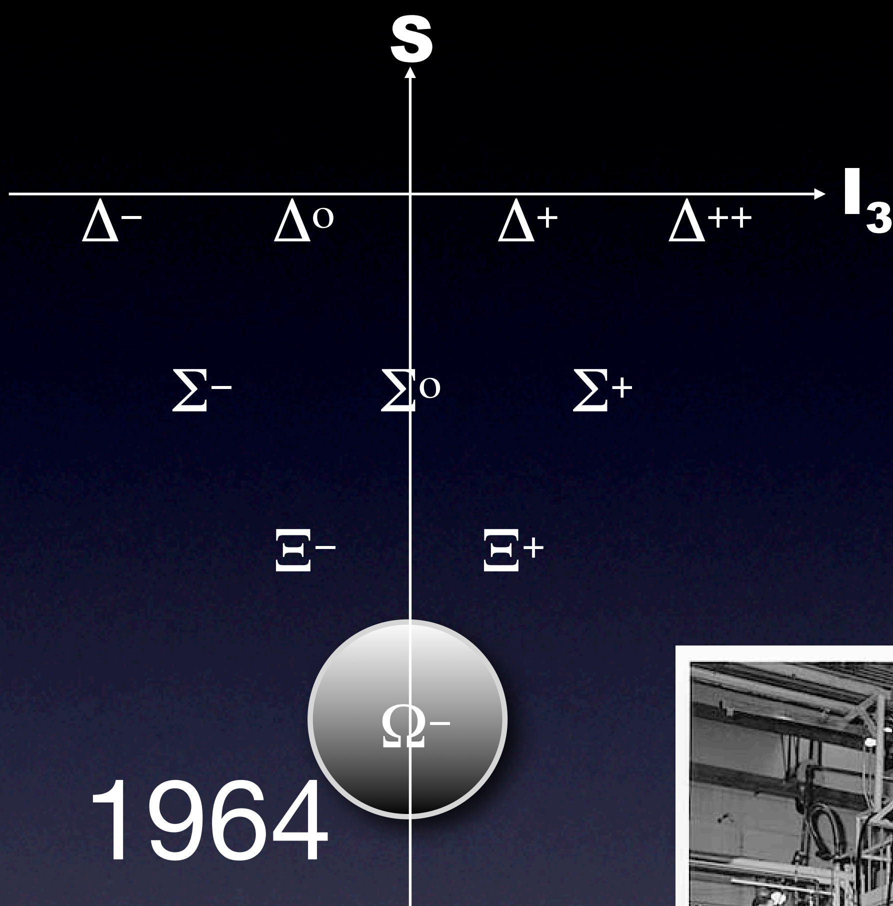


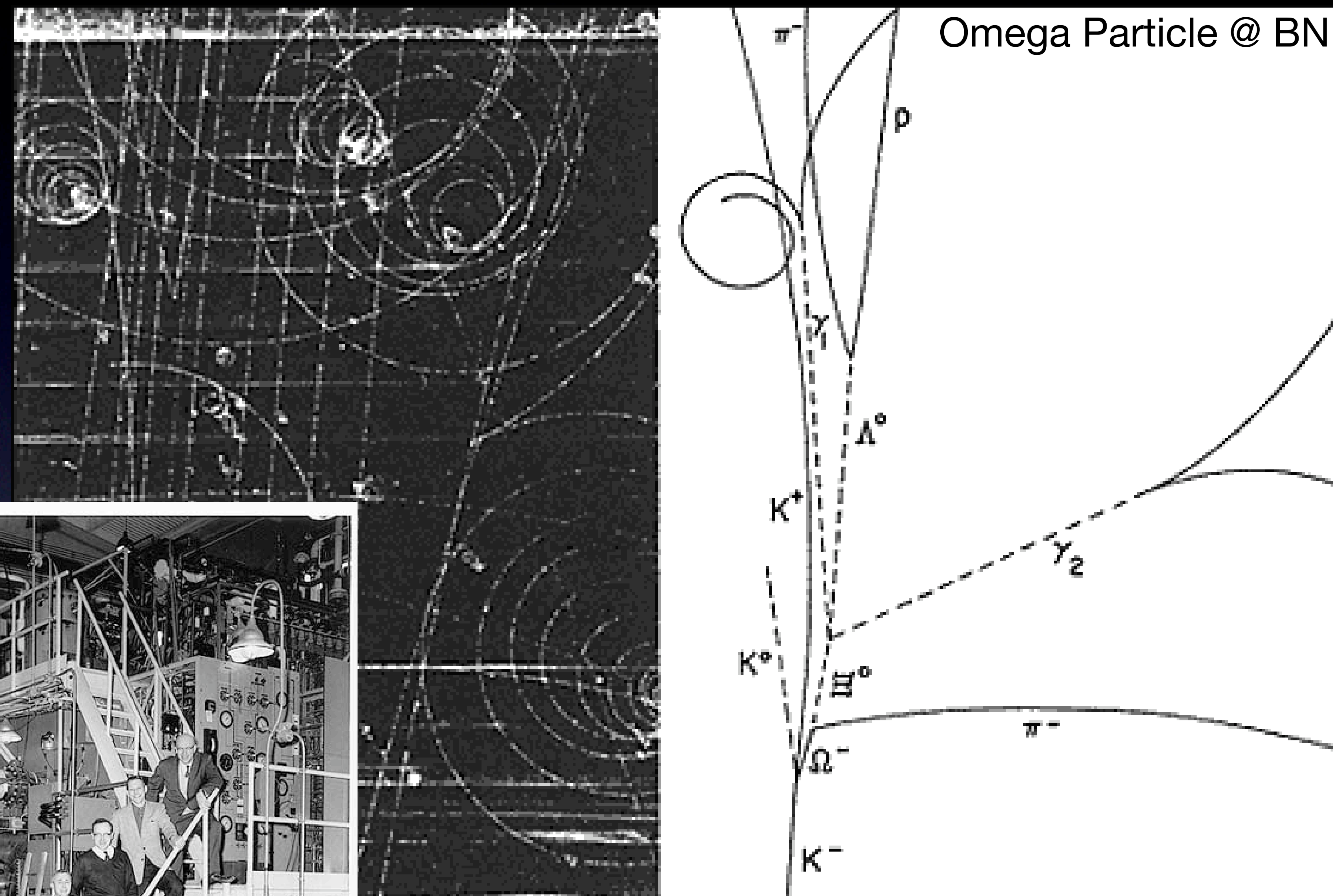


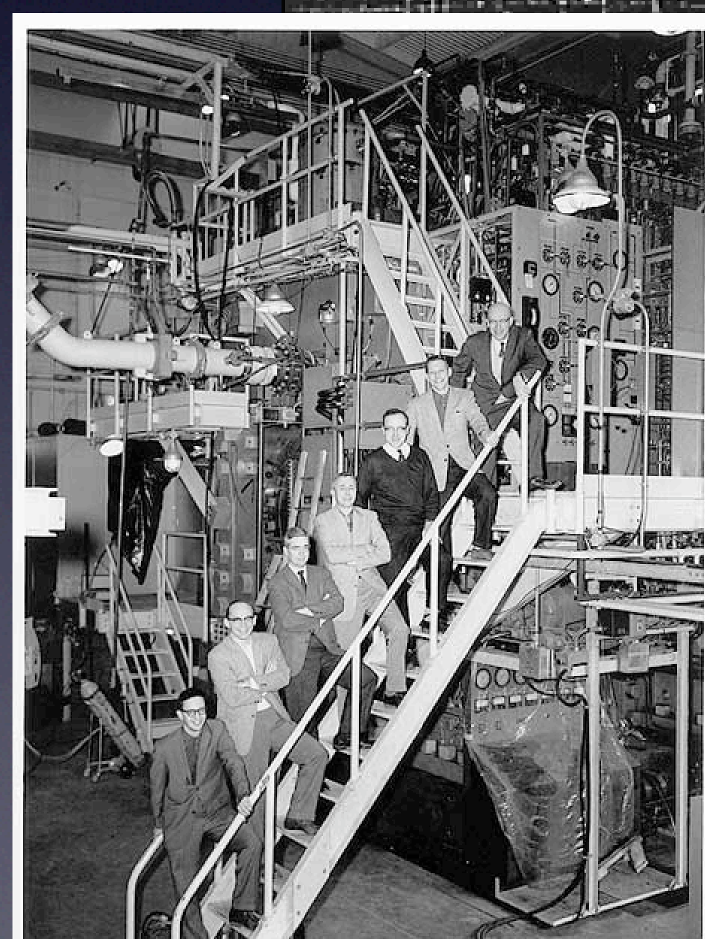
M. Gell-Mann

Gell-Mann and Ne'eman proposed "quarks" as a way to understand the particle zoo, kind of like the way the periodic table makes sense of the known elements

The Quark Model





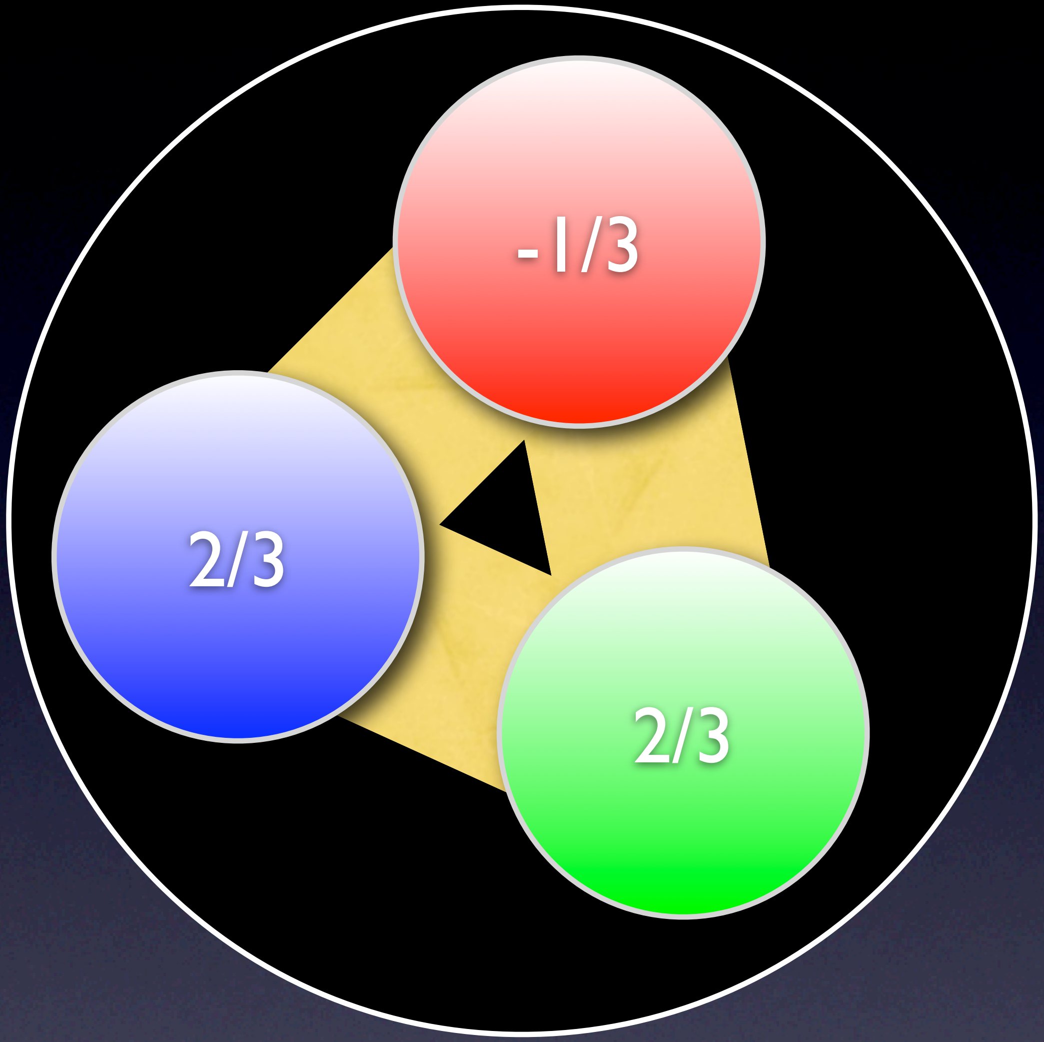


Omega-minus group: (T to B) Ralph Shutt, Jack Jensen, Medford Webster, William Tuttle, William Fowler, Donald Brown, Nicolas P. Samios

Discovery of Omega (sss) verified quark model

The Quark "Glue"

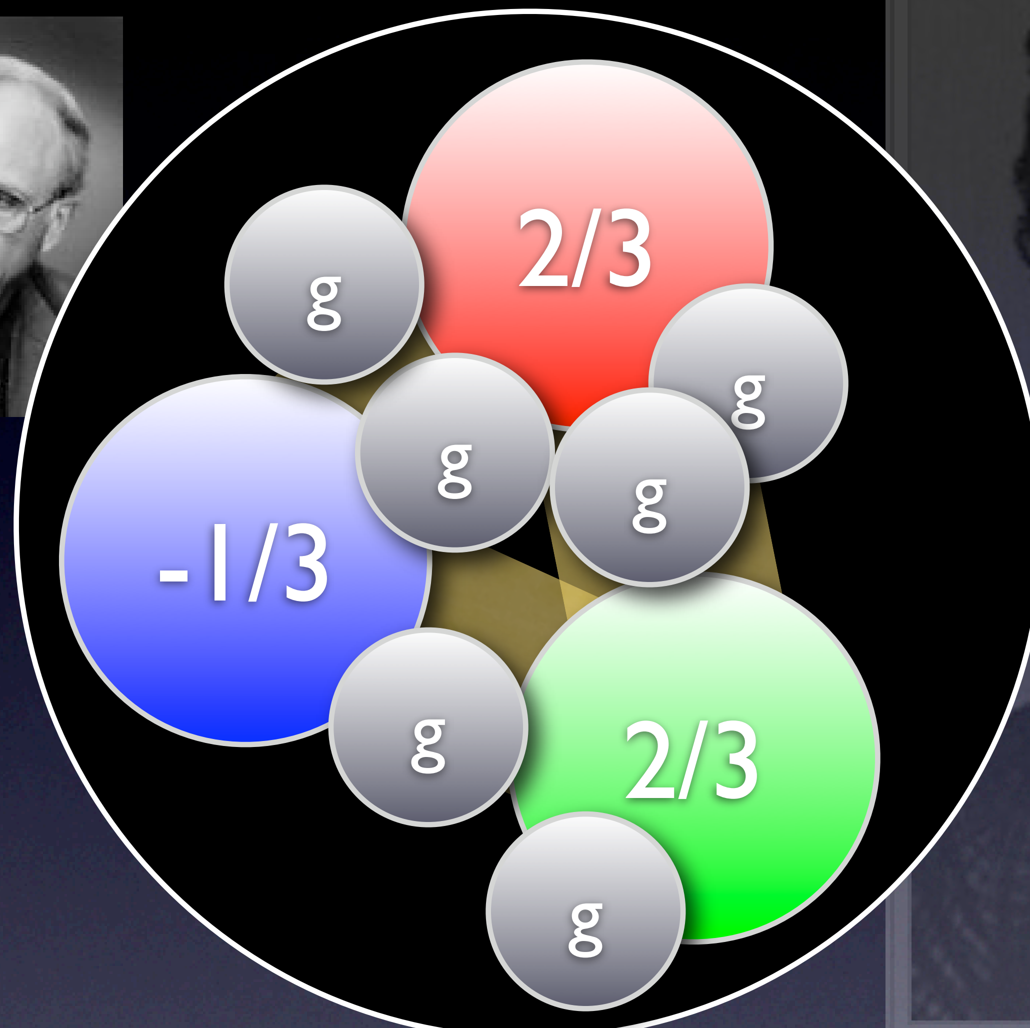
Yang & Mills
(1954 BNL)



After quarks were discovered theoretically and experimentally, it was a matter of time until people began to understand the forces (i.e fields) holding them together

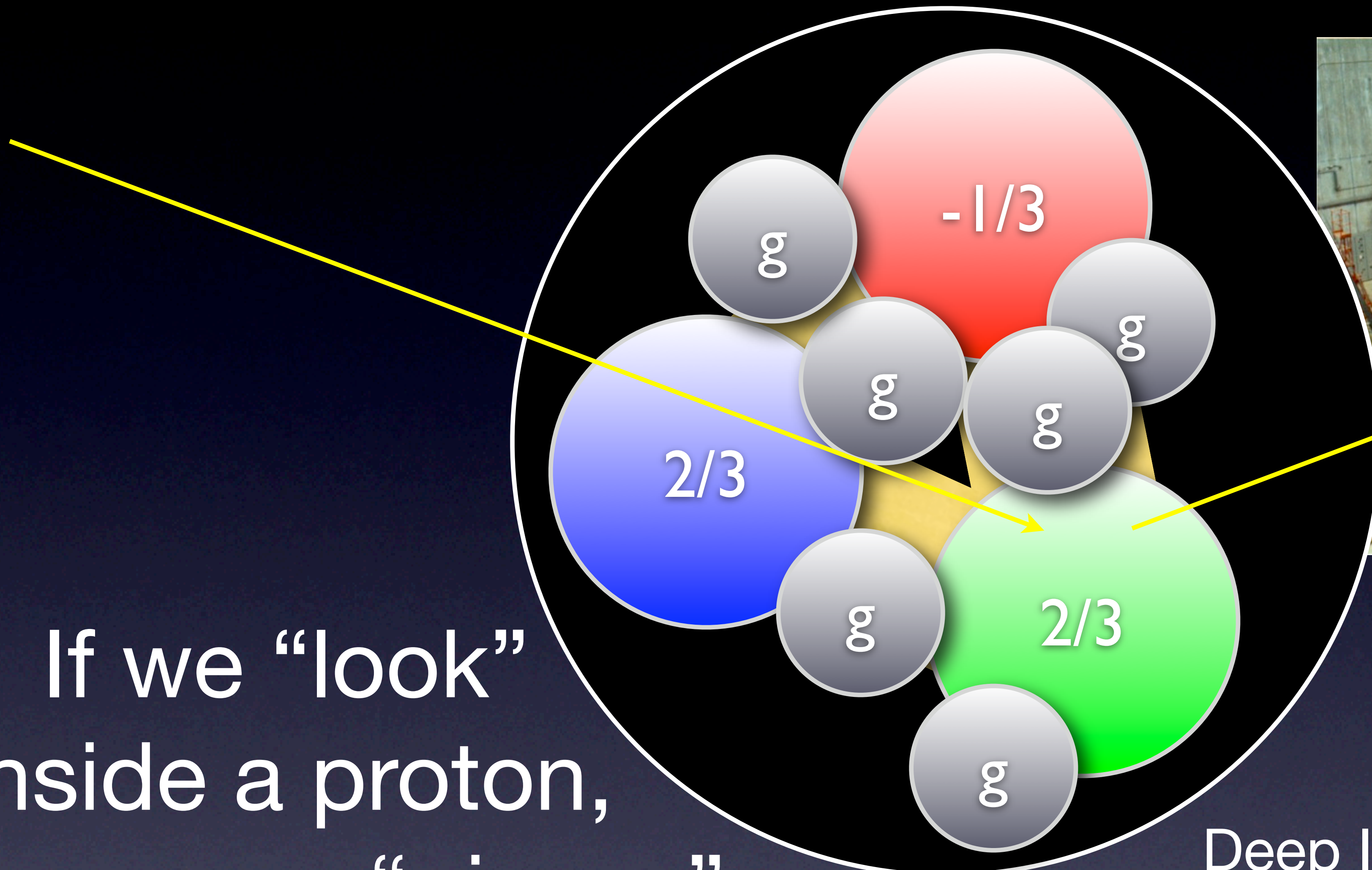
Quantum Chromodynamics

2004 Nobel Prize



Just as photons are the "particles" of the electromagnetic field (1905!), the **"gluon"** is the carrier particle of the "color" field of QCD, **Quantum Chromodynamics**

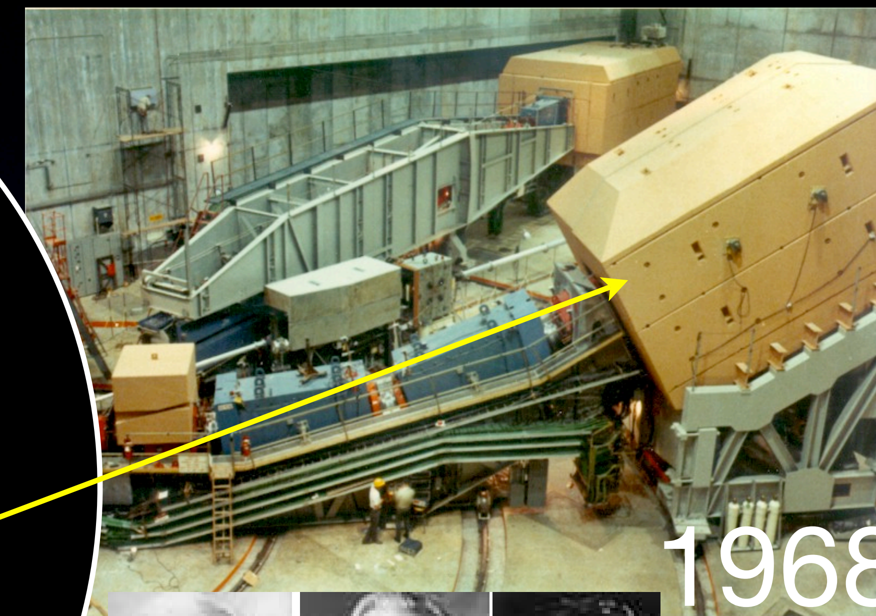
Probing a Proton

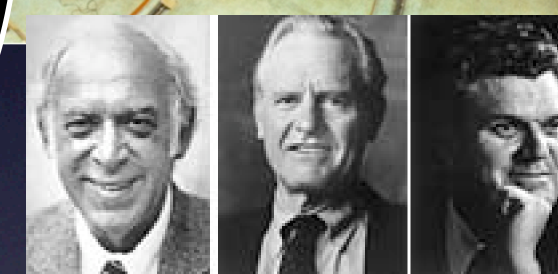


If we "look" inside a proton,
Can we see "pieces" of it fly out?

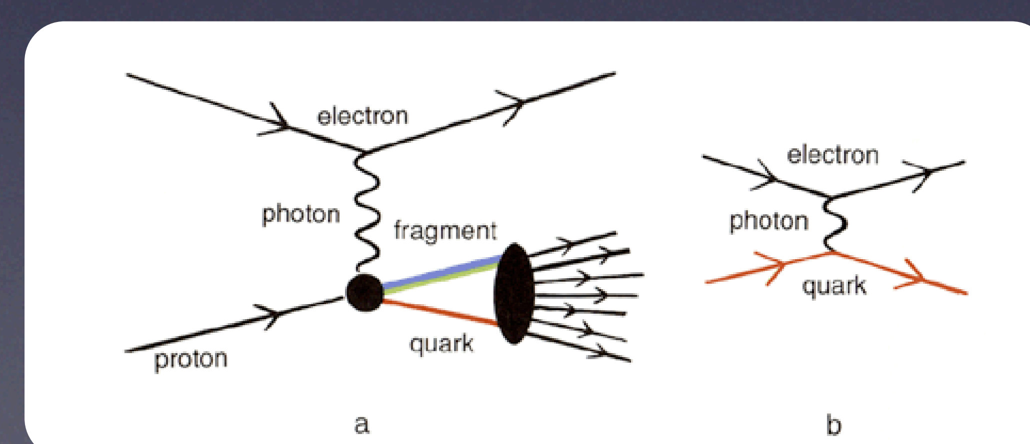

Feynman


Bjorken

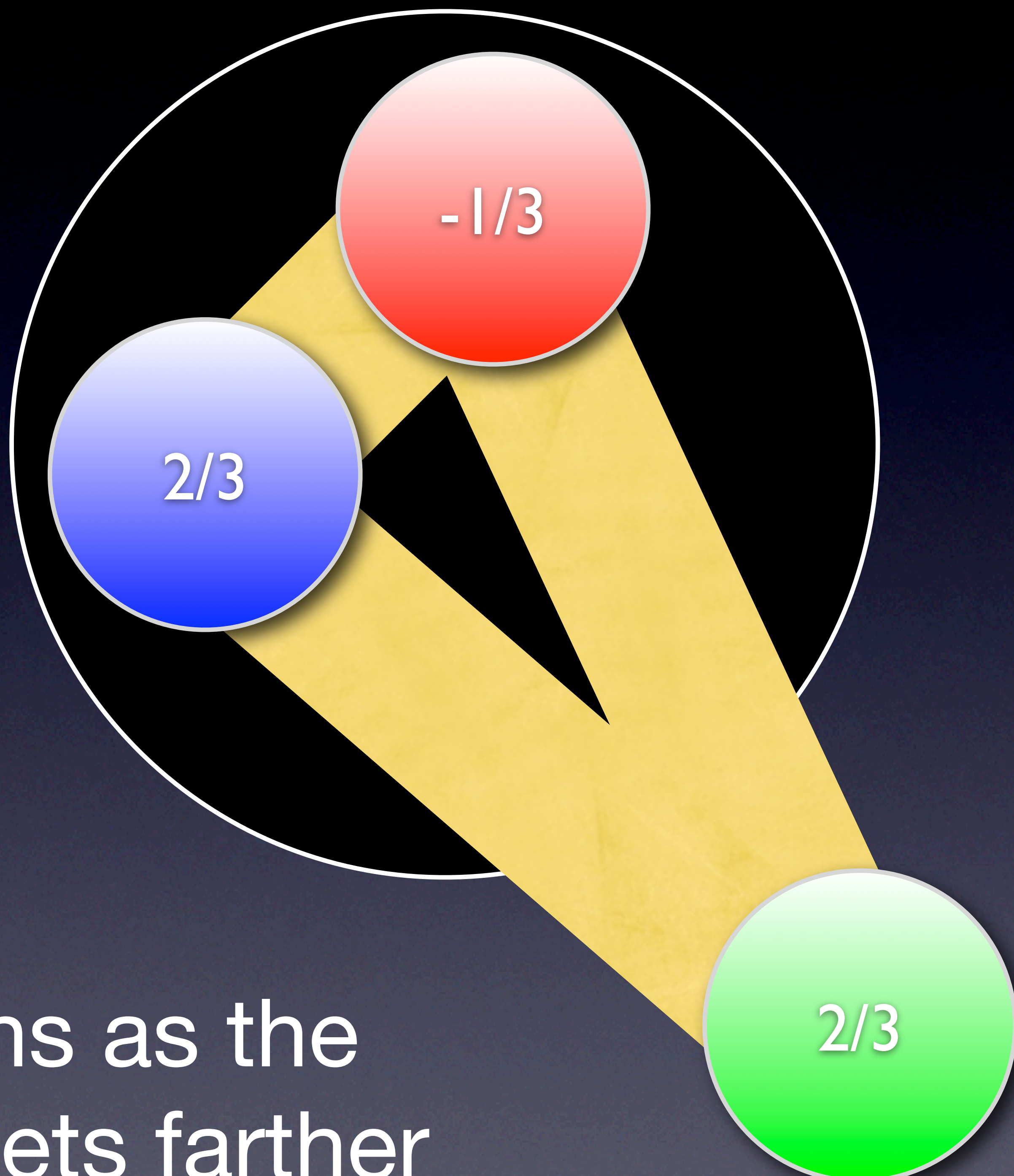



Nobel Prize

Deep Inelastic Scattering @ SLAC

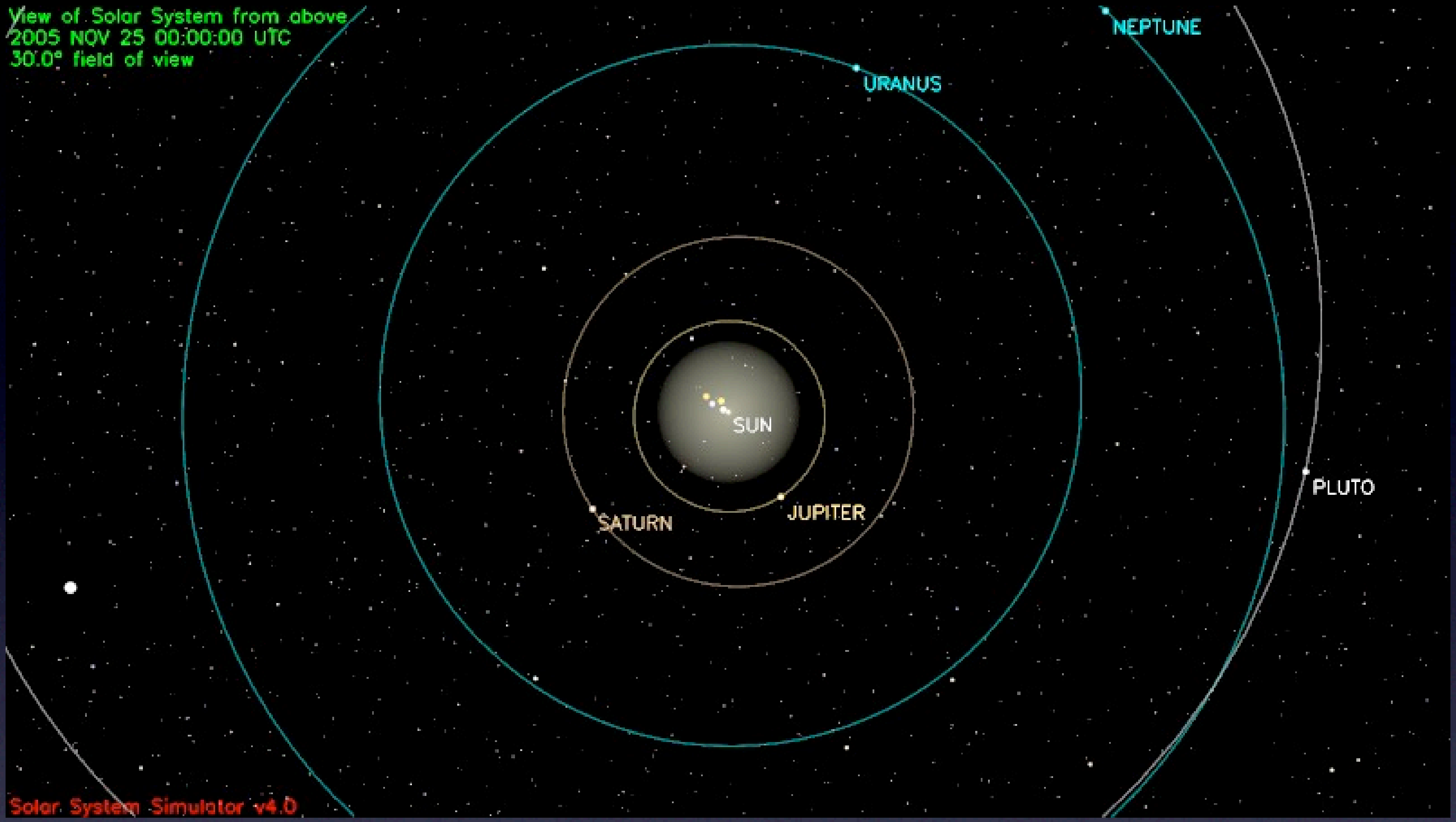


Probing a Proton

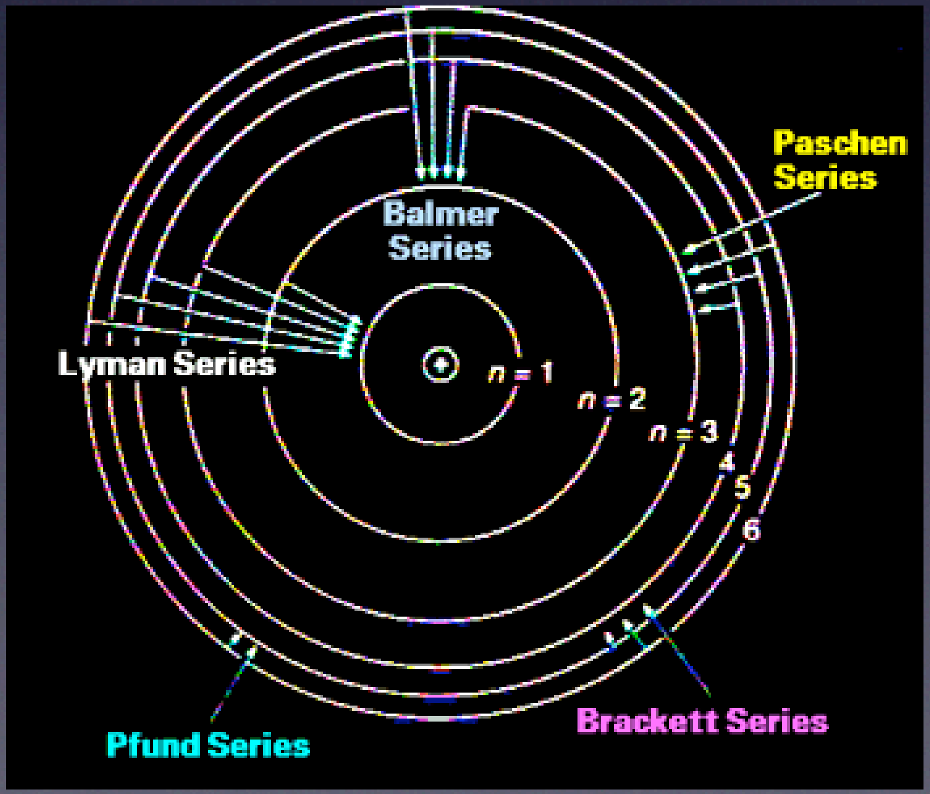


What happens as the struck quark gets farther from the proton?

Gravity & E&M



Gravity & Electromagnetism holds much of our world together (except the nucleus and nucleon)

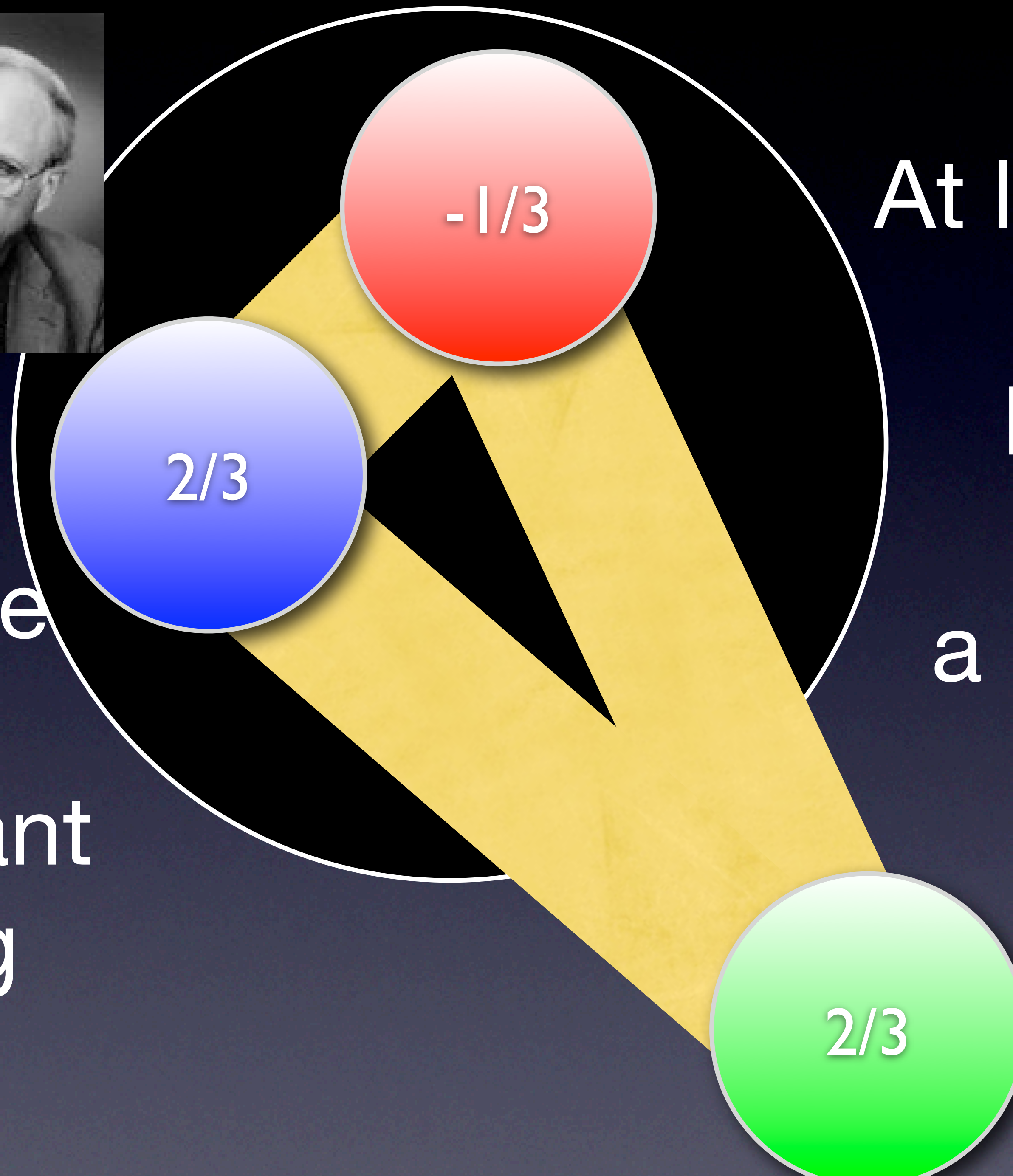


http://www.mps.mpg.de

The two most important forces in our everyday lives get weaker as the particles get farther away from each other!

