Lattice Gauge Theory and Heavy Ion Collisions

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Exploring the properties of strongly interacting matter

theoretical background:

Quantum Chromo Dynamics (QCD)

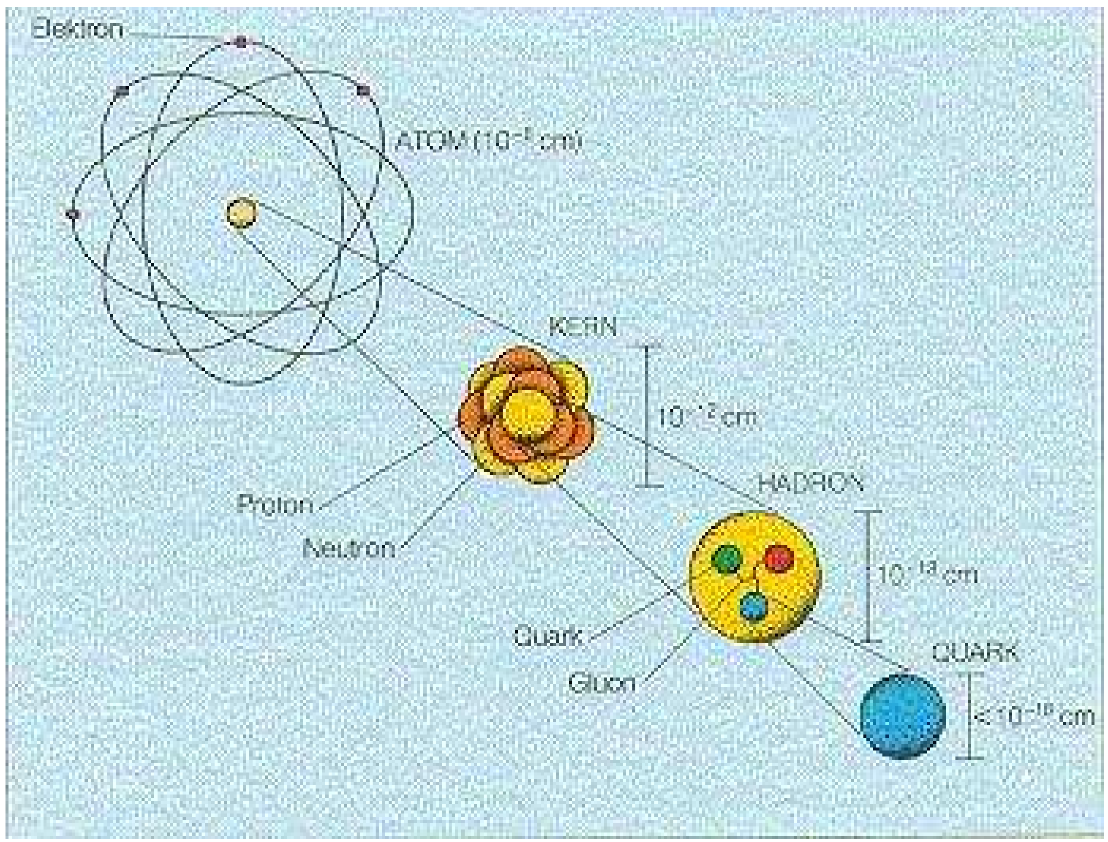
experimental approach:

collision of ultra-relativistic heavy ions

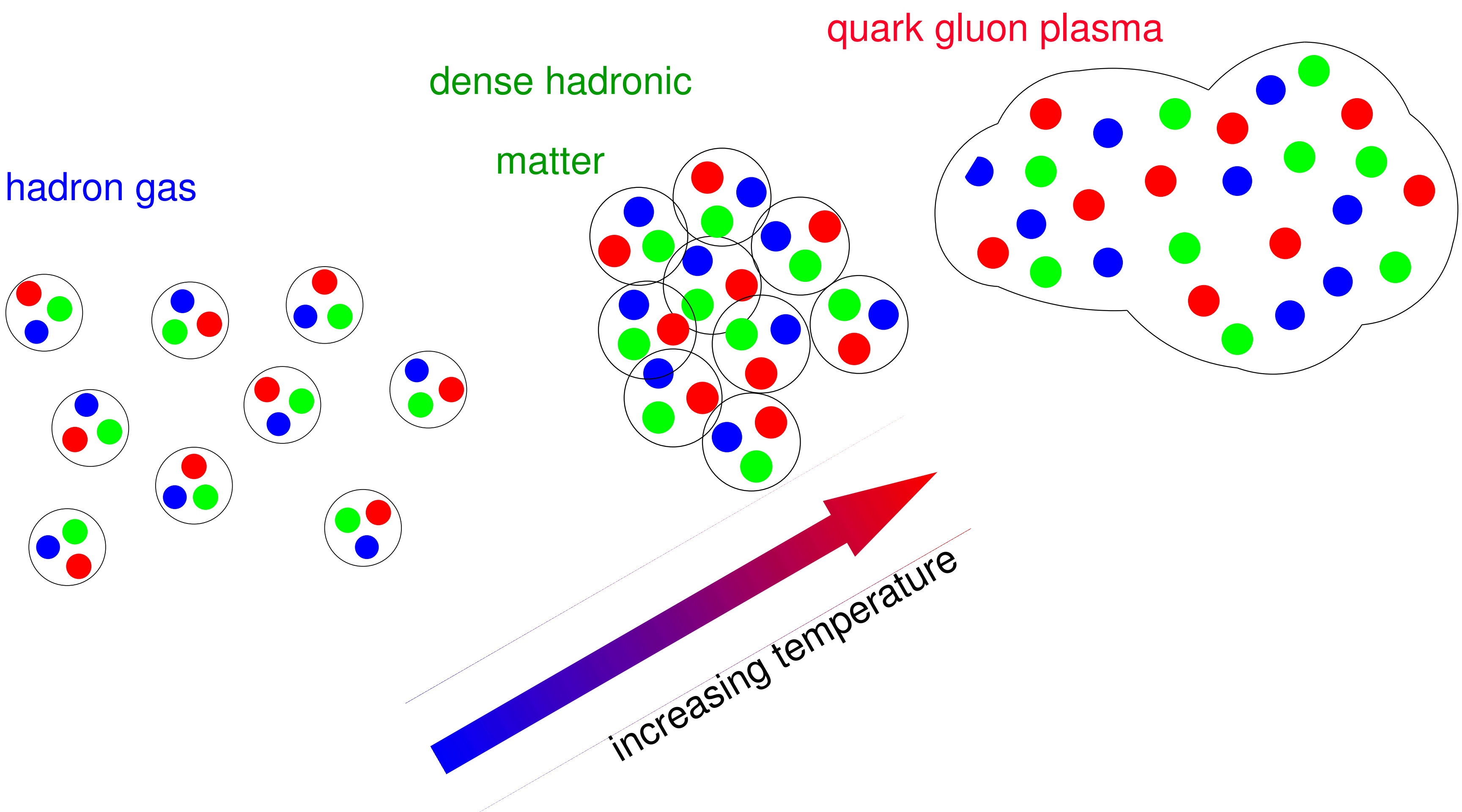
From matter to elementray particles

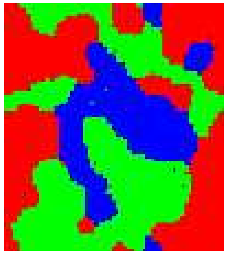
Substructure of Matter

from atoms to nuclei to nucleons to quarks and gluons



From matter to elementray particles
..to elementary particle matter

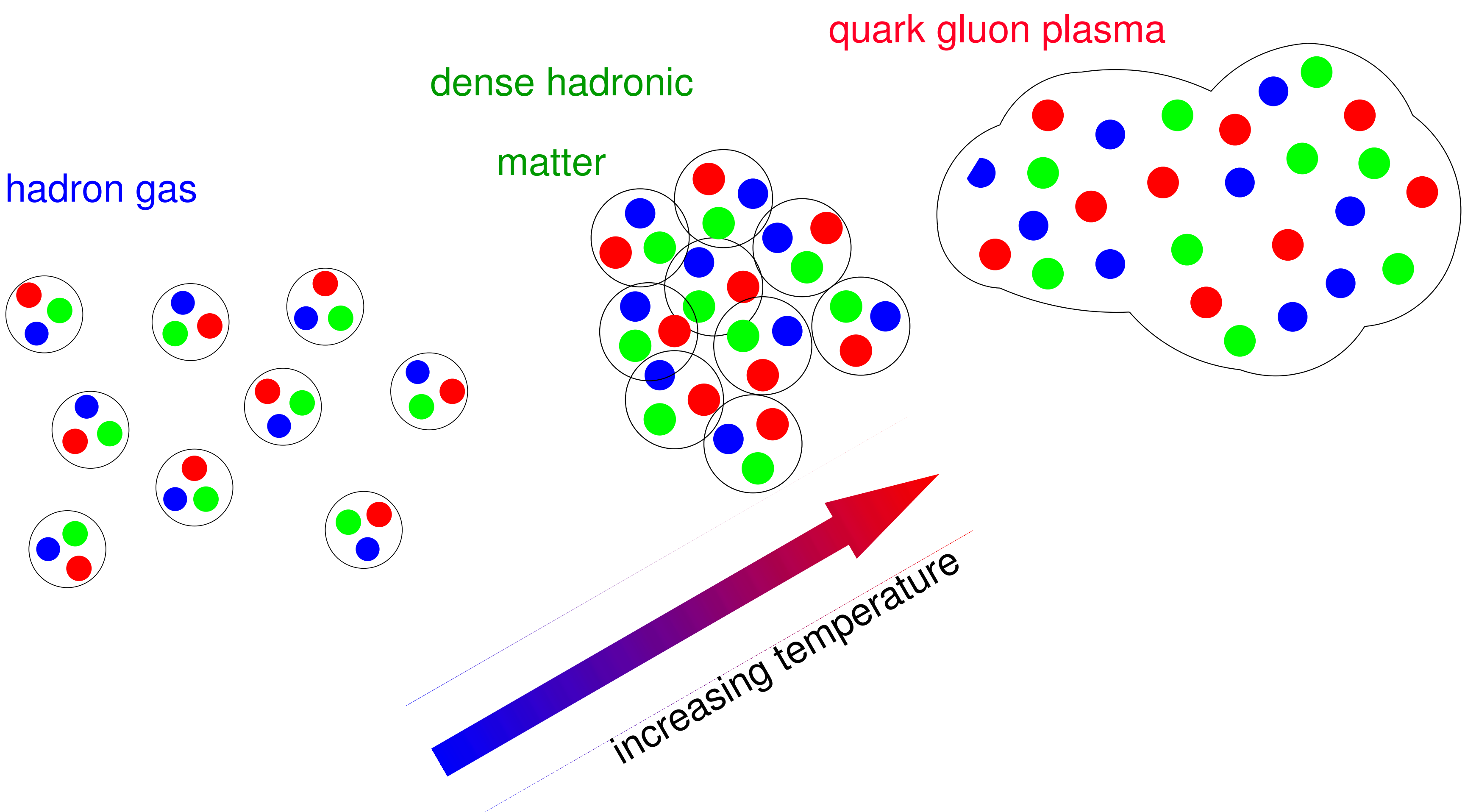




Phase Transition from a Hadron Gas to the Quark-Gluon Plasma

temperatures in the early universe after $\mathbf{10^{-6}}$ $\mathbf{sec}$: $\sim \mathbf{10^{12}}$ $\mathbf{K}$

density of neutron stars: $\sim$ (3-10)-times nuclear matter density



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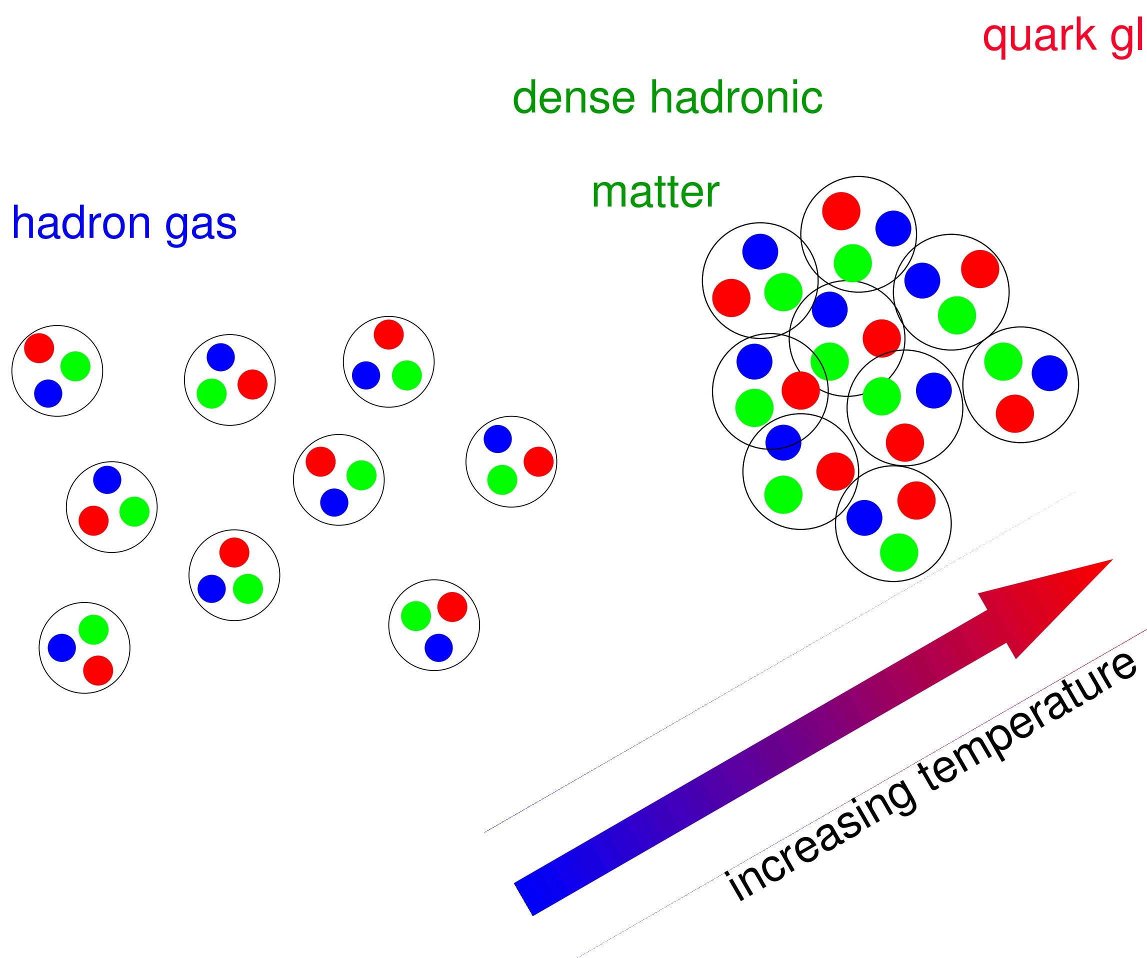

What are the properties of this new form of matter?

(equation of state, screening)

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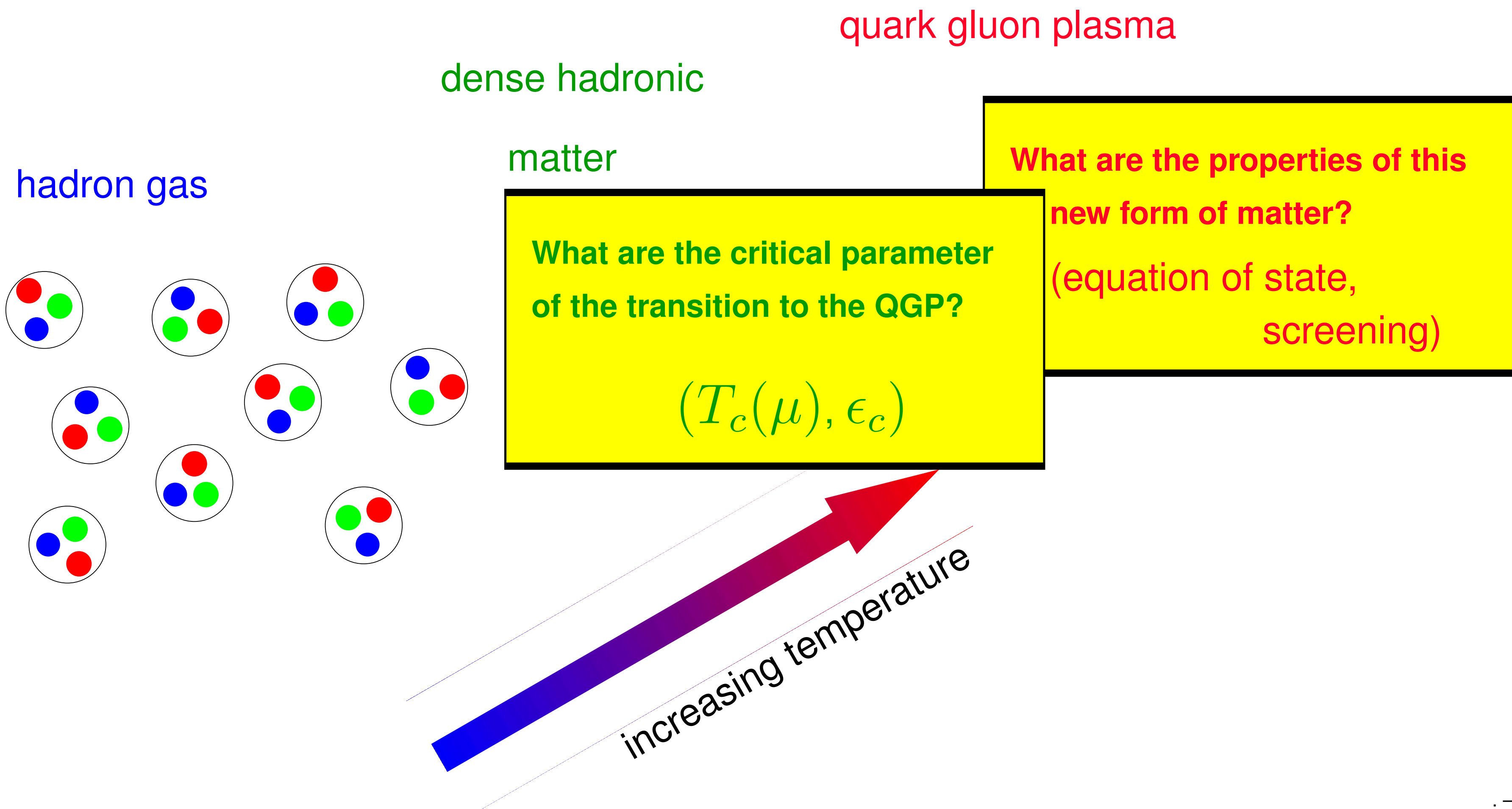

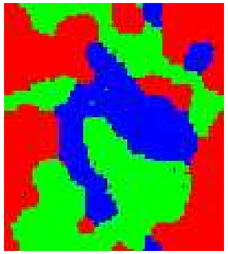

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quark gluon plasma

dense hadronic matter

hadron gas

What are the properties of this new form of matter?

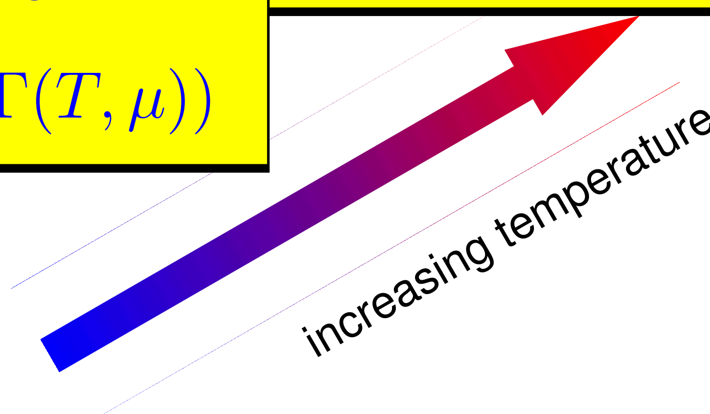
(equation of state, screening)

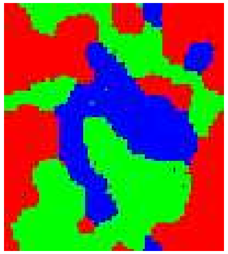
What are the critical parameter of the transition to the QGP?

$$(T_c(\mu), \epsilon_c)$$

What happens to resonances in a dense hadronic gas?

$$(m_H(T,\mu), \Gamma(T,\mu))$$

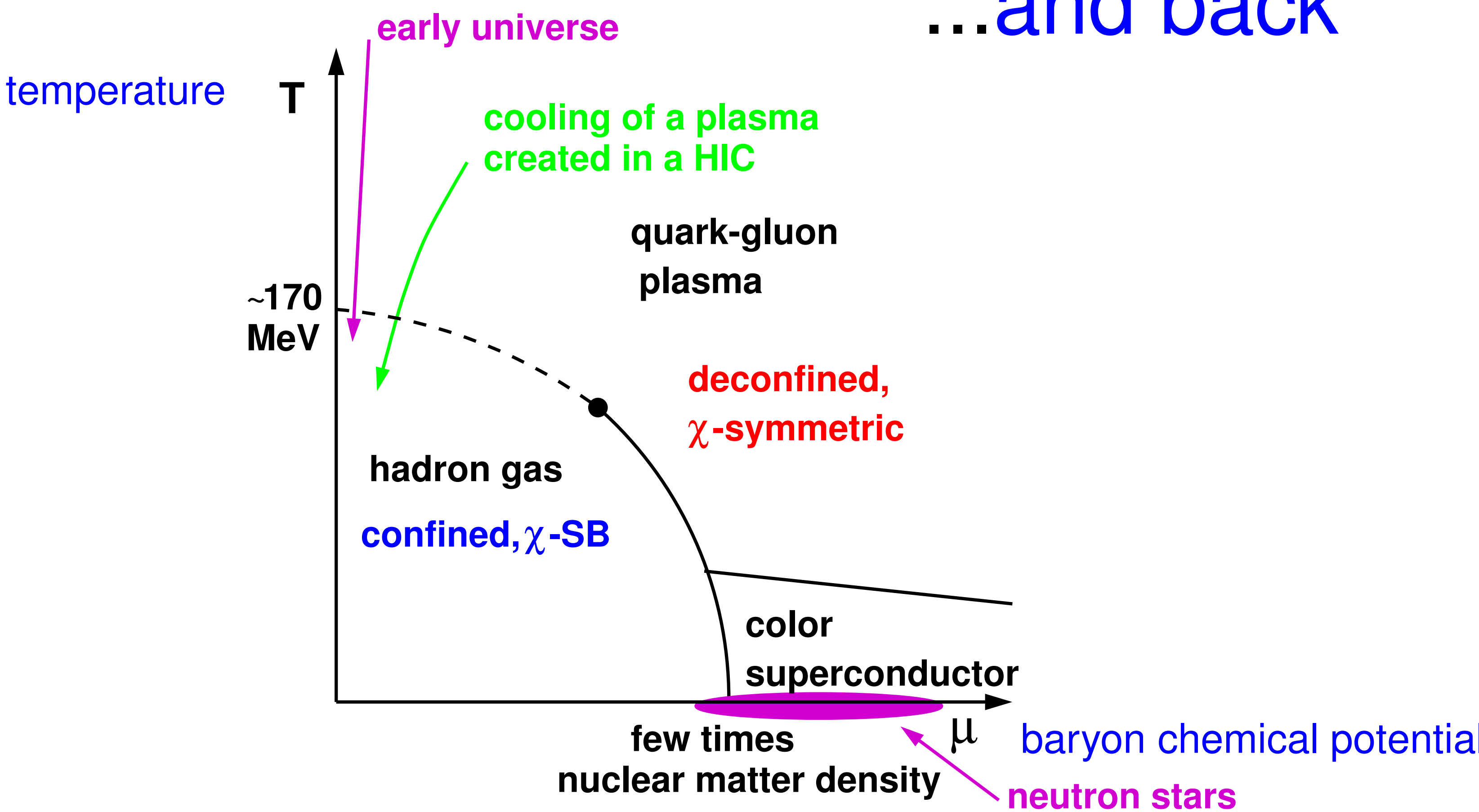




Phase diagram of strongly interacting matter

From Hadron Gas to Quark Gluon Plasma

...and back



PHYSICAL REVIEW D VOLUME 8, NUMBER 12 15 DECEMBER 1973

Highly Excited Nuclear Matter*

G. F. Chapline, M. H. Johnson, E. Teller, and M. S. Weiss
Lawrence Livermore Laboratory, University of California, Livermore, California 94550

(Received 4 September 1973)

It is suggested that very hot and dense nuclear matter may be formed in a transient state in "head-on" collisions of very energetic heavy ions with medium and heavy nuclei. A study of the particles emitted in these collisions should give clues as to the nature of dense hot nuclear matter. Some simple models regarding the effects of meson and N^* production on the properties of dense hot nuclear matter are discussed.

