# (What) Quarkyonic matter at FAIR?

Based on PRL107:152301,2011 and soon-to-be-submitted long paper with Stefano Lottini
Also , 1006.2471 (PRC ),with with Igor Mishustin ,1105.0188 (JHEP ) with Piero Nicolini

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EMMI

HIC for FAIR
Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

## Synopsis

**What is** quarkyonic matter

Bold claim n.1: I <u>can define and explain what it is!</u>

(Its <u>not</u> inhomogeneus chiral phases, <u>nor</u> the chirally restored but confined phase!)

**Large $N_c$** : A short introduction

**An estimate** from percolation theory

**Towards a pheonomenolgy** of quarkyonic matter in supernova and at FAIR

Bold claim n.2: I <u>might have experimental signatures for it</u>

Work in progress a lot of these signatures require <u>quantitative</u> calculations

## What is "Quarkyonic matter"

The "minimalist answer": A name invited 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, 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?

Why I believe the name is more than a gimmick .

Here is a list of theories which can treat $\mu_Q \geq \Lambda_{QCD}, T < T_c$ under rigorously controlled approximations

(This is also relevant for those who look for the critical point!)

Why I believe the name is more than a gimmick .

Here is a list of theories which can treat $\mu_Q \geq \Lambda_{QCD}, T < T_c$ under rigorously controlled approximations

# Yes, thats it!

Here is a list of theories which can not treat $\mu_Q \geq \Lambda_{QCD}, T < T_c$ under rigorously controlled approximations

**Hadronic or EFTs** ($\sigma$,NJL,PNJL etc): based under the assumption that

$p_i - p_j \ll \Lambda_{funamental}$

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 quaranteed $\hat{O}^n \ll \hat{O}^{n-1}$ for any $N$

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

**AdS/CFT** unless you can quantize gravity, based on $N_c \to \infty$ approximation, of which more later

## Summarizing

Any calculation "relevant to FAIR" 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)

The physical reason is that the regime around (de)confinement is not even qualitatively described by EFTs. This cannot be "tweaked away" (See Heinz+Giacosa, Phys.Rev. D85 (2012) 056005 )

FAIR is an experimental "shot in the dark" , requiring lots of 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 $N_c$"?

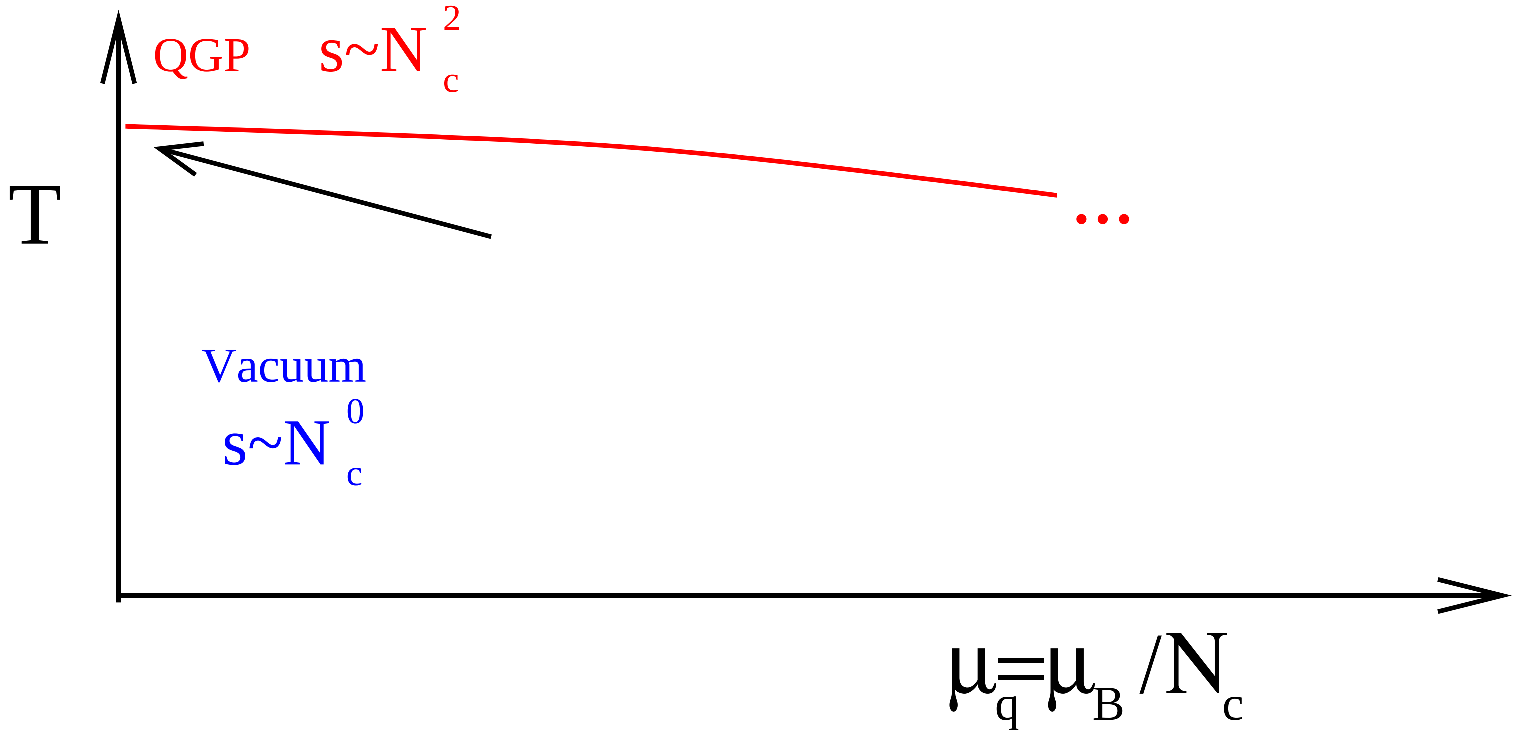
't Hooft, over 20 years ago, showed that provided a continuus limit exists where $N_c \to \infty, g_{YM} \to 0, g_{YM}^2 N_c \to \lambda$ ,

**Not solution to all problems:** $g_{YM}$ weak, but $\lambda$ has approximately same running as QCD, hence $\Lambda_{QCD} \sim N_c^0$
Theory still strongly coupled and confining below $\Lambda_{QCD}$

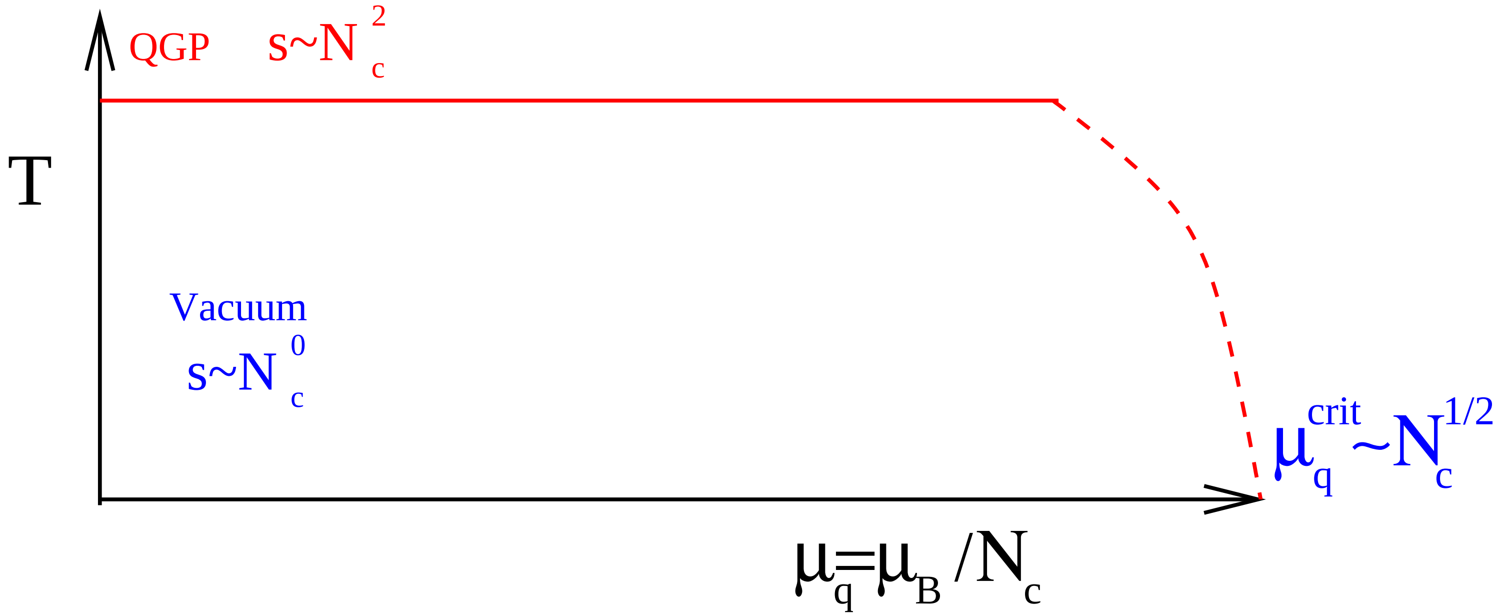
**but** in this limit drastic semplifications are possible, as some observables $\sim N_c^2$ , some $\sim N_c^0$ etc. Plugging in $N_c = 3 \to \mathcal{O}\left(10\right)$ hierarchy

$N_c$ 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...

