

Title: Resonant Dark Matter

Date: Jan 15, 2010 02:30 PM

URL: <http://pirsa.org/10010077>

Abstract: It is usually assumed that dark matter direct detection is sensitive to a large fraction of the dark matter (DM) velocity distribution. I will explain an alternative form of dark matter-nucleus scattering which only probes a narrow range of DM velocities due to the existence of a resonance, a DM-nucleus bound state, in the scattering - resonant dark matter (rDM). The scattering cross section becomes highly element dependent, has increased modulation and as a result can explain the DAMA/LIBRA results whilst not being in conflict with other direct detection experiments. I will describe a simple model that realizes the dynamics of rDM, where the DM is the neutral component of a fermionic weak triplet whose charged partners differ in mass by approximately 10 MeV.

Non-standard Dark Matter and its Direct Detection

Patrick Fox

 Fermilab

with Yang Bai
[JHEP 0911:052, 2009]

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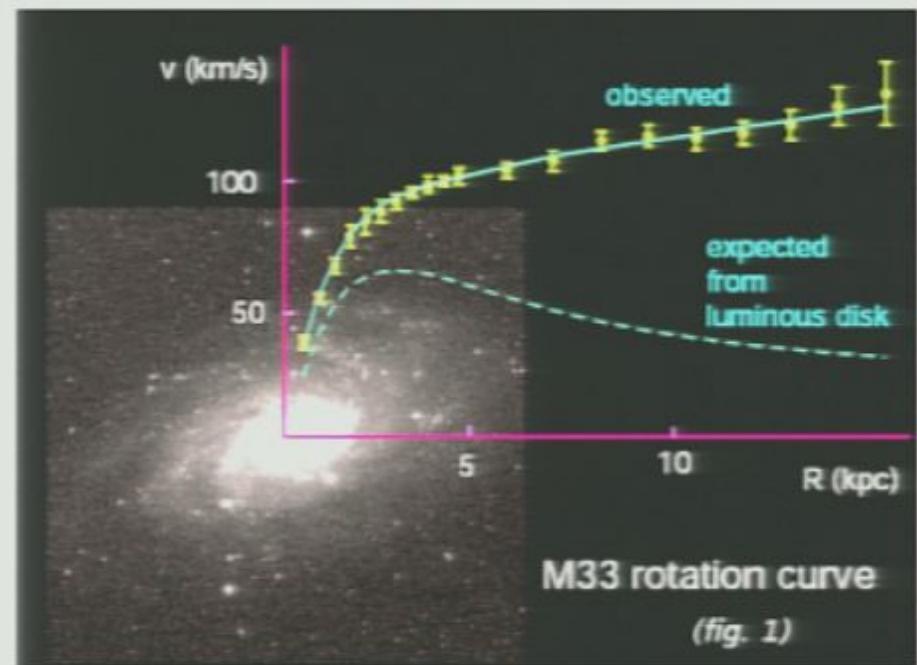
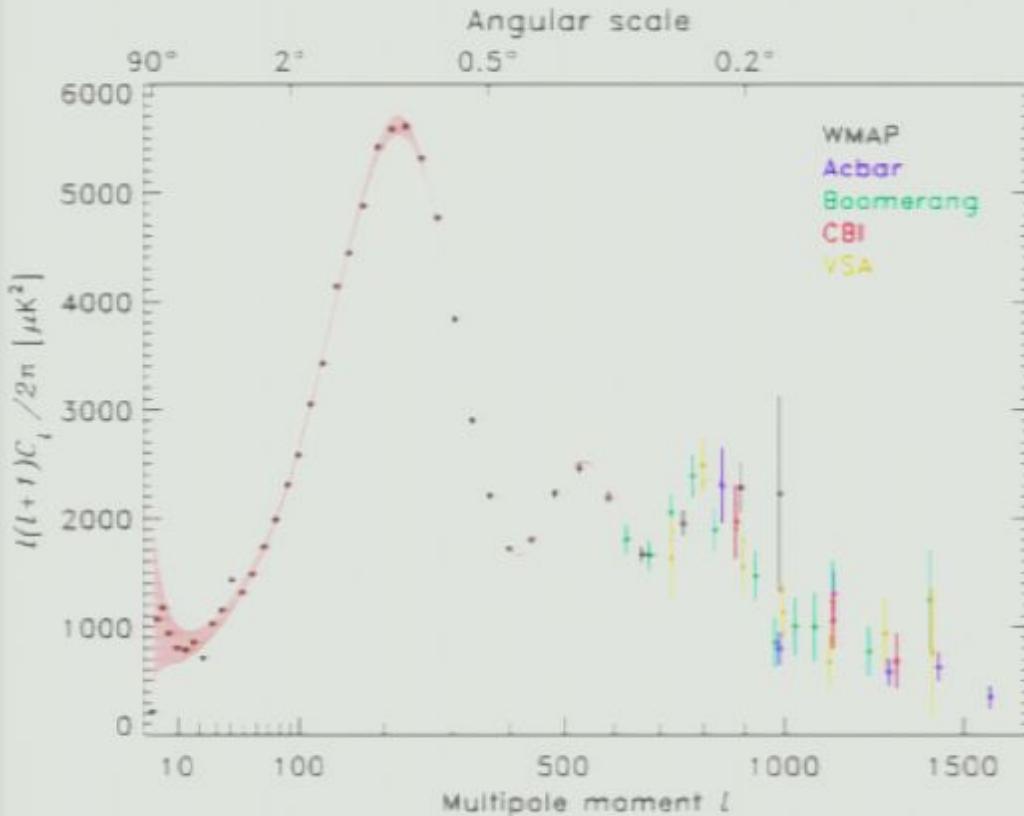
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Plan

- Dark Matter review
- Direct Detection experiments
- DAMA
 - iDM
 - FFDM
- rDM
 - A Model
 - Element dependence
 - Fits to DAMA
 - Signals
- Outlook

Dark Matter

Lots of evidence for non-baryonic matter:



Cosmological abundance

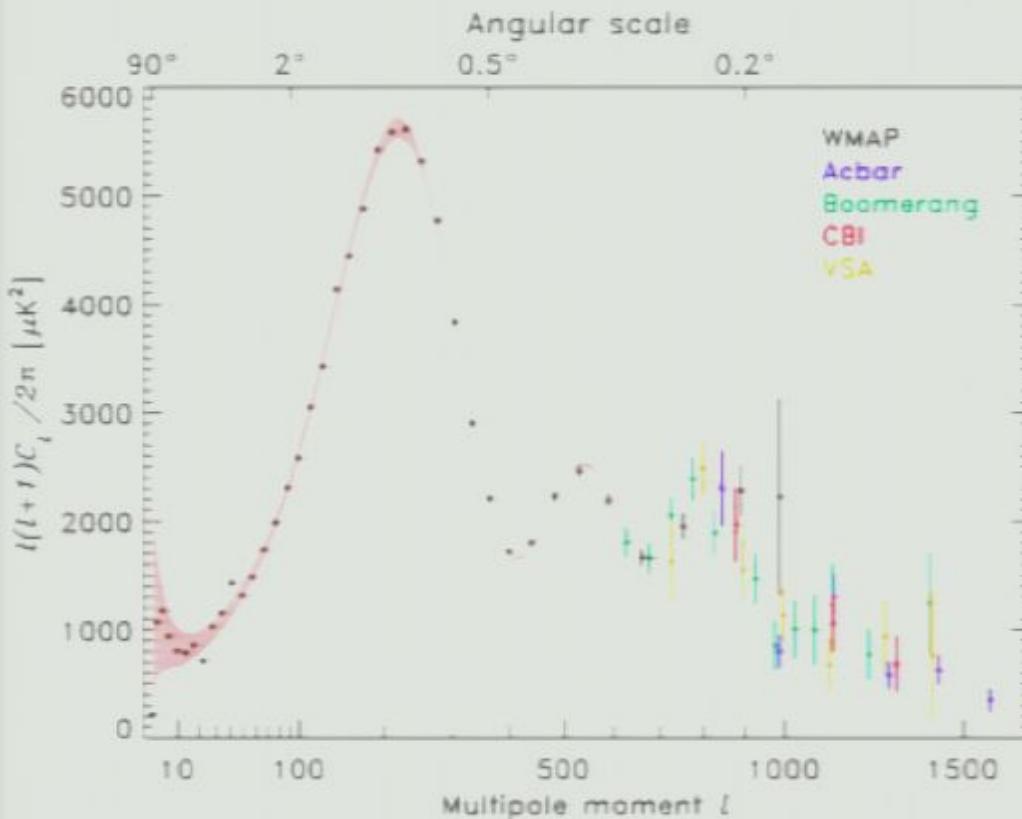
$$\Omega_{DM} \sim 0.2$$

Local abundance

$$\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$$

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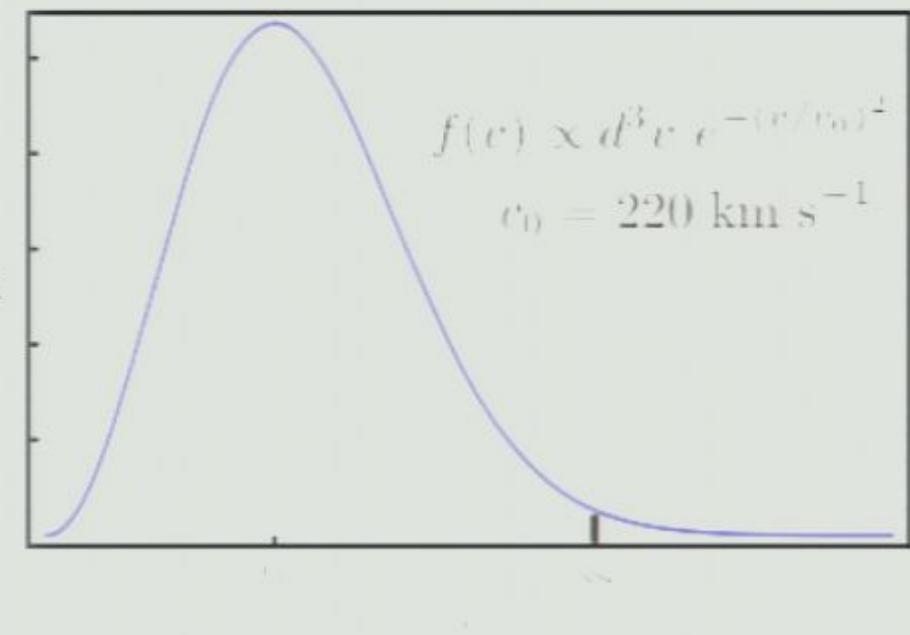
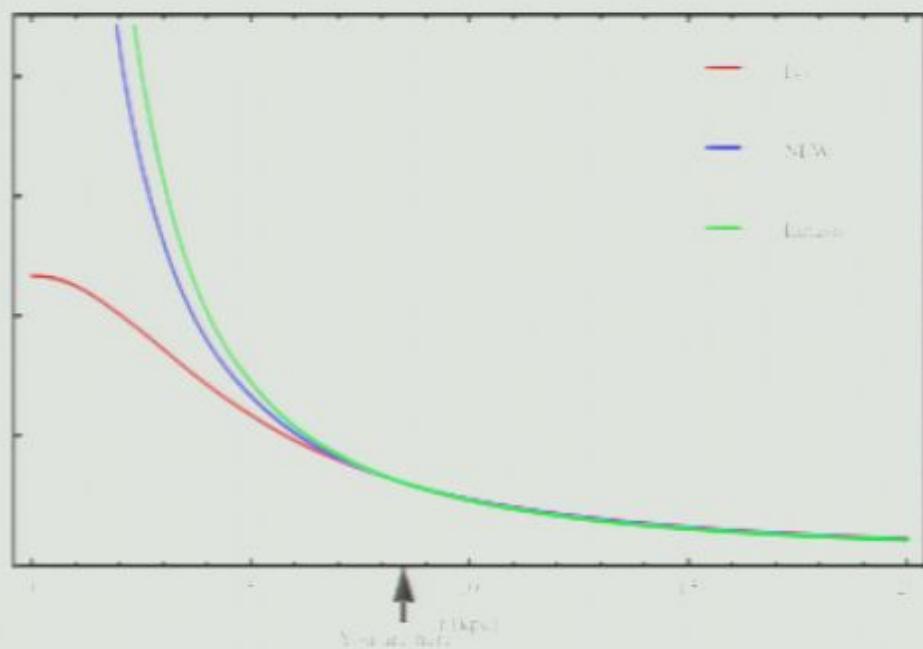
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Dark Matter

Near us: $\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$

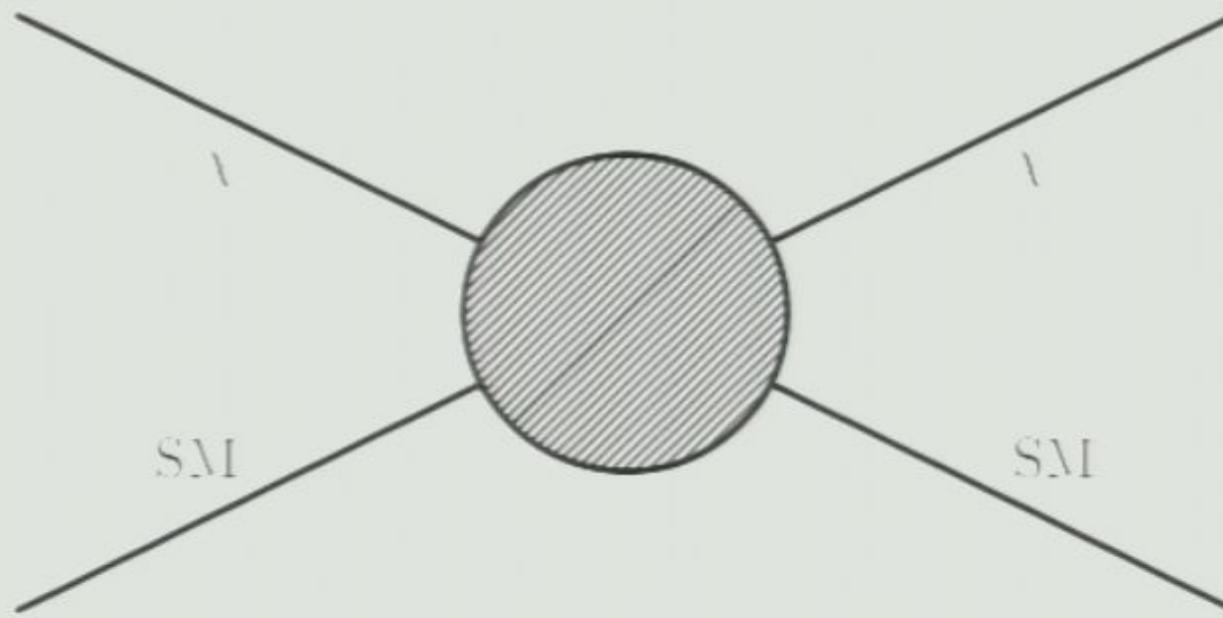
Maxwell-Boltzmann
velocity distribution



Escape velocity in galactic frame $498 \text{ km/s} \leq v_{esc} \leq 608$

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$$

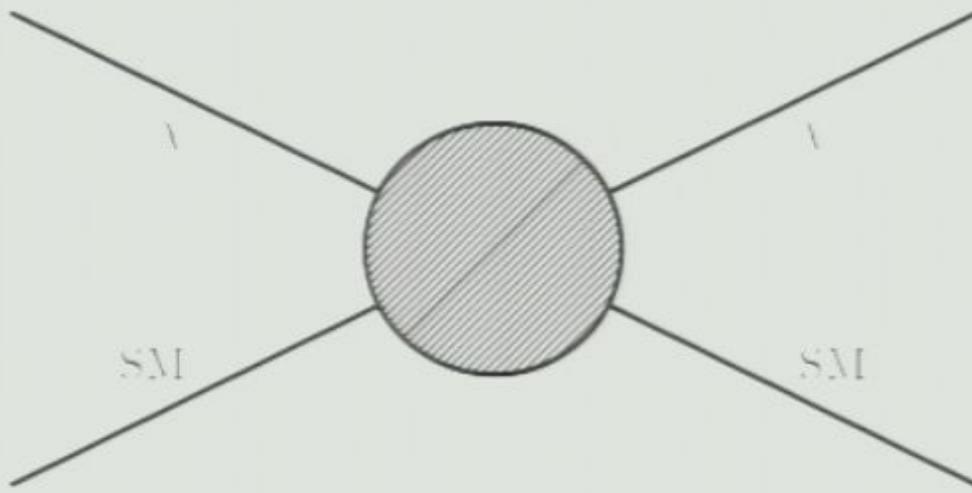
Direct Detection



$$m_\chi \sim 100 \text{ GeV}$$

$$q_\chi \sim 100 \text{ MeV}$$

Direct Detection



$$E_R \sim \frac{q_\chi^2}{2 M_T} \sim 100 \text{ keV}$$

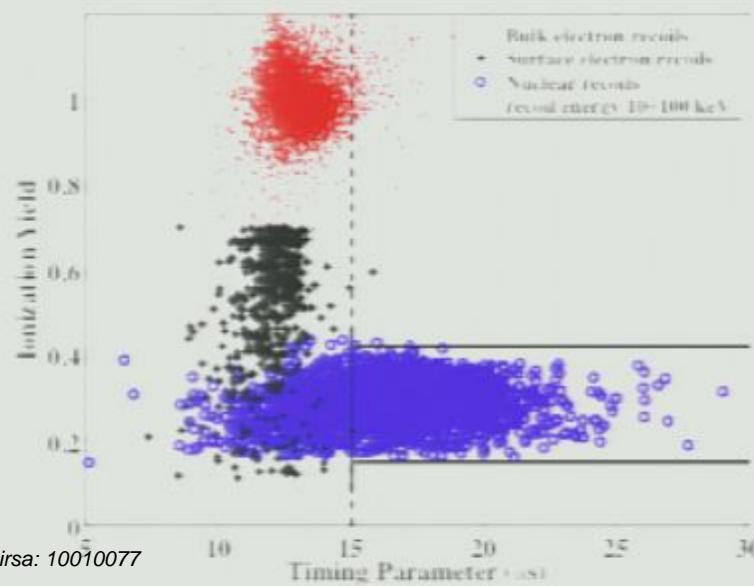
$$R \sim N_T \frac{\rho_\chi}{m_\chi} \langle \sigma v \rangle \approx 1 \text{ event/day/kg}$$

How to distinguish this small number of low energy events from backgrounds?

