Making and Detecting Supersymmetric Dark Matter

Manuel Drees

Bonn University
Contents

1 The need for DM
Contents

1 The need for DM
2 Supersymmetry
Contents

1 The need for DM
2 Supersymmetry
3 Making Supersymmetric Dark Matter
Contents

1 The need for DM
2 Supersymmetry
3 Making Supersymmetric Dark Matter
4 Detecting Supersymmetric Dark Matter
Contents

1 The need for DM
2 Supersymmetry
3 Making Supersymmetric Dark Matter
4 Detecting Supersymmetric Dark Matter
5 Summary
A typical spiral galaxy
Rotation curve

- Spiral galaxies rotate
- For object on stable circular orbit:

\[
\text{centripetal force} = \text{gravitational force} \\
\frac{v^2}{R} = G_N \frac{M(R)}{R^2}
\]

\(M(R)\): Mass w/in orbit

- For large \(R\): \(M(R) \rightarrow \text{const.}\), i.e. expect \(v(R) \propto 1/\sqrt{R}\)
- Observe: \(v(R) \simeq \text{const.}\)
- \(\Rightarrow M(R) \propto R\): Invisible, “Dark” Matter forms halo around visible galaxy
True picture of a galaxy
A typical galaxy cluster
Dark matter in clusters of galaxies

Virial theorem: \( \langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{pot}} \rangle \propto M_{\text{cluster}} \)

\[ \implies \text{total mass} > 10 \times \text{visible mass!} \]
Dark matter in clusters of galaxies

- Virial theorem: \( \langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{pot}} \rangle \propto M_{\text{cluster}} \)
  \[ \implies \text{total mass} > 10 \times \text{visible mass}! \]

- Similar argument holds for single atoms:
  Temperature of gas in cluster \( \propto M_{\text{cluster}}! \)
  Gives consistent result.
Virial theorem: \[ \langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{pot}} \rangle \propto M_{\text{cluster}} \]

\[ \implies \text{total mass} > 10 \times \text{visible mass}! \]

Similar argument holds for single atoms:
Temperature of gas in cluster \( \propto M_{\text{cluster}}! \)
Gives consistent result.

“Gravitational lensing”: Mass deflects light, by angle \( \propto \)
mass: Most direct way to measure
\[ M_{\text{cluster}} \geq 10 \times M_{\text{visible}}! \]
Same cluster in $X$–ray light
Example of gravitational lensing
Cosmic Microwave Background (CMB)

- Prediction: Gamov 1950; Discovery: Penzias und Wilson 1964
- Mean temperature: $2.7 \text{ K} \equiv -270^\circ \text{C}$
- Temperature variation: $\delta T \simeq 10^{-4} \text{ K}$
- From angular distribution and size of these variations: can determine cosmological parameters!
The Microwave Sky
Results of CMB Analysis

- Total mass $\sim 7 \times$ mass of “ordinary” (baryonic) matter
Results of CMB Analysis

- Total mass $\simeq 7 \times$ mass of “ordinary” (baryonic) matter
- Universe is flat (euclidian)
  $\implies$ total energy density $\simeq 3 \times$ mass density
Results of CMB Analysis

- Total mass $\simeq 7 \times$ mass of “ordinary” (baryonic) matter
- Universe is flat (euclidian)
  $\implies$ total energy density $\simeq 3 \times$ mass density
- About 2/3 of total mass/energy density in form of “Dark Energy”! Confirmed by observations of distant supernovae. Expansion of Universe is accelerating: Dark Energy has “negative pressure”!
Results of CMB Analysis

- Total mass $\simeq 7 \times$ mass of “ordinary” (baryonic) matter
- Universe is flat (euclidian)
  $\implies$ total energy density $\simeq 3 \times$ mass density
- About 2/3 of total mass/energy density in form of “Dark Energy”! Confirmed by observations of distant supernovae. Expansion of Universe is accelerating: Dark Energy has “negative pressure”!

