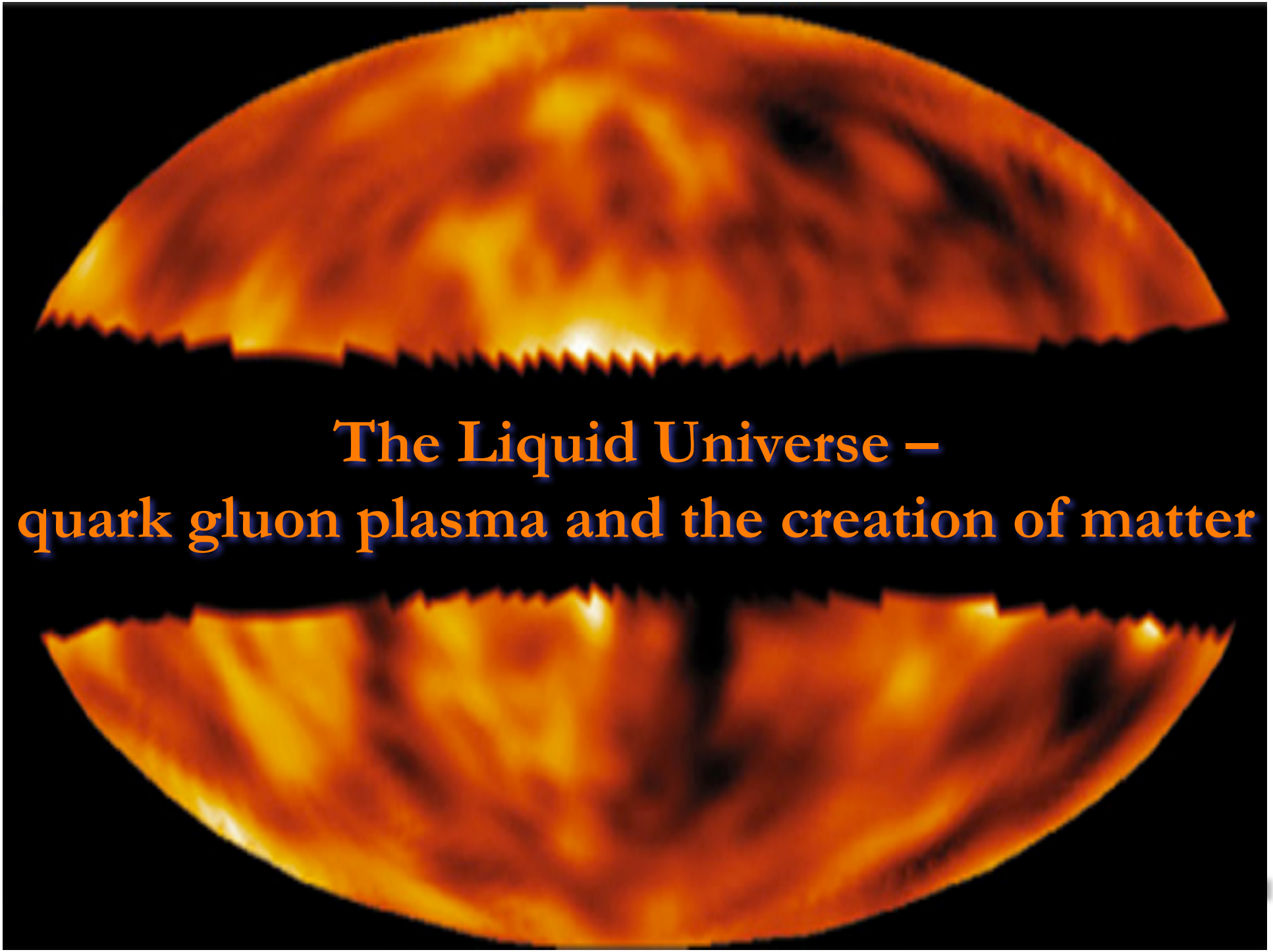
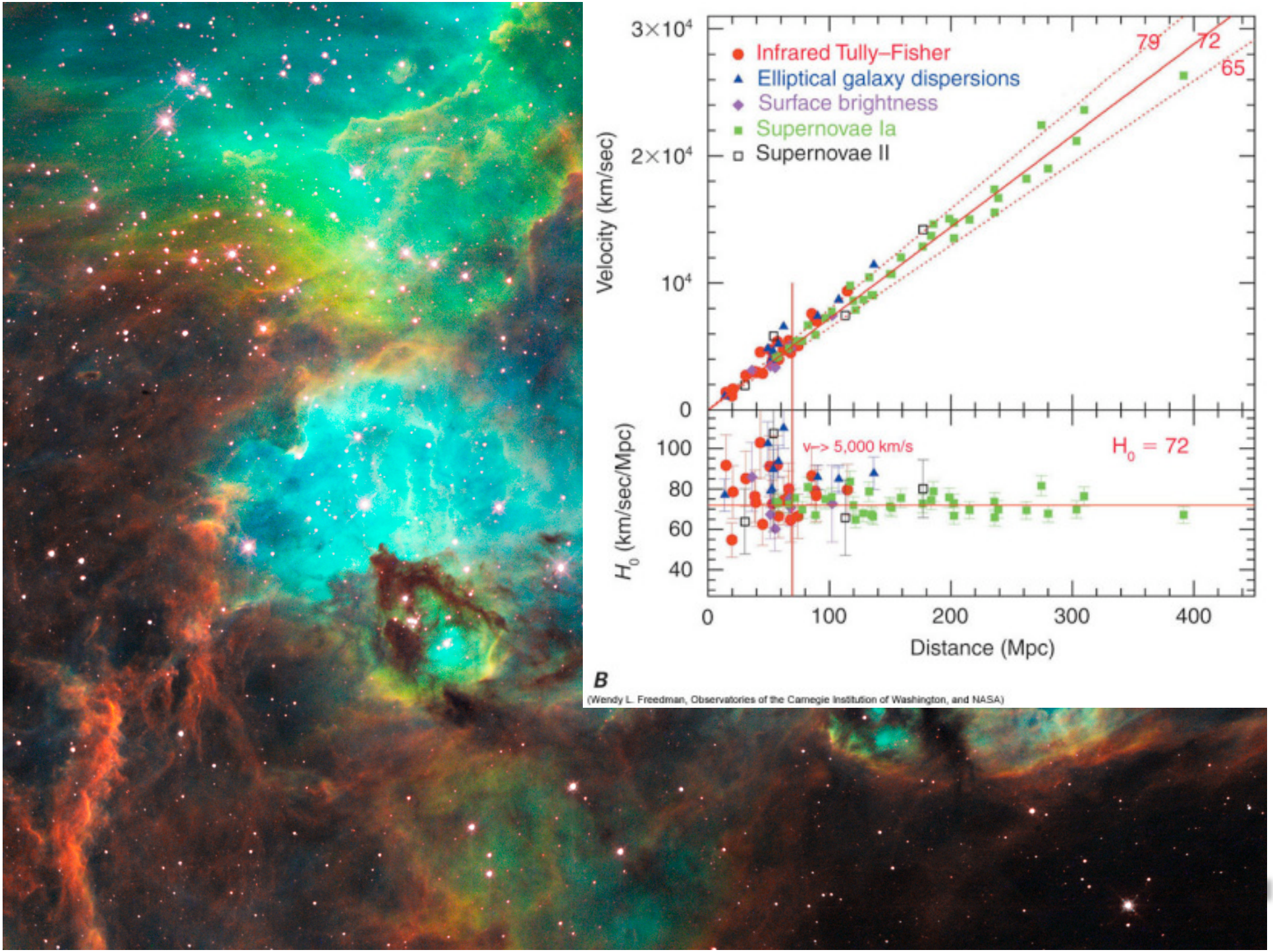

The Liquid Universe –
quark gluon plasma and the creation of matter



B

(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

The first second of the universe

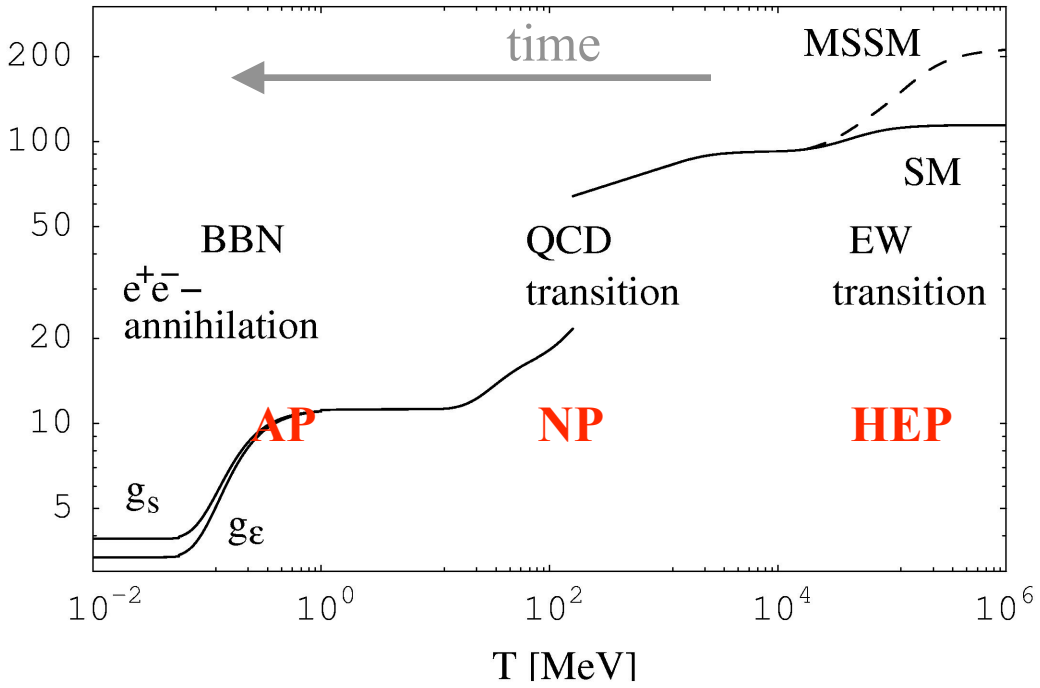


Fig. 1.1 The effective number of degrees of freedom $g_\epsilon(T) = \epsilon(T)/(\pi^2/30T^4)$. The full line is the prediction of the standard model of particle physics, the dashed line shows a minimal supersymmetric extension of the standard model (SPS1a) [6].

from D.J. Schwarz, astro-ph/0303574

History of the early universe

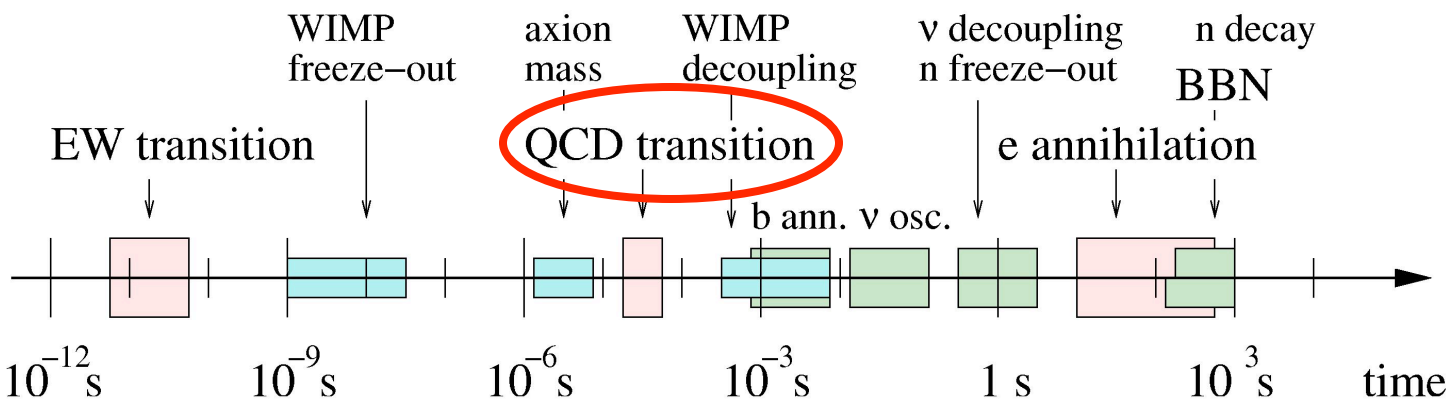


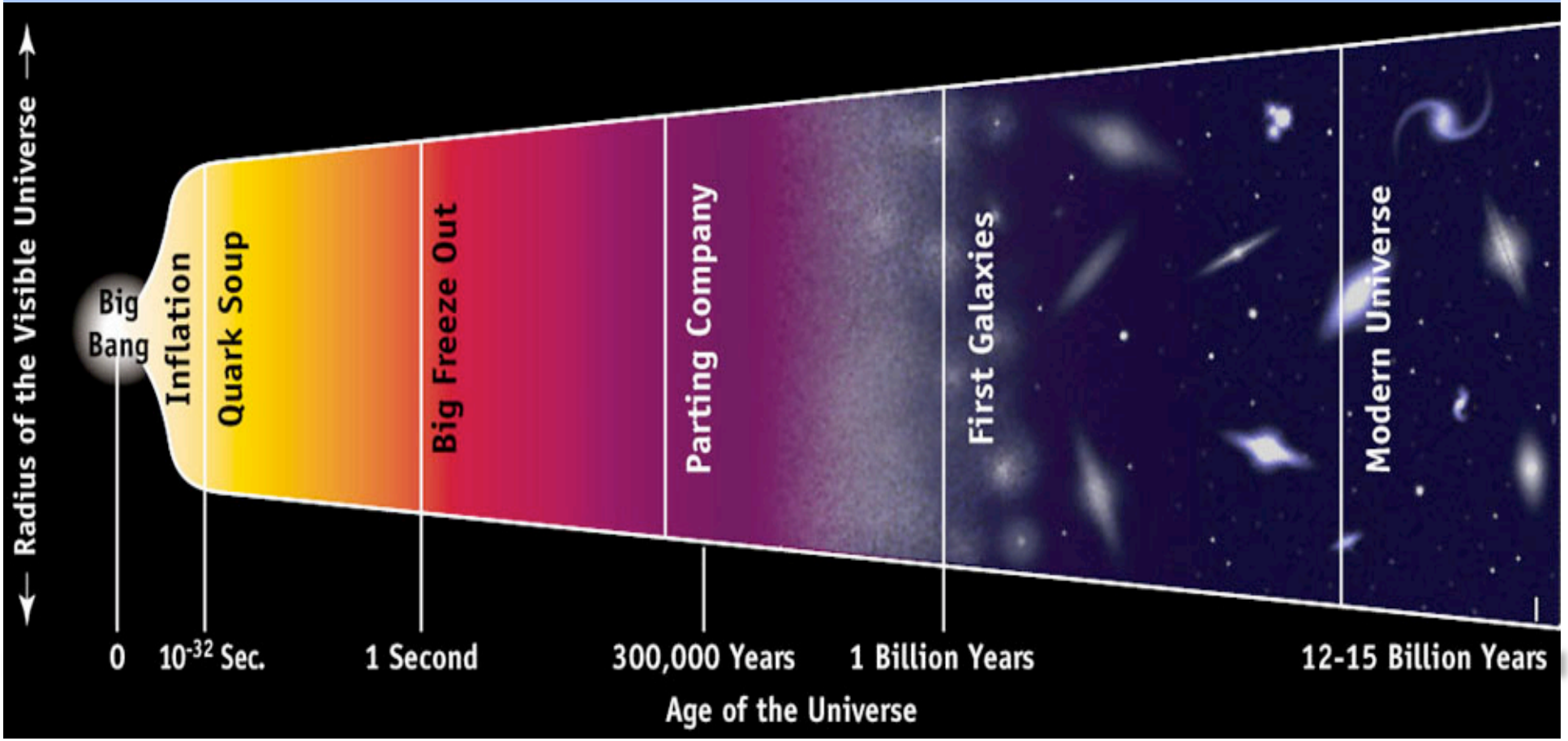
Fig. 10.1 History of the first second of the Universe and the epoch of BBN. A sequence of thermodynamic transitions takes place: the electroweak transition ($\sim$ 10 ps) is followed by the QCD transition ($\sim$ 10 μs) and by $e^{\pm}$ annihilation ($\sim$ 100 s). With respect to particles of the standard model, several important processes occur: baryons and antibaryons annihilate ($\sim$ 1 ms), neutrino oscillations set in at $\sim$ 0.1 s, neutrinos decouple and at the same time the neutron-to-proton ratio freezes out ($\sim$ 1 s). During the epoch of BBN ($\sim$ 3 min) this ratio changes slightly due to neutron decay ($\tau = 886$ s). Regarding the cold dark matter candidates, WIMPs freeze out at $\sim$ 10 ns and decouple kinetically at $\sim$ 1 ms. The axion mass is switched on close to the QCD transition at $\sim$ 1 μs.

