Understanding confinement via instanton-monopoles

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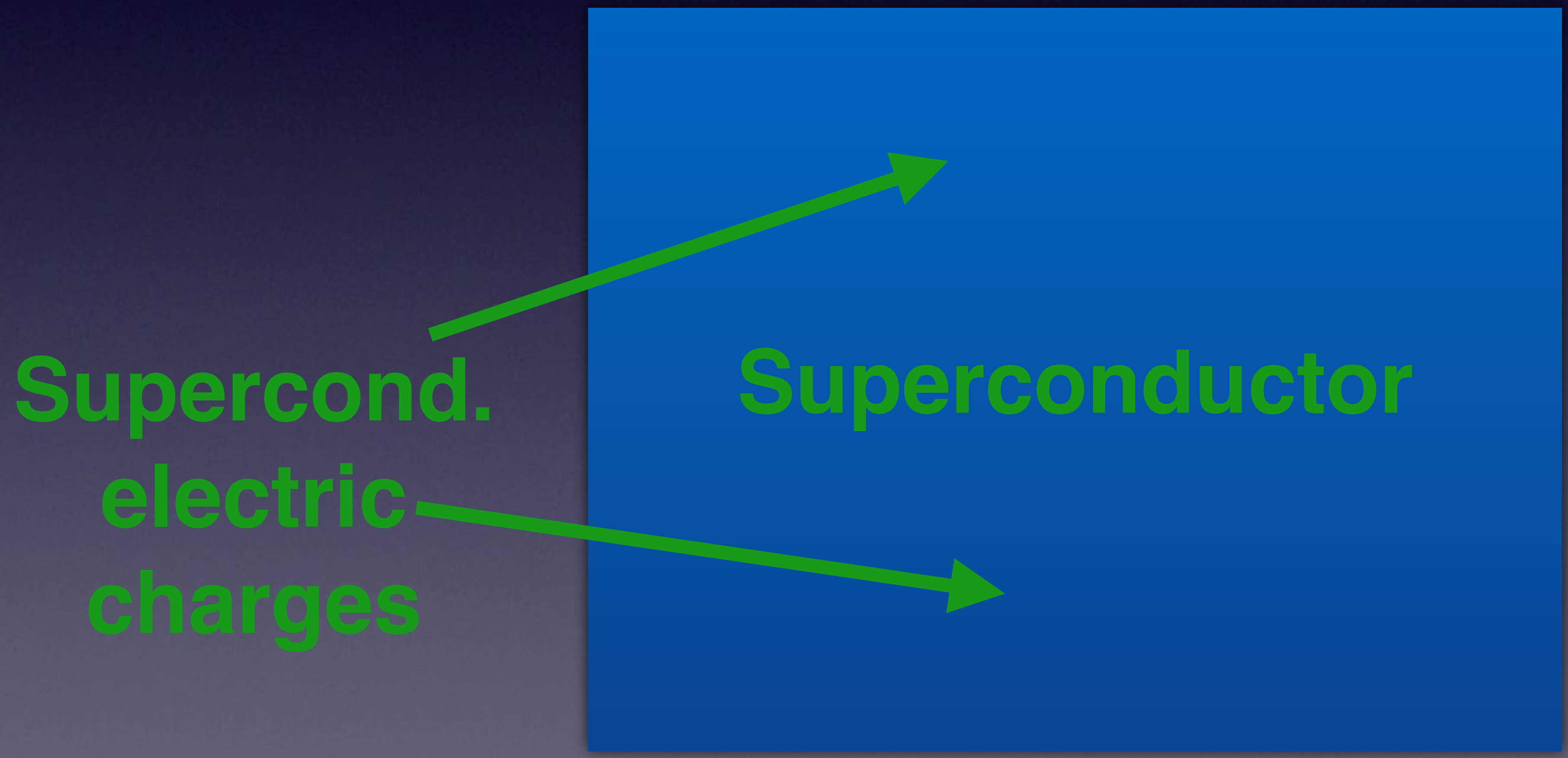
Outline

- Motivating monopoles
  - Dual superconductor
  - Georgi-Glashow
- YM and cousins on R3xS1
  - Super YM
  - SQCD
  - Pure Yang-Mills
- Conclusion

Introduction

- 30+ years non-perturbative aspects of Yang Mills theory are still puzzling
- No proof of mass gap and confinement: millennium problem
- Even with many models and conjectures, no consensus on what the underlying mechanism is
- However there is a favorite!

Favorite mechanism
Confinement a la ’t Hooft



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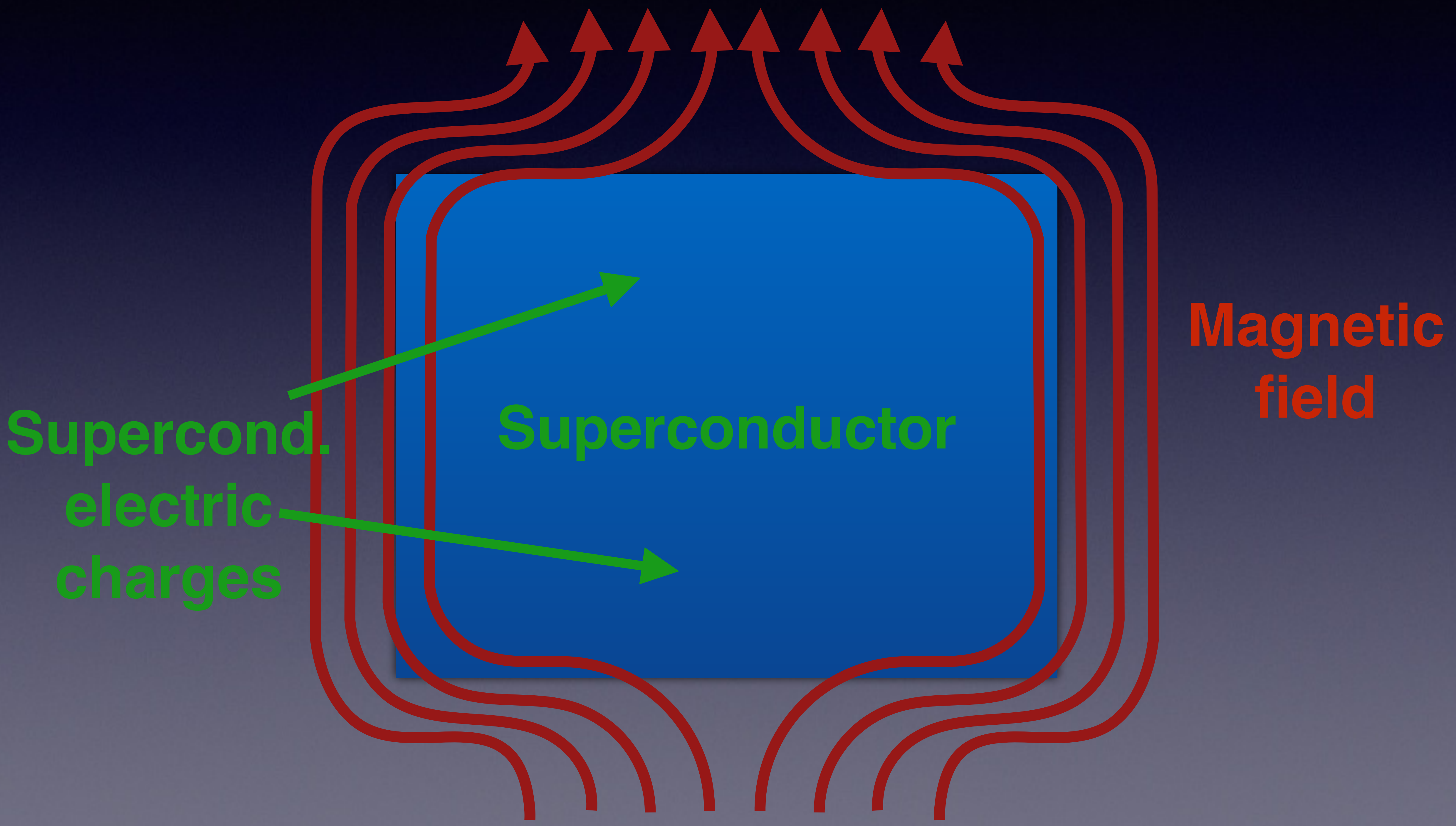

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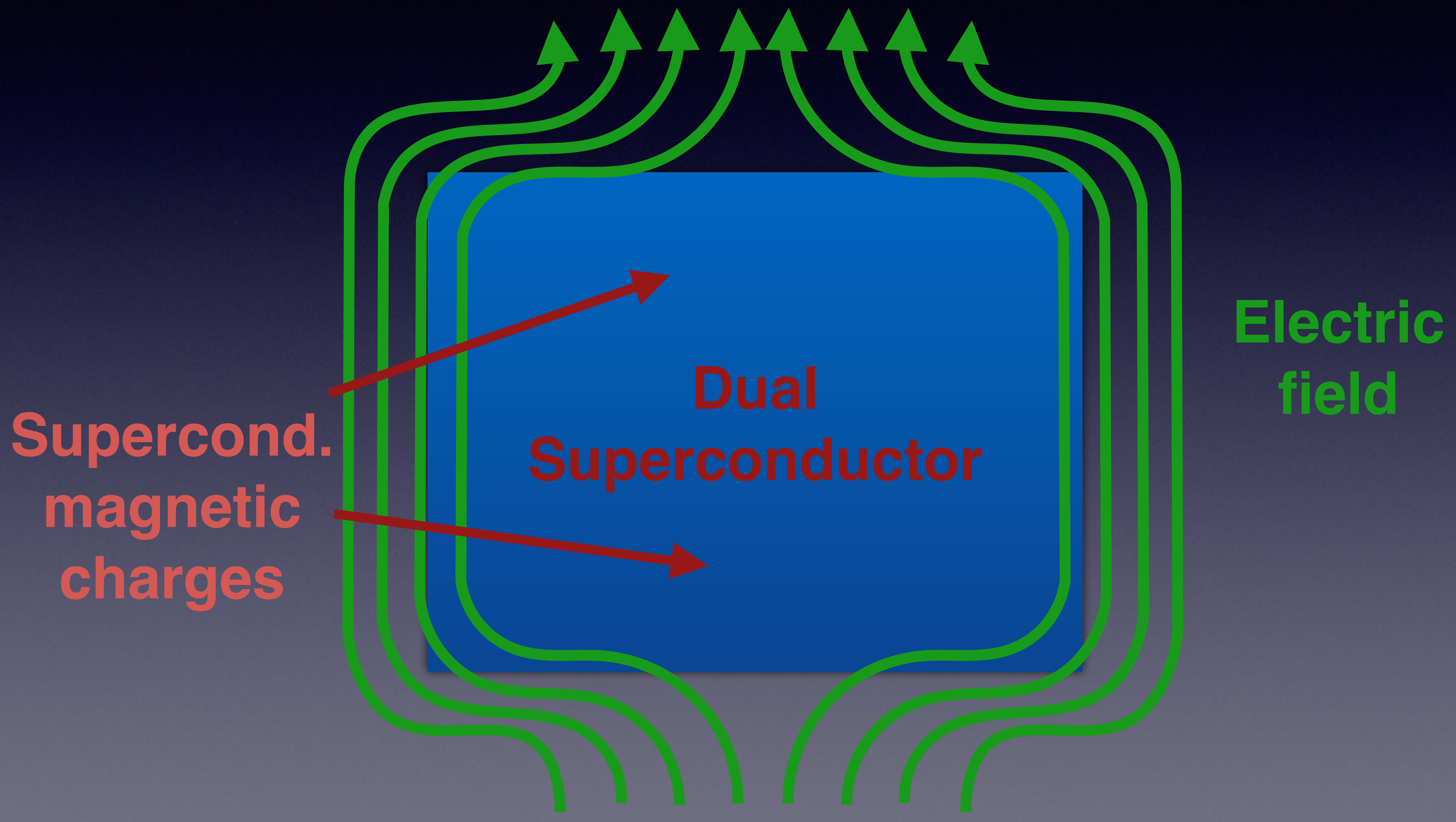

Favorite mechanism
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Electric field

Supercond. magnetic charges

Dual Superconductor

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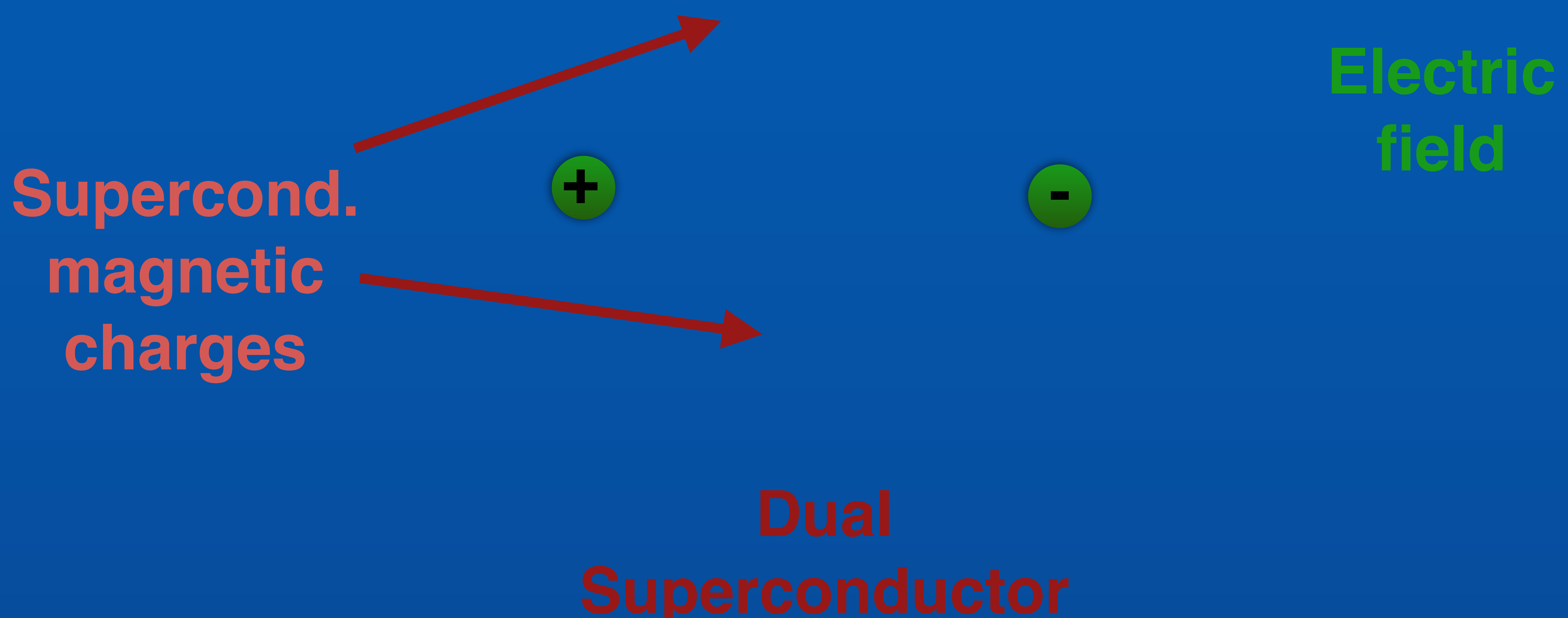

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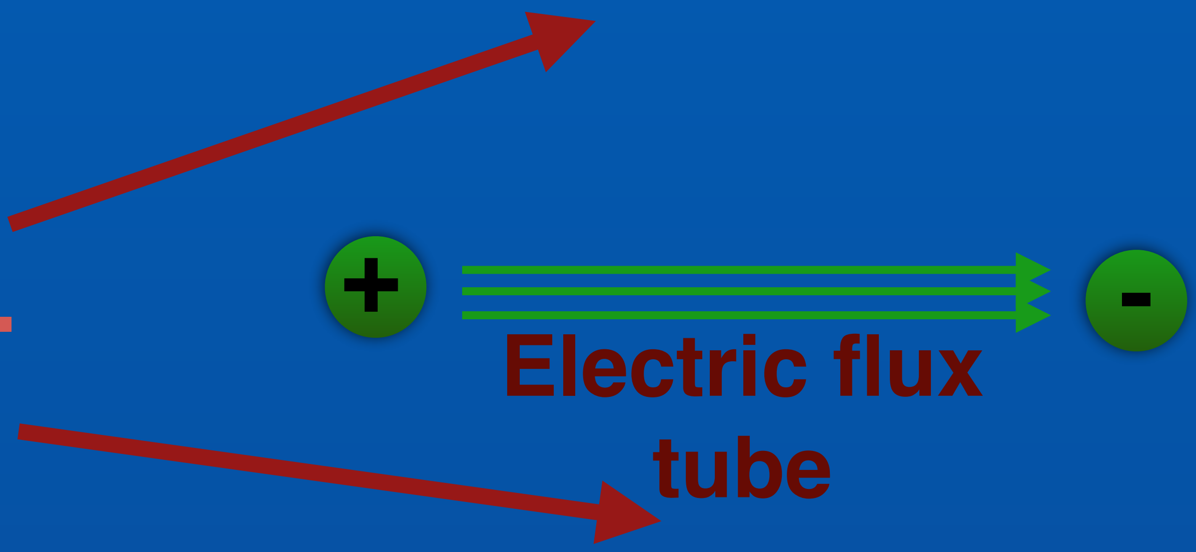
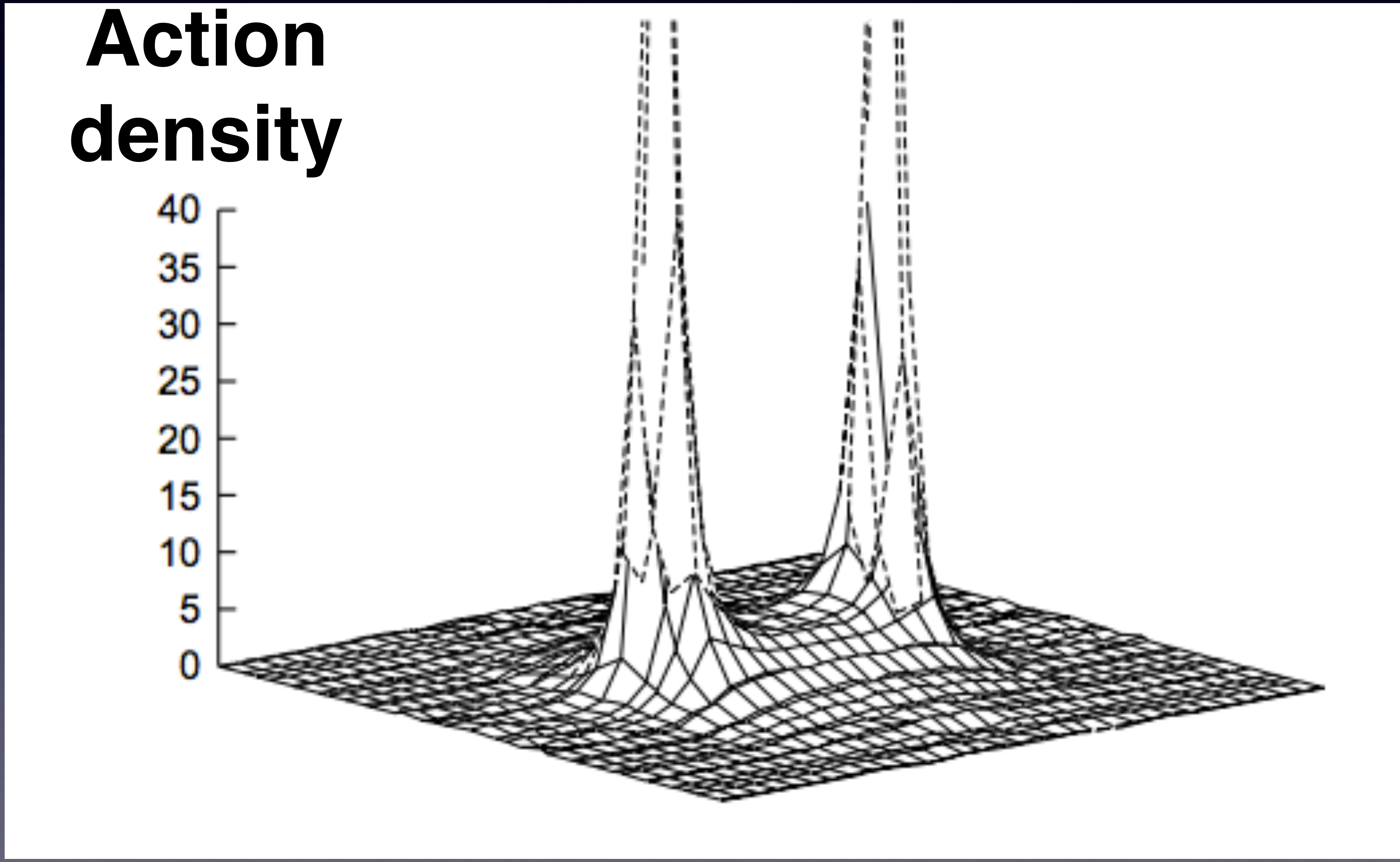


Dual Superconductor

This is what is seen on the lattice



G.S. Bali K. Schilling and Ch. Schlichter, Phys.Rev. D51 (1995) 5165.

