Dark Matter
and the LHC

Savas Dimopoulos
Stanford University
Outline

• Motivation for WIMPs

• LHC constraints on WIMPs

• Direct Detection constraints on WIMPs
Why go beyond the Standard Model?

Weakness of Gravity
Why go beyond the Standard Model?

Weakness of Gravity

proton

electron
Why go beyond the Standard Model?

Weakness of Gravity

\[
\text{Gravitational Force} = \text{Electric Force} = 0.0000000000000000000000000000000000000001
\]

proton

\[\cdot\]

electron
The hierarchy problem

\[ M_{\text{Planck}} = G_{\text{Newton}}^{-\frac{1}{2}} = 10^{19} \text{ GeV} \]

\[ M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^{3} \text{ GeV} \]

16 orders of magnitude
The hierarchy problem

\[ M_{\text{Planck}} = G_{\text{Newton}}^{-\frac{1}{2}} = 10^{19} \text{ GeV} \]

\[ M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^3 \text{ GeV} \]

\[ \frac{M_{\text{Planck}}}{M_{\text{weak}}} \]

In the Standard Model:
Quantum Corrections pull the weak scale up
The Supersymmetric Standard Model

- New Symmetry: Supersymmetry
- New Particles: Superparticles
- Every particle has a superpartner:
  
<table>
<thead>
<tr>
<th>Particle</th>
<th>Superpartner</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton</td>
<td>slepton</td>
</tr>
<tr>
<td>quark</td>
<td>squark</td>
</tr>
<tr>
<td>photon</td>
<td>photino</td>
</tr>
<tr>
<td>gluon, $W$</td>
<td>gluino, Wino</td>
</tr>
<tr>
<td>Higgs</td>
<td>Higggsino</td>
</tr>
</tbody>
</table>

 SD, Georgi ‘81
Superparticles and Quantum Corrections

If sparticles are at the weak scale so must be the higgs

\[ \propto M^2_{\text{Planck}} \]

\[ \propto -M^2_{\text{Planck}} + M^2_{\text{SUSY}} \]

\[ \propto M^2_{\text{SUSY}} \]
Gauge Coupling Unification

\[ \alpha^{-1} \]

Energy (GeV)

\[ 10^3 \quad 10^6 \quad 10^9 \quad 10^{12} \quad 10^{15} \]
Gauge Coupling Unification

\[ \alpha^{-1} \]

\[ E_{\text{GUT}} \]

Energy (GeV)
Gauge Coupling Unification

\[ \alpha^{-1} \]

Energy (GeV)

\[ E_{\text{GUT}} \]
Gauge Coupling Unification

\[ \sin^2 \theta_w \]

\[ \alpha^{-1} \]

Energy (GeV)

\[ E_{\text{GUT}} \]
Experiment vs Theory

\[ \sin^2 \theta_w \]

\[ \alpha_3 \]

SUSY GUT

non-SUSY GUT

1981

SD, Georgi ’81

Pati-Salam ’73

Georgi, Glashow ’74
Experiment vs Theory

\[ \sin^2 \theta_w \]

- **SUSY GUT**: SD, Georgi '81
- **non-SUSY GUT**: Pati-Salam '73
  - Georgi, Glashow '74

- **1981**: Gevorgian
- **1994**: Gevorgian

\[ \alpha_3 \]
Experiment vs Theory

$\sin^2 \theta_w$ vs $\alpha_3$

1981: Pati-Salam '73, Georgi, Glashow '74

1994: SD, Georgi '81

Present: non-SUSY GUT

SUSY GUT
Proton Stability in Supersymmetry

New particles ⇒
new ways to mediate proton decay

\[ u \rightarrow \tilde{d} \rightarrow e^+ + \bar{u} \]

\[ d \rightarrow \tilde{d} \rightarrow \bar{u} \]
Proton Stability in Supersymmetry

New particles ⇒
new ways to mediate proton decay

\[ u \rightarrow \tilde{d} \rightarrow e^+ \rightarrow \bar{u} \]
Proton Stability in Supersymmetry

New particles ⇒
new ways to mediate proton decay

Proton

u

\( \bar{d} \)

