Form Factor Dark Matter

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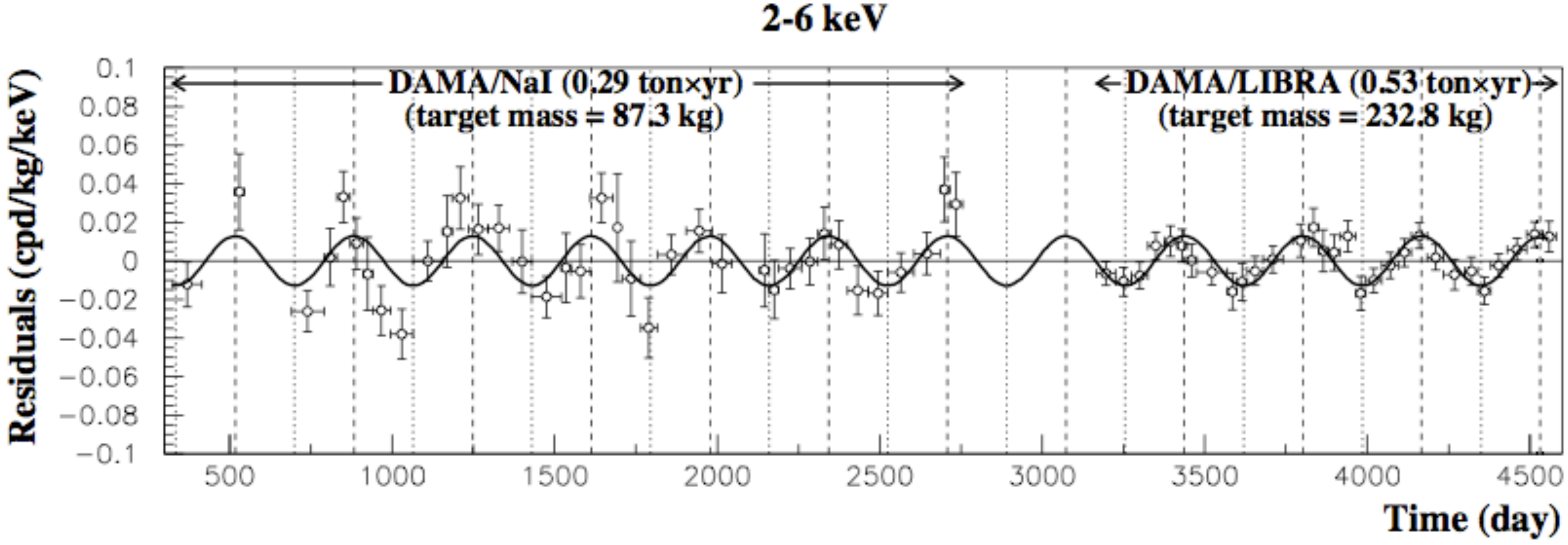
Outline

1. Introduction and review.
2. A form factor approach to reconciling DAMA with the rest of the world.
3. Particular models that realize a form factor.
4. Channeling with a dipole interaction.
5. Conclusions.

Introduction

After 11 years of running the DAMA experiment sees modulation, increasingly in phase with the earth's motion through the DM halo:



The rest of the world - null exp.

- CDMS (Ge): ~170 Kg-days, 2 events.
- CRESST (W): ~40 Kg-days, 12 events.
- Xenon10 (Xe): ~320 Kg-days, 24 events.
- Zeplin-II (Xe): ~225 Kg-days, 29 events.
- Zeplin-III (Xe): ~127 Kg-days, 7 events.

Rate of events:

DM-nucleon
crossection

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2}\frac{\sigma_n}{\mu_n^2}\frac{(f_p Z + f_n(A-Z))^2}{f_n^2} F_n^2(q^2 = 2m_N E_R)$$

DM-nucleon
reduced mass

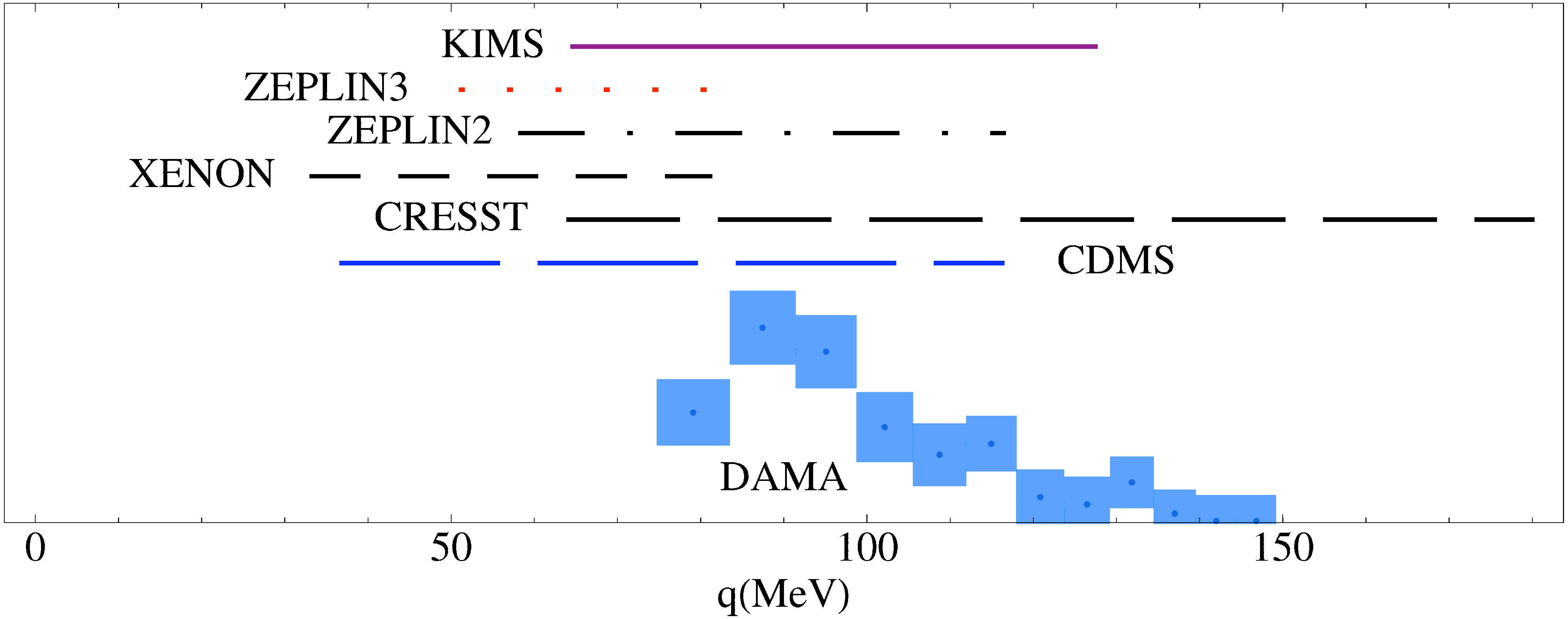
Nuclear form factor

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi}\int_{v_{min}}^{v_{esc}} dv f(v) v \frac{d\sigma}{dE_R}$$

