Robust Signals of DARK MATTER

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Dark Attack
Ascona
July 17, 2012

Unknown unknowns and DM

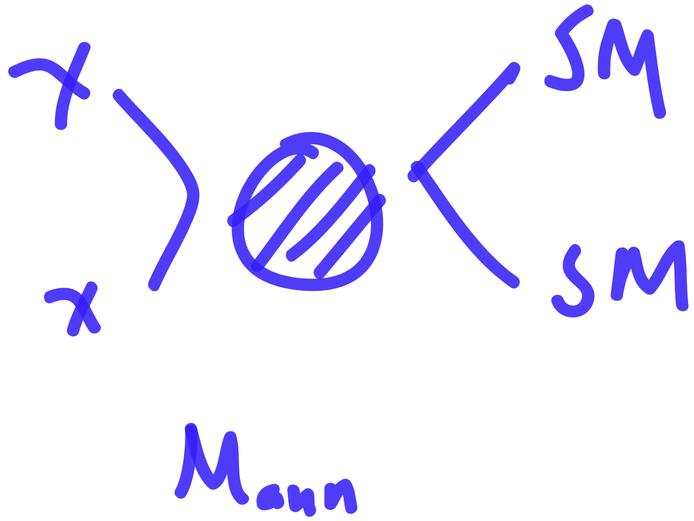
- We have enough uncertainties about DM
- What kinds of signals or constraints can we make that do not depend on so many things?

Plan

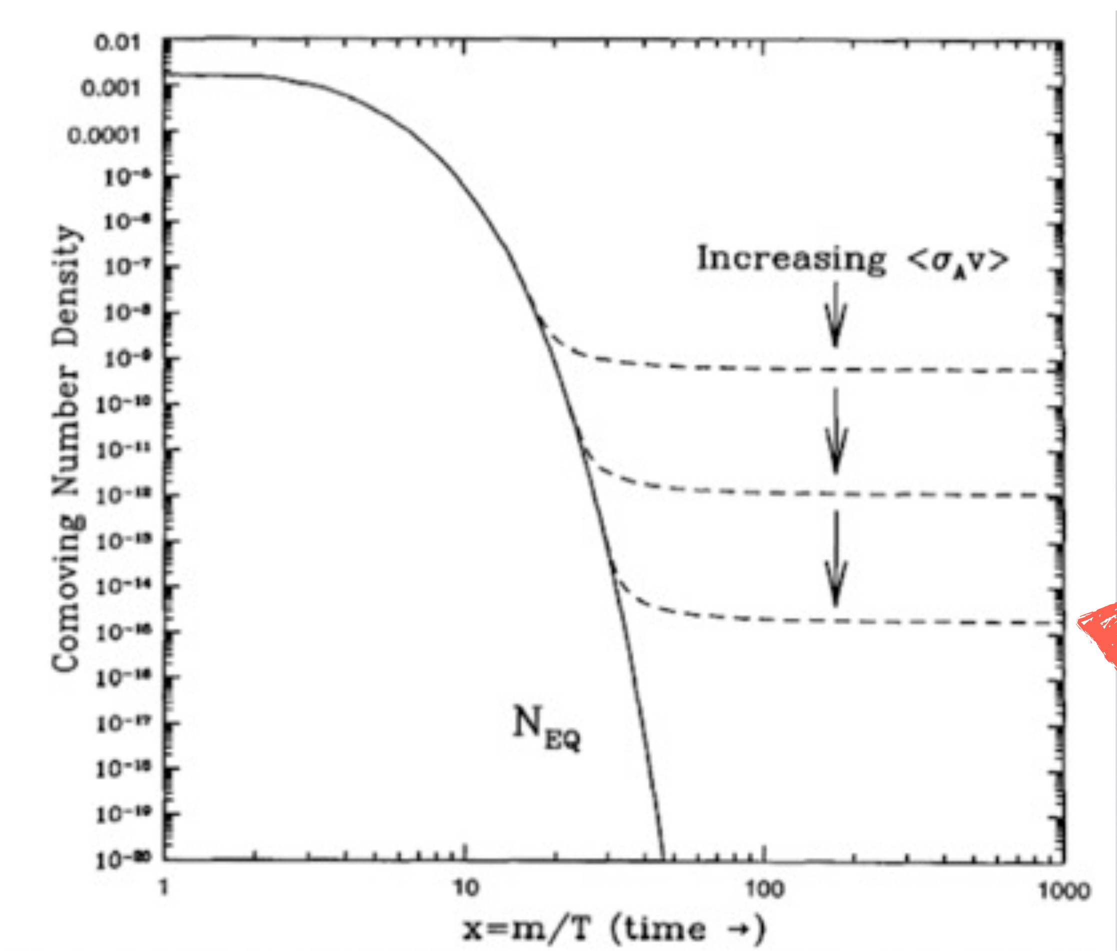
- Robust signals of DM (what is the DM is not “the” DM?)
- Robust limits on DM (removing astrophysics)

Robust signals

- Why should we care about a WIMP that is not “the” DM?
  - (Anthropic multiverse landscape discussion here)
  - Already know 5 stable fundamental particles that are not “the” DM
  - Know 253+34 composite particles that are cosmologically stable



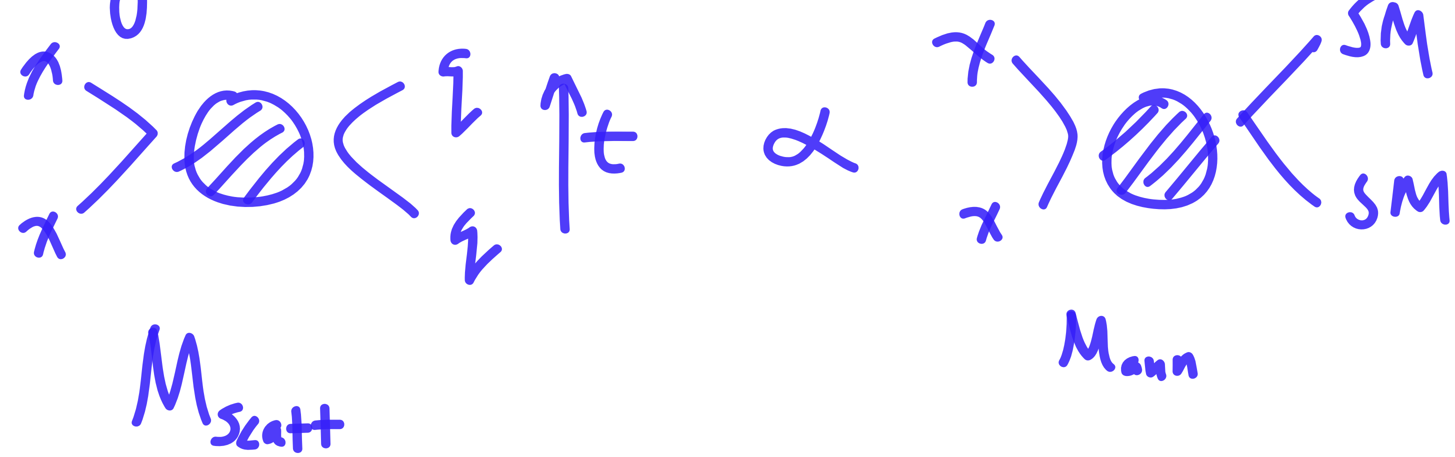
$$\rho \sim \frac{1}{\sigma v} \sim \frac{1}{M_{ann}^2}$$



what about stable particles here?

what can we learn from simple scaling arguments?

Scaling relationships:

if 

$$R \sim n_\chi \sigma \sim n_\chi M_{scatt}^2 \qquad \rho \sim \frac{1}{\sigma v} \sim \frac{1}{M_{ann}^2}$$

$$\Rightarrow R \sim \frac{1}{M_{ann}^2} \times M_{scatt}^2 \sim \text{const}$$

Scattering rate is approximately invariant

e.g. Duda & Gelmini
0102200

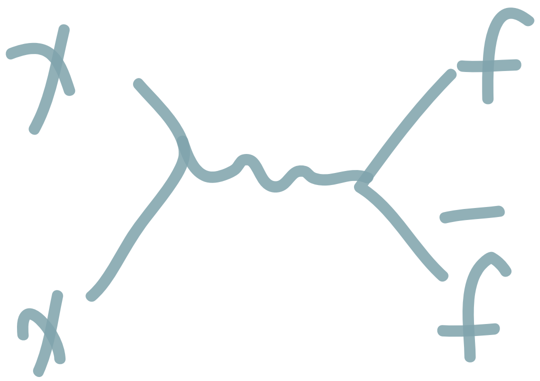
Even subdominant WIMPs are plausibly detectable

weak coupling ⟷ strong coupling
more DM ⟷ less DM

rate ~ constant

How true is this?

Consider vector exchange

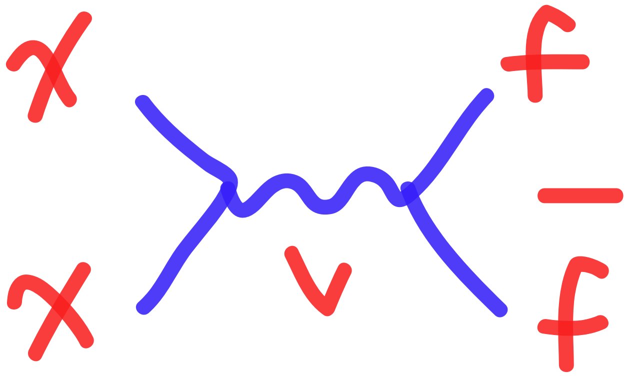


$$\sigma = \frac{G_F^2}{2\pi} \mu_{\chi n}^2 \frac{1}{A^2} \left((1-4\sin^2\theta_W) Z - (A-Z)\right)^2$$

$$\sim 10^{-39}\, \text{cm}^2$$

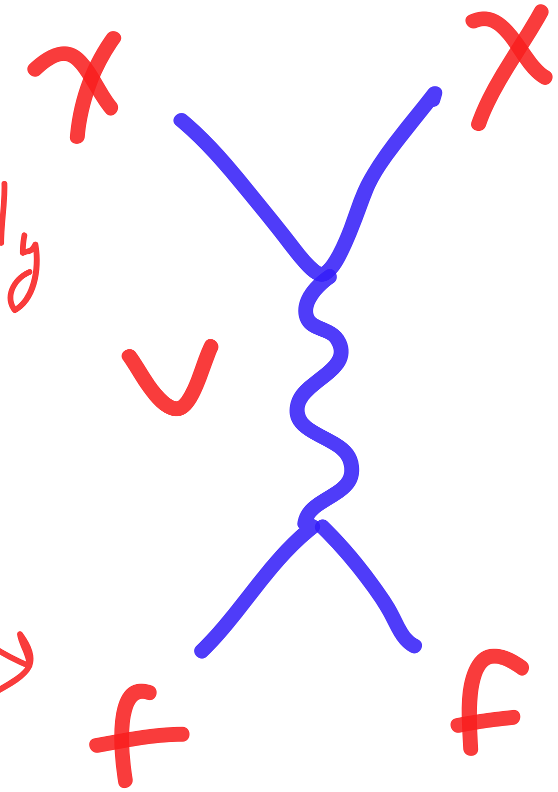
$$\sim \text{const}$$

Scaling is for <u>dimensionless</u> couplings

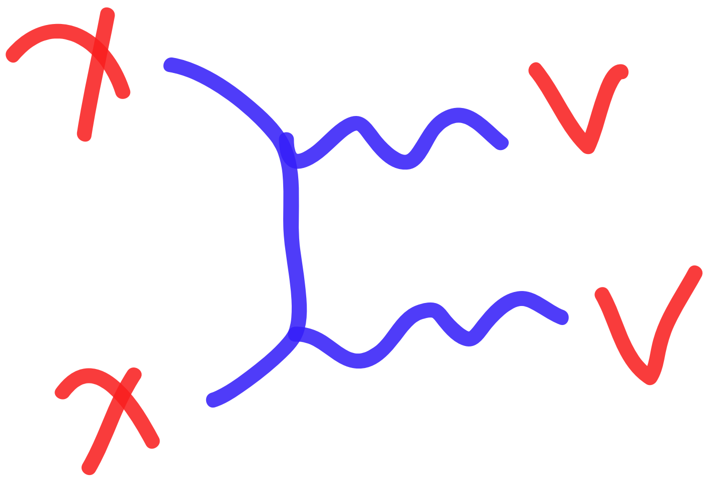


$$\frac{g_\chi^2 g_f^2 m_\chi^2}{m_V^4}$$

parametrically related



$$\frac{g_\chi^2 g_f^2 \mu^2}{m_V^4}$$



$$\frac{g_\chi^4}{m_\chi^2}$$

parametrically distinct

The heuristic argument that subdominant WIMPs have the same scattering rate as dominant WIMPs is limited

that said, the failure of the argument goes both ways (up or down) so the *qualitative* point that subdominant WIMPs are detectable seems robust

What about indirect detection?

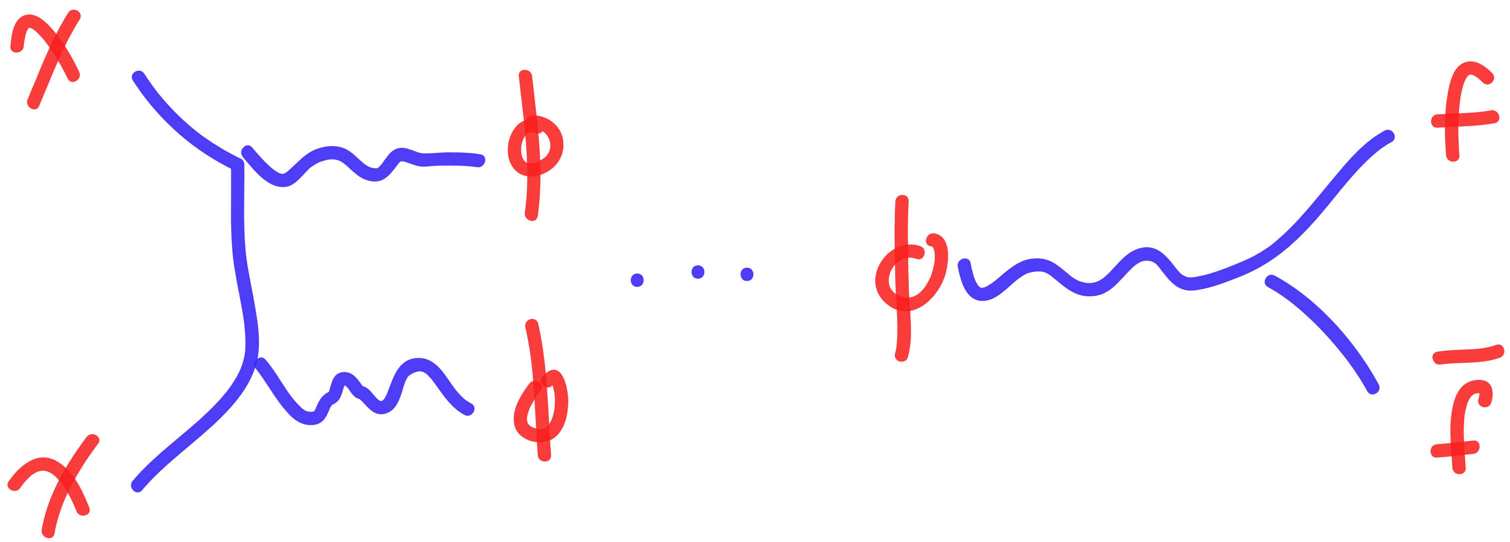
$$\rho \sim \frac{1}{\sigma_{ann}}$$

$$R \sim \rho^2 \sigma_{ann} \sim \frac{1}{\sigma_{ann}^2} \sigma_{ann} \sim \frac{1}{\sigma_{ann}}$$

$\Rightarrow$ Seems to prefer low σ

i.e. "the" DM

Or does it...?



