# Equilibration in “small systems” and dynamics of QCD strings

Edward Shuryak
Stony Brook

**Equilibration Workshop INT, Aug 2015**

Based on works with Tigran Kalaydzhyan, Ismail Zahed, Ioannis Iatrakis, Adith Ramamurti

# outline

- **Introduction: macro and micro sides**
- **explosions in small systems: femtoscopy**
- **Pomerons and strings: holography.Stringy Hagedorn transition of the Pomeron**
- **QCD strings on the lattice and in holographic models**
- **string and “spaghetti” collapse Pomeron amplitude from a “tube” (Zahed+)**
- ***String balls***

# Introduction

**Naive argument:**
**AA (UU,AuAu, PbPb, CuCu) are "large" :**
**macro scale R (10 fm) >> micro scale (1/T) (1 fm)**
**pA and pp collisions produce "small systems",**
**both R and 1/T are comparable (1 fm) => grey area**

**But, sQGP is strongly coupled with means its free path is corrected by small viscosity/entropy, reducing micro scale by 1/2pi or so**

$$\frac{v_n}{\epsilon_n} \sim \exp\left[-Cn^2\left(\frac{\eta}{s}\right)\left(\frac{1}{TR}\right)\right]$$

works well for all n

**Furthermore, selecting higher multiplicity bins one increases the entropy and thus $T_i$ so the micro scale shrinks further till "small systems" eventually get large!**

**Last but not least: experiment does show collective effects appearing in such bins.**
**In fact the radial flow in those is even stronger than in AA!**

# THE SMALLEST DROPS OF QGP

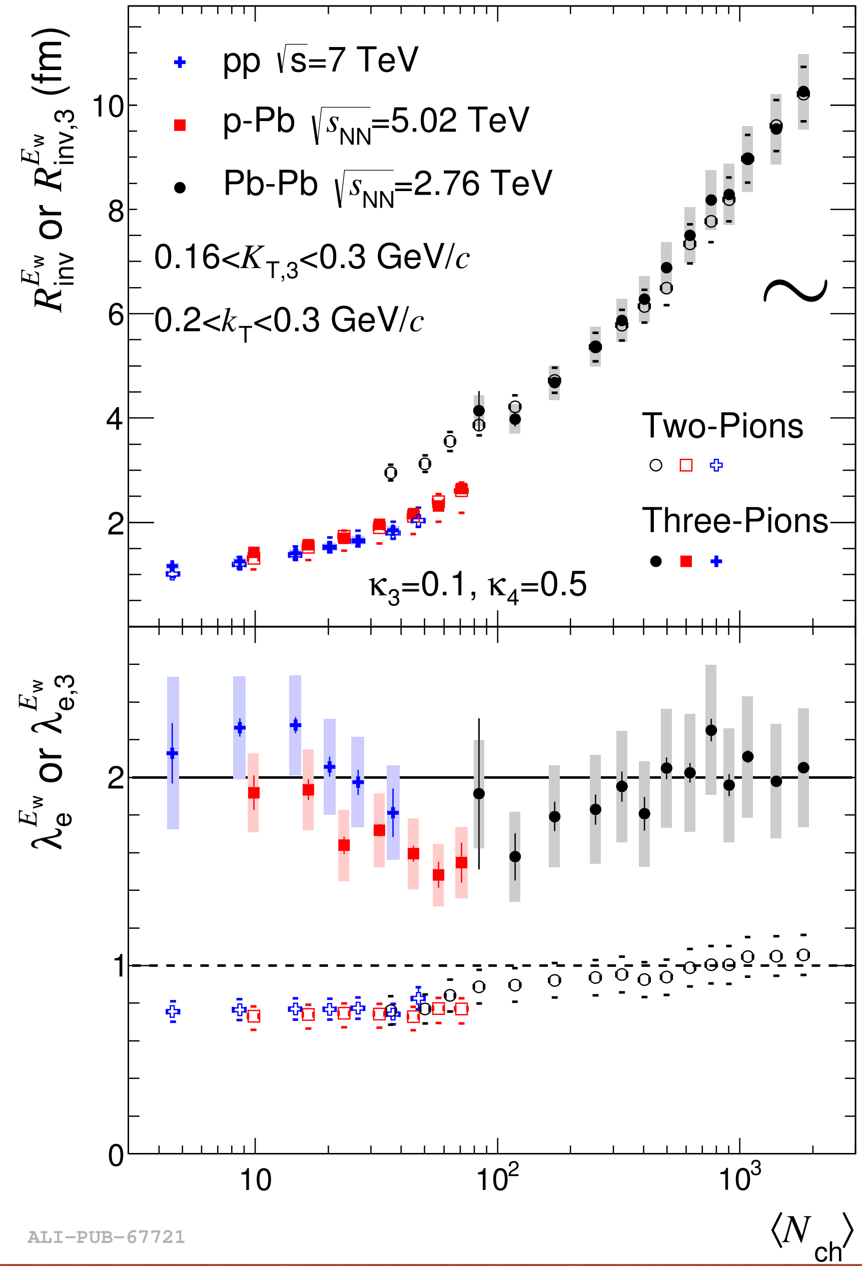
AA data follow N^1/3 curve => fixed freeze out density

Yet the pp, pA data apparently fall on a different line

Why do those systems get frozen at higher density, than those produced in AA?
(hint #1)

$$< n\sigma v >= \tau_{coll}^{-1}(n) \sim \tau_{expansion}^{-1} = \frac{dn(\tau)/d\tau}{n(\tau)}$$

So, more "explosive" systems, with larger expansion rate, freezeout earlier, at higher density.




$\sim N_{ch}^{1/3}$

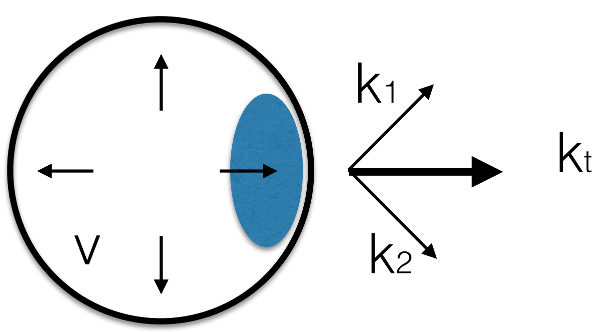
(up-
unc-

Where is the room for that, people usually ask, given that even the final size of these objects is not large but even smaller than in peripheral AA, which has weak radial flow.
Well, the only space left is at the beginning: those systems must start accelerating earlier, from even smaller size,

# Femtoscopic Signature of Strong Radial Flow in High-multiplicity *pp* Collisions

Yuji Hirono* and Edward Shuryak
*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA*
(Dated: December 2, 2014)

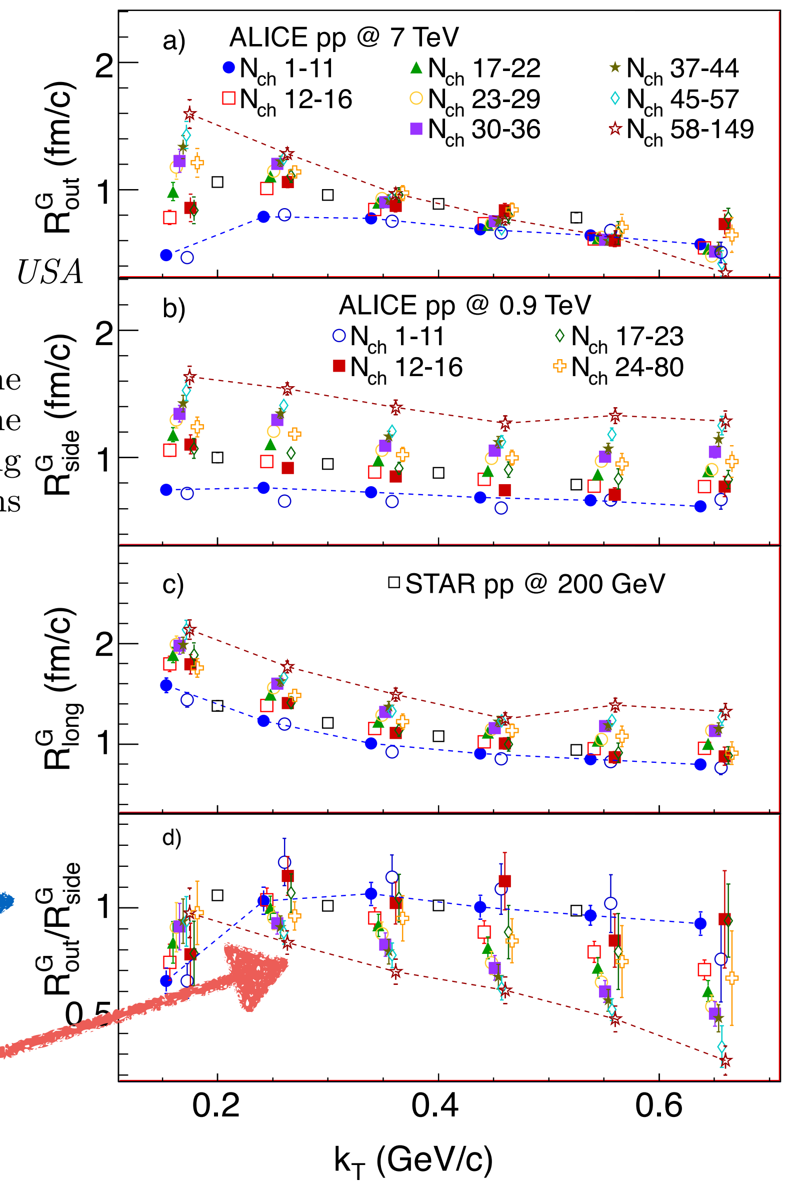
Hydrodynamic simulations are used to calculate the identical pion HBT radii, as a function of the pair momentum $k_T$. This dependence is sensitive to the magnitude of the collective radial flow in the transverse plane, and thus comparison to ALICE data enables us to derive its magnitude. By using hydro solutions with variable initial parameters we conclude that in this case fireball explosions starts with a very small initial size, well below 1 fm.




Makhlin,Sinyukov

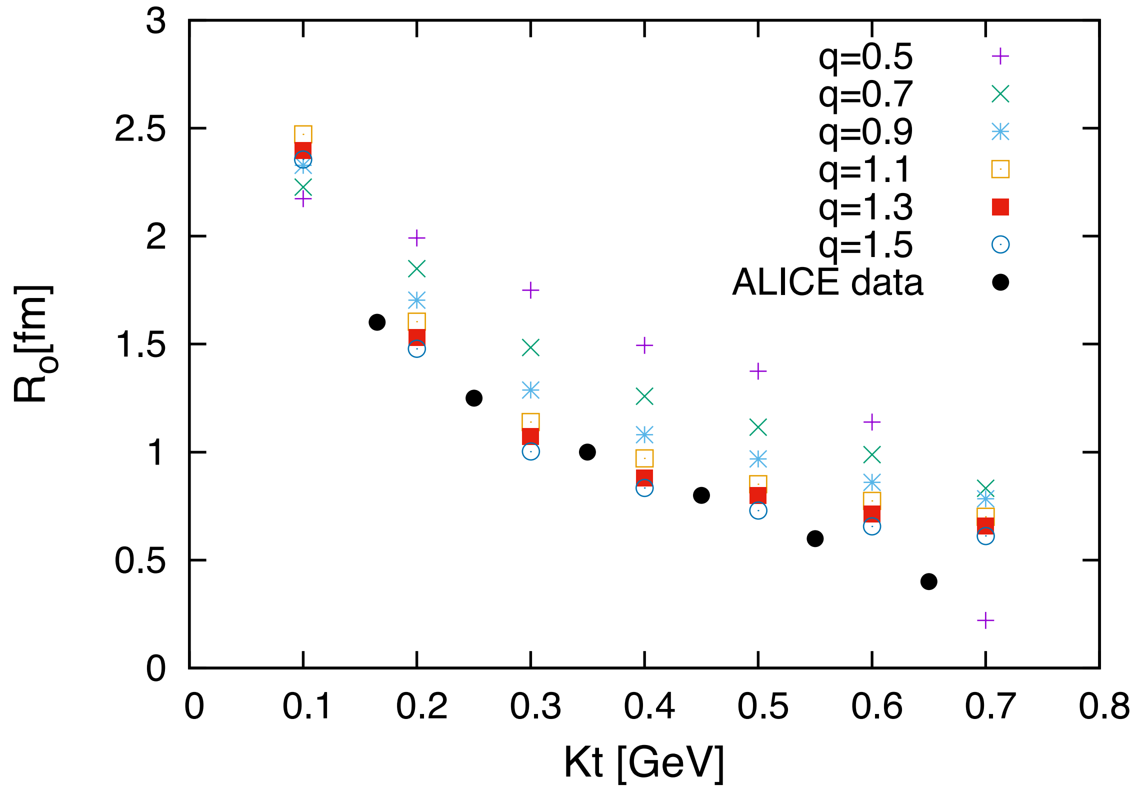
no flow

flow




momentum
rom ALIC

For most multiplicity bins the radii
do not depend on kt of the pair,
but the largest multiplicity one shows strong reduction:
this is a signature of the radial flow




