Surprises in (Inelastic) Dark Matter

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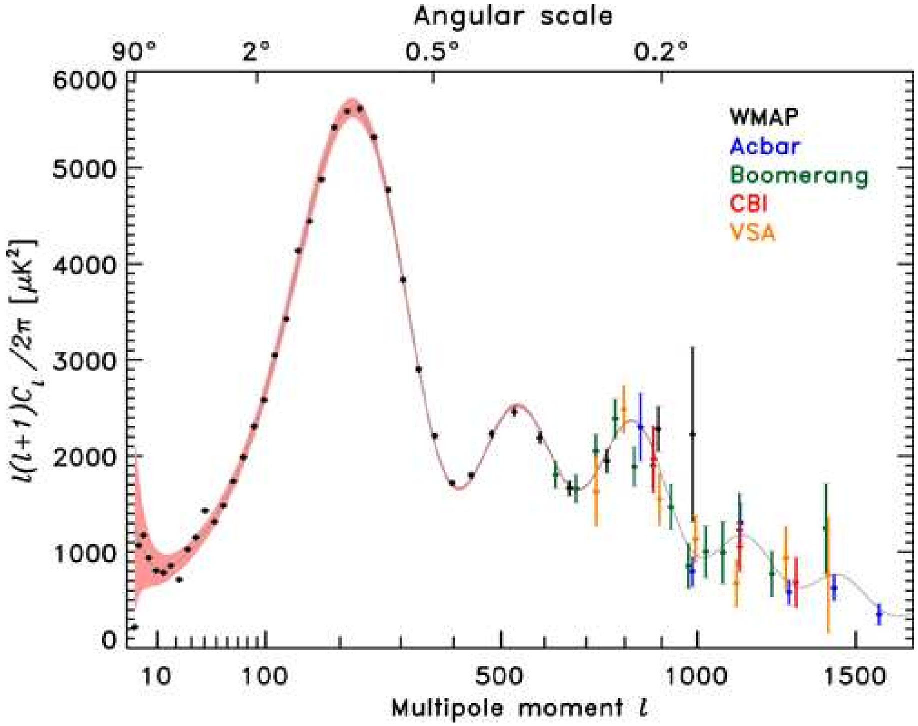
Outline

- Evidence and Hints for Dark Matter (DM)
- DAMA and Inelastic DM
- Inelastic DM vs. Data
- General IDM Properties
- Candidates for IDM

Evidence and Hints
for Dark Matter

Gravitational Evidence for Dark Matter

- CMB TT:



- Shape depends on the total matter and baryon densities:

$$\Omega_{matter}h^2 = 0.134 \pm 0.006, \quad \Omega_{baryons}h^2 = 0.0227 \pm 0.0006.$$

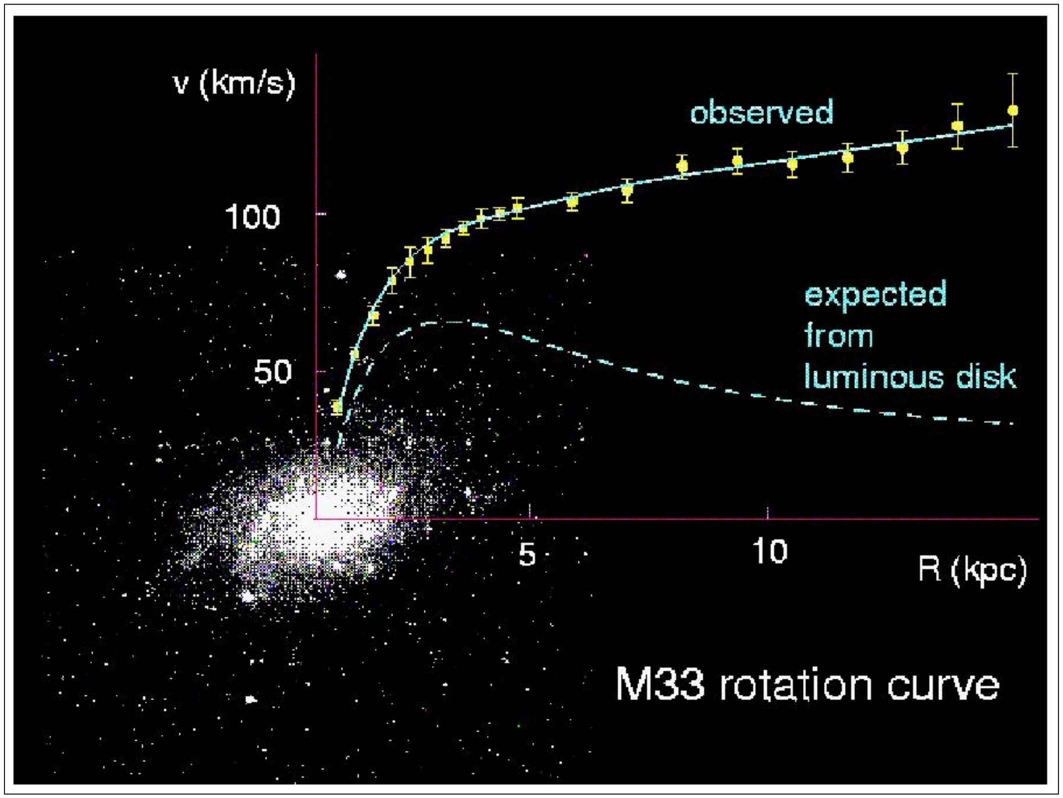
- The difference is the dark matter density:

$$\Omega_{DM}h^2 = 0.111 \pm 0.006.$$

- Dark matter is required to explain galaxy formation.

- Gravitational lensing probes suggest DM.

- Galactic rotation curves:



[Corbelli *et al.*]

Dark Matter and New Physics

- No Standard Model particle can be the DM.
- A new heavy stable particle can generate the DM.

  → falls out of thermal equilibrium and remains as a relic

  → "thermal freeze-out"
- Thermal relic DM density:

$$\Omega_{DM}^{therm} h^2 \simeq \frac{T_0^3}{H_0^2 M_{\mathrm{Pl}}^3} \frac{1}{\langle \sigma\, v \rangle}$$

$$\sim 0.1 \left(\frac{m_{DM}}{1000\,\mathrm{GeV}} \right)^2 \quad \text{for} \quad \langle \sigma\, v \rangle \sim \frac{g^4}{m_{DM}^2}.$$

DM from new physics stabilizing the ElectroWeak scale?

DM production at the LHC?

Non-Gravitional Dark Matter Signals

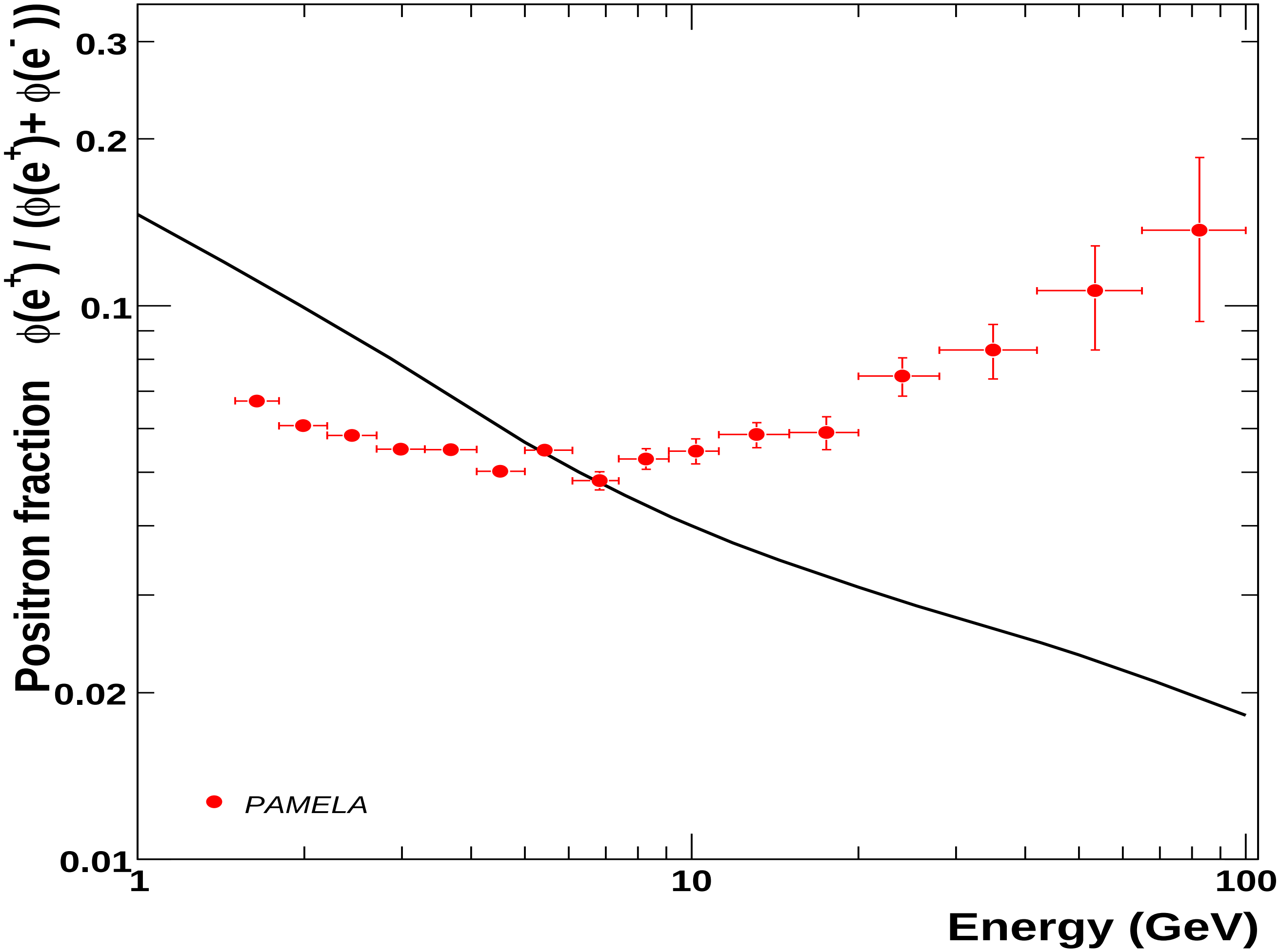
- Dark matter in our galaxy can annihilate producing cosmic rays, photons, and neutrinos.
  "Indirect Detection"
  PAMELA, ATIC, INTEGRAL, WMAP see excess fluxes.

