Inelastic, Exothermic, & Magnetic Dark Matter

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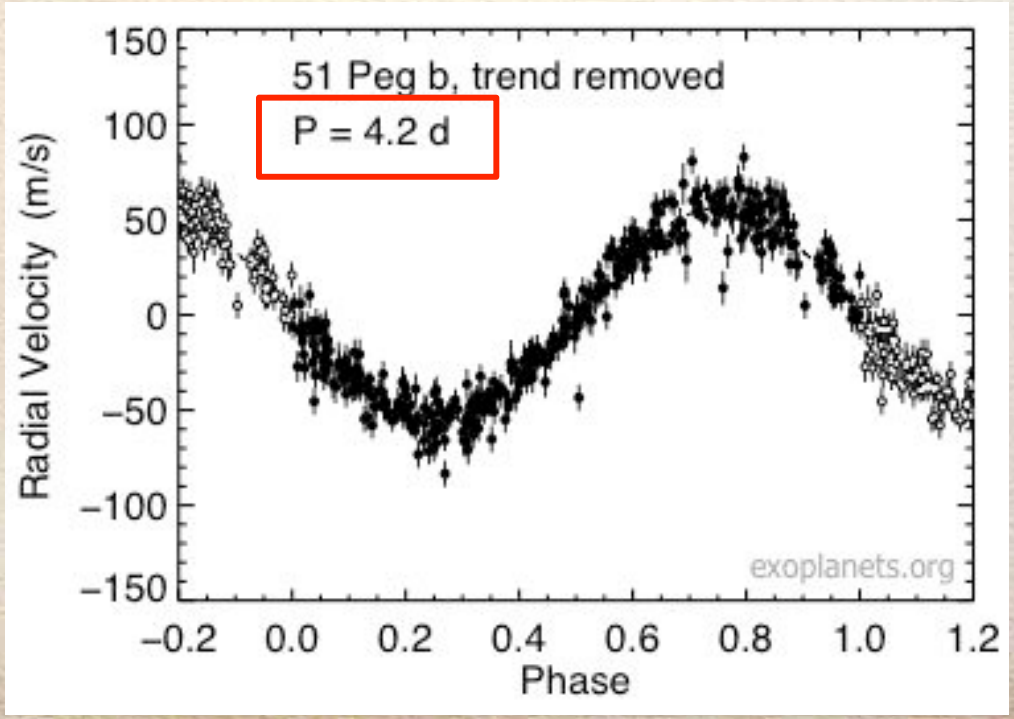
Succinct Statements

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."

Exoplanet Searches

People have been searching for exoplanets for many years. The most common detection scheme involved the search for temporal oscillations in the radial velocity of the parent star.

When Mayor and Queloz announced the discovery of the first planet around a main-sequence star, it had pretty different characteristics than what was predicted/expected by the planet formation theories at the time.



Radial velocity of 51 Pegasi over time, caused by the orbit of an unseen companion.

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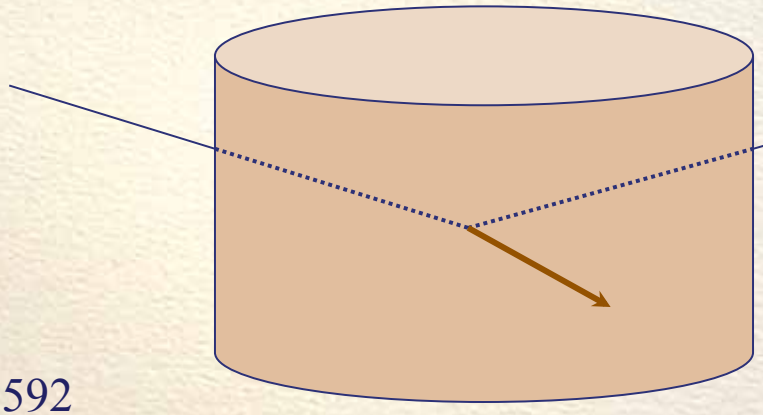
DM Direct Detection

