Supersymmetry and its breaking

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IAS

The LHC is around the corner

What will the LHC find?

- We do not know.
- Perhaps nothing

  Is the standard model wrong?
- Only the Higgs particle

  Most boring. Unnatural. Is the Universe Anthropic?
- Additional particles without new concepts

  Unnatural. Is the Universe Anthropic?
- Natural Universe
  - Technicolor (extra dimensions)
  - Supersymmetry (SUSY) – new fermionic dimensions
- Something we have not thought of

I view supersymmetry as the most conservative and most conventional possibility.

In the rest of this talk we will describe supersymmetry, will motivate this claim, and will discuss some of the recent developments in this field.

Three presentations of supersymmetry

- Supersymmetry pairs bosons and fermions – integer spin particles and half integer spin particles.
- Supersymmetry is an extension of the Poincare symmetry.
- Supersymmetry is an extension of space and time. It describes additional dimensions which are intrinsically quantum mechanical (fermionic).

Supersymmetry as an extension of the Poincare symmetry

- The Poincare symmetry includes four translations P .

- One way to present supersymmetry is through adding fermionic symmetries Q which satisfy

$$\{Q, Q\} = P$$

Note, these are anti-commutation relations – no obvious classical analog.

The spectrum

- Normally, translations P relate a particle at one point to a particle at a nearby point.
- Because of the larger symmetry there must be more particles. Q relates one particle to another. Every particle has a superpartner.
- The symmetry pairs bosons and fermions – integer spin particles and half integer spin particles:

$$Q|fermion\rangle = |boson\rangle$$

$$Q|boson\rangle = |fermion\rangle$$

Supersymmetry as new quantum fermionic dimensions (more abstract)

- In addition to the four classical (bosonic) coordinates x, we introduce four fermionic coordinates θ with spin 1/2.
- Q implement translations in θ.
- Since they are fermionic, $(\theta)^2 = 0$. Therefore functions of superspace, (x, θ), can be thought of as a finite number of ordinary functions of space, x,

$$\Phi(x, \theta^\alpha) = \phi(x) + \psi_\alpha(x)\theta^\alpha +$$

$$\ldots + \theta^1\theta^2\theta^3\theta^4 F(x)$$

These ordinary functions represent ordinary particles.

Motivations for supersymmetry at the TeV range

- Dark matter
  - Connection to cosmology
- Coupling constant unification
  - Relation to shorter distance physics
- Hierarchy problem:
  - Dirac’s problem of large numbers
  - Enhanced by lack of naturalness
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Additional motivations for supersymmetry

- String theory
  - Supersymmetry arises naturally in string theory.

