GGI Florence, Oct 27, 2009

Form Factor Dark Matter

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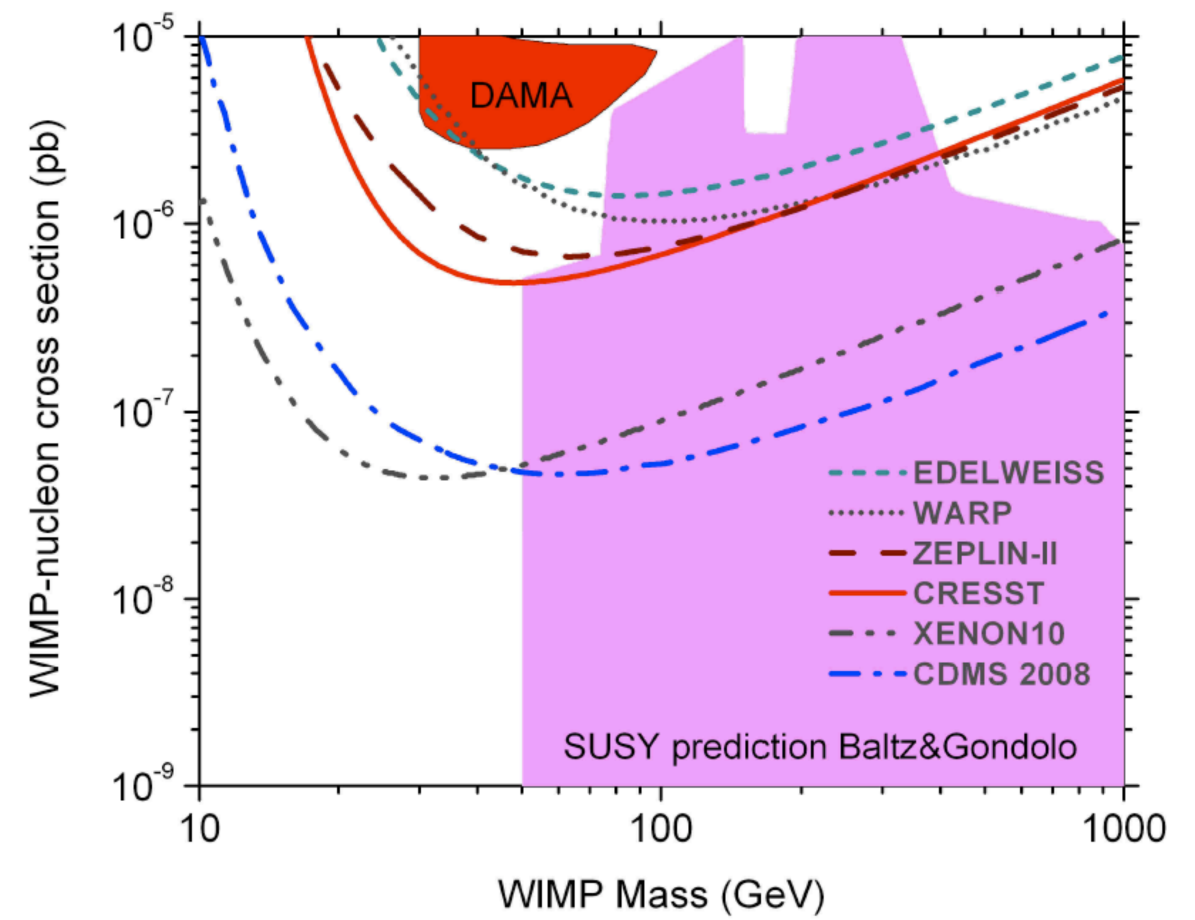
arXiv:0908.2991 :
B. Feldstein, ALF, E. Katz
arXiv:0910.0007 :
B. Feldstein, ALF, B. Tweedie, E. Katz

Outline

- Direct Detection Review
- Form Factor Dark Matter w/o channeling
- Form Factor Dark Matter w/ channeling

Direct Detection

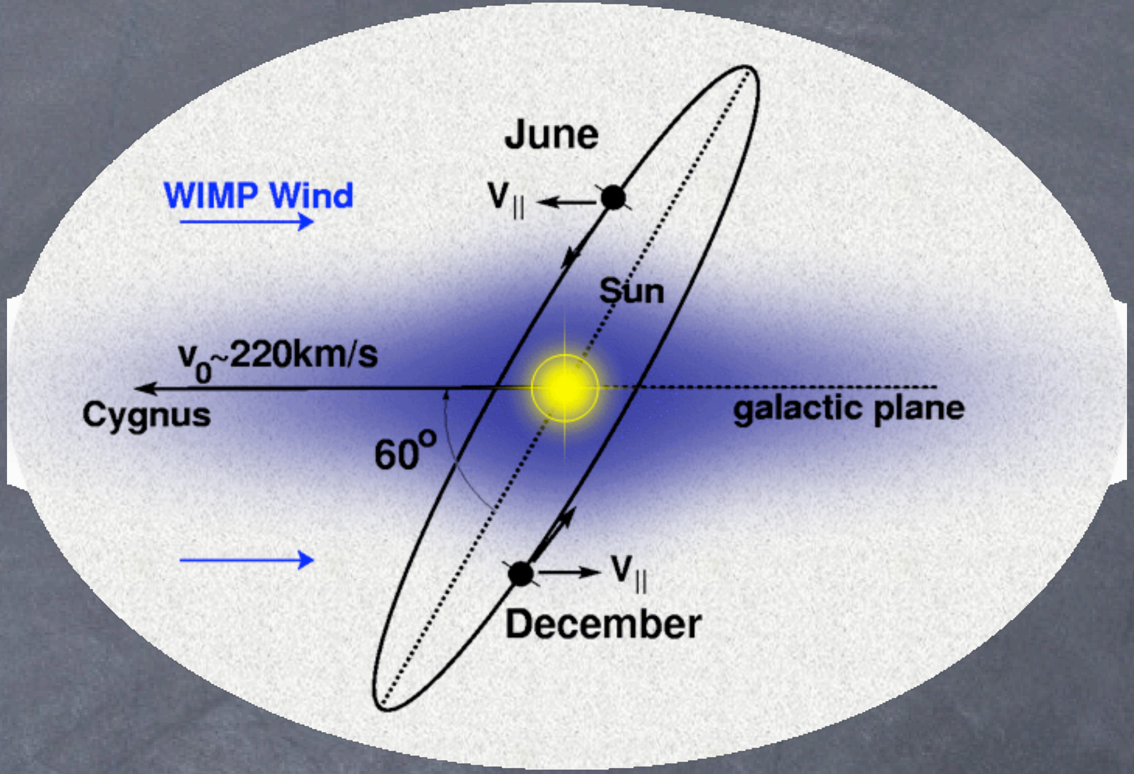
- Observe nuclear recoils due to Dark Matter scattering
- Put constraints on cross-section vs. mass
- Lots of experiments: DAMA, CDMS, CRESST, XENON...

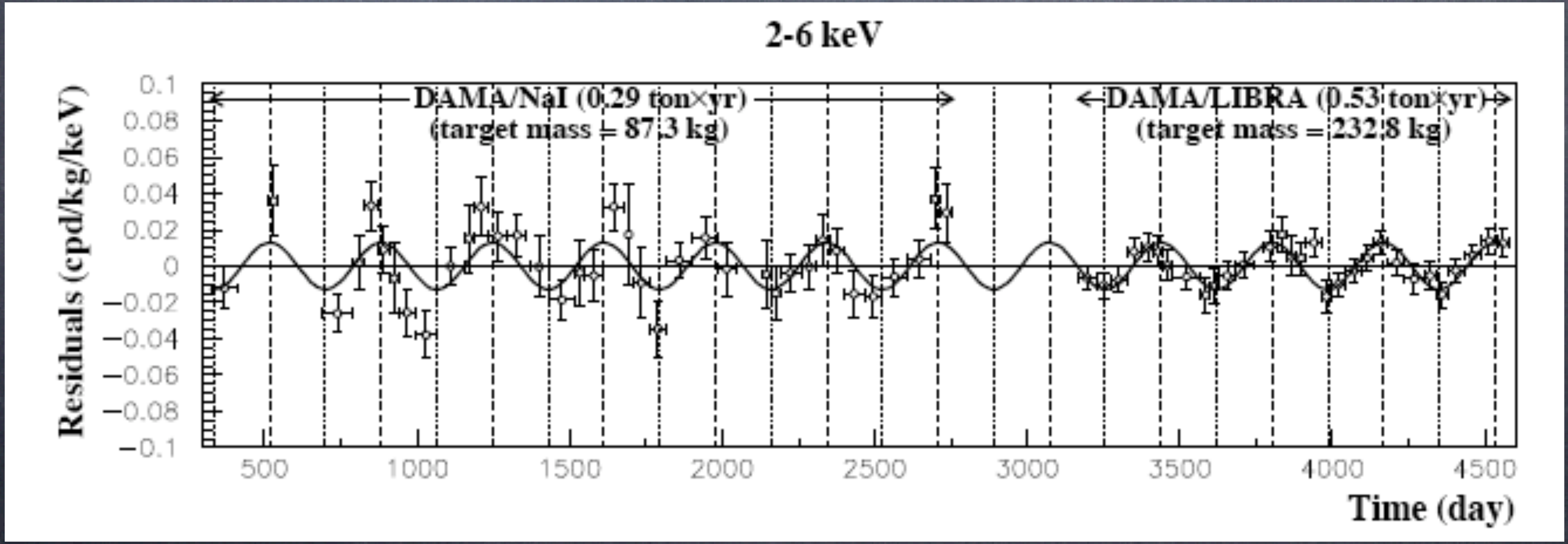


arXiv:0809:1829

DAMA Annual Modulation

- DAMA sees 8σ effect, increasingly in phase with earth's motion





- No proposed background to explain DAMA's observation
- Known backgrounds are much too small: DAMA considered neutrons, muons, neutrinos, temperature...
- Standard WIMP explanation is completely ruled out by other direct detection experiments

WTF?

