Making and Detecting Dark Matter Particles

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Contents

1 Introduction: The need for DM
Contents

1 Introduction: The need for DM
2 “Sterile” neutrinos
Contents

1 Introduction: The need for DM
2 “Sterile” neutrinos
3 Super-/E–Wimps
Contents

1 Introduction: The need for DM
2 “Sterile” neutrinos
3 Super–/E–Wimps
4 WIMPs
Contents

1 Introduction: The need for DM
2 “Sterile” neutrinos
3 Super–/E–Wimps
4 WIMPs
5 MeV Dark Matter
1 Introduction: The need for DM
2 “Sterile” neutrinos
3 Super-/E–Wimps
4 WIMPs
5 MeV Dark Matter
6 Summary
Introduction: the need for Dark Matter

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$\Omega$: Mass density in units of critical density; $\Omega = 1$ means flat Universe.

$h$: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$ (?)
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- Models of structure formation, X-ray temperature of clusters of galaxies, . . .

- Cosmic Microwave Background anisotropies (WMAP) imply $\Omega_{DM} h^2 = 0.105^{+0.007}_{-0.013}$

Spergel et al., astro-ph/0603449
Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis → talk by K. Olive
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$\implies$ Need non–baryonic DM!
Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!
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Make hot DM: do not describe structure formation correctly

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$\Rightarrow$ Need exotic particles as DM!
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Make hot DM: do not describe structure formation correctly
\[ \Omega_\nu h^2 \lesssim 0.01 \]

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

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

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- 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
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)
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- 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!
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Observation of merging cluster 1E0657-56 ("bullet cluster"):  
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Resulting bound on DM–DM scattering cross section constrains models of interacting DM! Markevitch et al., astro–ph/0309303
Bullet cluster
Sterile keV neutrinos

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- Are unstable!
Decays of “sterile” neutrinos

\[ \Gamma(\nu_s) = \frac{G_F m_s^5}{192\pi^3} \sin^2 \theta \]

\[ B(\nu_s \rightarrow \gamma \nu_i) \approx 1\% \]
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\[ \nu_i + f \rightarrow \nu_s + f ; \quad \nu_i + f \rightarrow \nu_s + f' \]
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Right diagram gives only way to detect \( \nu_s \): monochromatic (X–ray) photon at \( E_\gamma = m_{\nu_s}/2 \).
Standard sterile neutrinos are excluded!

Viel et al., astro-ph/0605706
Standard sterile neutrinos are excluded!

Loophole: Use non–standard production mechanism: large lepton asymmetry ($\Delta L \sim 0.1$), $\nu_s$ coupling to inflaton, . . .
Super-/E-WIMPs

Are massive particles whose interactions with ordinary matter are much weaker than weak.

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  - Thermal production: E.g.  $g + g \rightarrow \tilde{g} + (\tilde{G} \text{ or } \tilde{a})$:
    $$\Omega_{\tilde{G}} h^2 \simeq 0.1 \left( \frac{M_{\tilde{g}}}{1 \text{ TeV}} \right)^2 \frac{1 \text{ GeV}}{m_{\tilde{G}}} \frac{T_R}{2.4 \times 10^7 \text{ GeV}}$$
    $T_R$ : re–heat temperature of Universe
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    \]
    
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  - From NLSP decay: E.g. \( \tilde{\tau}_1 \rightarrow \tau + \tilde{G} \text{ or } \tilde{a} \):
    \[
    \Omega_{\tilde{G} \text{ or } \tilde{a}} h^2 = \tilde{\Omega}_{\text{NLSP}} h^2 \frac{m_{\tilde{G} \text{ or } \tilde{a}}}{m_{\text{NLSP}}}
    \]
Super–/E–WIMPs (cont.d)

Can make SUSY scenarios giving $\Omega_{\tilde{\chi}_1^0}h^2 \gg 0.1$ DM safe, by setting $m_{\tilde{G}}$ or $\tilde{a} = \frac{m_{\tilde{\chi}_1^0}}{\Omega_{\tilde{\chi}_1^0}h^2} m_{\tilde{\chi}_1^0}$, and low $T_R$. 
Can make SUSY scenarios giving $\Omega_{\tilde{\chi}_1^{0} = \text{LSP}} h^2 \gg 0.1$ DM safe, by setting $m_{\tilde{G}}$ or $\tilde{a} = \frac{0.1}{\Omega_{\tilde{\chi}_1^{0} h^2} m_{\tilde{\chi}_1^{0}}}$, and low $T_R$

