RHIC and the Hunt for the Plasma Brothers

Quark &

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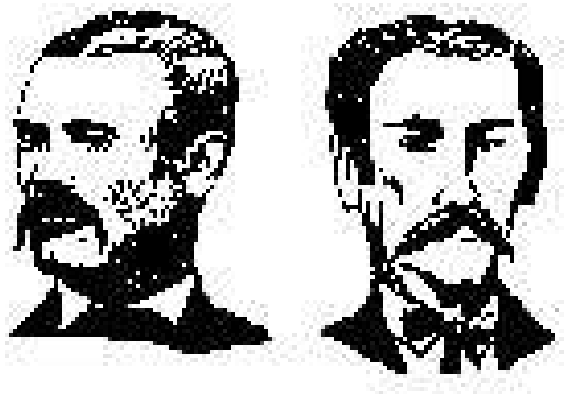
The Hunt for the Plasma Brothers: Briefing Outline

- **The Suspect:** The Elusive Quark & Gluon Plasma (QGP) Brothers.

  The suspects are known informants.

- **The Mission:** Confirm the whereabouts of the QGP Brothers and bring them in for questioning.

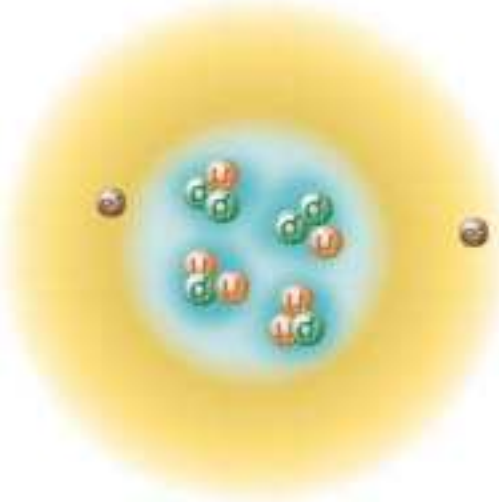
- Quark Gluon Plasma: Dossier and Modus Operandi
- Quark Gluon Plasma: Known Hide-outs
- Flushing out Quark & Gluon Plasma
- Surveillance Techniques and Results
- Current Status of the Hunt



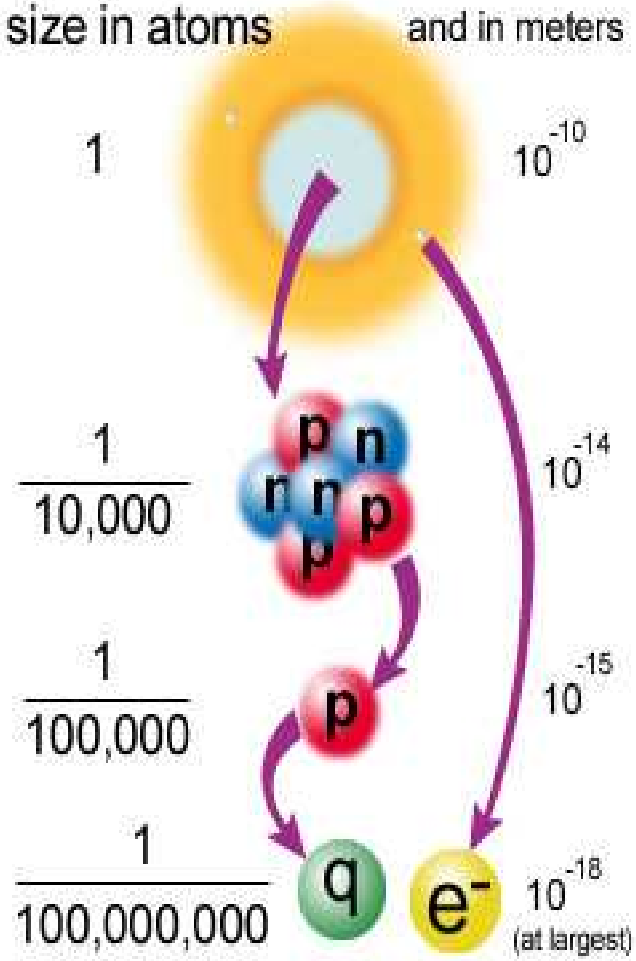
Quark & Gluon Plasma: Dossier

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

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

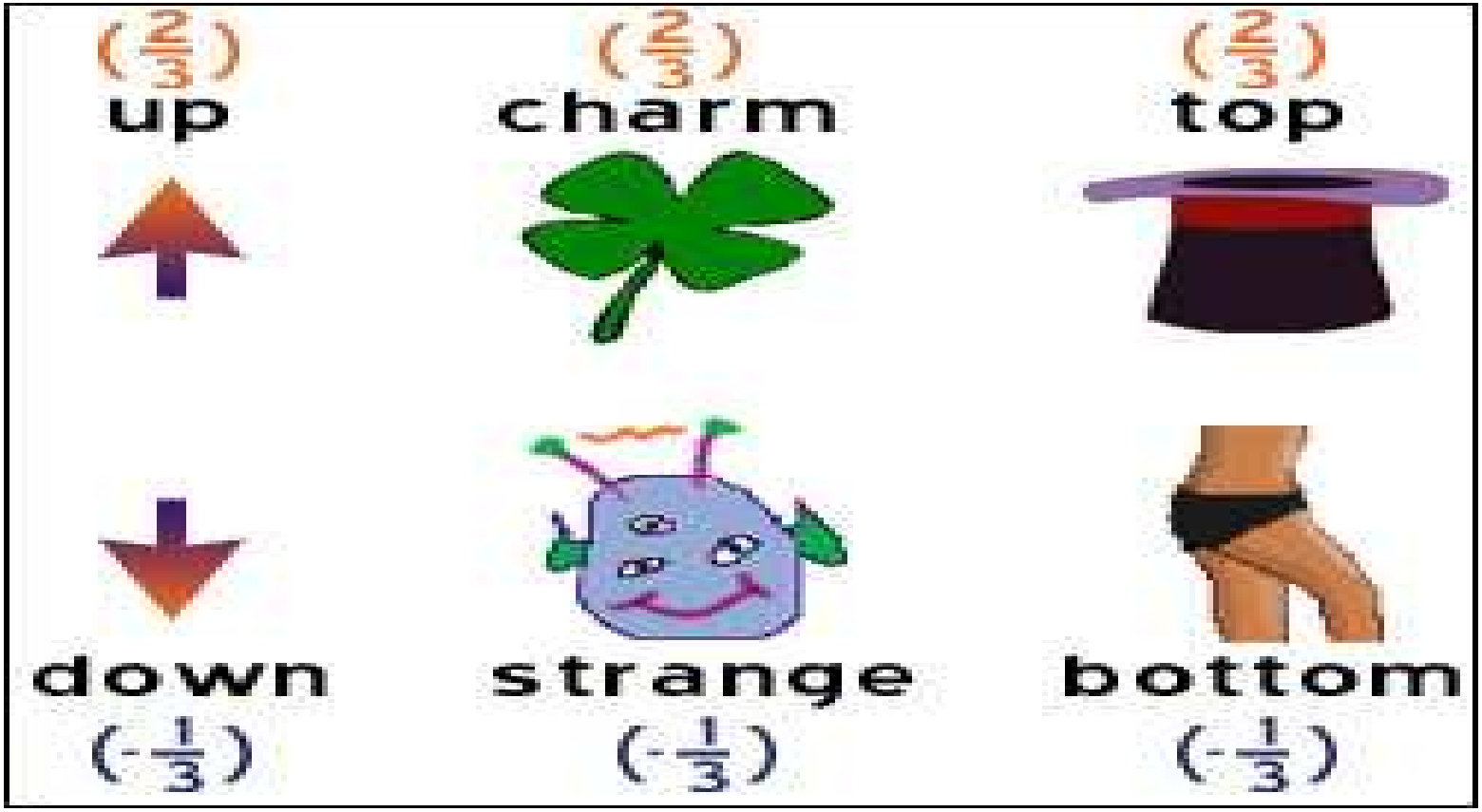


…which contain *up* and *down* *quarks*.



A Briefing on the Quark Brothers

"Aliases", or "Flavors", of the Quark Brothers

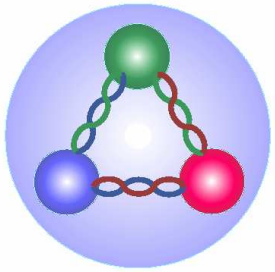


Light and abundant

Heavier, harder to produce

Very heavy, very rare

Quark & *Gluon* Plasma Dossier



The QGP is known to use force...

	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

Quark & Gluon *Plasma*: Modus Operandi

Quark brothers always hang out in gangs of 2's or 3's *(hadrons)*.

… and Gluon brothers hold them together…

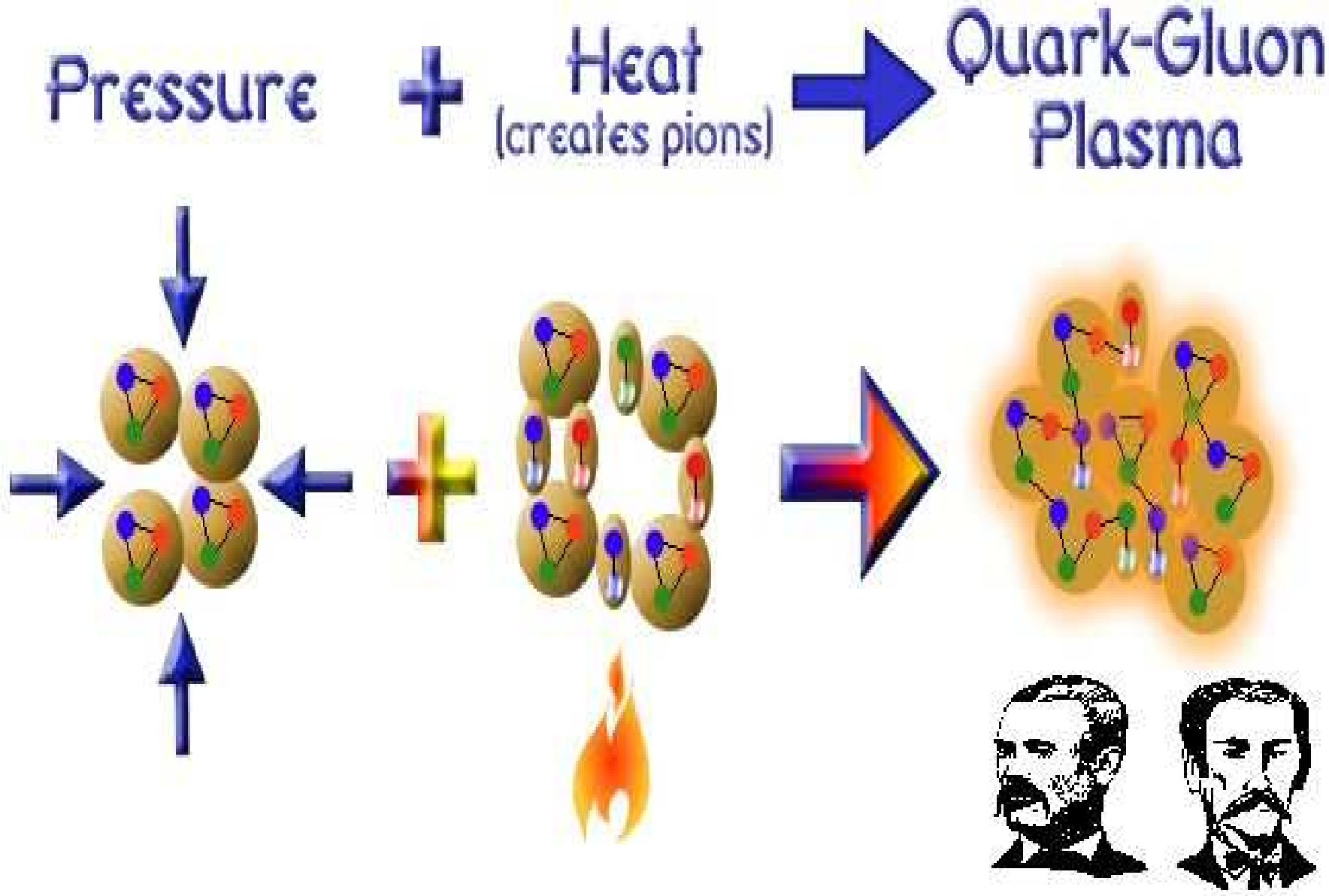
Creating a Plasma lets Quark Brothers roam free as individuals !!!

We want to catch them in the act.

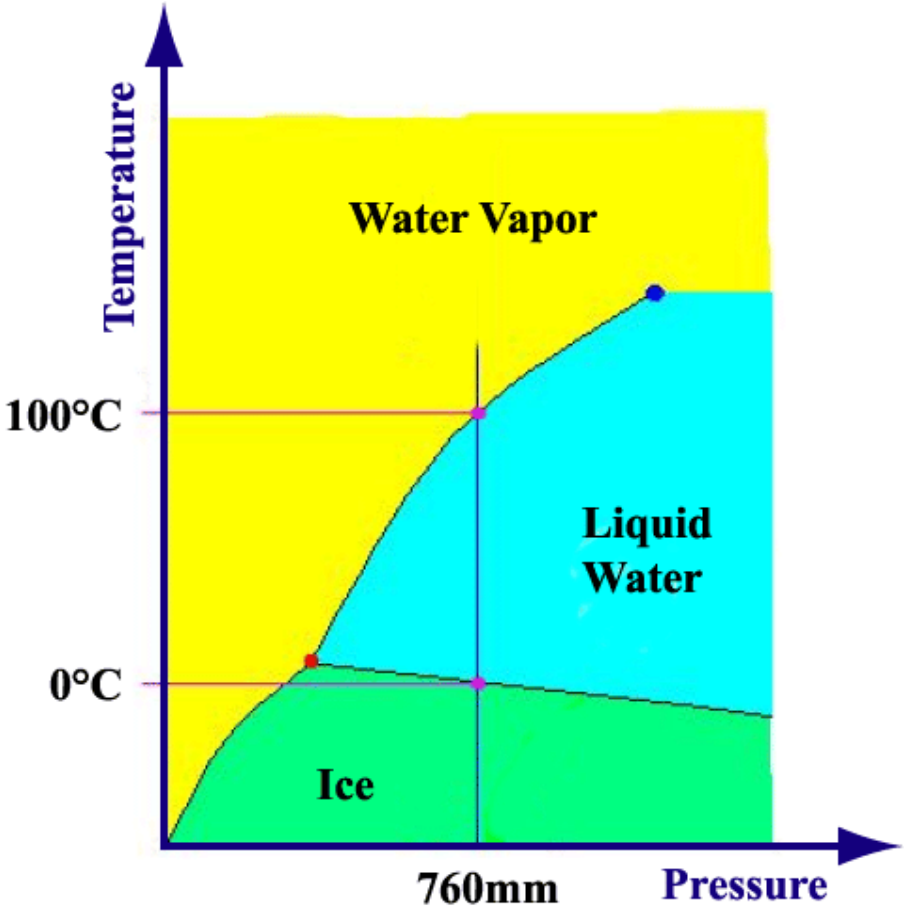
BARYONS = qqq*		quarks	electric charge	mass (GeV/c^2)	spin
p	proton	u u d	+ 1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\,\bar{u}\,\bar{d}$	- 1	0.938	1/2
n	neutron	u d d	0	0.940	1/2
Λ^0	lambda	u d s	0	1.116	1/2
Ω^-	omega	s s s	- 1	1.672	3/2
Σ_c	sigma-c	u u c	+ 2	2.455	1/2
Many others ! !					

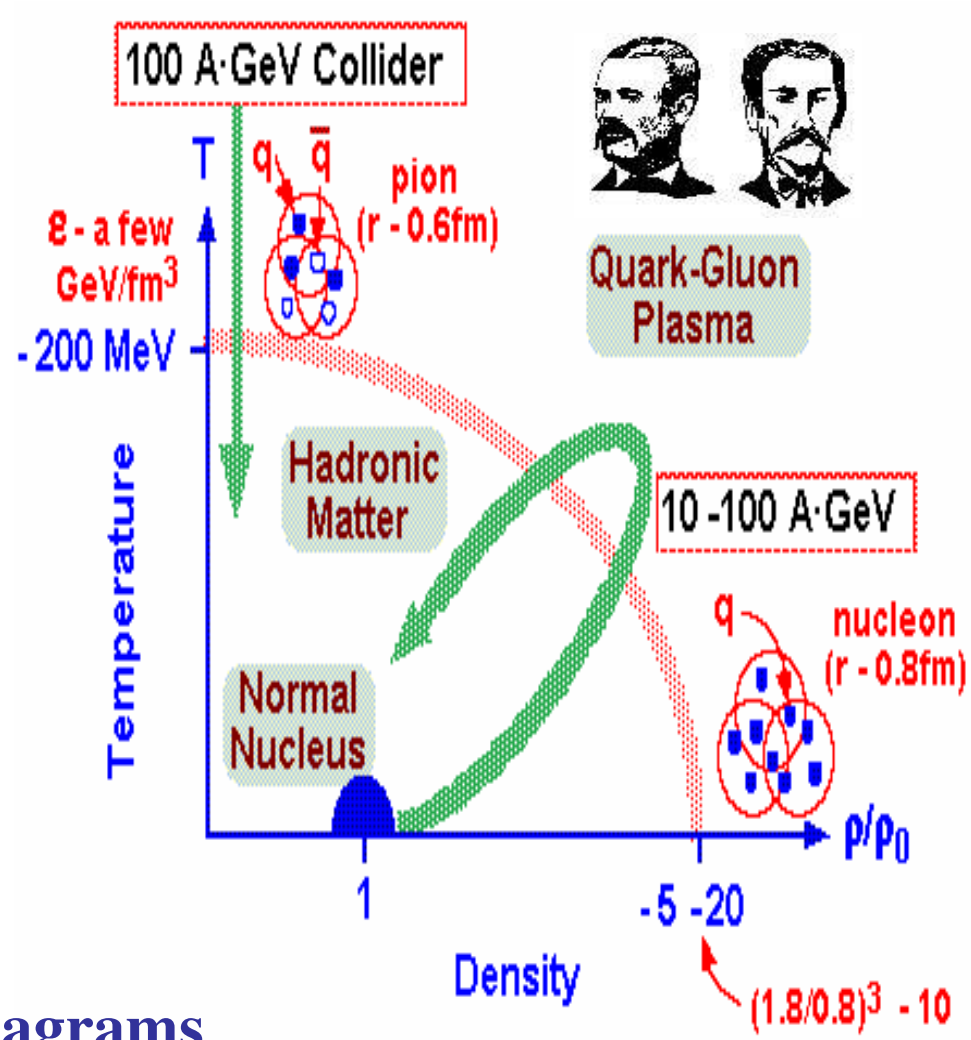
MESON = $q\bar{q}$		quarks	electric charge	mass (GeV/c^2)	spin
π^+	pion	$u\,\bar{d}$	+ 1	0.140	0
K^-	kaon	$s\,\bar{u}$	- 1	0.494	0
K^0	kaon	$d\,\bar{s}$	0	0.498	0
ρ^+	rho	$u\,\bar{d}$	0	0.770	1
D	D	$c\,\bar{d}$	+ 1	1.869	0
η_c	eta-c	$c\,\bar{c}$	0	2.980	0

