PA C I F I C

many features of the world are not - as we've heard on this workshop - exPlAined by the Current Idea of the Fundamental InteraCtions - the "Standard Model" of particle physics

to this end, in the past 30+ years, theorists have come up with a multitude of so-called "Beyond the Standard Model" scenarios, which have raised many questions:

for example:

is “the Higgs” a fundamental scalar field?

is it a composite object?

is strongly-coupled dynamics involved?

is there supersymmetry?

is the theory “natural”?

...

(dark matter, CP, baryogenesis, inflation)

...

time has now come to pay the piper...

What will the LHC discover?

resonaances.blogspot.com

Blogger Jester says:

Higgs boson.
...
Non-SM Higgs boson.
...
New Beyond SM Particles.
...
Strong Interactions.
...
Dark matter.
...
Little Higgs and friends.
...
Supersymmetry.
...
Dragons.
...
Black Holes.

What will the LHC discover?

resonaances.blogspot.com

Blogger Jester says:

Here are my expectations.
The probabilities were computed using all currently available data and elaborated Bayesian statistics.

Higgs boson. Probability 80%

...

Non-SM Higgs boson. Probability 50%

...

New Beyond SM Particles. Probability 50%

...

Strong Interactions. Probability 20%

...

Dark matter. Probability 5%

...

Little Higgs and friends. Probability 1%

...

Supersymmetry. Probability 0.1%

...

Dragons. Probability $e^{-S_{dragon}}$

...

Black Holes. Probability $0.1 * e^{-S_{dragon}}$ ...

What will the LHC discover?

My purpose here is not to discuss "scenarios"
aka "model-building" - a separate and very long subject

just offer a few remarks:

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Supersymmetry.
...

we have come up with many scenarios

it is not clear which (if any) of these scenarios are true

weakly-coupled scenarios generally suffer from fine-tuning problems

e.g., $\frac{M_Z^2}{2} \sim 4{,}050 \;=\; 1{,}924{,}050 \;-\; 1{,}920{,}000 \quad (\mathrm{GeV}^2)$

strong-coupling ideas are plagued by our inability to calculate

It is important to understand the signatures of the various scenarios and the discovery potential at the LHC [much work, understandably so!].

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strong-coupling ideas are plagued by our inability to calculate

It is also of interest to understand the "theory space" involved [less work...].
My focus will be on this...

What will the LHC discover?

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Non-SM Higgs boson.
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Supersymmetry.
...

In all "scenarios" for "Beyond the Standard Model" physics, new gauge dynamics is invoked, at some scale.

...unless "supersplit supersymmetry" turns out to be nature's choice...

When the weak force is turned off, these gauge theories can be "chiral" (L-R asymmetric) or "vectorlike".

What is the "theory space" involved? How well do we understand the dynamics? Is there any progress we can make, without using numerics or assuming extensive amount of supersymmetry? *(Is it "useful" progress?...)*

P A C I F I C 2 0 1 1

Moorea, French Polynesia

Deformations, topological molecules, and (de)confinement

Erich Poppitz UofToronto

with Mithat Ünsal SLAC/Stanford (2008–present)

and Mohamed Anber, Toronto (2011)

also based on works of Unsal w/ Shifman, Simic, Yaffe 2007-2010,
and inspired by earlier work of others, to be mentioned as time goes on

What I will talk about applies to the entire “gauge theory space”, as described below...

“gauge theory space” conventional wisdom:

pure YM - “formal” but see www.claymath.org/millennium/

Yang–Mills Existence and Mass Gap. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [45, 35].

[45] R. Streater and A. Wightman, *PCT, Spin and Statistics and all That*, W. A. Benjamin, New York, 1964.

[35] K. Osterwalder and R. Schrader, *Axioms for Euclidean Green's functions*, Comm. Math. Phys. **31** (1973), 83–112, and Comm. Math. Phys. **42** (1975), 281–305.

“gauge theory space”   conventional wisdom:

pure YM - “formal” but see www.claymath.org/millennium/

SUSY - very “friendly” to theorists
beautiful - exact results

gauge theories with boson–fermion degeneracy: new spacetime symmetry

“applications”:
superpartner masses; supersymmetry breaking in chiral SUSY theories or metastable vacua in vectorlike theories; SUSY compositeness, flavor...

I believe that one of the most important “applications” of supersymmetry is to teach us about the many strange things gauge field theories could do - often very much unlike QCD:

- massless monopole/dyon condensation-confinement and chiral symmetry breaking
- “magnetic free phases” - dynamically generated gauge fields and fermions
- chiral-nonchiral dualities
- last but not least: gauge-string duality made concrete - AdS/CFT!

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QCD-like (vectorlike) - hard, leave it to lattice folks
but (m, a, V, $)

gauge theories with varying number of massless vectorlike fermions

“applications”:
W-, Z-boson masses: “walking” (or “conformal”) technicolor
“unparticles”

– upon increasing the number of fermion “flavors” believed to become conformal
– large current lattice effort to determine phase diagram (proves to be not easy!)

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non-SUSY chiral gauge theories - poorly understood strong dynamics
...almost nobody talks about them anymore

massless fermions with L/R asymmetric coupling

“applications”: extended technicolor: fermion mass generation; quark and lepton compositeness; speculations on W, Z, t masses by monopole condensation

- non-QCD-like behavior, e.g. “confinement without chiral symmetry breaking”: massless composite fermions (probably true)
- ”tumbling” - dynamical generation of different scales (no idea if true... after 30 years!)

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moral:

We don’t know that much about generic non-supersymmetric gauge dynamics.

Nature’s analogue computer is not (yet) available and the theory tools are limited:

“gauge theory space”

nonperturbative tools:

SUSY

- ‘t Hooft anomaly matching
- “power of holomorphy”
- mass and flat direction “deformations”
- semiclassical expansions
- strings/branes
- gauge-string dualities

QCD-like (vectorlike)

- lattice
- the others mentioned already for QCD (EFT...)
- semiclassical expansions

non-SUSY chiral theories

- ‘t Hooft anomaly matching
- semiclassical expansions

“classic”:
- “MAC” (most attractive channel)
- truncated Schwinger-Dyson equations

“postmodern”:
- postulated thermal inequality
- AdS/QCD
- postulated beta functions
- extrapolating semiclassical results outside region of validity

...

“gauge theory space”

nonperturbative tools:

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QCD-like (vectorlike)

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- the others mentioned already for QCD (EFT...)
- semiclassical expansions

non-SUSY chiral theories

- ‘t Hooft anomaly matching
- semiclassical expansions

tools one trusts

tools you don’t really trust - unless confirmed by experiment or the tools on the left

“voodoo QCD”

[Intriligator]

“classic”:
- “MAC” (most attractive channel)
- truncated Schwinger-Dyson equations

“postmodern”:
- postulated thermal inequality
- AdS/QCD
- postulated beta functions
- extrapolating semiclassical results outside region of validity

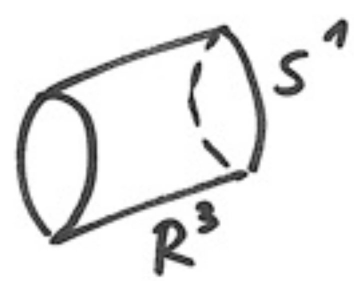
...

In the remaining time, I will describe a development, which is:

- relatively recent, having shown some unexpected features
- gives another example of ideas borrowed from strings/SUSY, which usefully apply to more general situations!
- finally, all of this turns out to be quite theoretically elegant...

The general theme is about inferring properties of infinite-volume theory by studying (arbitrarily) small-volume dynamics.

