Evidence for dark matter: overwhelming, and from numerous disparate sources!

Properties: massive, neutral, cold (warm...)

Of particles in the Standard Model (SM), only neutrinos have the right properties: but they constitute hot dark matter, and abundance is known

Dark matter must be some particle state not contained in the SM: NEW PHYSICS NEEDED!
Some dark matter candidates: mass vs. interaction strength plane

Some Dark Matter Candidate Particles

- neutrinos
- neutralino
- KK photon
- branon
- LTP
- axion
- axino
- gravitino
- KK graviton
- SuperWIMPs:
  - wimpzilla
  - Black Hole Remnant

- fuzzy CDM

mass (GeV) vs. interaction cross-section ($\sigma_{int}$) (pb)
While some candidates are made up specifically to solve the DM problem, others emerge as part of solutions to long standing problems in particle physics:

- Peccei-Quinn solution to strong CP problem: axions

- Supersymmetry: at least 3 viable DM candidates: neutralino, gravitino, axino/(axion)
SUSY motivations:

- naturalness in quantum field theory (no quadratic divergences)
- means to unification with gravity (supergravity)
- gauge coupling unification provided superpartners at TeV scale
- precision EM corrections and Higgs mass
- radiative EWSB and the top mass
- accommodate baryogenesis: at least 3 ways
Supersymmetric models: how SUSY breaking is communicated from hidden sector to visible sector

- **GMSB:** solves SUSY flavor problem, very light gravitino: does not naturally yield CDM

- **AMSB:** solves flavor problem, tachyonic sleptons; does not usually yield measured abundance of CDM

- **AMSB → Mixed-moduli AMSB → CDM**

- **SUGRA:** 3 candidate DM particles: \( \tilde{G}, \tilde{Z}_1 \) or \( \chi, \tilde{a}/a \)
Simplest: mSUGRA or CMSSM

- embed MSSM into SUGRA gauge theory
- SUSY breaking in simple hidden sector
- parameter space:
  \( m_0, m_{1/2}, A_0 \tan \beta, \text{sign}(\mu) \)
Neutralino is an excellent WIMP candidate!
Calculation of relic density

Why $R$-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin, Kawamura, ...)

In thermal equilibrium in early universe

As universe expands and cools, freeze out

Number density obtained from Boltzmann eq'n

- $dn/dt = -3H n - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
- depends critically on thermally averaged annihilation cross section times velocity

Many thousands of annihilation/co-annihilation diagrams

Several computer codes available

- DarkSUSY, Micromegas, IsaReD (part of Isajet)
mSUGRA parameter space

Beware non-standard cosmology!

Gelmini–Gondolo

HB, Mustafayev, Park, Tata
Search for mSUGRA at LHC

★ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV

★ lengthy cascade decays of $\tilde{g}$ $\tilde{q}$ are likely

★ events characterized by multiple hard jets, isolated and non-isolated leptons $e$s and $\mu$s, and $E_T$ from $\tilde{Z}_1$ or $\tilde{G}$ or $\nu$s escaping

★ many jets are $b$ (displaced vertices due to long $B$ lifetime) and $\tau$ (1 or 3 charged prongs) jets

★ one way to classify signatures is according to number of isolated leptons

- $E_T$ + jets
- $1\ell$ + $E_T$ + jets
- opposite – sign (OS) $2\ell$ + $E_T$ + jets
- same – sign (SS) $2\ell$ + $E_T$ + jets
- $3\ell$ + $E_T$ + jets
- $4\ell$ + $E_T$ + jets
- $5\ell$ + $E_T$ + jets
SM backgrounds to SUSY

- numerous SM processes give same signature as SUSY!