Gubser solution at early time +numerical hydro at later stages

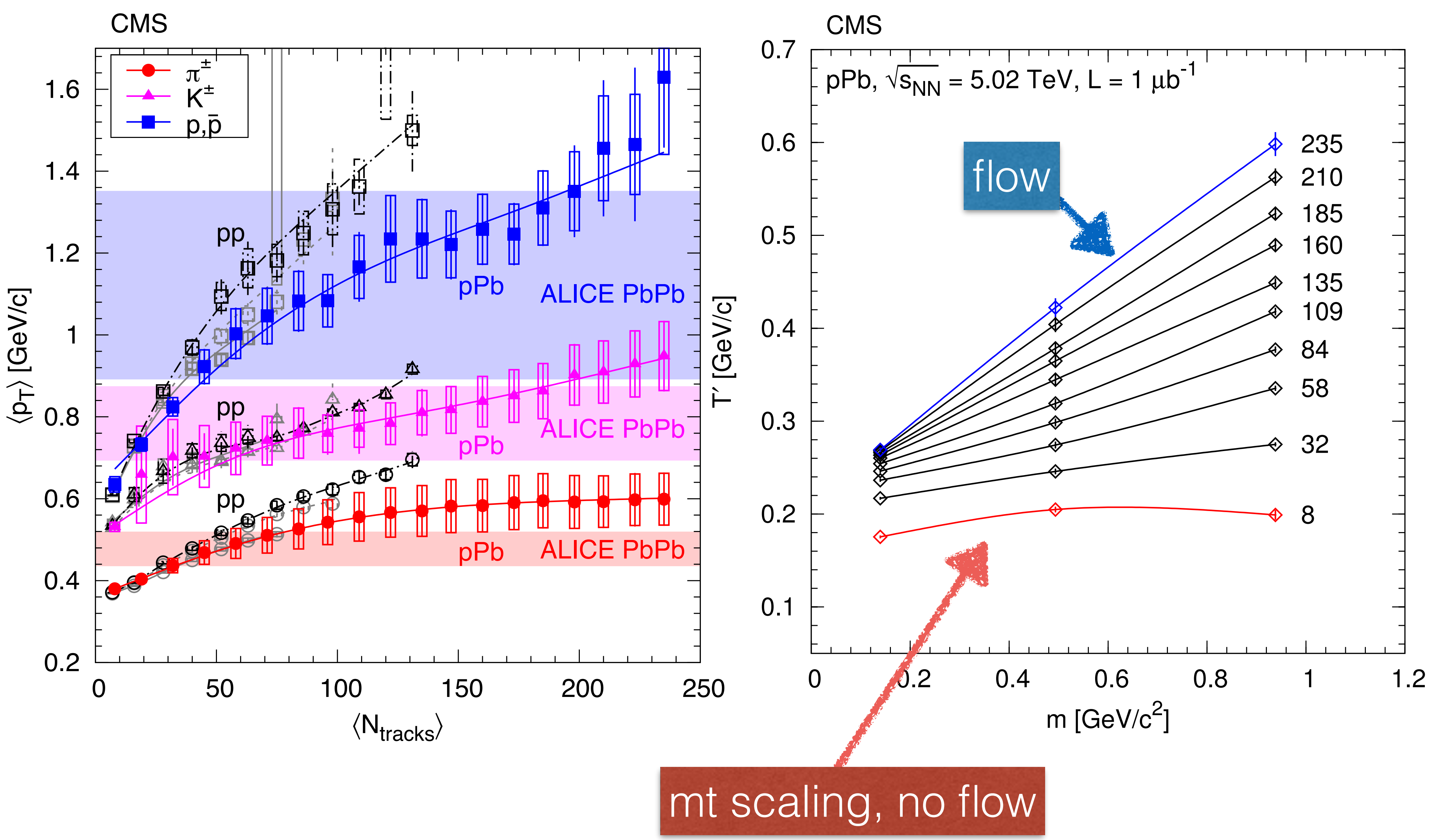
$$t = q\bar{\tau}, \quad r = q\bar{r}$$

$$\frac{\epsilon}{q^4} = \frac{\hat{\epsilon}_0 2^{8/3}}{t^{4/3}\left[1 + 2(t^2 + r^2) + (t^2 - r^2)^2\right]^{4/3}}$$

$$v_\perp(t, r) = tanh(y_\perp) = \frac{2tr}{1 + t^2 + r^2}$$

conclusion: in order to describe ALICE femtoscopy pp data one needs very strong flow => surprisingly small initial size1/q=2/3 fm

# the radial flow



# brief summary of hydro

- hydro describes well spectra and femtoscopy data for central pA and pp high multiplicity bin
- RHIC dAu and He3Au data directly show initial state effects, also well explained via hydro

P.Bozek and W.Broniowski, Phys.Lett.B 739 (2014) 308

- for detailed review, including discussion of first and second order viscosity effects, see

**Heavy Ion Collisions: Achievements and Challenges**
Edward Shuryak (SUNY, Stony Brook). arXiv:1412.8393

# Current views
# on the “initial state”

# Two historic views on hh coll. two faces of the Pomeron

$$\frac{d\sigma}{dt} \sim s^{\alpha(t)}$$

*Prehistoric: Regge, Pomeranchuk, Gribov*

$$\alpha(t) = \alpha(0) + \alpha' t + \dots$$

intercept +string scale

**1960's: Veneziano dual resonance amplitude => appearance of strings**

**1970's QCD Gribov,Lipatov => gluon ladders => BFKL**

**Yet we do not have two different Pomerons, soft (strongly coupled) and hard (weakly coupled) but a certain transition between regimes. Where is it? Is it smooth?**

# similarly, two views on AA collisions

Lund model and its descendants (Hijing) based on strings

CGC-Glasma models based on classical glue, decaying into gluons

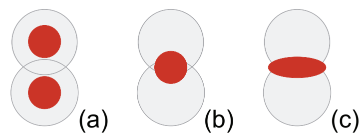
a transition between these regimes is expected

What is the density or Qs above which it is GLASMA ?

Is string-to-gluons transition smooth?

## Issues in small systems (p+p, p+A)

- MC-Glauber does not constrain energy density dist.




Where do we put the energy?

What shape does it have?

- IP-Glasma constrains energy density deposition
  However, it does not describe $v_n$ in p+Pb
- Proton substructure should matter
  (if main effect is of collective origin or not)
- Combine constituent quark model with JIMWLK evolution to get proton structure at small *x*

SCHENKE, SCHLICHTING, PHYS. LETT. B739, 313-319 (2014)

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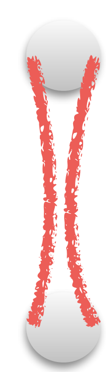
from Schenke's talk
at BNL users meeting
June 2015,
basically he said
we dont know
the shape in which
the energy is deposited
and gave possible examples

**1.Not the "proton structure" but that of the Pomeron**
**typical impact param. b=sqrt(sigma/pi)=1.6 fm**
**is much larger than the "dipole size" d=0.3-0.5 fm**

**2.Here is my sketch**
**for a stringy Pomeron**
**model to be discussed,**
**the exchange of two strings**



# Strongly coupled (stringy holographic) Pomeron

**Holographic Pomeron and the Schwinger Mechanism**
**Gokce Basar, Dmitri E. Kharzeev, Ho-Ung Yee, Ismail Zahed**
**Phys.Rev. D85 (2012) 105005**
**arXiv:1202.0831**

**New Regimes of Stringy (Holographic) Pomeron**
**Edward Shuryak, Ismail Zahed Phys.Rev. D89 (2014) 9, 094001**
**arXiv:1311.0836**

# the “tube”

flying dipole with a string

a hole is produced

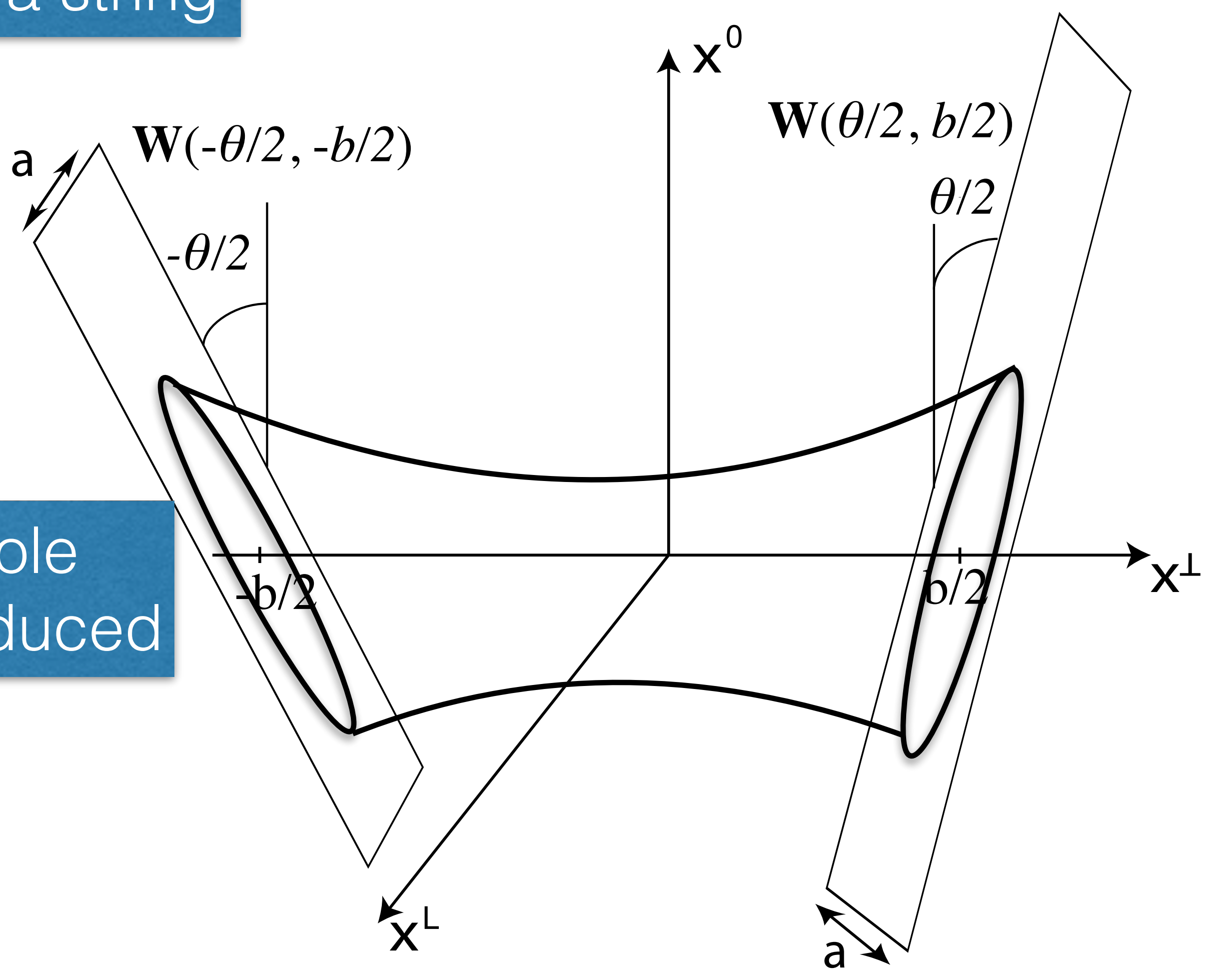



FIG. 1: Dipole-dipole scattering configuration in Euclidean space. The dipoles have size $a$ and are $b$ apart. The dipoles are tilted by $\pm\theta/2$ (Euclidean rapidity) in the longitudinal $x_0 x_L$ plane.

- **If cut horizontally, it describes production of a pair of open strings**
- **If cut vertically, it describes an exchange by a closed string**
- **string fluctuations are include mode-by-mode**

$$\frac{1}{-2is}\mathcal{T}(s,t) \approx \frac{\pi^2 g_s^2 a^2}{2} \sum_{k=1}^{k_{\max}} \sum_{n=0}^{\infty} \frac{(-1)^k}{k} \left(\frac{k\pi}{\ln s}\right)^{D_\perp/2-1} \times d(n)\, s^{-2n/k + D_\perp/12k + \alpha' t/2k}, \qquad (70)$$

**k=1 in SU(3), n is excitation**

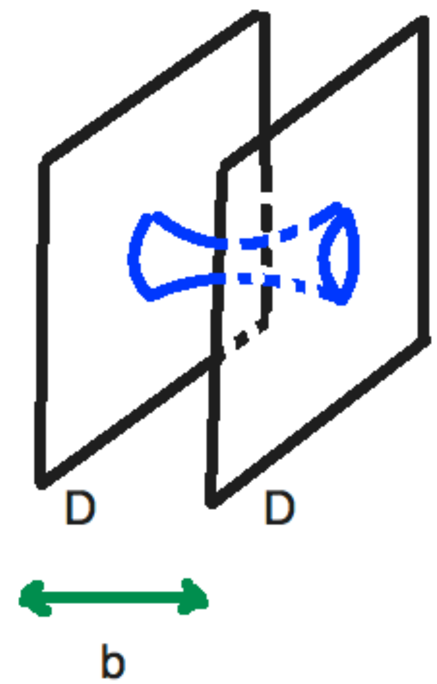
The previous literature focuses on what we call the "cold" regime of the string

$$\mathbf{b} \gg \beta \gg \tilde{\beta}_H \quad (17)$$

where the former inequality follows from large collision energy (14) and the latter implies that the string is nearly straight, with small effective excitations (small effective $T$). The meaning of

$$\beta = \frac{1}{T} = \frac{2\pi \mathbf{b}}{\chi}$$

$$\chi = log(s)$$




We will now review the Pomeron results in this setting. The amplitude of the elastic dipole-dipole scattering reads [2–4]

$$\frac{1}{-2is}\mathcal{T}(s,t;k) \approx g_s^2 \int d^2\mathbf{b}\, e^{iq\cdot\mathbf{b}}\, \mathbf{K}_T(\beta, \mathbf{b}; k) \quad (15)$$

$$\mathbf{K}_T(\beta, \mathbf{b}; 1) = \left(\frac{\beta}{4\pi^2 \mathbf{b}}\right)^{D_\perp/2}$$

$$\times e^{-\sigma\beta\mathbf{b}\left(1-(\tilde{\beta}_H/\beta)^2/2\right)}$$

$$\times \sum_{n=0..\infty} d(n) exp(-2\chi n)$$

*classical action b^2*
*vibrations b-independent*

**Linear Regge trajectories, daughters shifted by 2 down**

As we mentioned, the expression (18) has been derived in [4] from the semiclassical approach to a Polyakov string, but ( to leading order in $1/\lambda$) it can alternatively be derived from a diffusion equation

$$\left(\partial_\chi + \mathbf{D}_k \left(\mathbf{M}_0^2 - \nabla_\mathbf{b}^2\right)\right)\mathbf{K}_T = 0 \quad (20)$$

where the rapidity $\chi$ interval is the time and the diffusion happens in the (curved) transverse space with the diffusion constant $\mathbf{D}_k = \alpha'/2k = l_s^2/k$. This diffusion (20) is nothing else but the Gribov diffusion of the Pomeron, leading on average to an impact parameter $\langle \mathbf{b}^2 \rangle = \mathbf{D}_k\chi$ for close Pomeron strings. If the "mother dipoles"

