MODEL INDEPENDENT APPROACH TO INELASTIC DARK MATTER

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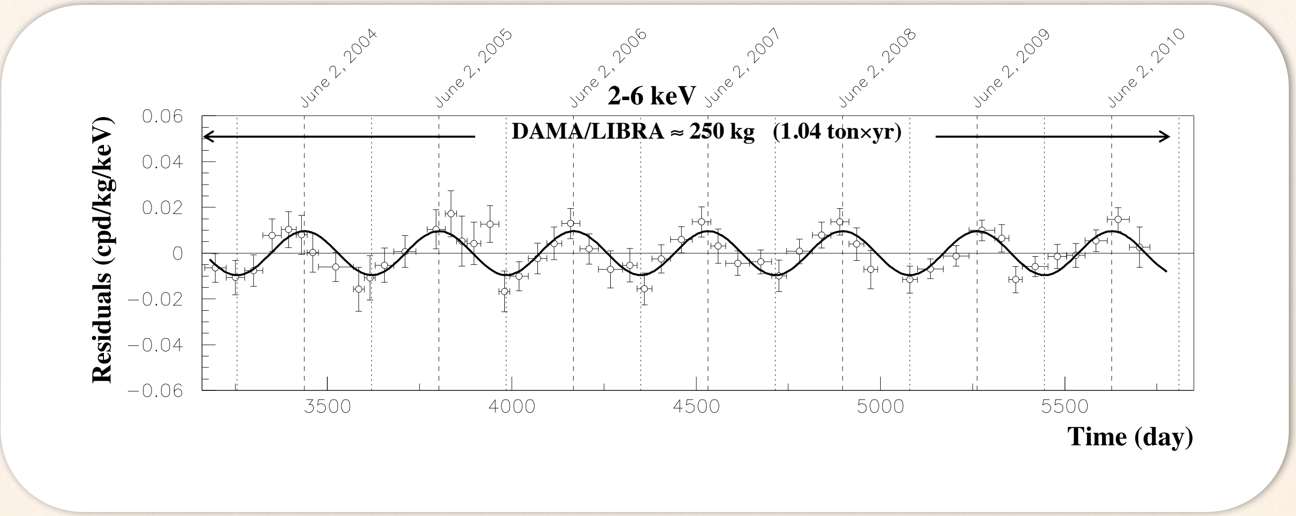
OUTLINE

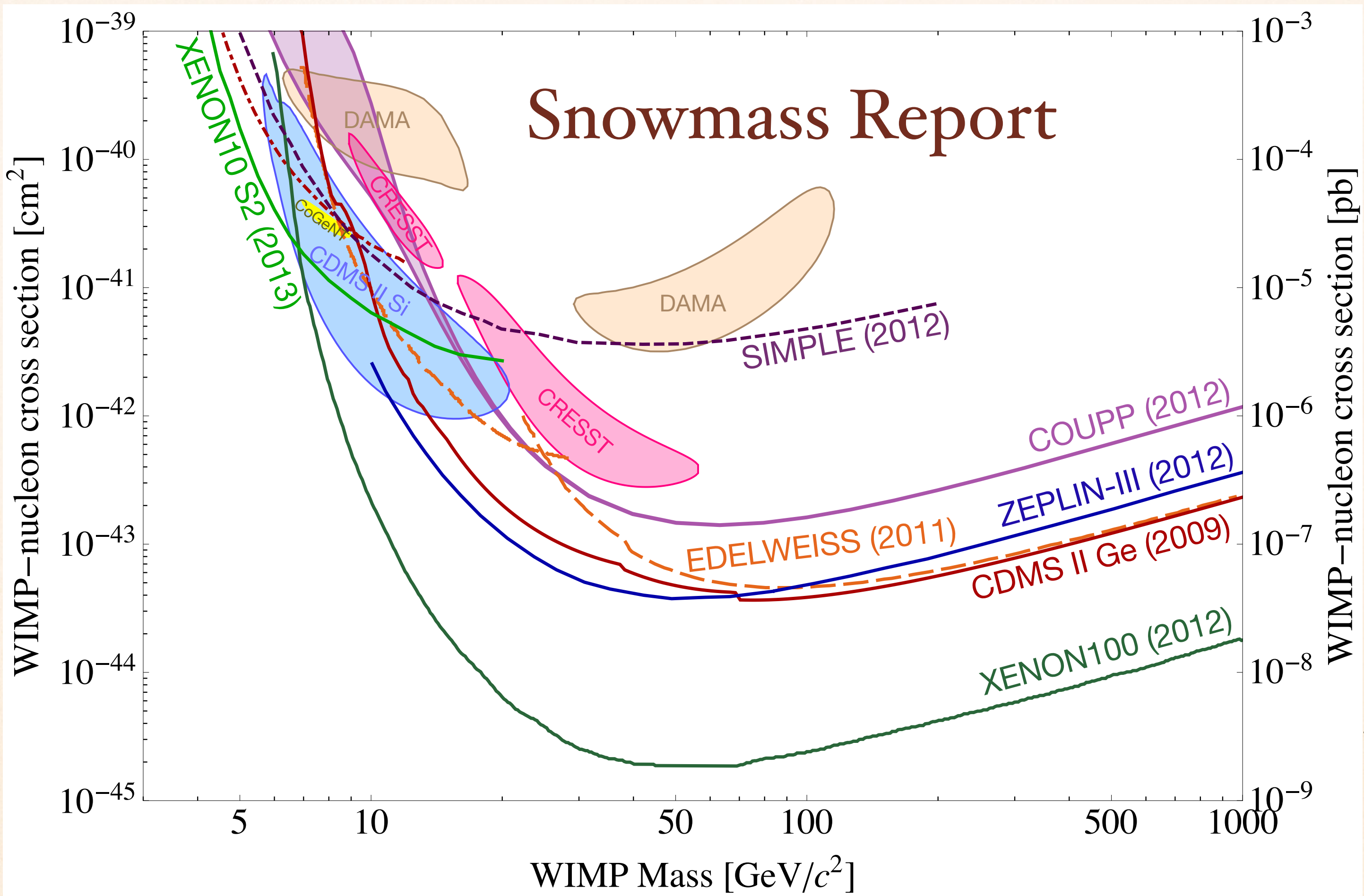
- Model independent approach to inelastic dark matter scattering
- Modify Fitzpatrick et al. Mathematica code to calculate form factors
- Revisit inelastic explanations of DAMA

DAMA



DM modulation is expected due to modulating Earth velocity through Galactic rest frame

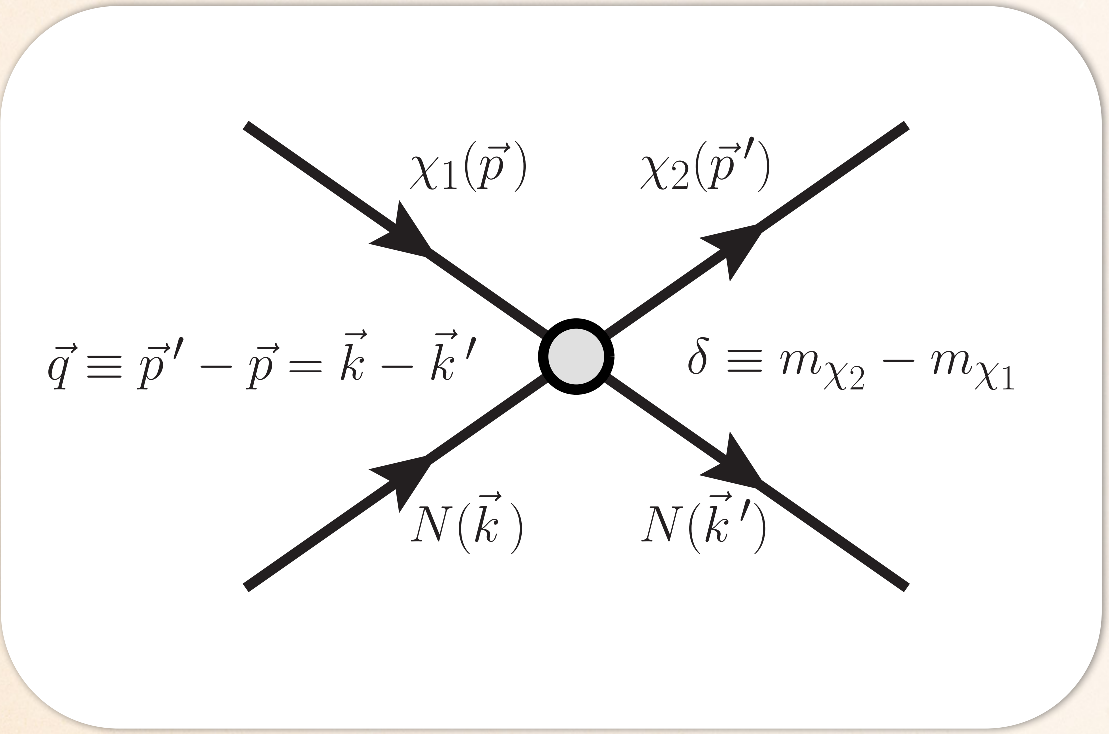
DAMA



Snowmass Report
WIMP−nucleon cross section [cm^2]
WIMP−nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
5
10
50
100
500
1000
DAMA
DAMA
CRESST
CRESST
CoGeNT
CDMS II Si
XENON10 S2 (2013)
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011)
CDMS II Ge (2009)
XENON100 (2012)