The small volume may be



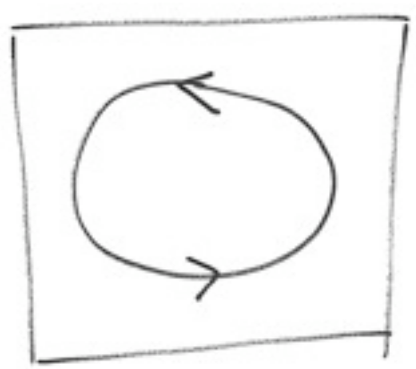
or

of characteristic size “L”

some history:

Eguchi and Kawai (1982) showed that "loop eqns" (=the infinite set of Schwinger-Dyson eqns) for Wilson loops in pure Yang-Mills theory are identical in small-V and infinite-V theory, to leading order in 1/N, **provided**:

- "center-symmetry" unbroken
- translational symmetry unbroken (see Yaffe, 1982)



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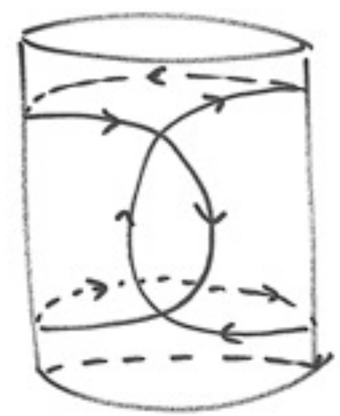


+ O(1/N) **provided**

topological nontrivial (winding) Wilson loops have vanishing expectation value (= unbroken center)

expectation value of any Wilson loop at infinite-L

expectation value of (folded) Wilson loop at small-L

"EK reduction" **"large-N reduction"** **"large-N volume-independence"**

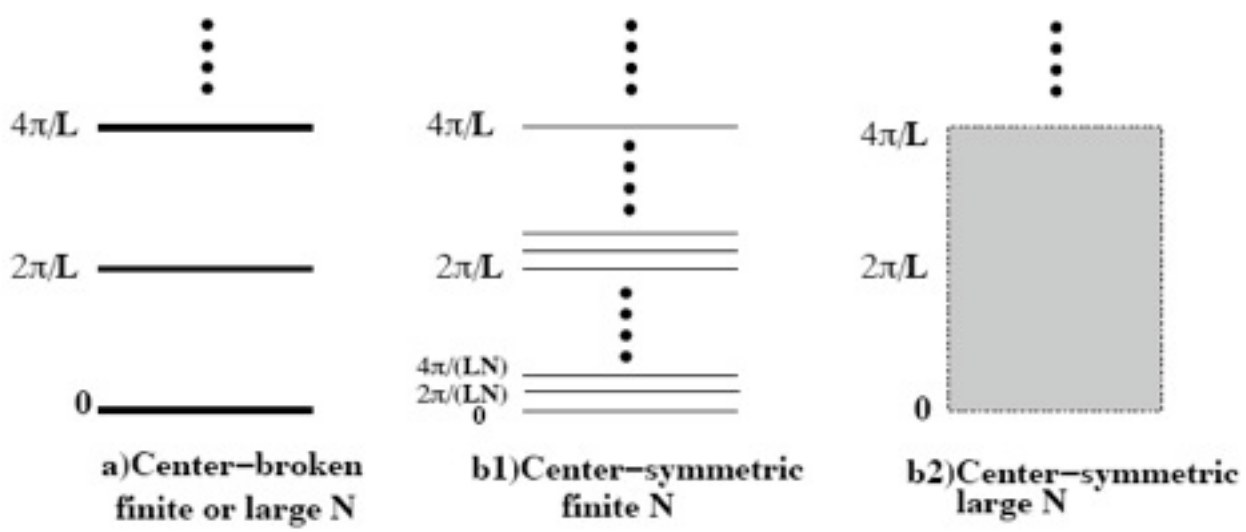
- one of the few exact results in QFT (albeit not widely known yet, for a reason, see below)

If it can be made to work, **potentially exciting**, for:

1) **simulations may be cheaper** (use single-site lattice?)
2) **raises theorist's hopes** (that small-L, single-site, easier to solve?)

Some intuition of how EK reduction - valid at any coupling - works:

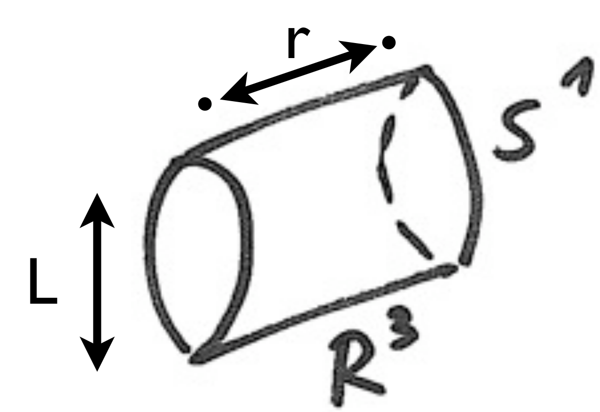
in perturbation theory:
from spectra (& Feynman graphs)
in appropriate backgrounds



effective space size = L N - so even L=1 OK if large N

at strong coupling:
gravity dual of N=4 SYM - a conformal field theory - Wilson loops, appropriate correlators - insensitive to box **if** center-symmetric

V(r) ~ 1/r : CFT result obtains
in center-symmetric vacuum
for any r (<L or >L)
insensitive to box size



Unsal, EP 2010

the "modern" point of view on EK reduction/large-N orbifold equivalence is that of a volume reducing orbifold *(e.g., orbifold by translations)*

Kovtun, Unsal, Yaffe (2004)

Essentially, VEVs and correlators of operators that are center-neutral and carry momenta quantized in units of 1/L (in compact direction) are the same on, say  as in infinite-L theory in the large-N limit.

calculating vevs (symmetry breaking, phase structure)

- OK, even if all dimensions small

calculating spectra (for generic theories/reps no Gross-Kitazawa trick)

- need at least one large dimension

"EK reduction" **"large-N reduction"** **"large-N volume-independence"**

- one of the few exact results in QFT (albeit not widely known yet, for a reason, see below)

However, Bhanot, Heller, Neuberger (1982) noticed immediate problem

- center symmetry breaks for $L < L_c$ remedies: e.g., Gonzales-Arroyo, Okawa (1982) - TEK... + others later argued to have problems

Recently realized remedy, allowing reduction to arbitrarily small L (single-site)

Unsal, Yaffe (2007)

if adjoint fermions (more than one Weyl) - no center breaking, so reduction holds at all L

double-trace deformations (deform theory to prevent center breaking; deformation "drops out" of loop equations at infinite-N)

used for current lattice studies of "minimal walking technicolor" (Sannino)

is 4 (...3,5...) Weyl adjoint theory conformal or not?

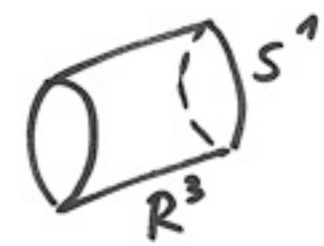
small-L(=1) large-N simulations (2009-)
Hietanen-Narayanan; Bringoltz-Sharpe; Catterall et al

small-N large-L simulations (2007-)
Catterall et al; del Debbio et al; Hietanen et al...

(many issues to still be resolved... including who wins!)

other uses are in lattice supersymmetry and numerical studies of AdS/CFT...

theoretical studies



Unsal;
Unsal-Yaffe;
Unsal-Shifman;
Unsal-EP 2007-9

fix-N, take L-small - semiclassical studies of confinement in center symmetric vacuum- Polyakov's 3d mechanism works also in a locally 4d theory - now due to novel strange (nonselfdual) topological excitations, whose nature depends on fermion content (vectorlike or chiral)

