Inelastic Dark Matter and DAMA

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work in collaboration with
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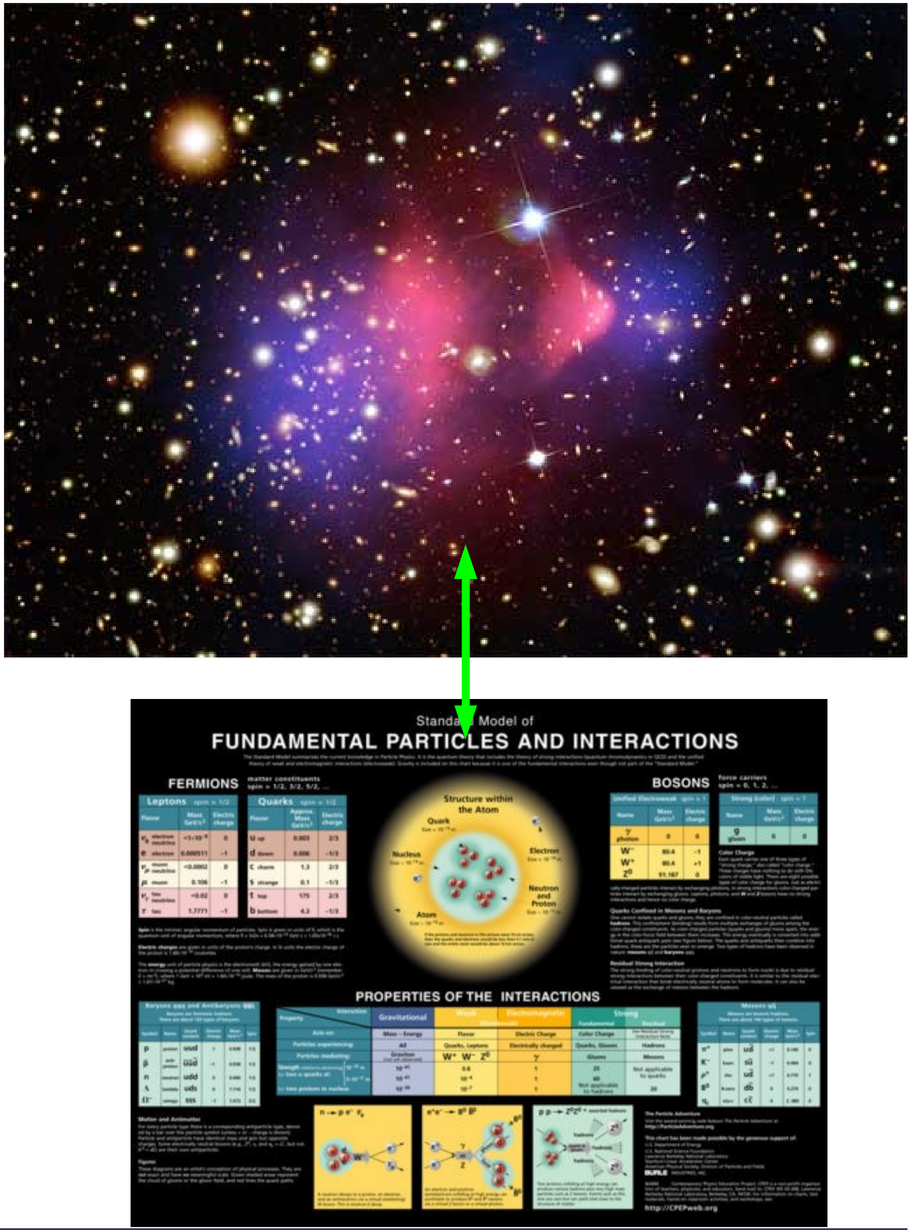
hep-ph:0807.2250

Also see David Morrissey's talk

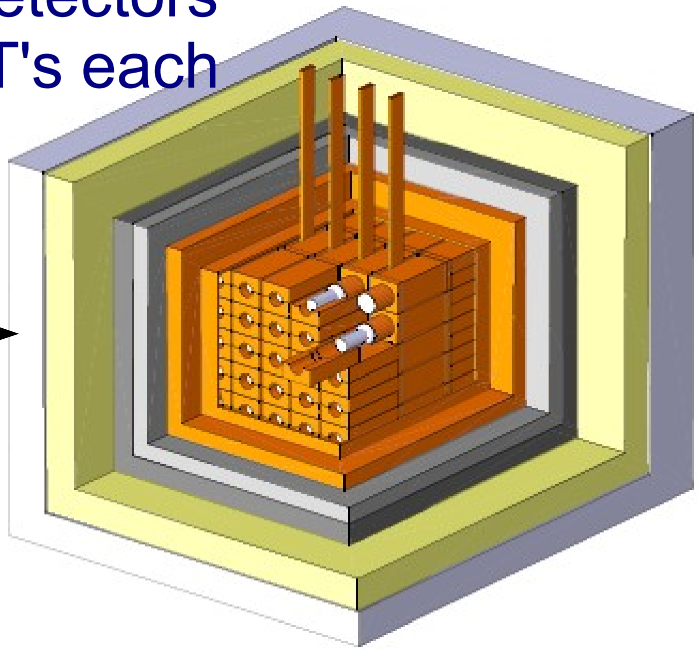
Dark Matter Mystery

- Dark matter implied by astronomy and cosmology, but mysterious from particle physics view
- Many experiments will probe it: collider, direct and indirect detection experiments



