Quarkyonic matter:theory and phenomenology

Based on PRL107:152301,2011 , 1204.3272 Stefano Lottini , PRL111 012301 with Sascha Vogel and Bjoern Beauchle
Also , 1006.2471 (PRC),with with Igor Mishustin ,1105.0188 (JHEP) with Piero Nicolini

G. Torrieri

IN LVMINE TVO VIDEBIMVS LVMEN

EMMI

HIC for FAIR
Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

Synopsis

What is quarkyonic matter
Bold claim n.1: I can define and explain what it is!

Large N_c : A short introduction

An estimate from a percolation Ansatz

Towards a pheonomenolgy of quarkyonic matter in supernova and at FAIR/NICA/SPS/RHIC@low$\sqrt{s}$
Bold claim n.2: I might have experimental signatures for it

What is "Quarkyonic matter"

Name introduced in L.MacLerran,R.Pisarski, NPA796 (2007) 83-100
300 Citations, 5 conferences, 1 wikipedia entry. So its a big deal! but definitions found in the literature so far include,these and more...

- Coexistance between Confinement+pQCD (Mclerran,Pisarski,2007)
- Confinement+Chiral restoration (Fukushima,McLerran, 2008)
- Deconfinement+Chirally broken (Satz, Csernai,...)
- Chiral spiral inhomogeneities (Kojo,Pisarski,Tsvelik, 2009)
- Generic chirally inhomogeneus regions (Buballa et al)
- Condensation of "baryons" in 2-color QCD (Hands,Skullerud,Giudice)

All relevant for “high density low temperature” matter, produced in neutron stars or “low energy” uRHICs

- RHIC low energy scan
- SPS experiment NA61
- FAIR
- NICA

What is "Quarkyonic matter"

The "minimalist answer": A name invented in a highly cited paper, Nucl. Phys. A **796**, 83 (2007) , by McLerran and Pisarski, to describe matter at $\mu_Q \geq \Lambda_{QCD}, T < T_c$.
In "physical terms", of chemical potential of more than "one baryon per baryonic volume" but "low temperature wrt deconfinement".

By definition , this is the matter we hope to produce at FAIR/NICA/RHIC scan, and which should exist in neutron stars! So "quarkyonic matter" is simply "quark matter" dense enough that a Fermi surface forms

Was the name a gimmick, Or is there something more to this?

The issue: QCD at $\mu_Q \geq \Lambda_{QCD}, T < T_c$ is really not understood

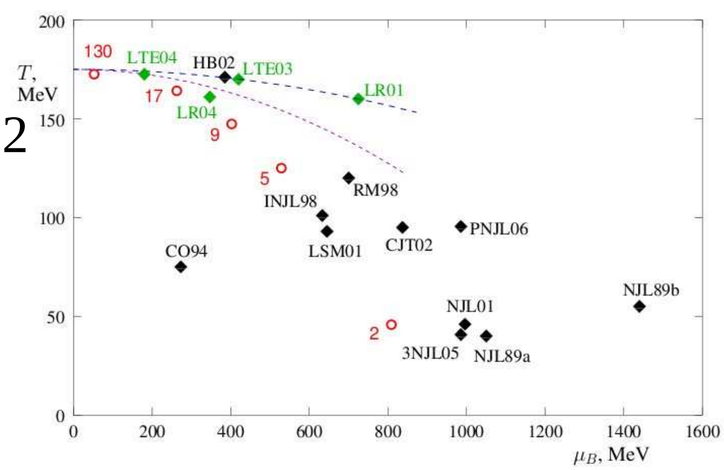
Hadronic or EFTs (σ,NJL,PNJL etc): assume $p_i - p_j \ll \Lambda_{funamental}$

Only scale in QCD is $\Lambda_{fundamental} = \Lambda_{QCD}$, and $p_i - p_j \sim \mu_Q \sim \Lambda_{QCD}$

So EFT at $\mu_Q \simeq \Lambda_{QCD}$ means Taylor-expanding around 1!

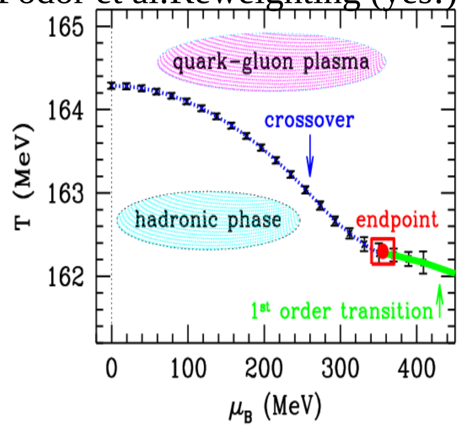
For any operator $\hat{O}(x)$ (e.g. $q, P, ...$) Not guaranteed $\hat{O}^n \ll \hat{O}^{n-1}$ The critical point illustrates this painfully: different models (σ,NJL,PNJL, give wildly different predictions...

M.Stephanov
hep−lat/0701002

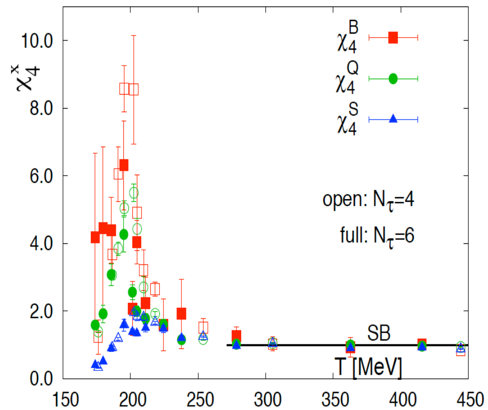


Lattice QCD has the sign problem, any expansion is good for $\mu_q \ll T$

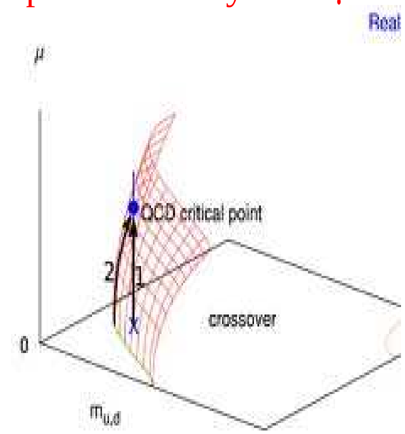
Fodor et al:Reweighting (yes!)



Karsch et al. (Taylor) maybe



Philipsen et al. Taylor+i μ No?



By arguments in the previous slide, most Taylor-expanding methods fail at critical point. We are still not sure critical point exists!

AdS/CFT apart from the many unrealistic assumptions, classical Gauge dual depends on $N_c \to \infty$, on which more later

Any high density calculation is an essentially educated guess. Expect surprizes, dont be disappointed if your favourite model not even qualitatively correct. No reason for it to be!!!! (eg, the critical point might not exist, no matter how many models predict it. Separation of confinement and chiral symmetry, or any chiral inhomogeneus phases, also in doubt)

Chiral symmetry breaking likely 80% due to confinement (since $M_{baryon} \sim 80\% N_c/R_{baryon}$) so models incorporating chiral symmetry without confinement unreliable

eg, Heinz+Giacosa, PRD85 (2012) 056005 ,

$T_c^{\sigma-model} \sim \langle \phi_0(T=0) \rangle \sim \sqrt{N_c} f_\pi \quad , \quad T_c^{QCD} \sim \Lambda_{QCD} \sim N_c^0$

Confinement quintessentially non-perturbative , EFTs problematic

FAIR/NICA/RHICbes is a “shot in the dark”, requiring what if phenomenology ("If in FAIR regime X happens, we should see Y")

The only hyerarchy that seems to be roughly correct is the large N_c limit

$$N_c \simeq 3 \gg 1, N_c^{-1} \ll 1$$

You may laugh, but it estabilishes a rigorous hyerarchy: "fast" quarks (quantum degrees of freedom) vs "slow" baryons (immobile heavy classical background)

- Quasi-particle picture of mesons
- Quasi-classical structure of baryons (Skyrme model)
- OZI rule

all compatible with this hyerarchy

What do we mean by "varying N_c"?

't Hooft, over 20 years ago, showed that provided a continuus limit exists where $N_c \to \infty, g_{YM} \to 0, g_{YM}^2 N_c \to \lambda$,

Not solution to all problems: g_{YM} weak, but λ has approximately same running as QCD, hence $\Lambda_{QCD} \sim N_c^0$

Theory still strongly coupled and confining below Λ_{QCD}

but in this limit drastic semplifications are possible, as some observables $\sim N_c^2$, some $\sim N_c^0$ etc. Plugging in $N_c = 3 \to \mathcal{O}(10)$ hierarchy

N_c scaling results...

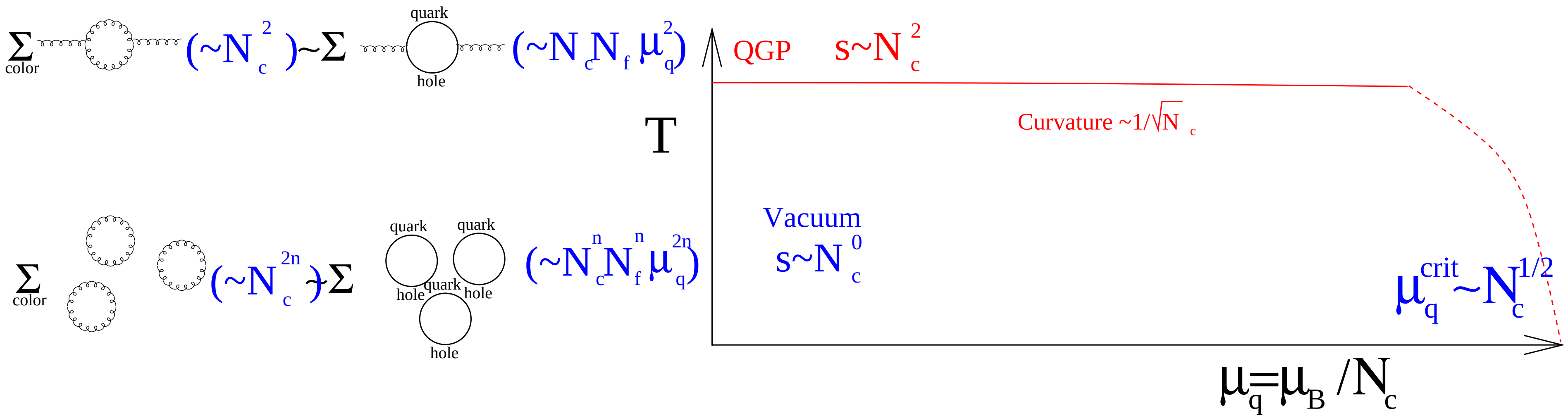
- Planar diagrams dominate, $\Rightarrow$ Strong force $\leftrightarrow$ strings
  Tension $\sim \lambda$,breaking probability $\sim N_c^{-1}$
  AdS/CFT ultimately comes from this analogy!

- Mesons $\rightarrow$ weakly interacting quasiparticles
  Confinement "survives" in $\sim N_c^{-1}$ coupling constant

- Baryons $\rightarrow$ strongly interacting semi-classical states

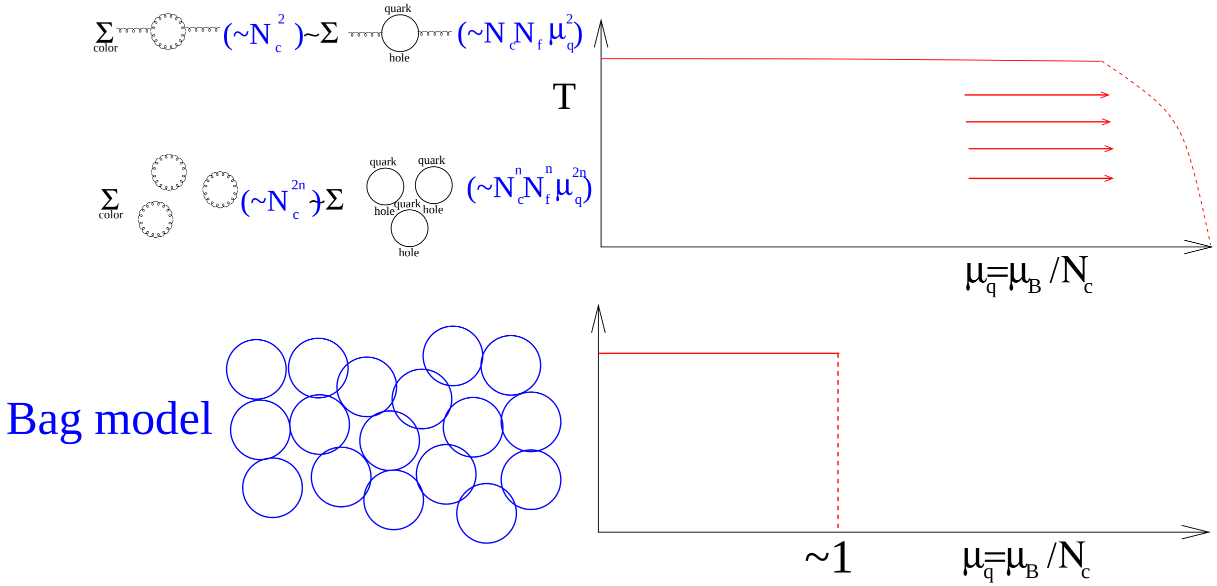
- The phase diagram...

If deconfinement ⇔ quark-hole loops "beat" gluon antiscreening...



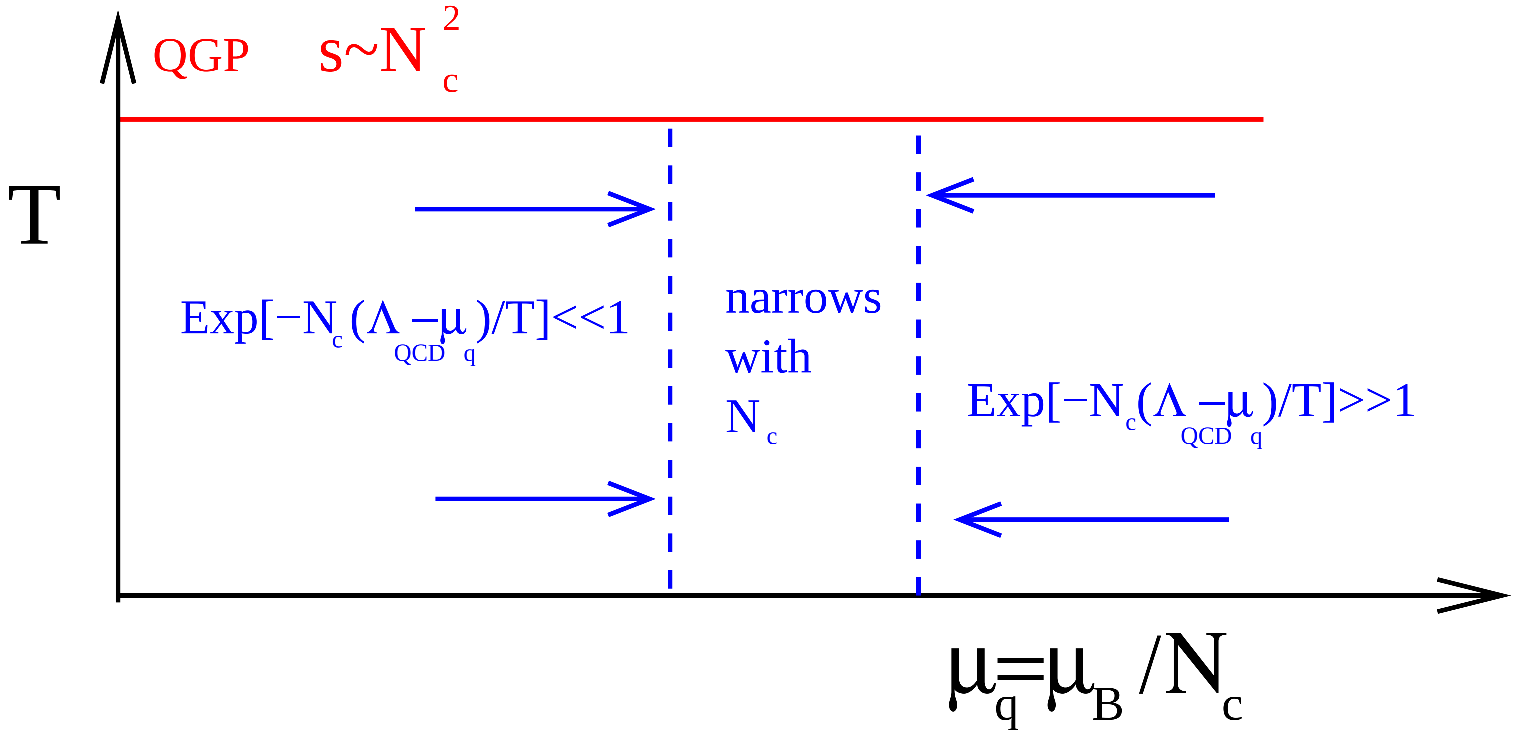
Deconfinement line flattens,for deconfinement $\mu_Q \sim N_c^{1/2} N_f^{-1/2} \Lambda_{QCD}$

NB: higher n order hyerarchy $\sim (N_c/N_f)^{n(n-1)}$, does not help!