**connection to the Gribov diffusion, strings instead of gluons however**

# The Hagedorn phenomenon

*(Polyakov,Susskind,1970's)*

$$Z \sim \int dE exp(-E/T) exp(E/T_H)$$

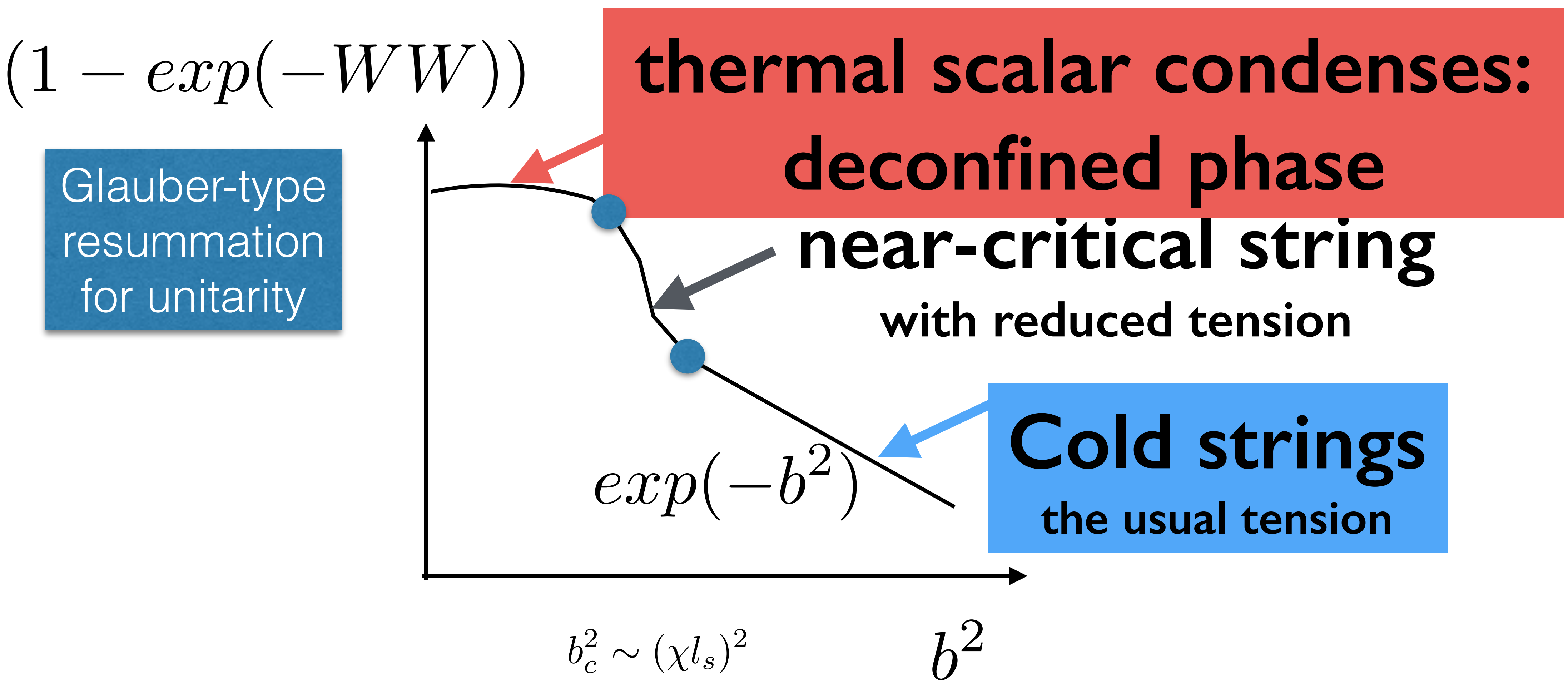
stringy density of state grows exponentially
(Veneziano et al)
thus when T approaches the Hagedorn temperature
TH exponents cancel and strings gets highly excited

**effectively string tension drops and alpha' changes**

**It was studied in detail on the lattice for pure gauge theories**
**(Teper et al )**
**and TH/Tc is about 1.04**

*Can transition between regimes be seen in the elastic amplitude?*

***Tube geometry allows to use Matsubara time and T***




**After integration over b and dipole sizes, can one still be able to see such shape in A(t) ?**

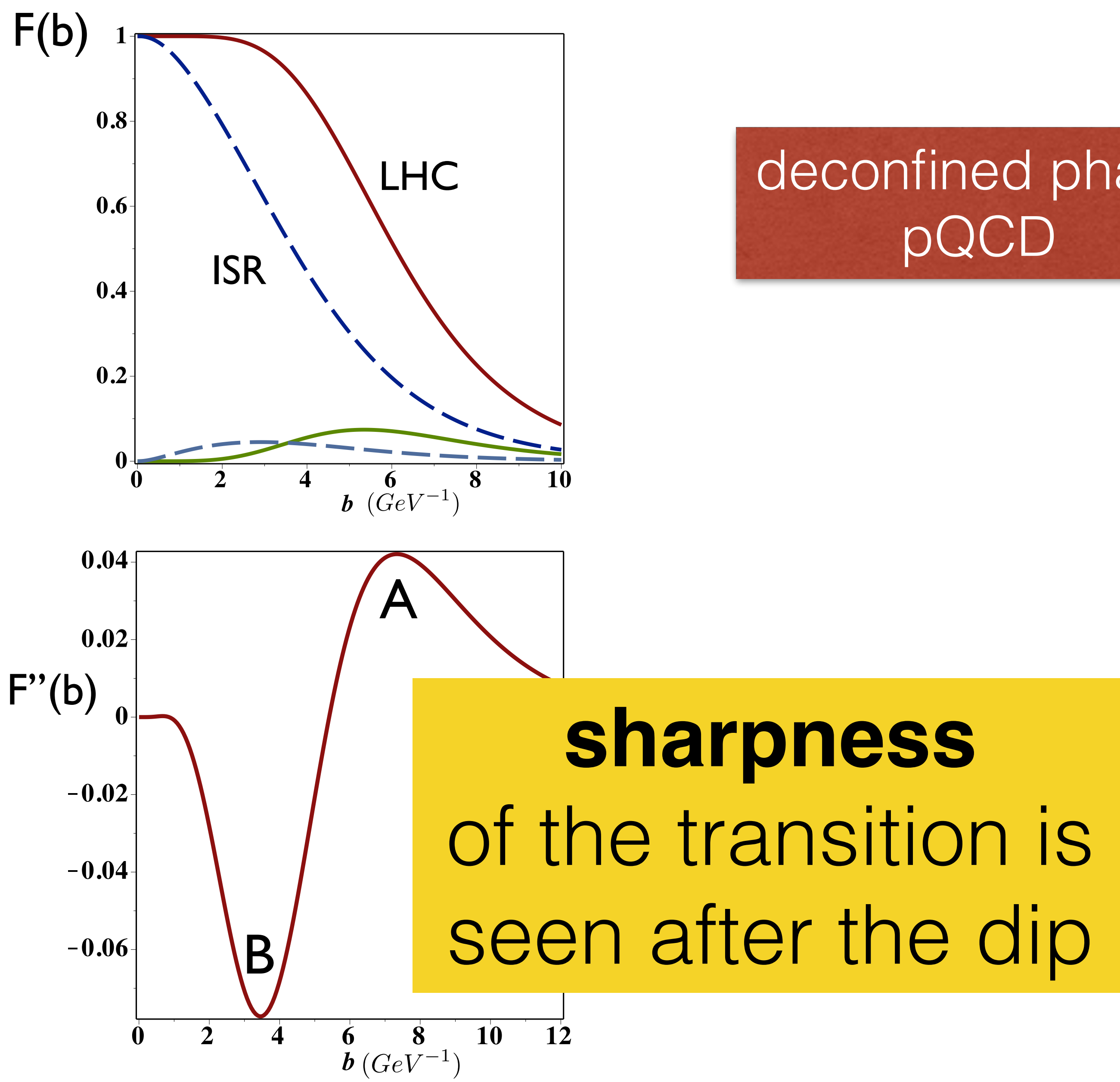



FIG. 4: (Color online) The upper figure shows the imaginary (upper) and real (down) parts of the profile function $F(s, b)$ versus $\mathbf{b}(\mathrm{GeV}^{-1})$ for $\sqrt{s} = 7\,\mathrm{TeV}$ (solid) and $\sqrt{s} = 63\,\mathrm{GeV}$ (dashed). The lower plot shows the second derivative over $b$ for $\sqrt{s} = 7\,\mathrm{TeV}$ . Two maxima correspond to the same points $A, B$ as in the sketch in Fig. 1.

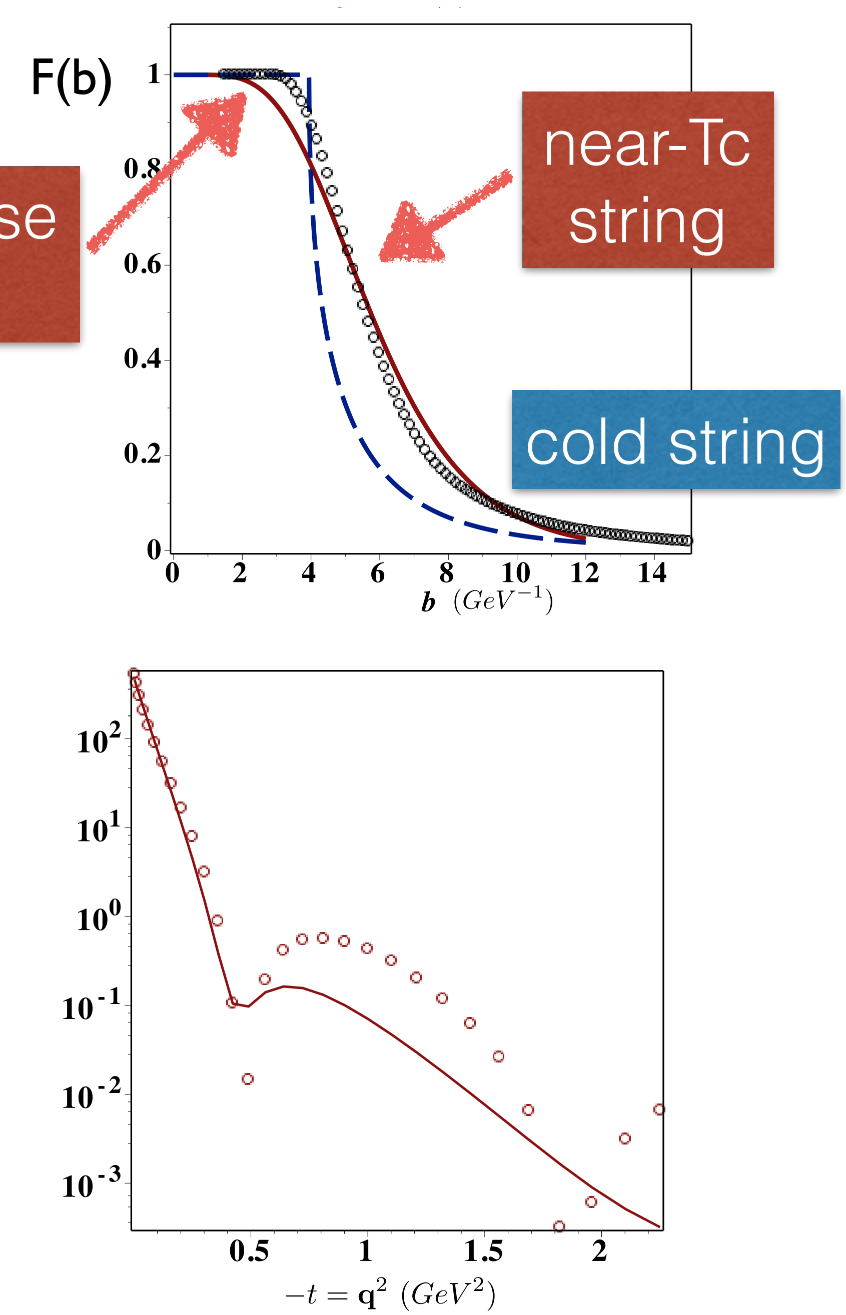



FIG. 12: (Color on-line) The profile function $F(\mathbf{b})$ versus the impact parameter $\mathbf{b}$ is shown in the upper plot for LHC $\sqrt{s} = 7\,\mathrm{TeV}$ energy. The solid line is the same curve as in Fig.4 corresponding to the BSW data parametrization. The dashed line is the shape corresponding to the approximation (59) for fixed sizes of the dipoles $u_1 = u_2$, while the circles correspond to the profile with the fluctuating dipoles. The lower plot shows the corresponding absolute value squared of its Bessel transform as a function of momentum transfer.

**Now back to theory/phenomenology of AA, pA and pp collisions:**

**if the string-GLASMA transition depends on density, what are their ranges and systematics?**

Transition between two picture is naturally expected when the diluteness of the QCD strings become of the order 1, so they can be separated

$$\frac{N_{string}}{Area} \sim \frac{1}{\pi r^2_{string}} \sim 10\, fm^{-2} \tag{43}$$

where in the numerical value we use the field radius in the string $r_s \approx 0.17\, fm \sim 1/GeV$. (Note, that this argument confirms, that the smallest value of $Q_s$ which makes sense for GLASMA must be about $1\, GeV$, as we already argued

**as for the Pomeron, it is hard to argue from pQCD sid while strings have sizes and that helps to tell when the string picture is no longer adequate**

(i) Our most studied case, the central AuAu or PbPb, is the obvious benchmark. With the total multiplicity about $N_{AA} \approx 10^4$ and transverse area of nuclei $\pi R_A^2 \approx 100\, fm^2$ one gets the density

$$n_{AA} = \frac{N}{\pi R_A^2} \sim 100\, fm^{-2} \qquad (24)$$

which can be transformed into entropy if needed, in a standard way.

