Candidates for Inelastic Dark Matter

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with

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(See also talks by S.Chang, N.Weiner, I. Yavin)

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Toto, we're not at SPS1a' anymore

Surprises in Dark Matter

- DAMA observes an annual modulation signal.

- PAMELA, ATIC, PPB-BETS, INTEGRAL, and WMAP find signals above the expected astrophysical background.

Dark matter in our galaxy?

- None of these signals is what we were expecting:

  - DAMA "seems" inconsistent with CDMS.

  - PAMELA *et al.* need a high annihilation rate and leptons.

  - INTEGRAL requires very light or exciting DM.

Annual Modulation at DAMA

- The Earth encounters a varying DM flux due to its annual motion around the Sun. [Drukier,Freese,Spergel '86]

  DM-nucleus recoil rate $\propto$ DM flux.

- DAMA/NaI and DAMA/LIBRA searched for an annual variation in nuclear recoils using NaI-based detectors.
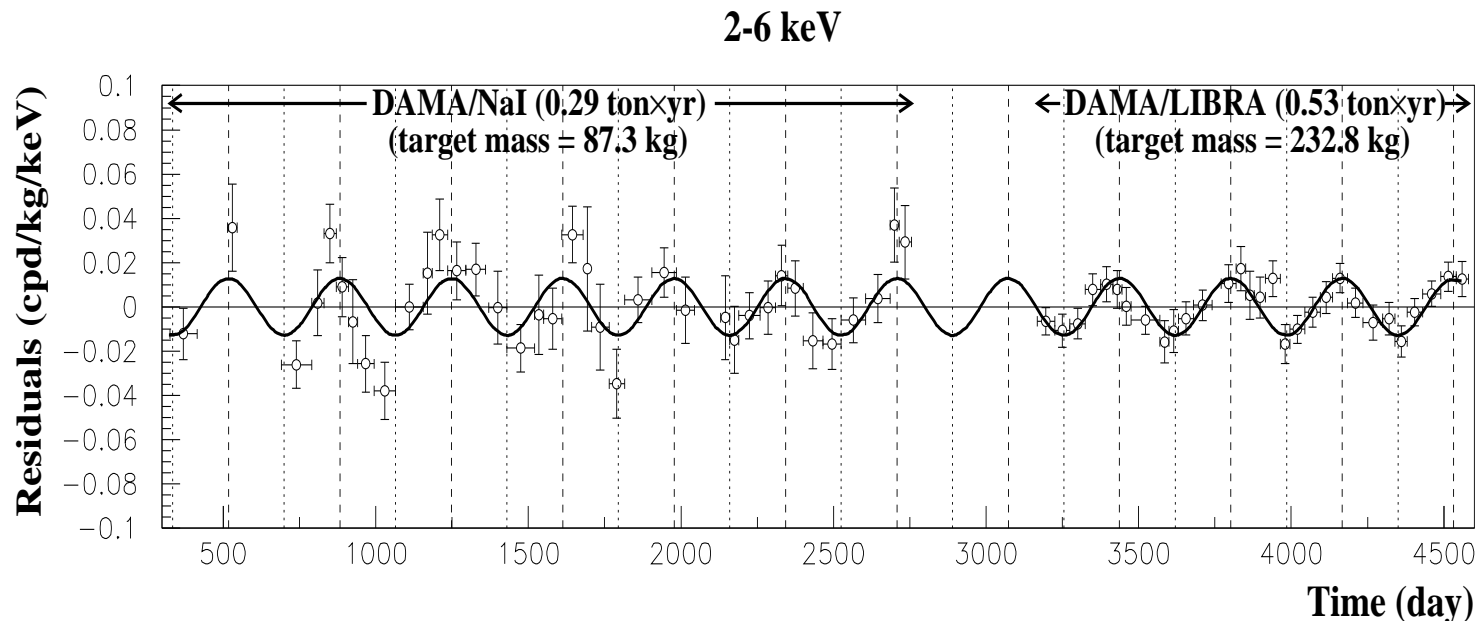
Explanations for DAMA

- Focus exclusively on DAMA, assume it is DM.
  What does this imply about the DM properties?

- Ordinary coherent DM scattering off Iodine is ruled out.
  Light DM scattering off Sodium is strongly constrained.
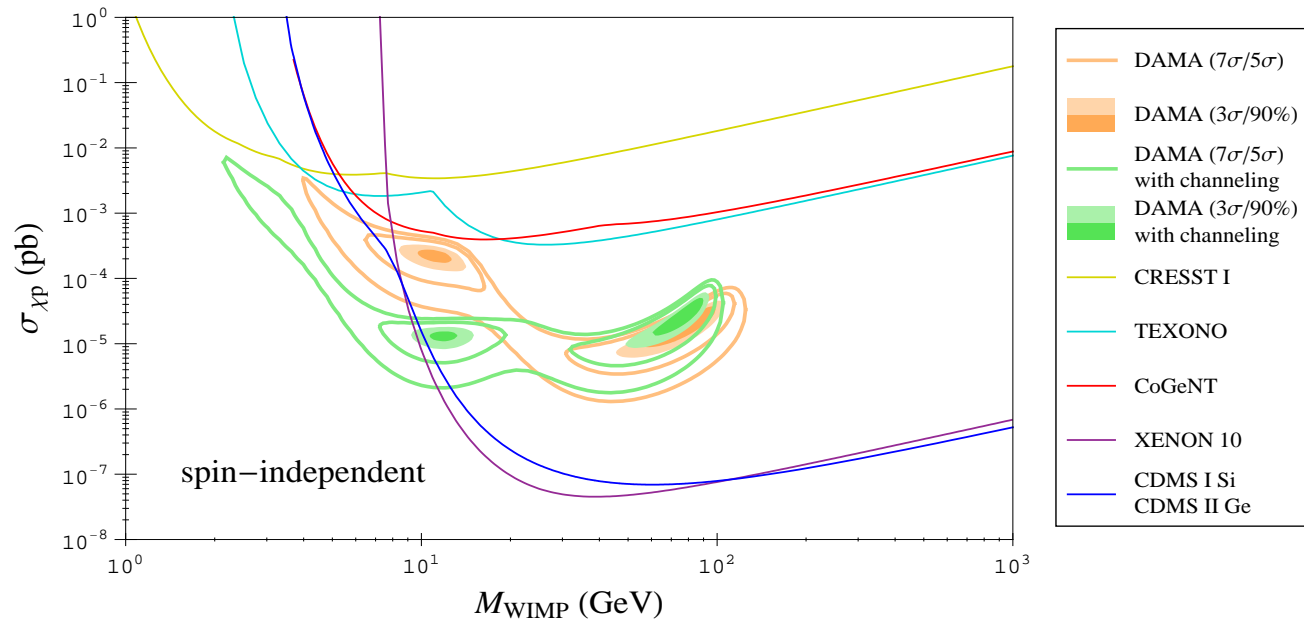
[Freese,Gelmini,Gondolo,Savage '08]

