Dark Matter and Colliders

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Counter–examples: axions; Gravitinos; FIMPs; dark atoms; primordial black holes; keV neutrinos: not covered in this talk. **Note:** Proves that LHC does *not* “recreate conditions of the early universe”!
The “WIMP Miracle”

*Assume* $\chi$ was in full thermal equilibrium with SM particles at sufficiently high temperature $T$:

$$\chi \text{ production rate } n_\chi \langle \sigma(\chi \chi \rightarrow \text{SM})v_\chi \rangle > \text{ expansion rate } H$$
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$$\implies \Omega_\chi h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma(\chi \chi \rightarrow \text{SM})v \rangle}$$
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\[ \Rightarrow \Omega_\chi h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma(\chi\chi \rightarrow \text{SM})v \rangle} \]

Indicates weak–scale $\chi\chi$ annihilation cross section:

\[ \langle \sigma(\chi\chi \rightarrow \text{any})v \rangle \simeq (2 \text{ to } 4.5) \cdot 10^{-26} \text{cm}^3\text{s}^{-1} \]
$\Omega_{\chi} h^2$ can be changed a lot in non–standard cosmologies (involving $T \gg T_{\text{BBN}}$):

- **Increased**: Higher expansion rate $H(T \sim T_F)$; additional non–thermal $\chi$ production at $T < T_F$; ...
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Determining $\sigma(\chi\chi \rightarrow \text{SM})$ allows probe of very early Universe, once $\chi$ has been established to be “the” DM particle! e.g. MD, Imninniyaz, Kakizaki, arXiv:0704.1590
Direct WIMP production

Even for a standard thermal WIMP, in general one cannot predict the size of the missing $E_T$ signal from $\chi\chi$ production!
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- $\Omega_\chi h^2$ determined from $\sigma(\chi \chi \rightarrow \text{SM})$ near threshold ($T_F \simeq m_\chi/20 \implies s \simeq 4m_\chi^2$). At colliders need $\geq 3$ body final state to get signature (e.g. $e^+e^- \rightarrow \chi \chi \gamma$, $q\bar{q} \rightarrow \chi \chi g$) $\implies$ typically need $\sigma(\chi \chi \rightarrow \text{SM})$ at $s \gtrsim 6$ to $10m_\chi^2$!
Parameterize $\chi$ interaction with relevant SM fermion through dim–6 operator; e.g. for hadron colliders:

$$\mathcal{L}_{\text{eff}} = G_{\chi,q} \bar{\chi} \Gamma \chi \bar{q} \Gamma q q$$
“Model-independent” approach


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$\chi$ Majorana $\Rightarrow \Gamma_{\chi} \in \{1, \gamma_5, \gamma_\mu \gamma_5\}$

$\Gamma_q \in \{1, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5\}$

If $\Gamma_{\chi}, \Gamma_q \in \{1, \gamma_5\}$: $G_{\chi,q} = m_q/(2M^3_*)$ (chirality violating!),

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Compare monojet signal from $q\bar{q} \rightarrow \chi\chi g$ with monojet limits (current bound) and background (ultimate reach)!
UV completion

Approach can only work if the “mediator” mass $m_M$ is (much) larger than the highest relevant momentum scale:

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$$m_M \gg 2m_\chi, \text{ missing } E_T \simeq 400 \text{ GeV}$$

LHC can only hope to be sensitive if $\chi$ couples to quarks at tree level. Two options:

$s$–channel

$$G_{\chi,q} = \frac{g_\chi g_q}{m_M^2}$$

$t$–channel

$$G_{\chi,q} = \frac{g_M^2}{m_M^2}$$
Types of interactions

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$\Rightarrow$ Focus on spin–dep interaction: $\Gamma_\chi = \gamma_5\gamma^\mu$, $\Gamma_q = \gamma_5\gamma^\mu$

For spin $-1/2$ WIMP: from spin $-1$ exchange in $s$–channel and/or spin $-0$ exchange in $t$–channel
**Types of interactions**

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Case \( \Gamma_\chi = \Gamma_q = \gamma_5 \) also has poor LHC reach. Gives velocity–dependent interaction for \( \chi p \rightarrow \chi p \) \( \Rightarrow \) very poor reach in direct detection as well
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Contributing diagrams:

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\[ G_{q,q'} = \begin{cases} 
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Bound on \( \Lambda^2 \equiv 1/G_{\chi,q} \) depends on ratio \( g_{\chi}/g_q \)!

