

# Candidates for Inelastic Dark Matter

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with

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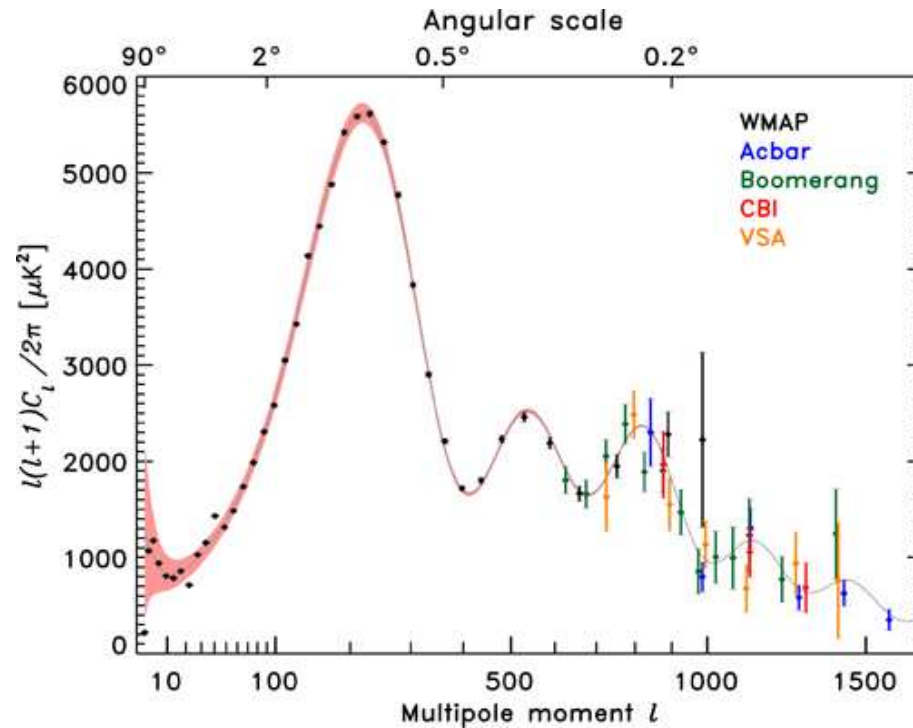
(hep-ph/0901.0557)

*Fermilab Theory Seminar, March 26, 2009*

# Evidence and Hints for Dark Matter

# Gravitational Evidence for Dark Matter

- CMB TT:



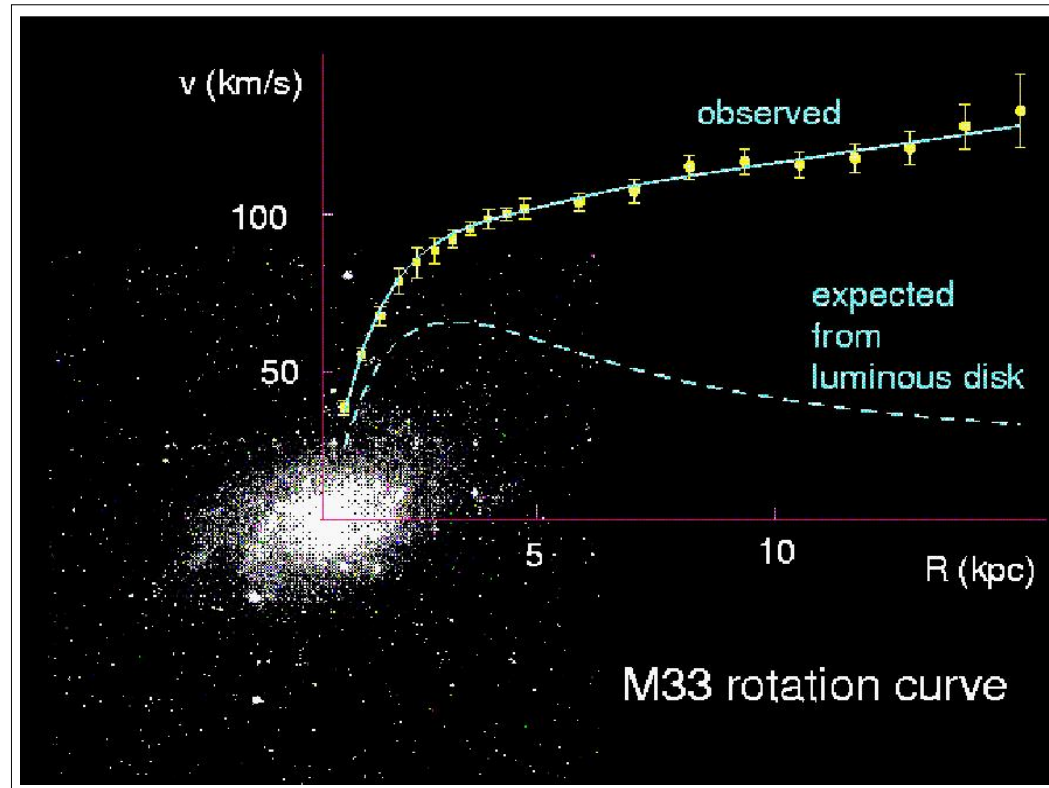
- Shape depends on the **total matter** and **baryon** densities:

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

- 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:

$$\begin{aligned}\Omega_{DM}^{therm} h^2 &\simeq \frac{T_0^3}{H_0^2 M_{Pl}^3} \frac{1}{\langle \sigma v \rangle} \\ &\sim 0.1 \left( \frac{m_{DM}}{1000 \text{ GeV}} \right)^2 \quad \text{for } \langle \sigma v \rangle \sim \frac{g^4}{m_{DM}^2}.\end{aligned}$$

DM from new physics stabilizing the ElectroWeak scale?

DM production at the LHC?

# Non-Gravitational 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”

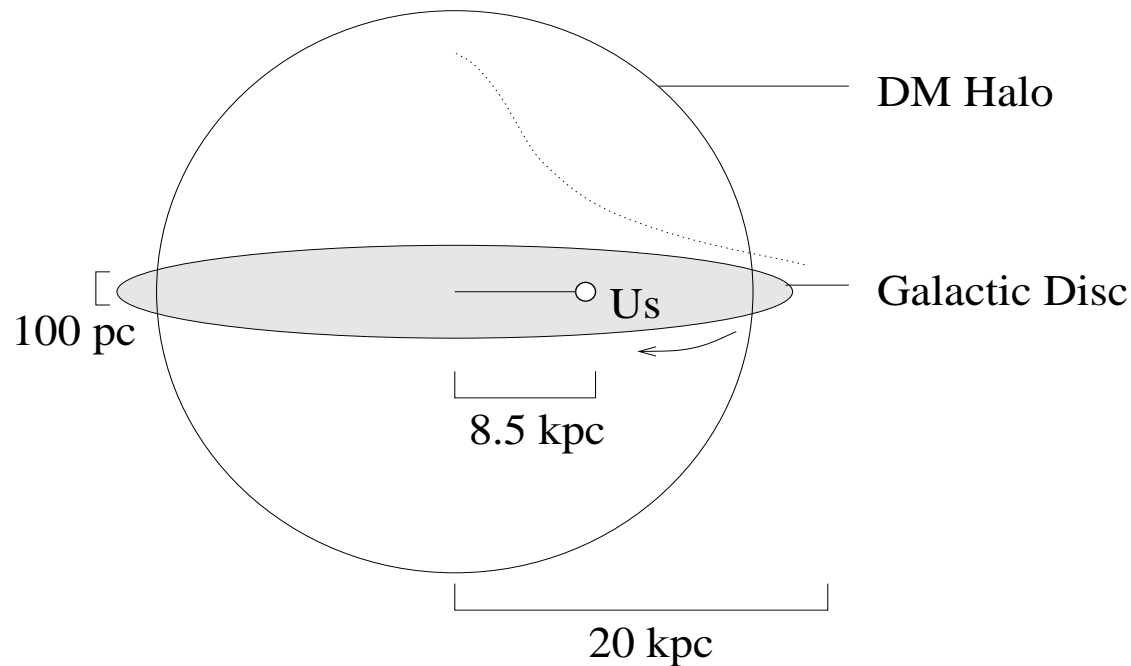
DAMA observes unexplained nuclear recoils.

→ Inelastic Dark Matter?