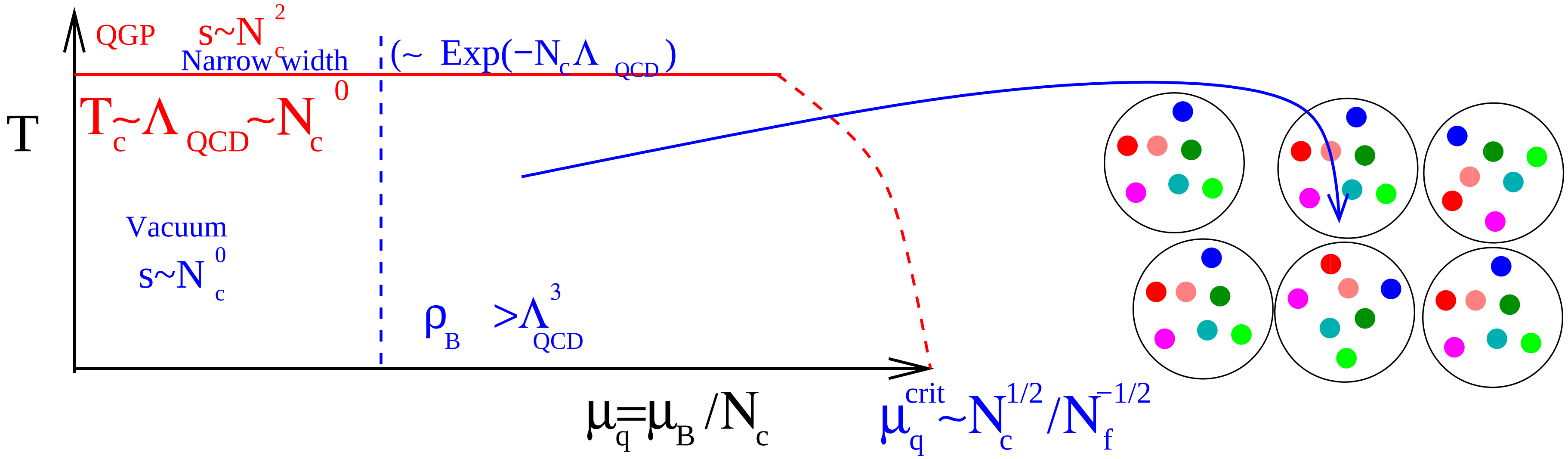


Note: Above is a big if

Above reasoning contradicts, for example, bag model intuition, where $\mu_Q^{crit} \sim T_c \sim \Lambda_{QCD} \sim N_c^0$. The "trick is" it assumes non-perturbative contributions to β-function/confinement order parameters don't have a different N_c dependence, which could dominate at $N_c = 3$. Lets continue to assume this , but its unproven! either alternative is instersting



line separating "vacuum" from "dense nuclear matter" narrows , since baryon abundance in vacuum phase $\sim \exp(-N_c \Lambda_{QCD}/T) \to 0$

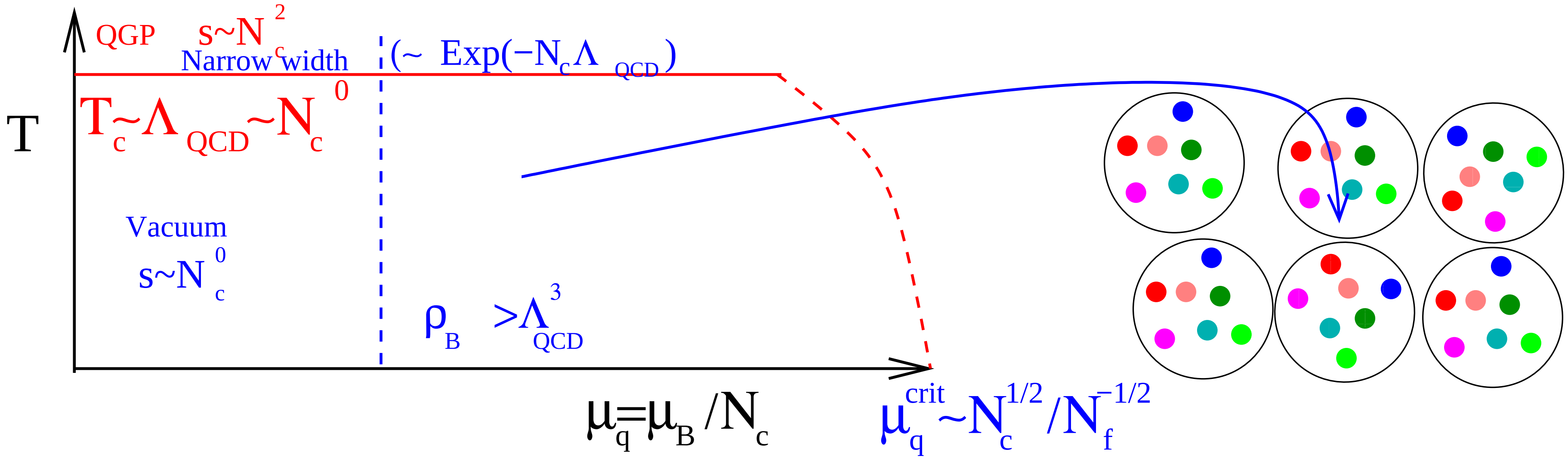


McLerran+Pisarski, arXiv:0706.2191: line at

$$\Lambda_{QCD} \leq \mu_Q \leq \sqrt{N_f/N_c}\Lambda_{QCD}$$

defines new "quarkyonic" phase!

NB: AGS,SIS $\mu_B \simeq 800$ MeV $< m_N$,so it might still be out there!



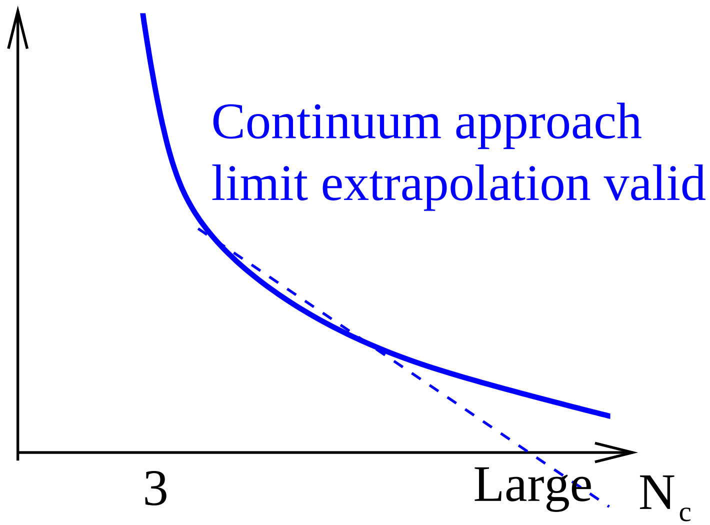
Inter-quark distance in this phase $\sim N_c^{-1/3} \to 0$, asymptotic freedom in configuration space! . Confined but quasi-free quarks below fermi surface and $P \sim N_c$ (quark-hole?)

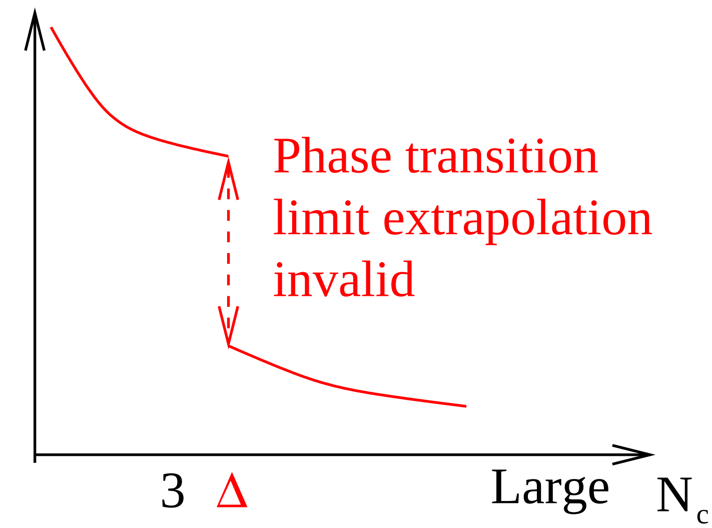
NB: If color can propagate at inter-baryonic distances, "quarkyonic matter"$\equiv$ QGP, "bag model intuition" correct). otherwise , A new phase to look for at low energy, high density (Neutron stars, FAIR, NICA, etc.), In alternative to critical point,but...

Even if we assume our large N_c limits are under control....

Can we exclude phase transitions in N_f/N_c?

Quantity	$N_c \to \infty$	QCD
$E^{binding}_{Nucleus}$	$N_c \Lambda_{QCD}$	$\ll \Lambda_{QCD}, m_\pi$
$\Delta E_{spin-flip}$	$\sim \Lambda_{QCD}/N_c$	$\sim \Lambda_{QCD}$
Ground state	Crystal	Liquid





When you are expanding around the right vacuum, a $\sim 30\%$ correction is OK. When you are expanding around the wrong vacuum, any correction is catastrophic. Sometimes its easy to see this (tachyons!), sometimes not (confinement?)

In fact, phase transitions in N_c are certain to happen I

Confined $SU(N_c)_{N_f=0}$ invariant under symmetry Z_N , spontaneously broken by deconfinement at high T.
These symmetry principles dictate that deconfinement is a phase transition, at $N_f = 0$

At $N_f/N_c \sim 1$, according to the lattice, deconfinement is a cross-over.

So, unless something weird is going on (GW point?) , there is a critical point in N_c for confinement.
"finding" a dual gravity description of this critical point,and measuring its critical exponents, an important test for Gauge/Gravity duality
(M.Sprenger,P.Nicolini,M.Kaminski,GT, work in progress)

In fact, phase transitions in N_c are certain to happen II

At $N_c \to \infty, \mu_B/N_c \sim \Lambda_{QCD}$, the ground state of nuclear matter is widely understood to be a Skyrme crystal I.Klebanov, Nucl.Phys.B262:133,1985

From that paper... *Of course , this treatment ignores the kinetic energy of skyrmions. It can be roughly estimated to be* $1/Mca^2 \sim 100\ MeV$*. Energy of this order is enough to unbind the crystal at* $N_c = 3$
Roughly speaking... baryon mass $\sim N_c$, baryon Fermi motion energy $\sim N_c^0$ so baryon Fermi motion momentum $\sim N_c^{1/2}$, inter-baryon binding energy $\sim N_c$. As we go down in N_c, crystal melts into a fluid; This must be a phase transition, as symmetries change!

The Landau algorithm:

a) Formulate simple picture of the problem
b) Solve it

The best physicist in the USSR is Yakov Frenkel, who uses in his papers only quadratic equations.
I am slightly worse, I sometimes use differential equations.

L.D.Landau, quoted in
BULLETIN OF THE American Mathematical Society
Volume 43, Number 4, October 2006, Pages 563−565

The Feynman algorithm
a) Write down the problem
b) Think REALLY hard
c) Write down solution

The rest of this talk: Toy models which hopefully reproduce the issues discussed until now!

Nuclei and their interactions at large N_c use the Van Der Waals EoS

$$\left(\rho^{-1} - b\right)\left(P + a\rho^2 - g\rho^3\right) = T$$

b Is the excluded volume

a,g are the interaction. For <u>any</u> radial interaction $V(r)$,they came out as terms in the expansion of $\prod_{ij} \int dx_{ij} e^{-\frac{V\left(x_{ij}\right)}{T}}$

Solvable analytically, universal, connected to black holes (A. Chamblin, R. Emparan, C. V. Johnson and R. C. Myers, PRD 60, 064018 (1999))

Only scale at of theory large N_c is Λ_{QCD} ! This is the inverse of the confinement scale (empirically $\Lambda_{QCD}^3 \sim \langle \psi \overline{\psi} \rangle$.).

It is therefore natural to decompose VdW equation into dimensionless components (functions of N_c) and the appropriate power of Λ_{QCD}

$$\left(\rho^{-1} - \alpha\right)\left(P + \beta\rho^2 - \gamma\rho^3\right) = T$$

α is in Λ_{QCD}^{-3}

β is in Λ_{QCD}^{2}

γ is in Λ_{QCD}^{5}

Factors of Λ_{QCD} neglected henceforward

BUT universality has limits ...

- No chiral symmetry (Ask me at the end!)

- in VdW, interactions integrated out so carry no entropy.

  inappropriate for measuring the entropy content of,say,electron gas (interaction-dominated).

  So might be inappropriate for understanding the liquid phase if its entropy resonance (or residual quark interaction)dominated as in the quarkyonic conjecture

  ...but can still give phase transition line!

How does α depend on N_c?

- α can't go below unity (deconfinement).
- In the large N_c limit, the only scale is Λ_{QCD} . It is therefore natural that

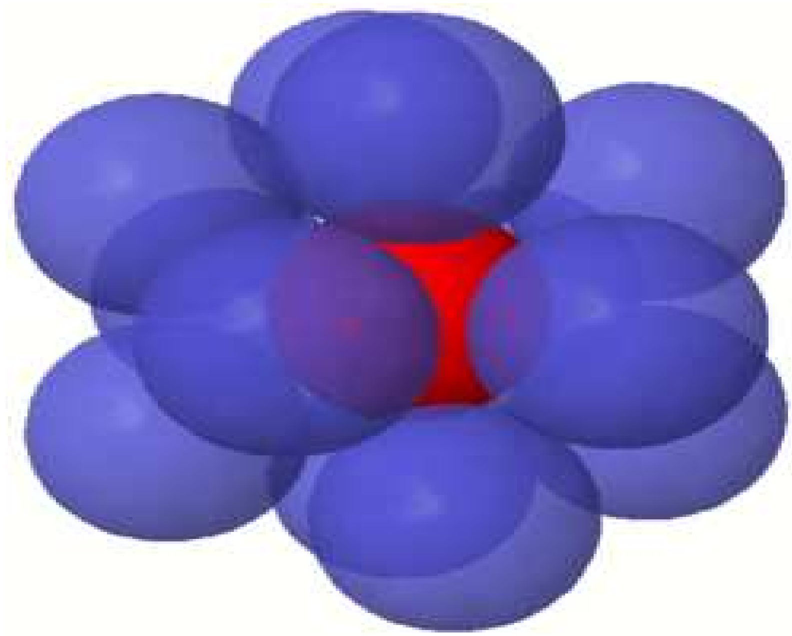
$$\lim_{N_c \to \infty} \alpha = \Lambda_{QCD}^{-3}$$

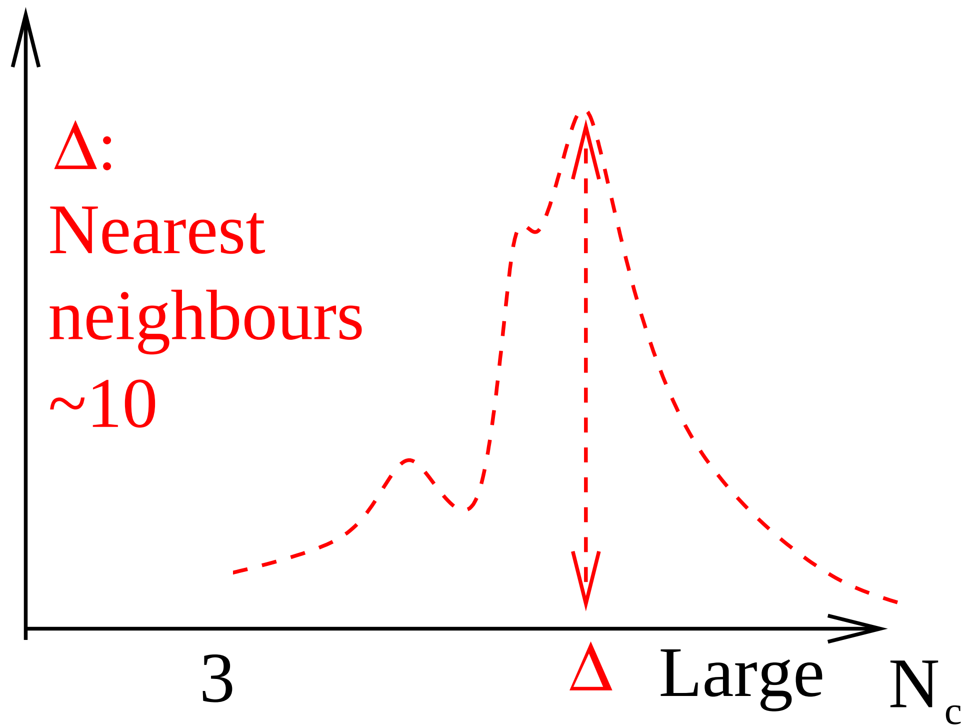
It can not have an $N_c^{a>1}$ leading term, since Baryon size does not diverge. But in our world, $\alpha \gg \Lambda_{QCD}^3$

$$\alpha \sim 1 + \frac{A}{N_c}$$

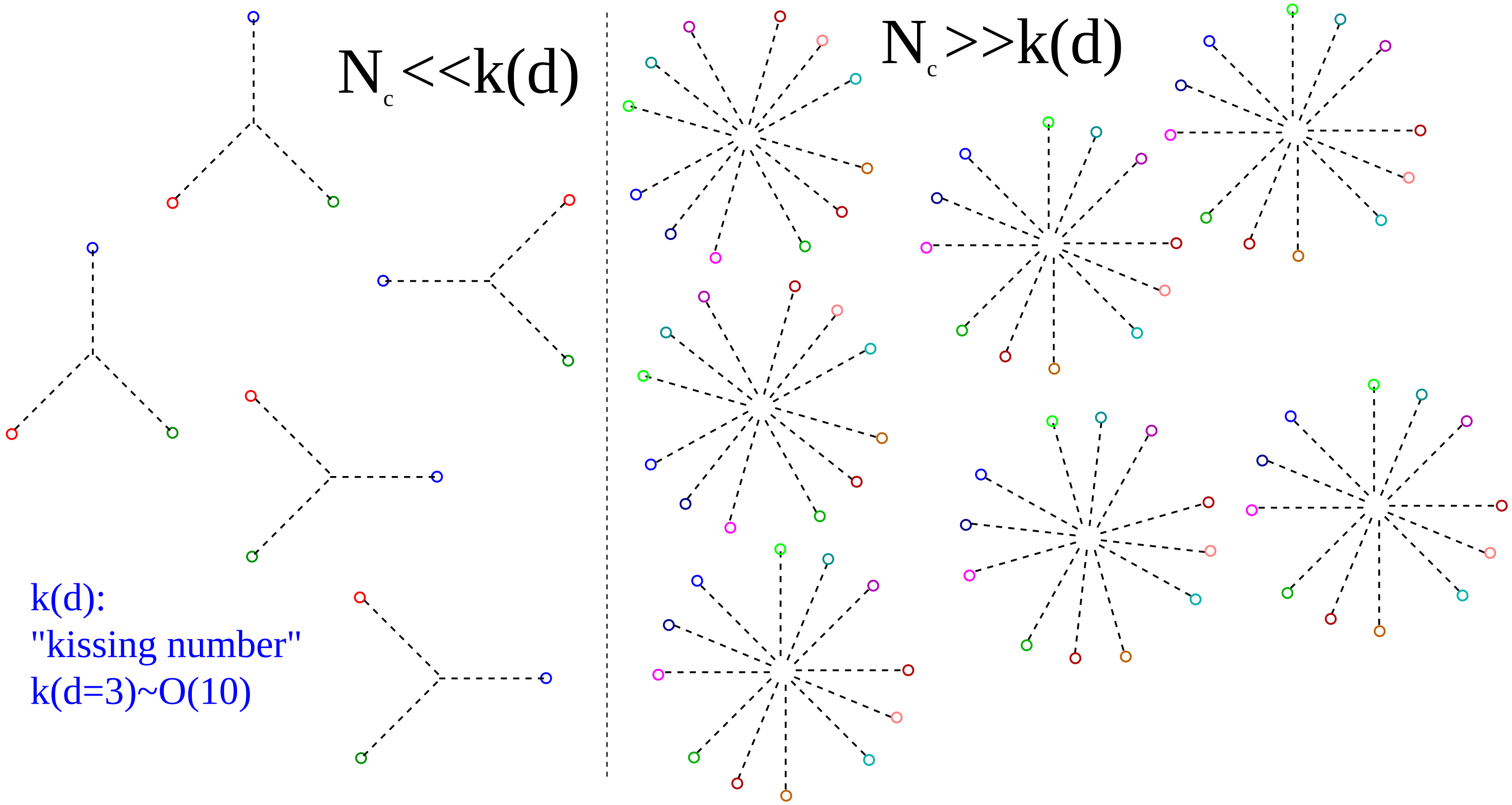
and the A term dominates!