DM rth

INELASTIC DARK MATTER



Proposed by D. Tucker-Smith, N. Weiner to ('01)
to explain DAMA modulation signal's consistency
with limits from CDMS

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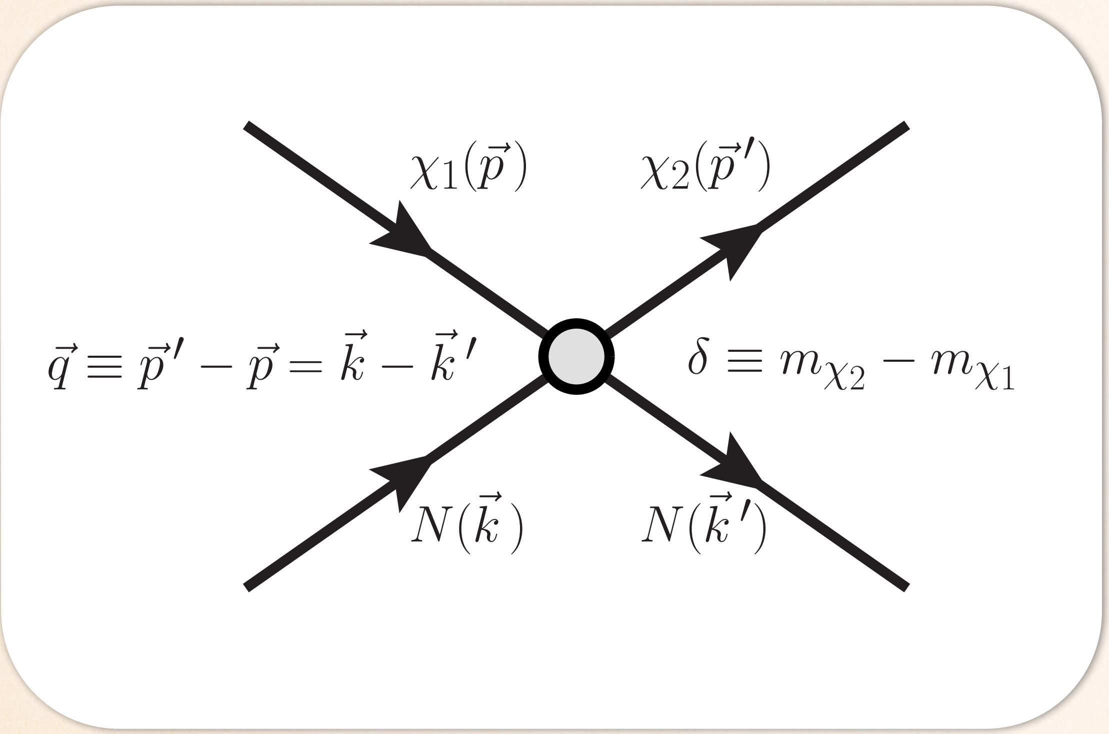

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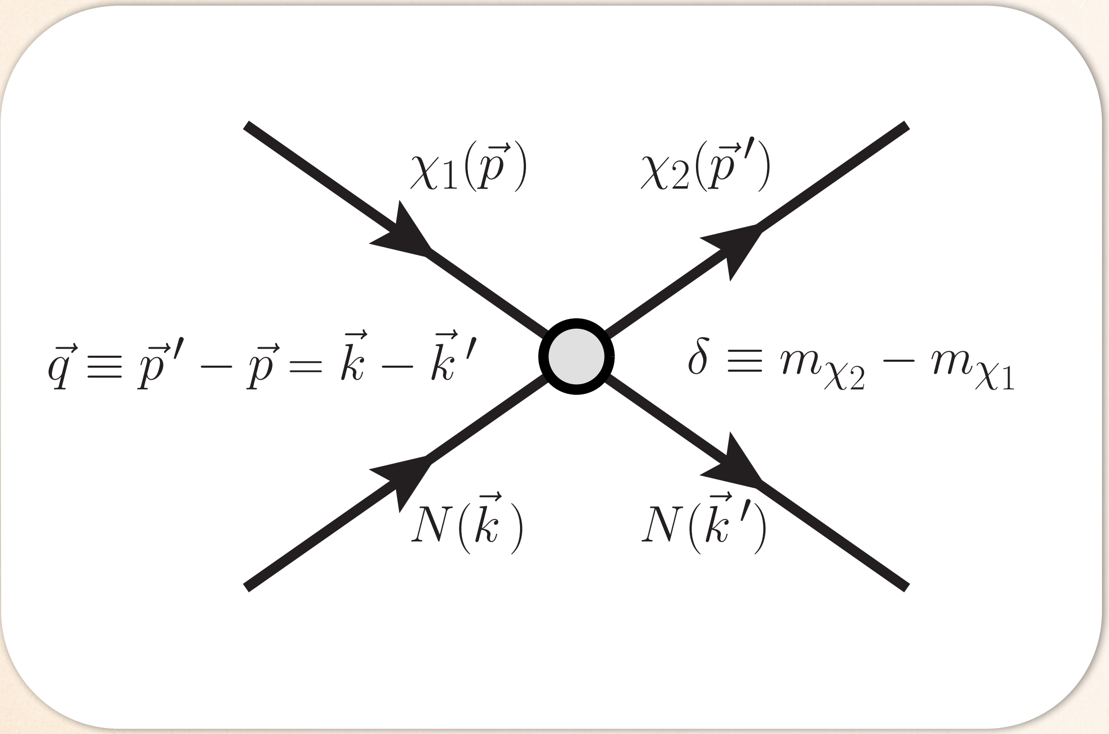

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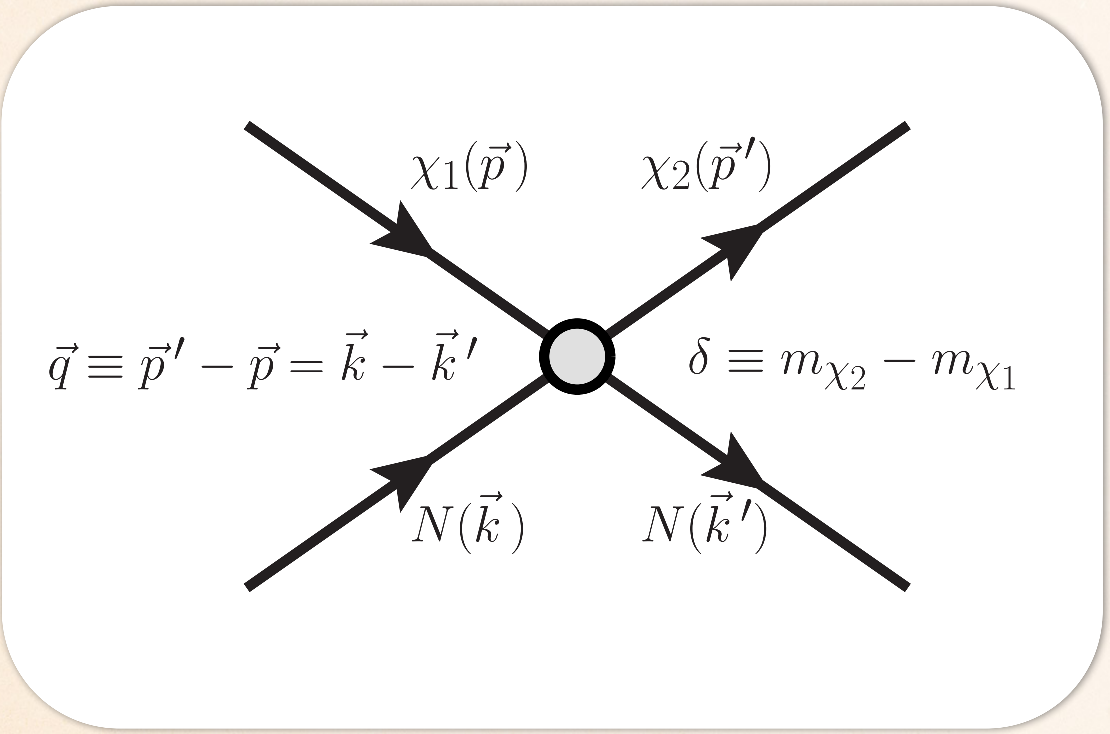