More then words: Confinement a la Polyakov

SU(2) Georgi-Glashow model

$$\mathcal{S} = \frac{1}{2g_3^2} \int d^3x \left[\mathrm{Tr} F_{ij}^2 + \mathrm{Tr}(D_i \Phi)^2 + V(|\Phi|^2) \right]$$

$$\Phi = \Phi^a \frac{\tau^a}{2}$$ - **Adjoint Higgs field**

$$D_i \Phi = \partial_i + i[A_i, \Phi]$$

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$$\mathcal{S} = \frac{1}{2g_3^2}\int d^3x \left[\mathrm{Tr}F_{ij}^2 + \mathrm{Tr}(D_i\Phi)^2 + V(|\Phi|^2)\right]$$

If $V(|\Phi|^2)$ **is minimized at** $|\Phi| = v$

$(D_i\Phi)^2 \propto v^2\left[(A_\mu^1)^2 + (A_\mu^2)^2\right]$ **massive W-bosons!**

Gauge choice: $\langle\Phi\rangle = v\dfrac{\tau^3}{2}$

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- Two out of three gauge bosons are heavy by Higgs mechanism, while one remains massles

- The low energy effective theory is a U(1) theory, i.e.

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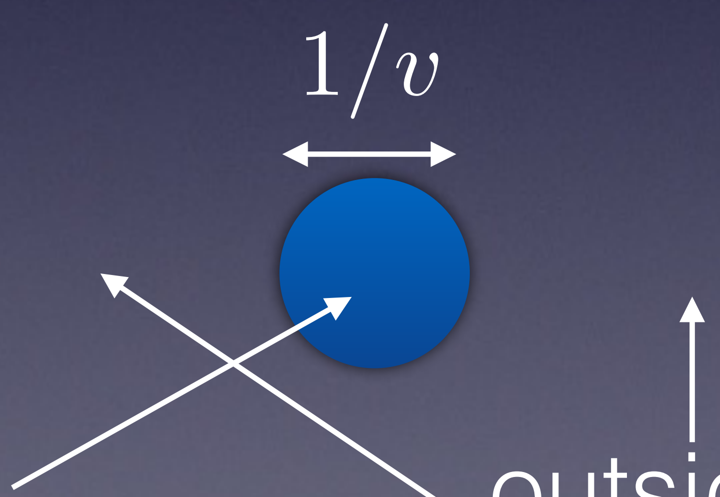

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$1/v$

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HOW TO TAKE THEM INTO ACCOUNT?

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$$\left\langle e^{i\sigma(\mathbf{X})} \right\rangle$$ A magnetic monopole at $\mathbf{X}$!

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resummation

⇒ $$\mathcal{L}_{mon} \propto -m^2 \cos\sigma \qquad m \propto e^{-S}, S \propto \frac{1}{g_3^2(v)}$$

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resummation ⇒

MASS GAP!

$$\mathcal{L}_{mon} \propto -m^2 \cos\sigma \qquad m \propto e^{-S}\, , S \propto \frac{1}{g_3^2(v)}$$

Area law: $\left\langle e^{i \int dx^i \; A_i} \right\rangle$

Electric current
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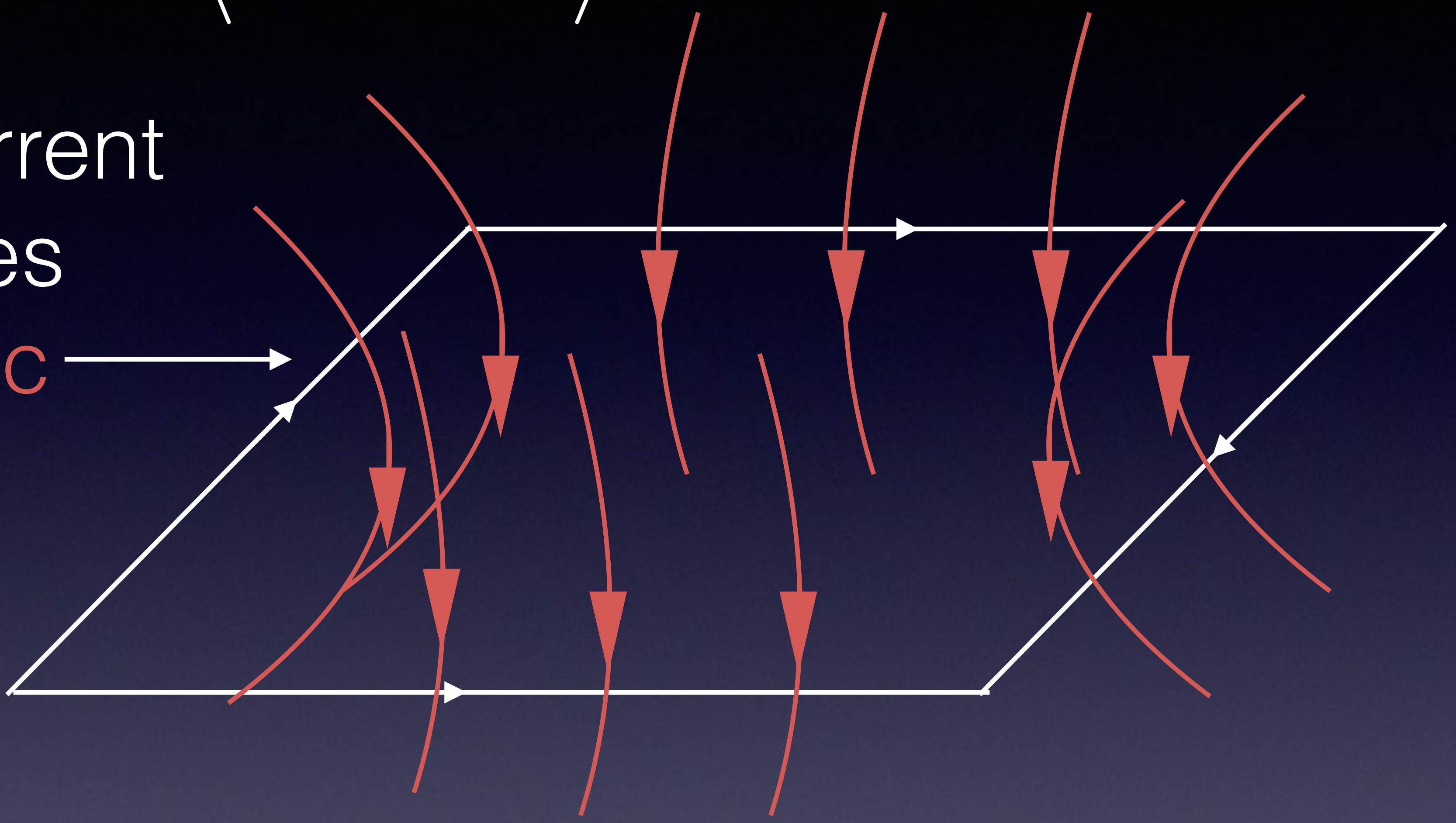

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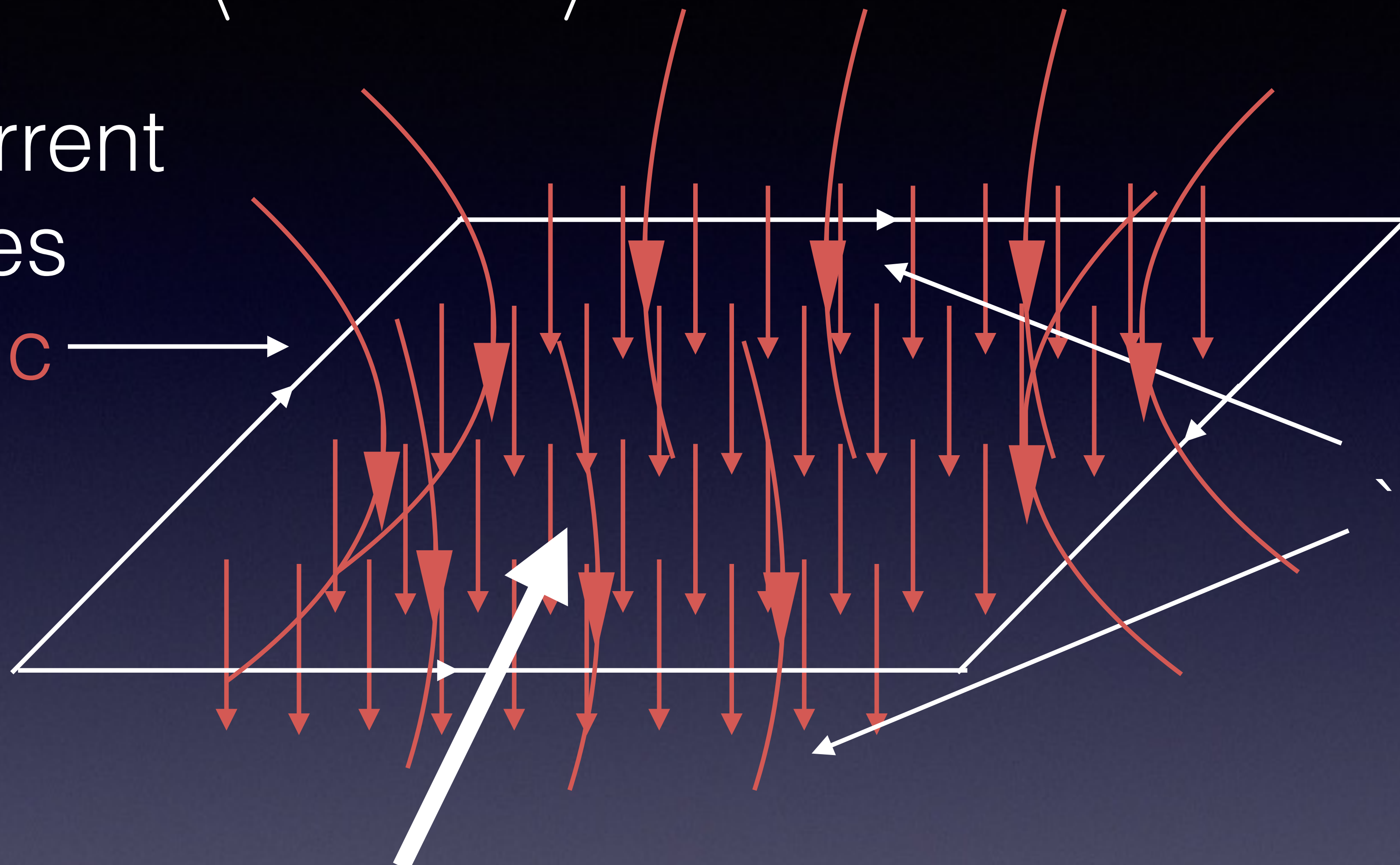
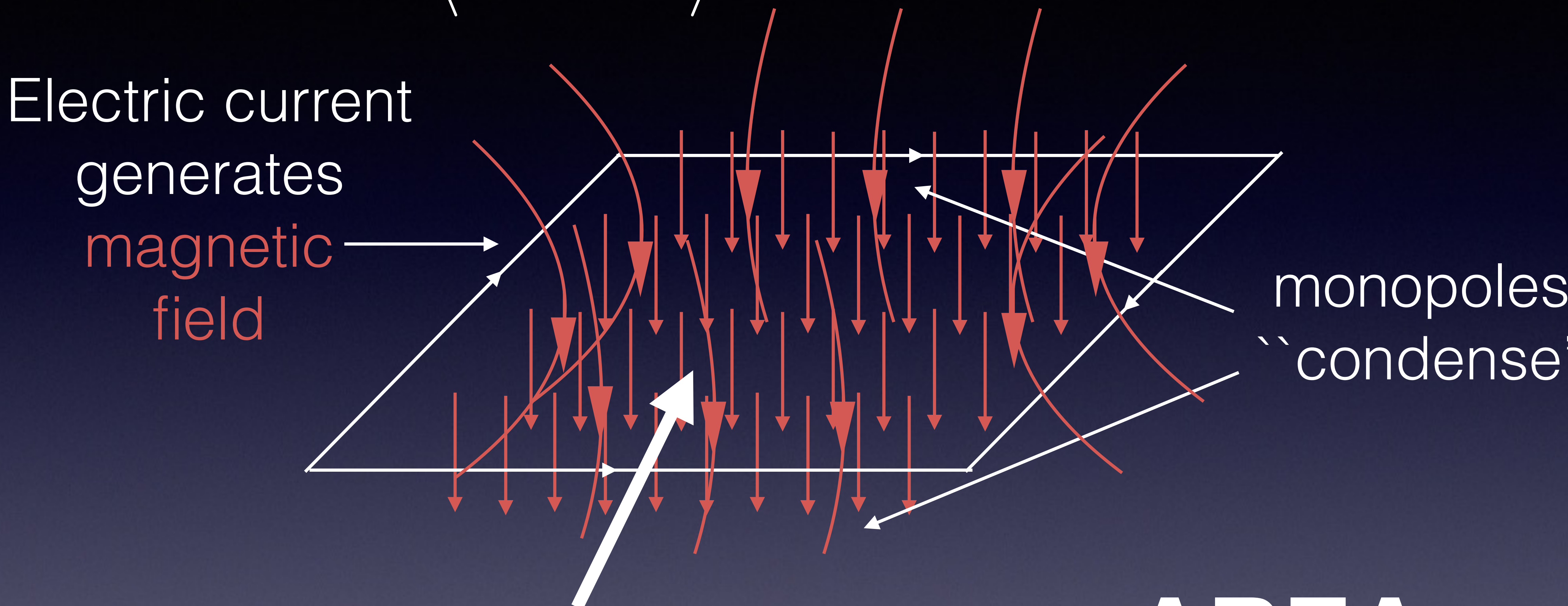


monopoles ``condense''

Magnetic ``energy'' density scales with area

Area law: $\left\langle e^{i \int dx^i \, A_i} \right\rangle$



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AREA LAW!

Yang Mills and its cousins in 4D (locally)

Quasi-4D SU(2) Yang-Mills

Compactify 4D on $R^3 \times S^1$

L - Radius of S^1

$$\mathcal{S} = \frac{1}{2g^2} \int d^4x \; \mathrm{tr} F_{\mu\nu}^2 \rightarrow \frac{L}{g^2} \int d^3 \mathrm{tr} \left(F_{ij}^2 + (D_i A_0)^2 \right)$$

Looks like the kinetic term of the adjoint Higgs

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BUT NO POTENTIAL FOR THE HIGGS!!! (classically)

$$A_0 = v\frac{\tau^3}{2}$$

$$v - 4\pi/L \text{ periodic} \Leftarrow \left(A_0 = U A_0 U^\dagger + iU\partial_0 U^\dagger\right)$$

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The Higgs field is a periodic field!

