Nonlinear realization of supersymmetry

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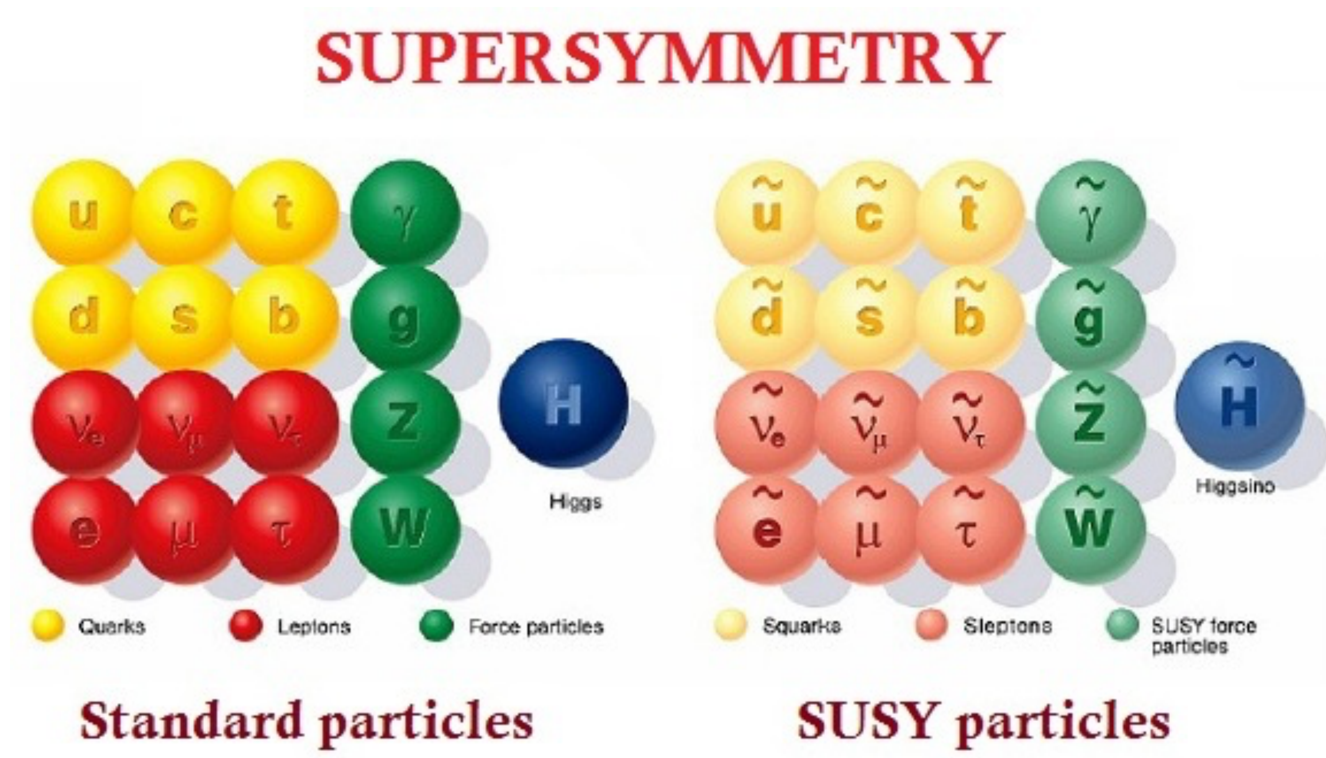
Introduction

