"All the World's ~~a Stage~~" (almost a) Critical Point

And all the men and women, merely players...
"As You Like It", Shakespeare.

Phase transitions:

liquid => gas: bubbles, *critical point.*

membranes & vesicles: ~*zero* surface tension => ~ critical point.

nuclei: deconfining "spins": ~ *critical point* for Quark-Gluon Plasma

Quark-Gluon Plasma & the "Unicorn"

New State of Matter in Heavy Ion Collisions? "Jets" get *eaten!*

Exact critical point for QGP? GSI.

Phase Transitions

Boil some water: change in phase from *liquid* => *gas*

"Order parameter": some #, changes between phases

Here: density. Liquid dense, gas dilute.

Liquid "obviously" different from gas.

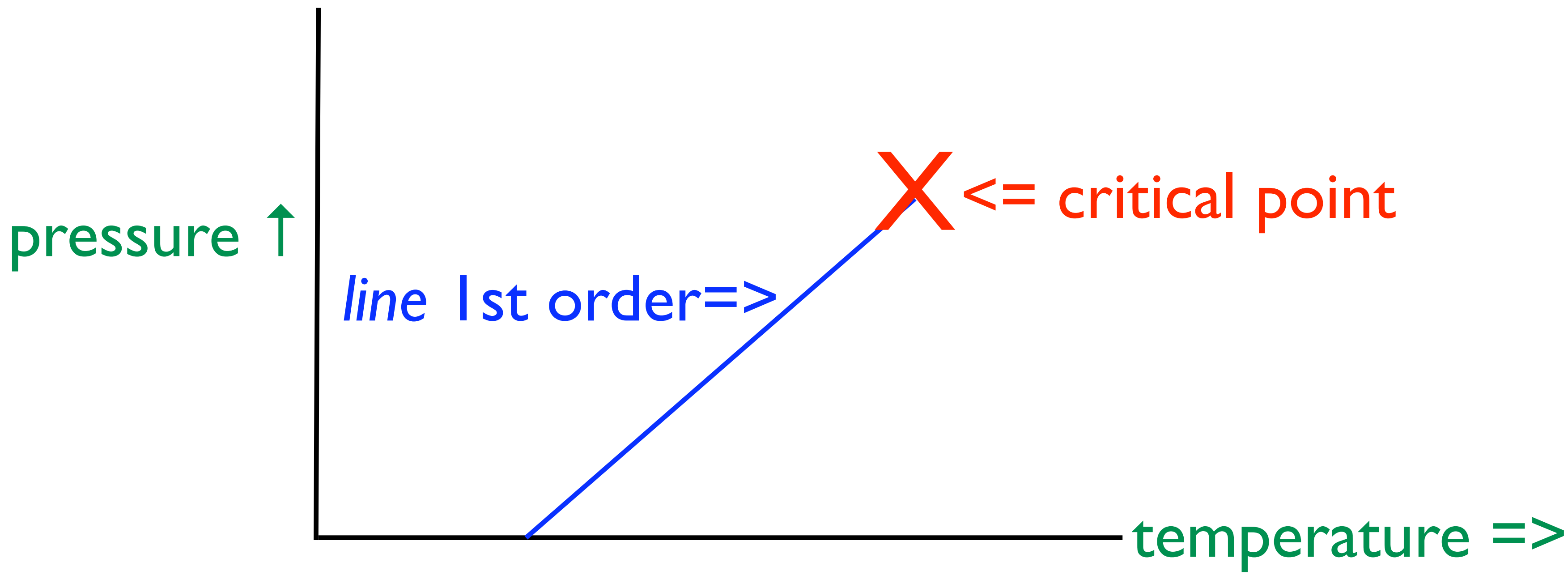
"First order transition": *there are bubbles!*

And: bubbles have a given *size.*

Bubbles => metastable states! supercooling, superheating...

"Critical Point": *BIG* Bubbles

OK, now boil water at *much* higher pressures:



Along line of first order transitions, finite size bubbles.

As => X = *critical point*, bubble size => *infinity*. Critical opalescence.

= second order phase transition.

Water: X = 218 Atm, 374° C.

Have to hunt for the critical (end) point. No *symmetry*.

Two state model

Consider model with two states, up ☝ or down ☟

Assume *symmetry* = interchange up and down.

Low temperature: "liquid" = (mostly) up OR (mostly) down

Symmetry => *domains* in liquid phase, either up or down.

High temperature: "gas" = mixture, up + down.

Find: at transition, *NO* bubbles. Correlations over ~*infinite* sizes.

"Critical fluctuations"

Can "see" in numerical (Monte Carlo) simulations.

Critical Point: with Symmetry!

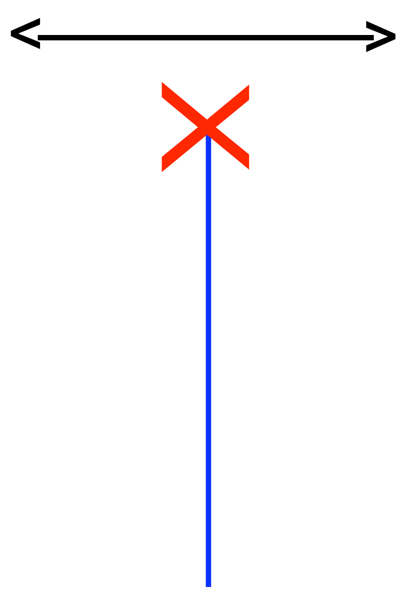
All critical points have symmetry.

Symmetry not enough to guarantee critical point.

"Universality": at critical point, depend *only* upon symmetry (& dimension) At large distances, *everything* unique. Wilson, '71.

Symmetry for liquid-gas? "Hidden" two state.

Rotate first order line in plane of P & T:



Symmetry = perpendicular to first order line.

Symmetries can show up in surprising places...

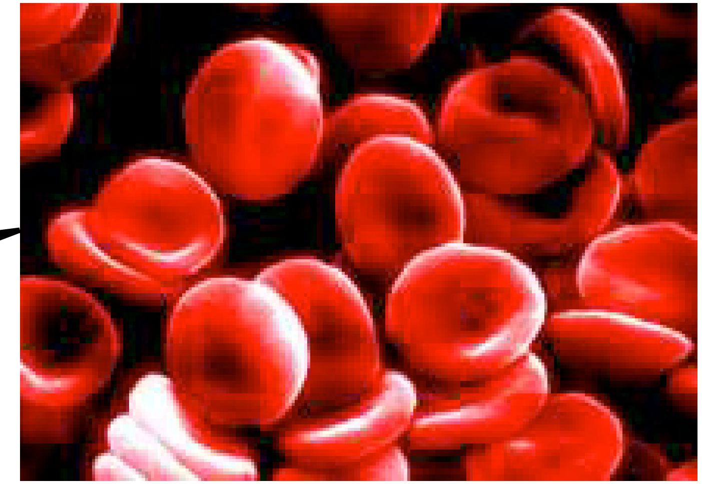
Another critical point: red blood cells

Red blood cell = *membrane.*

“Flicker” under microscope.

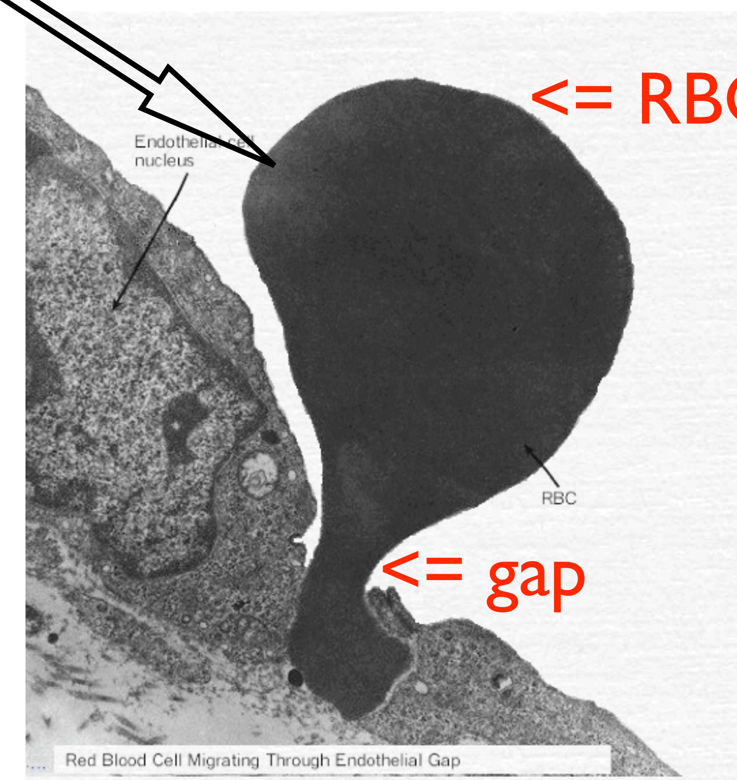
Equilibrium shape *not* spherical

very bendable



Exp.’y: minimize with respect with volume
and area *independently*

=> (renormalized) surface tension *vanishes*
=> = critical point.



