Continuity, deconfinement, and (super)-Yang-Mills theory

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works in collaboration with

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1205.0290 &1212.1238

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Toronto

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The theme of this talk:

While the LHC vigorously continues search of SUSY

- and may or may not see evidence for it -

the development I will describe is an(other) example of how ideas initially found in string theory and supersymmetry improve our understanding of "ordinary" non-SUSY gauge dynamics.

The recently found Higgs explains "origin of mass"- yet, >90% of the mass visible to us is, instead, due to the strong interactions. These exhibit the surprising* behavior of confining quarks and gluons.

*As surprising as a 40 year old phenomenon can be.

It is well known that Yang-Mills theories, when "heated up" - by hadron collisions, by the Big Bang, or in someone's computer - exhibit a deconfinement transition to a plasma of gluons and quarks. The transition occurs at T of order the strong scale and is thus hard to study analytically.

Numerical experiment - lattice - works.

Models are widely used, but dangers lurk -"voodoo QCD", i.e., you don't a priori know how far/when to trust - and any controlled analytical insight into the mechanism behind the deconfinement transition is of interest...

Our claim:

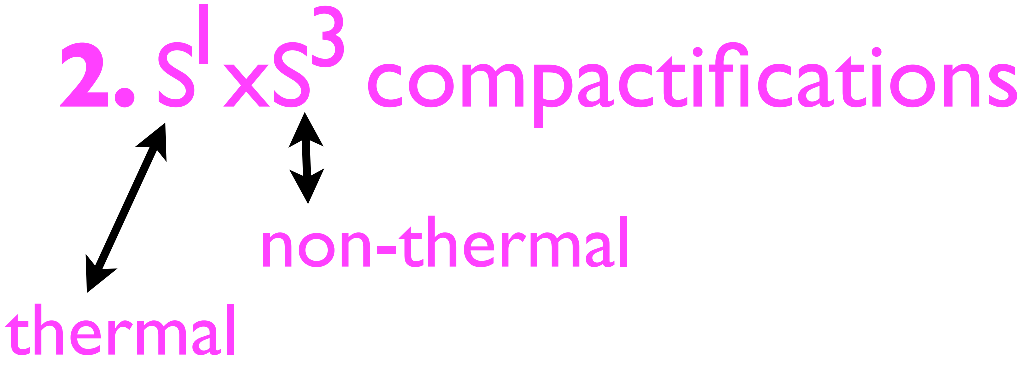
Supersymmetry has something to say about deconfinement in non-SUSY YM theory, by providing a setting where a phase transition, believed to be continuously connected to the deconfinement transition, can be studied by analytical means and its causes understood - by pen and paper, not expensive computers or collisions.

In the rest of my talk, I will attempt to give you a flavor as for the basis of this claim.

Before that, however, let me enumerate the few controlled analytical approaches to deconfinement we know:

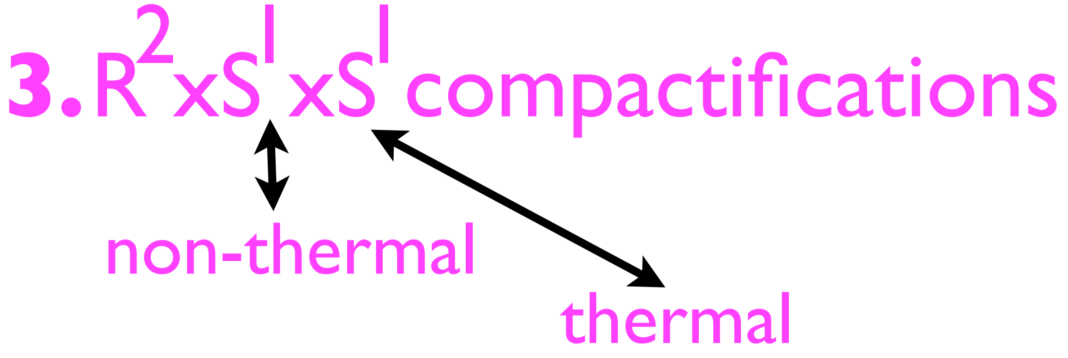
for brevity, will skip "pro-con" discussion! - these are useful: insight, stretch beyond validity...

1. Gauge-gravity duality at finite T [many, after Witten 1998, ...]



2. $S^1 \mathrm{x} S^3$ compactifications [Aharony, Marsano, Minwalla, Papadodimas, van Raamsdonk, 2003-5]

These authors rejected the possibility of finding a weak-coupling transition at infinite volume...



3. $R^2 \mathrm{x} S^1 \mathrm{x} S^1$ compactifications [Simic, Unsal 2010 Unsal 2012

"deformed" pure-YM

Anber, EP, Unsal 2011
Anber, Collier, EP 2012
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"QCD(adj)" = YM with many massless adjoint Weyl fermion

(cool El.-Magn. Coulomb gases, probably as close to real thing as one could dream of...)

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non-thermal

thermal

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THE TOPIC OF THIS TALK!

4. R^3xS^1 compactifications of super YM with $m_{gaugino}$

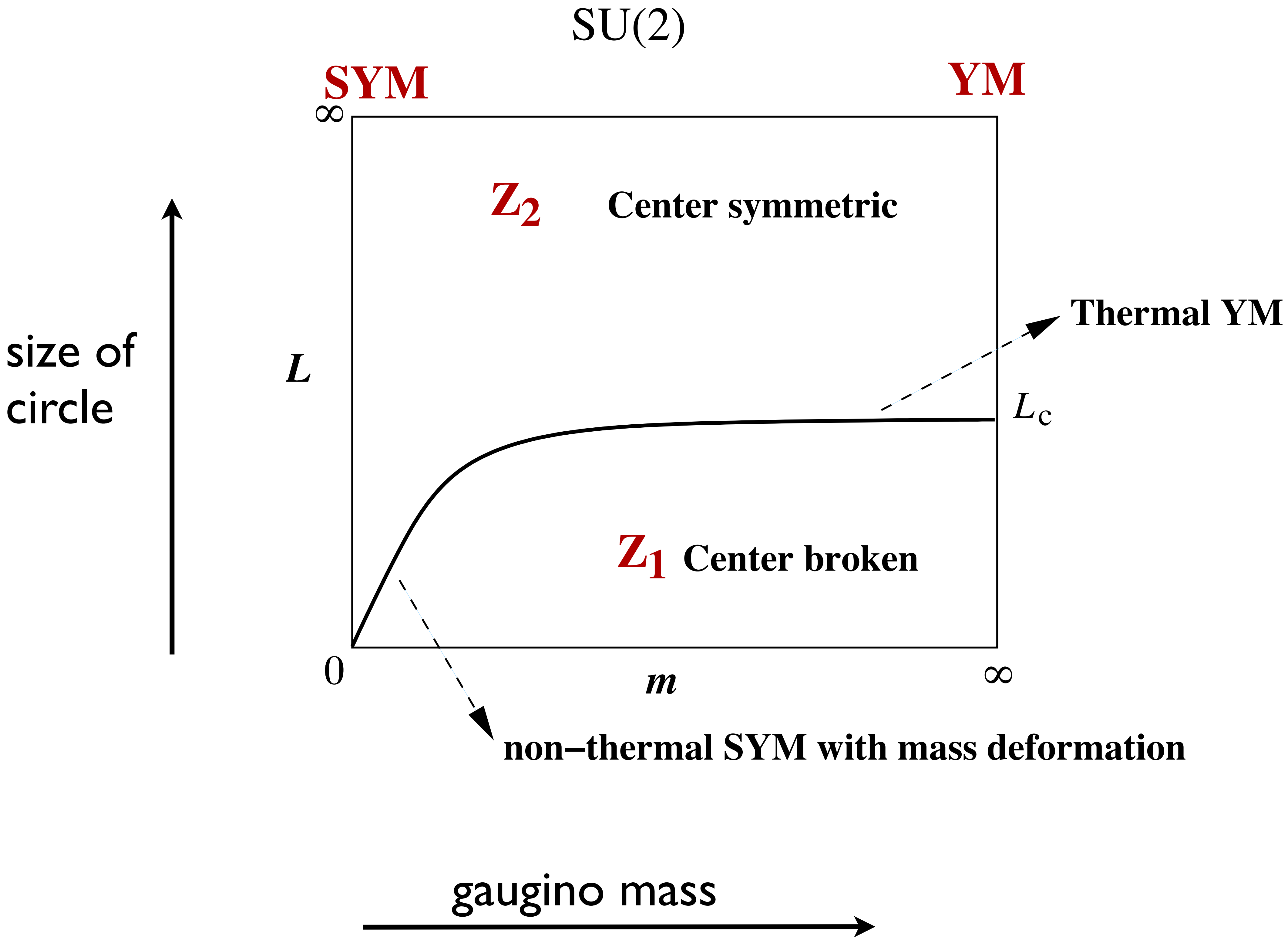
(non-) thermal

[EP, Schaefer, Unsal 1205.0290, 1212.1238; ...]