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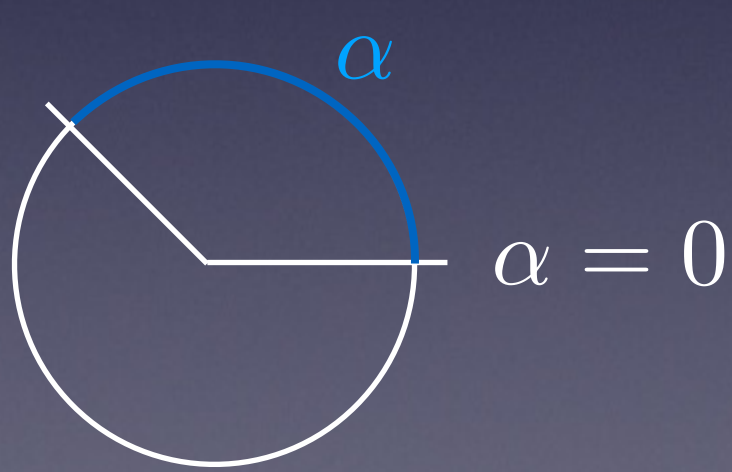

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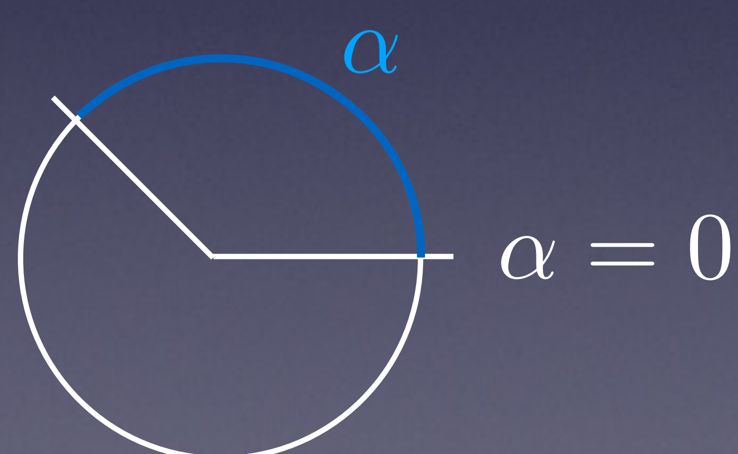

$$e^{-\frac{4\pi}{g^2}\alpha}$$

$\frac{4\pi}{g^2}\alpha$ → Action

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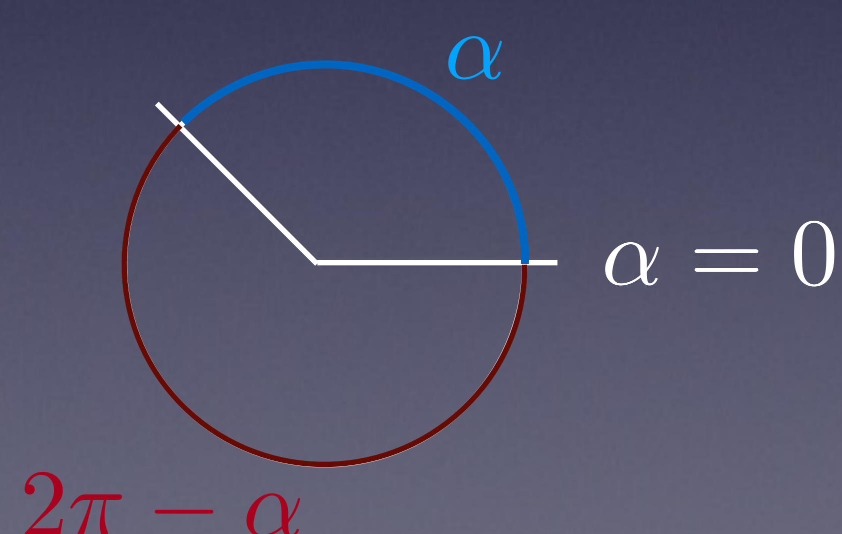

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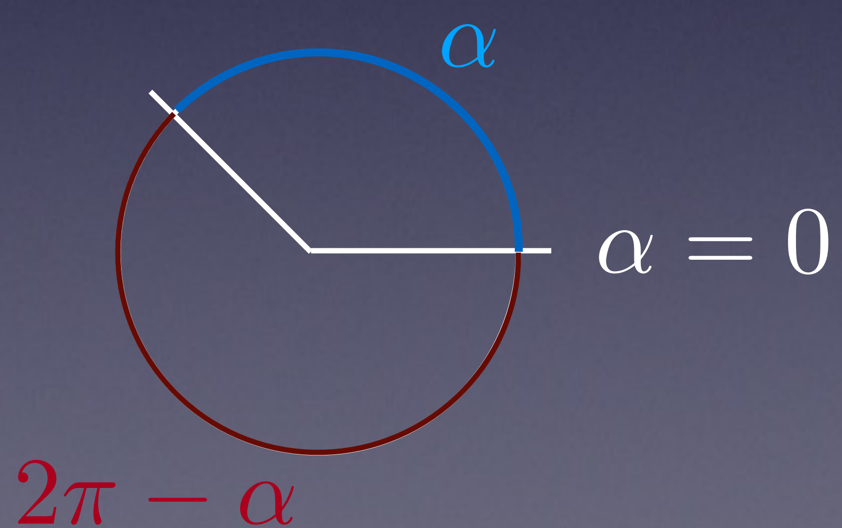

Action

$$e^{-\frac{4\pi}{g^2}\alpha}$$

$$e^{-\frac{4\pi}{g^2}(2\pi - \alpha)}$$

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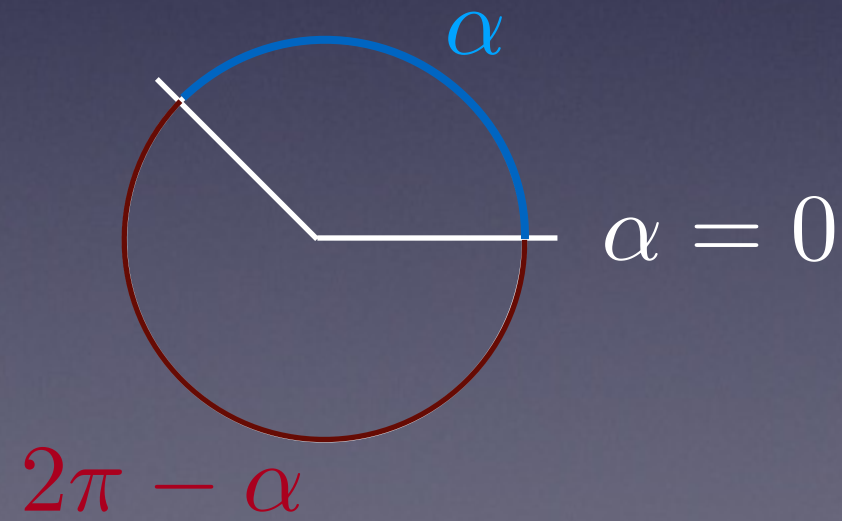

$$e^{-\frac{4\pi}{g^2}\alpha \pm i\sigma}$$

$$e^{-\frac{4\pi}{g^2}(2\pi - \alpha)\pm i\sigma}$$

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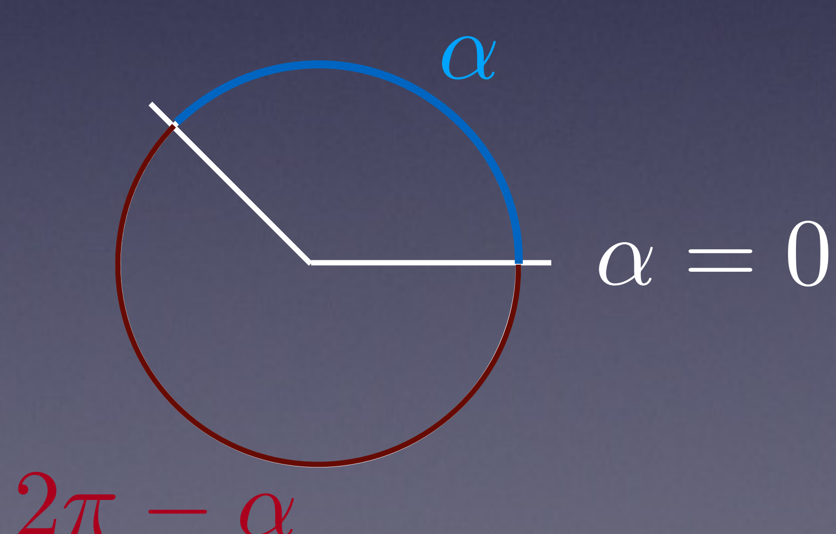

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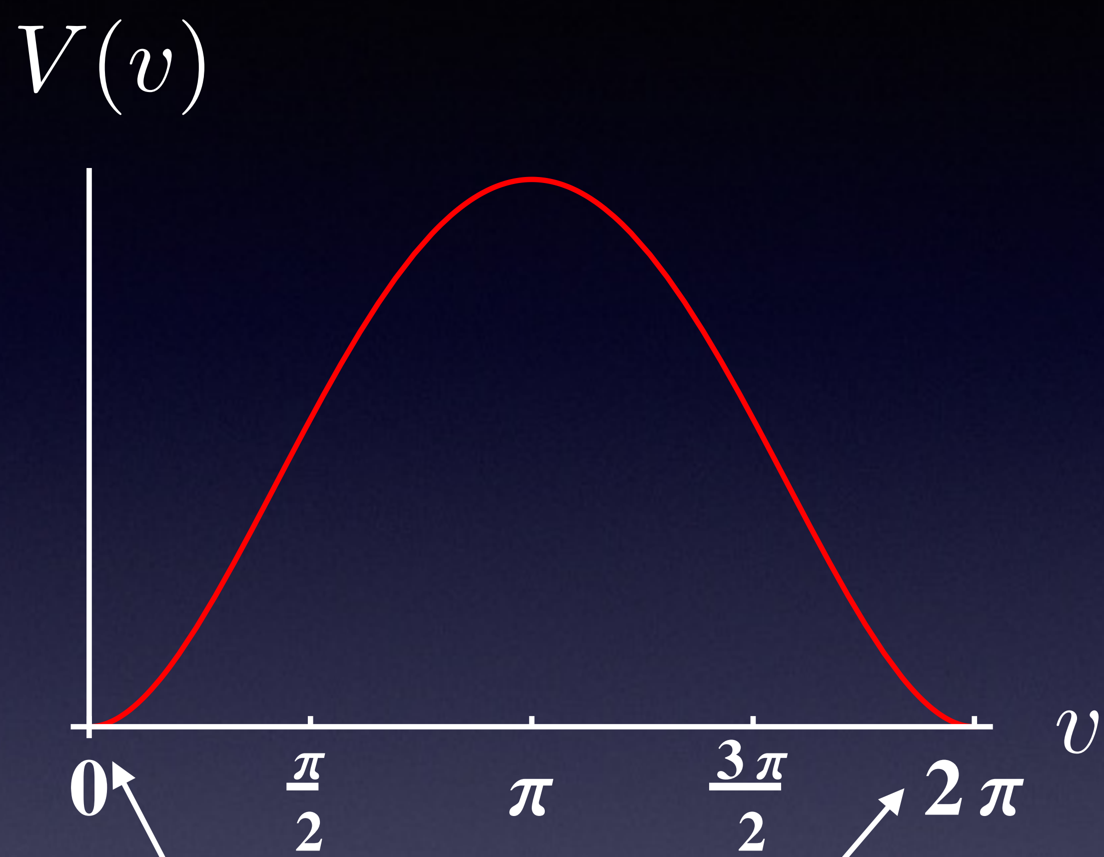
4 kinds of (anti-)monopoles!

Instanton-monopoles

One loop potential:



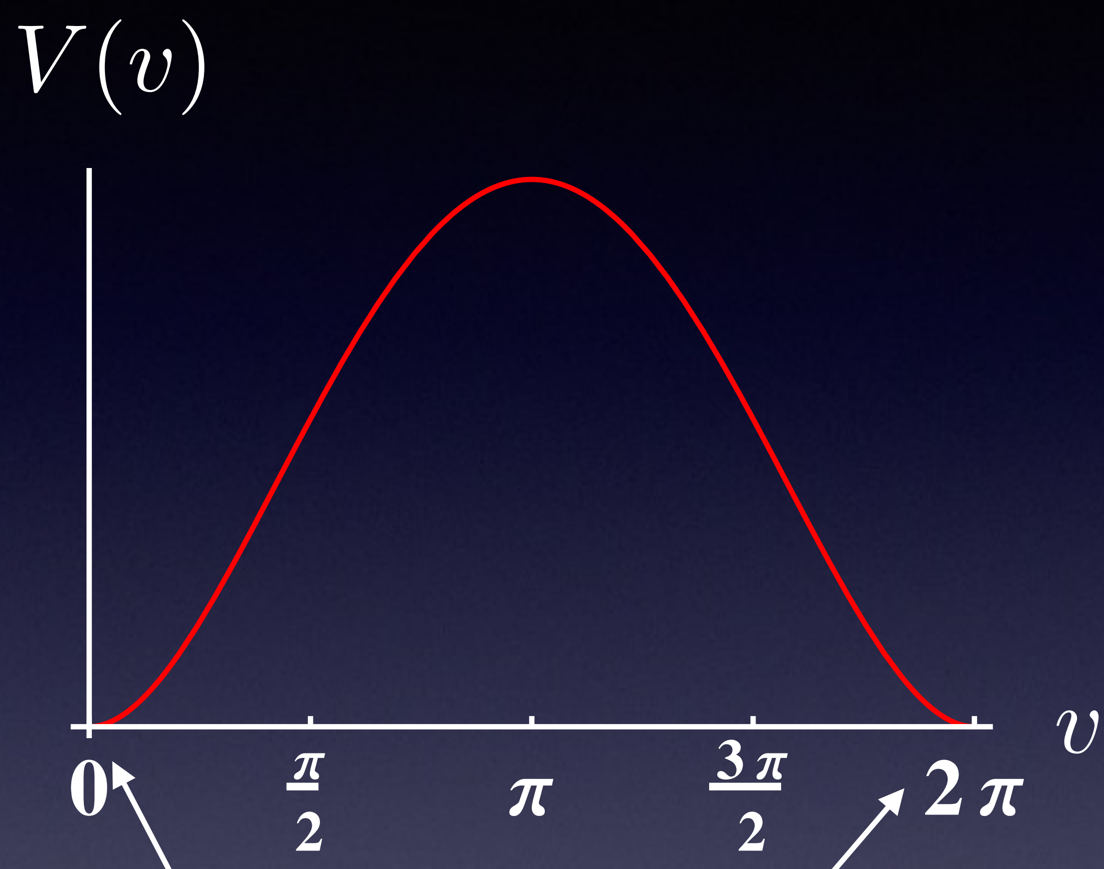
Minima
at
“trivial” points

One loop potential:

$$\langle \mathcal{L} \rangle = \left\langle e^{i \frac{Lv}{2} \tau^3} \right\rangle = 1$$

DECONFINED!

No Higgs mechanism!
No abelianization!



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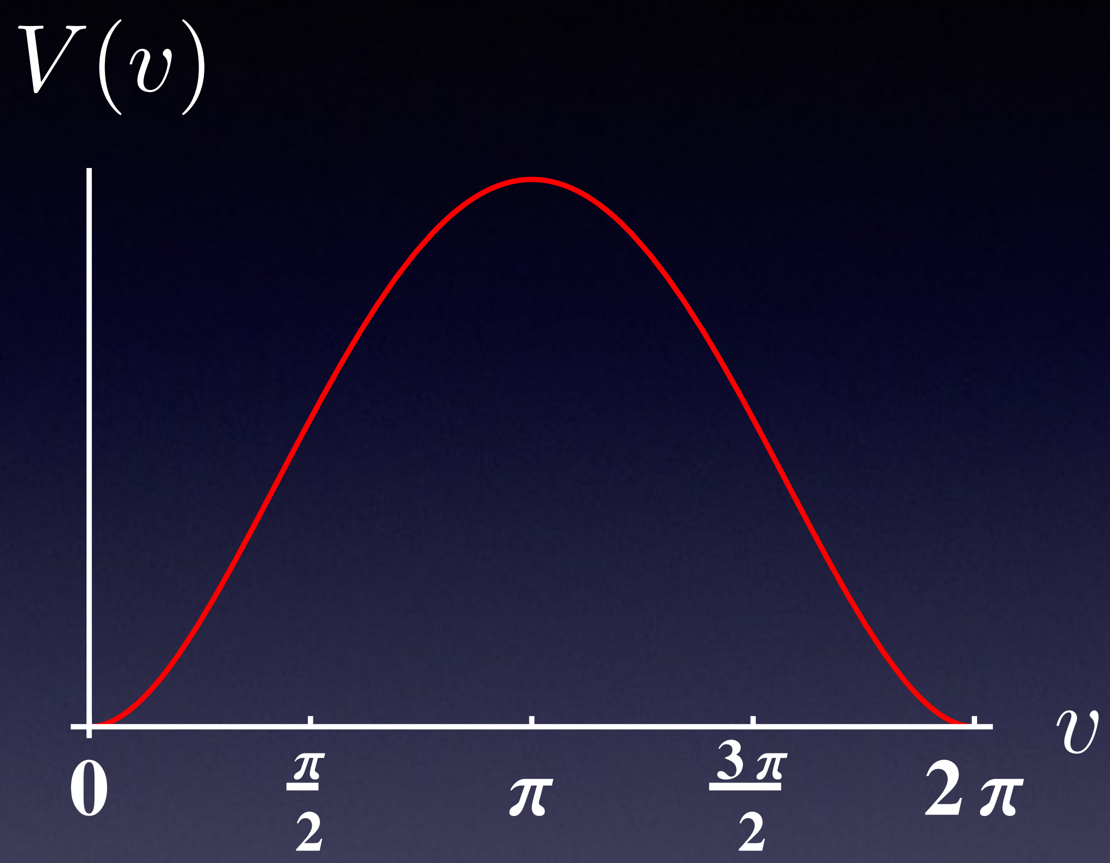


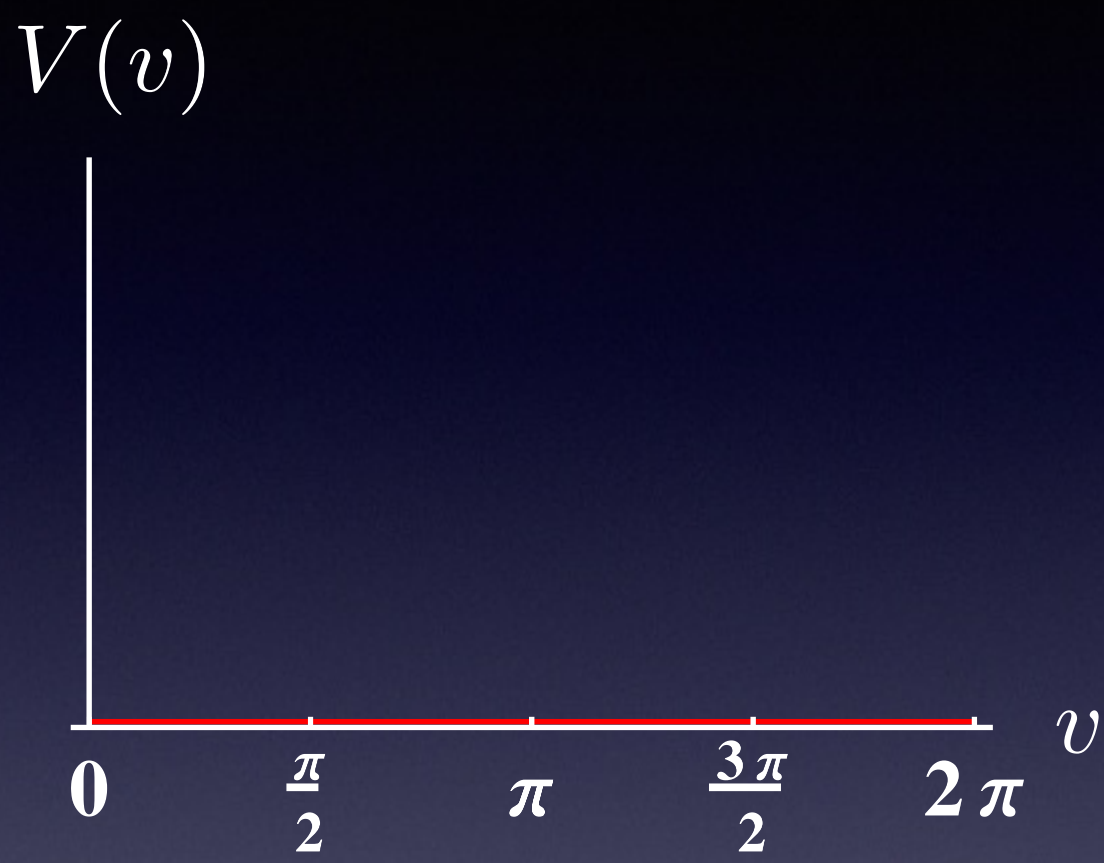
Now add one flavor of adjoint Weyl fermions!

SUSY THEORY!!!

One loop potential:

$$\langle \mathcal{L} \rangle = \left\langle e^{i \frac{Lv}{2} \tau^3} \right\rangle \stackrel{?}{=} 0$$

CONFINED??