Critical fluctuations => flickering.

Shape: determined by curvature terms.

Squeezing through gap ↑

Surfaces as critical point at *short distances*

Critical point in three dimensions: very hard to compute.
Correlation functions fall off as powers ("critical exponents")

In four dimensions, easy to compute: coupling constant
vanishes ~ 1/log(r) as r → ∞ = *large distances*

surfaces: free energy = sum of area + curvature^2.

Coupling for curvature term *asymptotically free:*
vanishes ~ 1/log(r) as r → 0 = *short distances*
flat surfaces: RDP '83; Peliti & Leibler '85, Polyakov '86
membranes in large # dim.'s: RDP '87 ("smooth" strings)

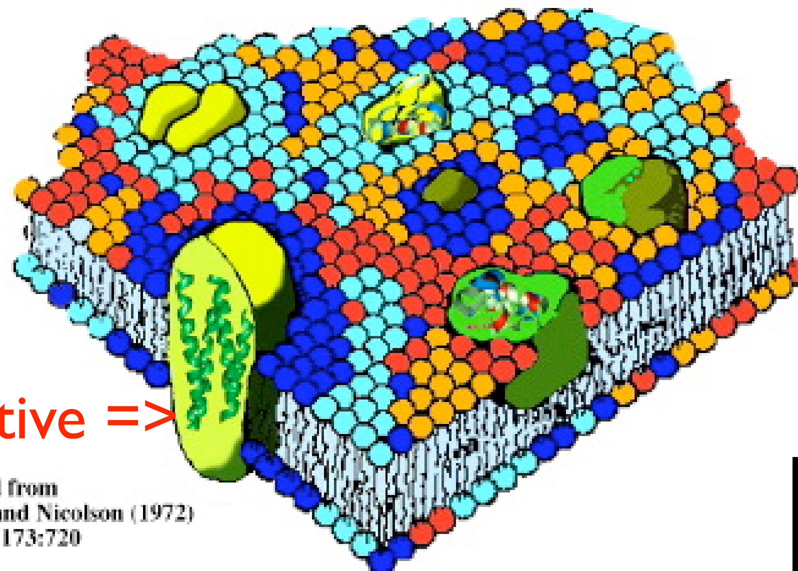
Another example (spin models in two dim.'s ~ gluons in four)

(Quarks) & gluons = strong interactions = *asymptotically free.*

Membranes & Giant Vesicles

Biological membranes = *proteins* embedded in lipid bilayer:

Proteins bind on/in surface. Diffuse freely in plane, biologically active =>



adapted from
Singer and Nicolson (1972)
Science 173:720

<= Singer & Nelson
"Fluid mosaic"
model

From just lipid bilayers, make giant vesicles=>
(W. Webb + ...)

Understand "patches"? = domain formation.

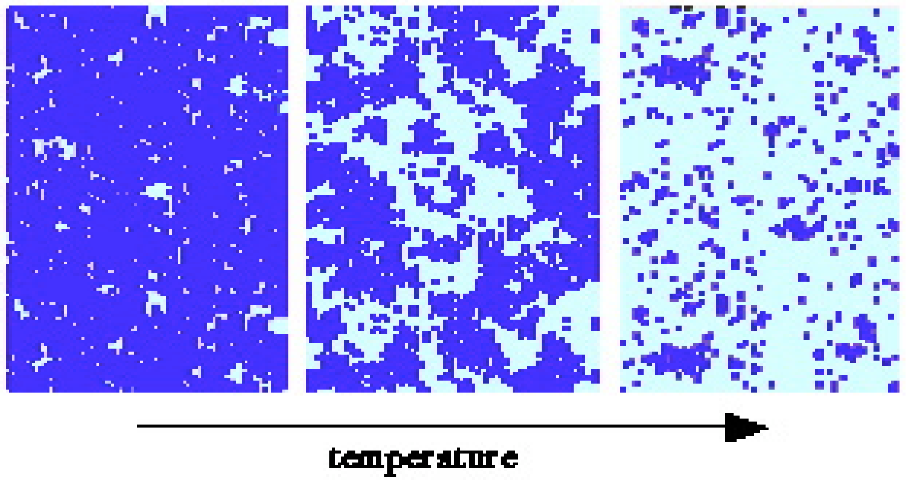
(Proteins may bind preferentially to domains.)

Melting of Lipid Bilayers

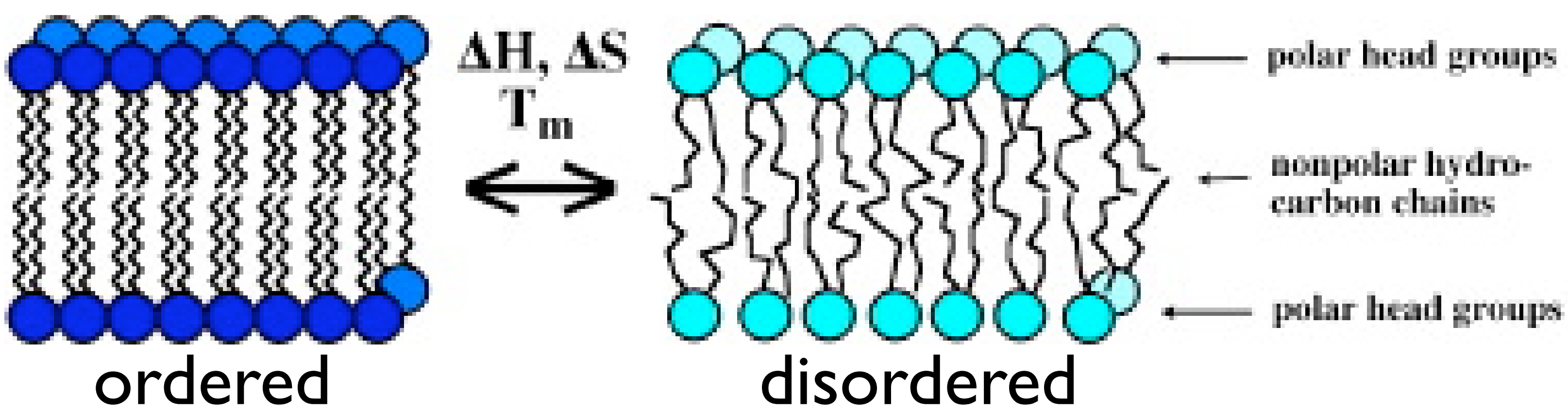
T. Heimburg: NBI & Gottingen

Transitions in lipid bilayers: domains "melt".

Monte Carlo simulation =>
~ like two states?



