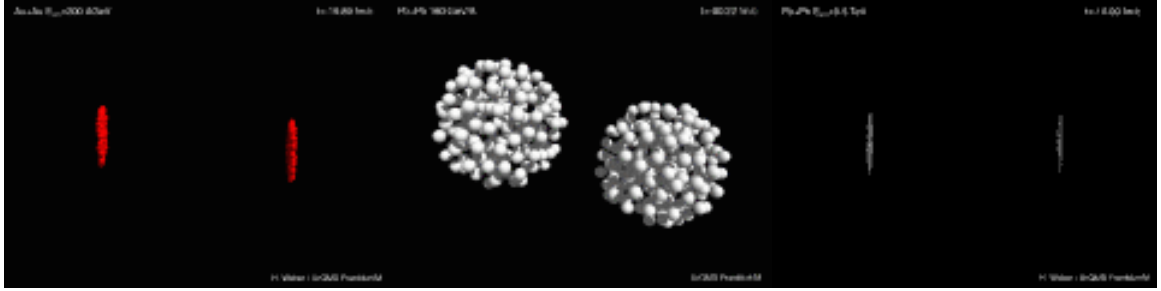


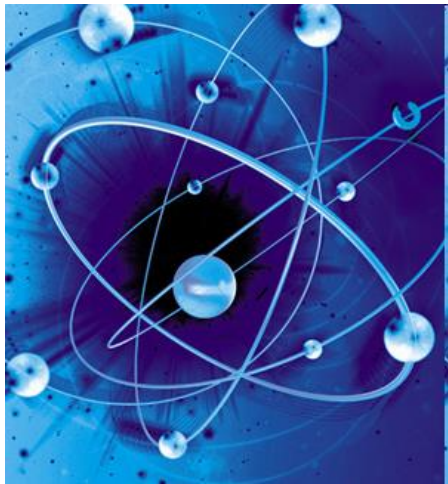
Relativistic nucleus-nucleus collisions: from Bevalac to LHC

Azwinndini Muronga[1,2]

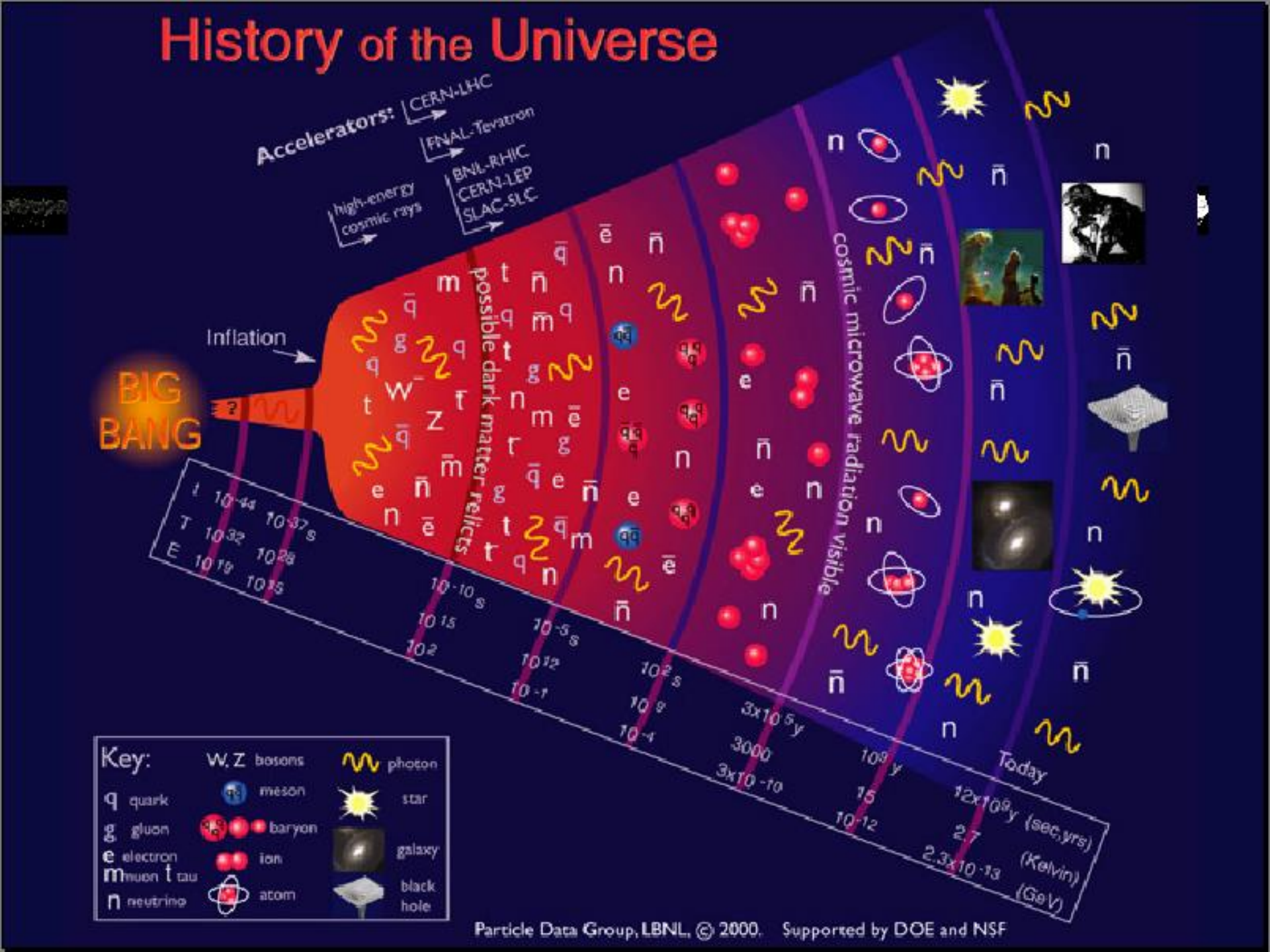
[1]Department of Physics, University of Johannesburg, Auckland Park

[2]UJ Soweto Science Centre,

University of Johannesburg, Soweto



High Energy Particle Physics Workshop,
iThemba LABS North, 11-13 February 2015


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Origins of Ultrarelativstic Heavy Ion Colisions:

Workshop on BeV Collisions of Heavy Ions: How and Why

Nov 29 - Dec 1 1974

Bear Mountain New York

Introduction and Summary:

“The history of physics teaches us that profound revolutions arise from a gradual perception that certain observations can be accommodated only by radical departures from current thinking. The workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable.”

Leon Lederman and Joseph Weneser

“It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.”

T. D. Lee

A long journey to discovery: from Bevalac to LHC

Bevalac

AGS-RHIC

SPS-LHC

A Brief History of Hadron Accelerators

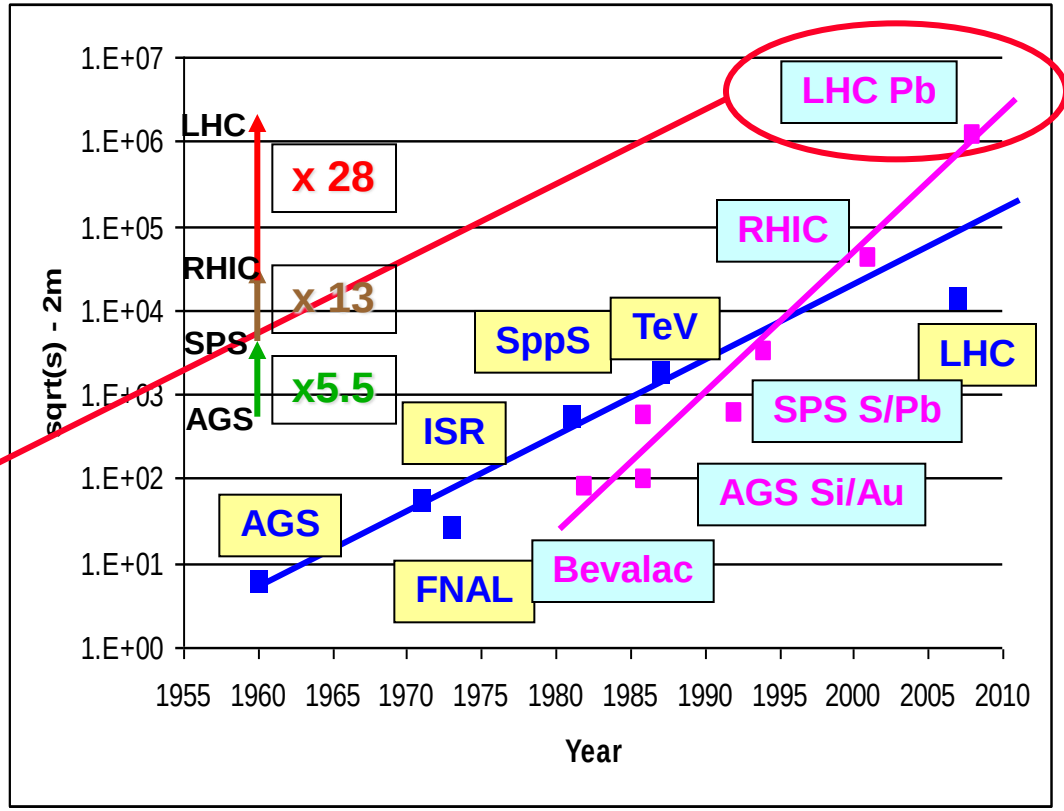
- **Particle Physics: energy doubling time ~ 4 years**
- **Heavy Ion Physics: doubling time ~ 1.7 years**
  - ⇨ starting 70'- to early 80's at Bevalac
    - ✪ field started by a few dozen physicists mostly from US, Germany, Japan
  - ⇨ energy increase by factor 10^4 in ~ 25 years with LHC in 2008
    - ✪ > 2000 physicists active worldwide today

Possible mostly by (re-) using particle physics machines.