Difference in DAMA vs. Others

- 1) Nuclear mass (DAMA uses NaI, CDMS uses Ge, etc.)
- 2) Different ranges in nuclear recoil energy
- 3) No other experiment looks at annual modulation
- 4) DAMA doesn't veto purely EM events
- 5) Crystal Structure
- 6) Spin of nuclei

Event Rate Formula

- Events per unit time per detector mass per unit recoil energy:

local DM density $\sim 0.3 GeV/cm^3$

$$\frac{dR}{dE_R} = N_T \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v_{\rm min}} d^3v f(v) v \frac{d\sigma}{dE_R}$$

DM/Nucleus Cross-section:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2} \frac{\sigma_p}{m_p^2} Z^2 F_N^2(E_R)$$

Nuclei/detector mass

Kinematic limit

Atomic Number

DM Halo Distribution:

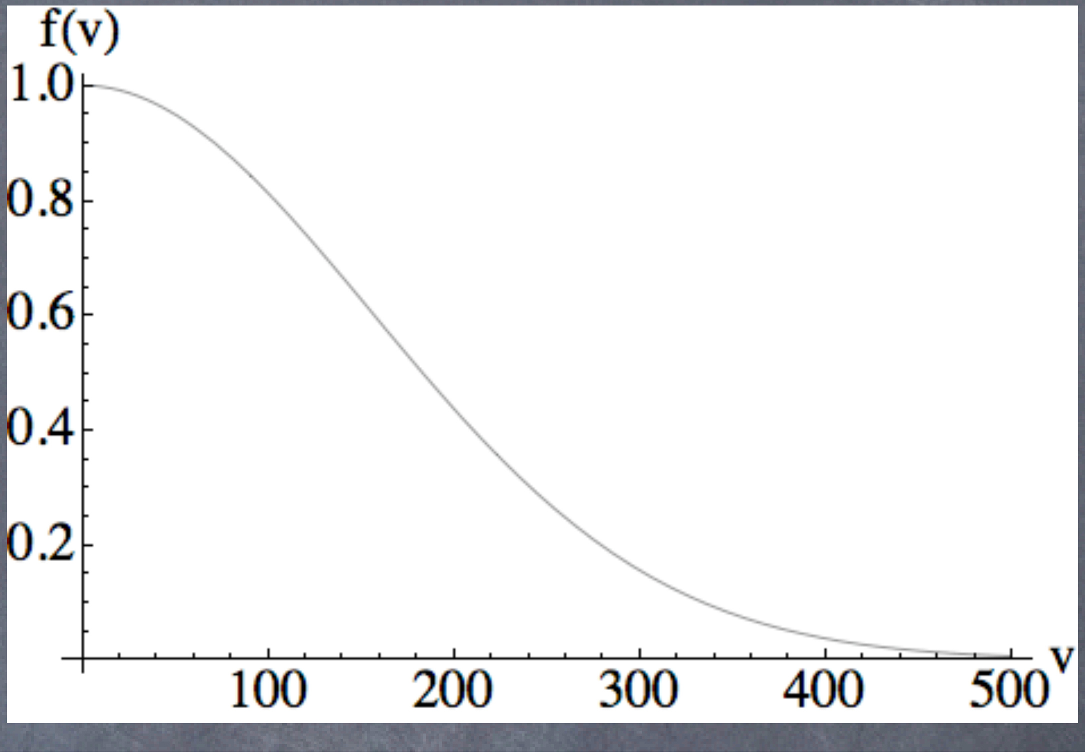
$$f(v) \sim e^{-(v/\bar{v})^2}$$

$$v_{\rm min} = \frac{q}{2\mu}$$

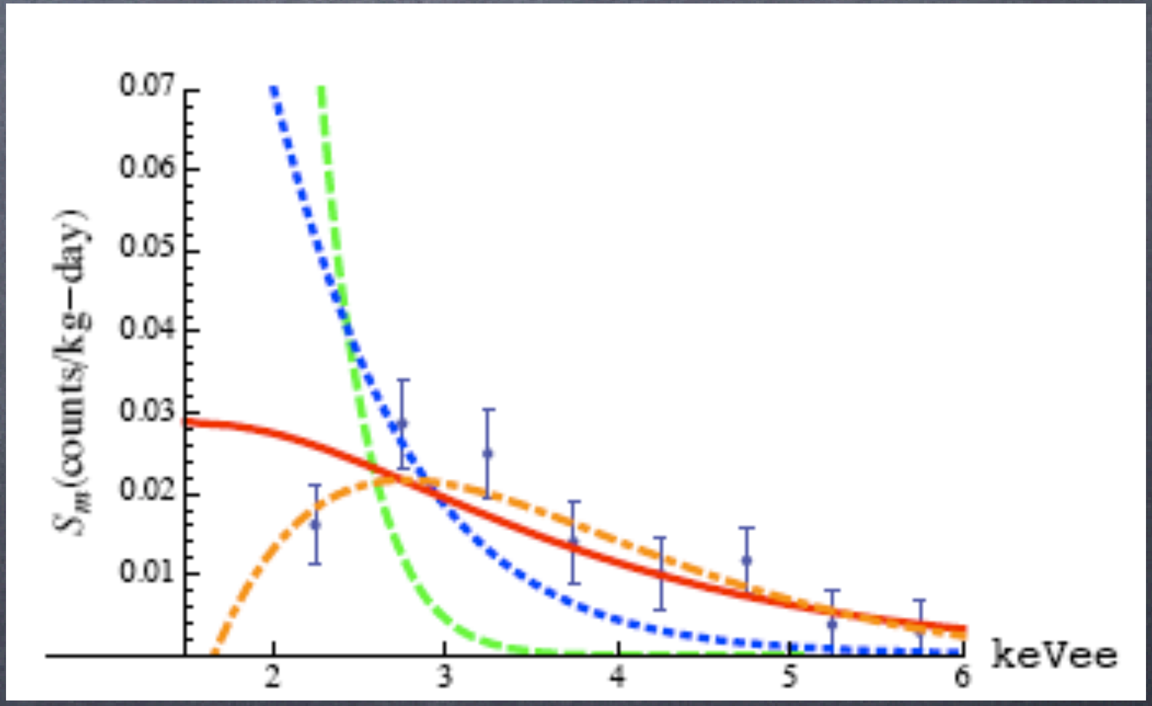
Nuclear Form Factor

Enhanced Modulation

$$v_{\min} = \frac{q}{2\mu}$$



Small mass -> larger modulation



But bad spectrum, overprediction at light nuclei

Chang, Pierce, Weiner 0808.0196

Proposed Explanations

- Light dark matter, sodium scattering

  Gelmini, Gondolo
- Purely electronic scattering

  Fox, Poppitz
- Channeling

  Drobyshevski
- Spin-dependent scattering

  Savage, Gondolo, Freese
- Inelastic scattering

  Tucker-Smith, Weiner

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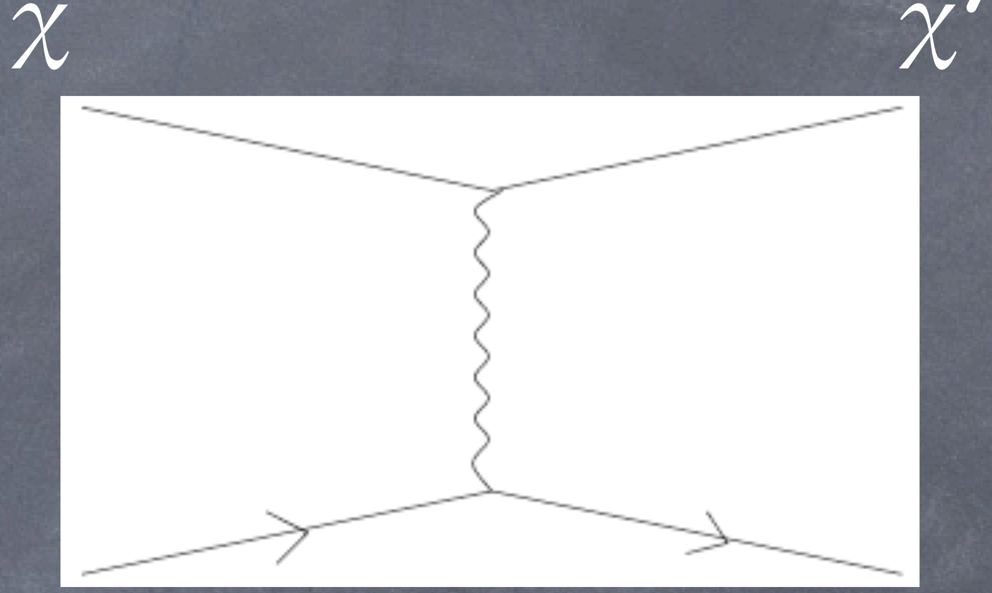
Only viable model

