WIMPs: An Introduction

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Counter–examples: axions; 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* χ was in full thermal equilibrium with SM particles at sufficiently high temperature T:

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- Indicates weak–scale $\chi\chi$ annihilation cross section: $\langle \sigma(\chi\chi \to \text{any}) v \rangle \simeq 3 \cdot 10^{-26} \text{cm}^3 \text{s}^{-1}$

WIMPs and Early Universe

$\Omega_\chi h^2$ can be changed a lot in non–standard cosmologies (involving $T \gg T_{\rm BBN}$):

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Determining $\sigma(\chi\chi \to {\rm SM})$ allows probe of very early Universe, once χ has been established to be “the” DM particle! e.g. MD, Iminniyaz, Kakizaki, arXiv:0704.1590

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Either way, χ interactions with SM particles are too weak to give missing E_T signal, unless χ has "partners" that can be produced via gauge interactions (ex.: gravitino $\tilde{G}$, axino $\tilde{a}$) Interactions are too weak for direct detection; indirect detection is possible only for unstable DM candidates.

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Momentum transfer $\lesssim 100$ MeV $\Longrightarrow$ may need to worry about elastic form factors; quite well understood (for spin–indep. scattering)

Recoil Spectrum

$$\frac{dR}{dQ} \propto |F(Q)|^2 \int_{v_{\min}}^{v_{\max}} \frac{dv}{v} f_1(v)$$

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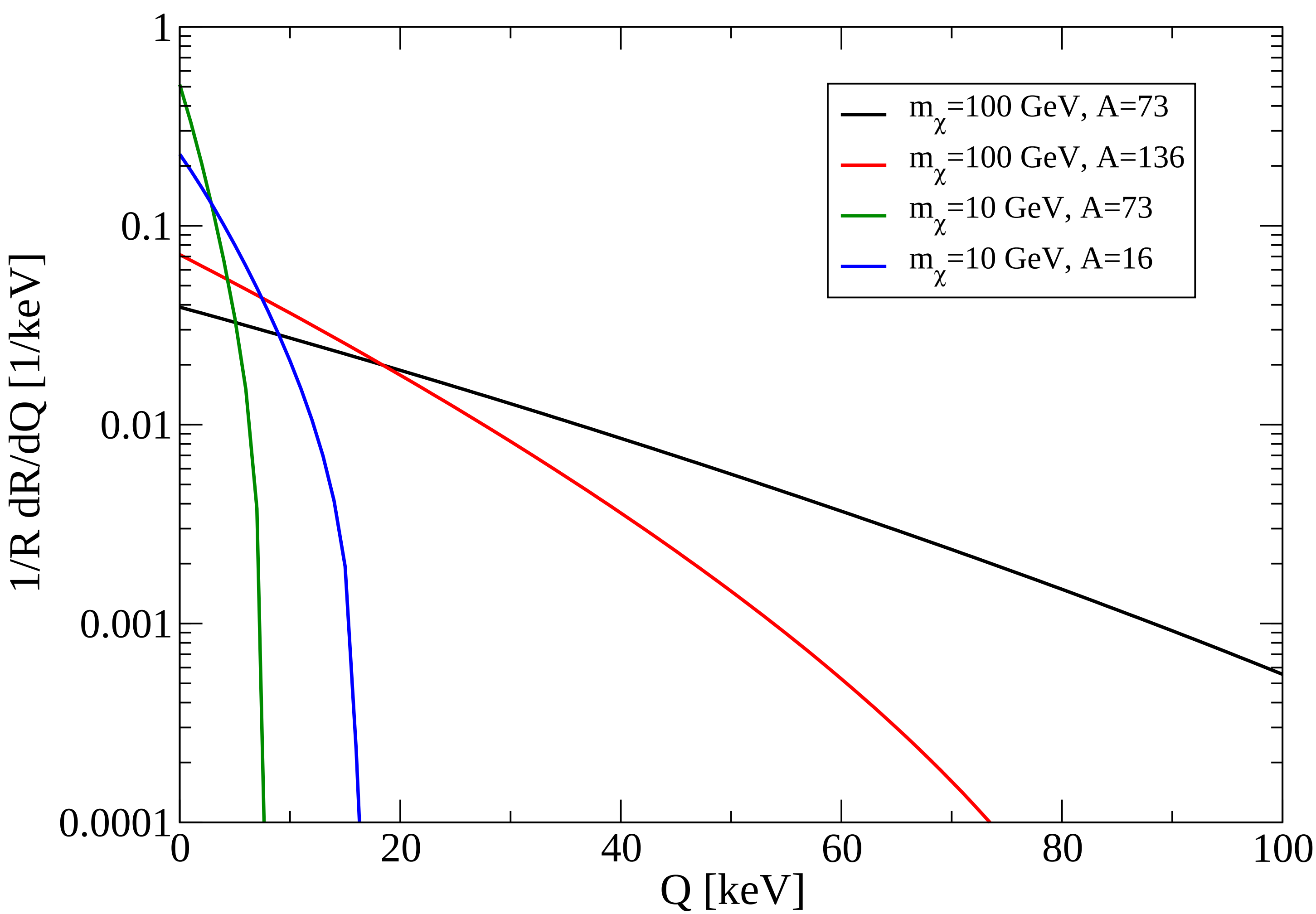
$f_1(v)$: WIMP velocity distribution. Usually assumed Maxwellian in rest frame of the galaxy, cut off at $v_{\mathrm{esc}} \Longrightarrow v_{\max}$. Gives roughly exponentially falling spectrum.

Normalized Recoil Spectra



Experimental Challenges

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- Rates of current interest $\ll$ background rate, e.g. from radioactive decay (for most materials)
  $\Longrightarrow$ try to discriminate between nuclear recoil (signal) and e/γ induced events (background)!
- Will go through three claimed signals: DAMA(/LIBRA), CoGeNT, CRESST.