NLSP $\rightarrow (\tilde{G} \text{ or } \tilde{a}) + X$ decays tend to mess up BBN: nearly as problematic as inverse decays
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- DM Super–/E–WIMPs cannot be detected

- Allow charged NLSP, e.g. $\tilde{\tau}_1$. In this case, scenario might be testable if NLSP is sufficiently long–lived, by collecting NLSPs produced at colliders and carefully measuring their decays. Hamaguchi et al., hep-ph/0409248; Feng & Smith, hep-ph/0409278; Brandenbyrg et al., hep-ph/0501287; Baltz et al., hep-ph/0602187. However, BBN?? (→ talk Olive)
WIMPs

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- Roughly weak interactions may allow both direct and indirect detection of WIMPs
Let $\chi$ be a generic DM particle, $n_\chi$ its number density (unit: GeV$^3$). Assume $\chi = \bar{\chi}$, i.e. $\chi\chi \leftrightarrow$ SM particles is possible, but single production of $\chi$ is forbidden by some symmetry.
WIMP production

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Evolution of $n_\chi$ determined by Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\text{ann}}v \rangle (n^2_\chi - n^2_{\chi,\text{eq}}) + \sum_{X,Y} n_X \Gamma(X \rightarrow \chi + Y)$$

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

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For $T < m_\chi$: $n_\chi \approx n_{\chi, \text{eq}} \propto T^{3/2} e^{-m_\chi/T}$, $H \propto T^2$
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Inequality cannot be true for arbitrarily small $T$; point where inequality becomes (approximate) equality defines decoupling (freeze–out) temperature $T_F$. 
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Gives

$$\Omega_{\chi} h^2 \propto \frac{1}{\langle v \sigma_{\text{ann}} \rangle} \sim 0.1 \text{ for } \sigma_{\text{ann}} \sim \text{pb}$$
Thermal WIMPs: Assumptions

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- No entropy production after $\chi$ decoupled: Not testable at colliders
- $H$ at time of $\chi$ decoupling is known: partly testable at colliders
- Universe must have been sufficiently hot: $T_R > T_F \simeq m_\chi/20$
Low temperature scenario

Assume $T_R \lesssim T_F$, $n_\chi(T_R) = 0$
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Introduce dimensionless variables

$$Y_\chi \equiv \frac{n_\chi}{s}, \quad x \equiv \frac{m_\chi}{T}$$

($s$: entropy density).

Use non–relativistic expansion of cross section:

$$\sigma_{\text{ann}} = a + bv^2 + \mathcal{O}(v^4) \implies \langle \sigma_{\text{ann}} v \rangle = a + \frac{6b}{x}$$
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Using explicit form of $H$, $Y_\chi,_{eq}$, Boltzmann eq. becomes

$$\frac{dY_\chi}{dx} = -f \left( a + \frac{6b}{x} \right) x^{-2} \left( Y_\chi^2 - cx^3 e^{-2x} \right) .$$

$$f = 1.32 \ m_\chi M_{\text{Pl}} \sqrt{g_*}, \quad c = 0.0210 \ g_\chi^2/g_*^2$$
For $T_R \ll T_F$: Annihilation term $\propto Y^2$ negligible: defines 0–th order solution $Y_0(x)$, with
\[ Y_0(x \to \infty) = f c \left[ \frac{a}{2} x_R e^{-2x_R} + \left( \frac{a}{4} + 3b \right) e^{-2x_R} \right]. \]
Note: $\Omega_\chi h^2 \propto \sigma_{\text{ann}}$ in this case!
Low temperature scenario (cont.’d)

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For intermediate temperatures, $T_R \lesssim T_F$: Define 1st-order solution $Y_1 = Y_0 + \delta$.

$\delta < 0$ describes pure annihilation:

$$\frac{d\delta}{dx} = -f \left( a + \frac{6b}{x} \right) \frac{Y_0(x)^2}{x^2}.$$

$\delta(x)$ can be calculated analytically: $\delta \propto \sigma_{\text{ann}}^3$.
Low temperature scenario (cont.’d)

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Get good results for $\Omega_\chi h^2$ for all $T_R \leq T_F$ through “resummation”:

$$Y_1 = Y_0 \left( 1 + \frac{\delta}{Y_0} \right) \simeq \frac{Y_0}{1 - \delta/Y_0} \equiv Y_{1,r}$$

$Y_{1,r} \propto 1/\sigma_{\text{ann}}$ for $|\delta| \gg Y_0$ MD, Imminniyaz, Kakizaki, hep-ph/0603165
Numerical comparison: $b = 0$