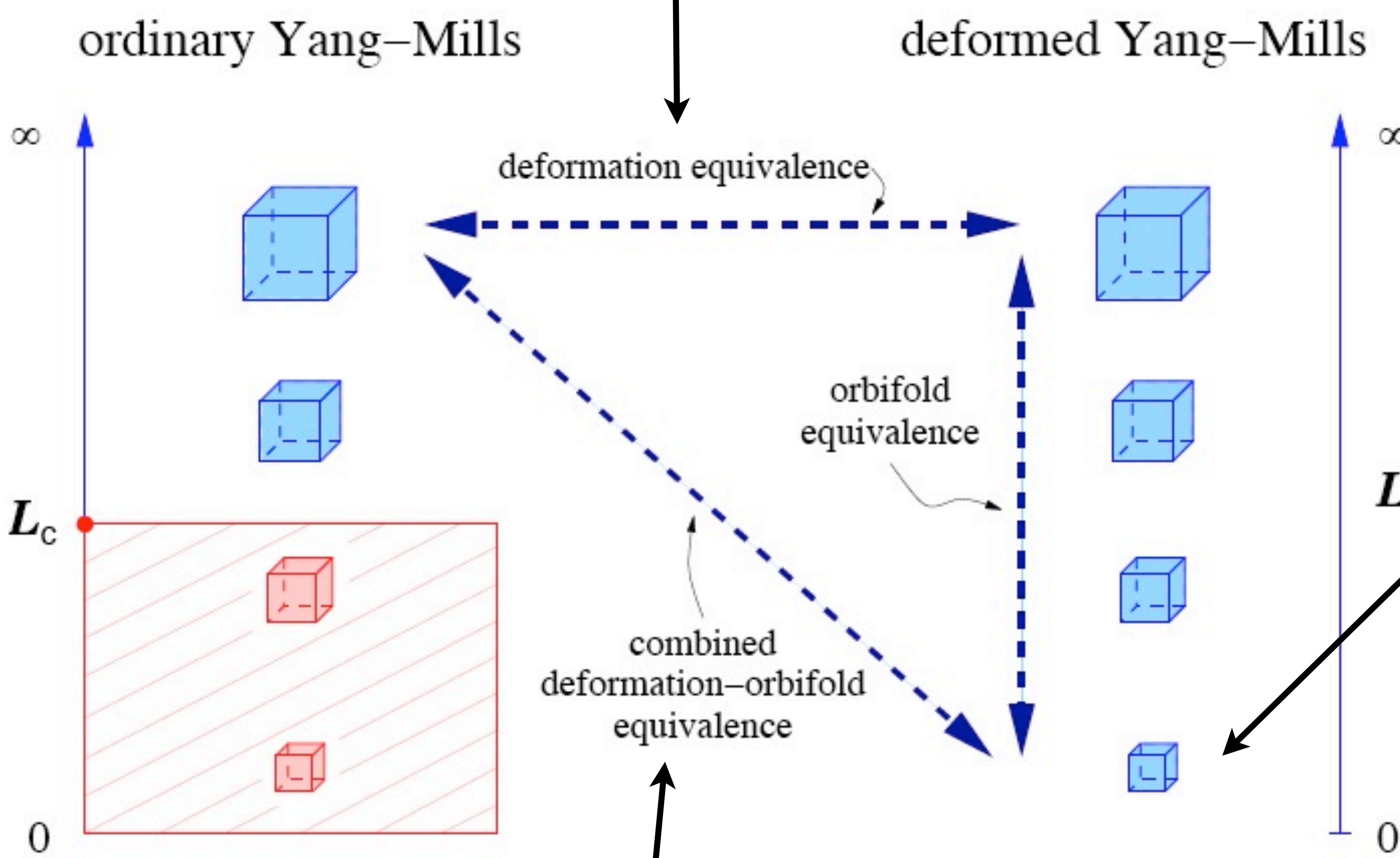
a complementary regime to that of volume independence - a (calculable!) shadow of the dynamics of the 4 dimensional "real thing"

one motivational slide with theoretical dreams for small-L large-N

not the regime I will discuss further, because:

- ***currently numerically explored on lattice***
- ***analytic approaches at large-N, small-L, any g need new ideas...*** ***(ambitious task: equivalent to solving!)***

use large−N “deformation equivalence” to avoid center breaking



with generic fermion representations phase transition, breaks center

now use volume−independence (valid to L=1)

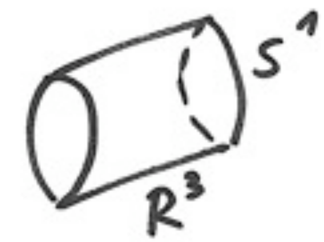
by commutativity of diagram, learn about the large-N theory you started with

instead, describe developments where controlled theoretical studies are possible and yield quite a pretty picture **- study fixed-N, small-L instead:**

double-trace deformations (deform theory to prevent center breaking; deformation "drops out" of loop equations at infinite-N)

if adjoint fermions (more than one Weyl) - no center breaking transition at small L

theoretical studies



Unsal;
Unsal-Yaffe;
Unsal-Shifman;
Unsal-EP 2007-9

fix-N, take L-small - **semiclassical studies of confinement in center symmetric vacuum-** Polyakov's 3d mechanism works also in a locally 4d theory - now due to novel strange (nonselfdual) topological excitations, whose nature depends on fermion content (vectorlike or chiral)

These studies provides a complementary regime to that of volume independence - give a (calculable!) shadow of the dynamics of the 4 dimensional "real thing"...

For this talk enough to consider 4d SU(2) theories

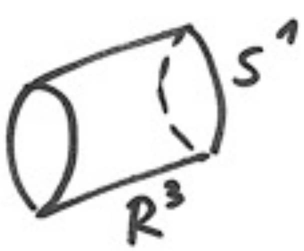
with N_W = multiple adjoints ***Weyl fermions***

"applications":

N_W=1 is N=1 SUSY YM ~ Seiberg-Witten theory with soft-breaking mass

N_W=4
- "minimal walking technicolor"
- happens to be N=4 SYM without the scalars

N_W=5.5 asymptotic freedom lost



MAIN CLAIMS:

In 4d theories with periodic adjoint fermions, for small-L, dynamics *of confinement, mass gap, chiral symmetry...* ***is semiclassically calculable.***

Polyakov's 3d mechanism of confinement by "Debye screening" in the monopole-anti-monopole plasma extends to locally 4d theories.

However, the "Debye screening" is now due to composite objects, the "magnetic bions", ***which only exist at L>0.***

In 4d theories with periodic adjoint fermions, for small-L, confining dynamics is semiclassically calculable.

$$S^1 : \quad x^4 \sim x^4 + L$$

A_4 is now an adjoint 3d scalar Higgs field $\quad \partial_4 + A_4 \longrightarrow \frac{2\pi n}{L} + A_4$

but it is a bit unusual -
a compact Higgs field: $\quad \langle A_4 \rangle \sim \langle A_4 \rangle + \frac{2\pi}{L}$

such shifts of A_4 vev absorbed into shift of KK number "n" $\quad A_4 \to A_4 + \partial_4\left(\frac{2\pi x_4}{L}\right)$

"large" gauge transform

thus, natural
scale of "Higgs vev" is $\quad \langle A_4 \rangle \sim \frac{\pi}{L} \quad$ leading to

$$SU(2) \xrightarrow{\frac{1}{L}} U(1)$$

hence, semiclassical if L << inverse strong scale

exactly this happens in theories with more than one periodic Weyl adjoints

follows from two things, without calculation:

1.) existence of deconfinement transition in pure YM and 2.) supersymmetry

in pure YM, at small L (high-T), Veff min at A_4=0 & max at pi/L (Gross,Pisarsky,Yaffe 1980s)

in SUSY Veff=0, so one Weyl fermion contributes the negative of gauge boson Veff

Q.E.D.

Polyakov's 3d mechanism of confinement by "Debye screening" in the monopole-anti-monopole plasma extends to (locally) 4d theories.

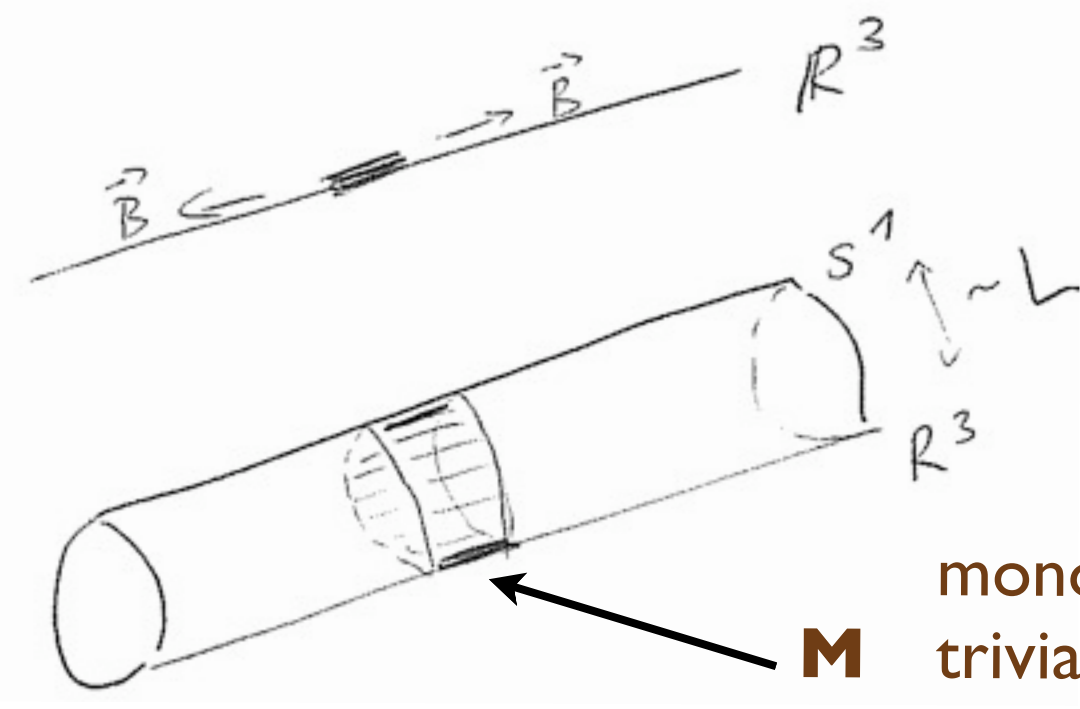
However, the "Debye screening" is now due to composite objects, the "magnetic bions" ***of the title.***