$\sigma_{ann} \sim \frac{\alpha^2}{m^2}$

$\rho \sim \frac{1}{\sigma} \sim m^2 \Rightarrow n = \frac{\rho}{m} \sim m$

$R \sim n^2 \sigma \sim m^2 \times \frac{1}{m^2} \sim$ const

$\Rightarrow$ if a WIMP annihilates into a dark force, it can show up even if it is not "the" DM

An interesting example

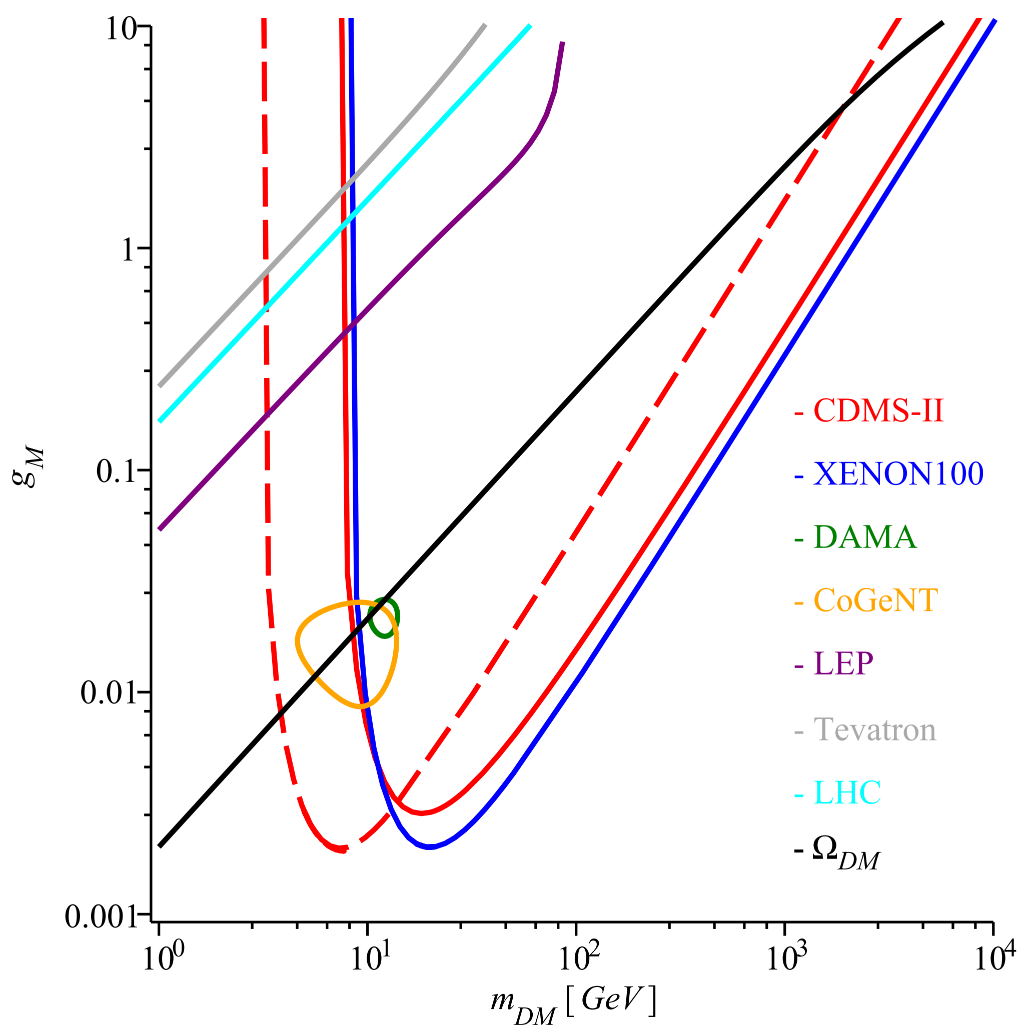
Consider DM with a magnetic dipole

$$\mu_\chi \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu}$$

NB: this operator is off-diagonal

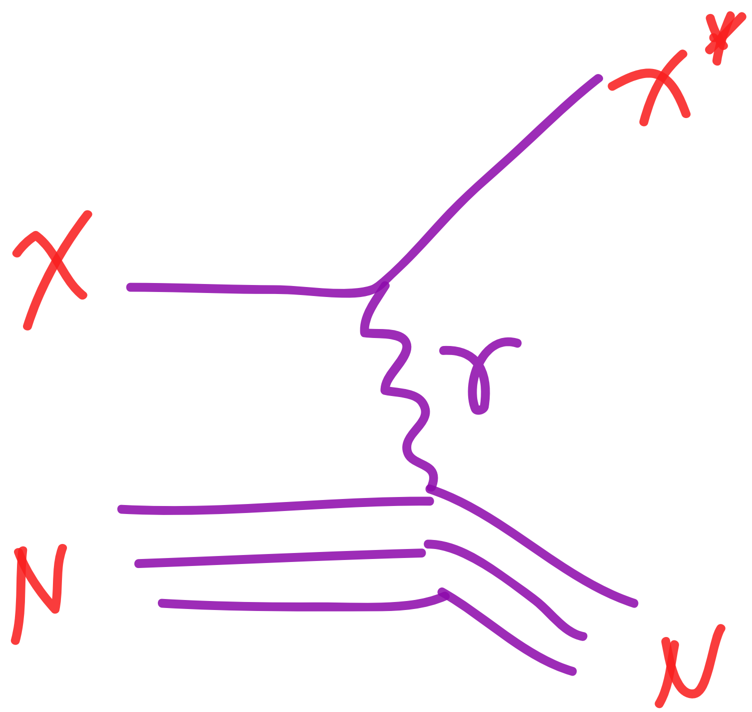
ie $\chi_1 \sigma^{\mu\nu} \chi_2 F_{\mu\nu}$

If $m_{\chi_1} = m_{\chi_2}$ (i.e., it's Dirac)
bad news

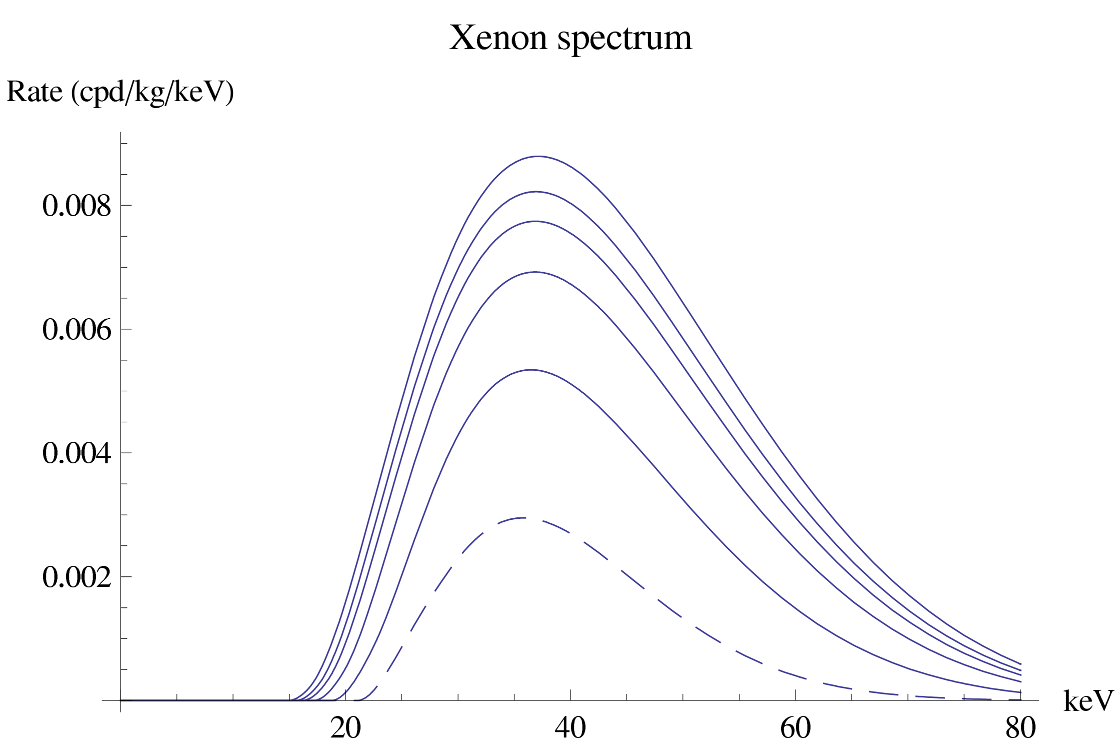


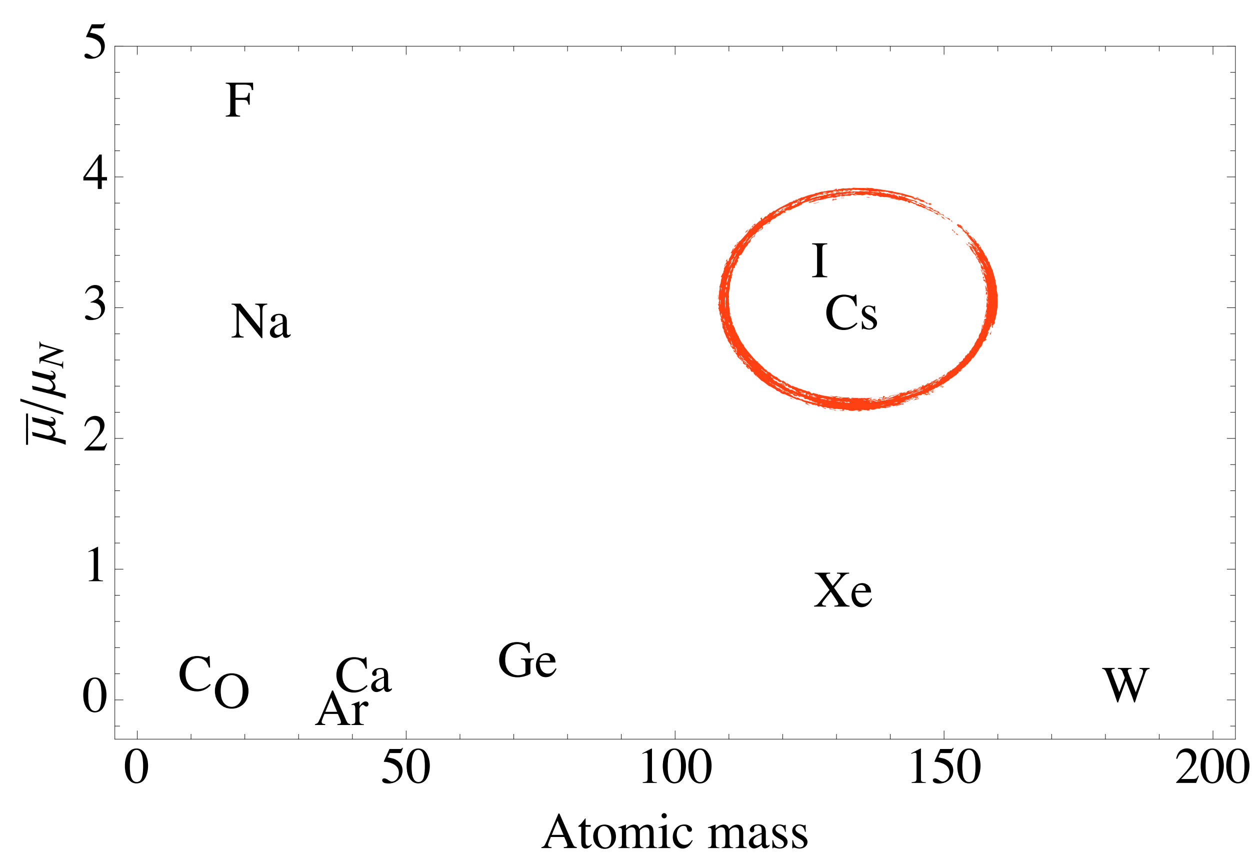
Fortin + Tait 1103.3289

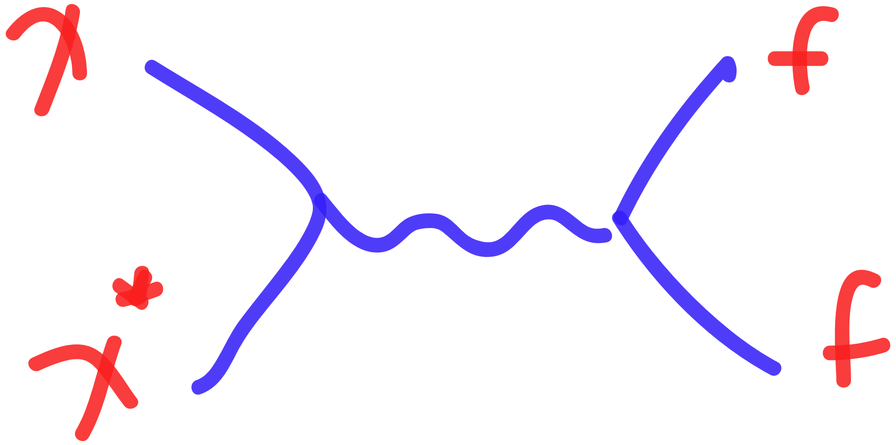
If it is inelastic, good news



"magnetic inelastic" DM



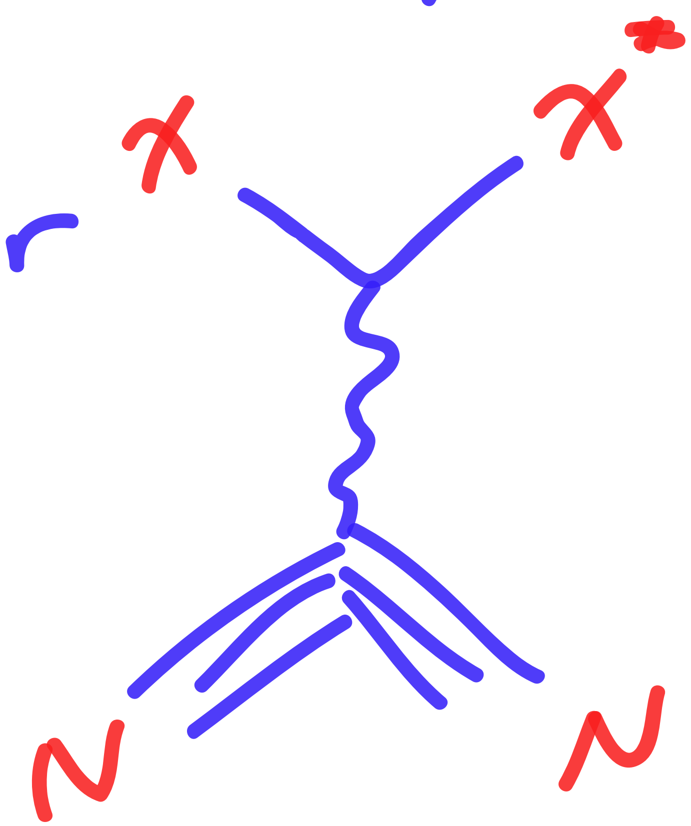




freezeout

$$\rho \sim \frac{1}{\mu_\chi^2}$$

scatter

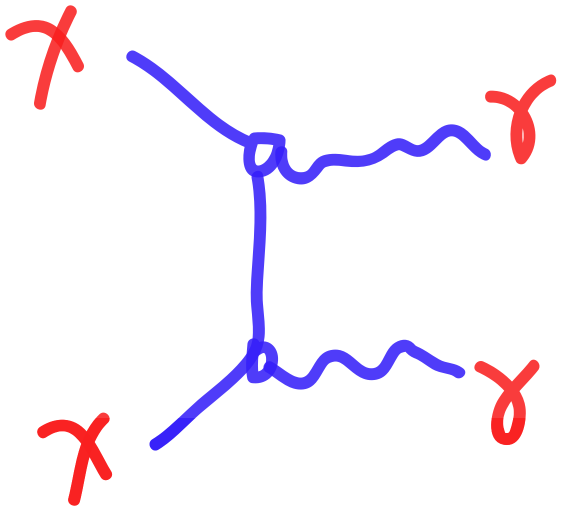


$$\sim \mu_\chi^2 \times n \sim \mu_\chi^2 \times \frac{1}{\mu_\chi^2}$$

$\sim$ constant

Indirect signals

Goodman et al 1009.0008



$\chi\chi \to \gamma\gamma$

$$R \sim \rho^2 \sigma_{\gamma\gamma} \sim \left(\frac{1}{m_\chi^2}\right)^2 m_\chi^4$$

$$\sim \text{const}$$

$$\sim \sigma_{\gamma\gamma} \simeq 3\times 10^{-29}\,\text{cm}^3/\text{s}$$

(a bit small for the 130 GeV line, but can have O(1) corrections)

$$R_{DD} \propto n_\chi \mu_\chi^2 = \frac{\rho_0}{m_\chi} \frac{\mu_{\rm thermal}^2}{\mu_\chi^2} \times \mu_\chi^2 = \frac{\rho_0}{m_\chi} \mu_{\rm thermal}^2$$

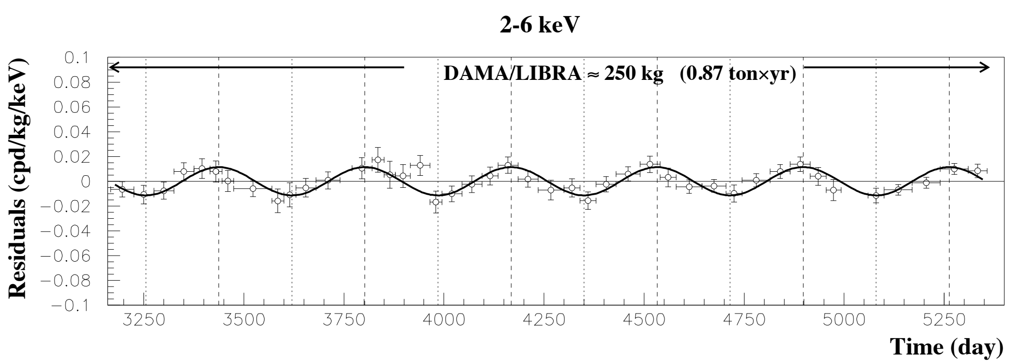
$$R_{\gamma\gamma} \propto n_\chi^2 \mu_\chi^4 = \frac{\rho_0^2}{m_\chi^2} \frac{\mu_{\rm thermal}^4}{\mu_\chi^4} \times \mu_\chi^4 = \frac{\rho_0^2}{m_\chi^2} \mu_{\rm thermal}^4$$

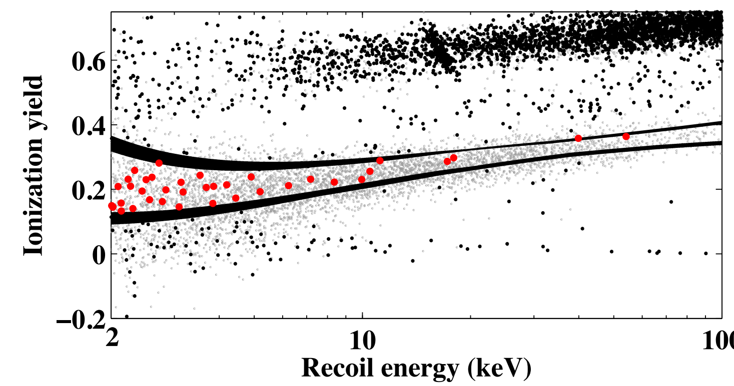
if an MiDM-like model exists, its signal sizes are pretty robust

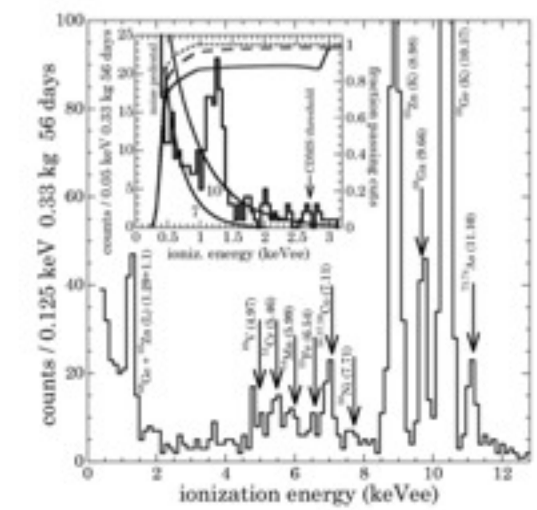
- Searches for DM are more robust than you'd have guessed
- DD signals pretty generic for stable WIMPs
- Sometimes ID signals (esp gamma gamma) are robust