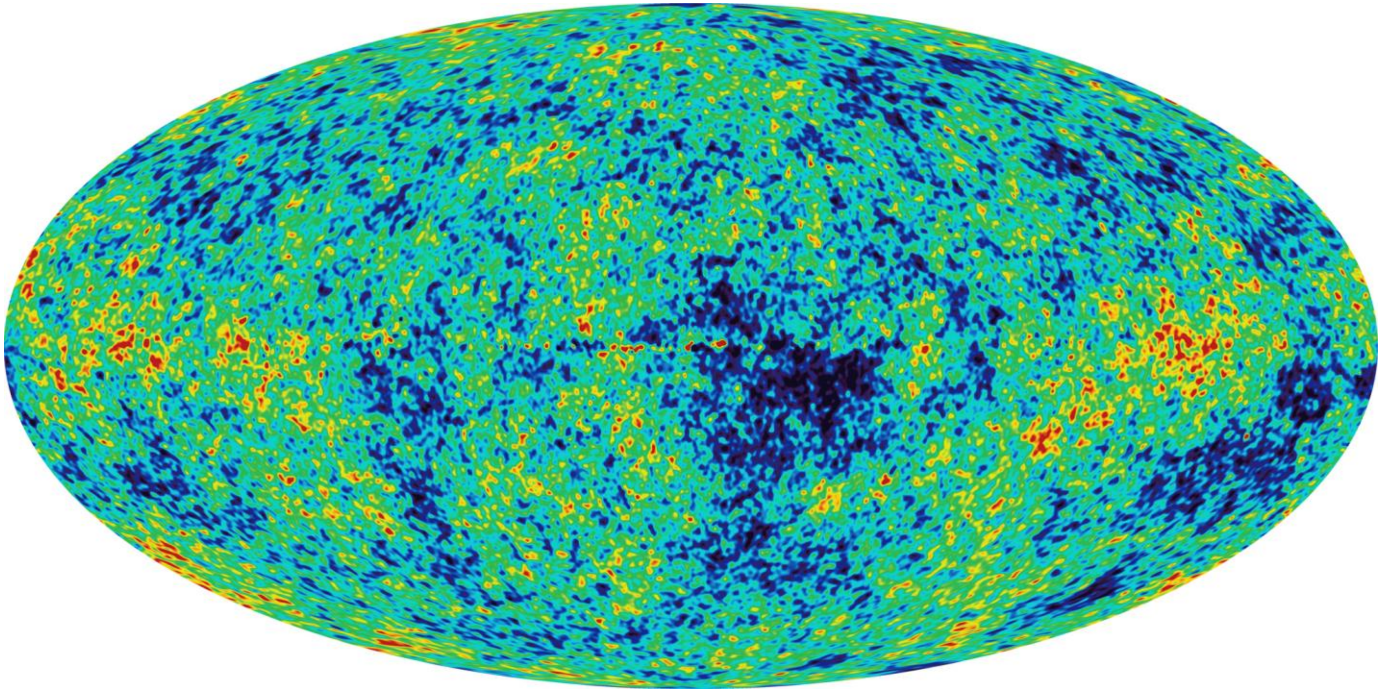
    It must be present at the Planck scale.

    Perhaps also at the TeV scale.
- Supersymmetry is a beautiful idea.
  - Many applications to mathematics and other branches of physics.

Any one of these motivations could be wrong.

Dark matter

Recent astronomical measurements show that only 18% of the matter in the Universe is made out of ordinary matter – the particles in the Standard Model. The remaining 82% of the matter is dark.



A dark matter candidate: Weakly Interacting Massive Particles (WIMP)

- They do not interact with electromagnetism and therefore they appear dark.
- They are massive, interact with gravity, and can be indirectly detected.
- They are stable and therefore cannot decay and disappear.
- Assuming they interact with electroweak strength and were in thermal equilibrium, a simple order of magnitude estimate leads to their mass $m \sim$ .1 – 1 TeV.

- If this is the origin of the dark matter, it is an indication for new physics at the TeV/LHC range. It is independent of supersymmetry.

