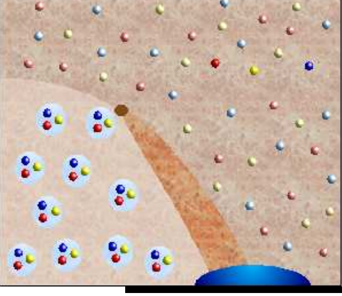
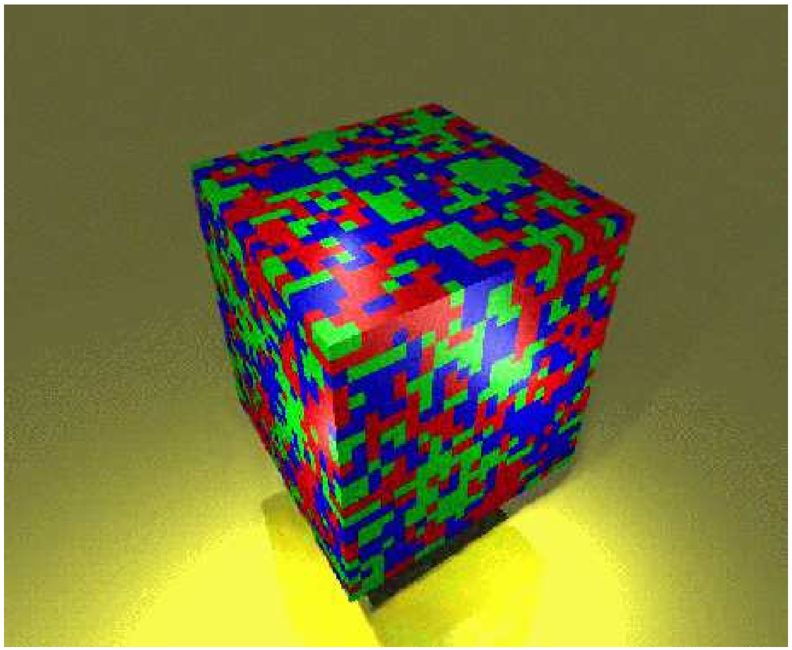
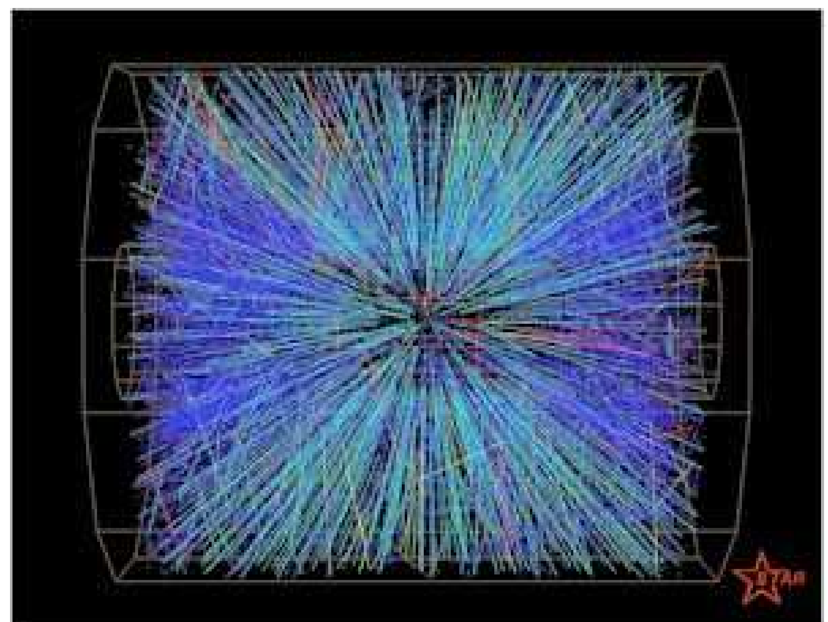
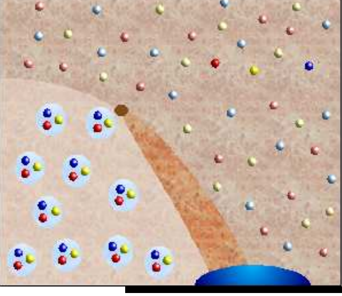


The future of LGT for HIC







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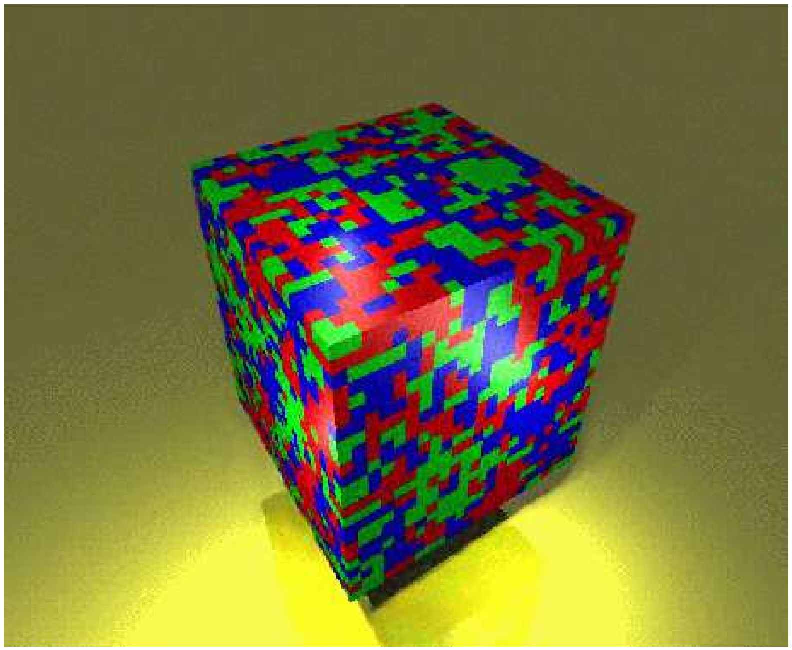
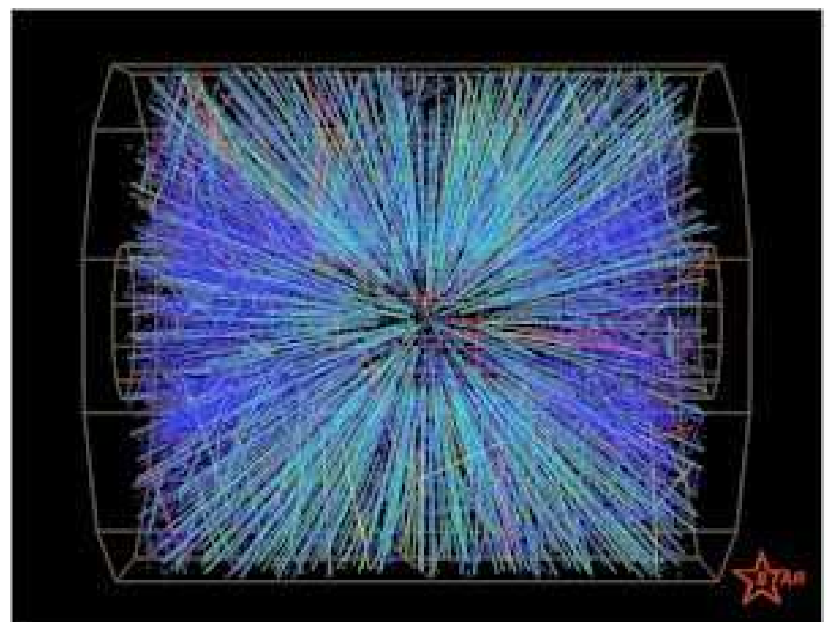
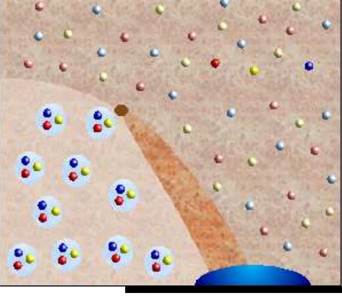


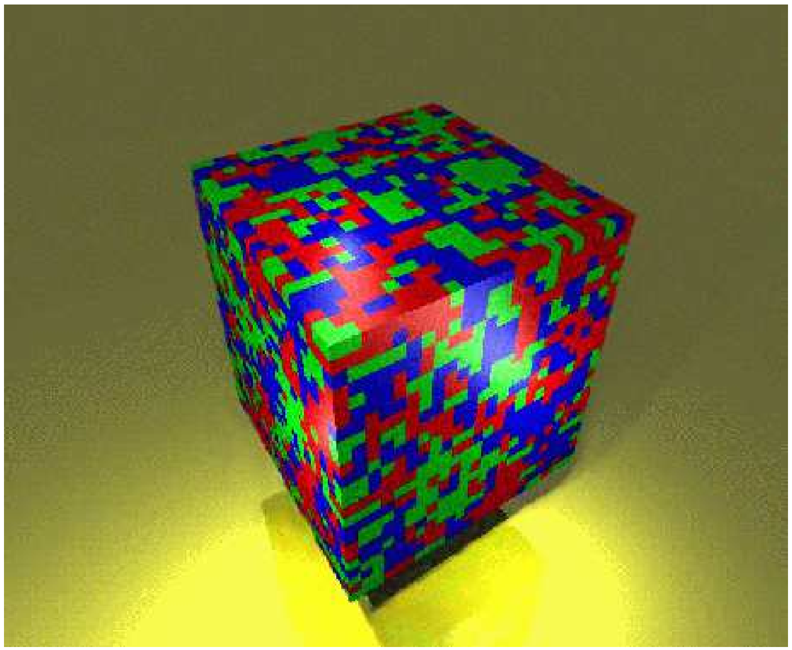


LGT:

- equilibrium thermodynamics of QCD;
- formulated in terms of basic degrees of freedom: quarks and gluons;
- observables expressed in terms of temperature and chemical potential



The future of LGT for HIC



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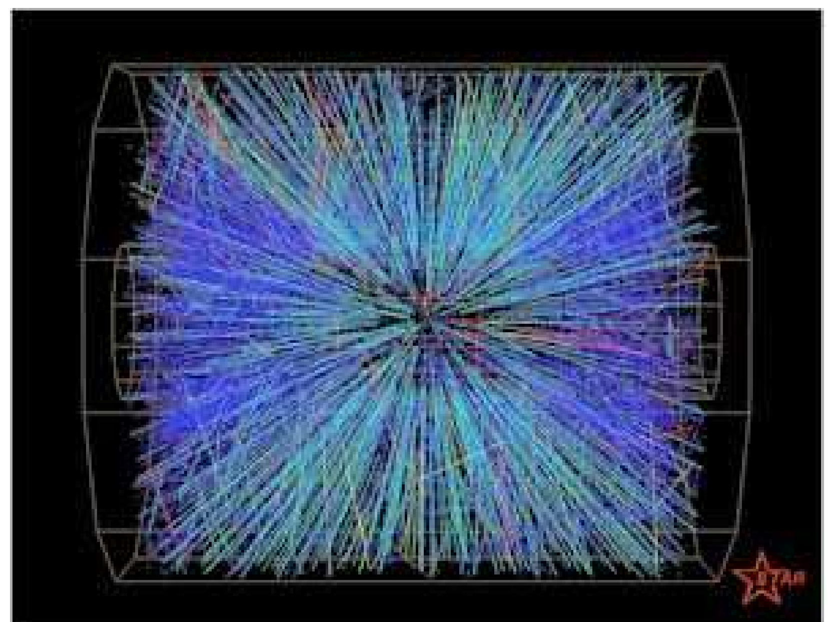
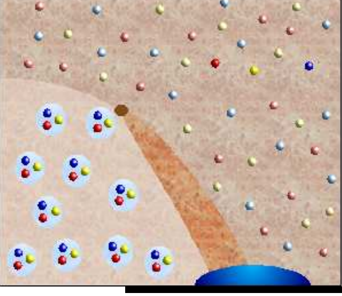
- evolution of a dense interacting medium described by QCD;
- observable properties in terms of hadrons, leptons and photons;
- observables parametrized in terms of energy and particle multiplicities





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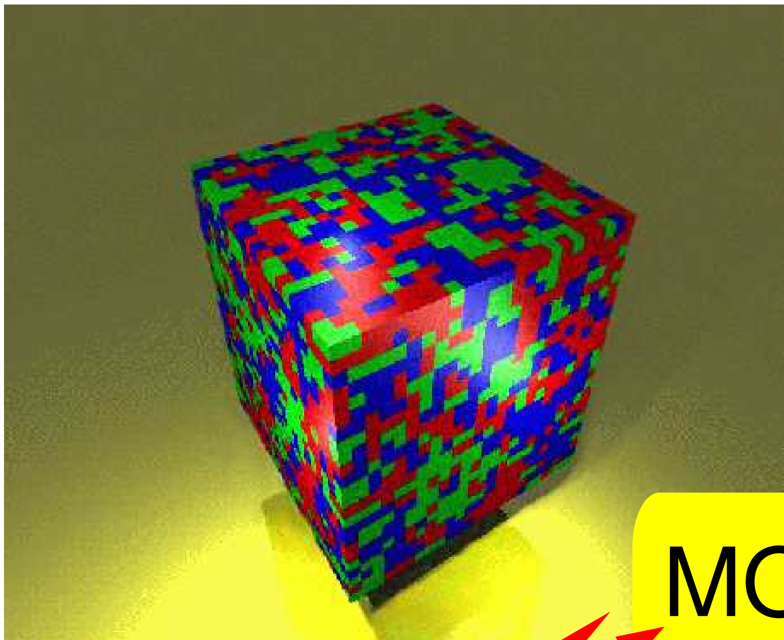

HIC:

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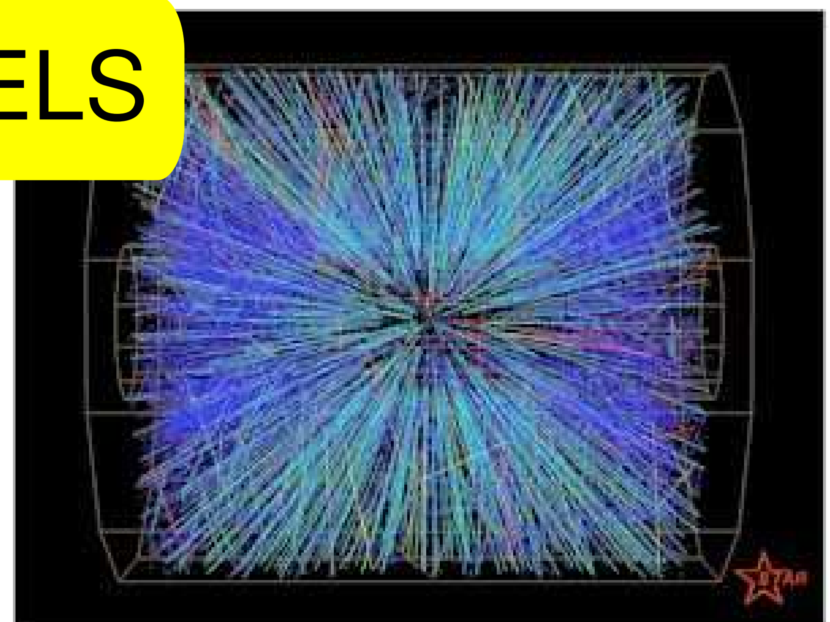
MODELS



LGT:

- equilibrium thermodynamics of QCD;
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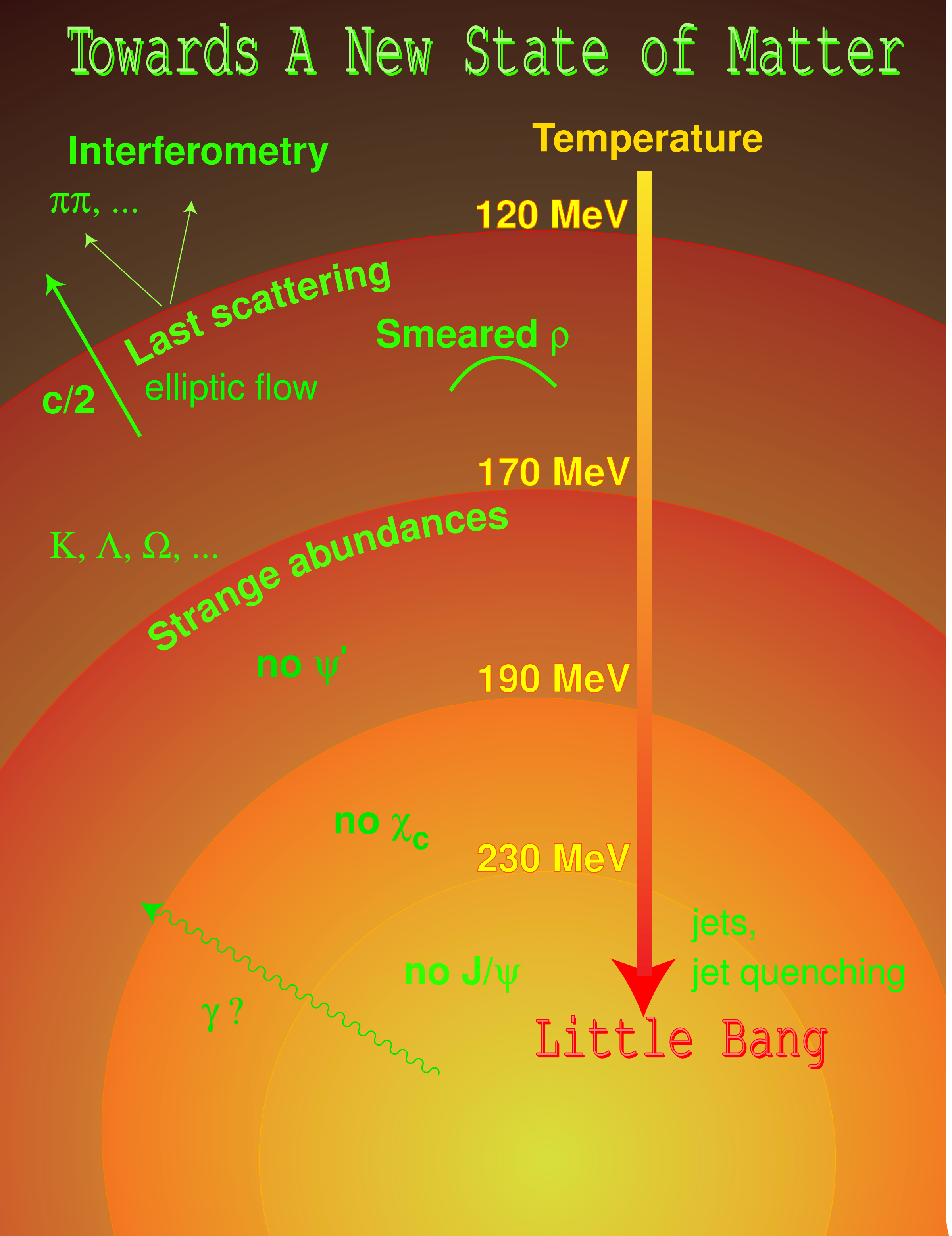
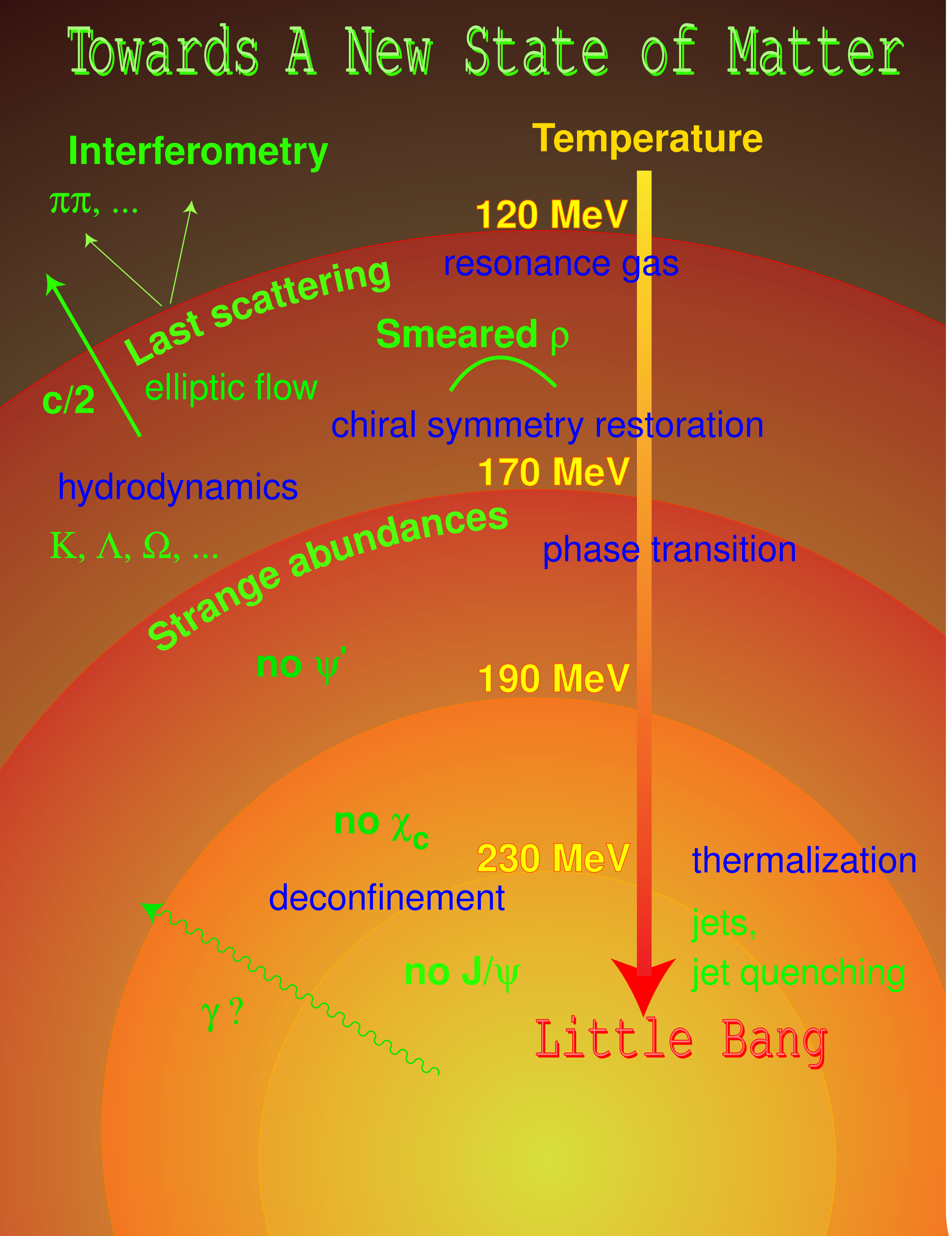