What will be the effect of higher resonances? Models of the strong interactions based on the "bootstrap" idea lead to a density of states that increases exponentially with mass. This results from the fact that each new resonant state can combine with particles of lower or equal mass to make more resonant states.[8] In particular, the statistical bootstrap model leads to a density of states of the form[9,10]

$$N(m) = Cm^{-3}e^{m/\theta_0}, \tag{3}$$

where θ_0, the "maximum temperature" of hadron matter, is about 174 MeV as determined from high-energy scattering experiments.[5] The param-

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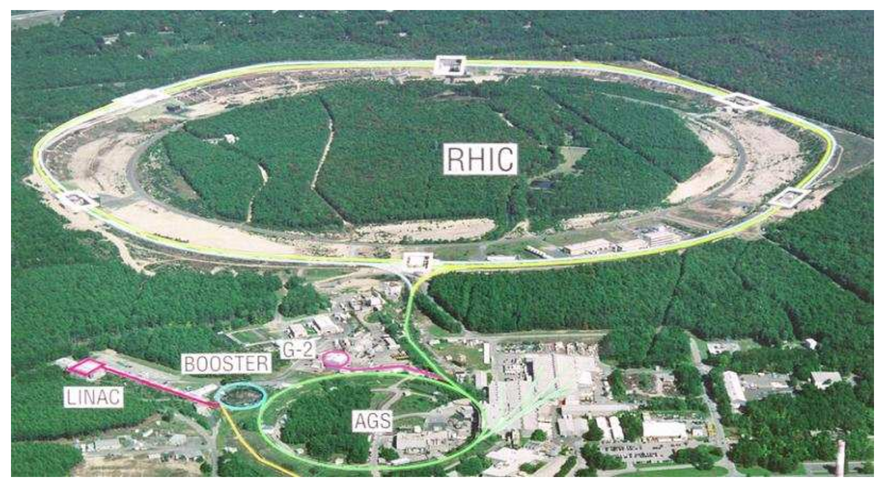
$$T_c \simeq 174\ MeV \quad (!!!)$$

Lattice Gauge Theory and Heavy Ion Collisions

Lattice Simulations of
Finite Temperature QCD
at Bielefeld University

Collision of Au-Au and other ions in the
Relativistic Heavy Ion Collider (RHIC)
at Brookhaven Nat. Lab. (BNL)



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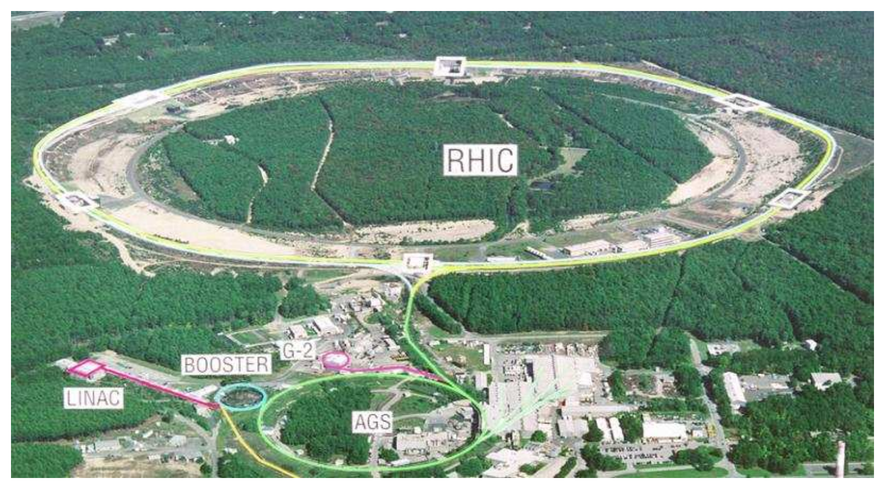
The machines

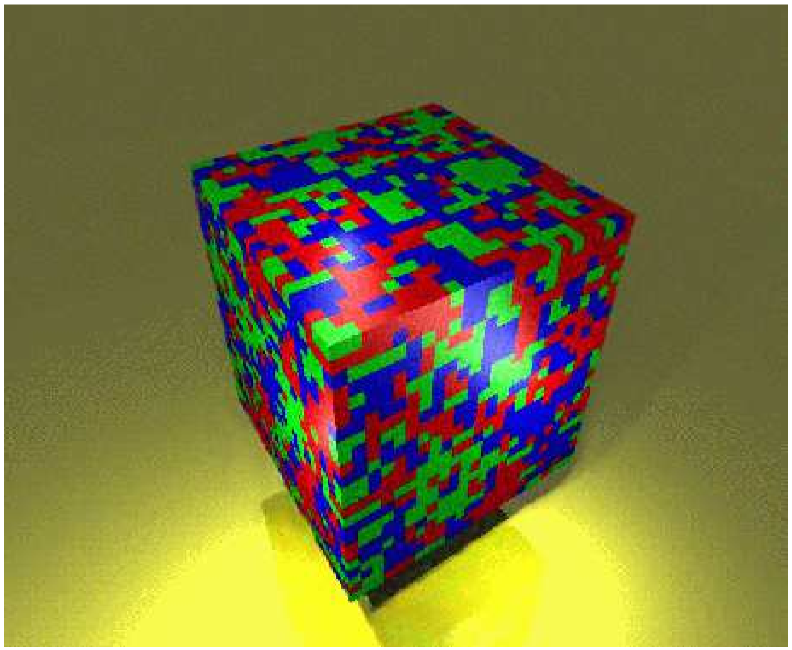
RHIC

circumference: $\sim$ 4 km

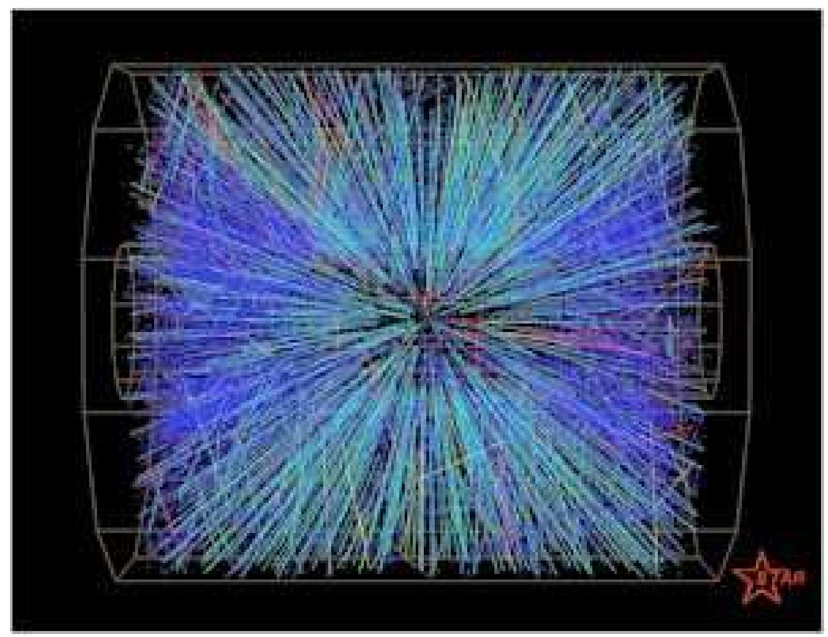
Au-Au collisions

beam energy: 200 GeV/A

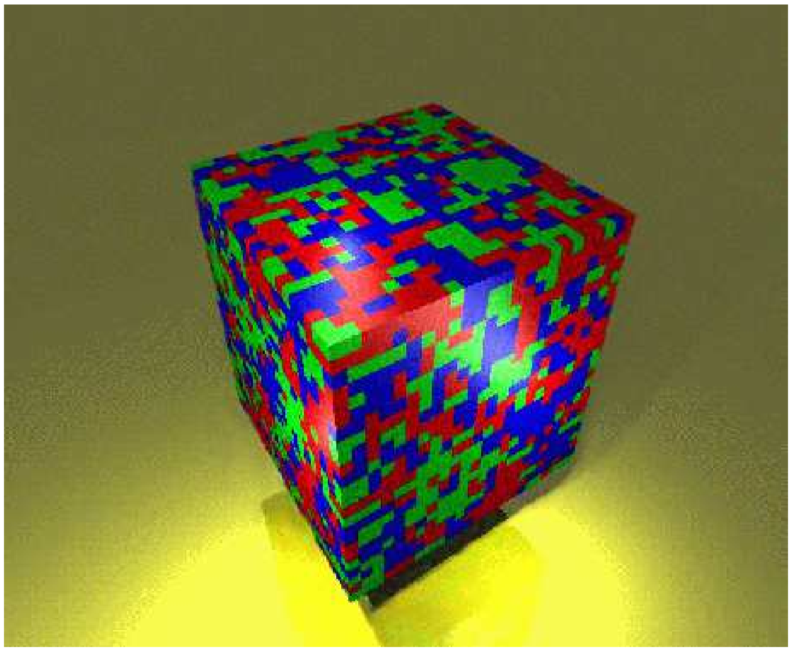




The events

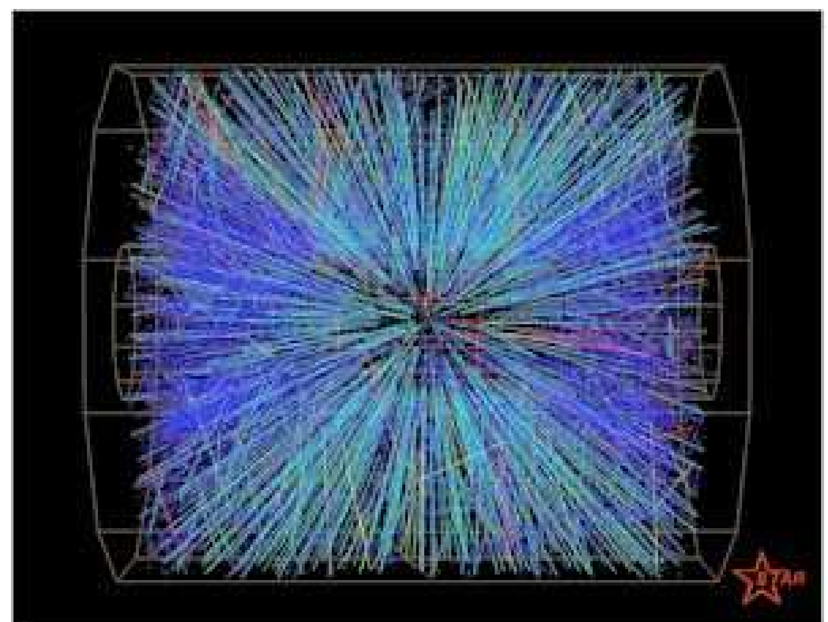


Lattice Gauge Theory and Heavy Ion Collisions



HIC:

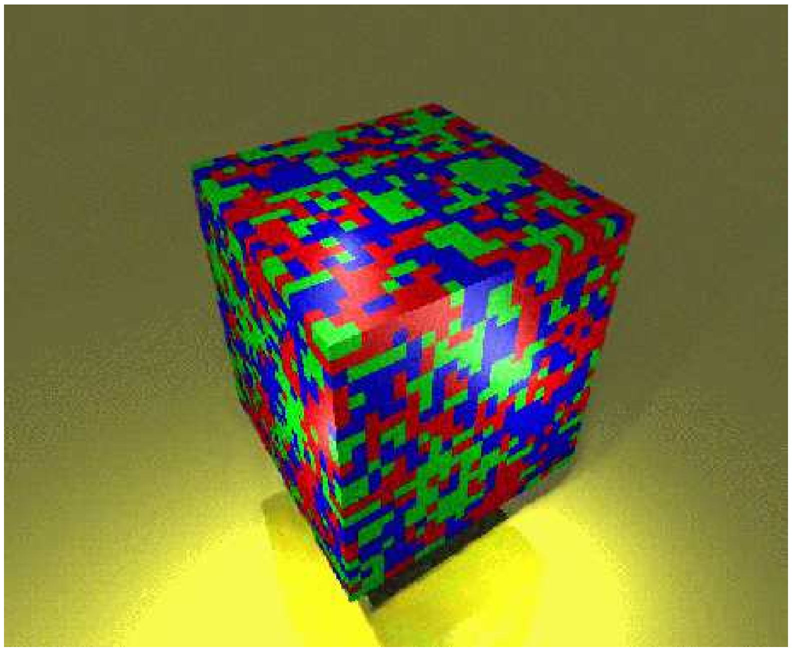
- evolution of a dense interacting medium described by QCD;



LGT:

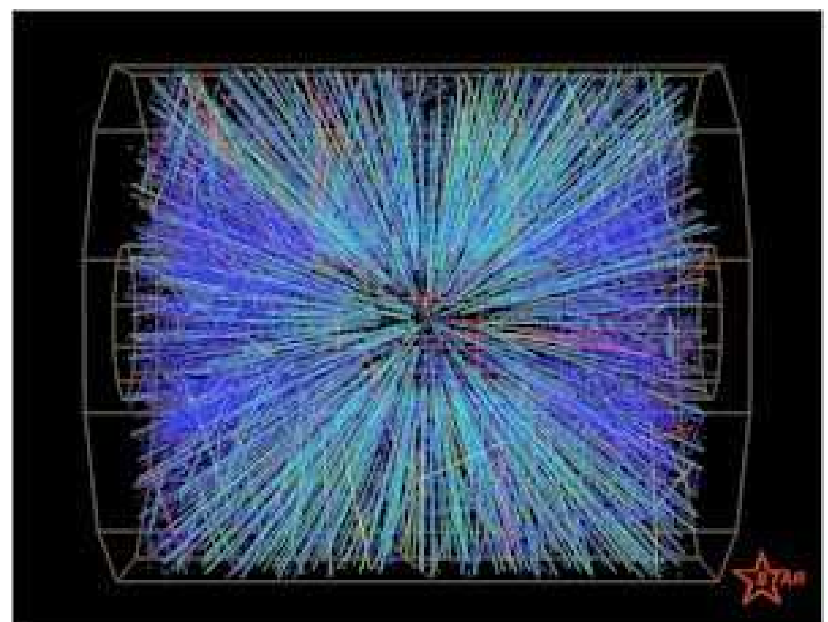
- equilibrium thermodynamics of QCD;

Lattice Gauge Theory and Heavy Ion Collisions



HIC:

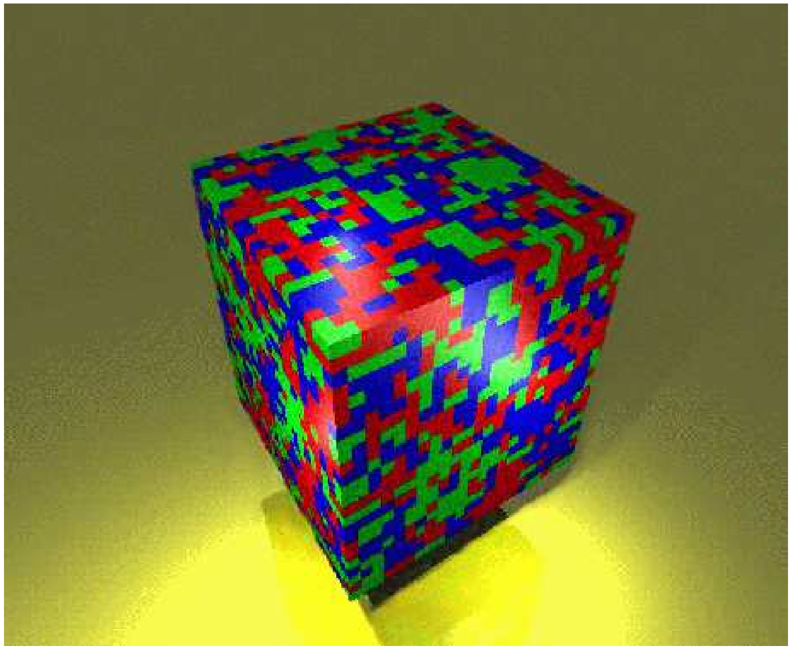
- evolution of a dense interacting medium described by QCD;
- observable properties in terms of hadrons, leptons and photons;



LGT:

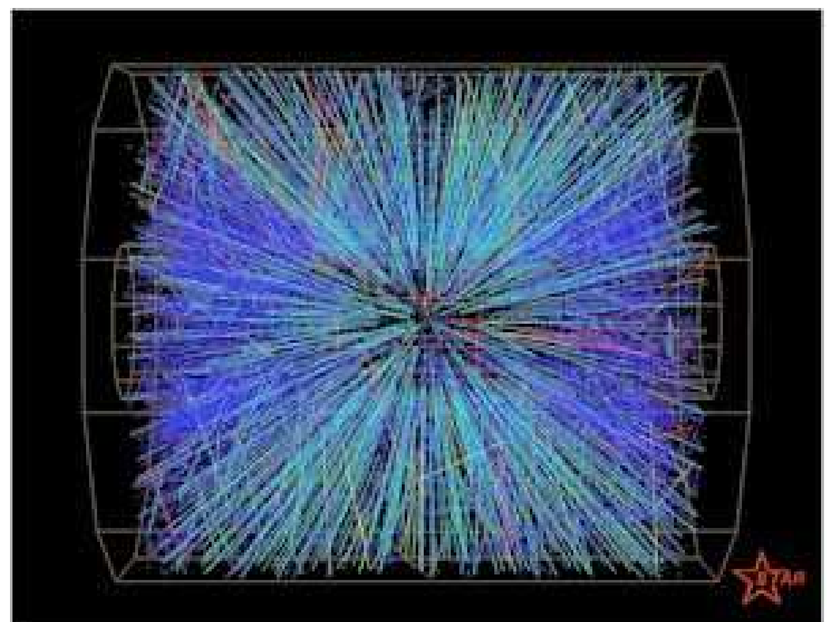
- equilibrium thermodynamics of QCD;
- formulated in terms of basic degrees of freedom: quarks and gluons;

Lattice Gauge Theory and Heavy Ion Collisions



HIC:

- evolution of a dense interacting medium described by QCD;
- observable properties in terms of hadrons, leptons and photons;
- observables parametrized in terms of energy and particle multiplicities



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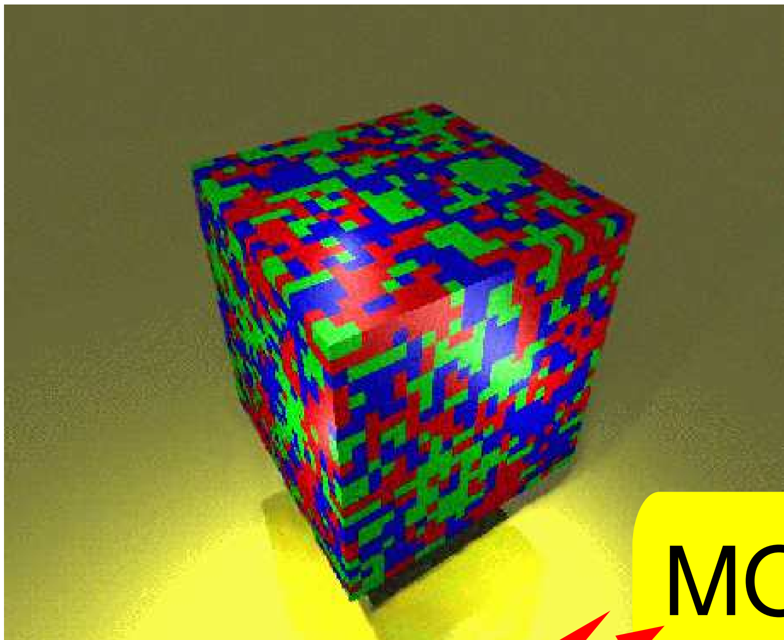

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MODELS

LGT:

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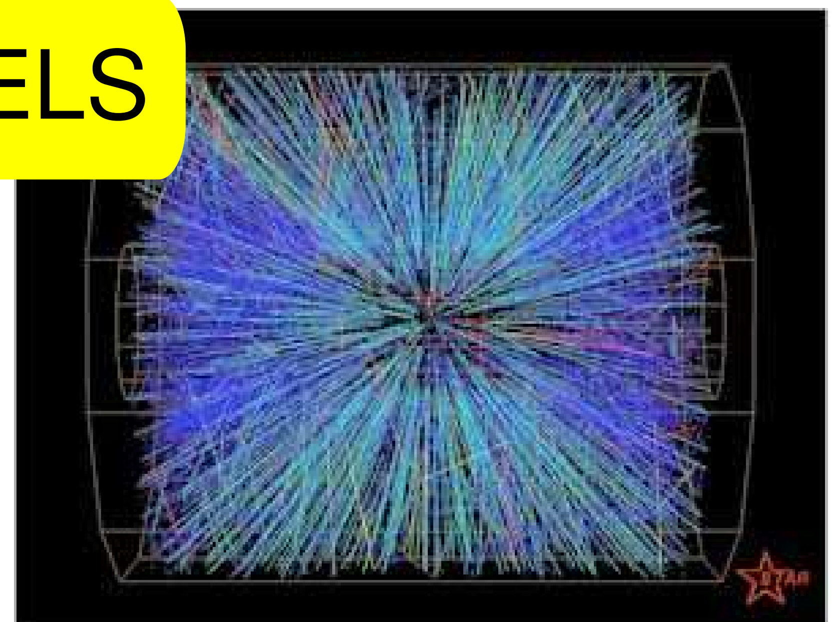
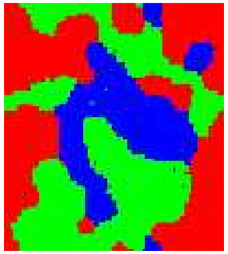
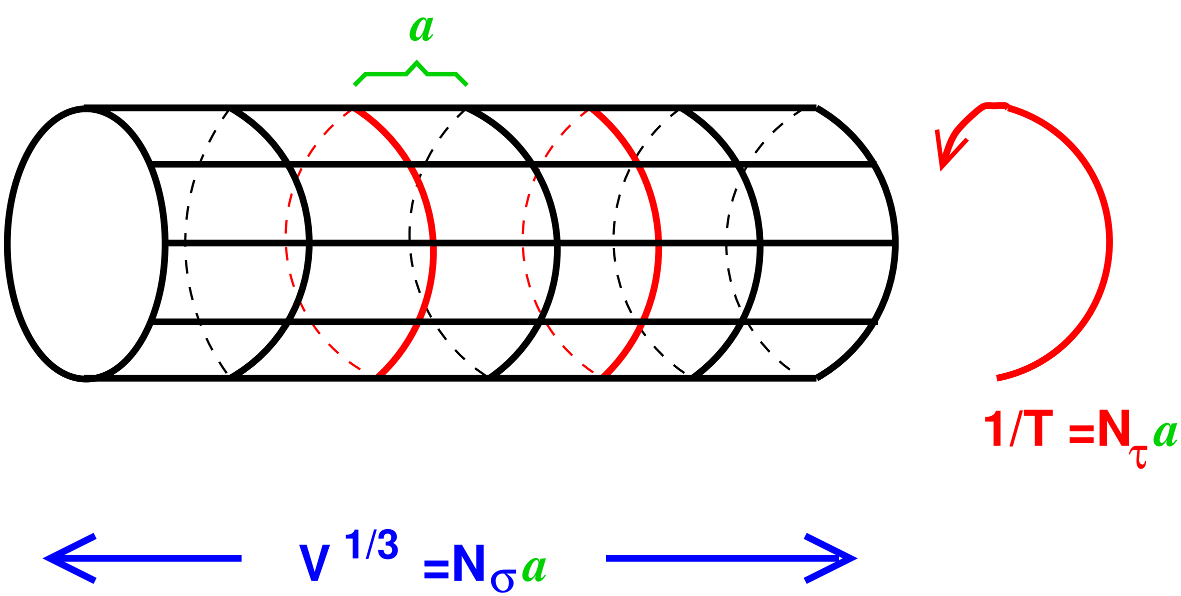




Analyzing hot and dense matter on the lattice: $N_\sigma^3 \times N_\tau$



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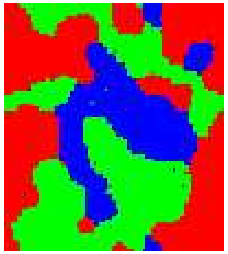
Quantum Chromo Dynamics

partition function: $Z(V, T, \mu) = \int \mathcal{D}\mathcal{A}\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \mathrm{e}^{-S_E}$

$$\boxed{S_E = \int_0^{1/T} dx_0 \int_V d^3x\ \mathcal{L}_E(\mathcal{A}, \psi, \bar{\psi}, \mu)}$$

temperature volume chemical potential



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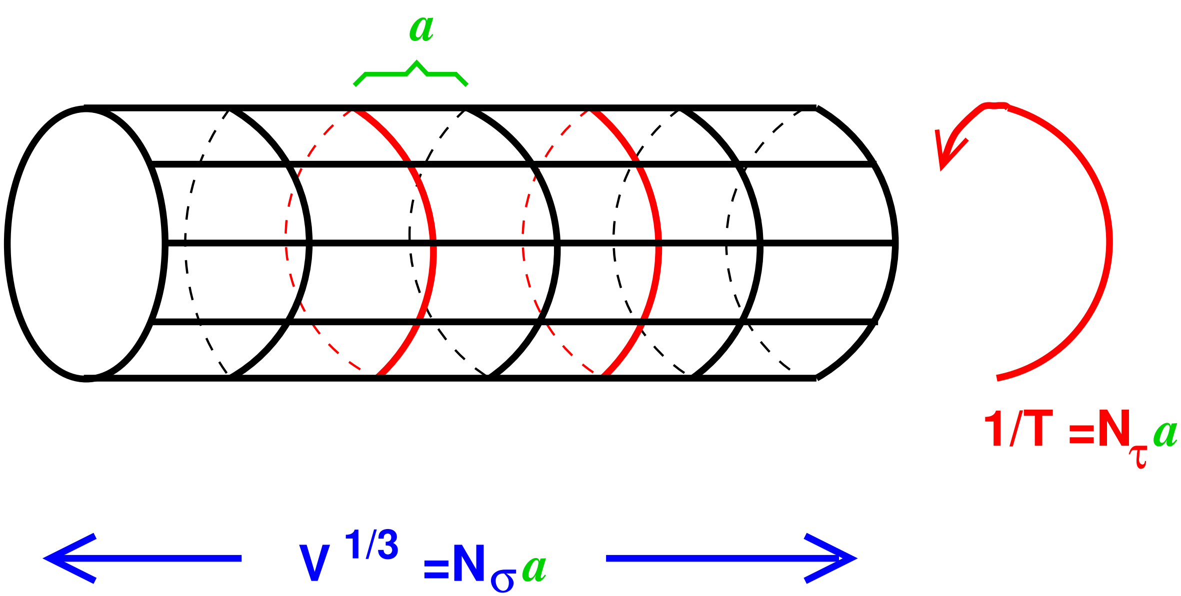

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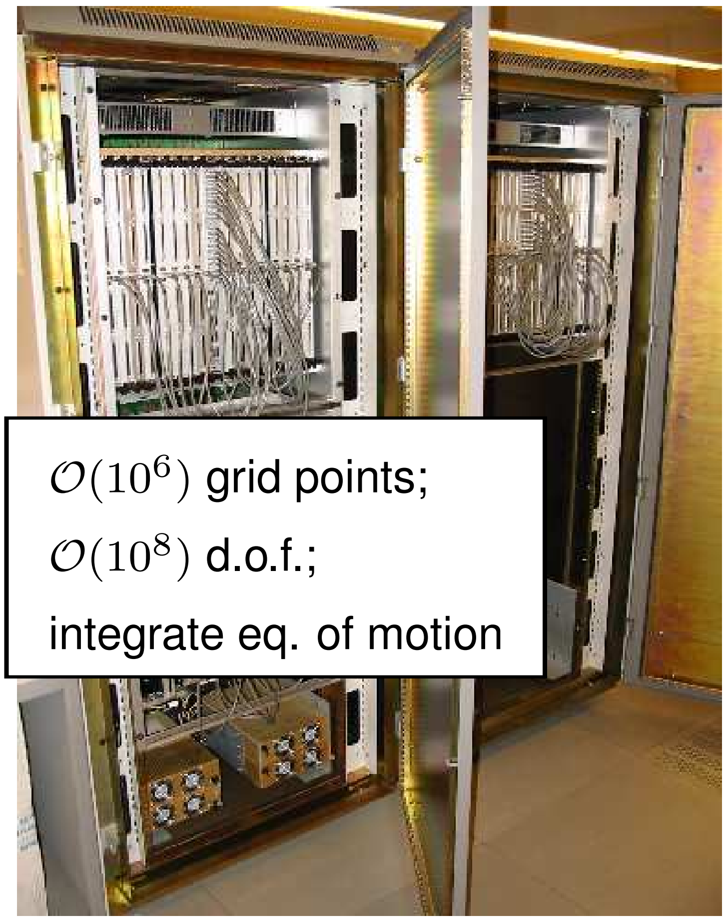

$\mathcal{O}(10^6)$ grid points;

$\mathcal{O}(10^8)$ d.o.f.;

integrate eq. of motion

Quantum Chromo Dynamics

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$$\boxed{S_E = \int_0^{1/T} dx_0 \int_V d^3x\ \mathcal{L}_E(\mathcal{A},\psi,\bar{\psi},\mu)}$$