(earlier remarks by Unsal, Yaffe 2010)

Let’s first flesh out the idea:

pure SYM on $\mathbb{R}^3 \times S^1_{\mathrm{L}}$ with periodic (supersymmetric) b.c. for gaugino
with gaugino mass “m”



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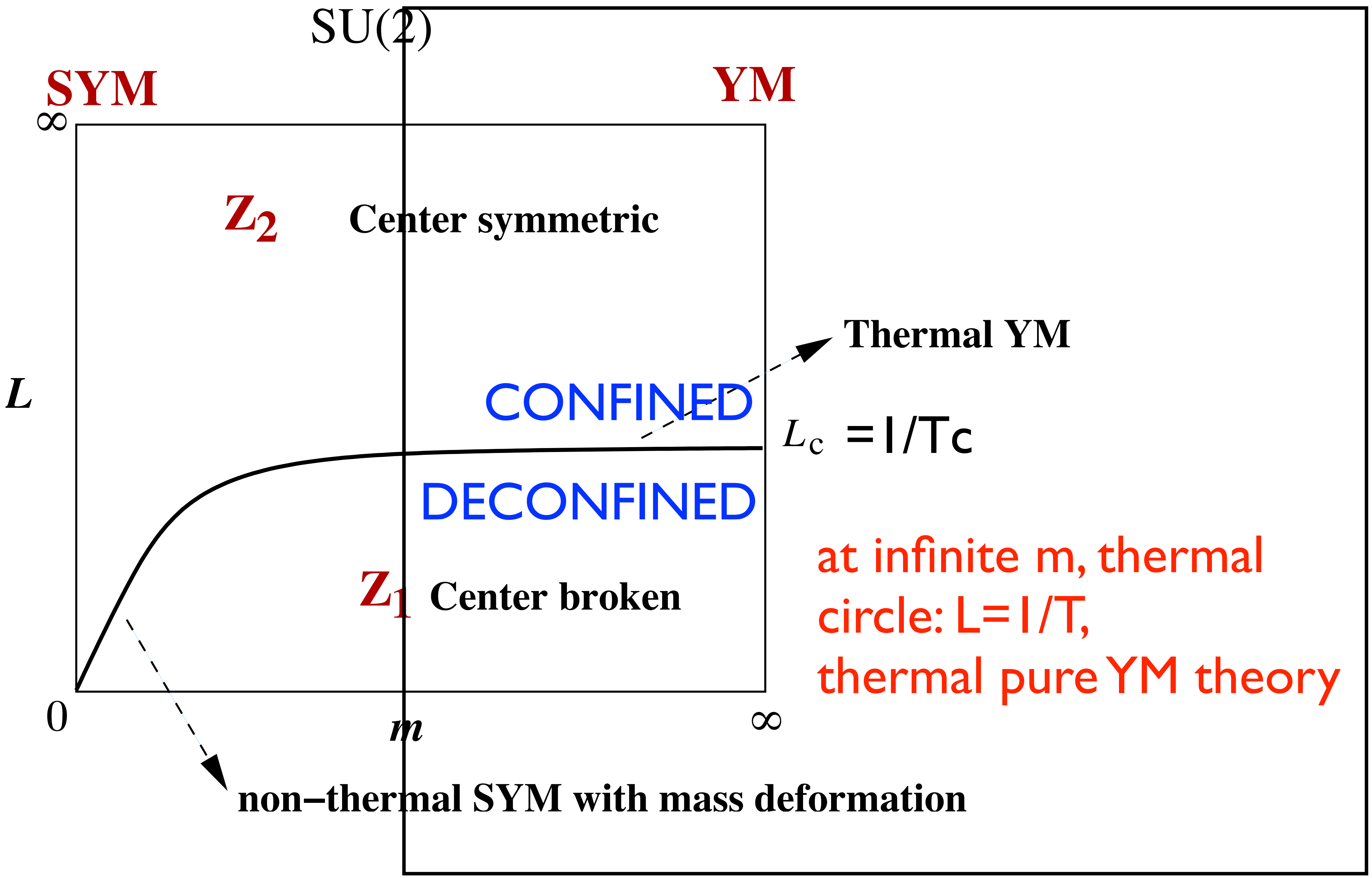

at infinite m, thermal circle: L=1/T, thermal pure YM theory

thermal deconfinement transition, e.g., from lattice experiment

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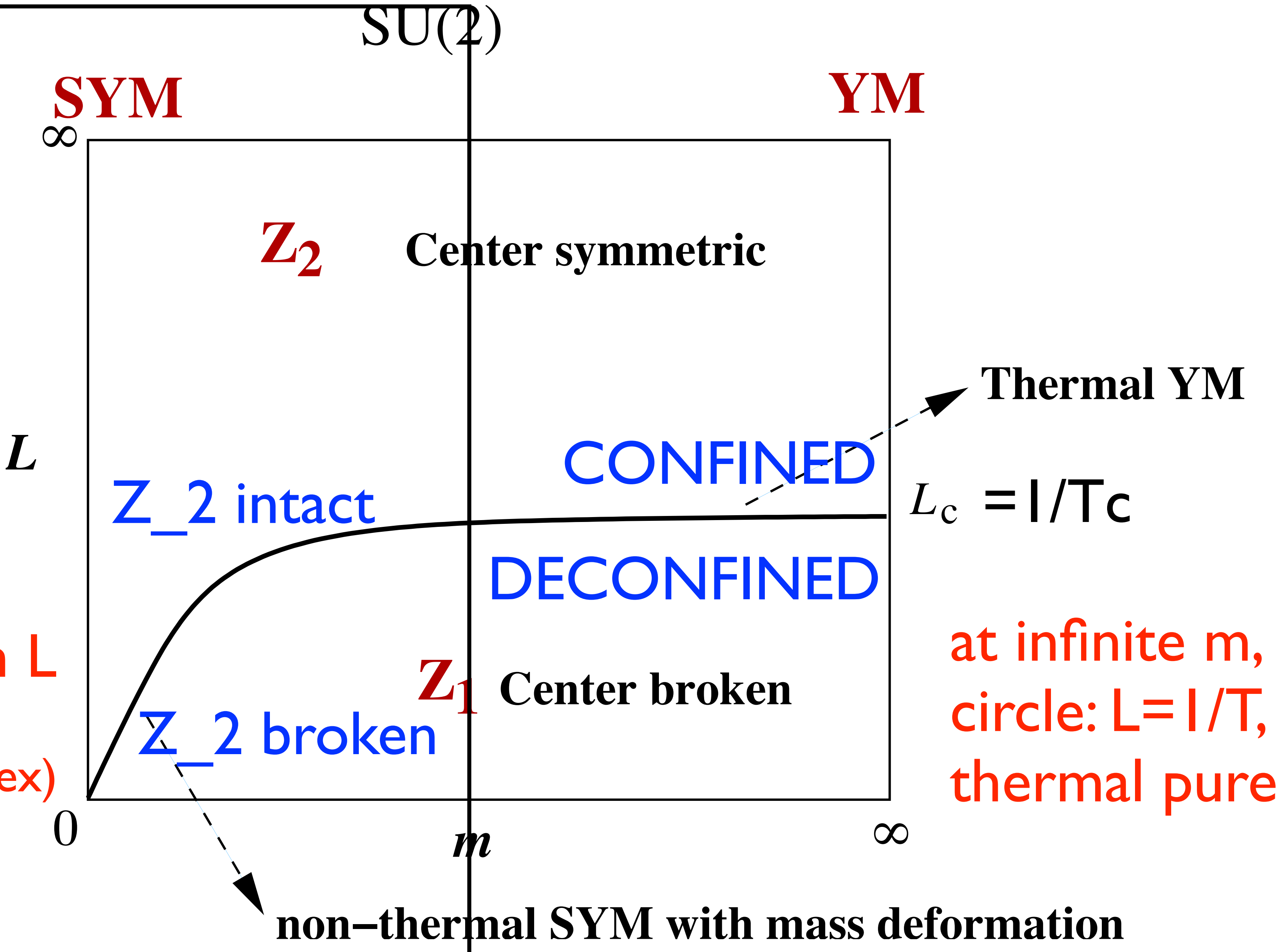
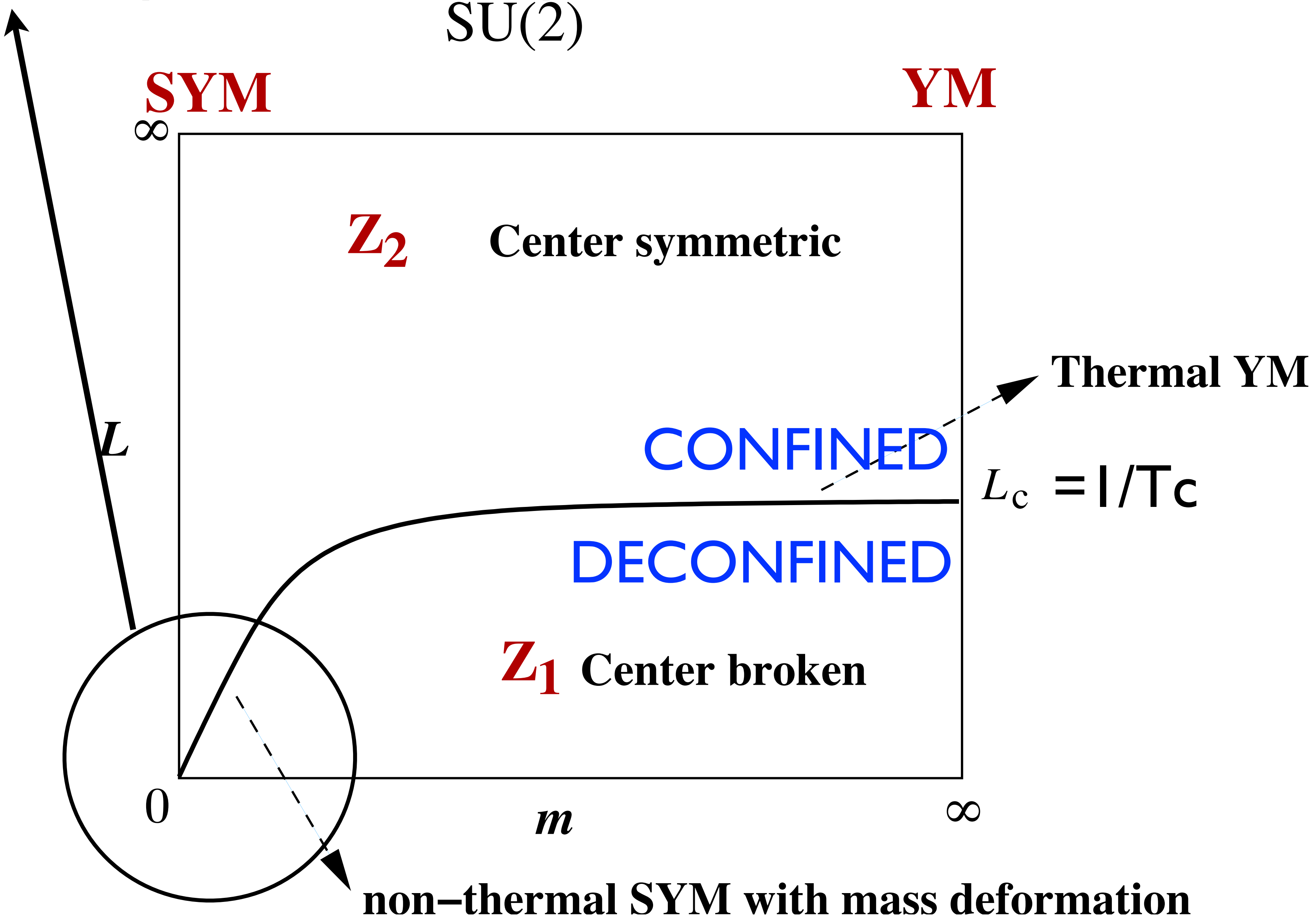