My guess is, we dont live in a large N_c world!





The other scale of the problem is the the number of neighbours in tightly packed syst
"kissing number", exact dependence on d unknown
$k(d) \sim 2^{\zeta d}, k(1,2,3,4) = 2,6,10,24$, of course $\sim N_c^0$, $k(d=3) \gg 3$



Pauli exclusion principle in valence picture irrelevant for $N_c \gg k(d)$, but not for $N_c = 3$. Keeps nuclei further apart than Λ_{QCD}^{-1}

$$\alpha \sim 1 + \frac{N_N}{N_c} \sim 1 + \frac{k(d)}{N_c} \sim 1 + \frac{10}{N_c}\Big|_{3d}$$

- Fits nuclear VdW at $N_c = 3$

- Compatible with strongly coupled nuclear matter at $N_c \gg 3$

- Understandable by Pauli exclusion principle
  Spin, flavor complicates things. But in our world $\Delta E|_{spin flip} \sim \Lambda_{QCD}$,
  flipping flavor suppressed

$$\alpha \sim 1 + \frac{N_N}{N_c} \sim 1 + \frac{k(d)}{N_c} \sim 1 + \frac{10}{N_c}\Big|_{3d}$$

What this means:

- confinement scale $\gg$ nuclear separation up to $\sim$ deconfinement potential!

- Expansion in $\rho^n/\Lambda_{QCD}^{3n}$ progressively worse but always converges

Trust diagram, but not factors of $\mathcal{O}(1)$

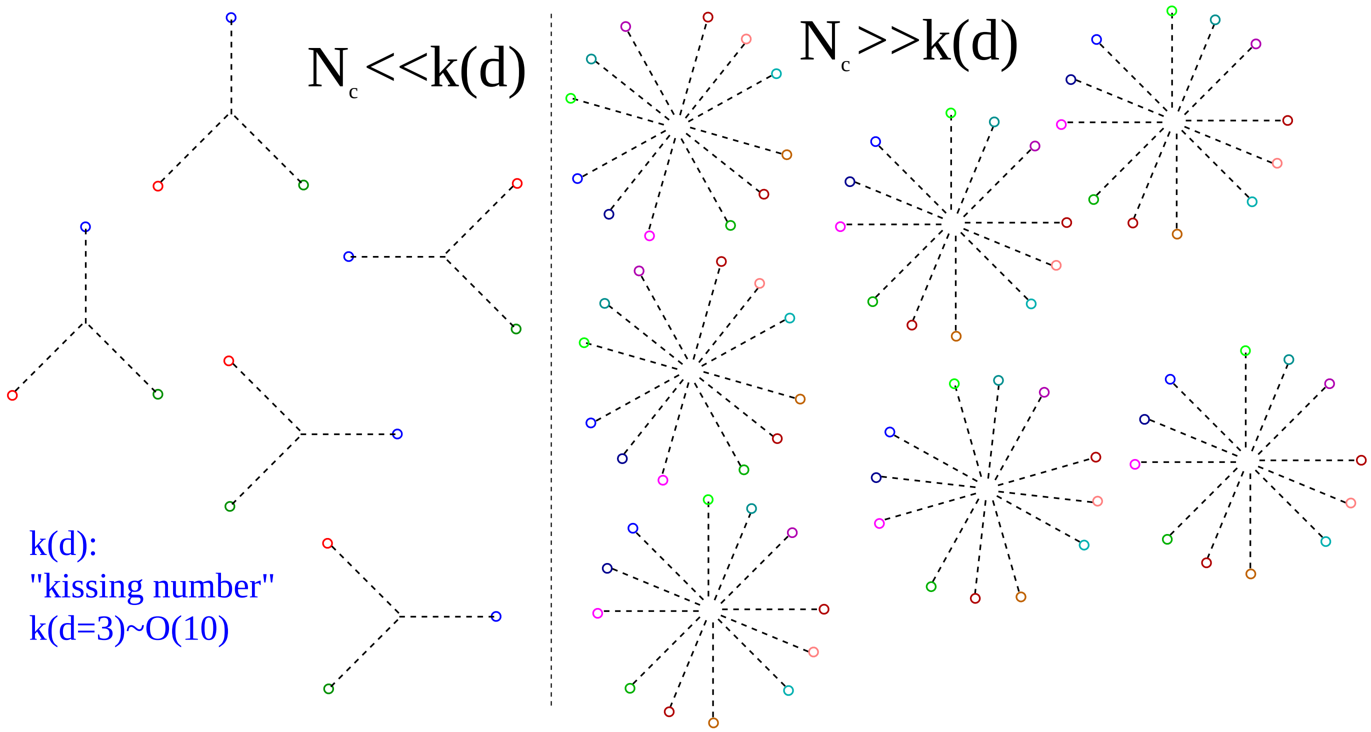
- β, γ Have to scale the same way, since same interaction

- Witten 's solitonic picture of the nucleon: $\beta, \gamma \sim N_c$
  Weak ($\ll$ even m_π) nuclear force an accidental cancellation.
  Witten says that all $(2,3,n)$ body forces scale as N_c . Weinberg 's hyerarchy, $n - body$ nuclear forces $\sim (k/\Lambda_{QCD})^n \sim \left(\rho^{1/3}/\Lambda_{QCD}\right)^n$ complementary:N body forces all $\sim N_c$ but $2 > 3 > ...n$ Same as VdW expansion! .

- Y. Hidaka, T. Kojo, L. McLerran and R. D. Pisarski, 1004.2261 : This picture is wrong (skyrmion unstable, stabilized by large quantum corrections which put $N_c - 1$ quarks into diquarks).
  Nuclear force carried by remaining quark,so $\beta, \gamma \sim N_c^0$ or $\sim \log N_c$ Weak nuclear force natural

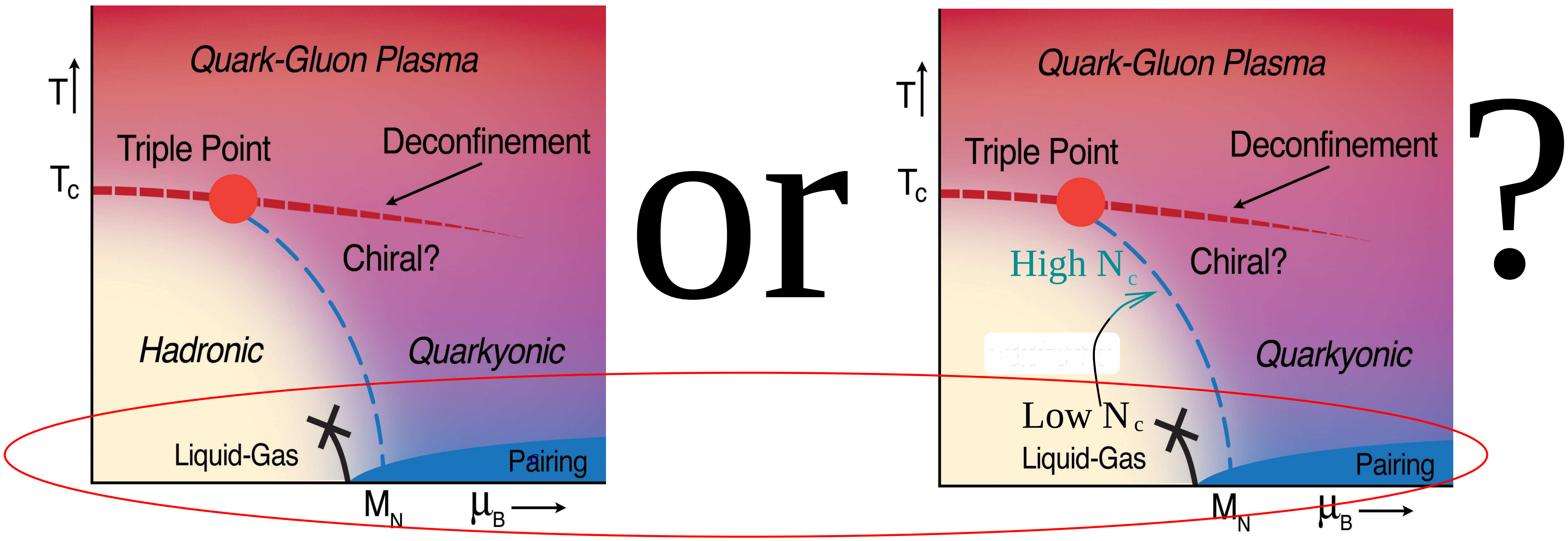
Room for phenomenological playing: Try $\beta, \gamma \sim N_c^\nu, \nu = 0, 1$

Can we say anything more about a critical N_c?



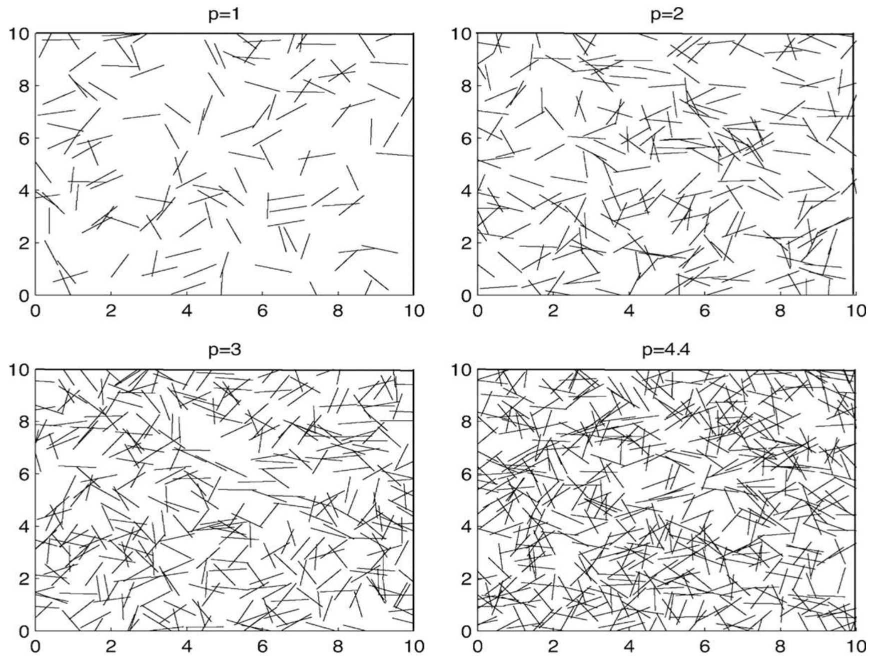
@$N_c \to \infty$ baryons classical. In-medium ($\rho_B \sim \Lambda_{QCD}^3$), $N_c \to \infty$ is when Pauli principle satisfied by color rotations :
$N_c \geq N_{neighbors} \sim k(d=3) \sim \mathcal{O}(10)$.

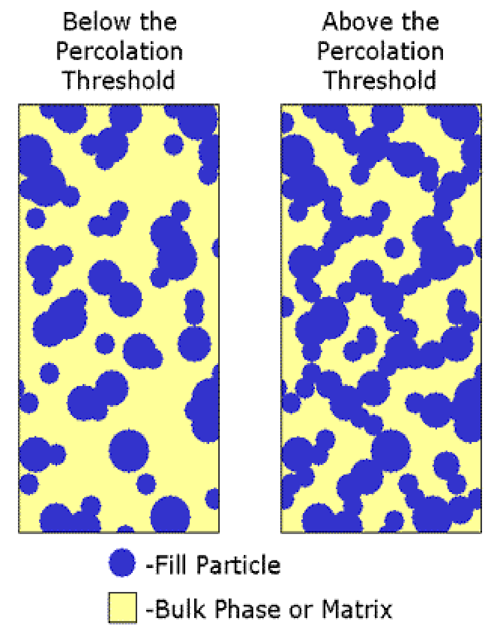
GT,I.Mishustin, PRC82 055202 such a quantum-to-classical transition might drive $E_{binding}^{NN} \sim \mathcal{O}(10)\, GeV \ll m_\pi, \Lambda_{QCD}$.



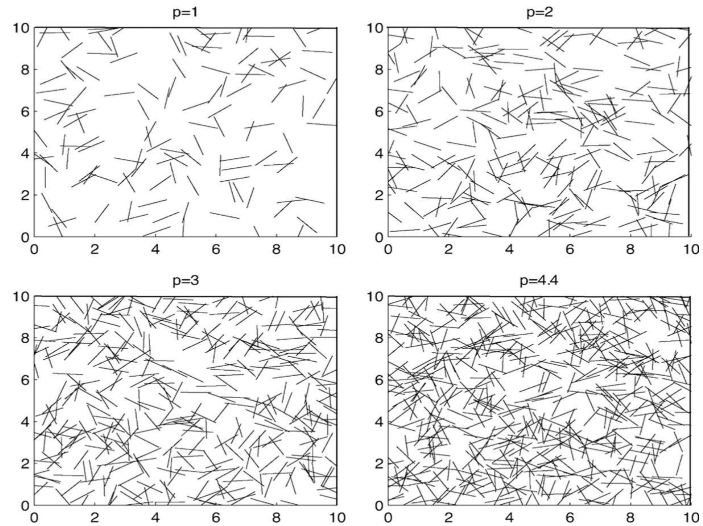
GT,I.Mishustin, PRC82 055202 "quarkyonic matter" might be nuclear matter at $N_c \gg N_{neighbours}$. Or not as depedence on flavor, density not so clear. But $N_{neighbors}$ scaling motivates percolation.

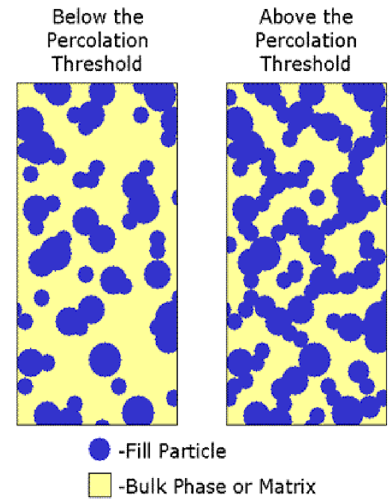
Percolation: the archetypal 2nd order transition





Basic idea: You have a (regular or irregular) lattice of sites, which can be "on" and "off" (links "switched on", particles "in sites", etc), with probability p . Count adjacent sites $\langle N_{sites} \rangle$. When $p \simeq p_c$, $\langle N_{sites} \rangle \to \infty$





- second order transition ($\langle N_{sites} \rangle \equiv$ correlation), with <u>critical behavior</u>.

- $p_c(1D) = 1, p_c(2D) \sim \mathcal{O}(0.5), p_c(3D) \sim \mathcal{O}(0.2)$ (depends on $N_{neighbors}$). So "small" $\sim N_c^{-1}$ correction could trigger it.

Some people have tried to describe <u>deconfinement</u> by percolation of strings/bags, but order of phase transition missed.

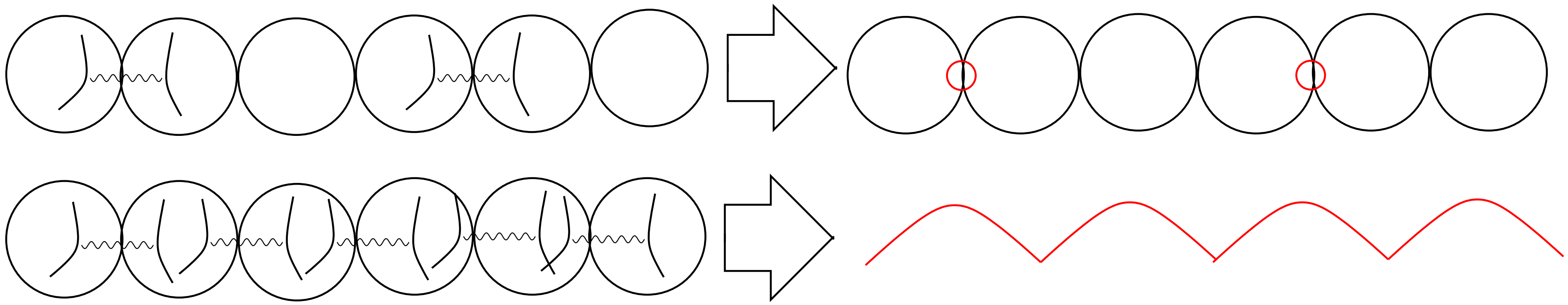
an EFT of $\mu_Q \sim \Lambda_{QCD}, N_c \gg 1$ matter

Baryons are heavy and immobile "background"

Quarks are delocalized, since $\rho_{baryon}^{-1/3} \leq R_{baryon}$ Such delocalization compatible with confinement

An immediate physical analogy: conductor in QED, with baryons playing the role of atoms.

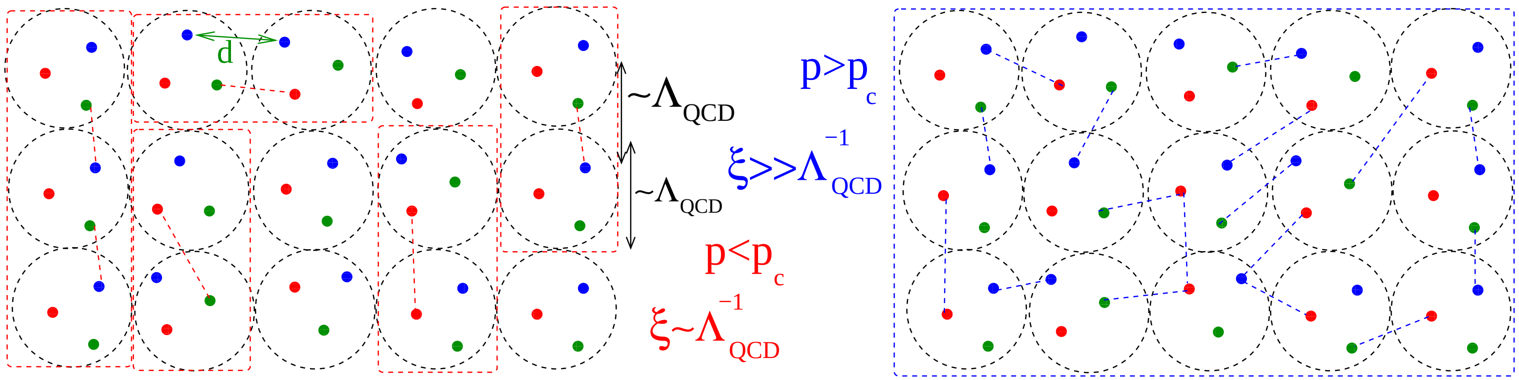
Such a "conducting phase", not predicted by any EFT, could be the "surprise" we were looking for



But remember, conductor insulator phase transition is governed by number of electrons in the "conducting band".