The tools need to study the early history of the universe:

- Accelerator based high energy and nuclear experiments (LHC, RHIC)
- Observational cosmology (LSST, HAWC, etc.)

Nuclear Physics and the Universe

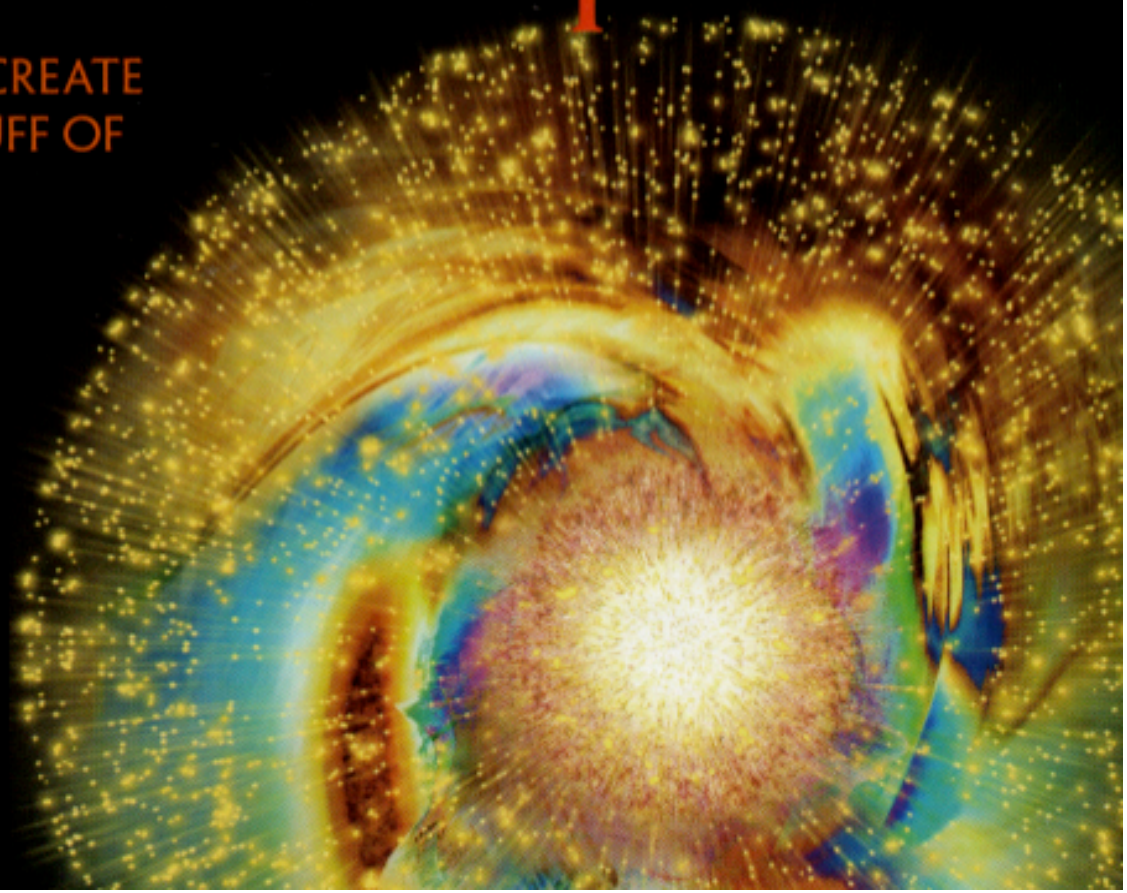
- Quark Gluon Plasma: quarks form protons and neutrons – RHIC, LHC
- Big Bang Nucleosynthesis – protons and neutrons form elements – F-RIB



SCIENTIFIC AMERICAN

Quark Soup

PHYSICISTS RE-CREATE THE LIQUID STUFF OF THE EARLIEST UNIVERSE



Theory:

Sean Gavin

Experiment:

Rene Bellwied

Tom Cormier

Claude Pruneau

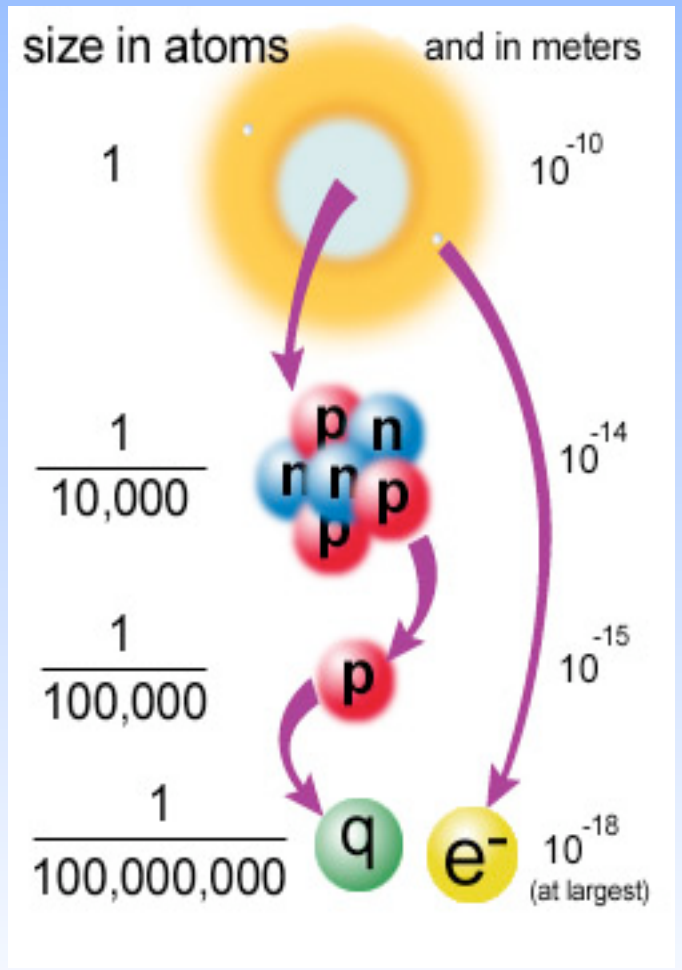
Sergei Voloshin

What is a Quark-Gluon Plasma?

An *atom* contains a *nucleus*...

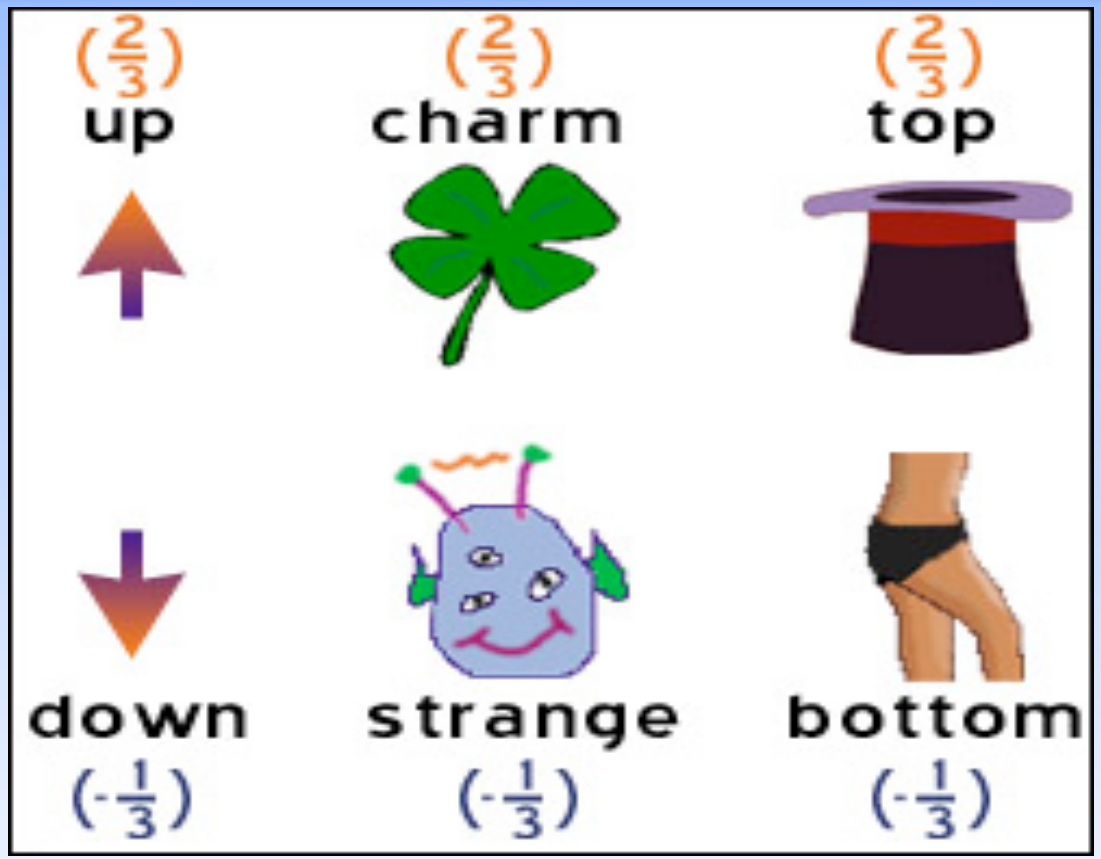
…which contains *protons* and *neutrons*...

…which contain *up* and *down quarks*.



What is a *Quark*-Gluon Plasma?

"Flavors" of Quarks

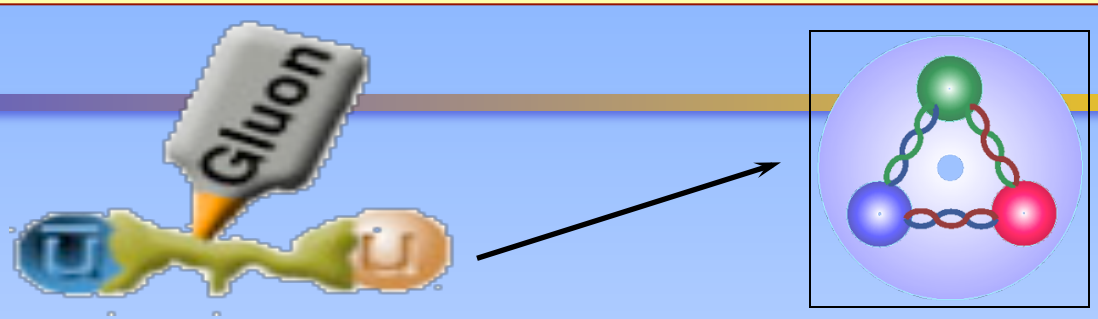


light and abundant

heavier, rare

very heavy, very rare

What is a Quark-*Gluon* Plasma?

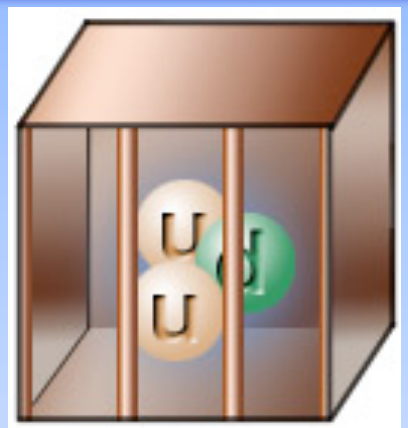


	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

What is a Quark-Gluon *Plasma*?

Quarks are confined *(hadrons)...*

… and gluons are the guards...



Set the Quarks Free !!!

How? Create a Quark-Gluon Plasma !

BARYONS = qqq*		quarks	electric charge	mass (GeV/c^2)	spin
p	proton	u u d	+ 1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\,\bar{u}\,\bar{d}$	- 1	0.938	1/2
n	neutron	u d d	0	0.940	1/2
Λ^0	lambda	u d s	0	1.116	1/2
Ω^-	omega	s s s	- 1	1.672	3/2
Σ_c	sigma-c	u u c	+ 2	2.455	1/2
Many others ! !					

