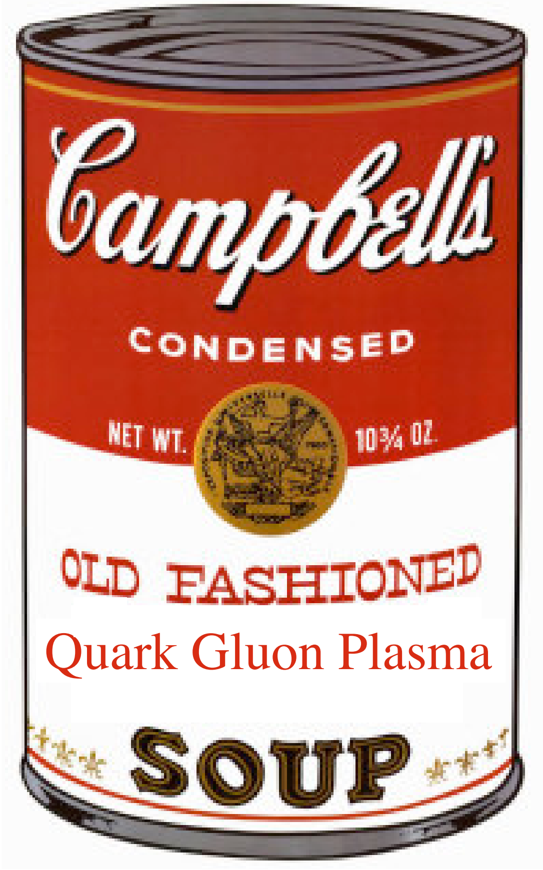
Creating Quark Soup



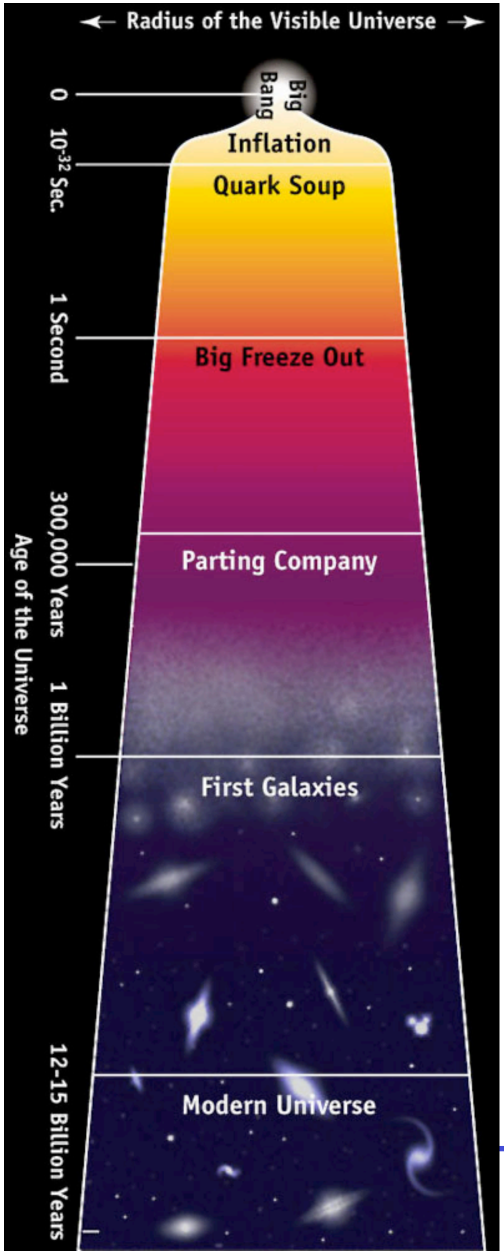
Andy Warhol

Helen Caines - Yale University

April 13th 2009

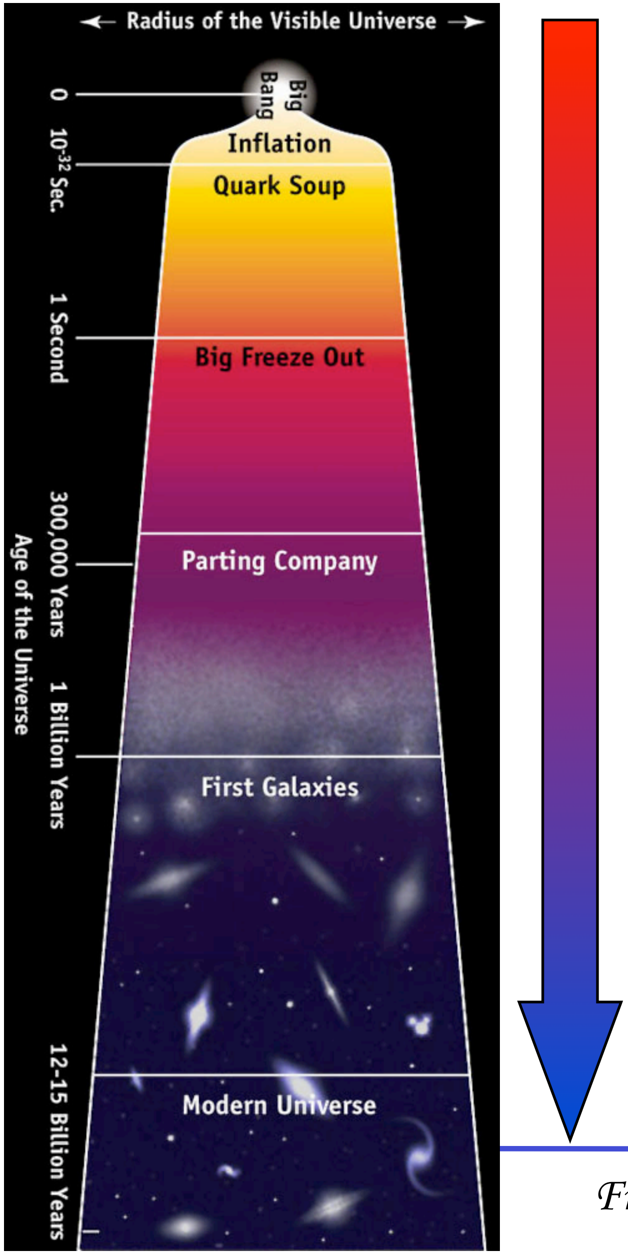
Franklin & Marshall College

Evolution of the universe



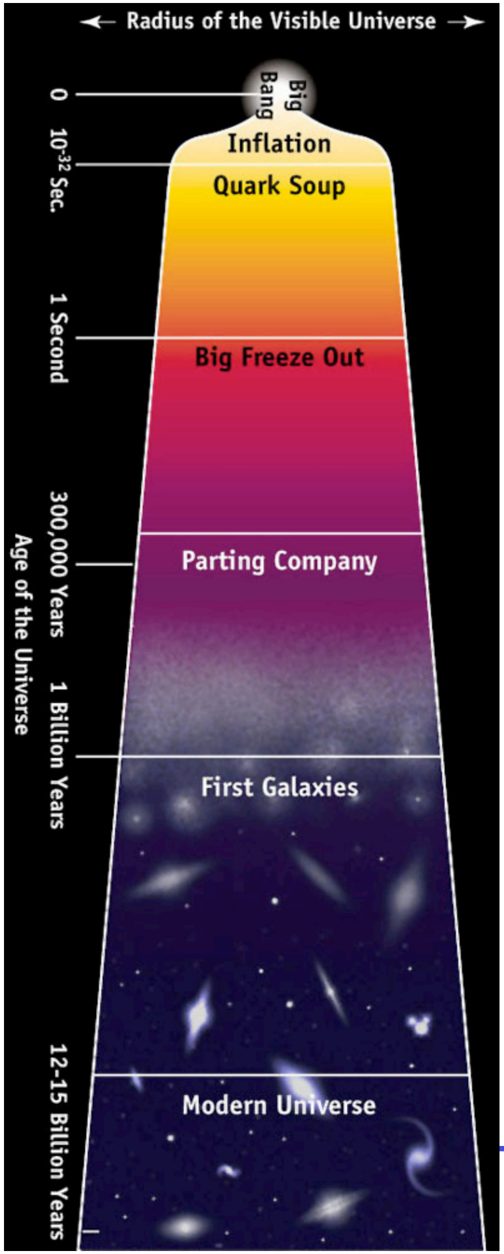
10^{-44} sec	Quantum Gravity	Unification of all 4 forces	10^{32} K
10^{-35} sec	Grand Unification	E-M/Weak = Strong forces	10^{27} K
10^{-35} sec ?	Inflation	universe exponentially expands by 10^{26}	10^{27} K
2 10^{-10} sec	Electroweak unification	E-M = weak force	10^{15} K
$2 \cdot 10^{-6}$ sec	**Proton-Antiproton pairs**	**creation of nucleons**	**10^{13} K**
6 sec	Electron-Positron pairs	creation of electrons	6×10^{9} K
3 min	**Nucleosynthesis**	**light elements formed**	**10^{9} K**
10^{6} yrs	Microwave Background	recombination - transparent to photons	3000 K
10^{9} yrs ?	Galaxy formation	bulges and halos of normal galaxies form	20 K

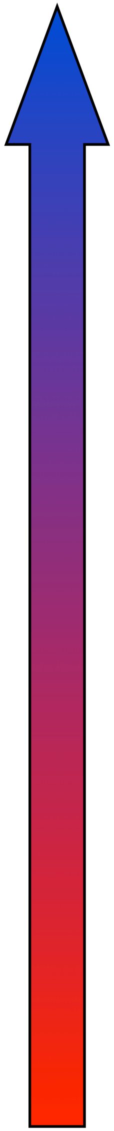
Evolution of the universe



The universe gets cooler !

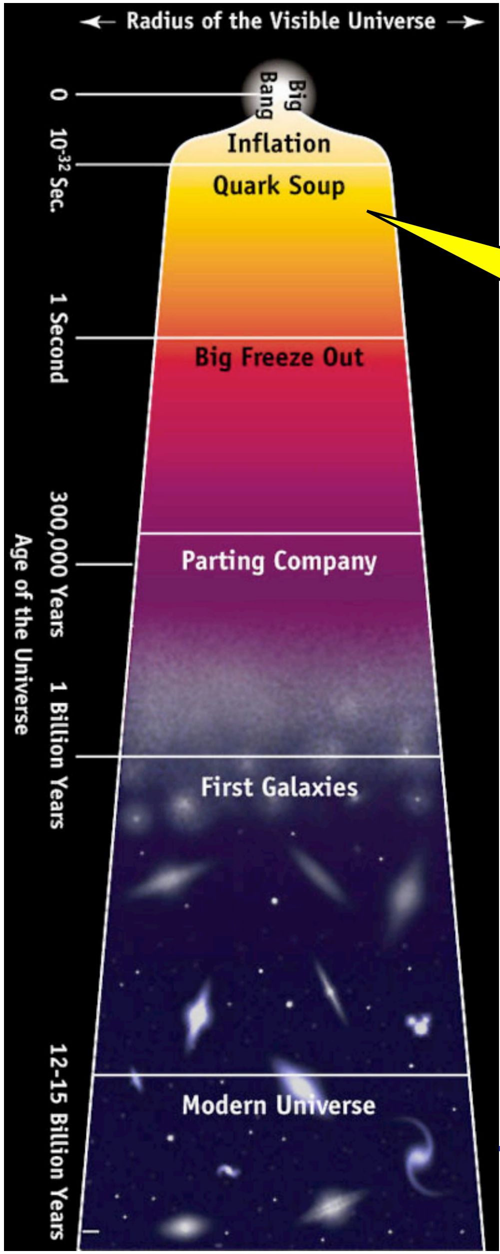
Evolution of the universe

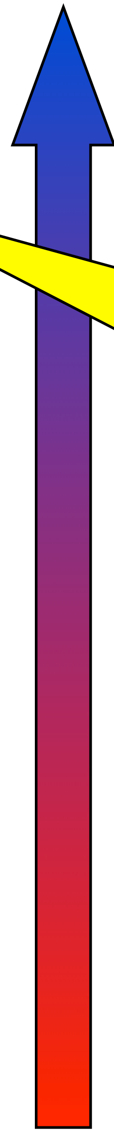




Reheating Matter ?

Evolution of the universe



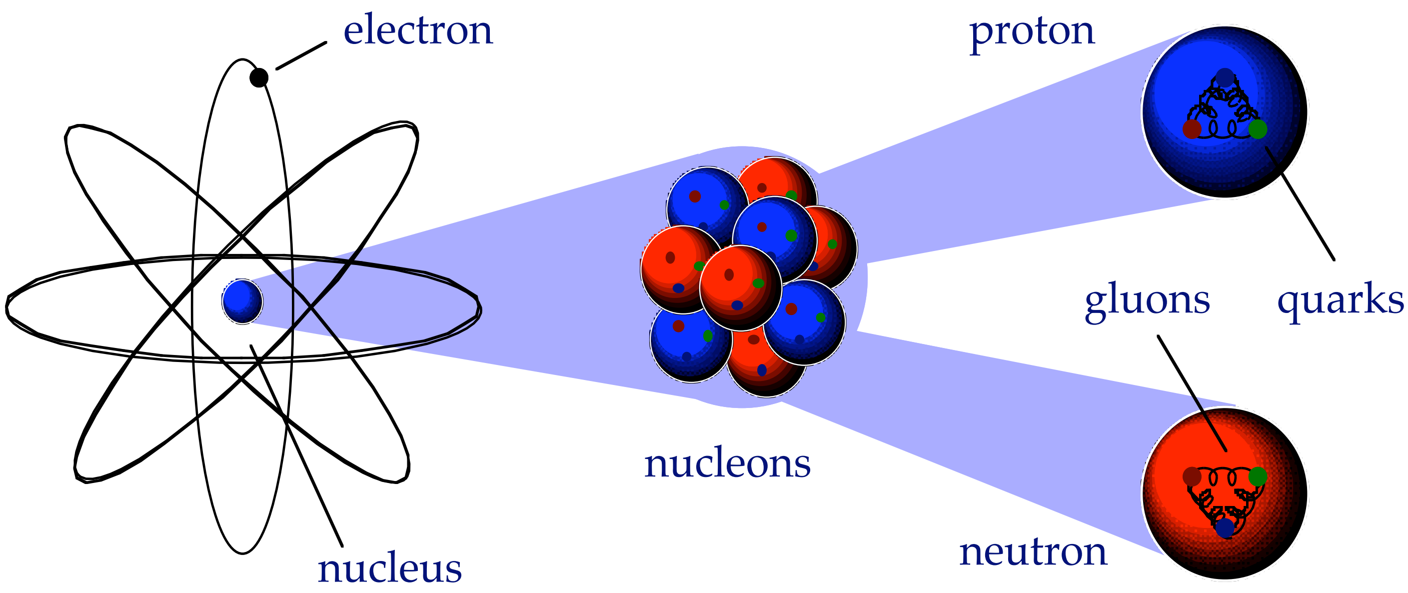


Reheating Matter ?

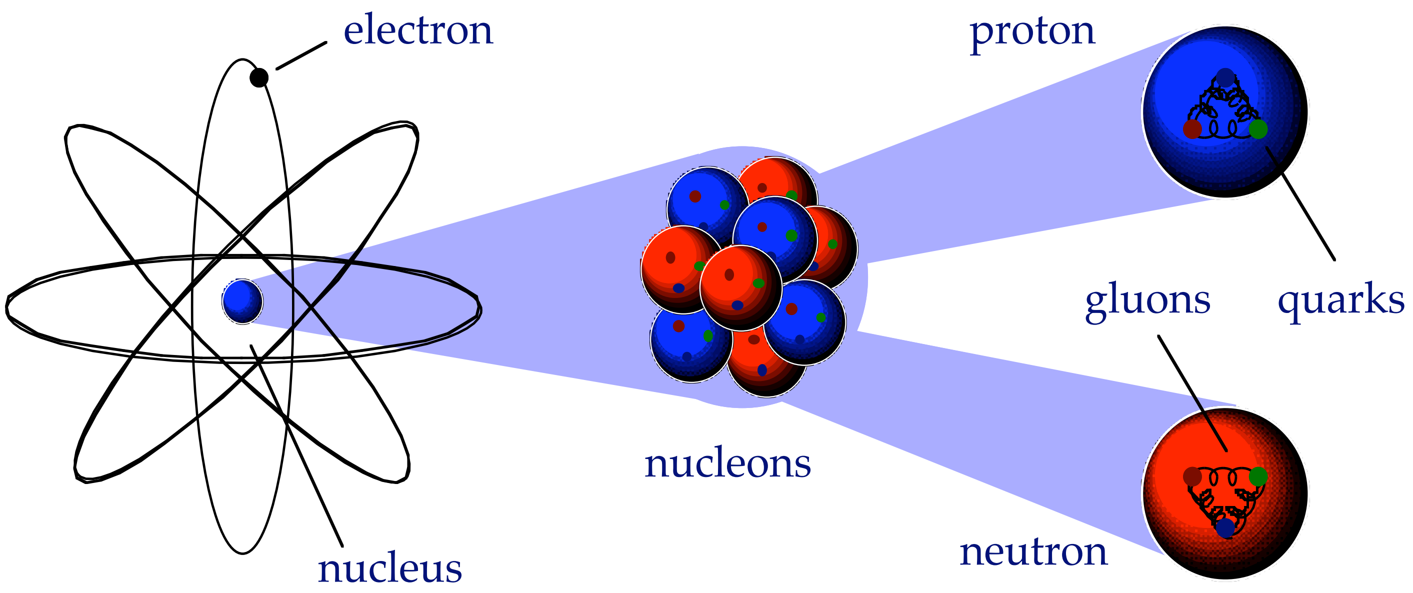
?

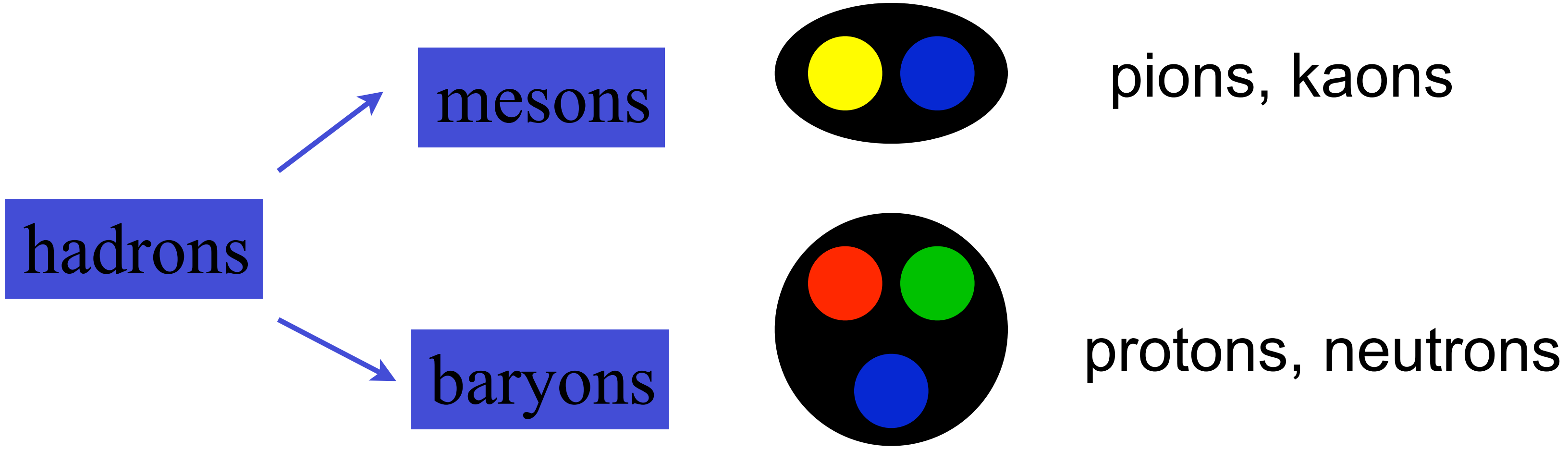
Need temperatures around $1.5 \cdot 10^{12}$ K (200 MeV) far hotter than center of the sun ($\sim 2 \cdot 10^{7}$K)

Essential ingredients of matter

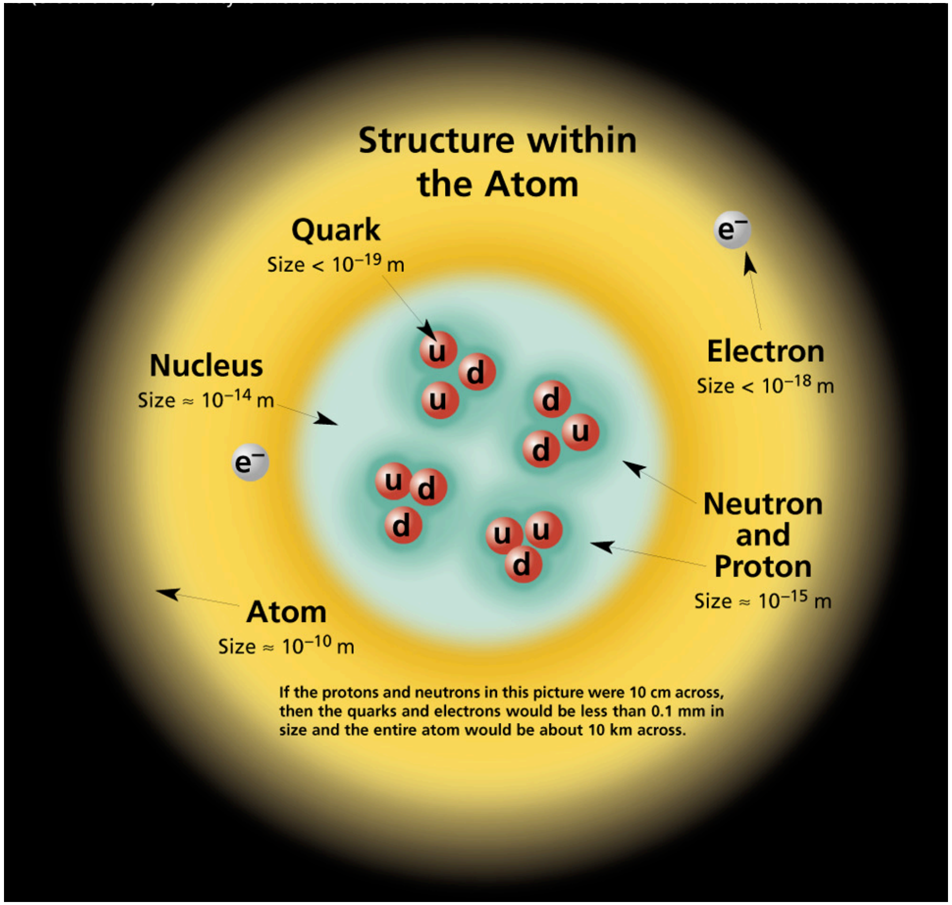


Essential ingredients of matter

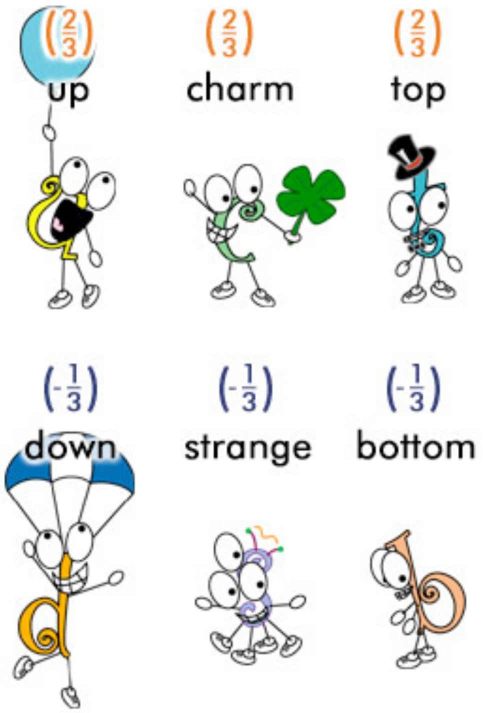




More about partons

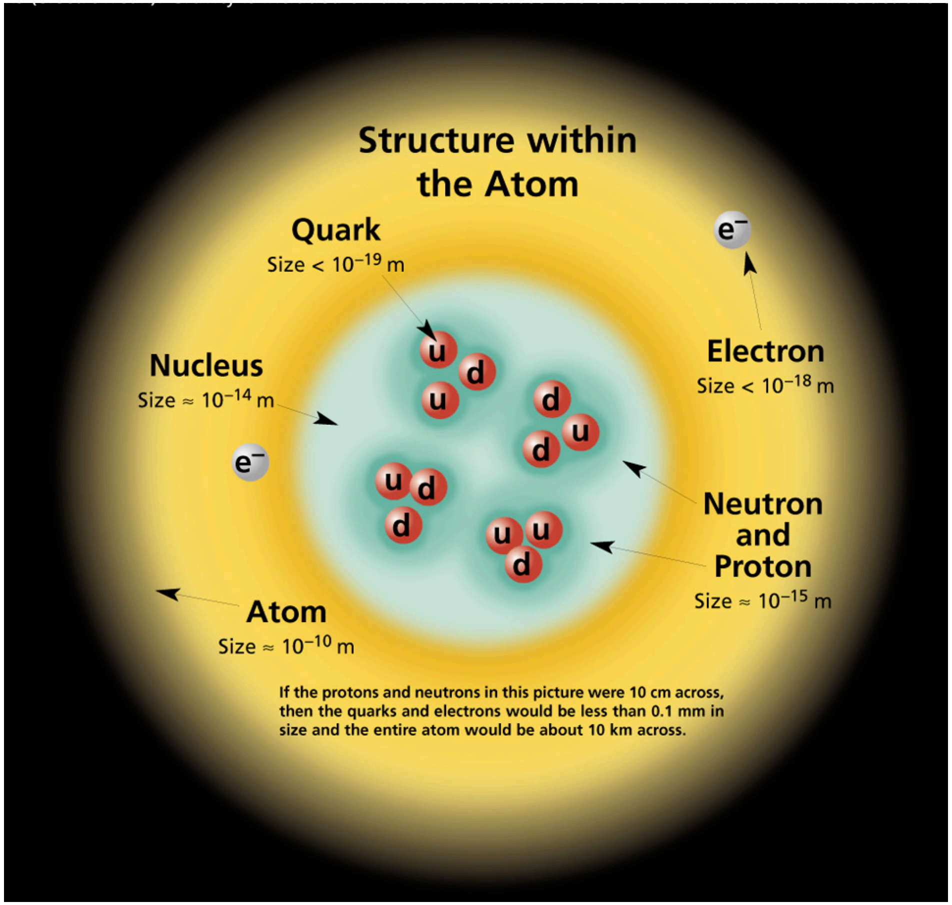


Ordinary matter made of **up** and **down** quarks

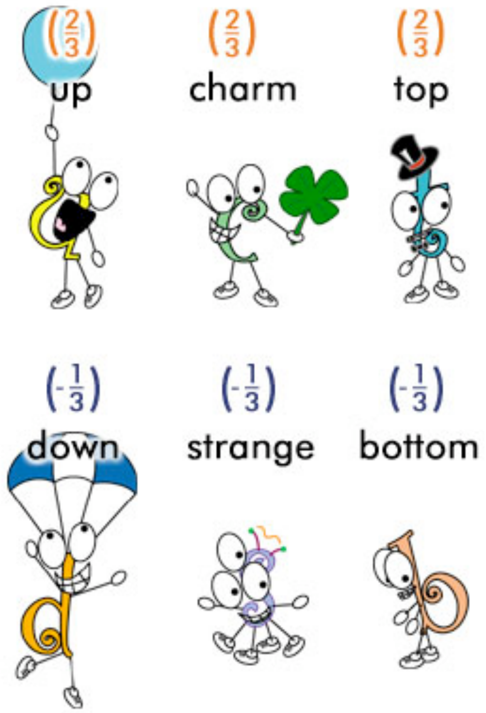


- Quarks interact by exchanging gluons
  - Nucleons are held together by gluons

More about partons



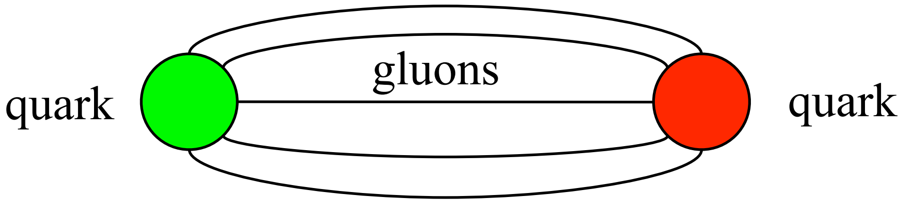
Ordinary matter made of **up** and **down** quarks



- Quarks interact by exchanging gluons
  - Nucleons are held together by gluons

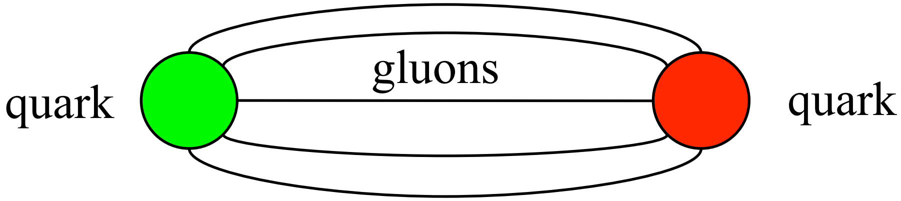
Free quarks have never been seen - distinctive non-integer charge

Why we don't see free quarks



The size of a nucleus is $1.2A^{1/3}$ fm where A is the mass number and a fm is 10^{-15} m

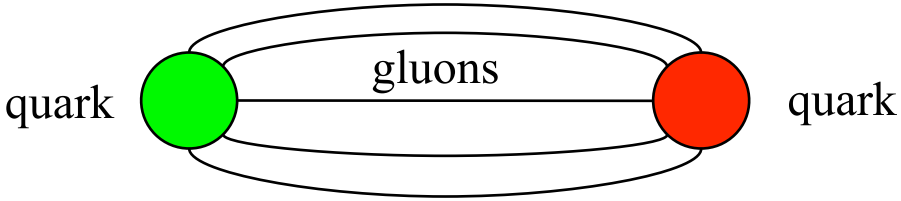
Why we don't see free quarks



The size of a nucleus is $1.2A^{1/3}$ fm where A is the mass number and a fm is 10^{-15} m

$$1\frac{GeV}{fm} = \frac{10^{9}eV}{10^{-15}m} \times \frac{1.6\times 10^{-19}J}{eV} = 1.6\times 10^{5}N$$

Why we don't see free quarks



The size of a nucleus is $1.2A^{1/3}$ fm where A is the mass number and a fm is 10^{-15} m

$$1\frac{GeV}{fm} = \frac{10^9 eV}{10^{-15} m} \times \frac{1.6 \times 10^{-19} J}{eV} = 1.6 \times 10^5 N$$

Compare to gravitational force at Earth's surface

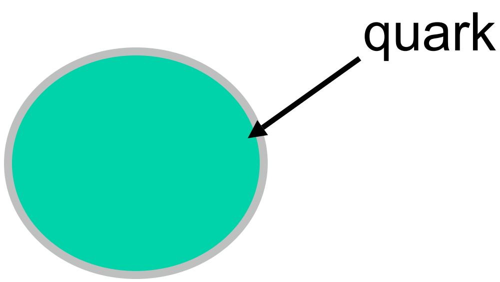
$$F = 1.6 \times 10^5 N = M \times g = M \times 9.8 m/s^2$$

$$\Rightarrow \quad M = 16,300 kg$$

Quarks exert 16 metric tons of force on each other!