# of target nuclei
per detector mass

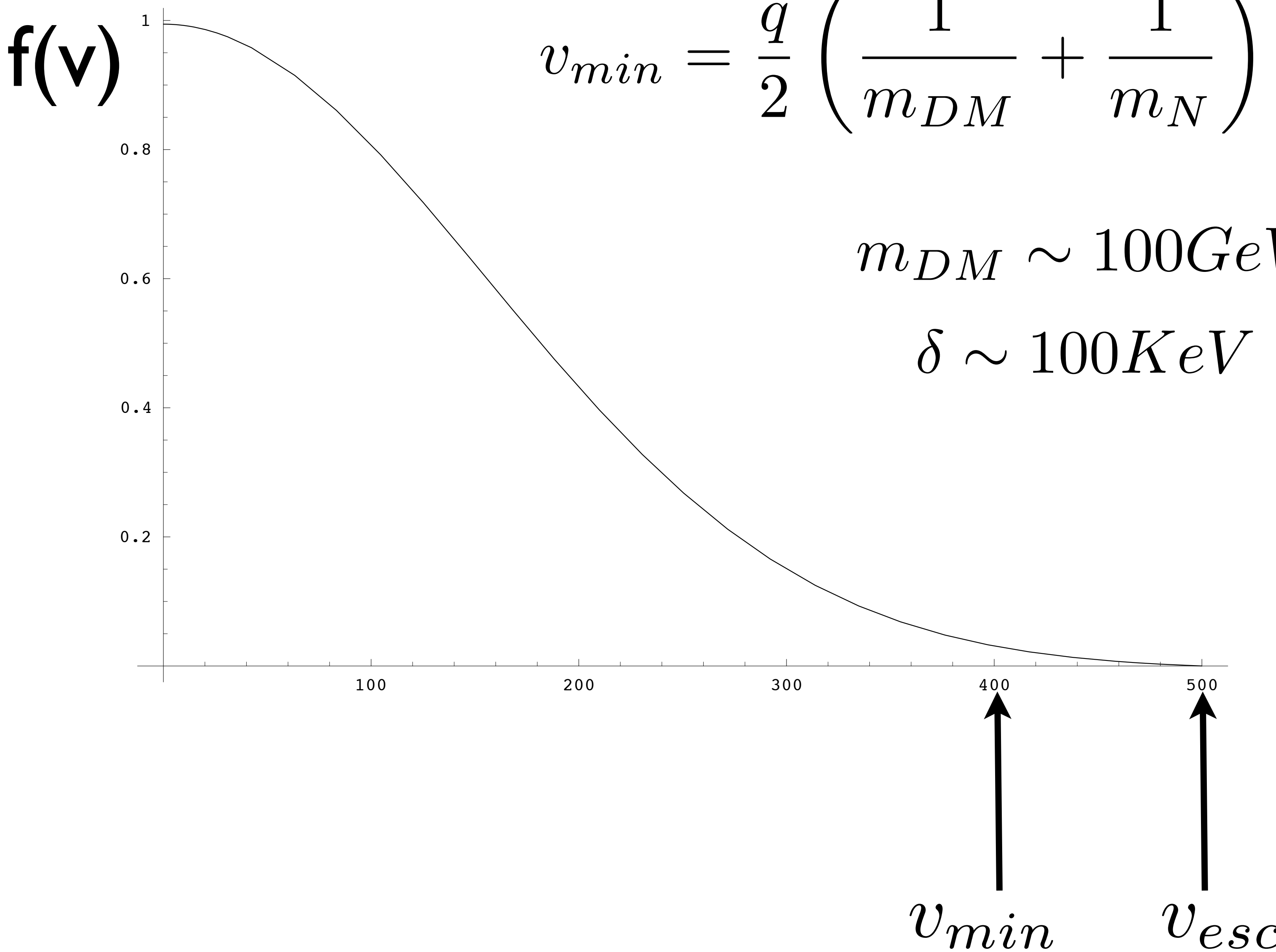
DM-Halo profile

Tension arrises from overlap in q of DAMA w/ other experiments:



$$\frac{dR}{dE_R} \sim N_T m_N A^2 F_n(q) \int_{v_{min}(q,m_N)}^{v_{esc}} dv f(v)/v$$

Inelastic DM: $v_{min} = \frac{q}{2}\left(\frac{1}{m_{DM}} + \frac{1}{m_N}\right) + \frac{\delta}{q}$



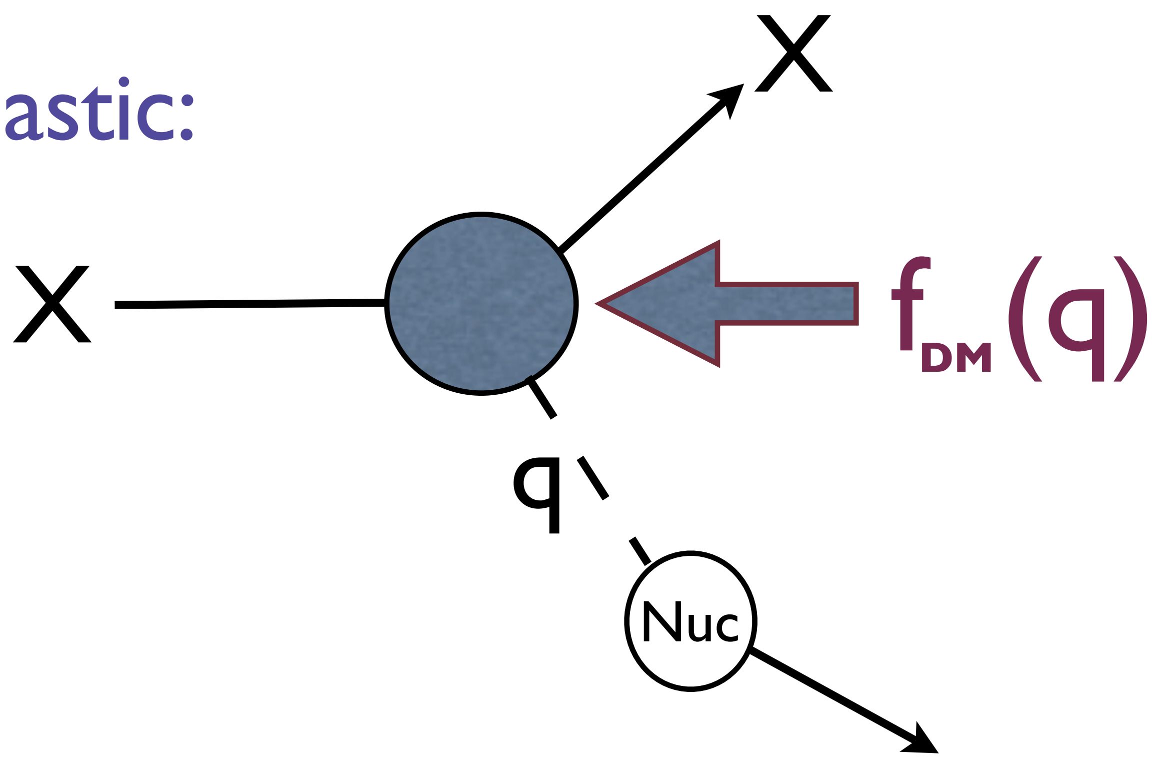
$$v_{min} = \frac{q}{2}\left(\frac{1}{m_{DM}} + \frac{1}{m_N}\right) + \frac{\delta}{q}$$