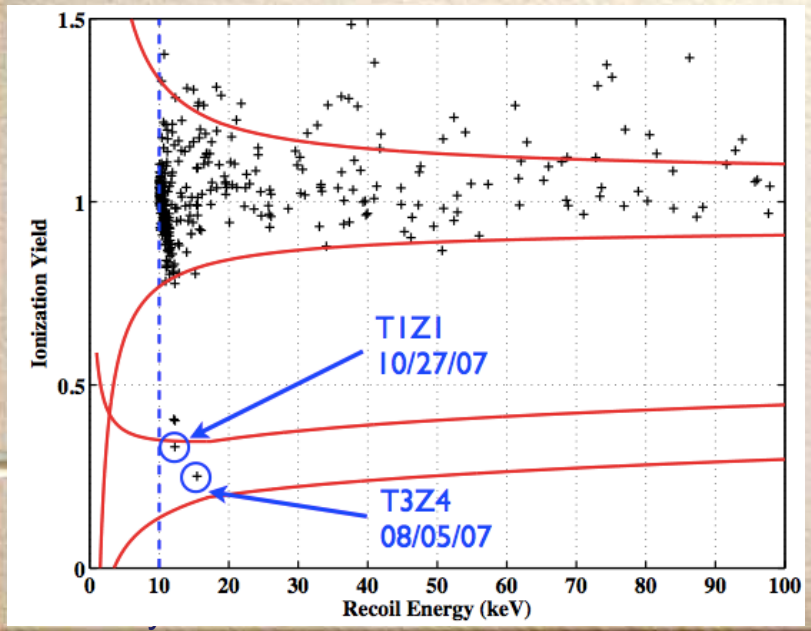
Dark Matter entering target



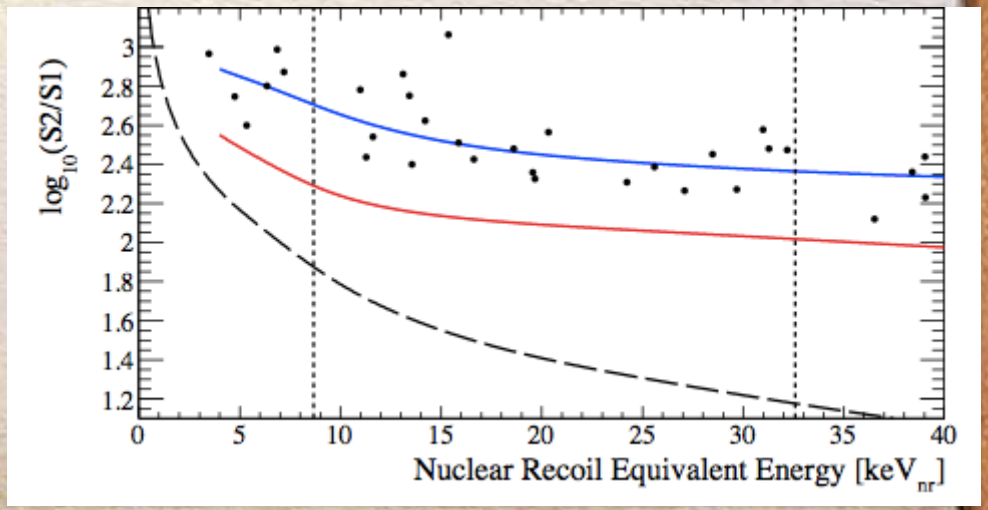
Dark Matter leaves

Nuclear recoil event

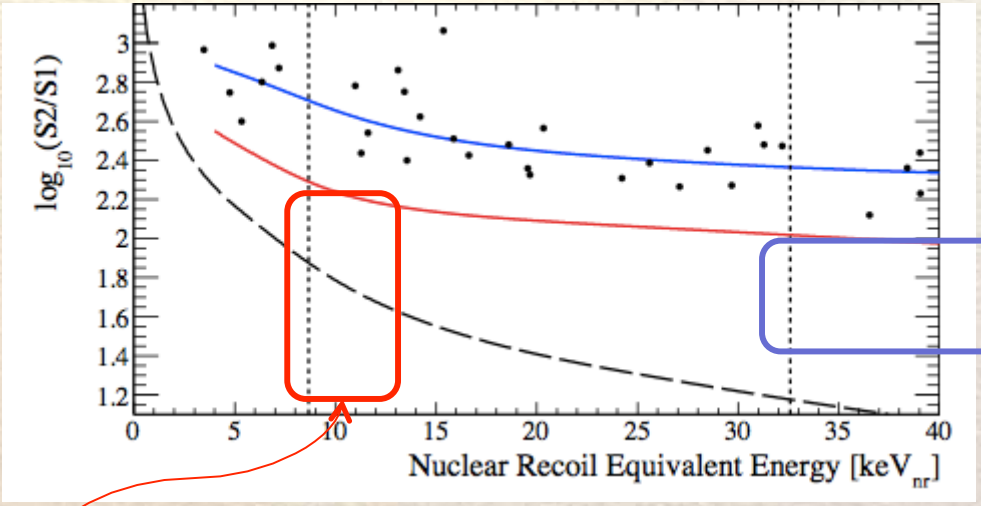
CDMS: 0912.3592



XENON100 : 1005.0380



Are we looking in the right place?



Elastic Scattering

Inelastic,
Exothermic,
Magnetic DM

Event Rate

$$\frac{dR}{dE_R} = N_{\rm T}\frac{\rho_{\rm DM}}{M_{\rm DM}}\int_{v_{\rm min}}^{v_{\rm max}} d^3v\, v f(v) \frac{d\sigma}{dE_R}$$

astrophysics

Particle physics

I will concentrate on the particle physics.