Confinement - QCD

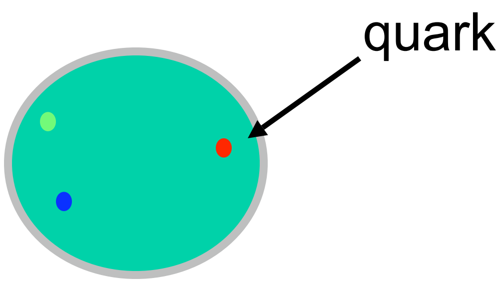
Confinement: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have ∞ energy in normal vacuum



"white" proton

Confinement - QCD

Confinement: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have ∞ energy in normal vacuum



"white" proton

Confinement - QCD

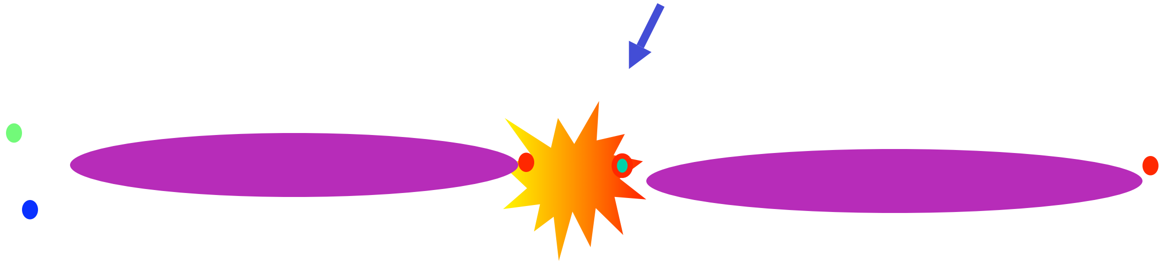
Confinement: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have ∞ energy in normal vacuum

Strong **color** field
Force *grows* with separation !!!

Confinement - QCD

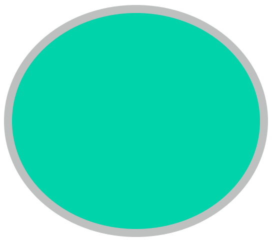
Confinement: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have ∞ energy in normal vacuum

quark-antiquark pair created from vacuum

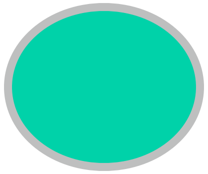


Confinement - QCD

Confinement: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have ∞ energy in normal vacuum



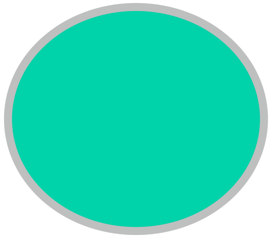
“white” proton
(confined quarks)



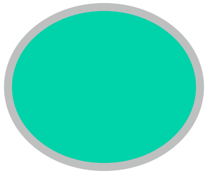
“white” π^0
(confined quarks)

Confinement - QCD

Confinement: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have ∞ energy in normal vacuum



"white" proton
(confined quarks)



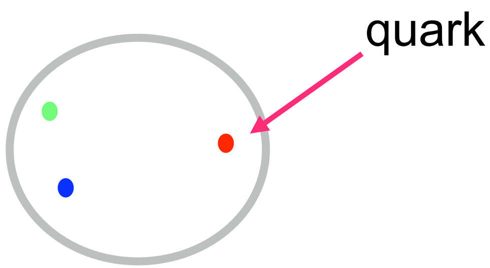
"white" π^0
(confined quarks)

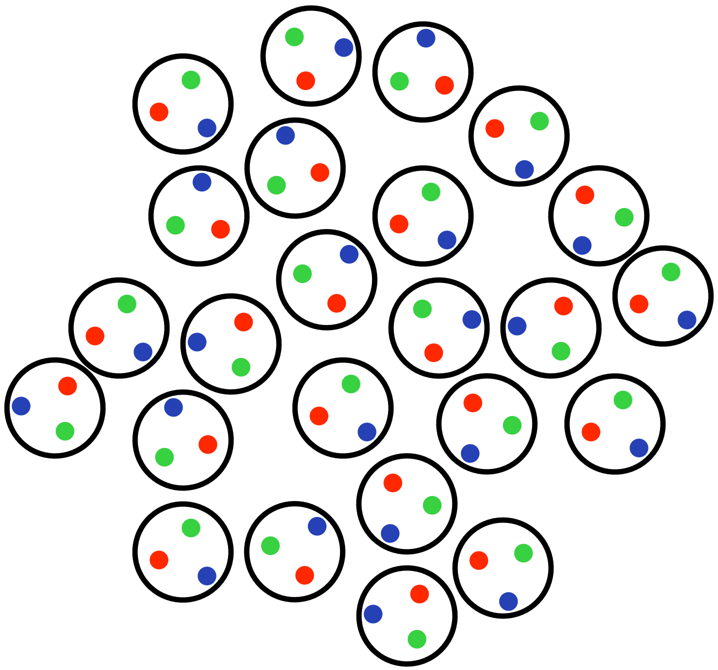
To understand the strong force and confinement: Create and study a system of deconfined colored quarks and gluons

Recreating in the laboratory

We try to make a deconfined state of matter

<u>Confinement</u>: feature of strong force
- colored objects (quarks)
have ∞ energy in normal vacuum

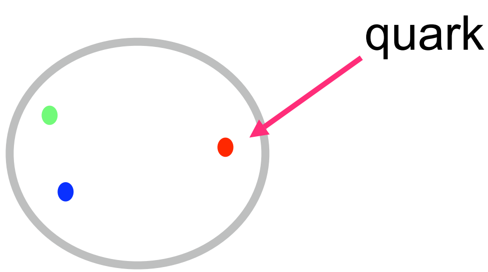


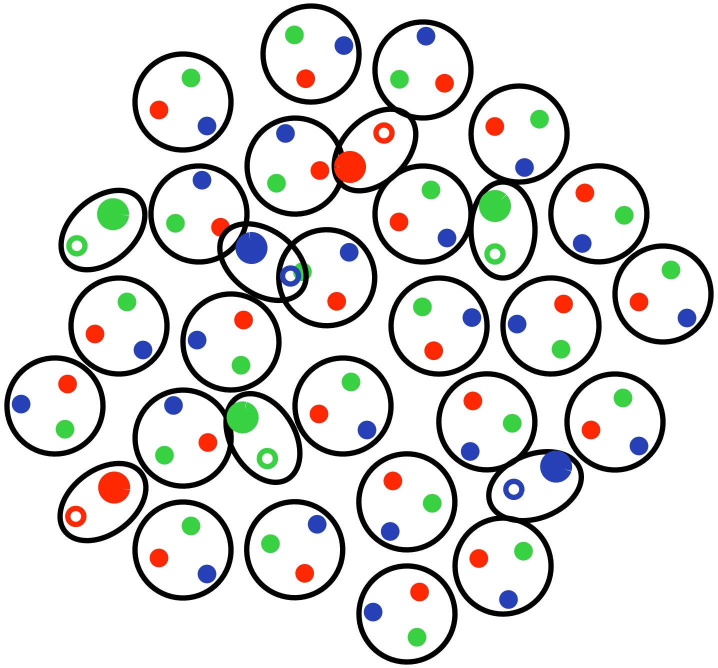


Recreating in the laboratory

We try to make a deconfined state of matter

<u>Confinement</u>: feature of strong force
- colored objects (quarks) have ∞ energy in normal vacuum



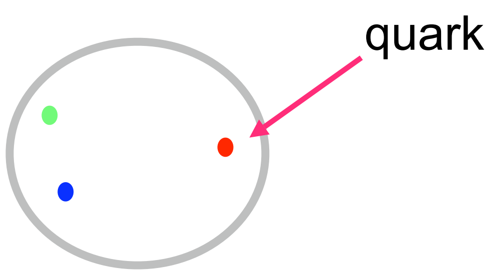


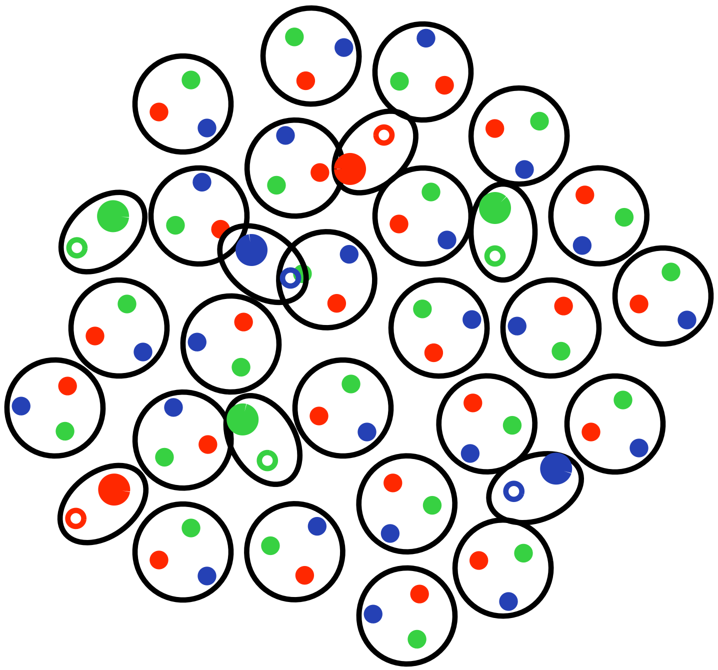
Quarks are also confined within mesons

Recreating in the laboratory

We try to make a deconfined state of matter

<u>Confinement</u>: feature of strong force
- colored objects (quarks) have ∞ energy in normal vacuum





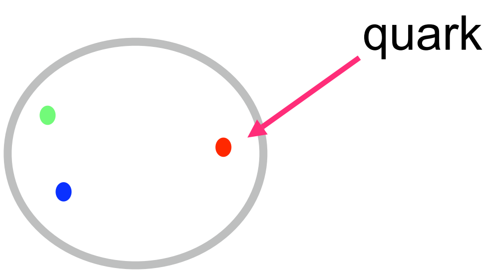
Quarks are also confined within mesons

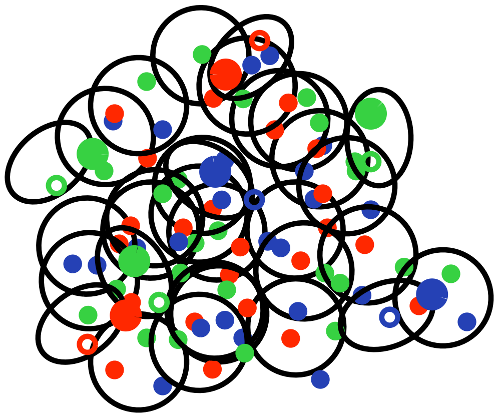
How can we create a deconfined state of QCD matter?

Recreating in the laboratory

We try to make a deconfined state of matter

Confinement: feature of strong force
- colored objects (quarks) have ∞ energy in normal vacuum





Quarks are also confined within mesons

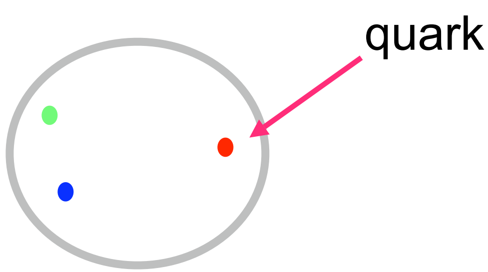
How can we create a deconfined state of QCD matter?

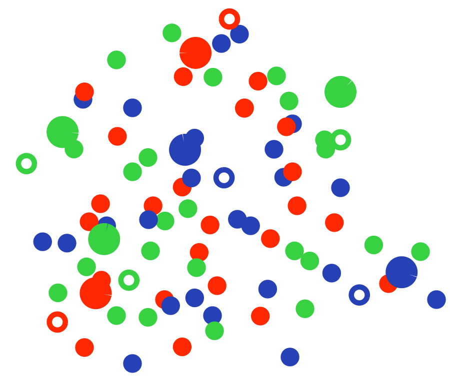
by heating or compressing

Recreating in the laboratory

We try to make a deconfined state of matter

Confinement: feature of strong force
- colored objects (quarks) have ∞ energy in normal vacuum





Quarks are also confined within mesons

How can we create a deconfined state of QCD matter?

by heating or compressing

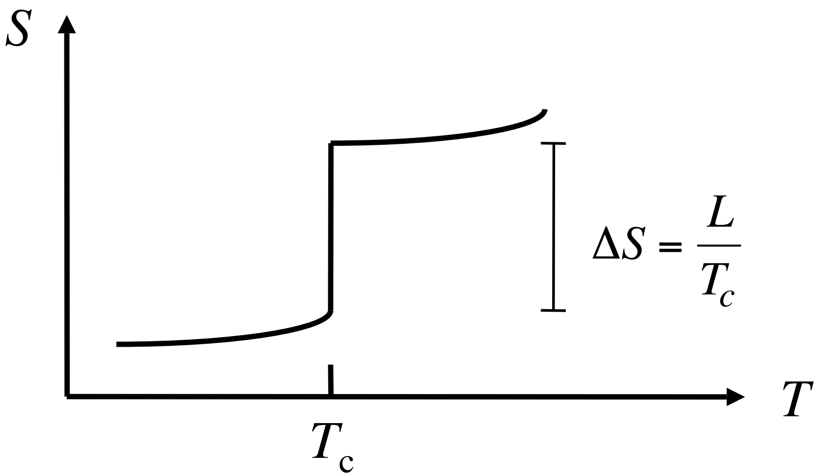
Quark Gluon Plasma
~6x Normal nuclear density

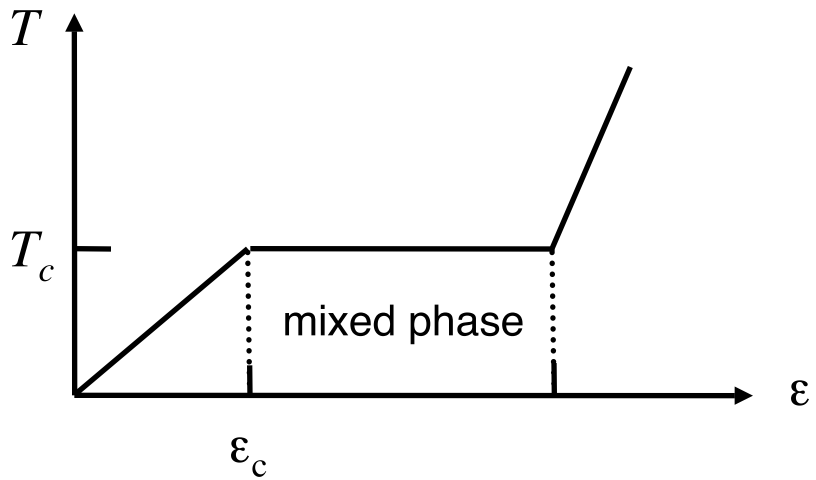
Thermodynamics - phase transitions

Phase transition or a crossover?

Signs of a phase transition:

1st order: discontinuous in entropy at T_c → Latent heat, a mixed phase



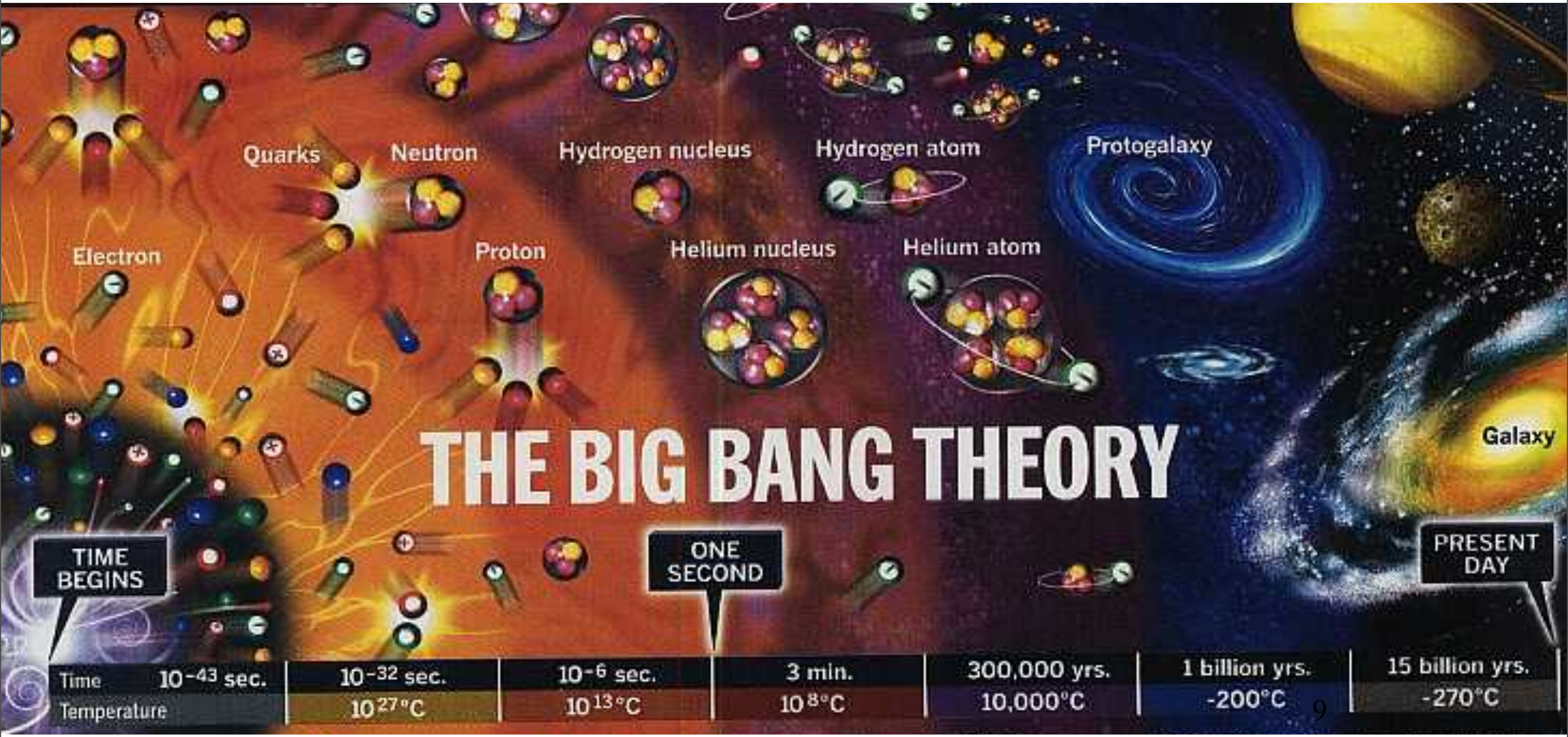


Higher order: discontinuous in higher derivatives of $\delta^n S/\delta T^n$ → no mixed phase - system passed smoothly and uniformly into new state (ferromagnet)

Temperature	⇔	transverse momentum	$T \propto \langle p_T \rangle$
Energy density	⇔	transverse energy	$\varepsilon \propto dE_T/dy \cong \langle m_T \rangle dN/dy$
Entropy	⇔	multiplicity	$S \propto dN/dy$

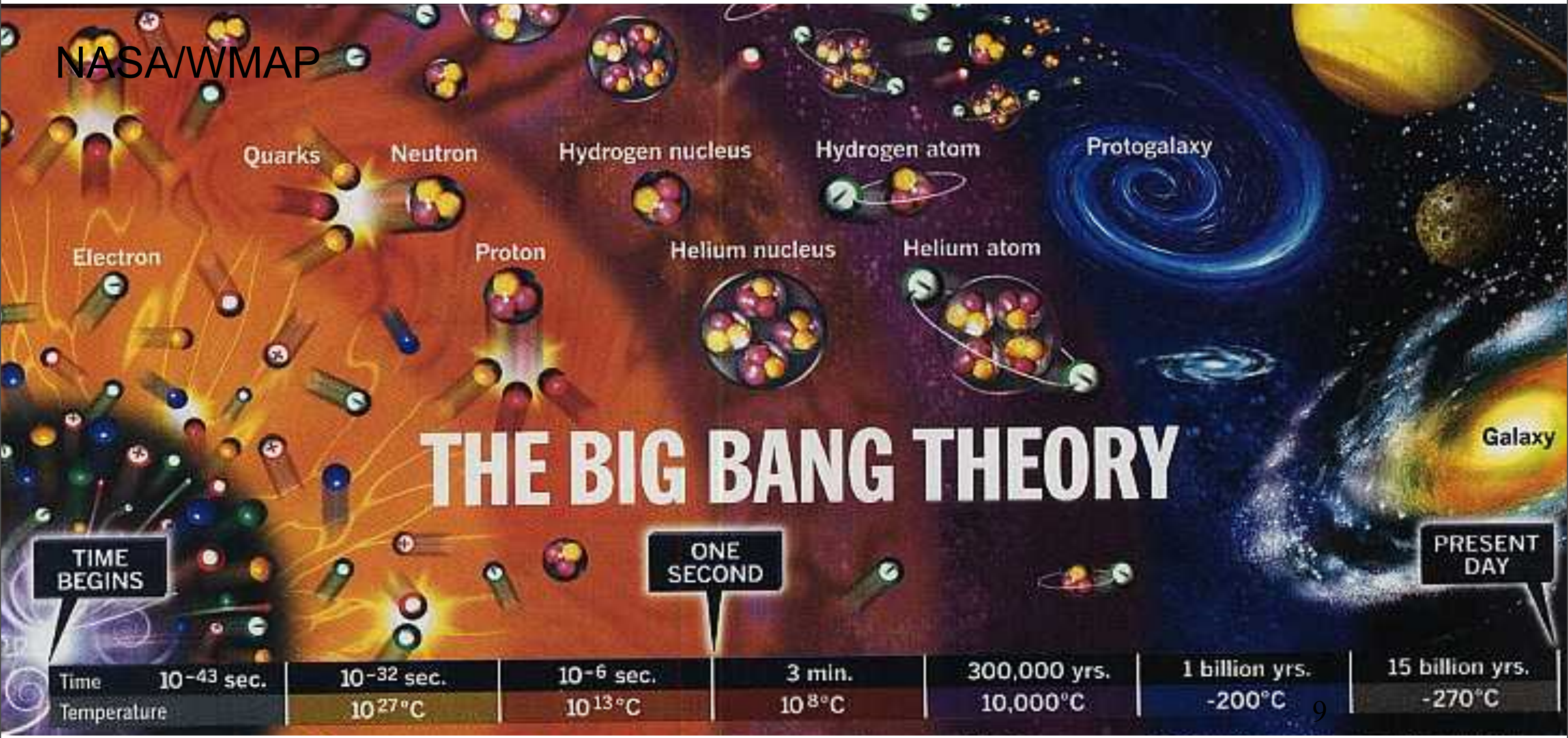
The order of the phase transition

"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario." Ed Witten, Phys. Rev. D (1984)



The order of the phase transition

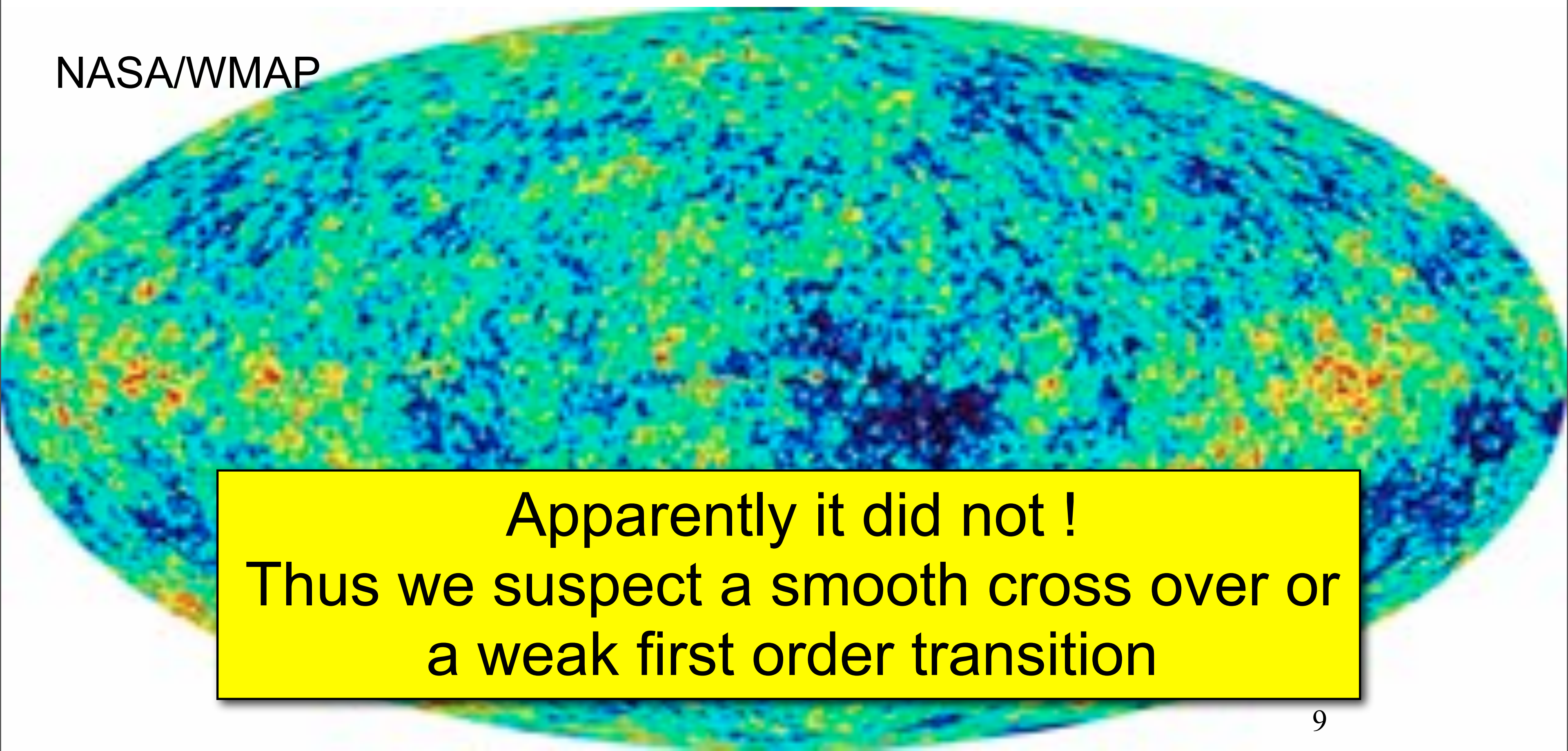
"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario."   Ed Witten, Phys. Rev. D (1984)



The order of the phase transition

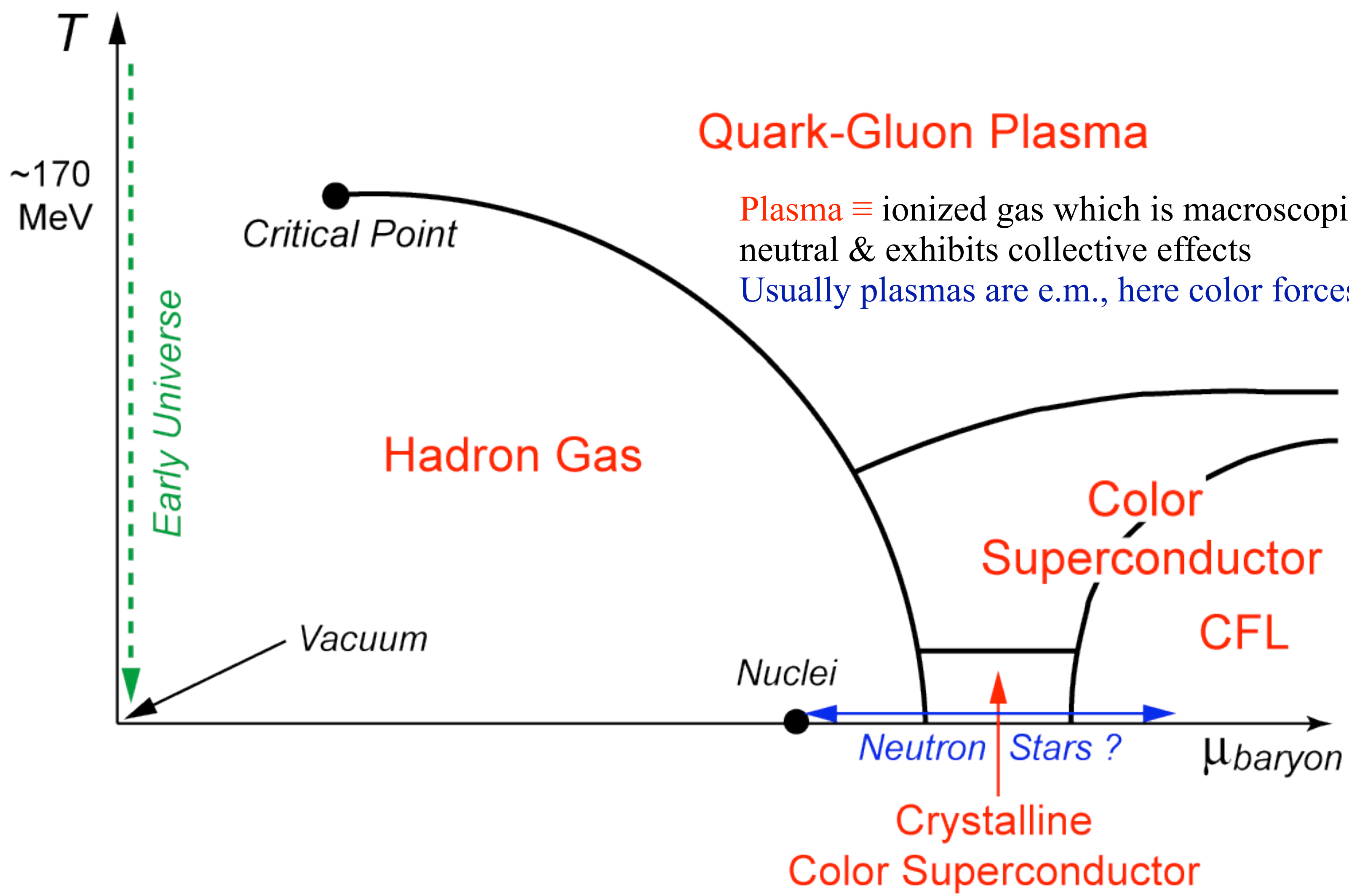
"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario."   Ed Witten, Phys. Rev. D (1984)

NASA/WMAP



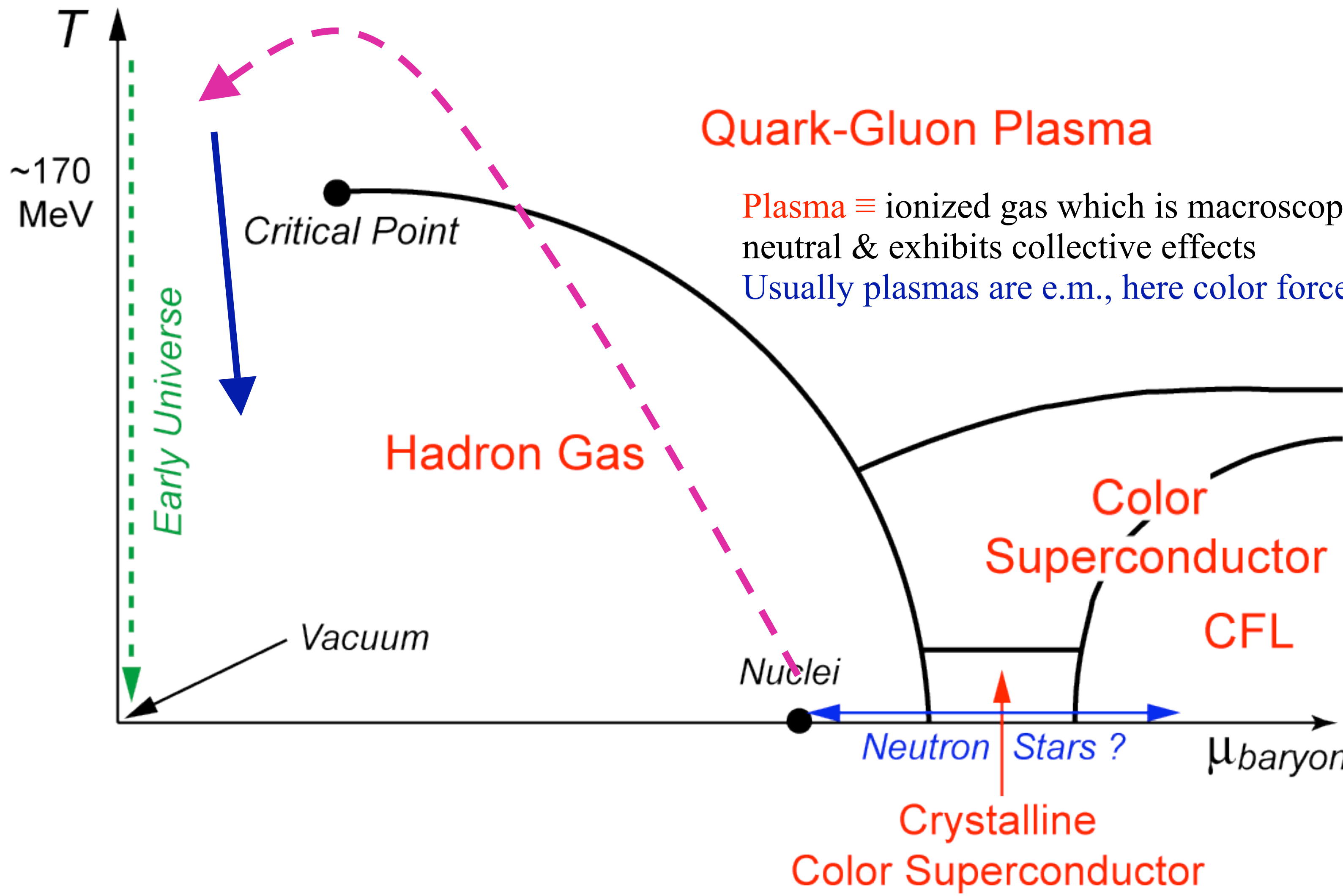
Apparently it did not !
Thus we suspect a smooth cross over or a weak first order transition