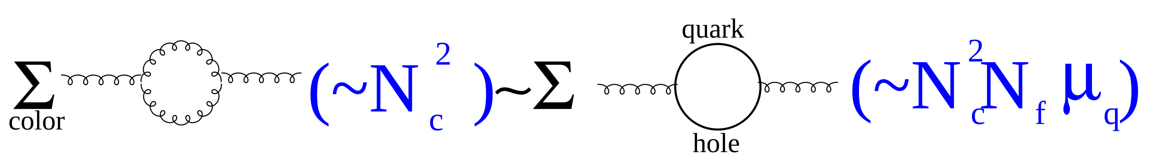


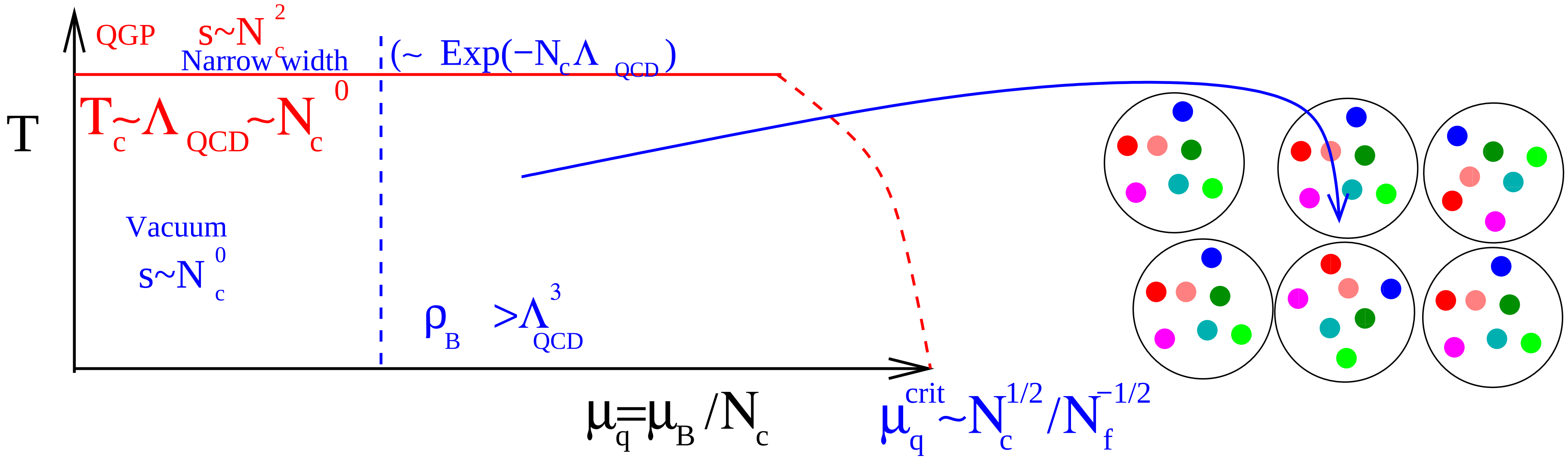

No critical point , since $N_c \gg N_f$ means confined phase acquires $Z_N$ global symmetry! Deconfinement always a phase transition!




Deconfinement line flattens, since for deconfinement $\mu_B \sim N_c^{1/2} N_f^{-1/2} m_B$

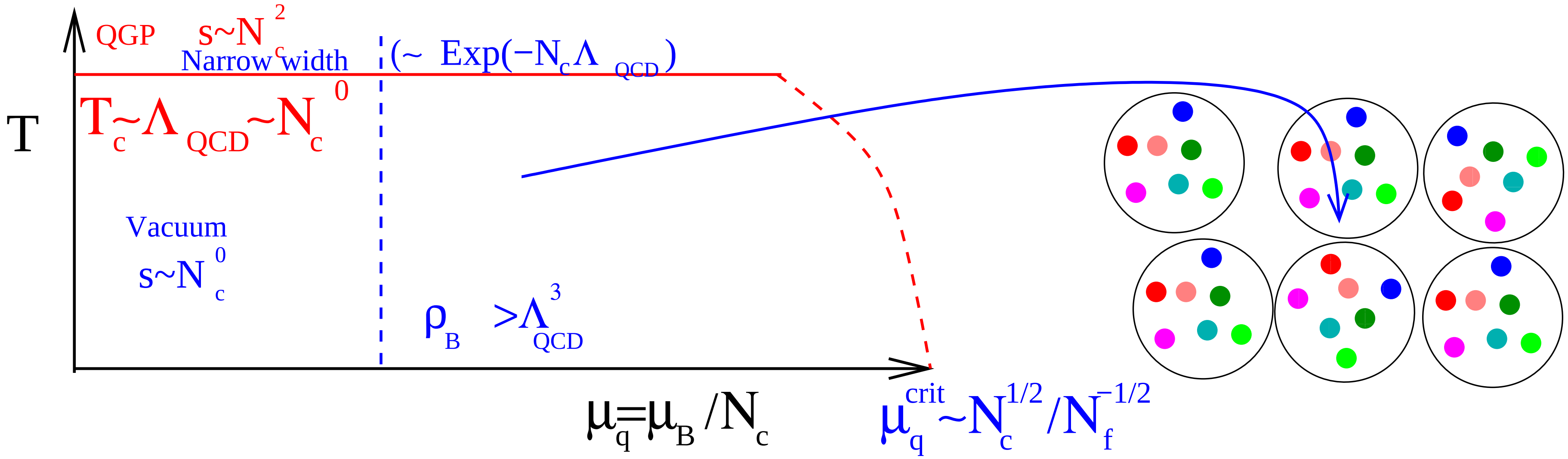
For deconfinement






line separating "vacuum" from "dense nuclear matter" narrows

McLerran+Pisarski, arXiv:0706.2191: line defines new "quarkyonic" phase!




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?) A new phase to look for at low energy, high density (Neutron stars, FAIR, NICA, etc.), In alternative to critical point

A nice idea, but is $N_c$ large? Can we exclude phase transitions in $N_f/N_c$?

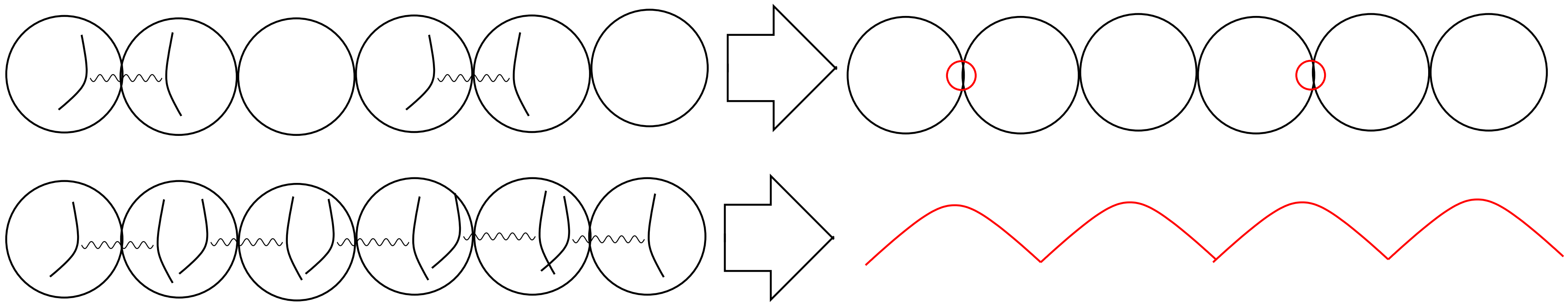
an EFT of $\mu_Q \sim \Lambda_{QCD}, N_c \gg 1$ matter

**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.

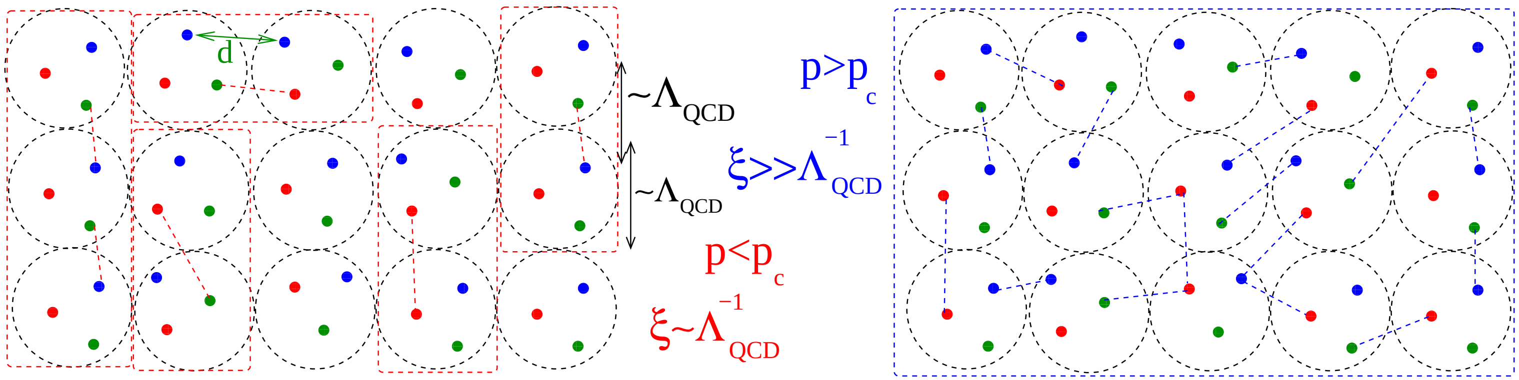
Such a "conducting phase", not predicted by any EFT, could be the "surprise" we were looking for



