Hard-core deconfinement & soft-surface delocalization from nuclear to quark matter

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Ref) K. Fukushima, T.K., and W. Weise, 2008.08436 [hep-ph]

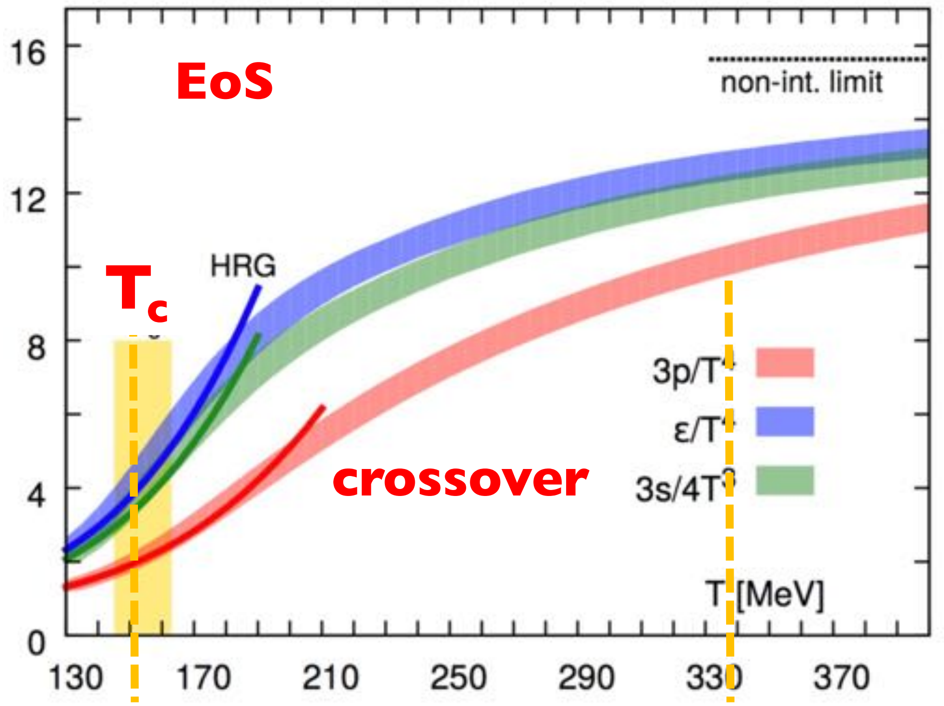
The purpose of this work

- propose notions of Soft- & Hard- Deconfinement
- offer a concrete description of quark-hadron continuity
- suggest new schemes of computations for dense QCD

Confinement-deconfinement in hot QCD

No order parameters, but the notion of conf-deconf trans. still makes sense :

Hot QCD case, lattice (e.g., Ding+, review '15)



Hadron resonance gas

semi-QGP

pQGP

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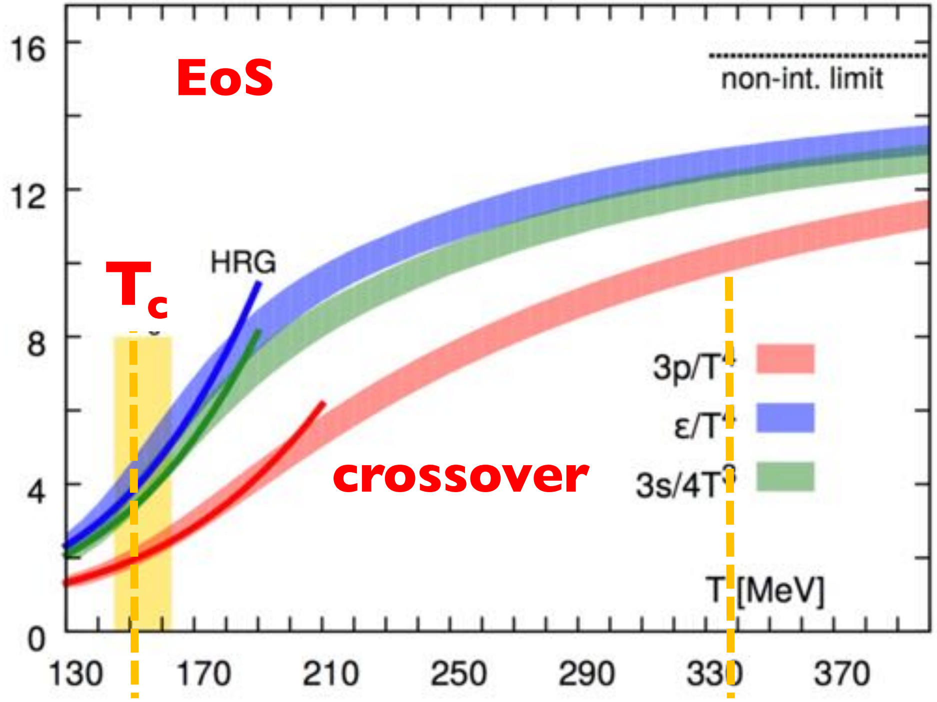


Hadron resonance gas

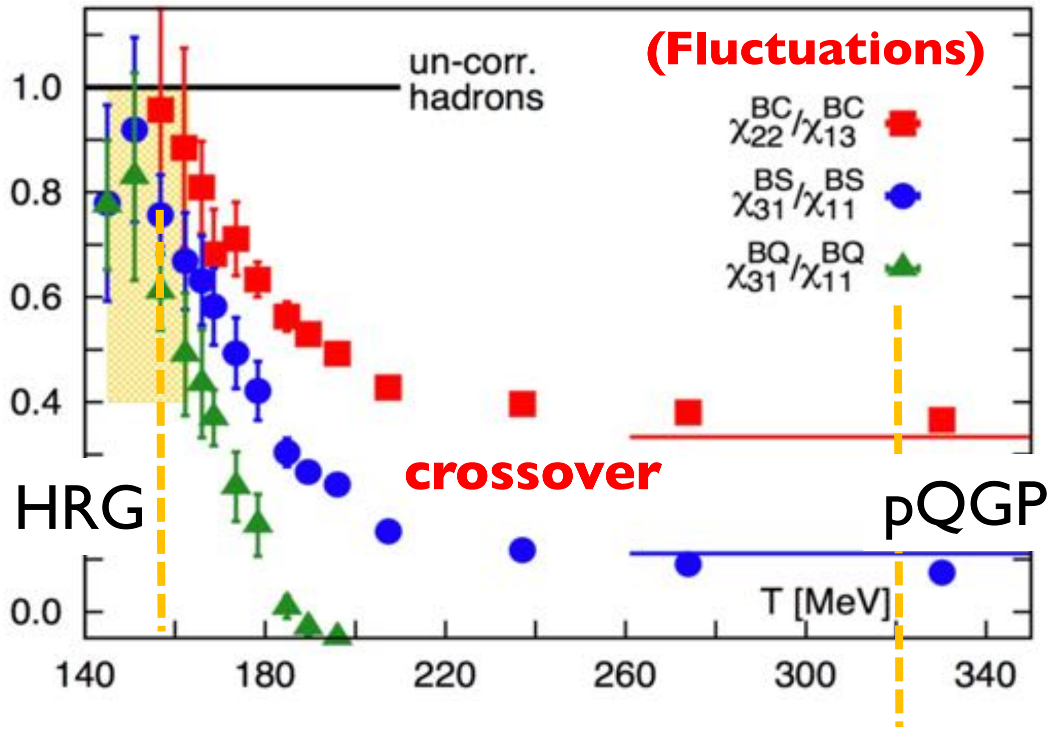
semi-QGP

pQGP

derivatives

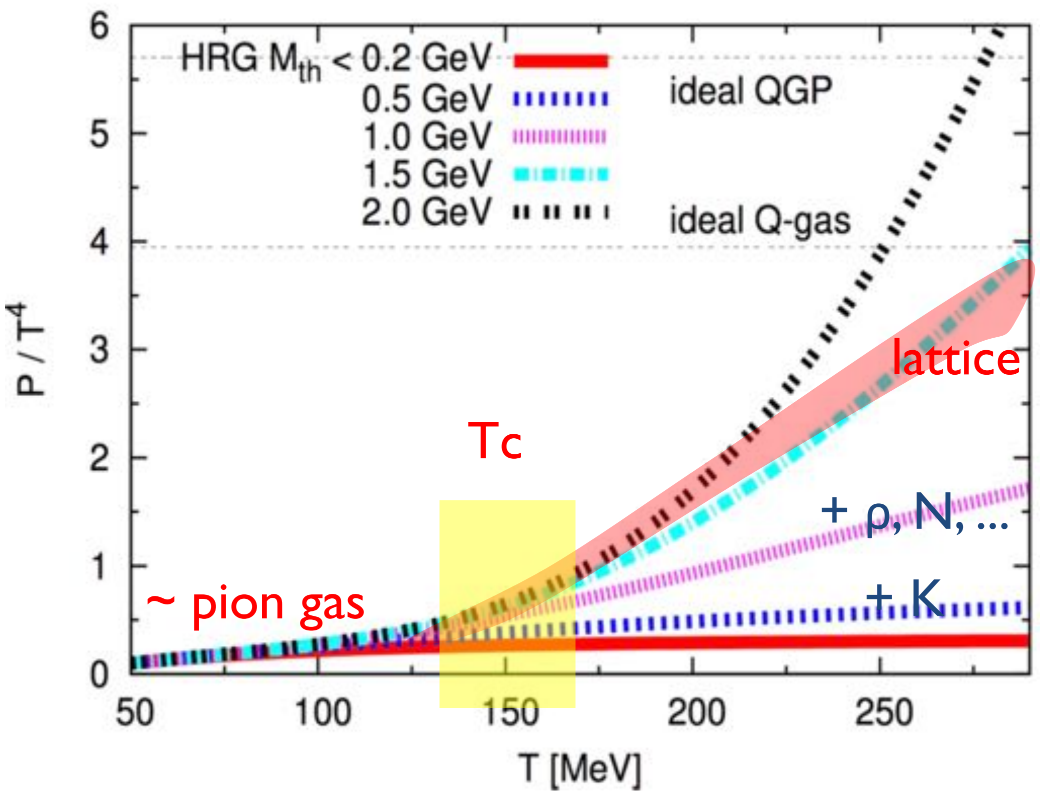
→ more info

$\mu_B, \mu_Q, \mu_S, \mu_C$



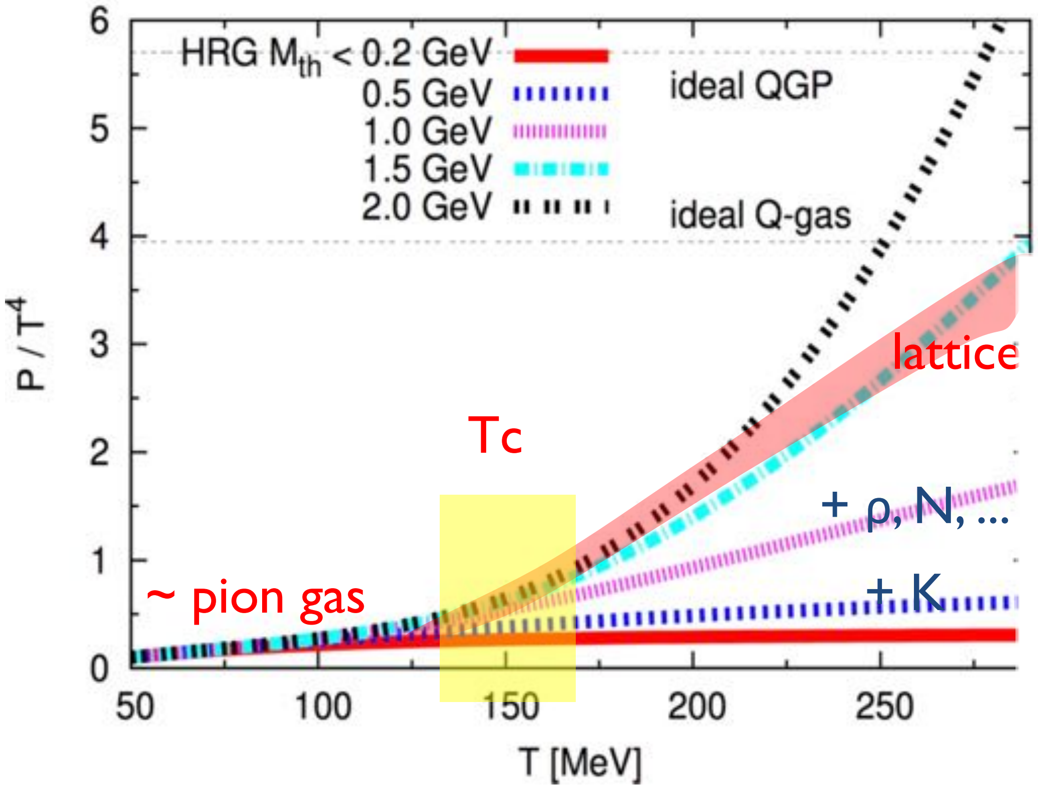
→ "T_c": universal for different flavors