QCD phase diagram of hadronic matter



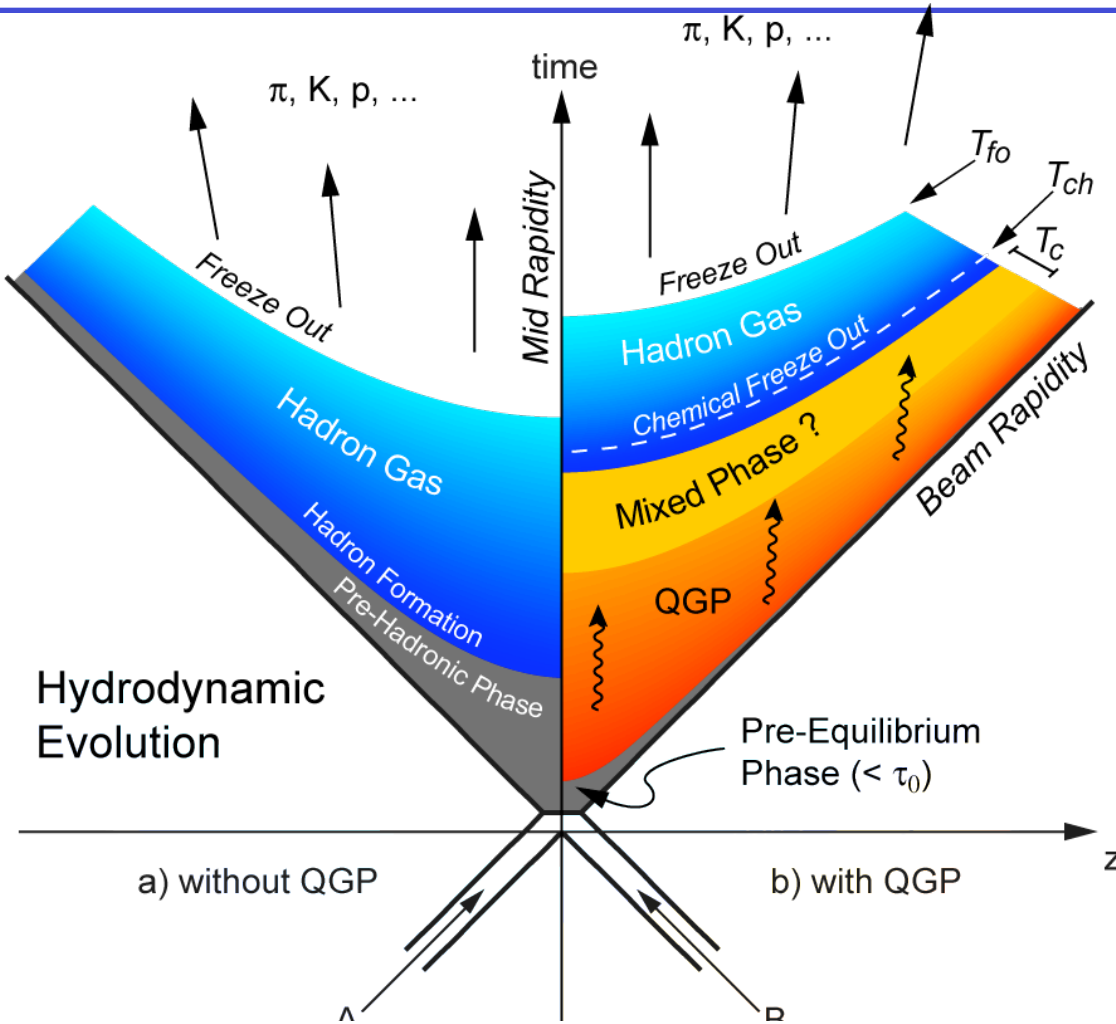
Plasma ≡ ionized gas which is macroscopically neutral & exhibits collective effects
Usually plasmas are e.m., here color forces

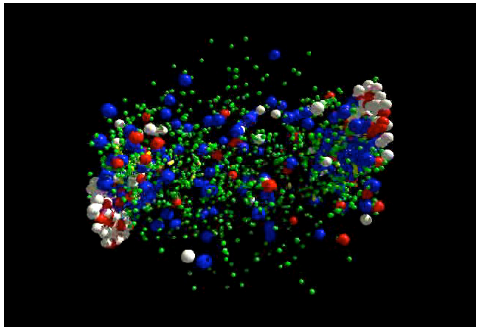
QCD phase diagram of hadronic matter

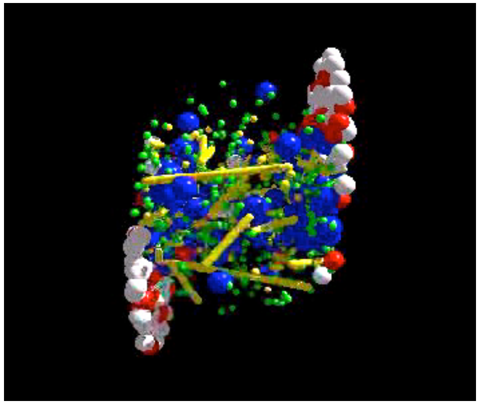


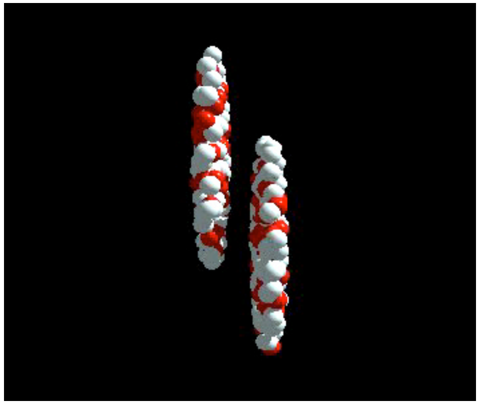
Plasma ≡ ionized gas which is macroscopically neutral & exhibits collective effects
Usually plasmas are e.m., here color forces

The phase transition in the laboratory









Chemical freezeout ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

RHIC @ Brookhaven National Lab

RHIC - Relativistic Heavy Ion Collider

3.8 km accelerator that can be seen from space

Unusual facts about RHIC

- RHIC's beam travels at 99.995% the speed of light (186,000 miles per second).

- RHIC's two rings consist of 1740 super-conducting magnets each cooled by liquid helium to -269^{o}C

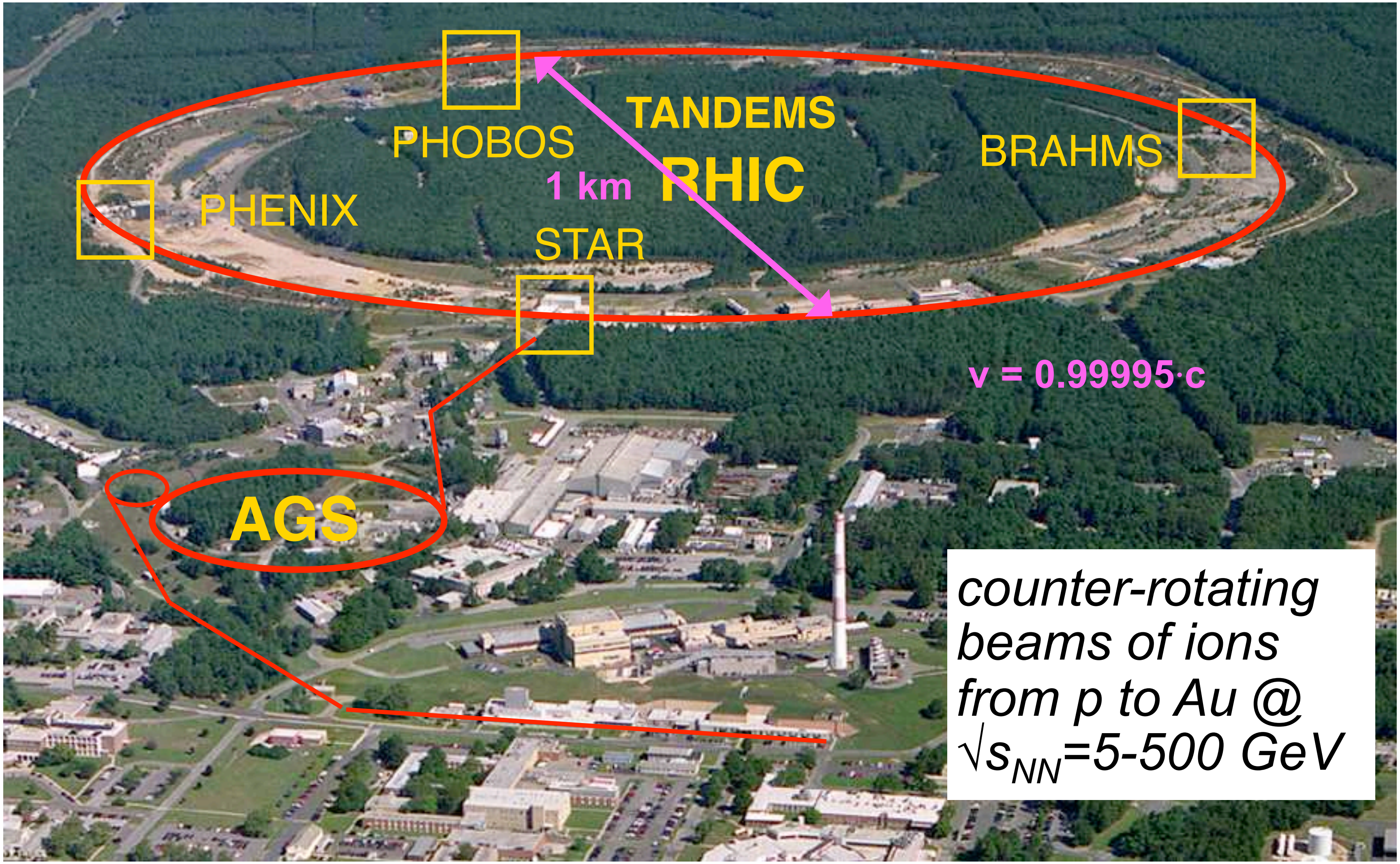
- RHIC contains seven tons of helium
  - enough to fill all the balloons in Macy's Thanksgiving Day Parades for the next 100 years

- The refrigerator to cool the helium needs a power of 15 MW (as much as 15000 homes! we shut down over the summer)

- Over 20 years less than one gram of gold is used in the beam.

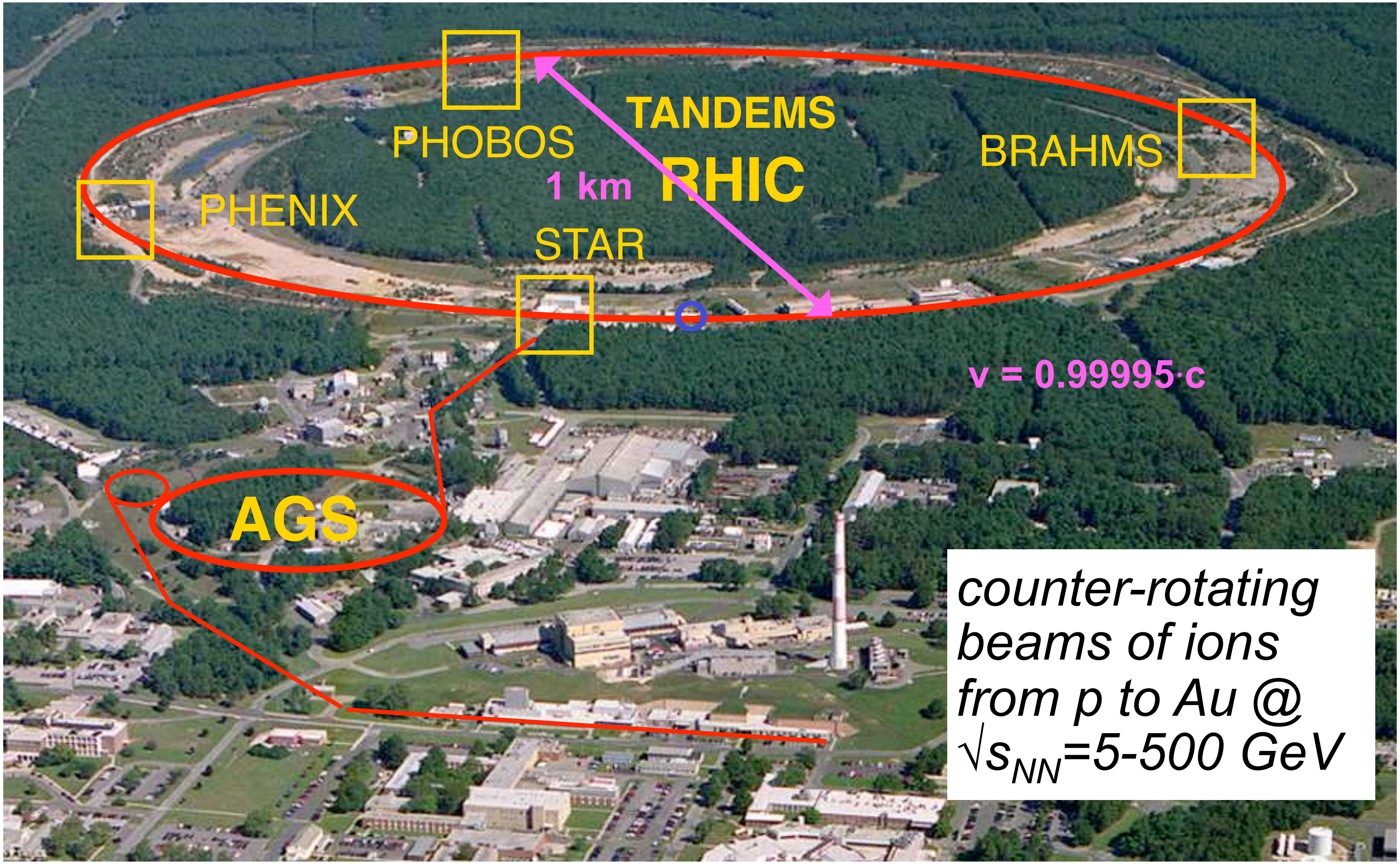
- At top energy: stored beam energy is 200kJ per ring
  - energy 2000 people get drinking a single drop of beer each

RHIC - the experiments

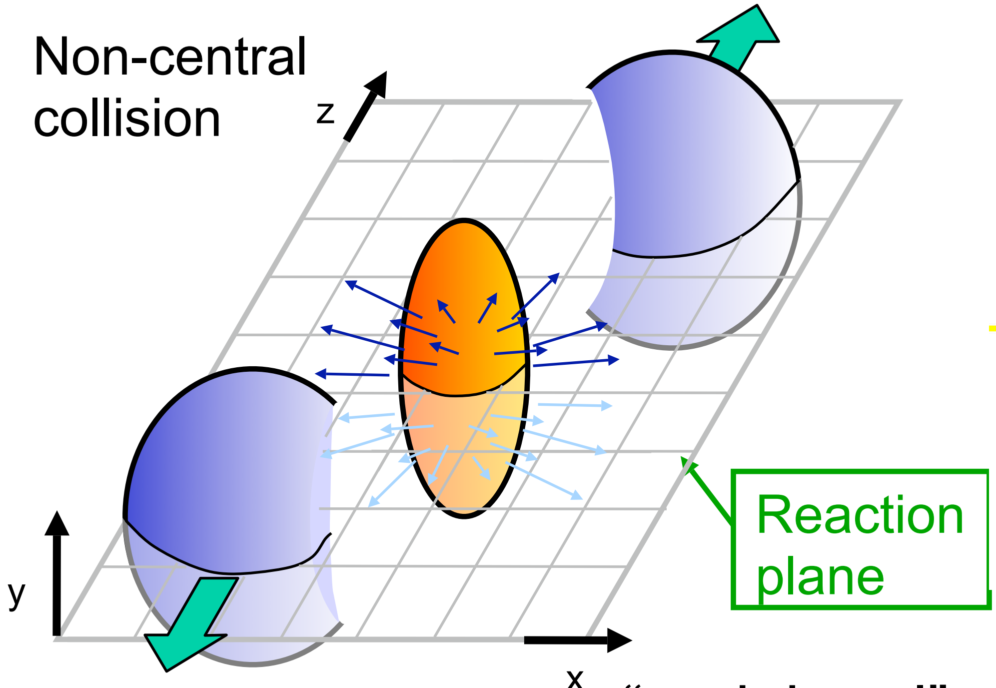


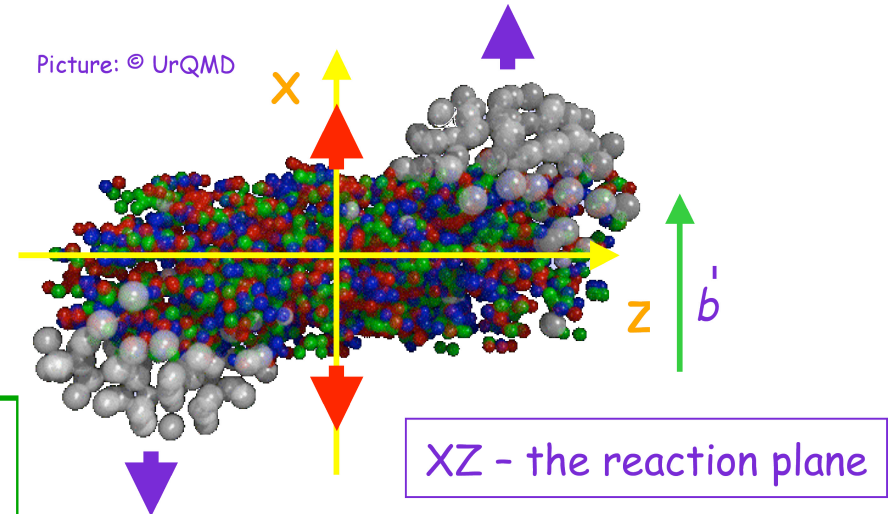
counter-rotating beams of ions from p to Au @ $\sqrt{s_{NN}}$=5-500 GeV

RHIC - the experiments



Geometry of a heavy-ion collision





"peripheral" collision ($b \sim b_{max}$)

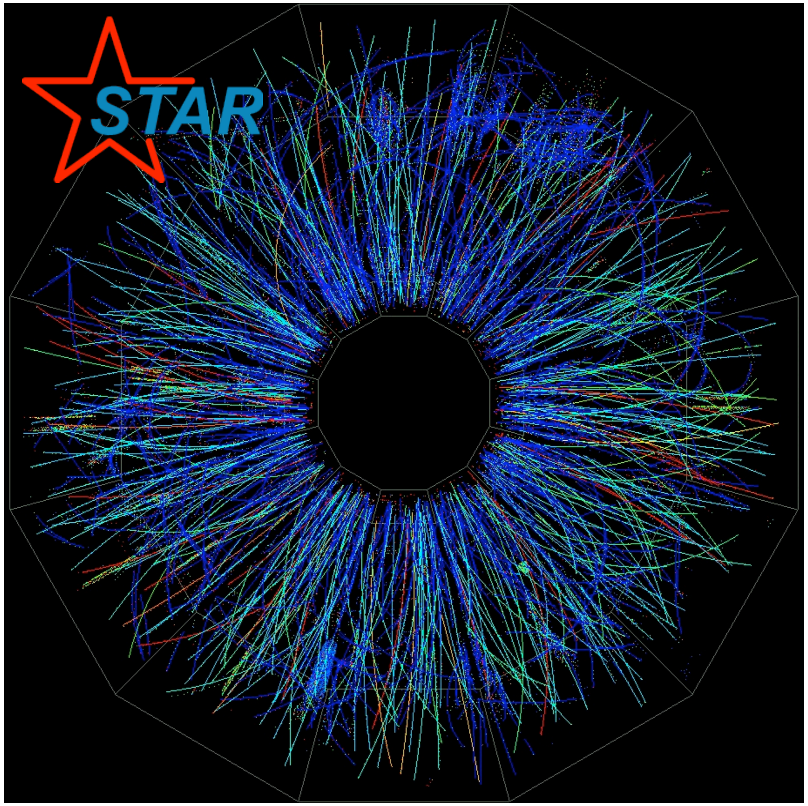
"central" collision ($b \sim 0$)

Number of participants (N_{part}): number of incoming nucleons (participants) in the overlap region

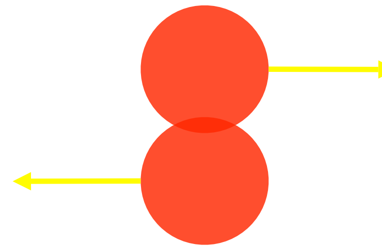
Number of binary collisions (N_{bin}): number of equivalent inelastic nucleon-nucleon collisions

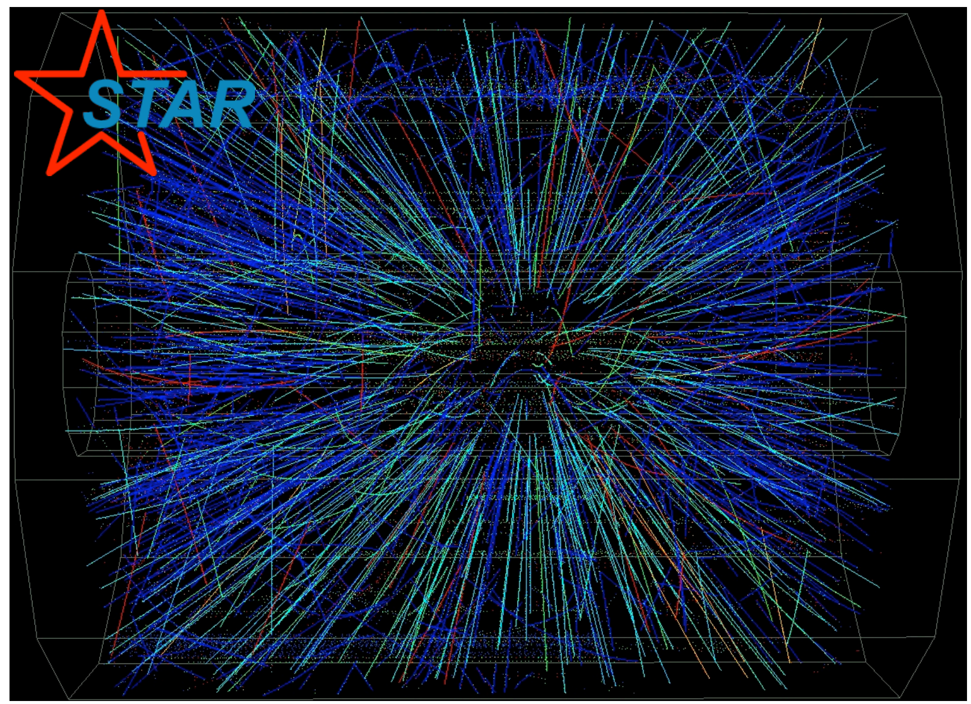
$N_{bin} \geq N_{part}$

A peripheral Au-Au collision



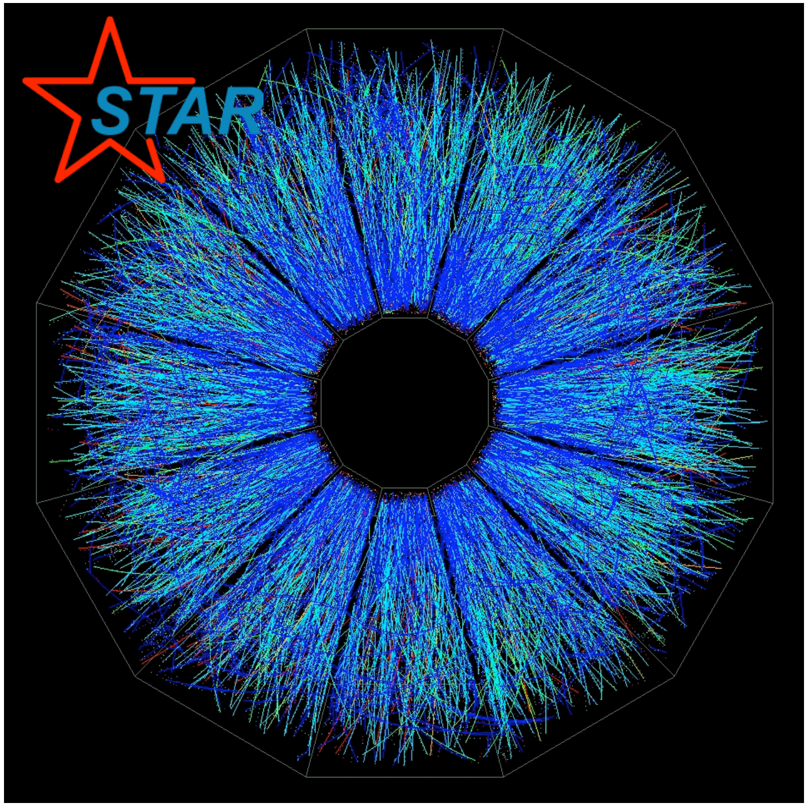
Peripheral Collision





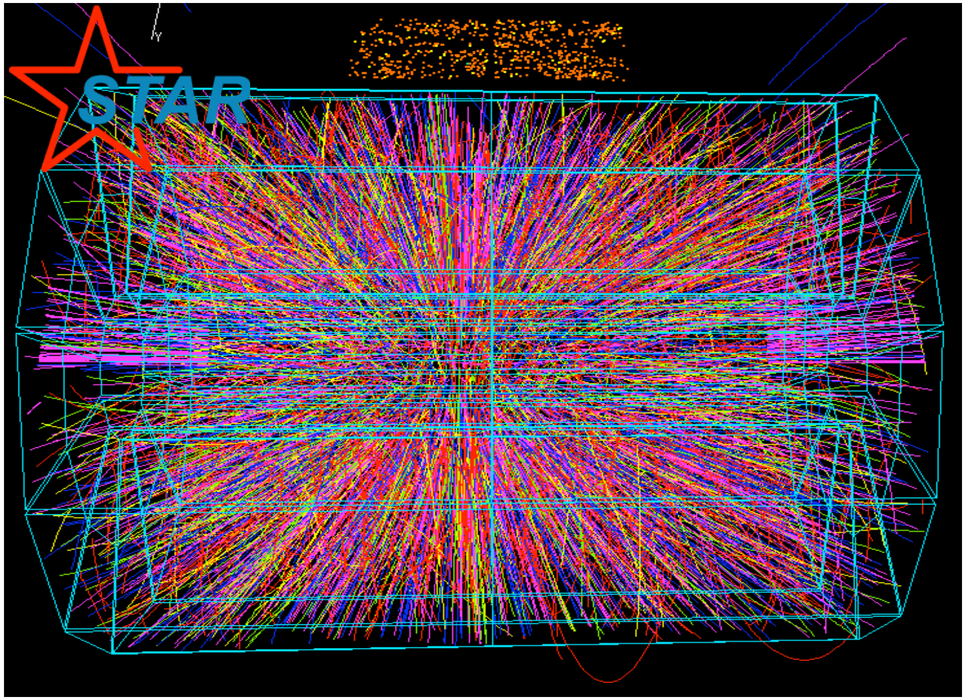
Color ⇒ Energy loss in TPC gas

39.4 TeV in central Au-Au collision

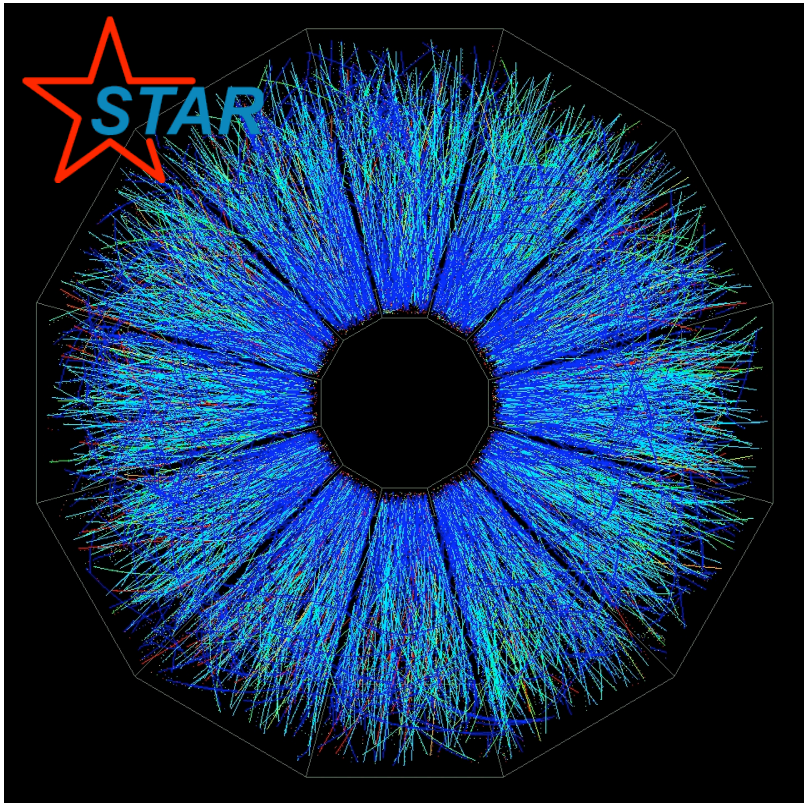


>5000 hadrons and leptons

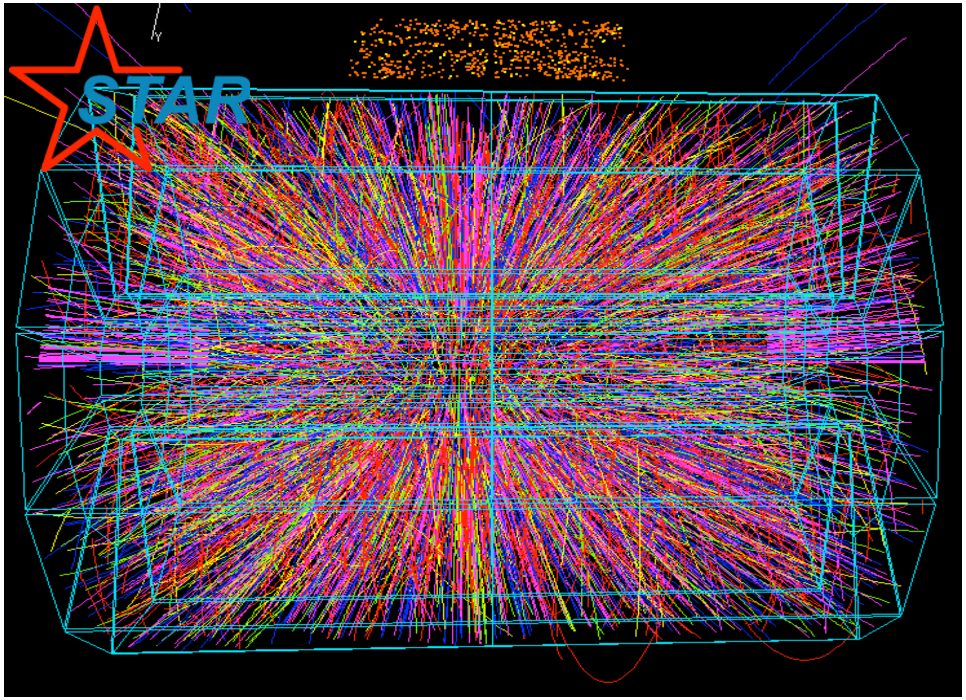
- Only charged particles shown
- Neutrals don't ionise the TPC's gas so are not "seen" by this detector.