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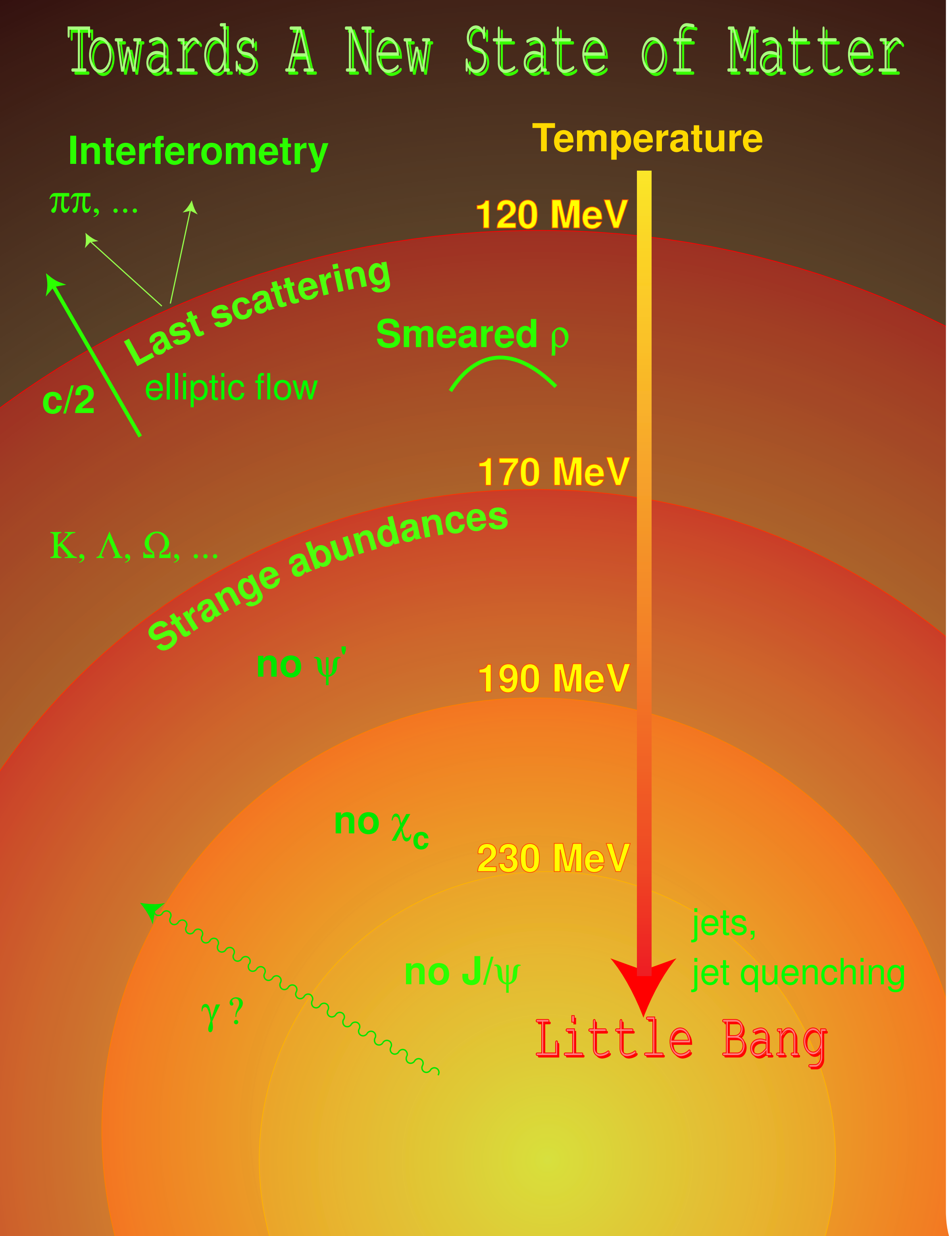
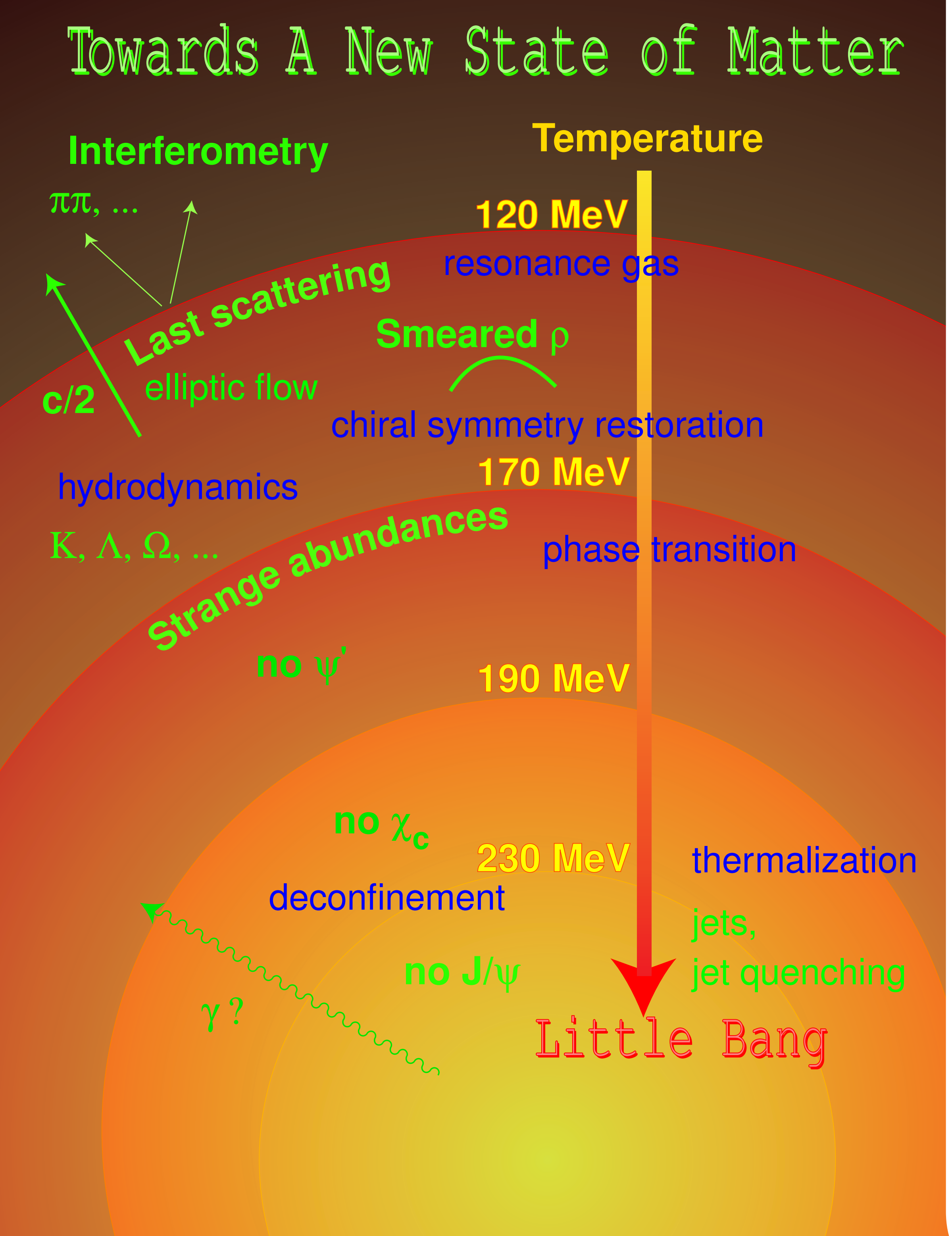


Where lattice calculations do/will contribute to the

development of theoretical concepts

and the

analysis of experimental observables



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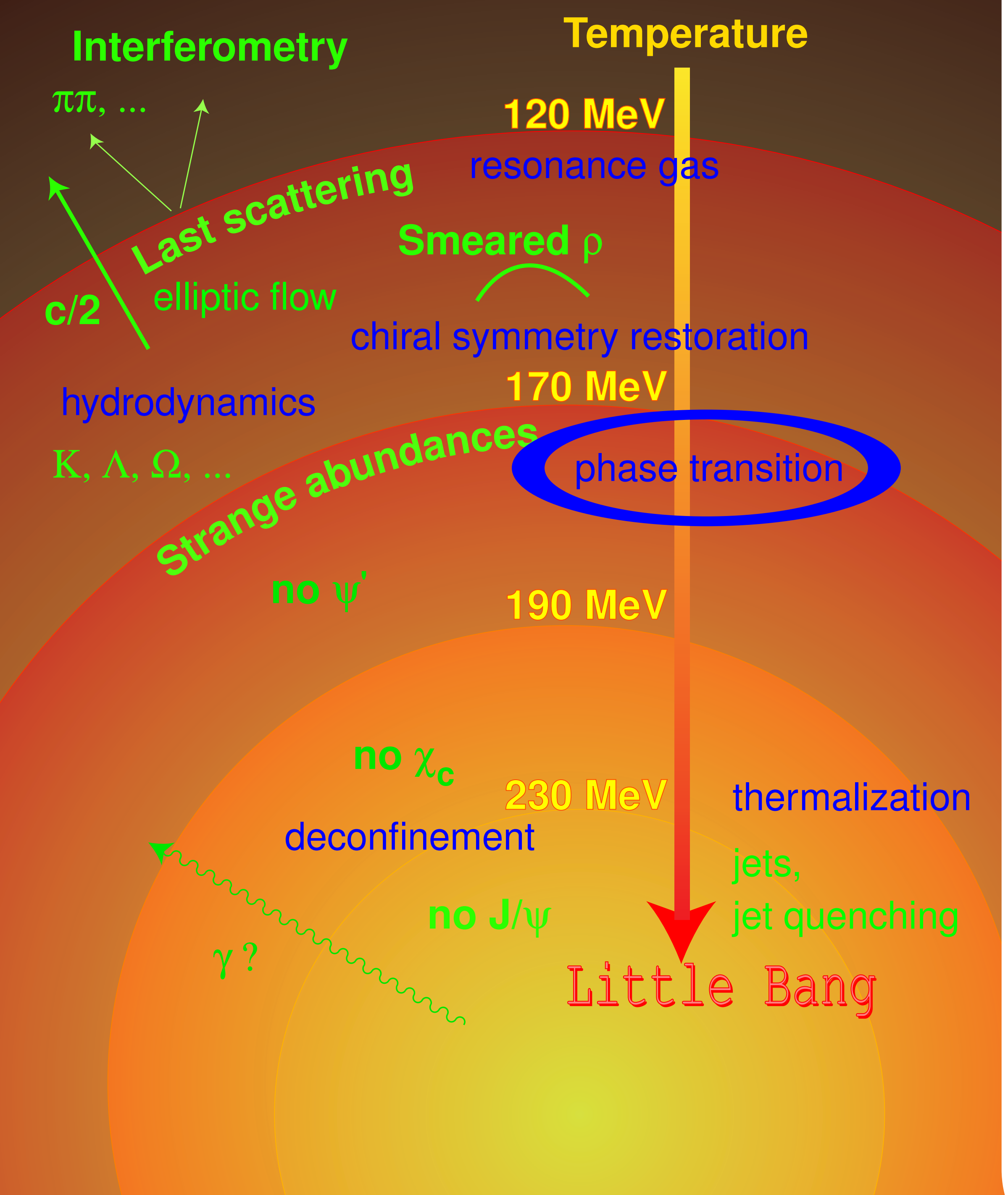
Towards A New State of Matter



Where lattice calculations do/will contribute to the

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$T_c,\ \epsilon_c$

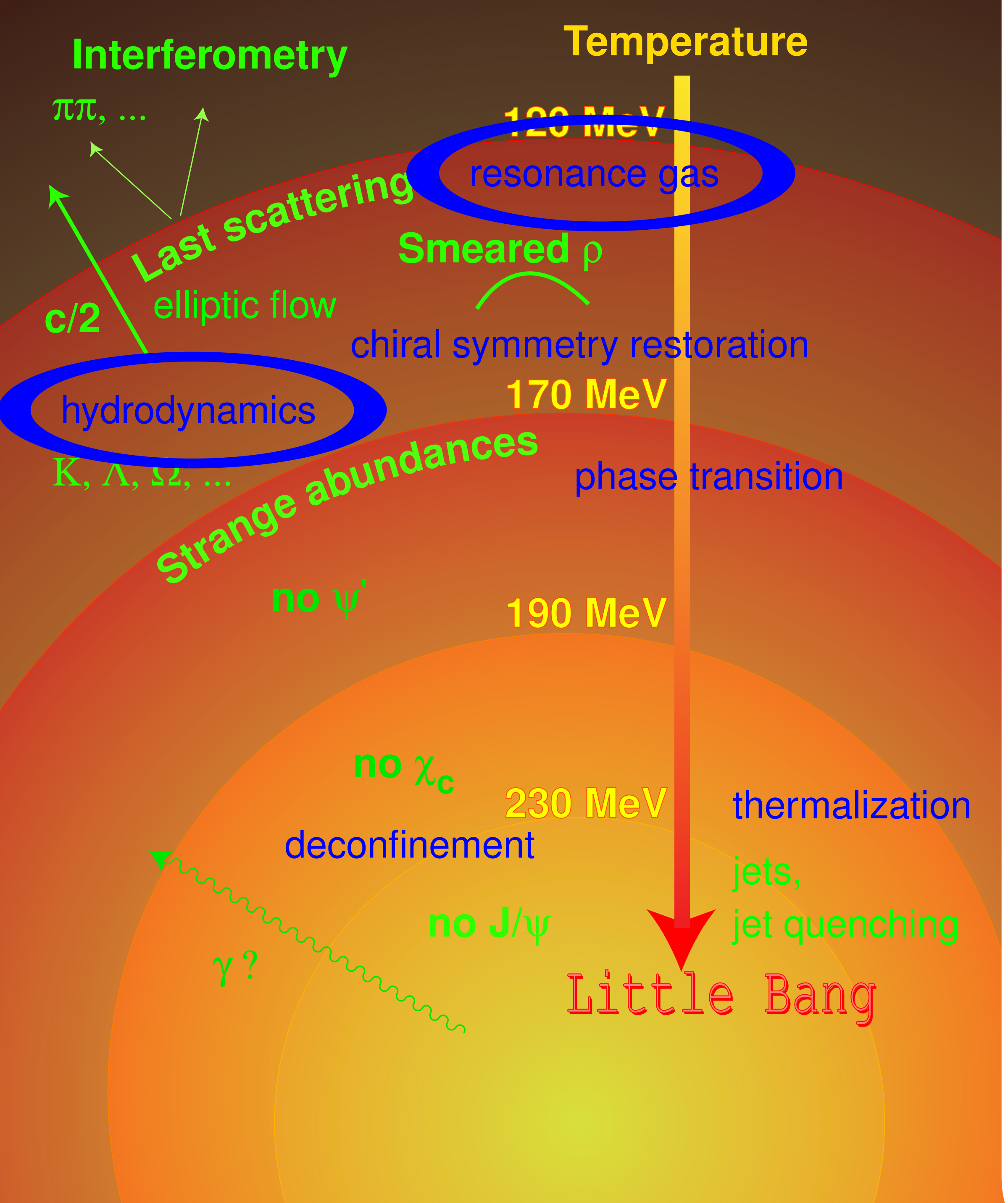
phase diagram in the $(T,\ \mu_B)$-plane;

$\mu \simeq 0$: RHIC (LHC)

$\mu > 0$: SPS (GSI future)

chiral critical point

Towards A New State of Matter



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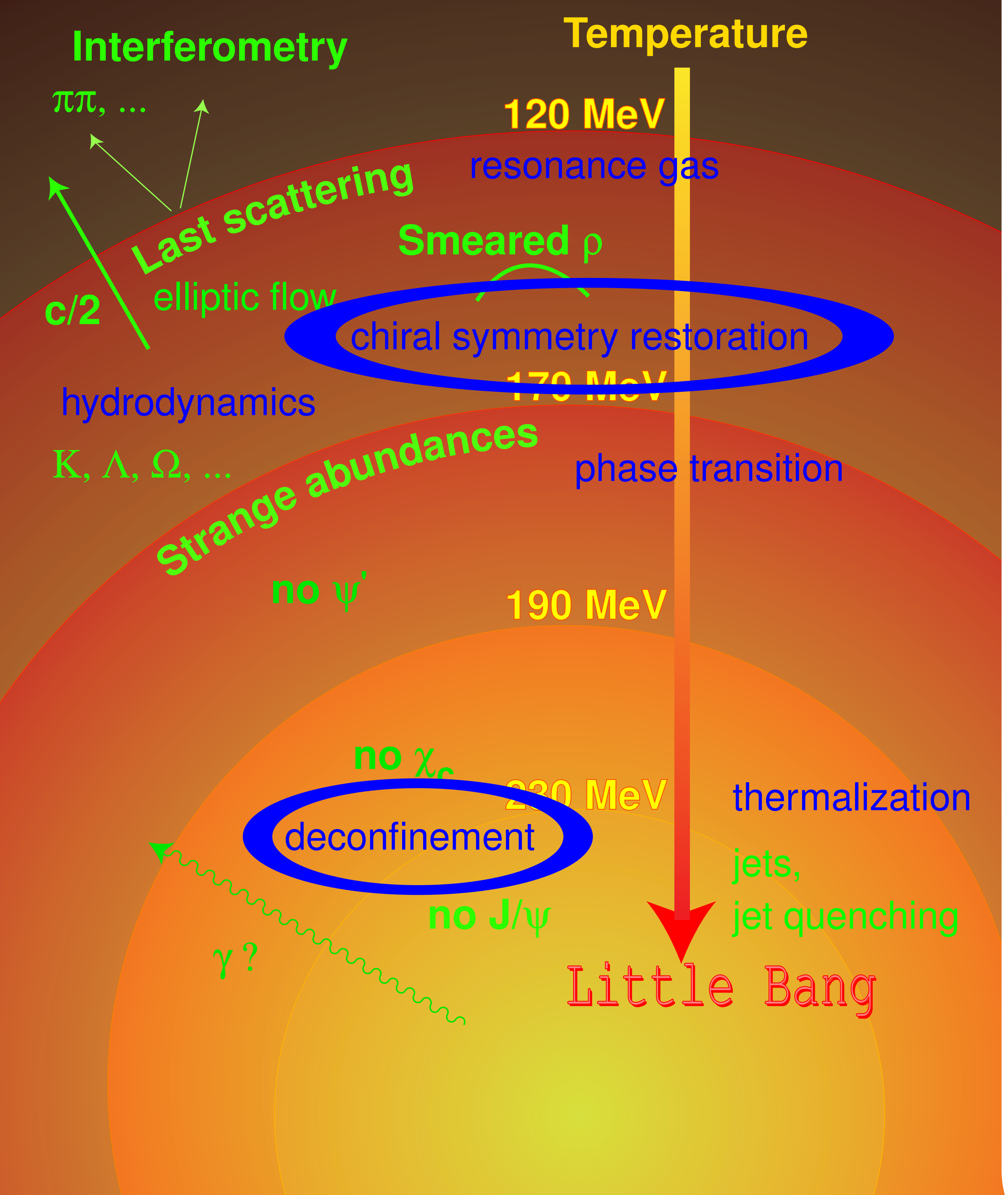
EoS

energy density, pressure, velocity of sound,...; susceptibilities (baryon number fluctuations);

strangeness contribution

Towards A New State of Matter



Where lattice calculations do/will contribute to the

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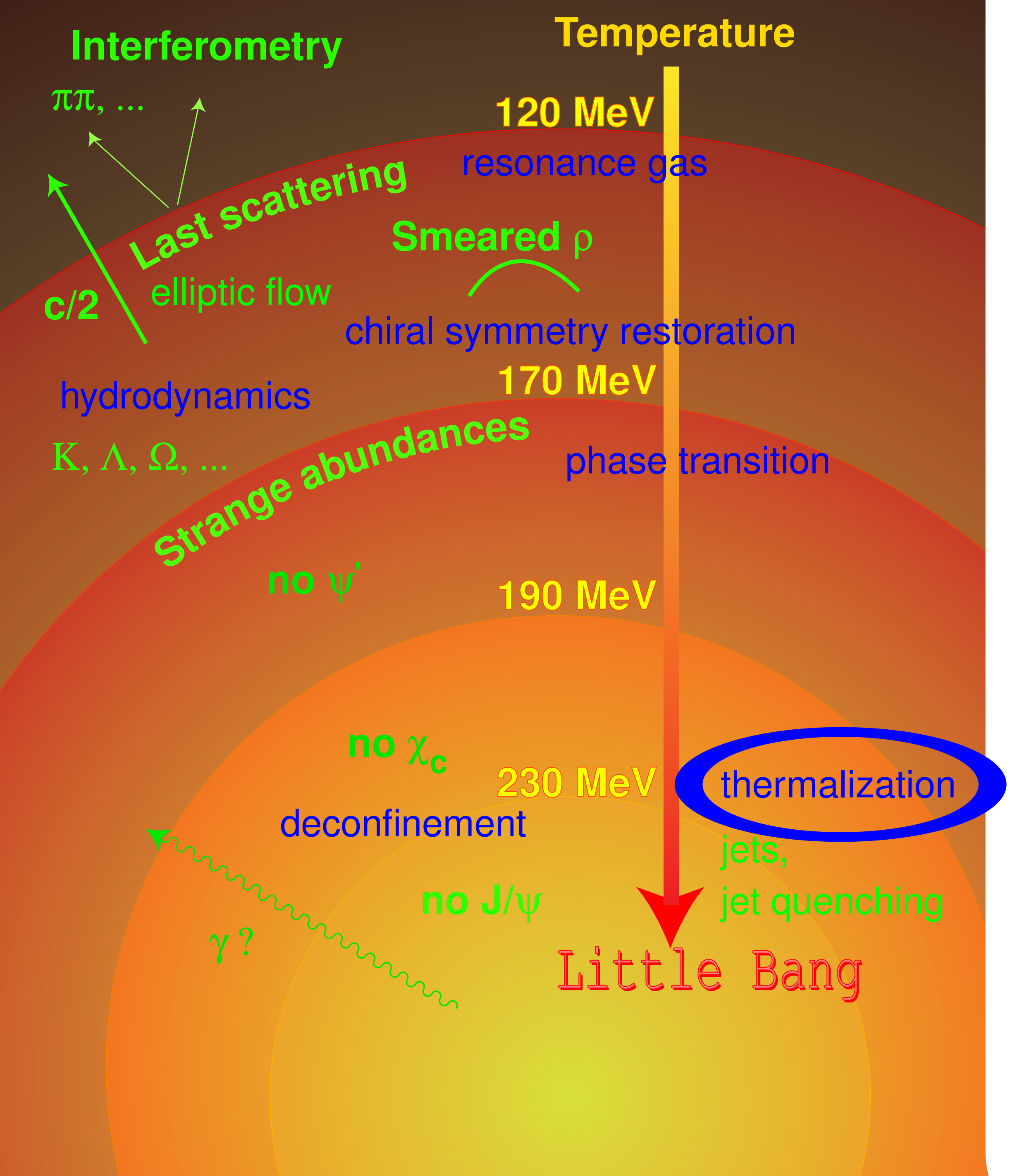
In − medium hadron properties

heavy quark potential, screening;
charmonium spectroscopy;
light quark bound states;

thermal dilepton rates

Towards A New State of Matter



Where lattice calculations do/will contribute to the

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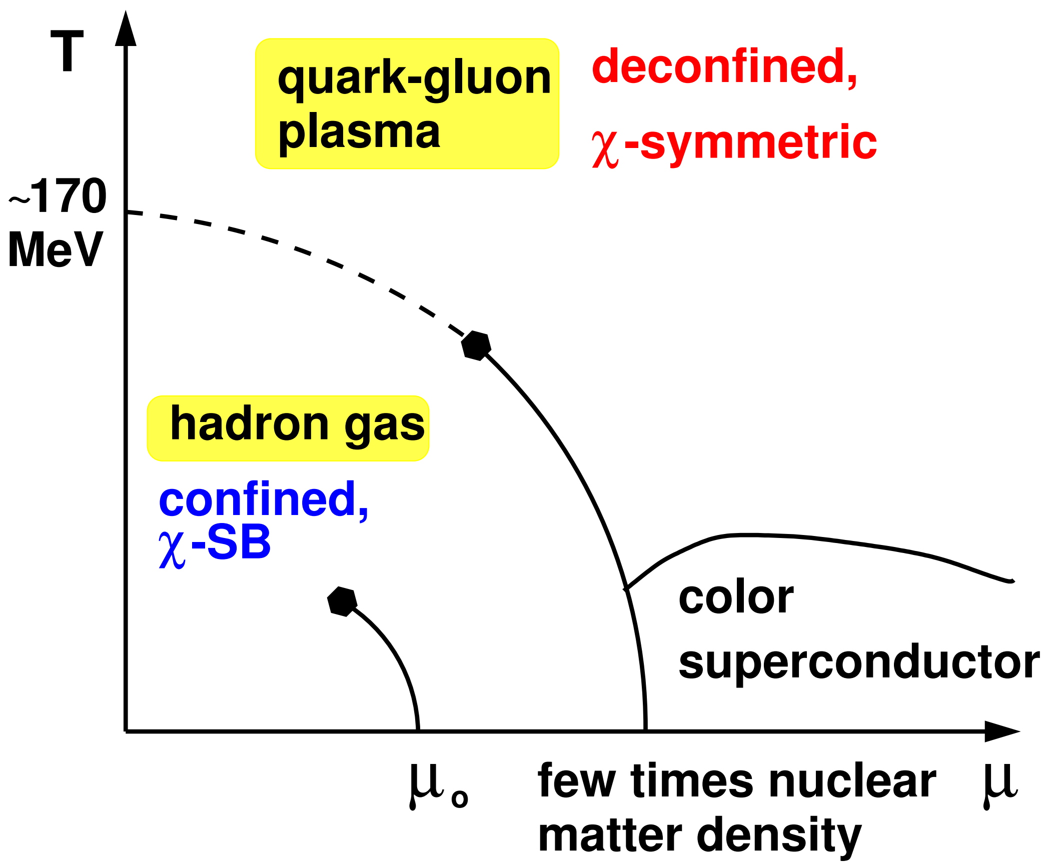
short vs. long distance physics

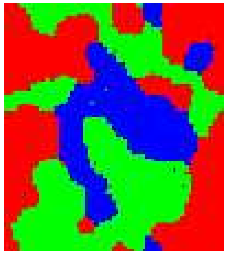
running coupling constant;
transport coefficients

Critical behavior in hot and dense matter: phase diagram

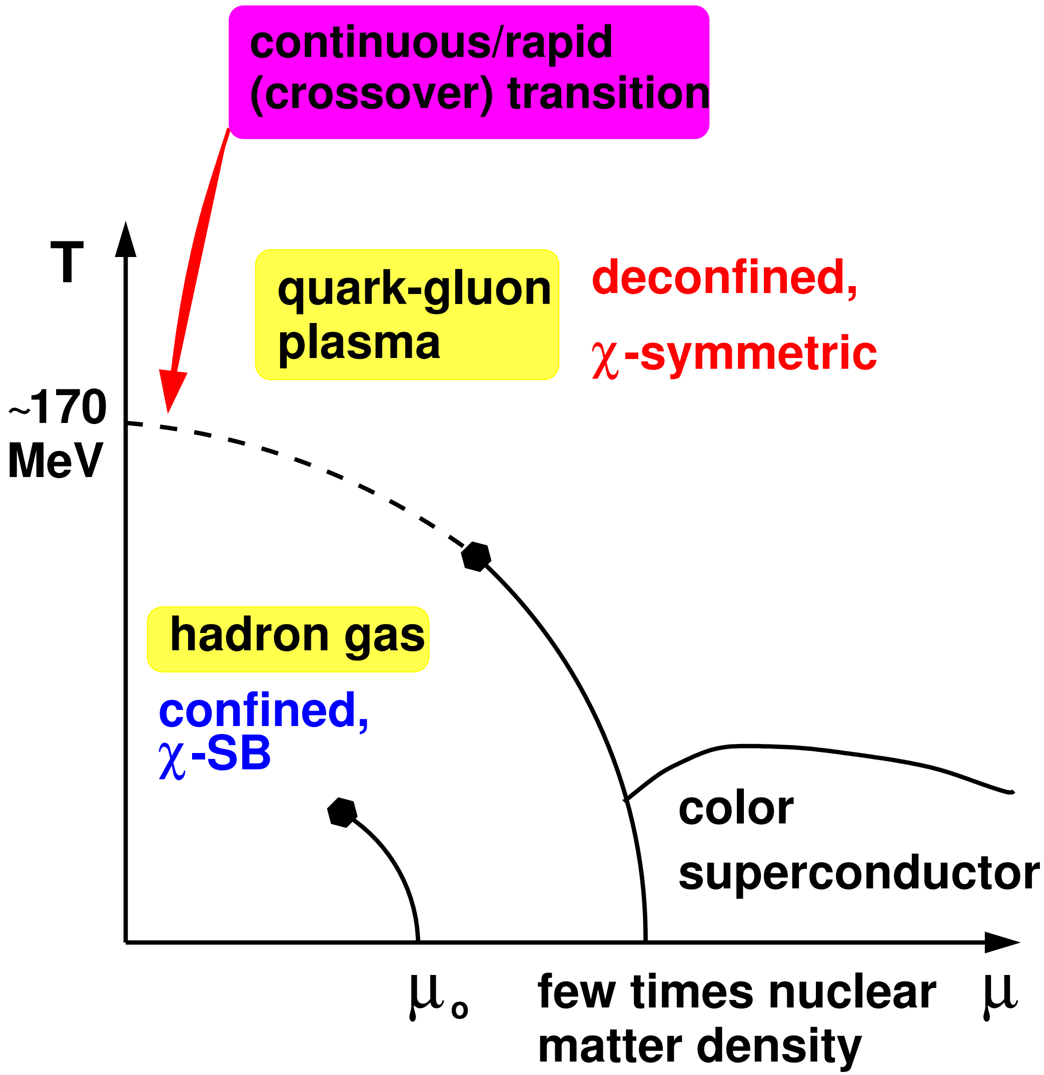
crossover vs.