Lipids = polar head + (long) nonpolar chain
Transition: both (hexatic) ordering of polar heads *and* "wiggling" of long chains



Giant Vesicles & *Two* Critical Points

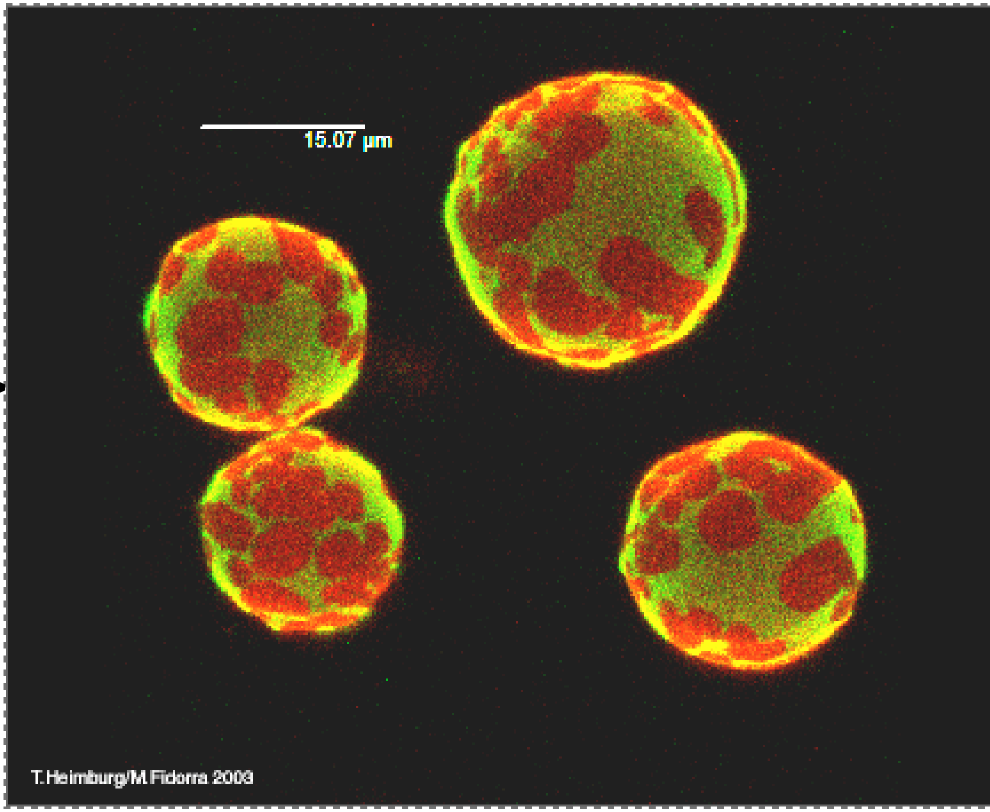
T. Heimburg + ... *two* order parameters:

Hexatic ordering of heads *and* wiggling of tails.

Describe by *two* two state models, *each* with a critical point, whose critical temperatures are close, but different.

Study: 1. Mean field theory.
2. Monte Carlo simulations.
3. Experiment.

Obtain good description of data: =>



(Almost) critical points are very important for biology!
And quarks & gluons, too.

Quark Model

Nucleons=neutrons & protons (N&P): strongly interacting particles.

From high energy experiments, discover each is made of

three quarks: N, P = qqq, q = quark.

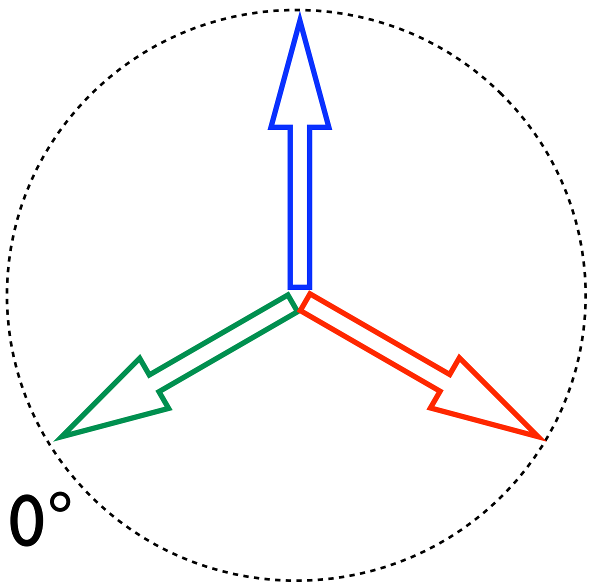
Also: "mesons" = quark + "anti"-quark (pions, kaons...)

Scales: mass proton = ~ 1 GeV = 10^9 eV.
All scales ~ 10^9 times usual biological scales; T ~ trillion degrees.

Quarks "confined" by *gluons:*
quarks & gluons "asymptotically free" =
critical point at *short* distances (like membranes)
('t Hooft) Gross, Politzer, Wilczek '72
things simple at short distances = high energy.

Gluons and a three state model

Confinement: gluons => individual quarks don't exist, only
nucleons & mesons.
= type of *three* state model.



For a given state, assume a transformation:
for *each* quark, rotate by 120°.

With three quarks, rotate by 3 x 120°= 360° = 0°
=> nucleons *invariant* under transformation.

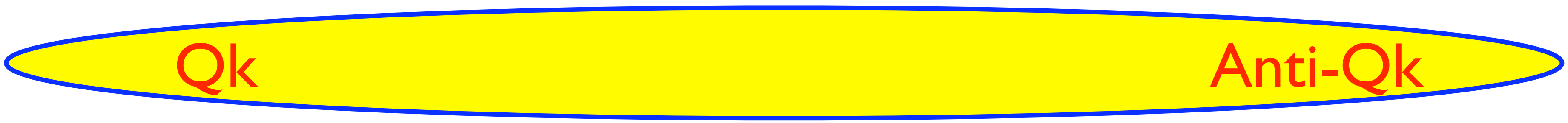
Anti-quark => rotation by -120°.
Mesons: rotate by +120° -120° = 0° => *invariant* under transf

Confinement: (at zero temperature) only *invariant* states exist.
i.e., don't rotate. 't Hooft '79.

Confinement and a Surface Tension

Meson = quark plus an anti-quark.

If you try to stretch them apart, gluons => *constant force*
=> mesons form flux tube:



At *one* instant in time, flux tube = *"string"*
(as in: "String theories" a.k.a. "Theory of Everything")

In *space-time*, string sweeps out *sheet = membrane.*

Surface tension ~ 14 tons (= string tension)

Confinement & Ordering

Confinement => all states *invariant* under 3-state rotations.

Valid at zero temperature, for some range of temp.'s

"Asymptotic freedom": coupling vanishes as T=> ∞,
=> ideal gas at infinitely high temperatures => *NO* confinement.

Transition to deconfined phase at T_d = deconfining trans. temp.
Above T_d, ok to have system with 1, 2, 3... quarks (anti-quarks)

In terms of 3-state model, "deconfinement" =

Ordering at *high,* instead of *low,* temperature!

't Hooft '79. Ordering not obvious: "duality"?

Quark-Gluon Plasma =
Deconfined Quarks and Gluons

To compute properties of the QGP:

Mean field theory

Monte Carlo simulations

(Experiment)

The QGP & the "Unicorn":
mythical creature(s)?

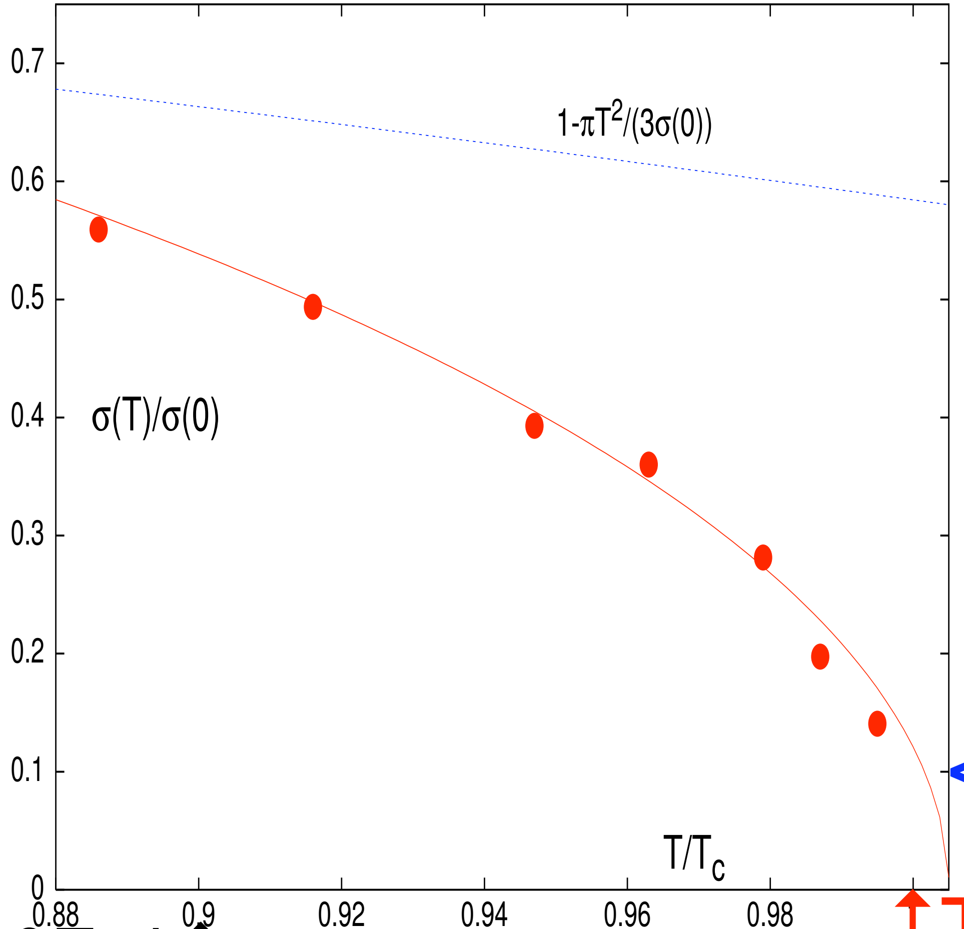
Monte Carlo for Gluons

Numerical simulations for three "colors" of gluons:

Deconfinement at T_d ~ .27 mass proton (~ 10^12° K)

"Surface tension" for confinement decreases by ~10 by deconfining transition => *almost* a critical point:

(Confining) surface tension at temperature T/value at T=0 ↑



Bielefeld

<= .1

.9 T_d ↑

↑T_deconf

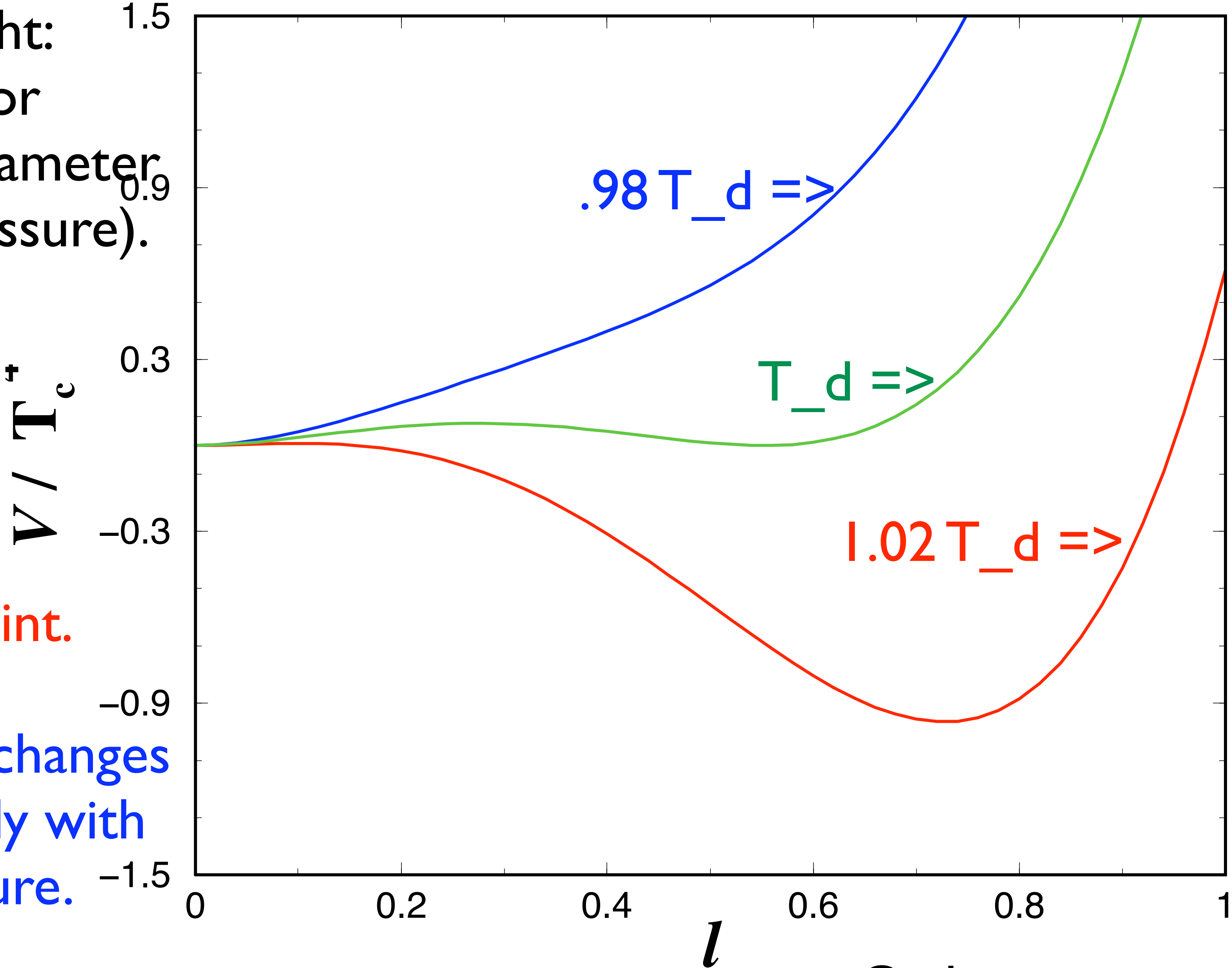
Deconfinement is almost a critical point

A. Dumitru & RDP '01

To the right: *potential* for order parameter (fit to pressure).

Potential *very flat* at T_d => *almost* critical point.

Potential changes *very rapidly* with temperature.