at small m, non-thermal compactification L (at m=0, partition function=Witten index)

at infinite m, thermal circle: L=1/T, thermal pure YM theory

quantum phase transition, Z_2 breaking

At small m,L, the transition can be studied in a theoretically controlled manner. A variety of novel topological excitations and perturbative contributions yield competing effects, resulting in a Z_2 breaking transition as m/(L^2 Lambda^3) varies.



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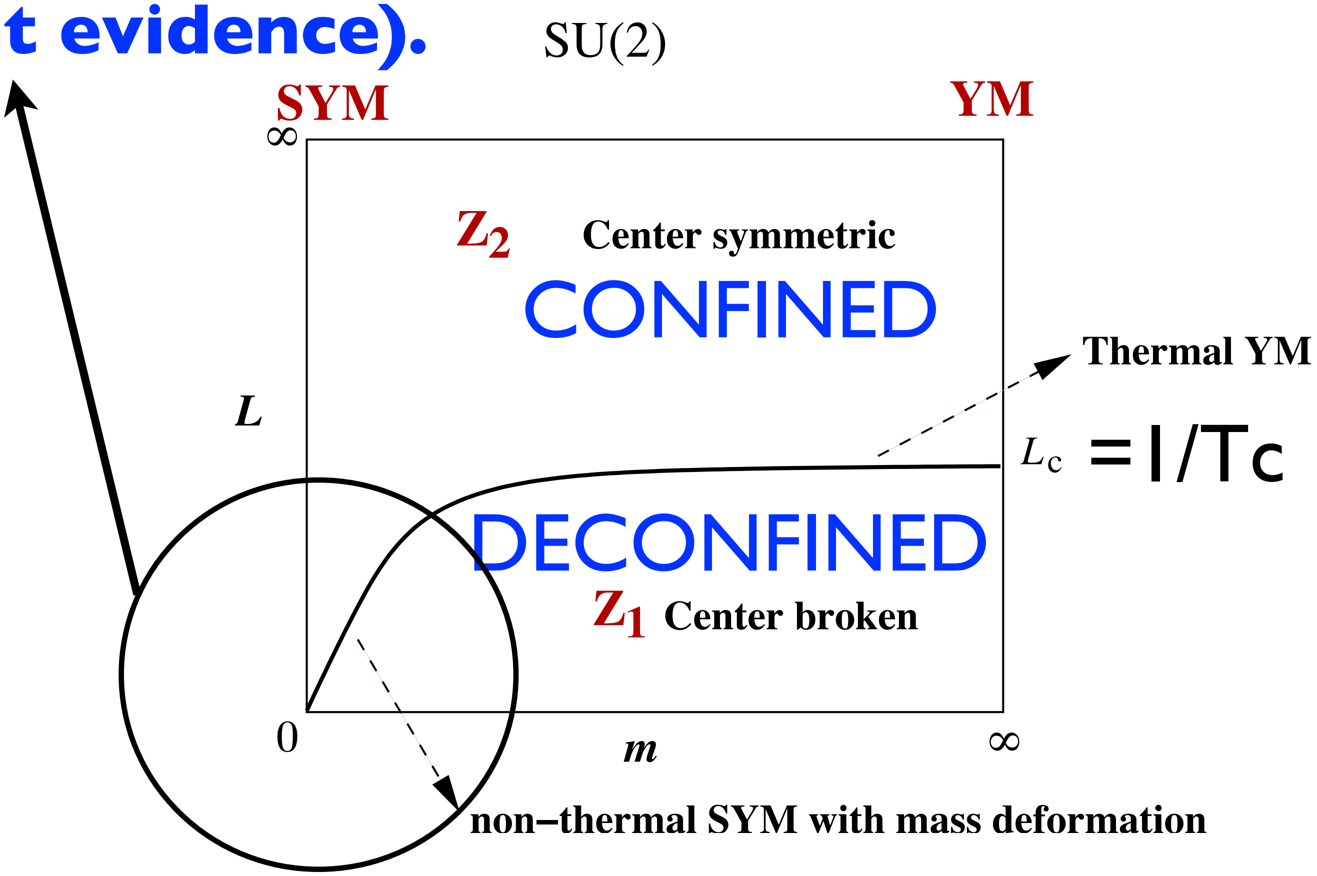
At small m,L, the transition can be studied in a theoretically controlled manner. A variety of novel topological excitations and perturbative contributions yield competing effects, resulting in a Z_2 breaking transition as m/(L^2 Lambda^3) varies.

Conjecture that continuously connected to deconfinement in pure YM (will present evidence).



Mechanism behind semiclassical transition is universal, valid for all gauge groups, with or without center.

Order of transition is same as in corresponding pure YM in all cases.

Some qualitative properties (theta-dependence of Tc), first predicted at small-m,L have been verified in recent experiments (lattice simulations of pure YM).

To get some idea of how this comes about, will need to recall two things.

A.) order parameter for deconfinement in YM

$$\Omega = \exp\left[i\int A_4 dx_4\right]$$

Polyakov loop (around thermal circle); its trace is gauge invariant but (SU(N)) transforms under Z_N center symmetry

$$<\mathrm{Tr}\,\Omega> \sim e^{-\frac{F^{fundamental}_{quark}}{T}}$$

low T - infinite free energy of static fundamental quark

- $L > L_c$: unbroken center symmetry

$$\langle \mathrm{tr}\ \Omega^n \rangle = 0$$

confined phase

high T - finite free energy of static fundamental quark

- $L < L_c$: broken center symmetry

$$\langle \mathrm{tr}\ \Omega^n \rangle \neq 0$$

deconfined plasma phase

$T >> T_c$ behavior has been understood for 30 years

[Gross, Pisarski, Yaffe, 1981]

high-T perturbation theory good, gives one-loop V(pert), which favors center-broken vacuum:

$$V_{\mathrm{pert.}}(\Omega) = -\frac{2}{\pi^2\beta^4}\sum_{n=1}^{\infty}\frac{1}{n^4}|\mathrm{tr}\Omega^n|^2(1+O(g^2)) \longrightarrow$$

roughly, shows negative mass squared for all winding modes

To get some idea of how this comes about, will need to recall two things.

B.) SYM on R^3 x S^1 (with supersymmetric b.c.)

B.1) Along Coulomb branch, where A_4 has a vev, breaking SU(N), the theory "abelianizes".

Seiberg,Witten 1996
Aharony, Hanany, Intriligator, Seiberg, Strassler 1997

exact superpotential, here for SU(2): $W \sim Y + \frac{1}{Y}$

Davies, Hollowood, Khoze 1999
important relevant details of instanton calculation only recent
EP, Schaefer, Unsal, 2012

B.2) Furthermore, at small L, the coupling is weak and semiclassics applies.

relevant bosonic fields: A_4 - gauge field in compact direction - and A_i - 3d gauge field - in the unbroken U(1) of SU(2), equivalent to:

σ - 3d dual to A_i = "dual photon" (potential for magnetic charge)
ϕ - deviation of A_4 from center symmetric value $\mathrm{Tr}\,\Omega = 0$

so that, with $Y \sim e^{i\sigma+\phi}$ the potential from W~Y+1/Y is then

$\cosh 2\phi - \cos 2\sigma$ with minimum at zero ϕ i.e., at $\mathrm{Tr}\,\Omega = 0$

B.3) Thus, SYM on R^3 x S^1 preserves center symmetry.

Physics behind this is interesting and is not done justice by the above quick SUSY-based derivation; furthermore, much of it transcends SUSY!