DAMA/NaI and DAMA/LIBRA

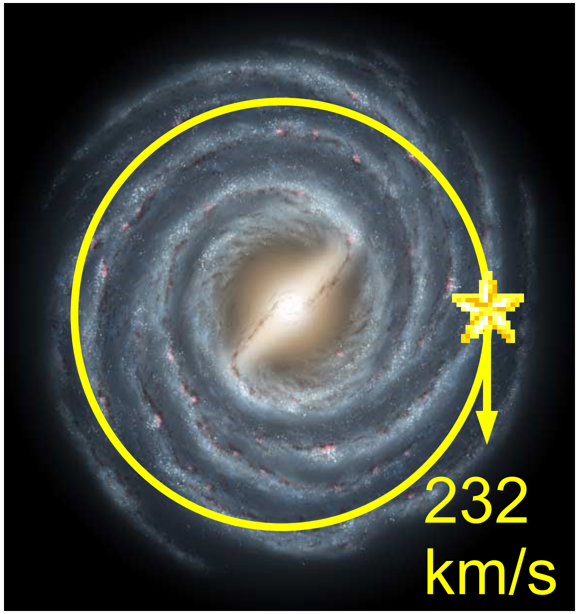
25 NaI detectors
w/ 2 PMT's each

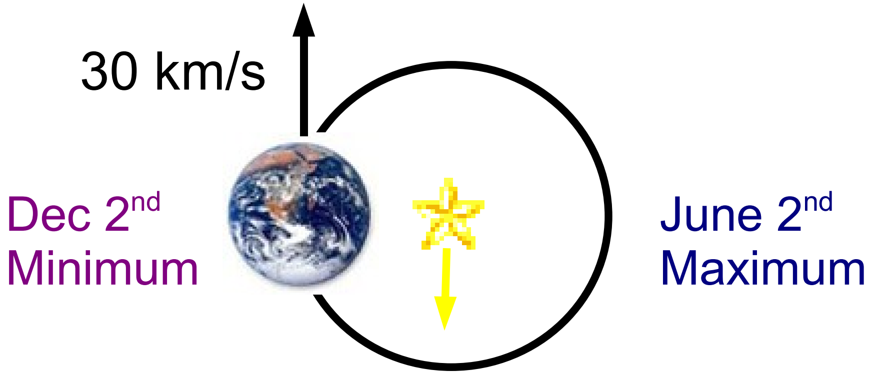


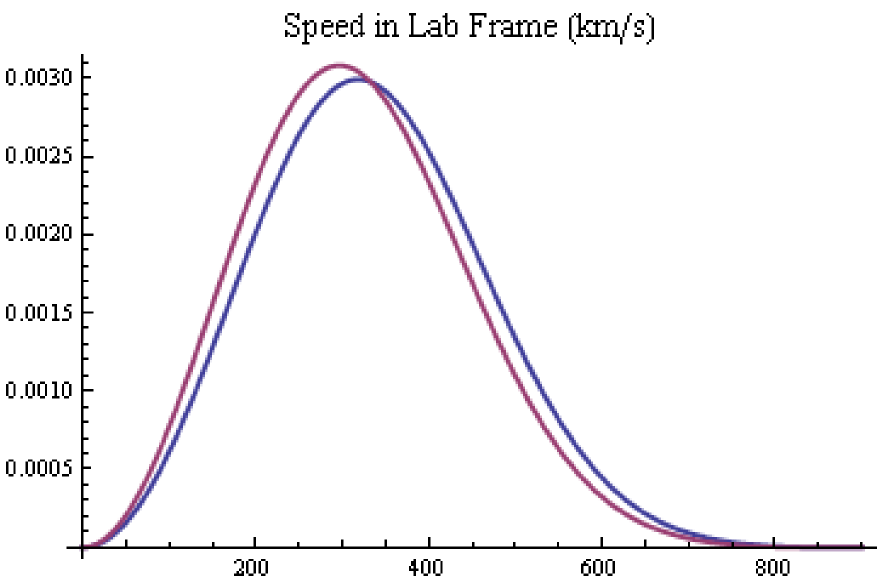
- DAMA only experiment focusing on modulation
- Has seen an excess consistent with expected behavior of DM scattering

Modulation

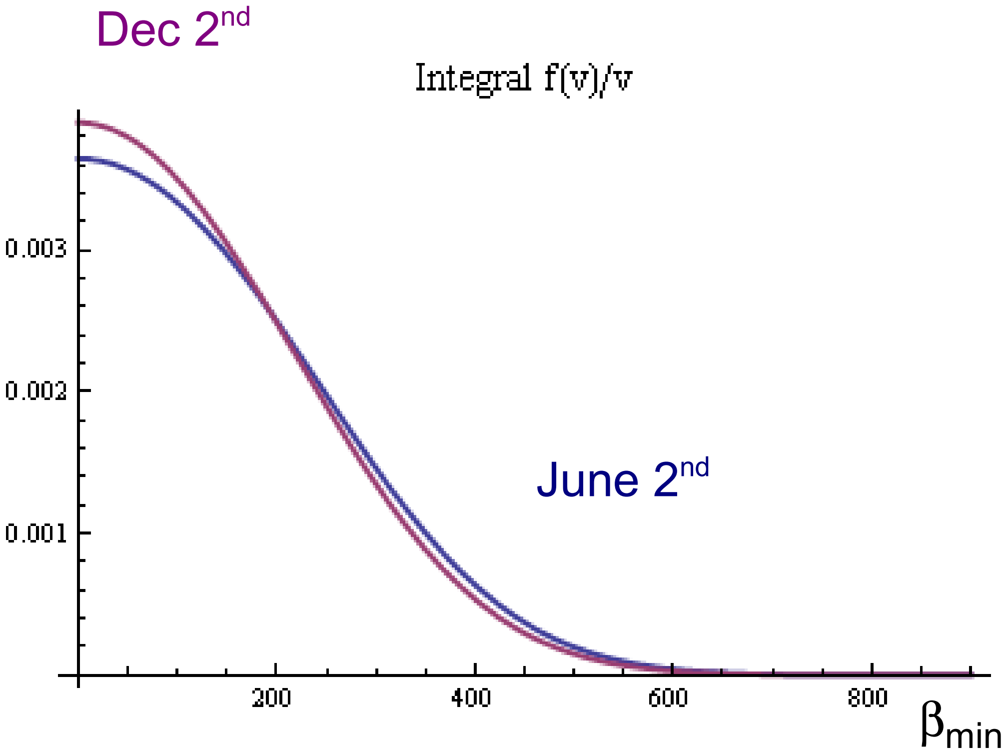
- Due to earth's (and sun's) orbit, velocity distribution changes seasonally







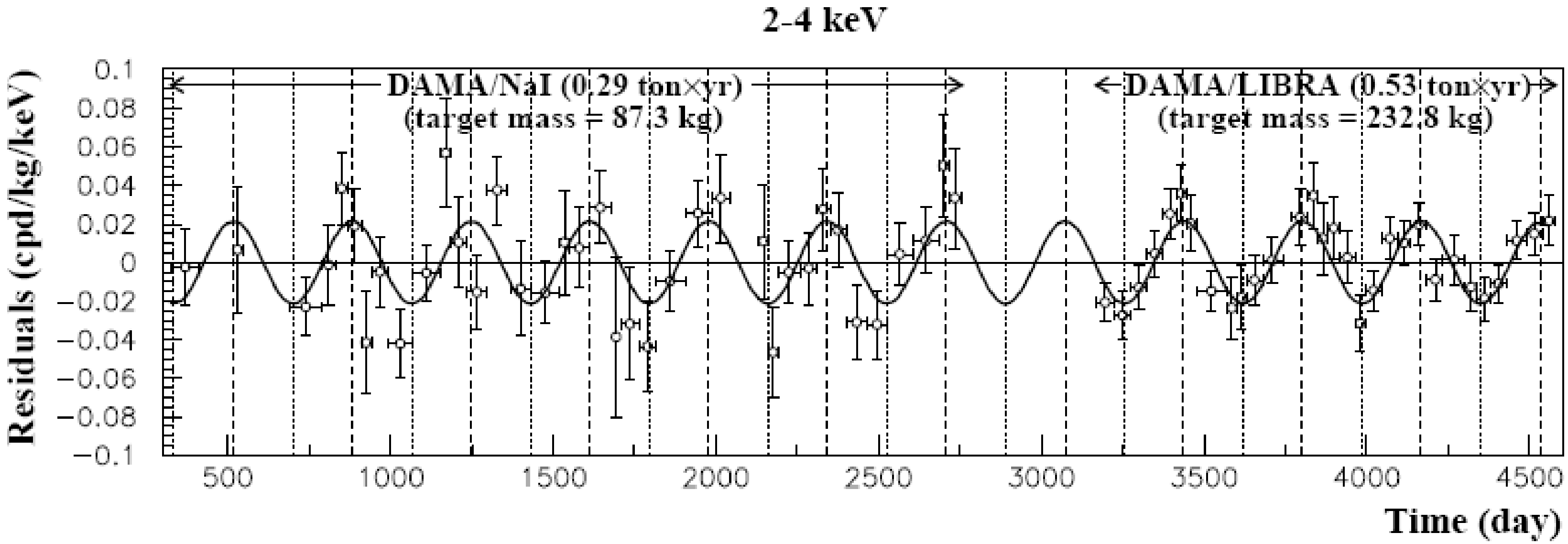
Modulation (cont.)



$$\beta_{min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}}$$

- $dR/dE_R = S_0 + S_m \cos[2\pi(t-t_0)/T]$
- Expect T = 1 year, t_0 = June 2nd (152nd day), S_m positive (negative) for large (small) ER