\( e^+ \)

pion

Proton

d

\( \bar{u} \)

u
Proton Stability in Supersymmetry

New particles $\Rightarrow$
new ways to mediate proton decay

Dangerous couplings
Proton Stability in Supersymmetry

New particles $\Rightarrow$
new ways to mediate proton decay

A new symmetry forbids odd-sparticle couplings: R-parity

Lightest Supersymmetric Particle (LSP) is stable
Dark Matter candidate
The WIMP Miracle: Calculable Dark Matter

\[
\frac{\rho_{\text{LSP}}}{\rho_{\text{Crit}}} \quad \text{time}
\]
The WIMP Miracle: Calculable Dark Matter

Equal rates

$\rho_{\text{LSP}}$

$\rho_{\text{Crit}}$

$\rho_{\text{Crit}}$
The WIMP Miracle: Calculable Dark Matter

Only Annihilation

$\rho_{\text{LSP}}$

$\rho_{\text{Crit}}$

$\text{time}$
The WIMP Miracle: Calculable Dark Matter

Number frozen in

$\rho_{\text{LSP}}$

$\rho_{\text{Crit}}$

$\text{time}$
The WIMP Miracle: Calculable Dark Matter

\[
\frac{\rho_{\text{DM}}}{\rho_{\text{critical}}} \sim \frac{1}{10^3\langle \sigma v \rangle} \frac{1}{3^\circ K \times M_{\text{Planck}}} \sim \frac{1}{10^3\langle \sigma v \rangle \text{TeV}^2}
\]
The WIMP Miracle: Calculable Dark Matter

\[ \frac{\rho_{\text{DM}}}{\rho_{\text{critical}}} \sim \frac{1}{10^3 \langle \sigma v \rangle} \times \frac{1}{3^\circ K \times M_{\text{Planck}}} \sim \frac{1}{10^3 \langle \sigma v \rangle \text{TeV}^2} \]

- Cross-section from cosmology:

\[ \langle \sigma v \rangle \sim \frac{1}{10^3 \text{TeV}^2} \sim 1 \text{ pb} \]
The WIMP Miracle: Calculable Dark Matter

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- **Cross-section from cosmology:**
  \[
  \langle \sigma v \rangle \sim \frac{1}{10^3 \text{TeV}^2} \sim 1 \text{ pb}
  \]

- **Mass from cosmology:**
  \[
  \langle \sigma v \rangle \sim \frac{1}{4\pi} \frac{\alpha^2}{m_{\text{LSP}}^2}
  \]
  
  for \( \alpha \sim 10^{-2} \), \( m_{\text{LSP}} \sim 100 \text{ GeV} \)
The WIMP Miracle: Calculable Dark Matter

\[
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for \( \alpha \sim 10^{-2}, m_{\text{LSP}} \sim 100 \text{ GeV} \)

Numbers from Cosmology:
100 GeV and \( 10^{-36} \text{ cm}^2 \)
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• Direct Detection constraints on WIMPs
Dark Matter at the LHC
Dark Matter at the LHC
Dark Matter at the LHC
Dark Matter at the LHC

proton → squark → jet
proton → squark → jet

Unbalanced Momentum

“Missing Energy” signatures
What has the LHC done to Supersymmetry?
Squark and Gluino Production at the LHC

The importance of the valence quarks

\[ \sigma_{\text{tot}}[pb]: pp \rightarrow \text{SUSY} \]

\[ \sqrt{S} = 7 \text{ TeV} \]

Prospino2.1

- u or d
- gluon
- up-squark or down-squark

\[ \tilde{q}\tilde{g} \]
\[ \tilde{q}\tilde{q} \]
\[ \tilde{q}\tilde{q}^* \]
\[ \tilde{g}\tilde{g} \]

\[ \tilde{\chi}_1^0\tilde{\chi}_1^+ \]
\[ \tilde{\chi}_2^0\tilde{\chi}_2^0 \]
\[ \tilde{\nu}_\tau\tilde{\nu}_\tau^* \]
\[ \tilde{\chi}_2^0\tilde{\chi}_1\text{LO} \]

m_{\text{average}} [GeV]
A Way out for Supersymmetry

Hierarchy Problem

Favors
light sparticles

LHC bounds

Favors
heavy sparticles
A Way out for Supersymmetry

SD, Giudice (1995)