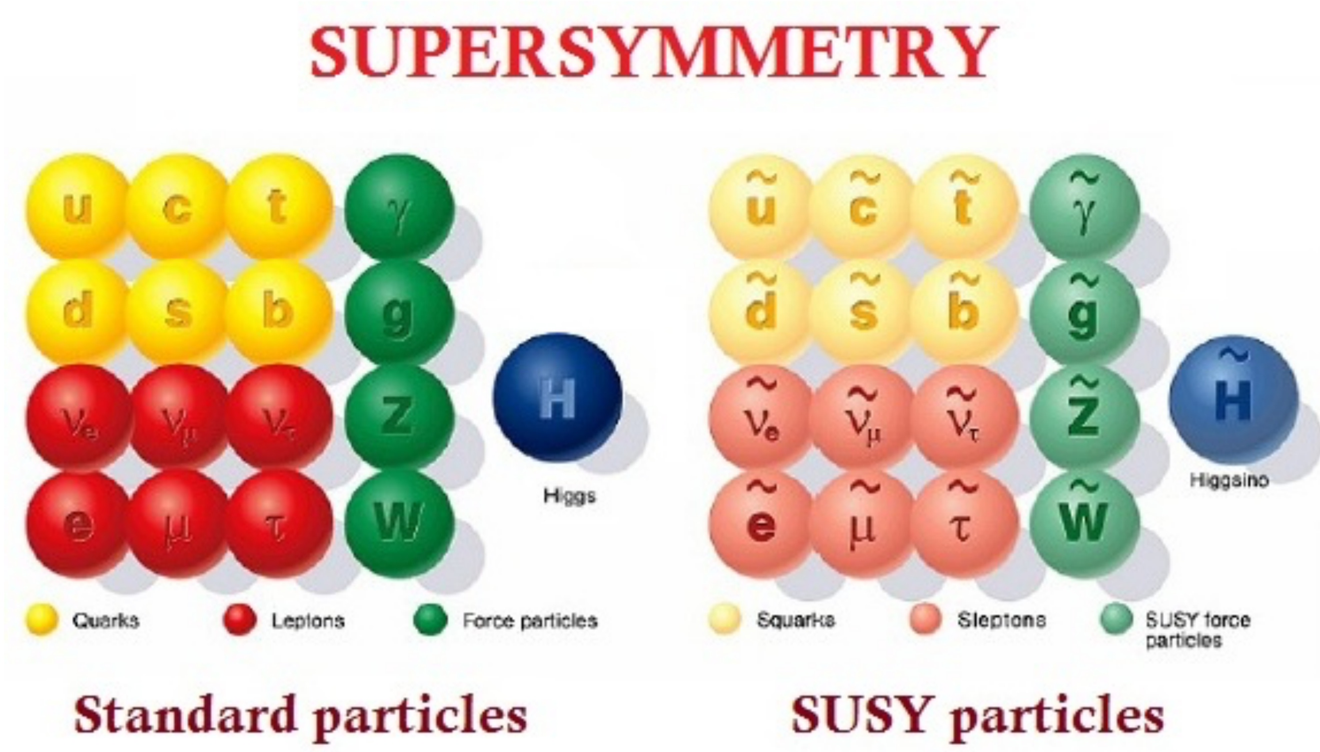


Symmetry between particles with different spins

- **stabilizes vacuum**
- **has better UV behavior (against quantum corrections)**
- **predicts new particles**
- **indicates GUT**

…etc.

Introduction

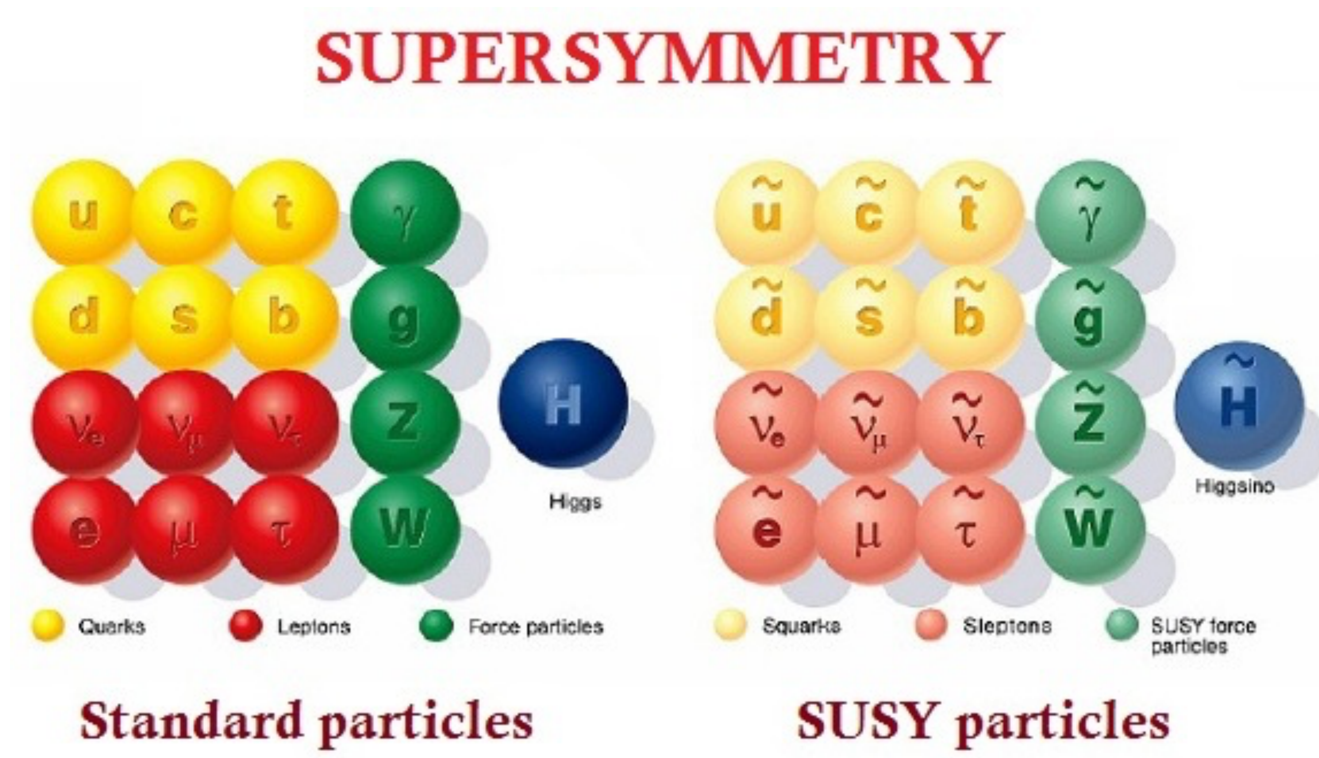


Supersymmetry is phenomenologically not favored:

We have not yet observed any superparticles in collider experiments

SM superparticles should be much heavier than SM particles

Introduction



Supersymmetric universe is not favored from cosmological observations:

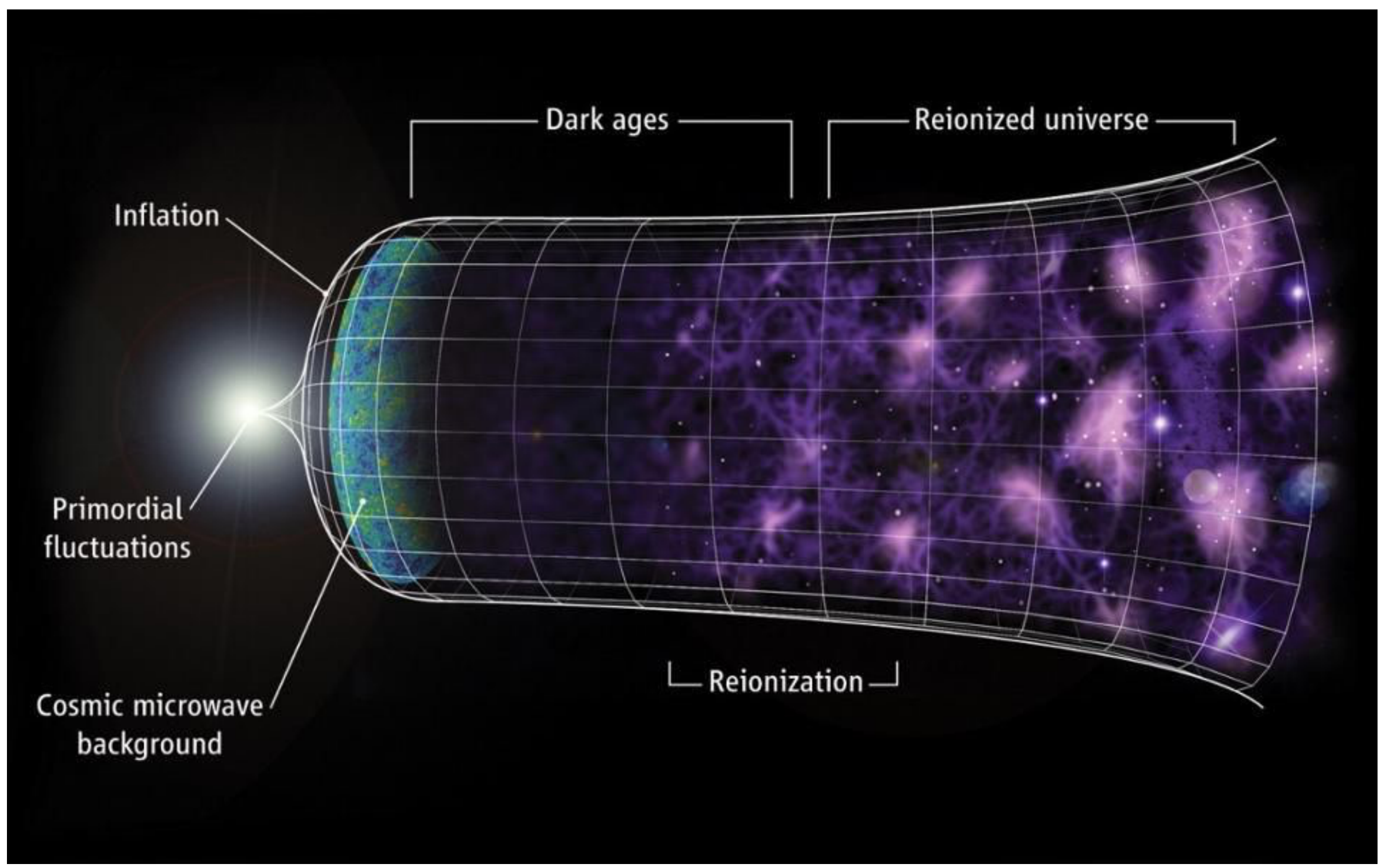
the present universe is very consistent with positive c.c.

In supersymmetric theory, $\langle \mathcal{H} \rangle \sim \langle 0 | Q^\dagger Q | 0 \rangle$ → $Q|0\rangle \neq 0$

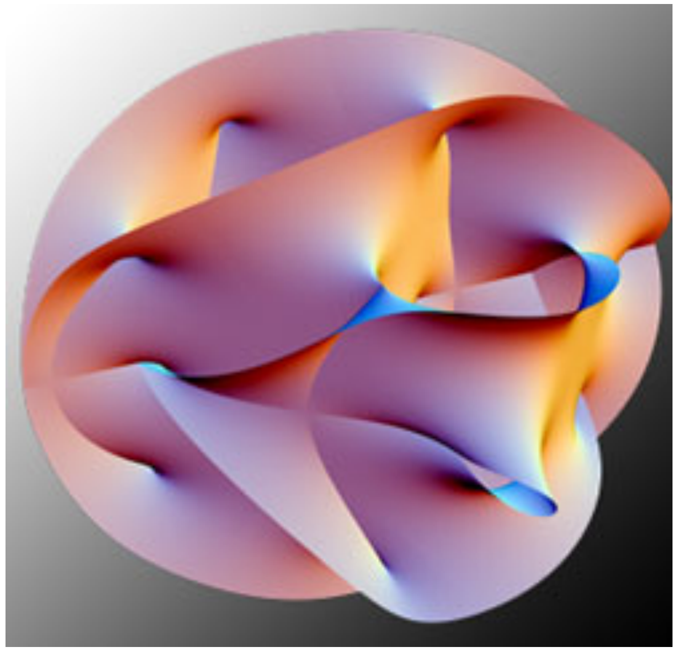
Introduction

SUSY has been broken from the beginning

Throughout the history of our universe, SUSY always needs to be broken



Introduction



However, SUSY often plays important roles in string compactification

Supersymmetry seems necessary at very high energy scale

Our universe may be described by the theory with spontaneously broken supersymmetry

