Integrating out astrophysical uncertainties in the search for Dark Matter

Patrick Fox

Fermilab

arXiv:1011.1915 [hep-ph]

PF, Liu and Weiner

Integrating out astrophysical uncertainties in the search for Dark Matter

or,

Dark Matter when astrophysics Don't Matter

Patrick Fox

Fermilab

arXiv:1011.1915 [hep-ph]

PF, Liu and Weiner

Plan

- Direct detection and the standard assumptions
- Comparing multiple experiments, extracting g(v)
- Some case studies
  - e.g. CoGeNT vs XENON
  - CRESST vs CDMS/XENON
  - DAMA vs XENON
- Future ideas, a nice plot, and how to use it
- Conclusions

Direct Detection

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

SI or SD dark matter:

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

$$\sigma_{SD}(E_R) = \frac{\sigma_p}{2J+1} \frac{\mu^2}{\mu_{n\chi}^2} \frac{\left(a_p^2 S_{pp}(E_R) + a_p a_n S_{pn}(E_R) + a_n^2 S_{nn}(E_R)\right)^2}{a_p^2}$$

Kinematics of DM scattering:

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

Direct Detection

[see also, Drees and Shan]

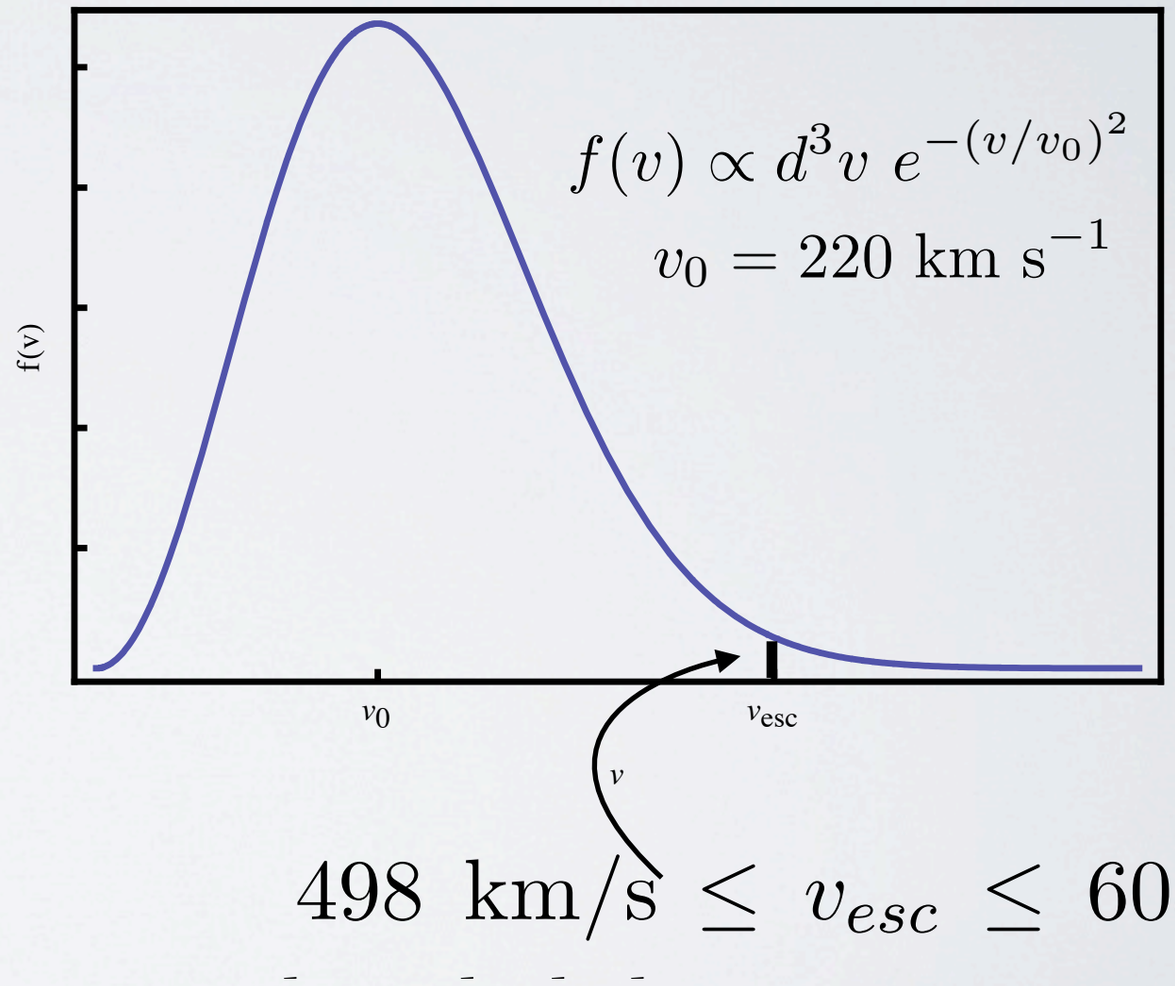
Is a signal a measurement of particle physics or astrophysics?

The only way we have of probing our **local** DM distribution

f(v) has considerable uncertainty

- streams
- voids
- escape velocity
- functional form

(differences in the large velocity tail)



$$498\ \mathrm{km/s} \leq v_{esc} \leq 608$$

Direct Detection

[see also, Drees and Shan]

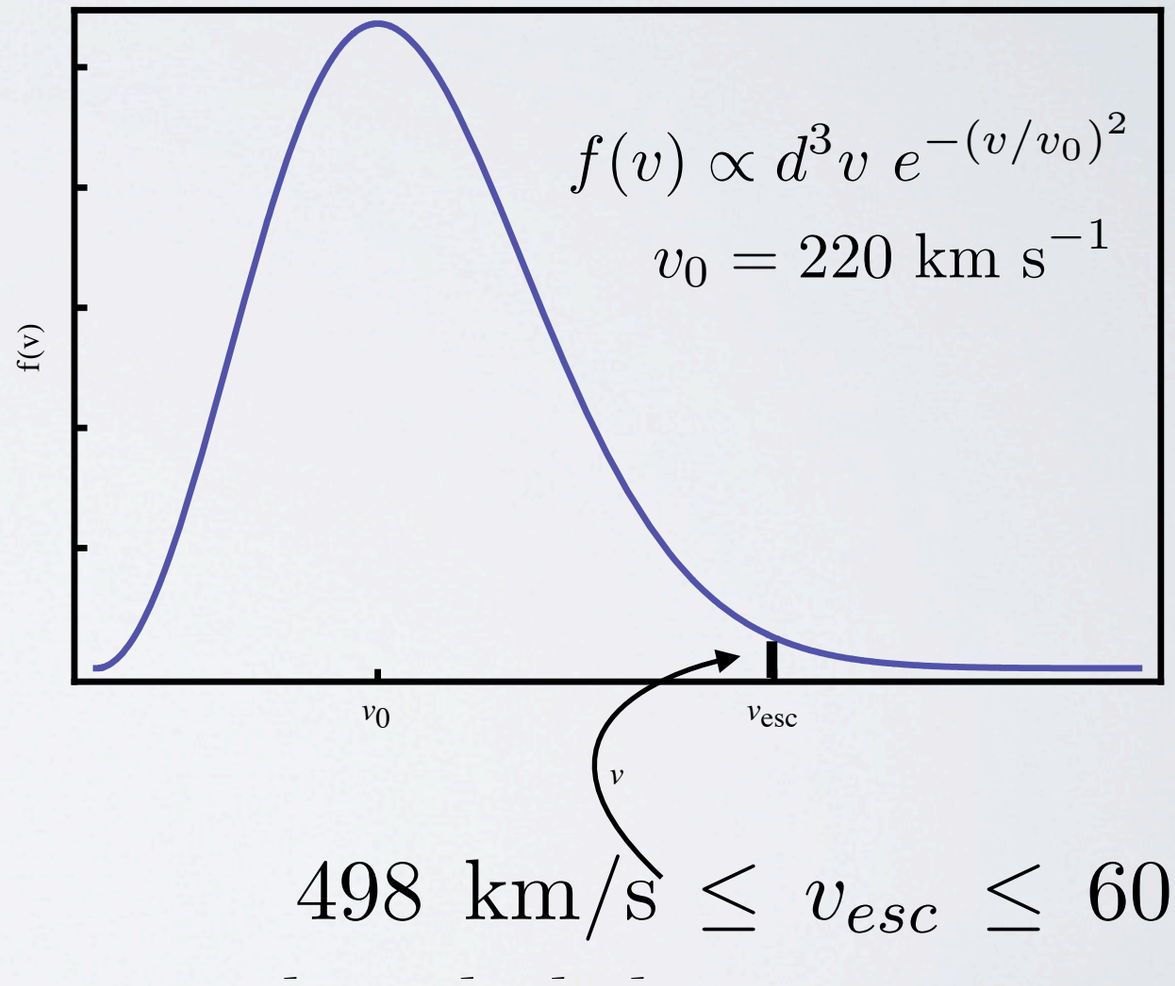
Is a signal a measurement of particle physics or astrophysics?

The only way we have of probing our **local** DM distribution

f(v) has considerable uncertainty

- streams
- voids
- escape velocity
- functional form

(differences in the large velocity tail)



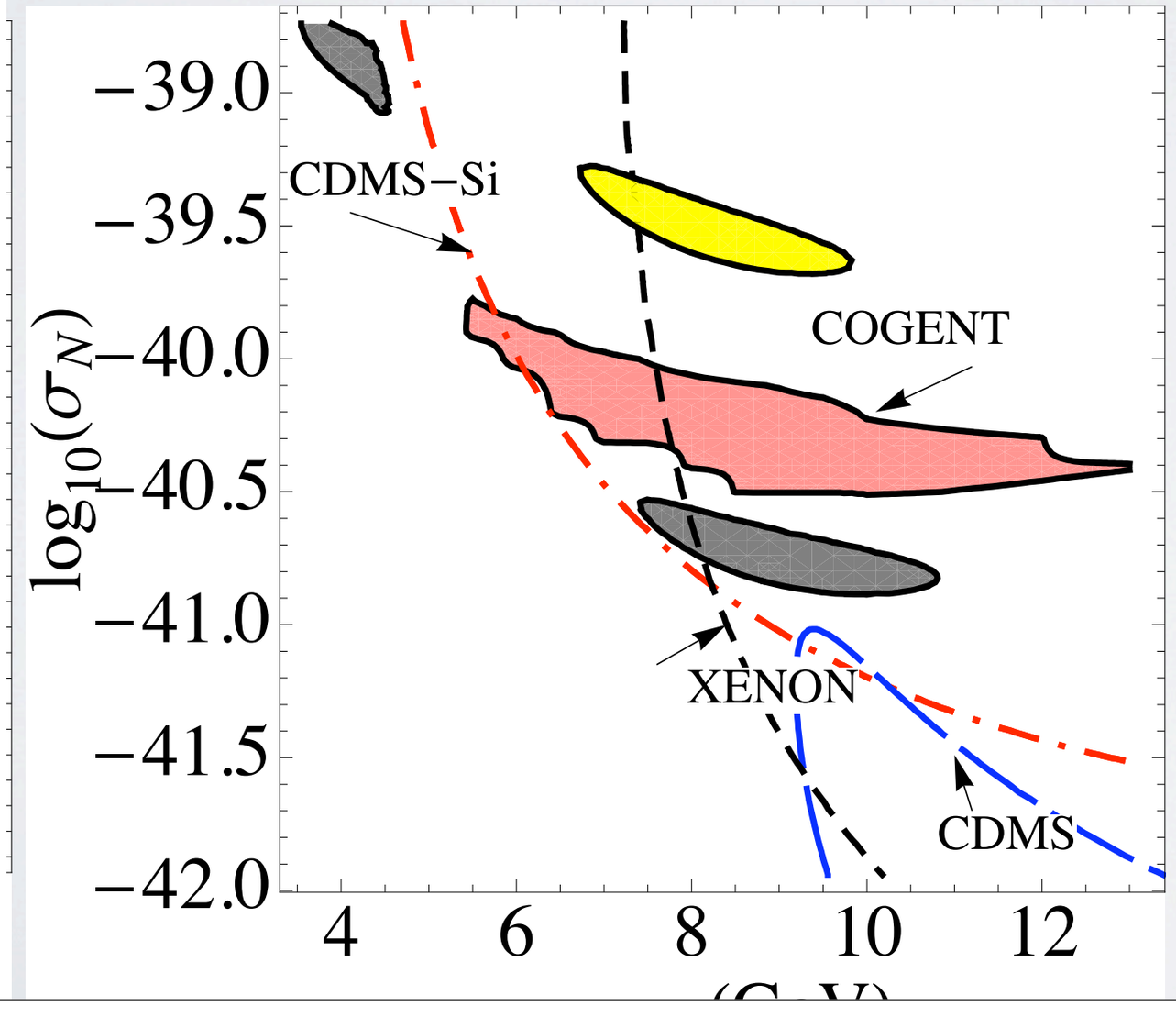
$$498\ \mathrm{km/s} \leq v_{esc} \leq 608$$