Order parameter =>

Monte Carlo vs mean field for three state order

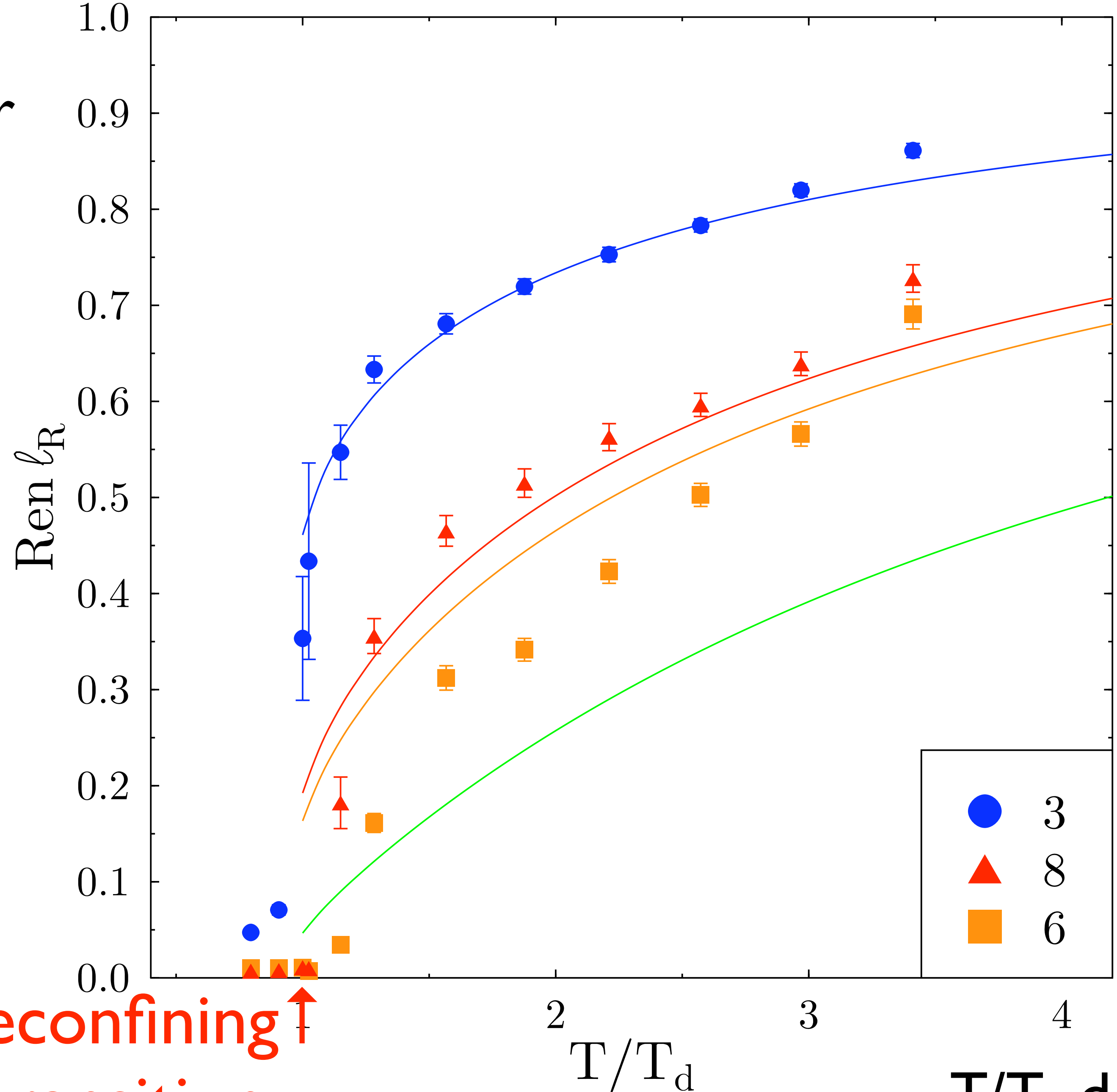
A. Dumitru + ... + RDP '03

Right: order parameter for three states

Points = Monte Carlo

Lines = Mean field

Not bad!
N=3 close to N = ∞



Blue = 1 quark

Red = quark + anti-qk ~ meson

Orange = 2 quarks

Green = 3 quarks ~ proton

Deconfining transition

T/T_d =>

The QGP Exists!
Hunting for the "Unicorn" in Experiment: Heavy Ion Collisions

"Unicorn" & the QGP: Scott, Stock, Gyulassy...

Why collide big nuclei at high energies?

One can collide:

pp: protons on protons. Benchmark for "ordinary" strong int.'s

AA: nucleus with atomic number A on same.

dA: deuteron (N+P) on nucleus. Serves as another check.

Why AA? Nucleons (N's & P's) are like hard spheres,

so nuclear size $r_A \sim A^{1/3}$

Biggest: Pb (lead) or Au (gold), A ~ 200 => r_A ~ 7.

Transverse radius of nucleus $\sim A^{2/3}$ => trans. size ~ 50 x proton.

A ~ 200 close to A $\rightarrow \infty$ $=$ *infinite* nuclear matter?

Colliders: Energy, Machines

Particles accelerated in rings. Either: one ring against fixed target, or *collider*, two rings, with particles travelling in opposite directions.

Machines	Total energy/nucleon	Type
SPS @ CERN	5 => 17 GeV	(fixed target)
**** RHIC @ BNL	20, 130, 200 GeV	(collider, > 2000)
LHC @ CERN	5500 GeV = 5.5 TeV	(collider, > 2007)
SIS200 @ GSI	2 => 6 GeV	(fixed target, > 2010)

SPS = Super Proton Synchotron: CERN @ Geneva, Switzerland.
RHIC = Relativistic Heavy Ion Collider: BNL @ Long Island, NY.
LHC = Large Hadron Collider.
SIS = SchwerIonenSynchrotron: GSI @ Darmstadt, Germany.

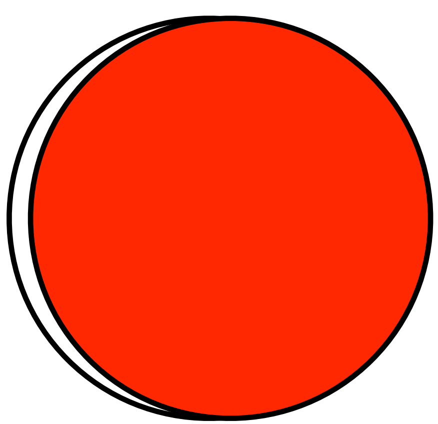
Essentials of AA collisions

At high energies, nuclei *slam* through each other (no “blob”).
Hence physics very different along beam, vs. transverse to beam.
Measure momenta of particles ~ relativistic measure of velocity.

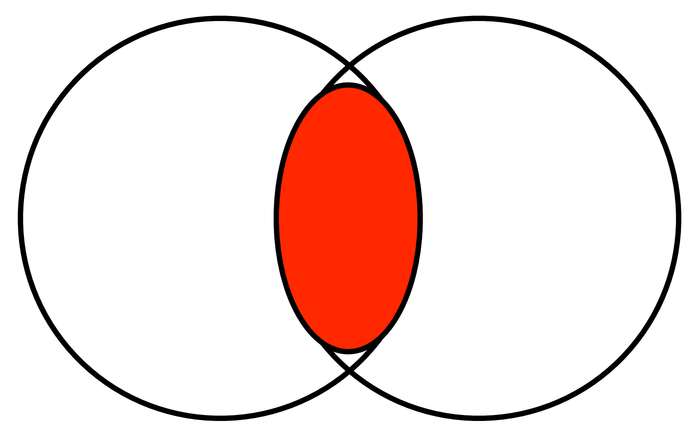
Look just at 90° to beam in collider = ”central” rapidity.
(rapidity = relativistic inv. for mom. along beam.)
90°~ free of incident nucl.’s => most likely to see nonzero temp.

Bulk of particles at 90°, peaked about transverse momentum.

Central:
Maximum
Overlap



Peripheral=>
“Almond” of
overlap region



Typical Heavy Ion Event @ RHIC

Experiments @ RHIC:

"Big" expts: ~ 400 people
STAR & PHENIX

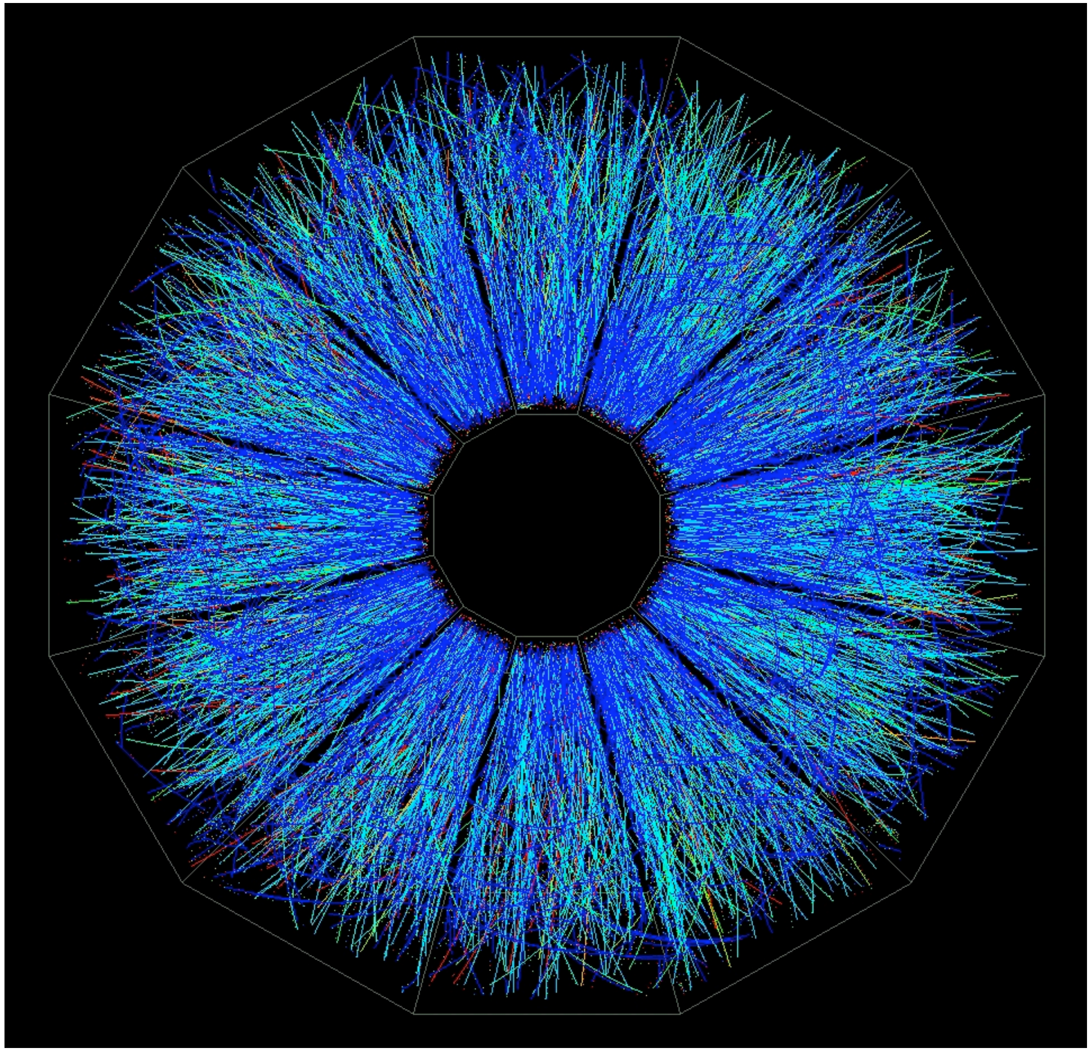
"Small" expts.: ~ 50 people
PHOBOS & BRAHMS

Note: total # particles ~
total # experimentalists
~ log(total energy)

theorists
~ log(log(total energy)).