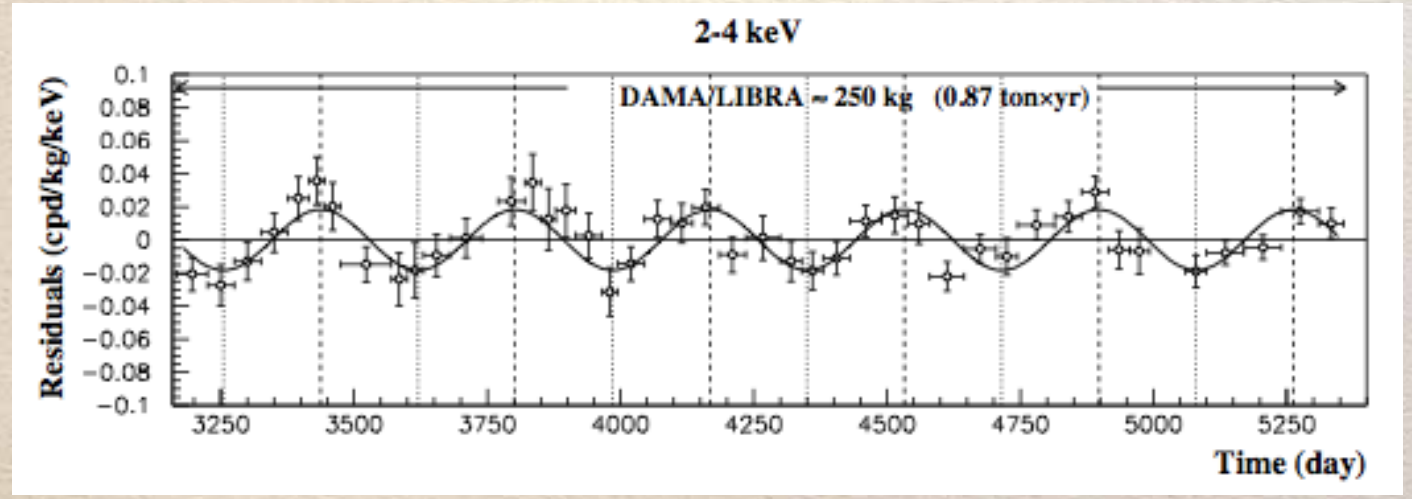
It is important to keep in mind that we have no empirical knowledge of the DM distribution in our immediate environment except for its mass density.

DAMA

.....

If you can bear to hear the truth you've spoken
twisted by knaves to make a trap for fools,
.....you'll be a Man my son!

(from "IF" by R. Kipling)



How to Reconcile

- Electron scattering
- Low mass WIMP – Na scattering
- Channeling
- Inelastic DM
- Resonant DM (Fox and Bai), Luminous DM (Harnik et al) , and etc.

Alternatives

I would like to discuss the following alternatives and their associated signatures:

- Inelastic DM
- Magnetic Inelastic DM
- Exothermic or Metastable DM

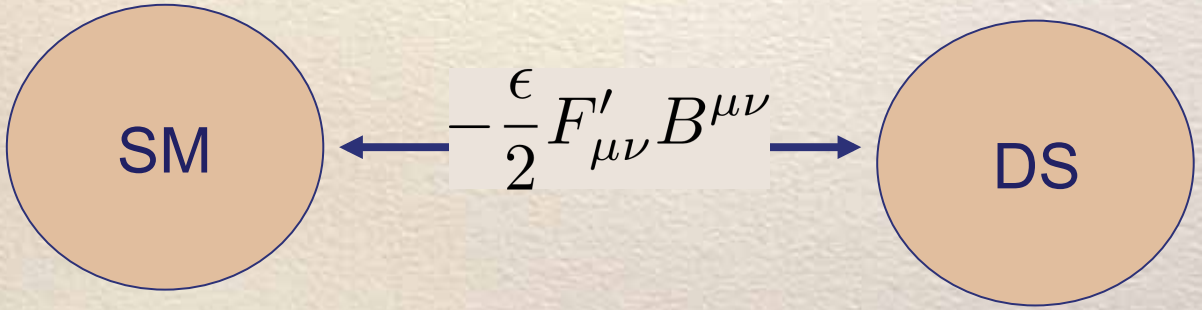
$$\mathcal{L}_{DM} = \bar{\chi}\gamma^\mu \partial_\mu \chi + M\bar{\chi}\chi$$

$$+ g\bar{\chi}\gamma^\mu A'_\mu \chi$$

$M \sim \text{TeV}$

$$-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2 A'_\mu A'^\mu$$

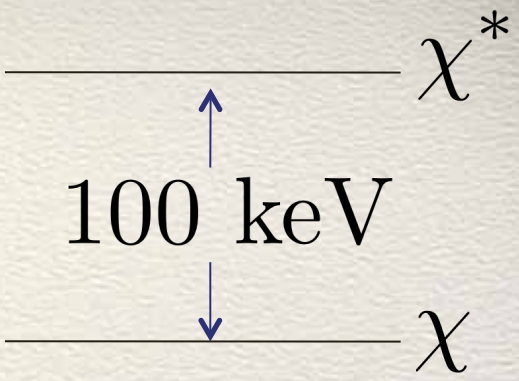
$m \sim \text{GeV}$



What if DM couples to another force?