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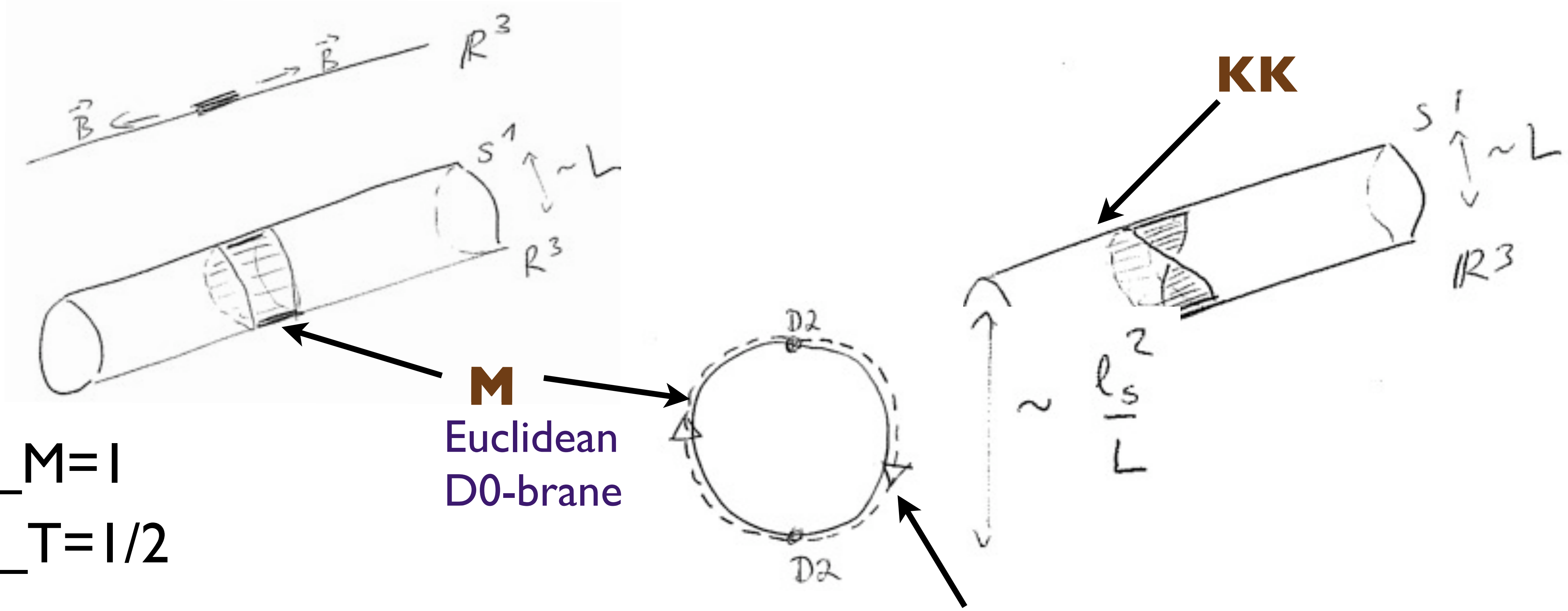
major players: monopole-instanton (M) and twisted (KK) [Piljin Yi, Kimeyong Lee, 1997]



M
Euclidean
D0-brane

KK
Euclidean
D0-brane

KK

Q_M=1
Q_T=1/2

Q_M=-1
Q_T=1/2

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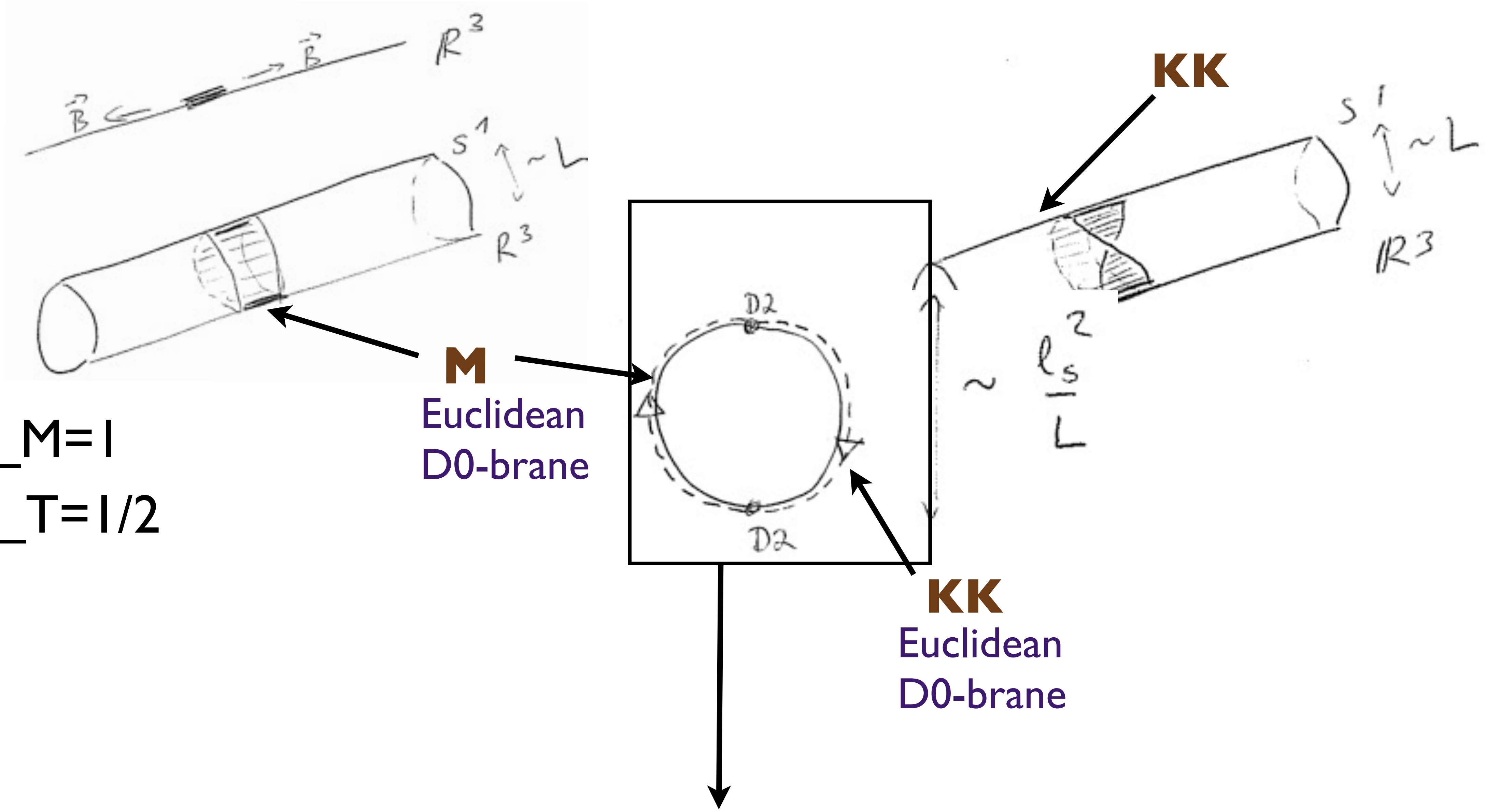


M

Euclidean D0-brane

KK

KK

Euclidean D0-brane

Q_M=1

Q_T=1/2

Q_M=-1

Q_T=1/2

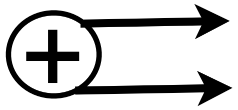
on the Coulomb branch, the two kinds of lowest-action monopole-instantons... best understood via D-branes

(N=4 SUSY not needed - same solutions exist even in pure YM w/ holonomy vev)

monopole-instantons - M,M*,KK,KK*

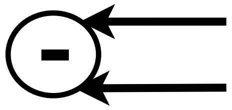
$$e^{-S_0} e^{+i\sigma-\phi} \lambda\lambda$$

M:

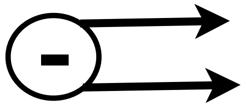


$$e^{-S_0} e^{-i\sigma-\phi} \overline{\lambda\lambda}$$

M*:



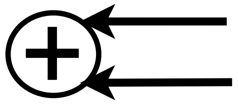
KK:



$$e^{-S_0} e^{-i\sigma+\phi} \lambda\lambda$$

$$e^{-S_0} e^{+i\sigma+\phi} \overline{\lambda\lambda}$$

KK*:



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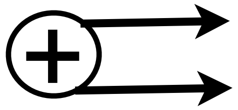

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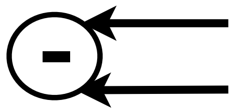
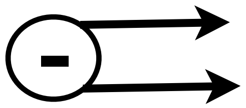


KK:



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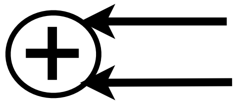
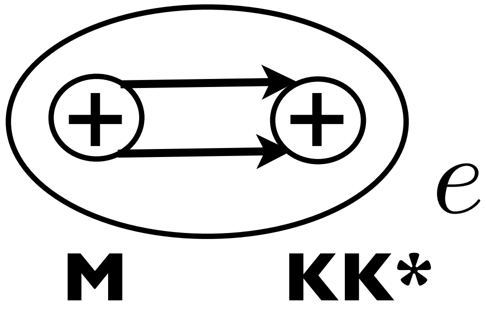


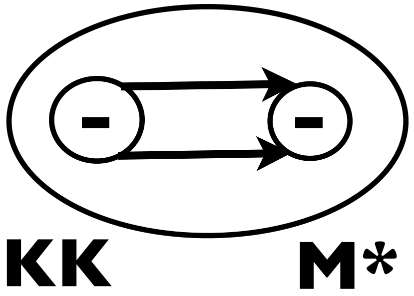
(M-KK* “molecules”) “magnetic bions” - confinement!