$E \sim 1/r$, $F \sim 1/r^2$

Probing a Proton



QCD

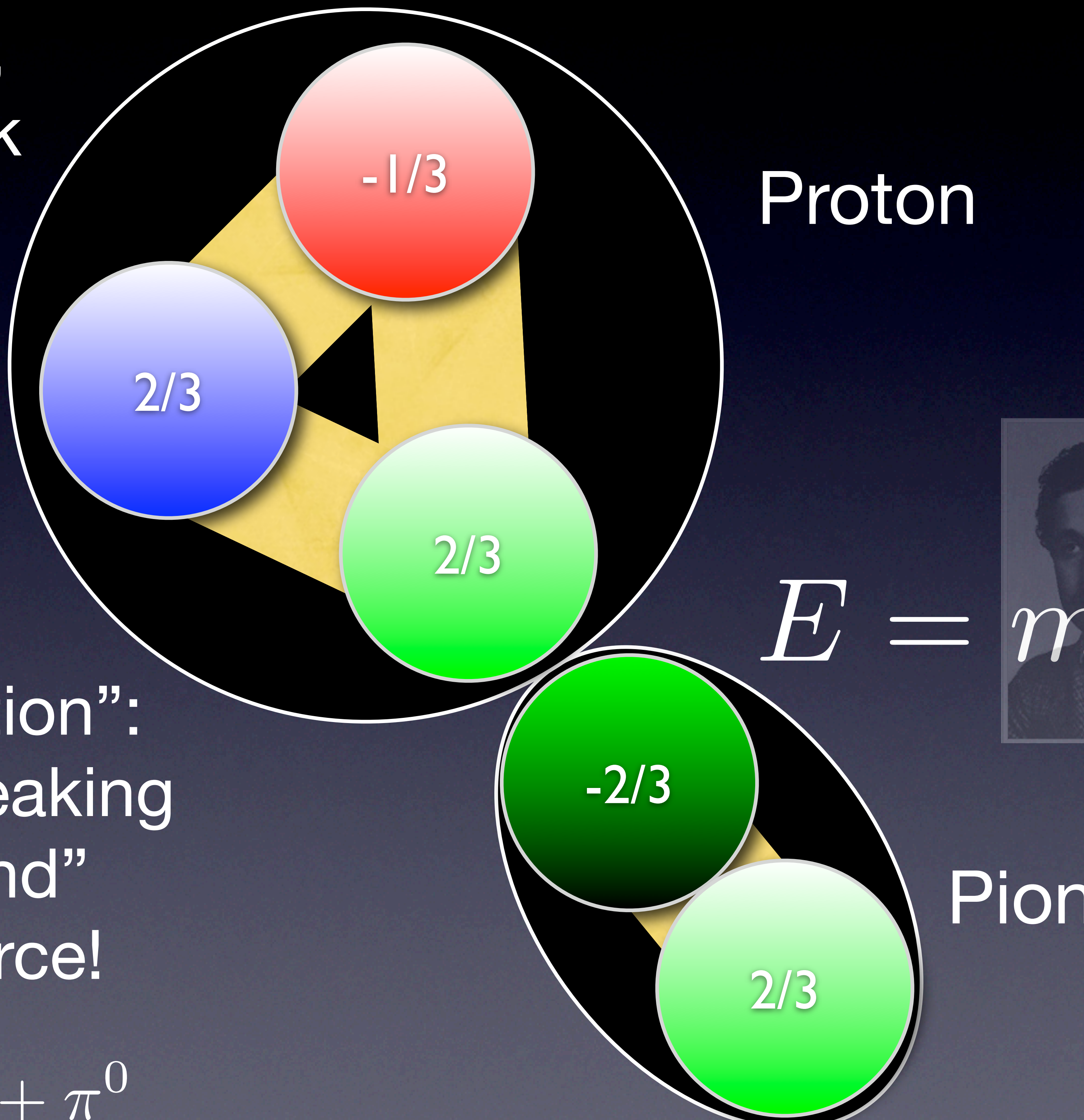
predicts that the force between quarks is constant with increasing distance

At long distance, Energy ~ r kind of like stretching a rubber band

(...and at short distance $F \sim 1/r^2$ again!)

SNAP!

Eventually, there's too much energy, and another quark and anti-quark "pop" out of the vacuum!



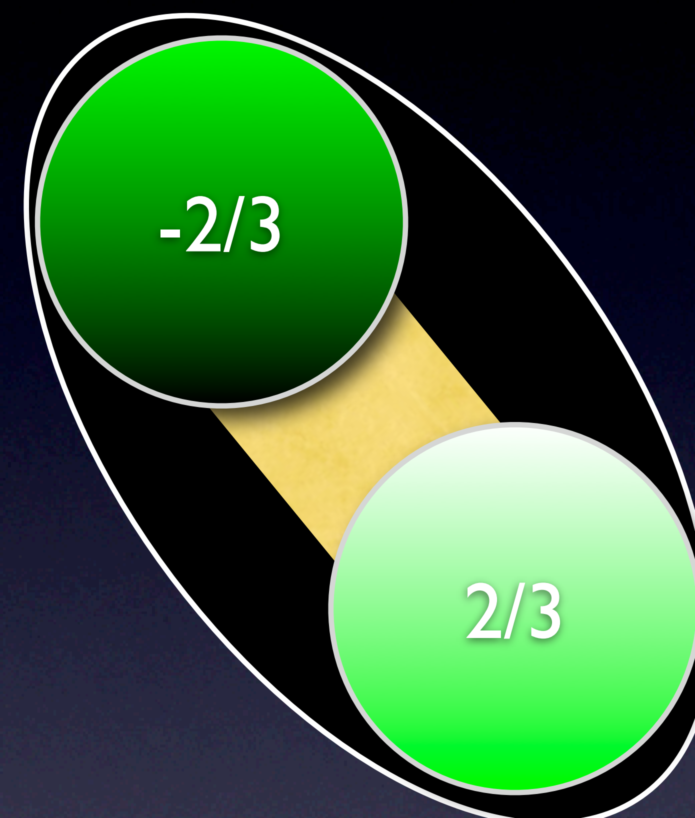
$$E = mc^2$$

"Particle production": stretching and breaking the "rubber band" of the strong force!

$$e^- + p \rightarrow e^- + p + \pi^0$$

“Hadrons”

A “Baryon” is 3 quarks: flavors, charge, spin, mass & CONSERVED



A “Meson” is quark & anti-quark: flavors, charge, spin, mass

Quantum Chromodynamics requires “colorless” particles

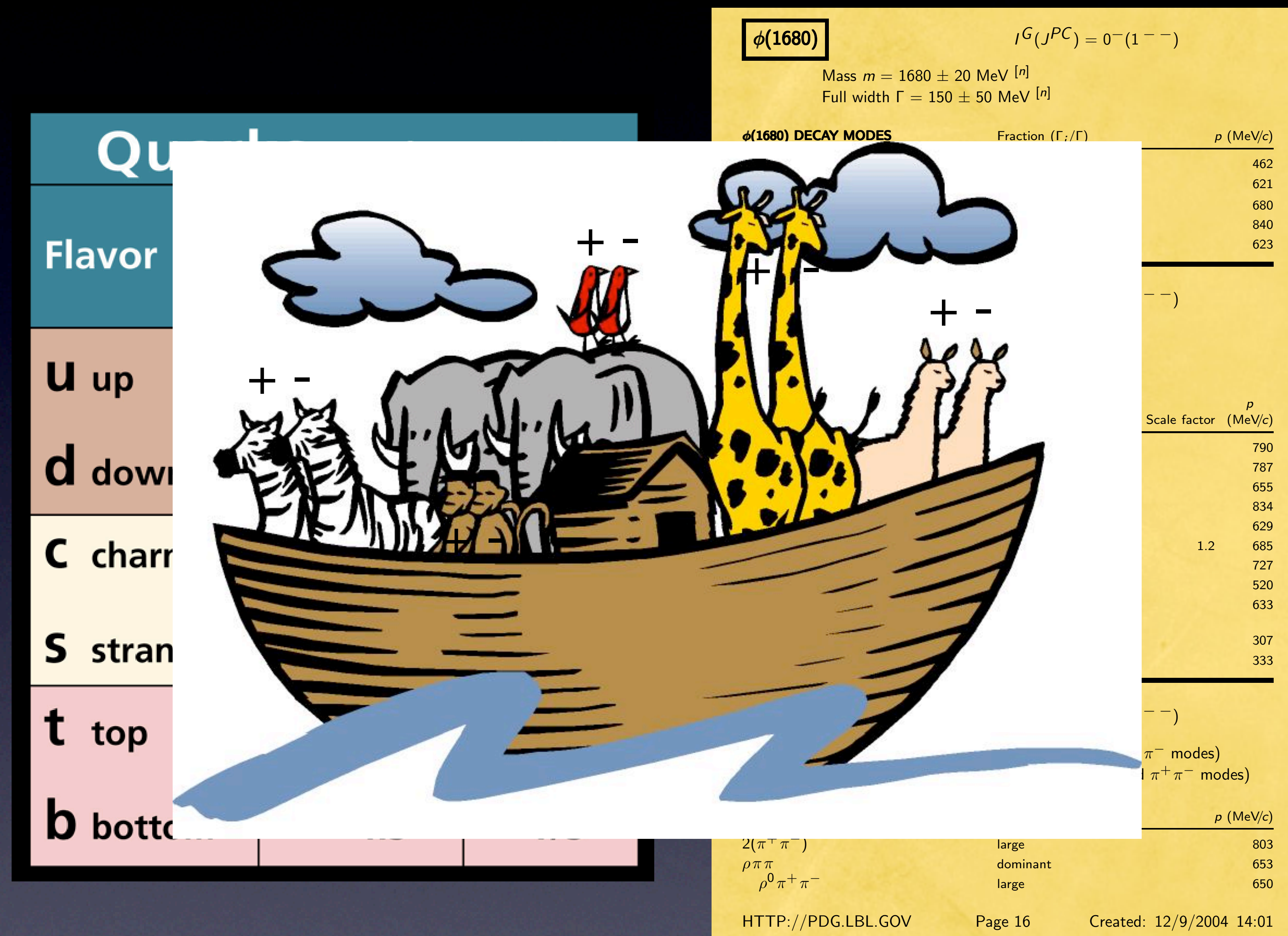
A Zoo? More like an

Σ Λ Ω p Δ Ξ n

Baryon
(3 q or $\bar{q}$)

ω ρ K π ϕ ρ

Meson
(1 q & $\bar{q}$)



1000's of "hadronic states" (particles & anti-particles) have been observed: more all the time

Heating

In the early 1960's Rolf Hagedorn predicted that the bound state spectrum would rise indefinitely
→ Singularity at <u>limiting temperature</u>
T_H~170 MeV

$$\rho(m) \sim m^a e^{m/T_0} \to Z$$

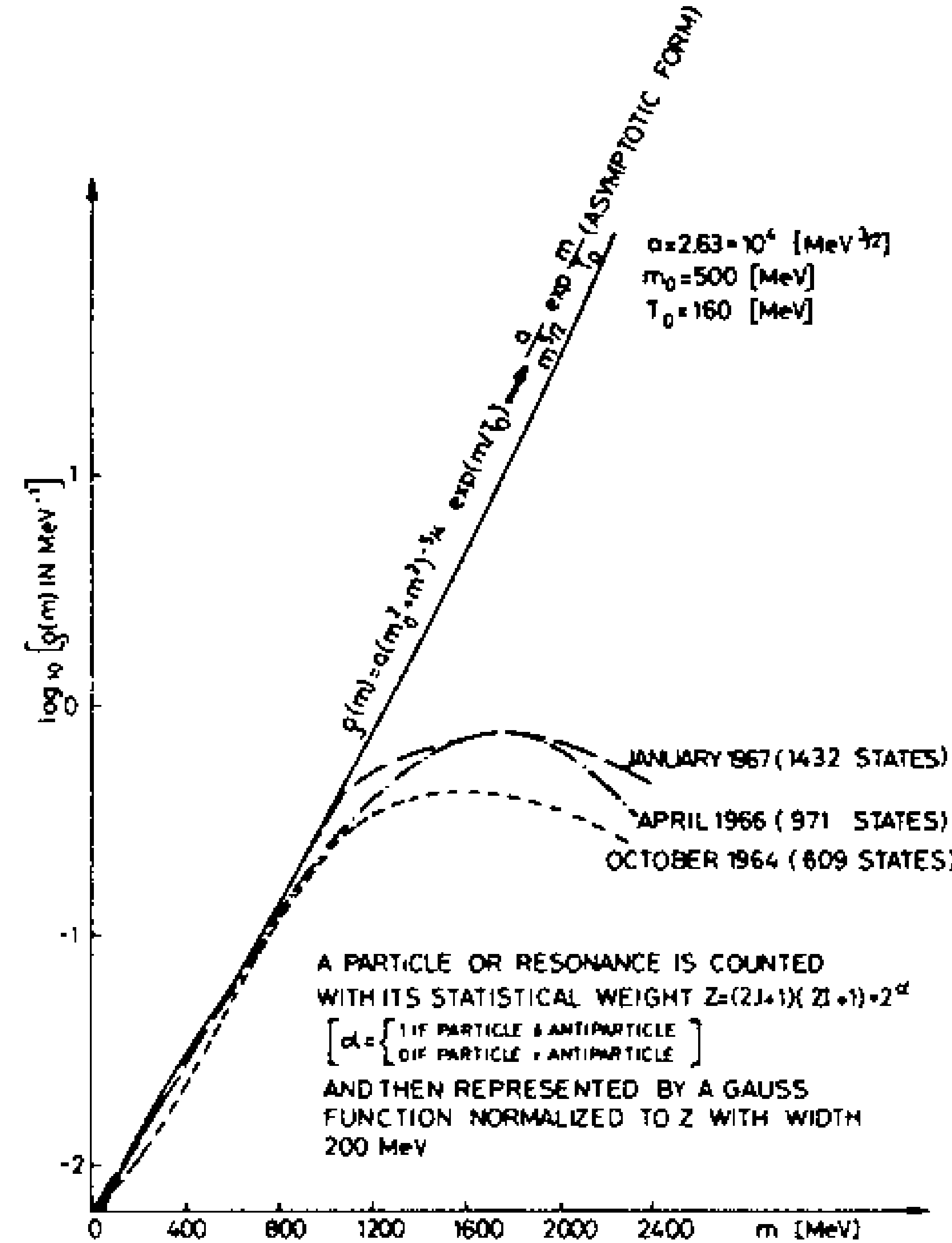
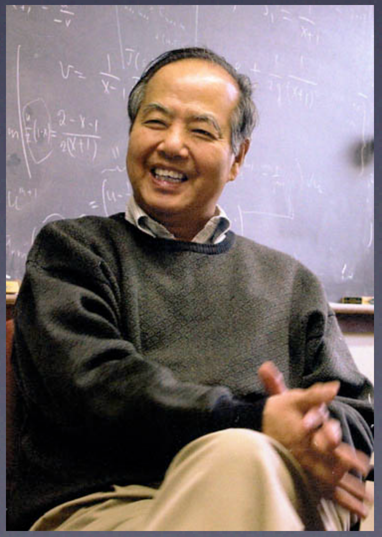


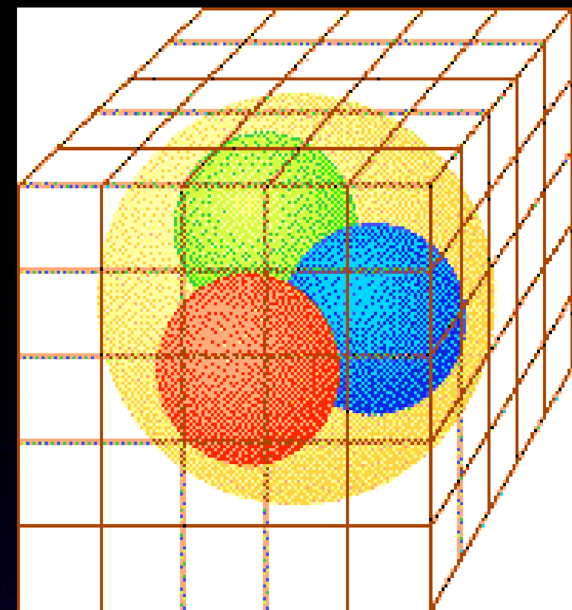
Fig. 3.1: The predicted and the experimental mass spectrum as it evolved from 1964 to 1967.

We've come a long way!

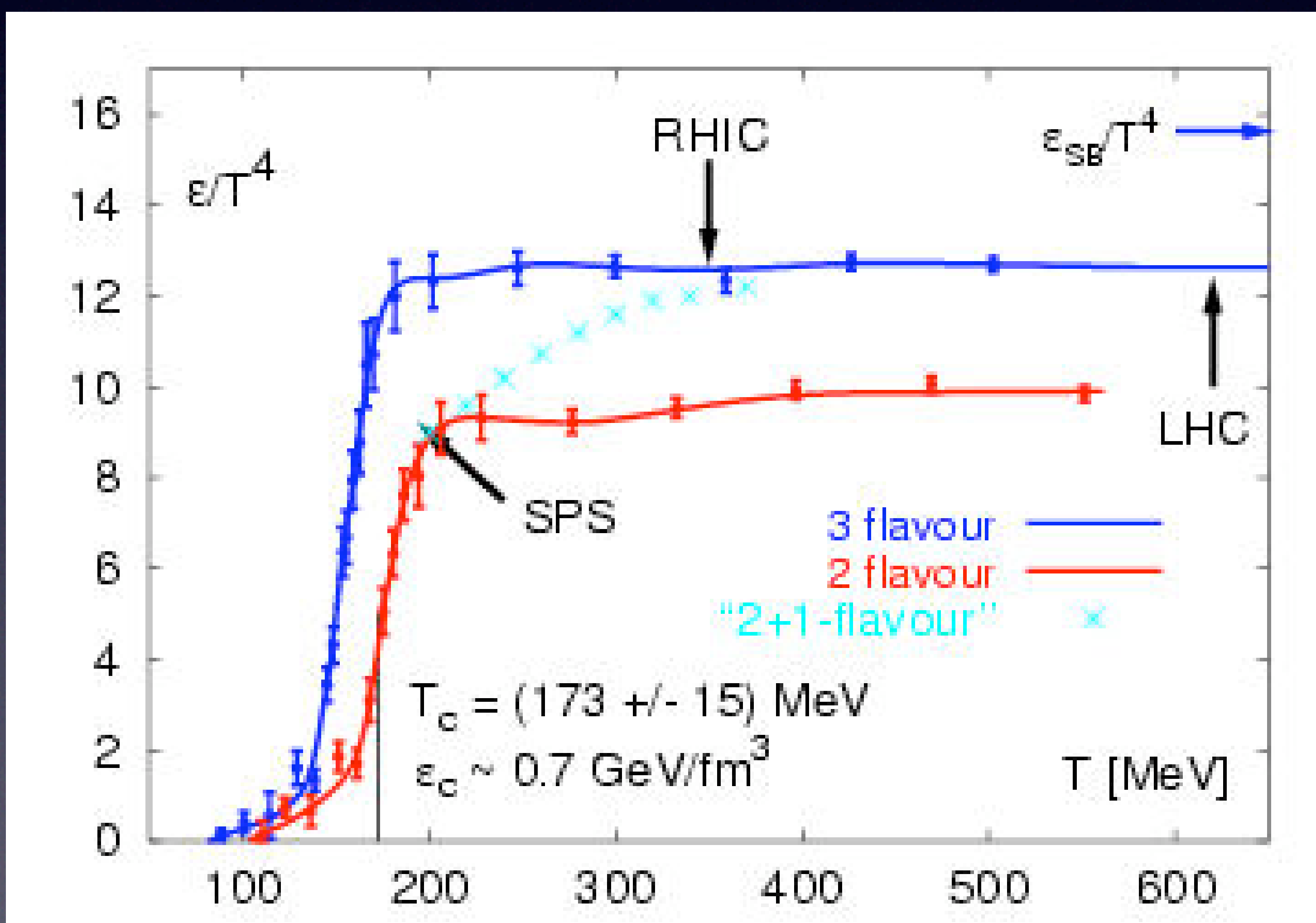
QCDOC 10 Teraflop computer
at RIKEN/BNL Research Center

T.D. Lee



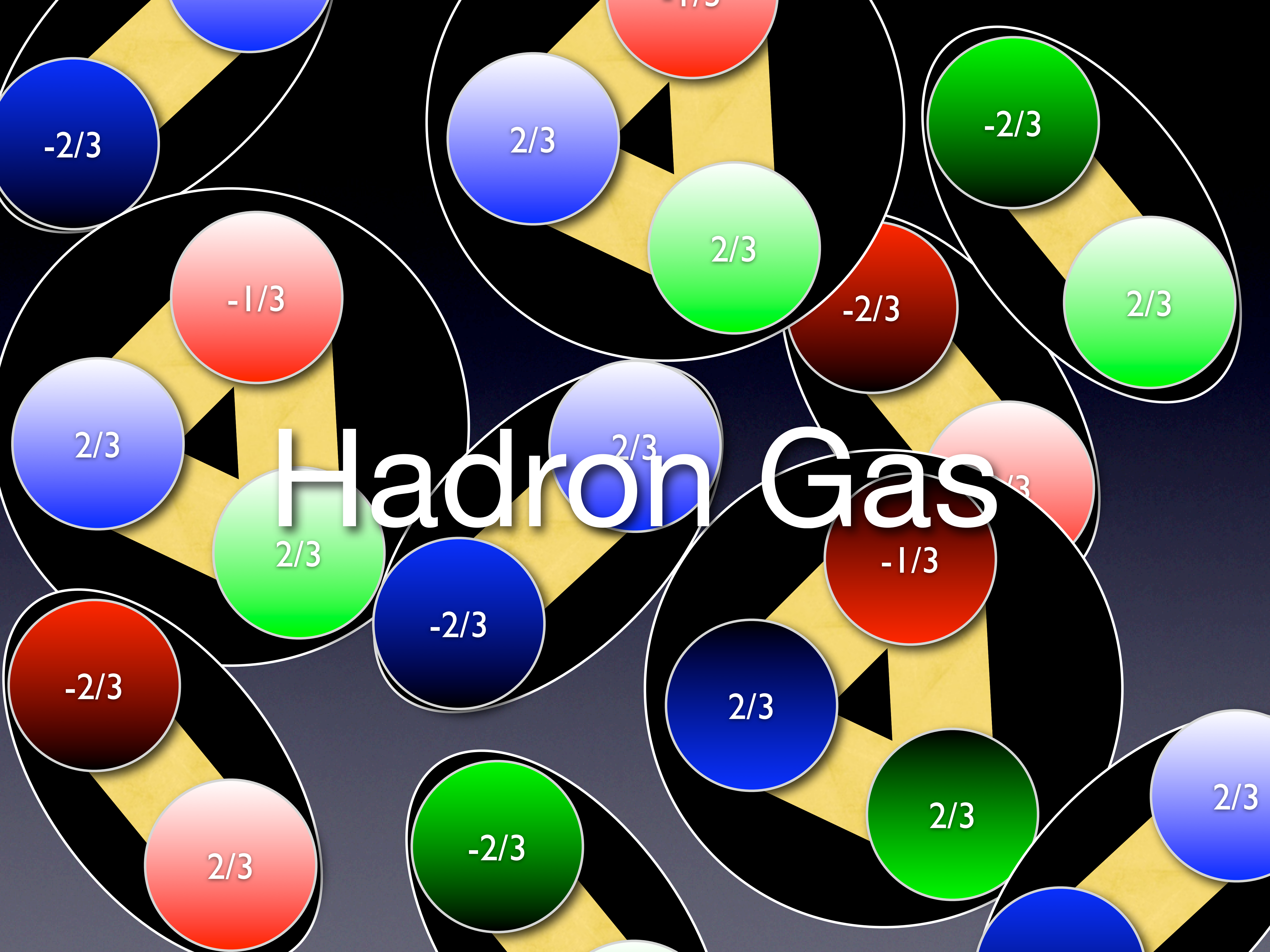


QCD is notoriously hard to solve for high temperature, so solved numerically on powerful machines!



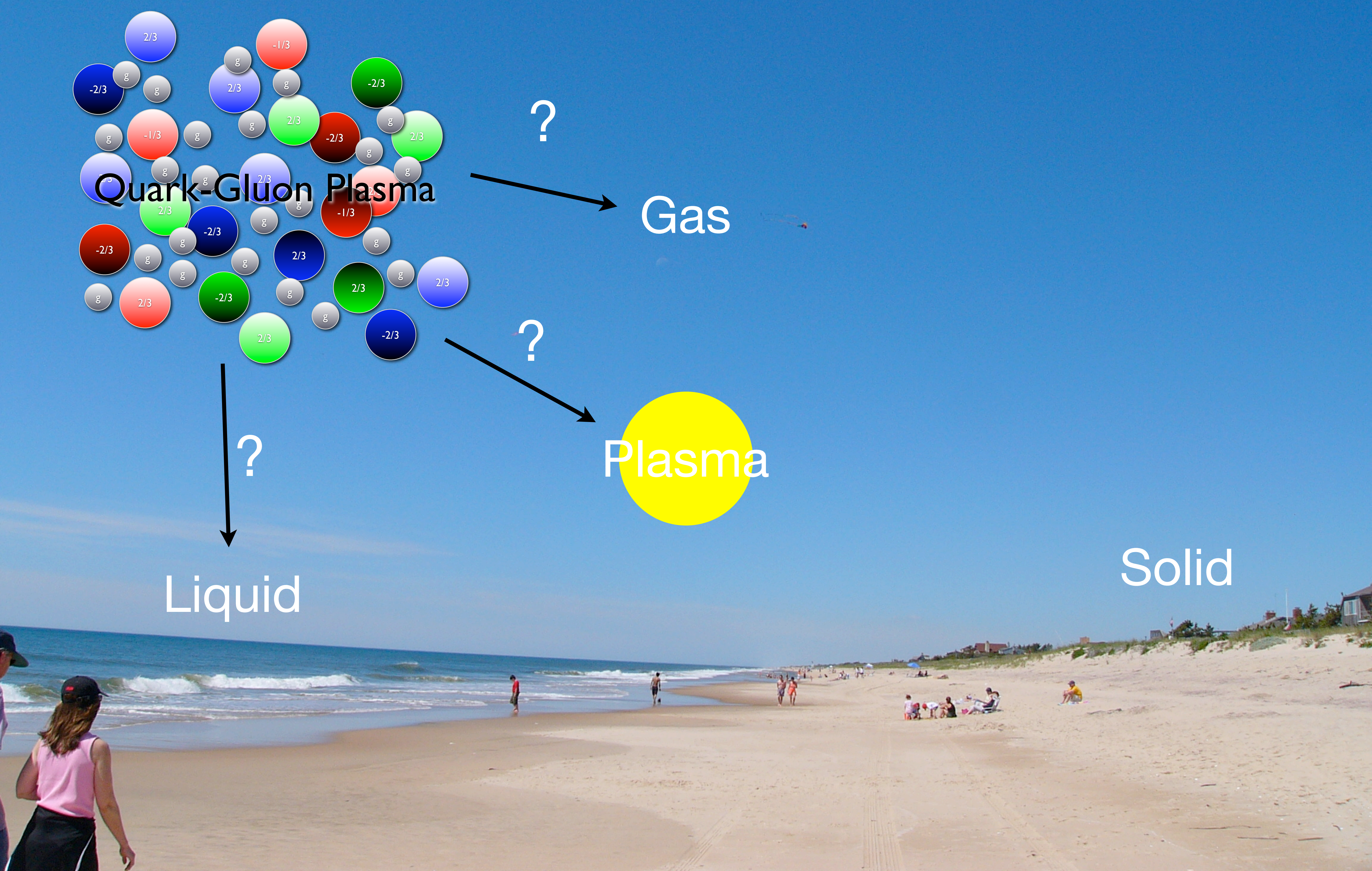
Years ago, it was discovered that there is a “jump” in the number of “degrees of freedom” at the Hagedorn temperature

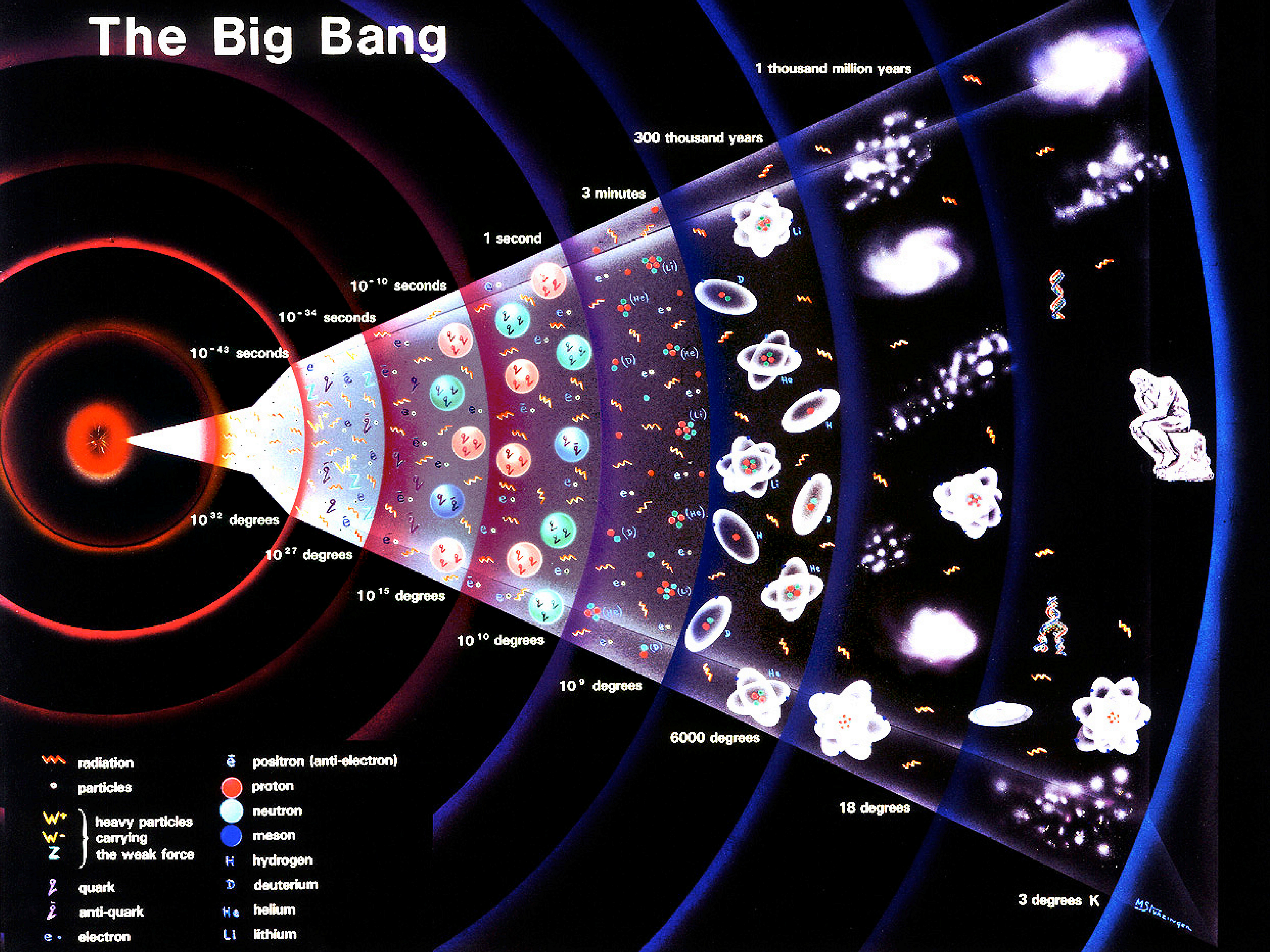
Hadron Gas



Quark-Gluon Plasma

QGP is a new state of matter




The Big Bang
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

What State of Matter?

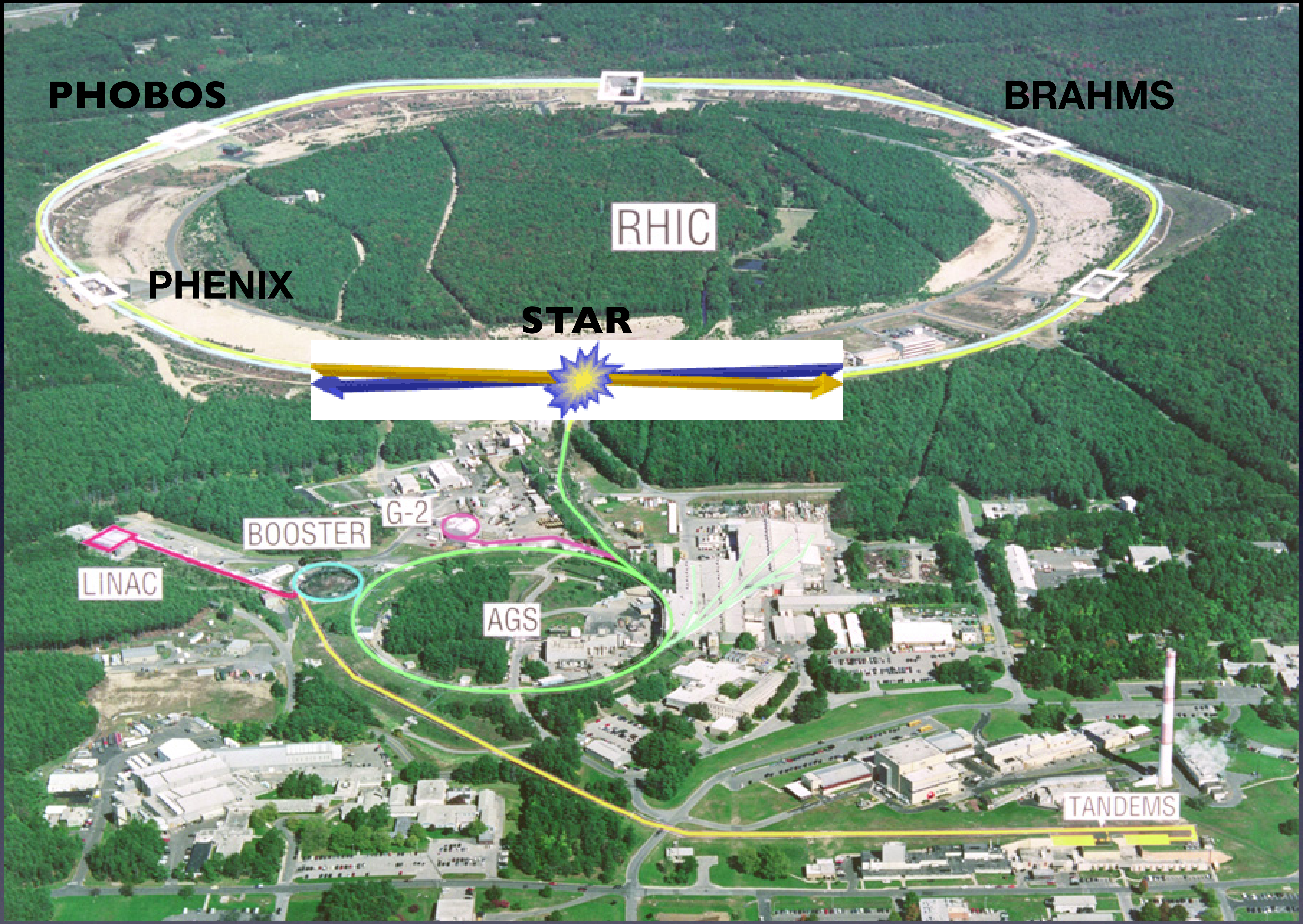
Does it act
like an ideal gas?

Does it flow,
like a (compressible) liquid?