- Dark matter around us can be detected directly by its scattering off nuclei.
  "Direct Detection"
  DAMA observes unexplained nuclear recoils.

- If these signals are from DM, the new particle must have some surprising properties.

PAMELA - Cosmic Ray Positrons

- PAMELA sees an an excess of e^+ over background.



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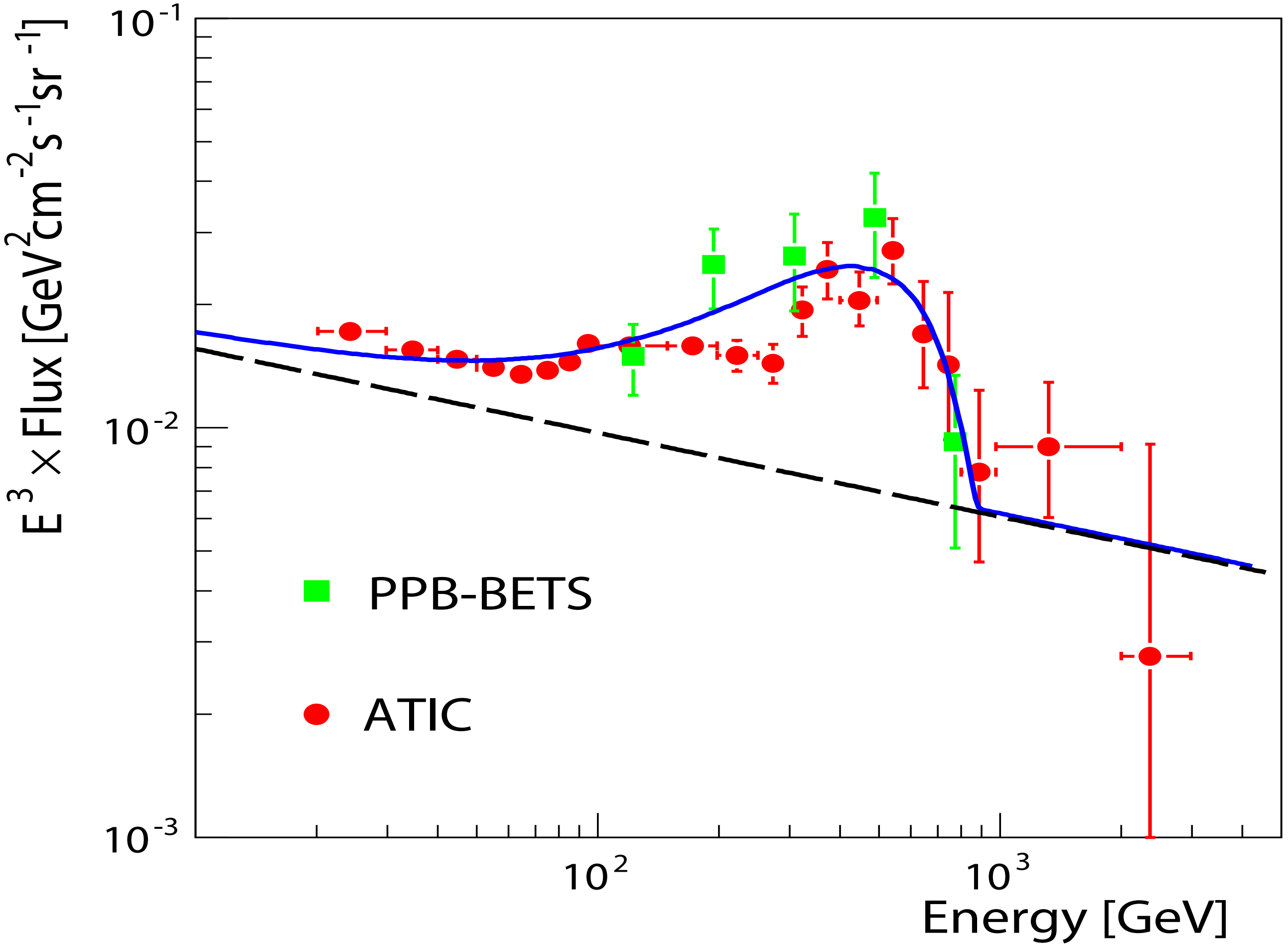
- No excess flux of anti-protons is observed.

ATIC and PPB-BETS - Cosmic Ray Electrons

- These experiments see excess $(e^+ + e^-)$ fluxes.



[Hamaguchi, Shirai, Yanagida '08]

- Spectral shape - the signal falls off for $E \gtrsim 700\,\mathrm{GeV}$.

Dark Matter Implications

- Dark Matter annihilation can account for these signals.
- Implications:

1. PAMELA+ATIC+PPB-BETS Spectrum:

   $\Rightarrow M_{DM} \gtrsim$ 700 GeV $\quad$ ($M_{DM} \gtrsim$ 100 GeV for PAMELA)

2. PAMELA does not see excess anti-protons:

   $\Rightarrow$ DM annihilates mostly into leptons.

3. PAMELA+ATIC+PPB-BETS event rate:

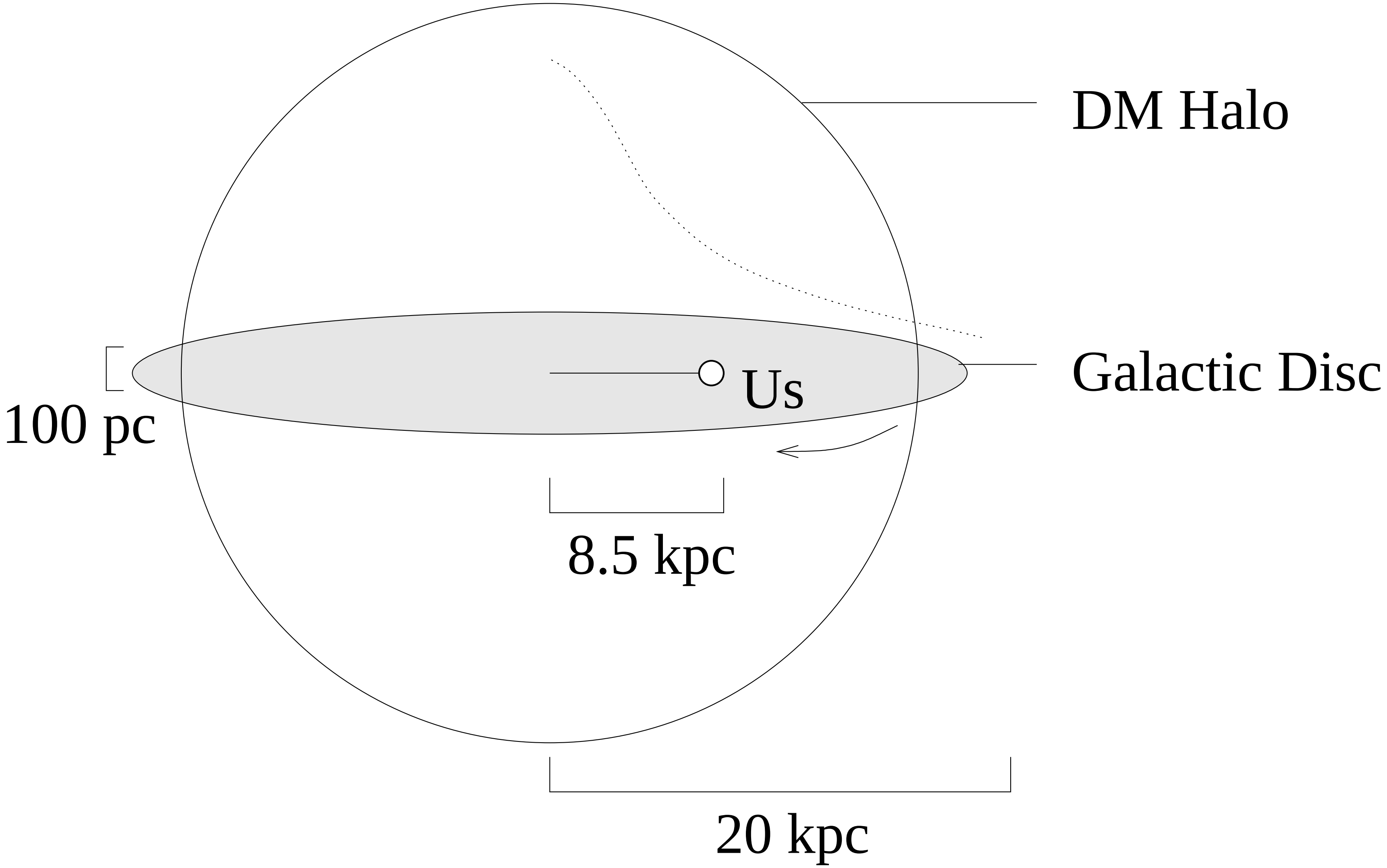
   $\Rightarrow \langle \sigma\, v \rangle^{today} > x\, \langle \sigma\, v \rangle^{freeze-out}$ for thermal freeze-out.