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Note: \( \Omega_{\chi}(T_R) \leq \Omega_{\chi}(T_R \gg T_F) \)
Application: lower bound on $T_R$ for thermal WIMP

If $n_\chi(T_R) = 0$, demanding $\Omega_\chi h^2 \simeq 0.1$ imposes lower bound on $T_R$: 
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Application: lower bound on $T_R$ for thermal WIMP

If $n_\chi(T_R) = 0$, demanding $\Omega_\chi h^2 \sim 0.1$ imposes lower bound on $T_R$:

$$\Omega_\chi h^2 \simeq \frac{0.1^{a}}{0.079} \quad (a)$$

\hspace{1cm}

$$\Omega_\chi h^2 \simeq \frac{0.119^{b}}{0.079} \quad (b)$$

\hspace{1cm}

\[ \implies T_R \geq \frac{m_\chi}{23} \]

Holds independently of $\sigma_{\text{ann}}$!
Best motivated WIMP: neutralino $\tilde{\chi}_1^0$

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- In simplest ($R_p$–invariant) version: LSP is stable: can be good candidate for DM particle! (Free bonus, not related to original motivation.)
Minimal Supergravity, mSUGRA

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- Way out: Postulate universal spectrum at GUT scale (“universal boundary conditions”): Spectrum parameterized by universal scalar mass $m_0$; universal gaugino mass $m_{1/2}$; universal trilinear scalar term $A_0$; ratio of Higgs vevs $\tan \beta$; sign of higgsino mass, sign($\mu$). (mSUGRA/CMSSM boundary conditions)
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- Radiative symmetry breaking: loop corrections drive (combination of) squared Higgs masses negative, leaving squared sfermion masses positive

- Over much of parameter space, $\tilde{\chi}_1^0$ is stable LSP!
Over most of collider–allowed parameter space, $\Omega_{\tilde{\chi}_1} h^2$ from standard cosmology comes out too large in mSUGRA. Regions with too small $\Omega_{\tilde{\chi}_1} h^2$ also exist.
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Following examples from Djouadi, MD, Kneurr, hep-ph/0602001
Example: \( m_t = 172.7 \text{ GeV}, \tan \beta = 10, A_0 = 0, \mu > 0 \)

Green: \( b \rightarrow s\gamma \) 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
Effect of varying $\tan \beta$

$\tan \beta = 5$

$\tan \beta = 30$

Blue: $g_\mu - 2$ favored
$(e^+e^- \text{ data})$

$\tan \beta = 50$
Varying $A_0$: $m_t = 172.7$ GeV, $\tan \beta = 30$, $\mu > 0$

$A_0 = 0$  \hspace{1cm}  $A_0 = -1$ TeV  \hspace{1cm}  $A_0 = -2$ TeV
Varying $m_t$: $\tan \beta = 50$, $A_0 = 0$, $\mu > 0$

$m_t = 167$ GeV

$m_t = 172.7$ GeV

$m_t = 178$ GeV
# 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>$\tilde{\chi}_1^0$</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^\pm$</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>$\tilde{\chi}_3^0$</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>
Indirect WIMP detection

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Indirect WIMP detection: signals

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Further discussion: talks by de Boer, Mannheim
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- 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

$A = \rho \sigma_0 / (2 m_x m_r) = \text{const.}$

$F(Q)$: nuclear form factor

$v$: WIMP velocity in lab frame

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

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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
$f_1(v)$: prediction and simulated measurement

500 events on Ge: stat. error only
$f_1(v)$: prediction and simulated measurement

A few moments of $f_1(v)$ may be measurable with relatively few events
MeV Dark Matter

Motivated by excess of 511 keV photons observed from direction of galactic center, by everyone who looked; most recently, by INTEGRAL satellite.

INTErnational Gamma Ray Astrophysical Laboratory: observes sky in $\gamma$ rays from highly eccentric orbit (perigee 10,000 km, aphogee 152,000 km, orbital period 3 days)
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Background: continuum plus CR-induced 511 keV line (from empty sky region)
INTEGRAL results (cont’d)

Source is extended
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Angular width (FWHM) $\sim 10^\circ$; resolution $\sim 2^\circ$
INTEGRAL results (cont’d)

Source is extended

Angular width (FWHM) \( \approx 10^\circ \); resolution \( \approx 2^\circ \)