WIMPs in SUSY

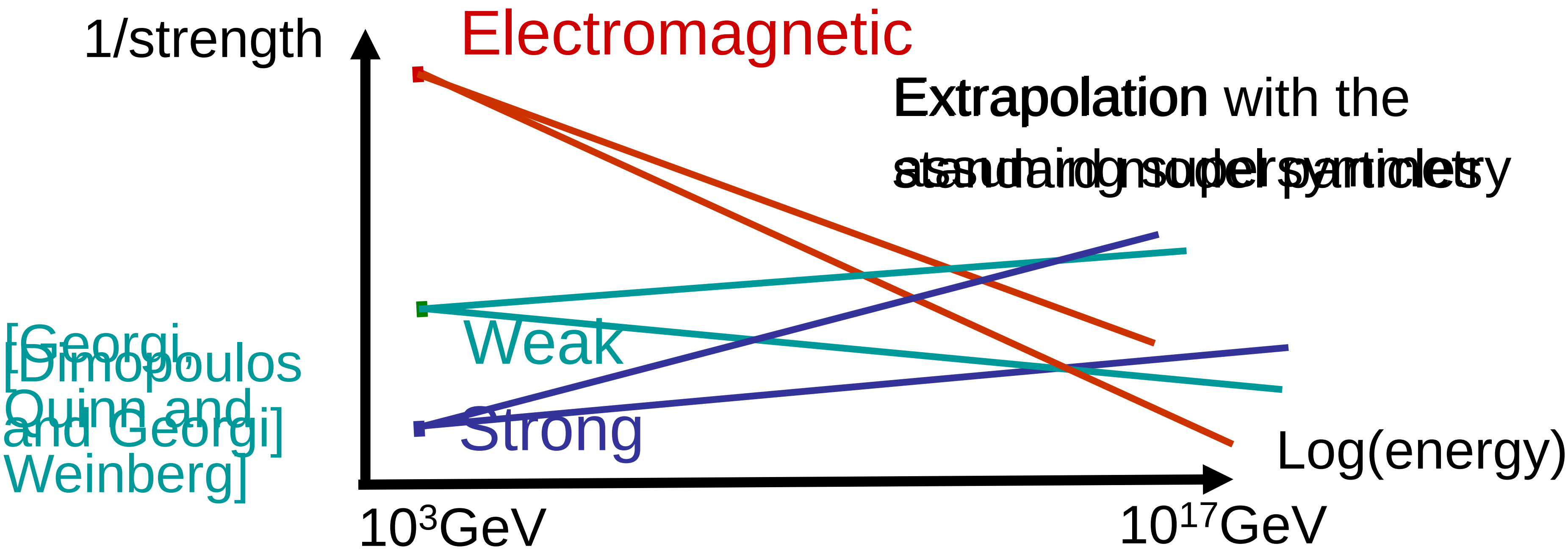
- Assuming supersymmetry, every standard model particle has a (heavier) superpartner. For example, the electron's partner is called selectron and the photon's partner is called photino.

- The lightest superpartner is typically the photino (or a linear combination of photino and Higgsino). It satisfies the requirements to be a WIMP.

- Ironically, the dark part of the mass of the Universe could be made of the superpartner of the particle of light – the photon.

Coupling constant unification

- The strength of each force depends on distance.
- Use the known measured values of the strengths and extrapolate them to shorter distances – higher energy:



- With supersymmetry the strengths of the distinct gauge interactions become equal around 10^{16}GeV.
- This suggests that they can be unified there to a simple gauge group – grand unification.
- Such grand unified theories (GUT) explain many other features of the quarks and the leptons; e.g. their quantum numbers.
- Discovering supersymmetry will thus lead to a window to shorter distance physics.

The hierarchy problem

- Why is the proton so much lighter than the Planck scale? [Dirac]

$$\frac{m_{proton}}{M_{Planck}} \sim 10^{-19}$$

- It is unnatural – failure of dimensional analysis. Is this merely an aesthetic problem?
- The modern version of Dirac's question: Why are the *W* and *Z* bosons so much lighter than the Planck scale or the unification scale?

$$\frac{m_{W,Z}}{M_{Planck}} \sim 10^{-17}$$

- This hierarchy is not stable [Wilson, Weinberg, Susskind, ‘tHooft, …].
  - Quantum fluctuations tend to restore dimensional analysis.
  - Like tuning to a critical temperature without a symmetry
  - Equivalently, extreme sensitivity to short distance parameters
- Technical naturalness: a number is small only when there is an enhanced symmetry when it vanishes [‘tHooft].
- $\frac{m_{W,Z}}{M_{Planck}} \sim 10^{-17}$ is (technically) unnatural.

The SUSY solution

- Supersymmetry offers a simple solution to this problem.
- The quantum fluctuations of the bosons and the fermions partially cancel each other and make the hierarchy stable. This addresses the technical naturalness problem.
- More about the aesthetic naturalness below.

Supersymmetry must be broken

- The superpartners are heavier than their counterparts. (Hopefully they'll be found at the LHC.)