phase transition



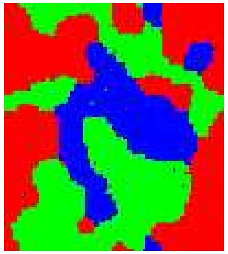


Critical behavior in hot and dense matter: phase diagram

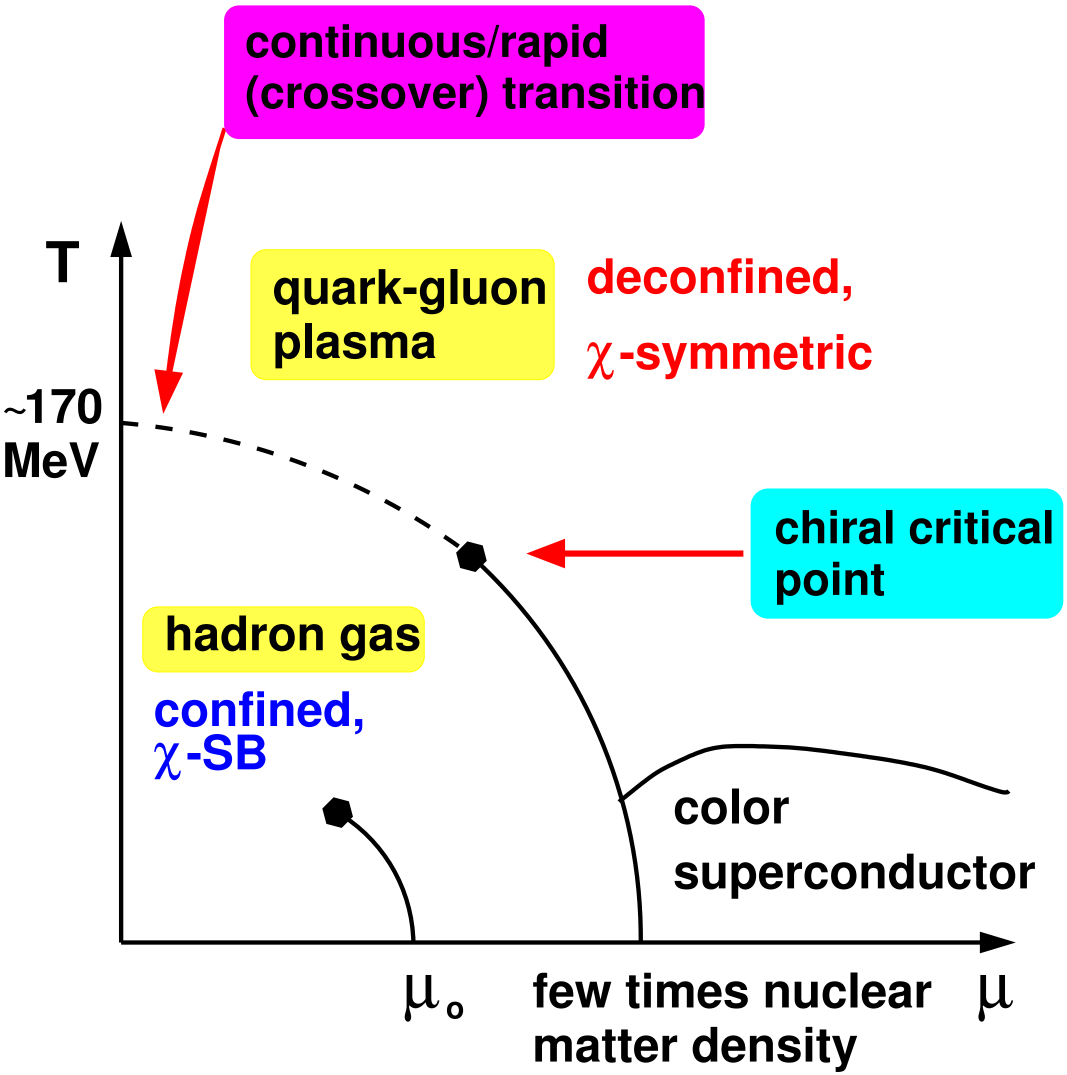


continuous transition for small chemical potential and small quark masses at

$$T_c \simeq 170\, MeV$$
$$\epsilon_c \simeq 0.7\, GeV/fm^3$$



Critical behavior in hot and dense matter: phase diagram



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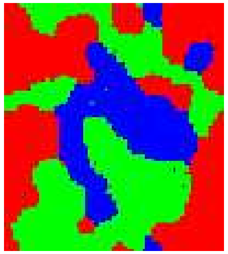
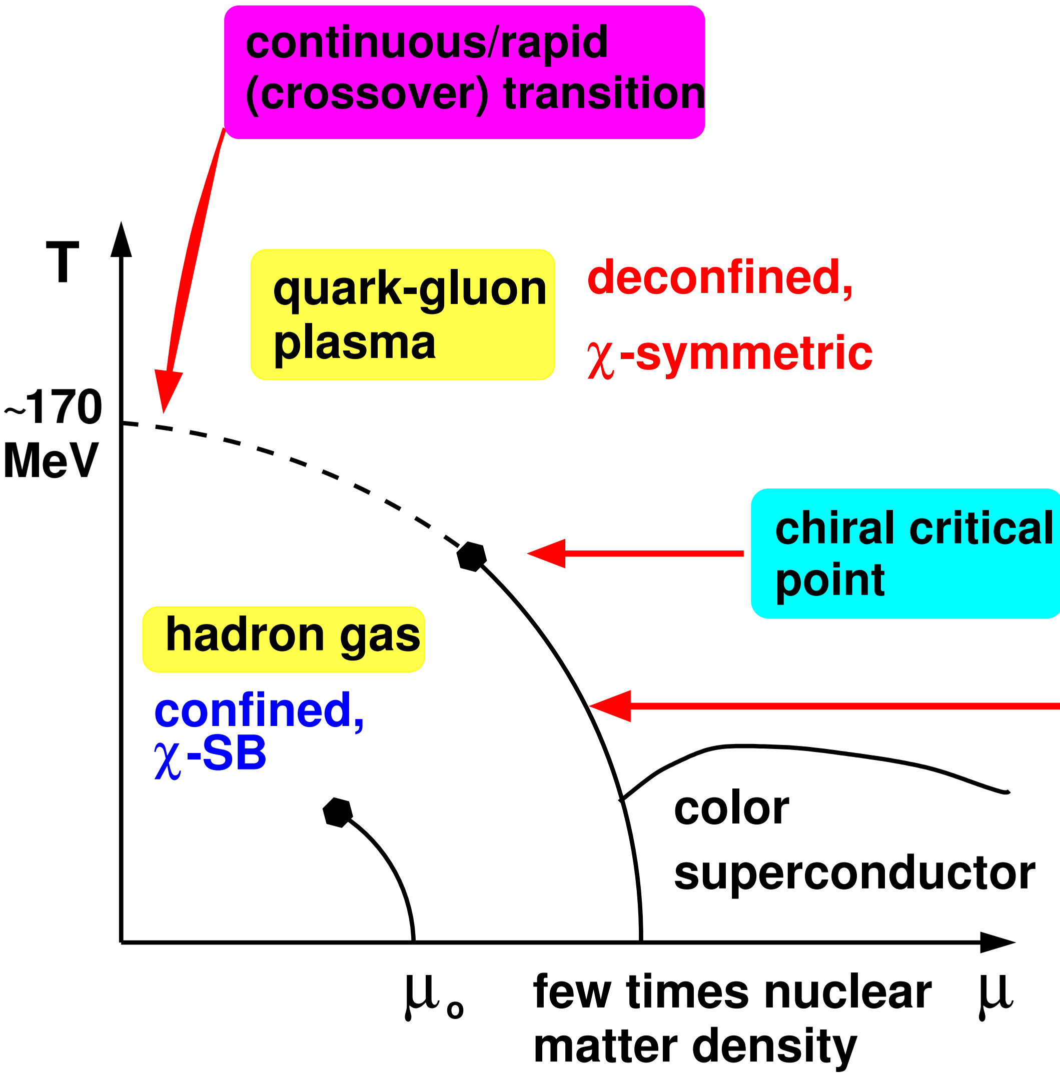
2nd order phase transition; Ising universality class

$T_c(\mu)$ under investigation



Critical behavior in hot and dense matter: phase diagram



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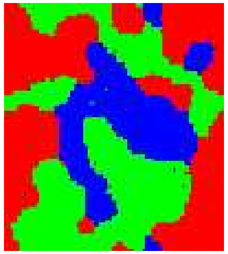
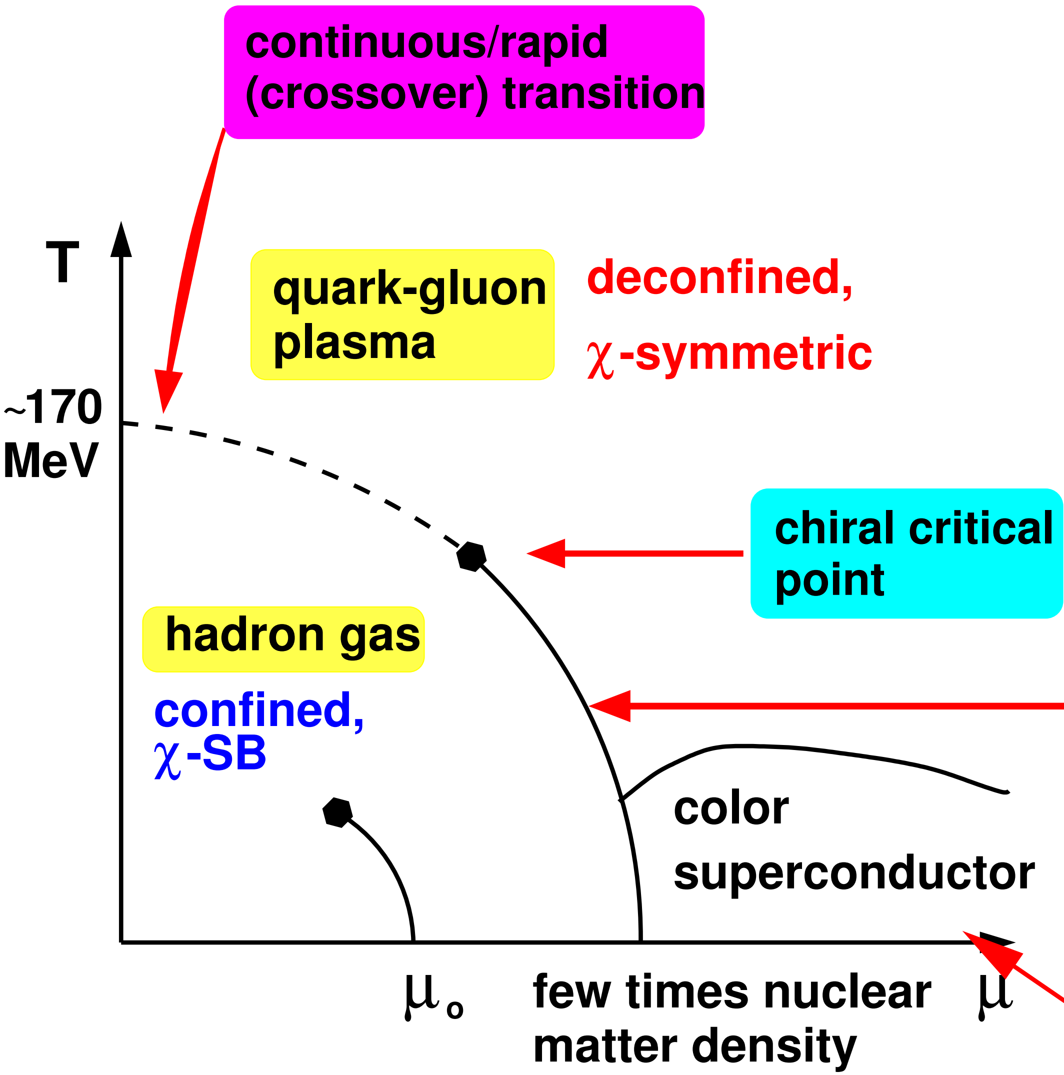
expected - however, so far no direct evidence from lattice QCD



Critical behavior in hot and dense matter: phase diagram



continuous transition for
small chemical potential
and small quark masses at

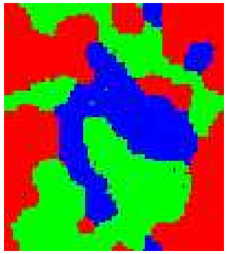
$$T_c \simeq 170\, MeV$$
$$\epsilon_c \simeq 0.7\, GeV/fm^3$$

2nd order phase transition;
Ising universality class
$T_c(\mu)$ under investigation

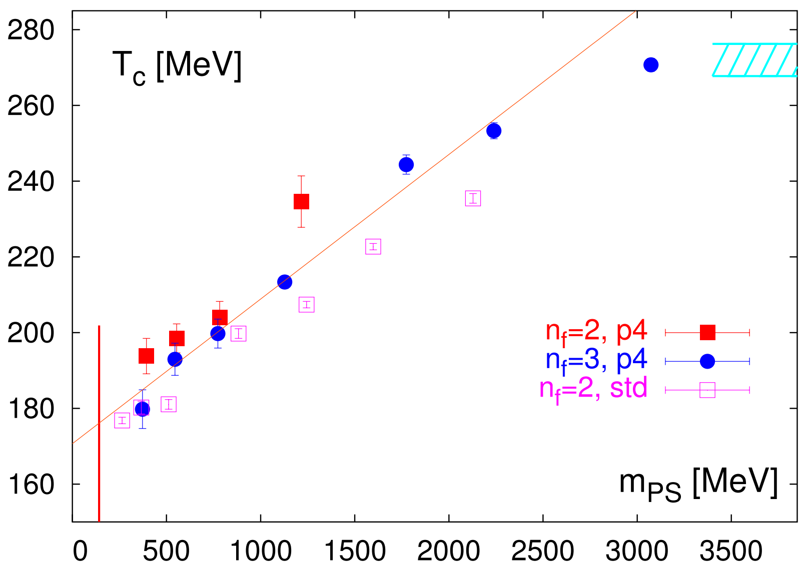
1st order phase transition ???

expected - however, so far no direct evidence from lattice QCD

**attractive 1–gluon exchange
=> qq–condensates**

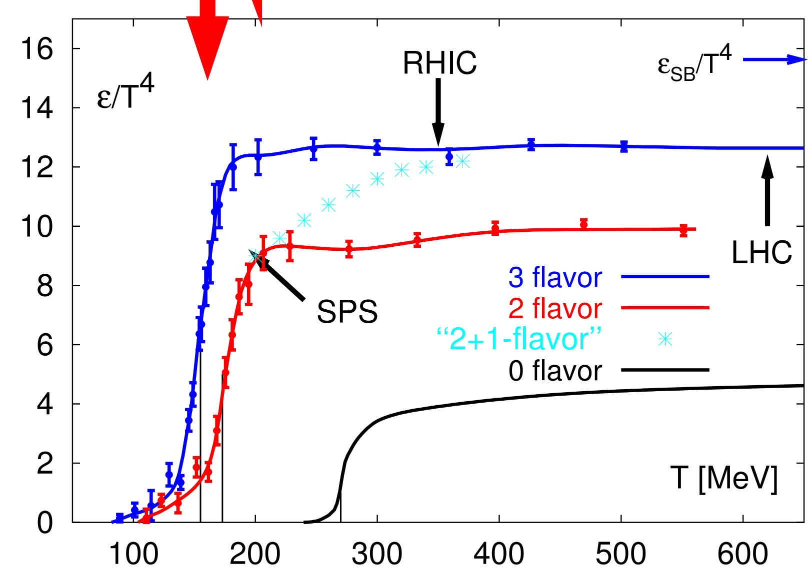


Critical temperature, equation of state



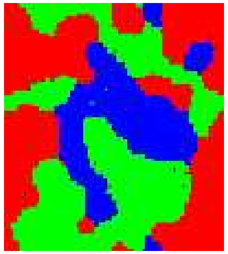
$$\epsilon_c \simeq (6 \pm 2)\, T_c^4$$
$$\simeq (0.3 - 1.3)\, GeV/fm^3$$

energy density for 0, 2 and 3-flavor QCD

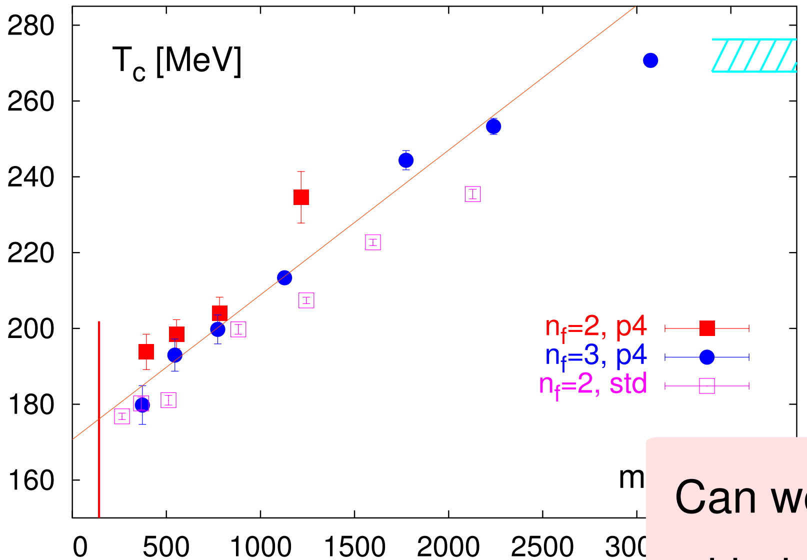


$$T_c = (173 \pm 8 \pm sys)\, MeV$$

FK, E. Laermann, A. Peikert, Nucl. Phys. B605 (2001) 579

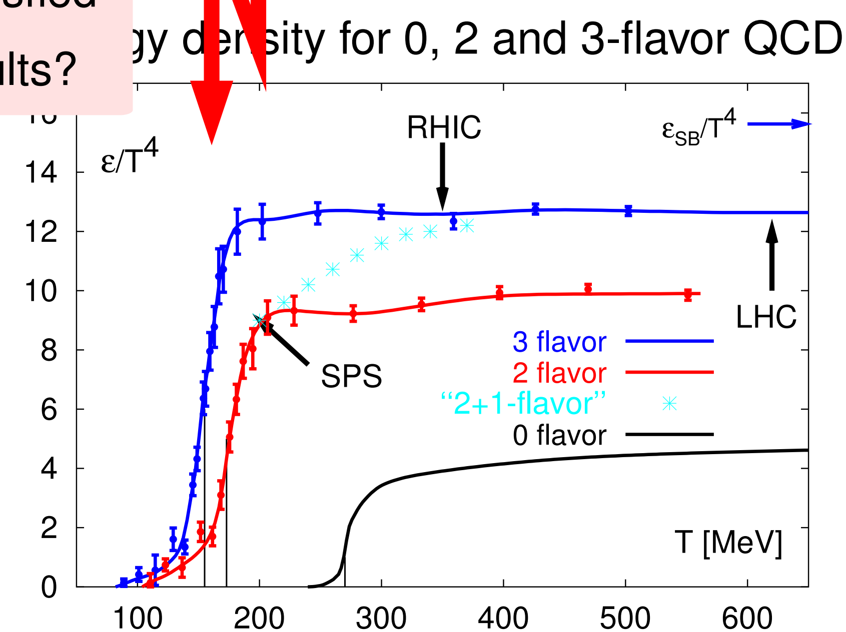


Critical temperature, equation of state



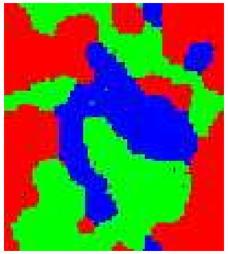
$$\epsilon_c \simeq (6 \pm 2)\, T_c^4$$
$$\simeq (0.3 - 1.3)\, GeV/fm^3$$

Can we be satisfied with these results?

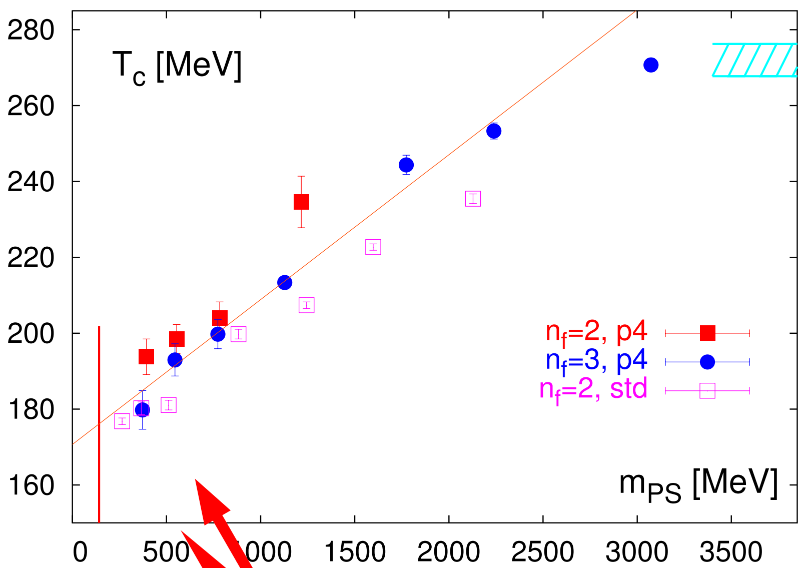


$$T_c = (173 \pm 8 \pm sys)\, MeV$$

FK, E. Laermann, A. Peikert, Nucl. Phys. B605 (2001) 579



Critical temperature, equation of state



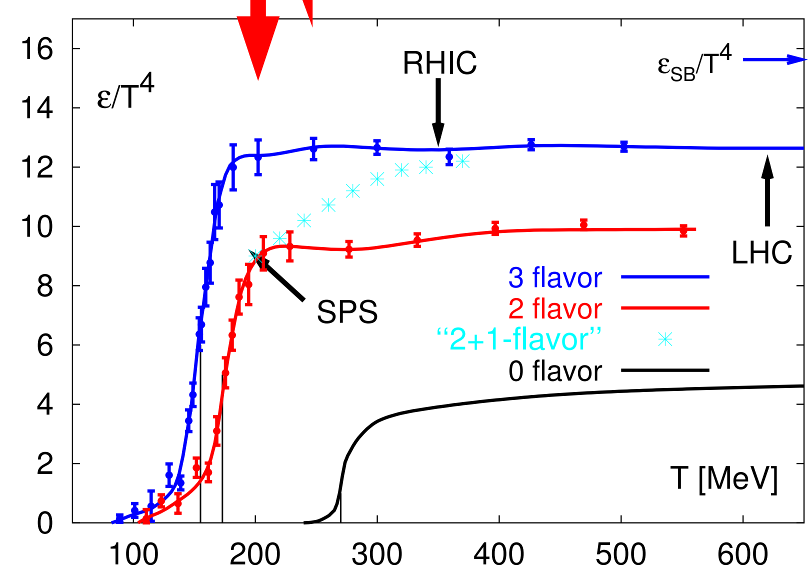
T_c

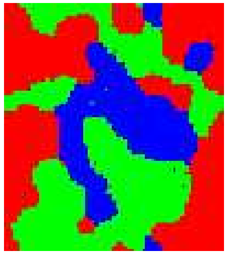
- $m_{PS} \gtrsim 300\ MeV$ (chiral limit??)
- $a \simeq 0.2\ fm$ (continuum limit??)
- improved staggered fermions,
  $\Rightarrow$ flavor symmetry breaking
  (need even better fermion actions)

ϵ_c

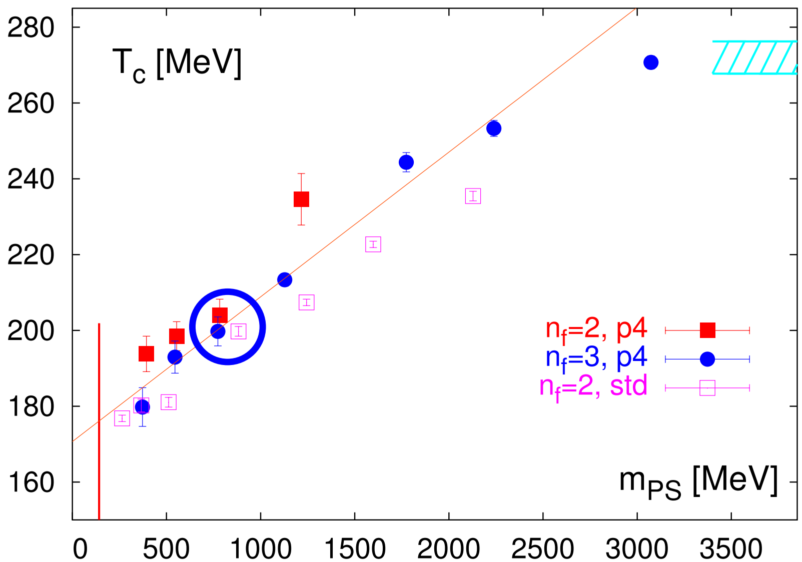
- $m_{PS} \simeq 770\ MeV$ (!!!)
- $V \simeq (4\ \mathrm{fm})^3$ (thermodynamic limit)

energy density for 0, 2 and 3-flavor QCD





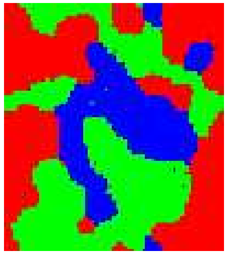
What triggers the transition in strongly interacting matter?



QCD transition in a world with

heavy pions: $m_\pi \simeq 770\ MeV$

not a ”true phase transition”



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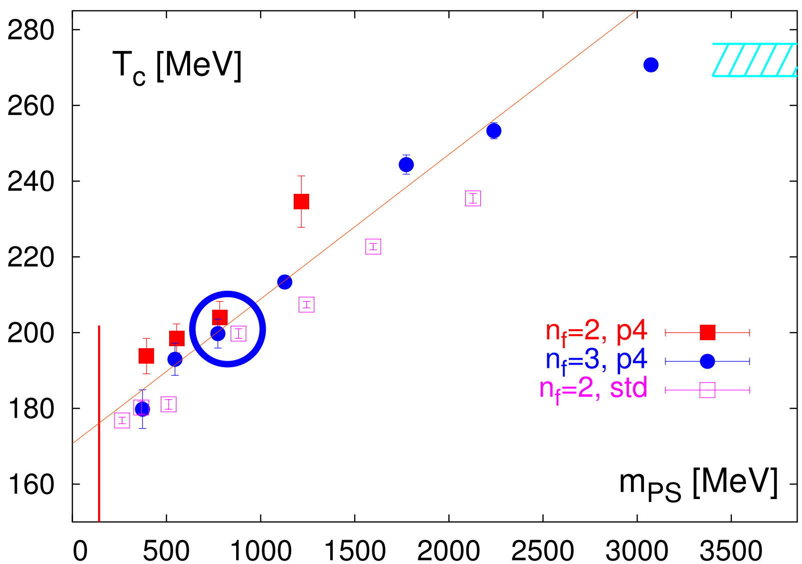
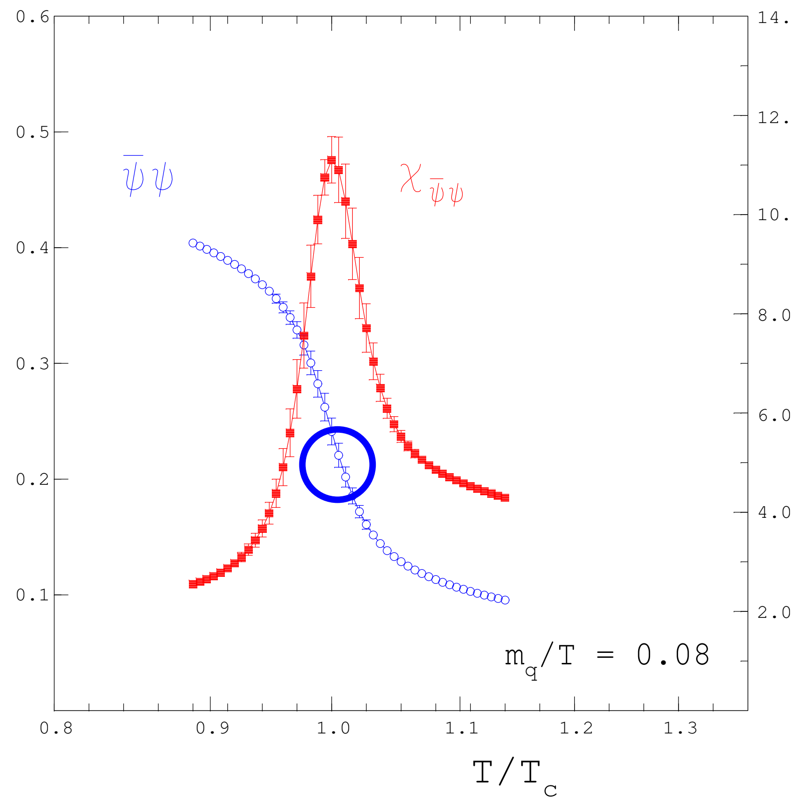
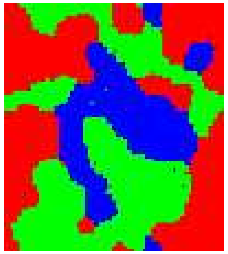