SUSY representation

SUSY is nicely described in superspace

$$z^A = x^\mu, \theta^\alpha, \bar{\theta}_{\dot{\alpha}} \qquad \alpha, \dot{\alpha} = 1, 2$$

SUSY representations are functions on superspace

$$\Phi(z^A) = \phi(x) + \theta^\alpha \chi_\alpha(x) + \bar{\theta}_{\dot{\alpha}} \bar{\lambda}^{\dot{\alpha}}(x) + \cdots + \theta^2 \bar{\theta}^2 \mathcal{D}(x)$$

SUSY transformation is “translation” of fermionic coordinates

$$Q_\alpha \sim \frac{\partial}{\partial \theta^\alpha}$$

SUSY representation

Irreducible representations:

Chiral superfield

$$\Phi(y,\theta) = \phi(y) + \sqrt{2}\theta^{\alpha}\chi_{\alpha}(y) + \theta^2 F(y)$$

$$y^{\mu} = x^{\mu} + i\theta\sigma^{\mu}\bar{\theta}$$

describing e.g. quarks, leptons, Higgs boson…etc.

Real vector superfield

$$V \sim -\theta\sigma^{\mu}\bar{\theta}A_{\mu}(x) + \left(\mathrm{i}\theta^2\bar{\theta}\bar{\lambda}(x) + \mathrm{h.c.}\right) + \frac{1}{2}\theta^2\bar{\theta}^2 D(x)$$

describing gauge bosons

Other components are unphysical: **Super-gauge** $V \to V + (\Lambda(z) + \bar{\Lambda}(z))$

Supersymmetry breaking

If SUSY is broken,
fermion's transformation becomes non-vanishing

$$\langle \delta\chi^\alpha \rangle \sim \langle F \rangle \epsilon^\alpha \neq 0$$

or

$$\langle \delta\lambda^\alpha \rangle \sim \langle D \rangle \epsilon^\alpha \neq 0$$

Goldstone fermion = Goldstino is massless due to the "shift" symmetry

Goldstino transformation: $\psi^\alpha(x) \to \psi^\alpha(x) + \epsilon^\alpha + \cdots$

c.f. U(1) case $\phi(x) = (v + h(x))e^{\mathrm{i}\rho(x)}$ $\quad \rho(x) \to \rho(x) + c$

Nonlinear realization of SUSY

Low energy effective theory of spontaneously broken symmetry:

described by Goldstone mode = nonlinear realization

In SUSY case, the EFT contains massless Goldstino ψ^α

the Goldstino action is universal:
Volkov-Akulov action

$$\delta\psi^\alpha = \frac{1}{\kappa}\epsilon^\alpha - \mathrm{i}\kappa(\psi\sigma^\mu\bar{\epsilon} - \epsilon\sigma^\mu\bar{\psi})\partial_\mu\psi^\alpha$$

D. V. Volkov, V. P. Alulov (1973)

$$\mathcal{L} = -\frac{1}{2\kappa^2}\mathrm{det}A_\mu^a$$

where $A_\mu^a = \delta_\mu^a - \mathrm{i}\kappa^2\partial_\mu\psi\sigma^a\bar{\psi} + \mathrm{i}\kappa^2\psi\sigma^a\partial_\mu\bar{\psi}$

Supersymmetry breaking

Historically, SUSY was broken from the beginning:

The very first paper of 4D SUSY was

Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

IS THE NEUTRINO A GOLDSTONE PARTICLE?

D.V. VOLKOV and V.P. AKULOV

Volkov and Akulov considered neutrino as Goldstino

$$\psi \to \psi' = \psi + \zeta \qquad \psi^+ \to \psi'^+ = \psi^+ + \zeta^+$$

$$x_\mu \to x'_\mu = x_\mu - \frac{a}{2i}(\zeta^+ \sigma_\mu \psi - \psi^+ \sigma_\mu \zeta) .$$

Now we know neutrino is not massless, and not the Goldstino

Supersymmetry breaking

Historically, SUSY was broken from the beginning:

Linearly realized SUSY was proposed after the VA paper

Nuclear Physics B70 (1974) 39–50. North-Holland Publishing Company

SUPERGAUGE TRANSFORMATIONS IN FOUR DIMENSIONS

J. WESS
Karlsruhe University

B. ZUMINO
CERN, Geneva

Received 5 October 1973

Nonlinear realization of SUSY

How can we describe Volkov-Akulov Goldstino action *in superspace*?

$$S(y,\theta) = s(y) + \sqrt{2}\theta^\alpha \chi^S_\alpha(y) + \theta\theta F^S(y)$$

Nilpotent constraint

M. Rocek (1978)
U. Lindstrom and M. Rocek (1979)
R. Casalbuoni et al. (1989)
Komargodski, Seiberg (2009)

$$S^2(y,\theta) = 0$$

Nontrivial solution of the constraint $s = \dfrac{\chi^{S\alpha}\chi^S_\alpha}{2F^S}$

$$S = \frac{\chi^S\chi^S}{2F^S} + \sqrt{2}\theta\chi^S + \theta\theta F^S = F^S\left(\theta + \frac{\chi^S}{\sqrt{2}F^S}\right)^2$$

Fermion & auxiliary scalar , no physical scalar partner!

