Capture of Inelastic Dark Matter in the Sun

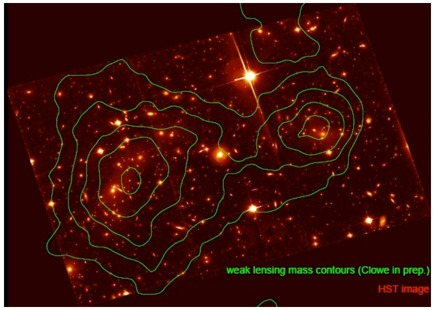
Itay Yavin

Princeton University

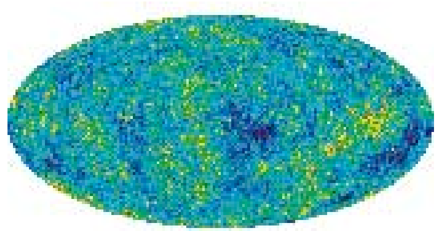
S. Nussinov, L. T. Wang, and I. Y. JCAP08(2009)037, hep-ph 0905.1333

Extended Workshop on DM, Cosmology and the LHC.
Korea, Seoul, August 27th - September 4th

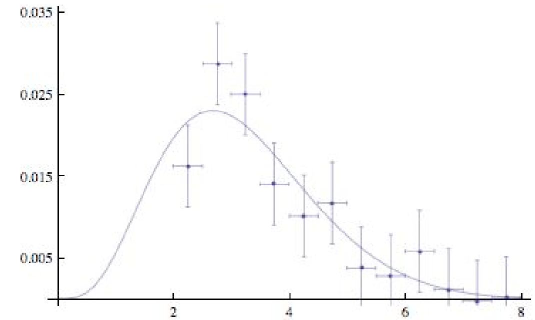
Bullet Cluster



WMAP

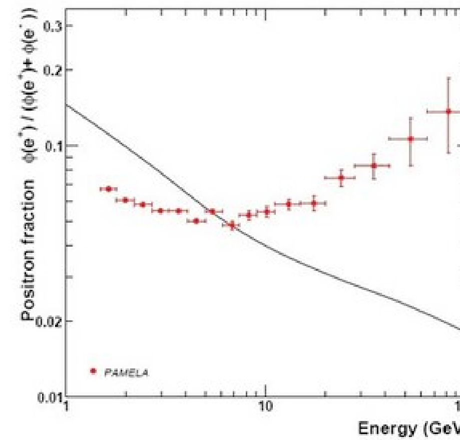


Direct Detection

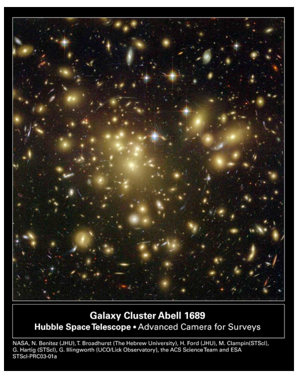


Dark Matter

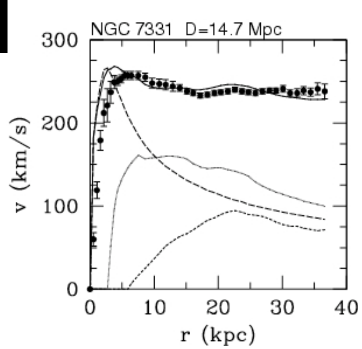
Indirect Detection



Lensing Effect



Rotation curves



Direct Production

???

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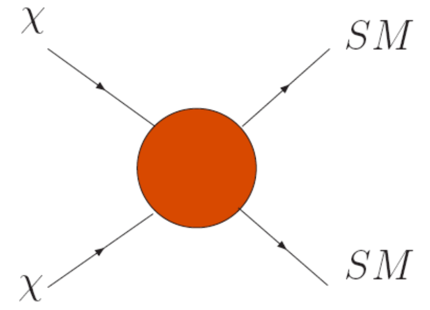

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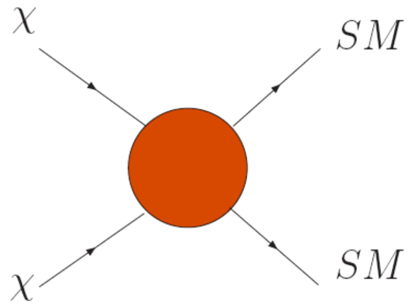

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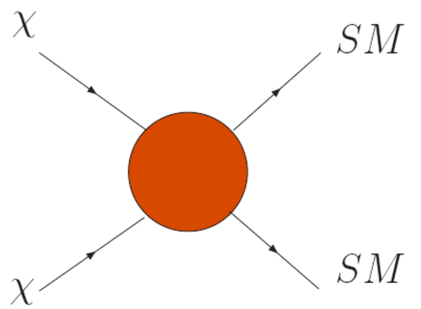

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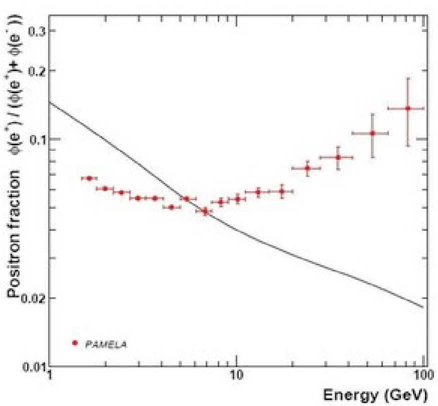

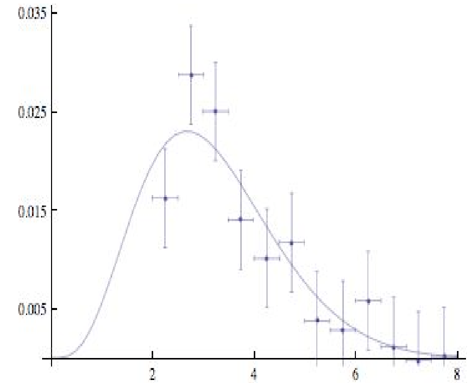

Content

- Inelastic Dark Matter
- Capture in the Sun
- Inelastic Dark Matter revisited

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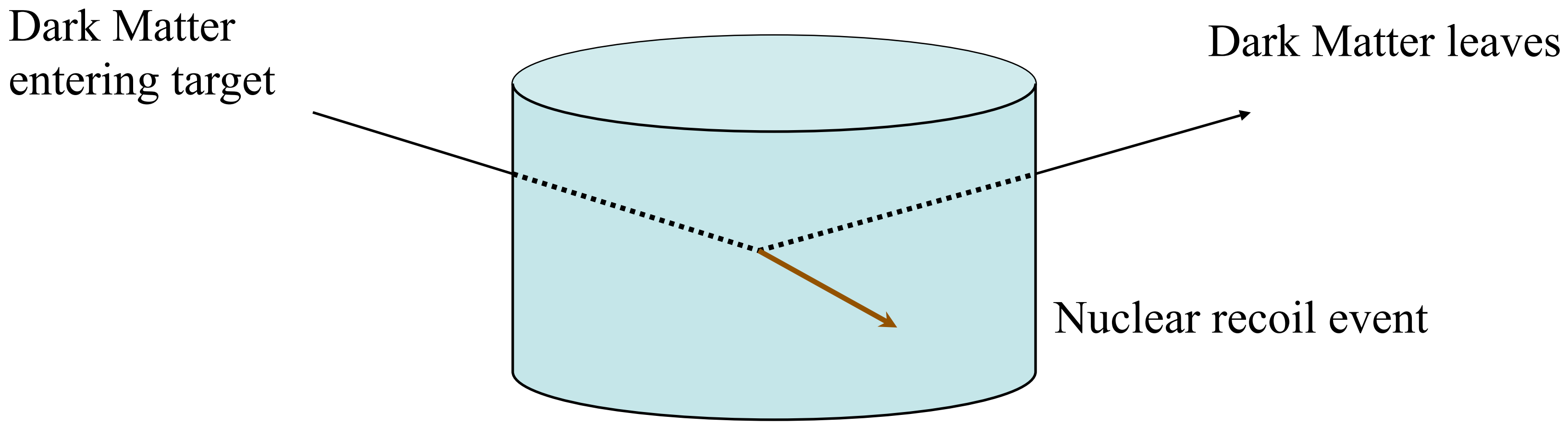

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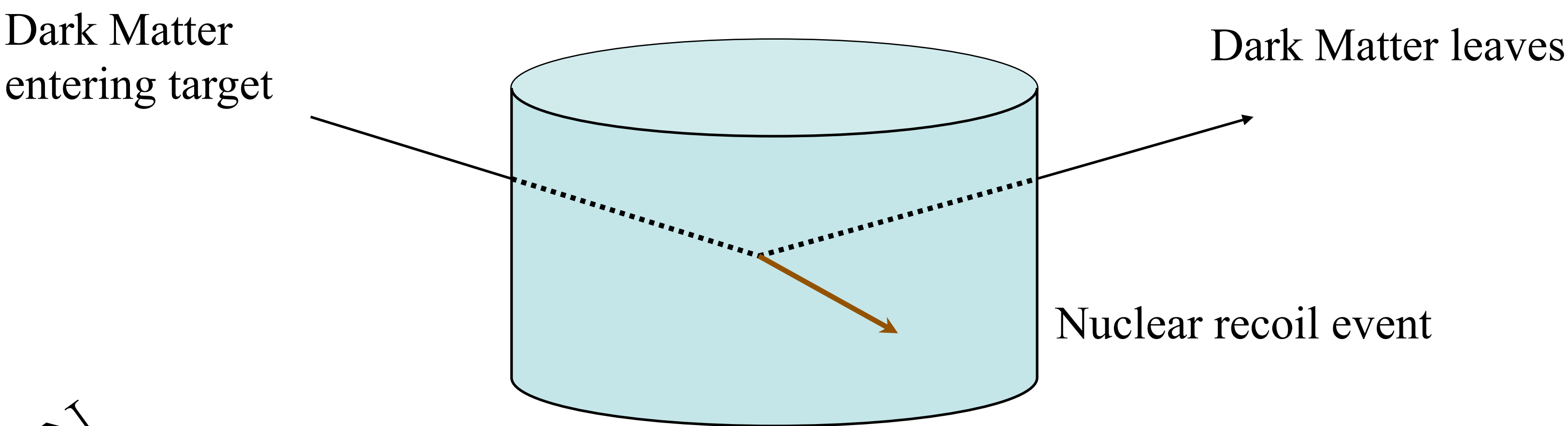