Where lattice calculations do/will contribute to the

development of theoretical concepts

and the

analysis of experimental observables



Where lattice calculations do/will contribute to the

development of theoretical concepts

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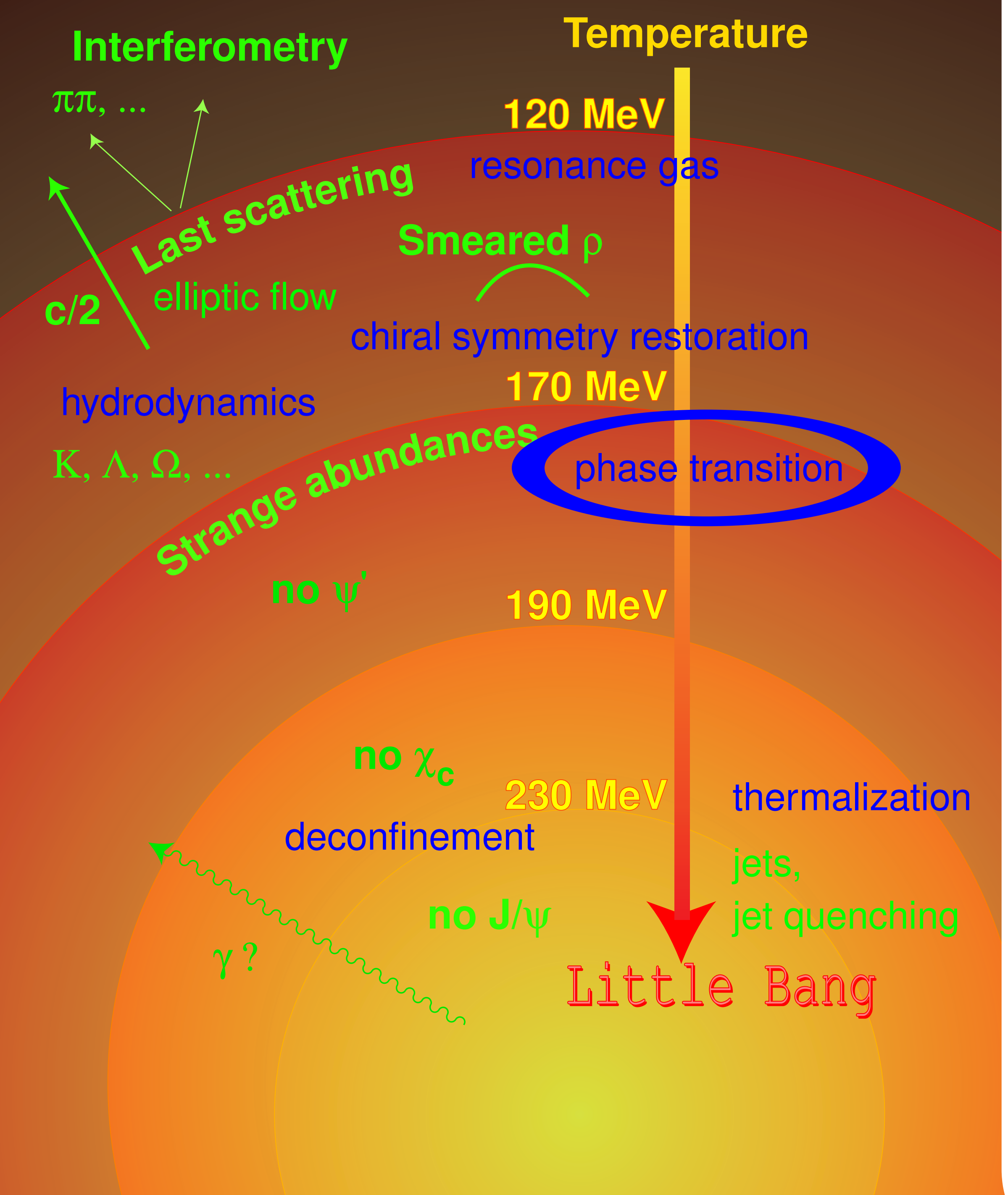
analysis of experimental observables

Towards A New State of Matter



Where lattice calculations do/will contribute to the

development of theoretical concepts

and the

analysis of experimental observables

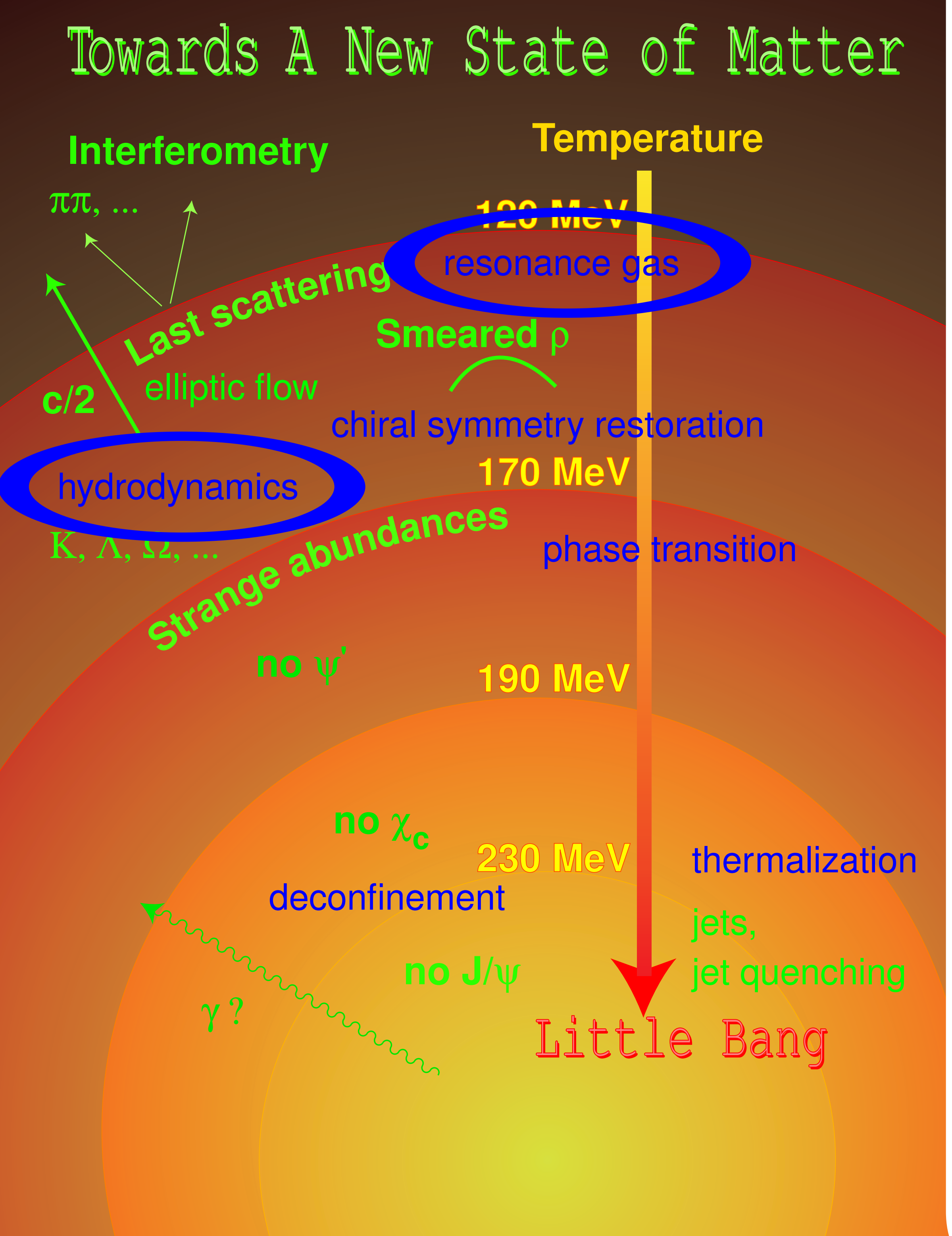
$T_c,\ \epsilon_c$

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

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

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

chiral critical point



Where lattice calculations do/will contribute to the

development of theoretical concepts

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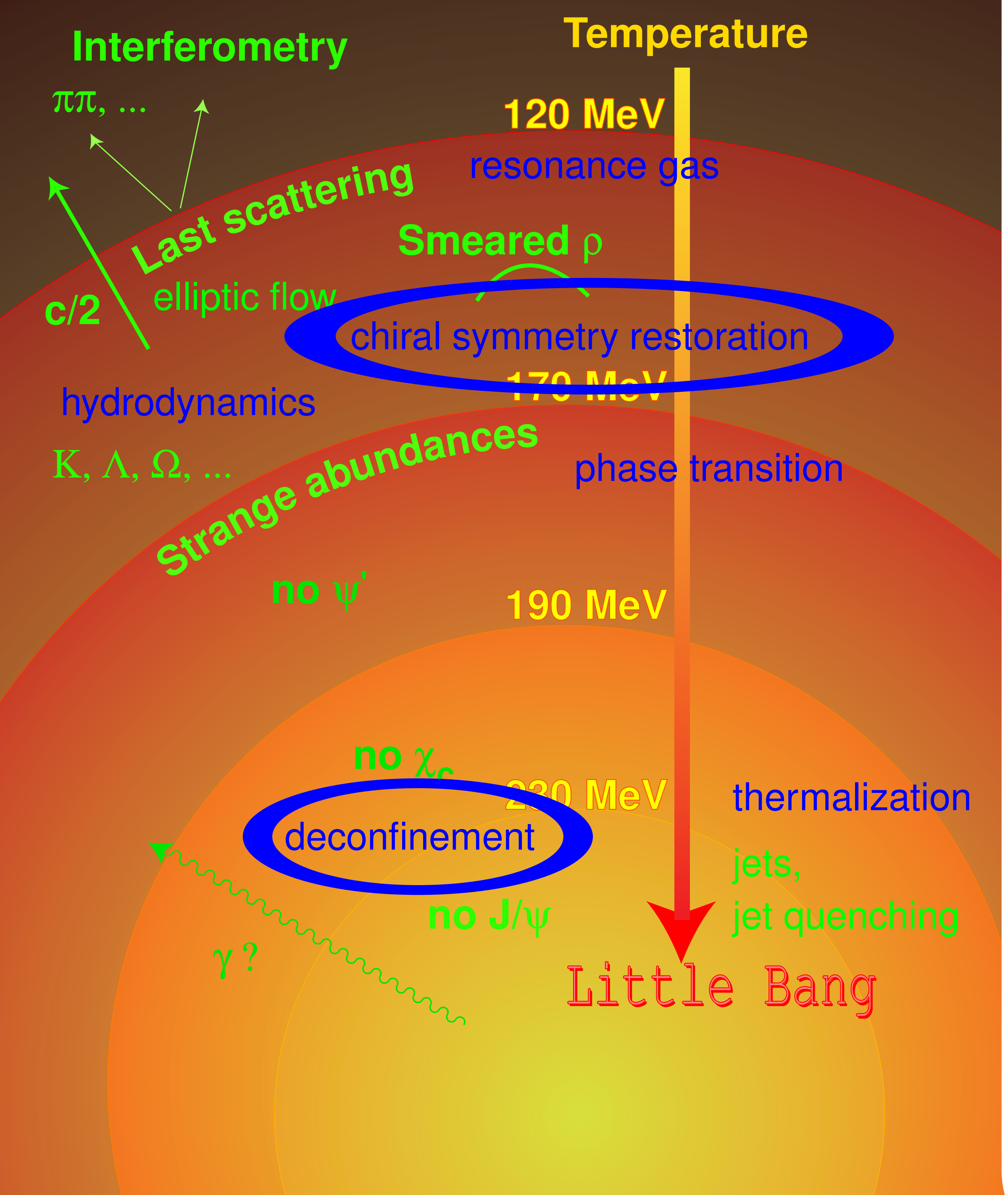
analysis of experimental observables

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

development of theoretical concepts

and the

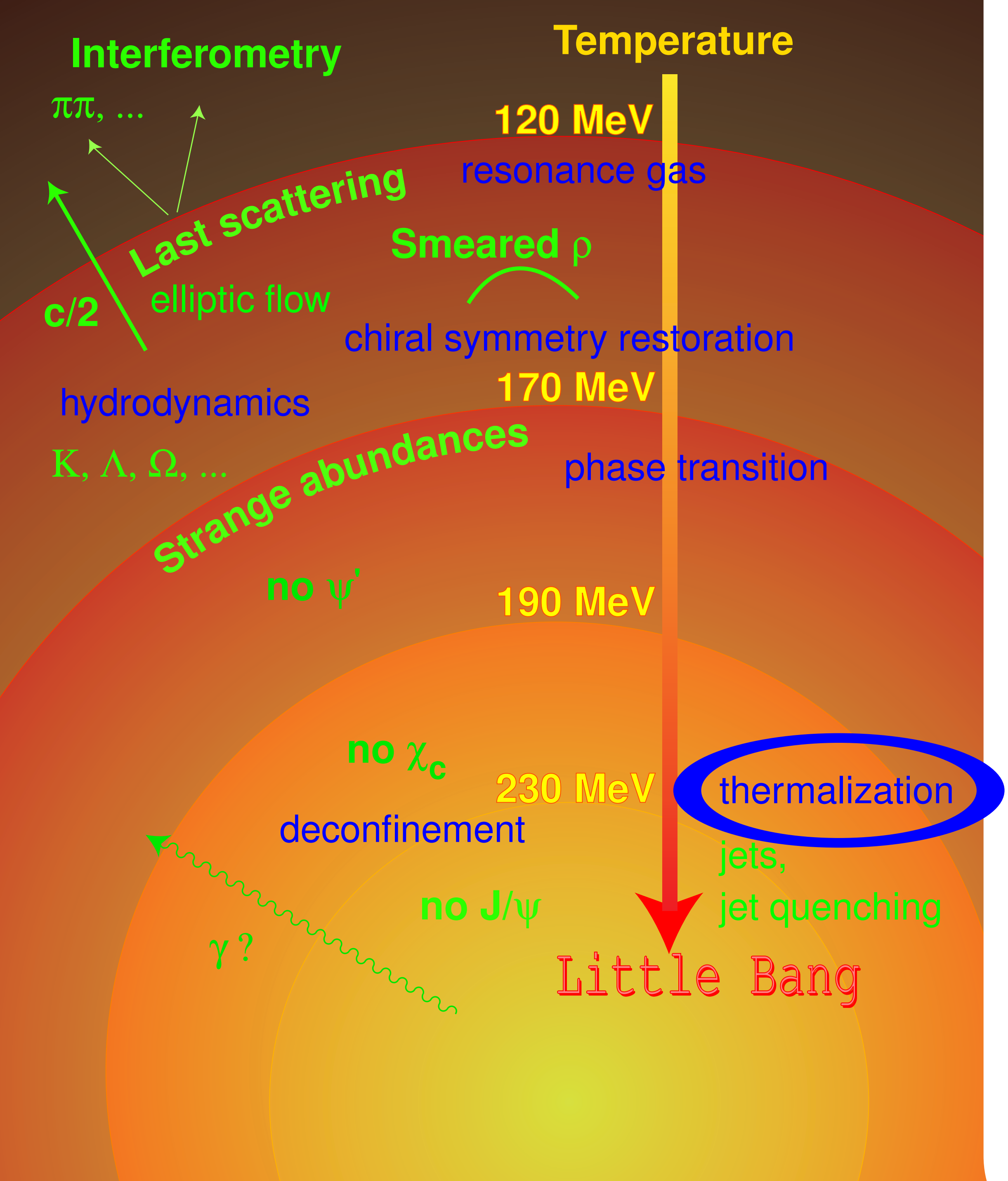
analysis of experimental observables

$$In-medium\ hadron\,properties$$

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

development of theoretical concepts

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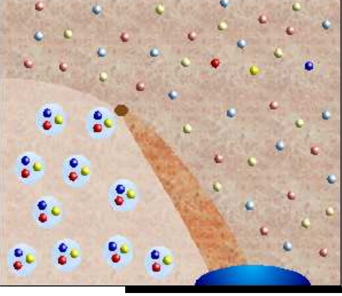
analysis of experimental observables

short vs. long distance physics

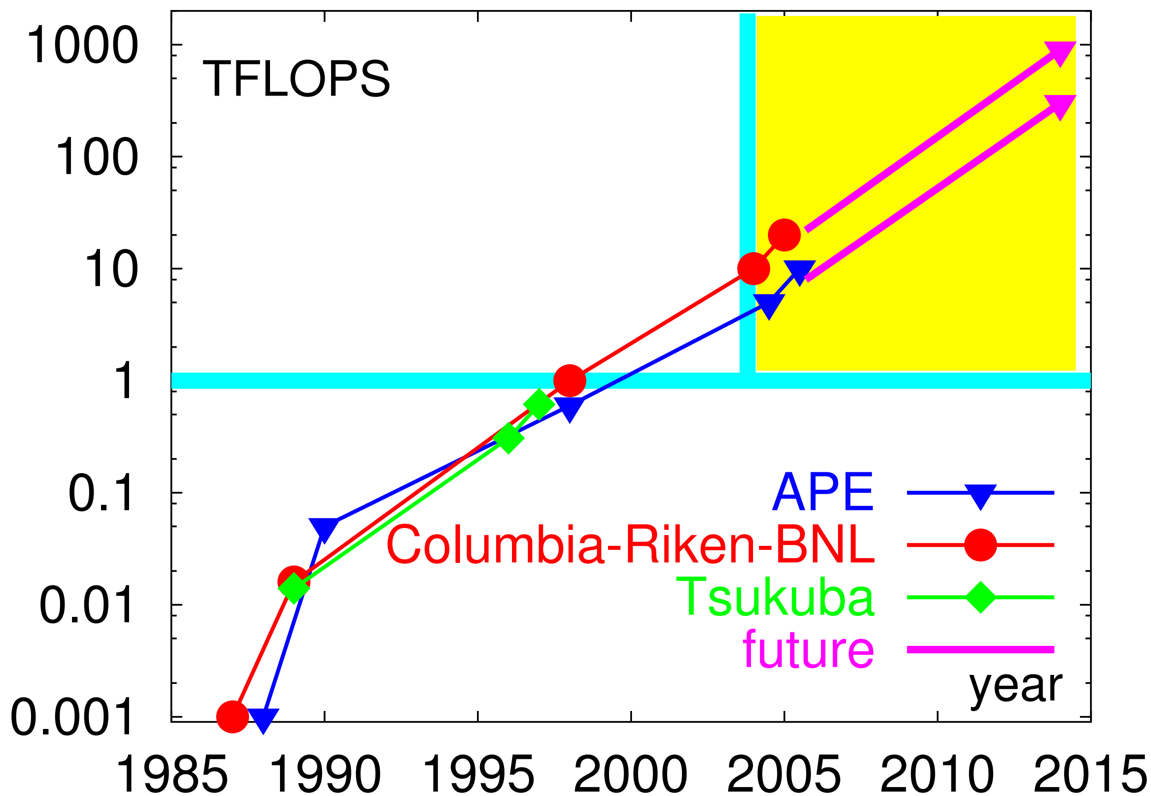
running coupling constant;
transport coefficients (??)