Nonlinear realization of SUSY

Minimal action

$$\int d^4\theta S\bar{S} + \left(\int d^2\theta \mu^2 S + \text{h.c.}\right)$$

$$\mathcal{L} = -\mathrm{i}\bar{\chi}^S\bar{\sigma}^a\partial_a\chi^S - \mu^4 + \frac{1}{4\mu^4}(\bar{\chi}^S)^2\partial^2(\chi^S)^2 - \frac{1}{16\mu^{12}}(\chi^S)^2(\bar{\chi}^S)^2\partial^2(\chi^S)^2\partial^2(\bar{\chi}^S)^2$$

the equivalence to VA action is proven: S. Kuzenko, S. J. Tyler (2010)

Only fermion (Goldstino) exists.
no boson, but the action is supersymmetric (nonlinearly)

Nonlinear realization of SUSY

What is the origin of the nilpotent constraint ?

$$\mathcal{L} = \int d^4\theta \left(S\bar{S} - \frac{M^2}{\mu^4}(S\bar{S})^2 \right) + \left(\int d^2\theta \mu^2 S + \text{h.c.} \right)$$

$$\mathcal{L} = -\partial s \partial \bar{s} - \mu^2 - 4M^2|s|^2 - i\bar{\chi}^S \sigma^a \partial_a \chi^S + \cdots$$

$M \to \infty$ **e.o.m** $S\bar{D}^2(\bar{S}^2) + \frac{1}{M^2}(\cdots) = 0$

$$\Rightarrow \quad S^2 = 0$$

Nilpotent condition corresponds to decoupling of sGoldstino

Nonlinear realization of SUSY

When SUSY is spontaneously broken,
soft terms split the mass spectrum of boson and fermion

Decoupling can happen not only for sGoldstino,
but also for other fields

Nonlinear realization of SUSY

When SUSY is spontaneously broken, soft terms split the mass spectrum of boson and fermion

Decoupling can happen not only for sGoldstino, but also for other fields

e.g. $$\int d^4\theta \alpha |\Phi|^2 |S|^2 \qquad \mathcal{L} \supset \alpha |F^S \phi + F^\phi s - \psi^\phi \psi^S|^2$$

This can be regarded as "soft mass" for complex scalar ϕ

$\alpha \to \infty$ **Scalar would decouple from the theory** $$\phi = \frac{\psi^\phi \psi^S}{F^S} - \frac{F^\phi \psi^S \psi^S}{(F^S)^2}$$

Nonlinear realization of SUSY

Once SUSY is spontaneously broken,
any components can decouple from theory

Komargodski, Seiberg (2009)

No scalar $$\Phi S = 0$$

No fermion $$\bar{S} D_\alpha \Phi = 0$$

Only a real scalar $\mathrm{Re}\Phi$ $$(\Phi - \bar{\Phi}) S = 0$$

No gaugino $$S W_\alpha = 0$$

Constraints removing various modes
= decoupling due to soft SUSY breaking mass

Nonlinear realization of SUSY

$$\Phi = \phi + \sqrt{2}\theta\chi^{\phi} + \theta\theta F^{\phi}$$

No scalar constraint $\Phi S = 0$

Nontrivial solution $$\phi = \frac{\chi^S \chi^{\phi}}{F^S} - \frac{(\chi^S)^2 F^{\Phi}}{2(F^S)^2}$$

Other fields are independent

Nonlinear realization of SUSY

$$\Phi = \phi + \sqrt{2}\theta\chi^{\phi} + \theta\theta F^{\phi}$$

No fermion condition $\bar{S} D_{\alpha}\Phi = 0$

$$\chi^{\phi} = \mathrm{i}\sigma^{\mu}\left(\frac{\bar{\chi}^{S}}{\bar{F}^{S}}\right)\partial_{\mu}\phi$$

$$F^{\phi} = -\partial_{\mu}\left(\frac{\bar{\chi}^{S}}{\bar{F}^{S}}\right)\bar{\sigma}^{\nu}\sigma^{\mu}\frac{\bar{\chi}^{S}}{\bar{F}^{S}}\partial_{\nu}\phi + \frac{(\bar{\chi}^{S})^{2}}{2(\bar{F}^{S})^{2}}\Box\phi$$

Only the first component scalar is independent

Nonlinear realization of SUSY

$$W_\alpha = -\mathrm{i}\lambda_\alpha + \left(D\delta_\alpha^\beta - \frac{\mathrm{i}}{2}(\sigma^{\mu\nu})_\alpha^\beta F_{\mu\nu} \right) \theta_\beta + \sigma_{\alpha\dot{\alpha}}^\mu \partial_\mu \bar{\lambda}^{\dot{\alpha}} \theta^2$$

No gaugino condition $SW_\alpha = 0$

$$\lambda_\alpha = \frac{\mathrm{i}}{\sqrt{2}F^S} L_\alpha^\beta \chi_\beta^S + \cdots$$

Other components (vector and D-term) are intact

Nonlinear realization of SUSY

What is the cut-off scale of nonlinear realization?