39.4 TeV in central Au-Au collision



- Only charged particles shown
- Neutrals don't ionise the TPC's gas so are not "seen" by this detector.

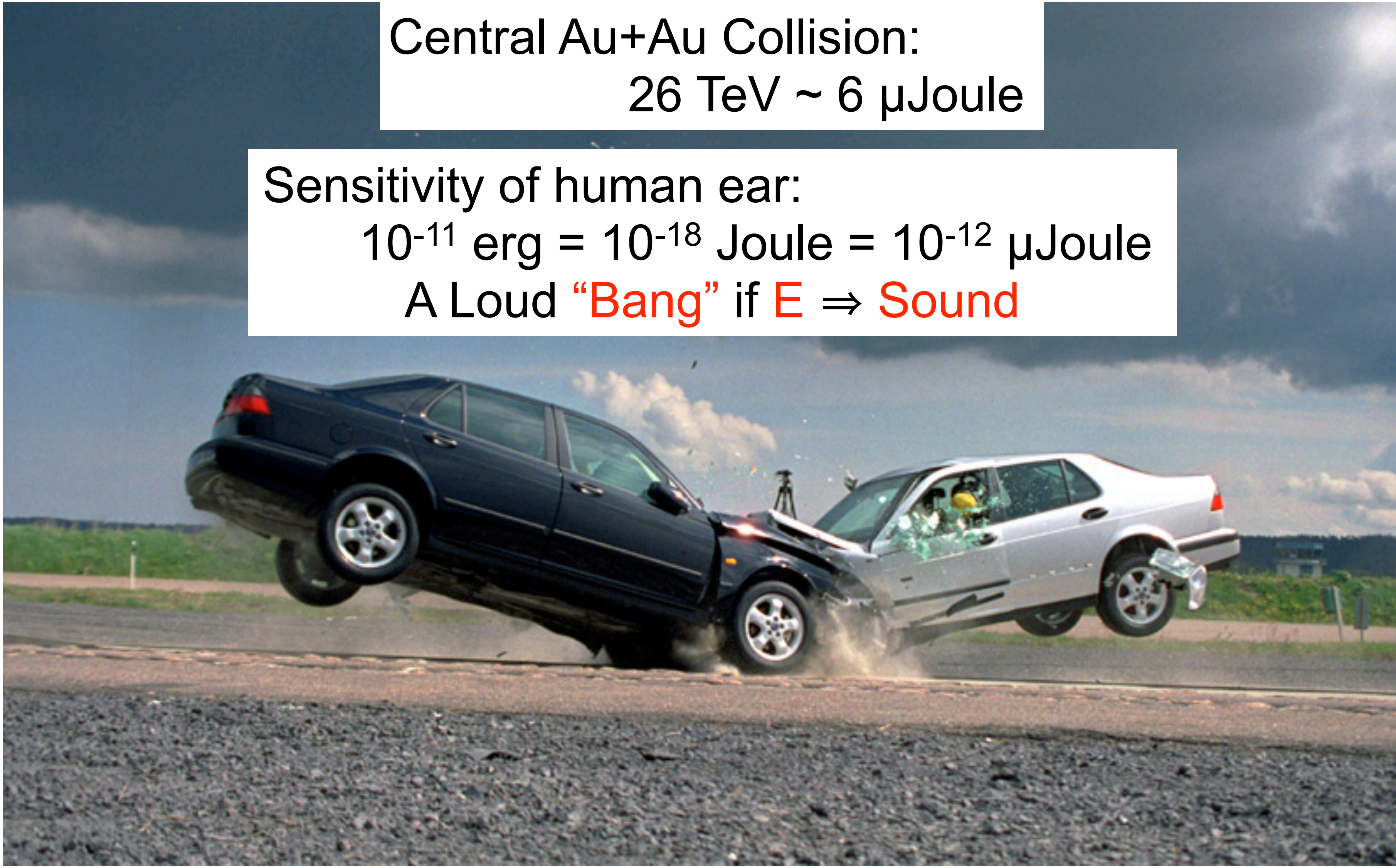


>5000 hadrons and leptons

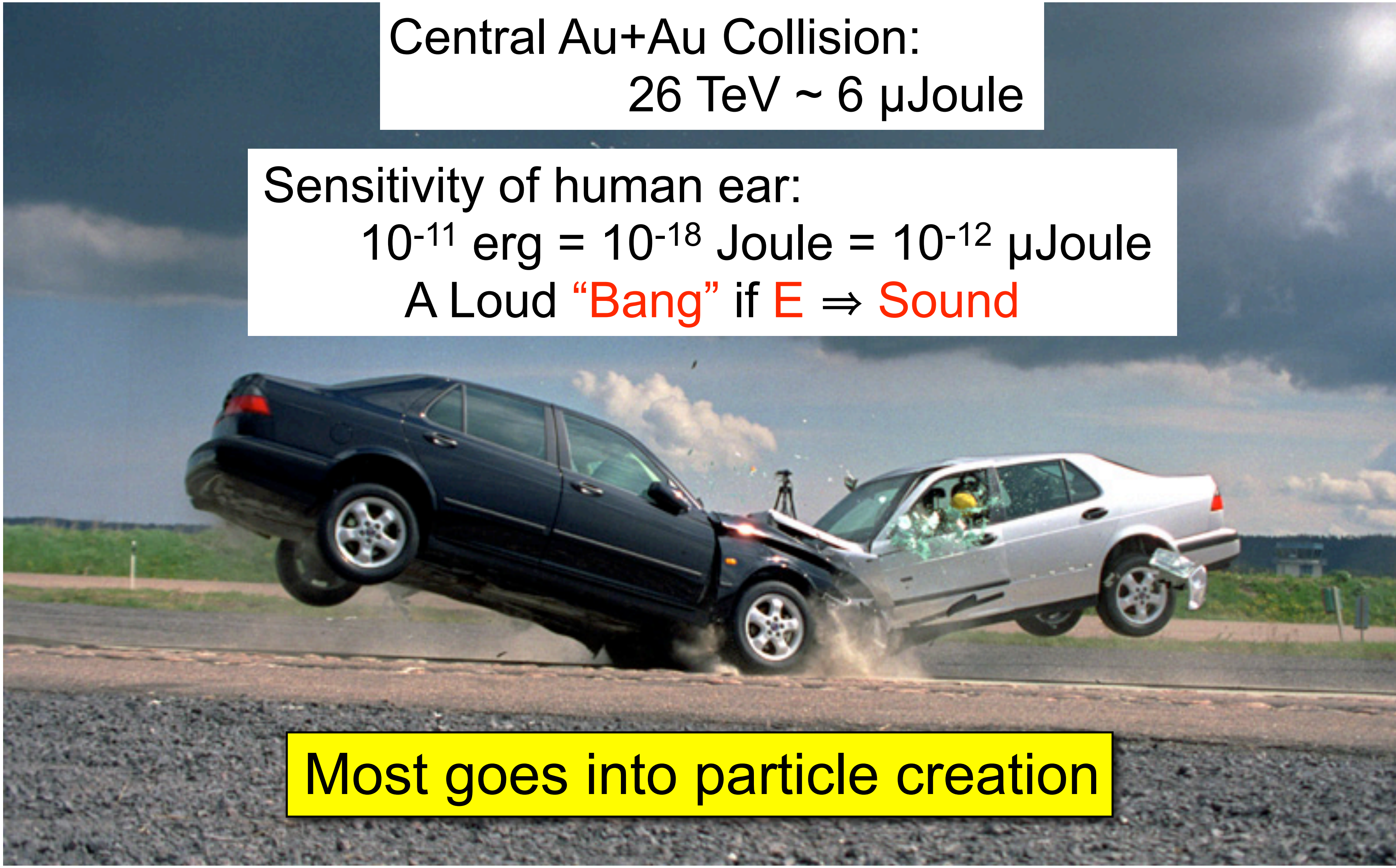
<u>26 TeV</u> is removed from colliding beams.

The energy is contained in one collision

The energy is contained in one collision



The energy is contained in one collision



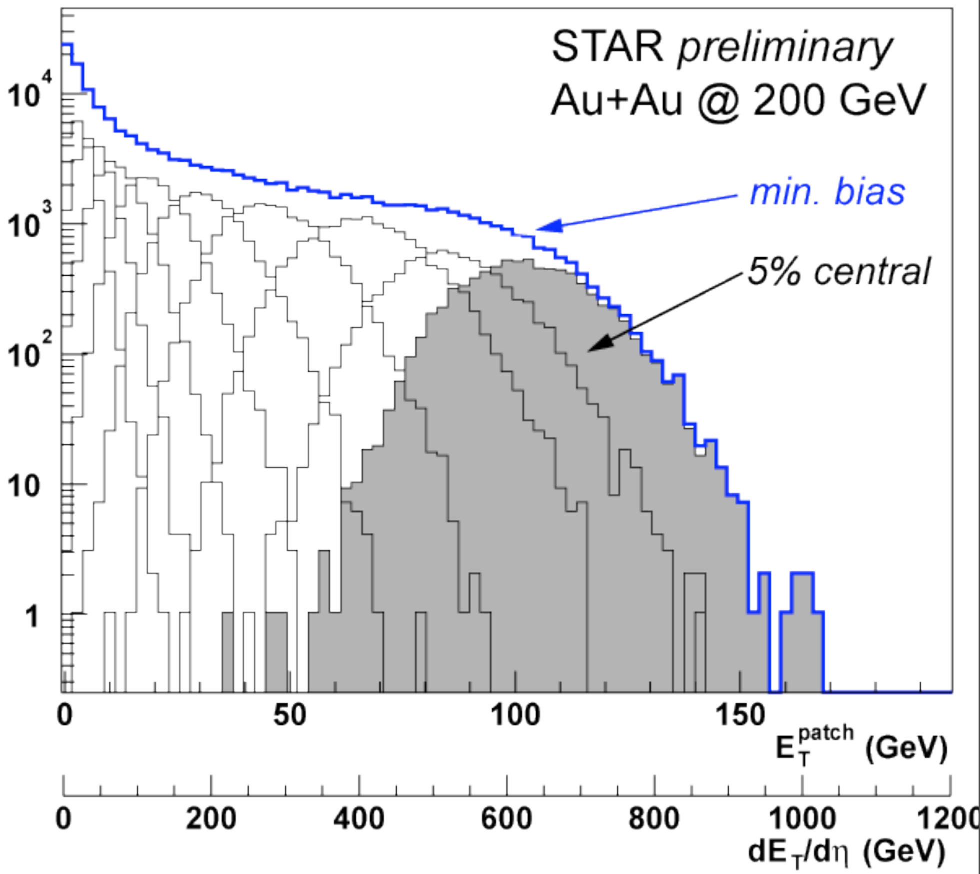
Central Au+Au Collision:
26 TeV ~ 6 μJoule

Sensitivity of human ear:
10^{-11} erg = 10^{-18} Joule = 10^{-12} μJoule
A Loud "Bang" if E ⇒ Sound

Most goes into particle creation

Energy density in central Au-Au collisions

- use calorimeters to measure total energy



Energy density in central Au-Au collisions

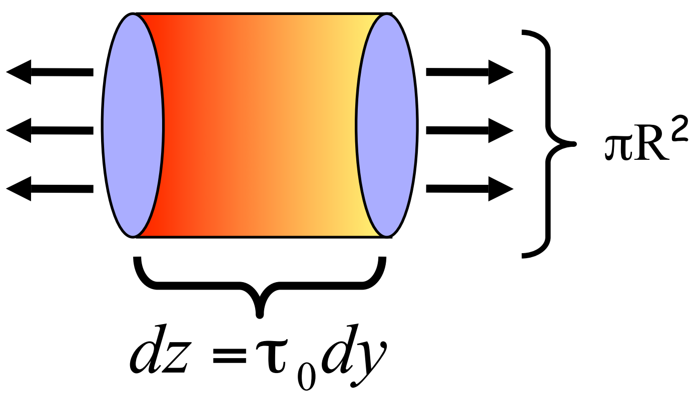
- use calorimeters to measure total energy
- estimate volume of collision

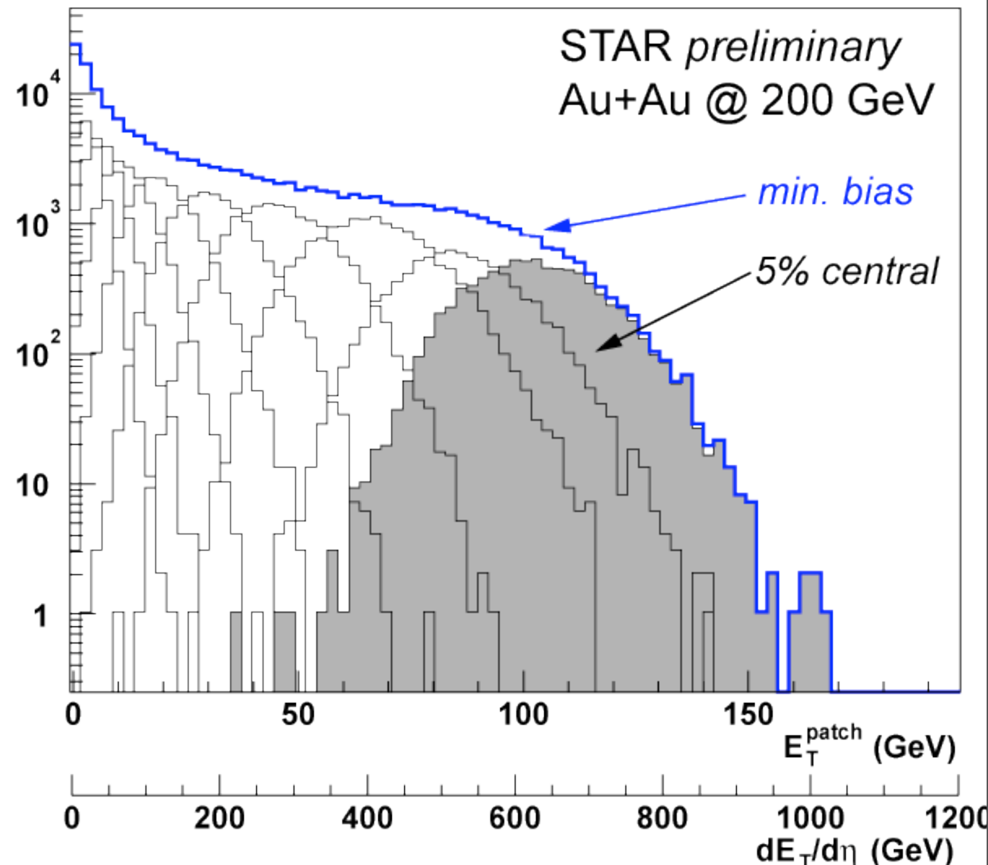
Bjorken-Formula for Energy Density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system (t_0 ~ 1 fm/c)





Energy density in central Au-Au collisions

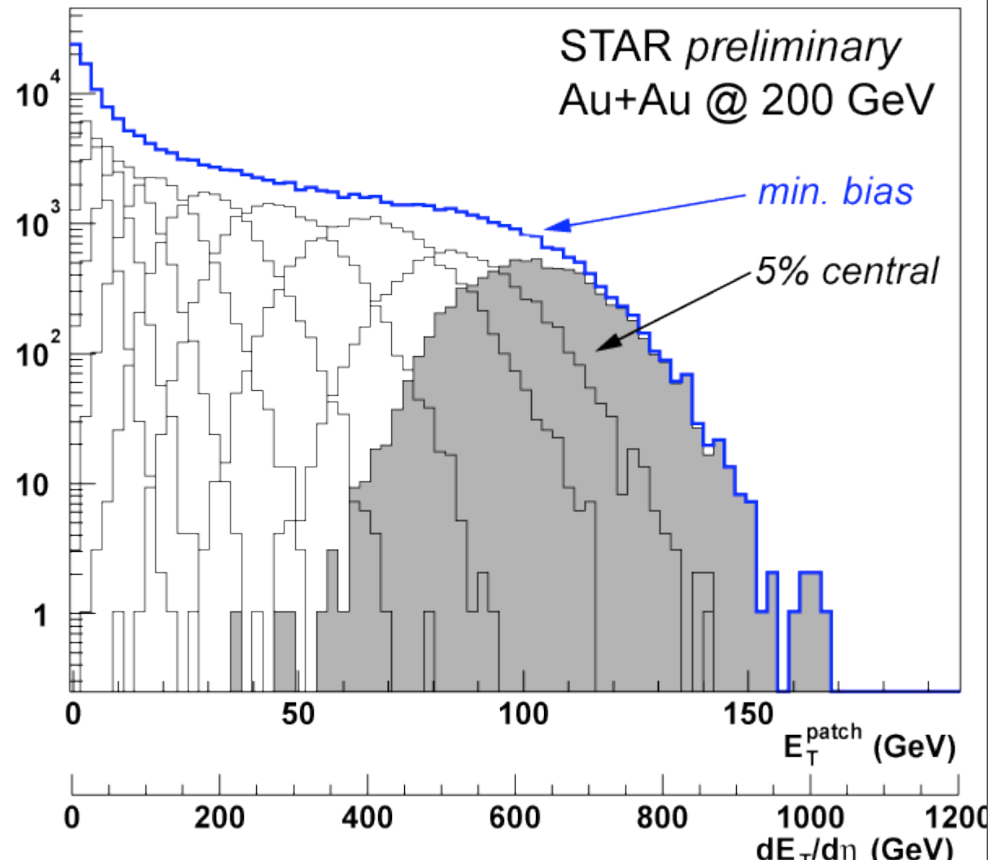
- use calorimeters to measure total energy
- estimate volume of collision

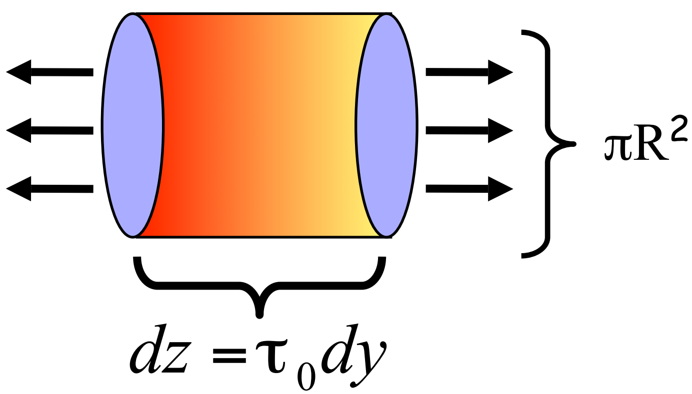
Bjorken-Formula for Energy Density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system (t_0 ~ 1 fm/c)





$\varepsilon_{BJ} \approx 5.0$ GeV/fm^3

~30 times normal nuclear density

~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

5 GeV/fm^3. Is that a lot?

In a year, the U.S. uses ~100 quadrillion BTUs of energy (1 BTU = 1 burnt match):

$$100 \times 10^{15} BTU \times \frac{1060 J}{BTU} \times \frac{1 eV}{1.6 \times 10^{-19} J} = 6.6 \times 10^{38} eV$$

5 GeV/fm^3. Is that a lot?

In a year, the U.S. uses ~100 quadrillion BTUs of energy (1 BTU = 1 burnt match):

$$100 \times 10^{15} BTU \times \frac{1060J}{BTU} \times \frac{1eV}{1.6 \times 10^{-19} J} = 6.6 \times 10^{38} eV$$

At 5 GeV/fm^3, this would fit in a volume of:

$$6.6 \times 10^{38} eV \div \frac{5 \times 10^{9} eV}{fm^3} = 1.3 \times 10^{29} fm^3$$

5 GeV/fm³. Is that a lot?

In a year, the U.S. uses ~100 quadrillion BTUs of energy (1 BTU = 1 burnt match):

$$100 \times 10^{15} BTU \times \frac{1060J}{BTU} \times \frac{1eV}{1.6 \times 10^{-19}J} = 6.6 \times 10^{38} eV$$

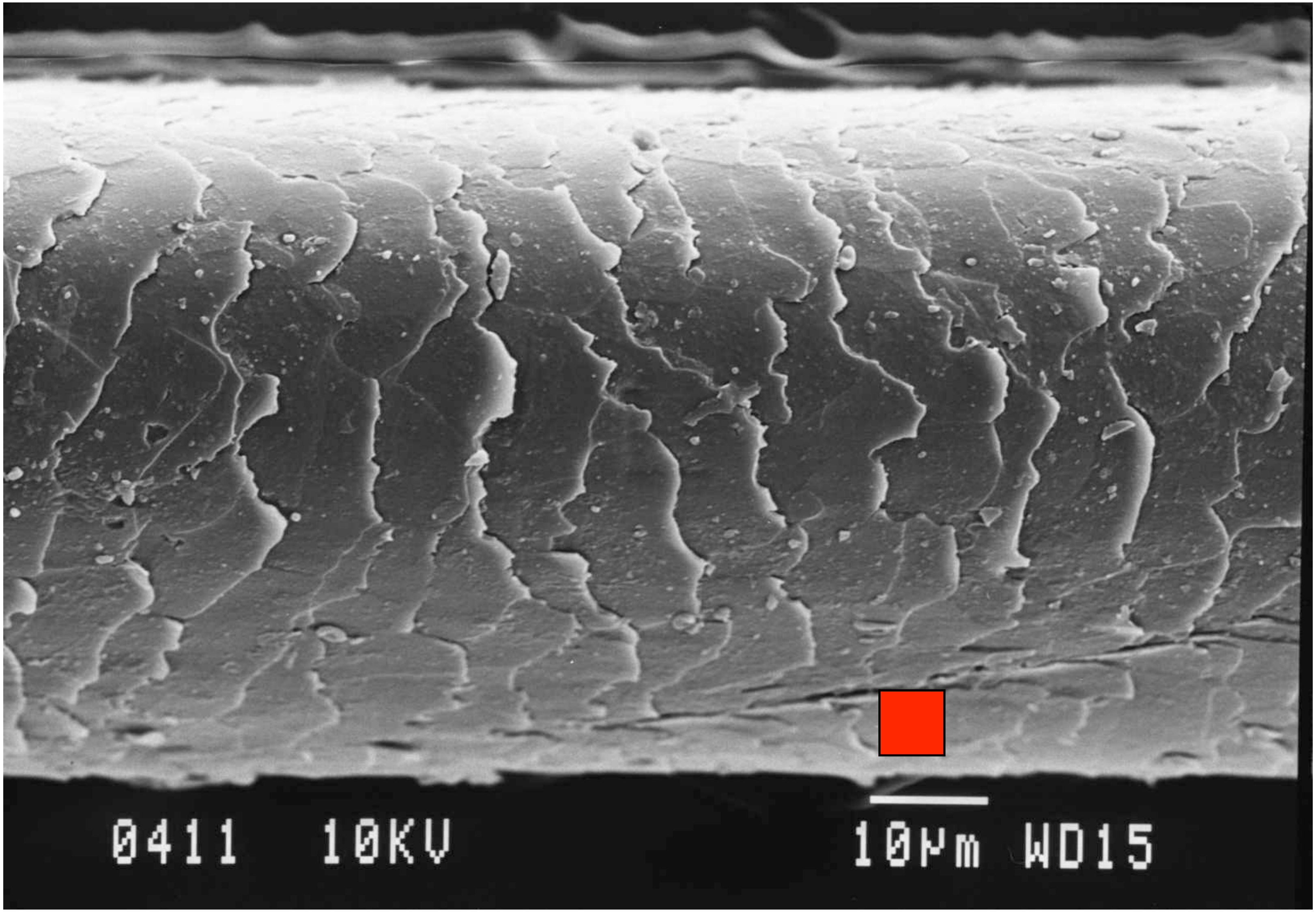
At 5 GeV/fm³, this would fit in a volume of:

$$6.6 \times 10^{38} eV \div \frac{5 \times 10^{9} eV}{fm^3} = 1.3 \times 10^{29} fm^3$$

Or, in other words, in a box of the following dimensions:

$$\sqrt[3]{1.3 \times 10^{29}\ fm^3} = 5 \times 10^{9}\ fm = 5 \mu m$$

A human hair



What is the temperature of the medium?

- Statistical Thermal Models:
  - Assume a system that is thermally (constant T_{ch}) and chemically (constant n_i) equilibrated
  - System composed of non-interacting hadrons and resonances
  - Obey conservation laws: Baryon Number, Strangeness, Isospin
- Given T_{ch} and μ 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

Fitting the particle ratios

Number of particles of a given species related to temperature

$$dn_i \sim e^{-(E-\mu_B)/T} d^3p$$

- Assume all particles described by same temperature T and μ_B
- one ratio (e.g., $\bar{p}$ / p) determines μ / T :

$$\frac{\bar{p}}{p} = \frac{e^{-(E-\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-2\mu_B/T}$$

- A second ratio (e.g., K / π) provides T → μ

$$\frac{K}{\pi} = \frac{e^{-E_K/T}}{e^{-E_\pi/T}} = e^{-(E_K-E\pi)/T}$$

- Then all other hadronic ratios (and yields) defined

Fitting the particle ratios

Number of particles of a given species related to temperature

$$dn_i \sim e^{-(E-\mu_B)/T} d^3p$$

- Assume all particles described by same temperature T and μ_B
- one ratio (e.g., $\bar{p}$ / p) determines μ / T :

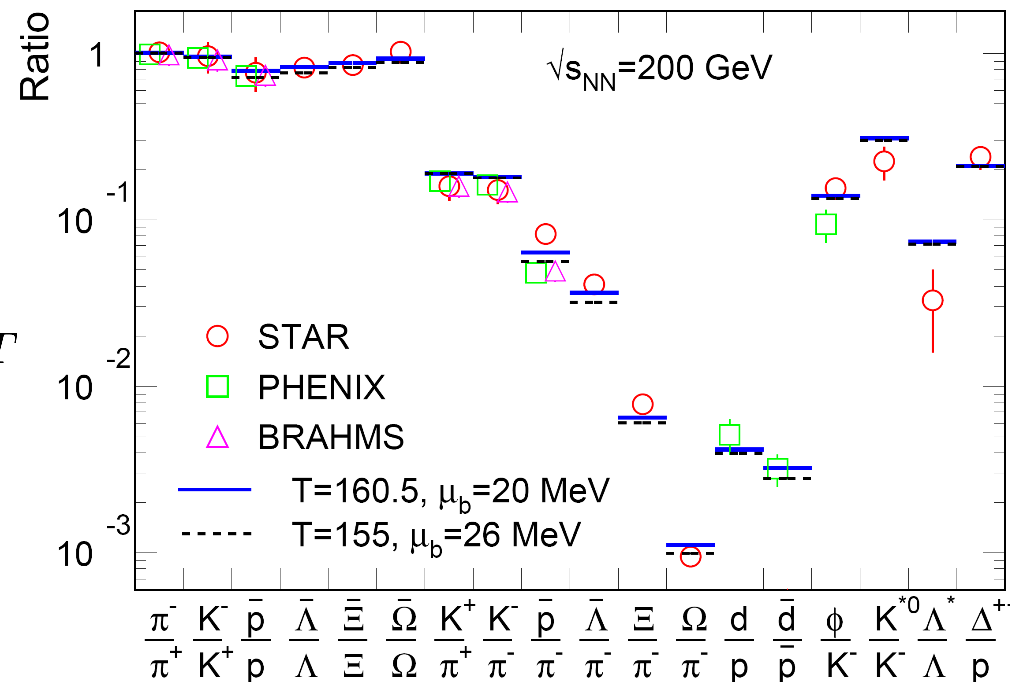
$$\frac{\bar{p}}{p} = \frac{e^{-(E-\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-2\mu_B/T}$$