- SM BGs include:
  - QCD: multi-jet $qq, q\bar{q}, qg, gg$ production where $E_T$ comes from mis-measurement, cracks, etc.
    - $t\bar{t}, b\bar{b}, c\bar{c}$
    - $W$ or $Z$+ multi-jet production
  - $WW, WZ, ZZ$ production, where $Z \rightarrow \nu\bar{\nu}$ or $\tau\bar{\tau}$
    - all of above embedded in Isajet, Pythia, Herwig
  - four particle processes: e.g. $t\bar{t}t\bar{t}$, $ttbb$, etc.
  - $WWW$, etc.
    - the $2 \rightarrow n$ for $n > 2$ processes usually need CalcHEP/Madgraph
  - overlapping events; fake $b$-jets; fake leptons, etc
Optimize cuts over parameter space

- Cuts and pre-cuts:
  - $E_T > 200$ GeV
  - $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$

- Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $E_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation

- $S > 10$ events for $100$ fb$^{-1}$
- $S > 5\sqrt{B}$ for optimal set of cuts
Reach of LHC for various signals and 100 fb$^{-1}$
Reach of LHC compared to Tevatron and ILC
Reach of LHC, ILC compared to DD/ID WIMP search

HB, Park, Tata

Tuesday, March 31, 2009
DD vs. LHC in mSUGRA:
Xenon-100 should cover FP region!
Well-tempered neutralinos
Arkani-Hamed, Delgado, Giudice

Scan over 10 models with and without universality; keep only models with correct relic abundance

Bulk of models asymptote at $10^{-8}$ pb! Accessible to next Xenon-100 run!
If WIMP seen in DD, then mass measurement

Study by Schnee; Green; Drees&Shan shows $m(WIMP)$ may be extracted from energy spectrum in DD experiments, for lower range of WIMP masses: crucial input for LHC?

Tuesday, March 31, 2009
Early search for SUSY at LHC: 0.1–0.5 fb⁻¹

- Can we make early discovery of SUSY at LHC without $\not{E}_T$?
- Expect $gg$ events to be rich in jets, $b$-jets, isolated $\ell$s, $\tau$-jets,....
- These are detectable, rather than inferred objects
- Inferred objects like $\not{E}_T$ require knowledge of complete detector performance
  - dead regions
  - “hot” cells
  - cosmic rays
  - calorimeter mis-measurement
Reach of LHC for SUSY via SS dimuons and *no* ETMISS

HB, A. Lessa, H. Summy
arXiv:0809.4719 (PLB)
Precision sparticle measurements at LHC

- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}}$, $m_{\tilde{q}}$ scale
- $m(\ell\ell) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ mass edge
- $m(\ell\ell)$ distribution shape
- combine $m(\ell\ell)$ with jets to gain $m(\ell\ell;j)$ mass edge: info on $m_{\tilde{q}}$
- further mass edges possible e.g. $m(\ell\ell;j;j)$
- Higgs mass bump $h \rightarrow b\bar{b}$ likely visible in $\not{E}_T + jets$ events
- in favorable cases, may overconstrain system for a given model
  - methodology very p-space dependent
  - some regions are very difficult e.g. HB/FP
Paige, Hinchliffe et al. studies

- examined many model case studies in mSUGRA, GMSB, high $\tan \beta$...
- $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu) = (100, 300, 0, 2, 1)$ in GeV
- dominant $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow q\tilde{q}_L \rightarrow qq\tilde{Z}_2 \rightarrow q_1 q_2 \ell_1 \tilde{\ell} \rightarrow q_1 q_2 \ell_1 \ell_2 \tilde{Z}_1$
  (string of 2-body decays)
- can reconstruct 4 mass edges; allows one to fit four masses:
  $m_{\tilde{q}_L}$, $m_{\tilde{Z}_2}$, $m_{\tilde{\ell}}$, $m_{\tilde{Z}_1}$ to 3 – 12%
- can also find Higgs $h$ in the SUSY cascade decay events
- if enough sparticle masses measured, can fit to MSSM/SUGRA parameters
Precision SUSY measurements and cosmology

Find which parameter space choices lead to precision measurements

Map parameters onto e.g. relic density, DD cross section, ID $<\sigma v>$

$\rightarrow$ Collider measurement of $\Omega_\chi h^2$, $\sigma(\chi p)$, $<\sigma \cdot v>$, ...
The gravitino problem in SUGRA models

- Gravitinos can be produced thermally in early universe
- Gravitino lifetime suppressed by $M_{Pl}^{-2}$
- Late decays disrupt successful BBN predictions
- Need either $m_{\text{grav}} > 5\,\text{TeV}$ or $T_R<10^5\,\text{GeV}$ (but then problems with baryogenesis)

Kawasaki et al; Ellis et al.
Gravitino DM

\[ m_{\tilde{G}} = F/\sqrt{3} M_\ast \sim \text{TeV} \text{ in Supergravity models} \]

