# Quarkyonic matter. What is it and how (maybe) to detect it?

Based on arXiv:1302.1119 and 1103.4824 PRL
1204.3272 and 1006.2471 PRC
with Igor Mishustin,Stefano Lottini and Sascha Vogel . Old stuff with open questions

G.Torrieri

UNICAMP

FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA
DO ESTADO DE SÃO PAULO

## Synopsis

**What is** quarkyonic matter. Definition from Nucl. Phys. A **796**, 83 (2007), by McLerran and Pisarski:
Coexistance of pQCD with confinement/baryonic degrees of freedom !
NOT confinement-chiral symmetry separation, chirally inhomogeneus phases etc!

**Does it exist?** An attempt at an estimate from percolation theory

**Towards a pheonomenolgy** of quarkyonic matter via electromagnetic signals

No conclusions as yet.

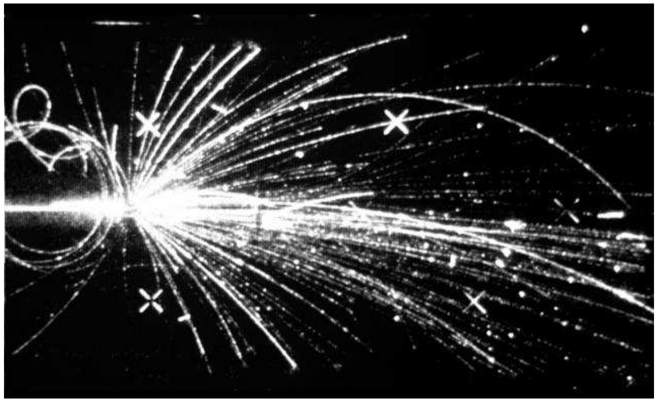
## “The other” heavy ion program

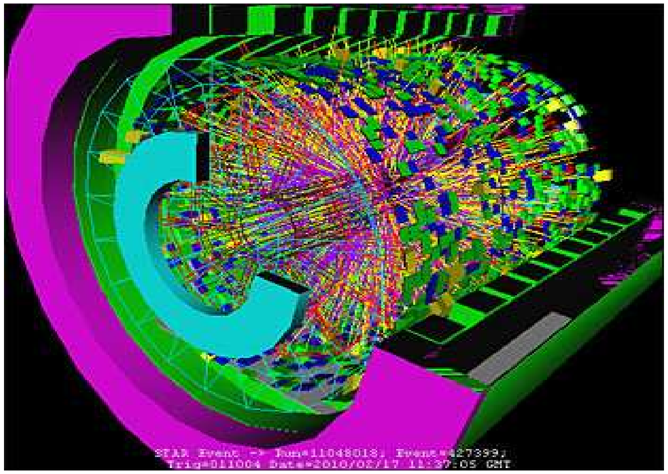
Recently you heard a lot about the LHC heavy ion program, but there is an equally exciting low energy program going on in parallel.

- RHIC low energy scan
- SPS experiment NA61 (CERN)
- FAIR (GIS,Darmstadt)
- NICA (Dubna,Russia)

## Revisiting low $\sqrt{s}$

1988
(BEVALAC)

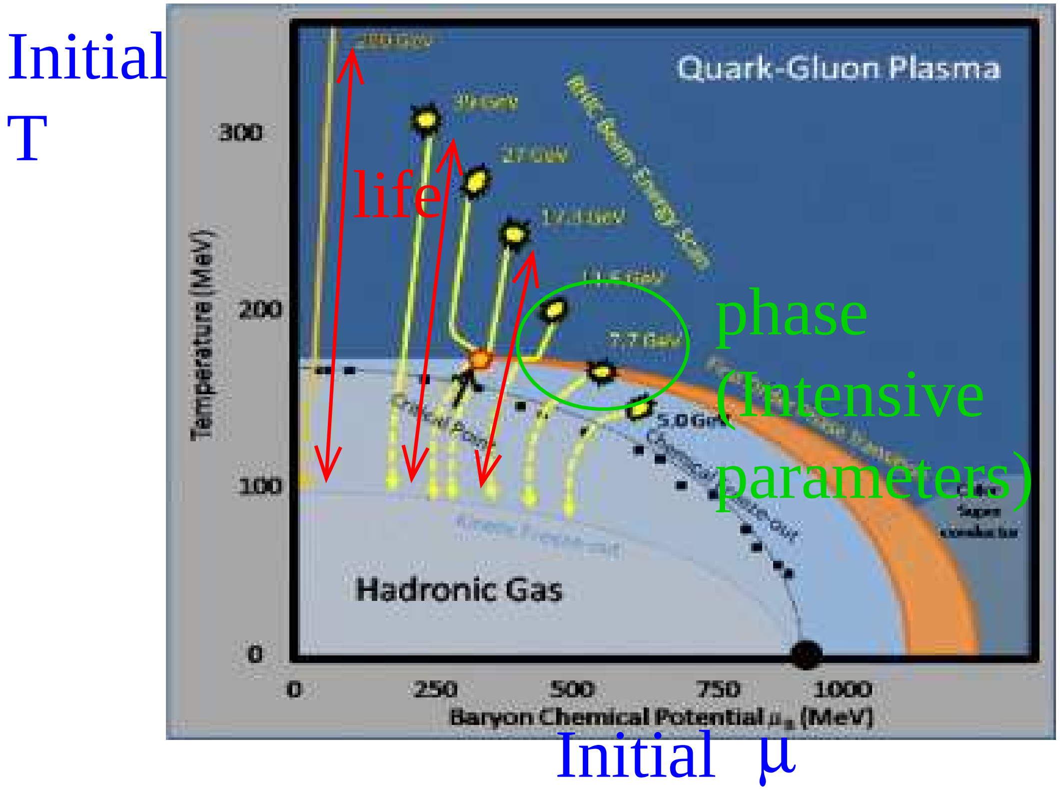




2012
(STAR)

Why low energy runs? Eliminating the $\sqrt{s}$-detector correlation!

To examine lower energies with modern dectectors and analysis. Luminosity/acceptance/triggering/analysis vastly progressed, allowing precision measurement of new observables at low $\sqrt{s}$. Since not all "interesting physics"@high $\sqrt{s}$

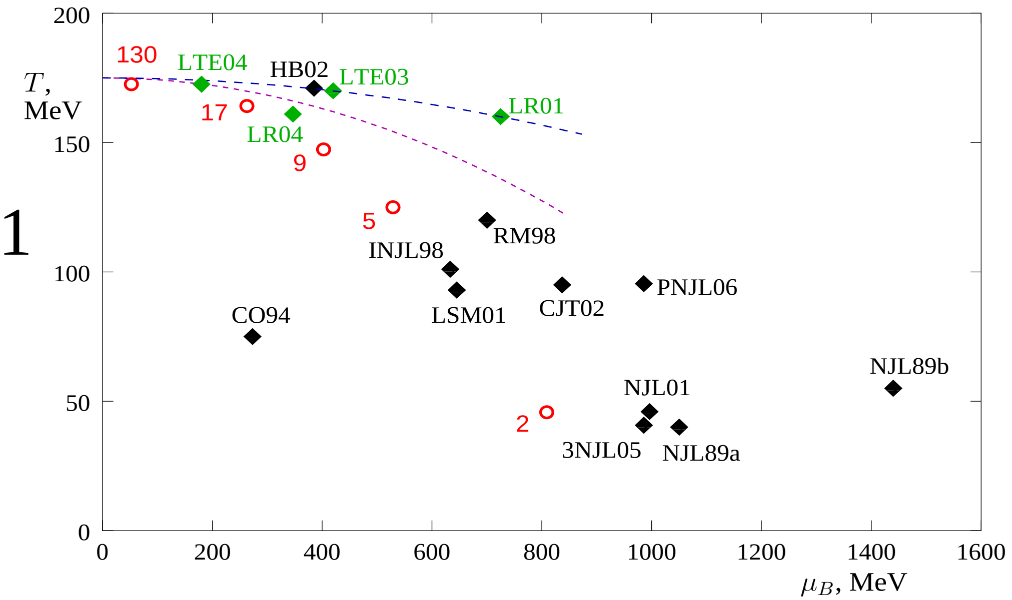



The basic idea: By scanning in $\sqrt{s}$ , we generally decrease temperature <u>but</u> increase density! This way we can study denser phases of the system, perhaps relevant to <u>neutron stars</u>.