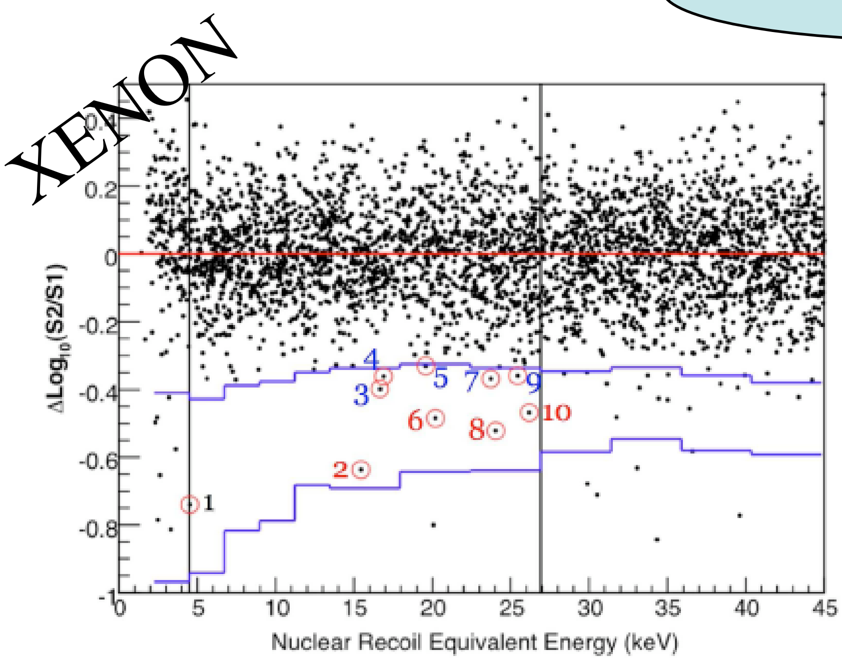

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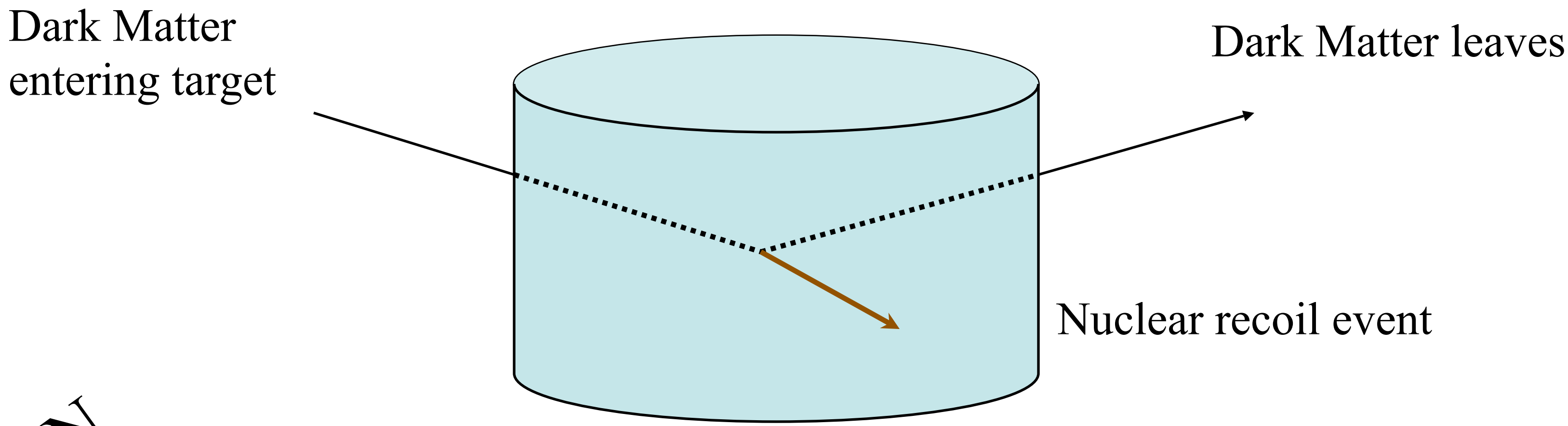
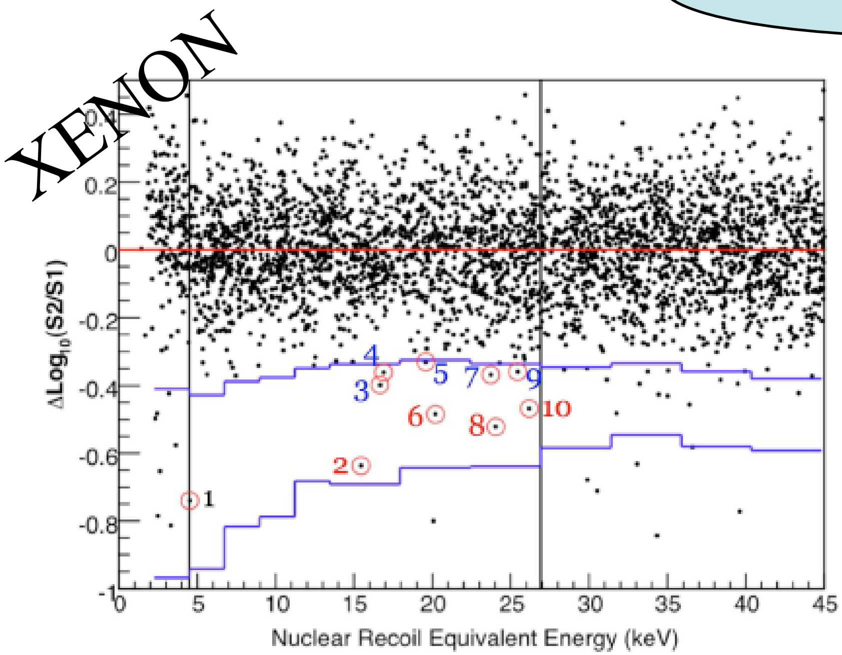
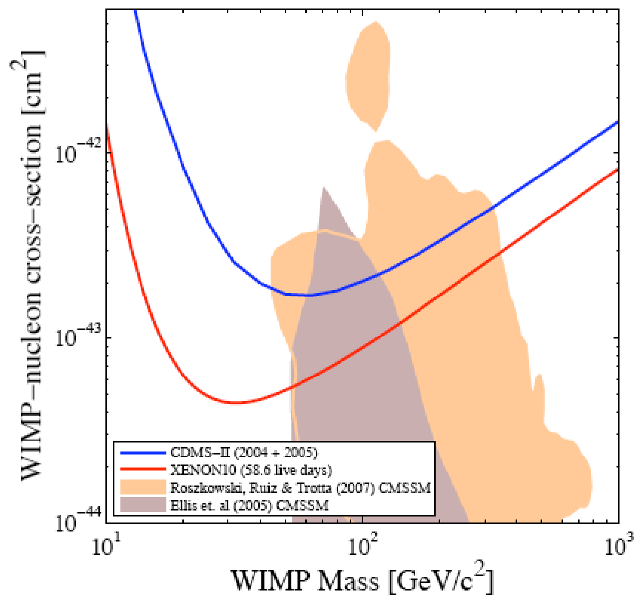
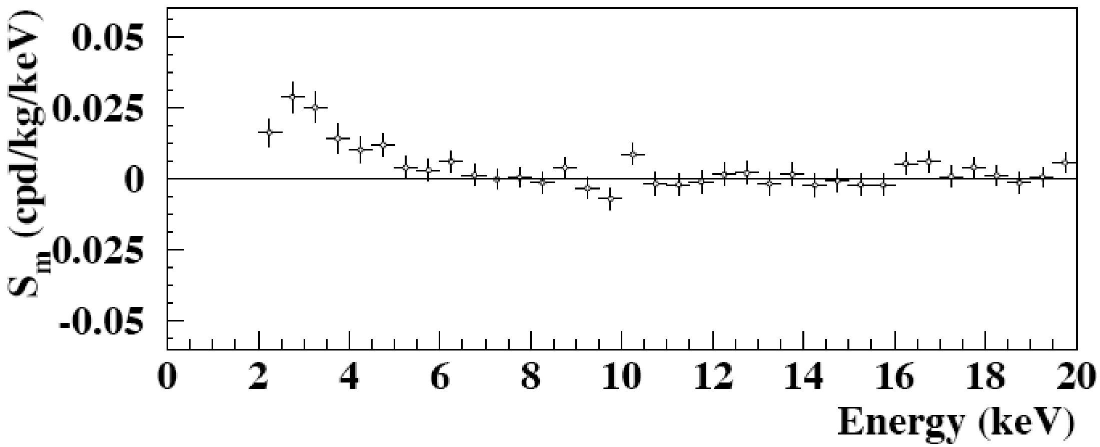




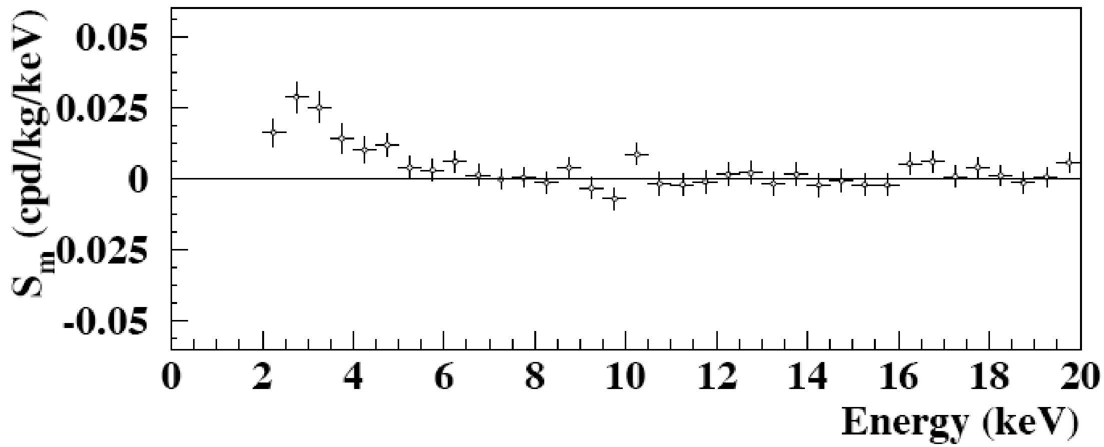


DAMA/LIBRA

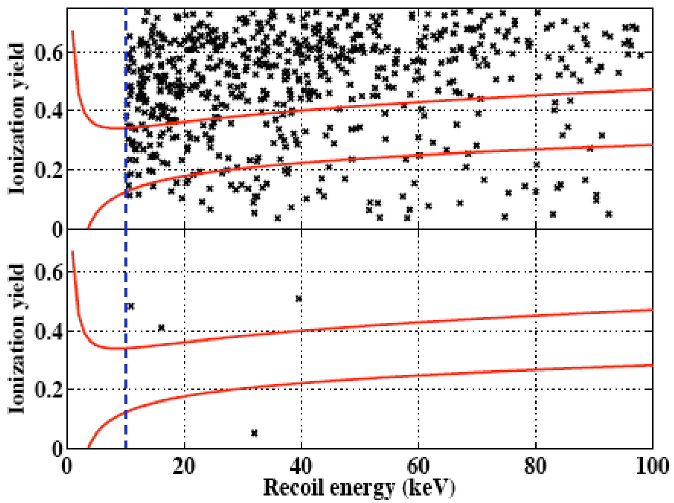


S_m (cpd/kg/keV)
0.05
0.025
0
-0.025
-0.05
0 2 4 6 8 10 12 14 16 18 20
Energy (keV)

DAMA/LIBRA



CDMS



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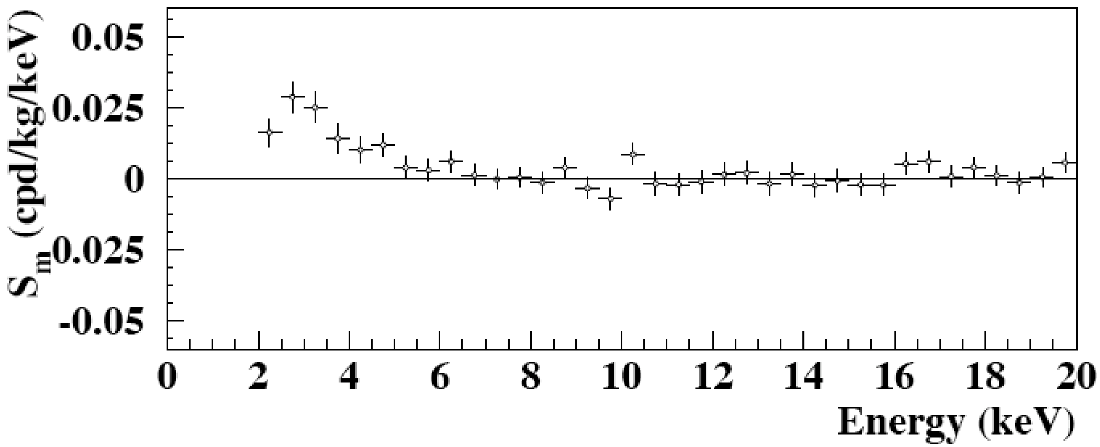
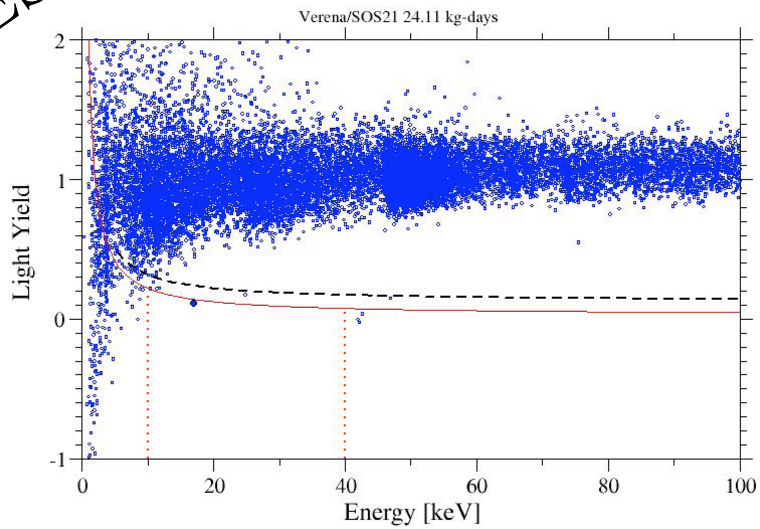


CRESST



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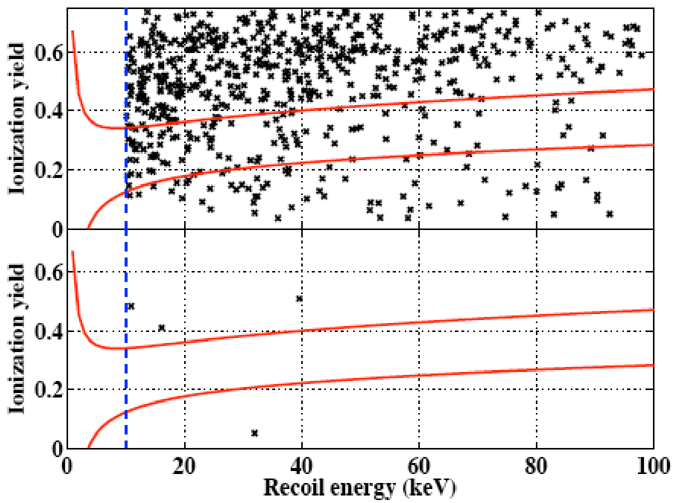