Universal Dark Matter density: $\Omega_{DM} h^2 = 0.105^{+0.007}_{-0.013}$

Spergel et al., astro–ph/0603449
Composition of the Universe

- 70% Dark Energy
- 25% non-baryonic DM
- 4.2% unknown baryons
- 0.8% known baryons
In this room

1 ℓ contains:

- Ca. 1 g baryonic matter (air)
In this room

1 ℓ contains:

- Ca. 1 g baryonic matter (air)
- Ca. $10^{-20}$ g Dark Matter (DM)
In this room

1 ℓ contains:

- Ca. 1 g baryonic matter (air)
- Ca. $10^{-20}$ g Dark Matter (DM)
- Ca. $10^{-25}$ g–equivalent Dark Energy (DE)
Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis
Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis
- Analyses of CMB data
Total baryon density is determined by:

- Big Bang Nucleosynthesis
- Analyses of CMB data

Consistent result: $\Omega_{\text{bar}} h^2 \approx 0.02$
Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis
- Analyses of CMB data

Consistent result: $\Omega_{\text{bar}} h^2 \simeq 0.02$

$\implies$ Need non–baryonic DM!
Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!
Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!

Make hot DM: do not describe structure formation correctly

\[ \Omega_\nu h^2 \lesssim 0.01 \]
Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!

Make hot DM: do not describe structure formation correctly

\[ \Omega_\nu h^2 \lesssim 0.01 \]

\[ \rightarrow \quad \text{Need exotic particles as DM!} \]
Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!

Make hot DM: do not describe structure formation correctly

\[ \Omega_\nu h^2 \lesssim 0.01 \]

\[ \Rightarrow \text{Need exotic particles as DM!} \]

Possible loophole: primordial black holes; not easy to make in sufficient quantity sufficiently early.
What we need

Since $h^2 \approx 0.5$: Need $\sim 20\%$ of critical density in

- **Matter** (with negligible pressure, $w \approx 0$)
What we need

Since $h^2 \approx 0.5$: Need $\sim 20\%$ of critical density in

- Matter (with negligible pressure, $w \approx 0$)
- which still survives today (lifetime $\tau \gg 10^{10}$ yrs)
What we need

Since \( h^2 \simeq 0.5 \): Need \( \sim 20\% \) of critical density in

- Matter (with negligible pressure, \( w \simeq 0 \))
- which still survives today (lifetime \( \tau \gg 10^{10} \) yrs)
- and has (strongly) suppressed coupling to elm radiation
Remarks

Precise “WMAP” determination of DM density hinges on assumption of “standard cosmology”, including assumption of nearly scale–invariant primordial spectrum of density perturbations: almost assumes inflation!
Remarks

- Precise “WMAP” determination of DM density hinges on assumption of “standard cosmology”, including assumption of nearly scale–invariant primordial spectrum of density perturbations: almost assumes inflation!

- Evidence for $\Omega_{DM} \gtrsim 0.2$ much more robust than that! (Does, however, assume standard law of gravitation.)
Possible problems with cold DM

Simulations of structure formation show some discrepancies with observations on (sub–)galactic length scales:

- **Too many sub–halos are predicted:** Might well be “dark dwarves” (w/o baryons; perhaps blown out by first supernovae)
Possible problems with cold DM

Simulations of structure formation show some discrepancies with observations on (sub–)galactic length scales:

- Too many sub–halos are predicted: Might well be “dark dwarves” (w/o baryons; perhaps blown out by first supernovae)
- Simulations seem to over–predict DM density near centers of galaxies (“cusp problem”). Warning: many things going on in these regions!
DM is collisionsless!

Observation of merging cluster 1E0657-56 ("bullet cluster"):  
- Using X-rays (CHANDRA): observes hot (baryonic) gas
DM is collisionsless!

Observation of merging cluster 1E0657-56 (“bullet cluster”):

- Using X–rays (CHANDRA): observes hot (baryonic) gas
- Using gravitational lensing: observes mass
DM is collisionsless!

Observation of merging cluster 1E0657-56 (“bullet cluster”):

- Using X–rays (CHANDRA): observes hot (baryonic) gas
- Using gravitational lensing: observes mass

Result: Collision shock slows down the (ionized) gas, but not the Dark Matter
DM is collisionsless!