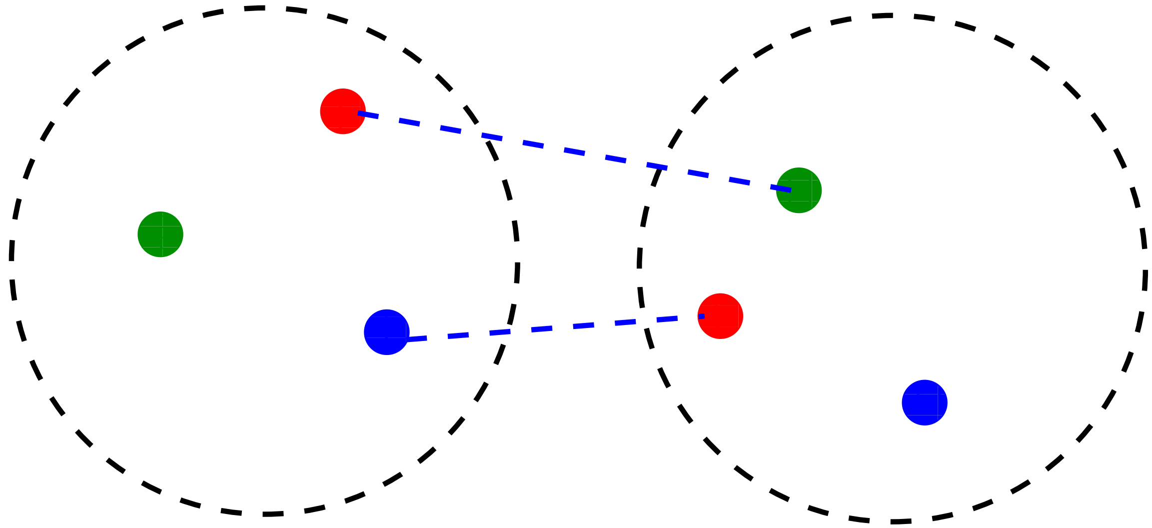
However , since Quark/baryon $\sim N_c$, conductor/insulator transition in full $T - \mu_Q - N_c$ space!

N_c scaling and Percolation at $\mu_Q = \Lambda_{QCD}$



Intuitively, relevance of percolation clear. With N_c colors, ways two baryons can interact with one another grows fast with N_c . Correlation length diverges at percolation, so existence of transition independent of microscopic details (within reason)

Calculating percolation probability at $\mu_Q = \Lambda_{QCD}$

p$\sim$ 

In large N_c limit, assume "perturbative" ($\sim \lambda N_c^{-1}$) interactions between "confining" quarks. Picture insensitive to further details

NB: all dependence on N_c only, the N_c vs $N_{neighbors}$ requirement for classical baryons also depends on N_f This transition different from VdW, as only scales with N_c!

An ansatz with confinement and correct N_c scaling

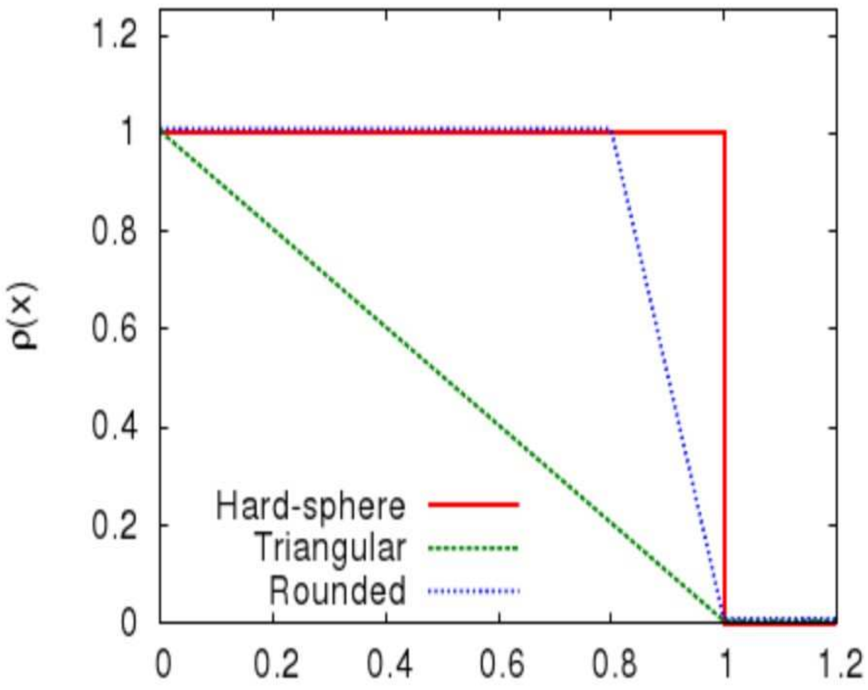
$$p = 1 - \left(q_{(1),ij}\right)^{(N_c)^\alpha} \quad , \quad q_{(1),ij} = \int f_A(x_i)\mathrm{d}x_i \int f_B(x_j)\mathrm{d}x_j \left(1 - F(|x_i - x_j|)\right)$$

Mathematically very similar to Glauber model, dont need to get σ exactly right to get N_{part} dependence. In same way, we put in sample propagators to get N_c dependence.

We assume a density distribution with a range of ρ s of the form

$$f_{A,B}(x) = \rho\left(\Lambda_{QCD}^{-1} - \left|x - x_{A,B}^{\text{center}}\right|\right)$$

A range of ρ considered



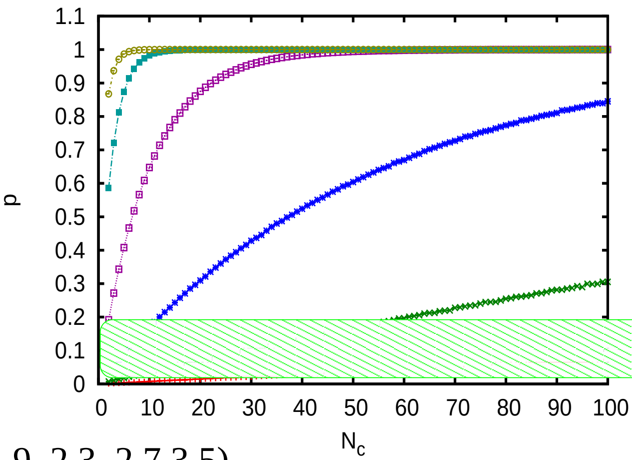
...and a range of probability amplitudes for the exchange $i \leftrightarrow j$ which respect

- Confinement (rapid fall-off at distances Λ_{QCD}^{-1})
- N_c scaling ($\sim \lambda/N_c$)

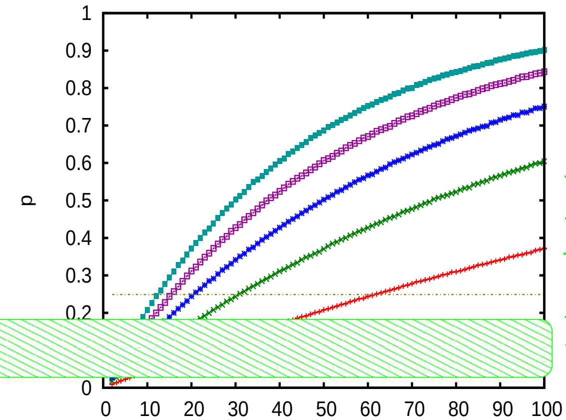
$$F(y) = \frac{\lambda}{N_c}\mathcal{N}\begin{cases} \theta(1-\frac{y}{r_T}) \\ \exp\left(-\frac{3}{4}\frac{y^2}{r_T^2}\right) \\ \frac{2r_T^2}{\pi y^2}\sin^2\left(\frac{y}{r_T}\right) \end{cases}$$

(Θ-function and Gribov-Zwanziger propagators)

Varying r_T/Λ_{QCD}



(=0.7,1.0,1.5,1.9, 2.3, 2.7,3.5)



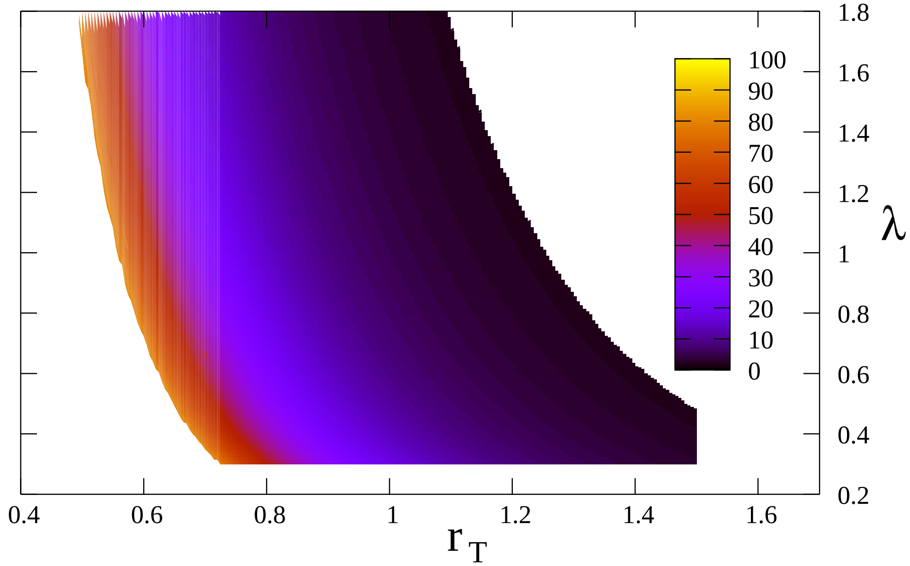
Varying λ

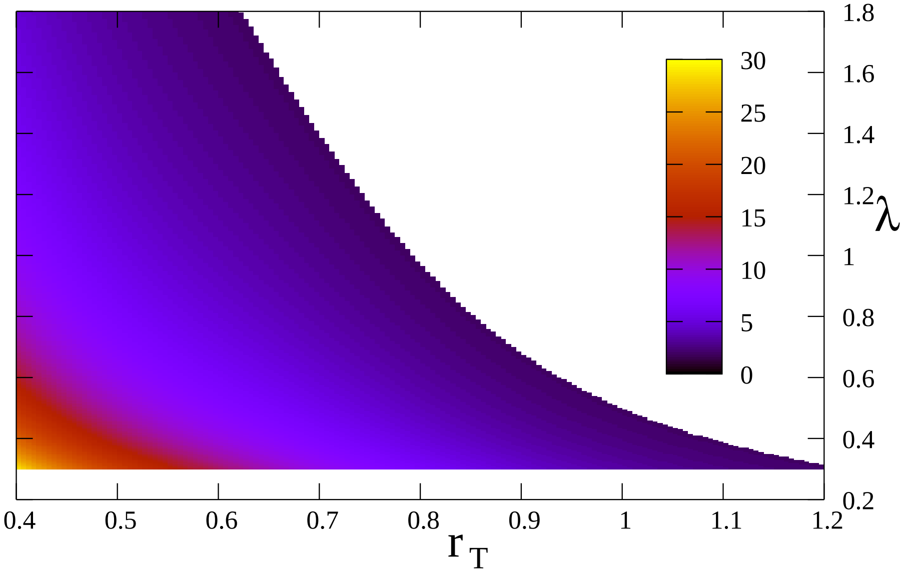
(=0.2,0.4,0.6,0.8,1.0)

Percolation thresholds for different packings

Rapid growth with N_c at $p = p_c$ independently of details of propagator. Transition seems universal at $N_c \sim \mathcal{O}(10)$

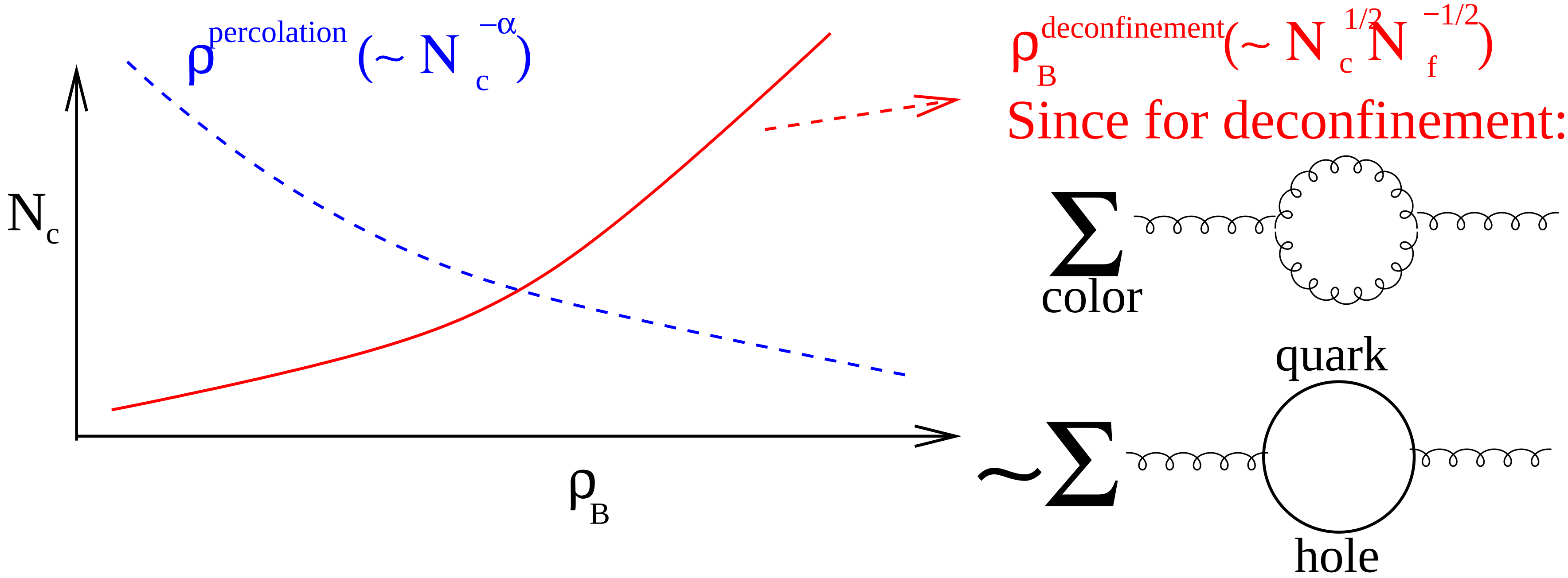
Critical N_c for Θ-function $P_{i\leftrightarrow j}$ in position and momentum





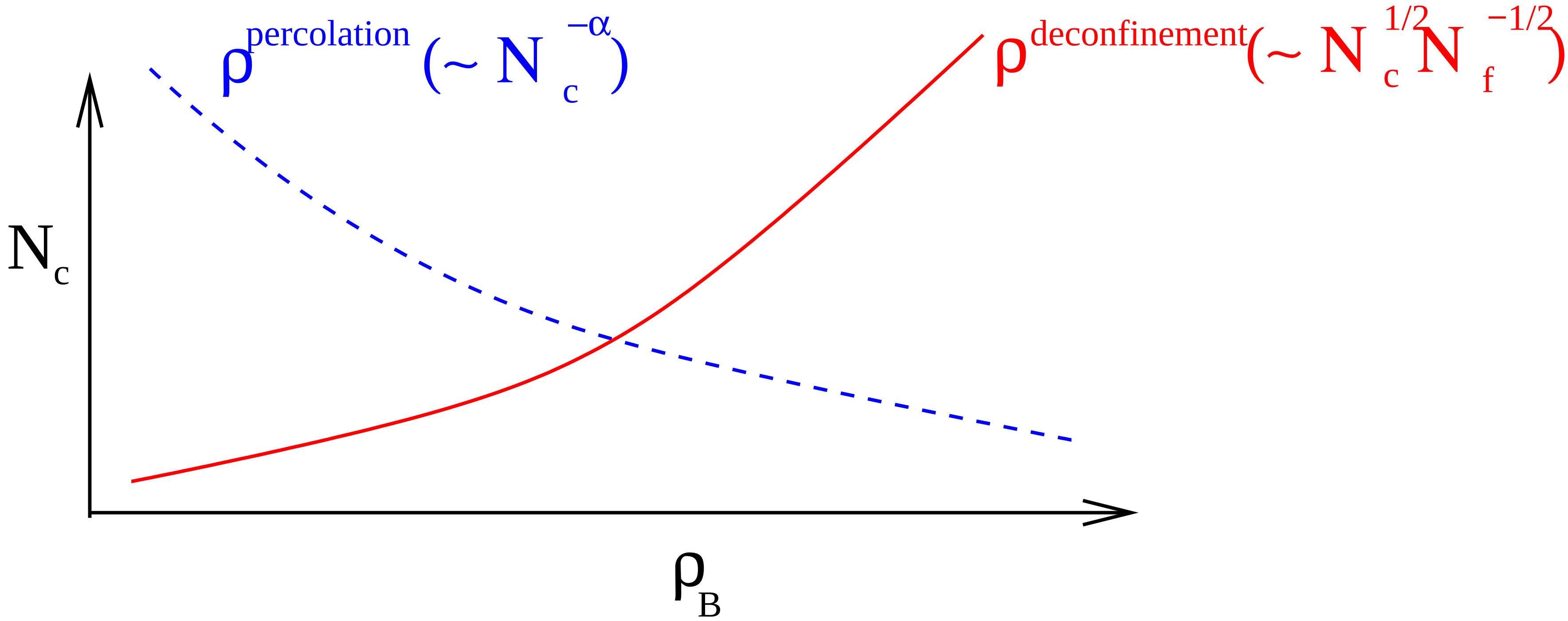
"typical" Parameters of order unity give a critical number of colors for percolation well above 3. These are lower limits, since we assume hexagonal lattice (Skyrme cubic and disordered p_c higher). So $N_c^{crit} = 3$ disfavored but not excluded at $\mu_Q = \Lambda_{QCD}, T = 0$.

But lets vary μ_Q:Percolation and deconfinement

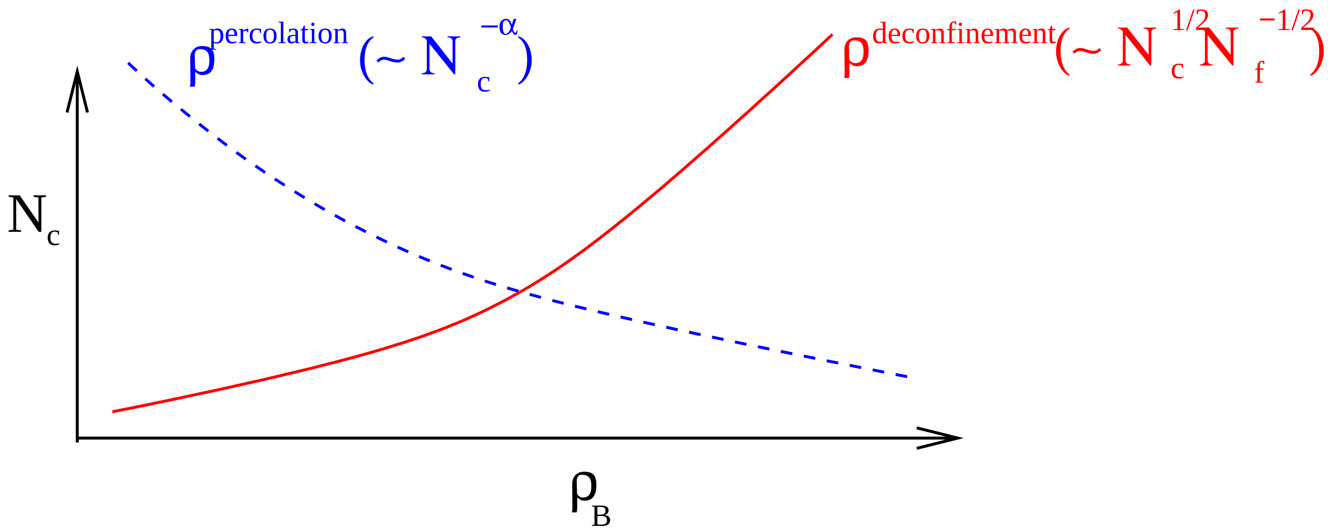


Percolation: $\rho - N_c$ anti correlated.

