Metastable SUSY breaking: Predicting the end of the Universe

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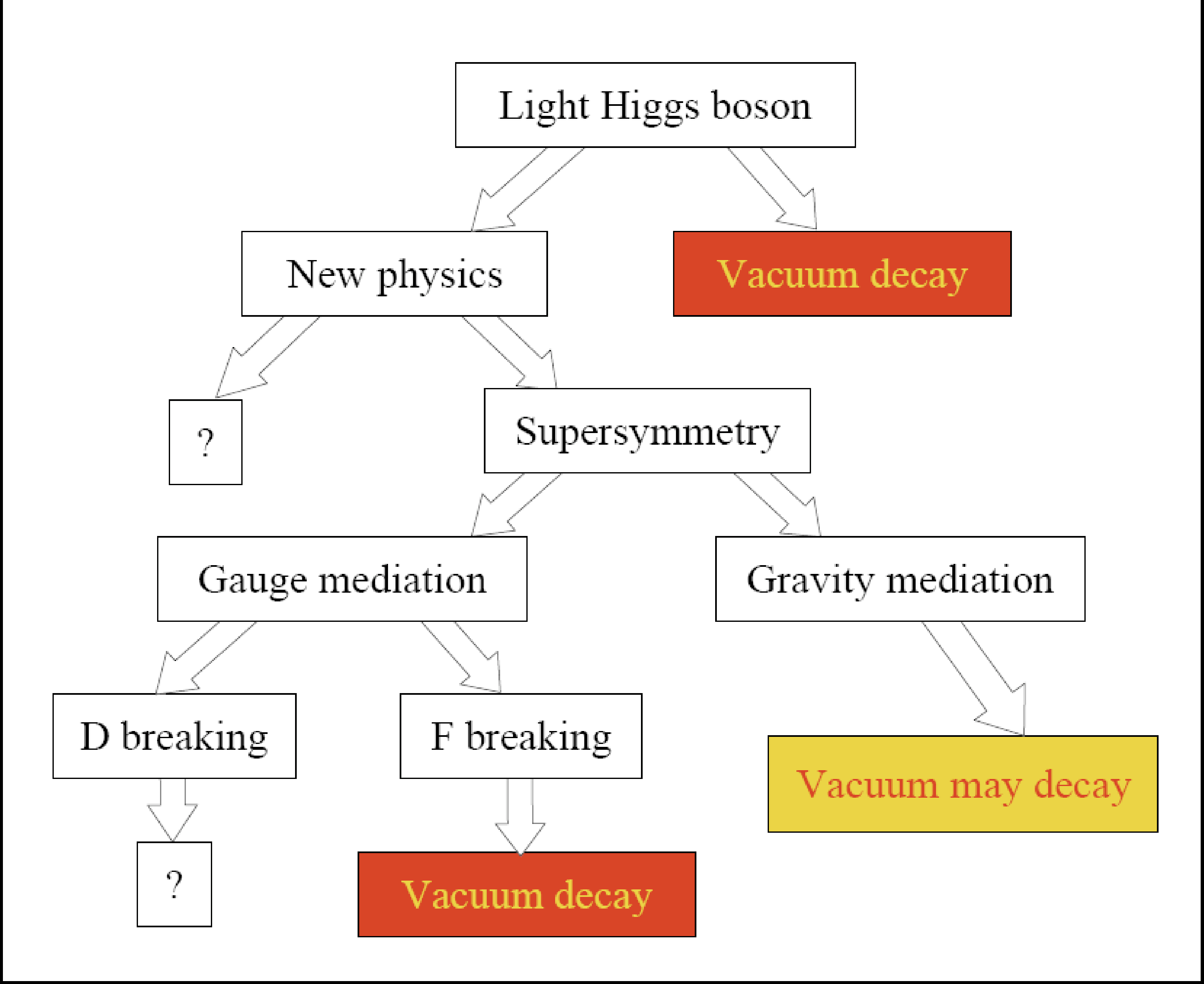
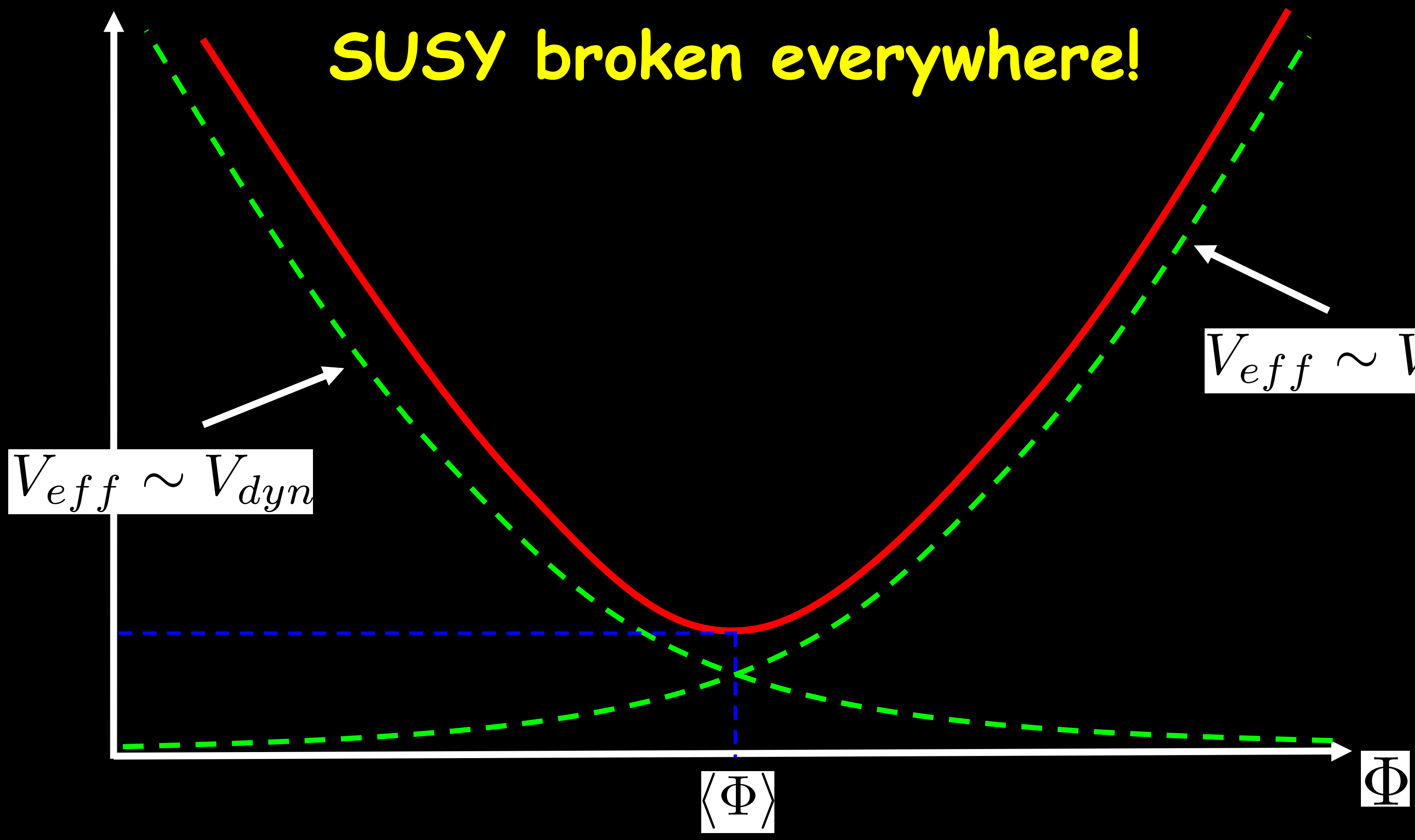
In Memory of…
1809
Prepare to follow.
MOWBRAY
AGED 62 YEARS
also
THOMAS MOWBRAY

1. Introduction

The LHC as a crystal ball for the fate of the Universe.



Conventional picture of SUSY breaking



Metastability hard to avoid!

- We consider low scale SUSY breaking;

$$M_{\mathrm{SUSY}} < 10^{11}\mathrm{GeV}$$

i.e. non-gravity mediated.

