Reheating Metastable O'Raifeartaigh Models

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NC, Patrick Fox, Jay Wacker
hep-th/0611006; PRD 075, 085006 (2007)

Related work:

Abel et al., hep-th/0610334;   Abel et al., hep-th/0611130

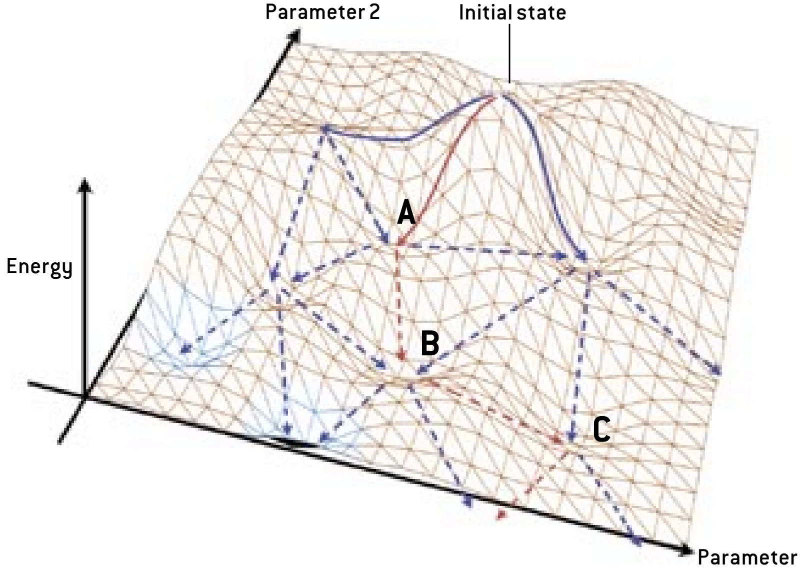
Fischler et al., hep-th/0611018

The Metastable Universe

Metastable vacua appear to be generic

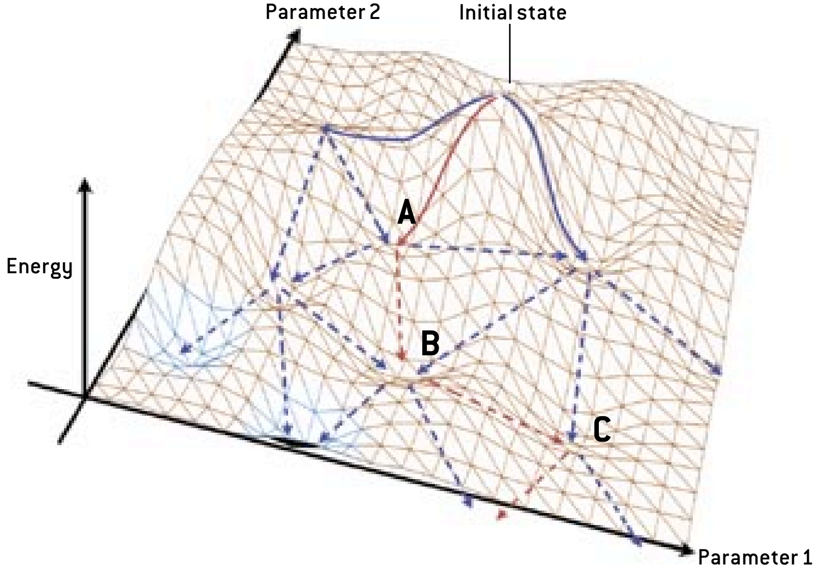
Arise in embedding MSSM into string theory

Enjoys the virtues of DSB (naturalness, etc.) with fewer constraints (e.g., Witten index)



The Metastable Universe

An old idea (Dine, Nelson, Nir, Shirman; Luty & Terning; Banks; Dimopoulos, Dvali, Giudice, Rattazzi)

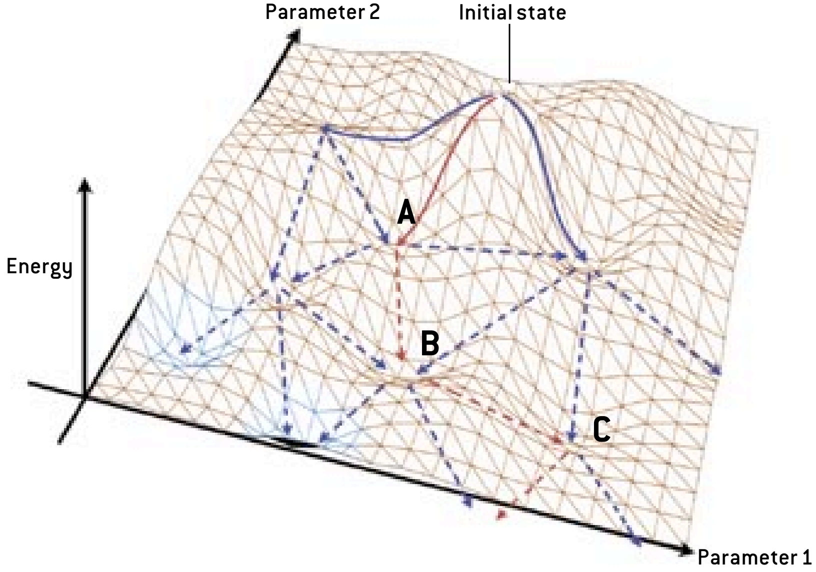


Intriligator, Seiberg, Shih (ISS) recently found metastable vacua in SQCD

The Metastable Universe

Validity rests on longevity of metastable vacua

Useful to ask: how do theories with metastable vacua evolve after reheating?



Outline

I. Cosmological constraints from reheating

II. Reheating metastable SQCD

III. O'Reheating O'Raifeartaigh models

IV. Lessons for metastable SUSY breaking

Reheating the DSB Sector: Cosmological constraints

DSB sector generically reheated by inflaton decays (democratic, or via low-scale mediation)

Influences evolution for $T_{RH} > \sqrt{F}$

Reheating the DSB Sector: Cosmological constraints

High T_{RH} introduces new cosmological constraints:

- Gravitino problem
- Polonyi problem
- Light moduli problem

Gravitino problem

Low scale SUSY breaking suggests gravitino LSP, since $m_{3/2} \sim F/M_{Pl}$

No bounds on reheating temperature provided $m_{3/2} < 1\text{keV}$
(i.e., $F_{1/2} \sim 100 - 1000\text{TeV}$)

Also high reheat allowed for $m_{3/2} > 10\text{TeV}$
--unstable enough to decay before BBN

Polonyi & Light Moduli

Polonyi fields in the early universe displaced far from the minimum of their potential; coherent oscillations can dominate the energy density of the universe. Cosmology similar to that of gravitino

May exist model-dependent light moduli from, e.g., string theory; can be stabilized at a high scale and decouple from cosmology through, e.g., flux compactification

Polonyi & Light Moduli

Not unreasonable to reheat to temperatures above $\sqrt{F}$ in, e.g., low-scale gauge mediation without incurring added cosmological problems

Metastable SQCD

Intriligator, Seiberg, & Shih uncovered a simple class of metastable SUSY-breaking theories: supersymmetric QCD with fundamental matter

Massive fundamental quarks drive F-term SUSY breaking; dynamical effects restore SUSY at distant vacua

Electric theory

$\mathcal{N}=1,\;\; SU(N_c)$ supersymmetric QCD

Fundamental matter Q, Q^c

$Q \sim (\Box_{N_C}, \Box_{N_{F\,L}}) \qquad Q^c \sim (\overline{\Box}_{N_C}, \overline{\Box}_{N_{F\,R}}).$

