Collider - Accelerator Department Seminar, BNL
March 14 2008

Phases of QCD Matter and Heavy Ion Collisions

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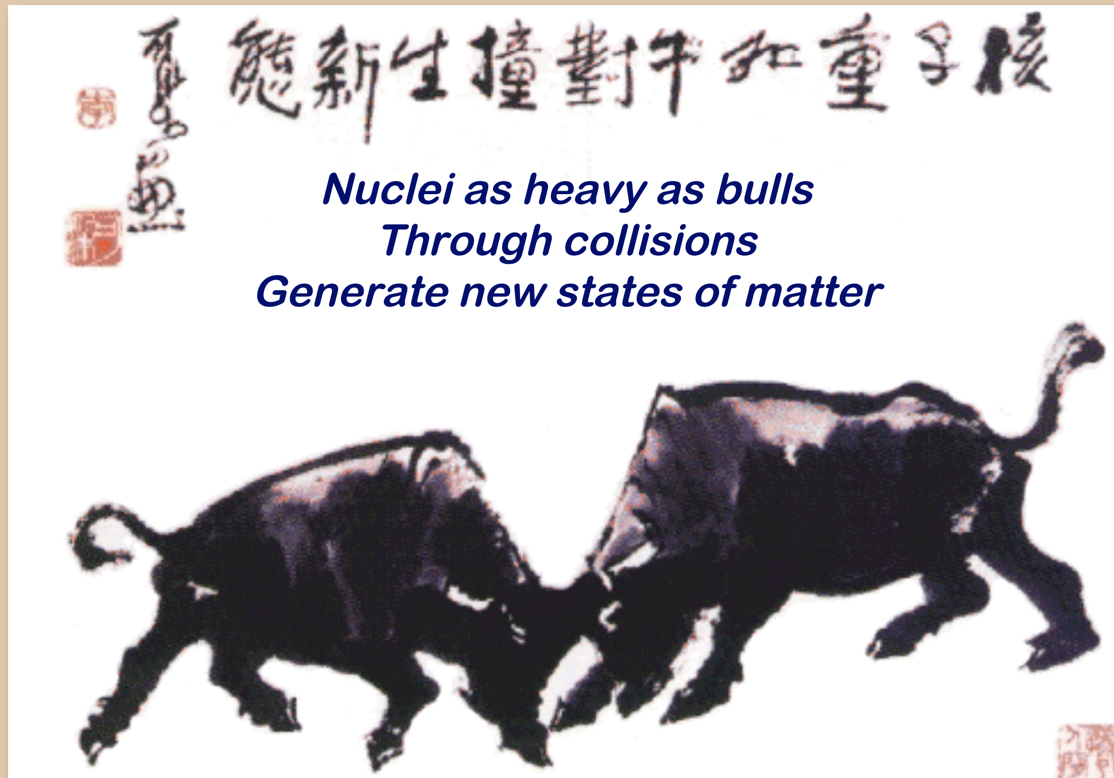
RIKEN BNL Research Center
Nuclei as heavy as bulls through collision generate new states of matter

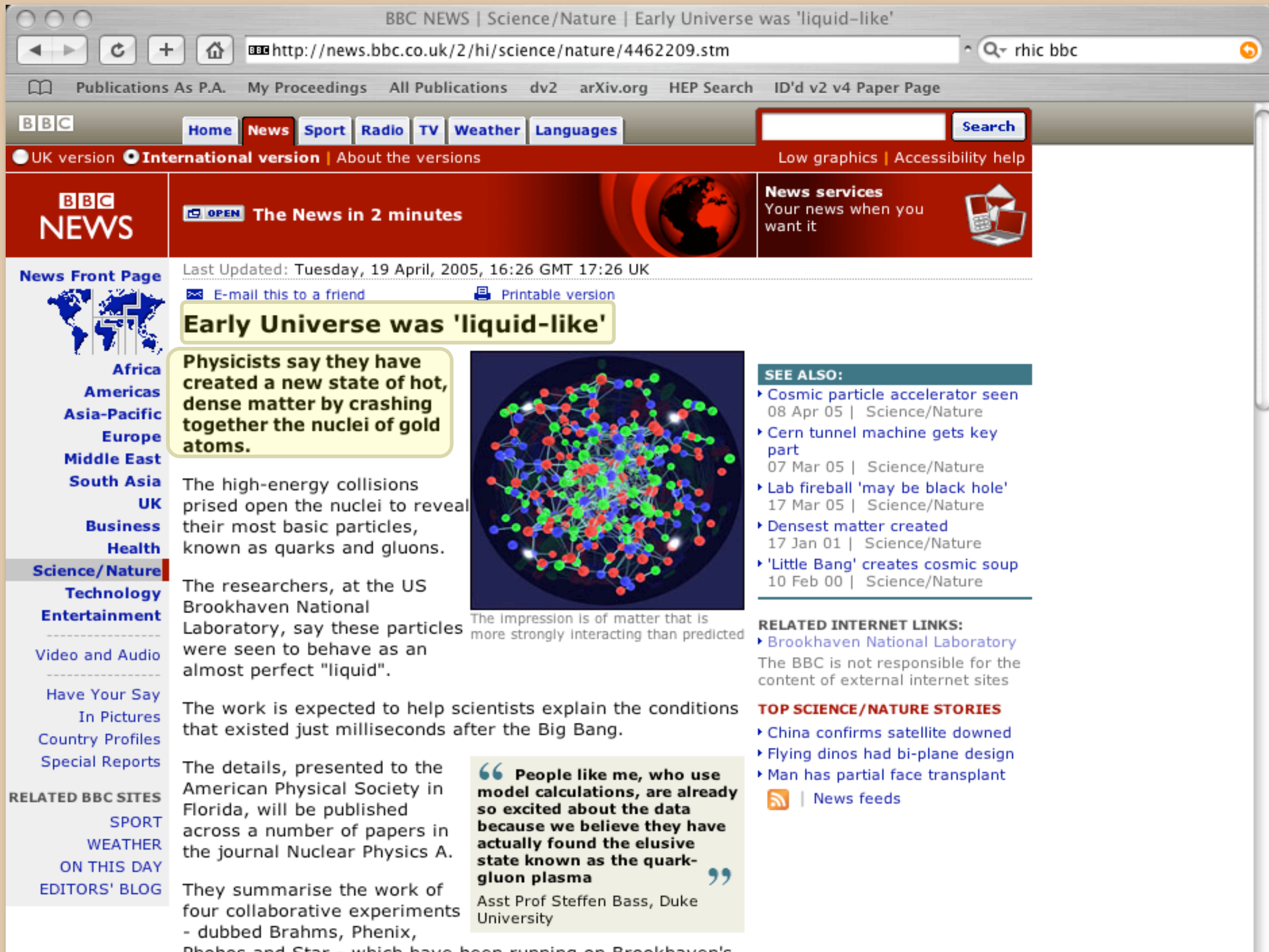
Some facts to get us started

① **In 1974 T.D.Lee suggested**



Some facts to get us started

② 30 years later



BBC NEWS | Science/Nature | Early Universe was 'liquid-like'

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Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The impression is of matter that is more strongly interacting than predicted

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

The details, presented to the American Physical Society in Florida, will be published across a number of papers in the journal Nuclear Physics A.

"People like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma"

Asst Prof Steffen Bass, Duke University

They summarise the work of four collaborative experiments - dubbed Brahms, Phenix, Phobos and Star - which have been running on Brookhaven's

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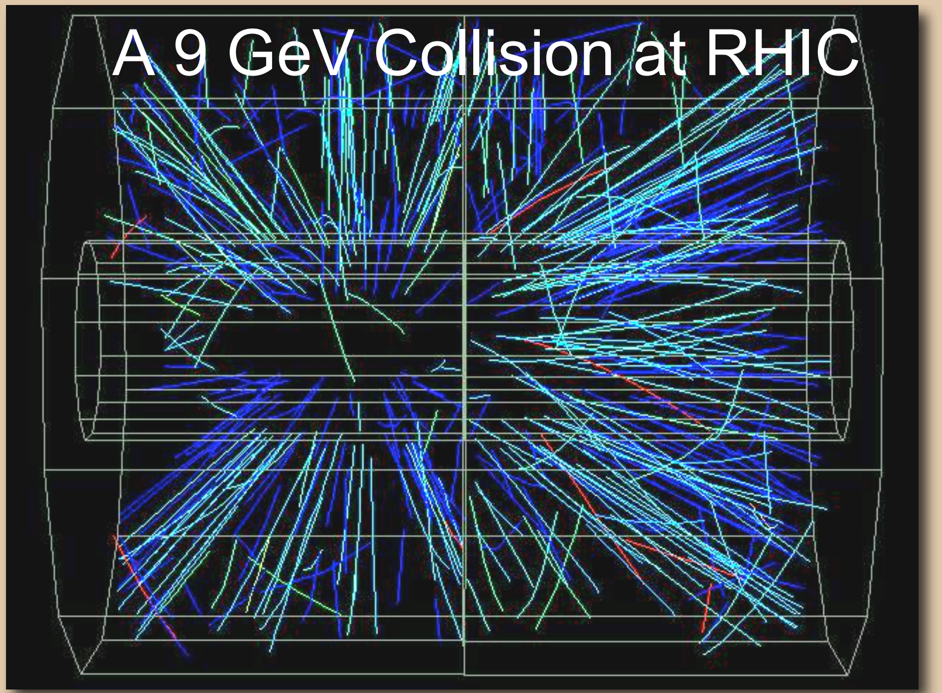
Some facts to get us started

③ **present and future: Beam Energy Scan and RHICII**



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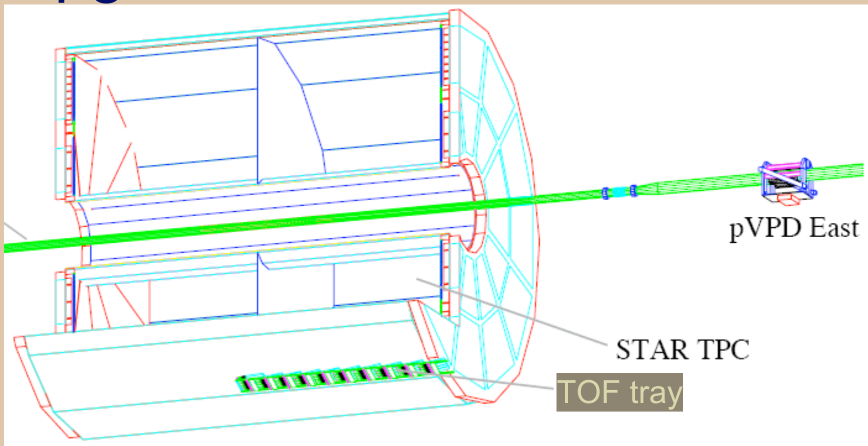

In This Talk

QCD

QGP

Relativistic Heavy Ion Collisions

Search for Deconfinement

Of course, I will only talk about some selected topics - so will not do justice to the entire field ...

But I hope I can tell you stuff that you'll find interesting, and perhaps useful in the future (e.g. terminology)

QCD

Quantum ChromoDynamics

QCD: accepted theory of strong interactions, field theory of color charged gluons and quarks

Gauge fields A_μ^a ***Fermion fields*** ψ^α

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \overline{\psi}^\alpha(\gamma_\mu D^\mu - m)\psi^\alpha$$

$$D_\mu = \partial_\mu - igA_\mu^a t^a$$

- $-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$: gluon kinetic energy
- ∂_μ: quark kinetic energy
- $igA_\mu^a t^a$: quark-gluon coupling
- m: quark mass matrix (diagonal in flavor)
- α: quark flavor

Free parameters: coupling g & quark mass m

Quantum ChromoDynamics

QCD: accepted theory of strong interactions, field theory of color charged gluons and quarks

Gauge fields A_μ^a *Fermion fields ψ^α*

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$$D_\mu = \partial_\mu - igA_\mu^a t^a$$

Renormalizable no terms of mass dimension higher than 4 (dim A_μ=1, dim ψ=3/2)

Gauge invariant invariance under a continuous symmetry group (symmetry under local phase rotation in color space)

Non-Abelian non-commuting local symmetry (the orthogonal phase rotation do not commute, i.e. operations not interchangeable)

Quantum ChromoDynamics

QCD: accepted theory of strong interactions,
field theory of color charged gluons and quarks

Gauge fields A_μ^a ***Fermion fields*** ψ^α

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$$D_\mu = \partial_\mu - igA_\mu^a t^a$$

Free parameters: coupling g & quark mass m

Gauge field strength:

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + igf^{abc}A^b_\mu A^c_\nu \Rightarrow$$ **cubic and quartic terms in** A_μ^a

gluon self-interactions

consequence of gluon color charge: interaction dictated by symmetry,
a non-commuting color rotation symmetry $[t^a, t^b] = if^{abc} t^c$

Quantum ChromoDynamics

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + igf^{abc}A^b_\mu A^c_\nu$$

gluon self-interactions

Asymptotic Freedom

At very short distances or very high momentum transfers (Q^2) quarks behave like weakly interacting point particles.

$$\alpha_s(Q^2) = \frac{g^2(Q)}{4\pi} \sim \frac{1}{\ln(Q/\Lambda)} \sim \frac{1}{\ln(1/r\Lambda)}$$

$$\Lambda = 200\, MeV$$

At short distances the effective coupling decreases logarithmically to zero.

The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

D. Gross D. Politzer F. Wilczek

Quantum ChromoDynamics

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + igf^{abc}A^b_\mu A^c_\nu$$

gluon self interactions

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$$\Lambda = 200\,MeV$$

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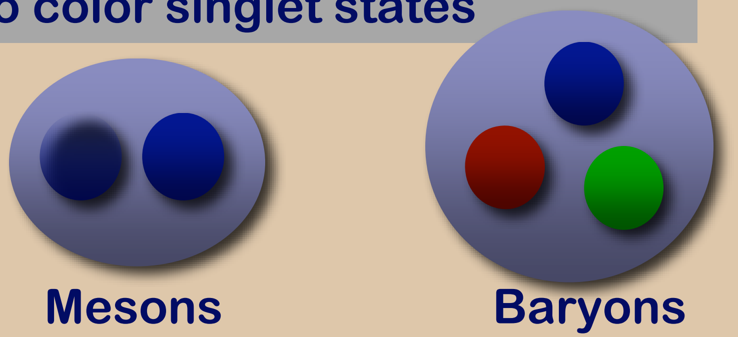
Confinement

The interaction of quarks at long distances or small momentum transfers explain the non-observation of isolated quarks.

Quarks and gluons cannot exist as free particles, but confined into color singlet states

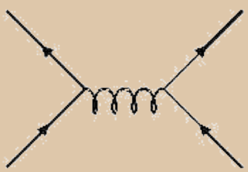


What tools we have to study QCD?