From a linear SUSY model in decoupling sGoldstino limit
(= nonlinear SUSY model)

Unitarity bound from 4-fermion scattering

$$A_{(+,+;+,+)} = A_{(-,-;-,-)}$$
$$= \frac{1}{6}\frac{1}{m_{3/2}^2 M_{Pl}^2}\left(s(m_S^2+m_P^2)+\frac{sm_S^4}{s-m_S^2}+\frac{sm_P^4}{s-m_P^2}\right) = \frac{1}{6}\frac{s^2}{m_{3/2}^2 M_{Pl}^2}\left(\frac{m_S^2}{s-m_S^2}+\frac{m_P^2}{s-m_P^2}\right)$$

R. Casalbuoni et al. (1989)

$$\sqrt{s_c} = \sqrt{6\sqrt{2\pi}M_{\rm pl}m_{3/2}}$$

Above this scale, we cannot trust perturbation theory

Nonlinear realization in supergravity

To describe our present universe with positive c.c., nonlinear realization in supergravity would be useful

Although expression is more complicated in curved superspace, constraints are the same as global SUSY case

$$S^2(x,\theta)=0 \to S^2(x,\Theta)=0$$

$$s=\frac{\chi^S\chi^S}{2F^S}$$

Pure de Sitter supergravity

Let us construct the minimal model of de Sitter universe

Minimal d.o.f. : graviton & (massive) gravitino

$$g_{\mu\nu} \qquad\qquad \psi_\mu$$

Massive gravitino can be decomposed as
transverse mode and longitudinal mode (= Goldstino)

Minimal model = supergravity with a nilpotent superfield

Without nilpotent condition, sGoldstino appears and system cannot be “minimal”

Pure de Sitter supergravity

The simplest de Sitter model in supergravity
= pure de Sitter supergravity

E. Bergshoeff et al. (2015)
F. Hasegawa, YY (2015)

$$S = \int d^4x \left[\int d^4\theta E(-3e^{-S\bar{S}/3}) + \left(\int d^2\Theta 2\mathcal{E}(\mu^2 S + W_0) + \text{h.c.} \right) \right]$$

Pure de Sitter supergravity

Usually, the auxiliary fields are up to quadratic order in the action

$$\mathcal{L} \supset F^I K_{I\bar{J}} \bar{F}^{\bar{J}} + F^I e^{K/2} D_I W + \cdots$$

easy to solve its E.O.M

$$F^I = -e^{K/2} K^{I\bar{J}} D_I W + \cdots$$

Pure de Sitter supergravity

Since F-term equation is no longer linear in F, the action becomes very complicated

$$s = \frac{\chi^S \chi^S}{2F^S}$$

F. Hasegawa, YY (2015)

$$\begin{aligned}
\mathcal{L} =& \frac{1}{2}(R - \bar{\psi}_\mu \mathcal{R}^\mu + \mathcal{L}_{SGT}) - \frac{1}{2}(\bar{G}P_L \nabla\!\!\!/ G + \bar{G}P_R \nabla\!\!\!/ G) - |f|^2 + 3|W_0|^2 - \frac{1}{8}(\bar{G}P_L G)(\bar{G}P_R G) \\
&+ \left[-\frac{f\bar{W}_0}{\bar{f}} \bar{G}P_L G + \frac{1}{\sqrt{2}} f \bar{\psi}_\mu \gamma^\mu P_L G + \frac{W_0}{2} \bar{\psi}_\mu P_R \gamma^{\mu\nu} \psi_\nu + \text{h.c.} \right] \\
&- \frac{1}{4|f|^2} \nabla_\mu (\bar{G}P_L G) \nabla^\mu (\bar{G}P_R G) - \frac{1}{2}(\bar{\psi}_\mu P_L G)(\bar{\psi}^\mu P_R G) + \frac{i}{16} \epsilon^{\mu\nu\rho\sigma} (\bar{\psi}_\mu \gamma_\nu \psi_\rho)(\bar{G}P_R \gamma_\sigma G) \\
&- \left(\frac{W_0}{2\sqrt{2} f} \bar{G}P_R G \bar{\psi}_\mu \gamma^\mu P_L G + \frac{f}{4\bar{f}} \bar{G}P_L G \bar{\psi}_\mu P_R \gamma^{\mu\nu} \psi_\nu + \text{h.c.} \right) \\
&- \frac{1}{2\sqrt{2}} \left[\frac{1}{f} \bar{\psi}_\mu \nabla\!\!\!/ (\bar{G}P_R G) \gamma^\mu P_L G + \text{h.c.} \right] \\
&+ \frac{i}{32|f|^2} \epsilon^{\mu\nu\rho\sigma} (\bar{\psi}_\mu \gamma_\nu \psi_\rho) \left(\bar{G}P_R G \nabla_\sigma (\bar{G}P_L G) - \bar{G}P_L G \nabla_\sigma (\bar{G}P_R G) \right) \\
&+ \frac{(\bar{G}P_L G)(\bar{G}P_R G)}{4|f|^2} \left[-4|f|^2 |\hat{C}|^2 + 4|f|^2 + 2|W_0|^2 + \left\{ \frac{W_0}{4} \bar{\psi}_\mu P_R \gamma^{\mu\nu} \psi_\nu + \text{h.c.} \right\} \right]
\end{aligned}$$

where $\hat{C} \equiv \frac{1}{2f^2} \left[2W_0 \bar{f} - \frac{\nabla_\mu \bar{G} P_L \nabla^\mu G}{2\bar{f}} - \frac{1}{\sqrt{2}} \bar{\psi}_\mu \gamma^\nu \gamma^\mu \nabla_\nu P_L G + \frac{\bar{f}}{2} \bar{\psi}_\mu P_L \gamma^{\mu\nu} \psi_\nu \right]$