$N_C < N_F < \frac{3}{2} N_C$ asymptotically free

Strong coupling scale Λ $\qquad m \ll \Lambda$

Superpotential $W_e = m \mathrm{Tr} Q Q^c$

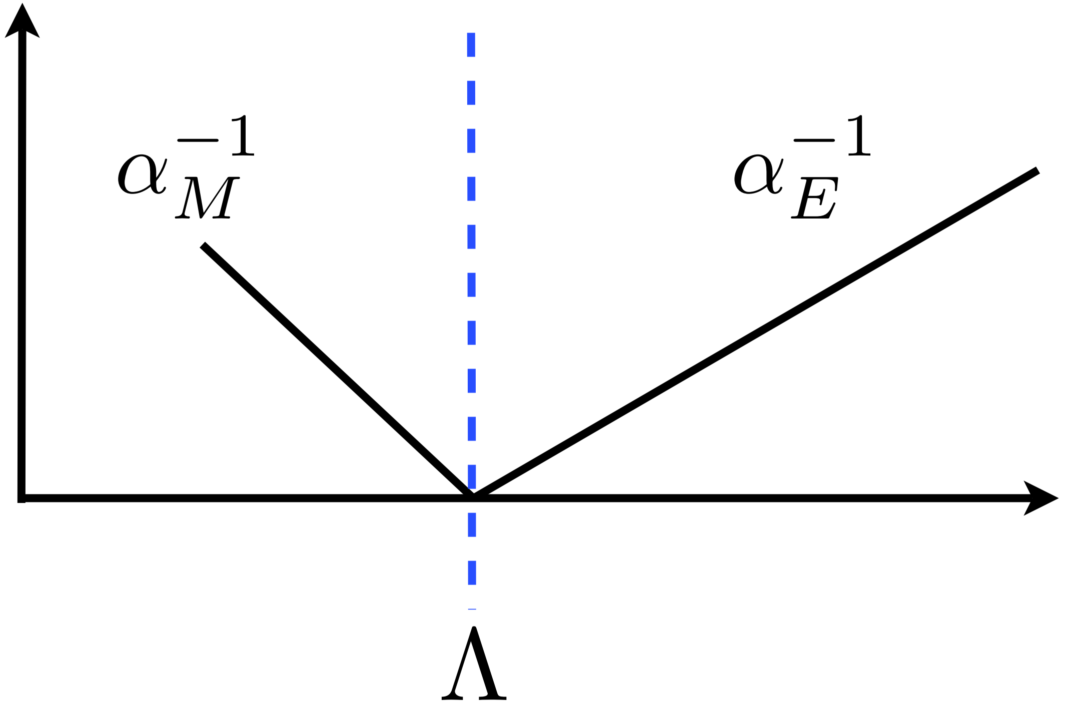
Seiberg duality

Electric theory dual to magnetic gauge theory w/ $SU(N_F - N_C)$

Magnetic dual is IR free for $N_C < N_F < \frac{3}{2} N_C$

Dual variables are magnetic quarks, meson

Seiberg duality



Magnetic theory

$$SU(N) \qquad N = N_F - N_C \qquad N_F > 3N$$

Magnetic quarks q, q^c, meson $M \sim QQ^c$

$$q \sim (\Box_N, \overline{\Box}_{N_{F\,L}}) \qquad q^c \sim (\overline{\Box}_N, \Box_{N_{F\,R}}) \qquad M \sim (\Box_{N_{F\,L}}, \overline{\Box}_{N_{F\,R}})$$

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$$W_m = y\,\mathrm{Tr}\,qMq^c - \mu^2 \mathrm{Tr}\,M,$$

Kahler potential smooth near origin, can be taken as canonical

$$\mu^2 \sim m\Lambda$$

SUSY breaking

$$F^{\dagger}_{M_i^j} = y\, q_i^a q_a^{c\,j} - \mu^2 \delta_i^j\,,$$

SUSY breaking

$$F^{\dagger}_{M^j_i} = \boxed{y\, q^a_i q^{c\,j}_a} - \boxed{\mu^2 \delta^j_i},$$

rank $N_F - N_C < N_F$ rank N_F

SUSY breaking

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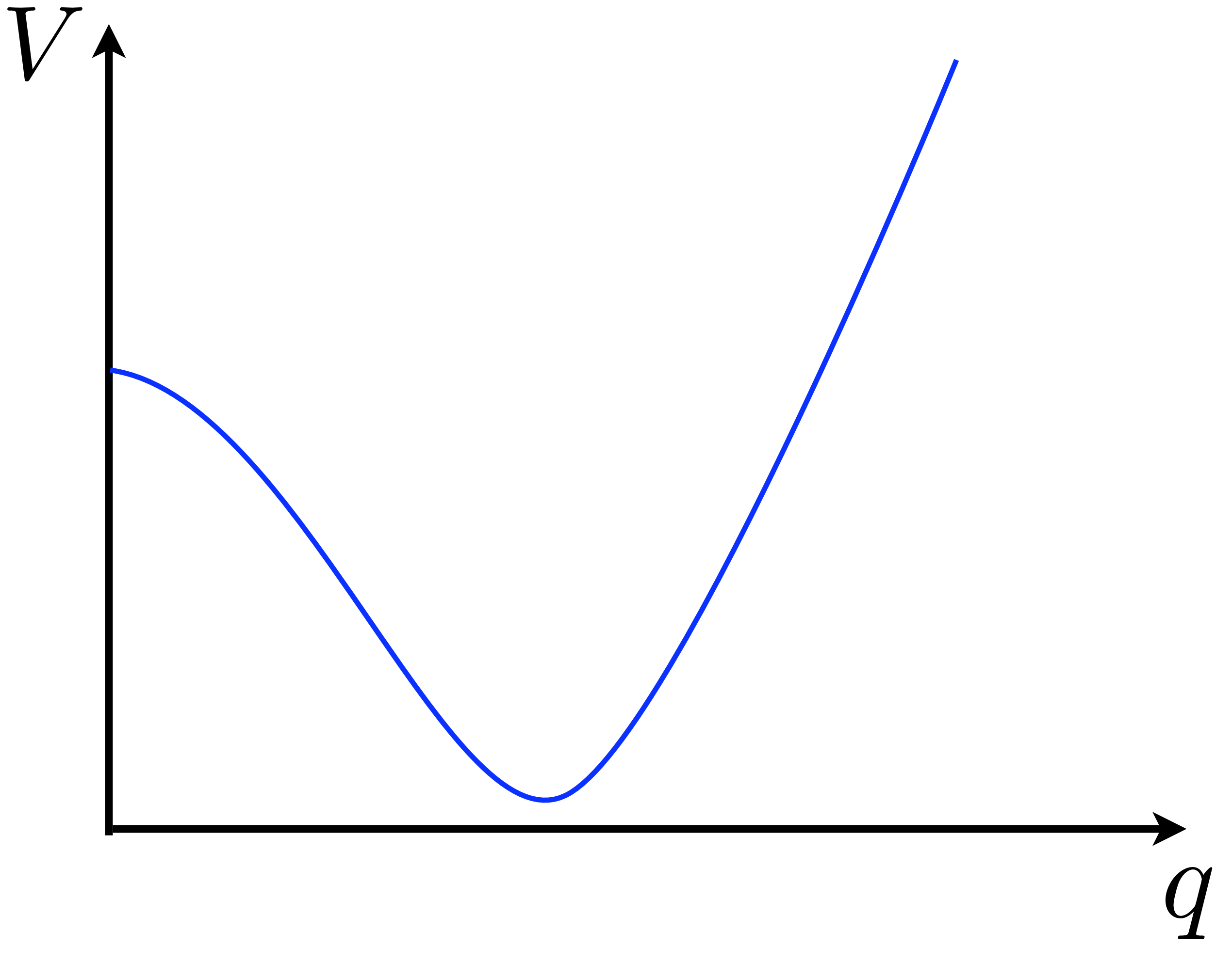
$$\langle M \rangle_{\mathrm{ssb}} = 0 \qquad \langle q \rangle_{\mathrm{ssb}} = \langle q^c \rangle_{\mathrm{ssb}} \sim N\mu \mathbf{1}_N$$

SUSY breaking



SUSY Restoration I

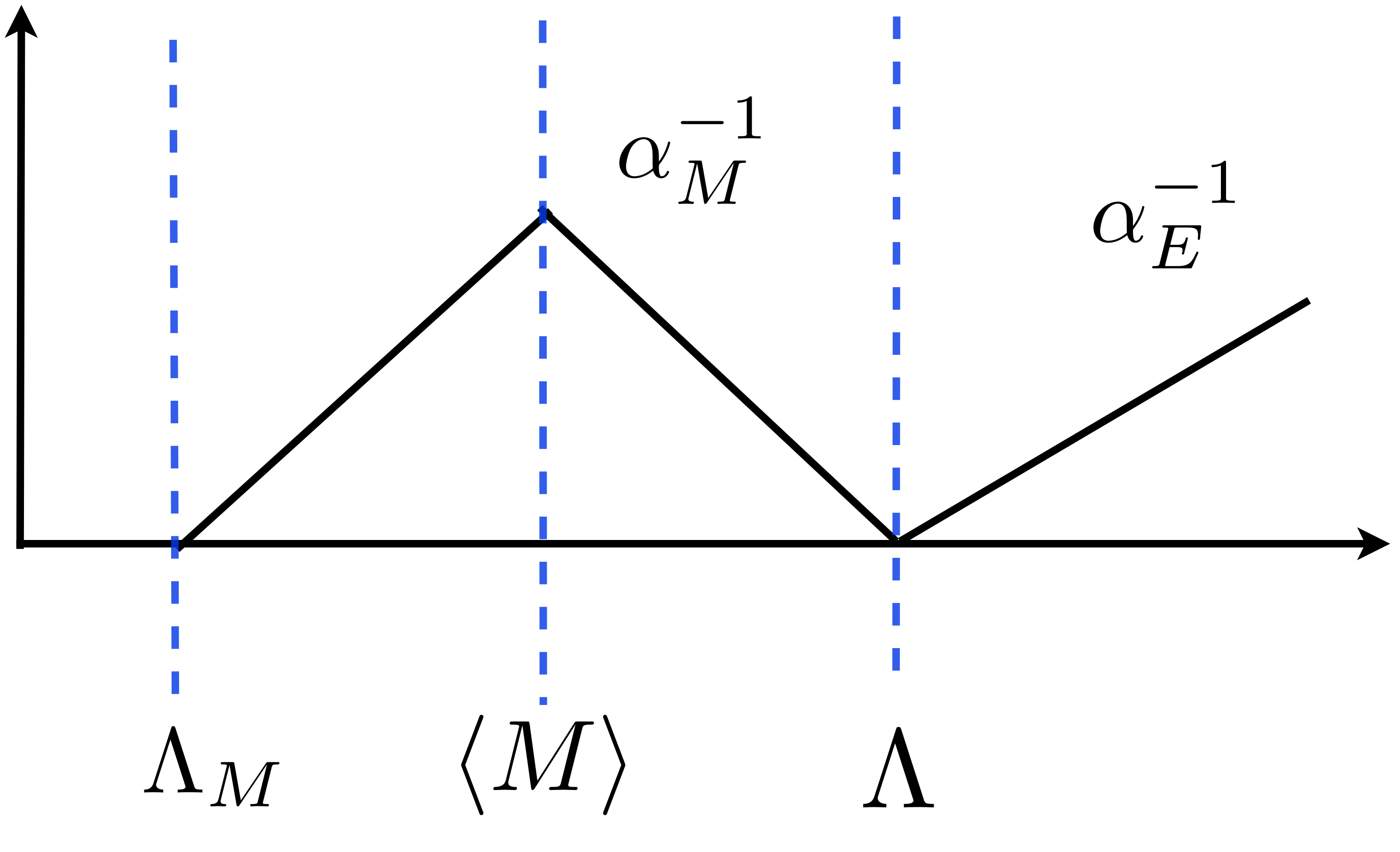
For $\langle M \rangle \neq 0$, magnetic quarks massive; integrate out $(W_m \supset y \mathrm{Tr} q M q^c)$