[Unsal, 2007]



$$e^{-2S_0} e^{+i2\sigma}$$

B*:



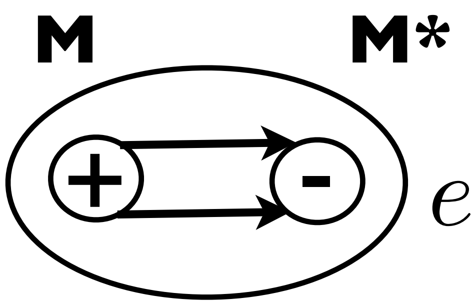
$$e^{-2S_0} e^{-i2\sigma}$$

(M-M*,KK-KK* “molecules”) “neutral bions”

[EP, Unsal, 2011]

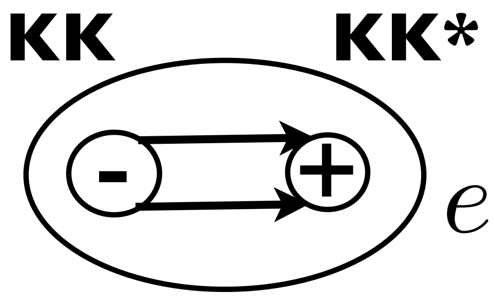
in pure-SYM: center-stabilizing

N:



$$e^{-2S_0} e^{-2\phi}$$

N*:



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$$e^{-S_0}e^{+i\sigma-\phi}\lambda\lambda$$

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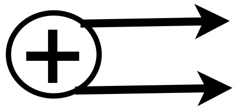

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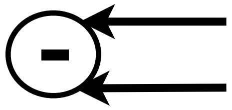
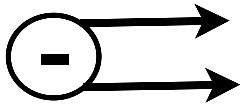


KK:



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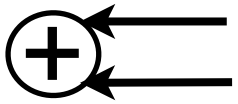

(M-KK* "molecules") "magnetic bions" - confinement!

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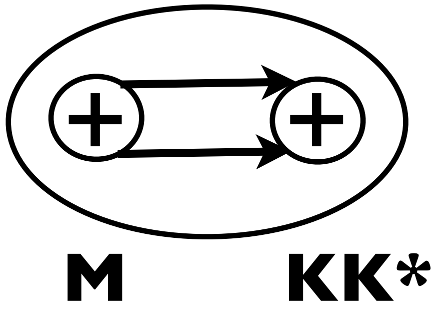

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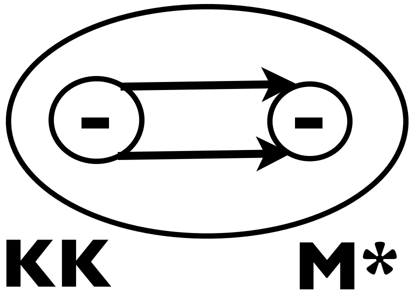
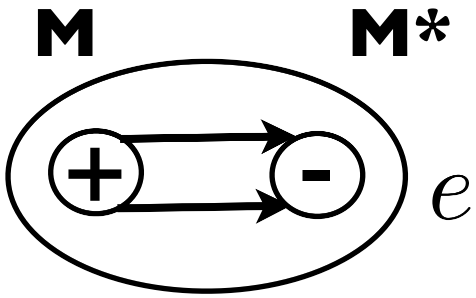


$$e^{-2S_0}e^{-i2\sigma}$$

(M-M*,KK-KK* "molecules") "neutral bions"

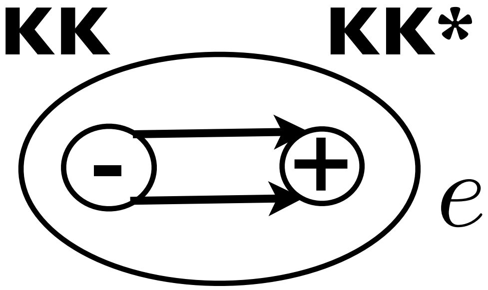
in pure-SYM: center-stabilizing

N:



$$e^{-2S_0}e^{-2\phi}$$

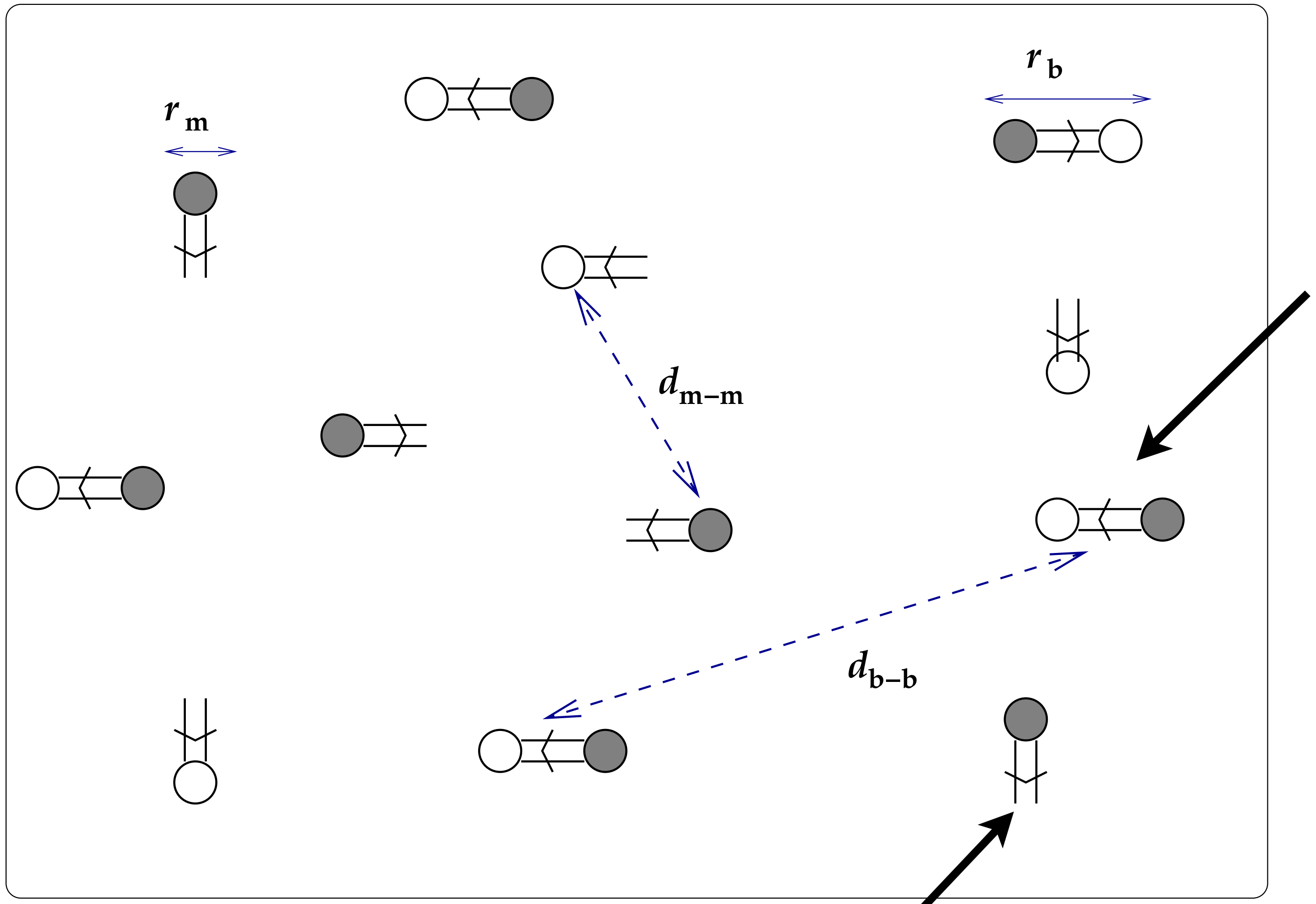
N*:



$$e^{-2S_0}e^{+2\phi}$$

$$\frac{1}{L^3}e^{-2S_0}\left(\cosh 2\phi - \cos 2\sigma\right)$$

A cartoon of the semiclassical vacuum... dilute gas of various topological excitations described above:



potential-producing
center-stabilizing

$$e^{-2S_0} e^{-2\phi}$$

or magnetic bions

$$e^{-2S_0} e^{-i2\sigma}$$

monopole-instantons
fermion interactions, e.g.: $e^{-S_0} e^{+i\sigma-\phi} \lambda\lambda$