chiral symmetry restoration

– rapid drop of $\langle\bar{\psi}\psi\rangle$

however: $\langle\bar{\psi}\psi\rangle(T_c) \;>\; 0$



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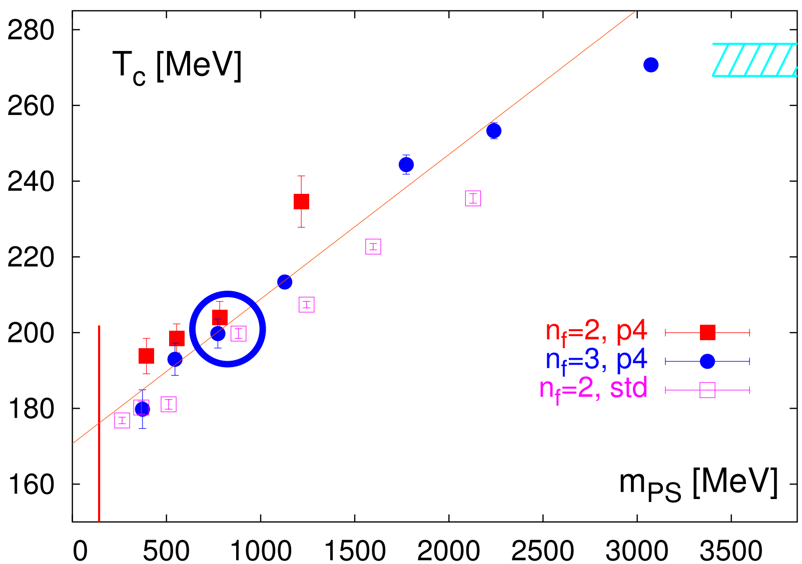
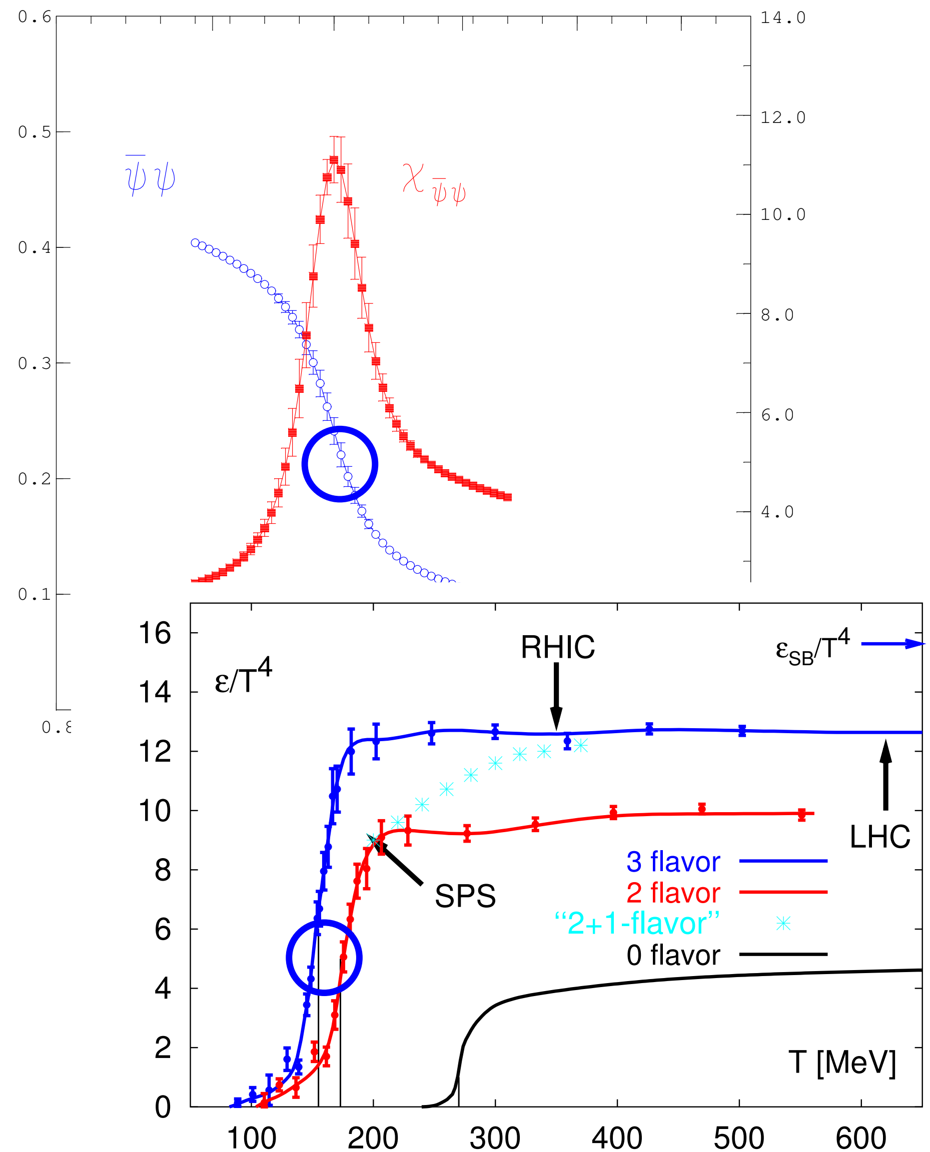




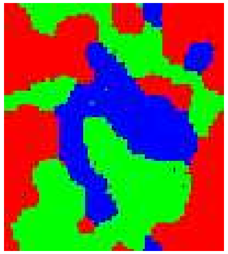
chiral symmetry restoration

– rapid drop of $\langle\bar{\psi}\psi\rangle$

however: $\langle\bar{\psi}\psi\rangle(T_c) > 0$

deconfinement

– rapid increase of d.o.f.



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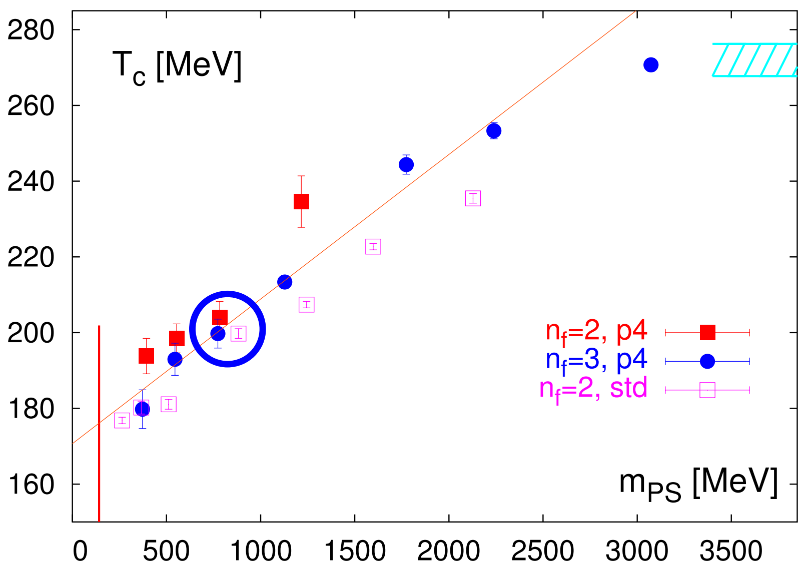
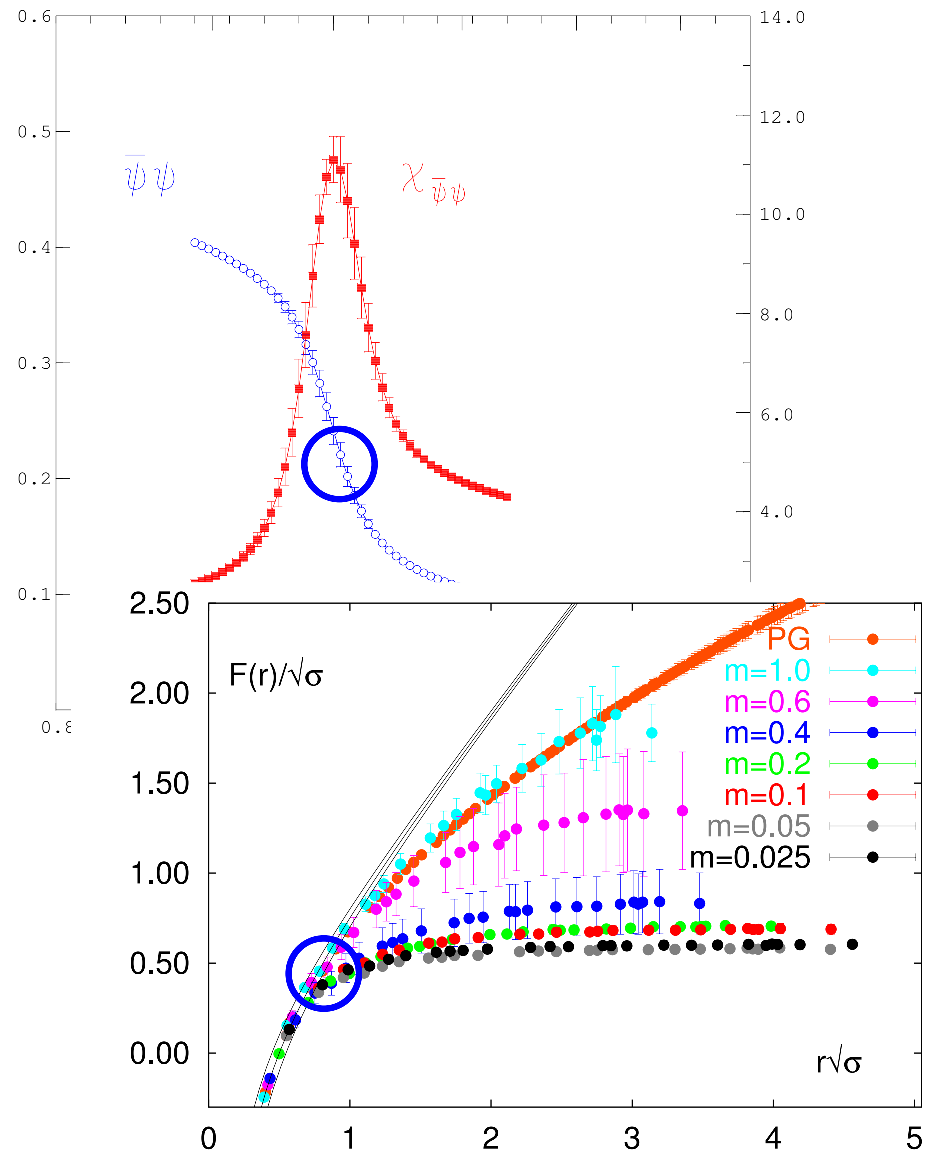




chiral symmetry restoration

– rapid drop of $\langle\bar{\psi}\psi\rangle$

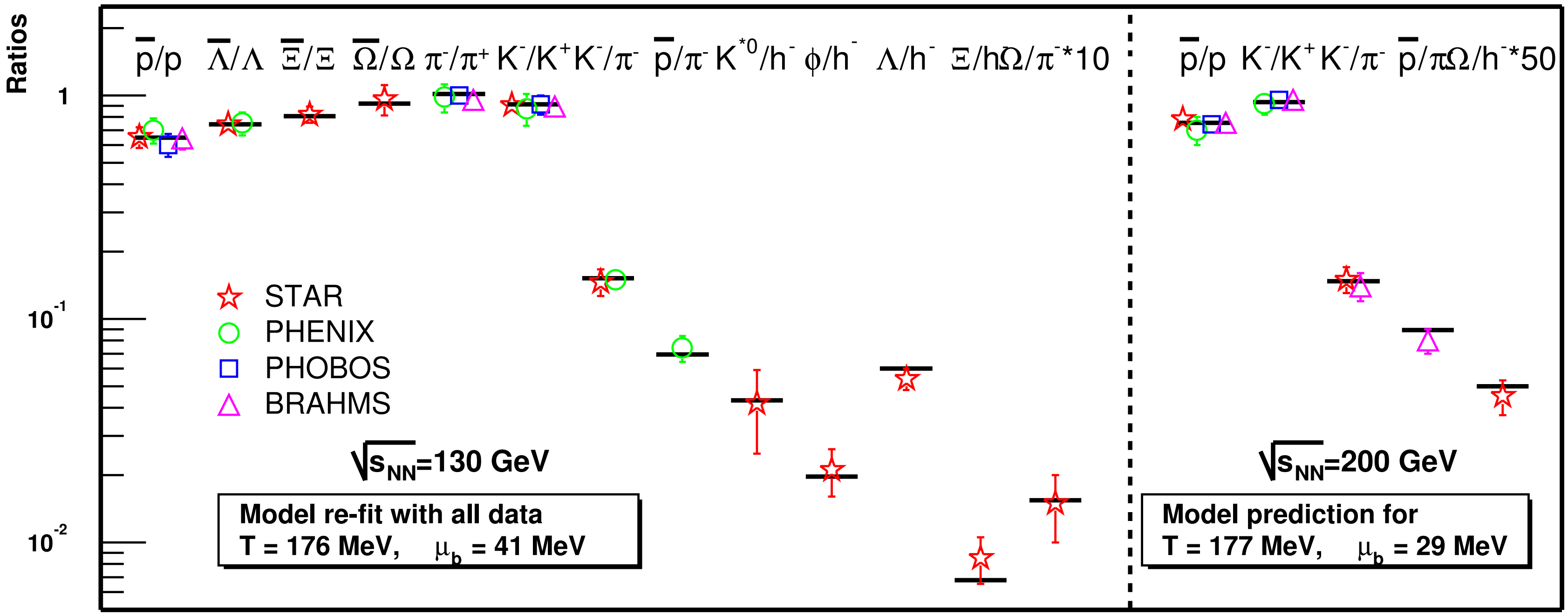
however: $\langle\bar{\psi}\psi\rangle(T_c) > 0$

deconfinement

– rapid increase of d.o.f.

however: "no rigorous confinement"

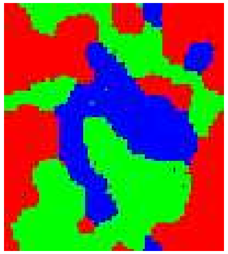
Particle ratios and freeze out conditions



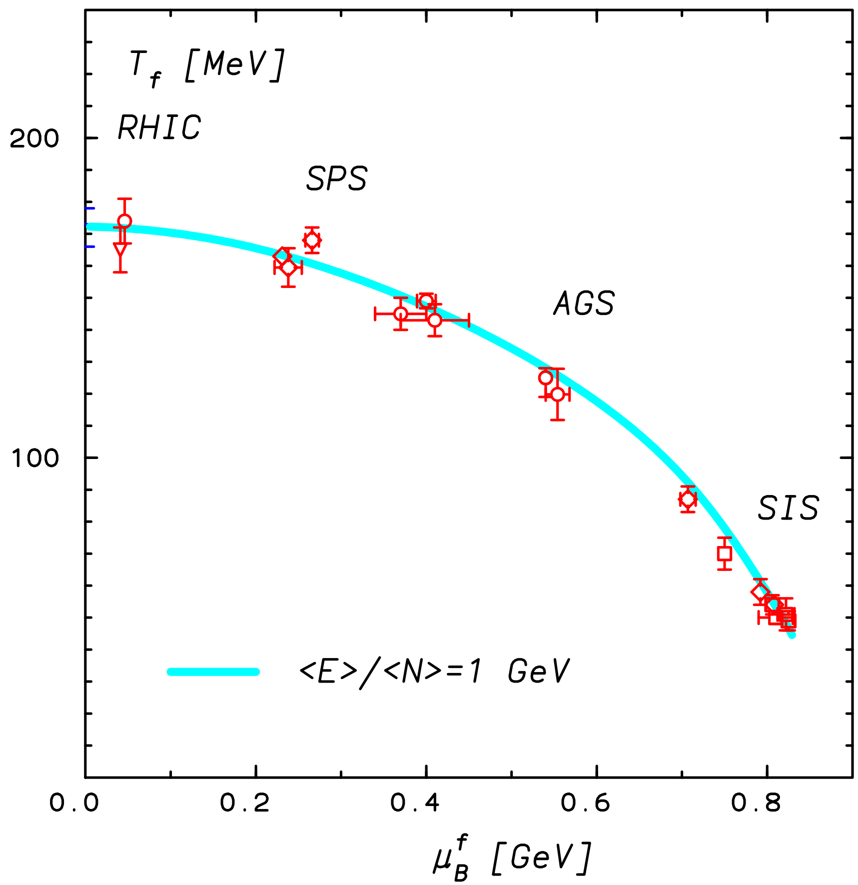
resonance gas: $Z(T,V,\mu_i) = \mathrm{Tr} e^{-\beta(H-\sum_i \mu_i Q_i)}$

describes observed particle ratios and freeze out conditions

P. Braun-Munzinger, D. Magestro, K. Redlich, J. Stachel, Phys. Lett. B518 (2001) 41



Particle ratios and freeze out conditions



resonance gas

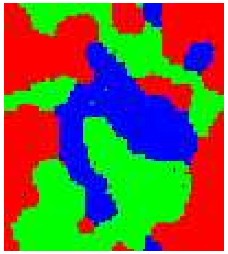
describes observed particle ratios and freeze out conditions

- Is the freeze out temperature the critical temperature of the QCD transition?

- Which role do resonances play for the occurence of the transition to the QGP?

- ... and what about deconfinement and chiral symmetry restoration?

$$\ln\ Z(T,V,\mu_B,..)\ = \sum_{m_i} \ln\ Z_i(T,V,\mu_B,..)$$

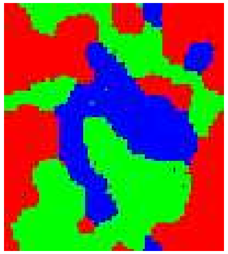


Critical temperature, equation of state and the resonance gas

$$\textbf{Hagedorn spectrum}: \quad \rho(m_H) \sim c\, m_H^a\, \mathrm{e}^{m_H/T_H}$$

$$\ln Z(T,\mu_B) \;=\; \int \mathrm{d}m_H\; \rho(m_H)\; \ln Z_{m_H}(T,\mu_B)$$

- $\int \;\Rightarrow\; \sum \;\sim$ experimentally known resonances



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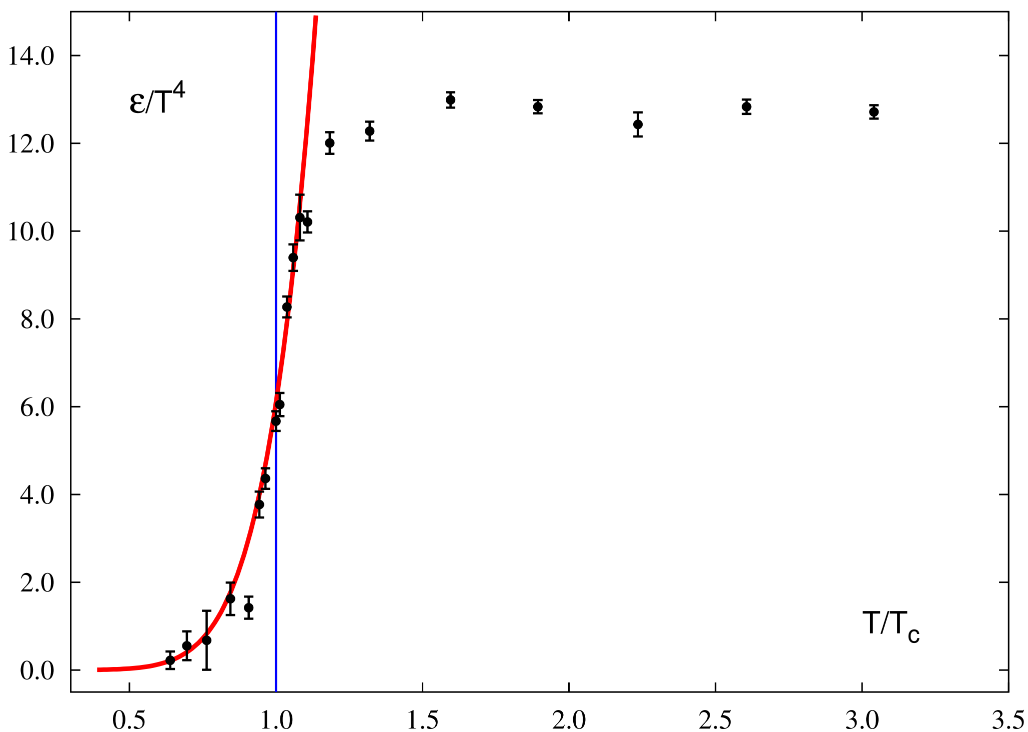


resonance gas:

$\sim$ 1500 d.o.f. from

$\sim$ 300 exp. known resonances

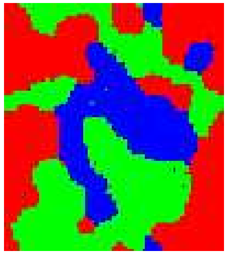
vs.

lattice calculation:

(2+1)-flavor QCD, $m_q/T = 0.4$

resonances give large contribution at T_c

- explain eos for $T \leq T_c$;



Critical temperature, equation of state and the resonance gas

$$\textbf{Hagedorn spectrum}: \ \rho(m_H) \sim c\, m_H^a\, e^{m_H/T_H}$$

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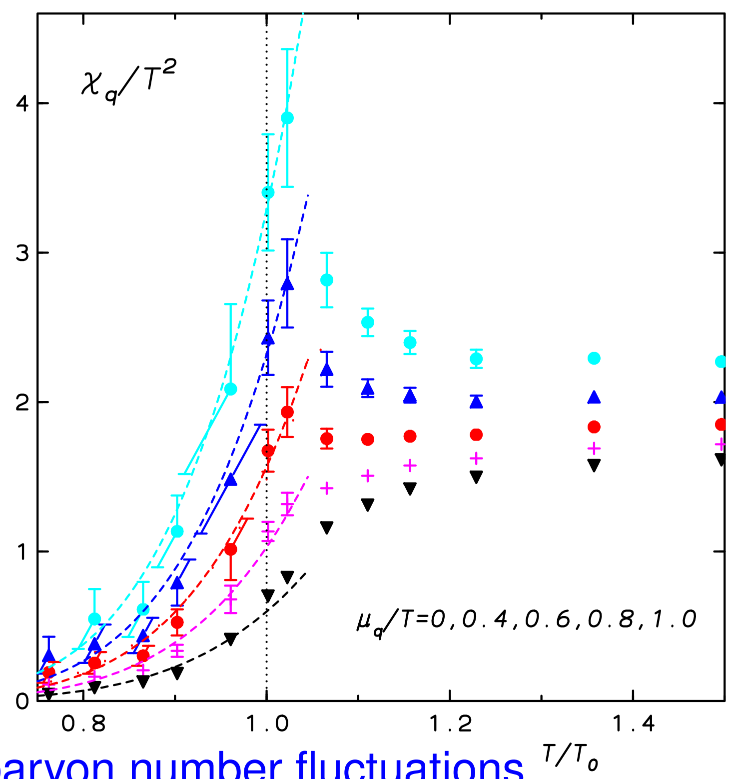
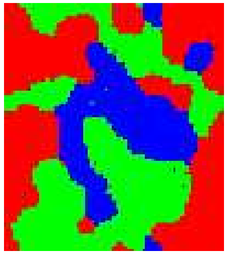


baryon number fluctuations

resonance gas:

resonances give large contribution at T_c

- explain eos for $T \leq T_c$;
- explain eos for $\mu_q > 0$ and $T \leq T_c$;

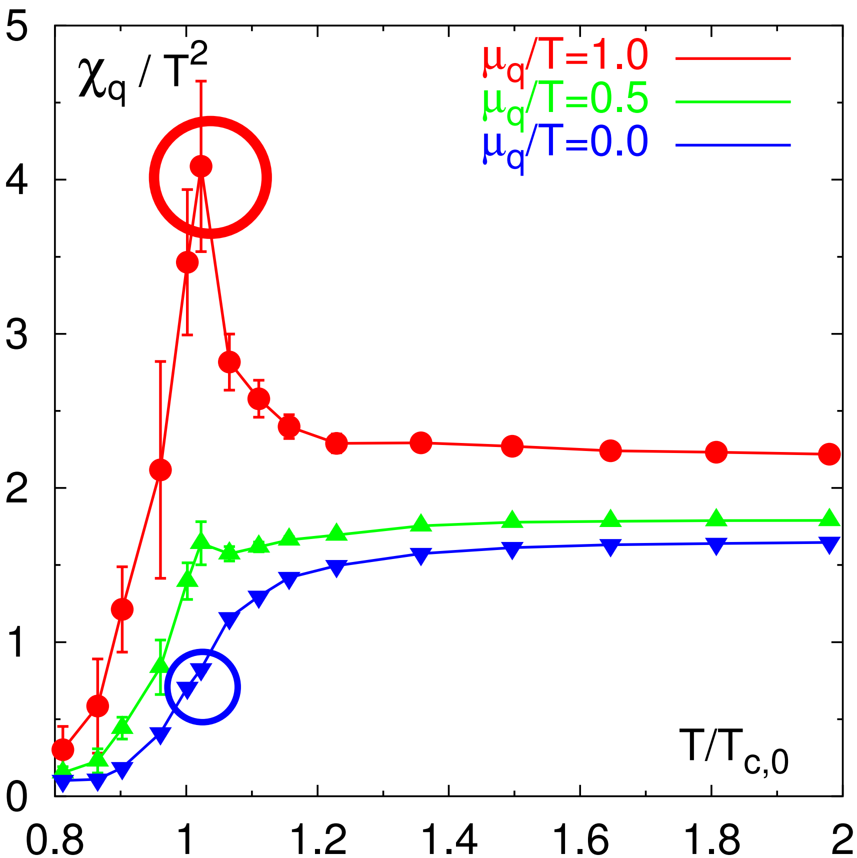


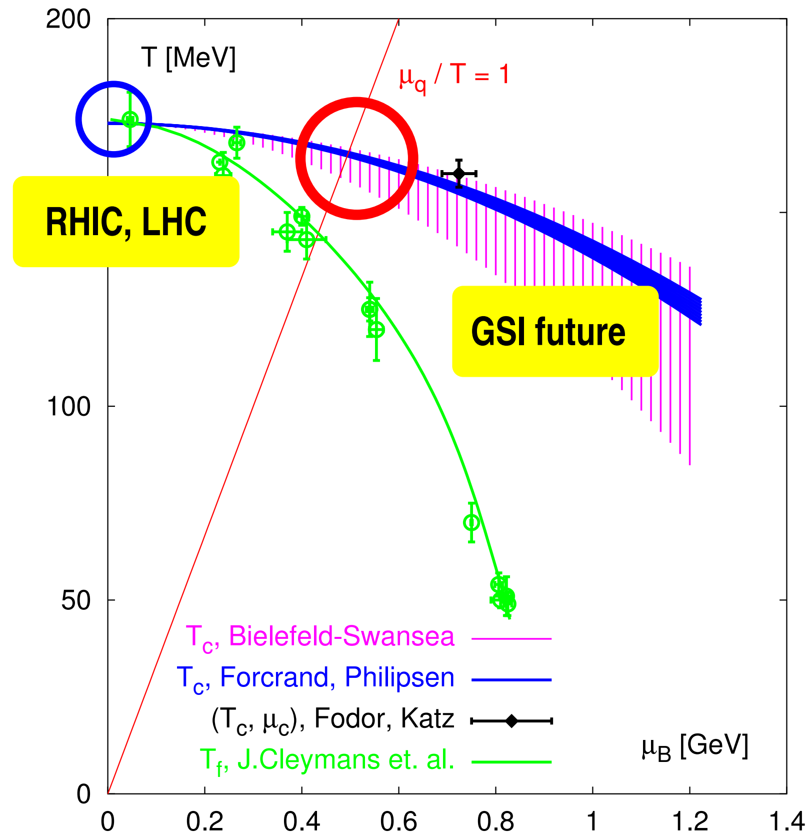
Fluctuations of the baryon number density ($\mu > 0$)

baryon number density fluctuations:
(Bielefeld-Swansea, PRD68 (2003) 014507)

$$\frac{\chi_q}{T^3} = \left(\frac{d^2}{d(\mu/T)^2} \frac{p}{T^4} \right)_{T\ \mathrm{fixed}}$$

$$= \frac{9\,T}{V} \left(\langle N_B^2 \rangle - \langle N_B \rangle^2 \right)$$





Extending the phase diagram to non-vanishing chemical potential

non-zero baryon number density: $\boldsymbol{\mu > 0}$

$$\begin{aligned} Z(V,T,\mu) &= \int \mathcal{DAD}\psi\mathcal{D}\bar{\psi}\ \mathrm{e}^{-S_E(V,T,\mu)} \\ &= \int \mathcal{DAD}\ det\ M(\mu)\ \mathrm{e}^{-S_E(V,T)} \end{aligned}$$

$\Uparrow$complex fermion determinant;

long standing problem

$\Longrightarrow$ three (partial) solutions for large T, small μ

Extending the phase diagram to non-vanishing chemical potential

non-zero baryon number density: $\mu > 0$

$$Z(V,T,\mu) = \int \mathcal{D}\mathcal{A}\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \mathrm{e}^{-S_E(V,T,\mu)}$$
$$= \int \mathcal{D}\mathcal{A}\mathcal{D}\ det\ M(\mu)\ \mathrm{e}^{-S_E(V,T)}$$