Need hunters more than dogs...

Total # particles(/unit rapidity)
~ 900↓

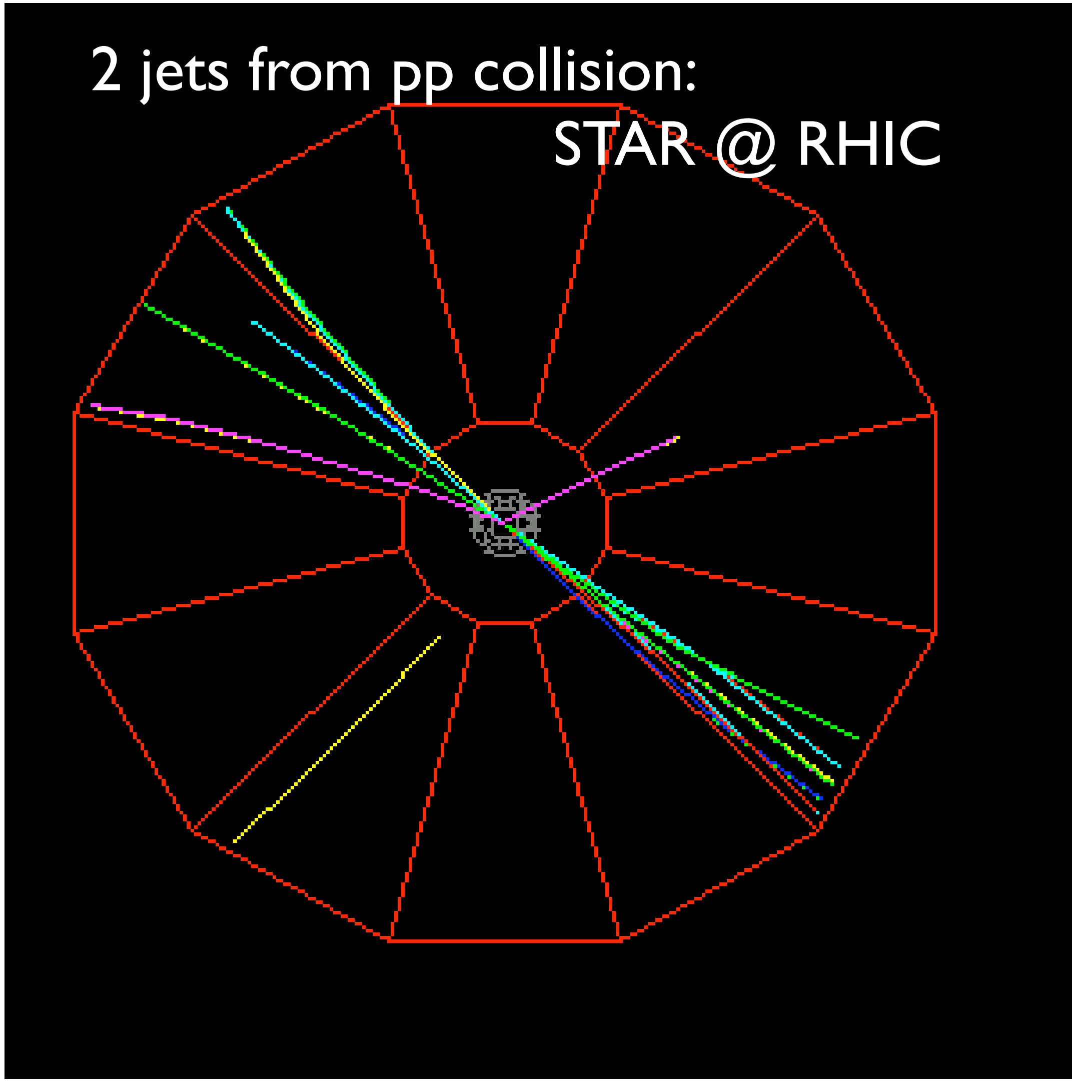


Jets: "seeing" quarks and gluons in QCD

Quarks & Gluons are
asymptotically free =>
simple at *short* distances.

At high energies,
"see" quarks & gluons as jets:
sprays of particles (see right=>)
quark or gluon => mesons & nucleons.

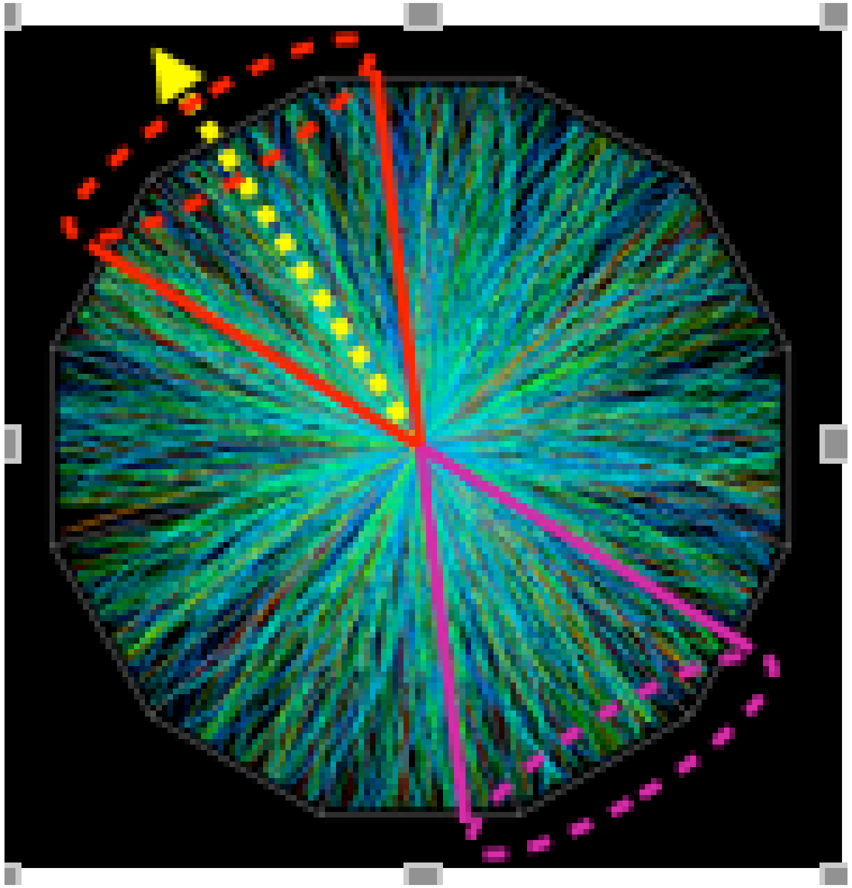
Not typical of most collisions,
but very striking. Can compute properties in weak coupling.



Note: also why Monte Carlo gives *unique* answer as lattice spacing => 0: "dimensional transmutation".

“Jets” in central AA collisions

pp collisions: ~ 4 particles/unit rapidity, vs 900 in central AA.
Hence cannot see individual jets in AA.



Can construct statistical measures.

p_t = momentum transverse to beam

Trigger on “hard” particle,
p_t: 4 => 6 GeV

Given a jet in one direction,
there *must* be *something* in the
opposite direction.