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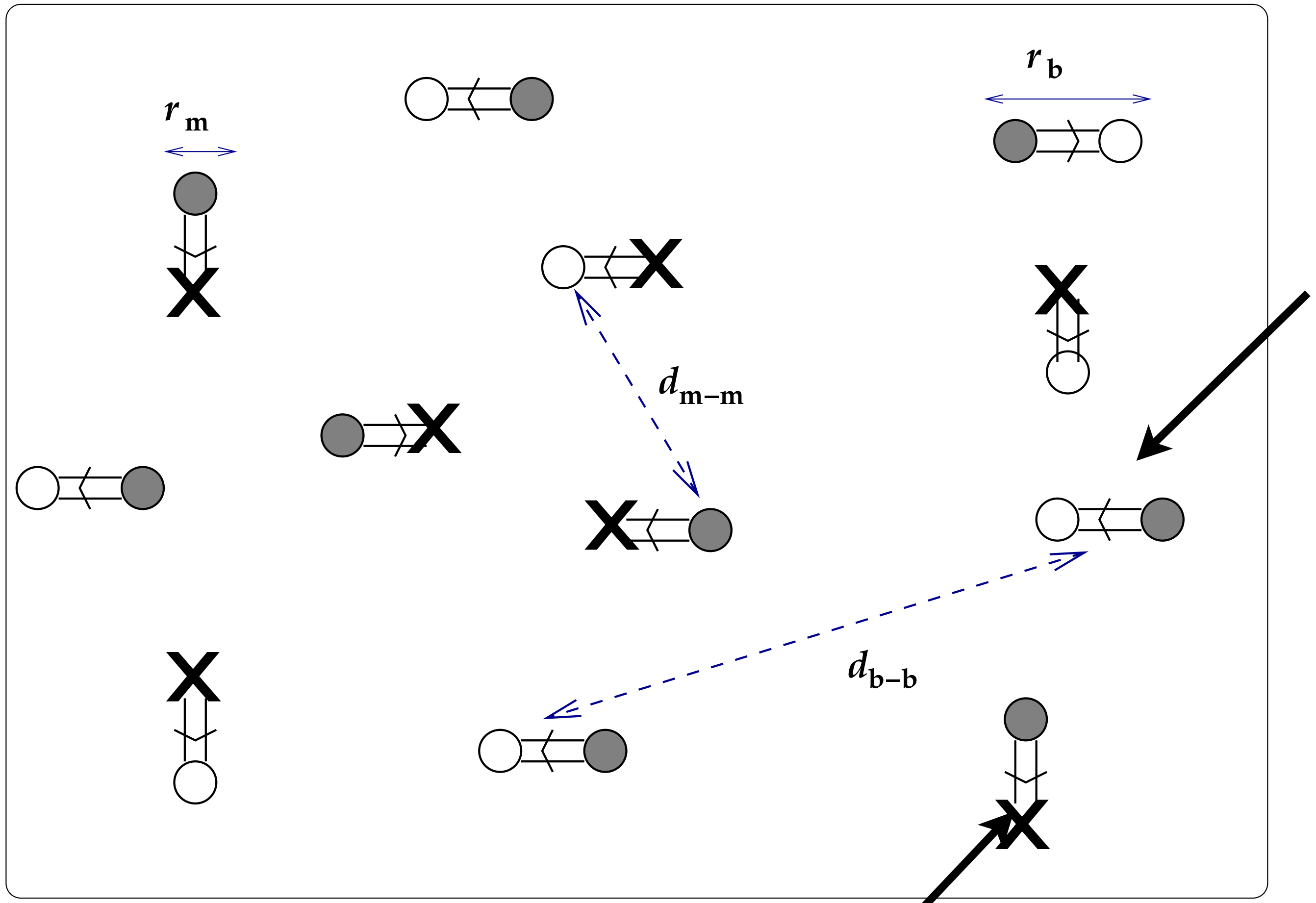


potential-producing center-stabilizing

$$e^{-2S_0}e^{-2\phi}$$

or magnetic bions

$$e^{-2S_0}e^{-i2\sigma}$$

x = gaugino mass insertion

monopole-instantons now also contribute to the potential

$$e^{-S_0}e^{+i\sigma-\phi}\xcancel{\bar{\lambda}}\lambda$$

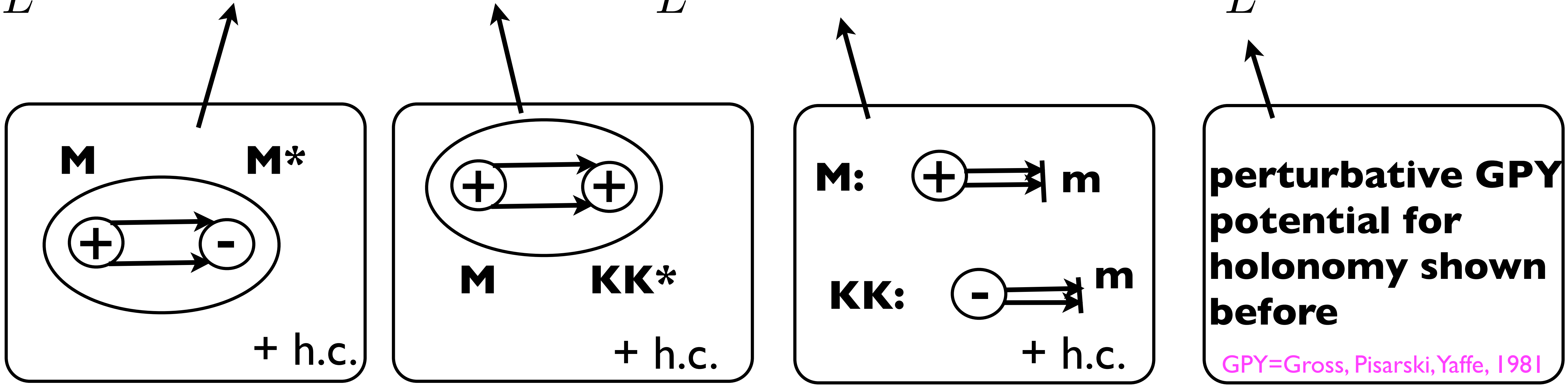
now turn on small gaugino mass “m”:

center-stabilizing “bions” - II and I

center-breaking (sigma=Pi is min) “monopole-instantons”

center-breaking

$$\frac{1}{L^3} e^{-\frac{8\pi^2}{g^2(L)}} (\cosh 2\phi - \cos 2\sigma) + \frac{m}{L^2} e^{-\frac{4\pi^2}{g^2(L)}} (\cosh \phi \cos \sigma) - \frac{m^2}{L} \phi^2$$



perturbative GPY potential for holonomy shown before

GPY=Gross, Pisarski, Yaffe, 1981

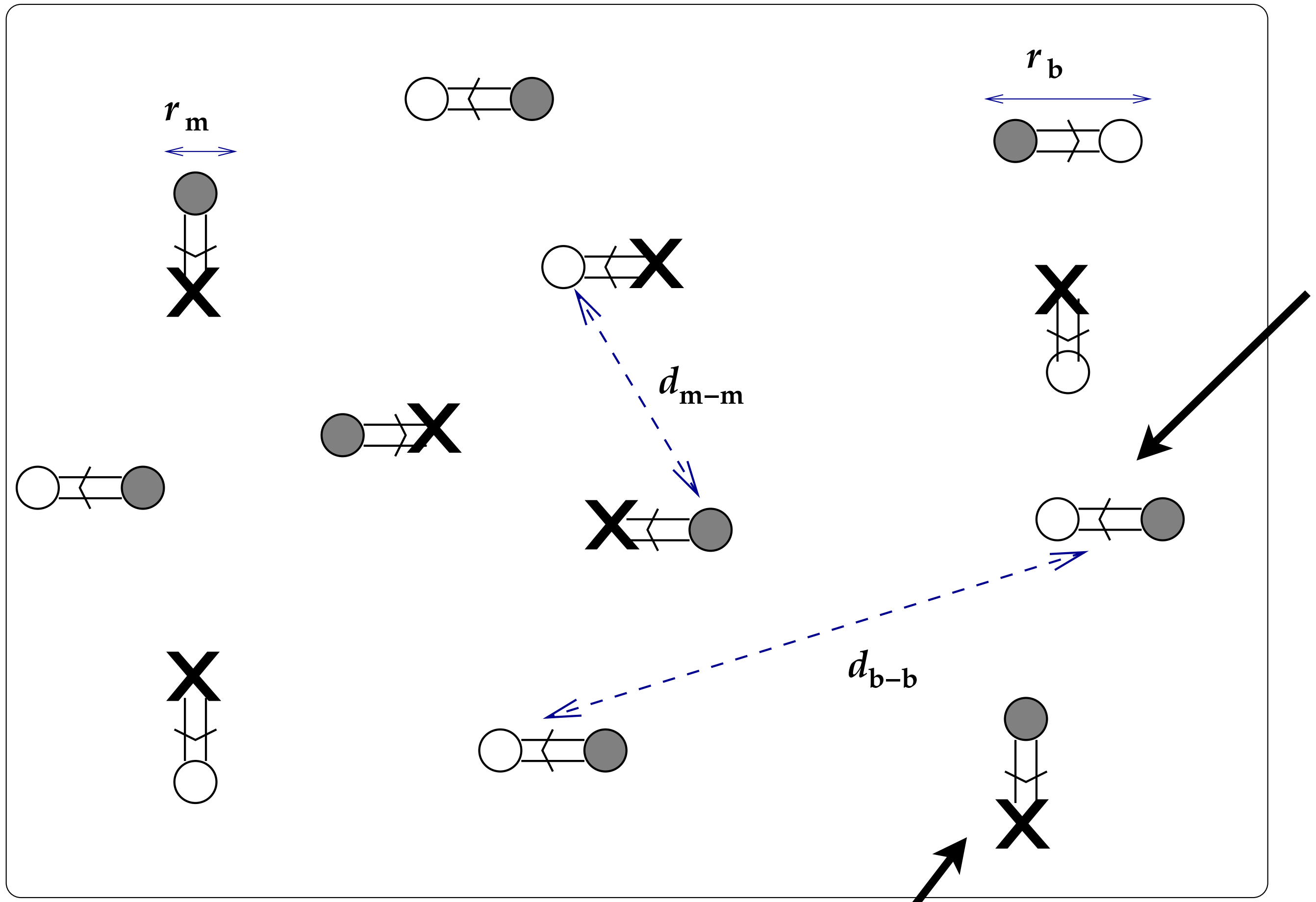
small SUSY breaking “m” allows us to have perturbative and nonperturbative contributions compete while under theoretical control, resulting in a center-breaking transition as $\frac{m}{L^2\Lambda^3}$ becomes O(1) (2nd order for SU(2); 1st for SU(N)...)