DAMA

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6 years with 100 kg (DAMA)
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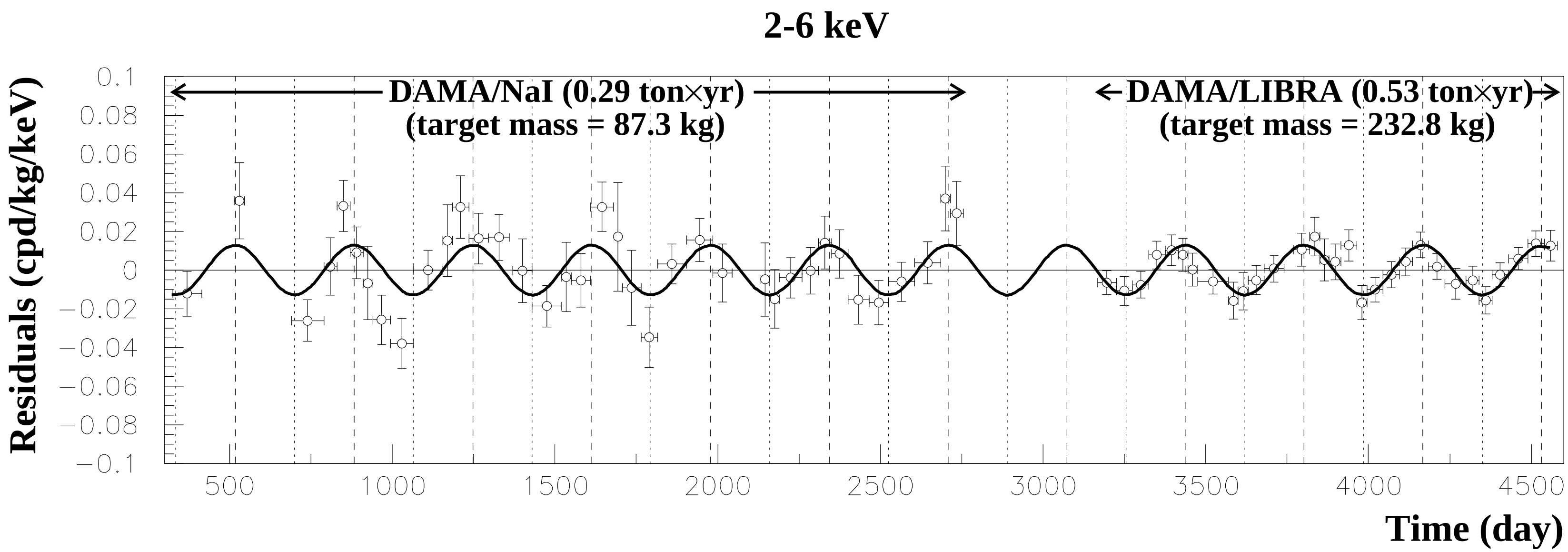
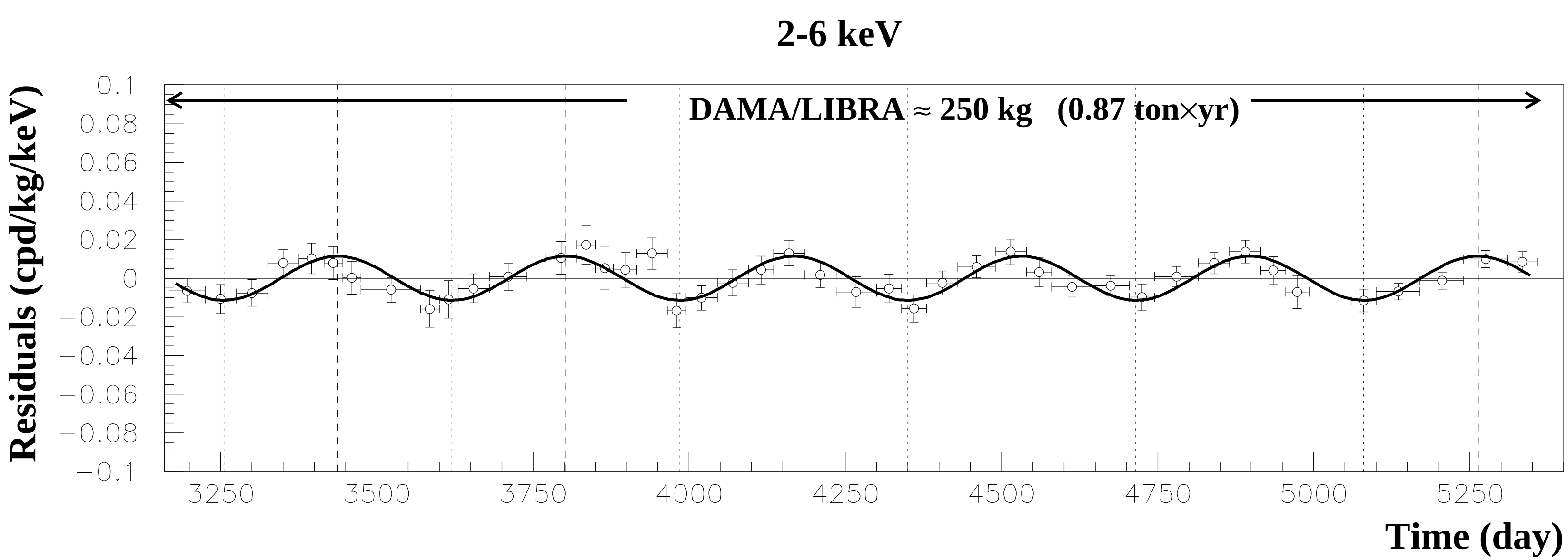
Compatible with ~ 50 GeV WIMP scattering off I, or ~ 10 GeV WIMP scattering off Na.

DAMA Results





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- Amplitude of modulation is getting smaller!
  E.g. in 2–6 keV$_{\rm ee}$ bin (in units of $10^{-3}/{\rm kg} \cdot {\rm day} \cdot {\rm keV}_{\rm ee}$):
  DAMA 1995–2001: 20.0 ± 3.2
  LIBRA 2003–2007: 10.7 ± 1.9
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  Ratio $\frac{\rm LIBRAII}{\rm DAMA} = 0.43 \pm 0.13$

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- No convincing non–WIMP interpretation of modulation known.

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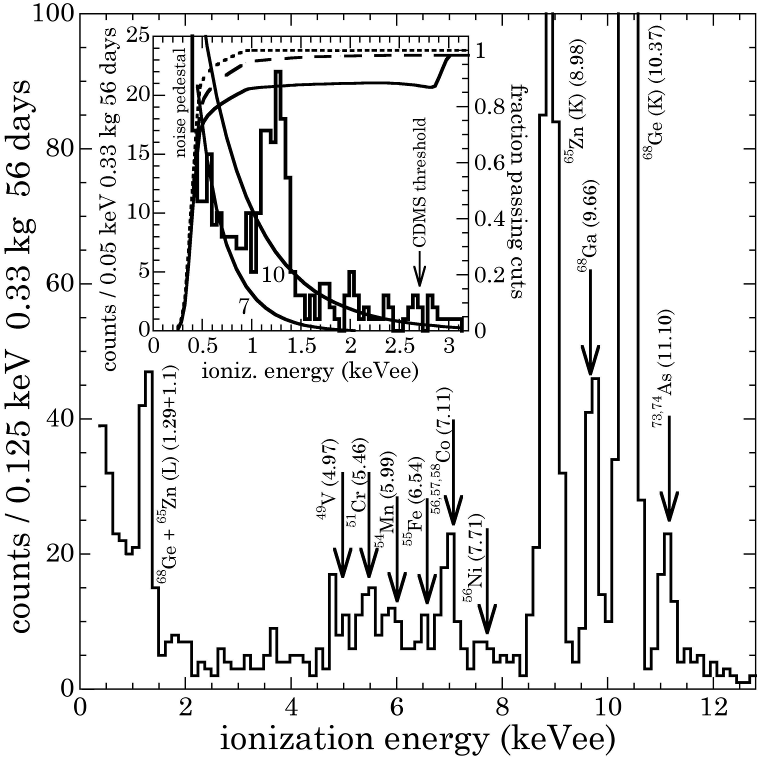
This September: More data, re–evaluateed background $\Longrightarrow$ size of possible "signal" reduced by $\sim$ factor 5!

CoGeNT: Results



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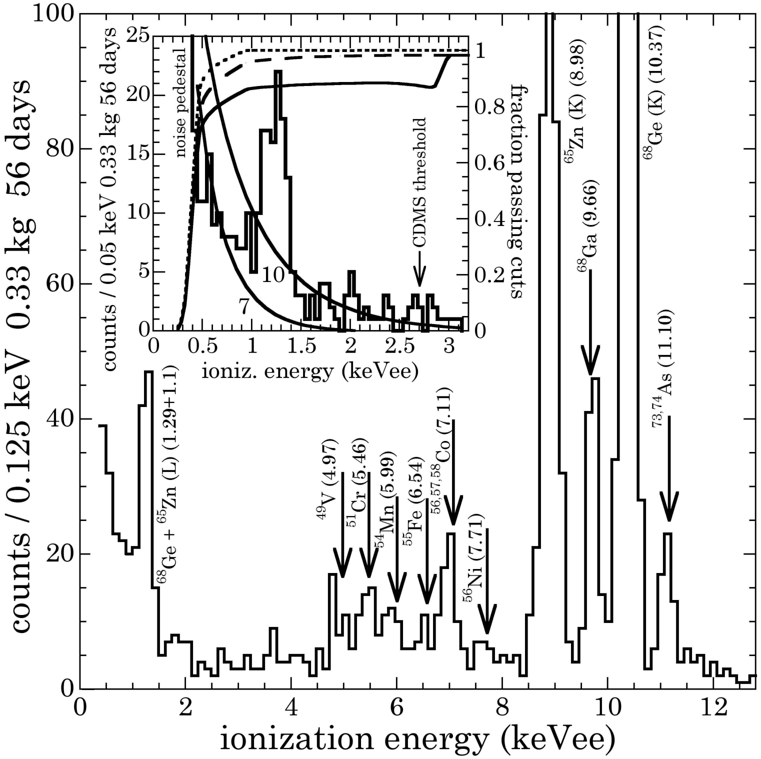

