Integrating out Astrophysical Uncertainties in Direct Detection Experiments

Patrick Fox

Fermilab

Based on work with G. Kribs,
J Liu, T. Tait and N. Weiner

Dark Matter when Astrophysics Doesn't Matter

Patrick Fox

Fermilab

Based on work with G. Kribs, J Liu, T. Tait and N. Weiner

Plan

- Direct detection and the standard assumptions
- Comparing multiple experiments, extracting g(v)
- CDMS recent results, some musings
- Conclusions

Direct Detection

$$\frac{dR}{dE_R} = \frac{N_T \rho_\chi}{m_\chi} \int_{v_{\min}}^{v_{\max}} d^3\vec{v}\, f(\vec{v}(t))\, \frac{d\,\sigma|\vec{v}|}{dE_R}$$

with,

$$\frac{d\sigma}{dE_R} = F_N^2(E_R)\frac{m_N}{\mu v^2}\bar{\sigma}(v, E_R)$$

$$\bar{\sigma}_i(v, E_R) = \begin{cases} \sigma_{i0} \\ \sigma_{i0} F_{\chi_i}^2(E_R) \\ \sigma_{i0}(v) F_{\chi_i}^2(E_R) \\ \sigma_{i0}(v, E_R) \end{cases}$$

Usual case (SI elastic WIMP)

$$\sigma_N = \frac{(Zf_p + (A-Z)f_n)^2}{f_p^2}\frac{\mu_{N\chi}^2}{\mu_{n\chi}^2}\sigma_p$$

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

Direct Detection

also talk by Anne Greene

$$\frac{dR}{dE_R} = \frac{N_T \rho_\chi}{m_\chi} \int_{v_{\min}}^{v_{\max}} d^3\vec{v}\, f(\vec{v}(t))\, \frac{d\,\sigma|\vec{v}|}{dE_R}$$

with,

$$\frac{d\sigma}{dE_R} = F_N^2(E_R)\frac{m_N}{\mu v^2}\bar{\sigma}(v, E_R)$$

$$\bar{\sigma}_i(v, E_R) = \begin{cases} \sigma_{i0} \\ \sigma_{i0} F_{\chi_i}^2(E_R) \\ \sigma_{i0}(v) F_{\chi_i}^2(E_R) \\ \sigma_{i0}(v, E_R) \end{cases}$$

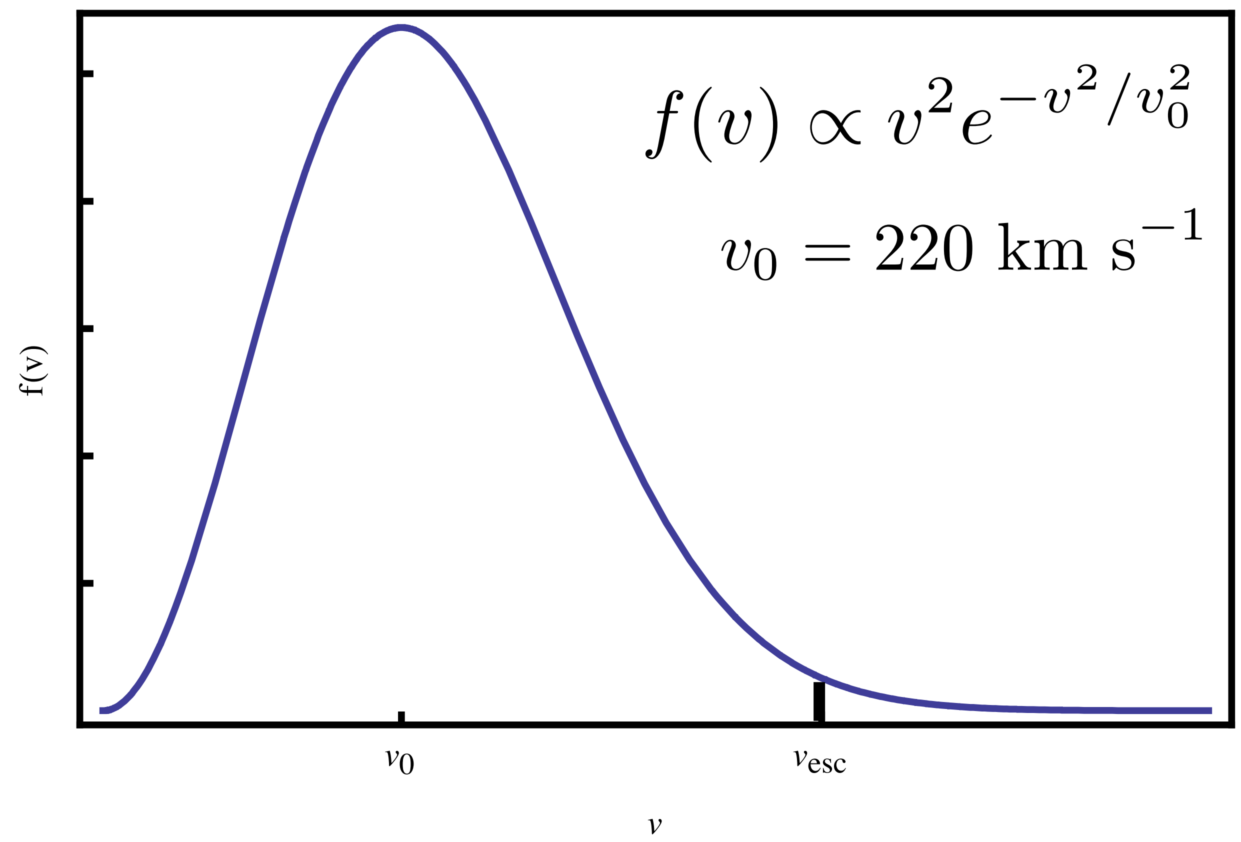
Usual case (SI elastic WIMP)

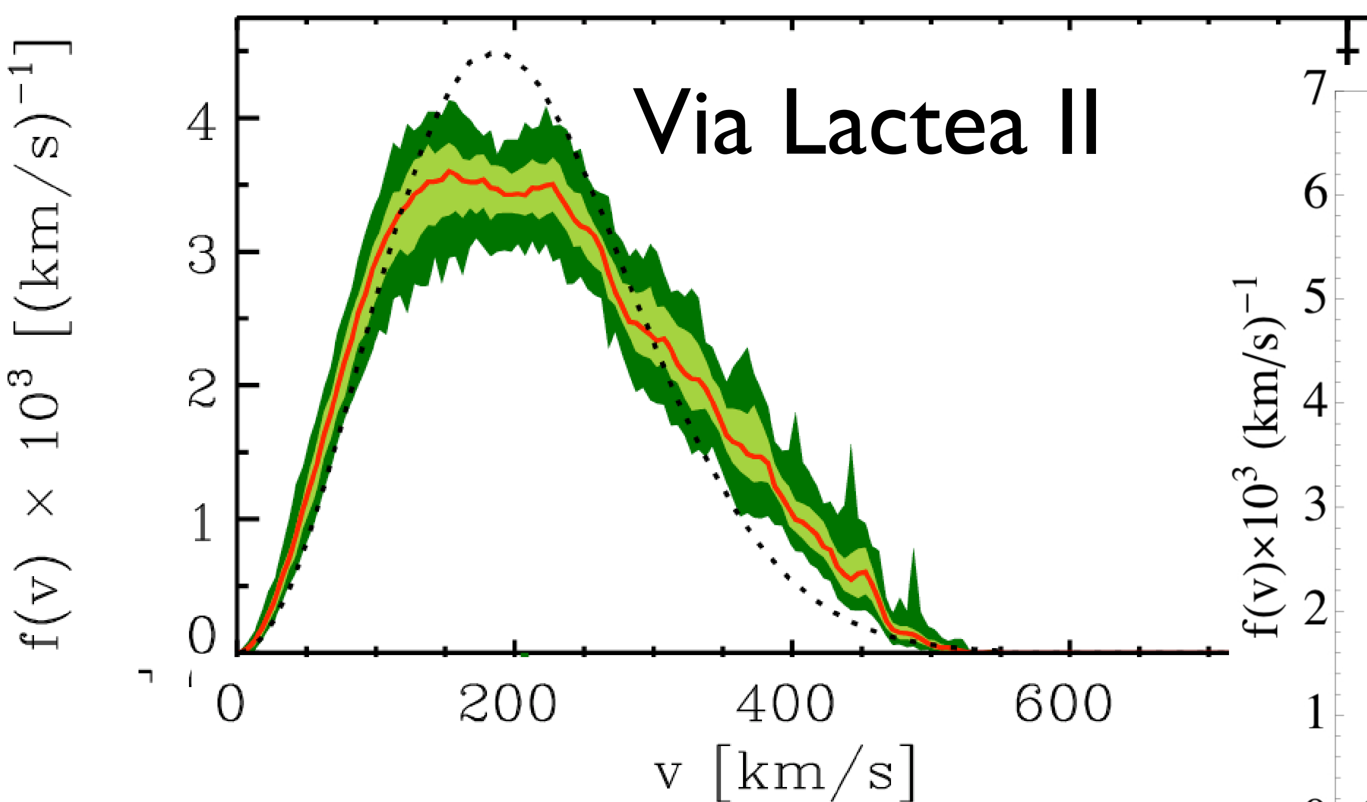
$$\sigma_N = \frac{(Zf_p + (A-Z)f_n)^2}{f_p^2}\frac{\mu_{N\chi}^2}{\mu_{n\chi}^2}\sigma_p \qquad v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