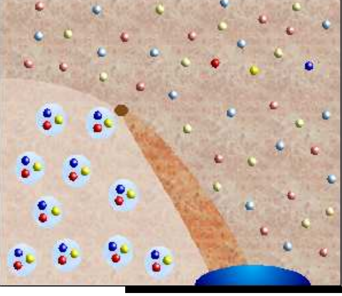


Progress in lattice calculations... depends on...

- development of (special purpose) computer hardware
-
-

development of
special purpose
computer hardware
⇓
towards PETAFLOPS
computing





Setting a standard: Computational requirements in EoS calculations

- only integrated luminosity counts (!), i.e.
  peak spead of a computer itself is of little significance

a PETAFLOP calculation

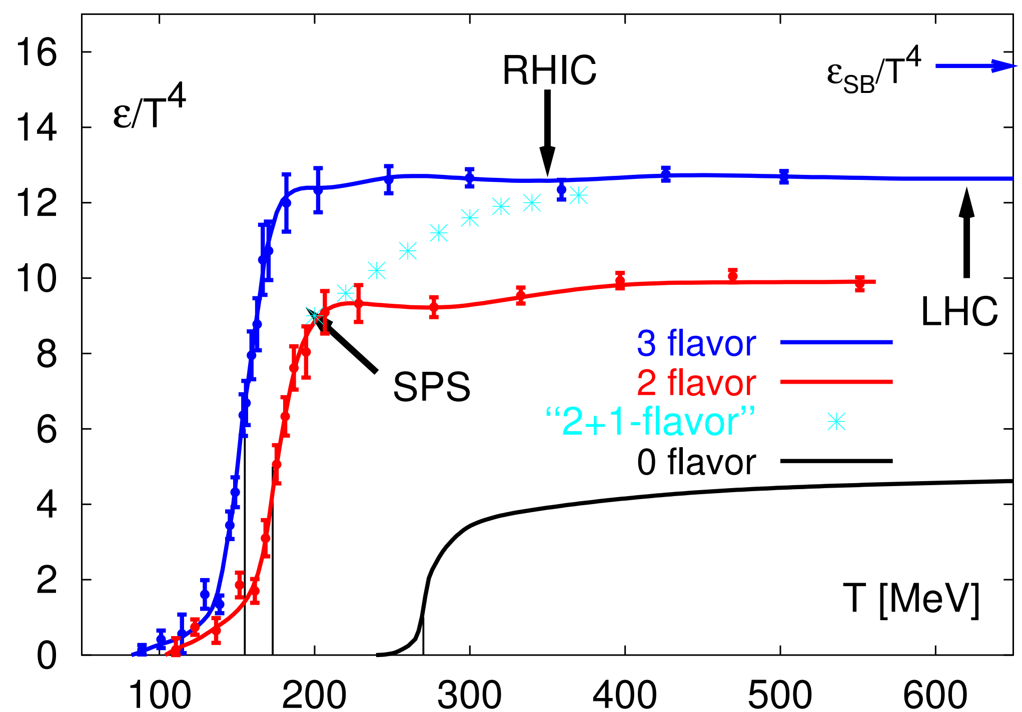
$\sim$ **6** months on a

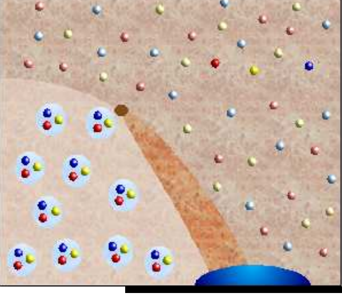
10 GFlops computer

$\Downarrow$

$$\sim \mathbf{100 \cdot 10^{15}}$$

floating point operations





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

- development of (special purpose) computer hardware
- progress in algorithm development
-

1987	invention of Hybrid Monte Carlo Algorithm
early ’90s	development of various preconditioning schemes
late ’90s	new algorithms: polynomial / shifted HMC; multi-boson algorithm

1987 - 2004: gain of factor 15 - 20 from algorithm development

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

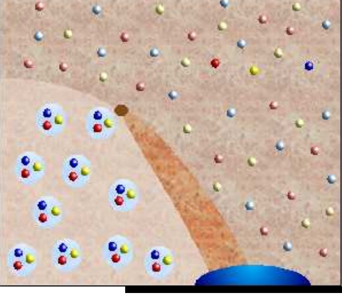
- development of (special purpose) computer hardware
- progress in algorithm development
- new ideas, new conceptual developments!!!

1988/89 multi-parameter Ferrenberg-Swendsen reweighting
$\Rightarrow$ accurate location of transition points, scaling analysis

1996 Non-perturbative definition of bulk thermodynamics
$\Rightarrow$ integral method for reliable pressure calculations

1999 Maximum Entropy Method (MEM) for QCD
$\Rightarrow$ spectral functions, in-medium properties of hadrons

2002 reweighting and Taylor expansion techniques for $\mu > 0$
$\Rightarrow$ QCD phase diagram at finite baryon density



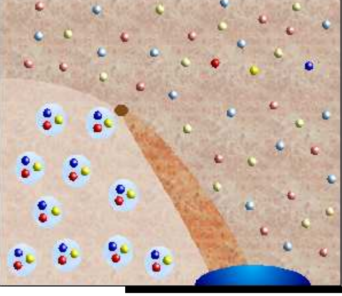
Outlook: Next generation computers for lattice gauge theory

today:

APEmille

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

RHIC vs. SPS: Running a dedicated machine makes a difference!

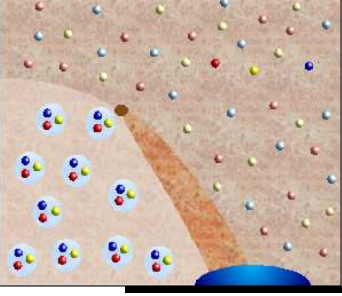


Outlook: Next generation computers for lattice gauge theory

QCDOC and apeNEXT

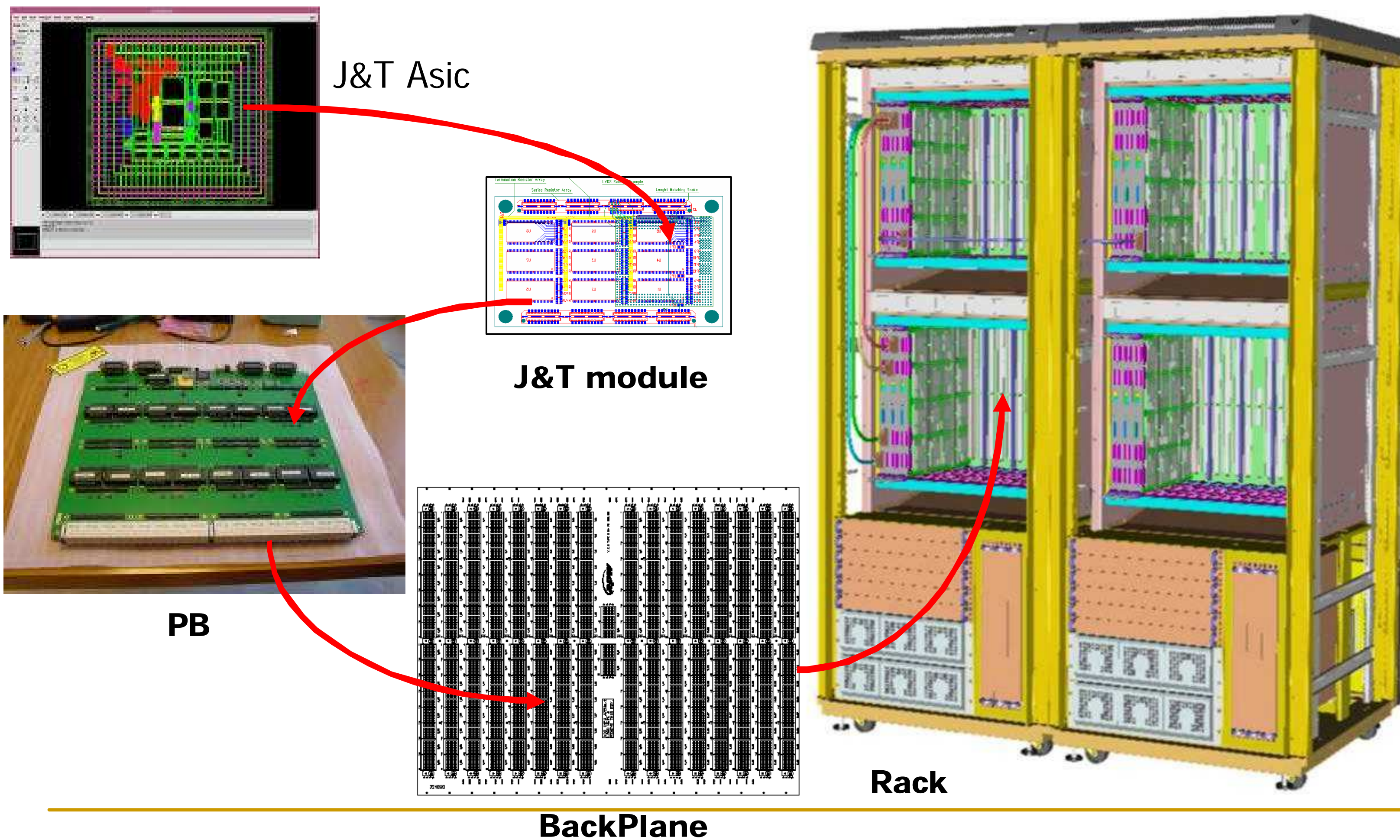
04/05: QCD thermodynamics on the next generation of special purpose dedicated QCD computers

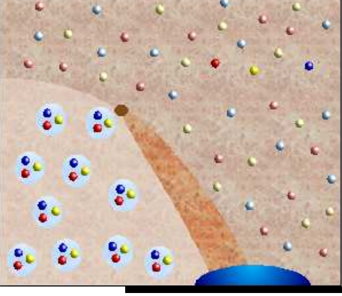
installations with (10-20) TFlops peak speed are planned in the USA and Europe



apeNEXT: Next generation of APE computers

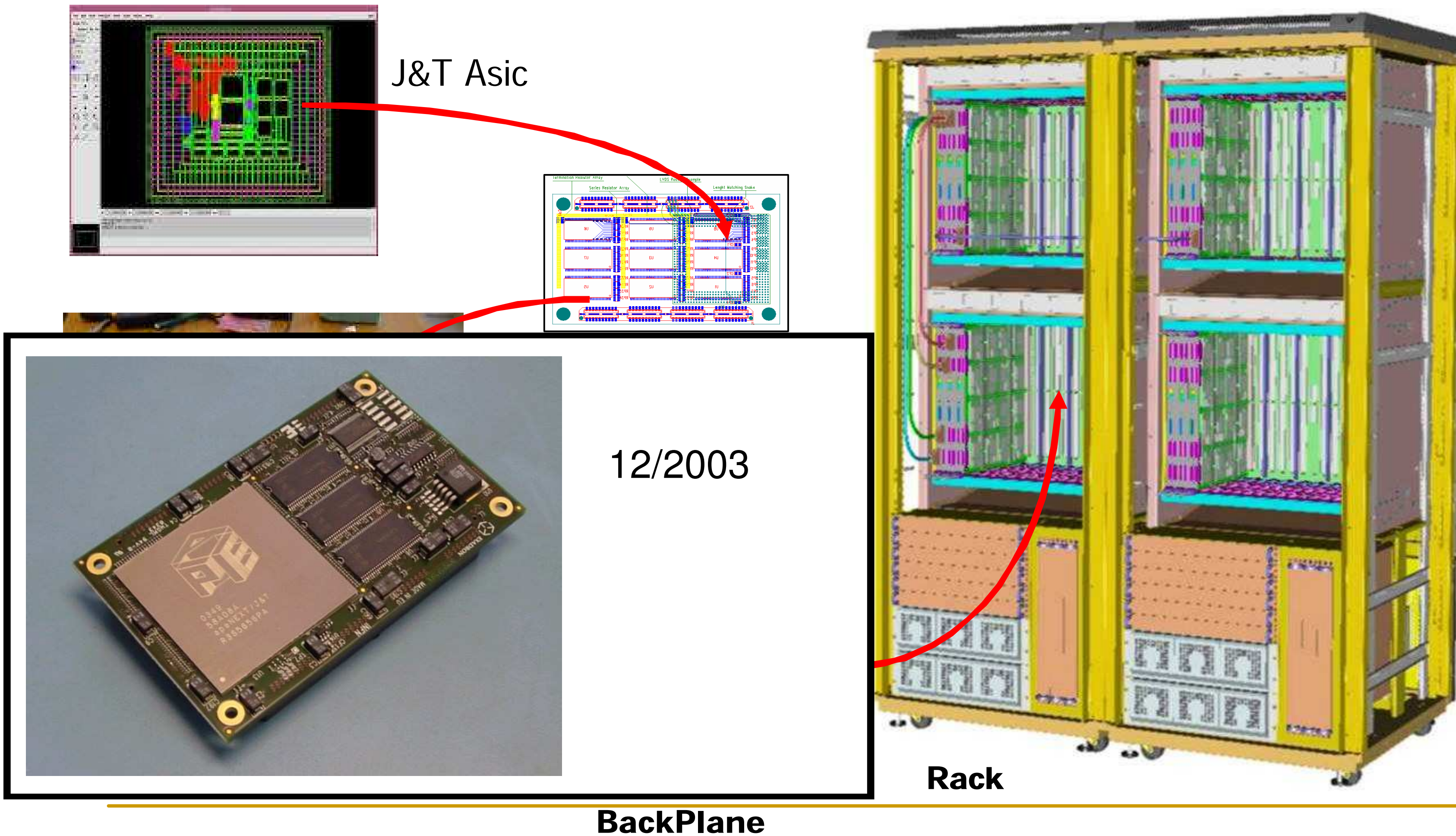
Assembling apeNEXT...

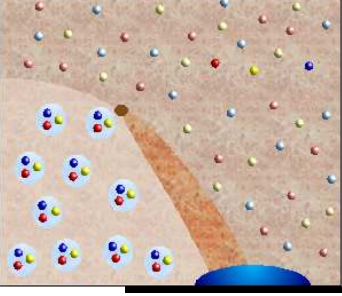




apeNEXT: Next generation of APE computers

Assembling apeNEXT...





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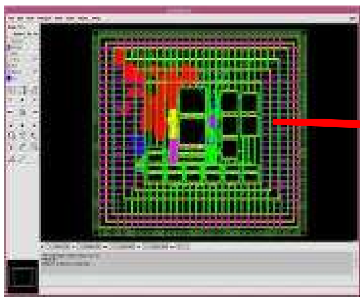
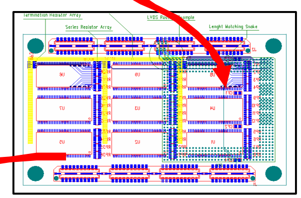
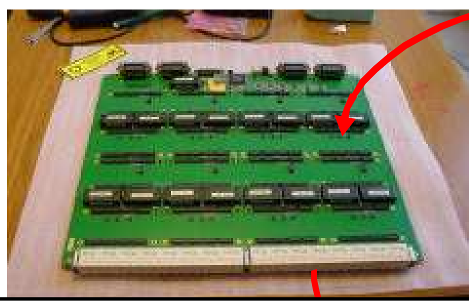
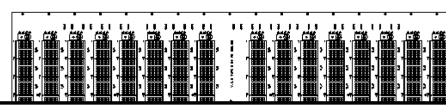
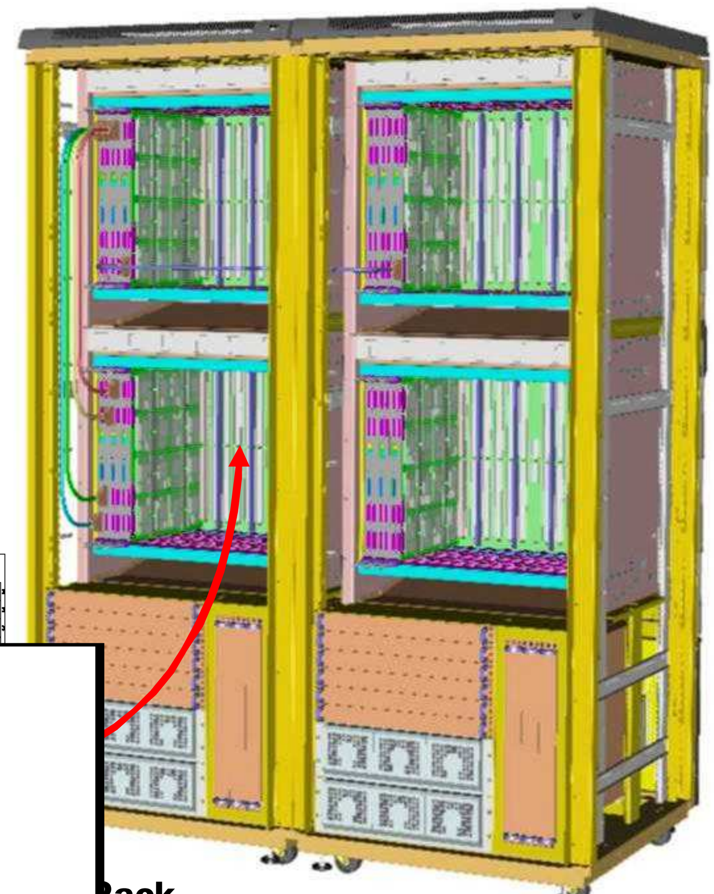




J&T module





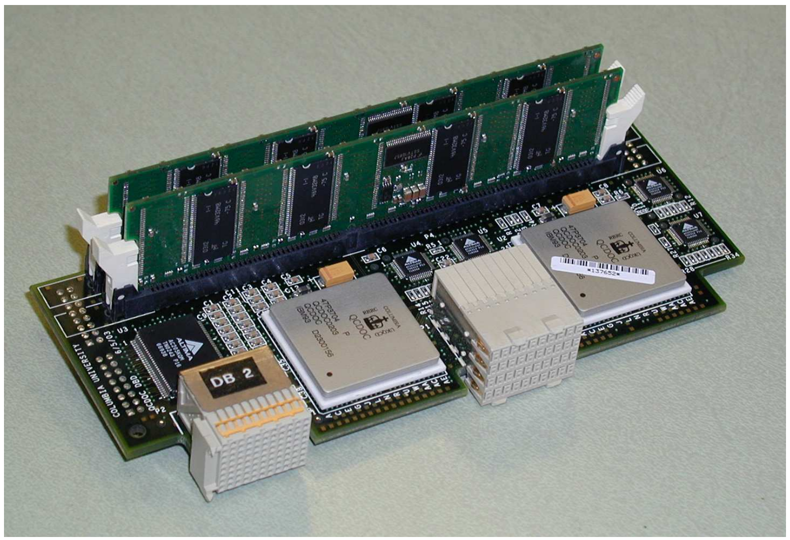


- first chips Dec. 2003
- two 0.8 TFlops prototypes ∼ autumn 2004
- first 3 TFlops installations in 2005