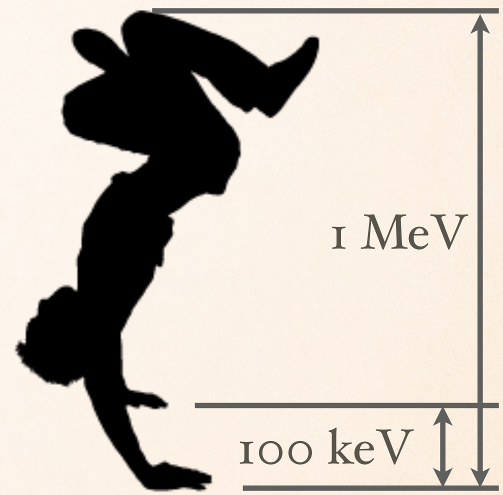

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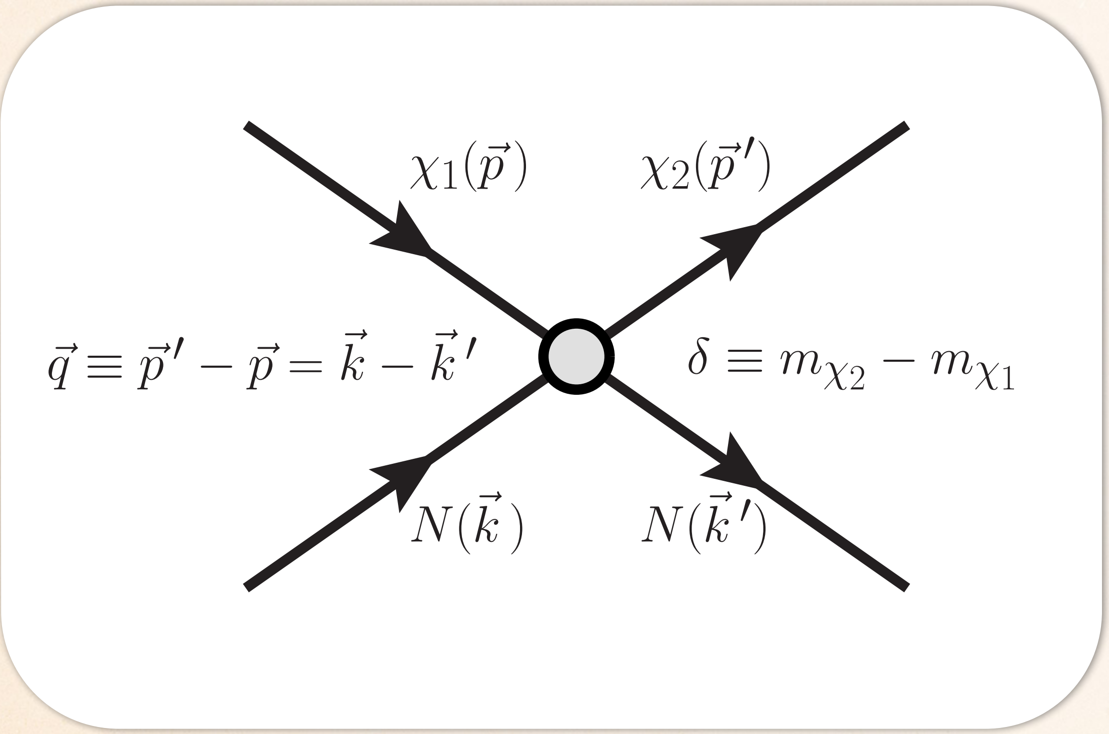

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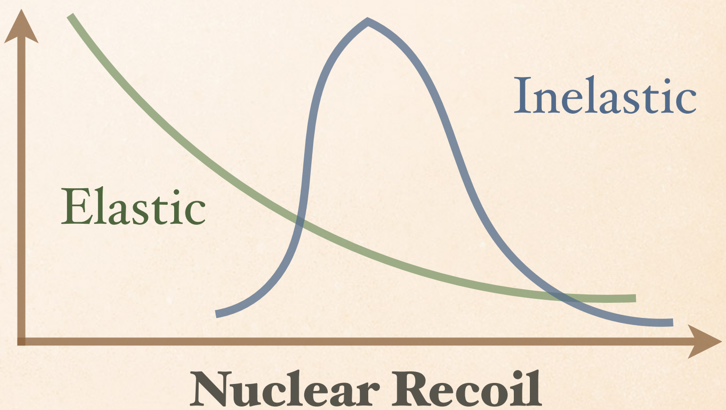
INELASTIC EFFECTS

Minimum velocity to scatter altered by kinematics

$$v_{\text{min}} = \frac{1}{\sqrt{2m_N E_R}} \left(\frac{m_N E_R}{\mu_{N\chi}} + \delta \right)$$

Three Important Effects

Raises velocity required leads to
i) suppressed rates for lighter nuclei
ii) larger modulation amplitudes
iii) Energy spectra change



CONSTRAINTS

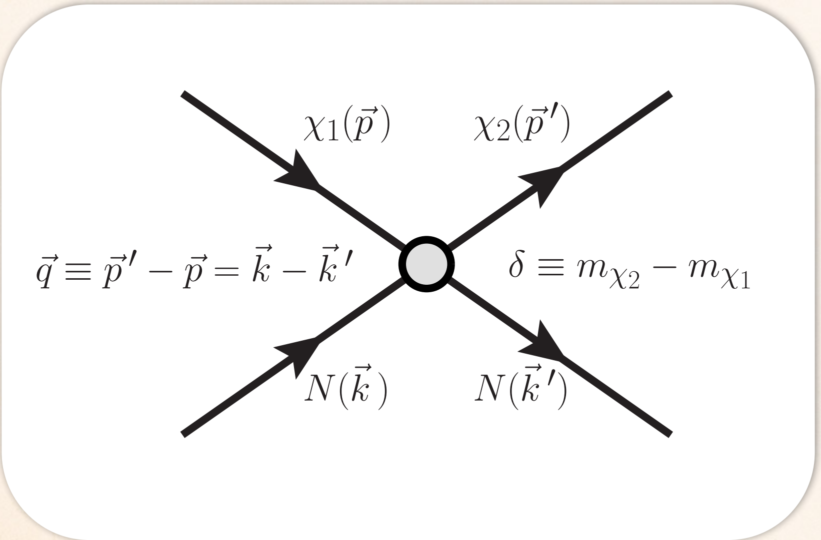
- Germanium and lighter targets no issue for IDM
- Xenon is heavier than DAMA's iodine, so XENON100, LUX limits place stringent constraints **if** form factors are similar
- Iodine experiments should have robust constraints, so KIMS and COUPP limits are hardest to avoid
- At any rate, inelastic dark matter is interesting and we need to analyze it properly

MODEL INDEPENDENT ANALYSIS

- Recently, effective theories of elastic scattering have been proposed (Fan et al., Fitzpatrick et al.)
- Model indpt. approach shows there are new form factors beyond spin independent, dependent cases
- Anand et al. provide Mathematica code to calculate form factors
- Lets see how to modify the Fitzpatrick approach

GALILEAN INVARIANTS

Following Fitzpatrick, nonrelativistic scattering is categorized by galilean invariants



$$\vec{q}, \vec{v}_\perp, \vec{S}_N, \vec{S}_\chi$$

Inelastic kinematic modifies velocity by a shift

$$\vec{v}^{\perp}_{\rm inel} = \vec{v} + \frac{\vec{q}}{2\mu_N} + \frac{\delta}{|\vec{q}|^2}\vec{q}$$