The Strategy: Build our own QGP hide-out and lure the brothers into our trap…



How to build a QGP Hide-out



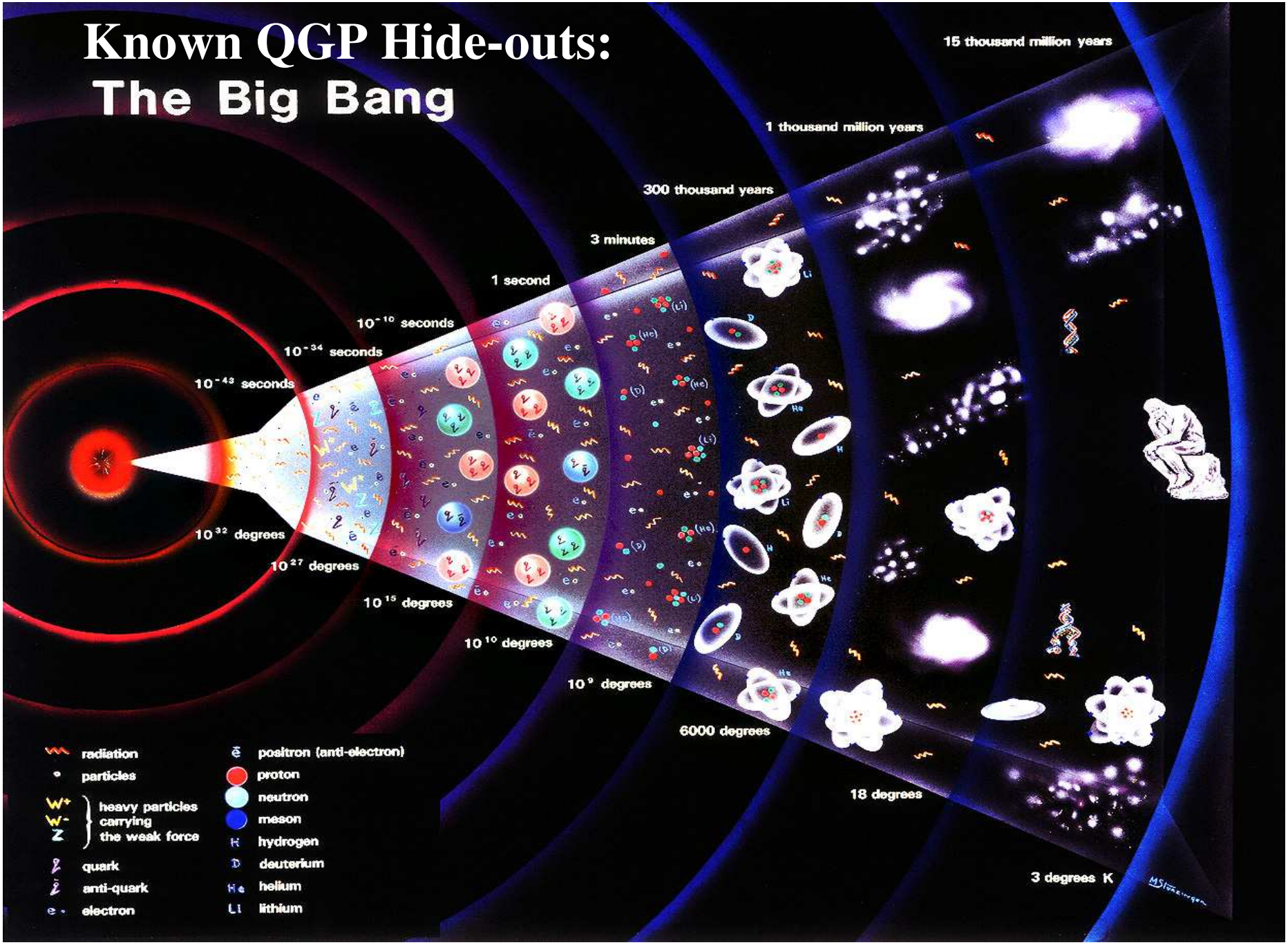


Phase Diagrams

Water

Nuclear Matter

Known QGP Hide-outs:
The Big Bang

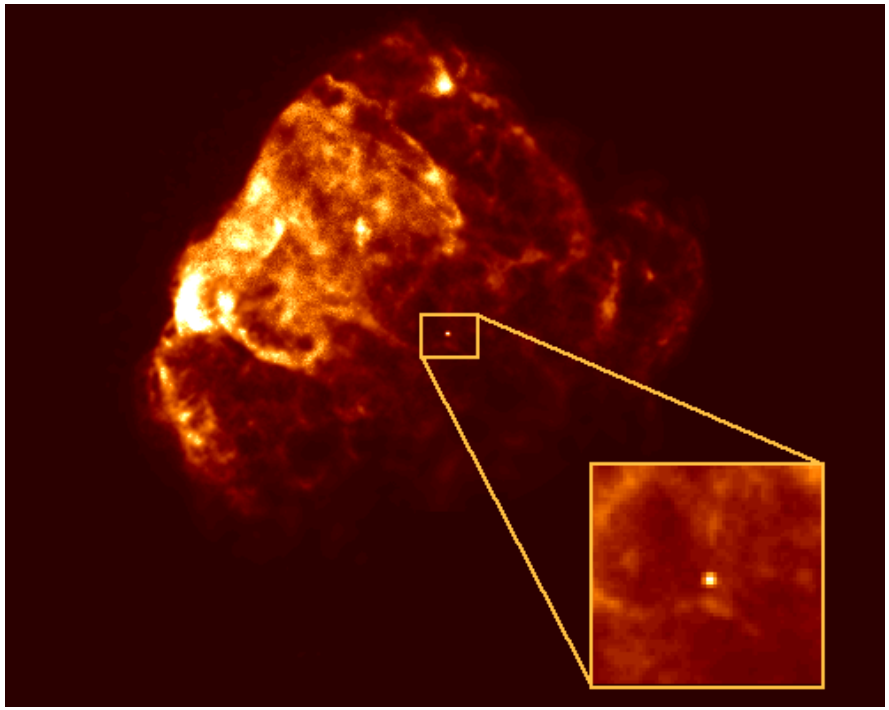


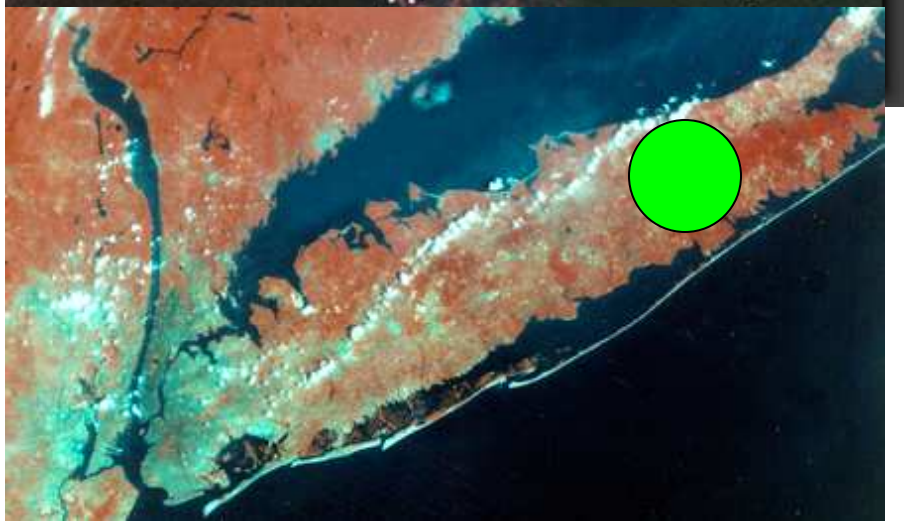

Formation of Hadrons


Formation of Hadrons
(detail)

Another Possible QGP Hide-Out:

The Center of Neutron Stars





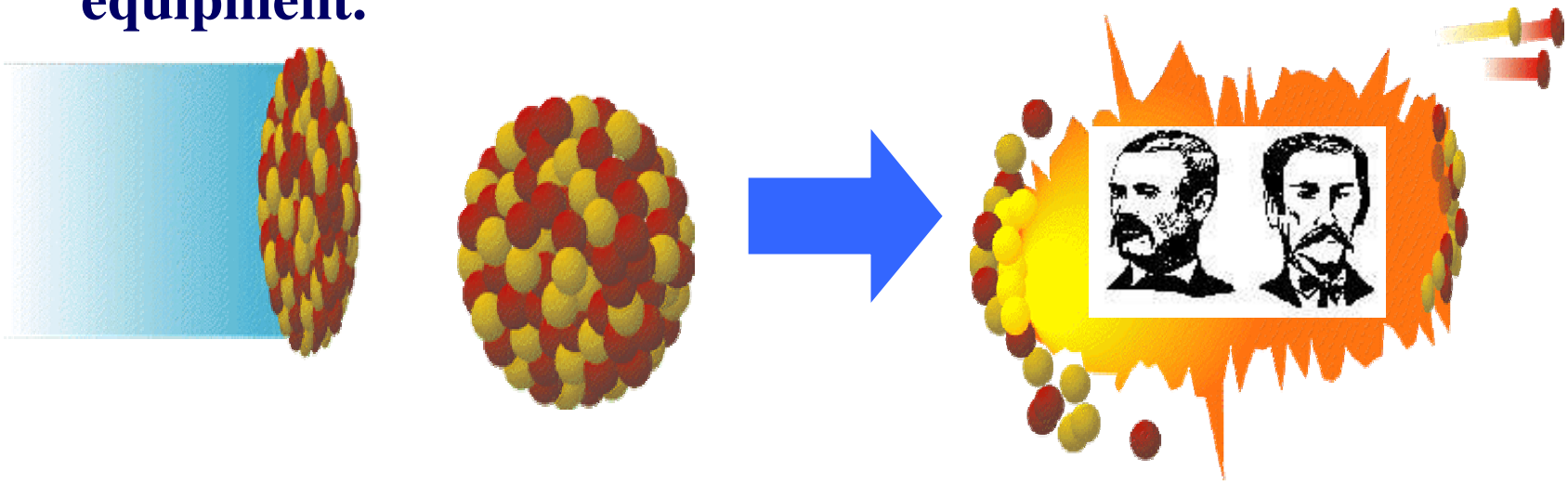
Neutron stars are the collapsed cores of a massive star.

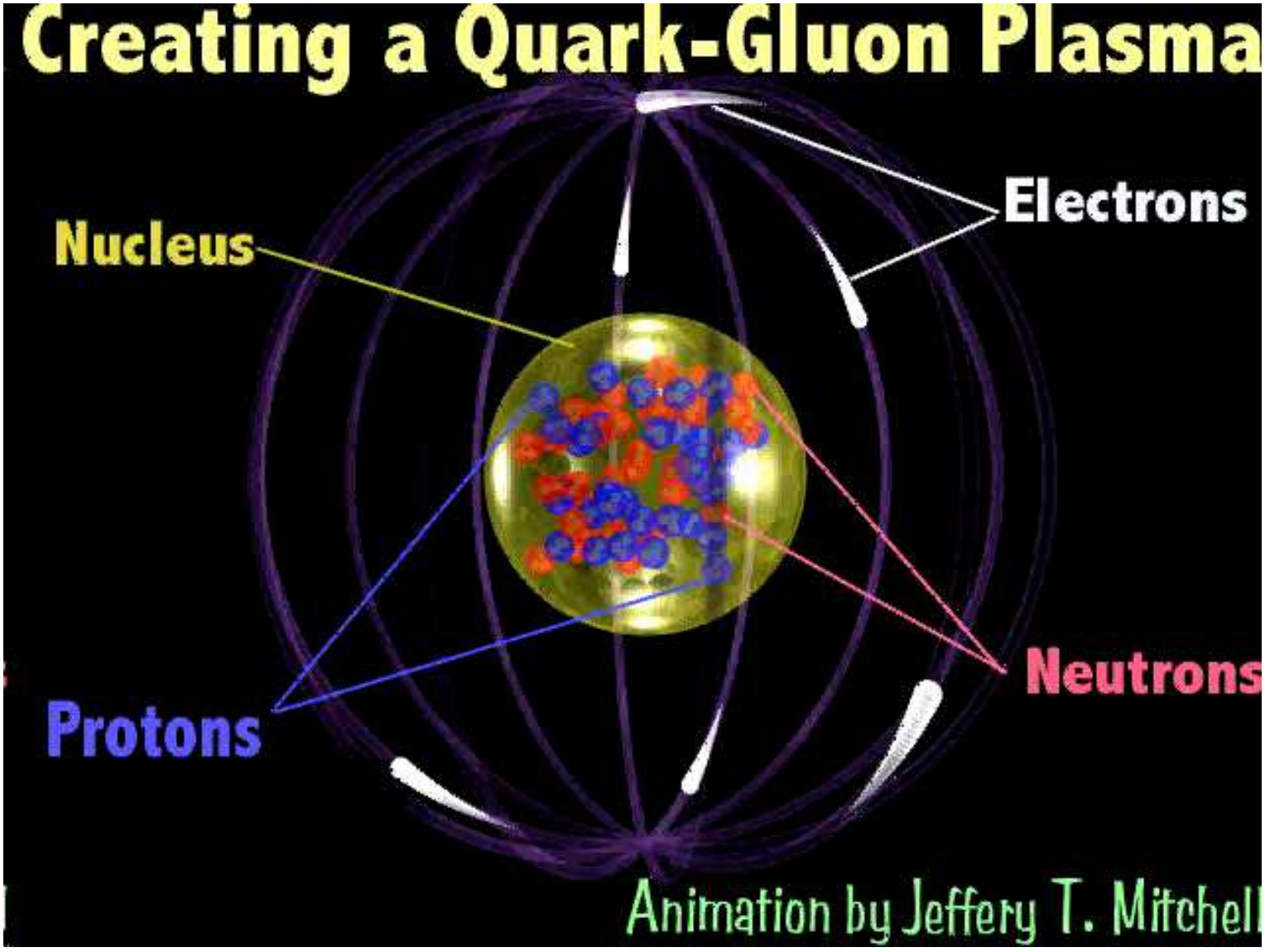
They pack the mass of the sun into the size of a city.

QGP Surveillance Technique

The Plan:

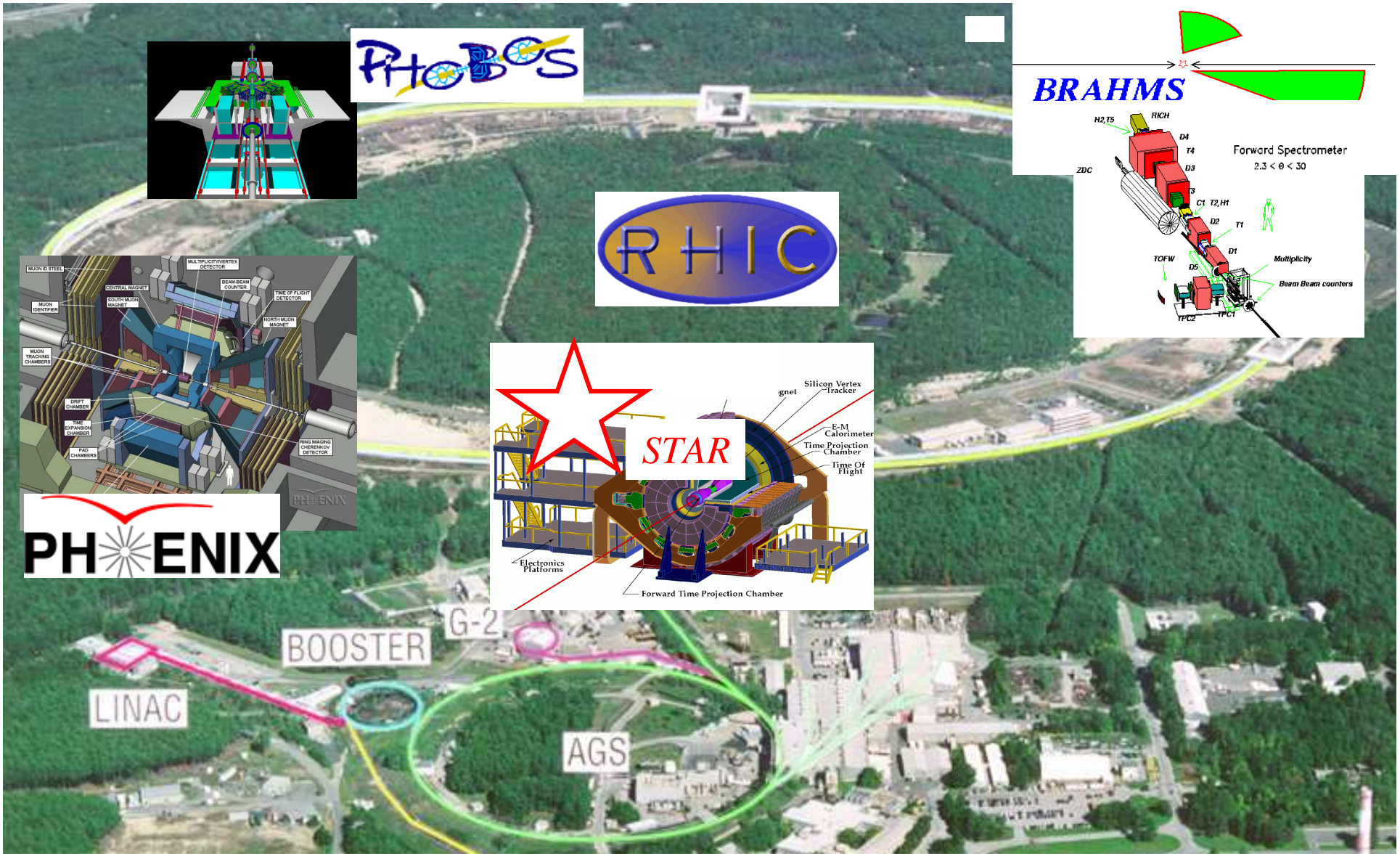
- **Take two of the heaviest nuclei we can get our hands on.**
- **Use a particle accelerator to accelerate them to relativistic speeds.**
- **Slam them together.**
- **Surround the collision point with "surveillance" equipment.**