Field went from the periphery into a central activity of contemporary Nuclear Physics.

Future of Ultra-Relativistic Heavy Ion Physics at the Energy Frontier is the LHC

Total center-of-mass energy versus time



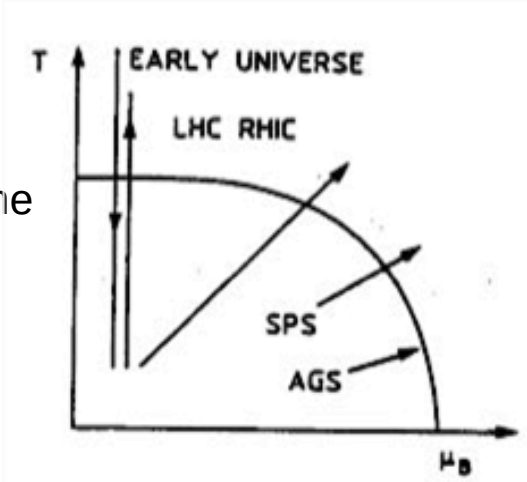
Matter under Extreme Conditions

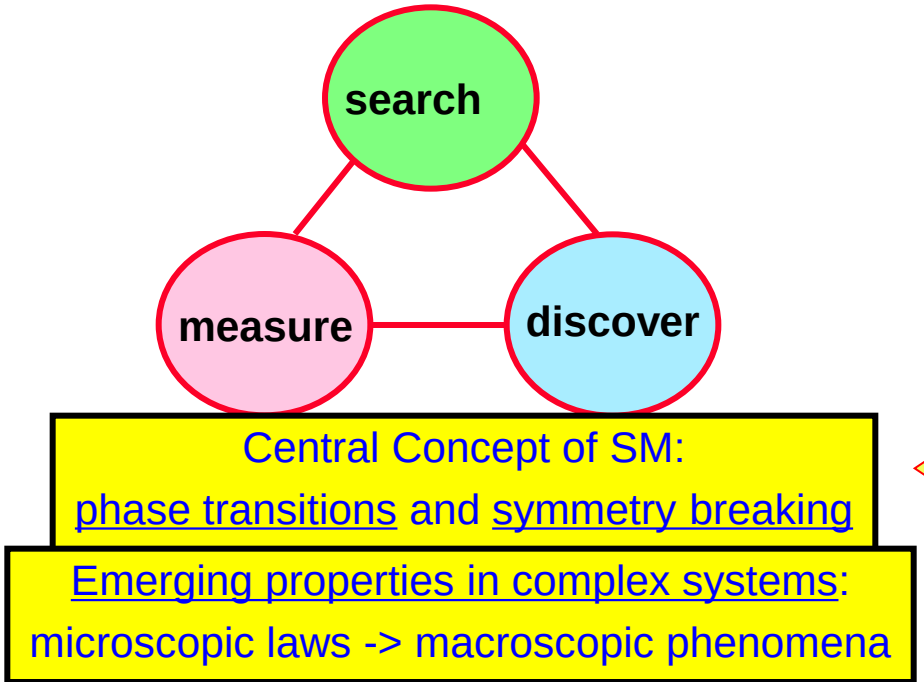
- 'state of matter' at high temperature & energy density: **'The QGP'**
  - ⇨ ground state of QCD & primordial matter of the Universe
    - ✪ partons are **deconfinend**
    - ✪ **chiral symmetry** is restored (partons are ~ massless)
  - ⇨ **'the stuff at high T where ordinary hadrons are no longer the relevant d.o.f'**

Theory

Experiment

- Mission of URHI
  - ⇨ **search** for the QGP phase
  - ⇨ **measure** it's properties
  - ⇨ **discover** QCD in its natural, strongly coupled non-pertubative regime





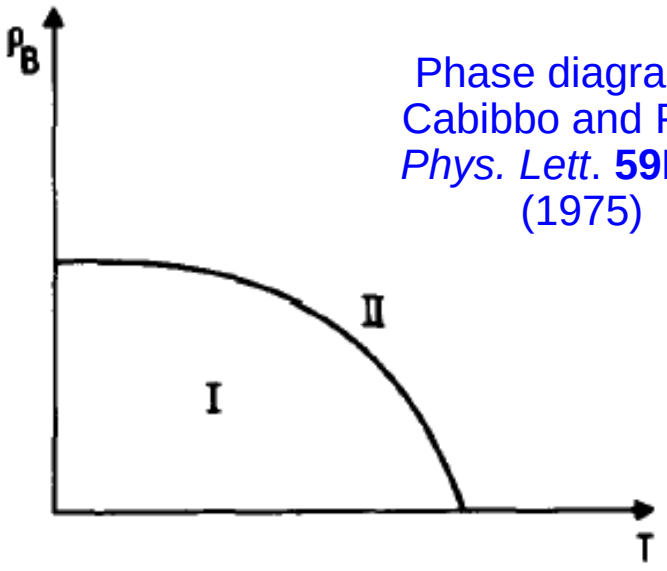
QCD transition is the only one accessible to experiment !

Early Work on the Phase Diagram of QCD

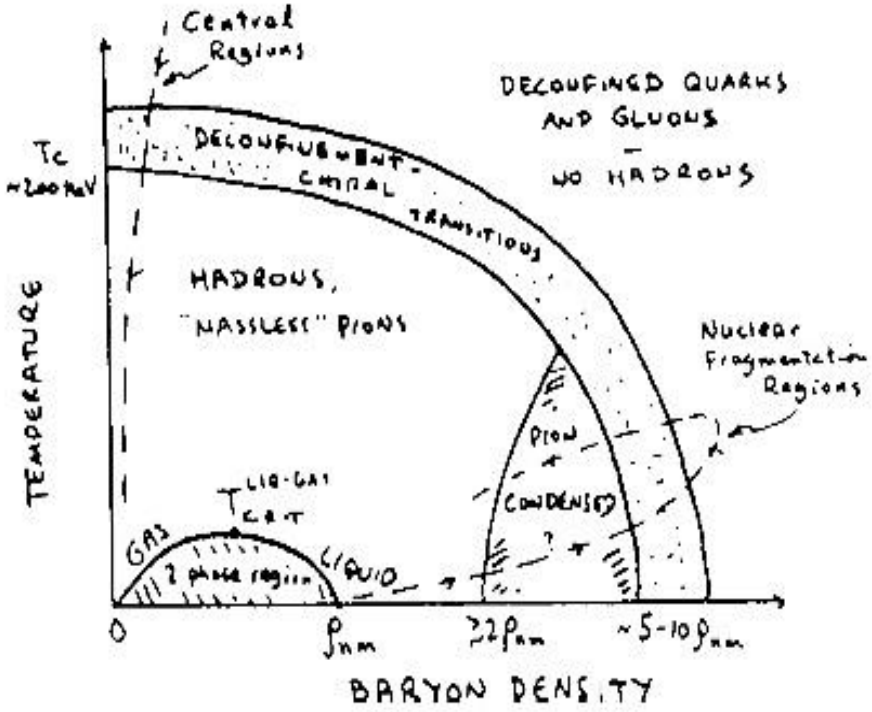
N. Itoh, *Prog. Theor. Phys*. **44**, 291 (1970)

P. Carruthers, *Coll. Phenom*. **1**, 147 (1973)

Arguments using asymptotic freedom by J. Collins and M. Perry, *Phys. Rev. Lett*. , **34**, 1353 (1975)



Phase diagram of Cabibbo and Parisi *Phys. Lett*. **59B**, 67 (1975)



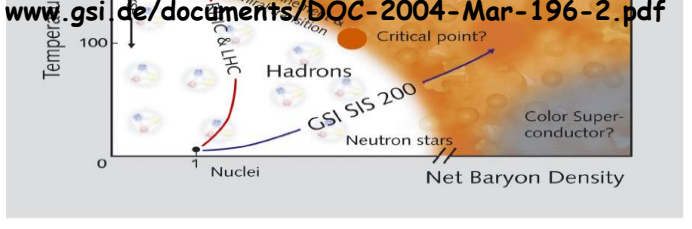
Higher order computations by Baym and Chin 1976; McLerran and Freedman 1977;

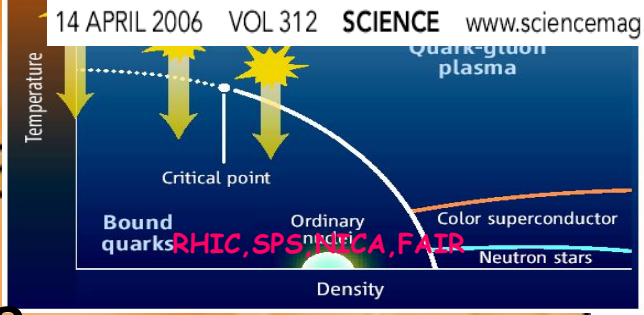
Finite T and name Quark Gluon Plasma by Shuryak 1978;

Kapusta 1979

Phase diagram of Baym from 1983 NSAC Long Range Plan

www.gsi.de/documents/DOC-2004-Mar-196-2.pdf





Quarks a

and Gluons

Critical point?