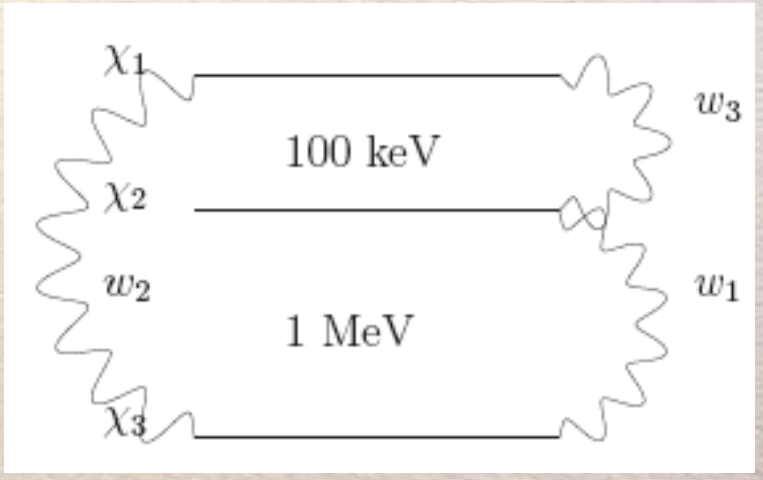
Mass Splitting

$$\mathcal{L}_{DS} \supset y h \chi\chi \rightarrow y\langle h\rangle \chi\chi$$



Radiative corrections

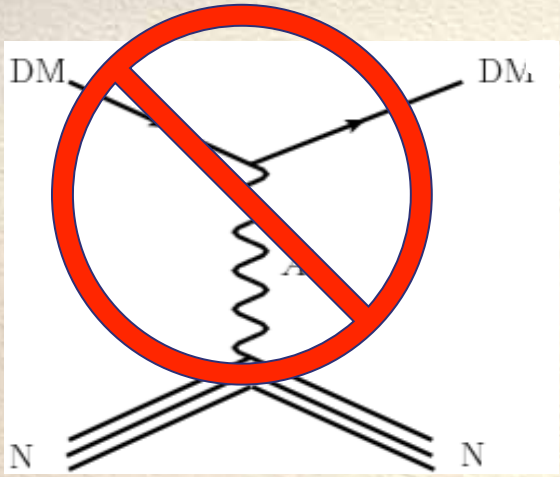
If the new force is non-abelian and
DM is a triplet of SU(2).
Break SU(2) --> U(1)

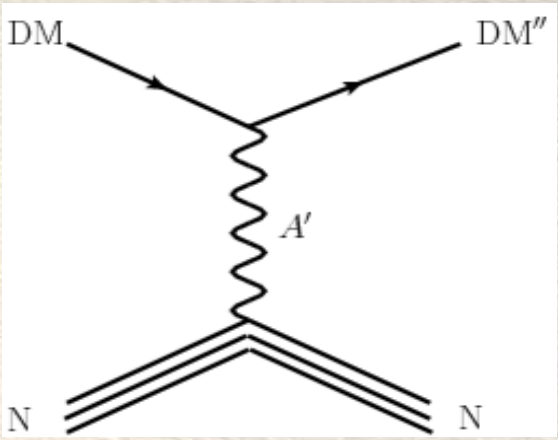


$$\Delta m_{ij} = \alpha' \left(q_i^2 - q_j^2\right) M_z$$

$$\sim \text{ MeV}$$

Inelastic Dark Matter (iDM)

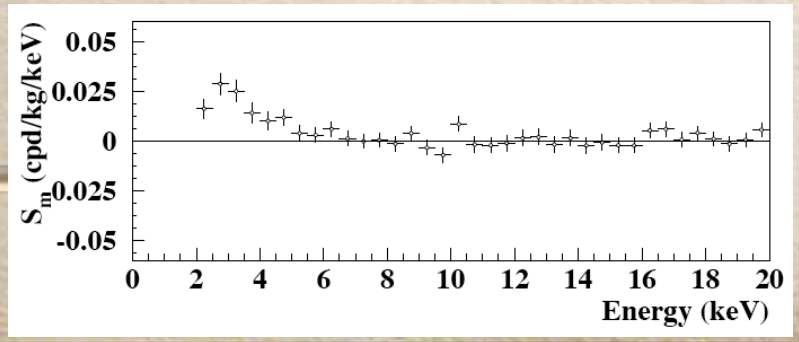




$$\mathcal{L} \supset y h_d \chi\chi \quad \rightarrow \quad y\langle h_d \rangle \chi\chi$$

