Lecture #1: Supersymmetry and dark matter

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OUTLINE

★ The Standard Model
★ Inconsistencies
★ Supersymmetry
★ neutralino dark matter
  • direct DM searches
  • indirect DM searches
★ gravitino DM
★ mixed axion/axino DM
The Standard Model of Particle Physics

★ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g, W^\pm, Z^0, \gamma$

★ matter content: 3 generations quarks and leptons

\[
\begin{pmatrix}
u \\ \phi_0
\end{pmatrix}
\]

★ Higgs sector \Rightarrow spontaneous electroweak symmetry breaking:

\[
\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}
\]

★ \Rightarrow massive $W^\pm, Z^0, \text{quarks and leptons}$

★ $\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{matter}} + \mathcal{L}_{\text{Yuk.}} + \mathcal{L}_{\text{Higgs}}$: 19 parameters

★ good-to-excellent description of (almost) all accelerator data!
Shortcomings of SM

Data

★ neutrino masses and mixing
★ baryogenesis (matter anti-matter asymmetry)
★ cold dark matter
★ dark energy

Theory

★ quadratic divergences in scalar sector ⇒ fine-tuning
★ origin of generations
★ explanation of masses/ mixing angles
★ origin of gauge symmetry/ quantum numbers
★ unification with gravity
The supersymmetry alternative

Supersymmetry: bosons ⇔ fermions

★ SUSY is a space-time symmetry!

★ space-time $x^\mu \Rightarrow (x^\mu, \theta_i) \ i = 1, \cdots, 4$ superspace

★ fields $\psi \Rightarrow \hat{\phi} \ni (\phi, \psi)$ superfields

★ gauge fields $A^\mu \Rightarrow \hat{W} \ni (\lambda, A^\mu)$ gauge superfields

★ superfield formalism $\Rightarrow$ general form for Lagrangian of (globally) supersymmetric gauge theory: quadratic divergences cancel!

★ SUSY can be broken by soft SUSY breaking terms: maintain cancellation of quadratic divergences
Weak Scale Supersymmetry

HB and X. Tata
Spring, 2006; Cambridge University Press

★ Part 1: superfields/Lagrangians
  – 4-component spinor notation for exp’ts
  – master Lagrangian for SUSY gauge theories

★ Part 2: models/implications
  – MSSM, SUGRA, GMSB, AMSB, · · ·
  – dark matter density/detection

★ Part 3: SUSY at colliders
  – production/decay/event generation
  – collider signatures
  – $R$-parity violation
Minimal Supersymmetric Standard Model (MSSM)

★ Adopt gauge symmetry of Standard Model
  • spin $\frac{1}{2}$ gaugino for each SM gauge boson
★ SM fermions $\in$ chiral scalar superfields: $\Rightarrow$ scalar partner for each SM fermion helicity state
  • electron $\Leftrightarrow \tilde{e}_L$ and $\tilde{e}_R$
★ two Higgs doublets to cancel triangle anomalies
★ add all admissible soft SUSY breaking terms
★ resultant Lagrangian has 124 parameters!
★ Lagrangian yields mass eigenstates, mixings, Feynman rules for scattering and decay processes
★ predictive model!
Physical states of MSSM:

★ usual SM gauge bosons, quarks and leptons

★ gluino: \( \tilde{g} \)

★ bino, wino, neutral higgsinos \( \Rightarrow \) neutralinos: \( \tilde{Z}_1, \tilde{Z}_2, \tilde{Z}_3, \tilde{Z}_4 \)

★ charged wino, higgsino \( \Rightarrow \) charginos: \( \tilde{W}_1^\pm, \tilde{W}_2^\pm \)

★ squarks: \( \tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R, \ldots, \tilde{t}_1, \tilde{t}_2 \)

★ sleptons: \( \tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e, \ldots, \tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau \)

★ Higgs sector enlarged: \( h, H, A, H^\pm \)

★ a plethora of new states to be found at LHC/ILC?!
Supergravity (SUGRA)

- $e^{i\alpha Q}$ with $\alpha(x)$: local SUSY transformation
  - forces introduction of spin 2 graviton and spin $\frac{3}{2}$ gravitino
  - resultant theory $\Rightarrow$ General Relativity in classical limit!