RHIC

Relativistic Heavy Ion Collider

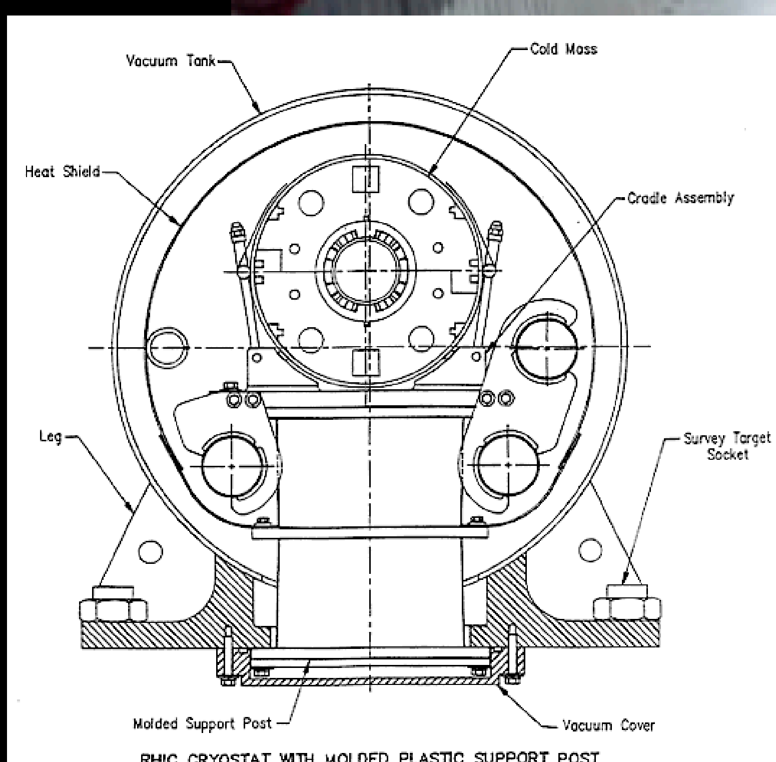
RHIC



Relativistic Heavy Ion Collider

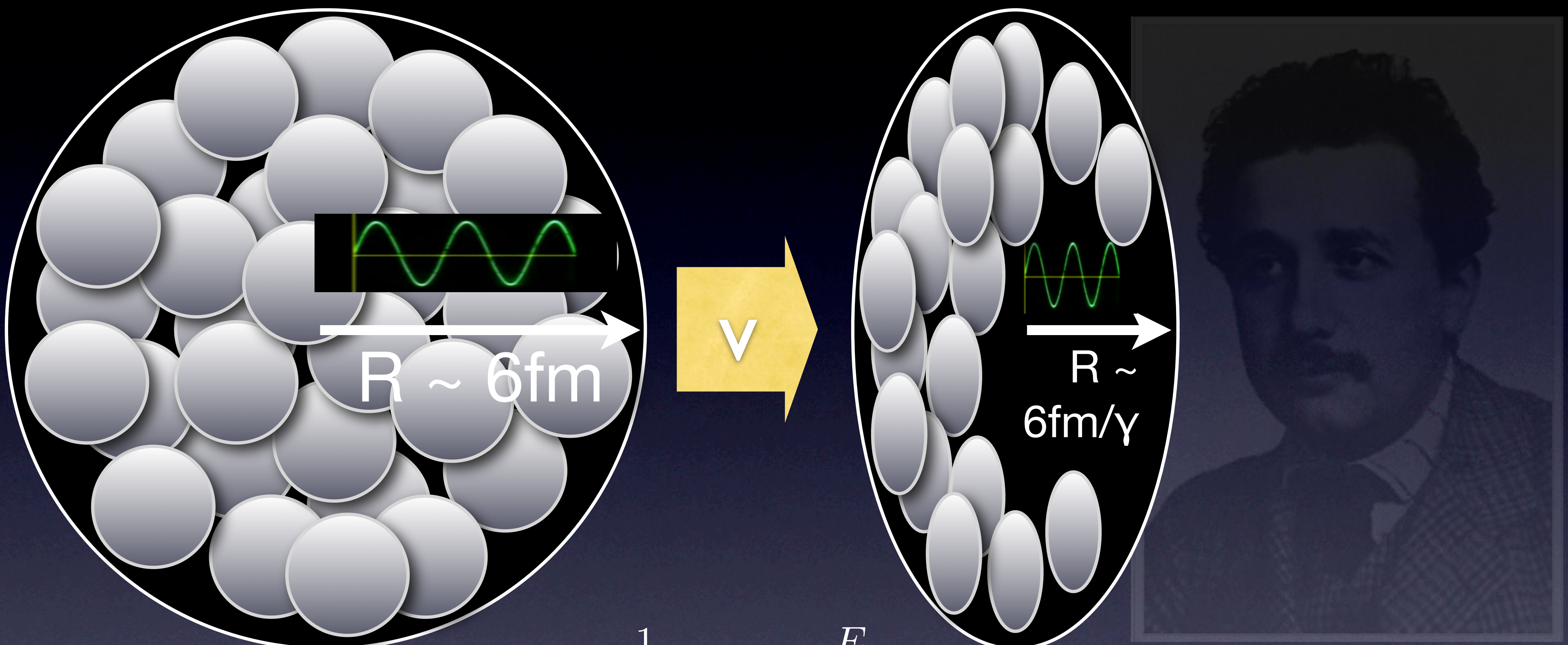
RHIC @ BNL


Tandems
Superconducting
Magnets (@ 4^oK)


Vacuum Tank
Cold Mass
Heat Shield
Cradle Assembly
Leg
Survey Target Socket
Molded Support Post
Vacuum Cover
RHIC CRYOSTAT WITH MOLDED PLASTIC SUPPORT POST


RF Cavities

"Lorentz Contraction"



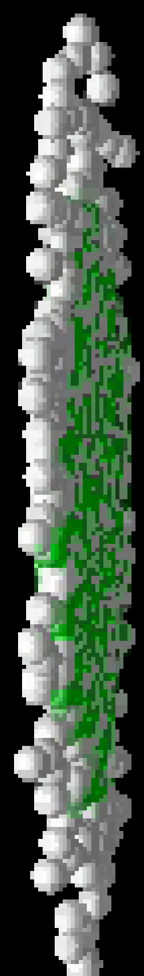
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{E}{mc^2}$$

Objects approaching speed of light appear "contracted"

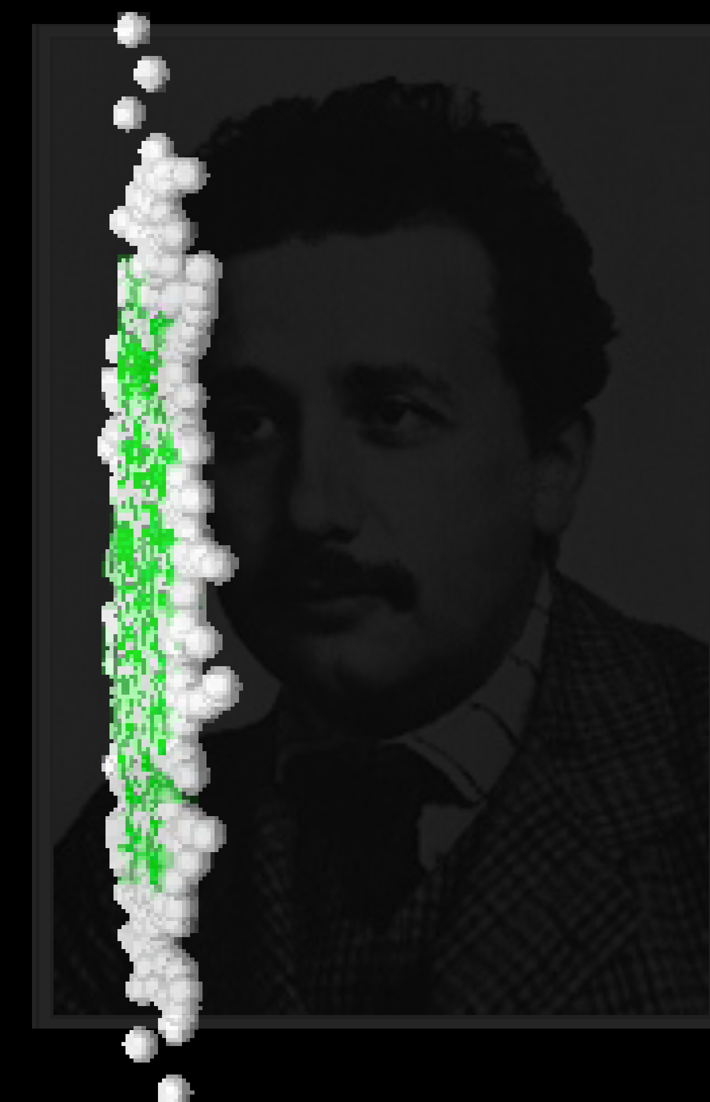
At RHIC, we accelerate gold ions to 99.995% of the speed of light -- a ~100x compression!

Time in units of fm/c = 3×10^{-24} sec

http://www.ccd.bnl.gov/visualization/gallery/au_on_au/



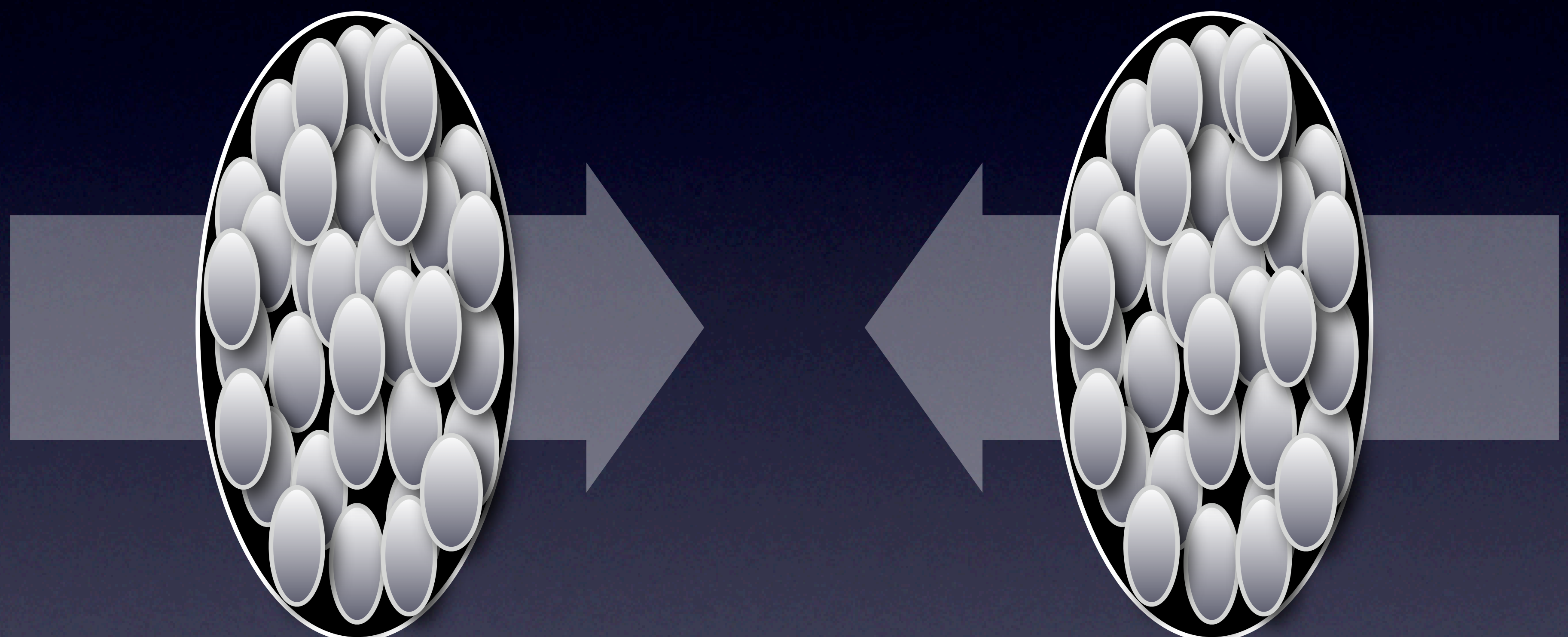
$$E = \gamma m c^2$$



t = -19.800

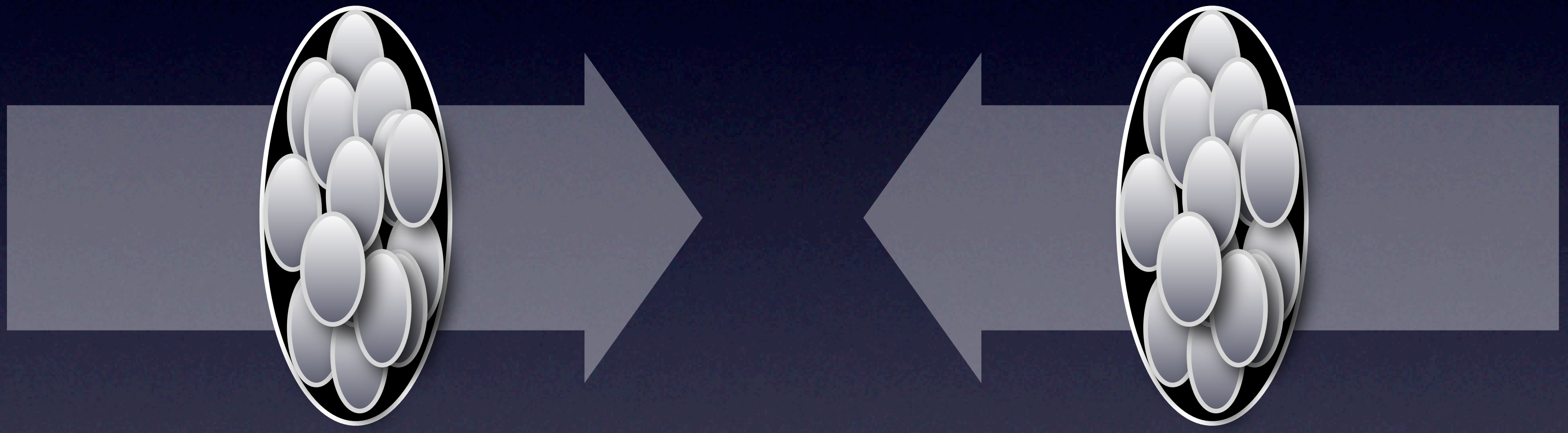
We then use $E=mc^2$ as a tool - colliding nuclei at high energy makes thousands of new degrees of freedom, possibly creating a Quark-Gluon Plasma

The Range of RHIC



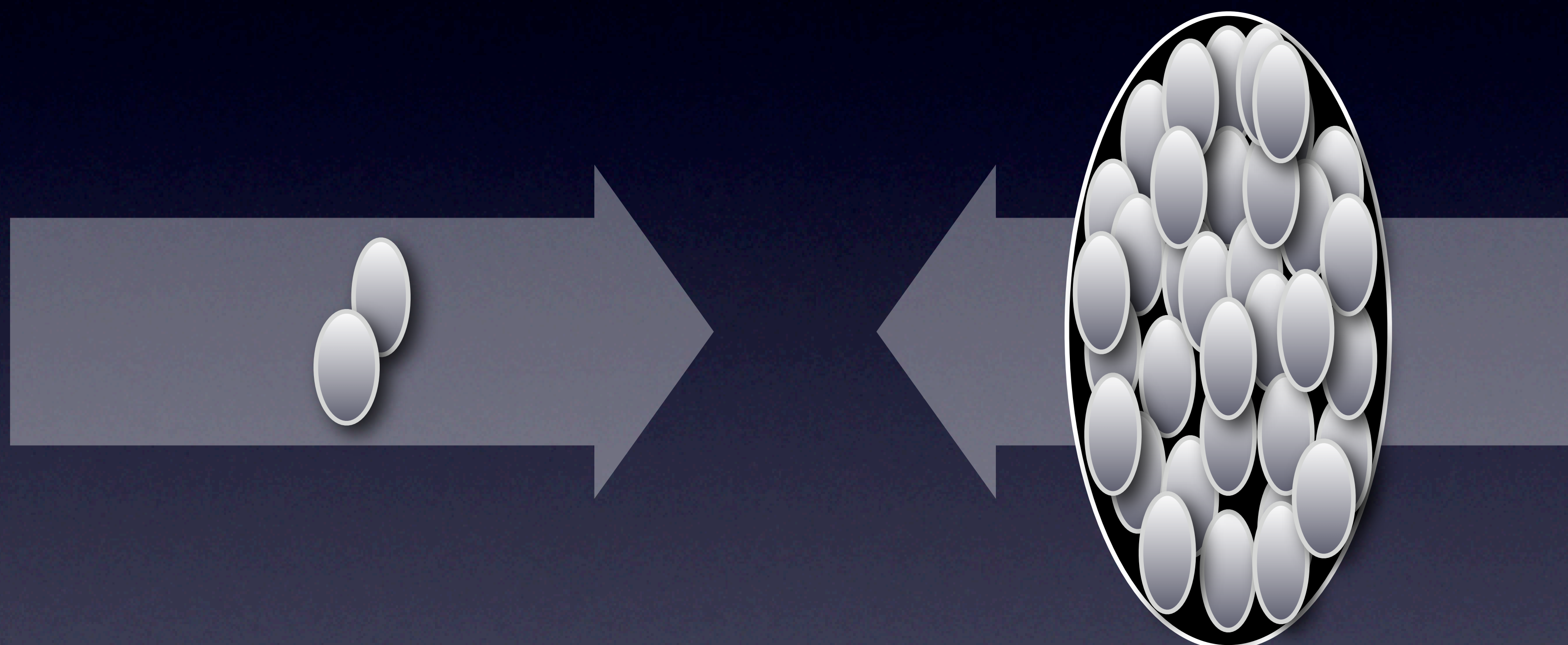
Au+Au collisions at 200 GeV/NN pair
are the RHIC standard-bearer
(with energy scan: 19.6-200 GeV)

The Range of RHIC



Cu+Cu collisions have been used to study properties of smaller systems (also scan 22.4-200 GeV)

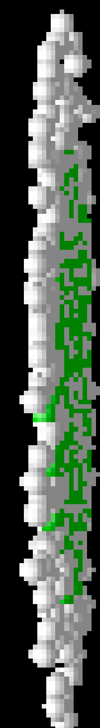
The Range of RHIC



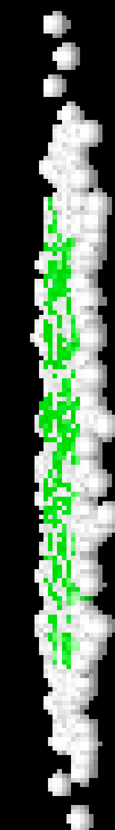
d+Au collisions have been used to
study the nuclear wave function at 200 GeV
(d had a closer Z/A ratio to Au than p)

The Range of RHIC

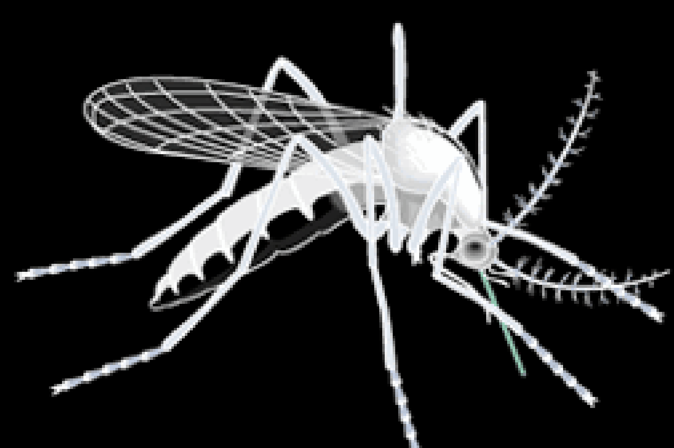
Proton-proton collisions are used as "reference data", assuming no medium effects are present (is this true?)



How much energy in each collision?



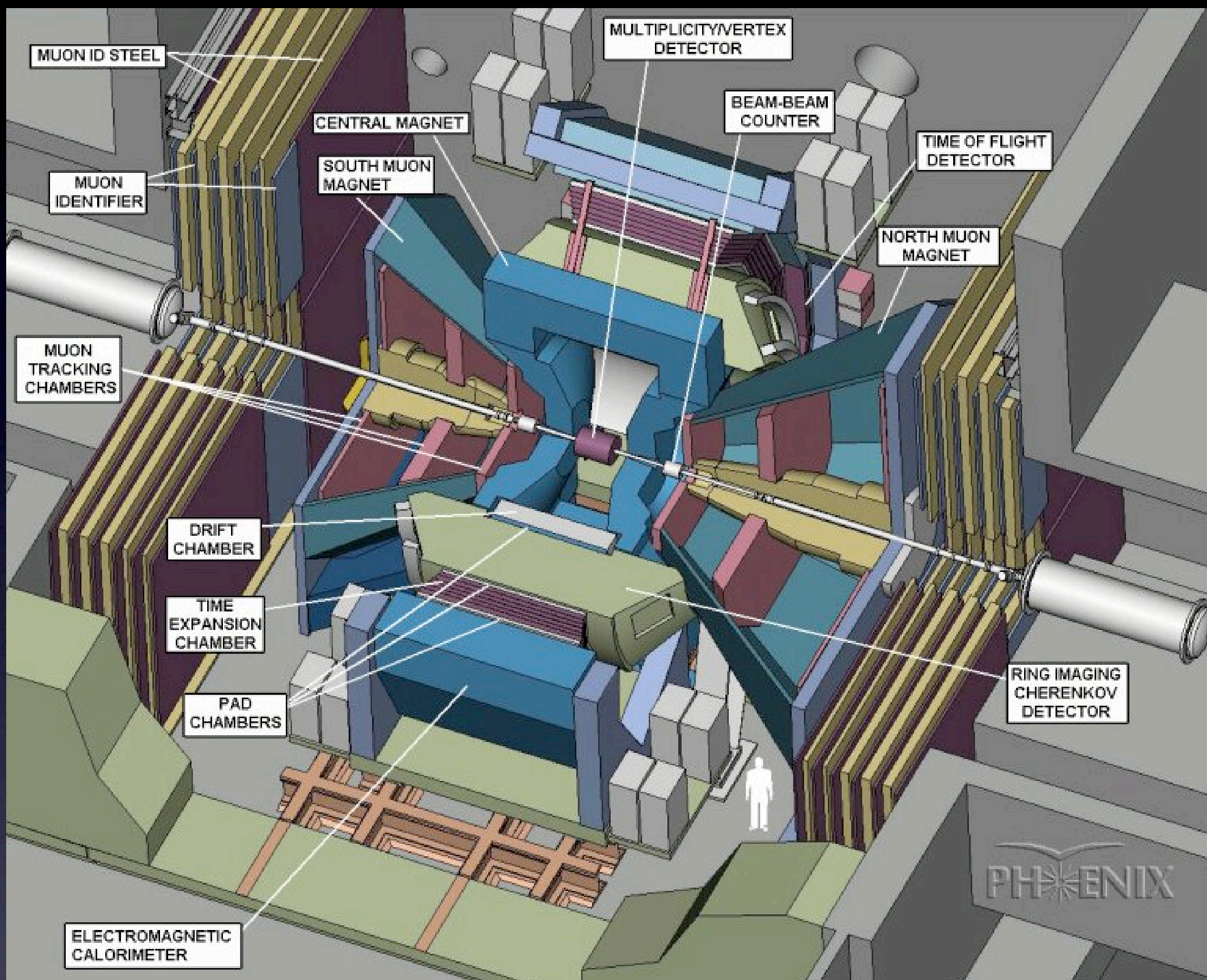
$$1.6 \times 10^{-19} \frac{J}{eV} \times 197 \times 200GeV \sim 6\mu J$$

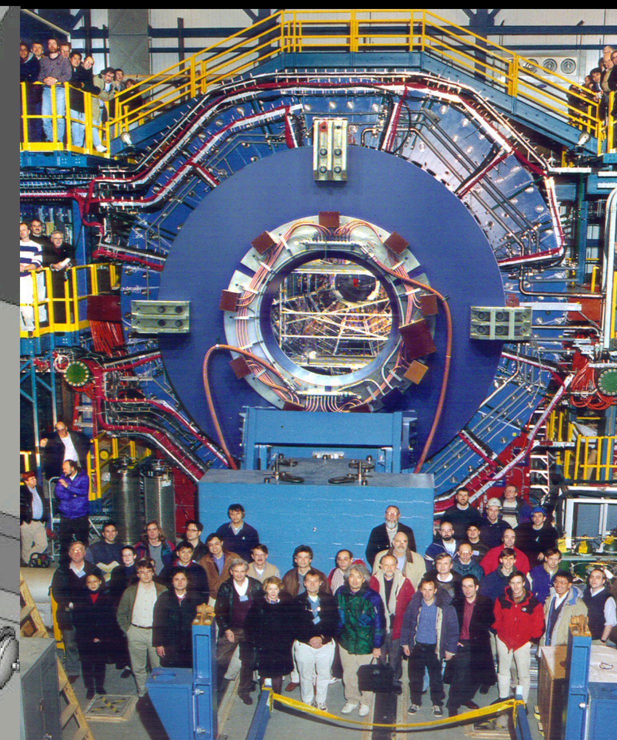


Consider two mosquitos colliding...

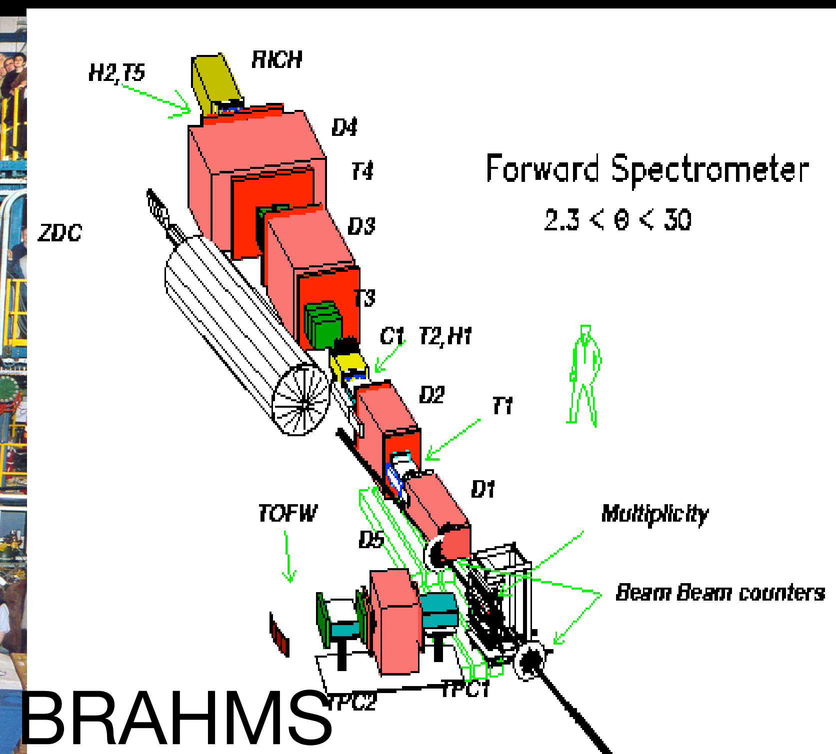
$$2 \times \frac{1}{2} mv^2 = (2.5mg) \times (2.5km/h)^2 = 1.2\mu J$$