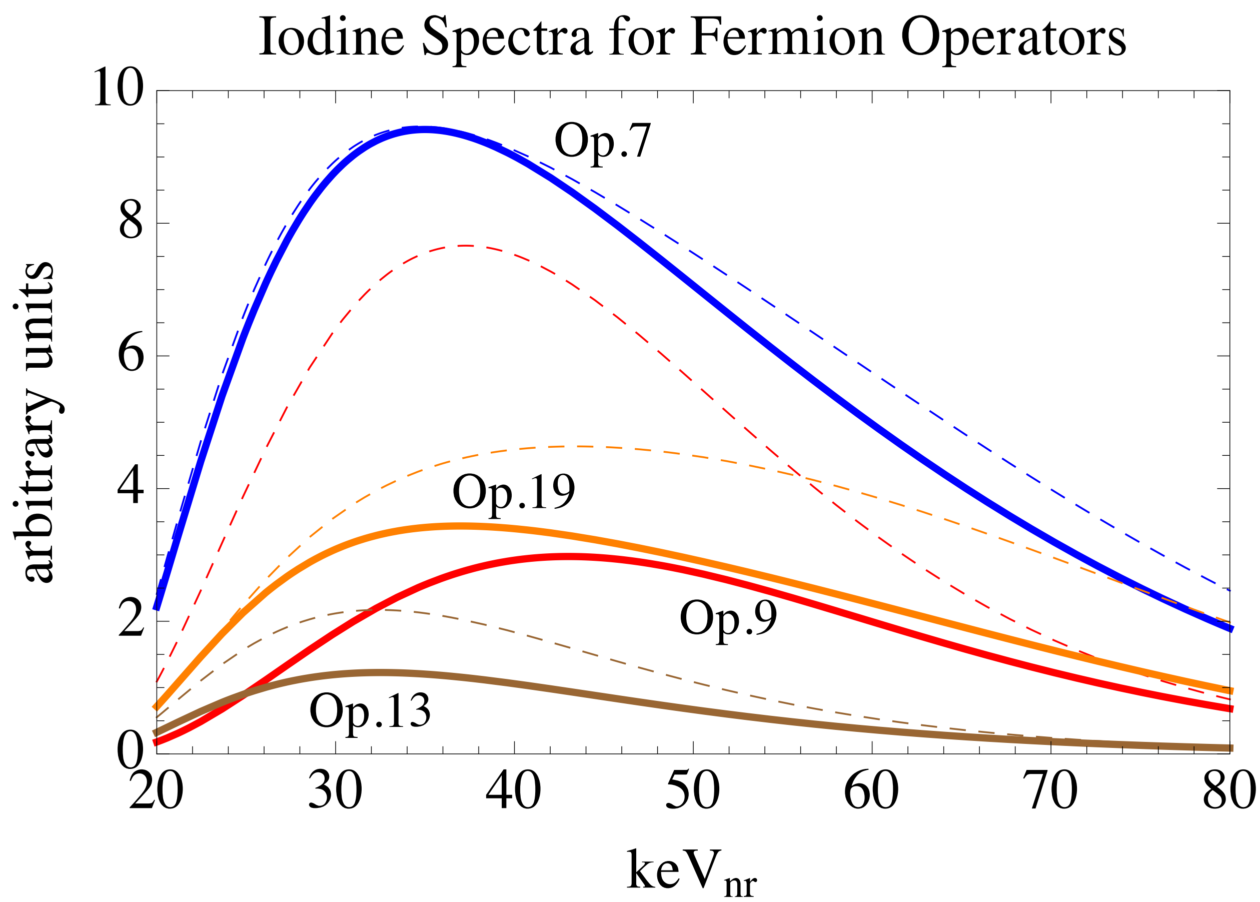
NONRELATIVISTIC OPS.

Just need to change to new vperp

$$|\vec{v}^{\perp}_{\text{inel}}|^2 = |\vec{v}|^2 - v_{min}^2$$

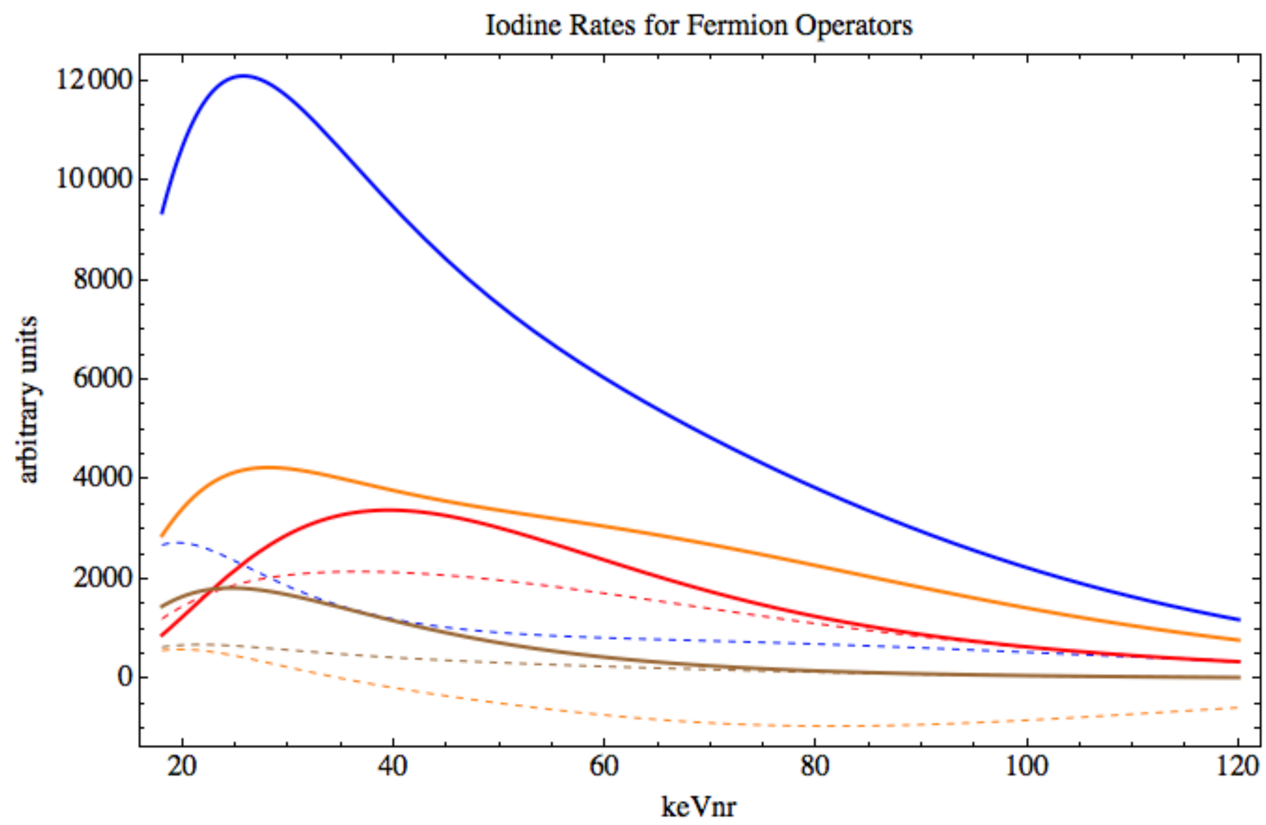
$$\begin{aligned}
&\mathcal{O}_1 = \mathbf{1}_\chi \mathbf{1}_N, \quad \mathcal{O}_2 = (v^\perp_{\text{inel}})^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\text{inel}}\right), \\
&\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\text{inel}}\right), \\
&\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right), \\
&\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp_{\text{inel}}, \quad \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp_{\text{inel}}, \\
&\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right), \quad \mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}, \\
&\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}, \quad \mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp_{\text{inel}}\right), \\
&\mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}^\perp_{\text{inel}}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right), \\
&\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \vec{v}^\perp_{\text{inel}}\right), \\
&\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left((\vec{S}_N \times \vec{v}^\perp_{\text{inel}}) \cdot \frac{\vec{q}}{m_N}\right),
\end{aligned} \tag{8}$$

FORM FACTORS



δ > 0
Solid - Correct
Dashed - Elastic
FF w/ inelastic
threshold

FORM FACTORS



δ < 0

Solid - Correct

Dashed - Elastic FF w/ inelastic threshold

REVISIT OF MAGNETIC INELASTIC DARK MATTER (SC, WEINER, YAVIN)

A dark matter magnetic moment transition is naturally off diagonal for split Majorana fermions

$$\mathcal{L} = \frac{\mu_\chi}{2} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 F_{\mu\nu} + h.c.$$

Large dipole of iodine (3.3 μ_N) relative to xenon (0.8 μ_N) and tungsten (0.08 μ_N) suppresses other heavy targets

At the time, we had an ad hoc form of form factor but now we can calculate it!