(ii) Central $pA$ (up to few percent of the total cross section) has CMS track multiplicity of about 100. Accounting for unobserved range of $p_t, y$ and neutrals increases it by about factor 3, so $N_{pA}^{central} \sim 300$. The area now corresponds to the typical impact parameter $b$ in $pp$ collisions, or $\pi < b^2 >= \sigma_{pp} \approx 10\, fm^2$. The density is then

$$n_{pA}^{central} = \frac{N_{pA}^{central}}{\sigma_{pp}} \sim 30\, fm^{-2} \qquad (25)$$

or 1/3 of that in central AA. Using the power of LHC luminosity CMS can reach – as a fluctuation with the probability $10^{-6}$ — another increase of the multiplicity, by about factor 2.5 or so, reaching the density $N_{pA}^{max}/\sigma_{pp}$

the case of central pA, we don't utilize standard Glauber and full cross section (maximal impact parameters): we address now a fluctuation which has small probability. In fact, nobody knows the answer to that. Based on the profile of $pp$ elastic scattering (to be discussed in section **??**) I think it should correspond to impact parameter $b$ in the black disc regime. If so $\pi b_{b.d.}^2 \sim 1/2\, fm^2$ and

$$n_{pp}^{max} \approx \frac{N_{pp}^{max}}{\pi b_{b.d.}^2} \sim 600\, fm^{-2} \qquad (26)$$

Other evidences about glue distribution in a proton comes from HERA diffractive production, especially of $J/\psi$: they also suggest a r.m.s. radius of only $0.3\, fm$, less than a half of electromagnetic radius.

strings | glasma

$$\frac{dN_{maximal}^{pA}}{dA_\perp} \sim \frac{dN_{peripheral}^{AA}}{dA_\perp} \ll \frac{dN_{central}^{AA}}{dA_\perp} \ll \frac{dN_{maximal}^{pp}}{dA_\perp} \qquad (27)$$

and may thus expect that the radial flow follows the same pattern. The data however show it is *not* the case.

$$y_\perp^{AA,central} < y_\perp^{pA,central} < y_\perp^{pp,highest}$$

**this is what I call "the pA flow puzzle"**

The v2 magnitude tells us about fluctuations in the initial state
in AA it is Glauber wounded nucleons: what is it in pA and pp?

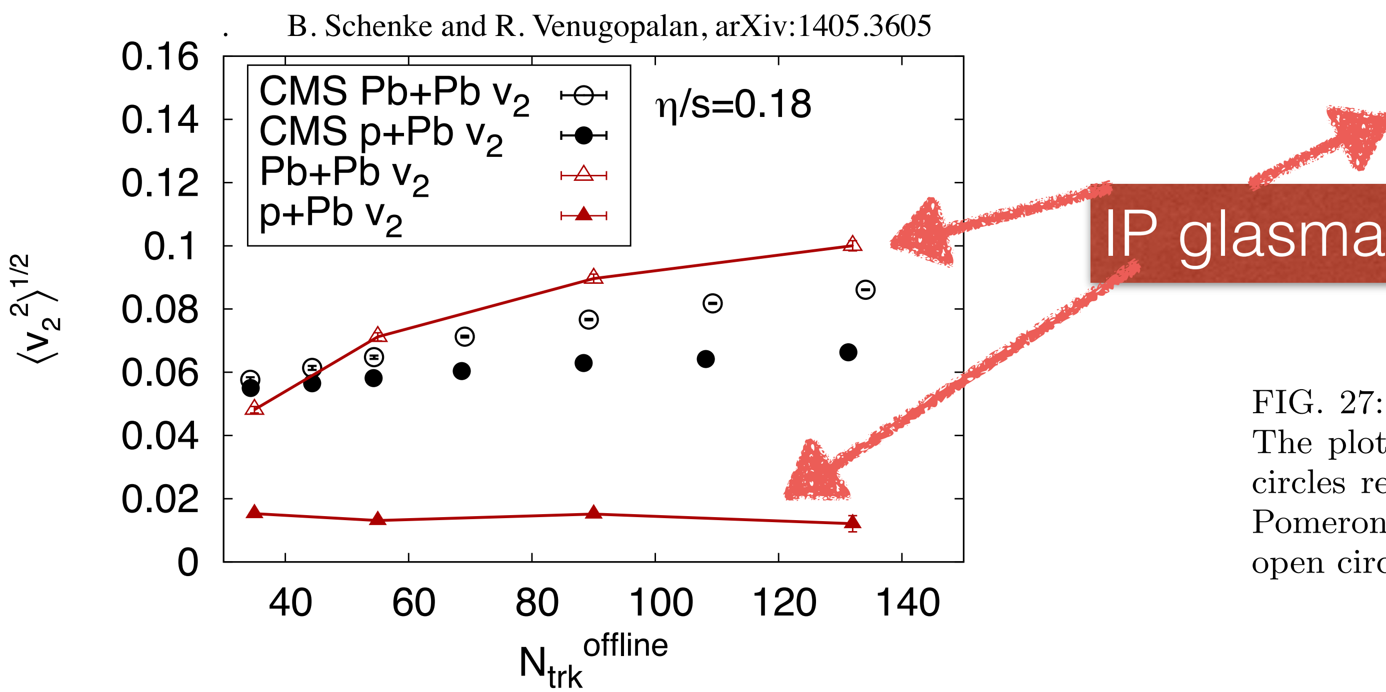



FIG. 25: (Color online) Multiplicity dependence of the root-mean-square elliptic flow coefficient v2 in Pb+Pb (open symbols) and p+Pb collisions (filled symbols) from the IP-Glasma+music model (connected triangles) compared to experimental data by the CMS collaboration.

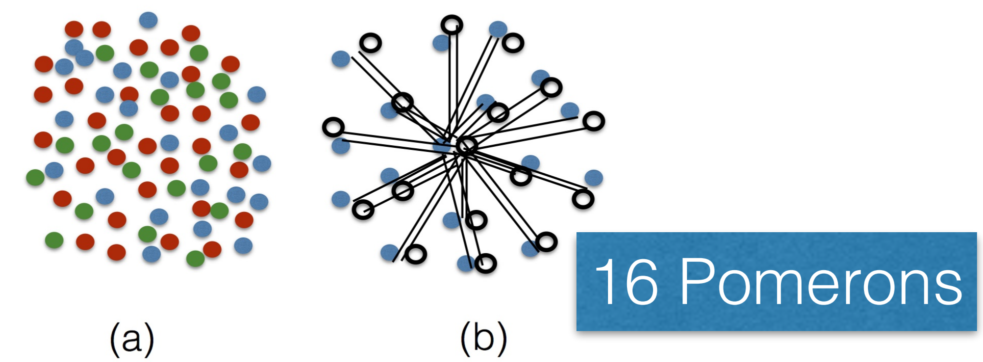



FIG. 27: Sketch of the initial state in central $pA$ collisions. The plot (a) corresponds to IP-glasma model, with colored circles representing multiple gluons. Fig.(b) is for $N_p = 16$ Pomerons, each represented by a pair of cold strings. The open circles are quarks and filled blue circles are diquarks.

where $N = N_p N_g$ for (a) and only $N = N_p$ for (b).

$$\epsilon_n \sim \frac{1}{\sqrt{N}} \qquad \frac{\epsilon_n^{(b)}}{\epsilon_n^{(a)}} \sim \frac{1}{\sqrt{N_g}} \sim 4$$

conclusion: no glasma in pA but Pomerons/strings instead

# QCD strings on the lattice

# 1 flux tube on the lattice

**The dual superconductor idea by**
**’t Hooft and Mandelstam works well:**
**(Higgs= the monopole condesate)**

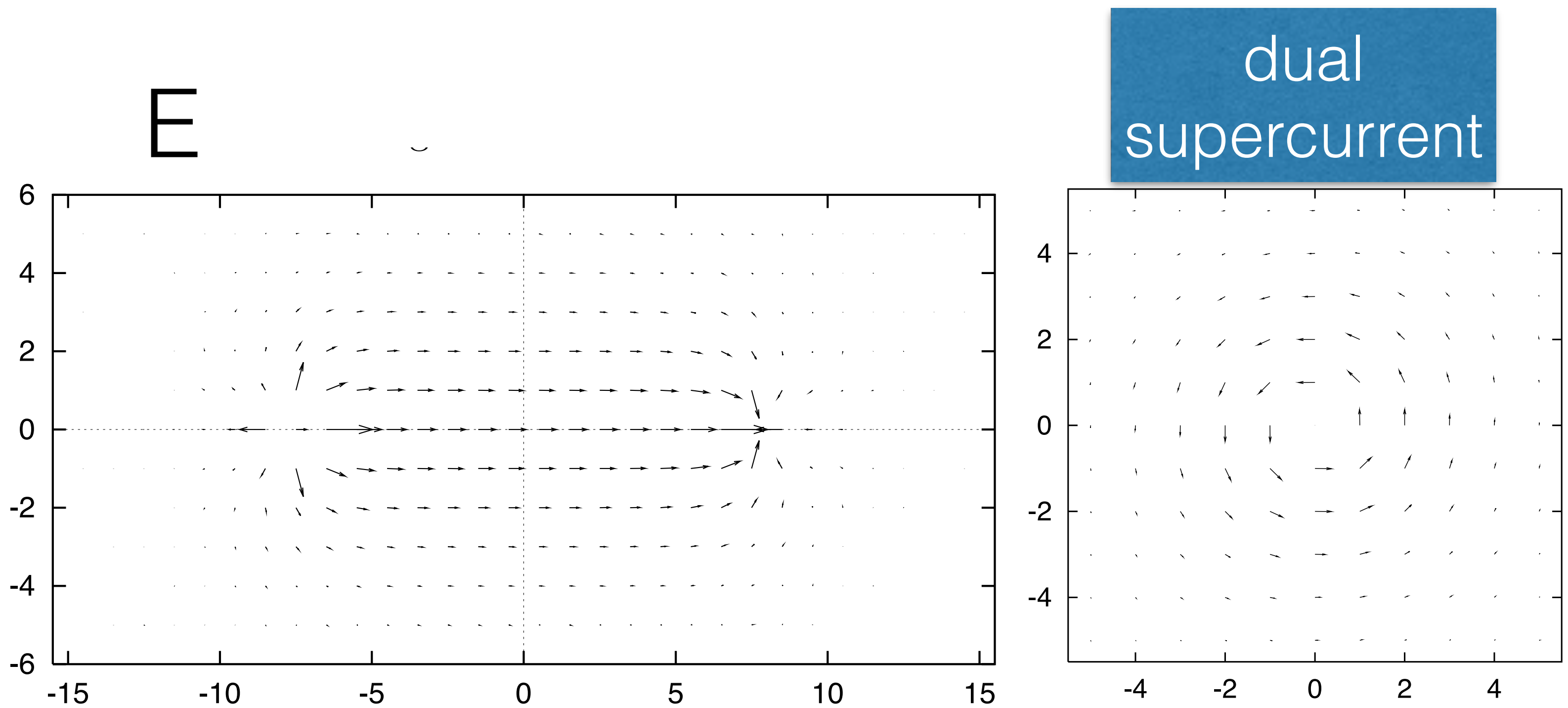
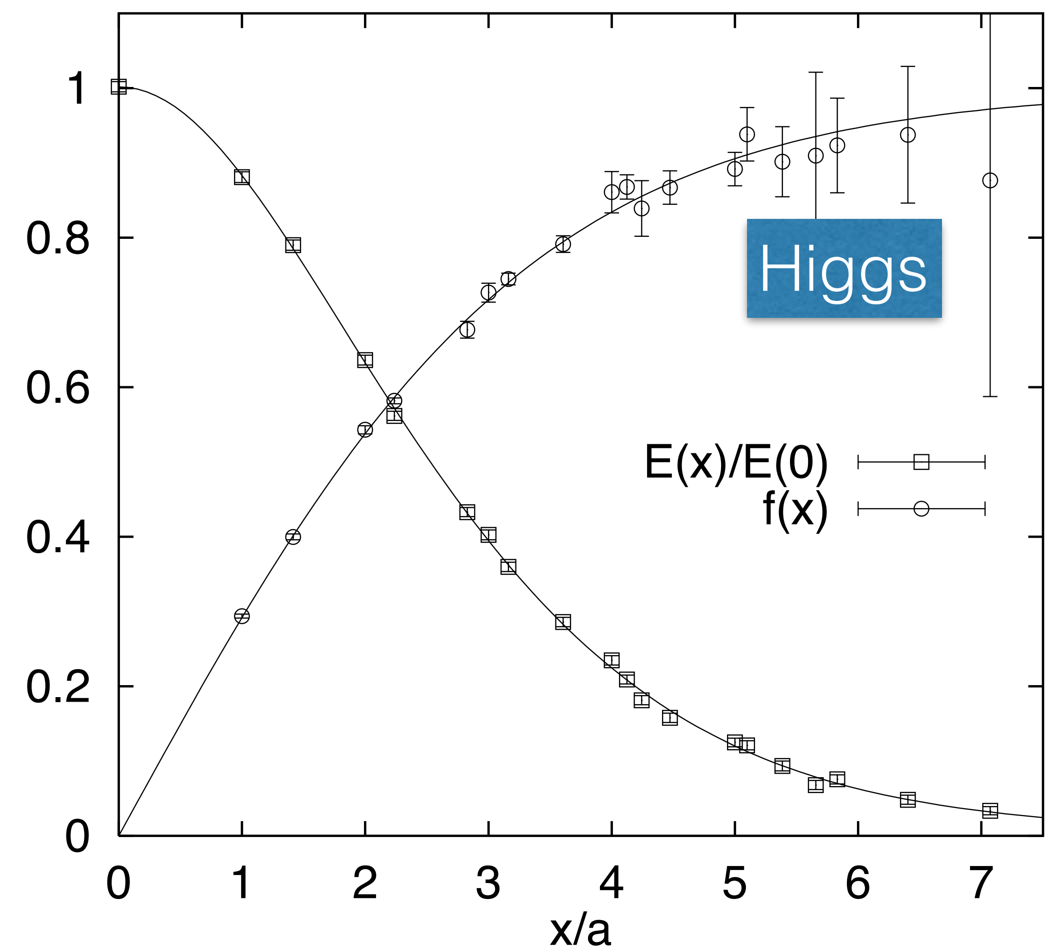



Fig. 7. Electric field **E** and magnetic super current **k** between two static sources.