- Theorem (Nelson Seiberg):

SUSY breaking requires R-symmetry

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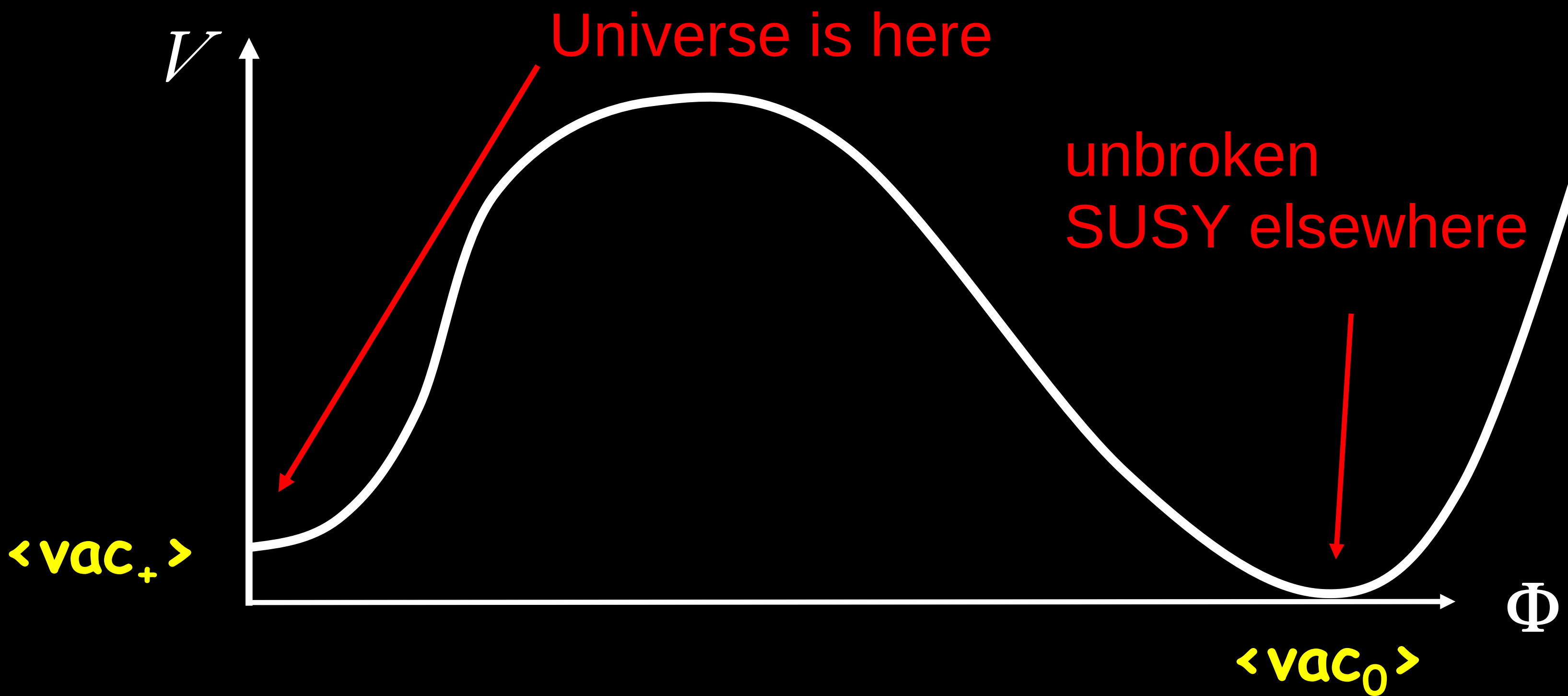
Massless gauginos or

Massless R-axion

↓

Both phenomenologically unacceptable!

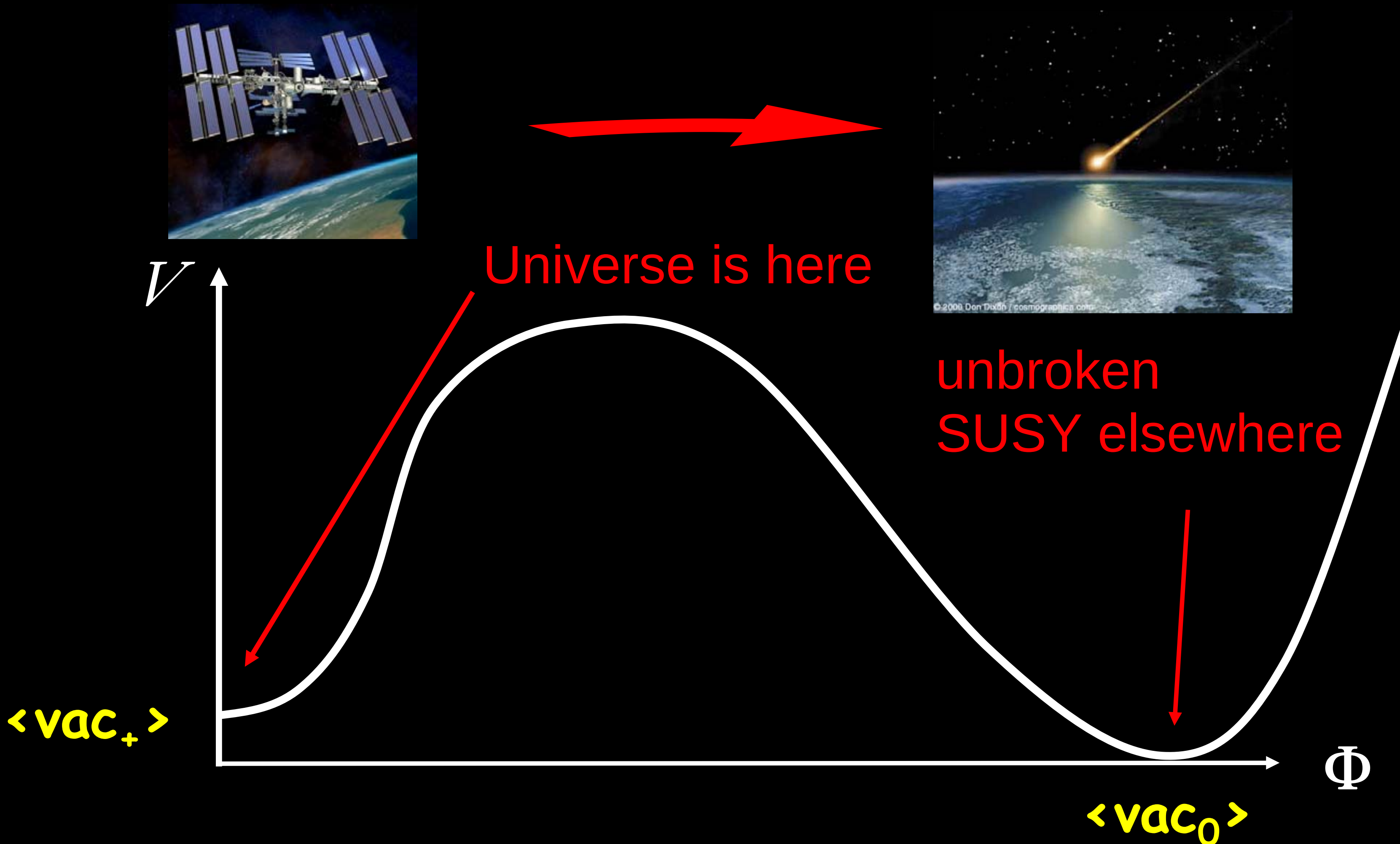
ISS picture of meta-stable SUSY breaking



Many constraints do not apply!!!

Sucessful Model Building!

ISS picture of meta-stable SUSY breaking

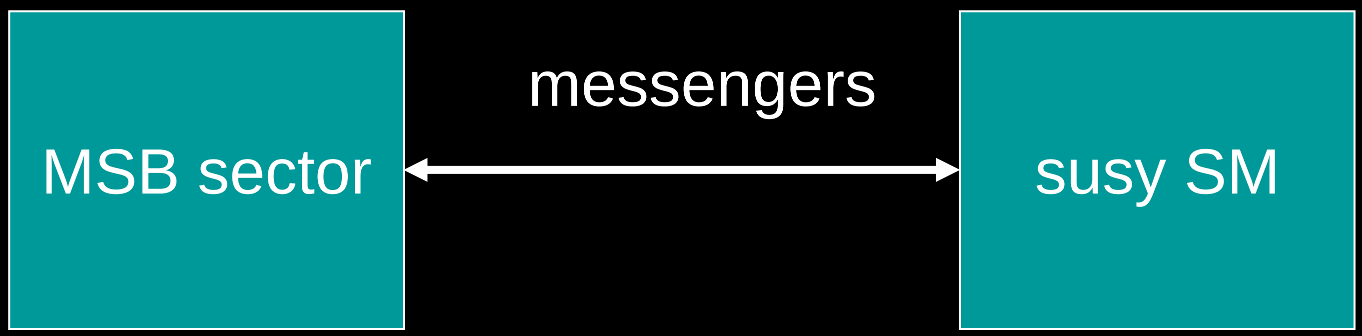


Cosmological questions

- Does the metastable vacuum live long enough?
- Why should we end up in this vacuum??