   ($x \gtrsim$ 10 for PAMELA, $x \gtrsim$ 100 for ATIC)

DAMA and Inelastic Dark Matter

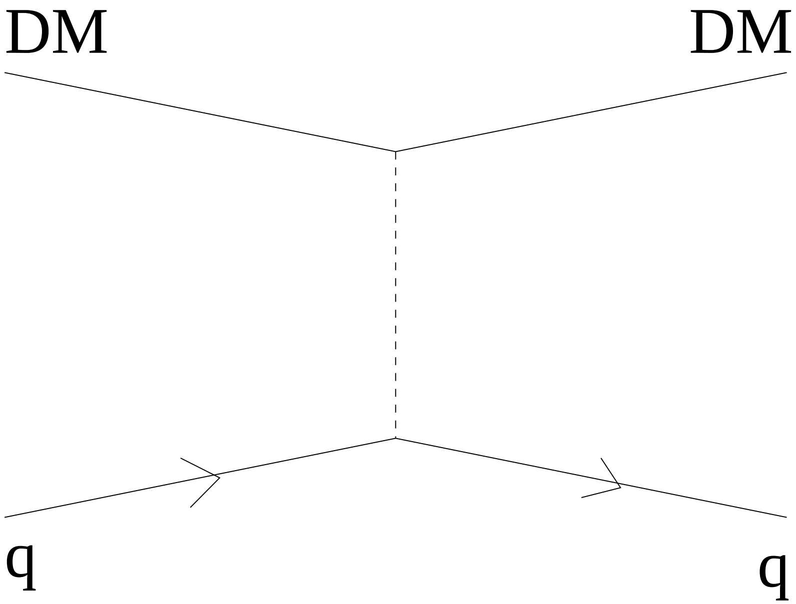
Dark Matter Direct Detection

- We encounter a DM “wind” from our galactic motion.



- This DM flux can scatter off nuclei.

  → look for nuclear recoils ~ 100 keV

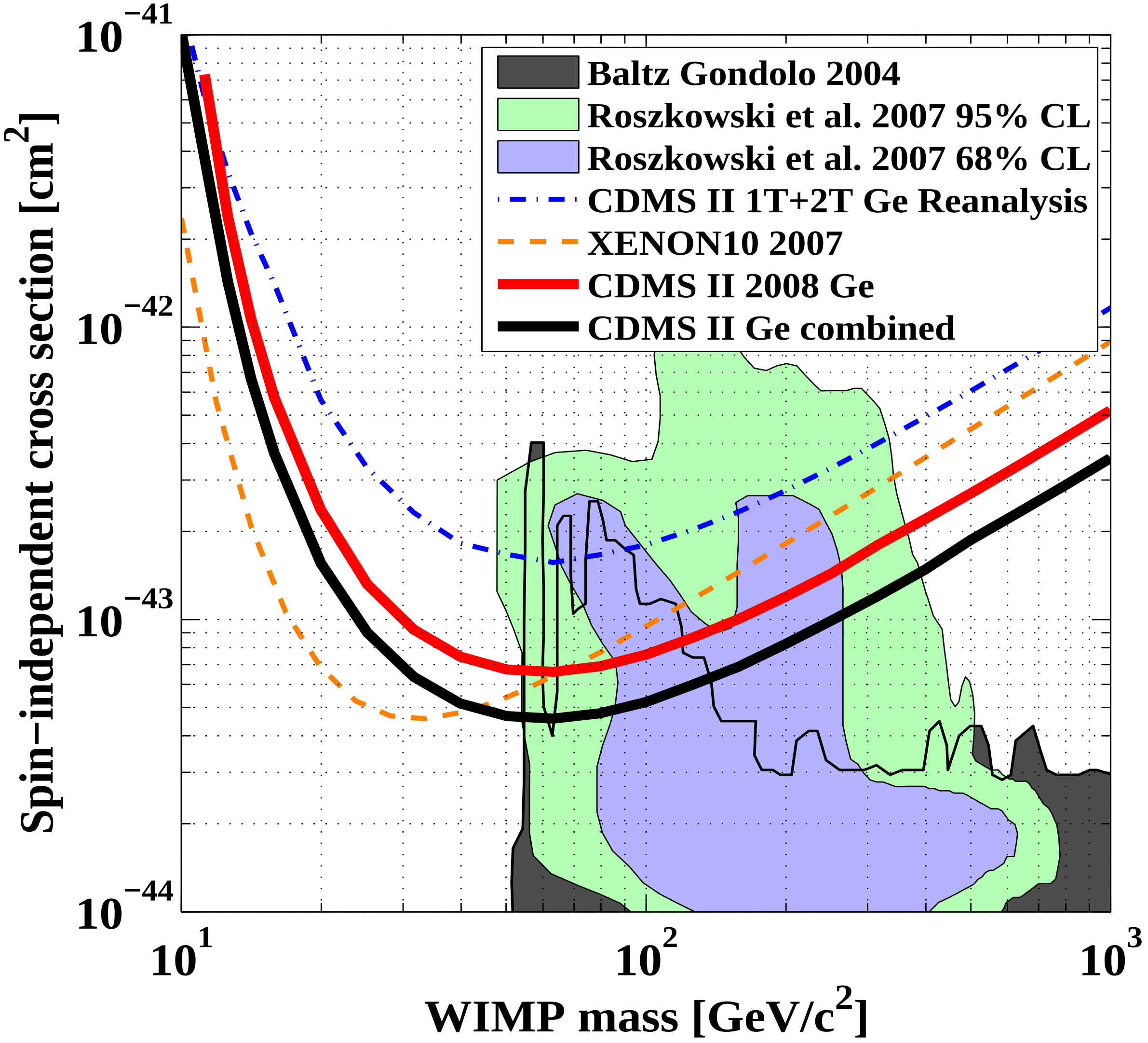


- Net scattering rate is proportional to the flux.

- Coherent Spin-Independent scattering:

$$\sigma_N^{SI} \propto \sigma_n^0 \frac{[(A-Z)f_n + Zf_p]^2}{f_n^2}$$

Experimental Limits (Low Background)



[CDMS '08]