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

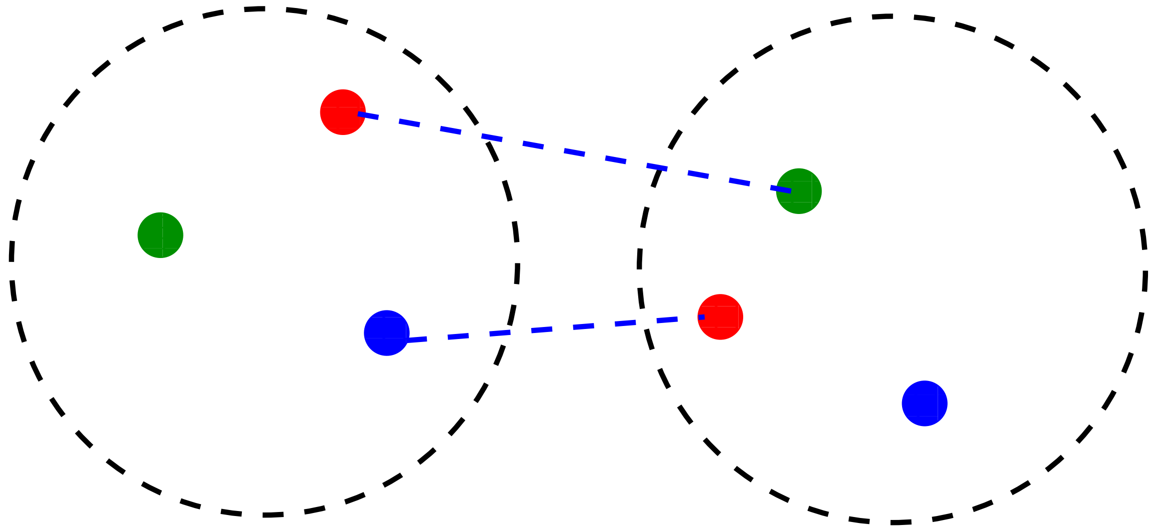
However , since Quark/baryon $\sim N_c$ , conductor/insulator transition in full $T - \mu_Q - N_c$ space!

## $N_c$ 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~ 

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

## An ansatz with confinement and correct $N_c$ scaling

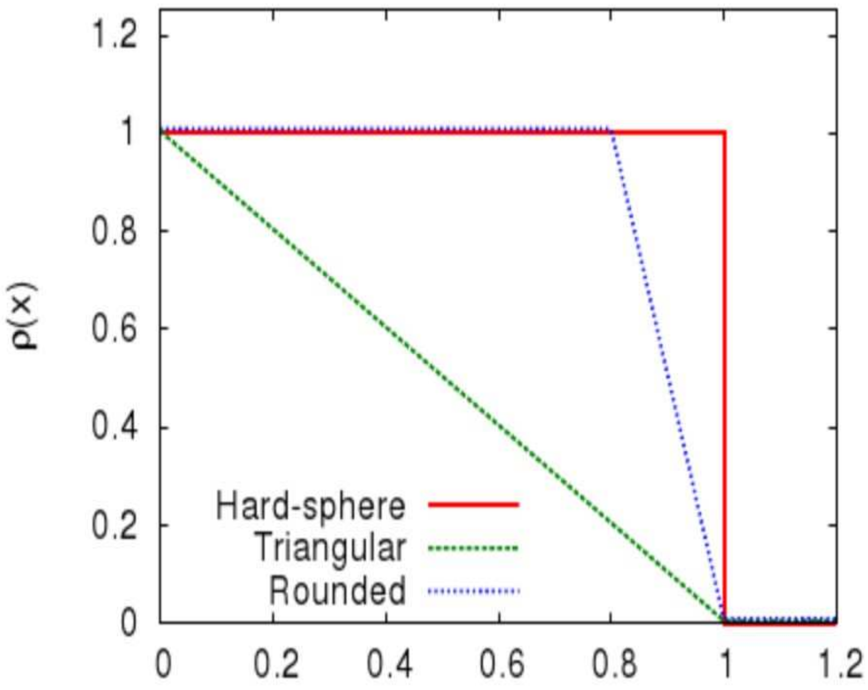
$$p = 1 - \left(q_{(1),ij}\right)^{(N_c)^{\alpha}} \quad , \quad q_{(1),ij} = \int f_A(x_i)\mathrm{d}x_i \int f_B(x_j)\mathrm{d}x_j \, (1 - F(|x_i - x_j|))$$

Mathematically very similar to Glauber model, dont need to get $\sigma$ 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 $\rho$ 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 $\rho$ considered

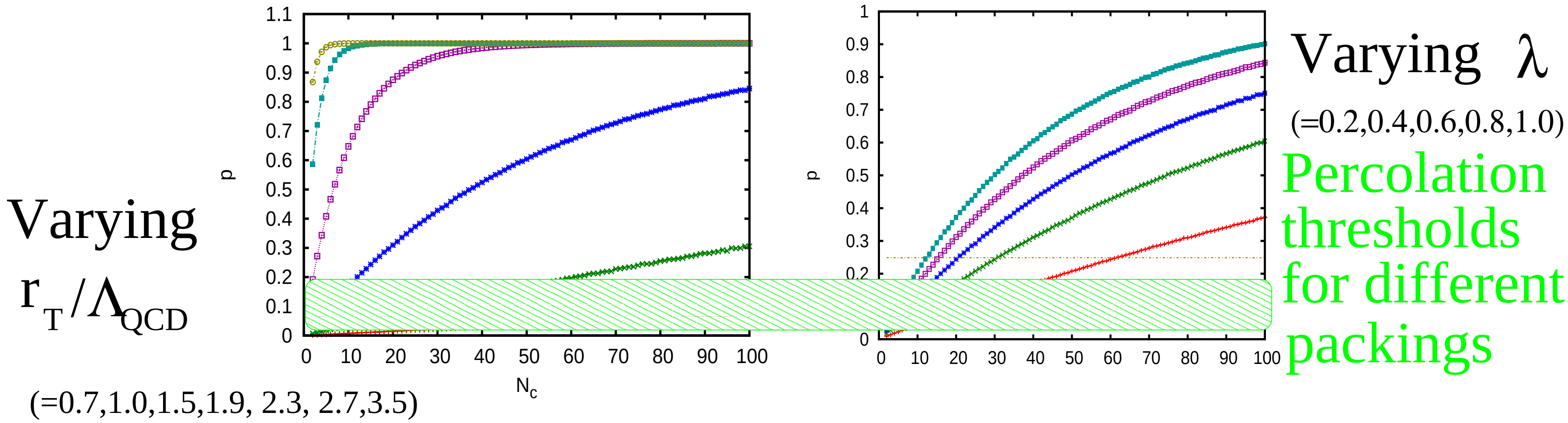


...and a range of probability amplitudes for the exchange $i \leftrightarrow j$ which respect

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

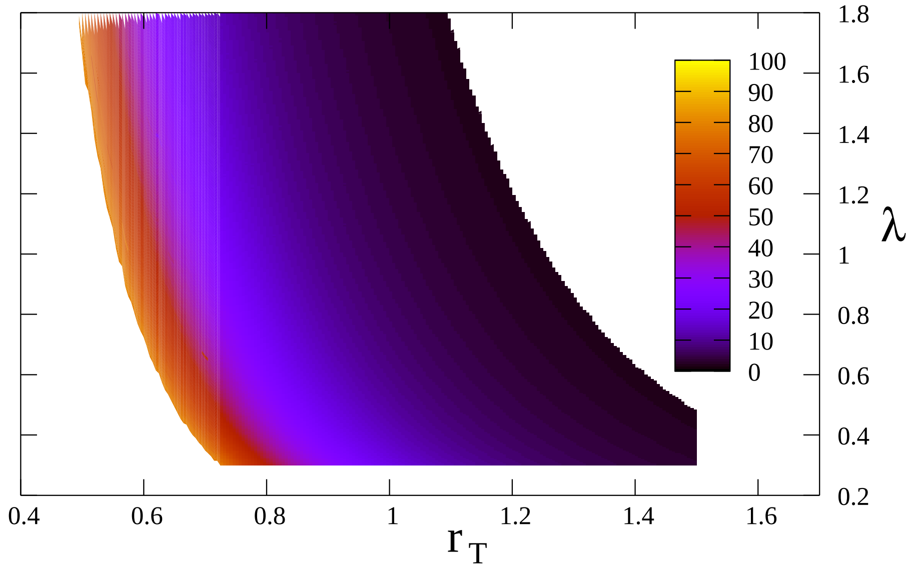
$$F(y) = \frac{\lambda}{N_c} \mathcal{N} \begin{cases} \theta(1 - \frac{y}{r_T}) \\ \exp\left( - \frac{3}{4} \frac{y^2}{r_T^2} \right) \\ \frac{2 r_T^2}{\pi y^2} \sin^2 \left( \frac{y}{r_T} \right) \end{cases}$$