What can we discover? the critical point

"clear" signatures: divergence of fluctuations,higher cumulants, softening of the EoS (with "softest point" in 1st order phase).

M.Stephanov
hep−lat/0701002v1




But why are the points so spread out?? Plus, De Forcrand and Philipsen believe no critical point

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

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

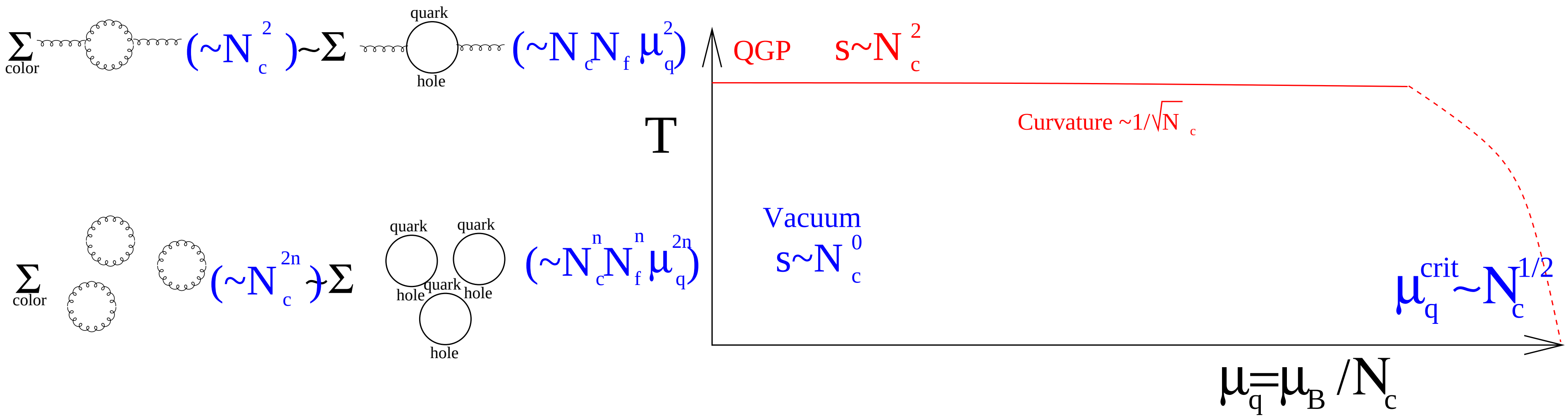
**Any high density calculation** is an essentially educated guess. Expect surprises

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

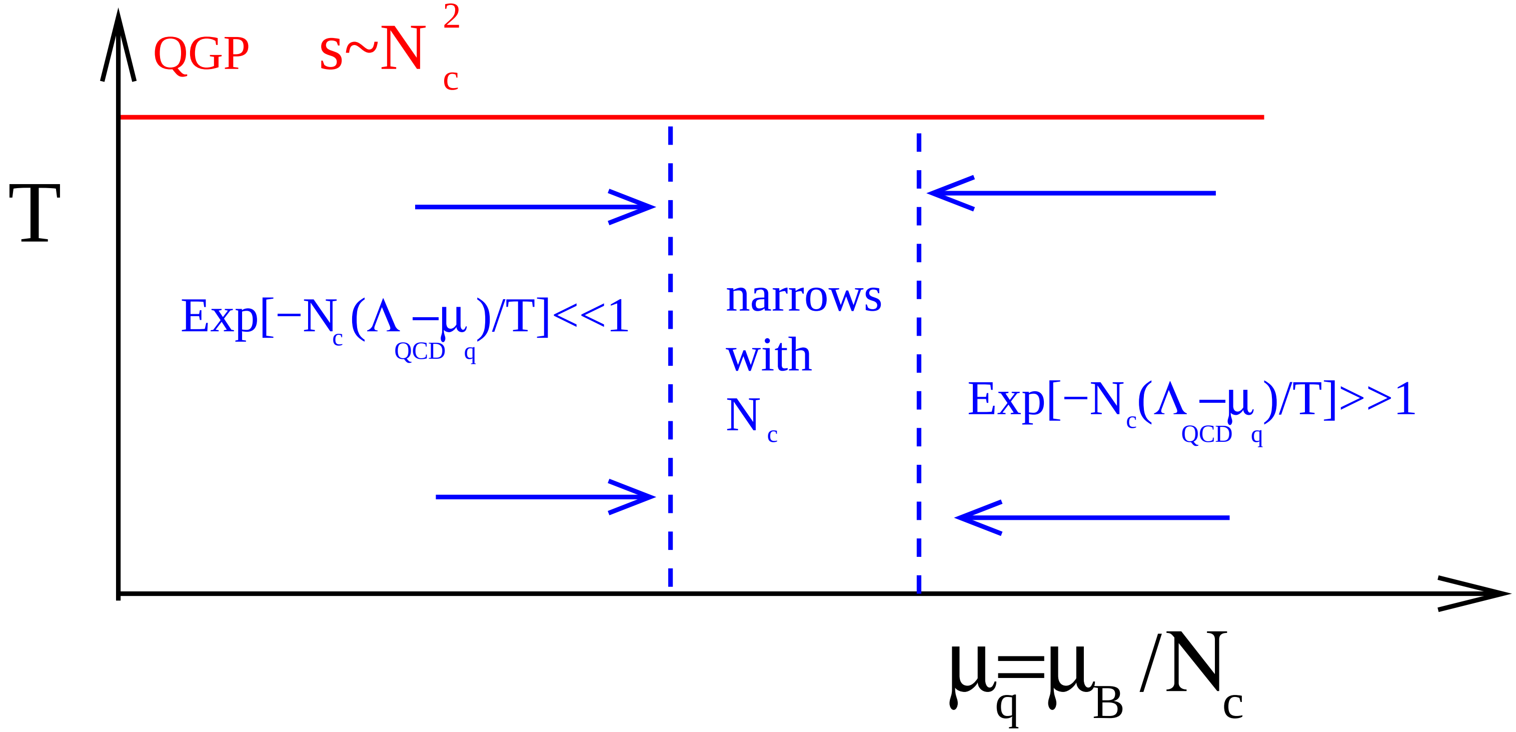
And indeed there have been plenty of speculation of what we could find

- Coexistance between Confinement+pQCD (Mclerran,Pisarski,2007)
- Confinement+Chiral restoration (Fukushima,McLerran, 2008)
- Chiral spiral inhomogeneities (Kojo,Pisarski,Tsvelik, 2009)
- Generic chirally inhomogeneus regions (Buballa et al)
- Deconfinement+Chiral breaking (Fukushima,Csernai, 2009)...