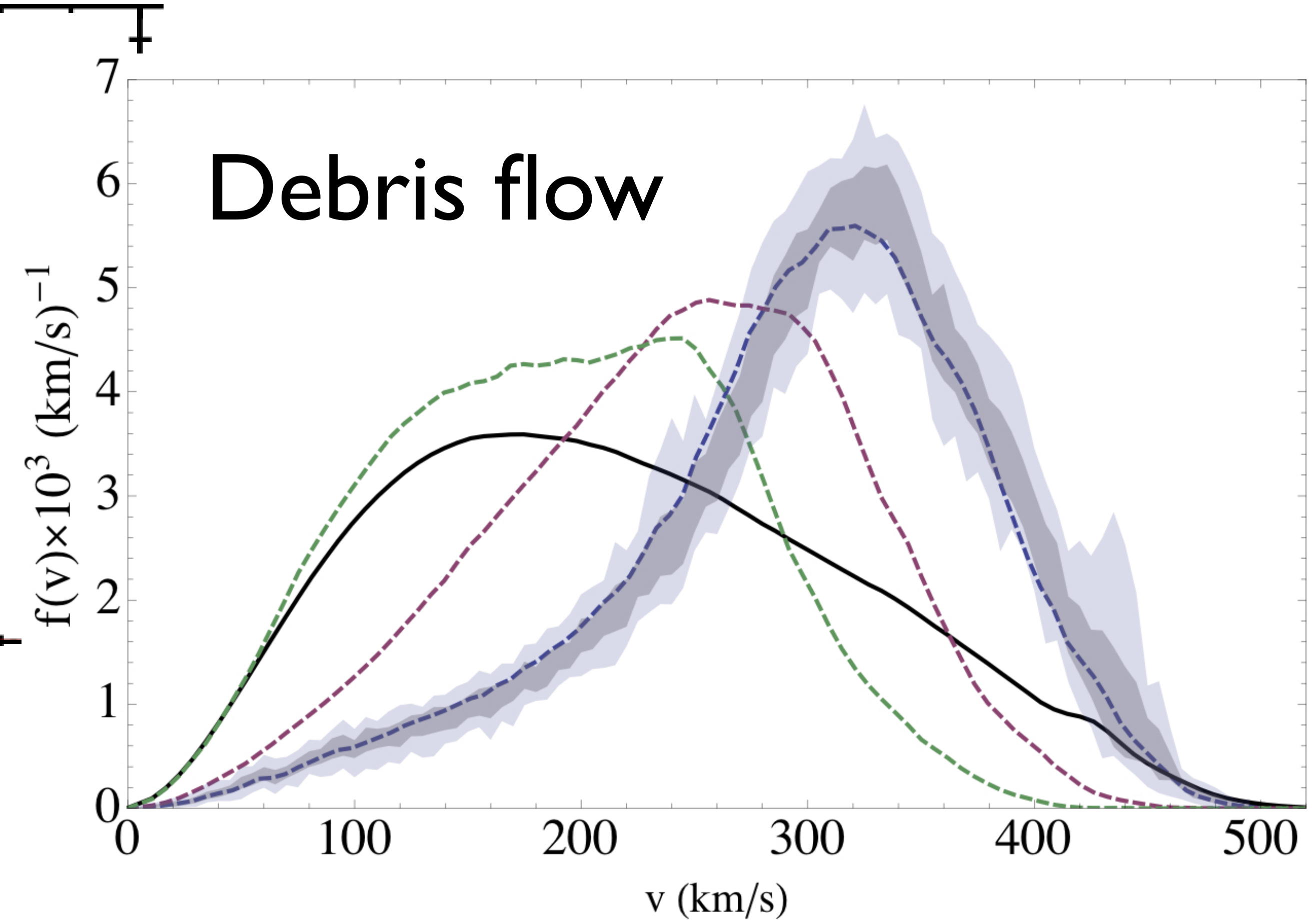
Astrophysical inputs

Local density

$$\rho_\chi \sim 0.3\ \mathrm{GeV/cm^3}$$





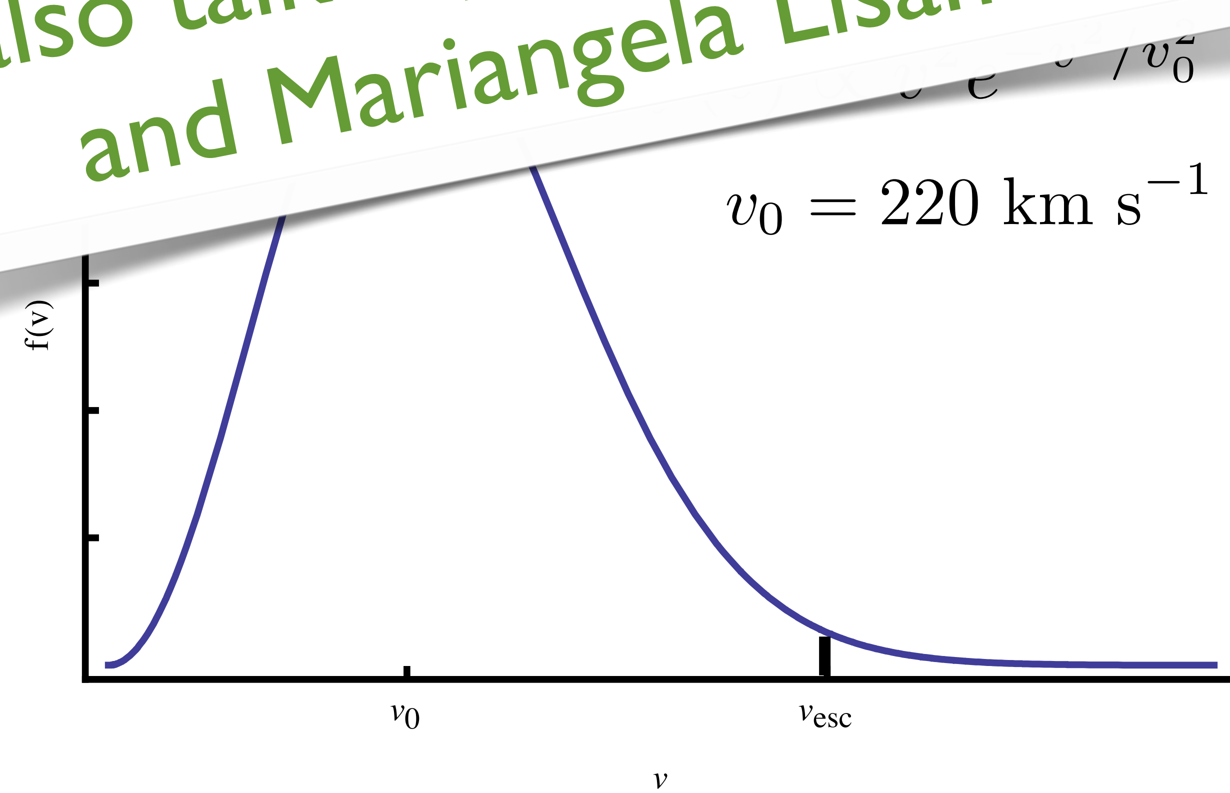


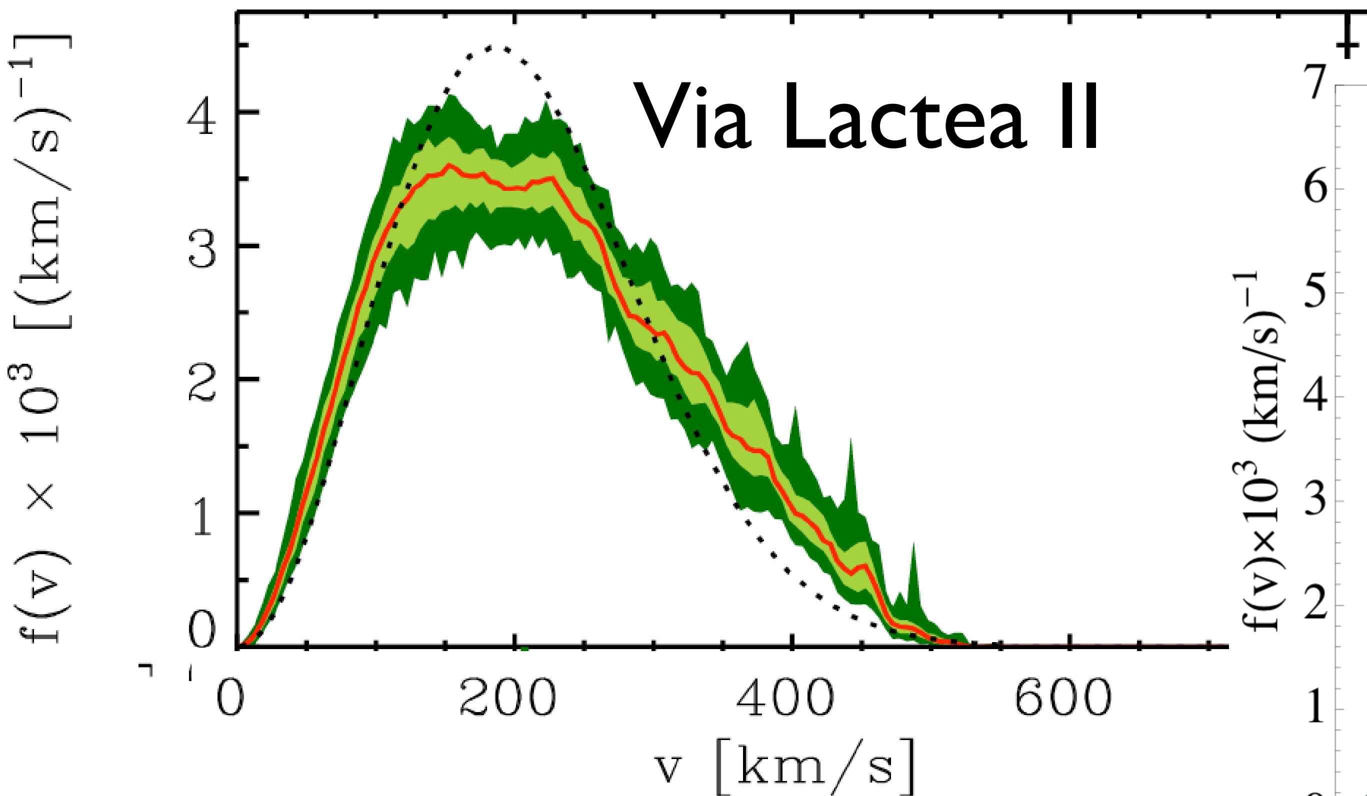
Astrophysical inputs

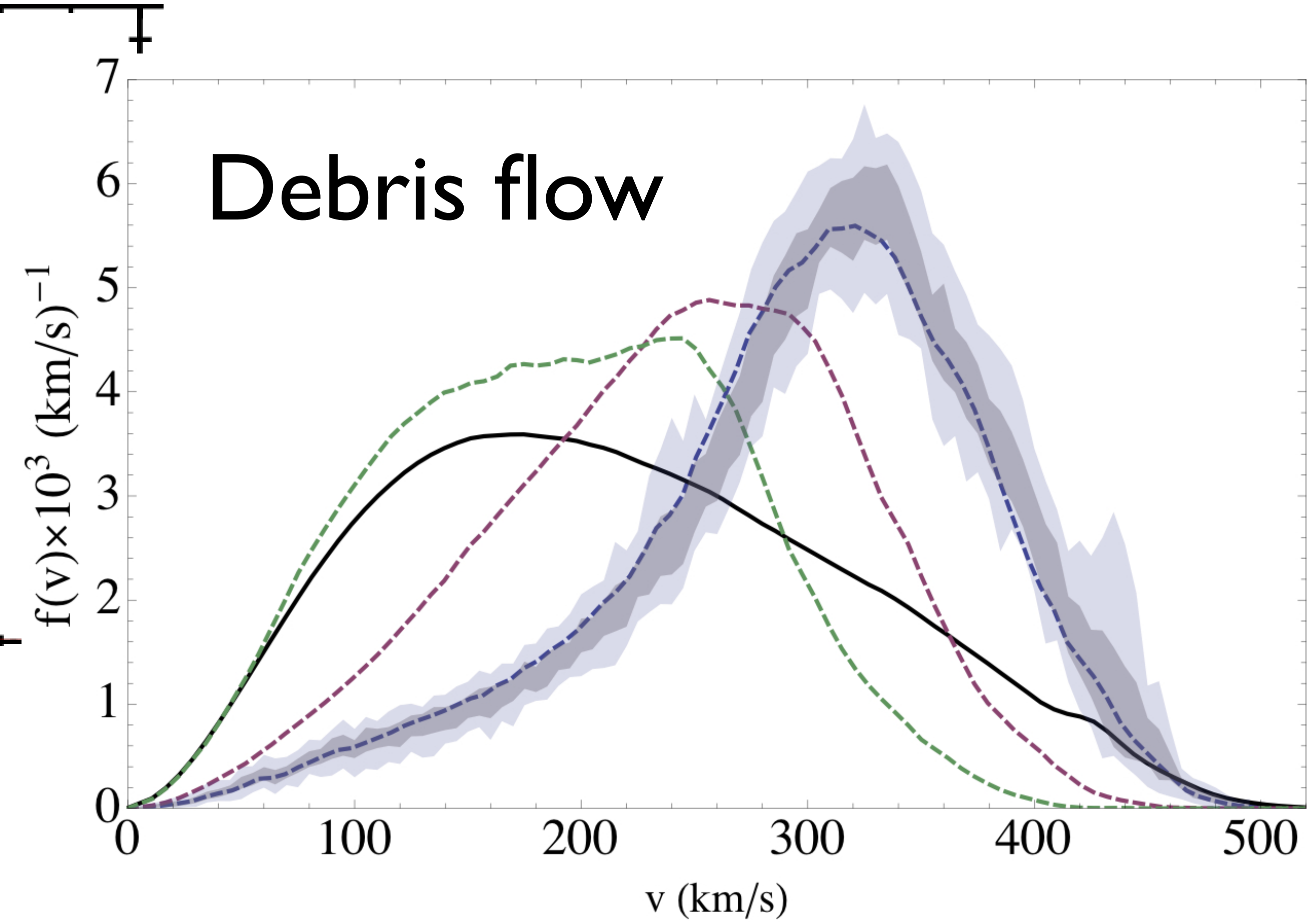
also talks by Anne Greene and Mariangela Lisanti