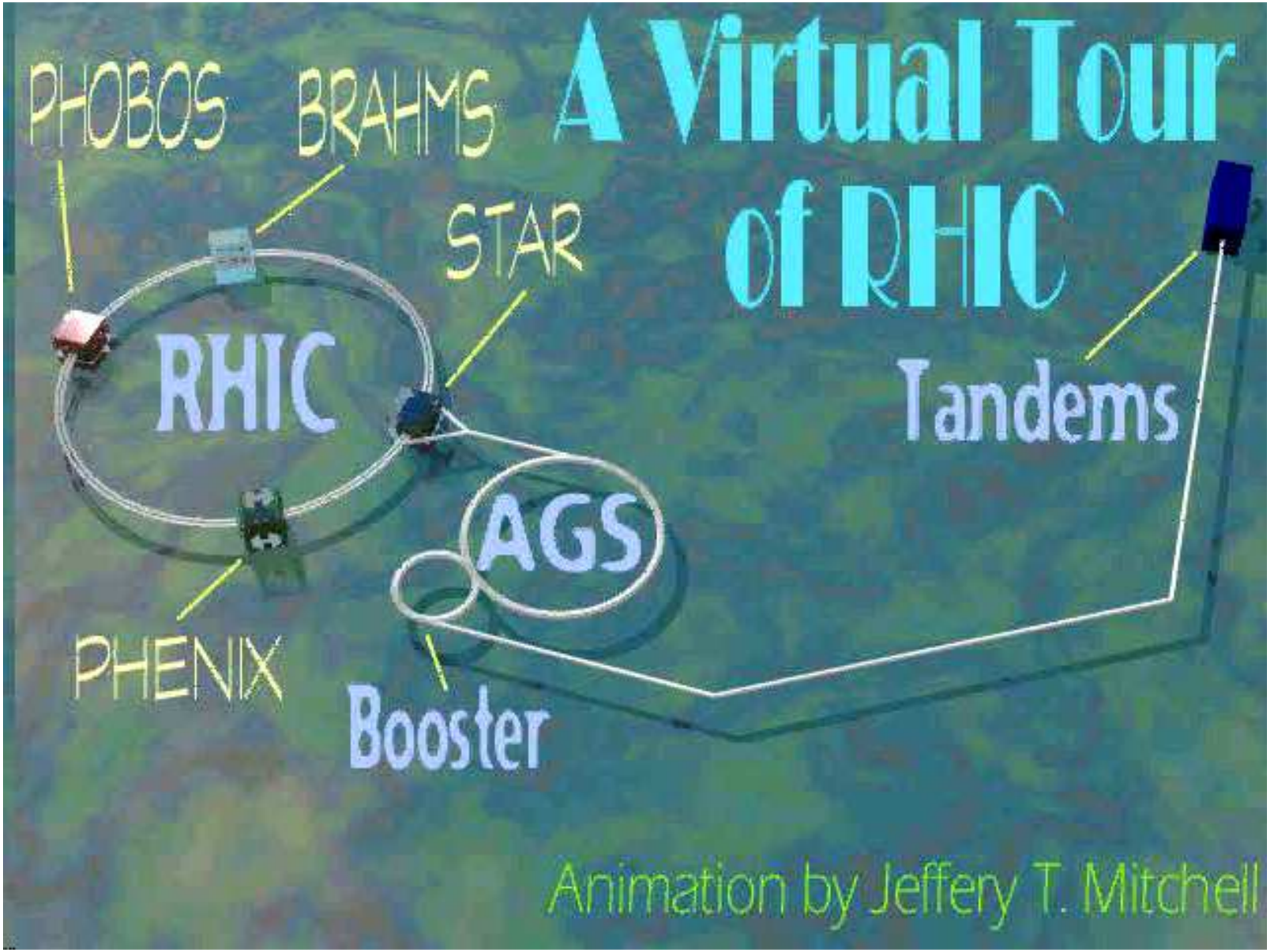



Creating a Quark-Gluon Plasma
Electrons
Nucleus
Neutrons
Protons
Animation by Jeffery T. Mitchell

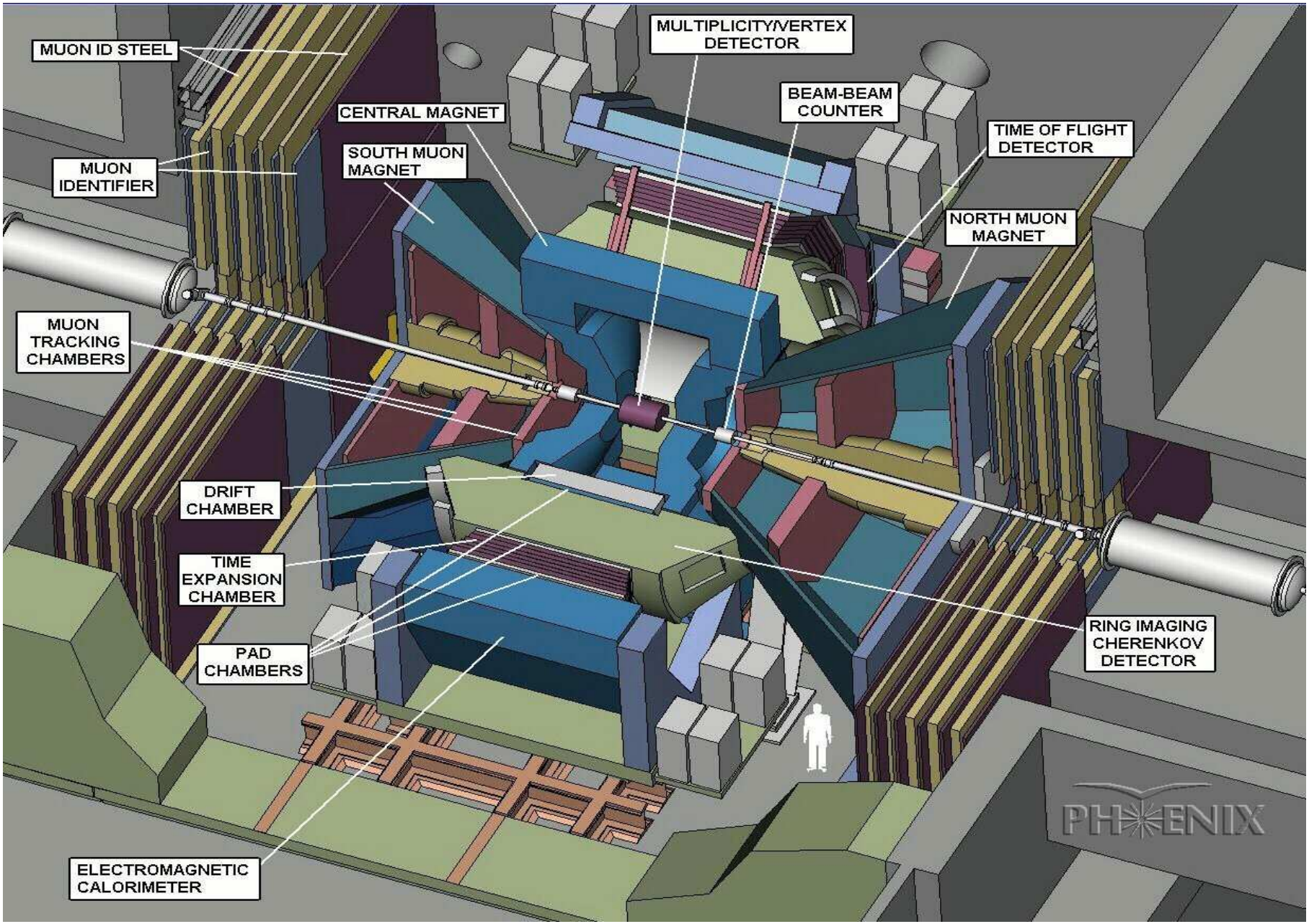
The QGP Hide-Out Complex

The Relativistic Heavy Ion Collider at BNL

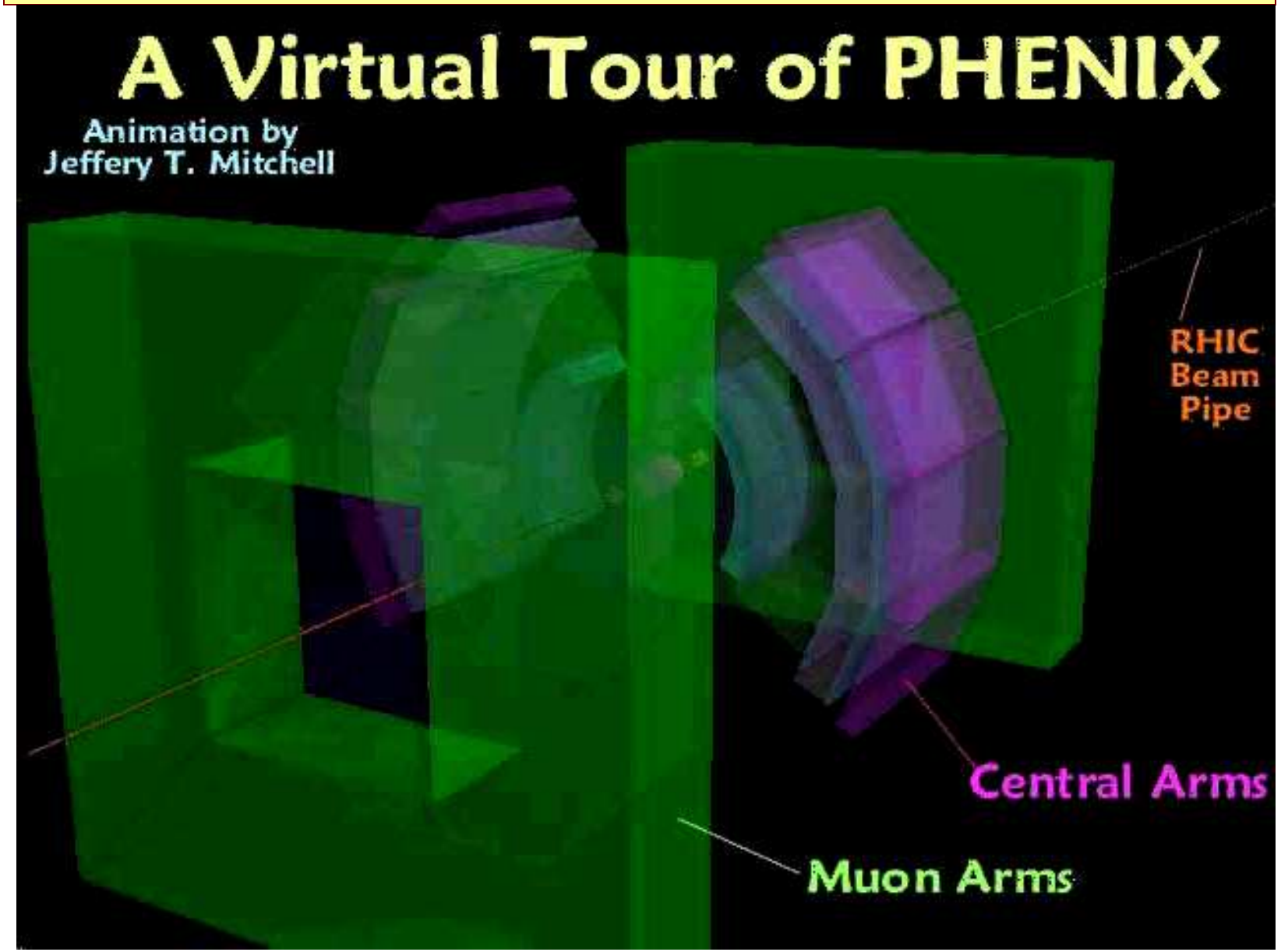



A Virtual Tour of RHIC
PHOBOS
BRAHMS
STAR
RHIC
Tandems
AGS
PHENIX
Booster
Animation by Jeffery T. Mitchell

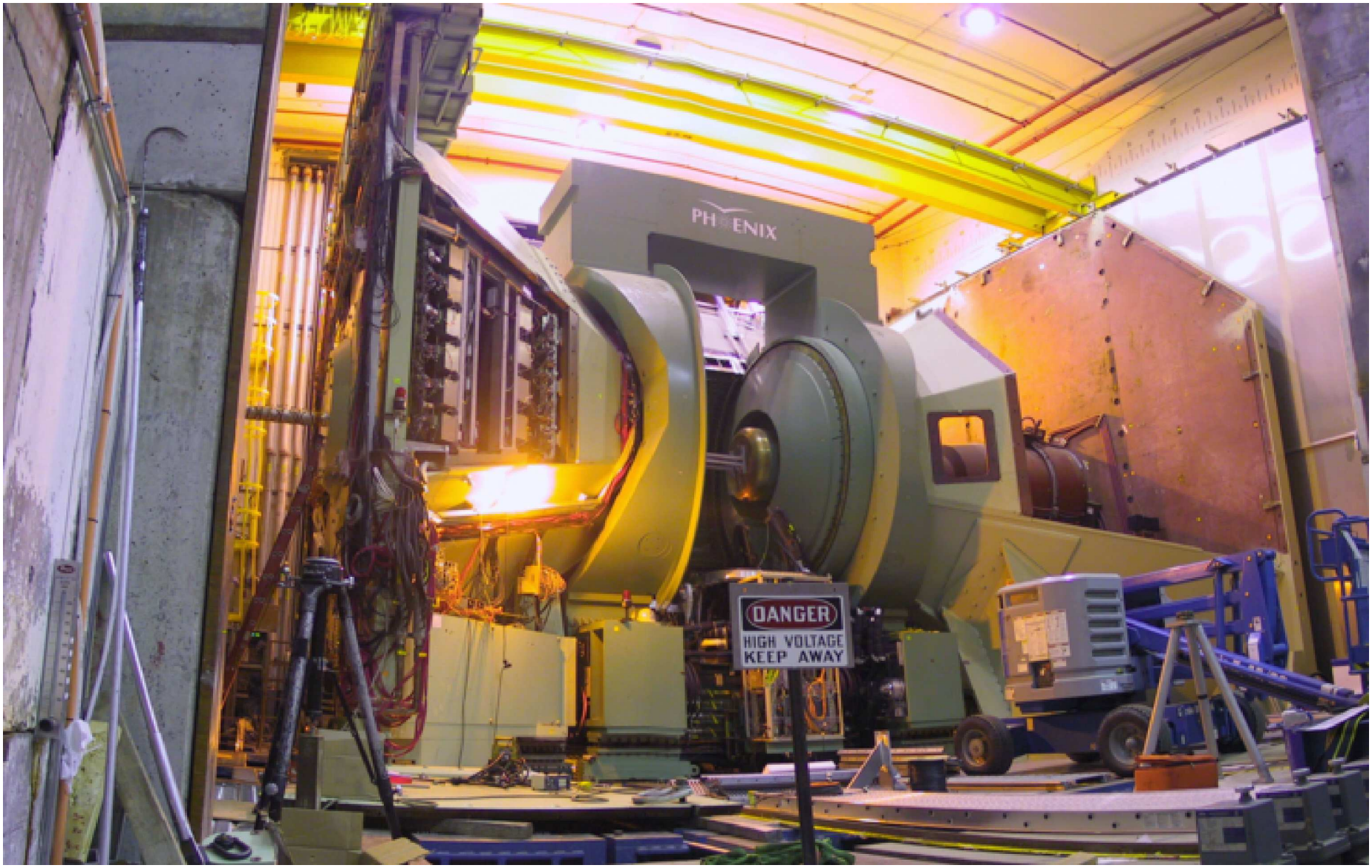
QGP Surveillance Equipment - Engineer's View