Deconfinement: $\rho - N_c$ correlated $\mu_B^{dec} \sim N_c^{1/2} N_f^{-1/2} m_B \sim N_c^{3/2} N_f^{-1/2} \mu_q$



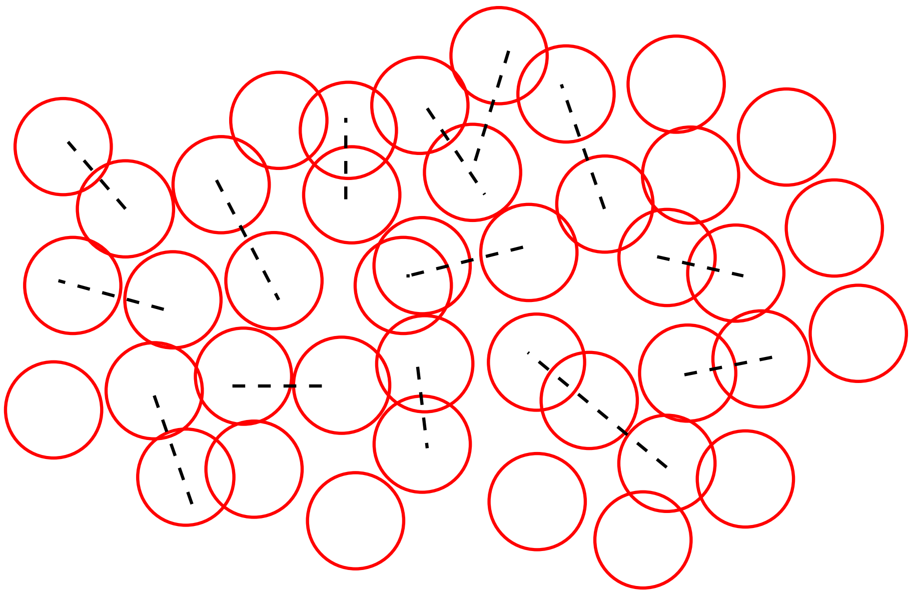
Remember 1 percolating quark negligible for wavefunction of hadron . Need $\mathcal{O}\left(N_c^{1/2} N_f^{-1/2}\right)$ or higher quarks to break hadron apart. But $N_c = 3$!!!



$N_c \leq N_c^{crit}$ Deconfinement happens below percolation, ie percolation transition does not exist separately from deconfinement

$N_c \geq N_c^{crit}$ Percolation, deconfinement separate (Quarkyonic phase?)

What is this critical N_c? Percolation in a "glass": Conceptually similar, technically more involved

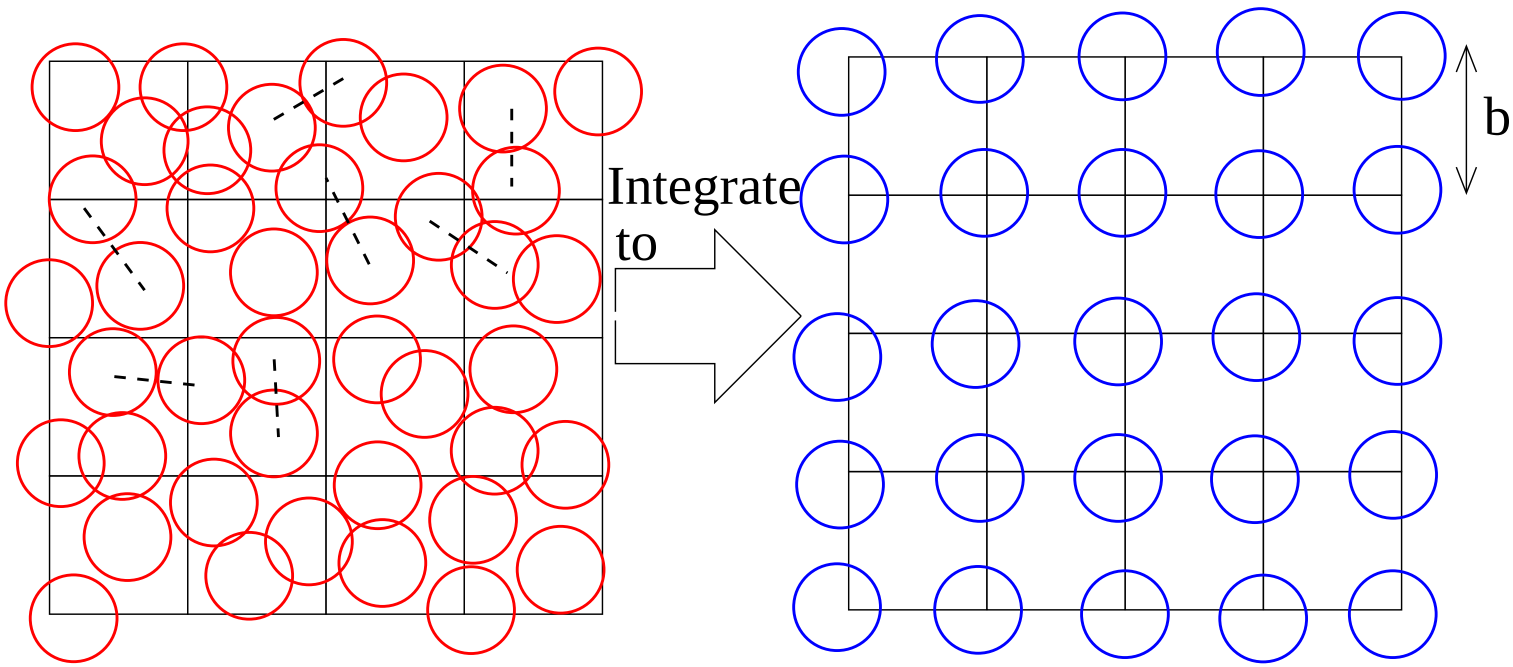


- "Nearest neighbor" <u>not</u> uniquely defined: Baryons <u>overlap</u>

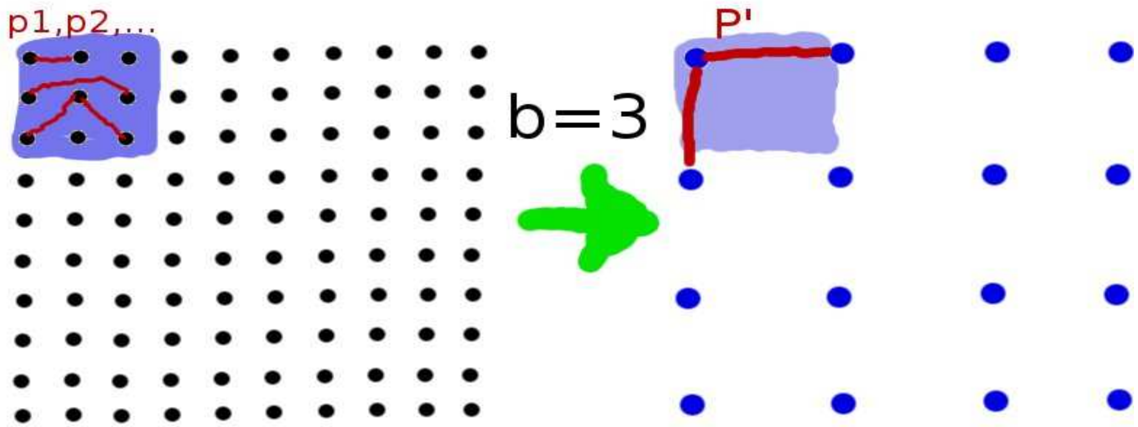
- Interactions to arbitrary distance $\rightarrow$ percolation for arbitrarily low tresholds?

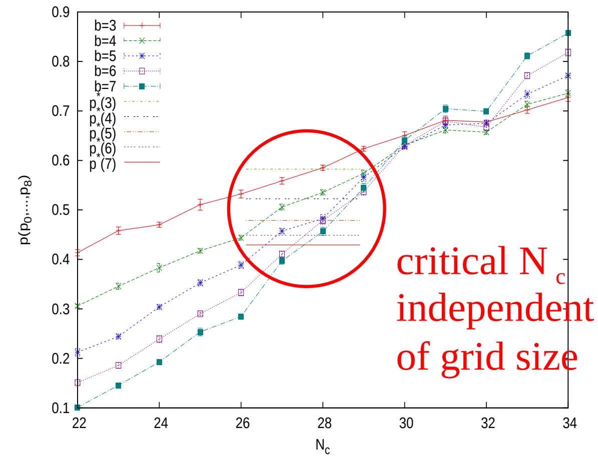
Solution:MC renormalization

Decimate glass to a cubic grid, over many "glass events". Do percolation over cubic grid



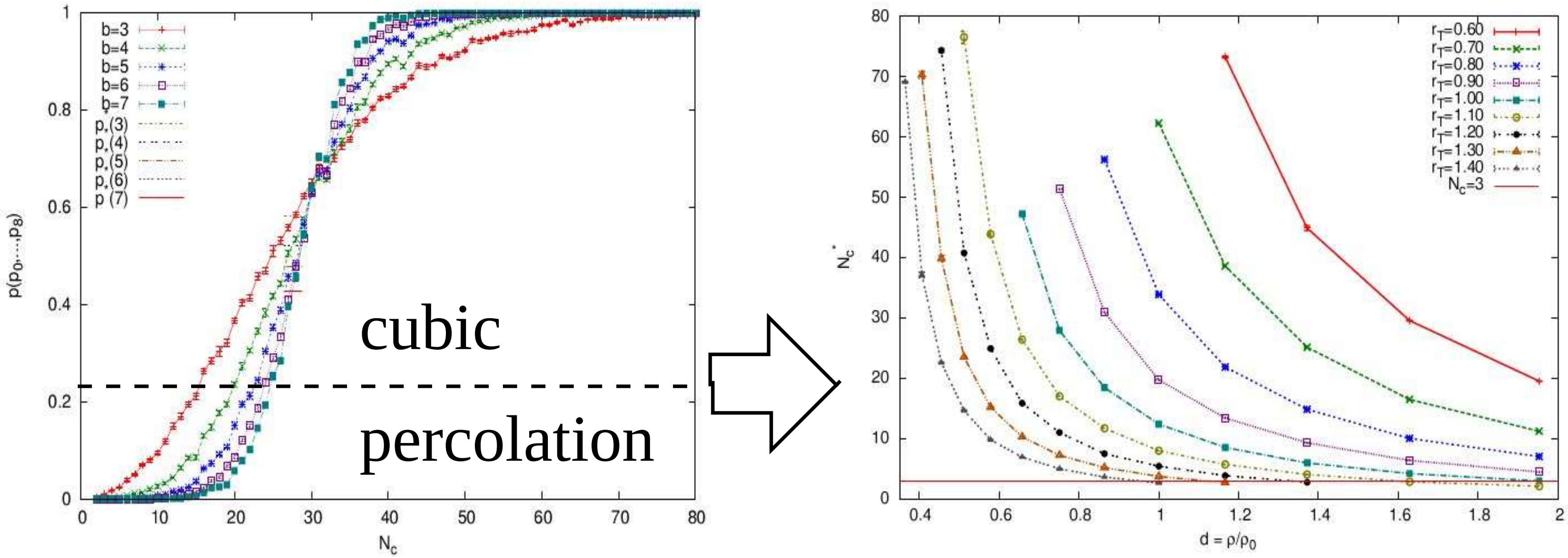
Since percolation at critical point, critical probability should be fixed point of renormalization step, independent of b





Gimel,Nicolai,Durand, J Phys A Math Gen 32 L515 (1999)

$$p^{*}\left(b,\Theta(x_T,\lambda,N_c)\right)=\Pi_{physical}\left(\Theta(x_T,\lambda,N_c)\right)+\beta b^{-y}\quad,\quad y=0.81$$



Density and N_c tightly correlated. Percolation at $N_c = 3$ excluded at $\rho_B \sim \Lambda_{QCD}^3$. But could there be percolating region at $\Lambda_{QCD}^3 < \rho_B < \rho_B^{deconfinement}$?

Equations for confinement: Ideal gas of non-relativistic baryons,mesons

$$\frac{n^{conf}}{\Lambda^3_{\rm QCD}} = \mathcal{G}\sum_{n=1}^{\infty}(-1)^n \frac{n\gamma^2}{\beta}\sinh\left((\sqrt{N_c}\beta)^n\right) K_2\left(n\gamma\beta\right)$$

$$\frac{e^{conf}}{\Lambda^3_{\rm QCD}} = \mathcal{G}\sum_{n=1}^{\infty}3(-1)^n \frac{n\gamma^3}{\beta}\cosh\left((\sqrt{N_c}\beta)^n\right)\left(\frac{3}{\gamma\beta}K_2(n\gamma\beta)+K_1(n\gamma\beta)\right)$$

Where $\mathcal{G} = \frac{4\pi g_f g_s(N_c)}{(2\pi)^3\sqrt{N_f}} N_c^{5/2 (T-T_c)^*}$ and

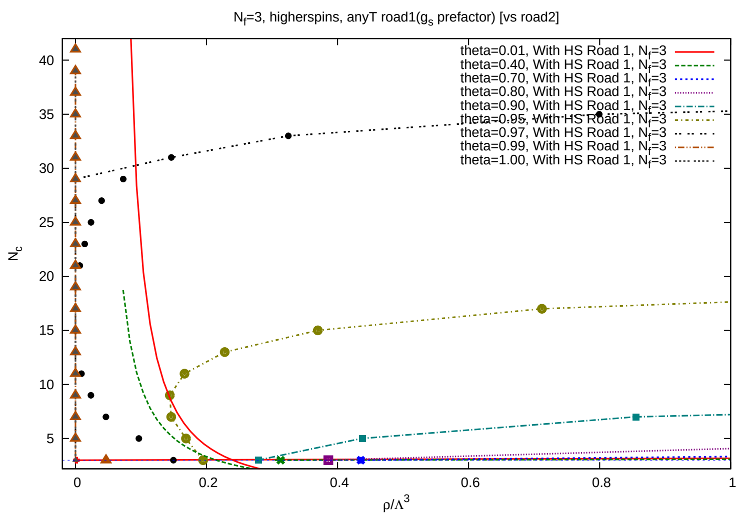
$$\frac{T}{\mu_B} = \frac{1}{\beta N_c^{1/2}} \quad , \quad \frac{m}{\mu_B} = \frac{\gamma}{N_c^{1/2}} \quad , \quad \frac{p}{\mu_B} = \frac{\alpha}{N_c^{1/2}} = 1\Big|_{deconfinement}$$

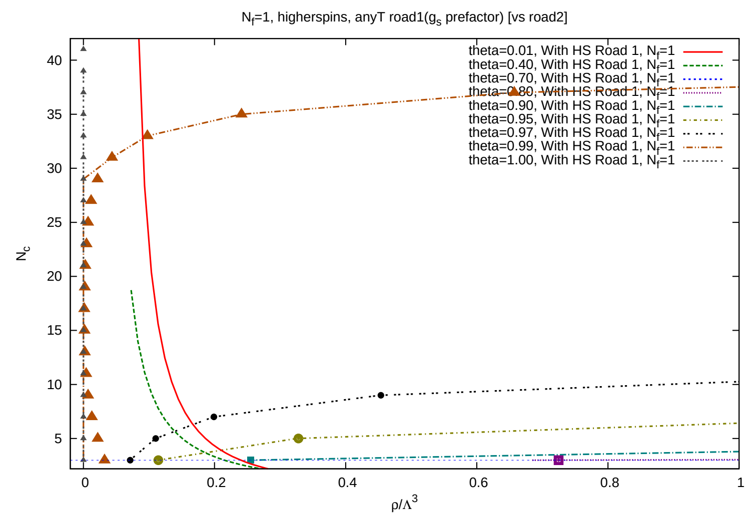
* $T \simeq 0$: All energy carried by baryons. $T \simeq T_c$: deconfinement happens at all μ_B : Parametrize confinement line by $T^2 + N_c^2\mu_q^2 = \mathcal{O}\left(1\right)\Lambda^2_{QCD}$

Quarkyonic phase <u>might</u> exist at $\Lambda_{QCD} \leq \mu_Q \leq N_c N_f^{-1} \Lambda_{QCD}$

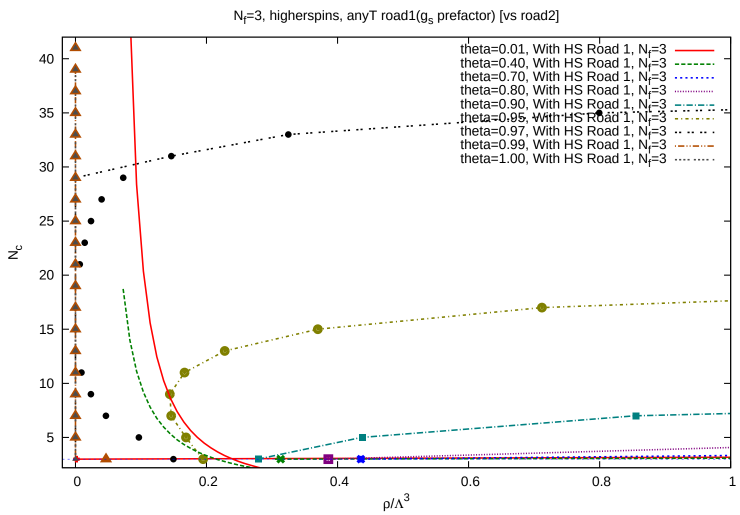
In PRL we neglected Density-N_c curvature and fixed density to $\mu_B \sim \Lambda_{QCD}$

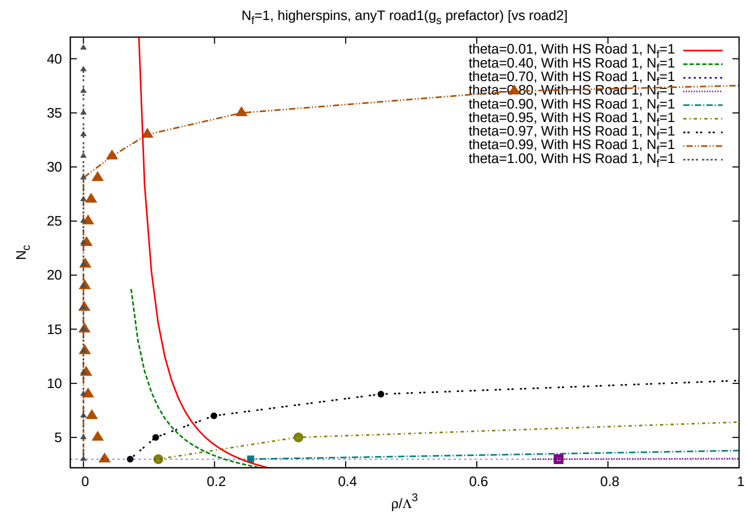
.