Unnecessary tension:
Depend on Different Sparticles

Hierarchy Problem

Favors
light sparticles

Stops

Favors
heavy sparticles

LHC bounds

1st family squarks

u or d
gluino
gluon

up squark or
down squark
Bounds on Natural Supersymmetry

- Stop up to ~500 GeV (except region around top)
- Gluino up to ~1.2 TeV
- Dark Matter candidate hardly constrained from the LHC
Outline

• Motivation for WIMPs

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• Direct Detection constraints on WIMPs
Naive Expectations from the WIMP Miracle

- If the DM annihilates to SM particles it will also interact with SM particles

- $\sigma_{\text{DM-nucleon}} \sim \sigma_{\text{DM-annihilation}} \sim 10^{-36} \text{ cm}^2$
Dark Matter Direct Detection Bounds

Direct detection bound: $10^{-44} \text{ cm}^2$
Dark Matter Direct Detection Bounds

Direct detection bound: $10^{-44} \text{ cm}^2$

Cross-section $[\text{cm}^2 ]$ (normalised to nucleon)

WIMP Mass $[\text{GeV}/c^2 ]$

DATA listed top to bottom on plot:
- DAMA/LIBRA, 2008, no ion channeling, 3sigma, SI
- CDMS II (Soudan), 2008, 121 kg–days, Ge detector, SI
- XENON100, 2011, 100.9 live days of data, SI
- XMASS, projection 2004/2007, 800 kg, FV, 0.5 ton–year, SI
- SuperCDMS, projection 2007, 25 kg (7–ST @SnoLab), SI
- LUX 300 kg Projected Sensitivity, 30000 kg–d, 5–30 keV, 45% eff.
- LUX–ZEPLIN, projection 2008, 3 tonne (3 tonne–year), SI
- XENON1T, projection 2009, 3 ton–yr, 2–30 keV, 45% eff. SI

http://dmtools.brown.edu/
Gaitskell, Mandic, Filippini
Dark Matter Direct Detection Bounds

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

Here now

CDMS II

XENON 100

Where we are

Where we’ll be soon

Where we’ll be soonish (knock wood)

Is there any reason to think this range is special?
Dark Matter Direct Detection Bounds

Where we are

Where we'll be soon

Where we'll be soonish (knock wood)

Is there any reason to think this range is special?

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Dark Matter Direct Detection Bounds

Direct detection bound: $10^{-44}$ cm$^2$

Where we are

- XENON1T, projection 2009, 3 ton yr, $2 \times 30$ keV, 45% eff. SI
- LUX ZEPLIN, projection 2008, 3 tonne (3 tonne year), SI
- SuperCDMS, projection 2007, 25 kg (7–5 ST @ Snolab), SI
- LUX 300 kg Projected Sensitivity, 30000 kg–d, 5–30 keV, 45% eff.
- XMASS, projection 2004/2007, 800 kg, FV 0.5 ton–year, SI

Where we’ll be soonish (knock wood)

- CDMS II
- XENON 100

In the not so near future

- CDMS II
- XENON 100

DATA listed top to bottom on plot

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Direct Detection Expectations for WIMPs

- Z boson exchange
- Higgs boson exchange
- 2 W bosons exchange
Expectations from the WIMP miracle I: Z exchange

Example:
Pure Higgsino Dark Matter

\[
\sigma_{\text{DM-nucleon}} \approx \frac{G_F^2 m_{\text{nucleon}}^2}{2\pi} \approx 10^{-38} \text{ cm}^2
\]
Direct Detection Bounds on Z exchange

Excluded by several orders of magnitude
Expectations from the WIMP miracle II: Higgs exchange

Example: Higgsino-Bino Dark Matter

\[ \sigma_{\text{DM-nucleon}} \approx \frac{g_{\text{DM}}^2 m_{\text{nucleon}}^2}{2\pi v^2} \frac{m_{\text{nucleon}}^2}{m_{\text{Higgs}}^4} \approx 10^{-45} \text{ cm}^2 \]