# DAMA and Inelastic Dark Matter

# Dark Matter in our Galaxy

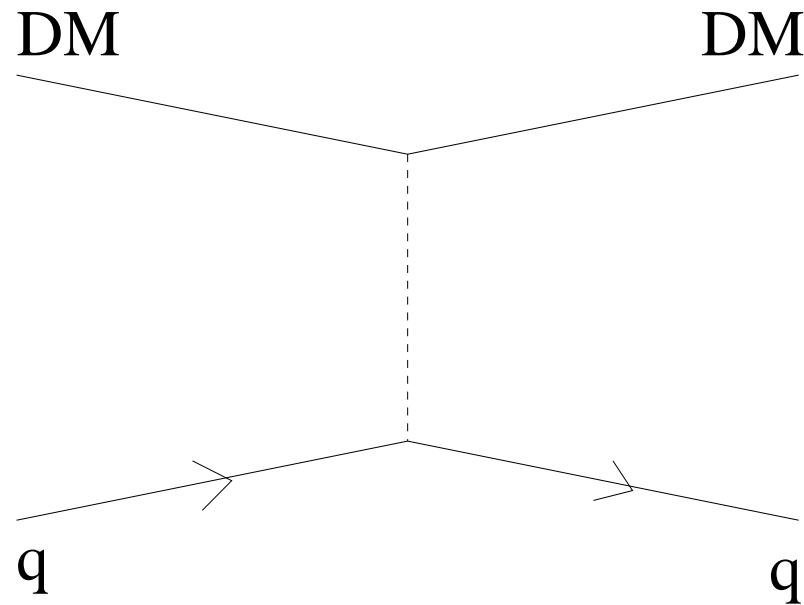
- Flat galactic disc surrounded by a spherical DM halo.



- $v_{us} \simeq (250 \text{ km/s}) + (30 \text{ km/s}) (0.51) \cos(2\pi t/\text{yr} - \text{June } 2)$ .
- $v_{DM} \sim$  Maxwell distribution with  $\langle v \rangle \simeq 250 \text{ km/s}$ .



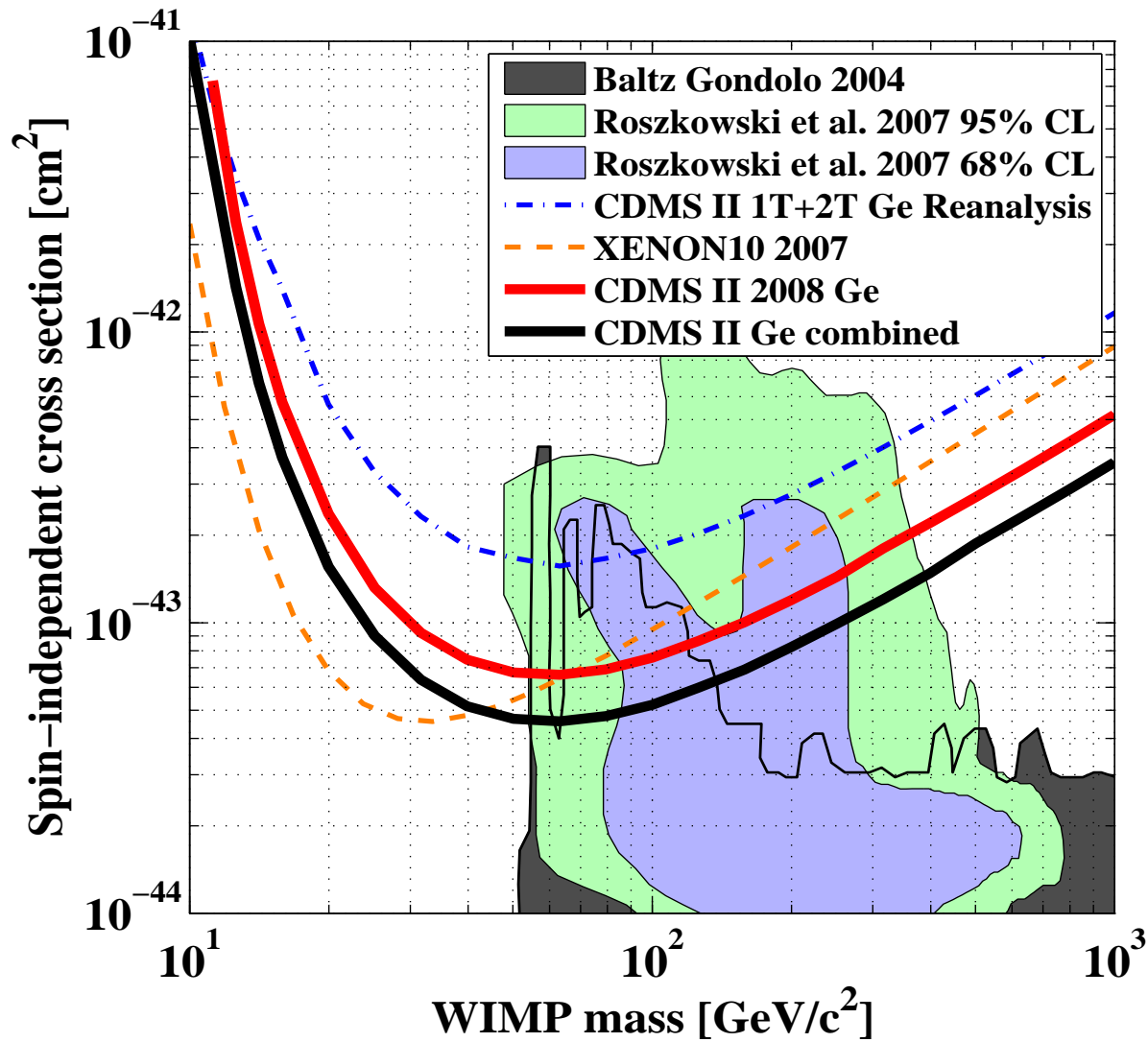
- This DM flux can scatter off nuclei.  
 → look for nuclear recoils with  $E \leq 2m_N v^2 \sim 100$  keV.



- Scattering rate is proportional to the net DM flux.
- Low momentum transfer → coherent scattering:

$$\sigma_N^{SI} \propto \sigma_n \frac{[(A - Z)f_n + Zf_p]^2}{f_n^2} \quad (\text{spin-independent}).$$

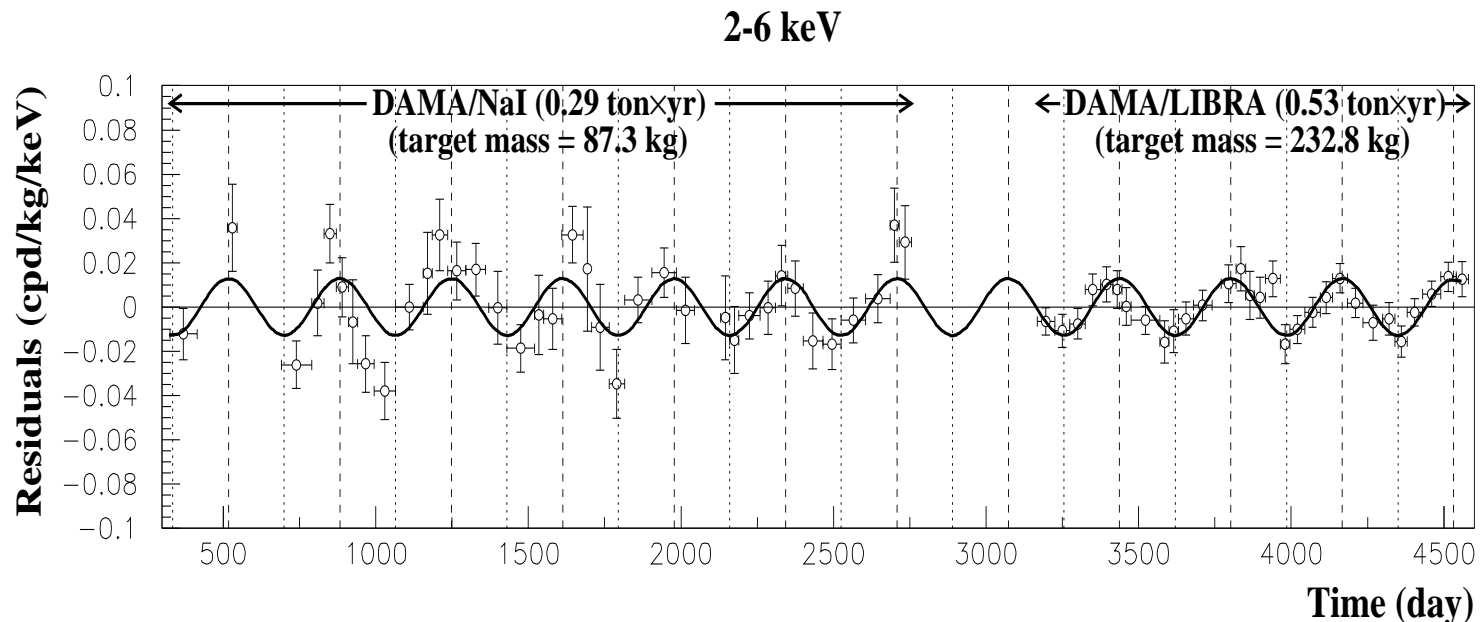
# Experimental Limits (Low Background)