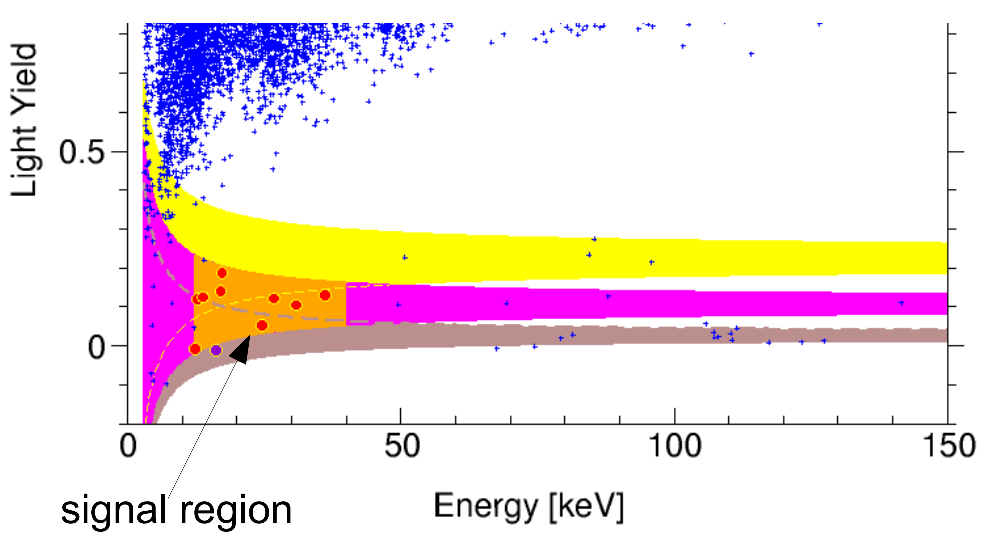
robust constraints on DM

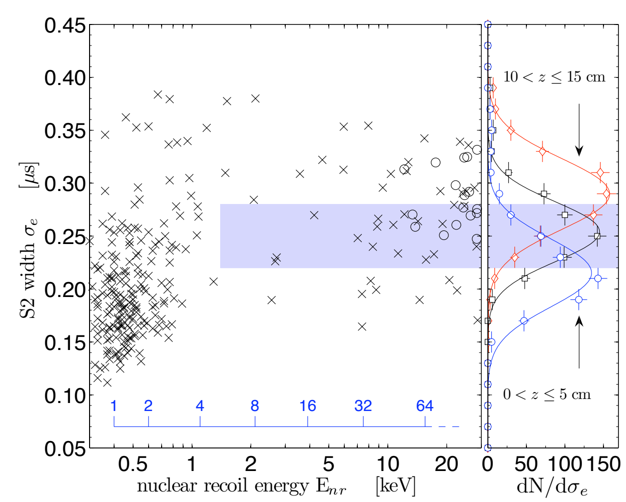
no shortage of signals

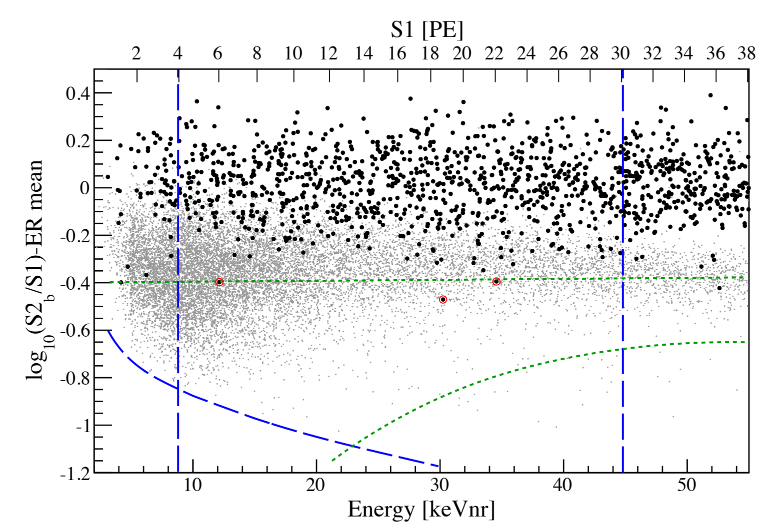




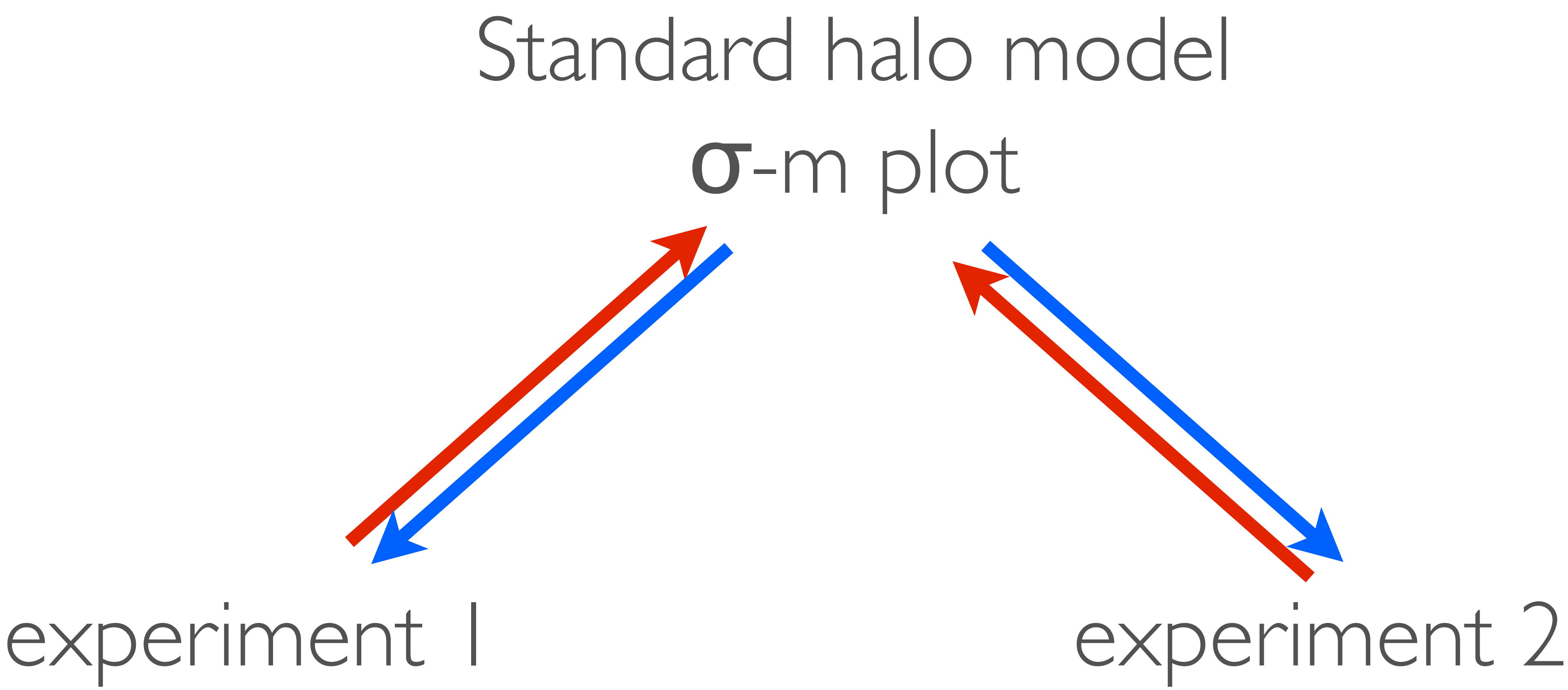


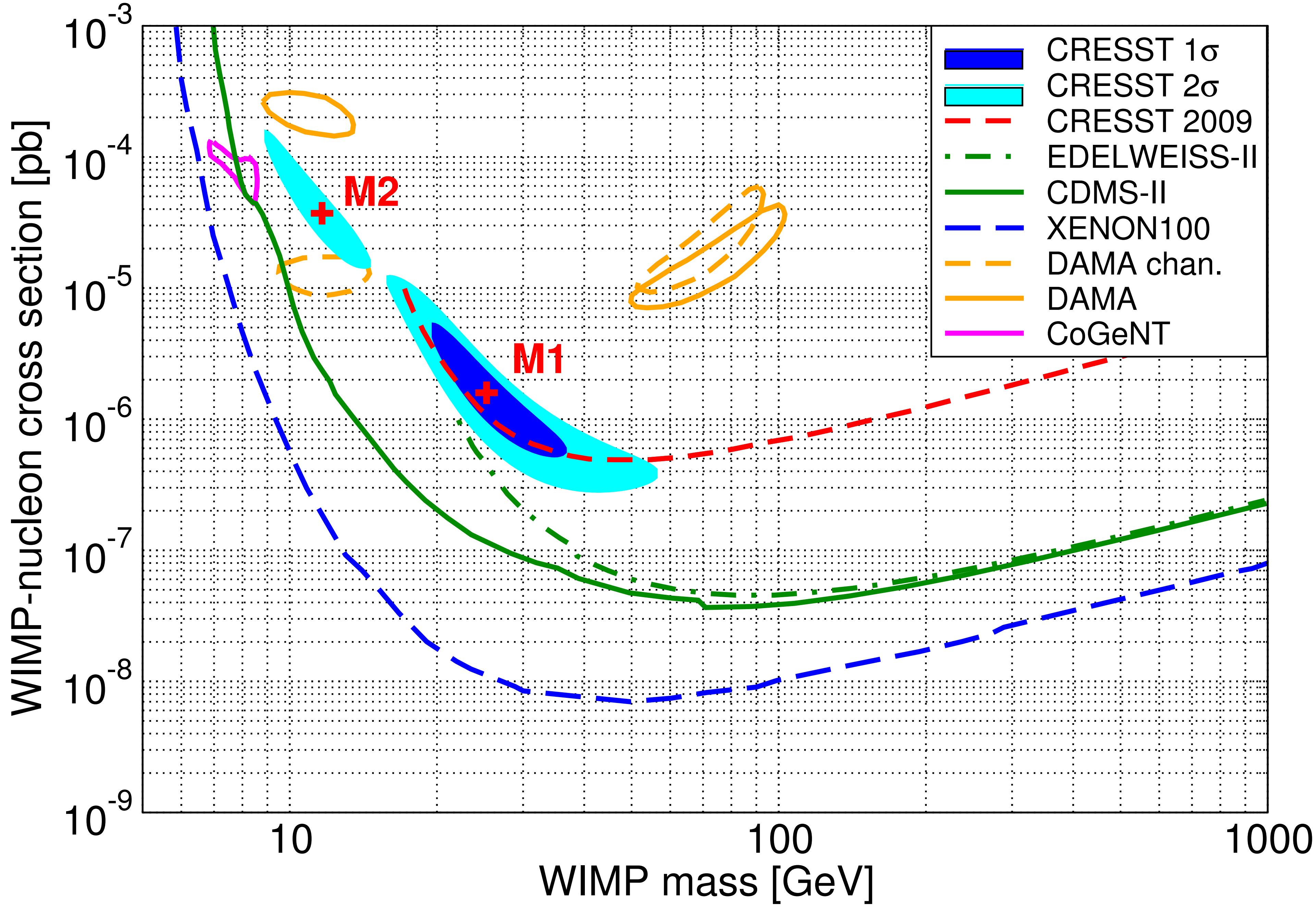






the problem with our approach

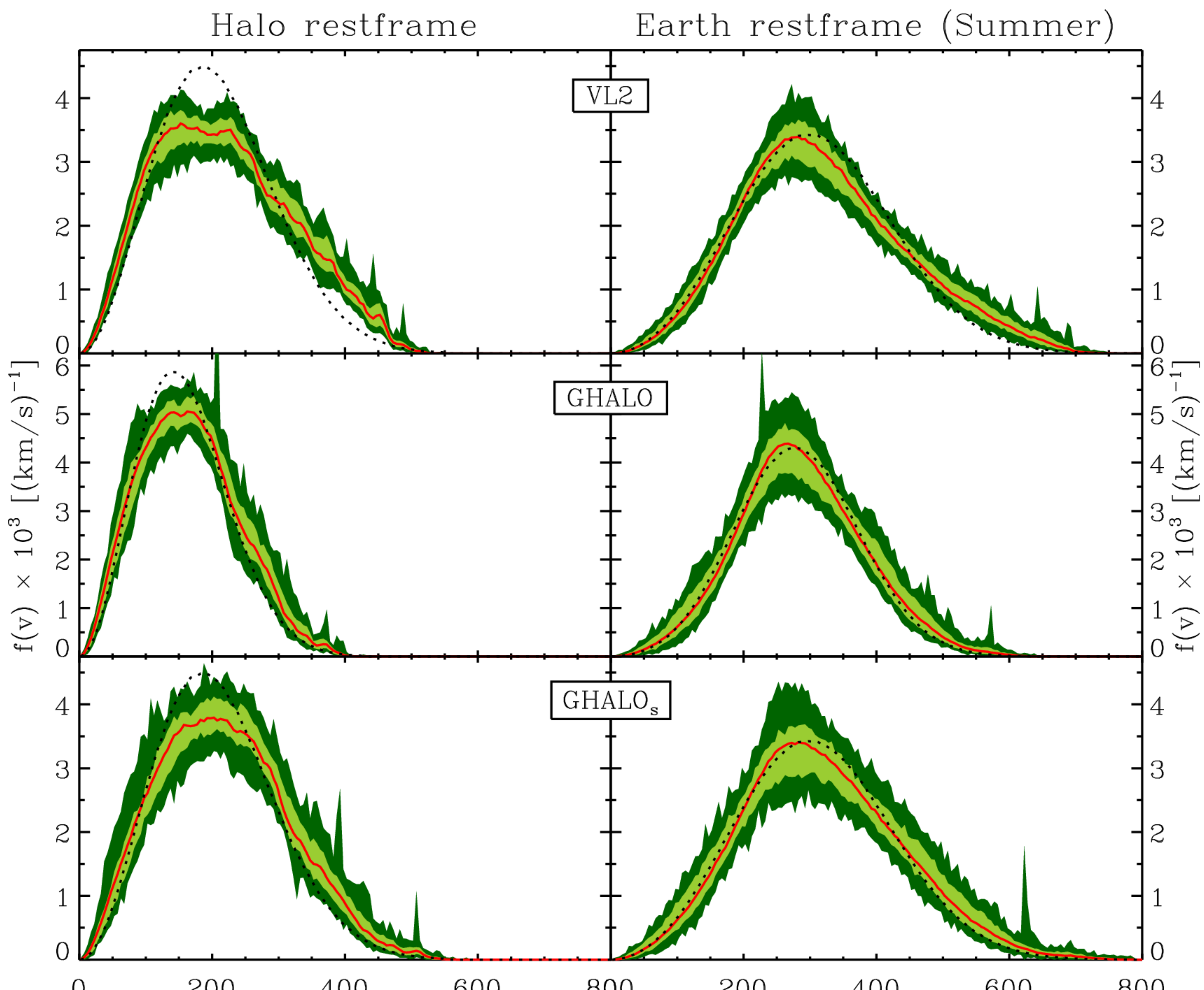




CRESST 1σ
CRESST 2σ
CRESST 2009
EDELWEISS-II
CDMS-II
XENON100
DAMA chan.
DAMA
CoGeNT
M1
M2
WIMP-nucleon cross section [pb]
WIMP mass [GeV]
10
100
1000
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9

WANT MODEL INDEPENDENT CONSTRAINTS

Kuhlen, et al



The goal

- What can we say about direct detection experiments without making any appeal to halo models?

- Find Dark Matter / test claims
- Determine DM mass
- Determine DM interaction strength

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- Find Dark Matter / test claims
- ~~Determine DM mass~~
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compare target to target

DAMA [**NaI**(**Tl**)] ⟷ KIMS [**CsI**(**Tl**)]

compare target to target

KIMS [**CsI**(**Tl**)]

DAMA [**NaI**(**Tl**)]

COUPP [**CF_3I**]

compare target to target

DAMA [**NaI**(**Tl**)] ⟷ KIMS [**CsI**(**Tl**)]

DAMA [**NaI**(**Tl**)] ⟷ COUPP [$\mathbf{CF_3I}$]

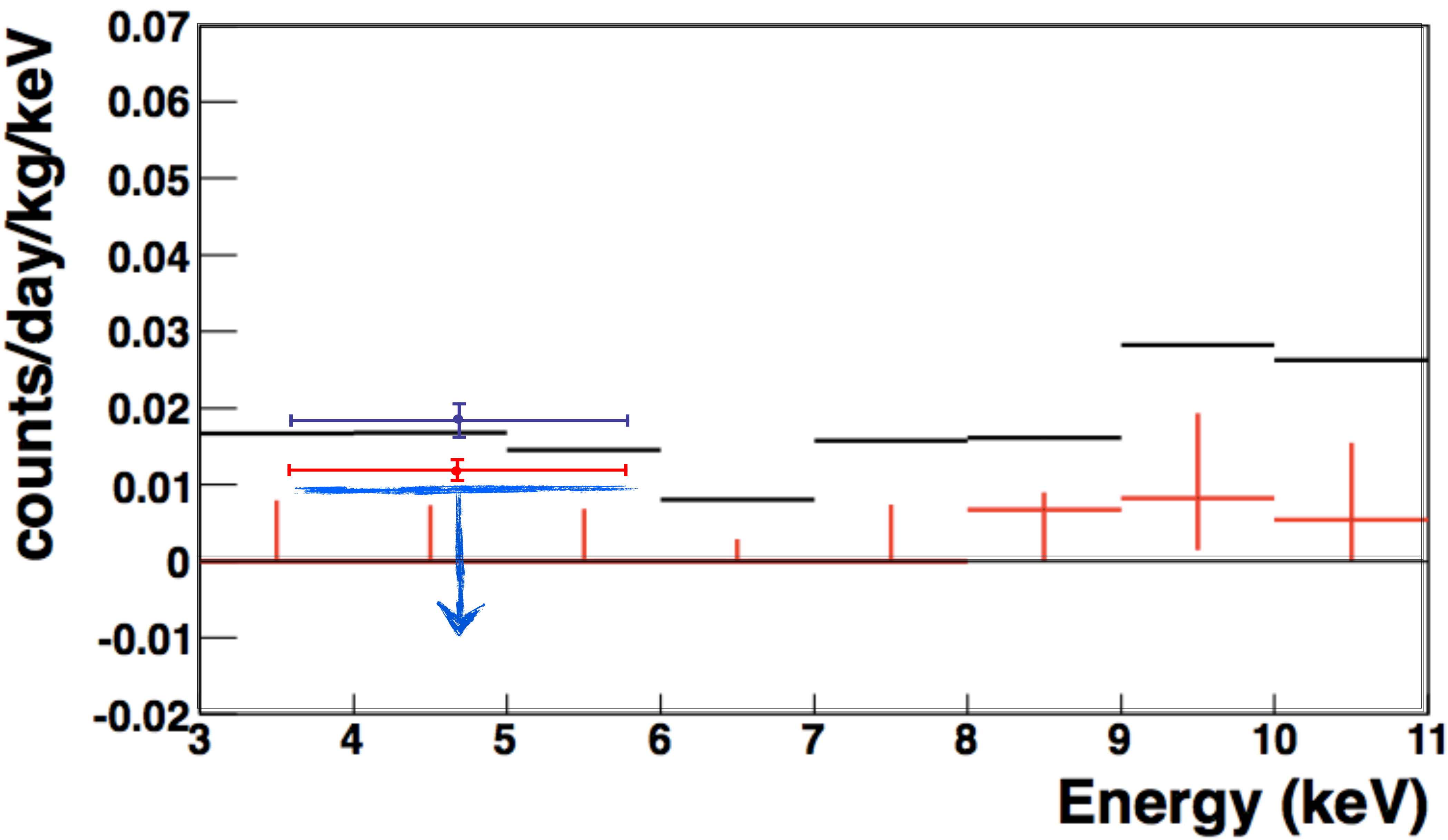
CoGeNT [**Ge**] ⟷ CDMS [**Ge**]