Obtain pure SUSY QCD; gaugino condensation at scale $\Lambda_M \sim M \left(\frac{M}{\Lambda}\right)^{\frac{N_F - 3N}{3N}}$

Generates ADS superpotential

$$W = \left(\frac{\det M}{\Lambda^{N_F - 3N}}\right)^{\frac{1}{N}}$$

SUSY Restoration I



SUSY Restoration II

$$W = -\mu^2 \,\mathrm{Tr}\; M + \left(\frac{\det M}{\Lambda^{N_F - 3N}} \right)^{\frac{1}{N}}$$

$$M \sim \eta \mathbb{1} \longrightarrow W = -\mu^2 \eta + \eta^{3+a} \Lambda^{-a}$$

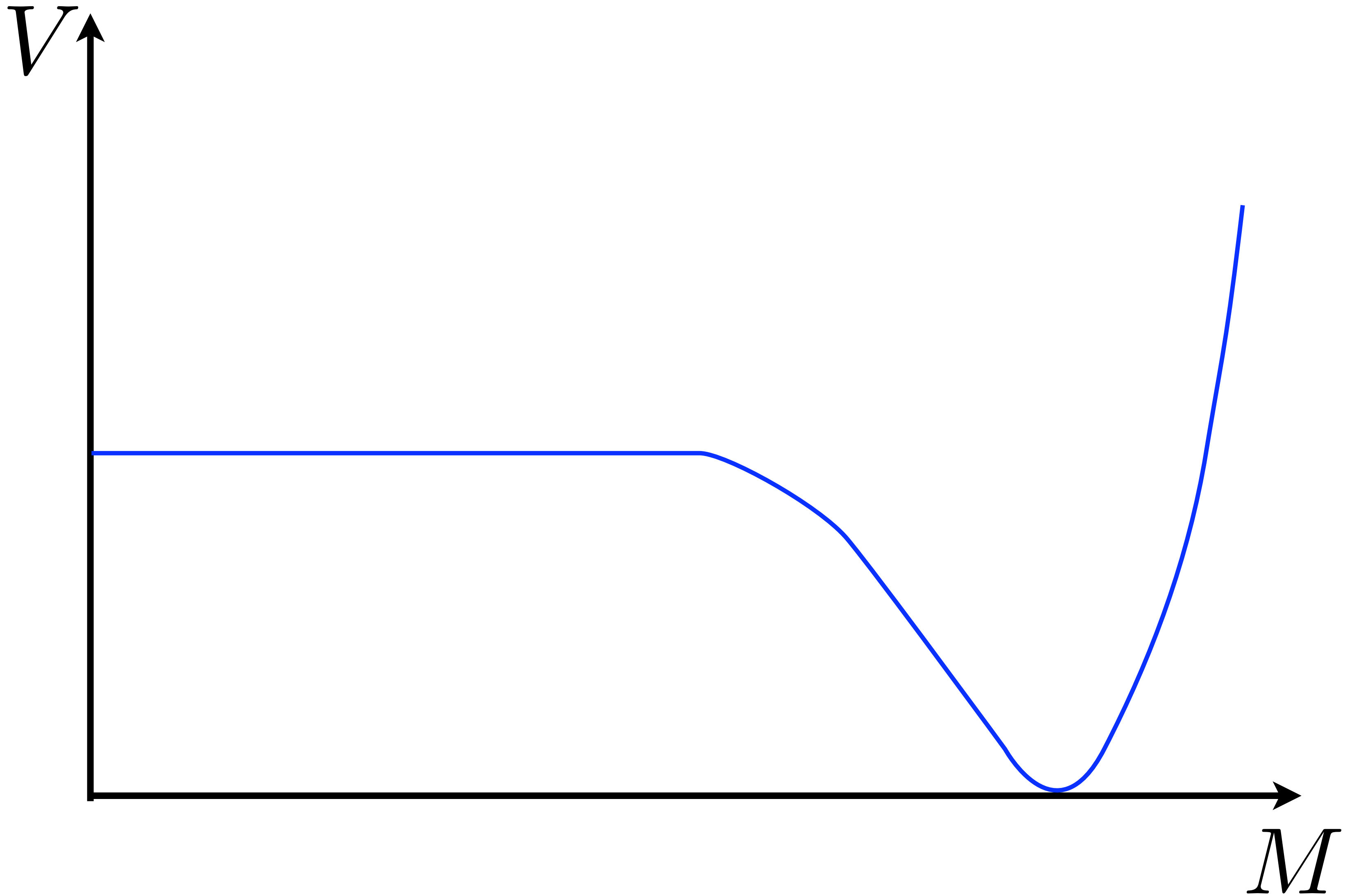
$$a = \frac{N_F - 3N}{N}$$

a parametrizes irrelvance of det superpotential

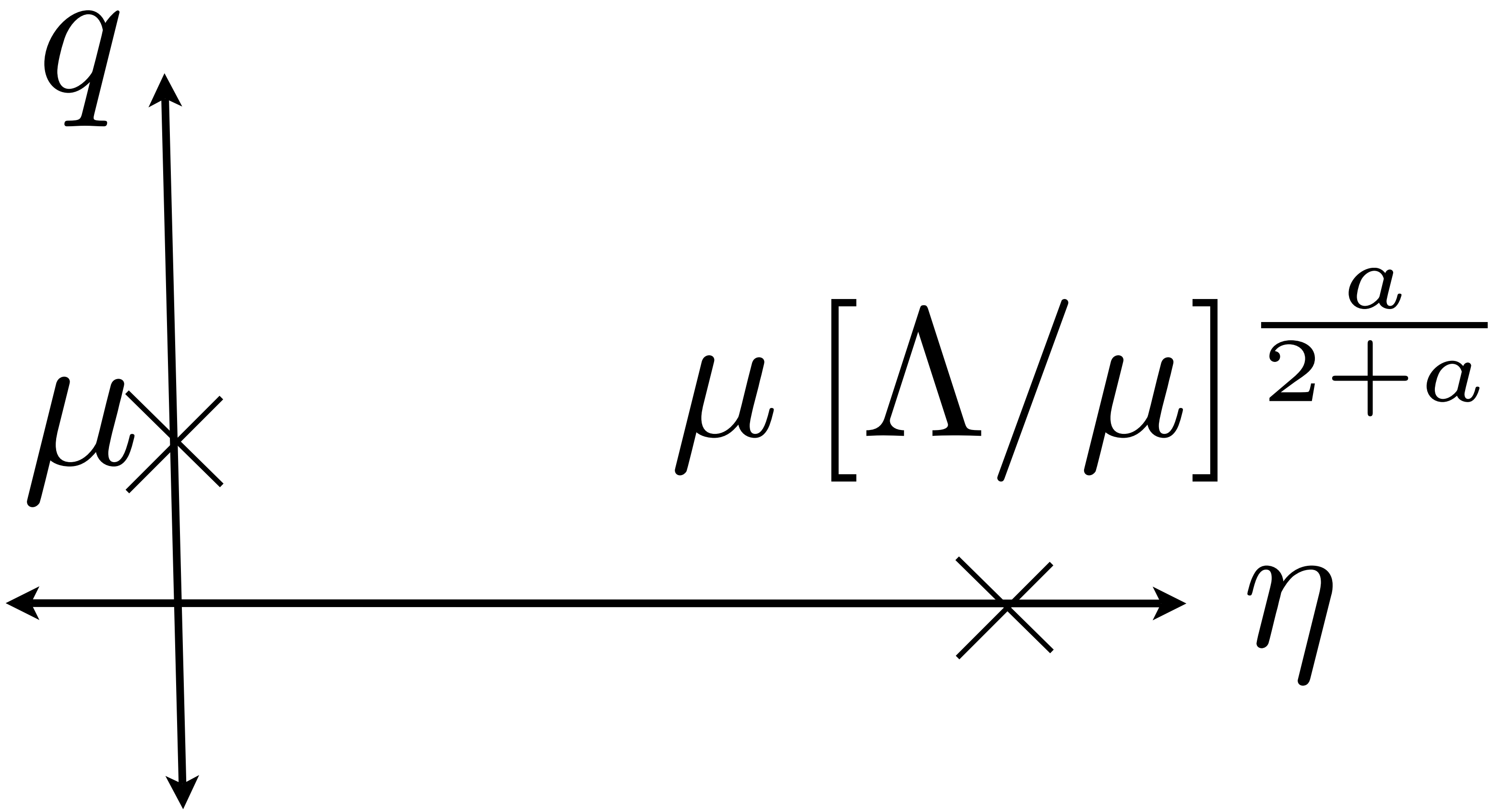
$$F_\eta^\dagger \sim -\mu^2 + \eta^{2+a} \Lambda^{-a} \qquad \langle \eta \rangle_{\mathrm{susy}} \sim \mu \left(\frac{\Lambda}{\mu} \right)^{\frac{a}{2+a}}$$