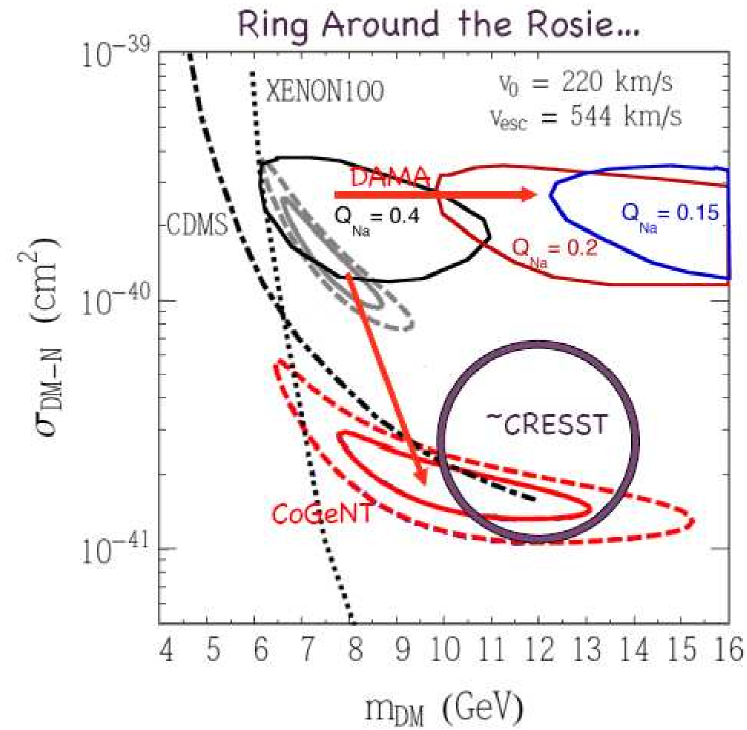

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- Modulation "signal" statistically very weak, and way too large

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No. of α events is correlated with no. of signal events after α subtraction.

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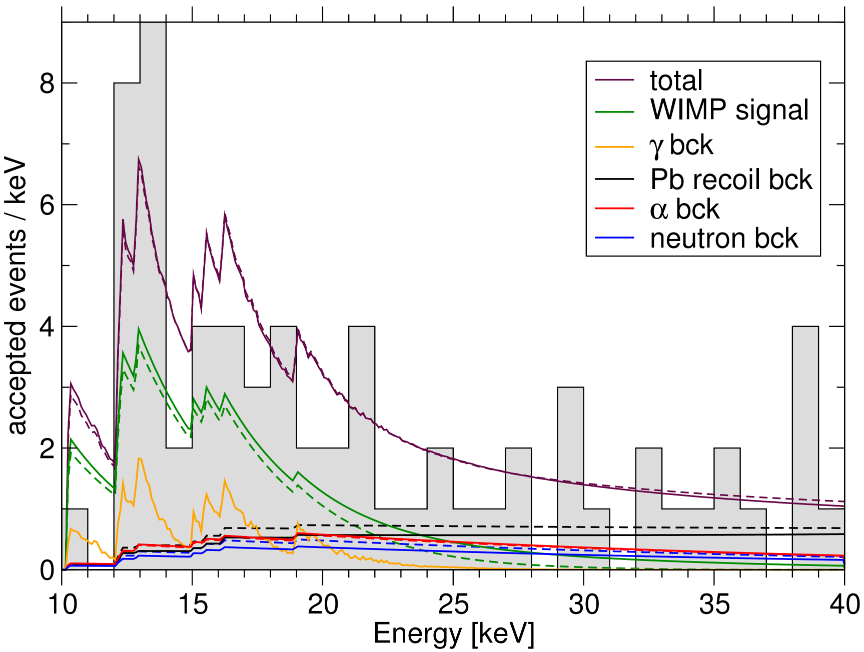

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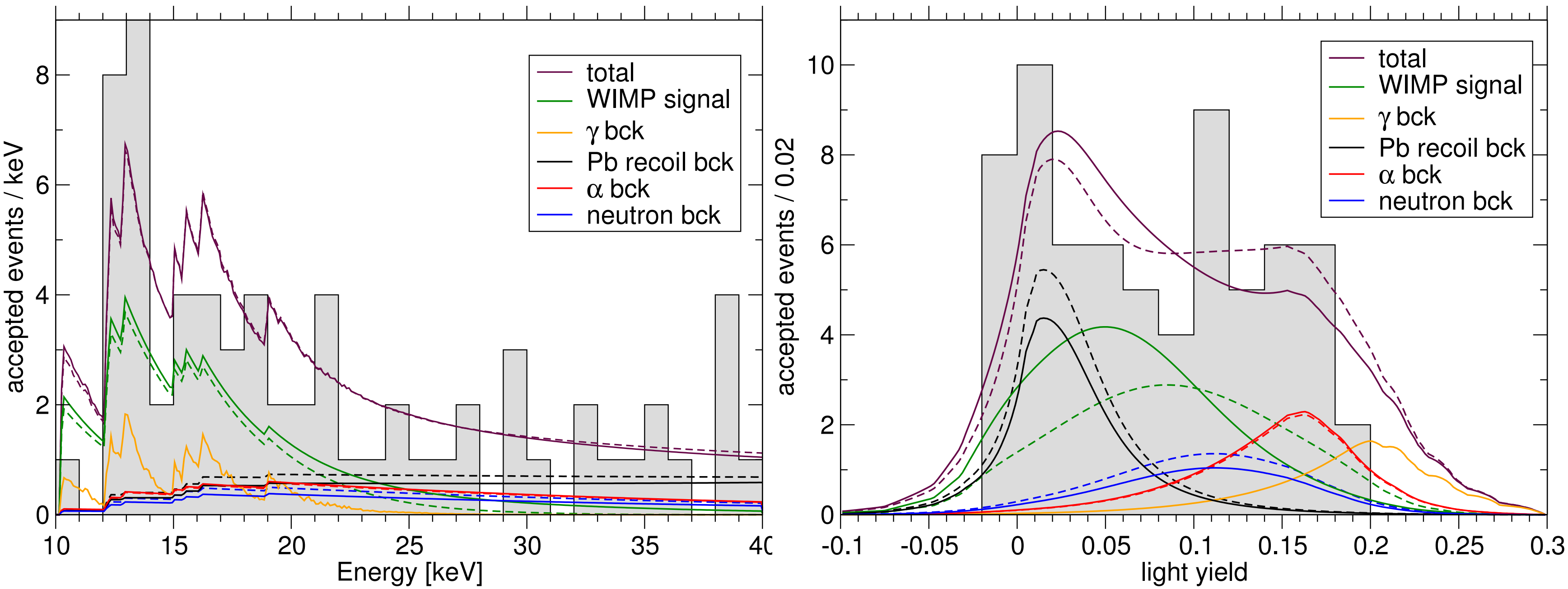