MESON = $q\bar{q}$		quarks	electric charge	mass (GeV/c^2)	spin
π^+	pion	$u\,\bar{d}$	+ 1	0.140	0
K^-	kaon	$s\,\bar{u}$	- 1	0.494	0
K^0	kaon	$d\,\bar{s}$	0	0.498	0
ρ^+	rho	$u\,\bar{d}$	0	0.770	1
D^+	D	$c\,\bar{d}$	+ 1	1.869	0
η_c	eta-c	$c\,\bar{c}$	0	2.980	0

Phase Transitions

ICE **WATER** **STEAM**

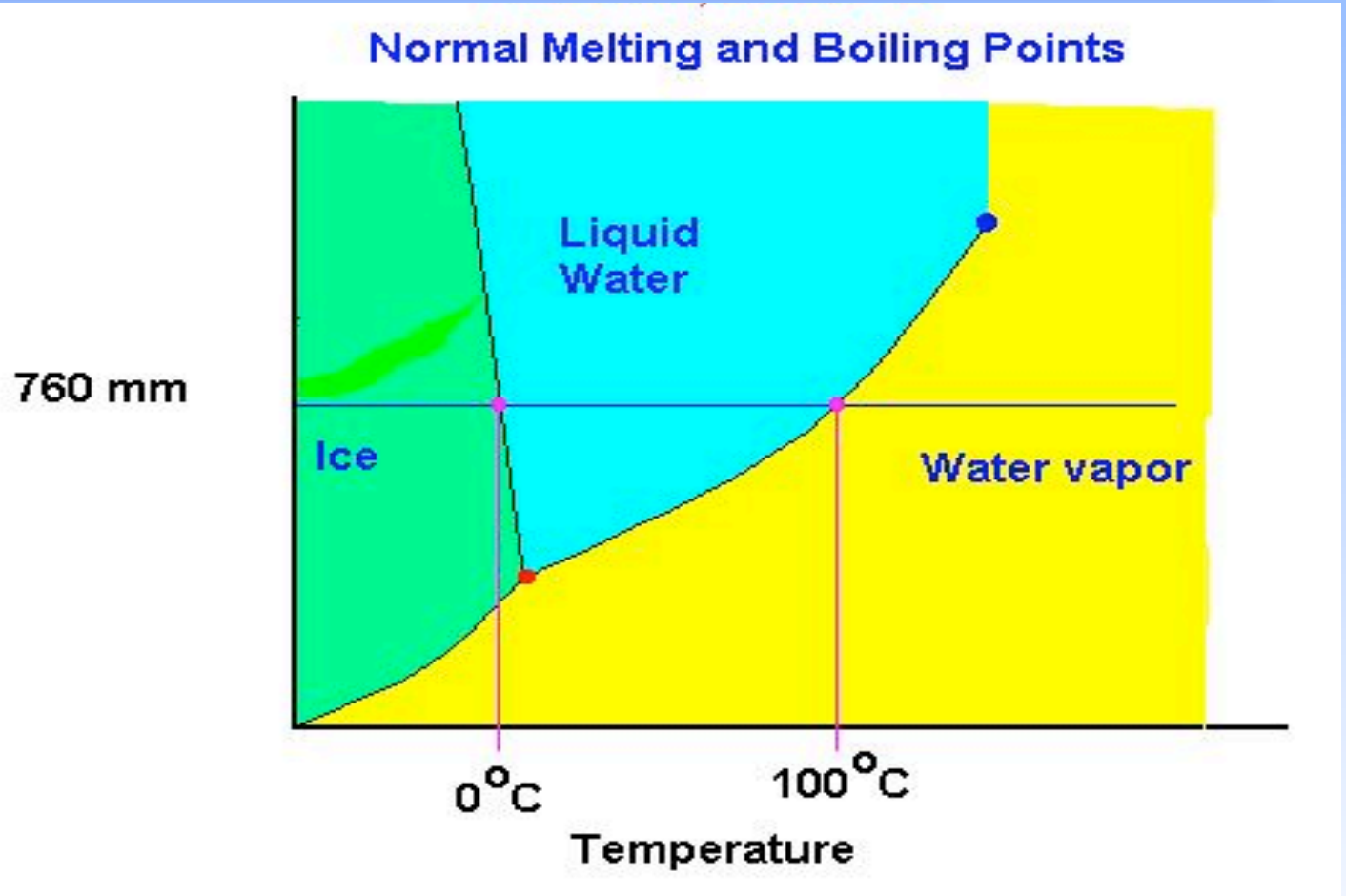
Add heat

Add heat

Quark Gluon Plasma is another phase of matter!

Phase Diagram

A familiar phase diagram...

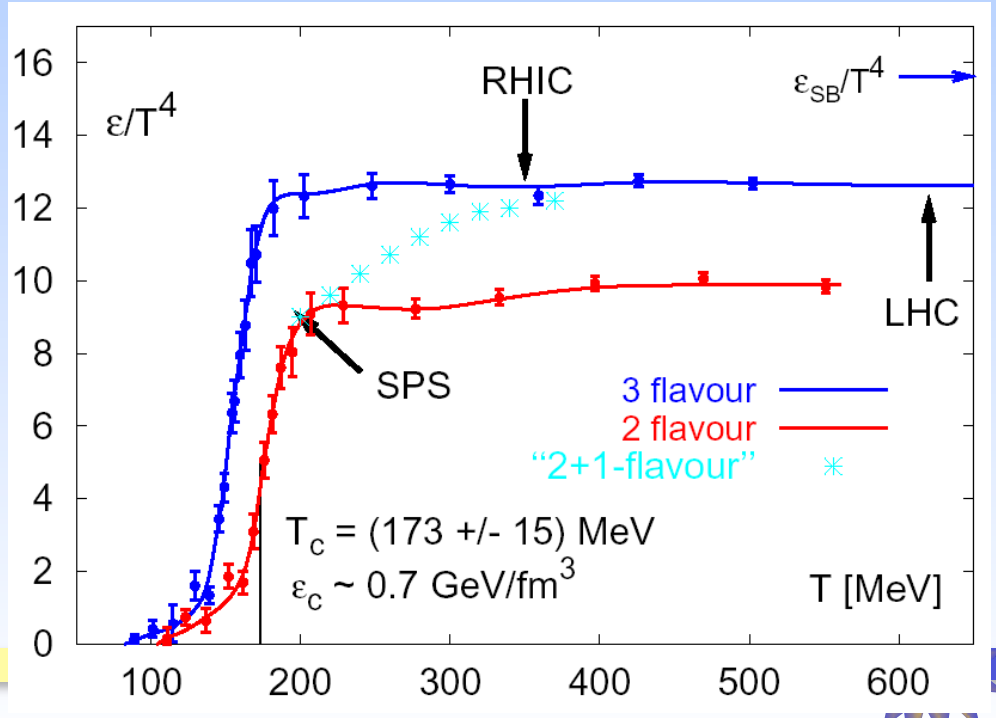


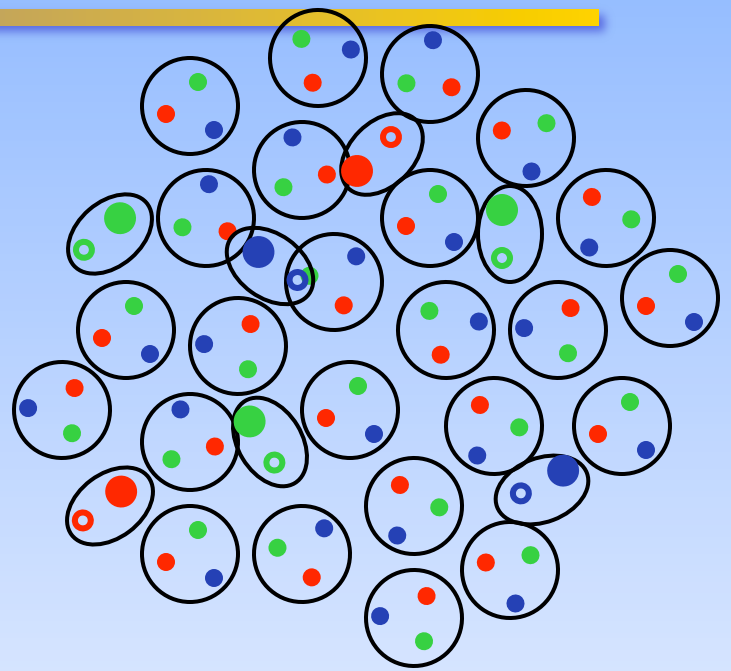
Generating a deconfined state

Present understanding of
Quantum Chromodynamics (QCD)

- heating
- compression

→ *deconfined color matter !*

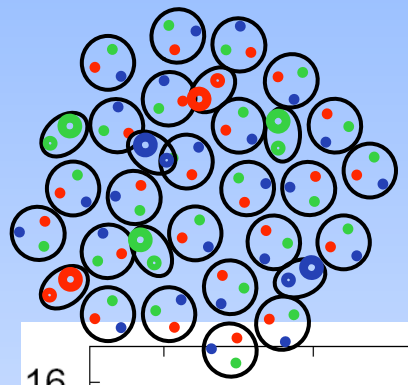




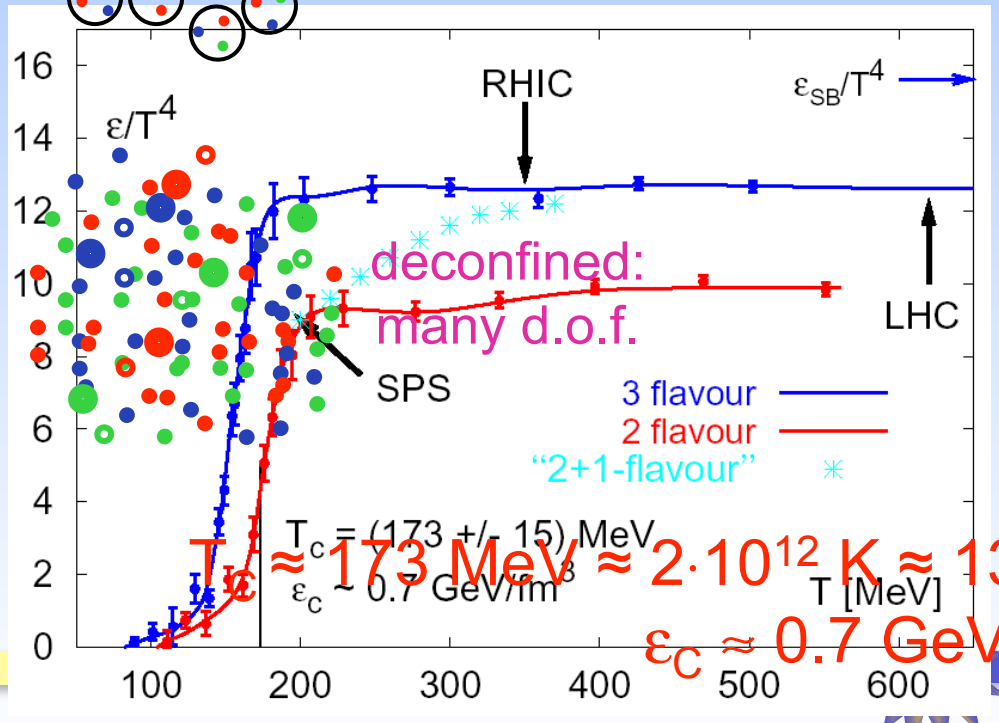
Quark Gluon Matter
deconfined!

Expectations from Lattice QCD

ε/T^4 ~ # degrees of freedom



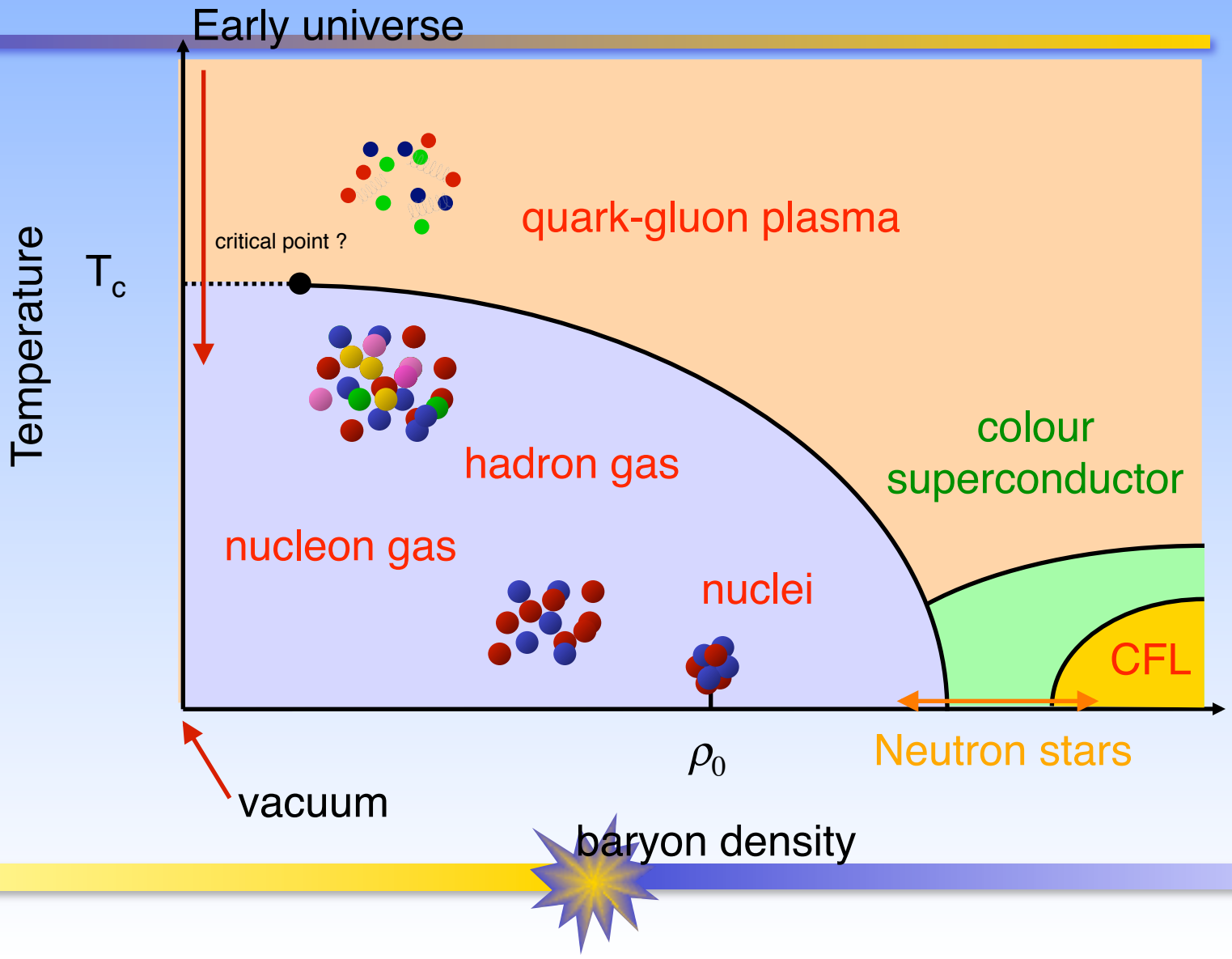
confined:
few d.o.f.