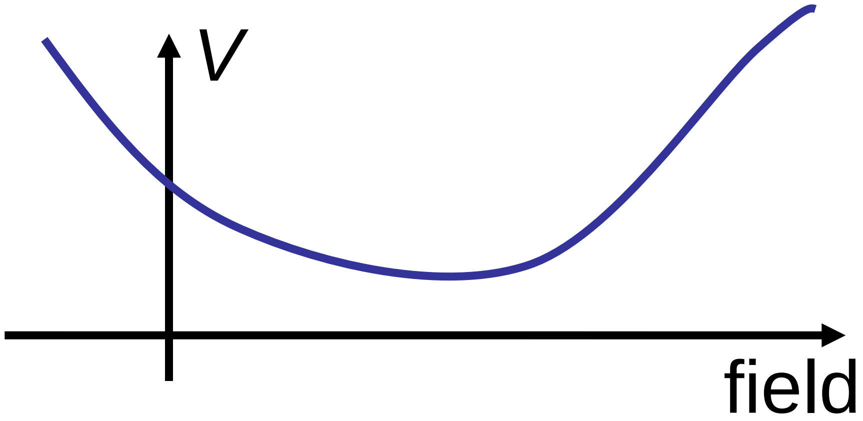
- Therefore, supersymmetry must be broken.

- The details of how supersymmetry is broken and how SUSY breaking is fed (mediated) to the light particles determines their spectrum and interactions. This will be studied at the LHC.

- We will now focus on supersymmetry breaking.

Spontaneous supersymmetry breaking

$$\mathcal{L} = \mathcal{L}_{SUSY}$$



The theory is supersymmetric, but its ground state is not (as in spontaneous symmetry breaking in a ferromagnet).

Using $\{Q, Q\} = P$ and the fact that the energy is a component of P ,

$$Q|0\rangle \neq 0 \Leftrightarrow E \neq 0$$

This vacuum energy is not the cosmological constant, which can be set to an appropriate value.

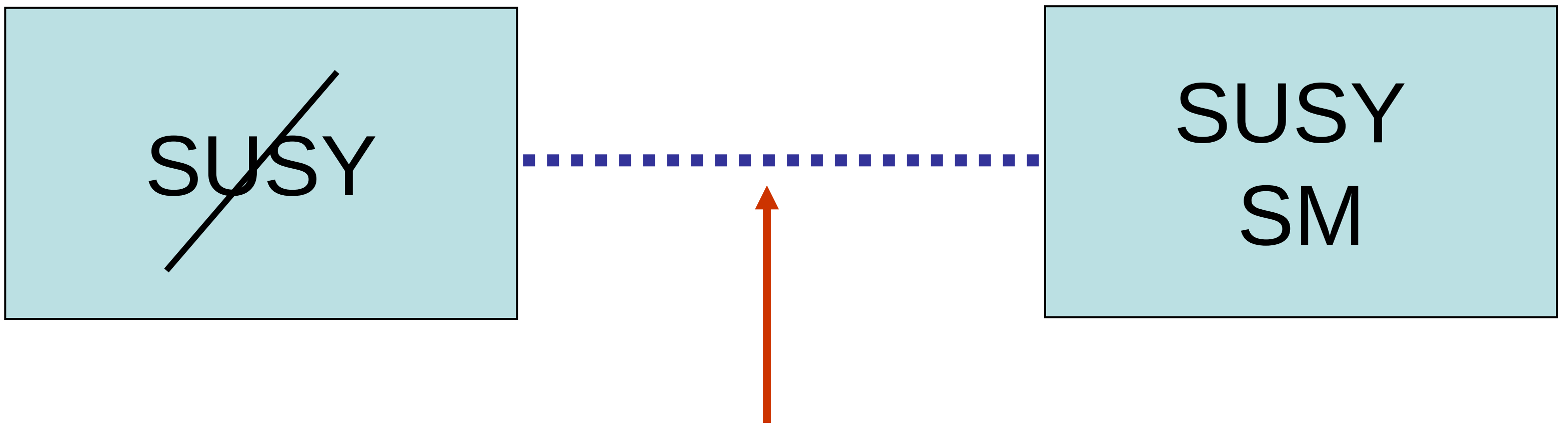
Supersymmetry breaking should be small

- We want the Universe to be approximately supersymmetric.
- Hope that supersymmetry is dynamically broken (like BCS) [Witten]:

$$m_W \sim \Lambda = M_{Planck} e^{-\frac{c}{g(M_{Planck})^2}} \ll M_{Planck}$$

- This will naturally explain why it is small – will solve both the technical and the aesthetic naturalness problems.
- For that we need a tiny nonperturbative effect in a gauge theory.

Mediation of supersymmetry breaking



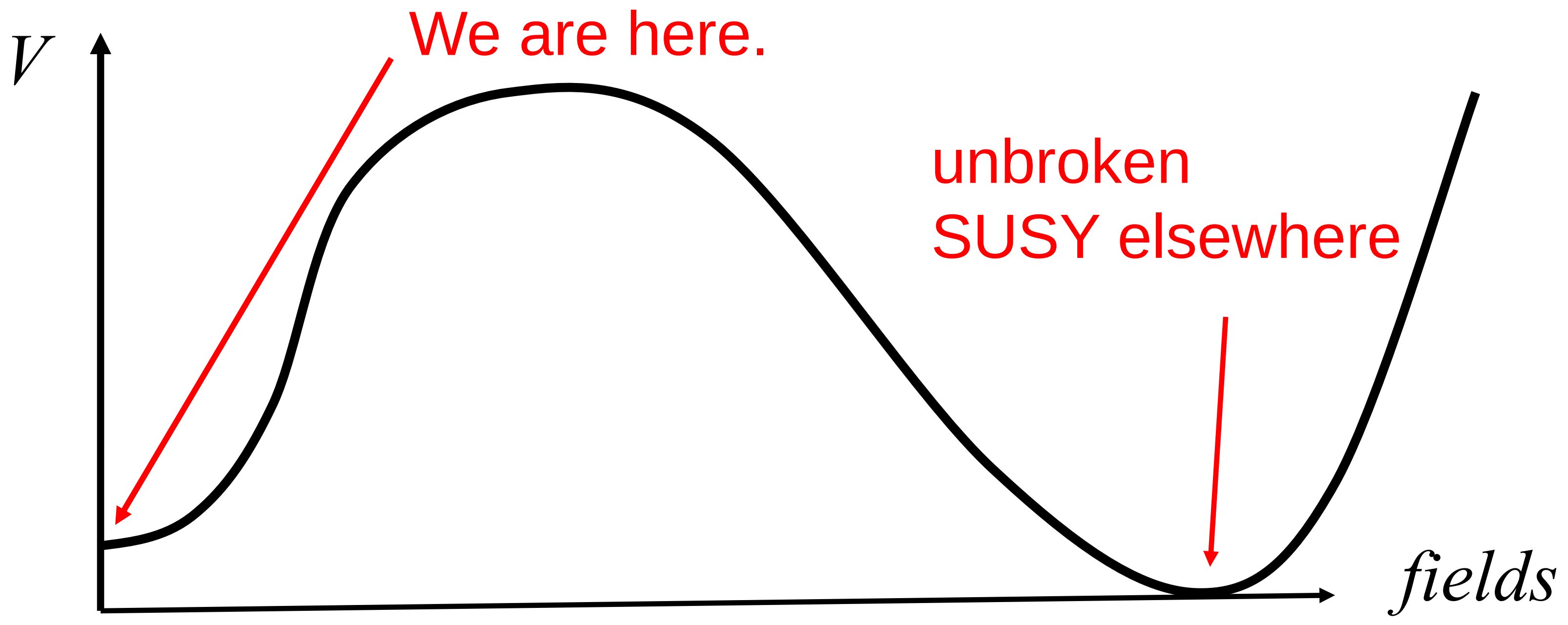
Gauge or gravitational interactions couple the supersymmetry breaking sector to the Supersymmetric Standard Model and mediate SUSY breaking.