An intuitive picture



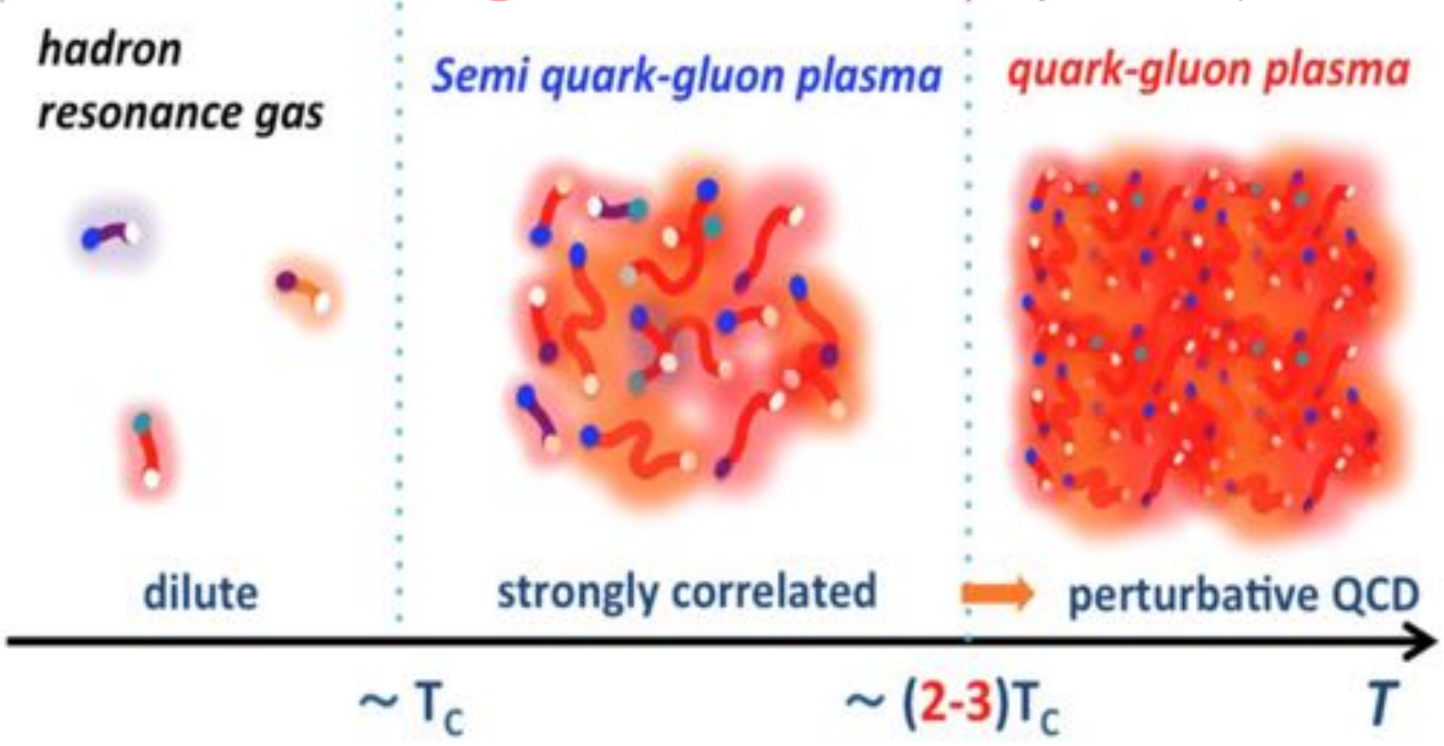
- At ~ T_c, many hadrons with $E >> T$
  (**entropic** effects > **energy cost**; Hagedorn)

An intuitive picture



- At ~ T_c, many hadrons with $E >> T$
  (**entropic** effects > **energy cost**; Hagedorn)

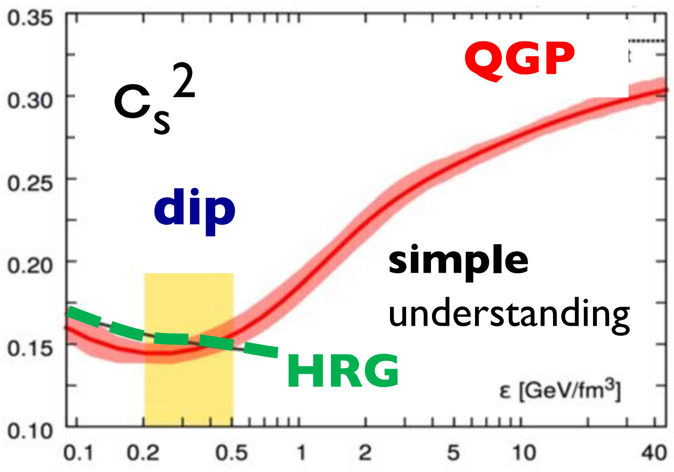
"string condensations" (Polyakov '77)



Can we draw this sort of cartoon for dense QCD ?

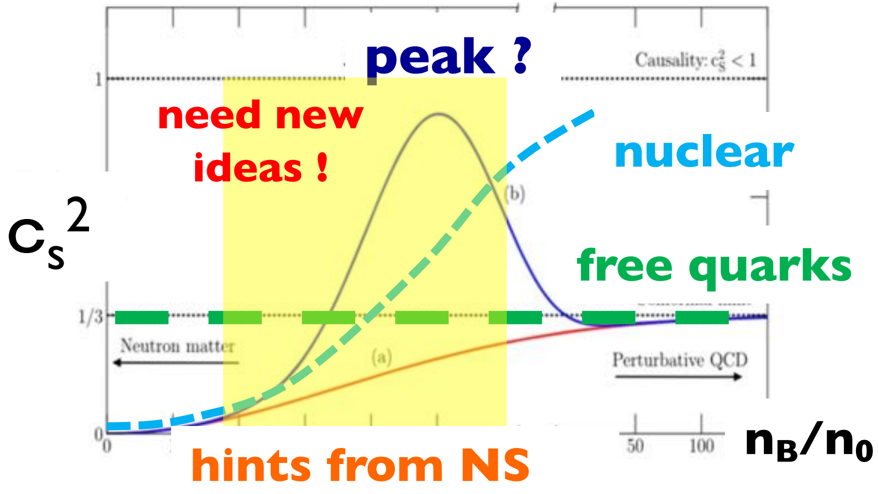
hot QCD vs cold, dense QCD

hot QCD		cold, dense QCD
Heavy Ion experiments	laboratory	**Neutron Stars**
lattice simulations	1^{st} principle	**no** lattice results (sign problem)
pQCD (**close** to exp. domain)	dense	pQCD (**far** from exp. domain)
HRG (**simple** calculations)	dilute	nuclear matter (**complicated !**)
crossover (HRG→QGP)	type of trans.	not known (nuclear→quark matter)

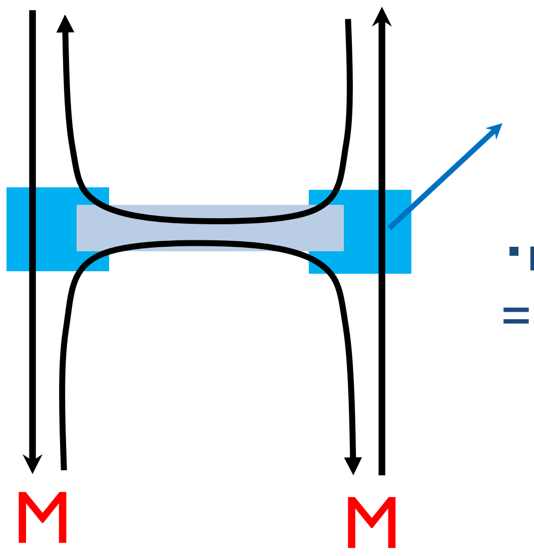


qualitative understanding

e.g.)
speed of sound,
d.o.f.,
....