$T_C \approx 173$ MeV $\approx 2 \cdot 10^{12}$ K $\approx 130{,}000 \cdot$ T[Sun's core]

$\varepsilon_C \approx 0.7$ GeV/fm^3

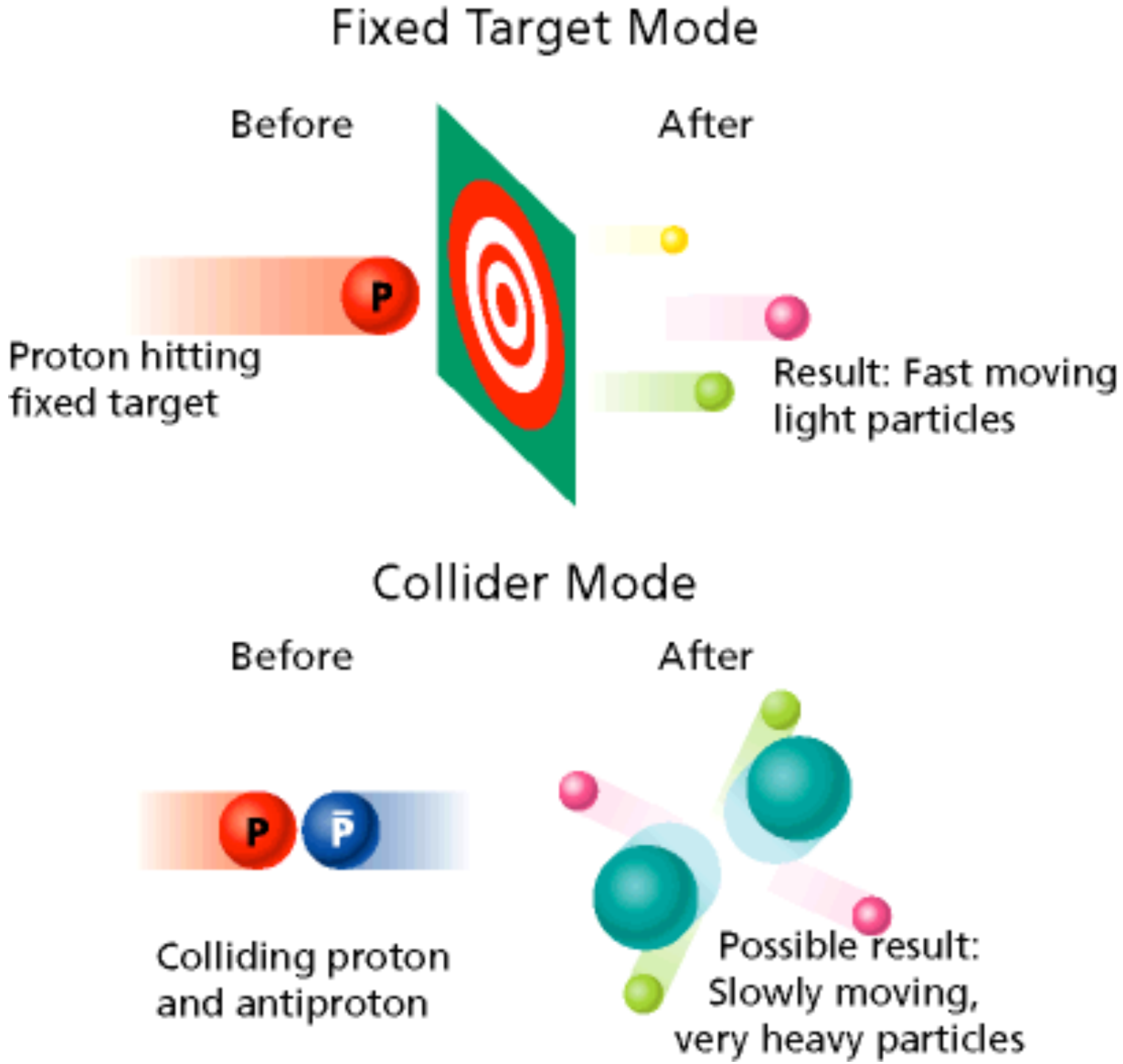
The phase diagram of QCD



Accelerating to discovery…

Previous Nuclear Collision Experiments.

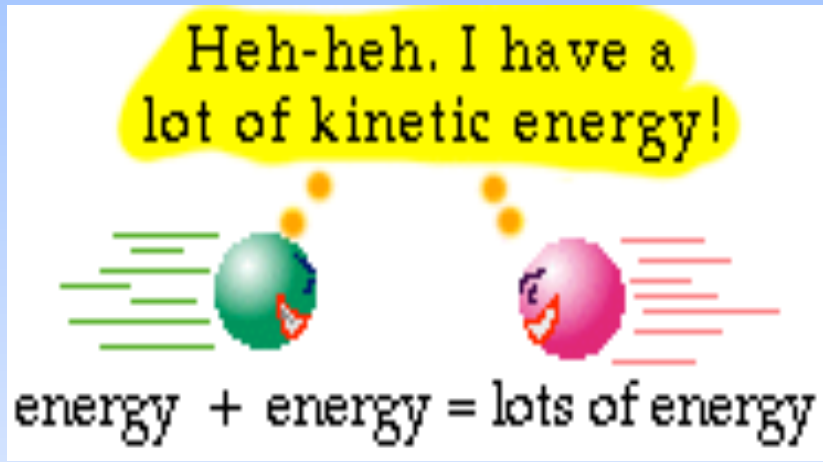
Laboratory	Accelerator	Collisions:
Berkeley Lab	Bevelac	2 GeV/A Oxygen
Brookhaven National Laboratory	AGS	11.6 Gev/A Gold
CERN	SPS	160 GeV/A Lead


Fixed Target Mode
Before
After
P
Proton hitting
fixed target
Result: Fast moving
light particles
Collider Mode
Before
After
P
P̄
Colliding proton
and antiproton
Possible result:
Slowly moving,
very heavy particles

The Relativistic Heavy Ion Collider

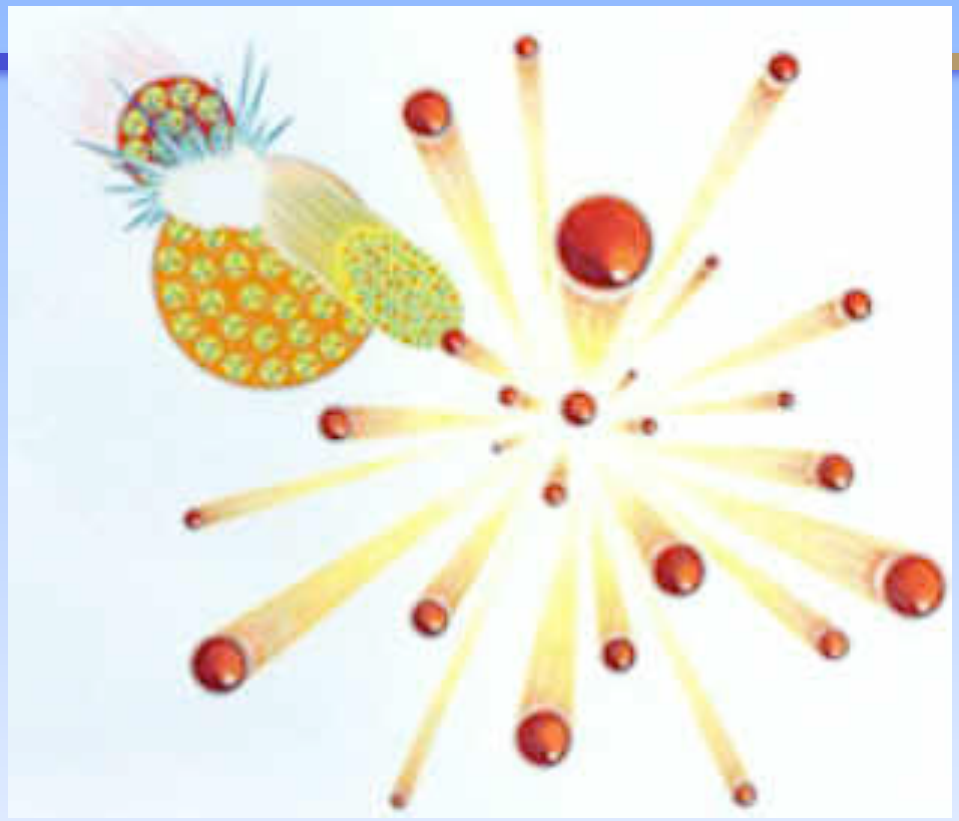
A Quark-Gluon Plasma Factory

- **RHIC is a very versatile collider.**
- **RHIC accelerates particles from protons to gold to an energy of 100 + 100 GeV/A**
- **RHIC can also accelerate protons with their spins aligned.**
- **Energy for particle production at RHIC is 10 times that at the CERN SPS.**

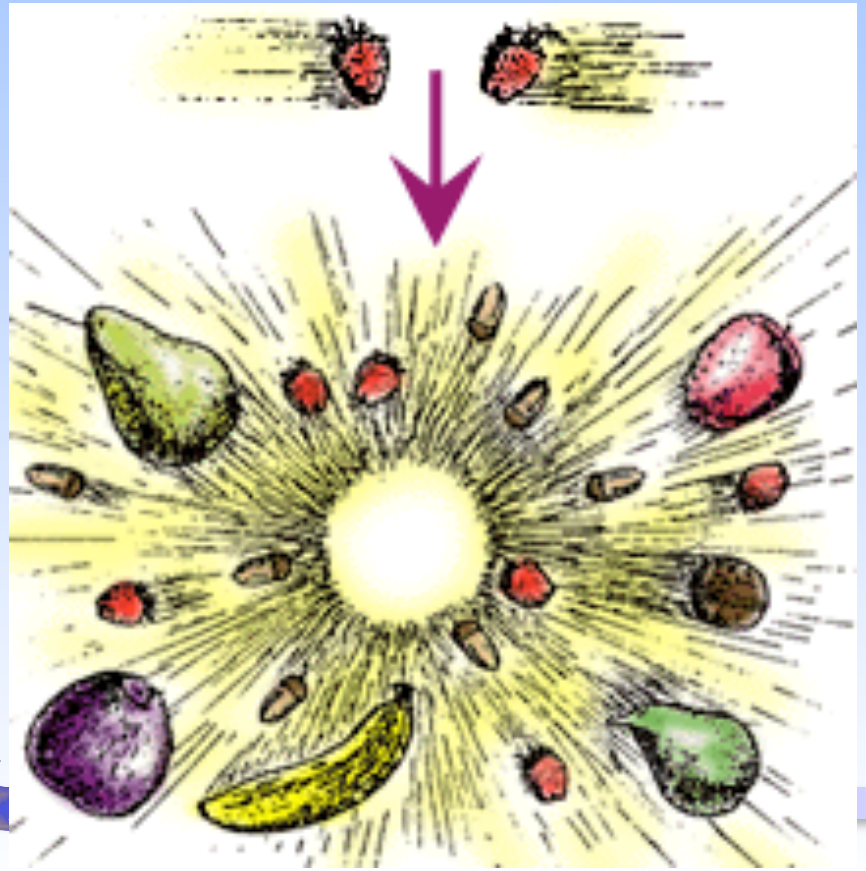


The Relativistic Heavy Ion Collider

A Quark-Gluon Plasma Factory?



The Collision...