- Light DM is constrained by the shapes of the DAMA modulated and unmodulated energy spectra.

[Chang,Pierce,Weiner '08]
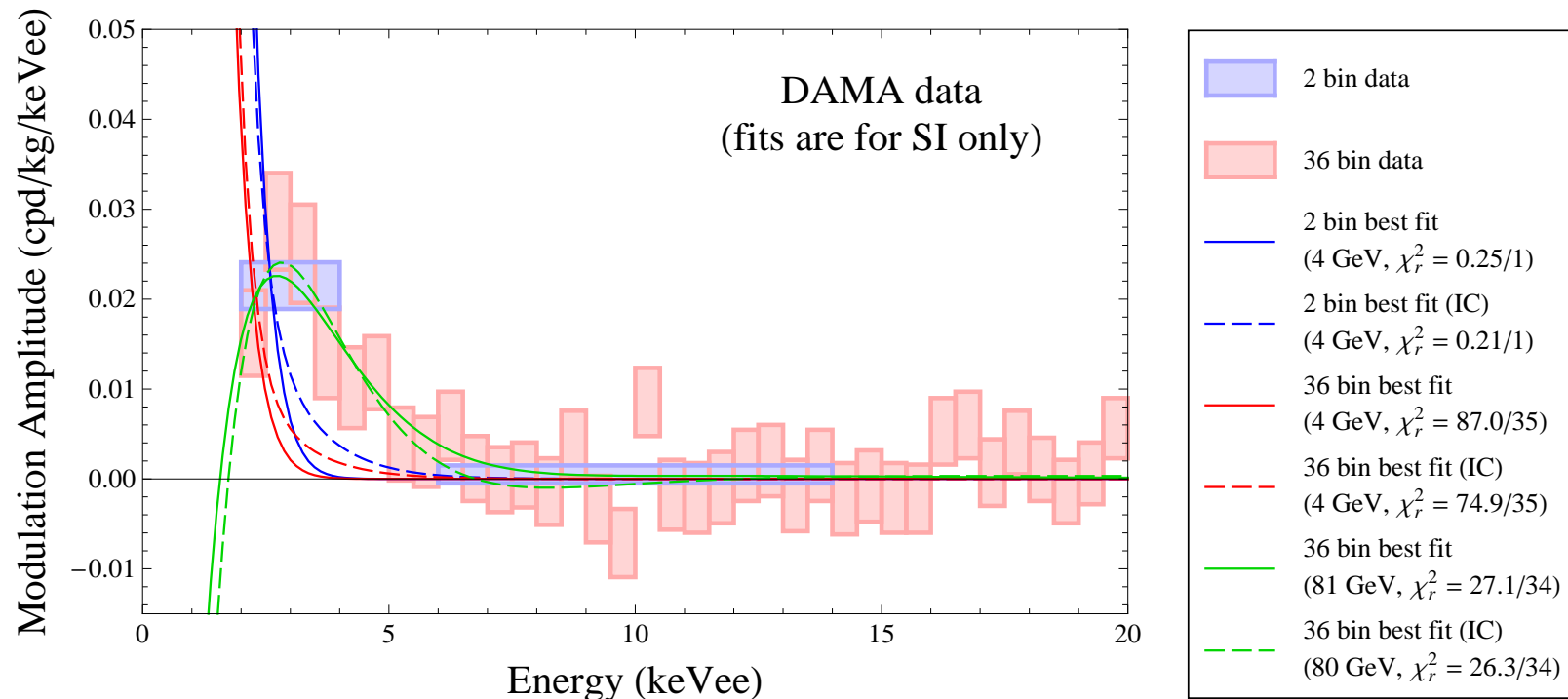
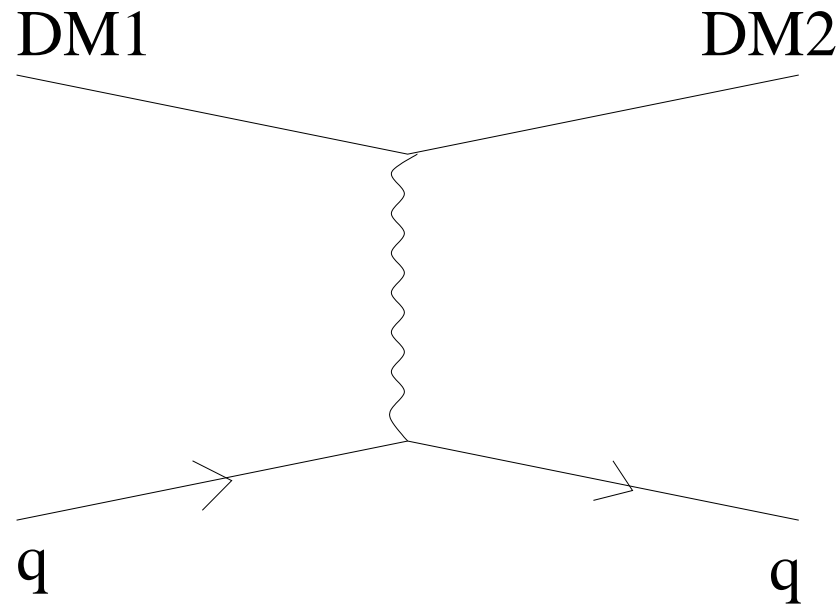

[Freese,Gelmini,Gondolo,Savage '08]

- Scattering of DM off detector electrons? [Bernabei *et al.* '07]
  Also very constrained by the DAMA spectral shape.