[CDMS '08]

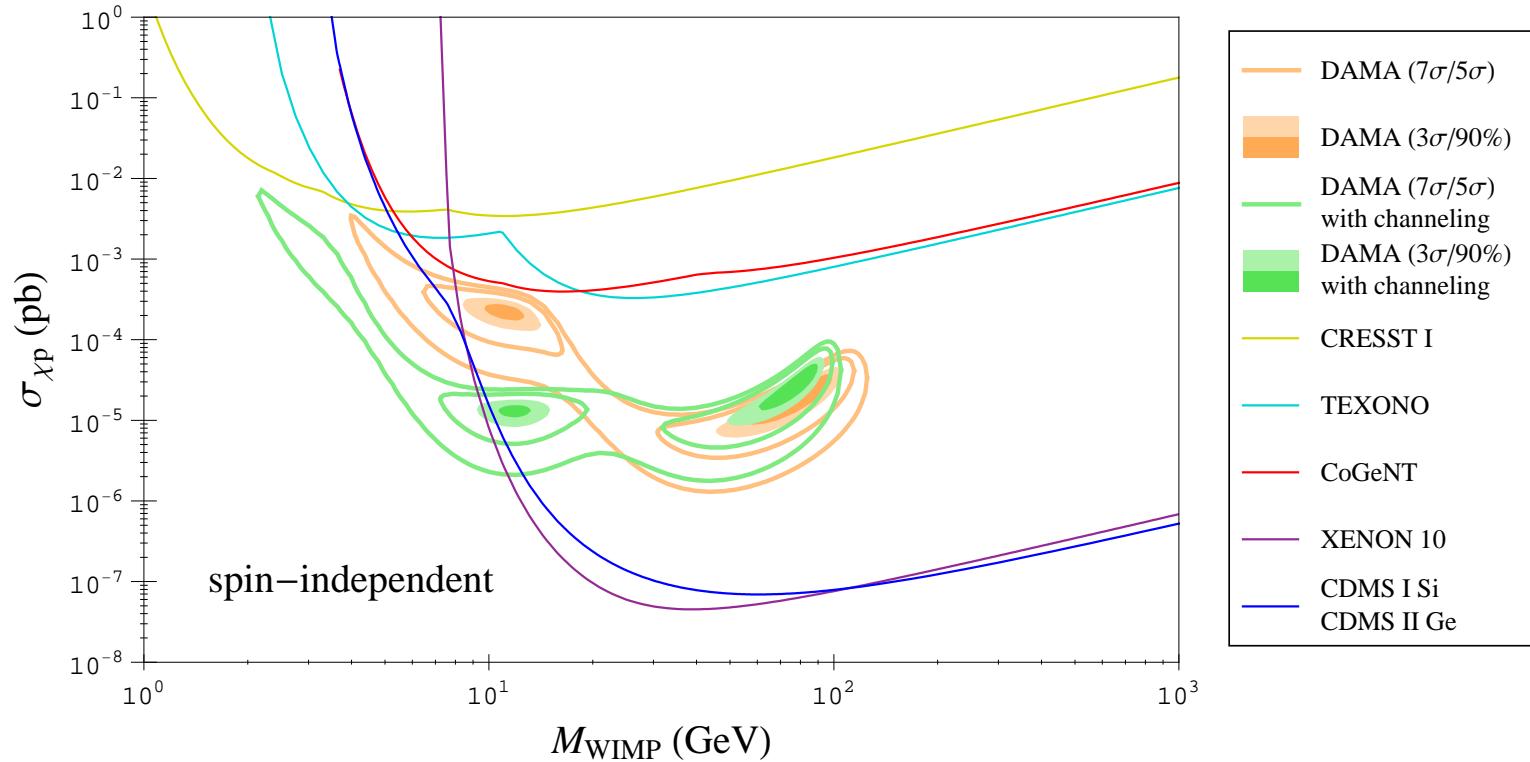
# Annual Modulation at DAMA

- 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 ( $A \simeq 127$ ) is ruled out.

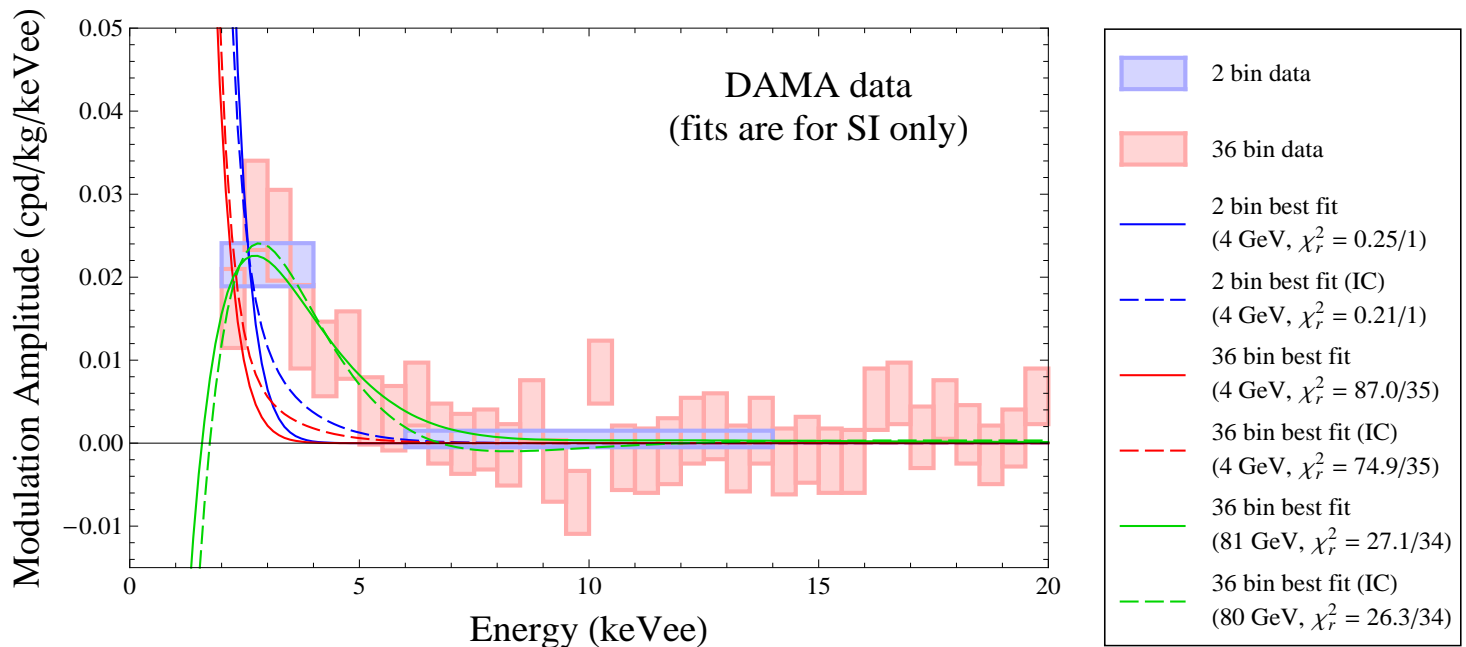


[Freese, Gelmini, Gondolo, Savage '08]

- Light DM? Electron scattering DM? Inelastic DM?

# Light Dark Matter and DAMA

- CDMS (Ge) is insensitive to lighter ( $m \lesssim 10 \text{ GeV}$ ) DM:  
→ recoil energy of the Ge ( $A=72$ ) nucleus is too small.
- DAMA contains Na ( $A=23$ ) → larger recoil from light DM.
- Light DM is constrained by the DAMA energy spectra.  
[Chang,Pierce,Weiner '08; Fairbairn,Zupan '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.