- rules for Lagrangian in supergravity gauge theory: Cremmer et al. (1983)

- fertile ground: supergravity $\cup$ grand unification: LE limit of superstring?

- minimal supergravity model (mSUGRA)

- $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$
  - $m_0 = \text{mass of all scalars at } Q = M_{GUT}$
  - $m_{1/2} = \text{mass of all gauginos at } Q = M_{GUT}$
  - $A_0 = \text{trilinear soft breaking parameter at } Q = M_{GUT}$
  - $\tan \beta = \text{ratio of Higgs vevs}$
  - $\mu = \text{SUSY Higgs mass term; magnitude determined by REWSB!}$
Some successes of SUSY GUT theories

★ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV

★ gauge coupling unification!
Gauge coupling evolution

![Graph showing the evolution of gauge couplings](image-url)
Some successes of SUSY GUT theories

- SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- Gauge coupling unification!
- Lightest Higgs mass $m_h \lesssim 135$ GeV as indicated by radiative corrections!
Precision electroweak data and the Higgs mass:

- Experimental errors 68% CL:
  - LEP2/Tevatron (today)
  - Tevatron/LHC

- Models:
  - SM
  - MSSM
  - Both models

- Masses:
  - $M_H = 400$ GeV
  - $M_H = 114$ GeV

Heinemeyer, Hollik, Stockinger, Weber, Weiglein '08

S. Heinemeyer et al.

Howie Baer, Karlsruhe/Freudenstadt meeting, Sept. 30, 2009
Some successes of SUSY GUT theories

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- Gauge coupling unification!
- Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!
- Radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
Soft term evolution and radiative EWSB
Some successes of SUSY GUT theories

- SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- Gauge coupling unification!
- Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!
- Radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
- Dark matter candidate: lightest neutralino $\tilde{Z}_1$
- Stable neutrino see-saw scale vs. weak scale
- $SO(10)$ SUSY GUT: baryogenesis via leptogenesis
- Can give dark energy via CC $\Lambda$ (but need huge fine-tuning...)
  - SUGRA = low energy limit of superstring?
  - Stringy multiverse: anthropic selection of small CC?
Evidence for dark matter in the universe

★ binding of galactic clusters (Zwicky, 1930s)
★ galactic rotation curves
★ large scale structure formation
★ inflation ⇒ $\Omega = \rho/\rho_c = 1$
★ gravitational lensing
★ anisotropies in cosmic MB (WMAP)
★ surveys of distant galaxies via SN (DE)
★ Big Bang nucleosynthesis
  - $\Omega_A \approx 0.7$
  - $\Omega_{CDM} \approx 0.25$
  - $\Omega_{baryons} \approx 0.045$ (dark baryons $\approx 0.040$
  - $\Omega_\nu \approx 0.005$
SUSY dark matter

★ R-parity conservation ⇒ conserved $B$ and $L$ ⇒ proton stability
  • $R(\text{particle}) = 1$; $R(\text{sparticle}) = -1$

★ Naturally occurs in $SO(10)$ SUSY GUT theories

★ Some consequences:
  • Sparticles are produced in pairs
  • Sparticles decay to other sparticles
  • Lightest SUSY particle (LSP) is absolutely stable (good candidate for dark matter)

★ LSP must be charge, color neutral (bound on cosmological relics)

★ Sneutrino would have been detected in direct detection experiments

★ lightest neutralino $\tilde{\chi}_1$ is LSP in wide range of models

★ $\tilde{\chi}_1$ is weakly interacting, massive particle (WIMP)
Calculating the relic density of neutralinos

★ At very high $T$, neutralinos in thermal equilibrium with cosmic soup

★ As universe expands and cools, expansion rate exceeds interaction rate (freeze-out)

★ number density is governed by Boltzmann eq. for FRW universe

- $\frac{dn}{dt} = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$

- $\Omega_{\tilde{Z}_1} h^2 = \frac{s_0}{\rho_c / h^2} \left( \frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{m_{Pl}} \frac{1}{\langle \sigma v \rangle}$