No potential perturbatively!

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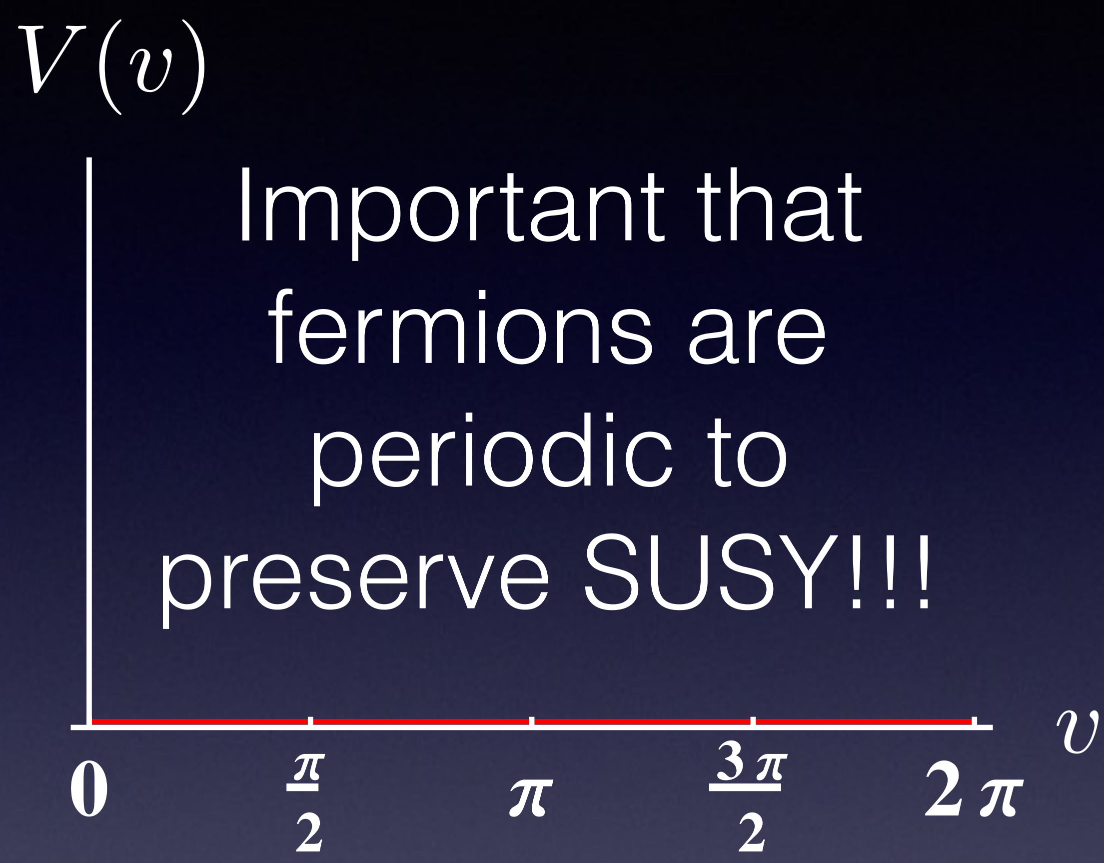

Important that fermions are periodic to preserve SUSY!!!

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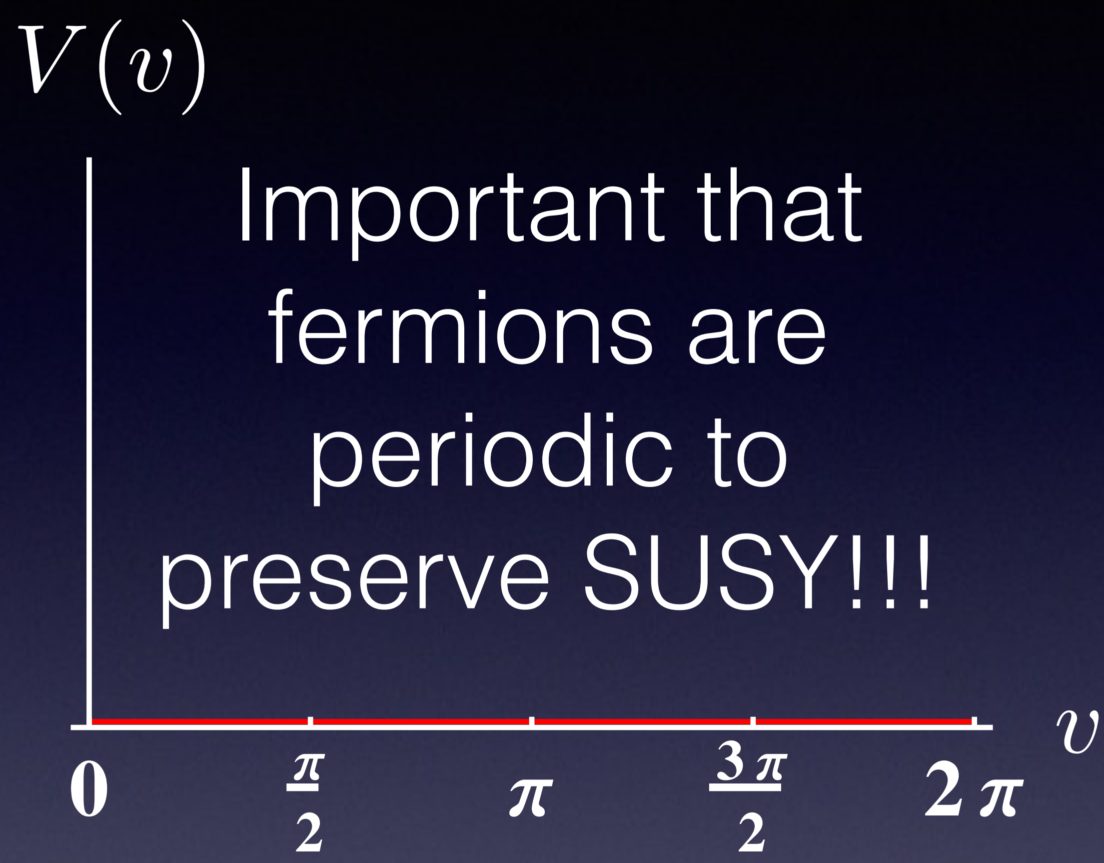

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SUSY THEORY!!!

NONPERTURBATIVE EFFECTS ARE IMPORTANT!!!

The monopoles

$$e^{-\frac{4\pi}{g^2}\alpha + i\sigma} \qquad e^{-\frac{4\pi}{g^2}\alpha - i\sigma}$$

$$e^{-\frac{4\pi}{g^2}(2\pi - \alpha) - i\sigma} \qquad e^{-\frac{4\pi}{g^2}(2\pi - \alpha) + i\sigma}$$

The monopoles

$$e^{-S_0+b+i\sigma} \qquad e^{-S_0+b-i\sigma}$$

$$e^{-S_0-b-i\sigma} \qquad e^{-S_0-b+i\sigma}$$

$$S_0 = \frac{4\pi^2}{g^2} \qquad b = \frac{4\pi(\pi-\alpha)}{g^2}$$

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($b = 0$ means confinement!!!)

The monopoles

$$\lambda\lambda\, e^{-S_0 + b + i\sigma} \qquad \bar{\lambda}\bar{\lambda}\, e^{-S_0 + b - i\sigma}$$

$$\lambda\lambda\, e^{-S_0 - b - i\sigma} \qquad \bar{\lambda}\bar{\lambda}\, e^{-S_0 - b + i\sigma}$$

't Hooft vertices (axial anomaly)

$$S_0 = \frac{4\pi^2}{g^2} \qquad b = \frac{4\pi(\pi - \alpha)}{g^2}$$

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Effective SUSY

- $\lambda\lambda e^{b+i\sigma}$ - $\lambda\lambda e^{-b-i\sigma}$ - $\bar{\lambda}\bar{\lambda} e^{b-i\sigma}$ - $\bar{\lambda}\bar{\lambda} e^{-b+i\sigma}$

Effective SUSY

Must have a superpotential description **i.e.**

$$\int d^2\theta \, W(B(y,\theta)) + c.c. =$$

$$B = b + i\sigma + \sqrt{2}\theta\lambda + \ldots$$

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$$+ e^{2b} + e^{-2b} - e^{2i\sigma} - e^{-2i\sigma}$$

Effective SUSY

Khoze et. al. 1998

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$$-\lambda\lambda e^{b+i\sigma} - \lambda\lambda e^{-b-i\sigma} - \bar{\lambda}\bar{\lambda} e^{b-i\sigma} - \bar{\lambda}\bar{\lambda} e^{-b+i\sigma}$$

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Magnetic bions
M. Unsal (2009-)

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Neutral bions
Poppitz, Schafer, Unsal (2012)

Magnetic bions
M. Unsal (2009-)

Breaking SUSY

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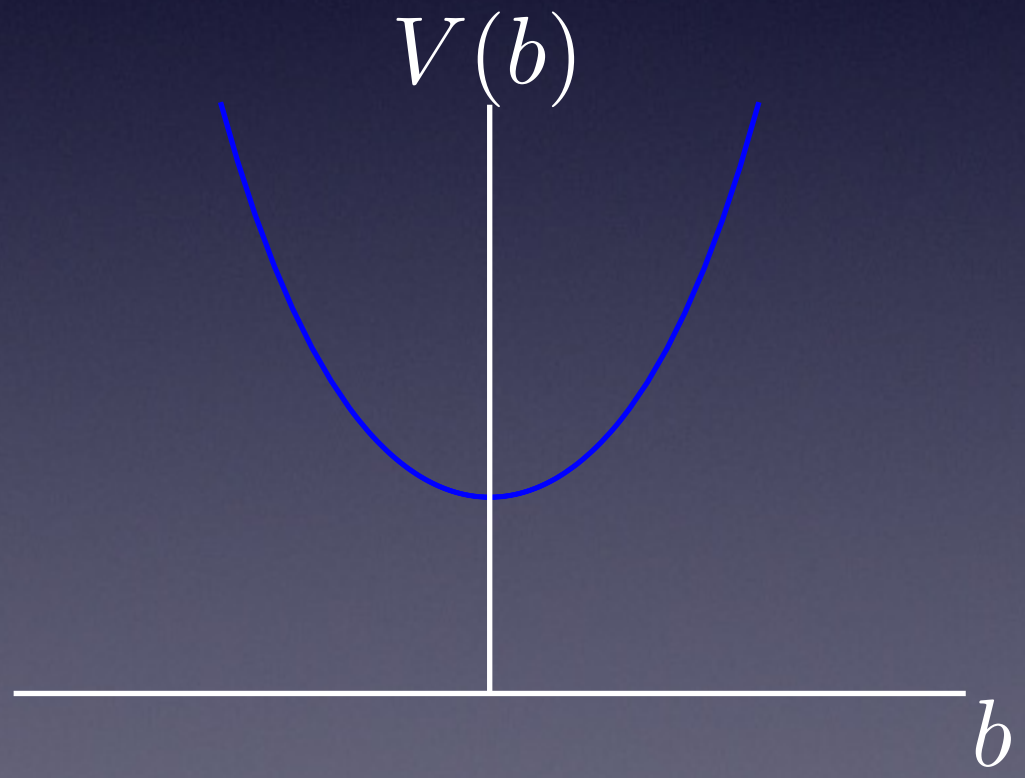
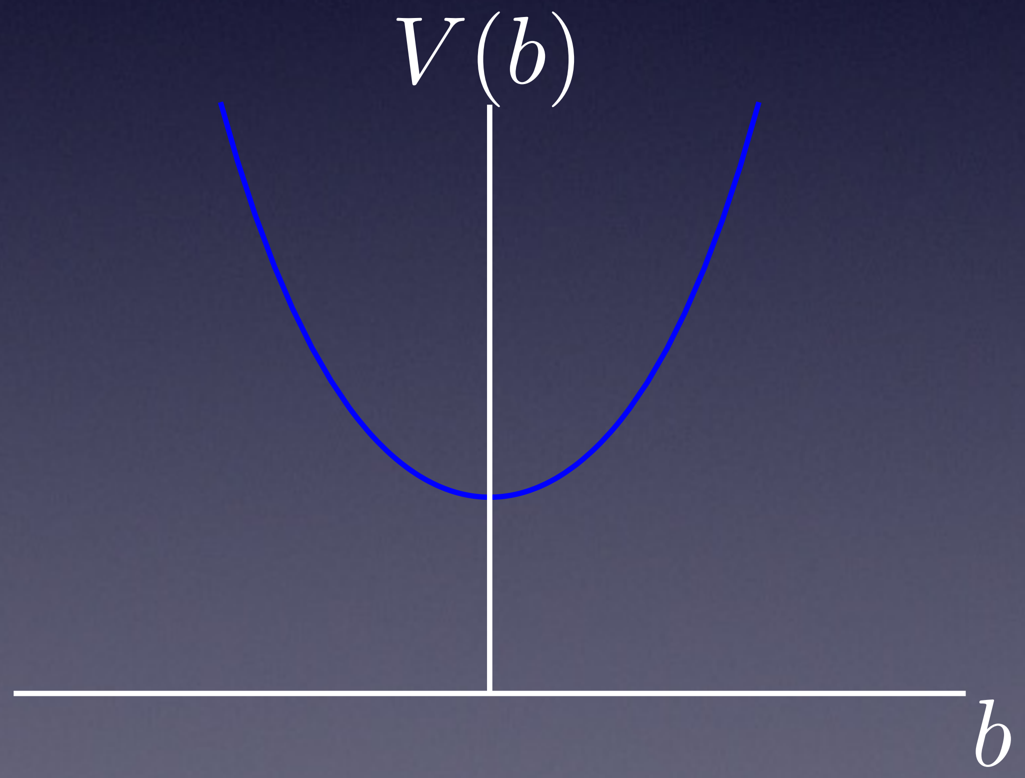
$$\propto \cosh(2b) - \cos(2\sigma)$$



Breaking SUSY

$$\lambda\lambda \to m \quad \bar{\lambda}\bar{\lambda} \to m$$

$$\propto \cosh(2b) - \cos(2\sigma) \;\; -c_1 \frac{m}{L^2} \cos b \cos \sigma$$



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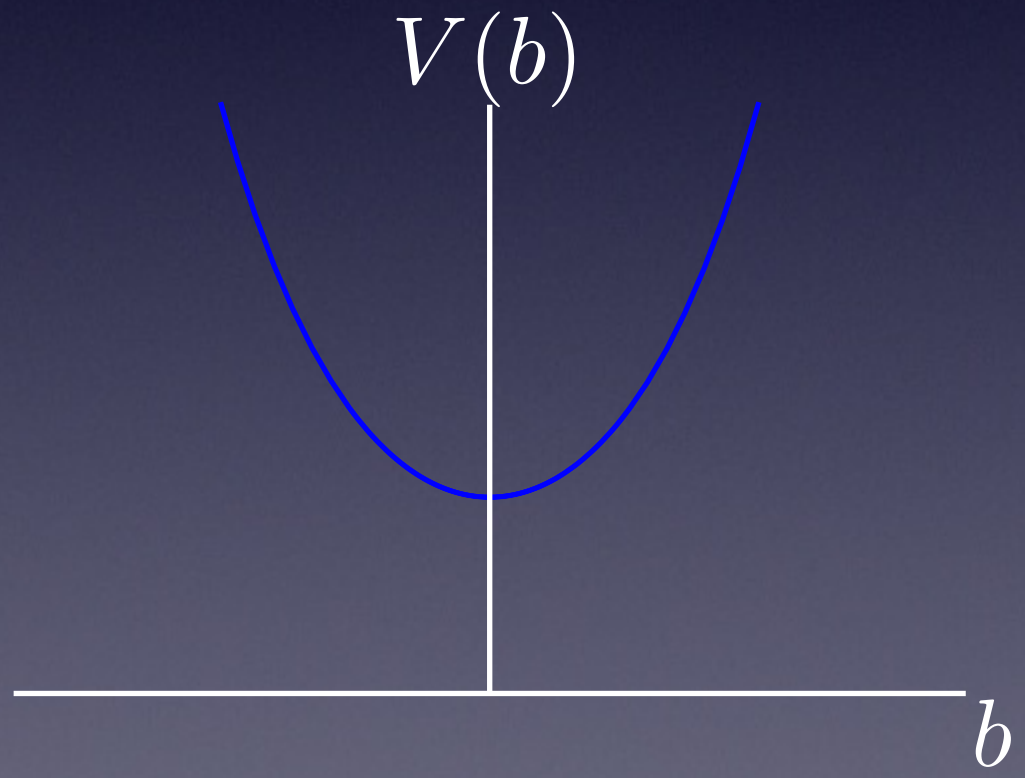
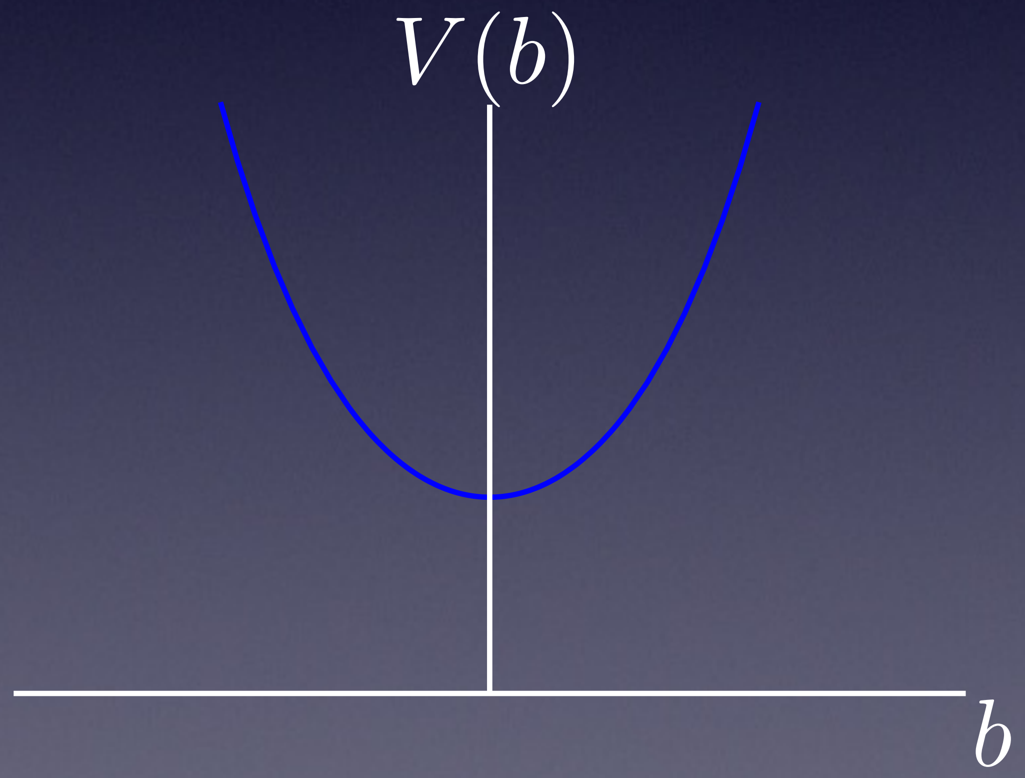