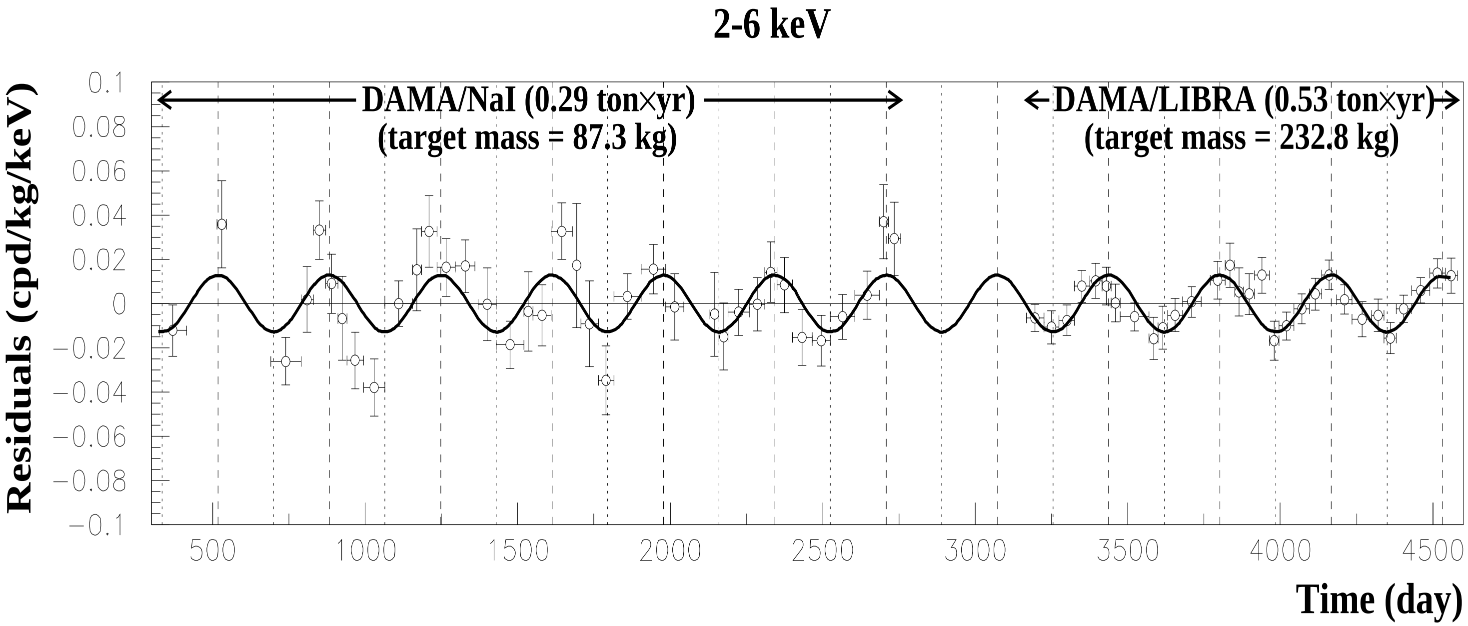
Annual Modulation at DAMA

- DM flux varies annually due to the motion of the Earth.

  ⇒ annual modulation of the DM scattering rate

  [Drukier,Freese,Spergel '86]

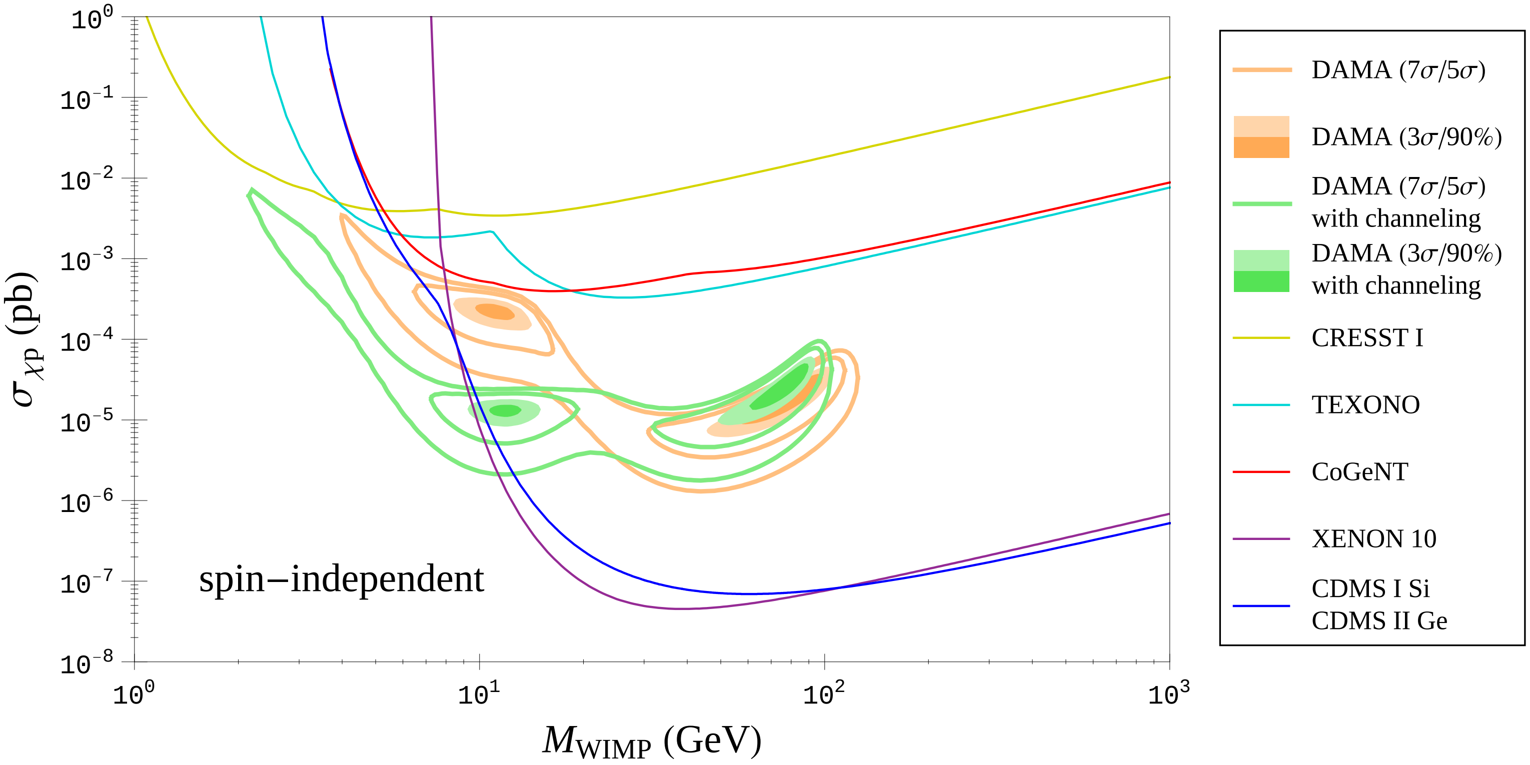
- DAMA/NaI and DAMA/LIBRA searched for this variation in nuclear recoils using NaI-based detectors.



Dark Matter Explanations for DAMA

- If the DAMA signal is DM what does it tell us?

- Heavy DM scattering off Iodine is ruled out.



[Freese,Gelmini,Gondolo,Savage ’08]

- Light DM? Electron scattering DM? Inelastic DM?

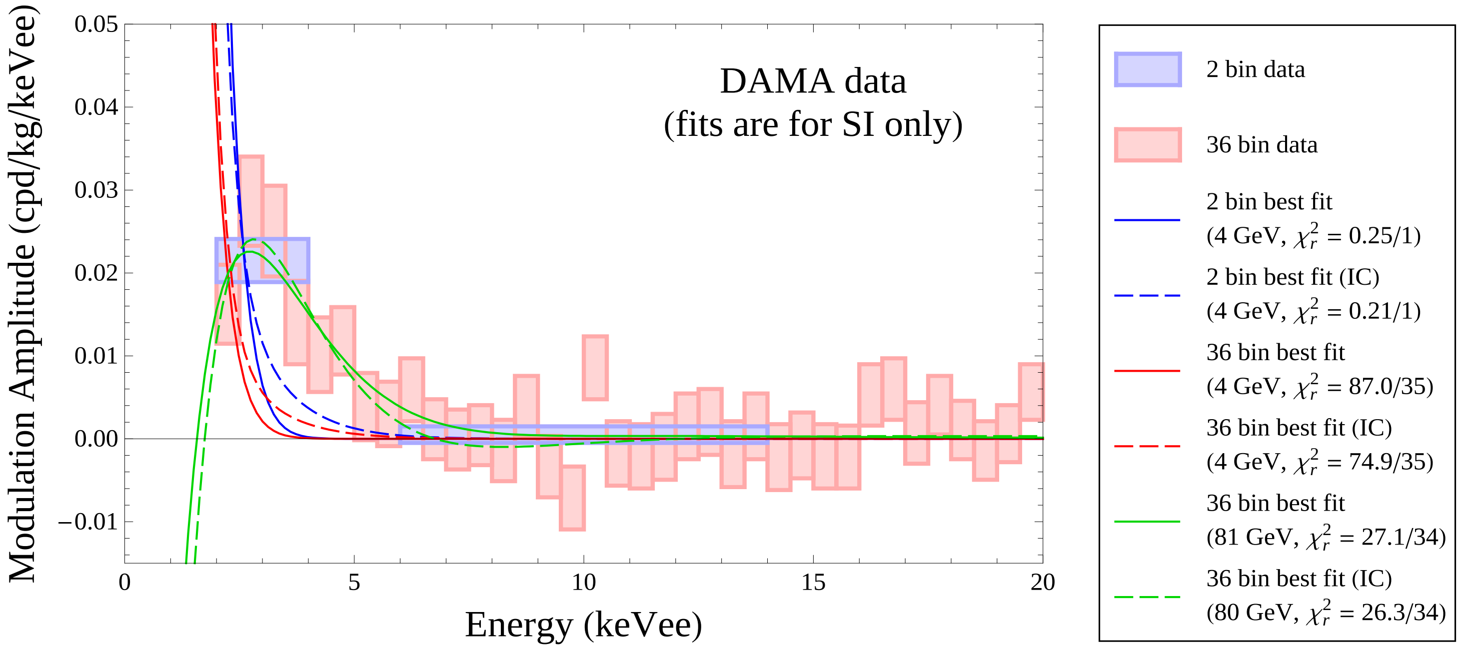
Light Dark Matter and DAMA

- CDMS (Ge) is insensitive to lighter ($m \lesssim 10\,\mathrm{GeV}$) DM:

  → recoil energy of the Ge (A=72) nucleus is too small.

- DAMA contains Na (A=23) → larger recoil from light DM.