$$V \sim \left| -\mu^2 + \eta^{2+a} \Lambda^{-a} \right|^2$$

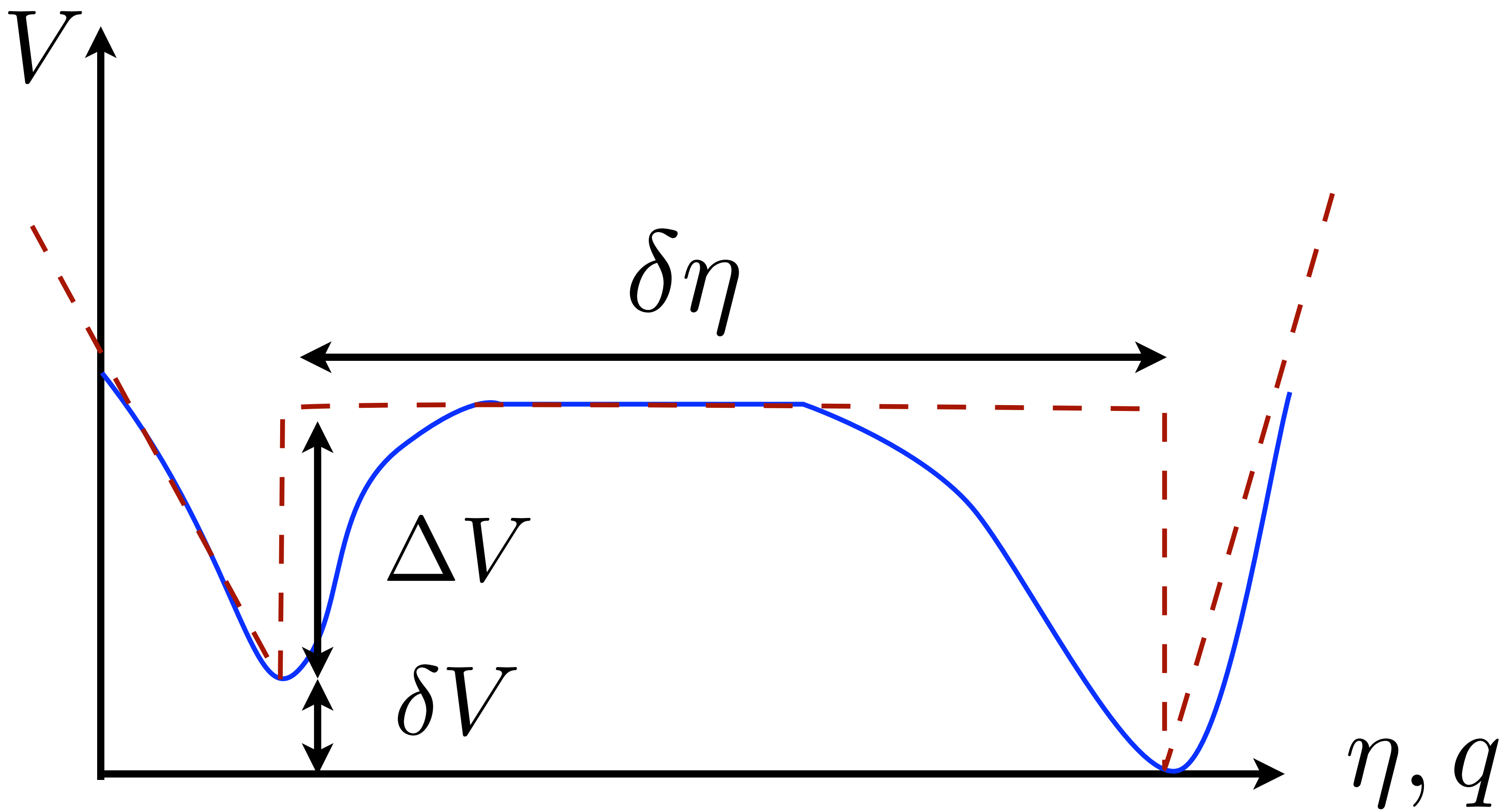
SUSY Restoration II



Metastability



Metastability



$\Delta V \sim \mu^4$ $\qquad \delta V \sim \mu^4$ $\qquad \delta\eta \sim \mu \left(\frac{\Lambda}{\mu}\right)^{\frac{a}{2+a}}$

Zero-temperature Metastability

Is the metastable vacuum sufficiently long-lived to be phenomenologically viable?

$$\Gamma \sim \mu^4 \exp(-S_4)$$

$$S_4 \sim 2\pi^2 \frac{\Delta\eta_{\rm susy}^4}{(V_{\rm peak} - V_{\rm susy})}$$

$$ISS : S_4 \sim \left(\frac{\Lambda}{\mu}\right)^{\frac{4a}{2+a}}$$

Zero-temperature Metastability

$$\frac{a}{a+2}\log\frac{\Lambda}{\mu} > 0.73 + 0.003\log\frac{\mu}{\text{Tev}} + 0.25\log N$$

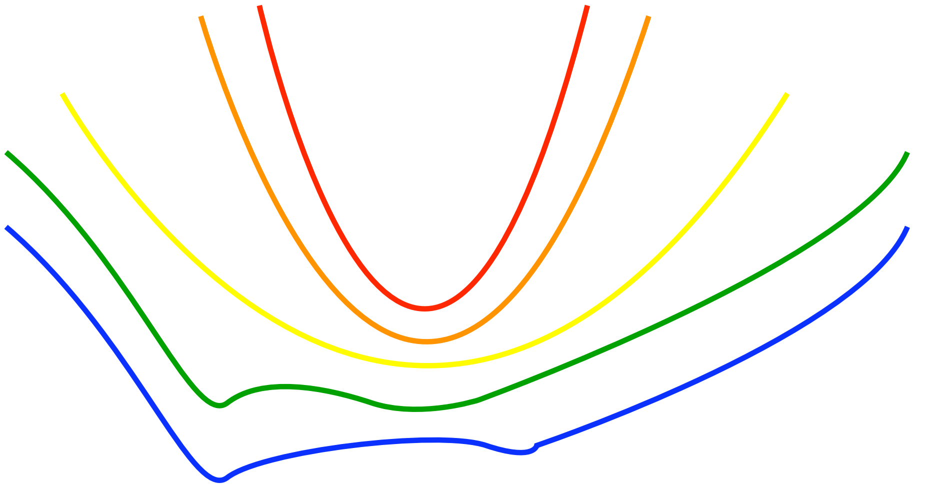
Metastable vacuum is parametrically long-lived at zero temperature

Reheating SQCD

Natural question: what happens in a finite-temperature universe?

What vacua are selected by cooling?

For temperatures $T \gg \mu$, do thermal effects stimulate transitions?



Thermalization

Analysis assumes hidden sector thermalization, but generically unlikely for the fields to lie in equilibrium configuration after reheating

Difficult to make precise statements (depends on mediation scheme), but some details universal.

Natural to consider regime $\langle Q \rangle \sim H \gg T, \Lambda$ where fluctuations of Q dominate.