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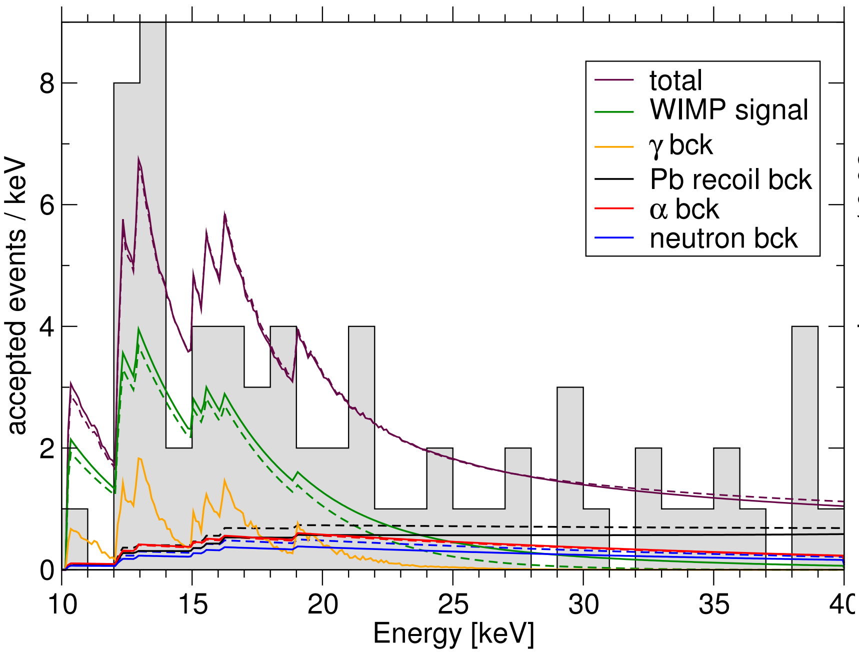
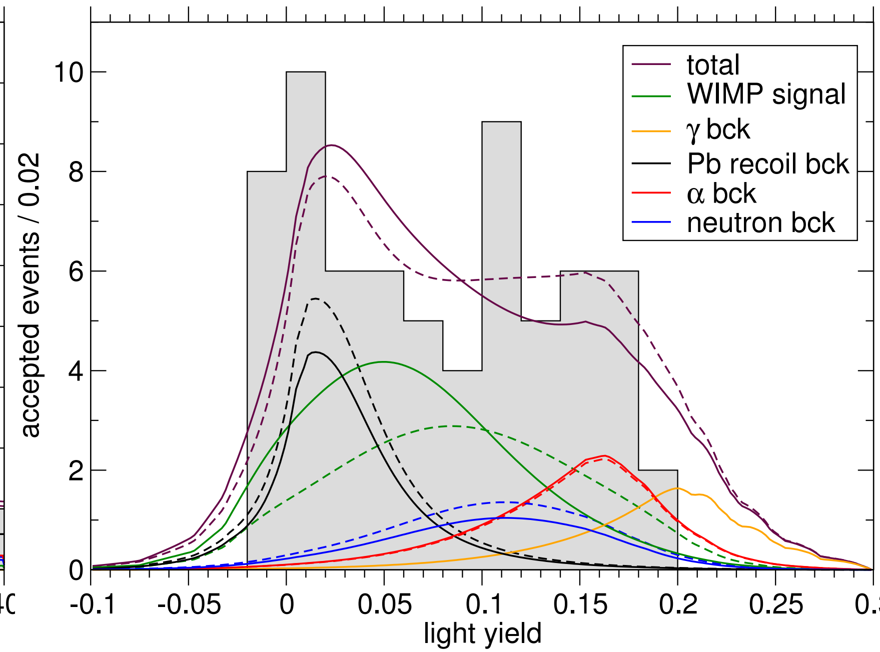
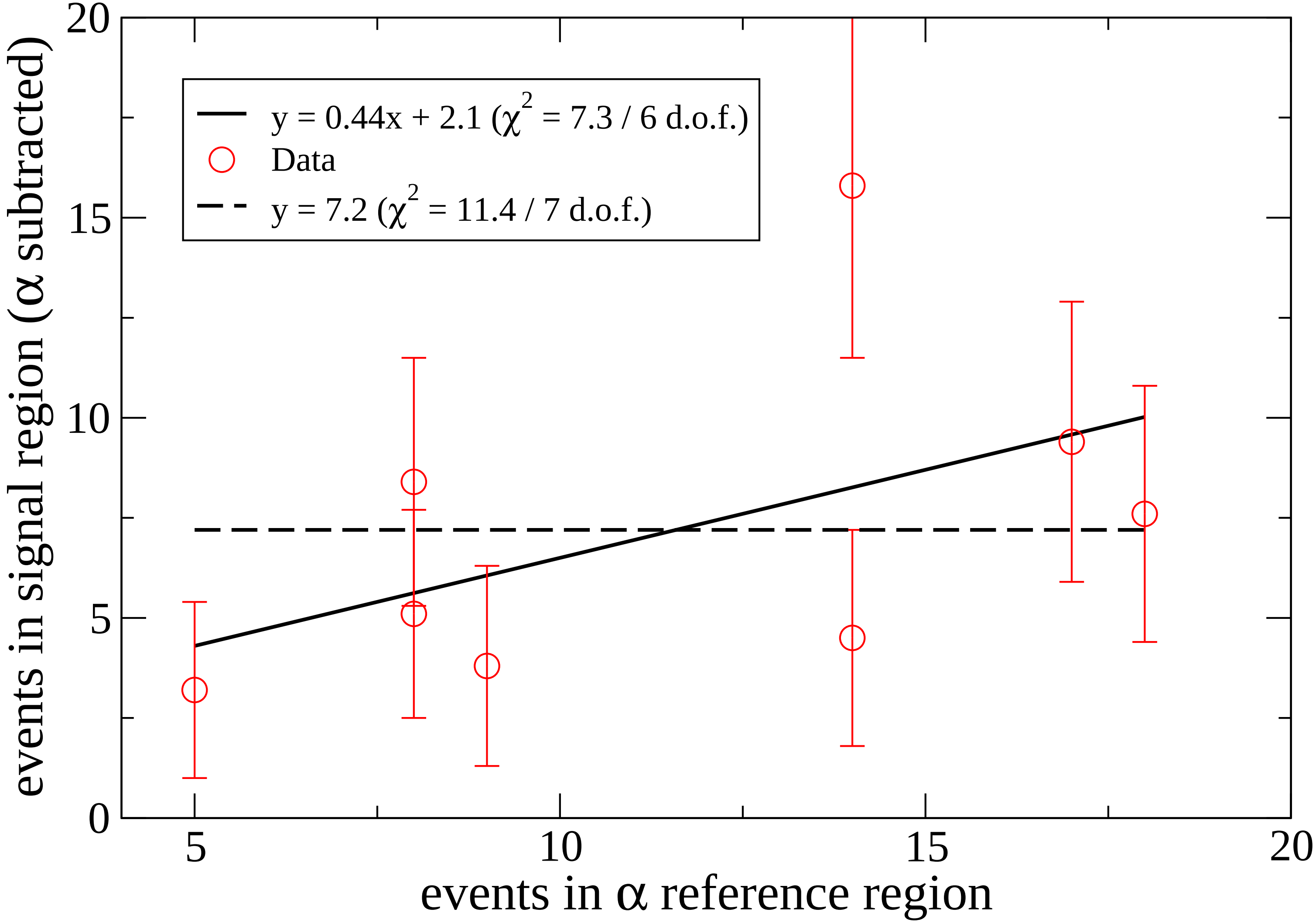




What is negative light yield?

CRESST: Correlation



Exclusion Limits from Other Expts

- Best limit for larger masses from Xenon100. Uses ionization and scintillation. Very few events after cuts. Alas, not safe for $m_\chi \leq 12$ GeV: bound strongly depends on high$-v$ tail of $f_1(v)$, and on experimental energy resolution.

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- SIMPLE heated droplet detector: Challenges DAMA.

Theory of WIMP–Nucleus Scattering

$$\mathcal{L}_{\rm eff} = c_N \bar{N} N \bar{\chi}\chi + a_N \bar{N}\gamma_\mu N \bar{\chi}\gamma^\mu \chi + b_N \bar{N}\gamma_\mu\gamma_5 N \bar{\chi}\gamma^\mu\gamma_5\chi$$

- For scalar χ: $\gamma^\mu \to i\partial^\mu$ in $2^{\rm nd}$ term; $3^{\rm rd}$ term absent
- For Majorana χ: $2^{\rm nd}$ term absent
- $1^{\rm st}$, $2^{\rm nd}$ term give spin–independent (s.i.) interaction, $3^{\rm rd}$ term gives spin–dependent (s.d.) interaction.
- “Usual WIMP”: same s.i. scattering on p and n!