We will now focus on the SUSY breaking sector.

The supersymmetry breaking sector

- Supersymmetry breaking is not generic.
- Many constraints on supersymmetry breaking.
- Most supersymmetric field theories do not break supersymmetry.

Perhaps we live in a long-lived false vacuum



A very old idea.
Find simpler models of DSB.
(Recall, the c.c. can be set to an appropriate value.)

Metastable supersymmetry breaking

- Cosmological metastability […Linde, Weinberg…]
- Easy to find examples with classical metastable supersymmetry breaking [Ellis, Llewellyn Smith, Ross (82)].
- All known examples of gauge mediation supersymmetry breaking restore supersymmetry somewhere in field space [Dine, Nelson… (94…)].
- Some early examples of metastable DSB […Dimopoulos, Dvali, Rattazzi, Giudice… (…97…)]
- Metastable DSB is easy to achieve and it is generic [Intriligator, NS, Shih... (06…)].

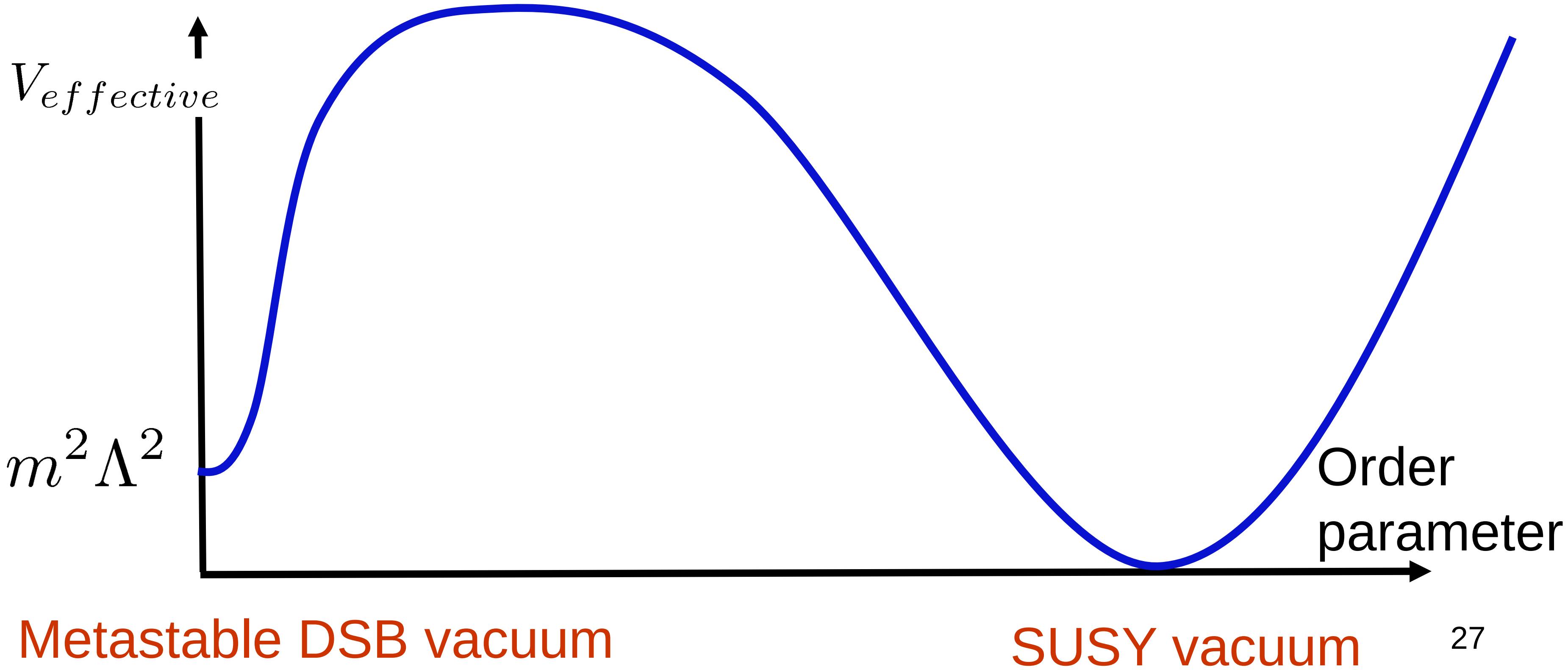
A simple example of metastable DSB

- Consider a supersymmetric gauge theory like QCD with N_c colors and N_f quark flavors with mass m (these should not be confused with the colors or flavors of ordinary QCD of the strong interactions).
- For $N_f < 3N_c$ the theory is weakly coupled at short distance but becomes strongly coupled at long distance (asymptotic freedom).
- The crossover scale between the short distance and the long distance descriptions is nonperturbative:

$$\Lambda = M_{cutoff} e^{-\frac{c}{g(M_{cutoff})^2}} \ll M_{cutoff}$$

The long distance theory

For $N_c < N_f < 3N_c/2$ the long distance theory admits another, dual, description in terms of another gauge theory, which is weakly coupled [NS]. It can be used to find the effective potential [Intriligator, NS, Shih].



Metastable DSB in SUSY QCD

- A complicated feature is generated in the effective potential. It is nonperturbative – very quantum mechanical.
- It involves directions in field space (order parameters), which do not have a semiclassical meaning.
- The potential is such that the lifetime of the metastable state is exponentially long.
- The phenomenon of metastable DSB appears generic – many other examples have been found.