Inelastic Dark Matter (IDM)

- Assumption: DM scatters coherently off nuclei preferentially into a slightly heavier state. [Tucker-Smith+Weiner '01]

$$M_{DM2} - M_{DM1} = \delta > 0$$

- Modified scattering kinematics enhances the modulated signal at DAMA and fixes the spectrum.

- To produce a nuclear recoil with energy E_R, the minimum DM velocity is

$$v_{min} = \frac{1}{\sqrt{2m_N E_R}} \left(\frac{m_N E_R}{\mu_N} + \delta \right).$$

- Signal Rate:

$$\frac{dR}{dE_R} \propto \int_{v_{min}} d^3v \, f(\vec{v}, \vec{v}_e) \, v \, \frac{d\sigma}{dE_R}.$$

- DM velocities are $\sim$ Maxwellian with a cutoff v_{esc}, with a net boost from the motion of the Earth:

$$f(\vec{v}, \vec{v}_e) = 0 \quad \text{unless} \quad |\vec{v} + \vec{v}_e| < v_{esc}.$$

- IDM: v_{min} is less for I ($A \simeq 127$) than for Ge ($A \simeq 72$). $\Rightarrow$ enhancement at DAMA relative to CDMS.

- IDM kinematics enhances the annual modulation.

- The signal is cut off at low E_R.
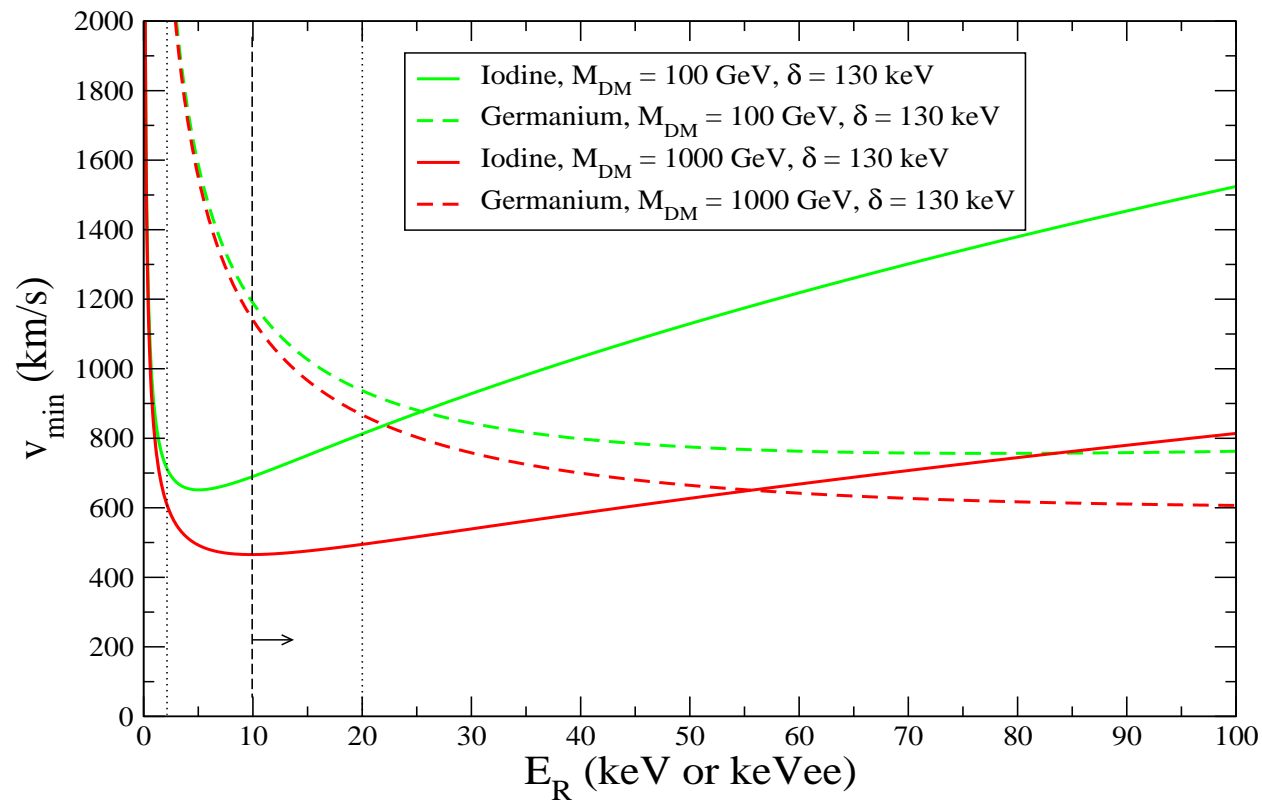
- Which IDM parameters fit the data?

- Where could IDM come from? LHC implications?

IDM vs. Data

IDM Fits

- DAMA (I)
  - lowest twelve 2-8 keV bins only
  - χ^2 *goodness of fit* estimator

- CDMS II (Ge)
  - combine 3 runs
  - treat events (2) in 10-100 keV as signal

- CRESST-II (W)
  - use latest commisioning run only
  - treat events (7) in 12-100 keV as signal

- ZEPLIN-III (Xe)
  - treat events (7) in 2-16 keVee as signal

- XENON, KIMS, *etc.* are less constraining.

- $M_{DM} = 100\,\text{GeV},\ 1000\,\text{GeV}$, 99 % $c.l.$ exclusion curves.