Deconfinement and chiral transition

Early universe

Hadrons

RHIC, LHC

FAIR SIS 300

NICA

Mixed phase

Neutron stars

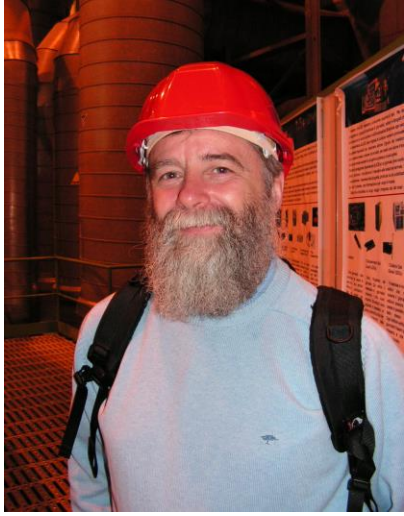
Color Super-
conductor?

1

Nuclei

Net Baryon Density N_B

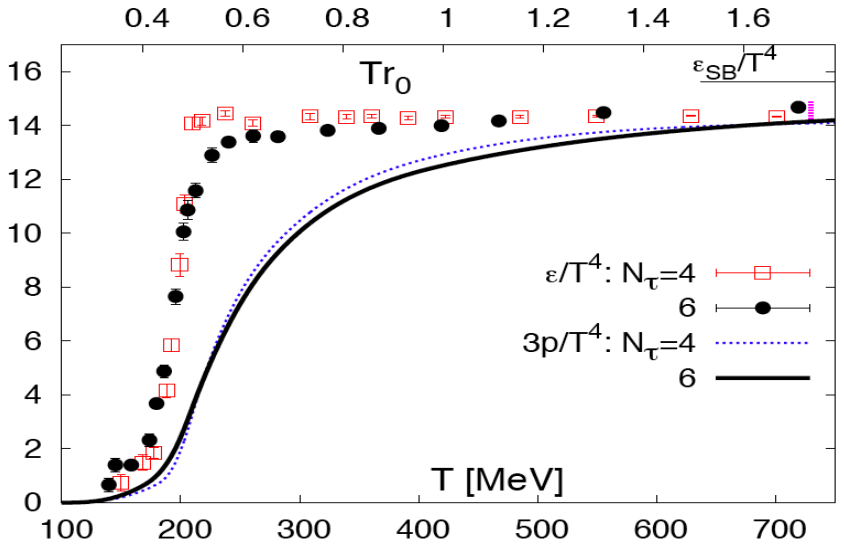
Lattice Gauge Theory and Deconfinement:



L is similar to a spin variable
=> Confinement-Deconfinement transition

Polyakov 1978 Susskind 1979

$$e^{-\beta F_q} = < L >$$



Wuppertal, Bielefeld,BNL, MILC, Mumbai …

First lattice computations at finite T; Kuti, Polonyi and Szlachanyi; McLerran and Svetitsky

Beginning of Bielefeld lattice gauge theory effort: Engels, Gavai, Karsch, Montvay and Satz

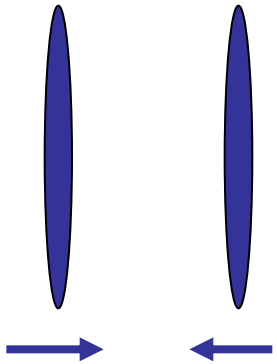
Space-Time Picture:

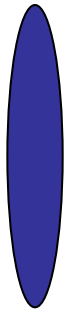
Early work on energy densities:

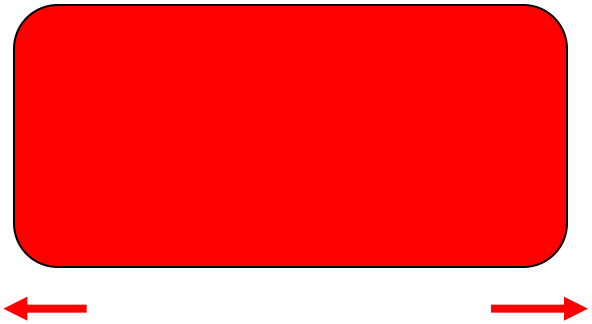
Shuryak 1974

Ansiehtty et. al. 1980

$$\epsilon = \frac{1}{2}\gamma^2\rho_0$$







$$\tau = \sqrt{t^2 - z^2}$$

$$R = 2R_0/\gamma$$

$$E = \gamma M_N V_0 \rho_0$$

Landau Hydrodynamics

$$\eta = \frac{1}{2} ln \left(\frac{t+z}{t-z} \right)$$

Colliding Nuclei

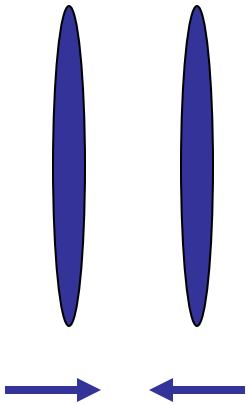
Collision

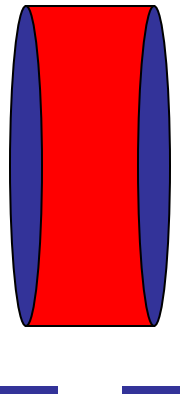
Expanding Fireball

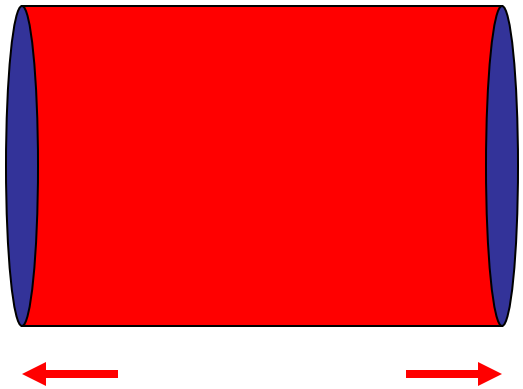
Landau

Feynman

Bjorken







Bjorken Hydrodynamics

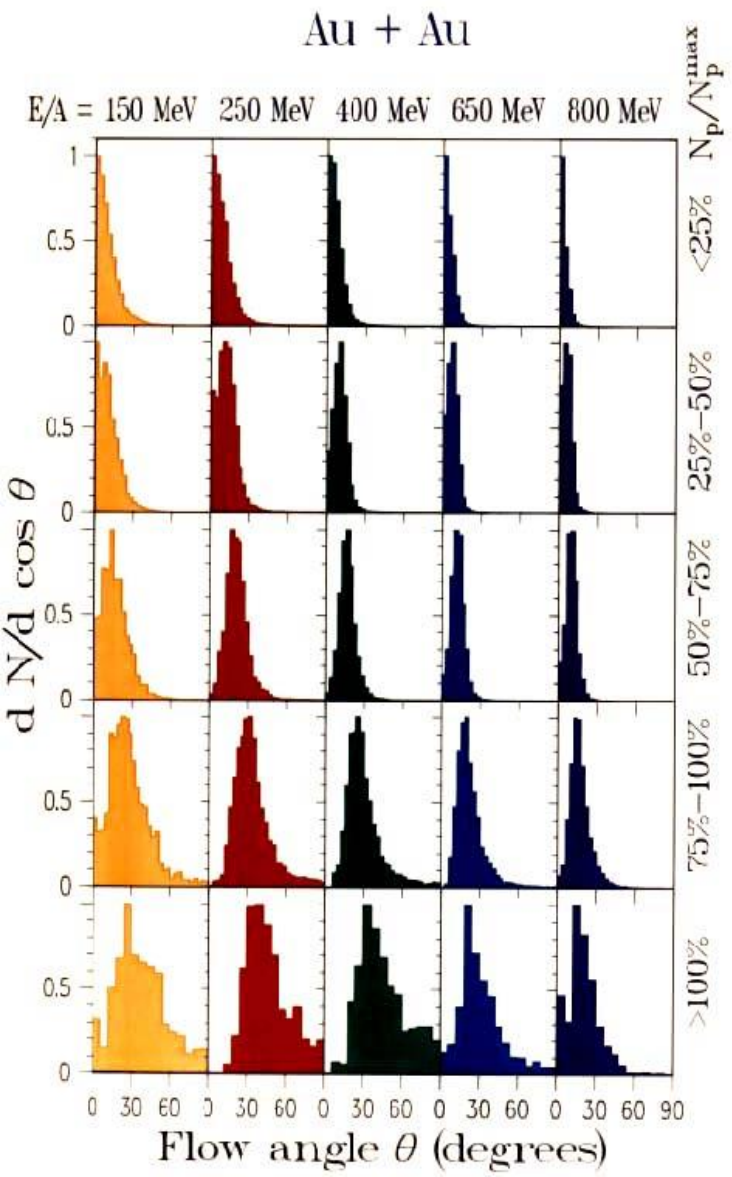
$$\epsilon_0 = \frac{1}{\pi R^2 \tau_0} \frac{dE_T}{dy}$$