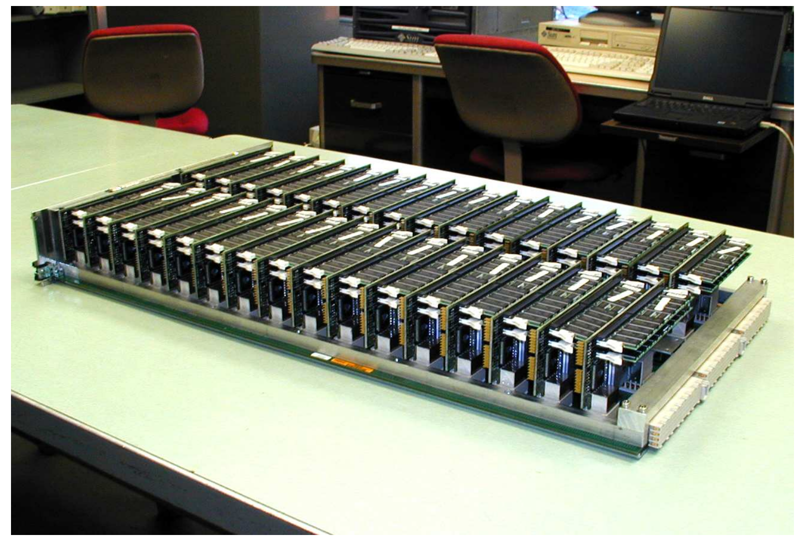
BackPlane

QCDOC: Next generation of Columbia-RIKEN computer

Columbia-RIKEN/BNL-UKQCD Collaboration

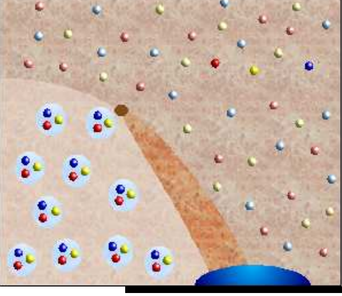


$2 - \text{node daughter card}$



$64 - \text{node mother board}$

- prototypes exist since 07/2003

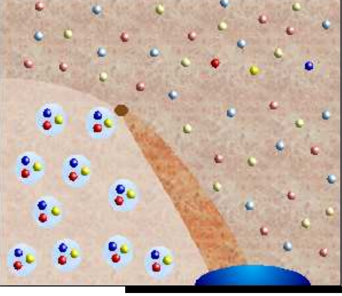


QCDOC: Next generation of Columbia-RIKEN computer

Columbia-RIKEN/BNL-UKQCD Collaboration

10/2004: 12288-node machine: $\sim$ 10 TFlops

- first QCDOC machine; built for UKQCD

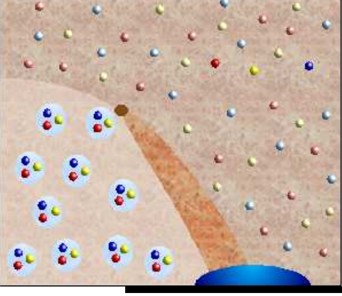


QCDOC: Next generation of Columbia-RIKEN computer

Columbia-RIKEN/BNL-UKQCD Collaboration

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

- 10 TFlops machine for RBRC: $\sim$ 12/2004
- 10 TFlops machine for american LGT community: $\sim$ early in 2005
- ... larger installations possible and needed!



Bulk Thermodynamics: What do we (want to) know?

$\mu = 0$:

- properties of transition in $2,\ (2+1)$-flavor QCD:

  crossover or phase transition, deconfinement vs. chiral symmetry restoration, universality, ...

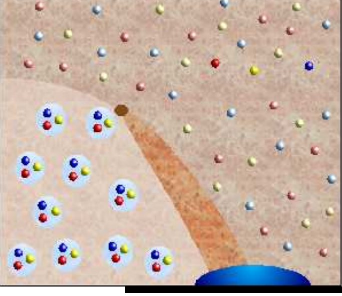
- $T_c,\ \epsilon_c,\ EoS$:

  confront resonance gas, quasi-particle gas, high-T pert. theory, HTL-resummation, ... with lattice calculations

$\mu > 0$:

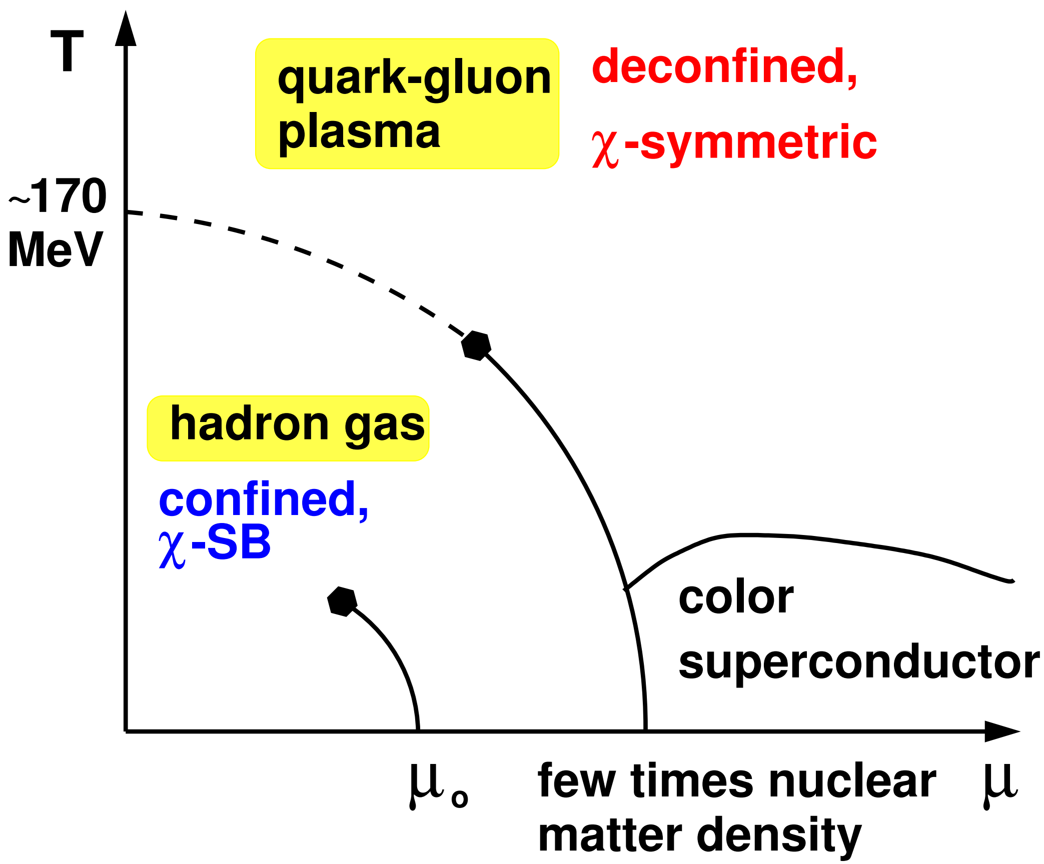
- $T_c(\mu) \;\Leftrightarrow\; T_{\rm freeze}(\mu)$:

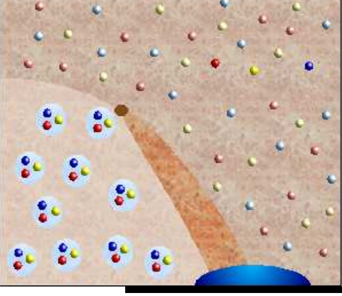
  location of the chiral critical point, direct evidence for $1^{\rm st}$ order regime; density fluctuations; $T_c(\mu) \equiv T_{\rm freeze}$?



Critical behavior in hot and dense matter: phase diagram

crossover vs.
phase transition





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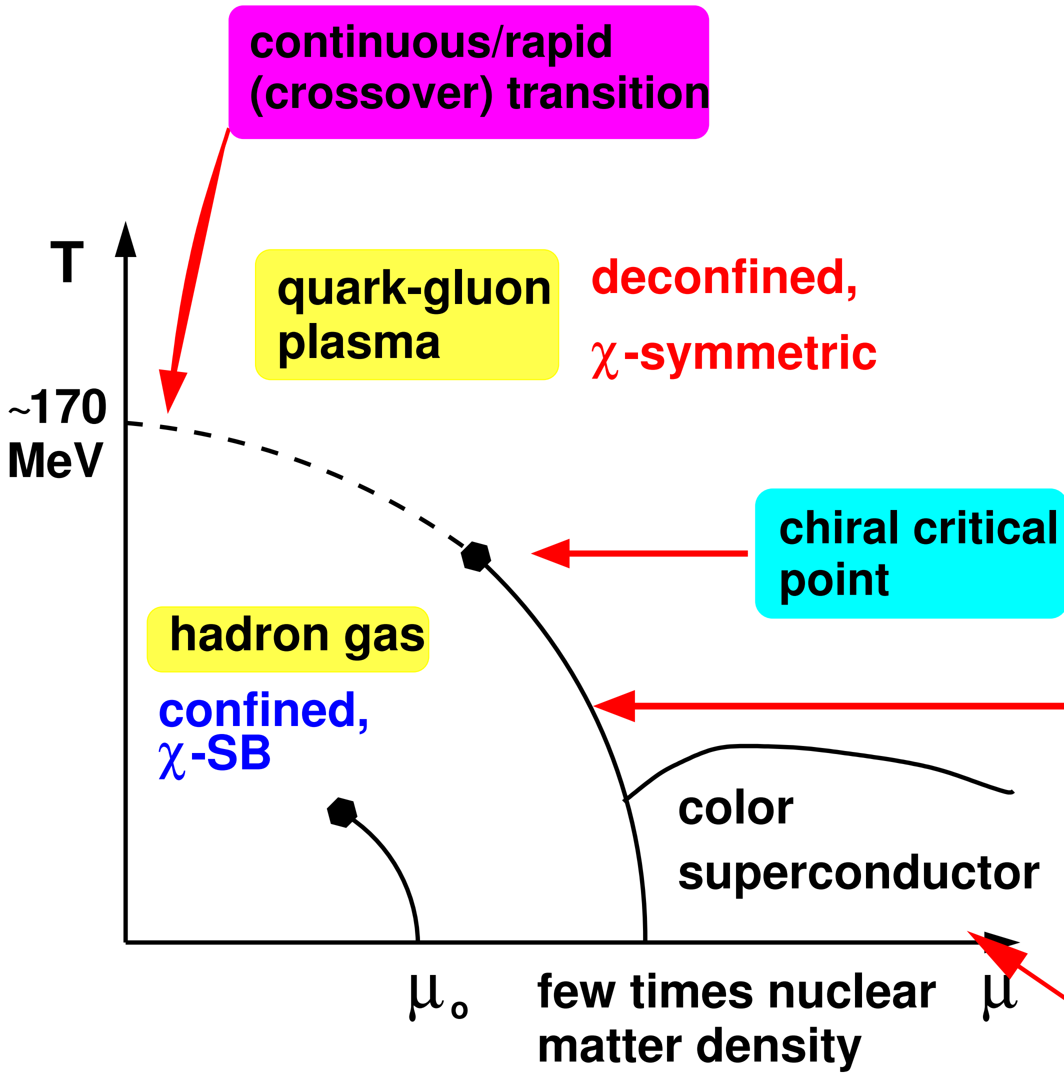


continuous transition for small chemical potential and small quark masses at

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

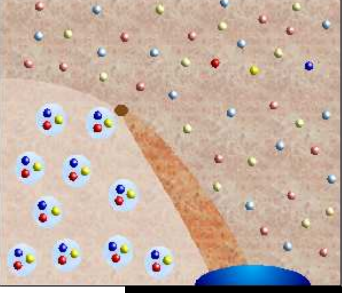
2nd order phase transition; Ising universality class

$T_c(\mu)$ under investigation

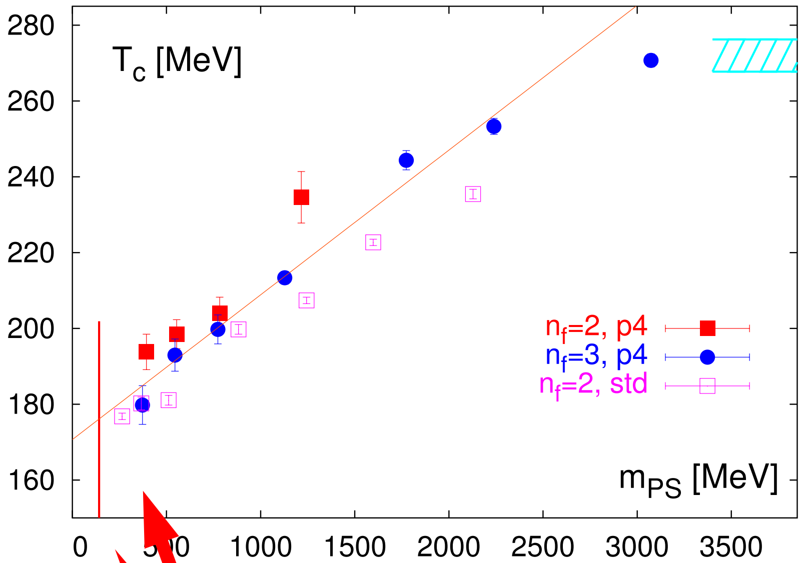
1st order phase transition ???

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

attractive 1–gluon exchange => qq–condensates



Critical temperature, equation of state



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

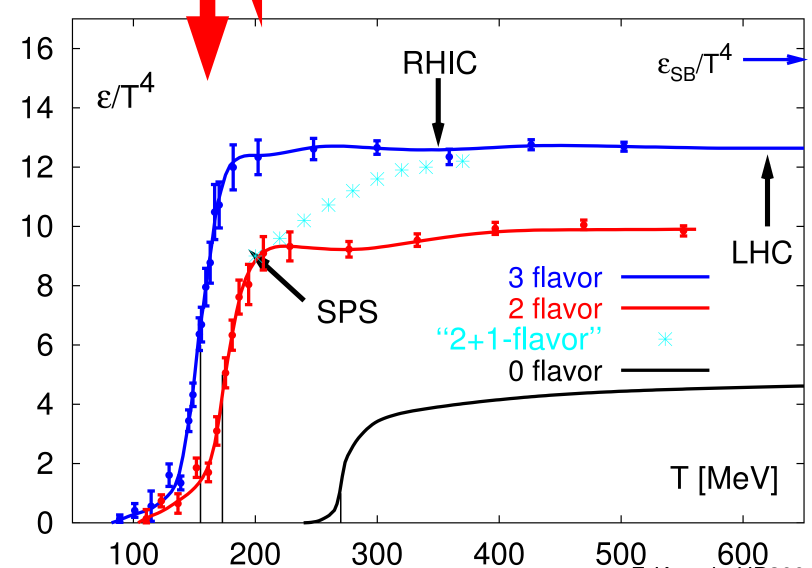
$$T_c = (173 \pm 8 \pm sys)\, MeV$$

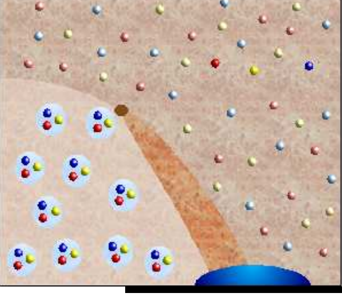
FK, E. Laermann, A. Peikert, Nucl. Phys. B605 (2001) 579

$$T_c = 167(13)\, [177(11)]\, MeV$$

MILC, hep-lat/0405029

energy density for 0, 2 and 3-flavor QCD





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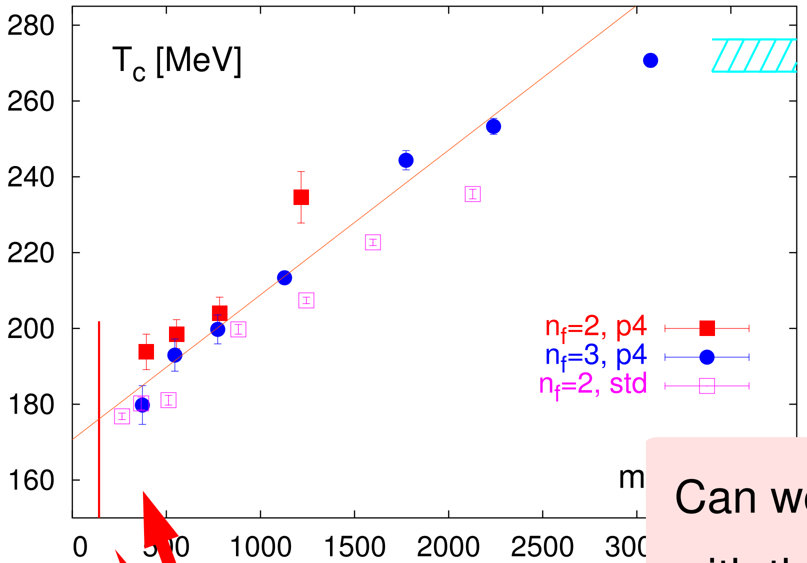
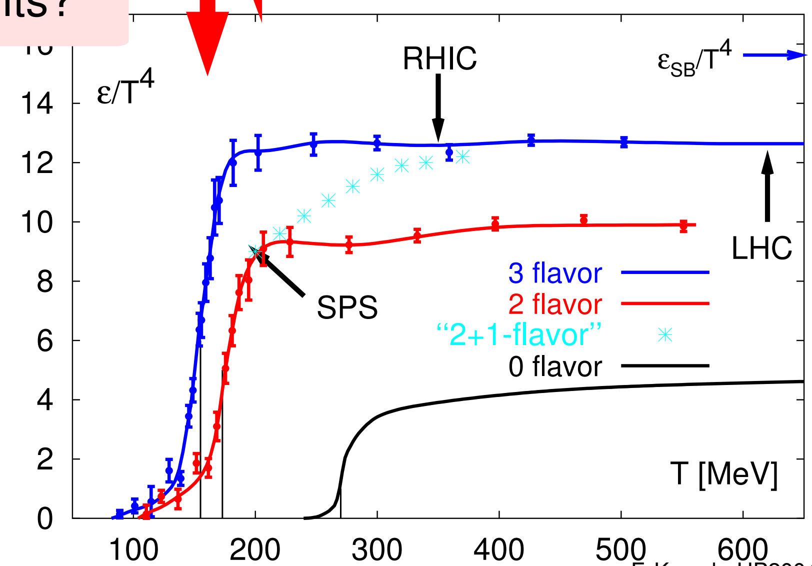


$$\epsilon_c \simeq (6 \pm 2)\, T_c^4$$
$$\simeq (0.3 - 1.3)\, GeV/fm^3$$

Can we be satisfied with these results?