Q >> 1 GeV

Note: $\alpha_s(Q = 1GeV) = 0.4$

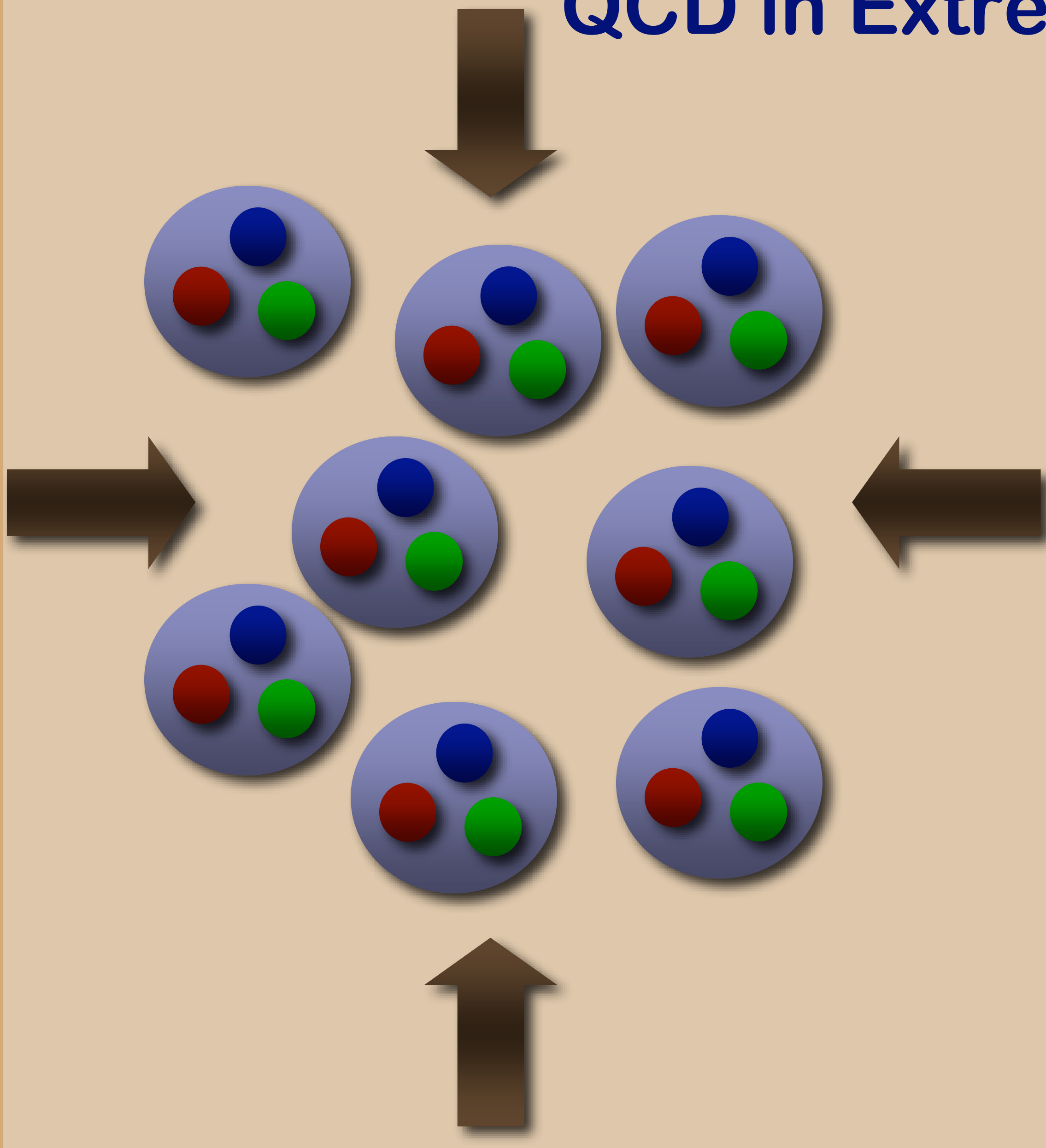
"Perturbative QCD" (pQCD)
means that rigorous calculations
can be done with partons (q,g)
Feynman integrals



Q < 1 GeV

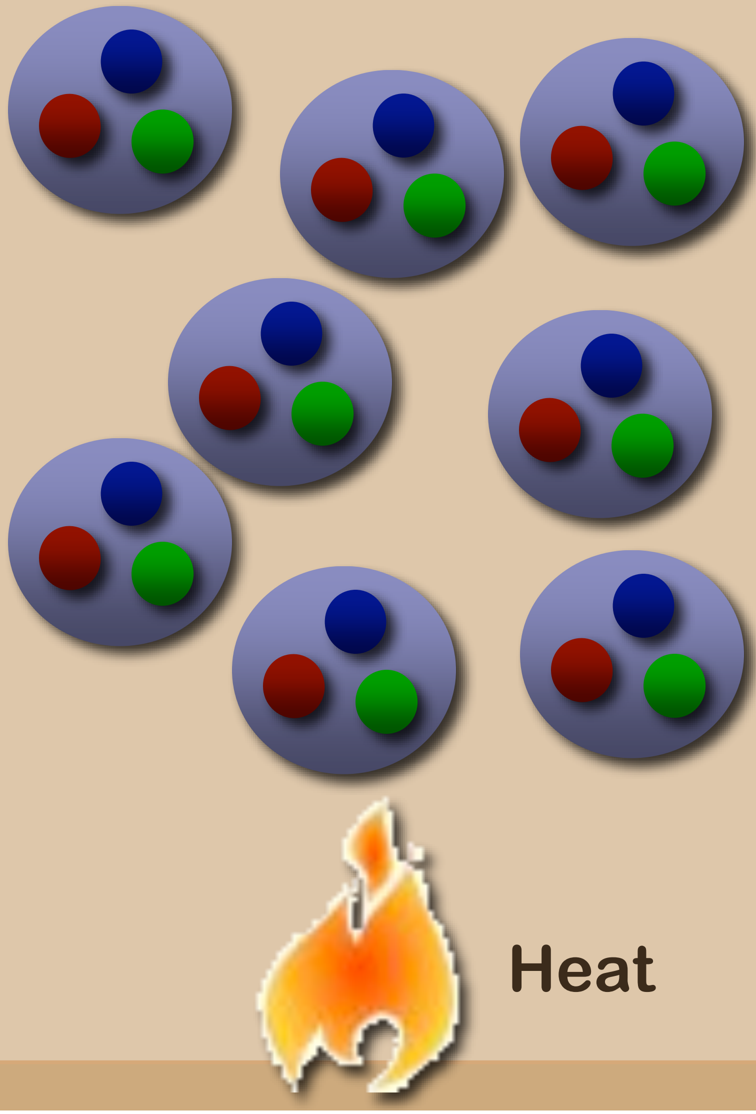
However, we observe nature
in the regime of
"Non-perturbative QCD":
baryons & mesons (hadrons)
Effective theories, Lattice QCD

QCD in Extreme



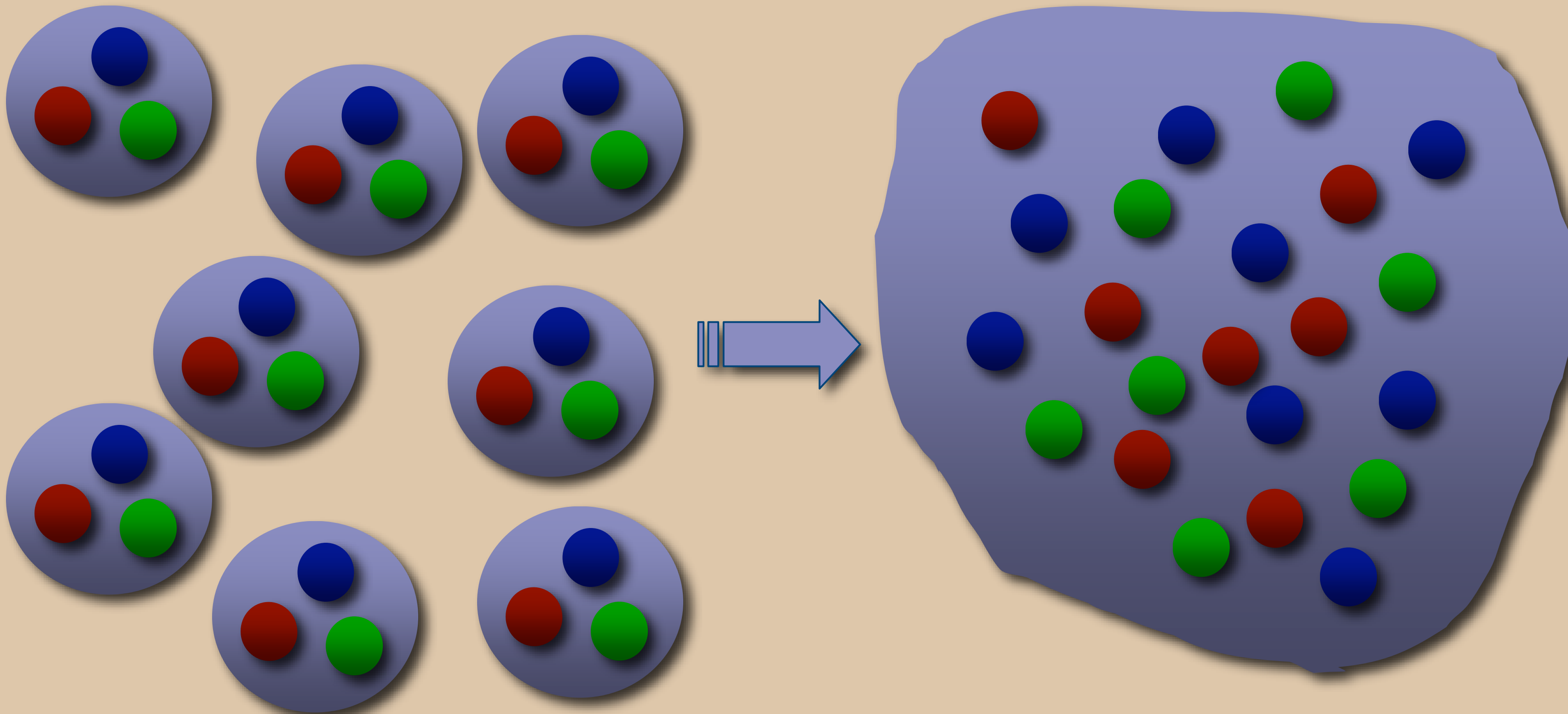
Compress

QCD in Extreme



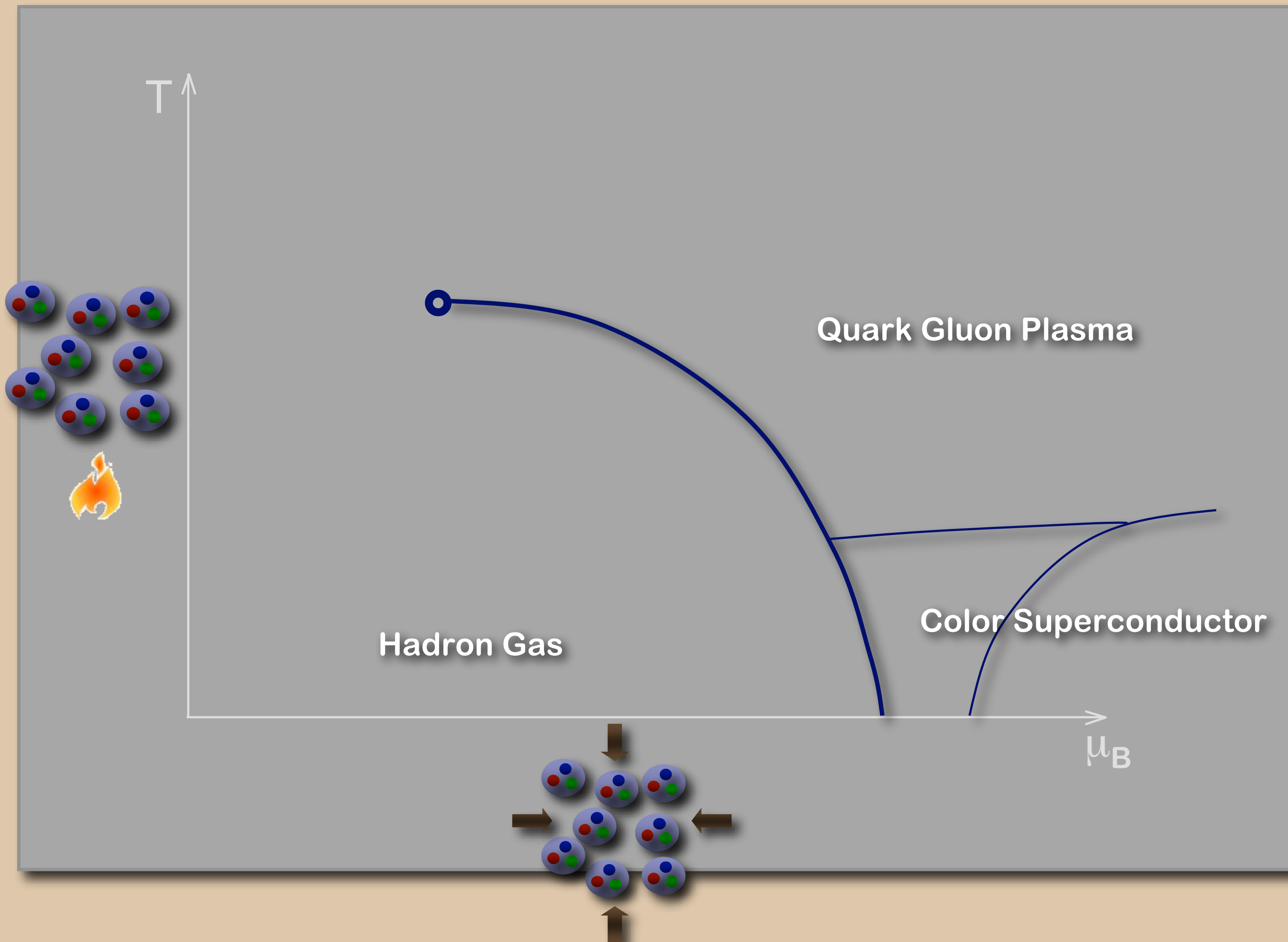
QCD in Extreme

A transition to QGP requires very large energy density.



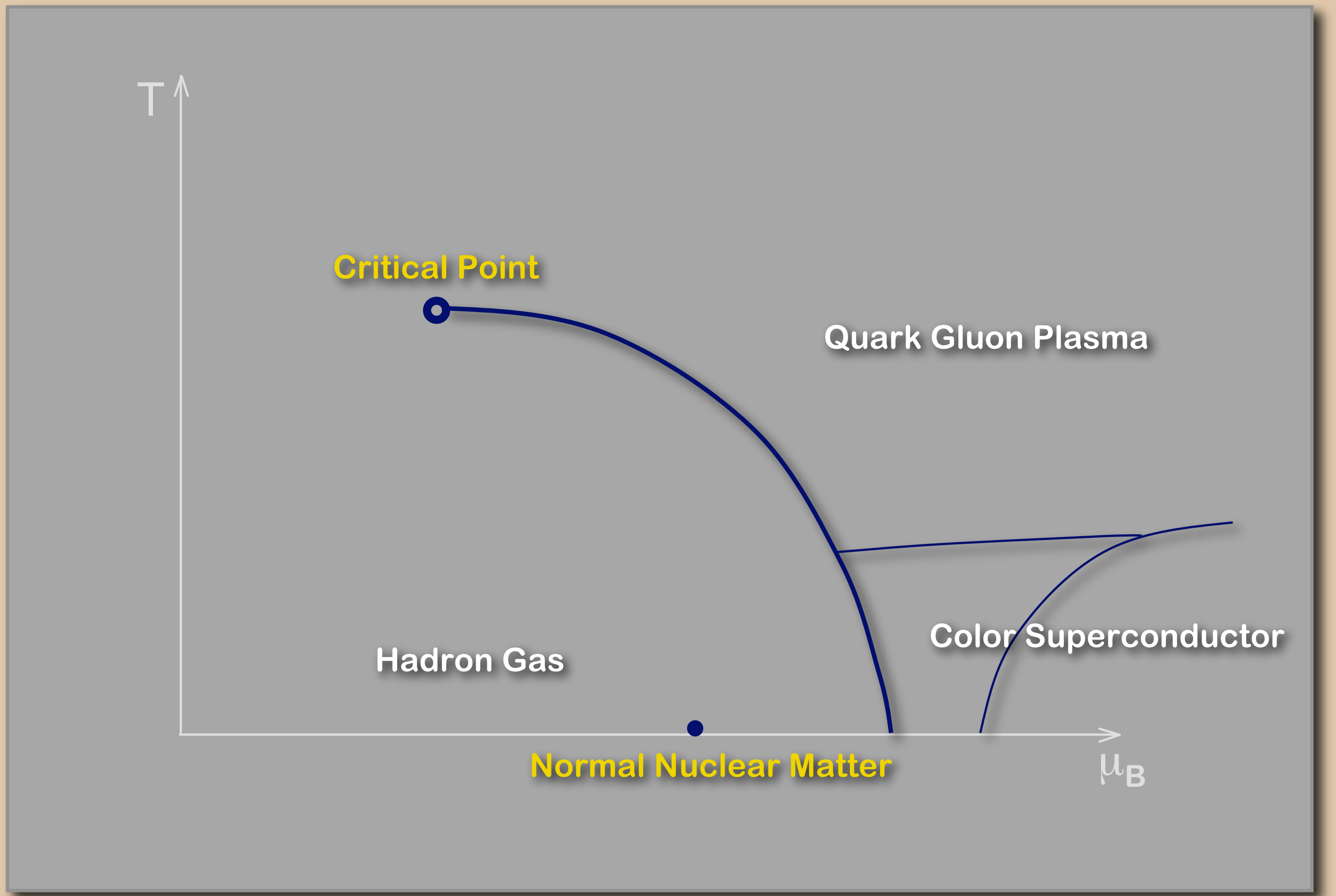
Confined hadronic matter → Deconfined Quark Gluon Plasma