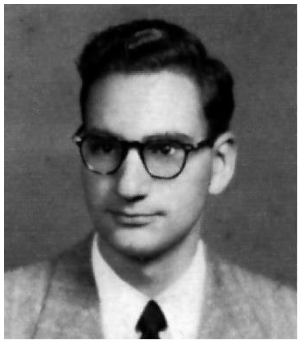
Longitudinal flow

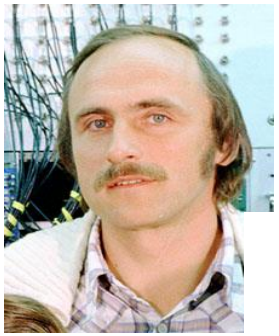
$$y = \eta$$

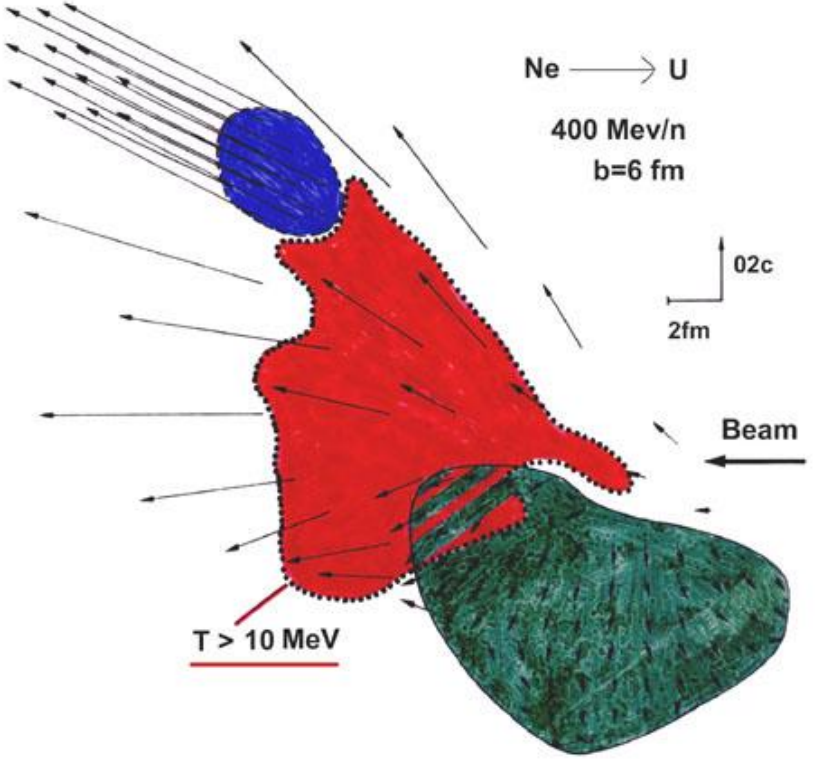
Discovery of Flow at the Bevalac

Plastic Ball and Streamer Chamber









Hydrodynamic Descriptions:

Bjorken 1983

Baym, Friman, Blaizot, Soyeur and Czyz 1983

Greiner, Stocker 1986

Ruuskanen et al 1986 ----

Teaney, Shuyrak 2000

U Heinz 2000 –

A Muronga 2002 --

Kovtun, Son and Starinets 2004 --

Successfully Predicts:

Momentum space distributions

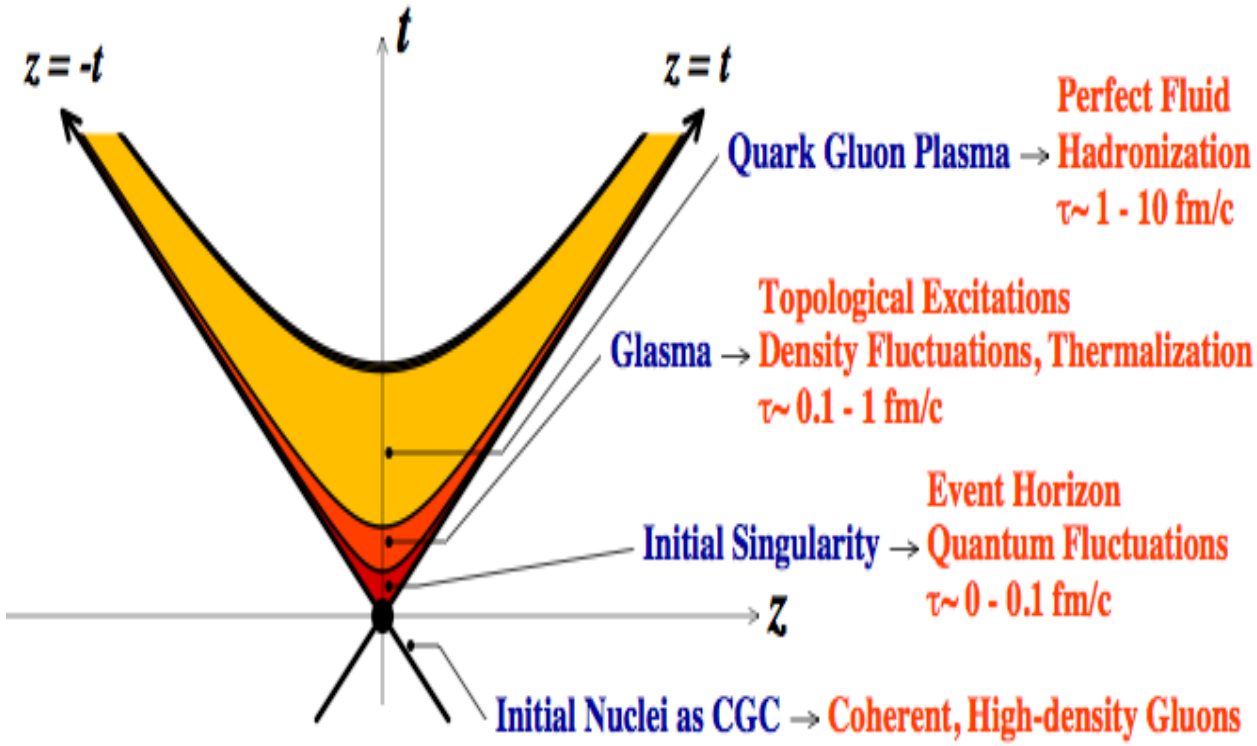
Collective effects

Space time evolution

Various correlations

Strongly Interacting Quark Gluon Plasma

An evolving story of rich variety of forms of high energy density matter



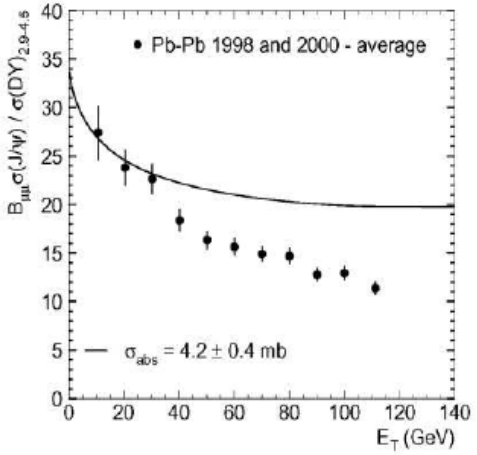
SPS Program:

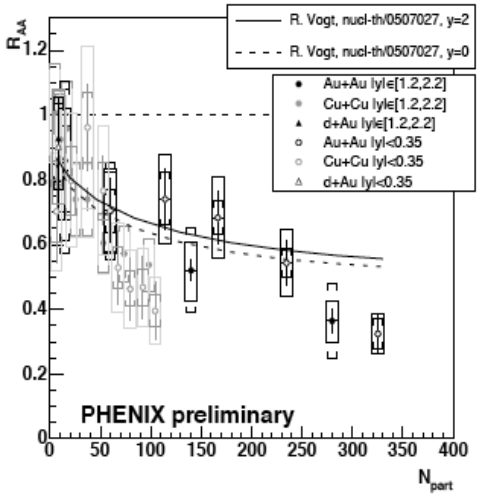
NA44, NA45/CERES, NA49, NA50, NA52/NEWMASS, WA97/NA57, WA98, NA60

Evidence for a New State of Matter:
An Assessment of the Results from the CERN Lead Beam Programme

Ulrich Heinz and Maurice Jacob
Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland

A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.