Particle physics application

- Use this kind of a model as a module which breaks supersymmetry using some of the known mediation mechanisms.

- Some of the known obstacles/difficulties in model building are viewed in a new light and some of them are easily solved.

Inevitability

Consider the limit of decoupling gravity.

Then, the following general considerations:

- Spontaneous SUSY breaking
- Generic theory
- Massive gauginos (superpartners of the standard model gauge fields)
- No massless bosons

necessarily lead to the conclusion: SUSY breaking must be due to a metastable state [Intriligator, NS, Shih].

Other (gravitational) reasons for metastability

- The cosmological constant is nonzero (hard to make sense of de Sitter space).
- Landscape of string vacua [Bousso and Polchinski; Kachru,Kallosh, Linde and Trivedi (KKLT); Susskind; Douglas…].

Cosmology

This SUSY breaking mechanism leads to many new cosmological questions.

- At high temperatures the lowest free energy state is at the origin of field space.
- As the Universe cools down, there is a second order transition to the broken SUSY vacuum [Abel, Chu, Jaeckel, Khoze; Craig, Fox, Wacker; Fischler, Kaplunovsky, Krishnan, Mannelli, Torres].
- At lower temperatures the SUSY vacuum becomes the lowest free energy state. There is a first order transition to that state, but it takes a long time.
- The cosmological evolution leads to the metastable SUSY breaking vacuum.

- Combine this story with inflation.
- Can the potential be used for the inflaton?

Conclusions and Outlook

- Supersymmetry is the most conventional expectation for TeV/LHC physics.
- Accepting metastability leads to surprisingly simple models of DSB.
- Metastable DSB is generic in SUSY field theory, and in the landscape of string vacua.
- The cosmology of this setup is interesting and it poses new questions.
- Find a good model for particle physics phenomenology – metastablity appears to be inevitable.

- Hopefully, there are distinct experimental signals, e.g. patterns of superpartner masses, which will be seen at the LHC.