Observation of merging cluster 1E0657-56 (“bullet cluster”):

- Using X–rays (CHANDRA): observes hot (baryonic) gas
- Using gravitational lensing: observes mass

Result: Collision shock slows down the (ionized) gas, but not the Dark Matter

Resulting bound on DM–DM scattering cross section constrains models of interacting DM! Markevitch et al., astro–ph/0309303
Bullet cluster
The Standard Model of Particle Physics

Basic ingredients:

- Matter particles: Spin–1/2 fermions (quarks and leptons)
Basic ingredients:

- Matter particles: Spin–1/2 fermions (quarks and leptons)
- Interactions determined by demanding invariance of $\mathcal{L}$ under $SU(3) \times SU(2) \times U(1)_Y$ transformations
Basic ingredients:

- **Matter particles**: Spin–1/2 fermions (quarks and leptons)
- **Interactions determined by demanding invariance of $\mathcal{L}$ under $SU(3) \times SU(2) \times U(1)_Y$ transformations $\Rightarrow$
- **Force carriers**: Spin–1 bosons (gluons, photon, $W^\pm$, $Z^0$)
The Standard Model of Particle Physics

Basic ingredients:

- **Matter particles**: Spin–1/2 fermions (quarks and leptons)

- **Interactions determined by demanding invariance of $\mathcal{L}$ under $SU(3) \times SU(2) \times U(1)_Y$ transformations $\implies$**

- **Force carriers**: Spin–1 bosons (gluons, photon, $W^\pm$, $Z^0$)

- $SU(2) \times U(1)$ invariance forbids all particle masses $\implies$
The Standard Model of Particle Physics

Basic ingredients:

- **Matter particles**: Spin–1/2 fermions (quarks and leptons)

- **Interactions determined by demanding invariance of** $\mathcal{L}$ under $SU(3) \times SU(2) \times U(1)_Y$ transformations $\implies$

- **Force carriers**: Spin–1 bosons (gluons, photon, $W^\pm$, $Z^0$)

- $SU(2) \times U(1)$ invariance forbids all particle masses $\implies$

- **Need Higgs mechanism for spontaneous symmetry breaking; requires elementary spin–0 Higgs boson(s)**

Dark Matter – p. 22/44
The naturalness/hierarchy problem

Standard Problem of Standard Model of particle physics: corrections to Higgs boson mass diverge quadratically!

\[ \delta m_{\phi,t}^2 = \frac{3f_t^2}{8\pi^2} \Lambda^2 + O(\Lambda/m_\phi) \]

\( \Lambda \): cut–off for momentum in loop.
The naturalness/hierarchy problem

Standard Problem of Standard Model of particle physics: corrections to Higgs boson mass diverge quadratically!

\[
\begin{align*}
\delta m_{\phi,t}^2 &= \frac{3f_t^2}{8\pi^2} \Lambda^2 + O(\Lambda/m_\phi) \\
\Lambda &: \text{ cut–off for momentum in loop.} \\
m_\phi &: \text{ Likes to be at highest relevant mass scale, e.g.} \\
M_{\text{GUT}} &\sim 10^{16} \text{ GeV, } M_{\text{Planck}} \sim 10^{18} \text{ GeV!}
\end{align*}
\]
The naturalness/hierarchy problem

Standard Problem of Standard Model of particle physics: corrections to Higgs boson mass diverge quadratically!

\[ \delta m^2_{\phi,t} = \frac{3f_t^2}{8\pi^2} \Lambda^2 + \mathcal{O}(\Lambda/m_\phi) \]

\( \Lambda \): cut–off for momentum in loop.

\( m_\phi \) Likes to be at *highest* relevant mass scale, e.g.

\[ M_{\text{GUT}} \sim 10^{16} \text{ GeV}, \quad M_{\text{Planck}} \sim 10^{18} \text{ GeV}! \]

If \( m^2_{\phi,\text{phys.}} = m^2_{\phi,0} + \delta m^2_{\phi} \approx (100 \text{ GeV})^2 \): Need to finetune \( m^2_{\phi,0} \) to 1 part in \( 10^{30} \)!
Quantum corrections to gauge or Yukawa couplings at worst diverge logarithmically: not so bad even for $\Lambda = M_{\text{Planck}}$. 
Nature abhors finetuning

- Quantum corrections to gauge or Yukawa couplings at worst diverge logarithmically: not so bad even for $\Lambda = M_{\text{Planck}}$.