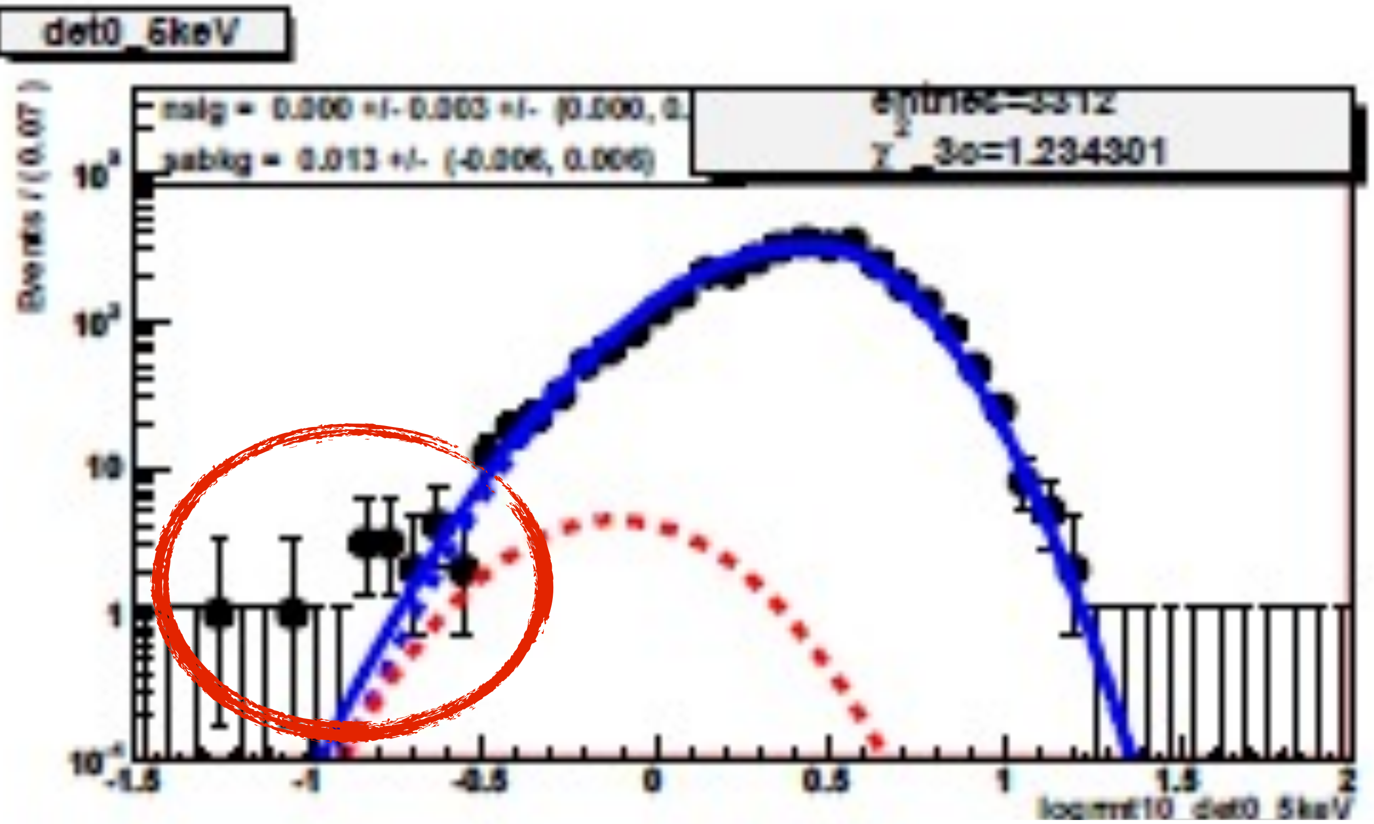
could DAMA come from Iodine?

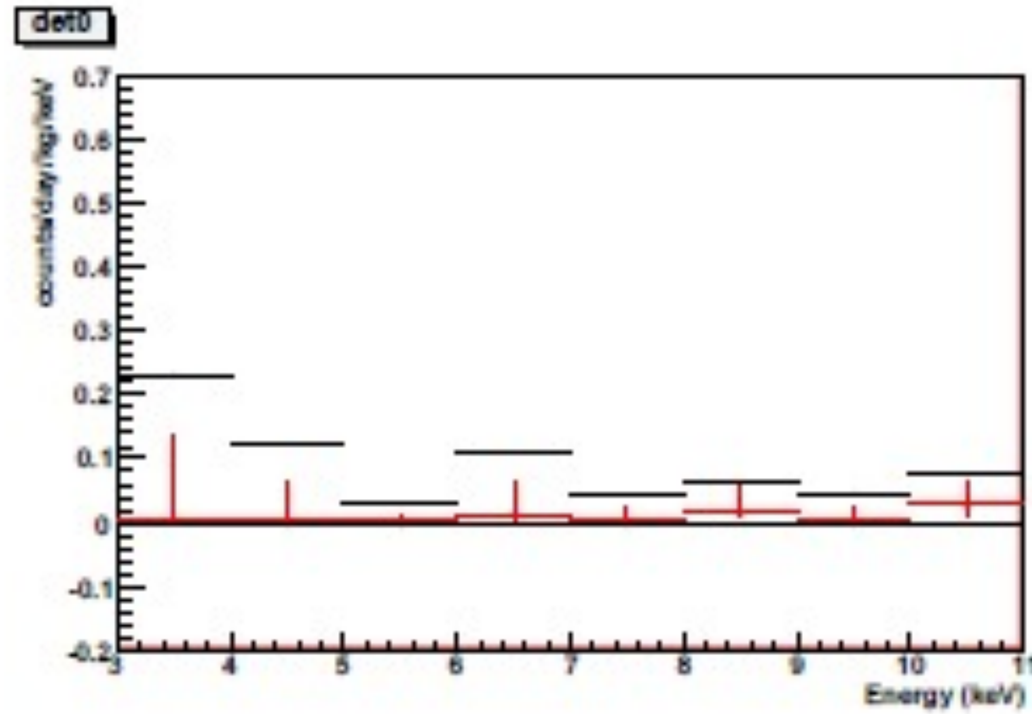
Experiments with iondine: KIMS, COUPP

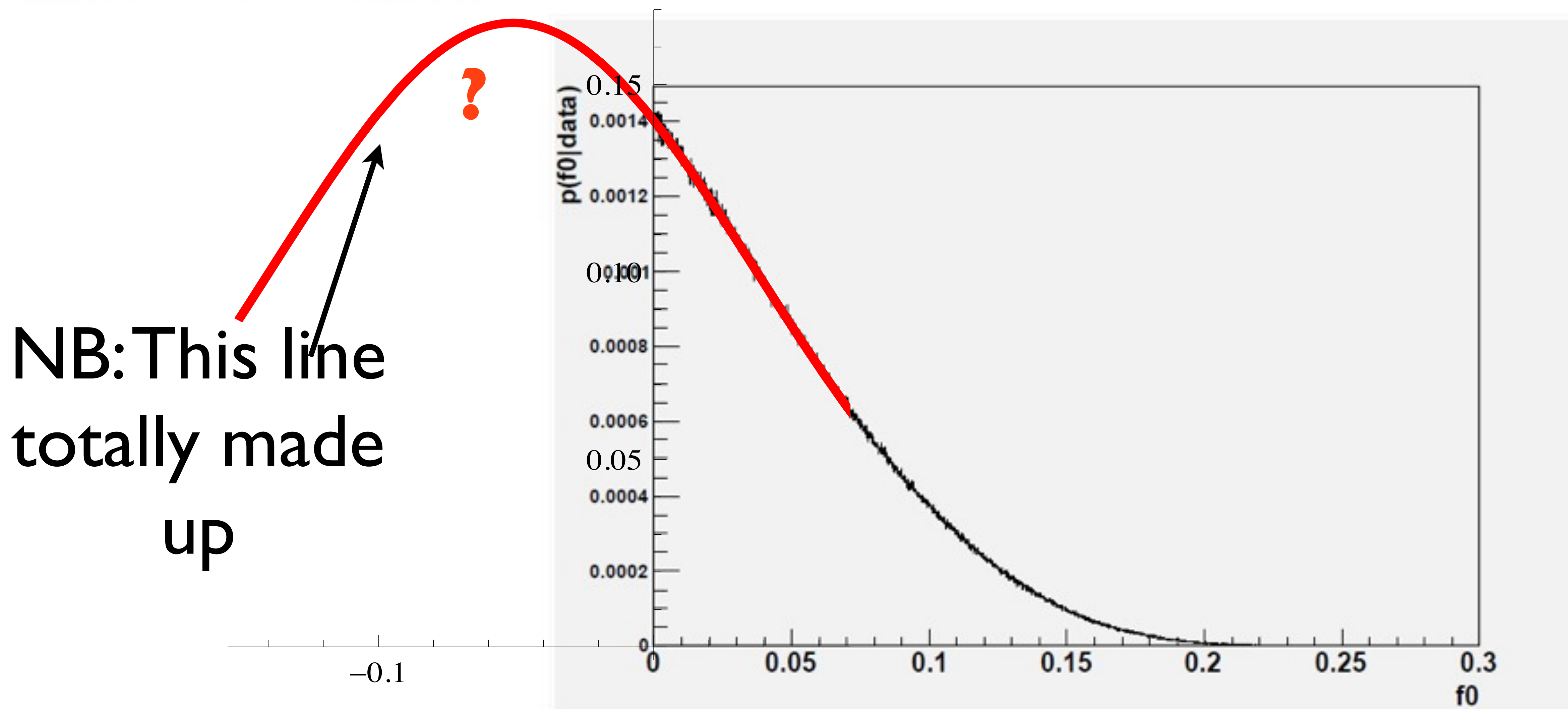
KIMS

KIMS Nuclear recoil event rate




det0_5keV


det0
Energy (keV)


?
p(f0|data)
f0
NB: This line totally made up

KIMS

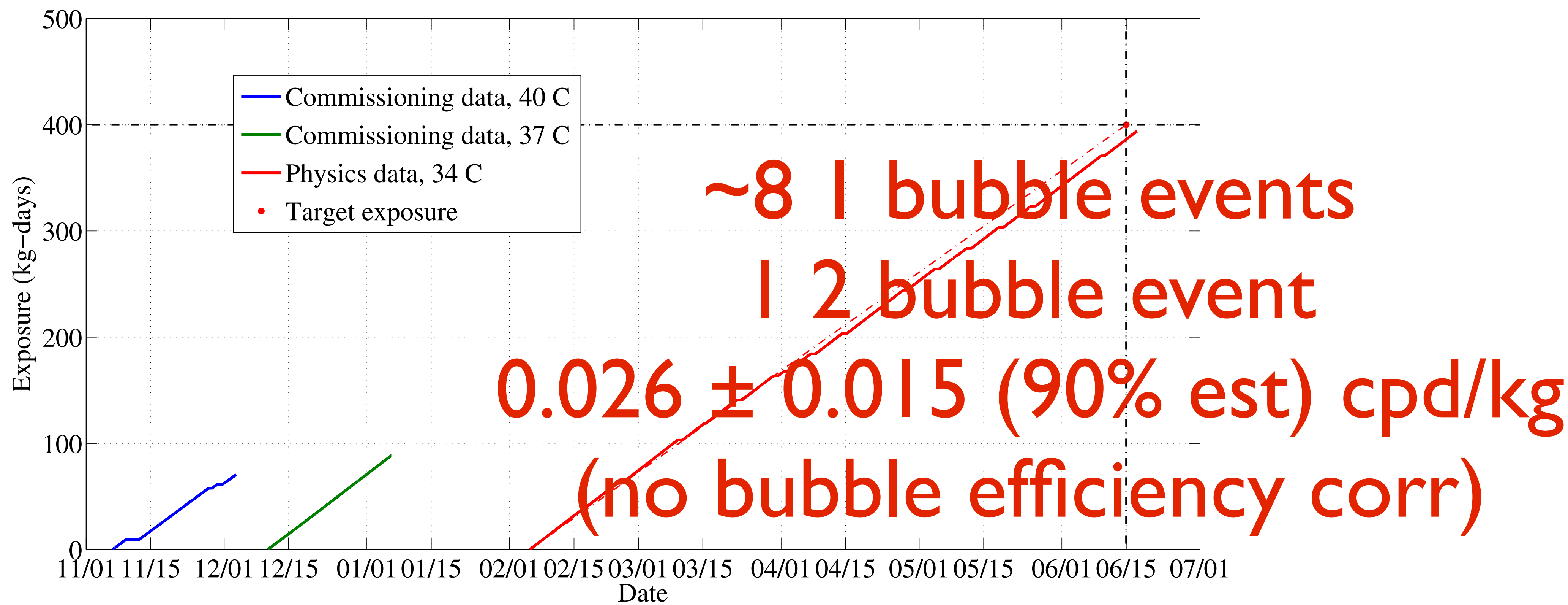
- KIMS potentially interesting constraints
- But concern about calibration/energy resolution/quenching factor - is this a limit on the fitting model or on a WIMP signal?
- Modulation analysis should be instructive

COUPP

COUPP-4 at SNOLAB

Talk by H.Lippincott TAUP 2011

- 17.4 live-days at 7 keV threshold
- 21.9 live-days at 10 keV threshold
- 97.3 live-days at 15 keV threshold ended June 16
- 79% acceptance for nuclear recoils after all cuts (including fiducial and acoustic)



For 100% DAMA modulation expect .

0.037±.007 (90%)

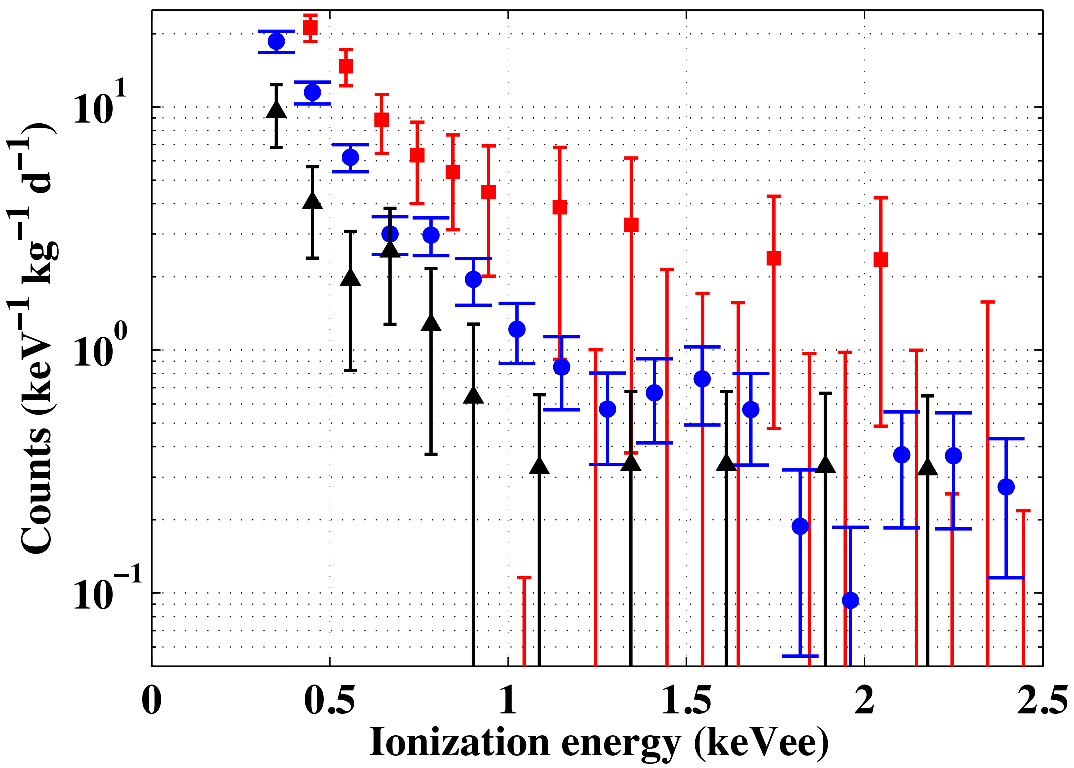
DAMA-I

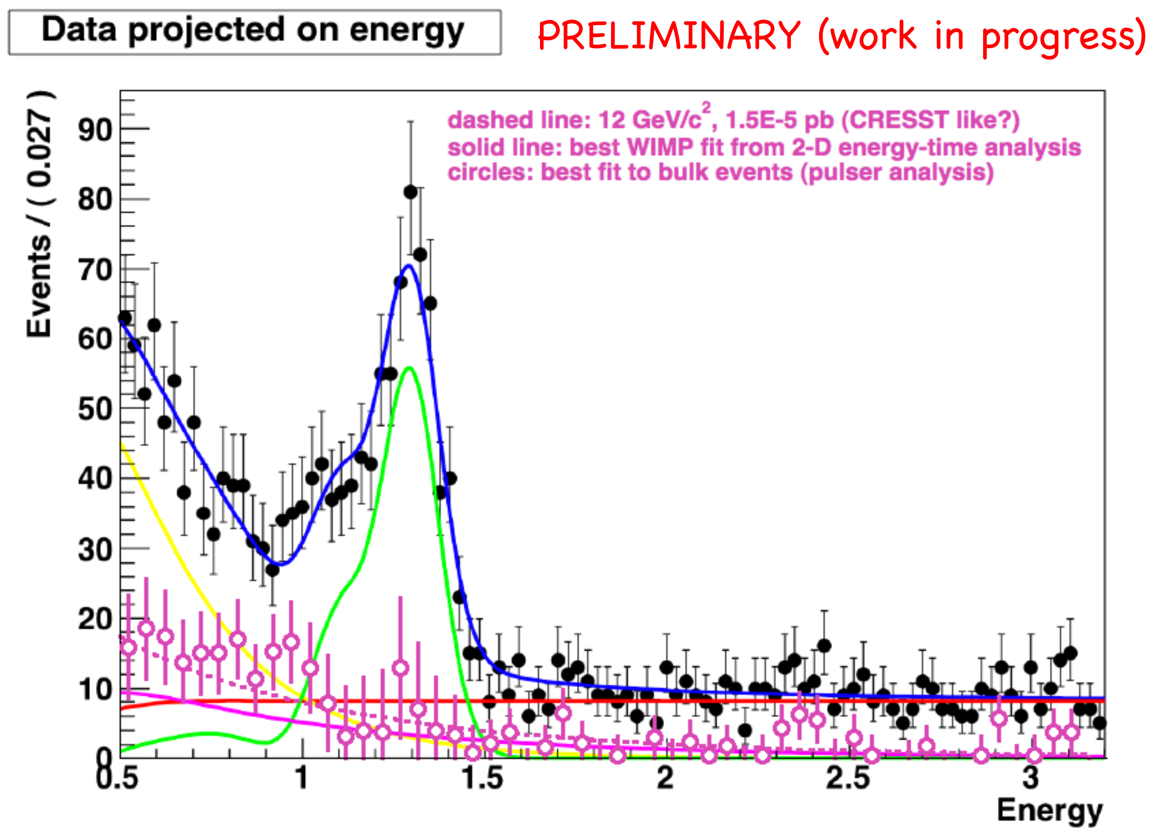
- Iodine rate from DAMA is marginal, but consistent for ~ O(1) modulated signal.
- Improvements in COUPP can definitively exclude the I interpretation

Could CoGeNT be dark matter?