BRIEF ASIDE ON QUENCHING FACTORS

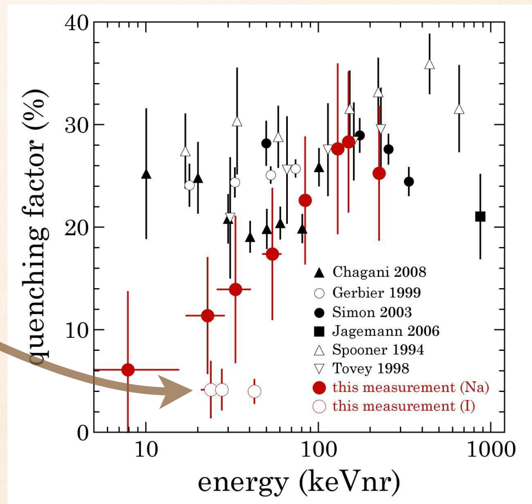
Not all of nuclear recoil energy is picked up requiring a quenching factor

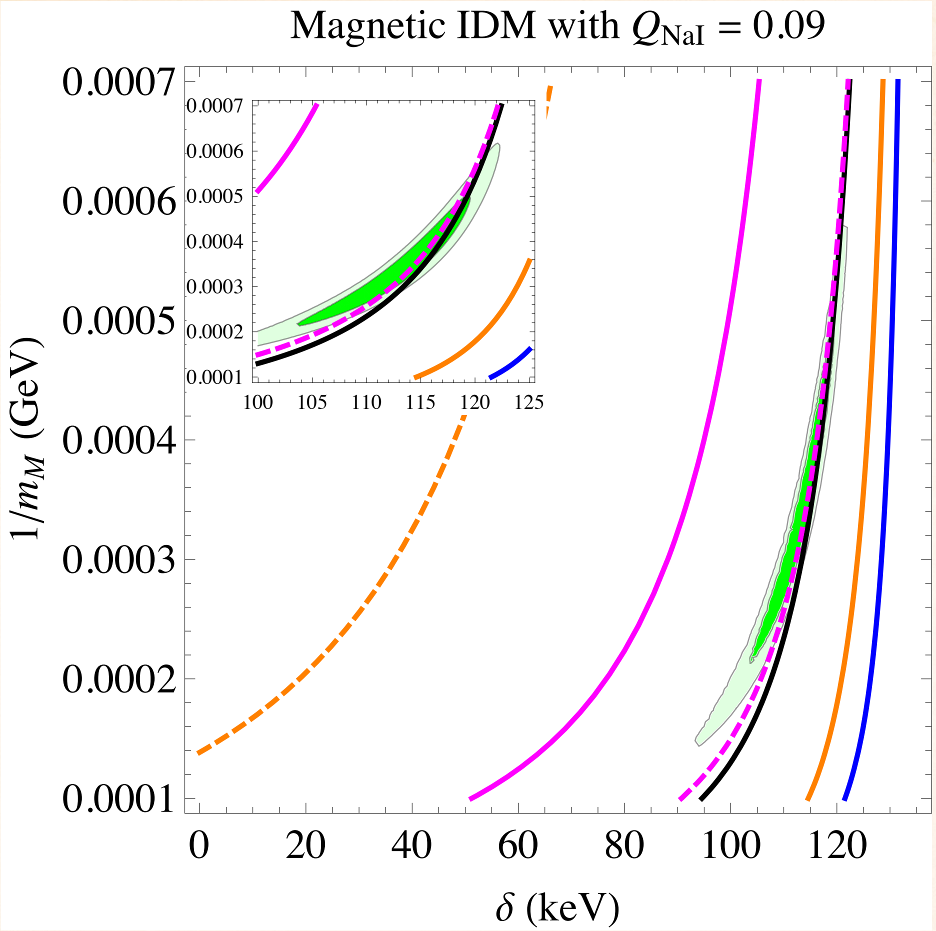
$$\mathrm{keV_{er}} = Q\ \mathrm{keV_{nr}}$$

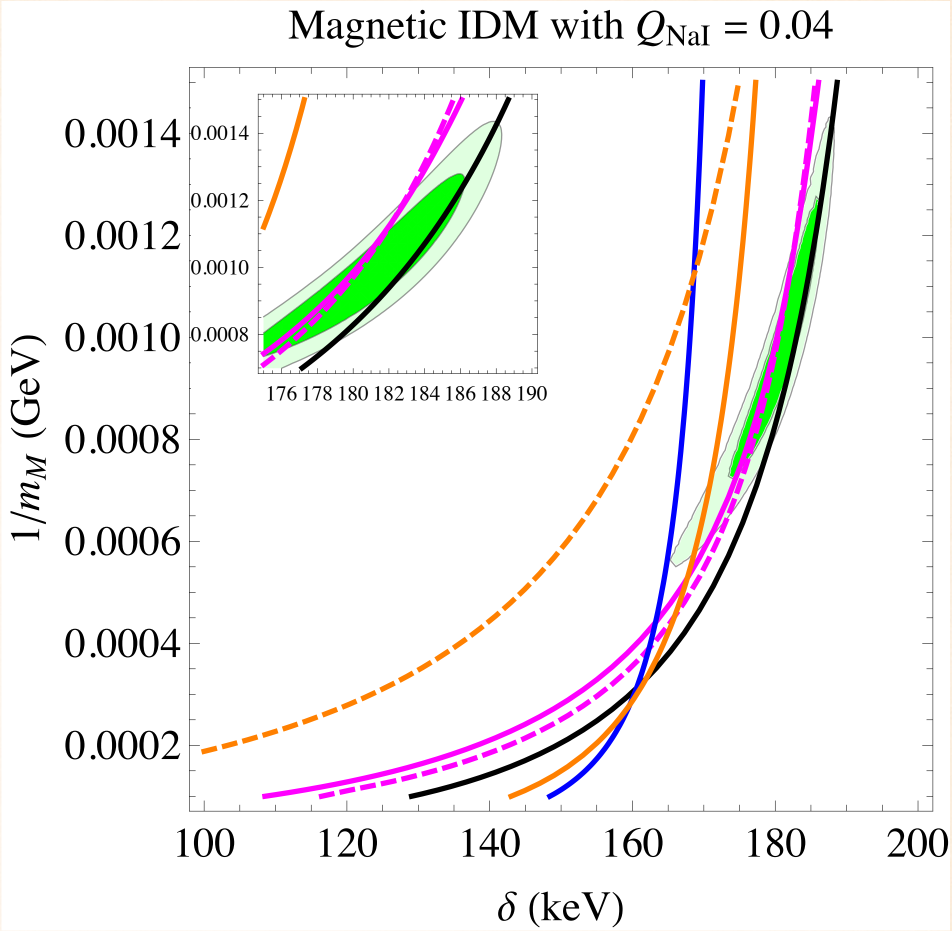
Iodine quenching factor in NaI and CsI has normally been taken to be .09-.11

Recent measurements are about half as big (J. Collar)

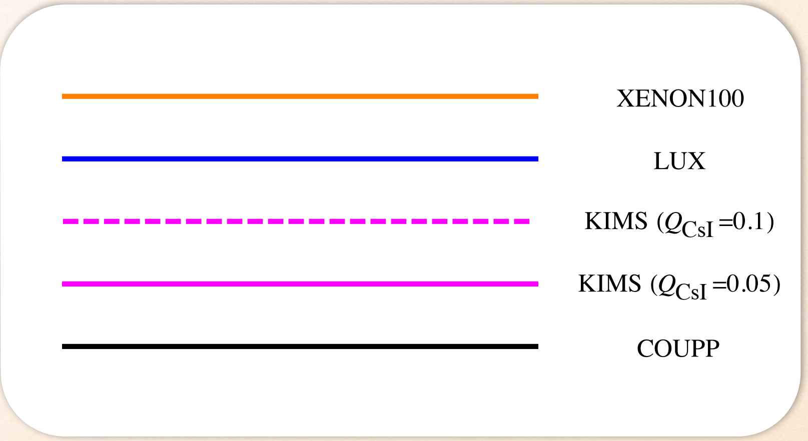
Strong effect on where scattering events occur