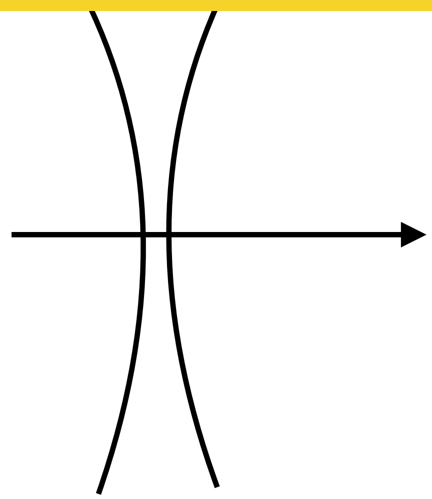



M.Baker et al: in 1980’s: dual Higgs model

G. S. Bali, hep-ph/9809351.

# 2 flux tubes on the lattice

**attractive interaction, which strongly grows near Tc**



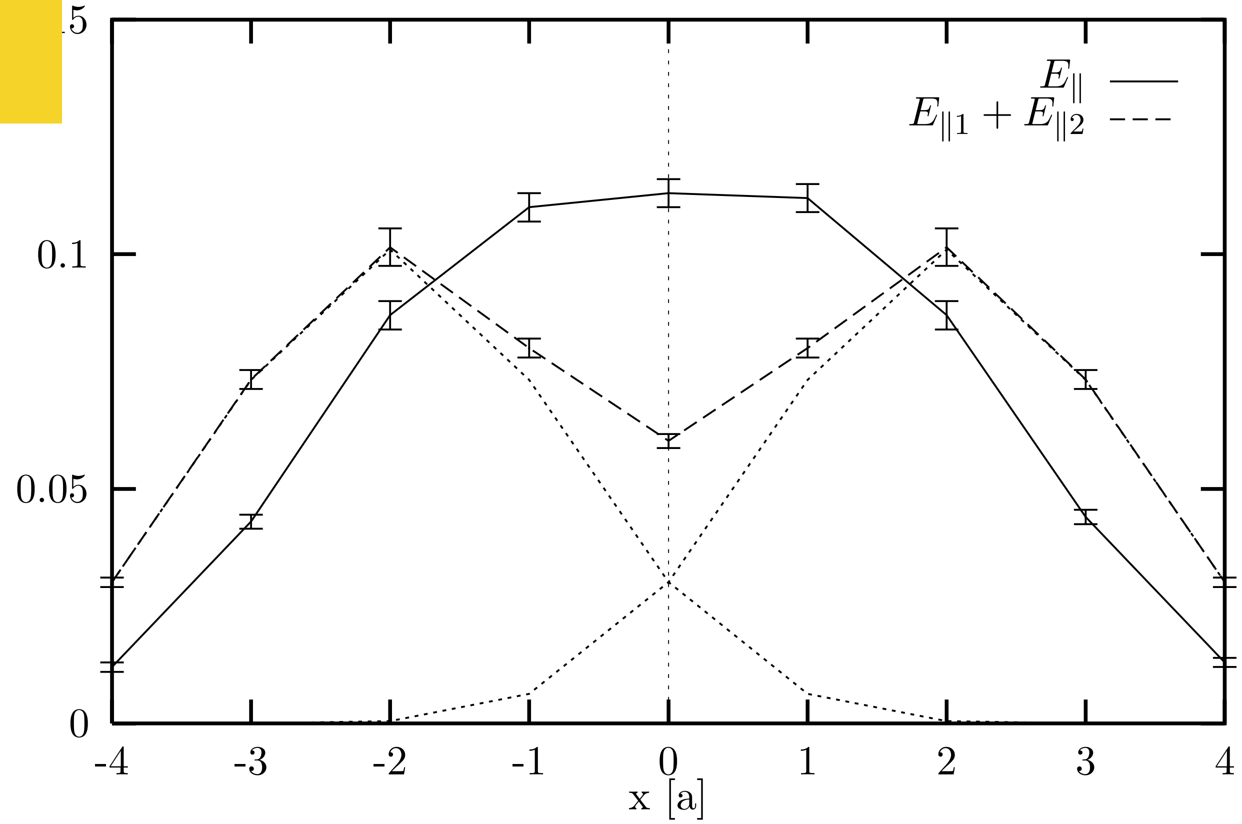



Figure 12: Longitudinal electric field profile of two interacting flux tubes in the symmetry plane ($E_{\|}$, solid line). The length of flux tubes is $d = 22a$, the transverse distance of equal charges is $4a$. For comparison, the dotted lines show the results for single flux tubes at $x = -2a$ and $x = +2a$, and the dashed line corresponds to the superposition $E_{\|1} + E_{\|2}$ of these two non-interacting flux tubes.

M. Zach, M. Faber and P. Skala, Nucl. Phys. B 529, 505 (1998) hep-lat/9709017.

# string interaction via sigma meson exchange

T. Iritani, G. Cossu and S. Hashimoto, arXiv:1311.0218

our fit uses
the sigma mass
600 MeV

$$\frac{\langle\sigma(r_\perp)W\rangle}{\langle W\rangle\langle\sigma\rangle} = 1 - CK_0(m_\sigma \tilde{r}_\perp)$$

$$\tilde{r}_\perp = \sqrt{r_\perp^2 + s_{string}^2}$$

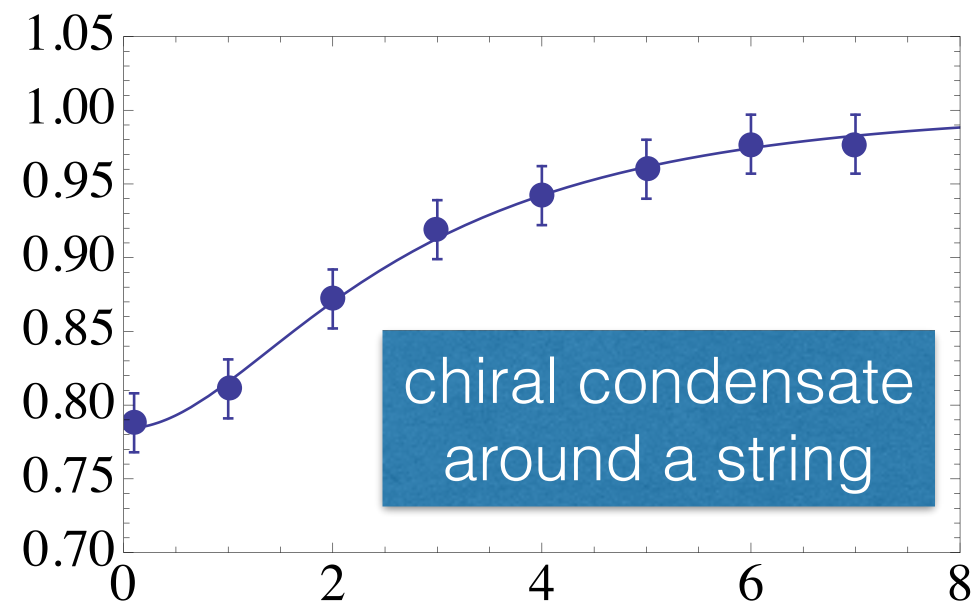



FIG. 2. (Color online). Points are lattice data from [12], the curve is expression (8) with $C = 0.26$, $s_{string} = 0.176\,\mathrm{fm}$.

**So the sigma cloud around a string is there!**
**thus they must attract at large distances**

**Self-interacting QCD strings and string balls**
Tigran Kalaydzhyan, Edward Shuryak (SUNY, Stony Brook). Feb 28, 2014. 15 pp.
Published in **Phys.Rev. D90 (2014) 2, 025031 arXiv:1402.7363**

# QCD strings in holography

Introduction to the subject will take too long…

For concreteness: this is the model we follow

Holographic Models for QCD in the Veneziano Limit
Matti Jarvinen , Elias Kiritsis
JHEP 1203 (2012) 002 arXiv:1112.1261

QCD is on the boundary of 5-d metric

Scalar dilaton represent coupling, its potential induces confinement and hadronic mass quantization

Bulk brane has fundamental fermions, their number Nf is as large as Nc, x=Nf/Nc=fixed (Veneziano limit) so there are mesons and glueballs

Reasonably good spectroscopy, Reggeons and even thermodynamics

: arXiv:1503.04759
Phys.Rev. D92 (2015) 1, 014011

No new parameters
or assumptions,
just straight calculations

# Collective string interactions in AdS/QCD and high multiplicity pA collisions

Ioannis Iatrakis, Adith Ramamurti and Edward Shuryak
*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA*
(Dated: March 2, 2015)

Recently there appeared interest in collective interaction of QCD strings. Intrinsic attractive interaction of strings in the context of holographic models of the AdS/QCD type, or $\sigma$ exchanges for QCD strings – can significantly affect properties of the multi-string systems. The high multiplicity pA collisions are the simplest example of the kind, producing "spaghetti" of many strings extended in the longitudinal (beam) direction. We study their collective field

TABLE I: The fields and fluctuations of our model.

| | |
|---|---|
| $\Phi = \log \lambda$ | Dilaton |
| $A$ | Metric conformal factor |
| $A_s = A + \frac{2}{3}\Phi$ | String frame metric conformal factor |
| $\tau$ | Tachyon ($\bar{q}q$ scalar) |
| $\chi = \delta\Phi$ | Dilaton fluctuation |
| $s = \delta\tau$ | Tachyon fluctuation |
| $\psi = \frac{e^{-2A}}{4}\delta g_i^i$ | Scalar part of metric fluctuation |
| $\zeta = \psi - \frac{A'}{\Phi'}\chi$ | Scalar glueballs as $x \to 0$ |
| $\xi = \psi - \frac{A'}{\tau'}s$ | Scalar mesons as $x \to 0$ |

The background and fields are defined in papers by Kiritsis et al. [6, 7]. The specific calculation we follow includes back reaction of the quarks in V-QCD with Potential I [11].

The action for gravity and the dilaton $\Phi$ is

$$S = M^3 N_c^2 \int d^5x \sqrt{-g}[R - \frac{4}{3} g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi + V(\Phi)] \quad (5)$$

The overall setting includes background with a (conformal) gravity metric of the form

$$g_{\mu\nu} = \exp(2A(z))[dz^2 + \eta_{ij}dx^i dx^j] \quad (6)$$

where $\eta_{ij} = \text{diag}(-,+,+,+)$ is the Minkowski metric.

The t' Hooft $\lambda$ coupling is directly related to the dilaton: $\lambda = \exp(\Phi)$.

# strings in the bulk and on the boundary

Z(t,z) string

$$\partial_t \left( e^{2A_s(Z)} \frac{\dot{Z}}{\sqrt{1-\dot{Z}^2}} \right) = \sqrt{1-\dot{Z}^2}\,\partial_z \left( e^{2A_s(Z)} \right)$$

$$A_s(z) = A(z) + \frac{2}{3}\Phi(z)$$

**gravity and antigravity (from dilaton) allows the strings to levitate**

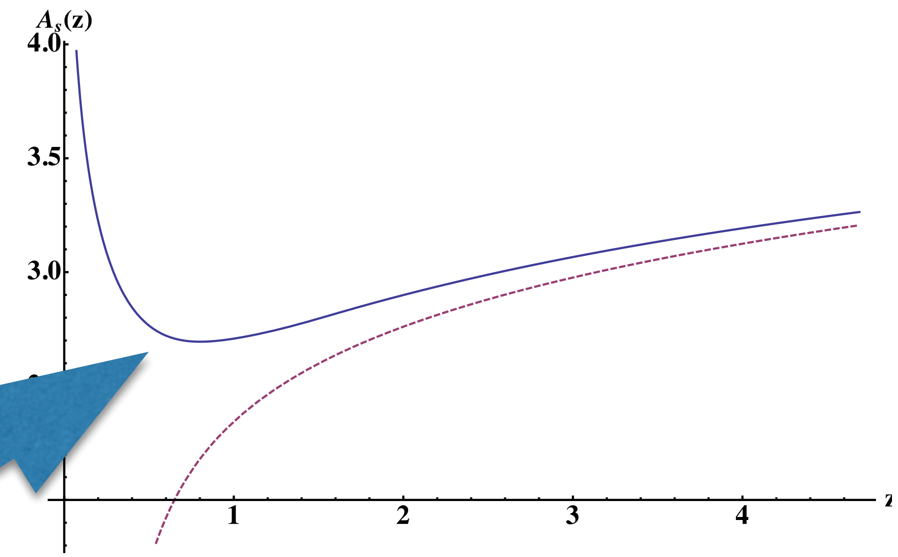



FIG. 2: The combination $A_s(z)$ as a function of the holographic coordinate $z$ (solid) compared to it's IR (large $z$) asymptotics (dashed). It is noticed that $A_s(z)$ has a minimum corresponding to the equilibrium scale of the QCD string.

**A holographic image of a bulk string is the QCD string**
**such model combines advantages of the string theory in 10d with QCD string phenomenology**

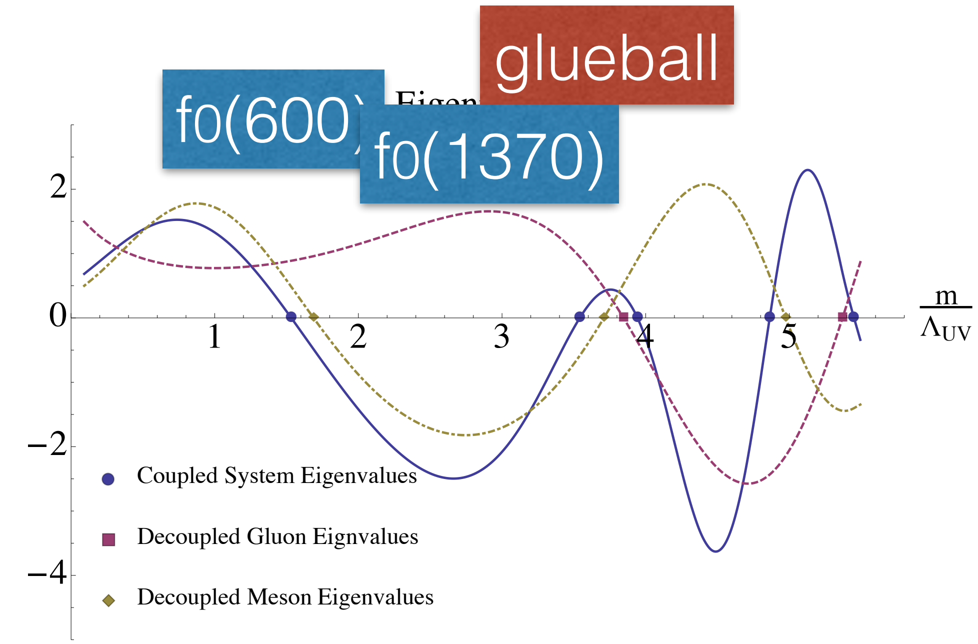
# Hadronic spectroscopy in AdS/QCD in Veneziano limit is needed to get sigma=f(600) and good chiral dynamics

$$N_c, N_f \to \infty \quad N_f/N_c = x = const$$

Next come a close pair of the second and third states, with mass ratios to the first one $m_3/m_1 \approx 2.6$. Since in the calculation the strange quark is as light as $u, d$, there should not be a separate $f_0(1710)$ state, and this pair can be identified with a close pair $f_0(1370), f_0(1500)$; at $x = N_f/N_c = 1$ their splitting is also correct. Different $x$-dependence of the third state from others hints that it is indeed mostly a glueball, but this feature is not robust, as it depends on the details of the potential.