- $\Omega_{CDM} h^2 \sim 0.1 \Rightarrow \langle \sigma v \rangle \sim 0.9 \text{ pb!}$

- $\langle \sigma v \rangle = \frac{\pi \alpha^2}{8m^2} \Rightarrow m \sim 100 \text{ GeV}$

★ “The WIMP miracle!”: cosmic motivation for new physics at weak scale

★ SUSY: 1722 annihilation/co-annihilation reactions; 7618 Feynman diagrams

★ IsaReD program (HB, A. Belyaev, C. Balazs)
Results of $\chi^2$ fit using $\tau$ data for $\alpha_\mu$:

$m_{\text{Sugra}}$ with $\tan\beta = 10, A_0 = 0, \mu > 0$

$m_{\text{Sugra}}$ with $\tan\beta = 54, A_0 = 0, \mu > 0$


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Direct detection of SUSY DM

Direct search via neutralino-nucleon scattering

\[ q \rightarrow \tilde{q}_{L,R} \tilde{z}_1 \]

\[ \tilde{z}_1 \rightarrow q \tilde{q}_{L,R} \]

\[ \tilde{z}_1 \rightarrow q h, H \]

\[ \tilde{z}_1 \rightarrow h, H g \]

\[ \tilde{z}_1 \rightarrow h, H t \]

\[ \tilde{z}_1 \rightarrow h, H g \]
Direct detection of neutralino DM: the race is on!

DATA listed top to bottom on plot
Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003 limit
DAMA 2000 58k kg-days NaI Ann. Mod. 3sigma w/DAMA 1996
WARP 2.3L, 96.5 kg-days 55 keV threshold
CDMS 2008 Ge
CDMS: 2004+2005 (reanalysis) +2008 Ge
XENON10 2007 (Net 136 Kg-d)
CDMS Soudan 2007 projected
SuperCDMS (Projected) 2-5T@Soudan
WARP 140kg (proj)
SuperCDMS (Projected) 25kg (7-5T@SnoLab)
XENON100 150 (100 project sensitivity
LUX 300 kg LXe Projection (Jul 2007)
XENON1T (proj)
Baer et. al 2003

http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini

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Indirect detection (ID) of SUSY DM: $\nu$-telescopes

$\tilde{Z}_1 \tilde{Z}_1 \rightarrow b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \rightarrow \mu$ in $\nu$ telescopes

- Amanda, Icecube, Antares
ID of SUSY DM: $\gamma$ and anti-matter searches

- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q \bar{q}, etc. \rightarrow \gamma$ in galactic core or halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q \bar{q}, etc. \rightarrow e^+$ in galactic halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q \bar{q}, etc. \rightarrow \bar{p}$ in galactic halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q \bar{q}, etc. \rightarrow \bar{D}$ in galactic halo
Direct and indirect detection of neutralino DM

HB, Belyaev, Krupovnickas, O’Farrill: JCAP 0408, 005 (2004)
Gravitinos: spin-$\frac{3}{2}$ partner of graviton

- gravitino problem in generic SUGRA models: overproduction of $\tilde{G}$ followed by late $\tilde{G}$ decay can destroy successful BBN predictions: upper bound on $T_R$

(see Kawasaki, Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive)
neutralino production in generic SUGRA models: followed by late time $\tilde{Z}_1 \rightarrow \tilde{G} + X$ decays can destroy successful BBN predictions:

(see Kawasaki, Kohri, Moroi, Yotsuyanagi)
Gravitino dark matter: if one can avoid gravitino problem

\( m_{\tilde{G}} = F/\sqrt{3} M_* \sim \text{TeV} \) in Supergravity models

- if \( \tilde{G} \) is LSP, then calculate NLSP abundance as a thermal relic: \( \Omega_{NLSP} h^2 \)
- \( \tilde{Z}_1 \rightarrow h\tilde{G}, Z\tilde{G}, \gamma\tilde{G} \) or \( \tilde{\tau}_1 \rightarrow \tau\tilde{G} \) possible
  - lifetime \( \tau_{NLSP} \sim 10^4 - 10^8 \) sec
  - also produce \( \tilde{G} \) thermally (depends on re-heat temp. \( T_R \))
  - DM relic density is then \( \Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}} \Omega_{NLSP} + \Omega_{TP}^{\tilde{G}} \)
  - Feng et al.; Ellis et al.; Brandenberg+Steffen; Buchmuller et al.
- \( \tilde{G} \) undetectable via direct/indirect DM searches
- unique collider signatures are possible:
  - \( \tilde{\tau}_1 = \text{NLSP} \): stable charged tracks
  - can collect NLSPs in e.g. water (slepton trapping)
  - monitor for \( NLSP \rightarrow \tilde{G} \) decays
Various leptogenesis scenarios