- A second ratio (e.g., K / π) provides T → μ

$$\frac{K}{\pi} = \frac{e^{-E_K/T}}{e^{-E_\pi/T}} = e^{-(E_K-E_\pi)/T}$$

- Then all other hadronic ratios (and yields) defined

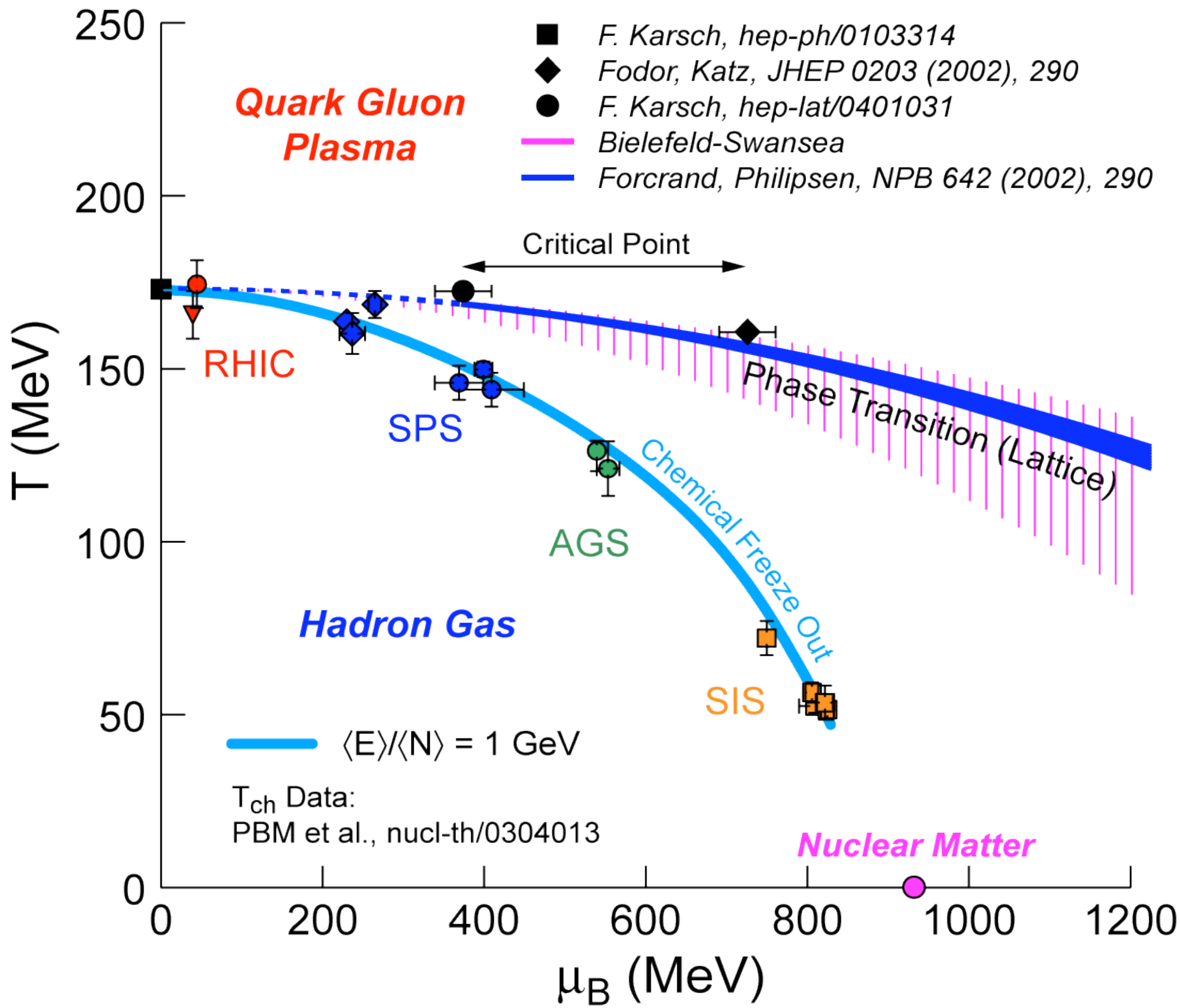
A. Adronic *et al.*, NPA772:167



T ~ 160 MeV, μ_b ~ 20 MeV

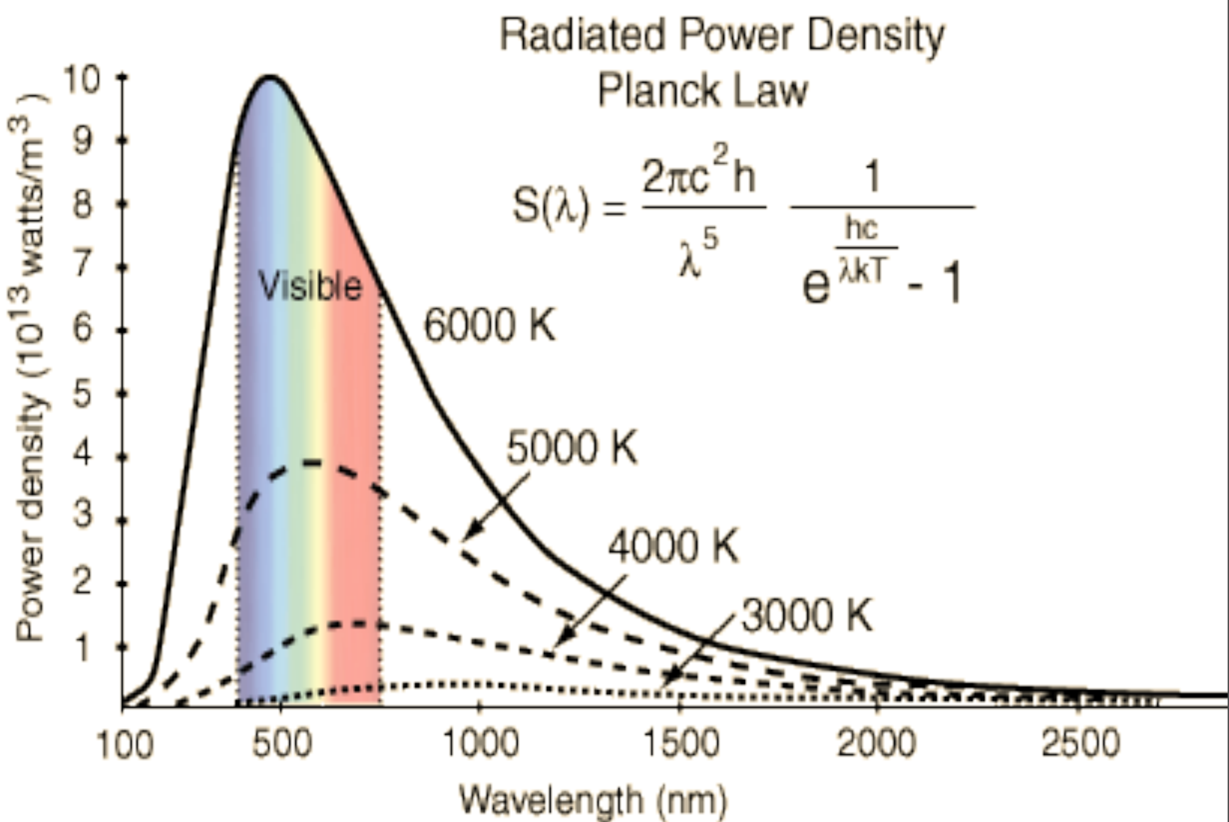
Temperature needed to make QGP

Where RHIC sits on the phase diagram



Blackbody radiation

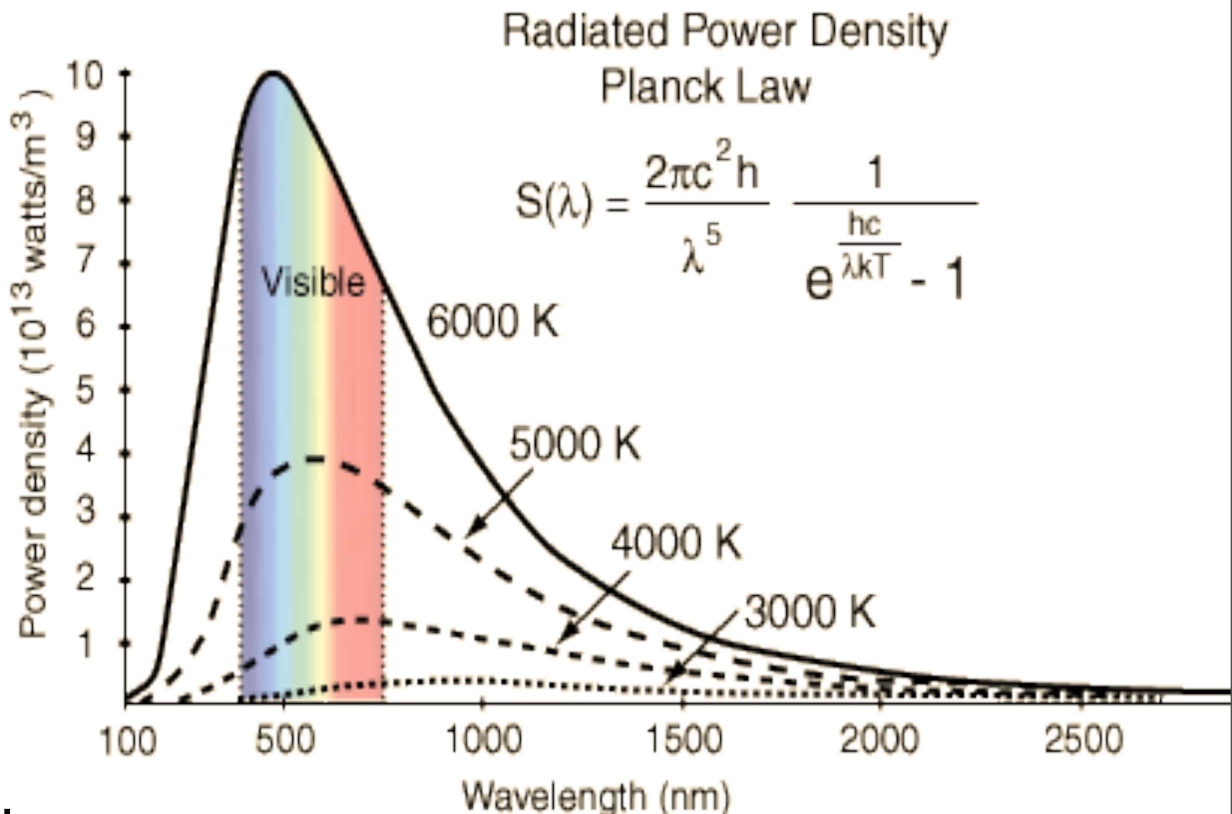
Planck distribution describes intensity as a function of the wavelength of the emitted radiation



Blackbody radiation

Planck distribution describes intensity as a function of the wavelength of the emitted radiation

"Blackbody" radiation is the spectrum of radiation emitted by an object at temperature T

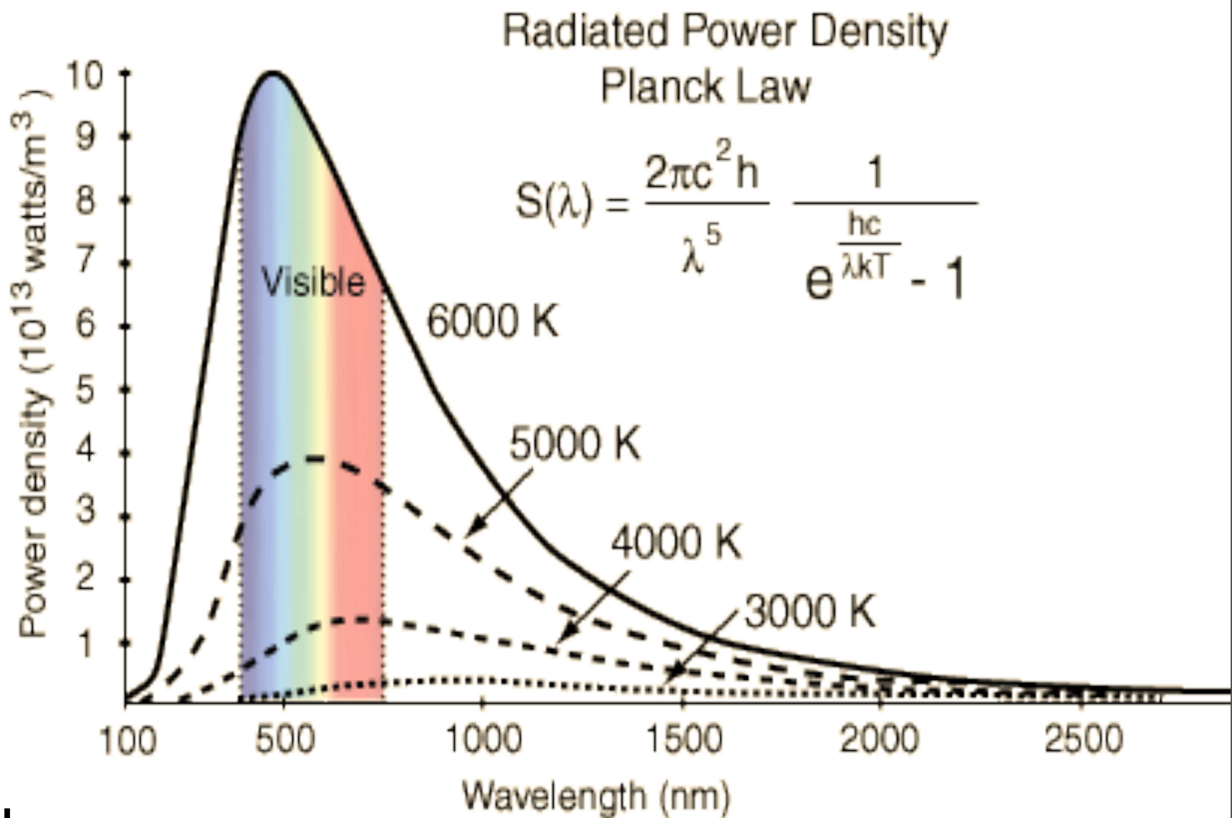


As T increases curve changes

Blackbody radiation

Planck distribution describes intensity as a function of the wavelength of the emitted radiation

"Blackbody" radiation is the spectrum of radiation emitted by an object at temperature T



As T increases curve changes

1/Wavelength ∝ Frequency ∝ E ∝ p

Determining the temperature

From transverse momentum distribution deduce temperature

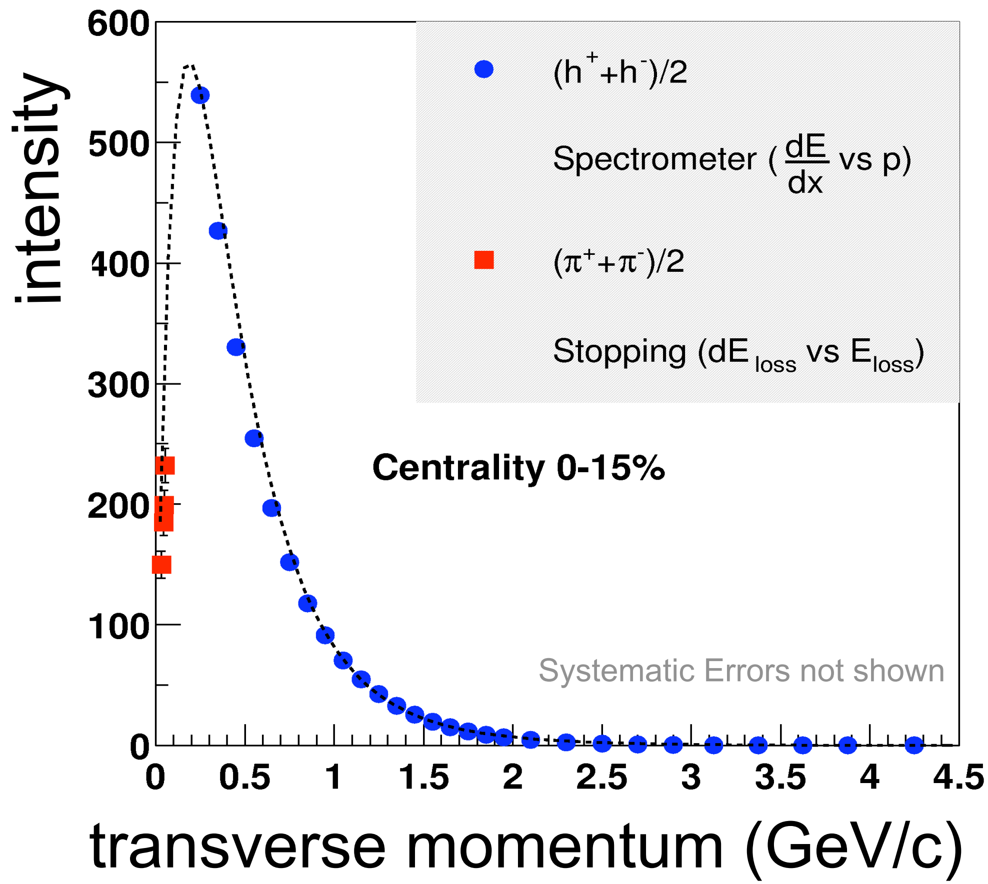
~120 MeV

$$E = \frac{3}{2}kT$$

$$T = \frac{2E}{3k}$$

$$= \frac{2 \times 120 \times 10^6}{3 \times 1.4 \times 10^{-23}} \times 1.6 \times 10^{-19}$$

$$\sim 9 \times 10^{11} K$$



Determining the temperature

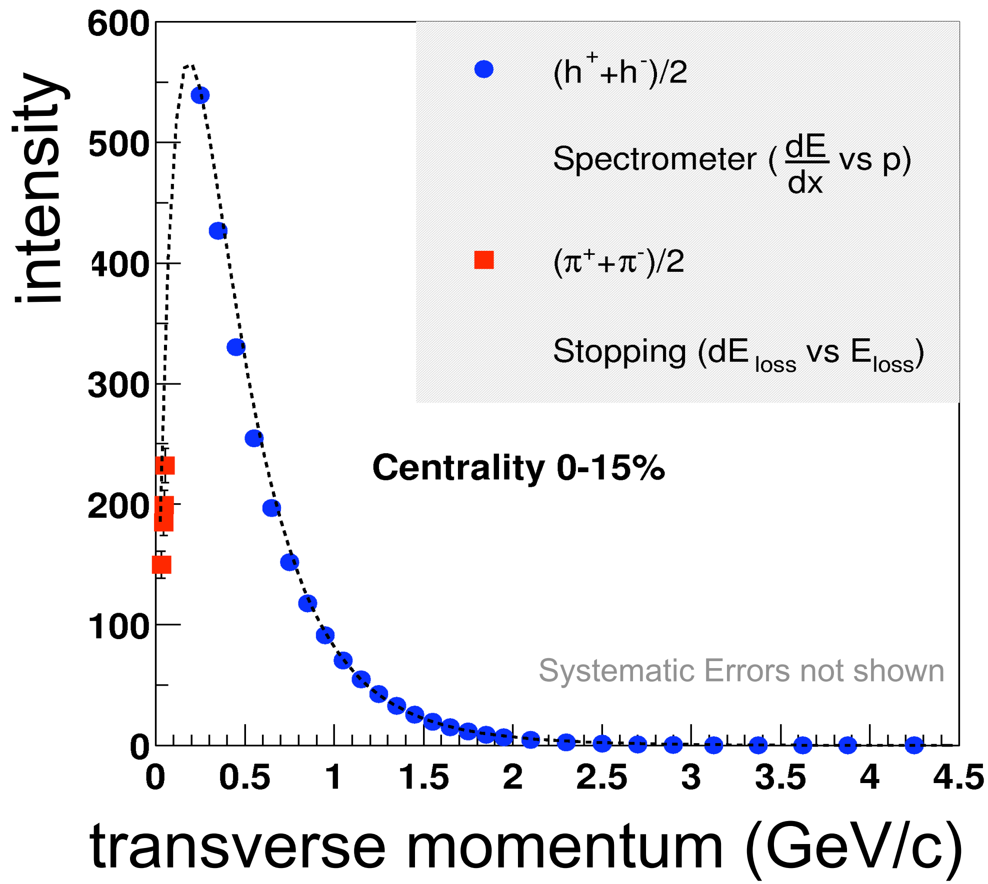
From transverse momentum distribution deduce temperature
~120 MeV

$$E = \frac{3}{2}kT$$

$$T = \frac{2E}{3k}$$

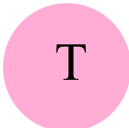
$$= \frac{2 \times 120 \times 10^{6}}{3 \times 1.4 \times 10^{-23}} \times 1.6 \times 10^{-19}$$

$$\sim 9 \times 10^{11} K$$

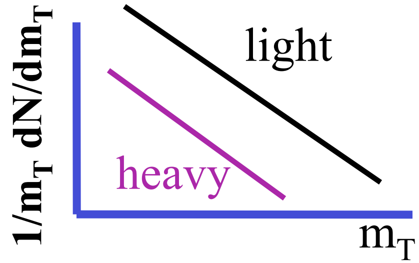


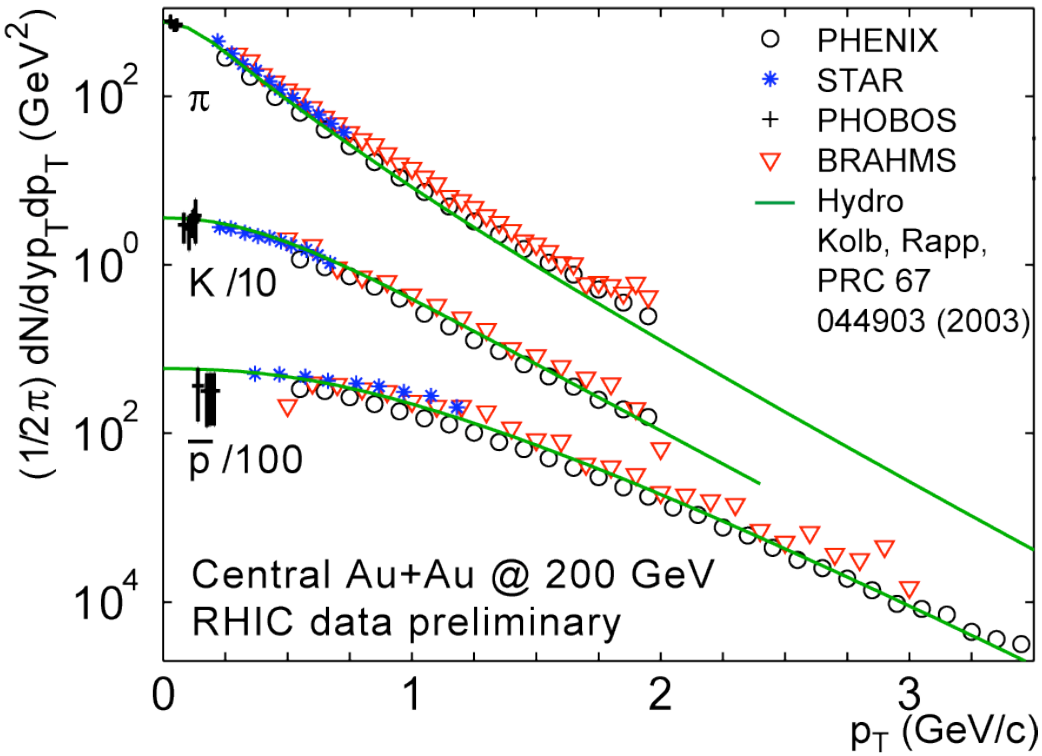
Again temperature needed to create QGP

Strong collective radial expansion

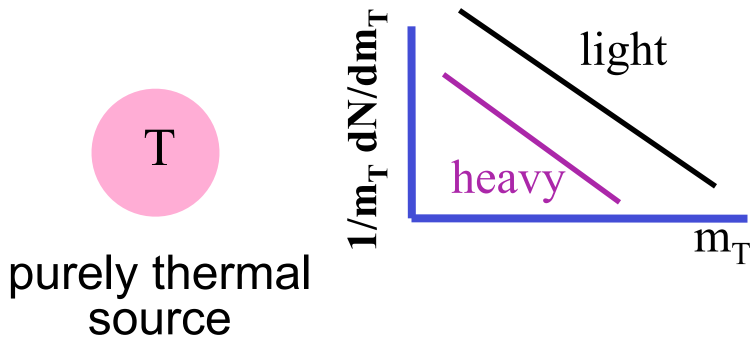


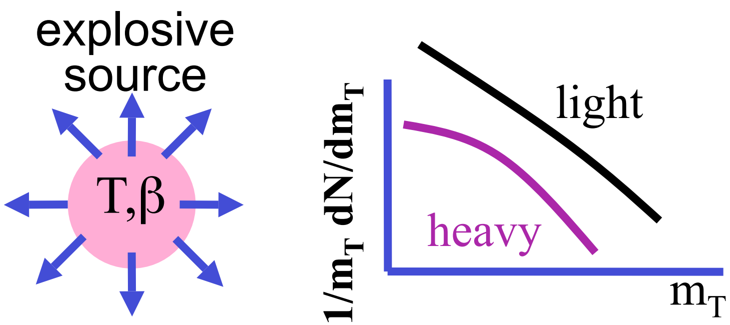
purely thermal source



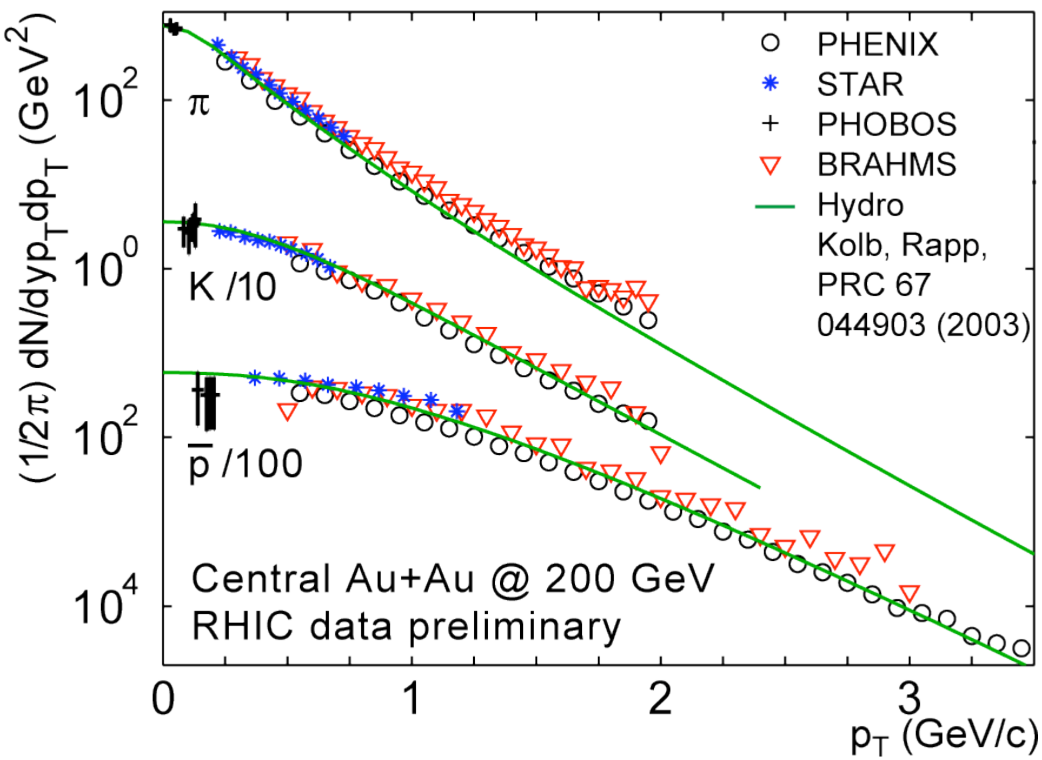


Strong collective radial expansion



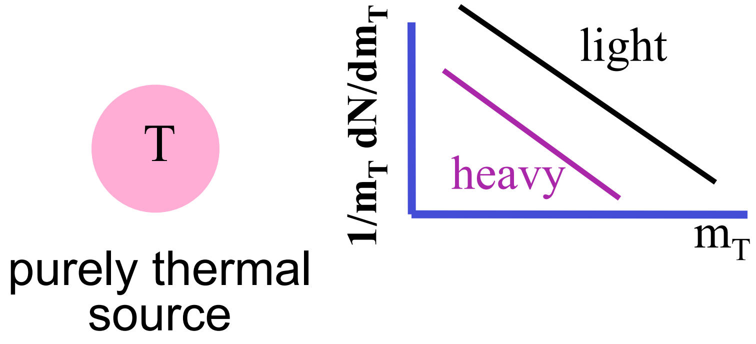


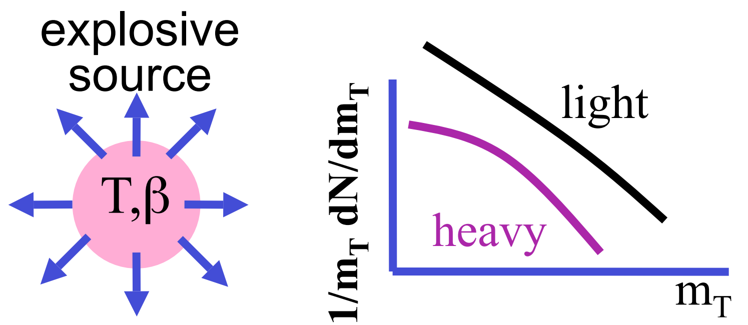
$m_T = (p_T^2 + m^2)^{½}$



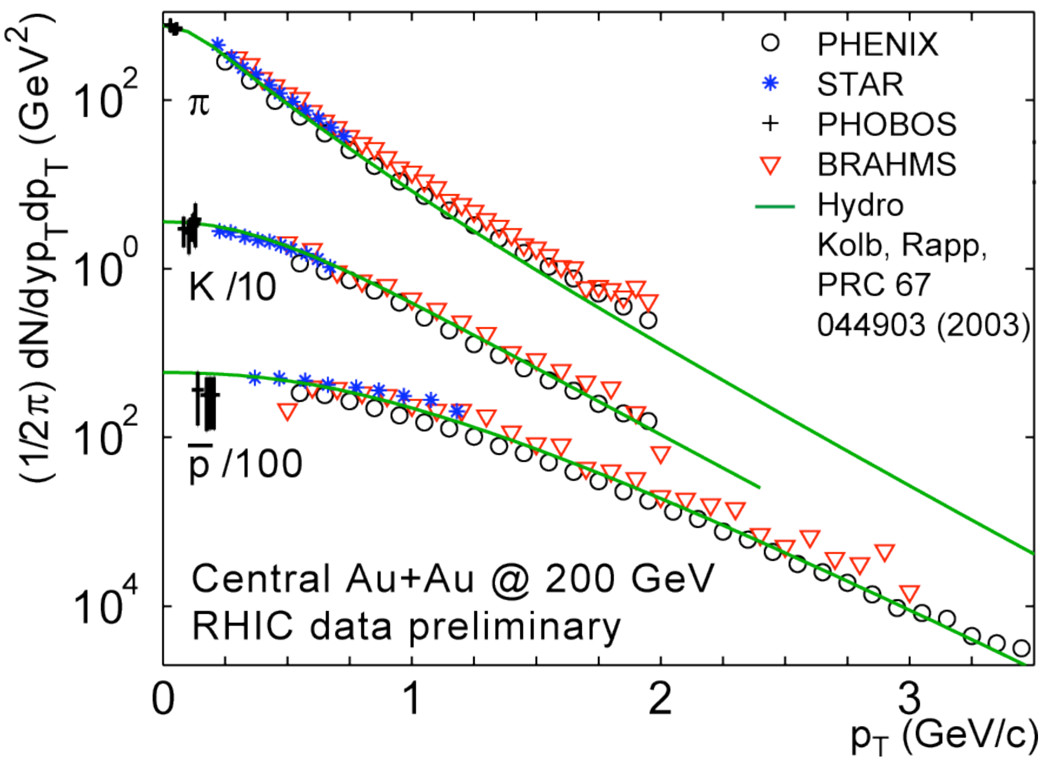
- Different spectral shapes for particles of differing mass → strong collective radial flow

Strong collective radial expansion





$m_T = (p_T^2 + m^2)^{½}$



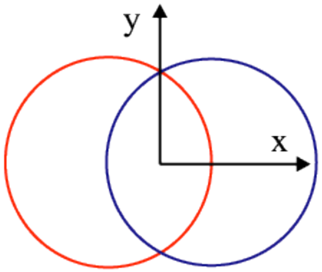
T_{fo}~ 100 MeV

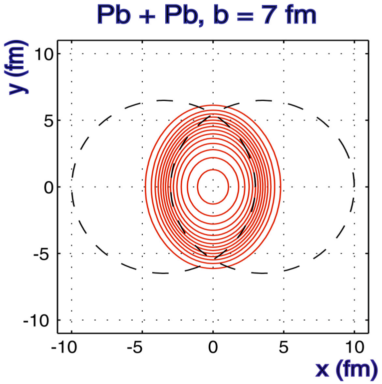
⟨ β_T ⟩ ~ 0.55 c

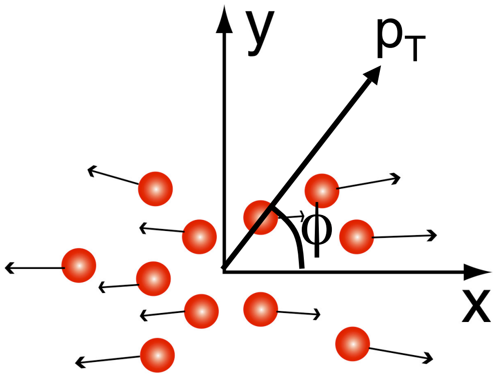
- Different spectral shapes for particles of differing mass → strong collective radial flow

Good agreement with hydrodynamic prediction for soft EOS (QGP+HG)

Anisotropic/Elliptic flow





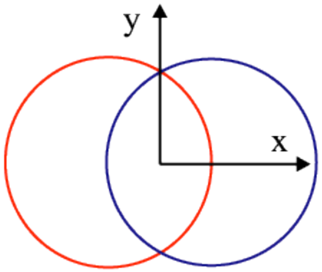


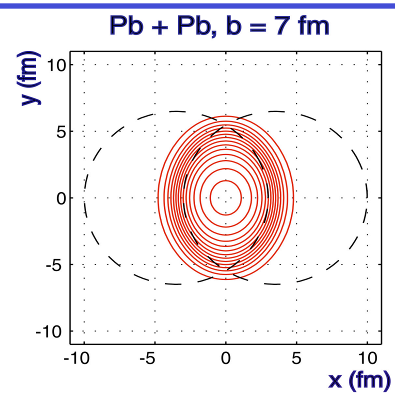
Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

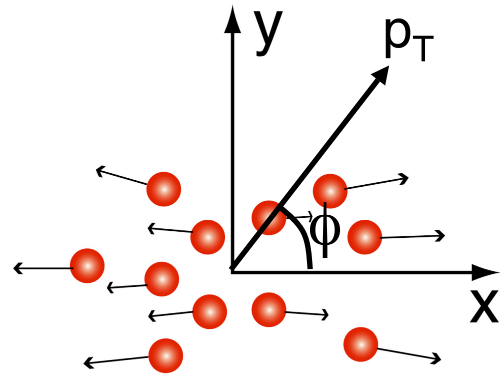
$dN/d\phi \sim 1+2\, v_2(p_T)\cos(2\phi) + \ldots$ $\phi = \mathrm{atan}(p_y/p_x)$ $v_2 = \langle \cos 2\phi \rangle$

v_2: 2^{nd} harmonic Fourier coefficient in $dN/d\phi$ with respect to the reaction plane