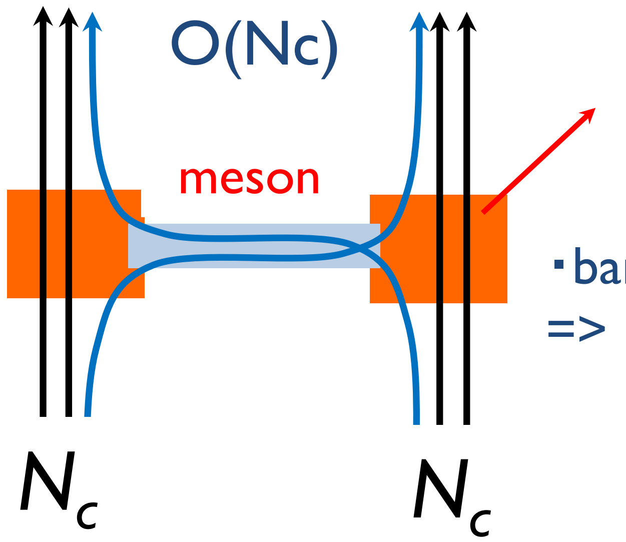
N_c counting : HRG vs Nuclear Matter



$g_{MM} \sim N_c^{-1/2}$

- mesons

=> weakly coupled

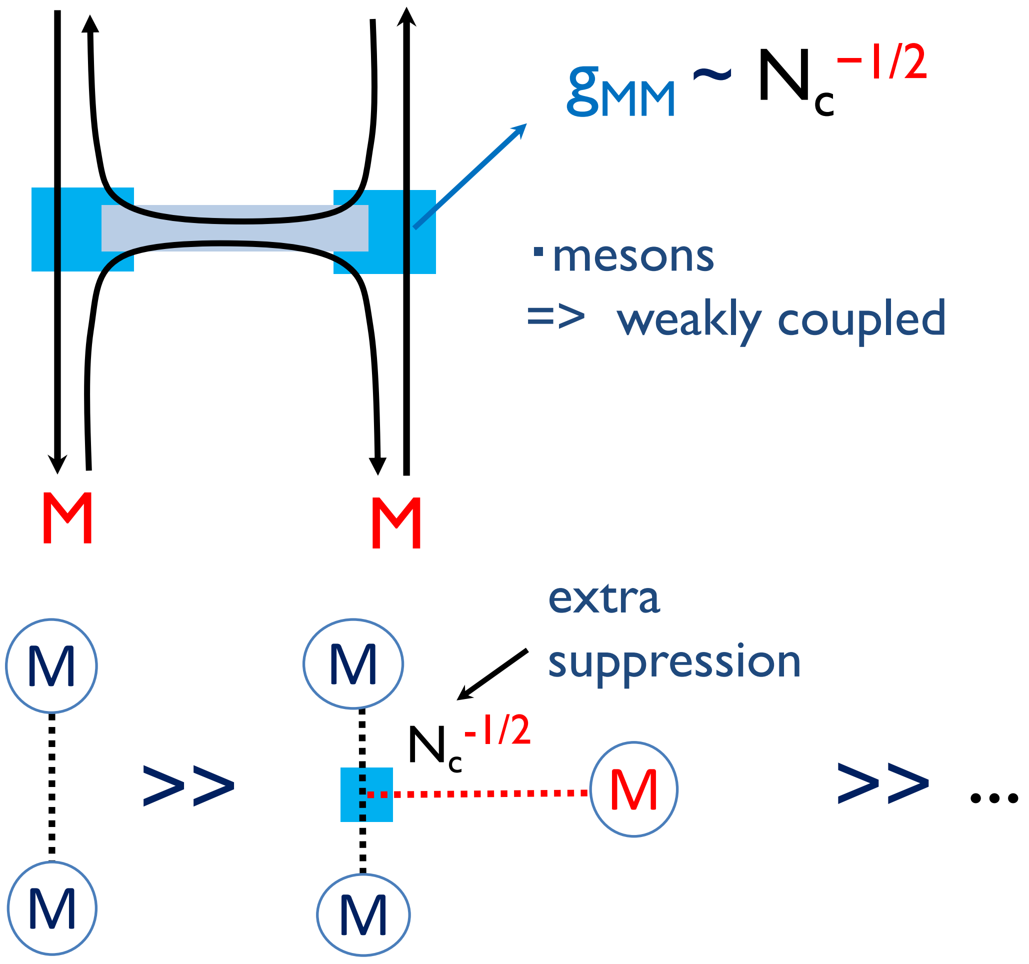


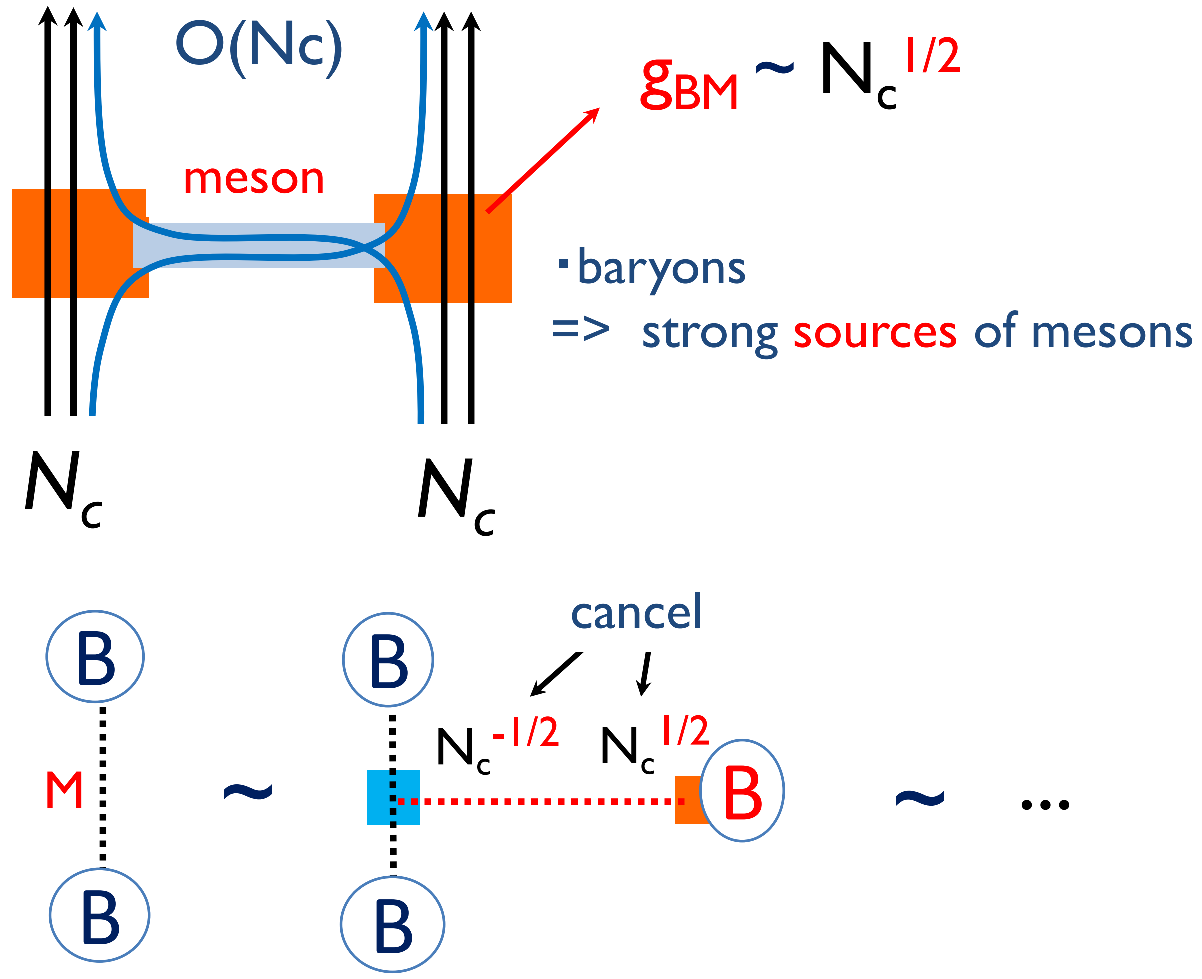
$g_{BM} \sim N_c^{1/2}$

- baryons

=> strong sources of mesons

N_c counting : HRG vs Nuclear Matter

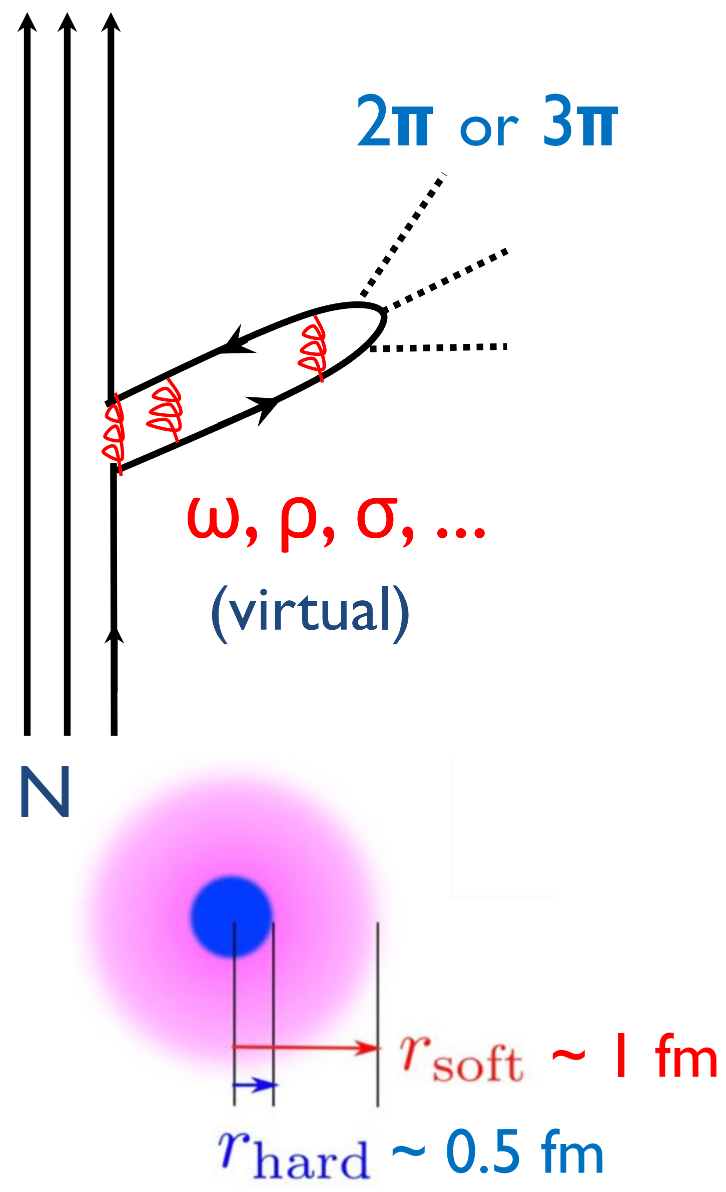




$\langle V_{2\text{-body}} \rangle \gg \langle V_{3\text{-body}} \rangle \gg \langle V_{4\text{-body}} \rangle \gg \dots$

$\langle V_{2\text{-body}} \rangle \sim \langle V_{3\text{-body}} \rangle \sim \langle V_{4\text{-body}} \rangle \sim \dots \sim O(N_c)$!

"Soft" & "Hard" scales in a nucleon



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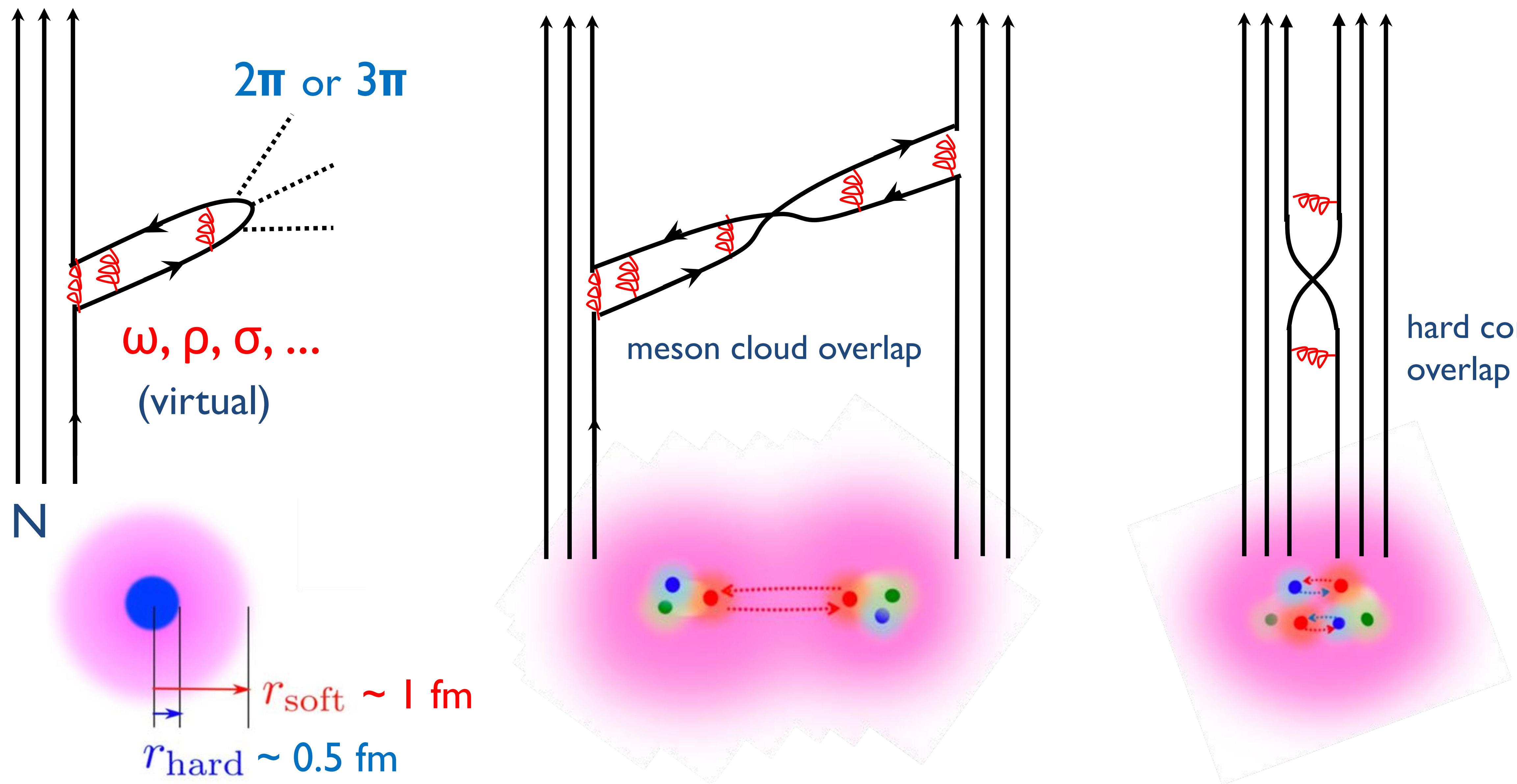
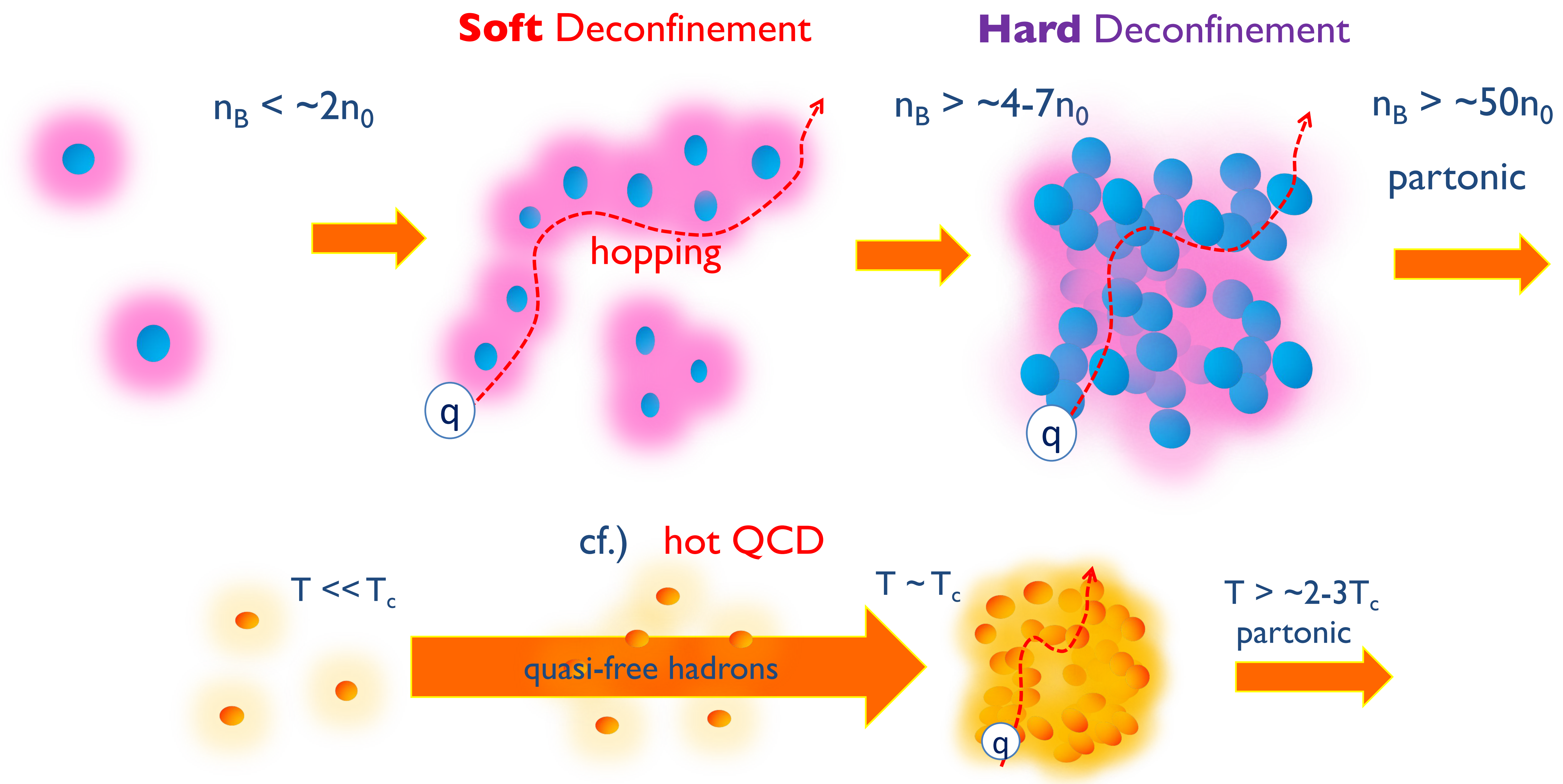