since SU(2) broken to U(1) at scale 1/L

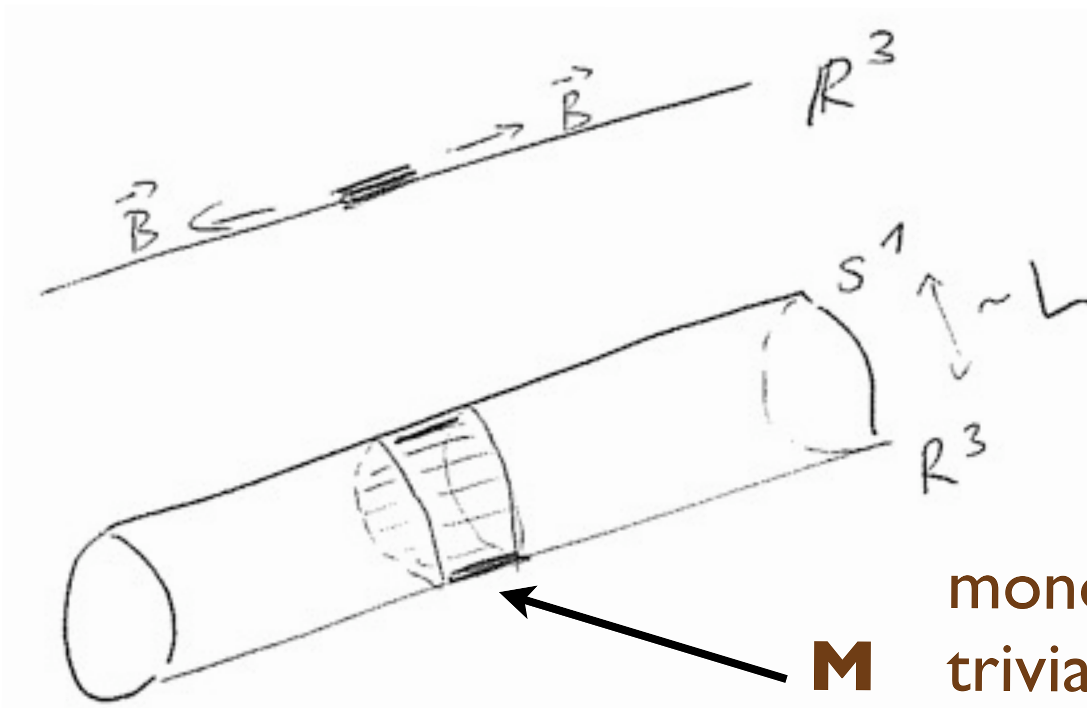
there are monopole-instanton solutions of finite Euclidean action,

(the 't Hooft-Polyakov static monopole on R^(3,1) with the time axis removed = 3d instanton)

constructed as follows:



M monopole-instanton trivially embedded in 4d

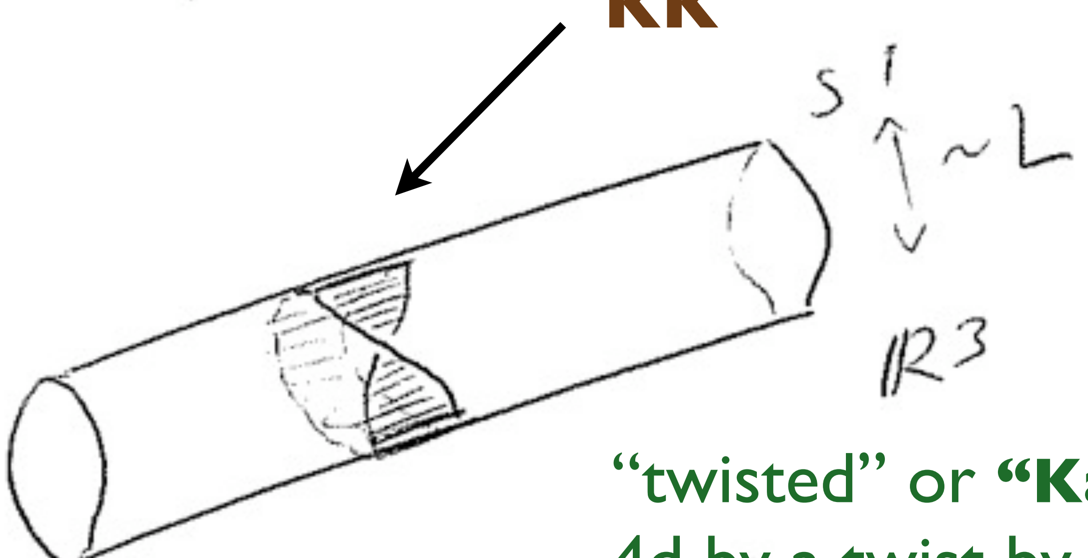


M

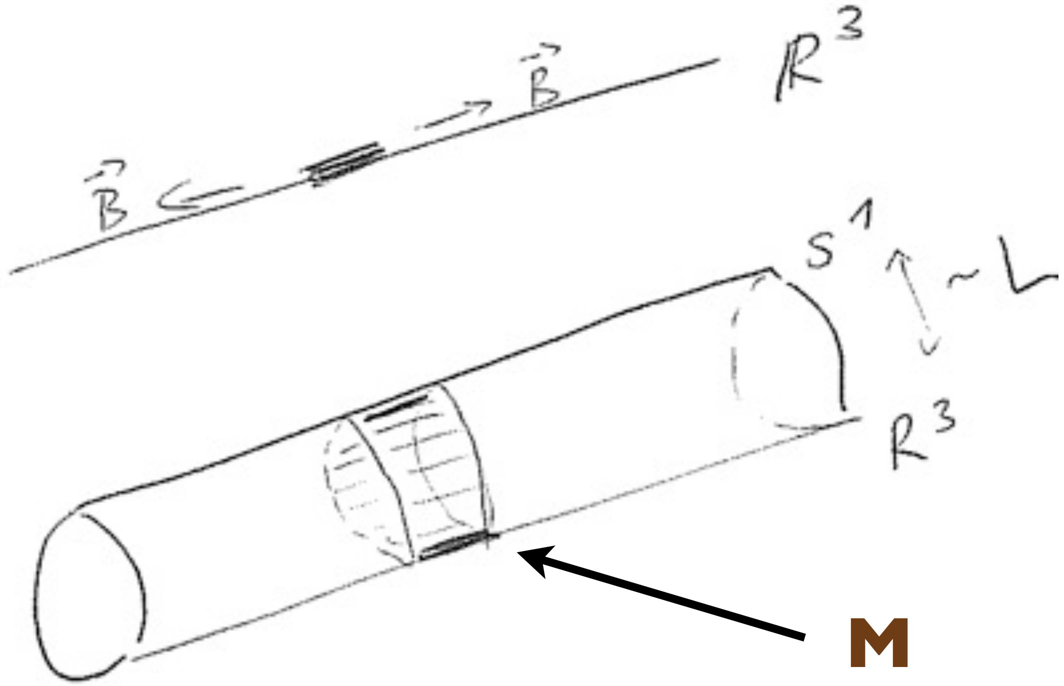
monopole-instanton
trivially
embedded in 4d

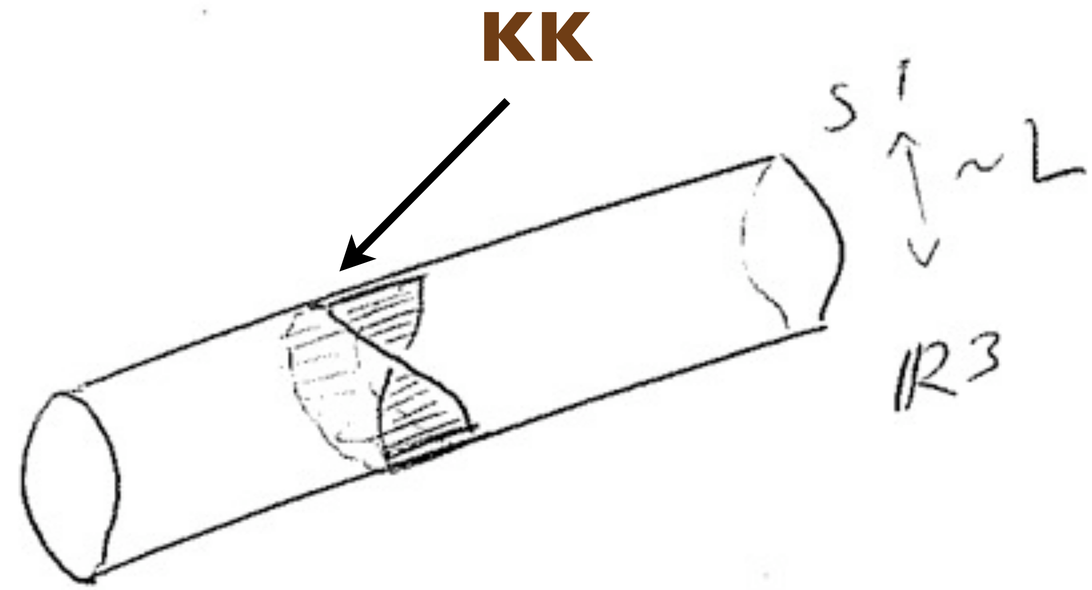
new input - first seen in D-brane physics - a "KK tower", whose
lowest action member of the tower can be pictured like this (as opposed to the no-twist):