Moduli trapping

SQCD electric theory a moduli space in the D-flat directions along which large-vev squarks will oscillate

Origin is an enhanced symmetry point; oscillating squarks dump energy into production of vectors

Moduli trapping

Oscillations damp rapidly in a time $t_{\mathrm{damp}} \sim \frac{2\pi}{m}\left(\frac{2\pi}{g}\right)^{3/2}$

Electric quarks localize at origin; thermal equilibrium reached at $T \gg \mu$

Similar analysis goes through for $\Lambda > \langle Q \rangle > T$

Thermal effective potential

Compactify Euclidean time with radius $R_\tau \sim T^{-1}$ to obtain finite-temperature 2-point function

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$$\delta V(\phi, T) = \sum_{\alpha,\text{boson}} \left(-\frac{\pi^2}{90} T^4 + \frac{1}{24} m_\alpha^2(\phi) T^2 + \cdots \right)$$
$$+ \sum_{\alpha,\text{fermion}} \left(-\frac{7}{8}\frac{\pi^2}{90} T^4 + \frac{1}{48} m_\alpha^2(\phi) T^2 + \cdots \right)$$

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↑ added entropy for light species

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added entropy for light species

symmetry restoration at high temp

Early Universe

At high temperatures, fields lie at minimum of free energy; for $T \gg \mu$ this is $\langle q \rangle,\ \langle M \rangle = 0$

Point of maximum symmetry

Early Universe

As temperature drops, two possible phase transitions:

1. To metastable vacuum, $\langle q \rangle \neq 0$
2. To the SUSY vacuum $\langle M \rangle \neq 0$

Which transition dominates depends on critical temperature, order of transitions.

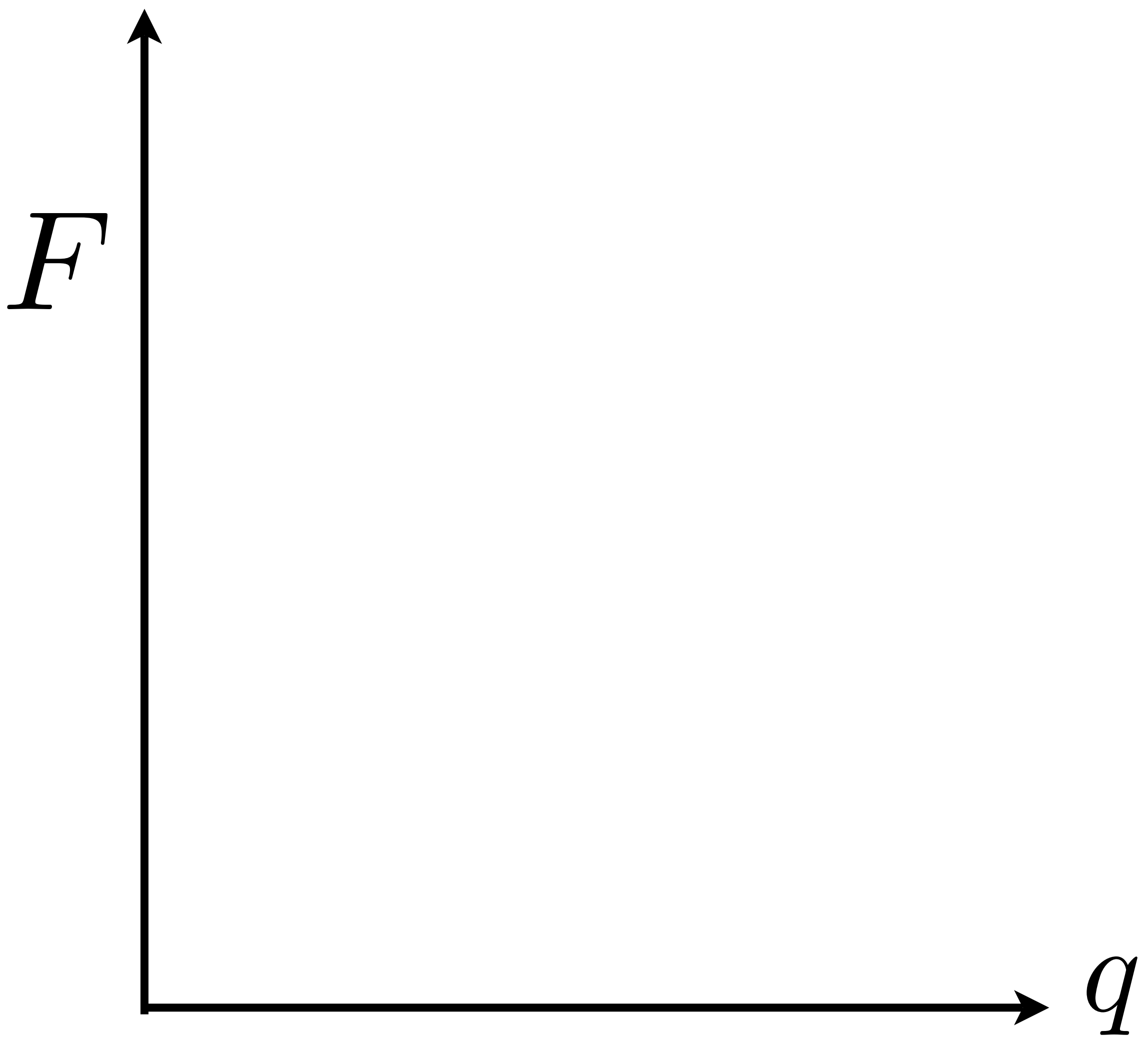
Transition to the metastable vacuum

$$F = N\left(\frac{yq^2}{N^2} - \mu^2\right)^2 - c_0 N_F^2 T^4 + (c_1^{(g)} g^2 + c_1^{(y)} y^2) N q^2 T^2 + \ldots$$

$$\sim (-y\mu^2 + y^2 T^2) q^2 + \ldots$$

Second-order transition at $T_{c,ssb} \simeq \mu$

Transition to the metastable vacuum



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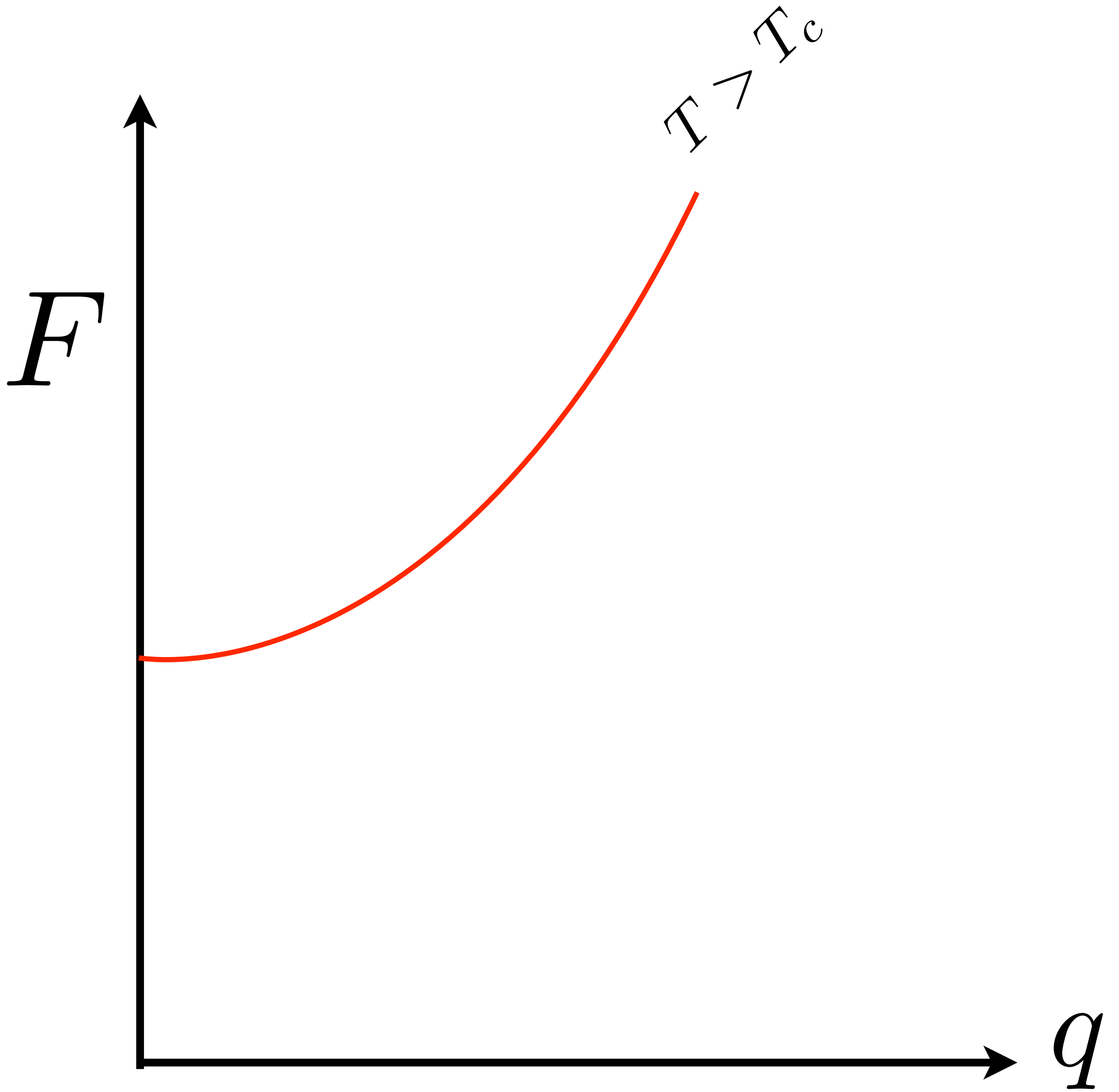