Elastic vs. inelastic



$$v_{\min} = \frac{q}{2\mu}$$

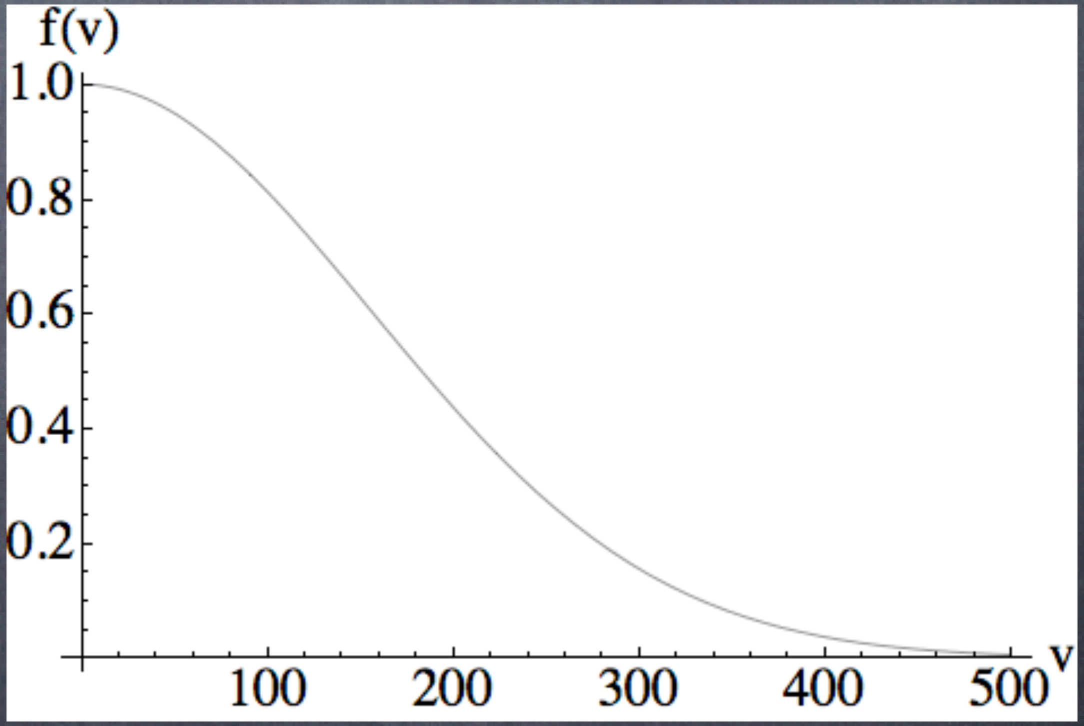
vs.

$$v_{\min} = \frac{q}{2\mu} + \frac{\delta}{q}$$

$$\delta = m_\chi - m_{\chi'}$$

Momentum Transfer:

$$q = \sqrt{2 m_N E_R}$$

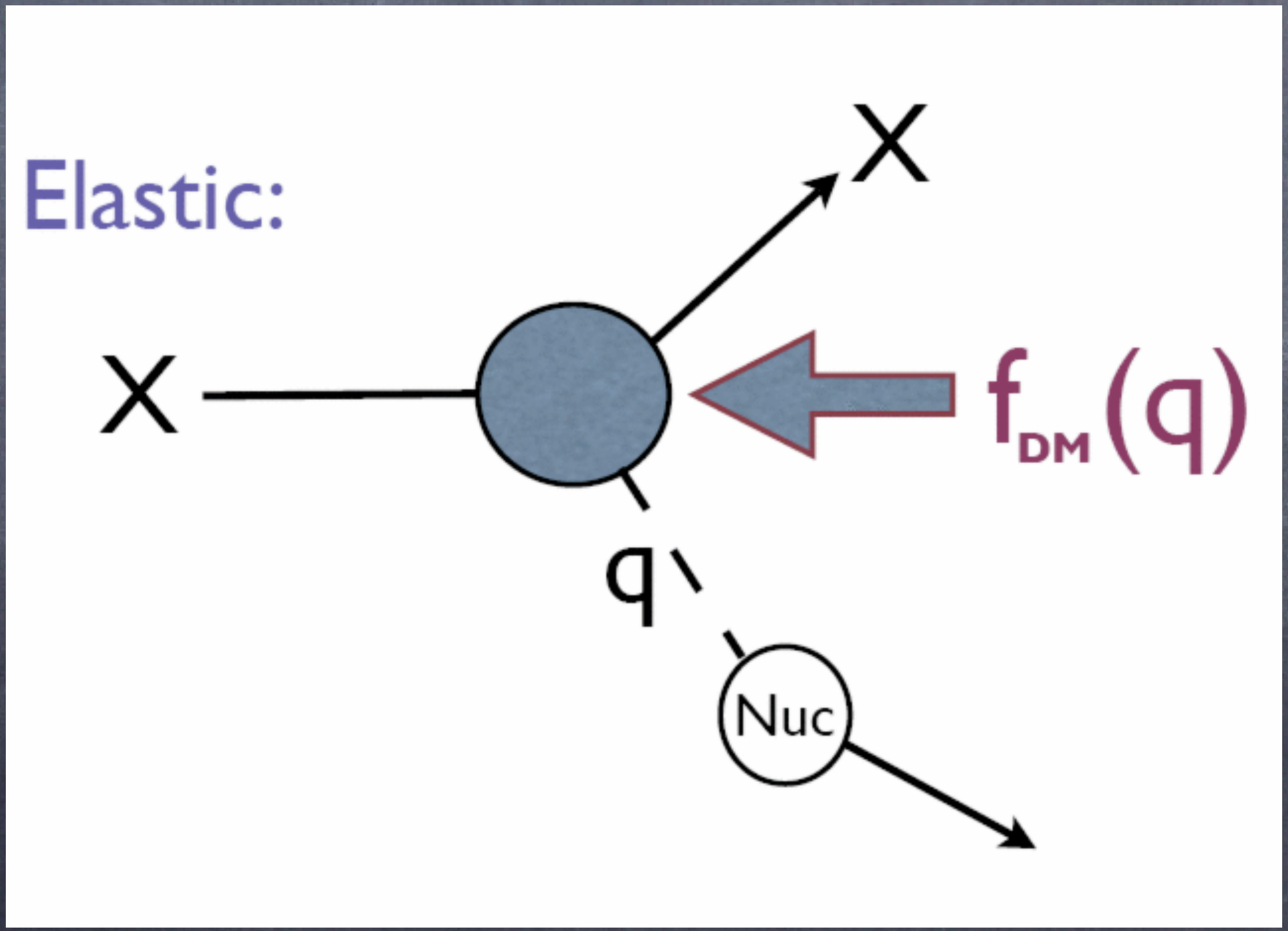


Form Factor Dark Matter

- Introduce form factor in dark matter scattering, coming from dark matter internal structure