A Virtual Tour of PHENIX



QGP Surveillance Equipment

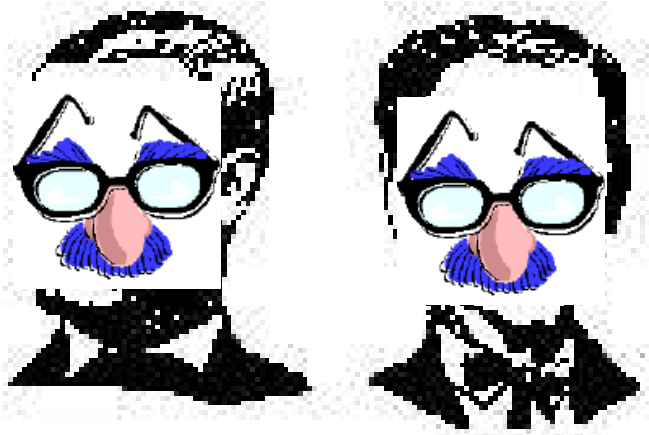


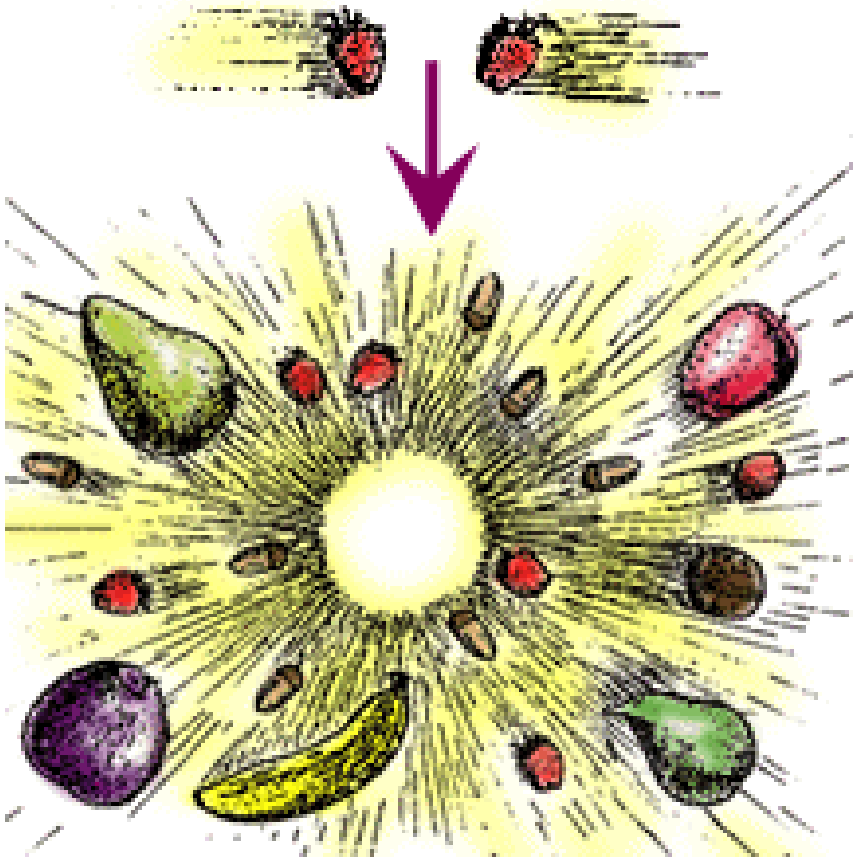
QGP Surveillance Teams

PHENIX

The Quark-Gluon Plasma

A Master of Disguise and Deception

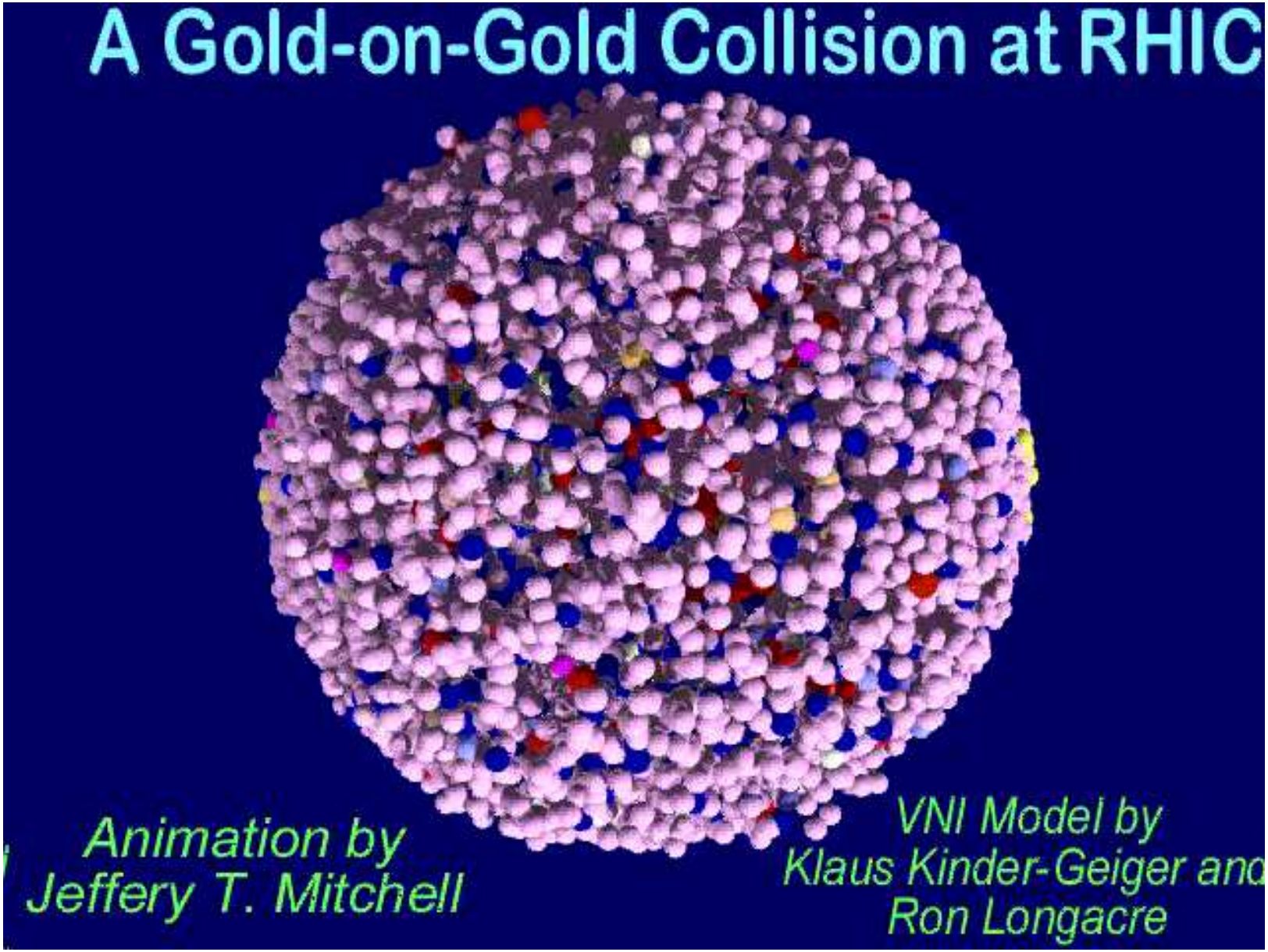


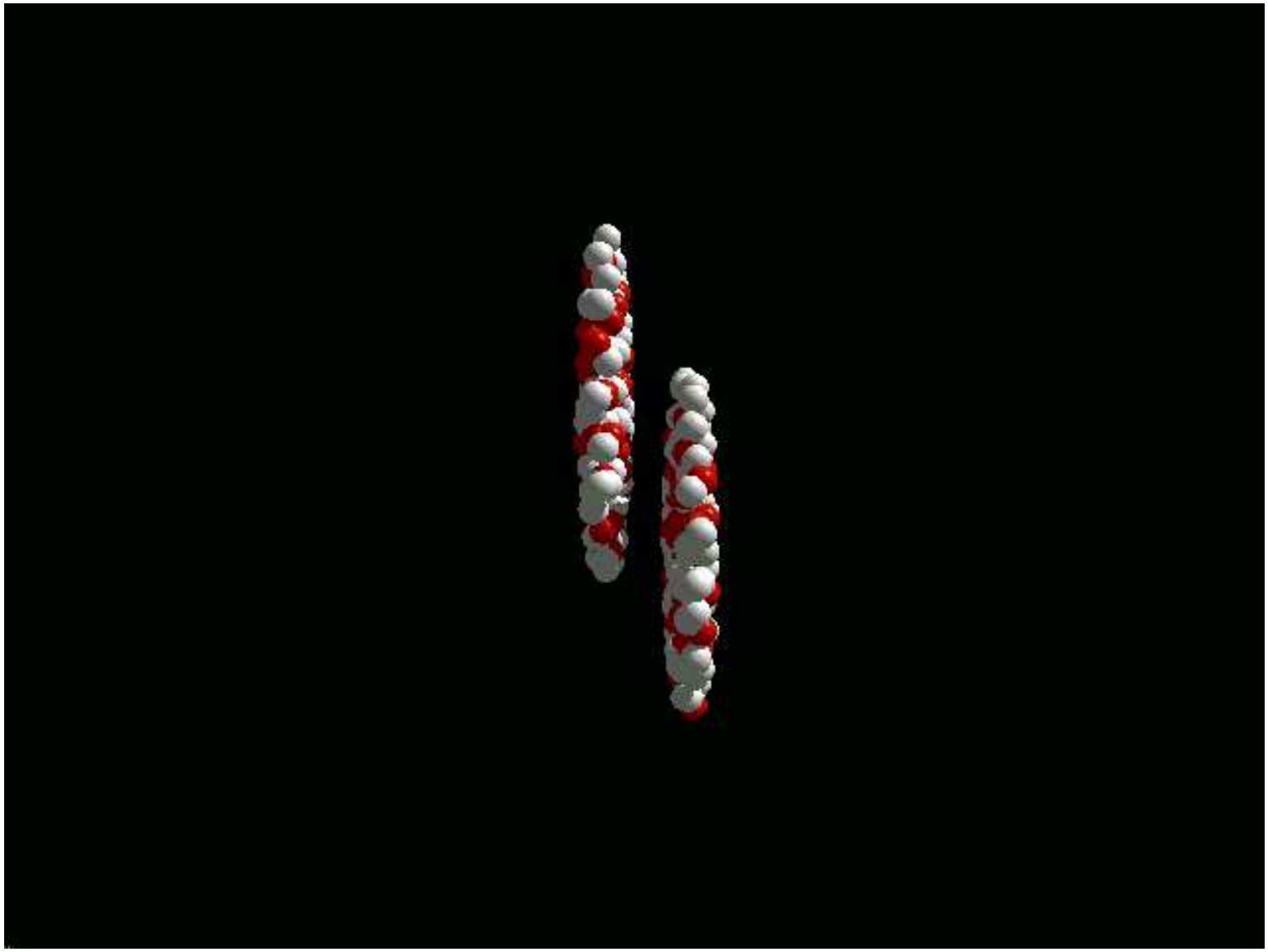


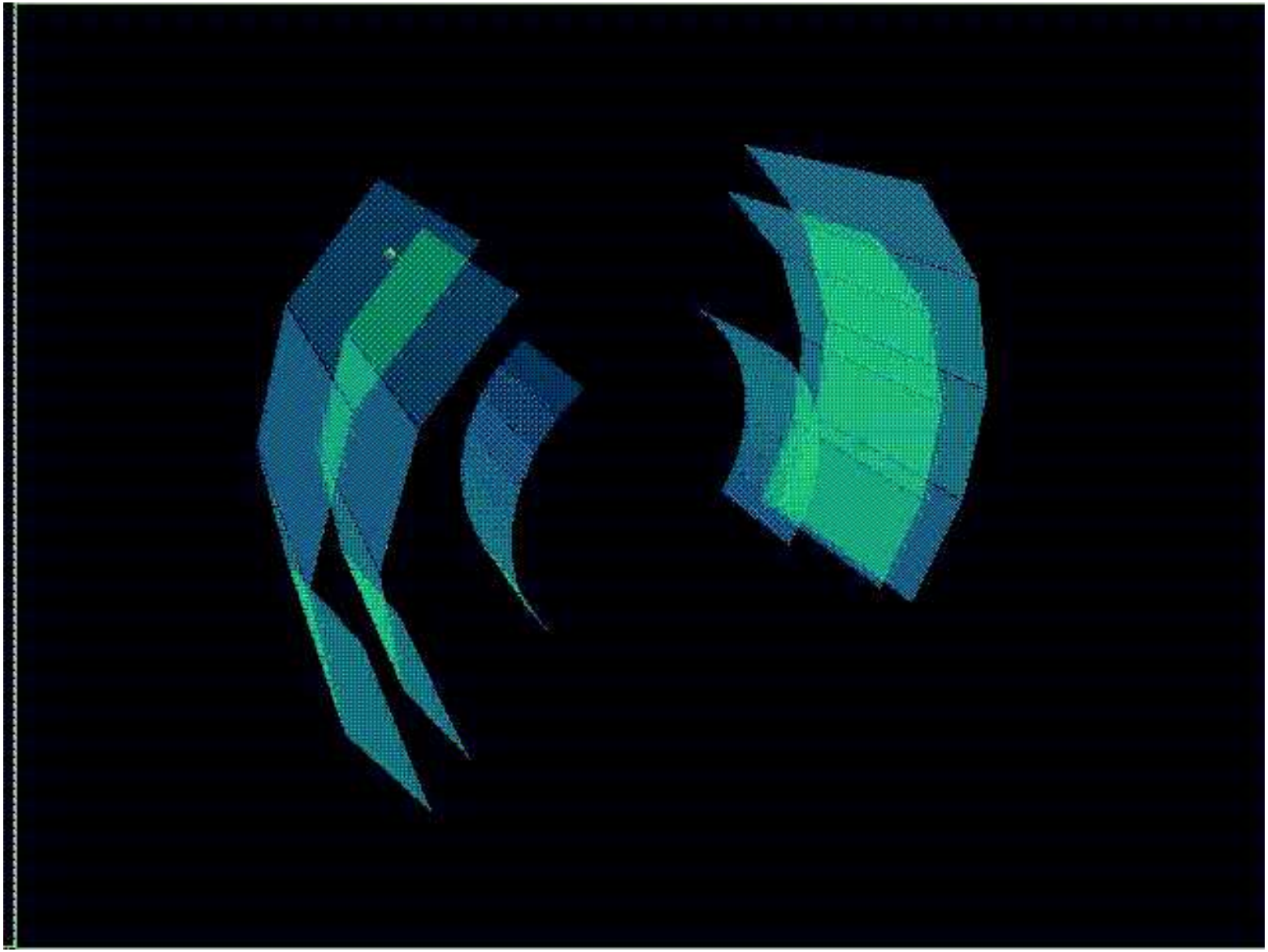
Special Relativity takes over!

$E=mc^2$

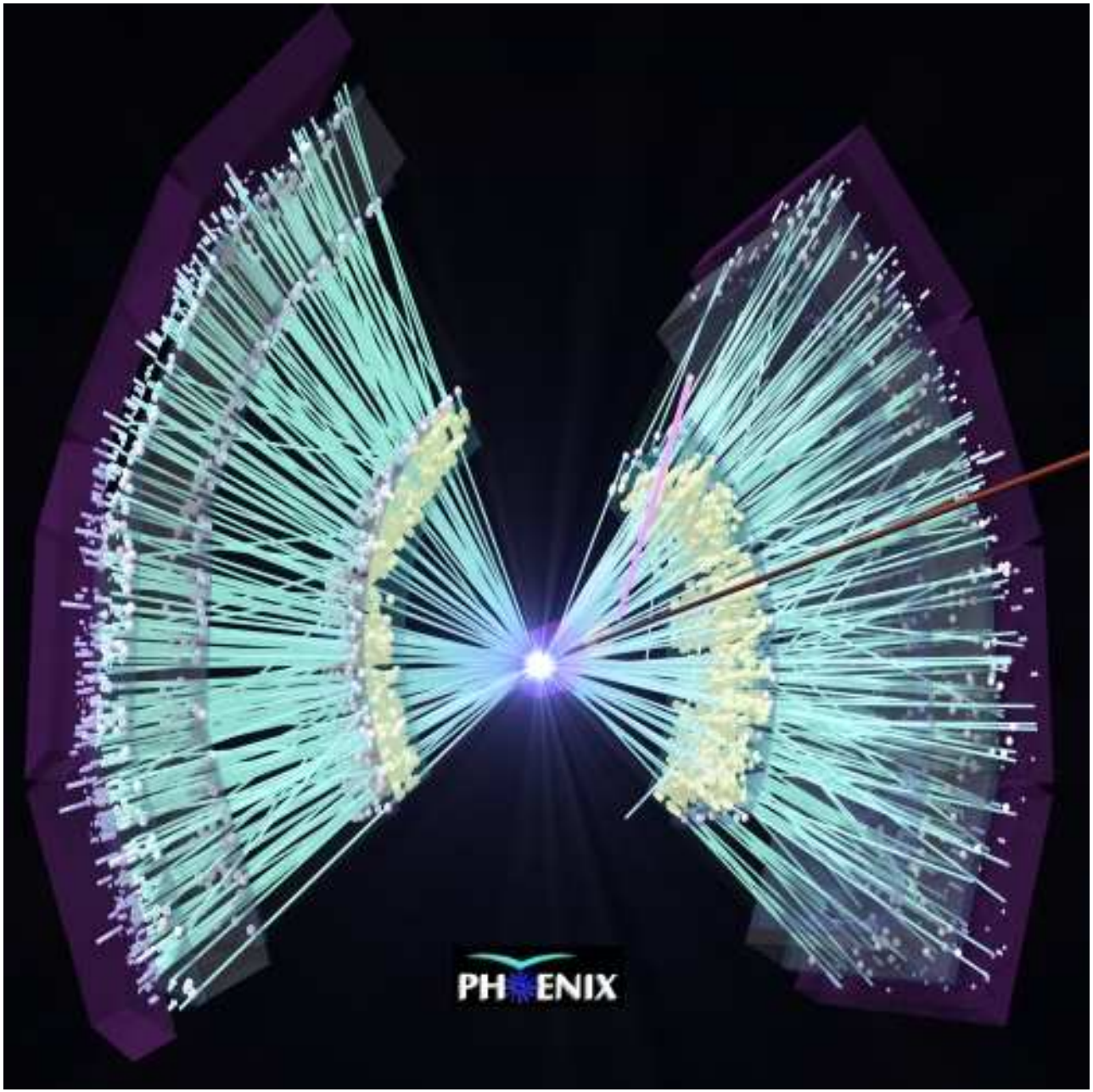
More than 5000 particles are produced


A Gold-on-Gold Collision at RHIC
Animation by
Jeffery T. Mitchell
VNI Model by
Klaus Kinder-Geiger and
Ron Longacre