$M_{DM} = 100\,\text{GeV}, V_{esc} = 500\ \text{km/s}, \rho = 0.3\ \text{GeV/cm}^3$

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——— CDMS .... CRESST–II .... ZEPLIN–III
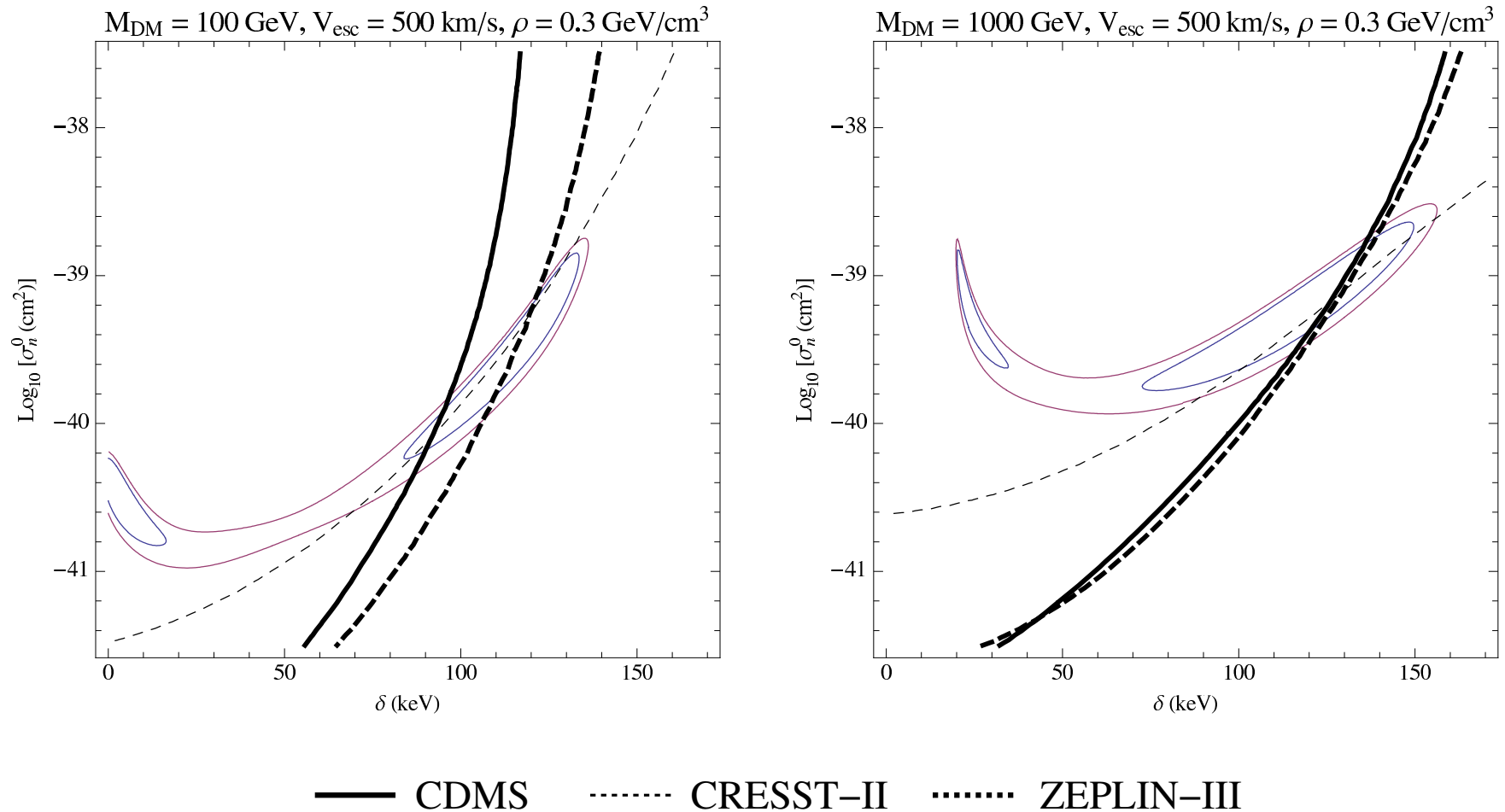
- Heavier IDM might work but is more constrained.

$$\text{Note:}\quad v_{min}(E_R) \rightarrow \frac{1}{\sqrt{2m_N E_R}}(E_R + \delta)\quad \text{for}\quad M_{DM} \gg m_N$$

- $v_{esc} = 500\,km/s,\ 600\,km/s,\ 99\,\%\,c.l.$ exclusion curves.

$M_{DM} = 1000\,\text{GeV}, V_{esc} = 500\,\text{km/s}, \rho = 0.3\,\text{GeV/cm}^3$