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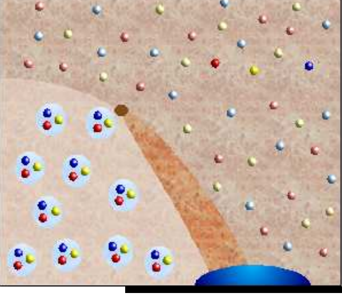

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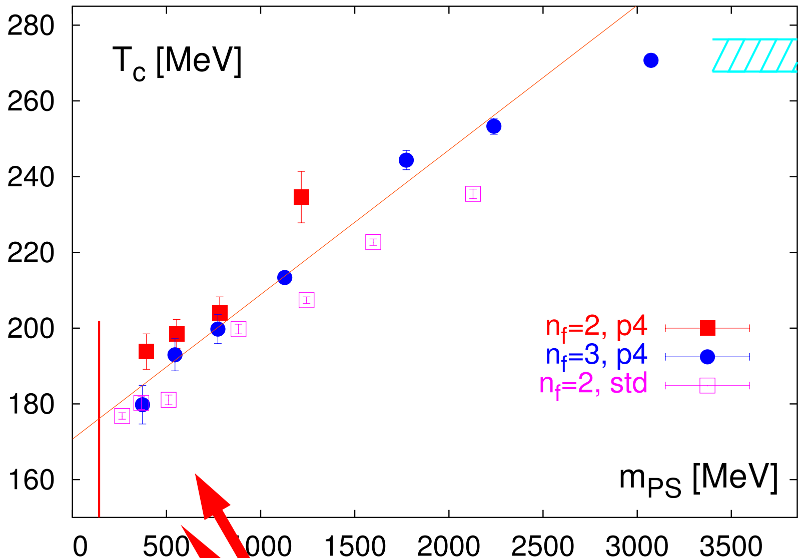
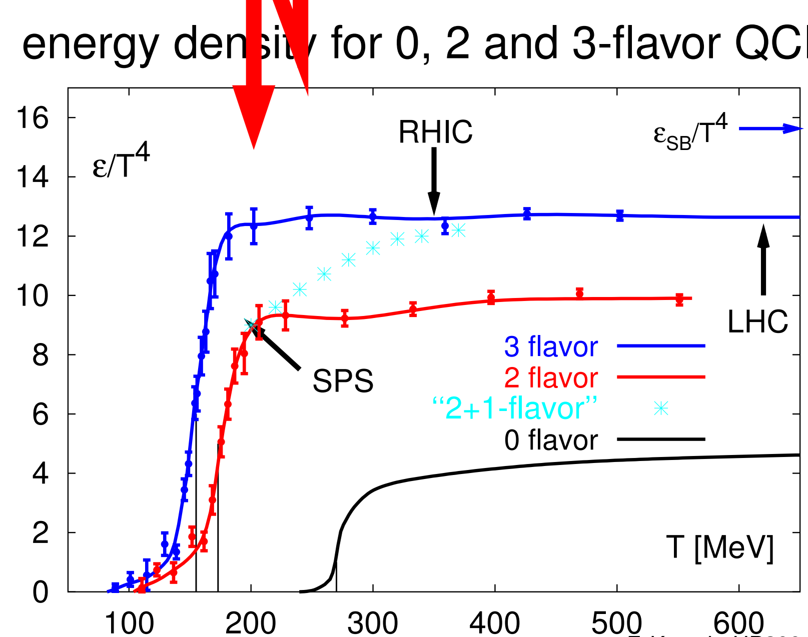


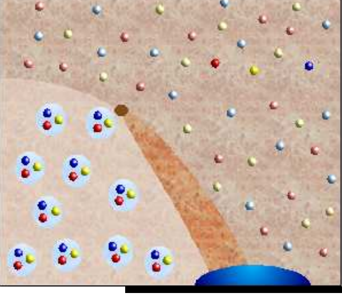
T_c

- $m_{PS} \gtrsim 300\ MeV$ (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)





Extending the phase diagram to non-vanishing chemical potential

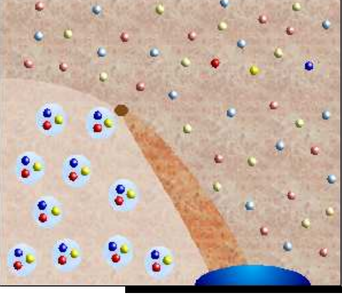
non-zero baryon number density: $\mu > 0$

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

⇑complex fermion determinant;

long standing problem

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



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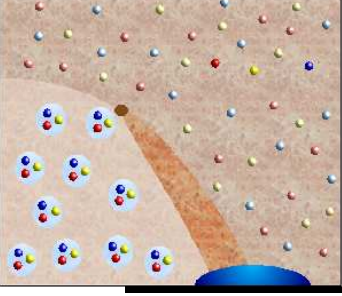
⇑complex fermion determinant;

long standing problem

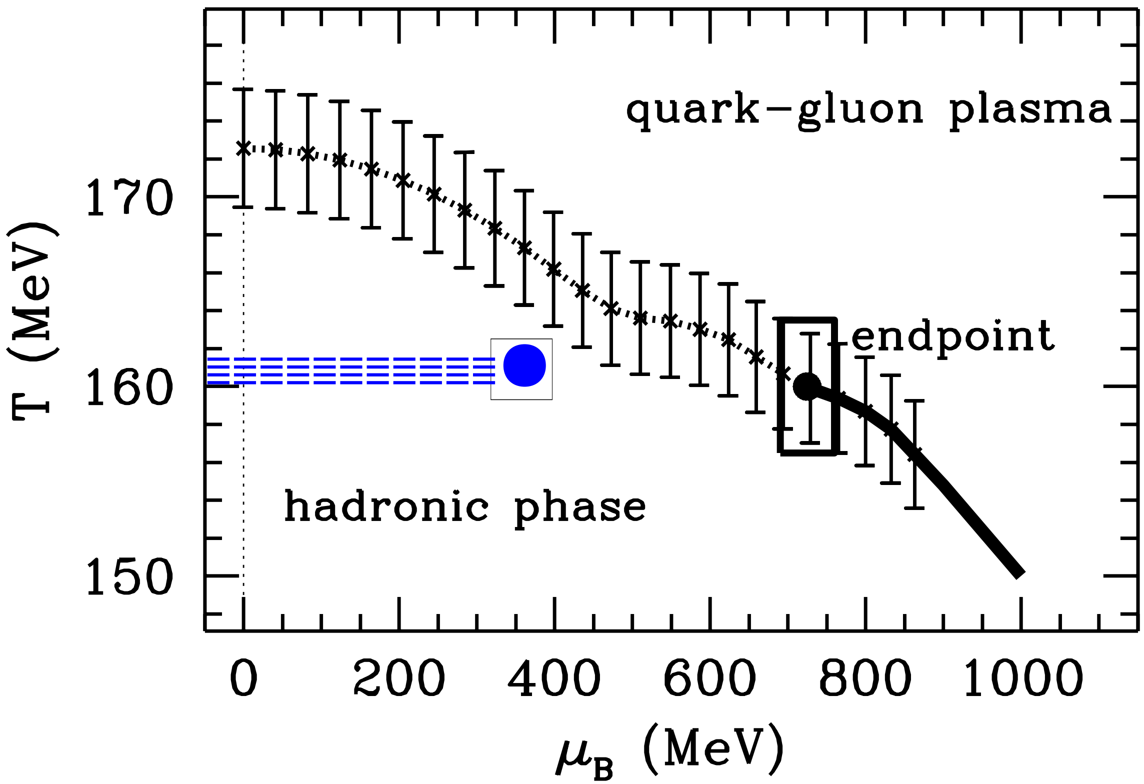
⇒ three (partial) solutions for large T, small μ

- exact evaluation of $det M$: 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

analysis of volume dependence of Lee-Yang zeroes for $\mu > 0$



Fodor & Katz, JHEP 0203 (2002) 014

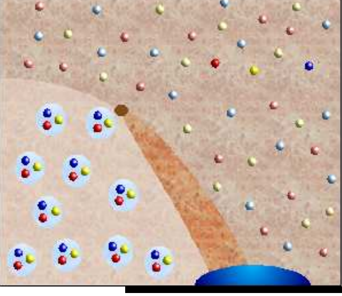
$V = 4^3,\ 6^3, 8^3$

Fodor & Katz, JHEP 0404 (2004) 050

$V = 6^3,\ 8^3, 10^3, 12^3$

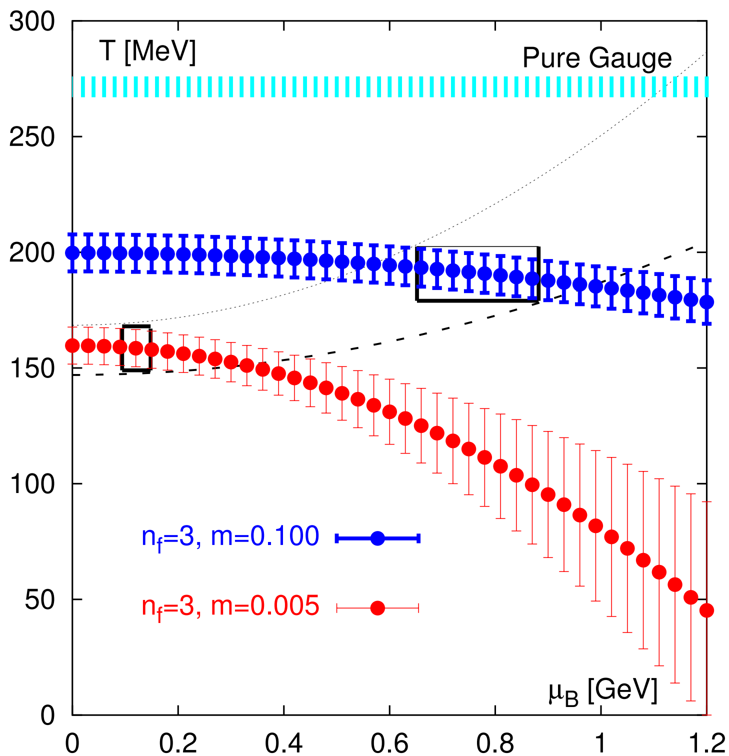
$$\mu^{crit} = 360(40)\ \mathrm{MeV}$$

$$T_c(\mu_B)/T_c(0) = 1 - 0.0032(1)\ (\mu_B/T_c(0))^2 \qquad \text{(pert.)}$$



Extending the phase diagram to non-vanishing chemical potential

first (exploratory) results on the quark mass dependence of the transition line:



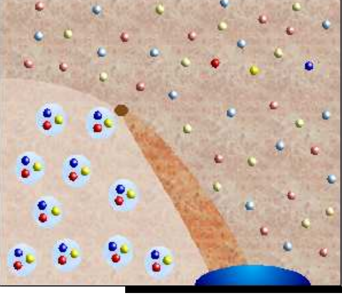
m_q-dependence

(3-flavor QCD, pert. β-function, Taylor expansion)

$$\frac{T_c(\mu)}{T_c(0)} : \quad 1 - 0.025(6)(\mu_q/T)^2 \; , \; ma = 0.1$$

$$1 - 0.114(46)(\mu_q/T)^2 \; , \; ma = 0.005$$

Bielefeld-Swansea
(hep-lat/0309116, Lattice 2003)



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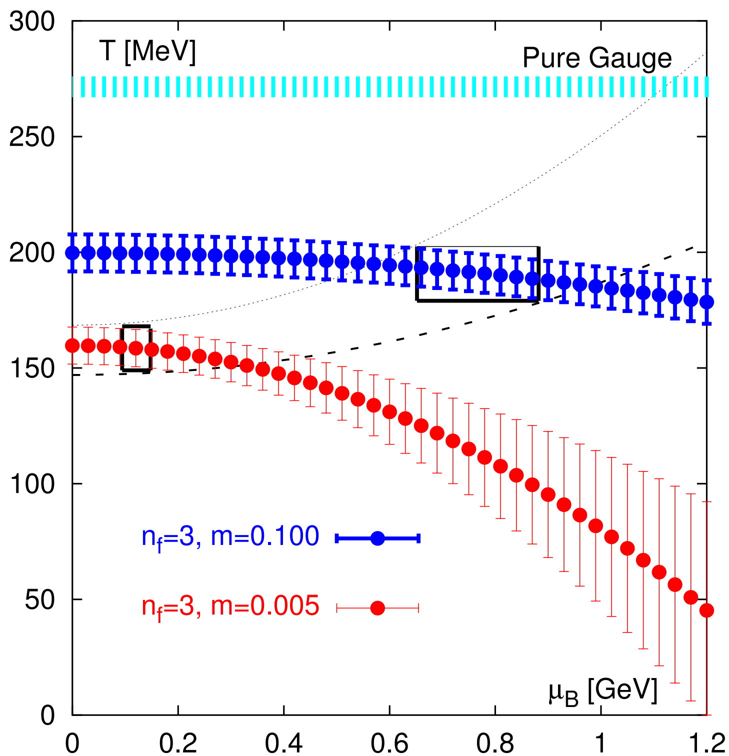

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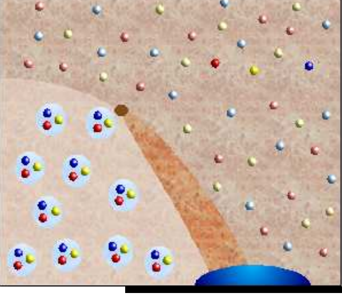
Bielefeld-Swansea
(hep-lat/0309116, Lattice 2003)

a systematic analysis of
cut-off effects, scaling violations
AND volume + truncation effects
still needs to be done

m_q-dependence not confirmed in simulations with imaginary μ

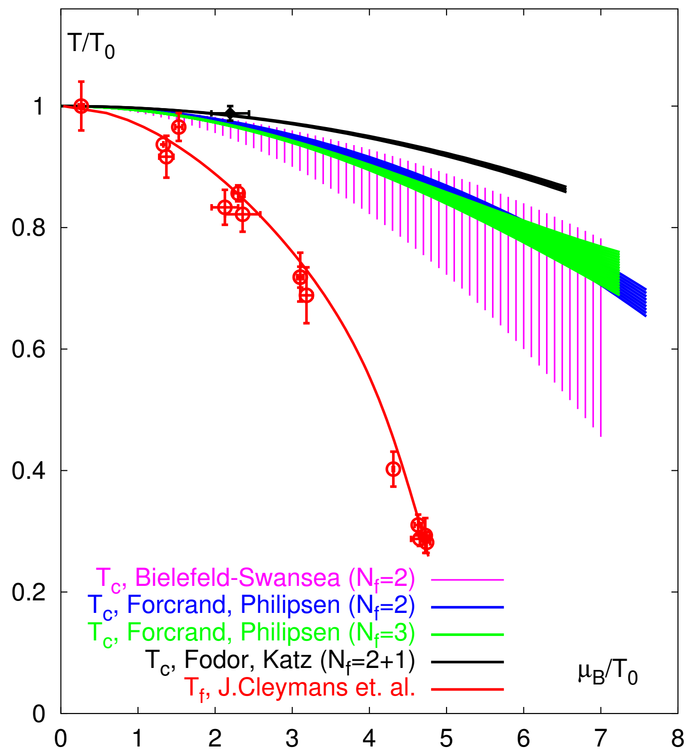
Ph. de Forcrand, O. Philipsen, NP B673 (2003) 170



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, pert)

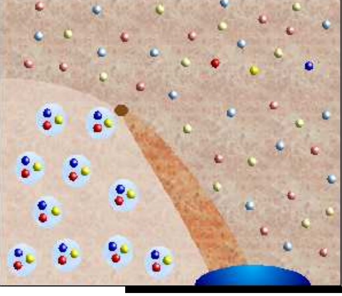
$1 - 0.0078(38)(\mu_B/T)^2$

Bielefeld-Swansea

($\mathcal{O}(\mu^2)$ reweighting, non-pert)

$1 - 0.0032(1)(\mu_B/T)^2$

Fodor,Katz(Lee-Yang zeroes, pert)



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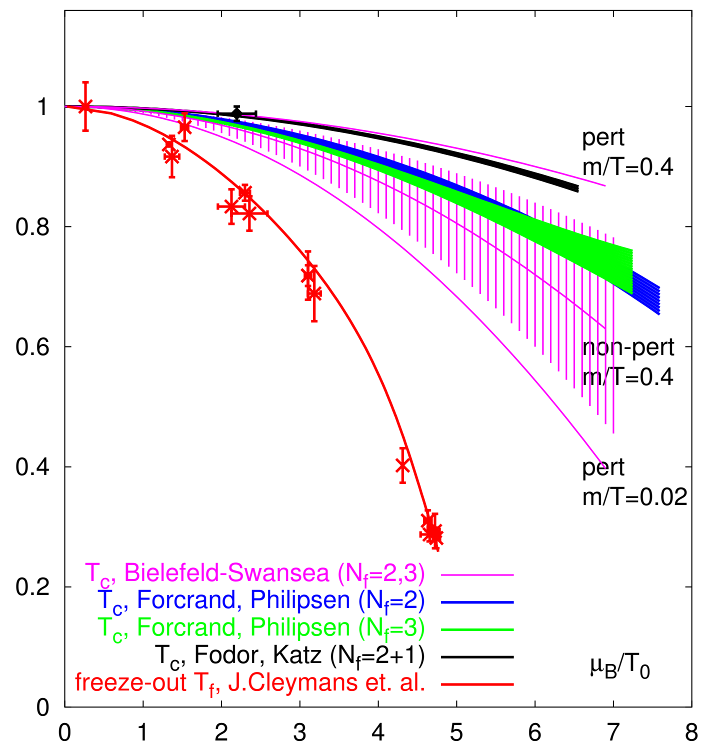
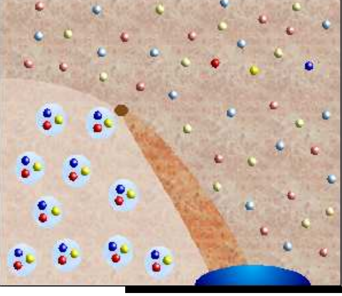


current studies of $T_c(\mu)$ are exploratory!

uncertainties in scale-determination and

systematics of quark mass dependencee



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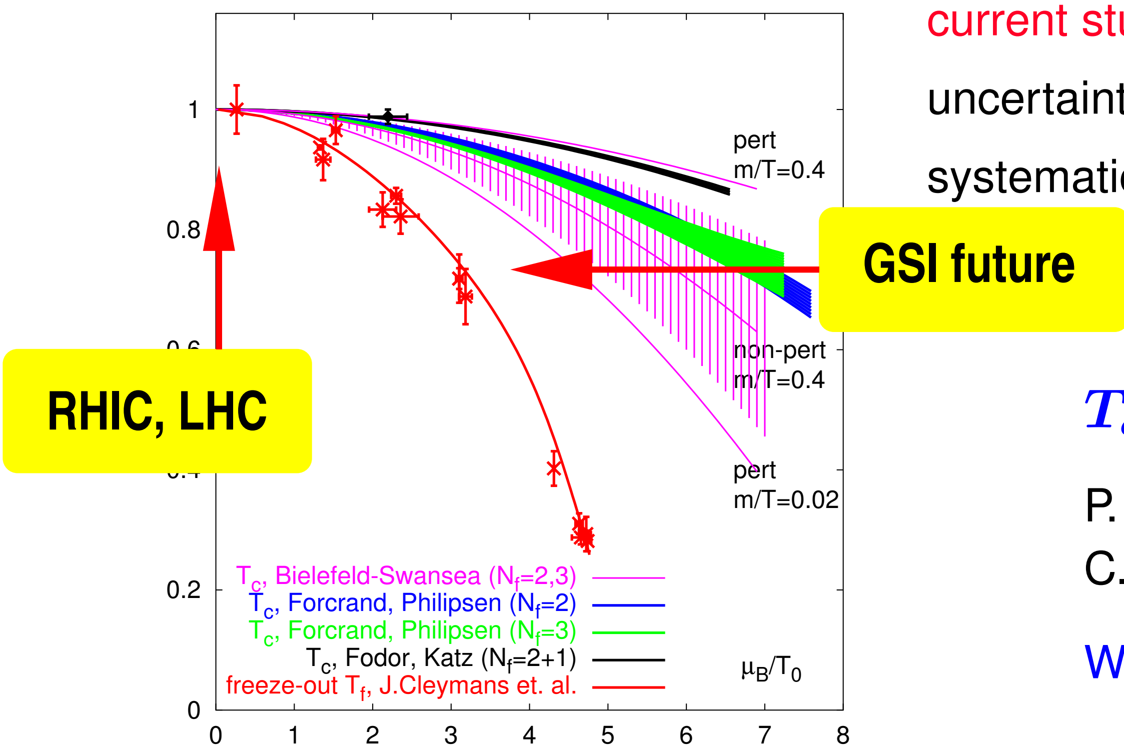


current studies of $T_c(\mu)$ are exploratory!