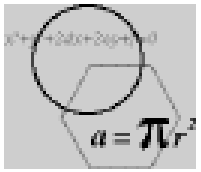




QGP Surveillance Photographs



Is the Hide-out the Correct Shape?
Collision Geometry



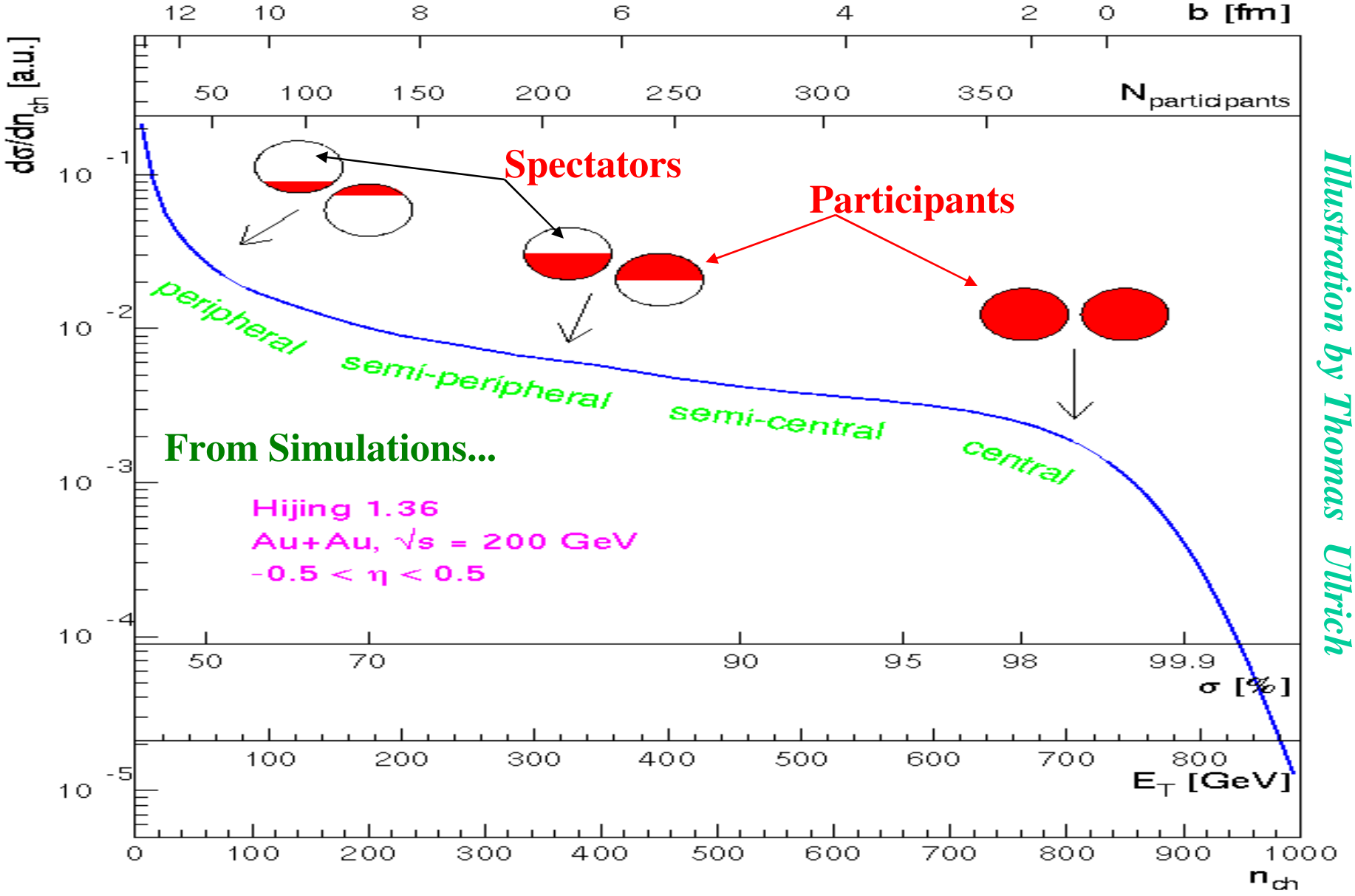
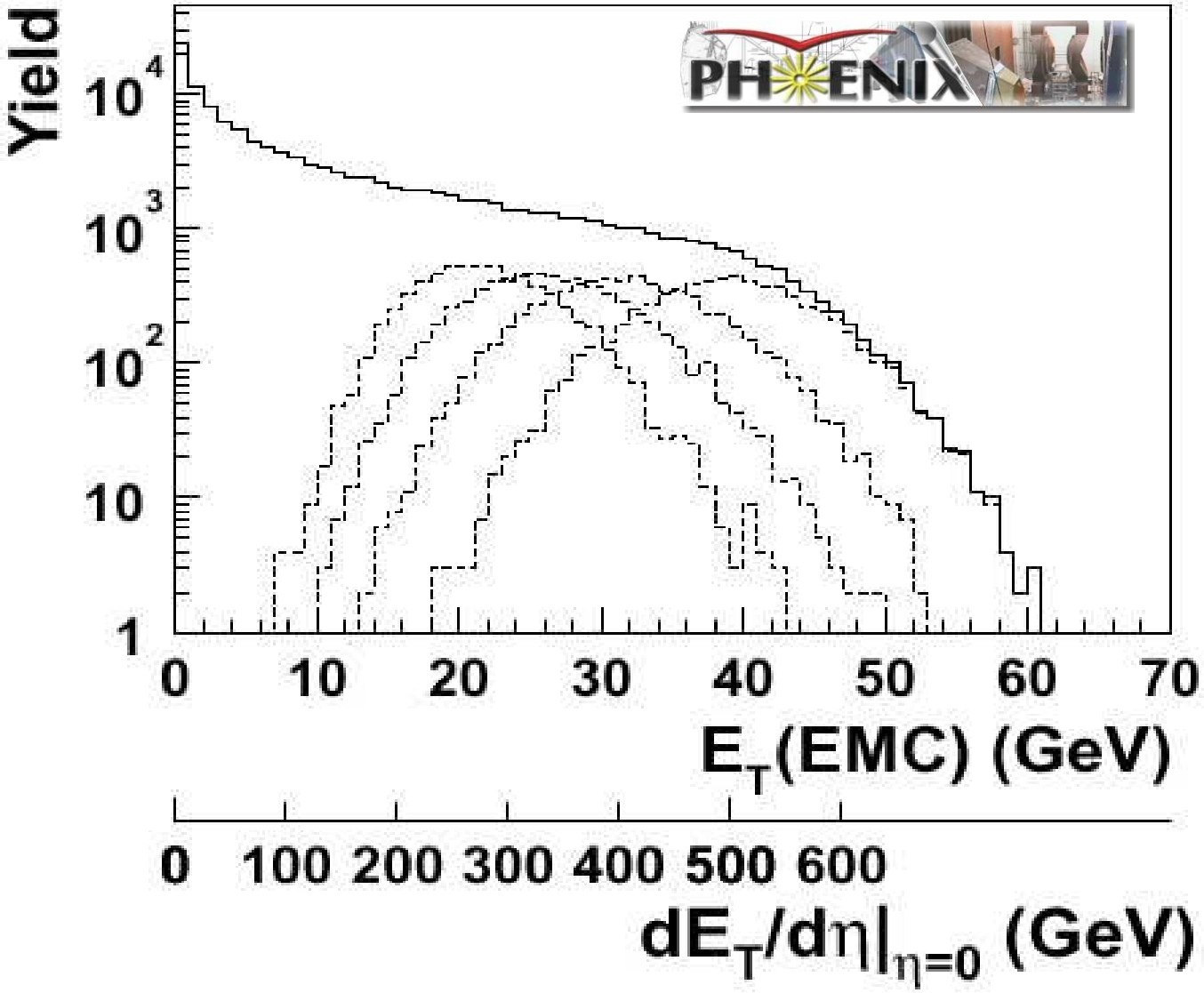
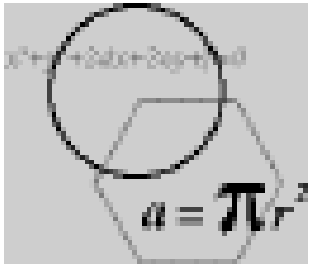


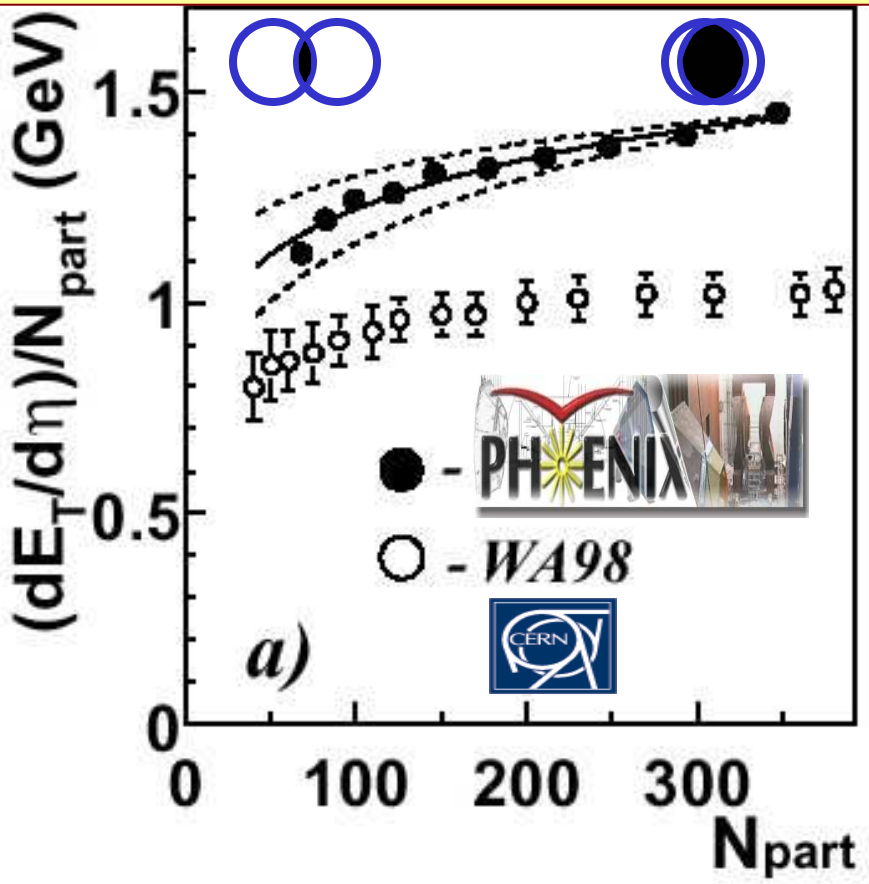
Illustration by Thomas Ullrich

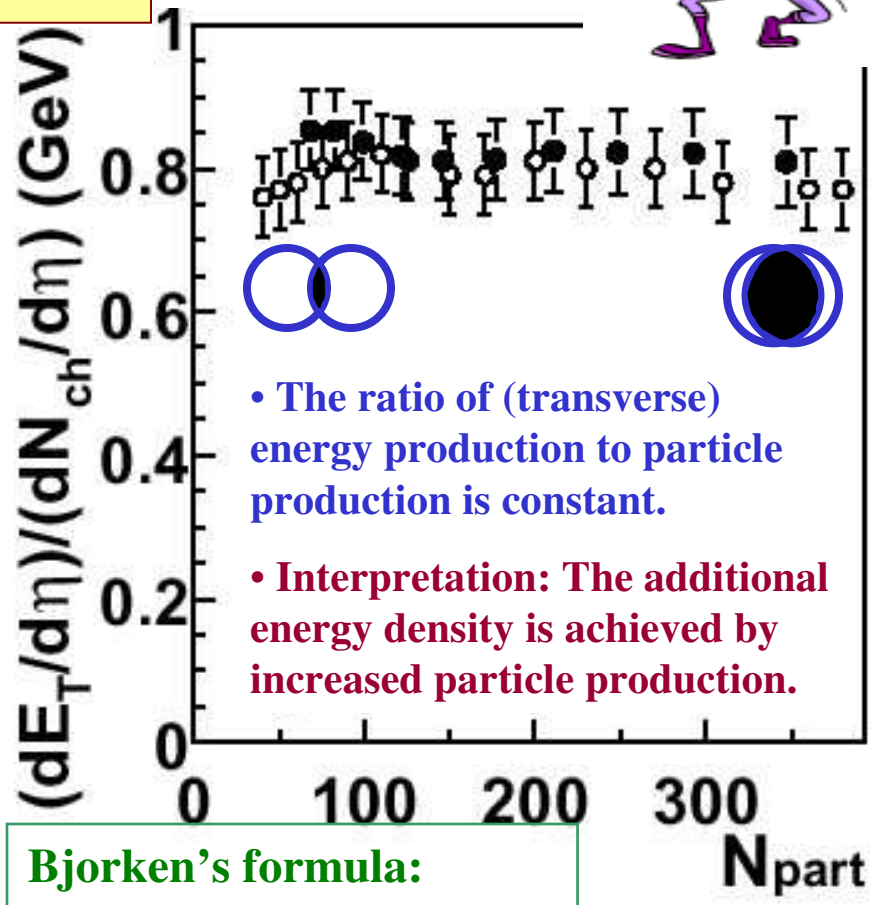
Is the hide-out the correct shape? Yes!





Is the Hide-out Violent Enough?
Energy Density



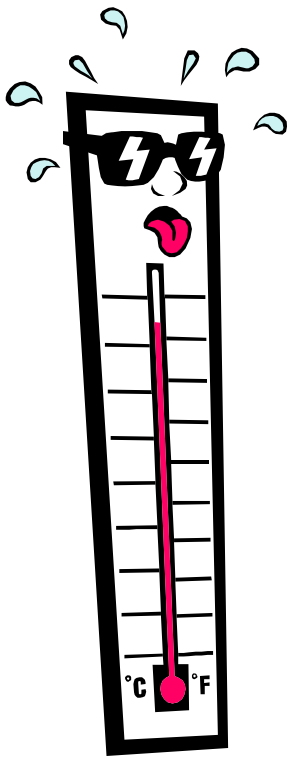


- The ratio of (transverse) energy production to particle production is constant.
- Interpretation: The additional energy density is achieved by increased particle production.

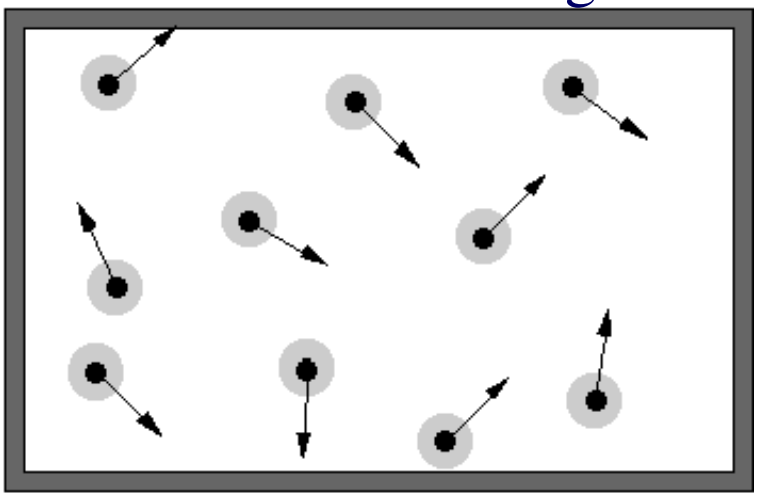
Bjorken's formula:
initial energy density
$\langle\varepsilon_0\rangle \sim 1/\pi R^2\tau_0\, dE_t/dy$

- Energy density = Energy per unit volume
- At CERN, the energy density produced is about 2.9 GeV/fm^3, or 18X normal nuclear matter!
- At RHIC, the energy density produced is about 5.3 GeV/fm^3, or 33X normal nuclear matter!

Is the hide-out hot enough? - Let's make a thermometer!



Let's assume that the center of the collision acts like a gas...

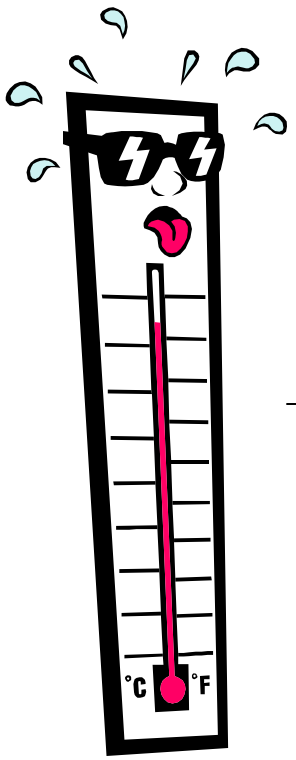


If the system is thermalized, the velocity distribution of the molecules is described by a Maxwell-Boltzmann distribution:

$$f(v)dv = 4\pi\left(\frac{m}{2k_BT}\right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2k_BT}\right)dv$$

Temperature

Is the hide-out hot enough? - Let's make a thermometer!



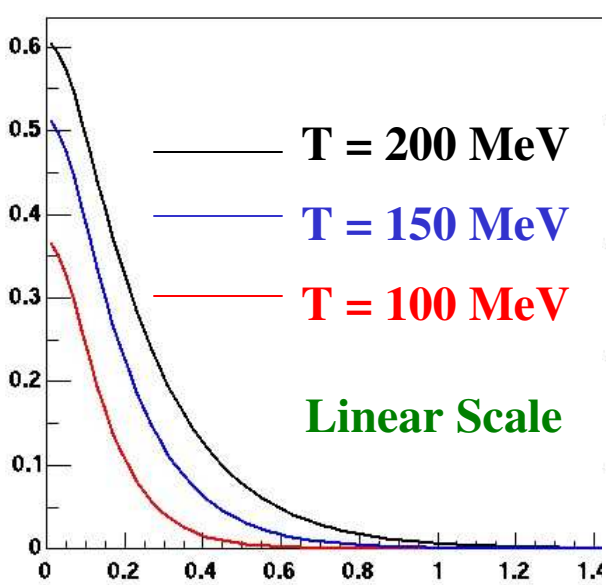
To *simplify* the data analysis, modify the Maxwell-Boltzmann equation to be expressed in a variable called transverse mass.

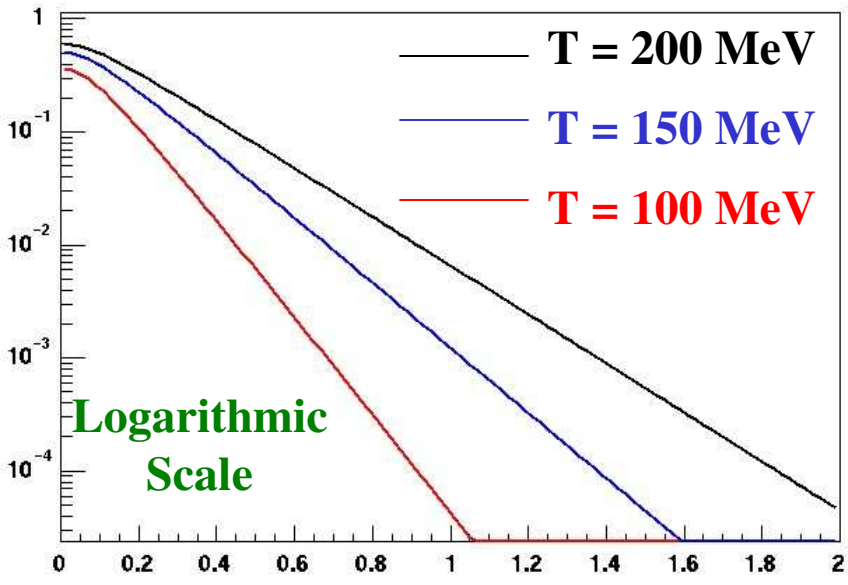
$$m_t = \sqrt{m_0^2 + p_t^2}$$

$$\frac{1}{p_t}\frac{dN}{dp_t} = \frac{1}{m_t}\frac{dN}{dm_t}$$

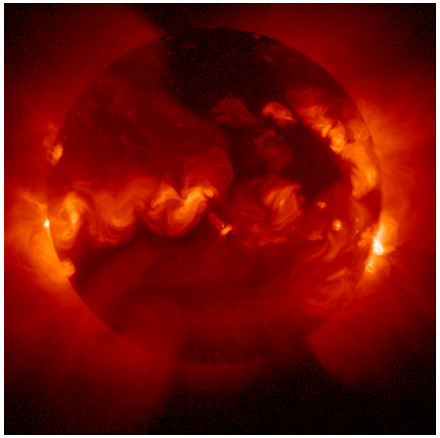
The distribution becomes exponential in the transverse mass.