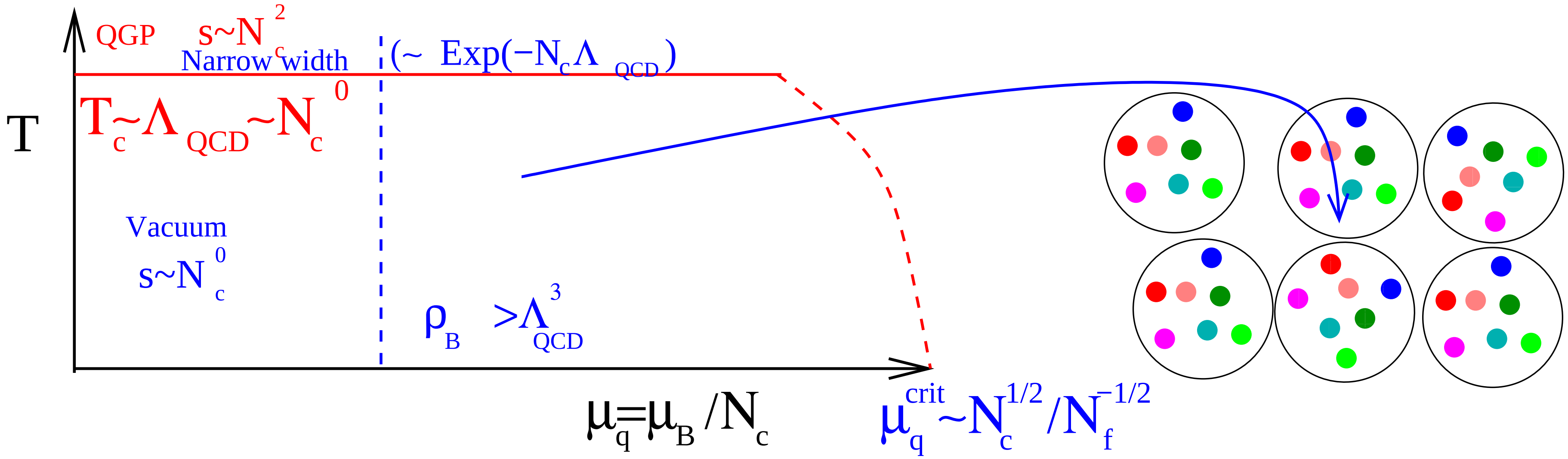
Lets get some insights in the large $N_c$ limit... $(N_c \simeq 3 \gg 1, N_c^{-1} \ll 1)$




Deconfinement line flattens, since for deconfinement $\mu_Q \sim N_c^{1/2} N_f^{-1/2} m_B$ (also No critical point , $N_c \gg N_f$ means confined phase has $Z_N$ global symmetry, Deconfinement always a phase transition! )




line separating "vacuum" from "dense nuclear matter" narrows
McLerran+Pisarski, arXiv:0706.2191: line defines new "quarkyonic" phase!




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

A <u>totally new phase</u> (FAIR,RHIC@low$\sqrt{s}$,Neutron stats,...) alternative to critical point, inaccessible to EFT! But...

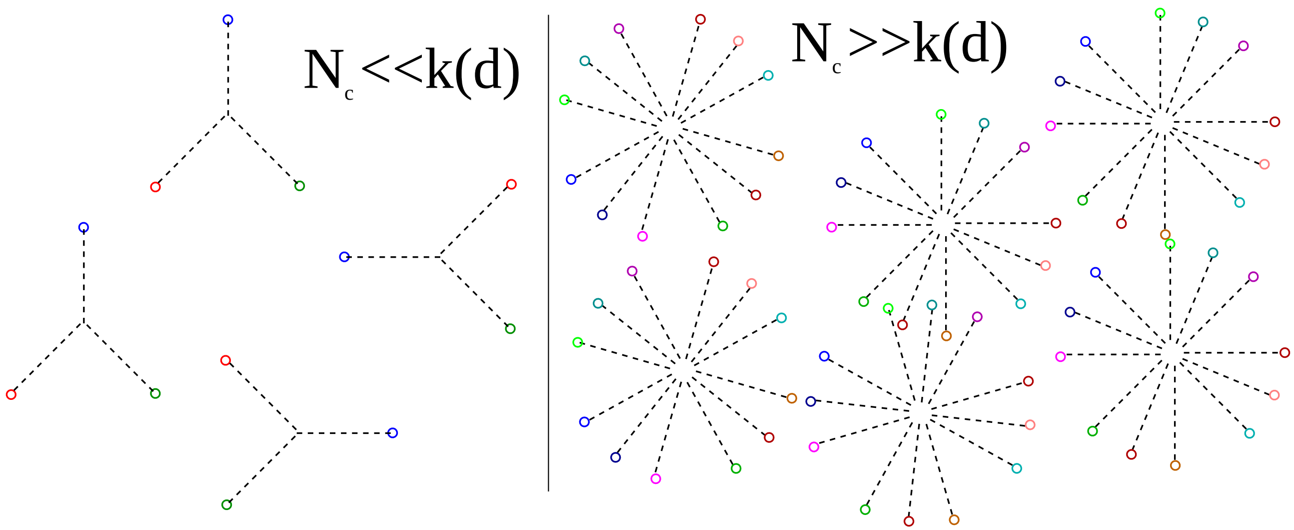
How close are we to the $N_c \to \infty$ limit?

In vacuum many qualitative ($\sim \mathcal{O}(30\%)$) agreements (Skyrme,planar diagrams, OZI rule,... ). In-medium remarkable ($\sim \mathcal{O}(1000\%)$) failures

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

Phase transitions in $N_c$ between $N_c = 3$ and $N_c = \infty$?
(Or is "quarkyonic matter" simply nuclear matter at large $N_c$?)

A conjecture: “in-medium” $N_c$ “not large” wrt number of neigbhors




G.Torrieri,S.Lottini
Phys.Rev.Lett. 107 (2011) 152301

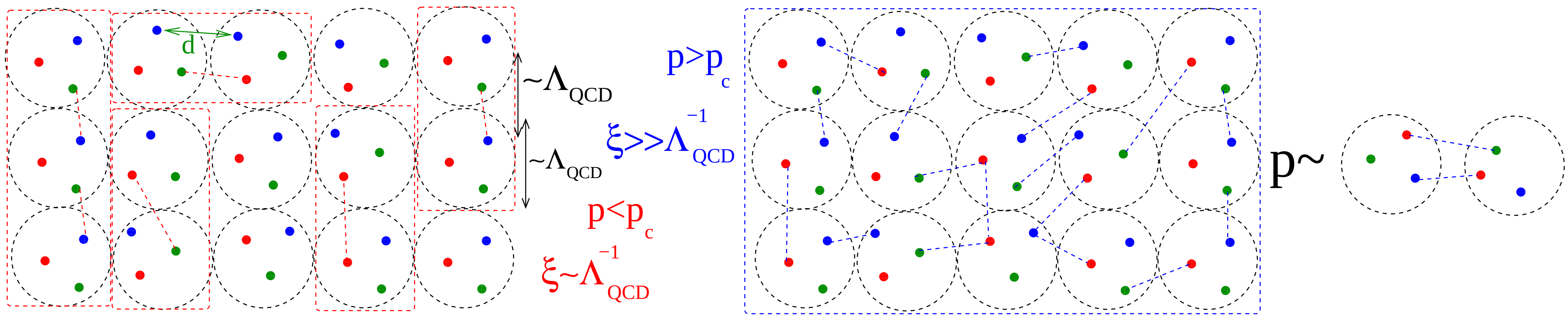
G.Torrieri,I.Mishustin
Phys.Rev. C82 (2010) 055202

**Pauli-blocking** of color wavefunctions in dense system ($\sim N_c/(N_f N_N)$ )

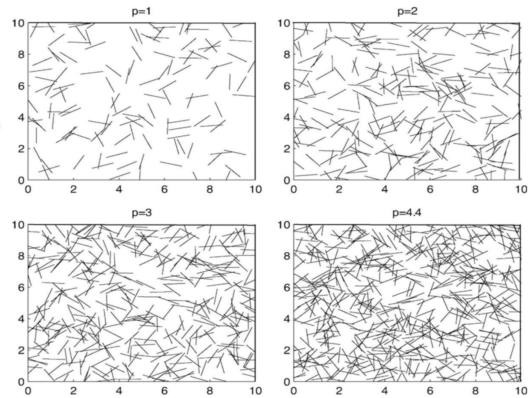
**Percolation** of any “perturbative” interactions ($\sim N_c/N_N$ )