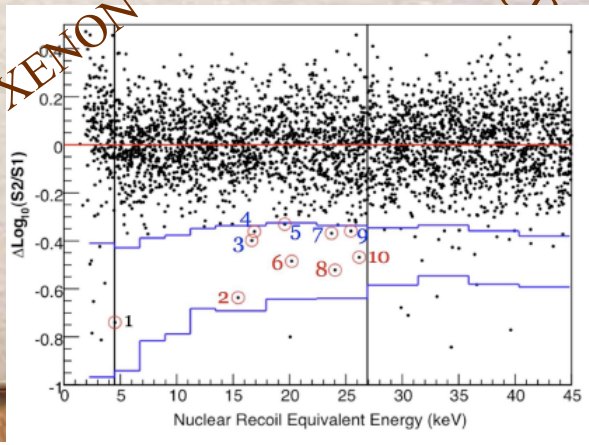
The spectrum contains an excited state, realizing the iDM proposal (Smith & Weiner).

DAMA



Vs.

XENON



Recoil Energy Spectrum

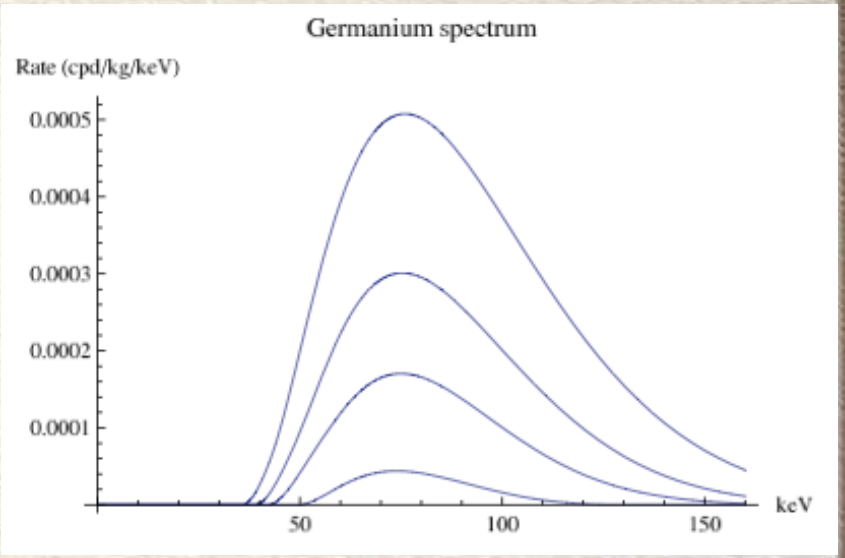
$$\beta_{min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \mathcal{E} \right)$$

m_N - Nucleus mass

$\mathcal{E}$ - Exictation Energy

E_R - Recoil Energy

μ - Nucleon-WIMP reduced mass



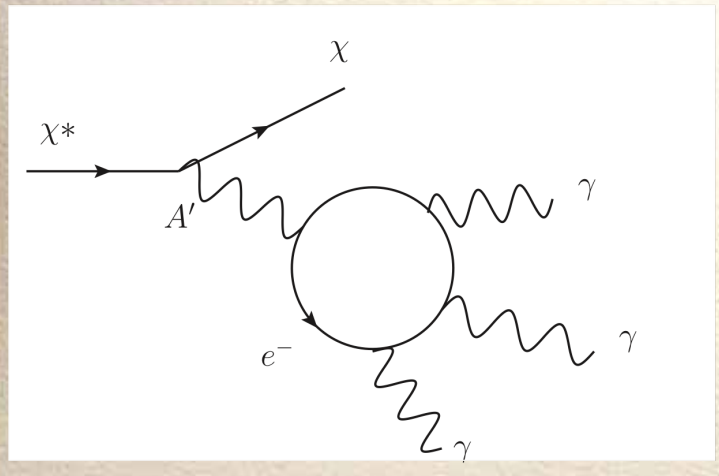
From Chang et al 0807.2250

1. Light element experiments may not see anything.
2. The spectrum of events has a maximum.
3. Probing the tail of the Boltzmann distribution ---> large modulations.

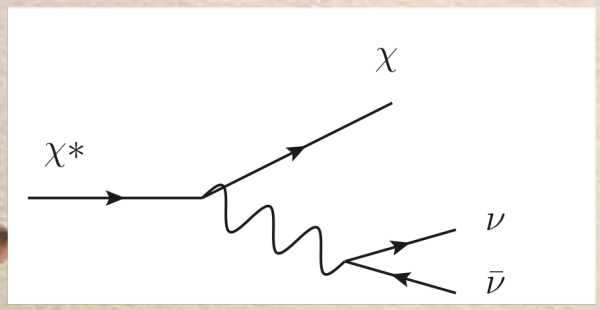
What about the excited state?