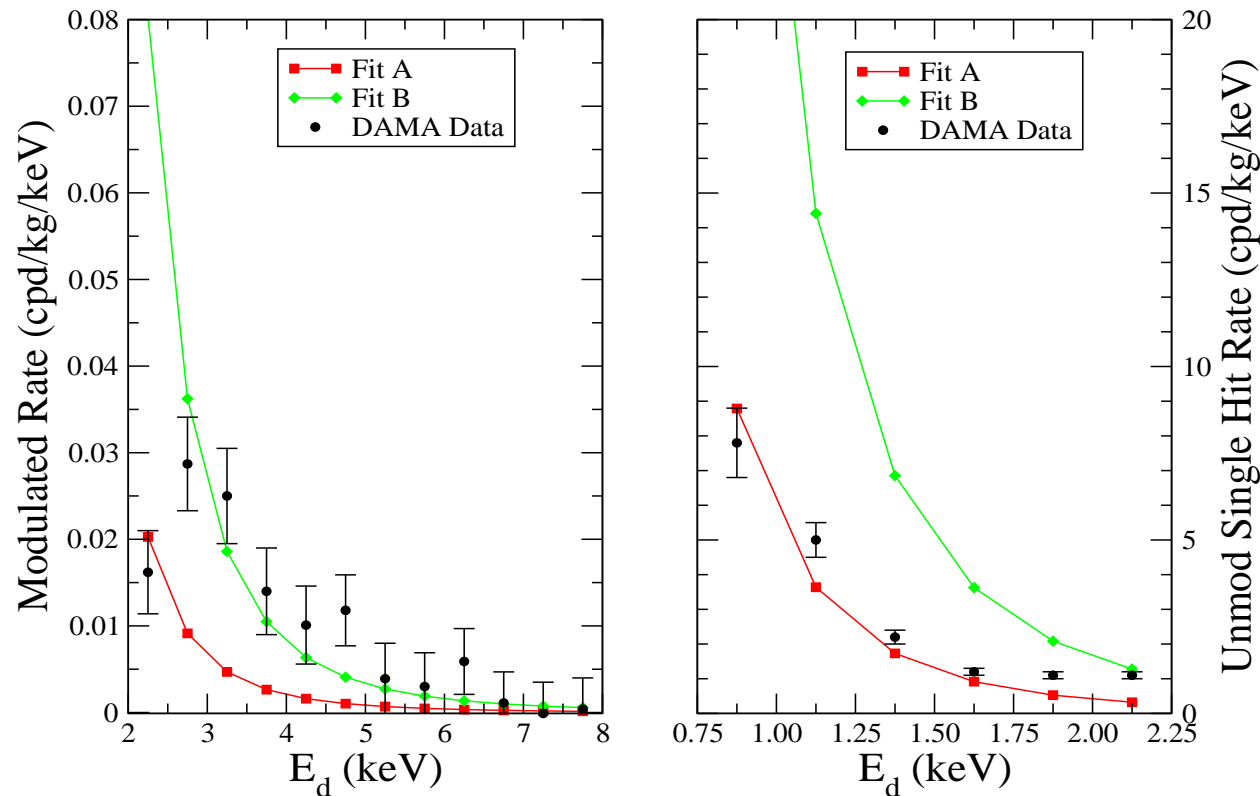
- $E_R \sim \text{eV}$  for Halo DM scattering off an electron at rest.

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

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

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

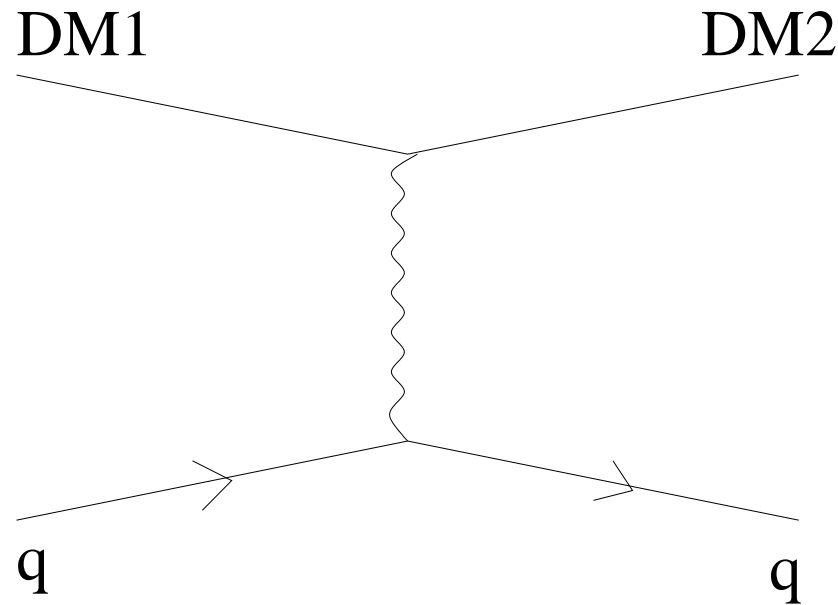
- For fermion DM with  $(V \pm A)$  couplings to quarks:



- 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  $\chi^2$ )
- 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

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

- 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:

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

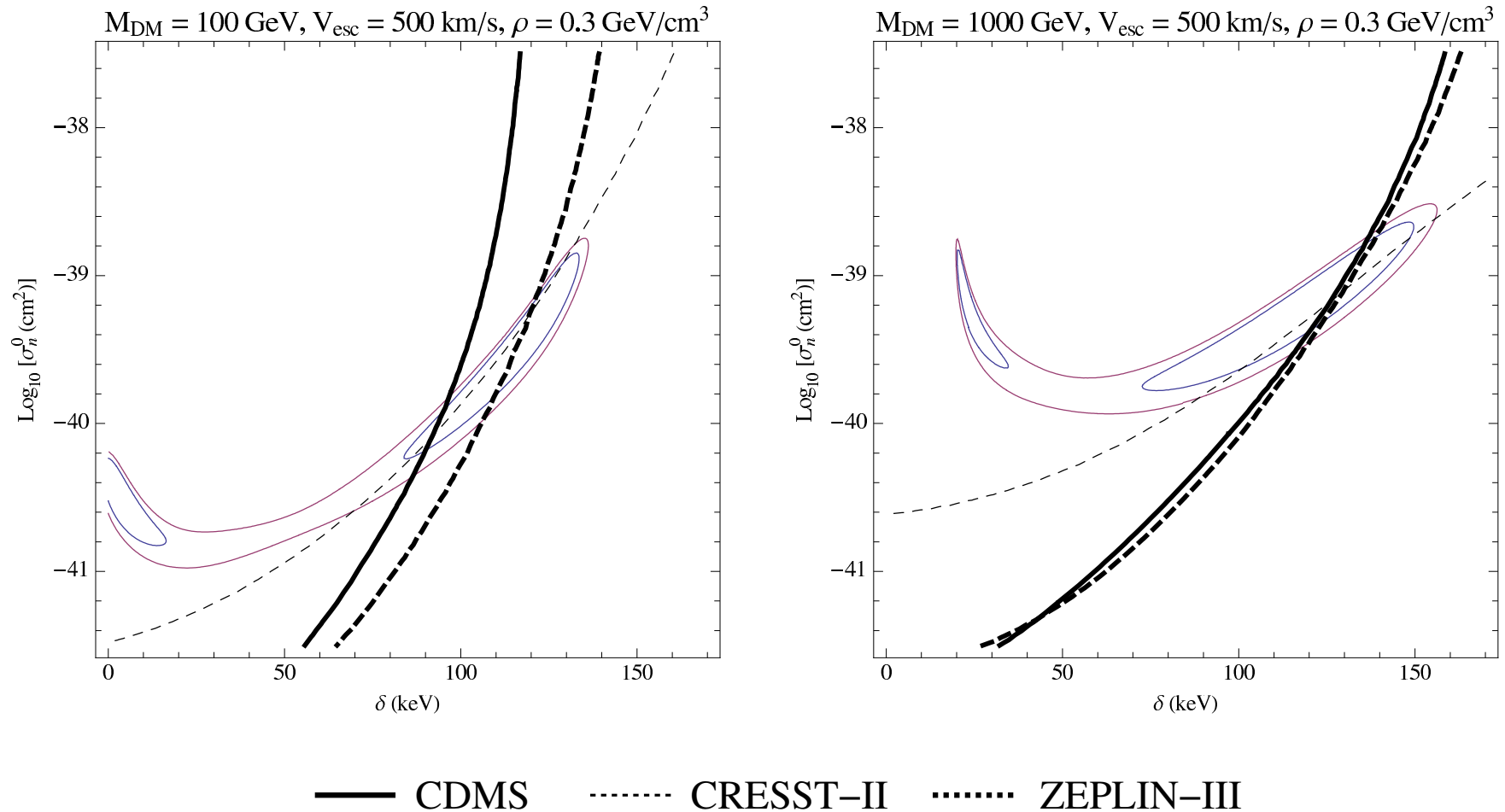
- IDM:  $v_{min}$  is less for **I** ( $A \simeq 127$ ) than for **Ge** ( $A \simeq 72$ ).  
 $\Rightarrow$  enhancement at DAMA relative to CDMS.