- Standard cosmology has “flatness problem”:
  \[ \Omega_{\text{BBN}} - 1 \simeq 10^{-16} (\Omega_{\text{now}} - 1) \]
  Here: $\Omega = \rho/\rho_{\text{crit}}$; $\Omega = 1$ means flat Universe.
  Is solved by inflation, which predicts:
  - $\Omega_{\text{now}} \simeq 1$
  - Approximately scale invariant spectrum of density perturbations
  Both predictions were confirmed by WMAP!
Supersymmetry solves finetuning problem

Postulate symmetry between bosons and fermions:
\[
\text{boson} \rightarrow \text{fermion, fermion} \rightarrow \text{boson}
\]
This is called a supersymmetry to distinguish it from the usual (gauge) symmetries.
Supersymmetry solves finetuning problem

Postulate symmetry between bosons and fermions:

\[
\text{boson} \rightarrow \text{fermion}, \quad \text{fermion} \rightarrow \text{boson}
\]

This is called a **supersymmetry** to distinguish it from the usual (gauge) symmetries.

Requires doubling of particle spectrum: each known particle gets superpartner!
Supersymmetry solves finetuning problem

Postulate symmetry between bosons and fermions:
\[ \text{boson} \rightarrow \text{fermion, fermion} \rightarrow \text{boson} \]
This is called a **supersymmetry** to distinguish it from the usual (gauge) symmetries.

Requires doubling of particle spectrum: each known particle gets superpartner!

**In particular:** higgsino \( \tilde{h} \) is superpartner of Higgs boson \( \phi \).
Supersymmetry solves finetuning problem

Postulate symmetry between bosons and fermions:

\[ \text{boson} \rightarrow \text{fermion}, \quad \text{fermion} \rightarrow \text{boson} \]

This is called a \textit{supersymmetry} to distinguish it from the usual (gauge) symmetries.

Requires doubling of particle spectrum: each known particle gets superpartner!

In particular: higgsino $\tilde{h}$ is superpartner of Higgs boson $\phi$.

Quantum corrections:

\[ \delta m_\phi^{\text{SUSY}} = \delta m_{\tilde{h}} \propto \ln \frac{\Lambda}{m_\phi} \]

No quadratic divergencies!
Diagrammatically: each chirality state of $t$ quark has scalar superpartner $\tilde{t}_L, \tilde{t}_R$: get new corrections:
Diagrammatically: each chirality state of $t$ quark has scalar superpartner $\tilde{t}_L, \tilde{t}_R$: get new corrections:

$$\delta m^2_{\phi, \tilde{t}} = -\frac{3f_t^2}{8\pi^2} \Lambda^2 + \cdots = -\delta m^2_{\phi, t} + \mathcal{O} \left( [m_t^2 - m_{\tilde{t}}^2] \ln \frac{\Lambda}{m_t} \right)$$

Quadratic divergencies cancel exactly!
Other arguments for Supersymmetry

- Biggest possible symmetry of interacting QFT:
  (Lorentz symmetry) $\otimes$ (gauge symmetry) $\otimes$ Supersymmetry

HLS theorem
Other arguments for Supersymmetry

- Biggest possible symmetry of interacting QFT:
  (Lorentz symmetry) $\otimes$ (gauge symmetry) $\otimes$ Supersymmetry !
  HLS theorem

- Local supersymmetry invariance implies invariance under coordinate trasfos, i.e. GR: local SUSY $\equiv$ SUGRA
Other arguments for Supersymmetry

- Biggest possible symmetry of interacting QFT: (Lorentz symmetry) $\otimes$ (gauge symmetry) $\otimes$ Supersymmetry
  HLS theorem

- Local supersymmetry invariance implies invariance under coordinate trafo$s$, i.e. GR: local SUSY $\equiv$ SUGRA

- New particles automatically lead to unification of gauge couplings at scale $M_{\text{GUT}} \approx 2 \cdot 10^{16}$ GeV.
Other arguments for Supersymmetry

- Biggest possible symmetry of interacting QFT: (Lorentz symmetry) \(\otimes\) (gauge symmetry) \(\otimes\) Supersymmetry!
  HLS theorem

- Local supersymmetry invariance implies invariance under coordinate trasfos, i.e. GR: local SUSY \(\equiv\) SUGRA

- New particles \textit{automatically} lead to unification of gauge couplings at scale \(M_{\text{GUT}} \approx 2 \cdot 10^{16}\) GeV.

- \textit{Automatically} contains good Dark Matter candidate (see below).
Interactions of superparticles

Are largely determined by supersymmetry!

\[ \gamma eQ_f \rightarrow f \], \[ \gamma \rightarrow f \bar{f} \], \[ \phi f_f \rightarrow f \bar{f} \], \[ \phi \rightarrow f_f \bar{f} \], \[ \phi \rightarrow f_f^2 \bar{f} \]
Interactions of superparticles

Are largely determined by supersymmetry!