Phases of QCD



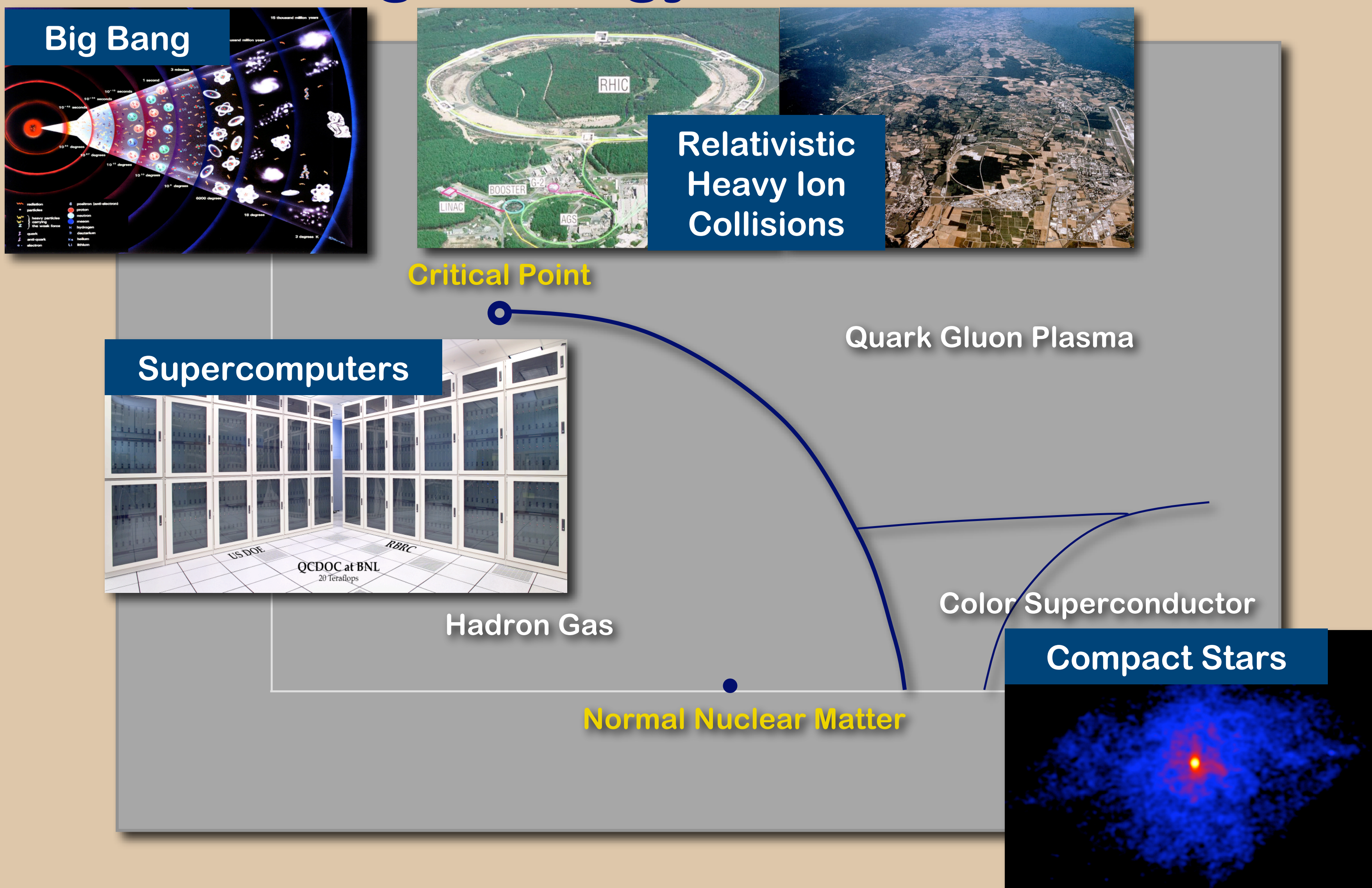
Phases of QCD

WANT TO LEARN



What phases exist & How are they formed & What are their properties

Where to find these phases? Where do large energy densities occur?



Recap

QCD is a very special theory:

Asymptotic freedom, confinement

At high energy densities expected deconfinement - quark-gluon plasma formation

Has a rich phase diagram with lots of stuff to explore

QGP

How can we tell there is a transition from one phase to another ?

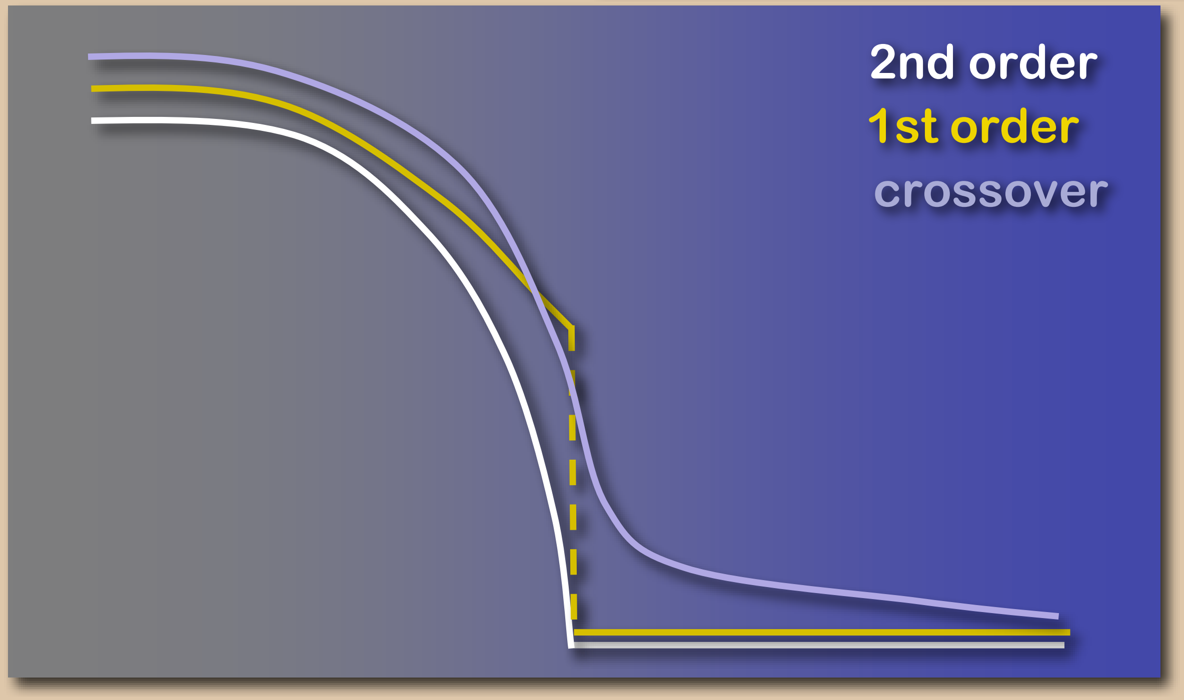
Phase transitions conveniently investigated using order parameters, associated to a symmetry of the theory.

In the symmetry broken phase:

$\langle$ order parameter $\rangle \neq 0$

In the symmetric phase:

$\langle$ order parameter $\rangle = 0$



Phase change controlled by a parameter (temperature)

"Order parameter" for deconfinement

Pure glue (N_f=0)

Order parameter: Polyakov loop (not an observable)

$\langle L \rangle = 0$ confined $T<T_c$

$\langle L \rangle \neq 0$ deconfined $T>T_c$

$L \sim e^{-F_Q(T)/T}$ = 0 means that infinite energy is needed to separate quarks

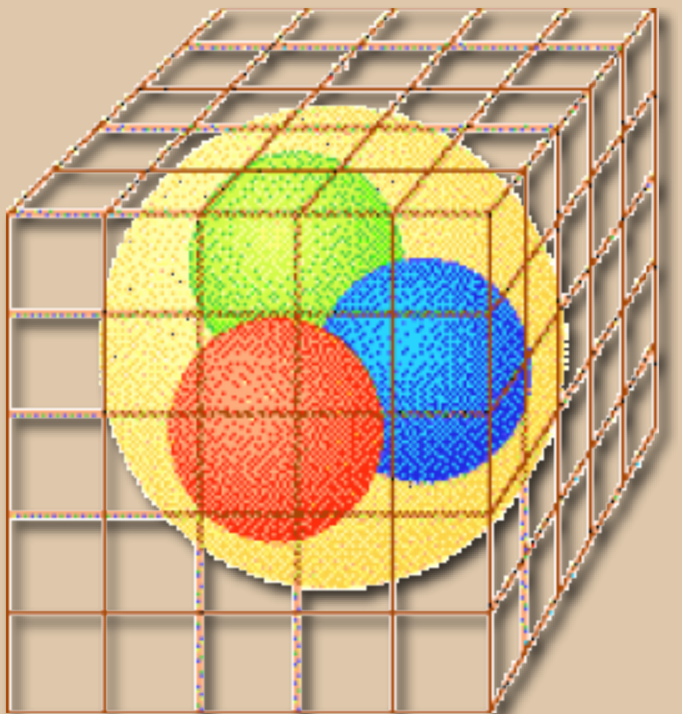
Free energy of static quark sources

Full QCD (N_f=2+1)

No exact order parameter.
But we can still follow L(T). This is done on the lattice.

Lattice QCD

1st principle calculations: Monte-Carlo simulations of discretized QCD (on 4D lattices) using supercomputers



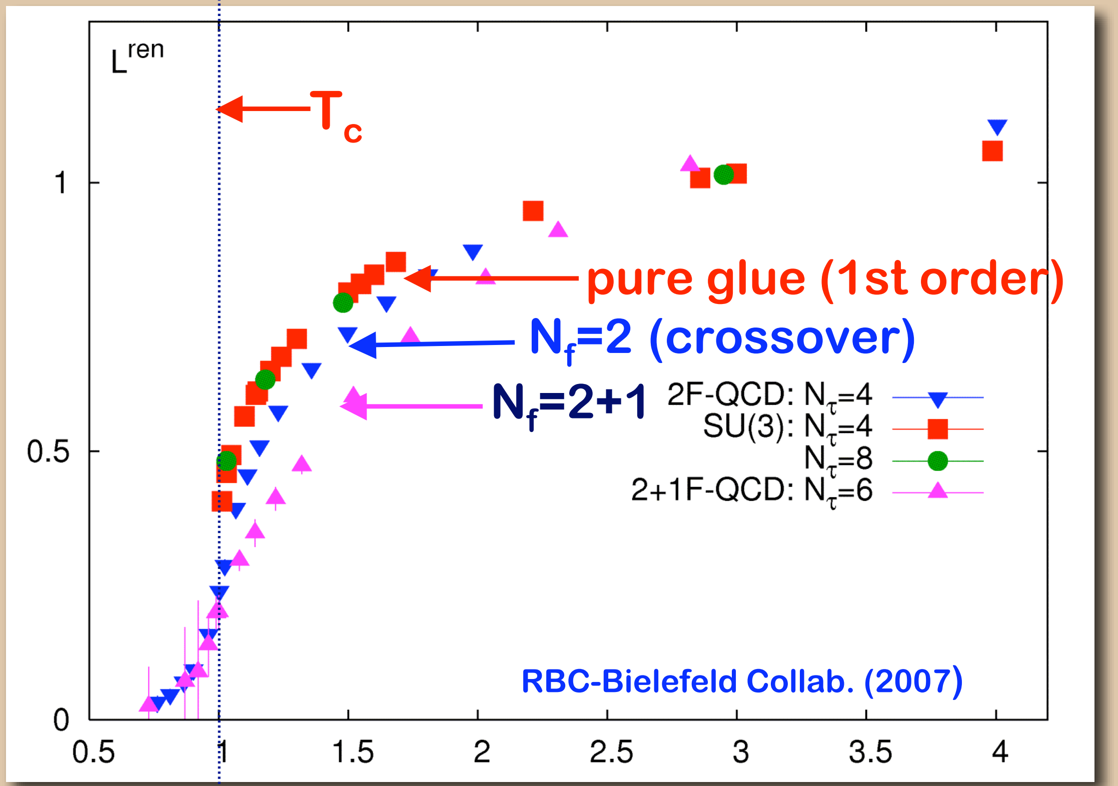
1Teraflop = 10^{12} operation/second

"Order Parameter" vs. T/T_c

as determined on the lattice

$L_{ren} \sim e^{-F_Q(T)/T}$

Rise in the Polyakov loop reflects change in the free energy of static quark sources



The transition is a rapid crossover.

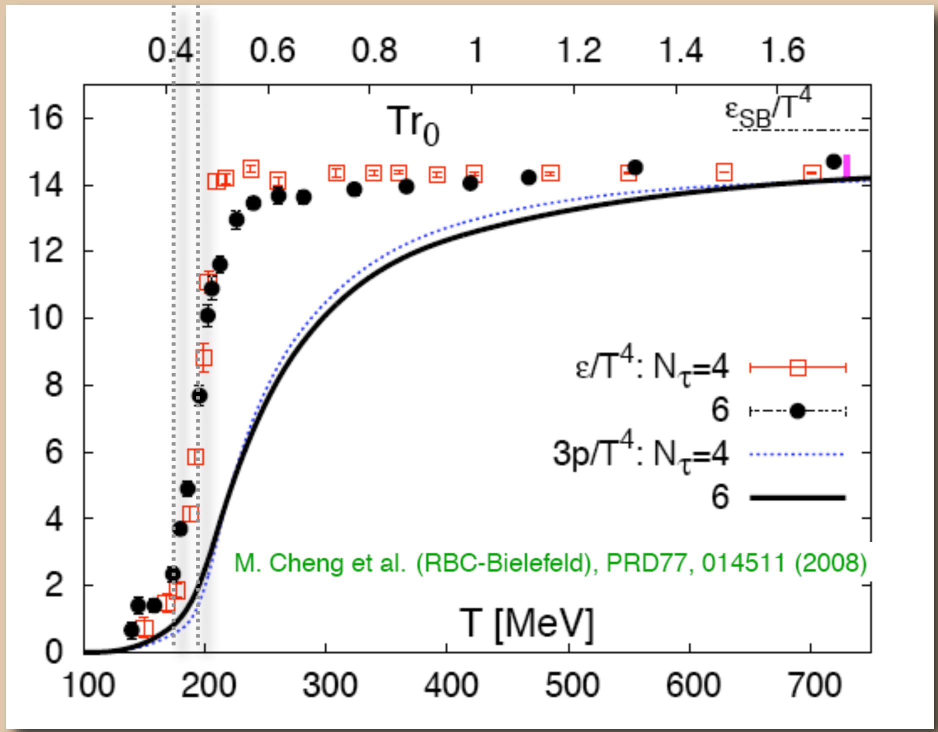
Deconfinement is seen in Lattice QCD !

Bulk thermodynamics

Energy density

~ number of degrees of freedom

pion gas:
3



free quark-gluon gas:
~ 8x2 + 3x2x2x3 = 52

Rapid rise in a narrow temperature interval

Liberation of new degrees of freedom - deconfinement

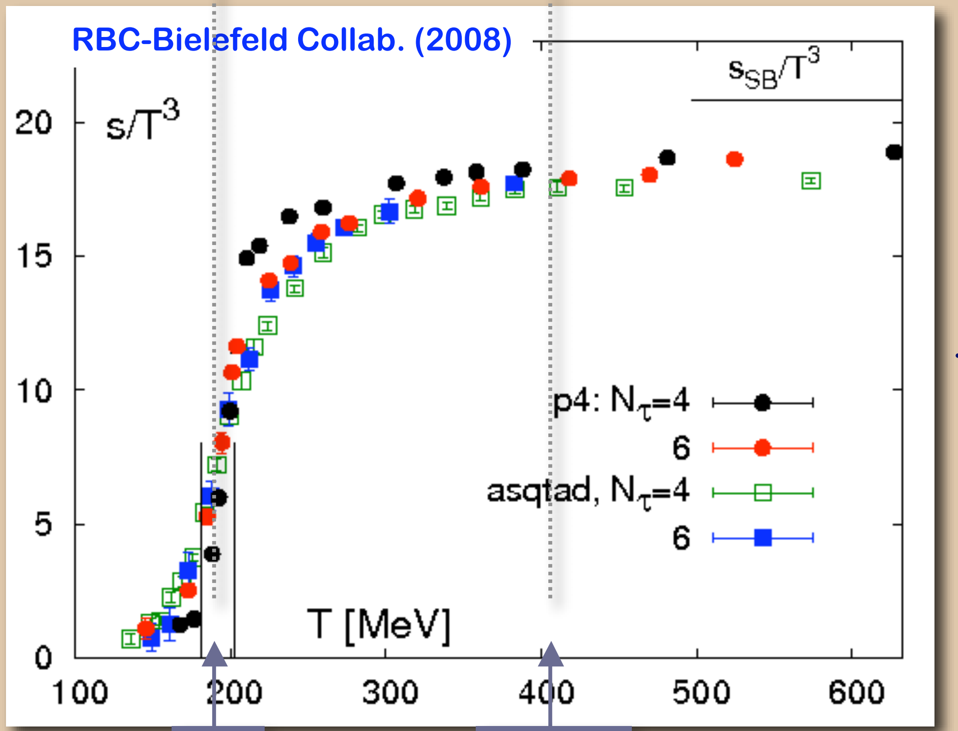
Crossover at the same temperature where the Polyakov loop raises.