IDM vs. Data

# IDM Fits to Data

- DAMA (I)
  - lowest twelve 2-8 keV bins only
  - $\chi^2$  *goodness of fit* estimator
- CDMS II (Ge)
  - combine 3 runs
  - treat events (2) in 10-100 keV as signal
- CRESST-II (W)
  - use latest commissioning run only
  - treat events (7) in 12-100 keV as signal
- ZEPLIN-III (Xe)
  - treat events (7) in 2-16 keV as signal
- XENON, KIMS, *etc.* are less constraining.

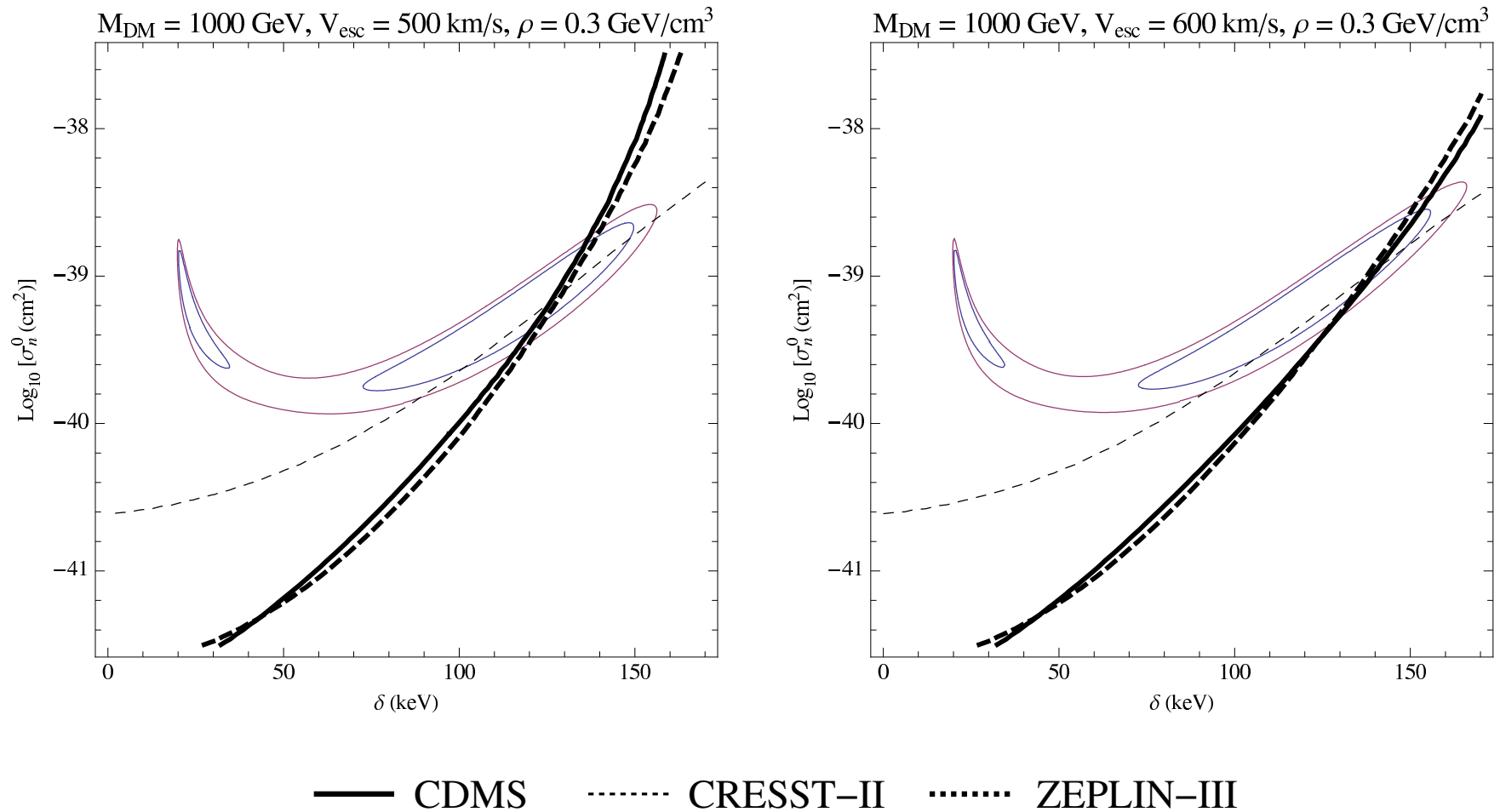
- $M_{DM} = 100 \text{ GeV}, 1000 \text{ GeV}, 99\% \text{ c.l.}$  exclusion curves.



- Heavier IDM might work but is more constrained.

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

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

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

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

- 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  $\sigma_{n,p}^0$  are too big:

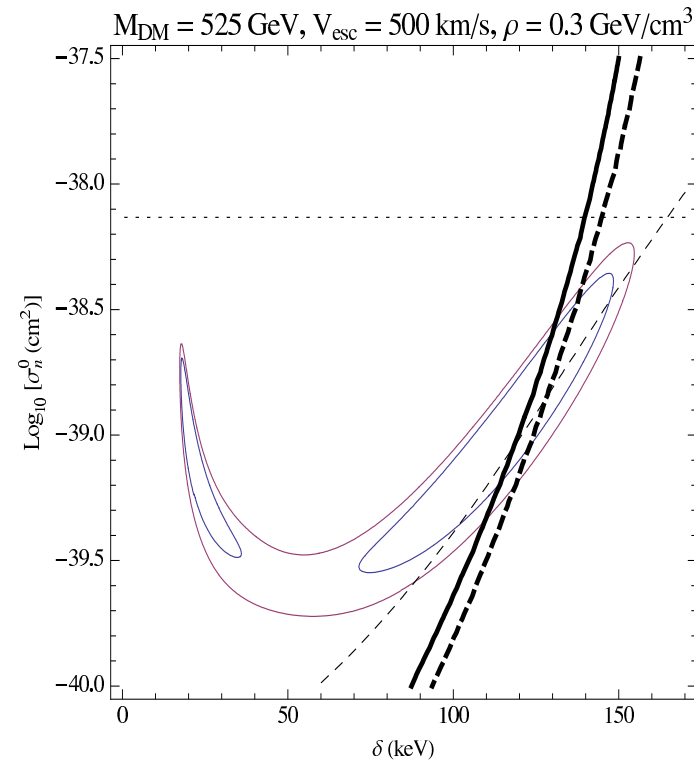
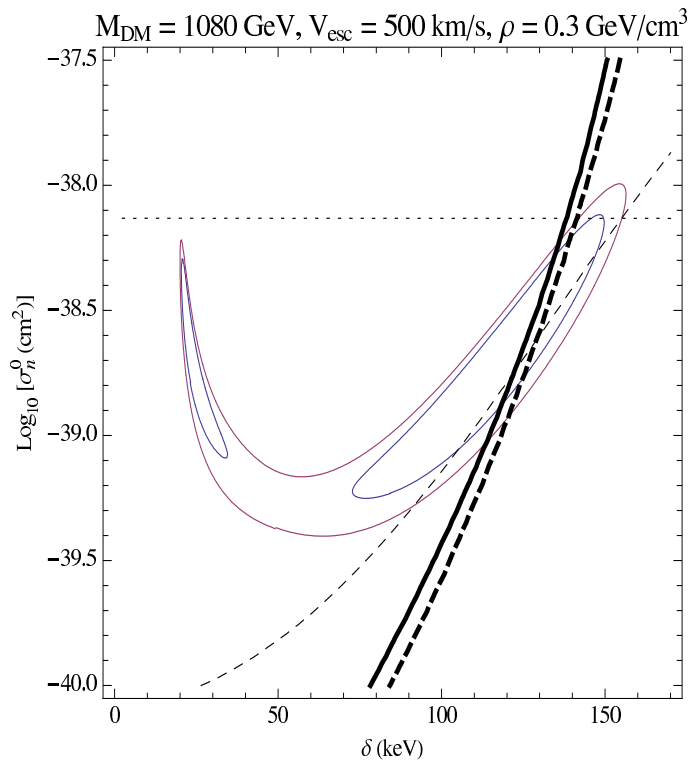
$$\sigma_n^0 = \frac{G_F^2}{2\pi} \mu_n^2 \simeq 7.44 \times 10^{-39} \text{ cm}^2 \quad (\text{vector doublet})$$

- IDM can only scatter in a limited region of phase space.  
→ need a large nucleon cross-section  $\sigma_{n,p}^0$ .
- 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:  $M_{DM} \simeq 525 \text{ GeV} \Rightarrow \Omega_{DM} h^2 \simeq 0.1$ .