A sliver of $n - \rho - N_c = 3$ space which is percolating but confined seems to be there, but...





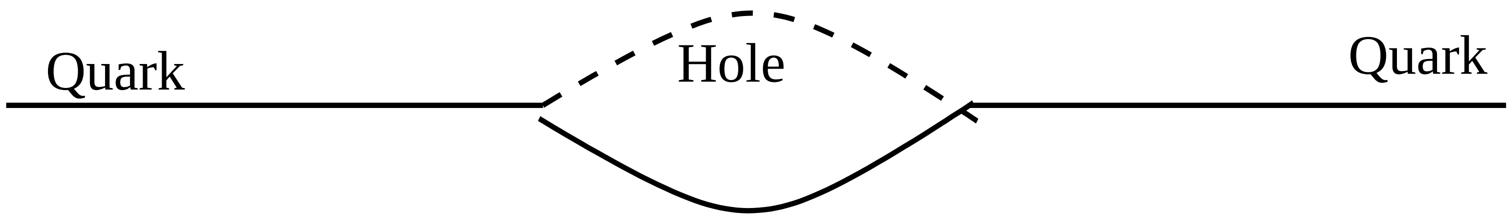
Width depends a lot on whether $N_f = 2$ or $N_f = 3$.

“Systematic error too big . Need phenomenology!

What does a percolating phase look like?

How do confinement and free quarks coexist? McLerran,Pisarski,Kojo : quark Fermi surface and baryonic excitations. But..

$$\frac{dS}{dV} = \frac{dP}{dT} = \frac{P+\rho-\mu n}{T}$$



And any diagrams of this type will give $T\mu_B$ contributions to pressure, and hence dS/dV . So need theory with confinement but free quarks! Physical example: Electrons in a metal

Confinement and quasi-free quarks: spin-color-flavor separation?

Confinement remains, so regions above $\sim 1fm$ can-not be color charged. (Same problem at $T \geq T_c$, but correlations required to maintain confinement can be $\left(N_c^0 \Lambda_{QCD}^{-1}\right) \ll s\,(T \geq T_c) \sim N_c^2 T^3$

Spin-color-flavor separation can achieve this and maintain N_c, N_f scaling! Pisarski,McLerran,Kojo, NPA843 (2010) 37-58 and subsequent works: implement this by 1D WZW model.

$$S = S_{2N_f}^{WZW}[h_{\rm color}] + S_{N_c}^{WZW}[h_{\rm flavor}]$$

which generalized spin-charge separation to $SU(N_f), SU(N_c)$.
Modifications to S_{2N_f} could localize color, maintain $\sim N_c$ degeneracy.
"Naively" WZW incompatible with percolation (1D) , but could work as EFT in percolation regime. Work in progress .

All of this is very nice, but let us recap the tower of assumptions!

Funamentally the linking of deconfinement with the perturbative β function scaling with $N_{f,c}$ might be incorrect.
Bag model intuition might hold!

N_c might be too low and N_f might be too high
(Counting on "2/3 being high because $m_s \gg \Lambda_{QCD}$ shaky!

Color-flavor-spin separation not yet worked out. Interplay of confinement and asymptotic freedom not clear

I do not see a way of investigating the theoretical validity of each of these in a model independent way. We need a quarkyonic phenomenology!

Quarkyonic phenomenology on the lattice

Quenched lattice very close to N_c invariant (Panero et al), but need at least 1 flavor for the effects described here. One would need to vary $N_{f,c}$ at finite μ_Q , possibly $\mu_Q \sim \Lambda_{QCD}$

I can already see you making such a poster!

But hear me out!

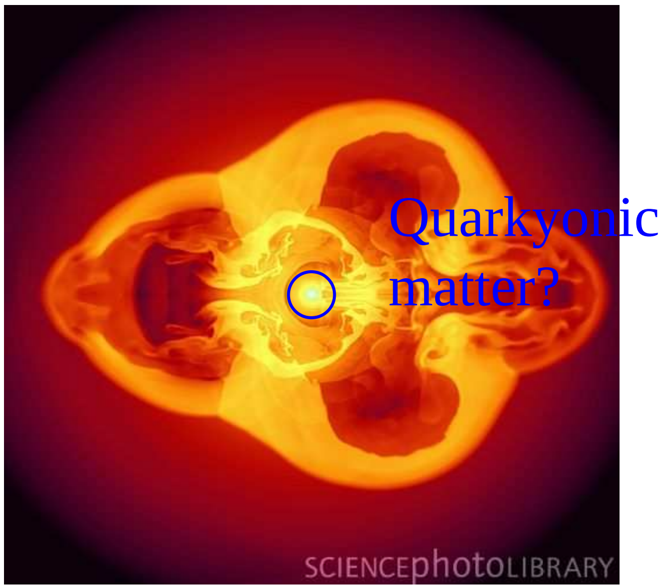
Strong coupling expansion Binding energy and EoS should drastically change with N_c, N_f (NB: Percolation sensitive to N_c, "kissing transition" to $N_c N_f$ so different)
Strong coupling expansion has no sign problem and relatively cheap!

"Baryon molecules" $T = 0$ wavefunction should drastically change shape with N_c

Hopping approximation and Reweighting found jump in baryon density at $N_c = 3, \mu_Q \simeq \Lambda_{QCD}$.
But this is "trivial" , due to high baryon mass!
Need to check pressure behavior with N_c . difficult but possible!

Astrophysical implications

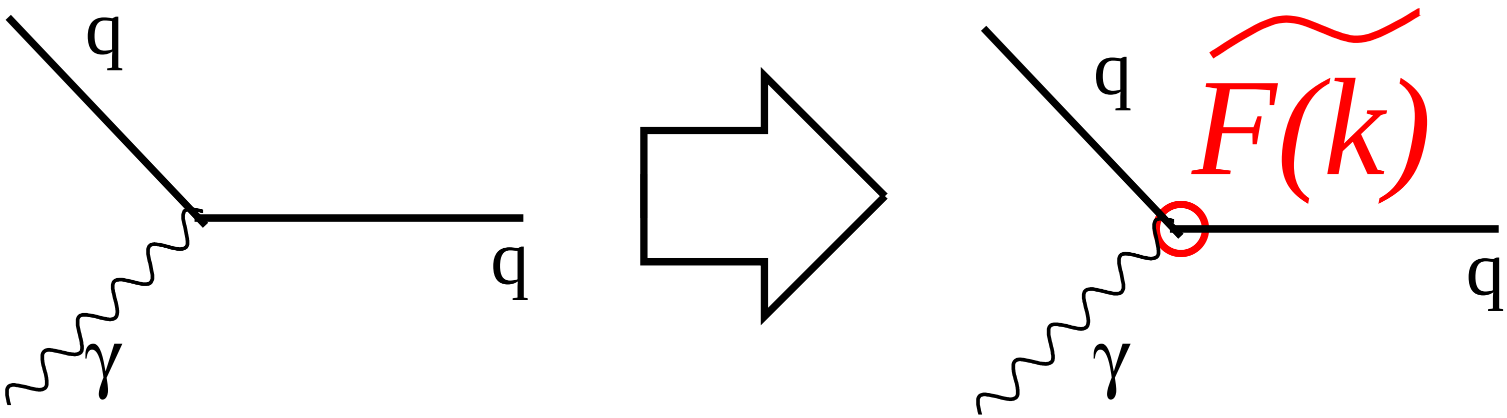
If quarkyonic phase realized in proto-neutron star , pressure, entropy $\sim \mathcal{O}(3)$ corresponding nuclear matter. EoS similar to pQCD (stiffer than nuclear matter), but no mixed phase/latent heat: Stiffness gradually turns on!.



Such an EoS might make it easier for supernovae to explode?

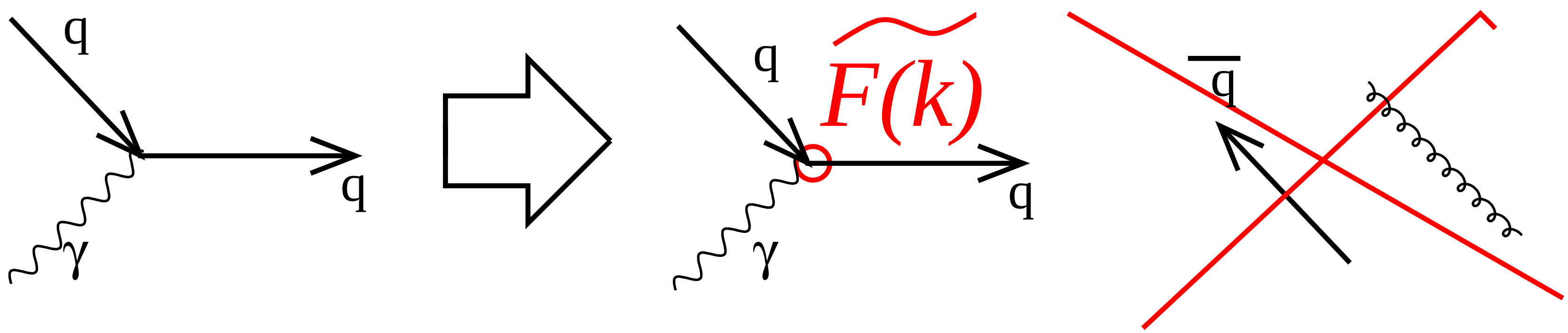
pQCD but not quite: the role of baryons

Unlike pQCD, quarkyonic matter's "vacuum" is a classical dense baryon state. Treating baryons as mean fields will give a momentum-dependent form factor



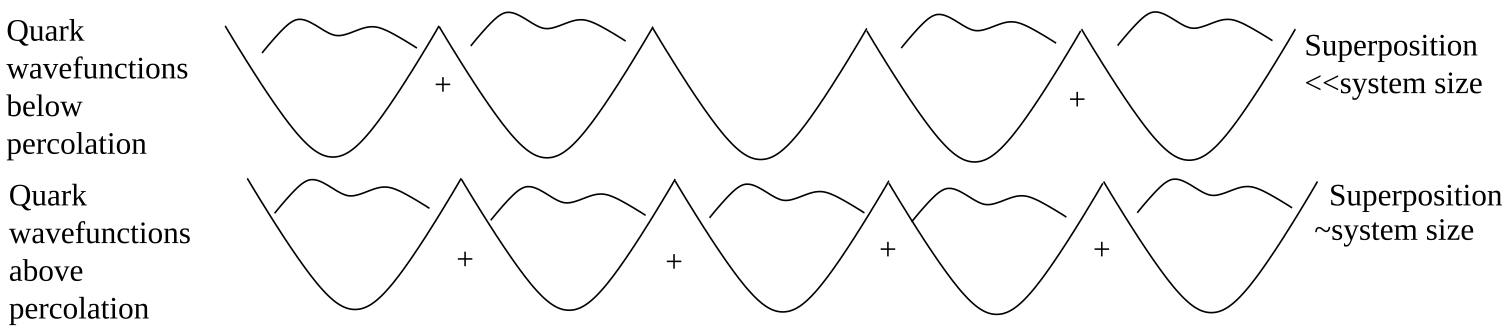
$F(k)$ gives the F.T. of the baryonic gluon content. For the equation of state, it should just be a $\mathcal{O}(1)$ normalization factor, but for scattering processes it is a qualitative difference from naive QCD. Spin-color-flavor separation can ensure color neutrality with quark-like degrees of freedom. Baryons motion doesent influence quarks up to N_c^{-1} corrections

NB: Quarks delocalized by tunneling, not confinement



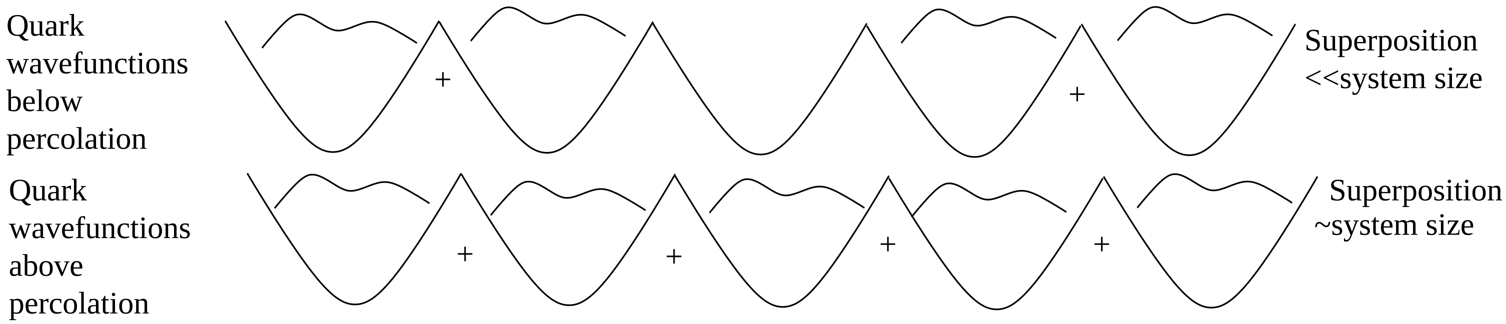
Gluons, antiquarks still confined, only processes with outgoing quarks allowed!

This description coincides with Larry and Rob's



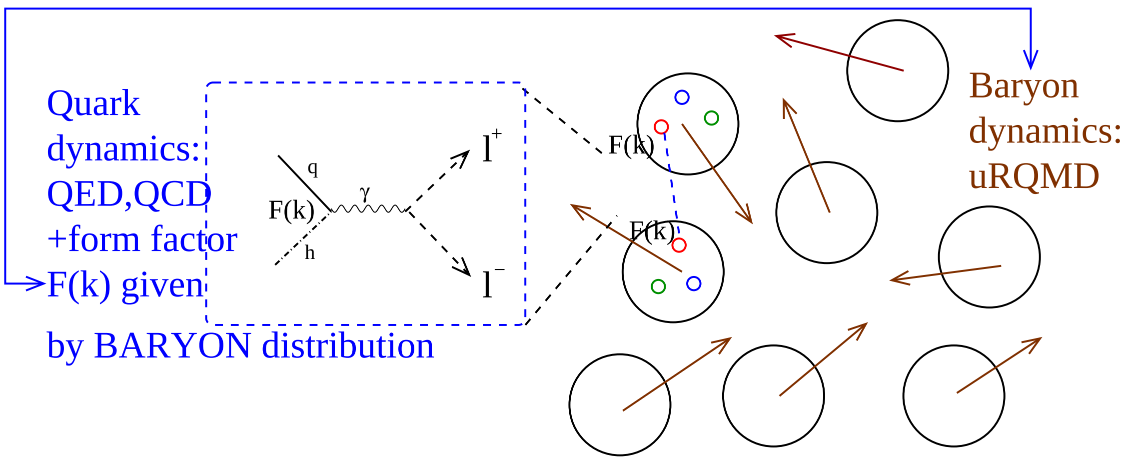
In momentum space lower-lying modes are quark-like. Since $\lambda \sim 1/p$ these are the most long-wavelength modes, which are exactly the modes feeling the mean field

From EoS to dynamics: An EFT of percolating matter



In percolation regime, asymptotically free quark wavefunctions of different baryons can superimpose across large distances.
Thus, even if $E_{state} \sim 1/L_{baryon} \sim N_c^0 \ll N_c^{1/2} \Lambda_{QCD}\Big|_{deconfinement}$ degrees of freedom quark-like, so $P \sim N_c, s \sim N_c$ (In the same way electrons in a metal have a much lower energy than ionization).
Periodic wavefunctions $\Rightarrow$ leading component <u>always</u> $p \geq \Lambda_{QCD}^{-1}$

Modeling quarkyonic matter for RHIC/NICA/FAIR

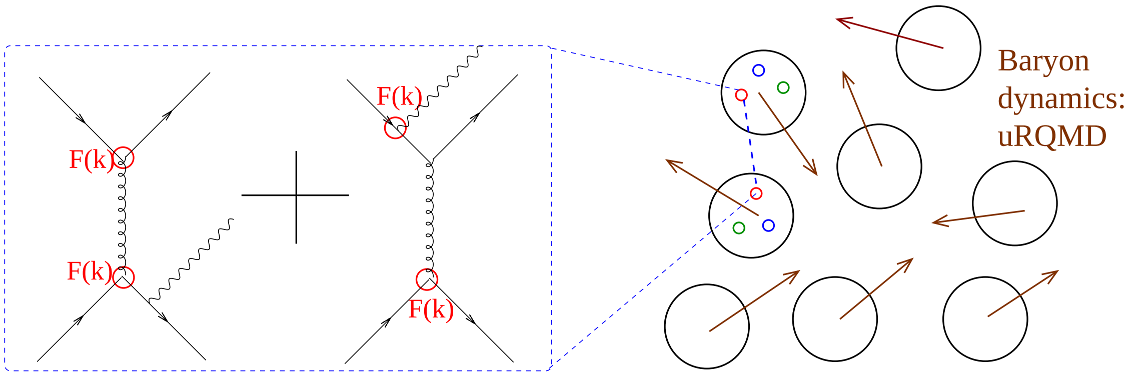


$R_{qq \to X} = \Psi(k)\Psi^*(k')M^2_{qq \to X}$ Where $M_{qq \to X}$ is the pQCD matrix element

$$\Psi(k) \sim \exp \sum_i \left[ikx_{0i}\right] F(k) \sim \exp\left[ikx_{0i} - \frac{k^2}{\Lambda_{QCD}}\right]$$

$F(k)$ is the quark function inside a "classical" proton potential well ($\sim$ Gaussian) and x_{oi} are the baryon locations. The latter is given by uRQMD.