Local density

$$\rho_\chi \sim 0.3 \text{ GeV/cm}^3$$





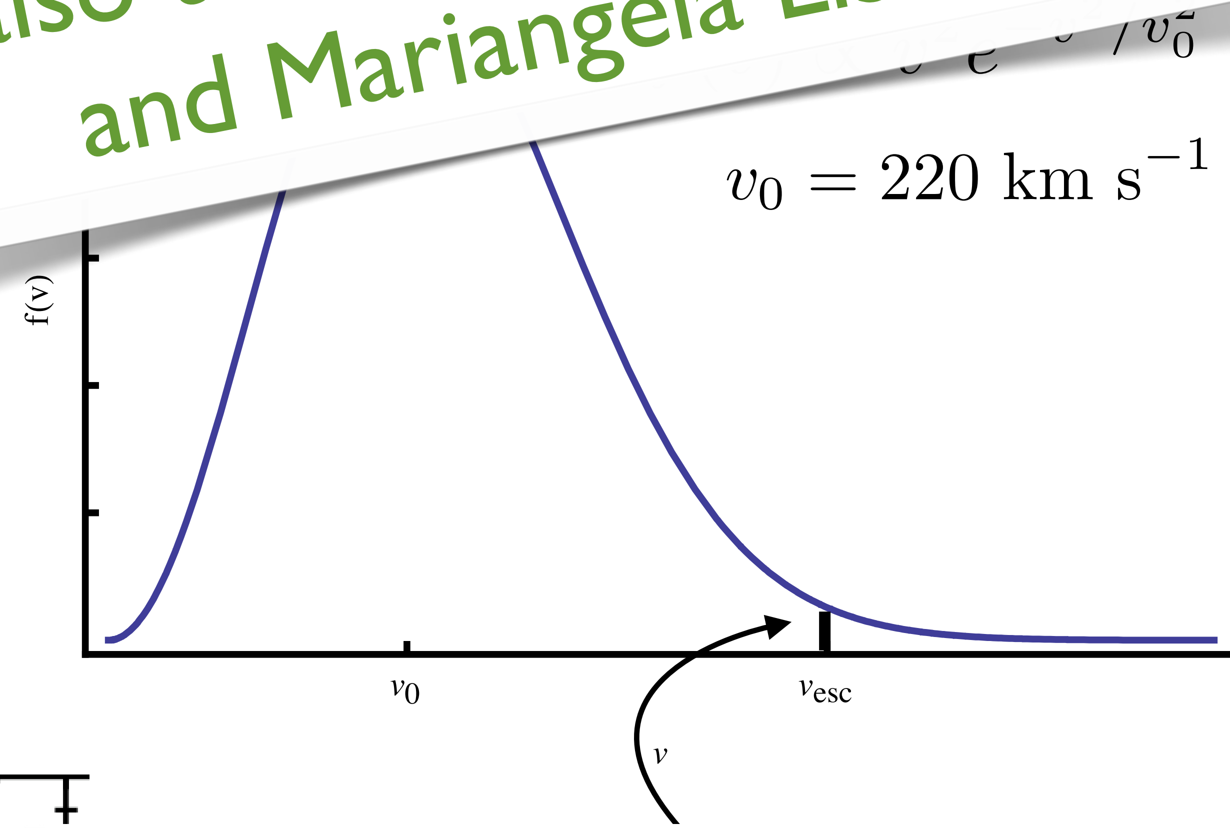


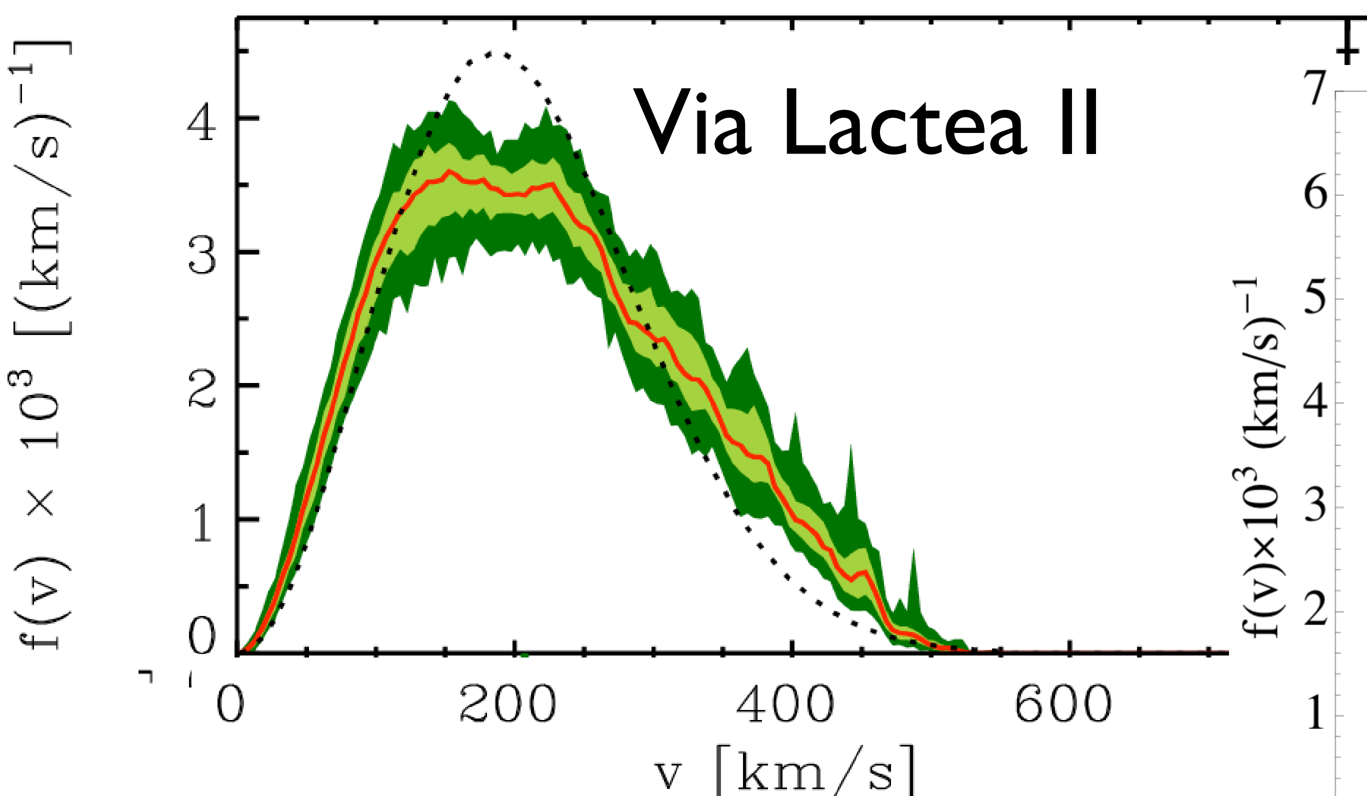
Astrophysical inputs

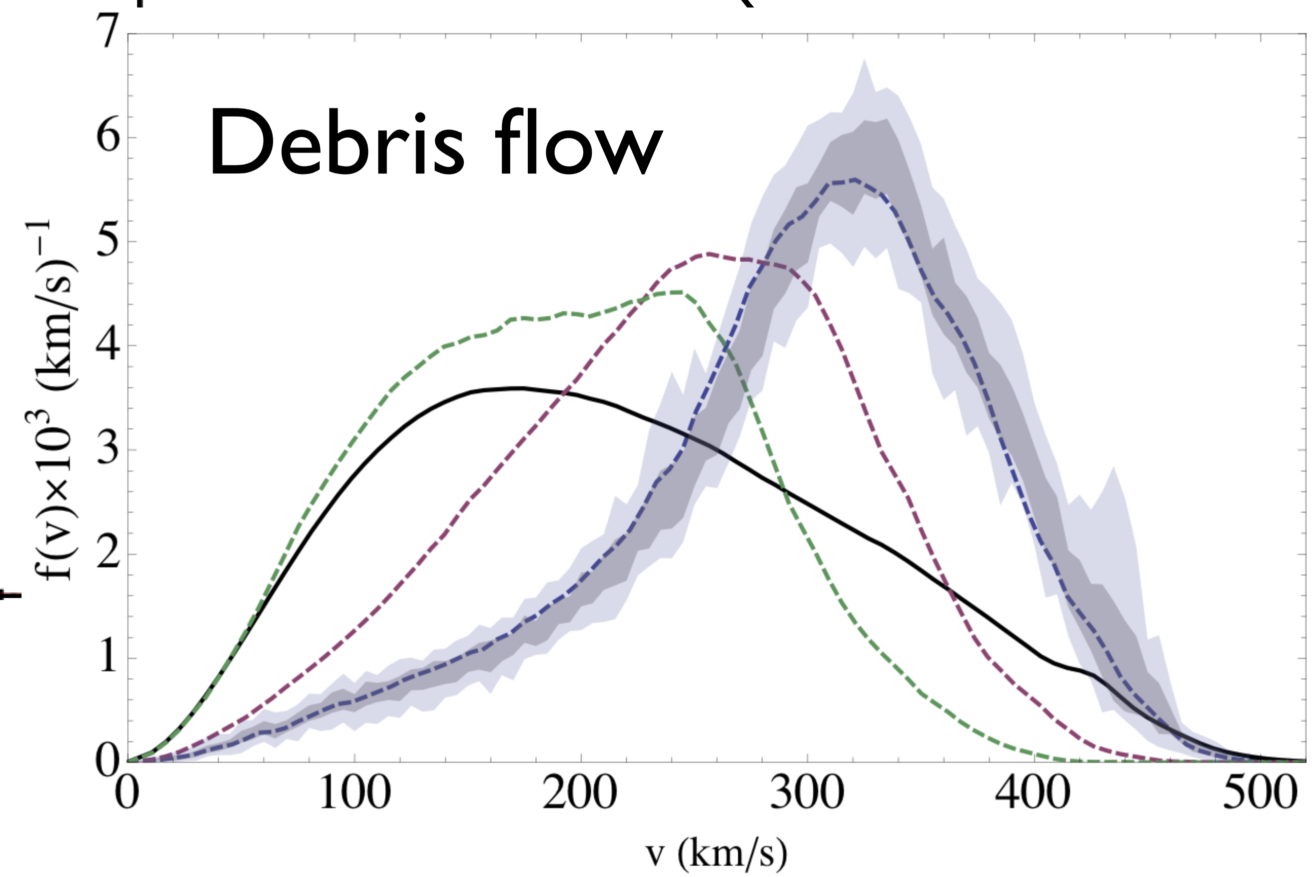
also talks by Anne Greene
and Mariangela Lisanti

Local density

$$\rho_\chi \sim 0.3 \text{ GeV/cm}^3$$





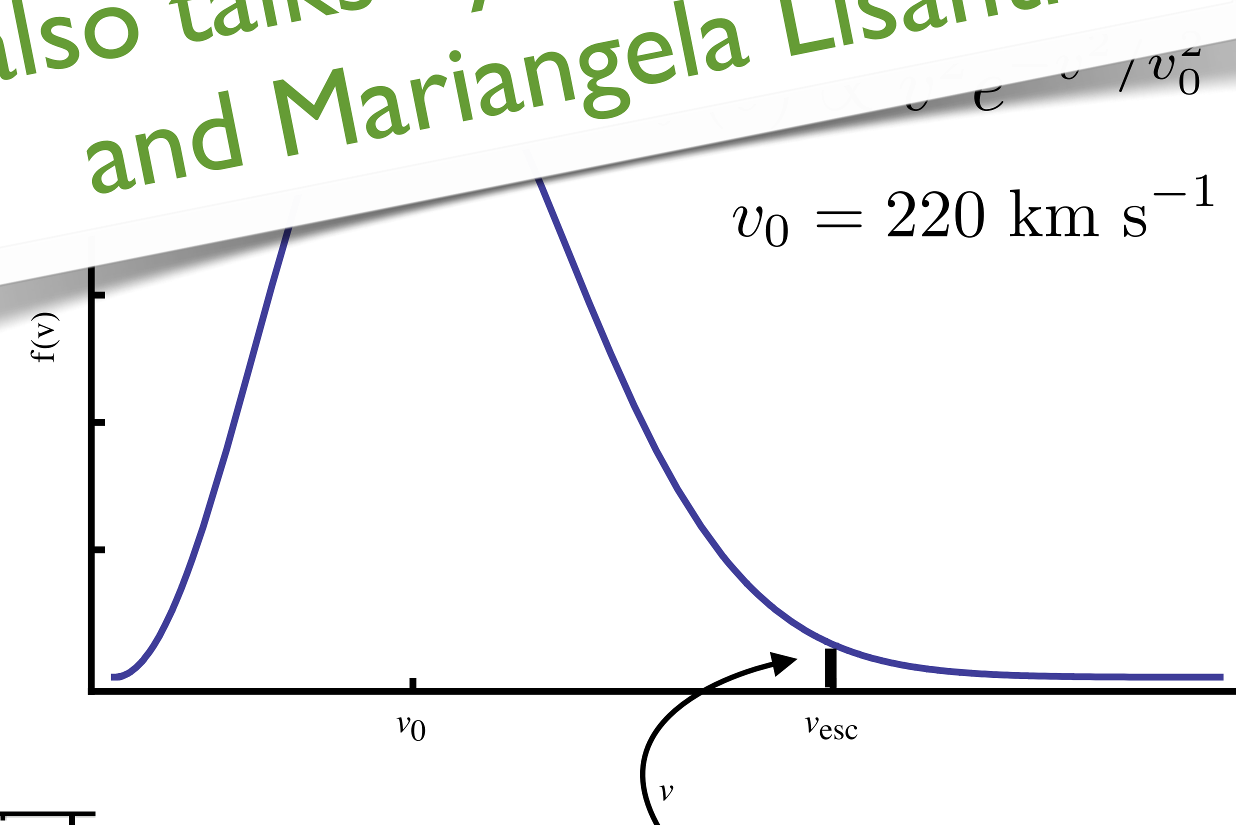


Astrophysical inputs

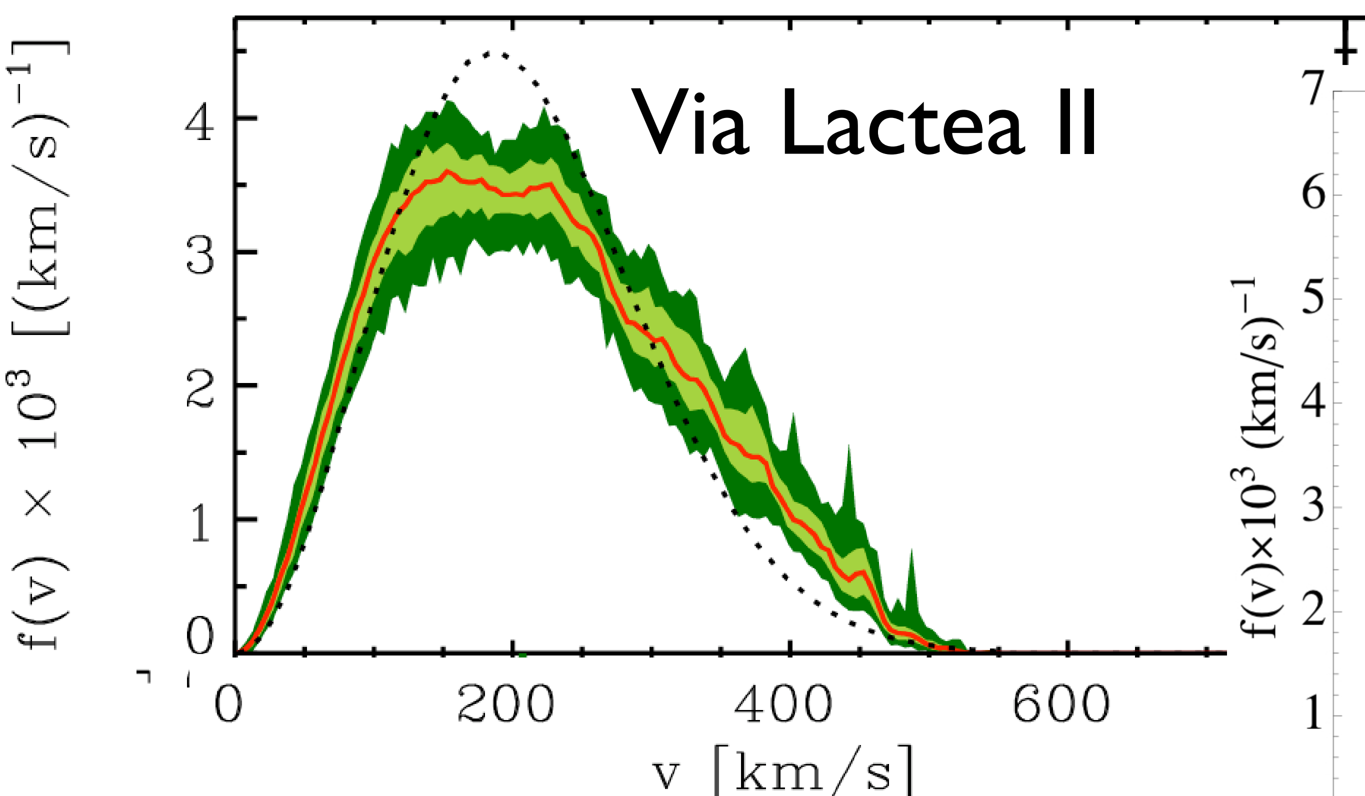
also talks by Anne Greene and Mariangela Lisanti

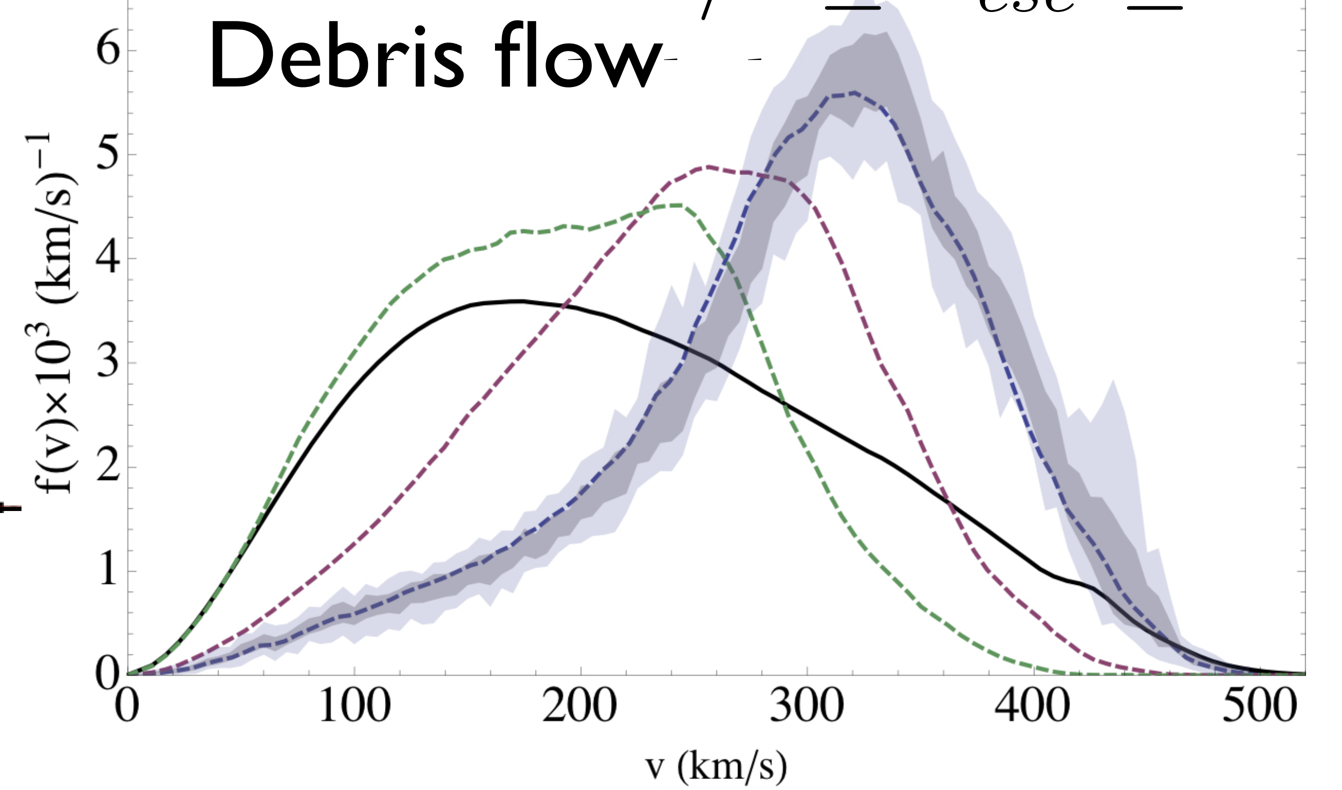
Local density

$$\rho_\chi \sim 0.3\ \mathrm{GeV/cm^3}$$



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





Direct Detection [see also, Drees and Shan, A. Peter, ...]

Is a signal a measurement of particle physics or astrophysics?

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

$$f_1(v_{\min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2} \frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)} \left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)} \frac{dF_\chi^2(E_R)}{dE_R} \right)$$

f-condition: $f(v) \geq 0$

(Deconvoluted) rate is a monotonically decreasing function, or there is non-standard particle physics e.g. inelastic or a increasing DM form factor

Direct Detection [see also, Drees and Shan, A. Peter, ...]

Is a signal a measurement of particle physics or astrophysics?

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

$$f_1(v_{\min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2}\frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)}\left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)}\frac{dF_\chi^2(E_R)}{dE_R}\right)$$

$$f_1(v) = \int d\Omega f(\vec{v})$$

f-condition: $f(v) \geq 0$

(Deconvoluted) rate is a monotonically decreasing function, or there is non-standard particle physics e.g. inelastic or a increasing DM form factor

Direct Detection [see also, Drees and Shan, A. Peter, ...]

Is a signal a measurement of particle physics or astrophysics?