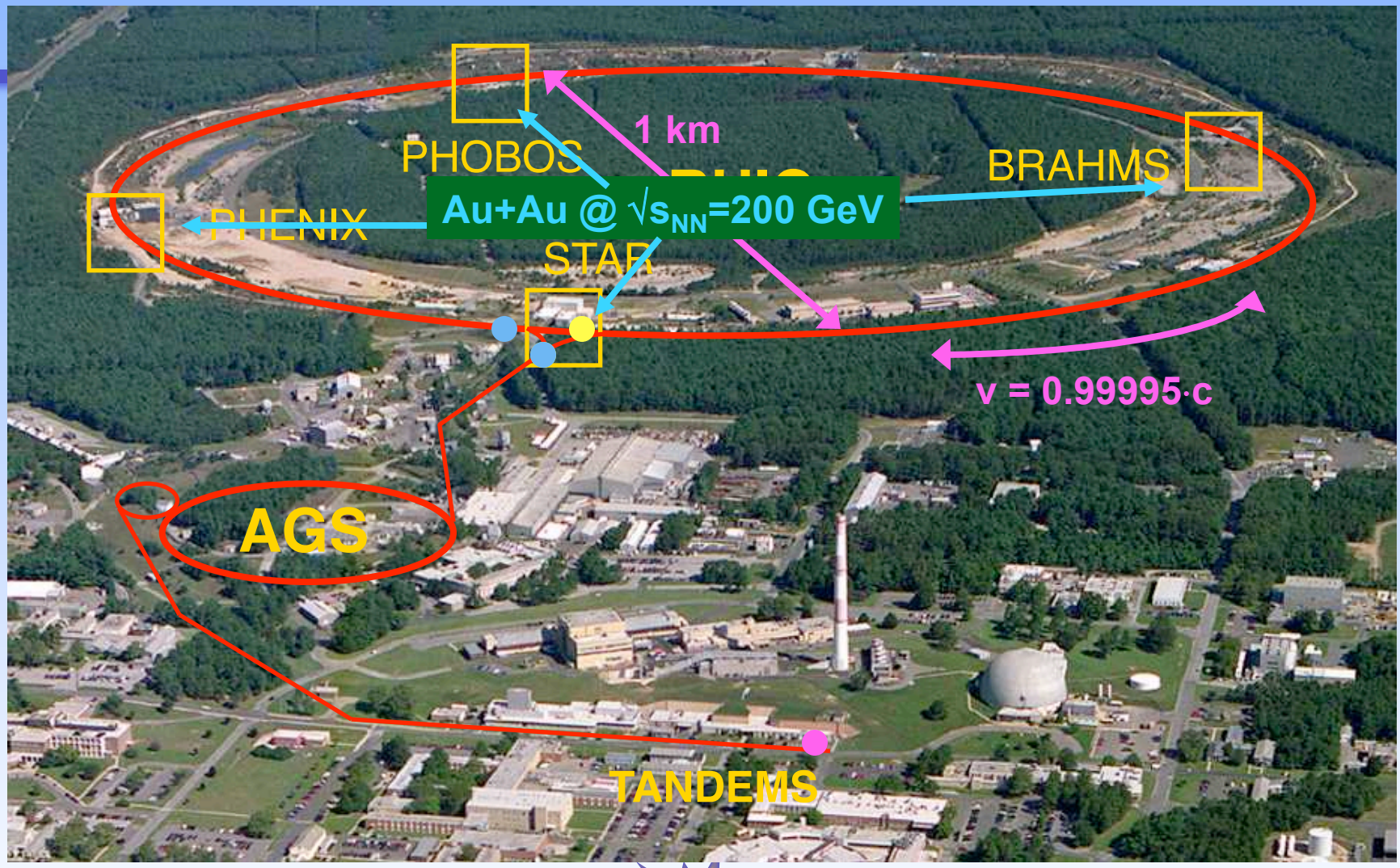


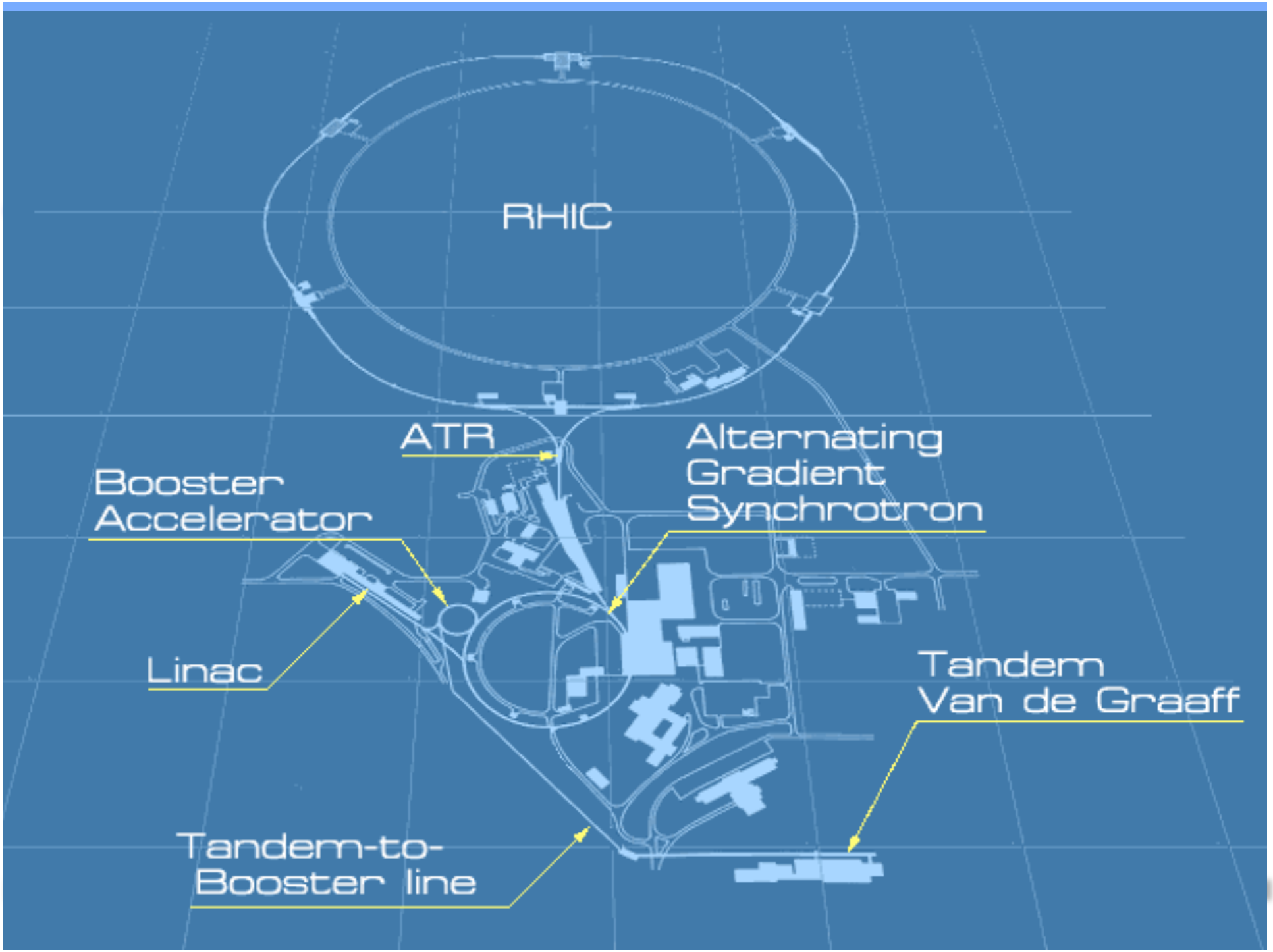
Special Relativity takes over!

$E=mc^2$

Where Is RHIC?

Relativistic Heavy Ion Collider (RHIC)

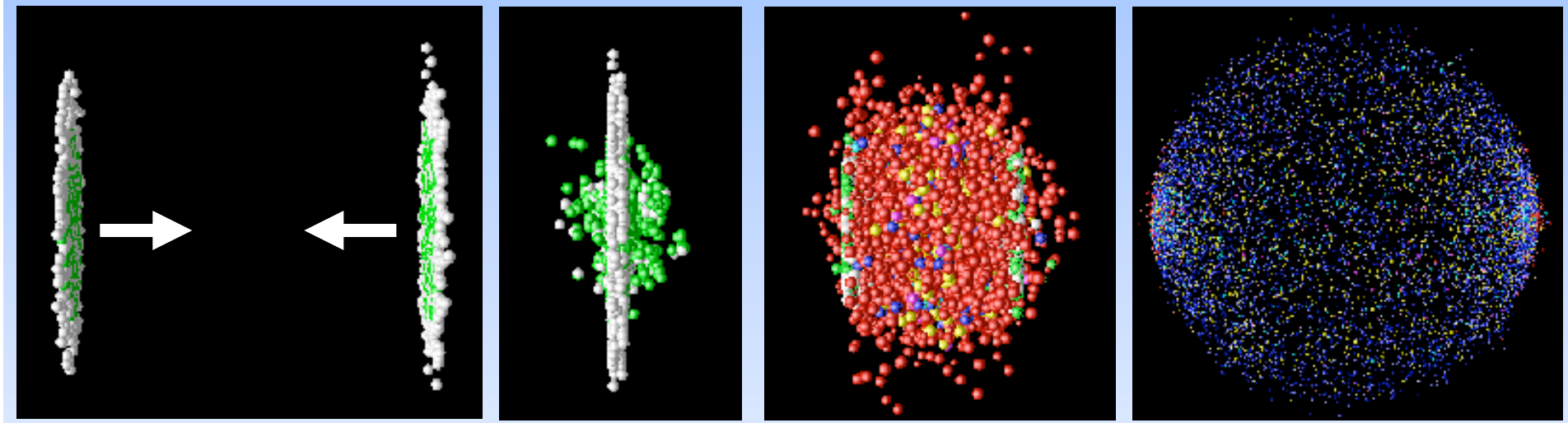



RHIC
ATR
Alternating
Gradient
Synchrotron
Booster
Accelerator
Linac
Tandem
Van de Graaff
Tandem-to-
Booster line

Inside the RHIC Ring

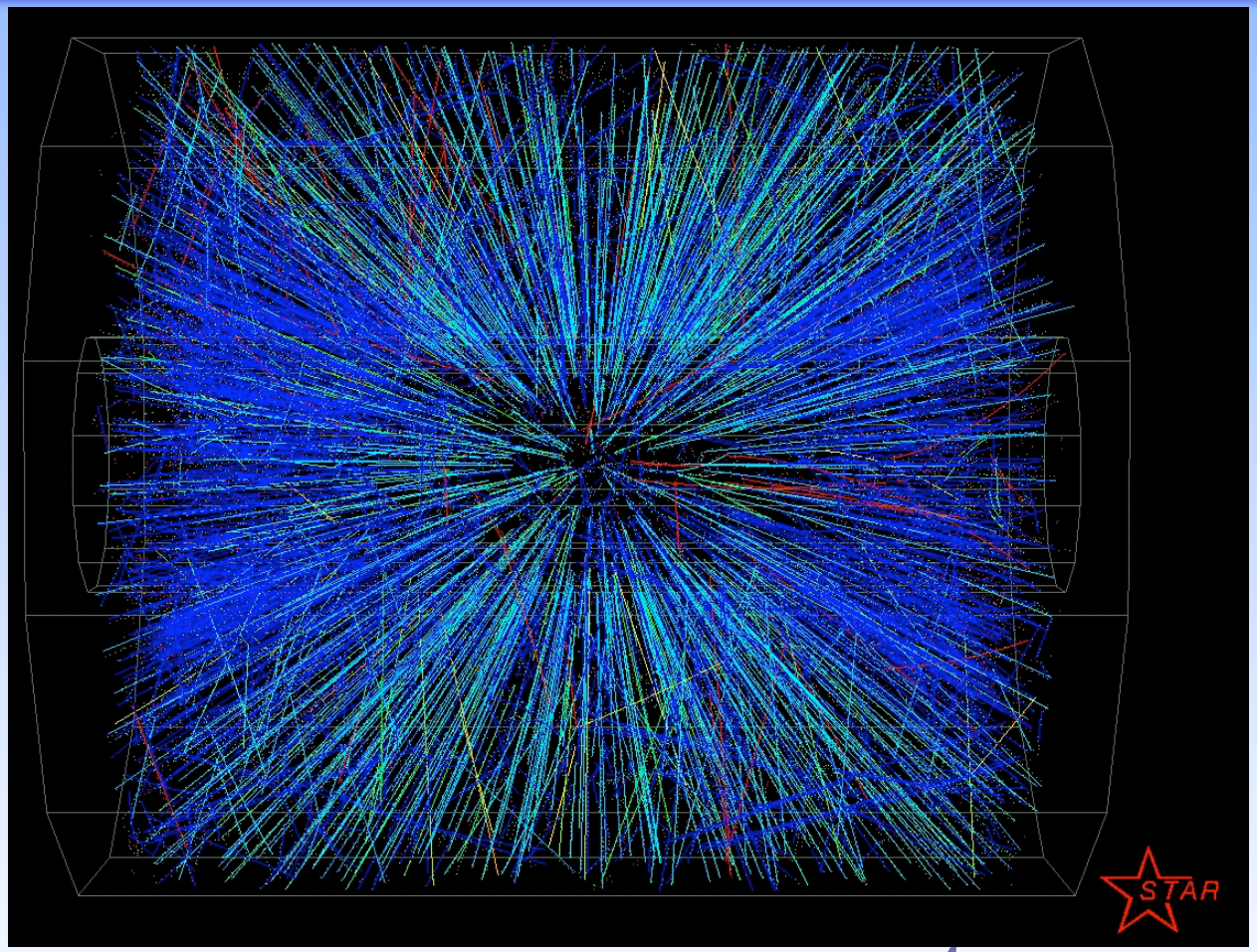
- Underground tunnel
- Super-conducting magnets
- Cooled by liquid helium

RHIC Beam Collisions



Approach Collision Particle Shower

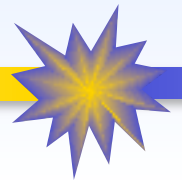
RHIC Collisions

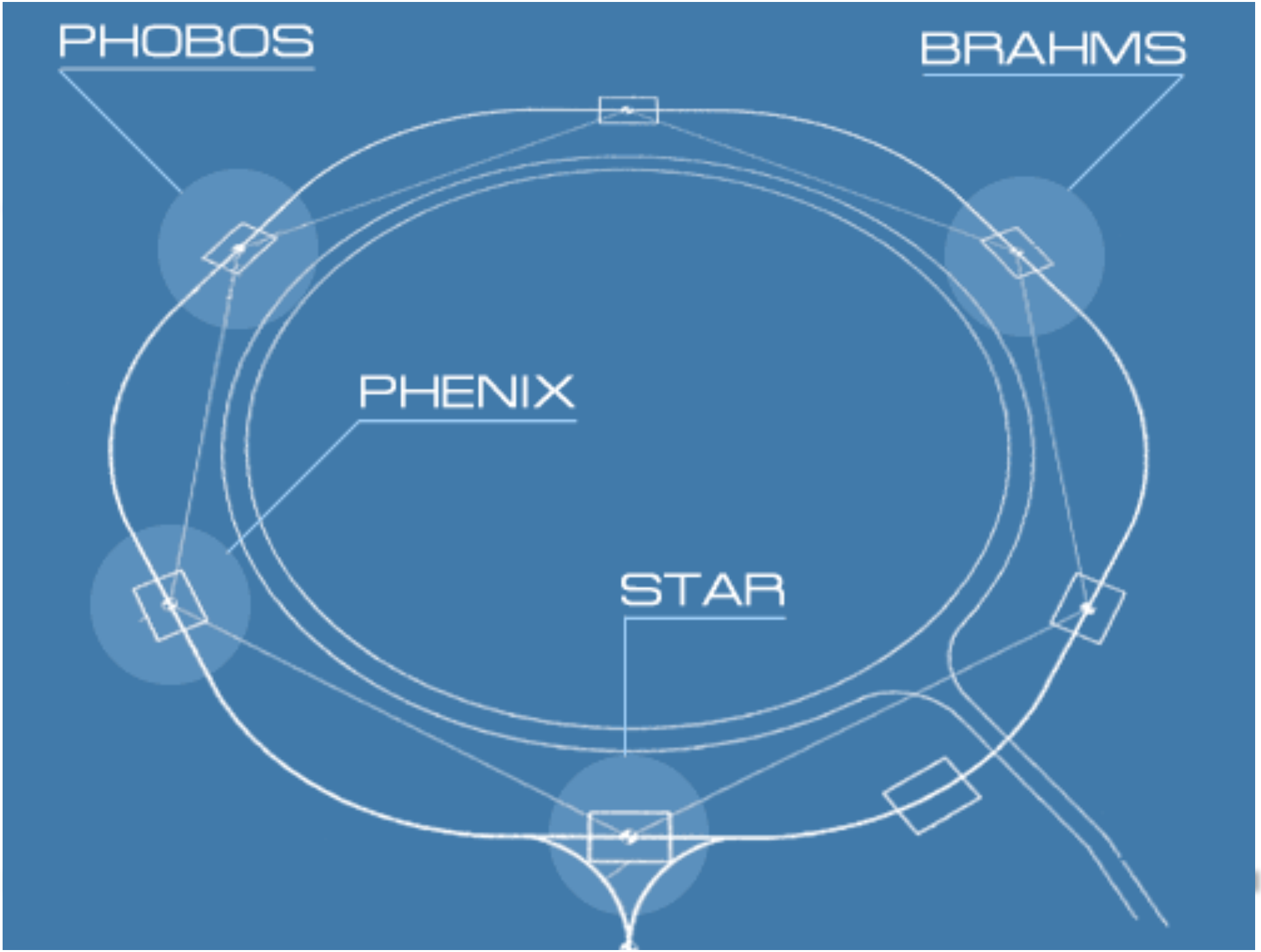


Each collision produces thousands of particles!

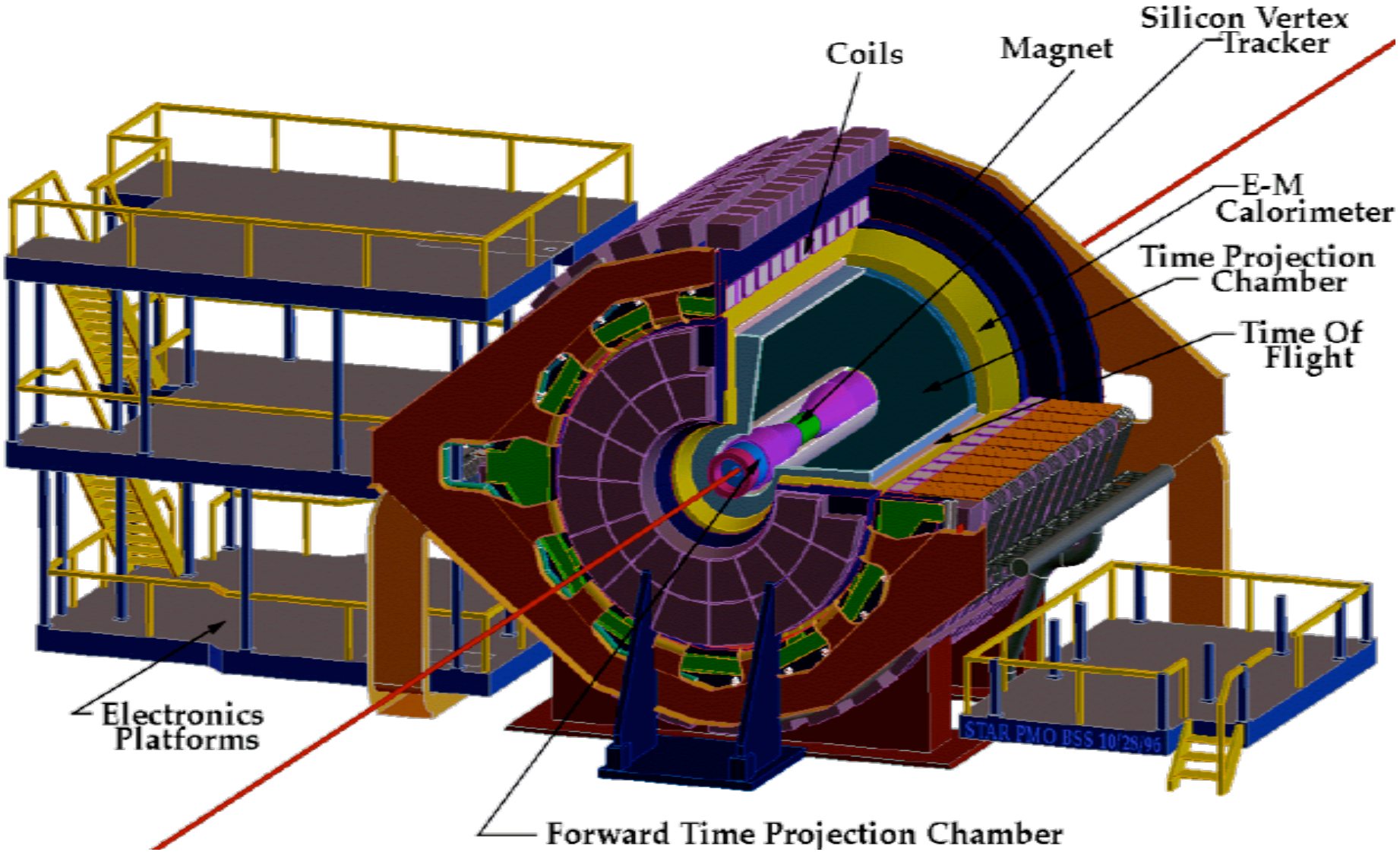
Measuring RHIC Collisions

- Detect particles
- Record information
- Reconstruct what happened
- Analyze data