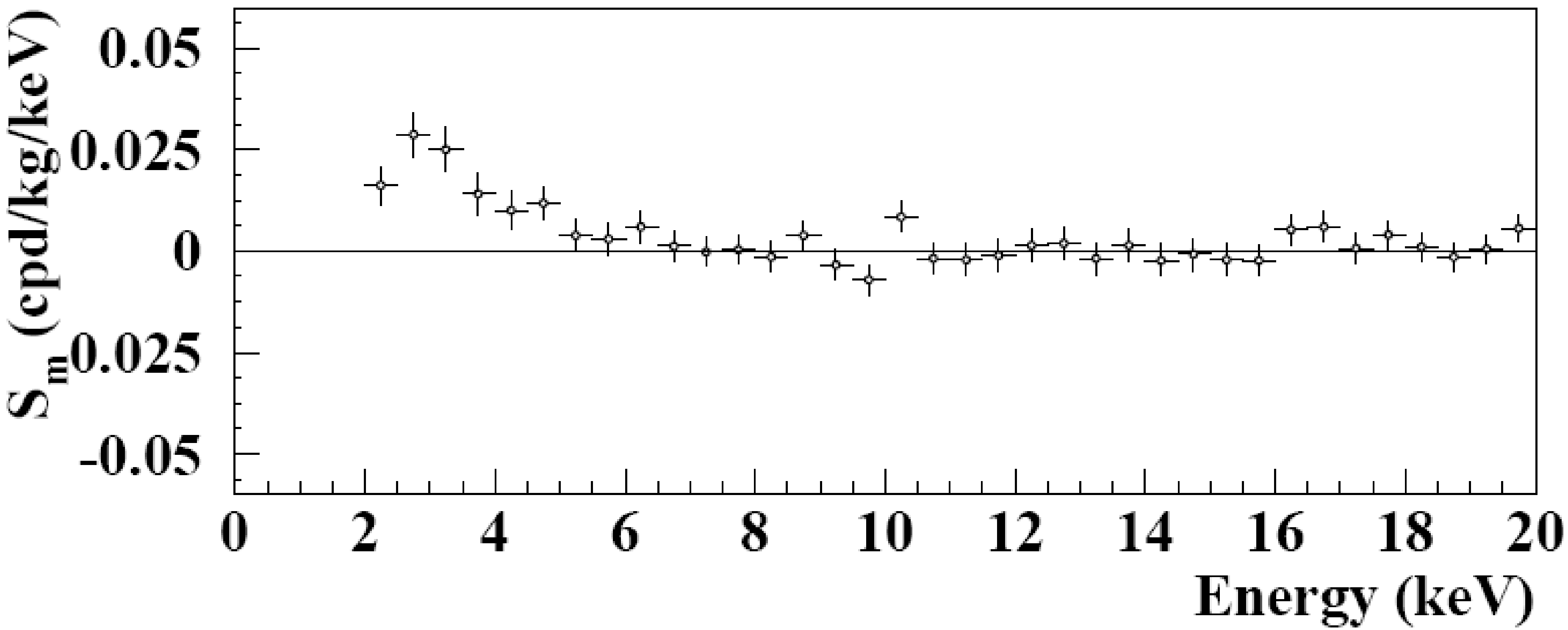
Data Consistent with DM modulation



	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2–4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2–5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2–6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA				
(2–4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7σ
(2–5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9σ
(2–6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6σ
DAMA/NaI+ DAMA/LIBRA				
(2–4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3σ
(2–5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9σ
(2–6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2σ

	Expectations	1	152	

Modulation Spectra



Most events expected at low energy

Consistent Models vs DAMA

- DAMA/LIBRA data is now detailed enough to pin down parameter space of dark matter candidates
- Can check if those models are allowed by other data
- Consider spin-independent scattering, focusing on inelastic dark matter

Inelastic Dark Matter

Smith, Weiner
SC, Kribs, Smith, Weiner

- Models where dark matter scatters dominantly inelastically off nuclei
- Adds extra parameter δ, mass splitting to heavier state
- Kinematics produces a few effects
- Originally proposed to reconcile CDMS and DAMA and appears in “Theory of DM” models, motivated by PAMELA and ATIC

Models of IDM

See D. Morrissey's talk

- Sneutrino with lepton number violation

$$\Phi = (R + i\,I)/\sqrt{2}$$

$$\bar{\Phi}\,\partial_\mu \Phi\, Z^\mu \supset (R\,\partial_\mu I - R\,\partial_\mu I)\, Z^\mu$$

- Pseudo-Dirac Neutrino

$$\Psi = \begin{pmatrix} \xi \\ \bar{\eta} \end{pmatrix} \qquad \chi_\pm = \xi \pm \eta$$

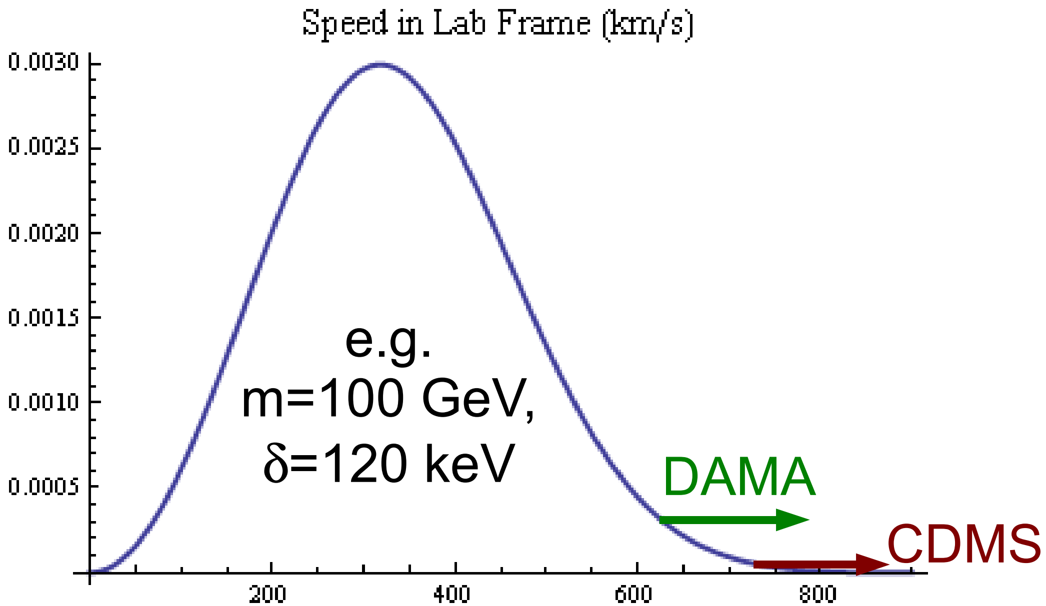
$$\bar{\Psi}\,\gamma_\mu Z^\mu \Psi \supset \bar{\chi}_+ \gamma_\mu Z^\mu \chi_-$$

Mass splitting technically natural due to breaking of U(1) symmetry

Preference for Heavy Targets

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

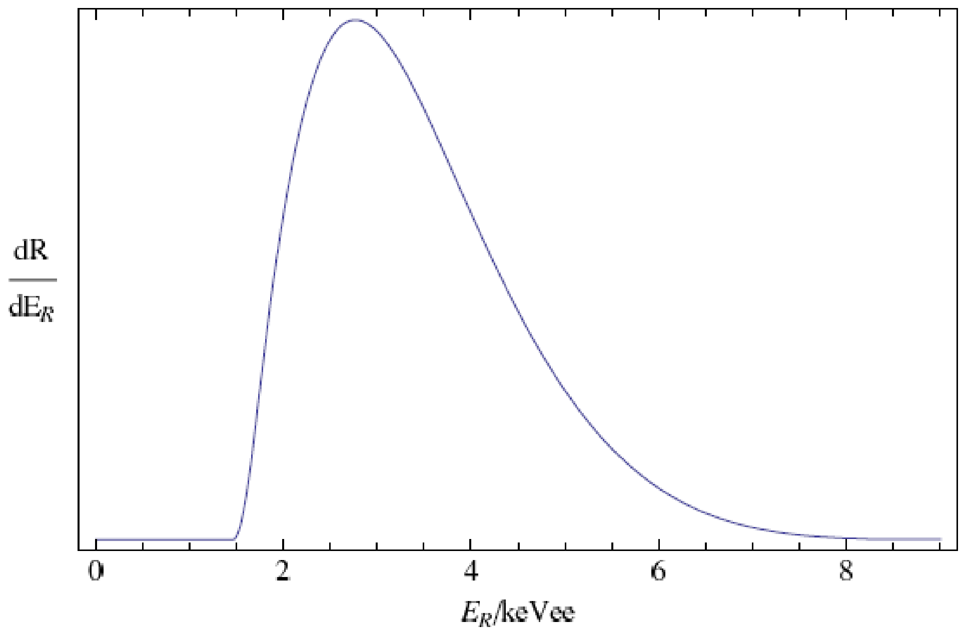
$$\beta_{threshold} = \sqrt{\frac{2\delta}{\mu_N}}$$