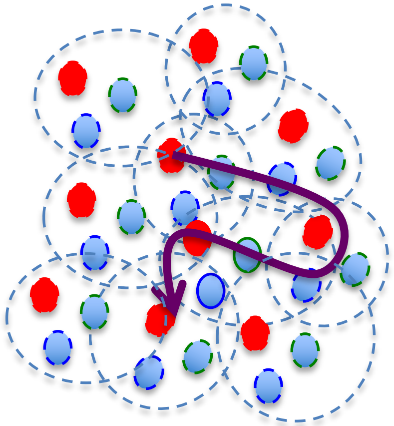
Soft & Hard Deconfinement



Hard Deconfinement

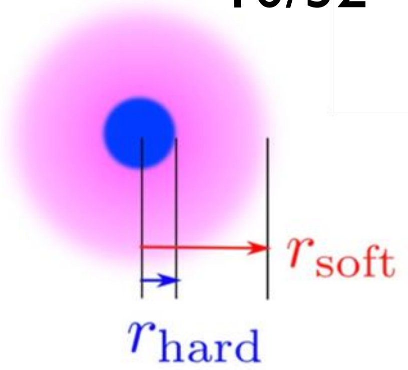
4-7 n_0 < n_B < ~ 50 n_0

hard core overlap



pQCD valid

Hard Deconfinement

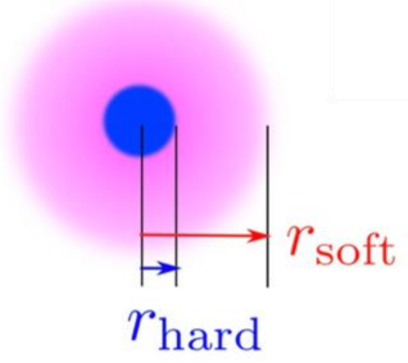


hard core overlap $\neq$ perturbative regime

core properties of a nucleon $\longrightarrow$ alternative baselines ?

e.g. ***mechanical*** **p** & **ε** in a nucleon

Hard Deconfinement



hard core overlap ≠ perturbative regime

core properties of a nucleon → alternative baselines ?

e.g. ***mechanical*** **p** & **ε** in a nucleon

gravitational form factors [Kobzarev-Okun('63), Pagels('66)]

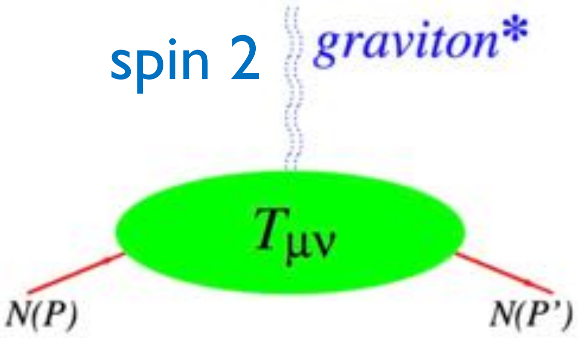
proton state

$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{U}(p_2)\left[M_2^q(t)\frac{P_\mu P_\nu}{M} + J^q(t)\frac{\imath(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]U(p_1)$$

energy mom. tensor — energy density — angular mom — pressure & shear forces

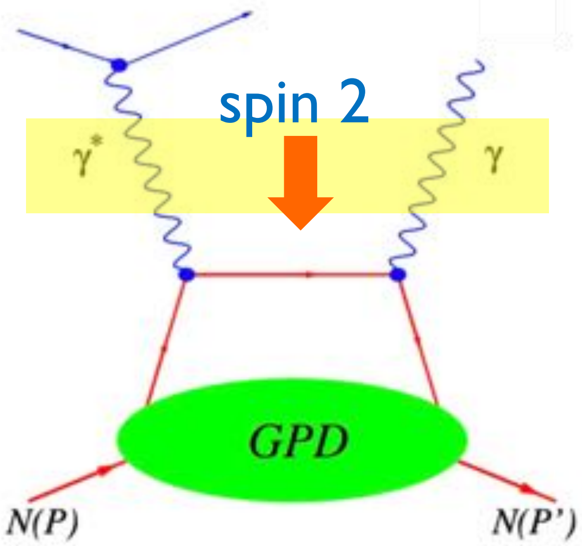
On-going programs

spin 2



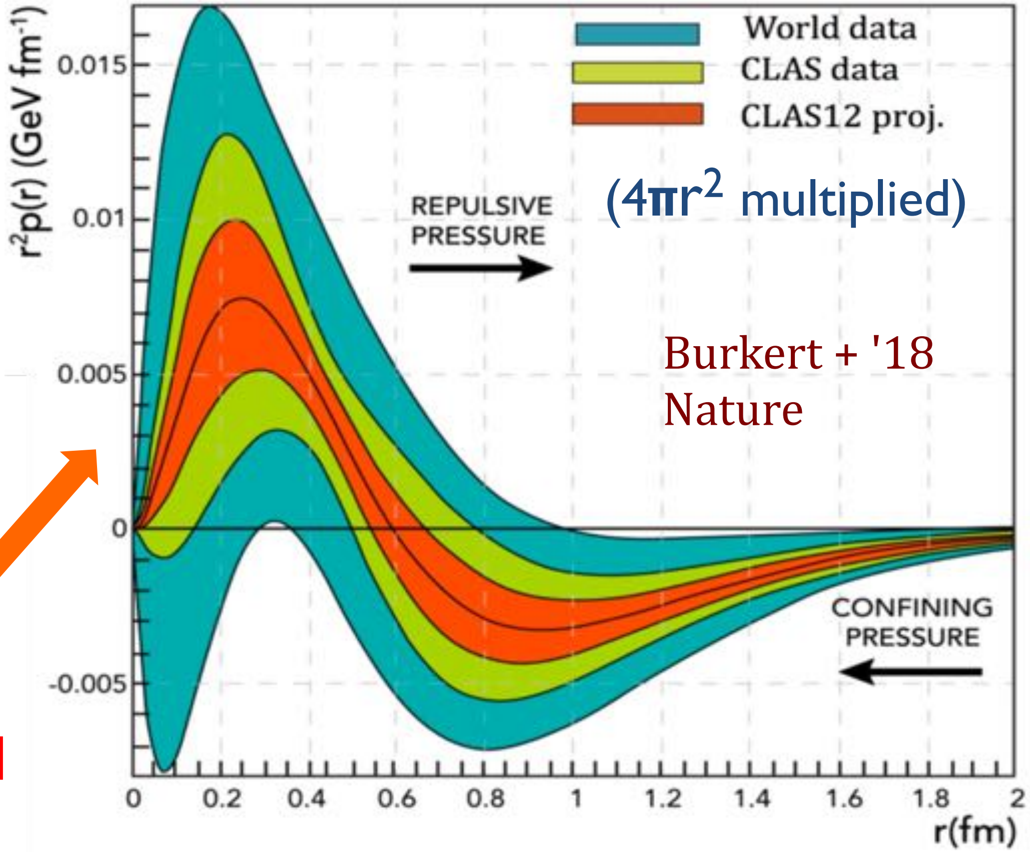
not practical

spin 2



a target in **EIC**

mechanical pressure distribution



($4\pi r^2$ multiplied)

Burkert + '18 Nature

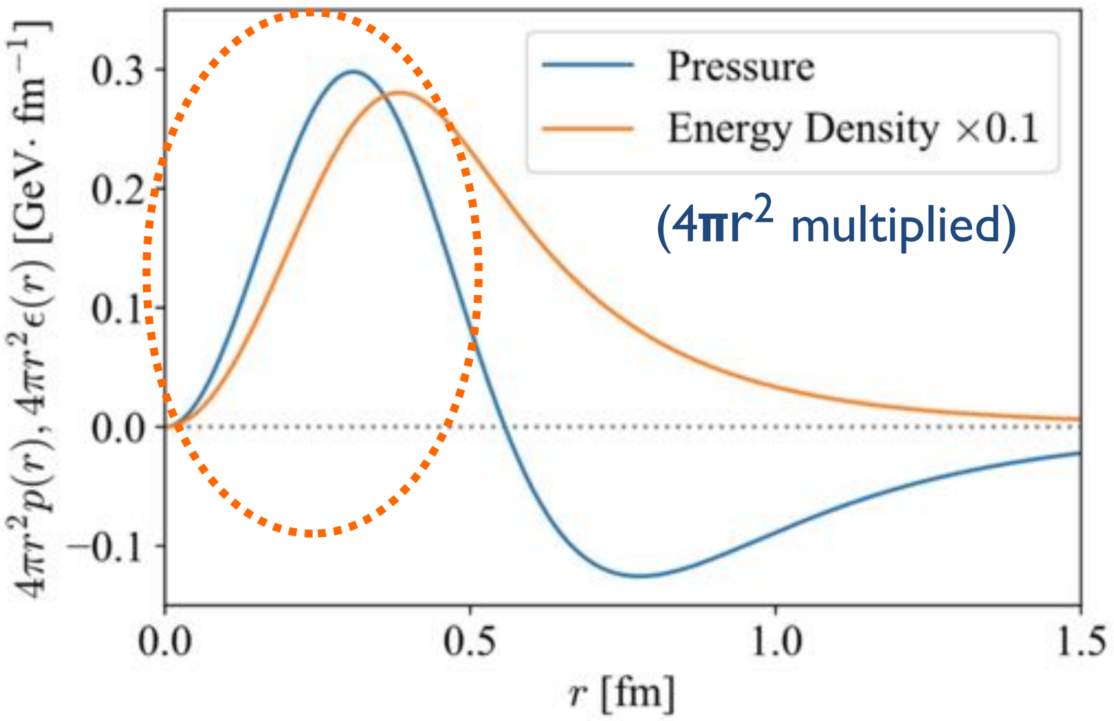
errors to be reduced

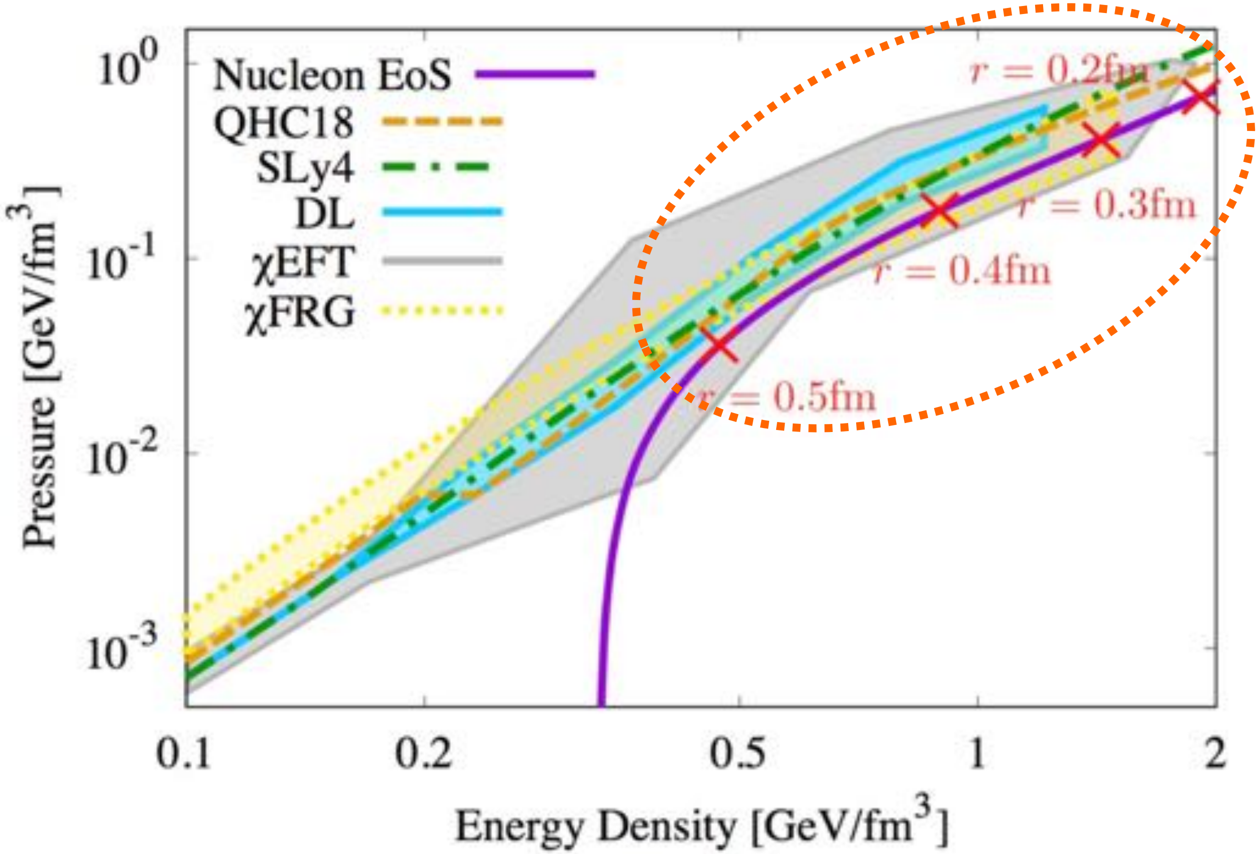
models on the market: bag model, chiral quark soliton, Skyme model,...