Evidence:

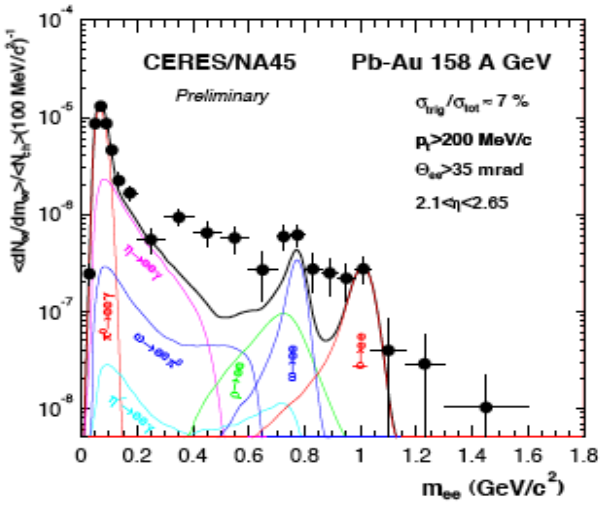
Bose-Einstein Interferometry

Flow

Rho melting

Flavor Abundances

J/Psi Melting



Flavor abundances consistent with decay of QGP

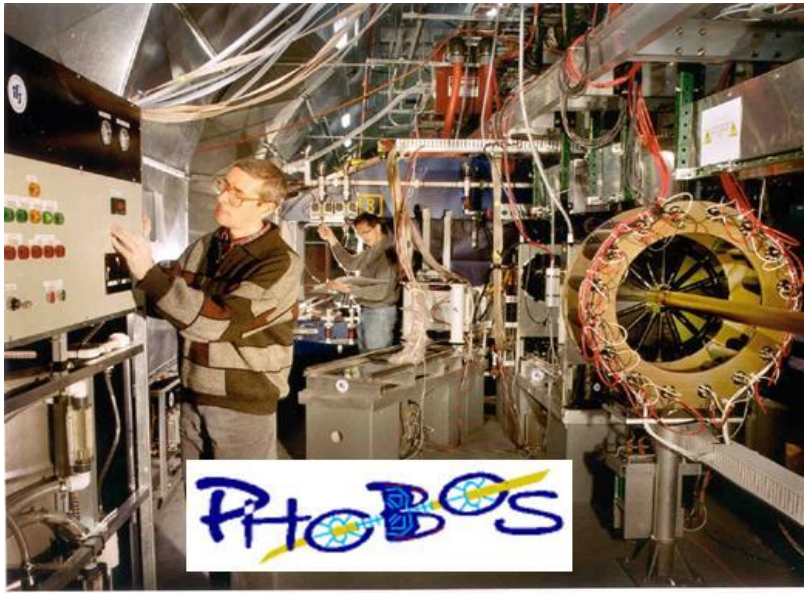
Bose-Einstein Interferometry consistent with extended system

Flow and transverse momentum distributions not well described by hydro

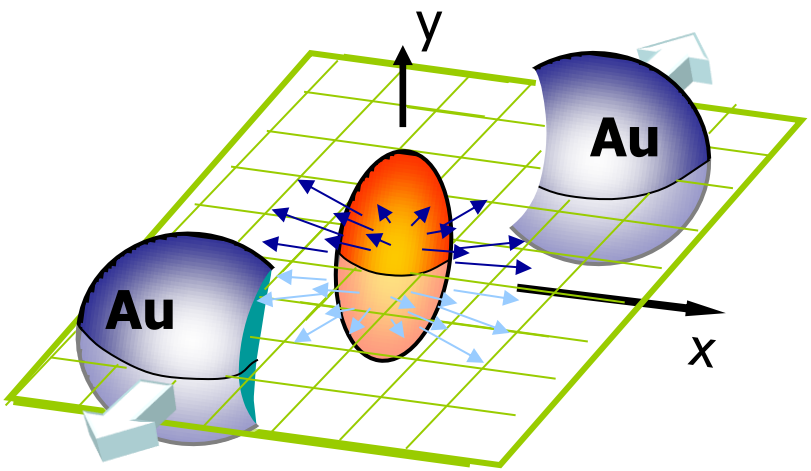
Rho melting and J/Ps proved more complicated

RHIC Program

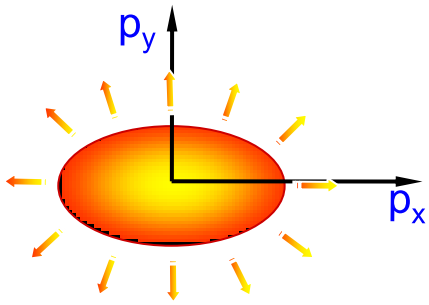
1200 Physicists 50 Countries 2000 Publications



Elliptic Flow (V2)

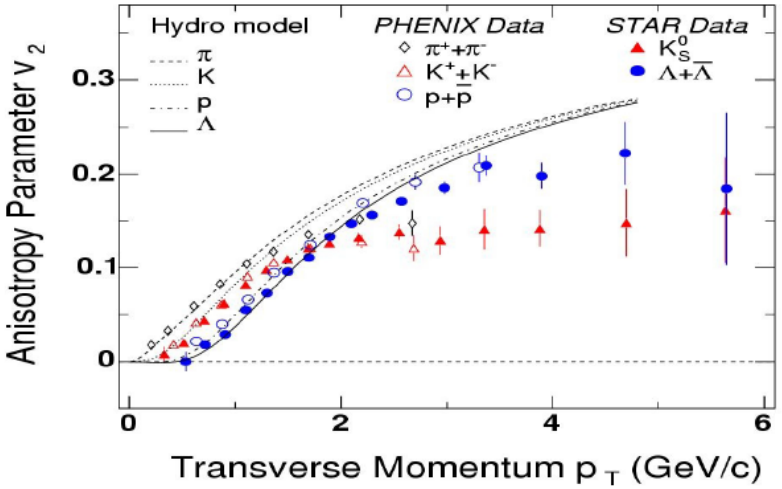


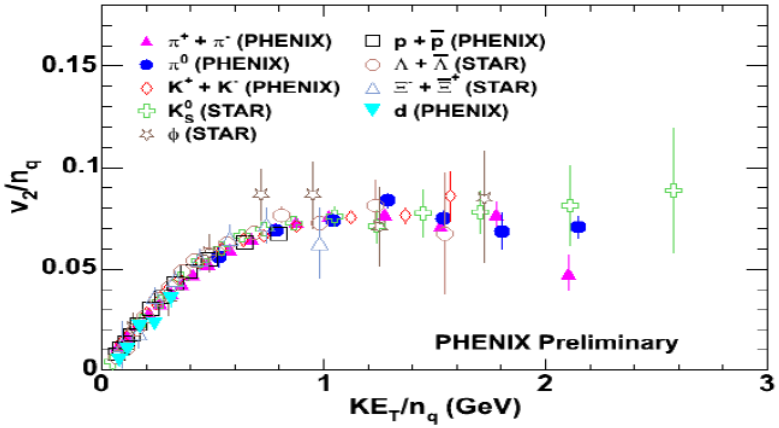
momentum space



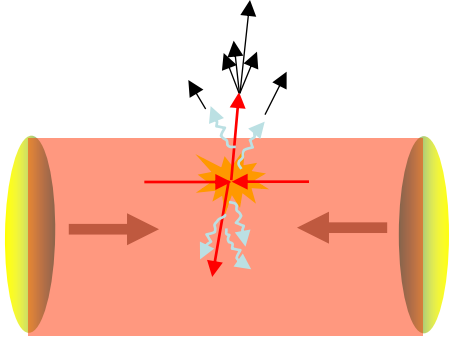
$dN/d\phi = 1 + 2\,V_2 \cos 2(\phi - \psi) + \ldots$

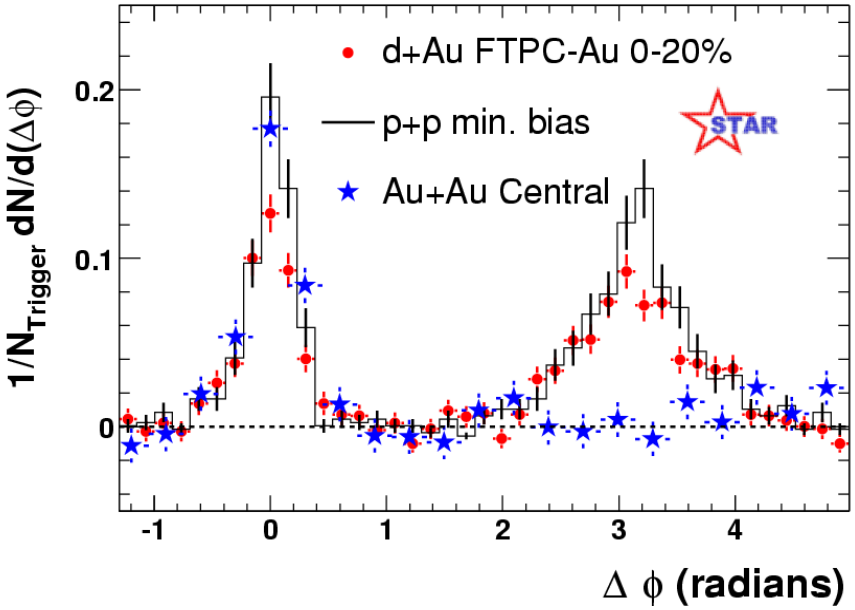
Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