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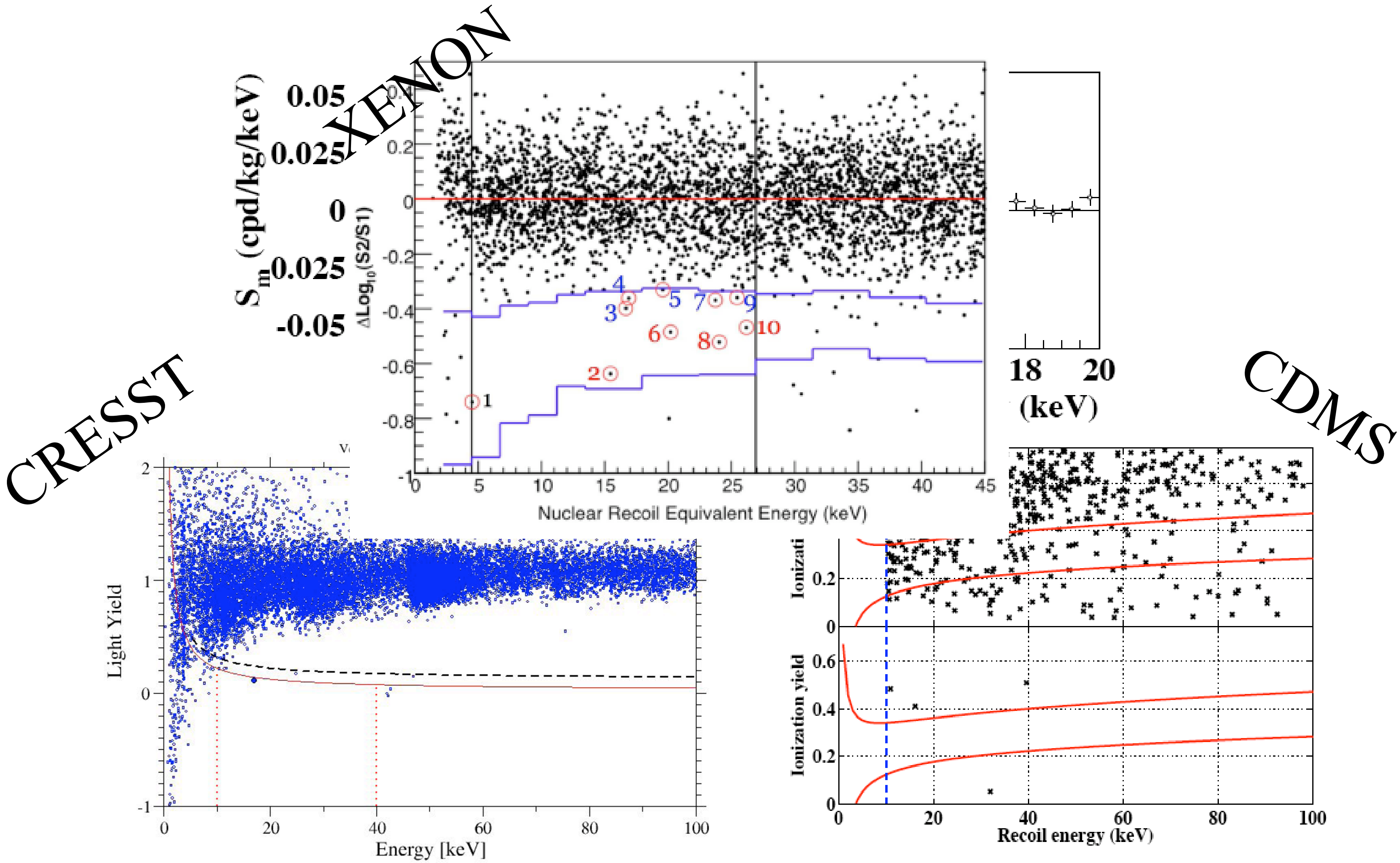
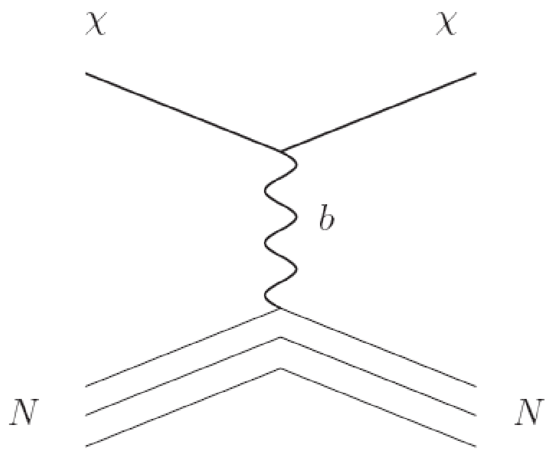


XENON
CRESST
CDMS
0.05
0.025
0
-0.025
-0.05
S_m (cpd/kg/keV)
18
20
(keV)
Nuclear Recoil Equivalent Energy (keV)
$\Delta Log_{10}(S2/S1)$
Light Yield
Energy [keV]
Ionization yield
Recoil energy (keV)

WIMP-Nucleus Recoil

Inelastic DM (Smith & Weiner) requires the WIMP to recoil inelastically against the nucleus.



Elastic Scattering

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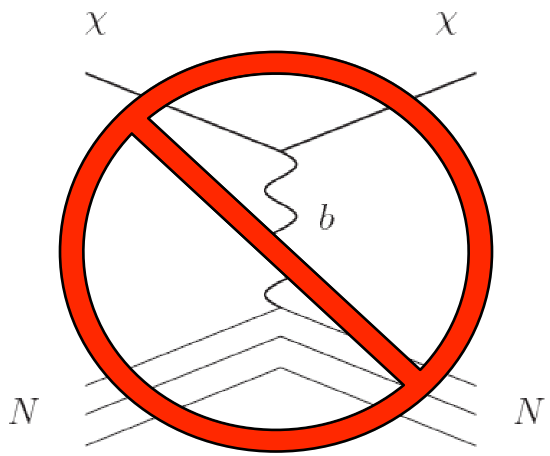

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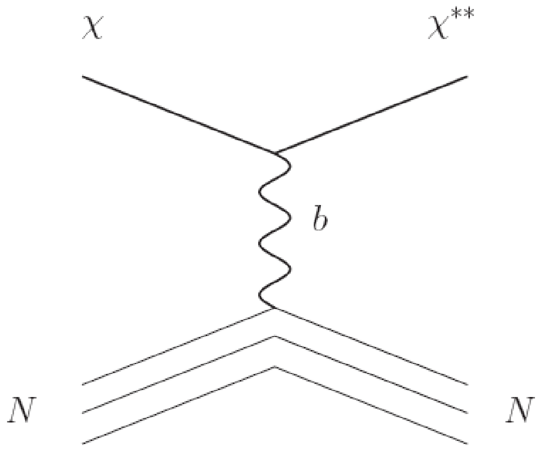

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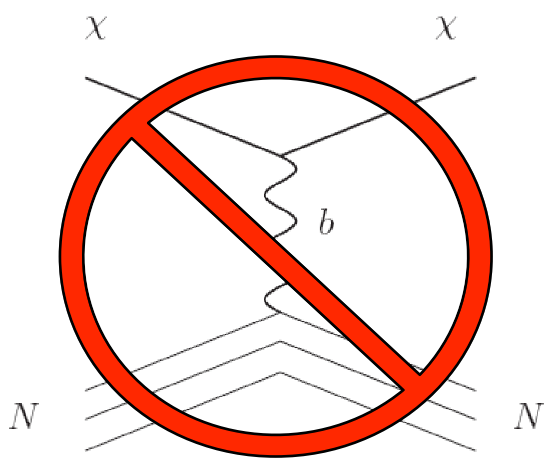

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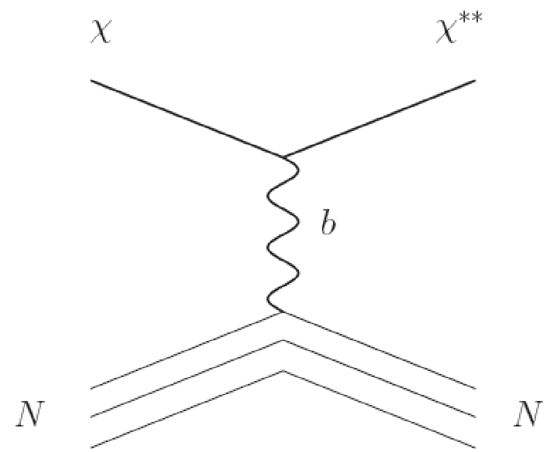

Inelastic Scattering

$$\beta_{min} = \sqrt{\frac{1}{2m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$

m_N - Nucleus mass

E_R - Recoil Energy

δ - Excitation Energy

μ - Nucleus-WIMP reduced mass

Inelastic Transitions

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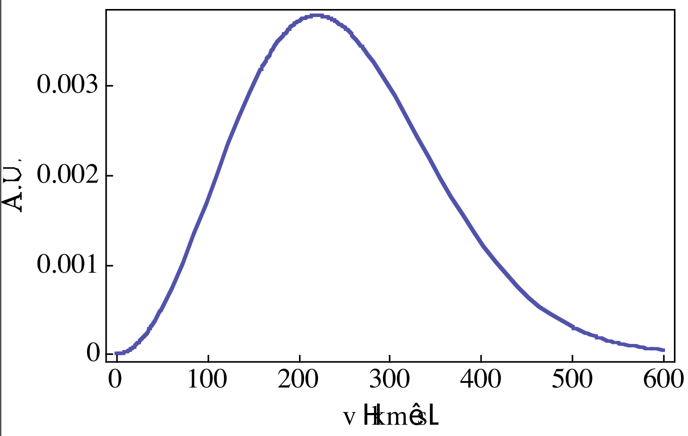

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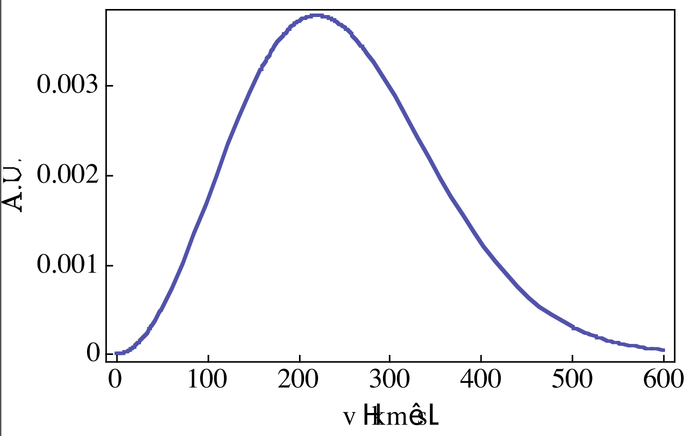

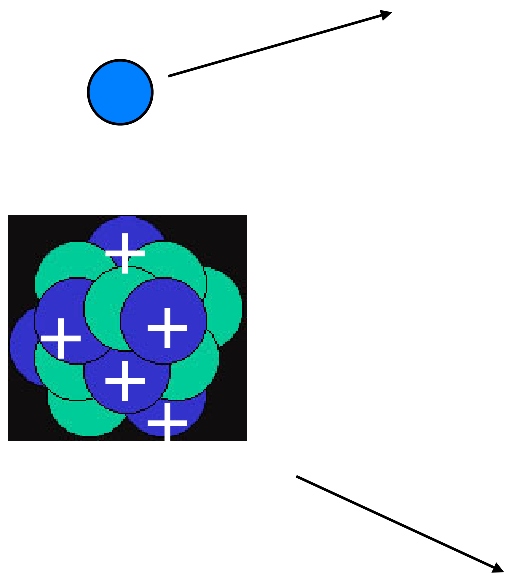

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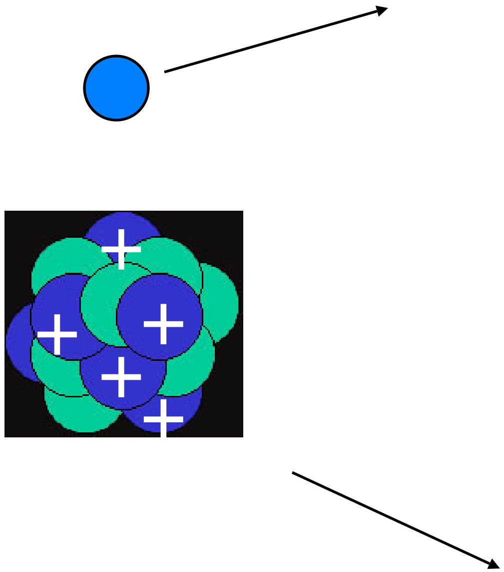