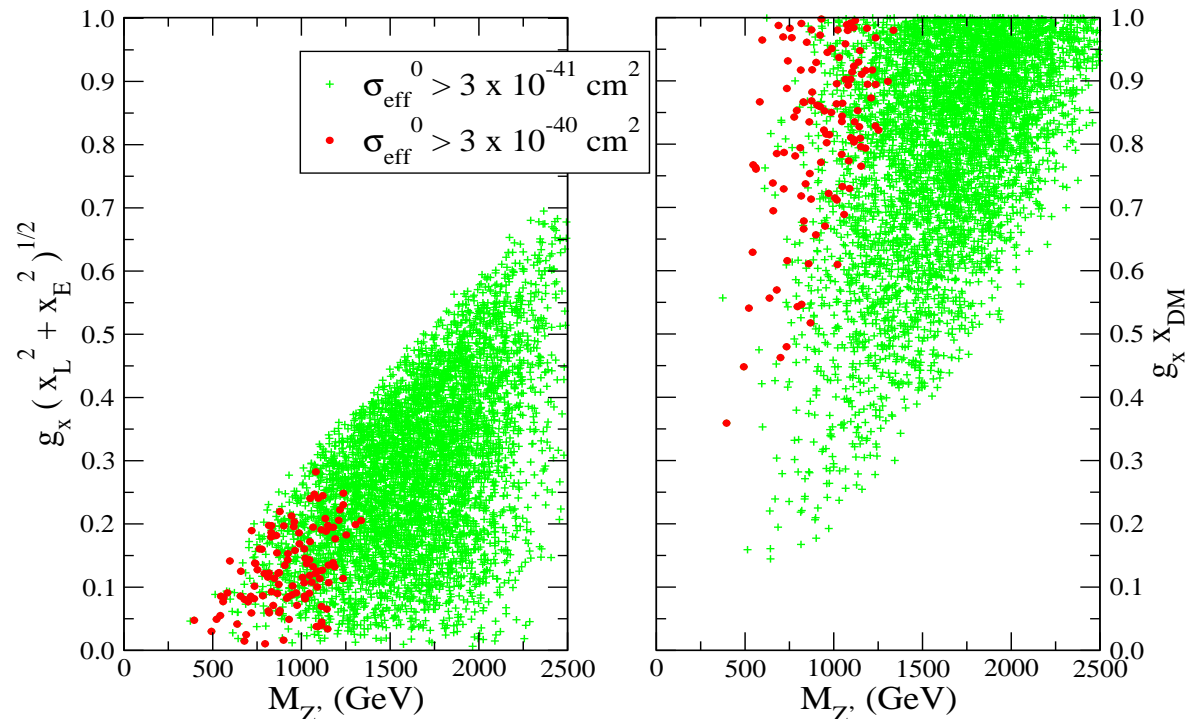


— CDMS    - - - - - CRESST-II    ······ ZEPLIN-III

- DAMA-allowed region is close to  $\sigma_n^0$  for a doublet.

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

- Visible  $Z'$ 's constrained by Tevatron, Precision Electroweak.  
→ heavier  $M_{Z'}$  is preferred
- But  $\sigma_{n,p}^0 \propto \left(\frac{g_x}{M_{Z'}}\right)^4$   
→  $M_{Z'}$  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,

$$\mathcal{L} \supset -\frac{1}{2}\epsilon B_{\mu\nu}X^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}.$$

$\epsilon \sim 10^{-4} - 10^{-2}$  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  $-e c_W Q \epsilon$ .

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

- 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:

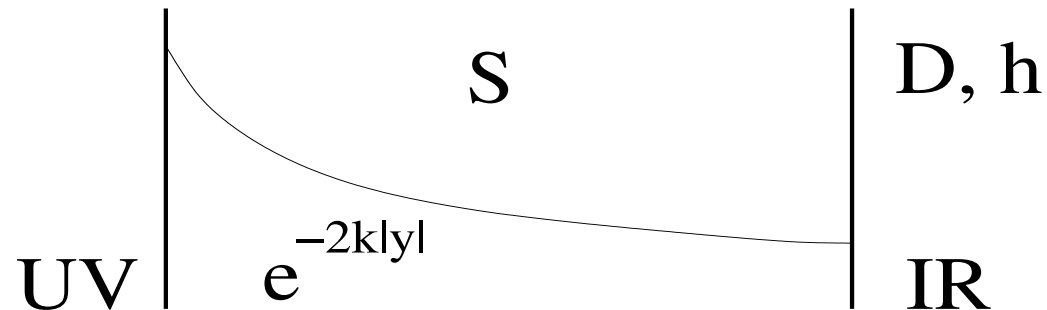
1. Warped fermion seesaw IDM

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:

$$\text{Bulk: } ck\bar{S}S$$

$$\text{IR Brane: } \lambda(\bar{D}_R S_L h + h.c.) + M\bar{D}D$$

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

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

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

- With natural values  $\lambda^2 = 1/M_{Pl}$ ,  $c = 0.13$ ,  $d_{UV} = 2$ ,  
 we find  $\delta \simeq 100 \text{ keV}$ , mostly doublet DM.
- This model is similar to warped neutrino mass models.

[Huber+Shafi '03, Perez+Randall '08, Carena *et al.* '09]

## 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:

$$\text{Bulk: } a k |S|^2$$

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

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

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



- No scalar zero mode in general.
- UV brane mass modifies the B.C.s:

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

⇒ 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  $kR \sim 2$ .

⇒ Little RS [Davoudiasl, Perez, Soni '08; McDonald '08]

### 3. Supersymmetric Fermion Doublet IDM

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

- 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.

- $N \rightarrow \langle N \rangle \sim \text{TeV}$  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  $\lambda' \sim 0.1$ ,  $\tan \beta \sim 30$ ,  $\xi \langle N \rangle \sim \text{TeV}$ .
- 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]

$$m_{hid} \sim \epsilon m_{Ec},$$
$$M_{\tilde{Z}_x} \lesssim \epsilon^2 M_1.$$

- $U(1)_x$  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,Cheung,Ruderman,Wang,Yavin '09]

- 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  $M_s \sim M_a \sim \text{TeV}$ ,  $\langle H^{(c)} \rangle \sim \mu' \sim \text{GeV}$ :

$$W_{eff} \supset -\frac{\lambda_1}{2M_s} (a^c H)^2 + \dots$$

- Multi- $\mu$  Mystery:  $\mu' \ll M_s, M_a$ ?
  - $\mu' \sim \text{GeV}$  from an NMSSM-mechanism in hidden sector.  
[Zurek '08, Chun+Park '08]
  - $M_a \sim M_s \sim \text{TeV}$  from an NMSSM in the visible sector.
  - Gaugino mediation with residual anomaly mediation in the hidden sector. [Katz+Sundrum '09]