$$m_{DM} \sim 100GeV$$

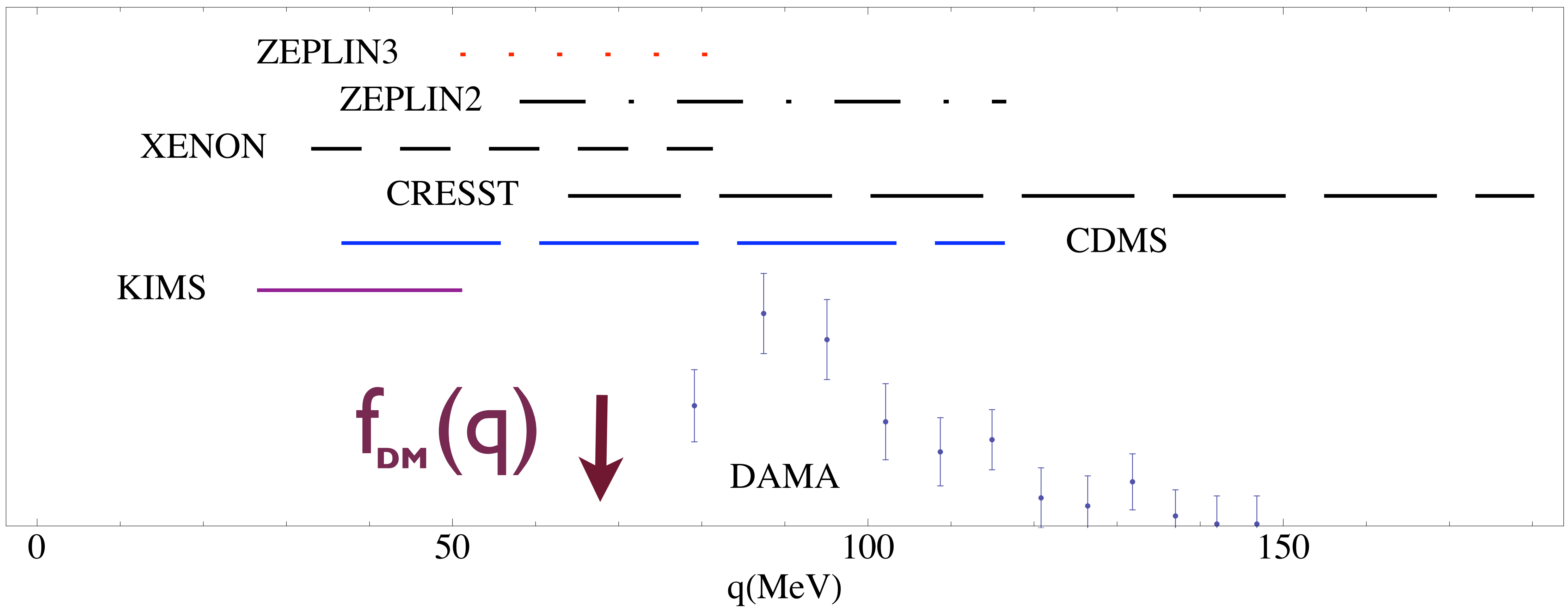
$$\delta \sim 100KeV$$

Introducing a DM form factor

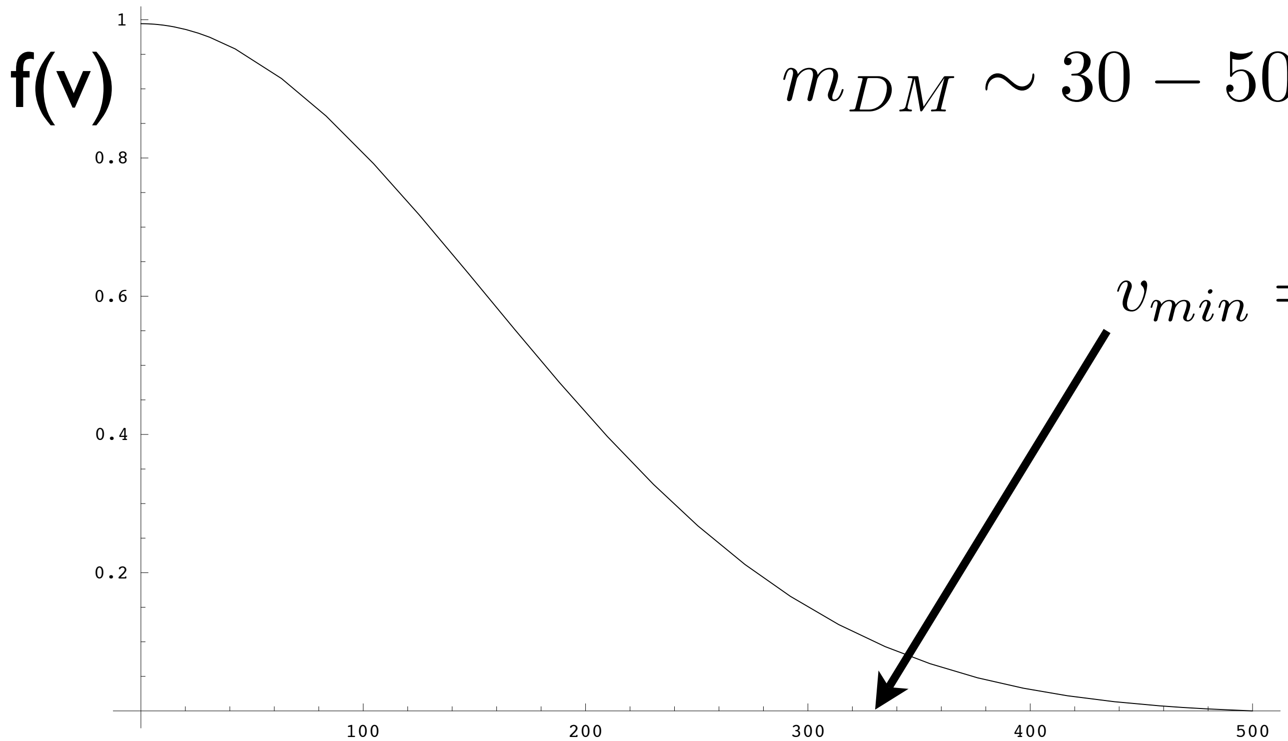
Elastic:



$$\frac{dR}{dE_R} \sim N_T m_N A^2 F_n(q) \int_{v_{min}(q,m_N)}^{v_{esc}} dv f(v)/v \, f_{DM}(q)^2$$



And for CDMS more suppression:



$$m_{DM} \sim 30 - 50 GeV$$

$$v_{min} = \frac{q}{2}\left(\frac{1}{m_{DM}} + \frac{1}{m_N}\right)$$

$$v_{min}^{CDMS} \sim 1.2 v_{min}^{DAMA}$$

The DM form factor - suppresses events a small q:

- Gets rid of the small q growth of elastic scattering.

$$\downarrow$$

- Allows for smaller DM masses which help with CDMS in the DAMA q-region.
- Small masses also allow for increased modulation at DAMA.
- Fits the DAMA spectrum better.

A “model independent” analysis of the DM form factor

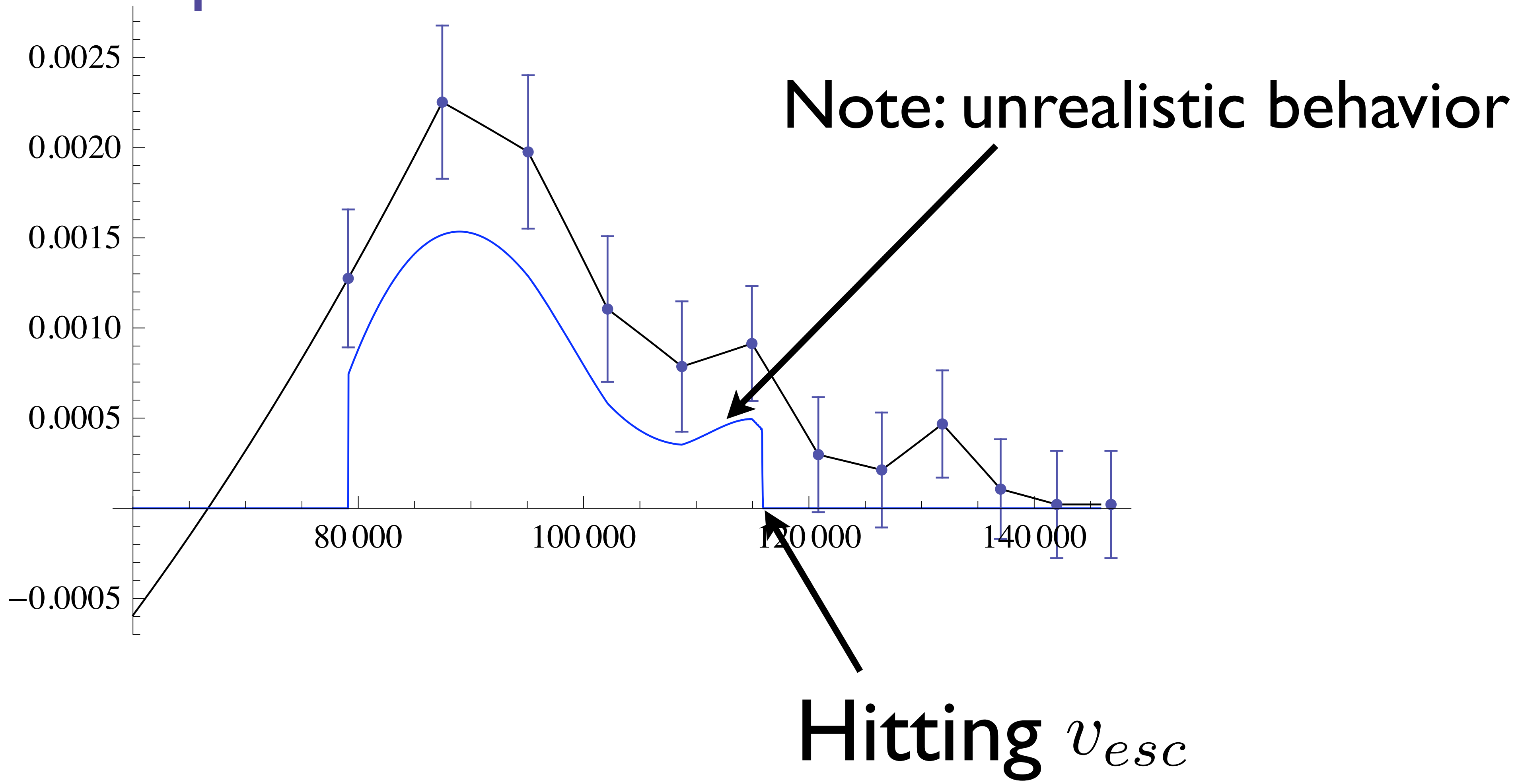
Minimum requirement for a form factor:

- An acceptable fit to DAMA (as kinematics allow).
- Consistent with null experiments at a given confidence level.

$$\Downarrow$$

- For a given DM-mass, choose an “ideal form factor” that goes near lowest portion of DAMA error bars (as kinematics allow).
- For null experiments (CRESST & CDMS) - look at the q-range which overlaps DAMA and find p-max likelihood.

For example:



Take the "form factor" that gave this shape at DAMA and find what is the chance that it is consistent with the null experiments.

Unfortunately, the answer depends on the DM-Halo model...