Direct Detection

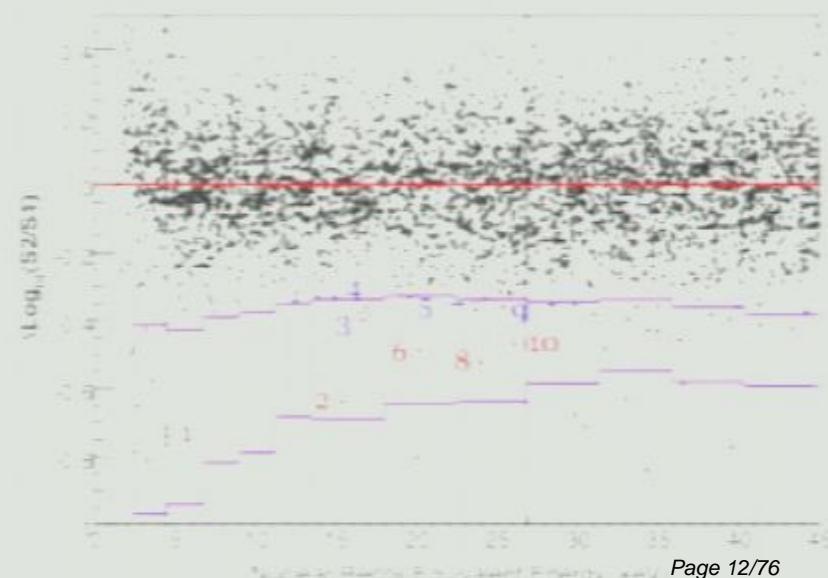
One Way:

- Remove cosmic backgrounds by going underground
- Shield experiment from radioactive elements
- Cool equipment
- Take multiple measurements to distinguish background from nuclear recoils e.g. ionization, scintillation, phonons



Pirsa: 10010077

(CDMS collaboration)

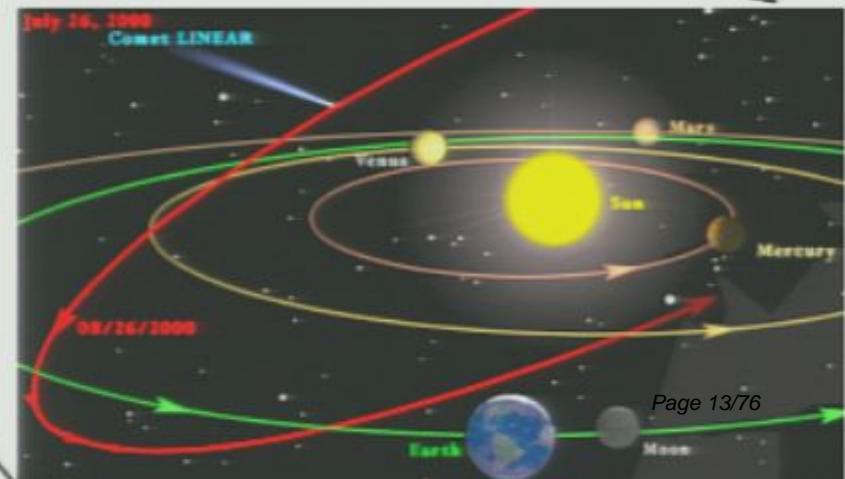
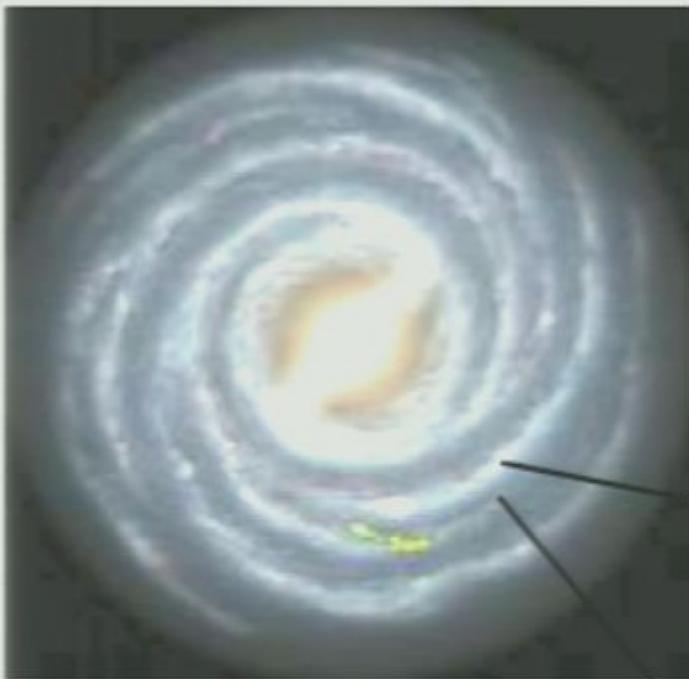


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(EXENON10 collaboration)

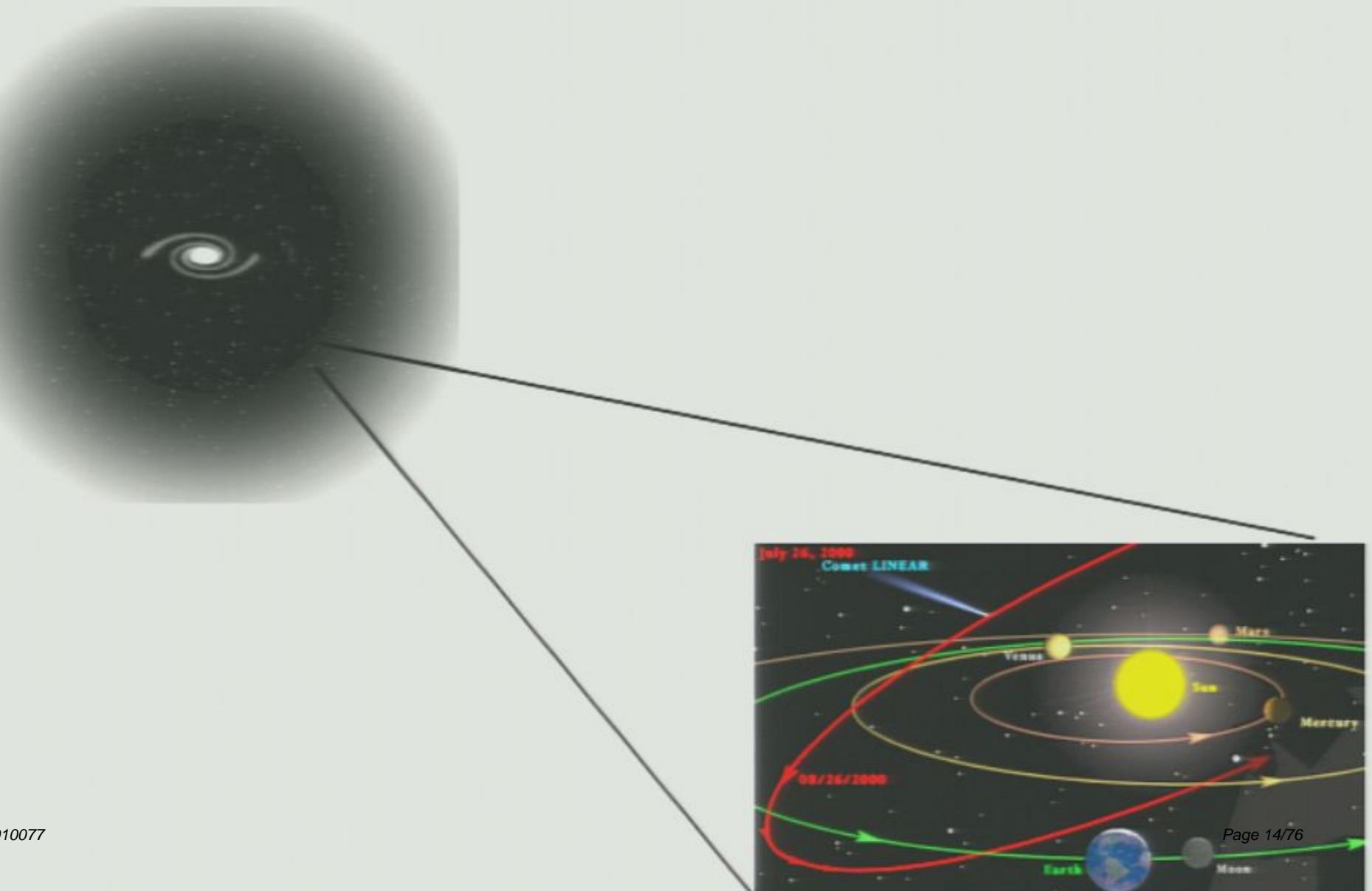
Annual Modulation

Another Way:



Annual Modulation

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Annual Modulation

In galactic frame:

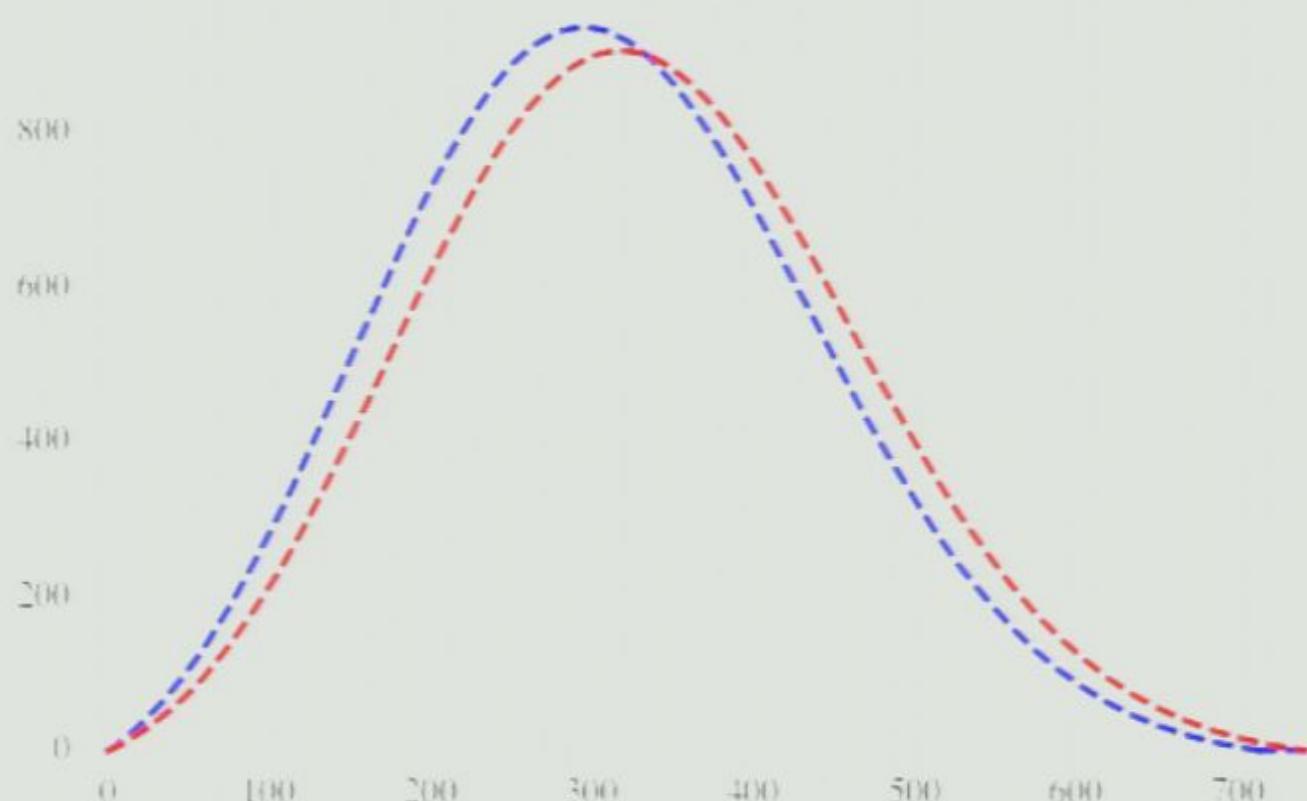
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$$f(\vec{v}, \vec{v}_E) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-(\vec{v} + \vec{v}_E)^2/v_0^2}$$

$$v_E \approx 227 + 14.4 \cos[2\pi(\frac{t-t_0}{T})] \quad t_0 = \text{June } 2^{\text{nd}}$$