Breaking SUSY

$$\lambda\lambda \to m \quad \bar{\lambda}\bar{\lambda} \to m$$

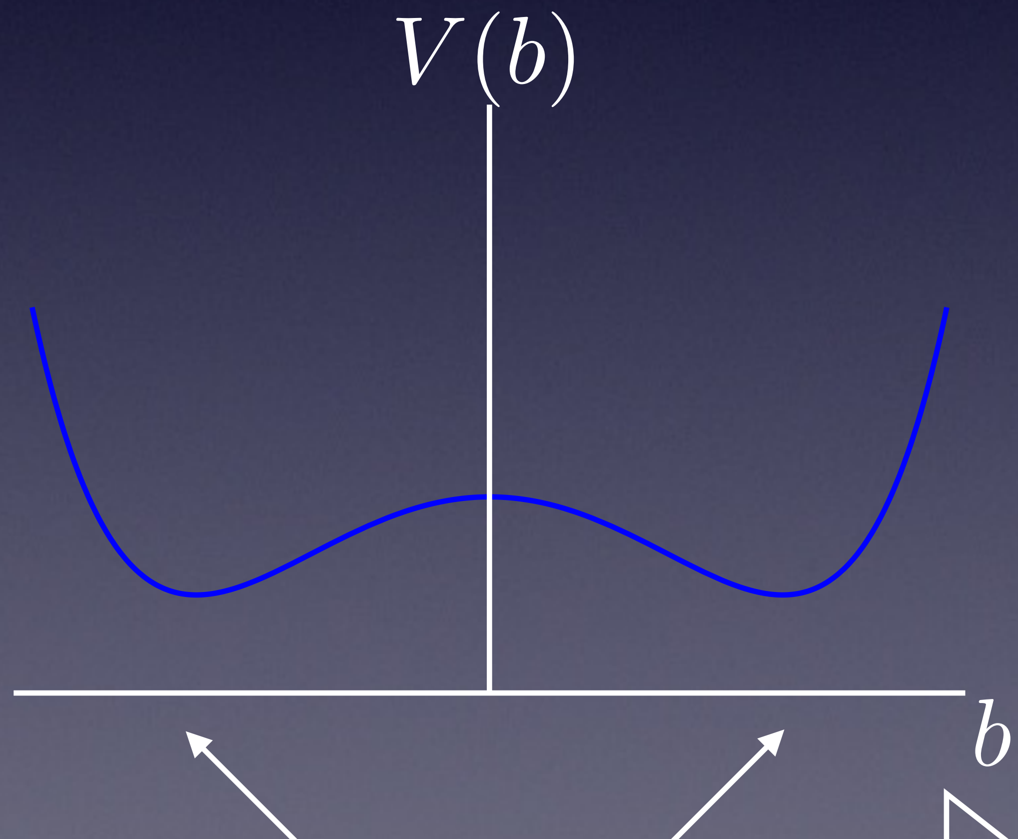
$$\propto \cosh(2b) - 1 \qquad - c_1 \frac{m}{L^2} \cos b \qquad + c_2 \frac{m^2}{L^2} (\text{perturbative})$$



Breaking SUSY

$$\lambda\lambda \to m \quad \bar{\lambda}\bar{\lambda} \to m$$

$$\propto \cosh(2b) - 1 \qquad - c_1 \frac{m}{L^2} \cos b \qquad + c_2 \frac{m^2}{L^2} (\text{perturbative})$$



nonzero b ⇒ Deconfined

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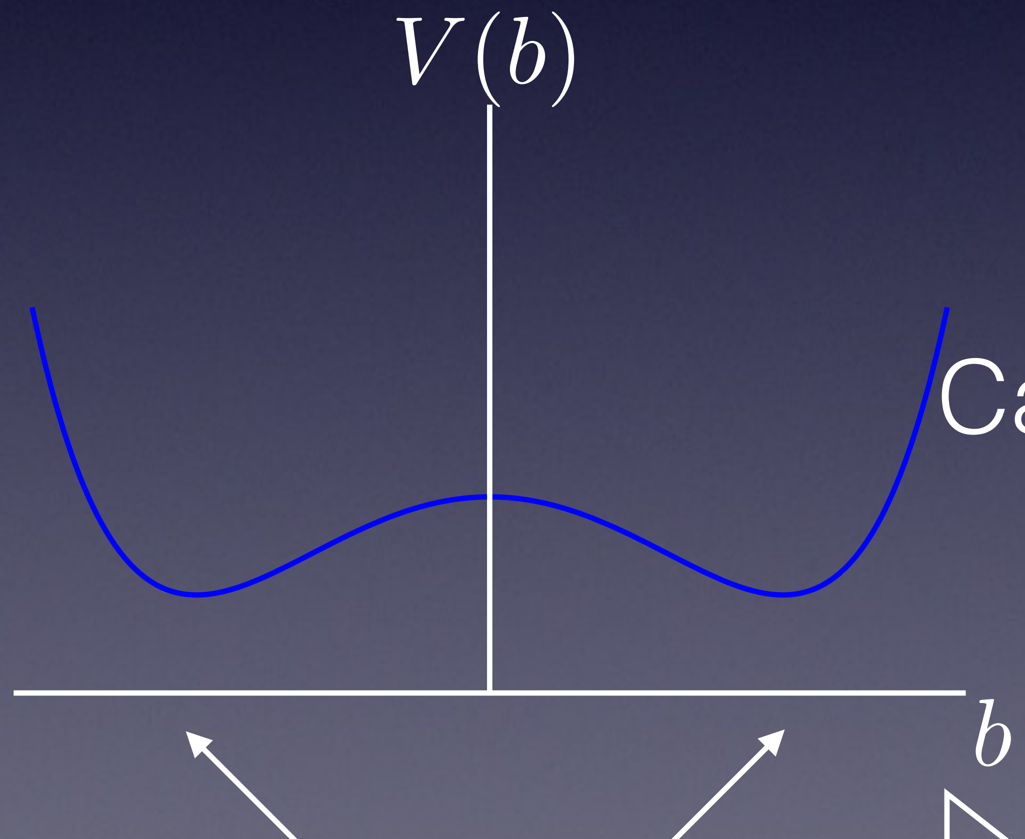

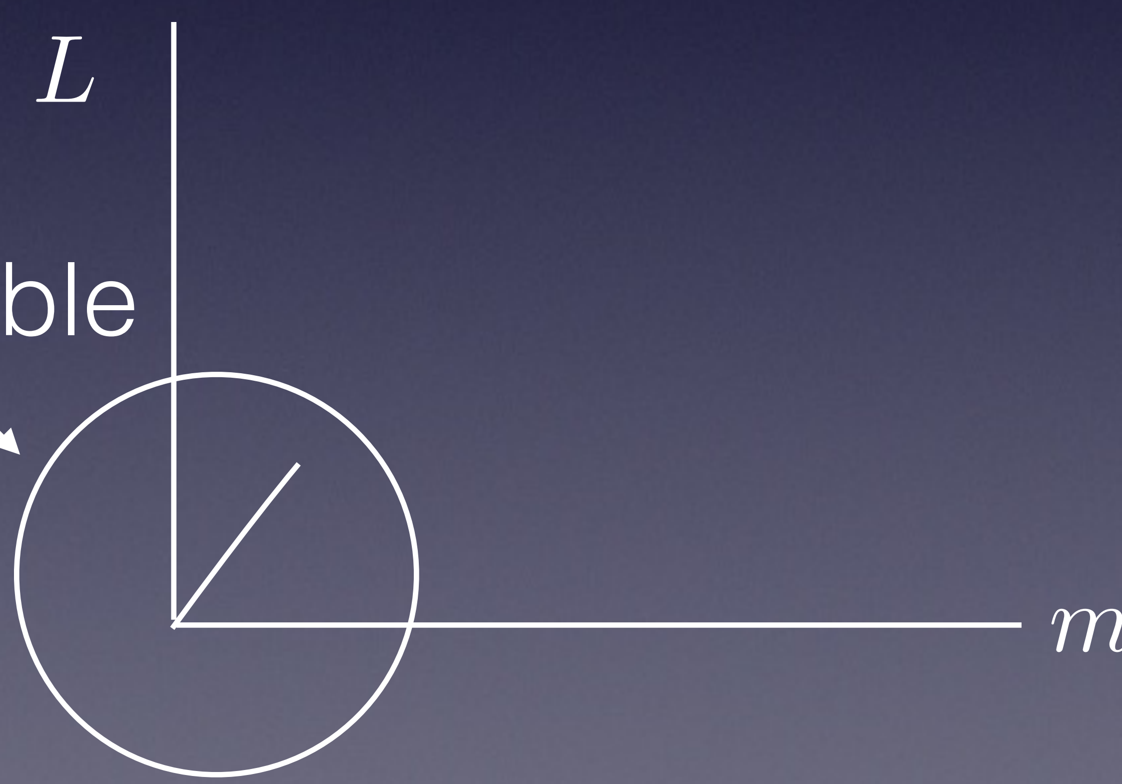

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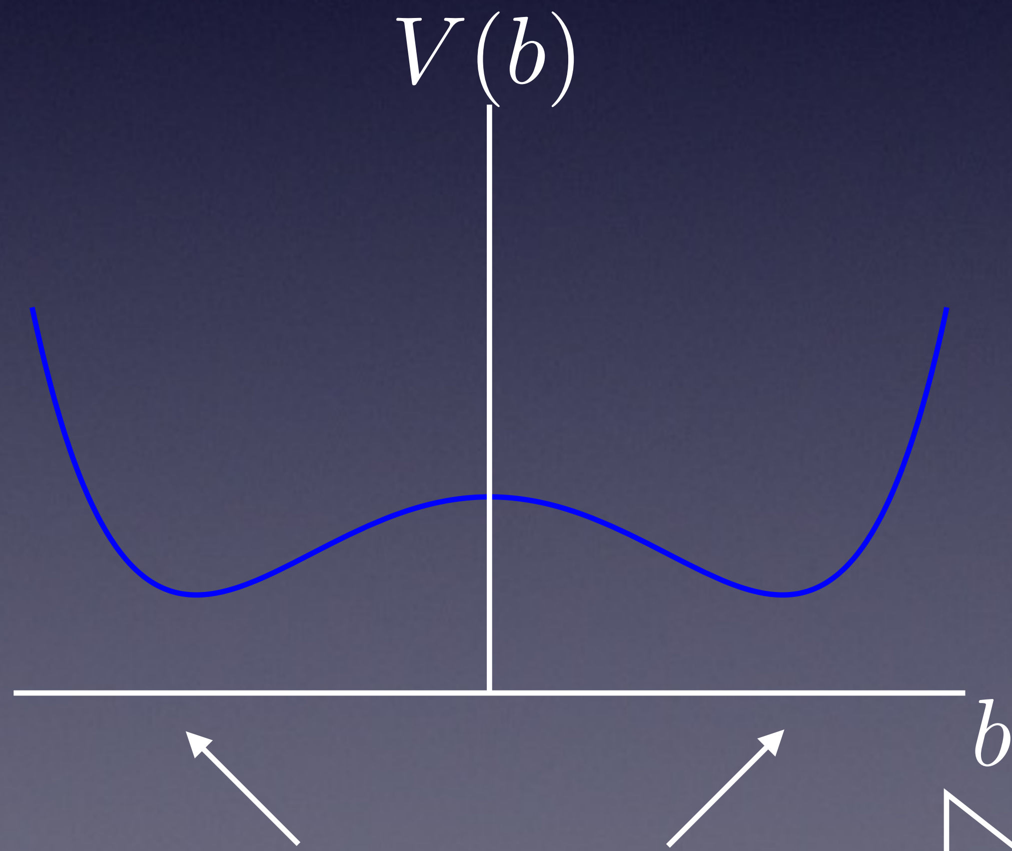

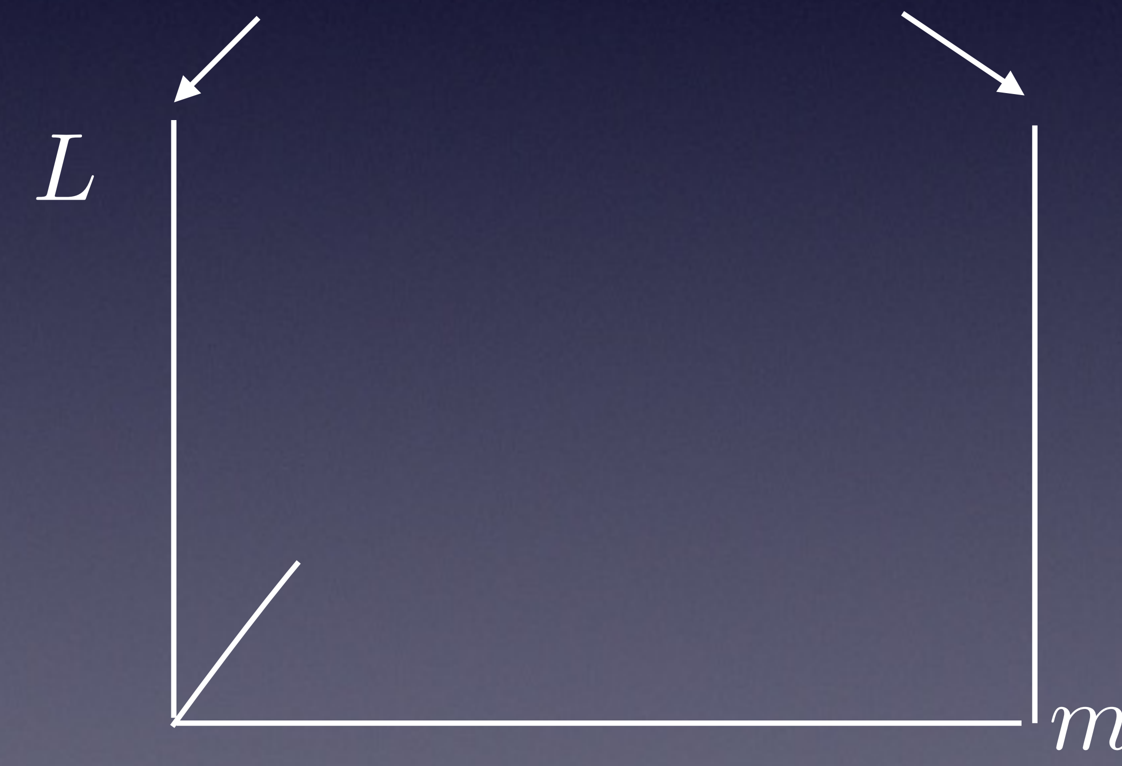

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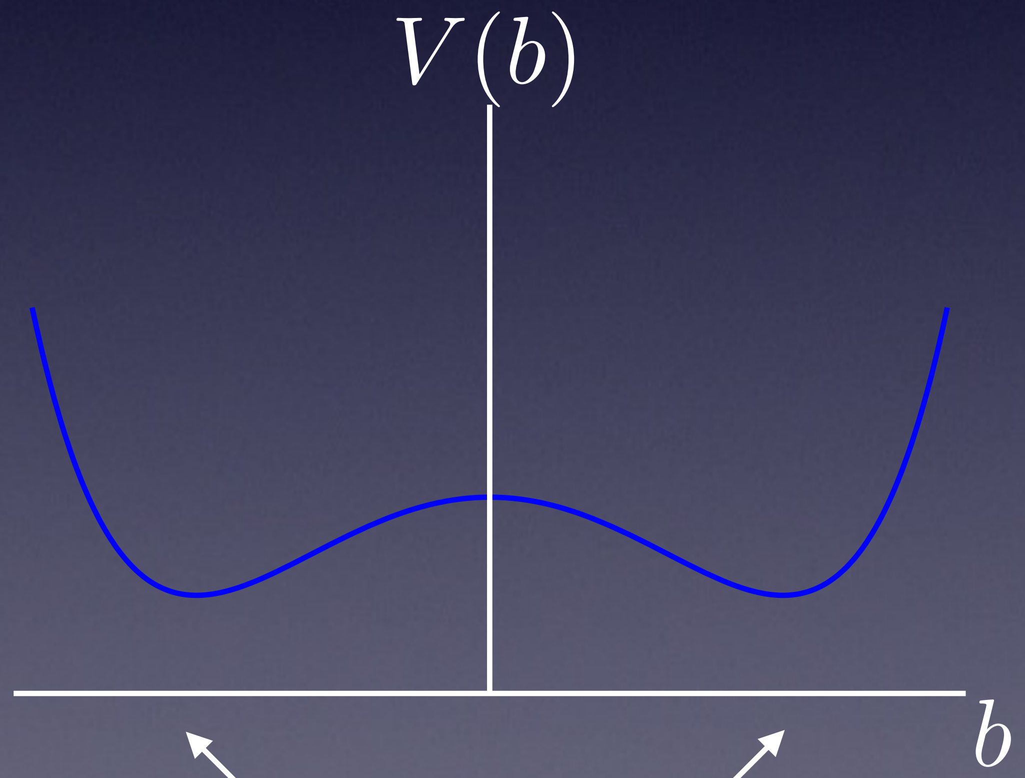