- Light DM gives a poor fit to the DAMA energy spectra.
  [Chang,Pierce,Weiner '08; Fairbairn,Zupan '08]



[Freese,Gelmini,Gondolo,Savage '08]

DM Scattering off Electrons

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

  This would generate a signal at DAMA.

  Other DM detectors filter out electromagnetic events.

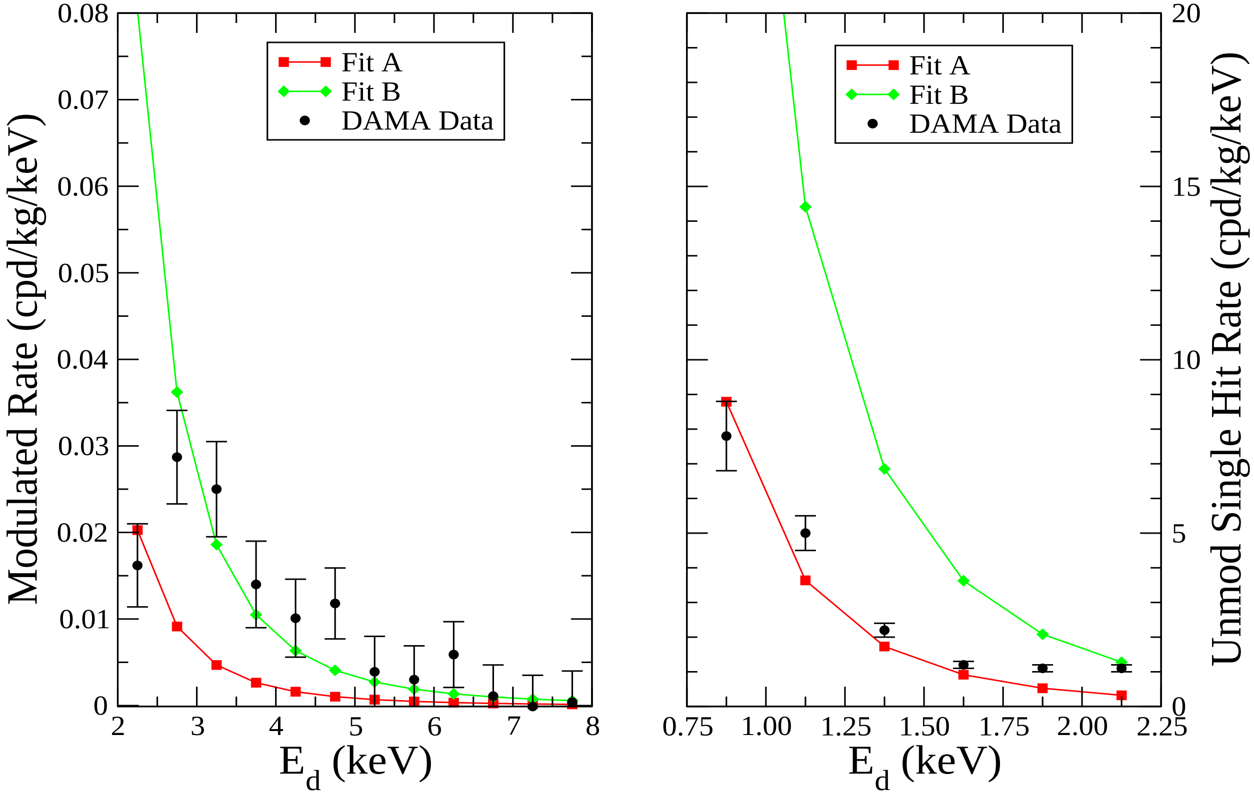
- $E_R \sim$ eV for Halo DM scattering off an electron at rest.

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

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

- Scattering signal falls off quickly with E_R, like light DM.

- For fermion DM with $(V \pm A)$ couplings to quarks:



- Using 12 lowest (2-12 keVee) modulated bins,

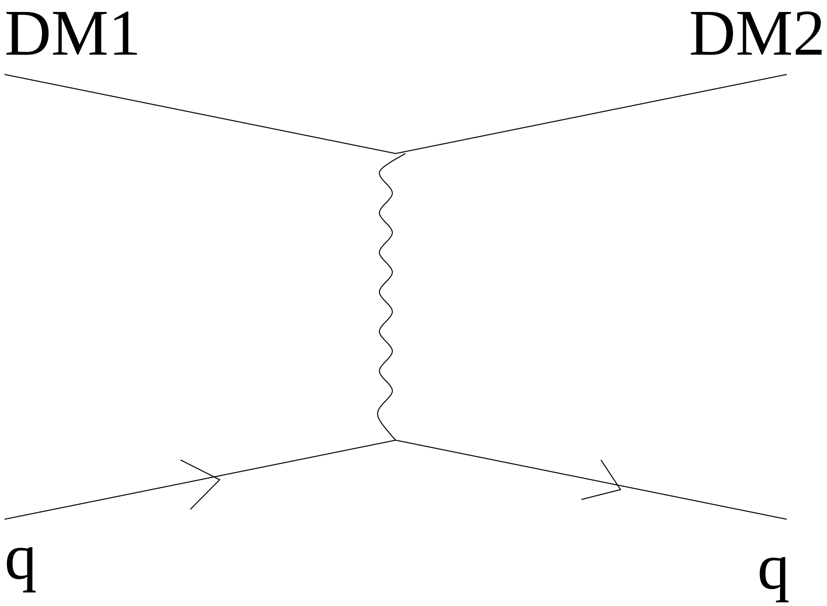
  6 lowest (0.875-2.125 keVee) unmodulated bins,

  the fit is very poor. ($>$ 99% exclusion using χ^2)

- Similar conclusion for other Dirac structures, scalar DM.

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

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

- Signal Rate:

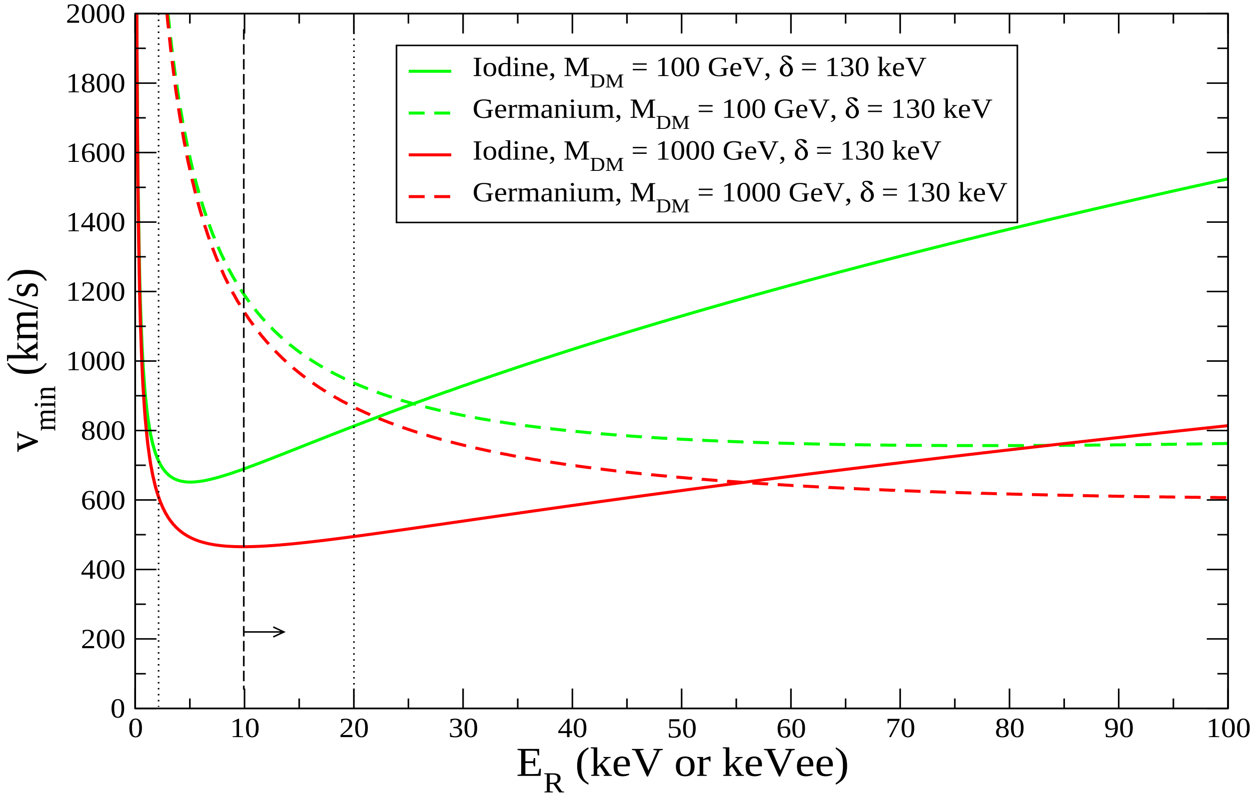
$$\frac{dR}{dE_R} \propto \int_{v_{min}} d^3v \, f(\vec{v}, \vec{v}_e) \, v \, \frac{d\sigma}{dE_R}.$$

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

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

- 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.