Annual Modulation

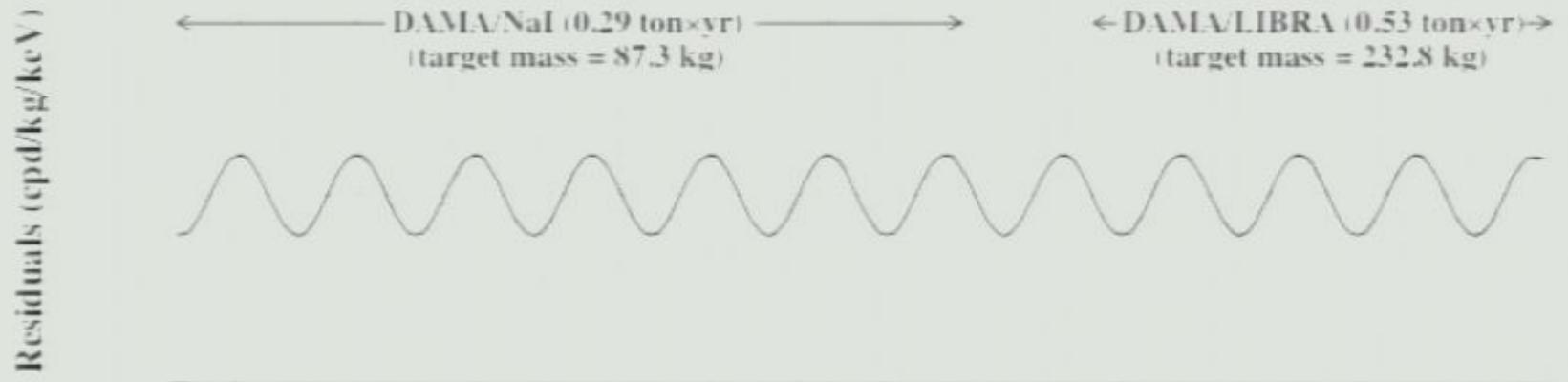
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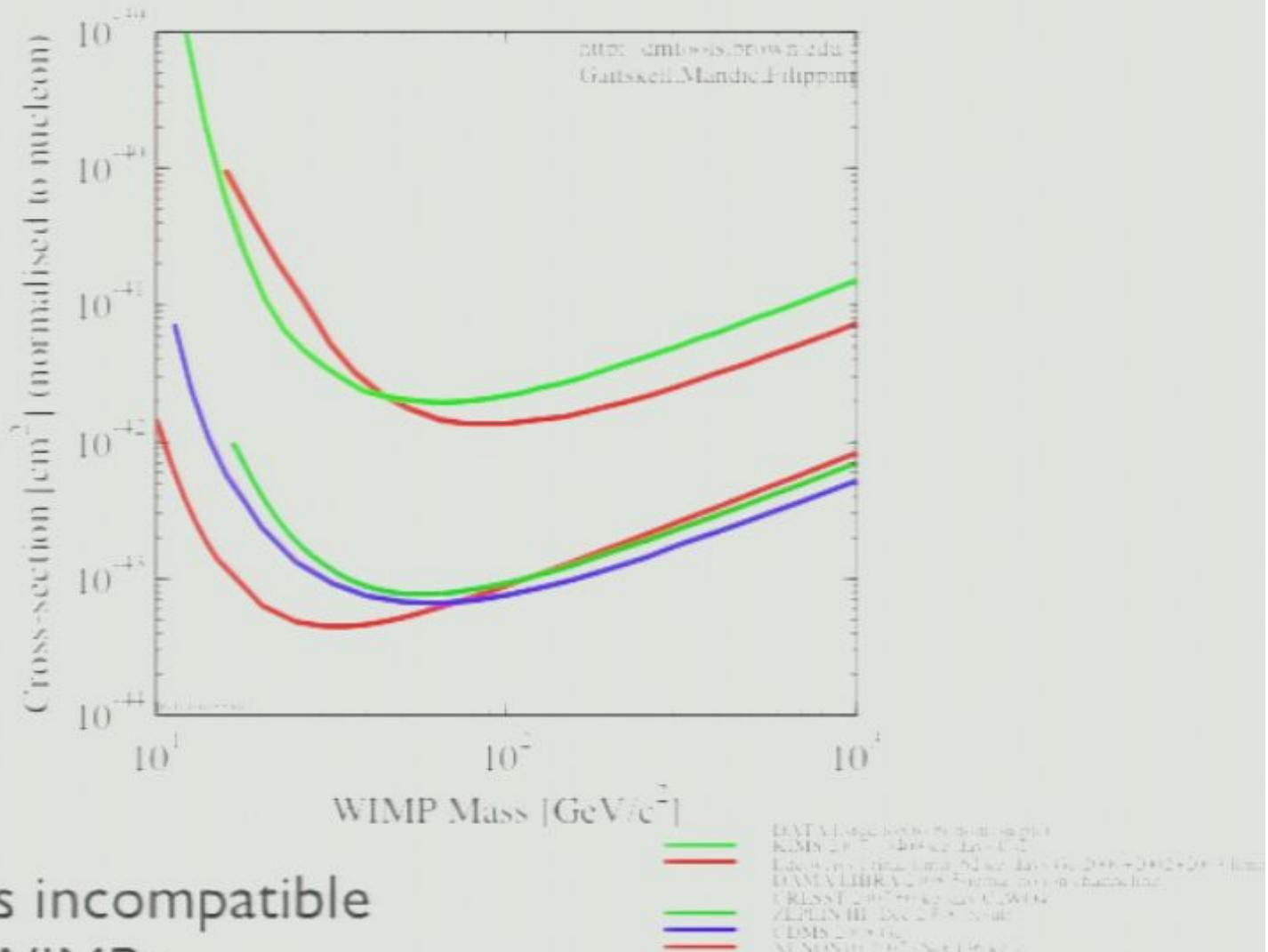
Does annual modulation = discovery of DM?

Many things modulate on a year timescale:

- temperature
- water loading
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But, very few line up year on year with June 2nd

Direct Detection

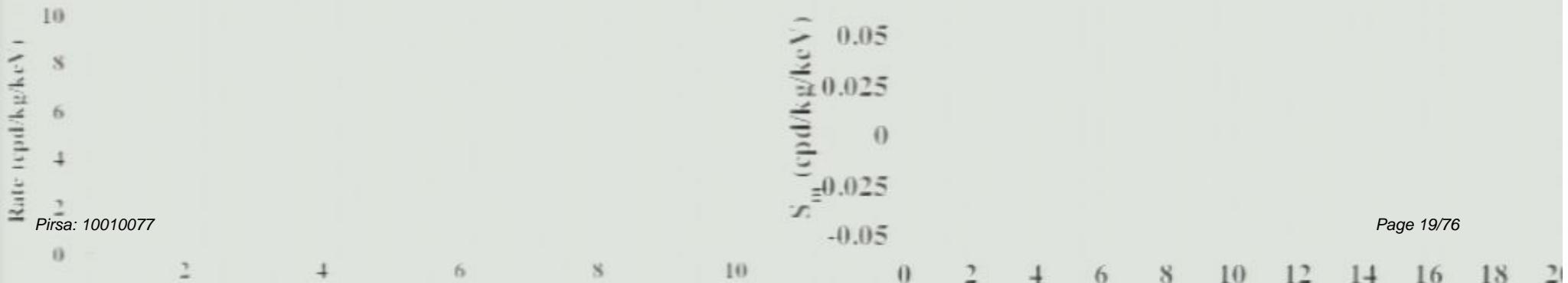
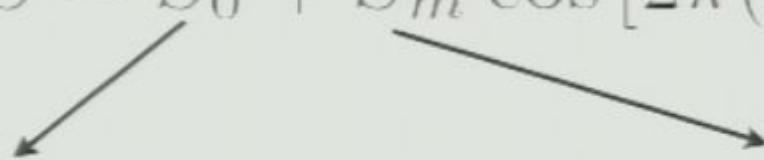


- DAMA and others incompatible
- Rule out normal WIMPs
- Suppressed coupling to Z, Y=0
- Many different experiments

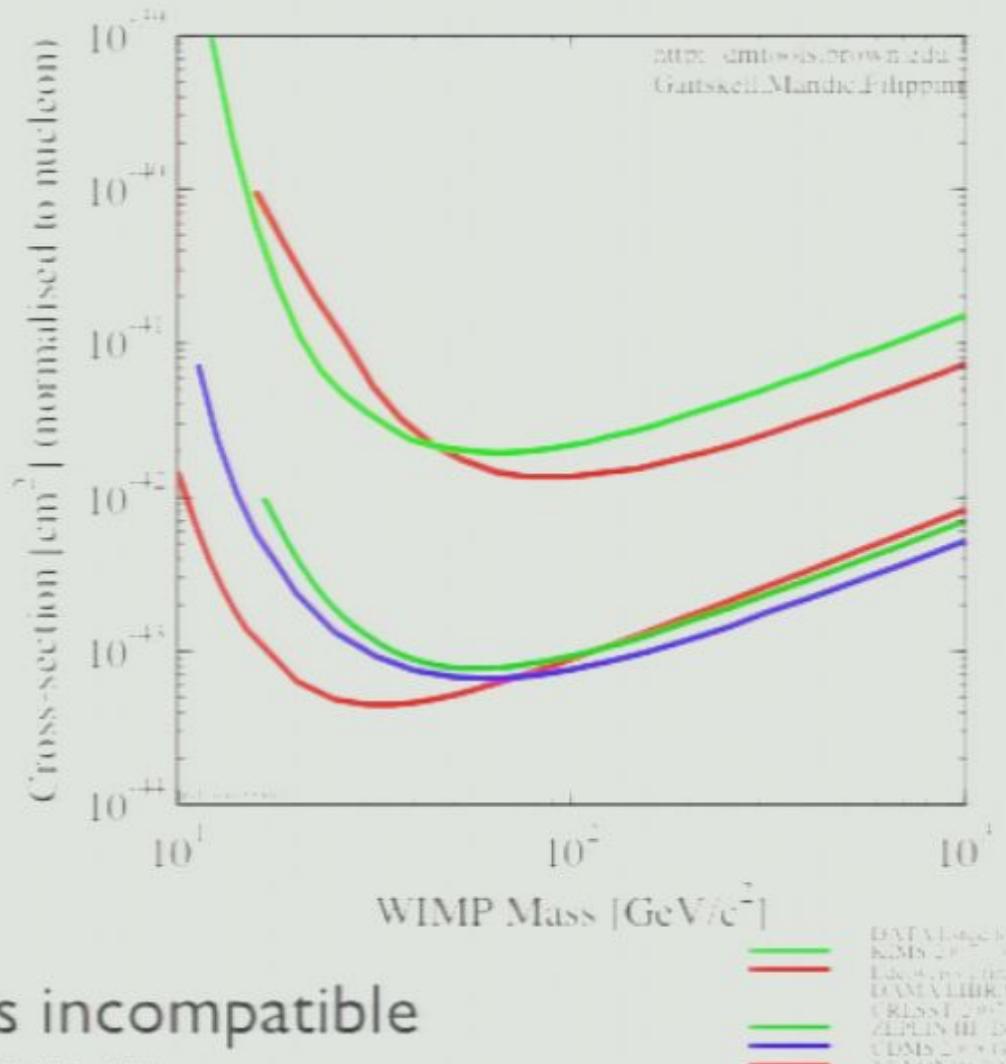
Possible explanations

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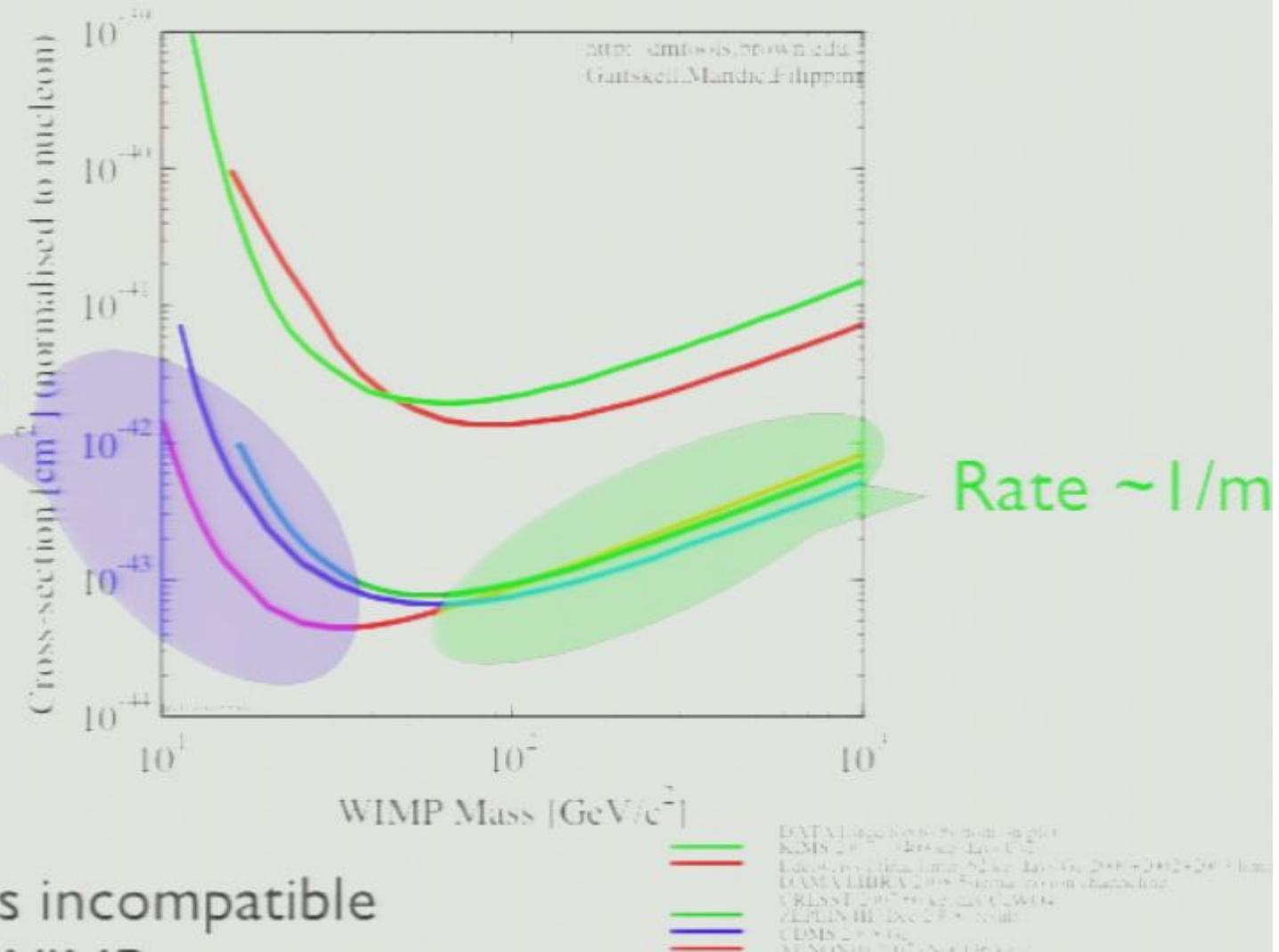
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Direct Detection