Experiments with Ge and low threshold: CDMS

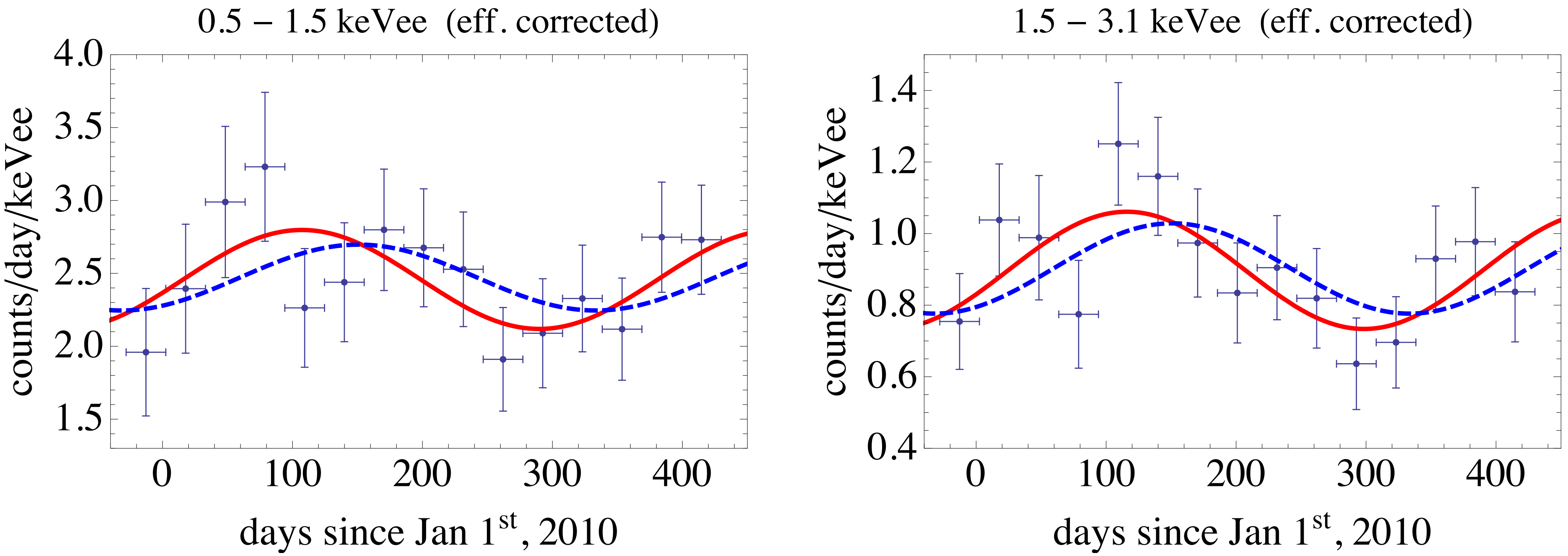
CoGent->CDMS

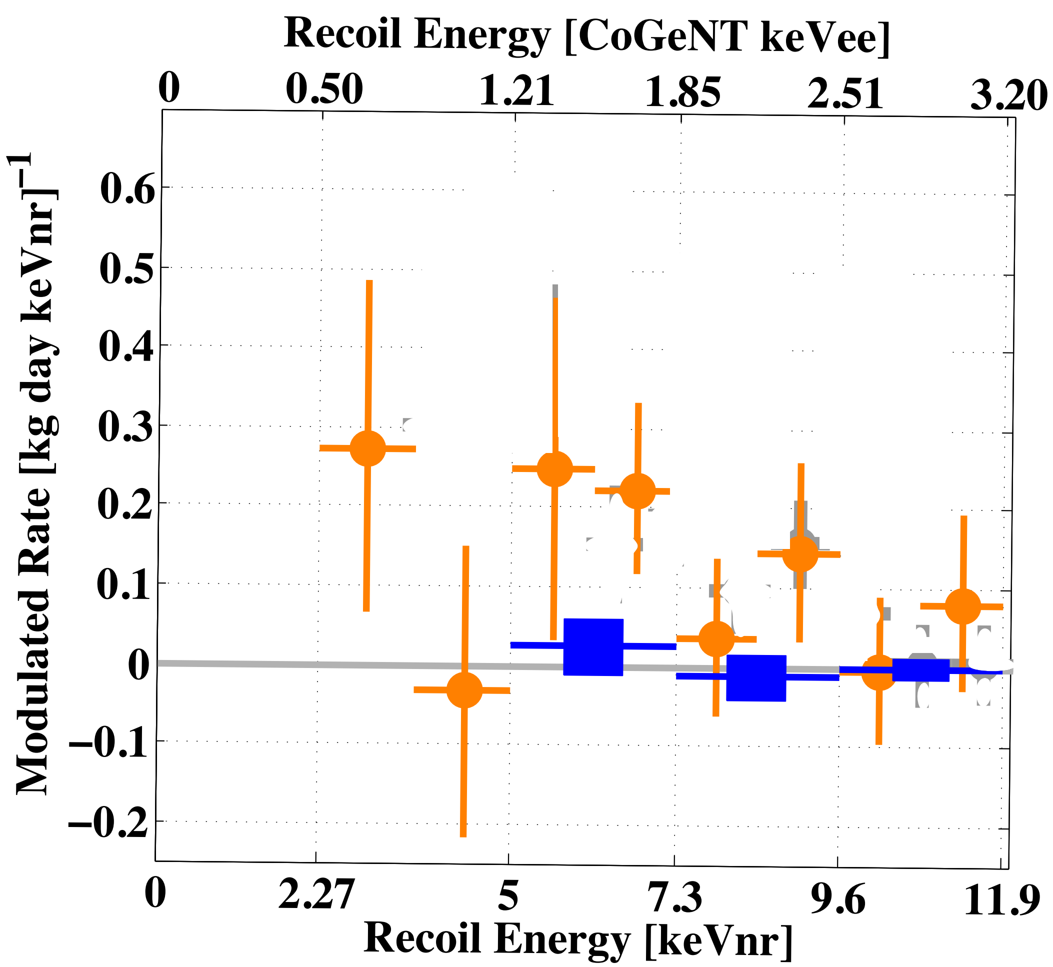




With surface event subtraction no a priori conflict

CoGeNT modulation





CoGeNT Mod

CDMS Mod

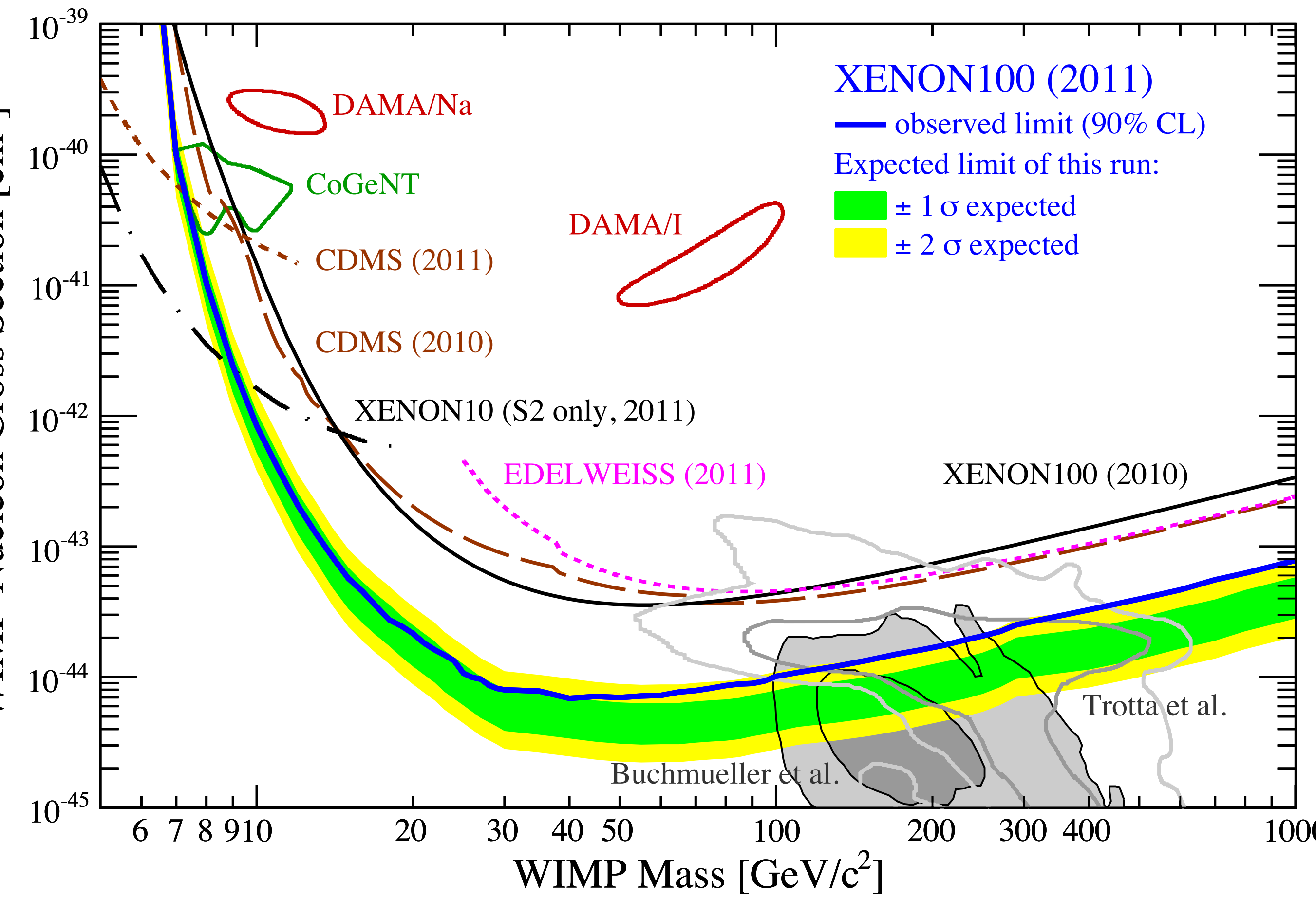
Same target story

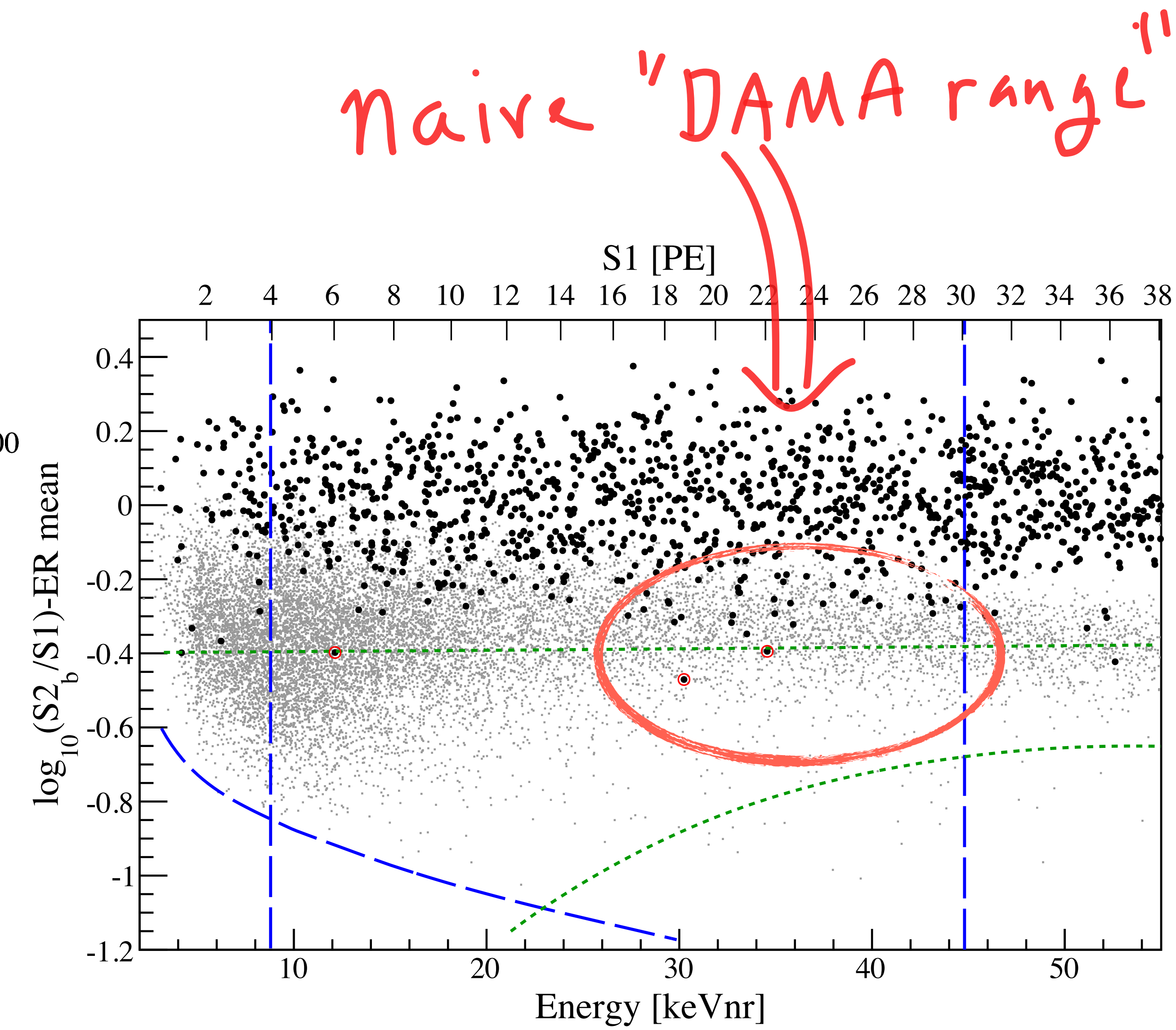
- DAMA - Iodine should be tested in the near future by COUPP+KIMS - already tense
- CoGeNT - Modulation tested by CDMS (none in higher energy range)

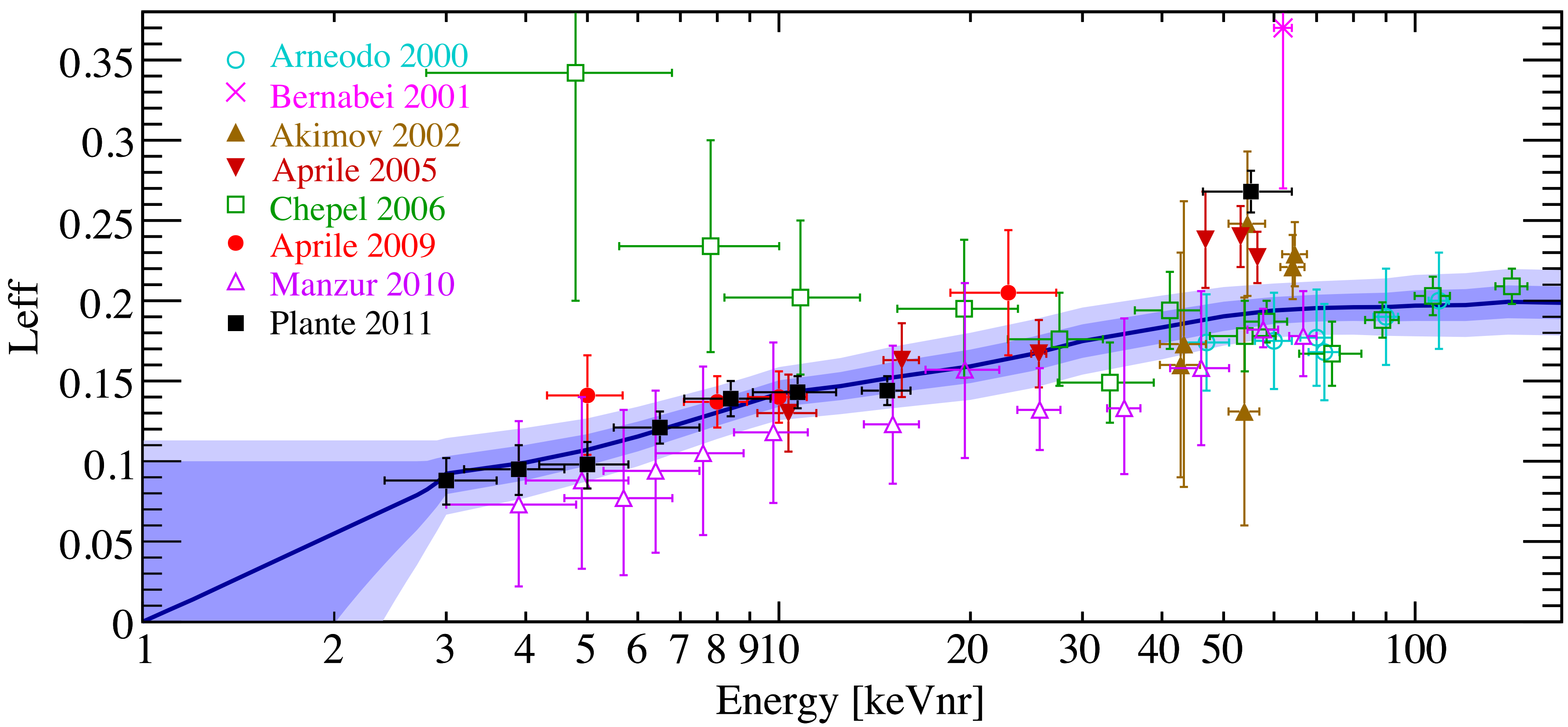
but can we go between experiments?