But, we have more than one experiment!

Two(+) experiments allow us to test particle physics independently of astrophysics

In the past all experiments were "projected" into x-sec--mass plane.

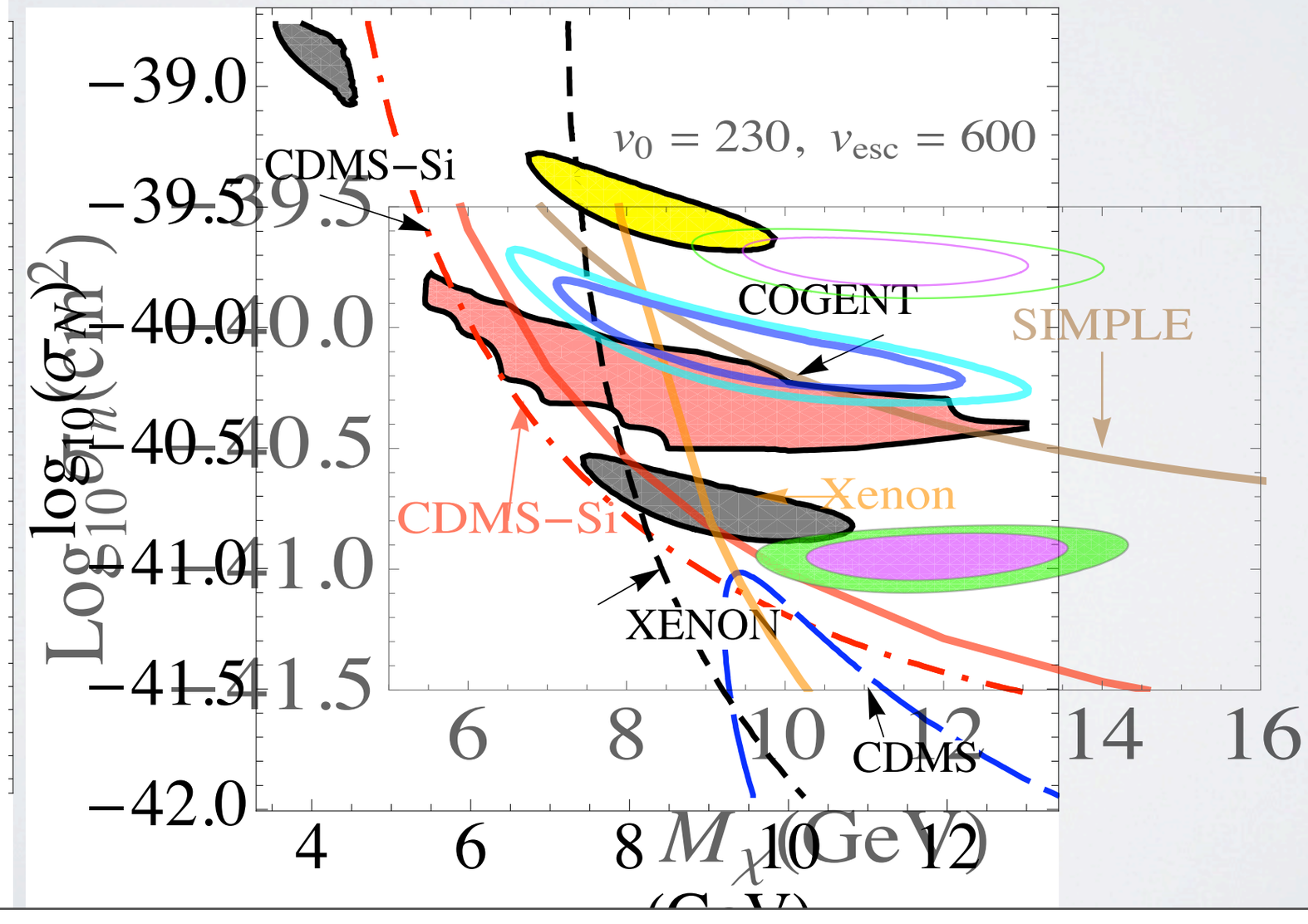
Confused discovering DM with measuring DM



Two(+) experiments allow us to test particle physics independently of astrophysics

In the past all experiments were "projected" into x-sec--mass plane.

Confused discovering DM with measuring DM



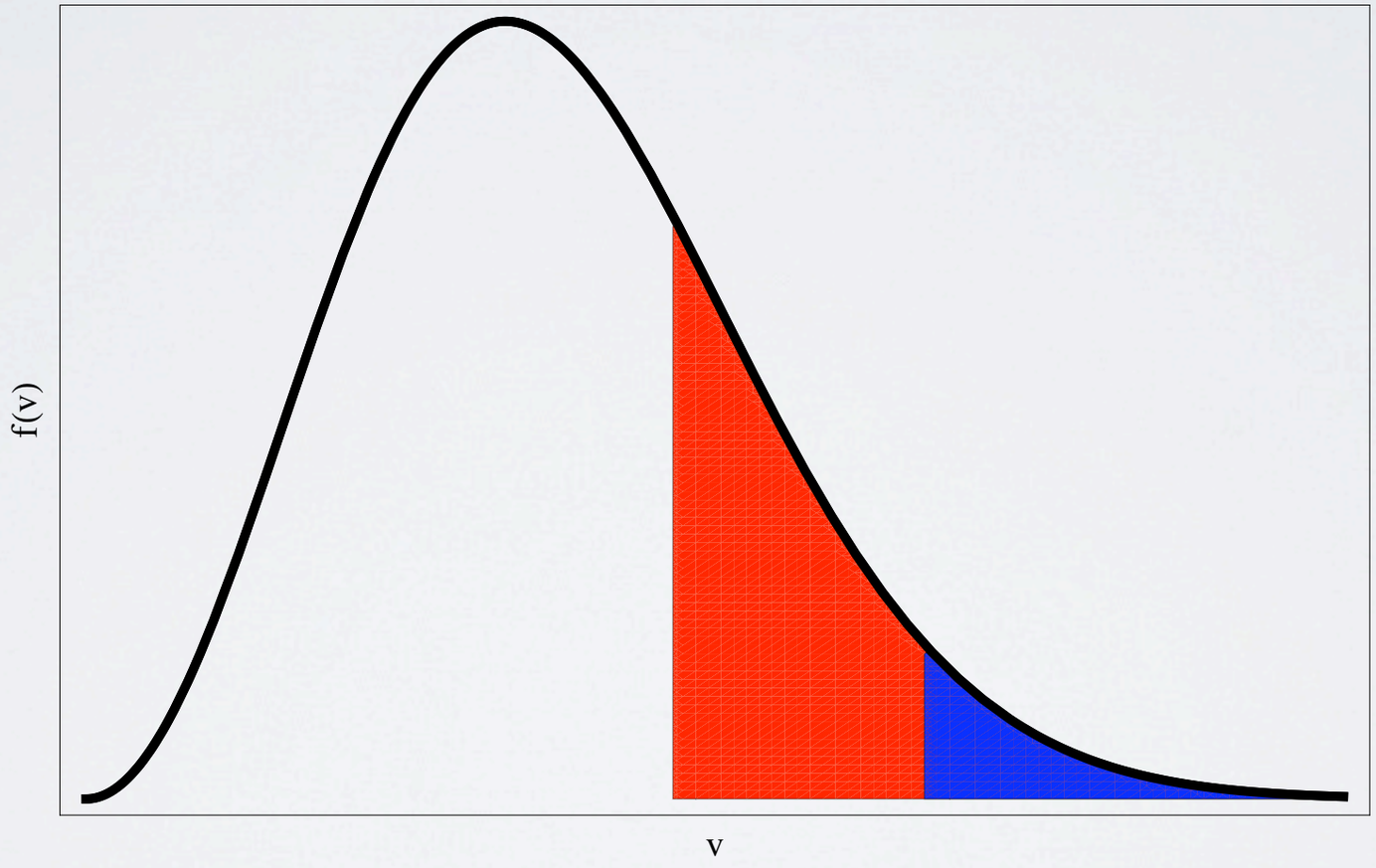
Two(+) experiments allow us to test particle physics independently of astrophysics

1) Make hypothesis about DM e.g. elastically scattering DM with mass 100 GeV and x-sec 10^{-43} cm^2
2) Use experiment A to extract astrophysics i.e. rho x g(v)
3) Use these extracted astrophysics properties to predict result at experiment B
4) Compare to B's measurement/bound
5) Rule in or out each particle physics hypothesis

Doesn't allow extraction of "unique" x-sec, mass
Need relatively large statistics ~10's events
Experiments must run over same part of year
Other uncertainties (nuclear, atomic etc) not addressed)

Enter vmin space

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \underbrace{\int_{v_{min}}^{v_{max}} d^3\vec{v} \frac{f(\vec{v}, \vec{v_E})}{v}}_{g(v)} \sigma(E_R)$$