Isospin violation in s.i. interaction?

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- Gauge boson exchange can break isospin: coefficients a_p, a_n may differ in sign! $\mathcal{M}(\chi q \rightarrow \chi q)$ is now linear in (new) quark charges.

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  $\Longrightarrow$ Need new light gauge bosons!
- Combined analyses: (e.g. Kopp, Schwetz, Zupan, arXiv:1110.2721 [hep-ph]) Still cannot explain all data consistently!

Weisskopf's (?) Theorem

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Competition between null experiments with few (background) events after cuts, and claimed "signals" with large, not always well understood backgrounds!

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- $\Omega_{\rm baryon}$ determined by baryon–antibaryon asymmetry, not by thermal decoupling of baryons: try same thing for WIMPs?
- Most attractive: $\chi - \bar{\chi}$ asymmetry related to baryon asymmetry [$\mathcal{O}(50)$ papers]
$\Longrightarrow$ number density $n_\chi \simeq n_p$ after annihilating away symmetric component

Asymmetric Dark Matter?

- Cosmology: $\Omega_{\rm DM} \simeq 5\Omega_{\rm baryon}$: strange coincidence?
- $\Omega_{\rm baryon}$ determined by baryon–antibaryon asymmetry, not by thermal decoupling of baryons: try same thing for WIMPs?
- Most attractive: $\chi - \bar{\chi}$ asymmetry related to baryon asymmetry [$\mathcal{O}(50)$ papers]
  $\Longrightarrow$ number density $n_\chi \simeq n_p$ after annihilating away symmetric component
- Needs 2 to 3 times larger $\chi\bar{\chi}$ annihilation cross section than for thermal WIMPs!

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  $\Longrightarrow$ Haven’t explained anything!
- Circular logic: ADM with $m_\chi \simeq 5$ GeV interesting because there are “signals” for low–mass WIMPs; low–mass WIMPs interesting because ADM “explains” $\Omega_{\rm DM}/\Omega_{\rm baryon}$??

WIMPs and Colliders

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4 Higgs Searches and Direct DM Detection

Cannot predict missing $\not\!E_T$ from $\chi\chi$ production

- Thermal WIMP: Only know *total* $\chi\chi \to \mathrm{SM}$ cross section; contribution of specific final states (e^+e^-, $u\bar{u} + d\bar{d}$) *not* known

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- $\Omega_\chi h^2$ determined from $\sigma(\chi\chi \to \mathrm{SM})$ near threshold ($T_F \simeq m_\chi/20 \Longrightarrow s \simeq 4m_\chi^2$). At colliders need ≥ 3 body final state to get signature (e.g. $e^+e^- \to \chi\chi\gamma,\ q\bar{q} \to \chi\chi g$) $\Longrightarrow$ typically need $\sigma(\chi\chi \to \mathrm{SM})$ at $s \sim 6 \text{ to } 10 m_\chi^2$!

“Model-independent” approach

Goodman et al., arXiv:1005.1286 and 1008.1783; Bai, Fox, Harnik, arXiv:1005.3797; Wang, Li, Shao, Zhang, arXiv:1107.2048; Fox, Harnek, Kopp, Tsai, arXiv:1103.0240

Parameterize χ interaction with relevant SM fermion through dim–6 operator; e.g. for hadron colliders:

$$\mathcal{L}_{\rm eff} = G_\chi \bar\chi \Gamma_\chi \chi \bar q \Gamma_q q$$

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

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If $\Gamma_\chi, \Gamma_q \in \{1, \gamma_5\}: \ G_\chi = m_q/(2M_*^3)$ (chirality violating!), else $\Gamma_\chi = 1/(2M_*^2)$ Rajamaran, Shepherd, Tait, Wijango, arXiv:1108.1196.

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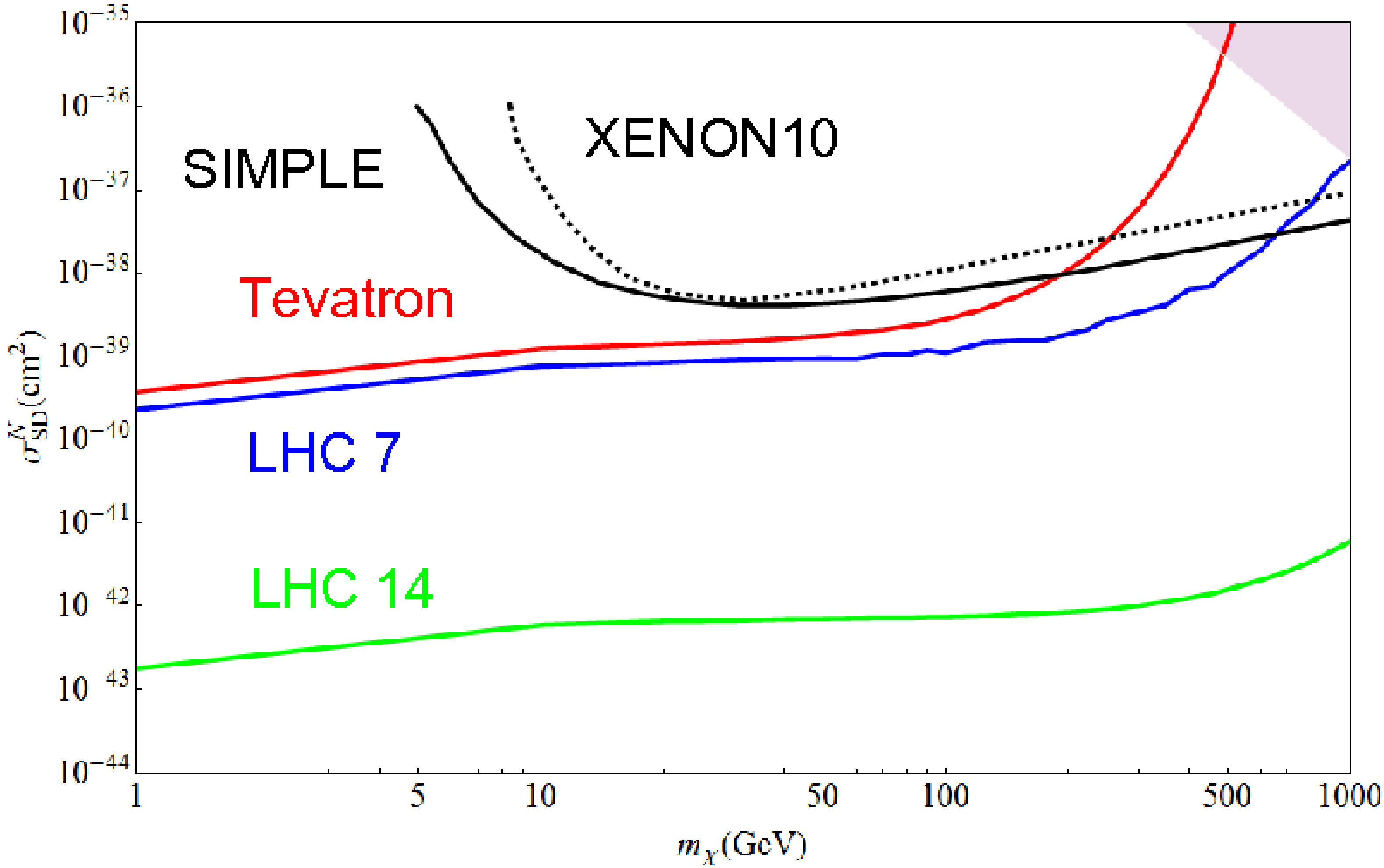
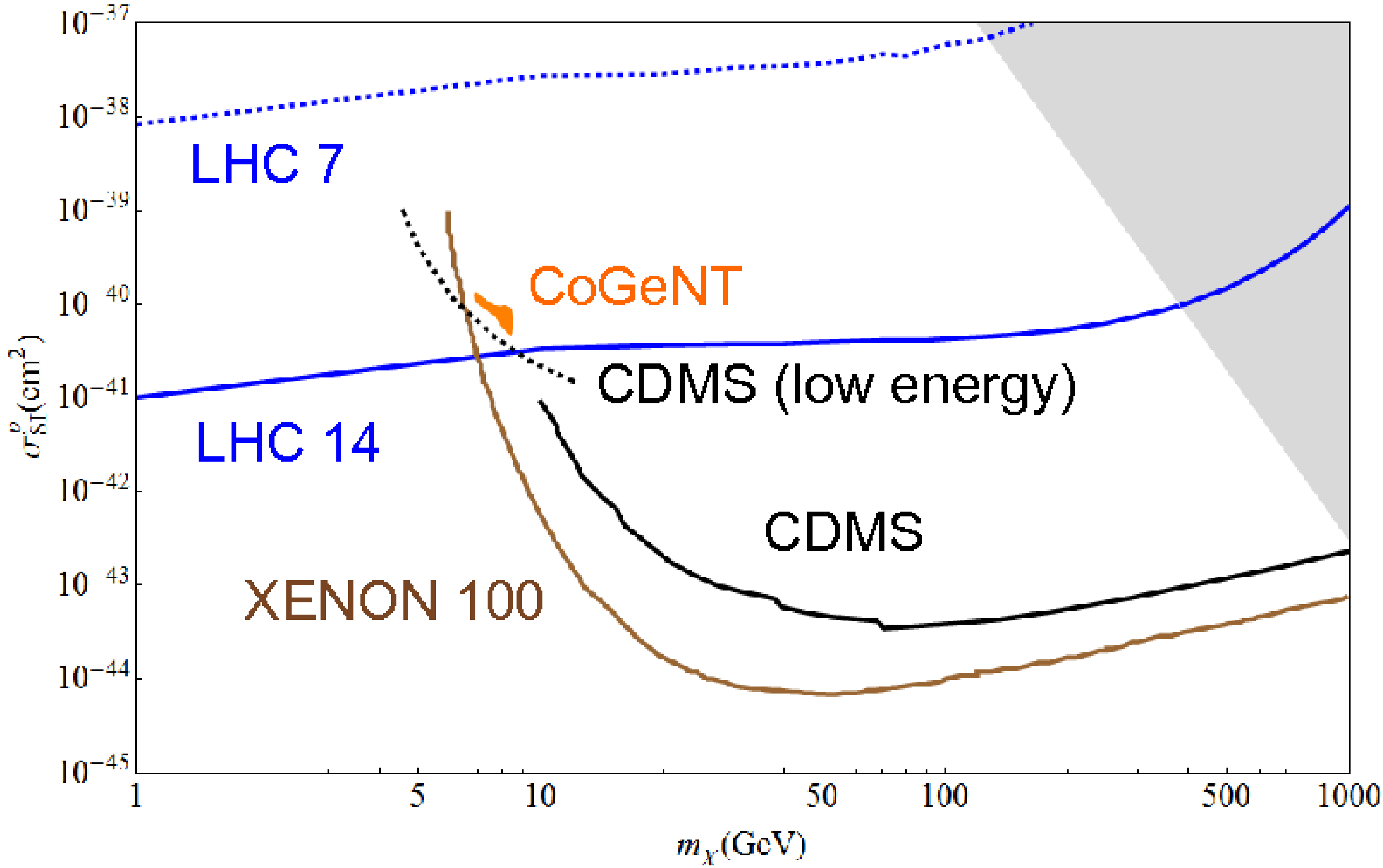
Compute monojet signal from $q\bar{q} \rightarrow \chi\chi g$, compare with monojet limits (current bound) and background (ultimate reach)!