$\Uparrow$complex fermion determinant;

long standing problem

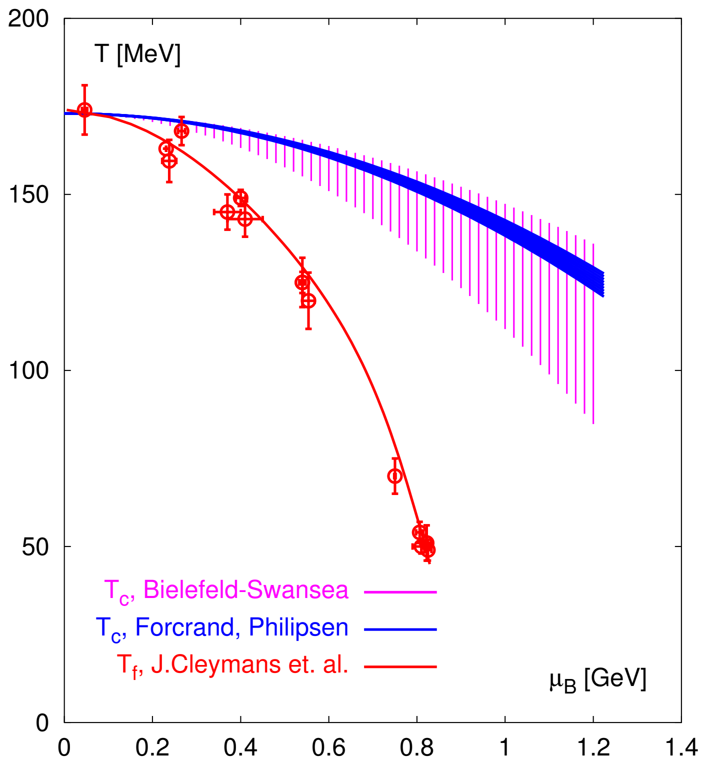
$\Rightarrow$ three (partial) solutions for large T, small μ

- exact evaluation of $detM$: works well on small lattices; requires reweighting
  Z. Fodor, S.D. Katz, JHEP 0203 (2002) 014
- Taylor expansion around $\mu = 0$: works well for small μ; requires reweighting
  C. R. Allton et al. (Bielefeld-Swansea), Phys. Rev. D66 (2002) 074507
- imaginary chemical potential: works well for small μ; requires analytic continuation
  Ph. deForcrand, O. Philipsen, Nucl. Phys. B642 (2002) 290

Extending the phase diagram to non-vanishing chemical potential

non-zero baryon number density: $\mu > 0$

$$Z(V, T, \mu) = \int \mathcal{D}\mathcal{A}\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \mathrm{e}^{-S_E(V,T,\mu)}$$
$$= \int \mathcal{D}\mathcal{A}\mathcal{D}\ det\ M(\mu)\ \mathrm{e}^{-S_E(V,T)}$$



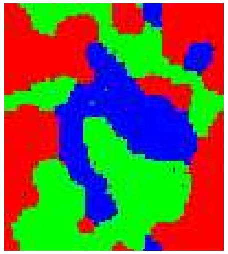
$\frac{T_c(\mu)}{T_c(0)}$: $1 - 0.0056(4)(\mu_B/T)^2$

deForcrand, Philipsen (imag. μ)

$1 - 0.0078(38)(\mu_B/T)^2$

Bielefeld-Swansea

($\mathcal{O}(\mu^2)$ reweighting)



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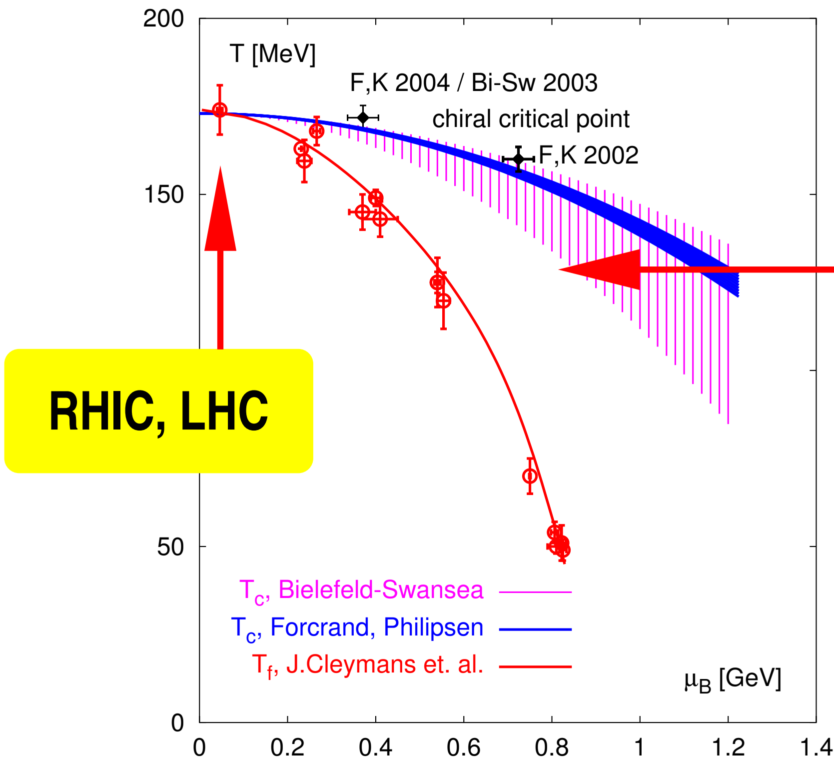

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deForcrand, Philipsen (imag. μ)

$1 - 0.0078(38)(\mu_B/T)^2$

Bielefeld-Swansea

($\mathcal{O}(\mu^2)$ reweighting)

chiral critical point

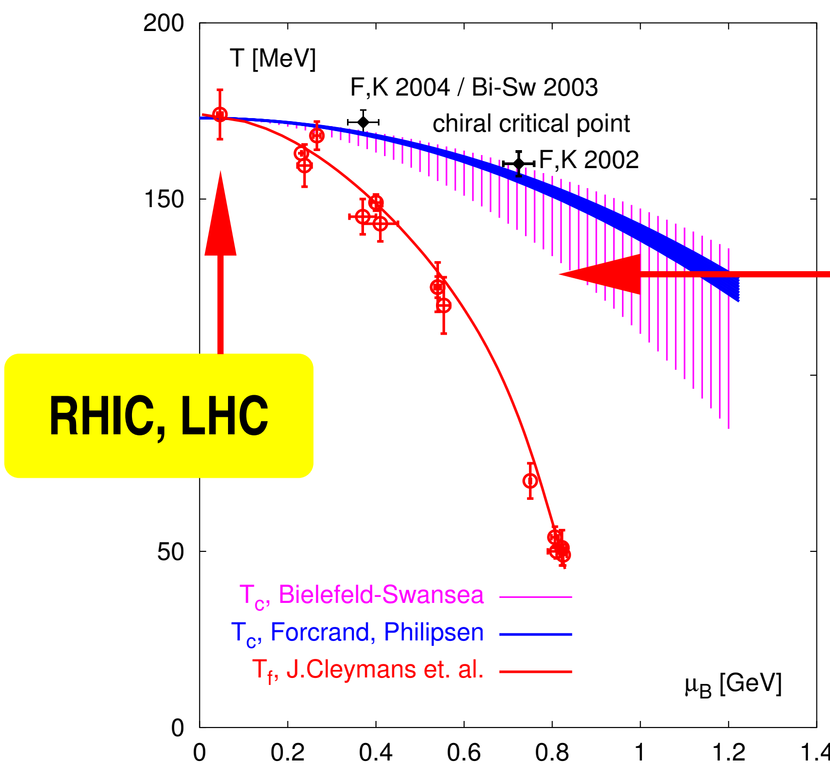
μ_c shifted from $\simeq 700\ MeV$ to $\simeq 400\ MeV$

Fodor, Katz (exact determinants $\Rightarrow$ small lattices)

Extending the phase diagram to non-vanishing chemical potential

non-zero baryon number density: $\boldsymbol{\mu > 0}$

$$Z(V,T,\mu) = \int \mathcal{D}\mathcal{A}\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \mathrm{e}^{-S_E(V,T,\mu)}$$
$$= \int \mathcal{D}\mathcal{A}\mathcal{D}\ det\ M(\mu)\ \mathrm{e}^{-S_E(V,T)}$$



GSI future

$\dfrac{T_c(\mu)}{T_c(0)}$: $1 - 0.0056(4)(\mu_B/T)^2$

deForcrand, Philipsen (imag. μ)

$1 - 0.0078(38)(\mu_B/T)^2$

Bielefeld-Swansea

($\mathcal{O}(\mu^2)$ reweighting)

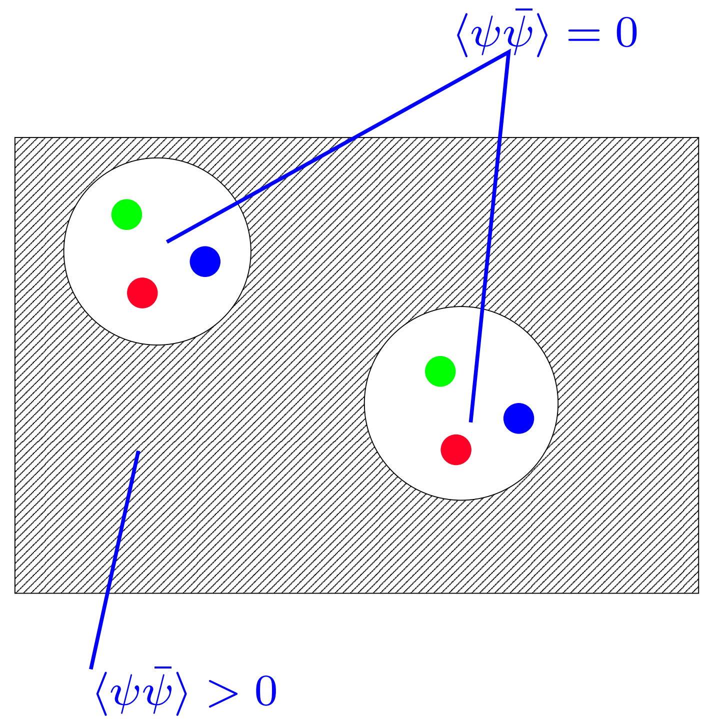
chiral critical point

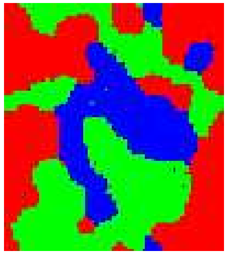
$\mu_c(m_q)$: discrepancies between calculations with real and imaginary μ

In-medium properties of hadrons

- properties of light quark hadrons reflect chiral symmetry breaking: Goldstone pion, non-degenerate parity partners

chiral symmetry restoration



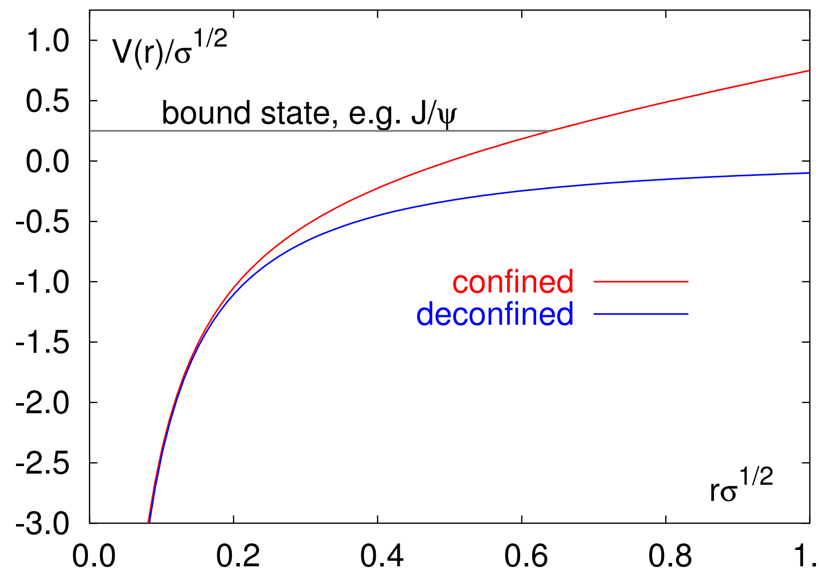


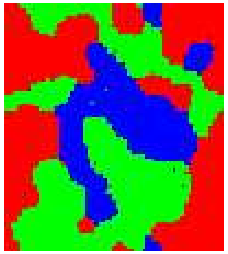
In-medium properties of hadrons

- properties of light quark hadrons reflect chiral symmetry breaking: Goldstone pion, non-degenerate parity partners

- properties of heavy quark hadrons reflect structure of the heavy quark potential: quarkonium spectra

Deconfinement



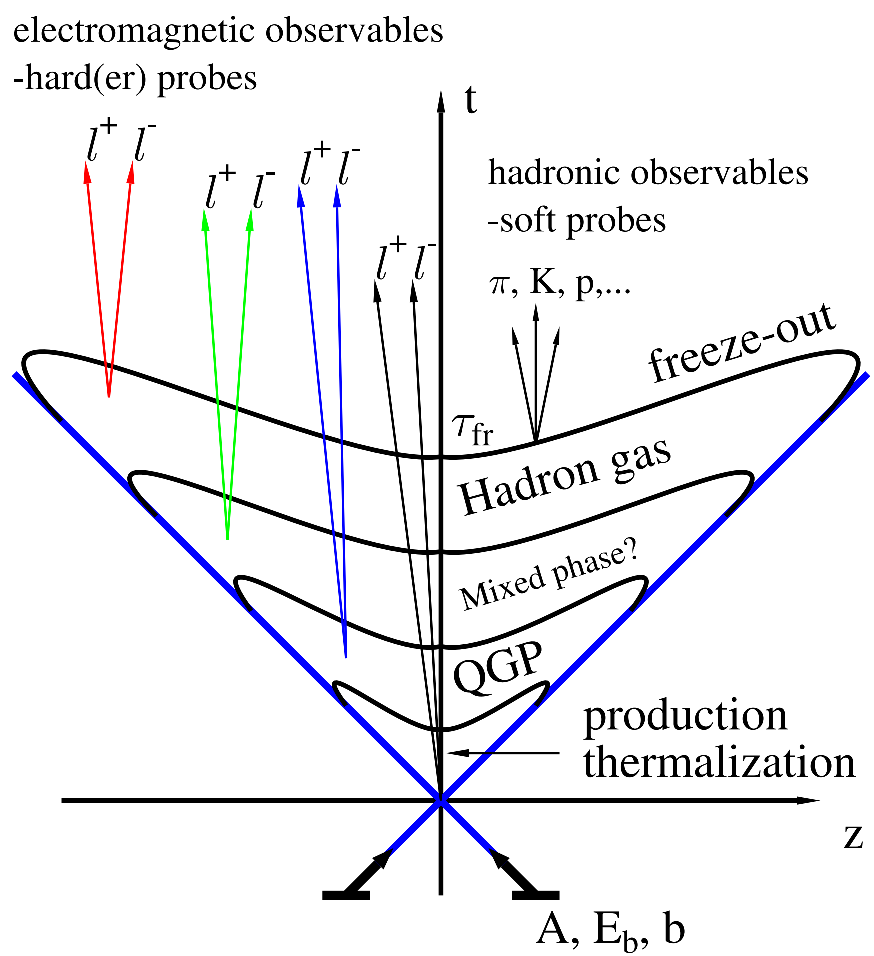


In-medium properties of hadrons

- properties of light quark hadrons reflect chiral symmetry breaking: Goldstone pion, non-degenerate parity partners

- properties of heavy quark hadrons reflect structure of the heavy quark potential: quarkonium spectra

thermal modifications of chiral condensate and heavy quark potential will influence the hadron spectrum

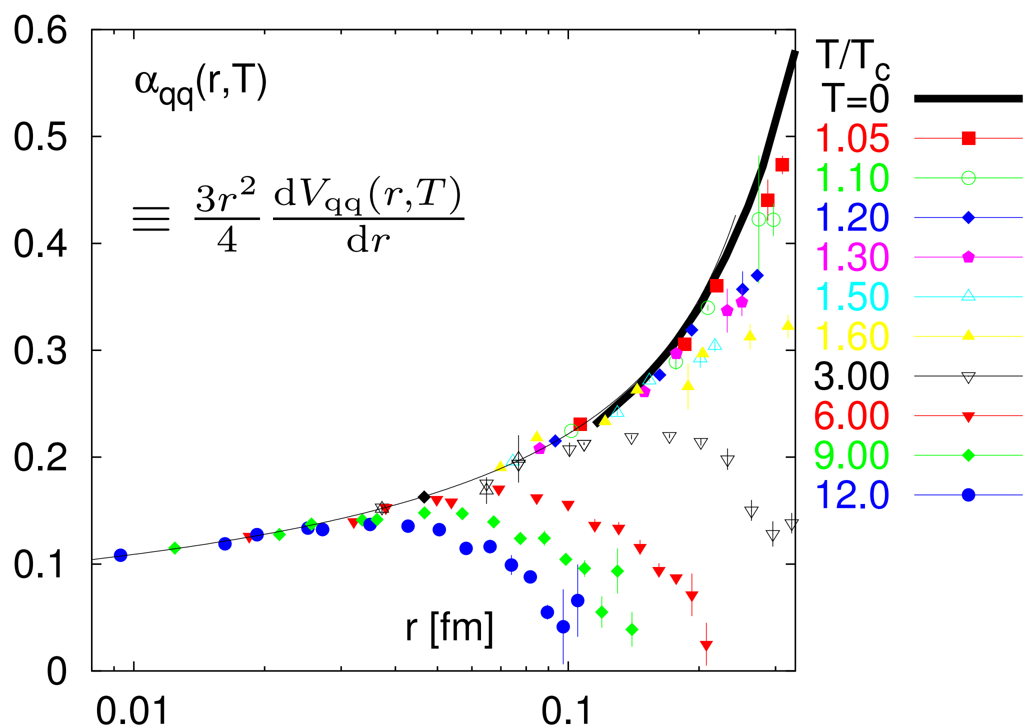


observable consequences in dilepton spectra

Running coupling at finite r and T... remnants of confinement in the QGP

up to $T \simeq 3T_c$: $\alpha_{qq}(r,T) \simeq \alpha_{qq}(r,0)$ for $r \ < \ 0.1$ fm

Do heavy quark bound states survive in the QGP?

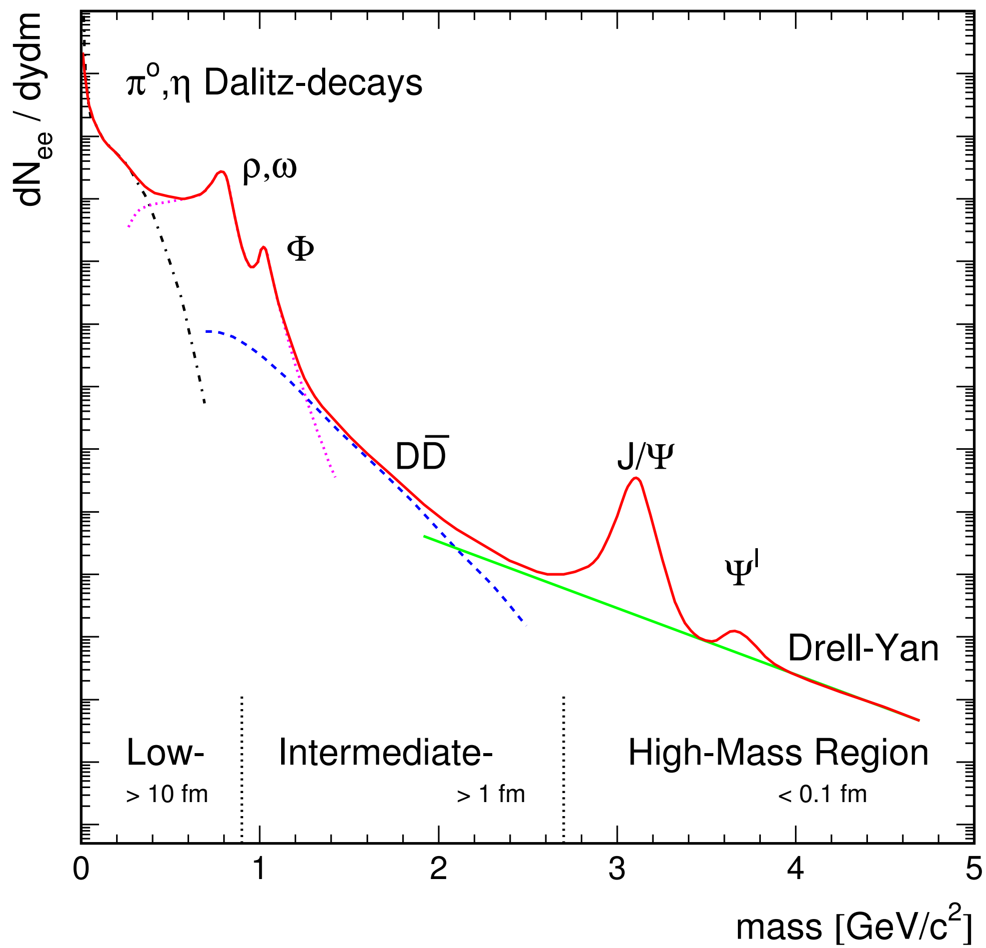


T = 0: S. Necco, R. Sommer, NP B622 (2002) 328.

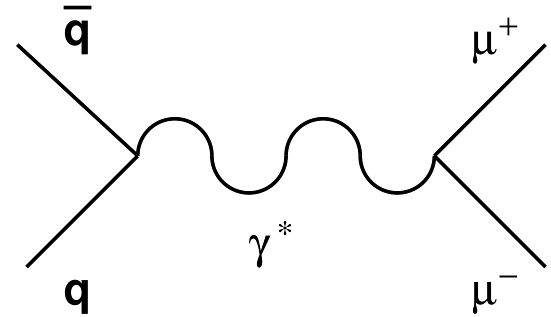
T > 0: O. Kaczmarek, FK, P. Petreczky and F. Zantow, hep-lat/0406036

Thermal vector meson properties from dilepton rates in heavy ion collisions

dilepton rate vs. invariant mass of l^+l^- pair



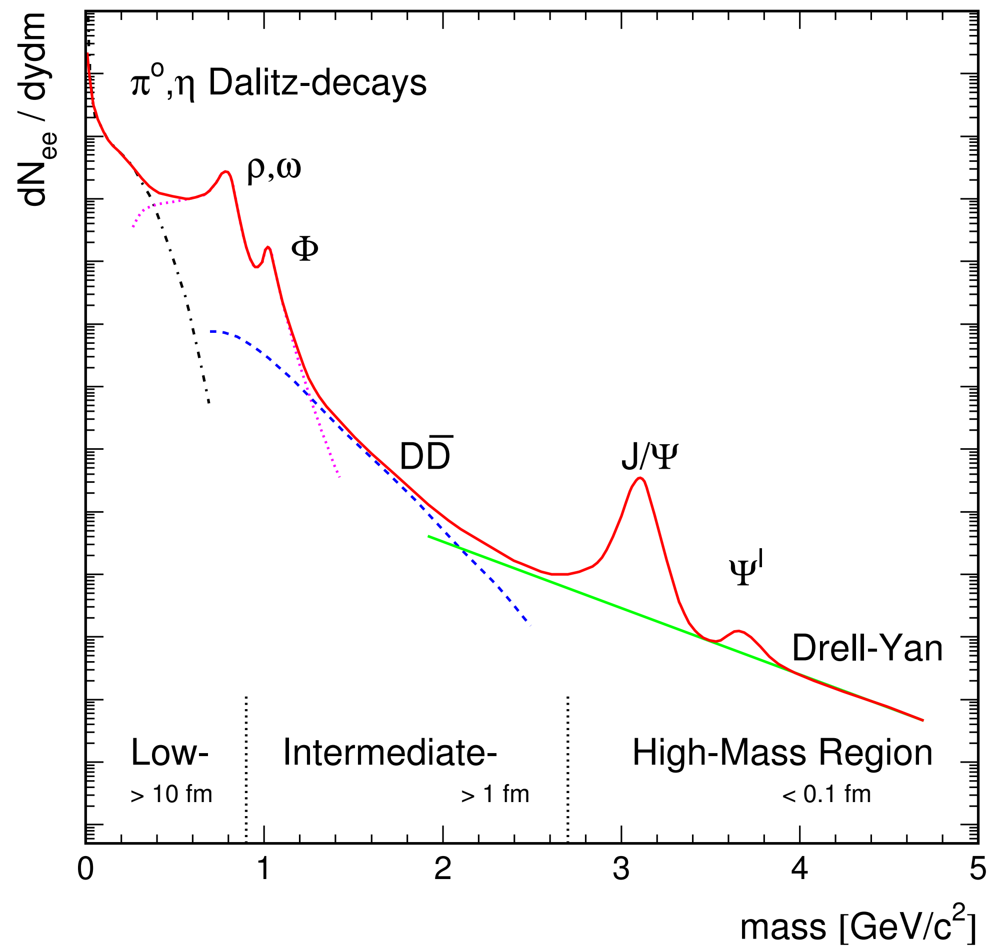
differential cross-section for $\mu^+\mu^-$ pair production



dilepton pair (e^+e^-, $\mu^+\mu^-$) production through annihilation of "thermal" $\bar{q}q$-pairs in hot and dense matter

Thermal vector meson properties from dilepton rates in heavy ion collisions

dilepton rate vs. invariant mass of l^+l^- pair



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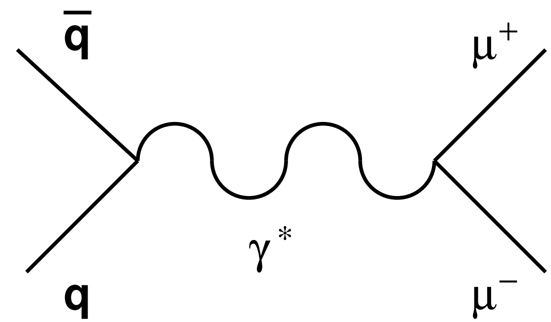
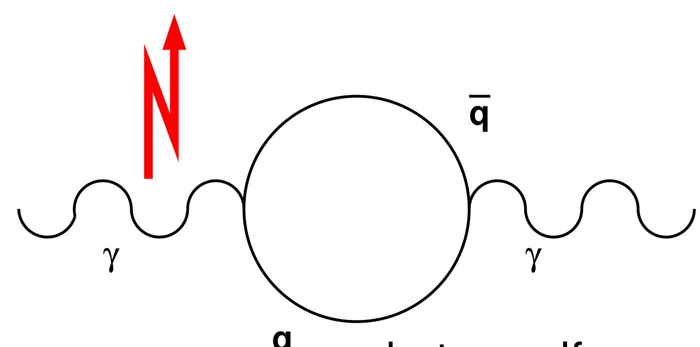


dilepton pair (e^+e^-, $\mu^+\mu^-$) production through annihilation of "thermal" $\bar{q}q$-pairs in hot and dense matter

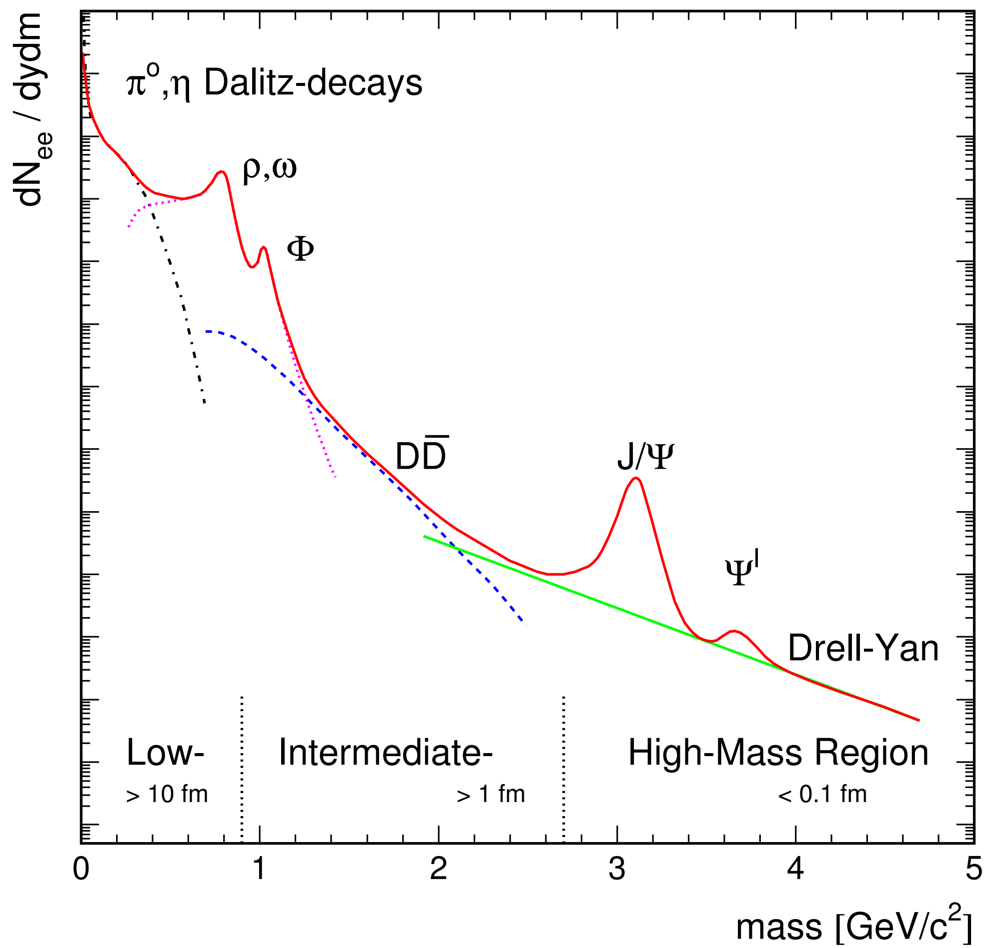
rate $\sim$ $|q\bar{q} \rightarrow \gamma^*|^2 \cdot |l^+l^- \rightarrow \gamma^*|^2$