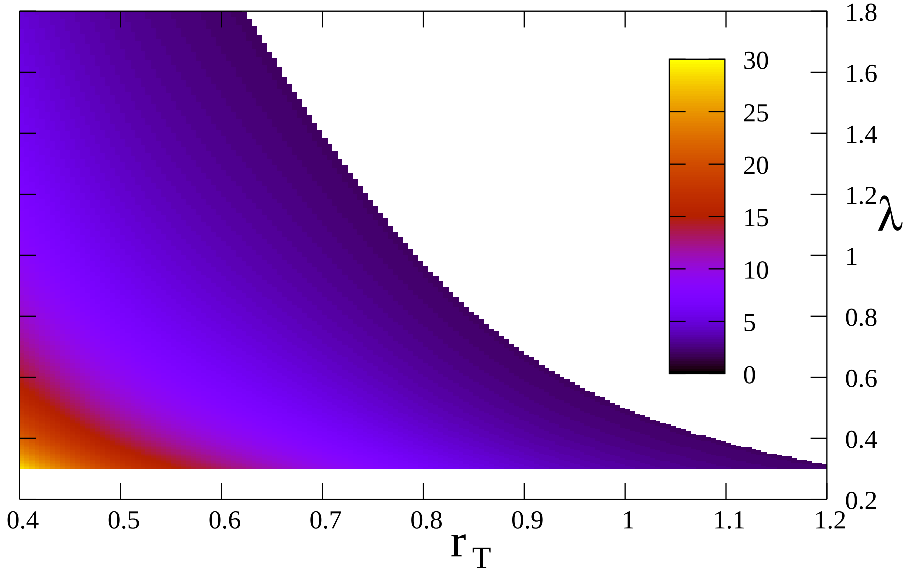
($\Theta$-function and Gribov-Zwanziger propagators)




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

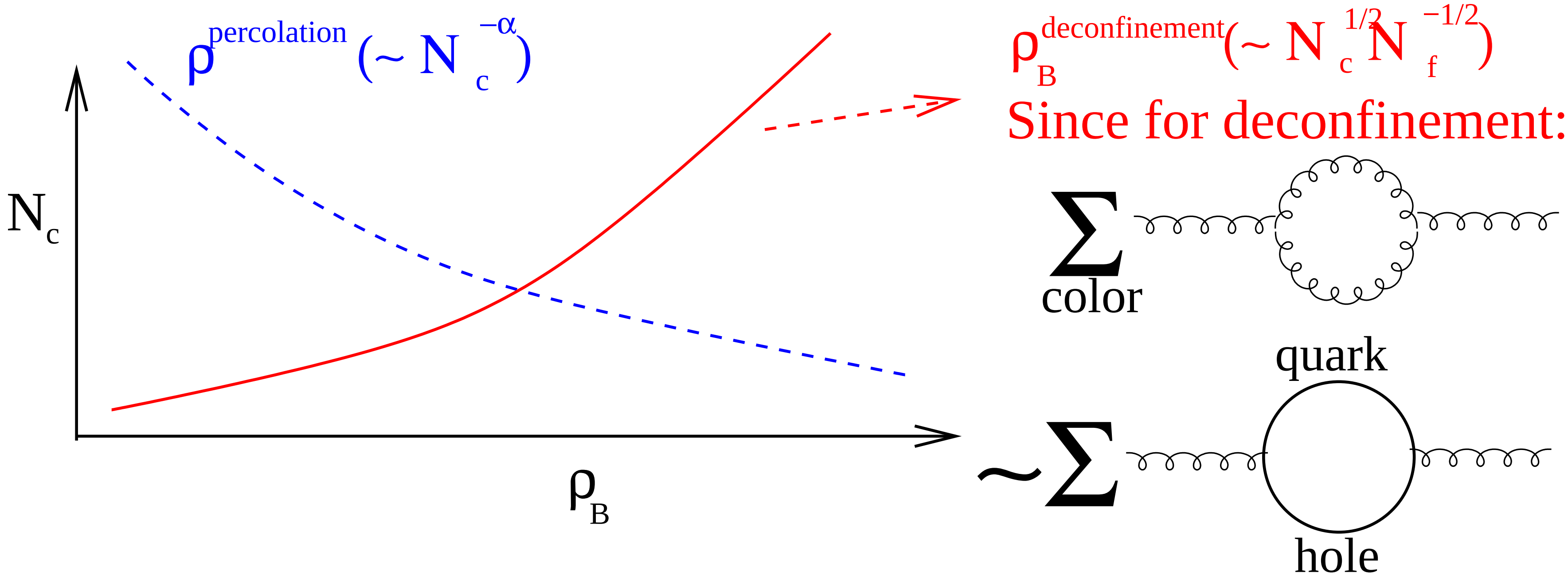
## Critical $N_c$ for $\Theta$-function $P_{i \leftrightarrow j}$ in position and momentum



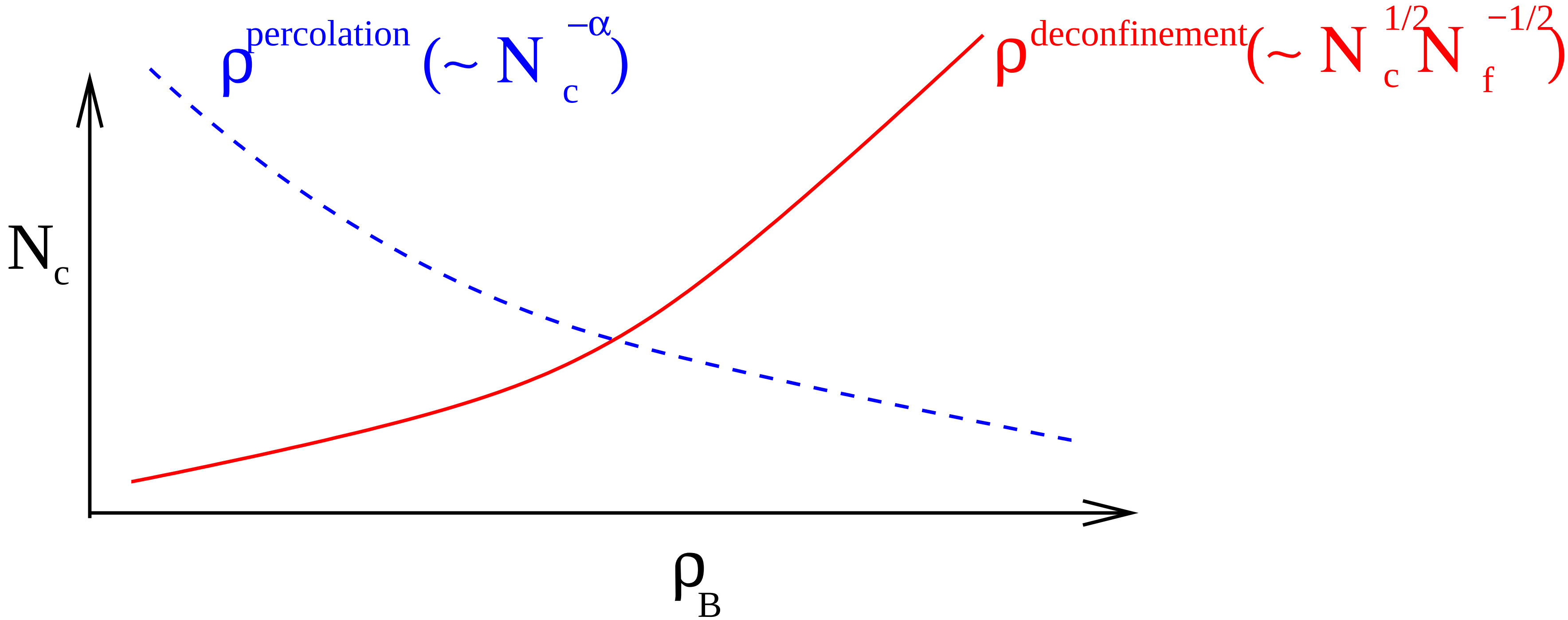

"typical" Parameters of order unity give a critical number of colors for percolation well above 3. These are lower limits, since we assume hexagonal lattice (Skyrme cubic and disordered $p_c$ higher). So $N_c^{crit} = 3$ disfavored but not excluded at $\mu_Q = \Lambda_{QCD}, T = 0$.