RHIC Detectors to Scale



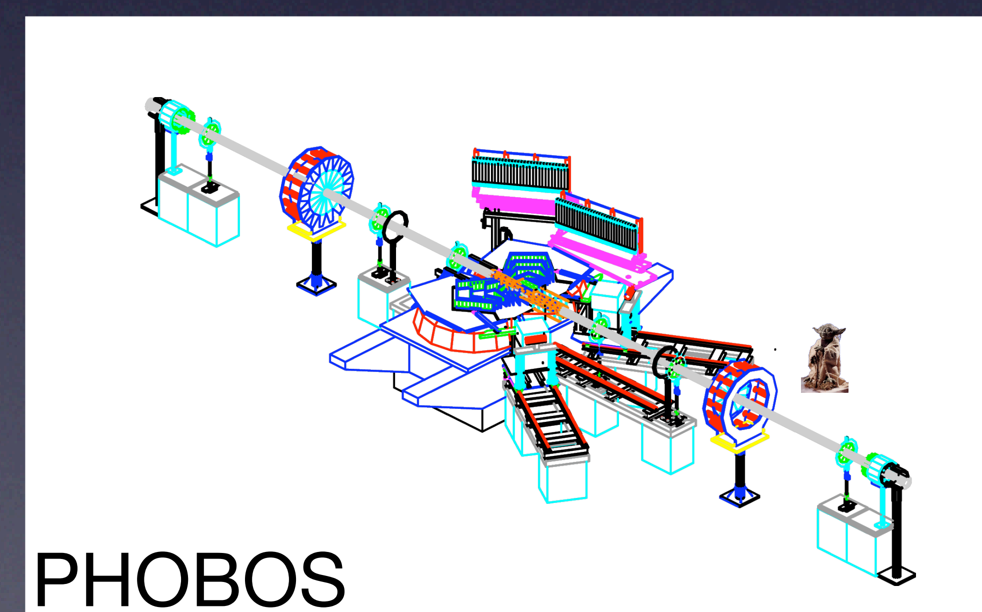


STAR



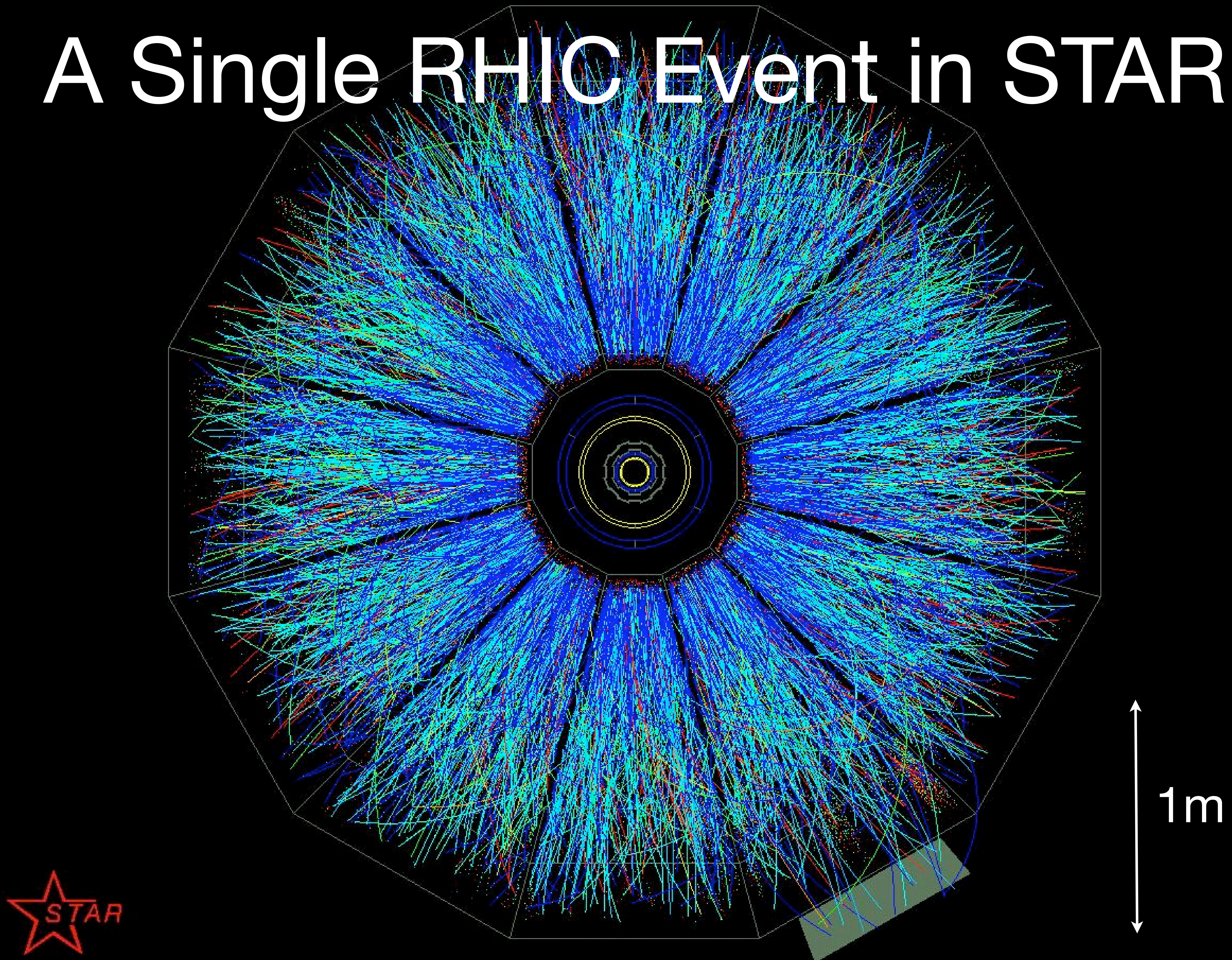
BRAHMS

PHENIX

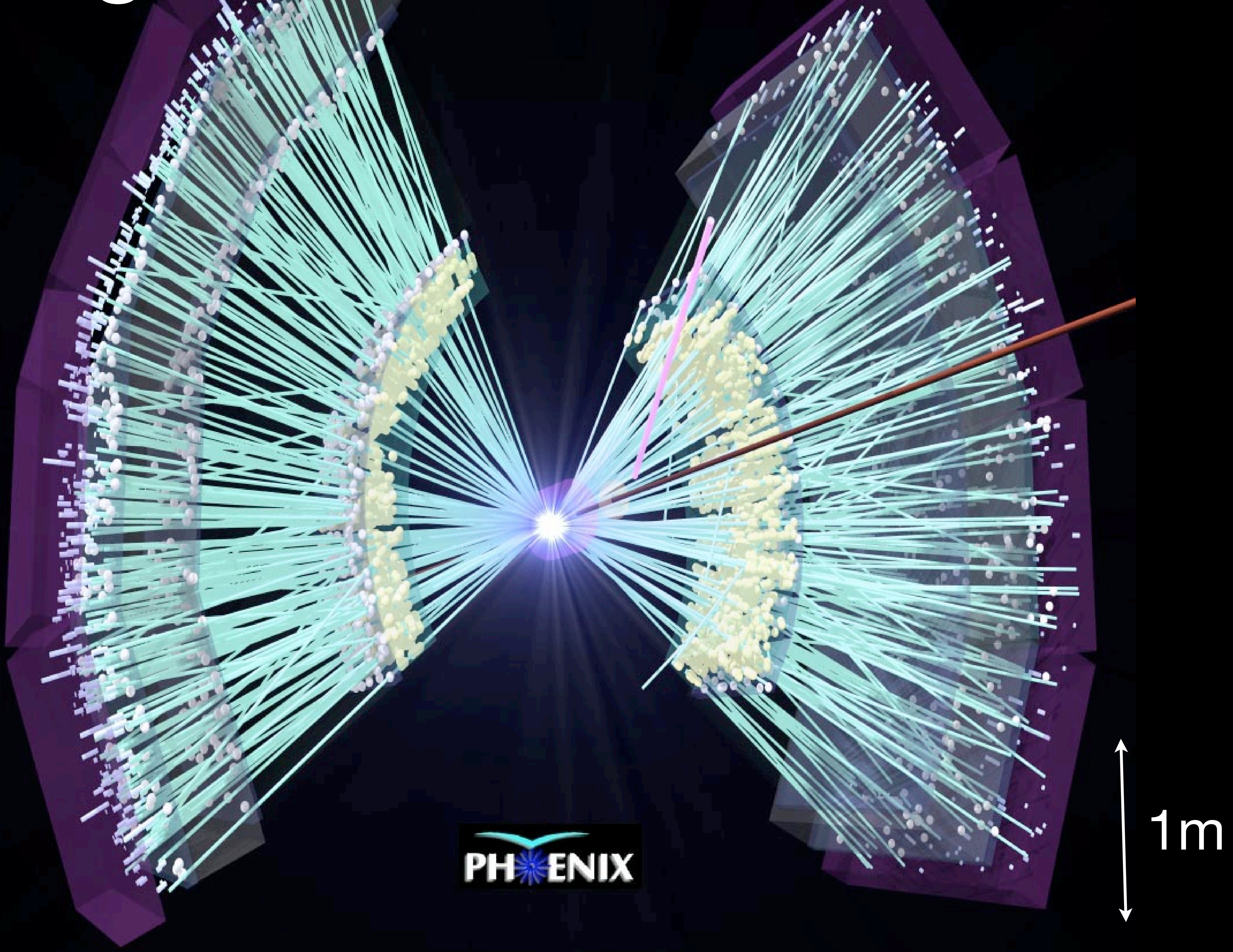


PHOBOS

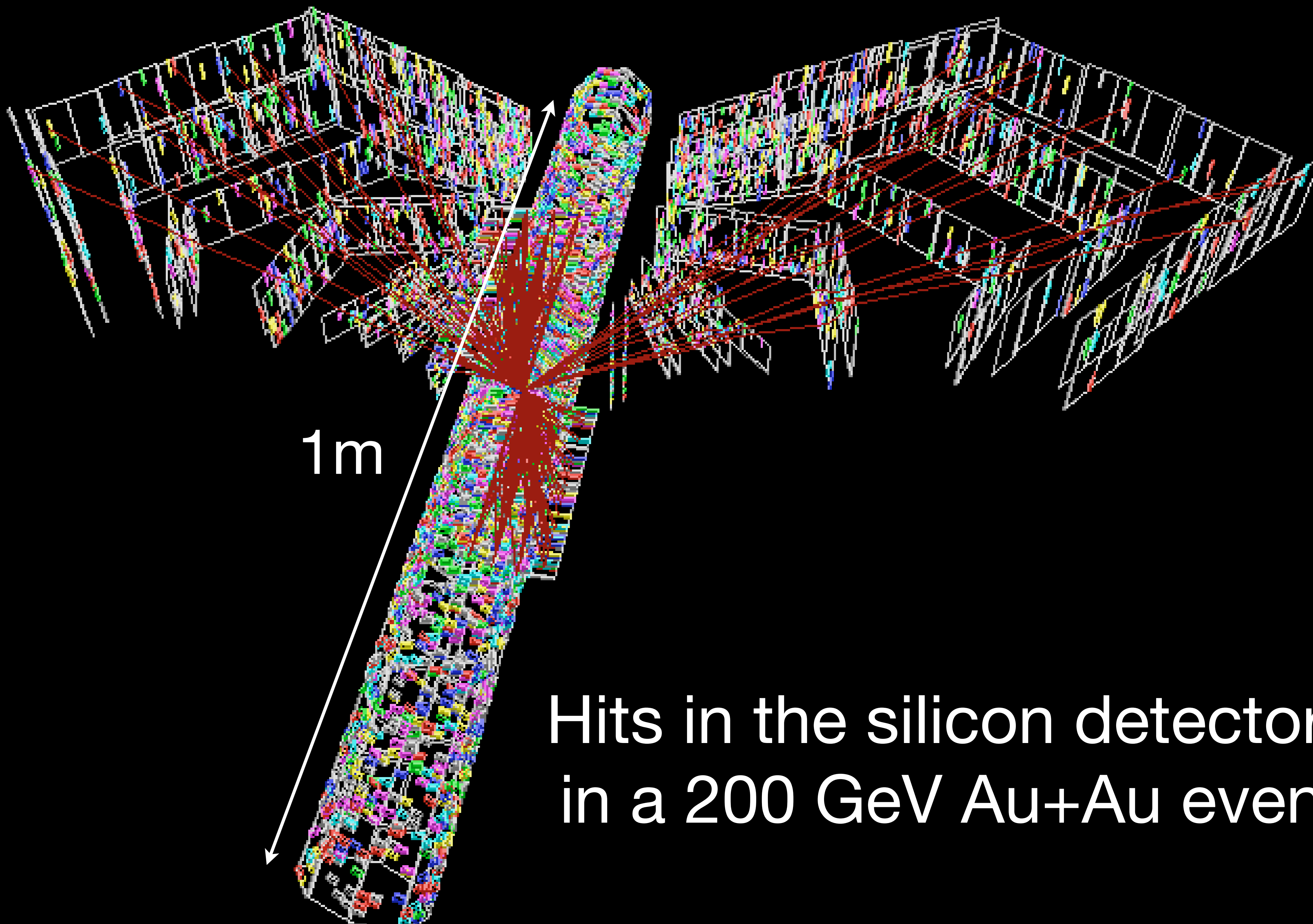
A Single RHIC Event in STAR



A Single RHIC Event in PHENIX

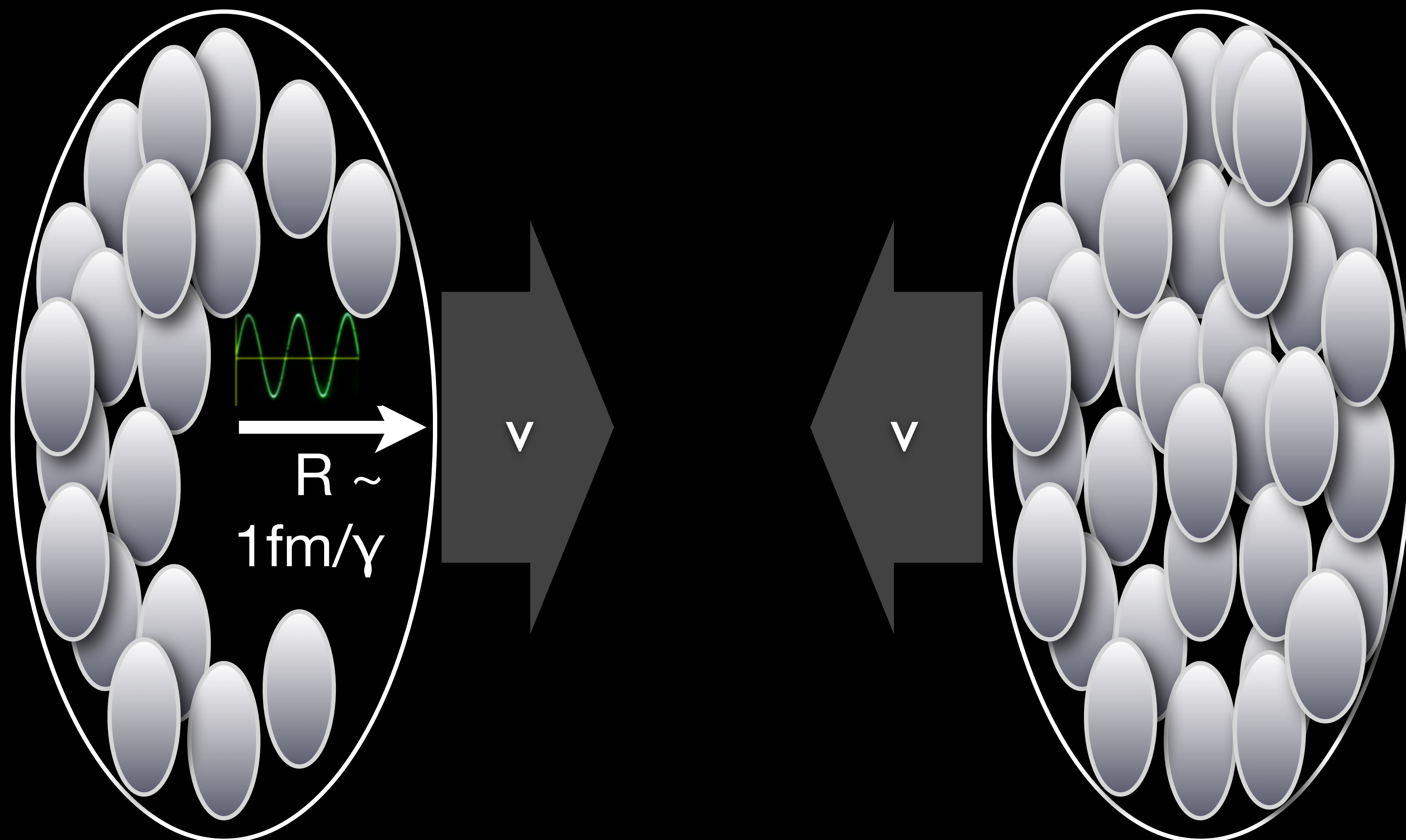


A Single Event in PHOBOS



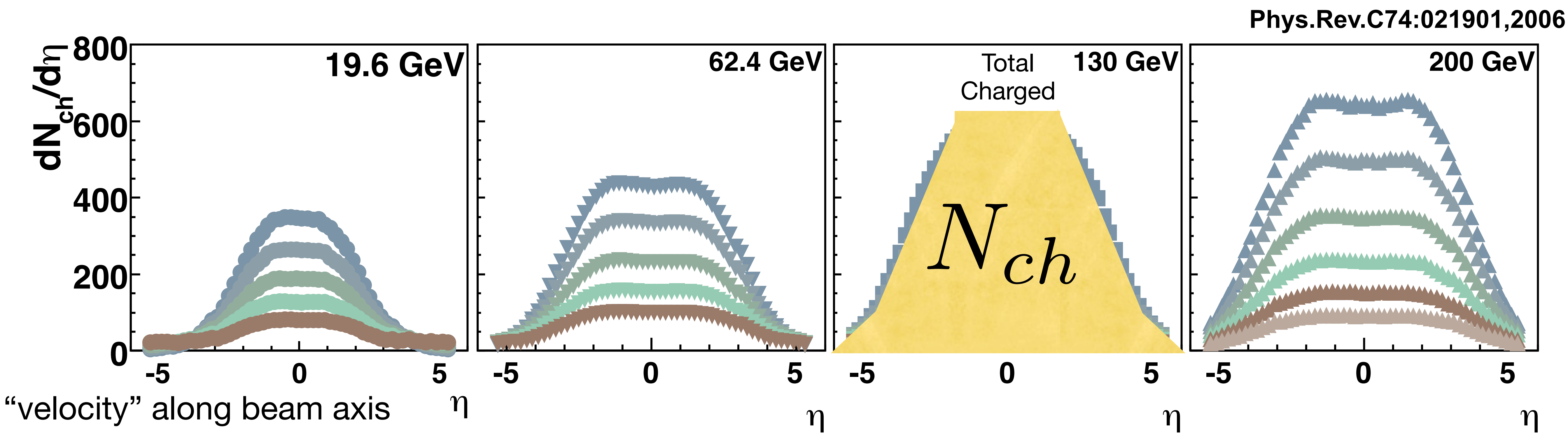
Hits in the silicon detectors in a 200 GeV Au+Au event

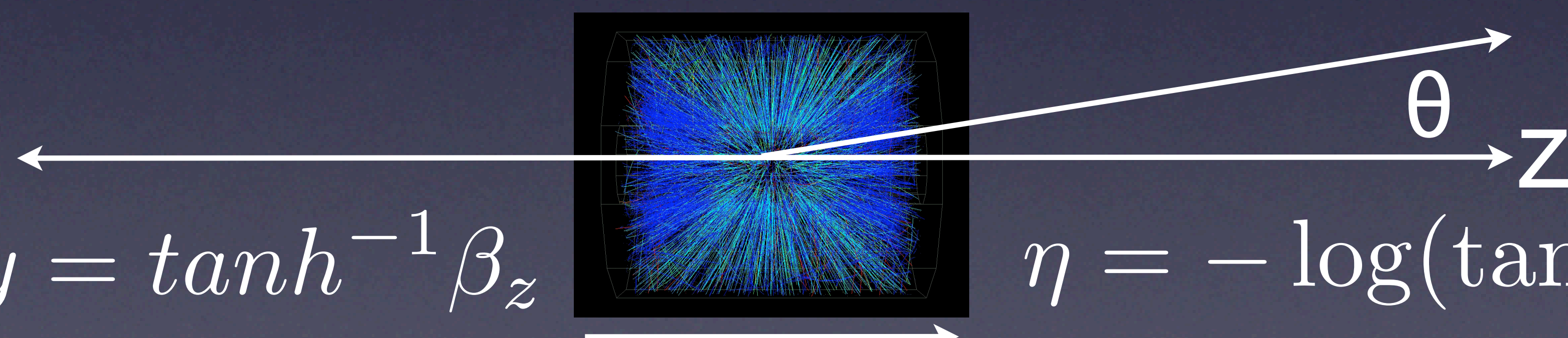
Bulk Features



Multiplicity
Particle spectra
Rapidity distributions
Azimuthal distributions

Angular Distributions & N_{ch}





"Rapidity" $y = tanh^{-1}\beta_z$ $\eta = -\log(\tan(\theta/2))$ Pseudo-rapidity

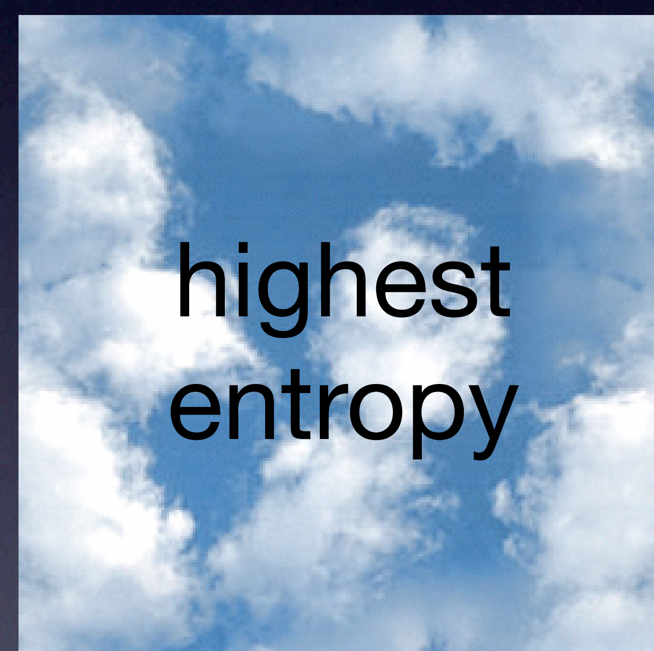
Angle tells us about velocity of particles along beam axis.

Most produced particles are relatively slow.

$E=mc^2$: Trade off of kinetic energy for matter

Entropy & Thermalization

Entropy reflects the number of degrees of freedom available to a system when it "thermalizes", i.e. erases all information about its initial state by randomizing the motion of the constituents



$$S = \frac{\Delta Q}{T}$$

Do collisions at RHIC thermalize? If so, we may be able to learn about its degrees of freedom by studying its entropy!

Entropy & Multiplicity

$$S = \frac{\Delta Q}{T}$$

Total amount of energy added as "heat"

Average energy per relevant degree of freedom

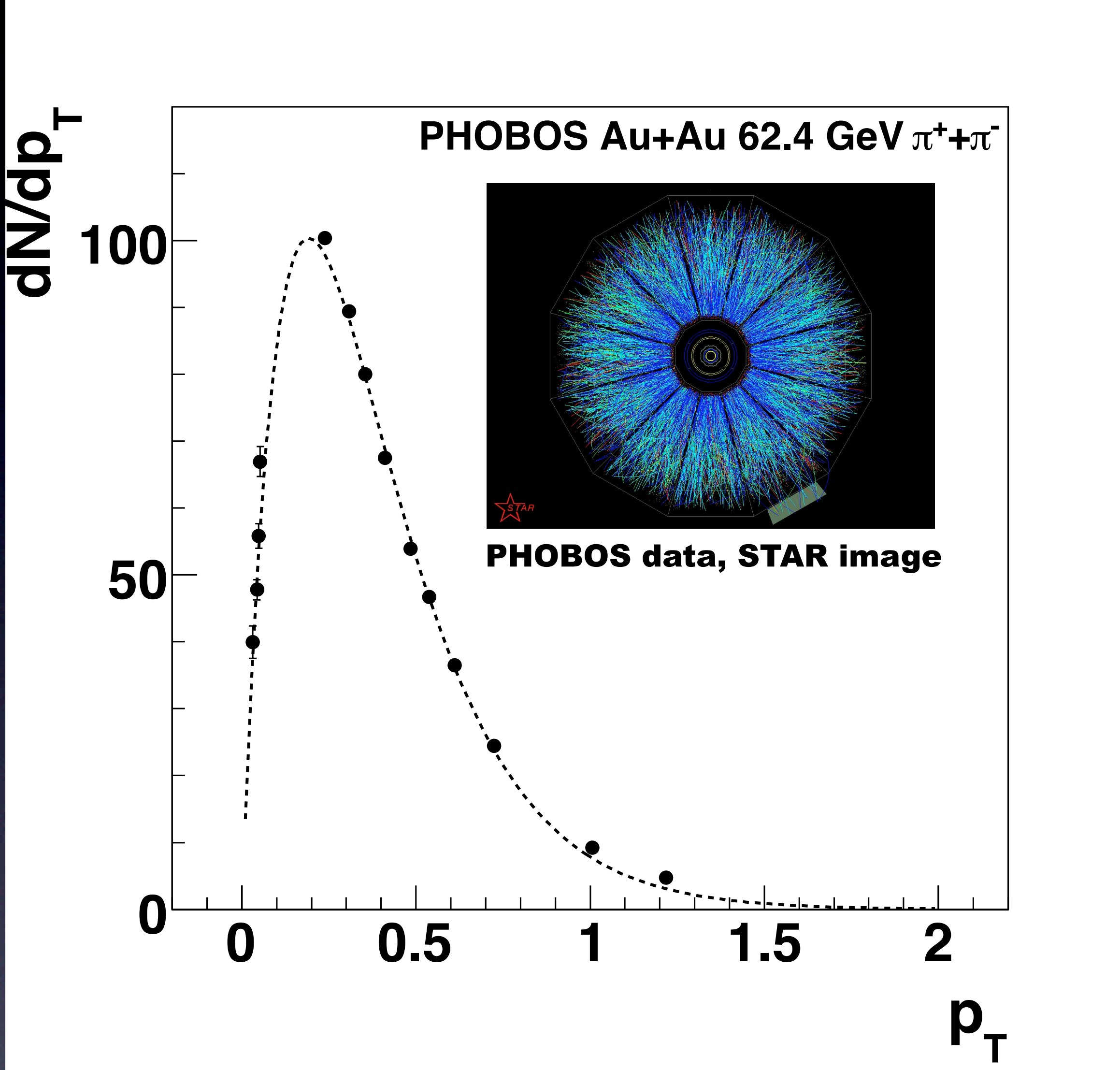
$$\propto N_{DOF} \propto N_{tot}$$

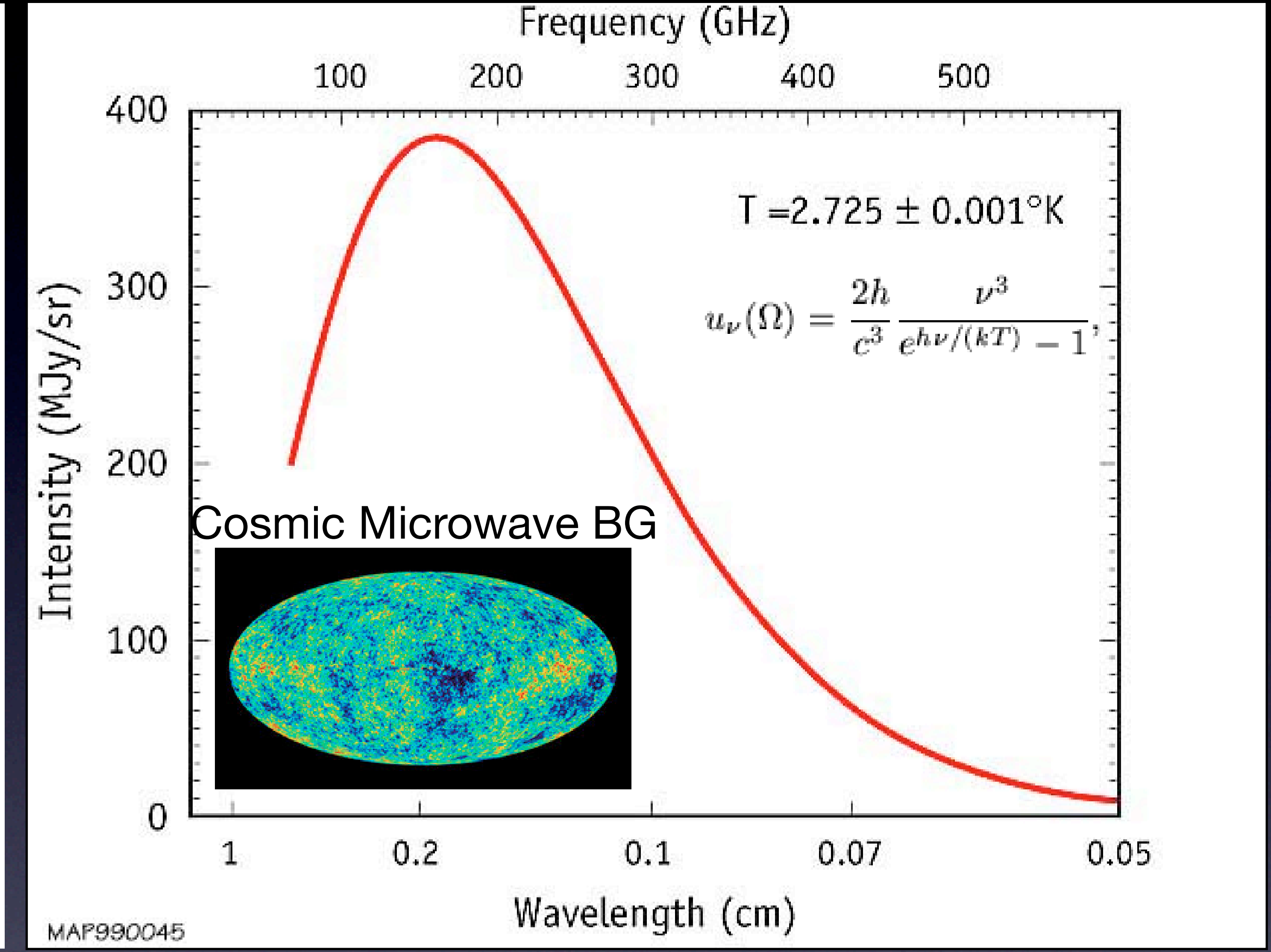
For entropy, <u>everything</u> "counts"...

The Final State @ RHIC

Can we see thermalization in the final state?

Strong Blackbody





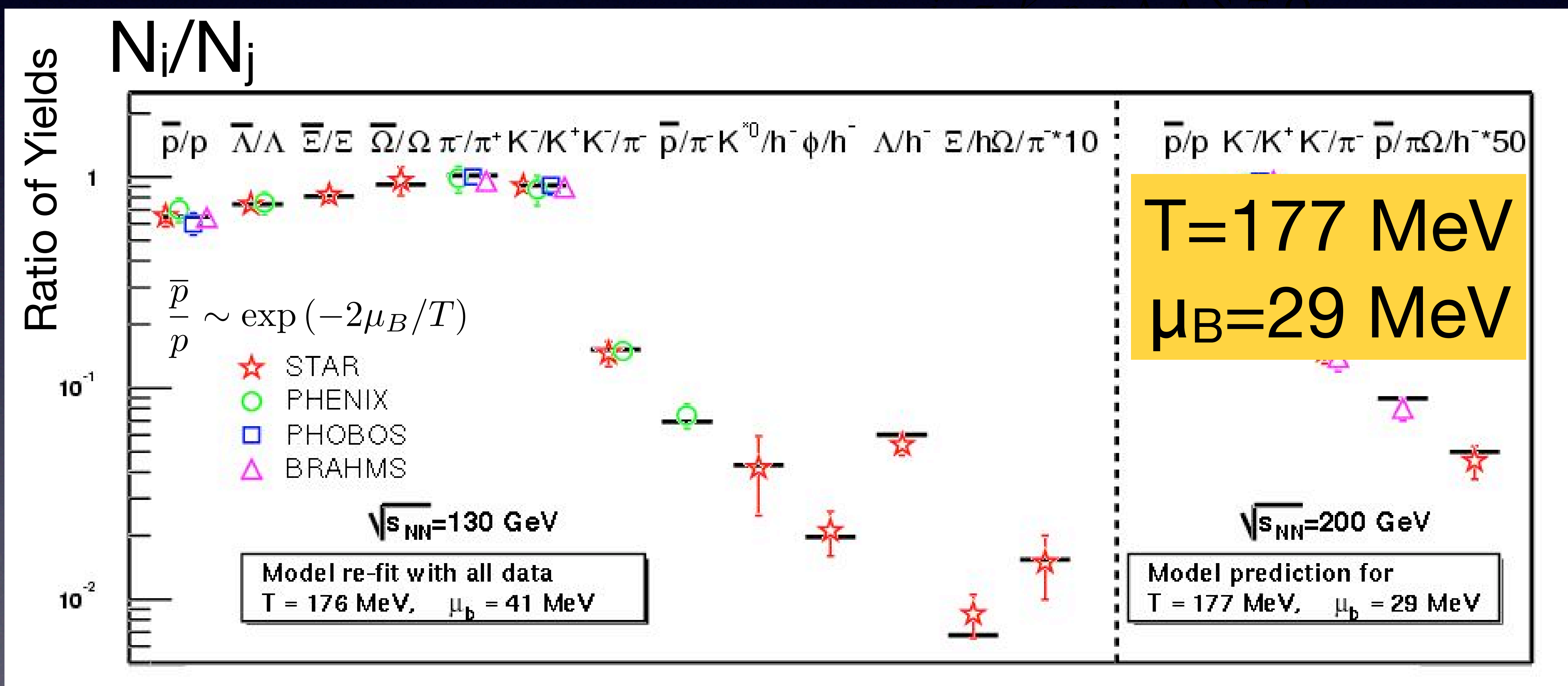
The spectrum of particles emerging from the collisions is similar to a blackbody shape, but with hadrons instead of photons

Particle Ratios

T	Chemical freezeout temperature
μ_B	Baryochemical potential (when you have more matter than antimatter!)

$$N_i \propto V \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B)/T} \pm 1}$$

Blackbody spectrum



Braun-Munzinger, Magestro, Stachel (2001)

The Temperature at RHIC

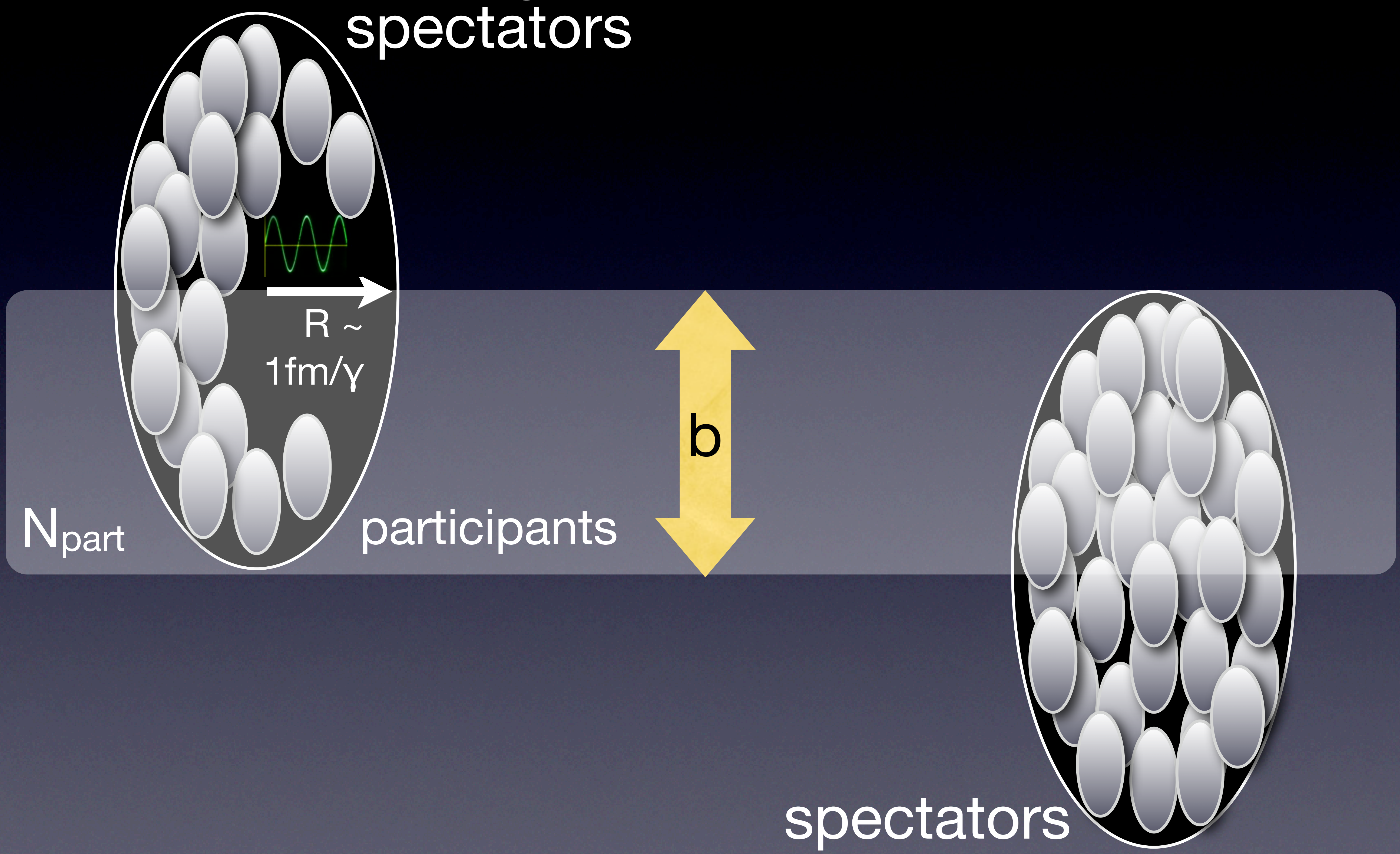
$k_B T = 177$ MeV

This is ~2×10^{12} degrees K

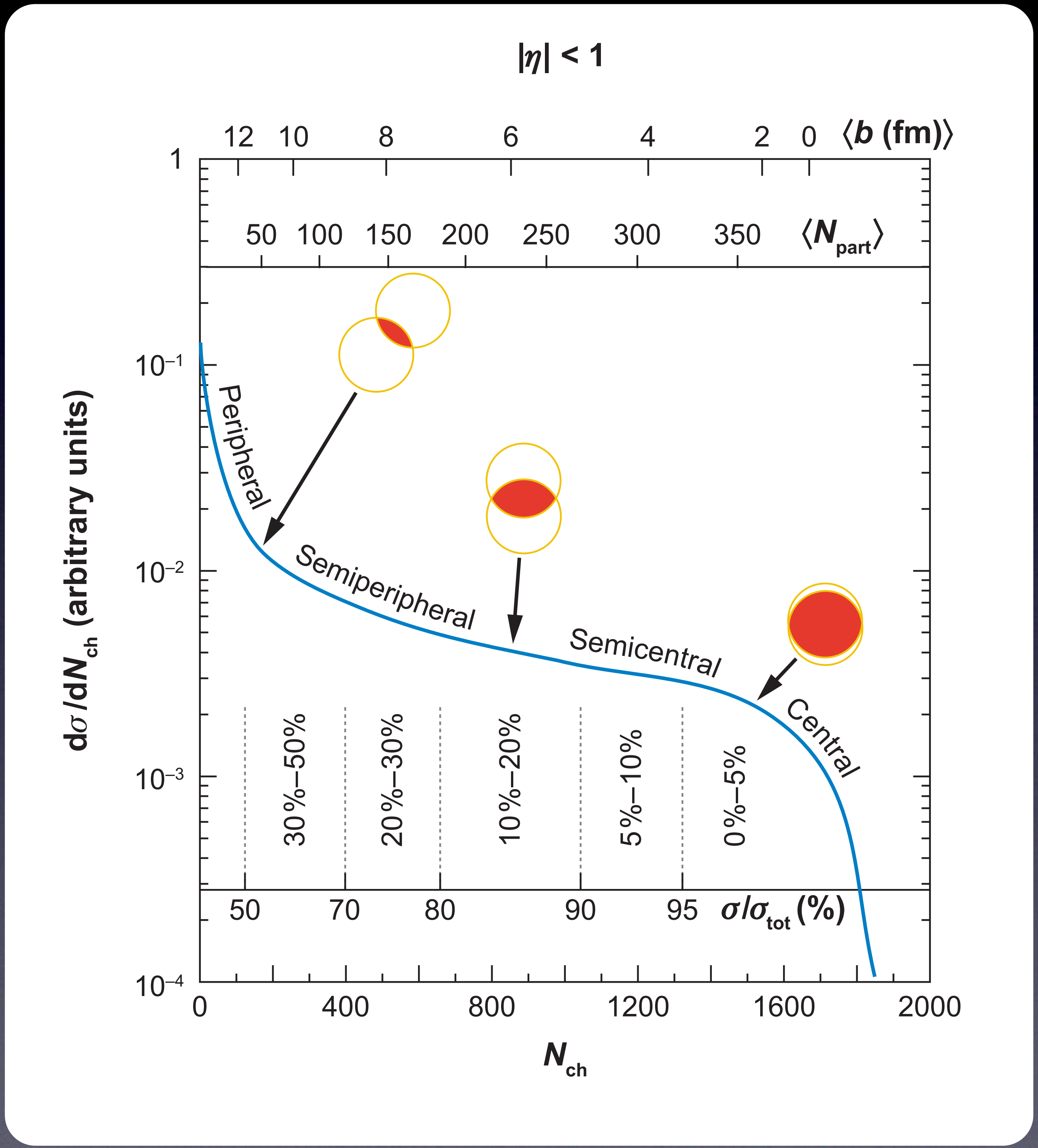
This is, in some sense, the
“final temperature”
of a RHIC collision, when
it “freezes” into hadrons

The earlier stages must have
been *much* hotter!