$$\frac{dR}{dE_R} \to \frac{dR}{dE_R} f_{\rm DM}^2(q)$$

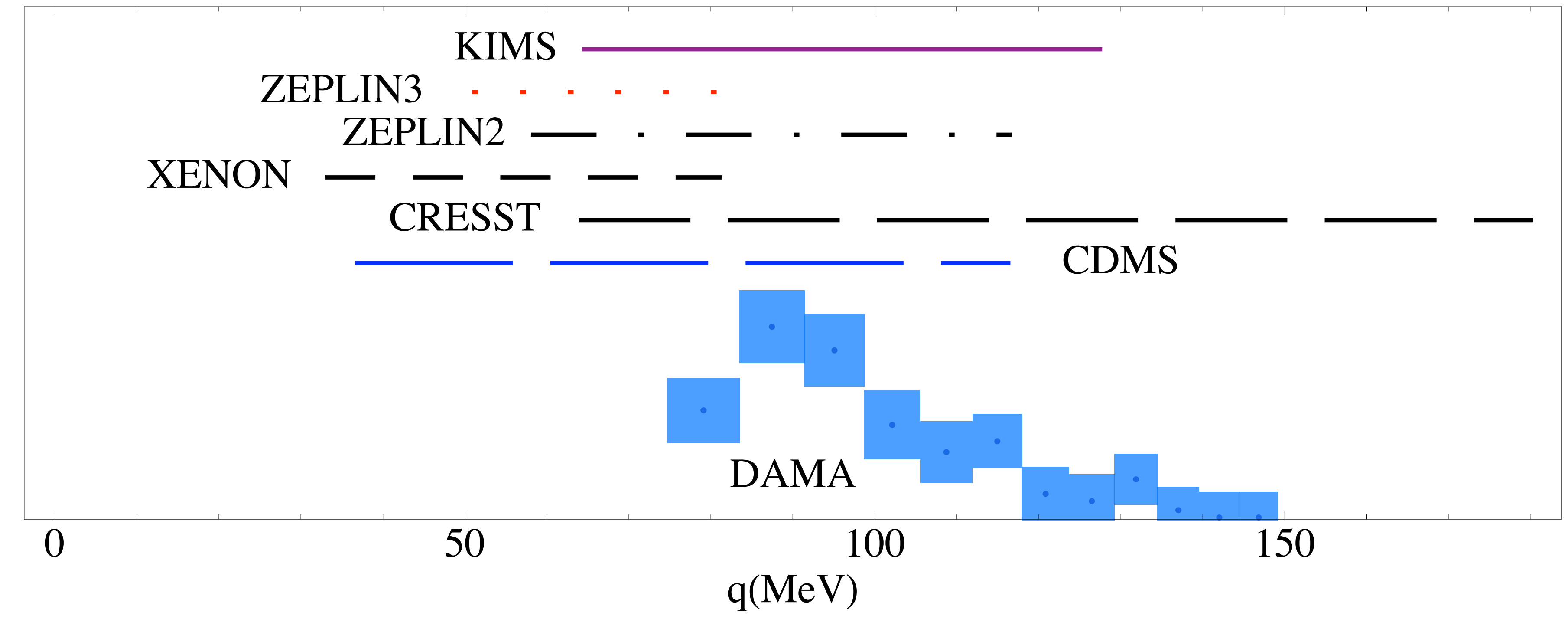
$$q = \sqrt{2m_N E_R}$$



Overlap in q

- F(q) drops at small q to fix DAMA spectrum, reduce number of events at CDMS (smaller m_N)
- Not immediately clear there even exists a form factor that works - smaller nuclear mass can be compensated for with larger recoil energy

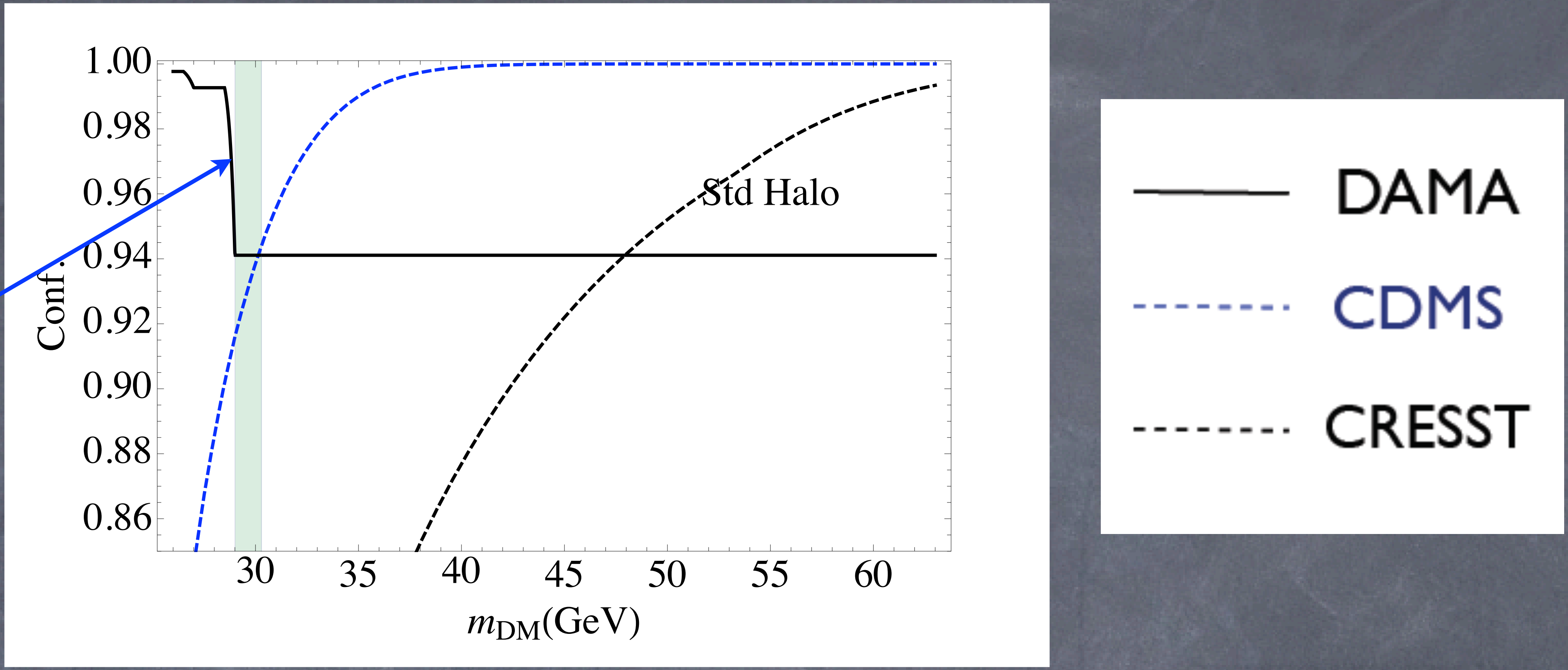
DAMA predicts events in $80\,\mathrm{MeV} < q < 120\,\mathrm{MeV}$



“Idealized” Form Factor

- Best case Scenario - Choose F(q) by hand so that:
- 1) Fit DAMA spectrum
- 2) Outside of DAMA window, set F(q)=0
- For a given dark matter mass, look at the events predicted at CDMS, CRESST, etc.