The five lowest masses in units of the UV scale of the model are

$$\frac{m_1}{\Lambda_{UV}} = 1.53\,, \quad \frac{m_2}{\Lambda_{UV}} = 3.54\,, \quad \frac{m_3}{\Lambda_{UV}} = 3.94\,,$$
$$\frac{m_4}{\Lambda_{UV}} = 4.86\,, \quad \frac{m_5}{\Lambda_{UV}} = 5.45 \qquad (17)$$




$m_2 = 1370\,\mathrm{MeV}\,, \quad m_3 = 1525\,\mathrm{MeV}\,,$
$m_4 = 1881\,\mathrm{MeV}\,, \quad m_5 = 2019\,\mathrm{MeV}\,.$

so a QCD string is combination of 2 holograms:
thin, via dilaton (glueballs),
and thick via sigma meson

**the bottom-line is that the model does a very good job even on the most complicated part of hadronic spectroscopy: the 0++scalars and their mixing**

Mixing
as a function
of x=Nf/Nc:

at x=1

the second meson
and the first glueball
cross at x=1.3

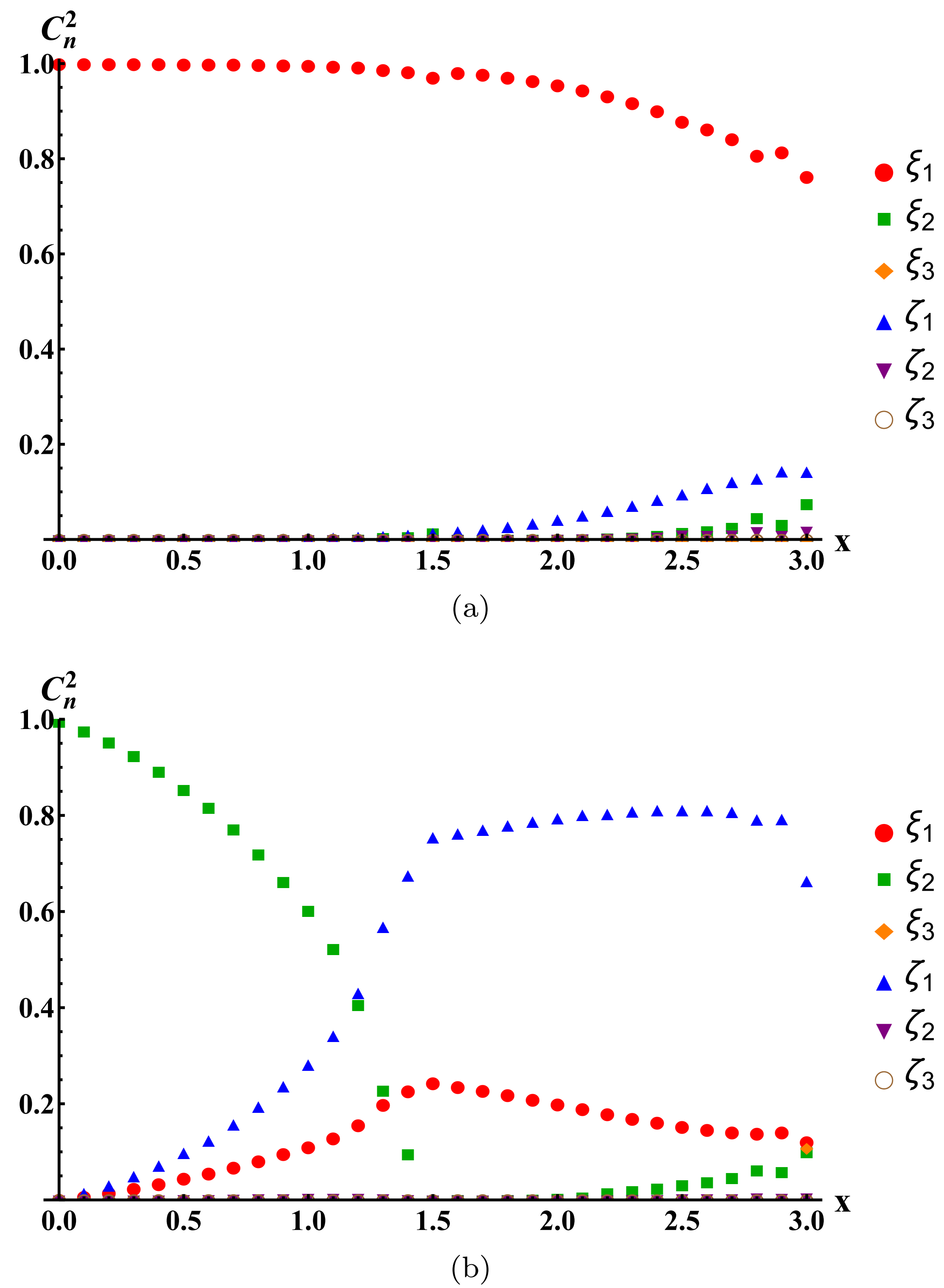
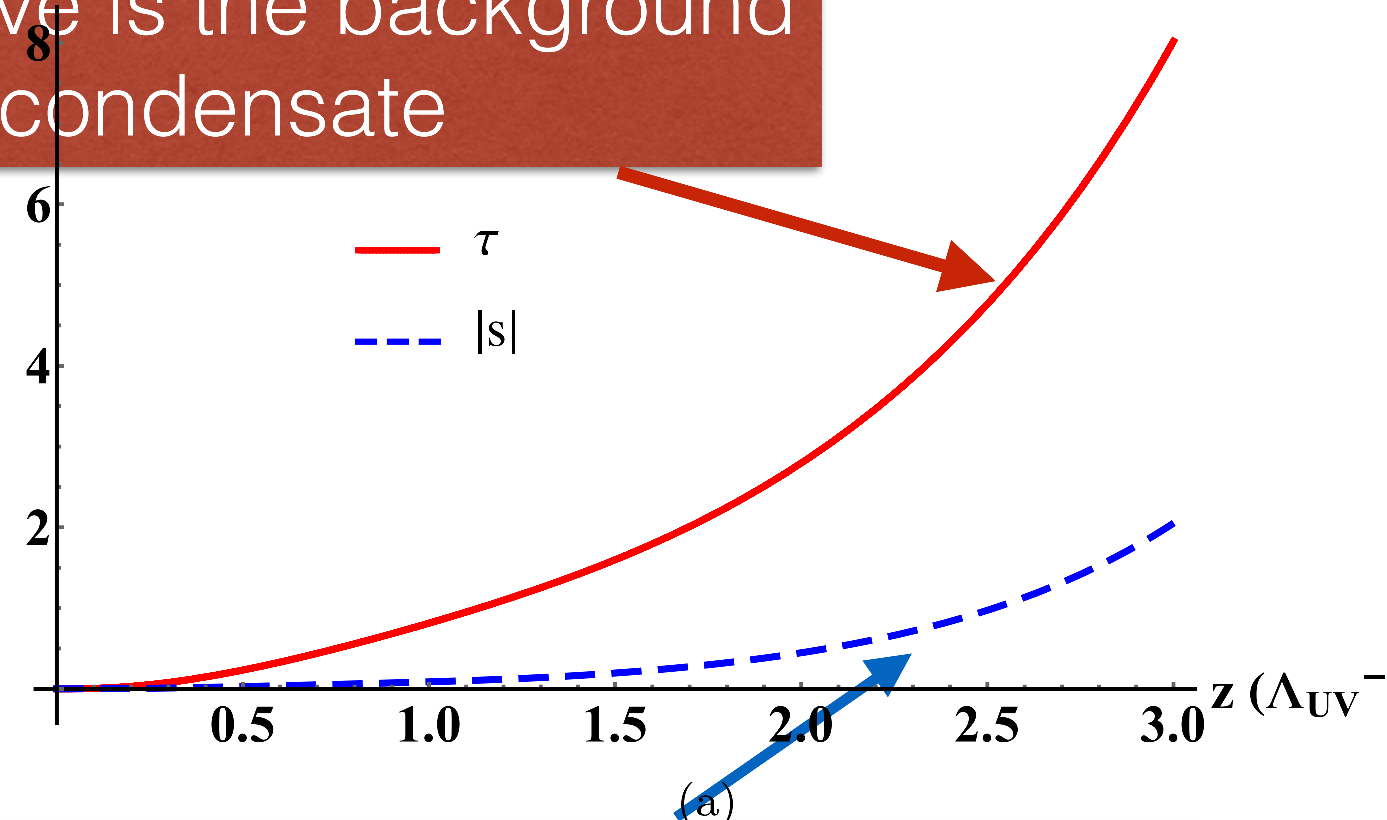



FIG. 5: The square of the decomposition coefficients of the (a) lowest mixed meson state and (b) the lowest mixed glueball state.

# string sigma field negatively affect the quark condensate

red dashed curve is the background quark condensate




Lattice (Iritani et al), need 5-6 strings to do so

blue is (with the opposite sign) the sigma field from 1 string: thus several strings can locally restore chiral symmetry!

**collective effect of multi string configurations**

**backreaction kills the levitation minimum and thus destabilize QCD strings!**

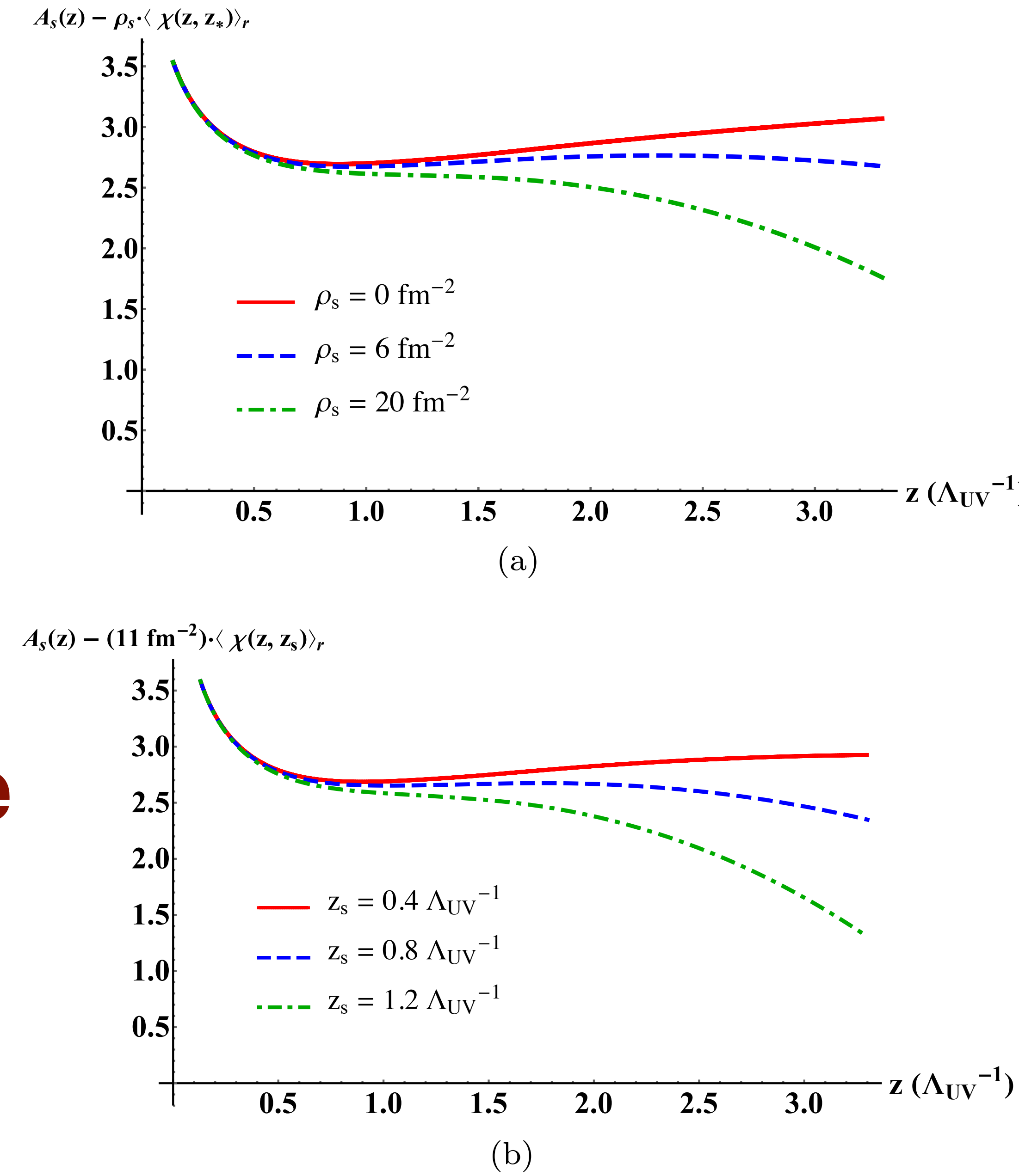



FIG. 8: The background potential, (a) without and with string-induced fluctuations, all placed at the minimum of the $z$ potential ($z_*$) with the denoted transverse density, and (b) induced by strings with density 11 $\mathrm{fm}^{-2}$, all placed at various points in the $z$ coordinate (denoted $z_s$). The $r$ dependence of $\chi$ is averaged out, leaving only the density dependence of the fluctuation.