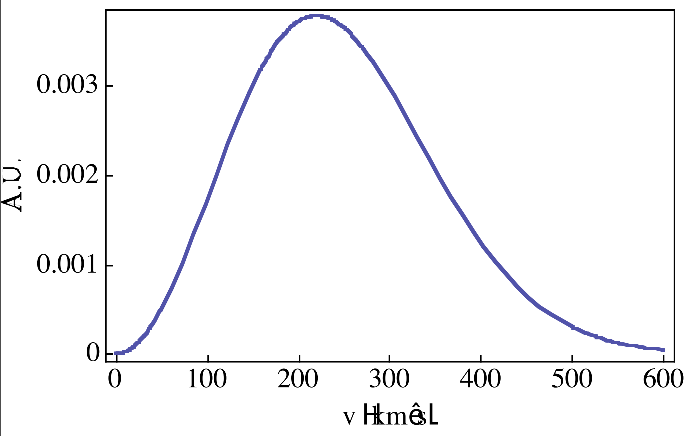

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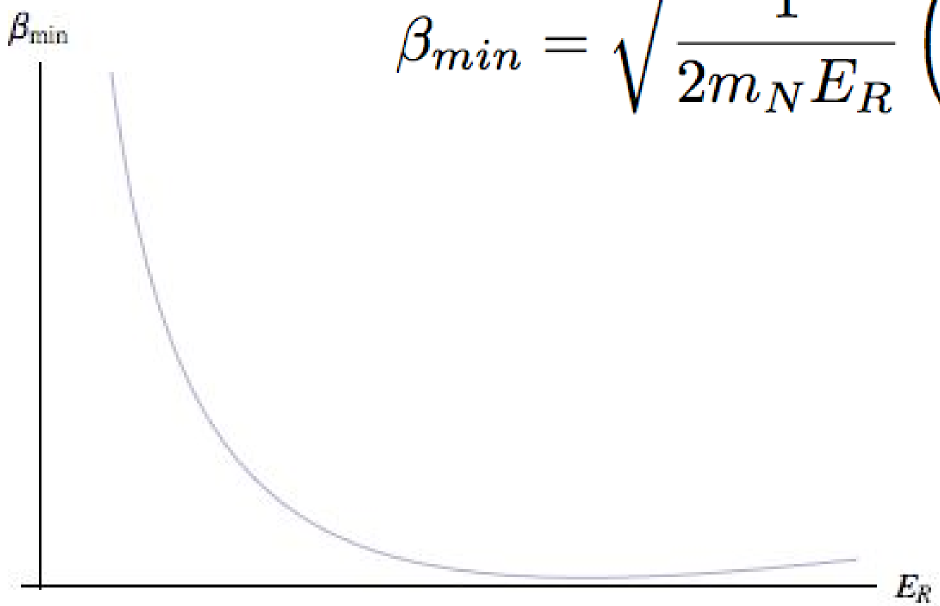

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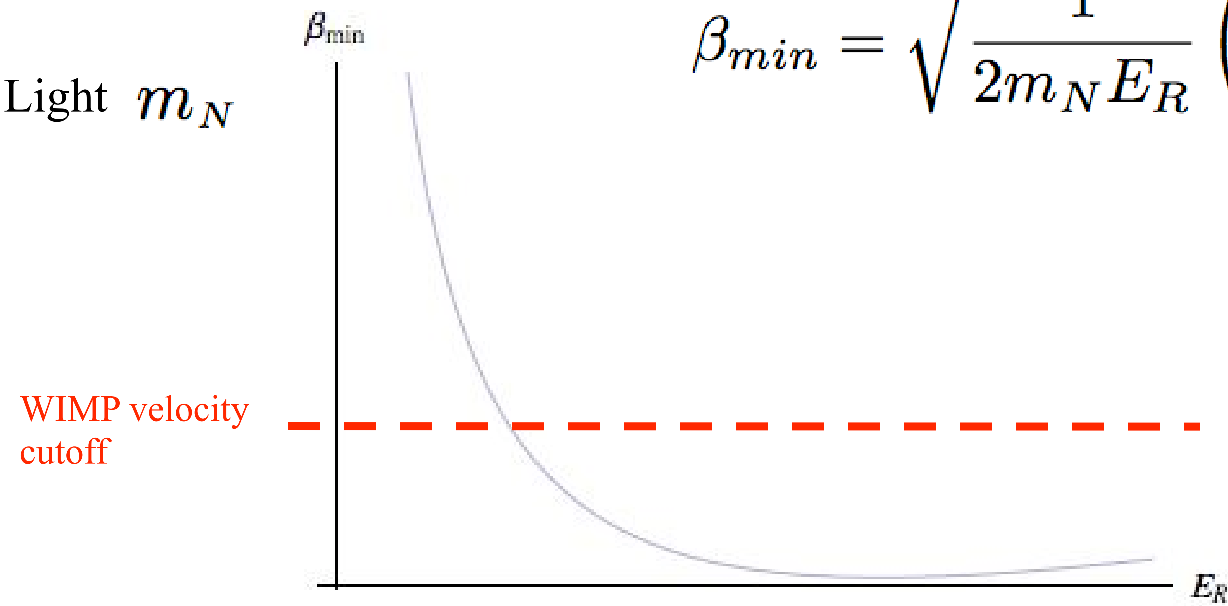

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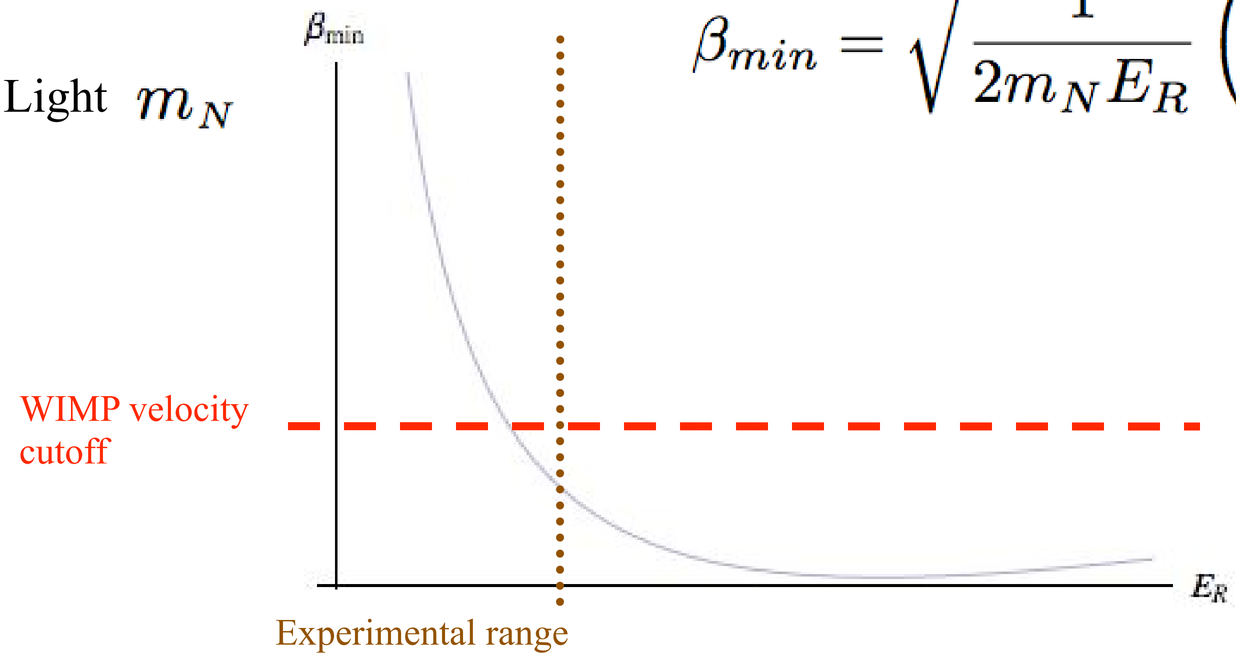

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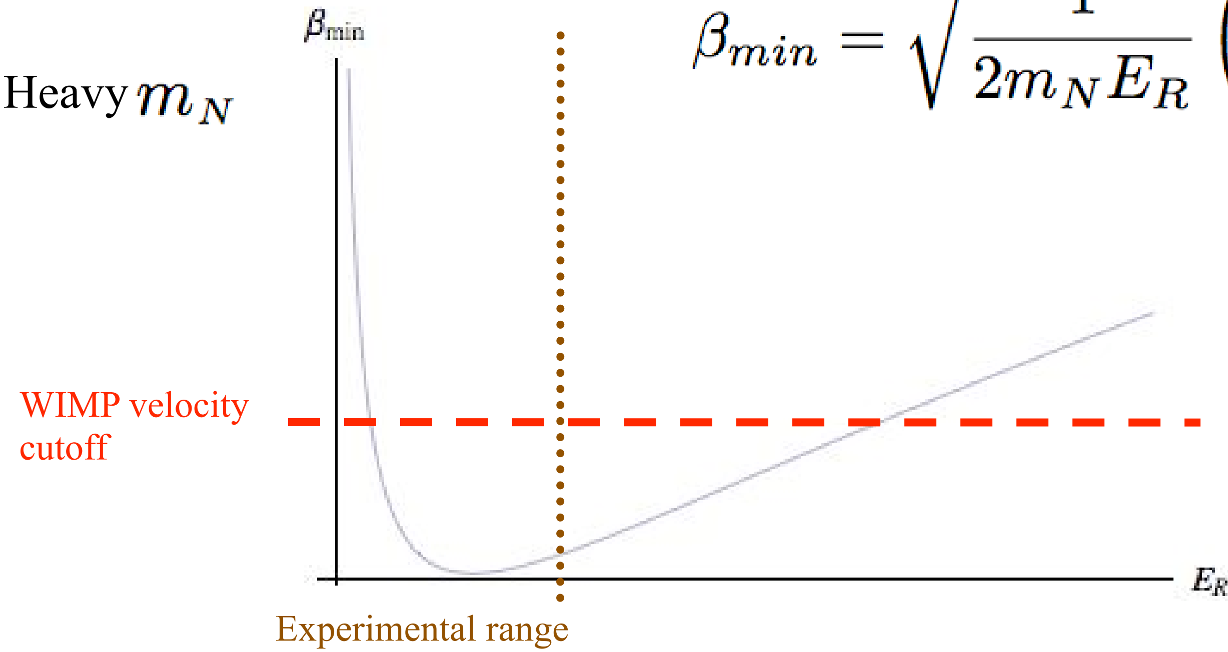

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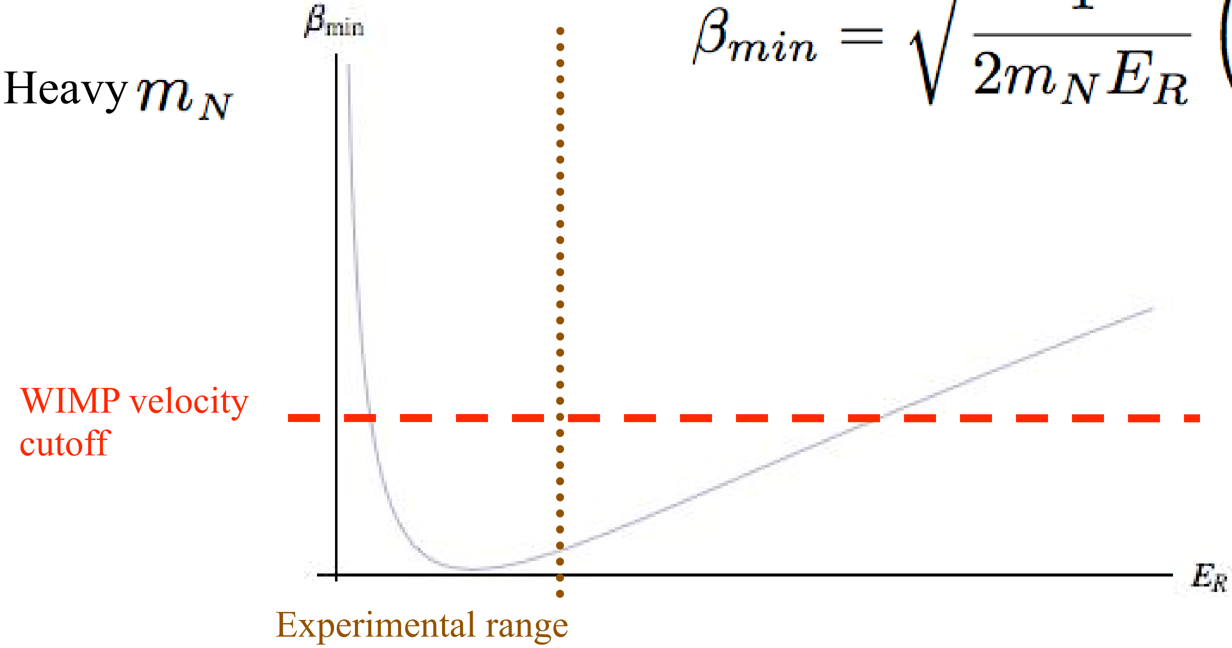

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Fit to DAMA

The differential event rate is given by,

$$\frac{dR}{dE_R} = N_T m_N \frac{\rho_\chi \sigma_n Q^2}{2 m_\chi \mu_{ne}^2} F^2(E_R) \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv$$