- Upper bound on $T_R$ from BBN is below that for successful thermal leptogenesis: need $T_R \gtrsim 10^{10}$ GeV (Buchmuller, Plumacher)

- Alternatively, one may have non-thermal leptogenesis where inflaton $\phi \to N_i N_i$ decay (Lazarides, Shafi; Kumekawa, Moroi, Yanagida)

- additional source of $N_i$ in early universe allows lower $T_R$:

  \[
  \frac{n_B}{s} \simeq 8.2 \times 10^{-11} \times \left( \frac{T_R}{10^6 \text{ GeV}} \right) \left( \frac{2 m_{N_1}}{m_\phi} \right) \left( \frac{m_{\nu_3}}{0.05 \text{ eV}} \right) \delta_{eff} \tag{3}
  \]

- Also, AD leptogenesis in $\phi = \sqrt{H \ell}$ D-flat direction: $T_R \sim 10^6 - 10^8$ GeV allowed (Dine, Randall, Thomas; Muarayama, Yanagida)

- WMAP observation: $n_b/s \sim 0.9 \times 10^{-10} \Rightarrow T_R \gtrsim 10^6$ GeV
Axions

- PQ solution to strong CP problem in QCD
- pseudo-Goldstone boson from PQ breaking at scale $f_a \sim 10^9 - 10^{12}$ GeV
- non-thermally produced via vacuum mis-alignment as cold DM
  - $m_a \sim \Lambda_{QCD}^2 / f_a \sim 10^{-6} - 10^{-1}$ eV
  - $\Omega_a h^2 \sim \frac{1}{2} \left[ \frac{6 \times 10^{-6} \text{eV}}{m_a} \right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-1}$ eV
  - $a$ couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches

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Axion microwave cavity searches

- ongoing searches: ADMX experiment
  - Livermore ⇒ U Wash.
  - Phase I: probe KSVZ
    for $m_a \sim 10^{-6} - 10^{-5}$ eV
  - Phase II: probe DFSZ
    for $m_a \sim 10^{-6} - 10^{-5}$ eV
  - beyond Phase II:
    probe higher values $m_a$
Axions + SUSY ⇒ Axino $\tilde{a}$ dark matter

- axino is spin-$\frac{1}{2}$ element of axion supermultiplet ($R$-odd; can be LSP)
  - Raby, Nilles, Kim
  - Rajagopal, Wilczek, Turner
- $m_{\tilde{a}}$ model dependent: keV → GeV
- $\tilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\tilde{Z}_1$ decay:
- axinos inherit neutralino number density
- $\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2$:
  - Covi, Kim, Kim, Roszkowski
Thermally produced axinos

- If $T_R < f_a$, then axinos never in thermal equilibrium in early universe
- Can still produce $\tilde{a}$ thermally via radiation off particles in thermal equilibrium
- Brandenberg-Steffen calculation:

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln \left( \frac{1.108}{g_s} \right) \left( \frac{10^{11} \text{ GeV}}{f_a/N} \right)^2 \left( \frac{m_{\tilde{a}}}{0.1 \text{ GeV}} \right) \left( \frac{T_R}{10^4 \text{ GeV}} \right)$$

(4)
mSUGRA model with mixed axion/axino CDM: $T_R$ fixed

- $(m_0, m_{1/2}, A_0, \tan \beta, sgn(\mu)) = (1000 \text{ GeV}, 300 \text{ GeV}, 0, 10, +1)$
- $\Omega_a h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} h^2 = 0.11$
mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

- $(m_0, m_{1/2}, A_0, \tan \beta, sgn(\mu)) = (1000 \text{ GeV}, 300 \text{ GeV}, 0, 10, +1)$
- $\Omega_a h^2 + \Omega_{\tilde{a} TP} h^2 + \Omega_{\tilde{a} NTP} h^2 = 0.11$
- model with *mainly* axion CDM seems favored!