- usually \( \tilde{G} \) decouples (but see Moroi et al. for BBN constraints)
- 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 \( \tau_{NLSP} \sim 10^4 - 10^8 \text{ sec} \)
  * constraints from BBN, CMB not too severe
  * DM relic density is then \( \Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}} \Omega_{NLSP} + \Omega_{\tilde{G}}^{TP}(T_R) \)
  * Feng, Rajaraman, Su, Takayama; Ellis et al; Buchmuller et al.
- \( \tilde{G} \) undetectable via direct/indirect DM searches
- unique collider signatures:
  * \( \tilde{\tau}_1=\text{NLSP} \): stable charged tracks
  * can collect NLSPs in e.g. water (slepton trapping)
  * monitor for \( NLSP \rightarrow \tilde{G} \) decays
BBN constraints on gravitino LSP: Kohri et al.
Axion DM: forms BEC, suppresses small scale structure, gives mechanism for galactic rotation

Axion microwave cavity search

- Ongoing searches: ADMX experiment
  - Livermore $\Rightarrow$ 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 => axinos

- Axino is spin-1/2, R-odd spartner of axion
- Axino mass is model dependent: keV -> GeV
- Axino is an EWIMP; coupling suppressed by Peccei-Quinn scale $f_a : 10^9 - 10^{12}$ GeV
- Good candidate for cold DM

For review, see Covi, Kim, Kim, Roszkowski JHEP 0105 (2001) 033
Non-thermal axino production via NLSP decay

- If $\tilde{a}$ is LSP, then it can be produced via decay of NLSP

- e.g. $\tilde{Z}_1 \rightarrow \tilde{a} \gamma$ or $\tilde{\tau}_a \rightarrow \tilde{a} \tau$

- NLSP lifetime: $10^{-3} - 10^1$ sec: (BBN safe)

- axinos inherit NLSP number density

\[
\Omega_{\tilde{a}}^{NT} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2
\]

- NTP axino is warm DM for $m_{\tilde{a}} < 1 - 10$ GeV
Thermal production of axinos

- Axinos likely never in thermal equilibrium
- Can be produced thermally via bremsstrahlung off particles in thermal equilibrium
- TP axinos are cold DM for \( m_\tilde{a} > 100 \) keV

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

- CKKR; Brandenberg, Steffen
SO(10) SUSY GUTs

- gauge coupling unification
- matter unification into 16-dim. spinor rep.
- 16th element contains RHN: see-saw
- explain anomaly cancellation in MSSM and SU(5)
- explain R-parity conservation
- allow for t-b-tau Yukawa unification
### SO(10) model parameter space

- $m_{16}$, $m_{10}$, $M_D^2$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$
- Here, $M_D^2$ parametrizes splitting of Higgs soft terms at $M_{GUT}$:

$$m_{H_{u,d}}^2 = m_{10}^2 + 2M_D^2$$

- The Higgs splitting only (HS) method gives better Yukawa unification than full $D$-term splitting (DT) model for $\mu > 0$ and $m_{16} \gtrsim 2 \text{ TeV}$

**Related work:** Blazek, Dermisek, Raby; Wells, Tobe; Dermisek, Raby, Roszkowski, Ruiz; Altmannshofer, Guadagnoli, Raby, Straub
t-b-tau unified solutions

\[ m_{16} \sim 10 \text{ TeV} \]

\[ m_{1/2} \text{ small} \]

- need \( m_{10} \approx \sqrt{2} m_{16} \)
- \( A_0 \approx -2 m_{16} \)
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: \( m_{H_u}^2 < m_{H_d}^2 \)

- \( m_{q, \ell} (1, 2) \sim 10 \text{ TeV} \)
- \( m_{\tilde{t}_1}, m_A, \mu \sim 1 - 2 \text{ TeV} \)
- \( m_{\tilde{g}} \sim 300 - 500 \text{ GeV} \)
Dark matter problem in Yukawa-unified models

- $m(16) \approx 10$ TeV with $m_{1/2}$ small
- neutralino is pure bino-like

relic density too high by factor $10^3 - 10^5$!
DM solution: three components:
warm axinos, cold axinos, cold axions!