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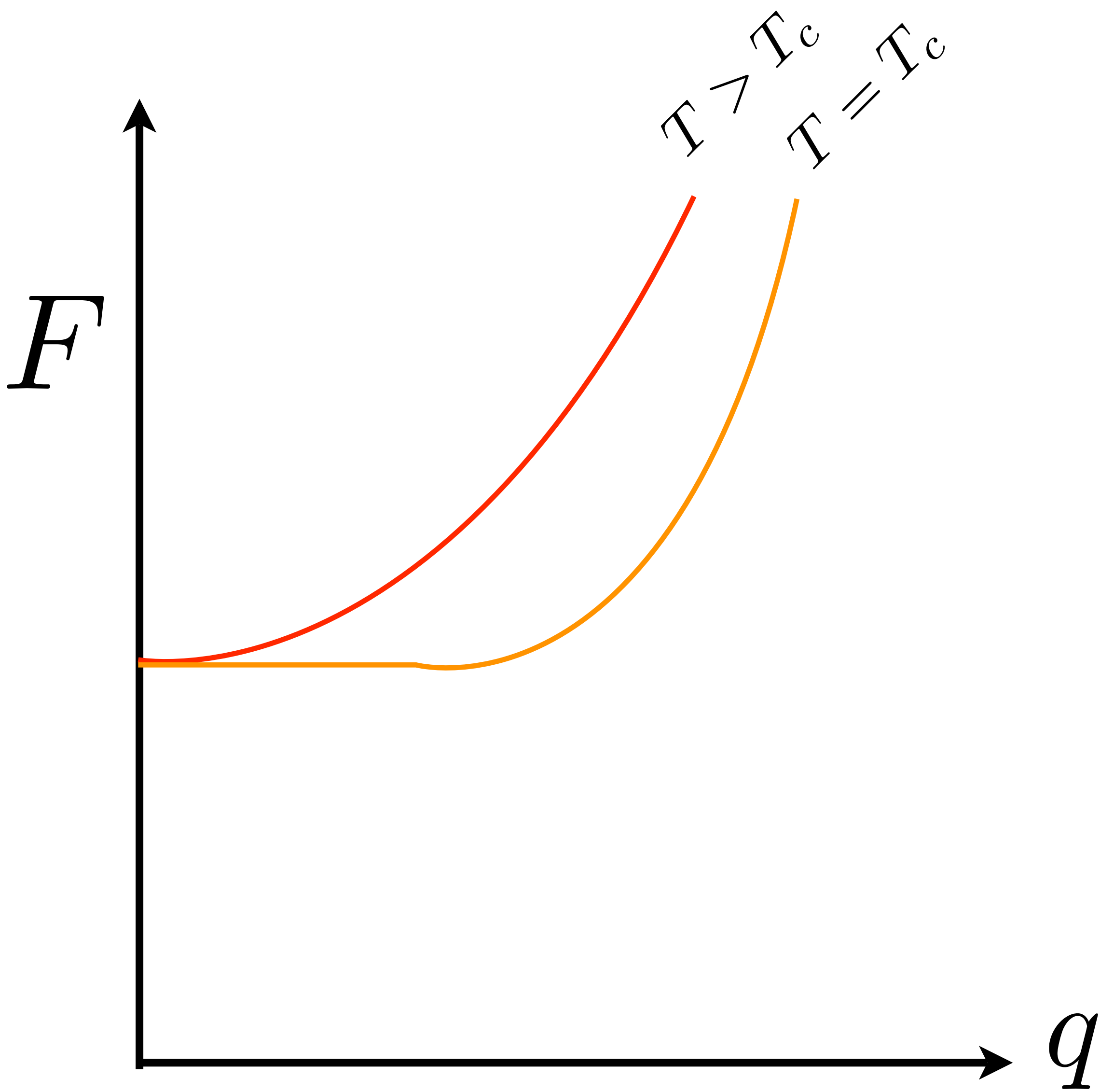

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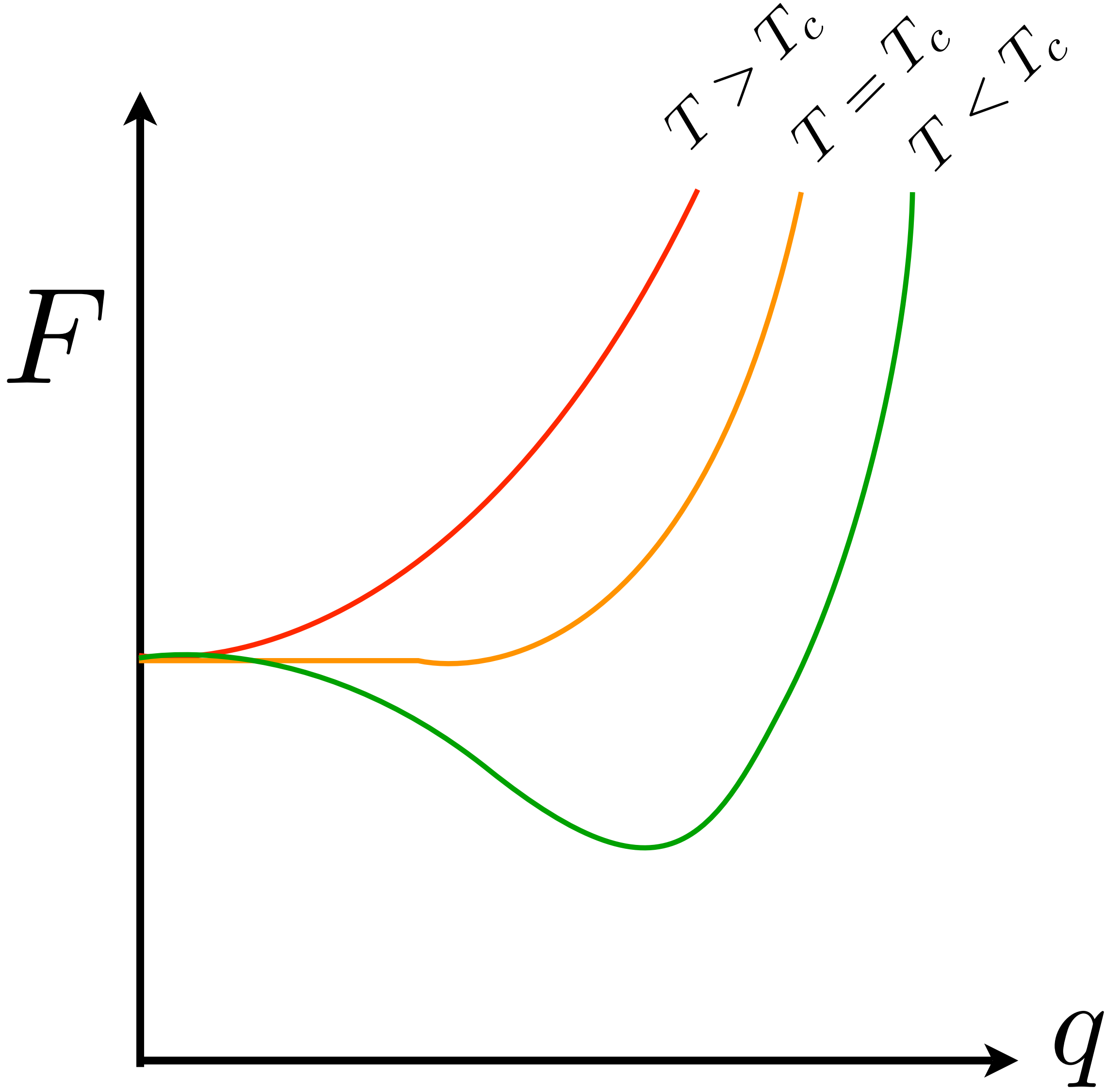