Threshold cuts off

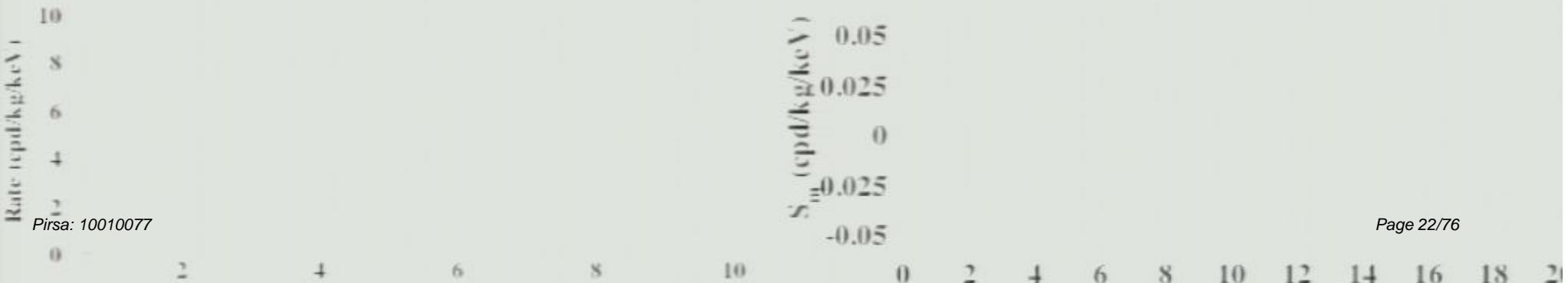


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THE ONE IMPORTANT SLIDE

Annual Modulation

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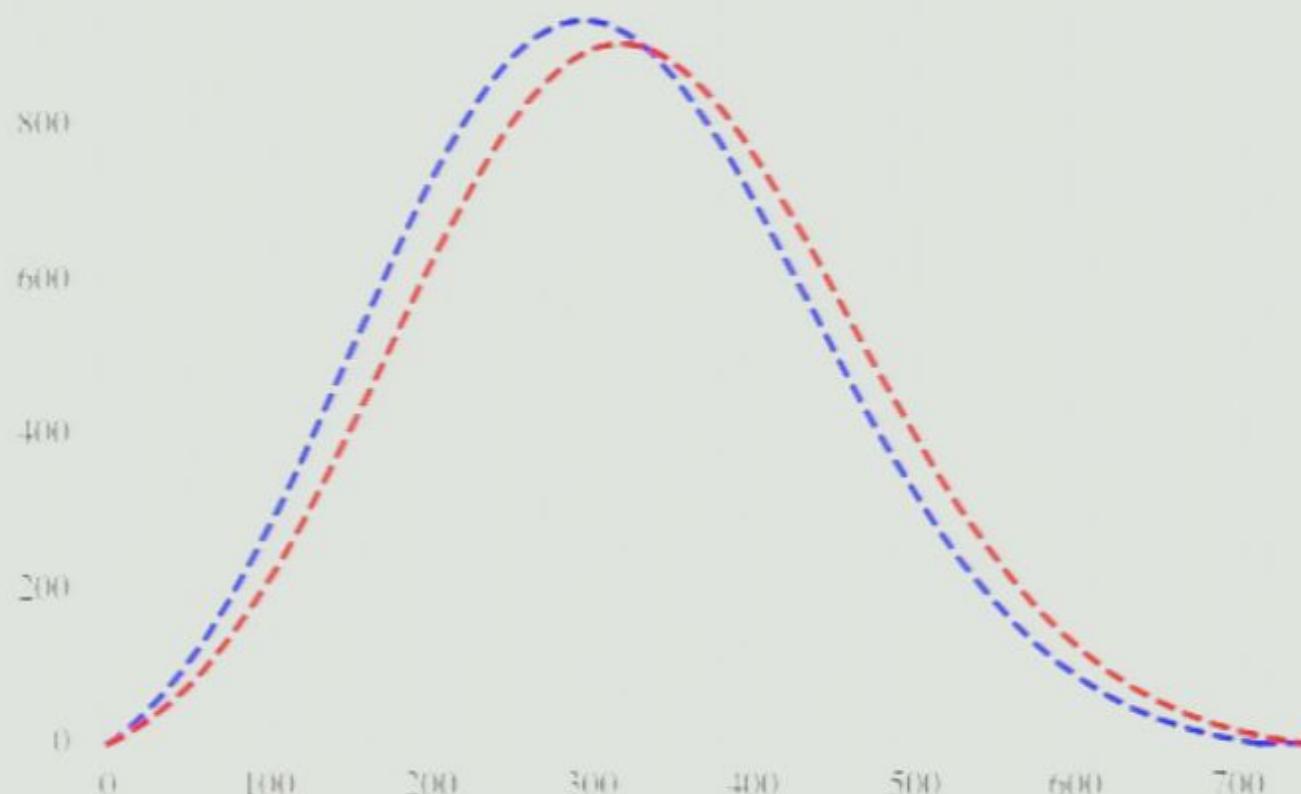
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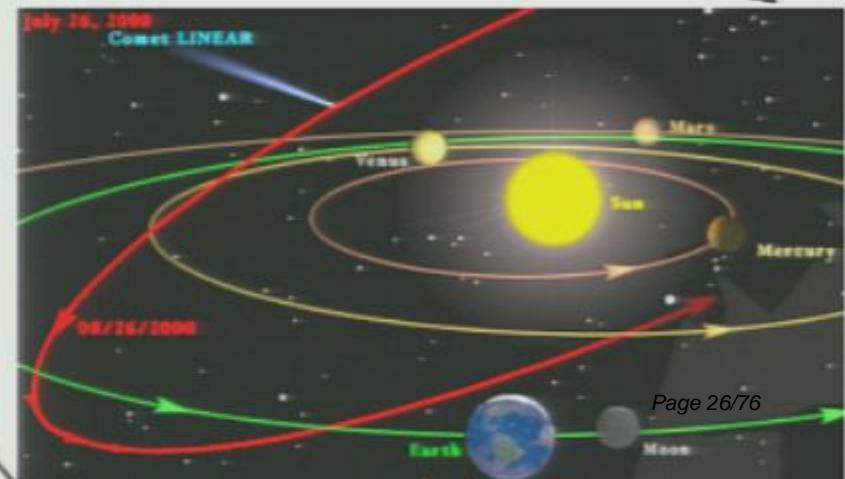
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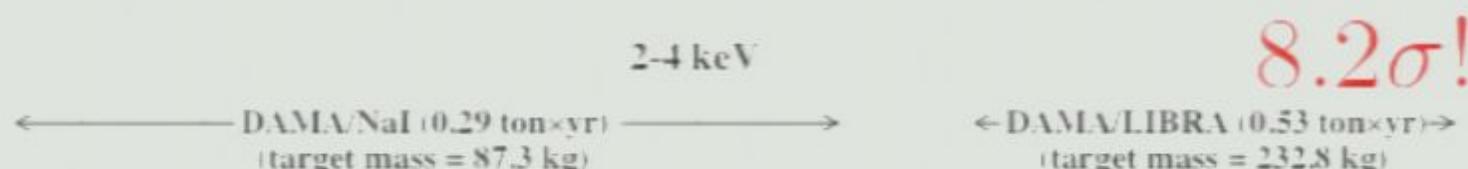
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Residuals (cpd/kg/keV)



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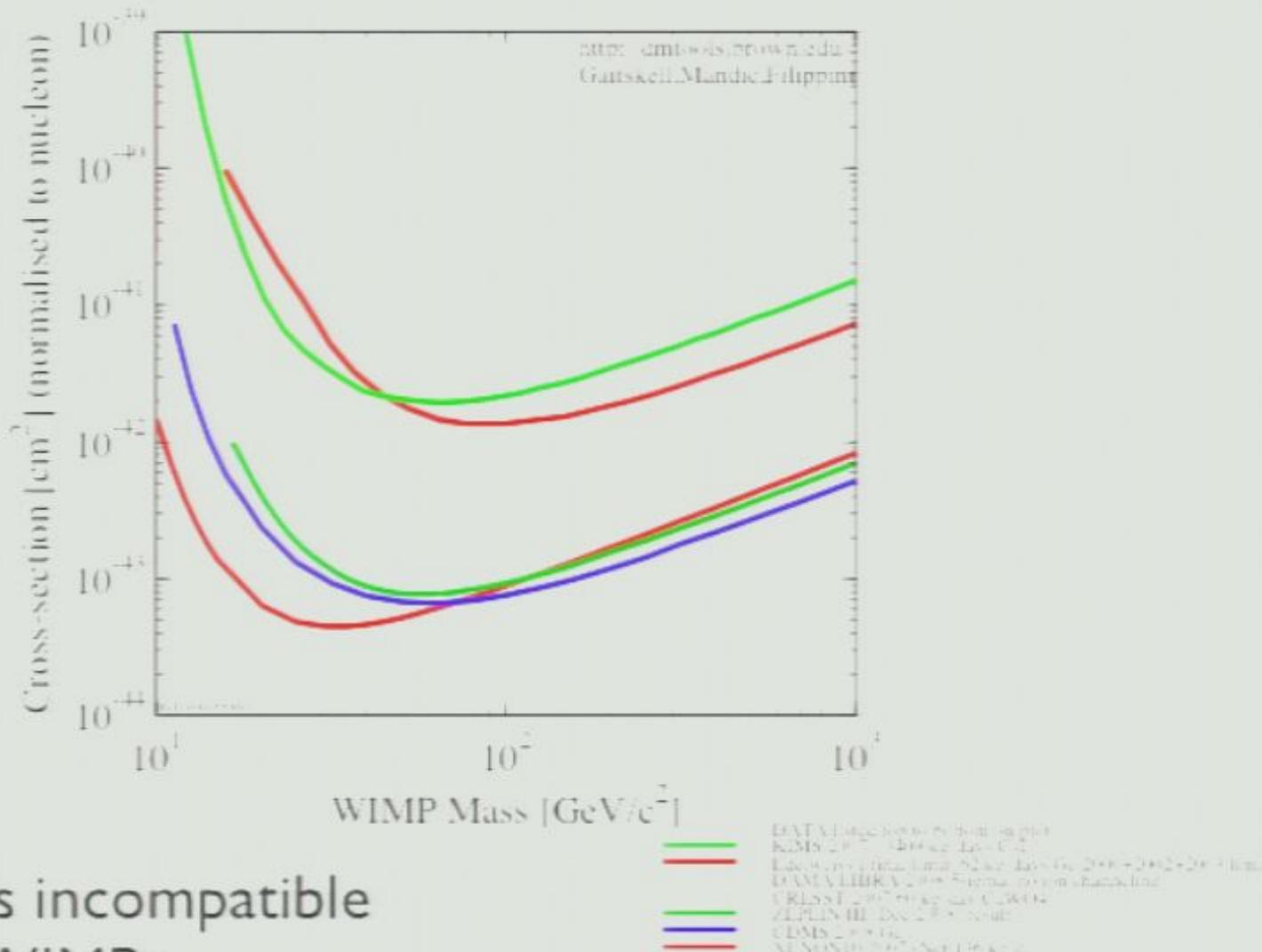
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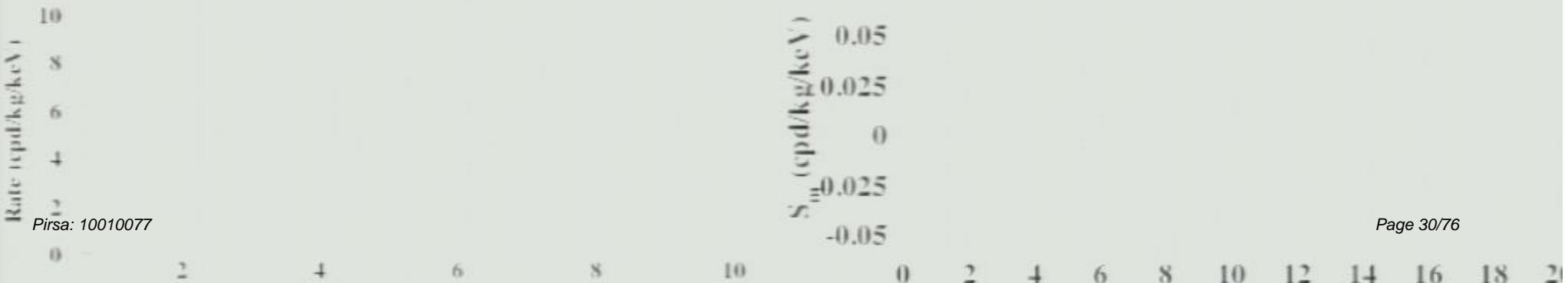


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THE ONE IMPORTANT SLIDE

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$$N_T = N_A / A \quad N_A = 6 \times 10^{26} \text{ kg}^{-1} \quad m_N = A m_p \quad \mu_{N\chi} = \frac{m_N m_\chi}{m_N + m_\chi}$$

σ_N = nuclear cross section

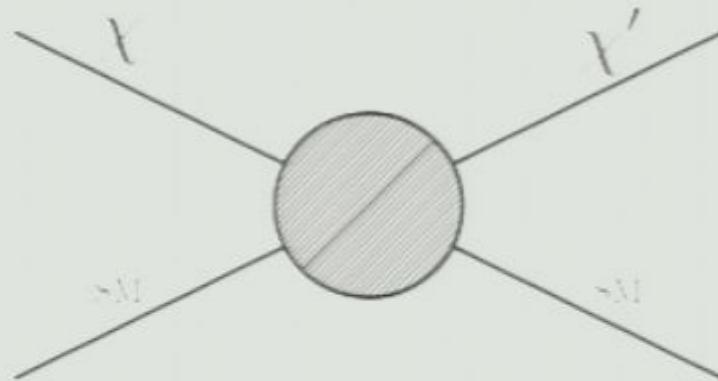
$F(E_R)$ = form factor

Usual case (WIMP)

$$\sigma_N = \frac{(Z f_p + (A - Z) f_n)^2}{f_p^2} \frac{\mu_{N\chi}^2}{\mu_{n\chi}^2} \sigma_p \quad v_{min} = \sqrt{\frac{m_N E_R}{2 \mu_{N\chi}^2}}$$

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



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$$m_\chi - m_{\chi'} = \delta \sim 100 \text{ keV}$$

- Requires “large” momentum exchange to upscatter
- Favours high velocity tail of MB distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
- Recoil spectrum has a peak, unique feature?

[Batell, Pospelov and Ritz]

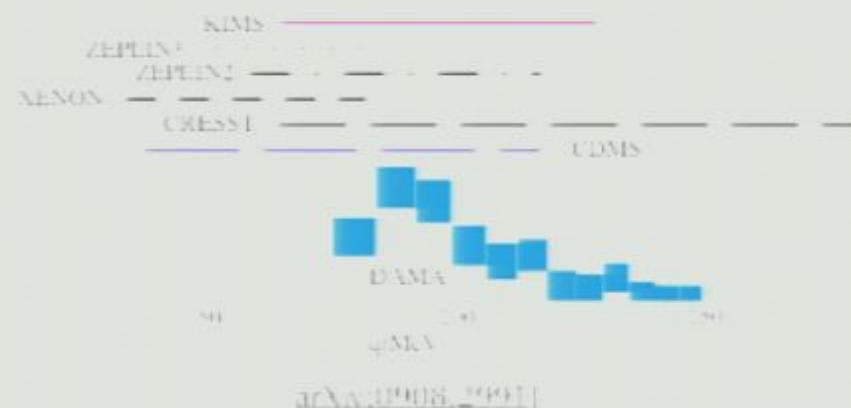
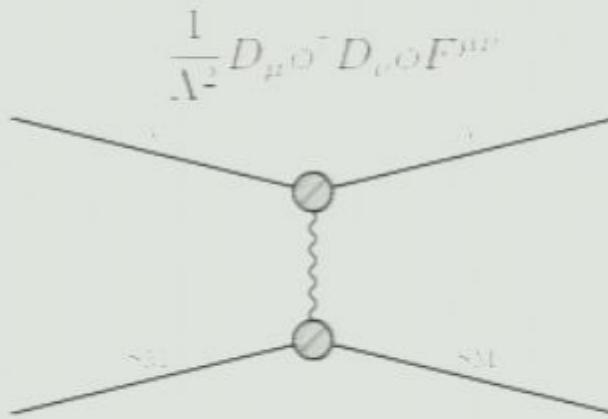
All of the above help to make DAMA consistent with CDMS. Predicts events at other heavy element detectors

Form Factor DM

[Chang, Weiner, Pierce and Feldstein, Fitzpatrick, Katz]

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DM has a form factor, dipole coupling to light gauge boson

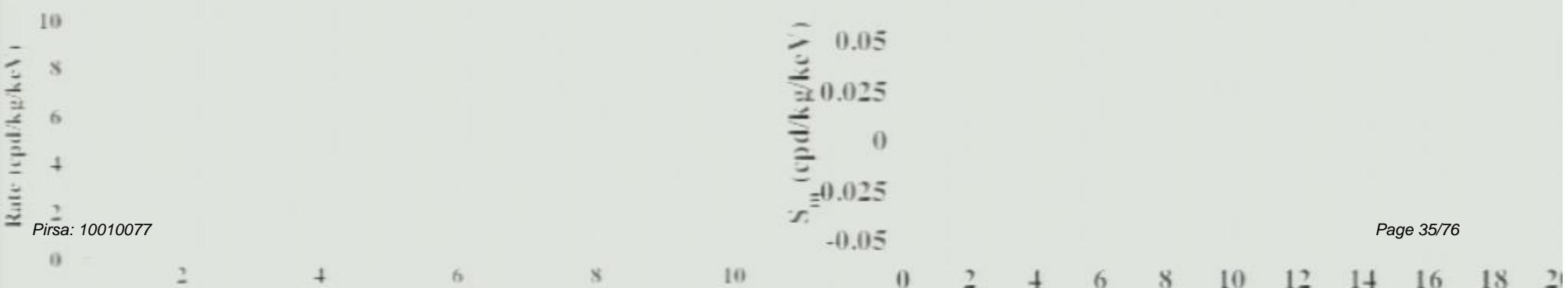


- Form factors suppress certain ranges of recoil energy
- Works best with SD couplings, or non-standard velocity distributions e.g. via Lactea
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- Peak in spectrum at non-zero recoil energy