## But lets vary $\mu_Q$:Percolation and deconfinement

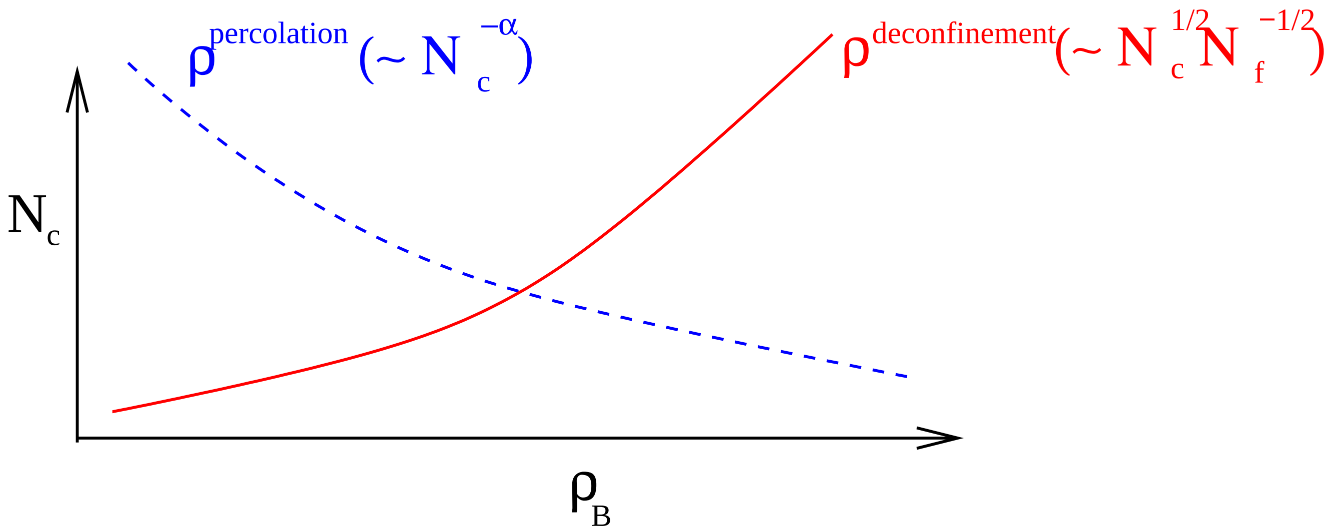



Percolation: $\rho - N_c$ anti correlated.

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



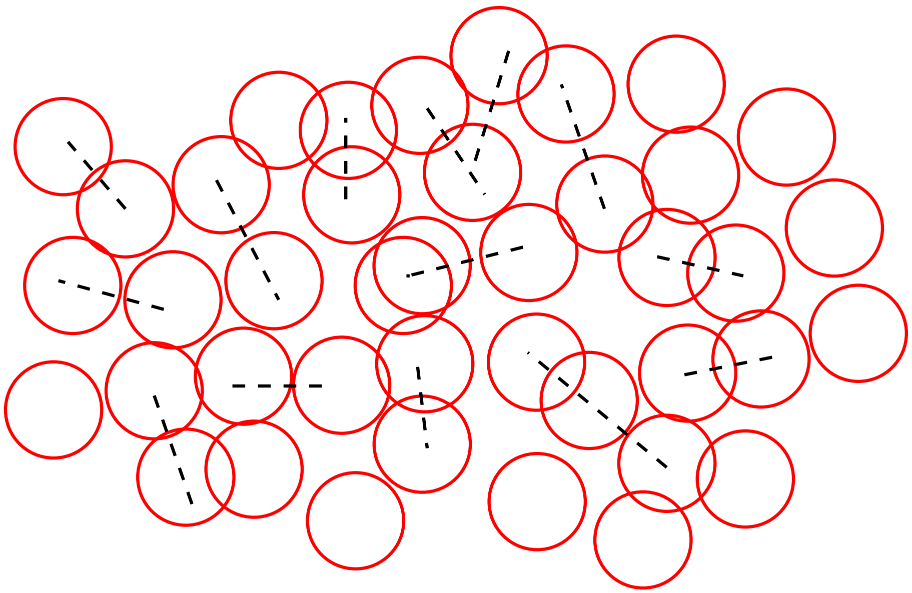

Remember 1 percolating quark negligible for wavefunction of hadron . Need $\mathcal{O}\left(N_c^{1/2} N_f^{-1/2}\right)$ quarks to break hadron apart. But $N_c = 3$ !!!




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

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

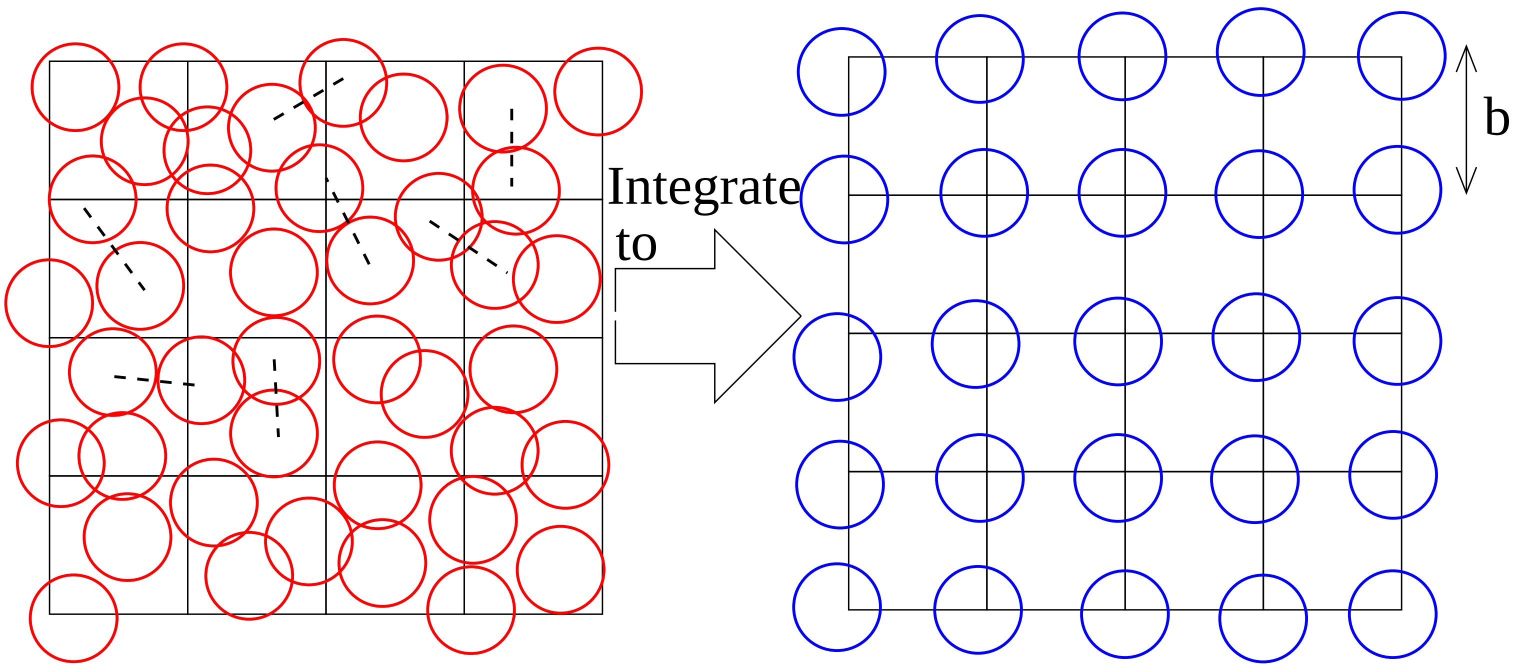
What is this critical $N_c$? Percolation in a "glass": Conceptually similar, technically more involved



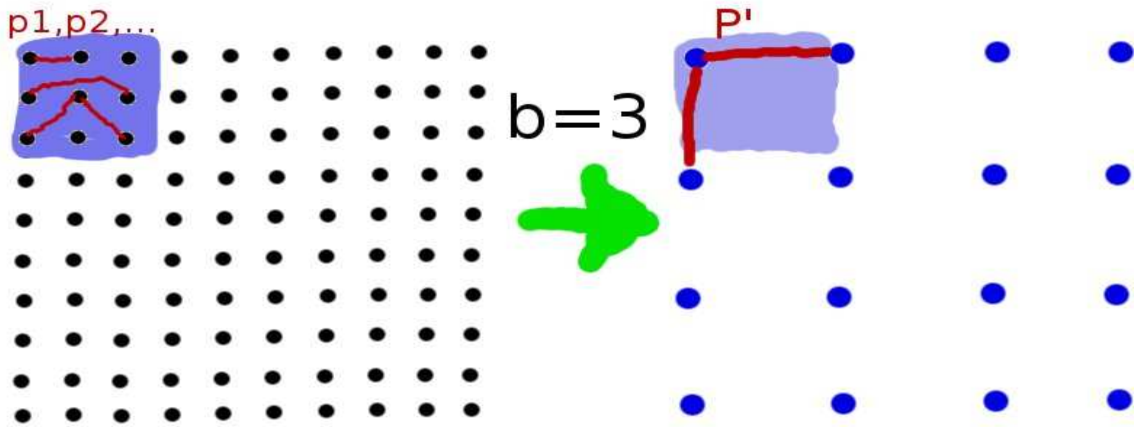
- "Nearest neighbor" not uniquely defined: Baryons overlap
- Interactions to arbitrary distance $\rightarrow$ percolation for arbitrarily low tresholds?