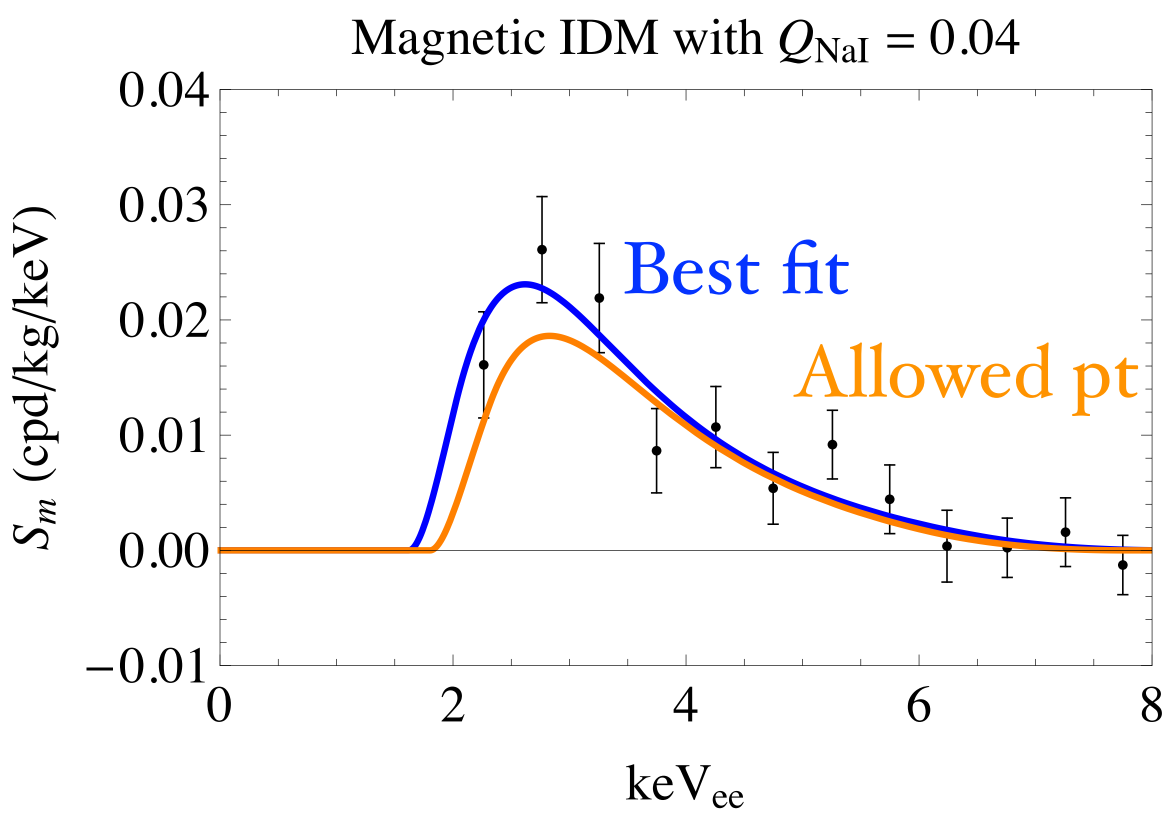




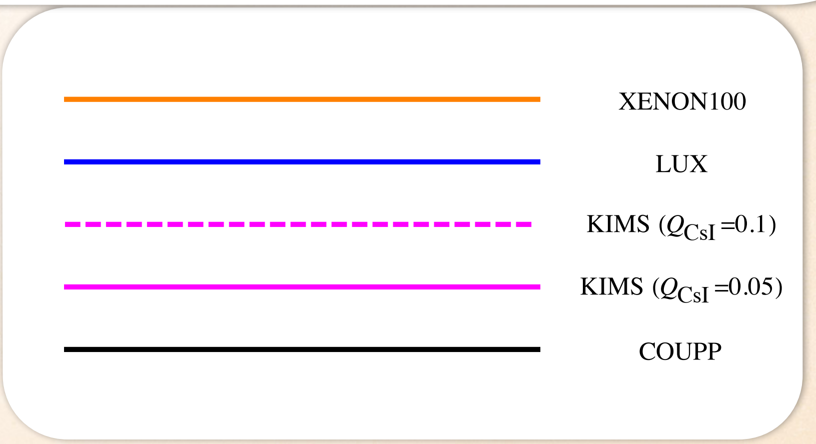


DAMA contours
68, 95% C.L.
parameter estimation

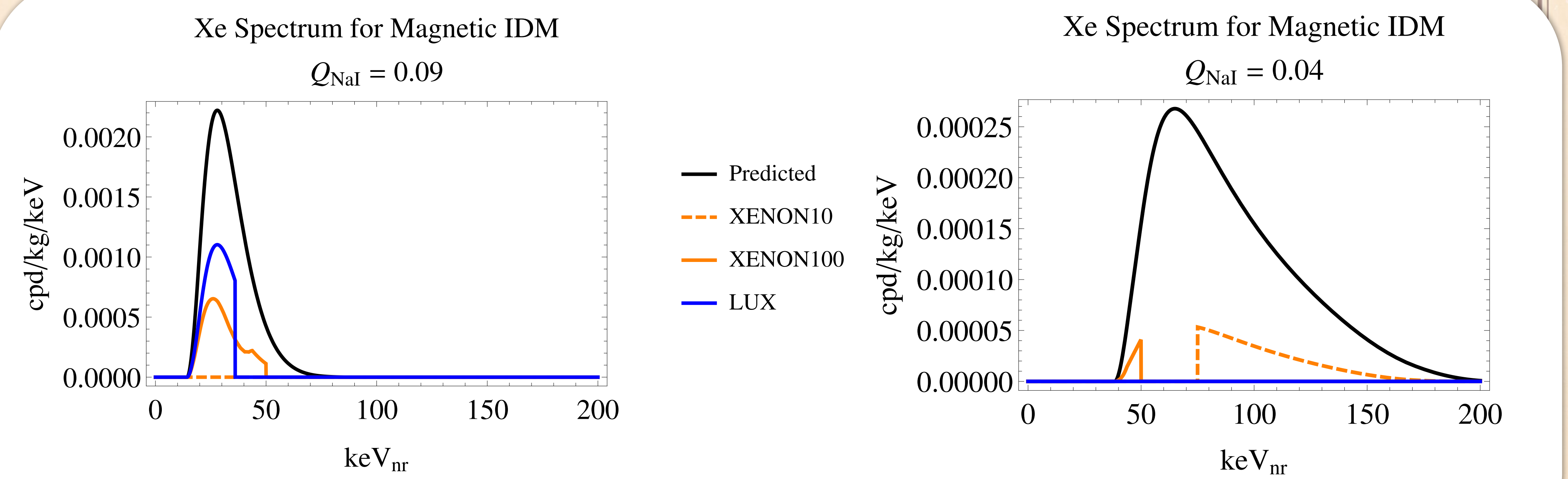




DAMA contours 68, 95% C.L. parameter estimation

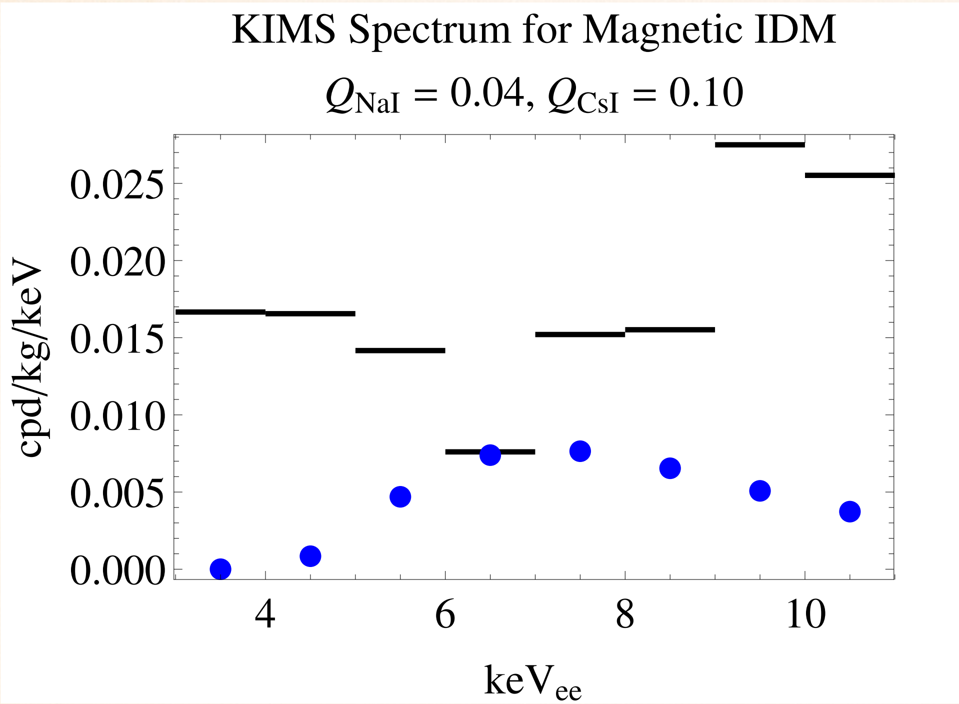


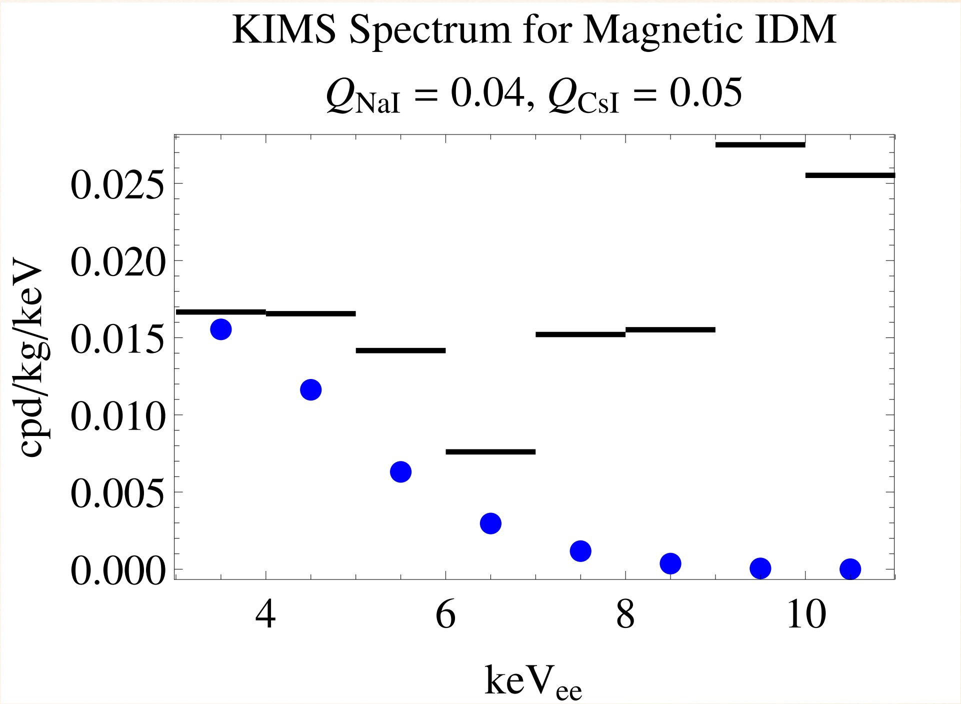
WHY Q MATTERS (XENON)