Bulk thermodynamics

Entropy density

confined | sQGP | resummed pQCD

Hadron gas phenomenology



T_c | $\sim 2T_c$

Highly non-perturbative

Resummed perturbation theory

explains 10% deviation from the ideal gas limit

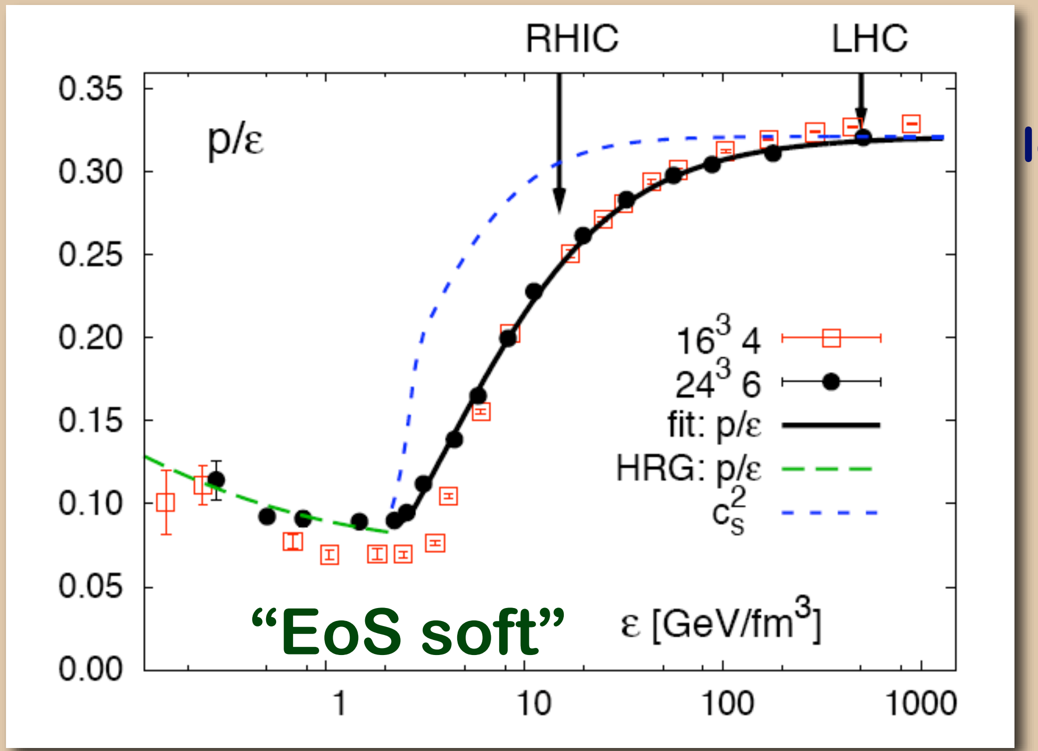
Blaizot et al (2003)

Bulk thermodynamics

Equation of state, speed of sound $c_s^2 = \frac{dp}{d\epsilon}$

Relation between energy density and pressure.
Determines the evolution of the matter.

Hadron gas



c_s^2=1/3
Ideal gas of quarks

"EoS stiff"

F. Karsch Talk at QM 2008

Softening of the QGP EoS near T_c . Can be looked for in flow patterns.

Recap

Lattice QCD tells us:

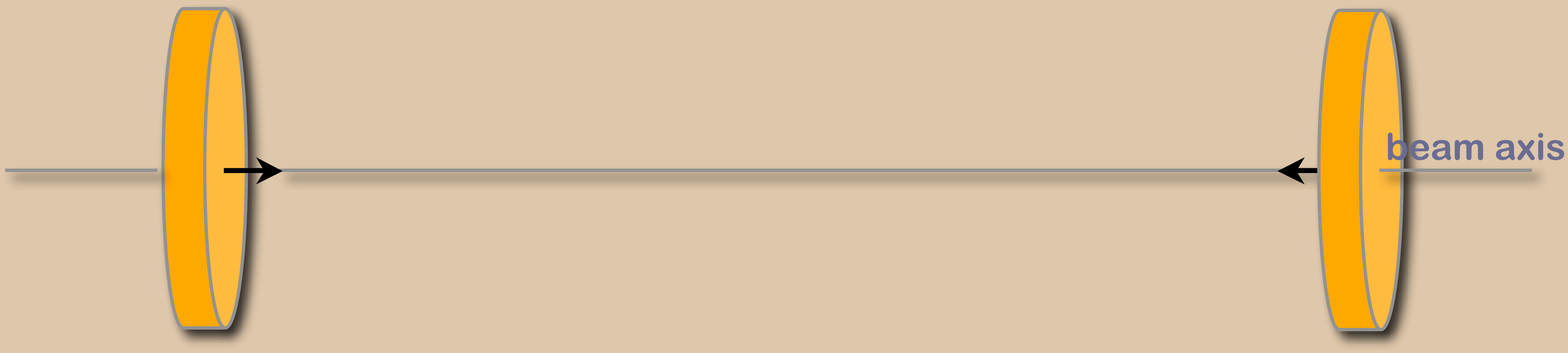
Prediction of deconfinement verified, liberation of degrees of freedom is seen.

QCD transition is a rapid crossover that happens about 190 MeV

Equation of state determined. Softening near T_c

Searching for Deconfinement: RHIC

The Coordinate System



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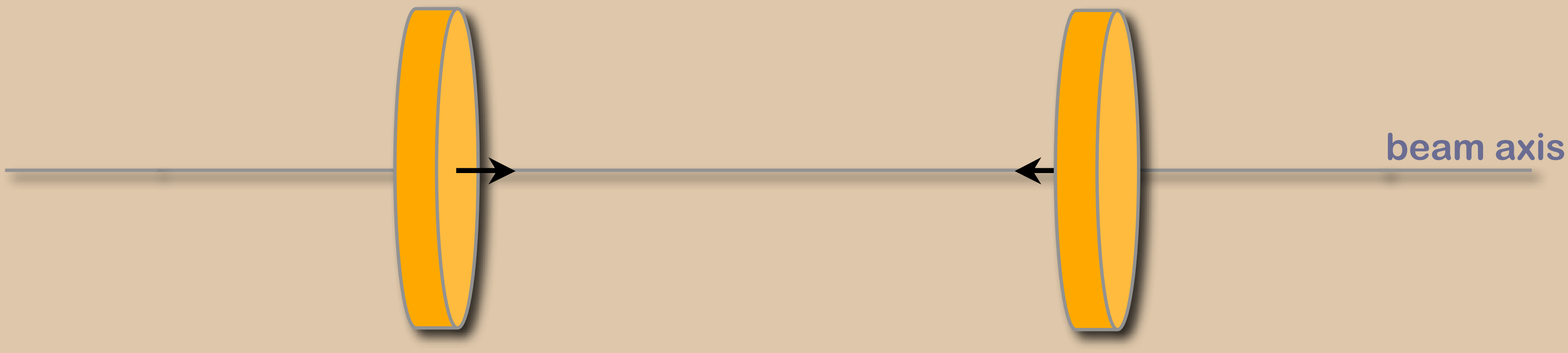
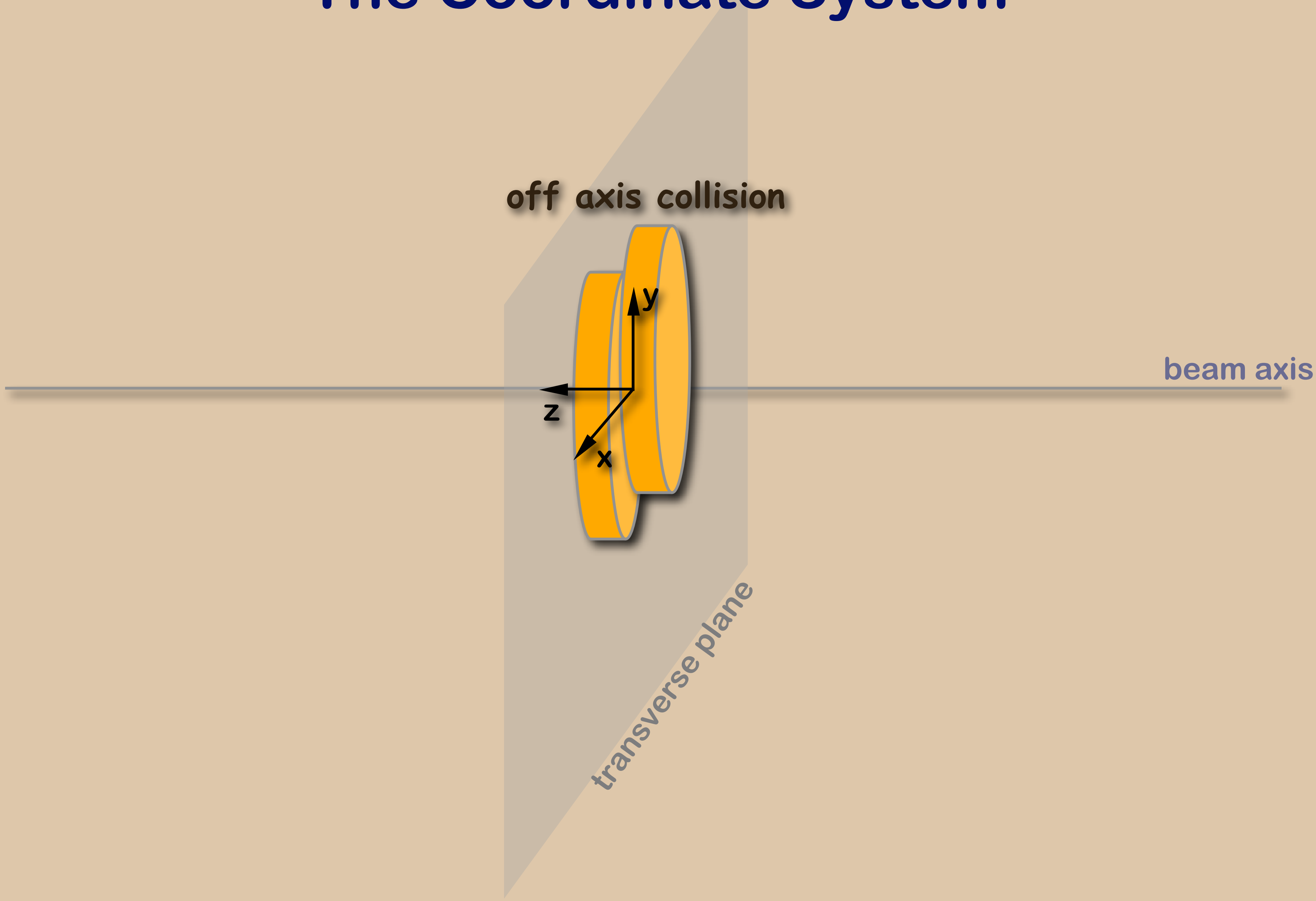


The Coordinate System



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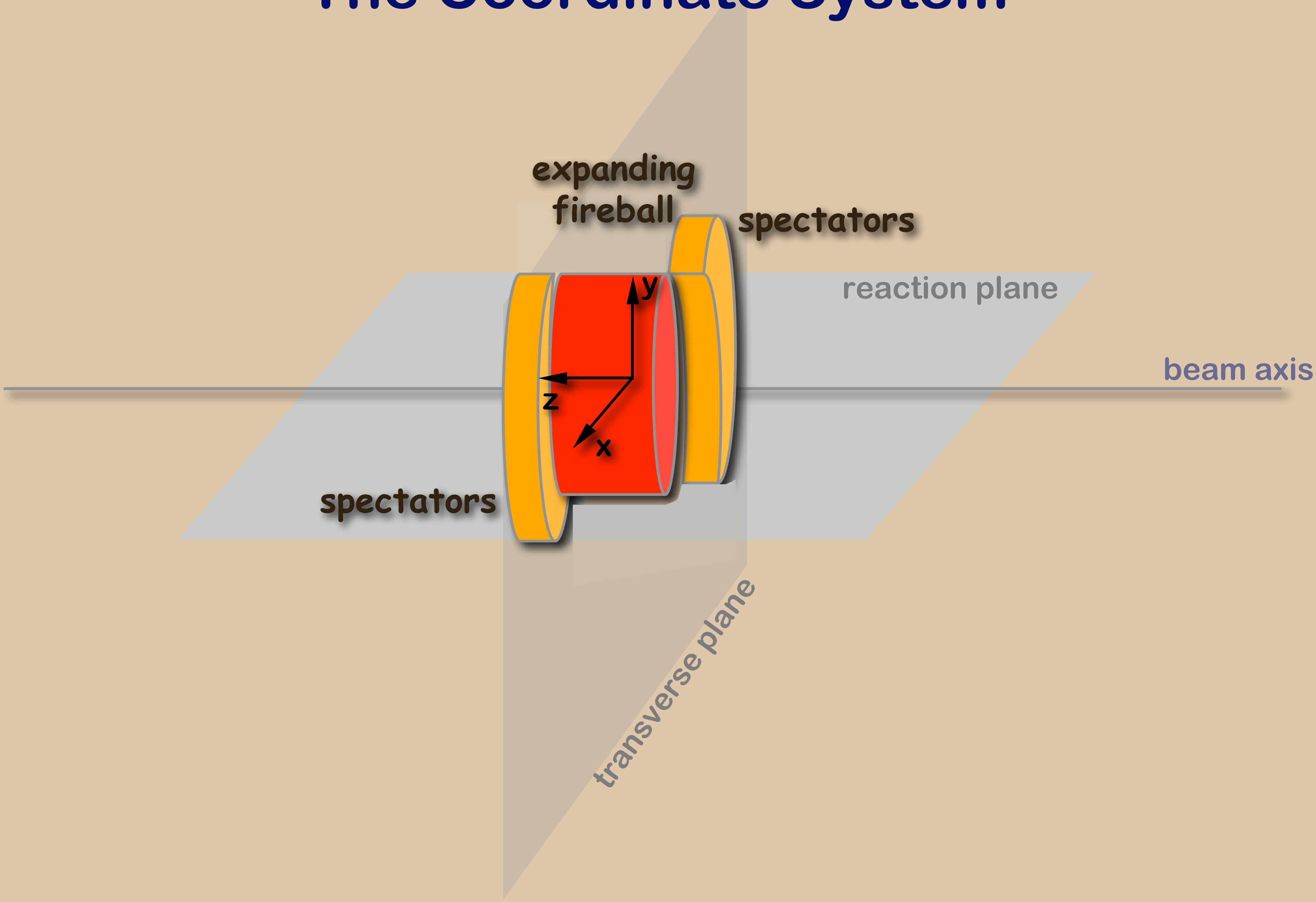