For \( s \)–channel: bound on \( 4q \) contact interaction stronger than bound from monojet searches, unless \( g_{\chi} \gg g_q \)!
Bounds on $\Lambda$

S. Belwal, MD, J.S. Kim, in preparation

95% CL limit on Lambda obtained as a function of WIMP mass

Lambda (GeV) vs WIMP mass (GeV)
Promising collider searches

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$t-$channel: mediator carries color $\Rightarrow$ can be pair-produced!

E.g. SUSY: $m_{\tilde{q}} \gtrsim 1.4$ TeV if $m_{\tilde{q}} \simeq m_{\tilde{g}}$ (for 1st, 2nd gen. squarks)
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For perturbative couplings: search for off-shell mediator $\rightarrow \chi\chi$ is hopeless!
E.g. SUSY: signal for $\tilde{\chi}\tilde{\chi} j$ is much smaller than $Z (\rightarrow \nu\bar{\nu}) j$ background, even for 100 GeV higgsino-like $\tilde{\chi}$

(Baer, Mustafayev, Tata, arXiv:1401.1162)
DM and Light (Gauge) Bosons

(At least) 3 kinds of WIMP models require light ($m \leq \text{few GeV}$) (gauge) bosons $U$:

- **MeV DM**: Suggested as explanation of 511 keV line ($\Rightarrow$ slow $e^+$) excess from central region of our galaxy (Boehm et al., astro-ph/0309686). **Should have** $m_\chi \leq 10$ MeV ($\gamma$ constraints)

  $\Rightarrow m_\chi \leq m_U \leq 200$ MeV to mediate $\chi\chi \rightarrow e^+e^-$; fixes $g_U\chi\chi g_{Ue^+e^-}/m_U^2$! (Unless $2m_\chi \simeq m_U$.)
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- **PAMELA/FermiLAT inspired TeV DM**: Needs light boson for Sommerfeld enhancement (e.g. Arkani-Hamed et al., arXiv:0810.0713(4)) \( \chi\chi \rightarrow UU \rightarrow 4l \) is also somewhat less constrained by \( \gamma \) spectrum than \( \chi\chi \rightarrow 2l \).
DAMA/CoGeNT inspired few GeV DM: Needs light mediator to achieve sufficiently large $\sigma_{\chi p}$. (2 different mediators for isospin violation to evade bounds: Cline, Frey, arXiv:1108.1391)
In all cases: $U$ couplings to (most) SM particles must be $\ll 1$ to evade bounds! ($g_\mu - 2$, meson decays, $\nu$ cross sections, APV, . . . ).
Light Gauge Bosons (cont’d)

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Possible explanation: kinetic mixing with $\gamma/B$ boson! Is 1-loop effect $\Rightarrow$ squared $U f \bar{f}$ coupling is $\mathcal{O}(\alpha^3)$. 
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$U \chi \chi$ coupling may well be large.
Signatures of light gauge bosons

If $m_U > 2m_\chi$: $U \to \chi\chi$ dominant! Is invisible $\Rightarrow$ need extra tag, e.g. $e^+e^- \to \gamma U \to \gamma +$ nothing.
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Borodatchenko, Choudhury, MD, hep-ph/0510147
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Instrumental backgrounds (not from $e^+e^-$ annihilation) seem large

Borodatchenkova, Choudhury, MD, hep-ph/0510147
Sensitivity at $B-$factories (100 fb$^{-1}$)