Estimating Nuclear Overlap



Estimating Geometry

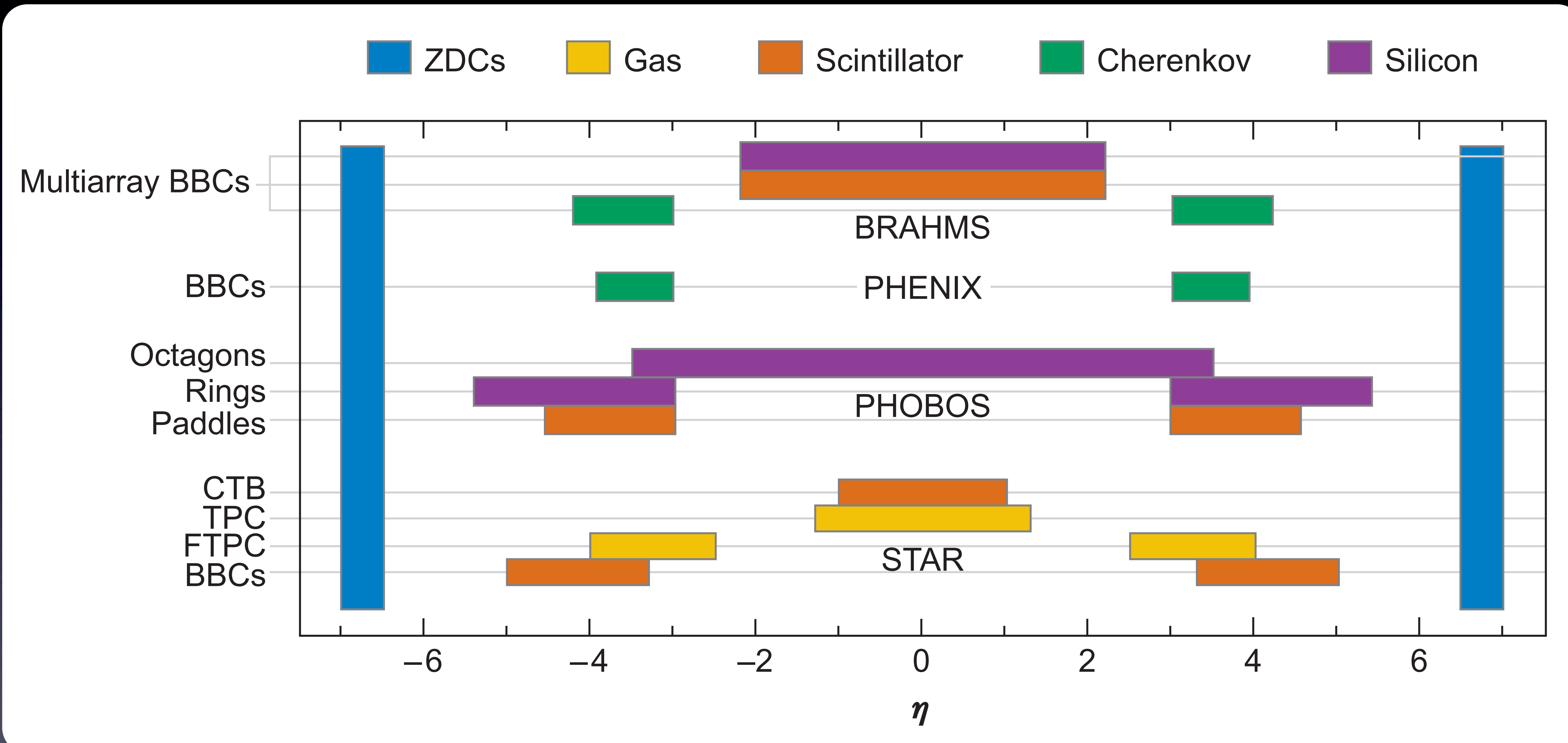


Extract unobserved geometric variables

Assume matching of fractional quantities

Measured quantity

Trigger Acceptance



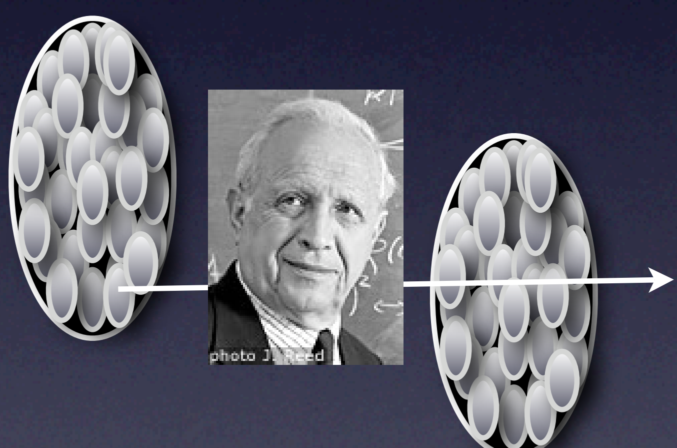
spectator nucleons

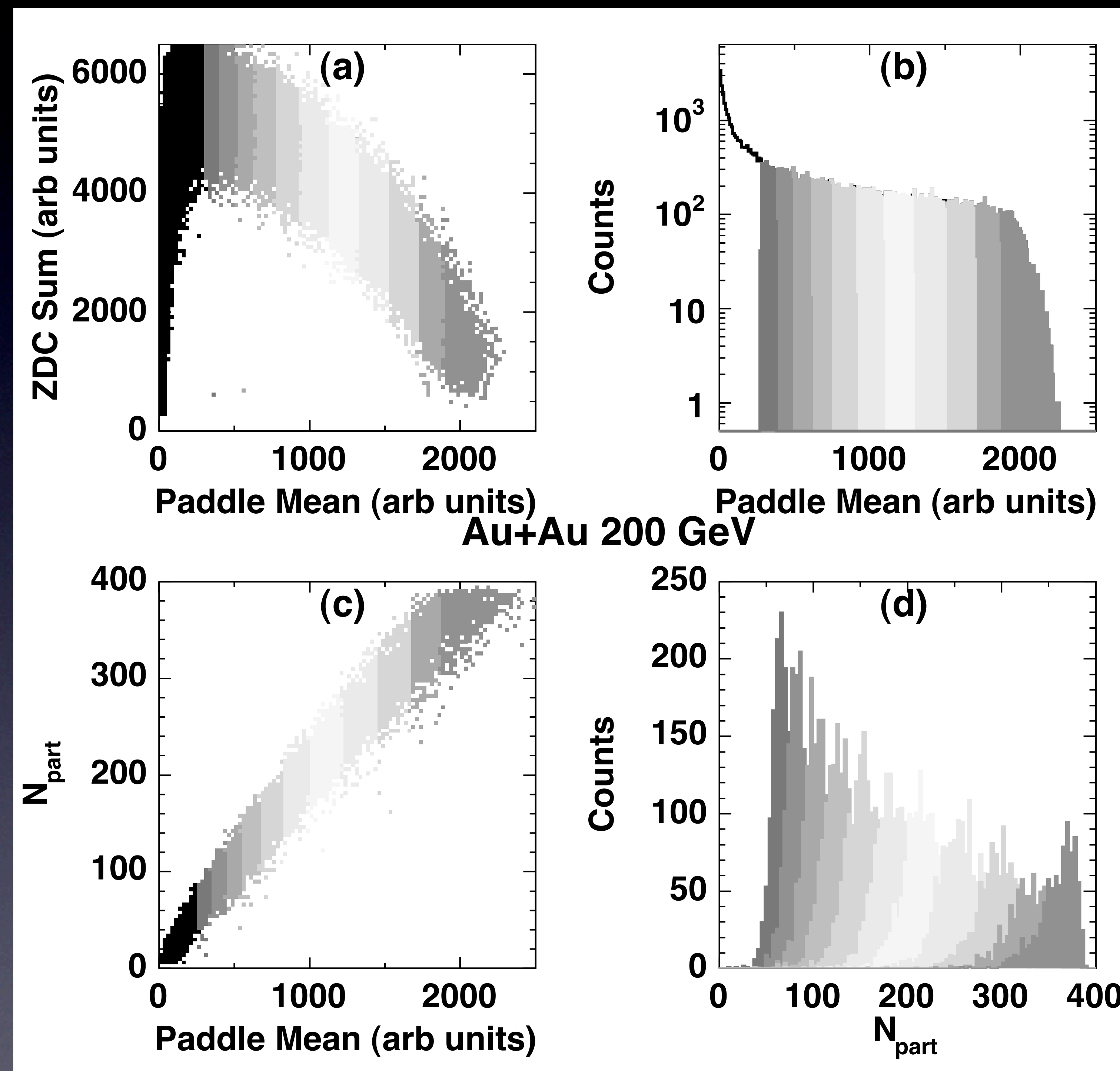
produced particles

spectator nucleons

Centrality Bins

Experimental observables

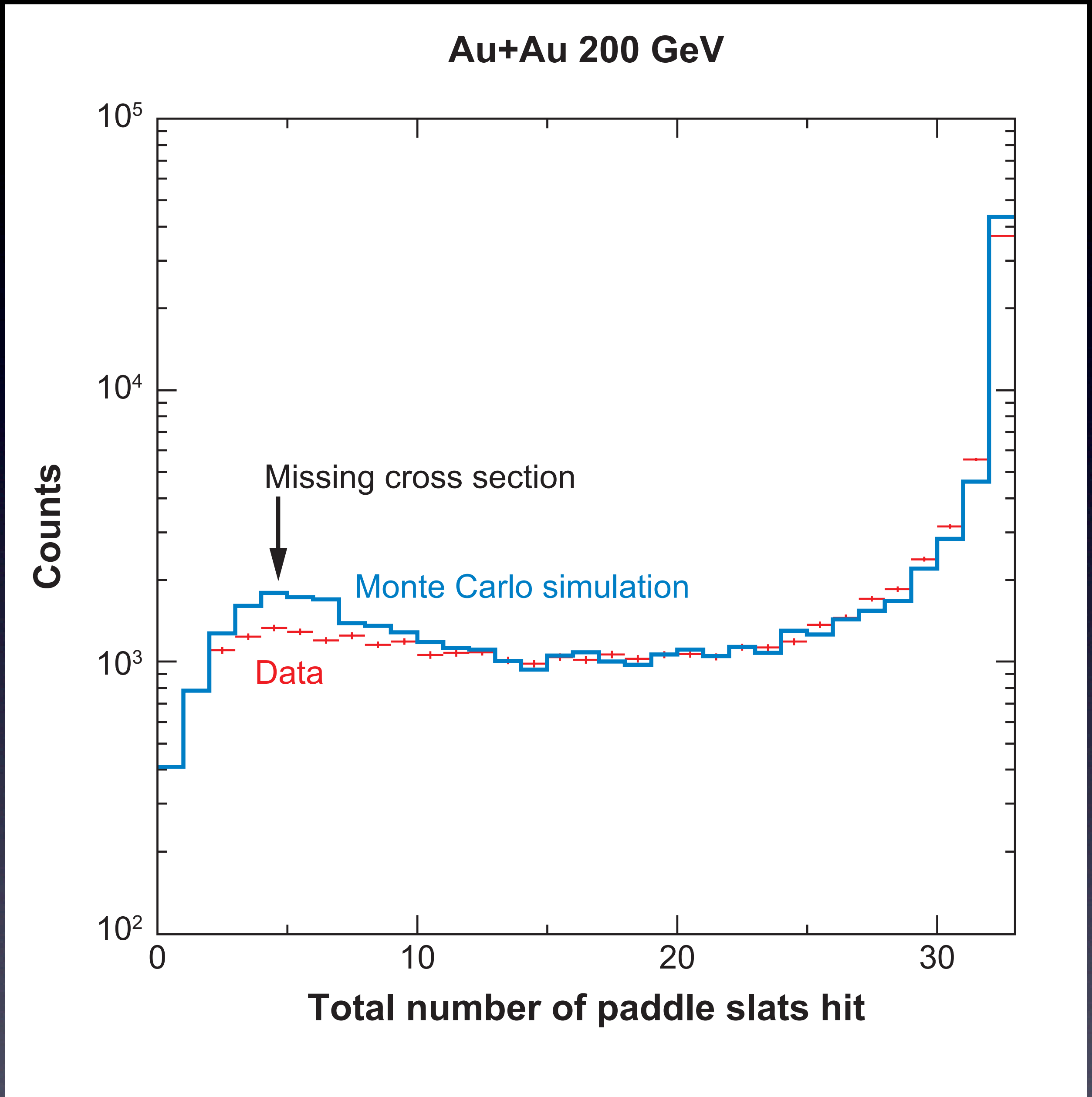




"Glauber model": nucleons follow straight paths, interact via σ_{NN}

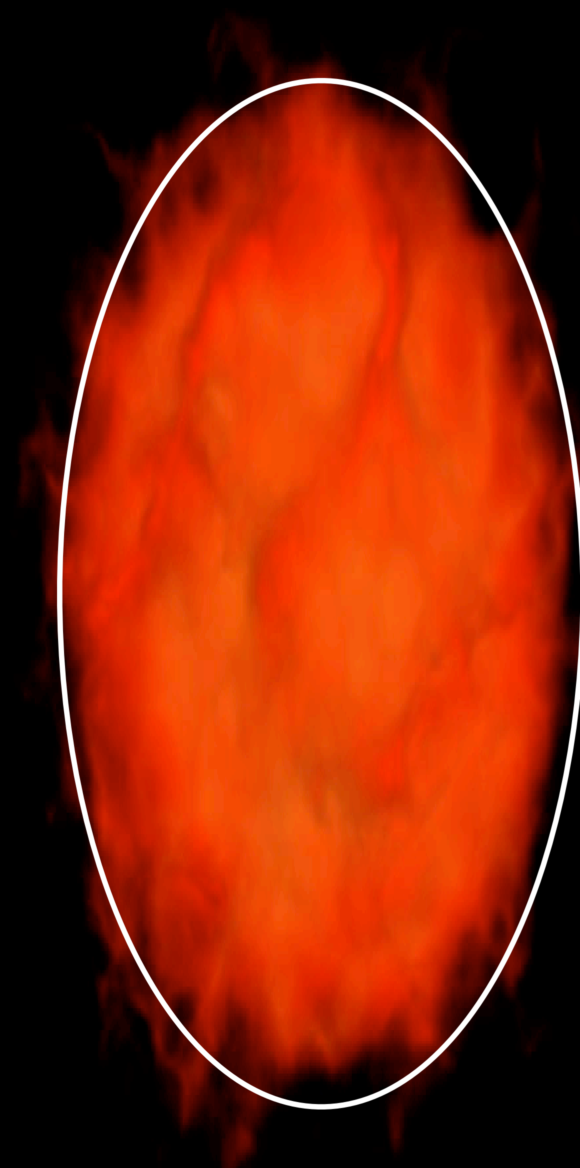
Feed geometry into dynamical model + detector simulation

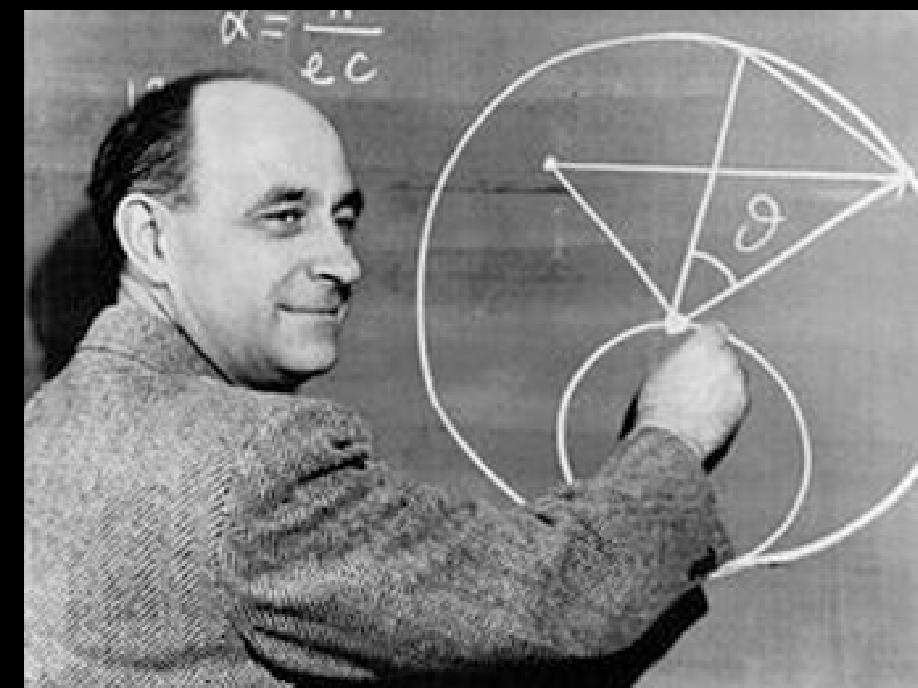
Fraction of Total



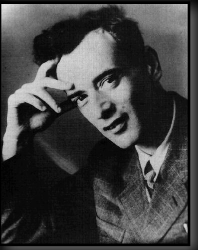
The fraction of events missed by the experimental trigger is the major source of uncertainty in any measurement of N_{part}, etc.

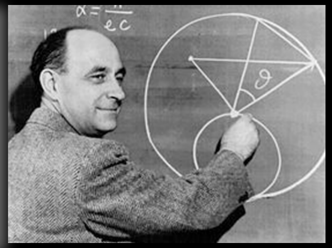
A Simple Model for Entropy





What if the system thermalized immediately,
in the Lorentz-contracted volume?
What would the entropy be?





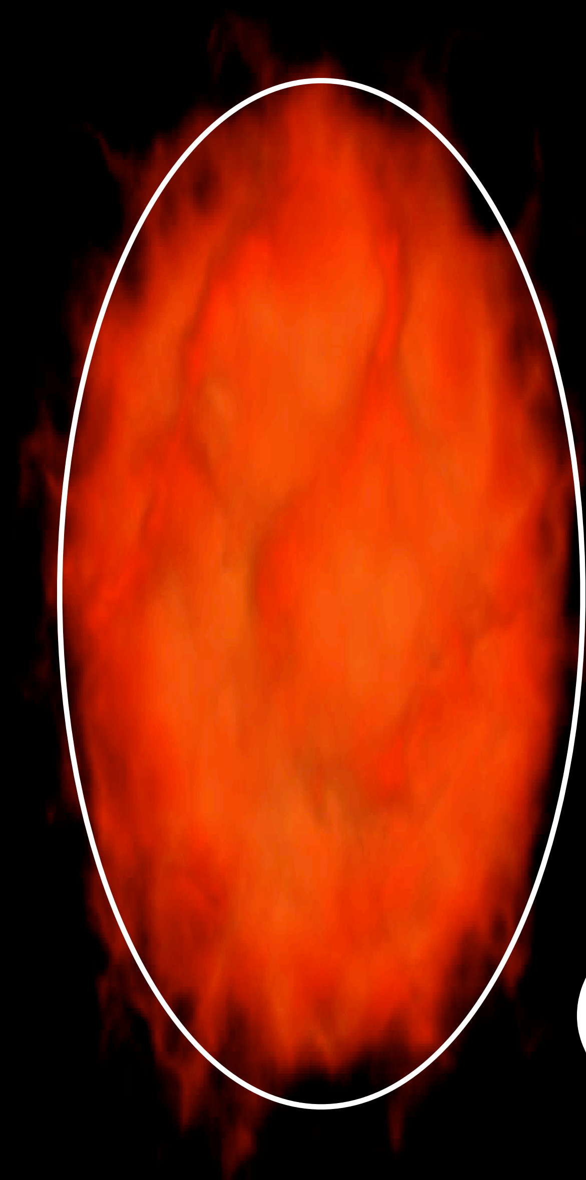
Fermi-Landau Model

$$E = A \times E_{NN}$$

Total Energy

$$V = \frac{A \times V_0}{E_{NN}/2m_N}$$

Total Volume



$$\epsilon = \frac{E_{NN}^2}{2m_N V_0}$$

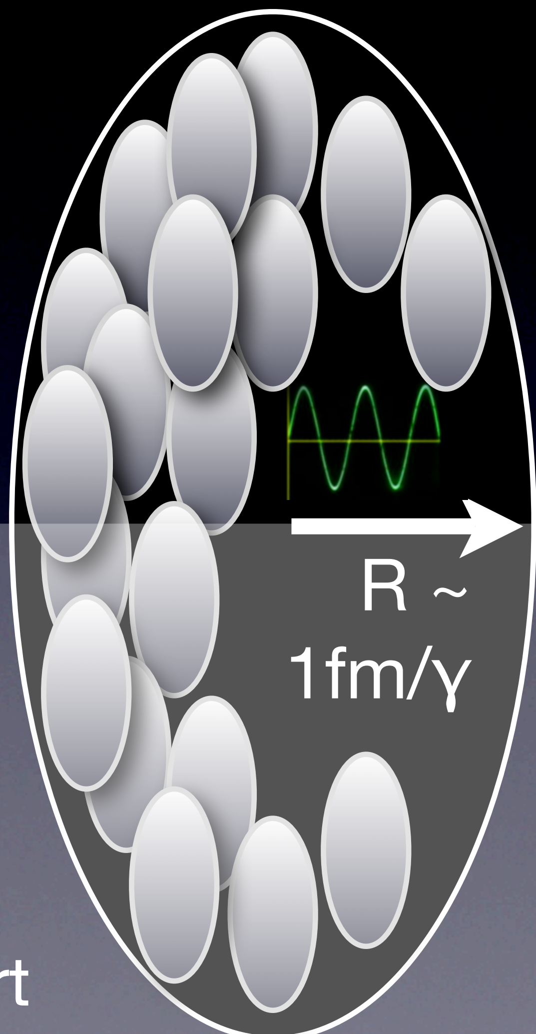
Energy Density E/V
(>3 TeV/fm^3 @ RHIC!)

$$s \propto \epsilon^{3/4}$$

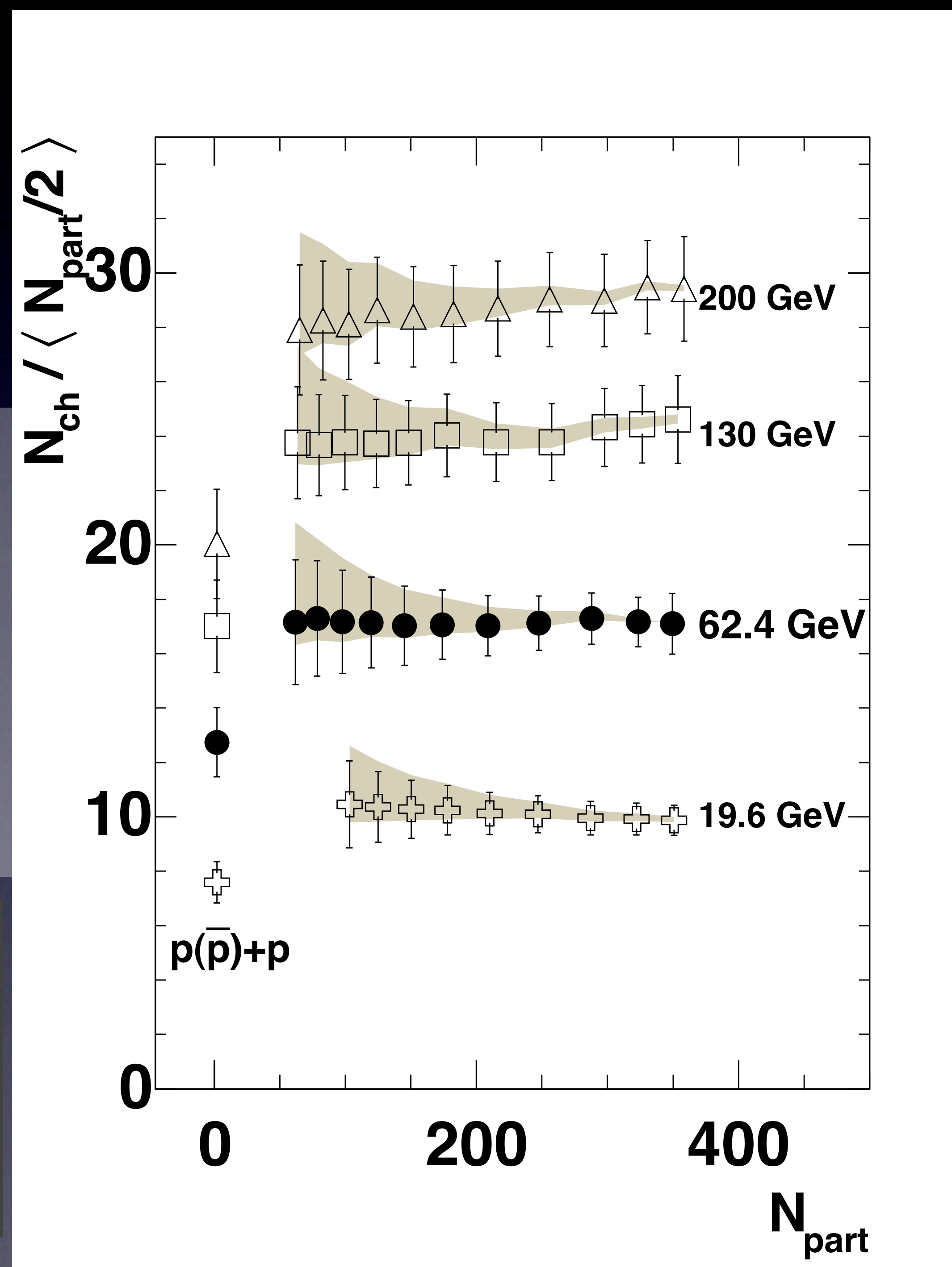
blackbody physics
p=ϵ/3

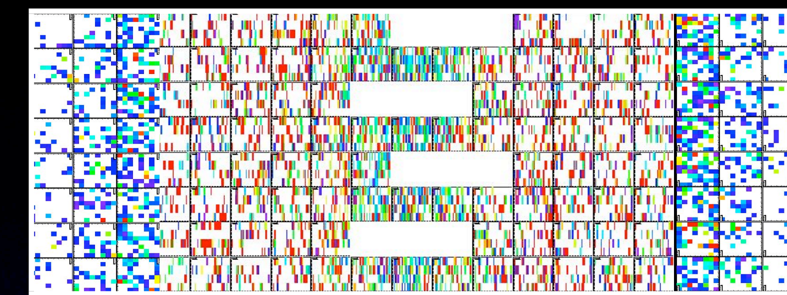
$$S = sV \propto N_{part} E_{NN}^{1/2}$$

N_{ch} Scaling With Volume

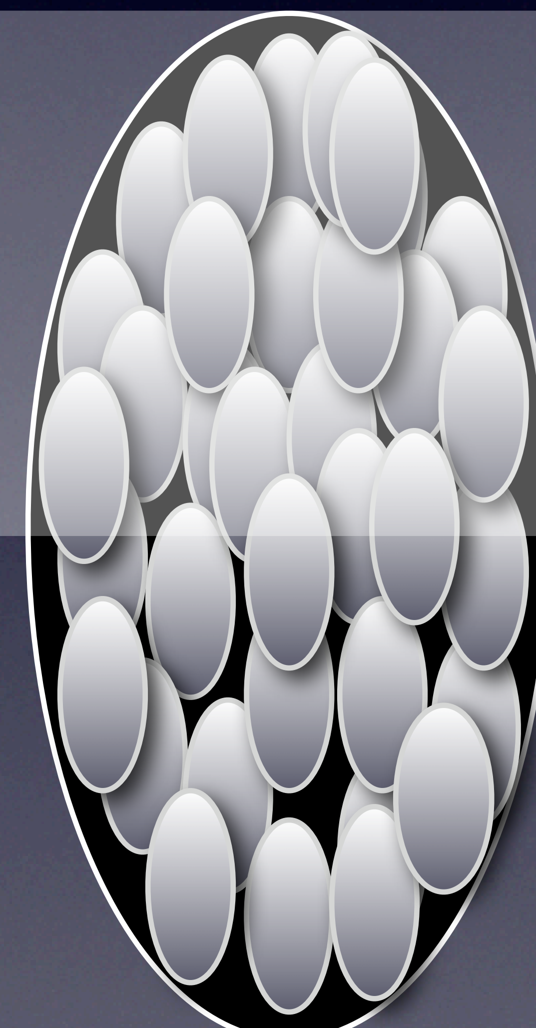


N_{part}





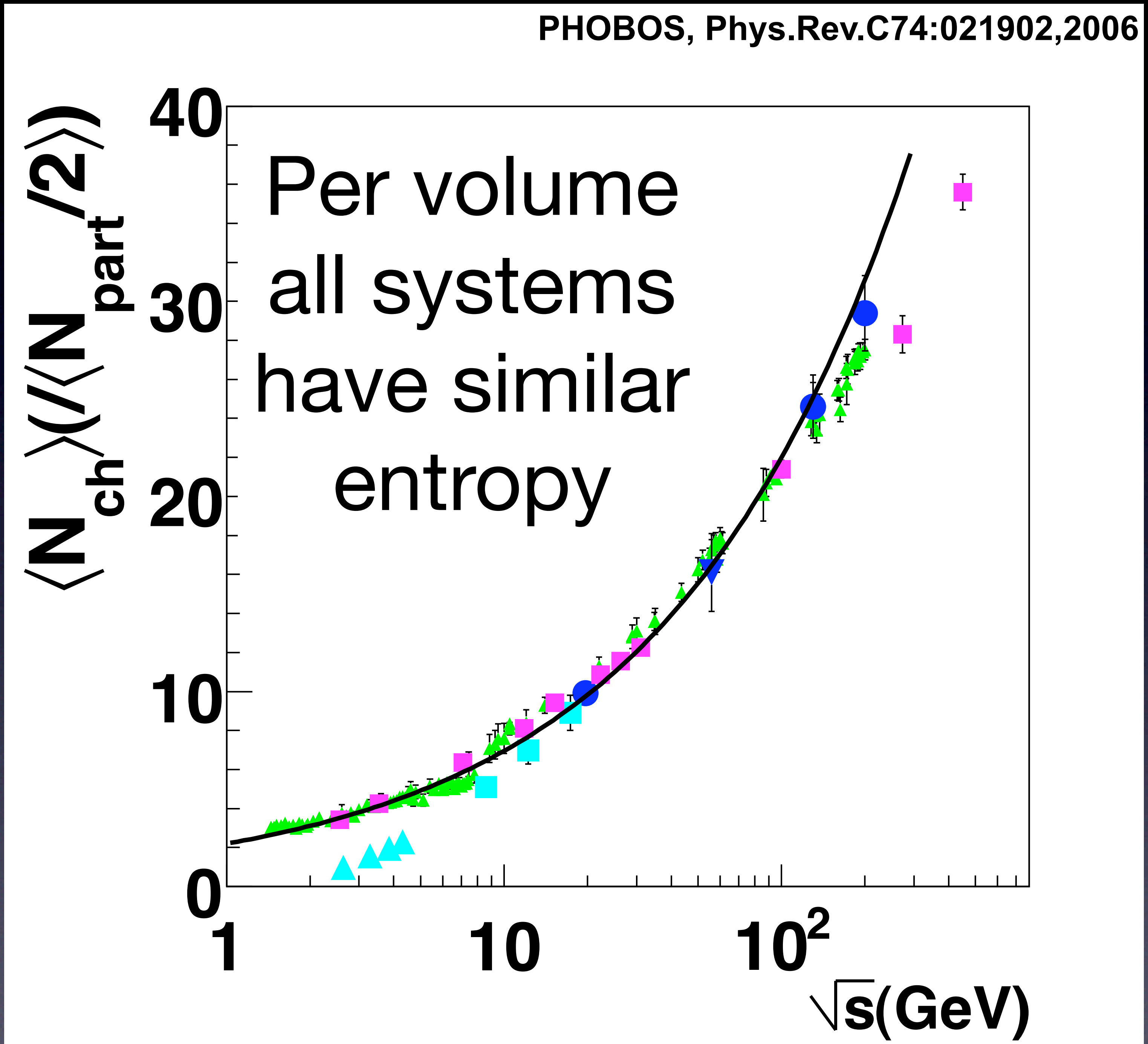
PHOBOS Event Display

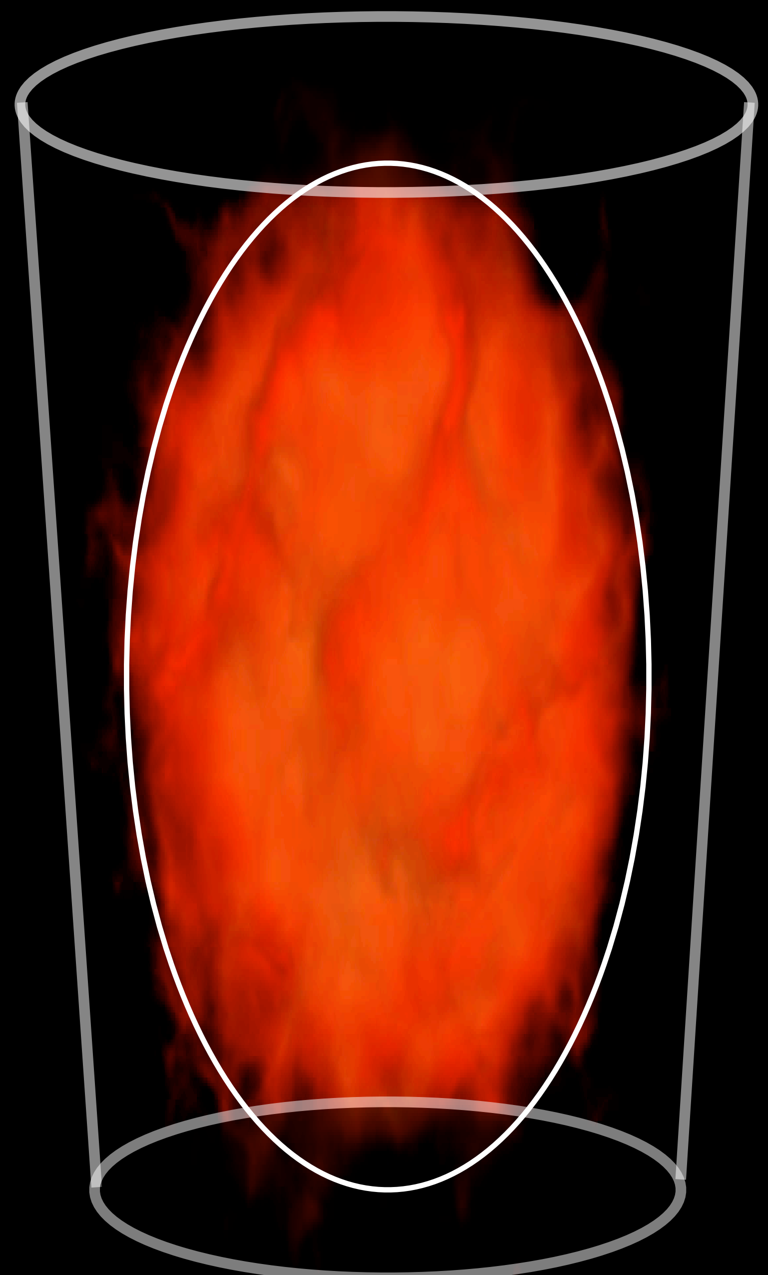


Total charged is <u>linear</u> with N_{part} i.e. volume

$$\frac{N_{ch}}{N_{part}/2} = f(E_{NN})$$

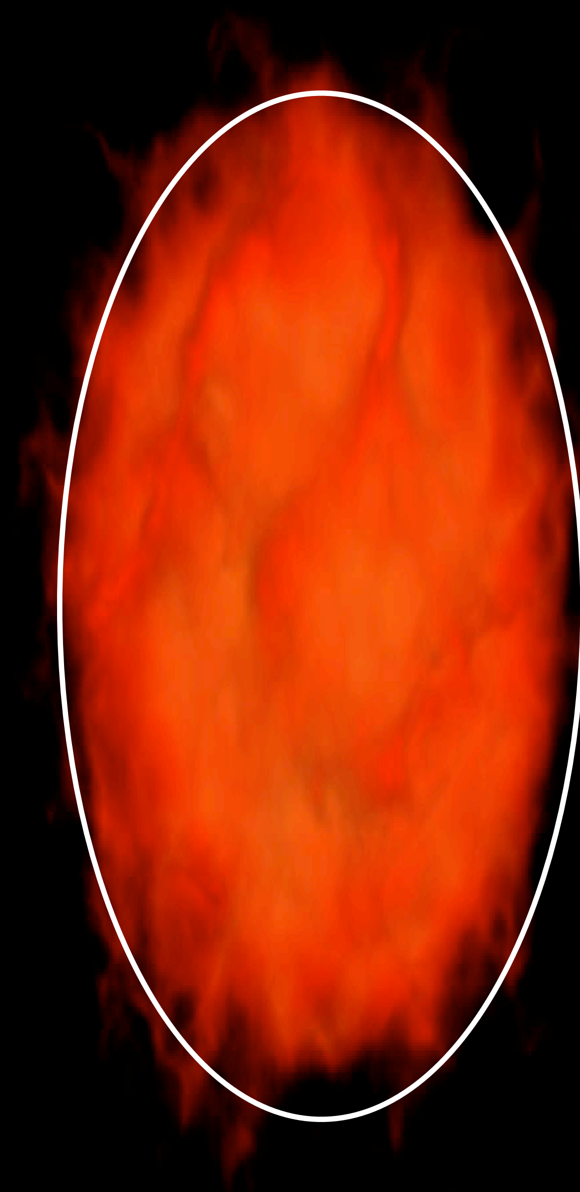
Fermi-Landau vs. Data





So far we've been treating the system as if it's sitting in a box (or test tube!)

Set the QGP Free!



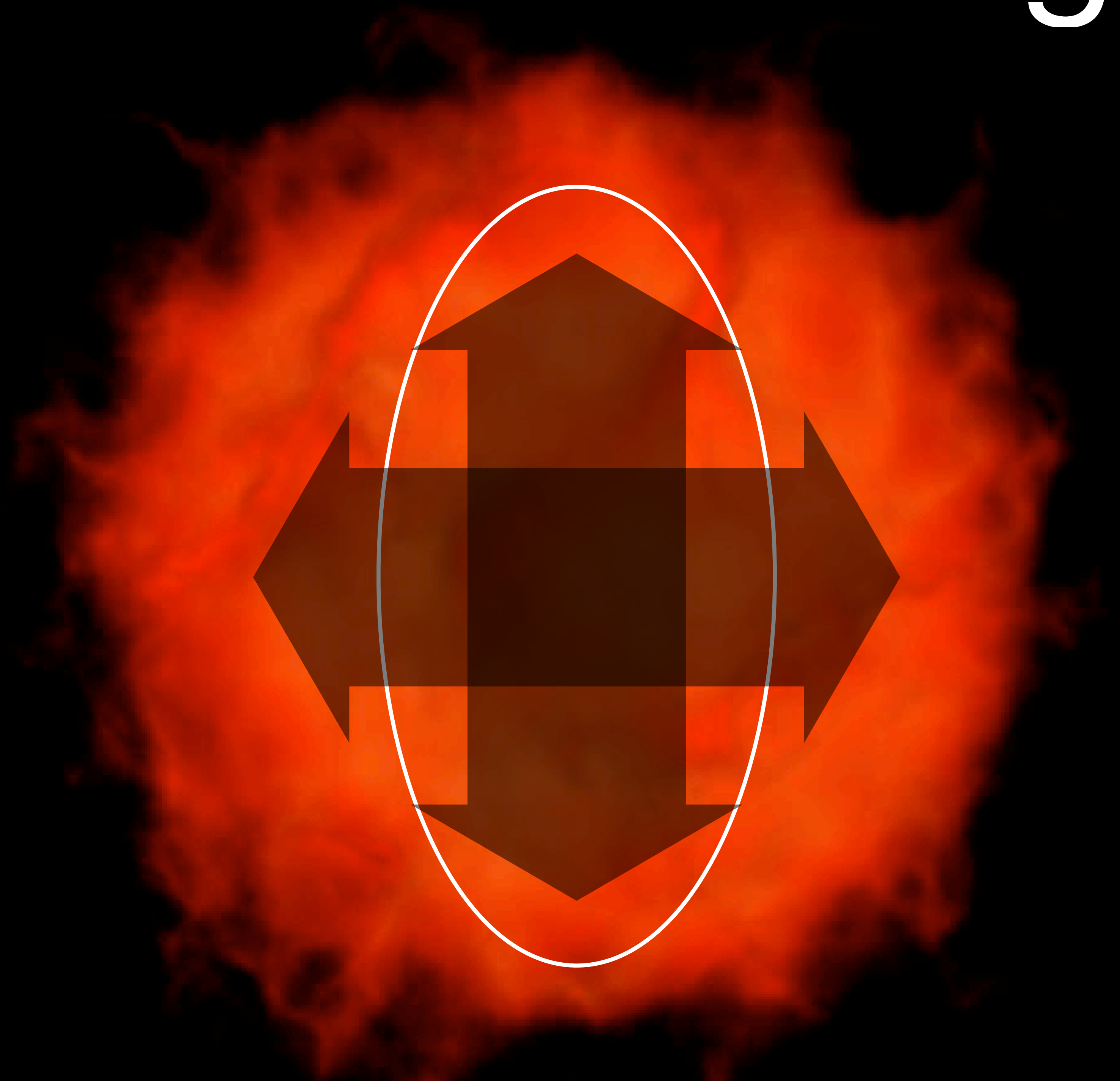
What happens when you take the glass away?