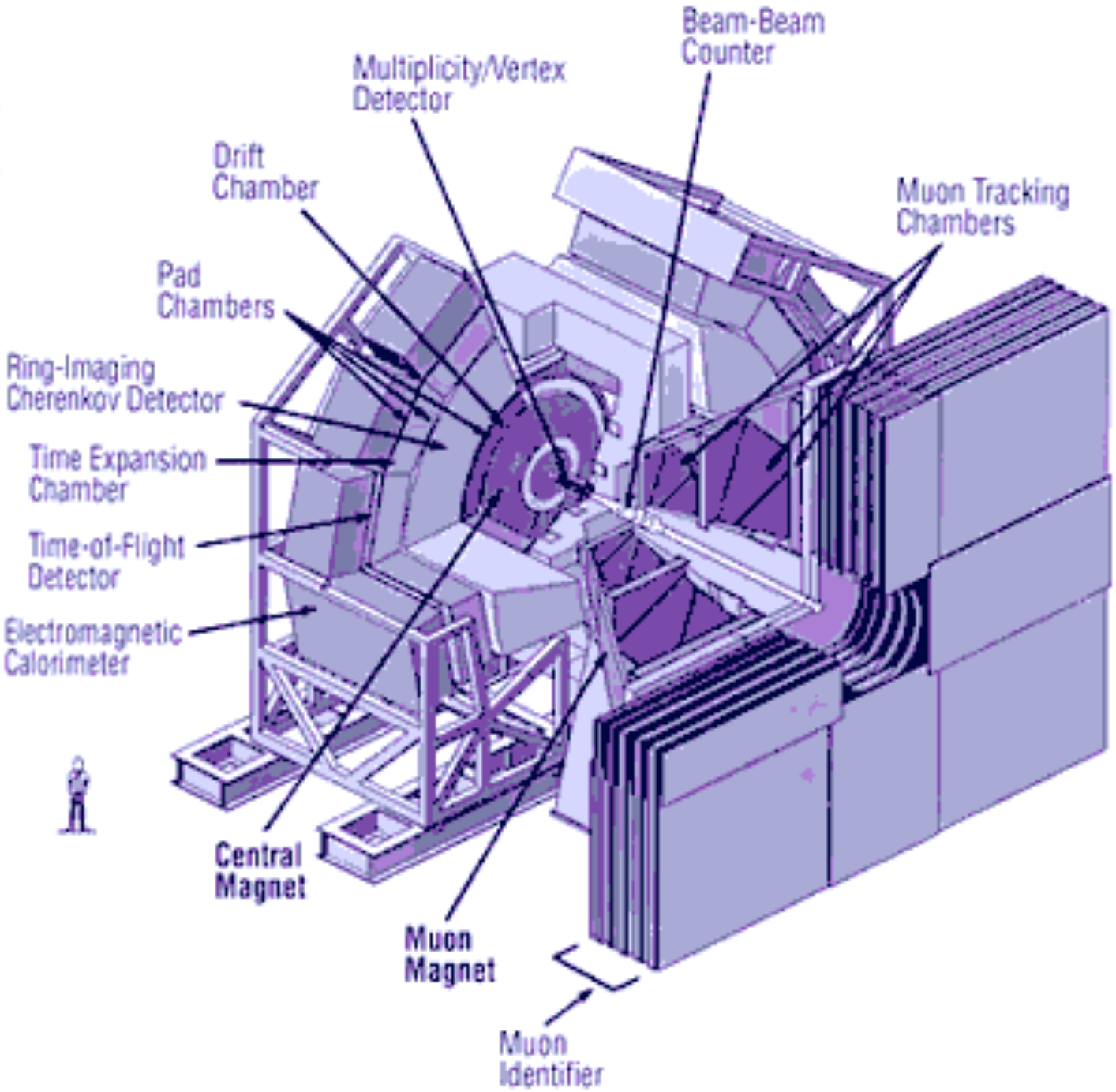



PHOBOS
BRAHMS
PHENIX
STAR

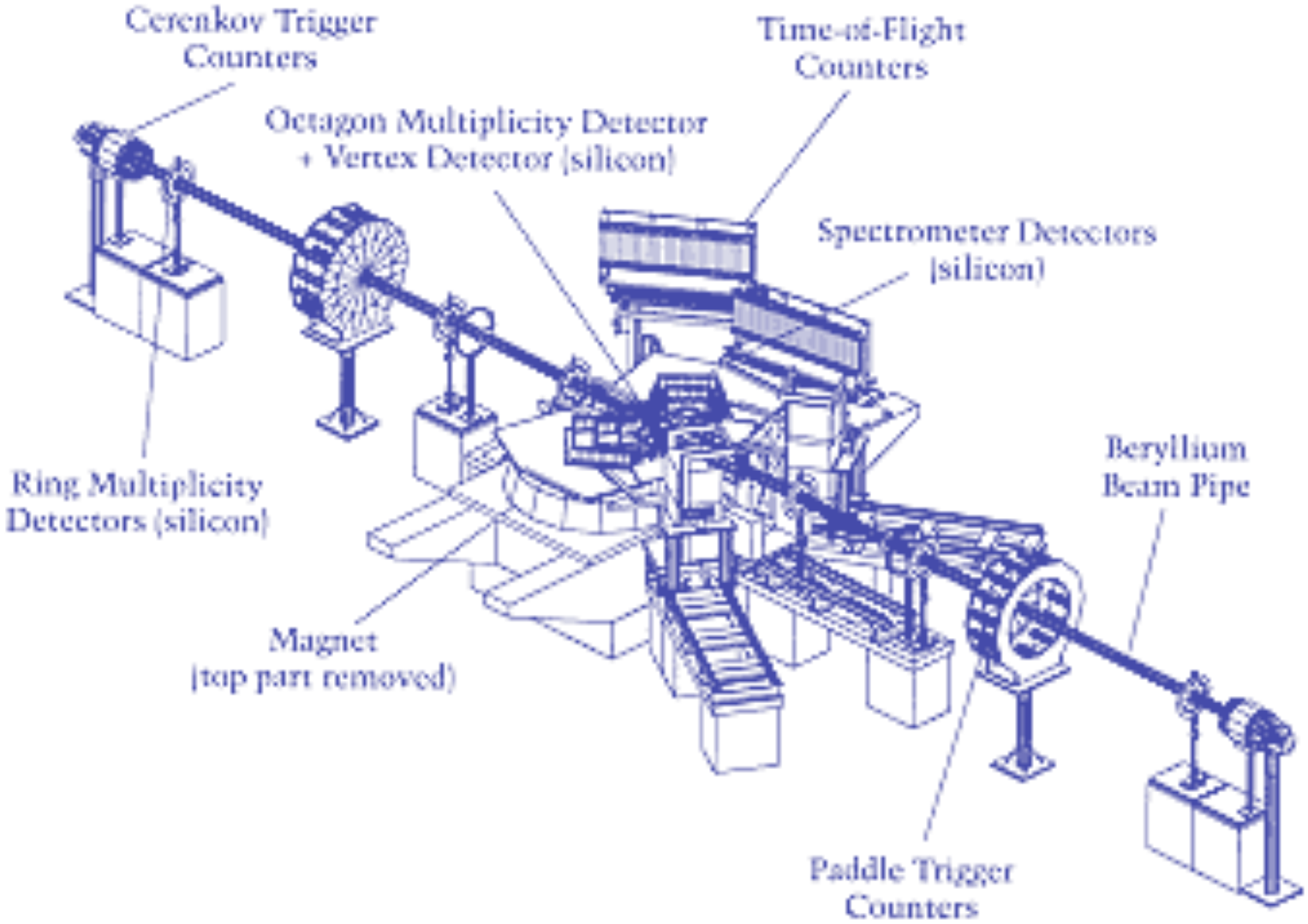
STAR


Silicon Vertex Tracker
Coils
Magnet
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber
STAR PMO BSS 10/28/96

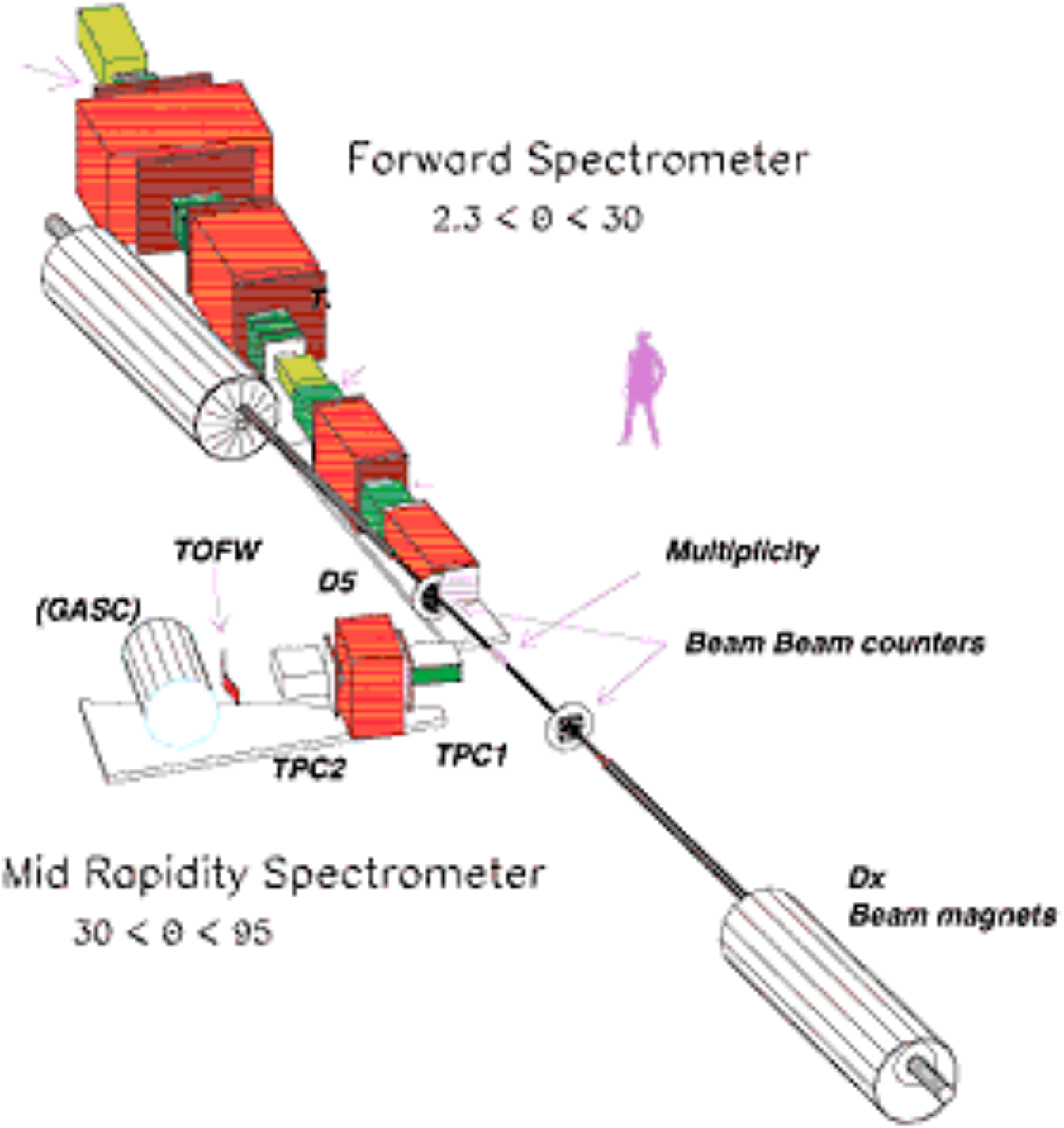
PHENIX


Beam-Beam Counter
Multiplicity/Vertex Detector
Drift Chamber
Muon Tracking Chambers
Pad Chambers
Ring-Imaging Cherenkov Detector
Time Expansion Chamber
Time-of-Flight Detector
Electromagnetic Calorimeter
Central Magnet
Muon Magnet
Muon Identifier