# High energy collisions and “spaghetti” of multiple strings

# the simplest multi-string state: the spaghetti in pA


**N(strings)=2N(Pomerons)**

**PPP vertices are for now ignored: calculated in the next paper**

**at small multiplicity => dilute, strings are broken independently (the Lund model),**

**What happens when their number grows?**

Collective interaction of QCD strings and early stages of high multiplicity pA collisions
Tigran Kalaydzhyan, Edward Shuryak Phys.Rev. C90 (2014) 014901
arXiv:1404.1888

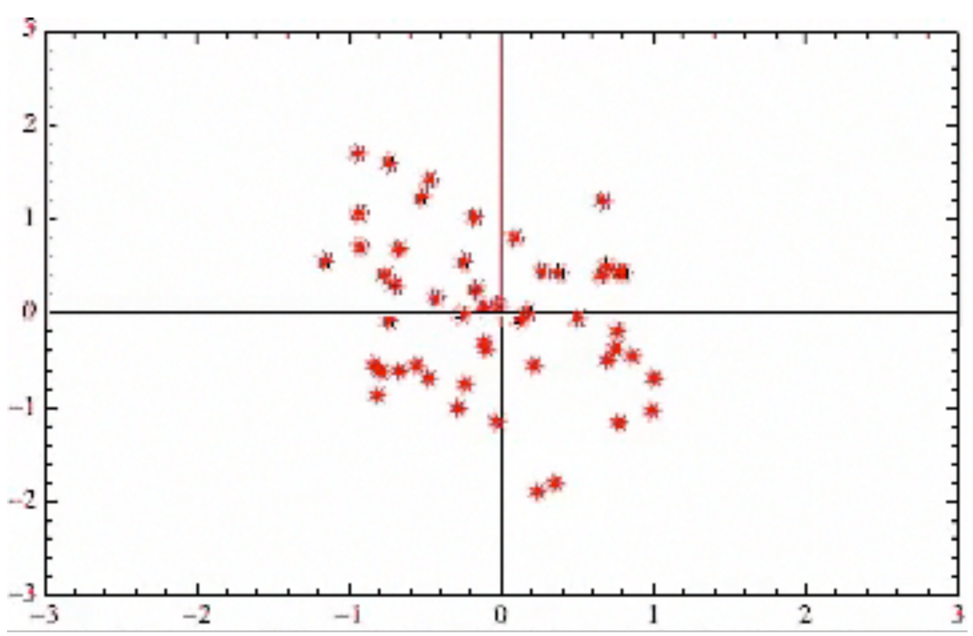
# when density reaches some value a 2d spaghetti collapse takes place

Basically strings can be viewed as a 2-d gas of particles with unit mass and forces between them are given by the derivative of the energy (8) , and so

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\tilde{r}_{ij}}(g_N\sigma_T)m_\sigma 2K_1(m_\sigma\tilde{r}_{ij}) \qquad (19)$$

with $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ and "regularized" $\tilde{r}$ (9).

$$E_{tot} = \sum_i \frac{v_i^2}{2} - 2g_N\sigma_T\sum_{i>j}K_0(m_\sigma r_{ij})$$



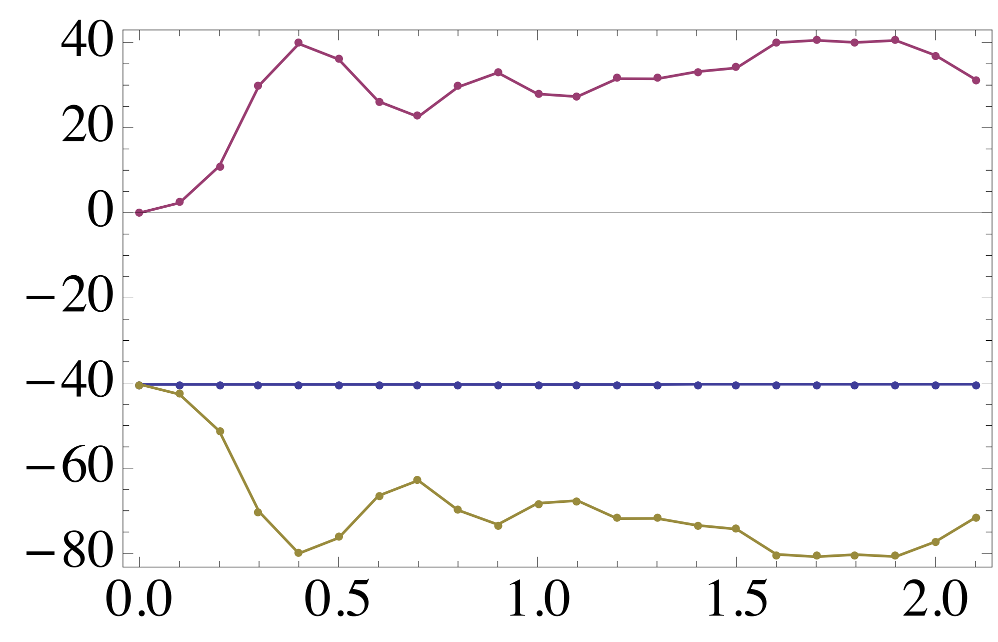




FIG. 4. (Color online) The (dimensionless) kinetic and potential energy of the system (upper and lower curves) for the same example as shown in Fig. 6, as a function of time $t$(fm). The horizontal line with dots is their sum, namely $E_{tot}$, which is conserved.

# collective sigma field

## before and after collapse

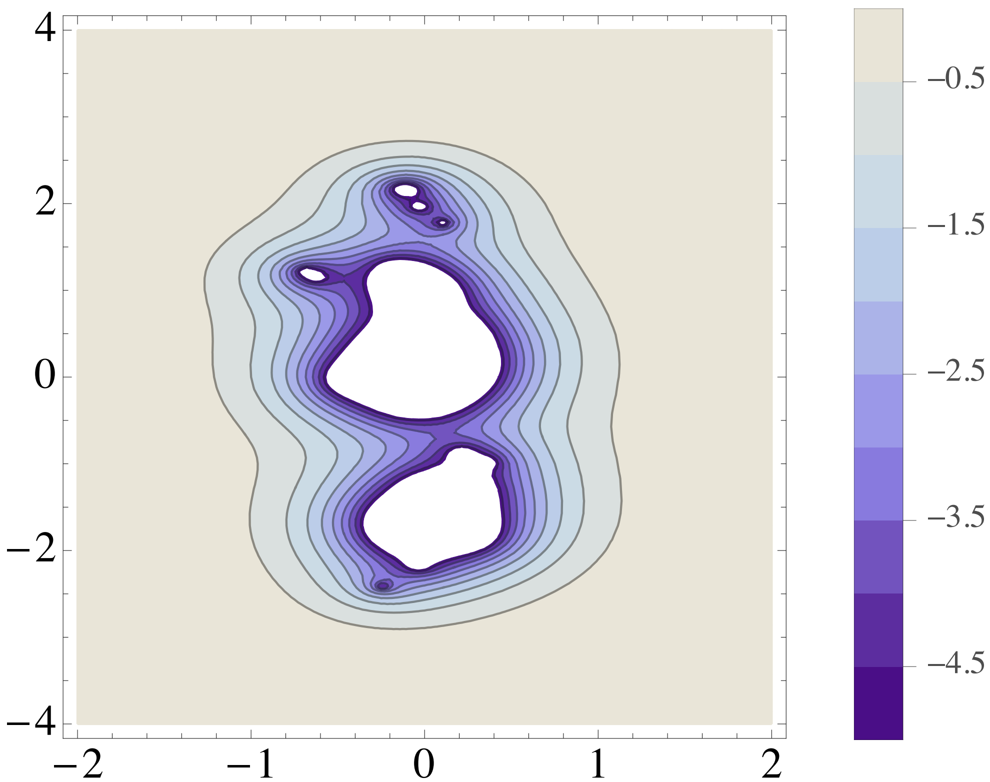



FIG. 10: Instantaneous collective potential in units $2g_N\sigma_T$ for an $AA$ configuration with $b = 11\,\mathrm{fm}$, $g_N\sigma_T = 0.2$, $N_s = 50$ at the moment of time $\tau = 1\,\mathrm{fm}/c$. White regions correspond to the chirally restored phase.

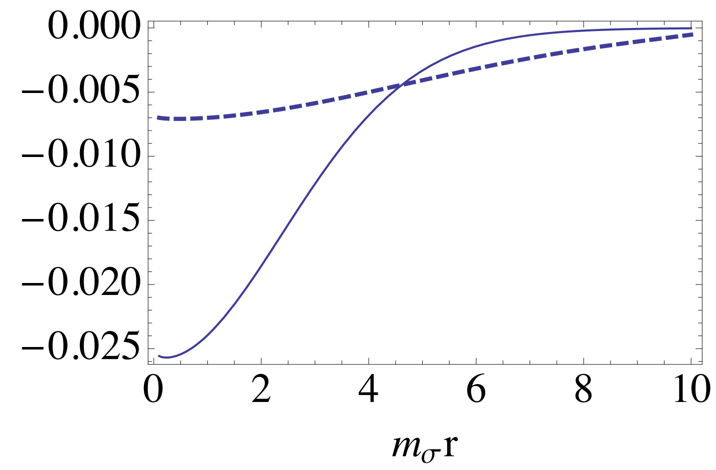
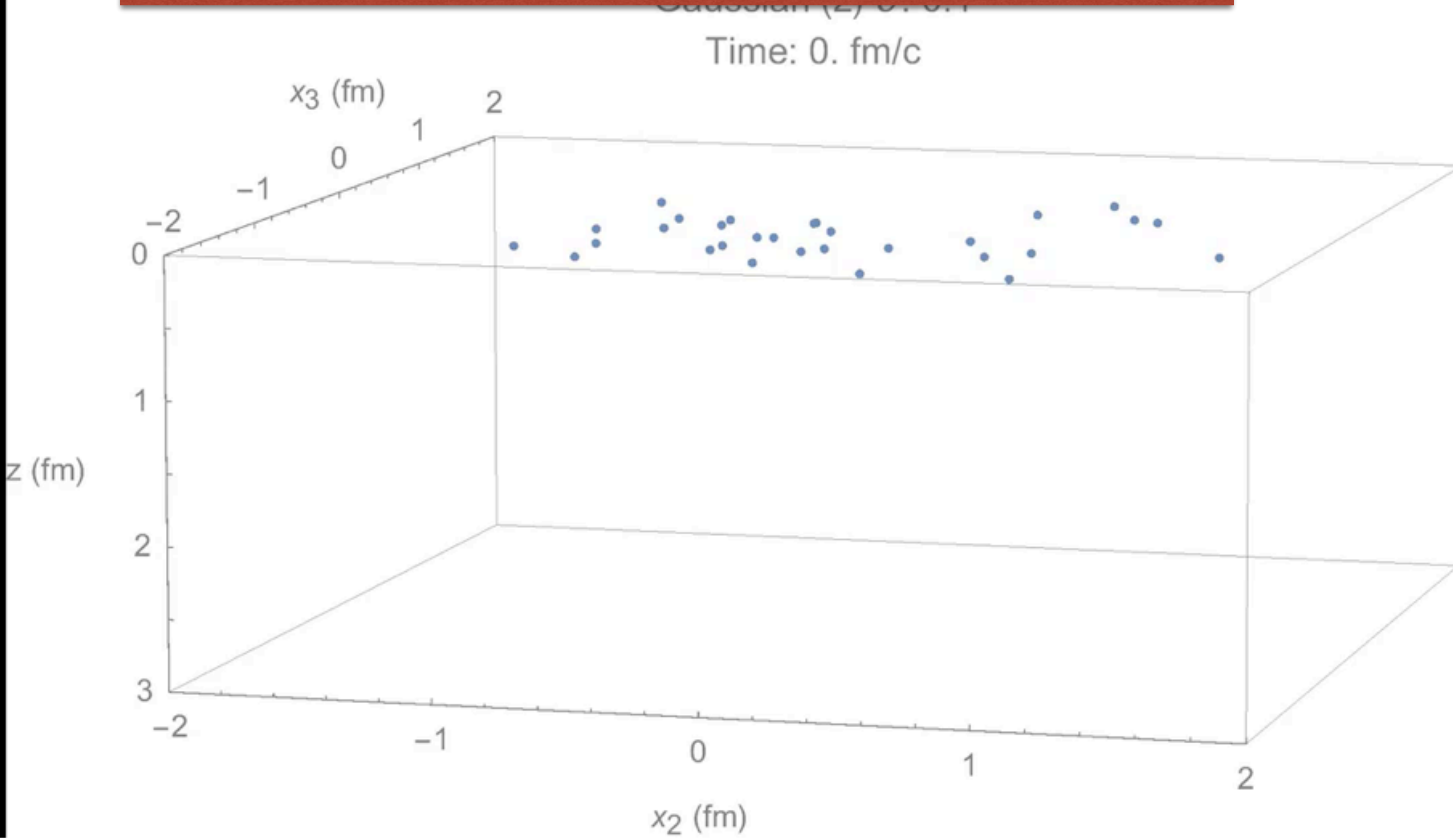



FIG. 4: The mean field (normalized as explained in the text) versus the transverse radius in units of inverse $m_\sigma$. The dashed and solid curves correspond to the source radii $R = 1.5$ and $0.7\,\mathrm{fm}$, respectively.