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

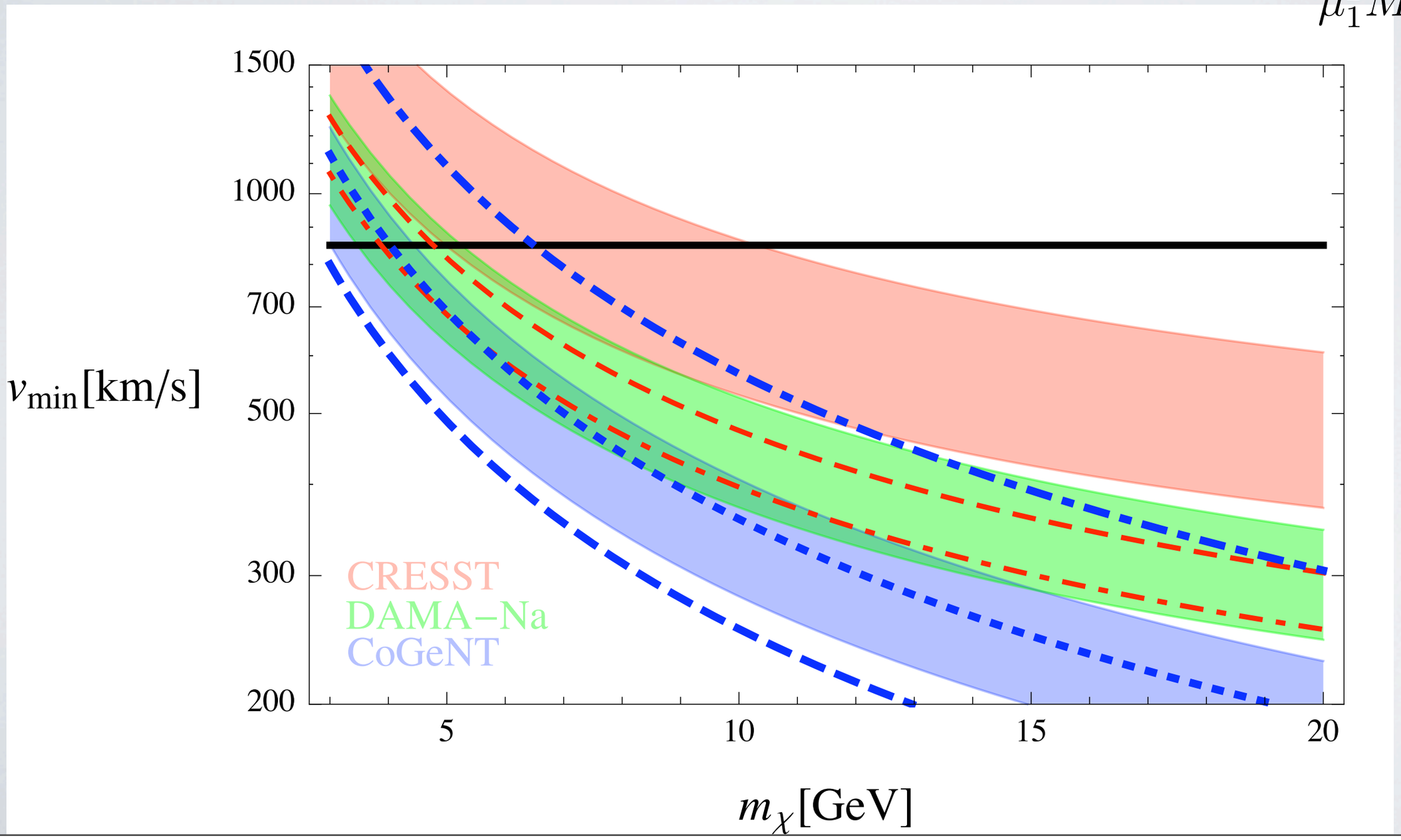
Recoil energy uniquely determines **minimum** DM velocity

Using vmin space

Experiment 1 $\longleftrightarrow$ Experiment 2

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

$$[E^{(2)}_{low}, E^{(2)}_{high}] = \frac{\mu_2^2 M_T^{(1)}}{\mu_1^2 M_T^{(2)}} [E^{(1)}_{low}, E^{(1)}_{high}]$$

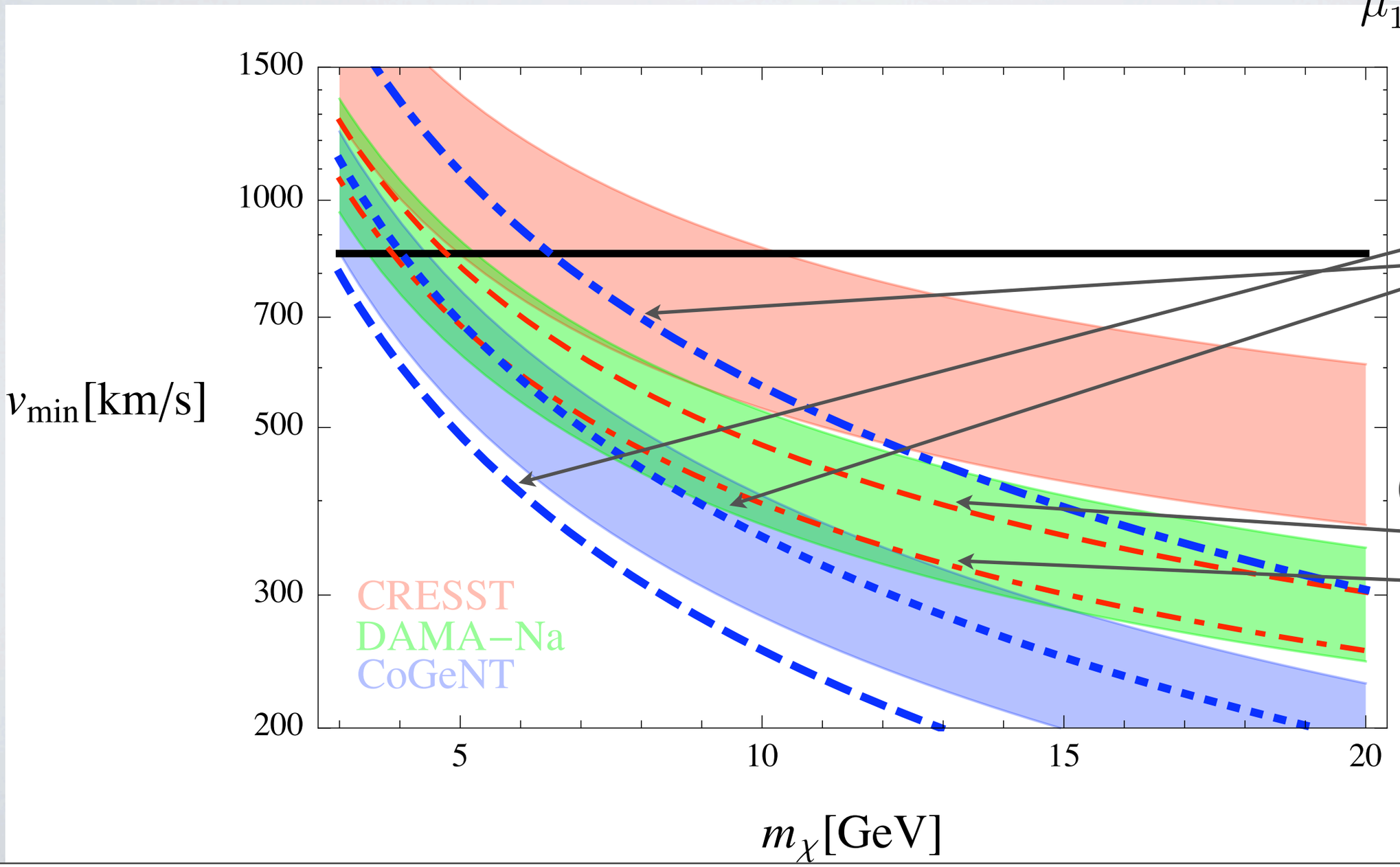


Using vmin space

Experiment 1 $\longleftrightarrow$ Experiment 2

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

$$[E^{(2)}_{low}, E^{(2)}_{high}] = \frac{\mu_2^2 M_T^{(1)}}{\mu_1^2 M_T^{(2)}} [E^{(1)}_{low}, E^{(1)}_{high}]$$



Xenon w/ 1,2,5 keV thresholds

CDMS-Si w/ 7,10 keV thresholds

Comparing experiments

e.g. $m_\chi = 10\,\mathrm{GeV}$

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

all energies in keV, undoing quenching etc

Now we know who compares with whom, how do we compare them?

Direct Detection without bias

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \underbrace{\int_{v_{min}}^{v_{max}} d^3\vec{v} \frac{f(\vec{v}, \vec{v_E})}{v}}_{g(v)} \sigma(E_R)$$

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

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

Recoil energy uniquely determines **minimum** DM velocity

Direct Detection without bias

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \underbrace{\int_{v_{min}}^{v_{max}} d^3\vec{v} \frac{f(\vec{v}, \vec{v_E})}{v}}_{g(v)} \sigma(E_R)$$

$$\frac{dR}{dE_R} = \underbrace{\frac{N_T M_T}{2\mu^2}}_{\text{Target specific}} \frac{\rho\sigma}{m_\chi} g(v)$$

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

Recoil energy uniquely determines **minimum** DM velocity

Direct Detection without bias

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \underbrace{\int_{v_{min}}^{v_{max}} d^3\vec{v} \frac{f(\vec{v}, \vec{v_E})}{v}}_{g(v)} \sigma(E_R)$$

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

Target specific

Target independent

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

Recoil energy uniquely determines **minimum** DM velocity

Comparing experiments

HW problem: solve for g(v)

$$N_T = \kappa N_A m_p / M_T$$

$$g(v_{min}) = \frac{2 m_\chi \mu^2}{N_A \kappa \, m_p \, \rho \, \sigma(E_R)} \frac{dR_1}{dE_1}$$

$$\frac{dR_1}{dE_1} \Longleftrightarrow g(v_{min}) \Longleftrightarrow \frac{dR_2}{dE_2}$$

The master formula (SI):

$$C_T^{(i)} = \kappa^{(i)} \left(f_p \, Z^{(i)} + f_n \, (A^{(i)} - Z^{(i)}) \right)^2$$

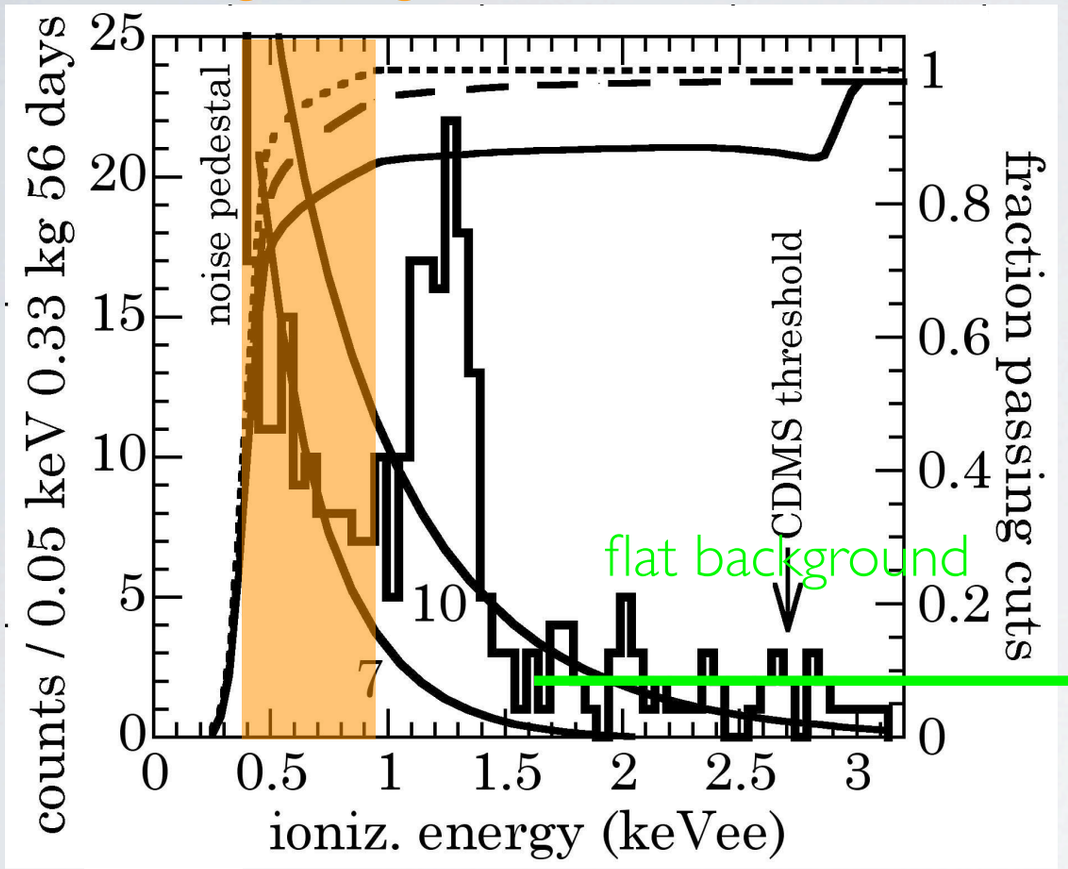
$$\frac{dR_2}{dE_R}(E_2) = \frac{C_T^{(2)}}{C_T^{(1)}} \frac{F_2^2(E_2)}{F_1^2 \left(\frac{\mu_1^2 \, M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2 \right)} \frac{dR_1}{dE_R} \left(\frac{\mu_1^2 \, M_T^{(2)}}{\mu_2^2 \, M_T^{(1)}} E_2 \right)$$