We tried 3 different models:

- Standard Halo model:

$$f(v) \sim e^{-\frac{v^2}{\bar{v}^2}} - e^{-\frac{v_{esc}^2}{\bar{v}^2}}$$

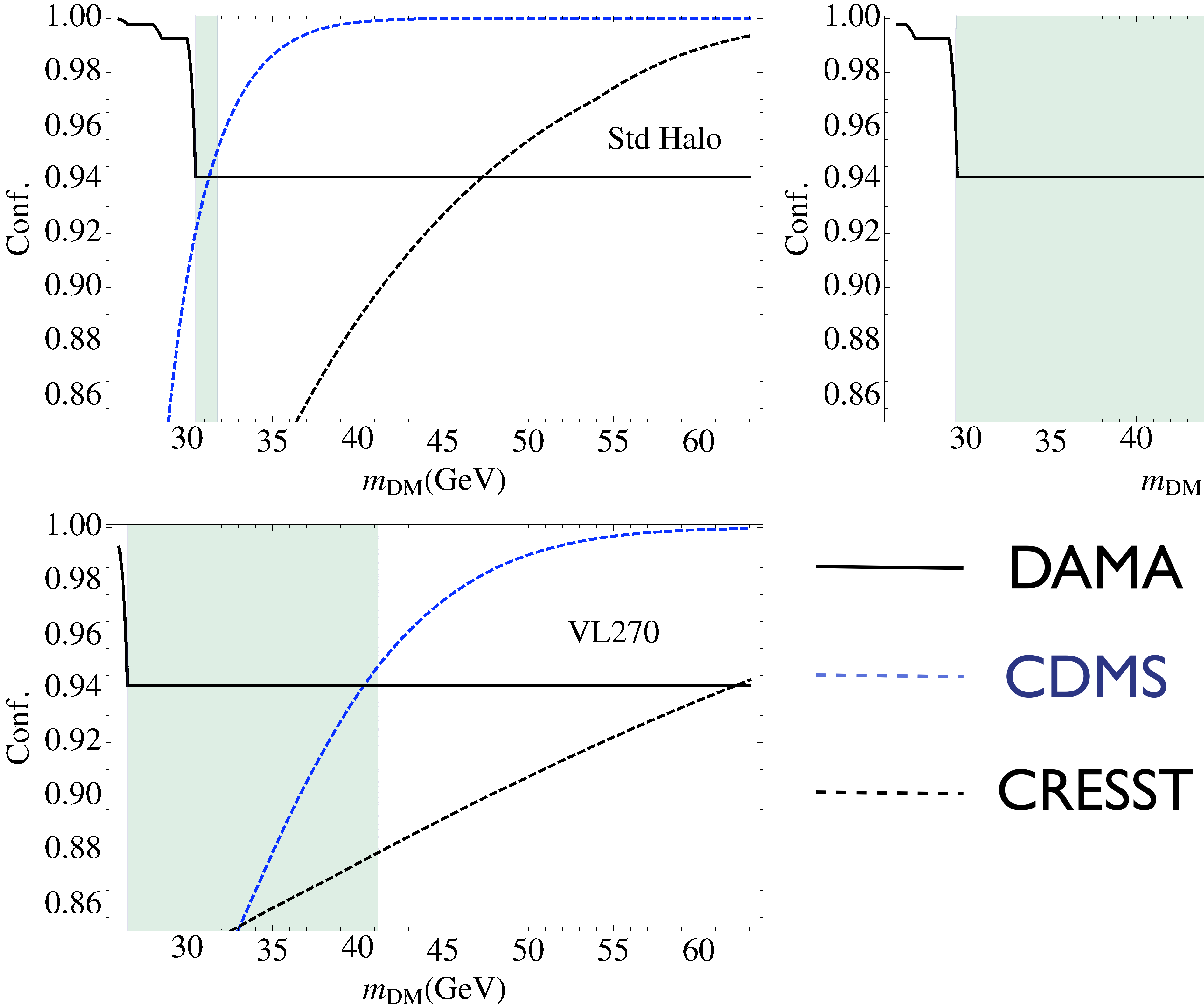
- Via Lactea 270:

$$f(v_R) \sim e^{-\left(\frac{v_R^2}{\bar{v}_R^2}\right)^{\alpha_R}} \quad f(v_T) \sim v_T e^{-\left(\frac{v_T^2}{\bar{v}_T^2}\right)^{\alpha_T}} \quad \bar{v}_{R,T} = c_{R,T}\sqrt{-U(r_0)}$$

$$\langle\sqrt{-U(r_0)}\rangle_{VL} = 270 km/s$$

- Via Lactea 220:

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



Std Halo
VL220
VL270
Conf.
m_{DM}(GeV)
DAMA
CDMS
CRESST

A word about statistics

P-max method is very sensitive to exact energy of events:

- Find the biggest gap in energy in the data.
- Assigns a probability that your theory function gives nothing in that energy gap.

As an example if we were to use Poisson Statistics:

At CDMS (2 events) we predict:

2.8 for Std. Halo, 1.9 for VL270, .96 for VL220

Form factor models

Use interfering gauge bosons coupling to DM via a dipole interaction:

Two gauge bosons

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

$$\mathcal{L} = i \left(\frac{g_1}{\Lambda^2} F^{(1)}_{\mu\nu} + \frac{g_2}{\Lambda^2} F^{(2)}_{\mu\nu} \right) \partial_\mu X^* \partial_\nu X$$

$$m_1, m_2, \Lambda \sim 1 GeV$$

Exchange of the 2 GB leads to an effective form factor:

$$F_{DM}(q^2) \sim \left(\frac{g_1^2 \; q^2}{q^2 + m_1^2} - \frac{g_2^2 \; q^2}{q^2 + m_2^2} \right)$$

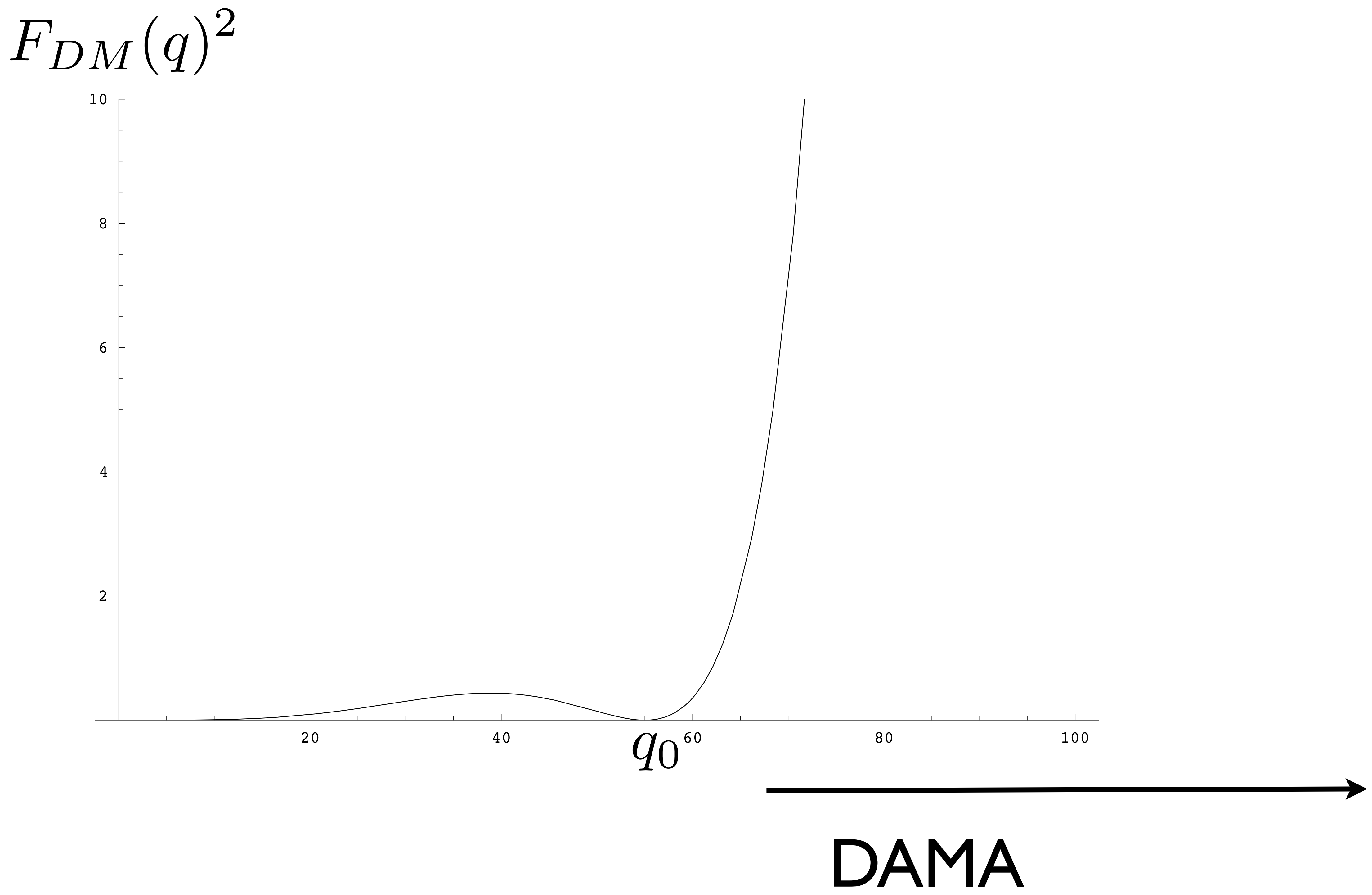
If Higgsing respects a custodial symmetry:

$$m_1^2 = g_1^2 v^2 + (\delta m)^2, \; m_2^2 = g_2^2 v^2, \; (\delta m)^2 \ll m_{1,2}^2$$

For q of interest, $q \ll m_{1,2}$:

$$F_{DM}(q^2) = cq^2(q^2 - q_0^2)$$ (2 parameter model)

Determines overall crossection



$F_{DM}(q)^2$
10
8
6
4
2
20
40
q_0
60
80
100
DAMA

An example of a Higgsing with custodial symmetry.