v_{esc} too small

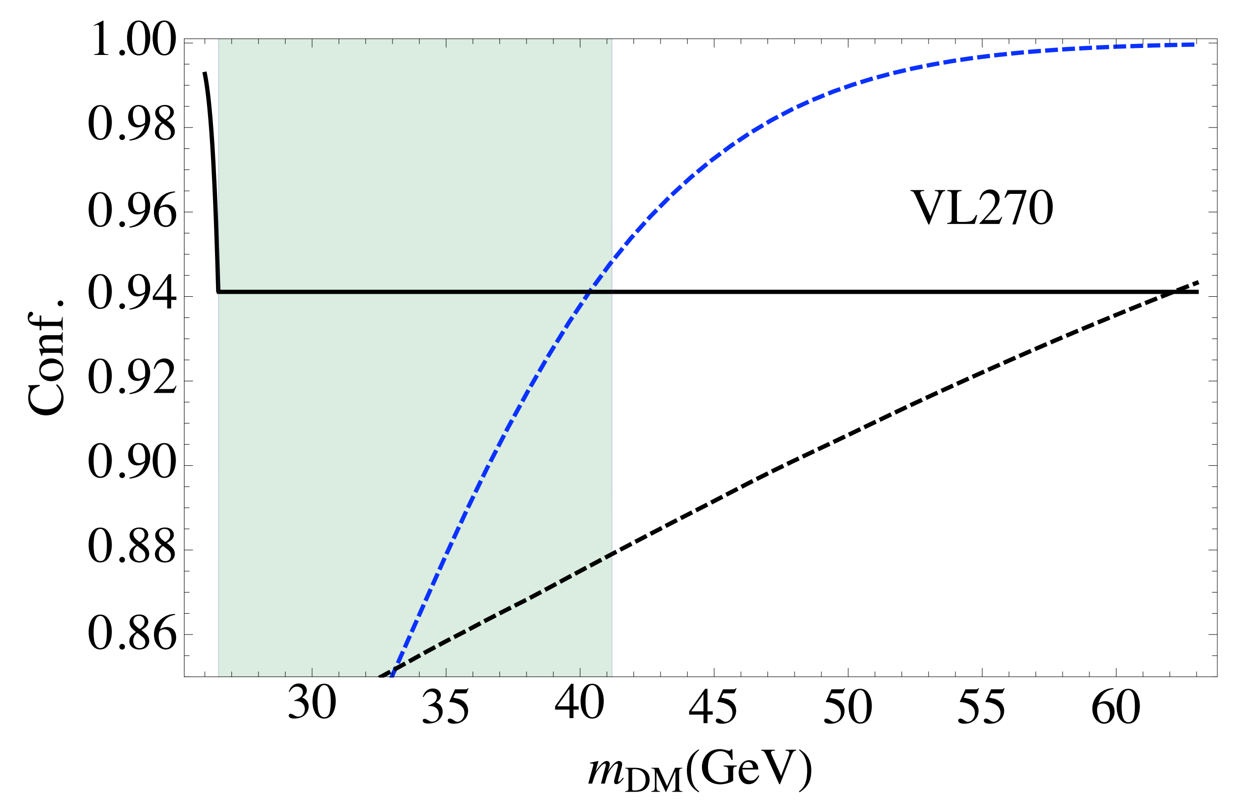


- Not much room to work with with Standard Halo
-

- Significant Halo Uncertainties
- Via Lactea simulations:
- Main effect: tighter distributions
- $$\begin{aligned} f(v_R) &\propto \exp\left[-\left(\frac{v_R^2}{\bar{v}_R^2}\right)^{\alpha_R}\right] \\ f(v_T) &\propto v_T \exp\left[-\left(\frac{v_T^2}{\bar{v}_T^2}\right)^{\alpha_T}\right] \end{aligned}$$

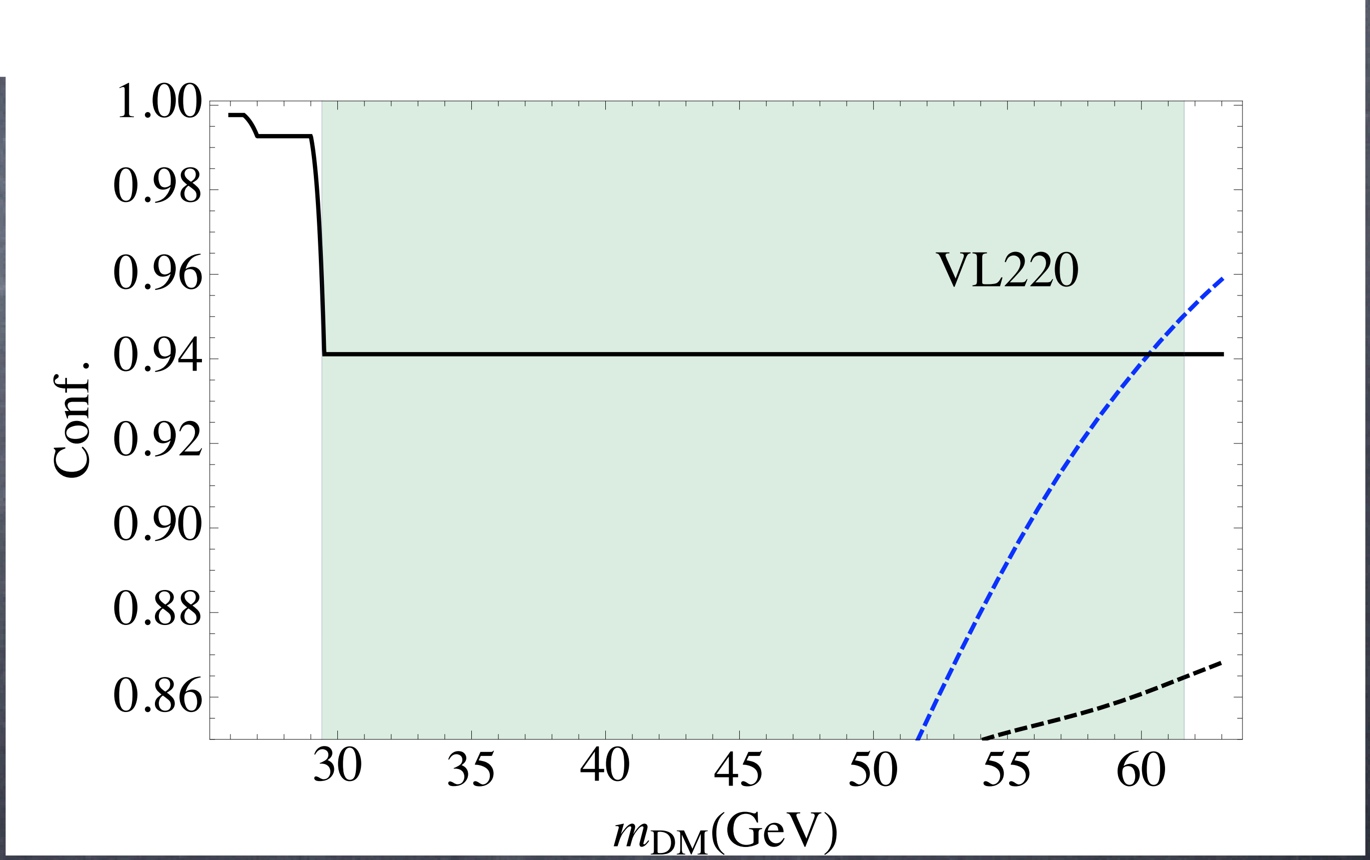
$$\alpha_R = 1.09, \alpha_T = 0.73, \bar{v}_R = 0.72\sqrt{-U(r_0)}, \bar{v}_T = 0.47\sqrt{-U(r_0)}$$

-Diemand, Kuhlen, Madau
-Fairbairn, Schwetz



$$\sqrt{-U(r_0)} = 270\mathrm{km/s}$$

$$\sqrt{-U(r_0)} = 220\mathrm{km/s}$$



-March-Russell, McCabe, McCullough

Models:

- Simple form factor: F(q)=q^2

  Easily generated from lowest dim G.I. operator $\mathcal{L} \supset \frac{i}{\Lambda^2}\partial^\mu \chi \partial^\nu \chi^* F_{\mu\nu}$
- But this is not sufficient (w/o channeling)!
- Look for more complicated "existence proof" model: Interfering gauge bosons

$$F(q) \propto q^2 \left(\frac{g_1^2}{q^2+m_1^2} - \frac{g_2^2}{q^2+m_2^2} \right) \rightarrow cq^2(q^2 - q_0^2)$$

2 Gauge Boson (2GB) Model

$$\mathcal{L} \supset \frac{i}{\Lambda^2}\partial^\mu \chi \partial^\nu \chi^* F_{\mu\nu}$$

DM is neutral, has charged consituents

$$\mathcal{L} \supset \epsilon \left(g_1 F^{(1)}_{\mu\nu} - g_2 F^{(2)}_{\mu\nu} \right) B^{\mu\nu}$$

- Dark Forces mix with hypercharge, but with opposite signs

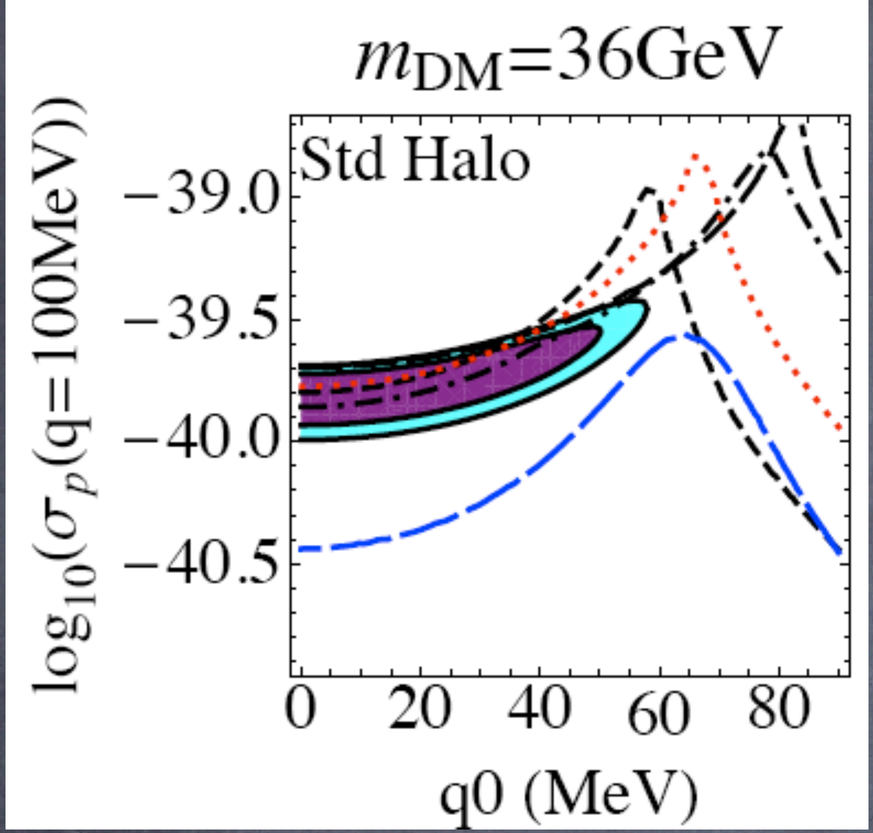
$$F(q) \propto q^2 \left(\frac{g_1^2}{q^2 + m_1^2} - \frac{g_2^2}{q^2 + m_2^2} \right) \rightarrow c q^2 (q^2 - q_0^2)$$