There's an app for that

CoGeNT

[Collar et al. (1002.4703)]

signal region



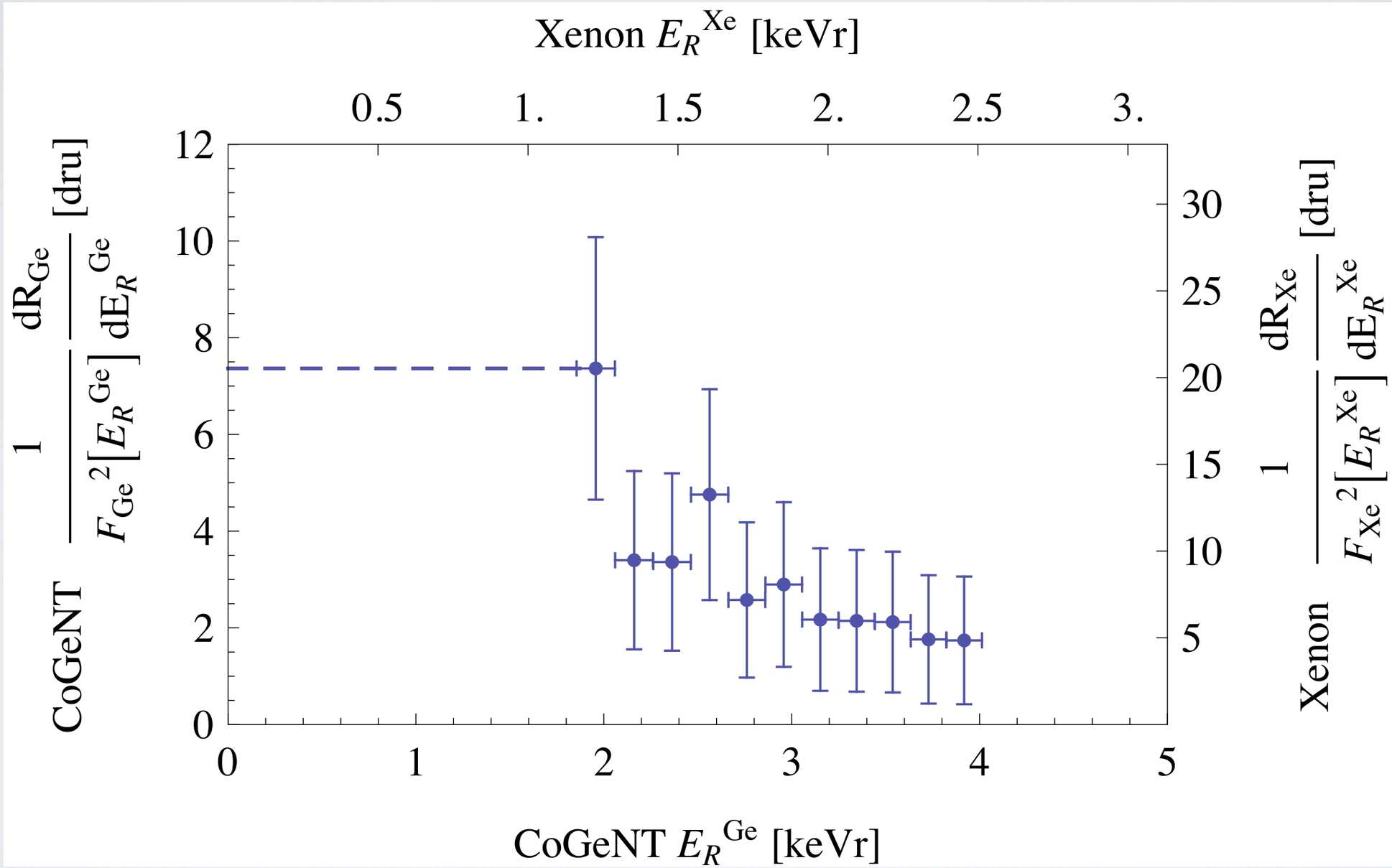
$$E_{obs} = 0.2(E_r/\mathrm{keV})^{1.12},$$

- Avoid cosmogenic peaks
- Large number of events, 92 events after background subtraction
- 11 bins
- Assume DM only couples to proton (e.g. kinetic mixing) gives most lenient bounds

Predict deconvoluted rate at XENON10...