KK



"twisted" or **"Kaluza-Klein":** monopole embedded in
4d by a twist by a "gauge transformation" periodic up
to center - in 3d limit not there! (infinite action)

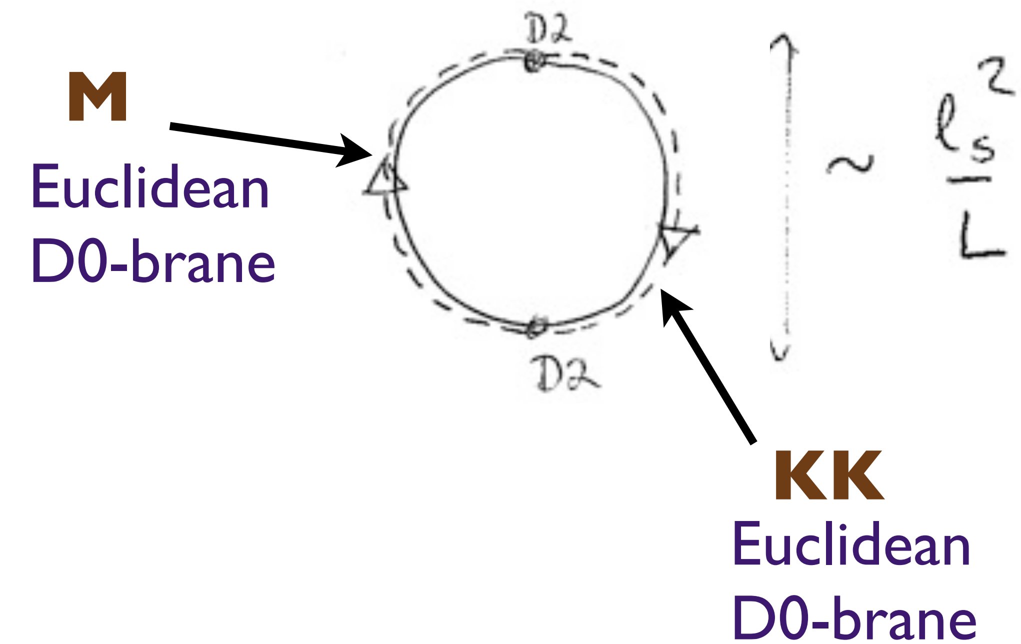




K. Lee, P. Yi, 1997

charges:

	magnetic	topological	suppression
M	+1	1/2	e^{-S_0}
KK	−1	1/2	e^{-S_0}
BPST	0	1	e^{-2S_0}

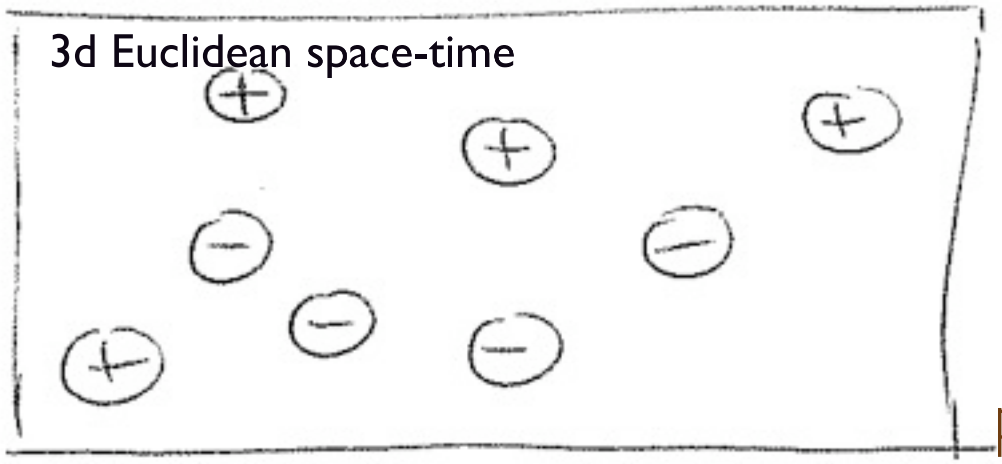


$$e^{-S_0} = e^{-\frac{4\pi v}{g_3^2}} = e^{-\frac{4\pi^2}{L g_3^2}} = e^{-\frac{4\pi^2}{g_4^2(L)}}$$

center-symmetric vev   coupling matching

in SU(2), 1/2 of the ‘t Hooft suppression

in a purely bosonic theory, vacuum would be a dilute M-M* plasma -
but interacting, unlike instanton gas in 4d (in say, electroweak theory)



physics is that of Debye screening; by analogy:

electric fields are screened in a charged plasma ("Debye mass for photon")
in the monopole-antimonopole plasma, the dual photon (3d photon ~ scalar)
obtains mass from screening of magnetic field:

$$\mathcal{L}_{eff} = g_3^2 (\partial\sigma)^2 + (\#)\, v^3 e^{-S_0}\left(e^{i\sigma} + e^{-i\sigma}\right) + \ldots$$

"(anti-)monopole operators"

aka **"disorder operators"** - not locally expressed in terms of original gauge fields (Kadanoff-Ceva; 't Hooft - 1970s)

also by analogy with Debye mass:

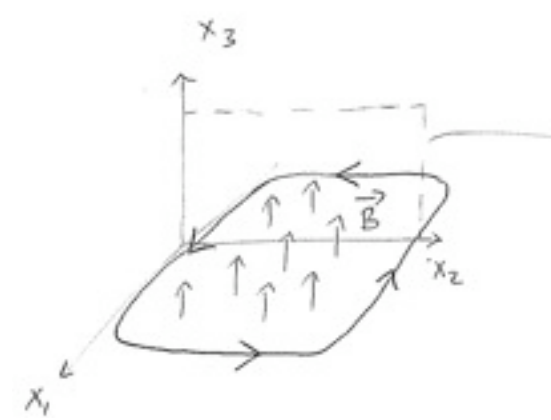
dual photon mass^2 ~ M-M* plasma density

$$m_\sigma \sim v\, e^{-S_0/2} = v\, e^{-\frac{4\pi v}{2 g_3^2}}$$

(for us, v = pi/L)

Polyakov, 1977: ***dual photon mass ~ confining string tension***

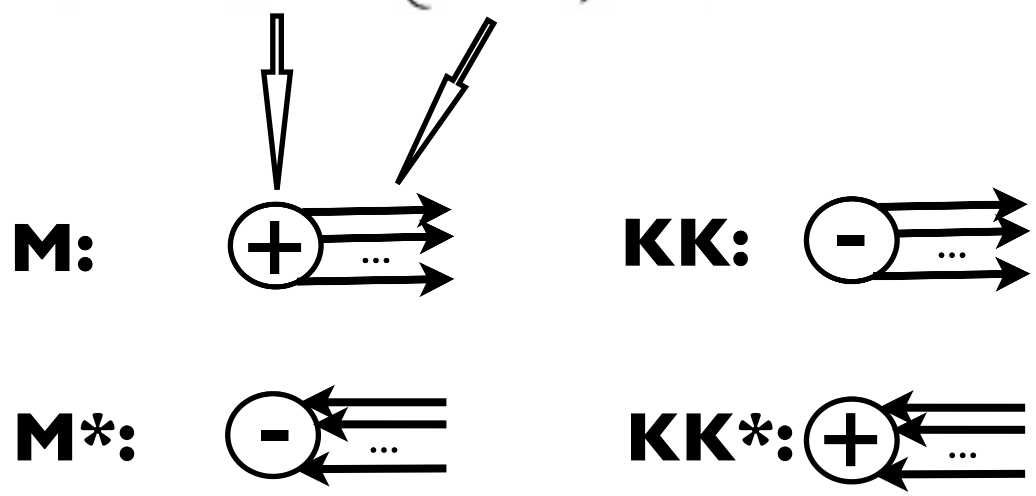
"Polyakov model" = 3d Georgi-Glashow model or compact U(1) (lattice)