No evidence for substructure
Interpretation

- Line is quite sharp $\implies$ must come from annihilation of non-relativistic $e^+e^-$
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- Dark Matter $\rightarrow e^+e^-$ annihilation: Can work!!
DM particles $\chi$ annihilate: $\chi\bar{\chi} \rightarrow e^+e^- \ (\chi \equiv \bar{\chi} \text{ is possible.})$
Interpretation in terms of MeV DM

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- In this case, DM distribution according to galactic models can reproduce angular distribution of signal reasonably well; less so, if flux $\propto n_\chi$ (decaying DM models)
Additional astrophysical constraints

Come from higher-order (radiative) process:

\[
\tilde{\chi} e^- \rightarrow \gamma \chi + \tilde{\chi} e^- \rightarrow \gamma \chi
\]
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\[ \chi \, \bar{\chi} \rightarrow e^+ e^- \]

Cross section \( \sigma_{\text{rad}} \propto \alpha \ln \frac{m_\chi}{m_e} \cdot \sigma(\chi \bar{\chi} \rightarrow e^+ e^-) \), \( E_\gamma \propto m_\chi \)
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To avoid overproduction of MeV photons: \(m_\chi \leq 20\) MeV!

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Come from higher-order (radiative) process:

\[
\begin{align*}
\bar{\chi} & \rightarrow e^- + \gamma \\
\chi & \rightarrow e^+ + \gamma \\
\end{align*}
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Bound reduced to \( \sim 3 \text{ MeV} \) if photons produced during slow–down of \( e^{\pm} \) are included. Beacom & Yuksel, Phys. Rev. Lett. 97, 071102 (2006)
To explain flux of 511 keV photons: need

\[ 10^{-3} \text{ fb} \leq v\sigma(\chi\bar{\chi} \rightarrow e^+e^-) \cdot \left(\frac{1 \text{ MeV}}{m_\chi}\right)^2 \cdot \kappa \leq 1 \text{ fb} \]

\[ \kappa = 1 \text{ (2) if } \chi = \bar{\chi} \text{ (} \chi \neq \bar{\chi} \text{). Expanded range in Boehm et al. by factor 10 in both directions. Note: } \rho_\chi \text{ fixed from galactic modelling } \Rightarrow n_\chi \propto 1/m_\chi. \]
Particle physics model

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Taken together, these constraints imply that \( \chi \) was in thermal equilibrium (using \( T_R > 0.7 \text{ MeV} \) from BBN; Guidice et al. 2001).
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- Relic density essentially fixes product $g_\chi^2 (g_{eR}^2 + g_{eL}^2)$ of $U-$boson couplings.
Model building aspects

For most purposes, scalar $\chi \simeq$ Majorana $\chi$ with $g_{e_L} = g_{e_R}$: both are pure $P$-wave
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- Did not attempt to build full (renormalizable) model.
Tests at low energy $e^+e^-\text{ colliders}$

$U-$boson must couple to electrons: can be produced at $e^+e^-\text{ colliders}!$

\[ e^- \rightarrow U \]
\[ e^+ \rightarrow \gamma \]
\[ e^- \rightarrow U \]
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Tests at low energy $e^+e^-$ colliders

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$$\frac{d\sigma(e^+e^- \rightarrow U\gamma)}{d \cos \theta} = \frac{\alpha \left(g_{eL}^2 + g_{eR}^2\right)}{4s (1-y) \sin^2 \theta} \left[2 \left(1 + y^2\right) - \sin^2 \theta \left(1 - y\right)^2\right]$$

$$y = \frac{M_U^2}{s} < 0.04 \text{ even at DAΦNE}.$$
Cross section $\propto 1/s \implies$ lower energy is in principle better!
Remarks

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  - $U \to e^+e^-$: have $e^+e^-\gamma$ final state
  - $U \to \nu\bar{\nu}, \chi\bar{\chi}$: have $\gamma+$ ‘nothing’ final state (trigger??)
Reach for DAΦNE

Allowed range of coupling for $g_{e_L} = 0$, $g_\chi = 10g_{e_R}$, Majorana-$\chi$

$g_{\chi e_R}$ (min, max)

$M_U$ [GeV]

upper bound from $g_{e_L} - 2$

$g_{\chi e_R}$

$m_\chi > M_U/2$

max. sensitivity (e$^+$e$^-$ channel)

$m_\chi < M_U/2$

max. sensitivity (invisible channel)
Reach for $B$–factories

Allowed range of coupling for $g_{e_L} = 0$, $g_\chi = 1$, scalar $\chi$

$10^{-8}$

$max. \ sensitivity$ 
$(e^+ e^- \ channel)$

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- WIMPs can be detected in a variety of ways; once detected, allow new probes of Universe