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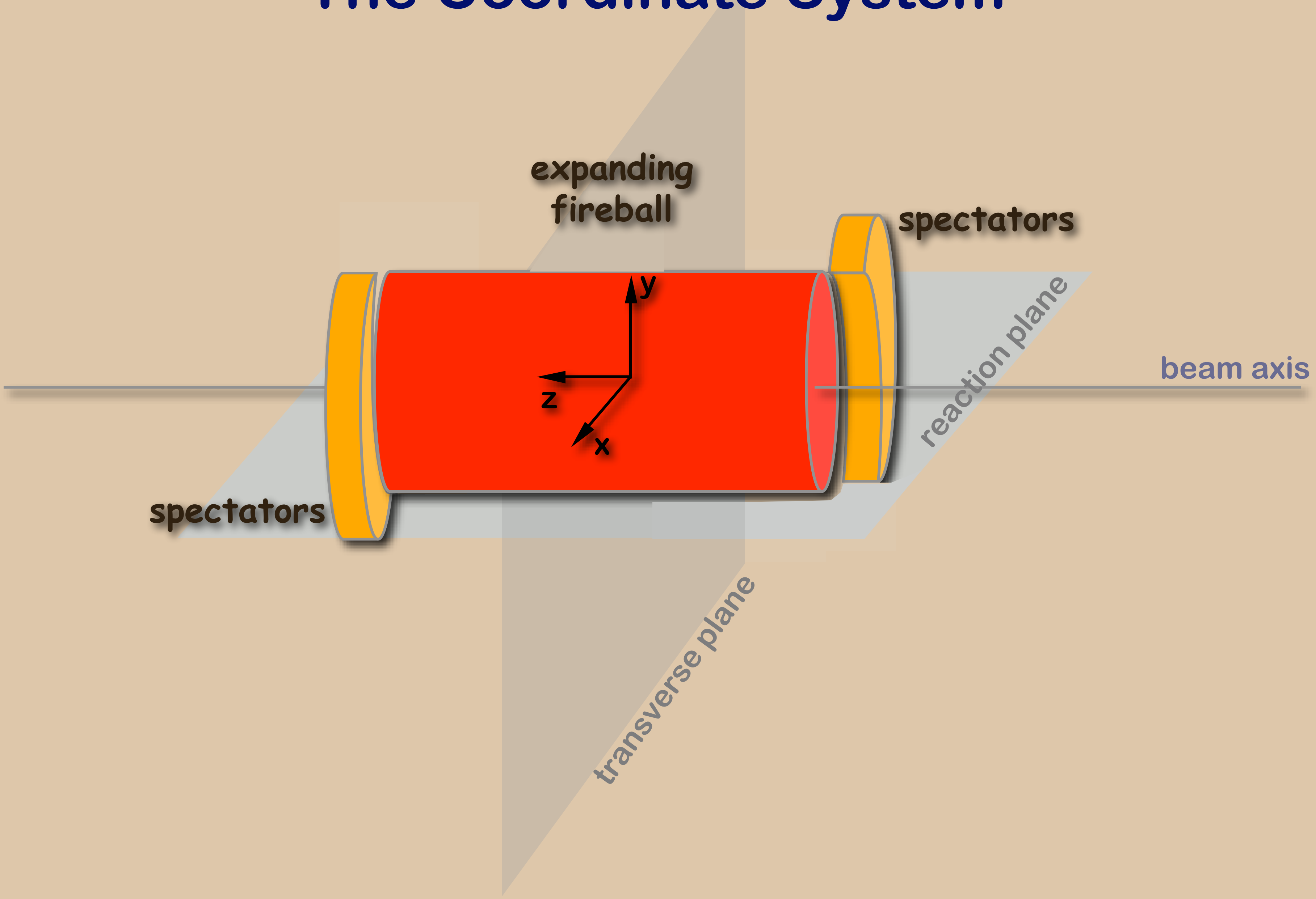
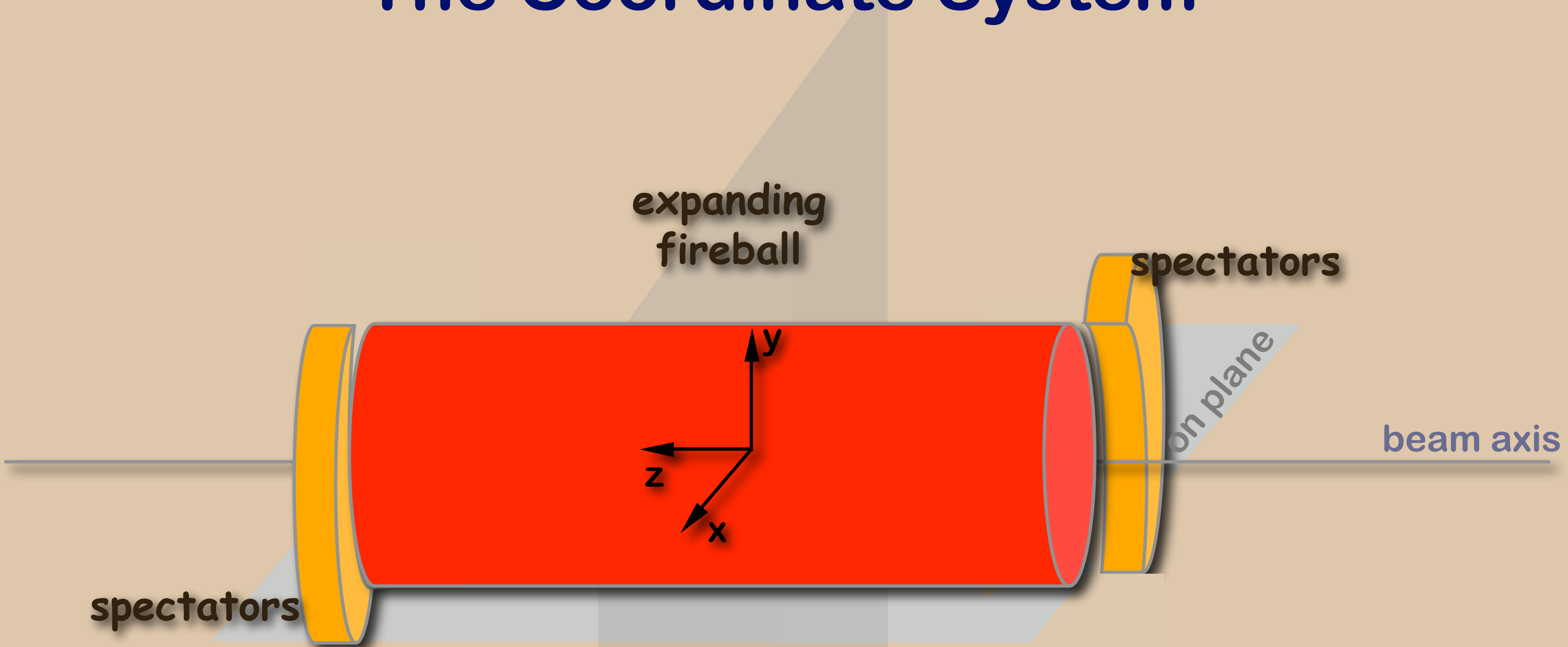


The Coordinate System



We can estimate the initial energy density in a slice of the fireball (neglecting radial expansion)

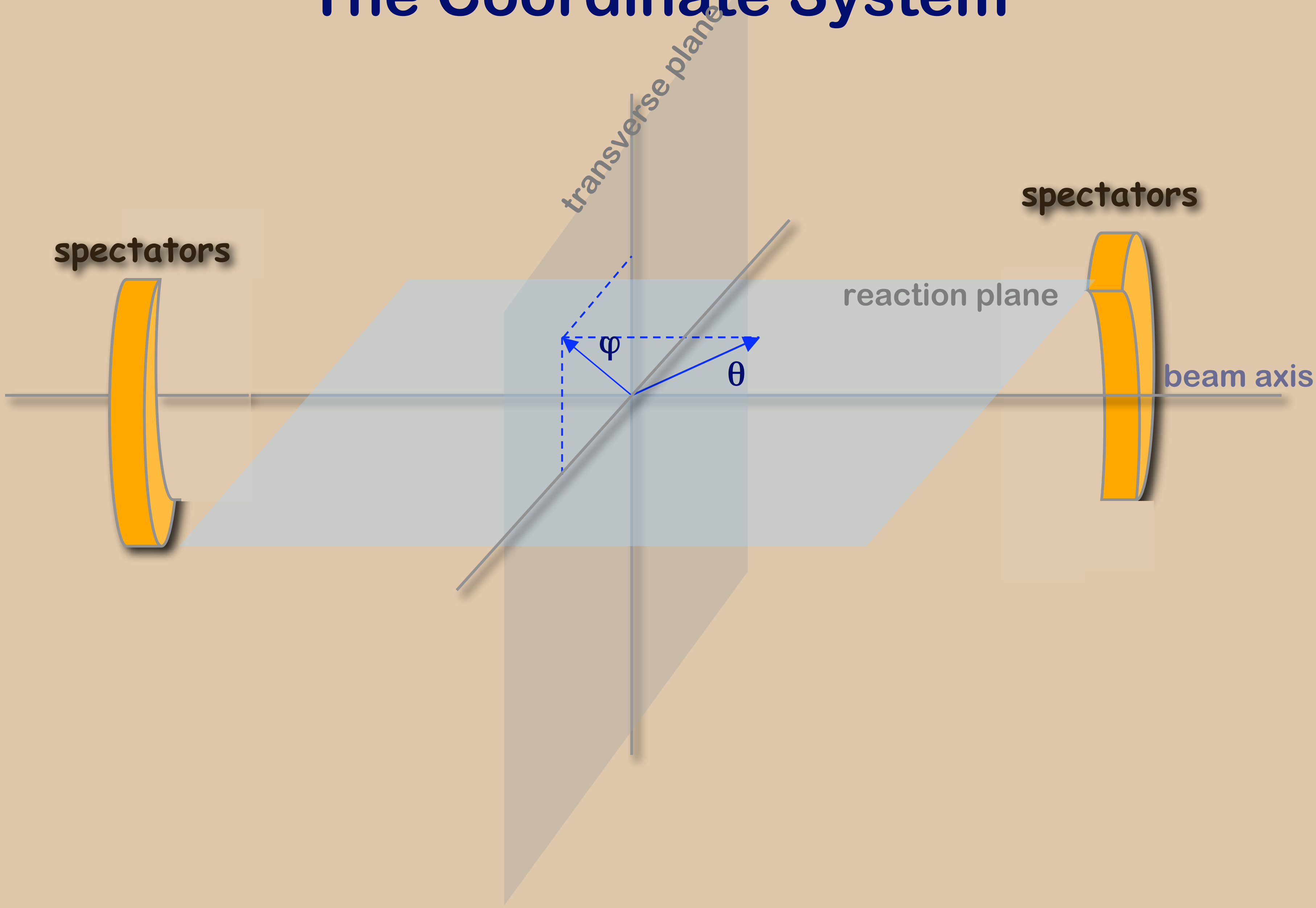
measured

For RHIC: ~4x larger than lattice critical energy

$$\varepsilon_{BJ} = \frac{dE_T/dy\big|_{y=0}}{\pi R^2 \tau_0} \approx 5\ GeV/fm^3$$

estimated

The Coordinate System



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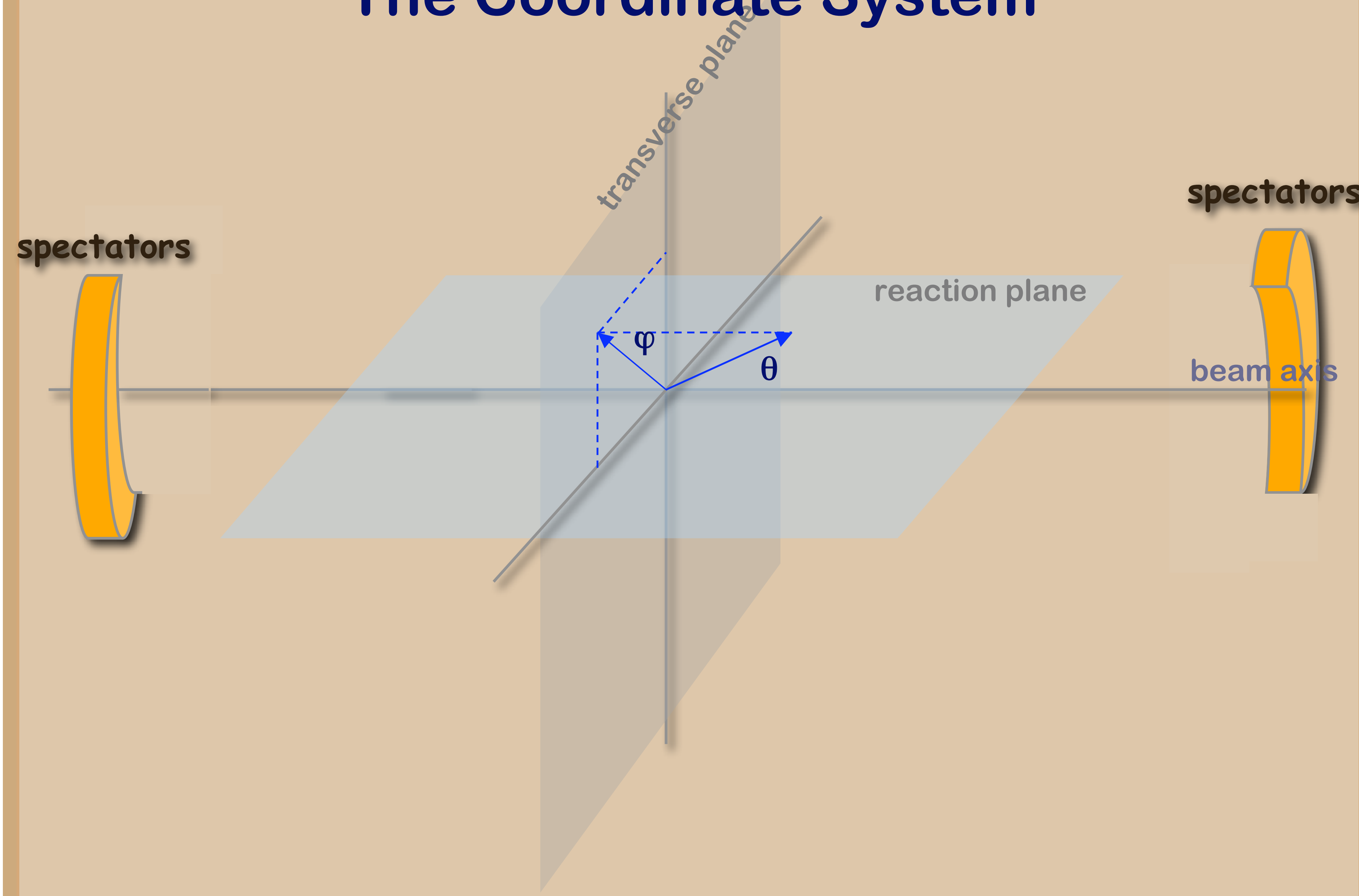
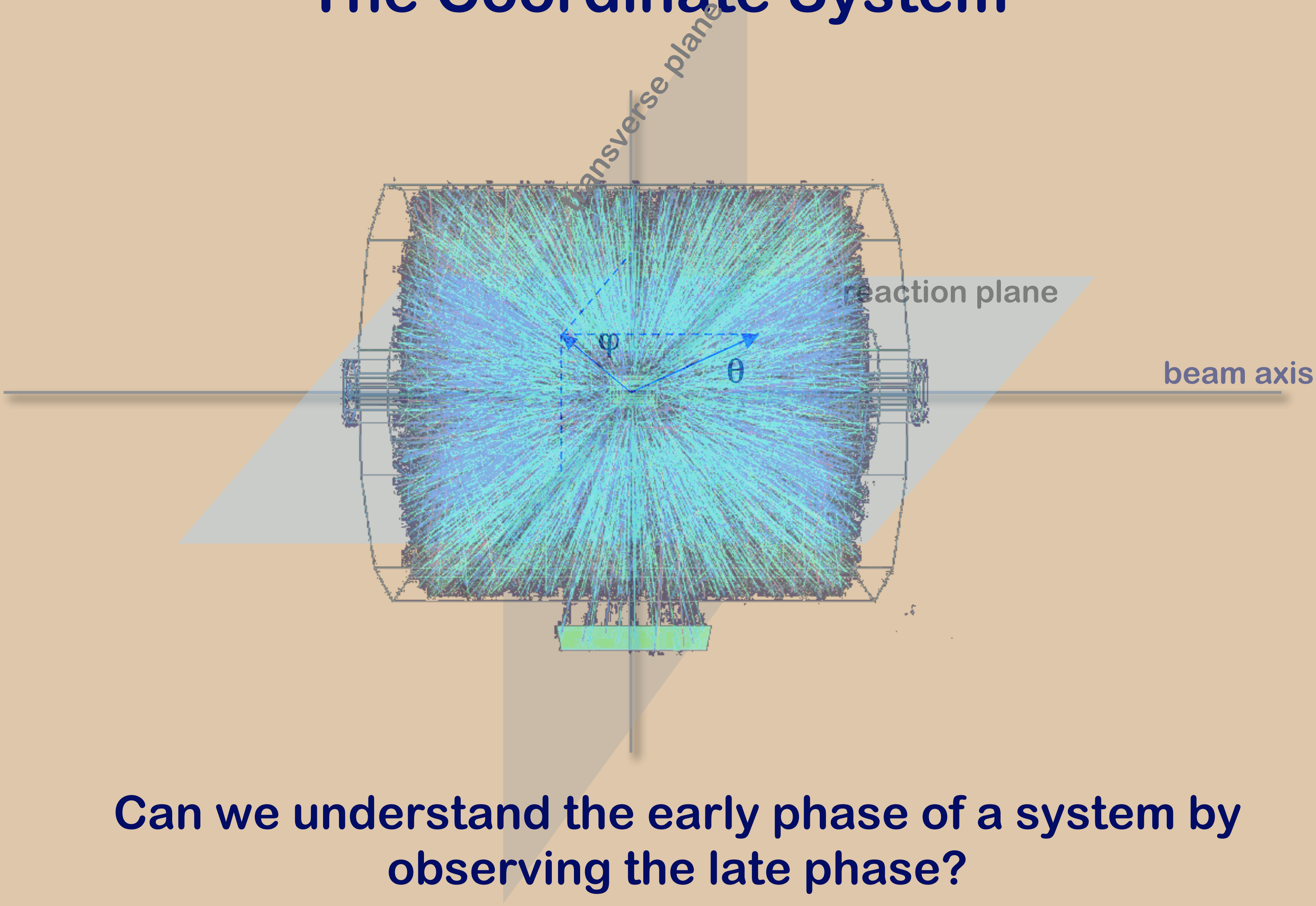
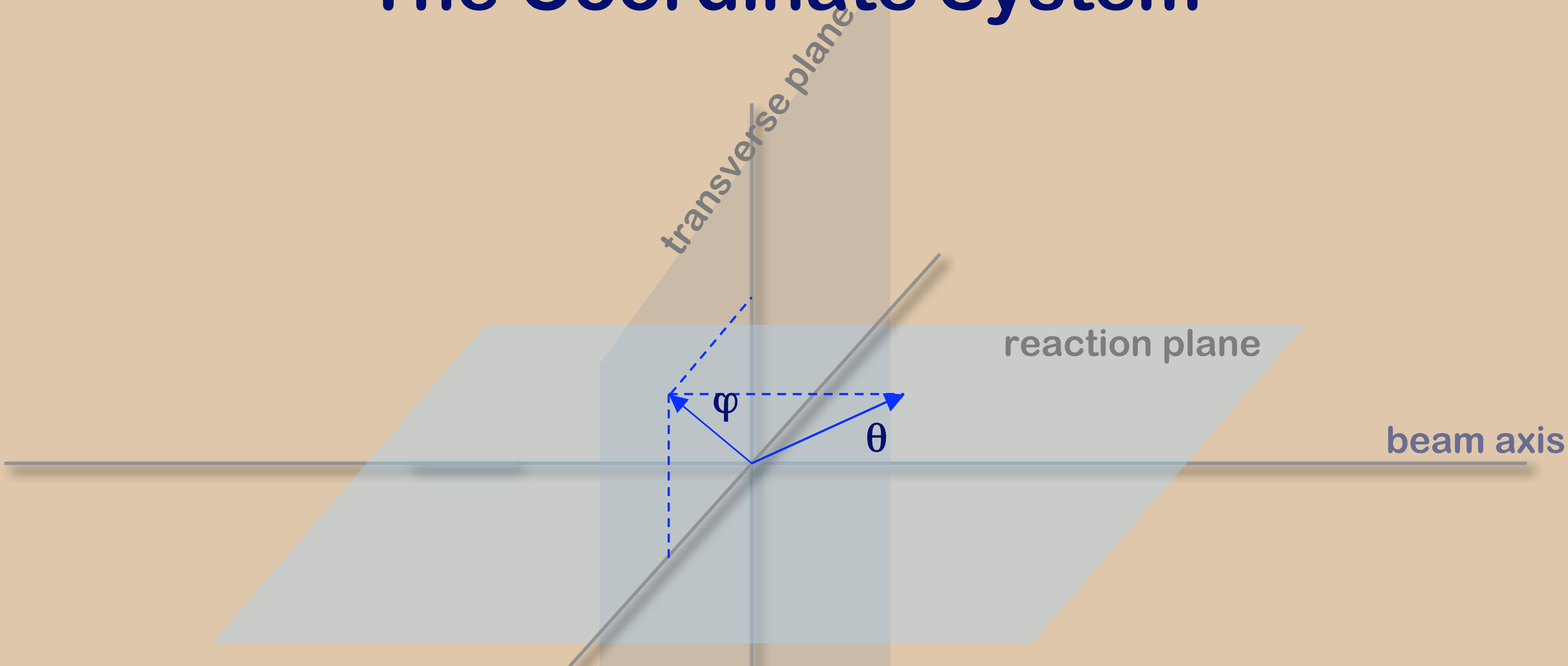