Note: Even number of superpartners at each vertex ⇒ the lightest superparticle (LSP) is stable!
Breaking supersymmetry

Exact SUSY predicts $m_{\text{particle}} = m_{\text{sparticle}} \Rightarrow \text{SUSY must be broken!}$
Breaking supersymmetry

Exact SUSY predicts $m_{\text{particle}} = m_{\text{sparticle}} \Rightarrow$ SUSY must be broken!

Two basic approaches:
- Postulate simple form of supersymmetry breaking at some high energy scale: Good for global analyses
Breaking supersymmetry

Exact SUSY predicts $m_{\text{particle}} = m_{\text{sparticle}} \implies$ SUSY must be broken!

Two basic approaches:

- Postulate simple form of supersymmetry breaking at some high energy scale: Good for global analyses

- Allow general values for parameters relevant for specific process: Good for dedicated phenomenological analyses
LSP $\tilde{\chi}_1^0$ has all properties of good DM candidate:
Supersymmetric Dark Matter

LSP $\tilde{\chi}_1^0$ has all properties of good DM candidate:

- It is neutral, hence dark (and evades constraints on exotic isotopes)
Supersymmetric Dark Matter

LSP $\tilde{\chi}_1^0$ has all properties of good DM candidate:

- It is **neutral**, hence dark (and evades constraints on exotic isotopes)
- It is **stable** (in simple SUSY models, with conserved $R$ parity)
Supersymmetric Dark Matter

LSP $\tilde{\chi}_1^0$ has all properties of good DM candidate:

- It is neutral, hence dark (and evades constraints on exotic isotopes)
- It is stable (in simple SUSY models, with conserved $R$ parity)
- It has the right (thermal) relic density for some range of model parameters
Supersymmetric Dark Matter

LSP $\tilde{\chi}_1^0$ has all properties of good DM candidate:

- It is neutral, hence dark (and evades constraints on exotic isotopes)
- It is stable (in simple SUSY models, with conserved $R$ parity)
- It has the right (thermal) relic density for some range of model parameters

Note: DM is free bonus of Supersymmetry!
Let $\tilde{\chi}$ be the LSP, $n_{\tilde{\chi}}$ its number density (unit: GeV$^3$).
Let $\tilde{\chi}$ be the LSP, $n_{\tilde{\chi}}$ its number density (unit: GeV$^3$).

Evolution of $n_{\tilde{\chi}}$ determined by Boltzmann equation:

$$\frac{dn_{\tilde{\chi}}}{dt} + 3Hn_{\tilde{\chi}} = -\langle \sigma_{\text{ann}} v \rangle \left( n_{\tilde{\chi}}^2 - n_{\tilde{\chi}, \text{eq}}^2 \right)$$

$H = \dot{R}/R$ : Hubble parameter
$\langle \ldots \rangle$ : Thermal averaging
$\sigma_{\text{ann}} = \sigma(\tilde{\chi}\tilde{\chi} \rightarrow \text{SM particles})$
$v$ : relative velocity between $\tilde{\chi}$’s in their cms
$n_{\tilde{\chi}, \text{eq}}$ : $\tilde{\chi}$ density in full equilibrium
Thermal LSP Dark Matter

Assume $\tilde{\chi}$ was in full thermal equilibrium after inflation.
Assume $\tilde{\chi}$ was in full thermal equilibrium after inflation.

Requires

$$n_{\tilde{\chi}} \langle \sigma_{\text{ann}} v \rangle > H$$
Assume $\tilde{\chi}$ was in full thermal equilibrium after inflation.

Requires

$$n_{\tilde{\chi}}\langle\sigma_{\text{ann}}v\rangle > H$$

For $T < m_{\tilde{\chi}}$: $n_{\tilde{\chi}} \simeq n_{\tilde{\chi},\text{eq}} \propto T^{3/2}e^{-m_{\tilde{\chi}}/T}$, $H \propto T^2$
Assume \( \tilde{\chi} \) was in full thermal equilibrium after inflation.