Field gradient at the edge leads to quark pair production: QCD analog of Hawking radiation

: arXiv:1503.04759

**Holographic model tells even more interesting story: strings are attracted but also get destabilized and explode themselves**



# summary

- transitions from low density (confining, QCD string) phase to high density (QGP, Glasma) phase happen sharply, not only as a function of T. It is easier to understand them from stringy side, as they have dimesionful parameters
- holographic Pomeron — 2 string production —can be described by Euclidean tunneling in effective string theory
- at LHC energies effective string temperature reaches the Hagedorn domain, in which they get strongly excited => transition from stringy (confined) do pQCD (deconfined) regime has a jump reminiscent of the thermal (pure gauge) transition. It is seen in the Pomeron profile
- lattice and holographic models both predict a "sigma cloud" around strings, creating quite weak attraction at large distances.
- moving from peripheral to central pA collisions one finds multi string "spaghetti", up to 40 or so strings. Collective collapse and even individual string explosion predicted => QGP and hydro explosion follow (as observed)

# The string balls

# fundamental string balls

A string ball can be naively generated by a "random walk" process, of $M/M_s$ steps, where $M_s \sim 1/\sqrt{\alpha'}$ is the typical mass of a straight string segment. If so, the string entropy scales as the number of segments

$$S_{ball} \sim M/M_s \tag{1}$$

$$\frac{R_{ball,r.w.}}{l_s} \sim \sqrt{M}$$

The Schwarzschild radius of a black hole in $d$ spatial dimensions is

$$R_{BH} \sim (M)^{\frac{1}{(d-2)}} \tag{2}$$

and the Bekenstein entropy

$$S_{BH} \sim Area \sim M^{\frac{d-1}{d-2}} \tag{3}$$

Can be matched for one M only => critical string ball
its Hawking T is the Hagedorn $T_H$

Damour and Veneziano

entropy of a self-interacting string ball of radius $R$ and mass $M$,

$$S(M,R) \sim M\left(1-\frac{1}{R^2}\right)\left(1-\frac{R^2}{M^2}\right)\left(1+\frac{g^2M}{R^{d-2}}\right) \tag{5}$$

where all numerical constants are for brevity suppressed and all dimensional quantities are in string units given

**even for a very small g,**
**the importance of the last term depends not on g but on $g^2M$. So, very massive balls can be influenced by a very weak gravity (what, indeed, happens with planets and stars)**

# Our lattice model for string balls

$$Z \sim \int \mathrm{d}L \exp\left[\frac{L}{a}\ln(2d-1) - \frac{\sigma_T L}{T}\right], \quad (18)$$

and hence the Hagedorn divergence happens at

$$T_H = \frac{\sigma_T a}{\ln(2d-1)}. \quad (19)$$

Setting $T_H = 0.30\,\mathrm{GeV}$, according to the lattice data mentioned above and the string tension, we fix the 3-dimensional spacing to be

$$a_3 = 2.73\,\mathrm{GeV}^{-1} \approx 0.54\,\mathrm{fm}. \quad (20)$$

$$E_{plaquette} = 4\sigma_T a \approx 1.9\,\mathrm{GeV}\,, \quad (21)$$

is amusingly in the ballpark of the lowest glueball masses of QCD. (For completeness: the lowest "meson" is one link or mass 0.5 GeV, and the lowest "baryon" is three links – 1.5 GeV of string energy – plus that of the "baryon junction".)

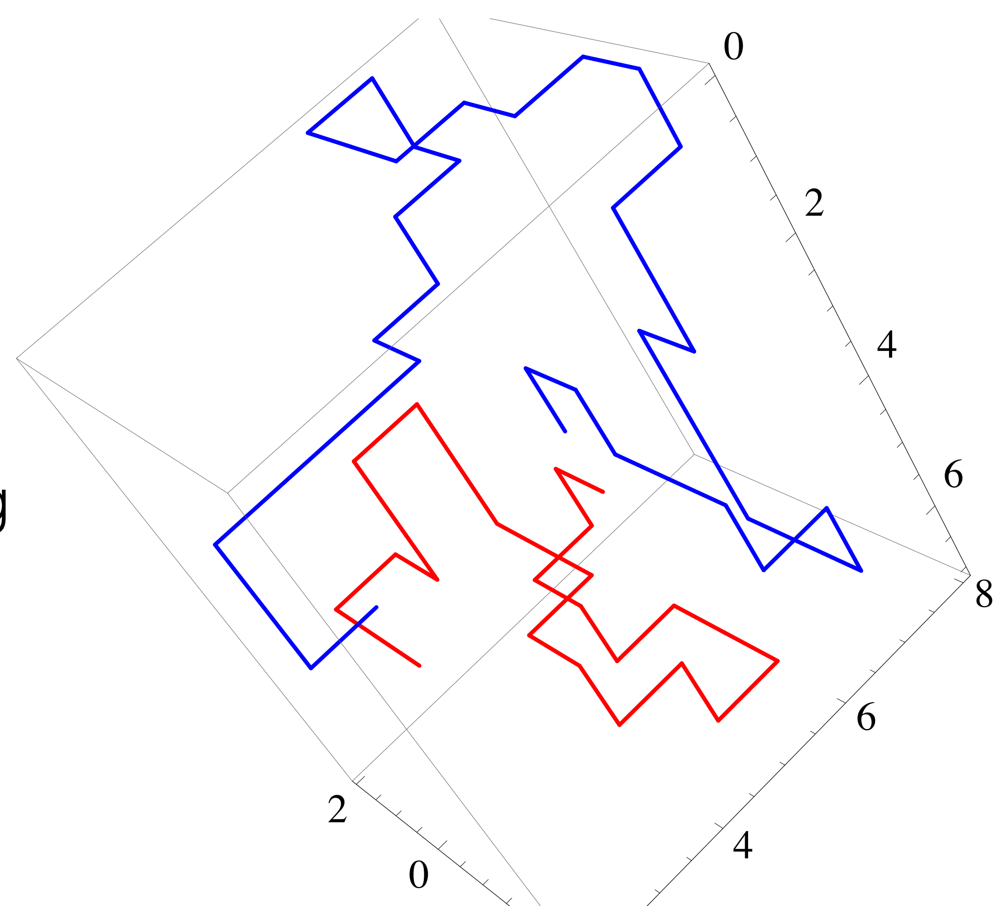
The most compact (volume-filling or Hamiltonian) string wrapping visits each site of the lattice. If the string is closed, then the number of occupied links is the same as the number of occupied sites. Since in $d = 3$ each site is shared among 8 neighboring cubes, there is effectively only one occupied link per unit cube, and this wrapping produces the maximal energy density,

$$\frac{\epsilon_{max}}{T_c^4} = \frac{\sigma_T a}{a^3 T_c^4} \approx 4.4 \quad (22)$$

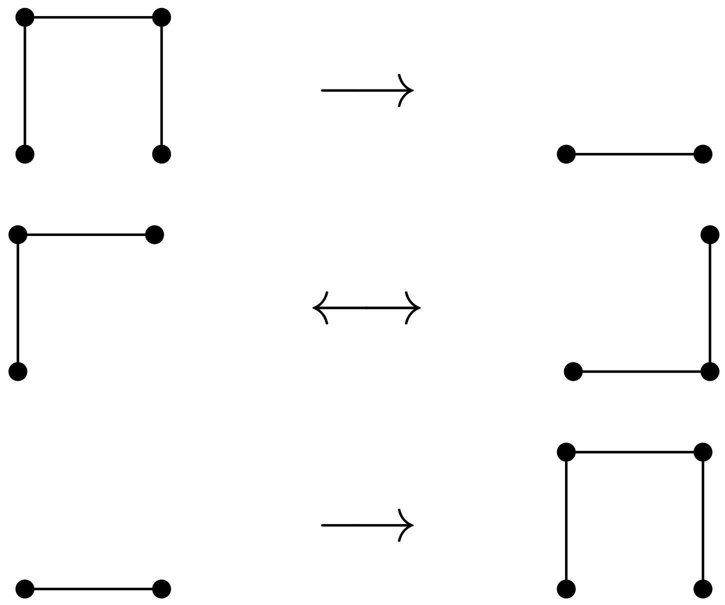
(we normalized it to a power of $T_c$, the highest temperature of the hadronic phase). It is instructive to compare it to the energy density of the gluonic plasma, for which we use the free Stefan-Boltzmann value

$$\frac{\epsilon_{gluons}}{T^4} = (N_c^2 - 1)\frac{\pi^2}{15} \approx 5.26 \quad (23)$$

Example of non-interacting strings



# Self-interacting string balls



Metropolis algorithm, updates,
T(x) instead of a box
Yukawa self-interaction

**we observe a new regime: the**

**entropy-rich self-balanced string balls**

**separated by 2 phase transitions**

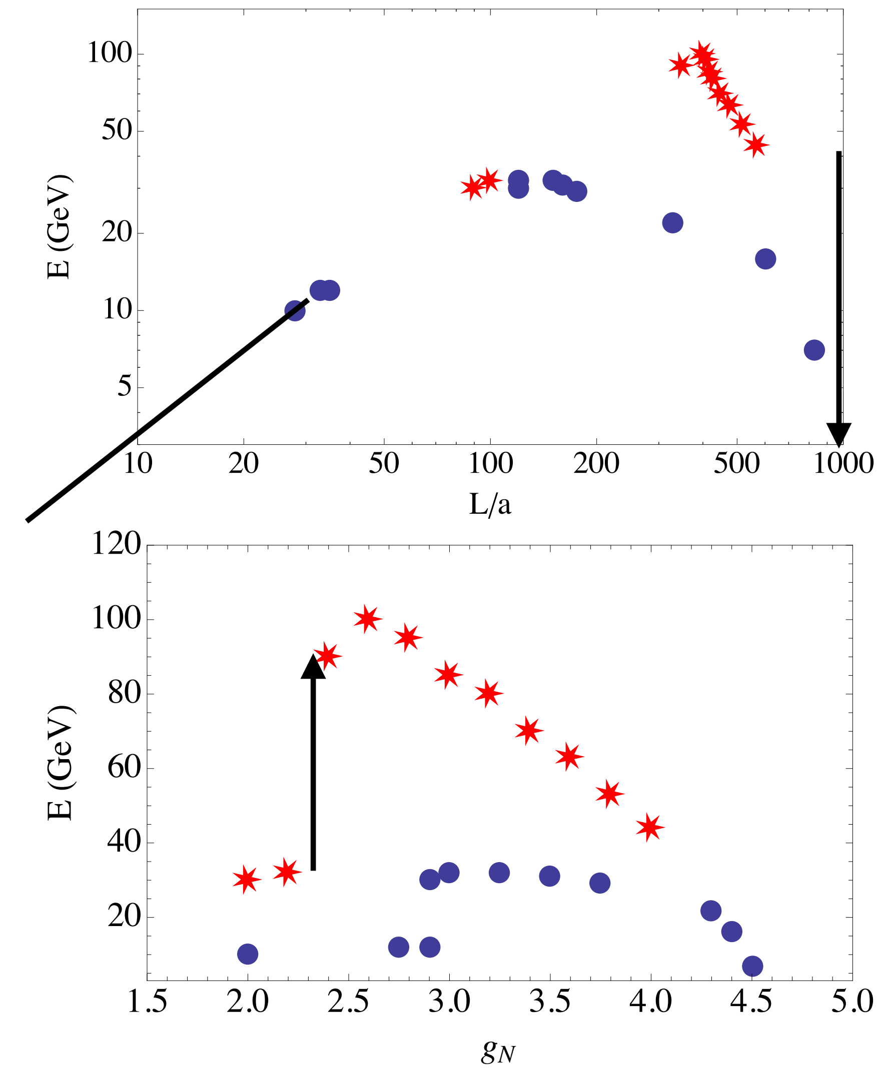



FIG. 7: Upper plot: The energy of the cluster $E\,(\mathrm{GeV})$ versus the length of the string $L/a$. Lower plot: The energy of the cluster $E\,(\mathrm{GeV})$ versus the "Newton coupling" $g_N\,(\mathrm{GeV}^{-2})$. Points show the results of the simulations in setting $T_0 = 1\,\mathrm{GeV}$ and size of the ball $s_T = 1.5a, 2a$, for circles and stars, respectively.

$\frac{\hat{q}}{s} \approx const$ ?

# Jet quenching during the mixed phase

It has however been pointed out long ago [24] that large experimental values of $v_2$ are difficult to explain by any simple model of quenching, in particular, they were in a strong contradiction with the simplest assumption (30). One possible solution to this puzzle has been suggested few years ago in Ref. [6]: the $v_2$ data can be reproduced, if $\hat{q}$ is significantly enhanced in the mixed phase. More

Here we want to point out that a natural explanation for the enhanced $\hat{q}$ in the mixed phase can be provided by the strings. As far as we know, the "kicks" induced by the color electric field inside the QCD strings has been ignored in all jet quenching phenomenology: only the fields of "charges" (quarks and gluons in QGP, hadrons alternatively) were included, in the spherical Debye approxima-

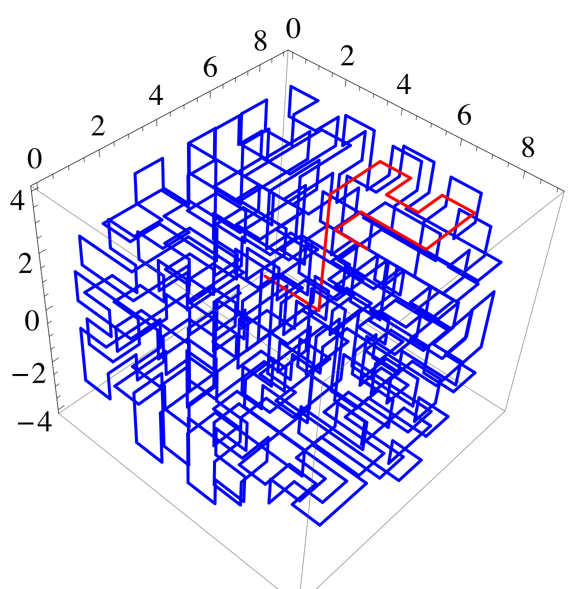
$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2\rangle}{\mathrm{d}l} \,, \qquad \langle p_\perp^2\rangle \approx (gEr_s)^2 \,, \qquad E(x) = \frac{\Phi_e}{2\pi r_s^2} K_0(x/r_s)$$

the string radius $r_s = 1/(1.3\mathrm{GeV}) = 0.15\,\mathrm{fm}$.

$$\hat{q} \approx \frac{16}{3}\alpha_s\sigma_T\frac{\bar{L}r_s}{\mathrm{fm}^3} \,.$$

string length inside 1 fm^3

$$\hat{q}_{min} = 0.028, \qquad \hat{q}_{max} = 0.10 \left(\frac{\mathrm{GeV}^2}{\mathrm{fm}}\right) .$$




across the mixed phase, to be compared with values by the Jet coll. at Tc $\hat{q}_{min} = 0.025, \qquad \hat{q}_{max} = 0.15 \left(\frac{\mathrm{GeV}^2}{\mathrm{fm}}\right)$

**But in high entropy self-supporting balls it can be up to one order of magnitude larger!**