N_T # Nuclear Targets

σ_n Nucleus Mass

m_χ WIMP Mass

μ_{ne} WIMP-nucleon reduced mass

$\rho_\chi = 0.3 \text{ GeV cm}^{-3}$ WIMP mass density

$F^2(E_R)$ Nuclear Form Factor

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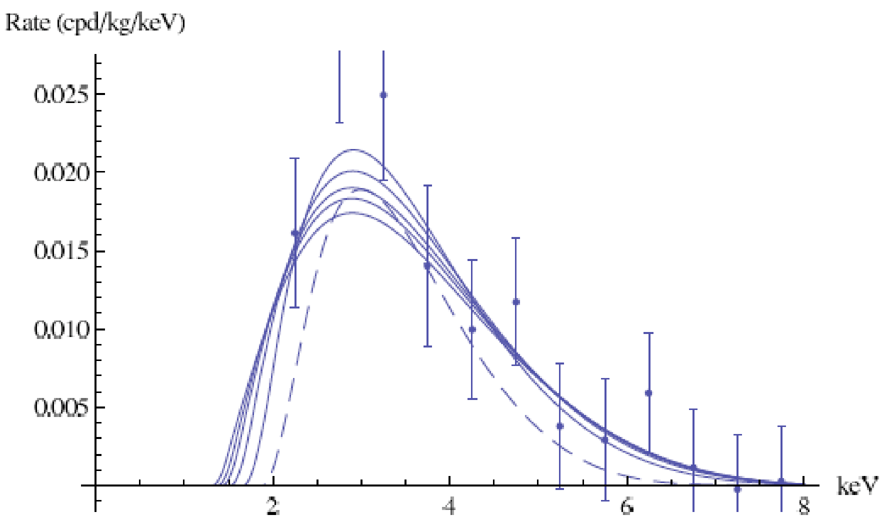

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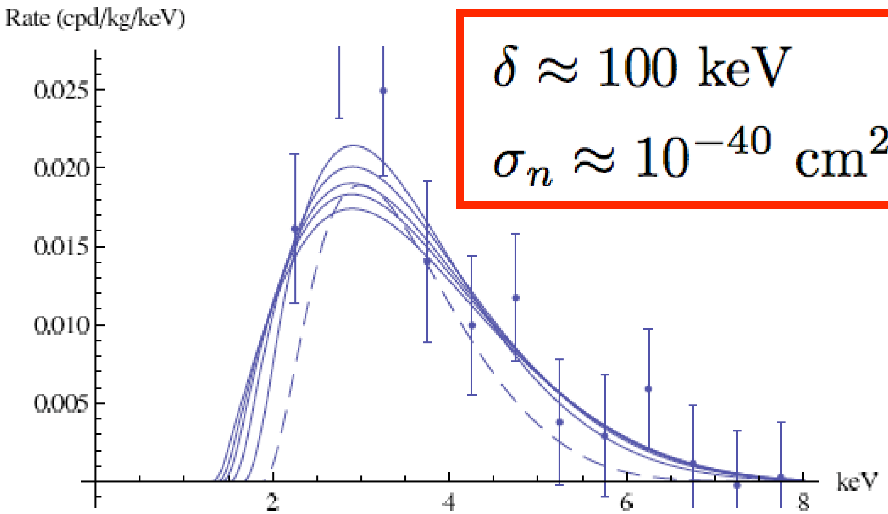

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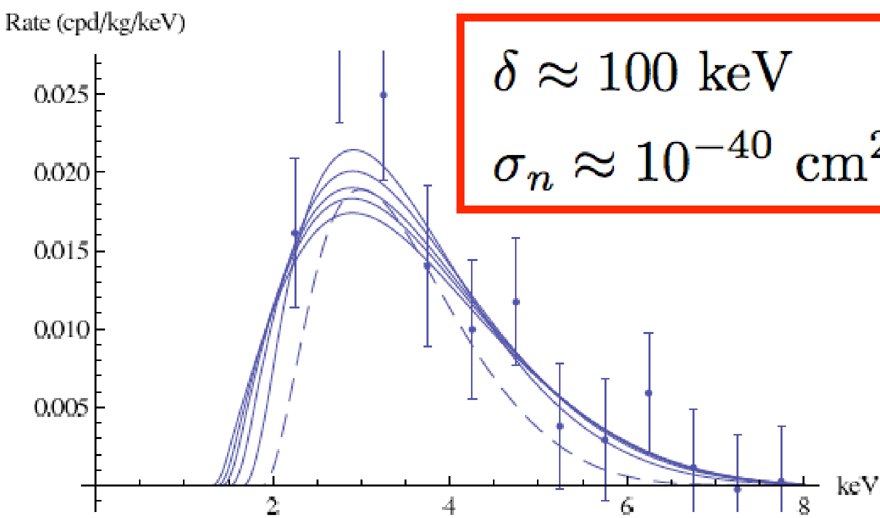

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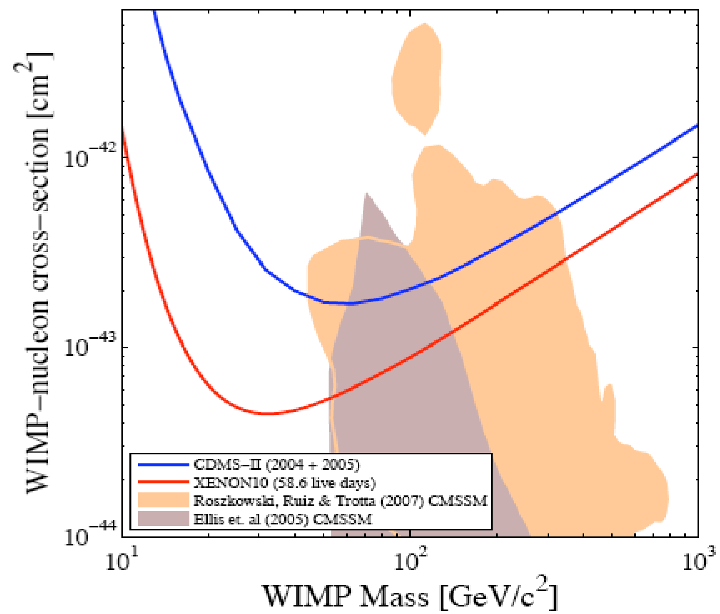
Capture in the Sun

KIAS



Biggest Targets

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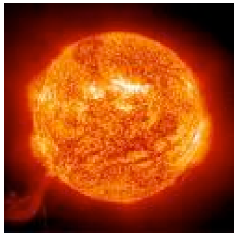

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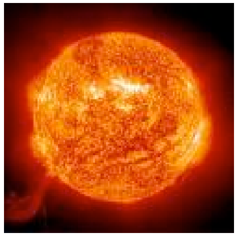

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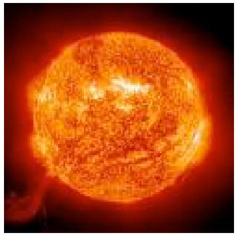

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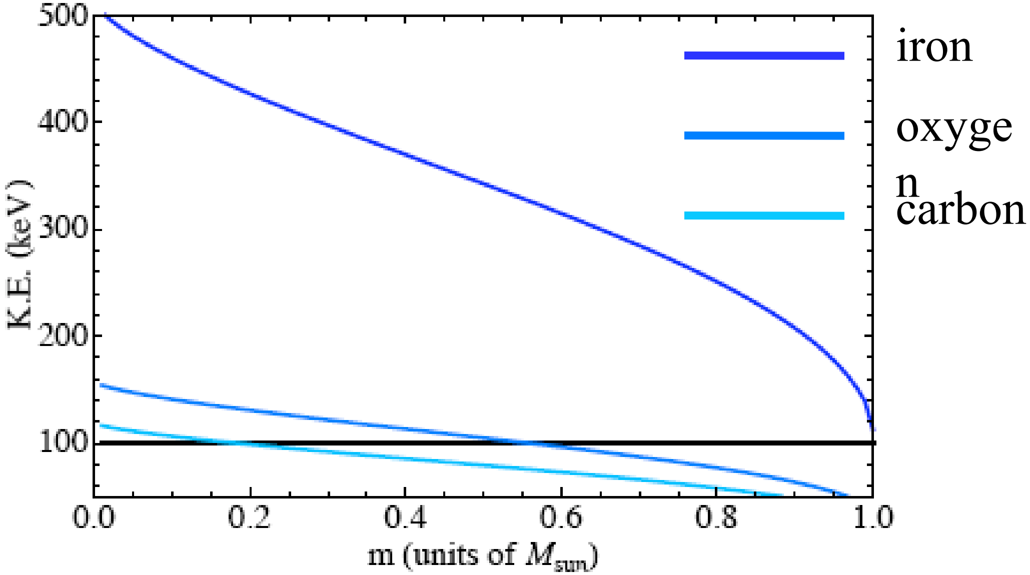

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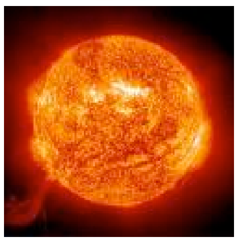

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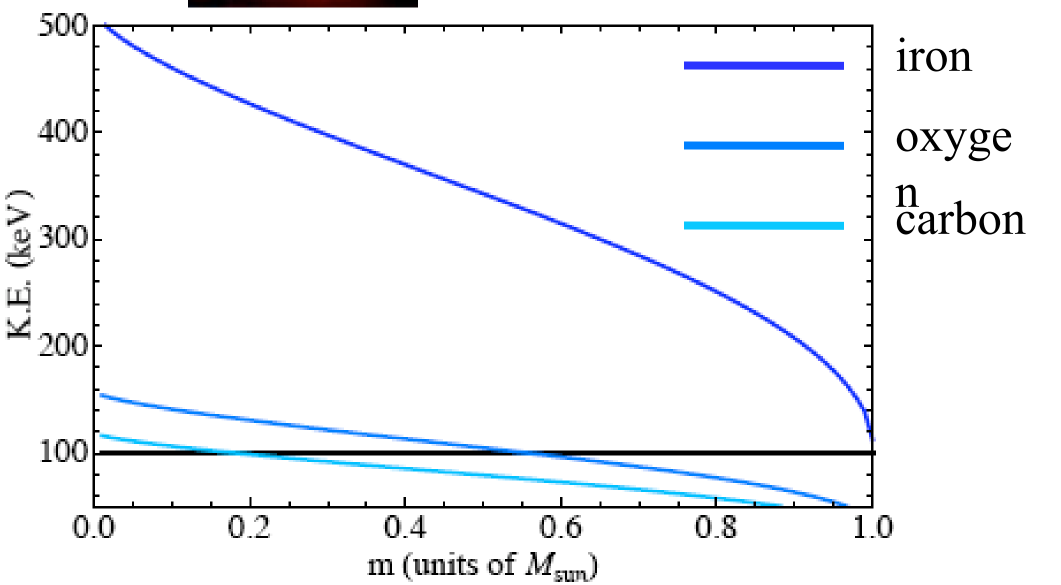
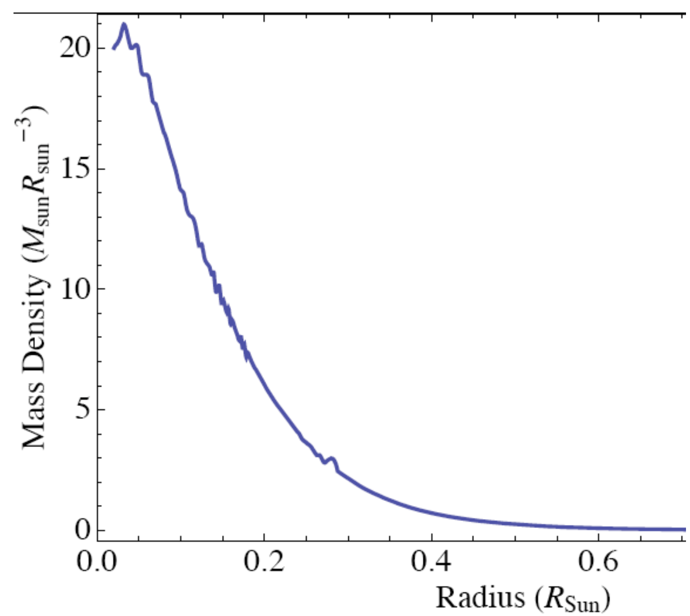