For tentative estimates, we use a chiral soliton model + ω, ρ mesons (next slide)

"Nucleon" EoS vs neutron star EoS

Distributions in a nucleon





close to realistic **NS EoS** : a useful **baseline ?** (like R_{AA} in HIC)

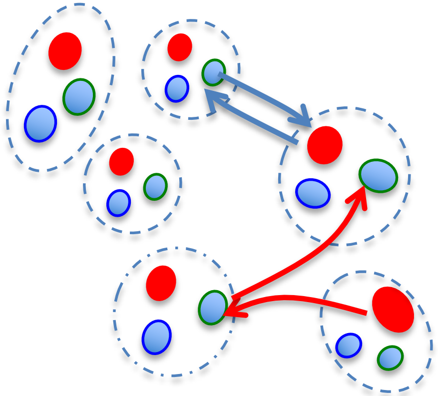
With this, can we quantify medium correlations such as BCS pairing?

Soft Deconfinement

$\sim 2\, n_0 \quad < \quad n_B \quad < \quad 4\text{-}7\, n_0$

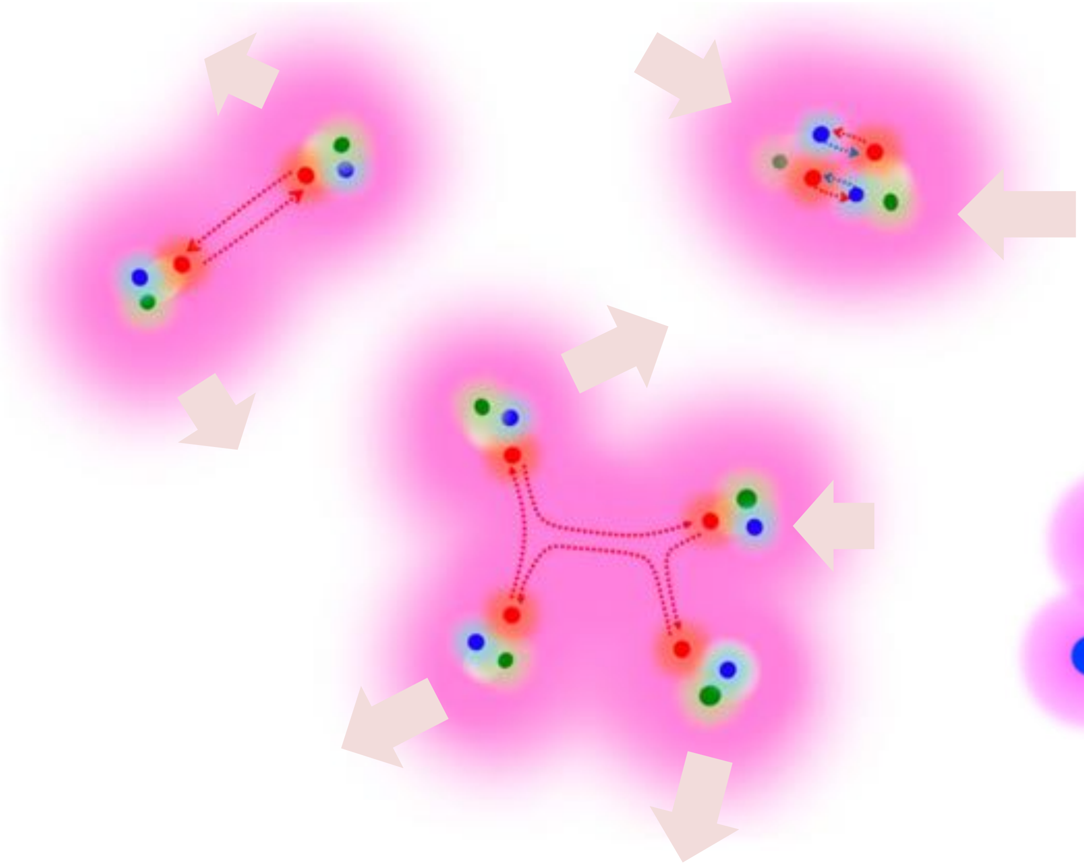
nuclear

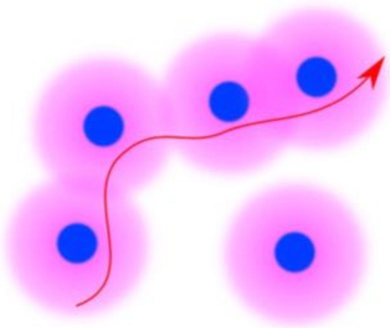
hard core overlap



Soft Deconfinement

relating "*multi-quark exchanges*" to "*delocalization of quark w.f.*"





Need

to solve
the dynamics of quarks
being exchanged
among moving baryons

looks very complicated...

strategy

Separate **fast** quark dynamics from **slow** baryon dynamics

=> *Born-Oppenheimer* descriptions

1, The velocity : $k_B/E_B \sim 1/Nc \ll k_q/E_q \sim 1$ $(k_B \sim k_q \sim n_B^{1/3})$

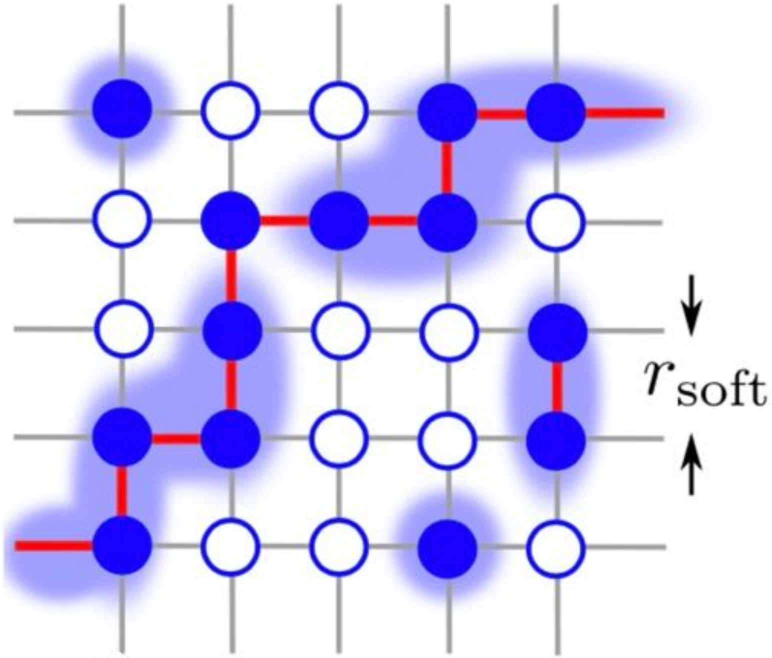
$n_B = n_q^R = n_q^G = n_q^B$

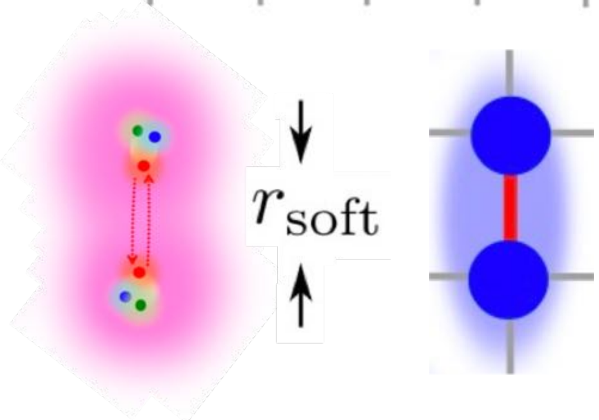
2, Find quark eigenstates for **a given** baryon configuration

3, Take the "**time** average" $\rightarrow$ "**ensemble** average" of baryons

A model of **classical** percolation

3D cubic lattice





probability

a site is occupied by a baryon : p

unoccupied : $1 - p$

$< N_B > = p$ x sites $= < n_B >$ x volume

$\rightarrow \quad p \sim < n_B > \times r_{soft}^3$

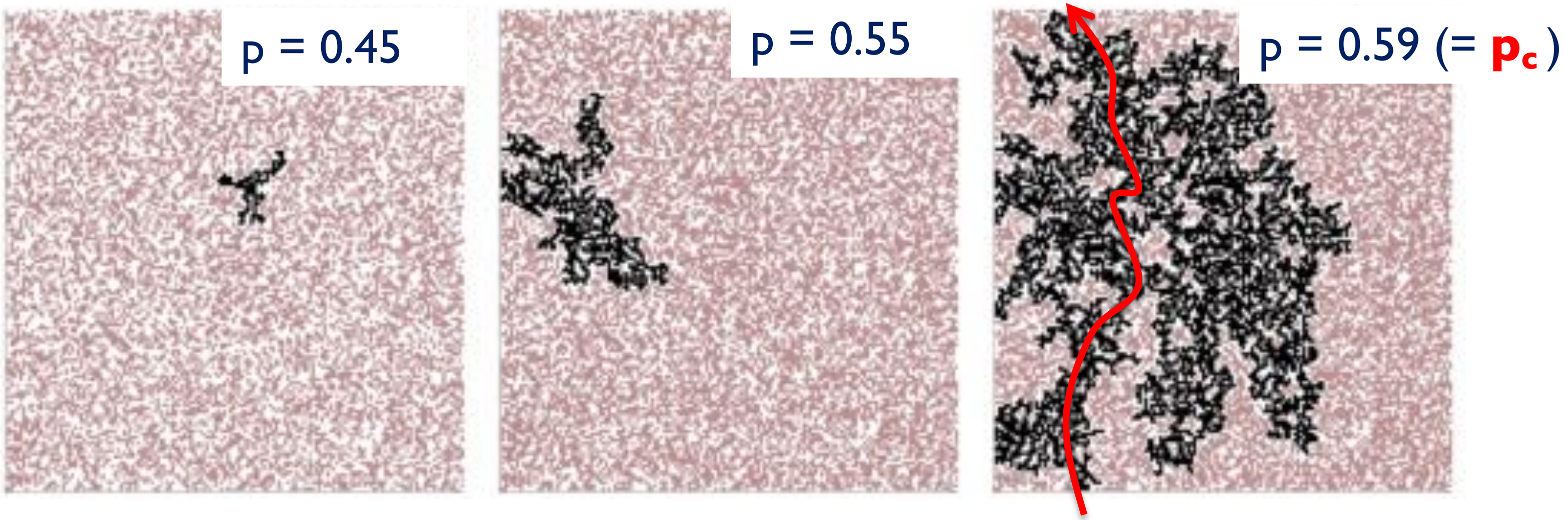
bonds for nearest neighbor hopping of quarks

Classical Percolation (no quark dynamics)

When do baryon clusters connect two opposite boundaries?

(for $V \to \infty$)

e.g. 2D lattice



p_c : critical probability (concentration)

def) at $p = p_c$, a cluster reaches opposite boundaries for the first time

Classical Percolation (no quark dynamics)

For 3D cubic lattice : $p_c = 0.34...$

A rough estimate of the critical density

Assuming $r_{soft} \sim 0.7$ fm

$$n_B^c \sim \mathbf{0.34} \times (4\pi\, \mathbf{r_{soft}}^3/3)^{-1} \sim 0.24\ \mathrm{fm}^{-3}$$

$$\sim \mathbf{1.4}\, n_0\ !$$

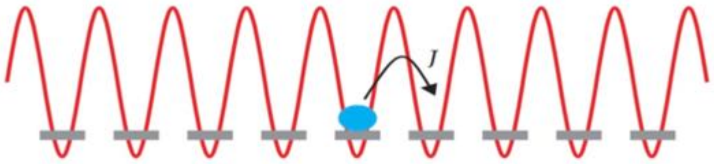
This may happen within the nuclear territory

But the CL percolation tells us only about the availability of paths for quarks...