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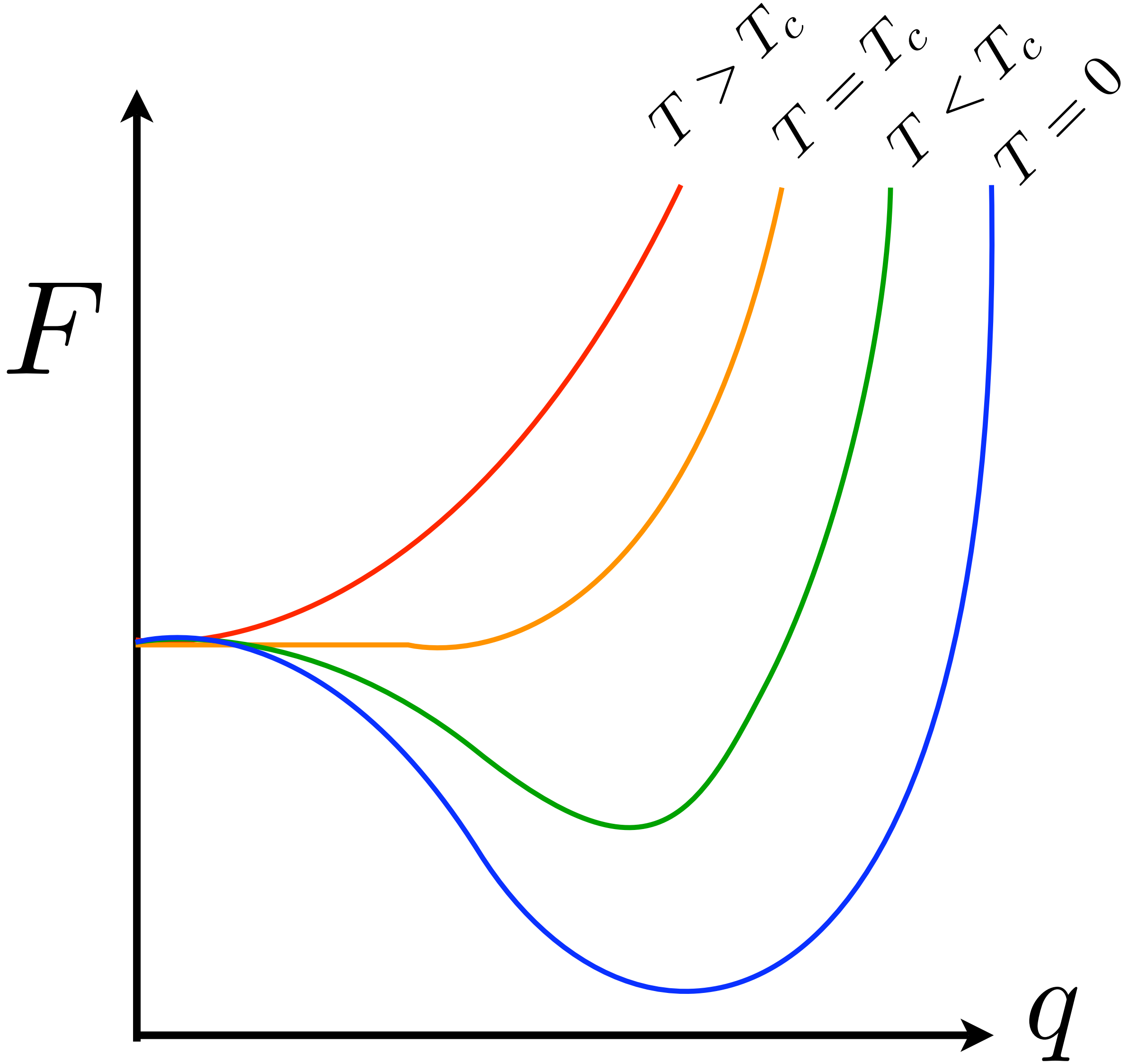

Transition to SUSY vacuum I

$$V = \begin{cases} \mu^4 + c_1\, y^2 N \eta^2 T^2 - c_0 (N N_F + N^2) T^4 + \cdots & T \geq \Lambda_m(\eta) \\ N\Lambda^4 \left| \left(\frac{\eta}{\sqrt{N_F}\Lambda} \right)^{2+a} - \frac{\mu^2}{\Lambda^2} \right|^2 & \\ \quad + c_1\, y^2 N \eta^2 T^2 - c_0 (N N_F + N^2) T^4 + \cdots & T \geq y\eta \\ N\Lambda^4 \left| \left(\frac{\eta}{\sqrt{N_F}\Lambda} \right)^{2+a} - \frac{\mu^2}{\Lambda^2} \right|^2 & T < y\eta \end{cases}$$

Near origin, $\sim y^2 \eta^2 T^2 - \mu^2 \Lambda^{-a} \eta^{2+a}$

$\rightarrow$ quarks stabilize origin even at low temp

First-order transition at $T_{c,susy} \sim \mu$

Transition to SUSY vacuum I

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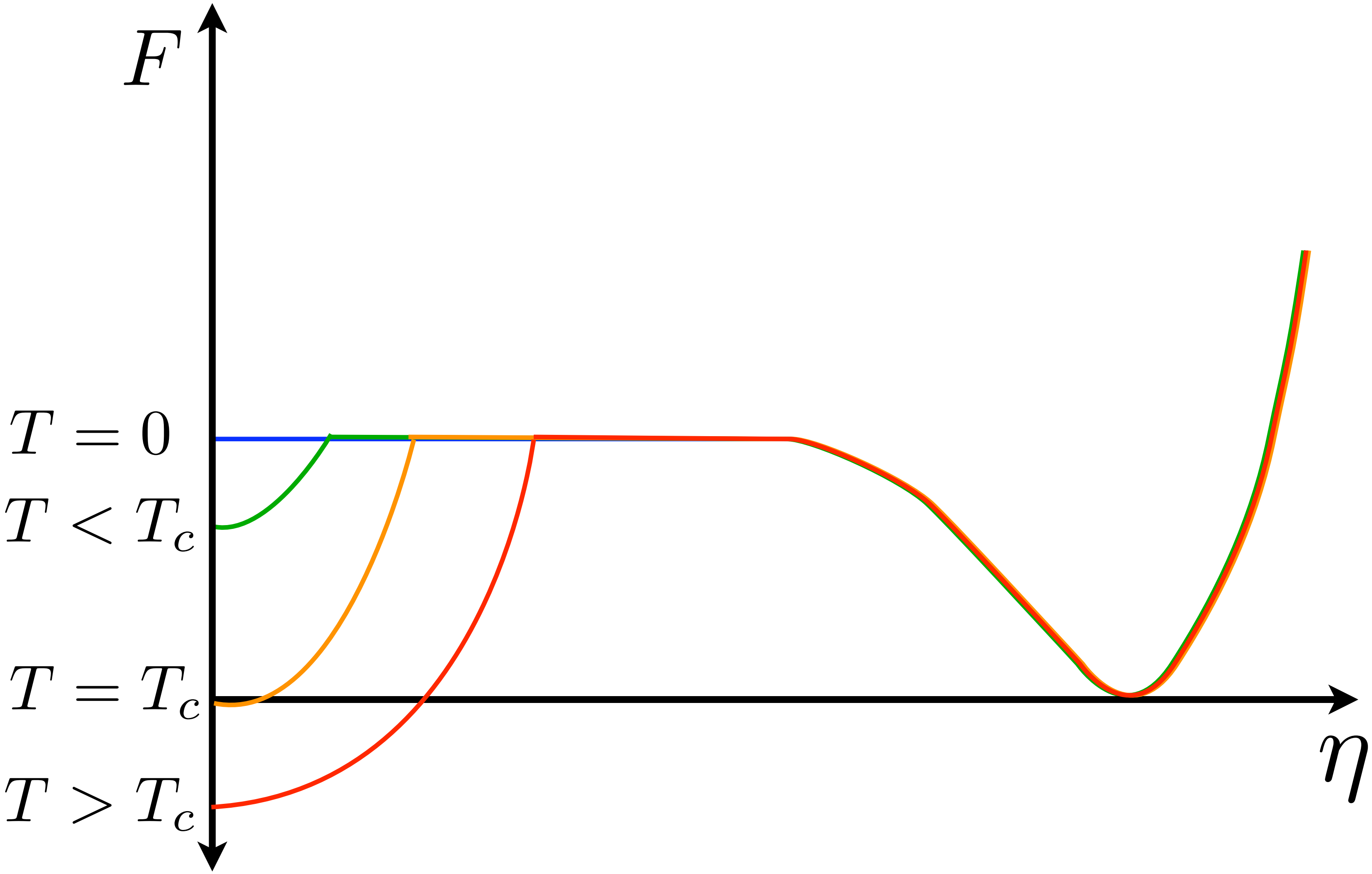
Transition temperatures into SUSY, metastable vacua are parametrically the same

Transition to SUSY vacuum I



Transition to SUSY vacuum: Bubble nucleation

$$\Gamma \sim T^4 e^{-S_3/T}$$

$$S_3 \sim \frac{4\pi}{3\sqrt{2}} \frac{\Delta\eta_{\rm susy}^3}{\left[(V_{\rm peak} - V_{\rm susy})^{\frac{1}{4}} - (V_{\rm peak} - V_0)^{\frac{1}{4}}\right]^2}$$

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$$R_c \sim \frac{\Delta\eta_{susy}\Delta V^{\frac{1}{2}}}{\delta V}$$

$$\Delta V \simeq \mu^4$$

$$\delta V \simeq \mu^4 \left(1 - \left(\frac{T}{T_c^{\rm susy}}\right)^4\right) .$$

Finite-temp longevity bound

$$\log \frac{\Gamma}{\mu^4} \simeq -\frac{9\pi}{\sqrt{2N}} \left(\frac{\Lambda}{\mu}\right)^{\frac{3a}{2+a}} .$$

$$\Gamma(T)\, a^3(T)\, \mathcal{V} \Delta t \simeq 0$$

Finite-temp longevity bound

$$\log \frac{\Gamma}{\mu^4} \simeq -\frac{9\pi}{\sqrt{2N}} \boxed{\left(\frac{\Lambda}{\mu}\right)^{\frac{3a}{2+a}}}.$$

same parametric dependence

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size of universe when bubble was active

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size of universe when bubble was active

duration of thermal tunneling epoch

Finite-temp longevity bound

$$\frac{a}{a+2}\log\frac{\Lambda}{\mu} > 0.64 - 0.010\log\frac{\mu}{\text{Tev}} + 0.17\log N$$

Same parameter ensuring the longevity of the metastable vacuum also favors its selection during thermal evolution

SQCD

Rule of thumb for evolution of theories with metastable SUSY-breaking vacua?