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

$$f_1(v_{\min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2}\frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)}\left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)}\frac{dF_\chi^2(E_R)}{dE_R}\right)$$

$$f_1(v) = \int d\Omega f(\vec{v})$$

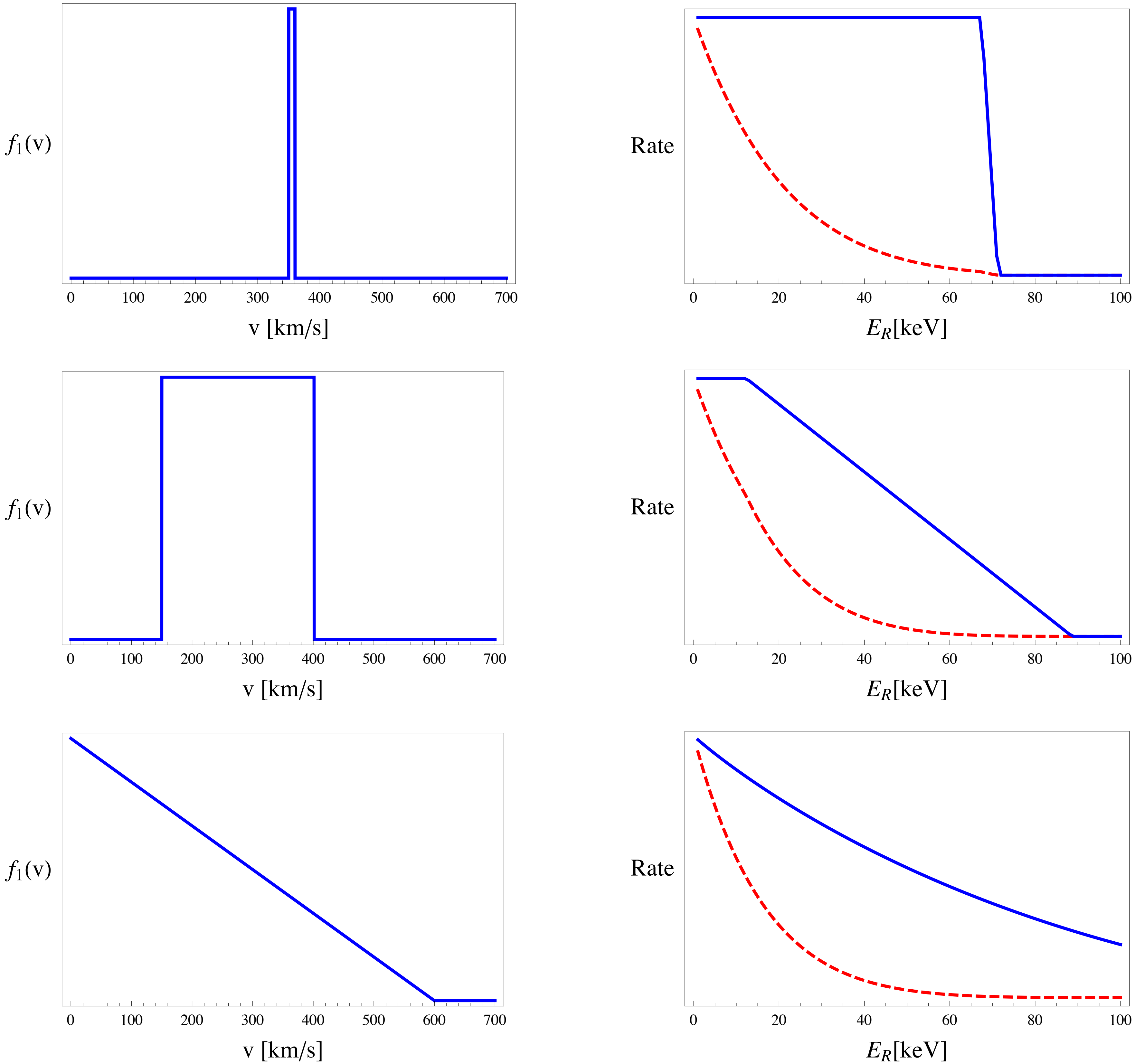
"Deconvoluted" rate

$$\mathcal{R} \equiv \frac{1}{F_N^2(E_R)}\frac{dR}{dE_R}$$

f-condition: $f(v) \geq 0$

(Deconvoluted) rate is a monotonically decreasing function, or there is non-standard particle physics e.g. inelastic or a increasing DM form factor

toy distributions Deconvoluted



Convoluted

Direct Detection without bias

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

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

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

Recoil energy uniquely determines **minimum** DM velocity

Direct Detection without bias

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

$g(v)$

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

Target specific

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

Recoil energy uniquely determines **minimum** DM velocity

Direct Detection without bias

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

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

Target specific

Target independent

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

Recoil energy uniquely determines **minimum** DM velocity

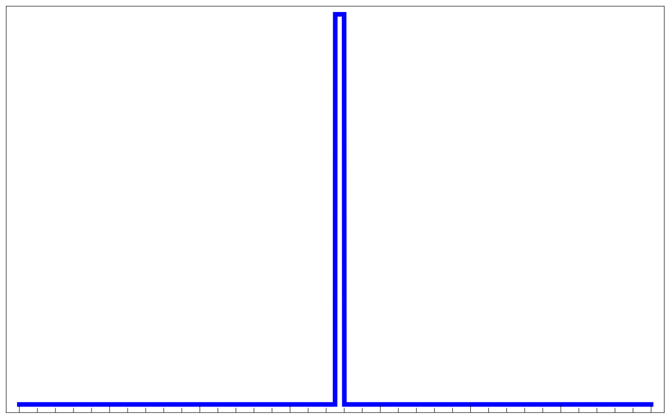
g(v)

Speed distribution is positive semidefinite $f(v) \geq 0$

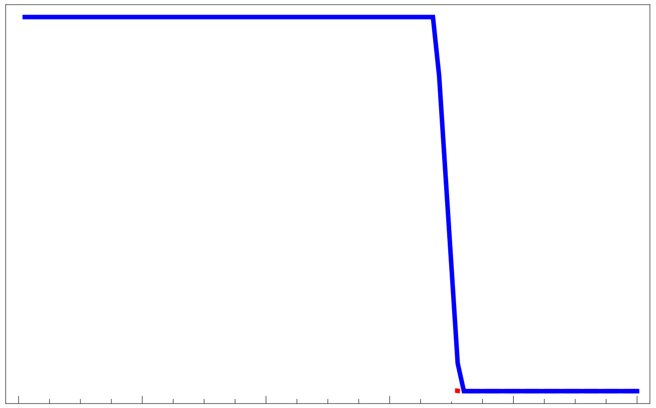
Integral monotonically decreases $\frac{d}{dv} g(v_{\rm min}) \leq 0$

"Least" monotonic function is a step function $\Theta(v_1 - v_{\rm min})$

$f(v)$



$g(v_{\rm min})$



Two experiments allow us to test particle physics independent of astrophysics

1) Make hypothesis about DM e.g. elastically scattering DM with mass 10 GeV and x-sec 10^{-41} 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

Experiments must run over same part of year

Other uncertainties (nuclear, atomic etc not addressed)

Comparing experiments

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

Solve for g(v)

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

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

The master formula (SI):

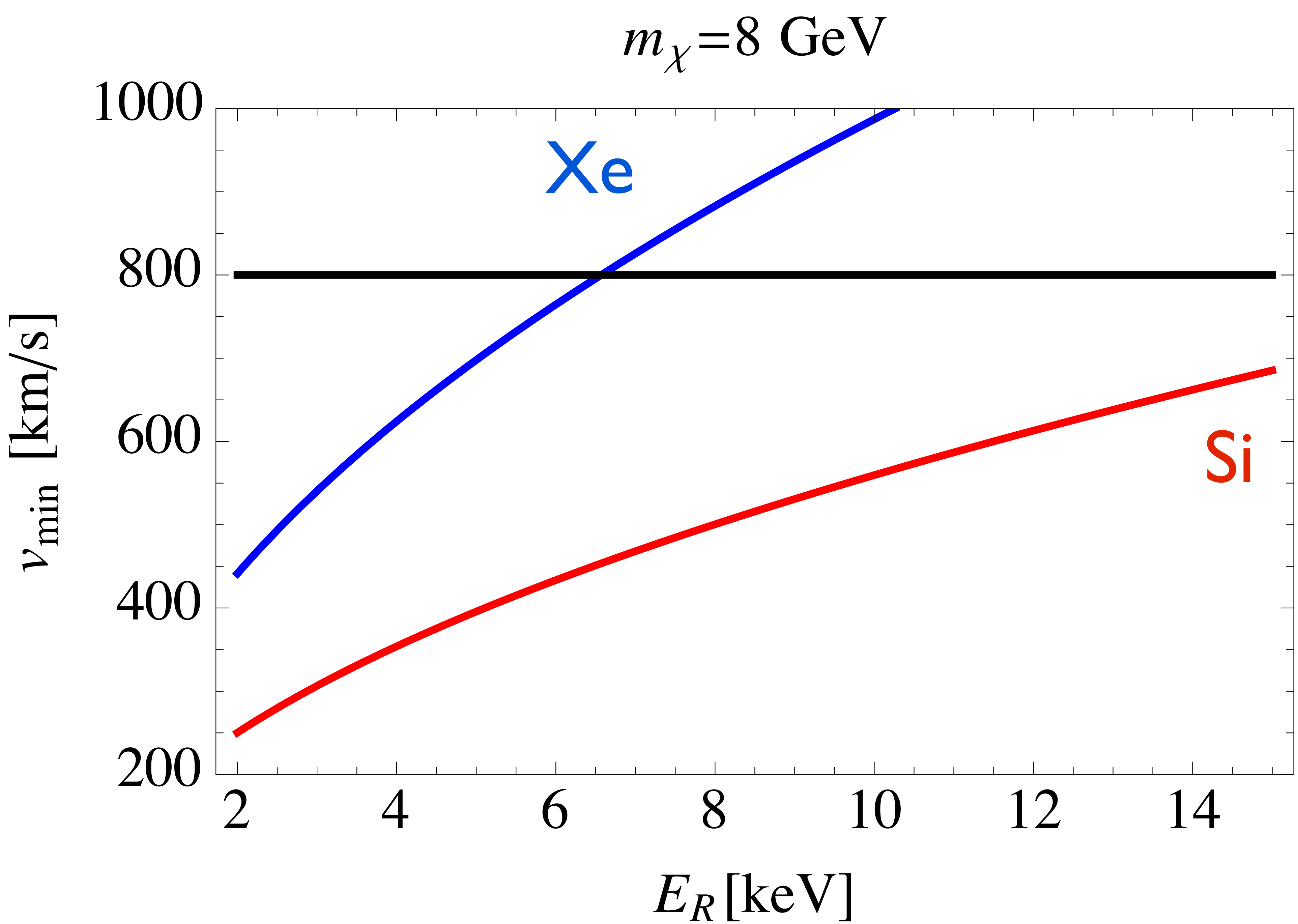
$$C_T^{(i)} = \kappa^{(i)} \left(f_p\, Z^{(i)} + f_n \left(A^{(i)} - Z^{(i)} \right) \right)^2$$

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

Using vmin space

Experiment 1 $\longleftrightarrow$ Experiment 2

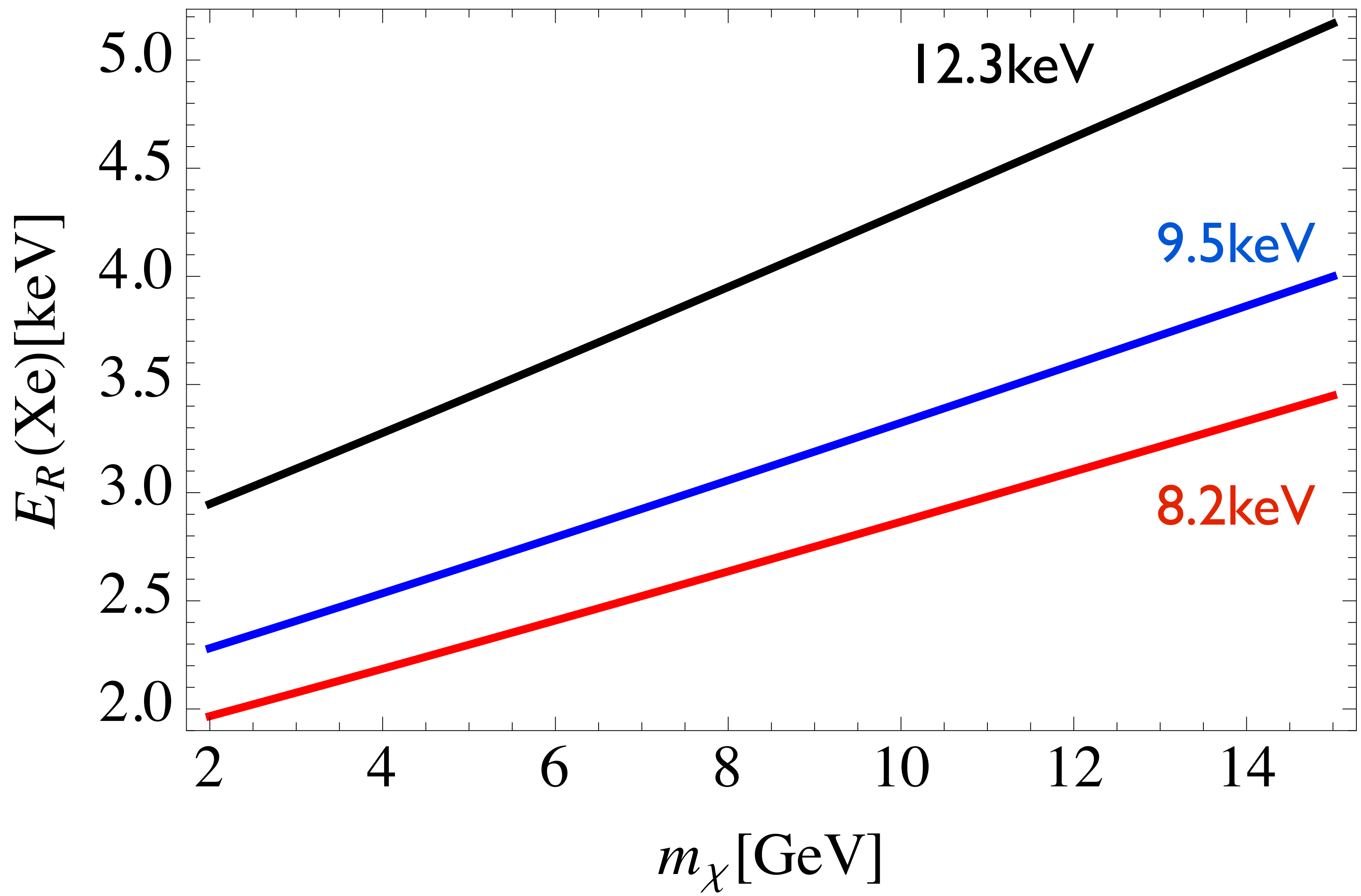
$$[E^{(1)}_{low}, E^{(1)}_{low}] \Longleftrightarrow [v^{low}_{min}, v^{high}_{min}] \Longleftrightarrow [E^{(2)}_{low}, E^{(2)}_{high}]$$