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \qquad D_\mu \Phi = \left(\partial_\mu - i\frac{g_1}{2} A_\mu^{(1)} - i\frac{g_2}{2} A_\mu^{(2)} \sigma_3 \right) \Phi$$

A general Higgs potential (consistent with the gauge interactions & $A_\mu^{(2)} \to -A_\mu^{(2)}$):

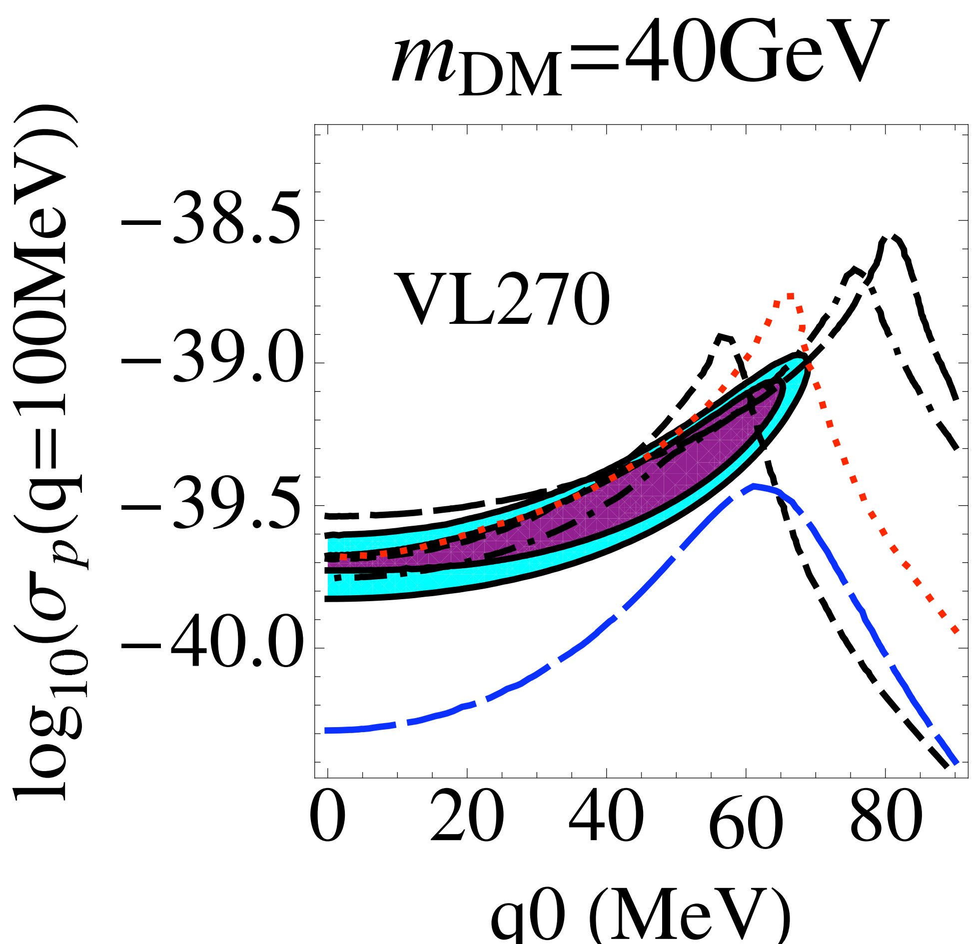
$$V(\Phi) = -m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + y(\Phi^\dagger \sigma_3 \Phi)^2$$

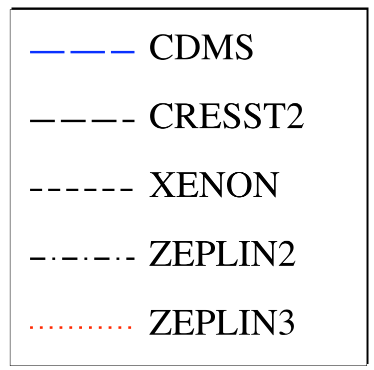
$$y > 0 \longrightarrow \Phi^\dagger \sigma_3 \Phi = 0$$

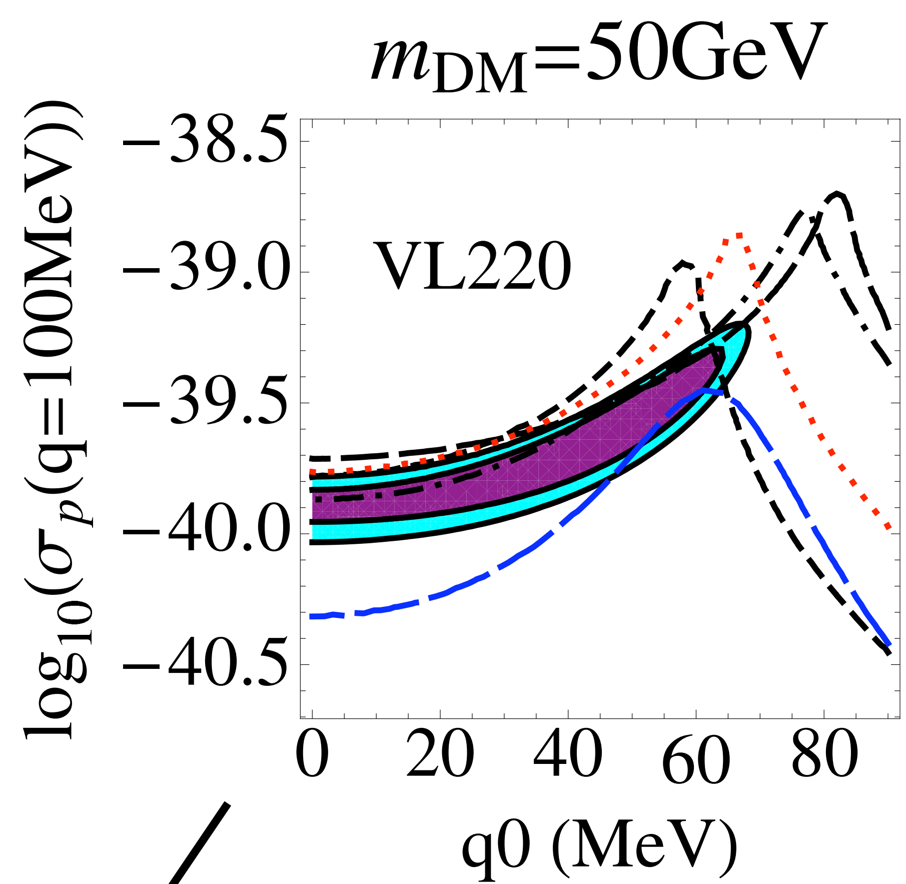
Gauge boson mass matrix: $\begin{pmatrix} g_1^2 \Phi^\dagger \Phi & g_1 g_2 \Phi^\dagger \sigma_3 \Phi \\ g_1 g_2 \Phi^\dagger \sigma_3 \Phi & g_2^2 \Phi^\dagger \Phi \end{pmatrix}$

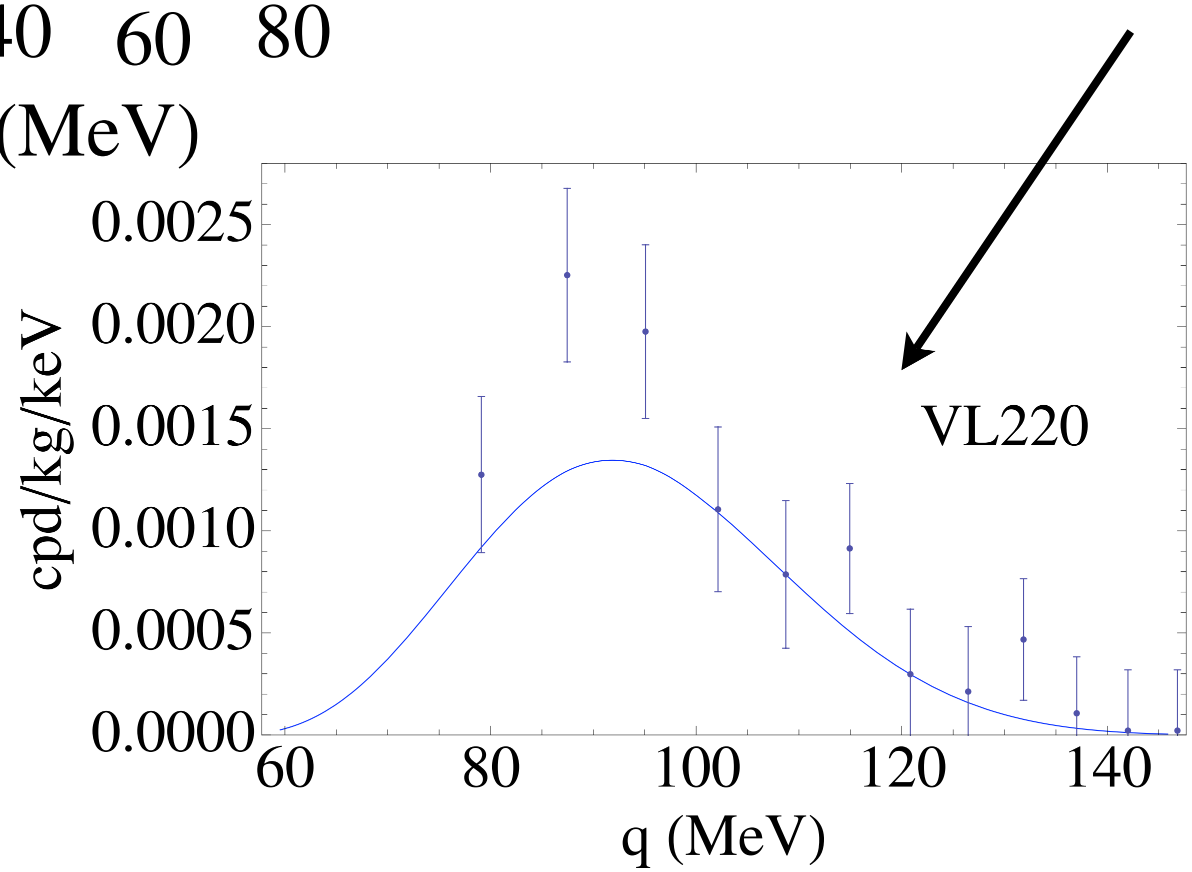
Mixing with $B_{\mu\nu}$ breaks $A_\mu^{(2)} \to -A_\mu^{(2)}$: $(\delta m)^2 \sim \dfrac{1}{16\pi^2} \epsilon^2 \Lambda_{cutoff}^2$