Look for the “away” side jet, p_t > 2 GeV.   (mass proton ~ 1 GeV)

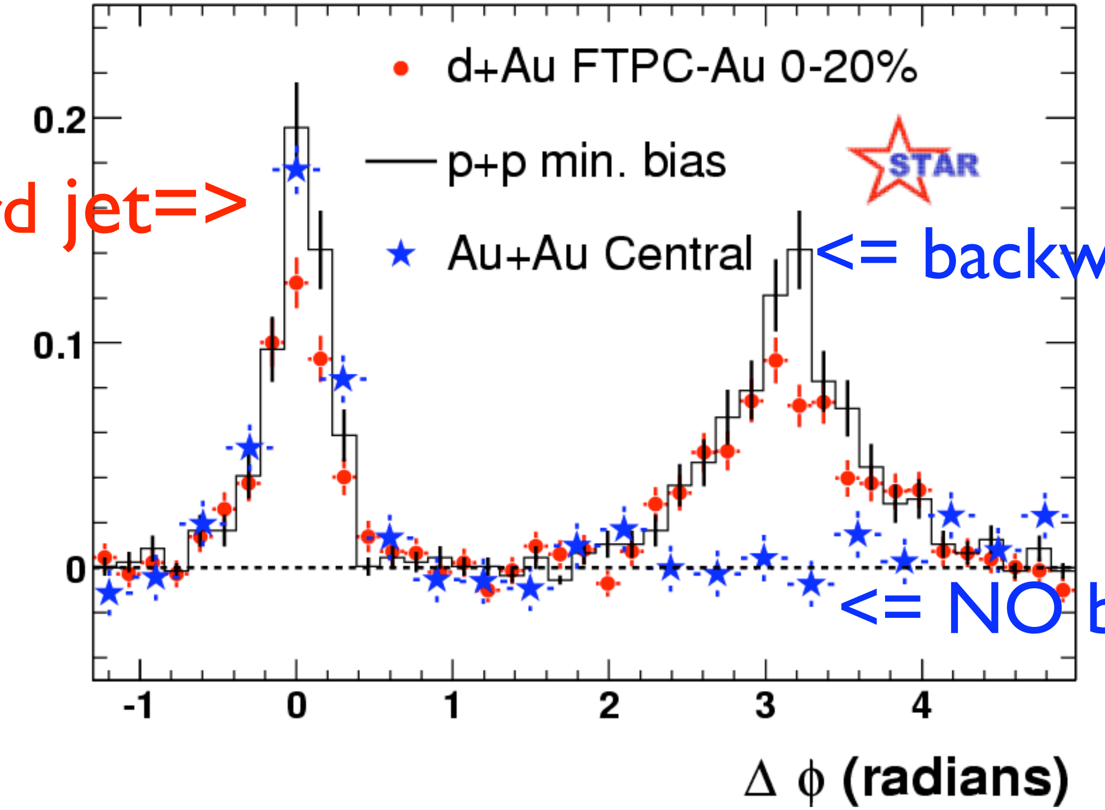
Central AA collisions "eat" jets!

In pp or dAu collisions, *clearly* see away side jet.

In central Au-Au, away side jet *gone: "stuff" in central AA "eats" jets!*

Fast jet tends to lose energy by many soft scatterings off "stuff".

Adams *et al.*, Phys. Rev. Let. 91 (2003)



forward jet=>

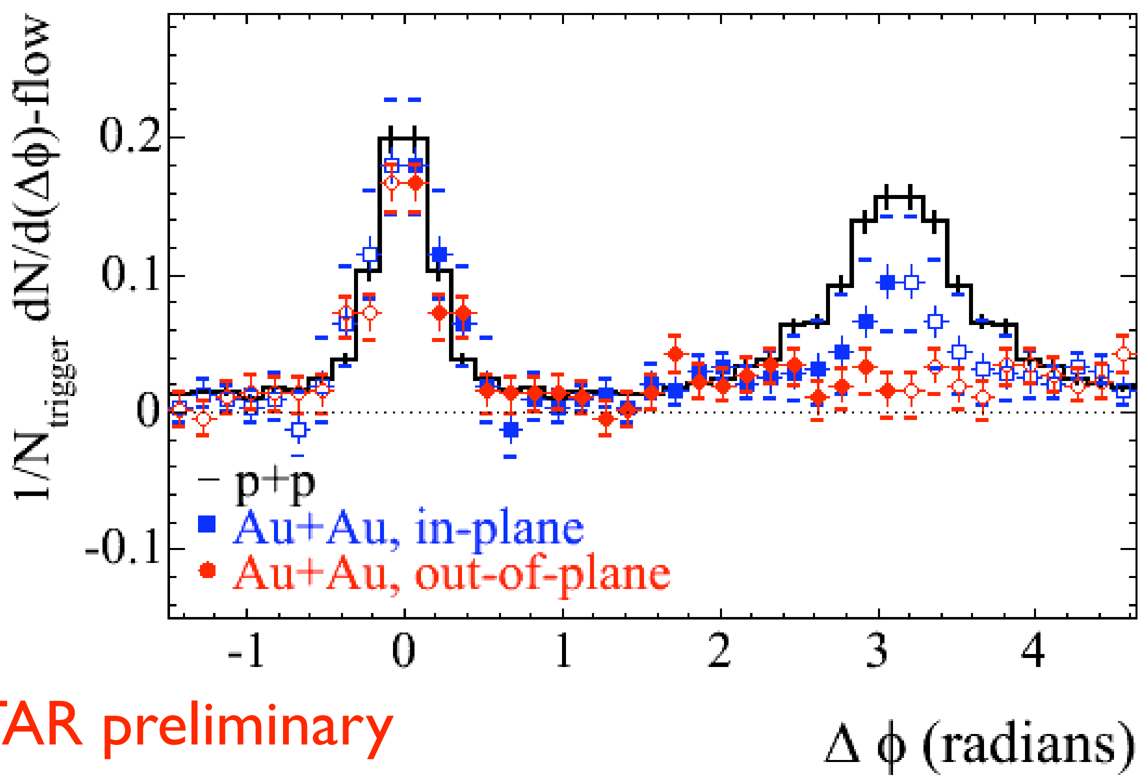
<= backward jet, pp

<= NO backward jet in central AA

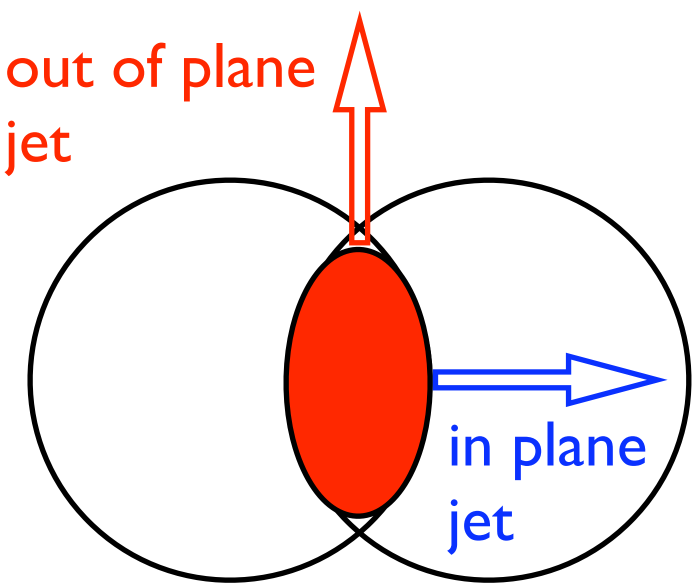
Peripherhal Coll.'s: *Geometrical* Test that AA *Eats* Jets

Peripheral collisions, "stuff" forms "almond": a jet travels farther through the almond, out of the reaction plane, than in the plane.

Exp.'y: backward jet more strongly suppressed *out* of plane than *in* plane => *geometrical* test that central AA "*eats*" jets



STAR preliminary



peripheral collision ↑
almond = "stuff"

Jets in central AA: to low momentum!