The Stuff at RHIC

Does it evaporate,
like a gas?

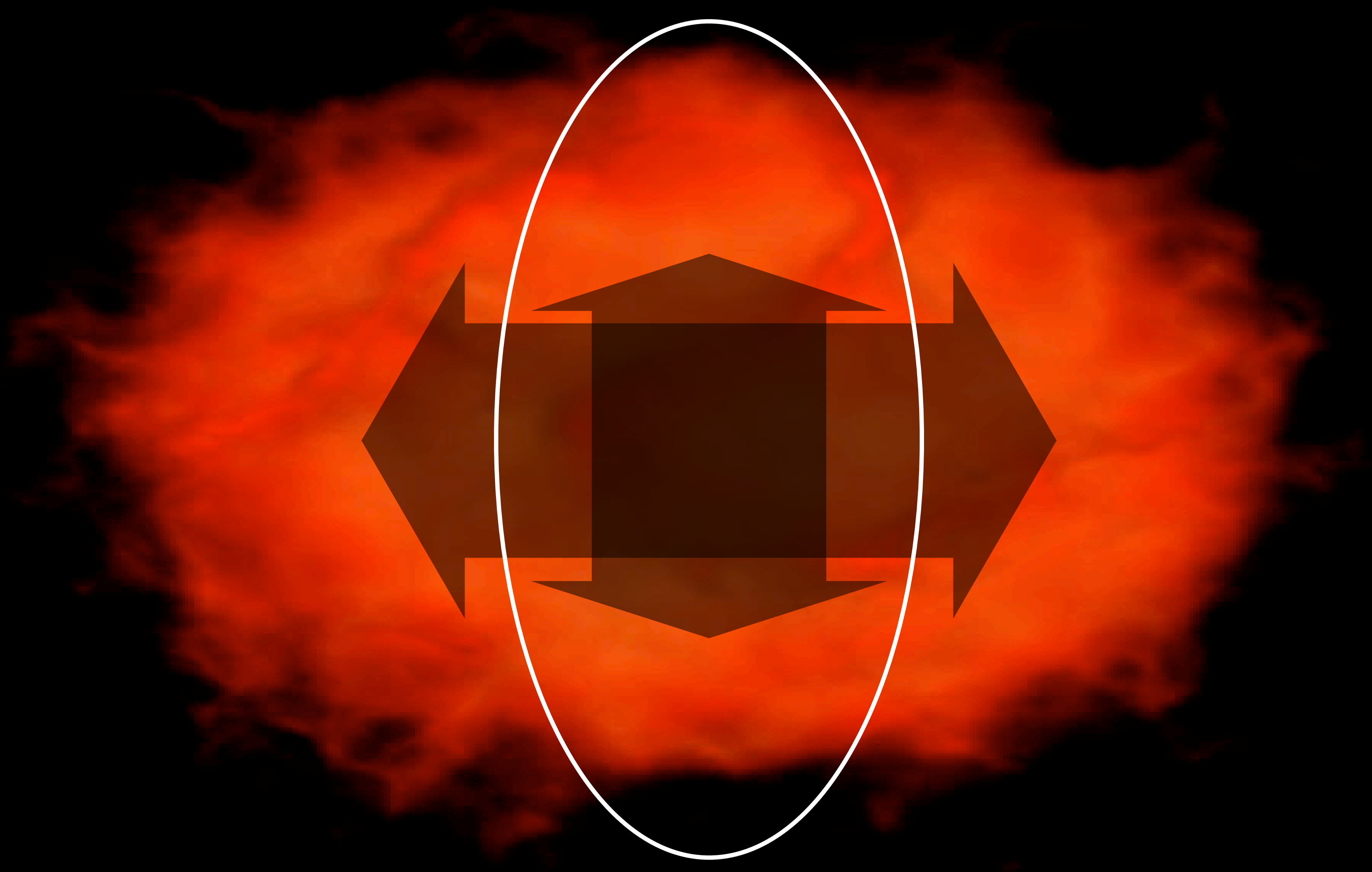
Does it flow,
like a liquid?

Is the material a gas?



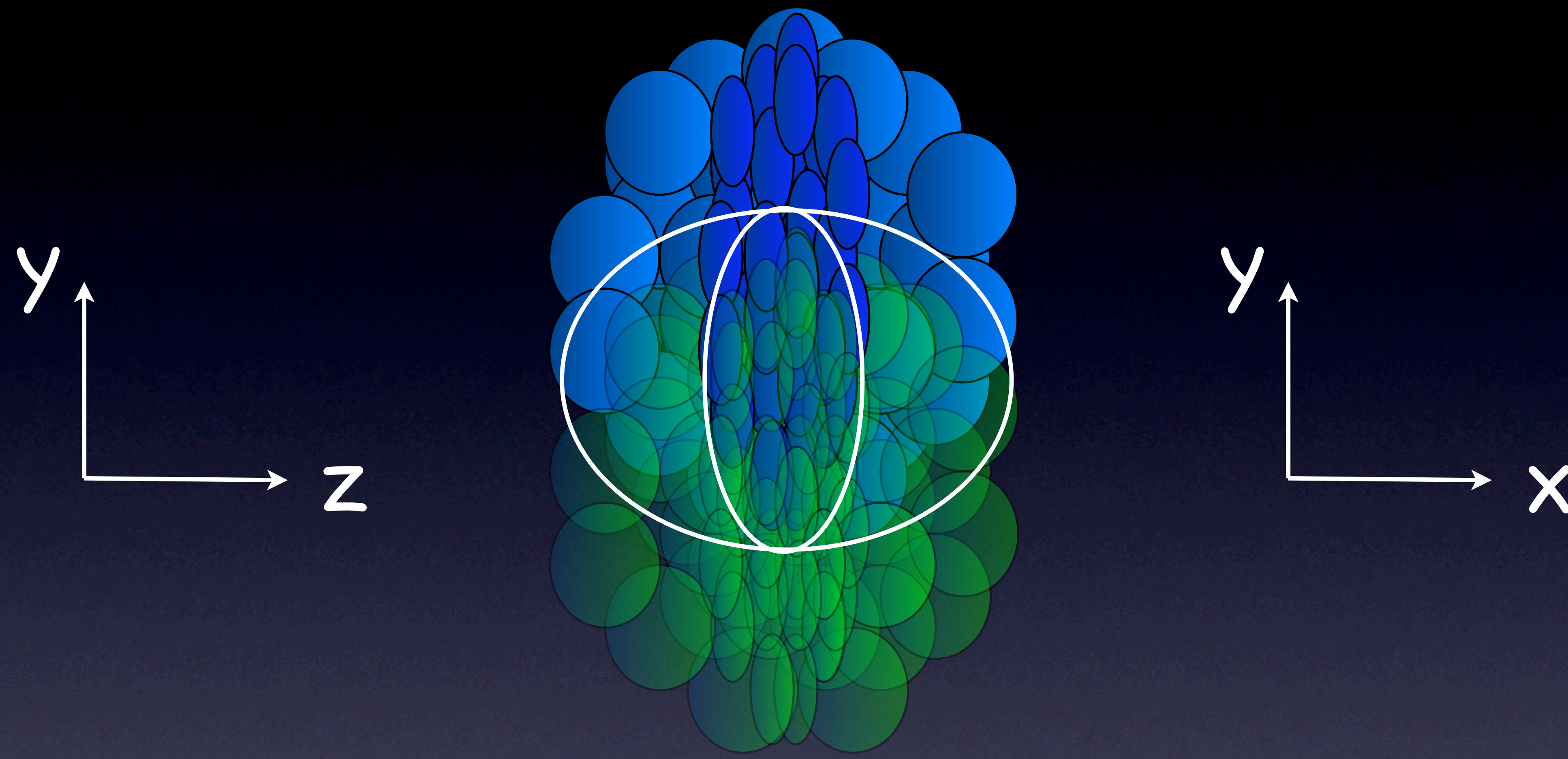
A gas flows down a pipe,
but just expands isotropically into space.

Is the material a liquid?



A liquid is its own container.
Its flow depends on its shape

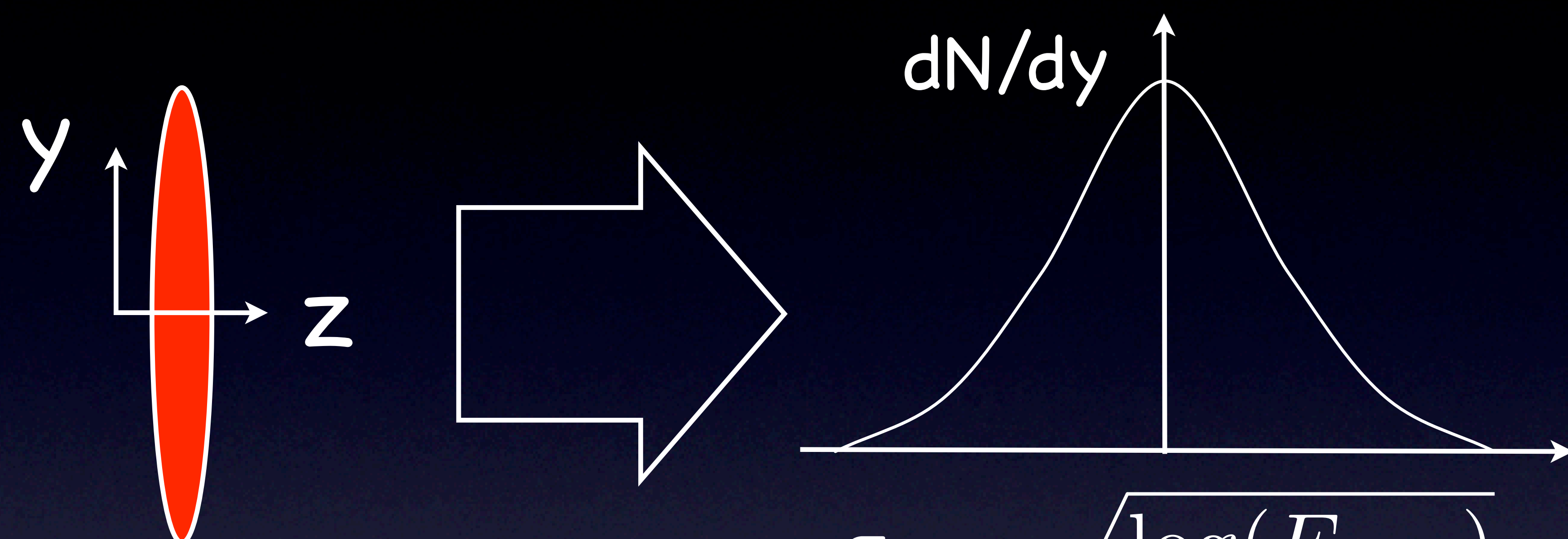
The “Shape” of Things



RHIC collisions have a special shape:

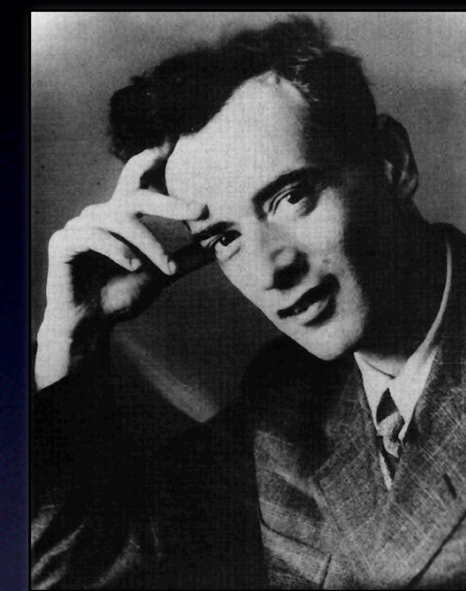
1. Compressed along the beam directions
2. Almond shaped in the “transverse” plane

Longitudinal Flow



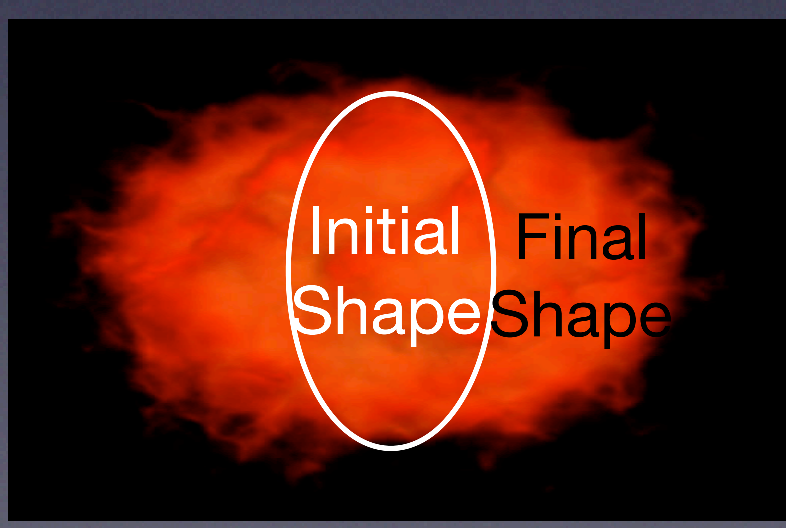
$$\Delta z \sim \frac{1}{\sqrt{s}}$$

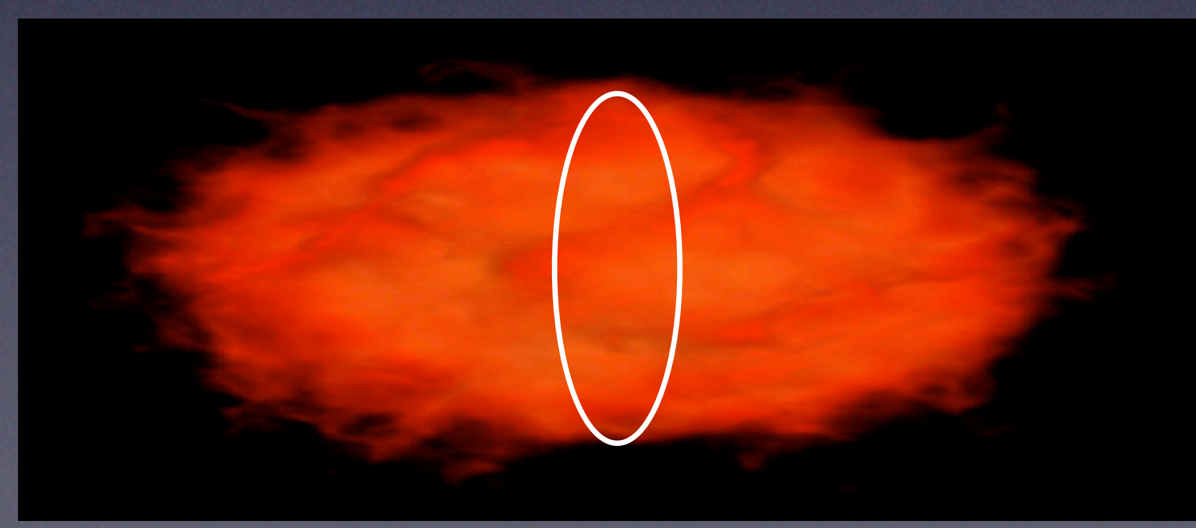
$$\sigma_y \sim \sqrt{\log(E_{NN})}$$



1955: Landau solves “Relativistic Hydrodynamics”

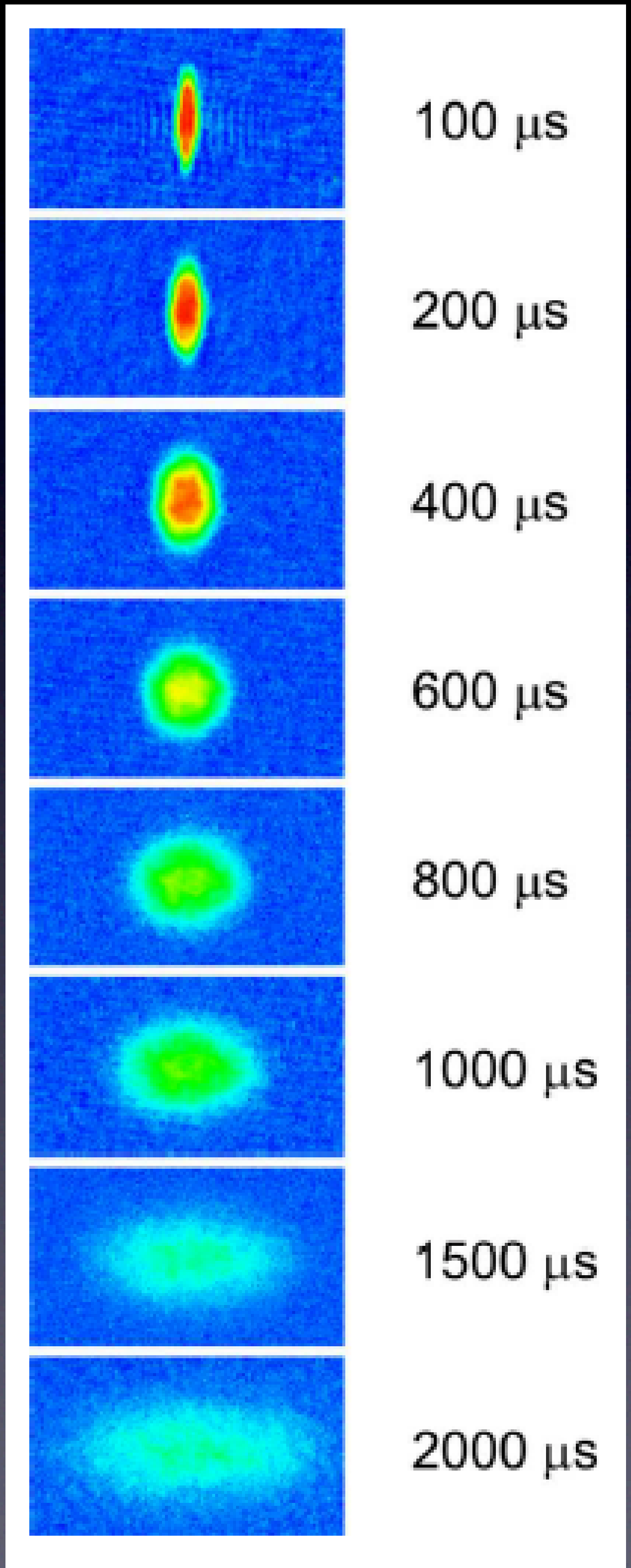
2007: Heinz, Kolb, Shuryak, Ollitrault, Hirano, etc.





The more you squeeze it, the faster it explodes!

Unique to RHIC?

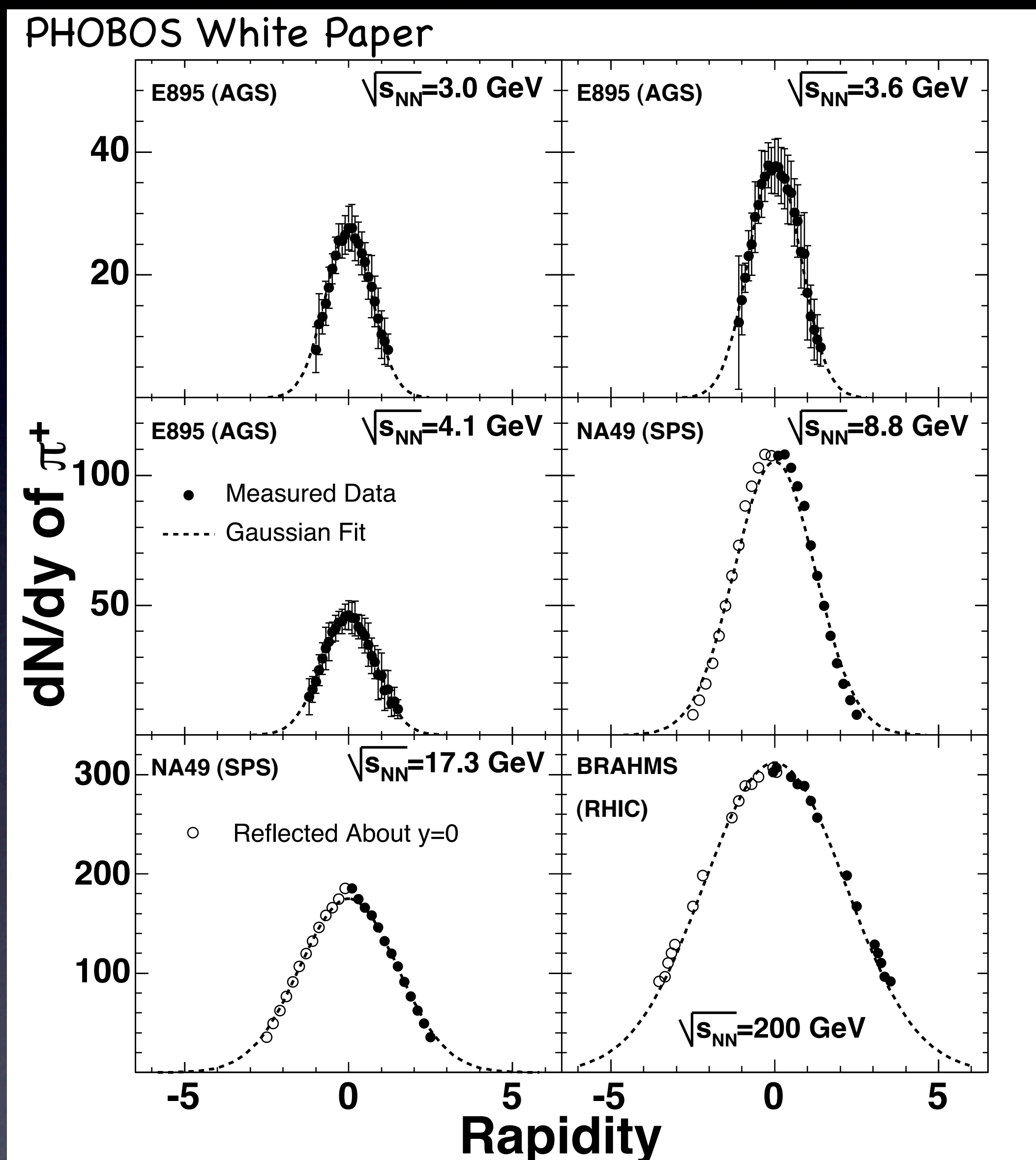


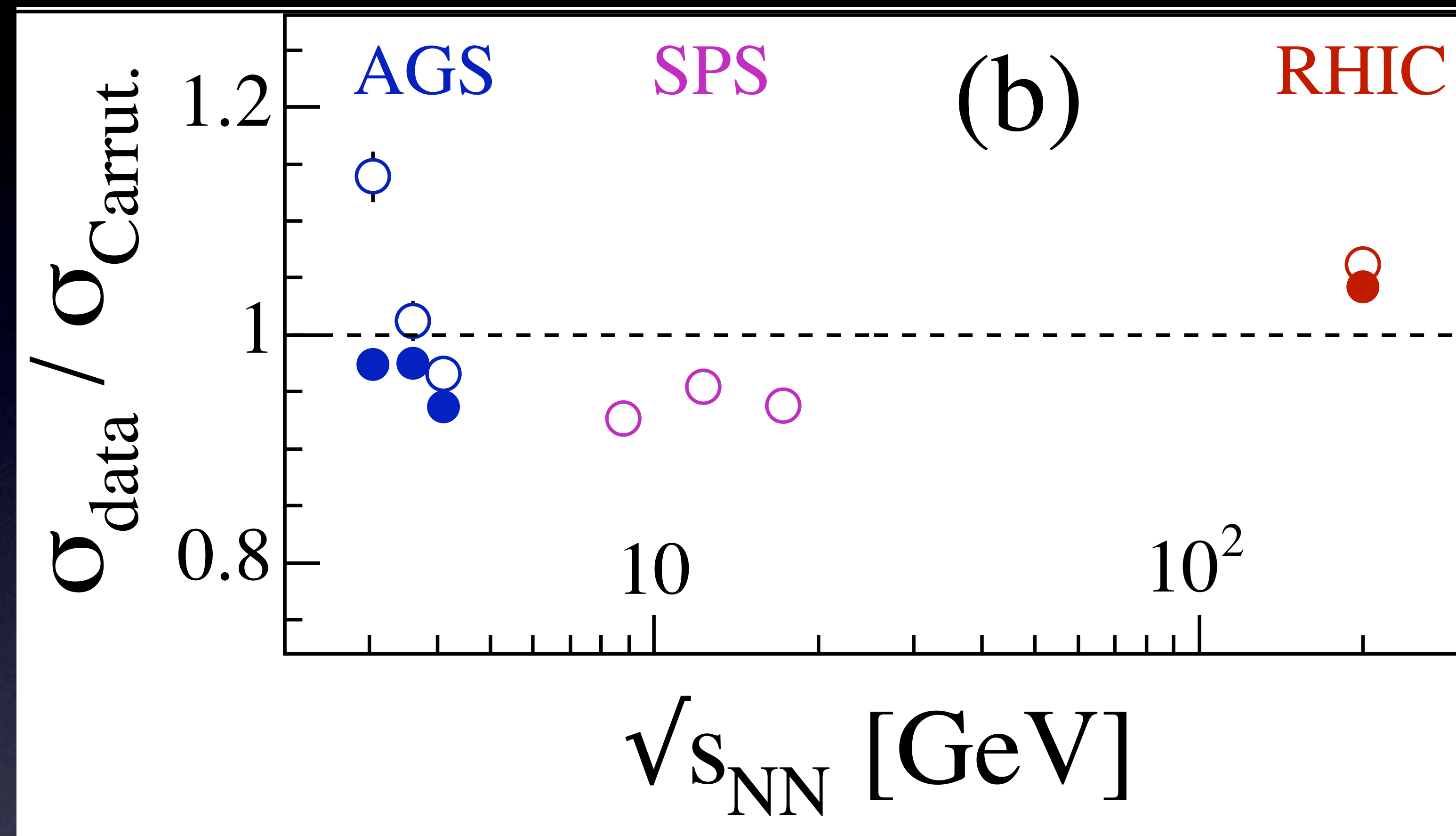
Strongly-coupled ^{6}Li atoms in a magnetic trap at the Feshbach resonance (O'Hara et al, 2003)

Any system with sufficiently-strong interactions will show "hydrodynamic" behavior

Ultracold atoms show it.
Do ultrahot RHIC collisions?

Landau Model vs. Data

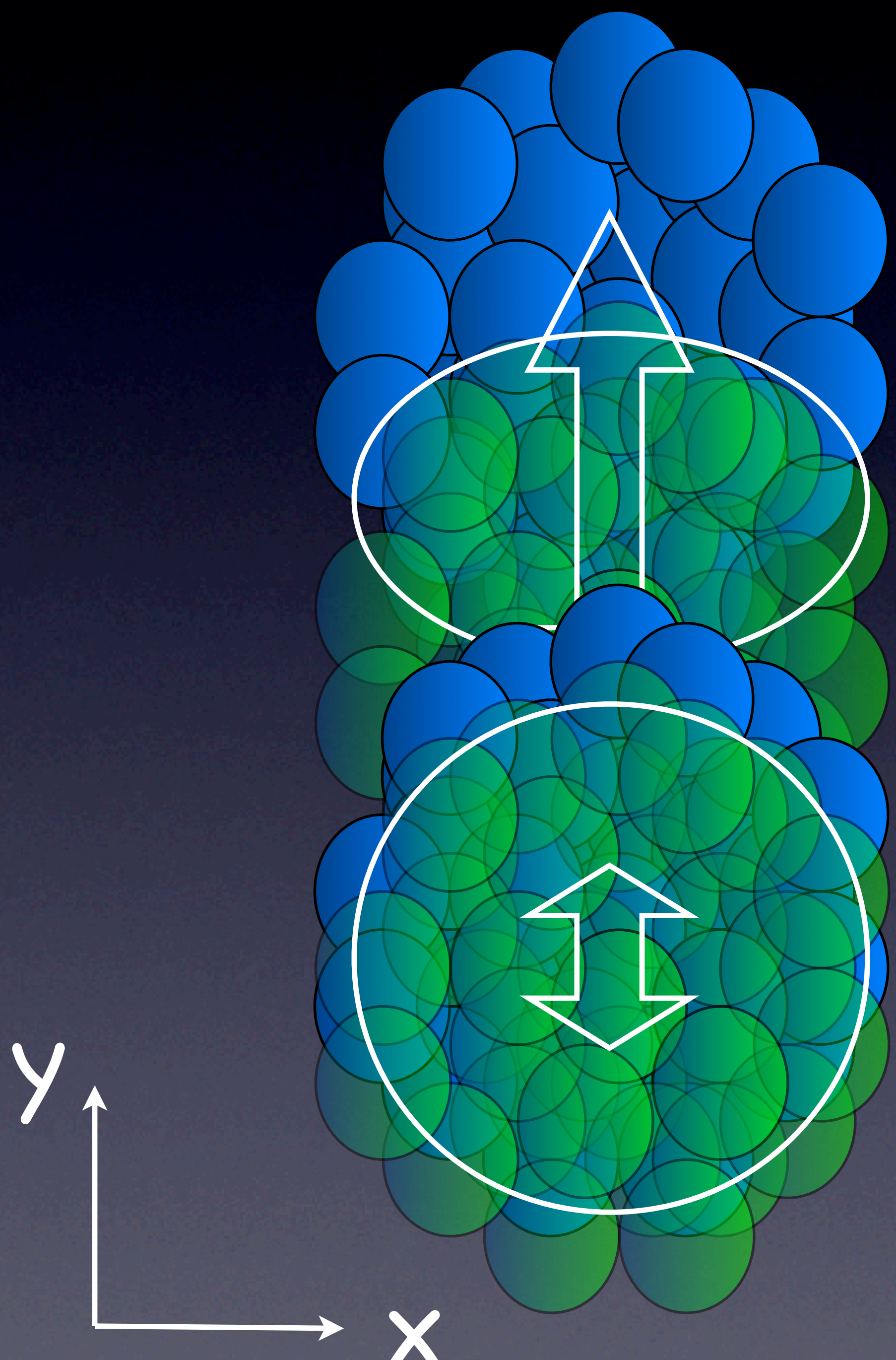


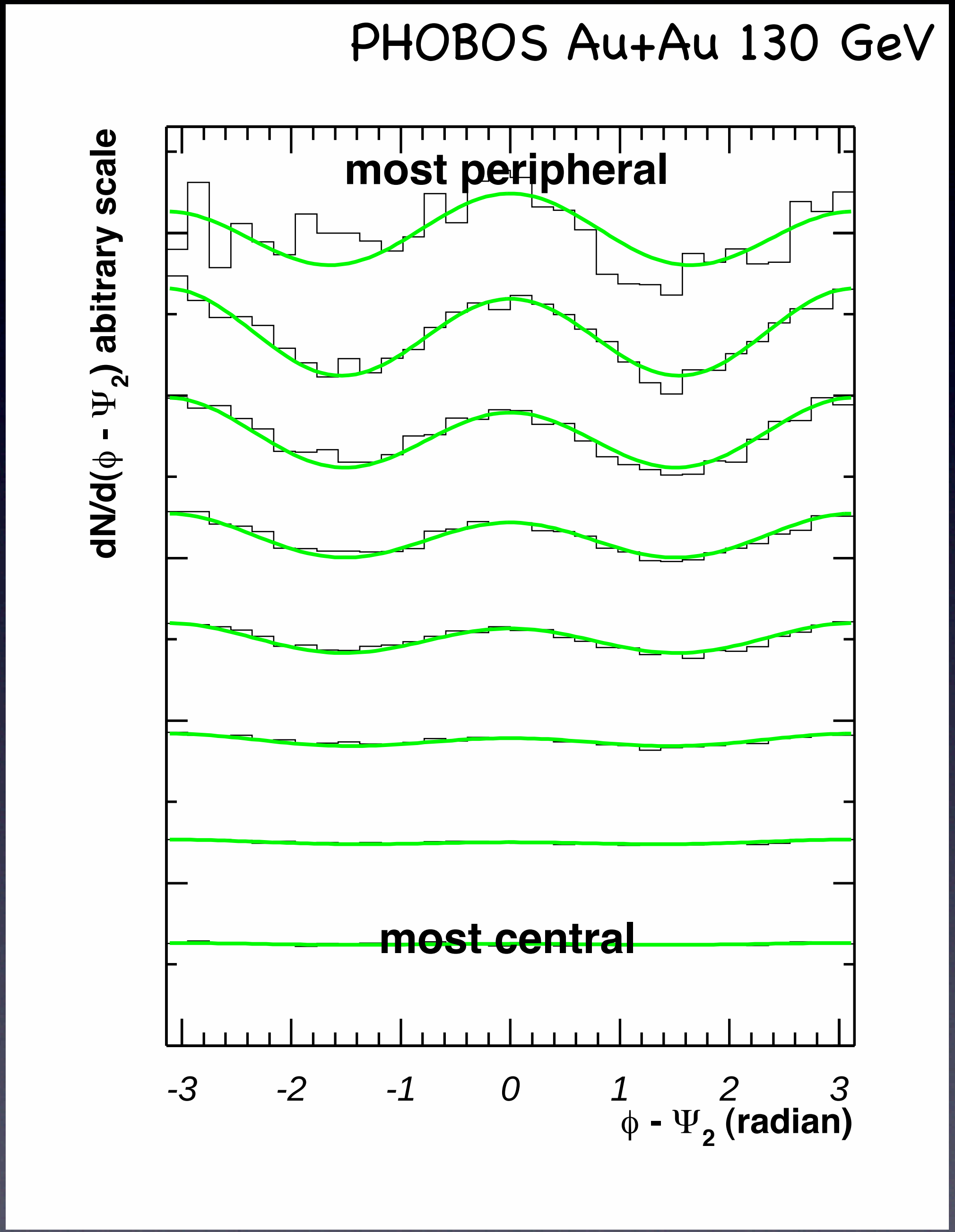


Landau's predictions from 1955 seem to be relevant in 2007!

The longitudinal explosion in heavy ion collisions acts like a rapidly-thermalized fluid!