The Coordinate System



Can we understand the early phase of a system by observing the late phase?

The Coordinate System



What is measured is energy and momentum: E, p_x, p_y, p_z

We prefer to use:

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\eta = -\ln[\tan(\theta/2)] \approx y$$

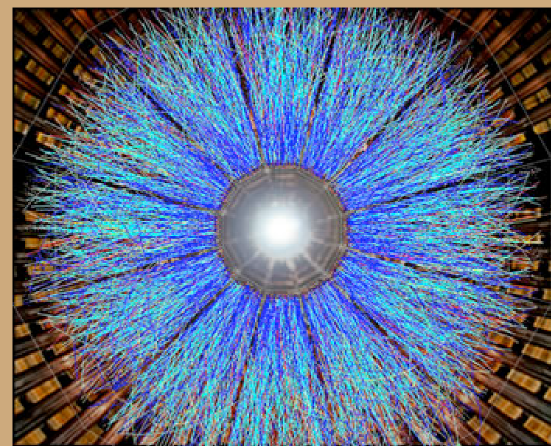
$$\varphi = \tan^{-1}(p_y/p_x)$$

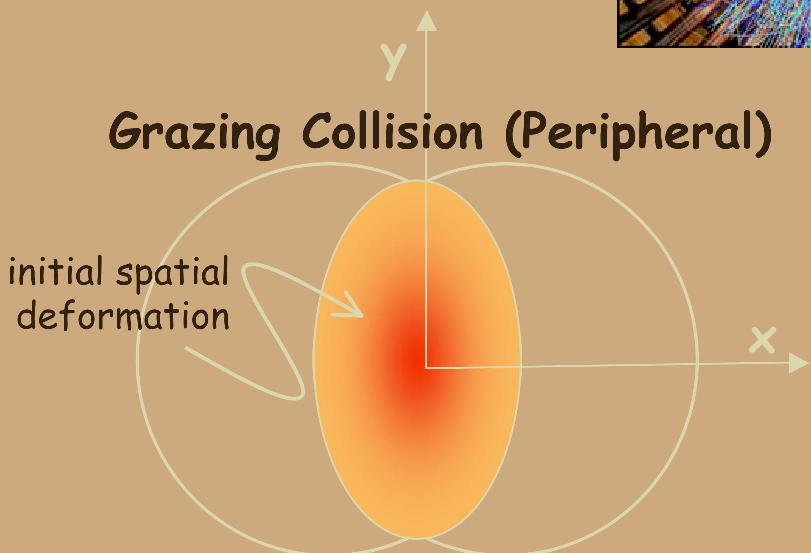
Rapidity y is a boost invariant quantity

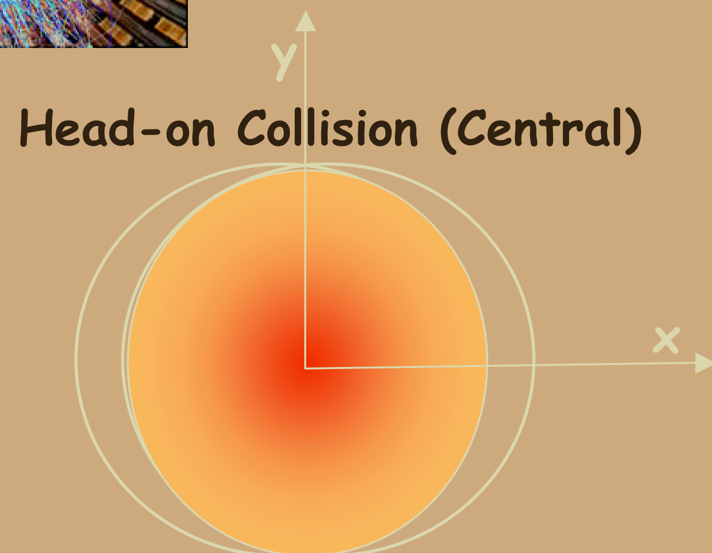
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \sim \ln(x)$$

$$y \overset{\beta}{\Rightarrow} y + \frac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right)$$

Transverse Plane

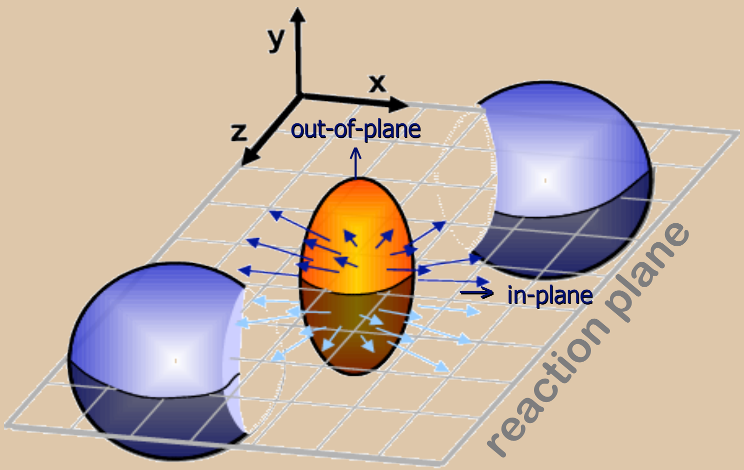




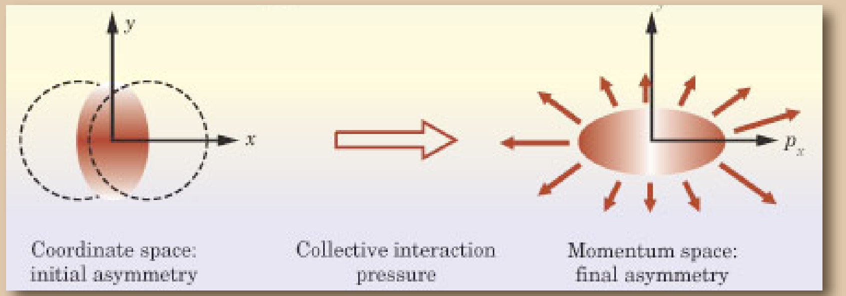


If there are interactions amongst the constituents, the initial spatial deformation can be transferred to the observed momentum distributions. Experimentalist use v_2 to characterize this conversion.

v_2: characterizing the "flow"



off-axis (non-central) Au+Au collision



Fourier decompose the azymuthal angle-dependence (measured with respect to the reaction plane) of the particle density

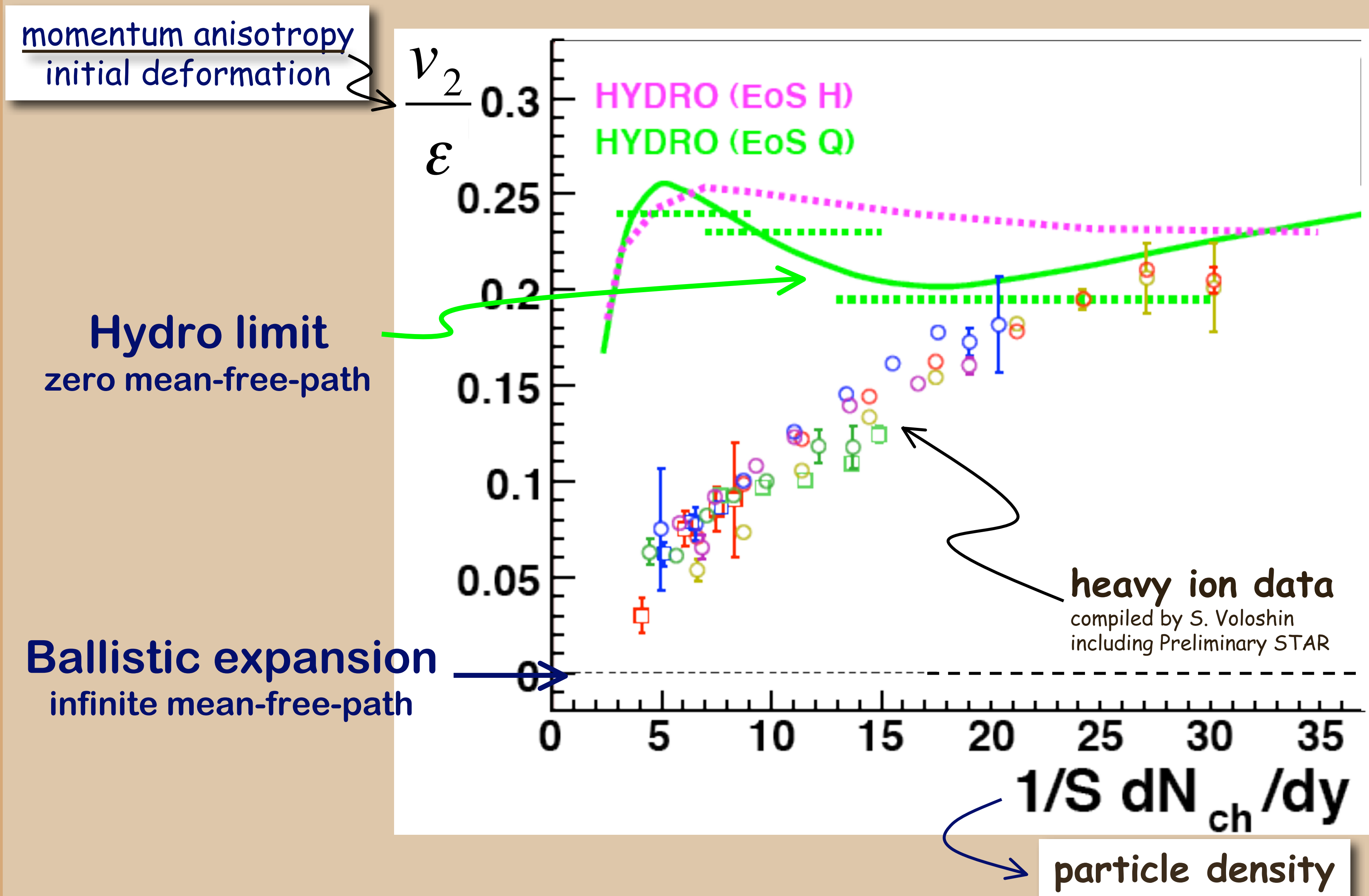
number of particles $\propto N[1 + 2v_2\cos(2\phi) + 2v_4\cos(4\phi) + \ldots]$

v_2 proven very important at RHIC: provides information about the interactions while the system was still oblong

shape washes out as it expands

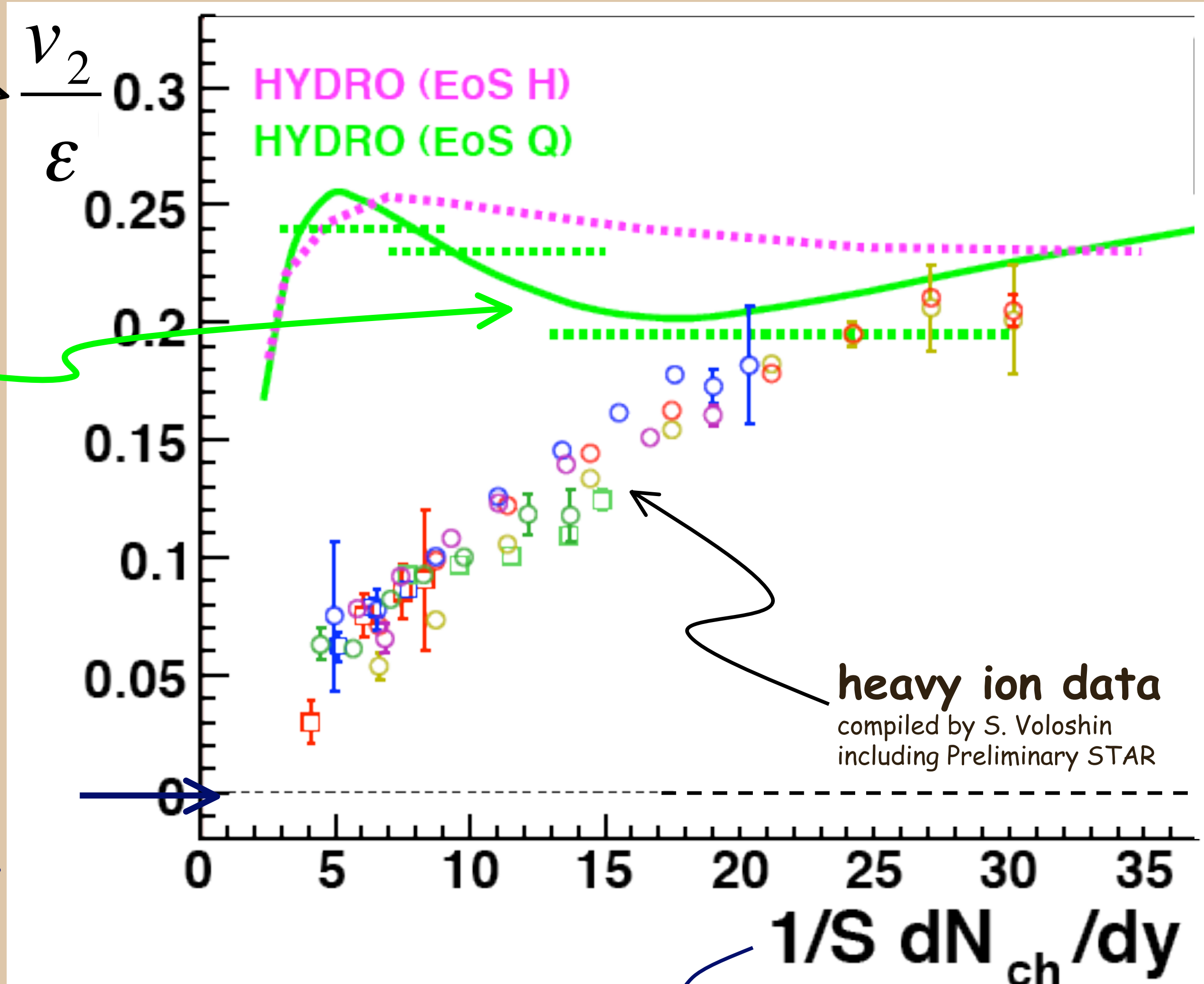
v_2 is sensitive to early interactions and (asymmetric) pressure gradients

Why do they call it “perfect” ?