- If we see light WIMPs/WIMPs sensitive to the tail of velocity distribution, how do we compare experiments?

a comparable mass target: XENON

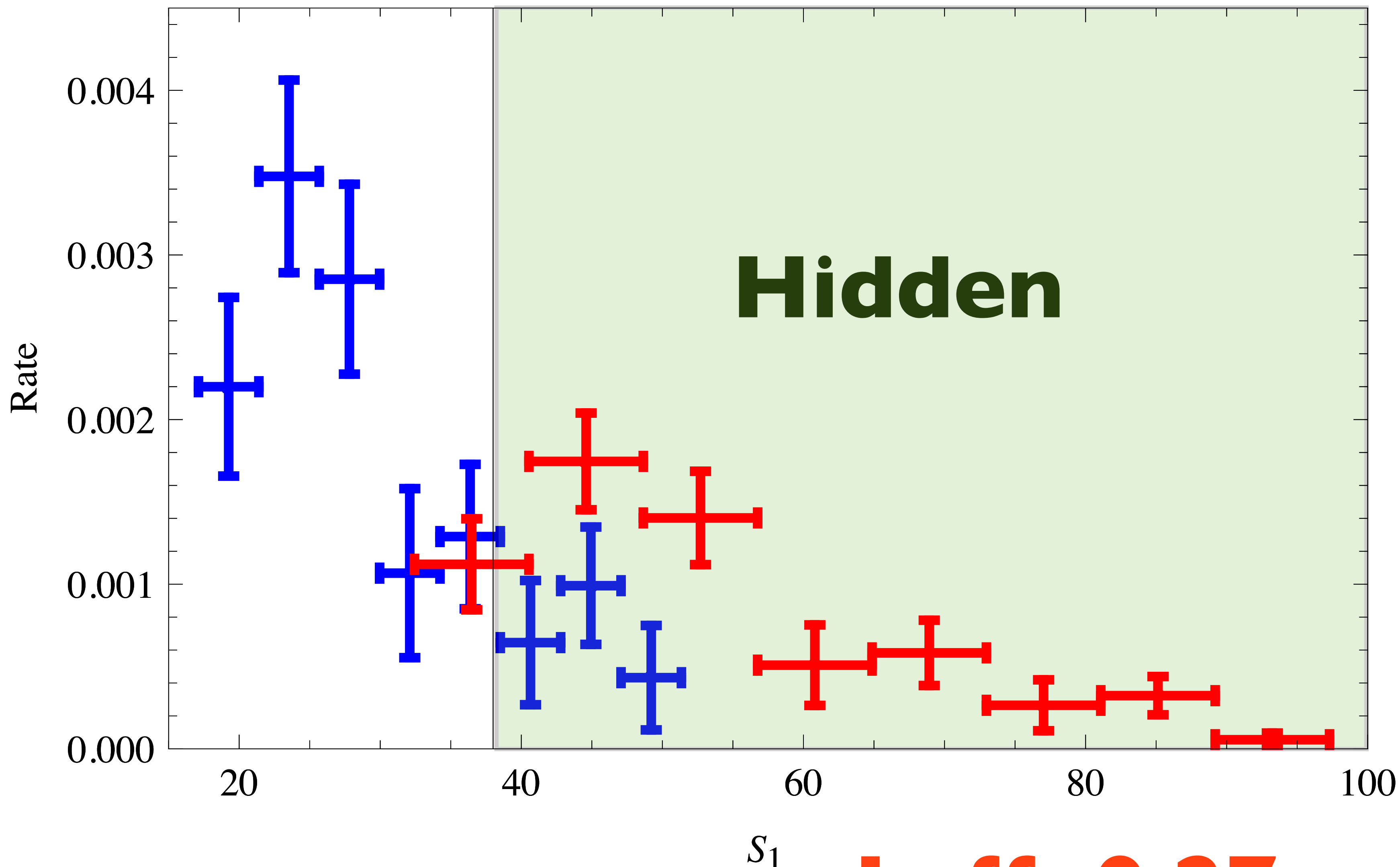






Arneodo 2000
Bernabei 2001
Akimov 2002
Aprile 2005
Chepel 2006
Aprile 2009
Manzur 2010
Plante 2011
Leff
Energy [keVnr]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
100

Leff=0.19, q=0.08



Leff=0.27, q=0.06

important to view whole energy range

- simple kinematics can only take you so far

WANT MODEL INDEPENDENT CONSTRAINTS

Usual: make assumptions on this

set limits on this

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \sigma(E_R) \int_{v_{min(E_R)}}^{\infty} \frac{f(v)}{v} d^3 v$$

Alternative: set limits on this

Fox, Liu, NW

Two key points

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \sigma(E_R)\, g(v_{min})$$

1) all the energy dependence is in two functions

$$g(v_{min}) = \int_{v_{min}}^{\infty} d^3v\, \frac{f(\mathbf{v}, t)}{v}$$

$$\sigma_{SI}(E_R) = \sigma_p \frac{\mu^2}{\mu_{n\chi}^2} \frac{(f_p Z + f_n (A - Z))^2}{f_p^2} F^2(E_R)$$

$$v_{min} = \sqrt{\frac{M_T E_R}{2\mu^2}}$$

2) there is a 1-1 mapping between velocity and energy

- Suppose you want to compare two experiments, 1 and 2

$$[E^1_{low}, E^1_{high}] \Rightarrow [v^{1,low}_{min}, v^{1,high}_{min}]$$

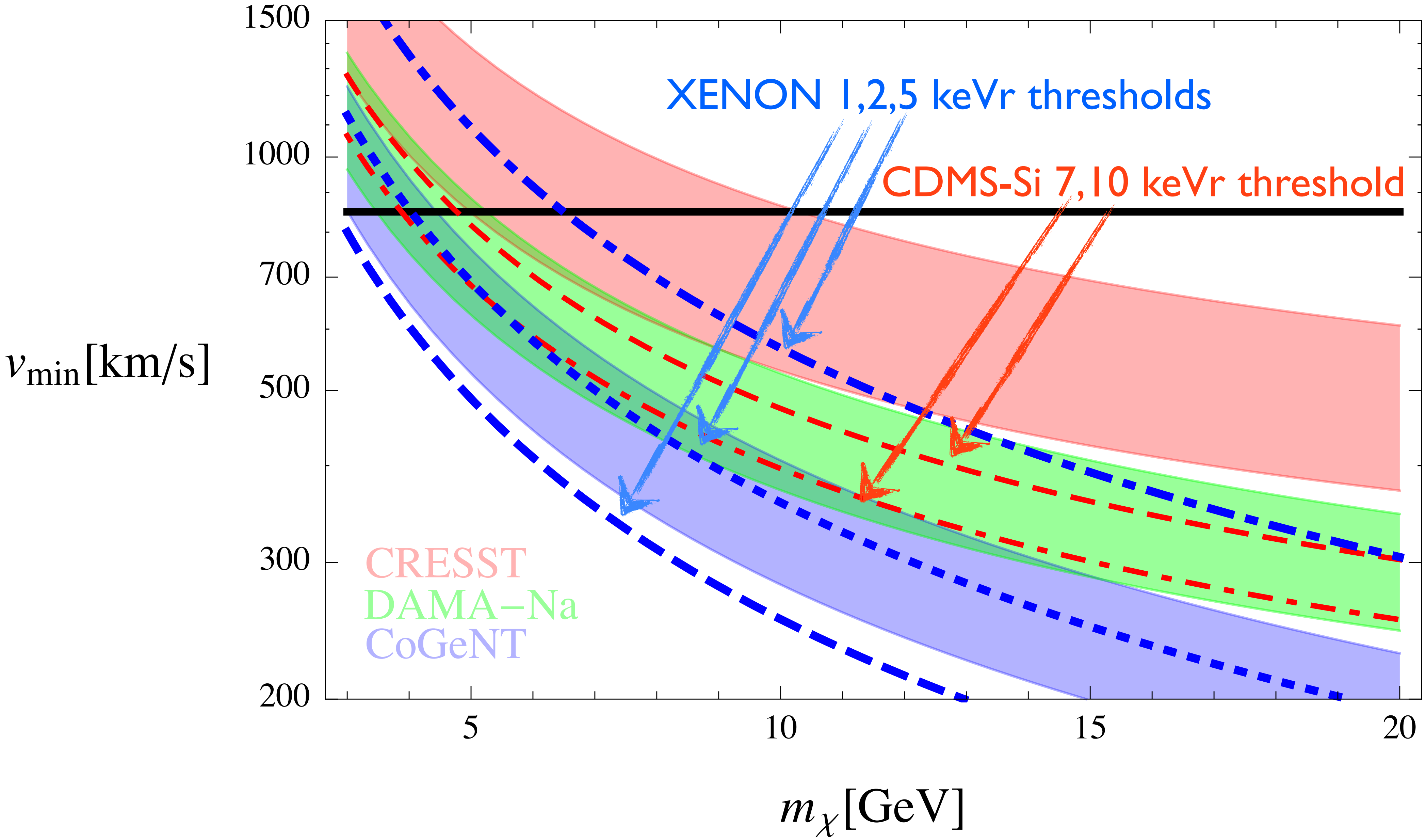
map the energy range studied in experiment 1 to a velocity space range

map velocity space range back to energy space for experiment 2

$$[v^{1,low}_{min}, v^{1,high}_{min}] \Rightarrow [E^2_{low}, E^2_{high}]$$

we now have an energy range where the experiments are studying the *same* particles

$$[E^1_{low}, E^1_{high}] \Leftrightarrow [E^2_{low}, E^2_{high}]$$



Approx. range	O	Na	Si	Ar	Ge	Xe
CoGeNT (Ge): 2 - 4	4.3 - 8.6	3.9 - 7.8	3.6 - 7.2	3.0 - 6.0	2 - 4	1.3 - 2.5
DAMA (Na): 6 - 13	6.6 - 14	6 - 13	5.5 - 12	4.6 - 10	3.1 - 6.7	1.9 - 4.2
CRESST (O): 15 - 40	15 - 40	14 - 36	12 - 33	10 - 28	6.9 - 19	4.3 - 12

TABLE I: Conversion of energy ranges (all in keV) between various experiments/targets for a 10 GeV DM particle, using the expression in (7).

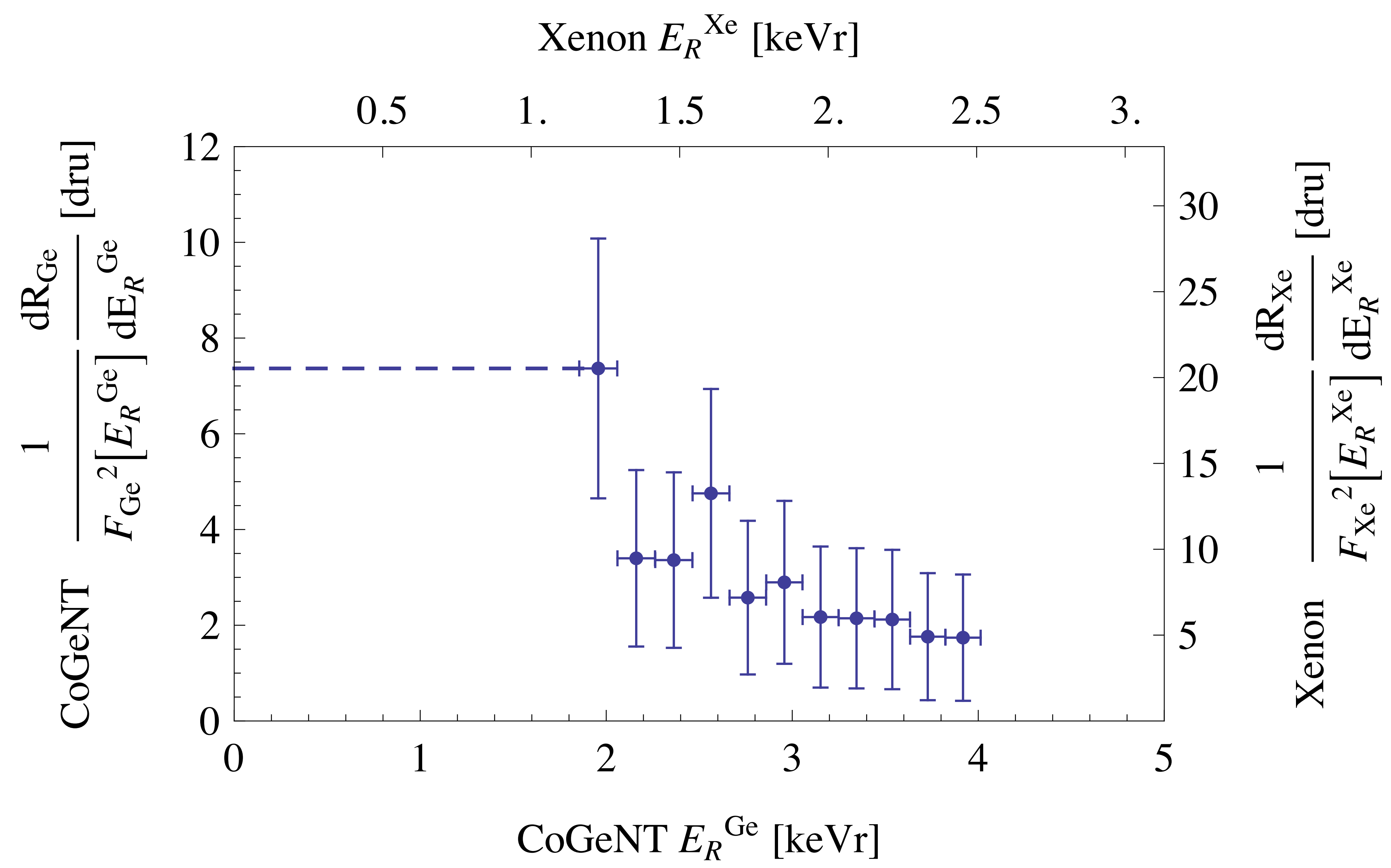
step 2

Invert:

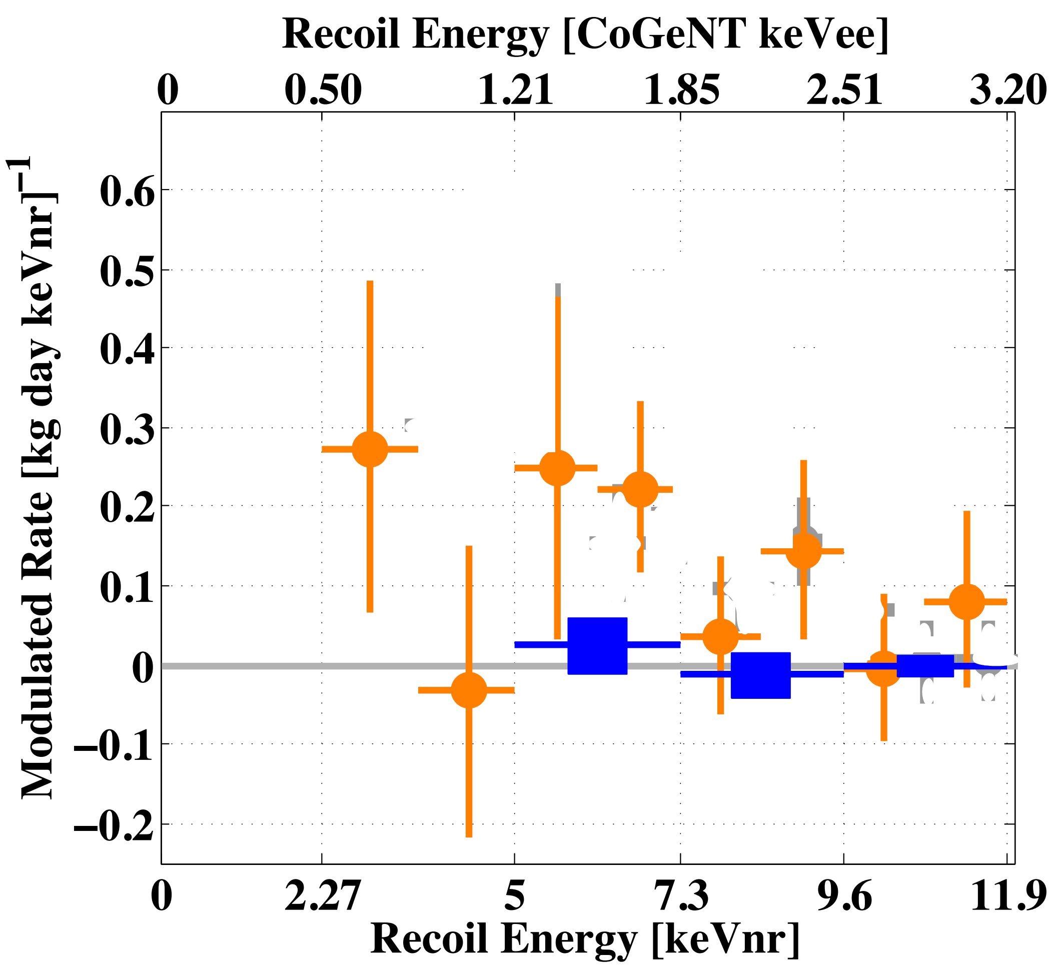
$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2m_\chi \mu^2} \sigma(E_R)\, g(v_{min}) \longrightarrow g(v) = \frac{2m_\chi \mu^2}{N_T M_T \rho \sigma(E_R)} \frac{dR_1}{dE_1}$$

$$\frac{dR_2}{dE_R}(E_2) = \frac{C_T^{(2)}}{C_T^{(1)}} \frac{F_2^2(E_2)}{F_1^2\left(\frac{\mu_1^2 M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2\right)} \frac{dR_1}{dE_R}\left(\frac{\mu_1^2 M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2\right)$$