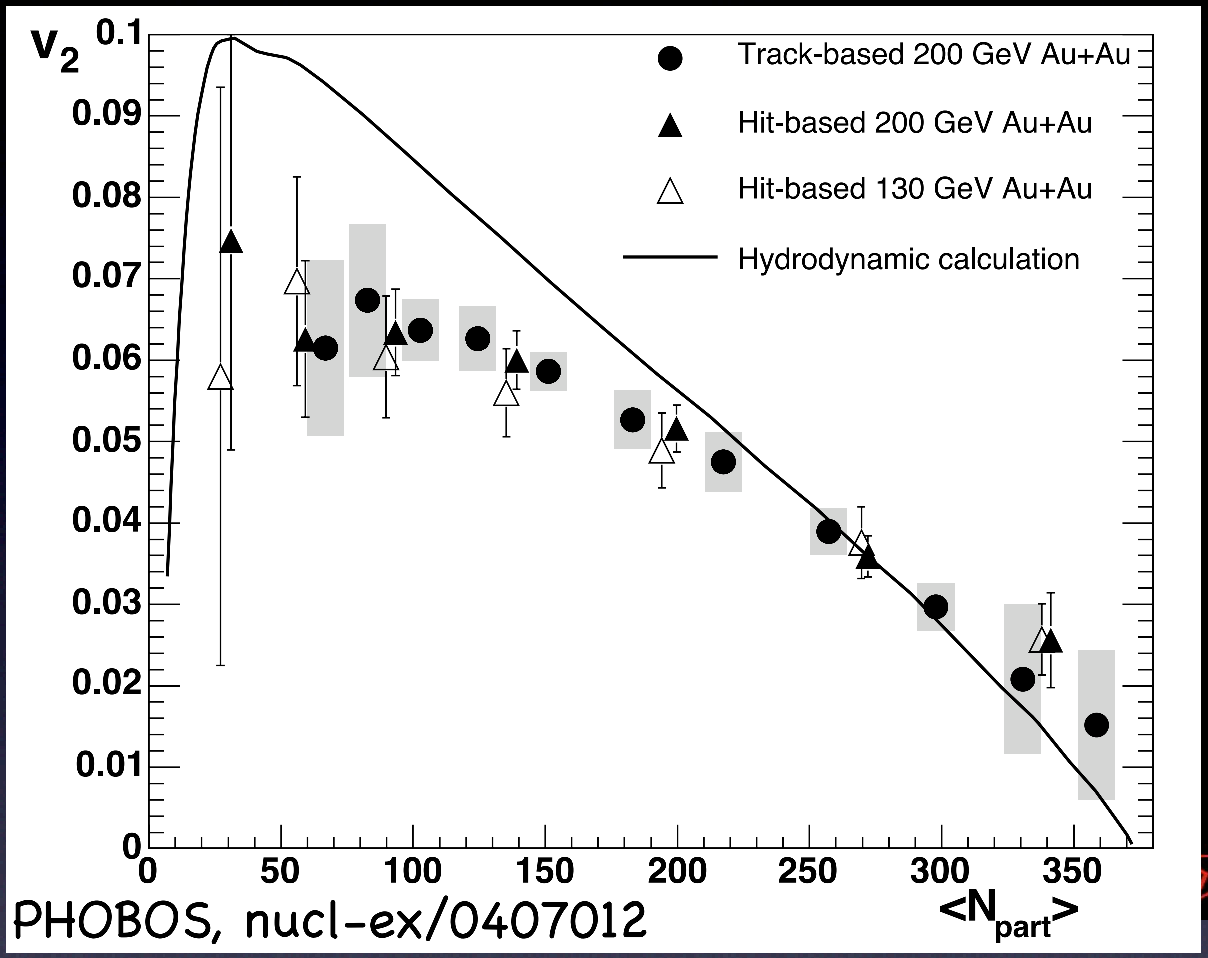
"Elliptic Flow"

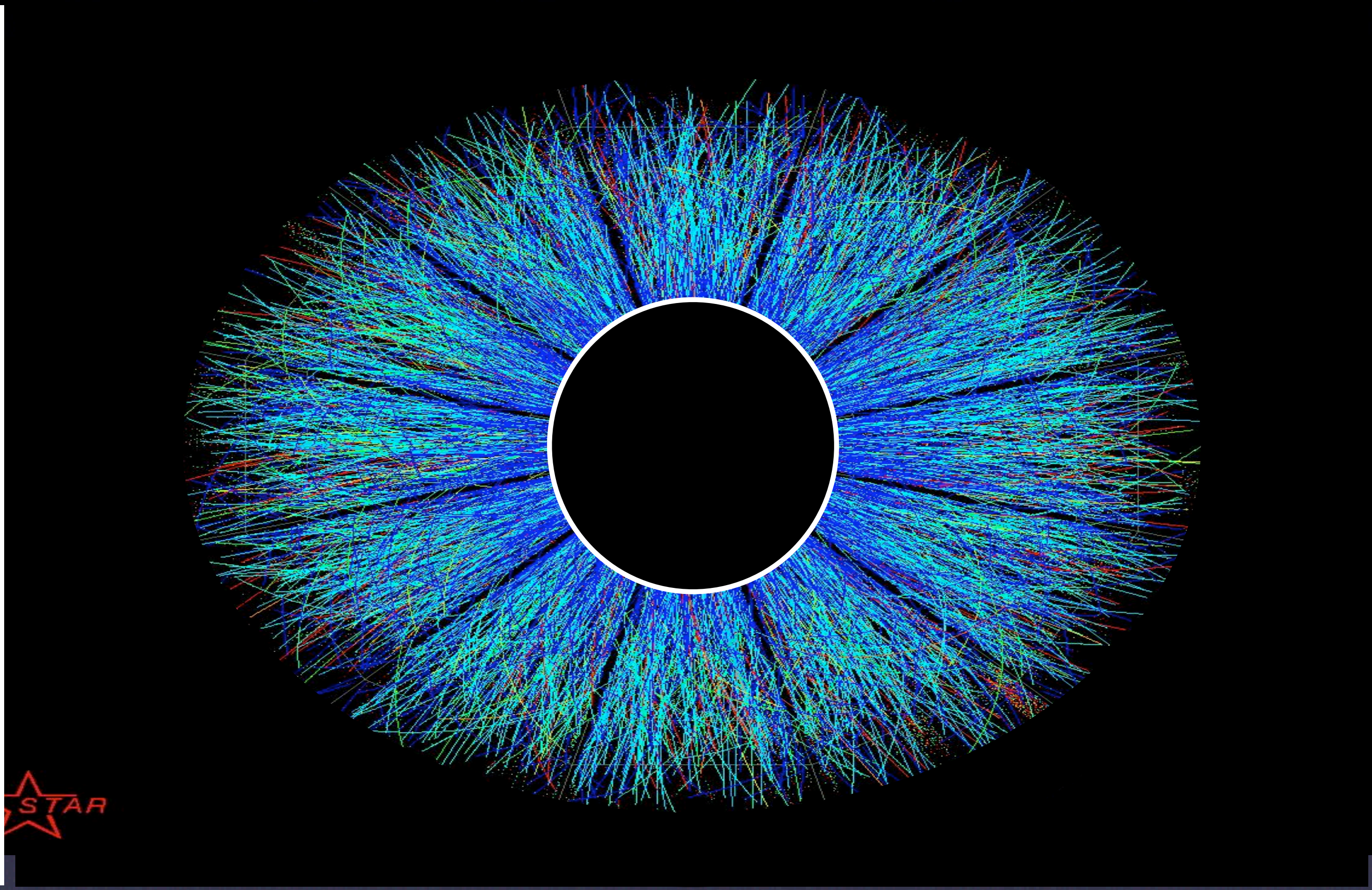




Modulation in the angle in the transverse direction

Agreement with Hydro

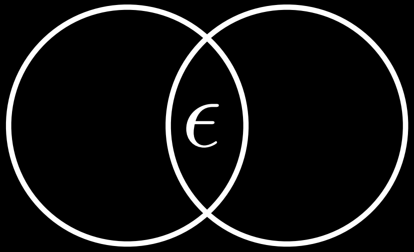


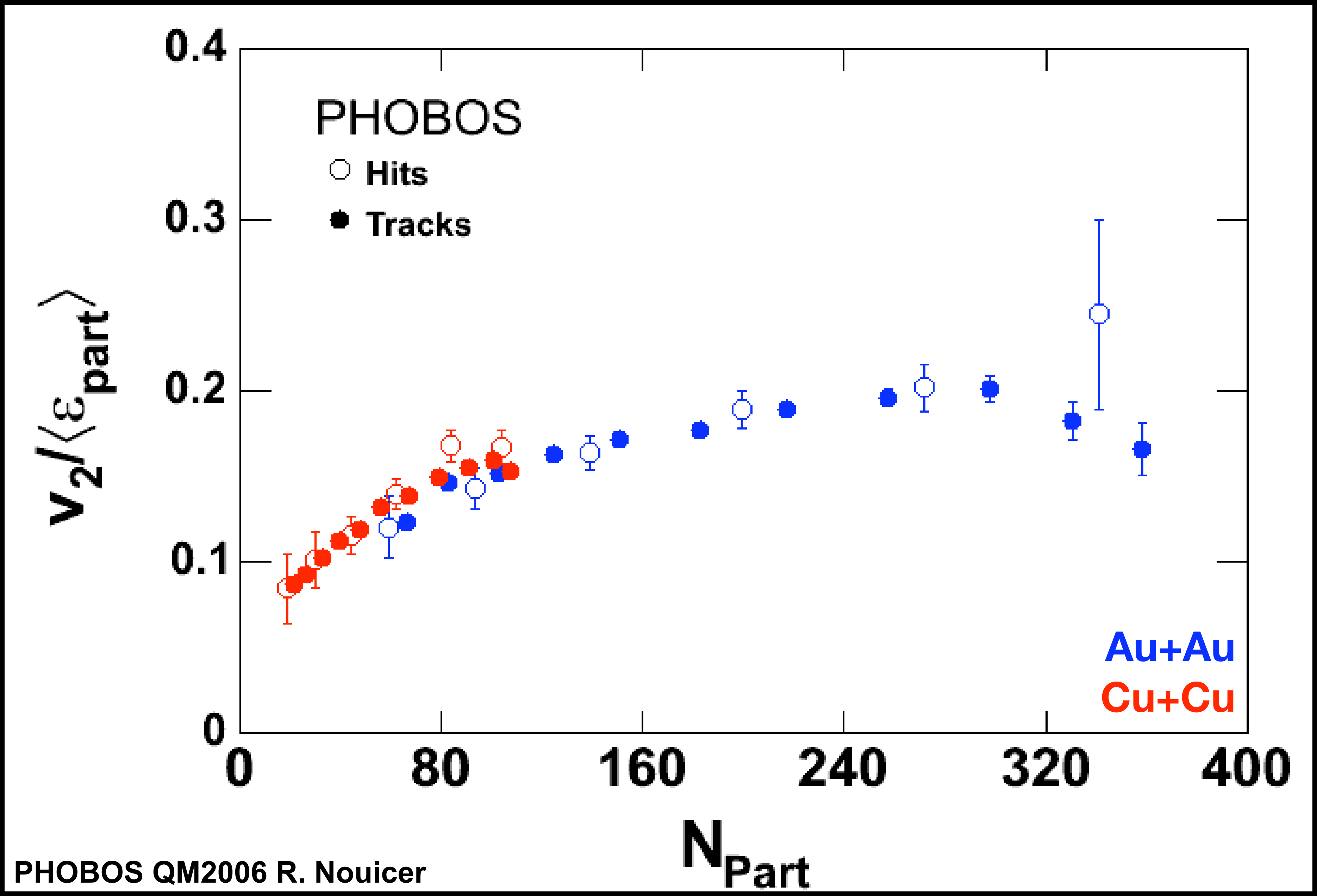


$$\frac{1}{N}\frac{dN}{d\phi} = 1 + 2v_1 \cos(\phi - \Phi_R) + 2v_2 \cos(2[\phi - \Phi_R]) + \ldots$$

Agreement with calculations of asymmetries, based on ideal liquid thermalizing in τ_0~0.6fm/c

Au+Au vs. Cu+Cu

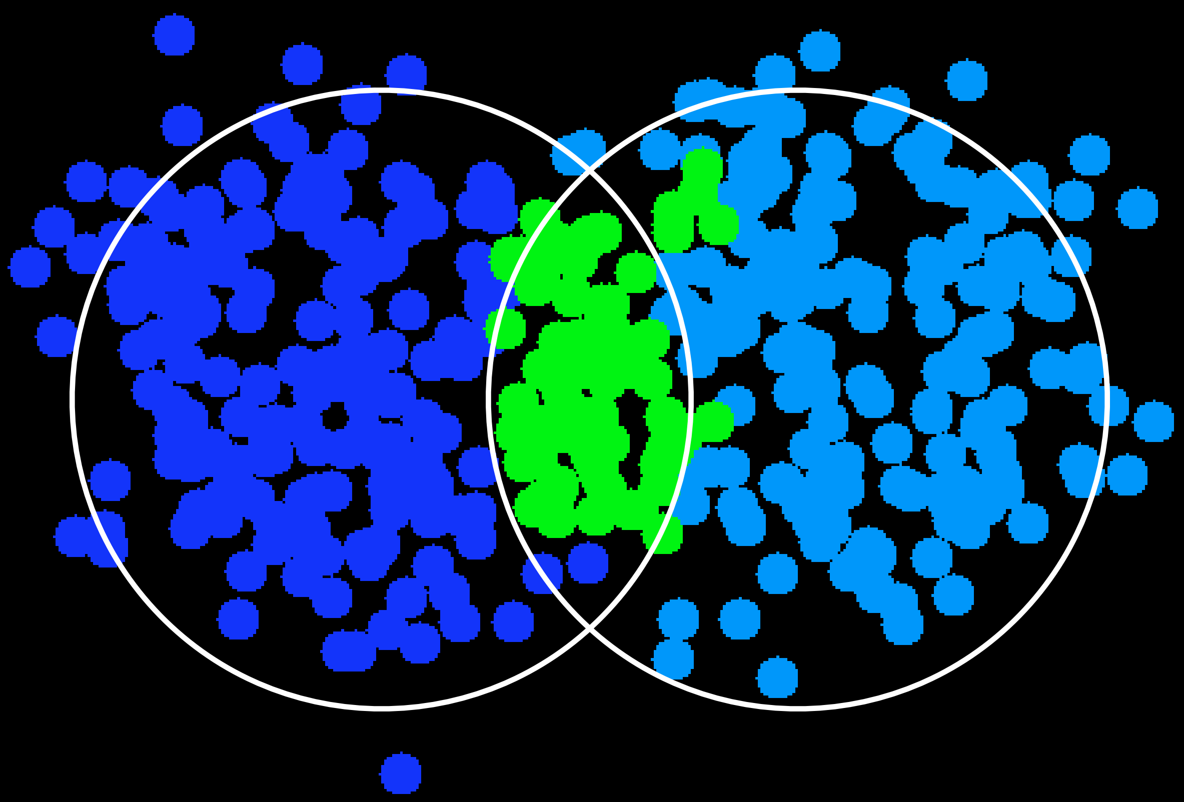




While no hydro calculations have been done for Cu+Cu, results agree with Au+Au after accounting for geometry

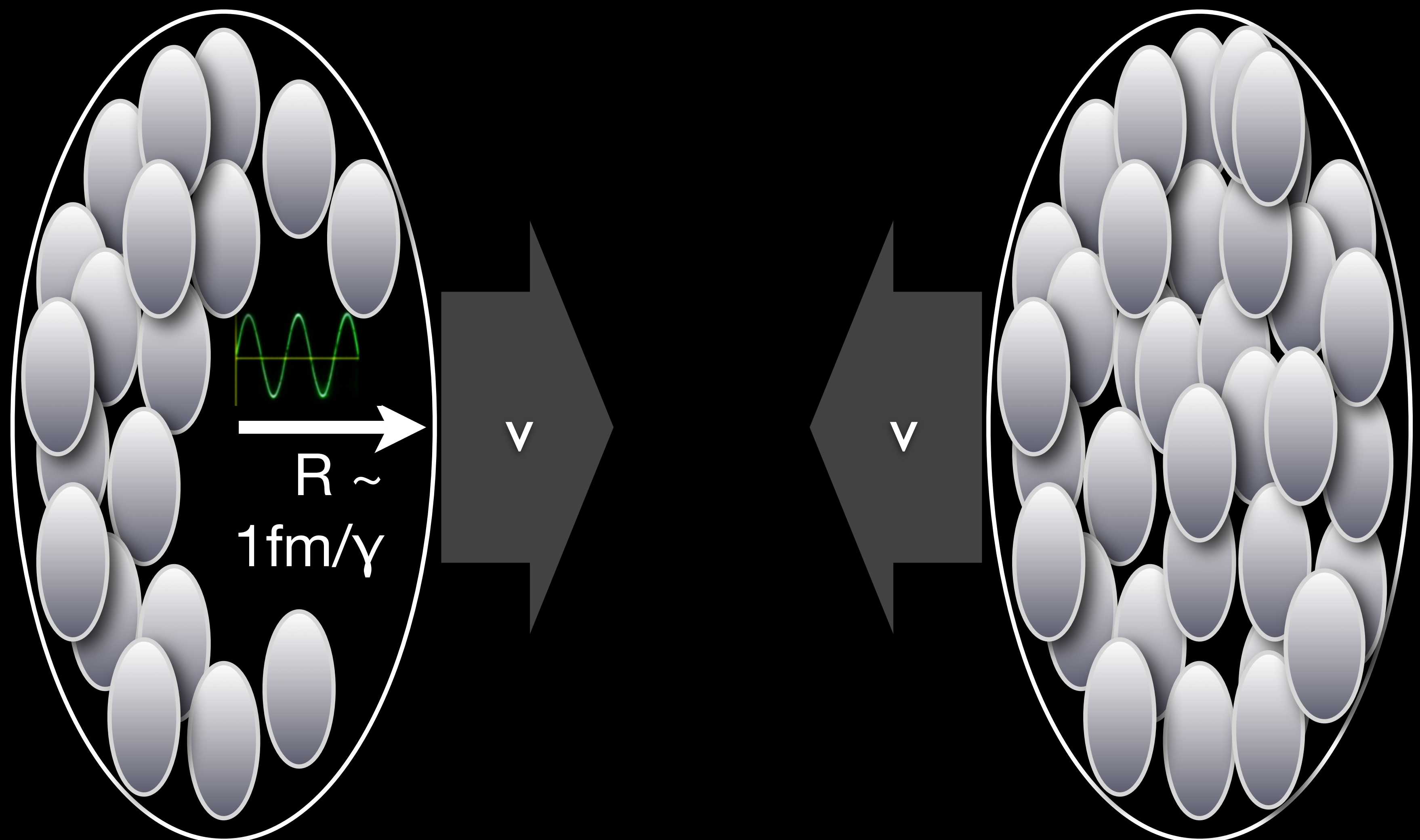
“Freeze-in”

2D projection of colliding Au+Au along beam axis



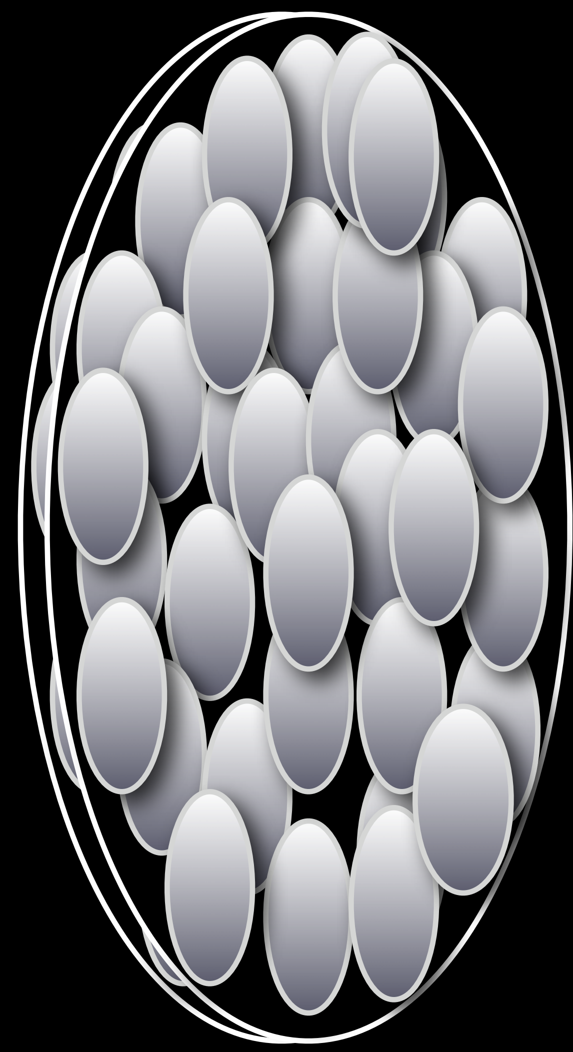
Configuration established <u>early</u> and <u>preserved</u>!

So What?



Try to imagine what is happening here:
Two nuclei racing towards each other at light speed...

So What?



They collide, and <u>something happens</u>...

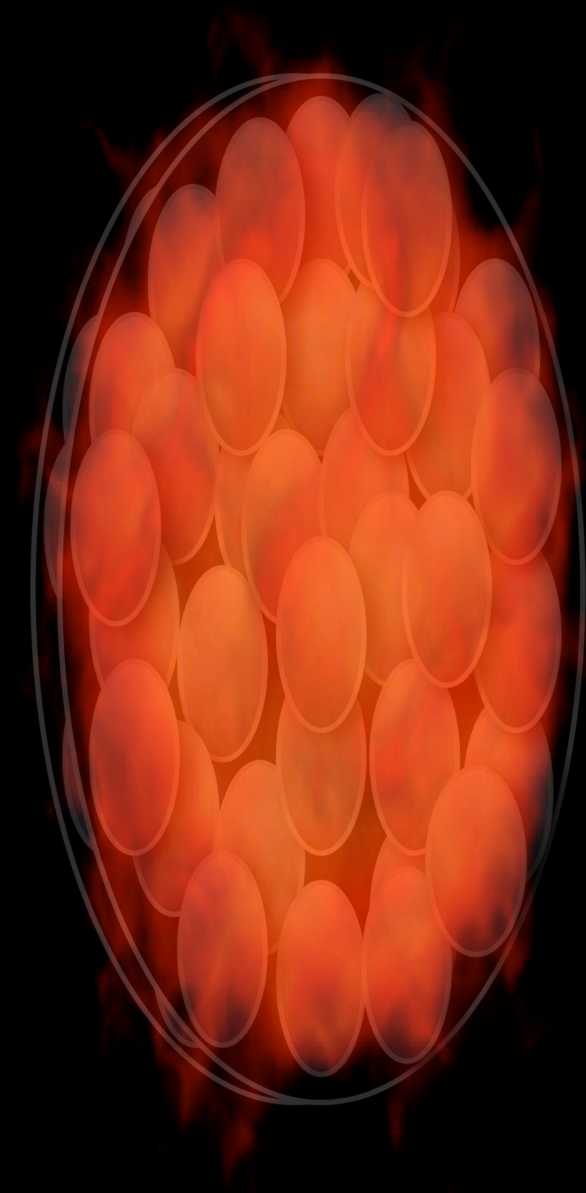
So What?

$t \sim 10^{-23}$ sec

$R \sim 10^{-15}$ m

$T > 2 \times 10^{12}$ °K

$\epsilon_0 > 3$ TeV/fm^3



Faster

Smaller

Hotter

Denser

...than anything you can imagine!

Something which makes the fastest, smallest, hottest, and most dense liquid created since the Big Bang!

What Makes RHIC Tick?

We can see that the matter created at RHIC forms quickly and is strongly interacting

But to be honest, we still don’t know exactly *which* degrees of freedom are interacting

Expected a “gas” of quarks and gluons, but models based on these interactions do not have sufficient coupling strength to allow a good description of the data

Strongly Coupled QGP? (sQGP)

Frontiers of RHIC Physics

Black Holes at RHIC?

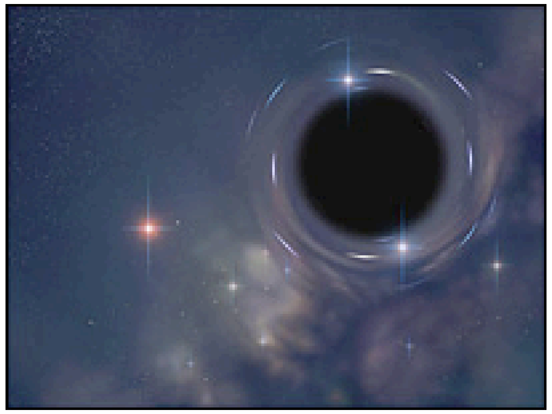
BBC NEWS UK EDITION

Last Updated: Thursday, 17 March, 2005, 11:30 GMT

E-mail this to a friend   Printable version

Lab fireball 'may be black hole'

A fireball created in a US particle accelerator has the characteristics of a black hole, a physicist has said.



Creating the conditions for the formation of black holes is one of the aims of particle physics

It was generated at the Relativistic Heavy Ion Collider (RHIC) in New York, US, which smashes beams of gold nuclei together at near light speeds.

Horatiu Nastase says his calculations show that the core of the fireball has a striking similarity to a black hole.

His work has been published on the pre-print website arxiv.org and is reported in New Scientist magazine.

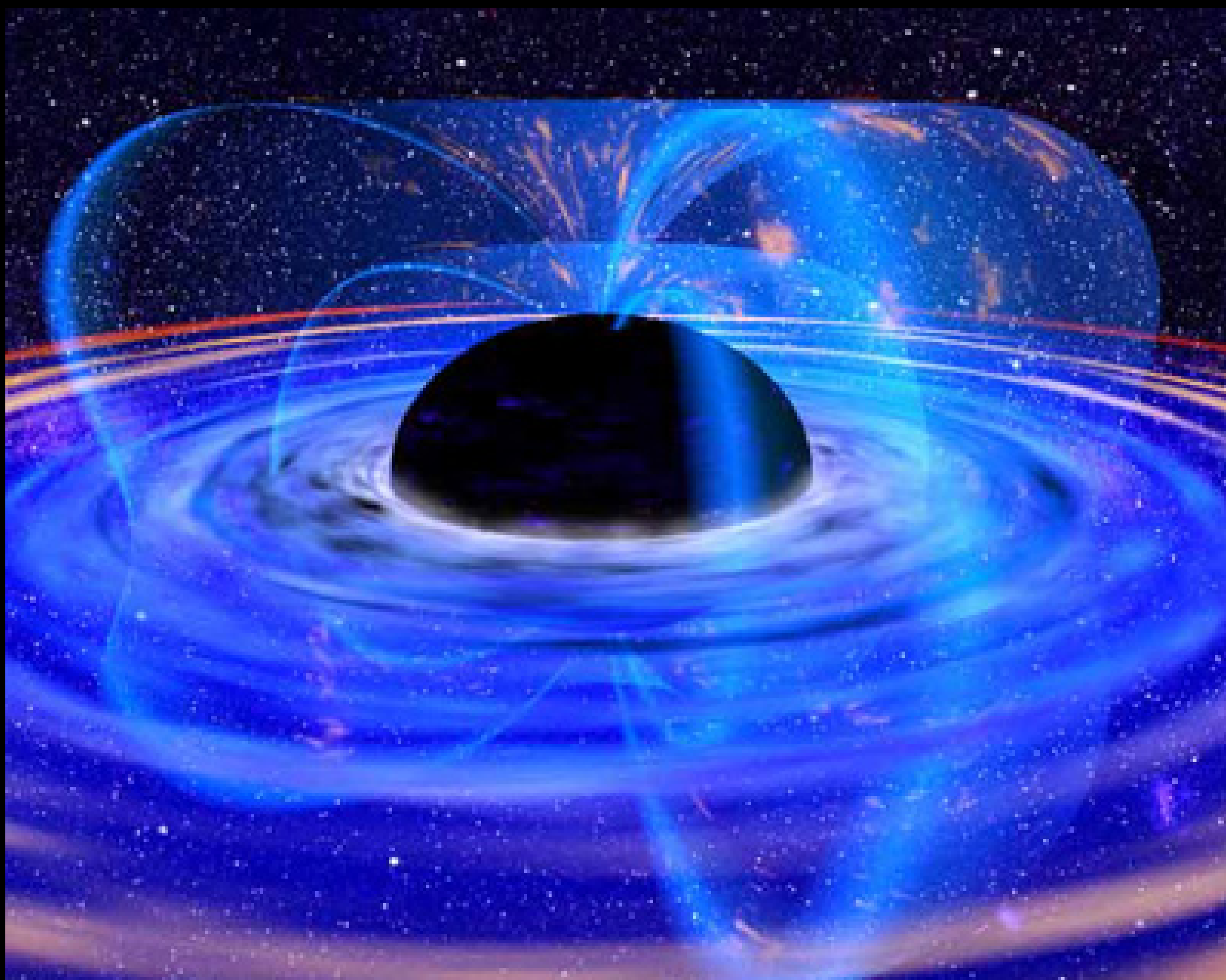
When the gold nuclei smash into each other they are broken down into particles called quarks and gluons.

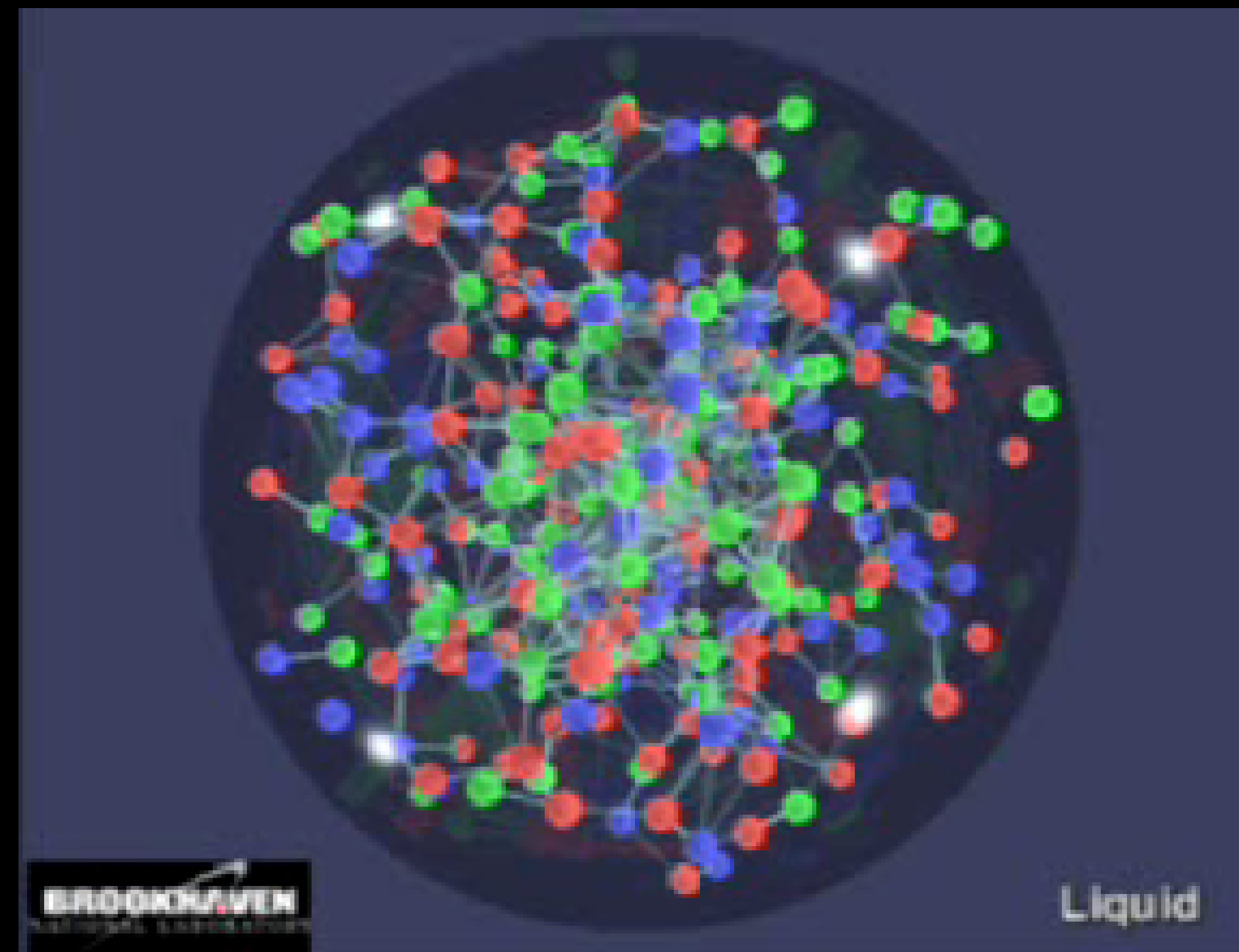
These form a ball of plasma about 300 times hotter than the surface of the Sun. This fireball, which lasts just 10 million, billion, billionths of a second, can be detected because it absorbs jets of particles produced by the beam collisions.

But Nastase, of Brown University in Providence, Rhode Island, says there is something unusual about it.

sorry, no...

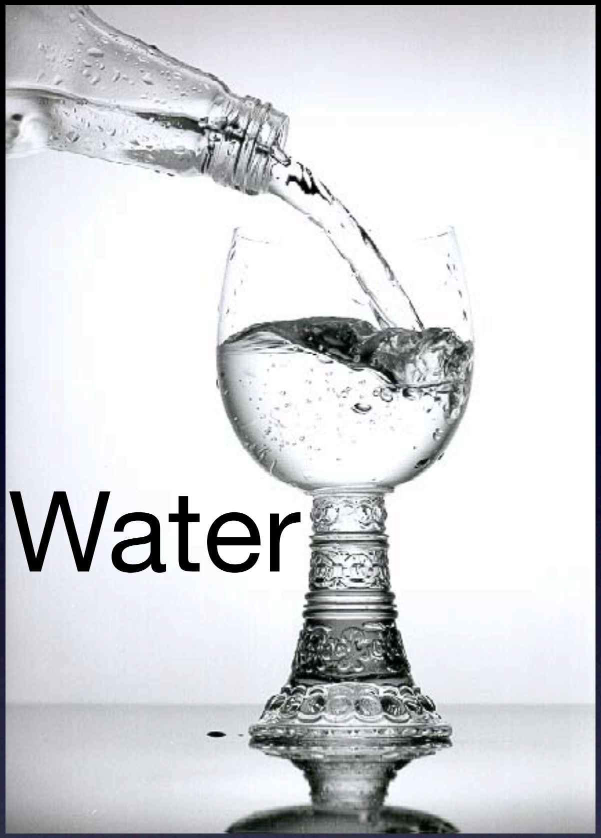
A Mathematical Connection

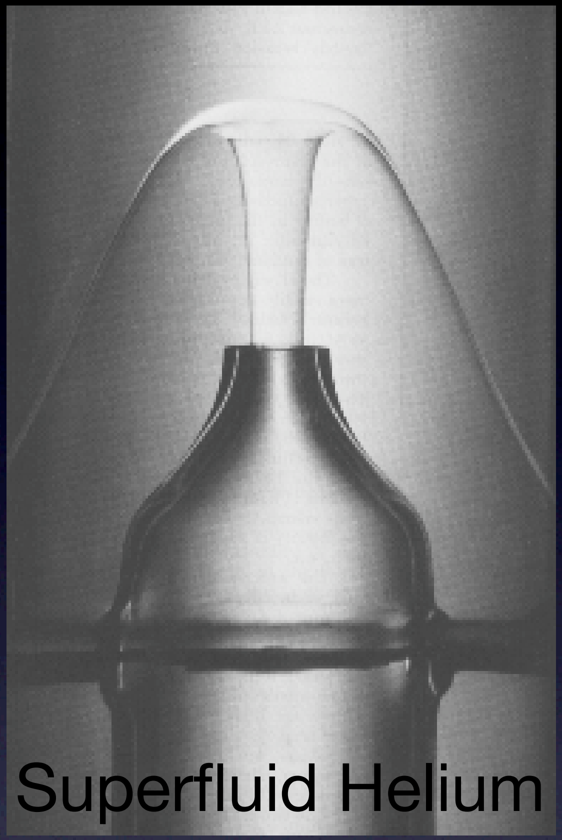




10-dimensional Black Hole (not a "real" black hole...) ↔ "Quark-Gluon Liquid"?

Keyword: Viscosity





Some liquids like to "flow" more than other liquids.

"Viscous" fluids (e.g. honey or motor oil) don't like to flow

A perfect fluid (no viscosity) only likes to flow!

PRL 94, 111601 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

sQGP String Theory!

Viscosity in ~~Strongly Interacting Quantum Field Theories~~ from ~~Black Hole Physics~~

P. K. Kovtun,[1] D. T. Son,[2] and A. O. Starinets[3]

[1]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

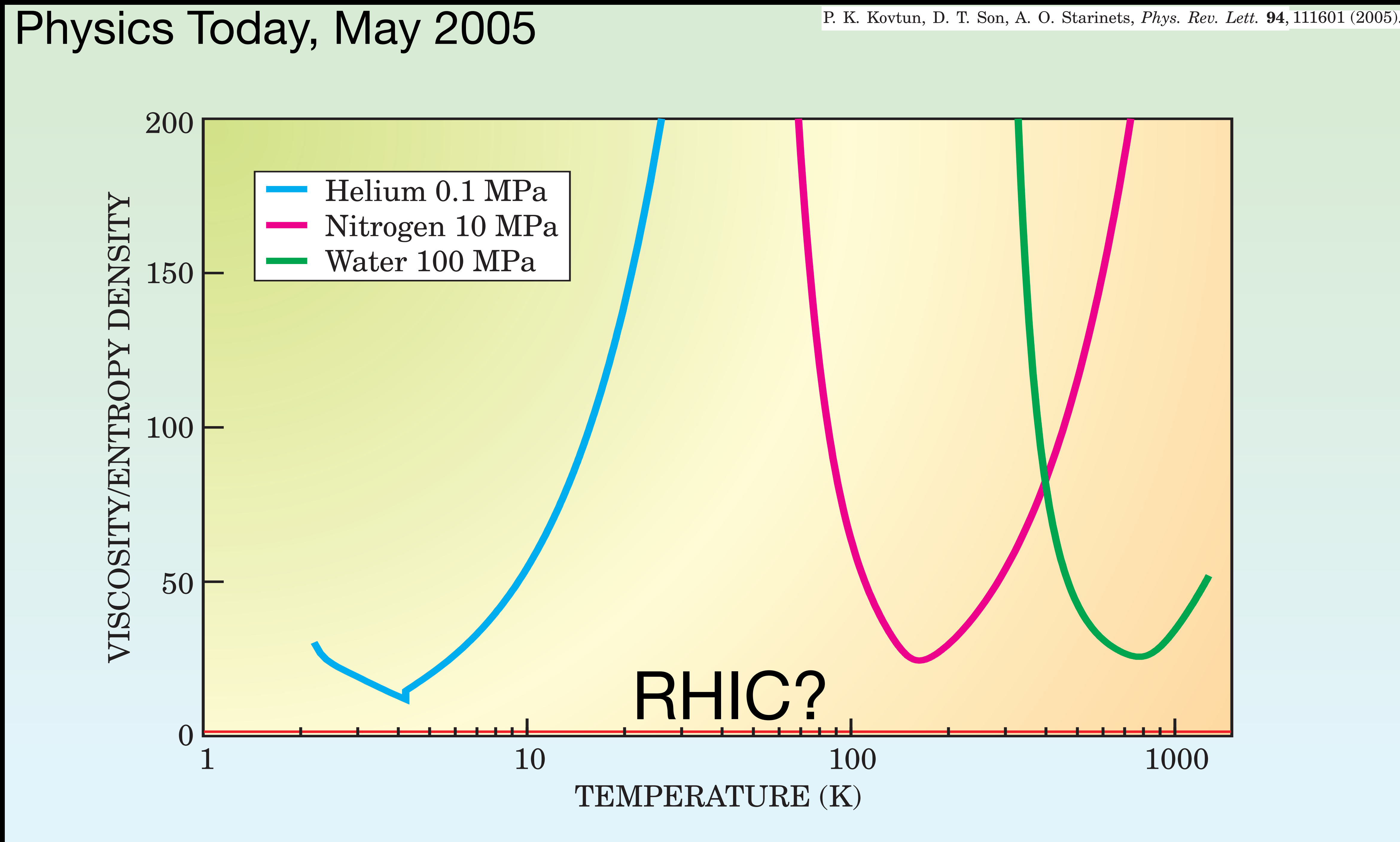
(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti−de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.