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—— CDMS ········ CRESST–II ········ ZEPLIN–III
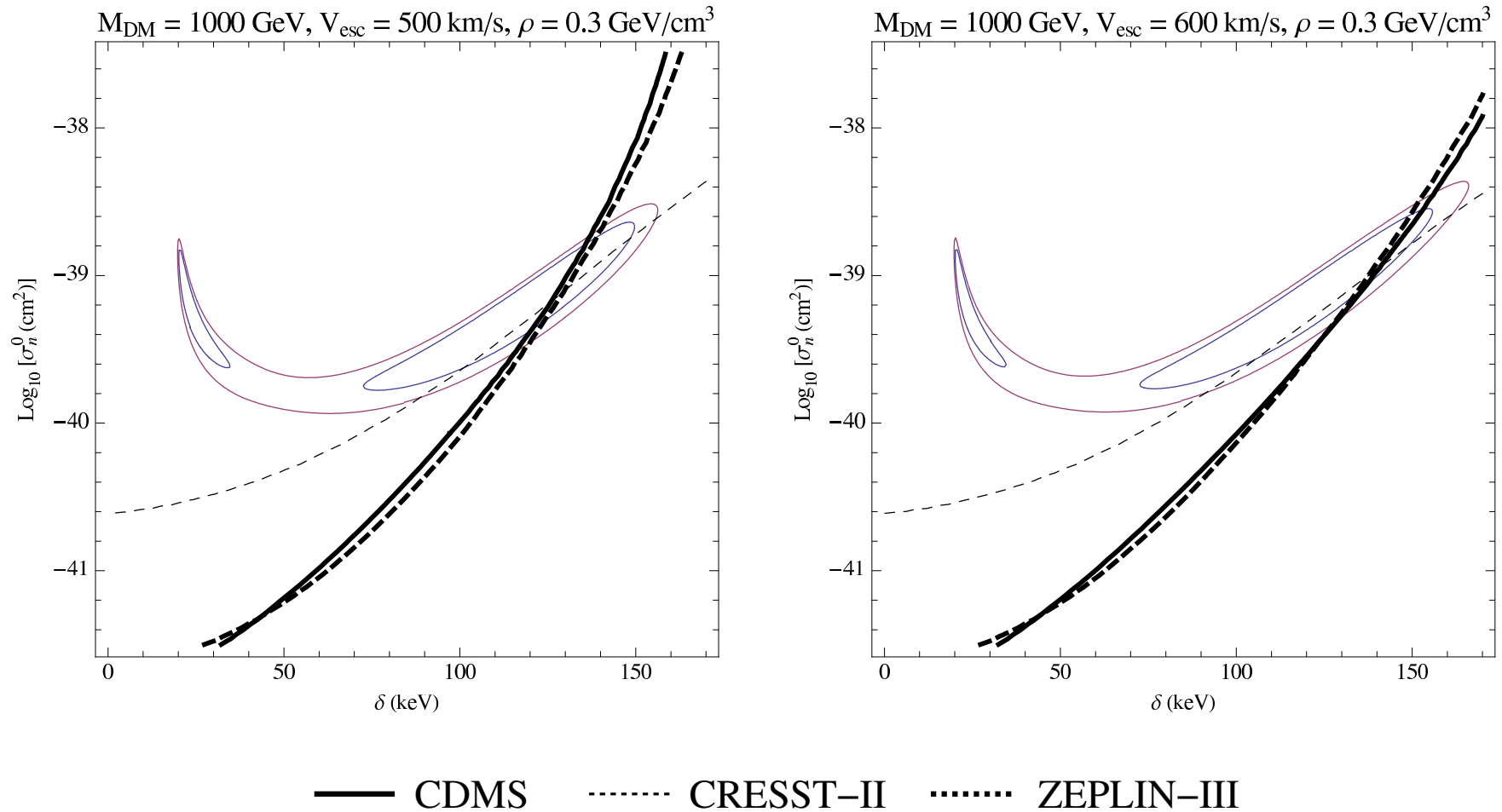
- Strong dependence on the DM velocity distribution.

[March-Russell, McCabe, McCullough '08]

General IDM Properties

General IDM Properties

- Inelastic nuclear recoils can arise naturally if:

  - nuclear scattering is mediated by a massive gauge boson

  - DM is a nearly Dirac fermion or complex scalar

  - a small mass splits the two components of the DM

e.g.

$$-\mathcal{L}_{mass} = M\,\bar{\psi}\psi + \frac{1}{2}m\,\bar{\psi}^c\psi, \quad \text{with} \quad M \gg m$$

$$= \frac{1}{2}(M-m)\bar{\Psi}_1\Psi_1 + \frac{1}{2}(M+m)\bar{\Psi}_2\Psi_2$$

$$-\mathcal{L}_{int} = -g\,Z'_\mu\bar{\psi}\gamma^\mu\psi = ig\,Z'_\mu\bar{\Psi}_2\gamma^\mu\Psi_1$$

- The complex scalar story is similar.
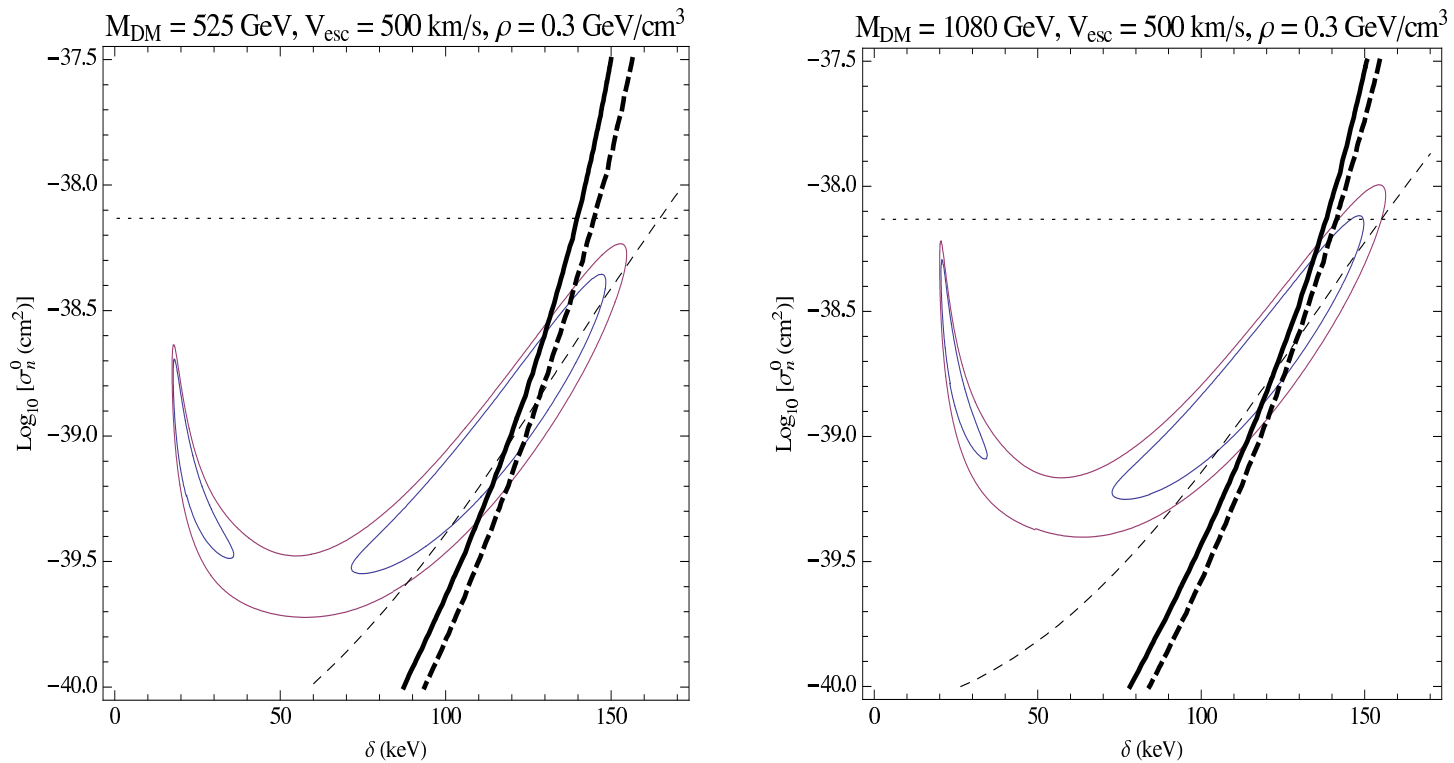
Nucleon Scattering from Gauge Bosons