Pure de Sitter supergravity

The simplest de Sitter model in supergravity
= pure de Sitter supergravity

E. Bergshoeff et al. (2015)
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$$S = \int d^4x \left[\int d^4\theta E(-3e^{-S\bar{S}/3}) + \left(\int d^2\Theta 2\mathcal{E}(\mu^2 S + W_0) + \text{h.c.} \right) \right]$$

In unitary gauge $\chi^S = 0$

$$\mathcal{L} = -e\left[\frac{1}{2}R + \varepsilon^{klmn}\bar{\psi}_k\bar{\sigma}_l\tilde{\mathcal{D}}_m\psi_n - W_0(\psi_a\sigma^{ab}\psi_b + \text{h.c.}) - (\mu^2 - 3W_0^2) \right]$$

By tuning the parameters, dS is realized

$$\Lambda^4 = \mu^4 - 3W_0^2$$

Physical D.O.F are graviton and massive gravitino

Pure de Sitter supergravity

Pure de Sitter supergravity

Eric A. Bergshoeff,[1,*] Daniel Z. Freedman,[2,3,†] Renata Kallosh,[2,‡] and Antoine Van Proeyen[4,§]

In closing we note that pure and complete anti–de Sitter supergravity [1] was first formulated in 1977, but the pure and complete de Sitter supergravity is first constructed now, 38 years later. The action and its local supersymmetry transformation are presented in Sec. II of this paper.

The complete action of pure dS SUGRA was formulated 38 years after the formulation of pure AdS SUGRA

Summary

Spontaneously broken SUSY & SUGRA can be described by constrained superfields

Decoupling of heavy components is expressed as constraints

Constrained superfield formulation can be used in supergravity as well

We can use the constrained superfields for constructing realistic models!

Pure de Sitter R^2 supergravity

A simple extension of Einstein gravity

$$\int d^4x\sqrt{-g}\left(\frac{1}{2}R+\frac{1}{12M^2}R^2\right)$$

$$\int d^4x\sqrt{-g}\left(\frac{1}{2}R-\frac{1}{2}(\partial\phi)^2-\frac{3M^2}{4}(1-e^{-\sqrt{\frac{2}{3}}\phi})^2\right)$$

Inflation is realized by the scalar d.o.f.
The spectrum of perturbations seems consistent with Planck 2018

Is it possible to realize
de Sitter in present universe, inflation, (SUSY breaking)
in pure dS supergravity?

Pure de Sitter R^2 supergravity

the pure AdS SUGRA action

$$S = \int d^4\theta E(-3\Phi_0\bar{\Phi}_0) + \left(\int d^2\theta \mathcal{E}\Phi_0^3 W_0 + \text{h.c.}\right)$$

Φ_0 : (unphysical) compensator

Pure de Sitter R^2 supergravity

the pure dS SUGRA action

$$S = \int d^4\theta E(-3\Phi_0\bar{\Phi}_0) + \left(\int d^2\theta \mathcal{E}\Phi_0^3 W_0 + \text{h.c.}\right)$$

Φ_0 : (unphysical) compensator

With modified nilpotent condition $$\left(\frac{\mathcal{R}}{\Phi_0} - \lambda\right)^2 = 0$$

E. Dudas et al. (2015)

Pure de Sitter R^2 supergravity

the pure dS SUGRA action

$$S = \int d^4\theta E(-3\Phi_0\bar{\Phi}_0) + \left(\int d^2\theta \mathcal{E}\Phi_0^3 W_0 + \text{h.c.}\right)$$

Φ_0 : (unphysical) compensator

With modified nilpotent condition $\left(\frac{\mathcal{R}}{\Phi_0} - \lambda\right)^2 = 0$

E. Dudas et al. (2015)

equivalent to

$$S = \int d^4x \left[\int d^4\theta E(-3e^{-S\bar{S}/3}) + \left(\int d^2\Theta 2\mathcal{E}(\mu^2 S + W_0) + \text{h.c.}\right)\right]$$

where $\mu^2 = \lambda - 3W_0$

Pure de Sitter SUGRA
= AdS SUGRA with a constrained curvature superfield

Pure de Sitter R^2 supergravity

Let us introduce higher-curvature couplings

$$S = -3\int d^4\theta E\left(\Phi_0\bar{\Phi}_0 - \frac{1}{\alpha}\mathcal{R}\bar{\mathcal{R}}\right) + \left(\int d^2\theta\mathcal{E}\Phi_0^3 W_0 + \text{h.c.}\right)$$

With a curvature constraint $\left(\frac{\mathcal{R}}{\Phi_0} - \alpha\right)^2 = 0$