Metastable States

If kinetic-mixing is the only portal to the Standard Model then the excited state is very long-lived,



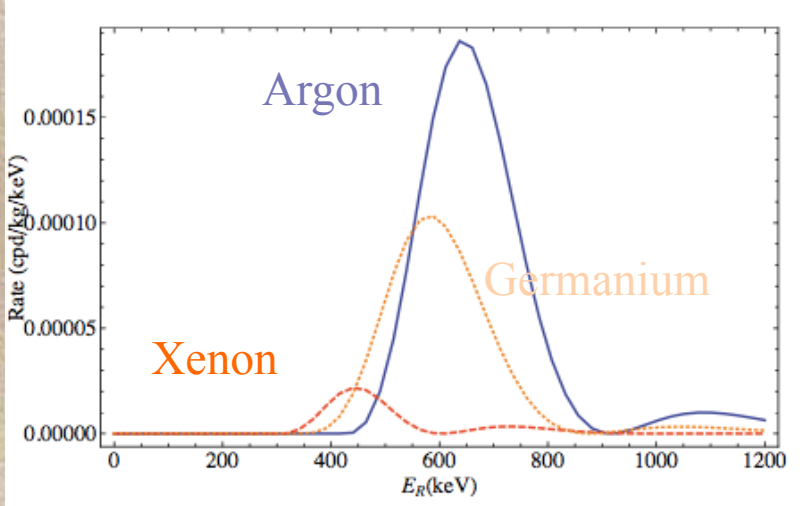
$$\tau_{3\gamma}^{-1} = 1.3 \times 10^{26}\text{sec} \left(\frac{\delta}{100\ \text{keV}}\right)^{13} \left(\frac{\epsilon}{10^{-3}}\right)^{2}$$



$$\tau_{\nu\bar{\nu}}^{-1} = 3 \times 10^{30}\text{sec} \left(\frac{\delta}{100\ \text{keV}}\right)^{9} \left(\frac{\epsilon}{10^{-3}}\right)^{2}$$

Exothermic Reactions

The excited state can down-scatter against any element, but the recoil energy may be fairly high,