Model building

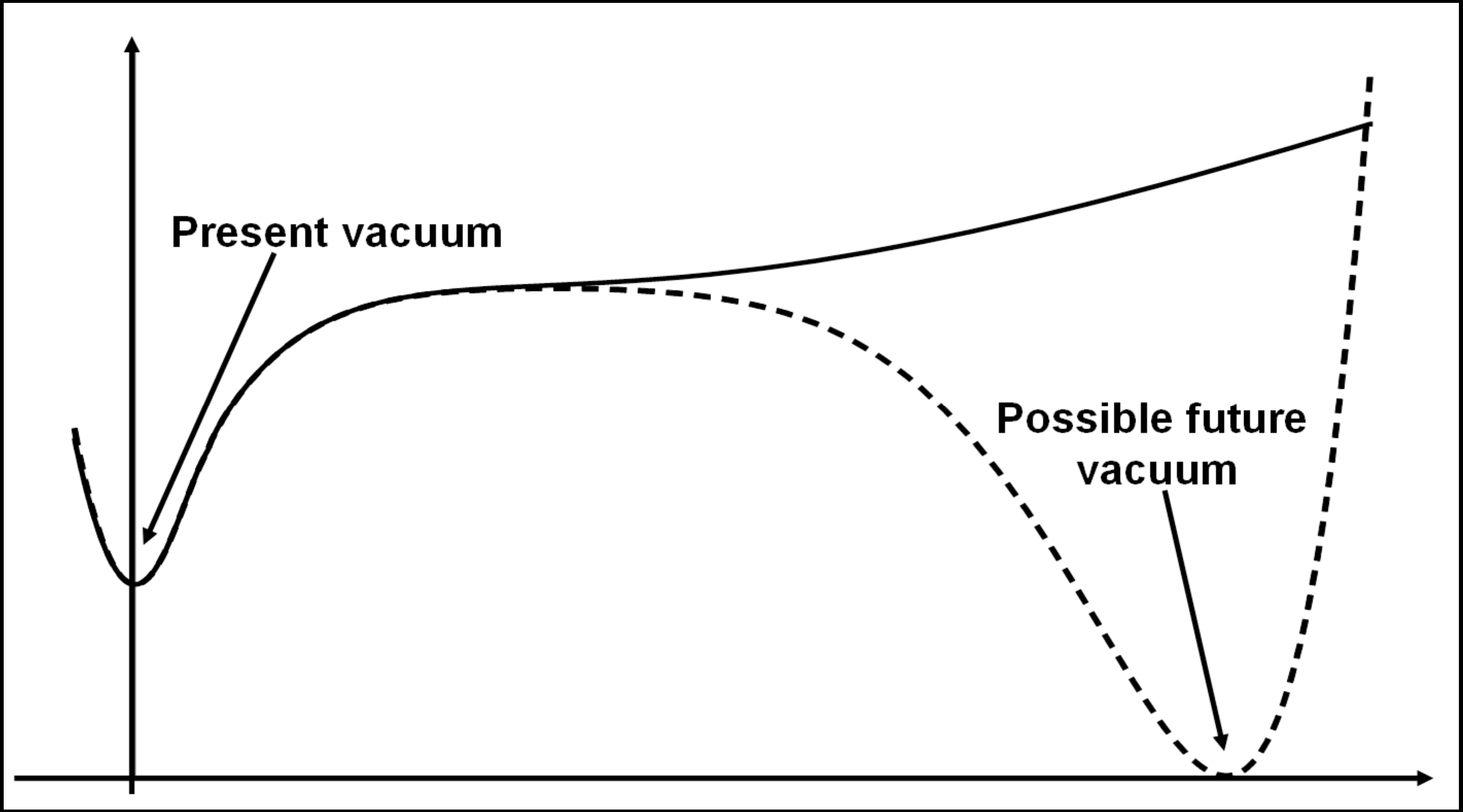
- Realistic models



- "Mediate" SUSY (and R) breaking to the SM!

Testing in the lab?

- Can we tell about metastability?



2. The ISS model

The ISS Model:

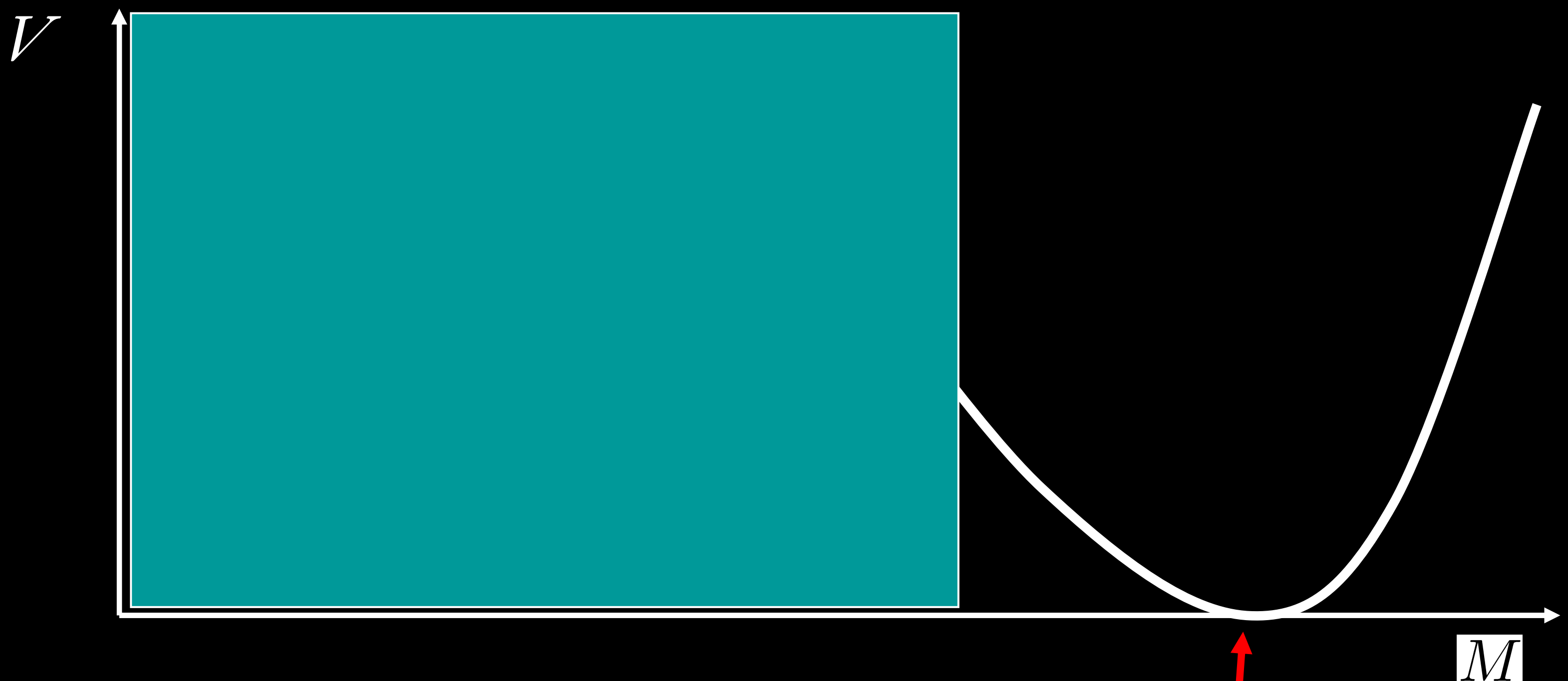
N=1 SQCD with massive Quarks

	$SU(N_c)_{\text{gauge}}$	$SU(N_f)$	$SU(N_f)$
Q	N_c	N_f	1
$\tilde{Q}$	$\overline{N}_c$	1	$\overline{N}_f$
$\Phi \sim M = Q\tilde{Q}$	1	N_f	$\overline{N}_f$

$$W_{tree} = \mathrm{Tr}\, mQ\tilde{Q} = m\mathrm{Tr} M = h\mu^2 \mathrm{Tr}\,\Phi$$

This is a massive vector-like theory, thus it has $\mathrm{Tr}\,(-1)^{\mathrm{F}} = \mathrm{N_c}$ supersymmetric vacua