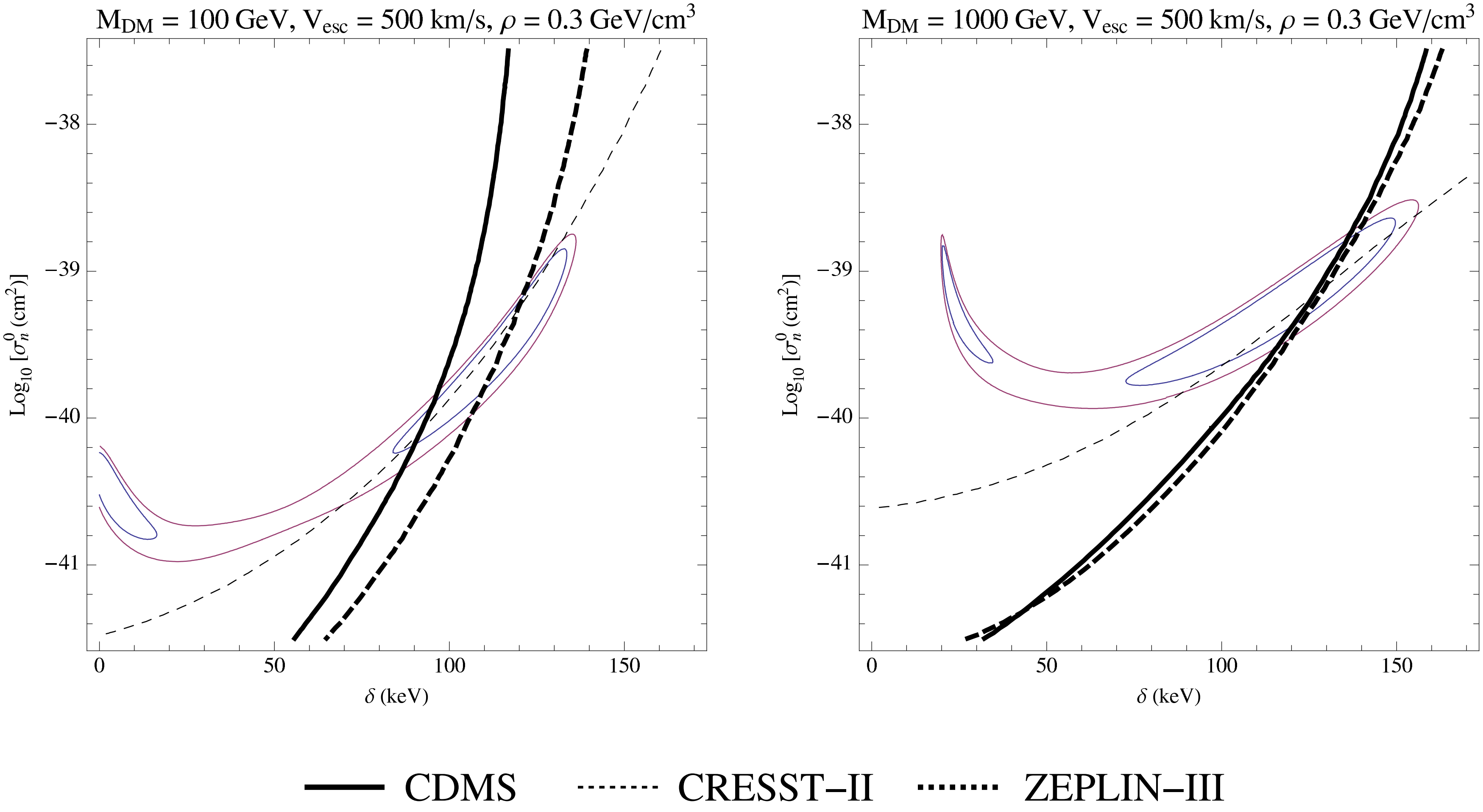
- Which IDM parameters fit the data?
- Where could IDM come from? LHC implications?

IDM vs. Data

IDM Fits to Data

- 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.

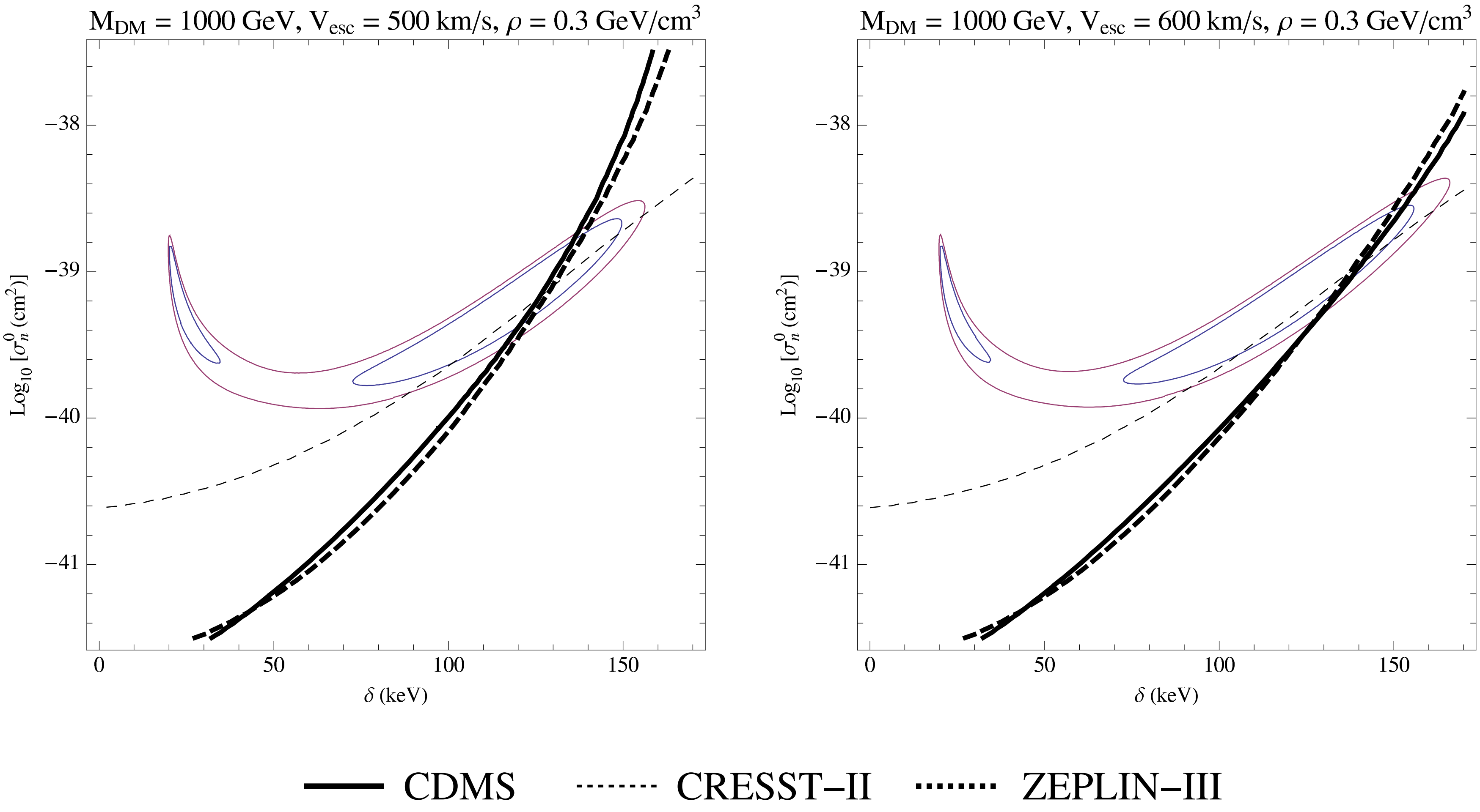
- $M_{DM} = 100\,\text{GeV},\ 1000\,\text{GeV}$, 99 % $c.l.$ exclusion curves.



- Heavier IDM might work but is more constrained.

Note: $v_{min}(E_R) \to \dfrac{1}{\sqrt{2m_N\,E_R}}(E_R + \delta)$ for $M_{DM} \gg m_N$

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



- 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.

$$\begin{aligned} -\mathcal{L}_{mass} &= M\,\bar{\psi}\psi + \frac{1}{2}m\,\bar{\psi}^c\psi, \qquad \text{with} \quad M \gg m \\ &= \frac{1}{2}(M-m)\bar{\Psi}_1\Psi_1 + \frac{1}{2}(M+m)\bar{\Psi}_2\Psi_2 \end{aligned}$$

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

- The complex scalar story is similar.

Nucleon Scattering from Gauge Bosons

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

  → 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.