$\Gamma_\chi = \gamma_\mu \gamma_5$ (corr. to spin-dep. interact.)



$\Gamma_\chi = 1$ (corr. to spin-indep. interact.)



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Altogether: very limited usefulness for most actual WIMP models.

2 DM and Light (Gauge) Bosons

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

- MeV DM: Suggested as explanation of 511 keV line ($\Longrightarrow$ slow e^+) excess from central region of our galaxy (Boehm et al., astro-ph/0309686). Should have $m_\chi \leq 10$ MeV (γ constraints)
  $\Longrightarrow m_\chi \leq m_U \leq 200$ 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 γ 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)

Light Gauge Bosons (cont'd)

In all cases: U couplings to (most) SM particles must be $\ll 1$ to evade bounds! ($g_\mu - 2$, meson decays, ν cross sections, APV, ...).

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$U\chi\chi$ coupling may well be large.

Signatures of light gauge bosons

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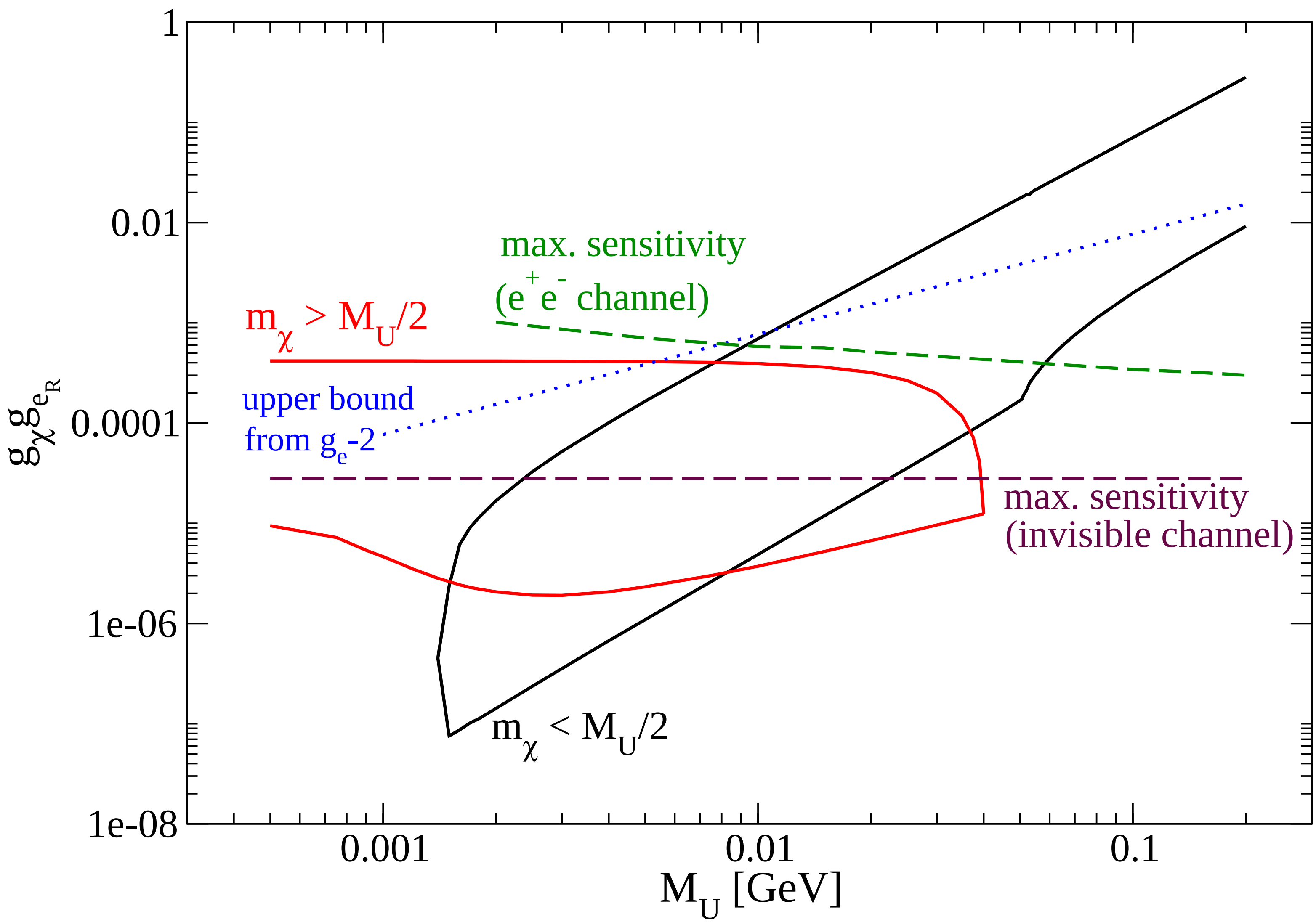
- Instrumental backgrounds (not from e^+e^- annihilation) seem large

Sensitivity at $B-$factories (100 fb^{-1})



Red, black: Regions allowed by Ω_χ, $\sigma(\chi\chi \to e^+e^-)$.