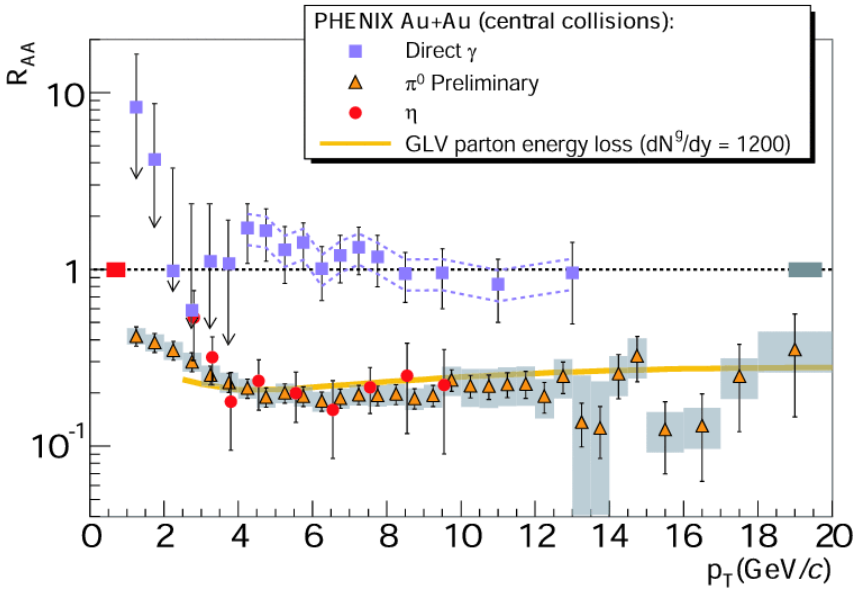




Jets Modified by the Medium







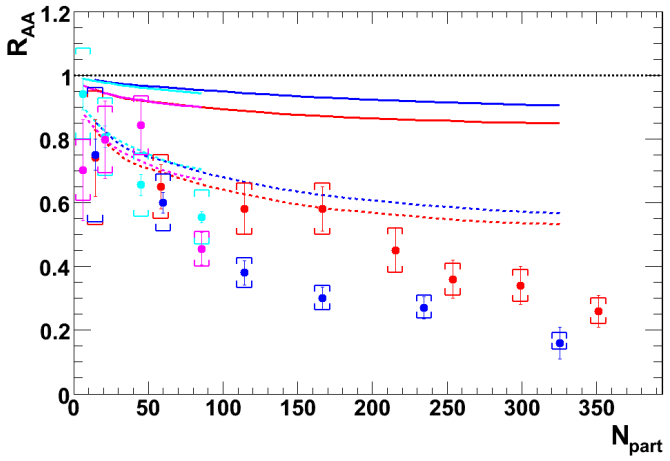
Away side suppression

$4 < p_T(\text{trig}) < 6$ GeV/c

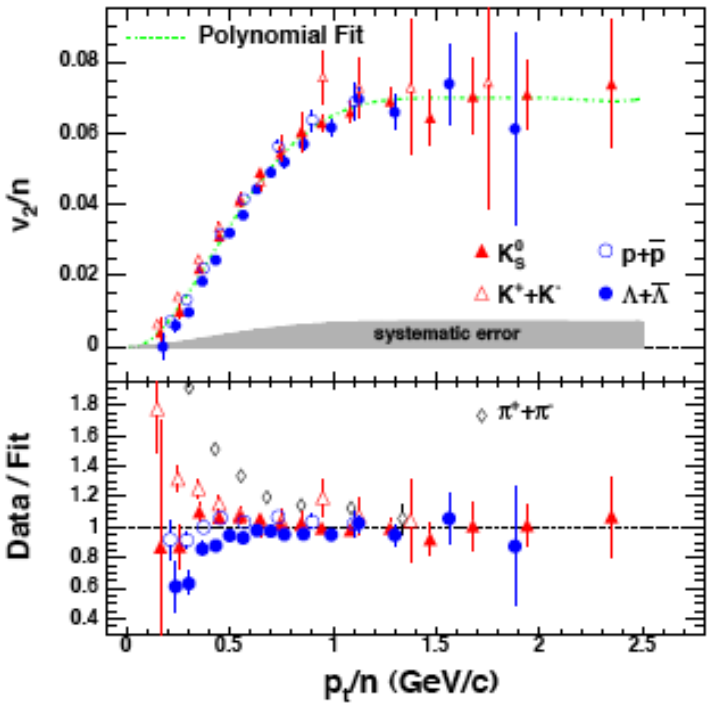
$p_T(\text{assoc}) > 2$ GeV/c

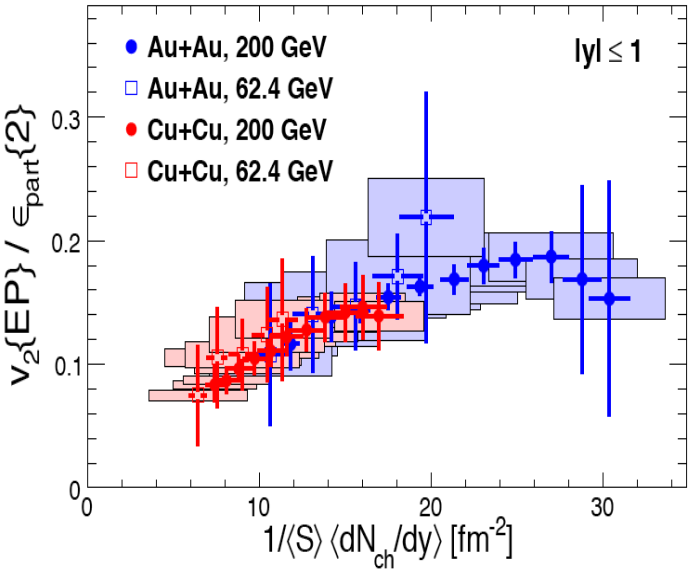
PHENIX

J/Ψ



Red : Au+Au |y|<0.35
Magenta : Cu+Cu |y|<0.35
Blue : Au+Au 1.2<|y|<2.2
Aqua : Cu+Cu 1.2<|y|<2.2





Flow and transverse momentum distributions consistent with ideal hydrodynamics

Jet quenching implies very opaque medium

Scaling laws in flow data consistent with naïve recombination picture

J/Psi and HBT data not simply understood

Heavy quark energy loss not understood

Laboratory News

BROOKHAVEN NATIONAL LABORATORY Home

RHIC Scientists Serve Up "Perfect" Liquid

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

April 18, 2005

Peer Reviewed Papers

- Experimental evaluation by the PHENIX collaboration
- The STAR Collaboration's Critical Assessment of the Evidence from RHIC Collisions
- The PHOBOS perspective on discoveries at RHIC
- The perspective from the BRAHMS experiment

Nuclear Physics ***A757*** (2005)

See also proceedings of New Discoveries at RHIC, RIKEN-BNL Center Workshop,

Nucl. Phys. **A750** (2005)

Future tools:

Stochastic beam cooling and increased luminosity

Detector improvements for dA studies

Low energy run and the phase diagram

Variable energy and beam A and Z

Physics:

Charmonium, charm and jet studies

dA and CGC

Phase diagram at finite baryon density

Event by event P and CP violation

What is left to do at LHC ?

Assumption: 'QGP' has been established at RHIC prior to LHC

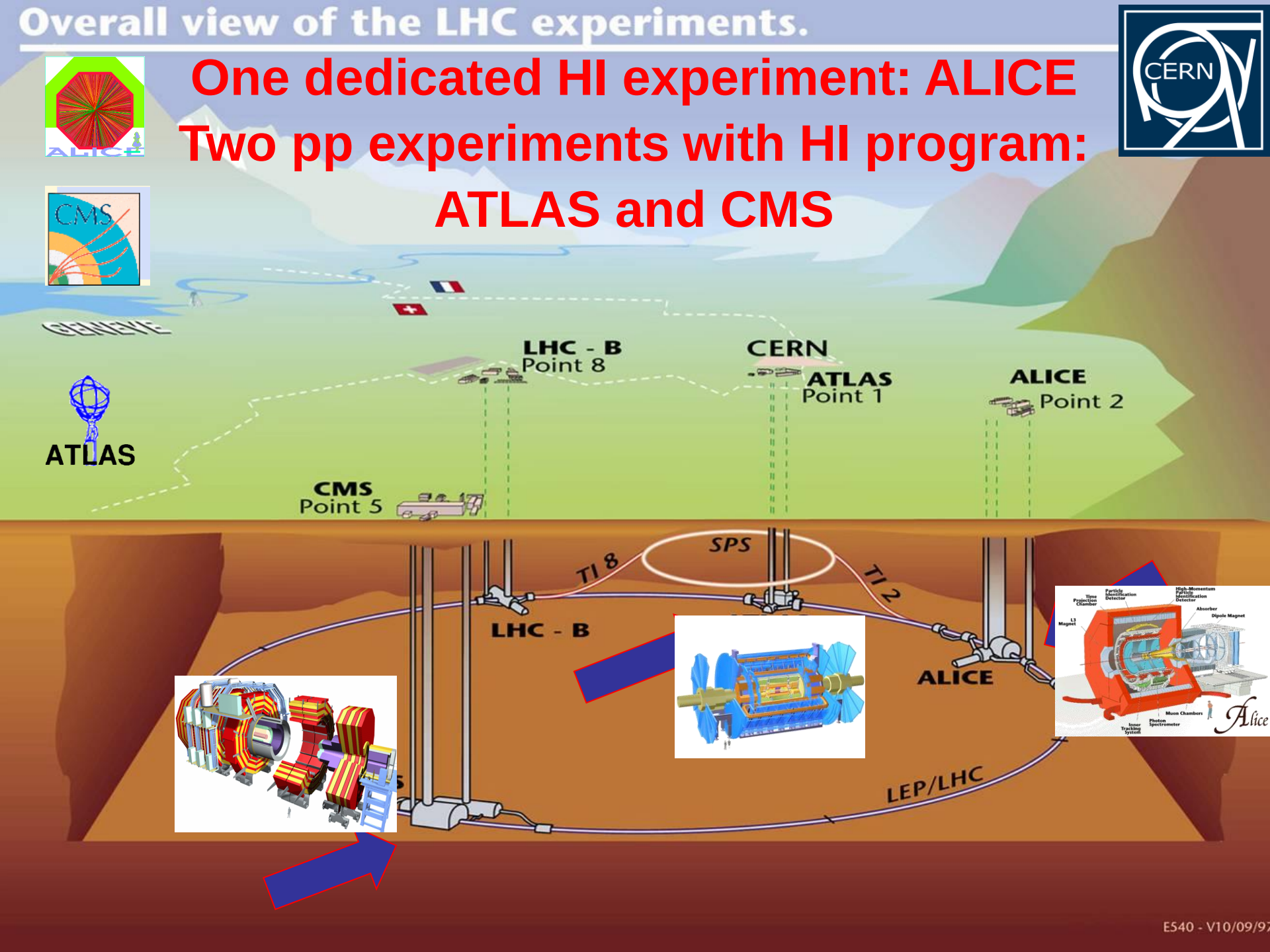
- ⇨ **Search** may be essentially over
- ⇨ **Discovery** is well under way (with fantastic results & surprises at RHIC)
- ⇨ **Measuring** has begun and is on-going