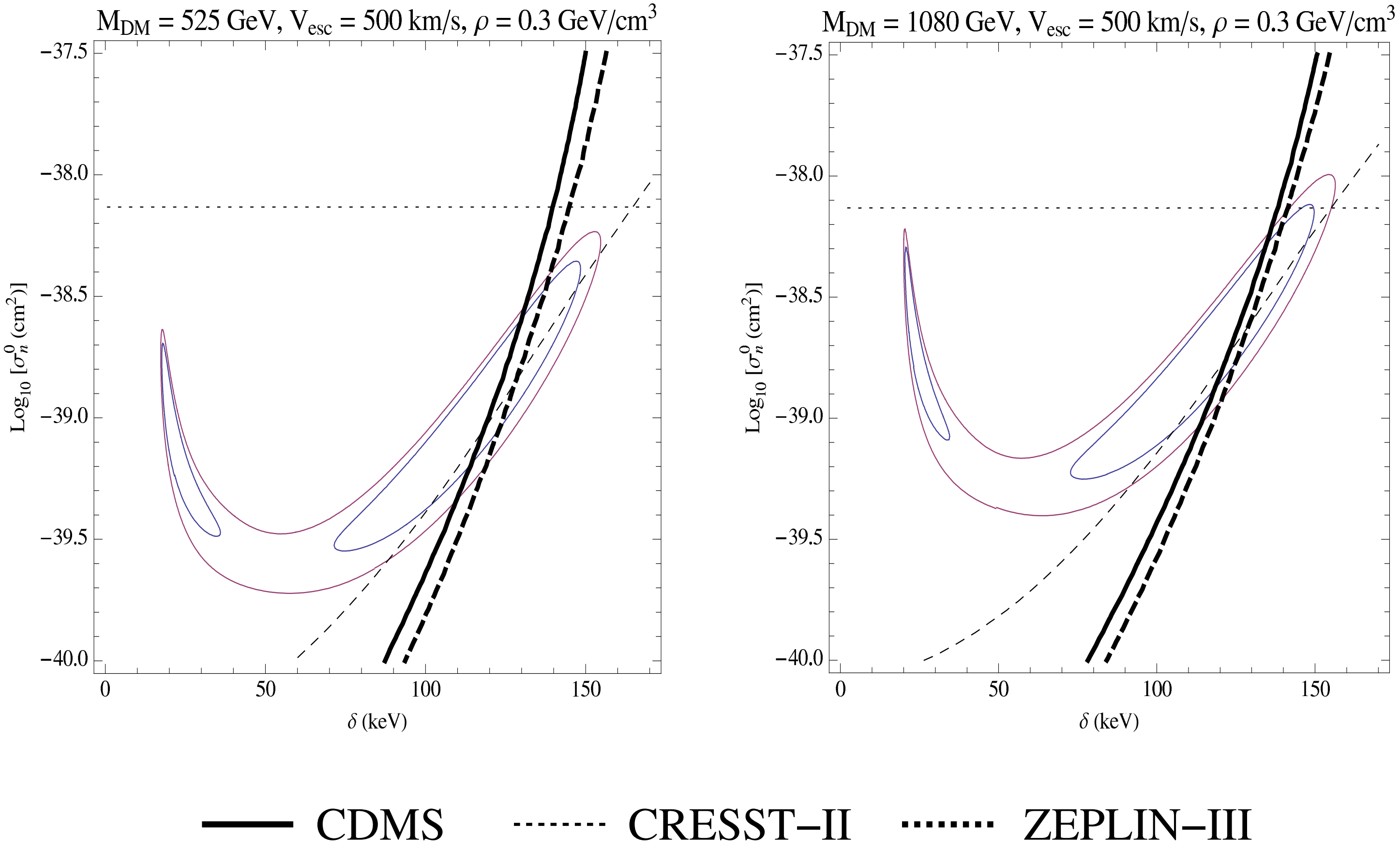
  → need a large nucleon cross-section $\sigma^0_{n,p}$.

- 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: $M_{DM} \simeq 1080\,\mathrm{GeV} \Rightarrow \Omega_{DM}\, h^2 \simeq 0.1$.
- Scalar Doublet: $M_{DM} \simeq 525\,\mathrm{GeV} \Rightarrow \Omega_{DM}\, h^2 \simeq 0.1$.



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

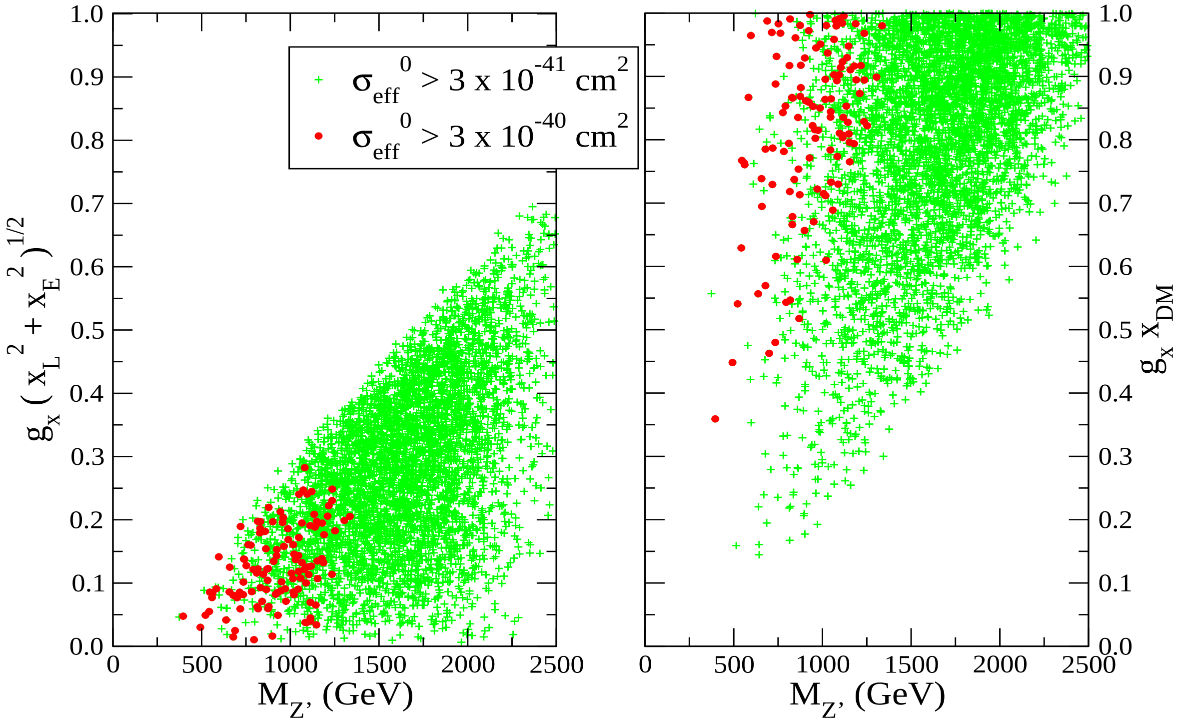
2. IDM Scattering through a Visible $U(1)_x$

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

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

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

  $\rightarrow$ $M_{Z'}$ 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,

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

$\epsilon \sim 10^{-4}$–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.

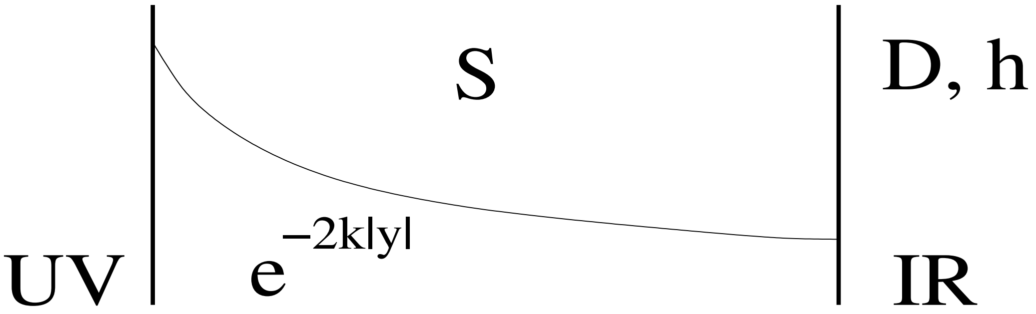
- Can arise from sneutrinos with small L violation.

  [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, Yavin *et al.* ’09]

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: $\frac{d_{UV}}{2}(\bar{S}^c_L S_L + h.c.)$

- $U(1)_{DM}$ 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:

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

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

  we find $\delta \simeq 100\,\mathrm{keV}$, 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:

  Bulk: $a\,k\,|S|^2$

  IR Brane: $(\lambda\, e^{2\pi kR} D S^* h + h.c.) + M^2 |D|^2$

  UV Brane: $\frac{m_{UV}}{2}(S^2 + h.c.)$

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

- No scalar zero mode in general.

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

$$\begin{aligned} \partial_y S_{\substack{R\\I}} \mp m_{UV} S_{\substack{R\\I}} &= 0|_{y=0} \\ \partial_y S_{\substack{R\\I}} &= 0|_{y=\pi R}. \end{aligned}$$

  $\Rightarrow$ 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

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

  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]

$$\begin{aligned} m_{hid} &\sim \epsilon\, m_{E^c}, \\ M_{\tilde{Z}_x} &\lesssim \epsilon^2\, M_1. \end{aligned}$$

- $U(1)_x$ 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, $\left\langle H^{(c)} \right\rangle \sim \mu' \sim$ 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.