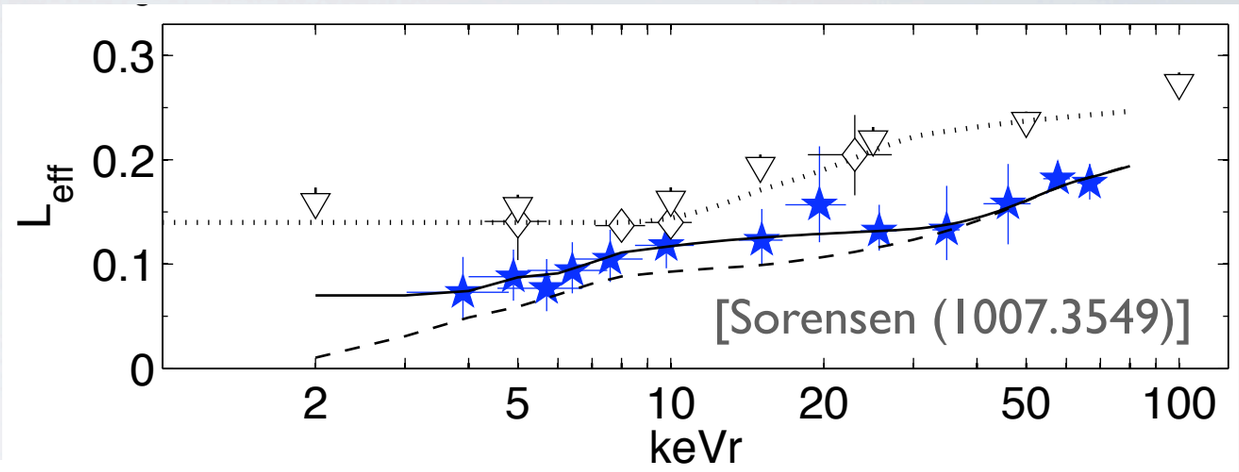
CoGeNT and XENON10

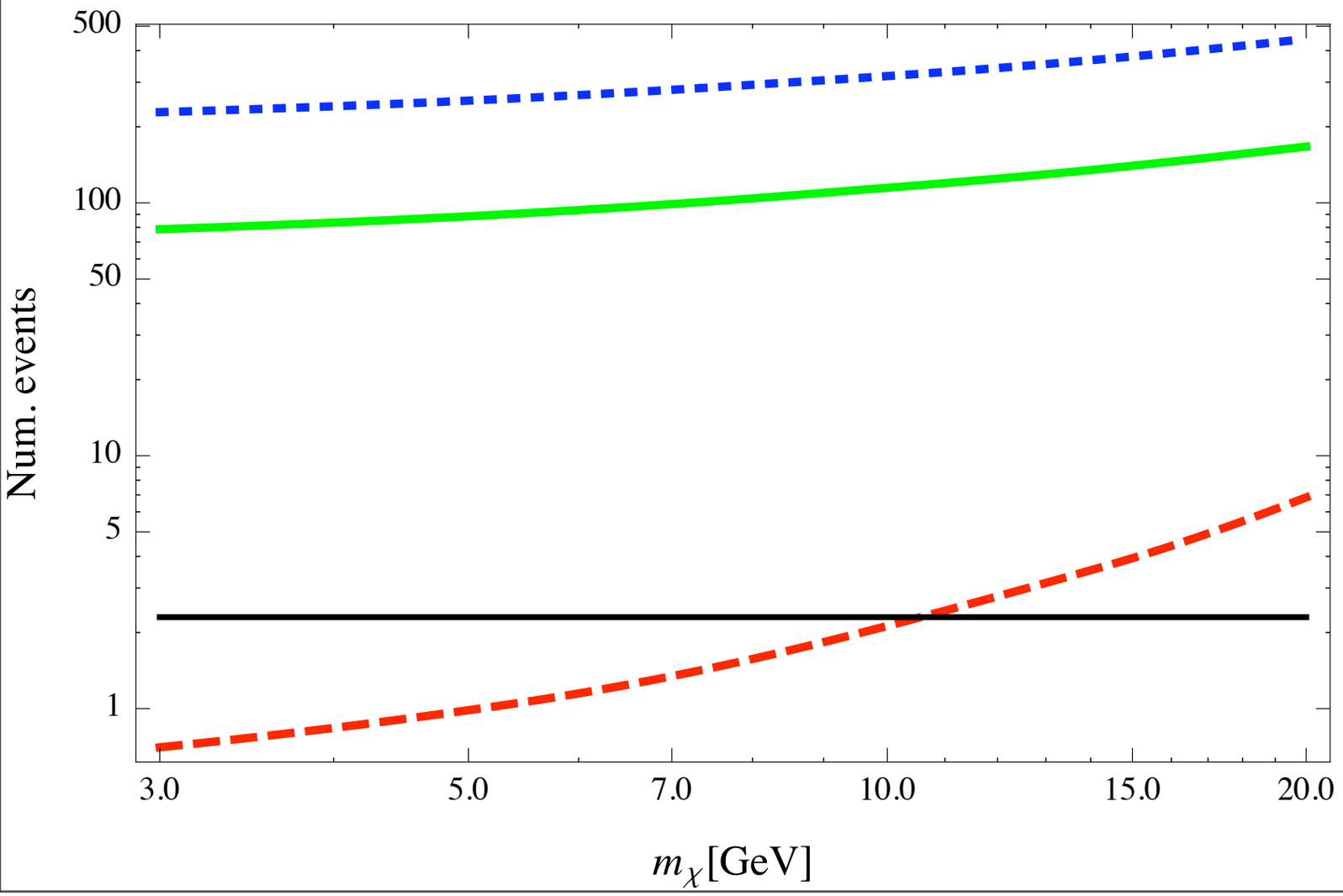
$$m_\chi = 10\,\mathrm{GeV}$$



CoGeNT and XENON10

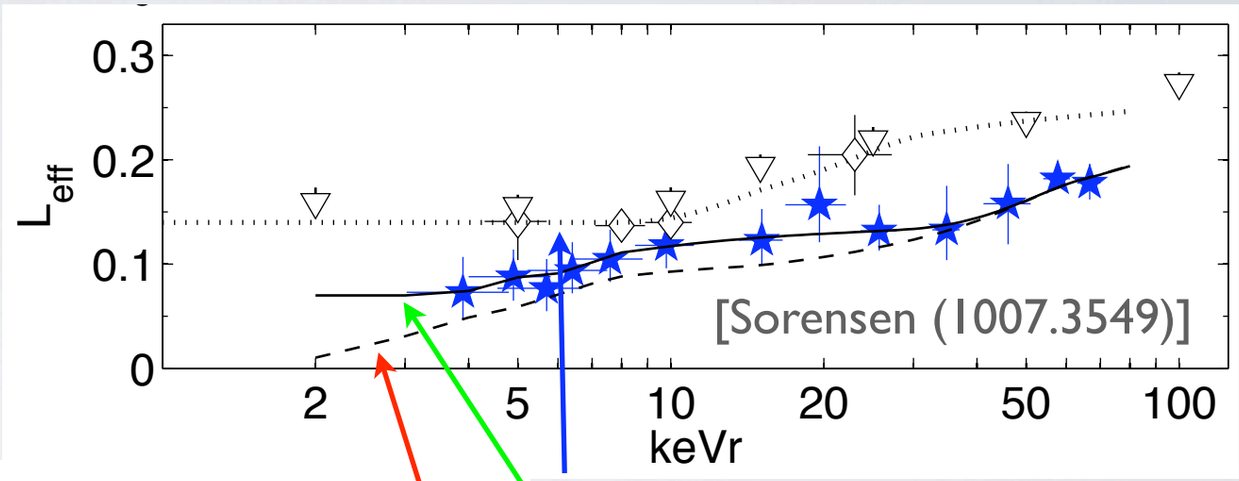
Predicted number of events at XENON10 (who saw 0 in relevant energy range)

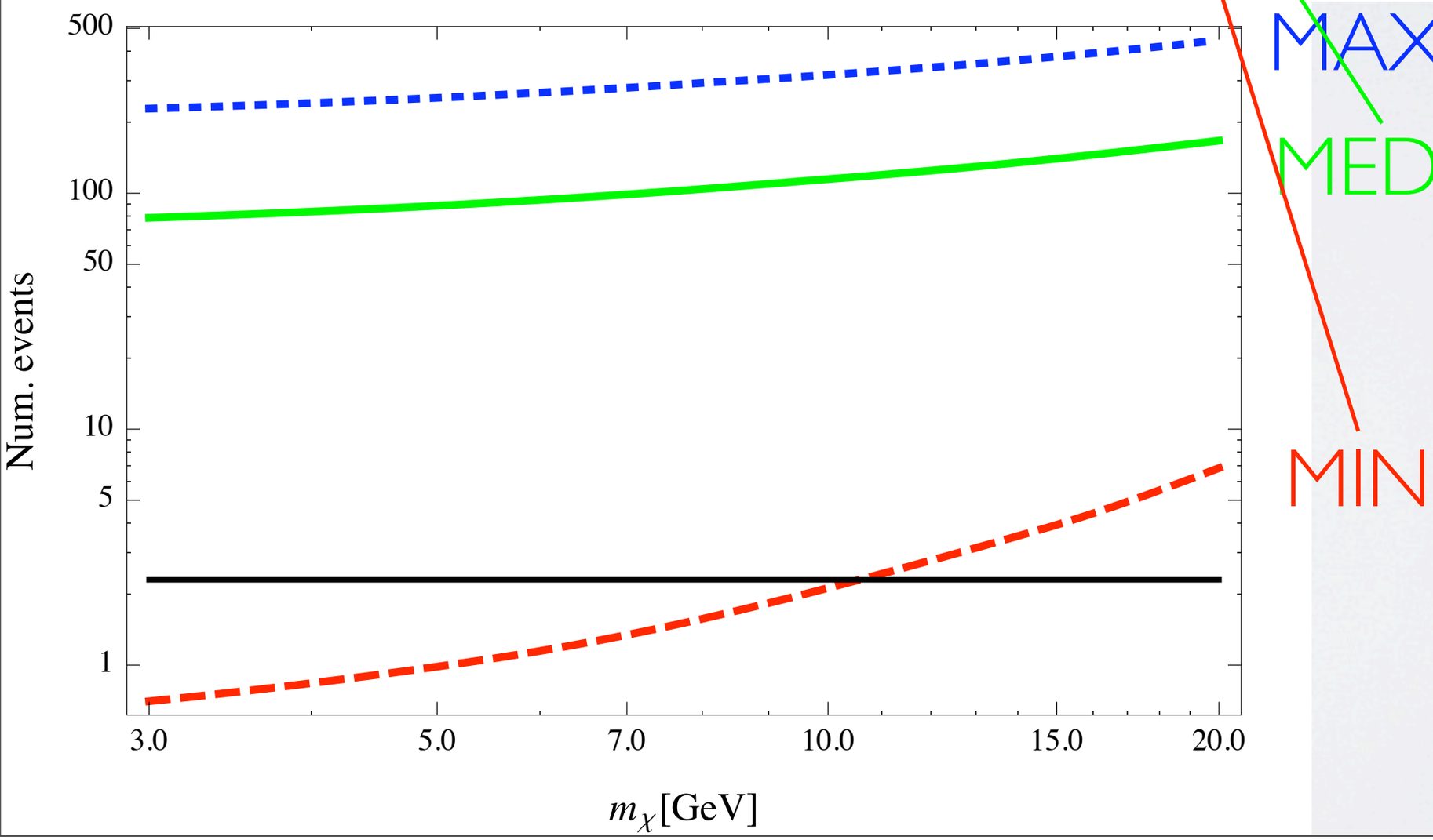




CoGeNT and XENON10

Predicted number of events at XENON10 (who saw 0 in relevant energy range)





MAX

MED

MIN

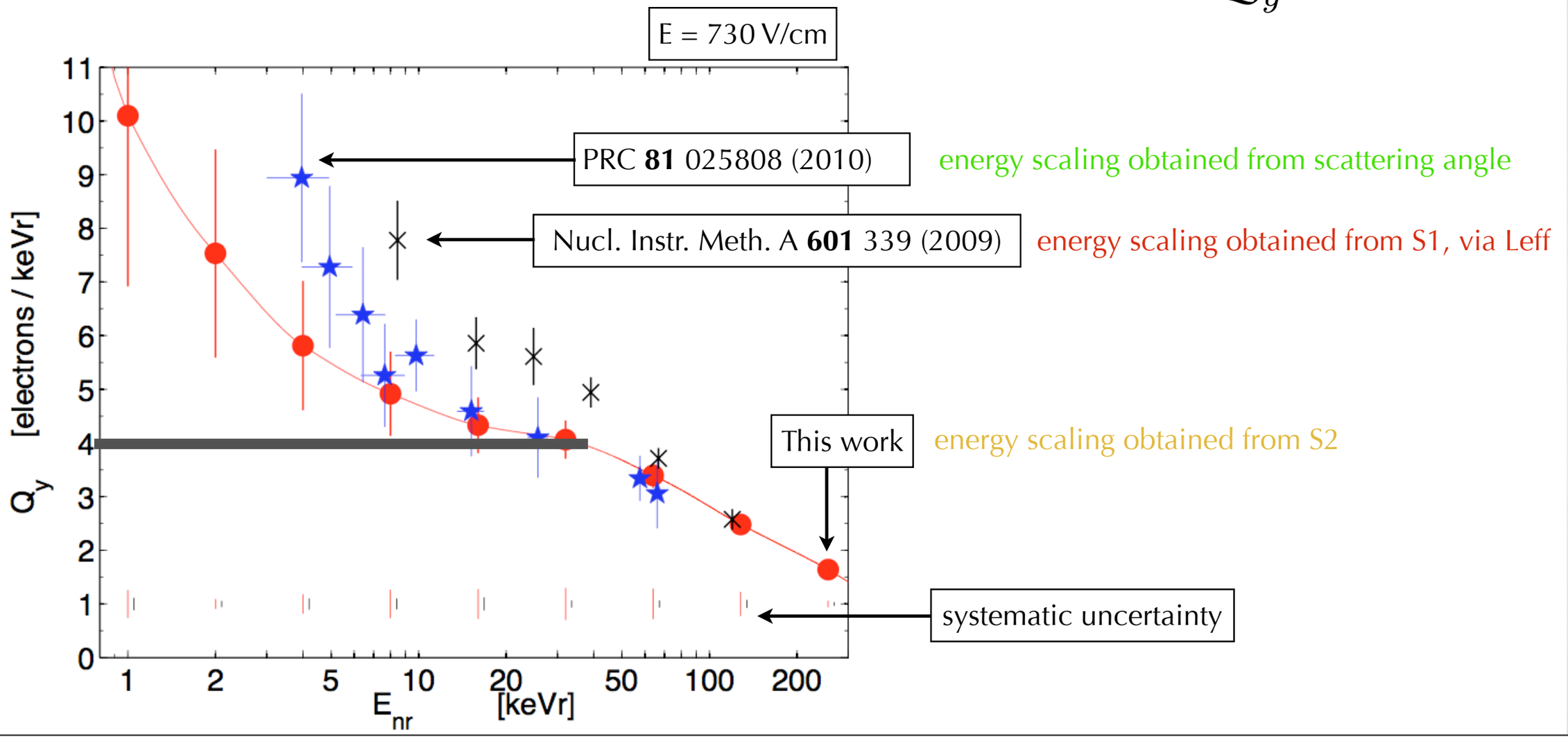
CoGeNT and XENON10 (S2 only analysis)

[see P. Sorensen's talk at IDM2010]

Using only ionization signal (S2) avoids confusions in measuring S1, and allows a lower threshold