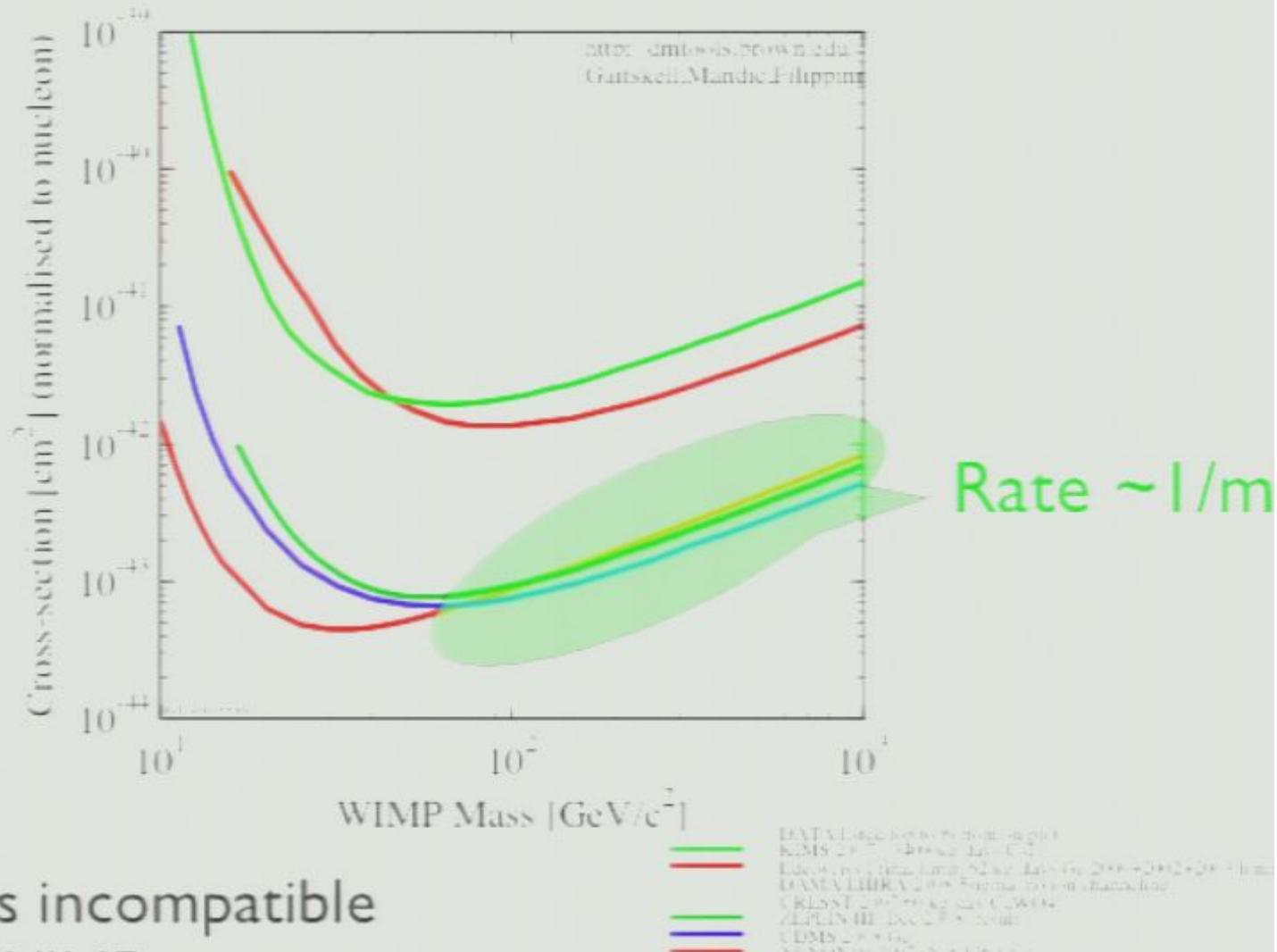
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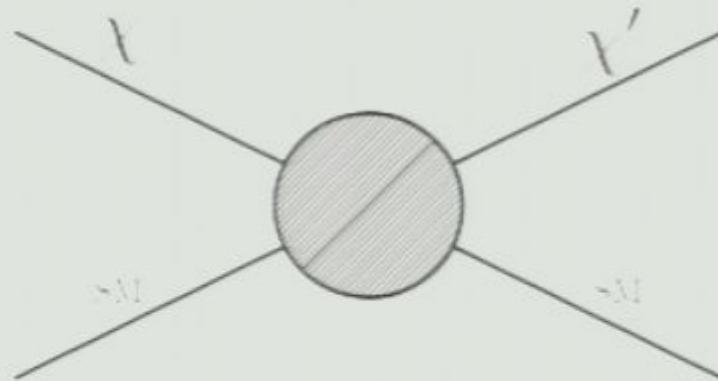
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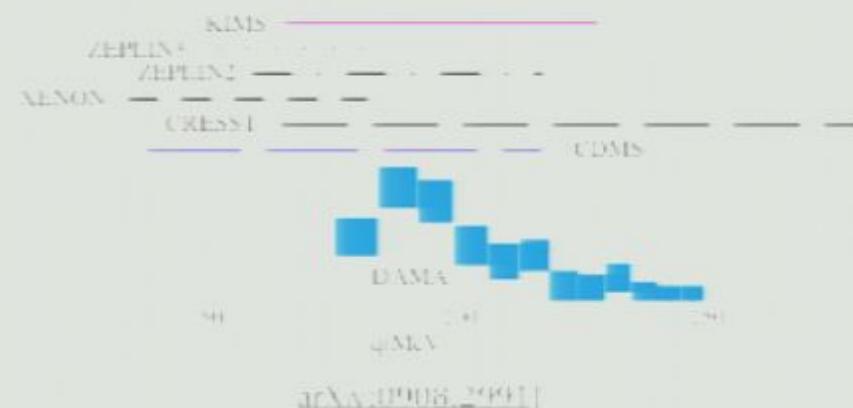
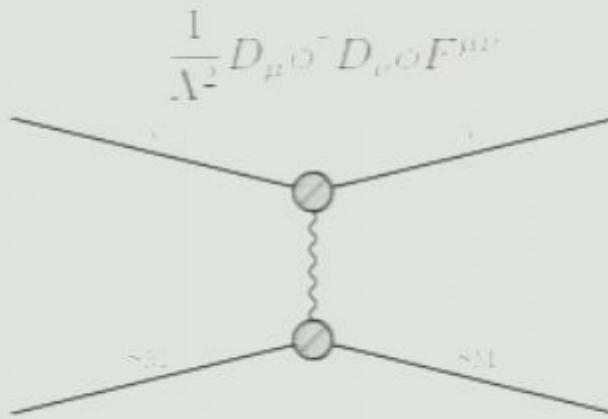
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- Cross section is velocity dependent
- In particular the velocity dependence is “resonant”
- Picks out small range of velocities
- Increases modulation
- In our particular model realisation scattering is highly element dependent



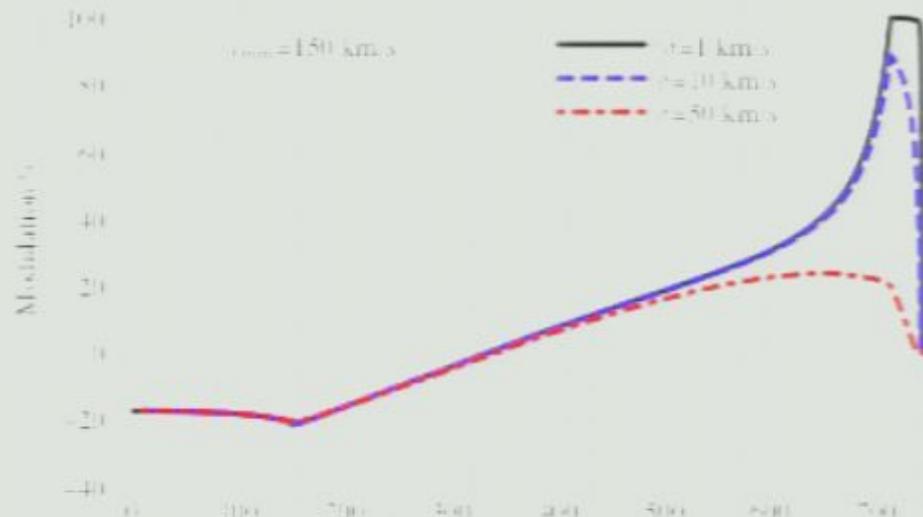
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“Resonant” velocity dependence

$$\sigma_N = \sigma_0 \frac{v_r^2}{v^2} \frac{\delta^2/\pi}{(v^2 - v_r^2)^2 + \delta^4}$$

Leads to increased modulation



A Model

[Pospelov and Ritz]

DM sits in an SU(2) triplet with zero hypercharge, odd under a Z_2

$$\chi = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix}$$

$$\Delta = m_{\chi^\pm} - m_\chi$$

Two sources:

$$\Delta_{e.m} \approx 166 \text{ MeV}$$

$$\frac{1}{\Lambda} (H^\dagger T^a H) (\bar{\chi} T^a \chi)$$

Will need a cancellation such that $\Delta \sim 10 \text{ MeV}$

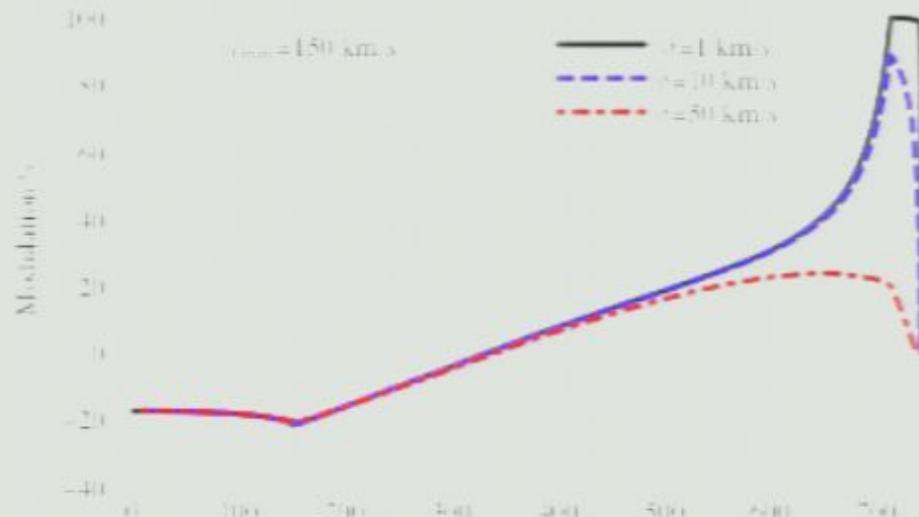
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A Model

Charged states are long-lived.

$$\Gamma \approx \frac{1}{15\pi^3} G_F^2 \Delta^5 \approx \left(\frac{\Delta}{15 \text{ MeV}} \right)^5 \times 2 \times 10^{-13} \text{ eV}$$

Evades BBN constraints

There are Tevatron bounds

$$m_\chi \approx m_{\chi^\pm} \geq 121 \text{ GeV at 95\% C.L.}$$

Thermal relic requires DM mass is $\sim 2 \text{ TeV}$

[Cirelli, Fornengo and Strumia]

Bound state

If the splitting is small enough there may be an accessible nucleus- χ^- bound state

4_N	${}^{23}_{11}Na$	${}^{28}_{14}Si$	${}^{74}_{32}Ge$	${}^{127}_{53}I$	${}^{129}_{54}Xe$	${}^{133}_{55}Cs$	${}^{184}_{74}W$
${}^A_{Z+1}N$	${}^{23}_{12}Mg$	${}^{28}_{15}P$	${}^{74}_{33}As$	${}^{127}_{54}Xe$	${}^{129}_{55}Cs$	${}^{133}_{56}Ba$	${}^{184}_{75}Re$
Δm (MeV)	3.8	13.8	2.1	0.15	0.7	0.01	1.0
S_n (MeV)	13.1	14.5	8.0	7.3	9.6	7.2	6.5
E_b (MeV)	5.8	7.5	13.5	19.1	19.4	19.6	23.3

CDMS: Si, Ge

DAMA: Na, I

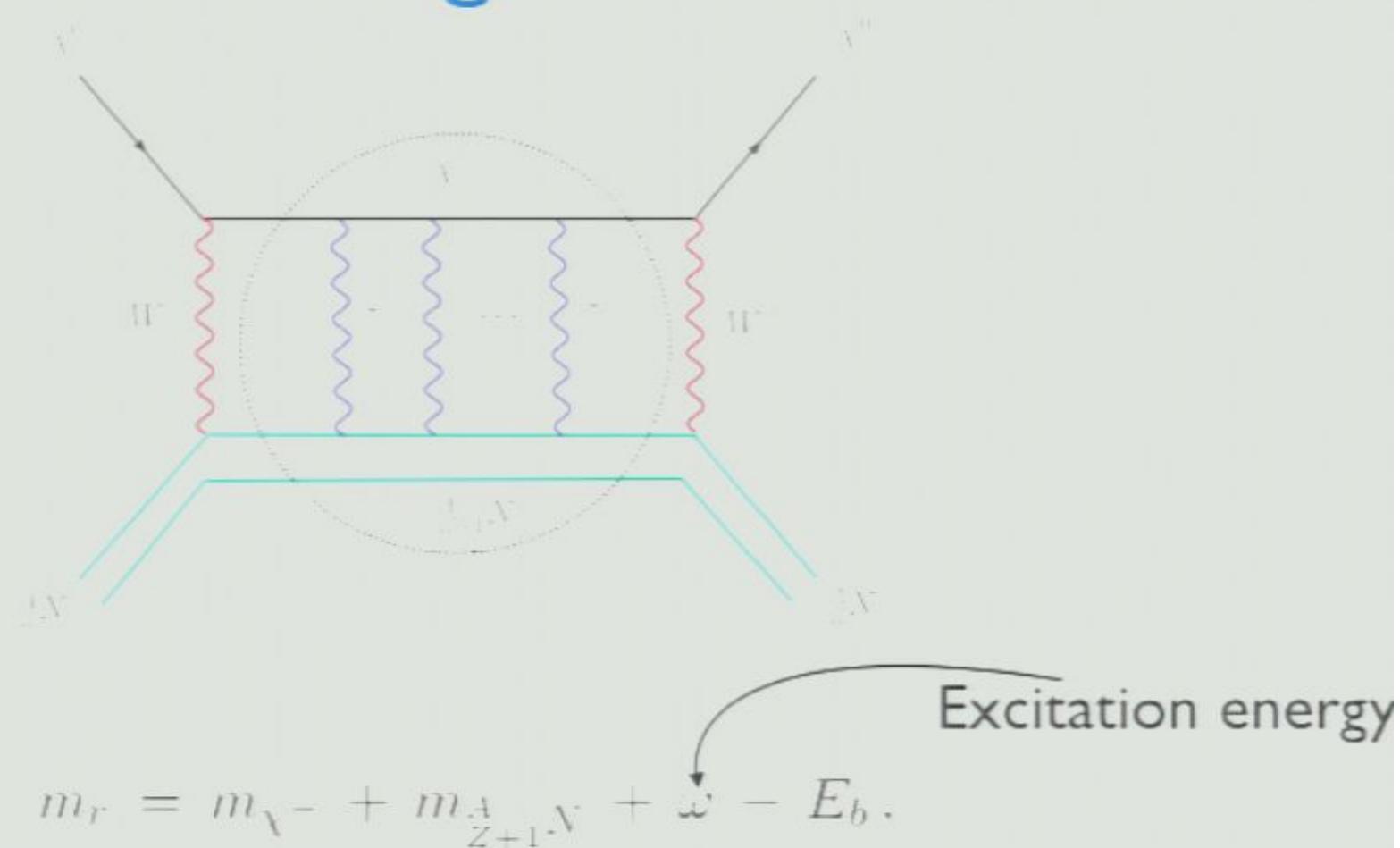
KIMS: Cs,I

Xenon: Xe

Zeplin: Xe

CRESST: Ca,W,O

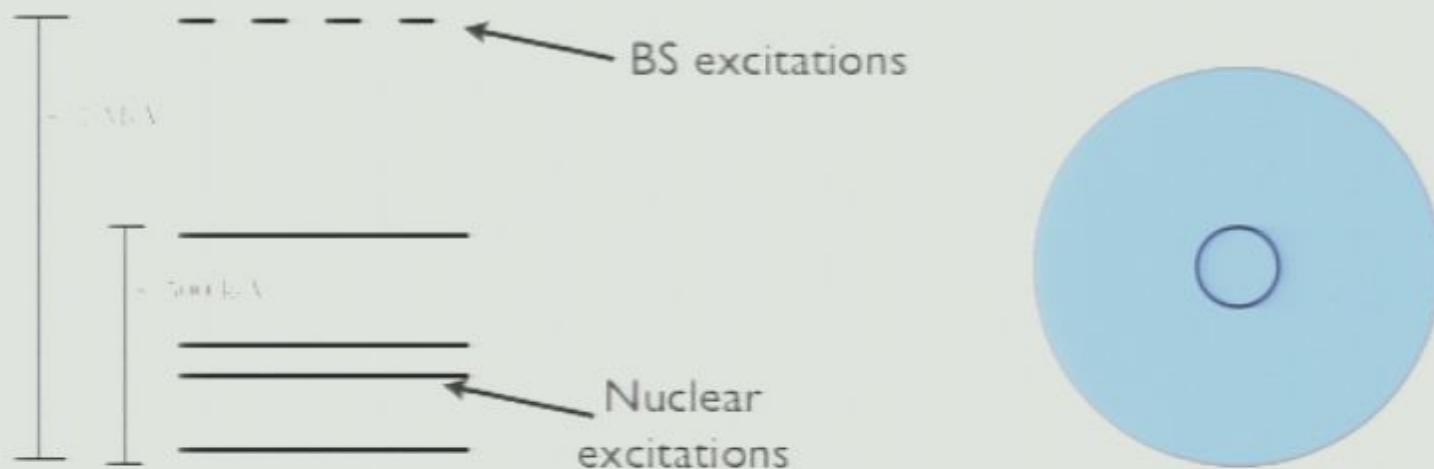
Resonant scattering



Speed of DM needed to hit resonance

$$v_r^2 = \frac{2(\Delta + m_{A_{Z+1}N} - m_{\chi N} + \omega - E_b)}{\mu_{\chi N}}$$