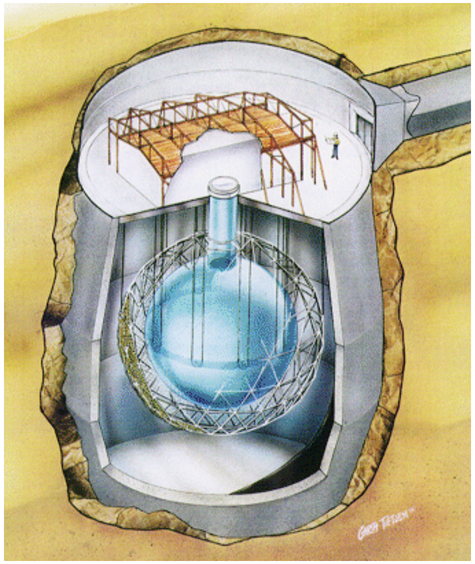


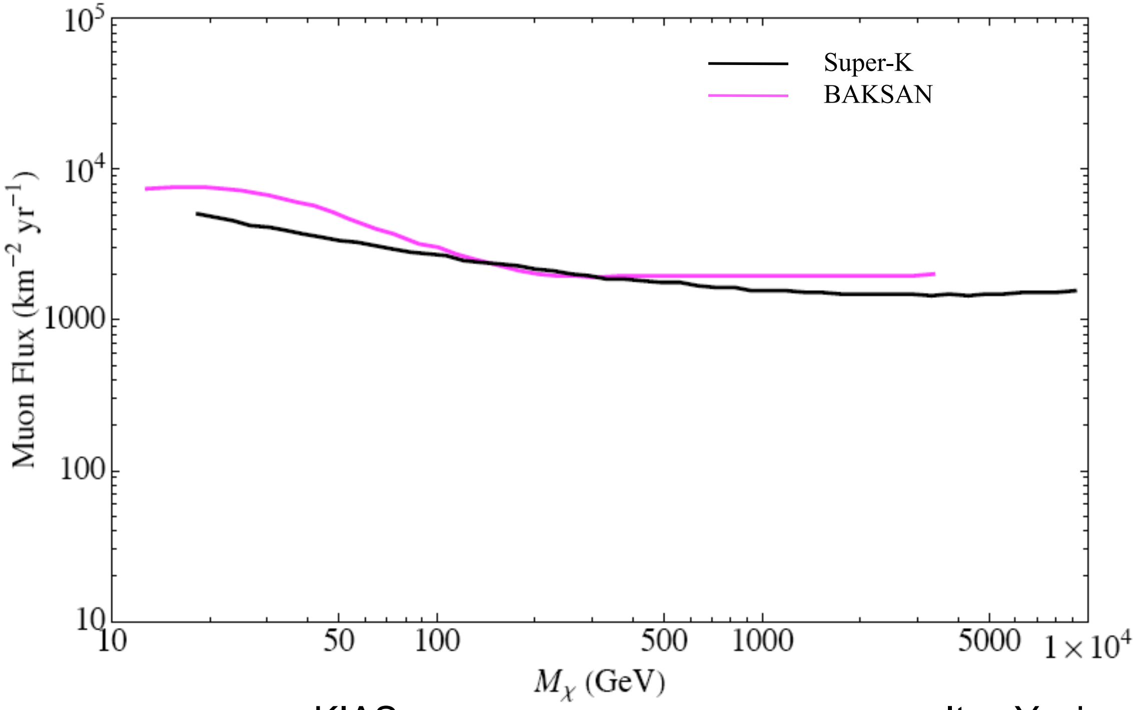
Detecting the Captured WIMPs

After they get captured, the WIMPs might eventually find each other and annihilate. If the annihilation products contain neutrinos, we can try to detect this flux coming from the Sun:

Underground Detectors: Observing the incoming neutrino through its conversion into a charged lepton and the subsequent .

Neutrino Telescopes: A muon-neutrino converts into a muon in the rock (or ice, or water) below the detector. The muon is subsequently detected with a large sparse array (Ice-Cube, Antares).



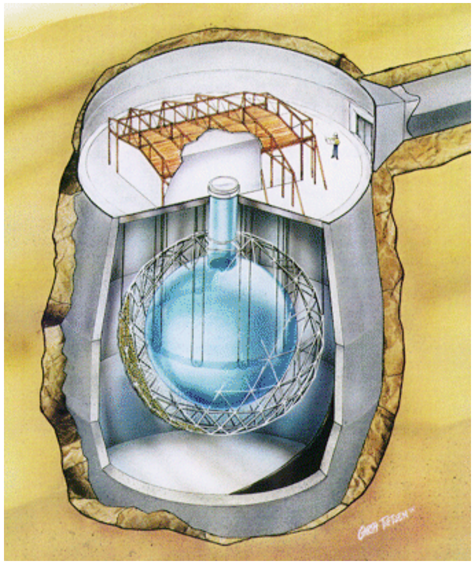


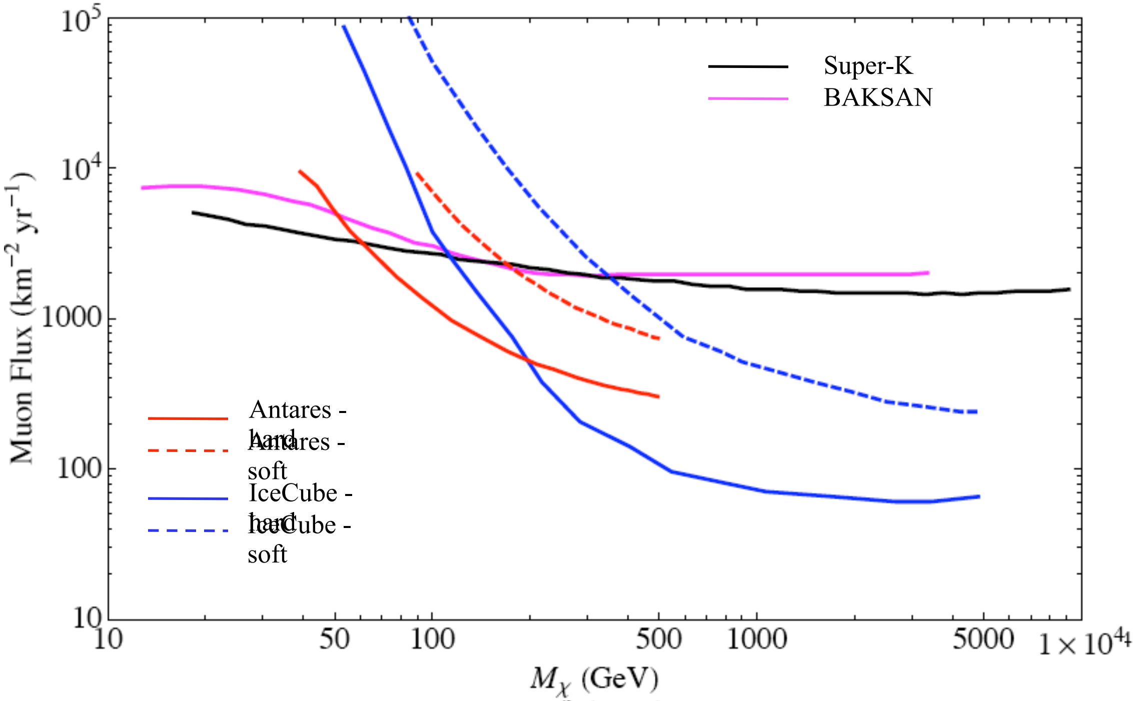
Detecting the Captured WIMPs

After they get captured, the WIMPs might eventually find each other and annihilate. If the annihilation products contain neutrinos, we can try to detect this flux coming from the Sun:

Underground Detectors: Observing the incoming neutrino through its conversion into a charged lepton and the subsequent .

Neutrino Telescopes: A muon-neutrino converts into a muon in the rock (or ice, or water) below the detector. The muon is subsequently detected with a large sparse array (Ice-Cube, Antares).





How to Compute Muon Flux

The computation can be separated into logically disjoint modules, as follows:

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Capture Rate
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(muon/sec/area)

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WIMP velocity distribution 4

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Properties of the Sun 4

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Many many things 4

Capture Rate - Back of the Envelope

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The capture rate per shell of radius *r*, is given by,

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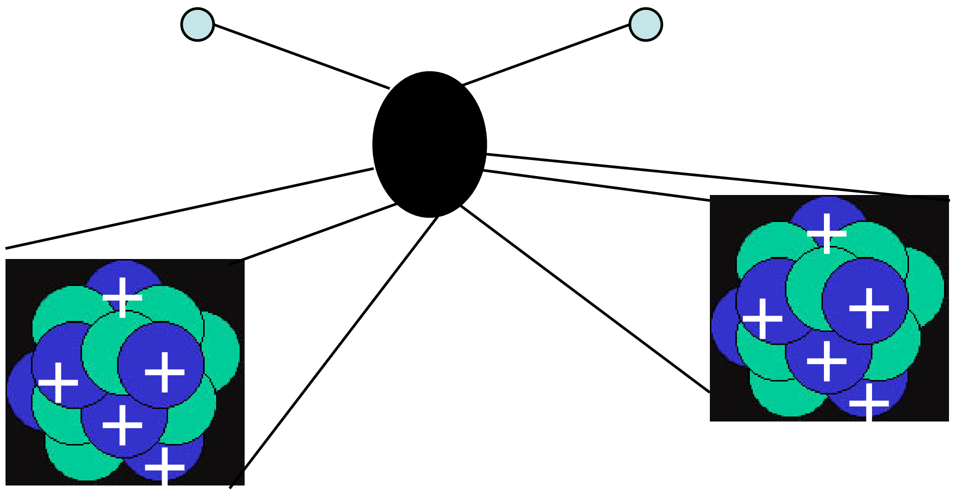
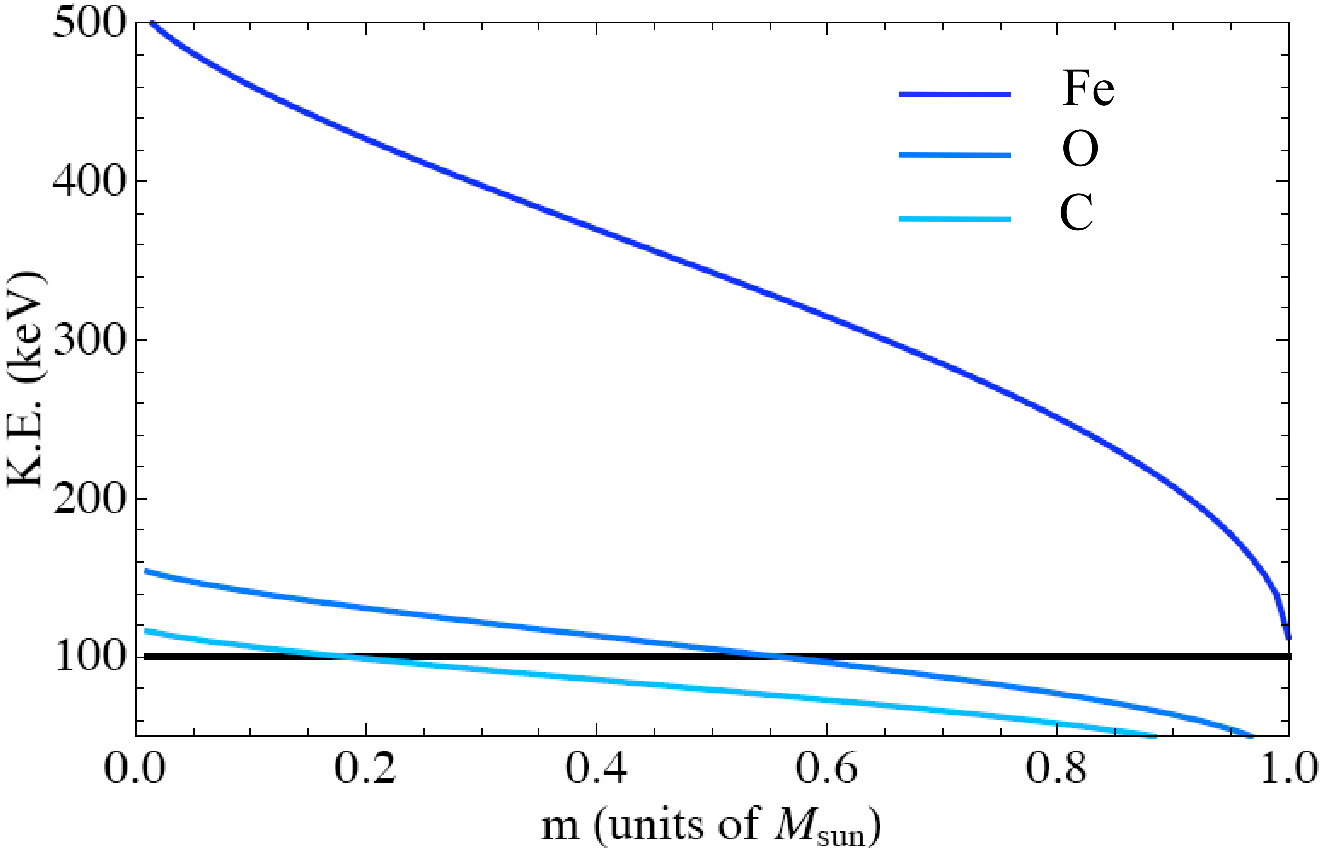
Nuclear Form Factors

For heavier elements, the WIMP no longer coherently scatters against the entire nucleus. This effect is captured by including a nuclear form factor,