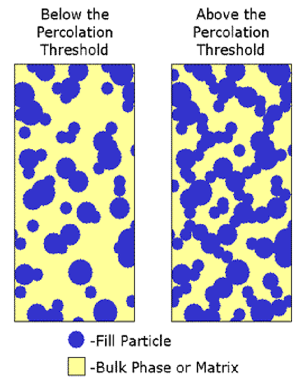
Any “quarkyonic” phase-line will curve in $N_c - \rho_B$

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




With $N_c$ colors, ways two baryons can interact with one another grows fast with $N_c$ . Correlation length diverges at percolation, existence of transition independent of microscopic details (percolation behavior universal! )




## 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) We assume a range of probability amplitudes for the exchange $i \leftrightarrow j$ with rapid fall-off at distances

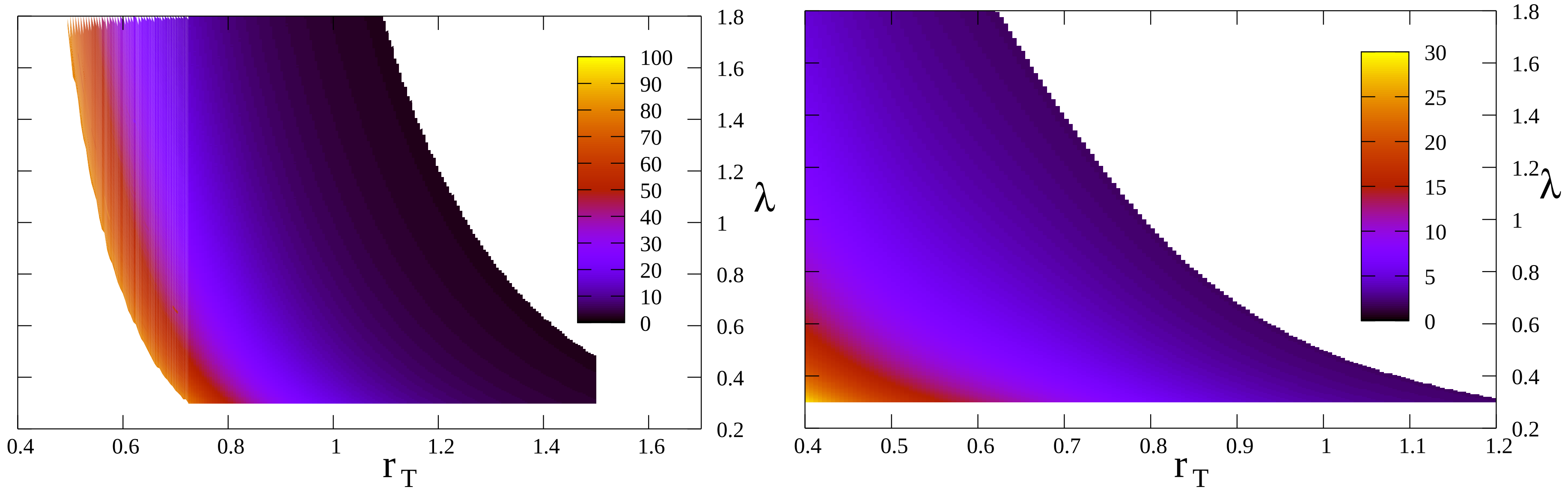
$\Lambda_{QCD}^{-1}$ ) (confinement) and right $N_c$ scaling ($\sim \lambda/N_c$ )

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

(Generic phenomenological propagators including confinement, eg Gribov-Zwanziger )

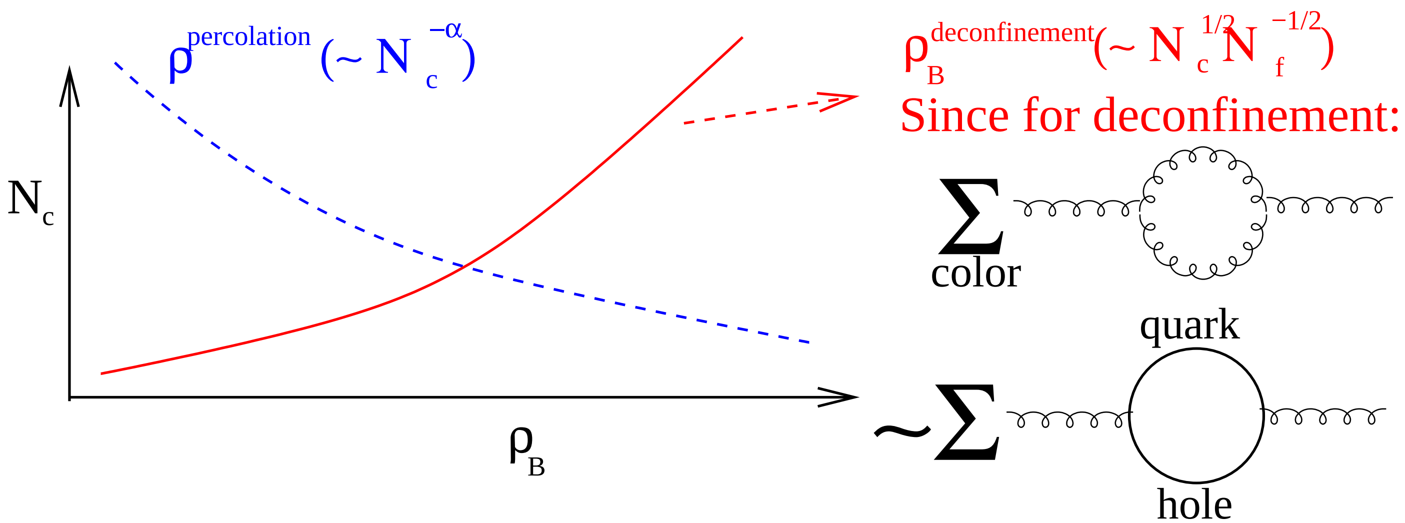
A percolation transition in $N_c$ was found .

Keeping density fixed, 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).

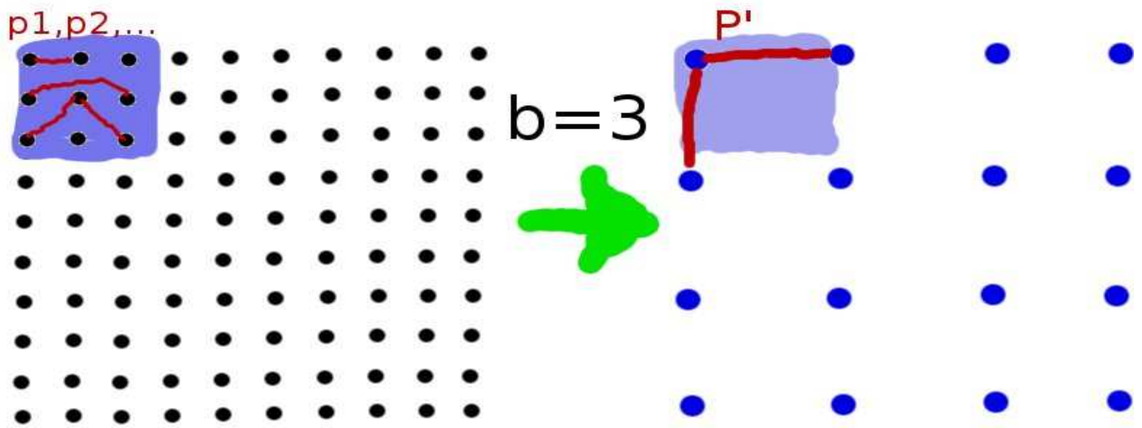
## But lets vary $\mu_Q$:Percolation and deconfinement