Quantum Percolation

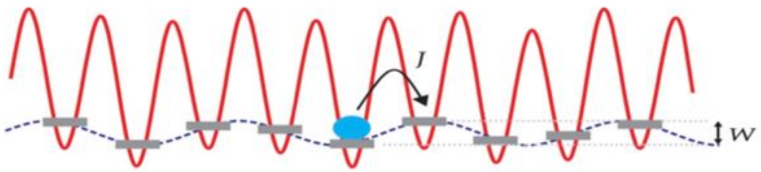
Quantum amplitudes from various paths may cancel: (destructive) **interference**

e.g. *Anderson localization* ('57)



clean

dirty



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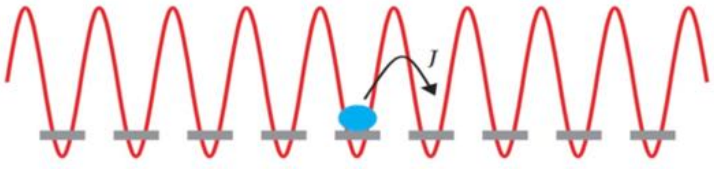

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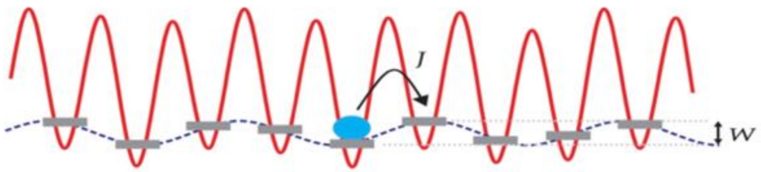
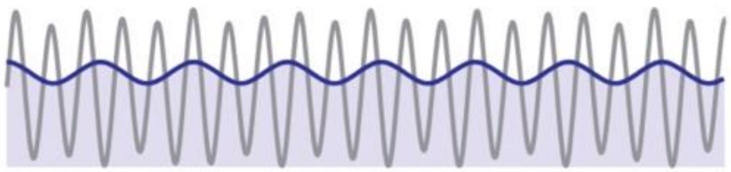
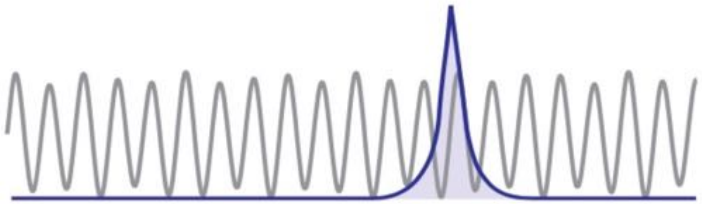


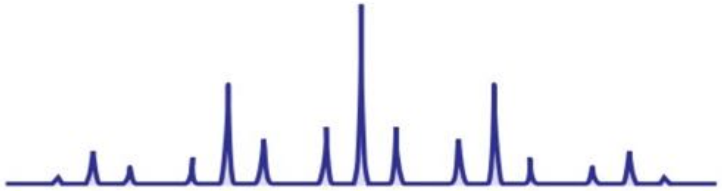
→ **Bloch waves** (phase coherence)

→ **Localized states** (random phase)



coordinate space





momentum space

Delineating quark wavefunctions

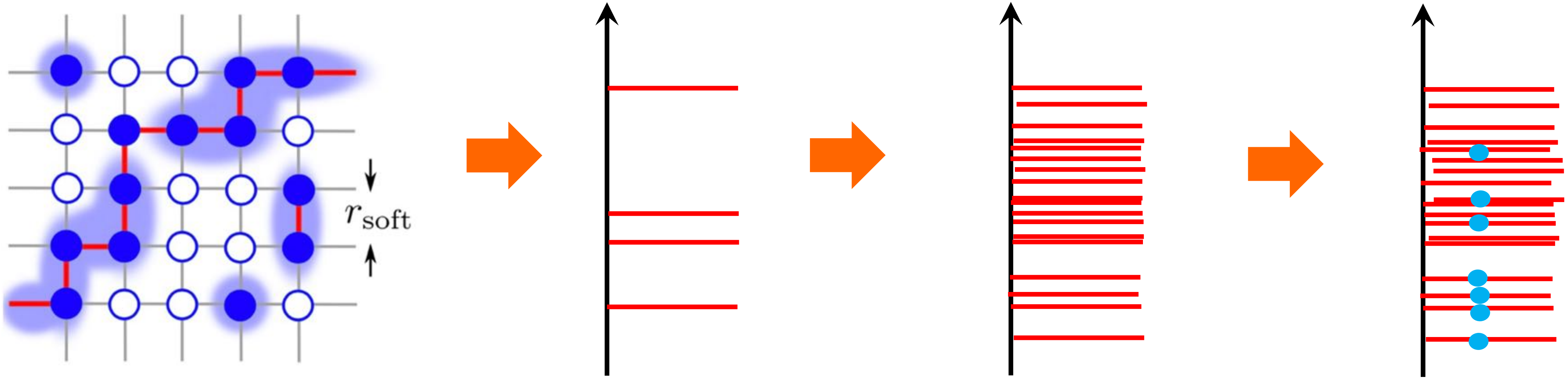
procedures

solve a **single** particle problem for **a given geometry**

prepare single particle levels

sum geometries (& normalize)

fill levels by quarks



=> we diagnose the **quark contents** of given baryon configurations

A model of **quantum** percolation

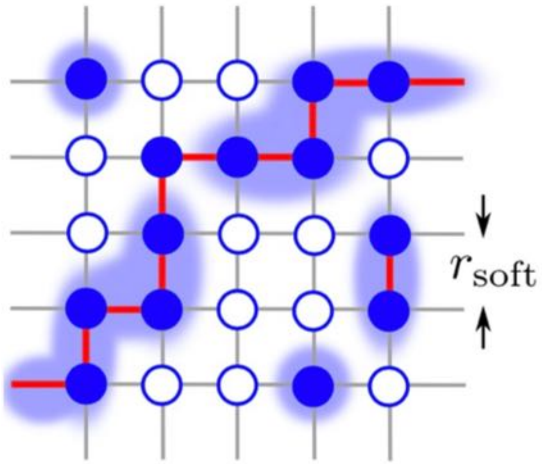
[Kirkpatrick-Eggarter '72,...]

tight-binding Hamiltonian

on-site energy — hopping

$$H = \sum_{n} |n\rangle \varepsilon_n \langle n| + \sum_{n\neq m} |n\rangle V_{nm} \langle m|$$

$|n>$: a quark state exists at a site n



$$V_{nm} = -V \ \ (V > 0)$$

nearest-neighbor hopping

the on-site energy is generated with probabilities

$$P(\varepsilon_n) = p\delta(\varepsilon_n - \varepsilon_{\rm on}) + (1-p)\delta(\varepsilon_n - \varepsilon_{\rm off})$$

$\varepsilon_{\rm on}$ = 6V (convenient choice)

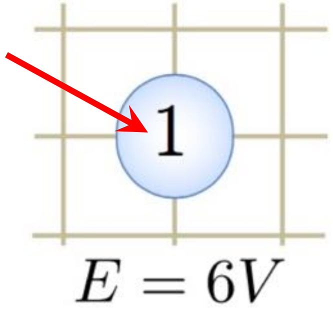
$\varepsilon_{\rm off} \to \infty$ (confinement)

quarks hop only within connected clusters

Examples of one-particle states

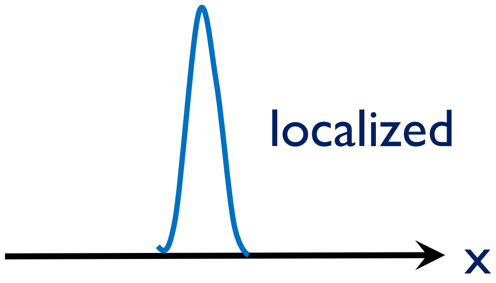
1) $p \to 0$ (dilute limit) : **isolated** baryons only

amp. of w.f.



localized in x, y, z-directions
(no hopping)

$E = \varepsilon_{\mathbf{on}} = 3 \times 2V$



$V \sim 1/ (2M_q\, r_{soft}^2)$

like kin. energy (NR)

Examples of one-particle states

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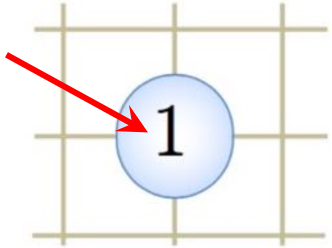
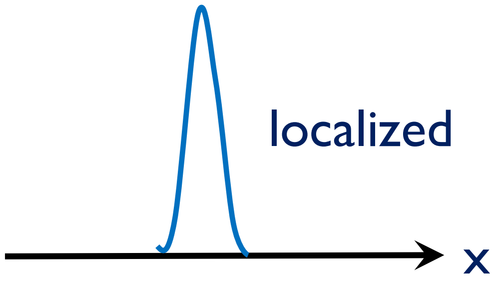


$E = 6V$

localized in x, y, z-directions
(no hopping)

$E = \varepsilon_{on} = 3 \times 2V$



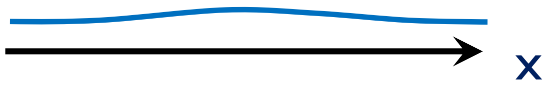
$V \sim 1/ (2M_q r_{soft}^2)$

like kin. energy (NR)

2) p → 1 (dense limit): **all** sites are **filled**

Eigenstates => plane waves with wavenumbers k_i

extended



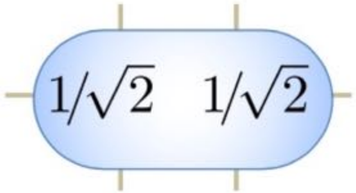
$$E(k) = 4V \sum_{i=x,y,z} \sin^2(k_i/2) \quad \rightarrow \quad V k^2$$

small k limit

Examples of one-particle states

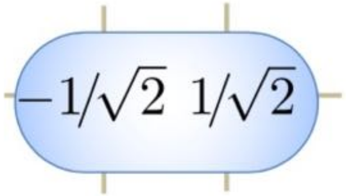
for few baryon clusters (localized in y, z-directions)

a) 2-baryons



$E = 5V$

0-node



$E = 7V$

1-node

Examples of one-particle states

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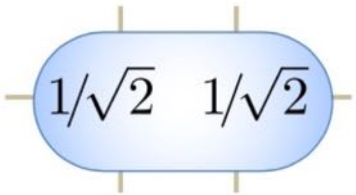
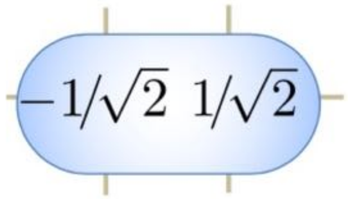
a) 2-baryons



$E = 5V$

0-node



$E = 7V$

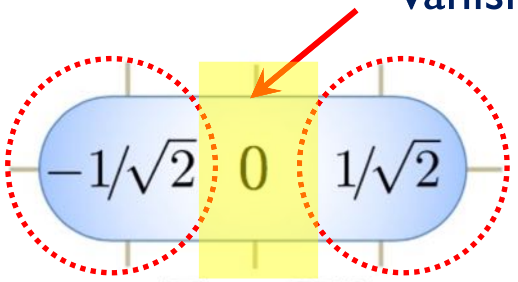
1-node

vanish (**interference** effects)