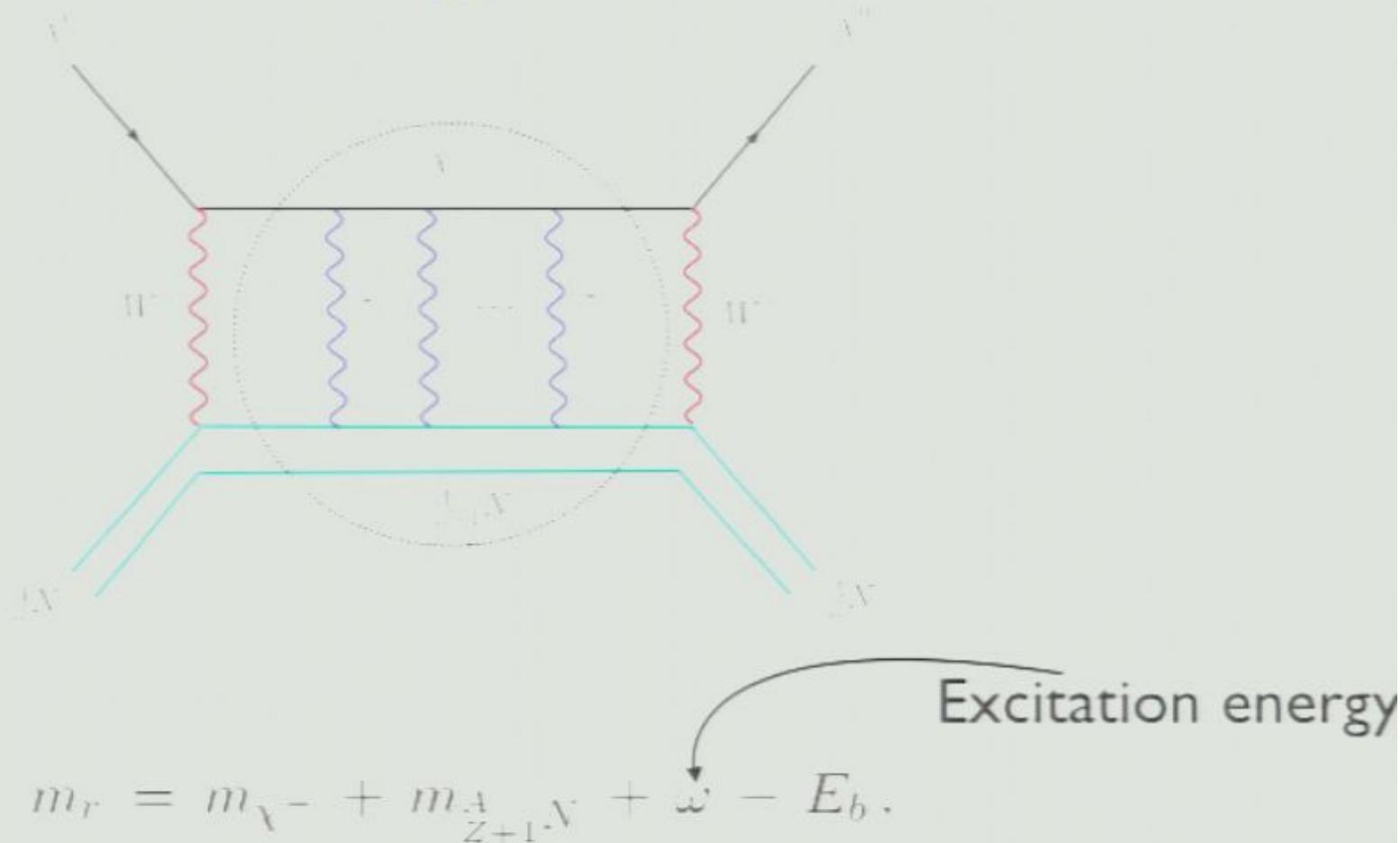
Bound state



Selection rules limit available nuclear levels

Possible decays of bound state depend on details of nuclear transitions

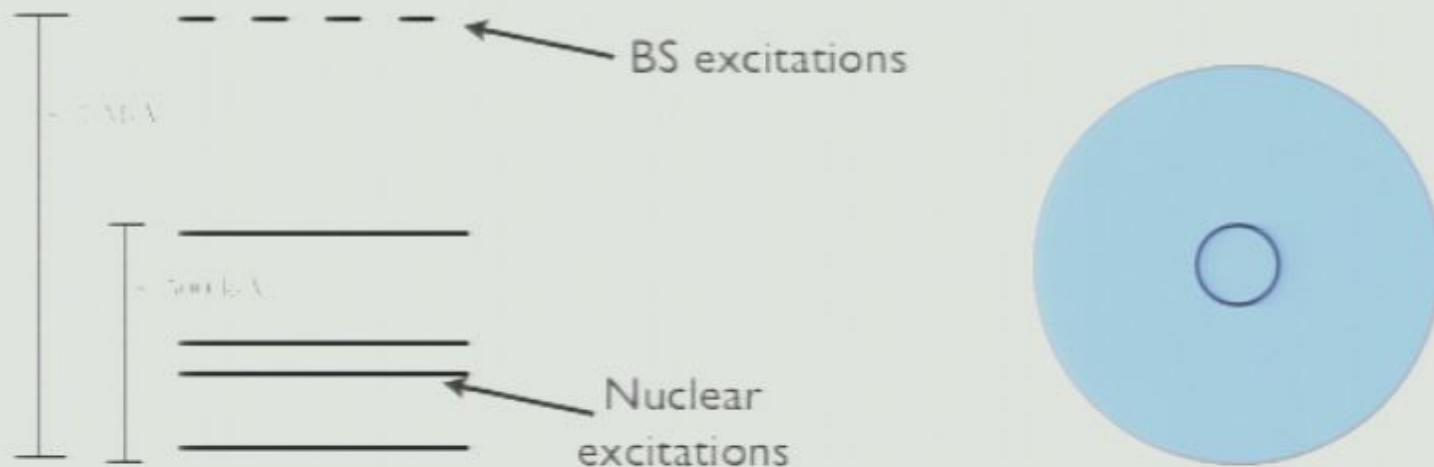
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$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_N}{2 \mu_{N\chi}^2 m_\chi} \int_{v_{min}}^{v_{max}} d^3 \vec{v} \frac{f(\vec{v}, \vec{v}_E)}{v} \sigma_N F^2(E_R)$$

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$$\sigma_N = \frac{2J_r + 1}{(2s_\chi + 1)(2s_N + 1)} \frac{\pi}{k^2} \frac{\Gamma_{r \rightarrow \chi N}^2}{(E - m_r)^2 + \Gamma_{tot}^2/4}$$

In terms of speeds

$$\sigma_N = \sigma_0 \frac{v_r^2}{v^2} \frac{\delta^2/\pi}{(v^2 - v_r^2)^2 + \delta^4} \xrightarrow{\delta \ll v_r} \sigma_0 \delta(v^2 - v_r^2)$$

Normalisations

$$\sigma_0 = \frac{2J_r + 1}{(2s_\chi + 1)(2s_N + 1)} \frac{4\pi^2 \delta^2 \Gamma_{r \rightarrow \chi N}^2}{\mu_{\chi N}^2 v_r^2 \Gamma_{tot}^2}$$
$$\delta^4 = \frac{\Gamma_{tot}^2}{\mu_{\chi N}^2}$$

Can rDM explain DAMA?

In general 4 params: m_χ , v_r , δ , σ_0

For given choice of first 3 vary cross section to get best fit to first 12 bins (2 keVee - 8 keVee) of DAMA modulated

Require inside 90% CL region of DAMA unmodulated *and* KIMS results

Use a quench factor at DAMA of 0.085

Use a quench factor at KIMS of $f_q(E_R) = 0.1 e^{-0.0135 E_R} + 0.06$

For DAMA used energy resolution of $\sigma(E)/E = 0.448/\sqrt{E} + 0.0091$

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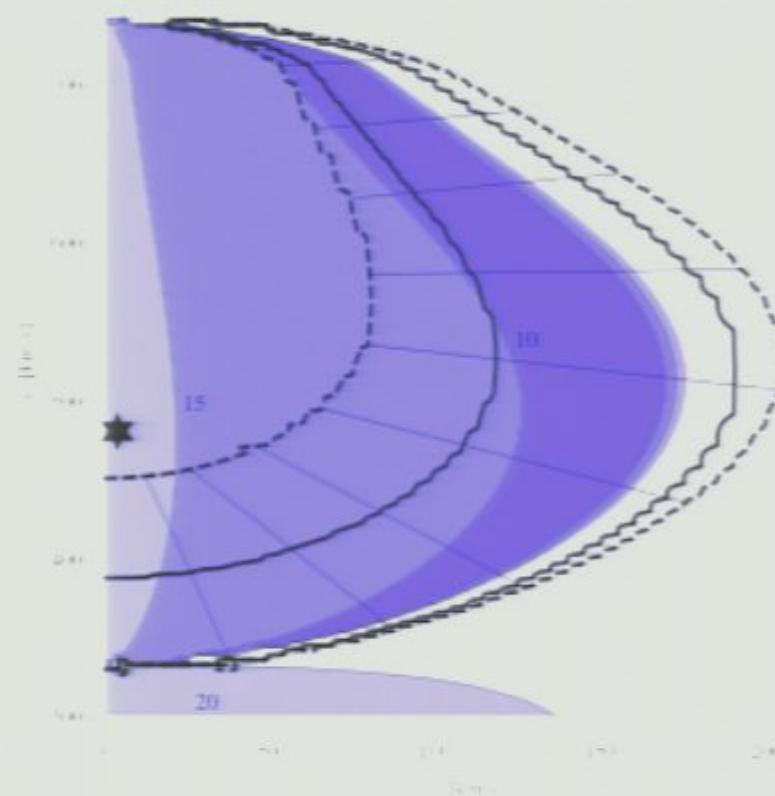
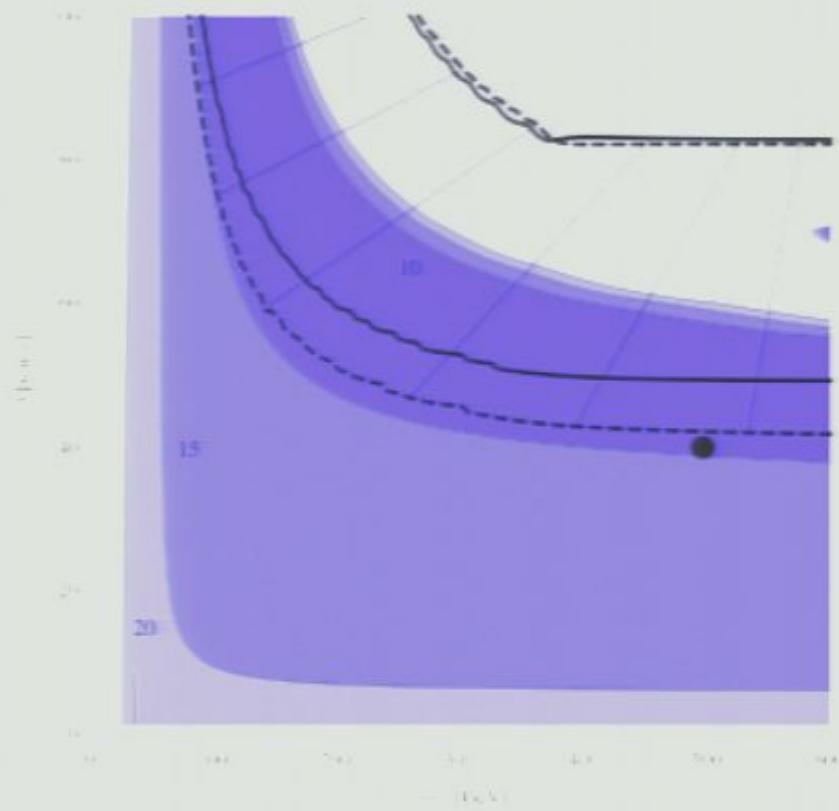
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Can rDM explain DAMA?

$$v_r = 725 \text{ km/s}$$

$$m_\chi = 500 \text{ GeV}$$



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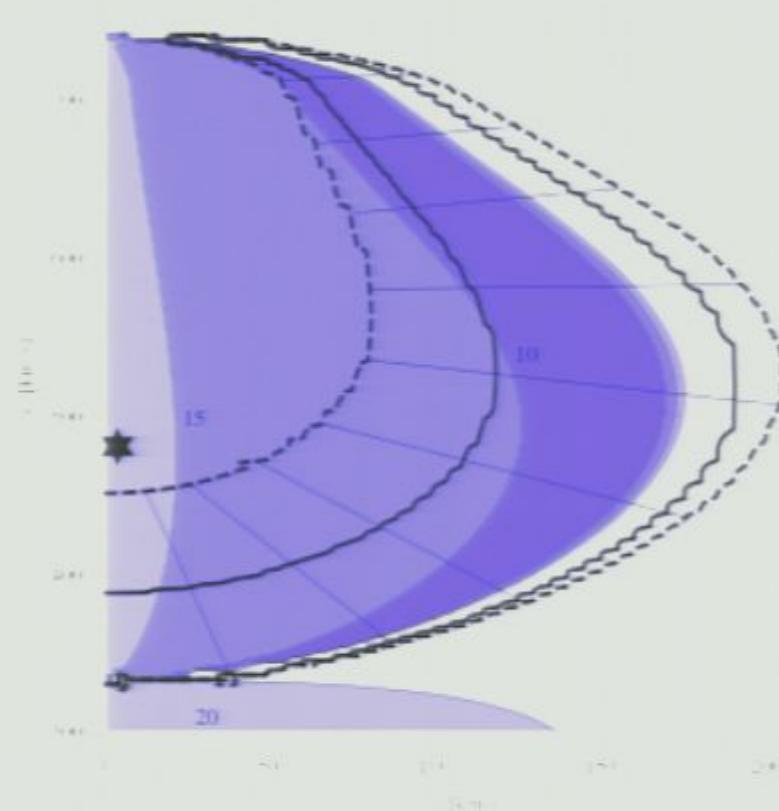
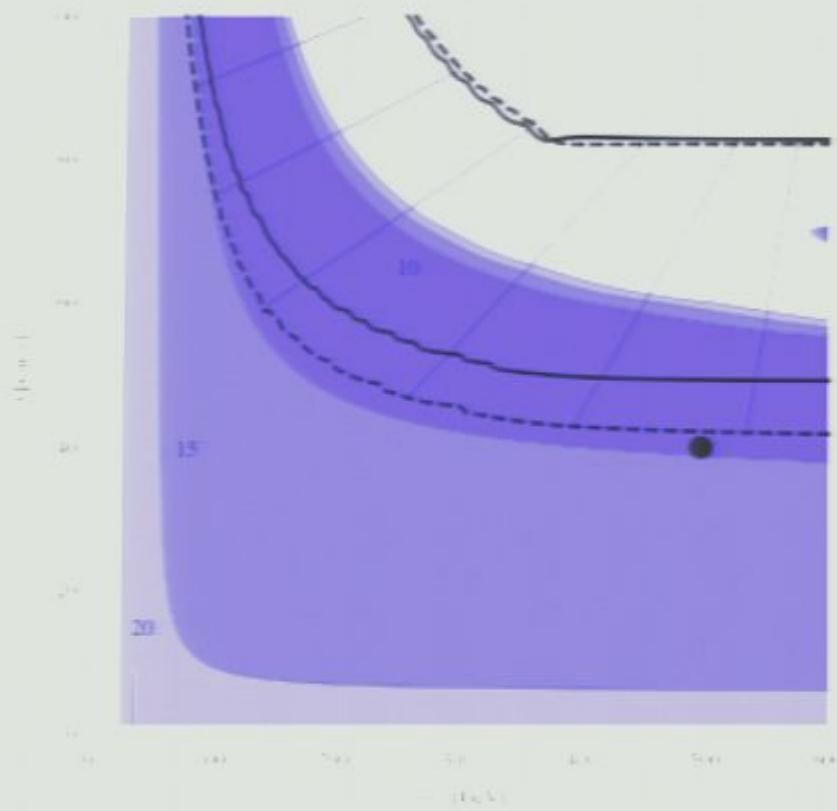
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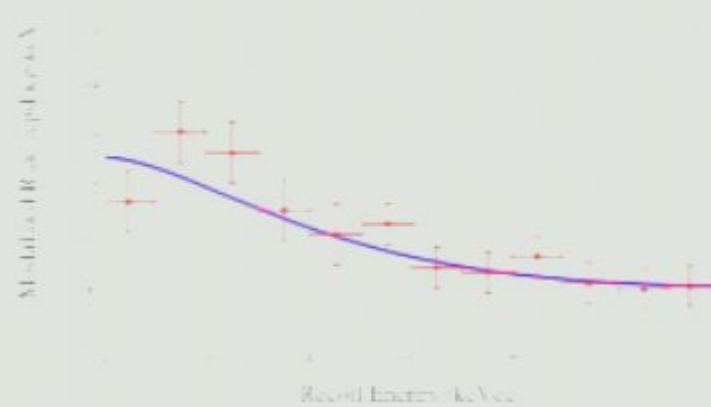
Can rDM explain DAMA?

$$v_r = 725 \text{ km/s}$$

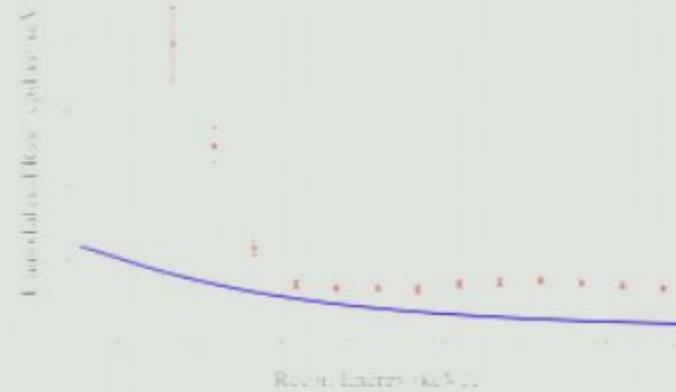
$$m_\chi = 500 \text{ GeV}$$



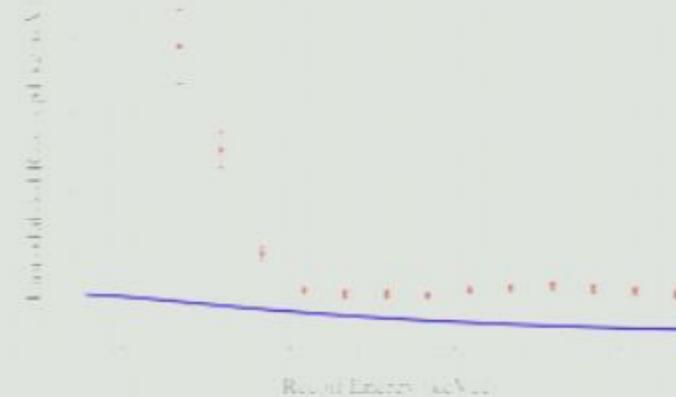
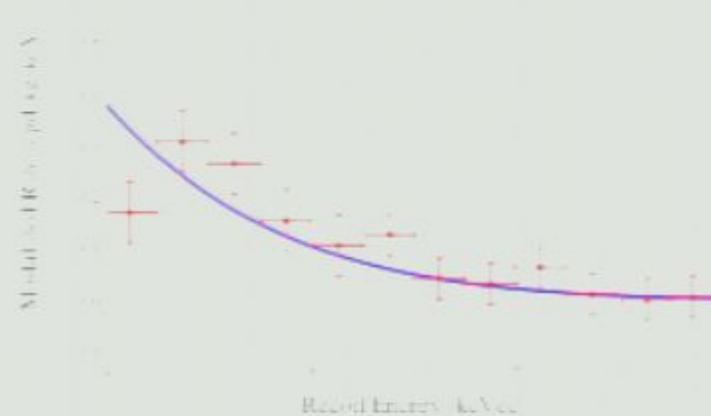
Can rDM explain DAMA?