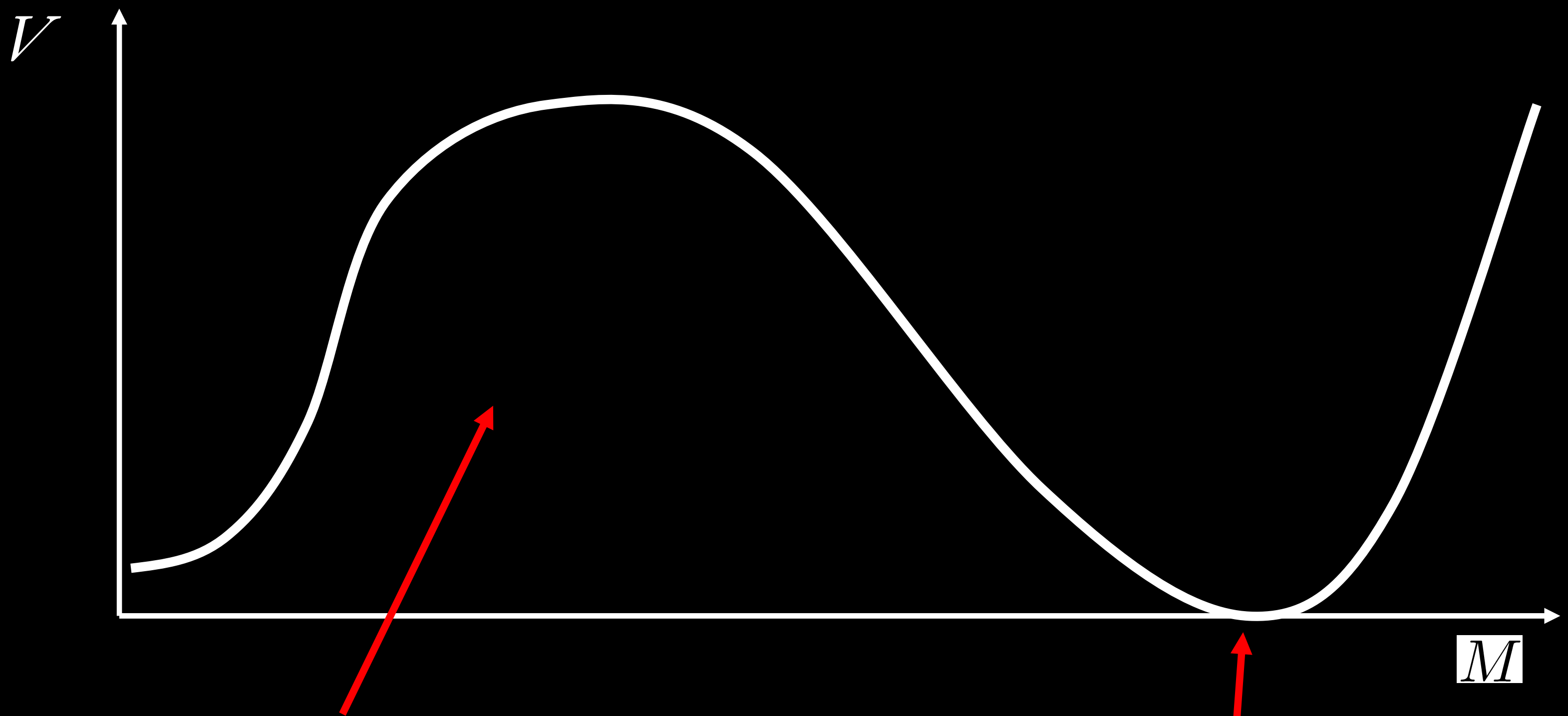
Effective potential of SQCD



N_c SUSY vacua

$$\langle M \rangle \sim \left(\Lambda^{3N_c - N_f} m^{N_f - N_c} \right)^{1/N_c}$$

Effective potential of SQCD



Potential near the origin can be uncovered using **Seiberg duality**

N_c SUSY vacua

$$\langle M \rangle \sim \left(\Lambda^{3N_c - N_f} m^{N_f - N_c} \right)^{1/N_c}$$

Seiberg duality sounds fancy…

- … but it is basically the same as a pion description of low energy QCD

- Weakly coupled theory using the `right'degrees of freedom

Seiberg Duality

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Microscopic:
(electric)

$$W_{\rm cl} = m \,{\rm Tr}\, Q\tilde{Q}$$

	$SU(N_c)_{\rm gauge}$	$SU(N_f)$	$SU(N_f)$
Q	N_c	N_f	1
$\tilde{Q}$	$\overline{N}_c$	1	$\overline{N}_f$

Electric

$SU(N_c)$

$\Lambda_{\rm L}$

Magnetic

$SU(N_f - N_c)$

Macroscopic:
(magnetic)

$$W_{\rm cl} = h \,{\rm Tr}\, \varphi \Phi \tilde{\varphi} + h\mu^2 \,{\rm Tr}\, \Phi$$

	$SU(N_f - N_c)_{\rm gauge}$	$SU(N_f)$	$SU(N_f)$
φ	$N_f - N_c$	N_f	1
$\tilde{\varphi}$	$\overline{N_f - N_c}$	1	$\overline{N}_f$
Φ	1	$\overline{N}_f$	N_f

Classically: Different gauge theories

Quantum: Describe the same physics in the IR.

From now on: macroscopic theory

We take $N_c + 1 < N_f \leq \frac{3}{2} N_c$ where the magnetic theory is IR free

	$SU(N)_{\rm gauge}$	$SU(N_f)$	$SU(N_f)$
φ	N	N_f	1
$\tilde{\varphi}$	$\overline{N}$	1	$\overline{N}_f$
Φ	1	$\overline{N}_f$	N_f

$N_f > 3N$

$N := N_f - N_c$

$$e^{-8\pi^2/g^2(E)} = \left(\frac{E}{\Lambda_L}\right)^{-b_0}$$

$$b_0 = 3N - N_f < 0$$

- β-function is positive,
- the theory is free in the IR and
- strongly coupled in the UV
- develops a Landau pole at scale Λ_L

Minimal model

- Smallest N_f, N_c?

$$N_c + 1 < N_f \leq \frac{3}{2} N_c$$

$$N_f = 7, \quad N_c = 5$$ electric/UV

$$N_f = 7, \quad N = 2$$ magnetic/IR

ISS model: Macroscopic theory

- Tree-level superpotential

$$W_{\rm cl} = h\,{\rm Tr}\varphi\Phi\tilde{\varphi} - h\,{\rm Tr}(\mu^2\Phi)$$

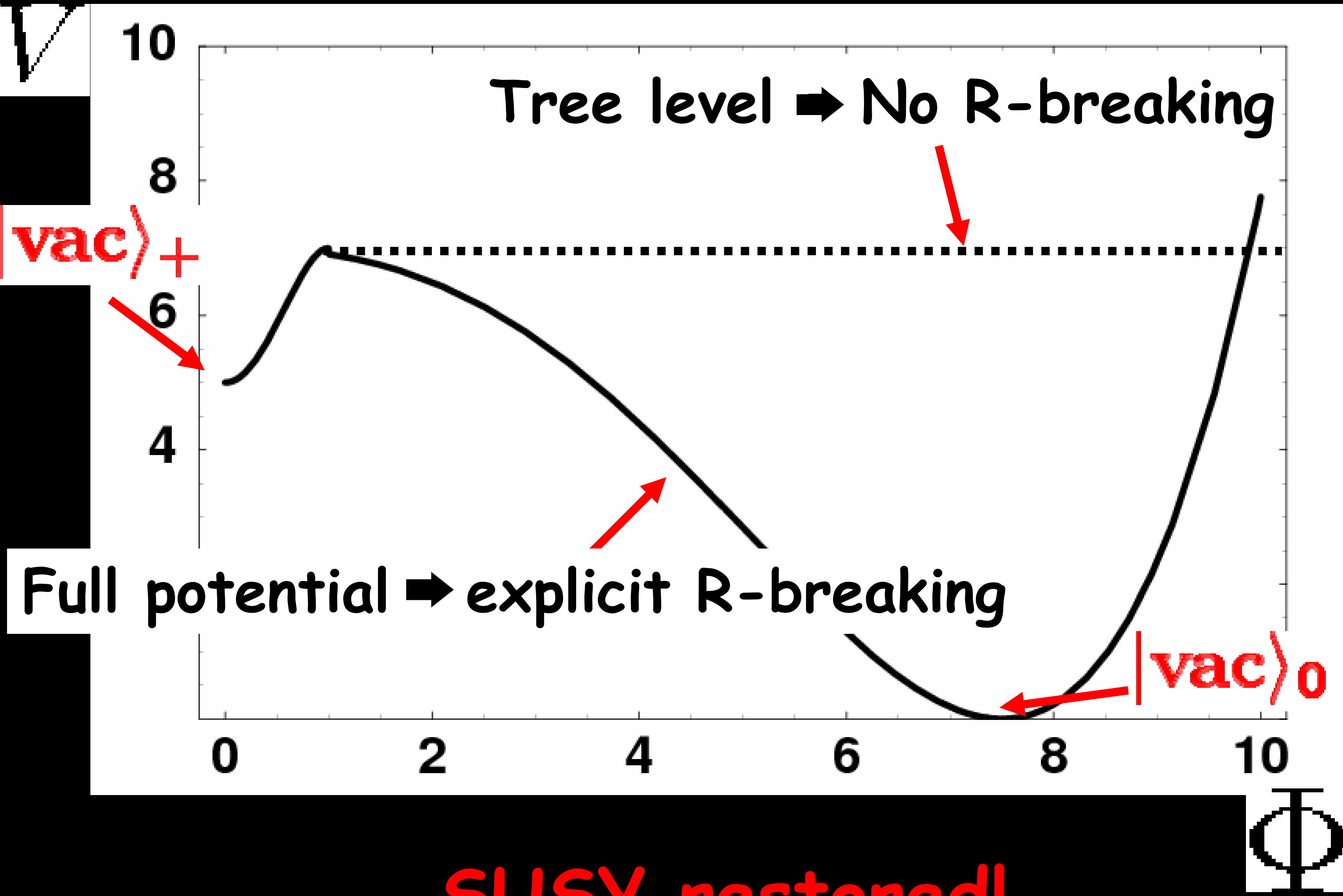
No corrections in perturbation theory!