Requires

\[
n_{\tilde{\chi}} \langle \sigma_{\text{ann}} v \rangle > H
\]

For \( T < m_{\tilde{\chi}} \): \( n_{\tilde{\chi}} \simeq n_{\tilde{\chi}, \text{eq}} \propto T^{3/2} e^{-m_{\tilde{\chi}}/T} \), \( H \propto T^2 \)

Inequality cannot be true for arbitrarily small \( T \); point where inequality becomes (approximate) equality defines decoupling (freeze–out) temperature \( T_F \).
Thermal LSP Dark Matter

Assume $\tilde{\chi}$ was in full thermal equilibrium after inflation.

Requires

$$n_{\tilde{\chi}} \langle \sigma_{\text{ann}} v \rangle > H$$

For $T < m_{\tilde{\chi}}$: $n_{\tilde{\chi}} \simeq n_{\tilde{\chi}}^\text{eq} \propto T^{3/2} e^{-m_{\tilde{\chi}}/T}$, $H \propto T^2$

Inequality cannot be true for arbitrarily small $T$; point where inequality becomes (approximate) equality defines decoupling (freeze–out) temperature $T_F$.

For $T < T_F$: LSP production negligible, only annihilation relevant in Boltzmann equation.
Assume \( \tilde{\chi} \) was in full thermal equilibrium after inflation.

Requires

\[ n_{\tilde{\chi}} \langle \sigma_{\text{ann}} v \rangle > H \]

For \( T < m_{\tilde{\chi}} \):

\[ n_{\tilde{\chi}} \simeq n_{\tilde{\chi}, \text{eq}} \propto T^{3/2} e^{-m_{\tilde{\chi}}/T}, \quad H \propto T^2 \]

Inequality cannot be true for arbitrarily small \( T \); point where inequality becomes (approximate) equality defines decoupling (freeze–out) temperature \( T_F \).

For \( T < T_F \): LSP production negligible, only annihilation relevant in Boltzmann equation.

Gives

\[ \Omega_{\tilde{\chi}} h^2 \propto \frac{1}{\langle v \sigma_{\text{ann}} \rangle} \sim 0.1 \text{ for } \sigma_{\text{ann}} \sim \text{pb} \]
Here: for mSUGRA $\equiv$ CMSSM: define spectrum through:
- $m_0$: Common scalar mass at GUT scale;
- $m_{1/2}$: Common gaugino mass at GUT scale;
- $A_0$: Common tri–linear scalar interaction at GUT scale;
- $\tan \beta$: Ratio of Higgs vevs; $\text{sign} \mu$.

Advantages of mSUGRA:

- FCNC small (but $b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$ do constrain parameter space)
Here: for \( \text{mSUGRA} \equiv \text{CMSSM} \): define spectrum through:

- \( m_0 \): Common scalar mass at GUT scale;
- \( m_{1/2} \): Common gaugino mass at GUT scale;
- \( A_0 \): Common tri-linear scalar interaction at GUT scale;
- \( \tan \beta \): Ratio of Higgs vevs; \( \text{sign} \mu \).

Advantages of mSUGRA:

- FCNC small (but \( b \rightarrow s\gamma \), \( B_s \rightarrow \mu^+ \mu^- \) do constrain parameter space)
- Radiative symmetry breaking: loop corrections drive (combination of) squared Higgs masses negative, leaving squared sfermion masses positive
Application: Constraining SUSY Parameter Space

Here: for mSUGRA $\equiv$ CMSSM: define spectrum through:

- $m_0$: Common scalar mass at GUT scale;
- $m_{1/2}$: Common gaugino mass at GUT scale;
- $A_0$: Common tri-linear scalar interaction at GUT scale;
- $\tan \beta$: Ratio of Higgs vevs; sign$\mu$.

Advantages of mSUGRA:

- FCNC small (but $b \to s\gamma$, $B_s \to \mu^+\mu^-$ do constrain parameter space)
- Radiative symmetry breaking: loop corrections drive (combination of) squared Higgs masses negative, leaving squared sfermion masses positive
- Over much of parameter space, $\tilde{\chi}^0_1$ is stable LSP!
**Example:** \( m_t = 172.7 \text{ GeV}, \tan \beta = 10, A_0 = 0, \mu > 0 \)

(Djouadi, MD, Kneur, hep-ph/0602001)