Doesn't allow signal/background discrimination

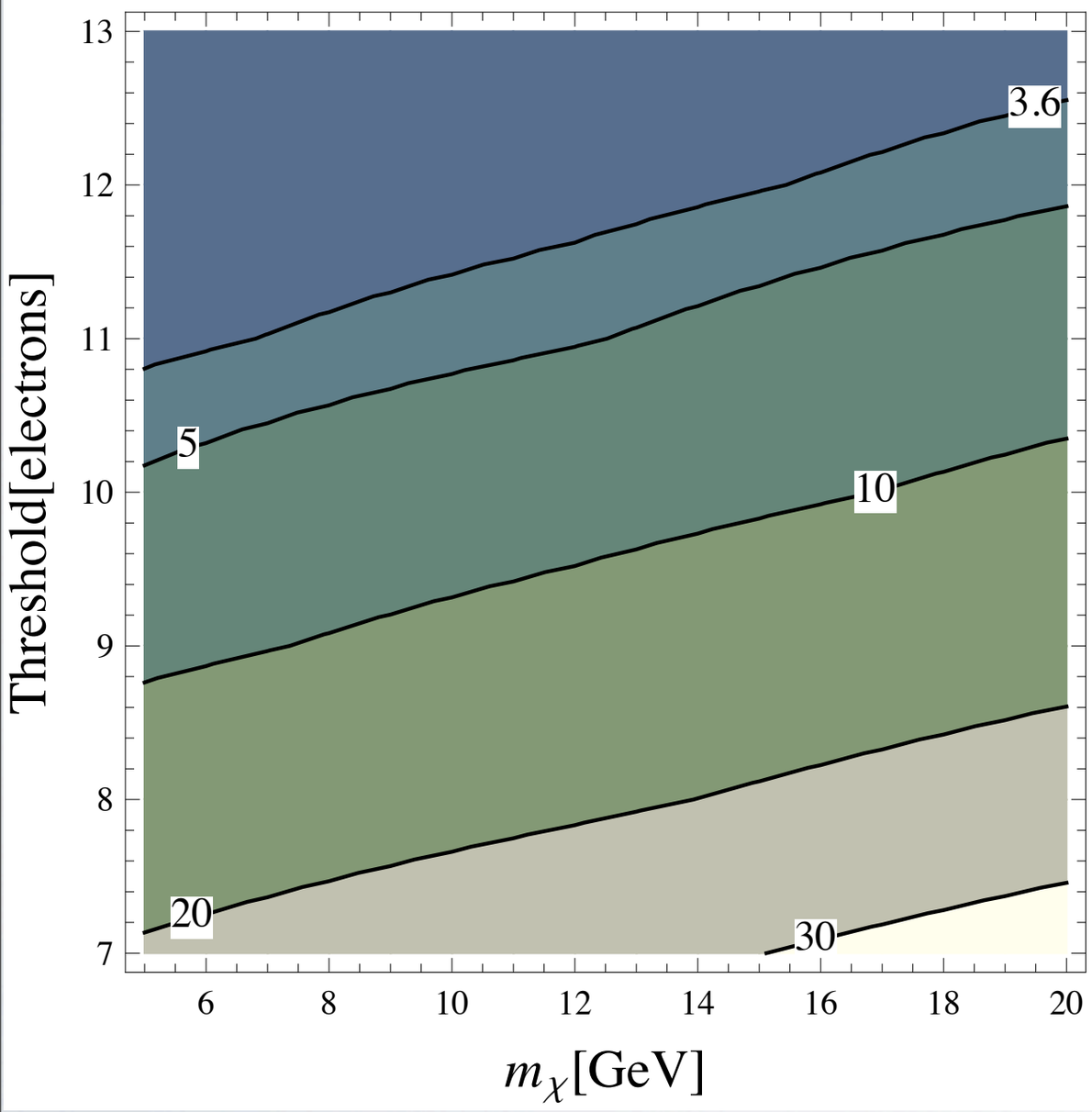
Equivalent of Leff is charge yield, Qy $E_{nr} = \frac{S2}{\mathcal{Q}_y}$



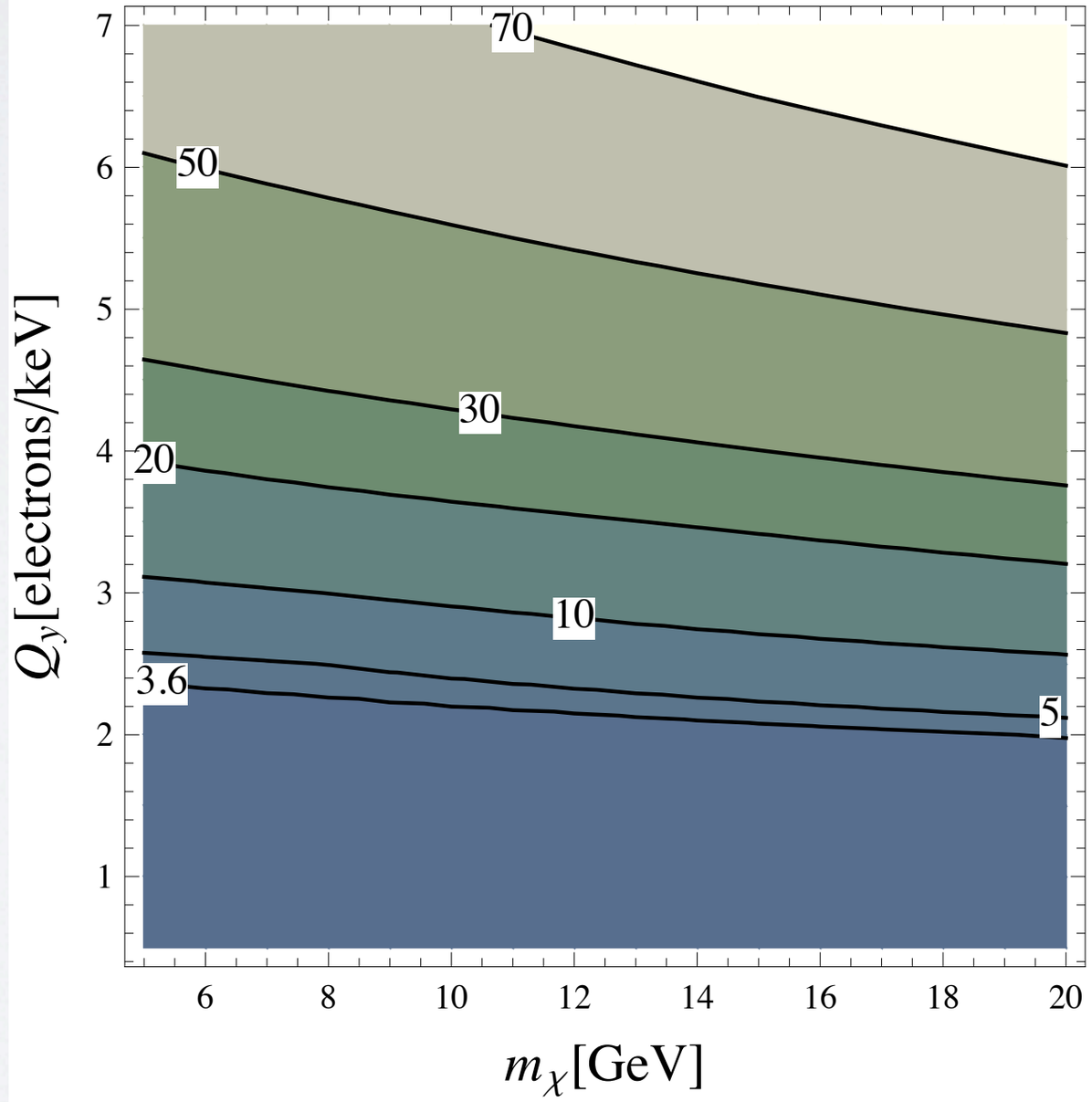
5.1kg-days of exposure
Poisson fluctuations can be important

S2 threshold is 7 electrons
1 event seen

$Q_y = 4\,\text{electrons/keV}$



Threshold = 7 e



CRESST (dealing with the unknown)

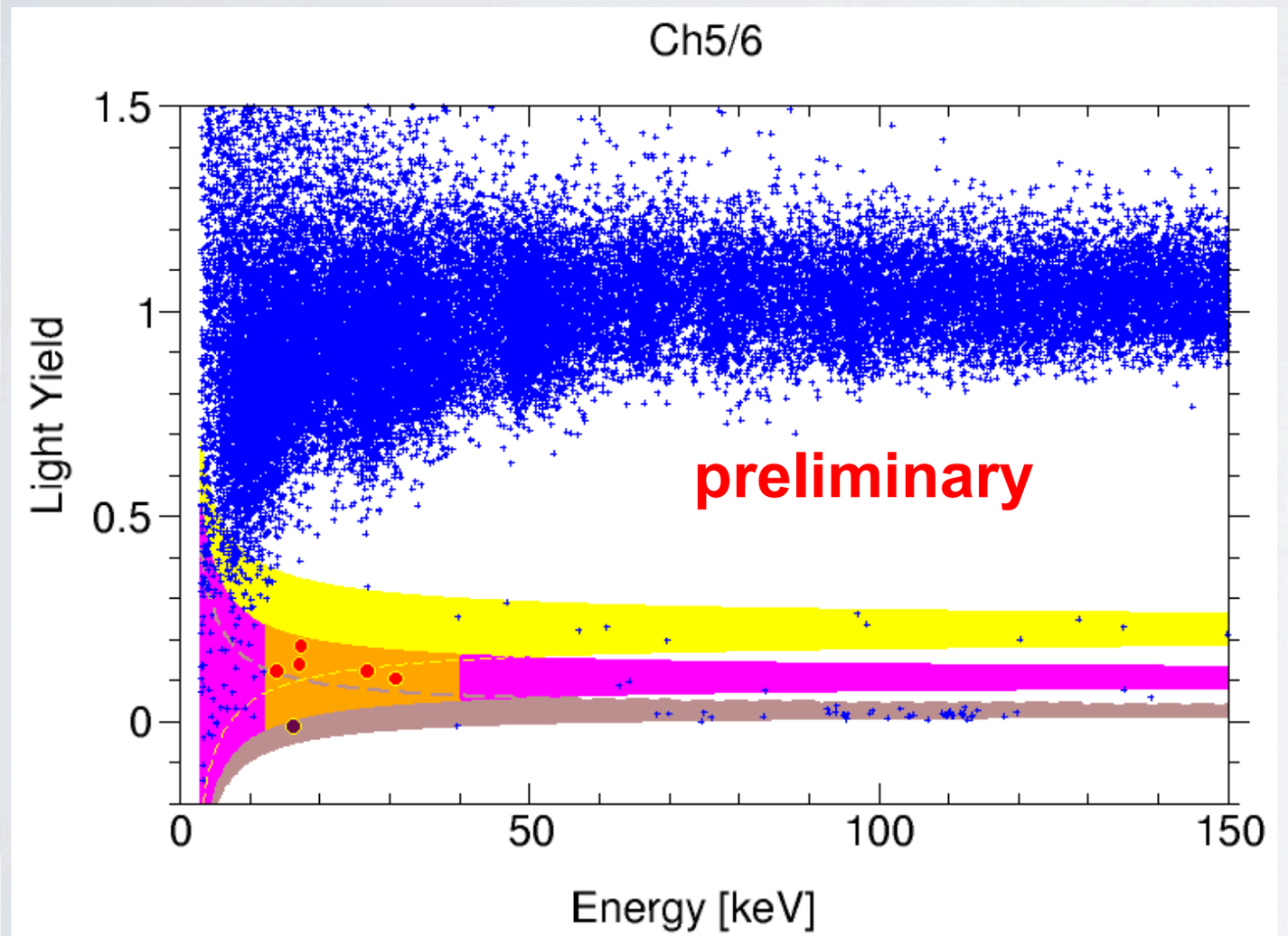
Don't know a spectrum, but can reverse engineer a total rate from what has been presented in conferences

[eg Seidel's talk at IDM2010]

Detector	E0.1[keV]	events
5	12.35	5
20	11.85	2
29	11.65	4
33	15.55	2
43	15.55	4
45	19.15	2
47	17.35	4
51	9.65	6
55	22.25	3
total		32

Neutron background	0.9
Alpha background:	6.9
Leakage from gamma band:	0.9
Sum of background estimates:	**8.7**
Observed oxygen recoil signals :	**32**

background estimate of 8.7 ± 1.4 not enough to explain observed 32 signals,



CRESST (dealing with the unknown)

Work out:

- 22 events above 15 keV (from 7/9 detectors), with (all n's and gamma's attributed to these detectors)
- 280 kg-days exposure