Low value of Q pushes scattering above acceptance regions of XENON100, LUX
Should have ~ 100 events at high energy on tape

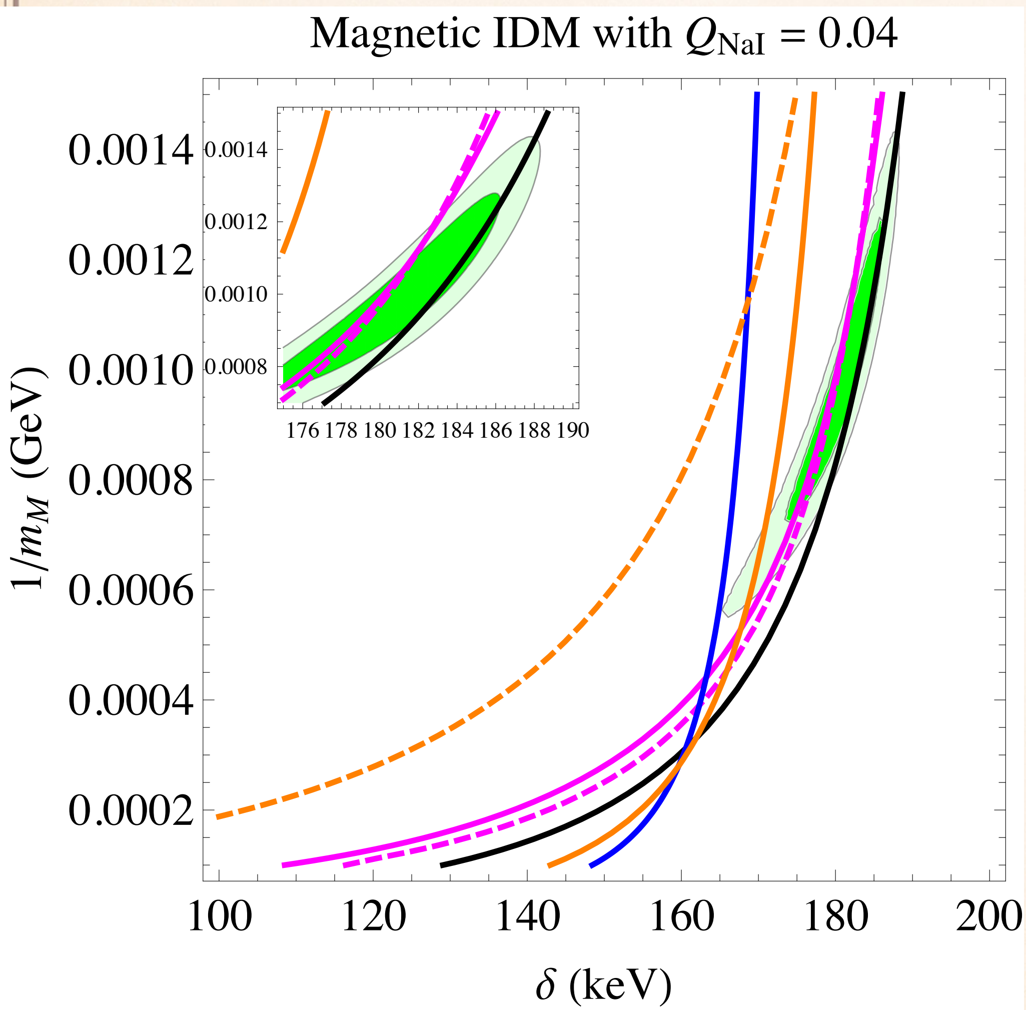
WHY Q MATTERS (KIMS)





Just changing iodine quenching in CsI crystal, moves spectrum around, potentially below KIMS threshold

COUPP



COUPP in black is a robust limit since it is sensitive to all energy recoils above 20 keV