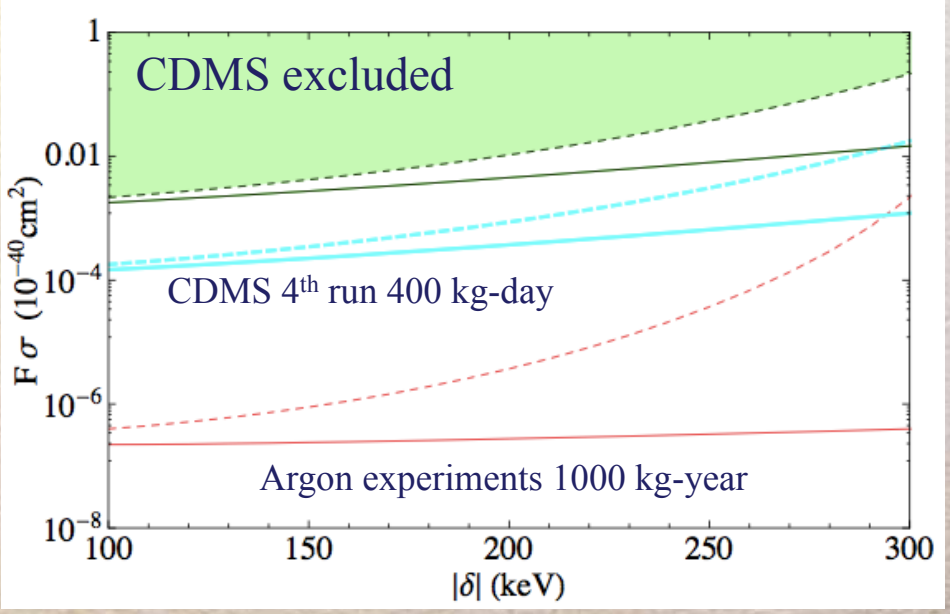


$m_\chi = 500$ GeV

$\delta = -900$ keV

$\sigma = 10^{-40}$ cm^2

$m_\chi = 200$ GeV

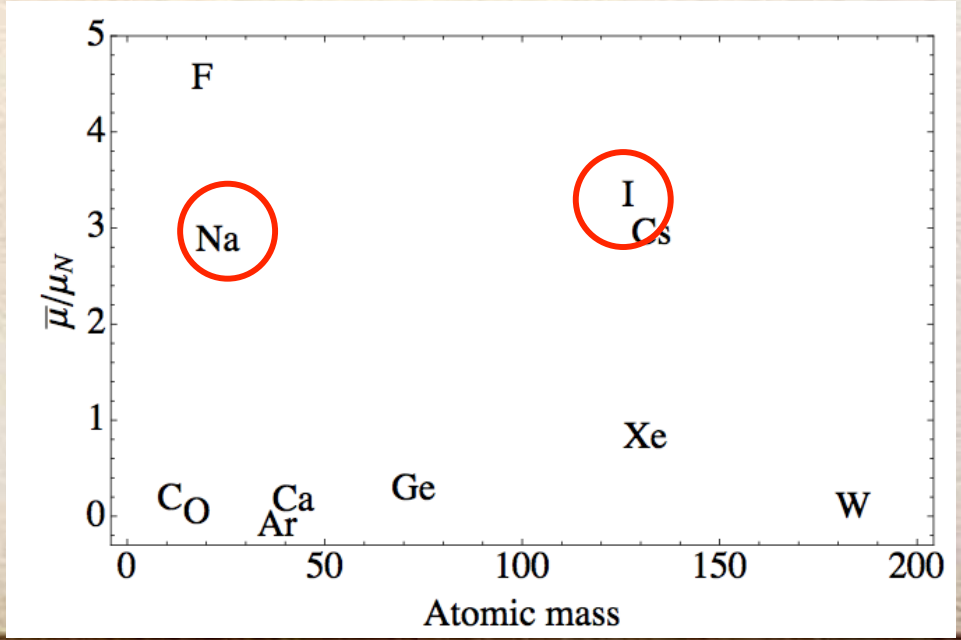


See also Harnik et al for a lighter version.

Can DM couple to photons?

$$\left(\frac{\mu_\chi}{2}\right)\bar{\chi}\sigma^{\mu\nu}F_{\mu\nu}\chi$$

How else is DAMA different?



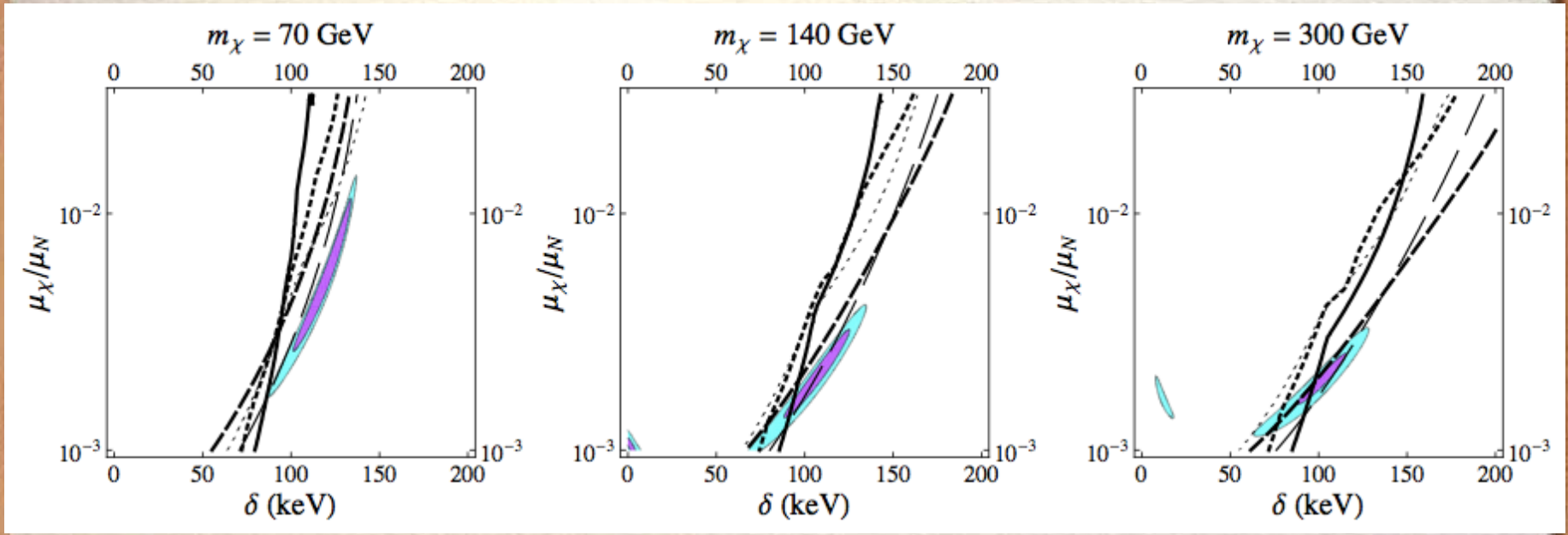
Magnetic iDM

$$\frac{d\sigma}{dE_R} = \frac{d\sigma_{\rm DD}}{dE_R} + \frac{d\sigma_{\rm DZ}}{dE_R}$$