Two gauge bosons - results









q0=50 MeV

$\chi^2 = 11.8$

CDMS: 97%

CRESST: 89%

Three gauge bosons

Similar setup - 3GB with approximate SO(3) custodial symmetry.

$$F_{DM}(q^2) \sim \left(\frac{g_1^2 \; q^2}{q^2 + m_1^2} - 2\frac{g_2^2 \; q^2}{q^2 + m_2^2} + \frac{g_3^2 \; q^2}{q^2 + m_3^2} \right)$$

Potential for Φ - a 4 of SU(4) symmetry.

$$\frac{1}{g_1^2} - \frac{2}{g_2^2} + \frac{1}{g_3^2} \ll \frac{1}{g_i^2}$$

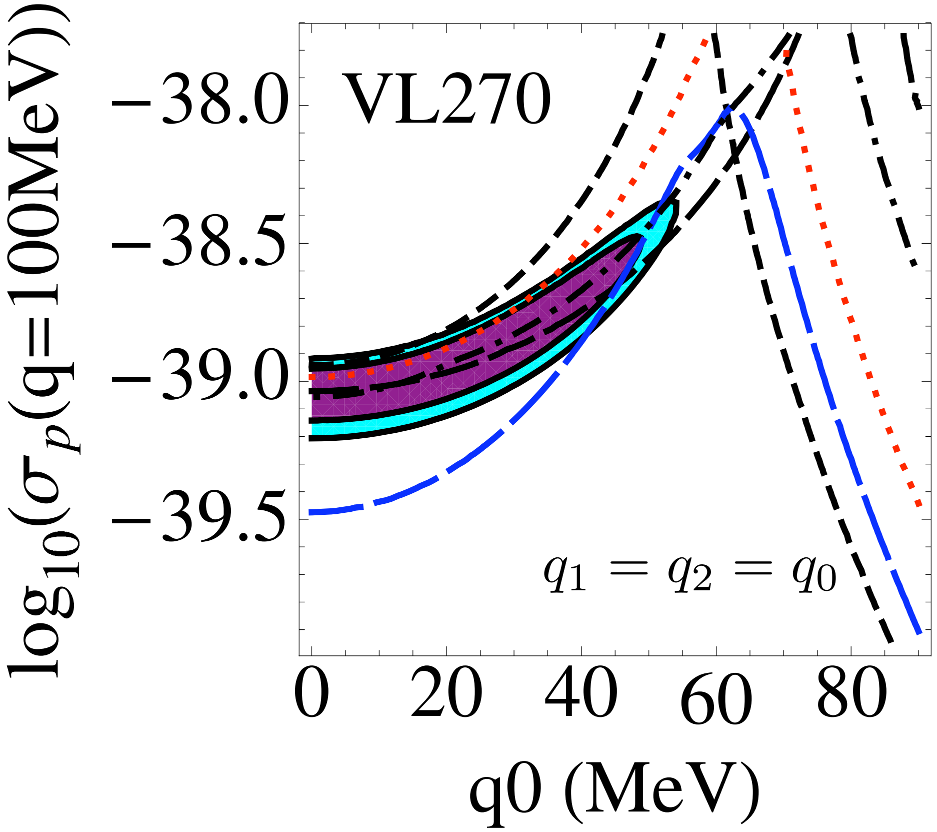
$$\Downarrow$$

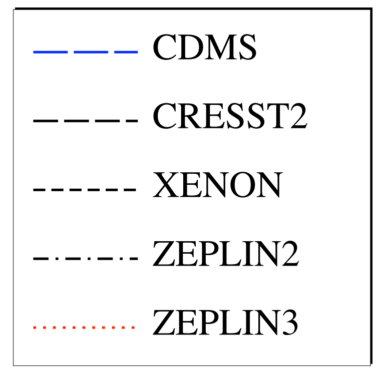
For $q \ll m_{1,2,3}$:

$$F_{DM}(q^2) = cq^2(q^2 - q_1^2)(q^2 - q_2^2)$$

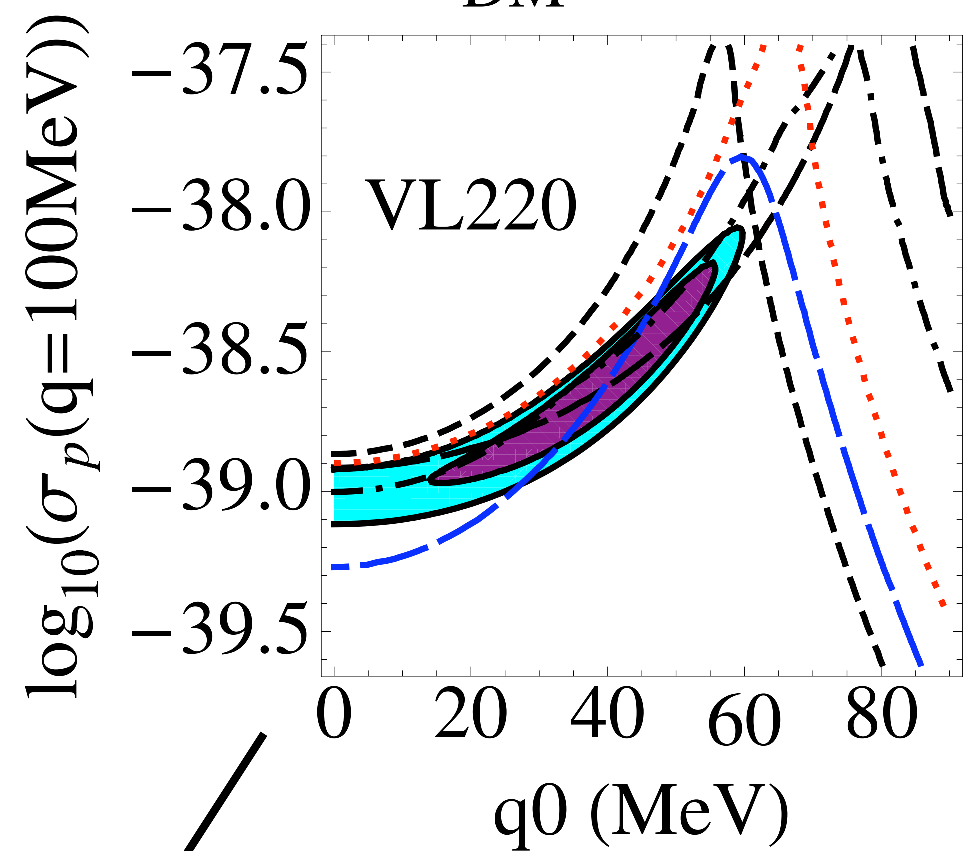
Three gauge bosons - results

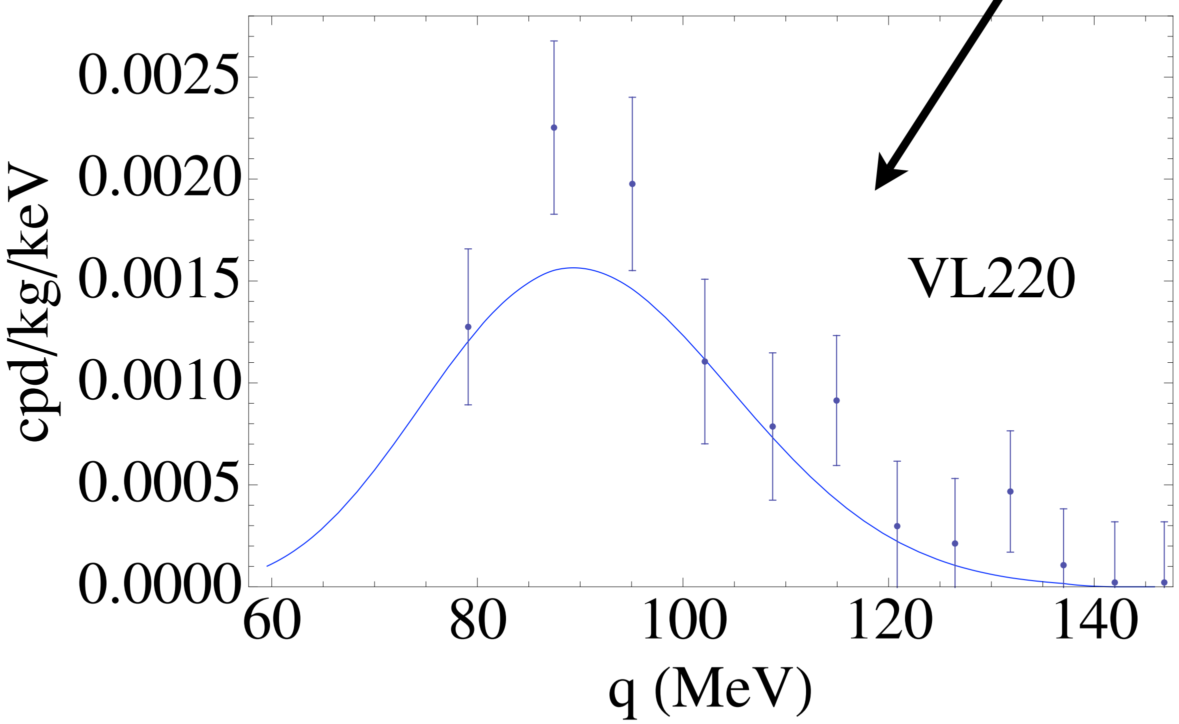
$m_{\rm DM}$=32GeV





$m_{\rm DM}$=36GeV





q1=42.5, q2=38 MeV

$\chi^2 = 8.9$

CDMS: 90%

CRESST: 90%

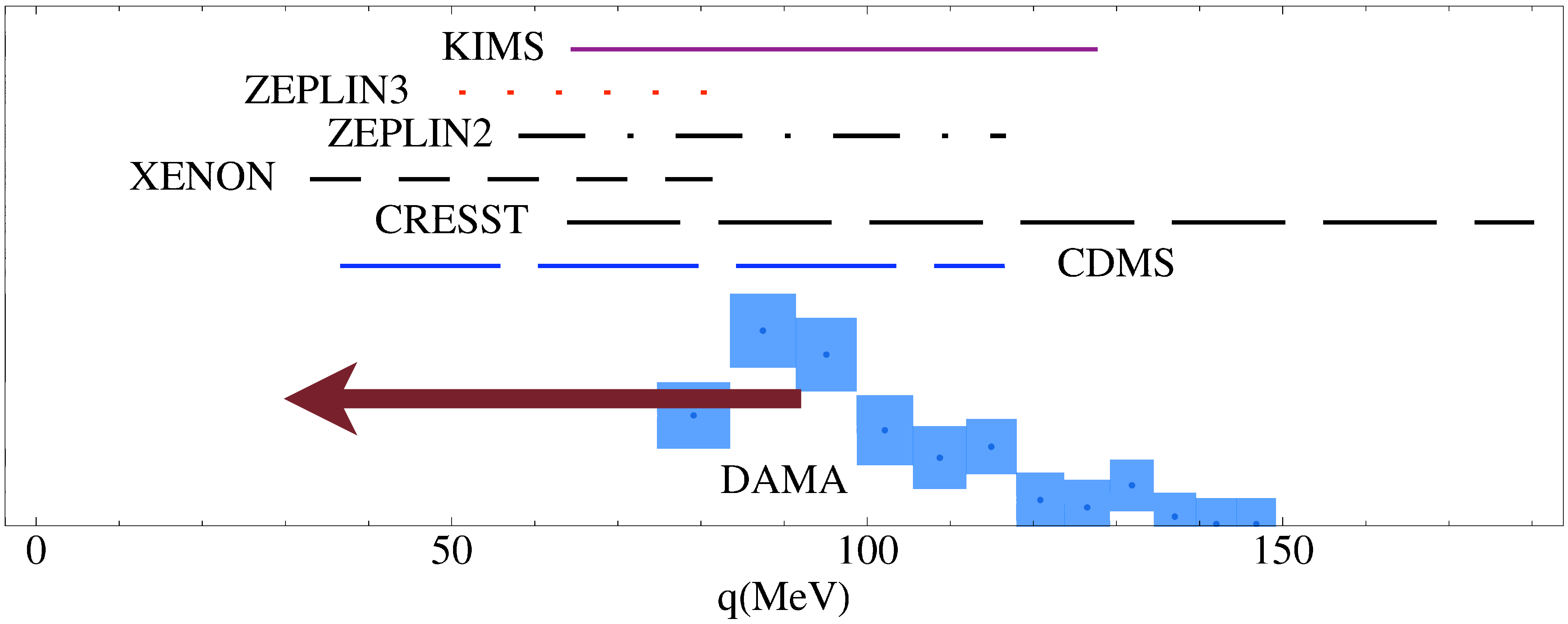
Channeling at DAMA

- After being hit by DM, some fraction of recoiling ions wind up in a channel of the NaI crystal.
- Such ions lose their energy mostly to electrons as they move through the channel (and not other nuclei).

↓

Electron energy measured by DAMA is the recoil energy.

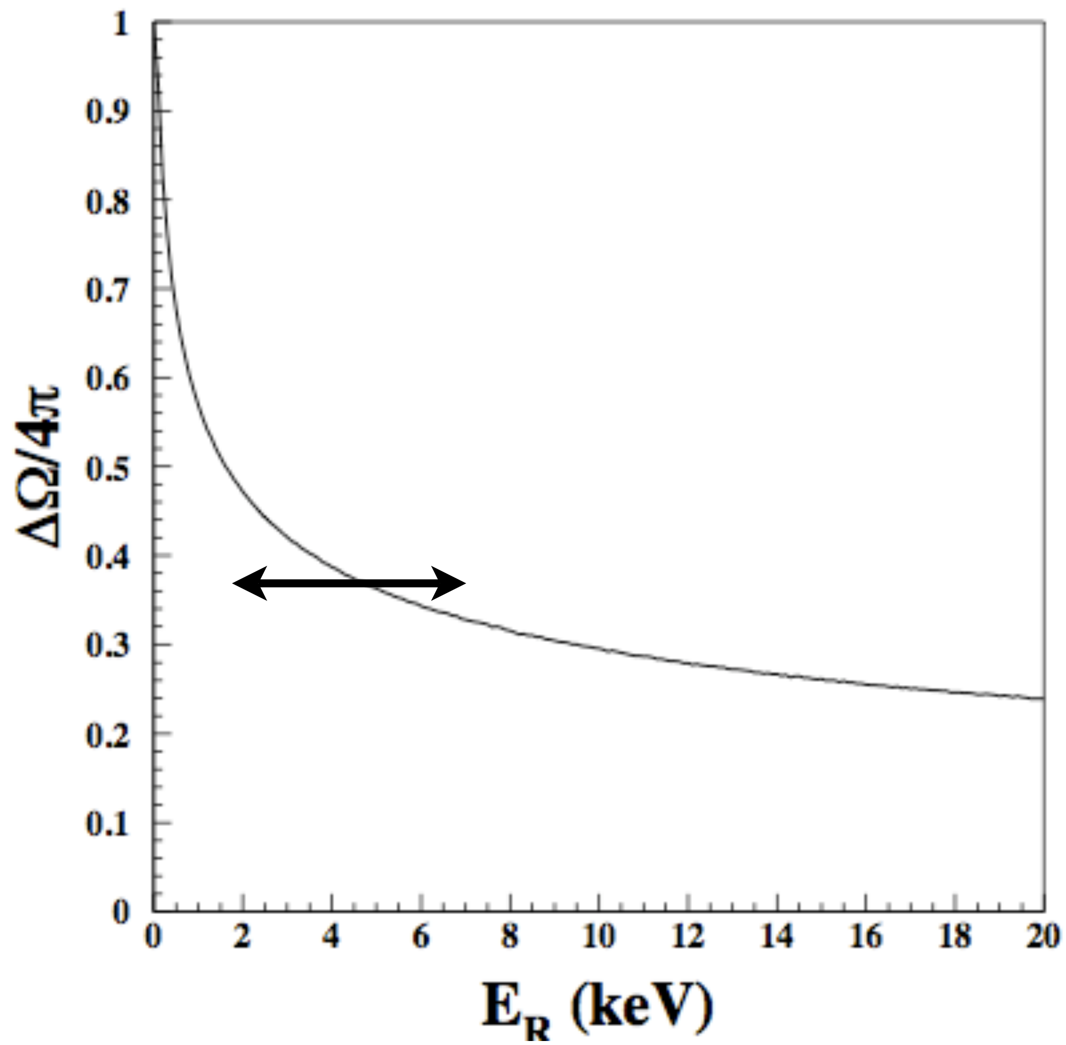
$$q_{chan} = \frac{q_{nochan}}{3.3}$$


KIMS
ZEPLIN3
ZEPLIN2
XENON
CRESST
CDMS
DAMA
0
50
100
150
q(MeV)