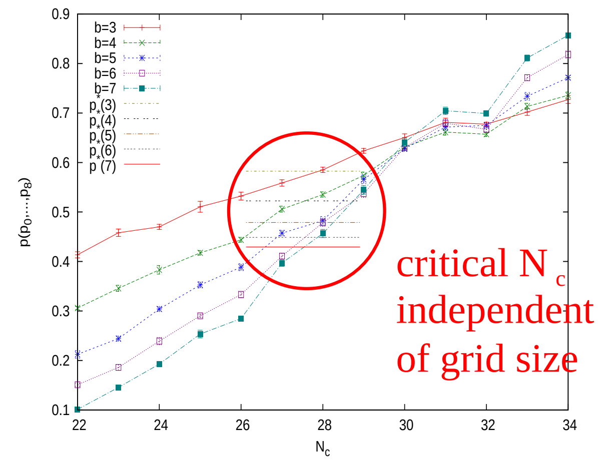



Percolation: $\rho - N_c$ anti correlated.
Deconfinement: $\rho - N_c$ correlated $\mu_B^{dec} \sim N_c^{1/2} N_f^{-1/2} m_B \sim N_c^{3/2} N_f^{-1/2} \mu_q$

$N_c \leq N_c^{crit}$ 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



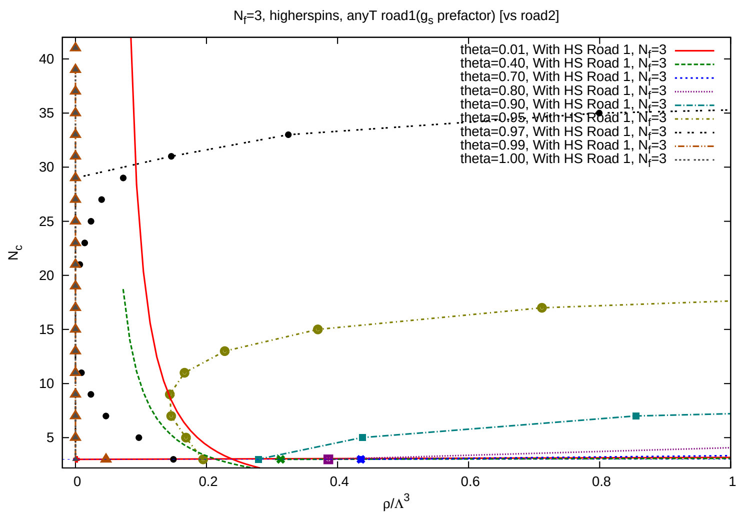

Gimel,Nicolai,Durand, J Phys A Math Gen 32 L515 (1999)

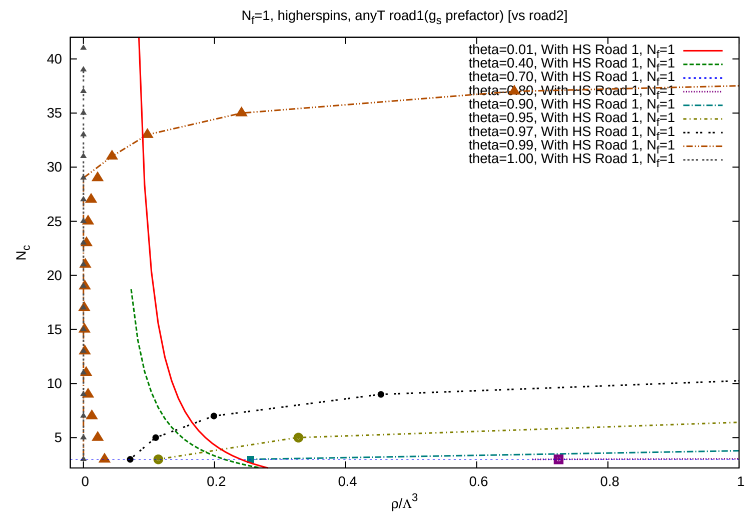
$$p^* \left(b, \Theta(x_T, \lambda, N_c)\right) = \Pi_{physical} \left(\Theta(x_T, \lambda, N_c)\right) + \beta b^{-y} \quad , \quad y = 0.81$$

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 <u>phenomenology</u> (an experimental signature for quarkyonic matter)!

## Quarkyonic phenomenology on the lattice: Old slide


I can already see you making such a poster!

But hear me out!

New slide O.Philipsen,J.Scheunert, 1812.02014 . For now in the strong coupling expansion, but who knows?

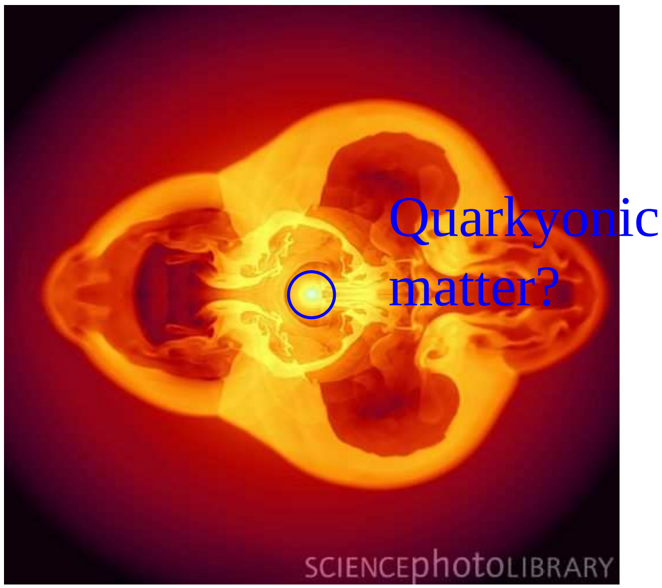
**Strong coupling expansion** Binding energy and EoS should drastically change with $N_c, N_f$ (NB: Percolation sensitive to $N_c$, "kissing transition" to $N_c N_f$ so different)
Strong coupling expansion has no sign problem and relatively cheap!

**"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

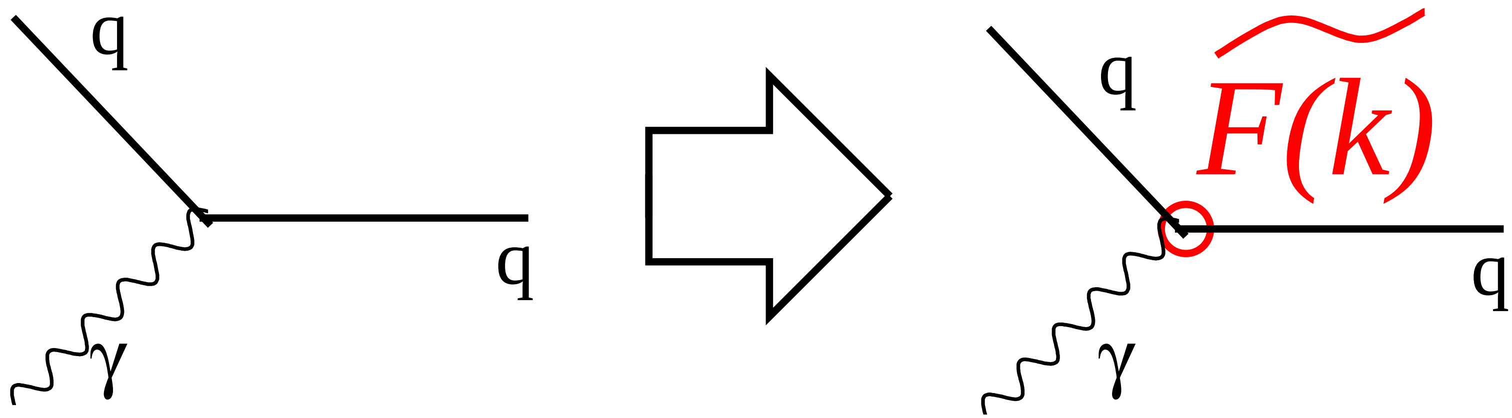
If quarkyonic phase realized in proto-neutron star , pressure, entropy $\sim \mathcal{O}(3)$ corresponding nuclear matter. EoS similar to pQCD (stiffer than nuclear matter), but no mixed phase/latent heat: Stiffness gradually turns on!.