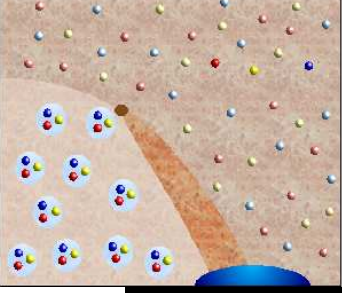
uncertainties in scale-determination and

systematics of quark mass dependencee

$T_c(\mu) \equiv T_{\mathbf{freeze}}$?

P. Braun-Munzinger, J. Stachel,
C. Wetterich, hep-nucl/0311005

Will be answered by LGT calculations



Analyzing the (quasi-particle) structure of HG and QGP phases

Response and correlation functions:

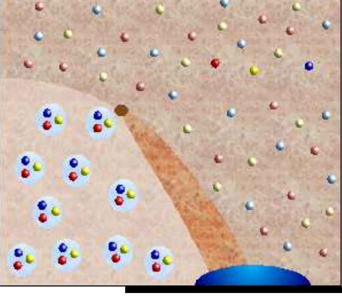
$T \leq T_c$: chiral symmetry restoration

- hadronic resonance gas;

  MEM analysis of thermal masses and widths, π, ρ, ...
- (baryon) density fluctuations, strangeness fluctuations, ...

$T > T_c$: deconfinement

- free energies, potentials and screening masses, running coupling at short and large distances,...
- MEM analysis of heavy and light quark bound states, quark and gluon propagators, dilepton and photon rates, ...



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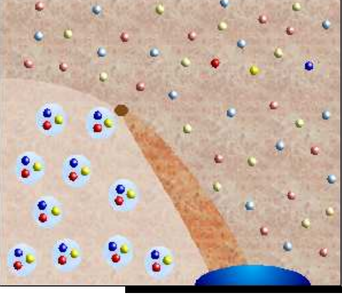
requires light
dynamical quarks
⇒ PETAFLOPs era

$T > T_c$: deconfinement

- free energies, potentials and screening masses,
  running coupling at short and large distances,...
- MEM analysis of heavy and light quark bound states,
  quark and gluon propagators, dilepton and photon rates, ...

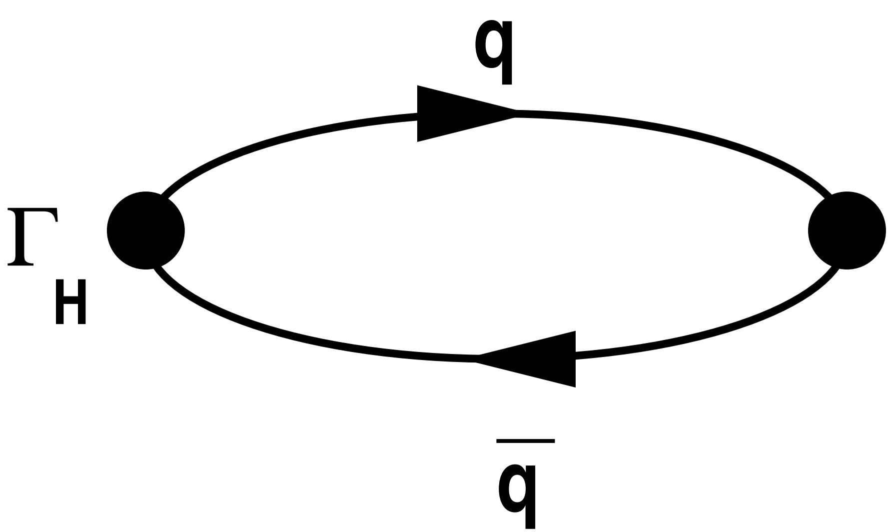
meaningful already
in quenched QCD
⇒ TERAFLOPs era



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: $\omega = |\vec{p}|$

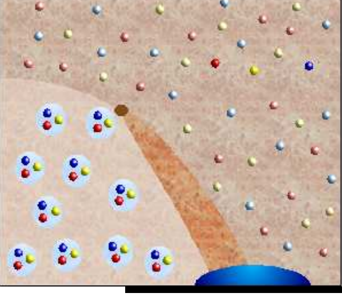
$$\omega \frac{d^3 R^\gamma}{d^3 p} = \frac{5\alpha}{6\pi^2} \frac{\sigma_V(\omega, \vec{p}, T)}{\omega^2 (e^{\omega/T} - 1)}$$

spectral representation of thermal dilepton rate

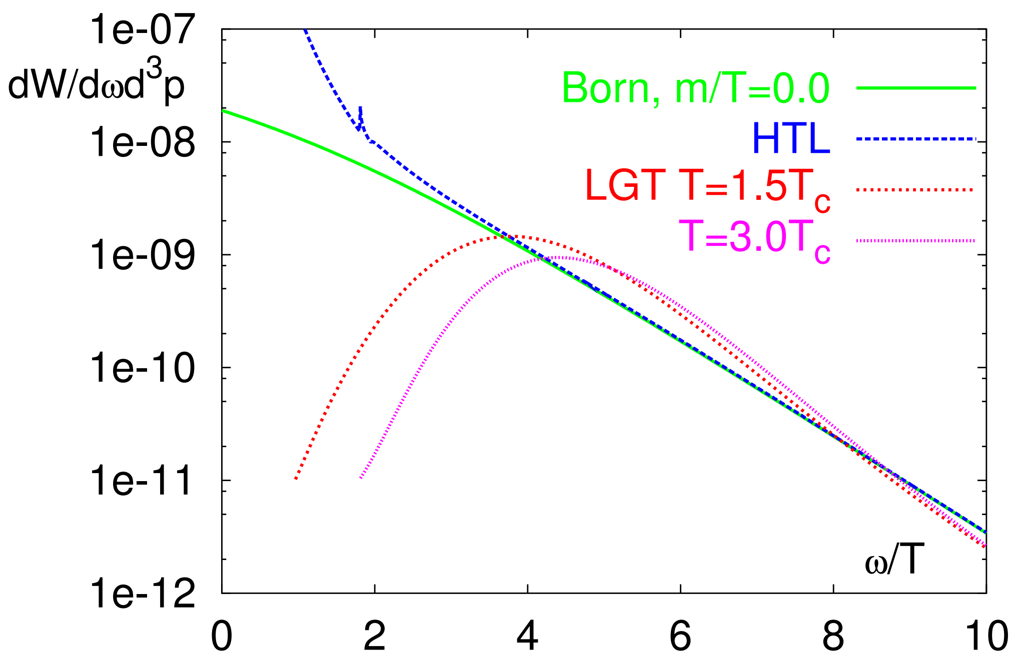
$$\frac{d^4 W}{d\omega d^3 p} = \frac{5\alpha^2}{27\pi^2} \frac{\sigma_V(\omega, \vec{p}, T)}{\omega^2 (e^{\omega/T} - 1)}$$

spectral representation of Euclidean correlation functions

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



Dilepton rate:
HTL and lattice calculations



thermal dilepton rate

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

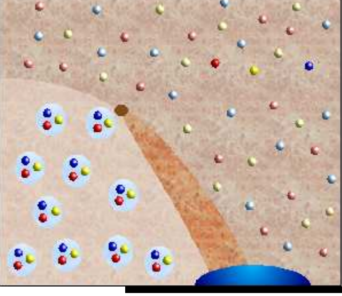
HTL and lattice disagree for

$\omega/T \lesssim (3-4)$

- infra-red sensitivity of HTL-calculations ⇔ "massless gluon" cut in HTL-propagator
- infra-red sensitivity of lattice calculations ⇔ thermodynamic limit, $V \to \infty$
- $VT^3 = (N_\sigma/N_\tau)^3 < \infty \quad \Rightarrow$ momentum cut-off: $p/T > 2\pi N_\tau/N_\sigma$

need large lattices to analyze infra-red regime

in future also thermal photon rates



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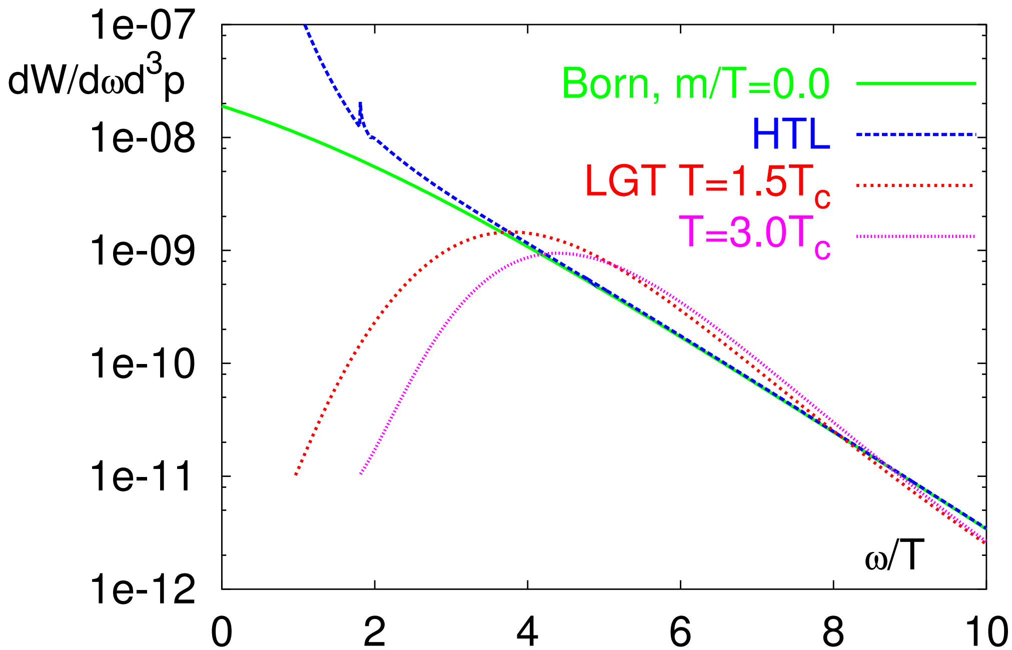

thermal dilepton rate

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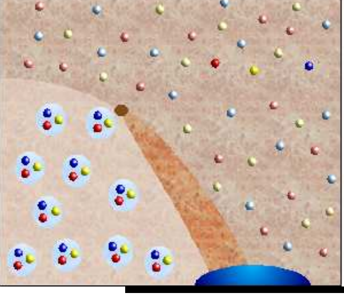
need large lattices to analyze infra-red regime

in future also thermal photon rates

need $N_\tau \sim \mathcal{O}(30)$ AND $N_\sigma \sim 6\, N_\tau$



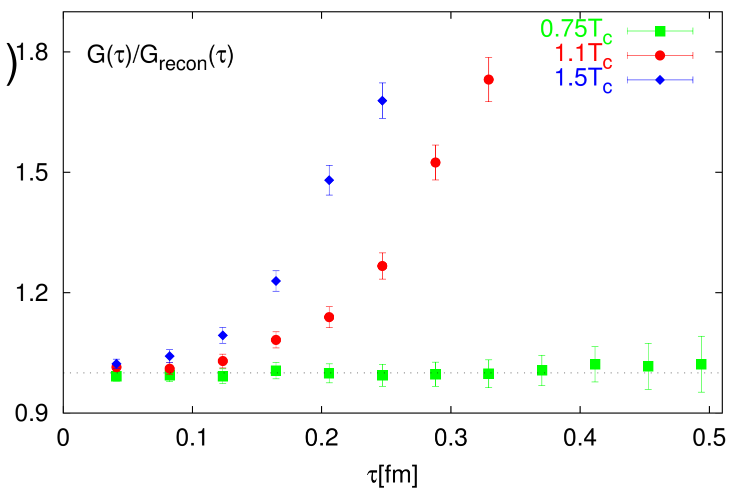
Heavy quark spectral functions and correlation functions

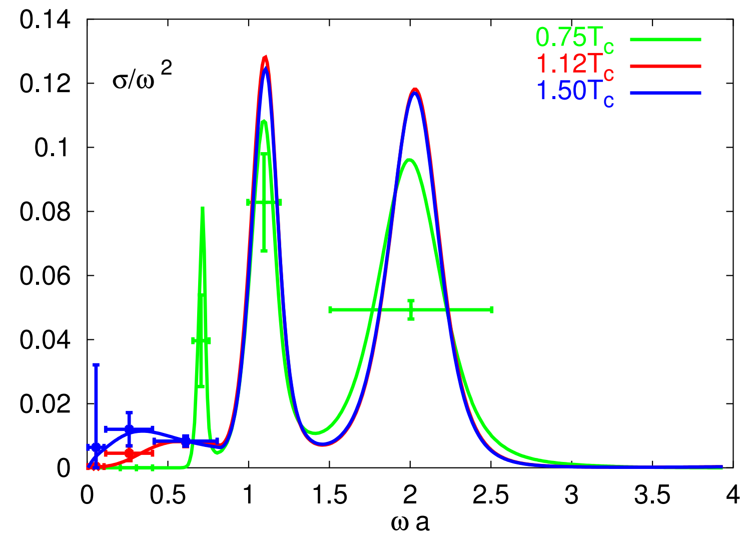
reconstructed correlation functions above T_c from data below T_c

reconstructed spectral functions using the Maximum Entropy Method

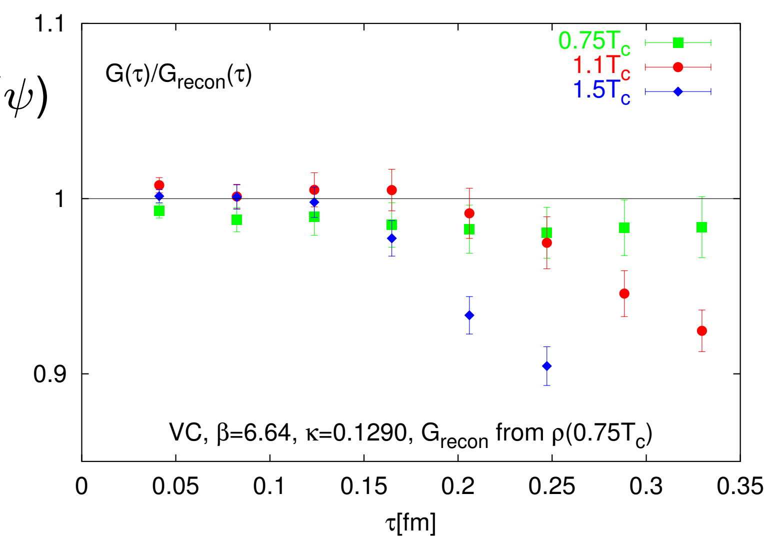
SC, β=6.64, κ=0.1290, G_{recon} from $\rho(0.75T_c)$

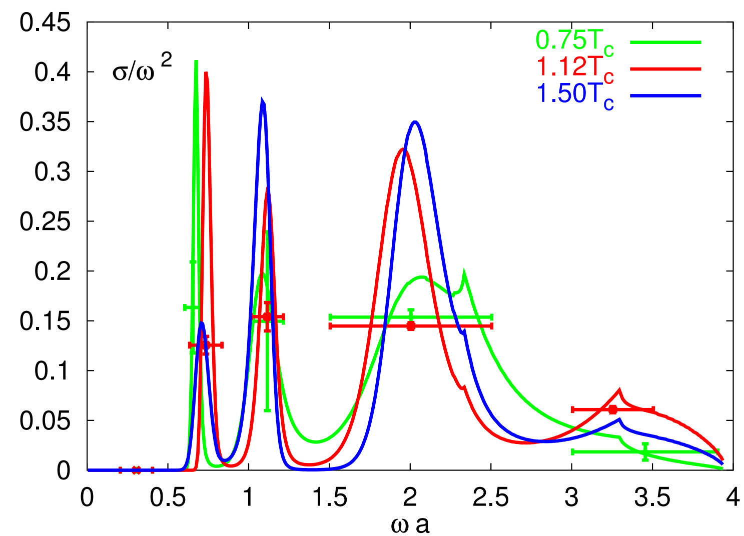
(χ_{c0})

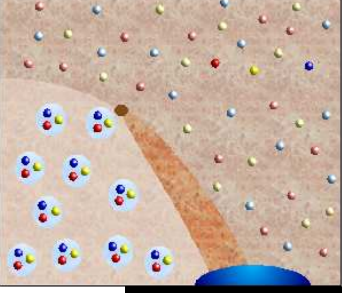




(J/ψ)







Heavy quark spectral functions and correlation functions

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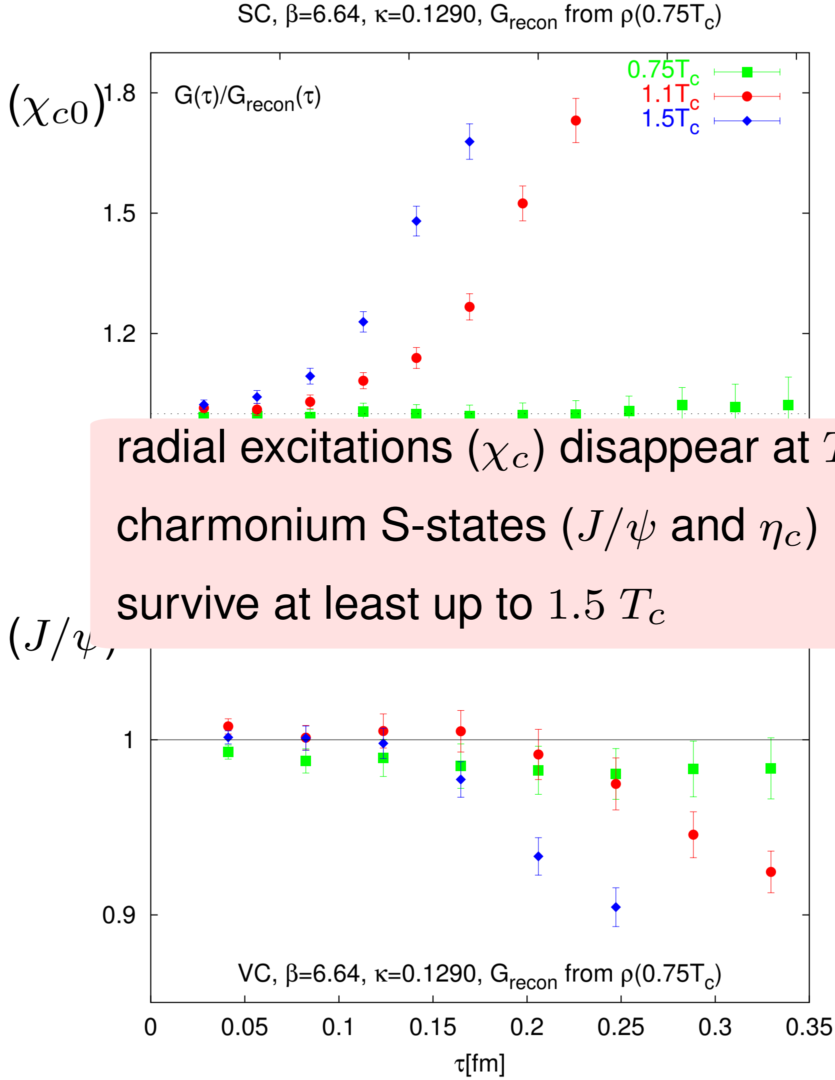
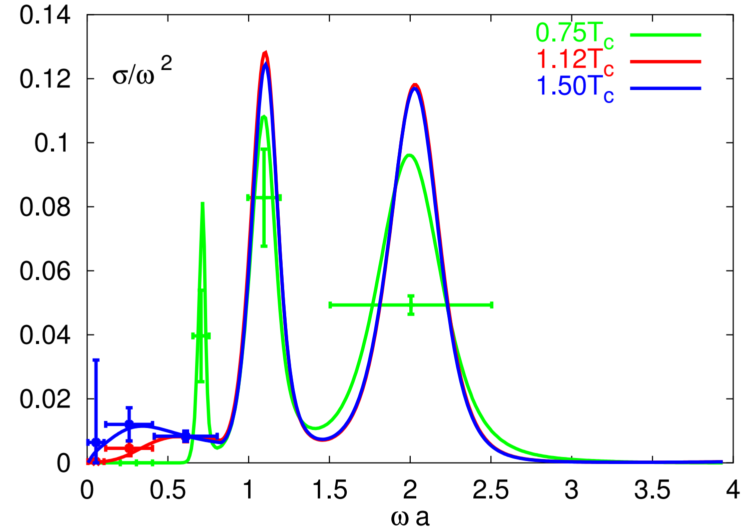
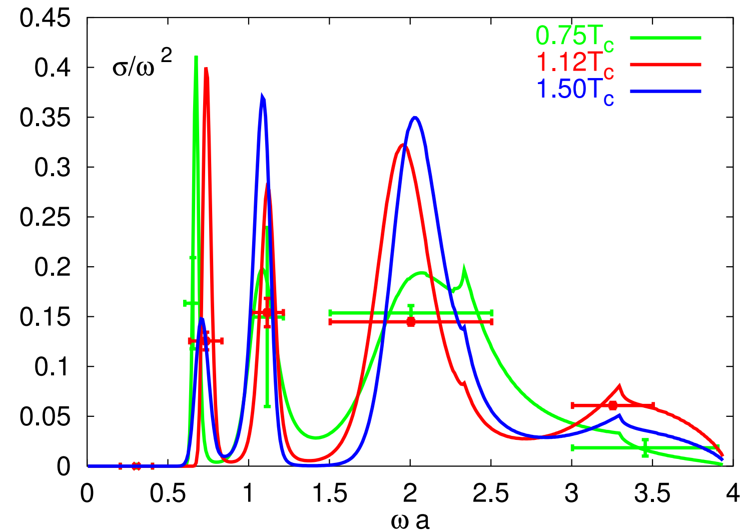