Anisotropic/Elliptic flow



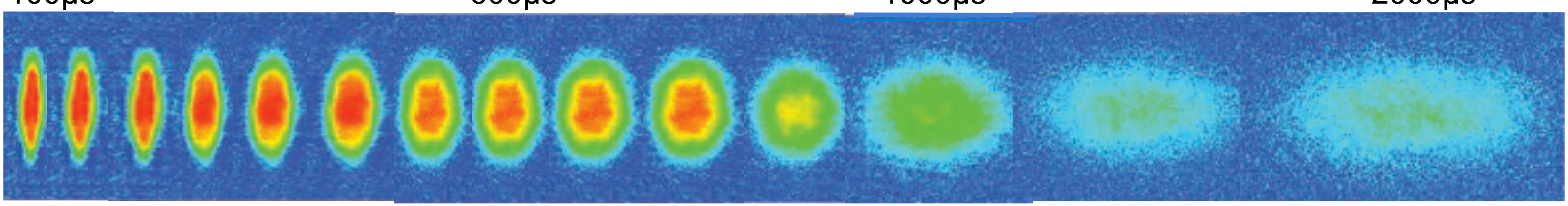




Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

$dN/d\phi \sim 1+2\, v_2(p_T)\cos(2\phi) + \ldots.$ $\phi = \mathrm{atan}(p_y/p_x)$ $v_2 = \langle \cos 2\phi \rangle$

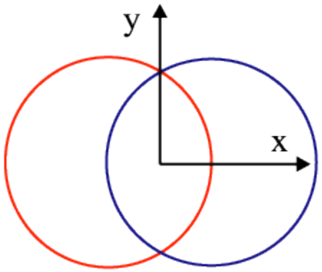
v_2: 2nd harmonic Fourier coefficient in $dN/d\phi$ with respect to the reaction plane

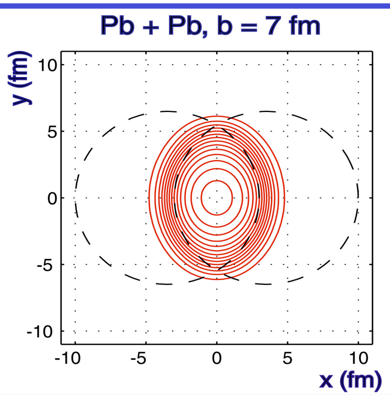


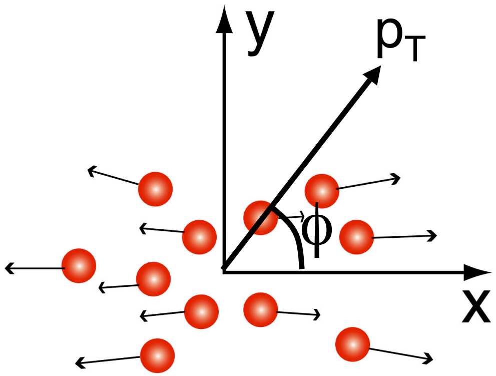
Time

–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Anisotropic/Elliptic flow



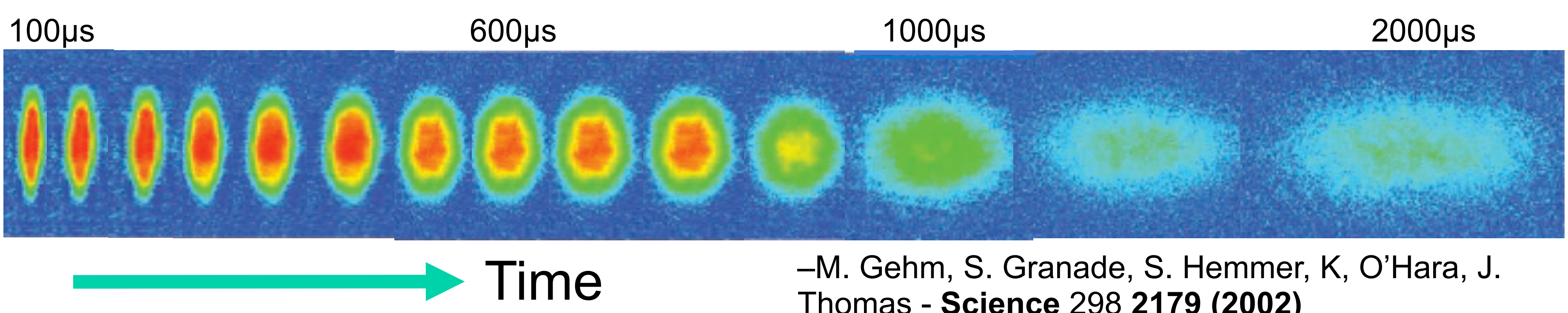




Elliptic flow observable sensitive to early evolution of system

Mechanism is self-quenching

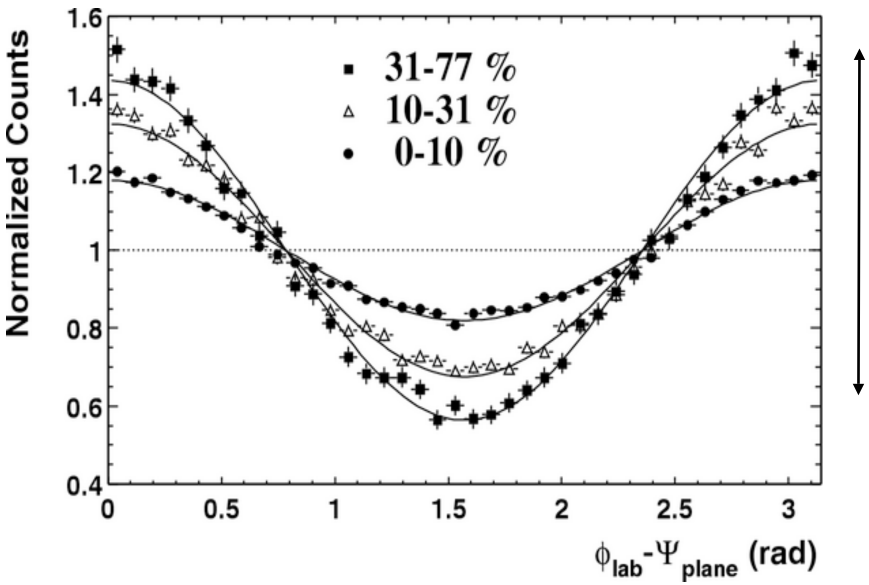
Large v_2 is an indication of ***early*** thermalization



–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Elliptic flow

Distribution of particles with respect to event plane, $\phi-\psi$, $p_t>2$ GeV; STAR PRL 90 (2003) 032301

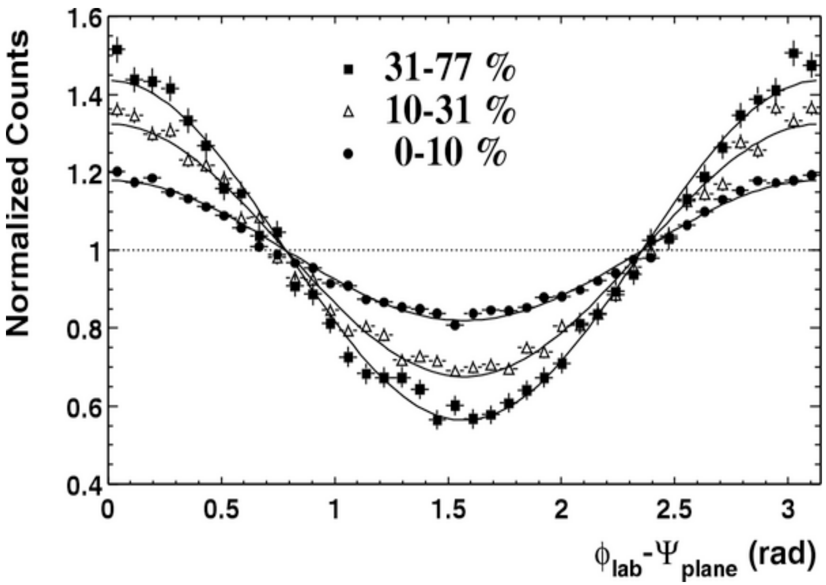


- Very strong elliptic flow → early equilibration

Factor 3:1 peak to valley

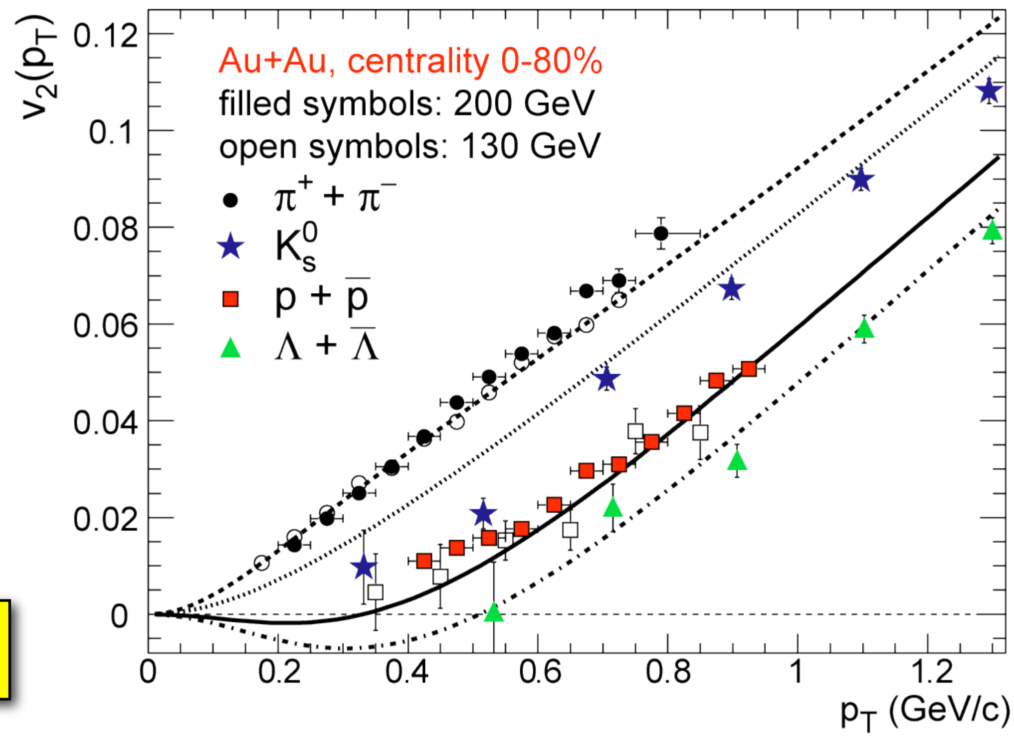
Elliptic flow

Distribution of particles with respect to event plane, $\phi-\psi$, p_t>2 GeV; STAR PRL 90 (2003) 032301



Factor 3:1 peak to valley

- Very strong elliptic flow → early equilibration



- Pure hydrodynamical models including QGP phase describe elliptic and radial flow for many species

QGP→ almost perfect fluid

The constituents "flow"

- Elliptic flow is additive.
- If partons are flowing the *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2 v_2(p_T)\cos(2\phi)$$

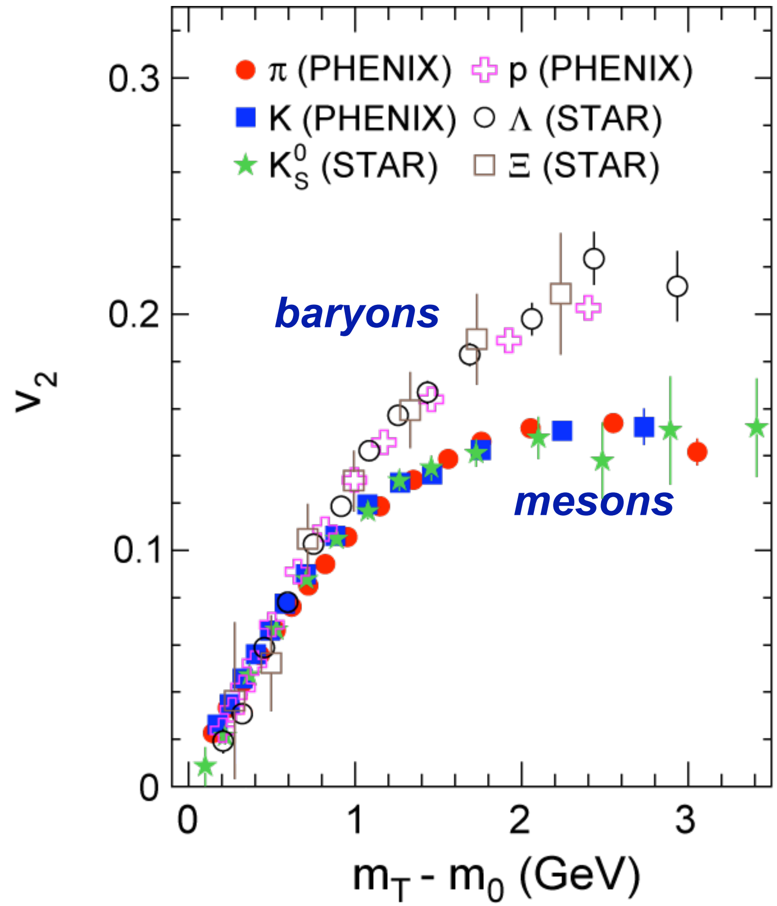
should become *simple* at the quark level

$p_T \rightarrow p_T / n$

$v_2 \rightarrow v_2 / n$,

n = (2, 3) for (meson, baryon)

$$m_T = \sqrt{p_T^2 + m_0^2}$$



The constituents "flow"

- Elliptic flow is additive.
- If partons are flowing the *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2 v_2(p_T)\cos(2\phi)$$

should become *simple* at the quark level

$p_T \rightarrow p_T / n$

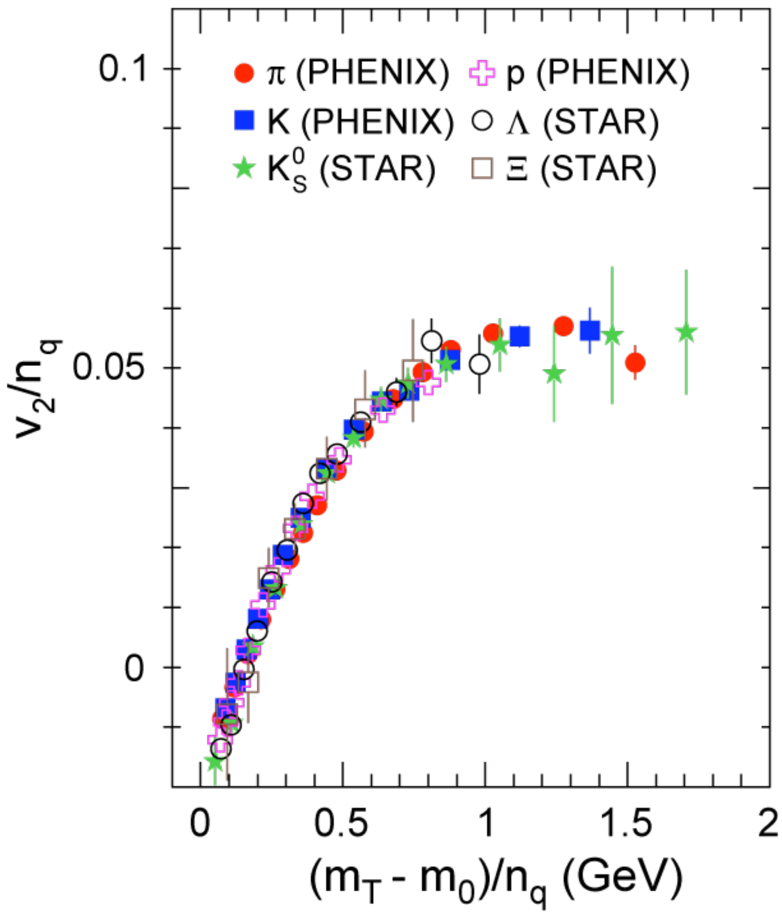
$v_2 \rightarrow v_2 / n$,

n = (2, 3) for (meson, baryon)

Works for p, π, K^0_s, Λ, Ξ..

$v_2^s \sim v_2^{u,d} \sim 7\%$

$$m_T = \sqrt{p_T^2 + m_0^2}$$



Constituents of QGP are partons

Summary of what we learned so far

- Energy density in the collision region is way above that where hadrons can exist

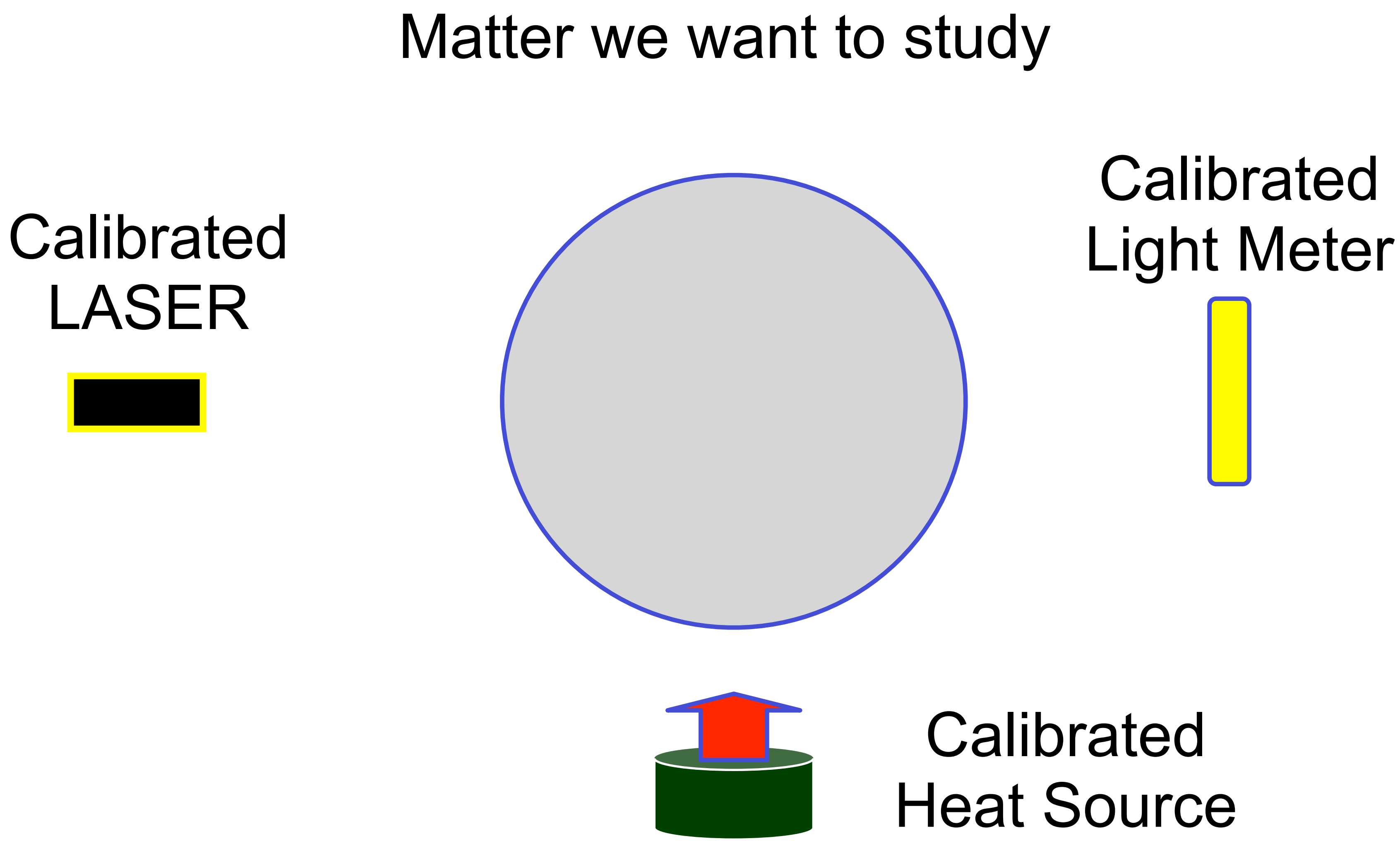
- The initial temperature of collision region is way above that where hadrons can exist

- The medium has quark and gluon degrees of freedom in initial stages

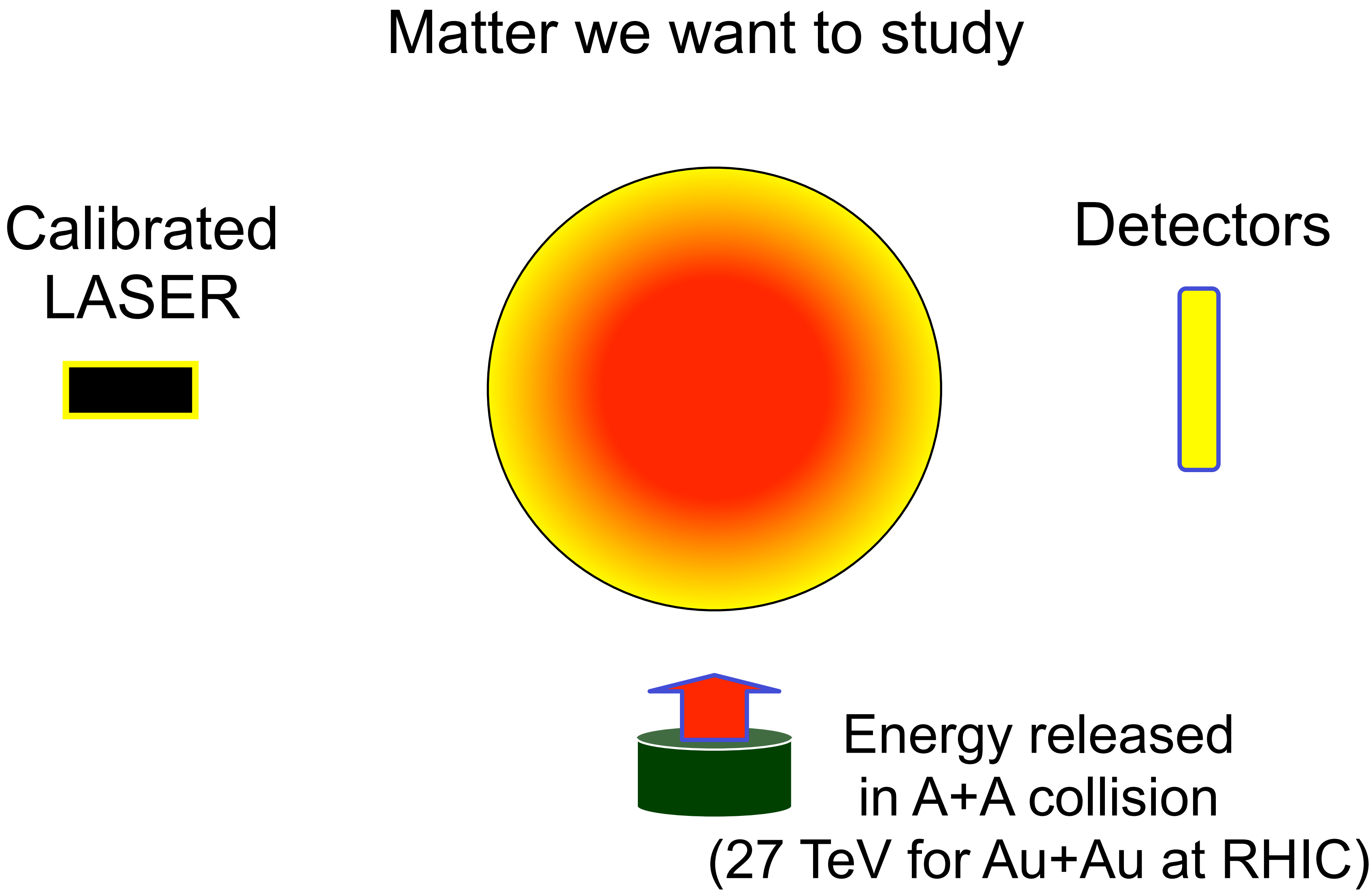
We have created a new state of matter at RHIC - the QGP

- The QGP is flowing like an almost "perfect" liquid

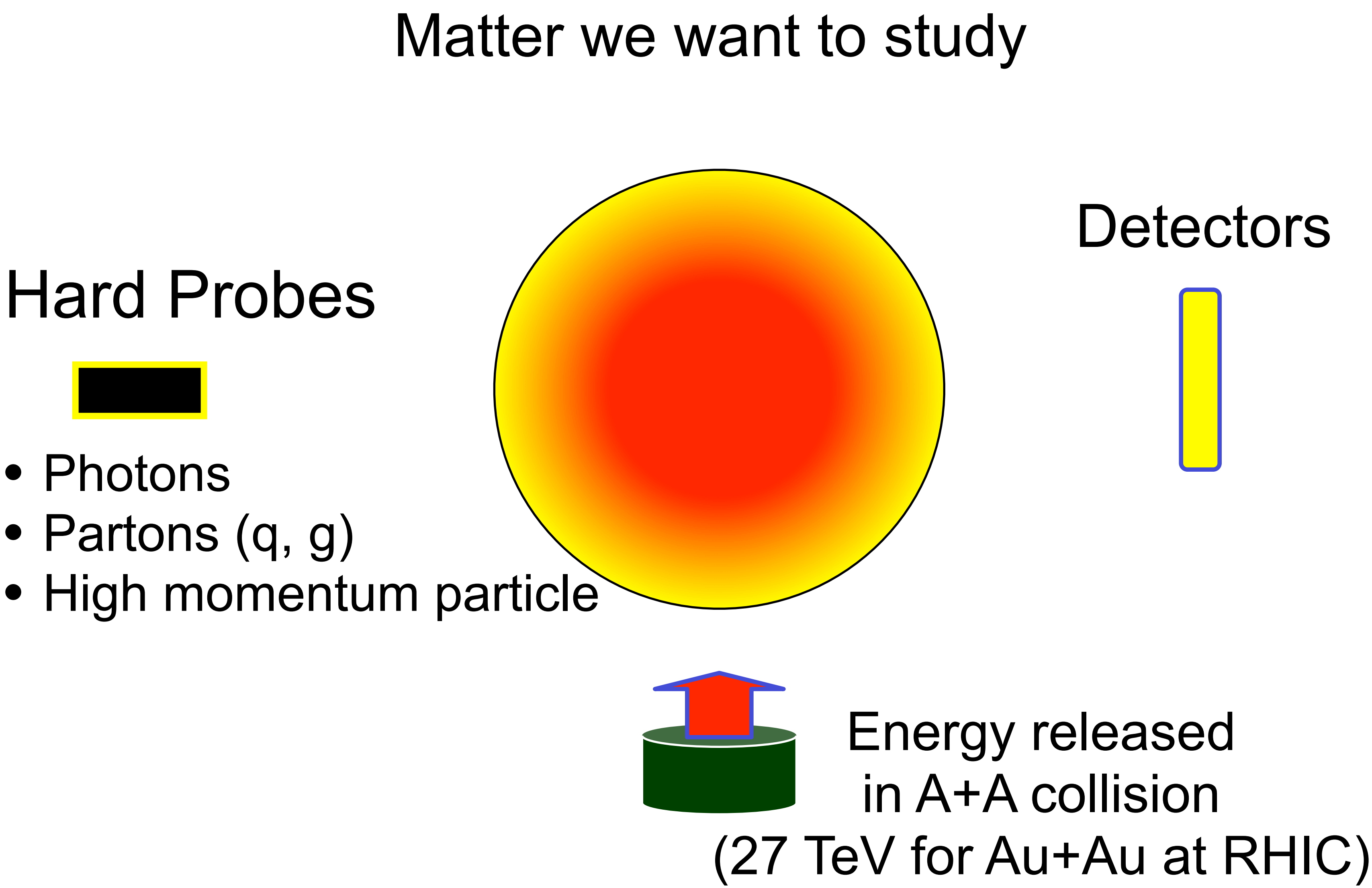
How to learn more about QGP?



How to learn more about QGP?



How to learn more about QGP?

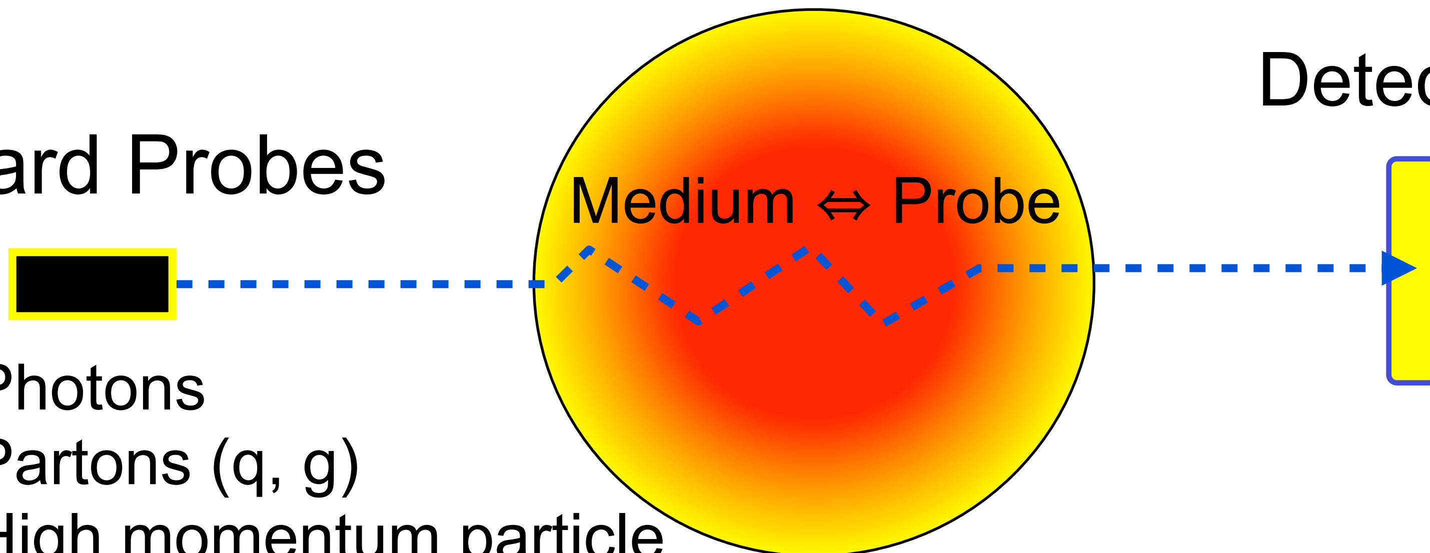


How to learn more about QGP?

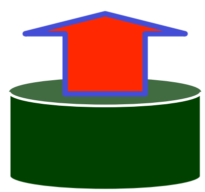
Matter we want to study

Detectors

Hard Probes



- Photons
- Partons (q, g)
- High momentum particle



Energy released
in A+A collision
(27 TeV for Au+Au at RHIC)

How to learn more about QGP?