    → additional contributions to hidden SUSY breaking
  - Gaugino mediation with residual anomaly mediation in the hidden sector. [Katz+Sundrum '09]

Summary

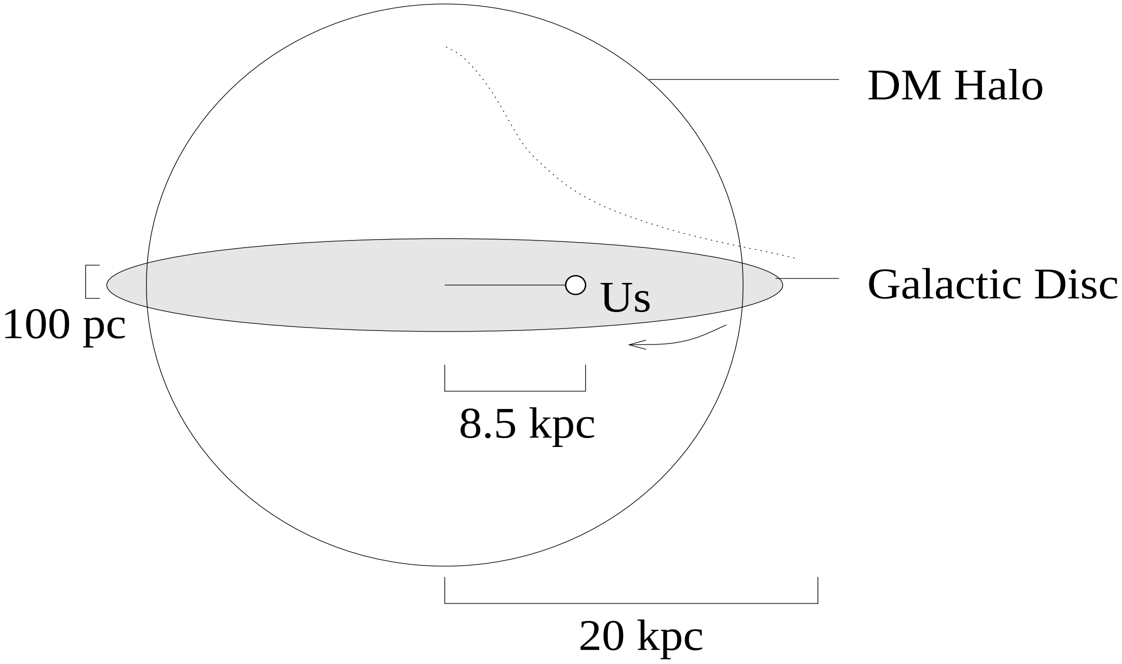
- Recent results could be non-gravitational DM signals!
- Inelastic DM can be consistent with the DAMA signal and other direct detection experiments.
- Heavier DM masses can also work, but are more constrained.
- IDM scattering can be mediated by the Z^0, a heavy visible Z', or a light hidden Z'.
- Reasonable models for IDM can arise in RS, SUSY.

Extra Slides

Indirect Detection Signals

DM in our Galaxy

- Flat galactic disc surrounded by a sherical DM halo:



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- DM density is largest at the galactic center.
- DM in the halo can annihilate producing particle fluxes.

$\rightarrow e^-, e^+, p, \bar{p}, \gamma$

Other Signals

- WMAP Haze: excess soft photons from around the galactic center. [Finkbeiner '04]

  Injected hard electrons will circulate in the galactic magnetic field and emit synchrotron radiation.

- INTEGRAL 511 keV line

  Soft e^+ injected near the galactic center will annihilate.

  [Hooper *et al.* '04]

- HESS sees hard γ rays from the galactic center.

- GLAST/Fermi telescope will test these further.

DM Annihilation to Leptons

- Most DM candidates decay too democratically.

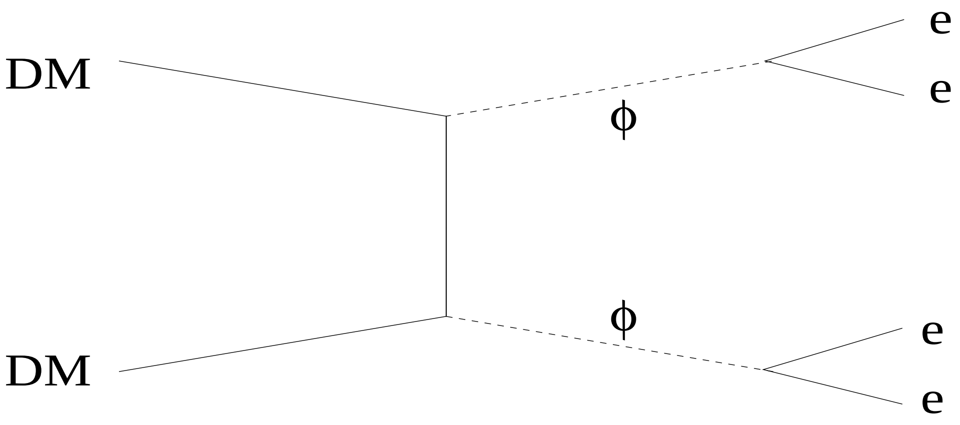
  e.g. $\chi\chi \to W^+W^- \to q\bar{q}, \ell\nu_\ell$ gives too many antiprotons.

- DM could be a heavy "lepton".

  [Kribs+Harnik '08; Pontón+Randall '08; Zurek '08; Phalen,Pierce,Weiner '09;. . .]

- DM decays to leptons can be enforced by kinematics:

  [Arkani-Hamed,Finkbeiner,Slatyer,Weiner '08]



$m_\phi < 280\,\text{MeV}$ allows only decays to e^+e^-, $\mu^+\mu^-$, ν's, γ's.

Enhanced DM Annihilation Today

- Need $\langle \sigma\, v\rangle^{today} \gtrsim 10^2 \langle \sigma\, v\rangle^{freeze-out}$ for thermal relic DM.
- DM could be produced non-thermally.
- DM properties can change after freeze-out. [Cohen,DM,Pierce '08]

  e.g. "Modulus" field phase transition after freeze-out

$$\begin{aligned} \mathcal{L} &\supset (m_{DM}^{(0)} + \zeta\, P)\, \Psi_{DM} \Psi_{DM} \\ P &\to \langle P \rangle \sim 100\,\text{GeV} \quad \text{at} \quad T < T_{f.o.} \simeq m_{DM}^{(0)}/20 \\ m_{DM} &: \; m_{DM}^{(0)} \to m_{DM}^{(0)} + \zeta\, \langle P \rangle. \end{aligned}$$

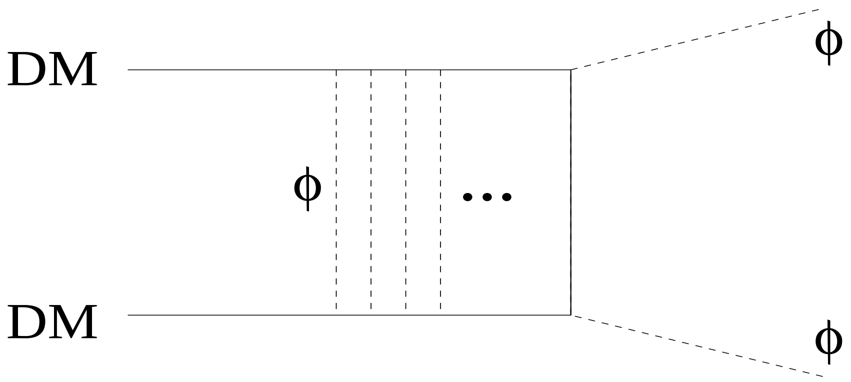
$\Rightarrow$ modified DM properties today relative to freeze-out

The excitation around $\langle P \rangle$ must be very light: $m_P \lesssim$ GeV.

- DM annihilation can get a Sommerfeld enhancement today.

  [Hisano *et al.* '04; Arkani-Hamed,Finkbeiner,Slatyer,Weiner '08; Pospelov+Ritz '08]

e.g. Scalar ϕ Exchange



$$v_{DM}^{today} \sim 10^{-3}, \qquad v_{DM}^{freeze-out} \sim 0.1,$$

$$\langle\sigma v\rangle^{today} \simeq \langle\sigma v\rangle^{f.o.}\frac{\alpha\, m_{DM}}{m_\phi} \quad \text{for } v \ll \sqrt{\frac{\alpha\, m_\phi}{m_{DM}}}.$$

$\Rightarrow m_\phi \lesssim 1\,\text{GeV}$ for sufficient enhancement

Alternatives to Dark Matter Annihilation

- New cosmic ray signals could come from pulsars.

  [Hooper *et al.* '08; Yuksel *et al.* '08; Profumo '08]

  - Large astrophysics uncertainties.
  - Not expected but could be possible?

- Decaying dark matter.

  [Hamaguchi+Yanagida '08, Dimopoulos *et al.* '08]

  - Annihilating DM can produce too many γ rays.
  - γ flux from annihilations ($\sim n_{DM}^2$) is enhanced in the GC.
  - γ flux from decays ($\sim n_{DM}$) is less enhanced.