Red, black: Regions allowed by $\Omega_\chi$, $\sigma(\chi\chi \rightarrow e^+e^-)$.
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Sufficiently light $U$ can even be produced in fixed–target experiments: $e^- N \rightarrow e^- e^+ e^- N$ (tridents), with peak in $M_{e^+ e^-}$
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Also, KLOE-2 performed search, mostly for $\phi \rightarrow U\eta$: no signal. arXiv:1107.2531
A1 results
Saw above: WIMP searches at colliders not promising, *if* WIMP is only accessible new particle. Fortunately, in many cases the WIMP is the lightest of *many* new particles! True in SUSY. (Also in Little Higgs, UED.)
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- HLS theorem, relation to superstrings: don’t single out weak scale.
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- In simplest, $R$–parity invariant scenario: lightest superparticle LSP is stable: satisfies one condition for DM candidate!
SUSY DM candidate: neutralino $\tilde{\chi}_1^0$

- Mixture of $\tilde{B}$, $\tilde{W}_3$, $\tilde{h}_u^0$, $\tilde{h}_d^0$
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- In “most” of parameter space: $\tilde{\chi}_1^0 \simeq \tilde{B}$, and predicted $\Omega_{\tilde{\chi}_1^0} h^2$ too large! $\mathcal{O}(1 \text{ to } 10)$ rather than $\mathcal{O}(0.1)$ in standard cosmology,
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- but DM–allowed regions of parameter space do exist even in constrained models!
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- Heavy higgsino: Needs $|\mu| \simeq 1.1$ TeV: naturalness? Can be arranged in cMSSM.
- Very heavy wino: Needs $|M_2| \simeq 3$ TeV: naturalness??? Not possible in cMSSM.
Regions with correct $\Omega_{\tilde{\chi}_1}^0 h^2$

- Co–annihilation region: $m_{\tilde{\chi}_1}^0 \simeq m_{\tilde{\tau}_1}$

- Higgs funnel(s): $m_{\tilde{\chi}_1}^0 \simeq m_h/2, \ m_A/2$

- Well–tempered neutralino: $\mu - M_1 \leq M_Z \implies \tilde{\chi}_1^0$ is $\tilde{B} - \tilde{h}^0$ mixture. (Requires $m_{\tilde{q}} \gg m_{\tilde{g}}$ in cMSSM; can be arranged “anywhere” in NUHM.)

- Heavy higgsino: Needs $|\mu| \simeq 1.1 \text{ TeV}$: naturalness? Can be arranged in cMSSM.

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- Note: DM–allowed region of $\left(m_0, m_{1/2}\right)$ plane of cMSSM depends on $A_0, \tan \beta$!
Generic SUSY searches at LHC

Strongly interacting sparticles have biggest cross sections; may decay via long decay “cascades”. Example:

\[ gg \rightarrow \tilde{g}\tilde{g} \rightarrow (\tilde{b}_1 \bar{b}) (\tilde{u}_L \bar{u}) \]
\[ \rightarrow (\tilde{\chi}^0_2 b\bar{b}) (\tilde{\chi}^+_1 d\bar{u}) \]
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Always contains two \( \tilde{\chi}^0_1 \), i.e. always contains missing \( E_T \)!
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\( \mathcal{O}(100) \) searches have been performed, but no signal has been found.
Impact of LHC searches

Is model dependent: mostly probe $\tilde{g}, \tilde{q}$ sector so far! Here: Assume cMSSM for definiteness.
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- **In pMSSM10: $m_{\tilde{\chi}_1^0} \simeq 50 \text{ GeV still ok!}$** de Vries et al., arXiv:1504.03260
Impact of direct WIMP Searches

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- Signals in other regions very small
Impact of Future WIMP Discovery at Collider

Generically: could determine:

- **WIMP mass**: Very useful for indirect searches (greatly reduced “look elsewhere” problem); less so for direct searches, once $m_\chi \geq m_N$
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- **Most interesting to me**: Predict $\Omega_\chi h^2$, compare with observation: Constrain very early universe!
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- Absence of missing $E_T$ signal at LHC is disappointing, but plenty of parameter space in reasonably well motivated WIMP models left to explore