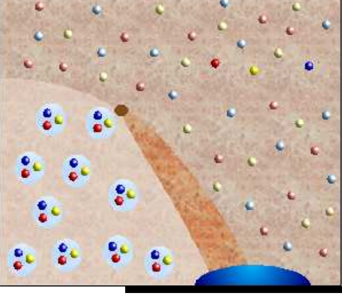
radial excitations (χ_c) disappear at T_c;

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

reconstructed spectral functions using the Maximum Entropy Method







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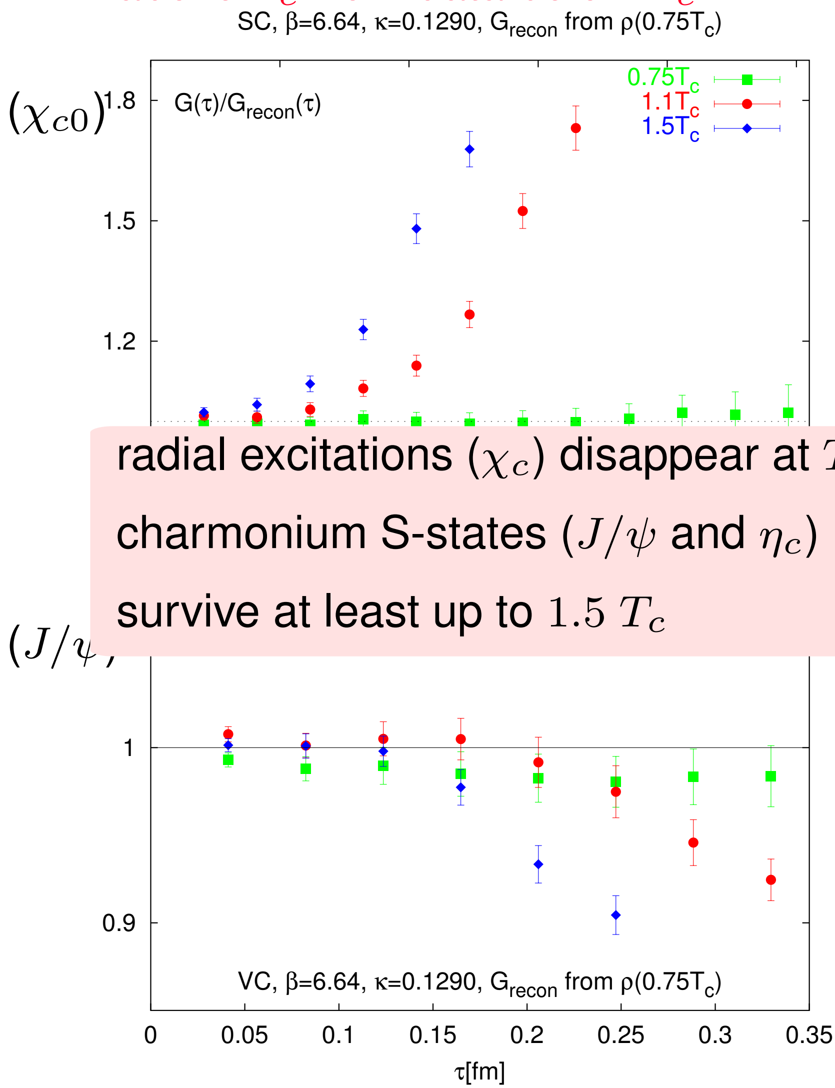

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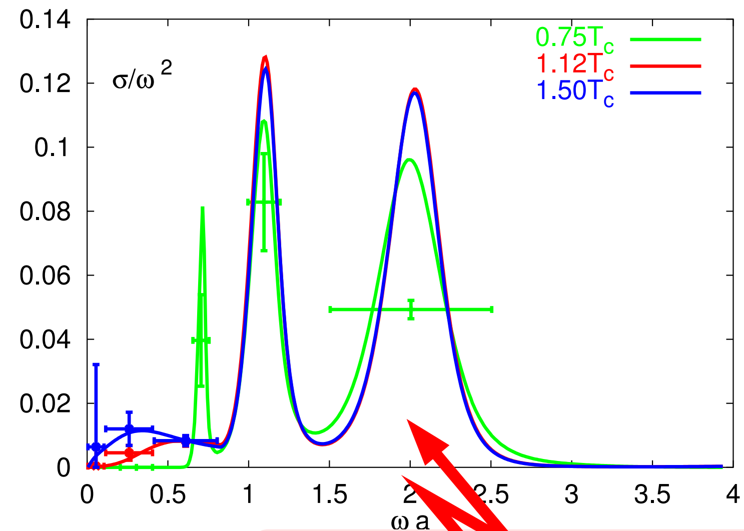
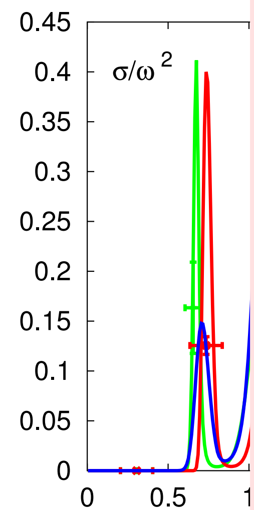
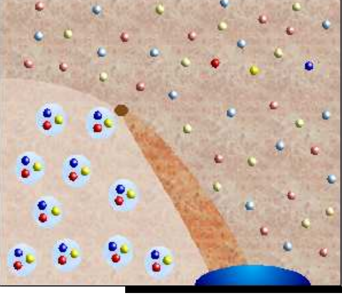




need to get better control over ultra-violet cut-off effects (Wilson-doublers)

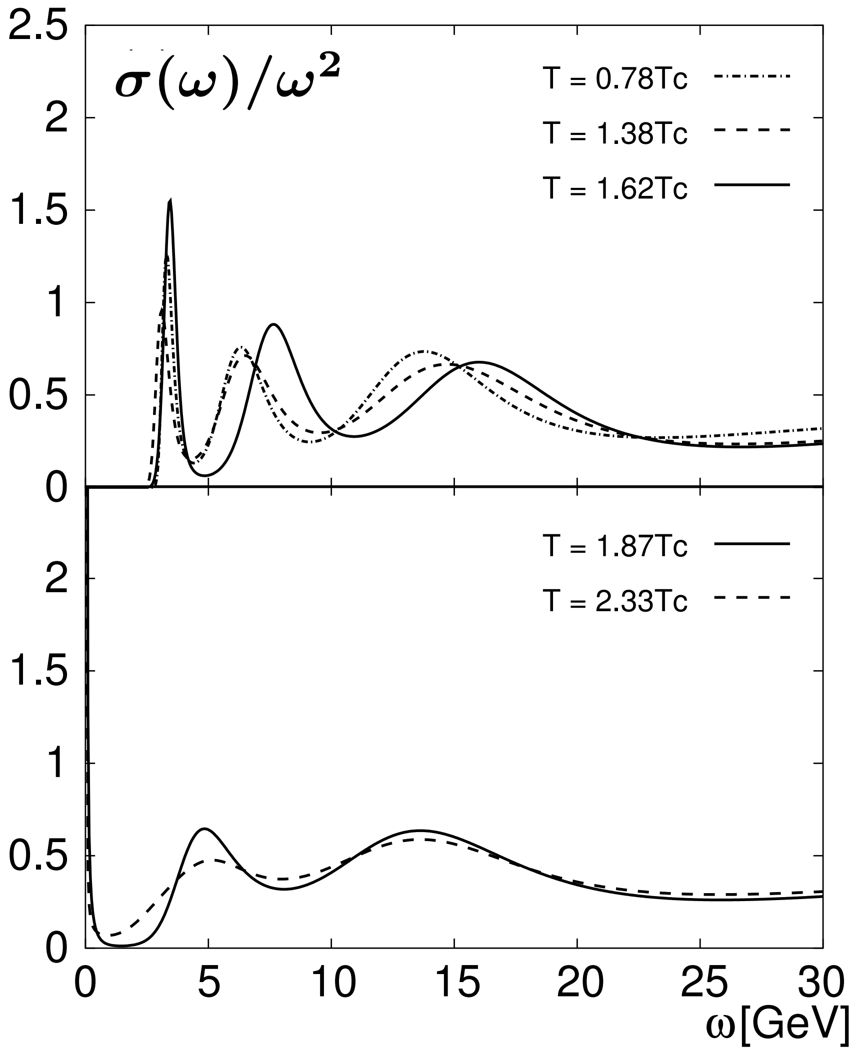
use better fermion actions
- overlap fermions
- domain wall fermions
- (truncated) perfect actions...

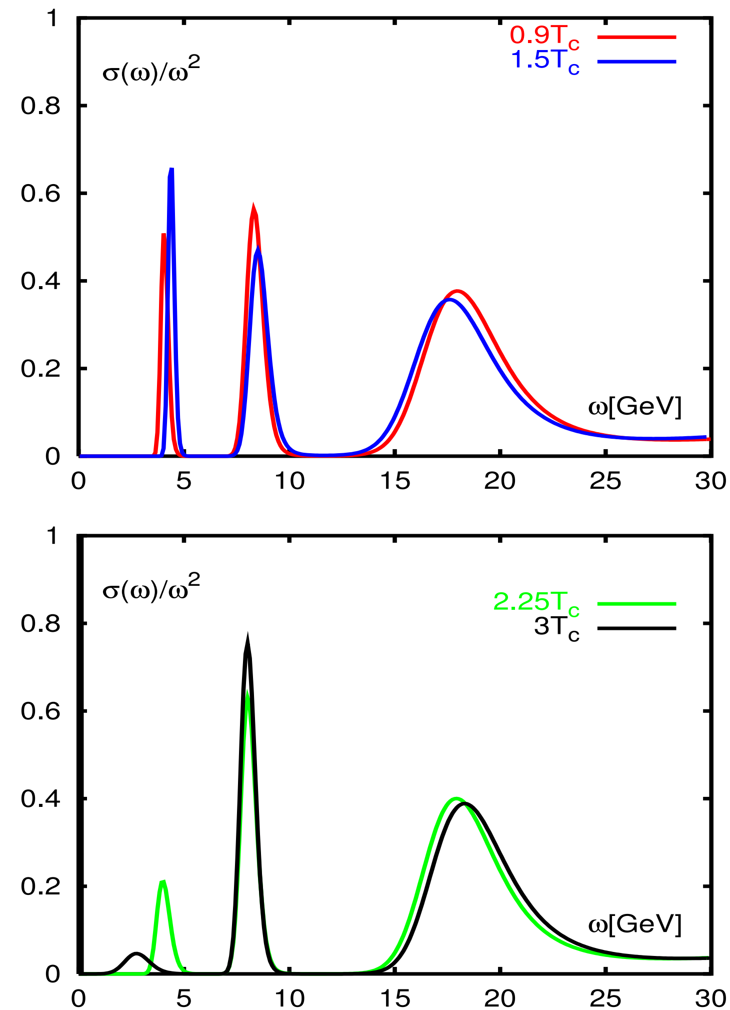


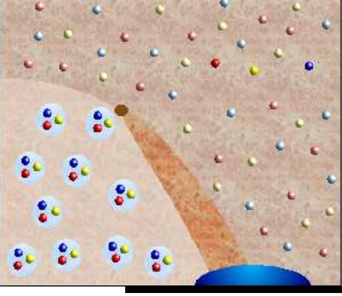
Heavy quark spectral functions
comparison of different approaches

M. Asakawa, T. Hatsuda, hep-lat/0308034 S. Datta et al., hep-lat/0312037

J/ψ spectral function







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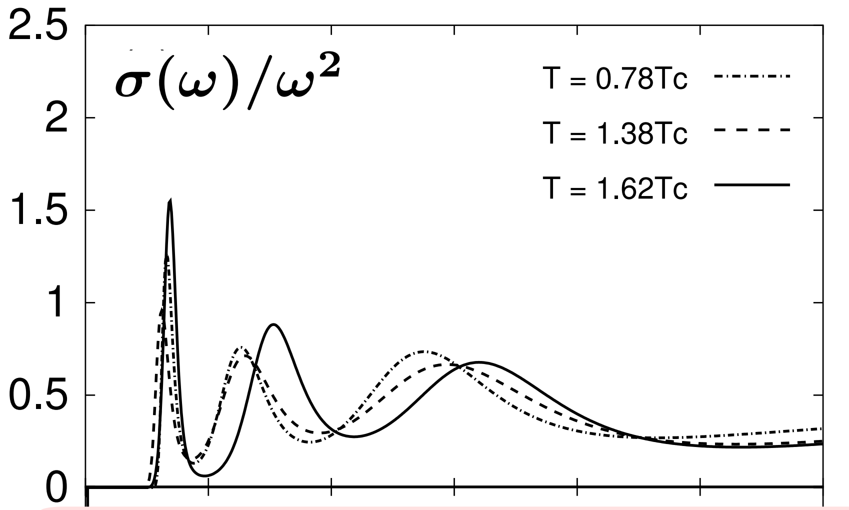
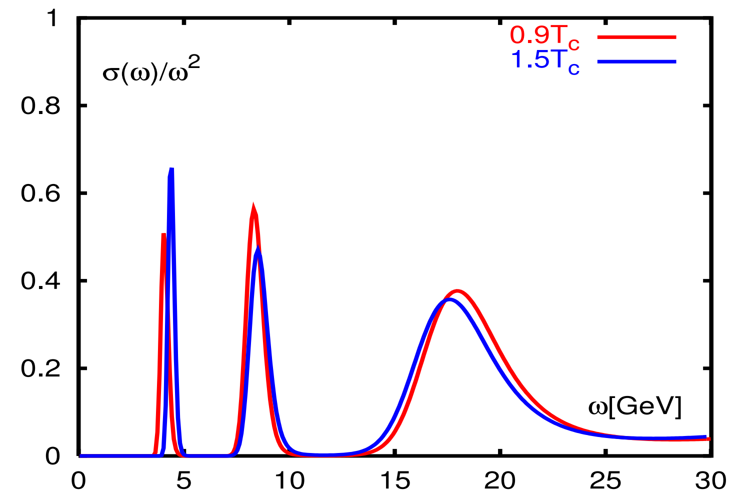
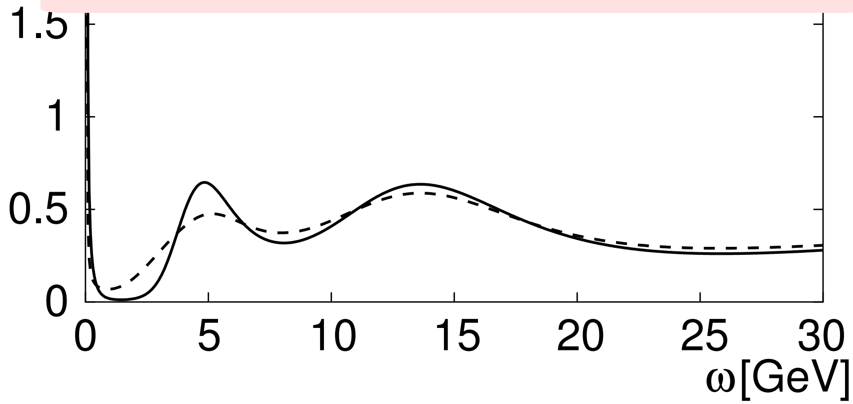
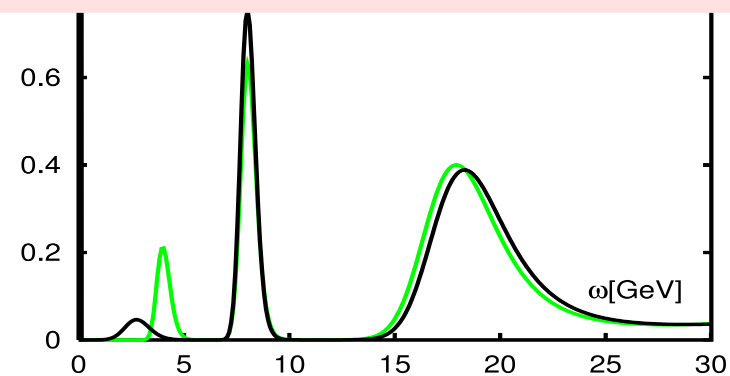


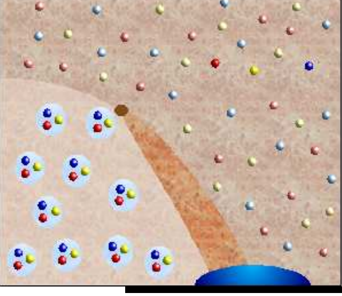


J/ψ dissociates for $1.6T_c \lesssim T \lesssim 1.9T_c$
rather abrupt disappearance of J/ψ

J/ψ gradually disappears for $T \gtrsim 1.5T_c$
J/ψ strength reduced by 25% at $T = 2.25T_c$