Problems with channeling:

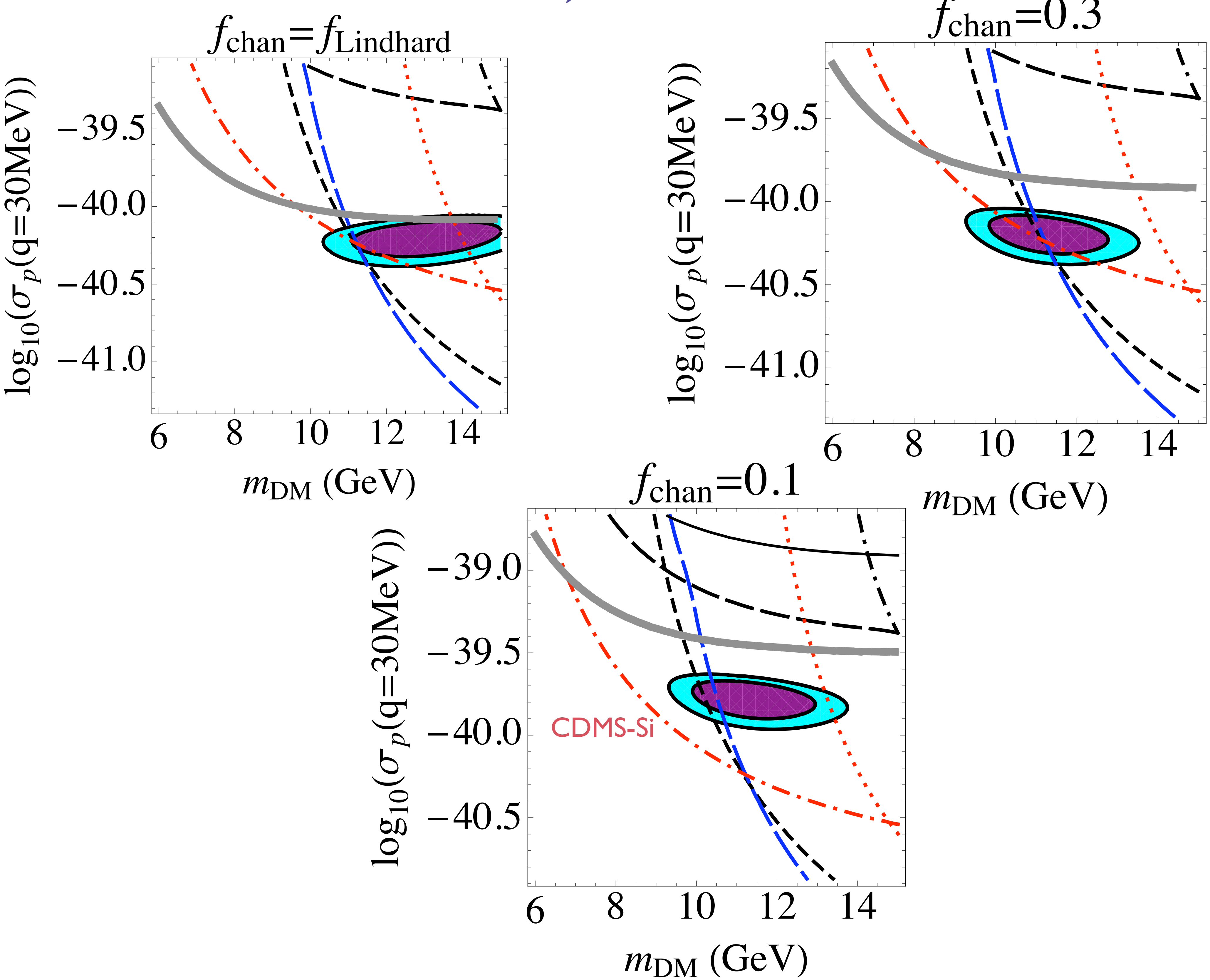
- Never been observed experimentally.
- Theoretically, difficult to treat analytically without relying on small angle scattering approximation (not valid in the regime of interest).
- There has not a been a check of how easy it would be for an ion starting at a lattice site to wind up in the channel.
- At least, a Monte Carlo method would be useful as a more realistic estimate.

DAMA's estimate for channeling fraction, f:

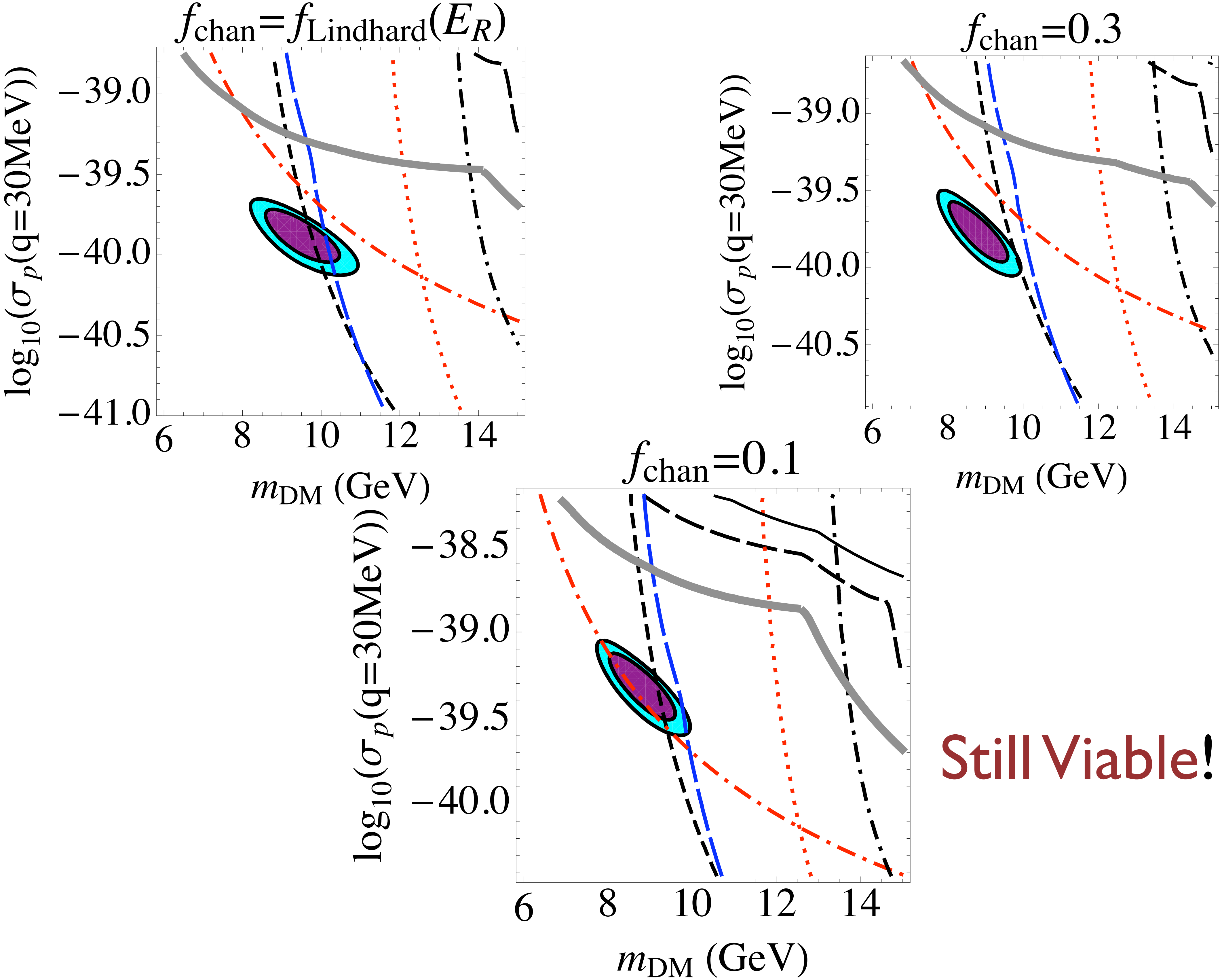


Not very reliable at low E

For a standard WIMP, standard halo:



For dipole DM ($\mathcal{L} = i\frac{g}{\Lambda^2}F^{\mu\nu}\partial_\mu X^*\partial_\nu X.$), standard halo:



Still Viable!

Conclusion

1. Given current DM-Halo uncertainties, a form factor solution is still a viable way of reconciling DAMA with other direct detection experiments.

2. A “model-independent” analysis suggest that the preferred range for DM masses $30 < M < 60$.

3. One can model-build form factors from interfering gauge bosons.

4. Dipole DM with small channeling fraction is still viable.

5. Much to do for future:

- Contrasting elastic form factor and inelastic DM:
  1. Directional detection experiments.
  2. Ratio of modulating to non-modulating amplitudes as a fcn of recoil energy.
- Other mechanisms for generating form factors (RS, nuclear models, etc).
- Collider phenomenology with multiple GeV dark sector gauge forces.