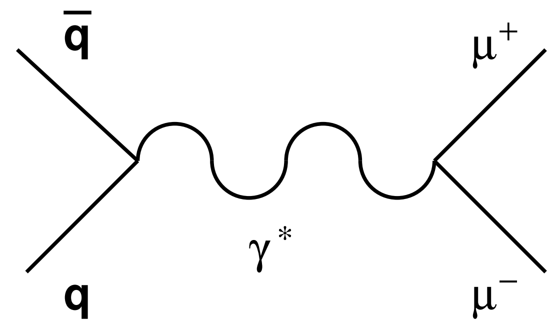


photon self-energy

Thermal vector meson properties from dilepton rates in heavy ion collisions

dilepton rate vs. invariant mass of l^+l^- pair





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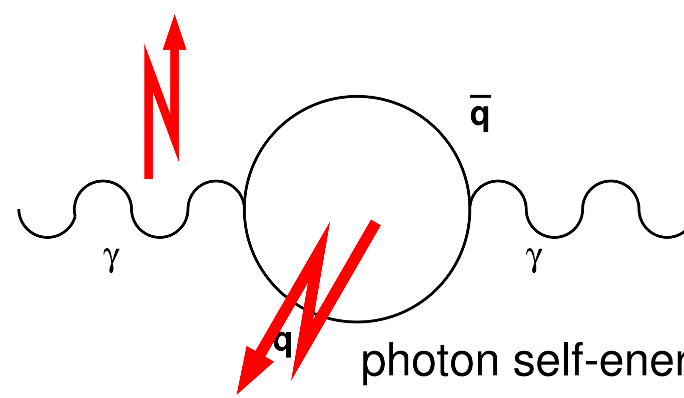
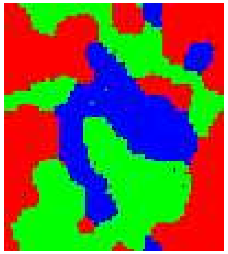


photon self-energy

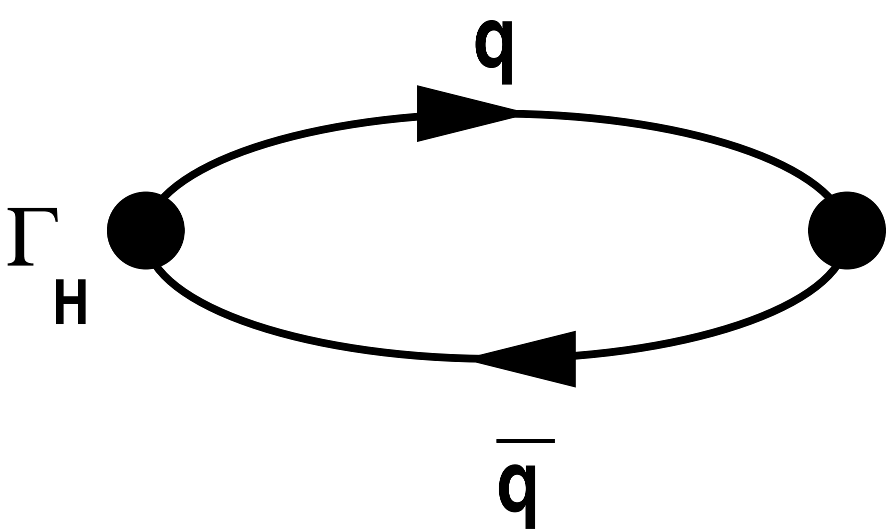
differential cross-section for $\mu^+\mu^-$ pair production $\Rightarrow$ thermal meson correlation function



Thermal meson correlation functions and spectral functions

Thermal correlation functions: 2-point functions which describe propagation of a $\bar{q}q$-pair

spectral representation of correlator $\Rightarrow$ dilepton and photon rates



spectral representation of
thermal photon rate: $\omega = |\vec{p}|$

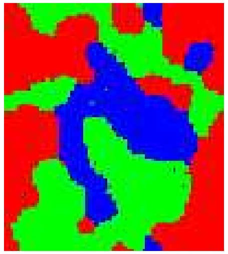
$$\omega \frac{\mathrm{d}^3 R^\gamma}{\mathrm{d}^3 p} = \frac{5\alpha}{6\pi^2} \frac{\sigma_V(\omega, \vec{p}, T)}{\omega^2 (\mathrm{e}^{\omega/T} - 1)}$$

spectral representation of
thermal dilepton rate

$$\frac{\mathrm{d}^4 W}{\mathrm{d}\omega \mathrm{d}^3 p} = \frac{5\alpha^2}{27\pi^2} \frac{\sigma_V(\omega, \vec{p}, T)}{\omega^2 (\mathrm{e}^{\omega/T} - 1)}$$

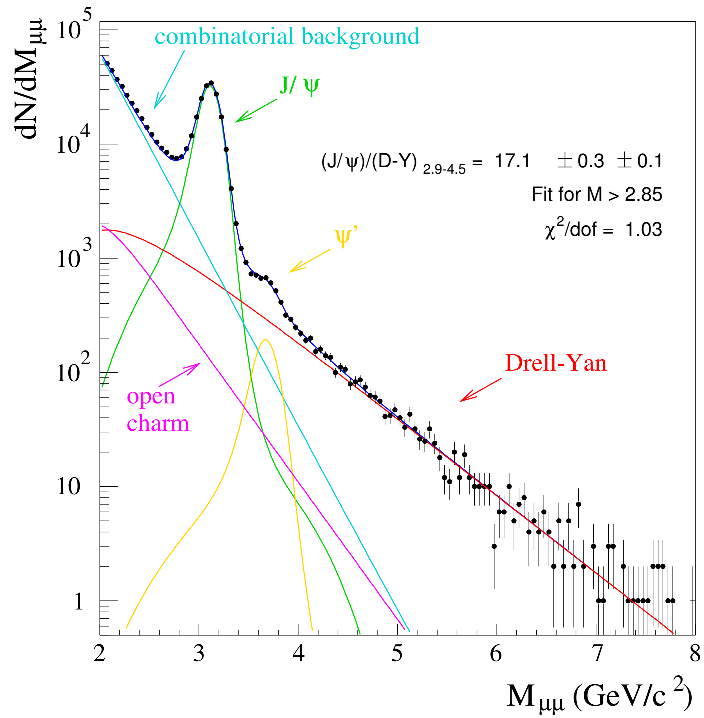
spectral representation of
Euclidean correlation functions

$$G_H^\beta(\tau, \vec{r}) = \int_0^\infty \mathrm{d}\omega \int \frac{\mathrm{d}^3\vec{p}}{(2\pi)^3} \, \sigma_H(\omega, \vec{p}, T) \, \mathrm{e}^{i\vec{p}\vec{r}} \, \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}$$



Charmonium suppression in heavy ion collisions (SPS, CERN)

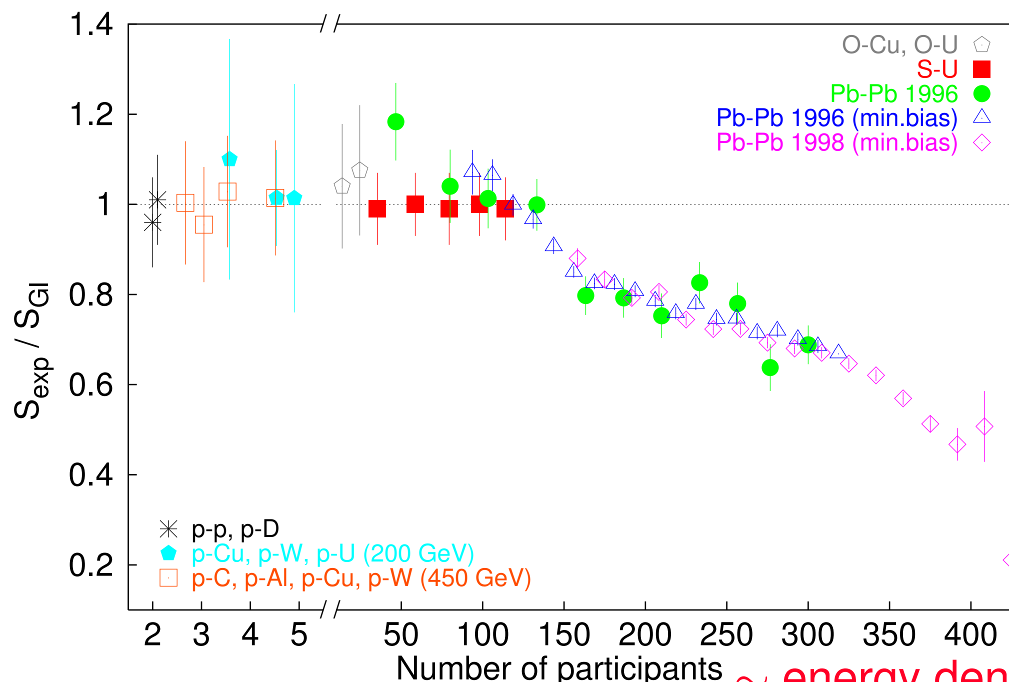
Charmonium Production: dilepton rate



invariant mass of the pair

differential cross-section for $\mu^+\mu^-$ pair production

Suppression Pattern



$\sim$ energy density

measured A-A rate normalized to rate expected from known p-A collisions

M.C.Abreu (NA50), Phys.Lett. B477 (2000) 28

Charmonium suppression in heavy ion collisions (SPS, CERN)

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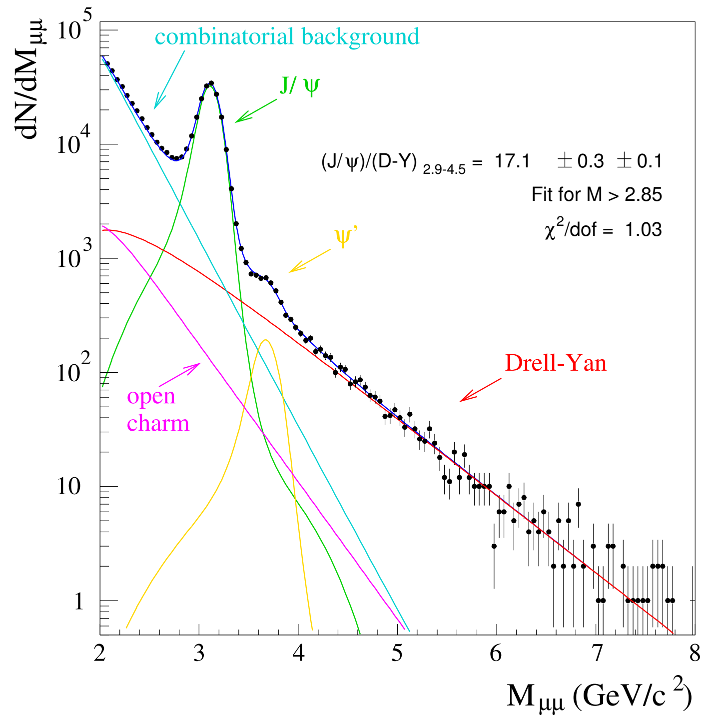

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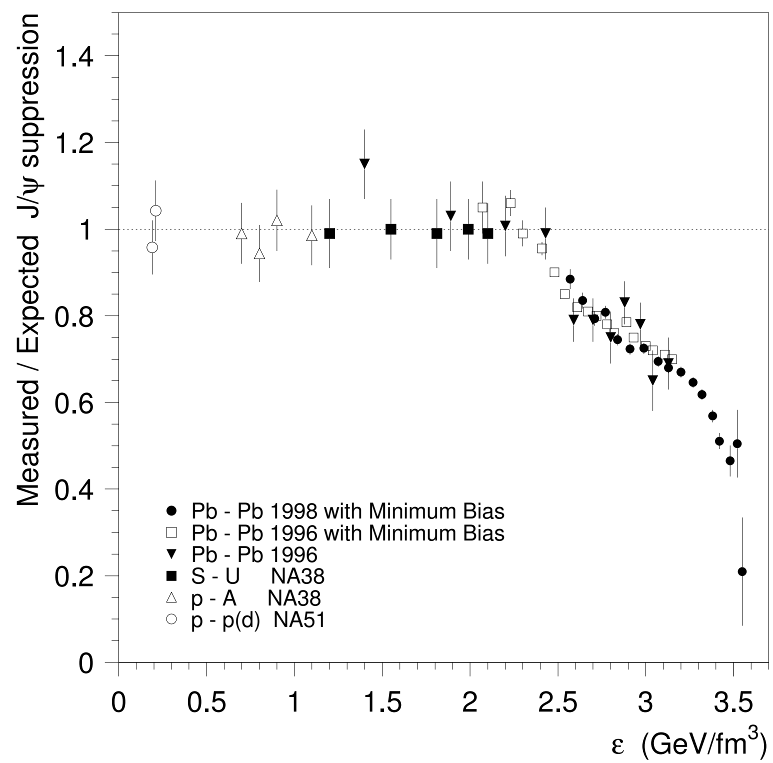
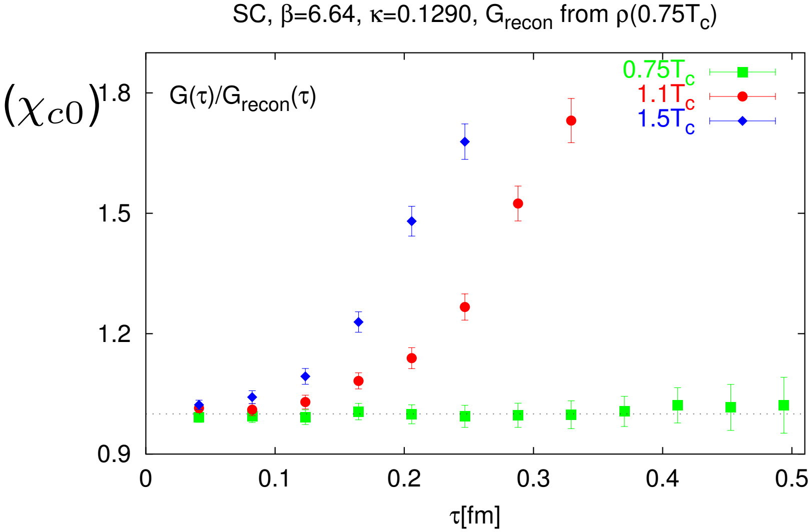


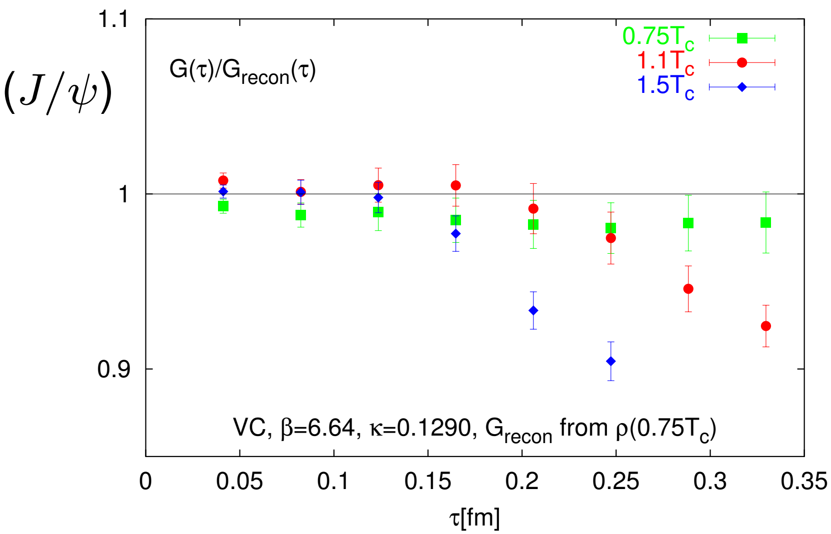
use Bjorken formula to convert participants to energy density

$$\epsilon \equiv \frac{1}{\tau_0 V_T}\left(\frac{\mathrm{d}E_T}{\mathrm{d}y}\right)_{y=0}$$

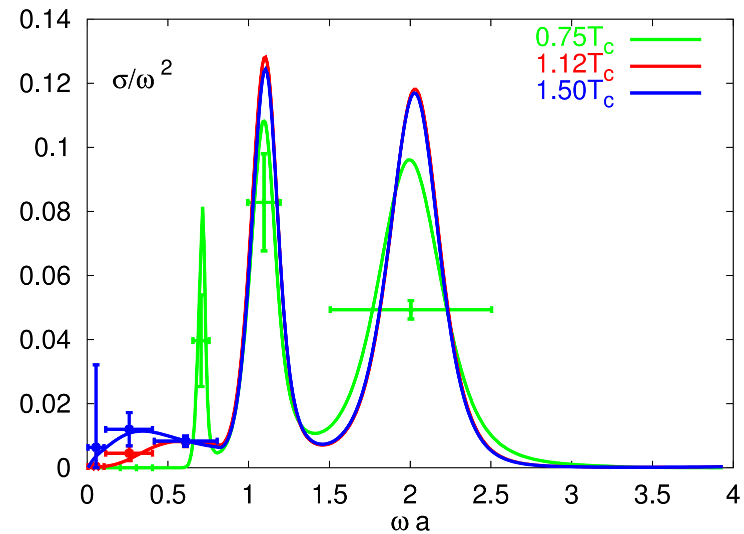
Heavy quark spectral functions and correlation functions

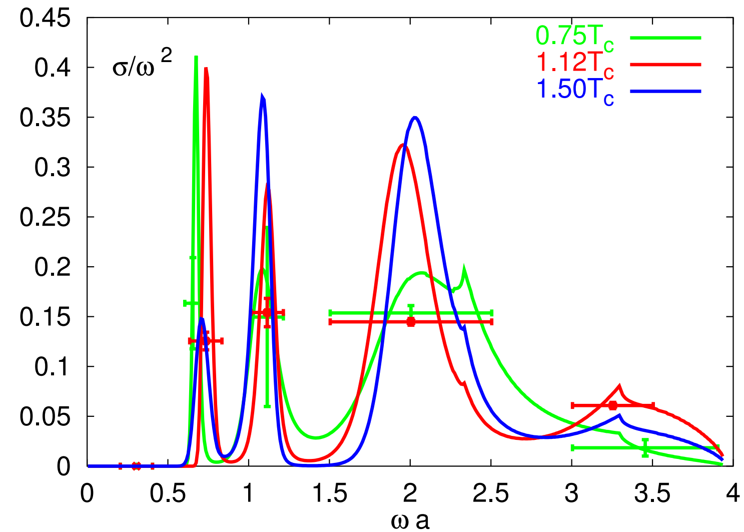
reconstructed correlation functions above T_c from data below T_c

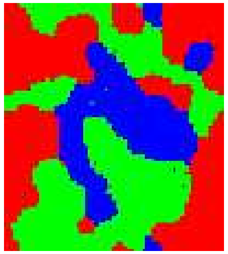




reconstructed spectral functions using the Maximum Entropy Method







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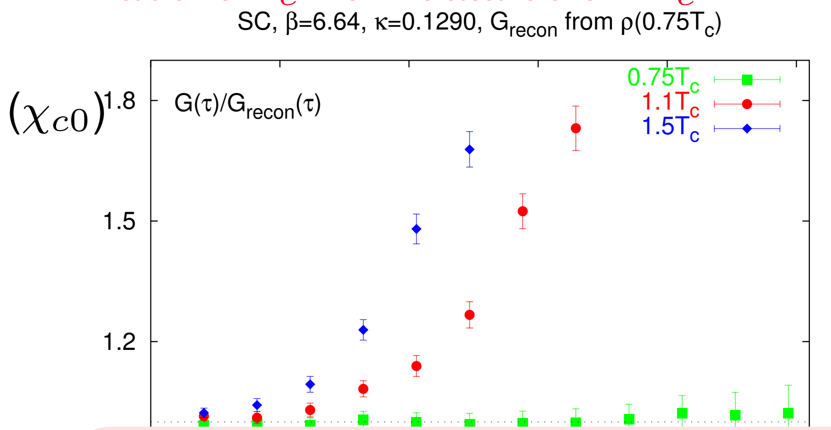
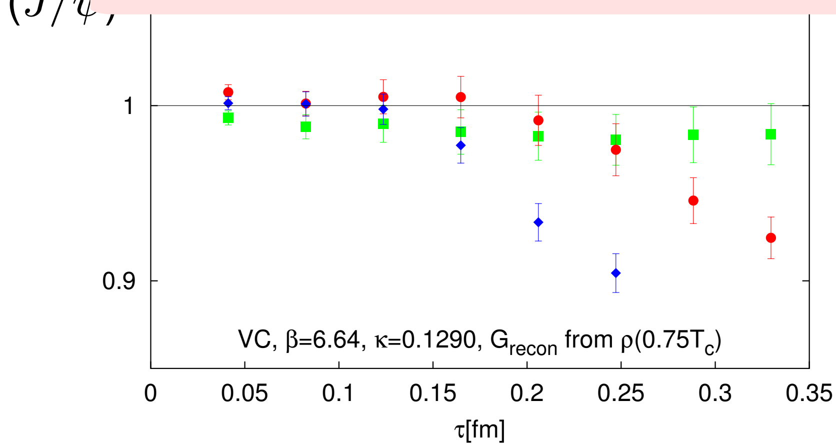


radial excitations (χ_c) disappear at T_c;

charmonium S-states (J/ψ and η_c) survive at least up to $1.5\ T_c$



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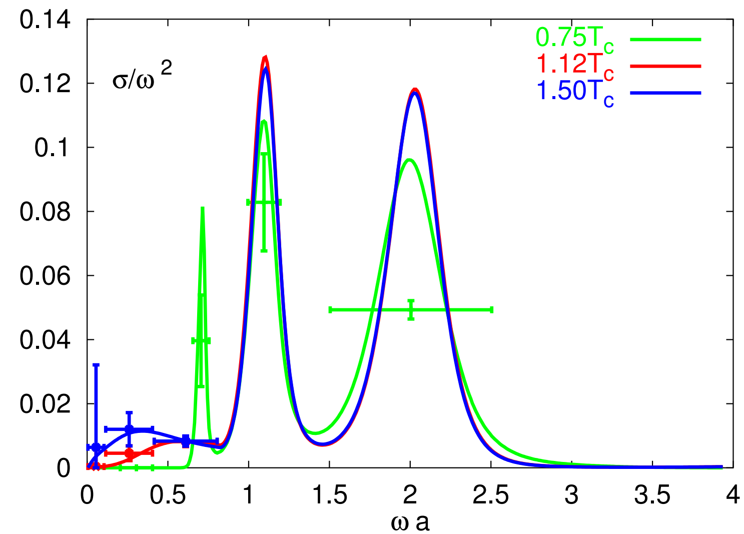
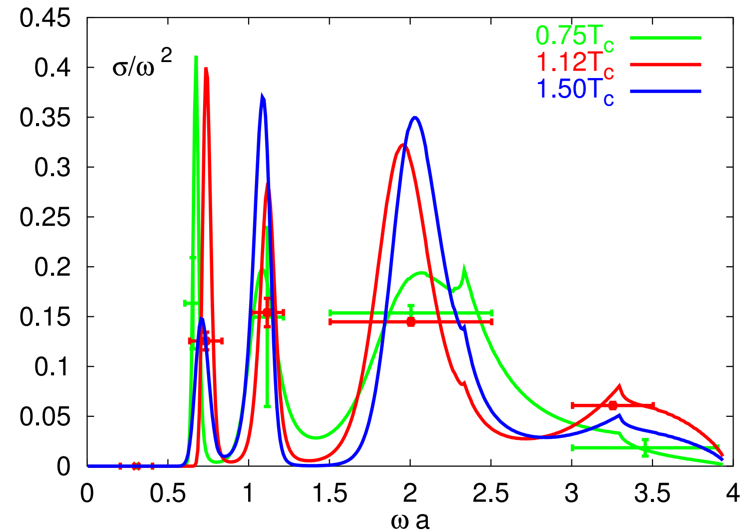
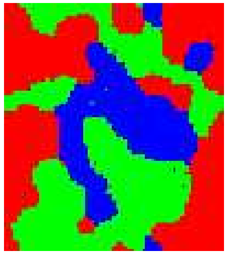


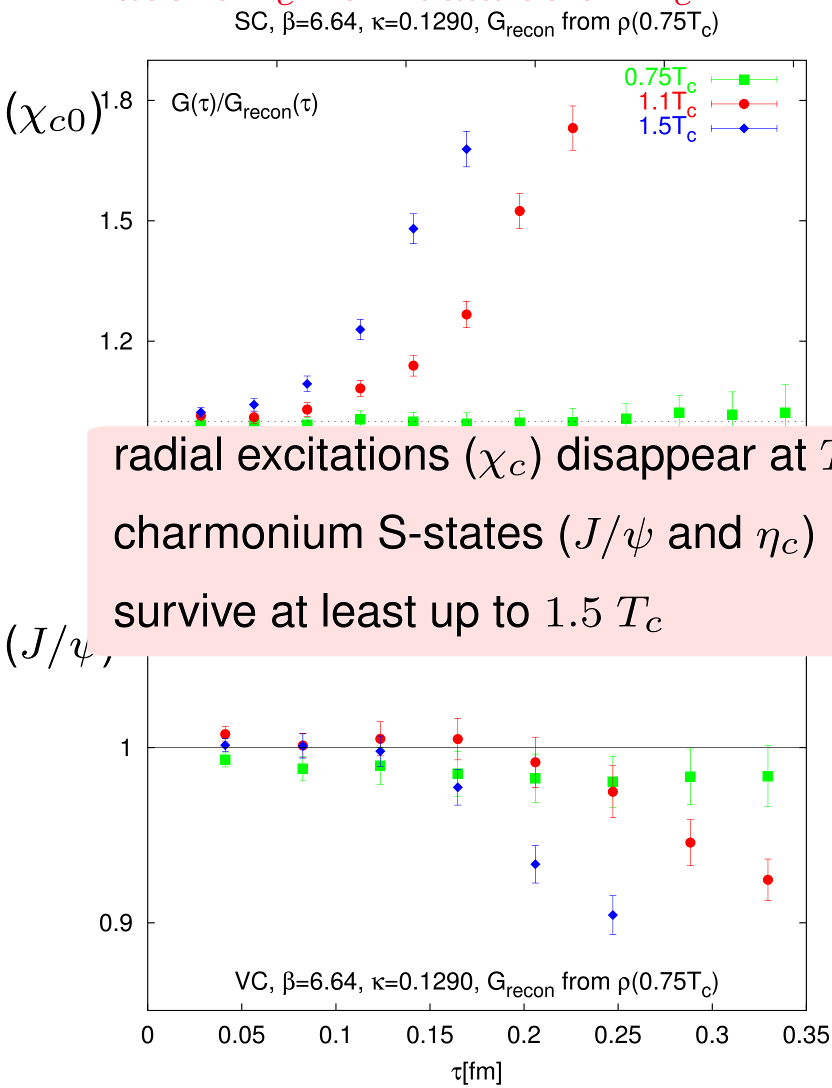




Heavy quark spectral functions and correlation functions

reconstructed correlation functions

above T_c from data below T_c



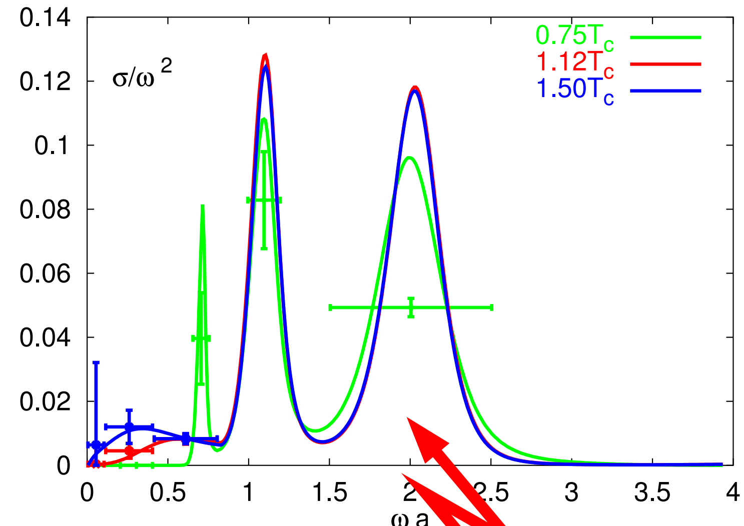
radial excitations (χ_c) disappear at T_c;

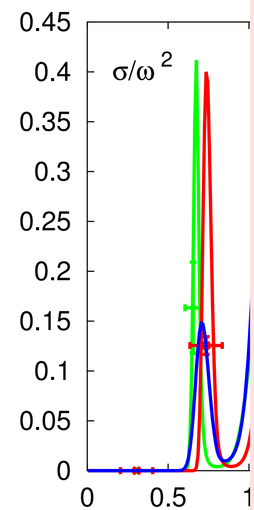
charmonium S-states (J/ψ and η_c)

survive at least up to $1.5\ T_c$

reconstructed spectral functions

using the Maximum Entropy Method





need to get better control over ultra-violet cut-off effects (Wilson-doublers)

use better fermion actions

- overlap fermions
- domain wall fermions
- (truncated) perfect actions...