PHOBOS

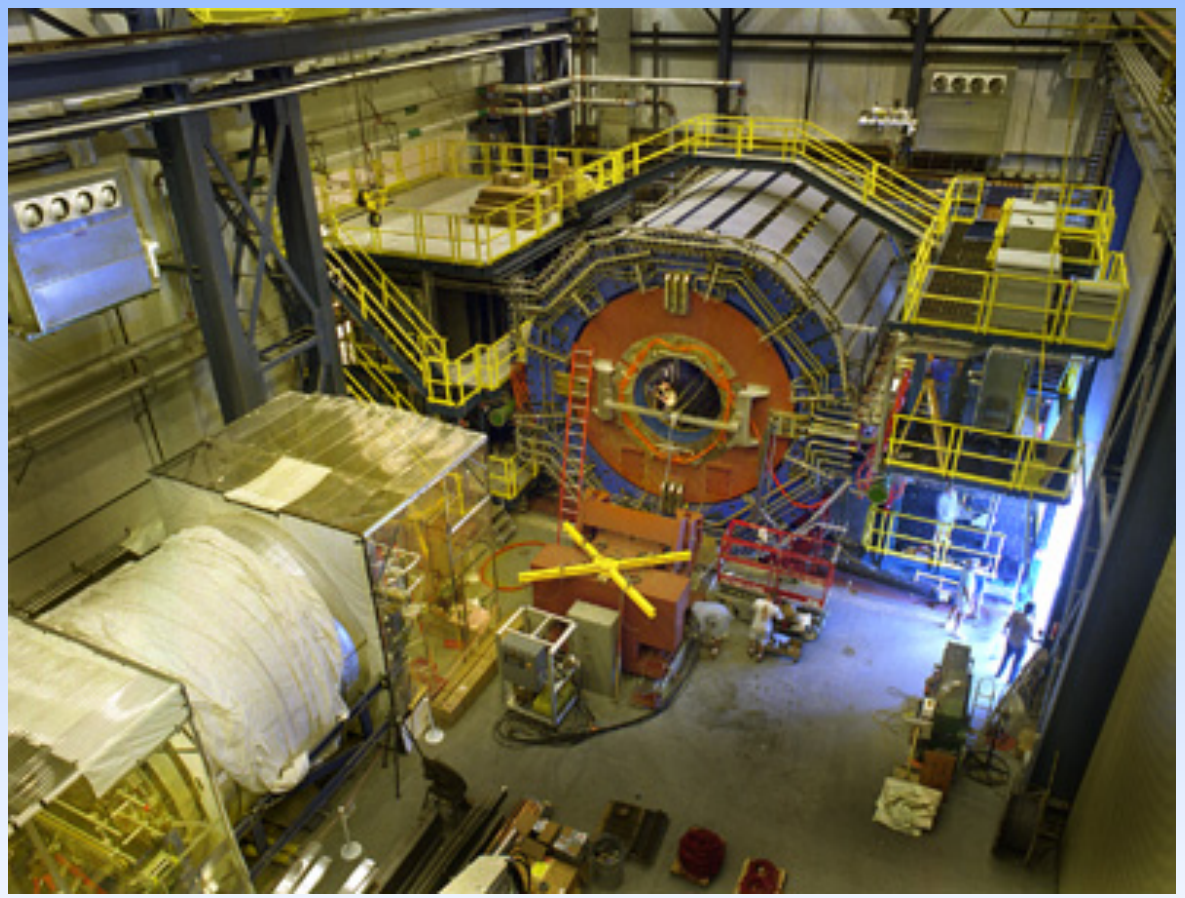

Cerenkov Trigger Counters
Time-of-Flight Counters
Octagon Multiplicity Detector + Vertex Detector (silicon)
Spectrometer Detectors (silicon)
Ring Multiplicity Detectors (silicon)
Beryllium Beam Pipe
Magnet (top part removed)
Paddle Trigger Counters

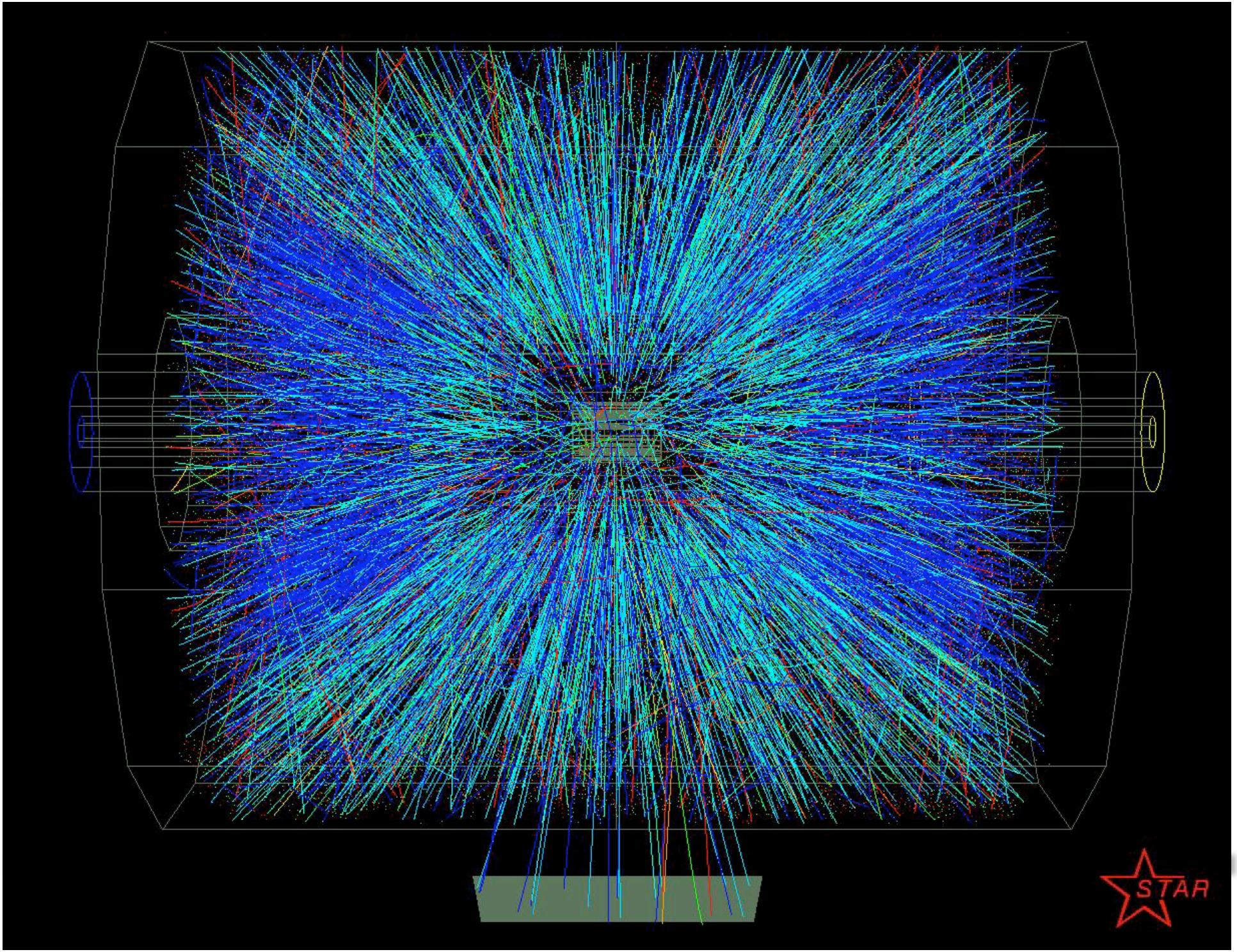
BRAHMS

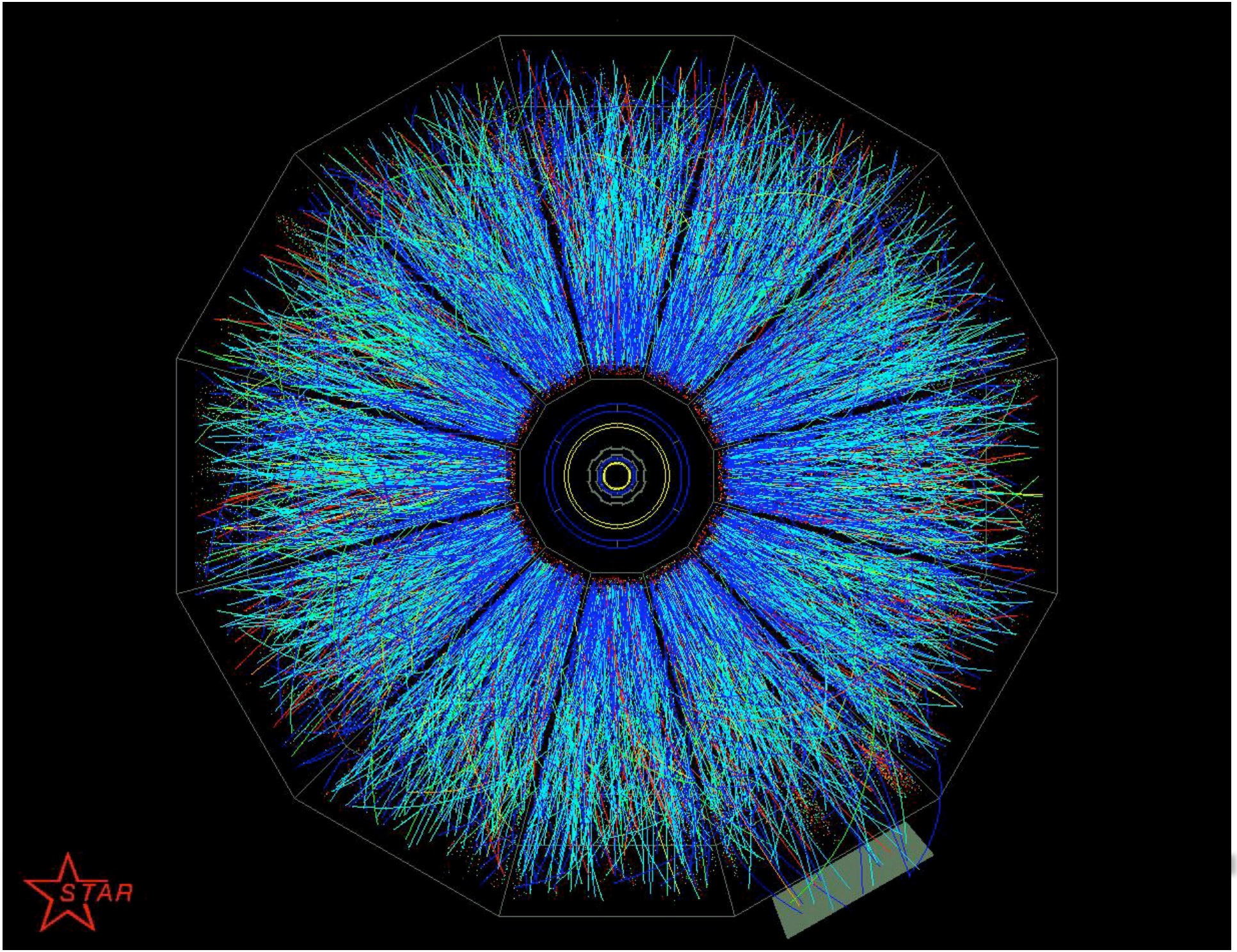

Forward Spectrometer
2.3 < θ < 30
TOFW
(GASC)
D5
Multiplicity
Beam Beam counters
TPC2
TPC1
Mid Rapidity Spectrometer
30 < θ < 95
Dx
Beam magnets

The STAR Experiment

Overview while under construction



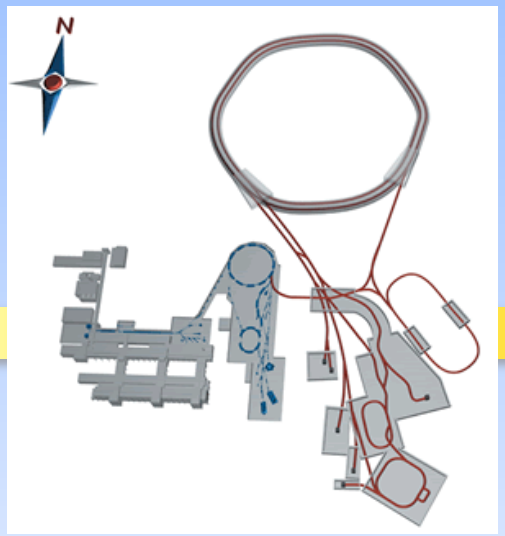

STAR

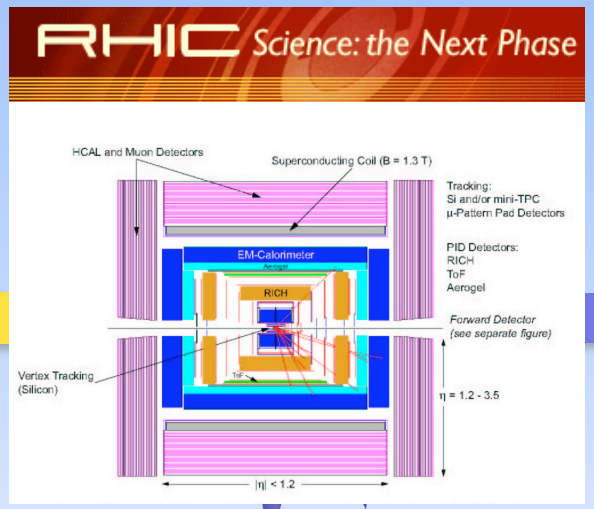

STAR

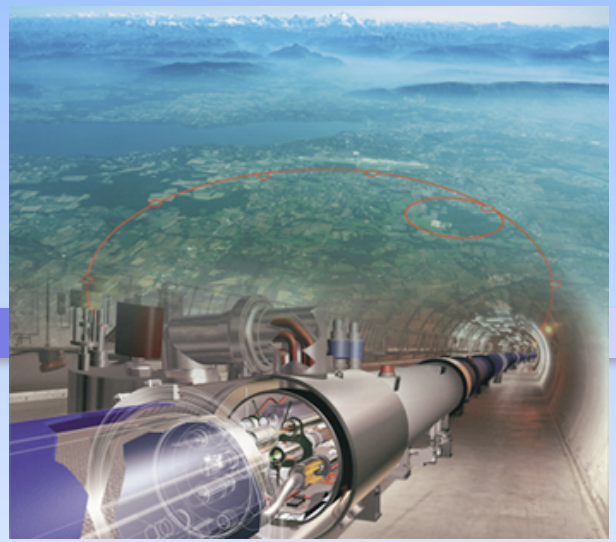
The future is bright

A three prong approach:

lower energy **better facility** **higher energy**







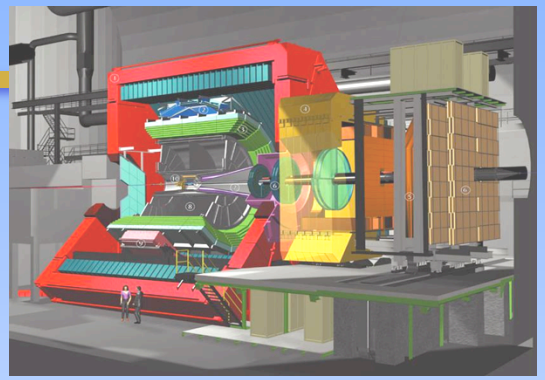
FAIR:
Facility for Antiproton & Ion Reseach

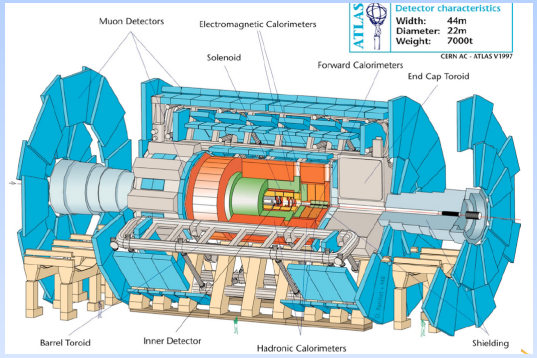
RHIC-II:
RHIC upgrade with higher luminosity and upgraded detectors

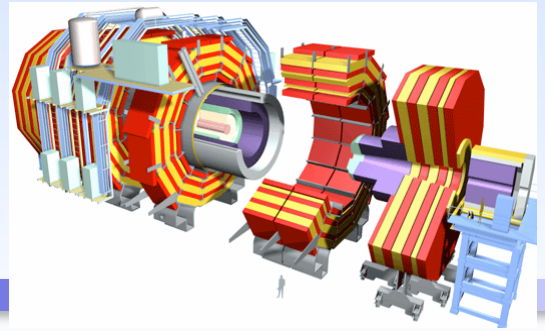
LHC:
Large Hadron Collider with ALICE, CMS, ATLAS

Measuring pp/AA in all LHC experiments

- **ALICE**
  - Dedicated & most versatile heavy ion detector
  - Important for particle identified fragmentation measurements in pp
- **CMS/ATLAS**
  - Dedicated & most versatile p+p detectors
  - Important for calorimeter based jet measurements in A+A.