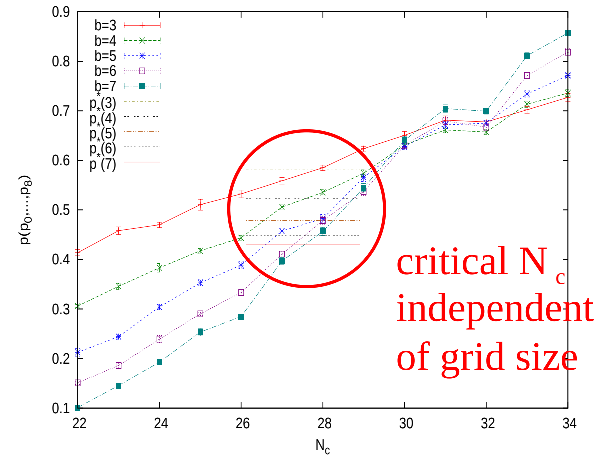
## Solution:MC renormalization

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



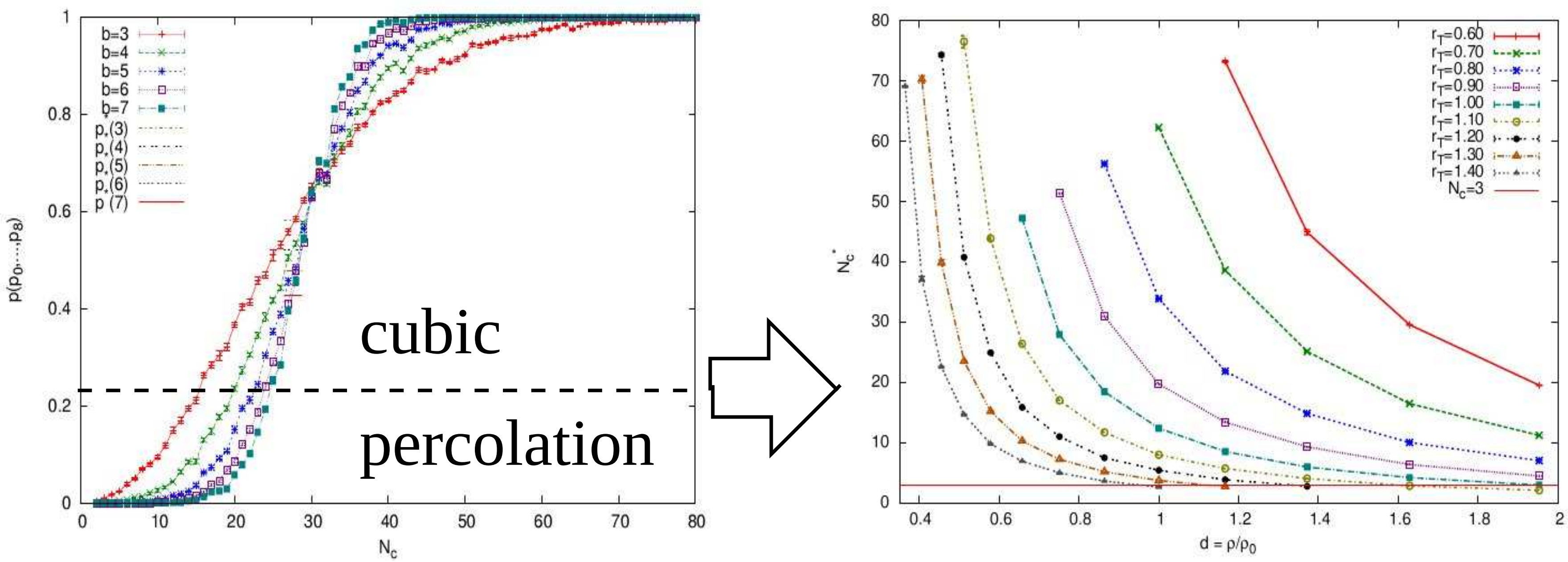

Since percolation at critical point, critical probability should be fixed point of renormalization step, independent of $b$




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

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




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

$$\frac{n^{conf}}{\Lambda_{\rm QCD}^3} = \frac{4\pi g_f g_s(N_c)}{(2\pi)^3\sqrt{N_f}} N_c^{3/2(T-T_c)^*} \sum_{n=1}^{\infty} (-1)^n \frac{n\gamma^2}{\beta} \sinh\left( (\sqrt{N_c}\beta)^n \right) K_2\left(n\gamma\beta\right)$$

$$\frac{e^{conf}}{\Lambda_{\rm QCD}^3} = \frac{4\pi g_f g_s(N_c)}{(2\pi)^3\sqrt{N_f}} N_c^{5/2(T-T_c)^*} \sum_{n=1}^{\infty} 3(-1)^n \frac{n\gamma^3}{\beta} \cosh\left( (\sqrt{N_c}\beta)^n \right) \left( \frac{3}{\gamma\beta} K_2(n\gamma\beta) \right.$$

Where $g_s(N_c), g_f$ are the degeneracy factors 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 $\mu_B$ : Parametrize confinement line by $T^2 + N_c^2 \mu_q^2 = \mathcal{O}\left(1\right) \Lambda_{QCD}^2$

Quarkyonic phase might 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 $\mu_B \sim \Lambda_{QCD}$

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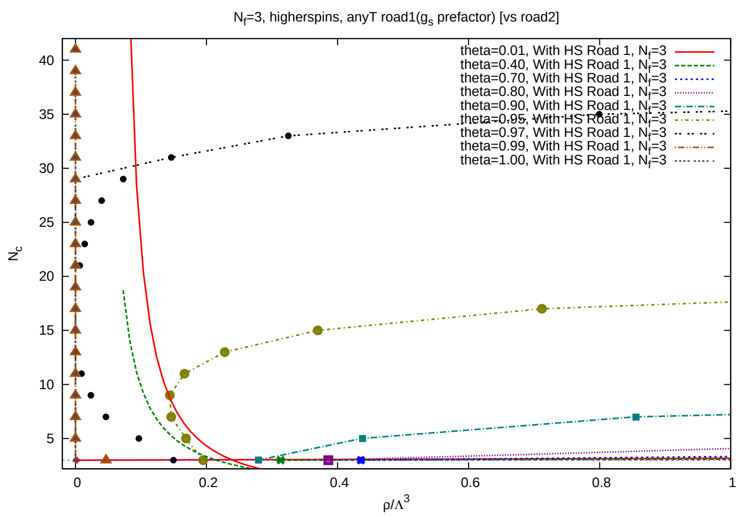
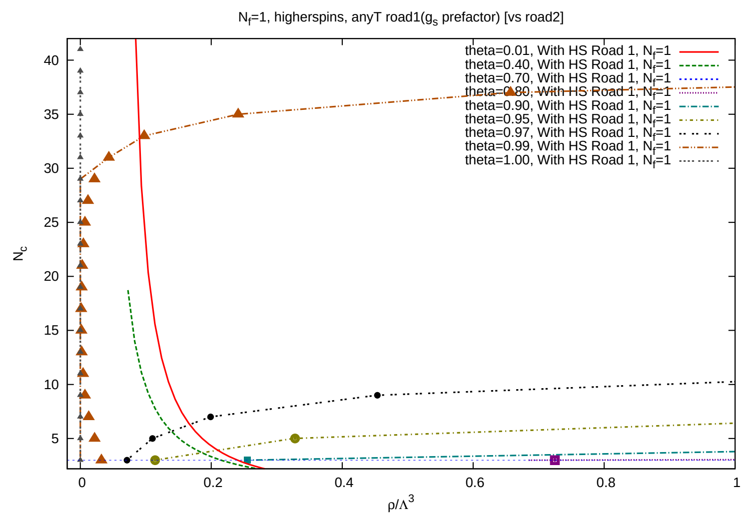
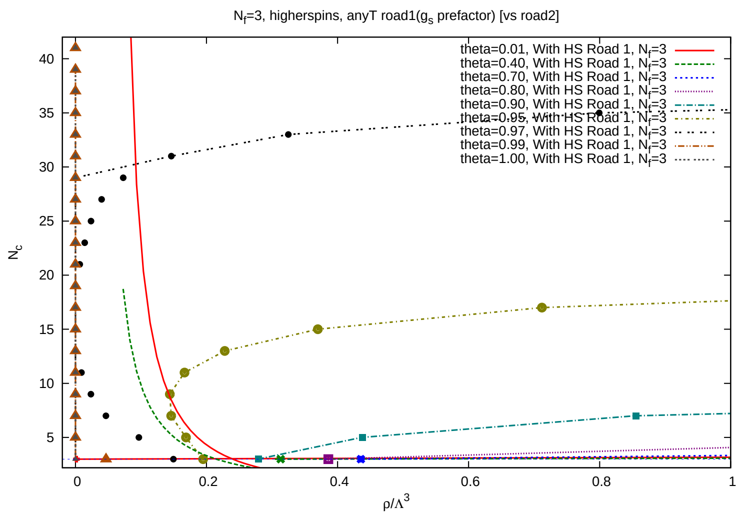
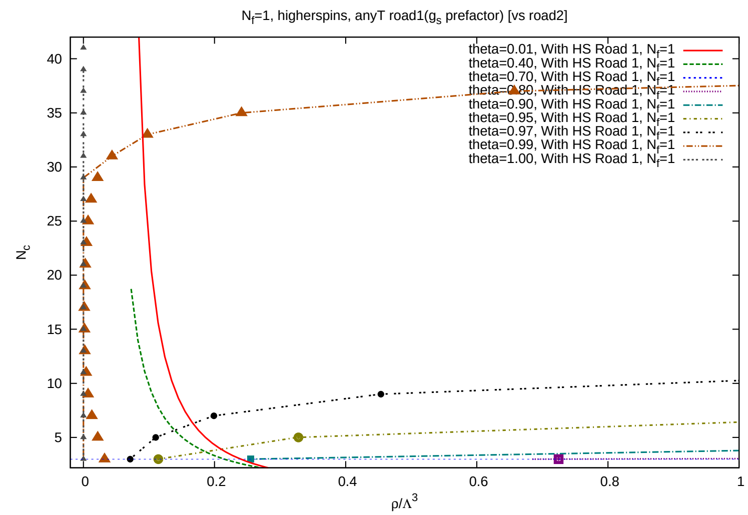