Dual action

$$K = -3\log\left(1 + T + \bar{T} - \frac{1}{3}|S|^2\right)$$

$$W = MTS + W_0$$

$$(S - M)^2 = 0 \qquad M = \sqrt{3\alpha}$$

constrained and unconstrained matter superfields

Pure de Sitter R^2 supergravity

$$K = -3\log\left(1 + T + \bar{T} - \frac{1}{3}|S|^2\right)$$

$$W = MTS + W_0$$

$$(S - M)^2 = 0$$

$$s = M + \frac{\psi^S \psi^S}{2F^S}$$

$$V = \frac{M^2}{(1 + T + \bar{T} - \frac{1}{3}M^2)^2}\left[\left|T - \frac{1}{3}M^2\right|^2 - \frac{M^4}{9} + \frac{M^2}{3} - 2W_0\right]$$

$W_0 \sim \frac{M^2}{6}\left(1 - \frac{1}{3}M^2\right)$ **Fine-tune to realize almost vanishing c.c.**

$$V = \frac{M^2}{(1 + T + \bar{T} - \frac{1}{3}M^2)^2}\left|T - \frac{1}{3}M^2\right|^2$$

A free parameter is only M

Pure de Sitter R^2 supergravity

$$\mathcal{L} \sim -\frac{3}{(1+2t)^2}(\partial t)^2 - \frac{M^2 t^2}{(1+2t)^2}$$

$$\mathcal{L} \sim -\frac{1}{2}(\partial\phi)^2 - \frac{M^2}{4}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2$$

Scalar perturbation power spectrum normalization

$$M \sim 10^{-5}$$

Now, SUSY breaking scale etc. are fixed

Pure de Sitter R^2 supergravity

SUSY breaking spectrum

$$\langle|F^T|\rangle \equiv \left\langle\sqrt{K_{T\bar{T}}F^T\bar{F}^{\bar{T}}}\right\rangle = \frac{M^2}{2\sqrt{3}}\left[\frac{\sqrt{1-M^2}}{1+\frac{M^2}{3}}\right] \sim \frac{M^2}{2\sqrt{3}}.$$

$$\langle|F^S|\rangle \equiv \left\langle\sqrt{K_{S\bar{S}}F^S\bar{F}^{\bar{S}}}\right\rangle = \frac{M^3}{\sqrt{3}}\sqrt{\frac{1+\frac{7M^2}{9}}{(1+\frac{M^2}{3})^3}} \sim \frac{M^3}{\sqrt{3}}$$

$$m_{3/2} = \langle e^{\frac{K}{2}}W\rangle = \frac{M^2}{6}\frac{1+\frac{5M^2}{3}}{\sqrt{(1+\frac{M^2}{3})^3}} \sim \frac{M^2}{6}$$

Gravitino mass is super heavy $m_{3/2} \sim 10^{-10} \sim 10^8\ \mathrm{GeV}$

Are all superparticles super heavy?

Pure de Sitter R^2 supergravity

A simple matter coupled extension shows that matters only couple to S

$$S = -3\left[S_0\bar{S}_0\left(T+\bar{T}-\frac{1}{3}\mathcal{N}(S,\bar{S},Q^I,\bar{Q}^{\bar{J}})\right)\right]_D$$
$$+\left[S_0^3 MTS + S_0^3 W_m(S,Q^I) + S_0^3 L(S-M)^2\right]_F$$
$$+\left[\frac{1}{4}f_{AB}(Q^I,S)\mathcal{W}^A\mathcal{W}^B\right],$$

$$M_A \sim \langle |F^S| \rangle h_A,$$

$$a_{IJK} \sim \langle |F^S| \rangle \tilde{y}_{IJK},$$

$$b_{IJ} \sim \langle |F^S| \rangle \tilde{\mu}_{IJ},$$

$$m^2_{I\bar{J}} \sim \langle |F^S| \rangle^2 c_{I\bar{J}}.$$

$$\langle |F^S| \rangle \equiv \left\langle \sqrt{K_{S\bar{S}}F^S\bar{F}^{\bar{S}}} \right\rangle = \frac{M^3}{\sqrt{3}}\sqrt{\frac{1+\frac{7M^2}{9}}{(1+\frac{M^2}{3})^3}} \sim \frac{M^3}{\sqrt{3}}$$

$$M_{SUSY} \sim \mathcal{O}(10^{-15}) \sim \mathcal{O}(1)\ \mathrm{TeV}$$

Anomaly mediation is suppressed due to no-scale property

Gravitino is heavy but MSSM sector can have TeV scale mass!!

Pure de Sitter R^2 supergravity

$$\Gamma(\tilde{T} \to \psi_{3/2} + \psi_{3/2}) \sim \frac{e^K |D_T W|^2}{288\pi} \frac{m_{\rm inf}^5}{m_{3/2}^4} \sim \frac{M}{96\pi}$$

Inflaton mostly decays to gravitino

Gravitino would dominate the universe

Gravitino problems would be avoided because gravitino is very heavy

$$T_{3/2} = \left(\frac{\pi^2 g_*}{90}\right)^{-\frac{1}{4}} \sqrt{\Gamma} \sim 150 \text{ GeV} \left(\frac{g_*}{80}\right)^{-\frac{1}{4}}$$

Thermal history is not well investigated yet…