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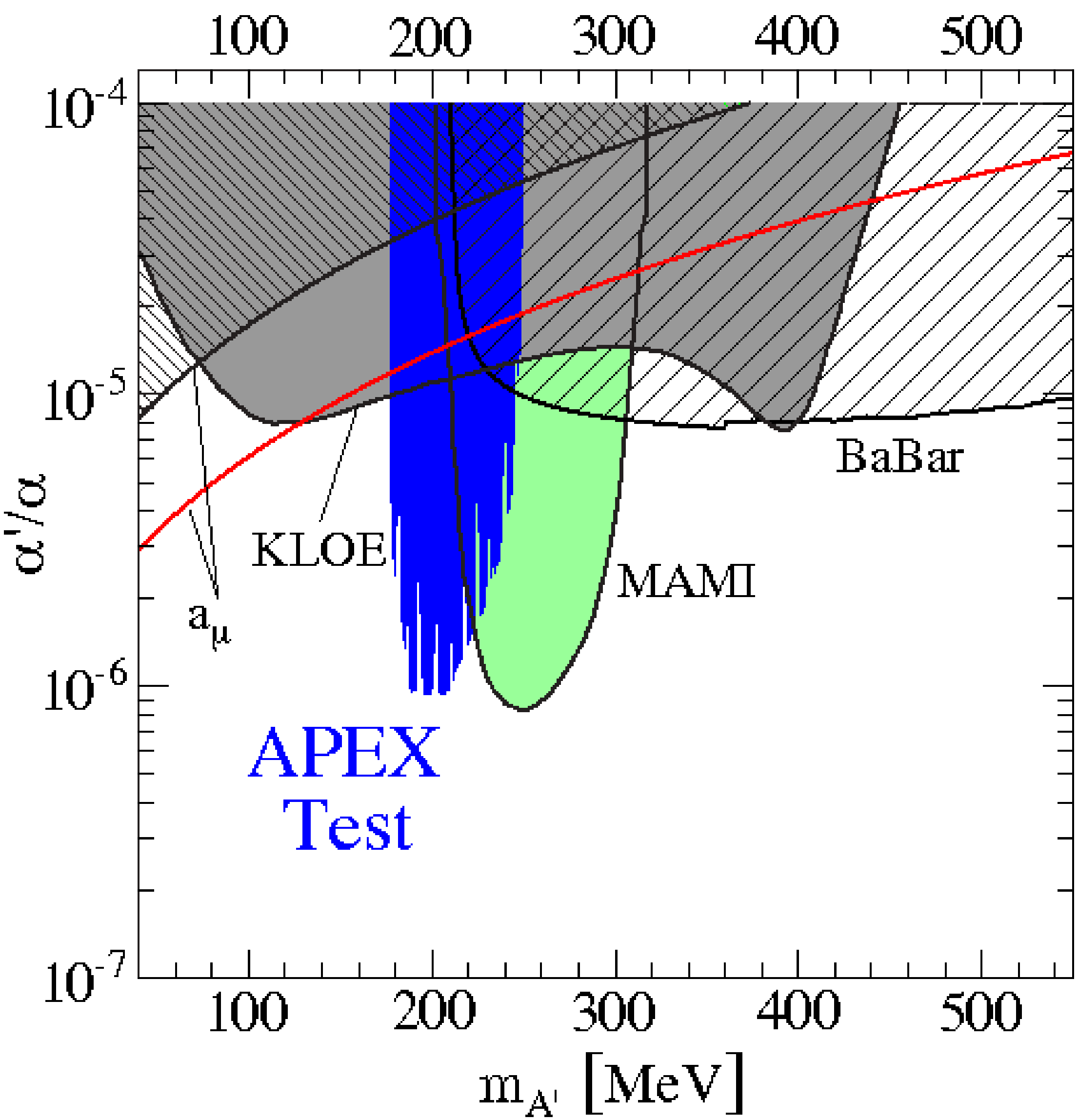
Also, KLOE-2 performed search, mostly for $\phi \to U\eta$: no signal. arXiv:1107.2531

A1 and APEX results



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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!

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- $\tilde{\nu}_R$ can be candidate in extended theories, e.g. with gauged $U(1)_{B-L}$ at TeV scale

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- but DM–allowed regions of parameter space do exist even in constrained models!

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

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- $\tilde{\tau}_1$ co–annihilation requires $m_{\tilde{q}} \leq m_{\tilde{g}}$: good for LHC searches; still plenty of allowed region left.

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- Most interesting to me: Predict $\Omega_\chi h^2$, compare with observation: Constrain very early universe!

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Two approaches: Case studies, broad scans of parameter space

Case study: $\tilde{\tau}_1$ co–annihilation region in cMSSM

Arnowitt et al., arXiv:0802.2968

- Needs $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} \leq 15$ GeV
  $\Longrightarrow \tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau,\ \tilde{\chi}_1^\pm \to \tilde{\tau}_1^\pm \nu_\tau$ have nearly unit branching ratio
  $\Longrightarrow$ no di–lepton edges!

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- $\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$ gives rather soft τ: Difficult to detect!
- Study three classes of final states:
  (i) $2\tau + 2j + \not{E}_T$
  (ii)$4 \ \mathrm{non} - b \ j + \not{E}_T$
  (iii) leading $b + 3j + \not{E}_T$

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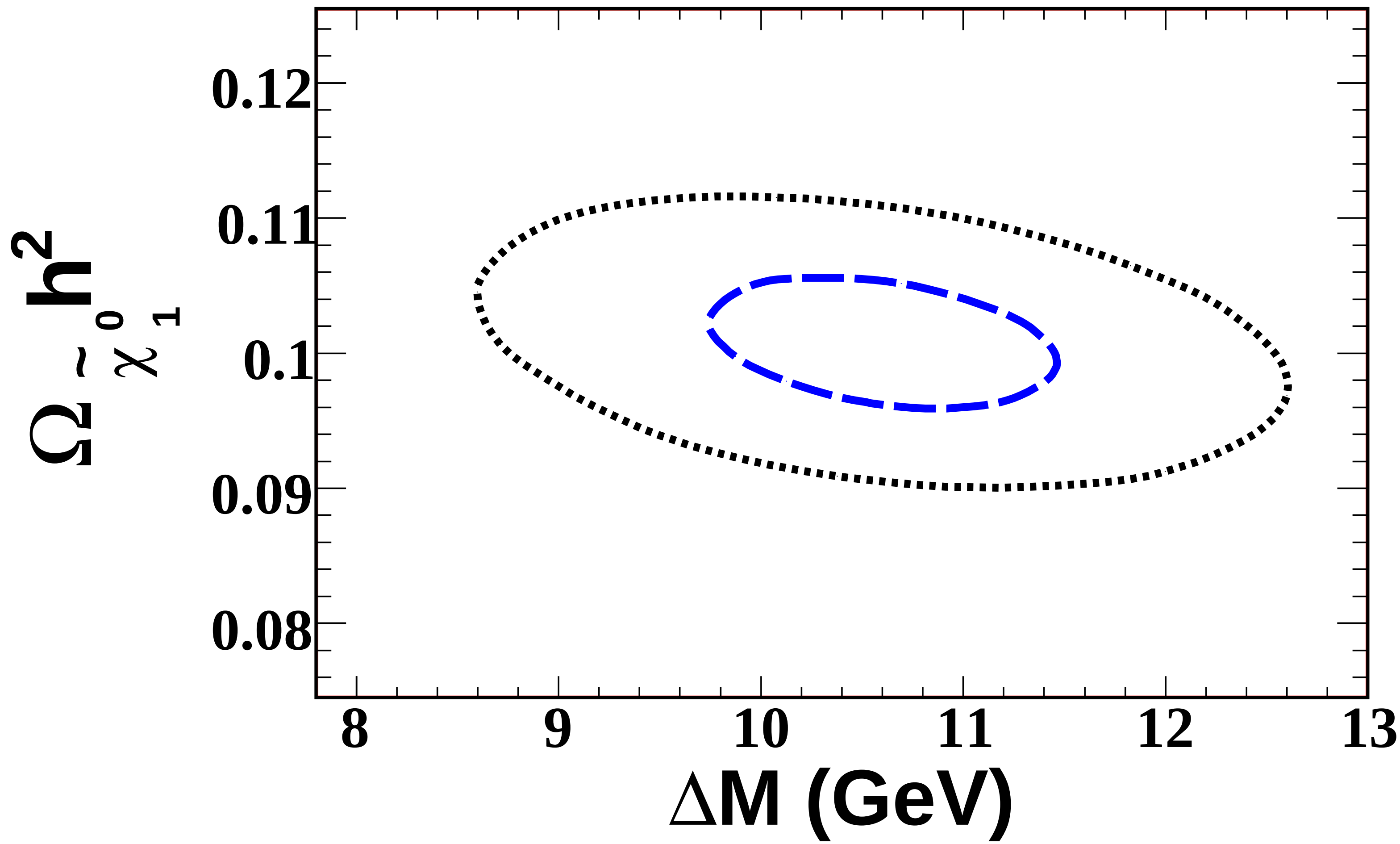
Arnowitt et al., arXiv:0802.2968