A sliver of $n - \rho - N_c = 3$ space which is percolating but confined seems to be there, but...



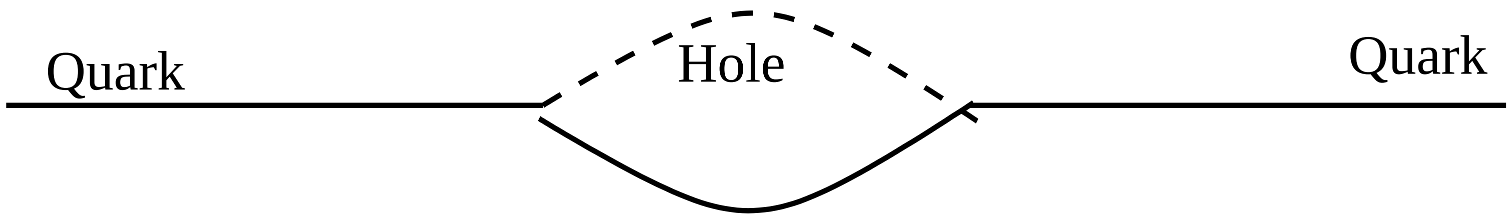




Width depends a lot on whether $N_f = 2$ or $N_f = 3$ .
“Systematic error too big . Need phenomenology!

Observing such a percolating phase: What does it look like?

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

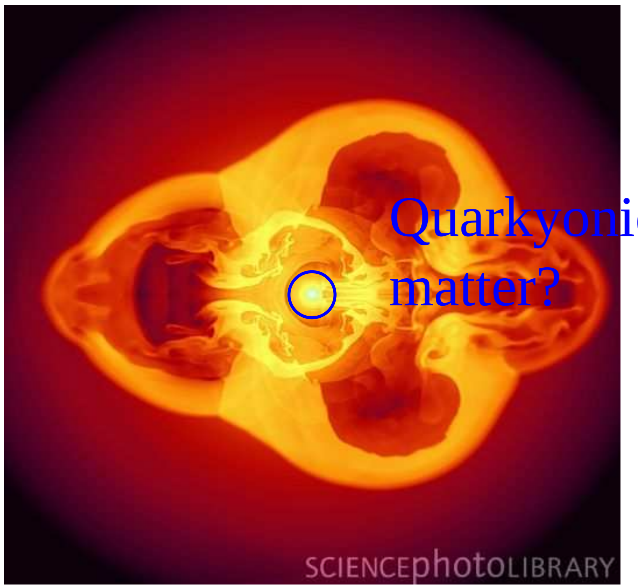
$$\frac{dS}{dV} = \frac{dP}{dT} = \frac{P+\rho-\mu n}{T}$$




And <u>any</u> 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

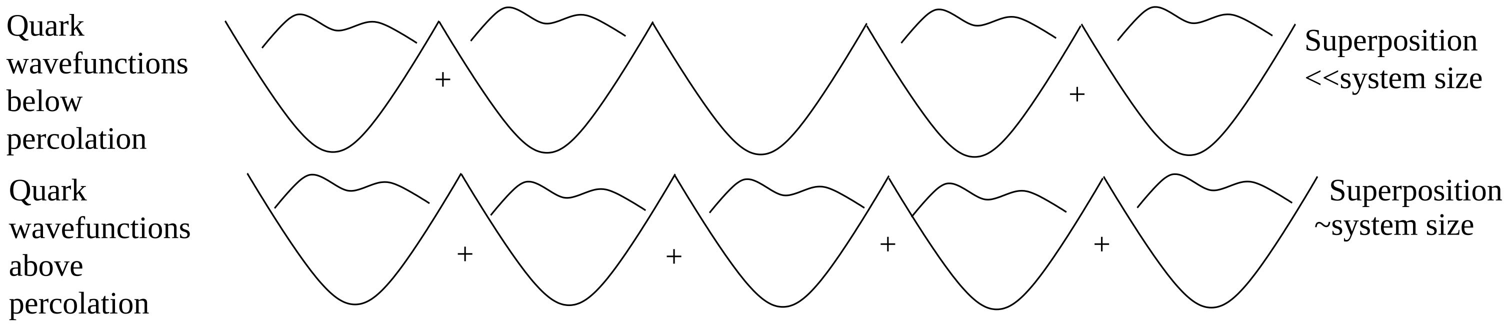
## Astrophysical implications

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?

## From EoS to dynamics: An EFT of percolating matter



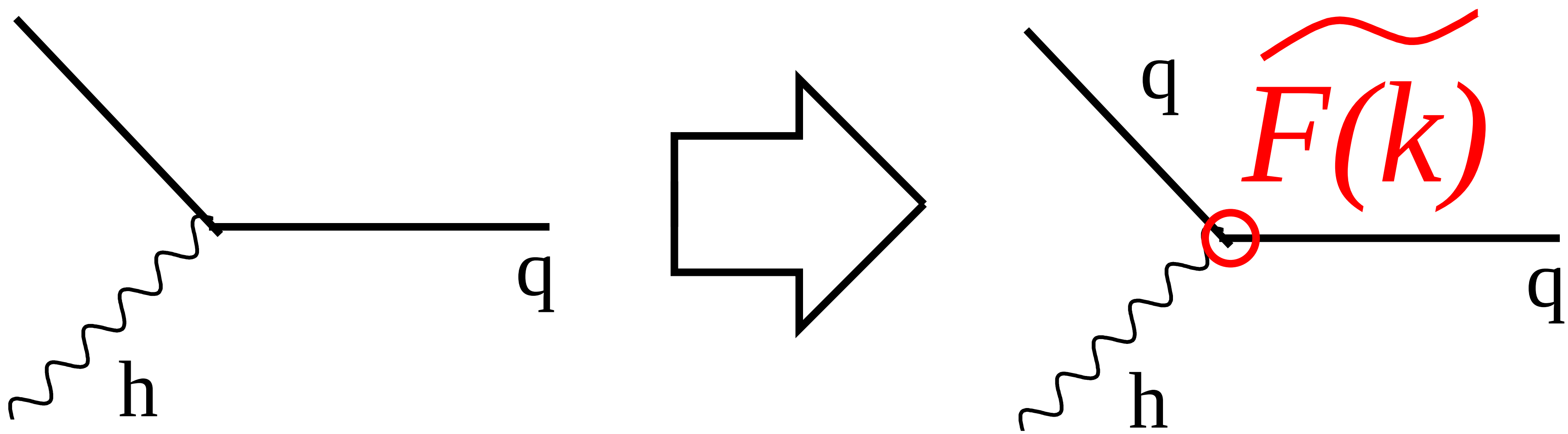

In percolation regime, asymptotically free quark wavefunctions of different baryons can superimpose across large distances.