$m_\chi = 500$ GeV, $\sigma_0 = 1.34$ pb, $v_r = 725$ km/s and $\delta = 40$ km/s.



$$\chi^2 = 9.5.$$



$$\chi^2 = 15.2$$

Details of Element Dependence

Decay possibilities of resonance:

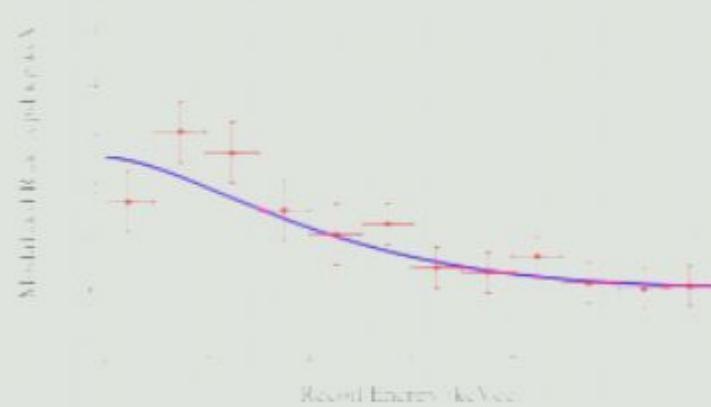
1. Falls apart to constituents
2. Photon emission
3. Photon emission and fall apart
4. Neutron emission

Features:

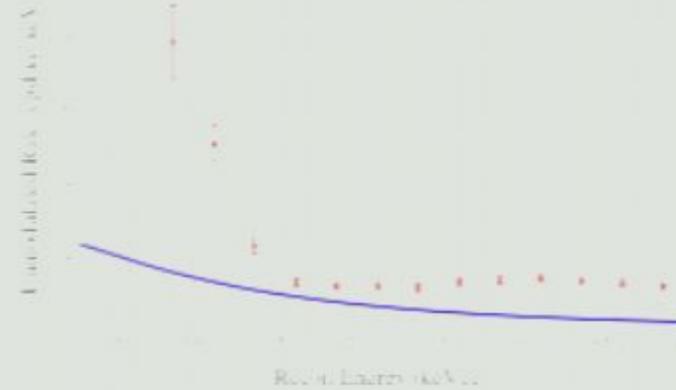
1. Very narrow, if resonance in ground state only possibility
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4. DM remains bound to nucleus, recoil spectrum is higher energy than usually searched for

Which occurs depends on details of nuclear physics, and
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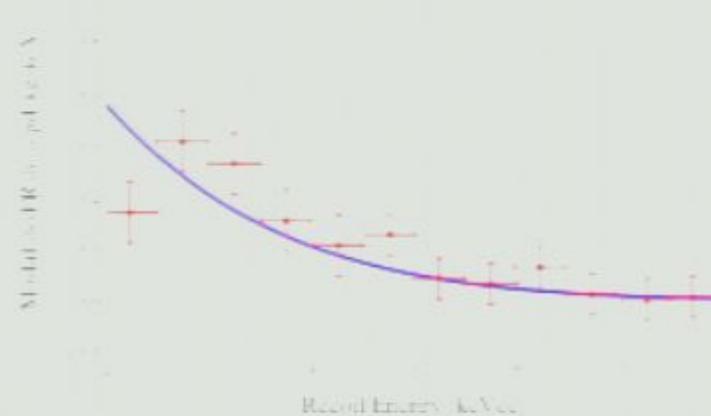
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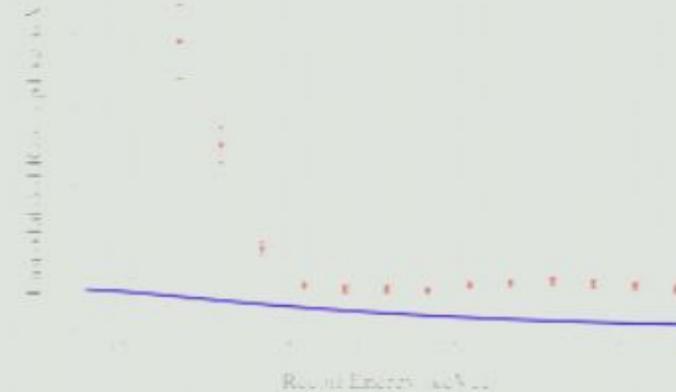
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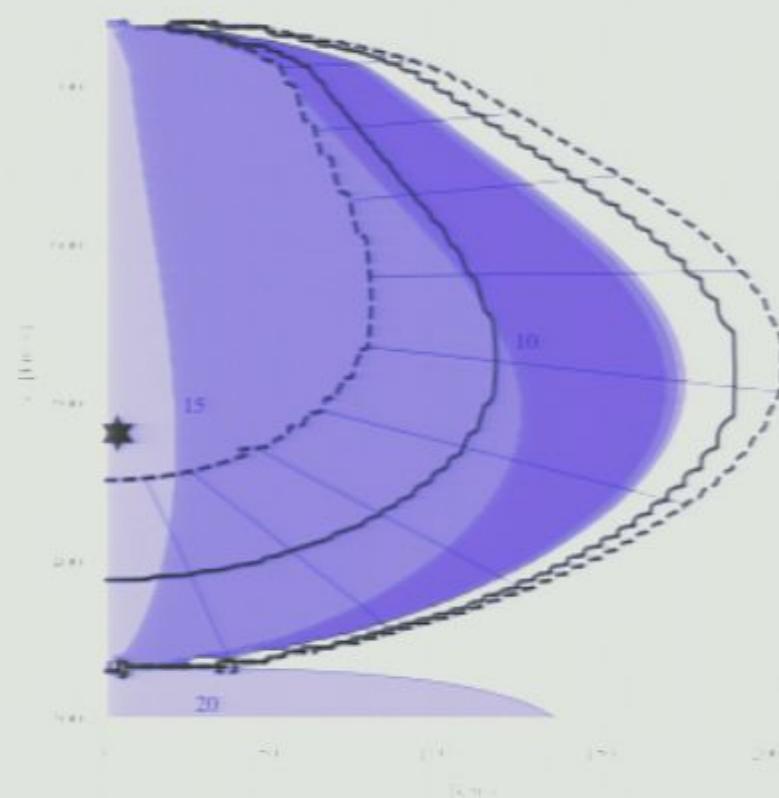
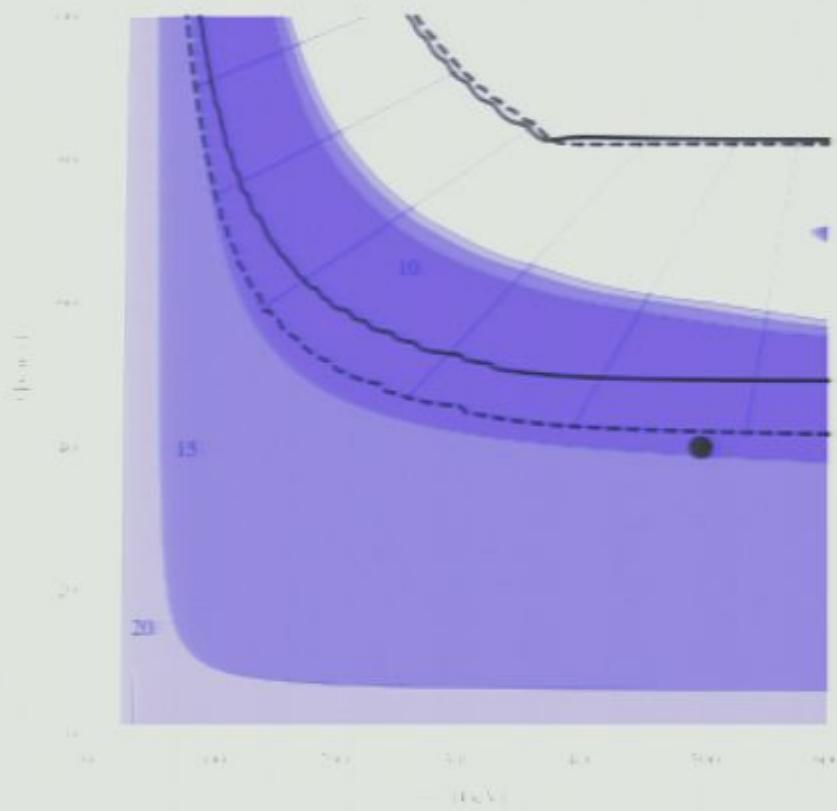
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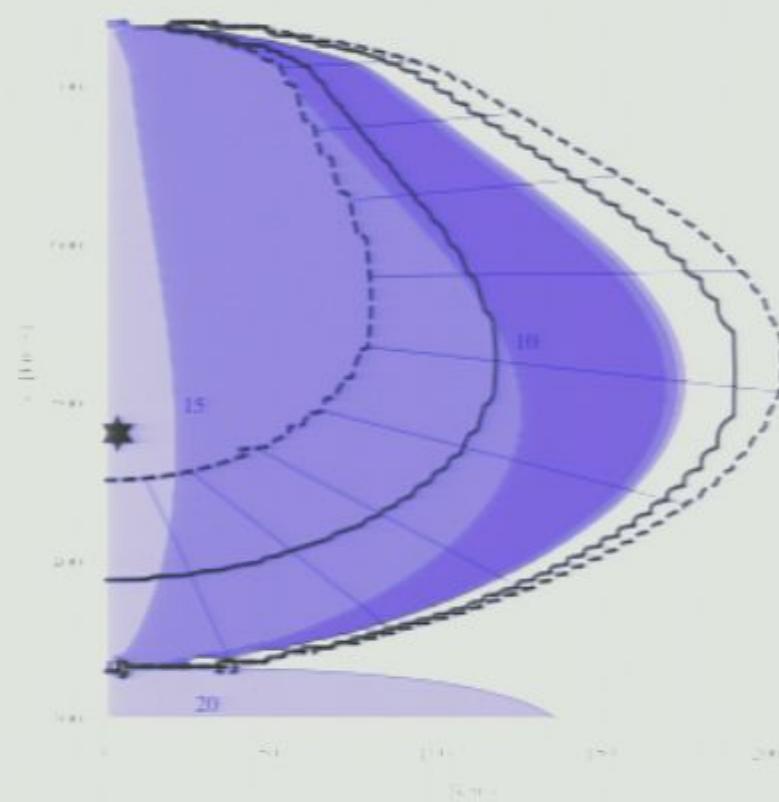
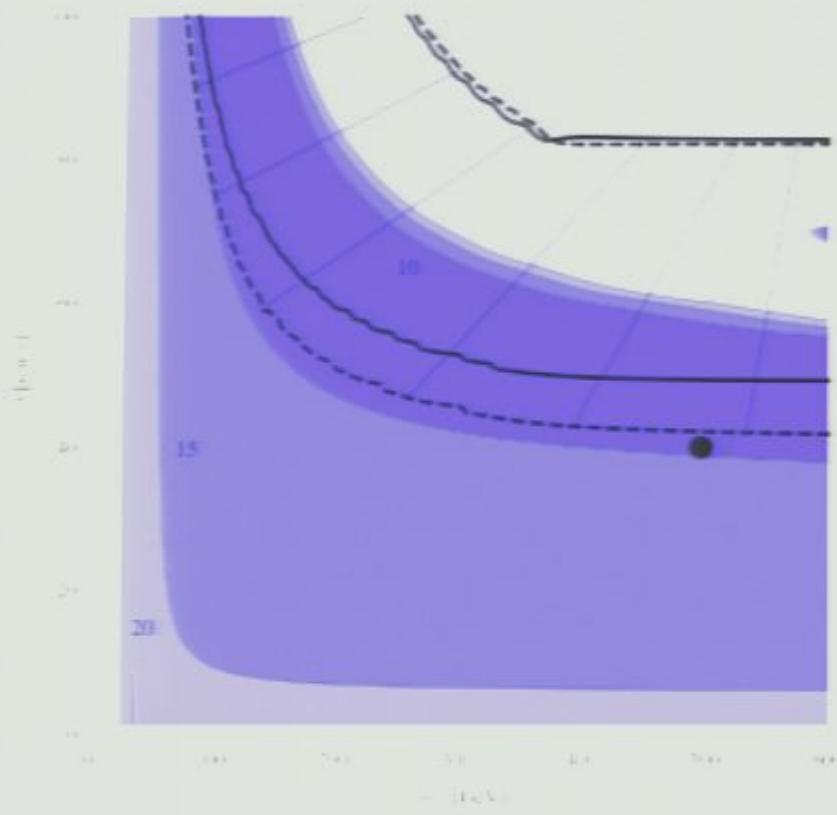
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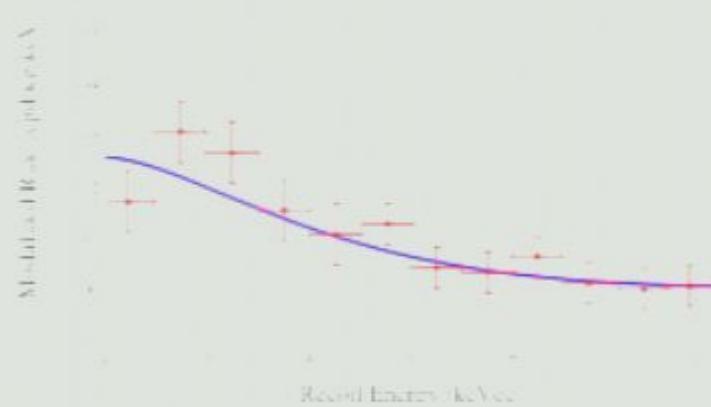
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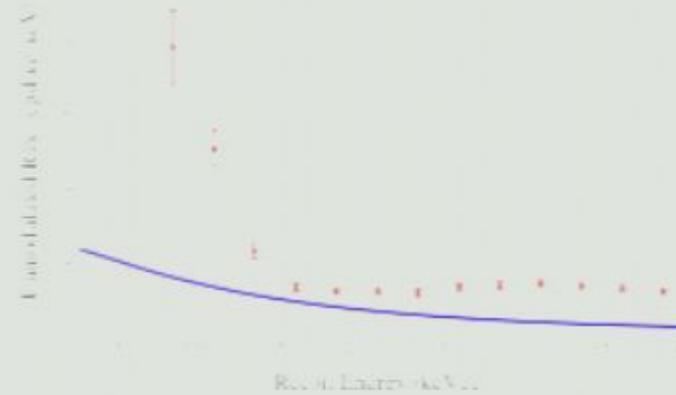
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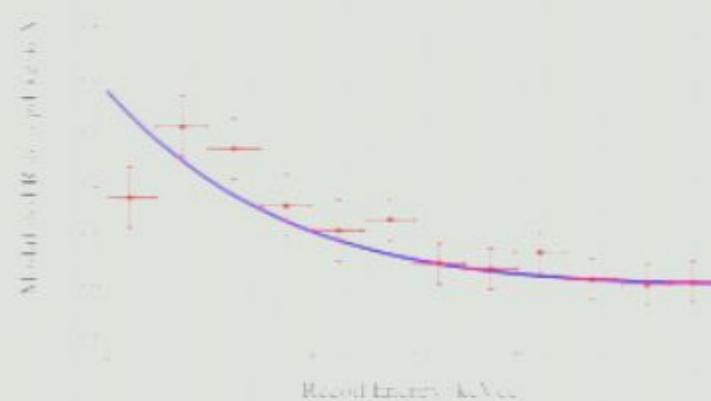
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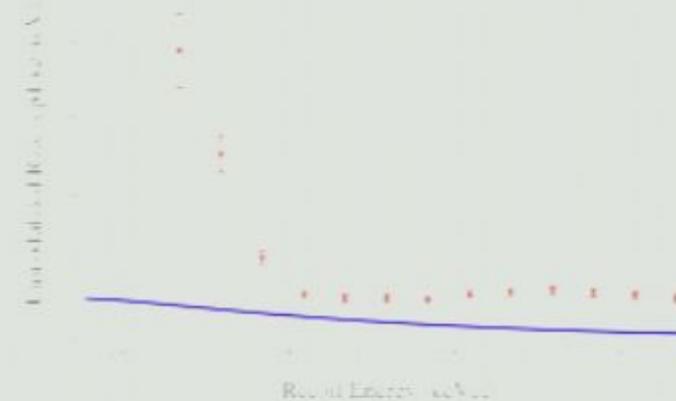
$m_\chi = 500 \text{ GeV}$, $\sigma_0 = 1.34 \text{ pb}$, $v_r = 725 \text{ km/s}$ and $\delta = 40 \text{ km/s}$.