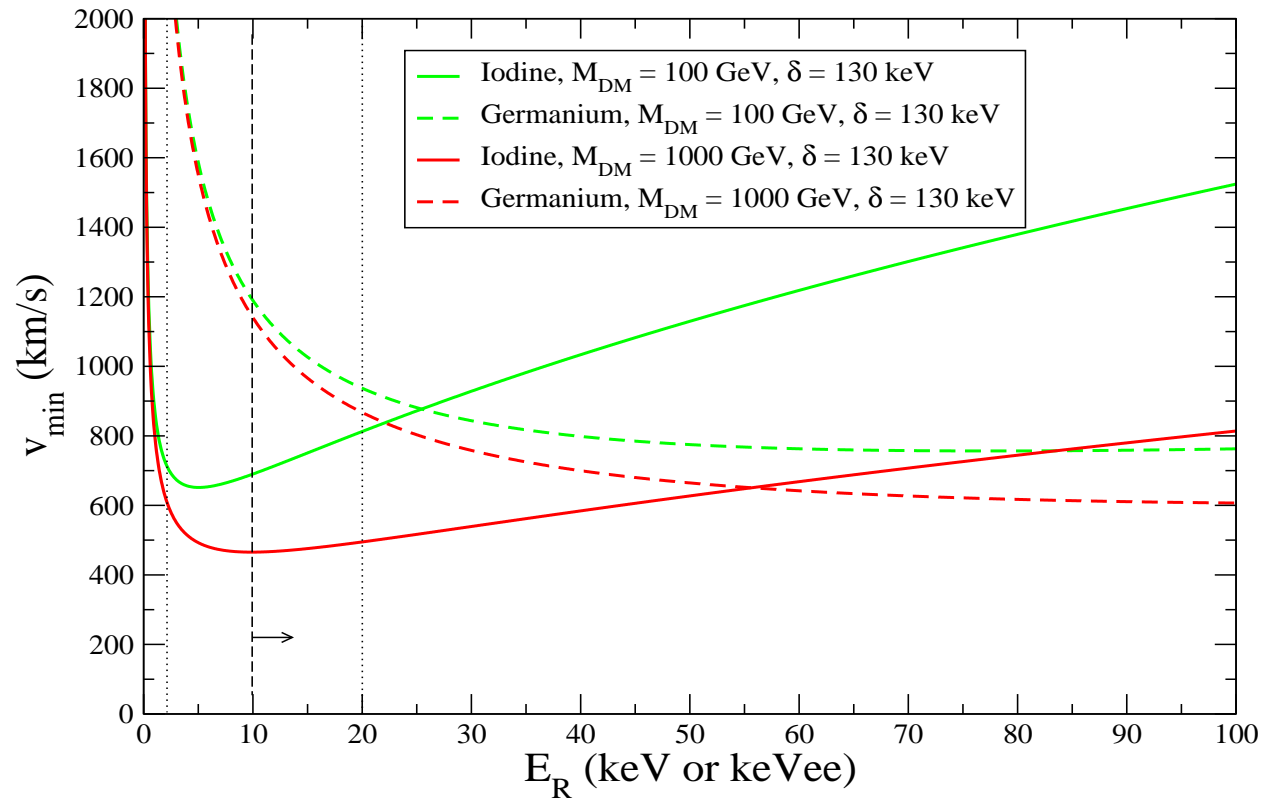
## Summary

- 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

# More IDM Kinematics

- IDM kinematics enhances the annual modulation.
- The signal is cut off at low  $E_R$ .

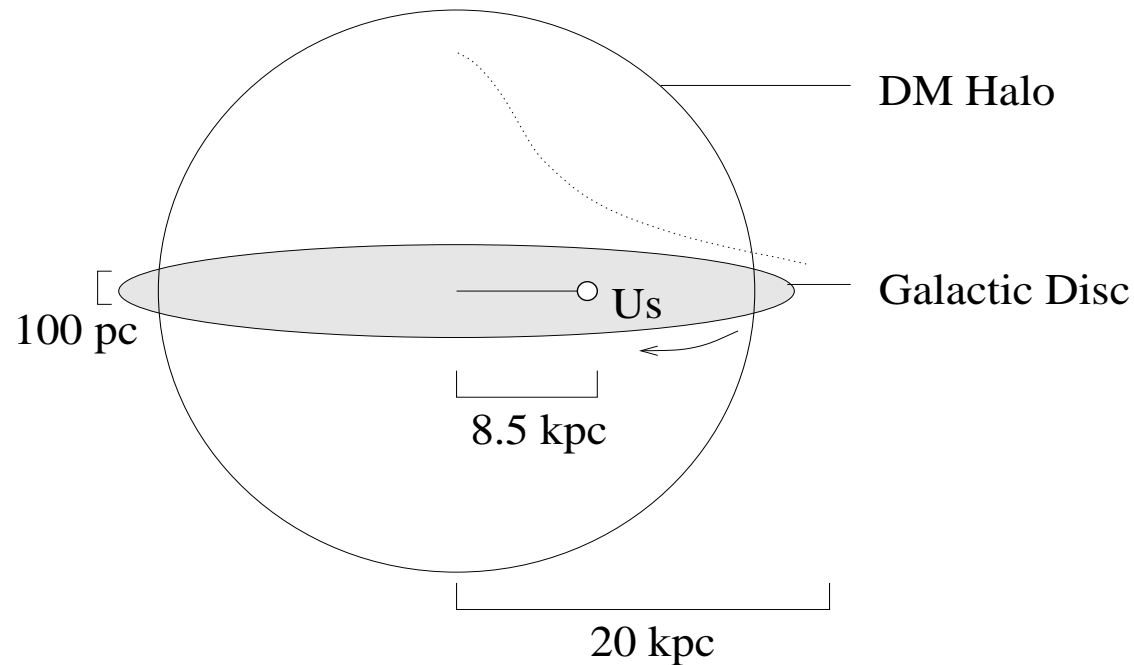


# Indirect Detection Signals



# DM in our Galaxy

- Flat galactic disc surrounded by a spherical DM halo:

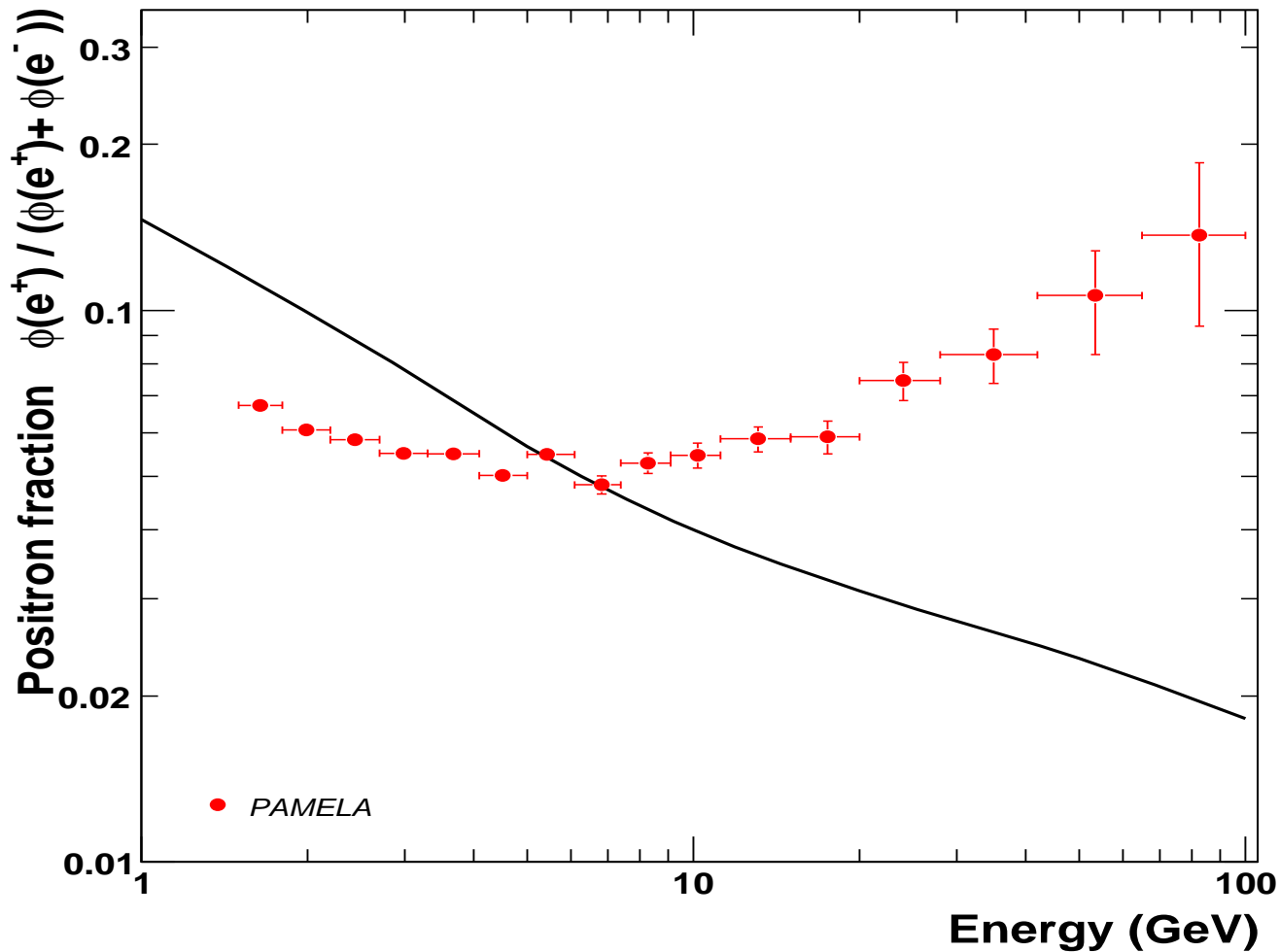


- DM density is largest at the galactic center.
- DM in the halo can annihilate producing particle fluxes.