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

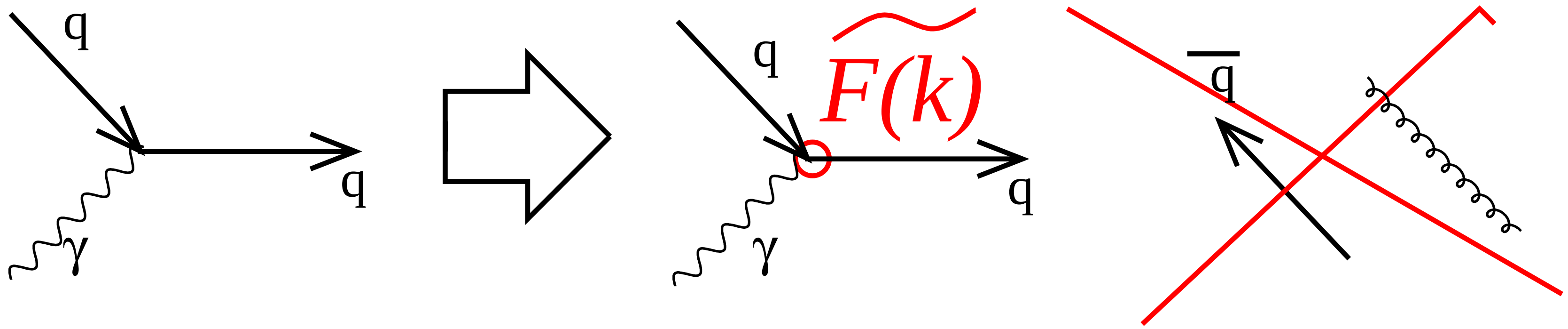
pQCD but not quite: the role of baryons

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



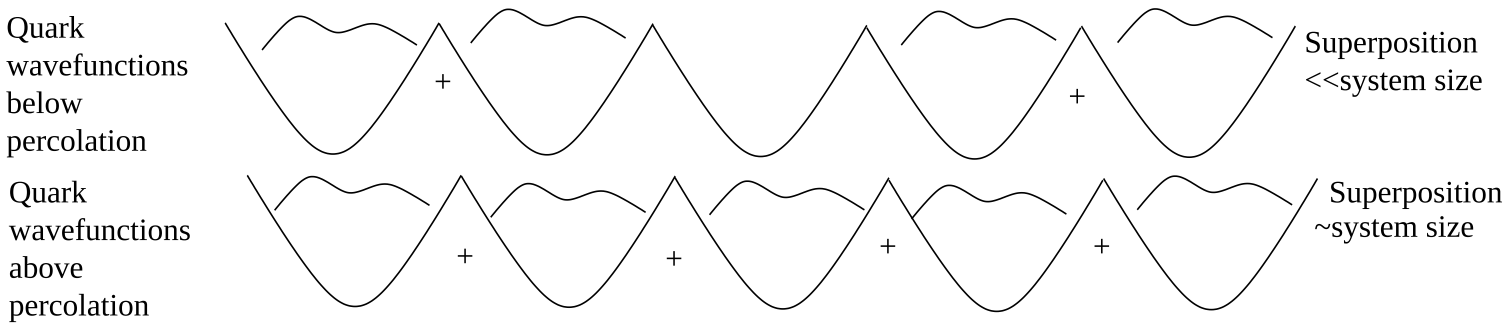

$F(k)$ gives the F.T. of the baryonic gluon content. For the equation of state, it should just be a $\mathcal{O}(1)$ normalization factor, but for scattering processes it is a qualitative difference from naive QCD. Spin-color-flavor separation can ensure color neutrality with quark-like degrees of freedom.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

# From EoS to dynamics: An EFT of percolating matter

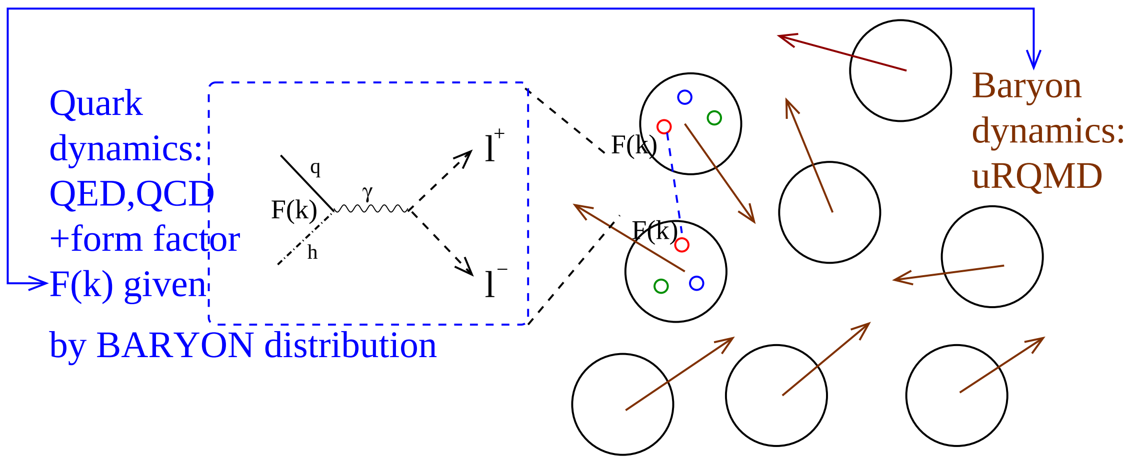



In percolation regime, asymptotically free quark wavefunctions of different baryons can superimpose across large distances.

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

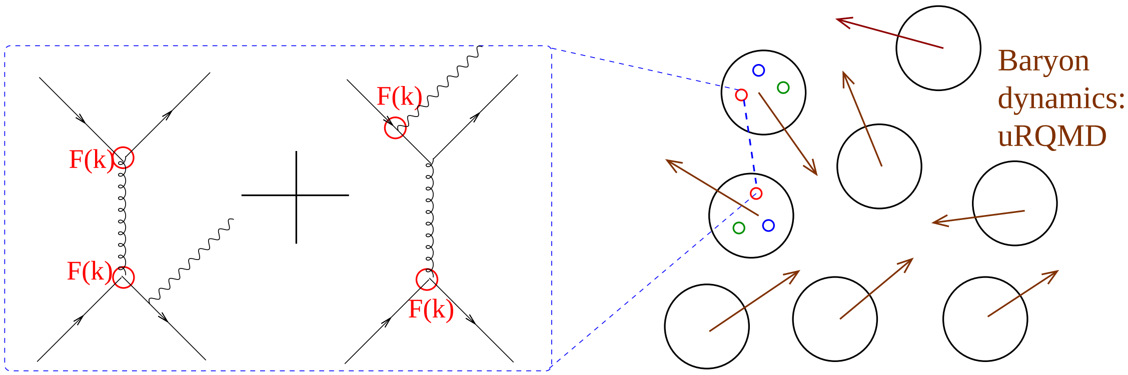



$R_{qq\to X} = \Psi(k)\Psi^*(k')M^2_{qq\to X}$ Where $M_{qq\to X}$ is the pQCD matrix element