The universe cools to the vacuum with the greater abundance of light states.

Favorable outcome for SQCD (and variations thereof, e.g., SQCD with adjoints)

Classic O'Raifeartaigh Models

Consider now thermal evolution of theories without massless fields around the origin

$$W = m\psi\psi^c + \lambda Z(\psi^2 - \mu^2)$$

Classic O'Raifeartaigh Models

Consider now thermal evolution of theories without massless fields around the origin

$$W = m\psi\psi^c + \lambda Z(\psi^2 - \mu^2)$$

$$F_Z = \lambda(\psi^2 - \mu^2)$$
$$F_{\psi^c} = m\psi$$
$$F_\psi = m\psi^c + 2\lambda\psi Z$$

Classic O'Raifeartaigh Models

Consider now thermal evolution of theories without massless fields around the origin

$$W = m\psi\psi^c + \lambda Z(\psi^2 - \mu^2)$$

$$\langle\psi\rangle_{\rm ssb} = \langle\psi^c\rangle_{\rm ssb} = \langle Z\rangle_{\rm ssb} = 0$$

$\mu < m$ Integrate out $\psi\psi^c$

Low-energy O'Raifeartaigh

$$W = -\lambda\mu^2 Z.$$

$$K = \left(1 - \frac{c\lambda^2}{16\pi^2}\log(1 + \frac{\lambda^2|Z|^2}{m^2})\right)|Z|^2.$$

$$V(Z) = \frac{|D_Z W|^2}{K_{Z\bar{Z}}}$$

Low-energy O'Raifeartaigh

$$
\begin{aligned}
V(Z) &\simeq \mu^4 + \frac{c\lambda^4\mu^4}{8\pi^2 m^2}|Z|^2 && Z \ll m \\
V(Z) &\simeq \frac{\mu^4}{1 - \frac{c\lambda^2}{16\pi^2}\log\frac{\lambda^2|Z|^2}{m^2}} && Z \gg m.
\end{aligned}
$$

O'Metastability

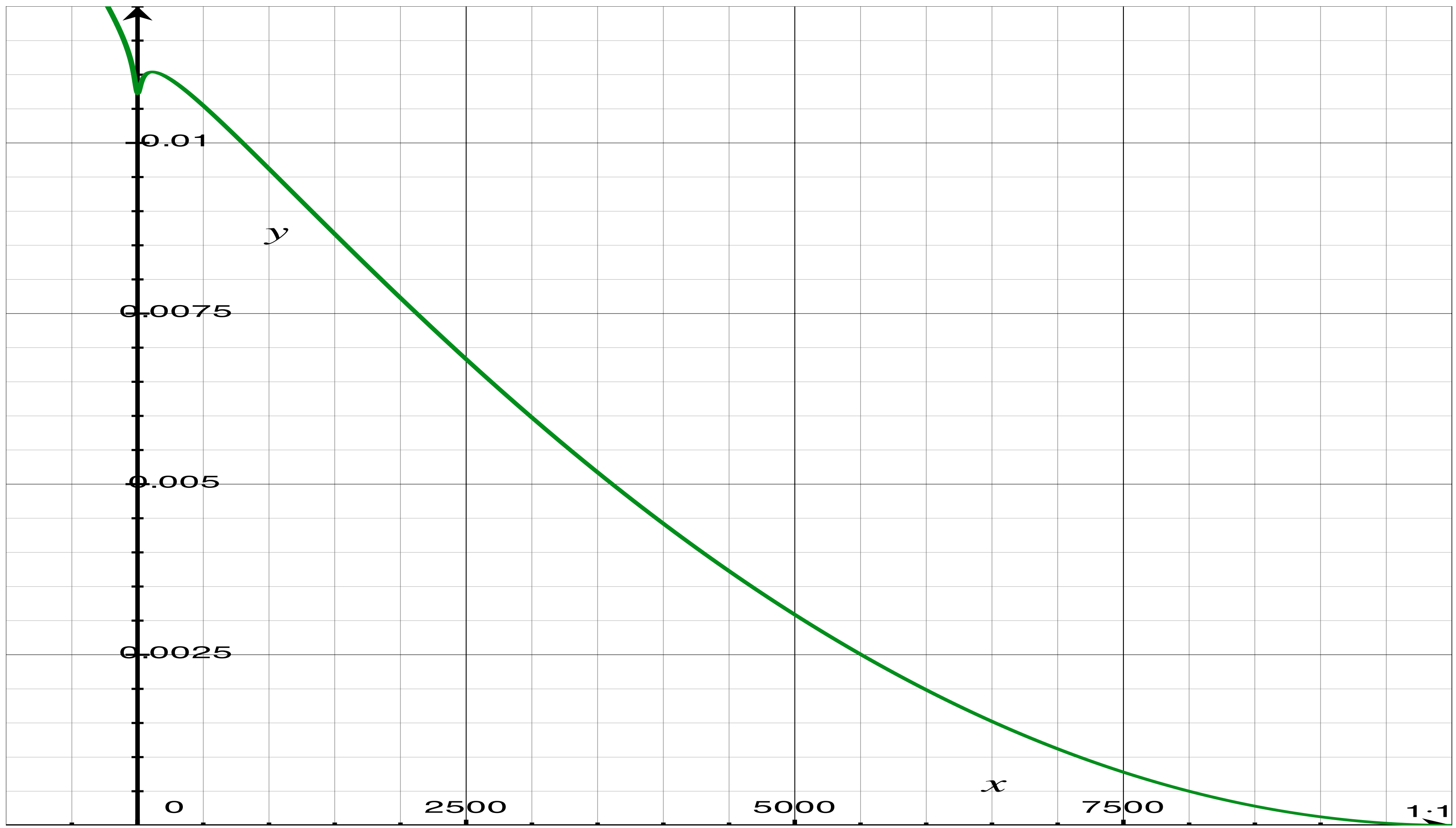
Whatever generates scale $\mu \ll M_{Pl}$ can also generate corrections

$$\delta W = \frac{1}{2}\epsilon\mu Z^2 \rightarrow \text{SUSY vacuum at}$$

$$\langle Z \rangle_{\text{susy}} = \epsilon^{-1}\mu \qquad\qquad \langle \psi \rangle_{\text{susy}} = 0$$

Often comes from dynamical retrofitting of scales

O'Metastability



O'Longevity

$$S_4 \simeq 2\pi^2 \frac{(Z_{\mathrm{peak}})^4}{\Delta V} = 2\pi^2 \left(\frac{\lambda^2}{16\pi^2} \right)^3 \epsilon^{-4}$$

Longevity guaranteed by $\epsilon \ll 1$

O'Longevity

But at finite temperatures, no light fields; $F = V(0) - T^4$

Possible to make large thermal excursions
away from metastable vacuum

$$S_3/T = 4\pi \frac{(\delta Z)^3}{(\delta V)^{\frac{1}{2}} T} = 4\pi \left(\frac{\lambda}{4\pi}\right)^5 \epsilon^{-3} \frac{\mu}{m}$$

O'Longevity

Thermal stability introduces parametrically new constraints; a feature of no light states around the origin

Relevance of the operator generating the SUSY vacuum NOT as important

Morals

- Vacua with light states preferentially selected at finite temperature
- Suggests the metastable vacuum of SQCD is preferentially chosen after reheating
- Parametrically new constraints in theories without light states

Outlook & Future directions

- Metastable DSB for direct gauge mediation (Dine & Mason; Kitano, Ooguri, & Ookouchi; Aharony & Seiberg; Murayama & Nomura; Csaki, Shirman, & Terning)
- Metastable SUSY breaking in string vacua (vast & ever-growing literature...)
- Inflation into the metastable vacuum?