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

# PAMELA - Cosmic Ray Positrons

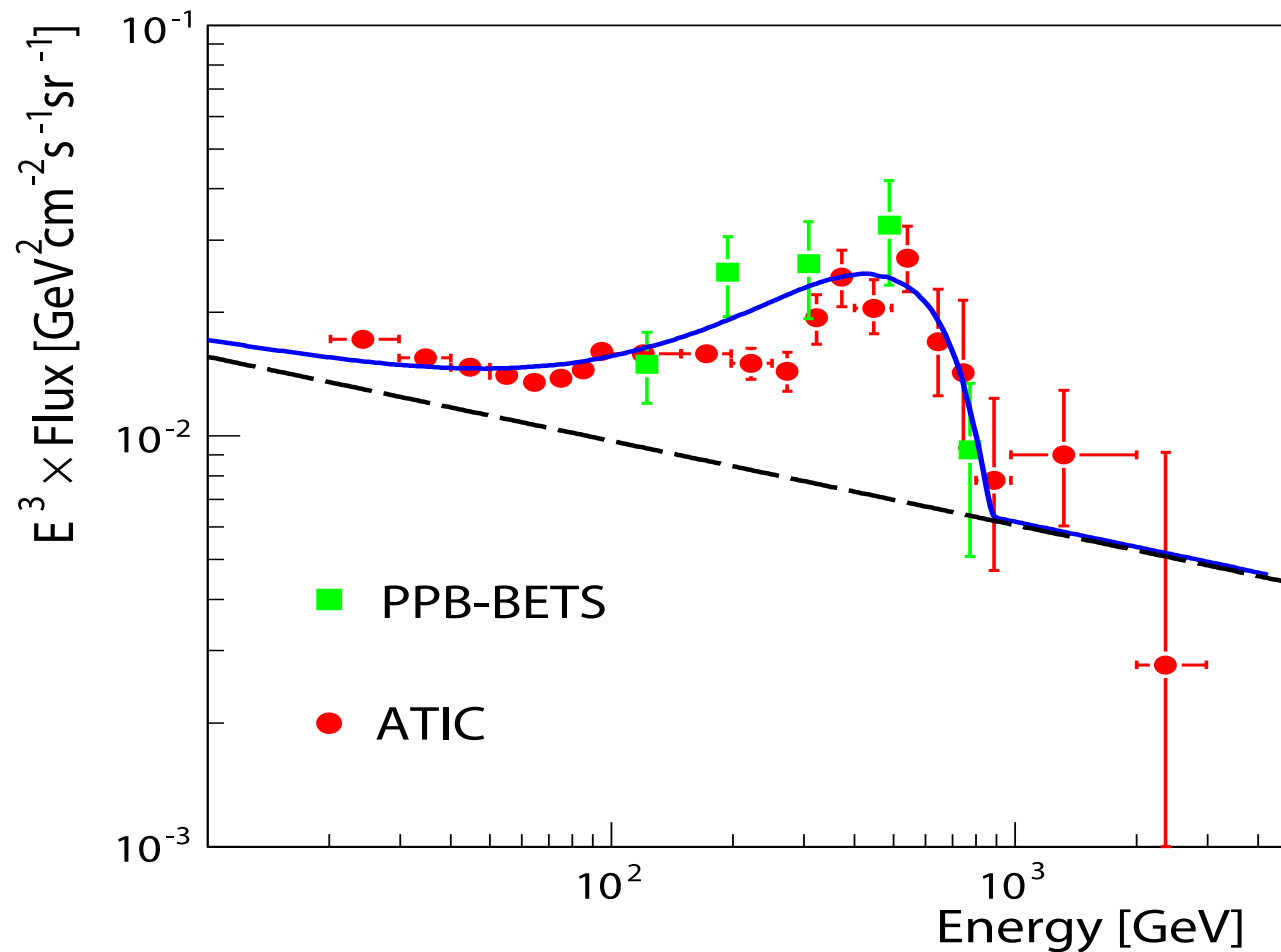
- PAMELA sees an an excess of  $e^+$  over background.



- No excess flux of **anti-protons** is observed.

# ATIC and PPB-BETS - Cosmic Ray Electrons

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



# Dark Matter Implications

- Dark Matter annihilation can account for these signals.
- Implications:
  1. PAMELA+ATIC+PPB-BETS Spectrum:  
 $\Rightarrow M_{DM} \gtrsim 700 \text{ GeV}$  ( $M_{DM} \gtrsim 100 \text{ GeV}$  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)

## 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  $\gamma$  rays from the galactic center.
- **GLAST/Fermi** telescope will test these further.

# DM Annihilation to Leptons

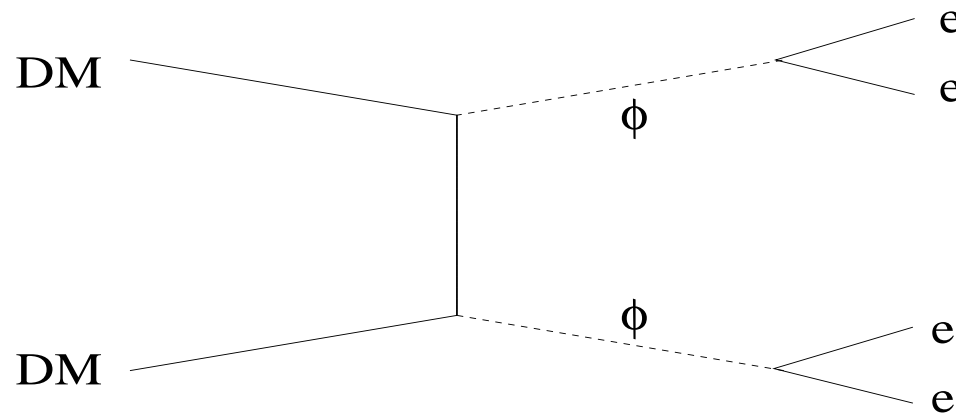
- Most DM candidates decay too democratically.  
*e.g.*  $\chi\chi \rightarrow W^+W^- \rightarrow q\bar{q}, \ell\nu_\ell$  gives too many antiprotons.

- 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  $e^+e^-$ ,  $\mu^+\mu^-$ ,  $\nu$ 's,  $\gamma$ '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

$$\mathcal{L} \supset (m_{DM}^{(0)} + \zeta P) \Psi_{DM} \Psi_{DM}$$

$$P \rightarrow \langle P \rangle \sim 100 \text{ GeV} \quad \text{at } T < T_{f.o.} \simeq m_{DM}^{(0)}/20$$

$$m_{DM} : m_{DM}^{(0)} \rightarrow m_{DM}^{(0)} + \zeta \langle P \rangle.$$

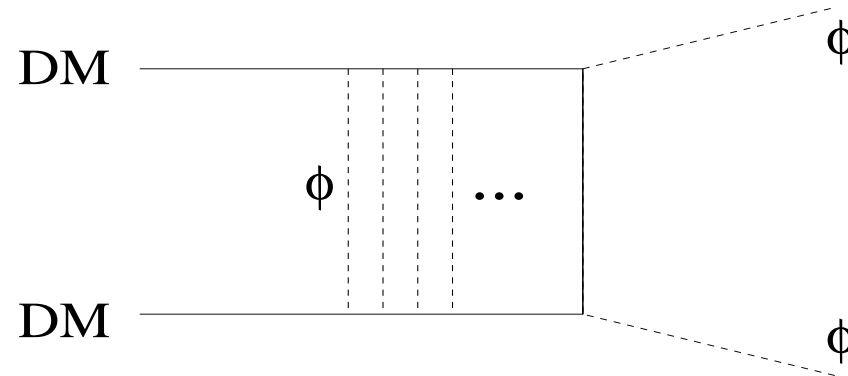
$\Rightarrow$  modified DM properties today relative to freeze-out

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

- DM annihilation can get a Sommerfeld enhancement today.

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

*e.g.* Scalar  $\phi$  Exchange



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

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

$\Rightarrow m_\phi \lesssim 1 \text{ GeV}$  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  $\gamma$  rays.
- $\gamma$  flux from annihilations ( $\sim n_{DM}^2$ ) is enhanced in the GC.
- $\gamma$  flux from decays ( $\sim n_{DM}$ ) is less enhanced.