3 Gauge Boson (3GB) model

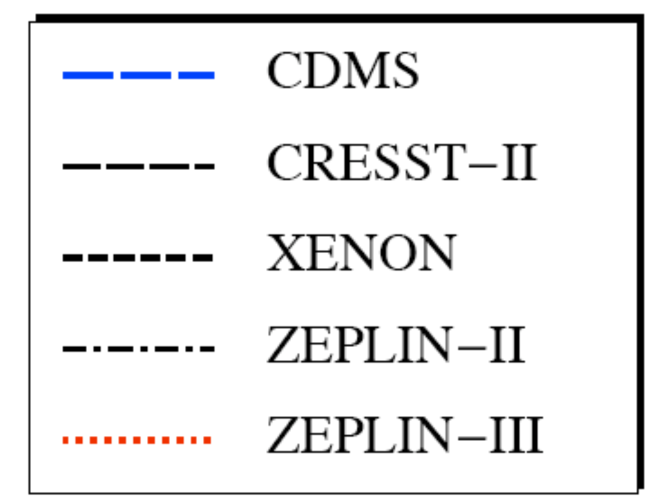
- Similar idea:

$$F(q) \propto q^2 \left(\frac{g_1^2}{q^2 + m_1^2} - 2\frac{g_2^2}{q^2 + m_2^2} + \frac{g_3^2}{q^2 + m_3^2} \right) \to c q^2 (q^2 - q_1^2)(q^2 - q_2^2)$$

Constraints:

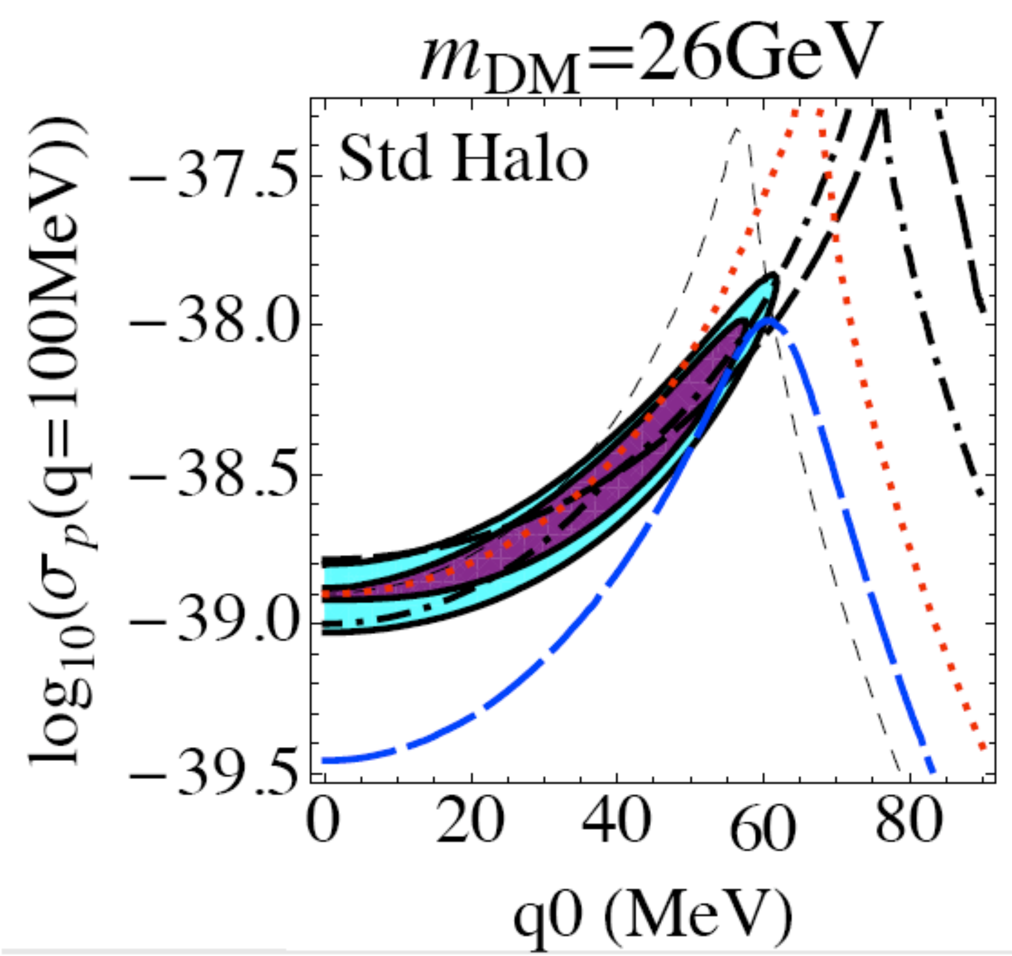


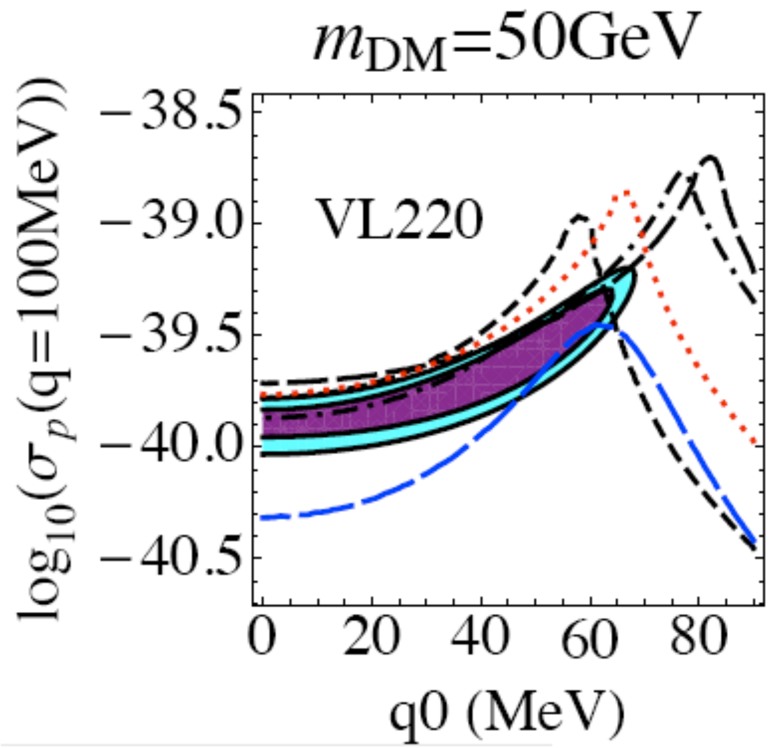
2 GB Model (99% constraint shown)



3 GB Model (95% Constraint shown)

The models don't work with Standard Halo





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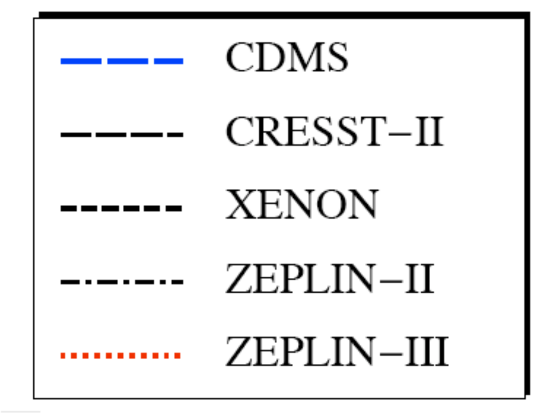
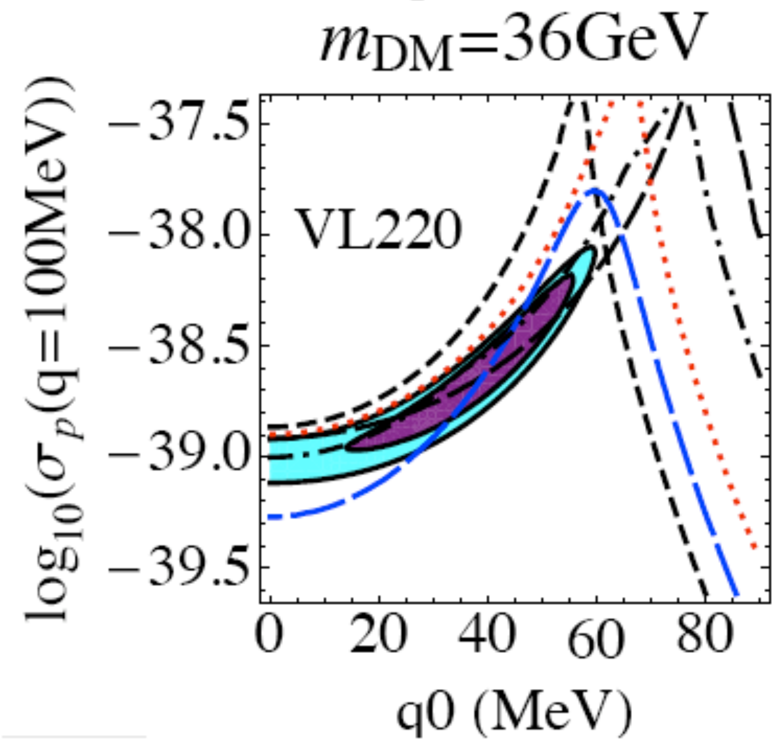