but our 4d theory has M and KK which have fermion zero modes

index theorem: Nye-Singer (2000), Unsal, EP (2008)

$$e^{-S_0}\, e^{i\sigma}\, (\lambda\lambda)^{N_w}$$



symmetries imply: topological excitations generating "Debye" screening must have

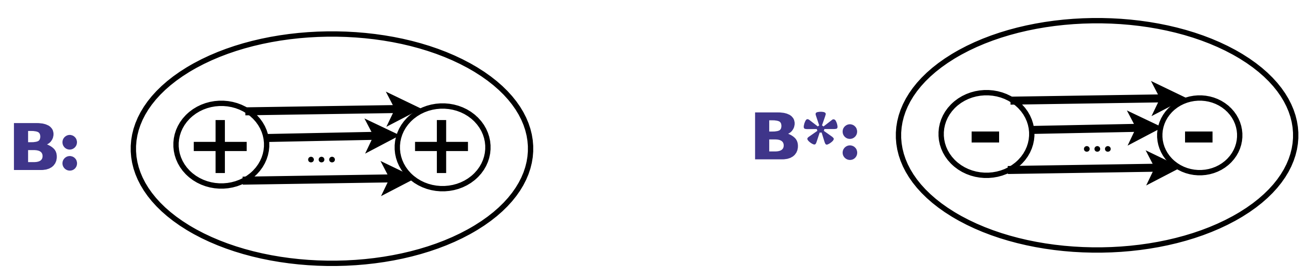
i. magnetic charge 2

ii. no fermion zero modes

M + KK* bound state?

- same magnetic charge ~ 1/r-repulsion
- fermion exchange ~ log(r)-attraction

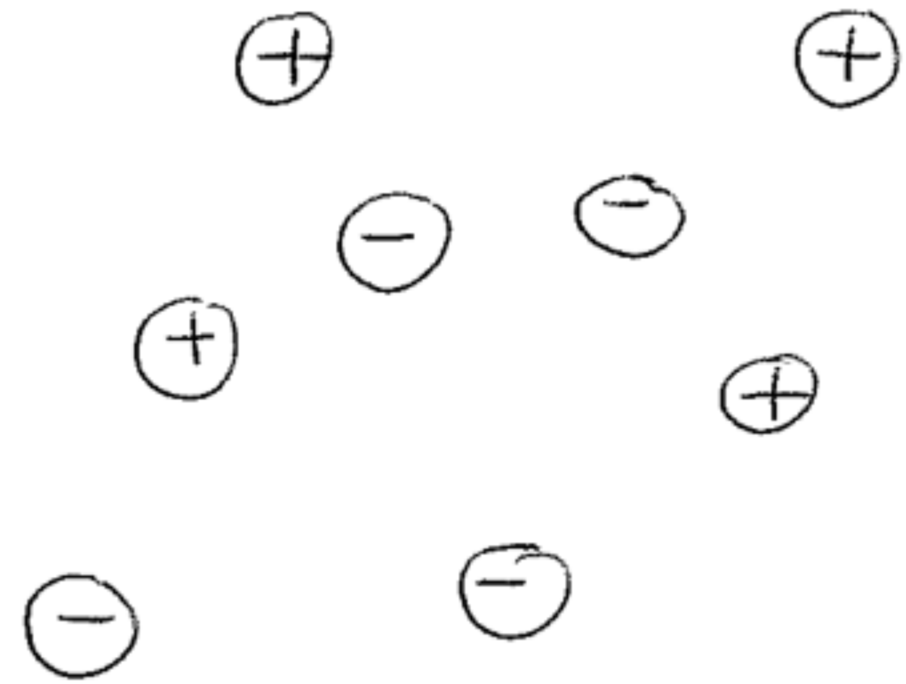
M + KK* = B - magnetic "bion" size ~ $L/g_4^2(L) >> L$ (our "lattice spacing")



Unsal 2007: **dual photon mass is induced by magnetic "bions" - the leading cause of confinement in SU(N) with adjoints at small L** (including SYM)

3d pure gauge theory vacuum monopole plasma

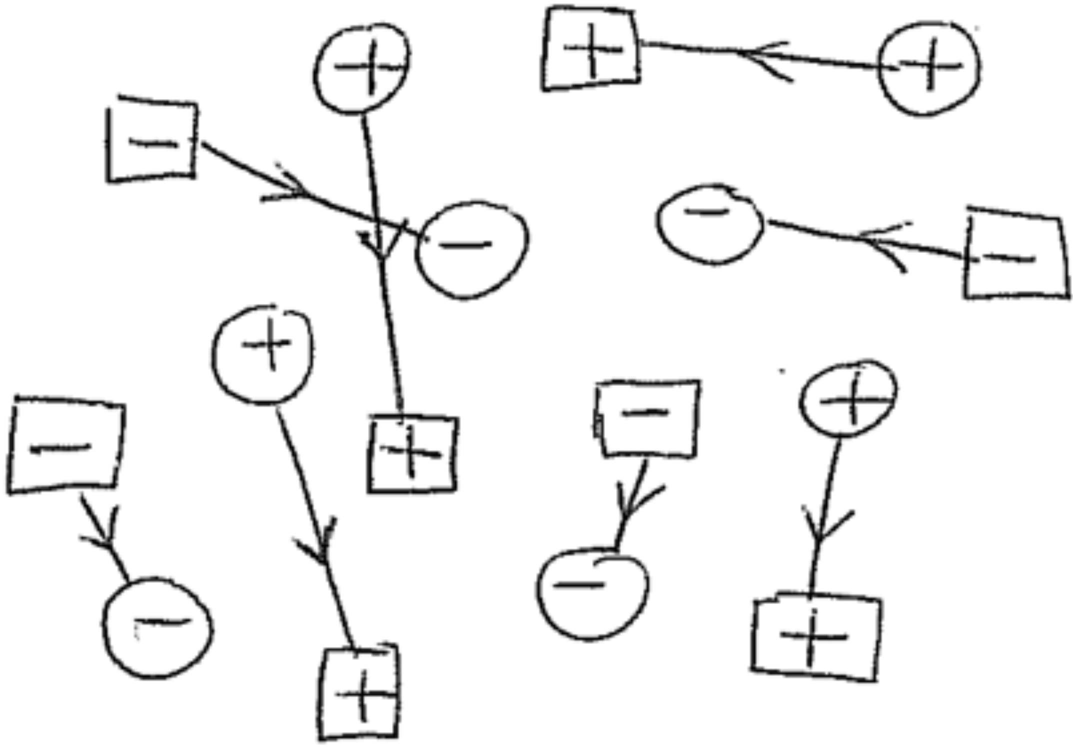
Polyakov 1977



circles = M(+)/M*(-)

4d QCD(adj) fermion attraction M-KK* at small-L

Unsal 2007, ...

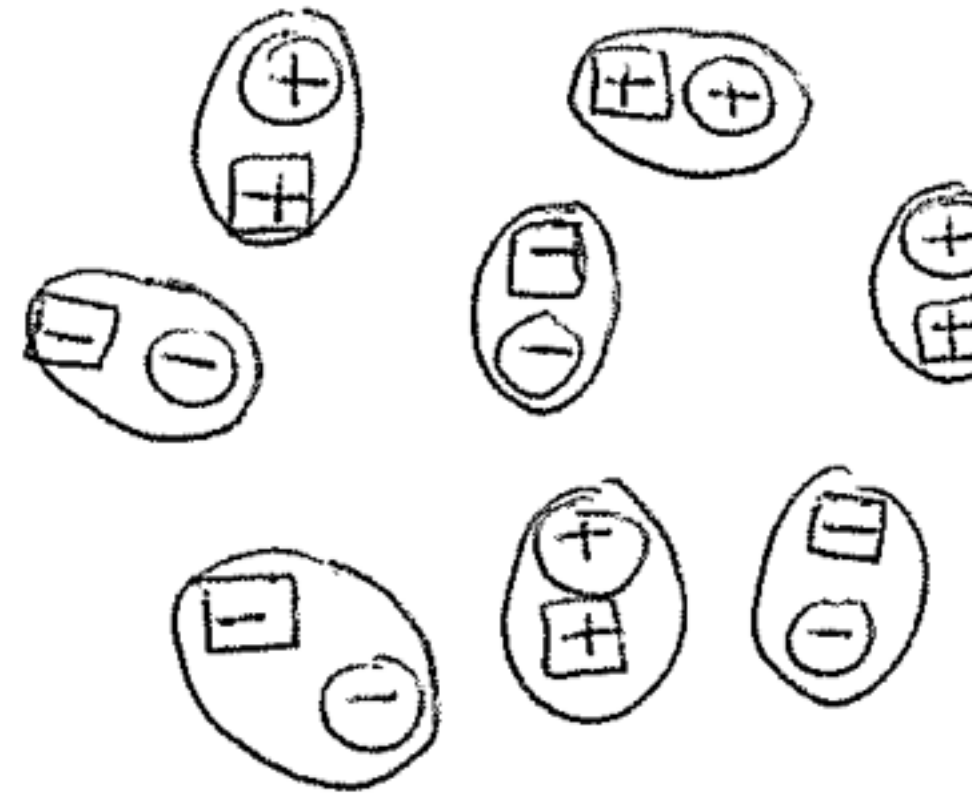


circles = M(+)/M*(-)

squares = KK(-)/KK*(+) - require nonzero L, i.e. 4d

4d QCD(adj) bion plasma at small-L

Unsal 2007, ...