- Threshold velocity in order to excite to higher DM state
- Heavier targets sample lower velocities, giving enhanced rates

Distinct Spectra

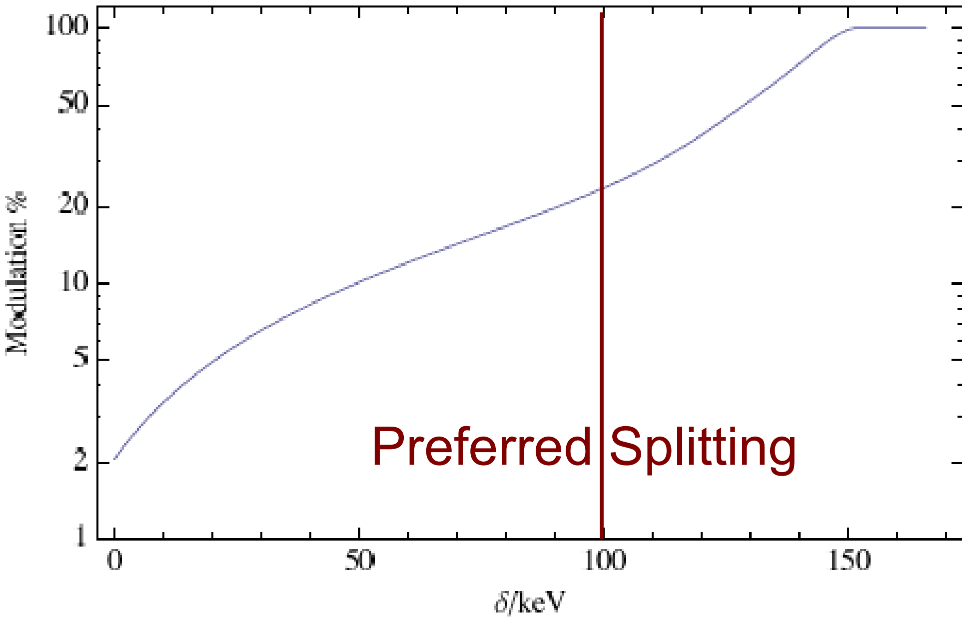
$$\beta_{min} = \frac{1}{\sqrt{2 m_N E_R}} \left(\frac{m_N E_R}{\mu_N} + \delta \right)$$



- Low energy recoils require higher velocities
- Full expt'l spectra is important, model, constraints depend strongly on event distribution

Enhanced Modulation

- Sampling of higher velocity tail, means more modulation
- Expt: Dates of data taking crucial to setting limits. Can search for enhanced modulation

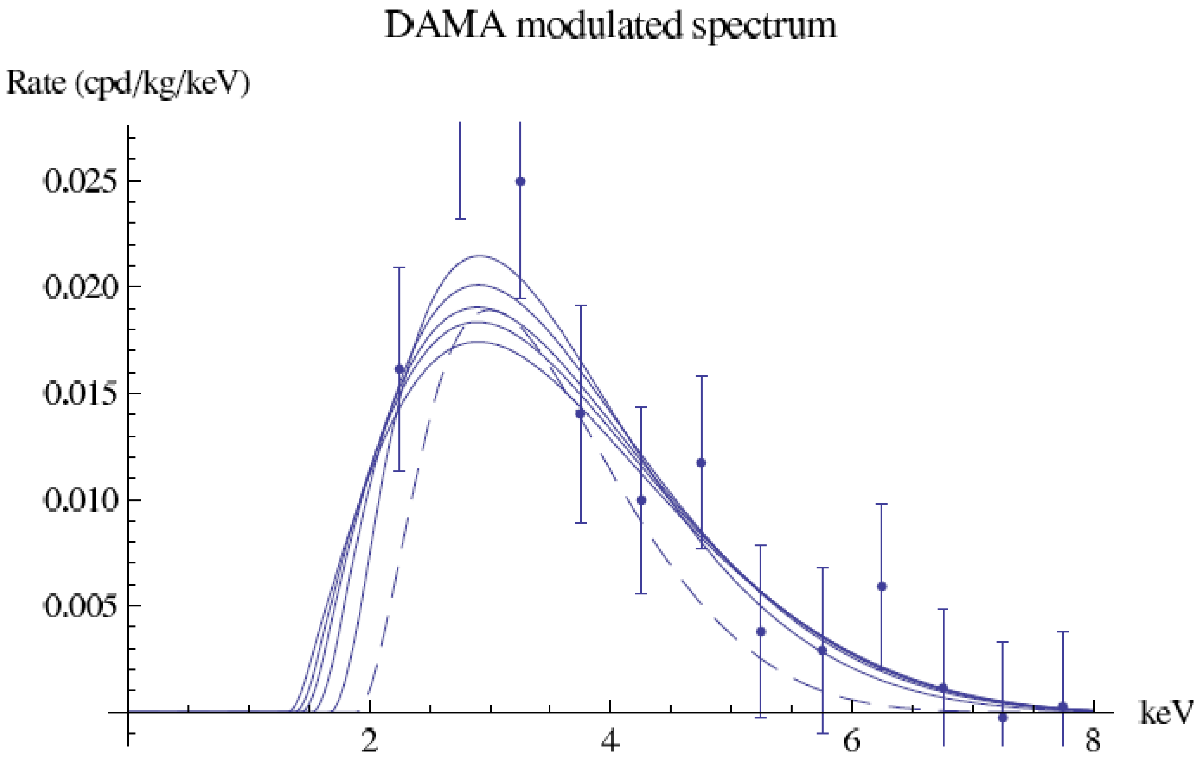


Modulation in observed DAMA range

Benchmark Values

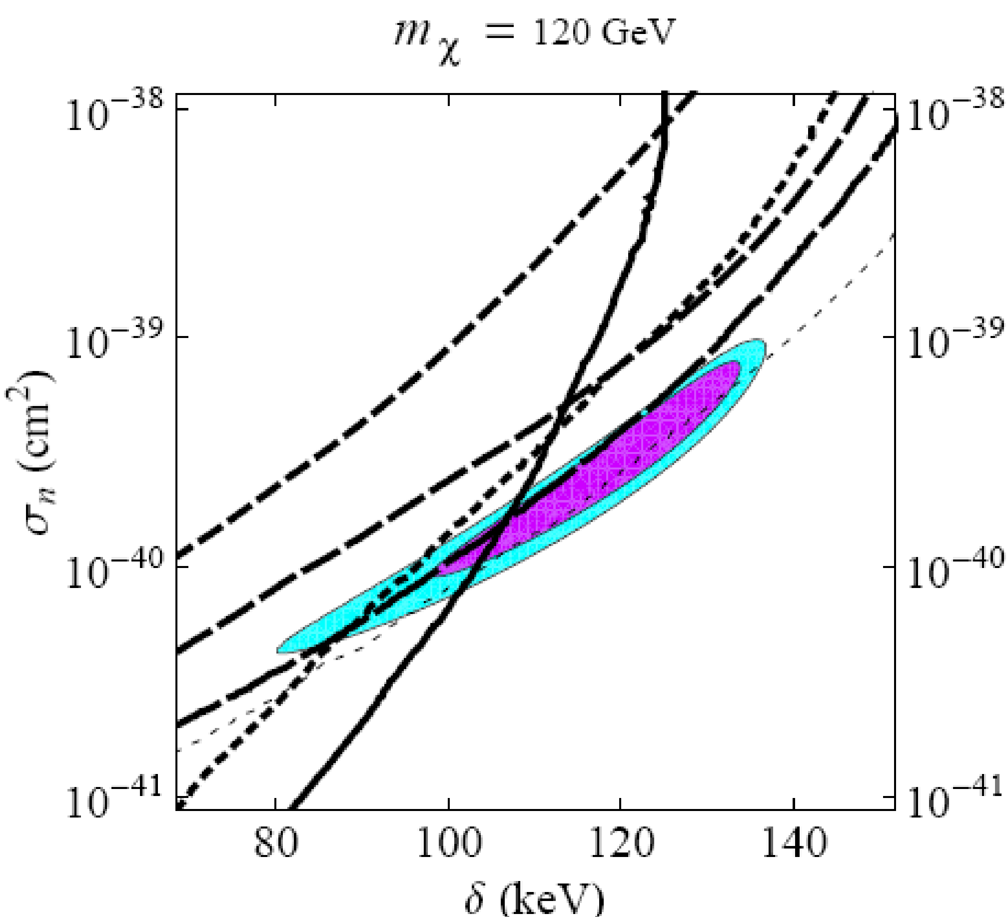
#	m_χ (GeV)	σ_n (10^{-40} cm^2)	δ (keV)	DAMA 2-6 keVee (10^{-2} dru)	XENON 4.5-45 keV (counts)	CDMS 10-100 keV (counts)	ZEPLIN 5-20 keVee (counts)	KIMS 3-8 keVee (10^{-2} dru)	CRESST 12-100 keV (counts)
expt				1.31 ± 0.16	24 (31.6)	2 (5.3)	29 (37.2)	5.65 ± 3.27	7 (11.8)
1	70	11.85	119	0.89	1.39	0	8.46	0.65	8.76
2	90	5.75	123	1.21	5.52	0	14.40	1.52	9.75
3	120	3.63	125	1.22	9.06	0.13	18.09	2.18	10.7
4	150	2.92	126	1.18	11.17	0.95	19.93	2.53	11.2
5	180	2.67	126	1.15	12.46	1.93	21.01	2.74	11.6
6	250	2.62	127	1.11	14.01	3.60	23.32	3.00	12.1