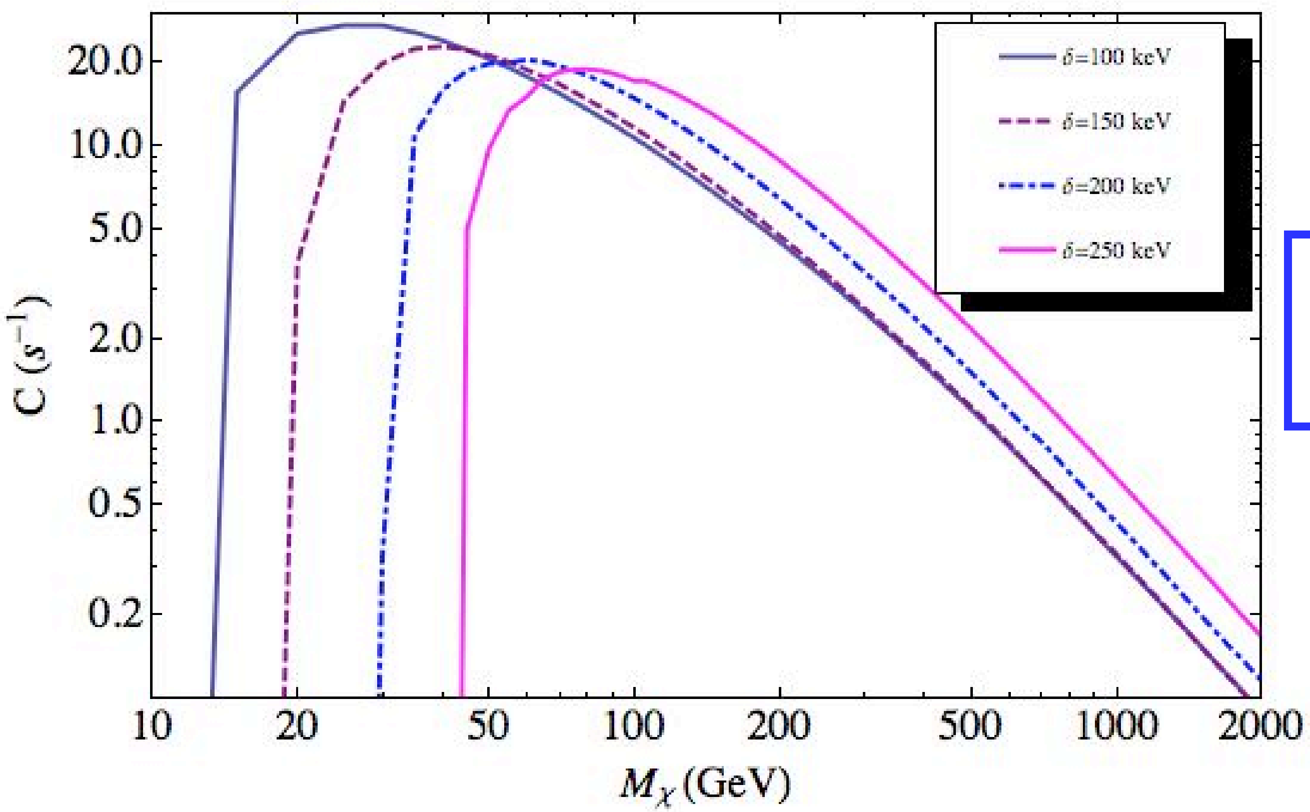
$$P_{cap} = \frac{1}{E_{max} - E_{min}} \int_{E_{cap}}^{E_{max}} e^{-E/E_0}$$

Which Elements Participate



$$M_\chi = 500 \text{ GeV} \qquad u_\infty = 220 \text{ km/s}$$

Capture Rate



$$\sigma_n \approx 10^{-40}\ \mathrm{cm}^2$$

It is easier to capture because some of the energy goes to excitation. Also, form-factor suppression is a little milder, especially for iron.

Annihilation Rate

The evolution of the WIMP population is governed by the equation,

capture rate

$$\dot{N} = C - C_A N^2$$

annihilation rate per WIMP^2

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$$\Gamma_A = \frac{1}{2} C \tanh^2(t/\tau_{eq})$$

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Is the solar lifetime long enough compared with the equilibrium time scale? **If not**, the signal is strongly reduced.

Equilibrium Time

$$C_A = \frac{\int d^3r \; n(r)^2 \; \langle \sigma_A v \rangle}{\left(\int d^3r \; n(r)\right)^2}$$

And usually, $n(r) = n_0 e^{-m_\chi \phi(r)/T}$

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$$\frac{t_\odot}{\tau_{\rm eq}} = 10^3 \left(\frac{C}{10^{25}\,\mathrm{sec}^{-1}} \right)^{1/2} \left(\frac{\langle \sigma_A v \rangle}{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{sec}^{-1}} \right)^{1/2} \left(\frac{7 \times 10^8\ \mathrm{cm}}{r_{th}} \right)^{3/2}$$

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So, equilibrium has been reached long ago, and the signal is full strength.

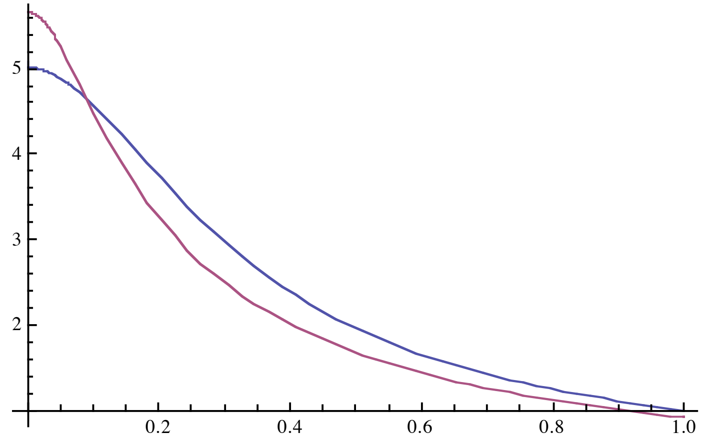
But, if the scattering is inelastic the WIMPs cannot thermalize!!! We need to compute the resulting density

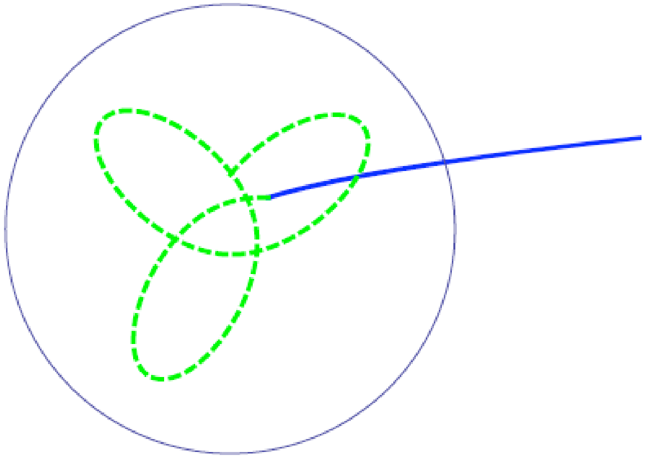
Orbits

Henon (1959) found closed form solutions for the orbits of the following potential:

$$U(r) = \frac{GM_\odot m_\chi}{2bR_\odot}\left(1 - \frac{2b}{b+\sqrt{b^2+r^2}}\right)$$

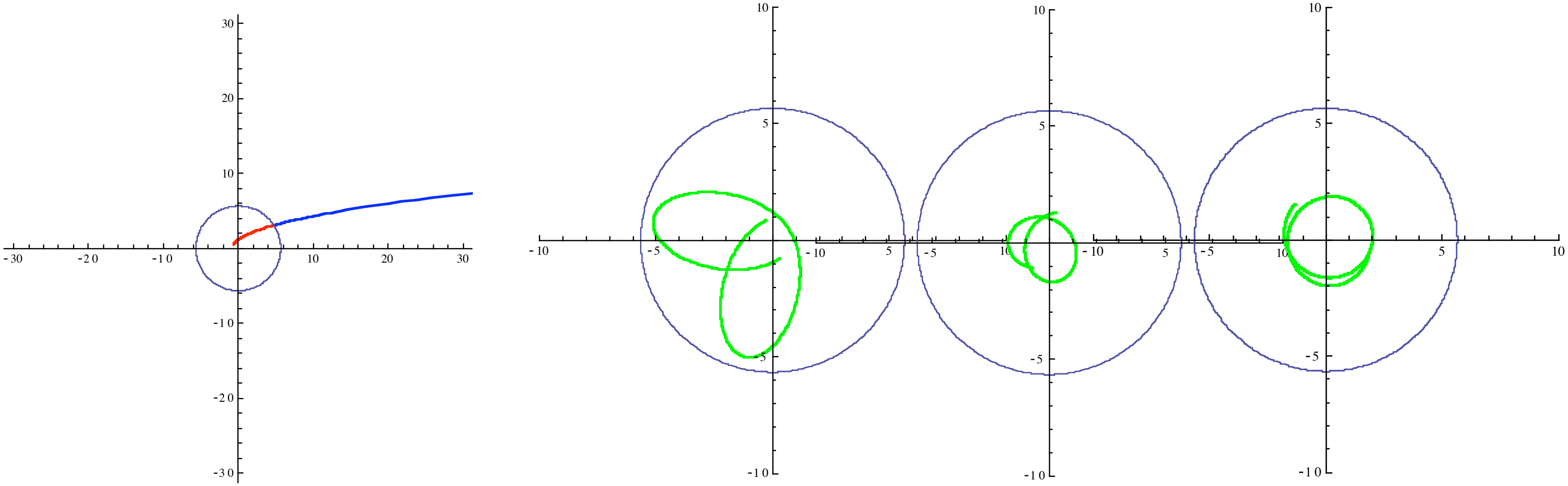
The potential in the sun can be fit fairly well to this potential,





Density

The WIMP will keep on colliding until it lost enough energy so it no longer have enough energy to undergo an inelastic transition.



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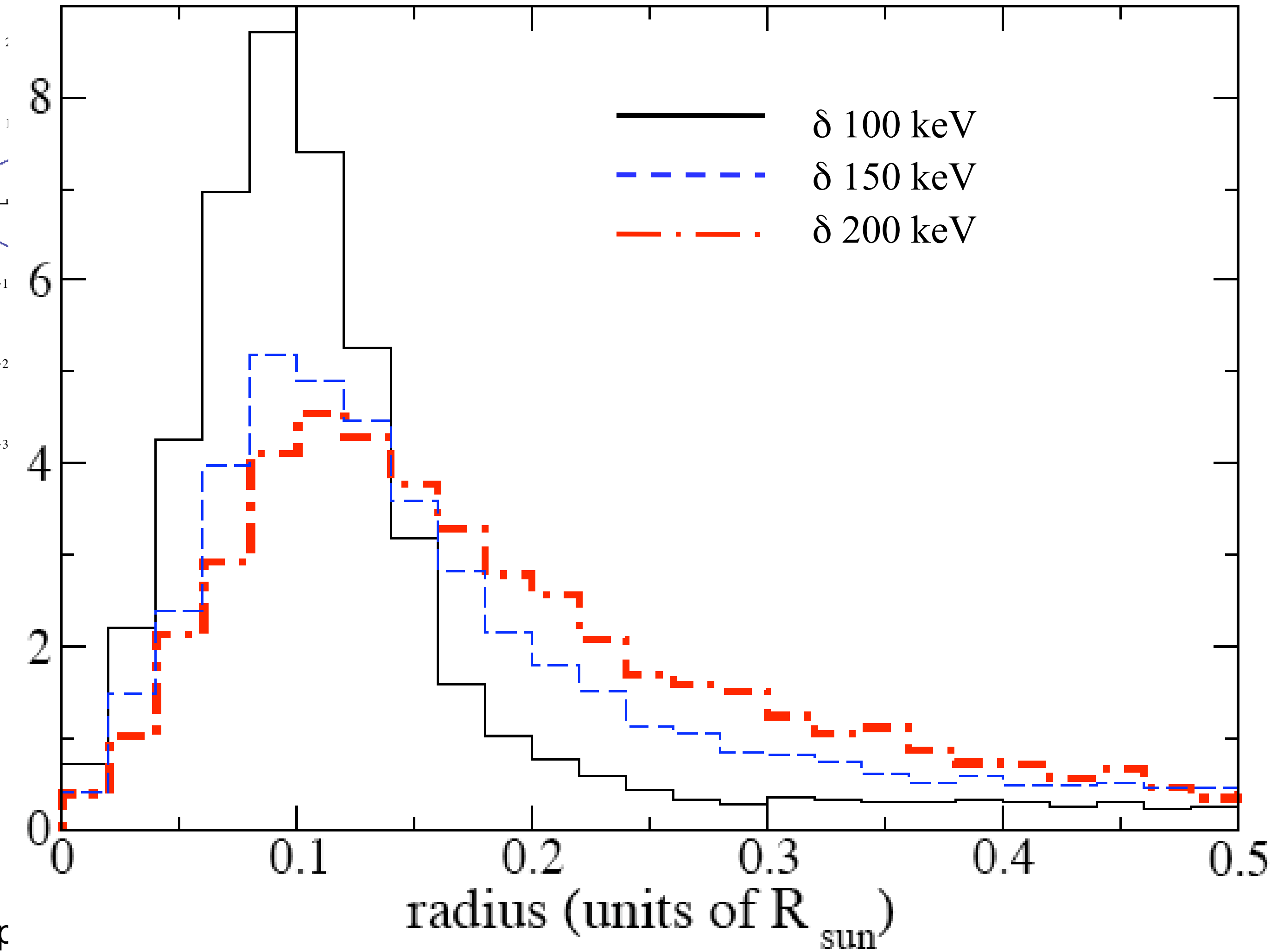
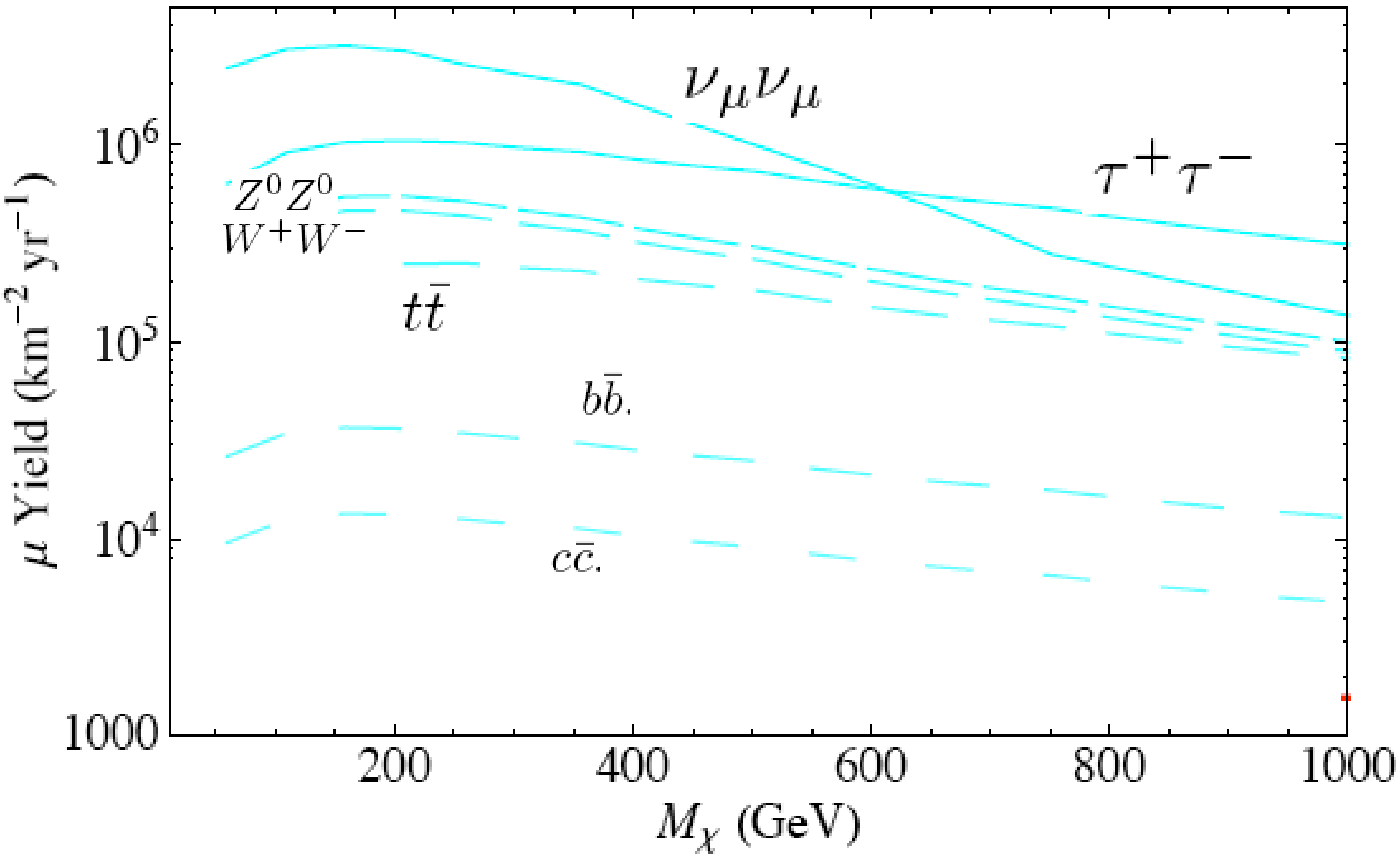