3 GB (95% shown)

Benchmark Models:

Halo Model	DM Model	m_{DM}	χ^2_{DAMA}	$\sigma_{p,100MeV}$	p_{CDMS}	p_{CRESST}
VL_{220}	2GB ($q_0 = 50$MeV)	50 GeV	11.8	2.34×10^{-40}cm^2	0.97	0.89
VL_{220}	3GB ($q_1 = 42.5, q_2 = 38$MeV)	36 GeV	8.9	2.00×10^{-39}cm^2	0.90	0.90
VL_{270}	3GB ($q_1 = 50, q_2 = 37.5$MeV)	32 GeV	10.3	2.10×10^{-39}cm^2	0.94	0.95
"	"	"	14.9	1.79×10^{-39}cm^2	0.90	0.90

Works better - 3GB benchmark consistent with all experiments at 90%

Channeling

- General Issue: Models that explain DAMA need coincidental parameters (δ in iDM, q_0 in ffDM, position of resonance in rDM) to escape null exp'ts
- Would be nice if DAMA were simply the most sensitive at the lowest energies, where the signal is
- Channeling! (considered by e.g.
  -Drobyshevski,
  -Bernabei et al.
  -Chang et al.
  -Fairbairn and Schwetz
  etc.
)

Channeling

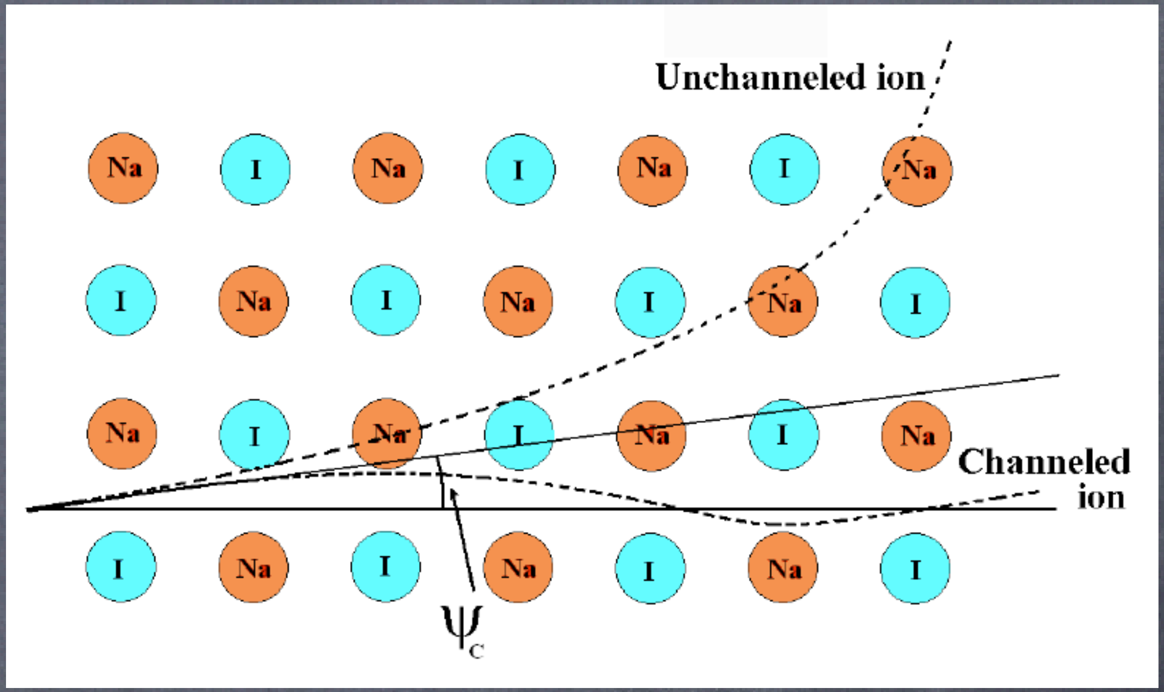
- Nuclear recoils usually lose only $\sim$ fractions of their energy electronically, most energy is lost to nuclear collisions -> heat.
- Fraction is called a "quenching" factor q, = 9% for iodine at DAMA
- Not measured directly at all relevant energies, and uncertainties can be important!
- Channeling: some events at very low DAMA energies have very different quenching factor, due to crystal structure

Channeling

- Along some directions, q may be much closer to 1, as scattering with lattice is shallow

If channeling at DAMA is real, then a 20keV event-> 2keV event!

DAMA would be sensitive to MUCH lower energies



$$m_{\rm DM}^{-1} = \frac{2(v_{\rm esc} + v_e)}{q_{\rm min}} - m_N^{-1}$$

Then: choose light DM masses, and push XENON, CRESST, etc above escape velocity

Channeling

- Theory worked out by Lindhard in ‘60s, considered (energy-dependent) solid angle in which traveling ion would not escape channel
- Based on “critical scattering angle”, above which the ion escapes the channel

$$\psi_c = \sqrt{\frac{a_{\rm TF}}{d_{\rm lattice}}}\left(\frac{3Z_1Z_2\alpha}{Ed_{\rm lattice}}\right)^{1/4}$$

- First discovered experimentally
- But not experimentally verified at DAMA

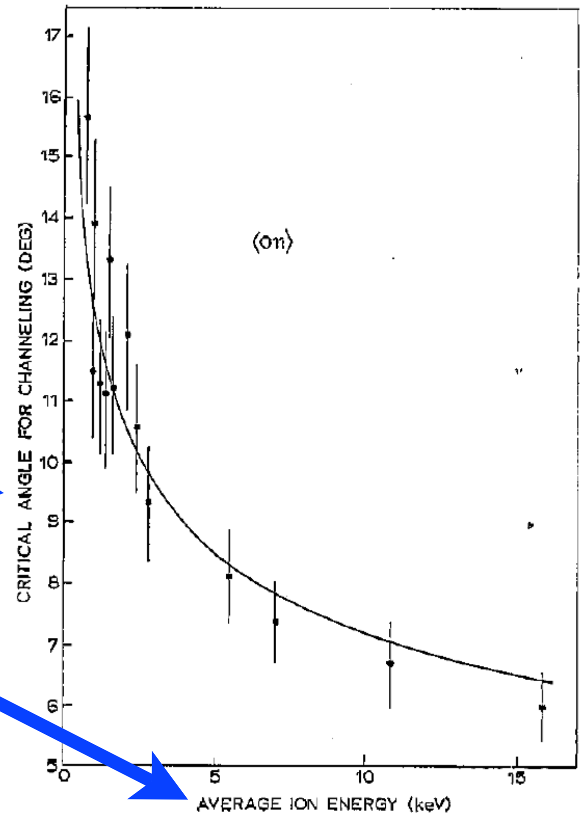


Fig. 2.29. Critical channelling angles of deuterons in gold crystals about 200 Å thick as a function of energy, compared with the predictions of Lindhard (1965) (after Andreen and Hines, 1966).

Channeling

- Unfortunately, not quite enough - too many events at CDMS-Si, XENON10 or bad fit to DAMA spectrum

-Fairbairn and Schwetz
-Chang, Pierce, Weiner
etc.