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 always $p \geq \Lambda_{QCD}^{-1}$

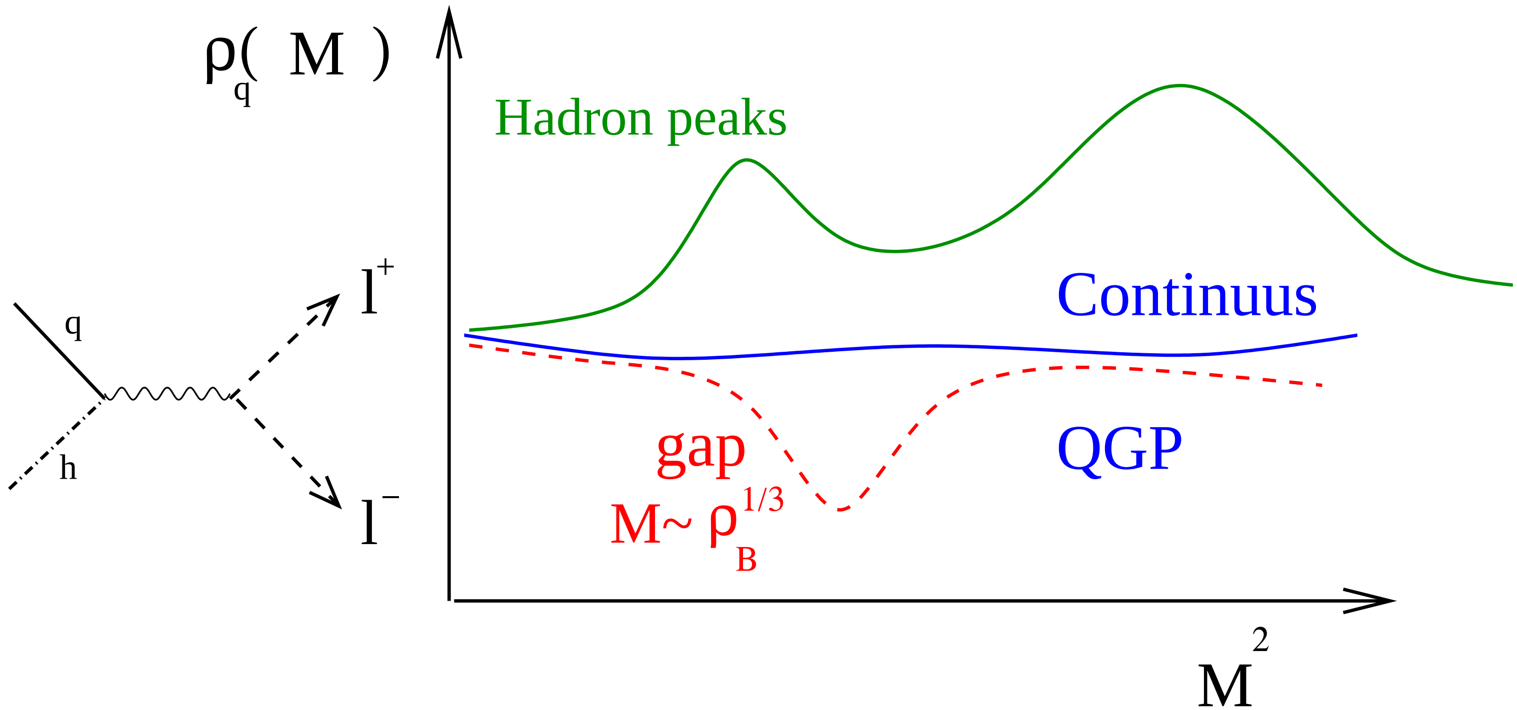
## pQCD but not quite: the role of baryons

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

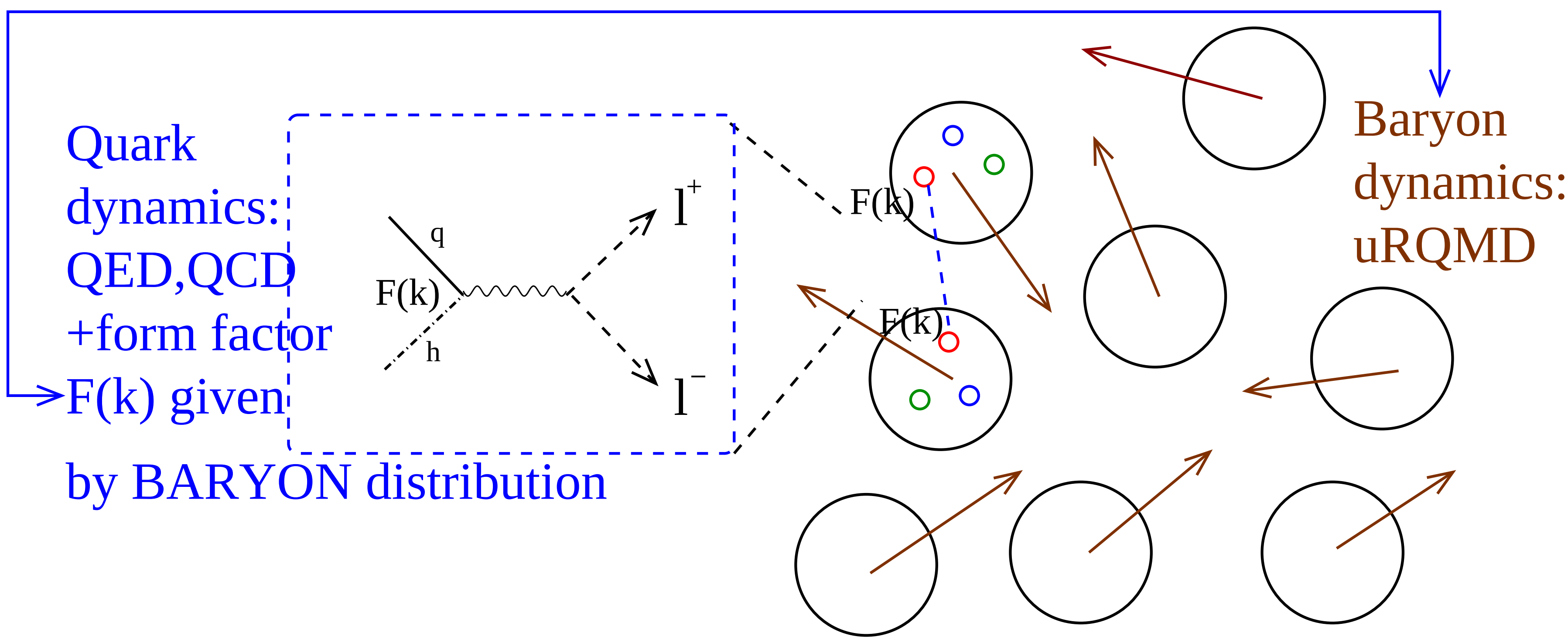



$F(k)$ gives the F.T. of the baryonic gluon content. For the equation of state, it should just be a $\mathcal{O}(1)$ normalization factor, but for scattering processes it is a qualitative difference from naive QCD.

## Experimental implications



# Modeling quarkyonic matter for FAIR

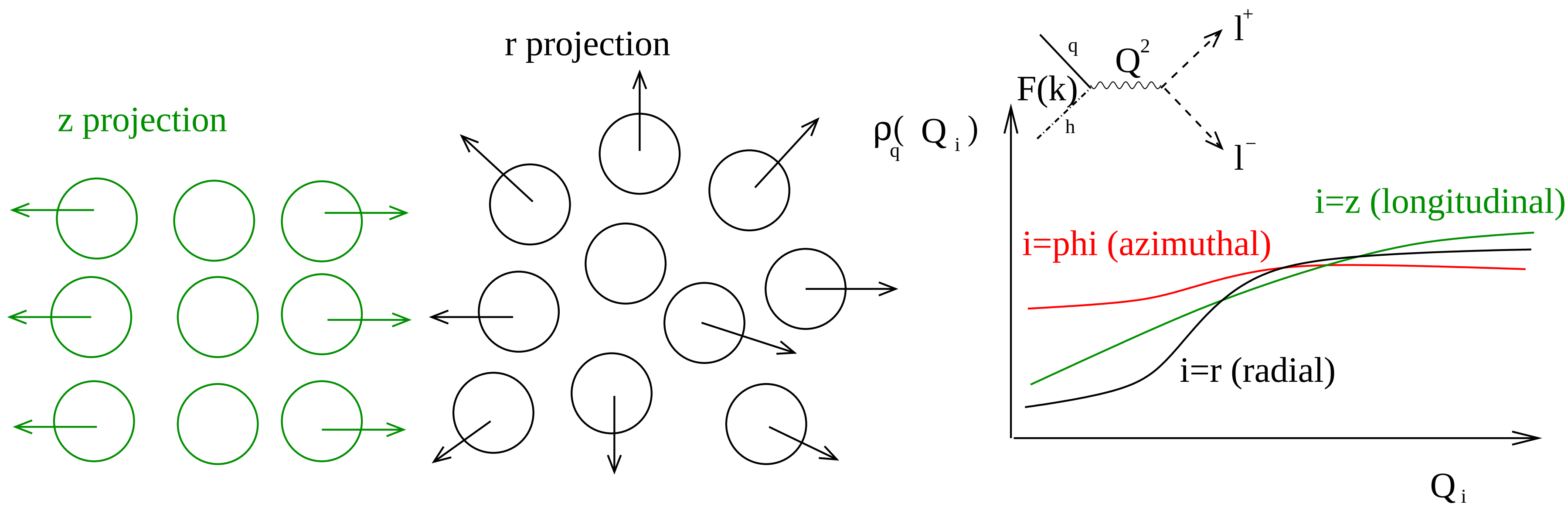


**Baryonic degrees of freedom** "classical", can be accounted for by baryonic transport (QMD,RQMD etc), gives you baryonic distribution $f(x)$ E-by-E

$\tilde{F}(k)$ **form factor** computed from baryonic degrees of freedom by F.Ting $f(x)$

**Rates for q-q processes** calculated from pQCD+Form factor

Any hadronic transport model on the market can be transformed into a quarkyonic model! Anyone interested?




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!

## 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.


@