- **Green:** \( b \to s\gamma \) excluded
- **Pink:** Higgs search excl.
- **Magenta:** \( 111 \text{ GeV} \leq m_h \leq 114 \text{ GeV} \)
- **Red:** \( 114 \text{ GeV} \leq m_h \leq 117 \text{ GeV} \)
- **Dark grey:** \( m_{\tilde{\tau}_1} < m_{\tilde{\chi}^0_1} \)
- **Light grey:** \( |\mu|^2 < 0 \) or sparticle search excl.
- **Black:** DM favored
Is the apparently small size of the allowed parameter space a problem? Not necessarily . . .
Mass Bounds

More meaningful than “size of allowed parameter space”
mSUGRA, all parameters scanned over allowed region

<table>
<thead>
<tr>
<th>particle</th>
<th>minimal mass [GeV]</th>
<th>min, max mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>basic</td>
<td>incl. ( b \rightarrow s\gamma )</td>
</tr>
<tr>
<td>( \tilde{\chi}^0_1 )</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>( \tilde{\chi}^{\pm}_1 )</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>( \tilde{\chi}^0_3 )</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>( \tilde{\tau}_1 )</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>( h )</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>( H^{\pm} )</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>( \tilde{g} )</td>
<td>359</td>
<td>380</td>
</tr>
<tr>
<td>( \tilde{d}_R )</td>
<td>406</td>
<td>498</td>
</tr>
<tr>
<td>( \tilde{t}_1 )</td>
<td>102</td>
<td>104</td>
</tr>
</tbody>
</table>
Found semi–analytic solution of Boltzmann eq. for low post–inflationary reheat temperature, $T_R \lesssim T_F$. MD, Immnniyaz, Kakizaki, hep-ph/0603165
Low Temperature Scenarios

Found semi–analytic solution of Boltzmann eq. for low post–inflationary reheat temperature, $T_R \lesssim T_F$. MD, Imminniyaz, Kakizaki, hep-ph/0603165

Assuming purely thermal LSP production: $(x_0 = m_{\tilde{\chi}}/T_R)$
Low Temperature Scenarios

Found semi–analytic solution of Boltzmann eq. for low post–inflationary reheat temperature, $T_R \lesssim T_F$. MD, Imminniyaz, Kakizaki, hep-ph/0603165

Assuming purely thermal LSP production: $(x_0 = m_{\tilde{\chi}}/T_R)$
Found semi–analytic solution of Boltzmann eq. for low post–inflationary reheat temperature, $T_R \lesssim T_F$. MD, Imminniyaz, Kakizaki, hep-ph/0603165

**Assuming purely thermal LSP production:** $\left(x_0 = \frac{m_{\tilde{\chi}}}{T_R}\right)$

Holds independently of $\sigma_{\text{ann}}$!
Dark Matter detection 1: “Indirect”

- LSPs are everywhere!
Dark Matter detection 1: ‘Indirect’

- LSPs are everywhere!
- In regions with increased LSP density: LSPs can annihilate into SM particles even today:
Dark Matter detection 1: “Indirect”

- LSPs are everywhere!
- In regions with increased LSP density: LSPs can annihilate into SM particles even today:
  - In halo of galaxies
Dark Matter detection 1: “Indirect”

- LSPs are everywhere!
- In regions with increased LSP density: LSPs can annihilate into SM particles even today:
  - In halo of galaxies
  - Near center of galaxies
Dark Matter detection 1: “Indirect”

- LSPs are everywhere!
- In regions with increased LSP density: LSPs can annihilate into SM particles even today:
  - In halo of galaxies
  - Near center of galaxies
  - Inside the Sun or Earth
Indirect Dark Matter detection: signals

- Slow $\bar{p}$, fast $e^+$: background? Propagation?
Indirect Dark Matter detection: signals

- Slow $\bar{p}$, fast $e^+$: background? Propagation?
- Slow $\bar{d}$: Propagation?
Indirect Dark Matter detection: signals

- Slow $\bar{p}$, fast $e^+$: background? Propagation?
- Slow $\bar{d}$: Propagation?
- Photons: Background?
Indirect Dark Matter detection: signals

- Slow \( \bar{p} \), fast \( e^+ \): background? Propagation?
- Slow \( \bar{d} \): Propagation?
- Photons: Background?
- GeV Neutrinos: Low rate
Indirect Dark Matter detection: signals

- Slow $\bar{p}$, fast $e^+$: background? Propagation?
- Slow $\bar{d}$: Propagation?
- Photons: Background?
- GeV Neutrinos: Low rate

At any given time, several claimed signals, but none is very reliable.
Dark Matter detection 2: “Direct”

- LSPs are everywhere!
LSPs are everywhere!