- pre-RHIC tasks: <u>precision measurements</u>
  - ⇨ quantitative and systematic study of this state of matter
    (' LEP after W/Z discovery at SppS')
    - ✪ different state (by large factors) in <u>energy density, lifetime, volume</u>
    - ✪ new signals ('hard probes') : heavy quark states (b,c), jets

- post – RHIC result tasks: <u>continue discovery</u>
  - ⇨ confirm interpretations by testing predictions/extrapolation to LHC
  - ⇨ is initial state dominated by yet another new state of matter (dense quantum state) ?
    - ✪ **Color Glass Condensate ?** (QCD in classical Field Theory limit)
- surprises may still lie ahead <u>more to search for ?</u>
  - ⇨ transition from strongly coupled QGP -> ideal QGP ?

Overall view of the LHC experiments.

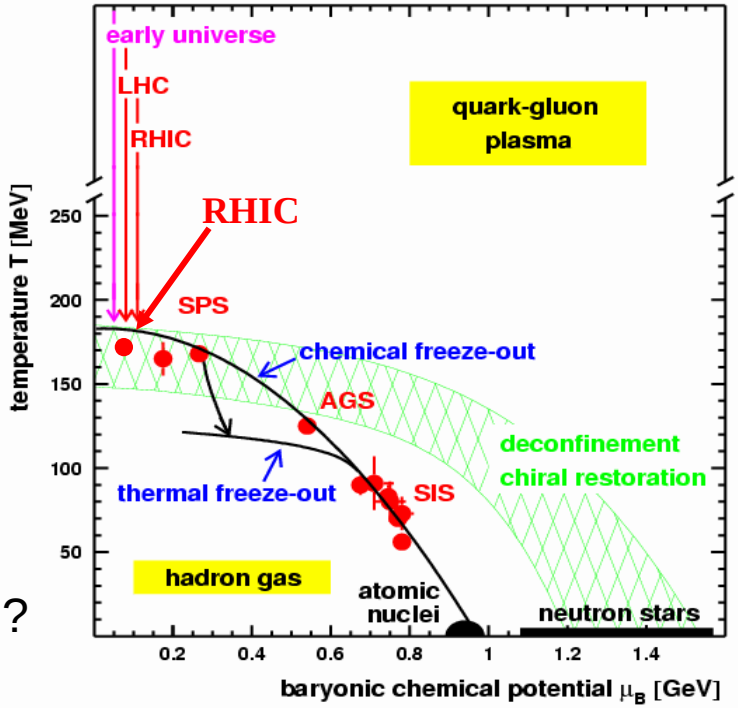
One dedicated HI experiment: ALICE
Two pp experiments with HI program: ATLAS and CMS

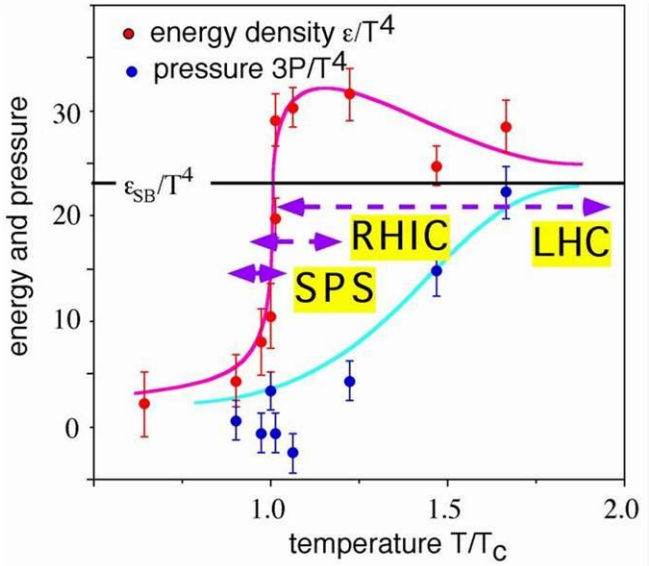


Past-Present-Future

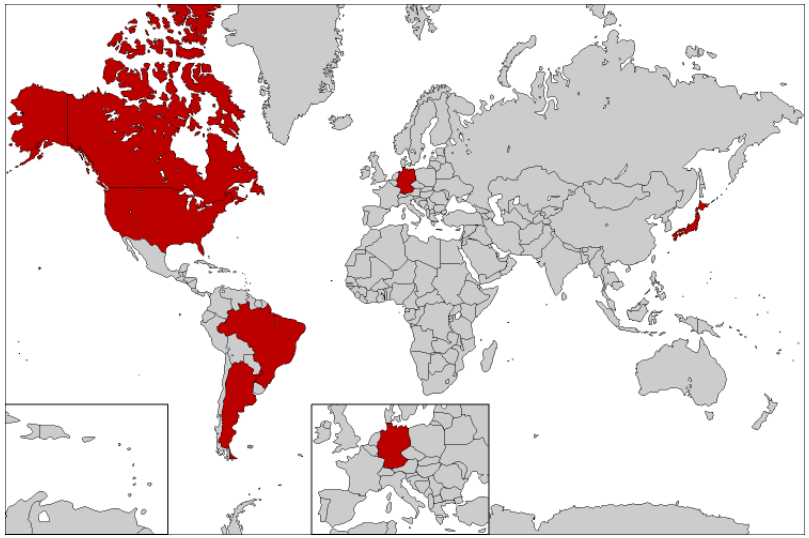
- **AGS/SPS: 1986 – 1994**
  - ⇨ existence & properties of **hadronic phase**
    - ✪ chemical & thermal freeze-out, collective flow,…
- **SPS: 1994 – 2003**
  - ⇨ '**compelling evidence** for **new state of matter** with many **properties** predicted for **QGP**'
    - ✪ J/Ψ (Ψ',χ ?) suppression (deconfinement ?)
    - ✪ low mass lepton pairs (chiral restoration ?)
- **RHIC: 2000 - ?**
  - ⇨ **compelling evidence** -> **establishing** the (s)**QGP** ?
    - ✪ parton flow
    - ✪ parton energy loss ('jet quenching)
- **LHC: 2008 - ??**
  - ⇨ **precision spectroscopy**, '**ideal** plasma '**QGP ?**
    - ✪ heavy quarks (c,b), Jets, Y, thermal photons
  - ⇨ continue **exploration** and **discovery** of QCD

LHC: will open the **next** chapter in HI physics
significant step over & above existing facilities
THE place to do **frontline research** after 2007