- Full superpotential: $W = W_{\rm cl} + W_{\rm dyn}$
- With the exact dynamical superpotential

$$W_{\rm dyn} = N\left(h^{N_f}\frac{\det\Phi}{\Lambda_L^{N_f-3N}}\right)^{\frac{1}{N}}$$

Breaks R-symmetry explicitly!

Nelson Seiberg @ work



SUSY restored!

Doomsday?

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- Lifetime of the metastable state

Transition rate: $$\frac{\Gamma_4}{V_4} \sim \exp(-S_4)$$

$$\begin{aligned} S_4 &= 2\pi^2 \int \mathrm{d}r\, r^3 \left(\frac{1}{2} Tr \left(\frac{d\Phi}{dr} \right)^2 + V_{T=0}(\Phi(r)) \right) \\ &\approx \frac{2\pi^2}{3h^2} \frac{N^3}{N_f^2} \left(\frac{\Phi_0}{\mu} \right)^4 \end{aligned}$$

Our survival requires:

$$S_4 \gtrsim 400 \Longleftrightarrow \left(\frac{\Phi_0}{\mu} \right) > 3\sqrt{h} \left(\frac{{N_f}^2}{N^3} \right)^{\frac{1}{4}} \sim 3 - 4$$

Our survival is easy to ensure!

3.Cosmology

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Getting to the metastable vacuum

Question:

Why did the Universe start from the non-supersymmetric vacuum in the first place ?

Our answer: thermal effects drive the Universe to the susy-breaking vacuum even if it starts after inflation in the susy-preserving one.

This happens for a large class of models that satisfy:

1. All fields of the theory (MSB, MSSM, messengers) are in thermal equilibrium. True for gauge mediation, direct mediation, and visible sector breaking. (Excludes gravity-mediation.)
2. SUSY preserving $\langle vac_0 \rangle$ contains fewer light fields than the meta-stable $\langle vac_+ \rangle$.

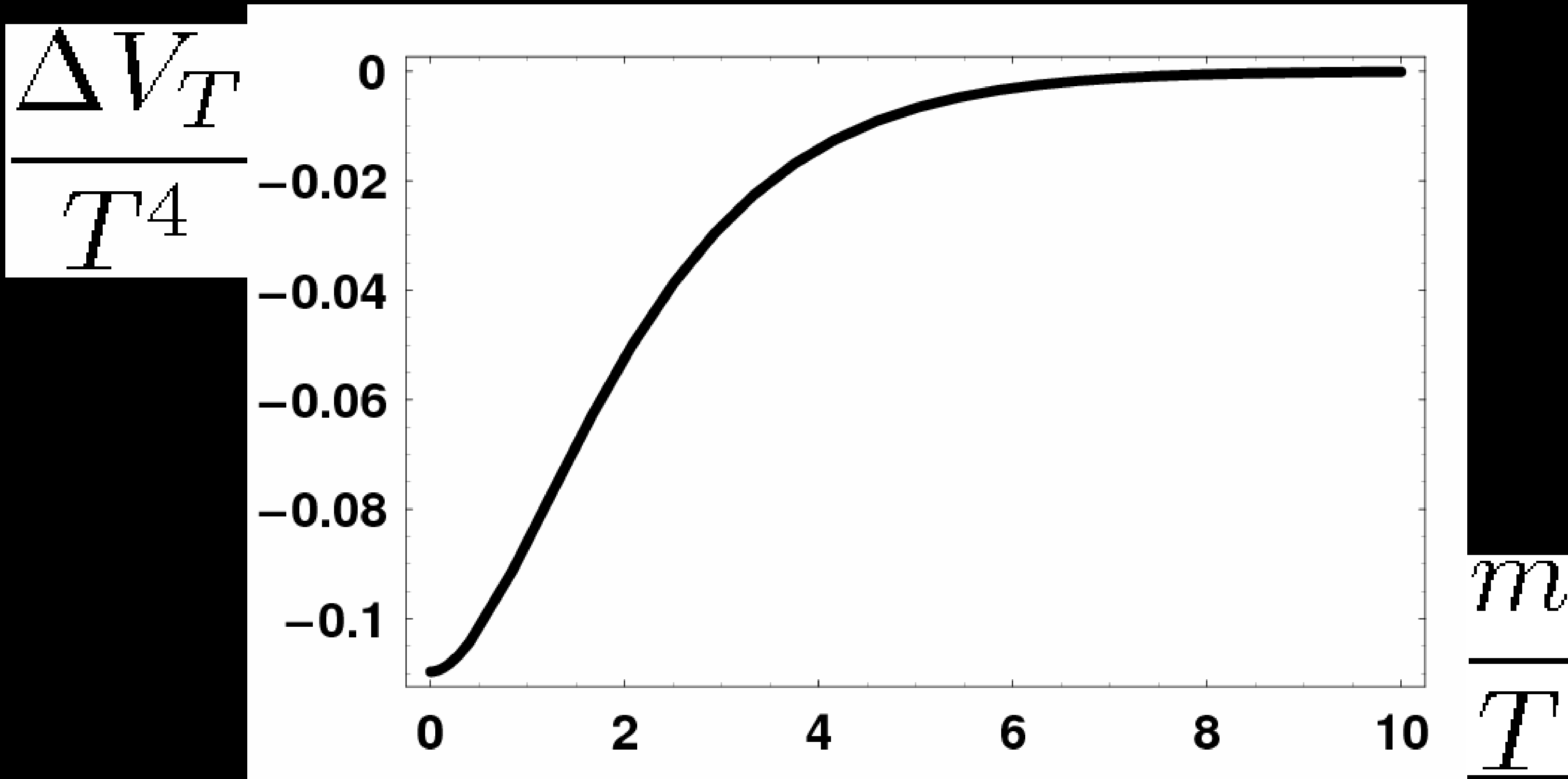
Thermal effective potential

$$V_T(\Phi) = V_{T=0}(\Phi) + \frac{T^4}{2\pi^2}\sum_i \pm n_i \int_0^\infty \mathrm{d}q\, q^2 \ln\left(1 \mp \exp(-\sqrt{q^2 + m_i^2(\Phi)/T^2})\right)$$

- 1-loop expression (Dolan-Jackiw).
- n_i are the numbers of degrees of freedom (+ corresponds to bosons; - to fermions.)
- $m_i^2(\Phi)$ are their masses as functions of $\langle\Phi\rangle$.
- Φ-dependence in the thermal correction is only through $m_i^2(\Phi)$
- We are talking about free energy!