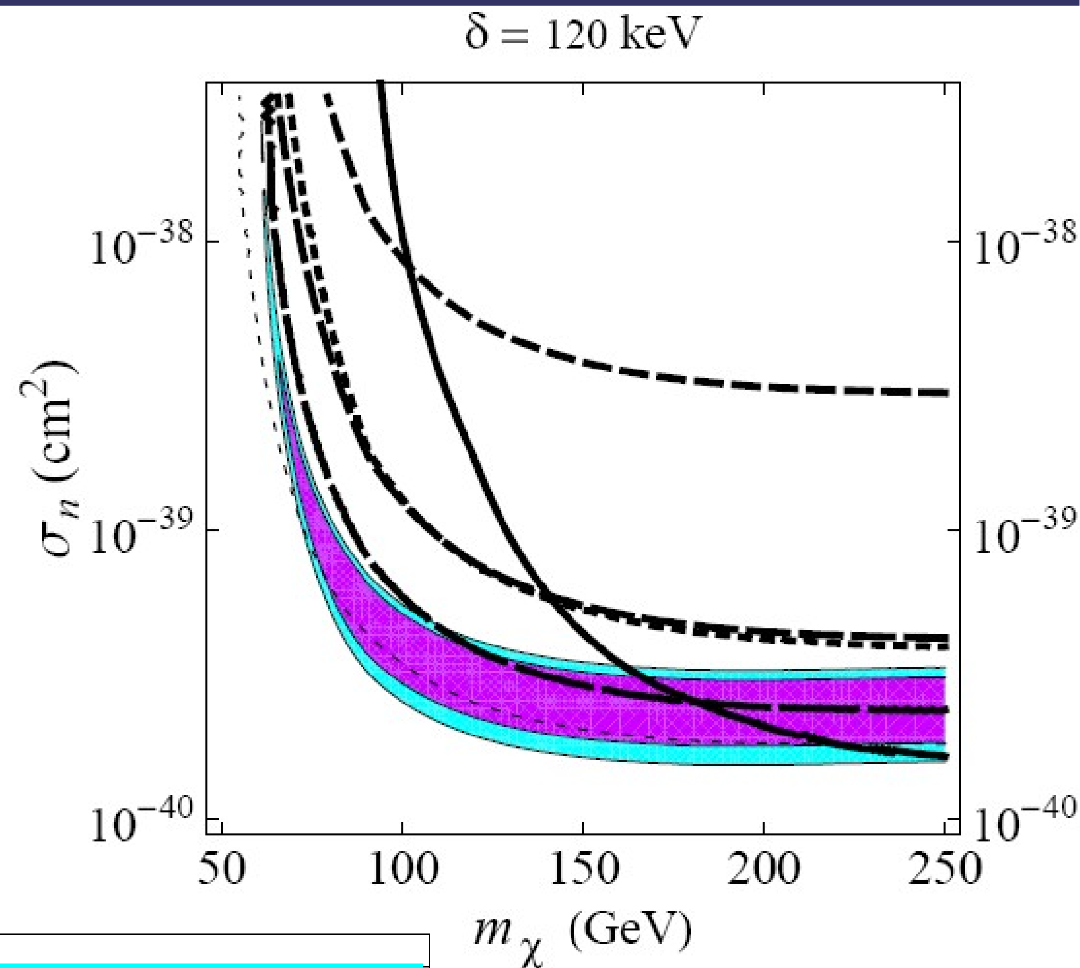
DAMA Spectra Benchmarks

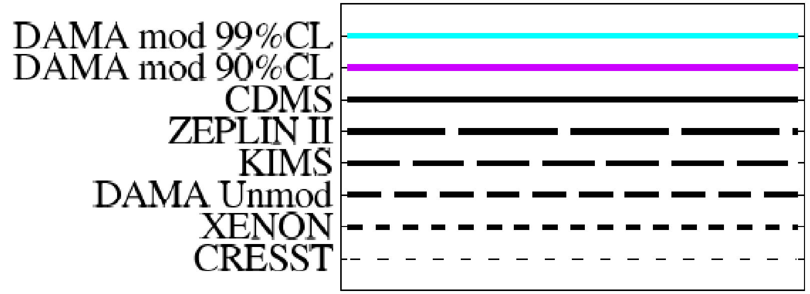


For different dark matter masses, each fit prefers a range for δ, as it shifts the peak