Integrate over energies to get total rate

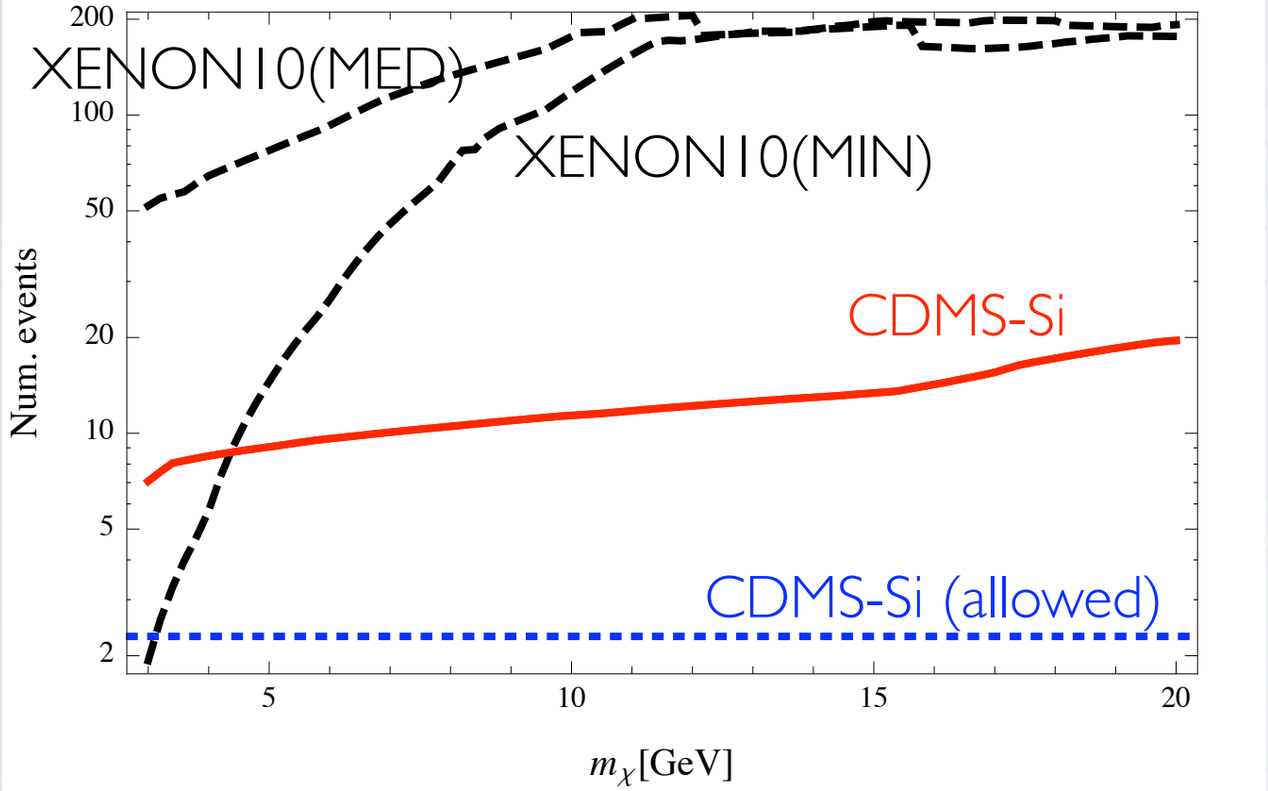
$$R = \left(\frac{2N_A\rho\,\sigma_p m_p}{m_\chi\,\mu_{n\chi}^2\,f_p^2}\right)\left(\frac{\mu^2 C_T}{M_T}\right)\int_{v_{low}}^{v_{high}} dv\,\epsilon(E_R)F^2(E_R(v))vg(v)\ ,$$

Evaluate at energy that makes comparison most conservative

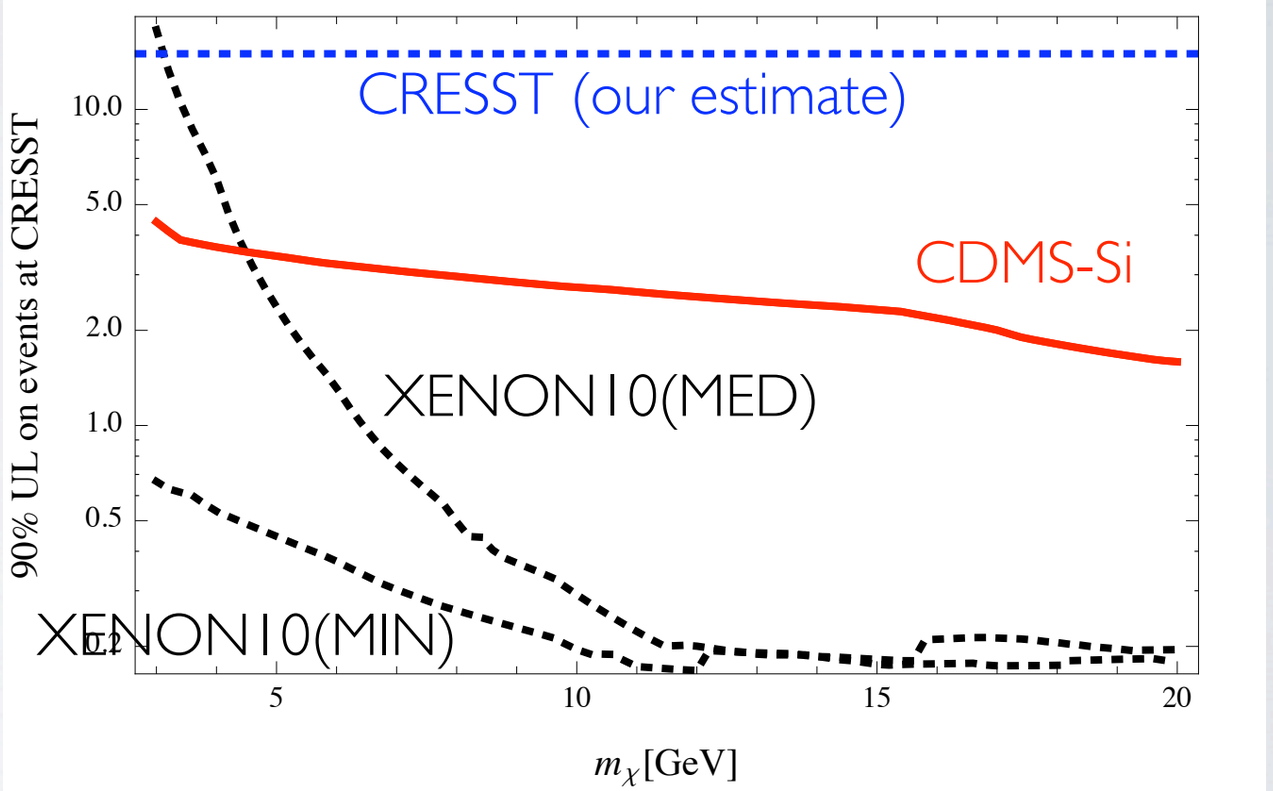
$$R_2 \leq \frac{\epsilon_2(\bar{E}_2)F_2^2(\bar{E}_2)}{\epsilon_1(\bar{E}_1)F_1^2(\bar{E}_1)}\frac{C_T^{(2)}}{C_T^{(1)}}\frac{M_T^{(1)}}{M_T^{(2)}}\frac{\mu_2^2}{\mu_1^2}R_1$$

CRESST and CDMS-Si/XENON10

CRESST predicts



CRESST expects



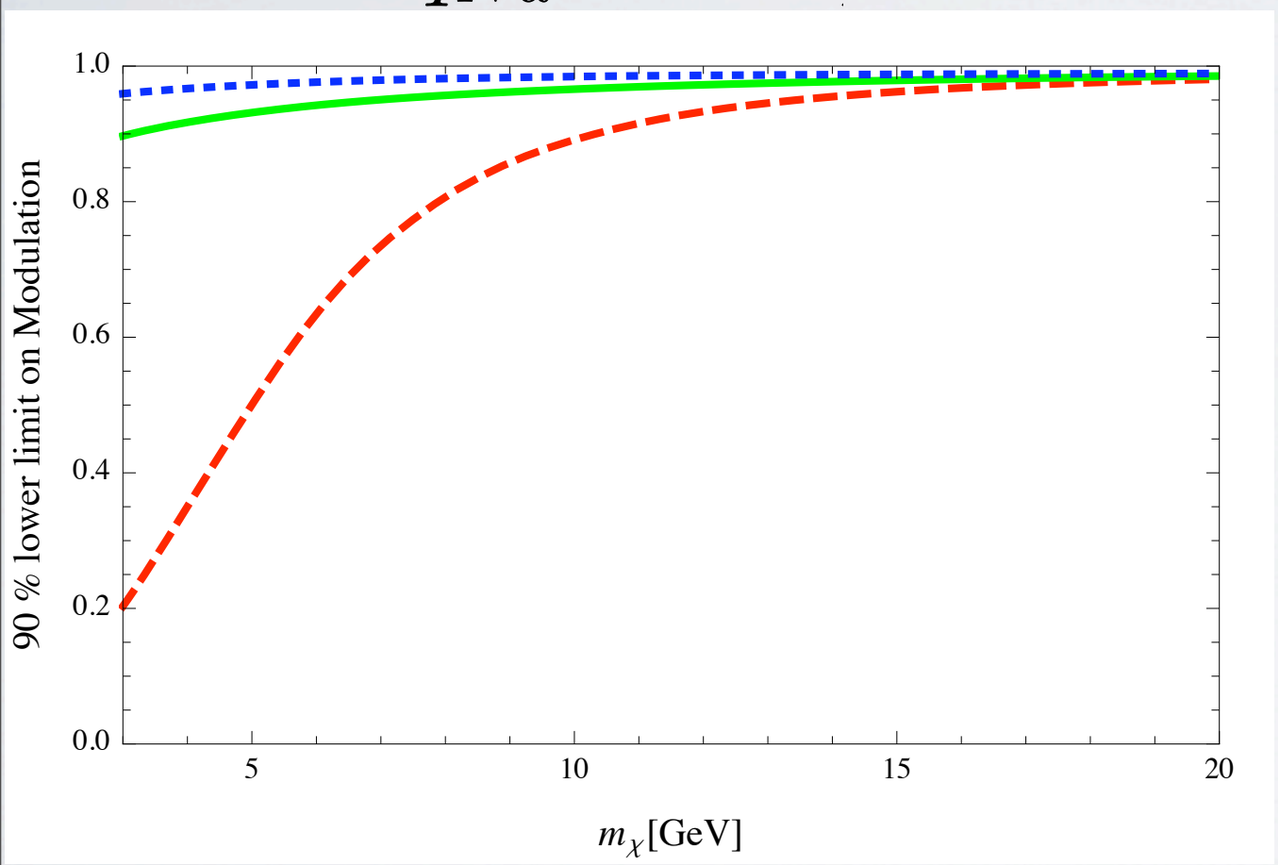
CRESST O-band events at odds with CDMS and XENON

Perhaps signal not eDM?