(assuming holds to m>O(Lambda), 1/L_c ~T_c ~ Lambda...)

Same objects can be identified in pure YM - but there can’t be a consistent semiclassical ‘fight’ between GPY and instantons there... but one can have models e.g.,

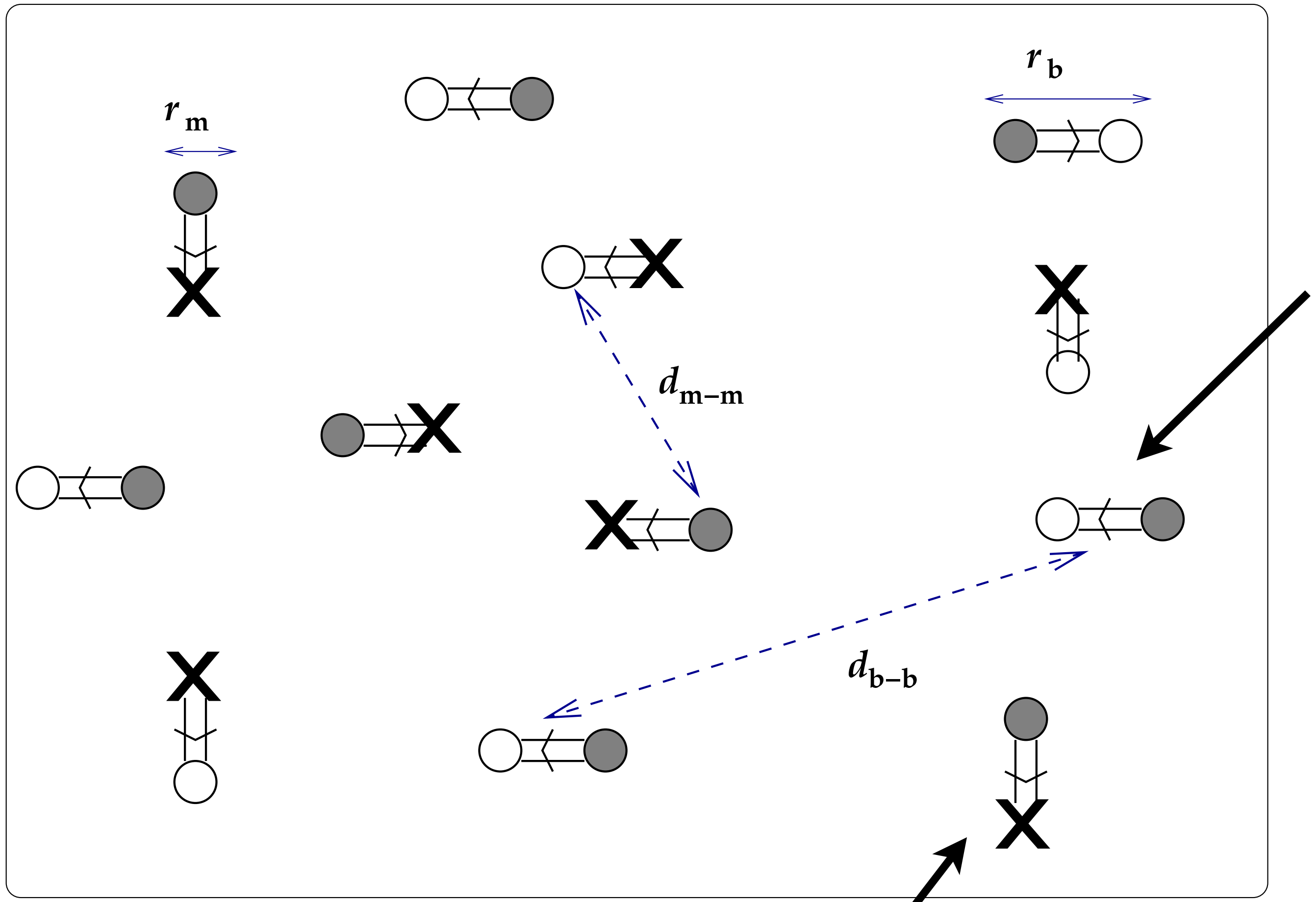
[Shuryak, Sulejmanpasic 2013

- instanton-liquid model (T=0 QCD vacuum) => monopole-instanton liquid model (T~T_c)]



neutral
“center-stabilizing” bions:

monopole-instantons:
-scalar interactions (likes attract)
-magnetic interactions (opposites attract)



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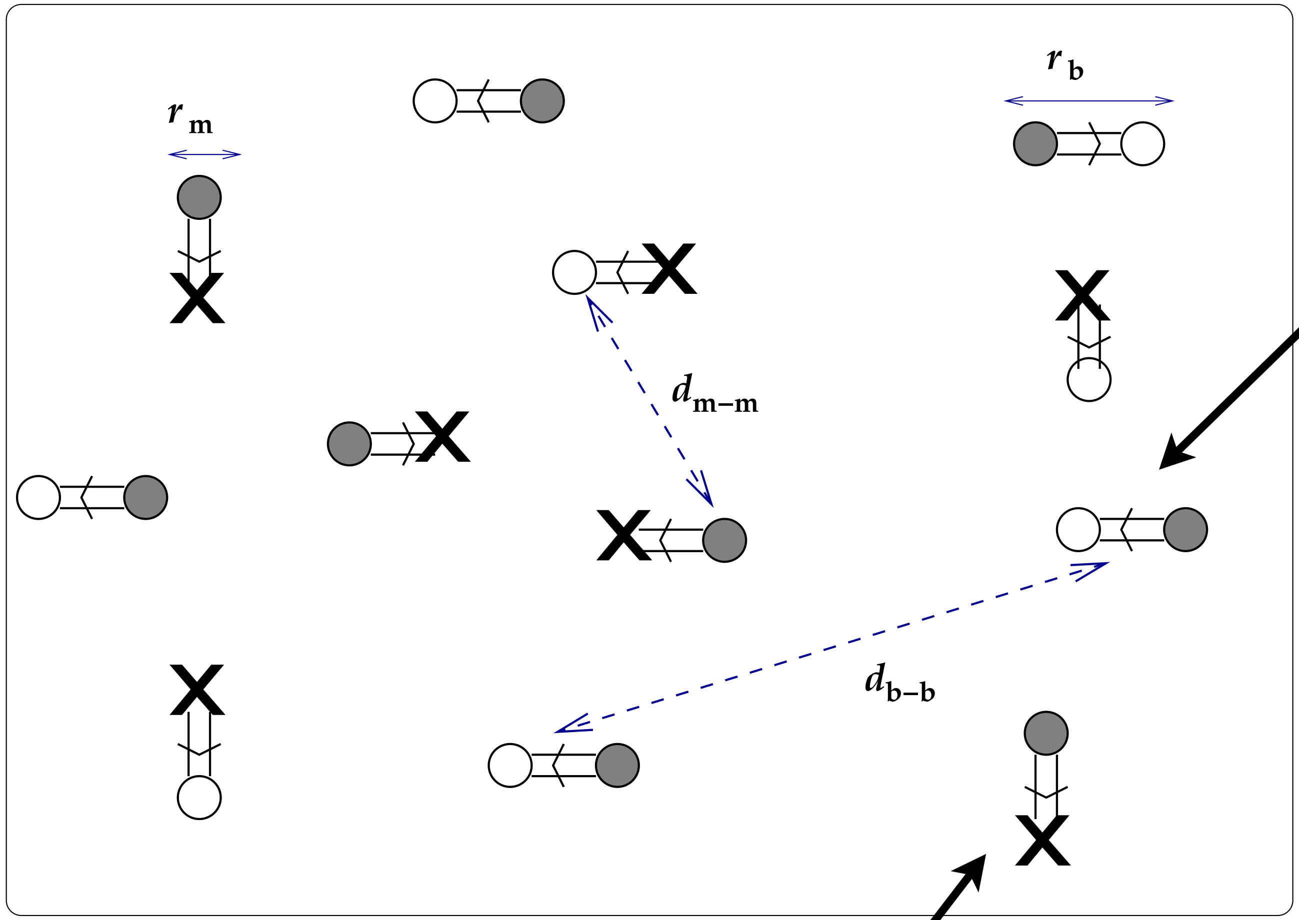
-scalar interactions (likes attract) ⟶ Dyson instability
-magnetic interactions (opposites attract) - center breaking



neutral
"center-stabilizing" bions:

-scalar interactions only
(likes attract)

however, Dyson stability
- center stabilizing -

negative fugacity (e.g., strange!) objects:
SUSY, BZJ [EP, Unsal 2011; Argyres, Unsal 2012] or
excluded volume [Shuryak ('80s) w/ Sulejmanpasic 2013]