$$F = E - TS$$

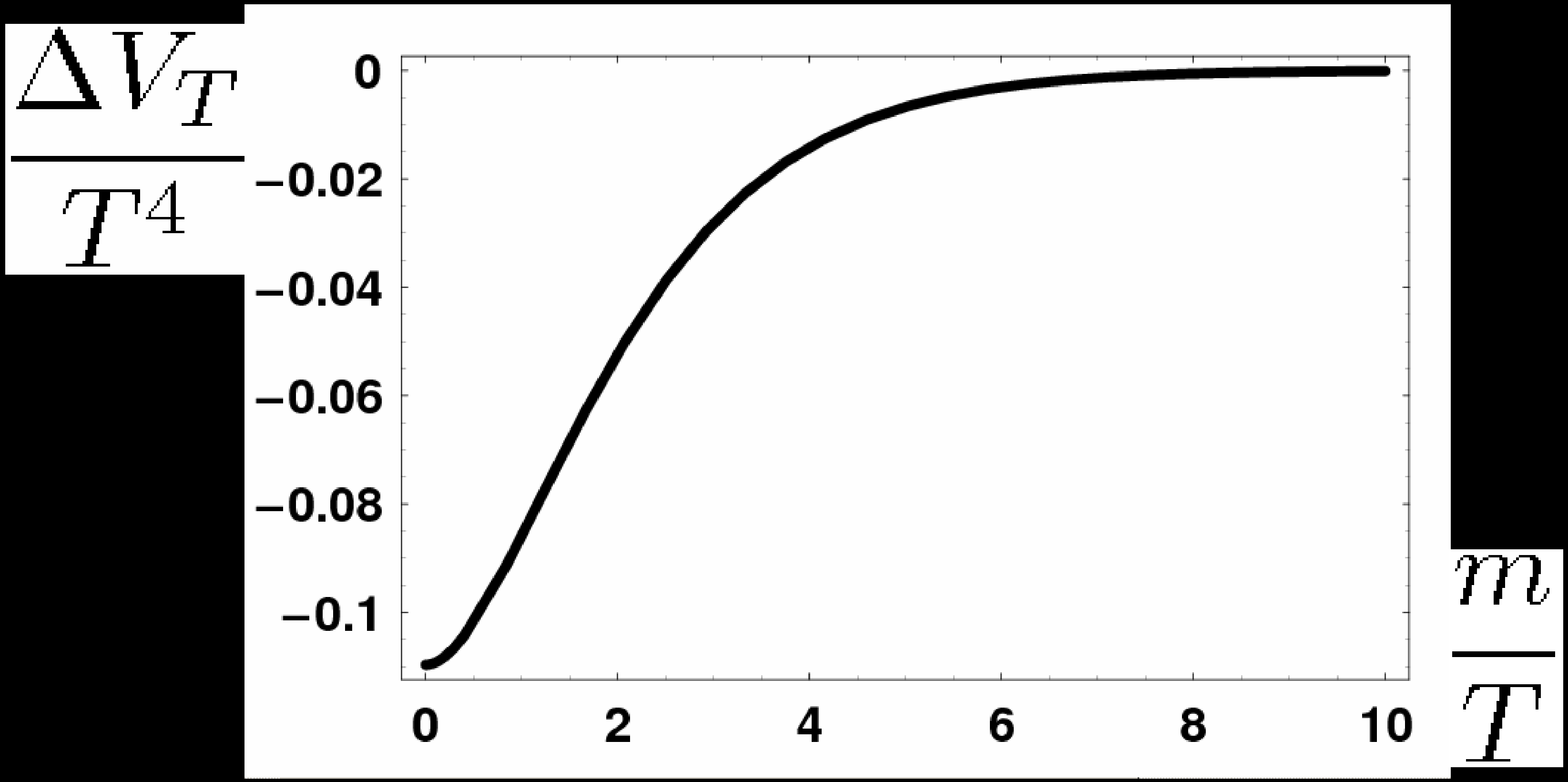
Thermal effective Potential



$$\Delta V_T(m=0) = \frac{\pi^2}{90}\begin{cases} 1 & bosons \\ 7/8 & fermions \end{cases}$$

$$\Delta V_T(m >> T) \approx 0$$

Thermal effective Potential



➡ Preference of the SUSY breaking vacuum at high T arises because the SUSY breaking vacuum has more light d.o.f.!

Particles get more massive with Φ

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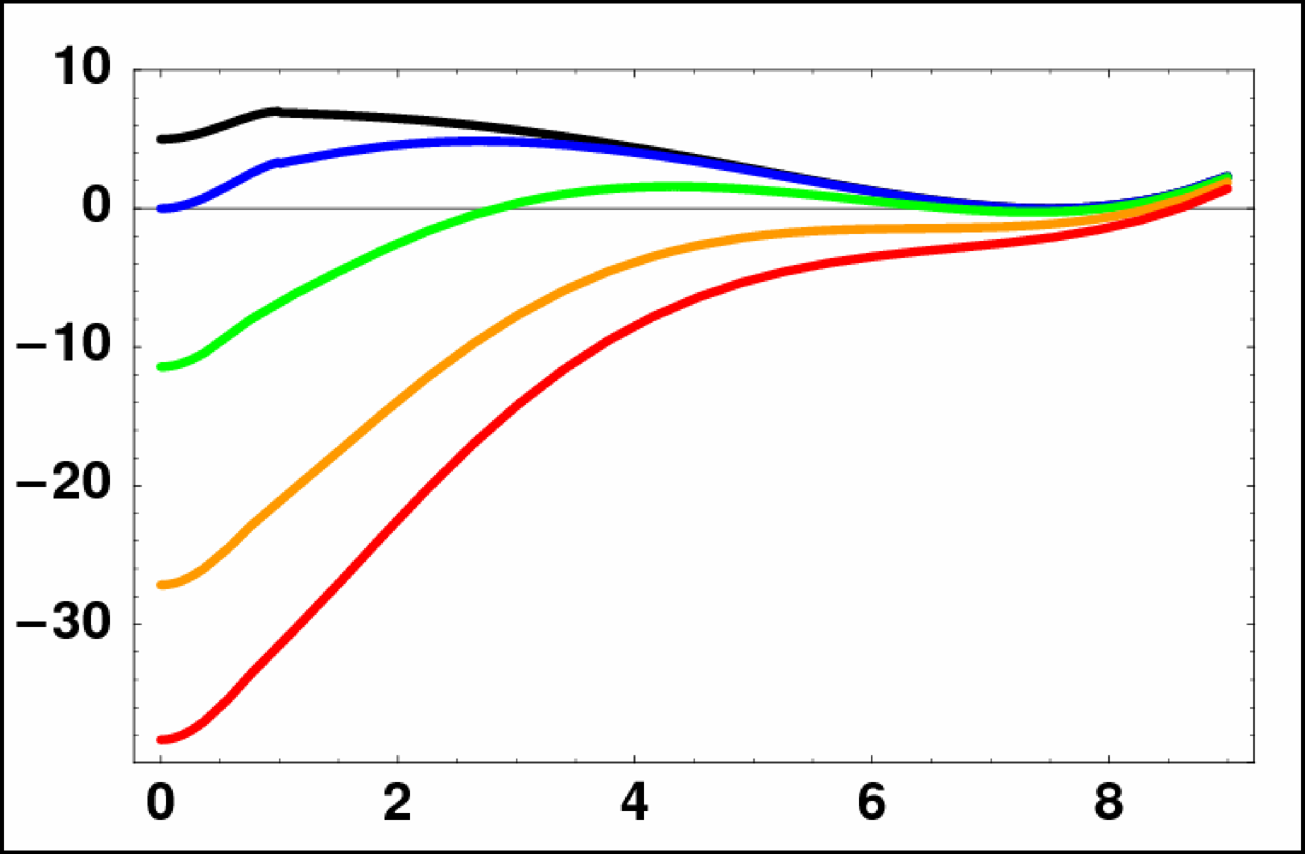
- Quark masses: $m_\varphi \sim \Phi$
- Gluon masses: $m_{gauge}(\Phi) \sim \Phi_0^{\frac{1}{3}}$

Particles are more massive at large Φ!