$$\frac{1}{m_t}\frac{dN}{dm_t} \propto e^{-\frac{m_t}{T}}$$

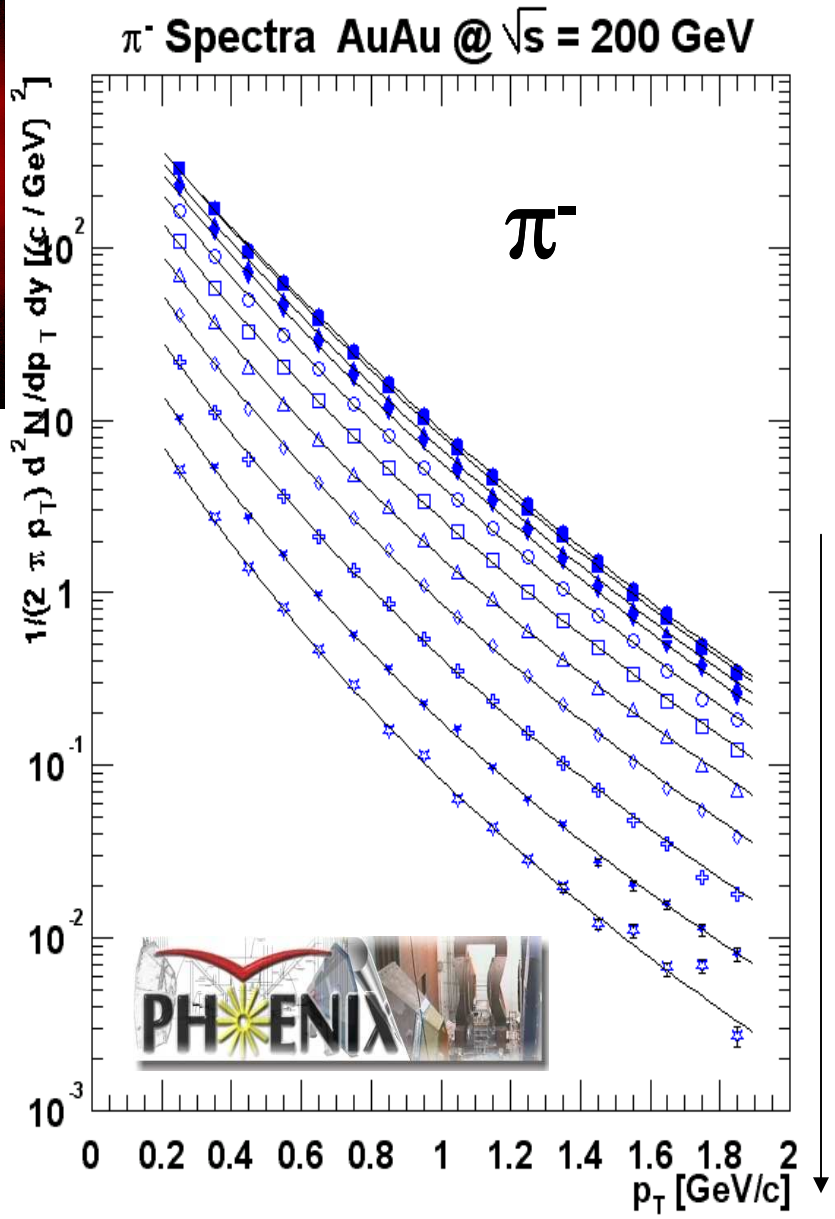




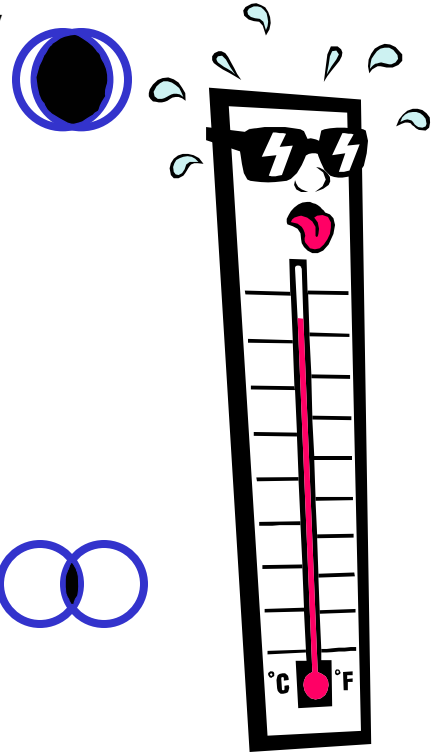
Is the hide-out hot enough? - Transverse Momentum Spectra



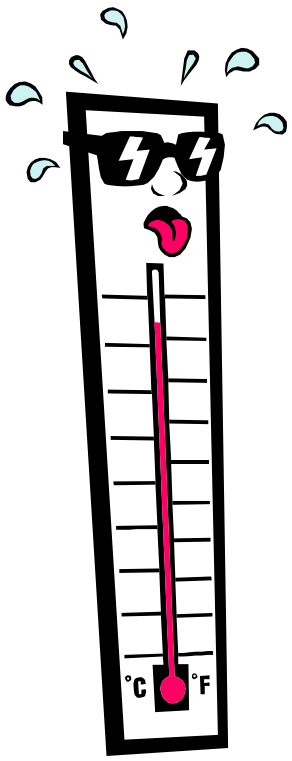
The hideout is 100,000 times the temperature at the center of the sun!



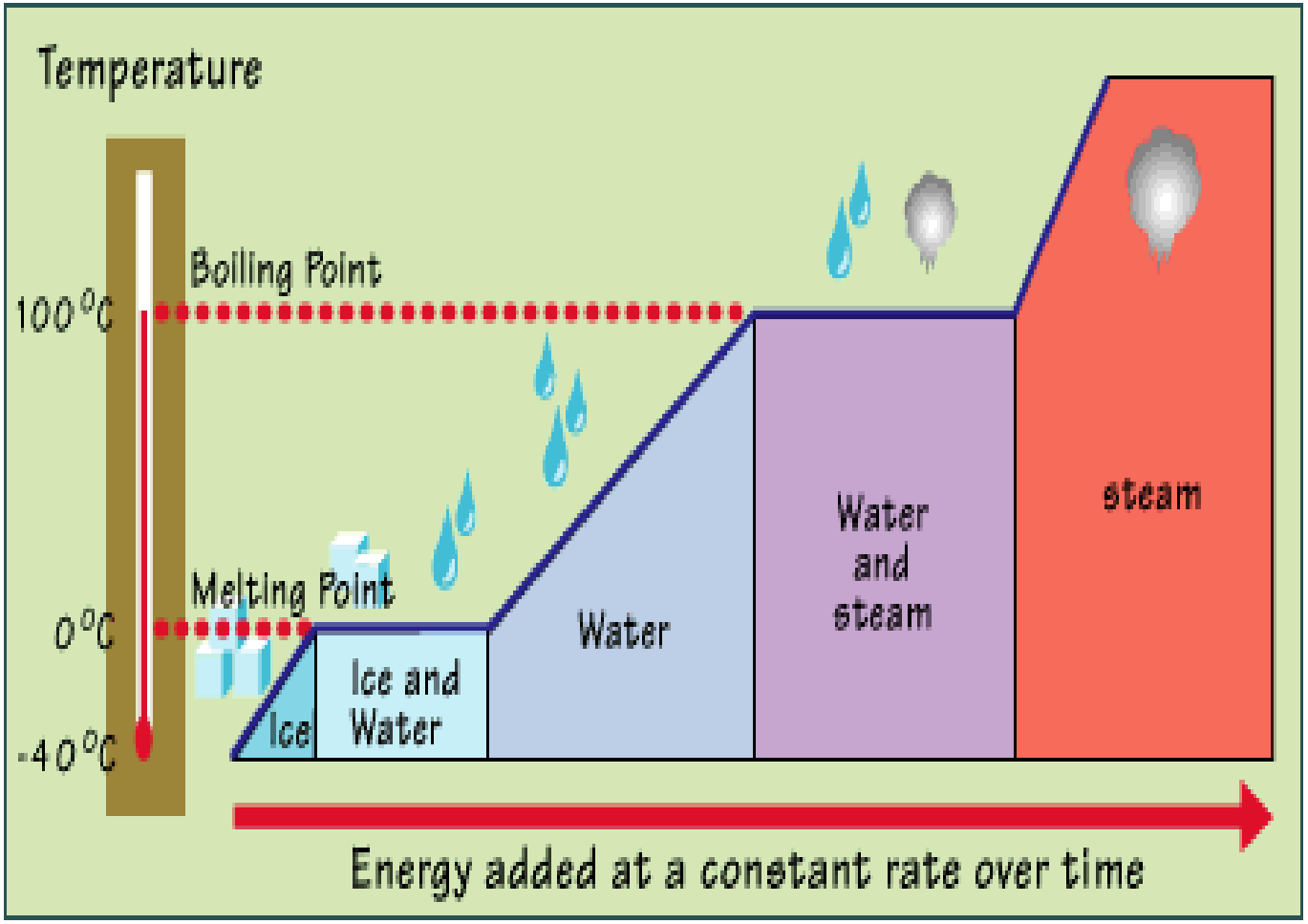
centrality
0 - 5 %
5 - 10 %
10 - 15 %
15 - 20 %
20 - 30 %
30 - 40 %
40 - 50 %
50 - 60 %
60 - 70 %
70 - 80 %
80 - 91 %



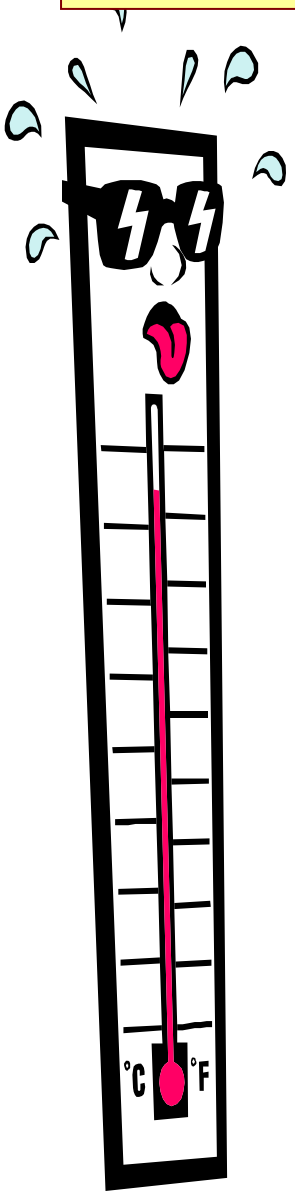
Is the hide-out hot enough? - Temperature in a Phase Transition



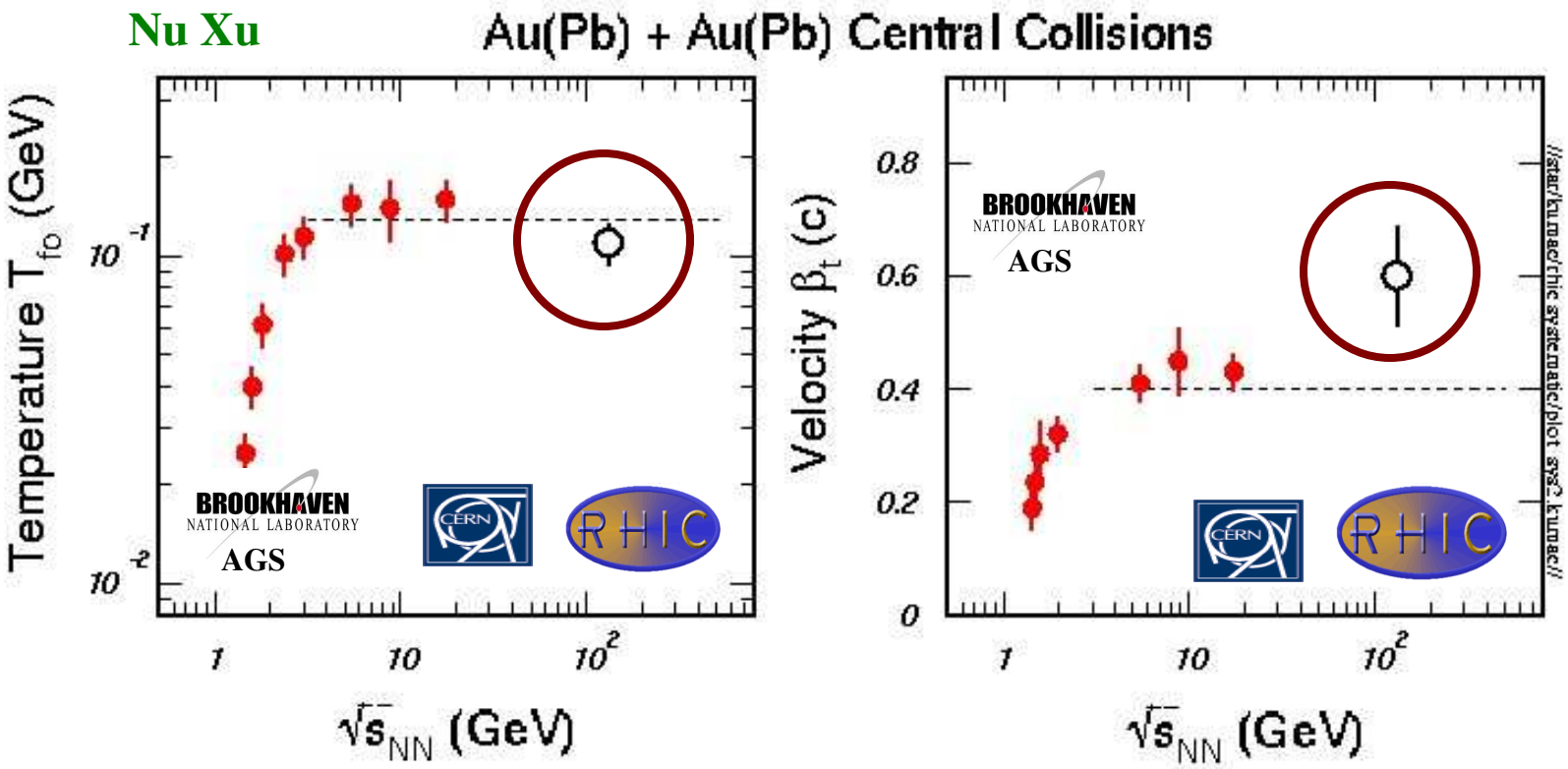
Heating Curve for Water



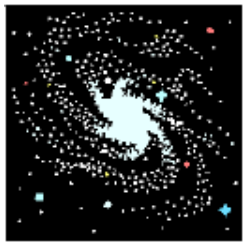
Is the RHIC hide-out hotter than previous hideouts?