Assuming \( g_{\text{DM}} \sim 1 \)
Direct Detection Bounds on Higgs exchange

To be probed by the next generation of experiments
Expectations from the WIMP miracle III: W-boson exchange

Example:
Pure Wino Dark Matter

\[ \sigma_{\text{DM–nucleon}} \sim 10^{-47} \text{cm}^2 \]
Direct Detection Bounds on Higgs exchange

Hard to see even with the next generation experiments
Lessons from Direct Detection

• Coherent coupling to the Z excluded

• Higgs exchange to be probed by the next round of experiments

• WIMP Dark Matter could also be hard to see
LHC Expectations from the WIMP miracle

- If the DM annhilates to quarks it can also be produced by quarks!
Direct Detection vs the LHC

FIG. 6: Razor limits on spin-independent (LH plot) and spin-dependent (RH plot) DM-nucleon scattering compared to limits from the direct detection experiments. We also include the mono-jet limits and the combined razor/monojet limits. We show the constraints on spin-independent scattering from COUPP [39], DAMA [38], PICASSO [40], SIM-LE [41], and XENON-10 [42]. We have assumed large systematic uncertainties on the DAMA quenching factors: PLE [41], and XENON-10 [42].

In addition to the direct detection bounds, we can also convert the collider bounds into a constraint on spin-dependent scattering from CDMS [2], CoGeNT [36], CRESST [37], DAMA [38], and XENON-100 [3], and 1000 (15) for sodium and 1000 (14) for iodine [43], which gives 1000 (13) for O [44].

The annihilation rate is proportional to the quantity DM annihilation cross-section, which is relevant to DM relic density calculations and indirect energy required to create a pair of DM.

For CRESST, we show the 1 level. For DAMA and CoGeNT, we show the 90% and 3 level.

The relative velocity of the annihilating DM is the DM annihilation cross section, 

\[ \frac{1}{2} m \mathcal{O}_i(D) \mathcal{O}_j(D) (\bar{\chi}_i \gamma^\mu \chi_j)(\bar{q} \gamma_{\mu q}) \]

\[ \mathcal{O}_i(D) \mathcal{O}_j(D) \]

All limits are shown at the 90% confidence level.
Other Dark Matter Candidates

The QCD Axion

The Strong CP problem:
Why is the neutron dipole moment so small?

\[ L_{\text{SM}} \supset \frac{g_s^2}{32\pi^2} \theta_{\text{QCD}} G^a \tilde{G}^a \]

Expect \( \theta_{\text{QCD}} \) to be \( O(1) \) find \( \theta_{\text{QCD}} \) to be \( 10^{-10} \)

**Solution:** Make \( \theta_{\text{QCD}} \) a dynamical field, the axion

\[ m_a \sim \frac{\Lambda_{\text{QCD}}^2}{f_a} \sim 10^{-10} \text{eV} \quad \frac{10^{16} \text{GeV}}{f_a} \]

\( f_a \): axion decay constant
The Axion as Dark Matter

The cosmic oscillator

- Overdamped regime:
  Axion mass smaller than Hubble

- Oscillating regime:
  Axion mass larger than Hubble
  \[ \rho_{DM} \propto m_a^2 \times \text{amplitude}^2 \]

- Unknown initial amplitude:
  Non-calculable Dark Matter candidate
<table>
<thead>
<tr>
<th>WIMP</th>
<th>Axion</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Well motivated</td>
<td>• Well motivated</td>
</tr>
<tr>
<td>• Abundance calculable and correct if WIMP at the weak scale, as suggested by the hierarchy problem</td>
<td>• Abundance arbitrary</td>
</tr>
</tbody>
</table>
Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek

Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy (< 0.41 MeV) pp ν's from the sun. We propose new detectors for bolometric measurement of low-energy ν interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum of pp, 7Be, and 8B solar ν's, and supernovae anywhere in our galaxy (~ 10 tons of Si).

Also, some dark-halo candidates (e.g., photinos or scalar neutrinos) could produce measurable event rates even in kilogram-size detectors.
Thank you Blas!