- Elastic DM scattering mediated by the SM Z^0 is ruled out.

  $\rightarrow$ effective nucleon cross-sections $\sigma^0_{n,p}$ are too big:

$$\sigma^0_n = \frac{G_F^2}{2\pi}\mu_n^2 \simeq 7.44 \times 10^{-39}\, cm^2 \quad \text{(vector doublet)}$$

- IDM can only scatter in a limited region of phase space.

  $\rightarrow$ need a large nucleon cross-section $\sigma^0_{n,p}$.

- Three 'Abelian' possibilities:

  1. SM Z^0

  2. Heavy visible $U(1)_x$

  3. Light hidden $U(1)_x$

1. IDM Scattering through the SM Z^0

- Dirac Doublet: $M_{DM} \simeq 1080\,\text{GeV} \Rightarrow \Omega_{DM}\,h^2 \simeq 0.1$.

- Scalar Doublet: $M_{DM} \simeq 525\,\text{GeV} \Rightarrow \Omega_{DM}\,h^2 \simeq 0.1$.

$M_{DM} = 525\,\text{GeV},\, V_{esc} = 500\,\text{km/s},\, \rho = 0.3\,\text{GeV/cm}^3$

$M_{DM} = 1080\,\text{GeV},\, V_{esc} = 500\,\text{km/s},\, \rho = 0.3\,\text{GeV/cm}^3$

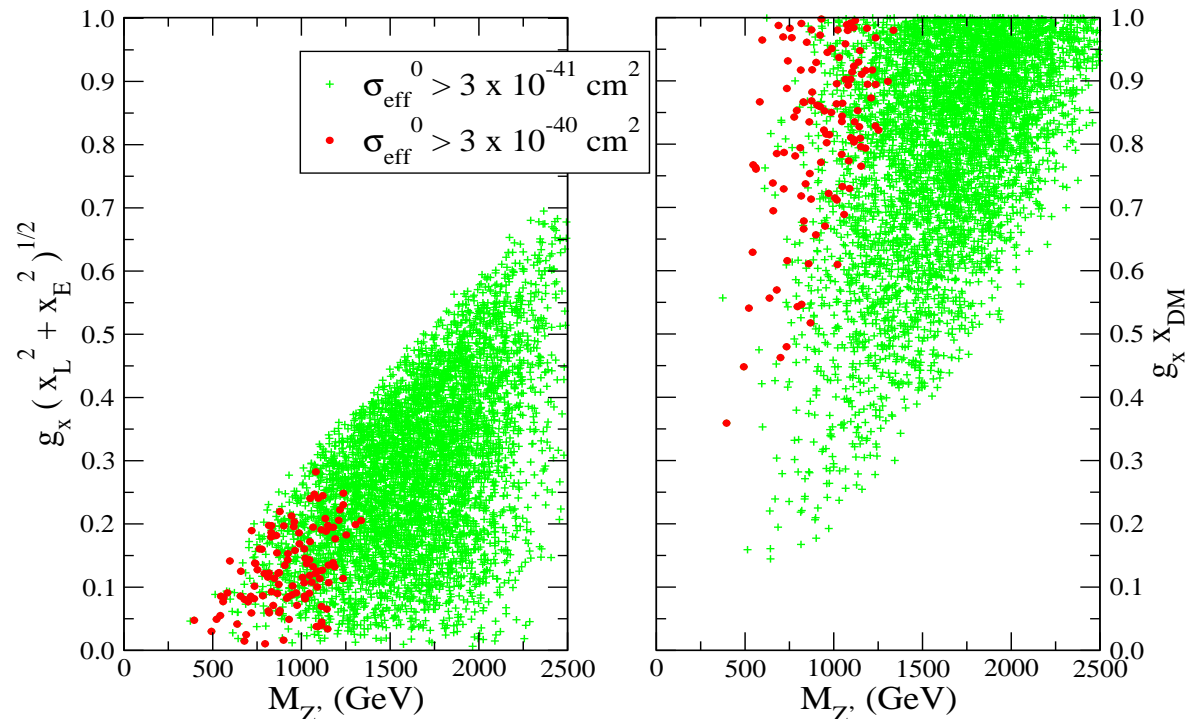——— CDMS   ········ CRESST–II   ······· ZEPLIN–III

- DAMA-allowed region is close to σ_n^0 for a doublet.

2. IDM Scattering through a Visible $U(1)_x$

- Visible Z's constrained by Tevatron, Precision Electroweak.

  $\rightarrow$ heavier $M_{Z'}$ is preferred

- But $\sigma^0_{n,p} \propto \left(\dfrac{g_x}{M'_Z} \right)^4$

  $\rightarrow M_{Z'}$ cannot be too large for IDM scattering

3. IDM Scattering through a Light Hidden $U(1)_x$

- Can arise if SM couplings come only from kinetic mixing,

$$\mathcal{L} \supset -\frac{1}{2}\,\epsilon\,B_{\mu\nu}X^{\mu\nu}.$$

  $\epsilon \sim 10^{-4}\text{--}10^{-2}$ from integrating out heavy states. [Holdom '86]

- $U(1)_x$ effectively mixes with $U(1)_{em}$ for $M_{Z'} \ll M_{Z^0}$.