Why do they call it "perfect" ?

momentum anisotropy / initial deformation



particle density

Hydro limit
zero mean-free-path

Unresolved issues:

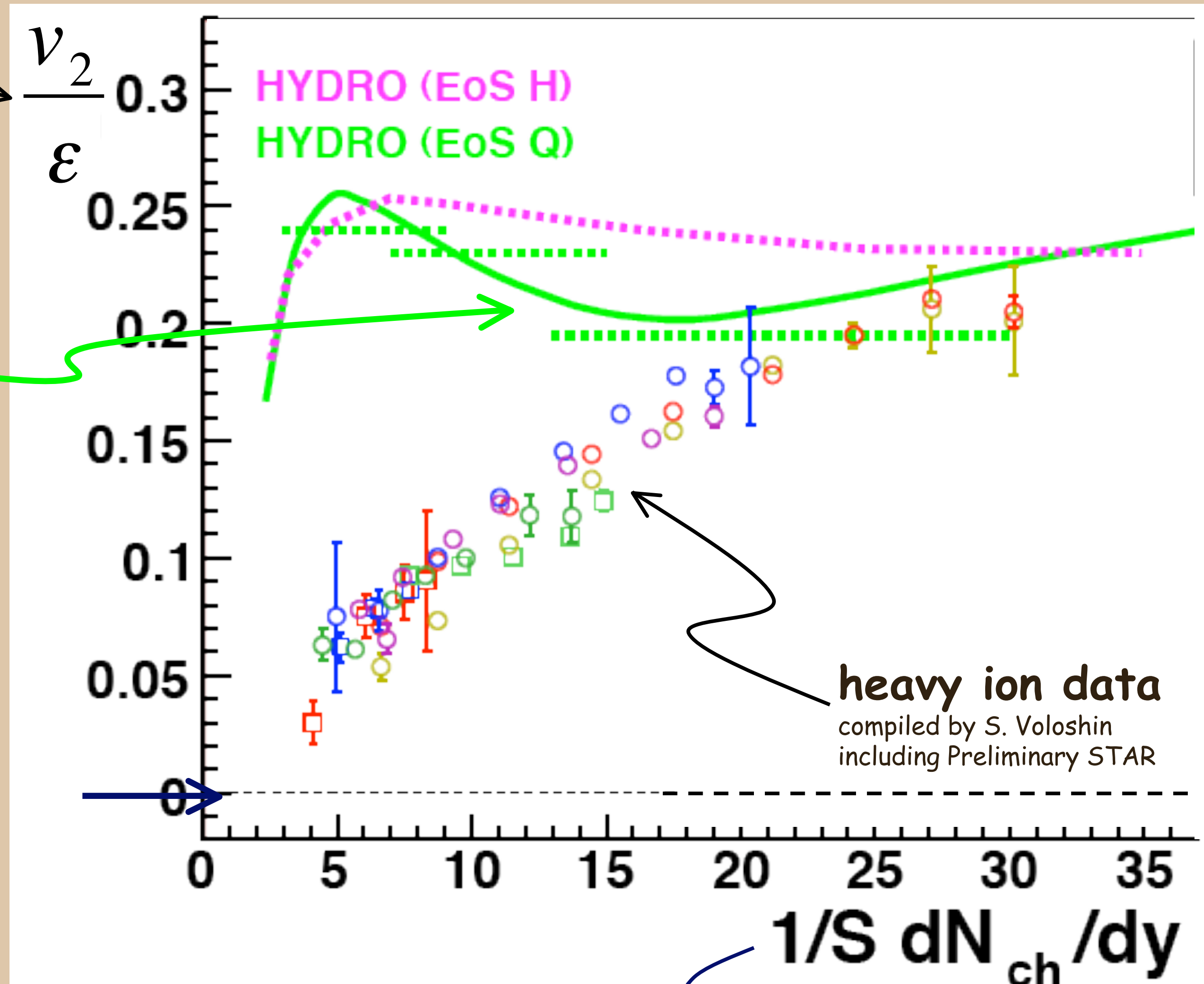
Uncertainty in eccentricity

Hydro parameter uncertainties

Why do they call it "perfect" ?

momentum anisotropy
initial deformation

Hydro limit
zero mean-free-path



particle density

Speculation:
This plot is like EoS. Data does not show softening?!

Recap

The estimated energy density is much larger than the critical energy density from Lattice QCD

The system converts spatial anisotropy to momentum-space anisotropy like a fluid would

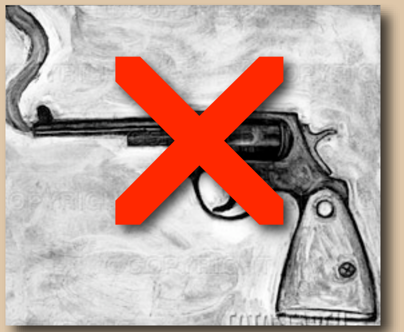
But can we observe deconfinement more directly?

perhaps with screening of Quarkonium

"J/Ψ suppression" Once the golden signal …

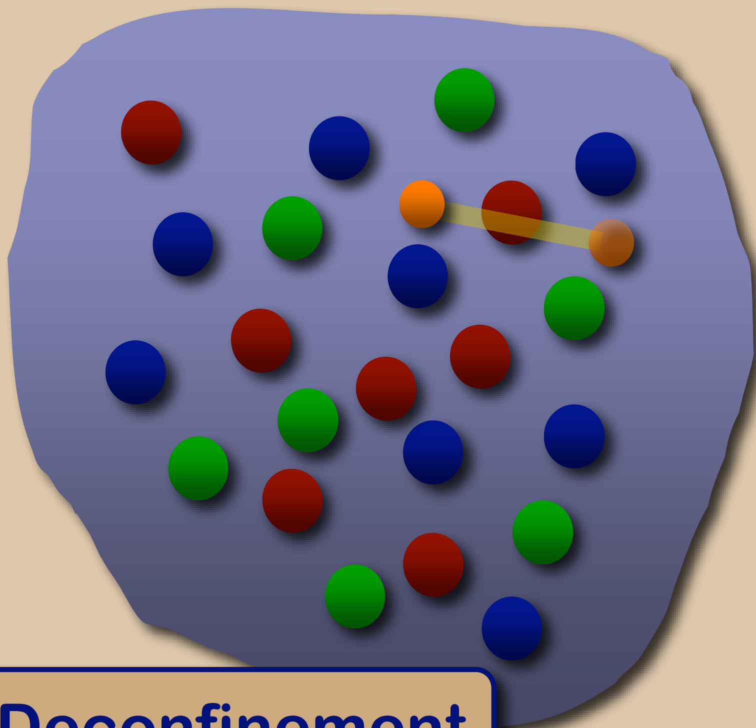
"… there appears no mechanism for J/ψ suppression in nuclear collisions except the formation of a deconfining plasma, and if such a plasma is produced, there seem to be no way to avoid J/ψ suppression. …the measurement of the dilepton spectrum from nuclear collisions should allow a clear test of this phenomenon."

Matsui and Satz, PLB (1986)



"J/Ψ suppression" Once the golden signal ...

Quarkonium = bound state of heavy ($m_{c,b} >> m_{u,d,s}$) quark & antiquark



Small in size.
Non-relativistic treatment.
Can only be produced in initial high energy parton collisions.

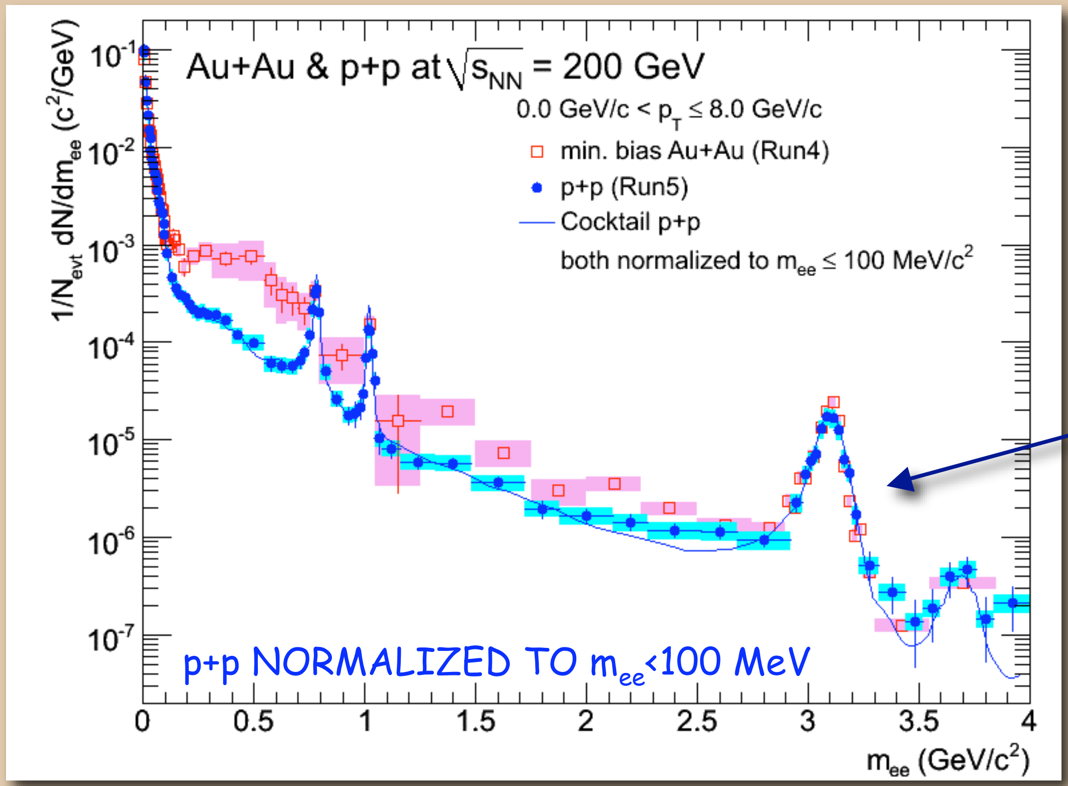
Screening in the deconfined matter weakens the potential (force) between the heavy quark and antiquark.

Deconfinement → Color Screening → J/Ψ melting → J/Ψ yield suppressed

J/Ψ yield at RHIC-BNL

J/Ψ has large decay branch to dileptons (e^+e^-)

In heavy ion collisions dilepton spectra measured:

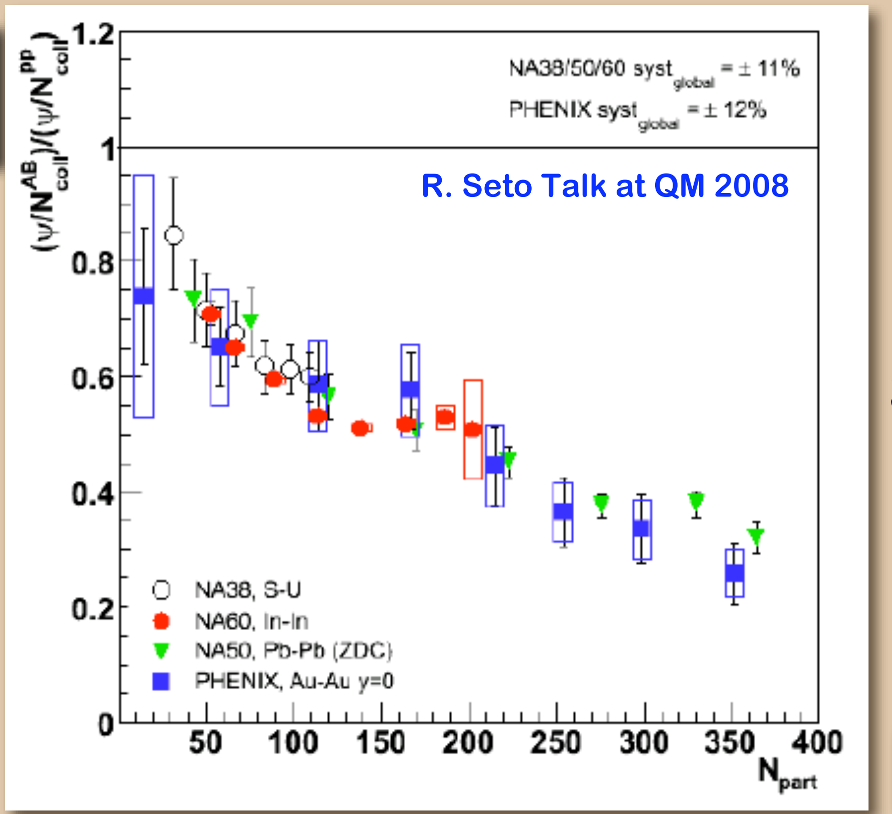


R. Seto Talk at QM 2008

J/Ψ suppression measurement R_{AA}

J/ψ nuclear modification factor

$$R_{AA}^{J\psi} = \frac{1}{N_{coll}} \frac{\dfrac{dN^{A+A\to J\psi+X}}{d^2kdy}}{\dfrac{dN^{p+p\to J\psi+X}}{d^2kdy}}$$



Suppression!