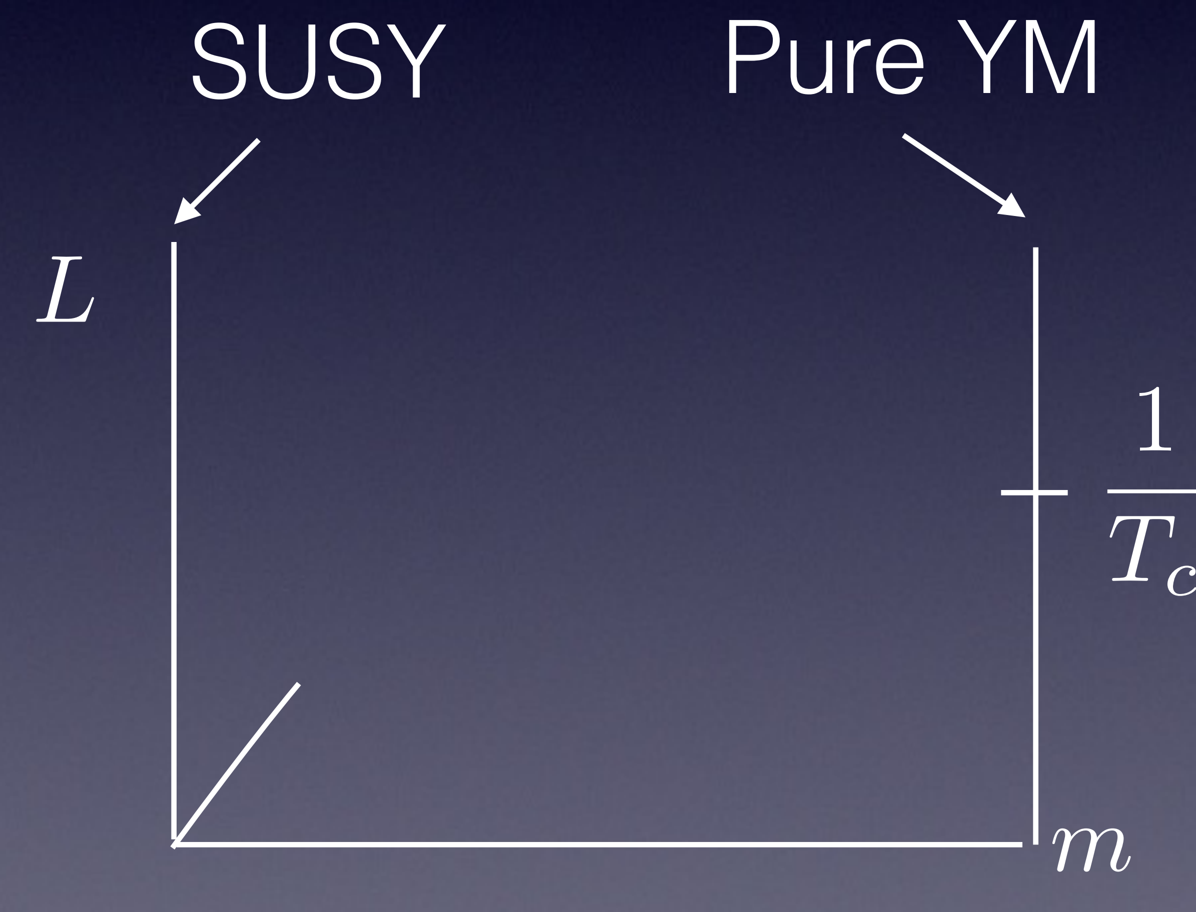

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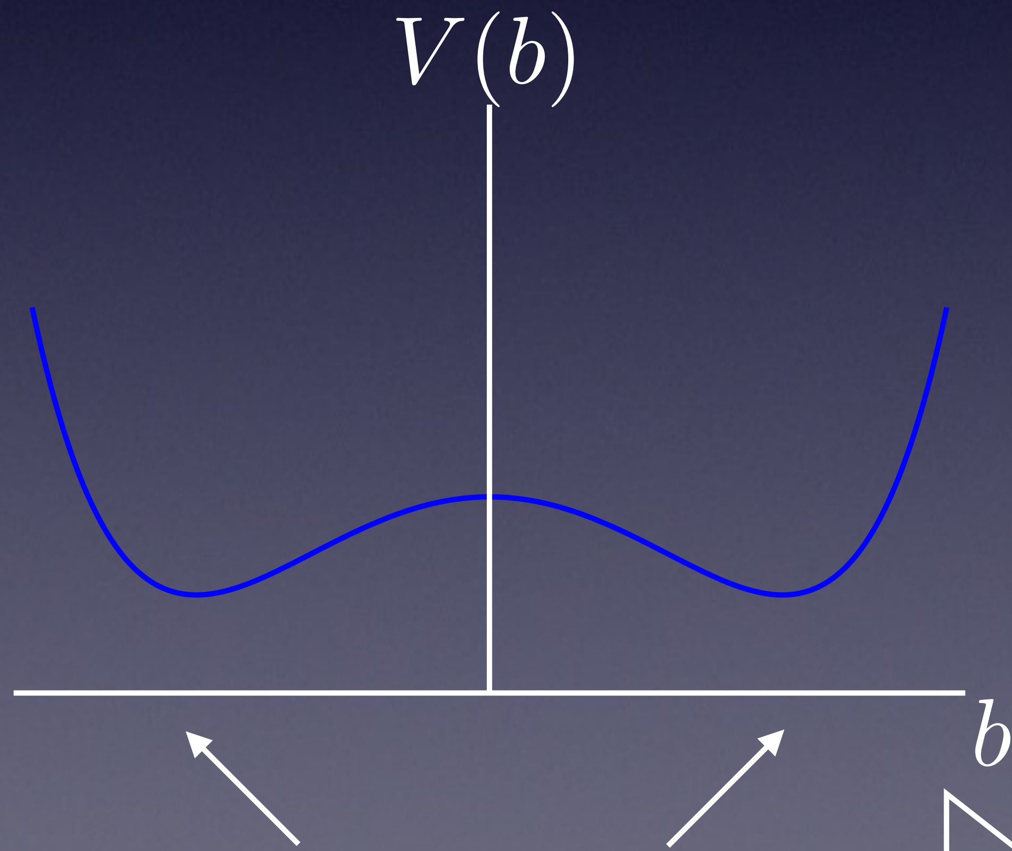

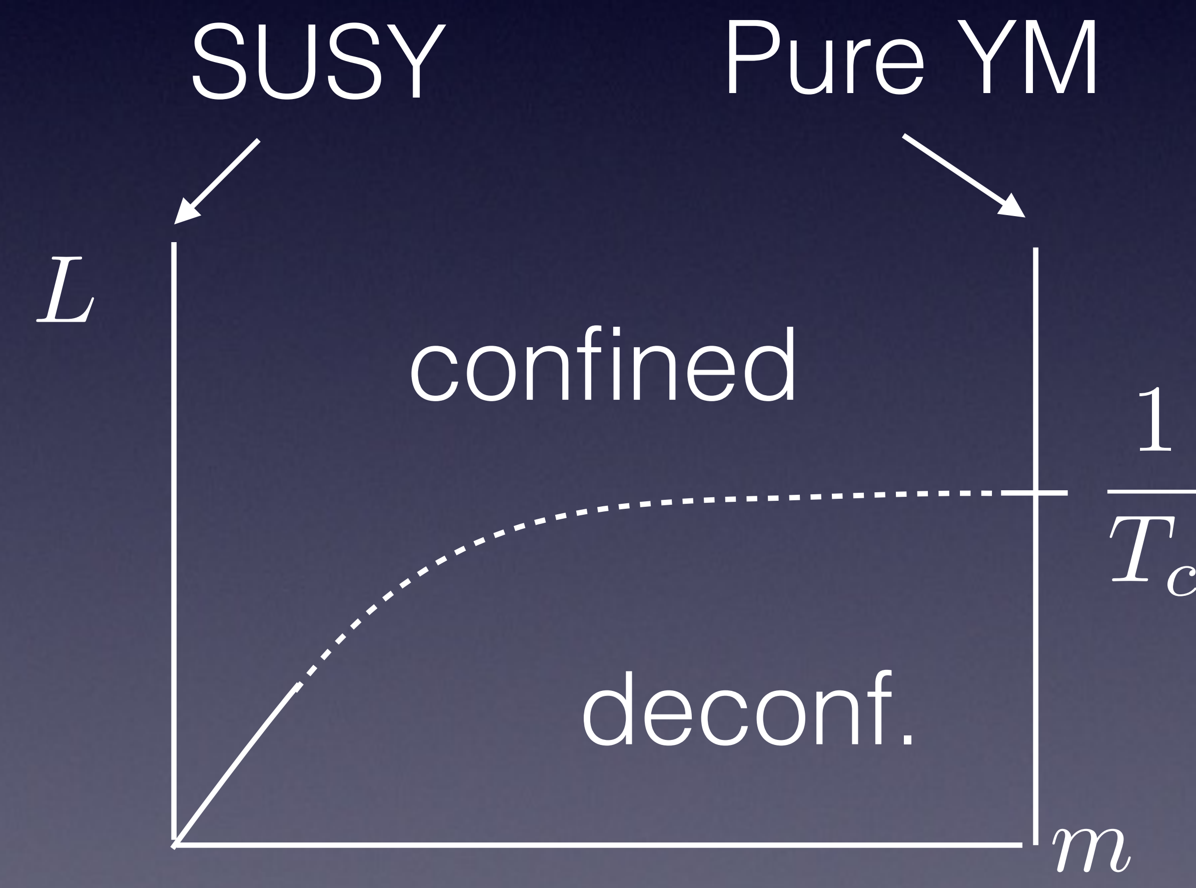

Poppitz, Schafer, Unsal (2012)
arXiv:1205.0290 [hep-th]

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Adding fundamental matter

EP, TS arXiv:1307.1317 [hep-th]

- How do things change when adding fundamental fermions (and scalars, to preserve SUSY)?

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$$\lambda\lambda\, e^{-S_0+b+i\sigma} \qquad \bar{\lambda}\bar{\lambda}\, e^{-S_0+b-i\sigma}$$

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$$\sigma \to \sigma + \gamma$$

Compensated by

$$\psi \to e^{-i\frac{\gamma}{N_f}}\psi$$

$$\lambda \to e^{i\gamma/2}\lambda$$

Gapless theory!

Adding fundamental matter

EP, TS arXiv:1307.1317 [hep-th]

- To that end we considered SQCD with 2Nf fundamental Weyl flavors with mass M

Fundamental fermions

$$\frac{\sqrt{\det(\Delta_- + M^2)\det(\Delta_+ + M^2)}}{\det(\Delta_+ + M^2)}$$

Fundamental scalars

$$\Delta_- = -D_\mu^2 + 2\sigma \cdot \mathbf{B}$$
$$\Delta_+ = -D_\mu^2$$

Effective SQCD

$$\int d^2\theta \, (e^B + e^{-B}) + c.c. =$$

$$- \lambda\lambda e^{b+i\sigma} - \lambda\lambda e^{-b-i\sigma} - \bar{\lambda}\bar{\lambda} e^{b-i\sigma} - \bar{\lambda}\bar{\lambda} e^{-b+i\sigma}$$

$$+ e^{2b} + e^{-2b} - e^{2i\sigma} - e^{-2i\sigma}$$

Effective SQCD

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Determinants can be different!

$$- \lambda\lambda e^{b+i\sigma} - \lambda\lambda e^{-b-i\sigma} - \bar{\lambda}\bar{\lambda} e^{b-i\sigma} - \bar{\lambda}\bar{\lambda} e^{-b+i\sigma}$$

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Effective SQCD

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Coefficients can be different!

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$$+ \; e^{2b} \quad + \; e^{-2b} \quad - \; e^{2i\sigma} \quad - \; e^{-2i\sigma}$$

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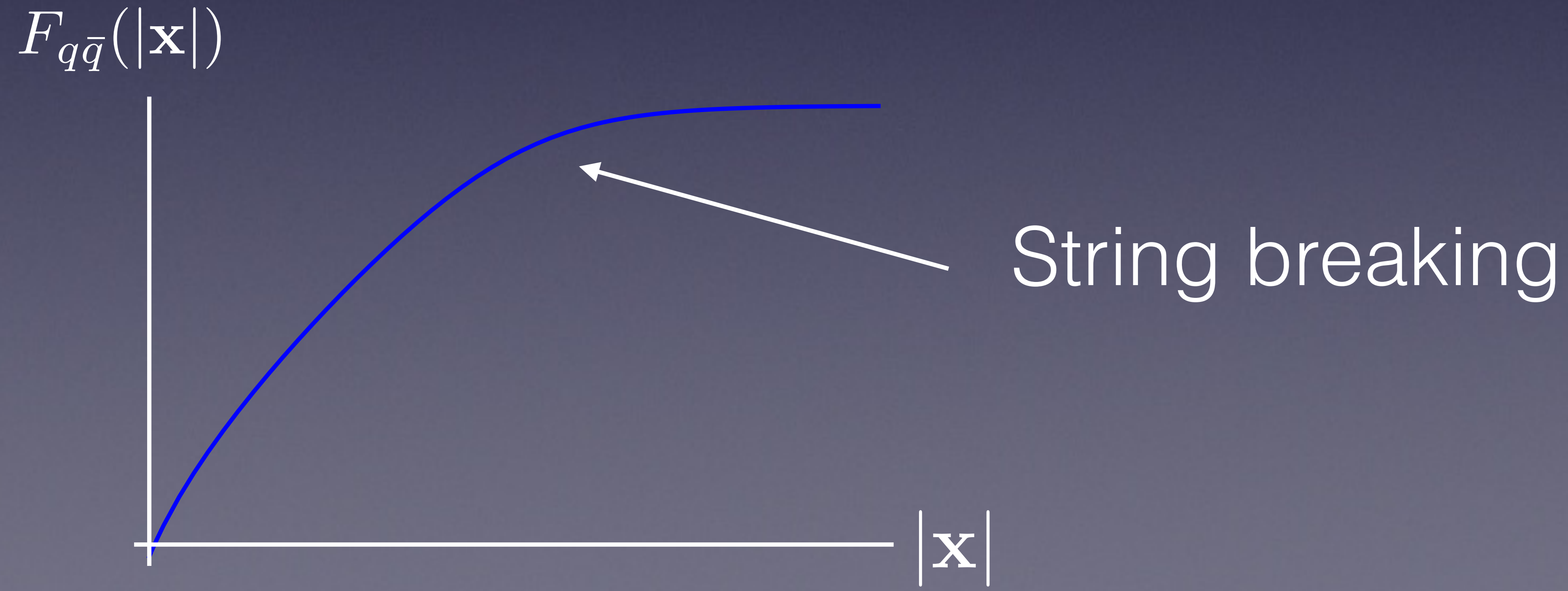

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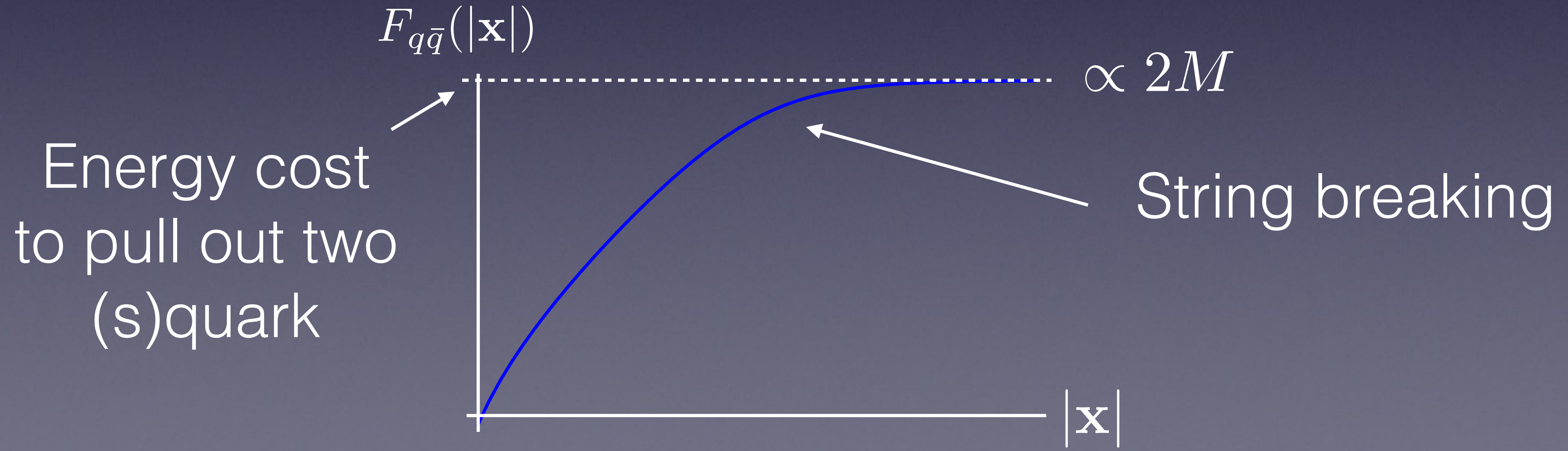

What about pure YM?

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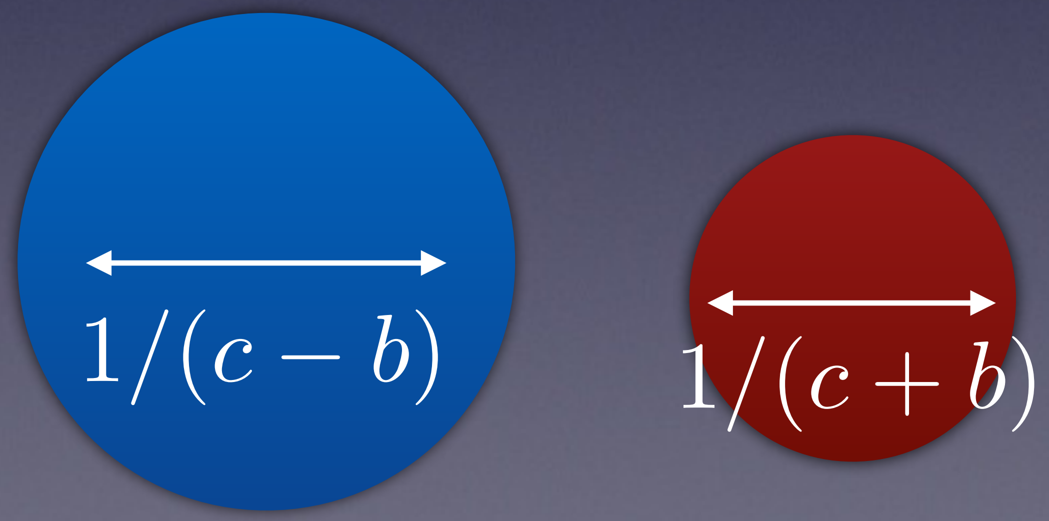

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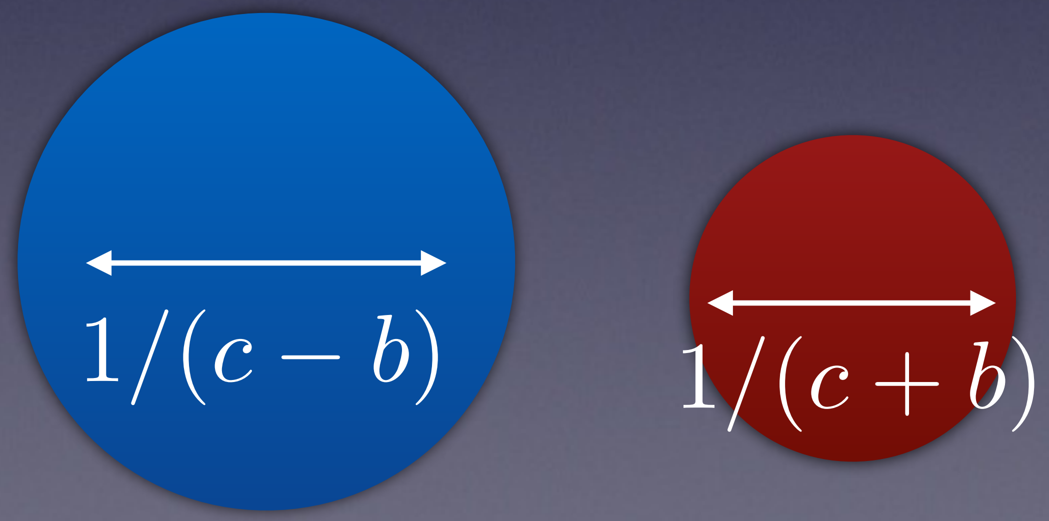
density
getting larger