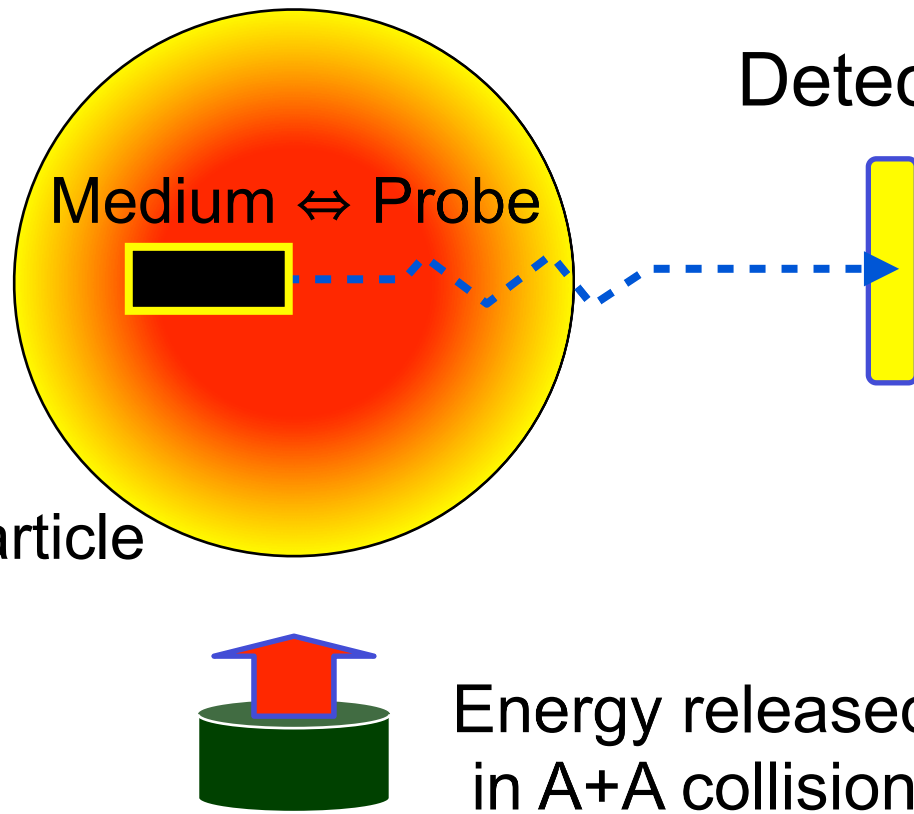
Matter we want to study

Detectors

Hard Probes

Self-generated probes

- Photons
- Partons (q, g)
- High momentum particle

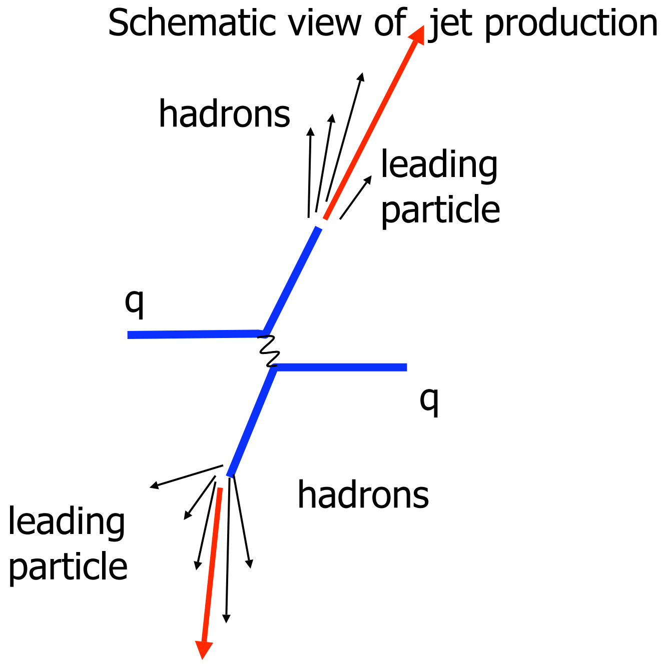


Energy released
in A+A collision
(27 TeV for Au+Au at RHIC)

Using high momentum particles as probes

Early production in parton-parton scatterings with large Q^2.

Direct interaction with partonic phases of the reaction



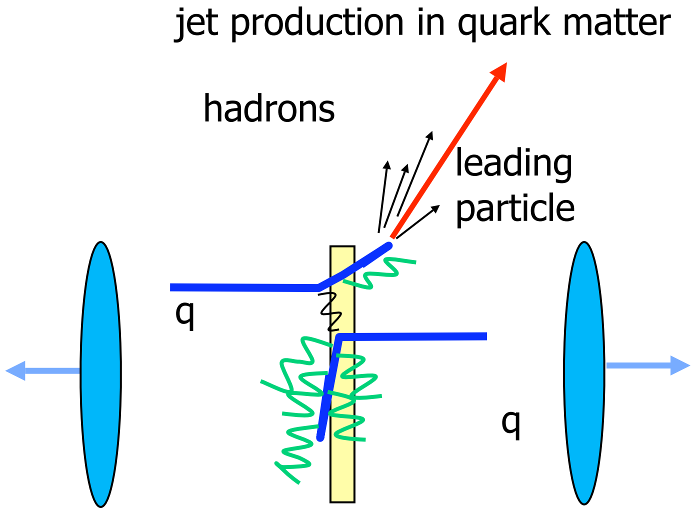
Using high momentum particles as probes

Early production in parton-parton scatterings with large Q^2.

Direct interaction with partonic phases of the reaction

Therefore use these high momentum products as probes at RHIC

- attenuation or absorption of high p_T hadrons



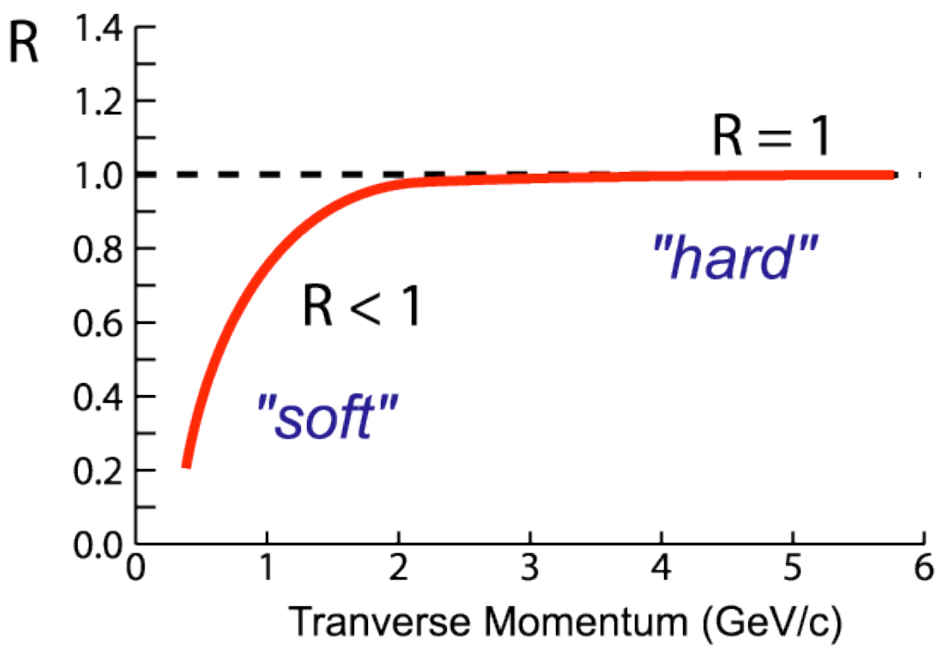
Looking for attenuation/absorption

Compare to p-p at same collision energy

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Average number of p-p collision in A-A collision

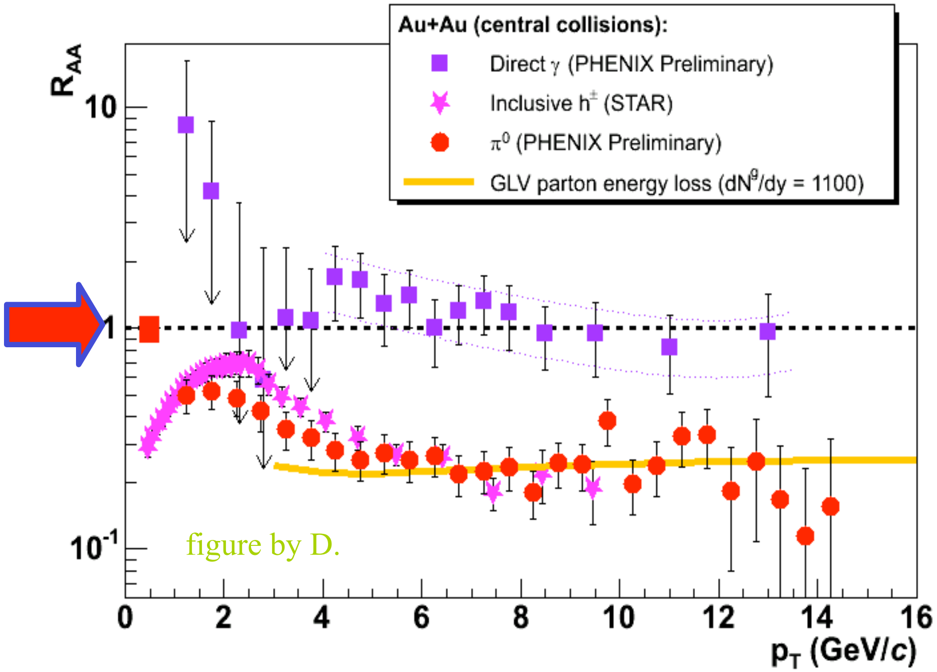


No "Effect":

- R < 1 at small momenta - production from thermal bath
- R = 1 at higher momenta where hard processes dominate

R<1 at high p_T if QGP affecting parton's propagation

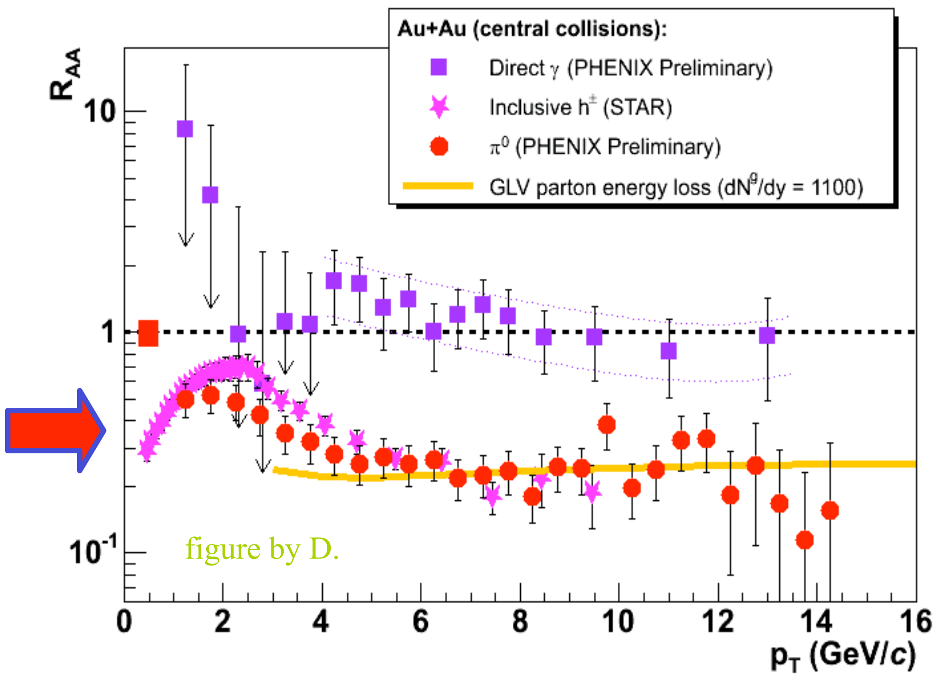
High-p_T suppression



Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works

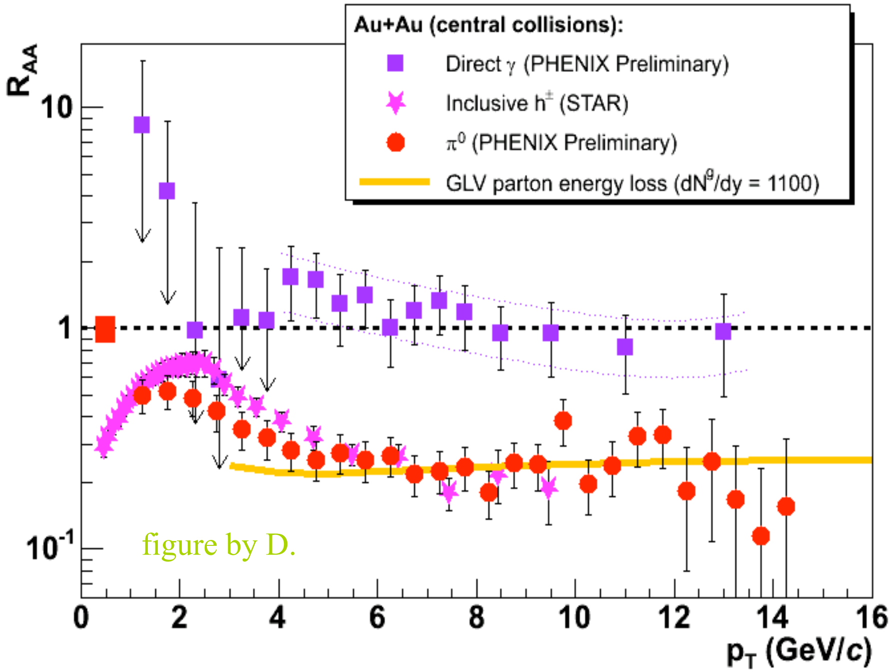
High-p_T suppression



Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works
2. Hadrons are suppressed in central collisions
   - Huge: factor 5

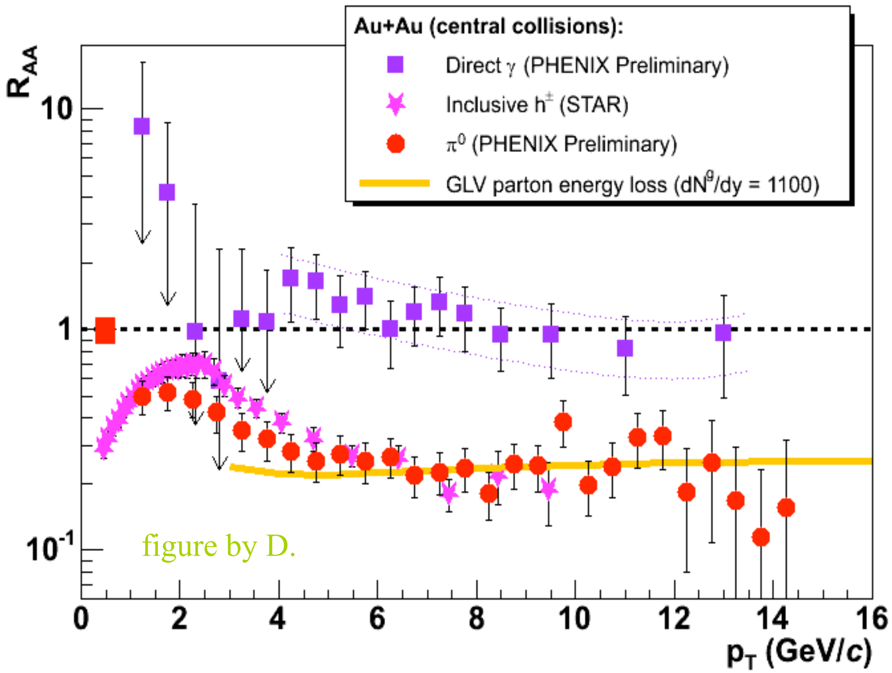
High-p_T suppression



Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works
2. Hadrons are suppressed in central collisions
   - Huge: factor 5
3. Hadrons are not suppressed in peripheral collisions
   - Good! medium less dense

High-p_T suppression

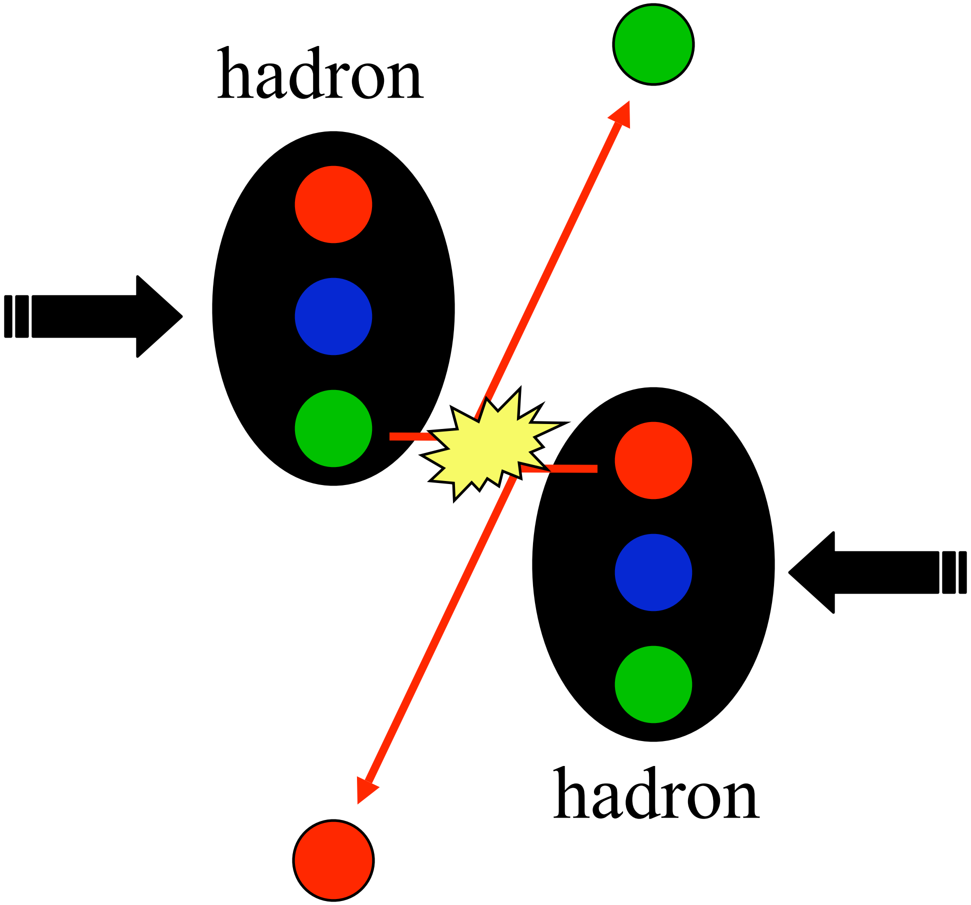


Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works
2. Hadrons are suppressed in central collisions
   - Huge: factor 5
3. Hadrons are not suppressed in peripheral collisions
   - Good! medium less dense

sQGP - strongly coupled - colored objects suffer large energy loss

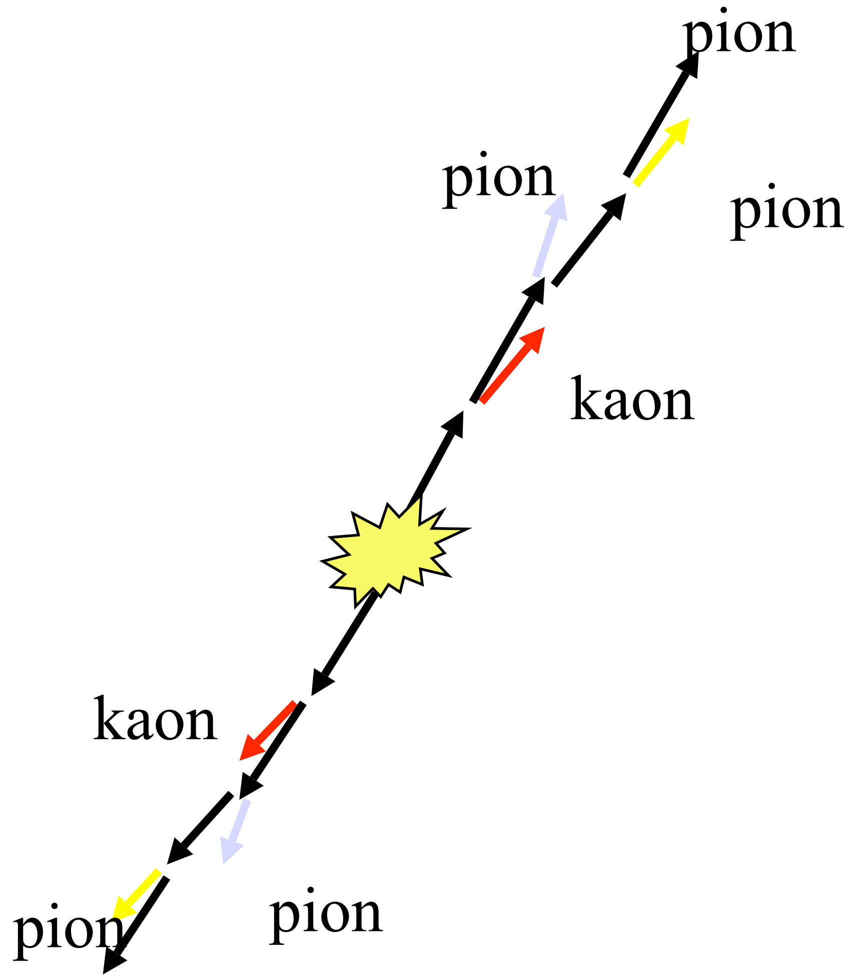
Definition of a "jet"



Definition of a "jet"

- Use Jets – the possible for "knock-on" collisions of partons
- The fragmented "bits" appear as "normal" subatomic particles

  pions, kaons,etc
- Seen in high-energy physics experiments since mid-1970's

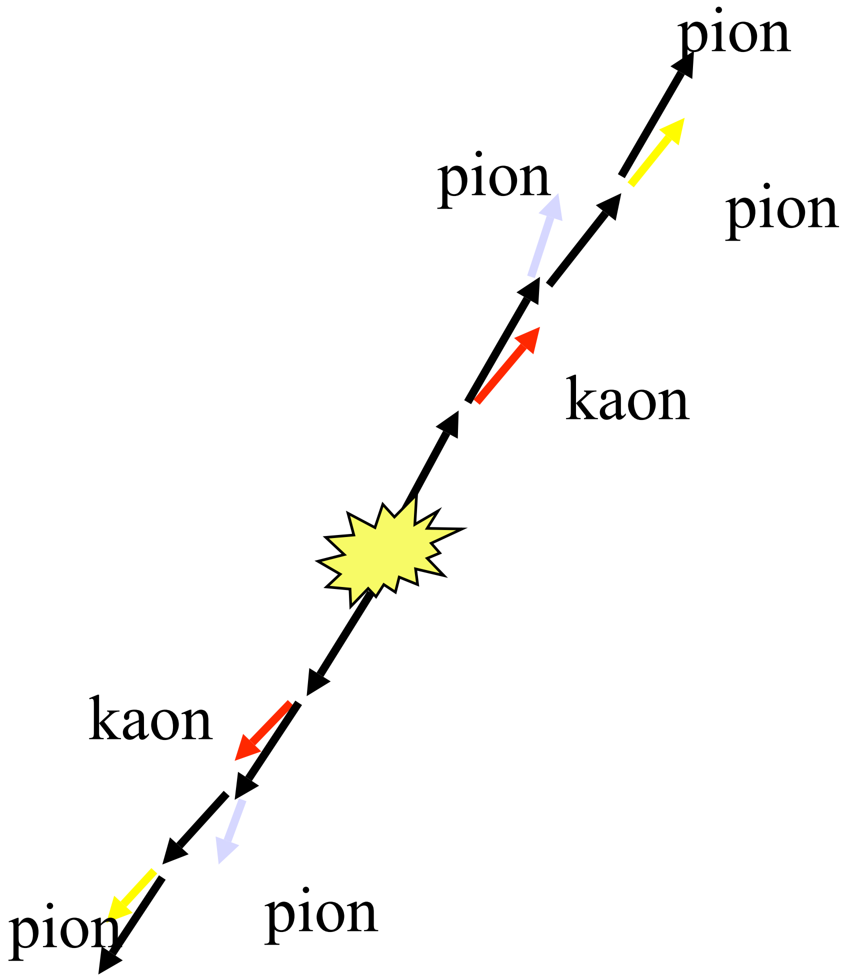


Definition of a "jet"

- Use Jets – the possible for "knock-on" collisions of partons
- The fragmented "bits" appear as "normal" subatomic particles

  pions, kaons,etc
- Seen in high-energy physics experiments since mid-1970's

Jets commonly come in pairs



Using jets to study the QGP properties

A case study: opacity of fog

- “is this thing on?”

Using jets to study the QGP properties

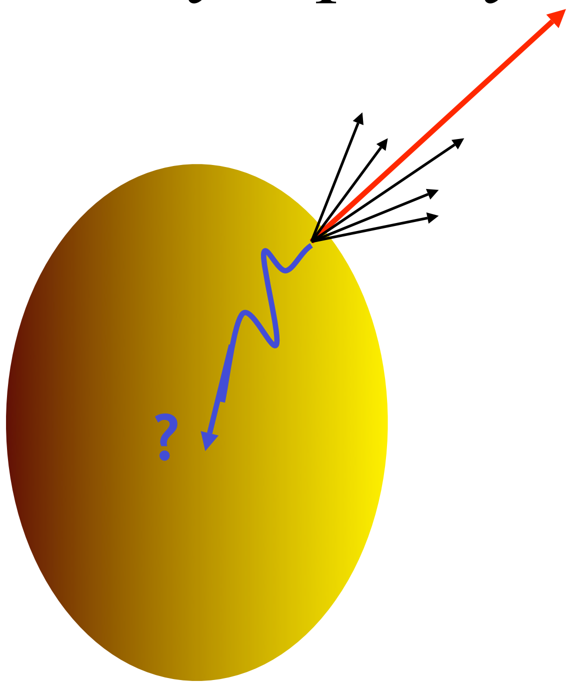
A case study: opacity of fog

- "is this thing on?"

- First beam - least know the source is on.
- Second beam intensity tells you a lot about matter passed through

Using jets to study the QGP properties

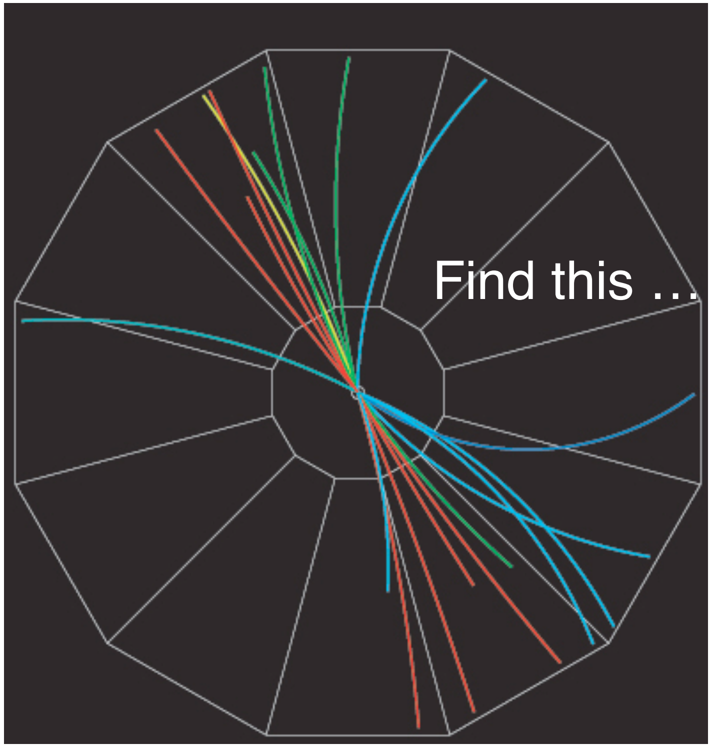
A case study: opacity of fog



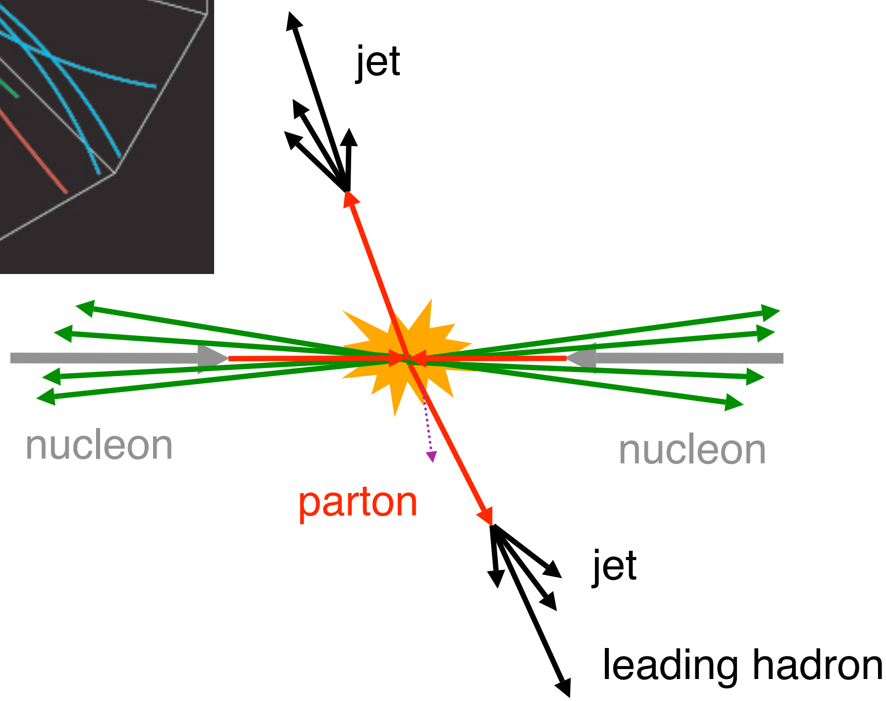
- First beam - least know the source is on.
- Second beam intensity tells you a lot about matter passed through

Predictions
QGP: "backwards" jet will be absorbed by medium
Hadron gas: "backwards" jet be less affected by medium

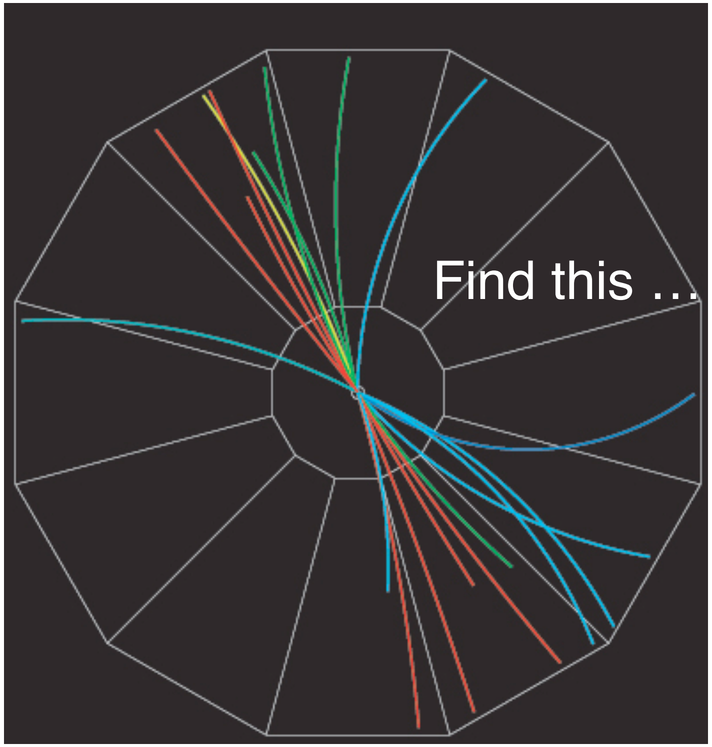
Finding a jet in a Au-Au event

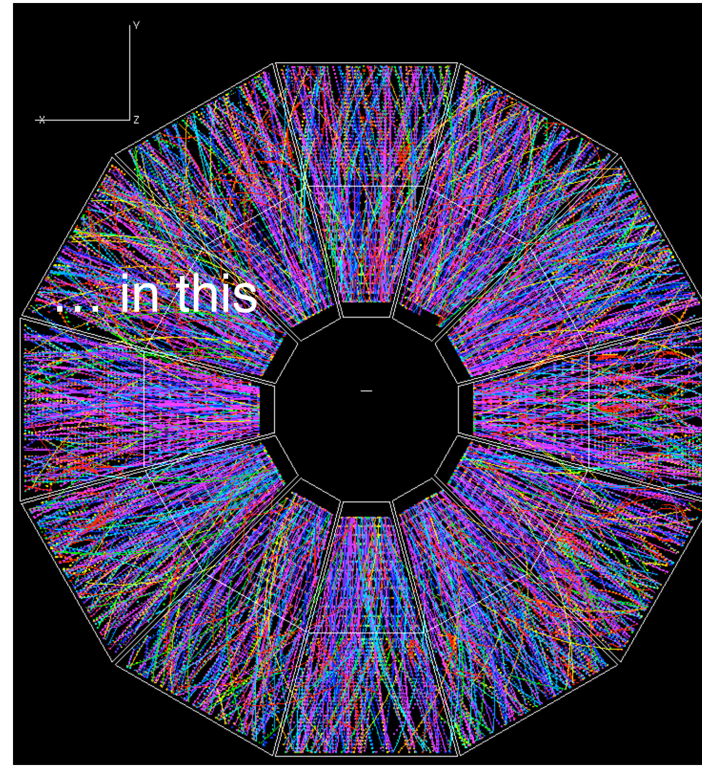


p+p →jet+jet
(STAR@RHIC)