Can only be reduced by modulation

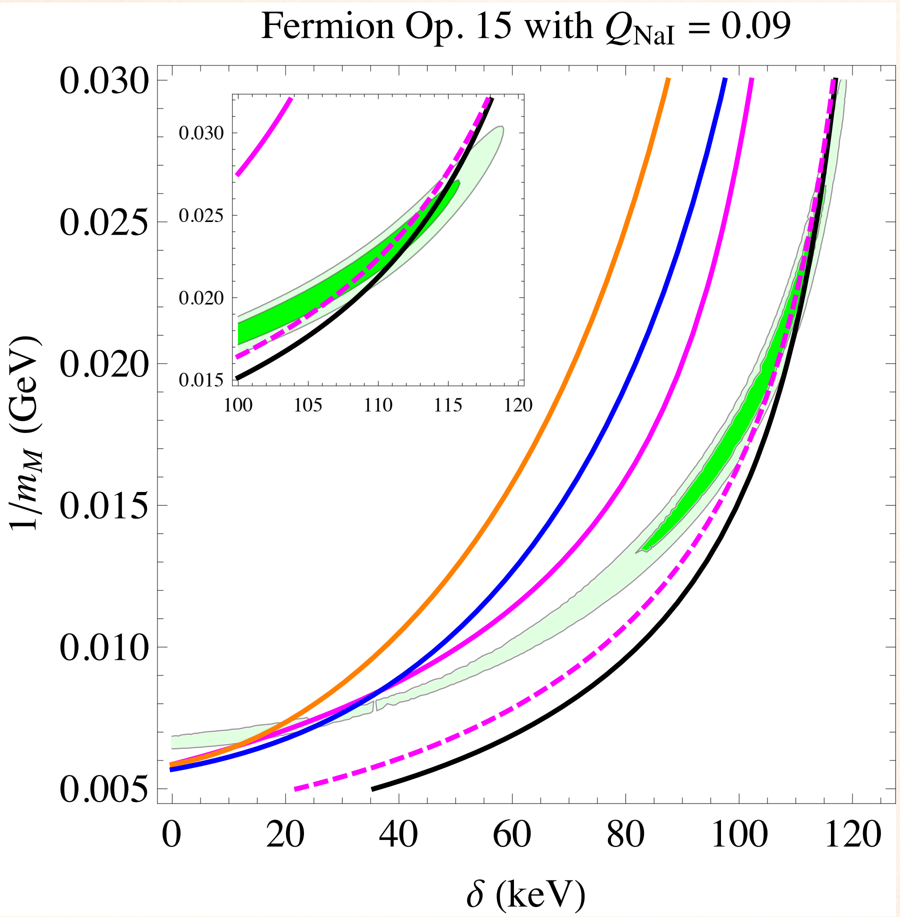
MODEL INDEPENDENT SURVEY

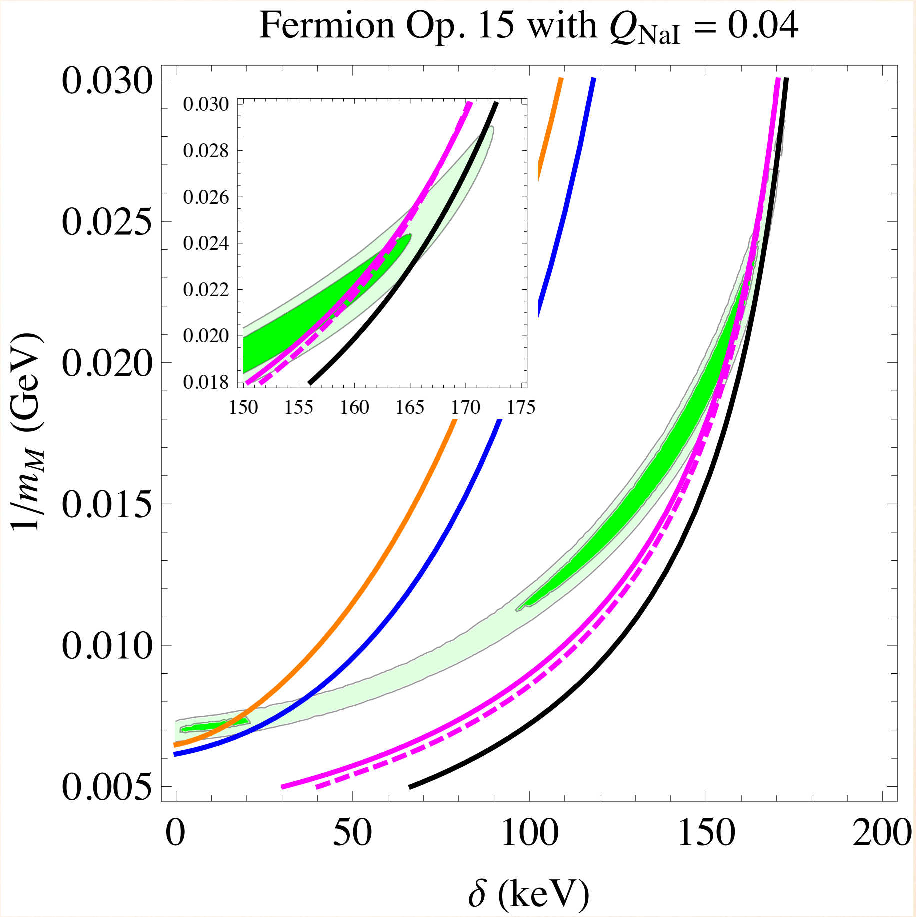
Consider relativistic operators which couple only to protons to negate xenon constraints

We find that operators involving proton spin are particularly suppressed, so that even larger XENON100, LUX energy range analysis would be allowed

EXAMPLE, SD PROTON IDM

ORIGINALLY CONSIDERED KOPP ET AL. JCAP1002





Xenon experiments are not an issue

Iodine experiments still constraining

FUTURE THEORY INPUT

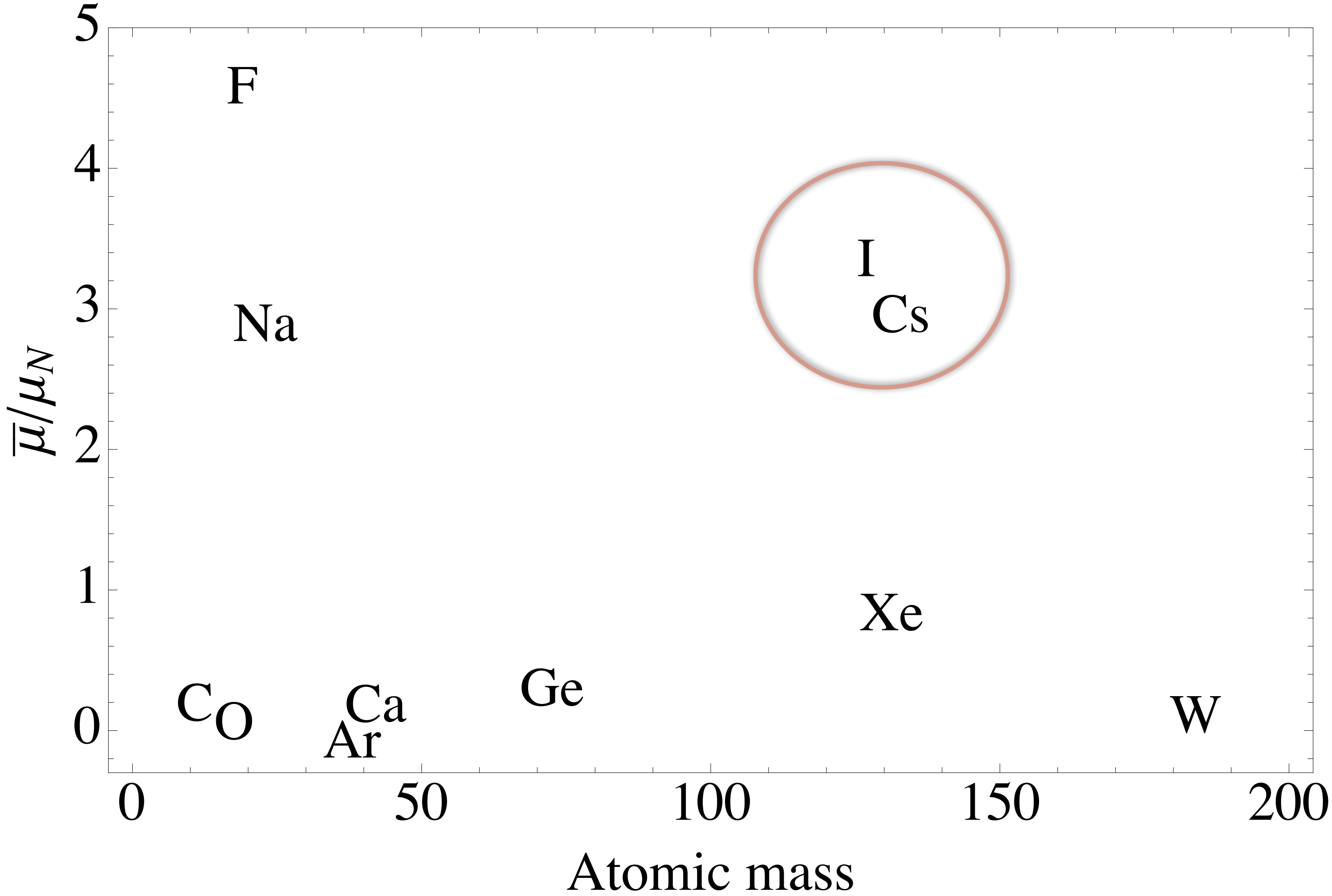
- Cesium and tungsten form factors need to be implemented in Mathematica code (untreated currently)
- Estimates of uncertainties on form factors
- Model building DAMA survivors (currently in progress)

FUTURE EXPT. INPUT

- Iodine experiments are robust (up to quenching factors) and IDM explanations of DAMA will be seen in next COUPP release
- Existing high energy data at XENON100, LUX is sensitive to some scenarios (constraints?, excesses?)
- Quenching factors need to be pinned down

THANKS!

ADDITIONAL SLIDES



5
4
3
2
1
0
$\overline{\mu}/\mu_N$
F
Na
I
Cs
Xe
C
O
Ca
Ar
Ge
W
0
50
100
150
200
Atomic mass