- best solution: axion/axino DM instead of neutralino
- each $\tilde{Z}_1 \rightarrow \tilde{a} \gamma$ so $\Omega_{\tilde{a}} h^2 \sim \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2$: $\Rightarrow$ warm DM
- also thermal component depending on $T_R$: $\Rightarrow$ CDM
- also axion DM via vacuum mis-alignment

HB, Kraml, Sekmen, Summy
JHEP 0803 (2008) 056

HB, Summy
PLB666 (2008) 5

HB, Haider, Kraml, Sekmen, Summy
arXiv:0812.2693
Can we find Yukawa-unified models with dominant CDM?

- Given $\Omega_{Z_1} h^2$ and $m_{Z_1}$ and $\Omega_{\tilde{a}}^{NTP} h^2$ can calculate $m_{\tilde{a}}$.
- Given $\Omega_{\tilde{a}}^{TP} h^2$, $m_{\tilde{a}}$ and $f_a/N$, can calculate re-heat temperature of universe.

★ Four cases:

1. Take $f_a/N = 10^{11}$ GeV so $\Omega_a h^2 = 0.017$. Bulk of DM must be thermally produced $\tilde{a}$. Take $\Omega_{\tilde{a}}^{TP} = 0.083$ and $\Omega_{\tilde{a}}^{NTP} = 0.01$

2. Take $f_a/N = 4 \times 10^{11}$ GeV so $\Omega_a h^2 = 0.084$. (Bulk of DM is cold axions.) Take $\Omega_{\tilde{a}}^{TP} = \Omega_{\tilde{a}}^{NTP} = 0.013$

3. Take $f_a/N = 10^{12}$ GeV and lower mis-align error bar so $\Omega_a h^2 = 0.084$. (Bulk of DM is cold axions.) Take $\Omega_{\tilde{a}}^{TP} = \Omega_{\tilde{a}}^{NTP} = 0.013$

4. Take $f_a/N = 10^{12}$ GeV but allow accidental near vacuum alignment so $\Omega_a h^2 \sim 0$. Bulk of DM must be thermally produced axinos. Take $\Omega_{\tilde{a}}^{TP} = 0.1$ and $\Omega_{\tilde{a}}^{NTP} = 0.01$
Mixed axion/axino cold and warm DM in Yukawa-unified models

Need:
1. large $f_a \sim 10^{12}$ GeV
2. solutions C2, C3 with dominant axion CDM
3. solution C4 has accidental vacuum alignment and dominant TP axino CDM
4. Solutions with $m_{16} > 8$ TeV have $TR > 10^6$ GeV
Many pieces of puzzle fit:

- PQ solution to strong CP problem
- Solve gravitino problem: $m(\text{Grav'ino}) \sim 10$ TeV
- CDM: dominated by axions, but also cold/warm axinos
- Allow high enough re-heat $10^6$-$10^9$ GeV for e.g. non-thermal leptogenesis
- Large $m_{\text{16}} \sim 10$ TeV suppresses FCNC, CPV, p-decay
- All within framework of simple SO(10) SUSY GUT
Cross sections/BFs, LHC signatures

HB, Kraml, Sekmen, Summy: JHEP 0810 (2008) 079
Testable consequences:

- $m(\text{gluino}) \sim 350-500$ GeV: abundant LHC signatures: early discovery via isolated multi-leptons plus jets (ETM\text{ISS} not needed)

- LHC dilepton mass edge: 50–90 GeV; no second edge implies bino-like neutralino

- high b-jet multiplicity

- reconstruct $m(\text{gluino})$ via $m(lljj)$

- possible axion signal at ADMX

- no direct/indirect WIMP signals
Conclusions:

- Role of LHC: produce matter states associated with dark matter; decay to stable DM candidate (LHT, UED, SUSY, etc) usually gives ETMISS signature (charged stable NLSP counter-example)

- In case of WIMP dark matter, additional signals from DD/ID of DM will provide complementary information (e.g. WIMP mass?)

- Xenon-100/LUX will soon test FP region of mSUGRA and well-tempered neutralino models

- Precision measurements may allow collider measurement of relic density, associated quantities

- SuperWIMP, EWIMP DM possible (gravitino, axino/axion)

- SO(10) Yukawa-unified SUSY with axion/axino DM very compelling!