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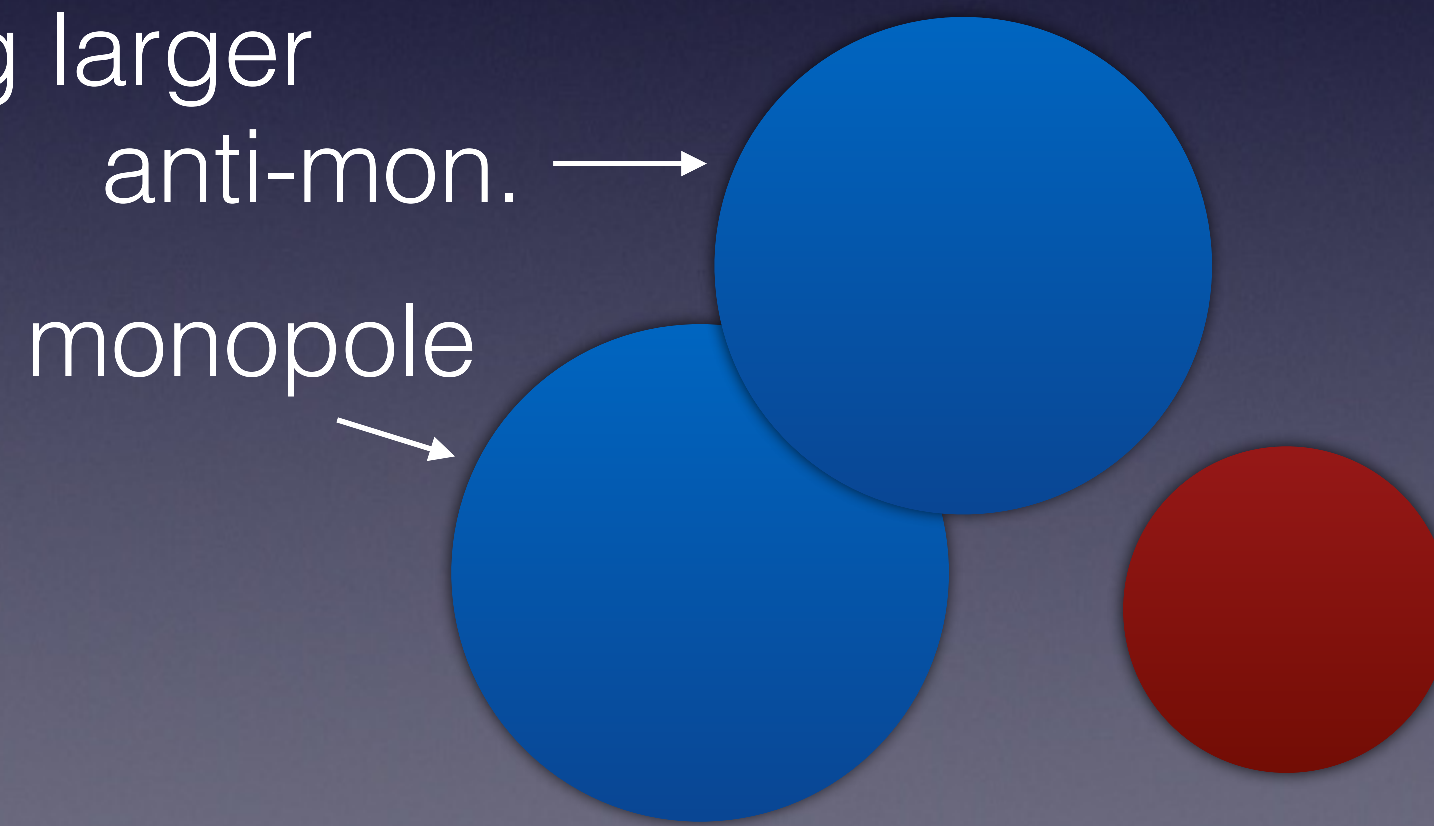

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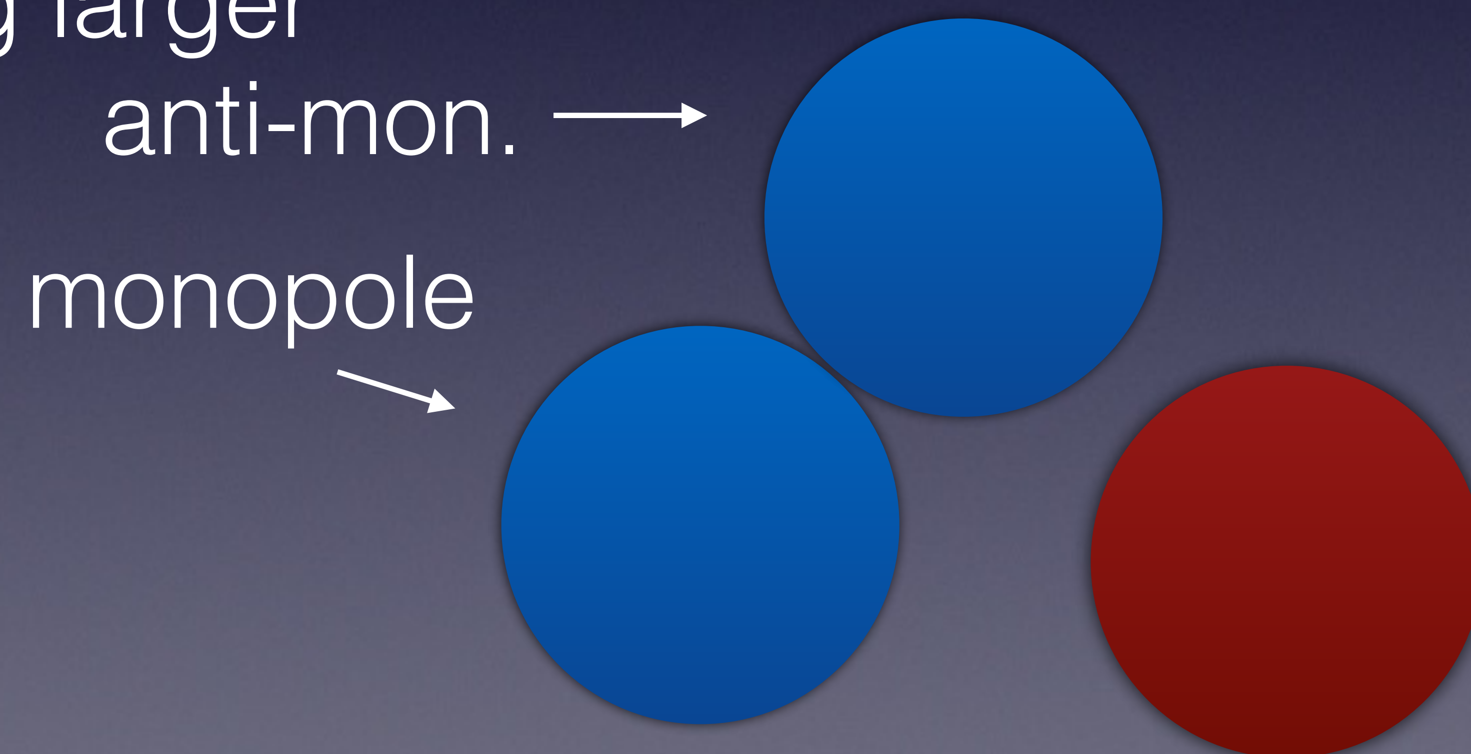
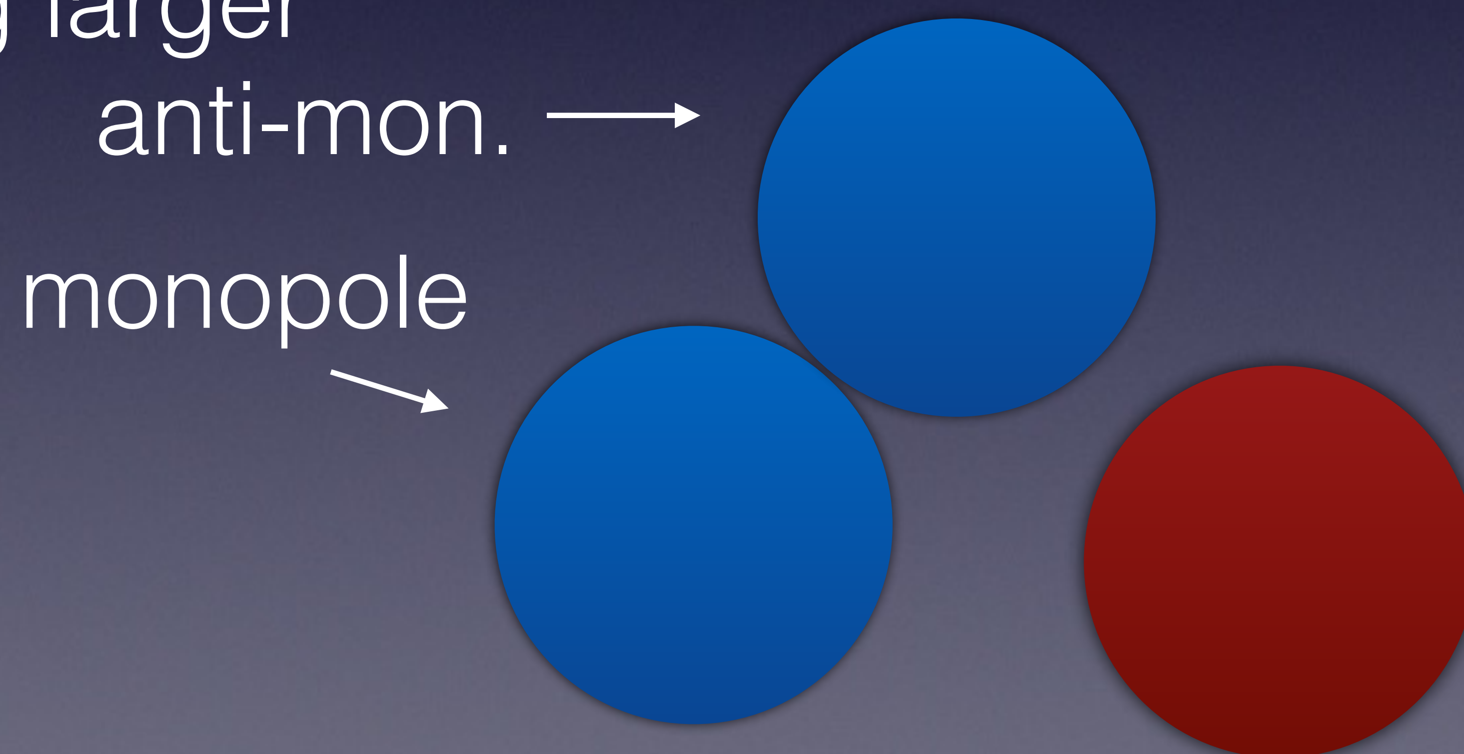


What about pure YM?

$$V_{eff} = \mathcal{A}e^{-2S_0}\cosh(2b) - e^{-S_0}\cosh(b) + \text{perturbative}$$

density
getting larger

The coefficient is
positive
(effective repulsion)



The monopoles and the lattice

ES, TS arXiv:1305.0796

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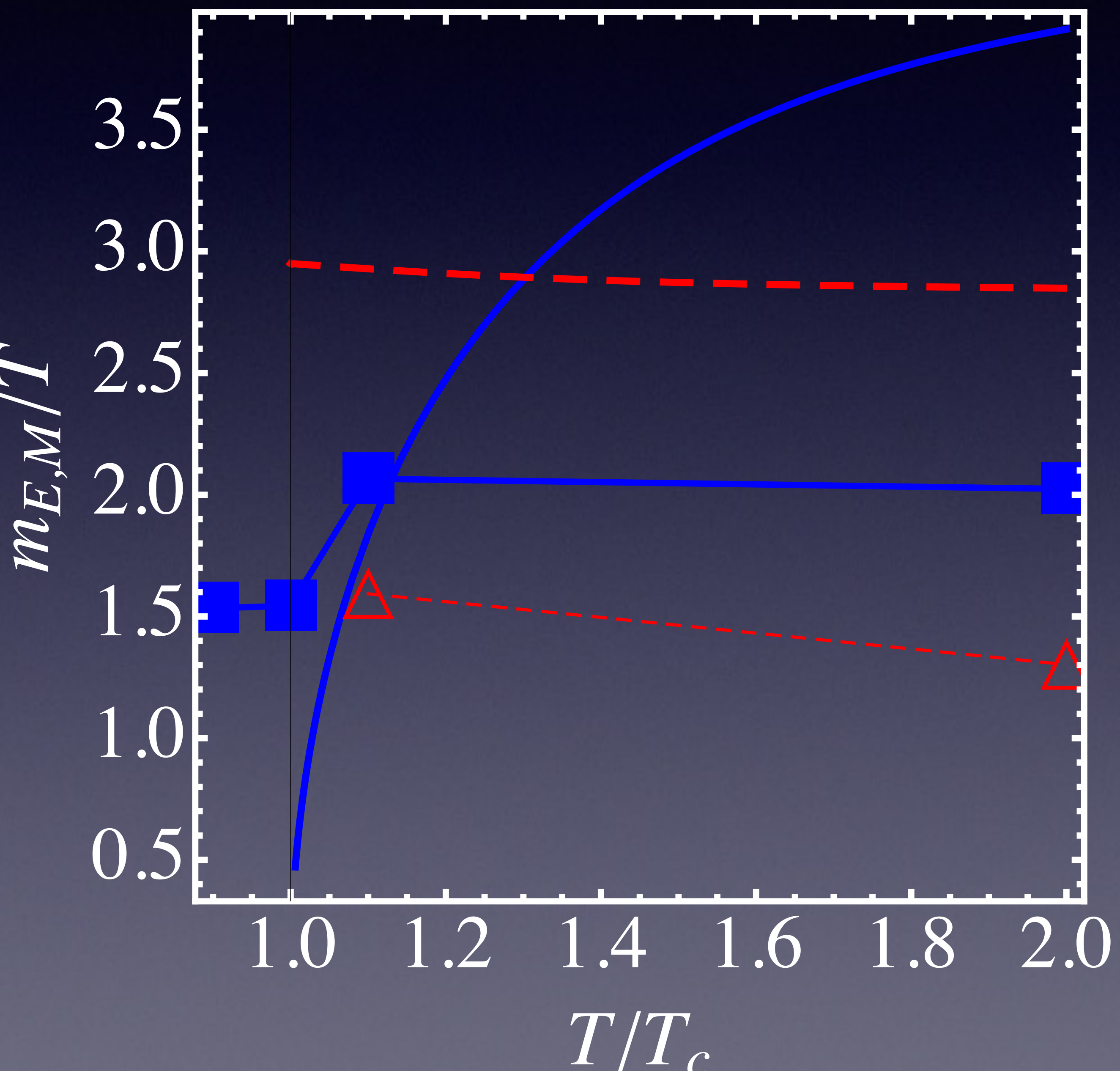

datapoints: V. G. Bornyakov et. al.[arXiv:1011.4790 [hep-lat], E. M. Ilgenfritz, et. al hep-lat/0602002], V. G. Bornyakov et. al. arXiv:0809.2142 [hep-lat]

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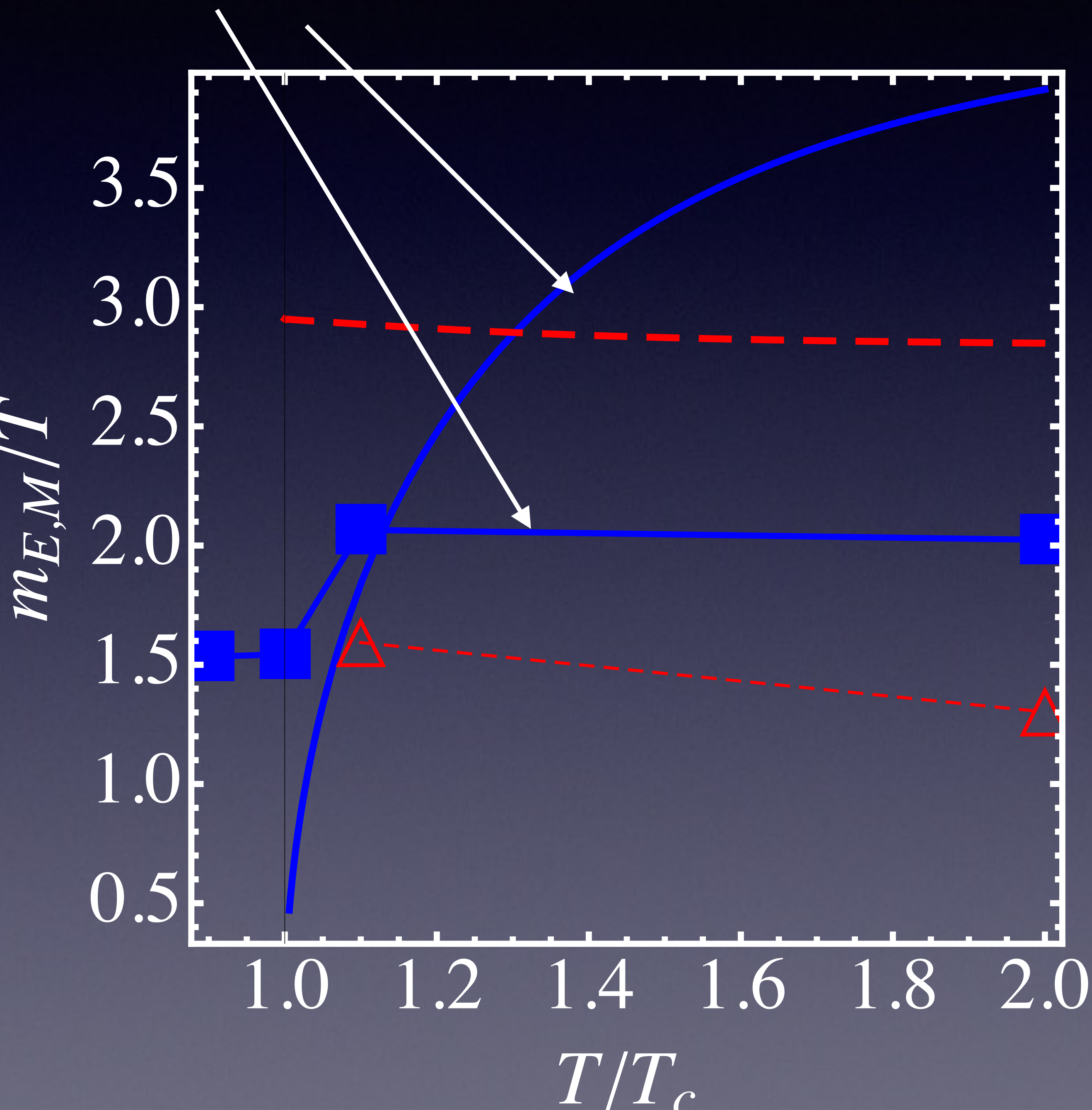
el. mass