  SM states acquire Z' couplings of $-e\,c_W\,Q\,\epsilon$.

$$\sigma_p^0 = \left(\frac{g_x\,x_{DM}}{0.5}\right)^2 \left(\frac{\text{GeV}}{M_{Z'}}\right)^4 \left(\frac{\epsilon}{10^{-3}}\right)^2 (2.1 \times 10^{-36}\,cm^2)$$

- A multi-GeV mass Z' is allowed for $\epsilon \lesssim 10^{-2}$ [Pospelov '08]

Some IDM Models

Candidates for IDM

- Need a large "Dirac" mass $M \sim 100\,\text{GeV}$,

  and a small "Majorana" mass $m \sim 100\,\text{keV}$.

- Technically Natural: m breaks a global $U(1)_{DM}$ symmetry.

- Can arise from sneutrinos with small L violation.

  [Tucker-Smith+Weiner '01]

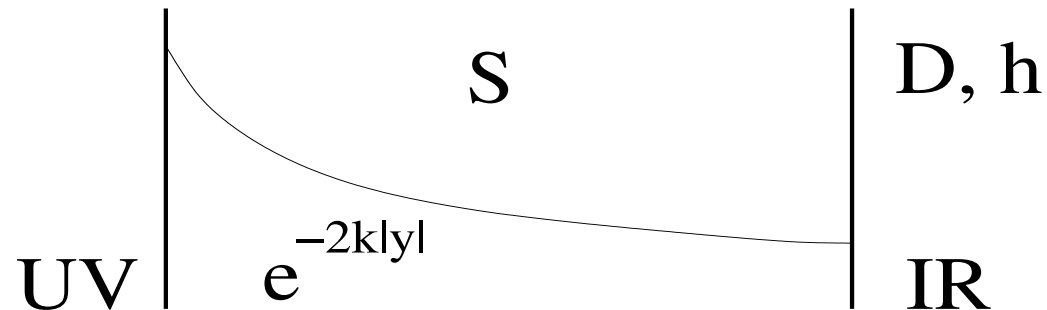- Some Other Candidates:

  1. Warped fermion seesaw IDM

  2. Warped scalar IDM

  3. Supersymmetric Doublet IDM

  4. Hidden Sector $U(1)_x$ IDM [Arkani-Hamed+Weiner '08, I.Yavin's talk]

1. Warped Fermion Seesaw

- Dirac Doublet $D = (D_L, D_R)$ on the IR brane.

  Dirac Singlet $S = (S_L, S_R)$ in the bulk.

  Both are odd under a $\mathbb{Z}_2$.

- Couplings:

Bulk:	$c\,k\,\bar{S}S$
IR Brane:	$\lambda\,(\bar{D}_R S_L\, h + h.c.) + M\bar{D}D$
UV Brane:	$\dfrac{d_{UV}}{2}(\bar{S}_L^c S_L + h.c.)$

- $U(1)_{DM}$ is broken only on the UV brane.

- Choose B.C.s such that S_L has a zero mode for $d_{UV} = 0$.

- Zero mode gets mass from the UV brane mass.

  KK modes get mass primarily from the Dirac bulk mass.

  $\Rightarrow$ integrate out S_L^0 to get the inelastic splitting:

$$-\mathcal{L} \supset -\frac{\lambda^2}{2d_{UV}}e^{-(c-1/2)\pi kR}\,hh\,\bar{D}_R^c D_R + h.c.$$

- With natural values $\lambda^2 = 1/M_{Pl}$, $c = 0.13$, $d_{UV} = 2$,

  we find $\delta \simeq 100\,\text{keV}$, mostly doublet DM.

- This model is similar to warped neutrino mass models.

  [Huber+Shafi '03, Perez+Randall '08]

2. Warped Scalar IDM

- Scalar Doublet $D = (D_R + iD_I)/\sqrt{2}$ on the IR brane.

  Scalar Singlet $S = (S_R + iS_I)/\sqrt{2}$ in the bulk.

  Both are odd under a $\mathbb{Z}_2$ discrete symmetry.

- Couplings:

$$
\begin{array}{ll}
\text{Bulk:} & a\,k\,|S|^2 \\[1em]
\text{IR Brane:} & (\lambda\,e^{2\pi kR}DS^*h + h.c.) + M^2|D|^2 \\[1em]
\text{UV Brane:} & \dfrac{m_{UV}}{2}(S^2 + h.c.)
\end{array}
$$

- $U(1)_{DM}$ is broken only on the UV brane.

- No scalar zero mode in general.

- UV brane mass modifies the B.C.s:

$$\partial_y S_{\substack{R \\ I}} \mp m_{UV} S_{\substack{R \\ I}} = 0|_{y=0}$$

$$\partial_y S_{\substack{R \\ I}} = 0|_{y=\pi R}.$$

$\Rightarrow$ splits the masses and profiles of S_R, S_I.

- Integrating out S KK modes yields a mass splitting for D. From the n-th KK mode:

$$\Delta m_D \sim \frac{v^2}{M} \left(\frac{1}{kR}\right) e^{-2\pi kR(2+\sqrt{4+a})} f_n^2(\pi R).$$

- Inelastic splitting requires $kR \sim 2$.

$\Rightarrow$ Little RS [Davoudiasl,Perez,Soni '08; McDonald '08]

3. Supersymmetric Fermion Doublet IDM

- Idea: gauge $U(1)_{DM} \to U(1)_z$.

- Chiral Doublets D, D^c

  Chiral SM Singlets S, N

  $$W \supset \lambda\, N\, H_u{\cdot}H_d + \lambda'\, S\, H_d{\cdot}D + \frac{\xi}{2}\, N\, S^2 + \zeta\, N\, DD^c.$$

  Only these couplings are allowed by $U(1)_z$ charges.