A direct prediction of the rate
at experiment 2 from experiment 1



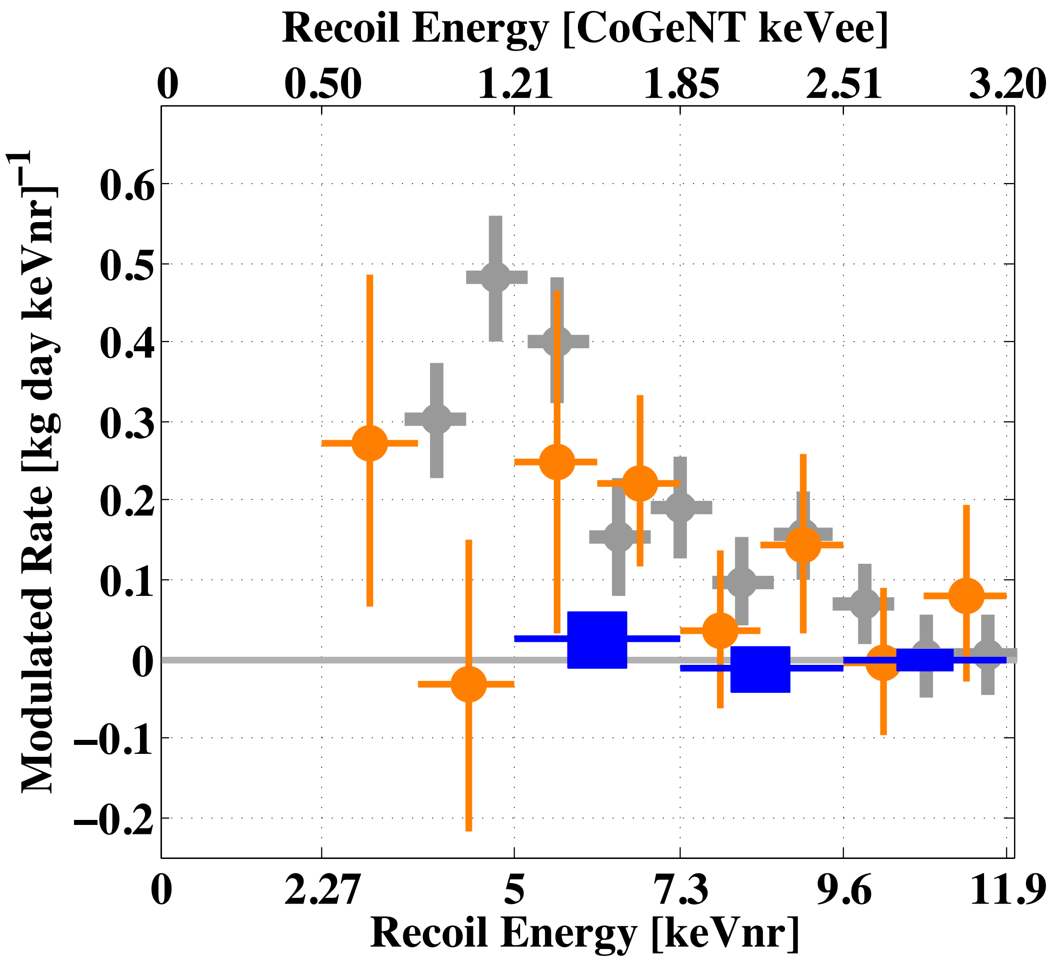
Xenon E_R^{Xe} [keVr]
0.5
1.
1.5
2.
2.5
3.
$\frac{1}{F_{Ge}^2[E_R^{Ge}]} \frac{dR_{Ge}}{dE_R^{Ge}}$ [dru]
CoGeNT
0
2
4
6
8
10
12
$\frac{1}{F_{Xe}^2[E_R^{Xe}]} \frac{dR_{Xe}}{dE_R^{Xe}}$ [dru]
Xenon
5
10
15
20
25
30
0
1
2
3
4
5
CoGeNT E_R^{Ge} [keVr]



CoGeNT Mod

CDMS Mod

10 GeV



DAMA

CoGeNT Mod

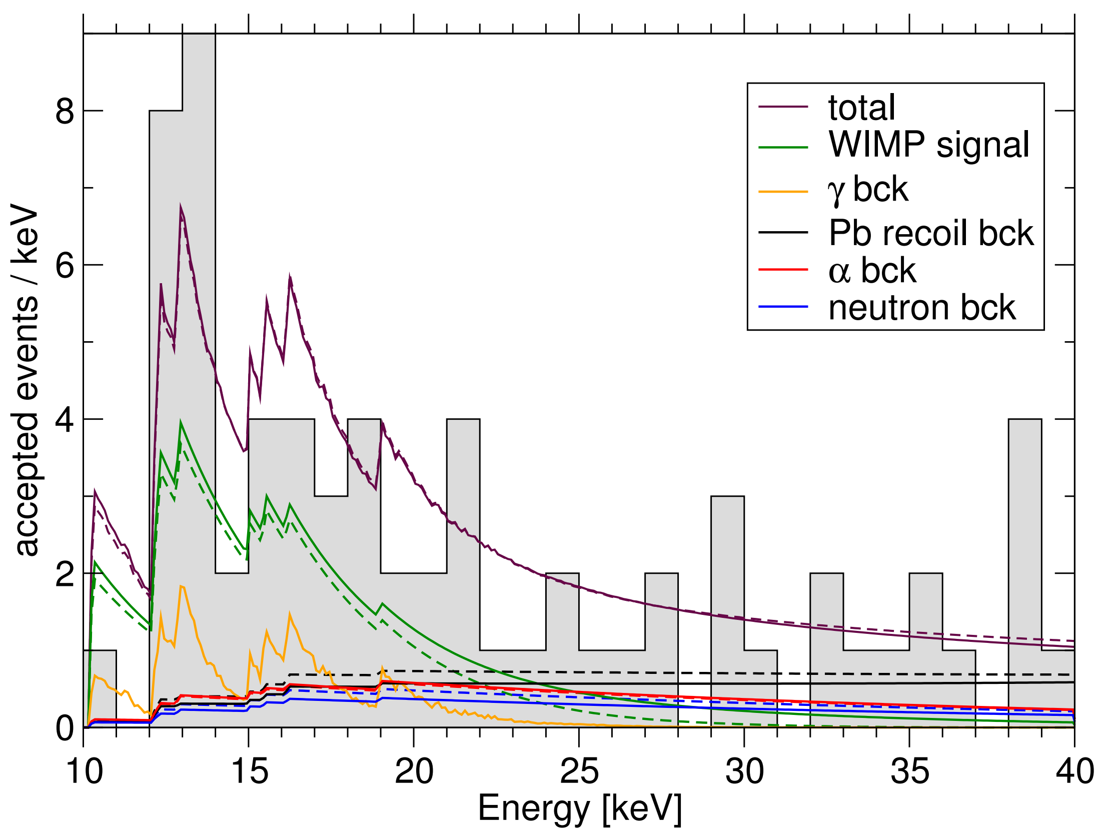
CDMS Mod

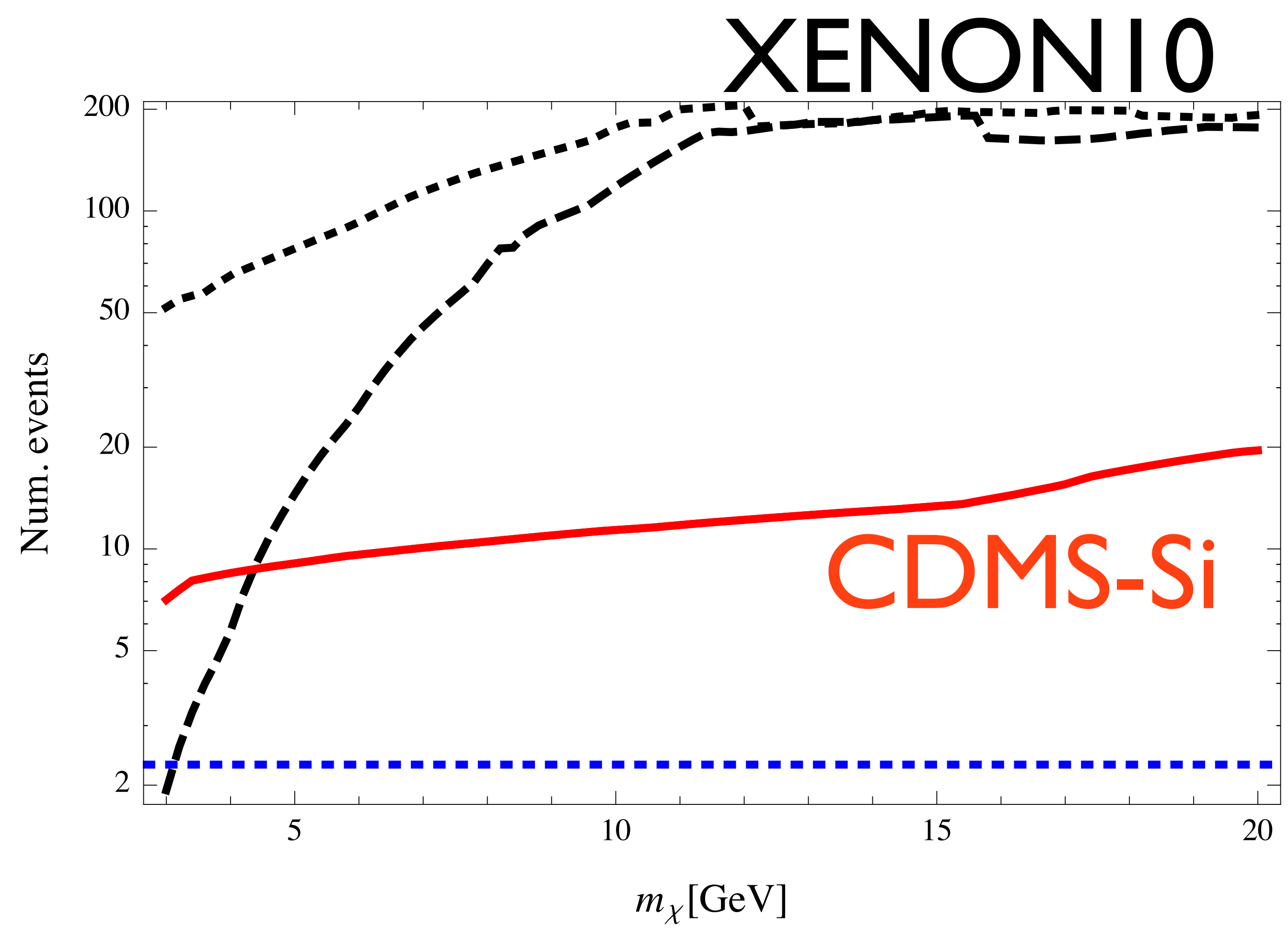
CoGeNT "exponential" signal

Bin	CoGeNT	Ge	Na (Q=0.3)	Si	O	Xe
1	[0.5,0.9] 0.90 ± 0.72	[2.3,3.8] 0.23 ± 0.18	[1.5,2.5] 0.078 ± 0.062	[4.5,7.6] 0.035 ± 0.028	[5.8,9.9] 0.011 ± 0.009	[1.4,2.3] 0.72 ± 0.58
2	[0.9,1.5] 0.37 ± 0.55	[3.8,6.1] 0.1 ± 0.149	[2.5,4.0] 0.035 ± 0.052	[7.6,11.9] 0.015 ± 0.023	[9.9,15.6] 0.005 ± 0.008	[2.3,3.7] 0.31 ± 0.46
3	[1.5,2.3] 0.48 ± 0.22	[6.1,8.9] 0.136 ± 0.063	[4.0,5.8] 0.049 ± 0.022	[11.9,17.5] 0.021 ± 0.01	[15.6,22.8] 0.007 ± 0.003	[3.7,5.4] 0.41 ± 0.19
4	[2.3,3.1] 0.27 ± 0.23	[8.9,11.6] 0.08 ± 0.068	[5.8,7.6] 0.029 ± 0.025	[17.5,22.8] 0.013 ± 0.011	[22.8,29.8] 0.004 ± 0.004	[5.4,7] 0.23 ± 0.2

CoGeNT modulation/CRESST signal

if 15 events at CRESST above 15 keV...





A side comment: don't forget CDMS-Si...

Constraints?

What if your experiment

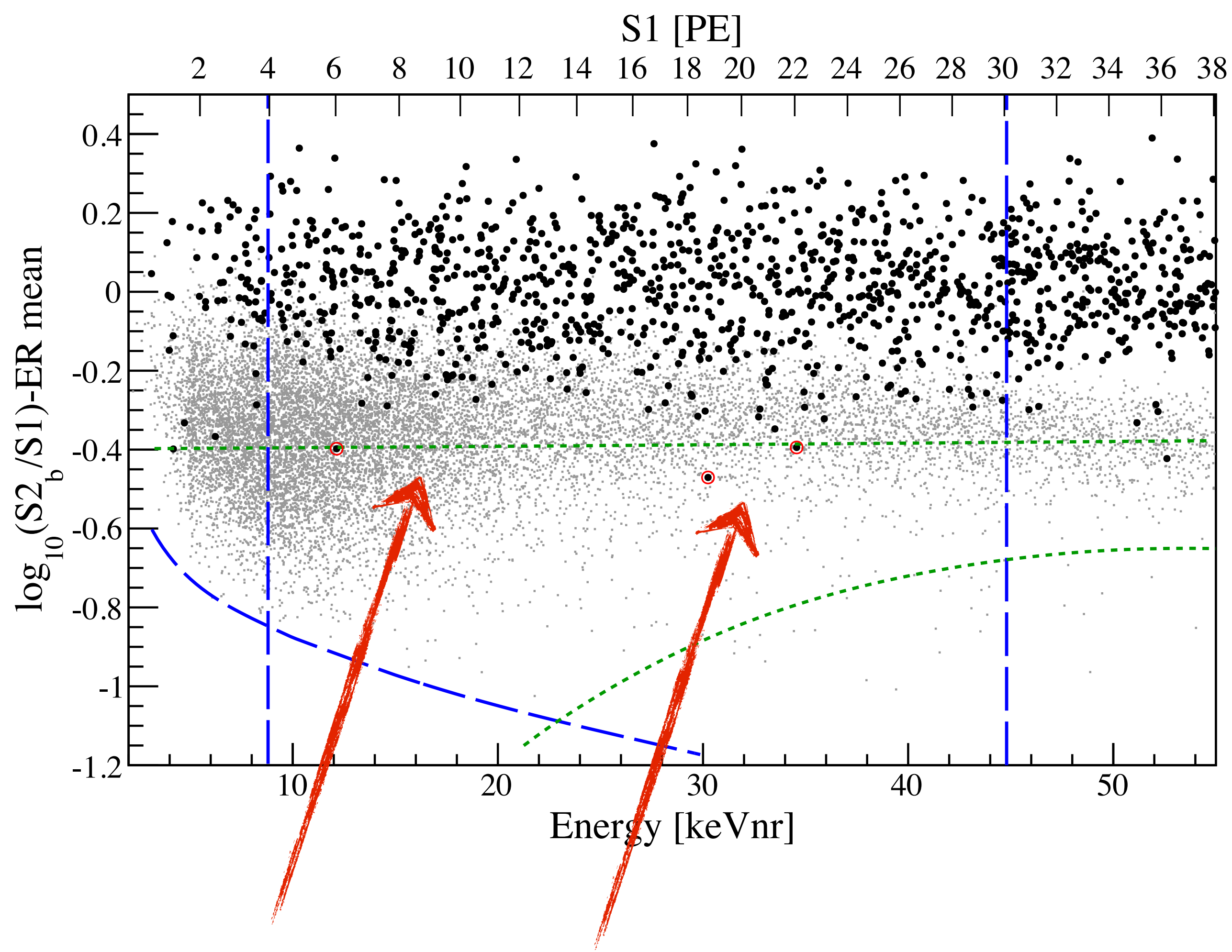
a) doesn’t probe the same v_{min} space?
b) doesn’t see anything?