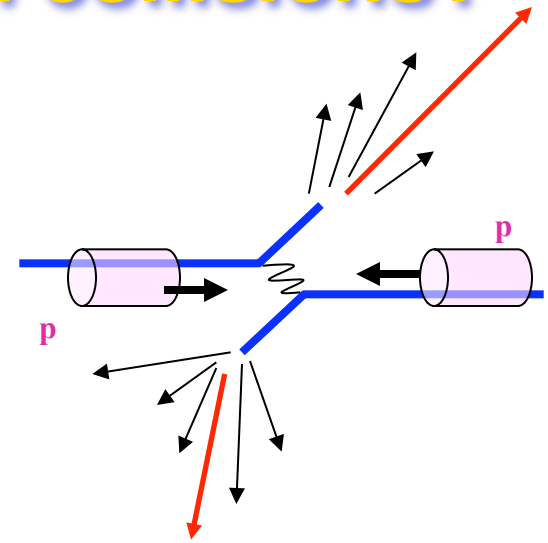






Fate of jets in heavy ion collisions?

idea: p+p collisions @ same $\sqrt{s_{NN}}$ = 200 GeV as reference

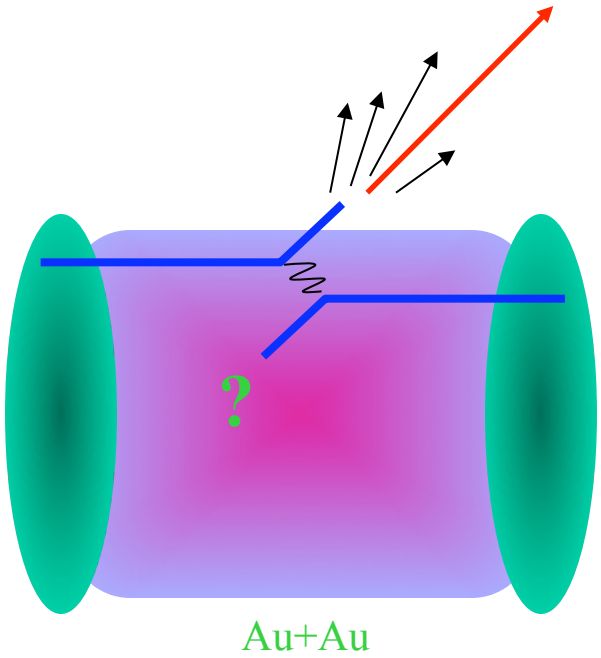


ask: what happens in Au+Au to jets which pass through medium?

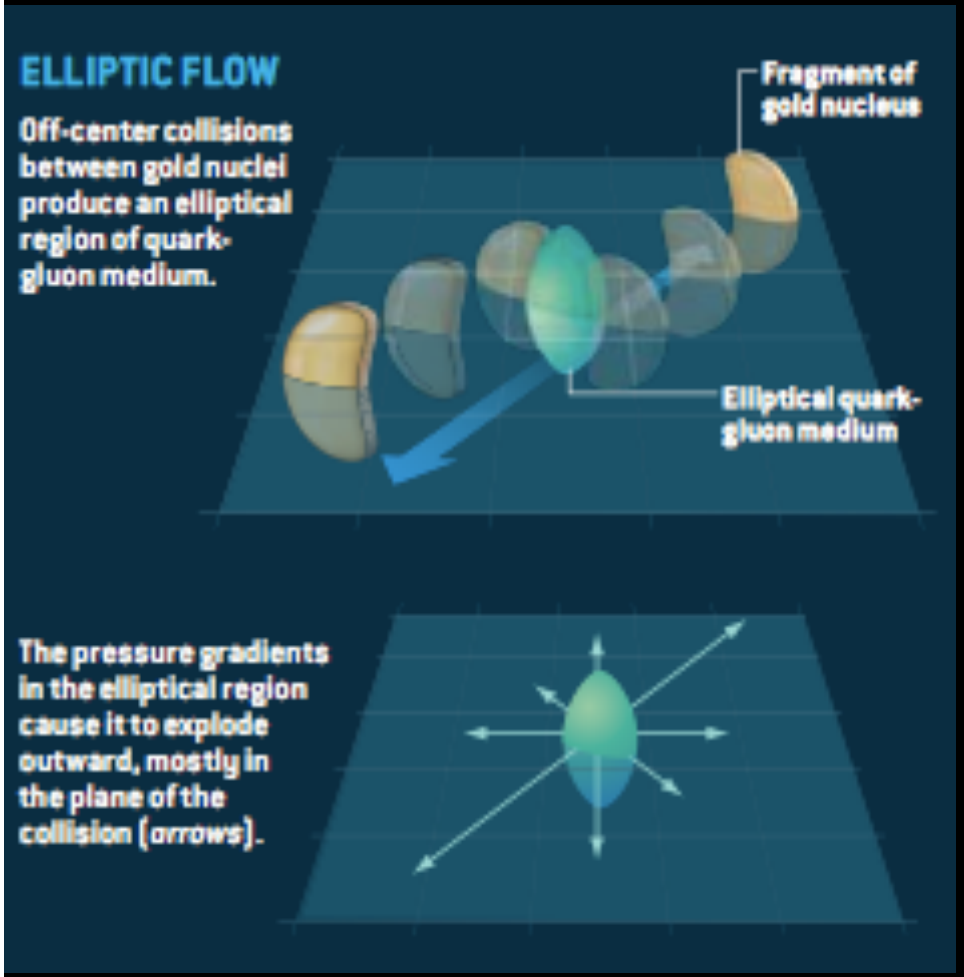
Prediction: scattered quarks radiate energy (~ GeV/fm) in the colored medium:

→ decreases their momentum (fewer high p_T particles)

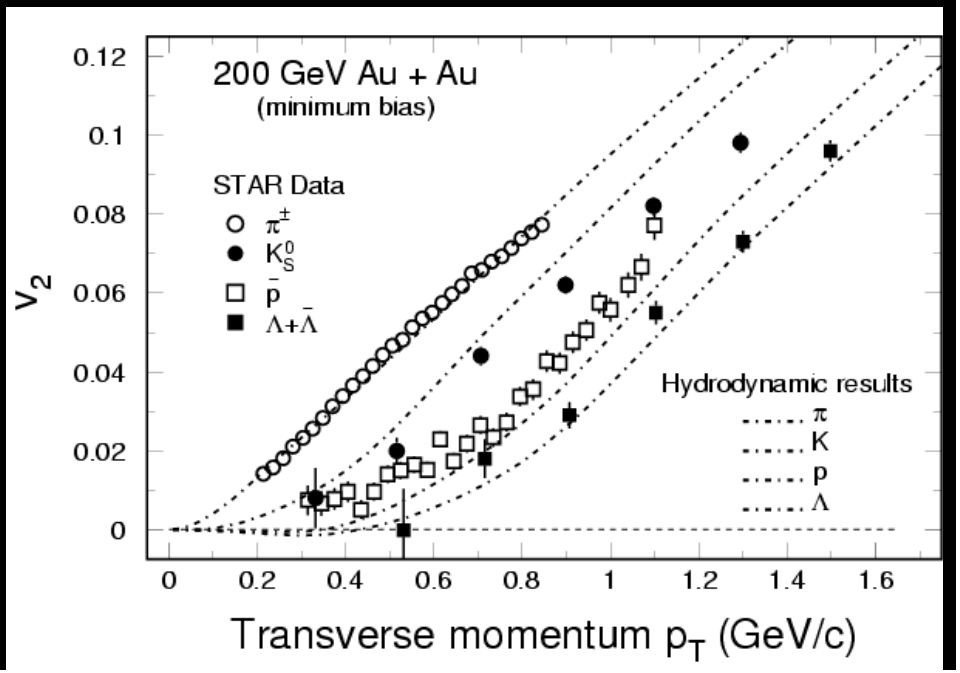
→ "kills" jet partner on other side



Perfect Liquid



Sergei Voloshin, STAR



How Perfect?

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Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions

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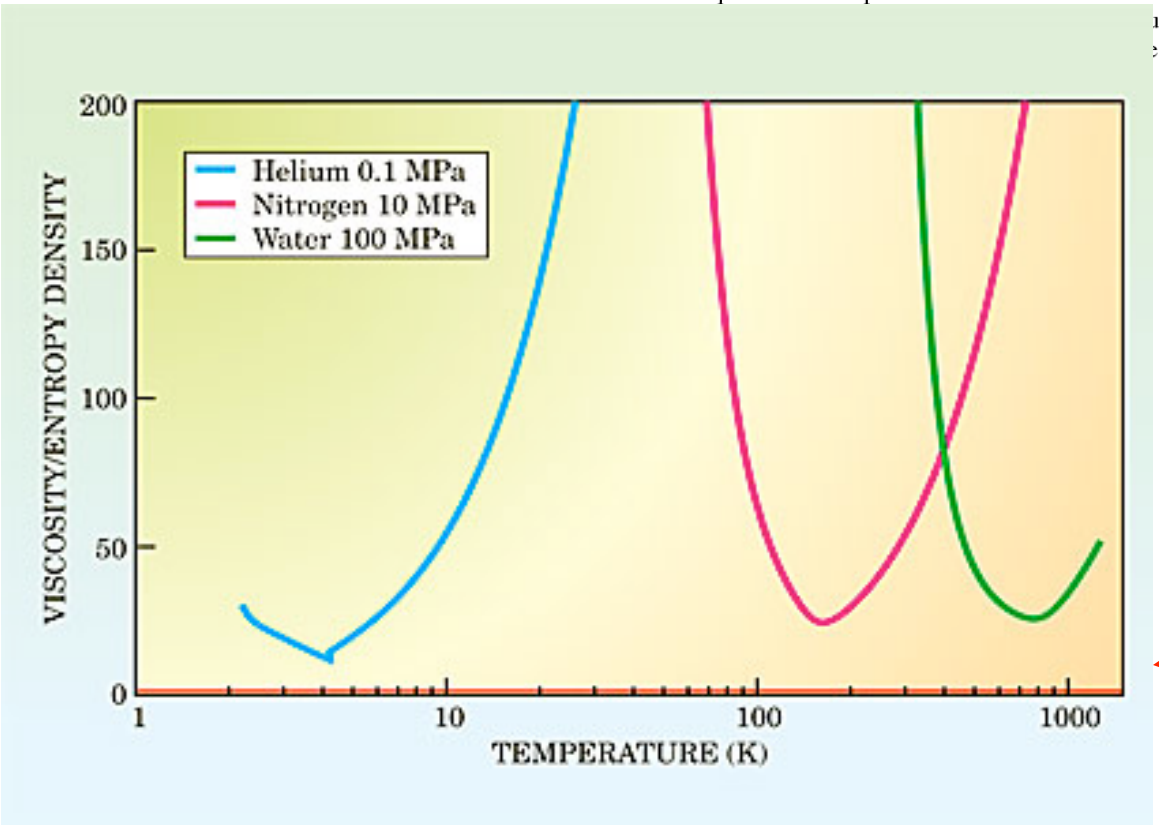
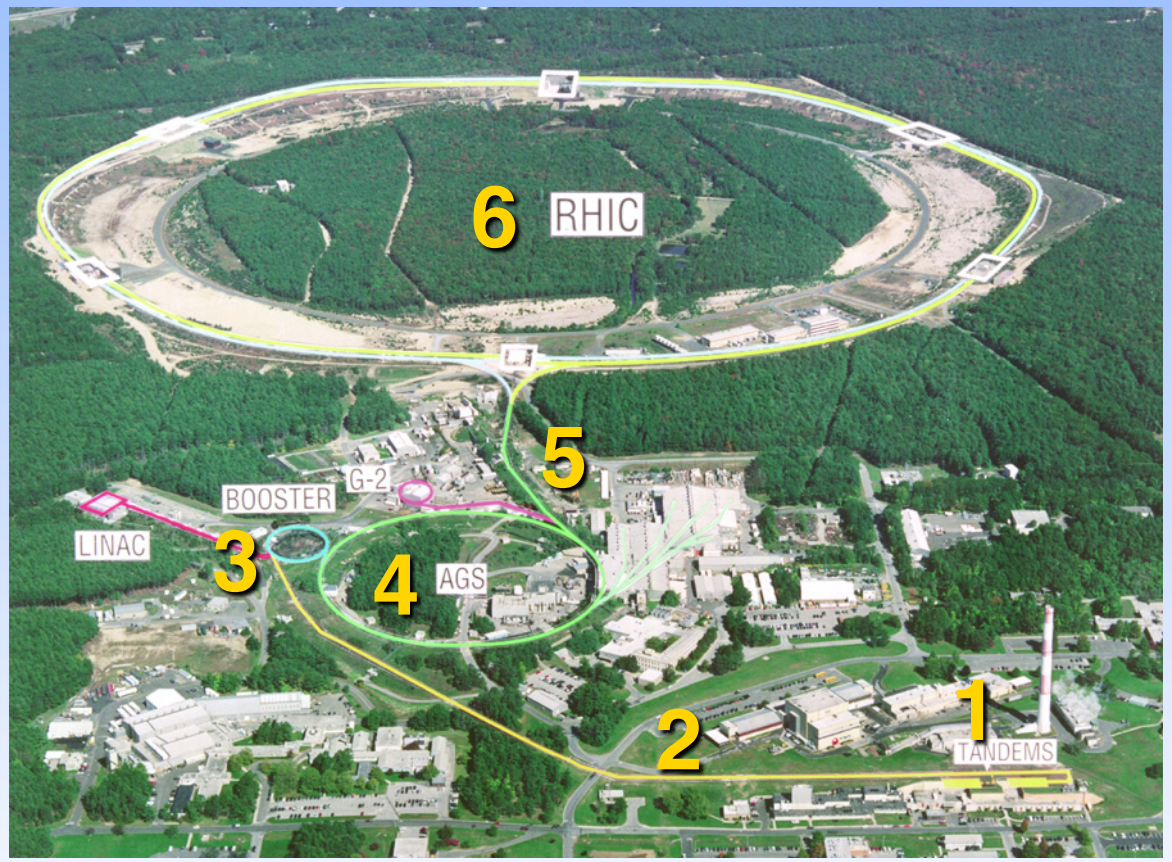
Elliptic flow measurements at the Brookhaven National Laboratory Relativistic Heavy Ion Collider suggest that quark-gluon fluid flows with very little viscosity compared to weak-coupling expectations, challenging theorists to explain why this fluid is so nearly "perfect." It is therefore vital to find quantitative experimental information on the [illegible] measurements of [illegible] current data to [illegible] measurements [illegible] determine the shea[illegible] from 0.08 to 0.3 and [illegible]



The RHIC Complex



1. Tandem Van de Graaff
2. Heavy Ion Transfer Line
3. Booster
4. Alternating Gradient Synchrotron (AGS)
5. AGS-to-RHIC Transfer Line
6. RHIC ring