- $N \to \langle N \rangle \sim$ TeV induced by SUSY breaking.

  Integrate out S:

  $$W_{eff} \supset -\frac{\lambda'^2}{2\xi\,\langle N \rangle}\, (D{\cdot}H_d)^2$$

- Fermion splitting for $\lambda' \sim 0.1$, $\tan\beta \sim 30$, $\xi\,\langle N \rangle \sim$ TeV.

- Scalar mass splitting is a bit too big.

4. Hidden $U(1)_x$ SUSY IDM

- Models #1.−3. carry over to heavy visible $U(1)_x$ models.

- SUSY is a natural setting for a light hidden $U(1)_x$.
  Gauge mediation in the visible sector breaks SUSY
  in the hidden sector through kinetic mixing, [Zurek '08]

$$m_{hid} \sim \epsilon\, m_{E^c},$$
$$M_{\tilde{Z}'} \sim \epsilon^2\, M_1.$$

- $U(1)_x$ breaking can be induced by soft masses,
  D-terms $(\sim \sqrt{\epsilon}\, v)$ naturally on the order of a GeV.

- D-terms can also contribute to hidden SUSY breaking.

[Baumgart *et al.* '09, talks by L.-T. Wang, I. Yavin]

- Minimal hidden $U(1)_x$ IDM Model:

$$W \supset \mu' \, H \, H^c + M_a \, a \, a^c + \frac{1}{2} M_s \, S^2 + \lambda_1 \, S \, a^c \, H + \lambda_2 \, S \, a \, H^c,$$

- IDM from a, a^c if $M_s \sim M_a \sim$ TeV, $\langle H^{(c)} \rangle \sim \mu' \sim$ GeV.

- a, a^c, S must be stabilized by a new symmetry.

  Residual unbroken $\mathbb{Z}_2$ subgroup of $U(1)_x$? [Hur,Lee,Nasri '07]

- Multi-μ Mystery: $\mu' \ll M_s, M_a$?

  − $\mu' \sim$ GeV from an NMSSM-mechanism in hidden sector.

    [Zurek '08, Chun+Park '08]

  − $M_a \sim M_s \sim$ TeV from an NMSSM in the visible sector.

    $\rightarrow$ additional contributions to hidden SUSY breaking

Summary

- Inelastic DM can be consistent with the DAMA signal
  and other direct detection experiments.

- Heavier DM masses can also work, but are more constrained.

- IDM scattering can be mediated by the Z^0,
  a heavy visible Z', or a light hidden Z'.

- Reasonable models for IDM can arise in RS, SUSY.

Extra Slides

DM Scattering off Electrons

- DM scattering off detector *electrons*? [Bernabei *et al.* '07]

  Would generate a signal at DAMA.

  Other DM detectors filter out electromagnetic events.

- $E_R \sim$ eV for Halo DM scattering off an electron at rest.

- $E_R \sim$ keV possible if the electron is boosted: $p_e \sim$ MeV.

  At large p_e, $P(p_e) \propto p_e^{-8}$ in atoms.

$$\left.\frac{dR}{dE_R}\right|_{tot} = \int dp\, P(p)\, \frac{dR}{dE_R}(p_e = p)$$

$$v_{min}^{DM} \simeq \frac{E_R}{2p}$$

- Signal falls quickly with E_R, like light DM. [Chang,Pierce,Weiner '08]

- For fermion DM with $(V \pm A)$ couplings to quarks:
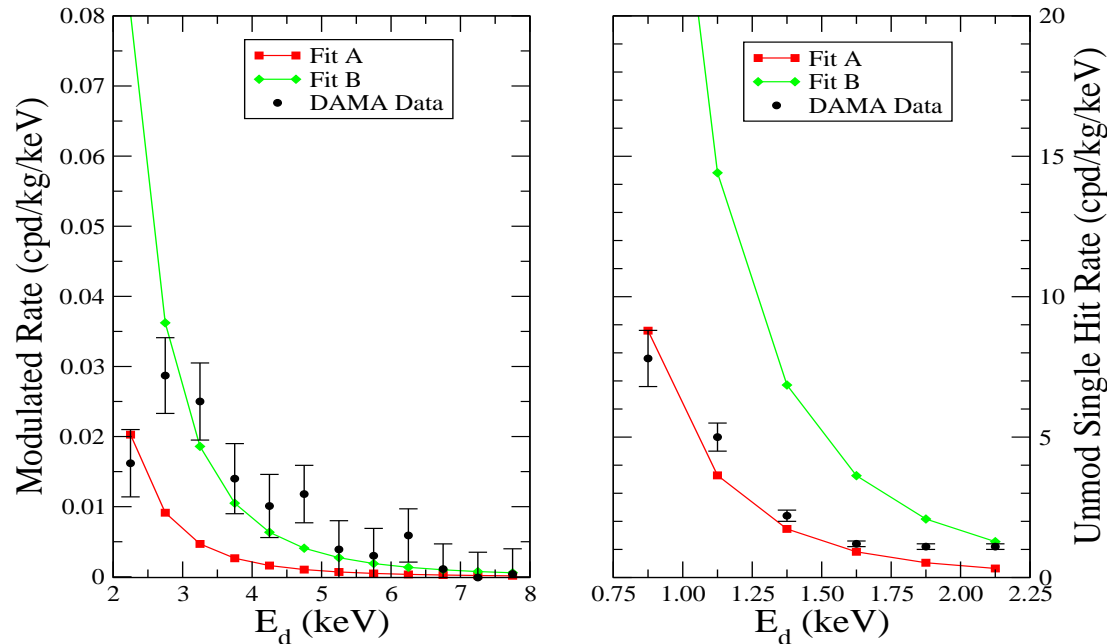
- Using 12 lowest (2-12 keVee) modulated bins,
  6 lowest (0.875-2.125 keVee) unmodulated bins,
  fit is very poor. $(> 99\%$ exclusion using $\chi^2)$

- Similar conclusion for other Dirac structures, scalar DM.