IDM Plots



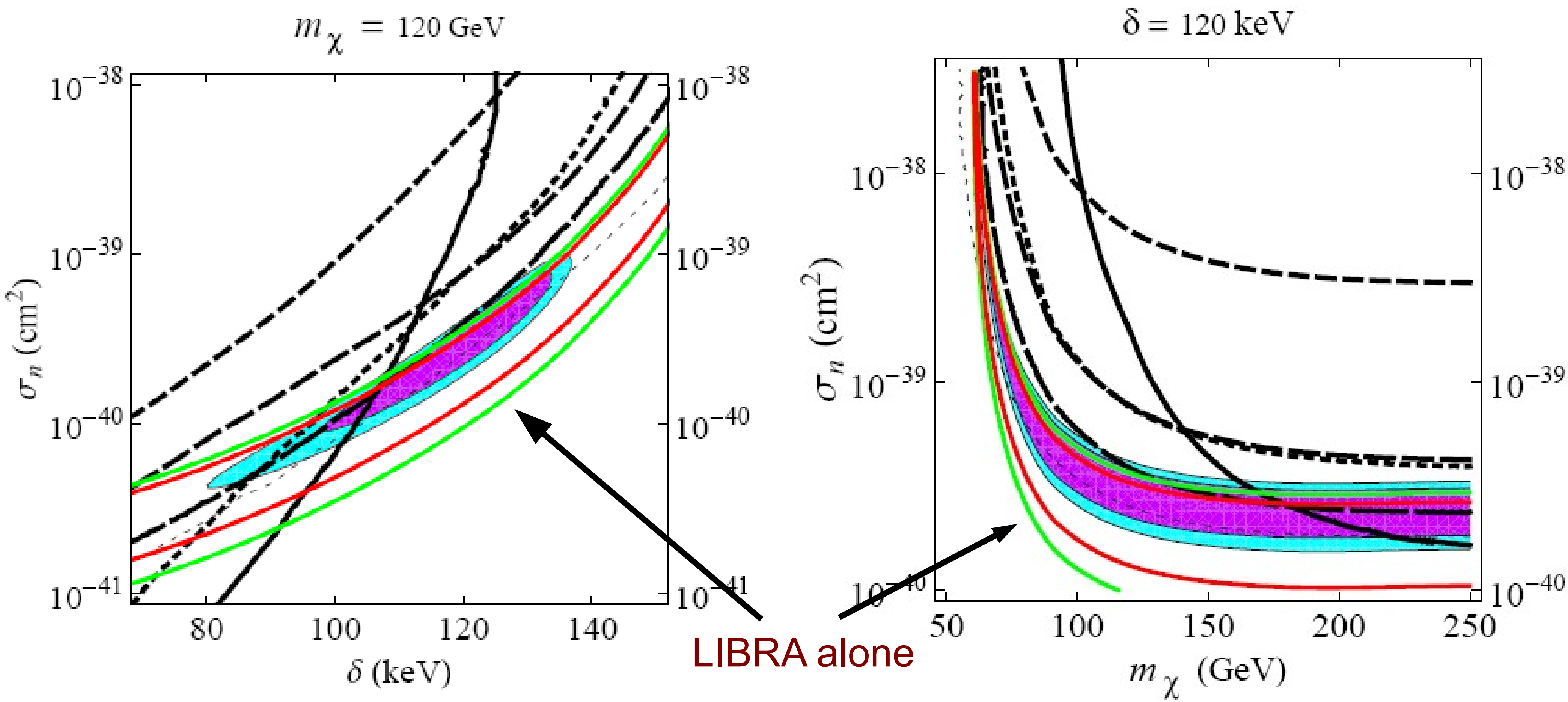




Constraints are p_{max} (Yellin)

CRESST and ZEPLIN strongest!

DAMA/LIBRA vs DAMA/NaI

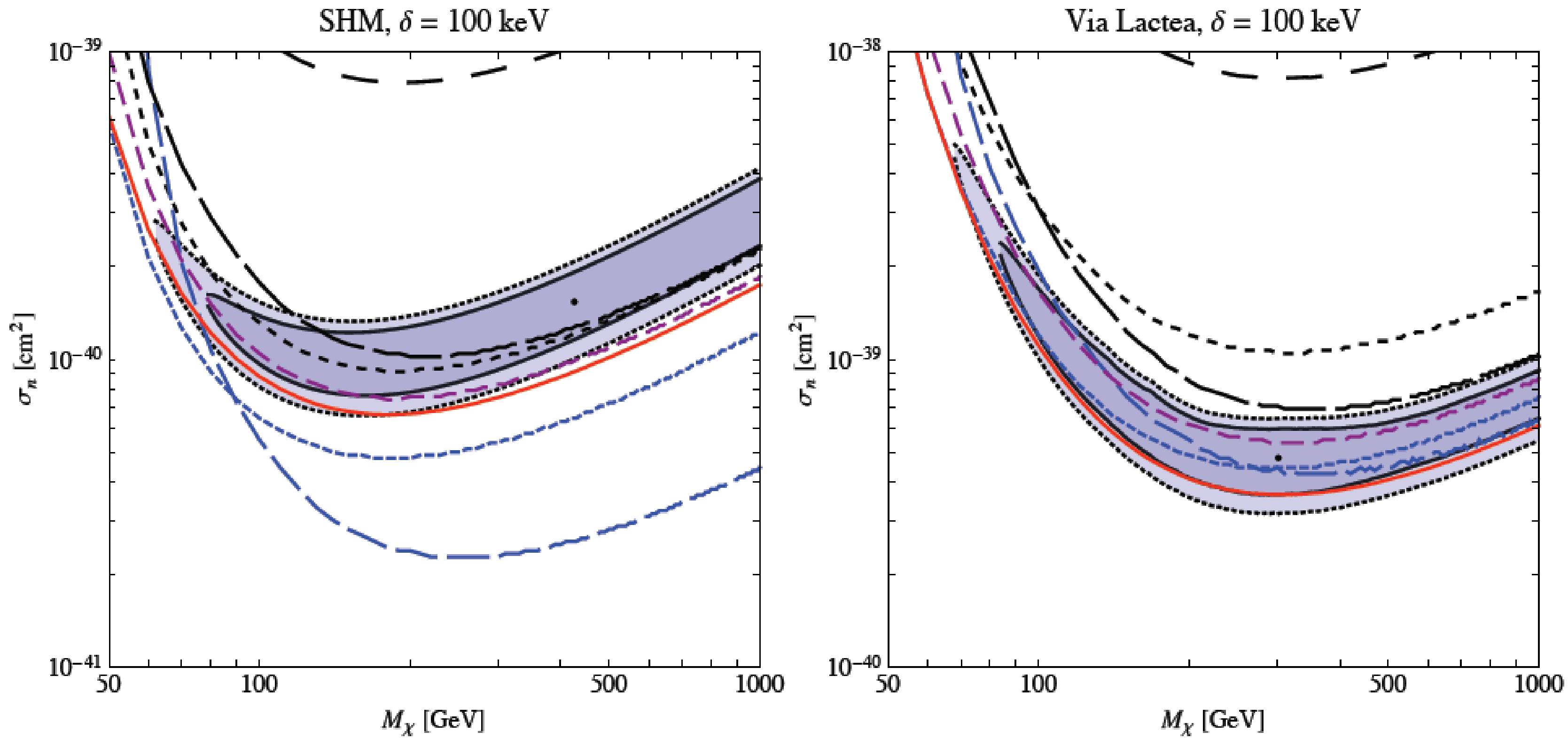


Potential systematic, DAMA/NaI modulation high compared to DAMA/LIBRA

In 2-6 keV, NaI: .0200 +/- .0032 and LIBRA: .0107 +/- .0019

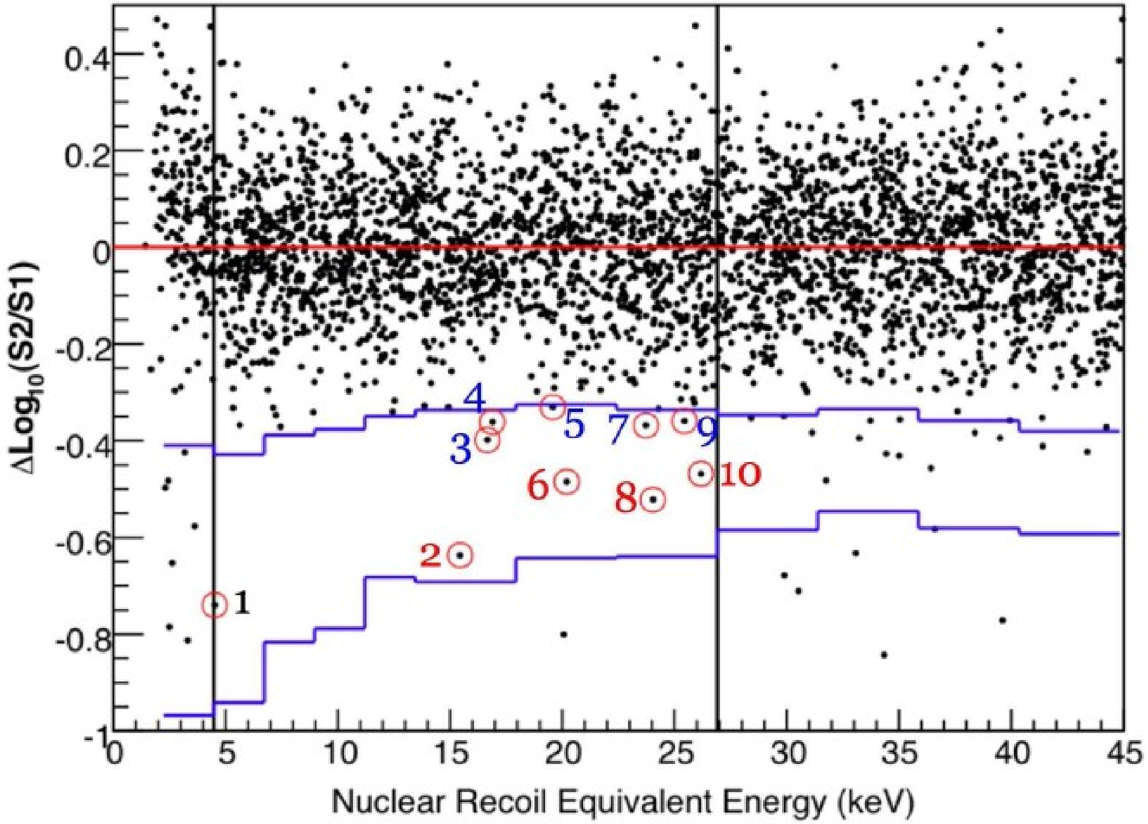
Complementary Analyses

March-Russell et.al.
Cui et.al.