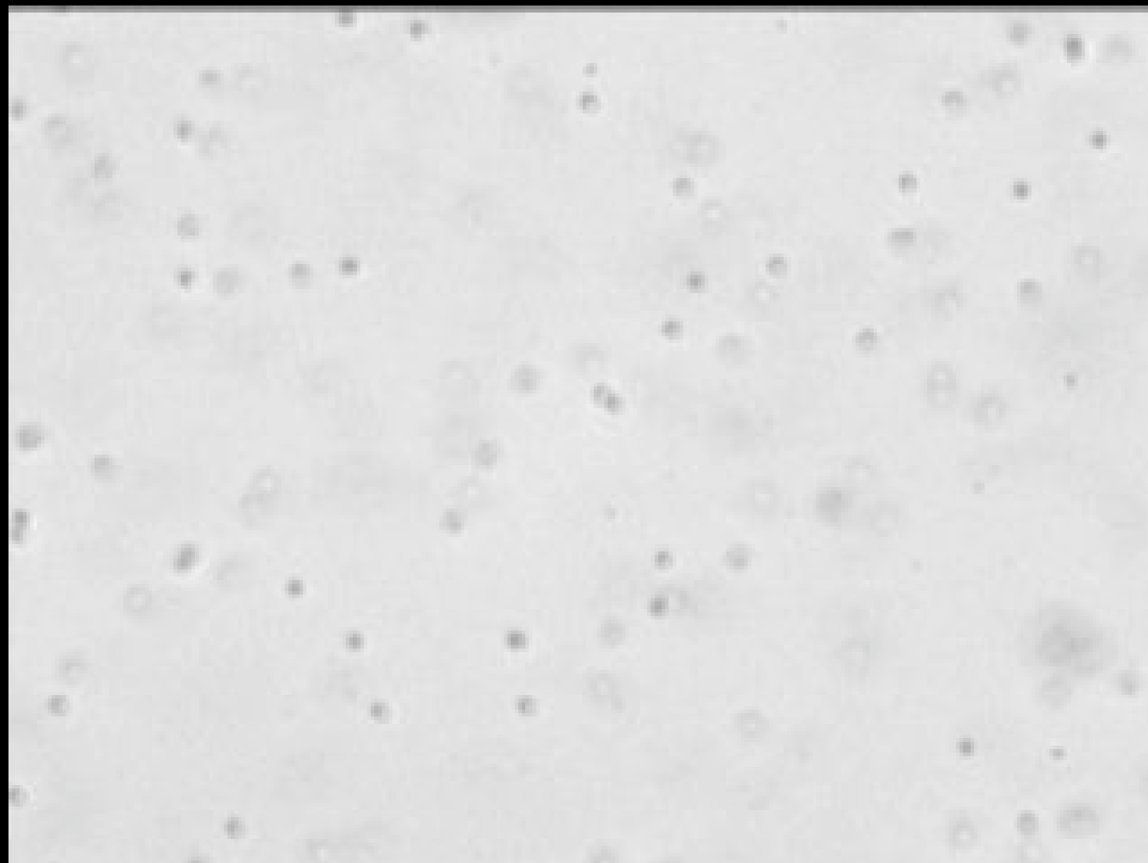
DOI: 10.1103/PhysRevLett.94.111601 PACS numbers: 11.10.Wx, 04.70.Dy, 11.25.Tq, 47.75.+f

Details aside, this paper makes a calculation about RHIC physics using a 10 dimensional black hole and gets a meaningful result about its viscosity...

Lower Viscosity Bound



A perfect liquid is impossible - but is RHIC the most perfect?



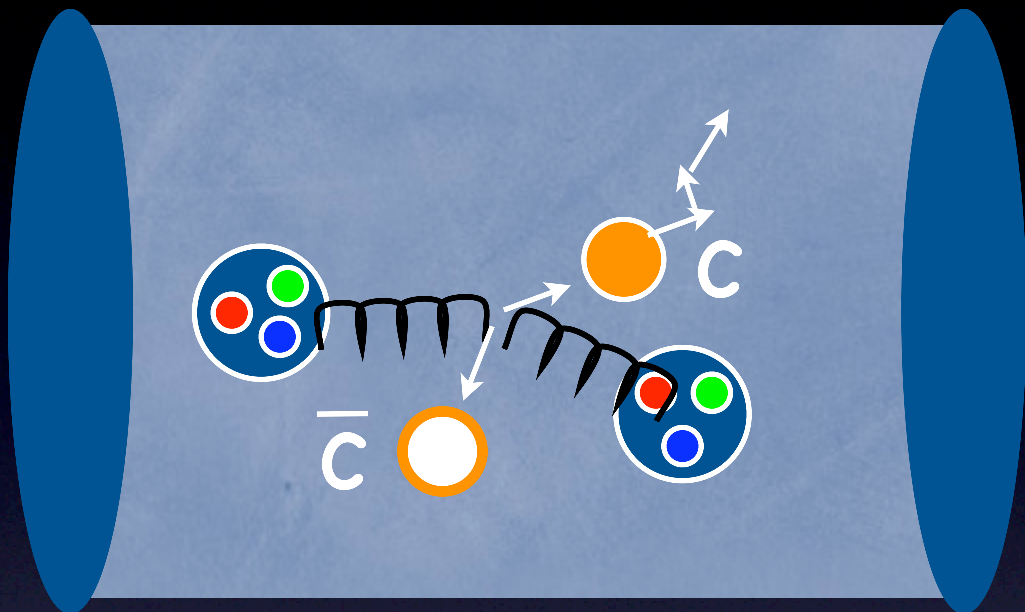
Viscosity is intimately connected to Brownian motion (1905!)

Can measure viscosity by measuring diffusion

How do we study such processes in a sQGP?...

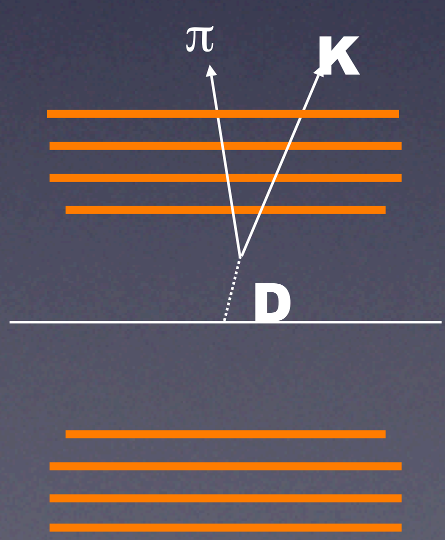
$$D = \frac{3kT}{\alpha}. \qquad \alpha = 6\pi\eta a$$

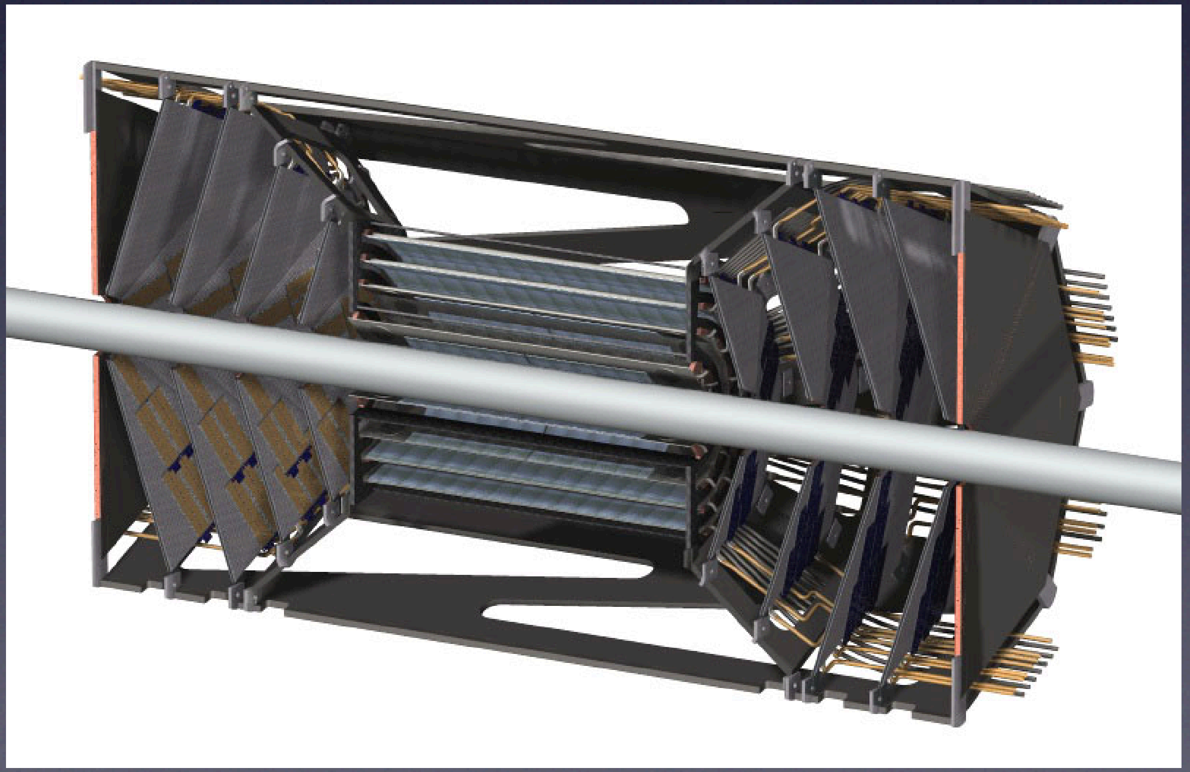
Heavy Flavor @ RHIC II



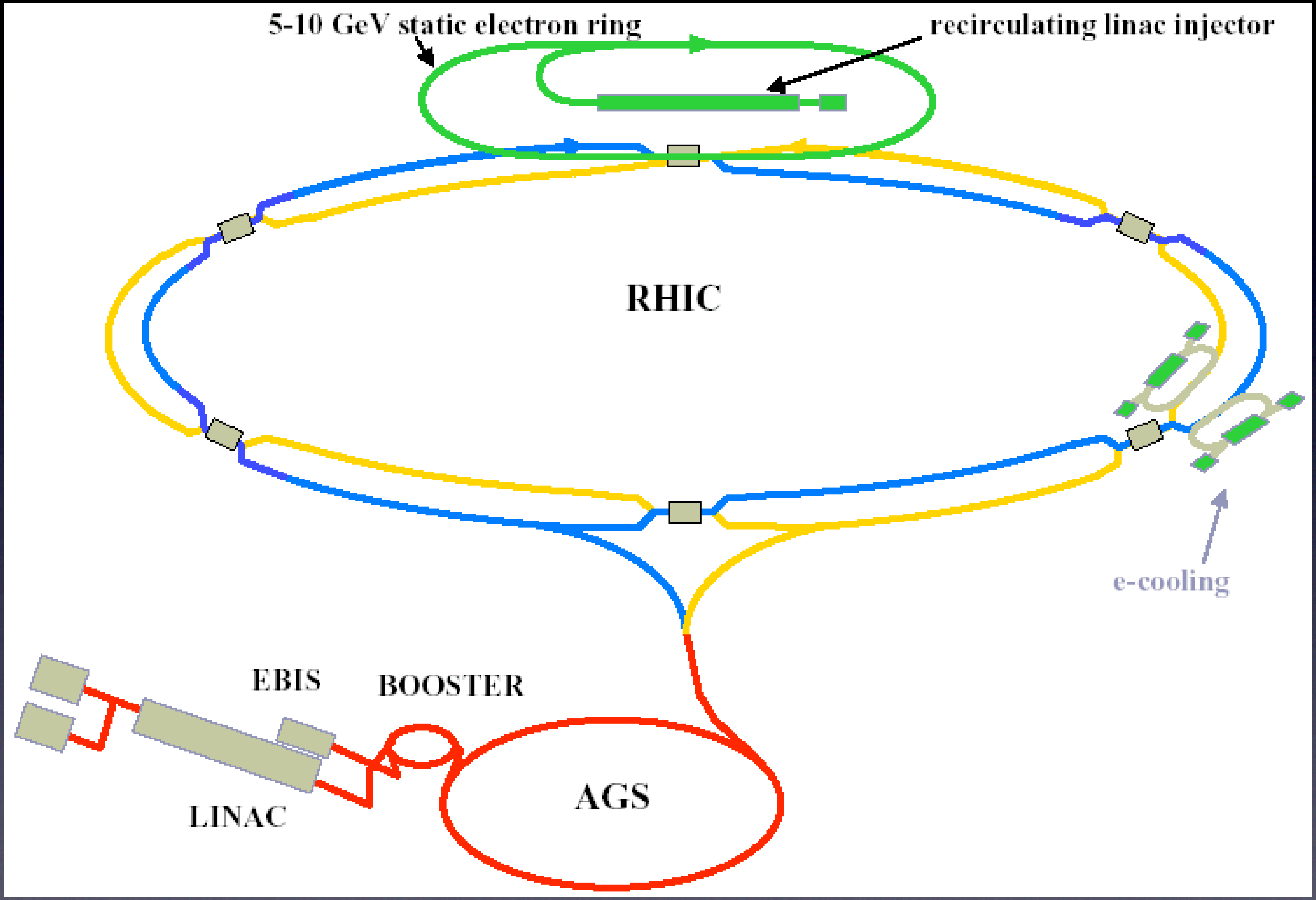
To probe the transport properties of the system, would be useful to study thermalization of heavier objects → e.g. heavy quarks

New silicon detectors being developed for PHENIX & STAR to study charm by means of displaced decay vertices



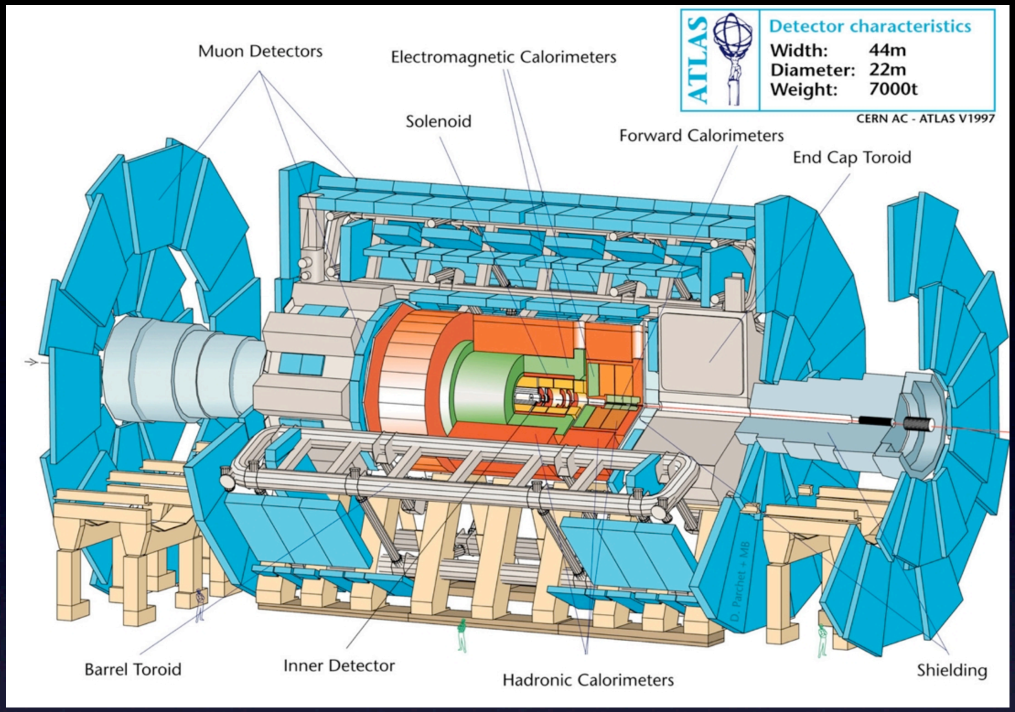


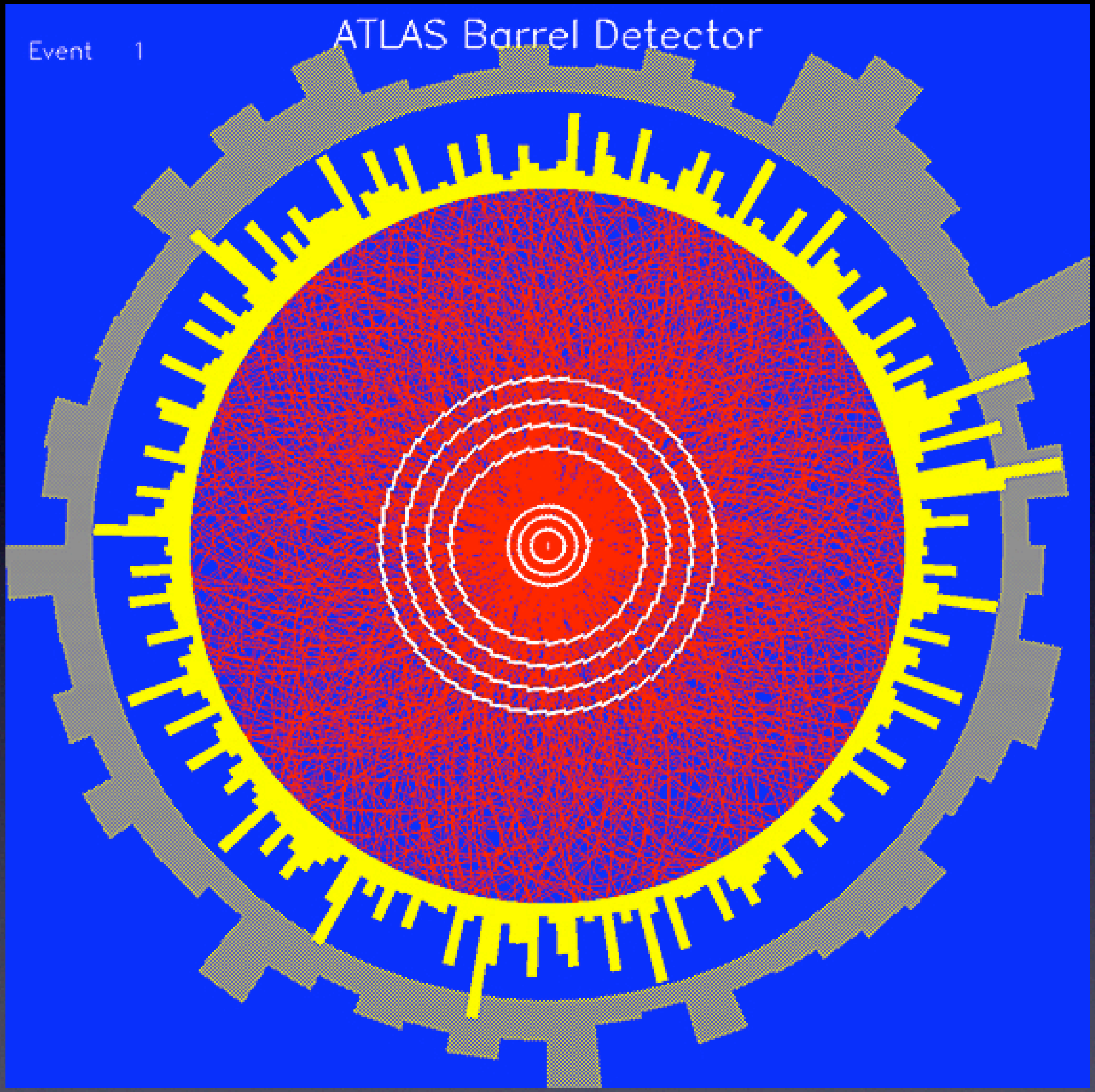
QCDLab (RHIC II)



10x the luminosity (event rate) of RHIC for gold-gold collisions!

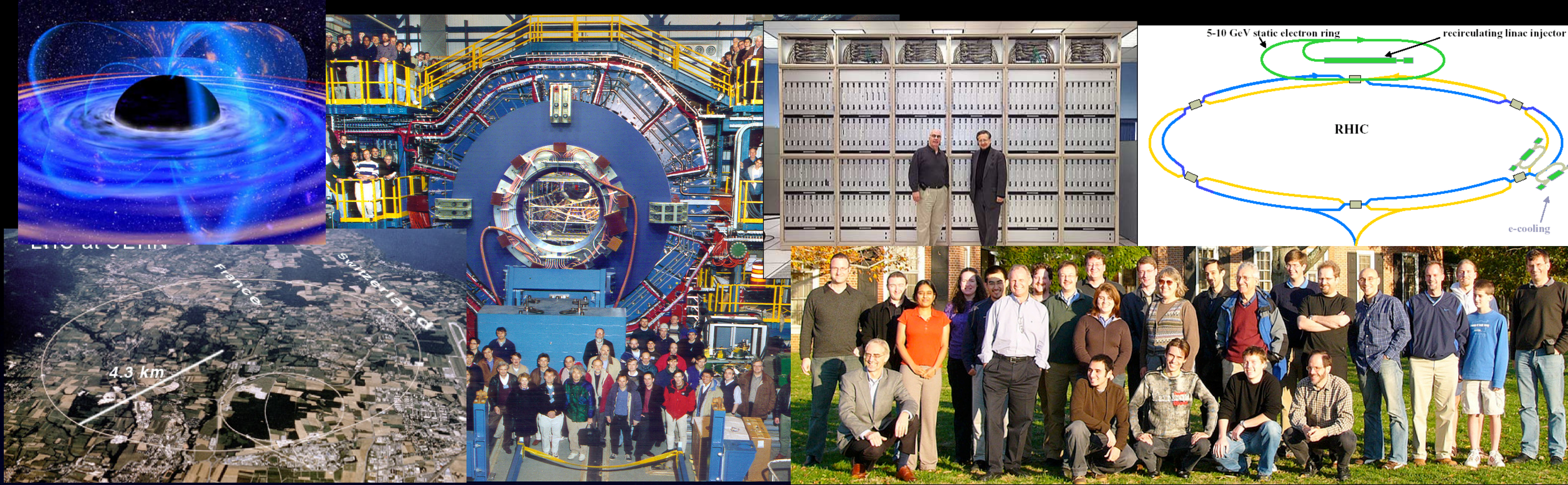
Pb+Pb @ LHC





High energies (x2250 contraction), huge multiplicities!
will the trends discussed here break down?

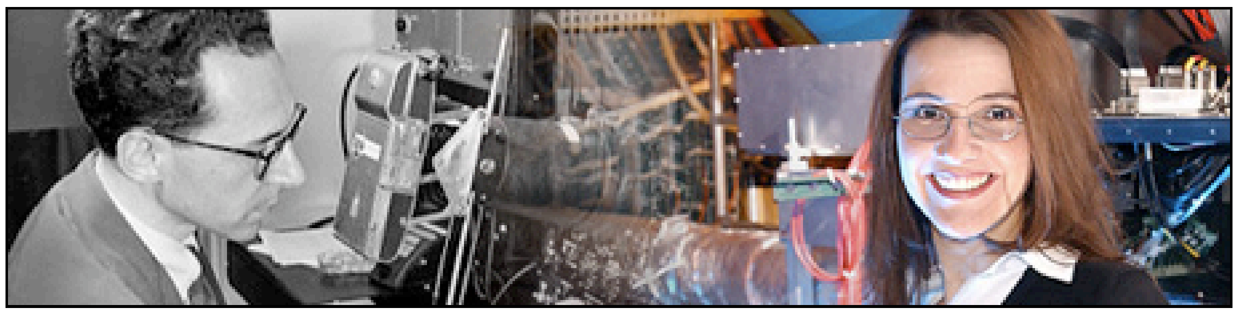
Understanding the strong interaction has a long history



But we still have a lot of work to do!

SIXTY YEARS OF DISCOVERY 1947-2007

Brookhaven National Laboratory



60 Years of Discovery

The U.S. Department of Energy's Brookhaven National Laboratory enters its seventh decade of science fueled by a *passion for discovery* that is stronger than ever. Through the years, Lab scientists plus thousands from around the world have used Brookhaven's unique facilities — including one-of-a-kind accelerators, research reactors, computers, and microscopes — to delve into the basic mysteries of physics, chemistry, materials science, and biology. This anniversary web site offers a glimpse at the spectrum of this research, looking back and looking forward.

Founding a Laboratory for Peacetime Research

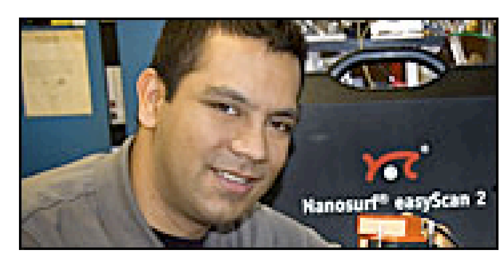
In 1946, representatives from nine major eastern universities — Columbia, Cornell, Harvard, Johns Hopkins, Massachusetts Institute of Technology, Princeton, University of Pennsylvania, University of Rochester, and Yale — formed a nonprofit corporation to establish a new science facility, and they chose a surplus army base "way out on Long Island" as the site. Thus, Brookhaven National Laboratory

Explore 60 Years...

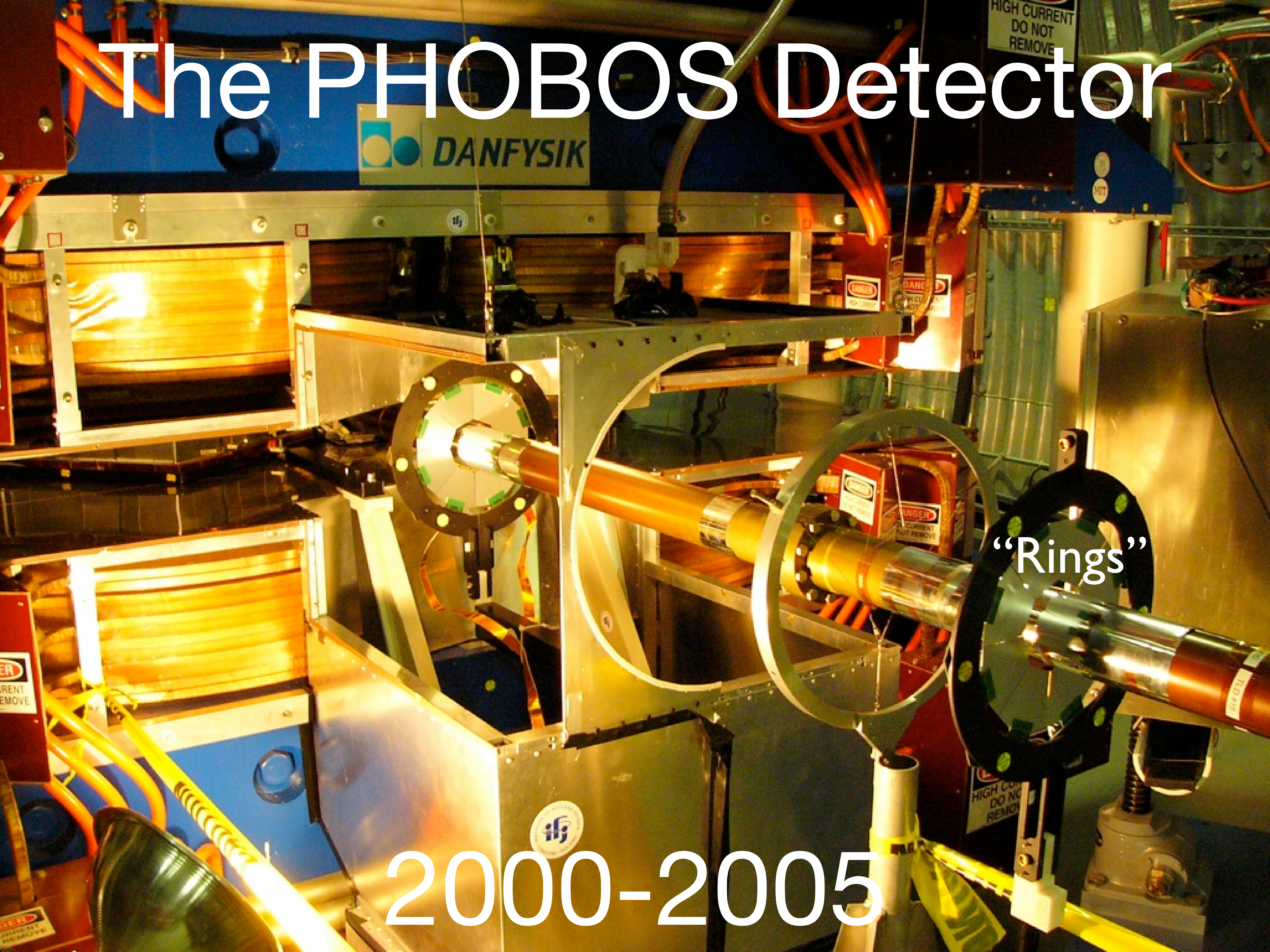
- Anniversary Home
- Accelerators
- Research Reactors
- Medical Research
- Biology Research
- Chemistry Research
- Nobel Prizes
- The Future

Today's BNLers

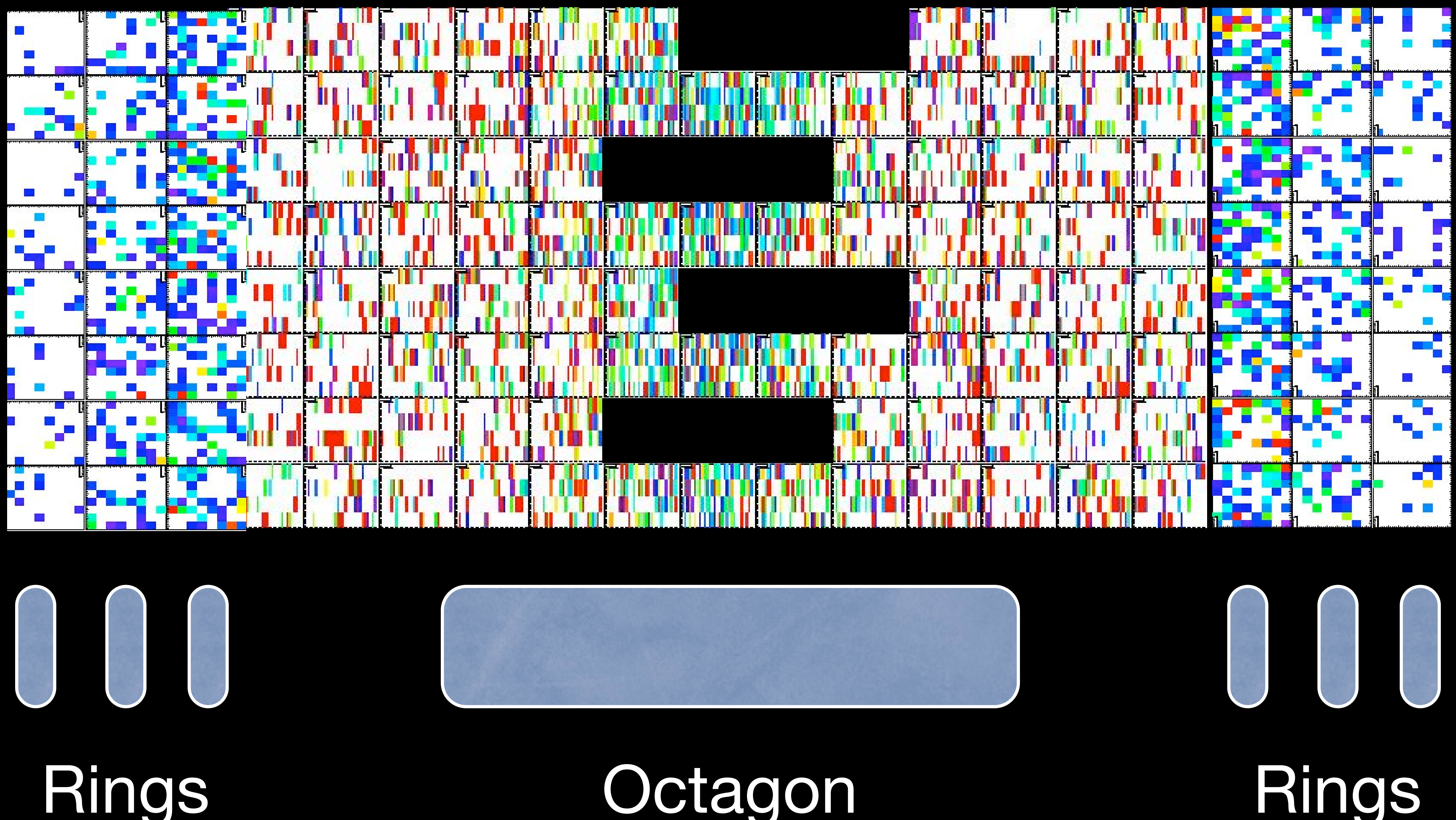
Who are the people that work at BNL? Meet some of the current faces at the Lab.



Celebrations


The PHOBOS Detector
"Rings"
2000-2005
HIGH CURRENT
DO NOT
REMOVE
DANFYSIK

A Single Event @ PHOBOS



Entropy Bound

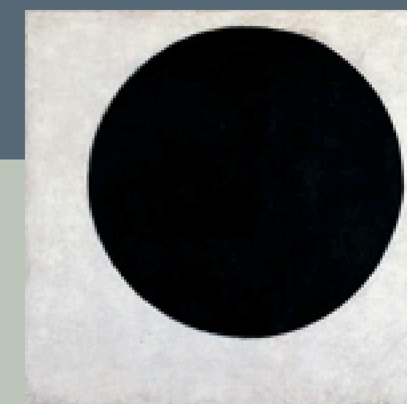
http://entropybound.blogspot.com/ RSS Google

News (1197) Services Experiments Conferences Apple (79) EB Blogs arXiv Physics

SEARCH BLOG FLAG BLOG Next Blog» Create Blog | Sign In

Entropy Bound

physical reflections and refractions at the boundaries of science and culture ...but really, things can only get so out of hand.



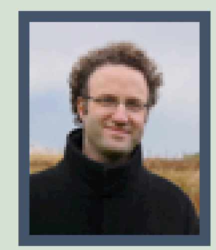
TUESDAY, MAY 15, 2007

Nuclear Physics: Not Just for Men

Just a follow up to the story which ran in the Times last week. As Paul pointed out in the comment to my post, it was an unfortunate example of the perception of physics as ultimately a boy's game. In this case, the story made working at RHIC sound literally like "grown men gathering around wide-screen TVs to watch collisions" -- or Star Trek -- despite showing several women in the photograph. Two of my colleagues at BNL and Stony Brook -- Sally Dawson (the chair of the physics department) and Barbara Jacak (recently-elected Spokesperson of PHENIX) -- have justly objected to this somewhat-skewed portrayal, in a letter to the Times:

> Nuclear physics experiments at Brookhaven Lab's Relativistic Heavy Ion Collider involve a lot more than men viewing wide-screen monitors in a control room rooting for collisions.
>
> The Phenix and STAR collaborations at RHIC are large teams that run these experiments. They include about a thousand scientists — women and men, young and old — from around the globe. And though exploration of the moment just after the Big Bang may sound like science fiction, house-sized detectors, fast electronics and large-scale computers are in use here and now, revealing that the early universe was a dense liquid of quarks and gluons.

About Me



Peter Steinberg

View my complete profile

Elsewhere

- Quantum Diaries Archive
- Brookhaven Home Page
- Flickr Photo Stream

Brookhaven RHIC CERN LHC Physics Cosmology

The Island Getting the Most Bang
New York Times, USA
... at Brookhaven National
Laboratory the other day were