Photon production in this approach



As antiquarks, gluons suppressed leading channel is quark Brehmsstrahlung.

$$\mathcal{M}^2 = L^2(k_1, k_2 \to k_3, k_4, p) + L^2(k_1 \leftrightarrow k_2, k_3 \leftrightarrow k_4)$$

$$L^2 = -\frac{1}{4} e^2 \lambda^2 N_c^{-2} (k_2 - k_4)^{-4} Tr \left[\not{k}_4 \gamma^\sigma \not{k}_2 \gamma_\rho \right] Tr \left[\not{k}_3 Z^\mu_\sigma \not{k}_1 Z^\rho_\mu \right]$$

$$Z^\beta_\alpha = \gamma_\alpha (k_1 - p)^{-1} \gamma^\beta + \gamma^\beta (k_3 + p)^{-1} \gamma_\alpha$$

$$\frac{dN_\gamma}{d^3p} = \int \frac{d^4k_1}{k_1^0}\frac{d^4k_2}{k_2^0}\frac{d^4k_3}{k_3^0}\frac{d^4k_4}{k_4^0} \left(\mathcal{M}\left(k_1,k_2 \to k_3,k_4,p\right)\Psi(k_1)\Psi(k_2)\right)^2$$

- Quarkyonic quark wavefunctions
  $\Psi(k) \sim \exp \sum_i \left[ikx_{0i}\right] F(k) \sim \exp\left[ikx_{0i} - \frac{k^2}{\Lambda_{QCD}}\right], uRQMD \Rightarrow x_{0i}$

- Can we go beyond $N_c \to \infty$ and incorporate baryon flow?
  "Boosted quarkyonic" : Same wavefunction as above boosted to flow of a "random" baryon: An upper limit to N_c^{-1} backreaction (effect of baryon flow on quark wavefunction)

Calculate

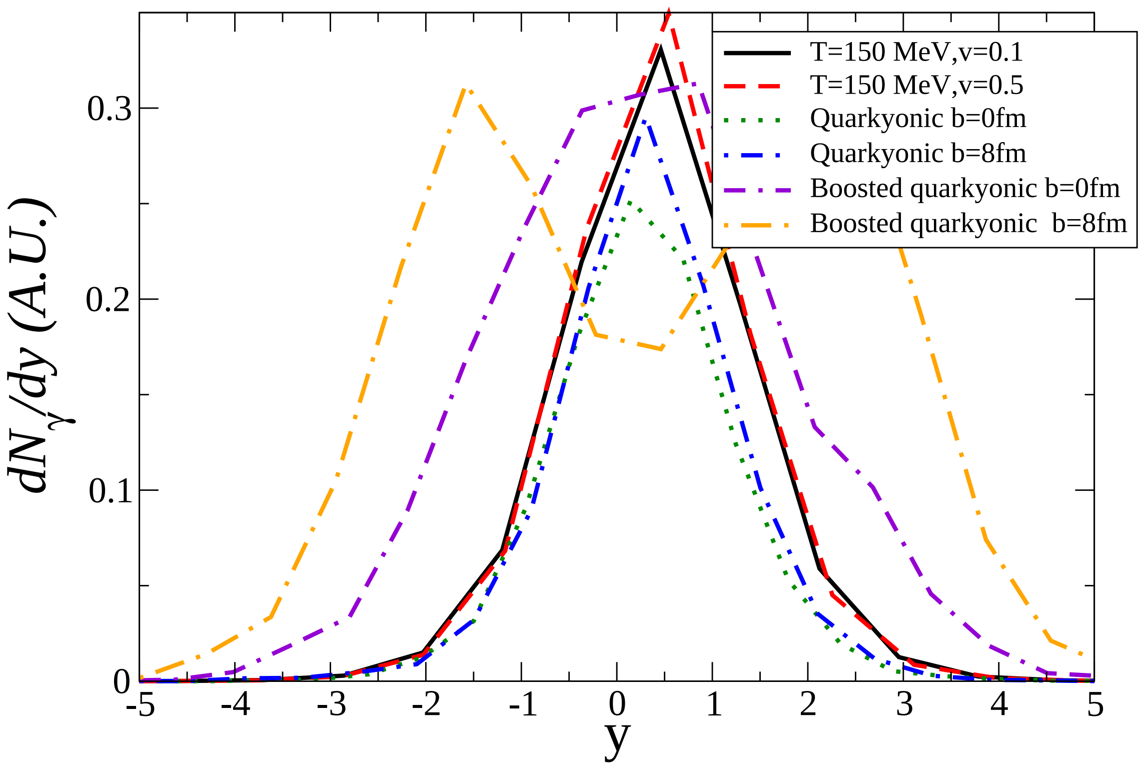
$$\frac{dN}{d^3p} = \frac{dN}{dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n\left(\phi - \Psi_{reaction}\right)\right)\right]$$

for

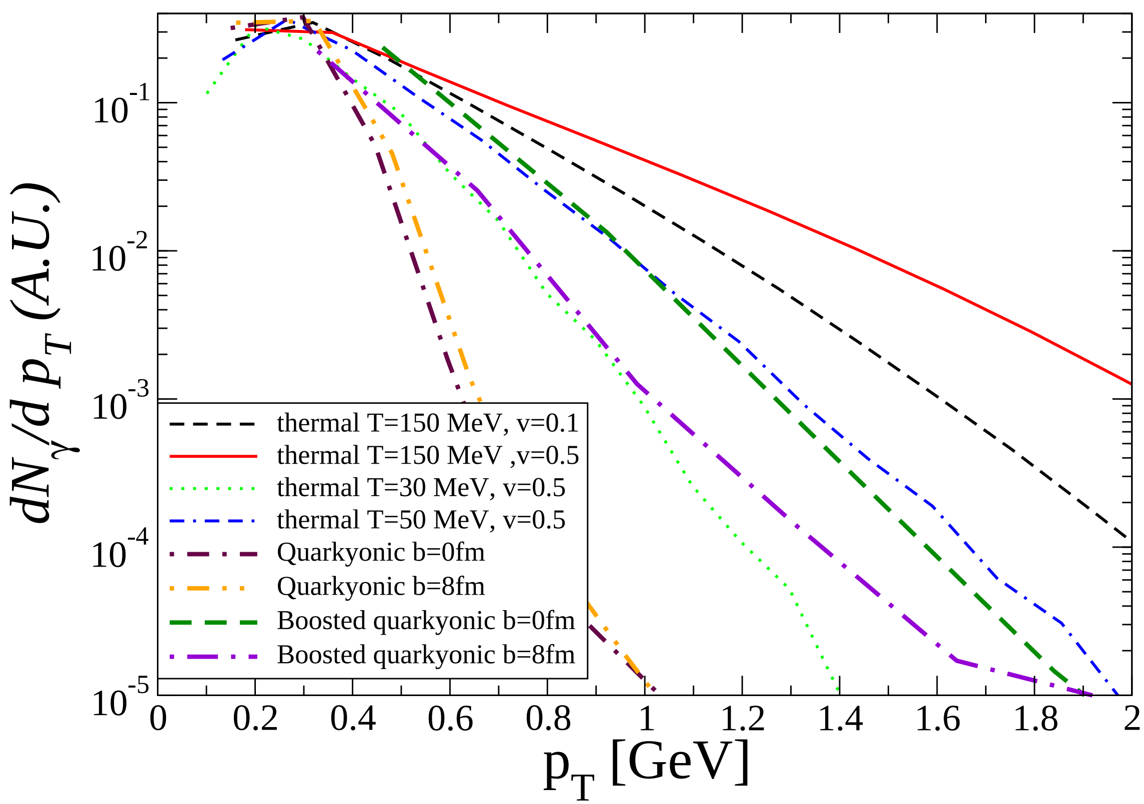
Quarkyonic and Boosted quarkyonic matter described above

thermalized QGP cross-sections described above and quark wavefunctions
$\Psi(k)\Psi(k') = \delta(k'-k)\exp\left[-k_\mu u^\mu/T\right]$

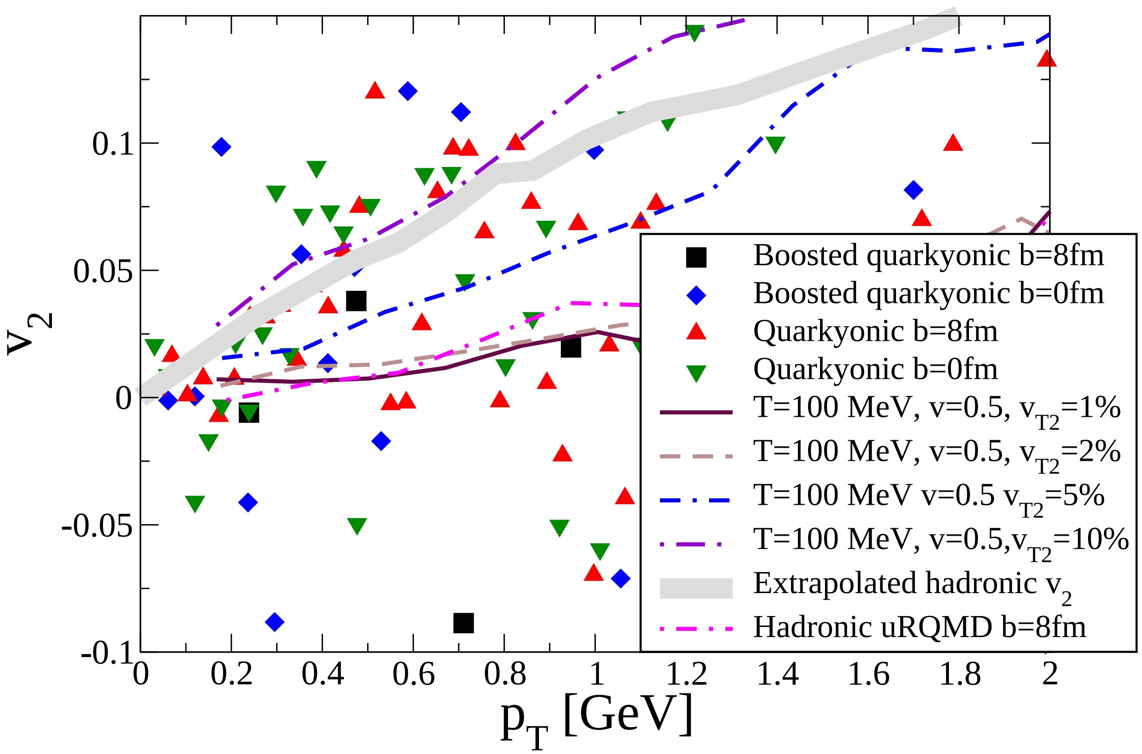
Hadron gas calculated with uRQMD molecular dynamics model (same as the one used for quarkyonic wavefunctions!)



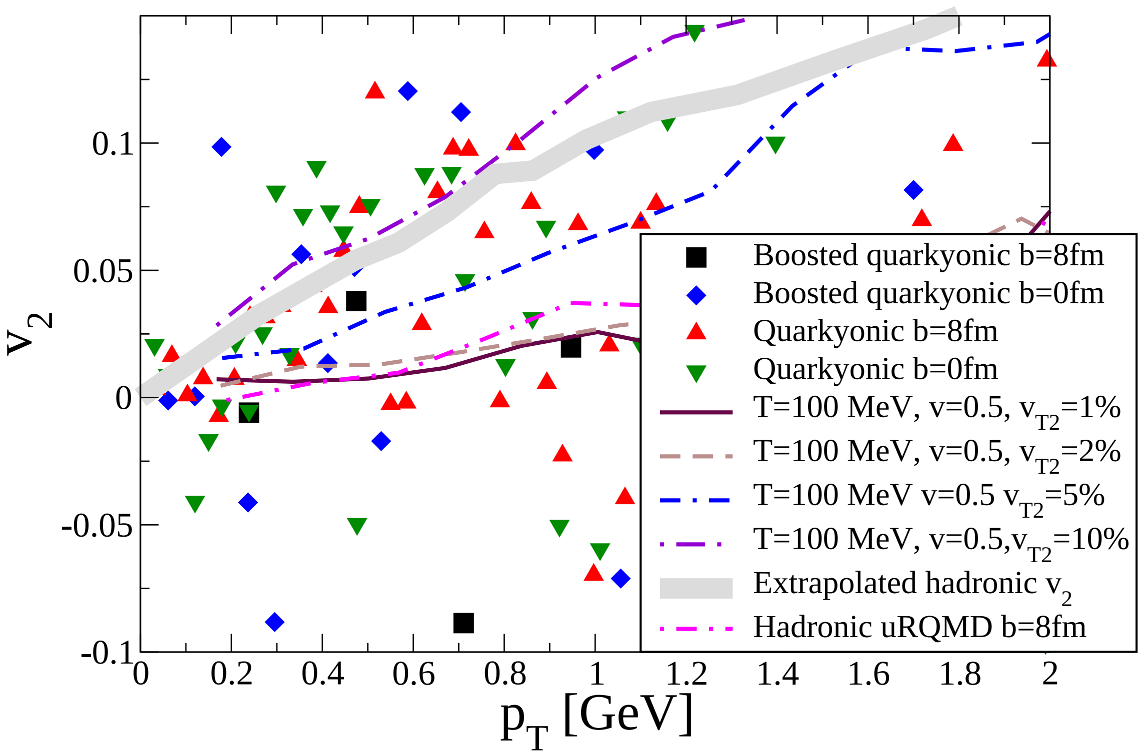
Very little difference. NB "static baryon" approximation breaks down away from mid-rapidity



Quarkyonic wavefunction similar to <u>cold</u> quark gluon plasma, unrealistic temperatures. NB: "boosted quarkyonic" increases flow, but still cold!



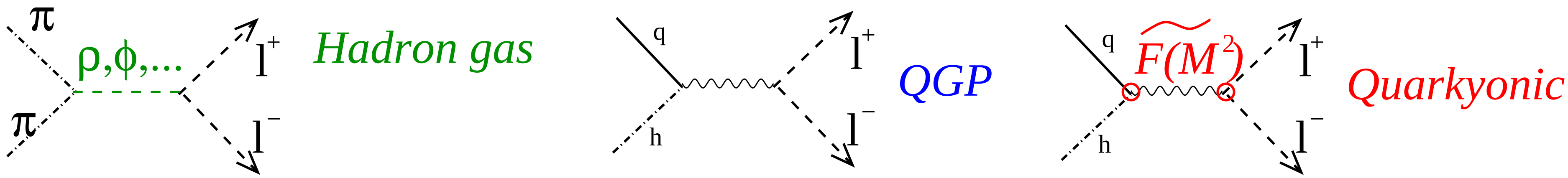
Random distribution of quark wavefunctions quenches total v_2 but produces big fluctuation in event and p_T : oscillation frequency $\sim p_T \rho_B^{-1/3}$



"pure" quarkyonic effect, it is due to sensitivity of quark wavefunctions to baryon location. signature?

dileptons potentially more direct probe but more complicated

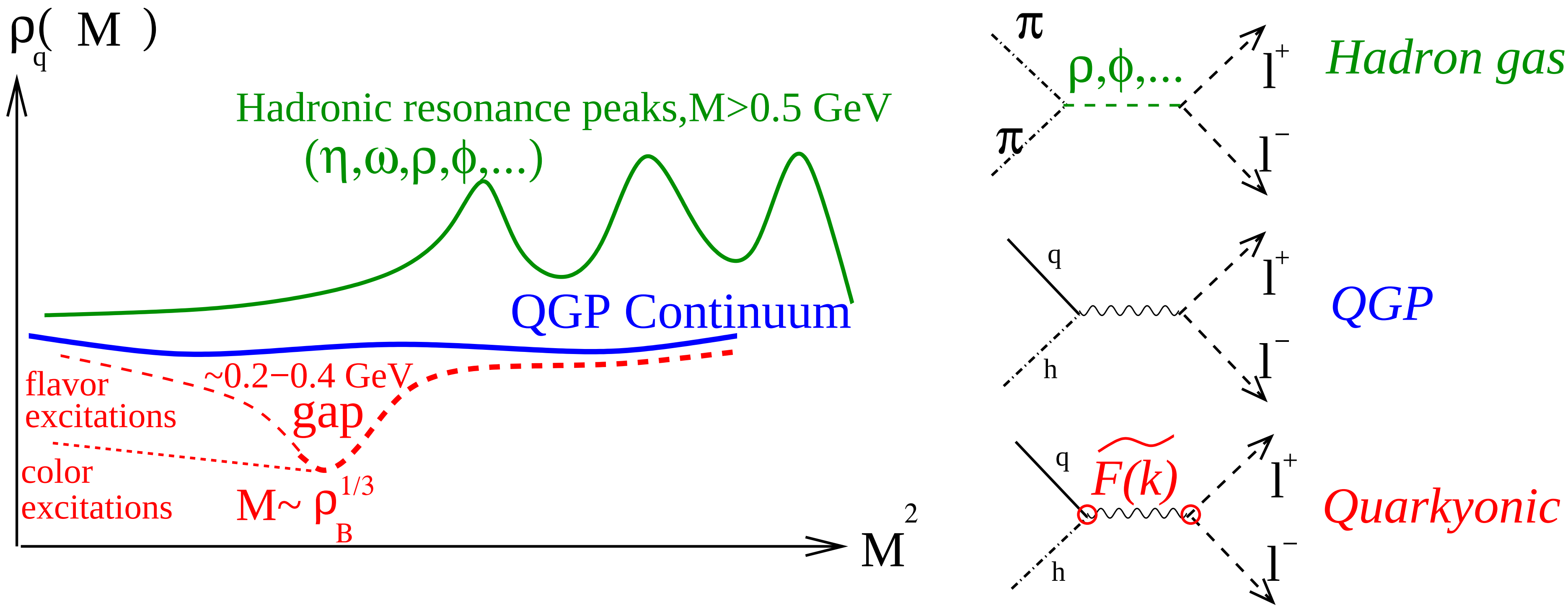
Both quarks and holes needed Sensitivity to equilibration



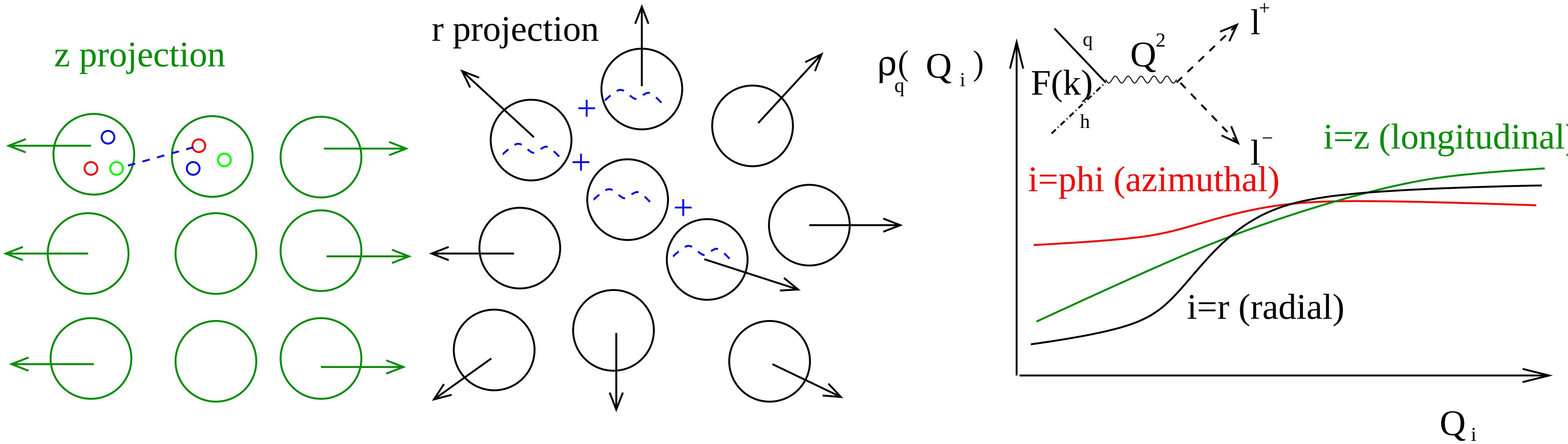
$\tilde{F}(M^2)$ connects baryon distribution to M^2 dilepton spectrum

$$\langle \hat{\Psi} \rangle = \mathrm{Tr} \left\{ \{\exp \left[\frac{\hat{H} - \mu_q \hat{N}}{T} \right] \left[\frac{1}{3N} \left(\sum_{i,j,k}^{N} \hat{a}_i(k_i) \hat{a}_j(k_j) \hat{a}_k(k_k) \right) \right] \right\}$$

where a_i solutuions of confining potential wells centered around baryons,
$\hat{H} = \sum \hat{k}_i^2 + \sum_i^{baryons} V \left(\hat{x}_i^{baryon} - v_i^{baryon} t \right)$



If baryons were regular (pasta phase?) one could observe bloch waves!
("upside down resonance"?)