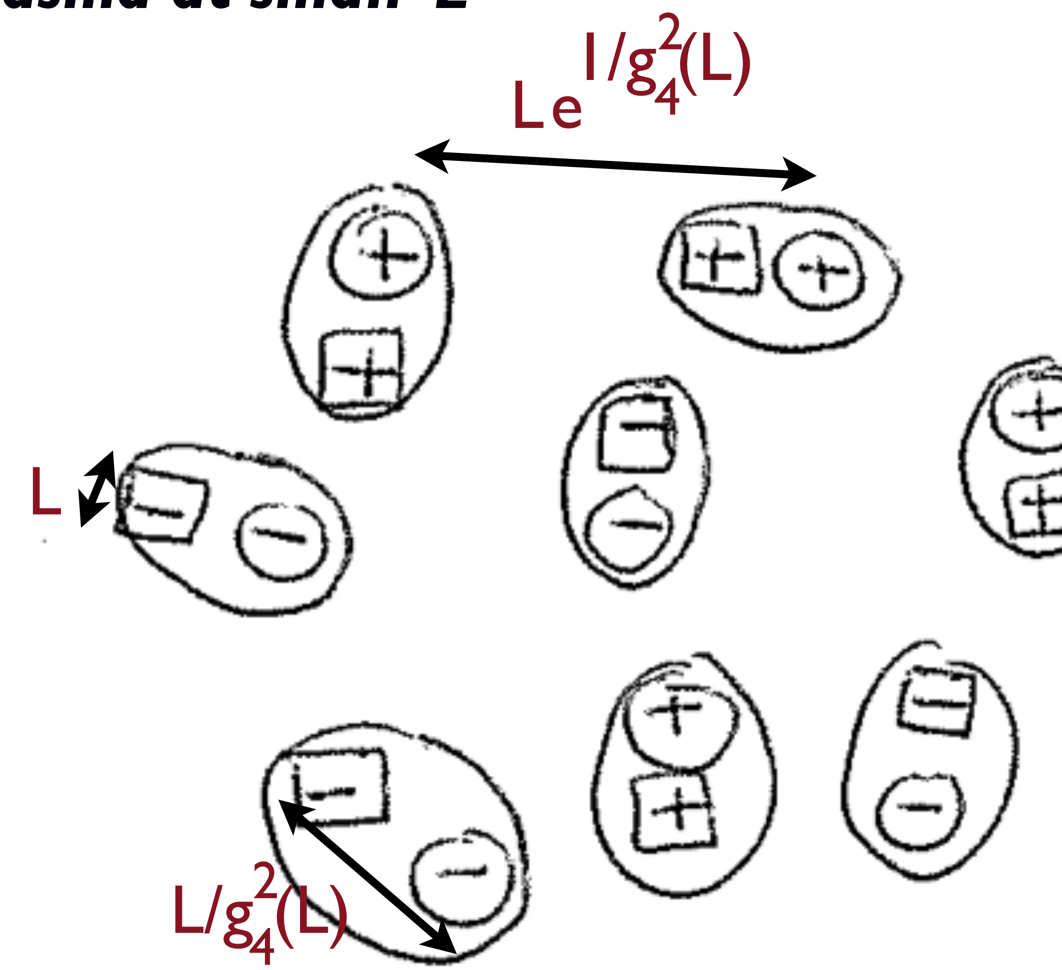
circles = M(+)/M*(-)

squares = KK(-)/KK*(+) - require nonzero L, i.e. 4d

blobs = Bions(++)/Bions*(--) - require nonzero L, i.e. 4d

4d QCD(adj) bion plasma at small-L

Unsal 2007, ...



M + KK* = B - magnetic "bions" -

- carry 2 units of magnetic charge
- no topological charge (non self-dual)

  (locally 4d nature crucial: no KK in 4d)

  bion stability is due to fermion attraction balancing Coulomb repulsion - results in scales as indicated
- bion/antibion plasma screening generates mass for dual photon

"magnetic bion confinement" operates at small-L in any theory with massless Weyl adjoints, including N=1 SYM (& N=1 from Seiberg-Witten theory)

it is "automatic" at small-L: no need to otherwise "deform" theory

first time confinement analytically shown in a non-SUSY, continuum, locally 4d theory

can calculate mass gap, string tension...

Unsal, EP 2009, Anber, EP 2011

$$\frac{\mathcal{M}}{\Lambda} \sim (\Lambda L)^{\frac{8-2n_w}{3}} e^{-2\pi\tilde{c}\left(\log\frac{1}{\Lambda L}\right)^{1/2}} \times (\text{less relevant contributions})$$

strong scale

O(1), positive

... how **dare** you study non-protected quantities?

can calculate mass gap, string tension... Unsal, EP 2009, Anber, EP 2011

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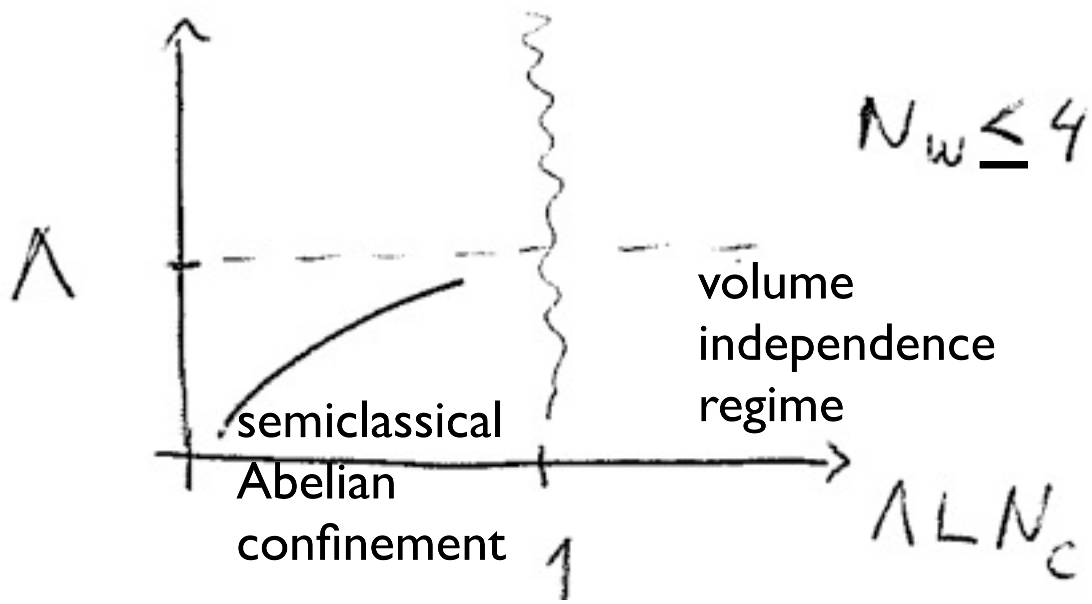