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mSUGRA p-space with mainly axion cold DM

★ contours of $\log_{10} T_R$: mSUGRA w/ $\tan \beta = 10$, $A_0 = 0$

★ $T_R \gtrsim 10^6$ consistent with non-thermal leptogenesis

★ most dis-favored mSUGRA regions with neutralino DM are most favored by mSUGRA with mainly axion DM! (HB, Box, Summy)
Fine-tuning in mSUGRA with neutralino CDM

★ contours of $\Omega_{\tilde{Z}_1} h^2$

★ regions of fine-tune: $\Delta \equiv \frac{\partial \log \Omega_{\tilde{Z}_1} h^2}{\partial \log a_i}$: (HB, A. Box)
Fine-tuning zoomed in stau-co-annihilation

★ contours of $\Omega_{\tilde{Z}_1} h^2$

★ regions of fine-tune: $\Delta \equiv \frac{\partial \log \Omega_{\tilde{Z}_1} h^2}{\partial \log a_i}$
Fine-tuning for mainly axion CDM in mSUGRA

- contours of $\Omega_{Z_1} h^2$
- regions of fine-tune: $\Delta \equiv \frac{\partial \log \Omega_{Z_1} h^2}{\partial \log a_i}$
Prediction for LHC: SUSY with $t - b - \tau$ Yukawa unification

- $m_{16}, m_{10}, M_D^2, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
- need $m_{16} \sim 10$ TeV and $m_{1/2}$ very small
- need $m_{10} \approx \sqrt{2}m_{16}; A_0 \approx -2m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$
- Auto, HB, Balazs, Belyaev, Ferrandis, Tata
- HB, Kraml, Sekmen, Summy
  - $m_{\tilde{q}, \tilde{t}}(1, 2) \sim 10$ TeV
  - $m_{\tilde{t}_1}, m_A, \mu \sim 1 - 2$ TeV
  - $m_{\tilde{g}} \sim 300 - 500$ GeV
- see also Blazek, Dermisek, Raby
- Altmannshofer, Guadagnoli, Raby, Straub

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Consequences of $t - b - \tau$ Yukawa unified SUSY

- for $m_{16} \sim m_{3/2} > 5$ TeV allow $T_R \sim 10^6 - 10^8$ GeV (solve gravitino problem and allow non-thermal or DRT leptogenesis)

- huge $\Omega_{\tilde{Z}_1} h^2 \sim 10^3 \Rightarrow$ dark matter is mixed axion/axino instead of neutralino

- $m_{\tilde{g}} \sim 400$ GeV $\Rightarrow \sigma(pp \rightarrow \tilde{g}\tilde{g}X) \sim 10^5$ fb at $\sqrt{s} = 14$ TeV LHC

- $\tilde{g} \rightarrow \bar{b}b\tilde{Z}_2$ dominant; also, $\tilde{g} \rightarrow tb\tilde{W}_1$

- expect beautiful mass edge in $m(\ell^+\ell^-)$

- testable at LHC with $\sim 0.1 - 1$ fb$^{-1}$

- reconstruct $m_{\tilde{g}}$ via $m(b\ell^+\ell^-)$

- possible axion signal at ADMX?

- WIMP direct/indirect searches yield null result
Conclusions

★ Supersymmetry is very compelling BSM theory
★ Irrefragable case for CDM has emerged
★ Direct search for WIMP/axion DM is underway
★ Indirect search for WIMP DM via Icecube $\nu$ telescope
★ Indirect search via $\gamma$, $\bar{p}$, $e^+$, $\bar{D}$ detection from galactic core/halo WIMP annihilations
★ Gravitino DM: possible, but suffers from “gravitino problem”
★ Mixed axion/axino as CDM: more compelling than neutralinos
★ Next: what can we learn from LHC about SUSY and DM?