$$\frac{d\sigma_{\rm DD}}{dE_R} = \frac{16\pi\alpha^2 m_N}{v^2}\left(\frac{\mu_{nuc}}{e}\right)^2\left(\frac{\mu_\chi}{e}\right)^2 \times \left(\frac{S_\chi+1}{3S_\chi}\right)\left(\frac{S_N+1}{3S_N}\right)F_D^2[E_R]$$

$$\frac{d\sigma_{\rm DZ}}{dE_R} = \frac{4\pi Z^2\alpha^2}{E_R}\left(\frac{\mu_\chi}{e}\right)^2\left[1-\frac{E_R}{v^2}\left(\frac{1}{2m_N}+\frac{1}{m_\chi}\right) - \frac{\delta}{v^2}\left(\frac{1}{\mu_{N\chi}}+\frac{\delta}{2m_N E_R}\right)\right]\left(\frac{S_\chi+1}{3S_\chi}\right)F^2[E_R] \quad (6)$$

Fit to DAMA and Constraints

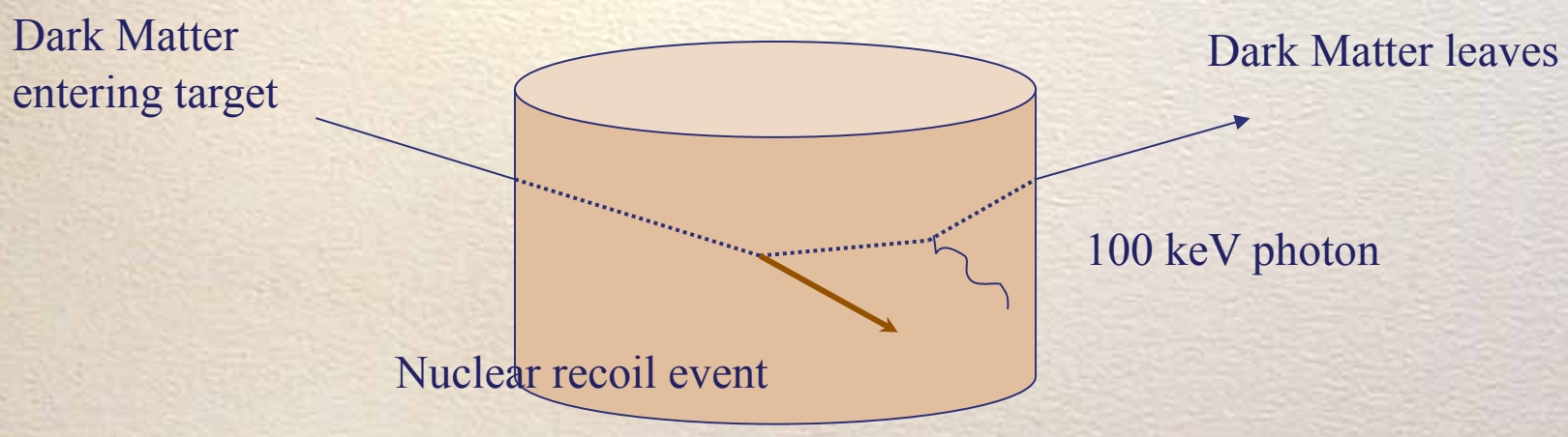


CDMS
CRESST-II
XENON10
KIMS
ZPELIN-III

Excited State's Lifetime

After the collision, the excited state travels some distance before it de-excite and emits a photon,

$$\tau^{-1} = \mu_\chi^2 \delta^3 / \pi$$

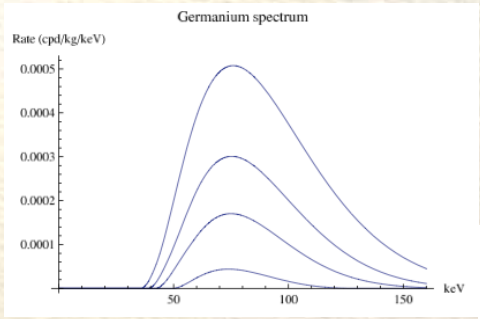


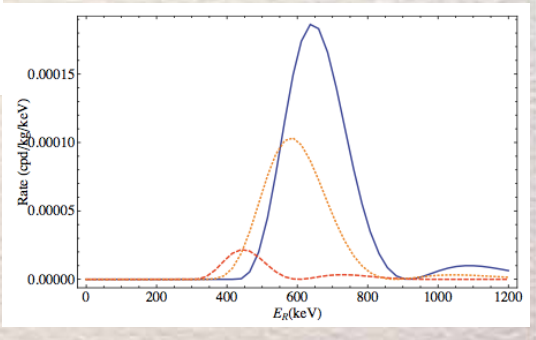
Standard cuts will likely miss these sort of events, but with some care it may not be hard to distinguish from background.

Conclusions

1. We should keep an open mind with regard to the signal. It may not show up at low recoil energies.

2. Inelastic DM





3. Metastable states

4. Magnetic iDM