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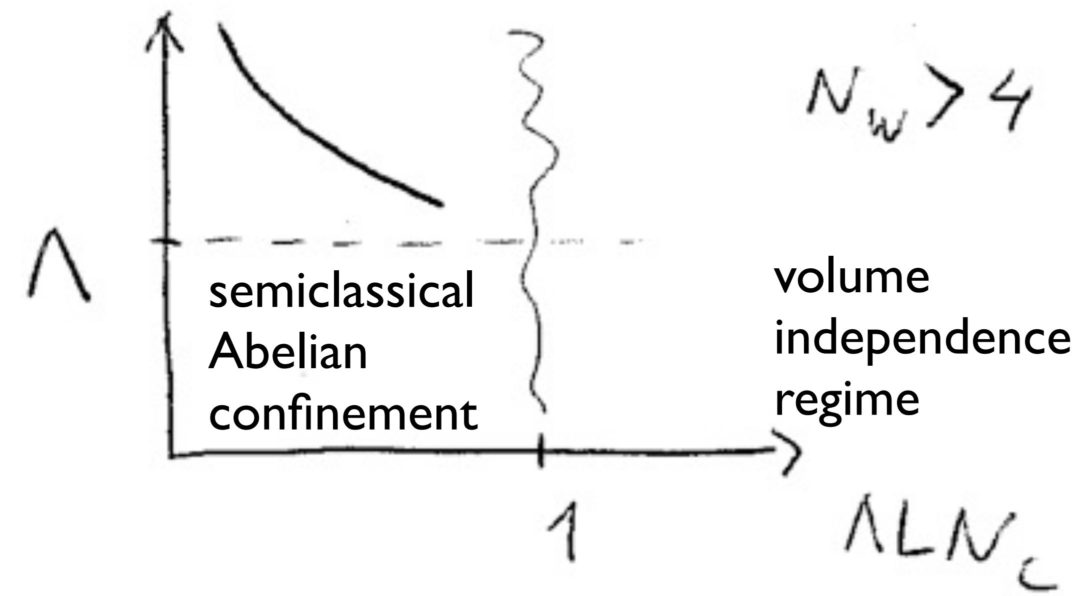


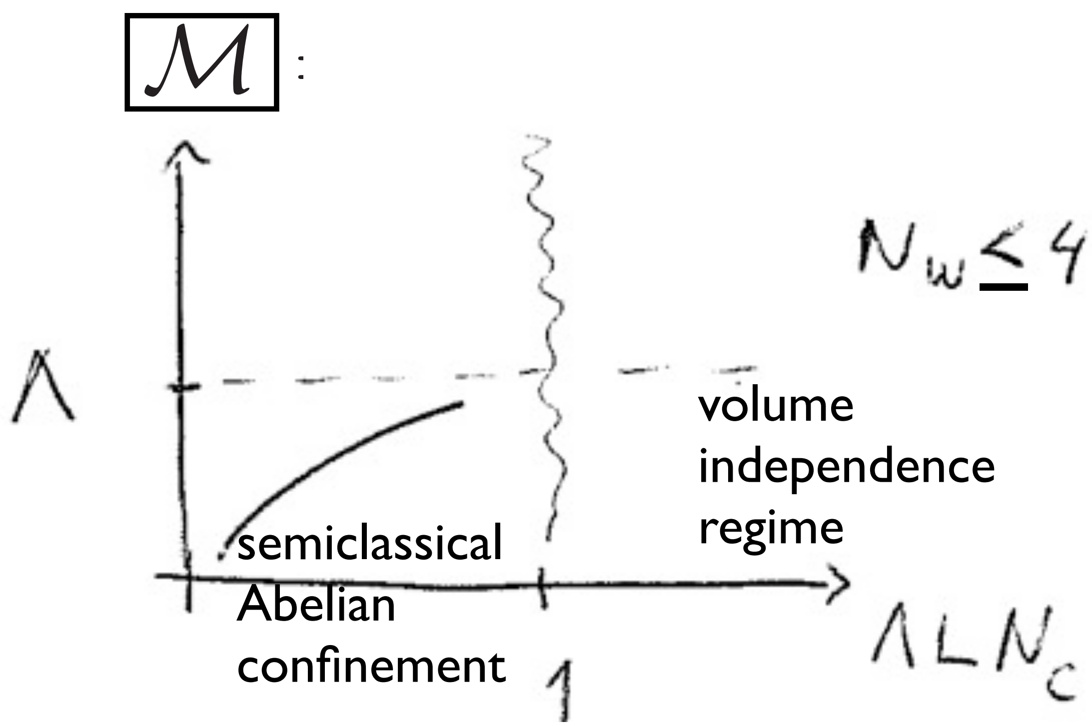
small # flavors: topological excitations become more dense with increasing L -
- indicates confinement at infinite L?

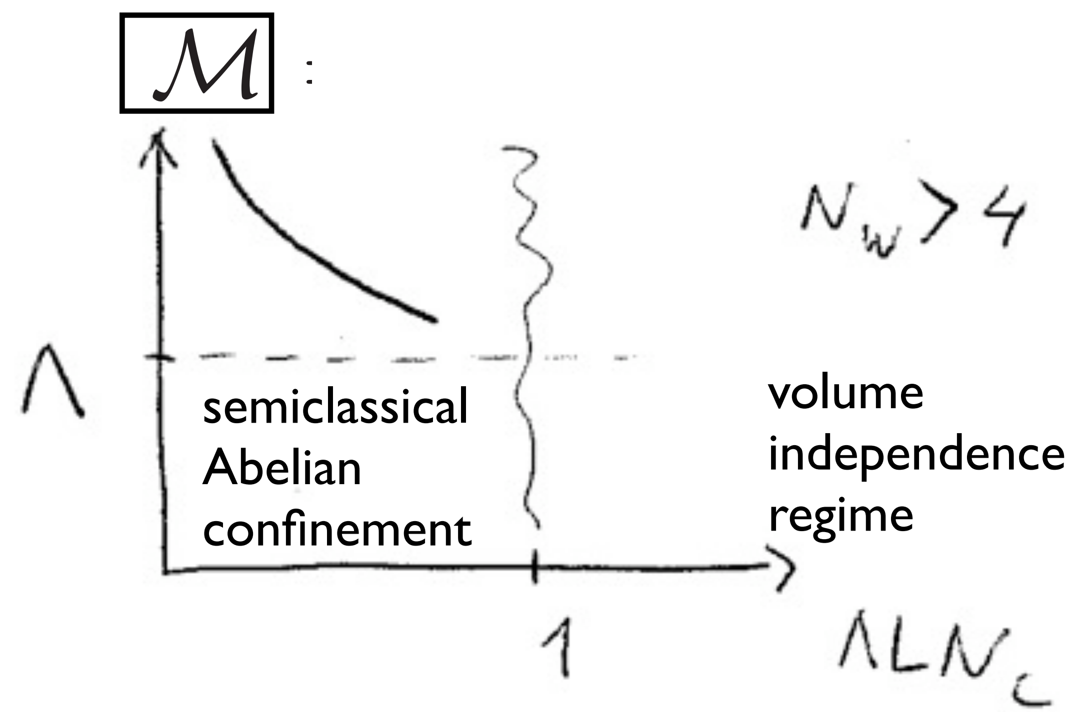
large # flavors: dilution of topological excitations with increasing L -
vanishing mass gap?
- indicates conformal at infinite L?

cf continuing lattice studies since 2007- & recall (m,a,V,$)

we knew already that small-L regime is complementary to that of volume independence *(if it was identical, I'd be talking at Clay...)*

- gives a calculable "shadow" of the 4d "real thing"
- calculability not often there in nonperturbative problems
- so, not to be taken lightly - *I think "it pays to calculate"*
  - bound to learn something...





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list, so far:

i. Polyakov's 3d mechanism of confinement by "Debye screening" due to monopoles extends infinitesimally into 4d - holds in all theories (some must be deformed to ensure abelianization)

study shows that massless fermion content plays crucial role in the confinement mechanism, contrary to what many thought

Unsal w/ Shifman, Yaffe, EP, Anber, Argyres.. '07-'11

ii. chiral symmetry (discrete/abelian) breaking due to disorder operator vevs generic

Unsal, EP '09

iii. all calculable abelian confinement mechanisms are continuously related: "Seiberg-Witten confinement" "=" "Polyakov-like bion confinement" Unsal, EP '11

iv. even in SUSY, power of small-L not fully explored yet, e.g. - gave yet another argument for ISS l=3/2 model does not break SUSY

Unsal, EP '09

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list, so far, contd.:

v. finite-T deconfinement transition at small-L due to "competing" electric and magnetic excitations

Simic, Unsal, '10
older speculation: Liao, Shuryak '06

vi. depending on gauge group and fermion matter content deconfinement transition at small-L described by various 2d models

- some solved long ago - Ising, Z_N parafermions, XY-spins with Z_K perturbation
- some new - "XY"-multi-spin models on root space w/ perturbations
- can study rank of transition, various critical exponents via analytic (new 2d CFTs?), numerical, cold atom (?) methods

Anber, Unsal, EP '11-'12

vii. one can even take messages for infinite-L deconfinement transition: Seiberg-Witten-inspired - role of new types "topological molecules"

Unsal, EP '11-'12
vs older work of Dyakonov '06

many questions remain - feel free to ask your own!