- Needs $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} \leq 15$ GeV
  $\Longrightarrow \tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau, \ \tilde{\chi}_1^{\pm} \to \tilde{\tau}_1^{\pm} \nu_\tau$ have nearly unit branching ratio
  $\Longrightarrow$ no di–lepton edges!
- $\tilde{\tau}_1 \to \tilde{\chi}_1^0 \tau$ gives rather soft τ: Difficult to detect!
- Study three classes of final states:
  (i) $2\tau + 2j + \not{E}_T$
  (ii)$4 \text{ non} - b \ j + \not{E}_T$
  (iii) leading $b + 3j + \not{E}_T$
- Fit many kinematical distributions simultaneously, including slope of softer p_T^τ spectrum in sample (i) $\Longrightarrow$ predict $\Omega_{\tilde{\chi}_1^0} h^2$ to 10%!

Result of fit



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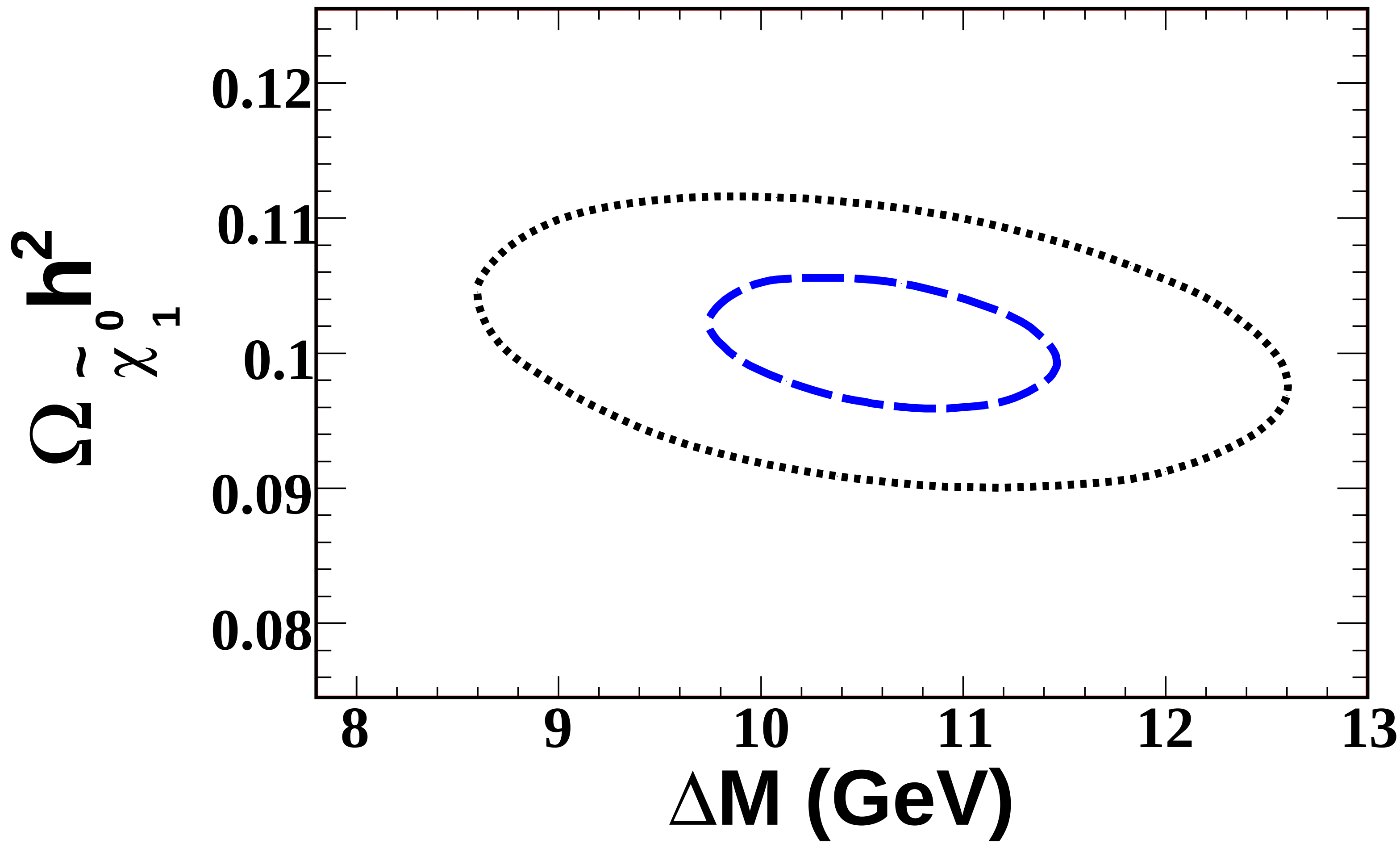

Unfortunately, chosen benchmark point ($m_{\tilde{g}} = 830$ GeV, $m_{\tilde{q}} \simeq 750$ GeV) is most likely excluded!

Scan of Parameter Space

Arkani-Hamed et al., hep-ph/0512190

15 parameter description of weak–scale MSSM

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$$(\Delta S_{AB})^2 = \frac{1}{n_{\rm sig}} \sum_{i=1}^{n_{\rm sig}} \left(\frac{s_i^A - s_i^B}{\sigma_i^{AB}} \right)^2$$

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MC: $(\Delta S_{AB})^2 > 0.285 \Longrightarrow$ models differ at > 95% c.l.

Results and Remarks

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- Statistics looks weird! Comparing two simulations of same “model”, get 611 (out of 2600) cases where some 2ℓ observable has $> 5\sigma$ discrepancy: *way* too many!

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Bornhauser and MD, in progress

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- Define proper χ^2, incl. corr. between $\langle n_j \rangle$, $\langle n_j^2 \rangle$, only including significant observables: test with MC.

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- With systematic errors and background: 71 pairs have $p > 0.05$.

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- Higgs searches can also be used to distinguish between WIMP models and to help determine parameters. E.g. m_h in MSSM constrains stop sector.

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- “Asymmetric Dark Matter” doesn’t explain $\Omega_{\rm DM} \simeq 5\Omega_{\rm baryon}$

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- Higgs sector also very important for WIMP physics!