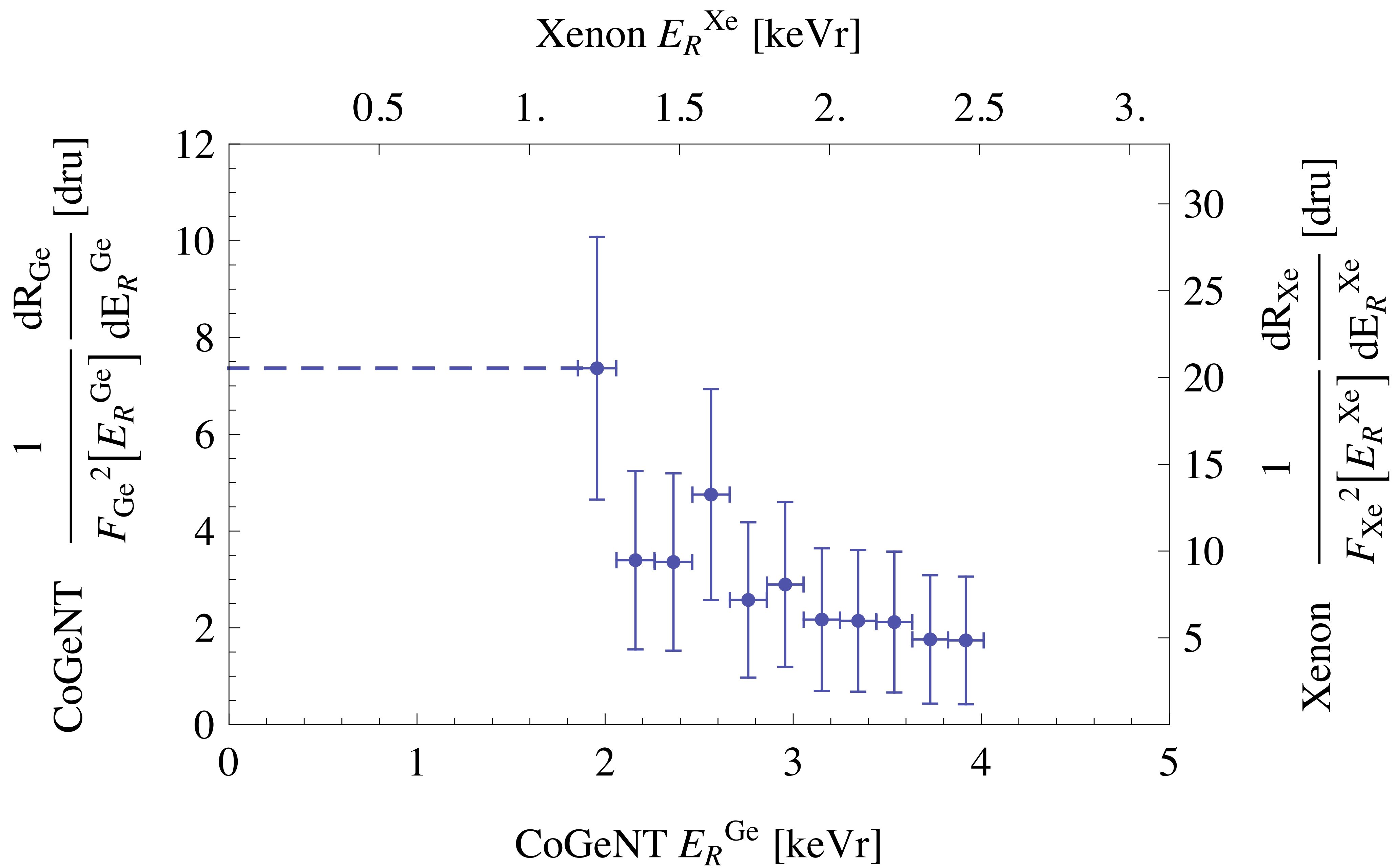
Using vmin space

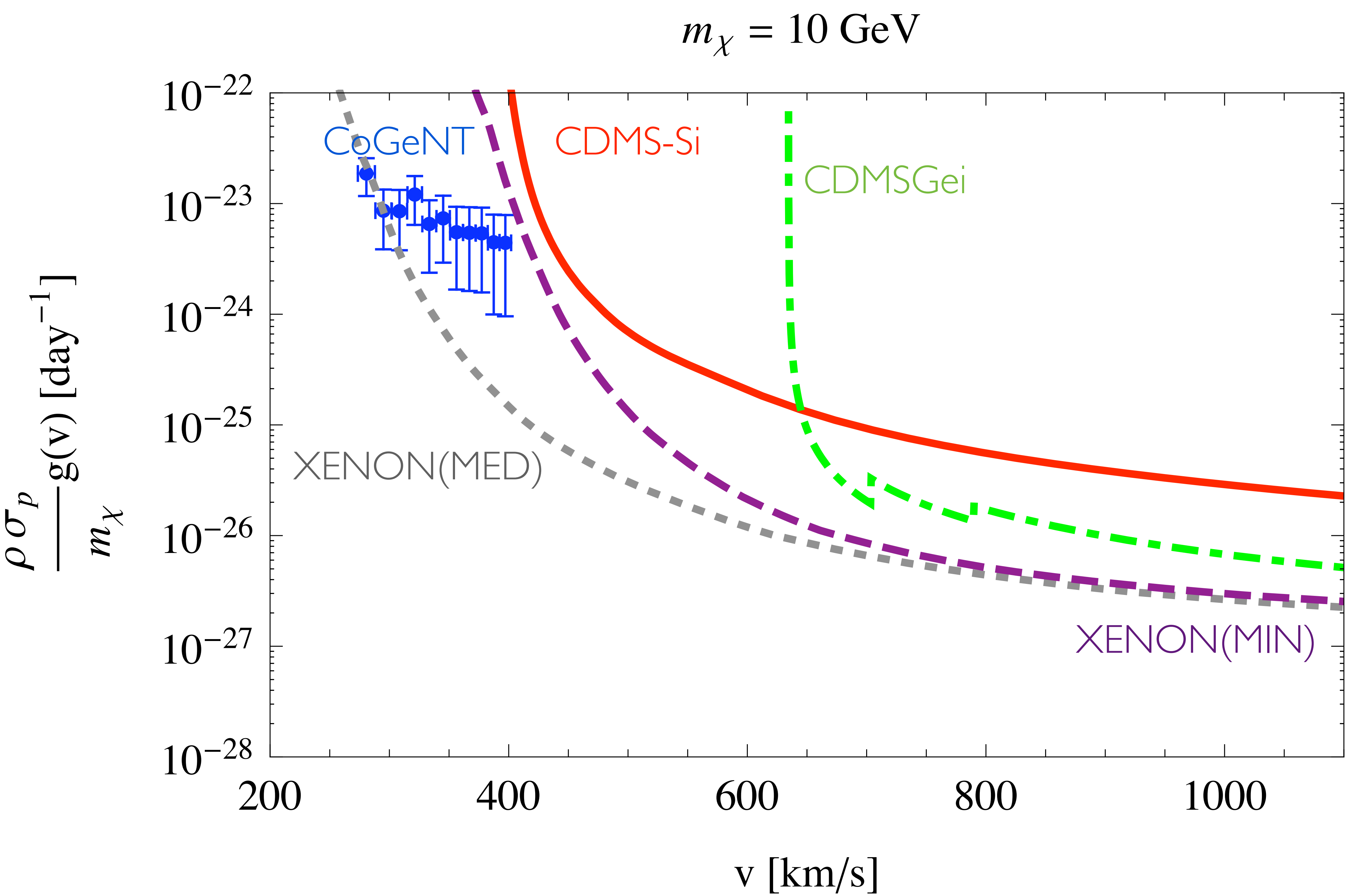
Experiment 1 $\longleftrightarrow$ Experiment 2

$$[E_{low}^{(1)}, E_{low}^{(1)}] \Longleftrightarrow [v_{min}^{low}, v_{min}^{high}] \Longleftrightarrow [E_{low}^{(2)}, E_{high}^{(2)}]$$