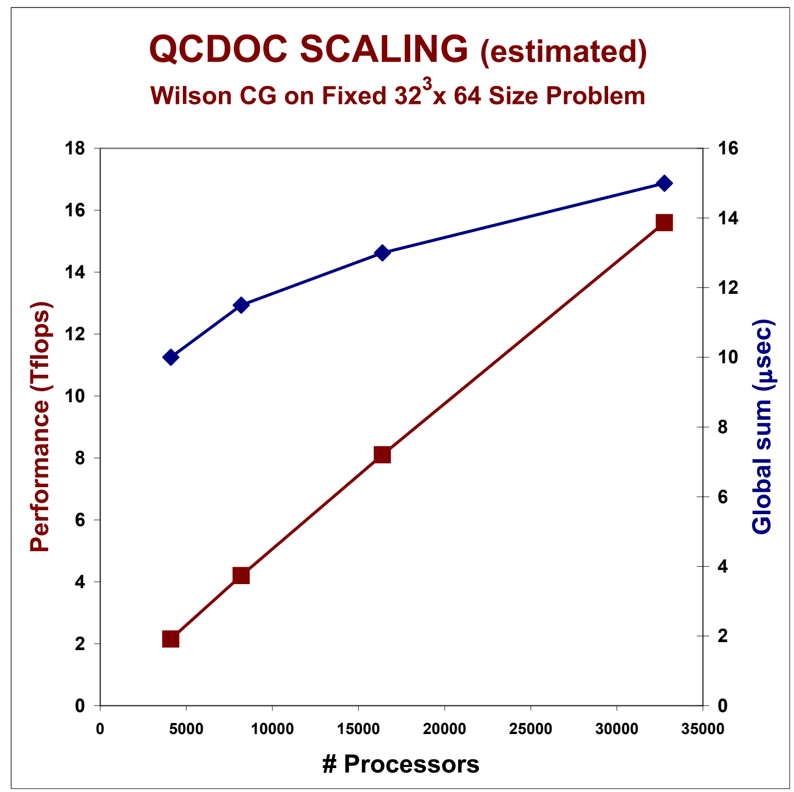
Outlook: Next generation lattice calculations

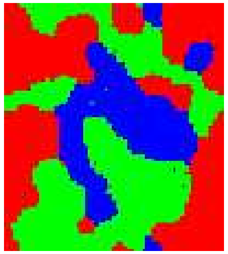
- Thermodynamics of pure gauge theory has been "solved" on (1-10)GFlops computers (1996)
- Thermodynamics of QCD with "still too heavy" quarks has been studied on (10-100) GFlops computers
- Analysis of "continuum and thermodynamic limit" of QCD thermodynamics with light quarks, requires computers with $\sim$10 TFlops peak speed.(LatFor, 2003)

QCDOC and apeNEXT:

scaling to 10's of Teraflops

with \$1/MFlops Cost/performance

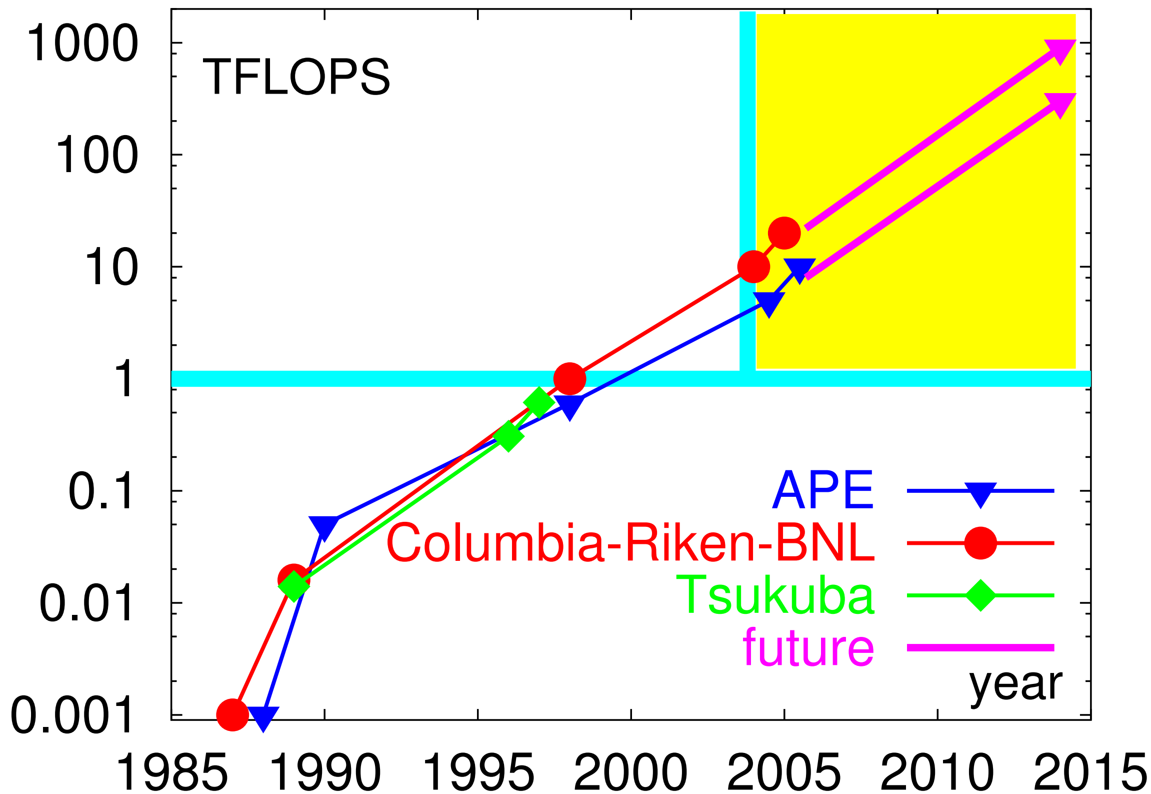


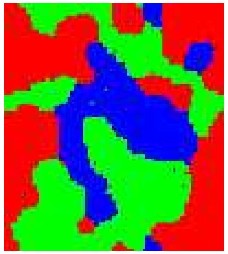


Progress in lattice calculations... depends on...

- development of (special purpose) computer hardware
-
-

development of special purpose computer hardware
⇓
towards PETAFLOPS computing

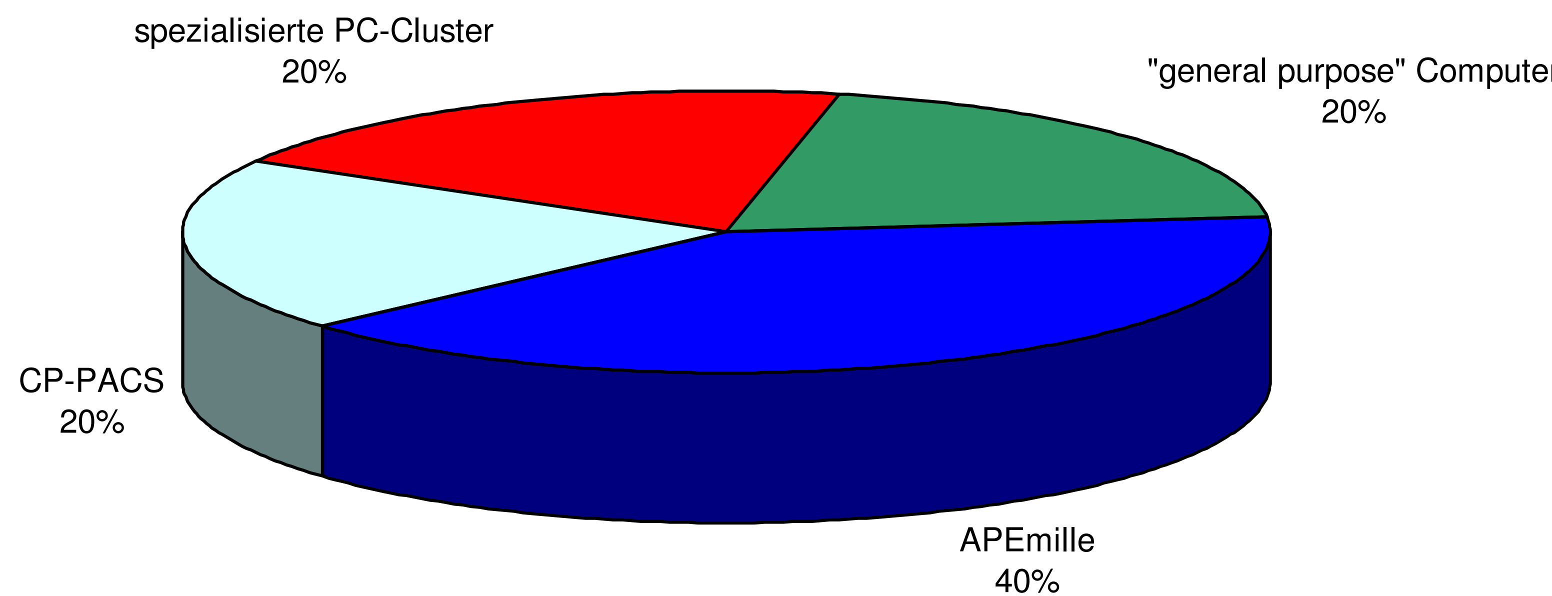




Progress in lattice calculations... depends on...

special purpose computer hardware

contribution of research done on special purpose computer
to 10 top cited papers in LGT (1999-2004)



Outlook: Next generation computers for lattice gauge theory

today:

APEmille

so far the only dedicated
large-scale computer installation used
predominantly for QCD thermodynamics
exists in Bielefeld: 120 GFlops

Outlook: Next generation computers for lattice gauge theory

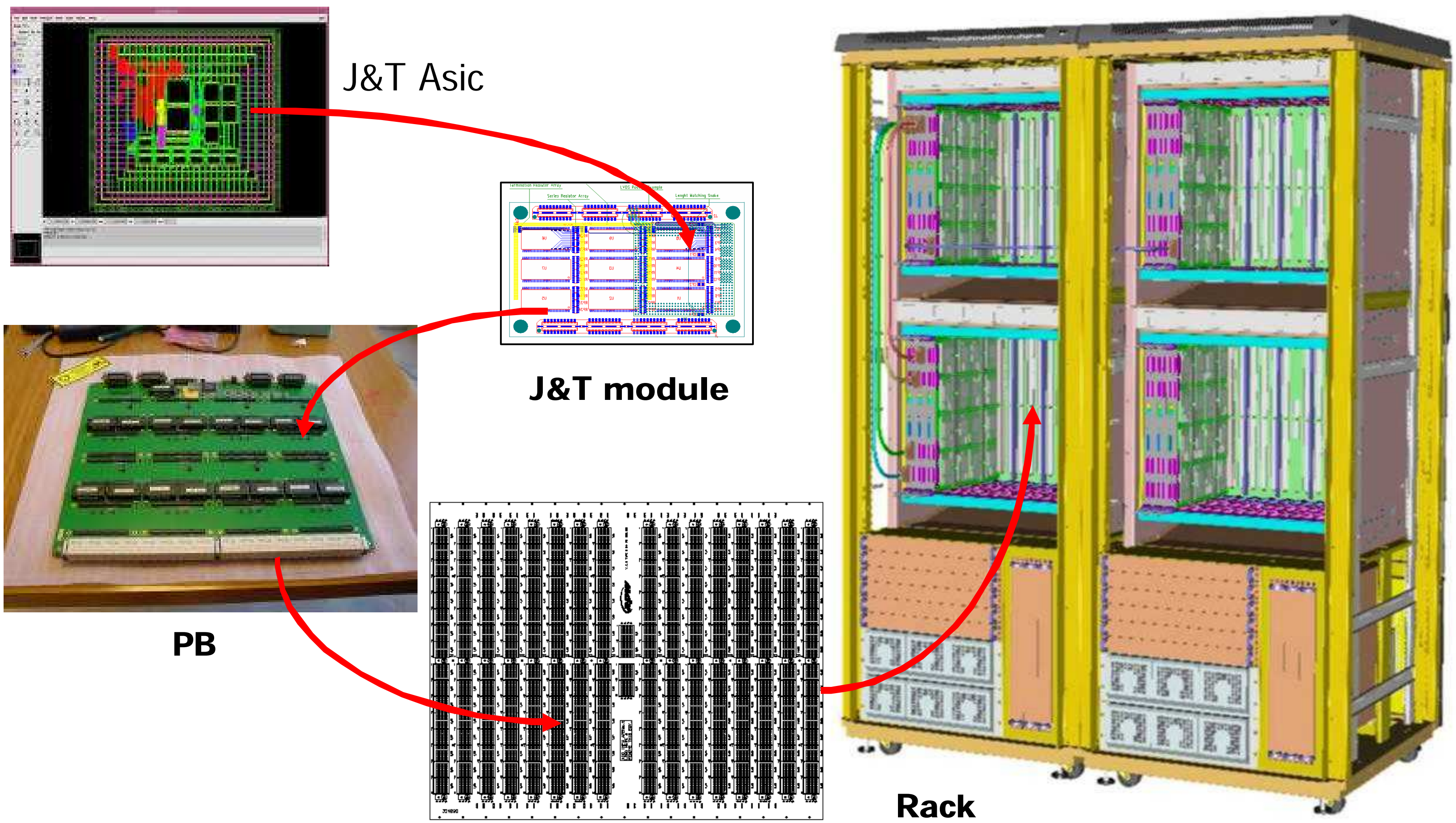
QCDOC and apeNEXT

2004: QCD thermodynamics on the next generation of special purpose dedicated QCD computers

installations with (10-20) TFlops peak speed are planned in the USA and Europe

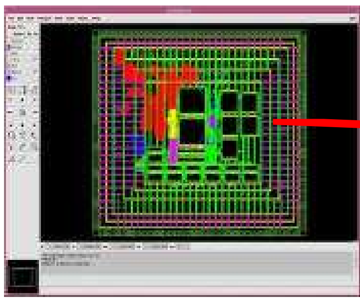
apeNEXT:
Next generation of APE computers

Assembling apeNEXT...

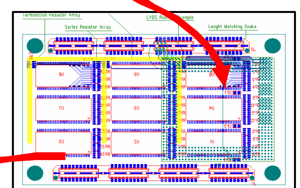


apeNEXT:
Next generation of APE computers

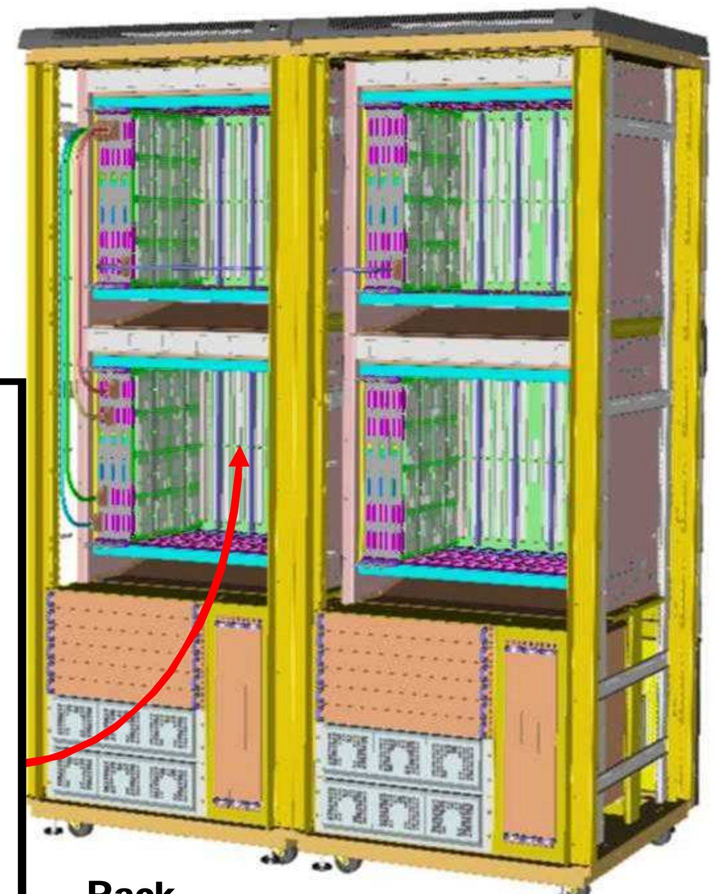
Assembling apeNEXT...



J&T Asic



12/2003

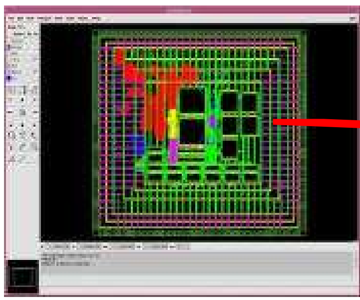


Rack

BackPlane

apeNEXT:
Next generation of APE computers

Assembling apeNEXT...



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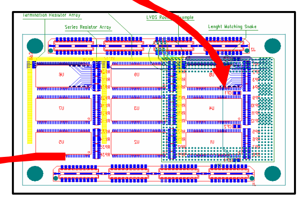
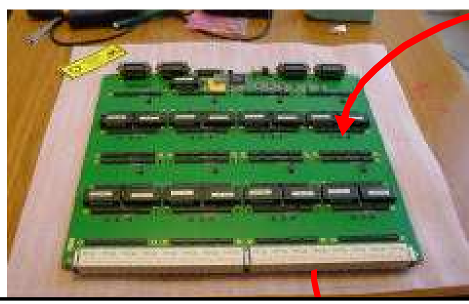
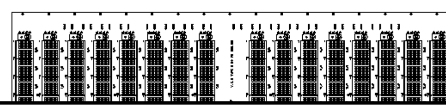
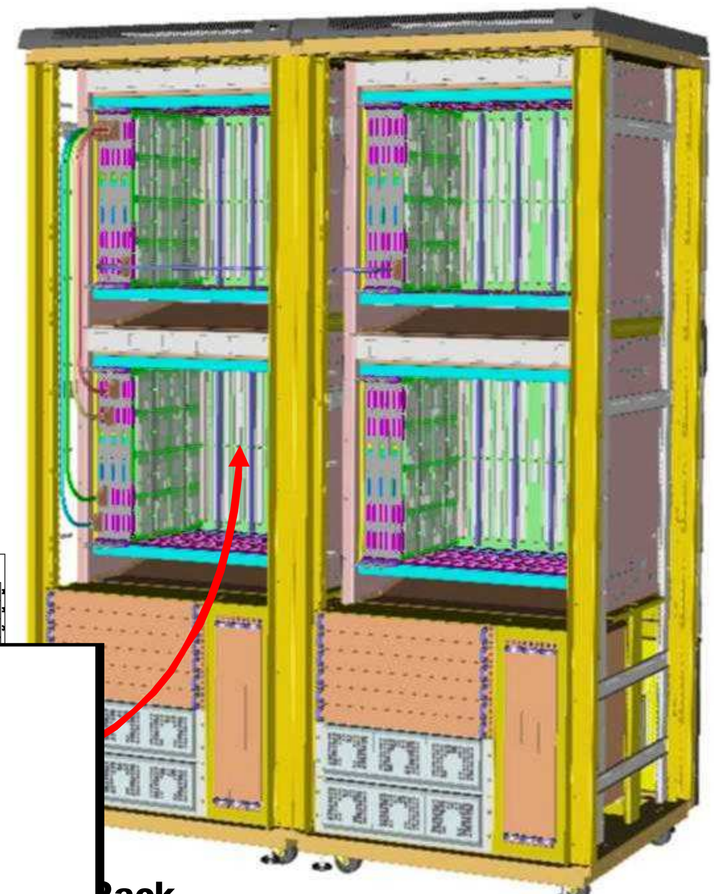


J&T module







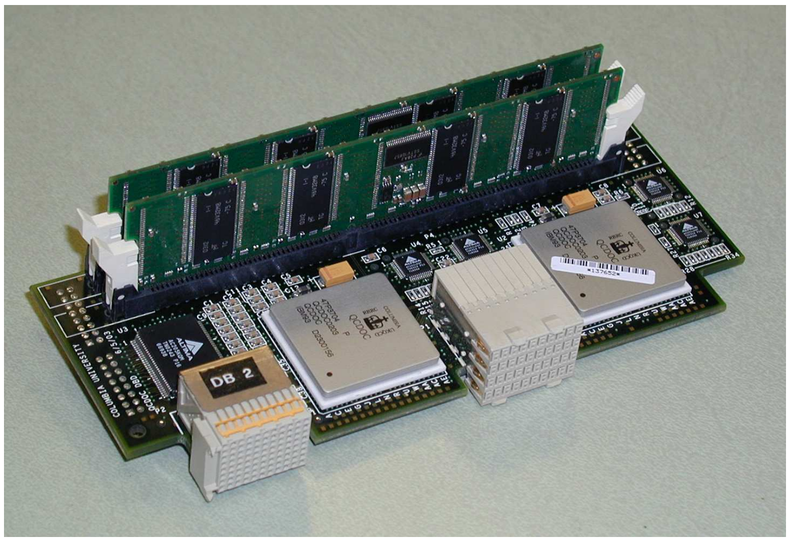
- first chips Dec. 2003
- two 0.8 TFlops prototypes $\sim$ summer 2004
- first 3 TFlops installations in 2005

Rack

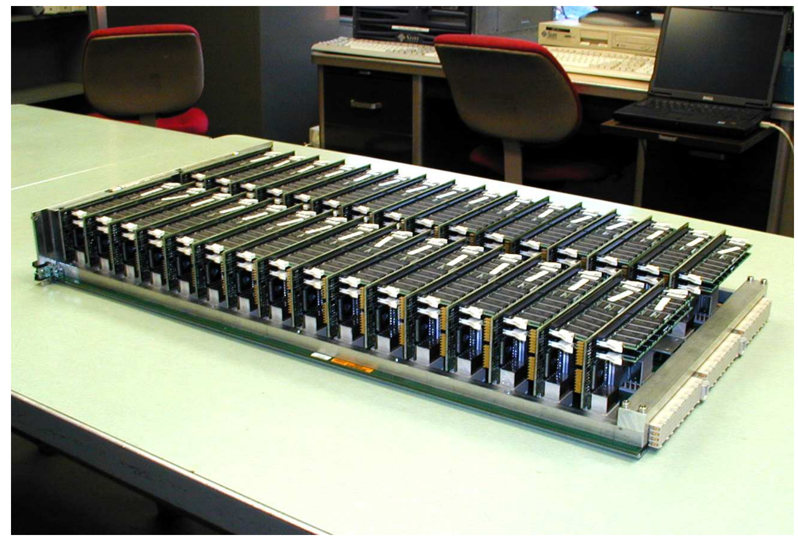
BackPlane

QCDOC: Next generation of Columbia-RIKEN computer

Columbia – RIKEN – UKQCD Collaboration



2 – node daughter card



64 – node mother board

- prototypes exist since 07/2003

QCDOC: Next generation of Columbia-RIKEN computer

Columbia – RIKEN – UKQCD Collaboration

$512 - \mathrm{node\,machine}: \ (360 - 450)\ \mathrm{GFlops}$

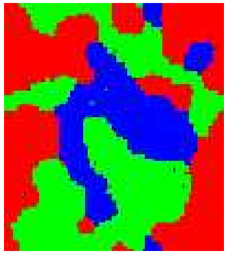
- currently being debugged prototype (05/2004):
  0.25 Tbyte memory; 6 Gbit/sec Ethernet I/O bandwidth

$QCDOC\ computing\ center\ at\ BNL:$

- 10 TFlops machine for RBRC: $\sim$ autumn 2004
- 10 TFlops machine for american LGT community: $\sim$ early 2005
- ... larger installations possible and needed!

Conclusions

- LGT calculations contributed a lot to the understanding/interpretation of HIC



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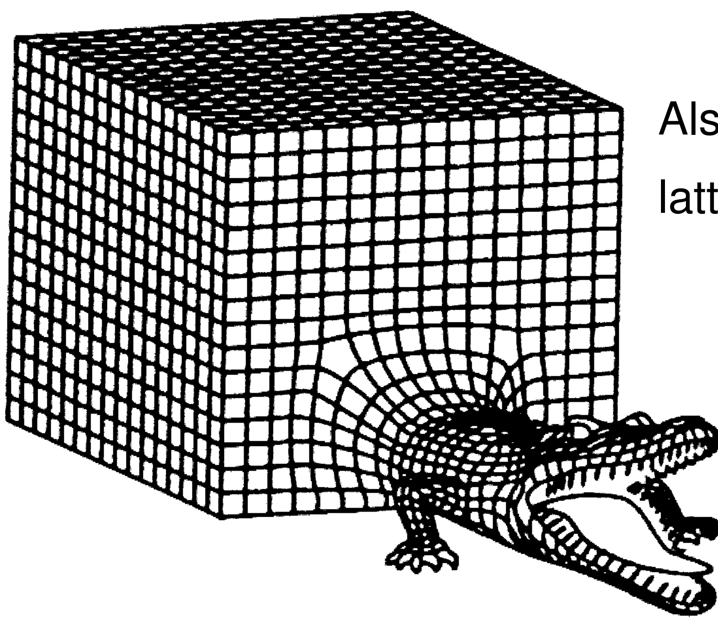
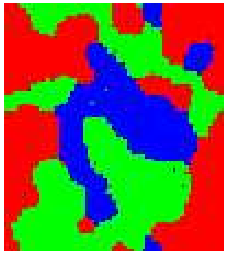


Also these calculations have to face the well-known lattice beasts: ultra-violet and infra-red problems



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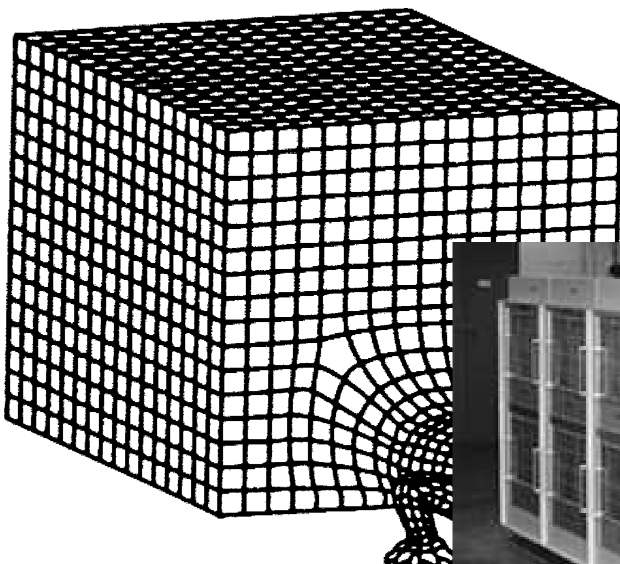

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QCDOC and apeNEXT will take care of a large fraction of these problems