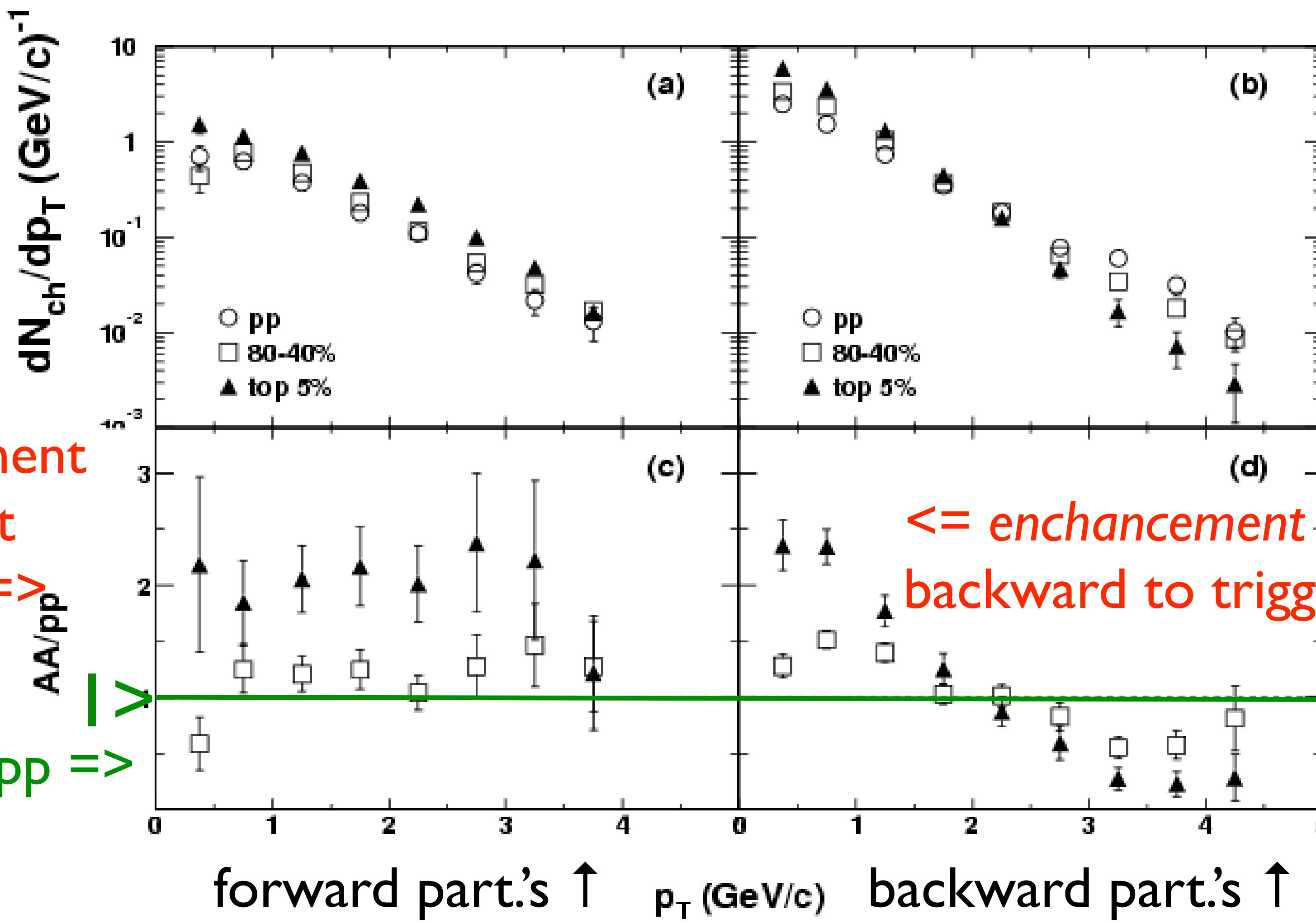
Trigger on all particles, p_t > .15 GeV.

Backward jet: high p_t suppressed, low p_t enhanced.

“Stuff” in central AA slows fast particle down.

Forward jet: enhanced at low momentum: “stuff” dragged along!

raw => spectra



STAR prelim.

enhancement at low p_t *along* jet =>

<= *enchancement* at low p_t backward to trigger jet

1 >

AA=pp

ratio, AA/pp =>

<=*suppression* at high p_t backward

forward part.'s ↑

backward part.'s ↑

Has RHIC found (tamed) the "Unicorn" = QGP?

New final state effects:

Suppression of backward jets

Clear exp. signal ≠ SPS: R_AA

Has the Quark-Gluon Plasma been found in central AA?

Certainly: there is "stuff" which suppresses jet. *Not* clear if it is equilibriated at nonzero temp.

Relationship to order parameter?

Perhaps: it is a different beast....

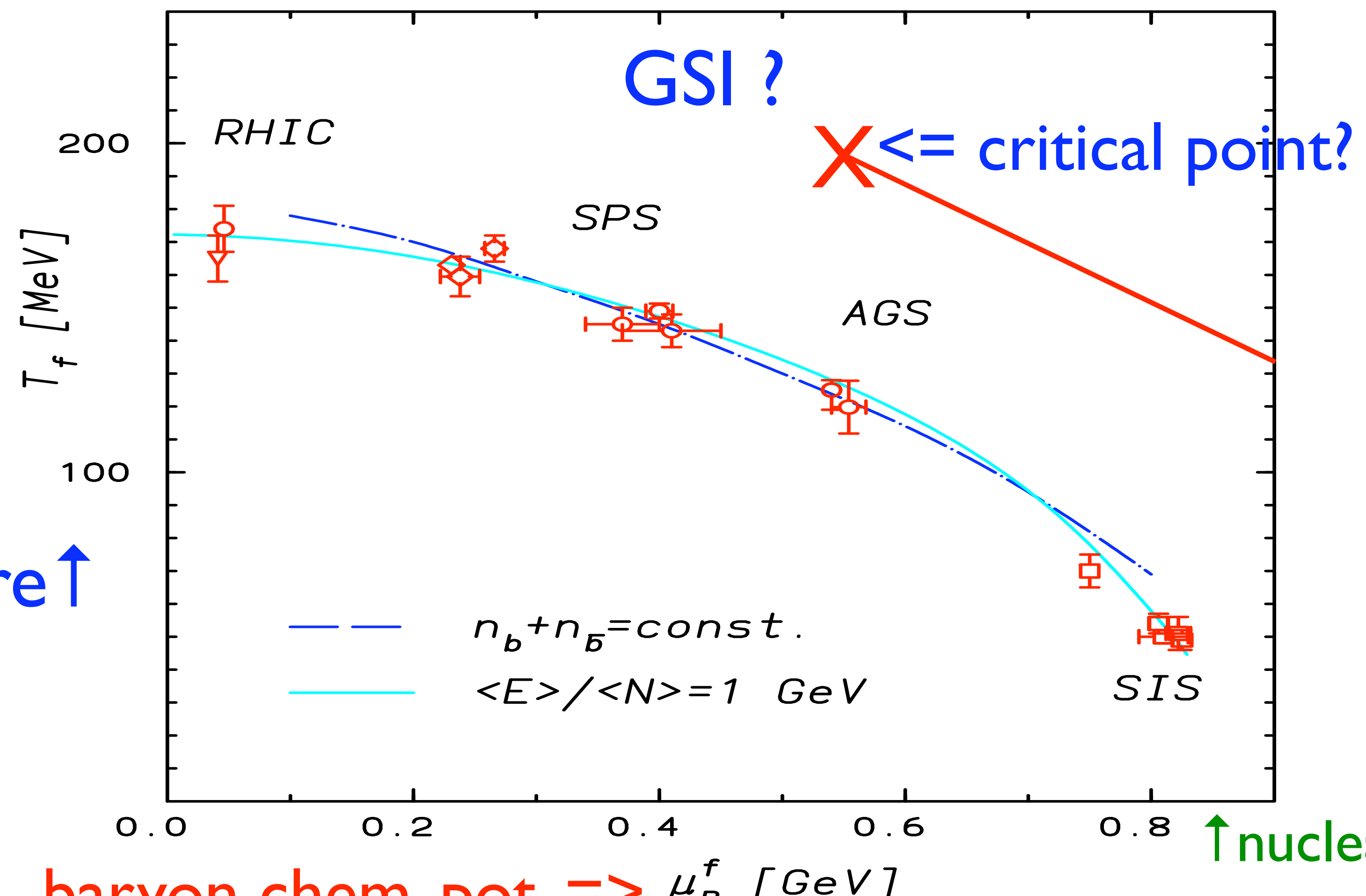
But its still a *NEW* beast!

Exact critical point in plane of T & μ

90° at RHIC probes ~ nucleon free region.

By going to *lower* energies (SIS200 @ GSI) will study region with baryon density: expect *exact* critical (end) point.

All the world's a....



Temperature↑

μ= baryon chem. pot. =>

↑nuclear matter

"A possible eureka."