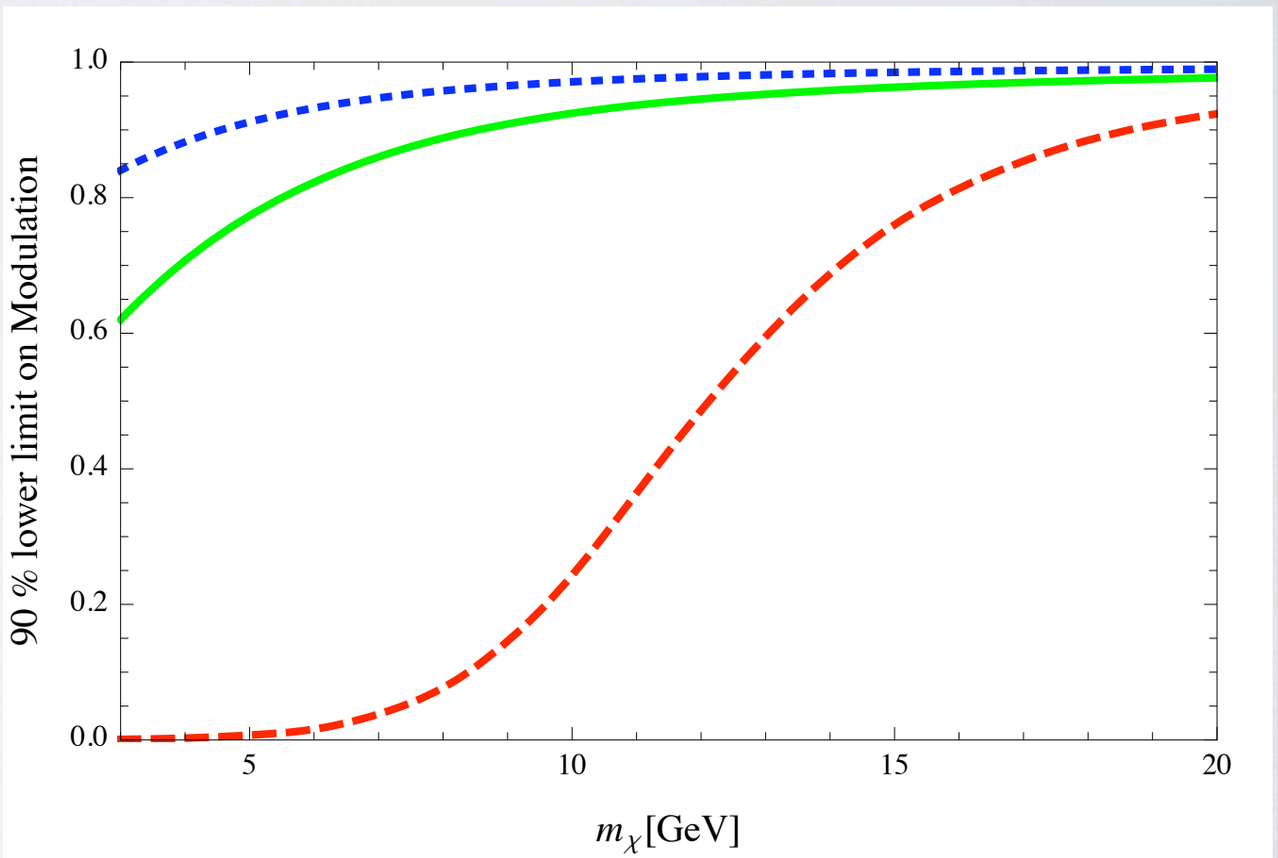
DAMA and modulation

XENON10 saw no events in winter $\Rightarrow$ upper bound (2.3)
Corresponding lower bound on % modulation at DAMA

$q_{Na} = 0.3$

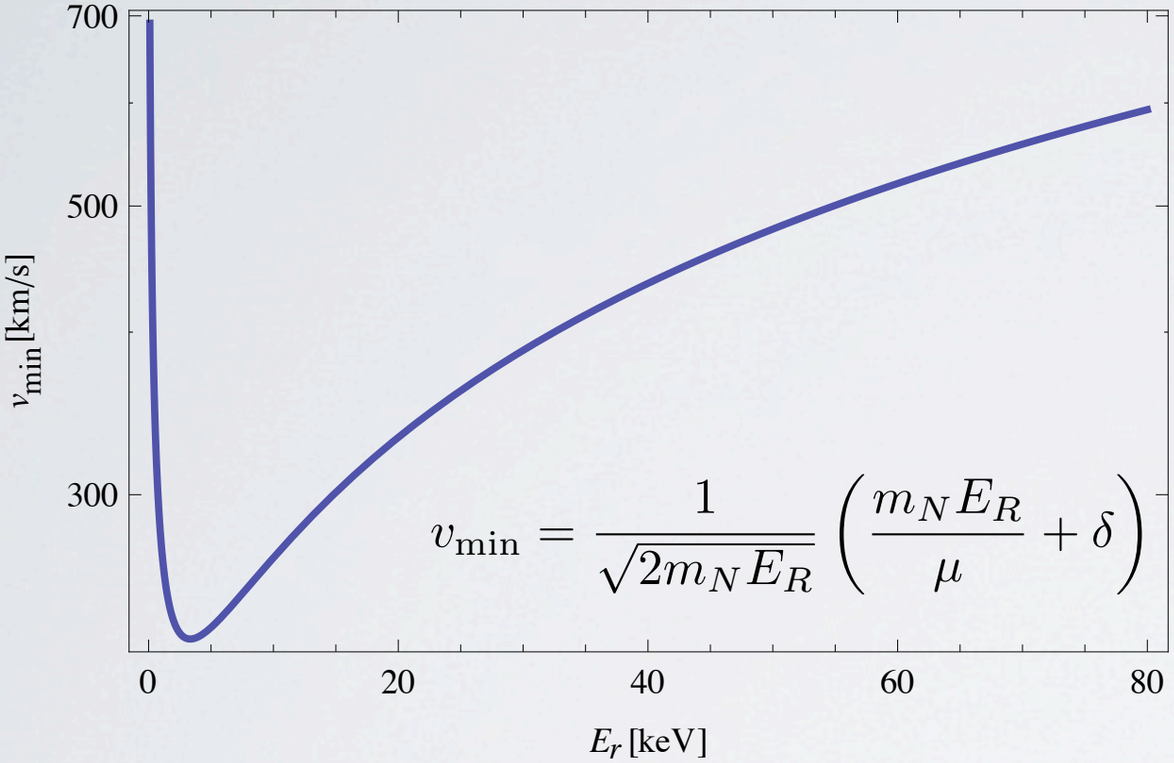


$q_{Na} = 0.45$,



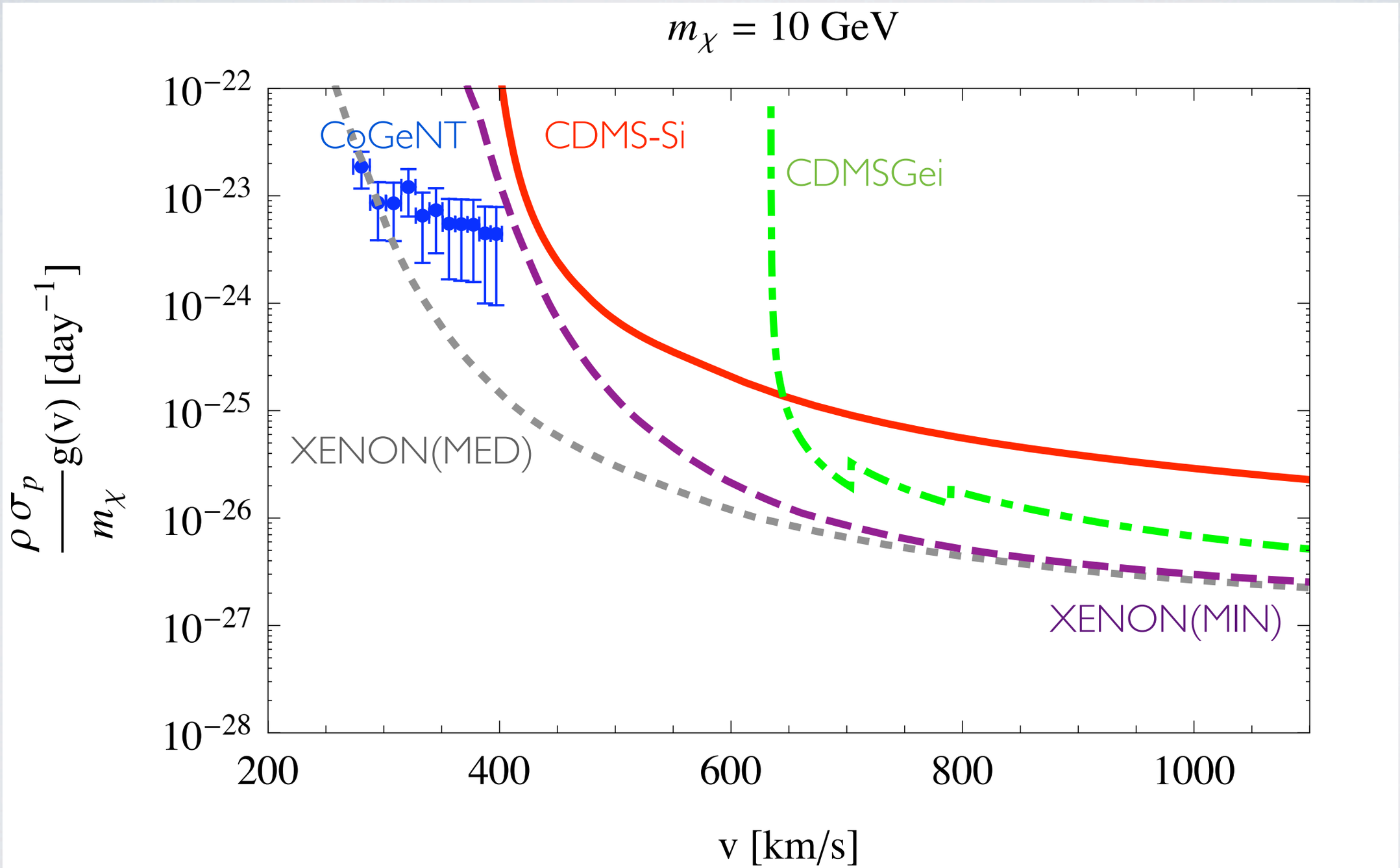
Onwards...

iDM and other "non-standard" models of DM



- vmin-ER relation no longer one-to-one
- compare experiment to itself?

A new plot


$m_\chi = 10$ GeV
CoGeNT
CDMS-Si
CDMSGei
XENON(MED)
XENON(MIN)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
200
400
600
800
1000
v [km/s]
$\rho \sigma_p \frac{g(v)}{m_\chi}$ [day^{-1}]

In addition to standard $\sigma - m$ plots because..

A more direct comparison of data than x-sec--m plots

Easy to derive from data

For eDM (and single target experiments) need only show

for one mass

Ultimately allows measurement of g(v)

Consistency of g(v) determines allowed DM params

Conclusions-theory

- There are large astrophysical uncertainties
- Should analyse data independent of them
- With multiple experiments should compare g(v)
- Allows mapping of experimental results between experiments
- Under particle physics assumption can compare multiple experiments, test consistency
- Ultimately find region of consistent parameter space

Conclusions-applications

- CoGeNT only consistent with XENON10 for low Leff
- For the S2 XENON10 analysis consistency requires a very low Qy
- For DAMA and XENON10 to be consistent requires >80% modulation for the standard Na quench factor
- For higher quenching factors modulation can be lower
- CRESST seems unlikely to be eDM due to constraints from CDMS-Si and XENON10