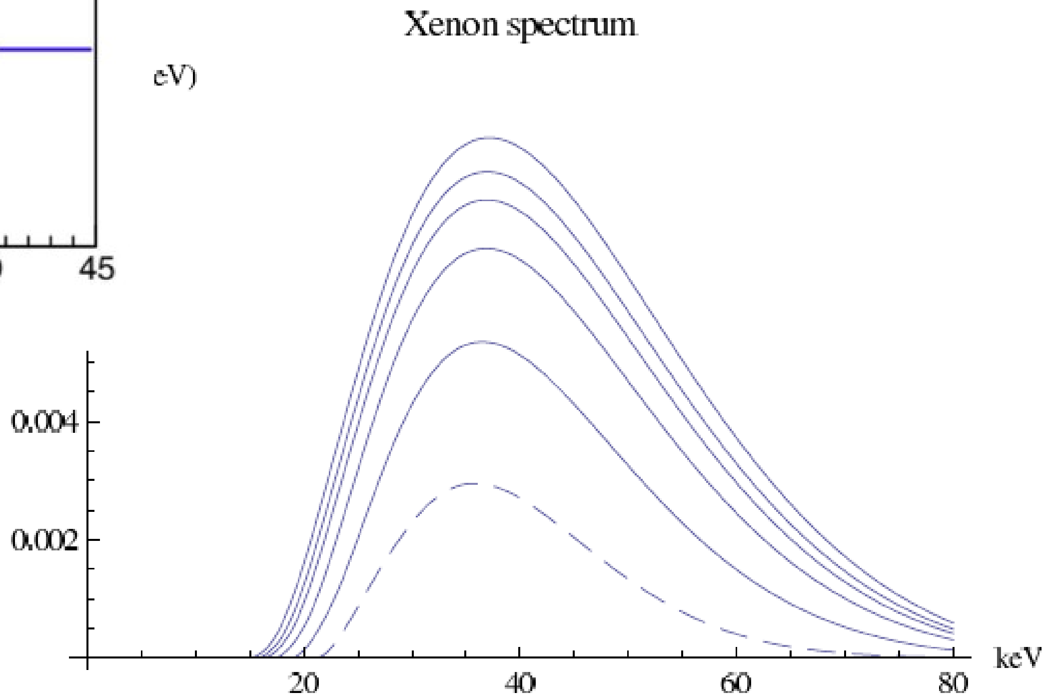


JMR et.al. found similar results and explored variations of DM velocity distributions, experimental unknowns, etc...

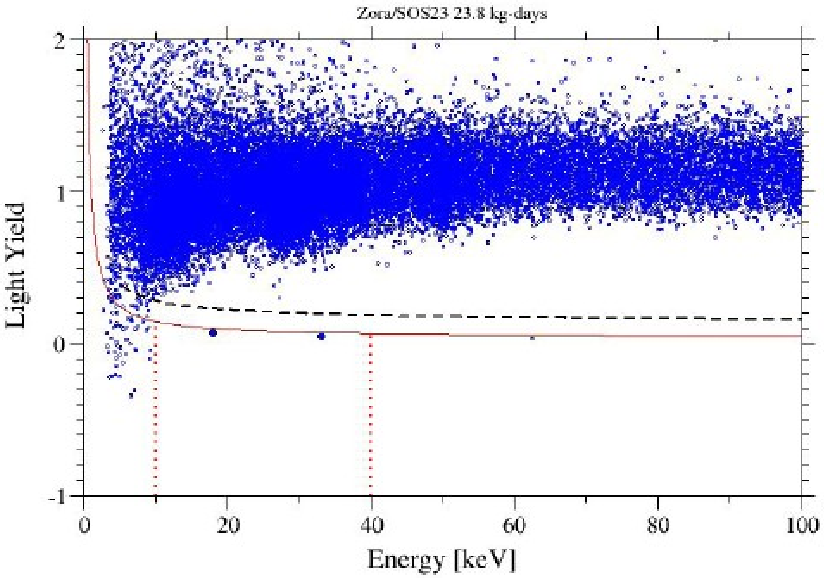
XENON Data

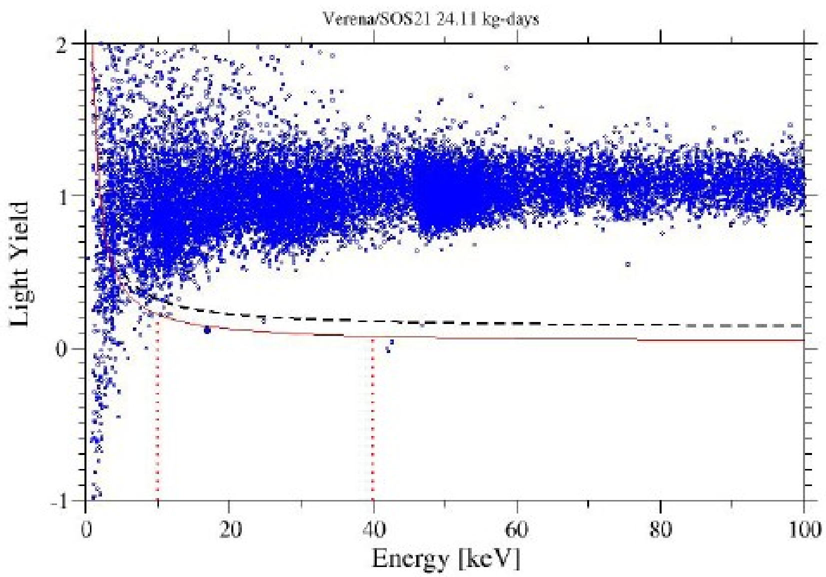


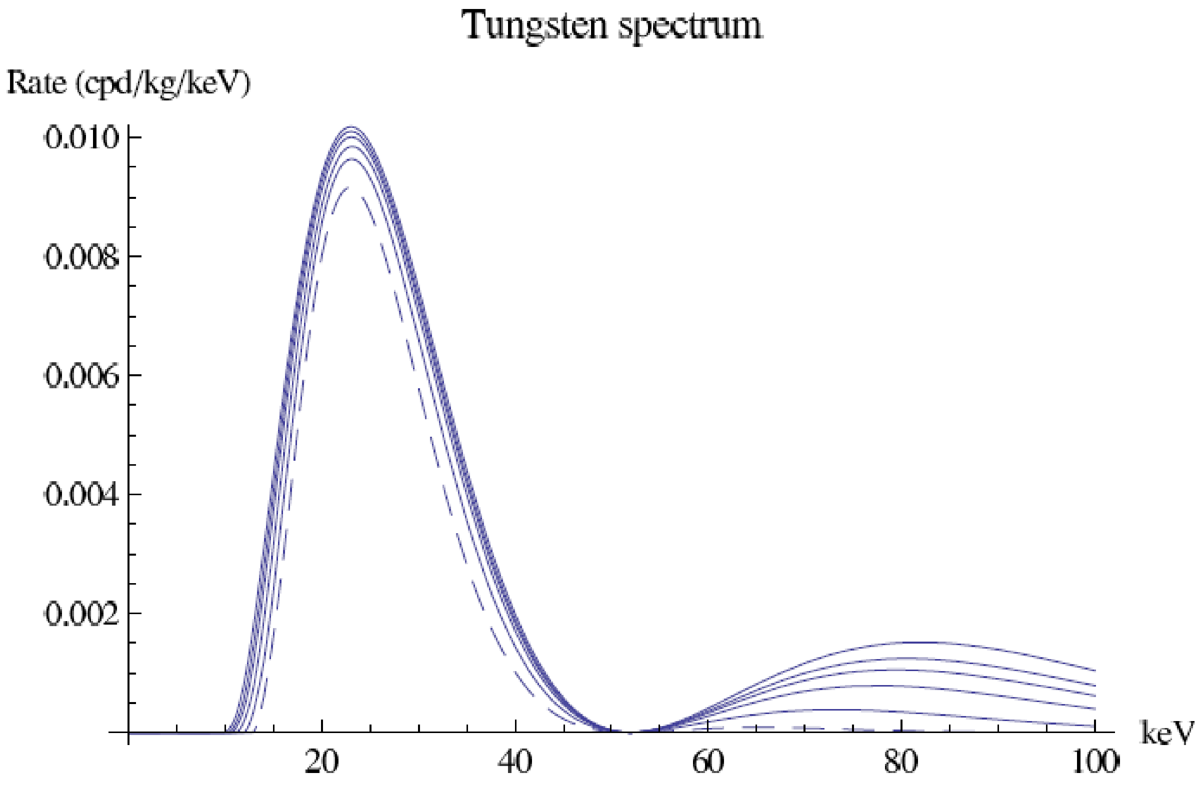
Analysis region (< 27 keV) misses most of the IDM recoils