$$\chi^2 = 9.5.$$

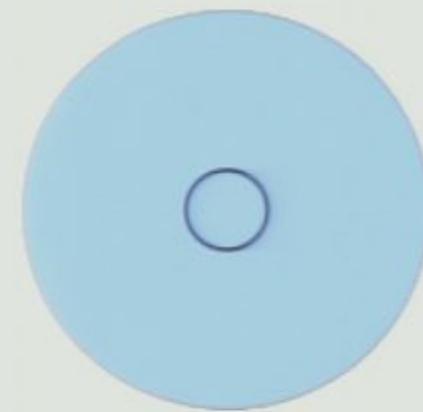
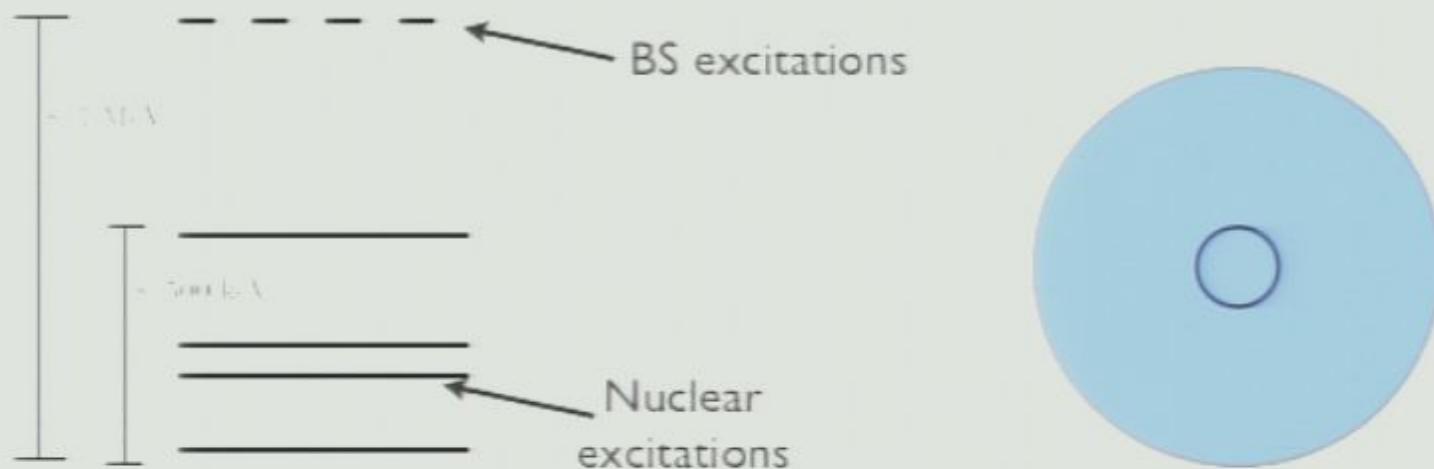


$m_\chi = 500 \text{ GeV}$, $\sigma_0 = 0.025 \text{ pb}$, $v_r = 170 \text{ km/s}$ and $\delta = 0.075 \text{ km/s}$.



$$\chi^2 = 15.2$$

Bound state



Selection rules limit available nuclear levels

Possible decays of bound state depend on details of nuclear transitions

Bound state

If the splitting is small enough there may be an accessible nucleus- χ^- bound state

$^{23}_Z N$	$^{23}_{11} Na$	$^{28}_{14} Si$	$^{74}_{32} Ge$	$^{127}_{53} I$	$^{129}_{54} Xe$	$^{133}_{55} Cs$	$^{184}_{74} W$
$^{A+1}_Z N$	$^{23}_{12} Mg$	$^{28}_{15} P$	$^{74}_{33} As$	$^{127}_{54} Xe$	$^{129}_{55} Cs$	$^{133}_{56} Ba$	$^{184}_{75} Re$
Δm (MeV)	3.8	13.8	2.1	0.15	0.7	0.01	1.0
S_n (MeV)	13.1	14.5	8.0	7.3	9.6	7.2	6.5
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CDMS: Si, Ge

DAMA: Na, I

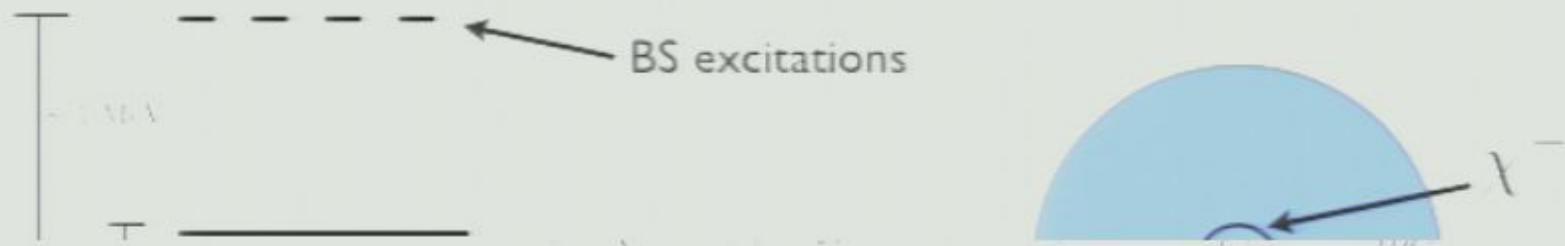
KIMS: Cs,I

Xenon: Xe

Zeplin: Xe

CRESST: Ca,W,O

Bound state



In terms of speeds

$$\sigma_N = \sigma_0 \frac{v_r^2}{v^2} \frac{\delta^2/\pi}{(v^2 - v_r^2)^2 + \delta^4} \xrightarrow{\delta \ll v_r} \sigma_0 \delta(v^2 - v_r^2)$$

Normalisations $\sigma_0 = \frac{2J_c + 1}{(2s_\chi + 1)(2s_N + 1)} \frac{4\pi^2 \delta^2 \Gamma_{c \rightarrow \chi N}^2}{\mu_{\chi N}^2 v_r^2 \Gamma_{tot}^2}$ $\delta^4 = \frac{\Gamma_{tot}^2}{\mu_{\chi N}^2}$

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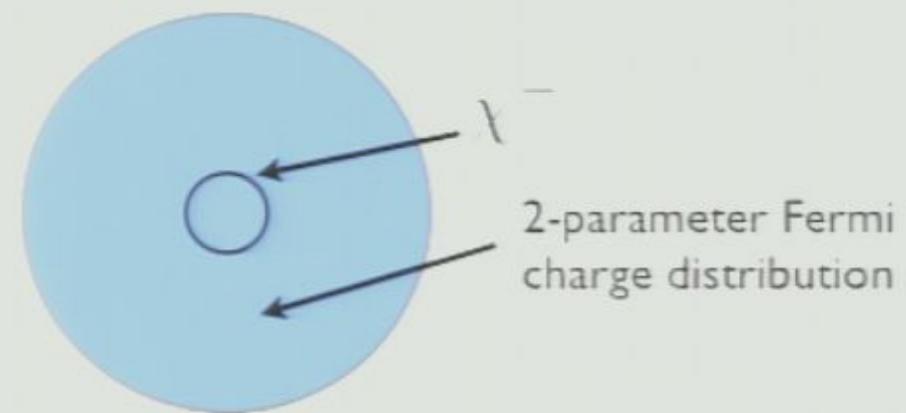
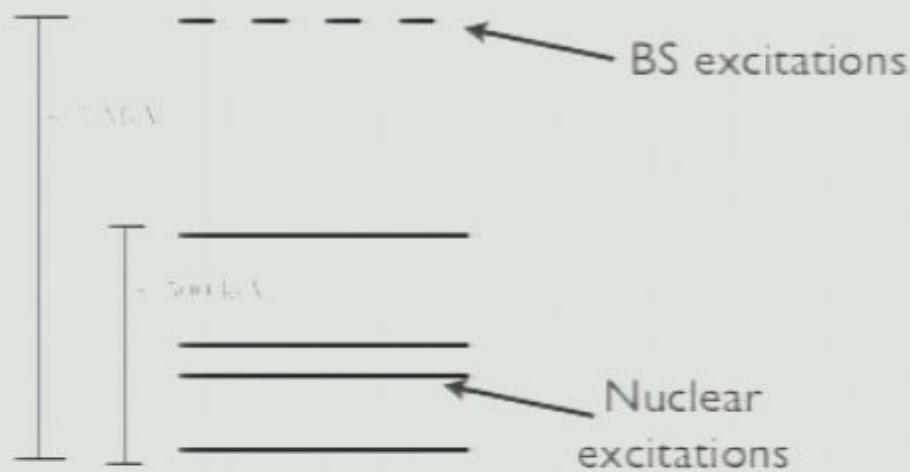
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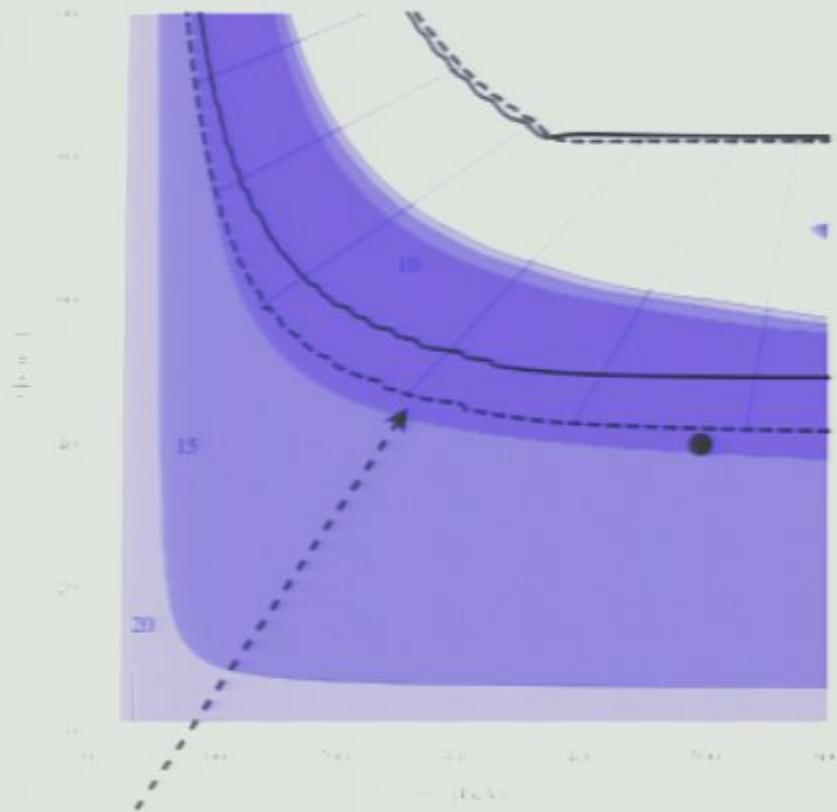
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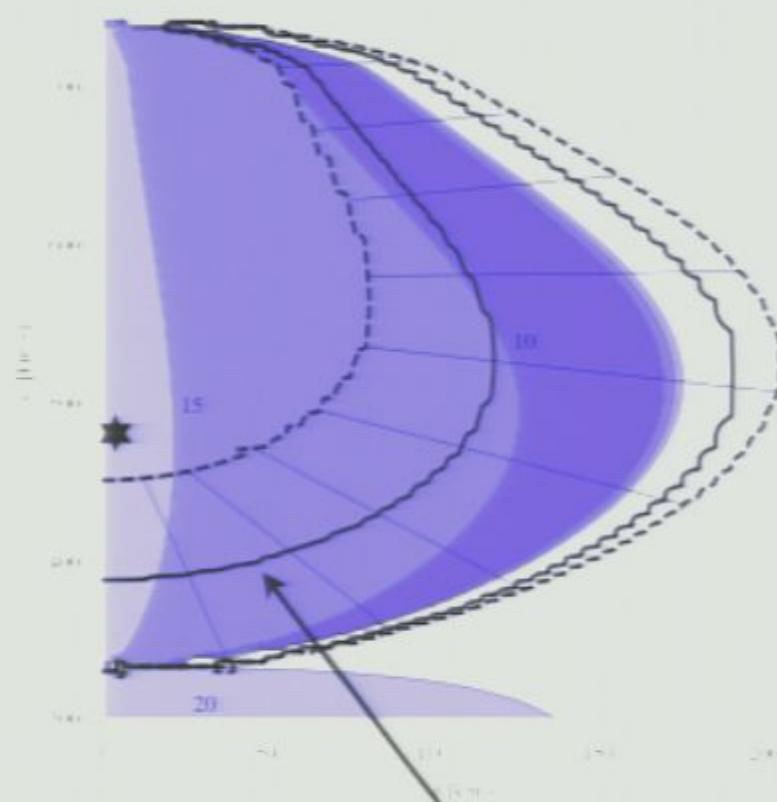
Can rDM explain DAMA?

$$v_r = 725 \text{ km/s}$$

$$m_\chi = 500 \text{ GeV}$$



KIMS 4 crystal average,
90% CL



DAMA unmodulated 90%
CL

Details of Element Dependence

Decay possibilities of resonance:

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2. Photon emission
3. Photon emission and fall apart
4. Neutron emission

Features:

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$\Delta \gtrsim 11$ MeV no events at CDMS (Si, Ge)

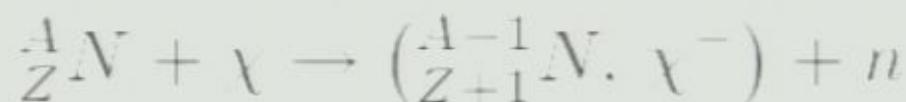
$\Delta \lesssim 16$ MeV neutron emission at CRESST (W)

KIMS and DAMA both contain iodine

- Xenon based experiments like ZEPLIN and XENON may have no resonance, or may have photon signal.
- Data was taken from Oct.-Feb.
- New data soon?

DM capture by heavy elements

Heavy elements with high binding energy may be capturing DM by neutron emission



Most heavy isotope searches are for light elements, very few for heavy elements

$$f_X = \langle \sigma v \rangle n_\chi \tau \approx 6 \times 10^{-13} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}} \right) \left(\frac{\tau}{10^9 \text{ yrs}} \right) \left(\frac{500 \text{ GeV}}{m_\chi} \right)$$

$$\rightarrow f_X \approx 10^{-12}$$

Present bounds for Au and Fe

[D Javorsek et al.]

Outlook

- Many possible DM candidates, each with different (non-standard) signals
- rDM has several unique features
 - Picks out only a narrow window of DM velocities, increases modulation
 - If resonance is e.m. bound state with nucleus experimental signatures become very element dependent
- Potential for no events at CDMS, but events at DAMA, KIMS
- Possibility of photon lines, DM capture
- Correlations with heavy element searches
- Future results from XENON100, etc much awaited.