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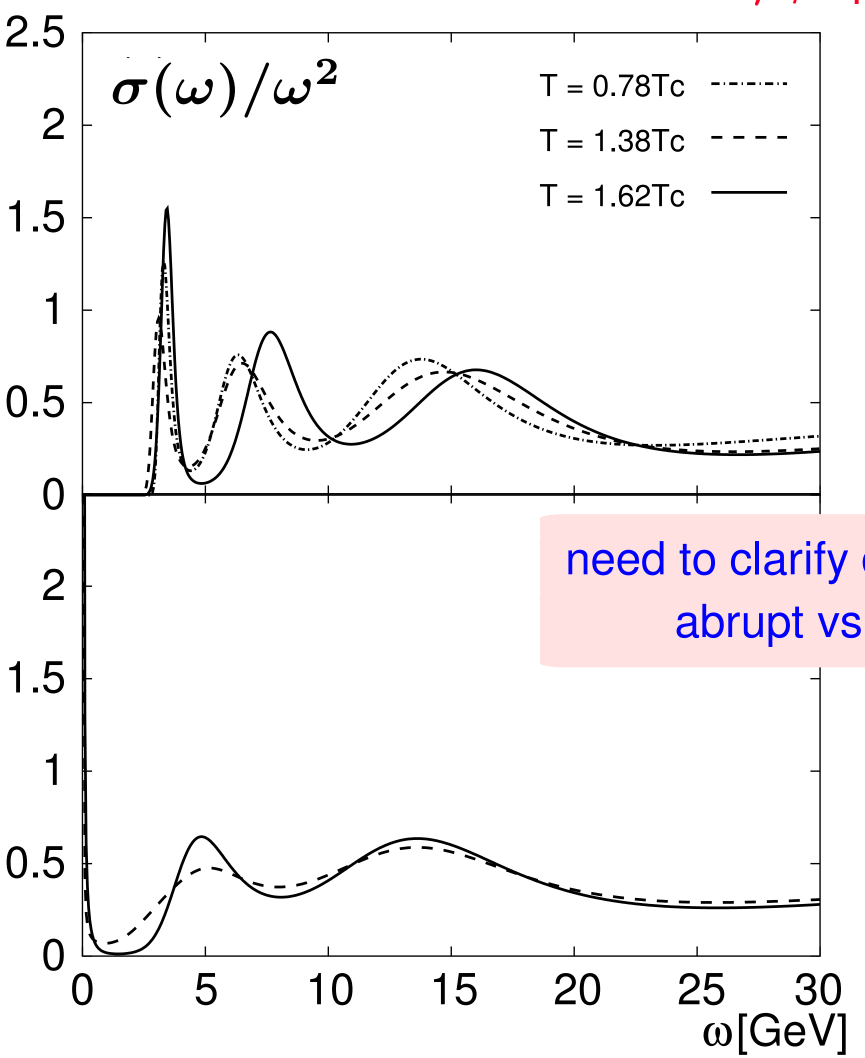
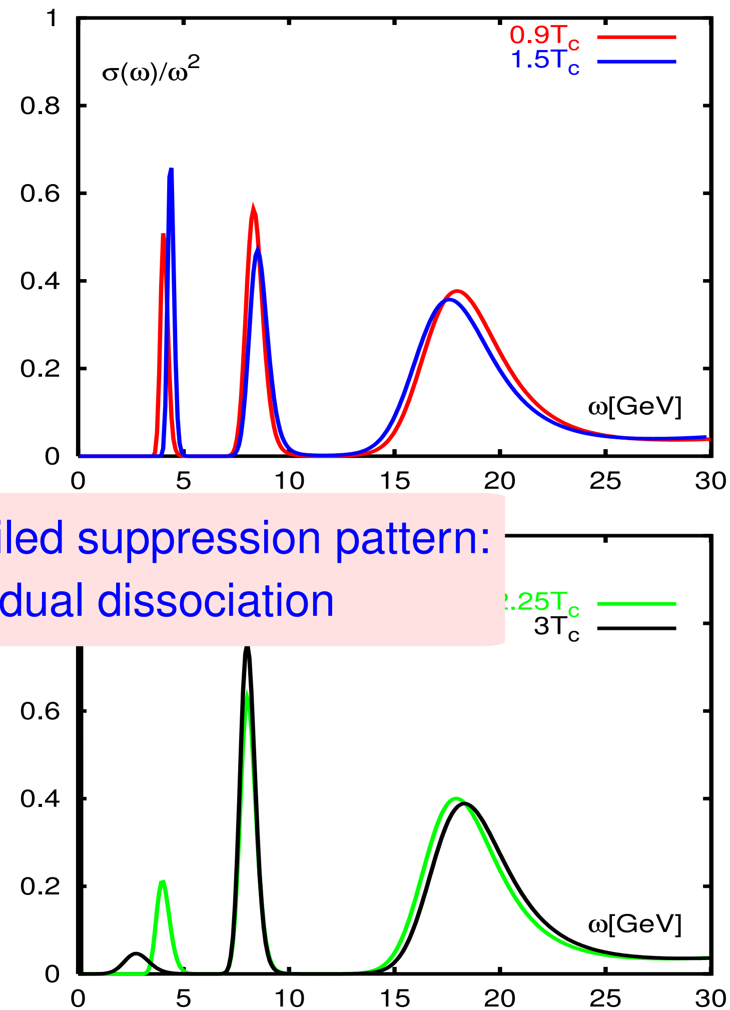
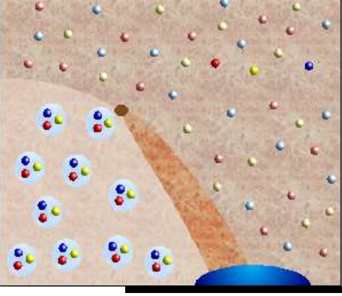




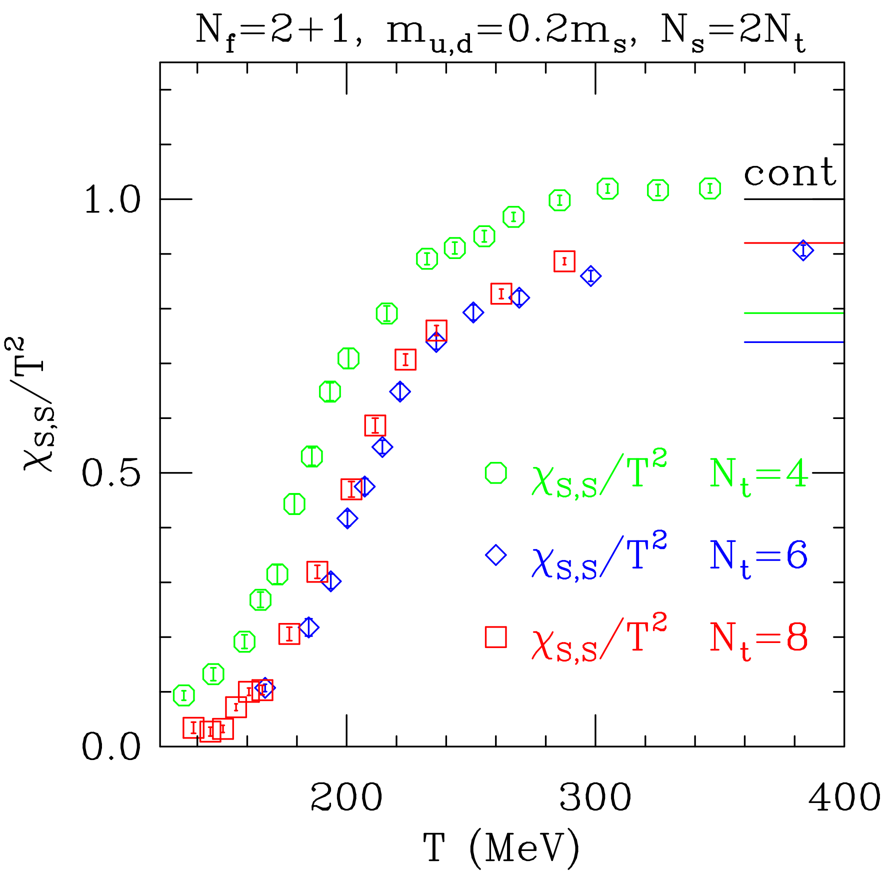
need to clarify detailed suppression pattern:
abrupt vs. gradual dissociation



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

baryon number density fluctuations:
(MILC coll., hep-lat/0405029)

$\mu = 0$

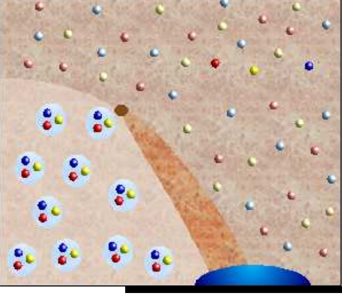


$$\frac{\chi_q}{T^3} = \left(\frac{d^2}{d(\mu/T)^2} \frac{p}{T^4} \right)_{T \text{ fixed}}$$

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

susceptibilities = integrated correlation functions
= integrated spectral functions

to be studied in event-by-event fluctuations

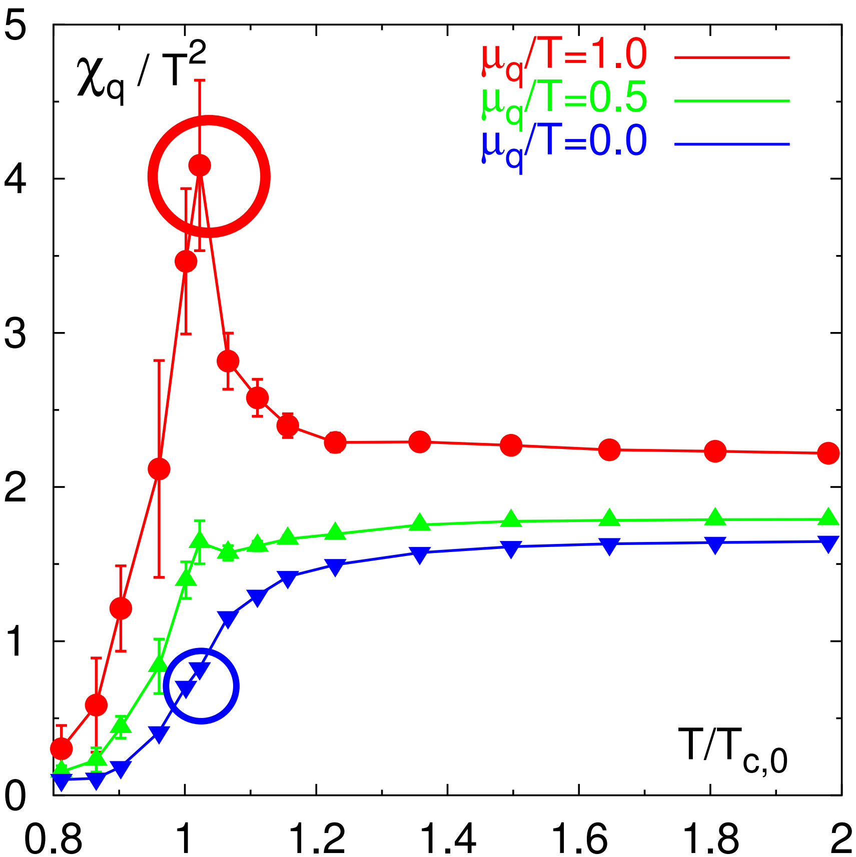


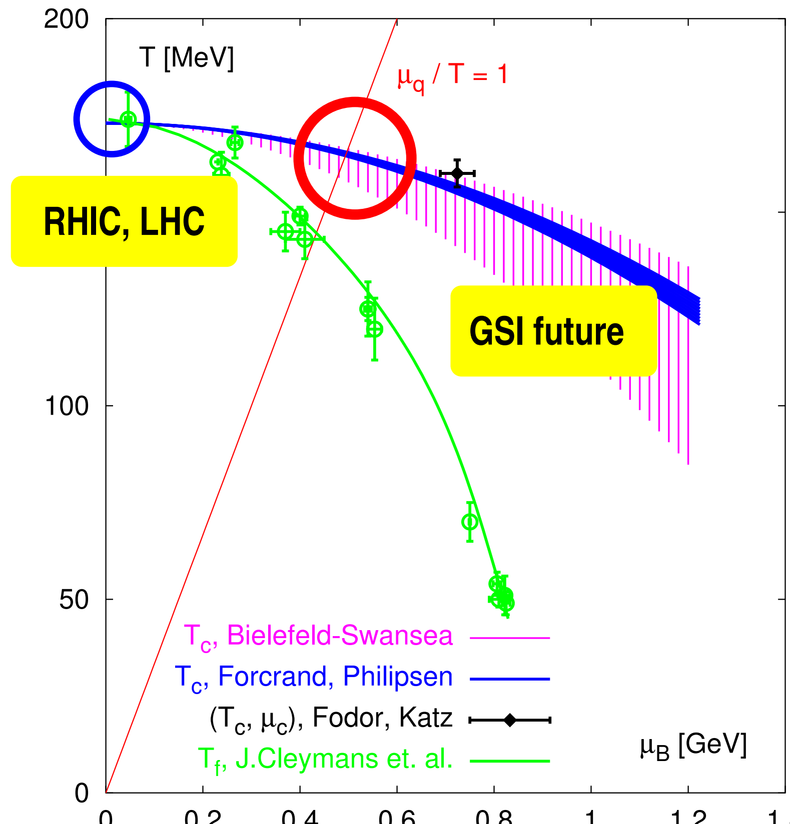
Fluctuations of the baryon number density ($\mu \geq 0$)

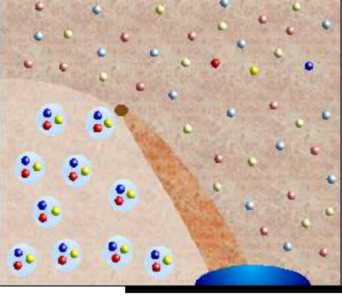
baryon number density fluctuations:
(Bielefeld-Swansea, PRD68 (2003) 014507)
$\mu \geq 0, n_f = 2$

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

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







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

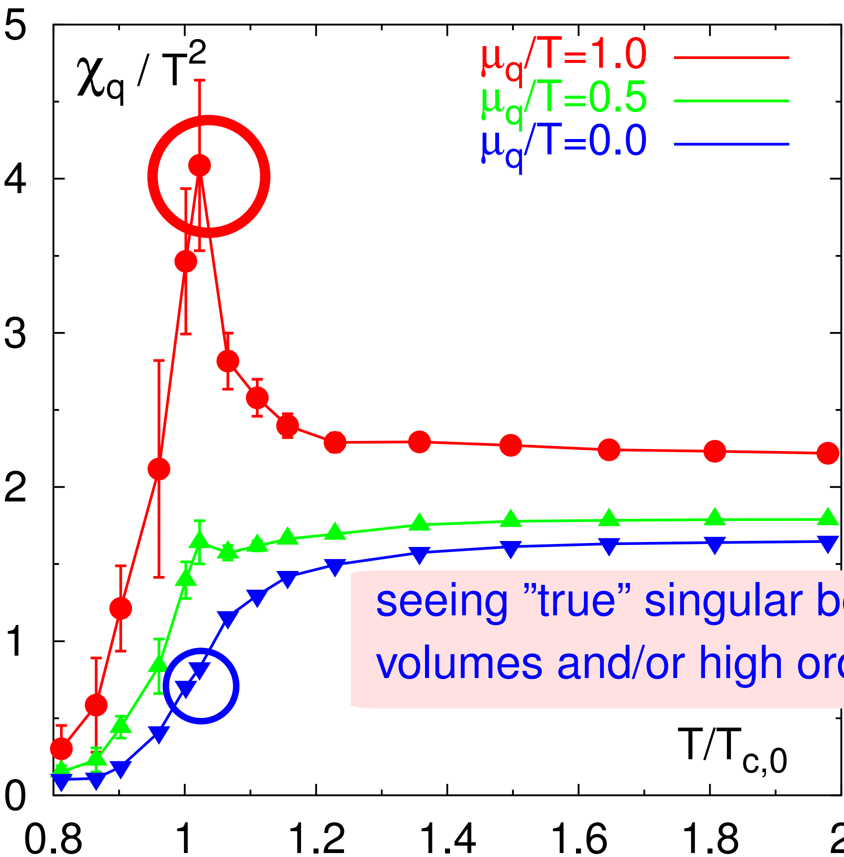
baryon number density fluctuations:

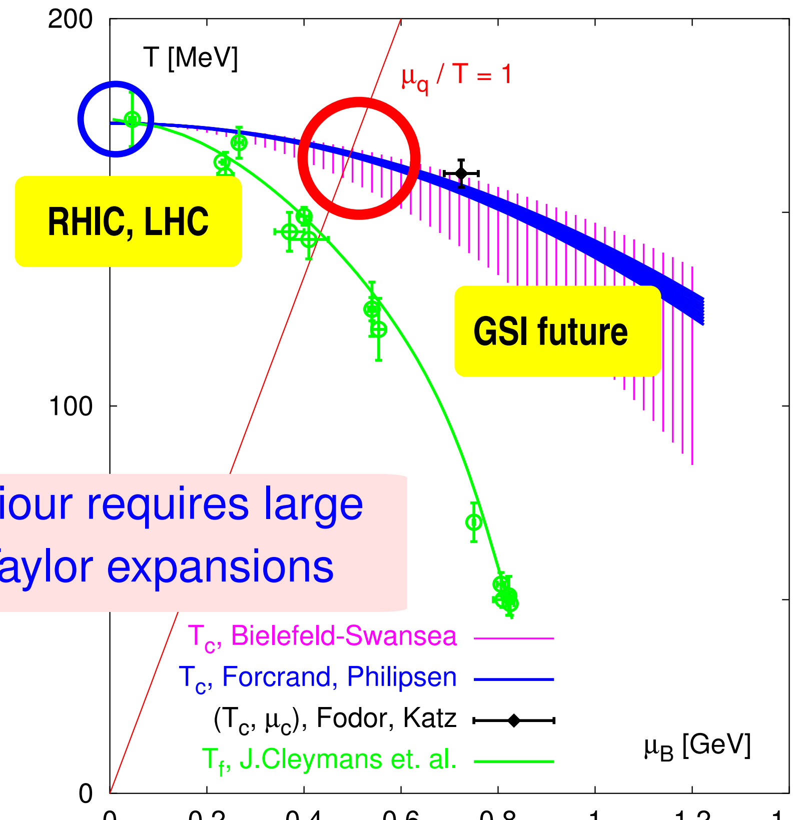
(Bielefeld-Swansea, PRD68 (2003) 014507)

$\mu \geq 0, n_f = 2$

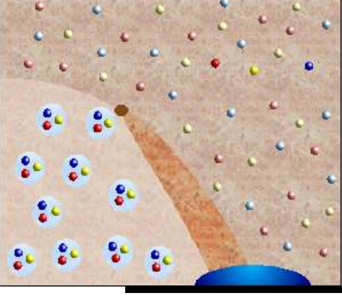
$$\frac{\chi_q}{T^3} = \left(\frac{d^2}{d(\mu/T)^2} \frac{p}{T^4} \right)_{T\ \mathrm{fixed}}$$

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





seeing "true" singular behaviour requires large volumes and/or high order Taylor expansions



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 bulk thermodynamics with light quarks and spectral functions in quenched QCD requires computers with $\sim$10 TFlops peak speed.

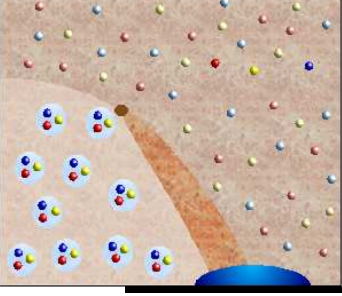
  Germany: LatFor proposal 2003

  http://www.zeuthen.desy.de/latfor/paper.pdf

  US: White Paper 2004

  http://www-ctp.mit.edu/˜negele/WhitePaper.pdf

- Studies of spectral functions of light quark bound states below T_c require simulations with light, dynamical quarks on computers with $\gtrsim$ 100 TFlops peak speed.



Outlook: projects coming soon...

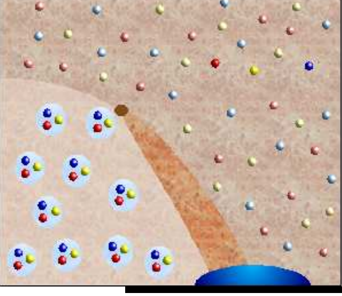
Thermodynamics on a 10 TFlops computer (5 TFlops sustained)

- T_c, EoS ($\mu = 0$ and $\mu > 0$) with light dynamical quarks:
  (2+1)-flavor QCD, close to physical m_π/m_K ratio;
  exploring the continuum limit: $a \simeq (0.1 - 0.2)$ fm
  analyzing the thermodynamic limit: $V \simeq 500$ fm^3

  $\Rightarrow$ lattice sizes up to: $32^3 \times 8$; CPU-time: $\sim$ 5 TFlops-years ($\mu = 0$)
  $\sim$ 5 TFlops-years ($\mu > 0$)

- In-medium hadron properties, charmonium, dilepton rates:
  quenched QCD on fine lattices ($a \simeq 0.02$ fm);
  analyzing light quark mesons with improved fermion formulations;
  exploring infra-red sensitivity of dilepton rates;
  analyzing charmonium spectra;

  $\Rightarrow$ lattice sizes up to: $128^3 \times 32$; CPU-time: $\sim$ 3 TFlops-years



Outlook: projects on future machines...

Thermodynamics on Petaflops computers
(exploratory studies already on up-coming TFlops computers)

- In-medium properties of light quark bound states:
  QCD with light, dynamical quarks on fine lattices become possible;
  mass shifts and modification of widths below T_c
- finite density QCD at low temperature:
  temperatures around $T \sim 0.5\, T_c$ should be accessible
- transport properties:
  calculation of ”gluonic correlator” (energy momentum tensor) should become possible; spectral functions in the $\omega \to 0$ limit may become accessible