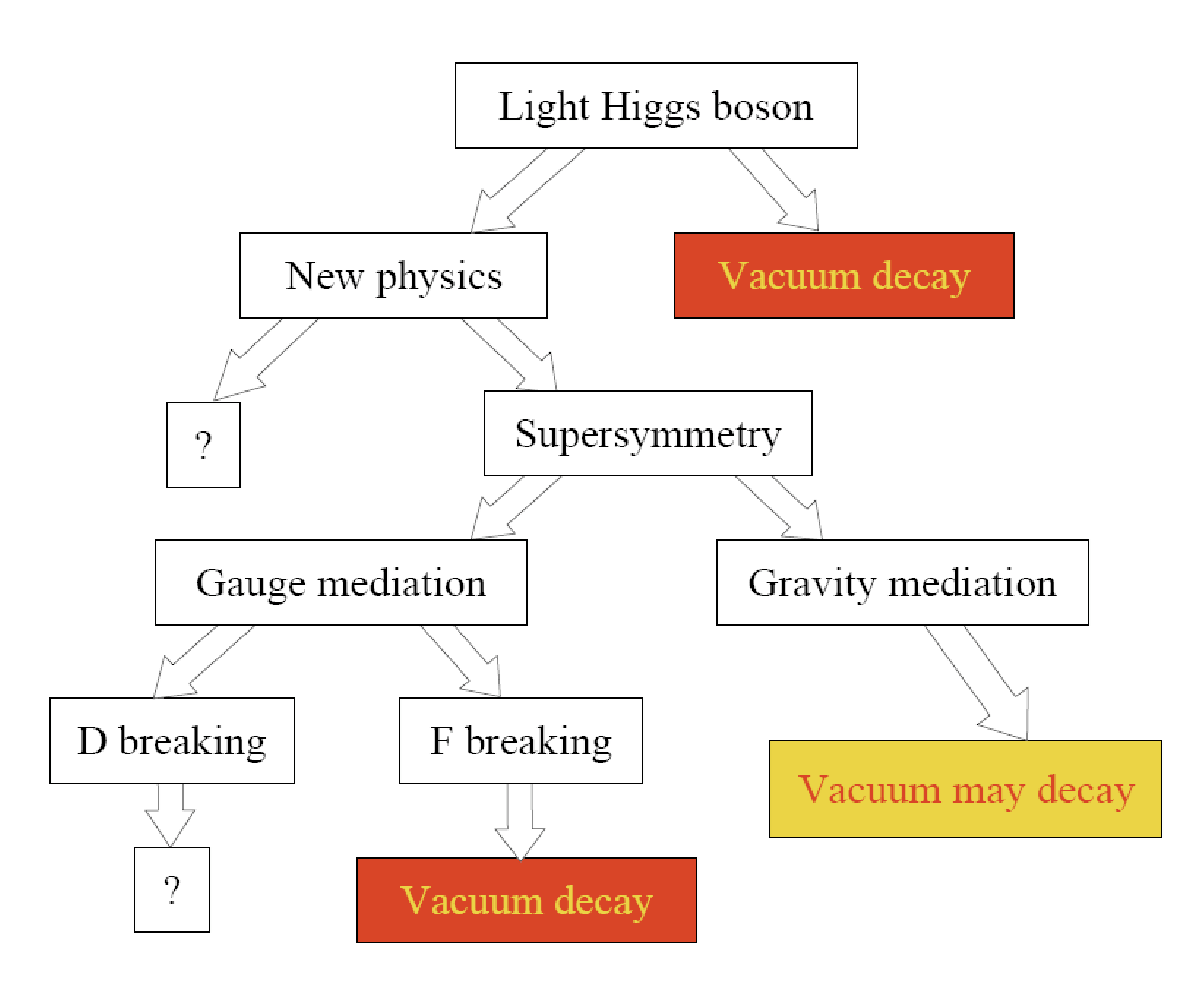
Thermal effect of magnetic quarks



No SUSY preserving Minimum $T > T_{crit}$!

4. `Detecting' Metastability

The LHC as a crystal ball for the fate of the Universe.

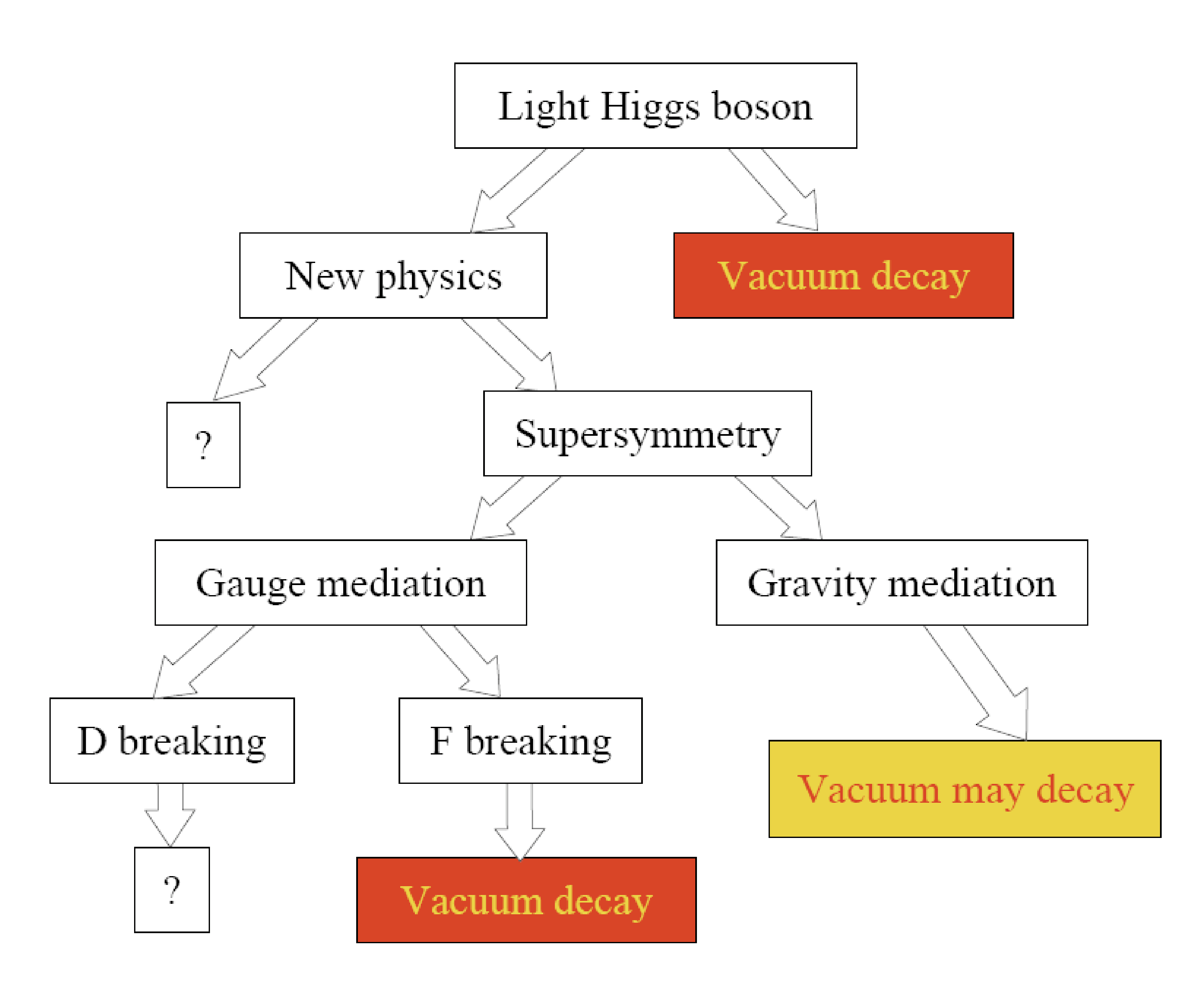


Gauge or gravity mediation?

Signatures for gauge mediation:

- Light gravitino!
  If NLSP decays within detector into gravitino we have a `smoking gun'
- Gaugino and sfermion masses scale with gauge couplings ➡ peculiar mass pattern! E.g. squarks heavier than sleptons!

The LHC as a crystal ball for the fate of the Universe.



D- or F-term?

- More difficult.
- Most D-term models have phenomenological problems (negative sfermion mass squareds).

  or are incalculable (strong coupling etc.)

- Theoretically F-term preferred.

5. Conclusions

Conclusions

- For `non-gravity' SUSY breaking metastability is nearly unavoidable
- Long lived metastable vacua can be realised
- In the early universe high temperatures typically favor the metastable state

  ➡ the universe automatically ends in the metastable vacuum
- Good chances to tell from future accelerators whether gauge mediation is realised. Then metastability is nearly unavoidable!


The End of the World is Nigh!

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Conclusions

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⇒ the universe automatically ends in the metastable vacuum

- Good chances to tell from future accelerators whether gauge mediation is realised. Then metastability is nearly unavoidable!

⇒ We are doomed!

Conclusions

- Metastable SUSY breaking allows for simple calculable models.