Muon Yield

To compute the resulting muon yield, we used DarkSUSY.
The inputs are: capture rate and annihilation channel.



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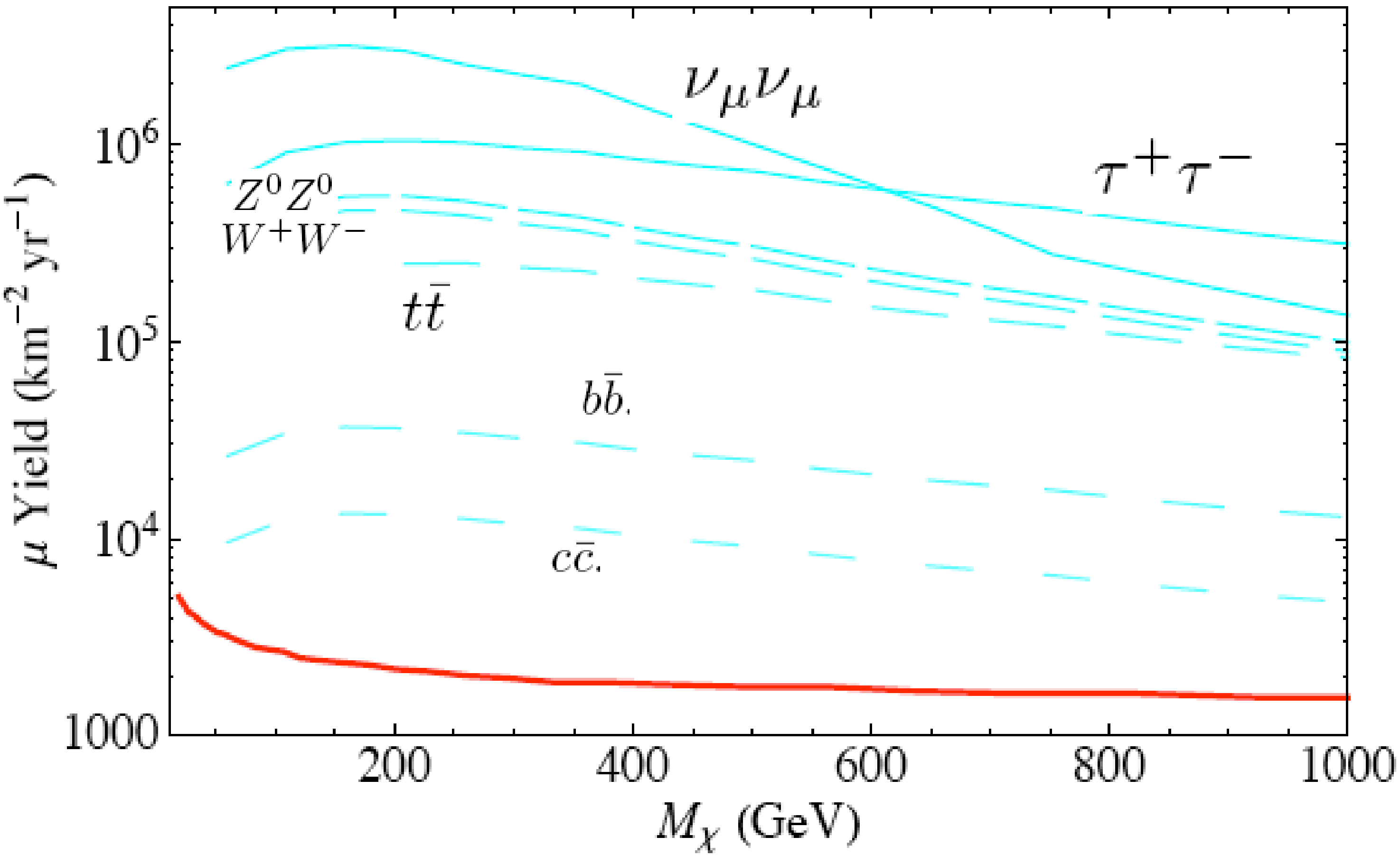
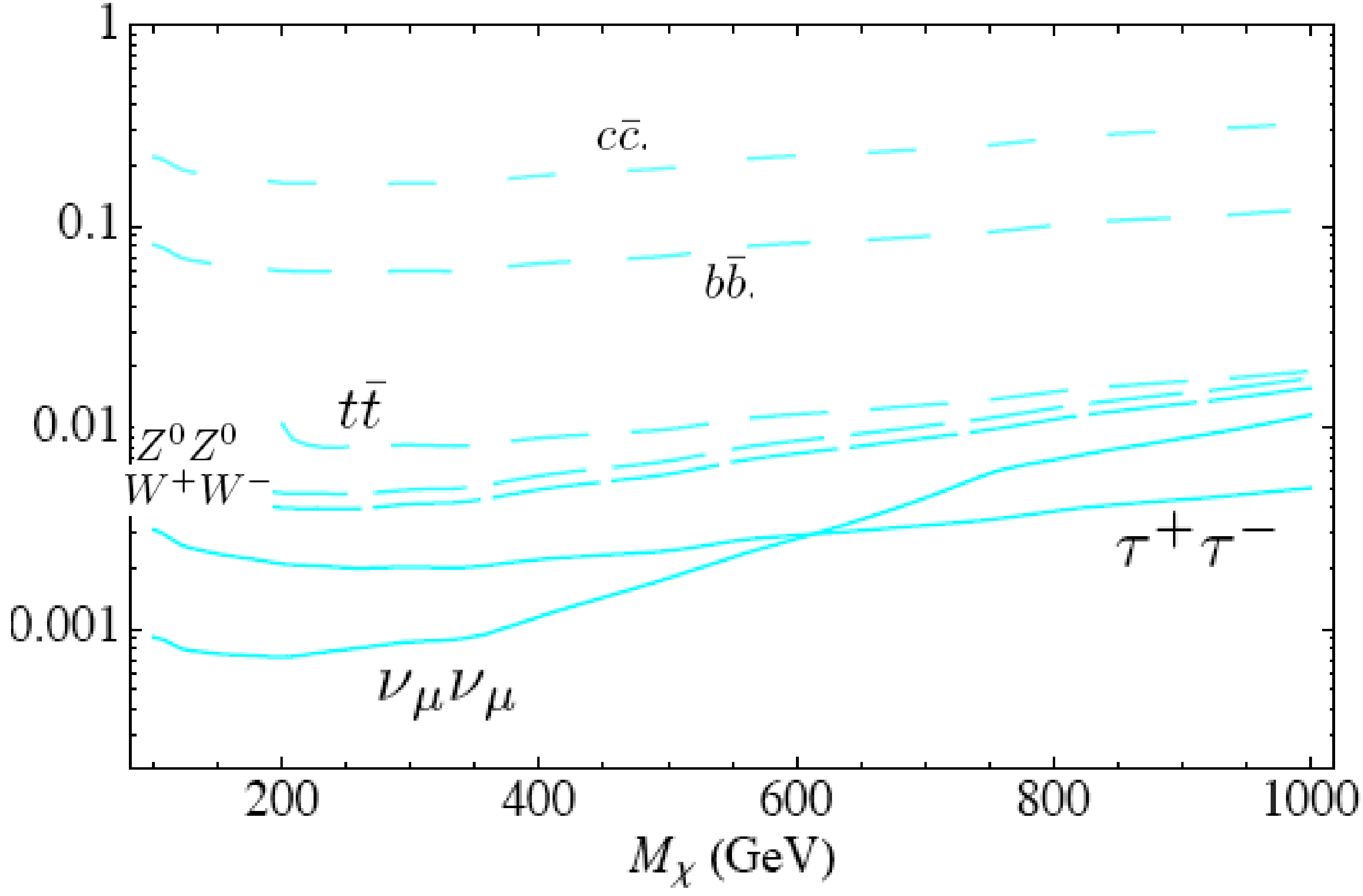


Excluded Annihilation Channels

So, current bounds from Super-K, already allow us to place extremely stringent bounds on the annihilation channels of any such model.



Reaction 1

Well, I didn't believe DAMA's results to begin with so… pfff

Reaction 2

If you love the MSSM, then you would take it as a sign that iDM models are ruled out.

Reaction 3

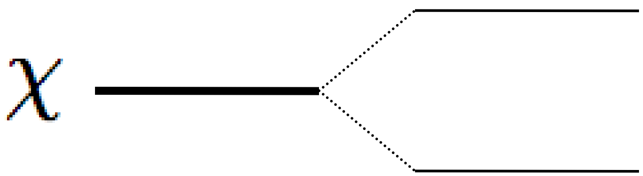
Conservatively, we can say:
If iDM is ever verified, then we know that DM annihilates in a very peculiar way.

Dark Gauge Groups?

Suppose DM is charged under some new dark abelian group:

$$\mathcal{L} = \bar{\chi}\gamma^{\mu}D_{\mu}\chi + M\bar{\chi}\chi + \frac{1}{\Lambda}\chi h \chi h + \text{ h.c.}$$

$$+ |D_{\mu}h|^2 - V(h) - \frac{1}{4}f_{\mu\nu}f^{\mu\nu} \qquad \langle h \rangle \approx \text{ GeV}$$



$$\frac{\langle h \rangle^2}{\Lambda} \approx \text{ 100keV}$$

Coupling to the SM can be achieved through kinetic mixing with hypercharge. Such a scenario will also yield the electron/positron excesses seen in PAMELA and possibly the CMB haze.

Conclusions

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- Inelastic DM models with generic couplings to the SM are excluded by neutrino telescopes.
- If DM is charged under some new abelian groups, PAMELA, ATIC and a few other observations can be accommodated. Inelastic scattering arises naturally and is NOT excluded by the present considerations.