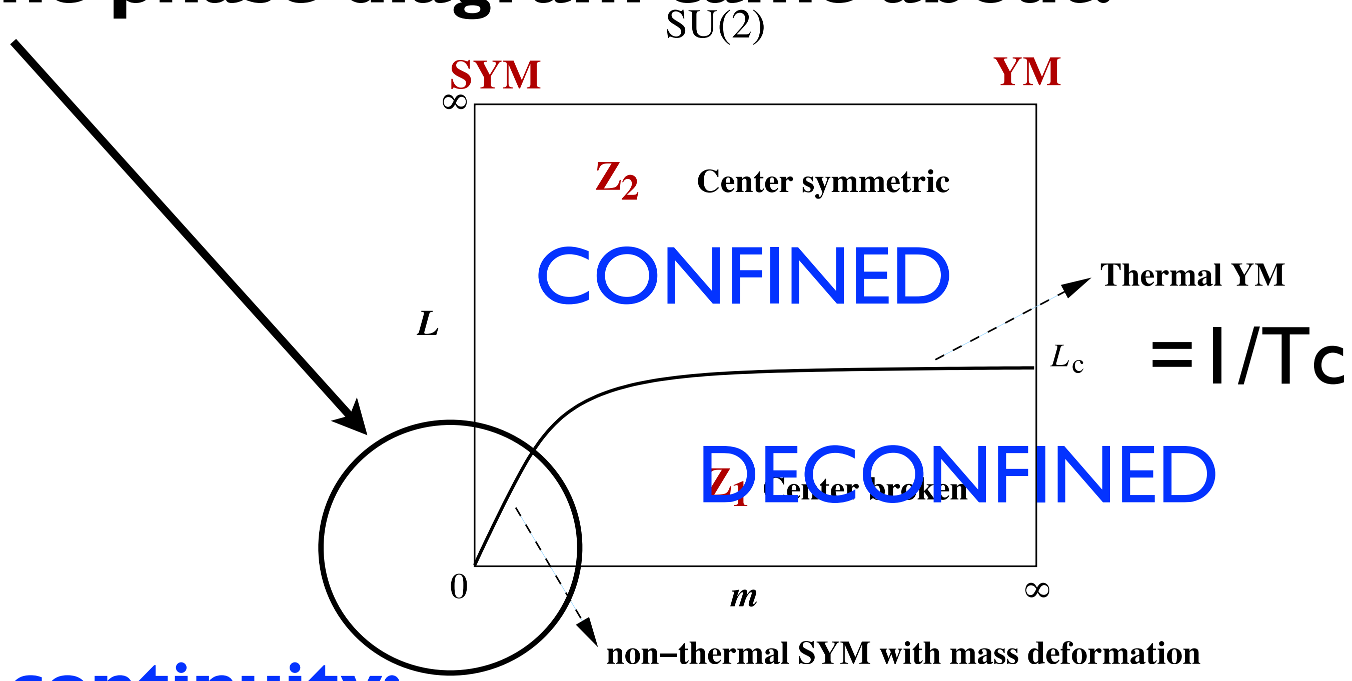
M ⊕→←⊖ **M***

M ± **M***

"objects" of scalar charge 2 only, with negative fugacity - exclude from Z!

monopole-instantons:
-scalar interactions (likes attract) → Dyson instability
-magnetic interactions (opposites attract) - center breaking

I told you how this part of the phase diagram came about.



Now, evidence in support of continuity:

- **same 'universality'** ('...': most 1st order) **class: Z_N breaking, for SU(N)**
- **same order of transition:**

  EP, Schaefer, Unsal, 2012

  - **1st order at N>2, as seen on lattice**
  - **1st order for G_2, as seen on lattice**

    not associated with symmetry breaking, as in real QCD with quarks

  EP, Sulejmanpasic, 2013

  - **with massive fundamental quarks transition becomes crossover**
- **theta-angle dependence of transition**

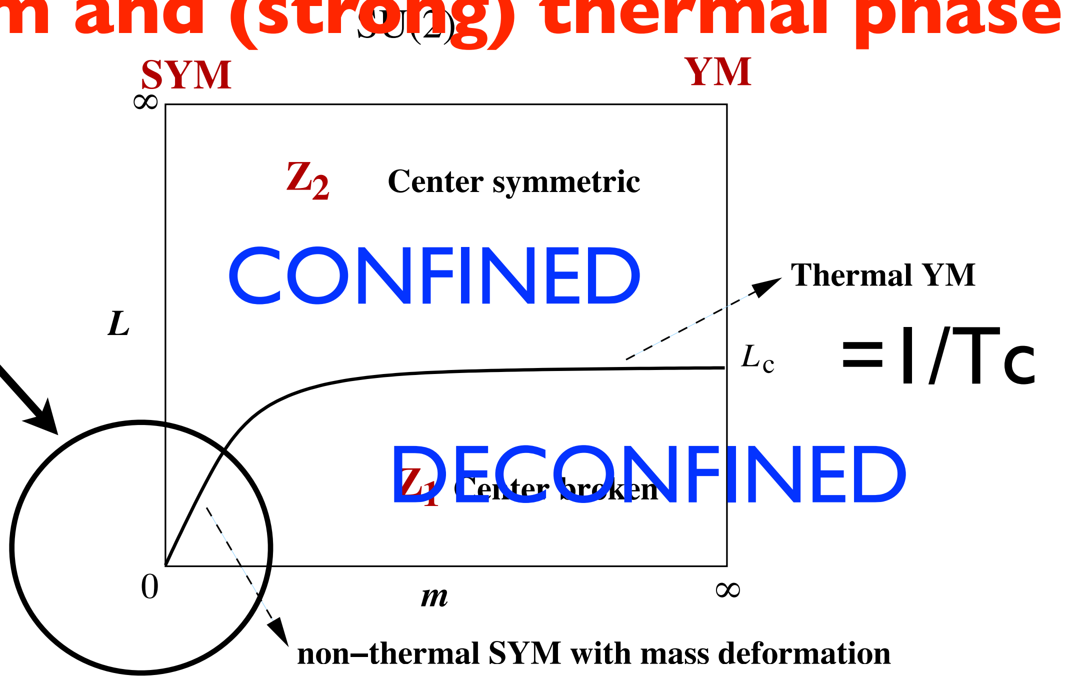
  these were actually predicted - Unsal 2012; EP, Schaefer, Unsal, 2012

  - **Tc decreases with increasing theta; seen on lattice** [D' Elia, Negro 2012]
  - **disc of Polyakov loop at Tc, for Nc>2, increases with increasing theta** [predicted Mohamed Anber 2013] **and seen on lattice** [D' Elia, Negro 2013]

SUMMARY AND OUTLOOK:

I told you how a (calculable) quantum and (strong) thermal phase transitions appear related...

...and gave some evidence in support of continuity conjecture, most of it coming from lattice simulations.



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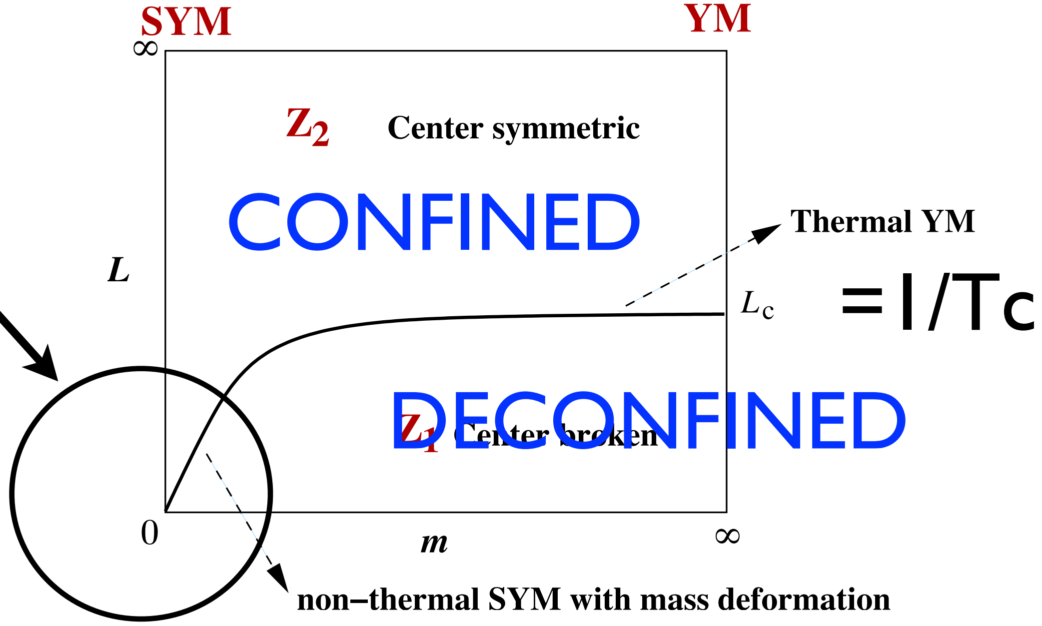

What's next?

- **SYM with gaugino mass can be simulated using current technology, so phase diagram can be verified**
- **lessons for models near Tc: 'center-stabilizing bions' due to excluded volume in instanton-monopole liquid model -**
  Shuryak w/ Sulejmanpasic, Faccioli 2013... claim crude models describe lattice data on E/M mass

Recall we started from D-branes and N=4 and are now in pure-YM theory!

Things I am looking at (w/ Anber, Sulejmanpasic)

- **pursuing calculable regime to next order in 'm' is possible (and fun); it is of interest to understand, e.g., topological susceptibility above Tc** as per lattice (also Zhitnitsky 2000, 2009)
- **center symmetry does not, in general, determine universality class (e.g., lattice SP(n) YM) - how does this play out here?**

& generally, aiming at better understanding (Dyson?)

Back to the theme of this talk:

I described an(other) example of how ideas initially found in string theory and supersymmetry improve our understanding of “ordinary” non-SUSY gauge dynamics.

I think there’s some use of SUSY, even if not found at LHC...

...hoping to be around for SUSY 20x3!