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

$F(k)$ 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

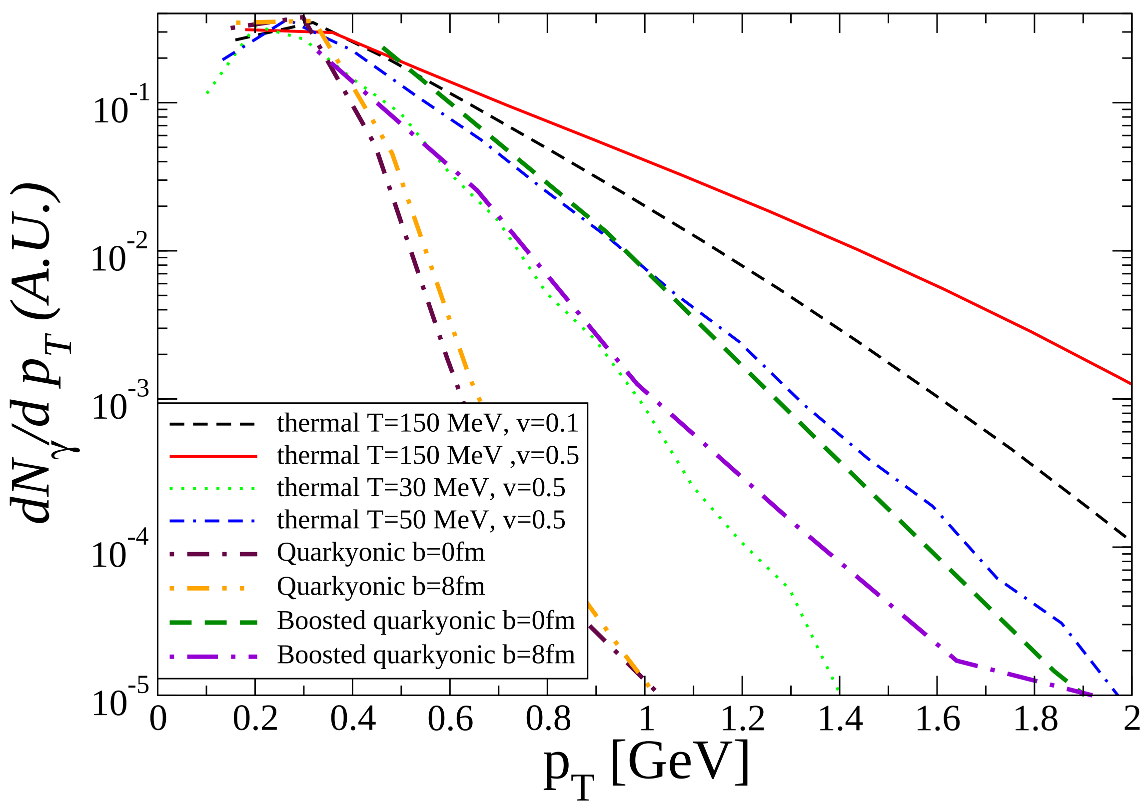
$$\frac{dN}{d^3p} = \frac{dN}{dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n\left(\phi - \Psi_{reaction}\right)\right)\right]$$

for

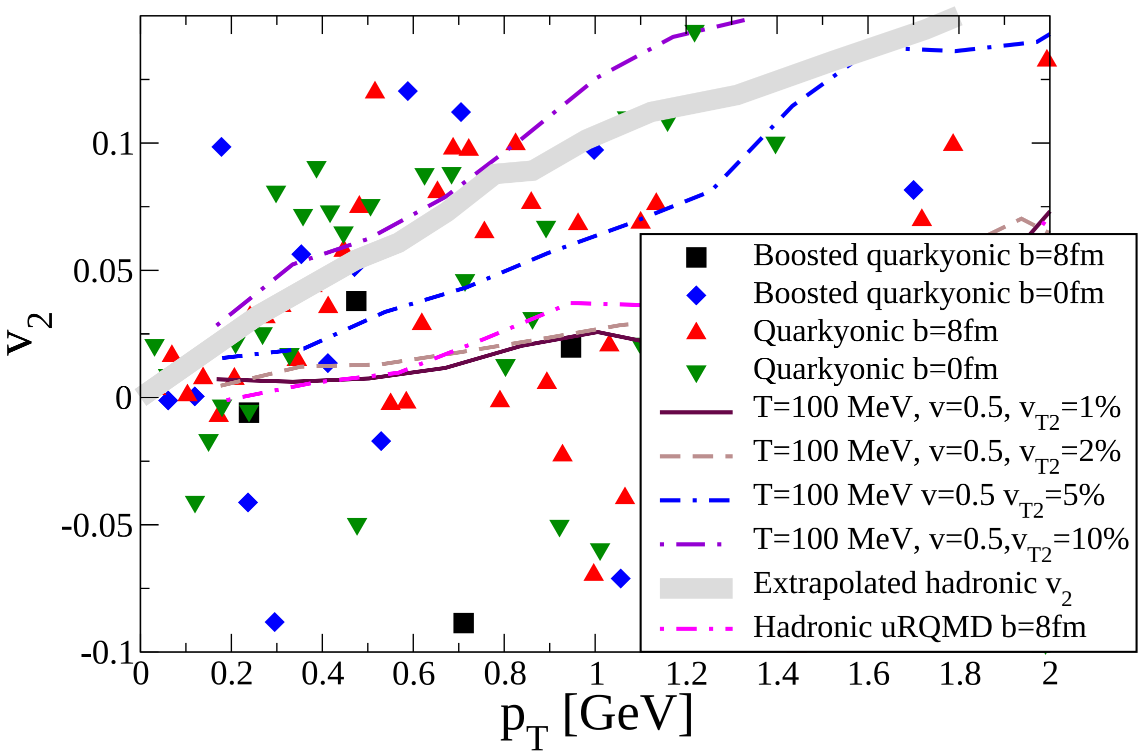
**Quarkyonic and Boosted quarkyonic matter** described above

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

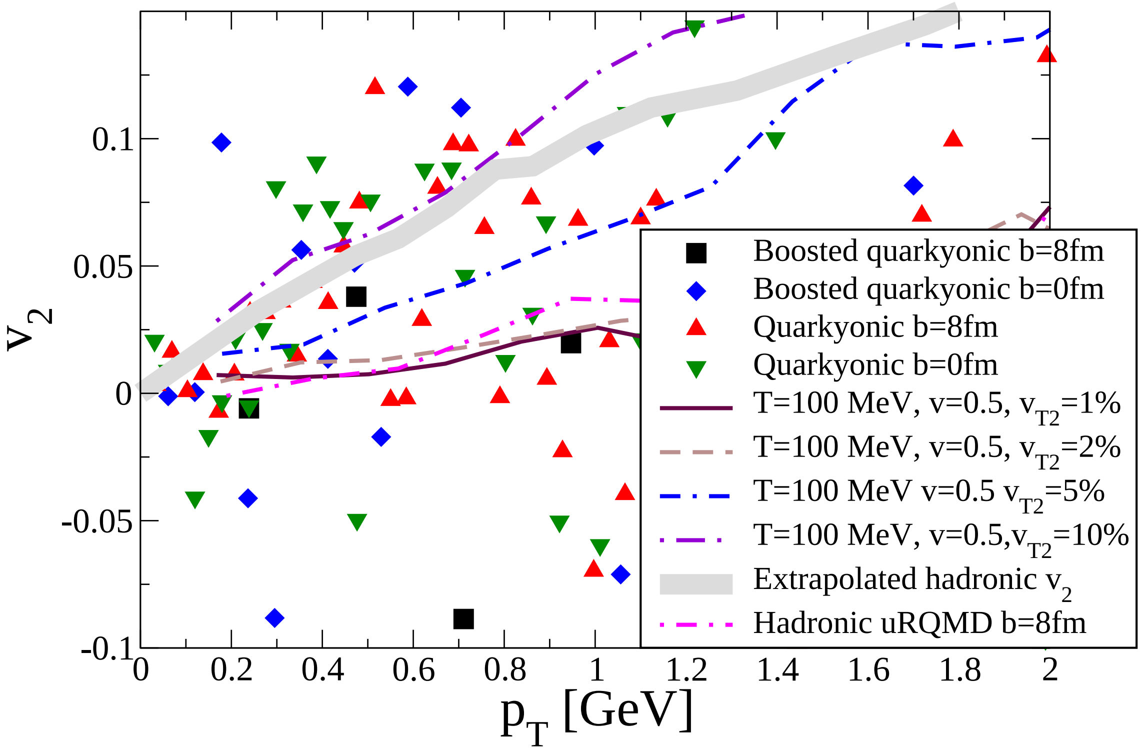
**Hadron gas** calculated with uRQMD molecular dynamics model (same as the one used for quarkyonic wavefunctions!)