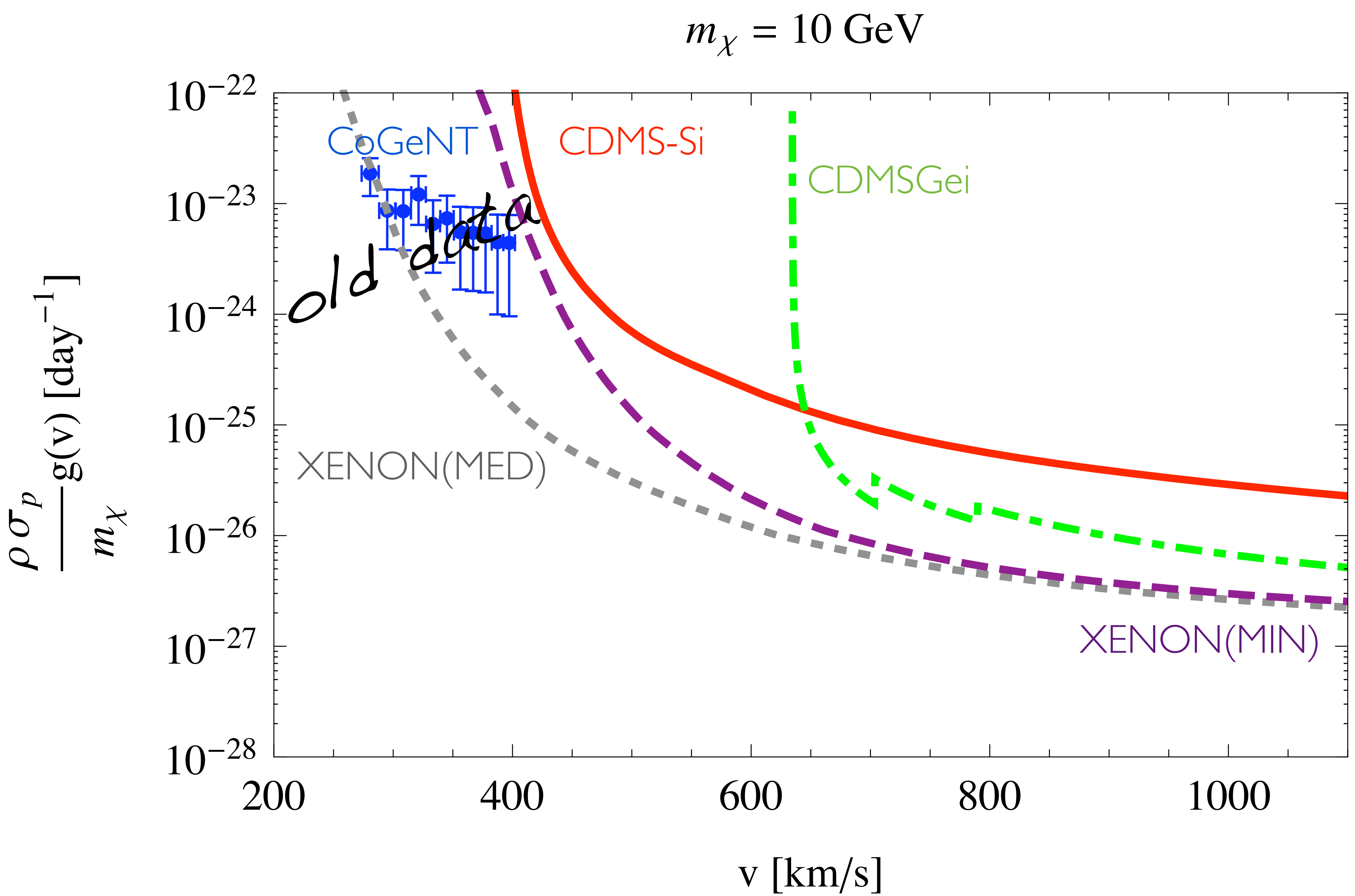


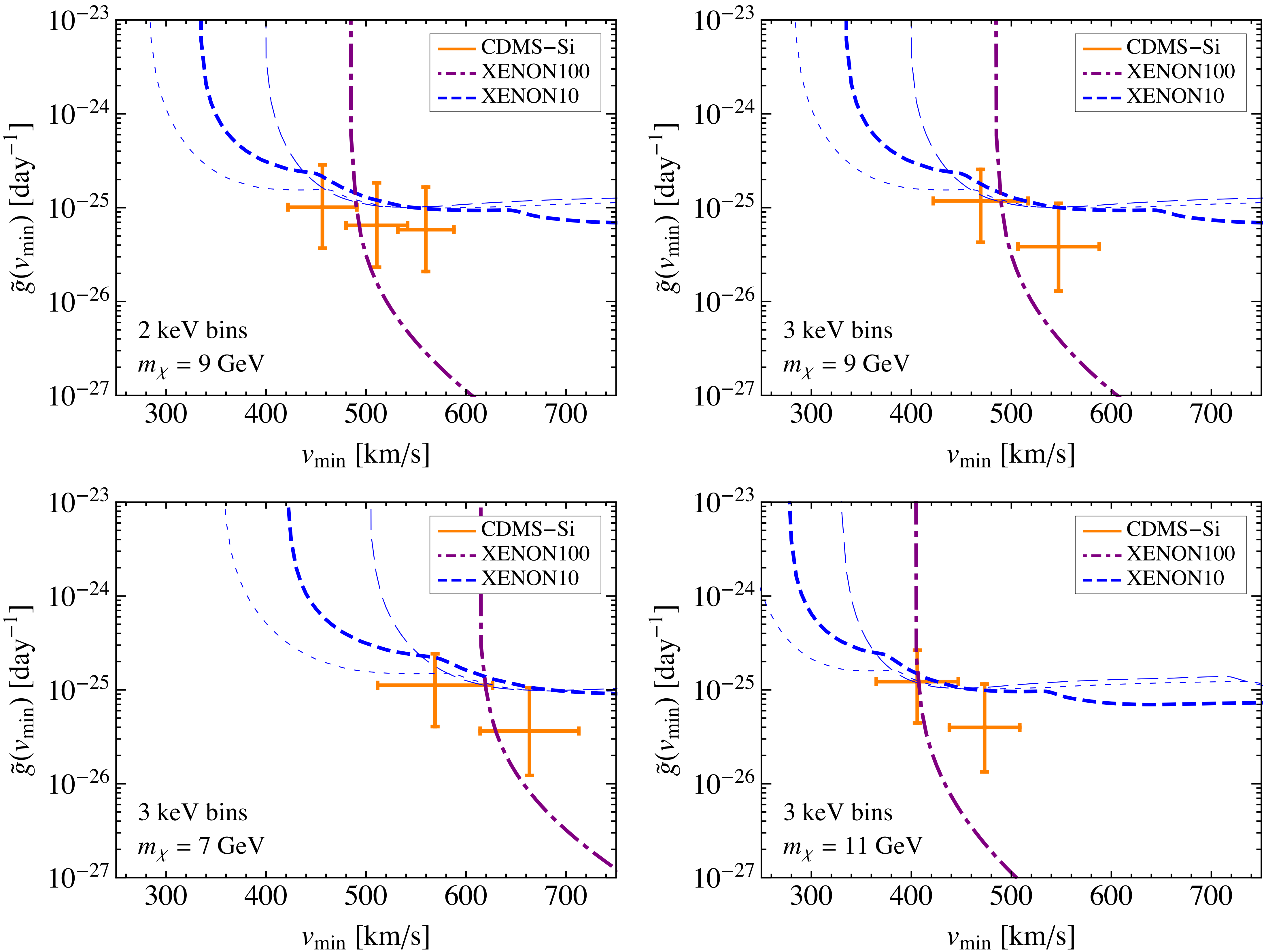
$$m_\chi = 10\,\mathrm{GeV}$$



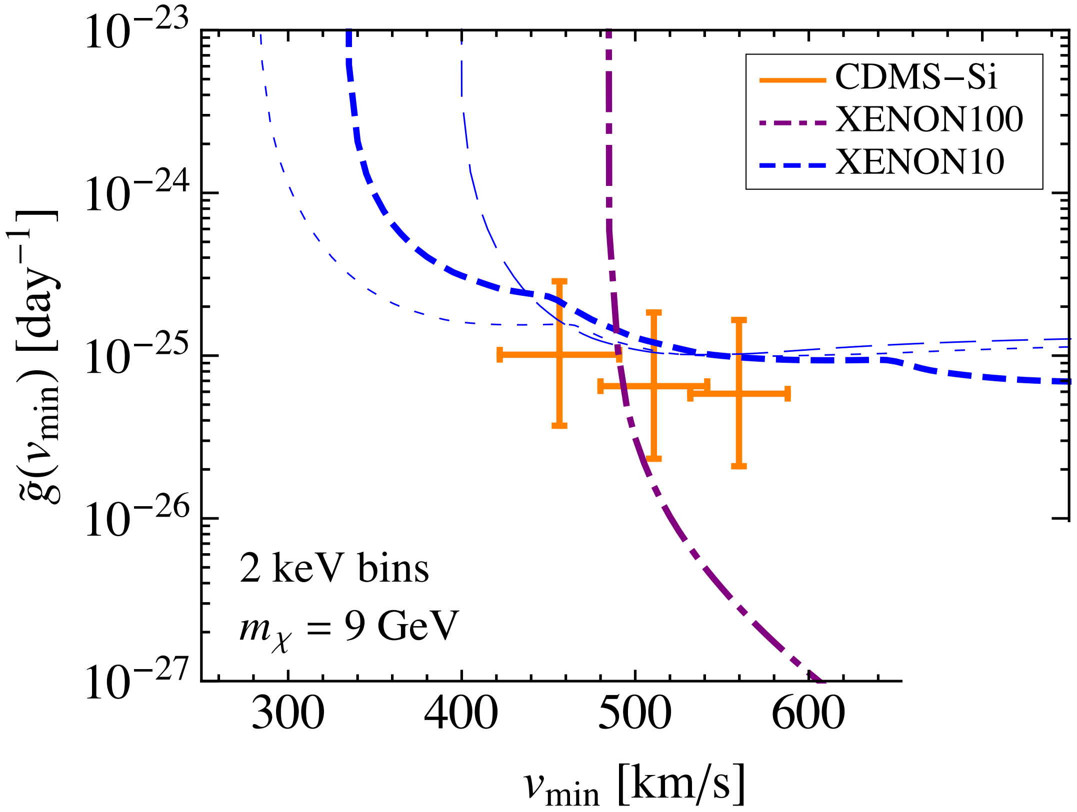


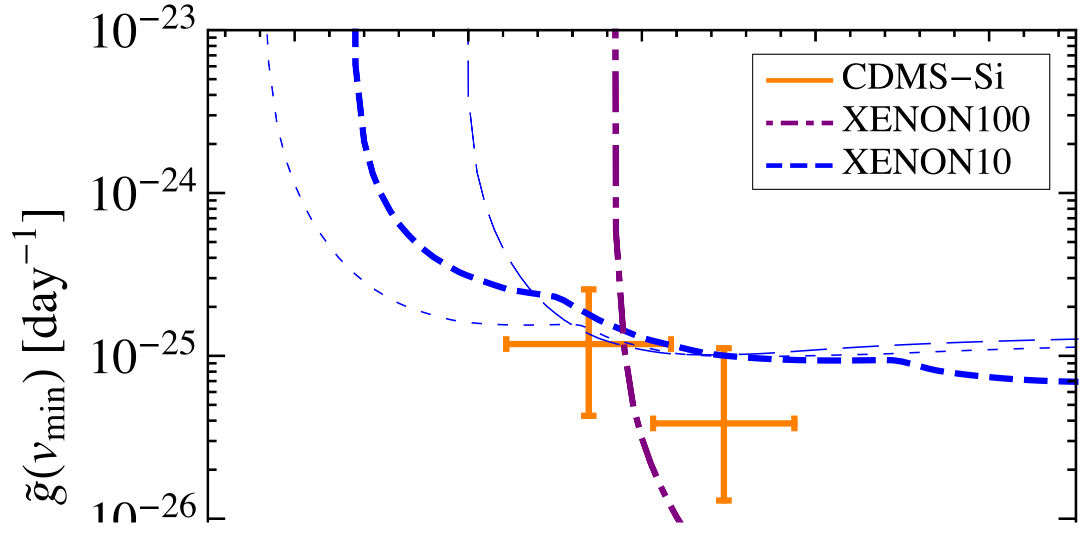
m_χ = 10 GeV
CoGeNT
CDMS-Si
CDMSGei
XENON(MED)
XENON(MIN)
$\frac{\rho\,\sigma_p}{m_\chi} g(v)$ [day^{-1}]
v [km/s]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
200
400
600
800
1000


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

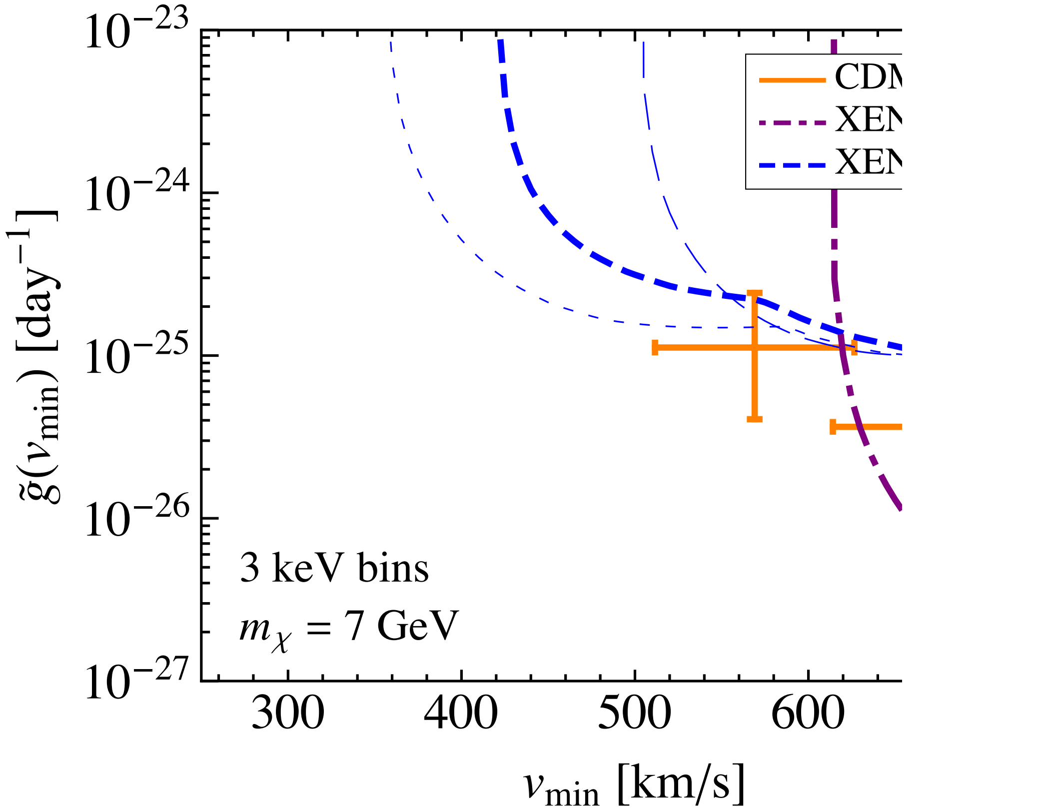


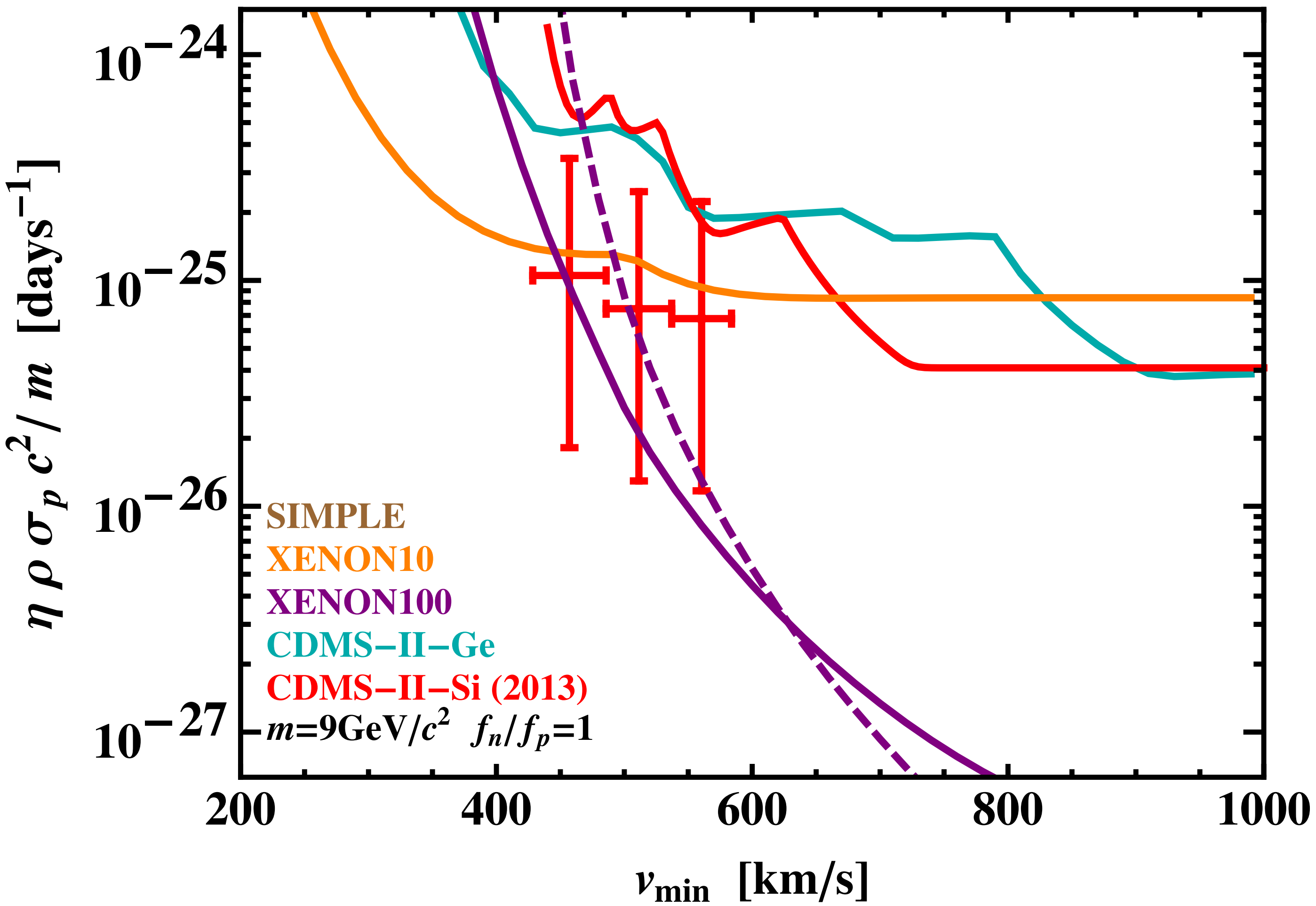
Frandsen et al.





Del Nobile et al.



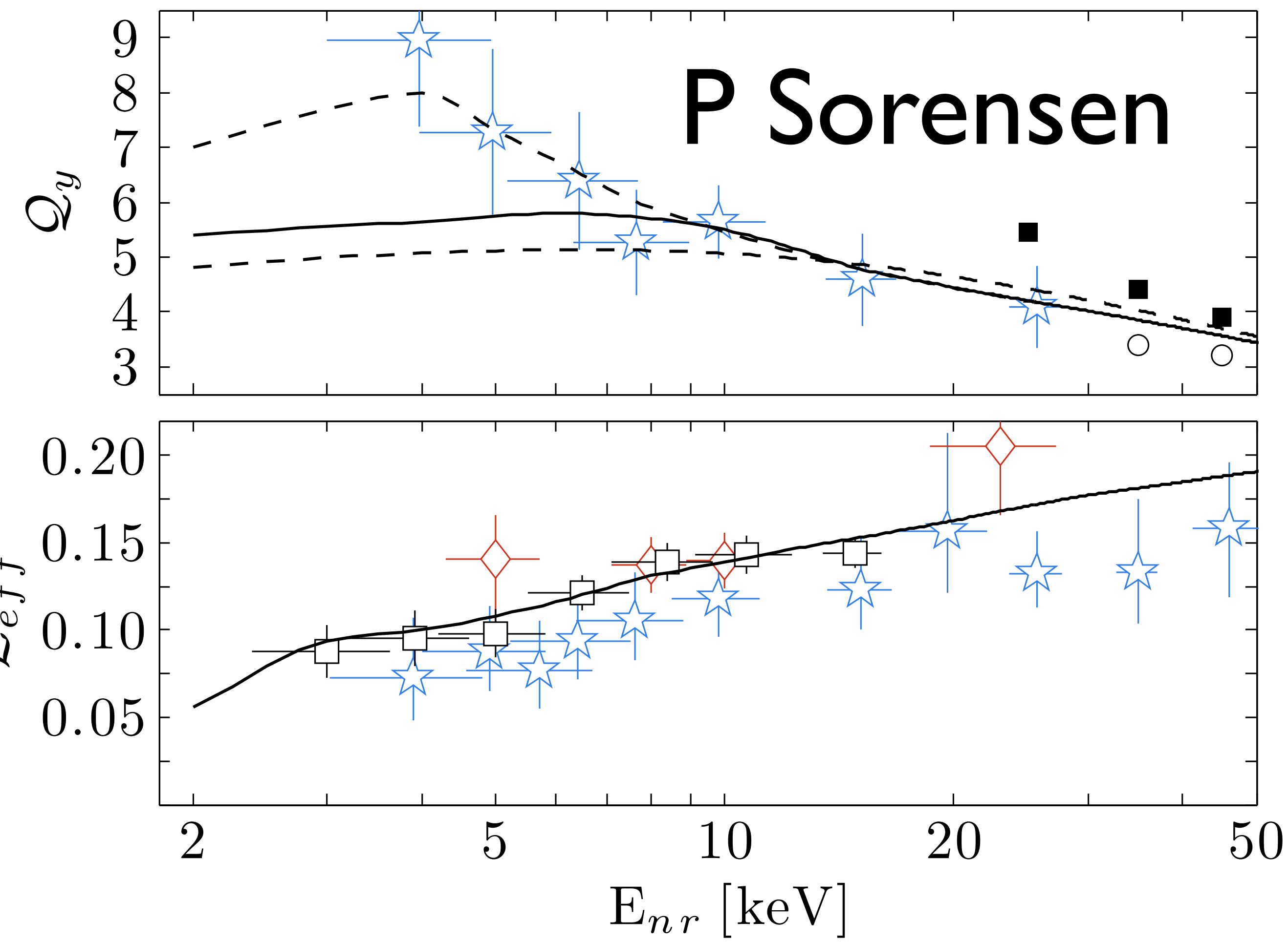


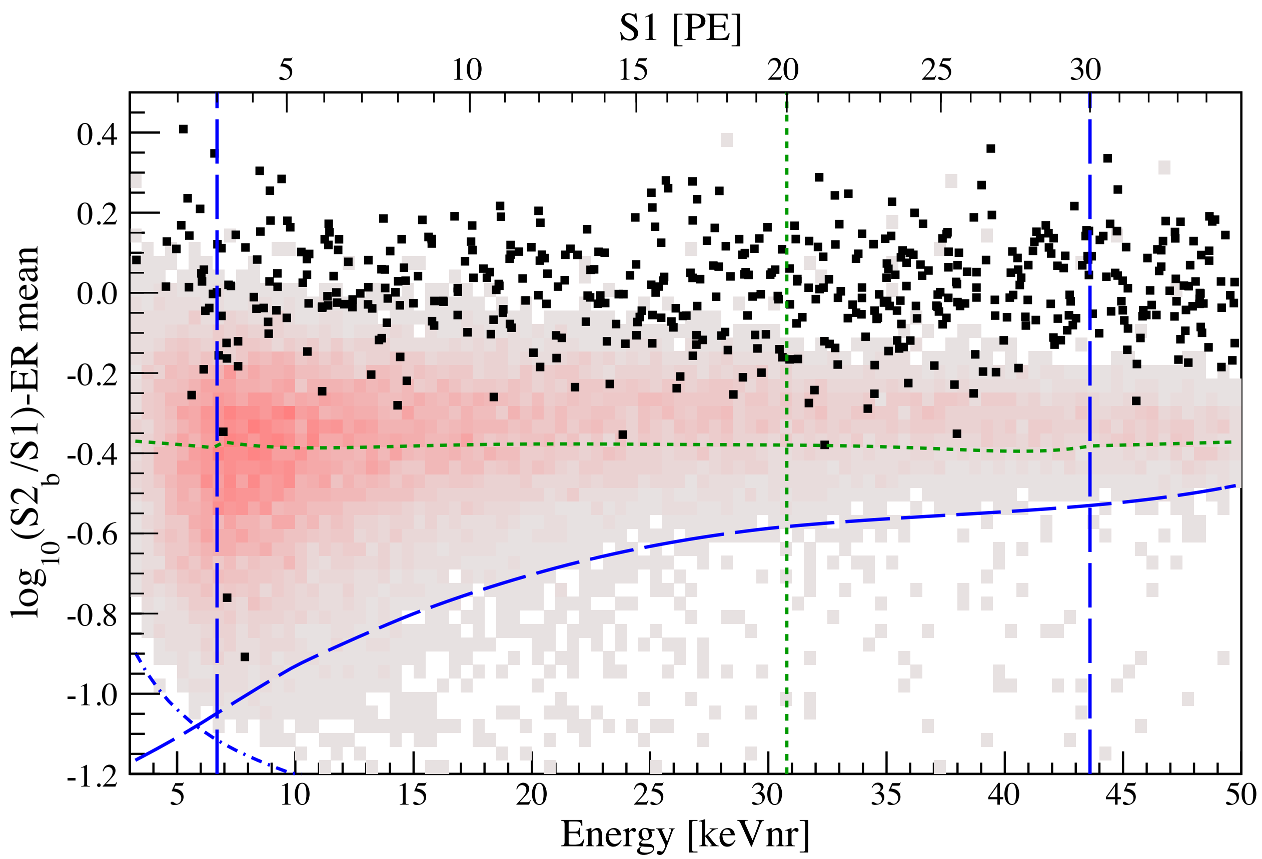
Frandsen et al.