Make a limit on g(v)

limiting g(v)

Note: g(v) is monotonic!

$$g(v_{min}) = \int_{v_{min}}^{\infty} d^3v \, \frac{f(\mathbf{v}, t)}{v}$$



Lack of events Gives constraints
at low E at high E

also Fox, Kribs, Tait 1011.1910; McCabe 1107.0741; ;Frandsen et al 1111.0292; Herrero-Garcia, Schwetz, Zupan 1112.1627, 1205.1345; Gelmini + Gondolo 1202.6539

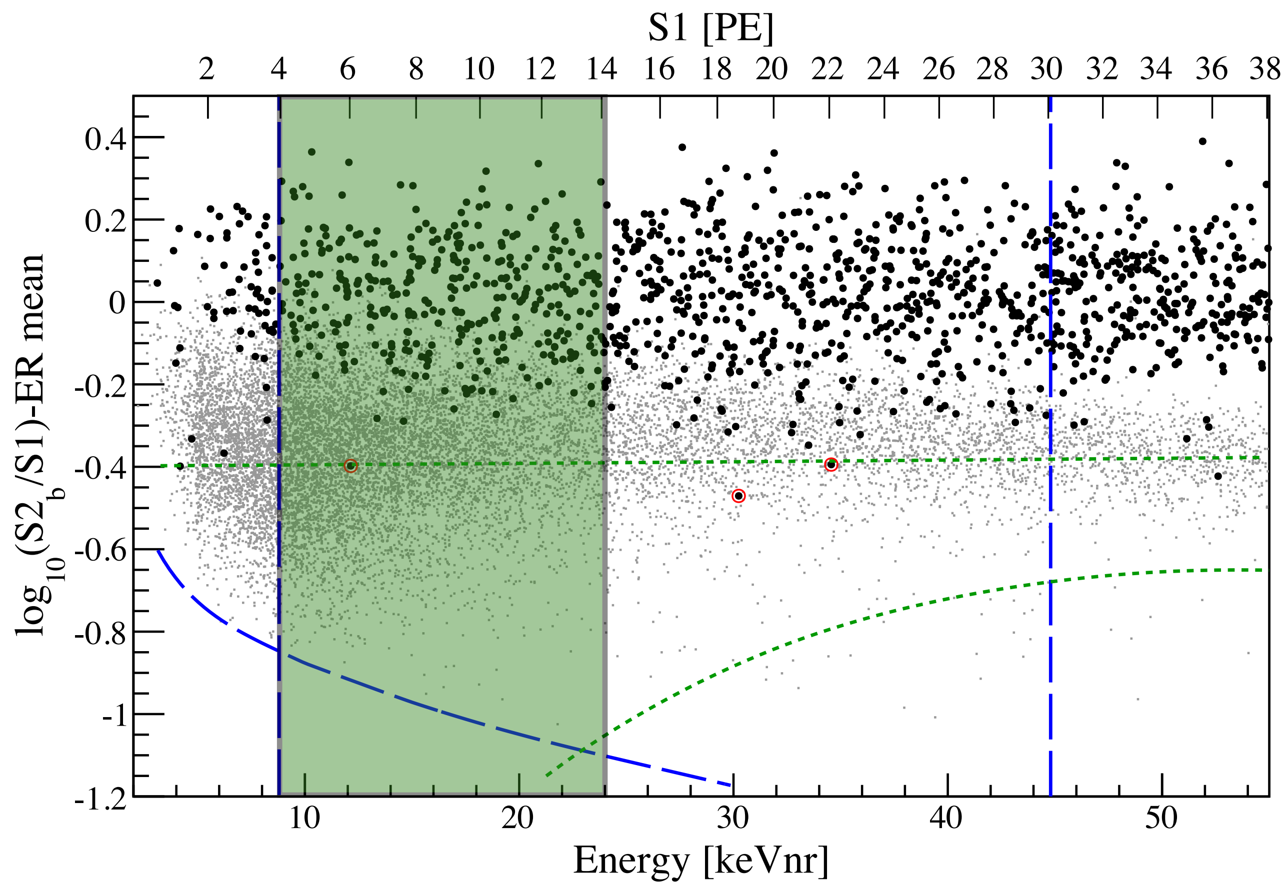
limiting g(v)

Most conservative assumption is theta function

$$g(v;v_1) = g_1\Theta(v_1 - v)$$

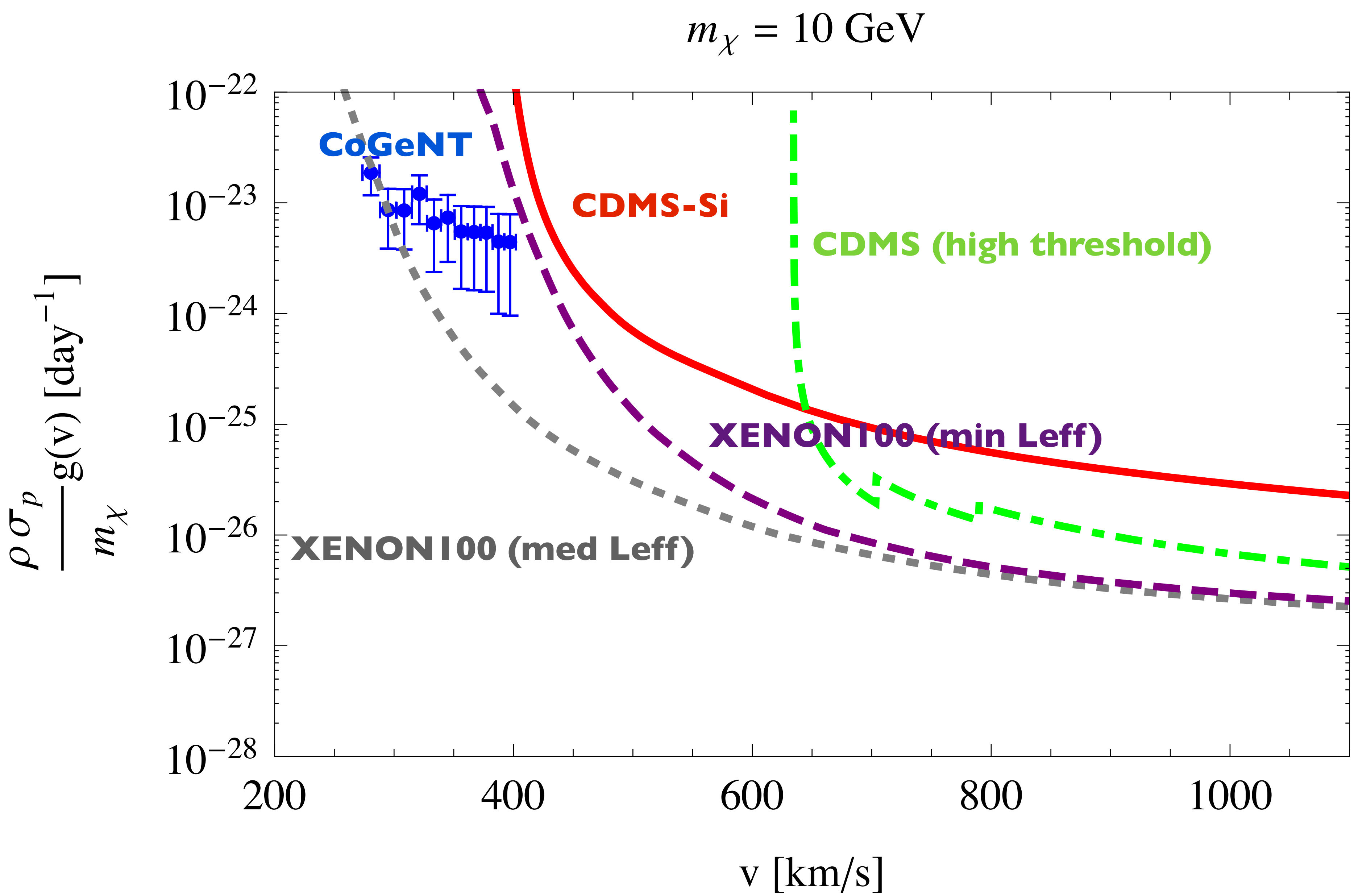
i.e., do not assume velocity extends to known but exponentially suppressed values at high velocity

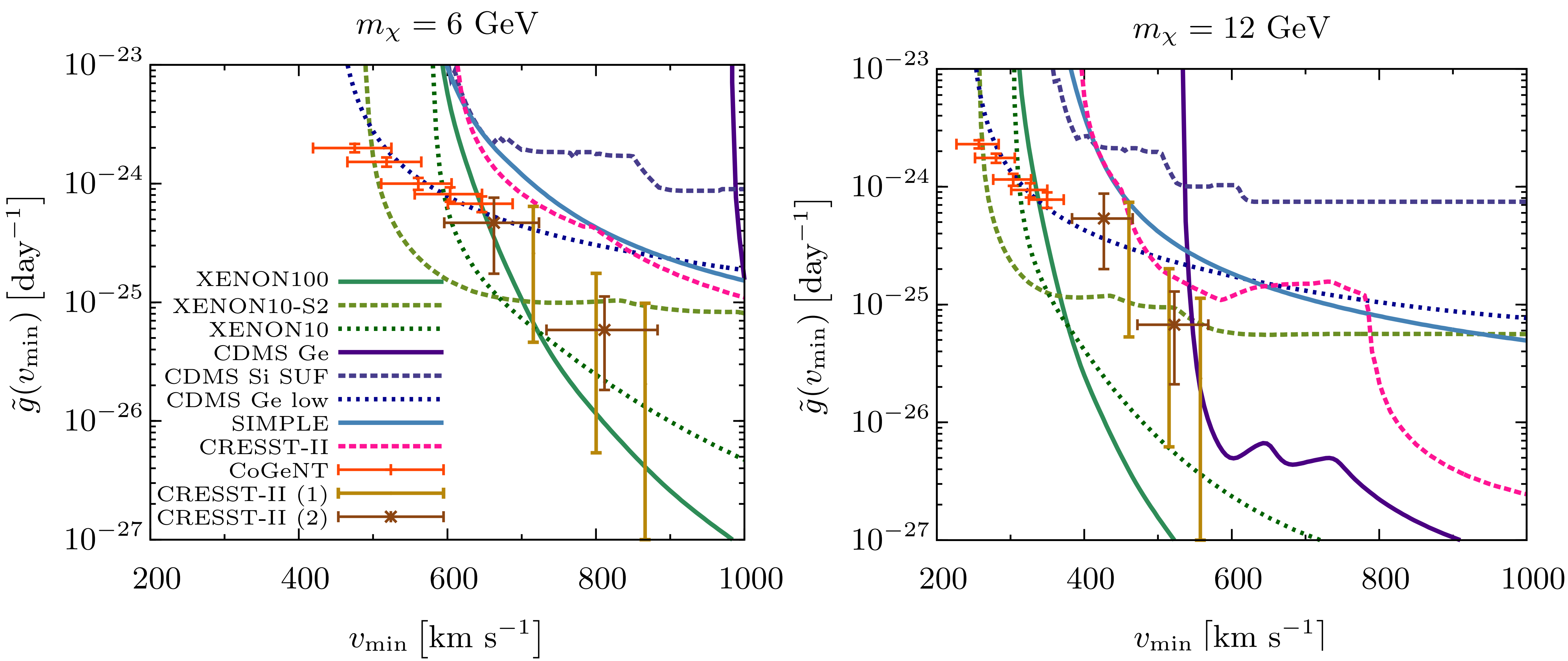
$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2m_\chi \mu^2}\sigma(E_R)\, g_1\Theta(v_1 - v_{min}(E_R))$$



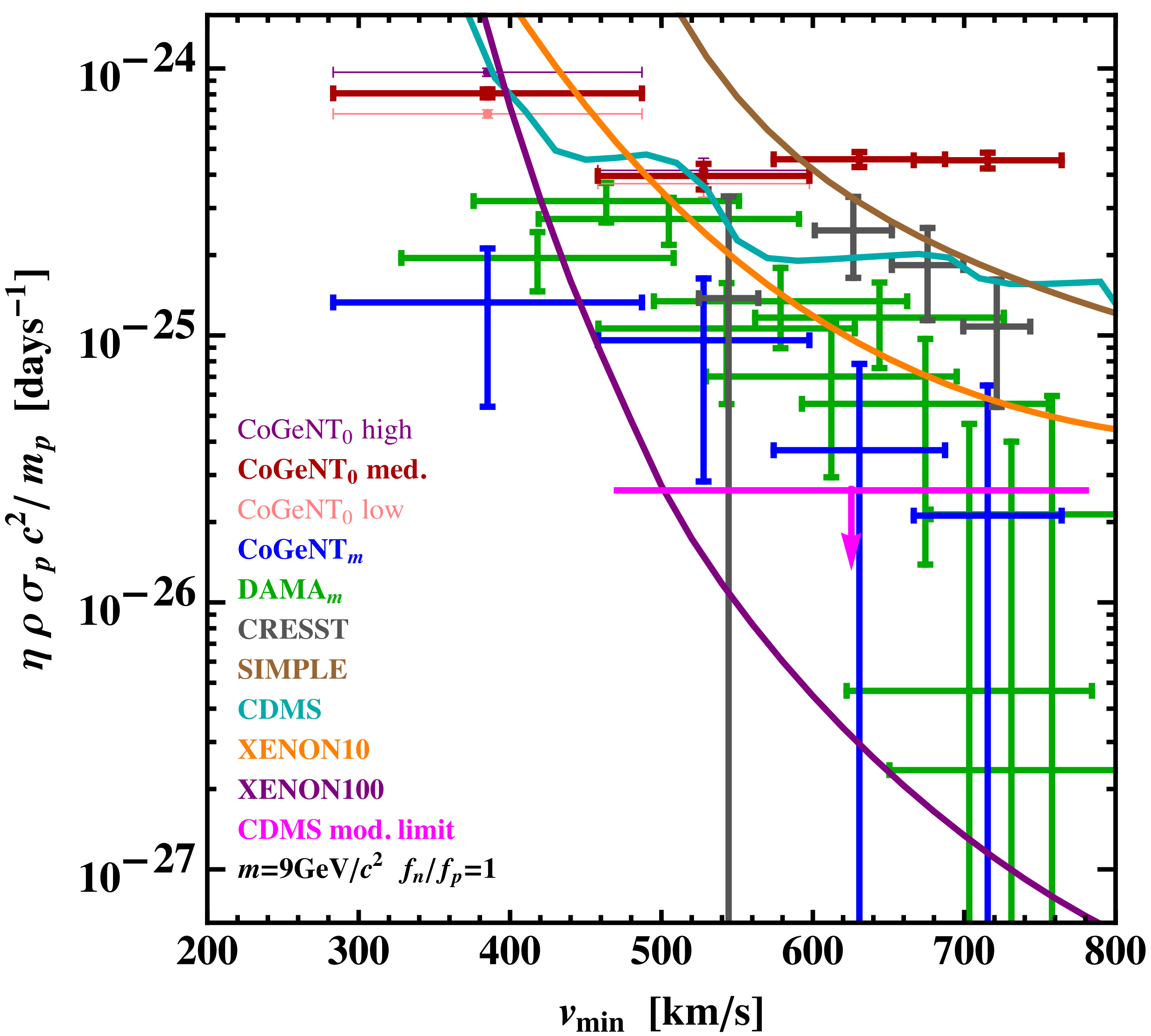
- (1) Pick some energy (velocity) upper bound
- (2) set a limit using your favorite technique (Poisson, Yellin...) for that velocity range on $\rho \sigma g_1 / m_\chi$
  - (i.e., just replace the usual g(v) with a theta function)

constraining g(v)

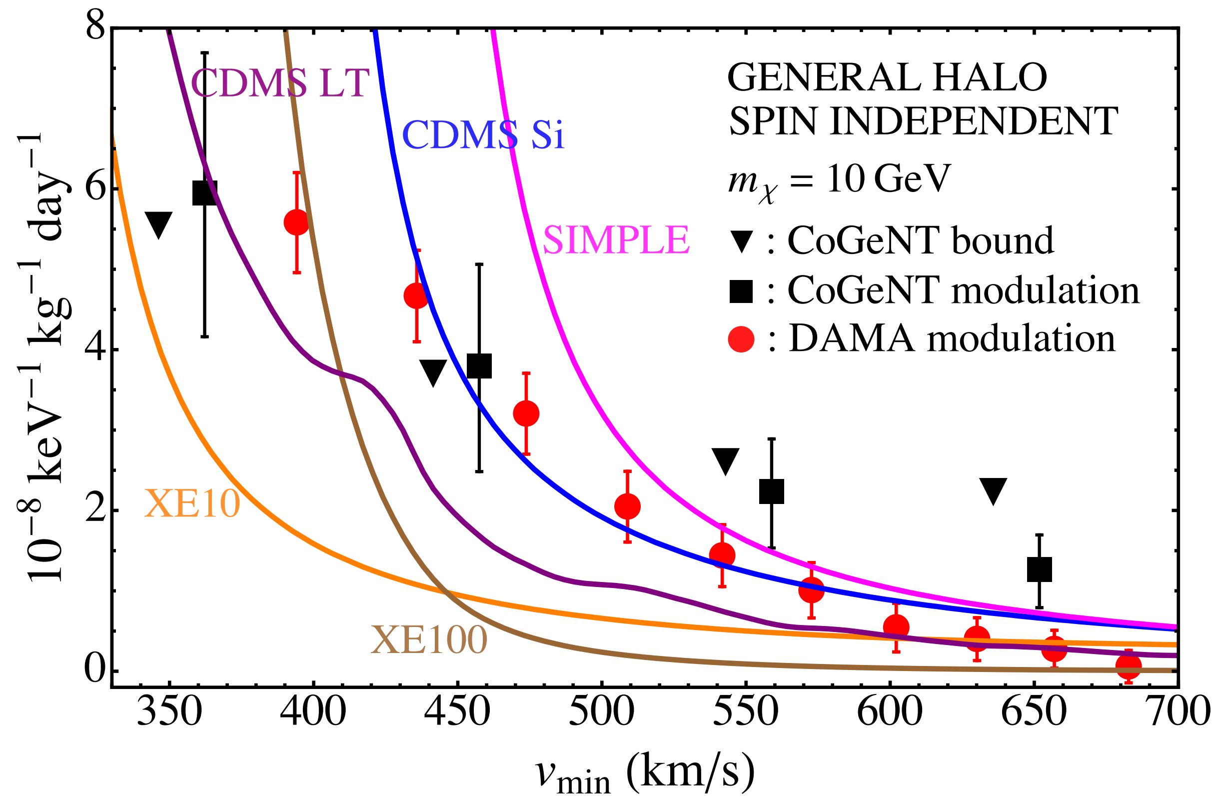




Frandsen et al, 1111.0292



Gondolo+Gelmini



Herrero-Garcia, Schwetz, Zupan

limiting g(v)

- you have to pick a mass
- but there is an unambiguous map between masses $m_1 \Leftrightarrow m_2$
- Could easily be output as supplement to usual σ-m plots

in summary

- DM searches are more robust than we might have guessed
    - Can find stable particles that are not "the" DM in both direct and indirect detection
- As a *complement* to standard σ-m plots, we can directly compare direct detection experiments, in maps and g(v) limits

in summary

- For astrophysics independent limits
  - iodine interpretations of DAMA are being squeezed
  - Important to see wide range of Xe energies to constrain scenarios (i.e., I can imagine 10^{-1} suppression easily but not 10^{-4})
  - CDMS may not necessarily kill the possibility of a signal at CoGeNT but does seem to kill the consistency of CoGeNT and DAMA
  - Evading XENON signals pushes you into the arms of CDMS-Si

in summary

- limits on g(v) are simple, clear baseline constraints
- Three final asides:
  - There is a certain intellectual honesty that is compelled by plotting things in many physical parameter spaces
  - “plots” need no longer be static things (e.g., DMtools)
  - Without these model independent constraints Subir will never pay up