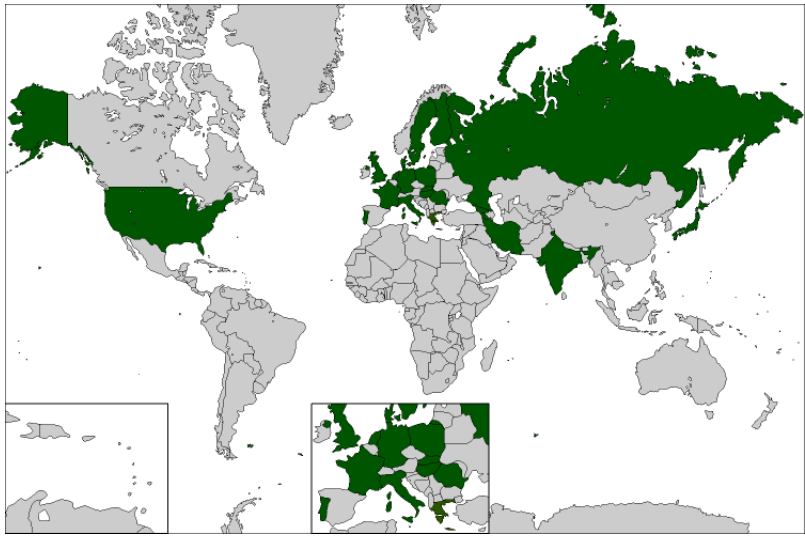




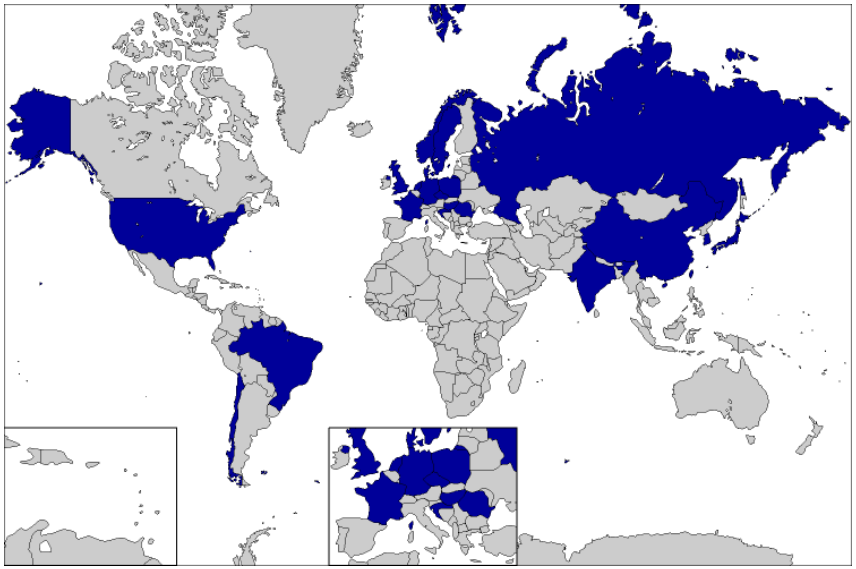
From the Bevelac to the LHC:



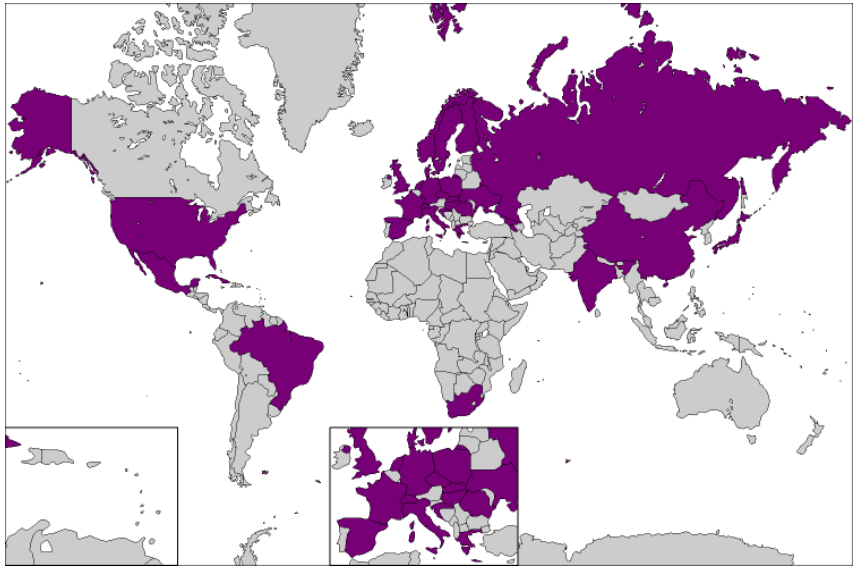
AGS



SPS

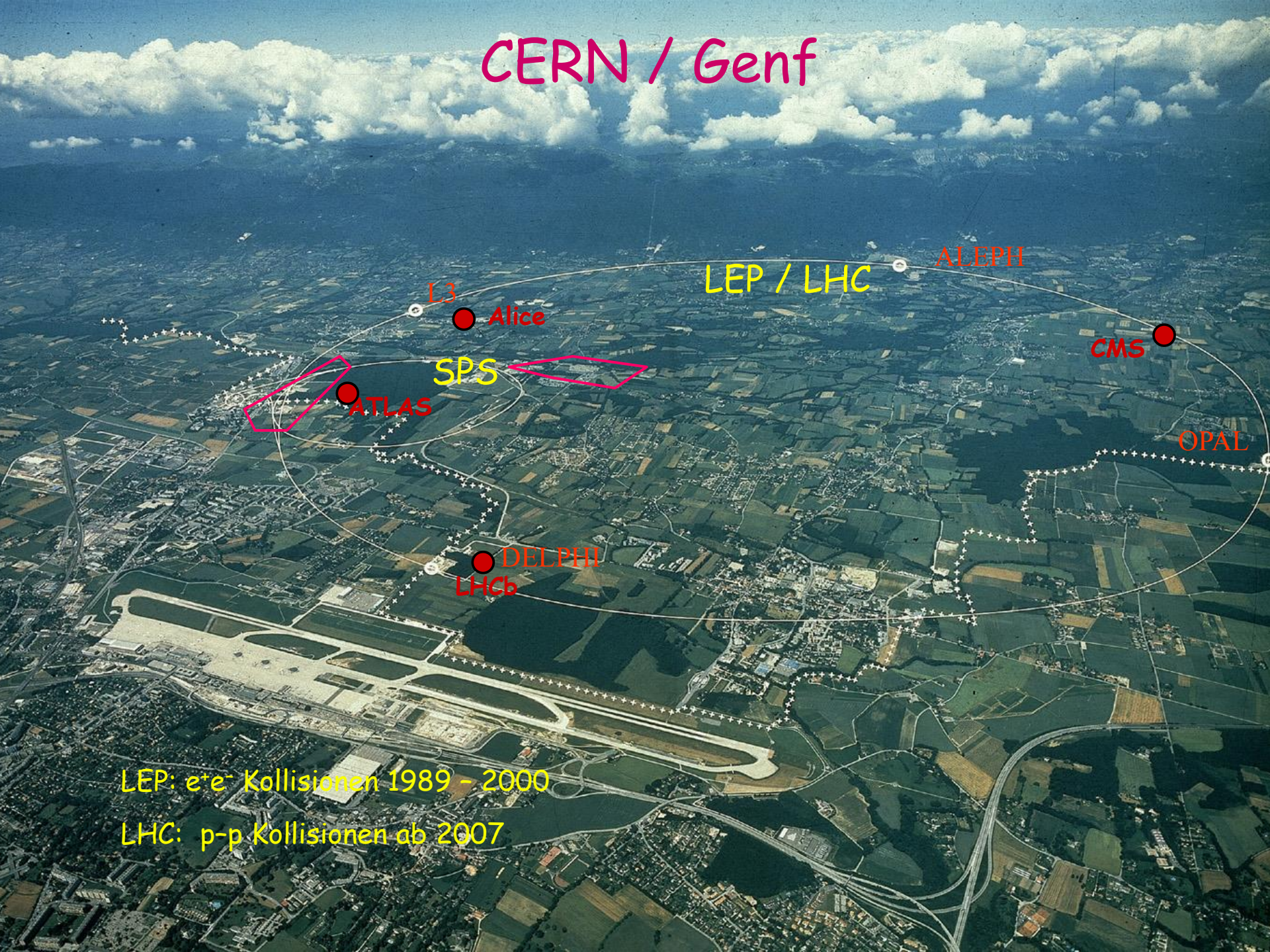


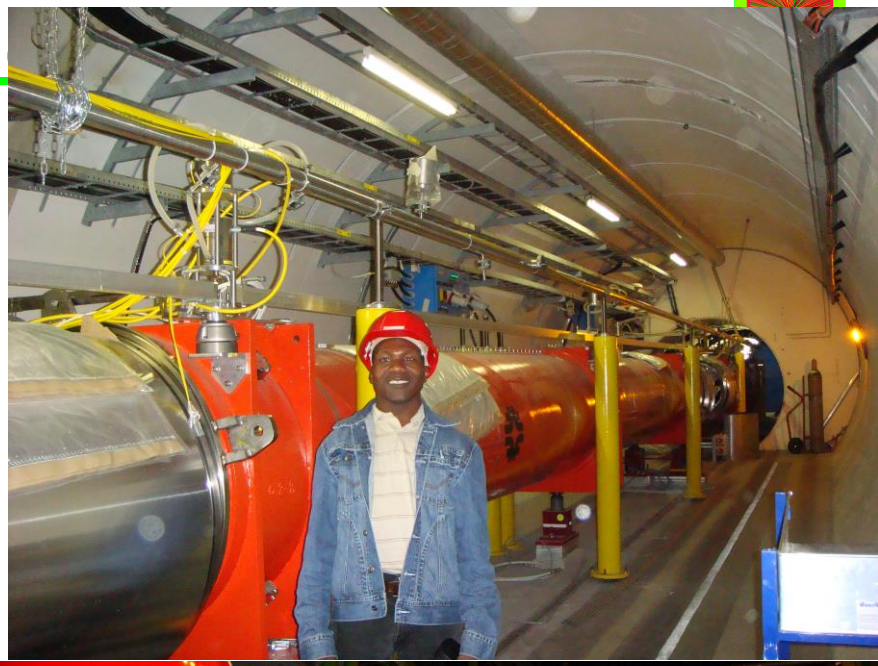
RHIC



Heavy Ions at LHC

CERN / Genf


LEP / LHC
ALEPH
L3
Alice
CMS
SPS
ATLAS
OPAL
DELPHI
LHCb
LEP: e+e- Kollisionen 1989 – 2000
LHC: p-p Kollisionen ab 2007

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IN THIS AREA

The Quark-Gluon Plasma

A Master of Disguise and Deception