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



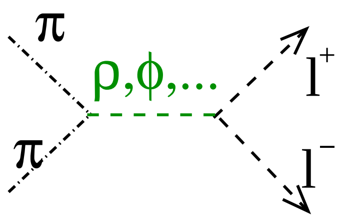

Random distribution of quark wavefunctions quenches total $v_2$ but produces big fluctuation in event and $p_T$ : oscillation frequency $\sim p_T \rho_B^{-1/3}$



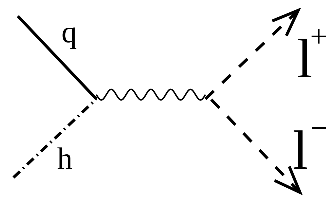

"pure" quarkyonic effect, it is due to sensitivity of quark wavefunctions to baryon location. signature?

dileptons potentially more direct probe but more complicated

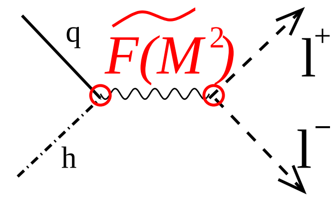
**Both quarks and holes needed** Sensitivity to equilibration




*Hadron gas*




*QGP*



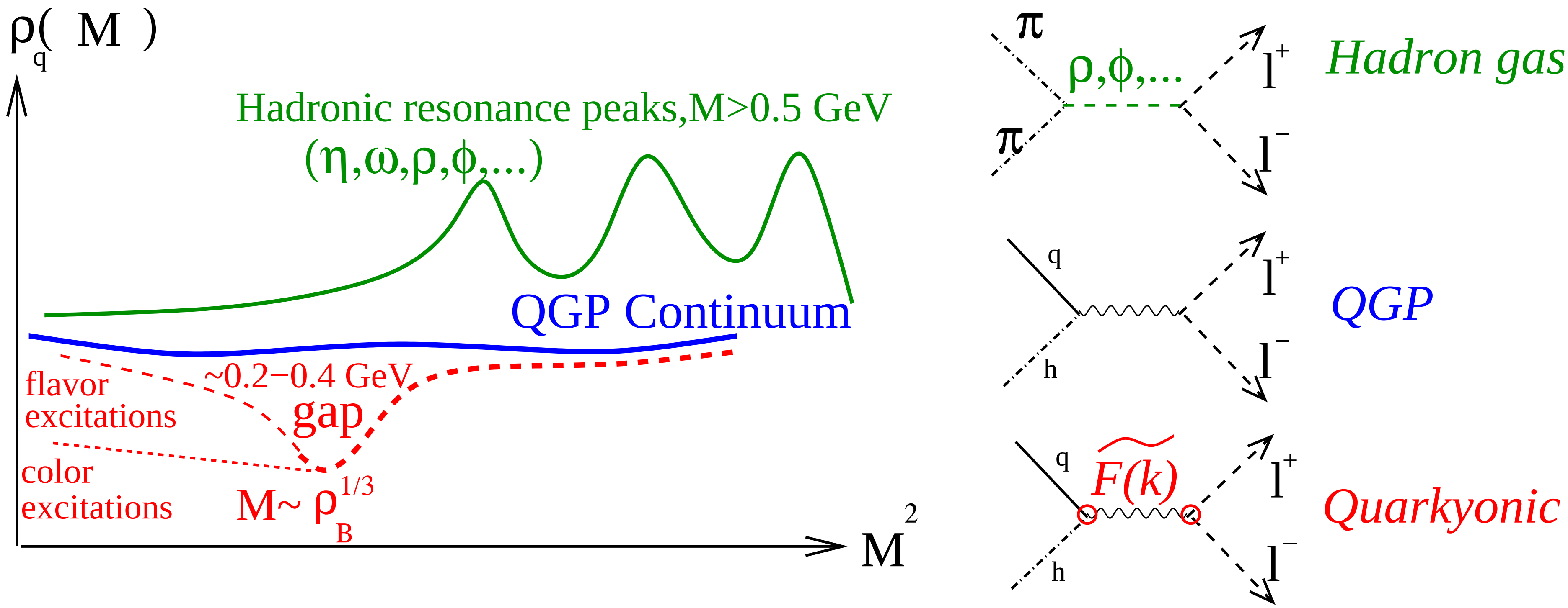

*Quarkyonic*

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

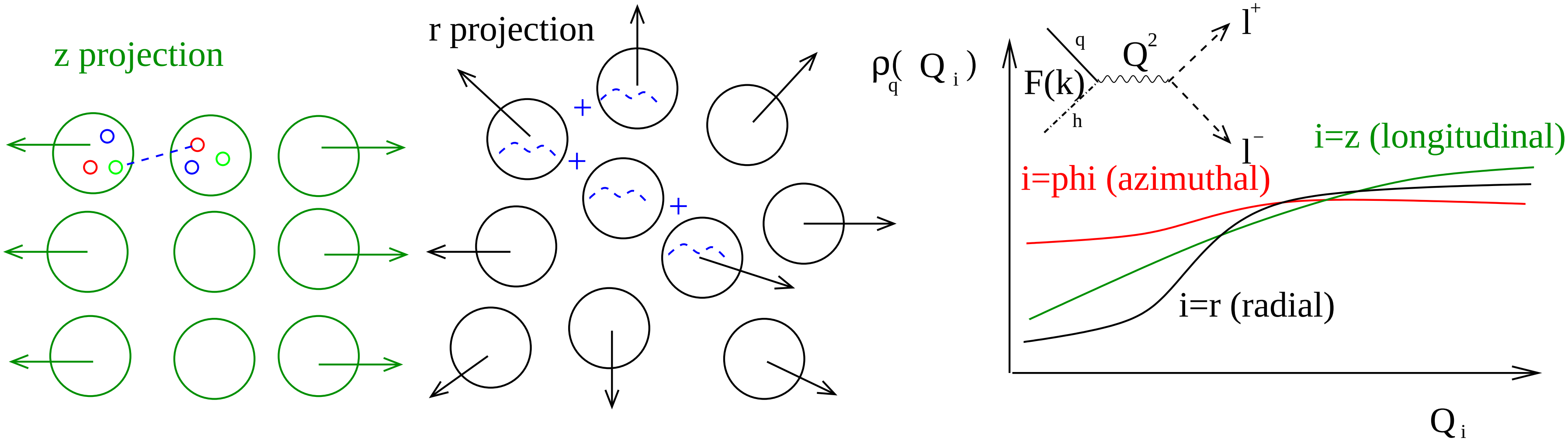
$$\langle\hat{\Psi}\rangle = \mathrm{Tr}\left\{ \{\exp\left[\frac{\hat{H}-\mu_q\hat{N}}{T}\right]\left[\frac{1}{3N}\left(\sum_{i,j,k}^{N}\hat{a}_i(k_i)\hat{a}_j(k_j)\hat{a}_k(k_k)\right)\right]\right\}$$

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 <u>regular</u> (pasta phase?) one could observe <u>bloch waves</u>!
("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!

## To conclude

- Physics at high chemical potential not understood
  Dont trust theorists, expect surprises!

- Large $N_c$ points to some conceptual paradoxes that could indicate novel phenomena

- Their existence is uncertain, phenomenology even more uncertain, but EM probes could give you something


@