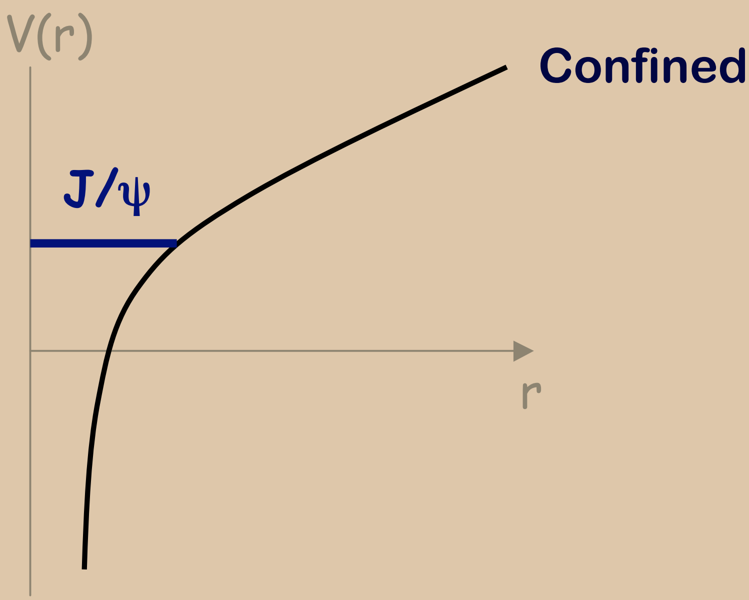
centrality

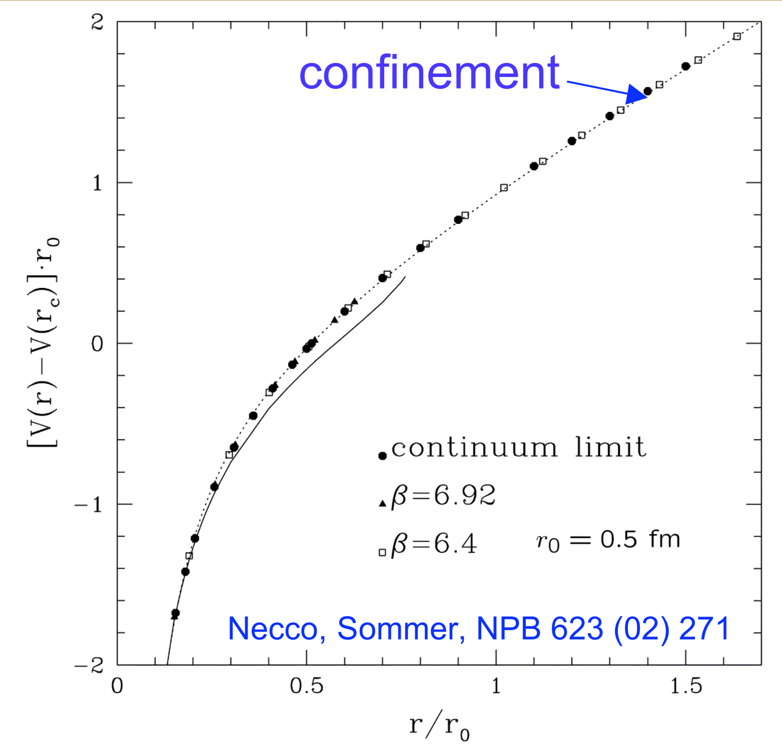
Due to effects of: 1. cold nuclear matter 2. hot matter 3. recombination

Need to disentangle.

One theory step: Must know in-medium quarkonium properties !

Theoretical studies: potential models,lattice

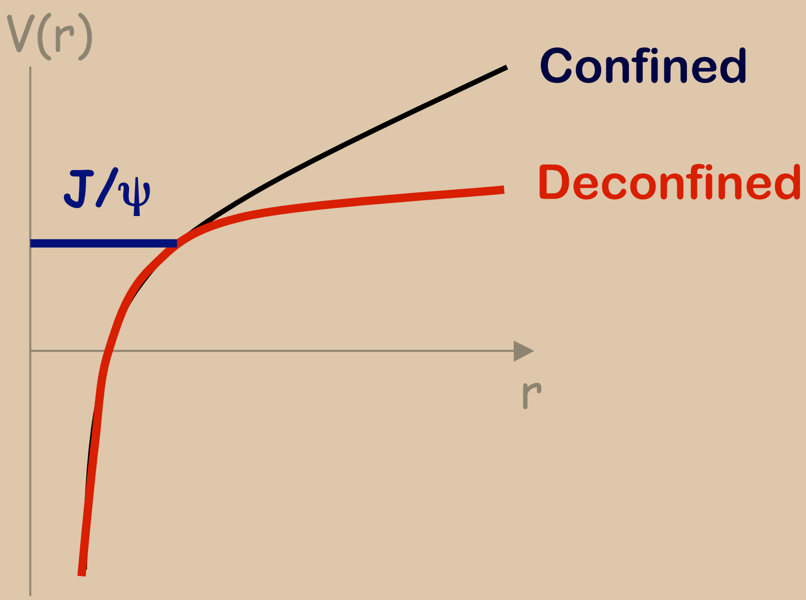


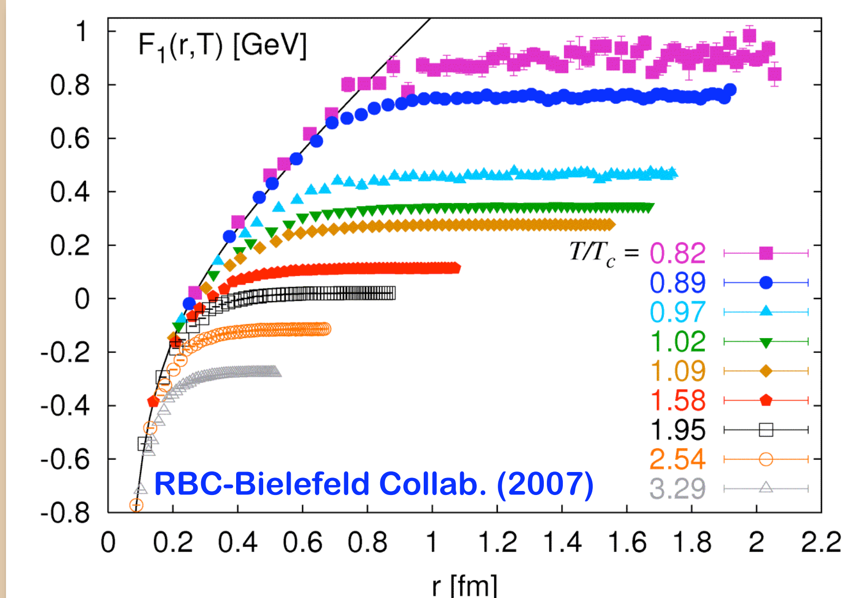


$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + \sigma r$$

NB: confinement verified on the lattice

Theoretical studies: potential models,lattice



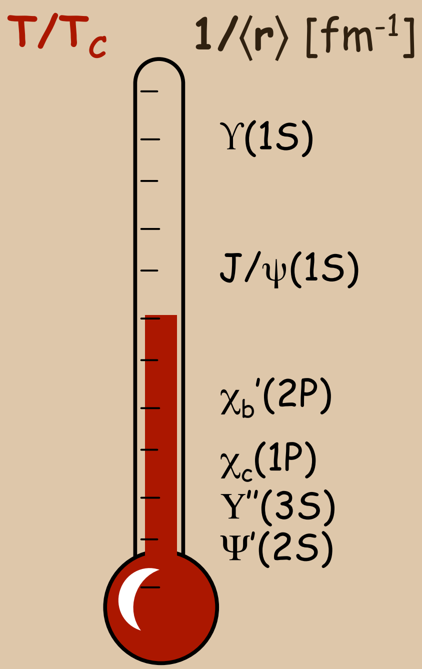


Free energy of a static Q-Qbar in N_f=2+1

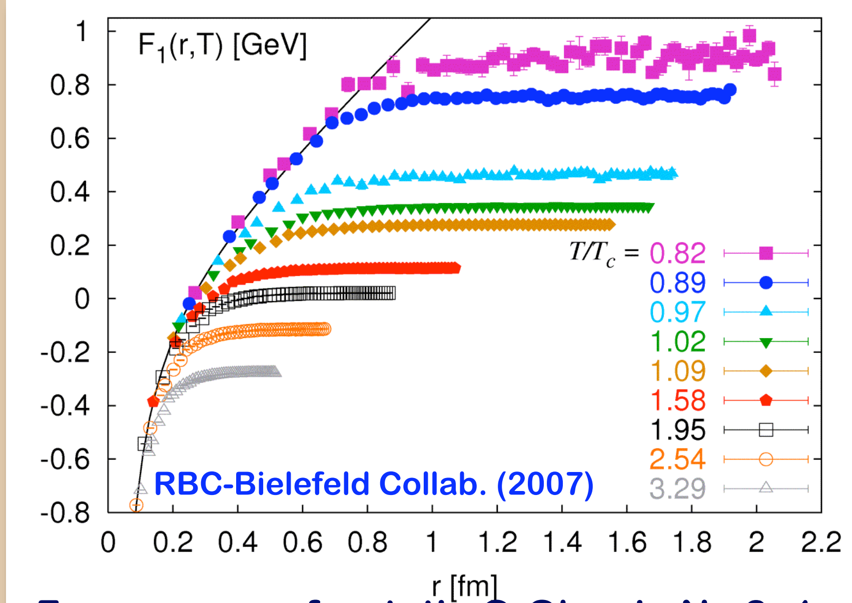
Strong screening seen in Lattice. Range of interaction between Q and antiQ is strongly reduced

With increasing temperature screening sets in at shorter and shorter distances

Theoretical studies: potential models,lattice



QGP thermometer



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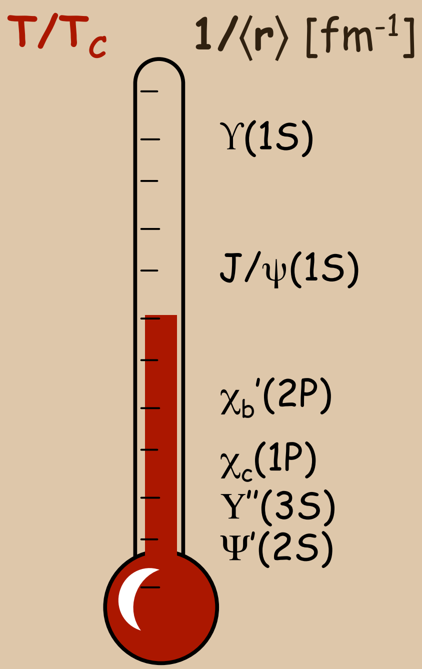
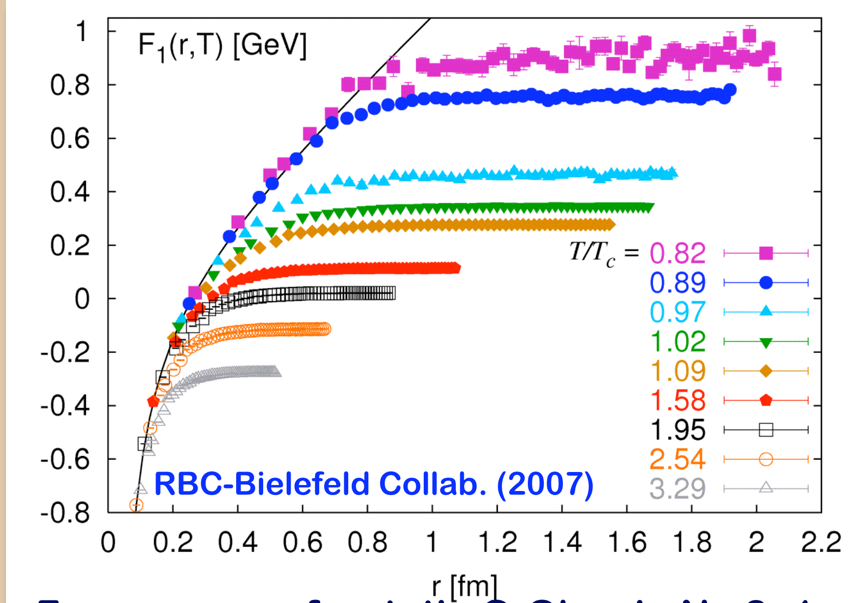


QGP thermometer

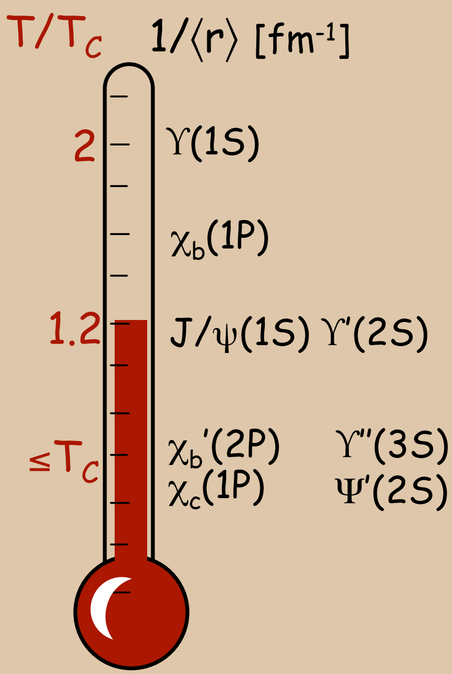


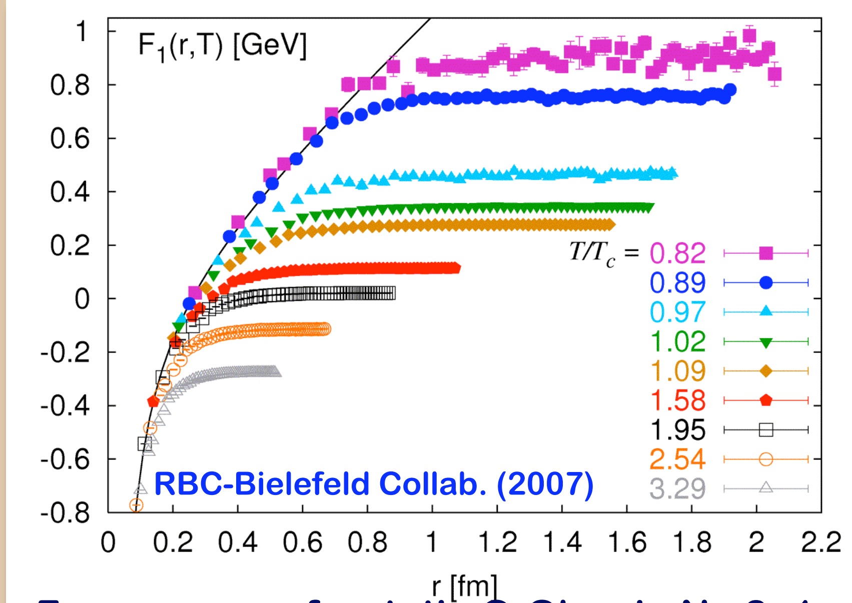
Free energy of a static Q-Qbar in N_f=2+1

Contrary to recent beliefs: most states are dissolved close to T_c except the ϒ and η_b , these melt by $2T_c$

Mócsy, Petreczky PRL (2007)

Theoretical studies: potential models,lattice





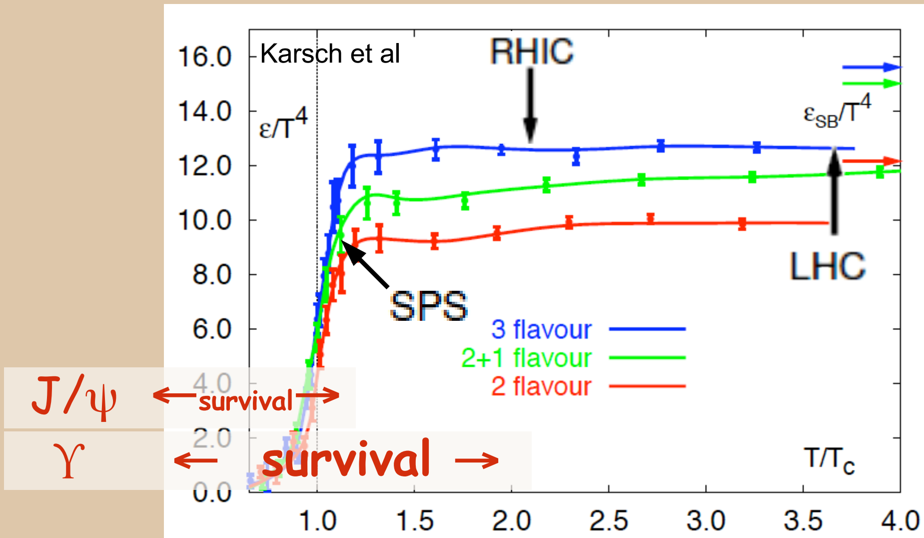
Free energy of a static Q-Qbar in N_f=2+1

calibrated QGP thermometer

Contrary to recent beliefs: most states are dissolved close to T_c except the Υ and η_b, these melt by $2T_c$

Mócsy, Petreczky PRL (2007)

Consequences for RHICollisions



state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

Mócsy, Petreczky PRL (2007)

Expect:

- **Similarity of J/ψ R_{AA} at SPS and RHIC**
- **Upsilon suppression at RHIC, and definitely at LHC**

Recap

Quarkonium suppression, the golden signal, is more complicated than originally thought.

Great experimental and theory progress, but we are not there yet ...

My last sentence(s):

Deconfined quark gluon plasma expected from QCD. Lattice calculations confirmed deconfinement. Heavy ion collisions in search of deconfinement provided wonderful data showing that new state of matter has been produced. Understanding the properties of this matter still needs more work. We look forward for the upgrades. Thanks for making it happen!

****The END****