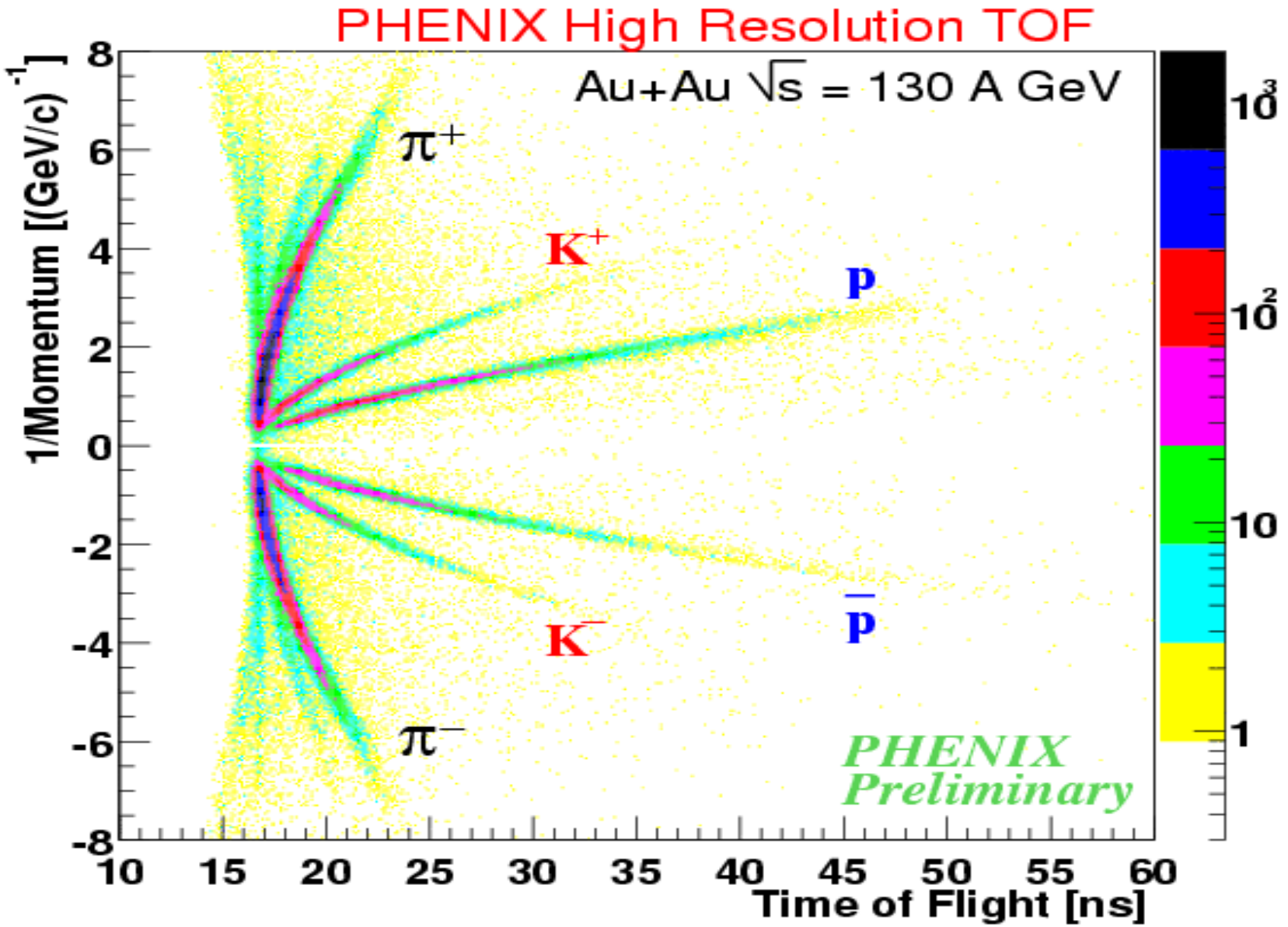


Compiled by
Nu Xu



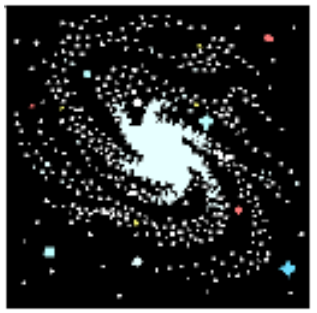
Particle Recognition





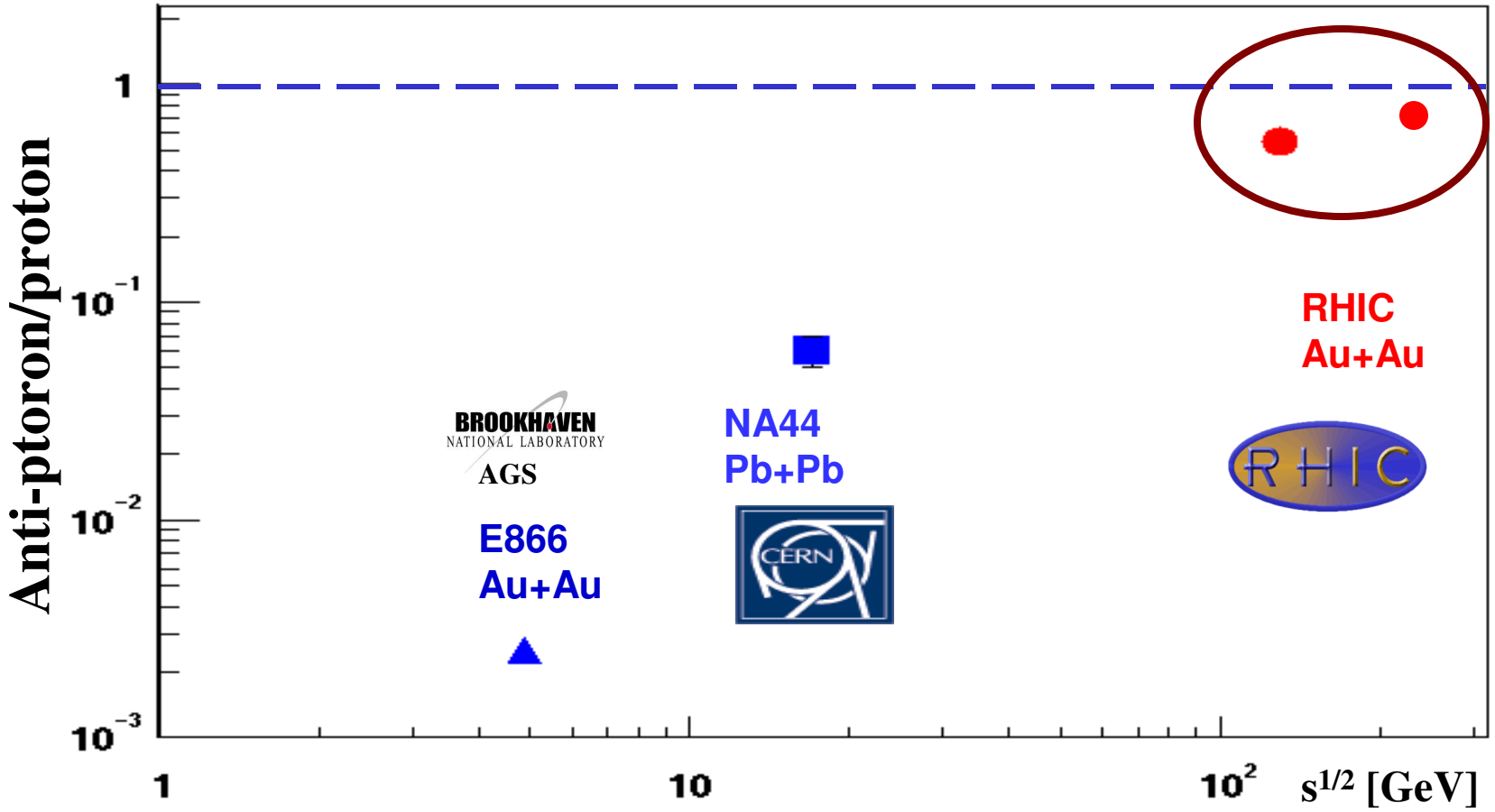
Is the hide-out disguised as the early universe?

Almost...

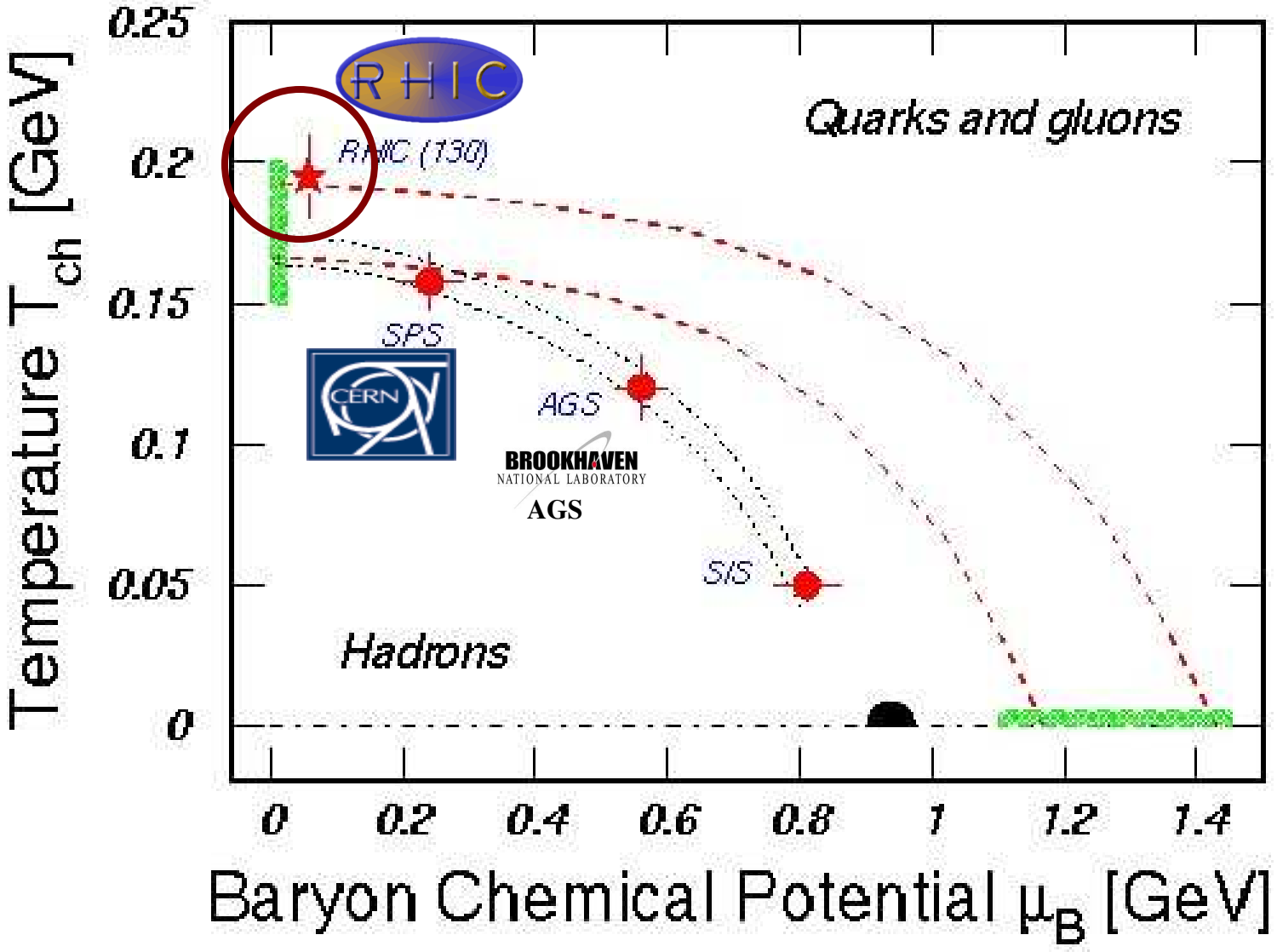


In the Early Universe, the

Anti-proton/proton = 0.999999999

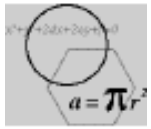
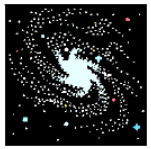


Speculation about the status of the hide-out



RHIC's First Results: Review So Far

Data Analysis Questions *(some of them):*

- **Hideout Characteristics:**
  - **Correct Shape?** 
  - **Violent Enough?** 
  - **Hot Enough?** 
  - **Early-Universe Like?** 
  - **Fluid Enough?** 
  - **Strange Enough?** 
- **Have we caught a glimpse of the QGP?** 

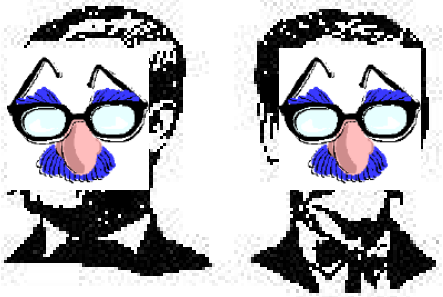
- **HOW DOES RHIC COMPARE TO PREVIOUS ATTEMPTS TO CATCH THE ELUSIVE QGP?**

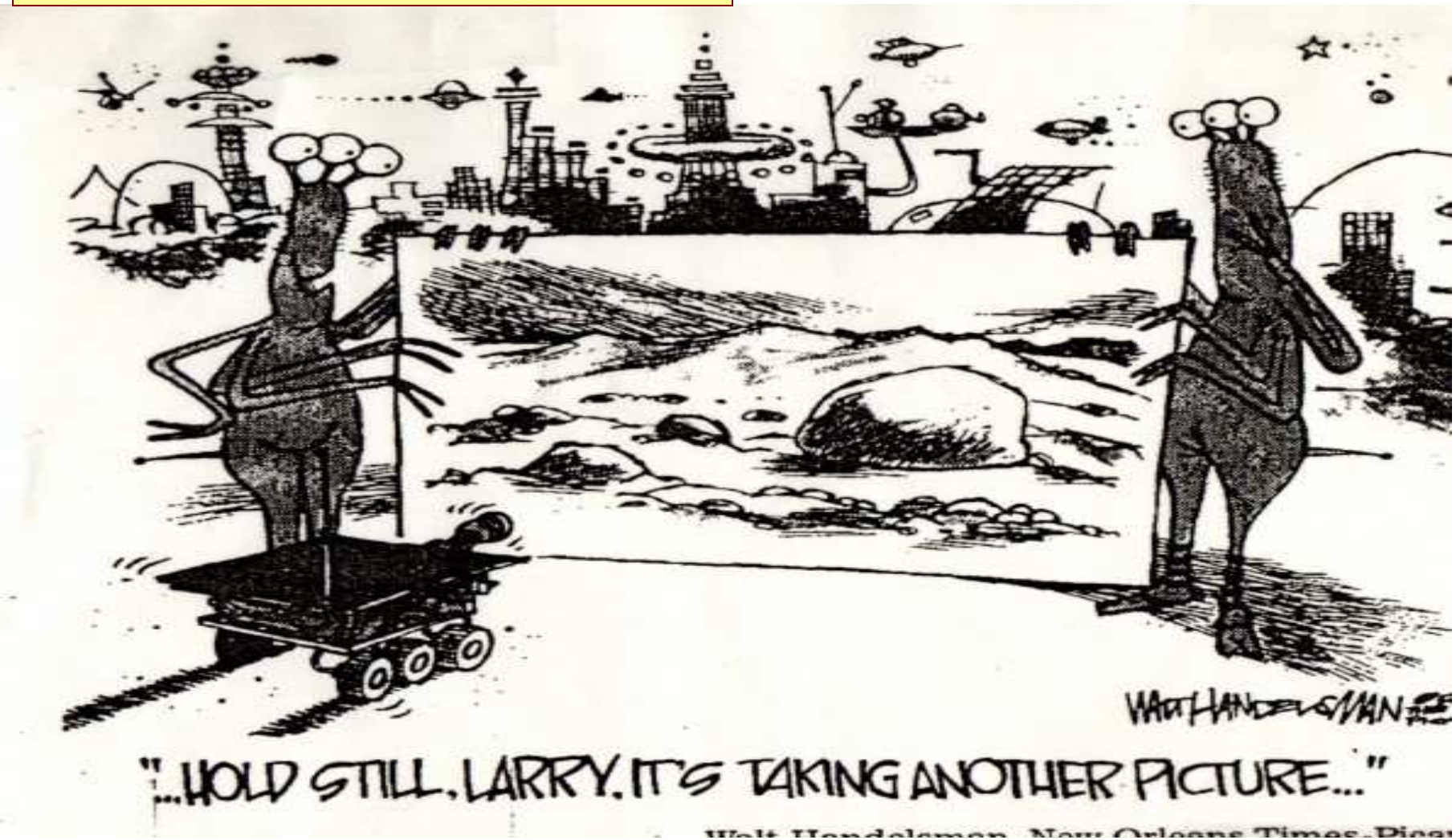
More violent, just as hot, more like the early universe, more fluid, and stranger!

The Quark-Gluon Plasma

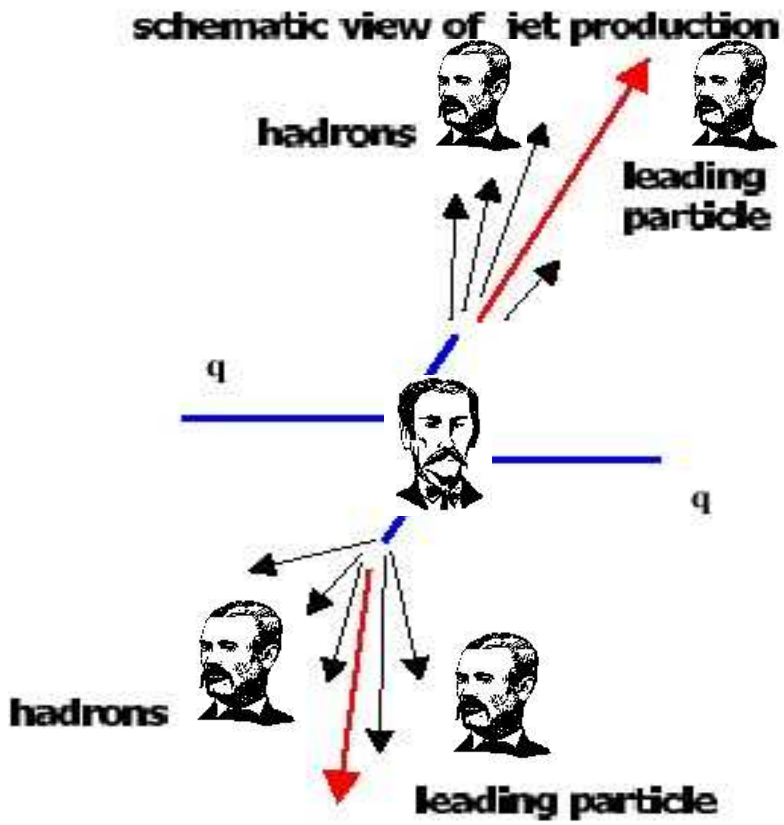
A Master of Disguise and Deception

Can we penetrate the disguise?





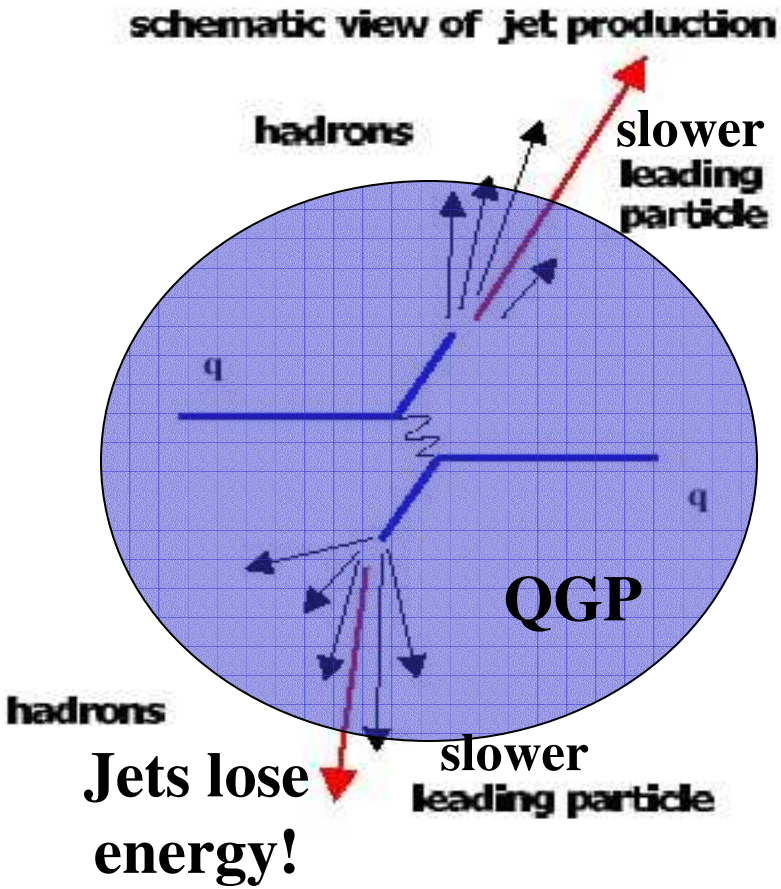
Have we caught a glimpse of the QGP? - Jets