b) 3-baryons

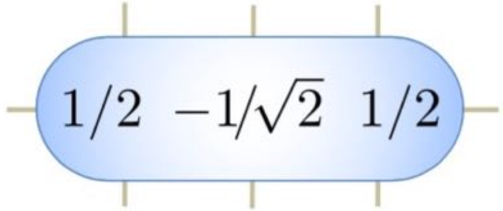
$E = (6 - \sqrt{2})V$

0-node



$E = 6V$

localized

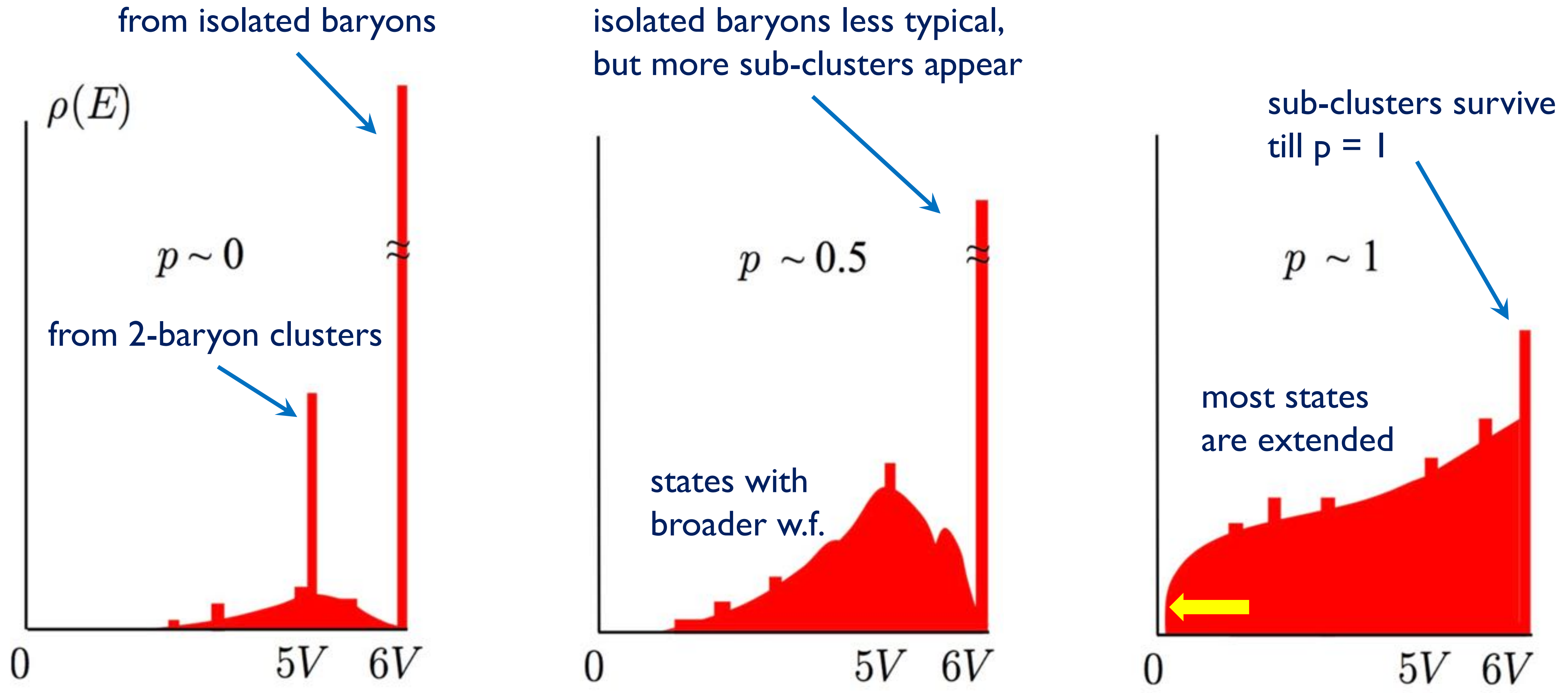


$E = (6 + \sqrt{2})V$

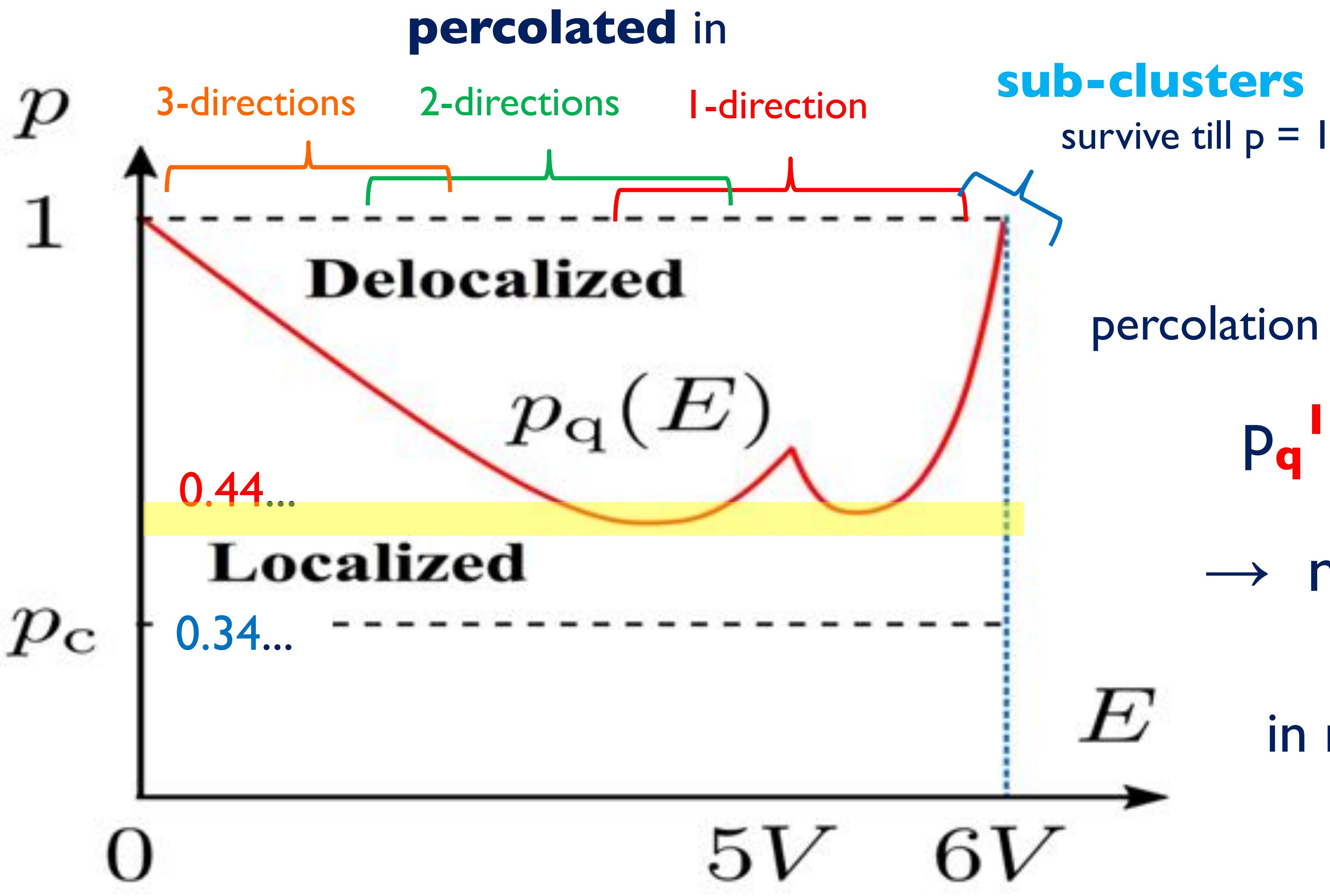
2-node

classically connected contain sub-clusters (localized states)

Histograms of quark eigenstates $\int dE \rho(E) = 1$



Mode-by-mode percolation



percolation proceeds from 1D to 3D

$p_q^{1D} \sim 0.44...$

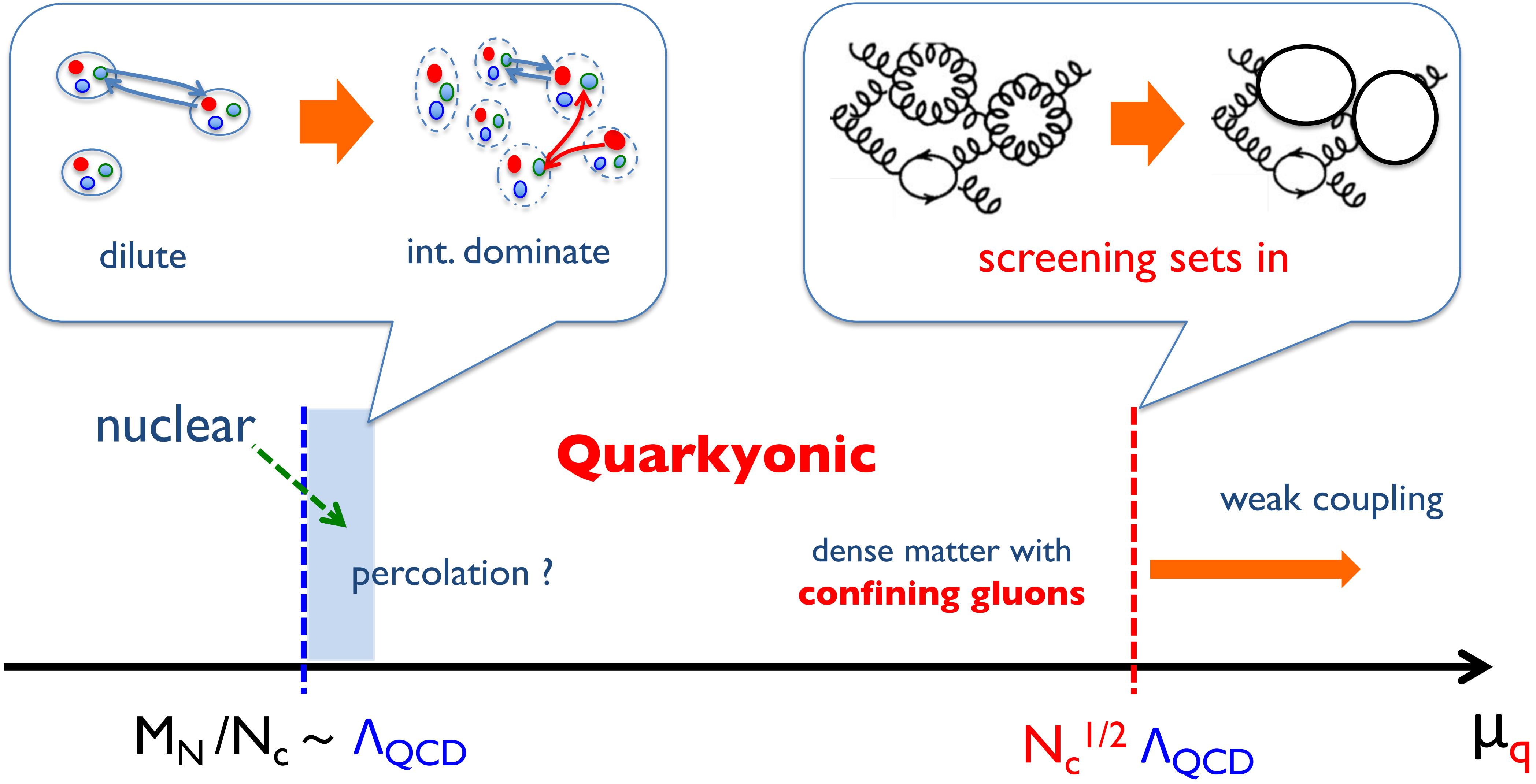
$\rightarrow n_B^{1D} \sim$ **1.8** n_0

in nuclear territory?

A momentum shell in Quarkyonic Matter

Quarkyonic Matter

[McLerran-Pisarski '07]



Momentum shell

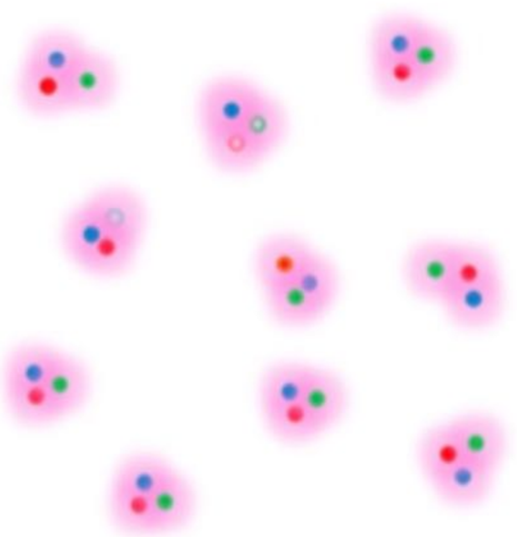
Dense matter with **confining gluons**

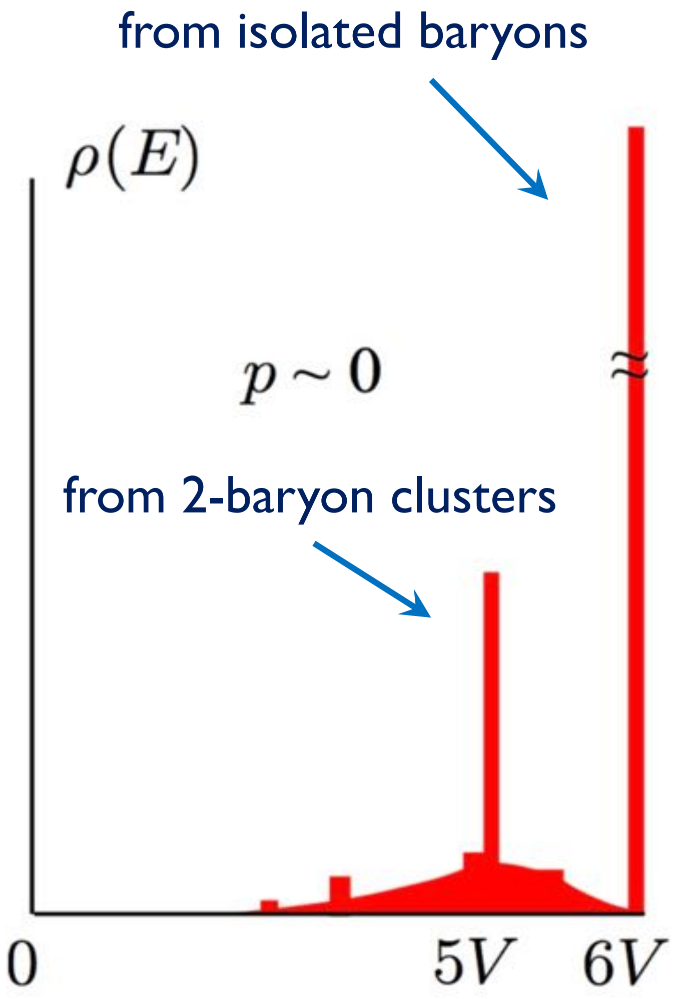
effective d.o.f ? (minimizing impacts of interactions?)