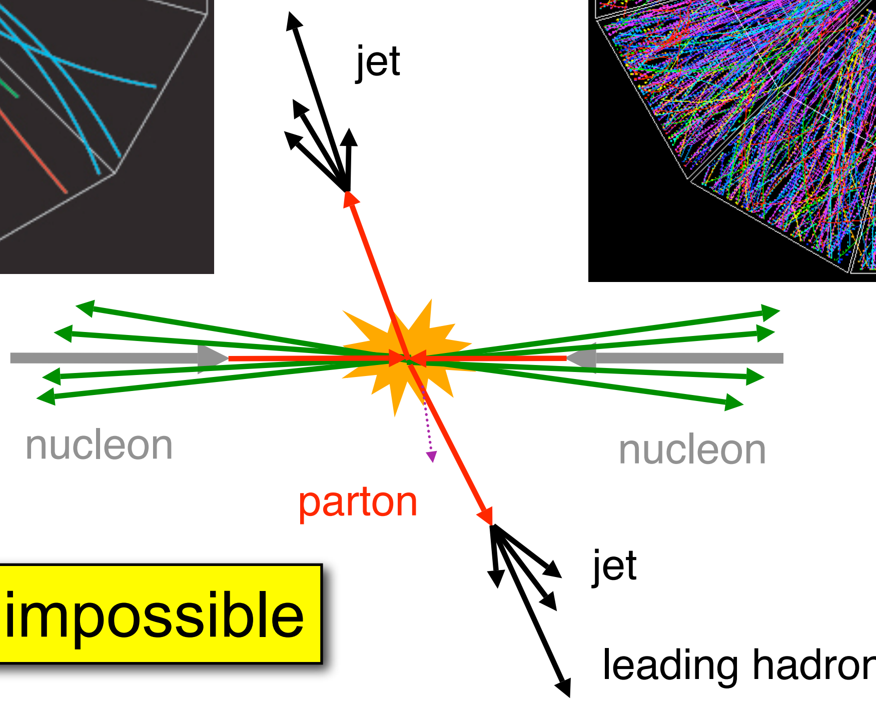


Finding a jet in a Au-Au event





p+p →jet+jet
(STAR@RHIC)



Au+Au →???
(STAR@RHIC)

Seems almost impossible

How to find a jet? - an algorithm

- How to locate the running of the bulls in Pamplona, Spain:

How to find a jet? - an algorithm

- How to locate the running of the bulls in Pamplona, Spain:
  - start by finding one fast moving bull

How to find a jet? - an algorithm

- How to locate the running of the bulls in Pamplona, Spain:
  - start by finding one fast moving bull
  - look others moving in roughly the same direction - where there's one bull there's usually another

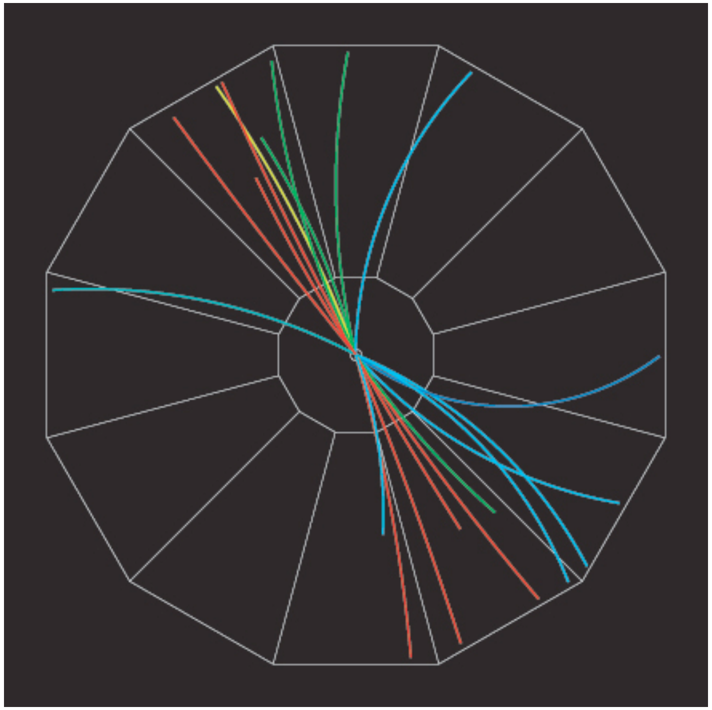
How to find a jet? - an algorithm

- How to locate the running of the bulls in Pamplona, Spain:
  - start by finding one fast moving bull
  - look others moving in roughly the same direction - where there's one bull there's usually another
  - if the bull density is high, you often find many people moving in opposite direction

Jet finding is now simple: just replace "bull" by "particle"

Jets in Au-Au collisions!

p+p → dijet

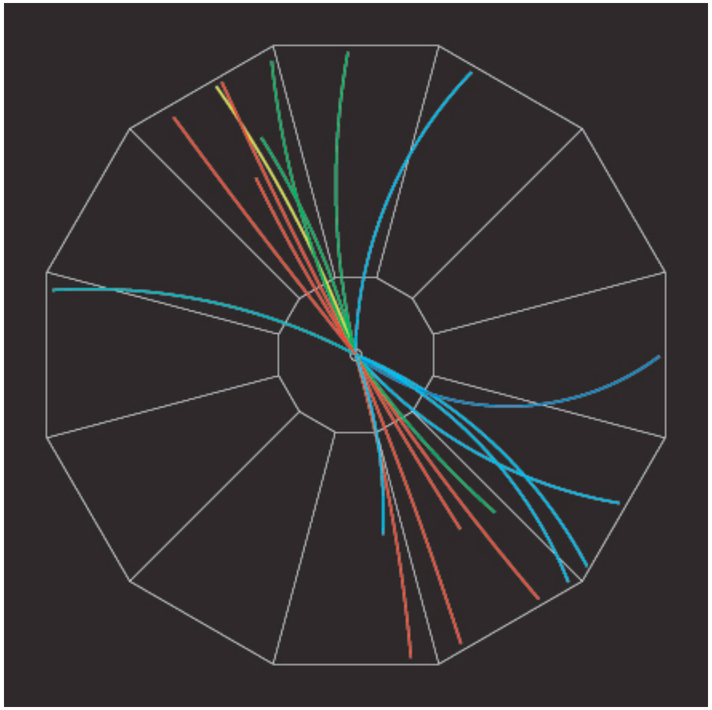


- Trigger: highest p_T track

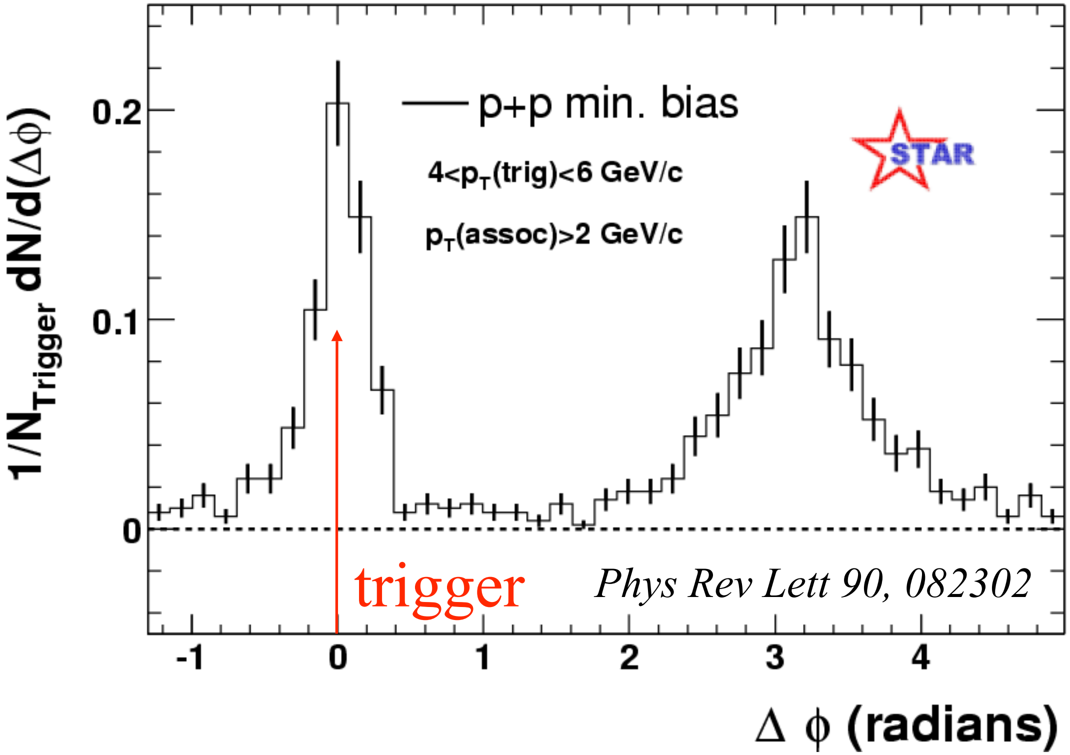
- Δφ distribution:

Jets in Au-Au collisions!

p+p → dijet

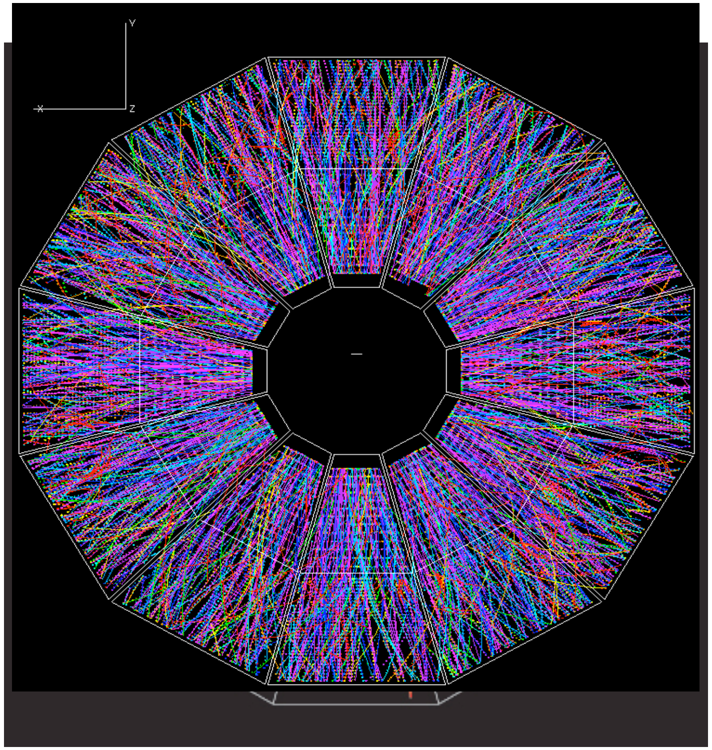


min. bias p+p collisions

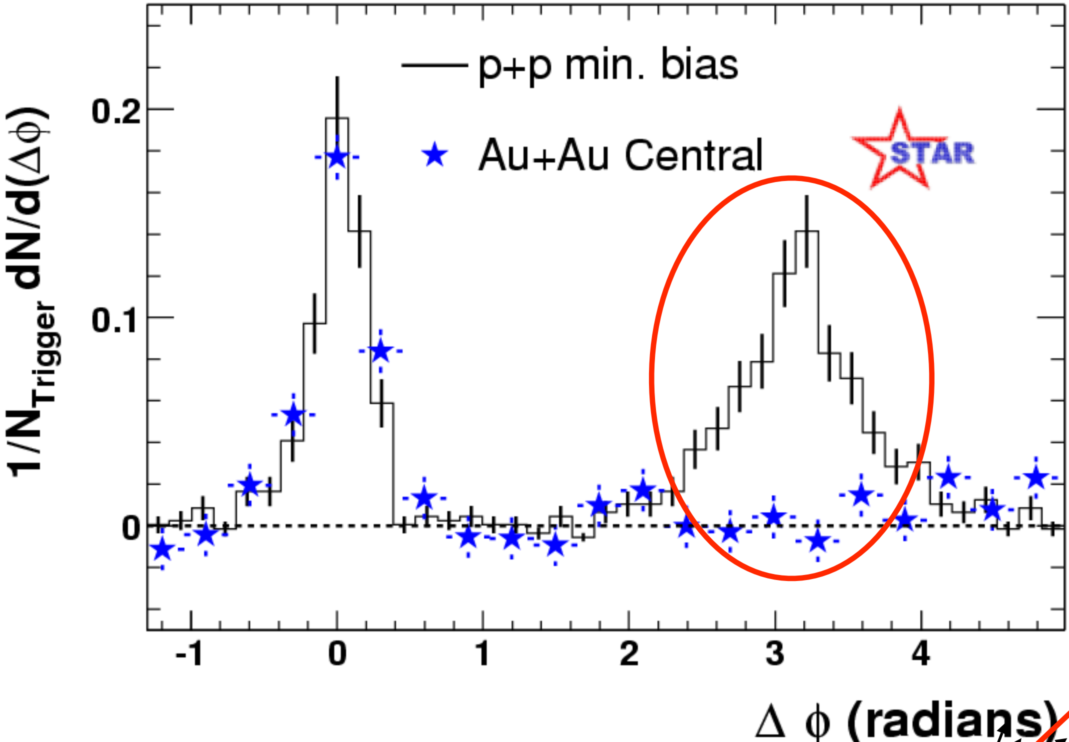


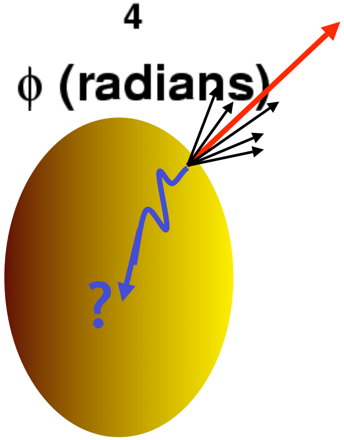
Jets in Au-Au collisions!

p+p → dijet



central Au+Au collisions

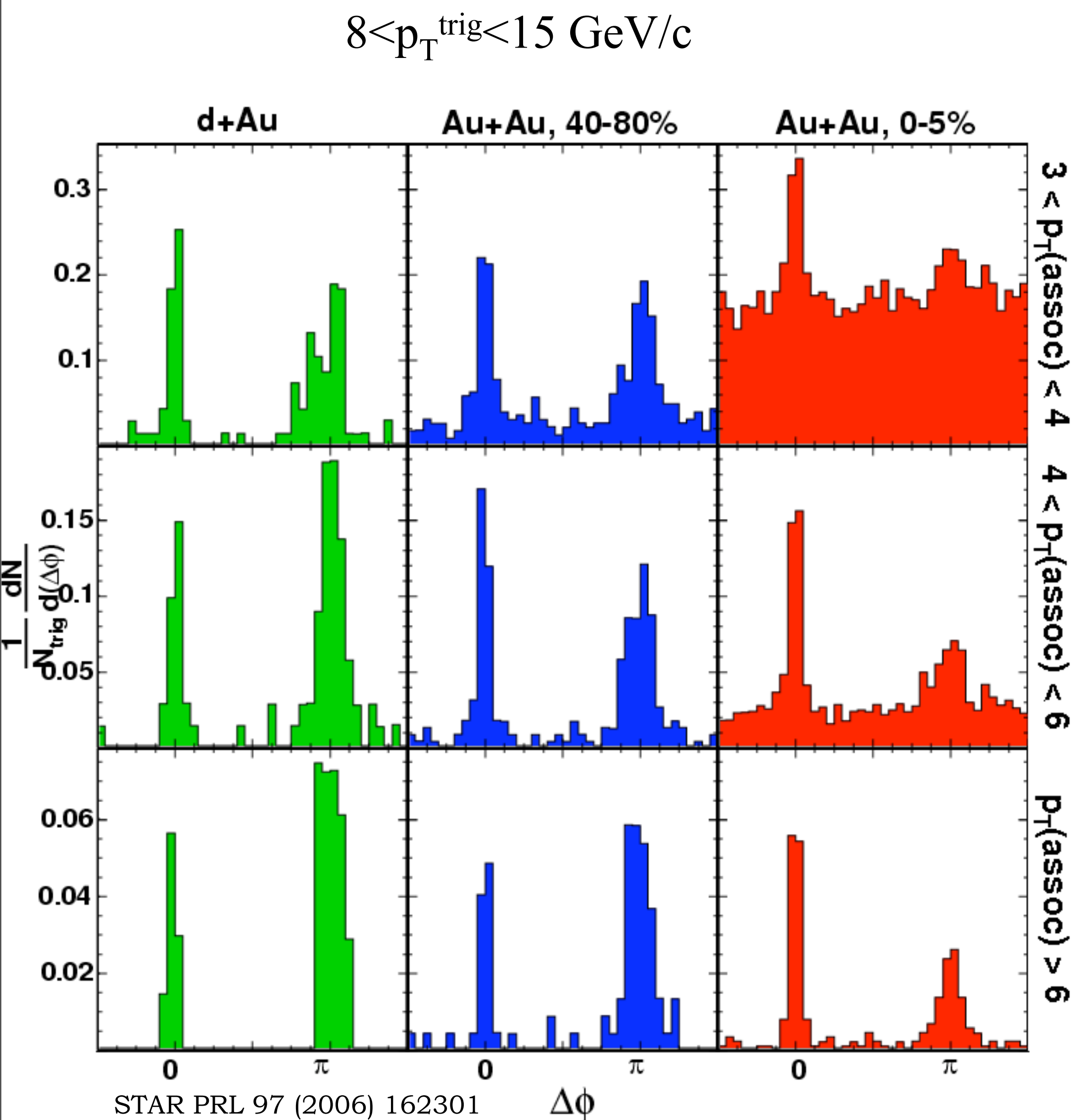




Δφ ≈ 0: central Au+Au similar to p+p

Δφ ≈ π: strong suppression of back-to-back correlations in central Au+A

Observation of "Punch through"

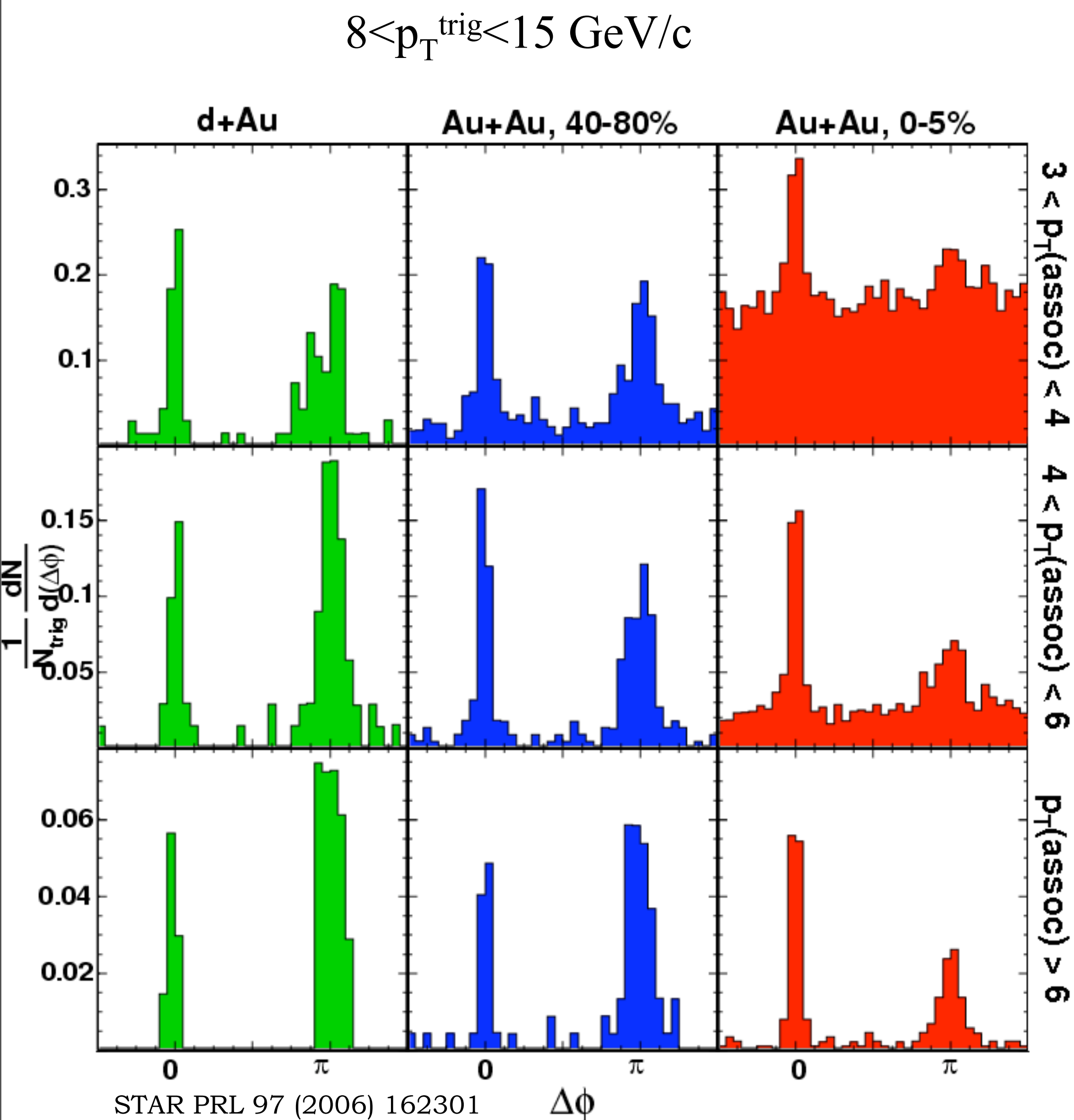


STAR PRL 97 (2006) 162301

If use high-p_T triggers:

- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
- Virtually no background

Observation of "Punch through"



STAR PRL 97 (2006) 162301

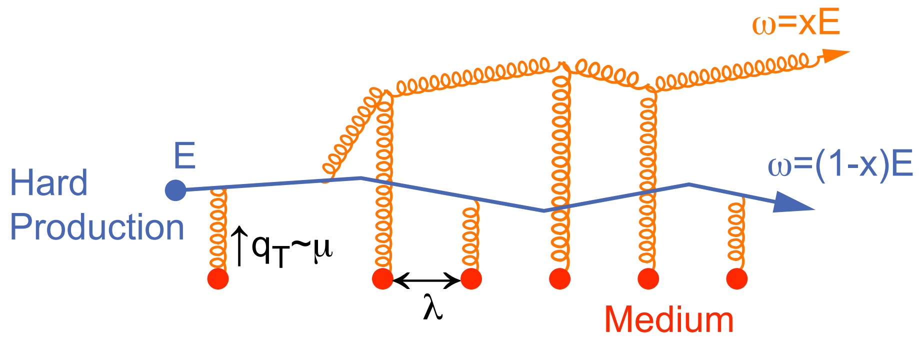
If use high-p_T triggers:

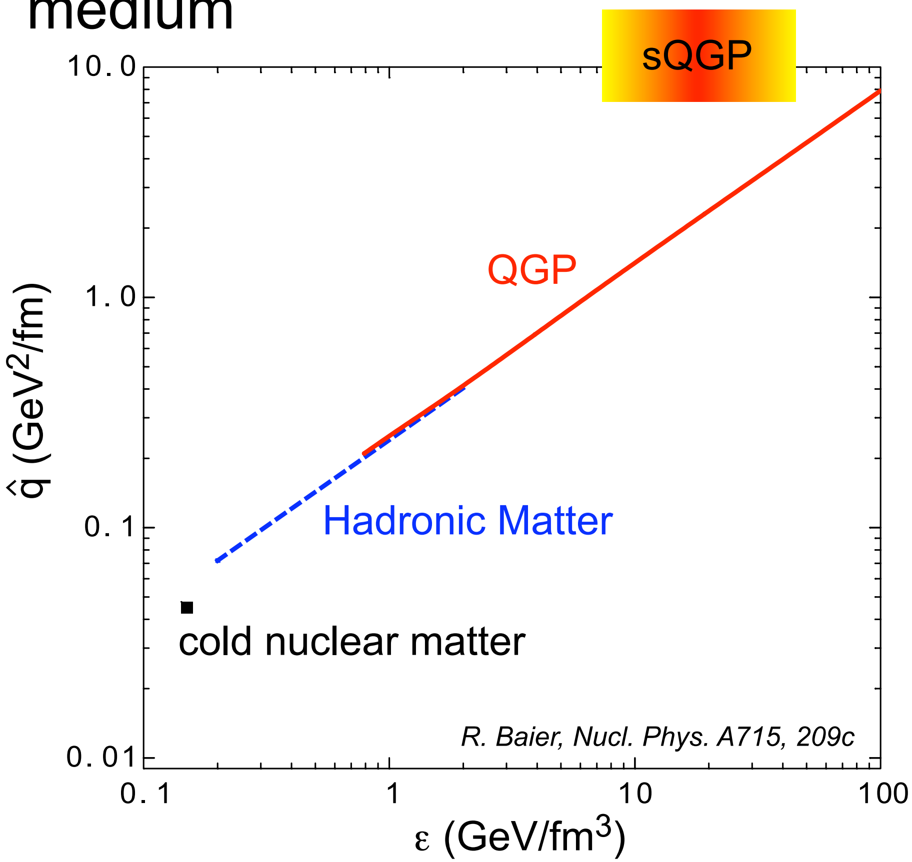
- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
- Virtually no background

High energy jets *"punch through"* the medium.

Interpretation

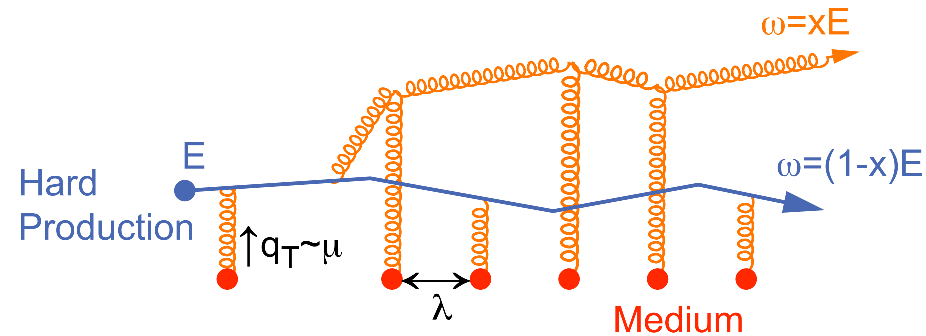
Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium

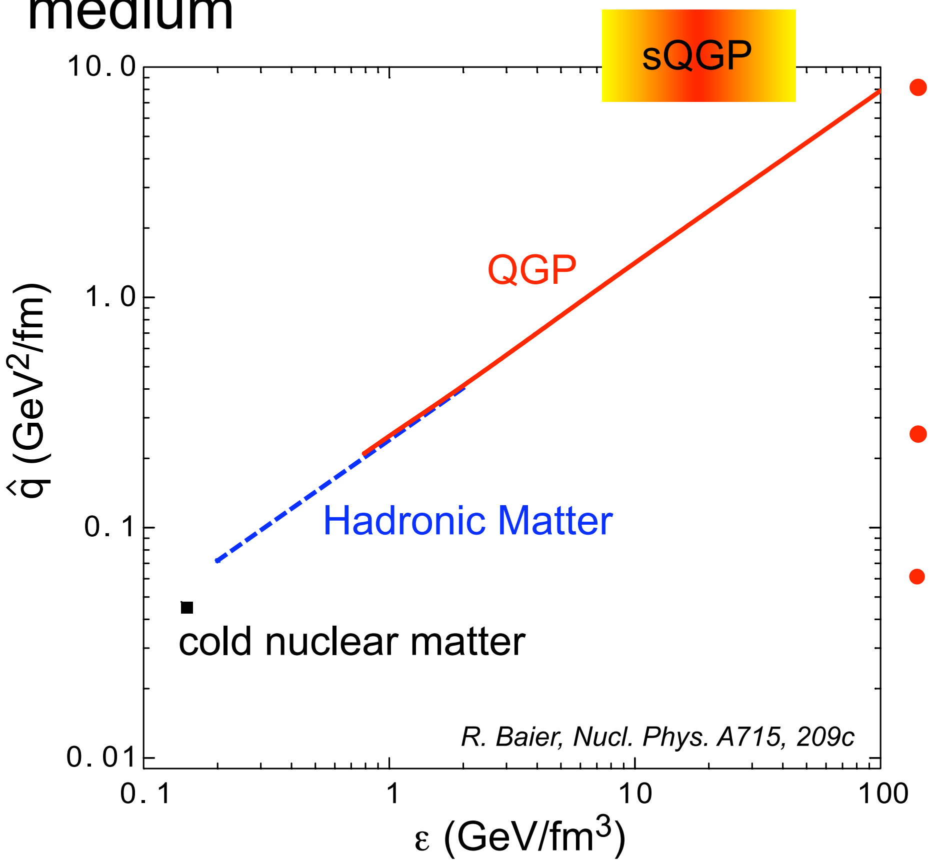




Interpretation

Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium





- Mean parton energy loss ∝ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - $\Delta E_{loss} \sim \Delta L^2$ (medium length)

    $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$
- is $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length

$\hat{q}$ ~5-10 GeV/fm

Summary

The matter we create at RHIC is a **sQGP** it is

fantastically hot

and has an

incredible energy density.

It

exists for only an instant

yet shows

many signs of being in equilibrium.

It flows like a

nearly "perfect" fluid

and appears to have

quark and gluon degrees of freedom

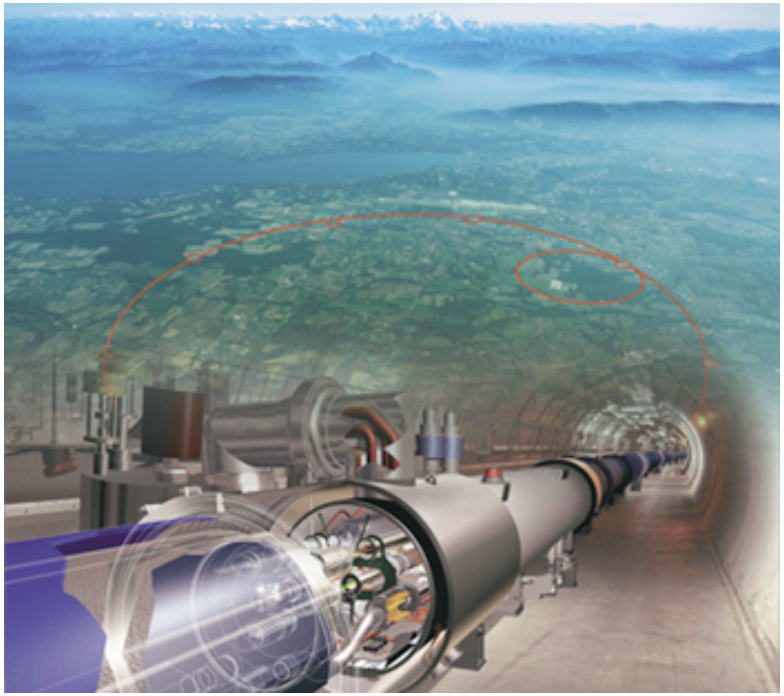
which causes

significant energy loss to partons passing through

The next energy frontier

The Large Hadron Collider (LHC) at CERN will be commissioned in 2008 with over an order of magnitude higher energy than at RHIC.

Instead of 40 TeV, 1000 TeV !



3 experiments with dedicated heavy-ion experiments

ALICE
ATLAS
CMS

sQGP: hotter,bigger,longer lived
more detailed measurements