Can elastically scatter on nucleus in detector:

\[ \tilde{\chi} + N \rightarrow \tilde{\chi} + N \]

Measured quantity: recoil energy of \( N \)
Dark Matter detection 2: “Direct”

- LSPs are everywhere!
- Can elastically scatter on nucleus in detector:
  \[ \tilde{\chi} + N \rightarrow \tilde{\chi} + N \]
  Measured quantity: recoil energy of \( N \)
- Detection needs ultrapure materials in deep–underground location; way to distinguish recoils from \( \beta, \gamma \) events; neutron screening; . . .
LSPs are everywhere!

Can elastically scatter on nucleus in detector:

\[ \tilde{\chi} + N \rightarrow \tilde{\chi} + N \]

Measured quantity: recoil energy of \( N \)

Detection needs ultrapure materials in deep–underground location; way to distinguish recoils from \( \beta, \gamma \) events; neutron screening; \ldots

Is being pursued vigorously around the world!
Direct WIMP detection: theory

Counting rate given by

\[
\frac{dR}{dQ} = A F^2(Q) \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{f_1(v)}{v} dv
\]

\(Q\): recoil energy

\(A = \rho \sigma_0 / (2m_\chi m_r) = \text{const.}\)

\(F(Q)\): nuclear form factor

\(v\): WIMP velocity in lab frame

\(v_{\text{min}}^2 = m_N Q / (2m_r^2)\)

\(v_{\text{esc}}\): Escape velocity from galaxy

\(f_1(v)\): normalized one–dimensional WIMP velocity distribution
Direct WIMP detection: theory

Counting rate given by
\[ \frac{dR}{dQ} = AF^2(Q) \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{f_1(v)}{v} dv \]

- \( Q \): recoil energy
- \( A = \frac{\rho \sigma_0}{(2m_\chi m_r)} = \text{const.} \)
- \( F(Q) \): nuclear form factor
- \( v \): WIMP velocity in lab frame
- \( v_{\text{min}}^2 = \frac{m_N Q}{2m_r^2} \)
- \( v_{\text{esc}} \): Escape velocity from galaxy
- \( f_1(v) \): normalized one–dimensional WIMP velocity distribution

In principle, can invert this relation to measure \( f_1(v) \)!
Recoil spectrum: prediction and simulated measurement
MD, Shan, in progress

500 events on Ge

$Q$ [keV]

$dR/dQ$ [arb. units]

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$
$f_1(v)$: prediction and simulated measurement

500 events on Ge: stat. error only
A few moments of $f_1(v)$ may be measurable with relatively few events
A few moments of $f_1(v)$ may be measurable with relatively few events.

Once $f_1(v)$ and $\sigma(\tilde{\chi}N \rightarrow \tilde{\chi}N)$ are known: Can measure local $\rho\tilde{\chi}$.  

$f_1(v)$: prediction and simulated measurement
Summary

- Compelling astrophysical evidence for exotic Dark Matter
Summary

- Compelling astrophysical evidence for exotic Dark Matter
- Neutralinos in mSUGRA remain well motivated, viable candidate
Summary

- Compelling astrophysical evidence for exotic Dark Matter
- Neutralinos in mSUGRA remain well motivated, viable candidate
- Thermal production of DM particles remains most attractive mechanism: least dependent on details of cosmology
Summary

- Compelling astrophysical evidence for exotic Dark Matter
- Neutralinos in mSUGRA remain well motivated, viable candidate
- Thermal production of DM particles remains most attractive mechanism: least dependent on details of cosmology
- If DM is made from thermal LSPs: lower bound on $T_R$ increases by factor $\sim 10^4$
Summary

- Compelling astrophysical evidence for exotic Dark Matter
- Neutralinos in mSUGRA remain well motivated, viable candidate
- Thermal production of DM particles remains most attractive mechanism: least dependent on details of cosmology
- If DM is made from thermal LSPs: lower bound on $T_R$ increases by factor $\sim 10^4$
- LSP Dark Matter can be detected in a variety of ways; once detected, allows new probes of Universe