CRESST Data







- Expected bkgd is zero
- Seven events observed, inconsistent with neutrons, but in tension with spectra

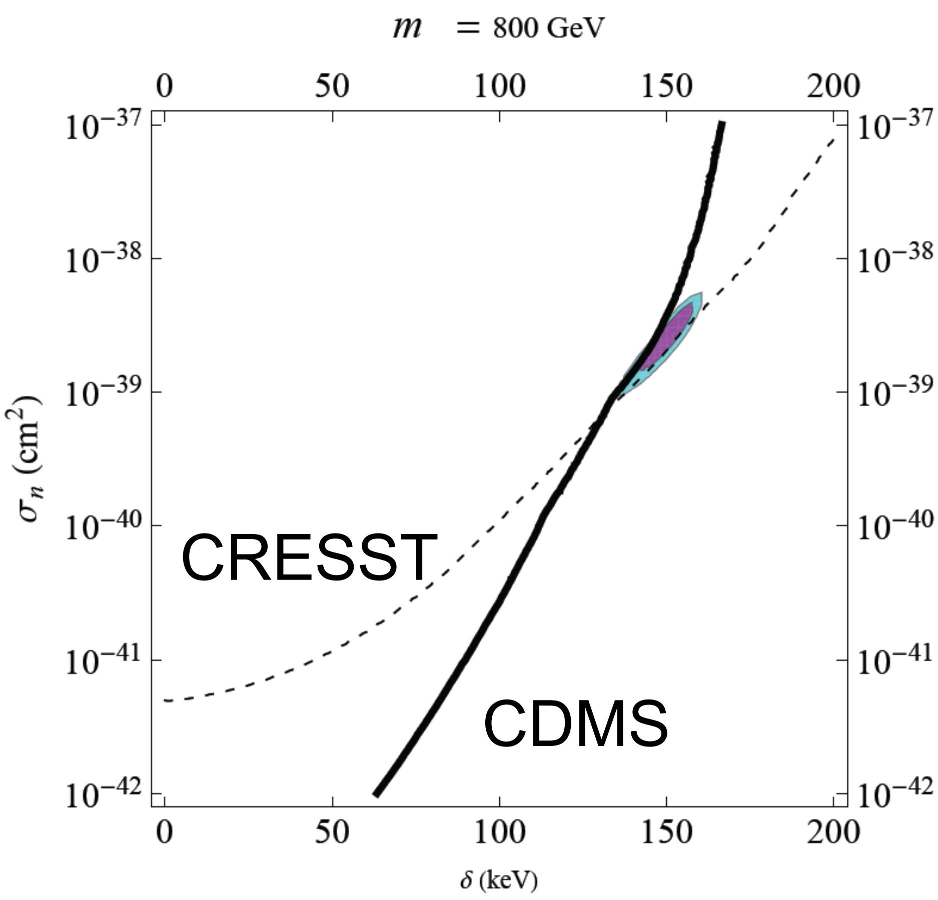
Theory of Dark Matter

See Neal and Lian-Tao's talks

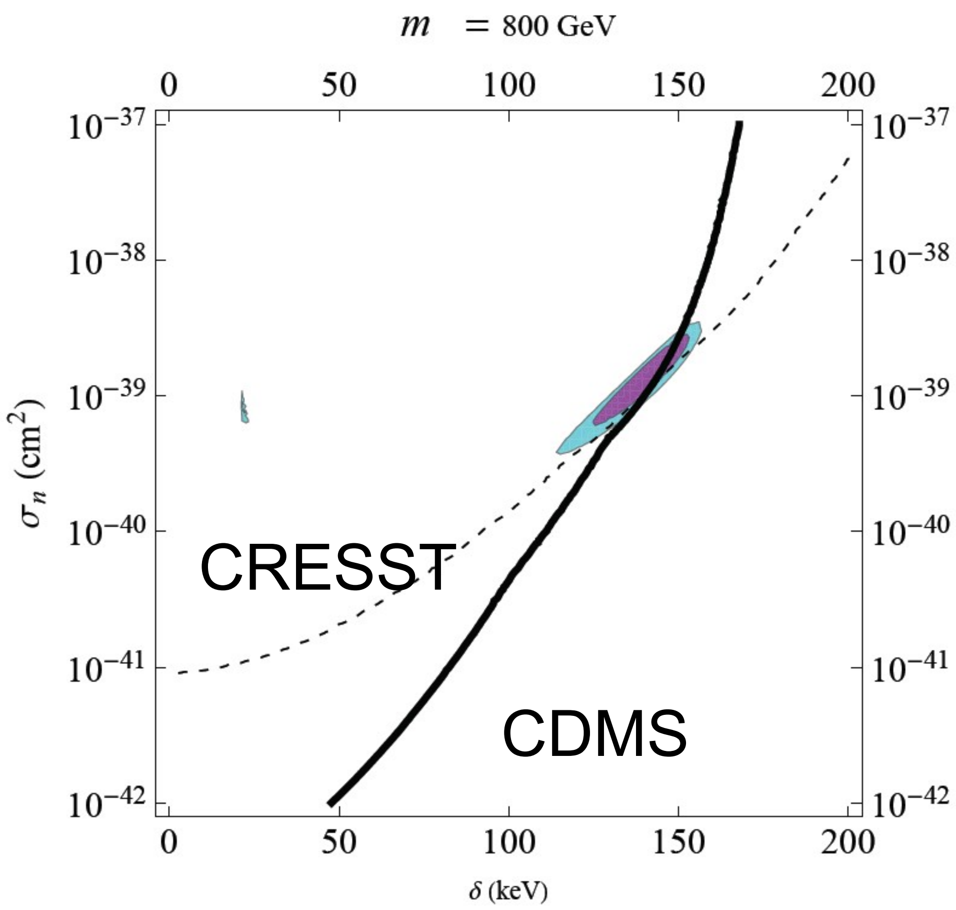
- Dark matter mass due to ATIC is 800 GeV – 1 TeV
- With dark gauge symmetry, broken ~ GeV, inelastic splitting and scattering can be generic
- Plots from before rule out m > 250 GeV.
- However, inelastic scattering is mediated by light vector ϕ, giving $1/(q^2-m_\phi^2)^2$ in rate

Preliminary Results: Pushes to larger $\delta \sim 140$ keV

$m_\phi \sim 8$ MeV



$m_\phi \sim 80$ MeV



Conclusions

- DAMA's new data is predictive enough to set up a non-moving target
- Inelastic Dark Matter not ruled out
- Has some features suggested by DAMA
- Heavy target expts: CRESST, XENON, LUX, KIMS, ZEPLIN should see high energy events and possibly modulation