- But - simple form factor from higher dim operator works!
- No new "coincidence" parameter - $F(q) = \frac{q^2}{\Lambda^2}$
- Λ gets absorbed into overall x-sec

Channeling

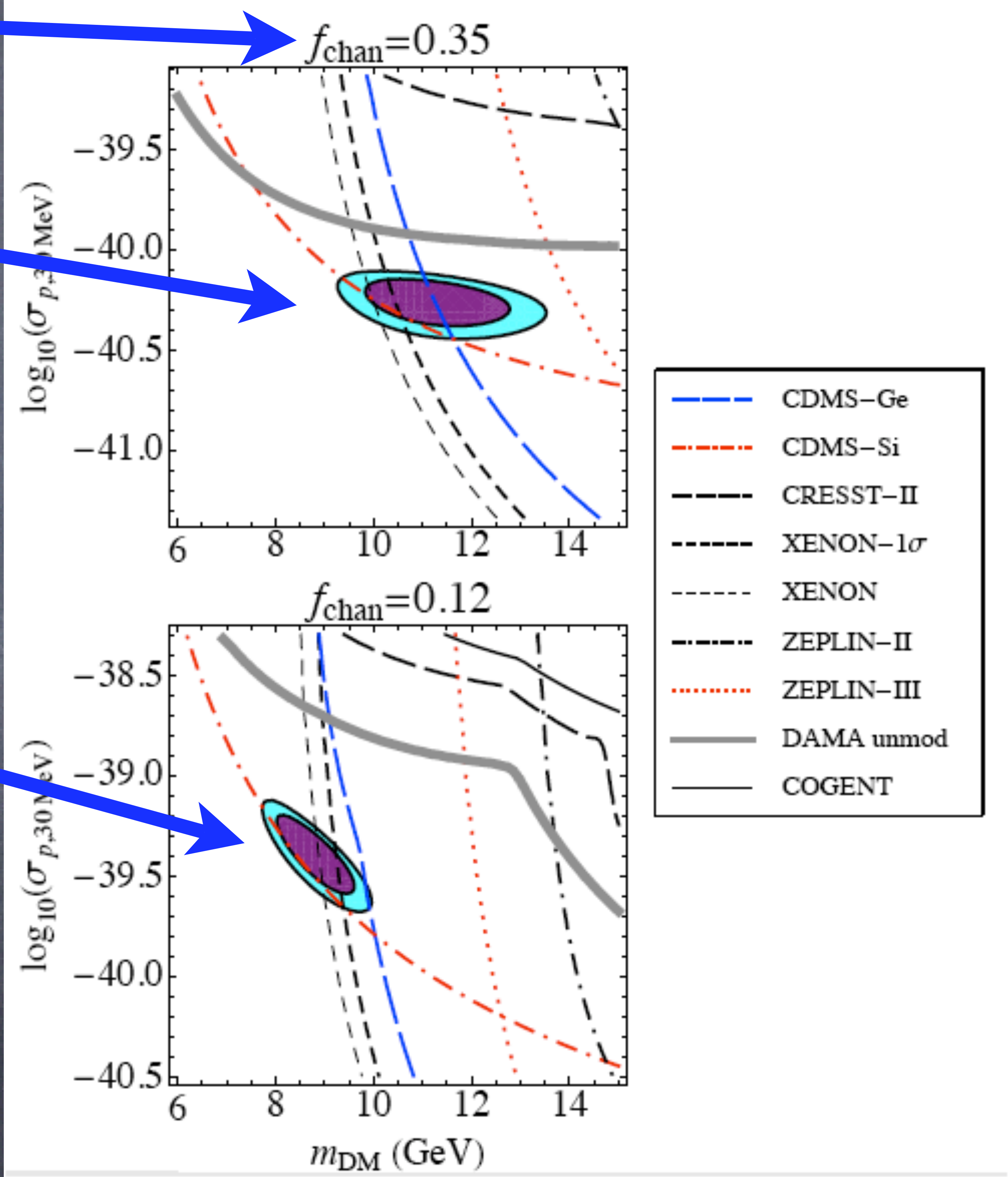
- Some idealizations: 1) "string" of atoms, 2) q=100% if channeled, 3) Thomas-Fermi potential for just a single string
- Also, at DAMA, ion starts out at a lattice site - "blocking" by nearby neighbors is potentially imporant
- How pessimistic can we be?
- We will proceed by parameterizing how much we can relax the fraction of channeled events, and the quenching fraction of channeled events
- Also vary the energy dependence of channeling fraction
- Even this is an idealization. Better: distributions of events with different q

Constraints

Energy-independent channeling fraction

No form factor

q^2 form factor



Constraints

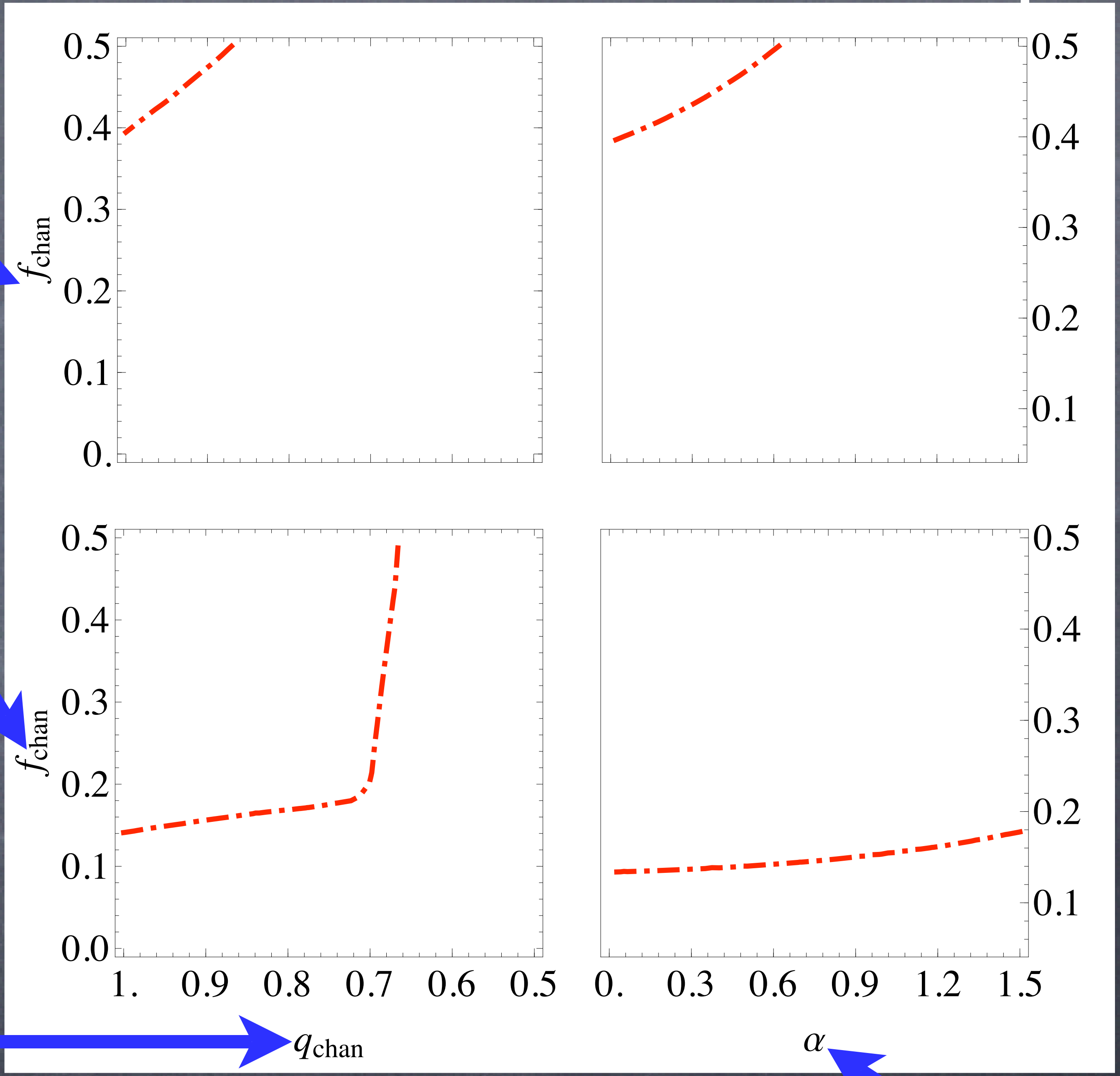
Channeling fraction
at 3keV

no form factor

q² form factor

"channeled"
quenching factor

<90% Constraint, all exp'ts



$$f_{\rm chan}(E_R) \propto E_R^{-\alpha}$$

Conclusions

- DAMA is potential signal of dark matter - worth considering alternative explanations
- Form Factor Dark Matter is a viable explanation for DAMA, requires some model-building to get appropriate form factors $30\mathrm{GeV} \lesssim m_{\mathrm{DM}} \lesssim 50\mathrm{GeV}$
- With very simple form factors, a channeling explanation for DAMA becomes much more conservative $7\mathrm{GeV} \lesssim m_{\mathrm{DM}} \lesssim 11\mathrm{GeV}$
- Exciting time for direct detection. Experiments are rapidly improving.

The End