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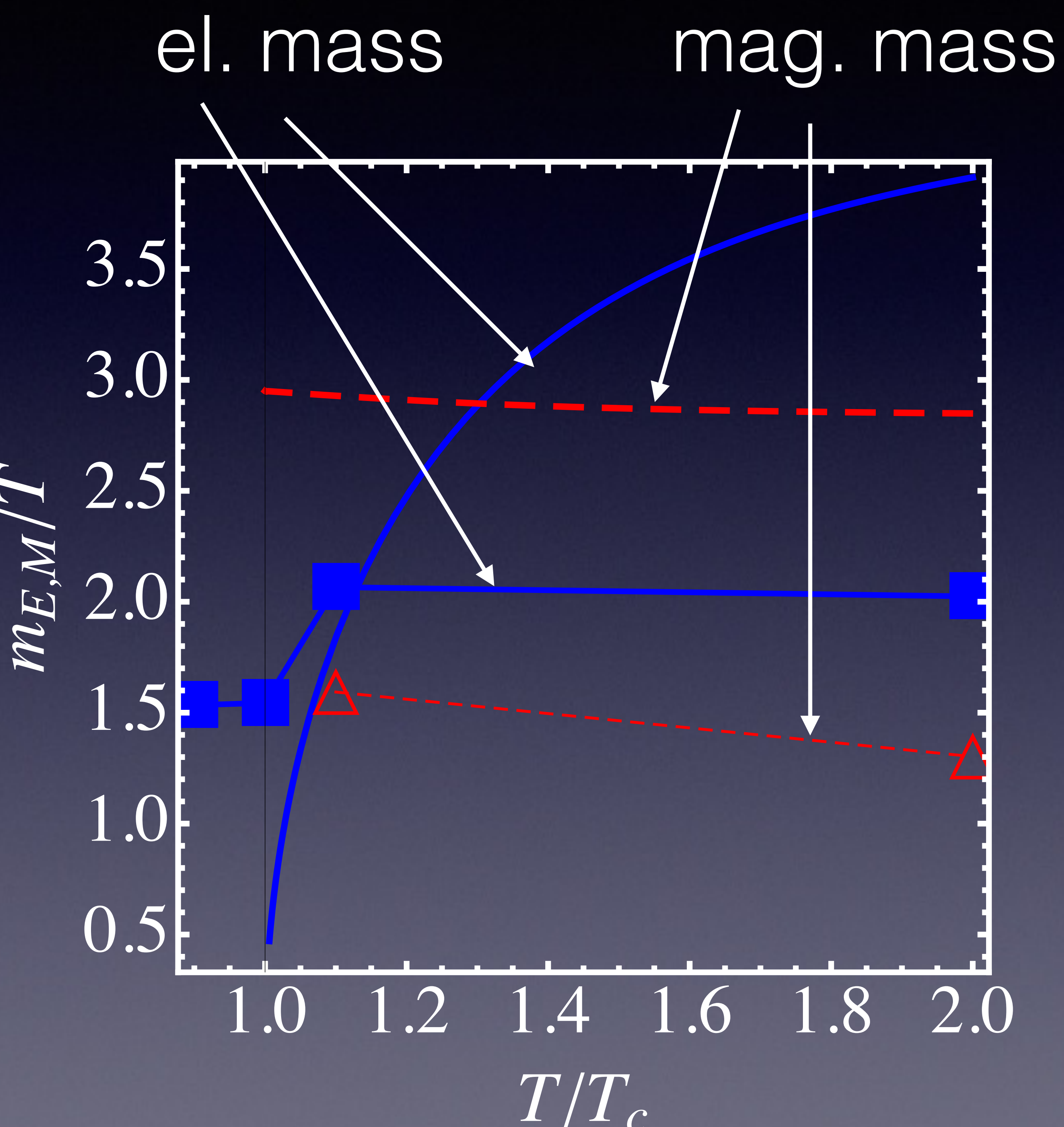

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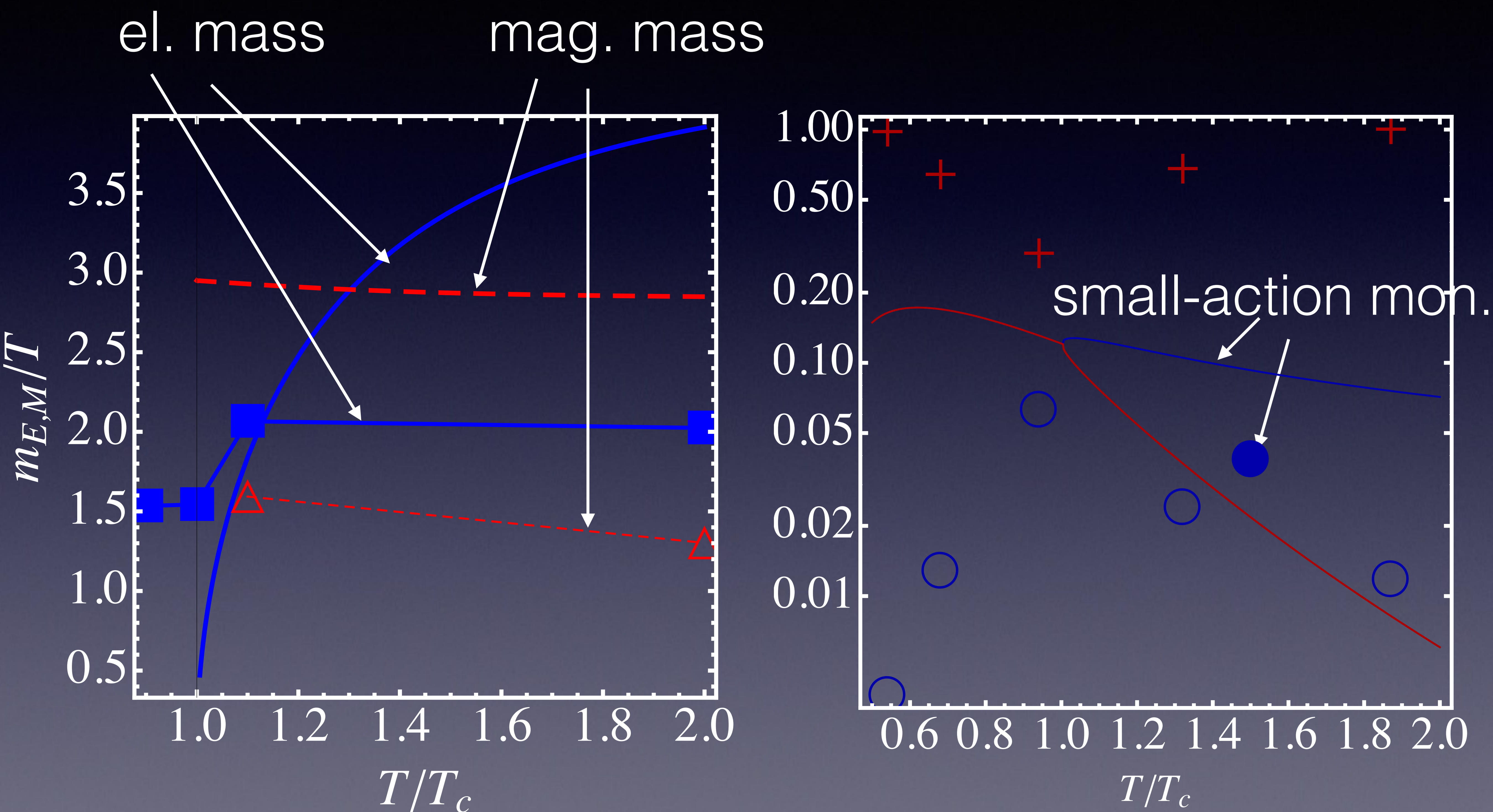

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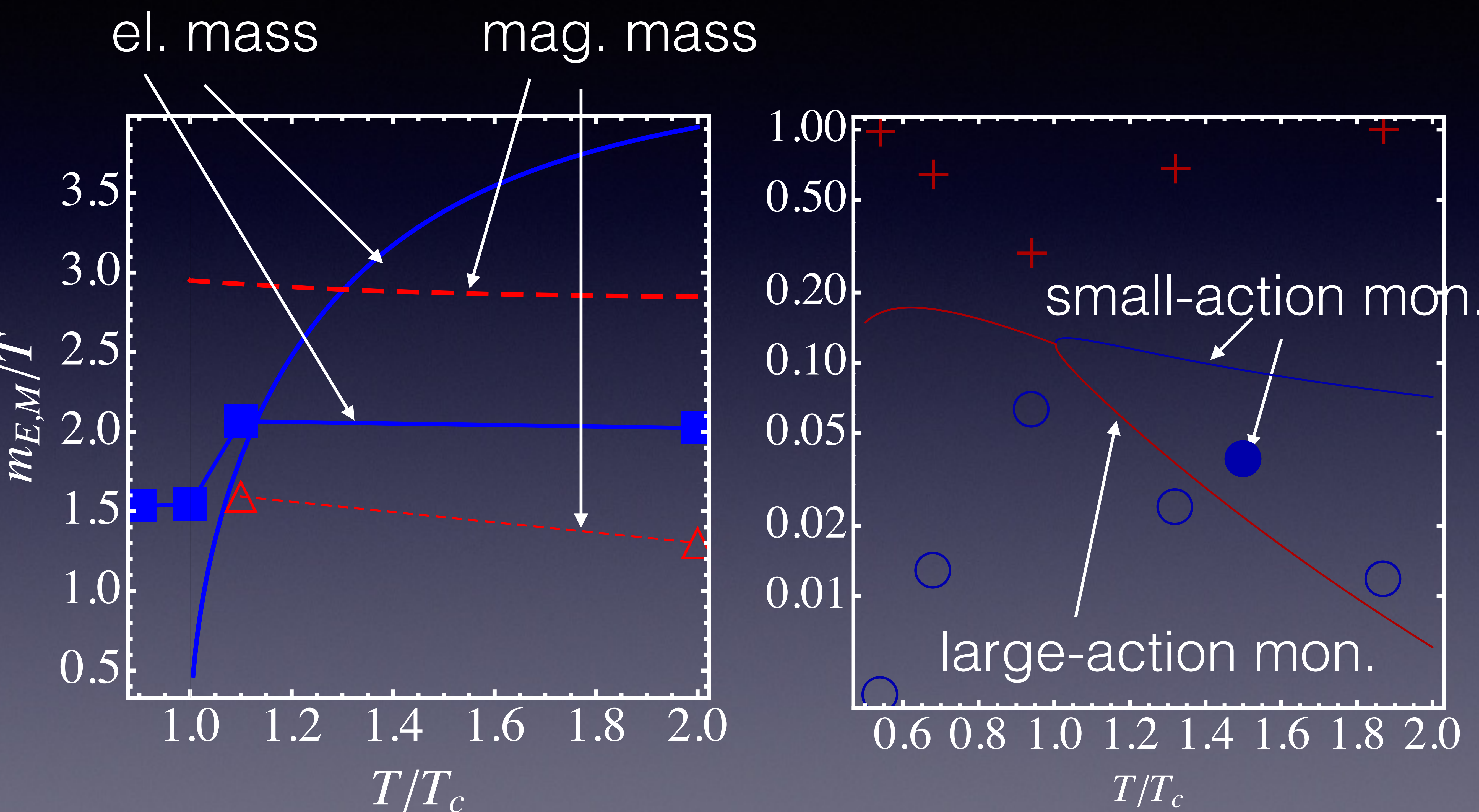

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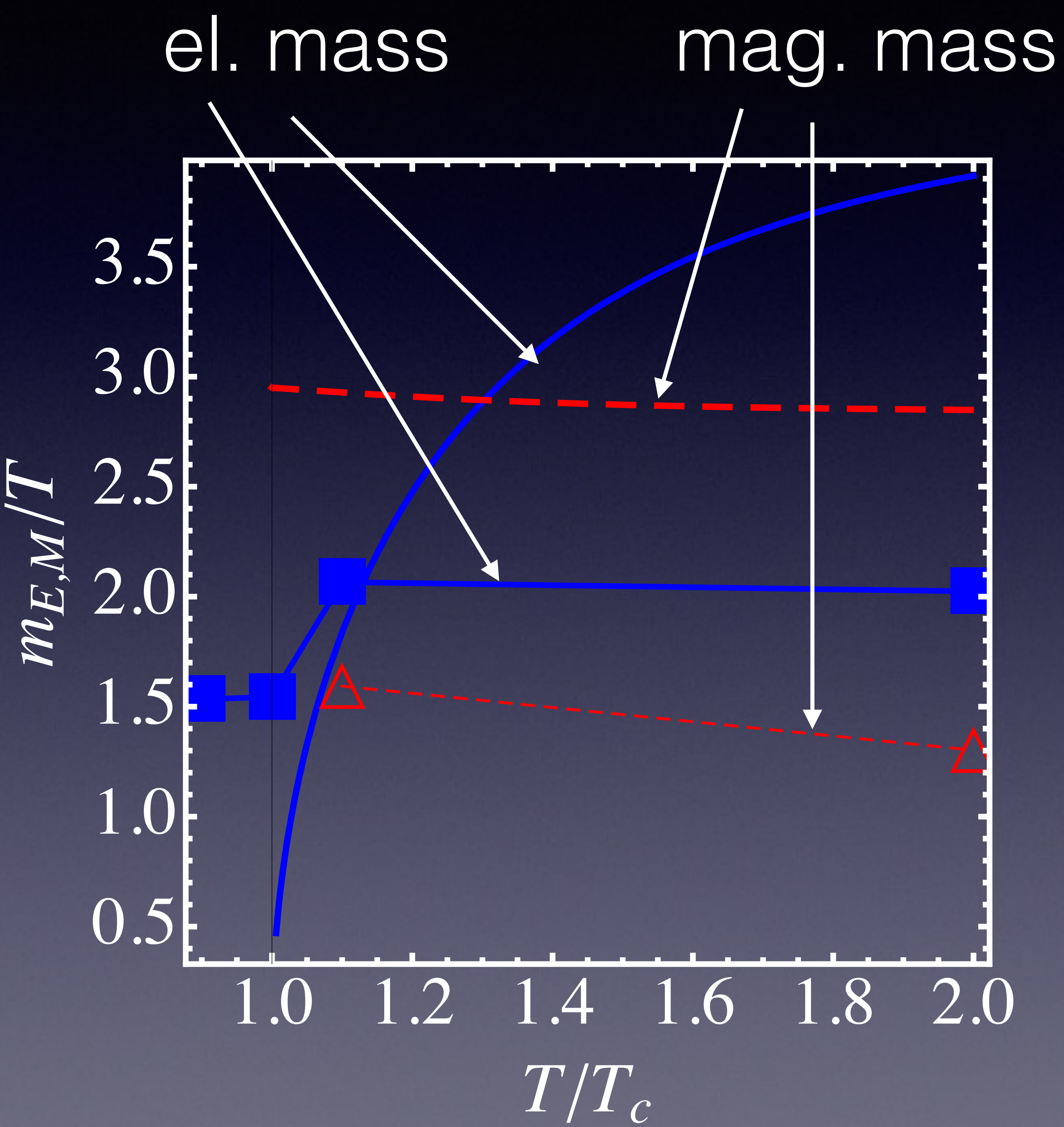

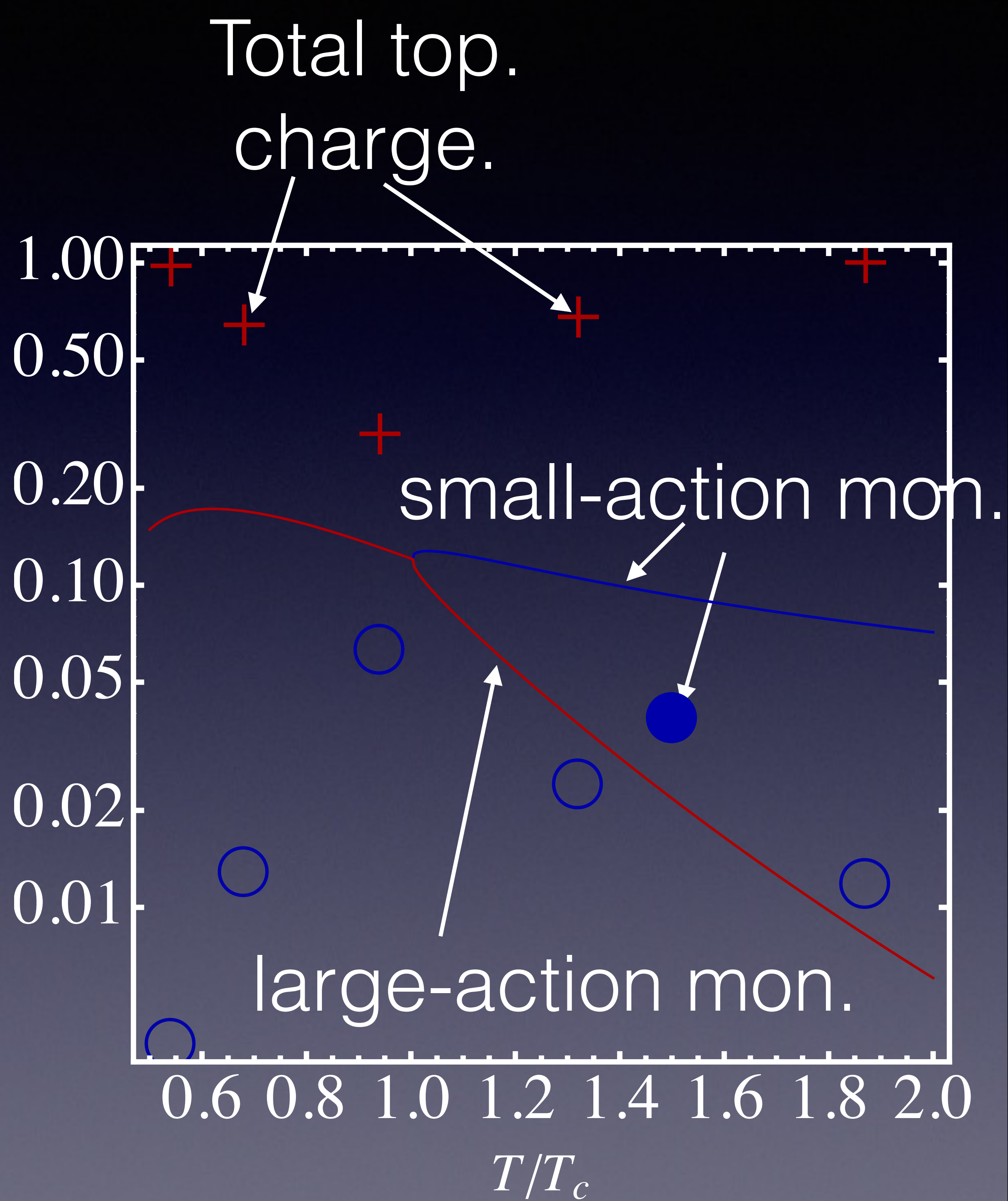

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deformed Yang-Mills (keep confinement,
e.g. periodic adjoint, twisted boudnary cond.,
other tricks?)

Is there any transition?

Conclusion

- The instanton monopoles explain confinement in Super Yang-Mills and Super QCD as well as in other theories (QCD(adj), deformed YM, N=2 SYM, CP(N))
- Many qualitative features are shared by pure YM and QCD: mass-gap, confinement, string breaking, theta angle dependence (not discussed)
- Cured renormalon singularities of the perturbative expansion? (resurgence) (Unsal et. al.)
- Absence of regime in YM and QCD where reliable calculation is possible makes any definitive tests and conclusions difficult.
- But there is hope in continuity!