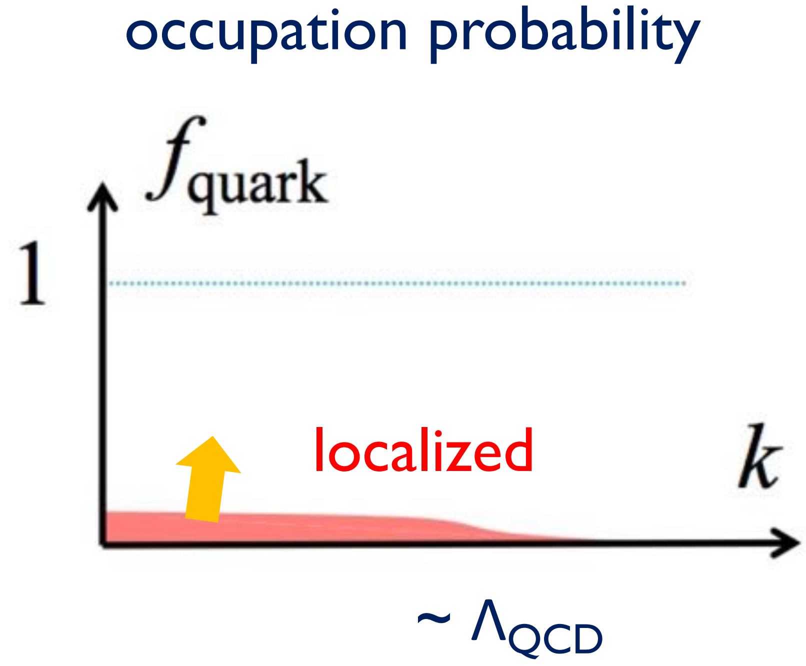
use only colorless d.o.f. | often claimed picture | Quarkyonic

quark Fermi sea & mode-by-mode percolation

$$\int dE \rho(E) = 1$$



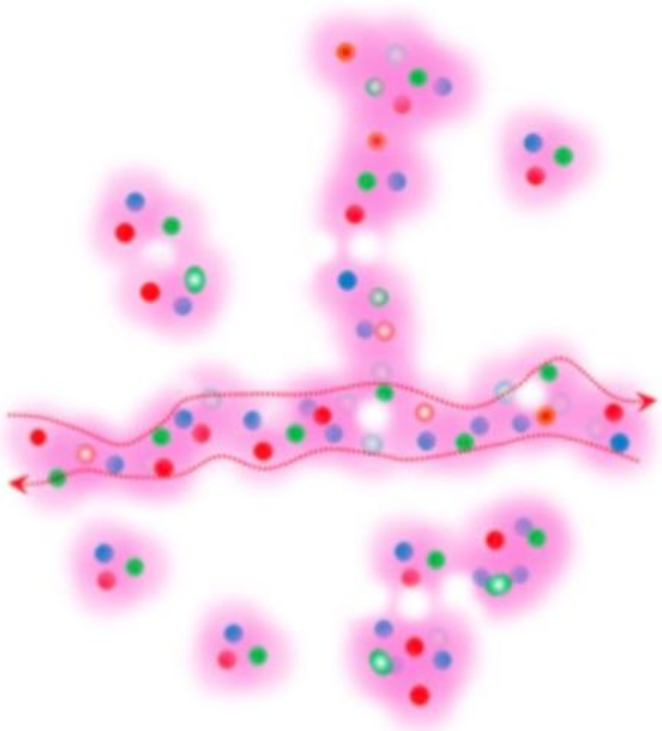




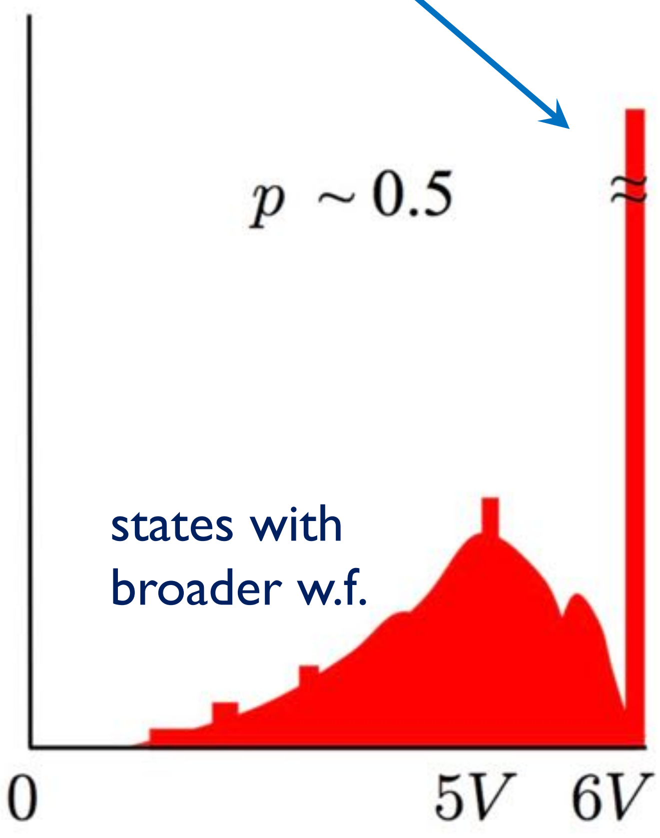
"nuclear"

quark Fermi sea & mode-by-mode percolation

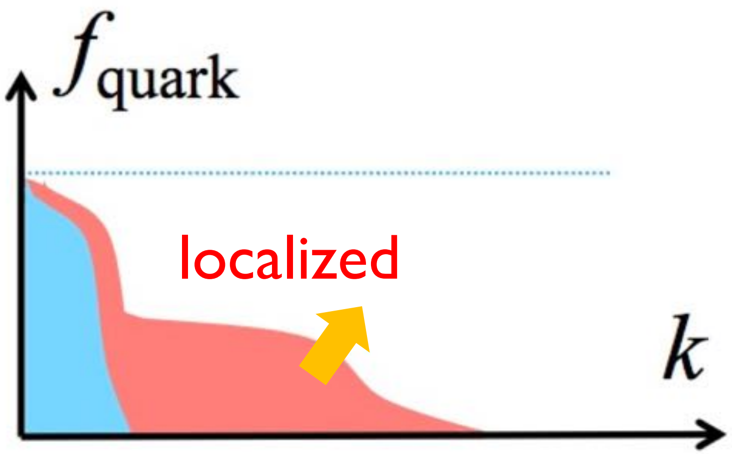
$$\int dE \rho(E) = 1$$



isolated baryons + sub-clusters



occupation probability



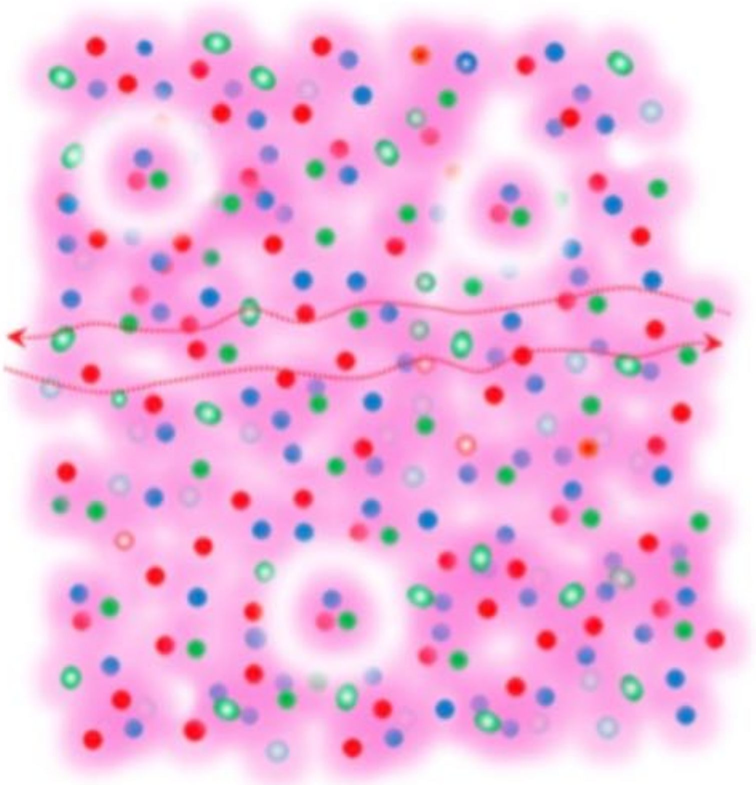
extended $\sim \Lambda_{QCD}$

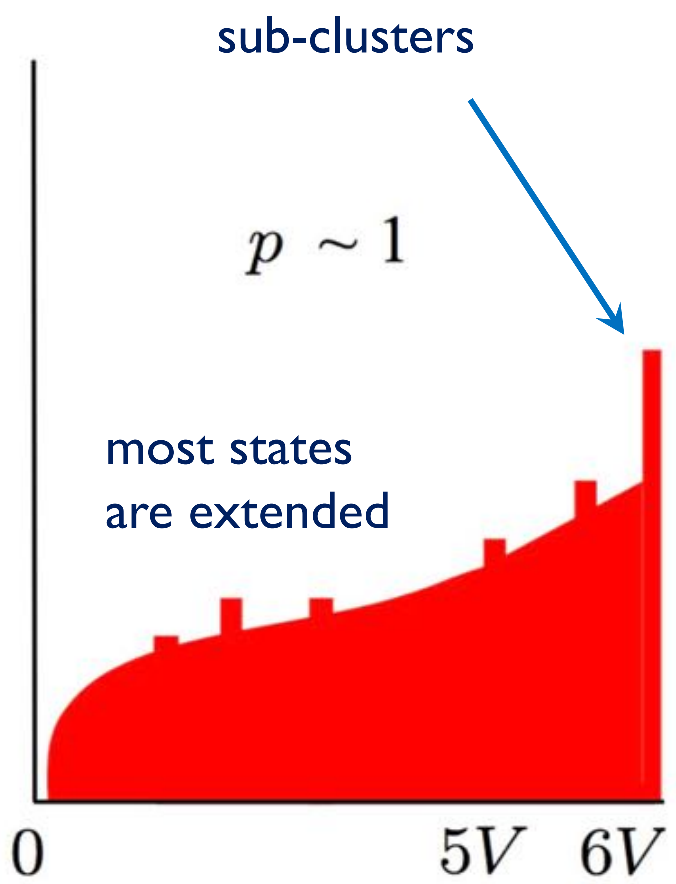
quark bases reasonable

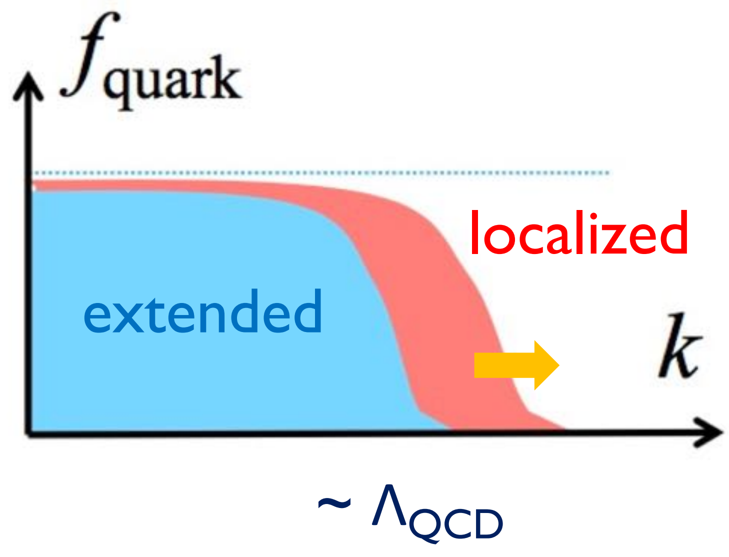
"quark-hadron continuity"

quark Fermi sea & mode-by-mode percolation

$$\int dE \rho(E) = 1$$







"quarkyonic"

Summary: a cartoon