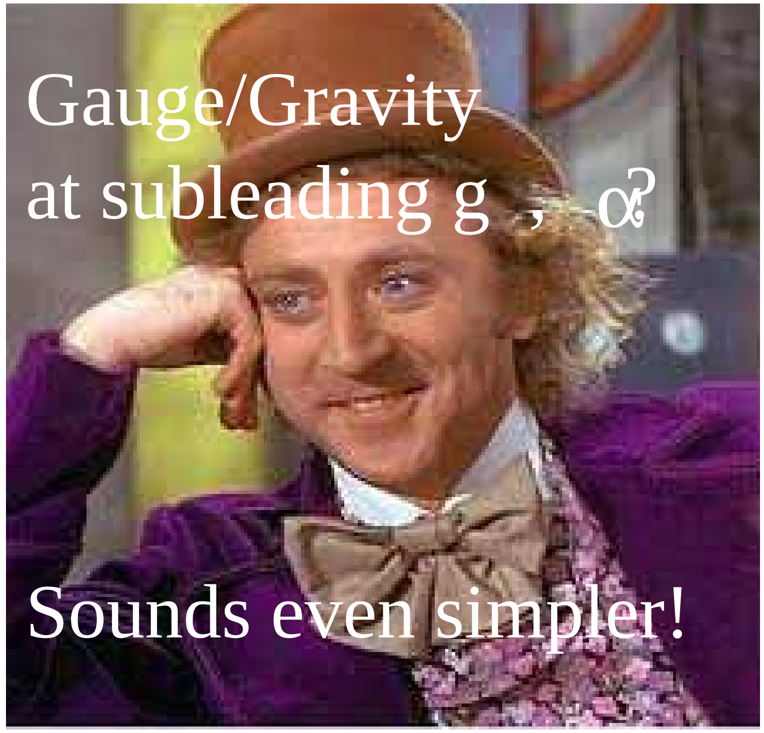
Event by event fireball structure not regular, but Collective structures exist in events flow profile (radial, longitudinal flow) and baryons have repulsive potential, soo structures in 3D dilepton spectral function $Q_{z,r,\phi}$ bound to exist!

Is there a Gauge/Gravity angle to all this?

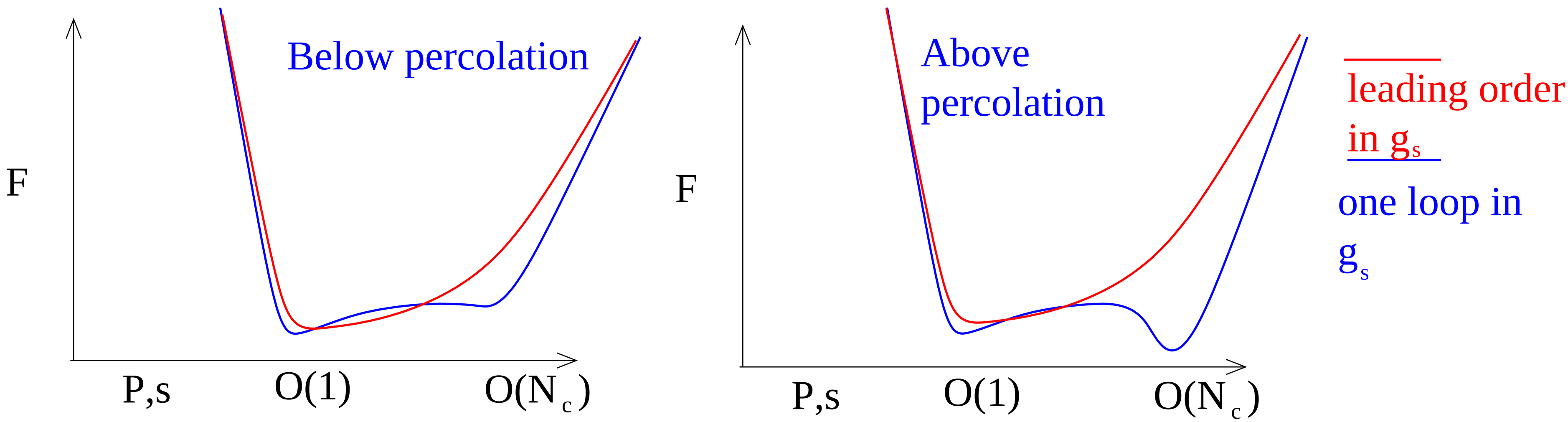
- Since phase transition happens at critical N_c , it can only be realized at subleading g_s . Asymptotic freedom limit for quark-quark interactions at large N_c also requires α' corrections!

- In string world flavor $\leftrightarrow$ D7,8 branes. So $N_c \sim N_f$ means so many overlapping branes string loops among them can not be neglected.

- This might explain why, despite compelling argument for $s \sim N_c @ \mu_q \geq \Lambda_{QCD}$, all AdS/CFT setups so far have $s \sim N_c^0$ in that regime.
  $P \sim s \sim N_c$ argument explicitly based on asymptotic freedom. Not implementable in supergravity.



I cannot see a sure road into percolation, but some qualitative insights could be obtained back at $\mu_Q \to 0$. remember the order of confinement!



Here is how to make arguments in previous slides compatible with AdS/CFT
Above leading order in g_s . Leading order misses auxiliary minimum where $s \sim N_c$ so only minimum at $s \sim N_c^0$. Van Der Waals example shows correction can be small (but not infinitesimal) for this to happen!

Confinement and black holes

In normal space, black hole decays and has a negative heat capacity $\rightarrow$ Thermodynamically unstable state!

Let's put the black hole in a reflecting box (One "physical way" of doing it: A negative cosmological constant,AdS!

Box large wrt black hole system (hole+gas) heat capacity still negative, black hole decays

Box small wrt black hole Hole and photons in box in thermal equilibrium, heat capacity positive, black hole stays

The two regimes connected by Hawking-Page phase transition (1st order). According to Witten, confinement in d-flat or spherical space is dual to the Hawking-Page phase transition of a black hole in d+1 AdS space

The phase transition in N_c and gravity

In Gauge world , confinement critical point is understood in terms of broken symmetries (Z_N).

In Gravity world , Hawking-Page is most likely a <u>transition</u> because of naked singularity conjecture. You either have a black hole, with a singularity, or you don't!
(This is why I don't believe "bottom-up" models where confinement is a cross-over!)

Hence, making confinement into a cross-over is equivalent to smoothening black hole singularity

We have no idea how to do this, so let's use a Quantum-Gravity ansatz:Gravity in non-commutative geometry-inspired ansatz.

- Some people think it could come out of string theory or any generic model of quantum gravity
  Impossible to probe scales $\leq l_p$ as this is the "size of the g_s string loop"/You'll create a black hole trying .

- Ansatz can be shown to be well-behaved (does not break unitarity and locality at distances long wrt l_p).

- Critical behaviour $\leftrightarrow$ universality! Insensitive to microscopic details of our model

Non-commutative geometry-inspired Schwarzschild ansatz

P. Nicolini, A. Smailagic, E. Spallucci, Phys.Lett.B632:547-551,2006

The basic idea: Maintain "gravity" part classical but smear out energy momentum tensor. Black hole problem reduces to solving Einstein's equations for infinitely rigid Gaussian energy distribution

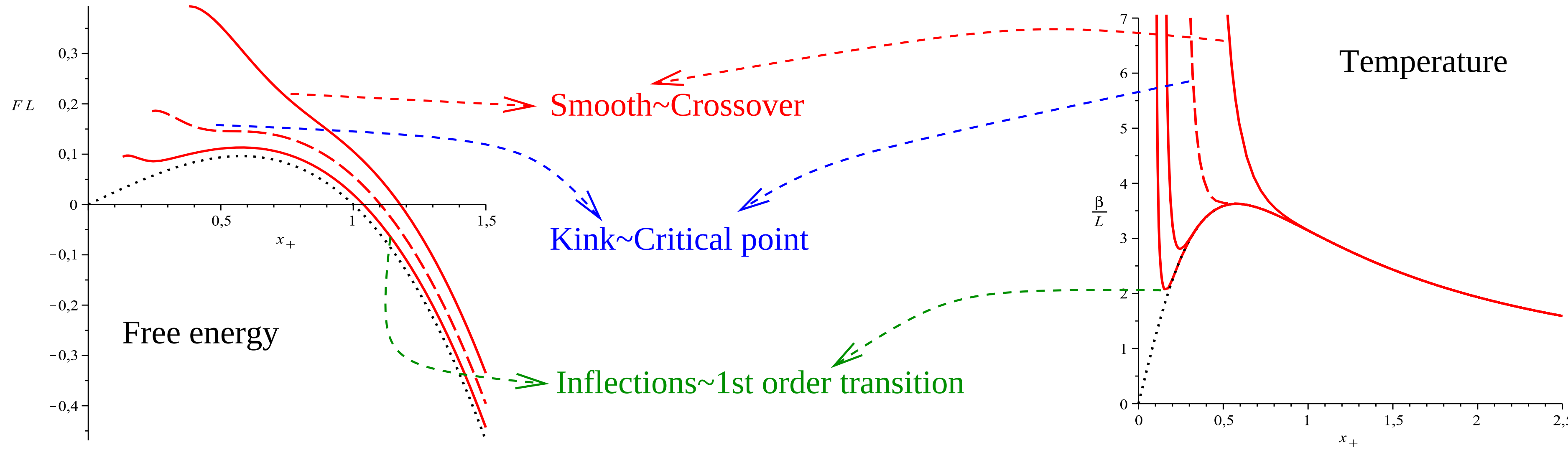
$$T_0^0 = \frac{1}{(2\pi l_p)^{3/2}} \exp\left[-\frac{x^2}{2l_p^2} \right] \underbrace{\Rightarrow}_{l_p \to 0} \delta(x)$$

Einsteins equations, spherical symmetry and $T^{\mu\nu}_{;\mu} = 0$ specify the problem uniquely. Entropy calculated via horizon area. Impossible to expand in l_p

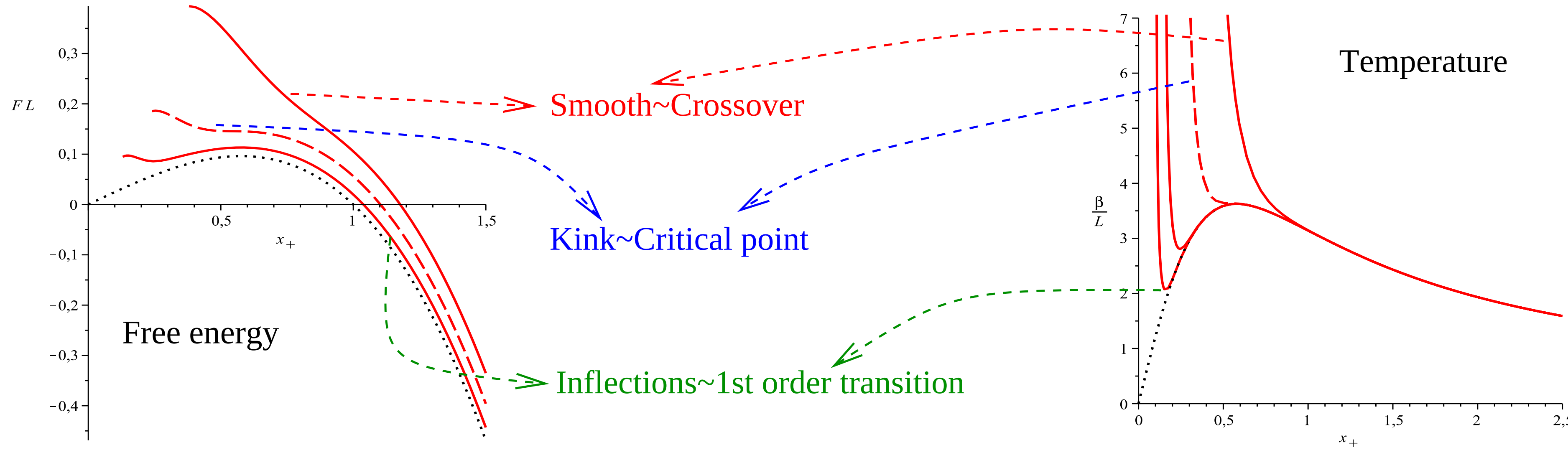
Hawking entropy calculated the usual way. But...

Flat space Black hole heat capacity becomes positive after critical radius $x_+^{planck} \sim l_p \rightarrow$ Ansatz used to study remnants

AdS space Van Der Waals-type phase diagram
If box small enough that $x_+^{planck} \sim L_{AdS}$, we reach critical point



At critical $q = l_p \Lambda_{AdS}$ Hawking-Page transition becomes a <u>cross-over</u>, similar to Van der Waals gas. Critical $q^* = 0.18243 \simeq 1/6$ If $\Leftrightarrow \mathcal{O}(1)\, N_f/N_c$ surprisingly close, for 1 flavor, to $N_c = 6 = N_N^{d=2+1}$

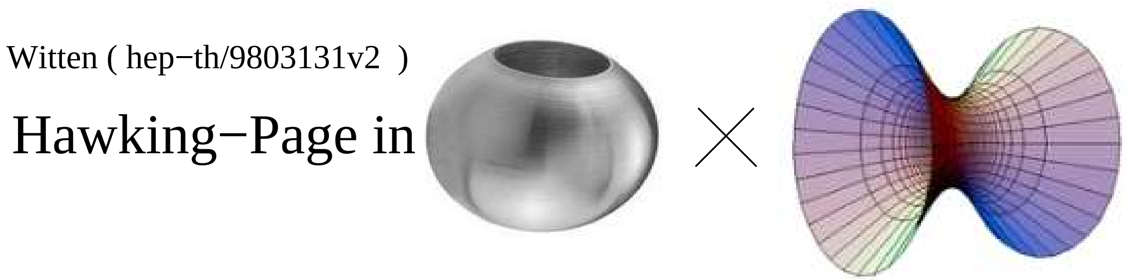


$$F = \underbrace{F_{\alpha=0}(T)}_{kink} + \underbrace{\Delta F(\alpha \geq 0)(T)}_{smoothens}$$

In gravity, $\alpha = l_p$ $\alpha \sim N_f/N_c$ in QCD? (NB: Can not Taylor-expand!)

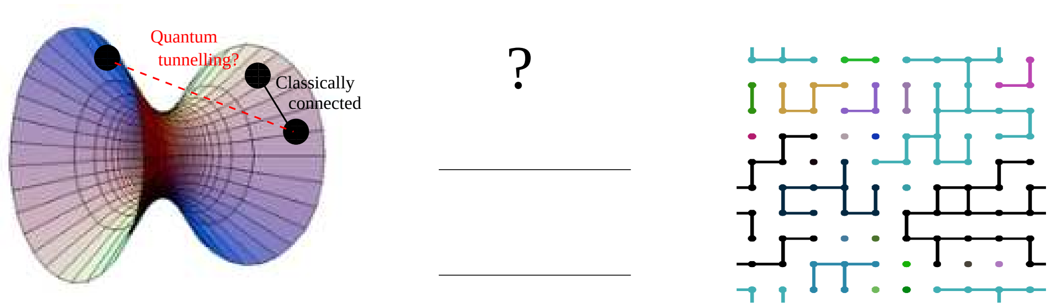
Work in progress... a model of this type in AdS/CFT

Does the Hawking page transition become a cross-over in Witten's original set-up, a Black hole on a sphere? ($AdS \times S_n$)?



$AdS_3 \neq AdS_1 \times S_n$ but is obvious that a similar critical point will happen in <u>all</u> setups with a Hawking-Page transition, although of course T_c and l_{pc} will change!

Is this the same as percolation? Not sure, but I think so!
Critical point behaviour identical to second order phase transition, and percolation is a 2nd order phase transition



Hawking-Page transition coincides with transition of a gas of black holes in AdS collapsing into a large black hole. It happens because of the interplay of black hole distance and the horizon. Non-commutativity fuzzes this over , so black holes can interact over super-horizon distances via quantum tunnelling. Very similar to percolation! Connection between Polyakov loops and percolation <u>not</u> trivial in Gauge picture, but understandable in gravity.

Can we make this ansatz testable?

The main effect of correction is to introduce a critical point of the Z_2 type (Shouldn't exist in a top-down system, and indeed doesent seem to!).

d	2	3	4	$Gravity$	$Gauge$
α	0	$0.110(1)$	0	R	$\langle L \rangle$
β	$1/8$	$0.3265(3)$	$1/2$	TdS/dT	C_V

In QCD can ,ideally, be read from the lattice, either in $T - N_f/N_c$ plane (hard) or $T - m$ plane (doable) In gravity,we can have a black hole in a Box or a brane setup. Universality can mean details of the theory secondary... critical exponents. And both sides are in Z_2 class!

If exponents match and remain critical, it would be very non-trivial: Stat Mech 101 says critical exponents set by universality class and number of dimensions. Holography is a counter-example! , as number of dimensions changes. In this setup we can measure critical exponents on both sides

Conclusions

- "naive" hadronic EFT unreliable for regime at $\mu_Q \simeq \Lambda_{QCD}$
- Large N_c expansion tells us quark degrees of freedom could appear even at confinement!
- On the other hand, not at all clear $\simeq \infty$
- Phenomenology of quarkyonic matter needed.

The best physicist in the USSR is Yakov Frenkel, who uses in his papers only quadratic equations.
I am slightly worse, I sometimes use differential equations.

L.D.Landau, quoted in
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