- In the early universe high temperatures typically favor the metastable state

  → the universe automatically ends in the metastable vacuum

- Knowledge of the SUSY breaking sector allows and is necessary for predictions of the mass spectrum.

Overview

- 1. Introduction
- 2. The ISS model
- 3. Cosmology –
  Getting to the metastable vacuum
- 4. Coupling to the SM –
  "Predictions" for accelerators
- 5. Conclusions

Corrections?

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- Theory is **weakly coupled in the IR**

↓

we can use **canonical Kähler potential**

$$K = \varphi\bar{\varphi} + \tilde{\varphi}\bar{\tilde{\varphi}} + \Phi\bar{\Phi}$$

SUSY breaking at tree level!

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- Tree-level superpotential

$$W_{cl} = h\varphi_i^a \Phi_j^i \tilde{\varphi}_a^j - h\mu^2 \delta_i^j \Phi_j^i$$

$$F_{\Phi_j^i} = h\left(\varphi_i^a \tilde{\varphi}_a^j - \mu^2 \delta_i^j\right) \neq 0$$

SUSY breaking because $\varphi_i^a \varphi_a^j$ has

Rank $N = N_f - N_c < N_f$!

Rank condition!

The metastable vacuum $\langle vac \rangle_+$

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- The SUSY breaking vacuum becomes the metastable vacuum of the full theory!

$$\langle \varphi \rangle = \langle \tilde{\varphi}^T \rangle = \mu \begin{pmatrix} \mathbb{1}_N \\ 0_{N_f - N} \end{pmatrix} , \quad \langle \Phi \rangle = 0 , \qquad V_+ = (N_f - N)|h^2 \mu^4|$$

- ~~SUSY~~ because $V_+ > 0$

- Classically stable, i.e. no tachyonic directions
- Gauge group is Higgsed $m_\gamma = g\mu$

Dynamical SUSY restoration

- We still need the N_c vacua required by the Witten index! ➡ study full superpotential

$$\varphi(\sigma) = \tilde{\varphi}^T(\sigma) = \sigma\mu \begin{pmatrix} \mathbb{1}_N \\ 0_{N_f - N} \end{pmatrix} , \quad \Phi(\gamma) = \gamma\mu\mathbb{1}_{N_f}$$

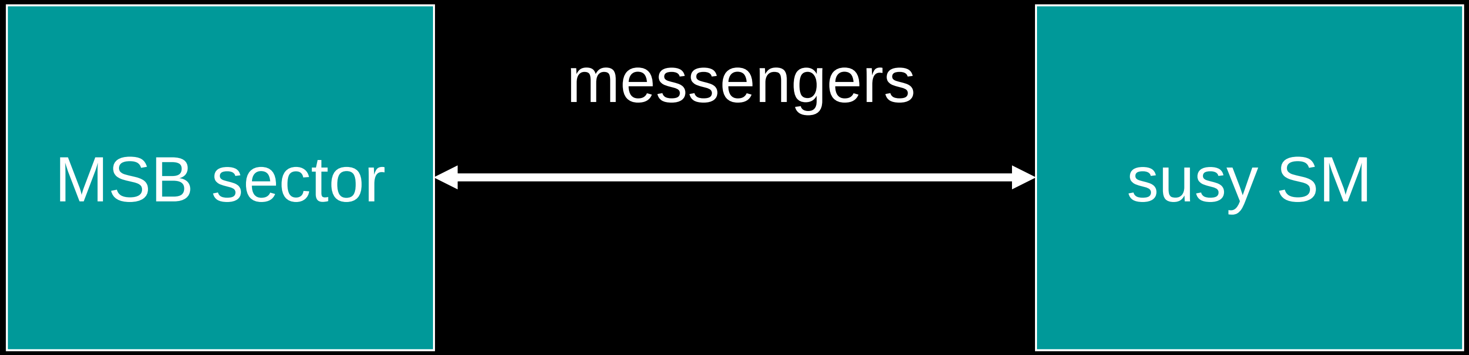
⬇

$$\frac{1}{|h^2\mu^4|} V_{\rm eff}(\sigma(\gamma),\gamma) = \begin{cases} N_f - N + 2N\gamma^2(1-\gamma^2) & 0 \le \gamma \le 1 \\ N_f\left(\left(\frac{\gamma}{\gamma_0}\right)^{\frac{N_f - N}{N}} - 1\right)^2 & 1 \le \gamma \end{cases}$$

Dynamical (nonperturbative) contribution to the potential

Model building

- Realistic models



- We need to "mediate" SUSY breaking to the SM!
- We need to get gaugino masses
  (broken R-symmetry)

R-Symmetry

- Symmetry where fermions and bosons of the same SUSY multiplet transform differently!
- $U(1)_R$: Superpotential W has charge 2! (under non-R-symmetries W is invariant!)
- Gauginos have R-charge 1:
  - Charged fermions cannot have Majorana masses!!

⇒ R-symmetry forbids gaugino masses!

⇒ Big Problem!

R-symmetry vs. SUSY breaking

- Theorem (Nelson-Seiberg):

  Generic potential with SUSY breaking in global minimum

  ➡ R-Symmetry

  ➡ Massless gaugino or
  Massless Goldstone boson (R-axion)

Metastability evades this theorem
SUSY breaking in a local minimum!

R-Symmetry: ISS model

- ISS model has accidental approximate R-symmetry in metastable minimum

→ We need to deform the model!

- Large explicit R-symmetry breaking is bad because it destabilises metastable vacuum!

R-symmetry: Solution.

- Deform ISS such that we have a (large) spontaneous R-symmetry breaking

→ Gaugino masses

R-axion is massive and therefore harmless
Because R-symmetry was only approximate

Baryon deformed ISS

- Take N_f=7, N_c=5, N=2 ISS and add a baryon to the superpotential

$$W_{\rm cl} = h\,{\rm Tr}\varphi\Phi\tilde{\varphi} - h\,{\rm Tr}(\mu^2\Phi) + \epsilon_{ab}\epsilon_{rs}\varphi^a_r\varphi^b_s$$

$$\mu^2_{ij} = \begin{pmatrix} \mu^2\mathbf{I}_2 & 0 \\ 0 & \hat{\mu}^2\mathbf{I}_5 \end{pmatrix}.$$

- This breaks the flavor symmetry SU(7) down to SU(2)×SU(5)

This model has spontaneous R-symmetry breaking!
(and a small anomalous one)

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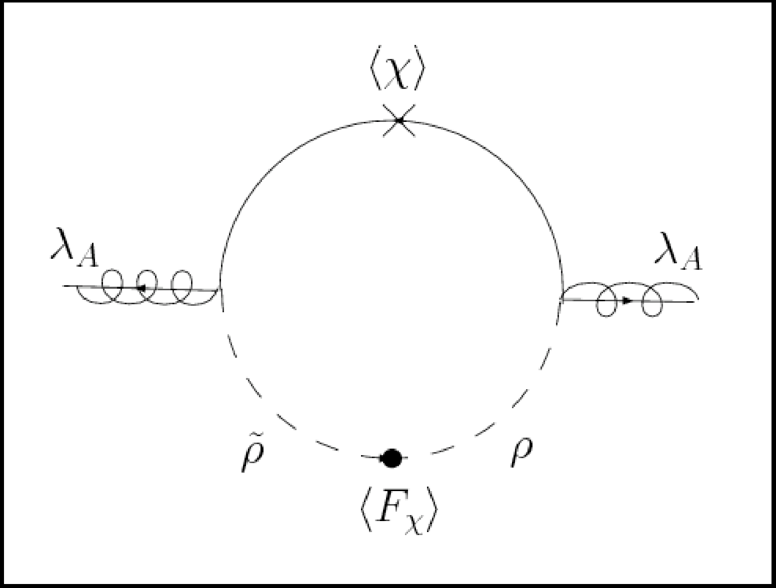
Messenging…

- Gauge SU(5) flavor group

➡ magnetic quarks act as messengers

E.g. gaugino masses



Phenomenology I: "Split SUSY"

- For $m \to 0$:

  R-symmetry restored

  ➡ no gaugino masses

  But: SUSY is still broken!!! $M_{SUSY} \sim \hat{\mu}$

  ➡ Squarks and sleptons get SUSY breaking masses! ➡ They are heavy!

- For $m \ll \hat{\mu}$:

  gauginos massive but much lighter than squarks and sleptons

  ➡ Split-SUSY

Phenomenology II

- For $m \sim \hat{\mu}$:

  Gauginos and sfermions have masses of similar size

  Similar to "standard" gauge mediation

⬇

Message: Knowledge of the (hidden) SUSY breaking sector is required.