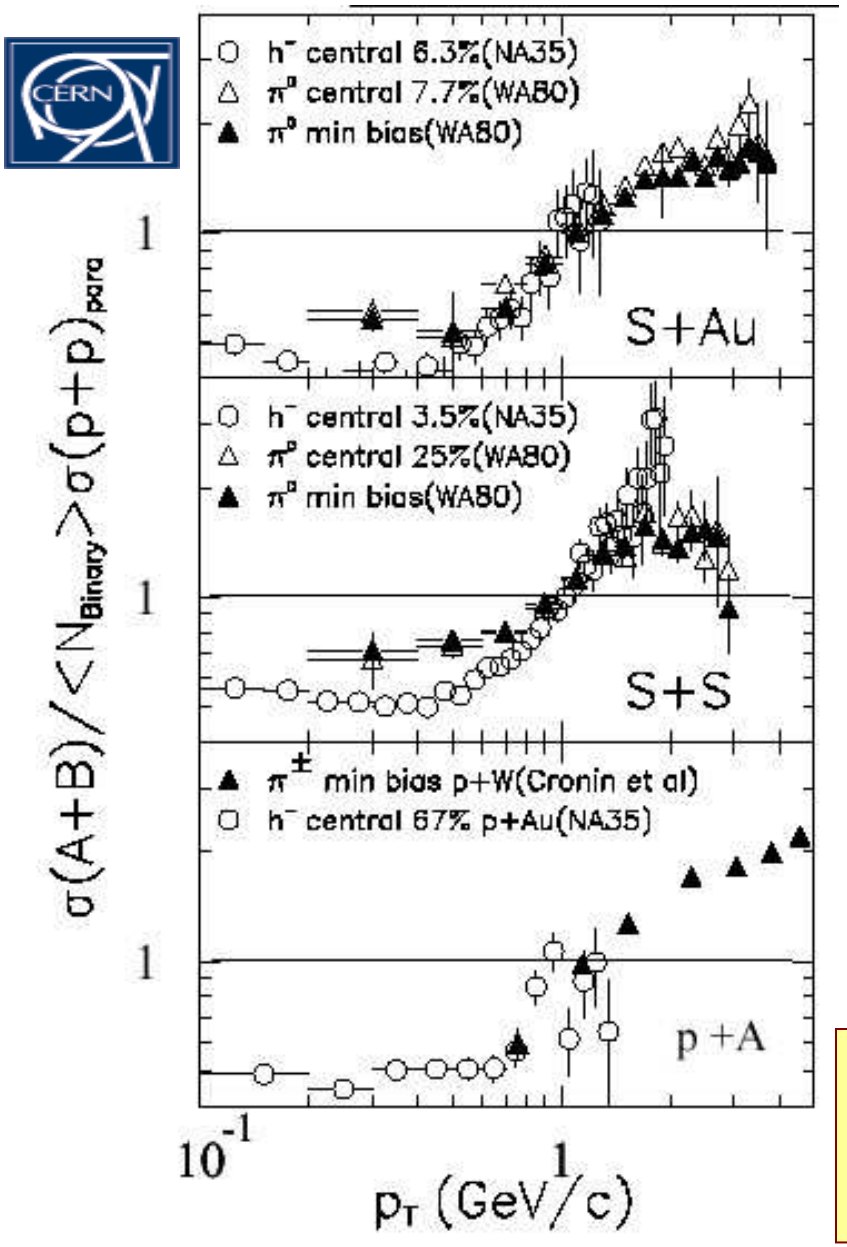
Outside of a QGP

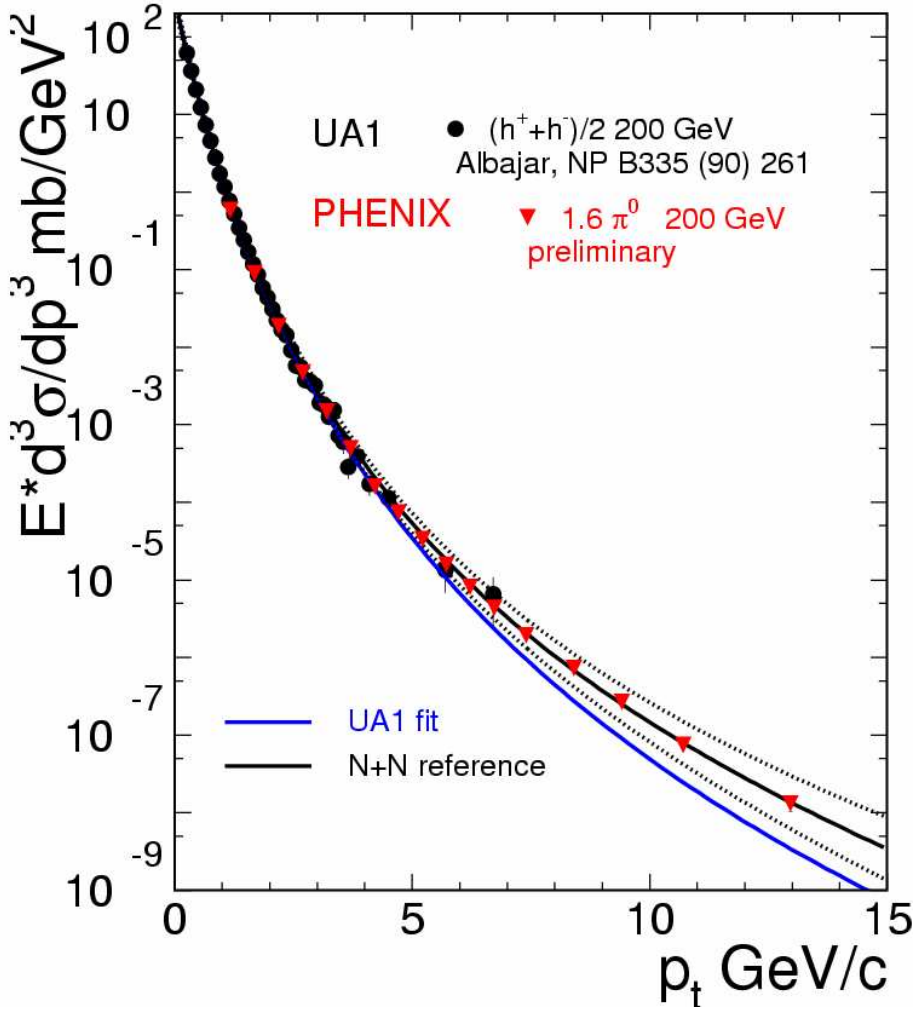
Strategy: Set a trap in the hide-out to slow down escaping jets

Inside a QGP



Have we caught a glimpse of the QGP? - Jets

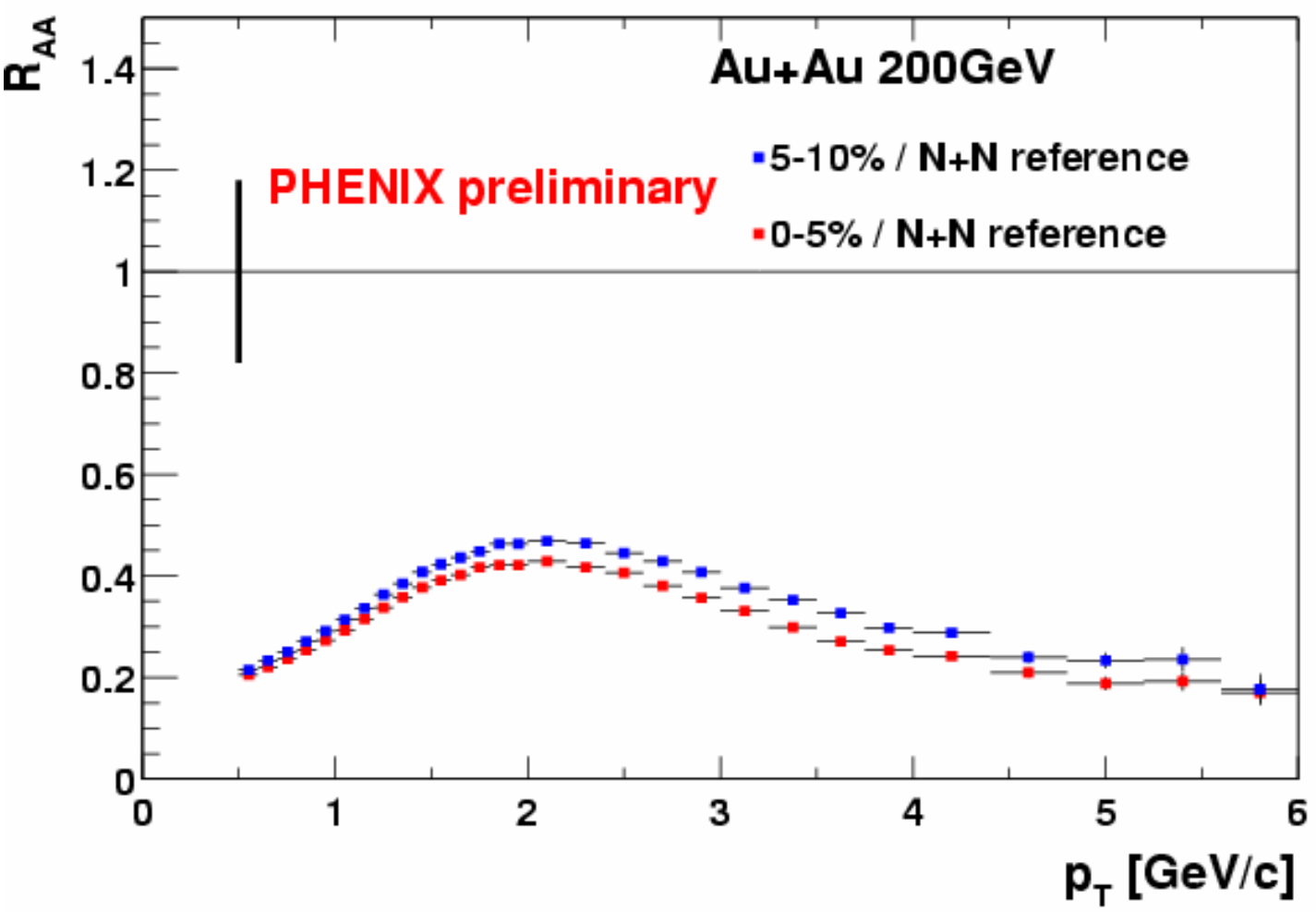




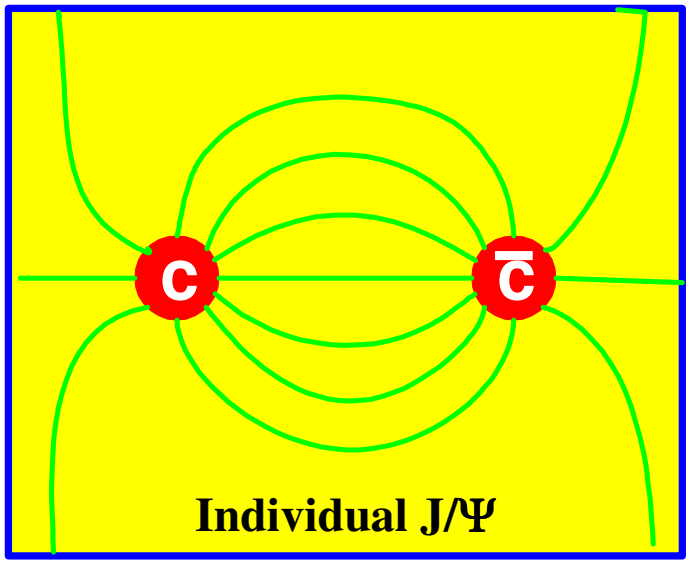
The strategy: Compare particle production to individual proton-proton collisions and look for differences.

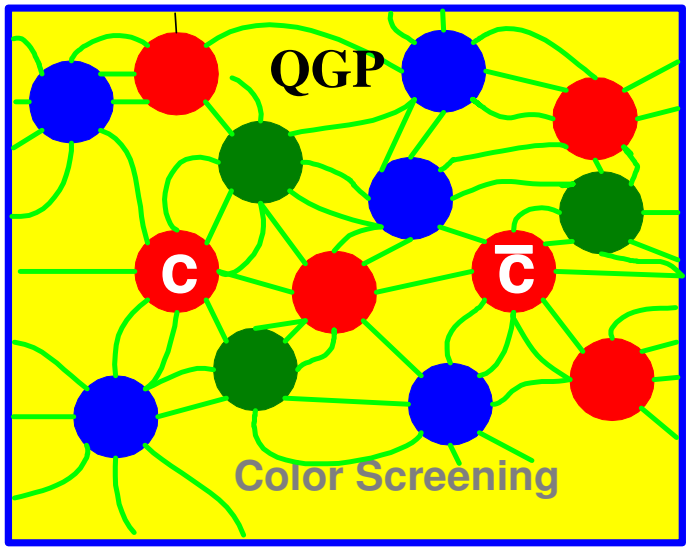
The behavior at RHIC is significantly different!

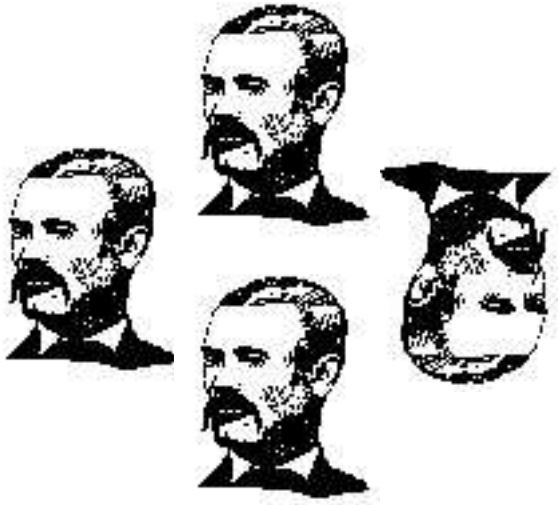
Have we caught a glimpse of the QGP? - Jets



Putting on the Squeeze: J/Ψ Measurements



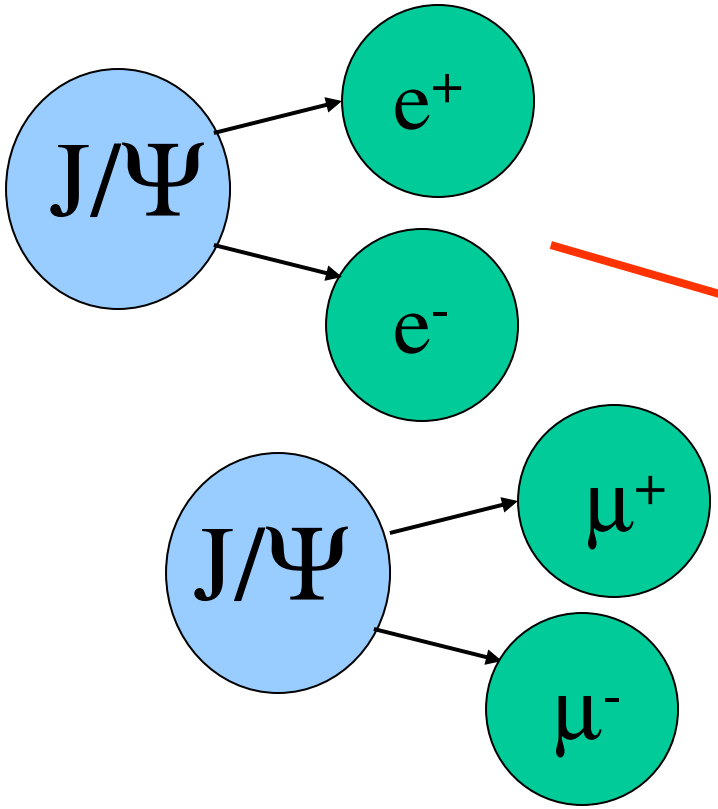


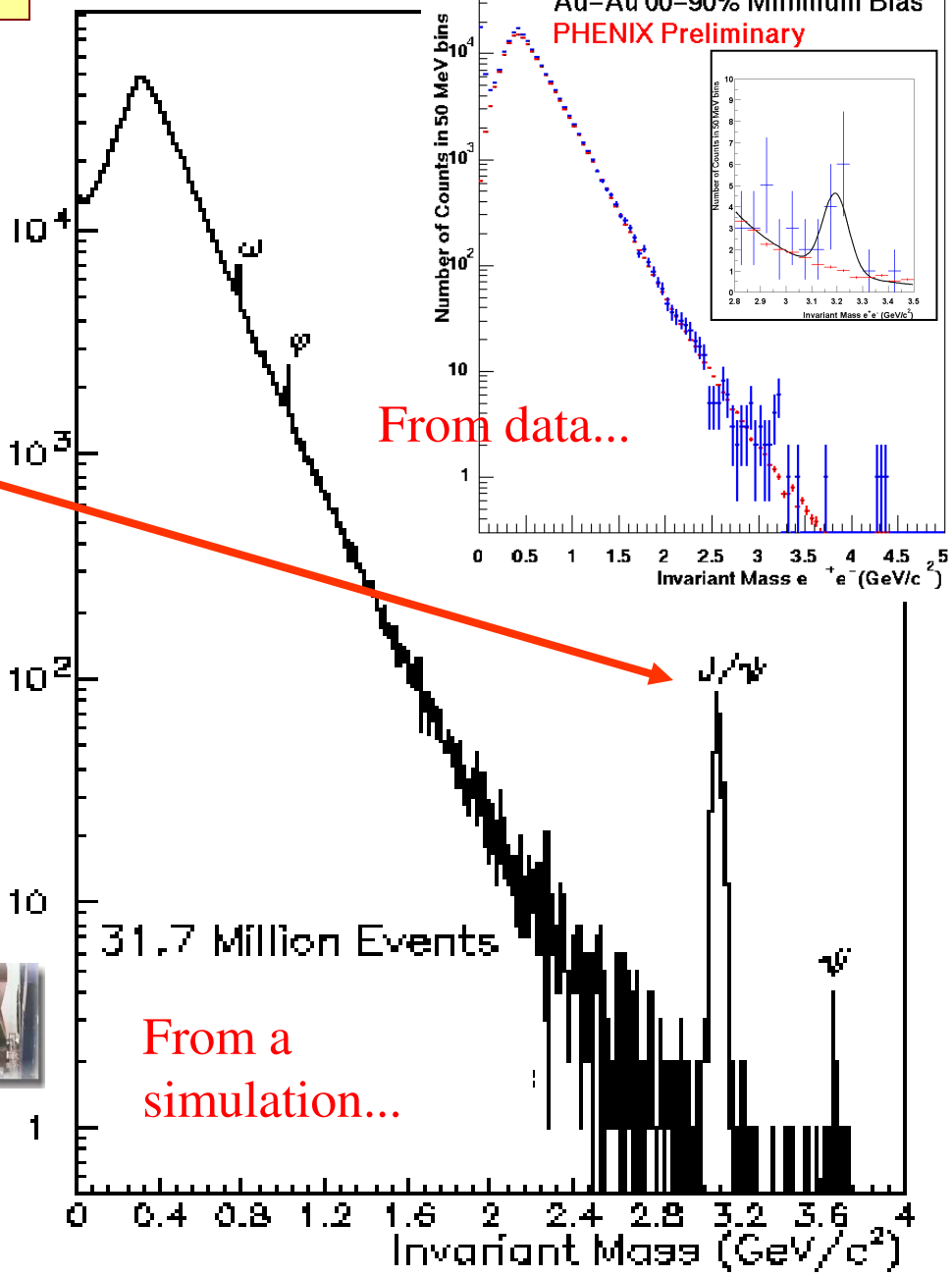


The J/Ψ Particle is a charm + anti-charm pair.

In a QGP, these quarks are "screened" from each other, and J/Ψ particles are suppressed.

Electron and Muon Pair Measurements





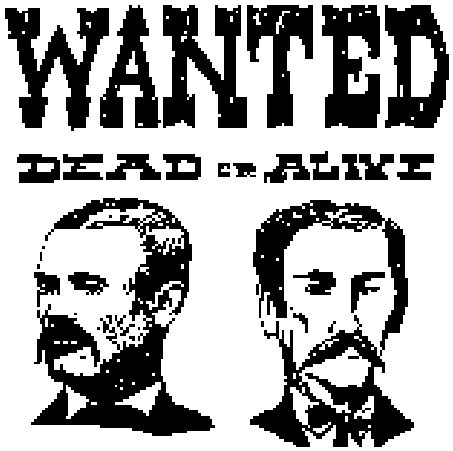
Summary

RHIC has taken mass quantities of data in the past 2 years!

Initial analysis of the data shows that the system sets world records in violence, explosiveness, fluidity, and strangeness.

Analysis of high transverse momentum jets may be providing a glimpse of the QGP...but more data and analysis are necessary before we know for sure.

Stay tuned for new results on jets, photons, muons, electrons, J/Ψ particles, etc.



The Quark & Gluon Plasma Brothers are still at large, but we are in hot pursuit and on their tail, so...

The Hunt continues.