Clearly some tension, but how much?

What do I have to believe in order to believe this result is DM?

$$\langle S_1 \rangle = L_y \mathcal{L}_{eff} \frac{S_n}{S_e} E_{nr}$$



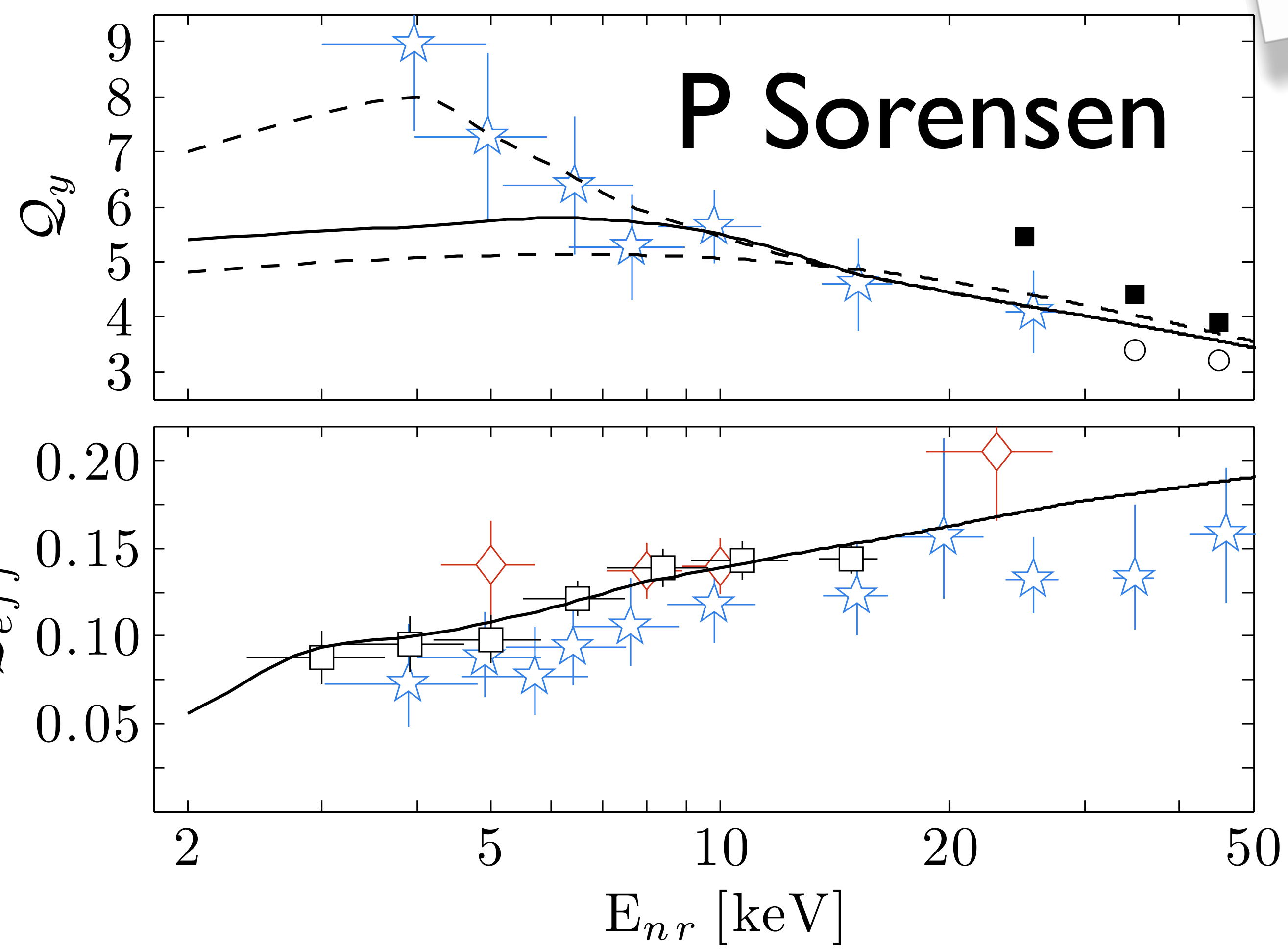


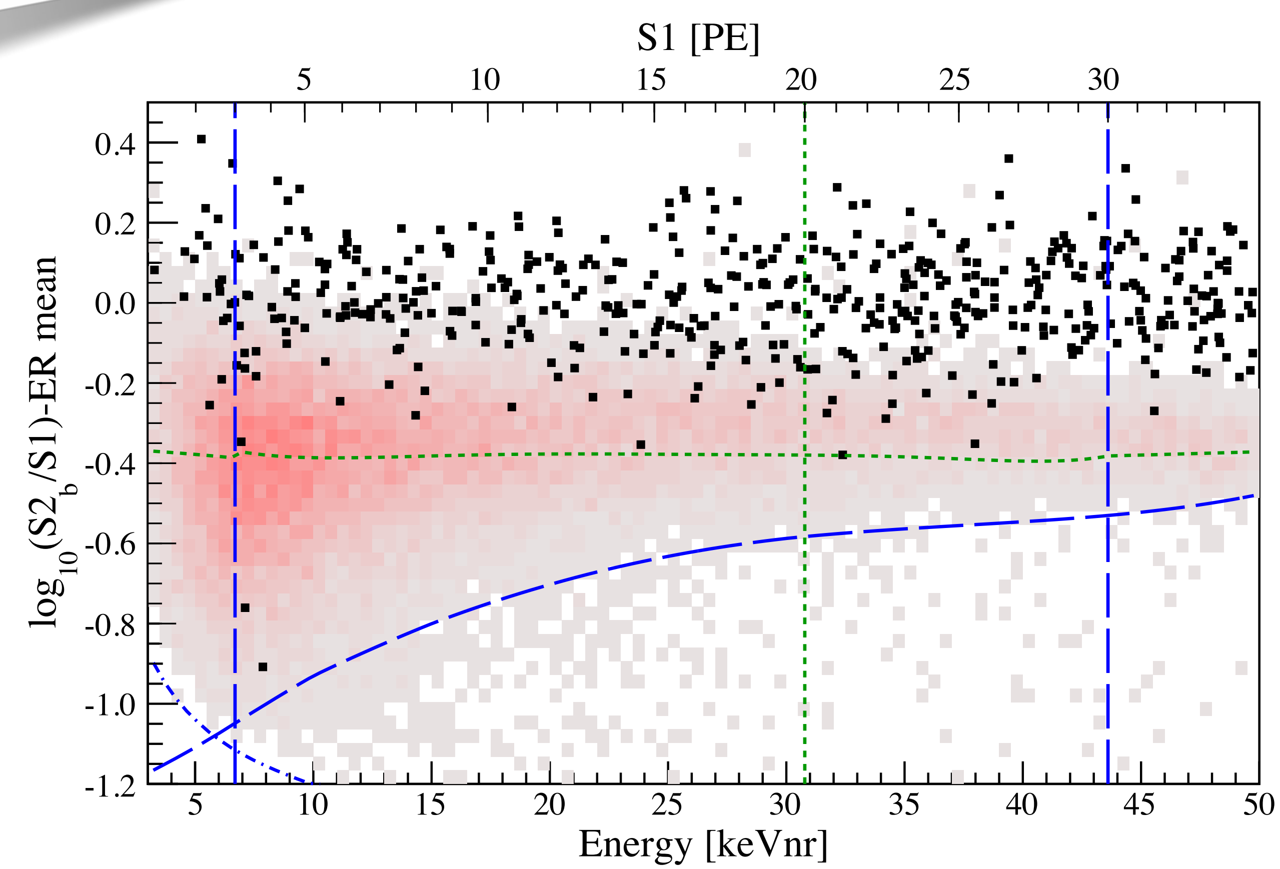
Clearly some tension, but how much?

What do I have to believe in order to believe this result is DM?

$$\langle S_1 \rangle = L_y \mathcal{L}_{eff} \frac{S_n}{S_e} E_{nr}$$

see talk by Rafael Lang



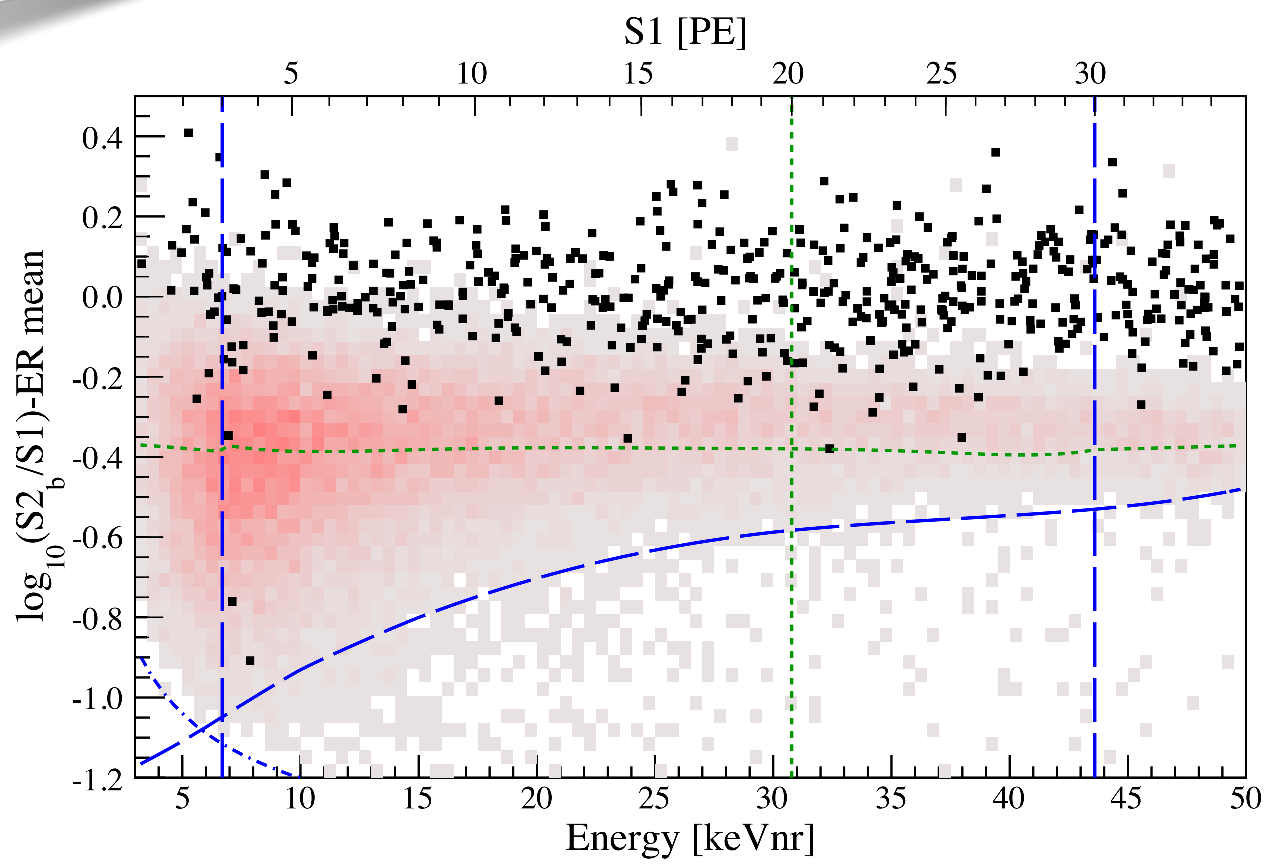


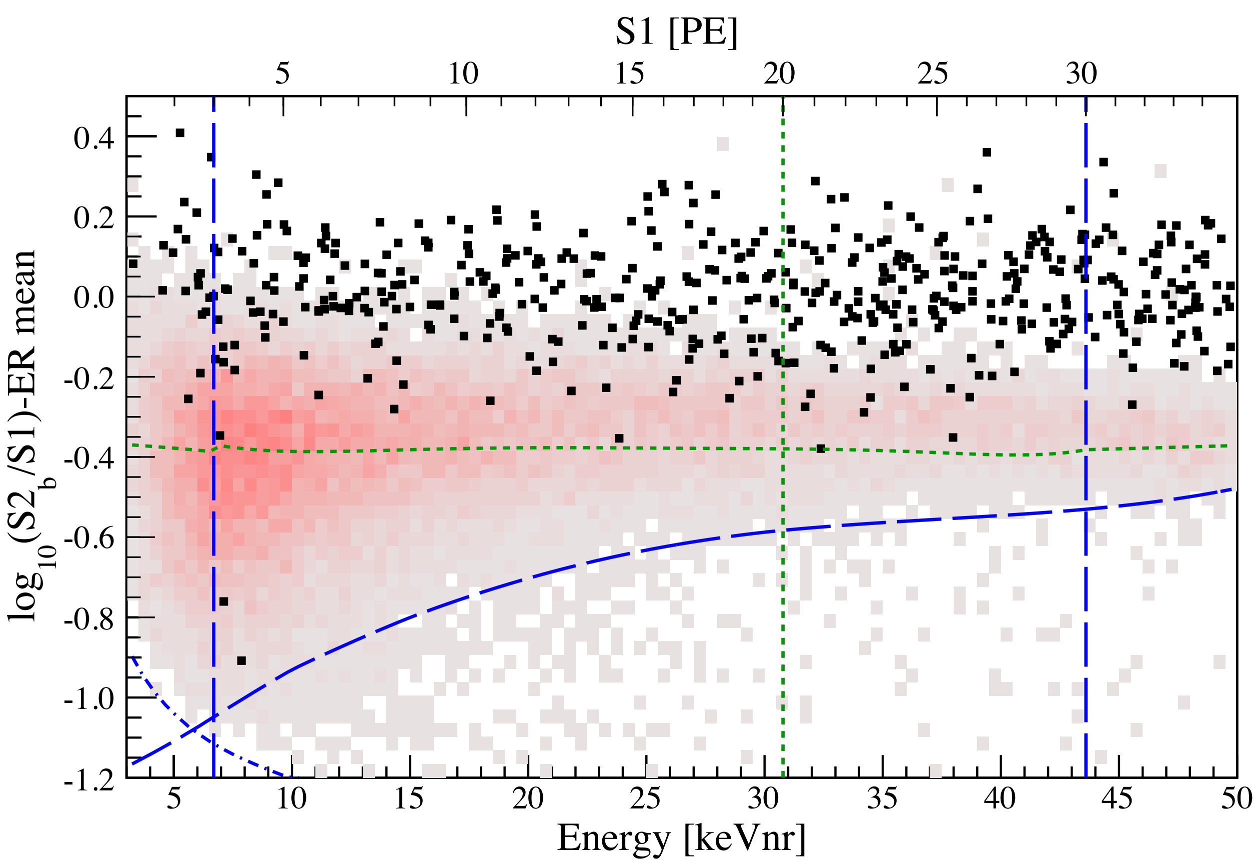
Clearly some tension, but how much?

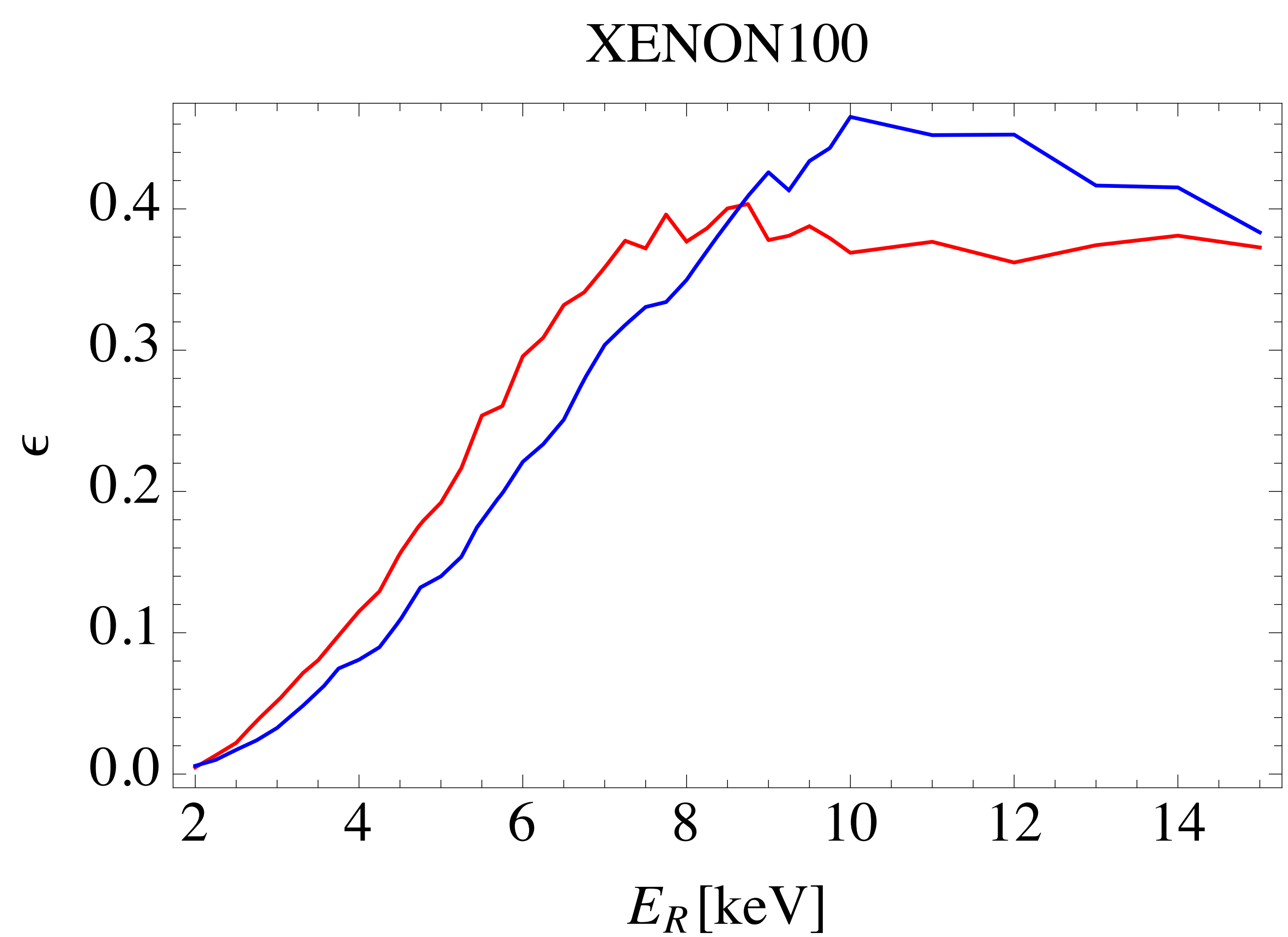
What do I have to believe in order to believe this result is DM?

$$\langle S_1 \rangle = L_y \mathcal{L}_{eff} \frac{S_n}{S_e} E_{nr}$$

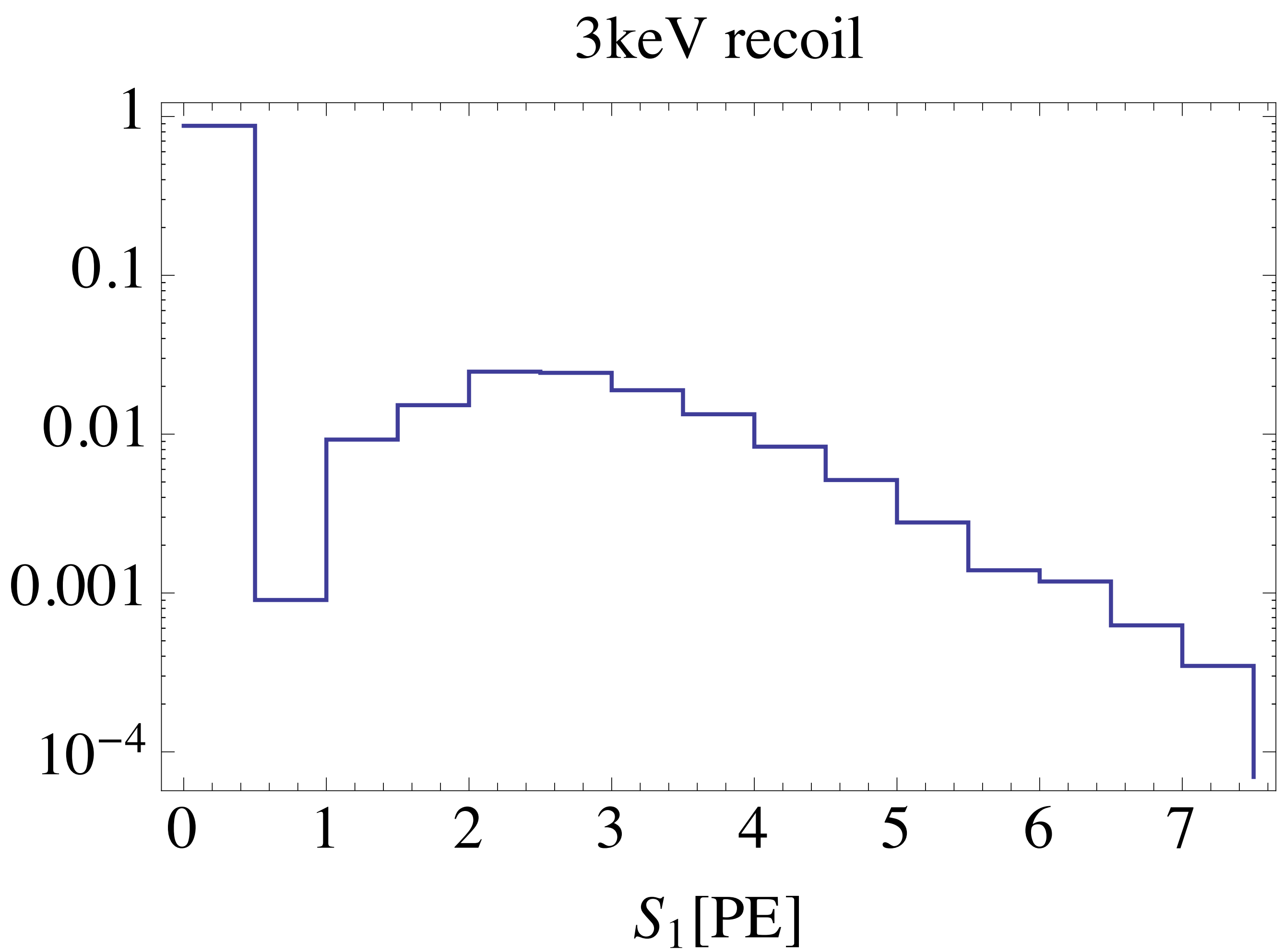
see talk by Rafael Lang

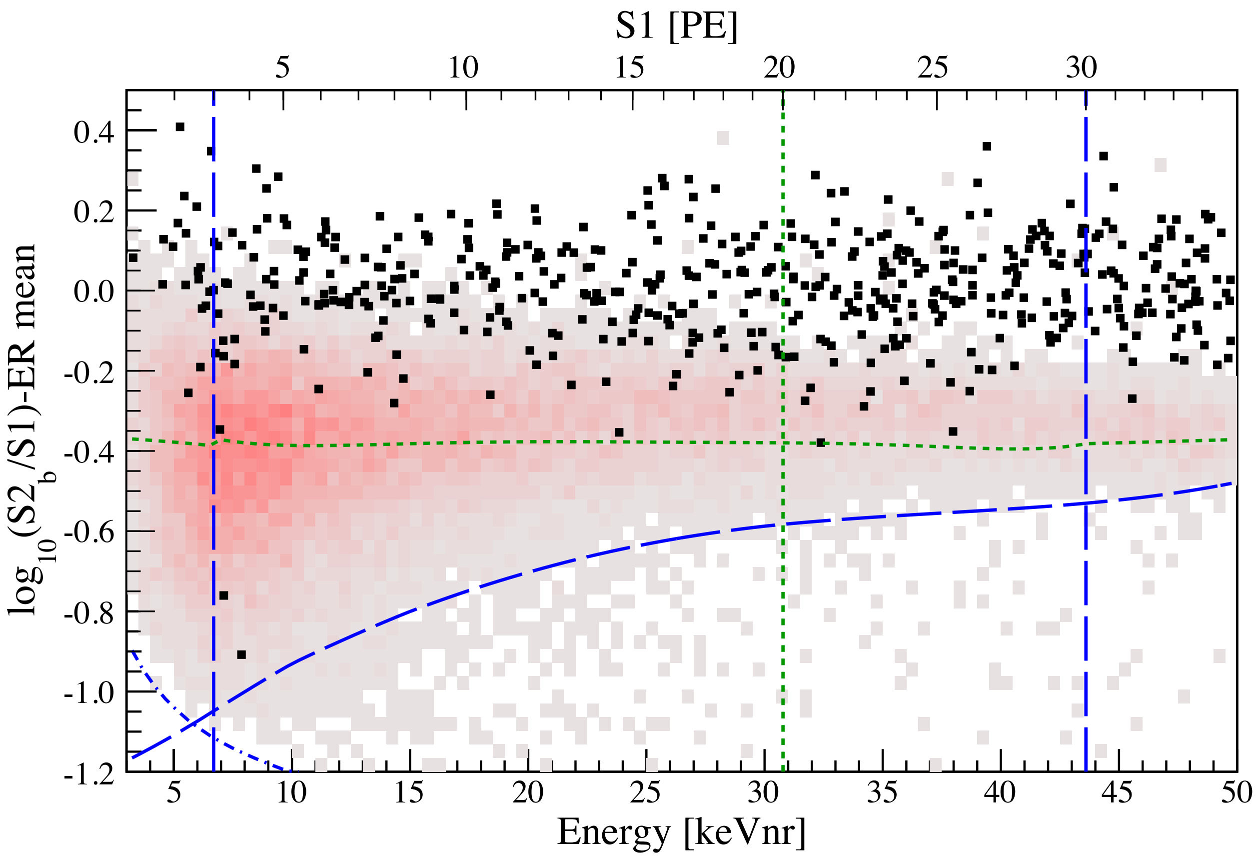




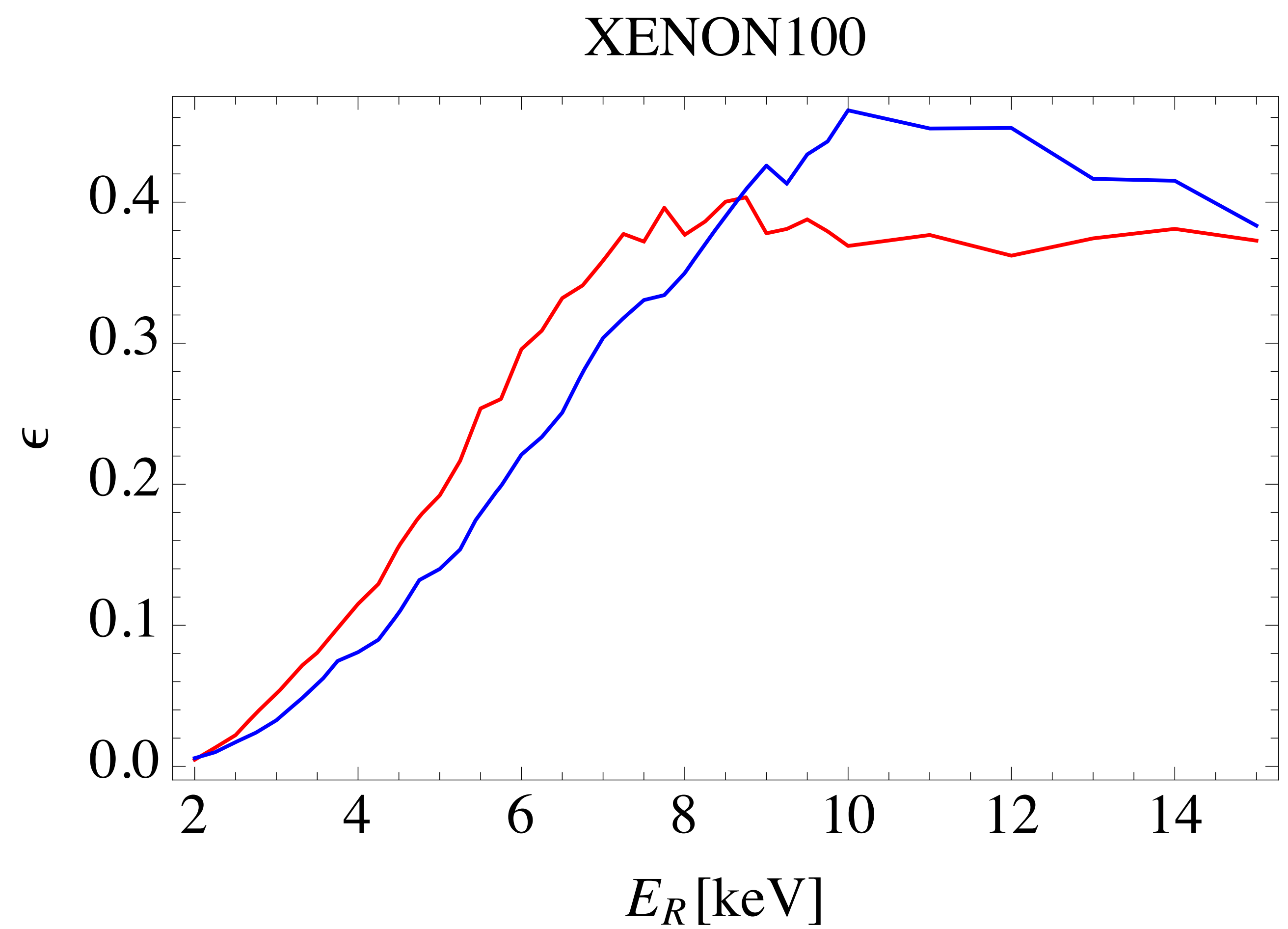


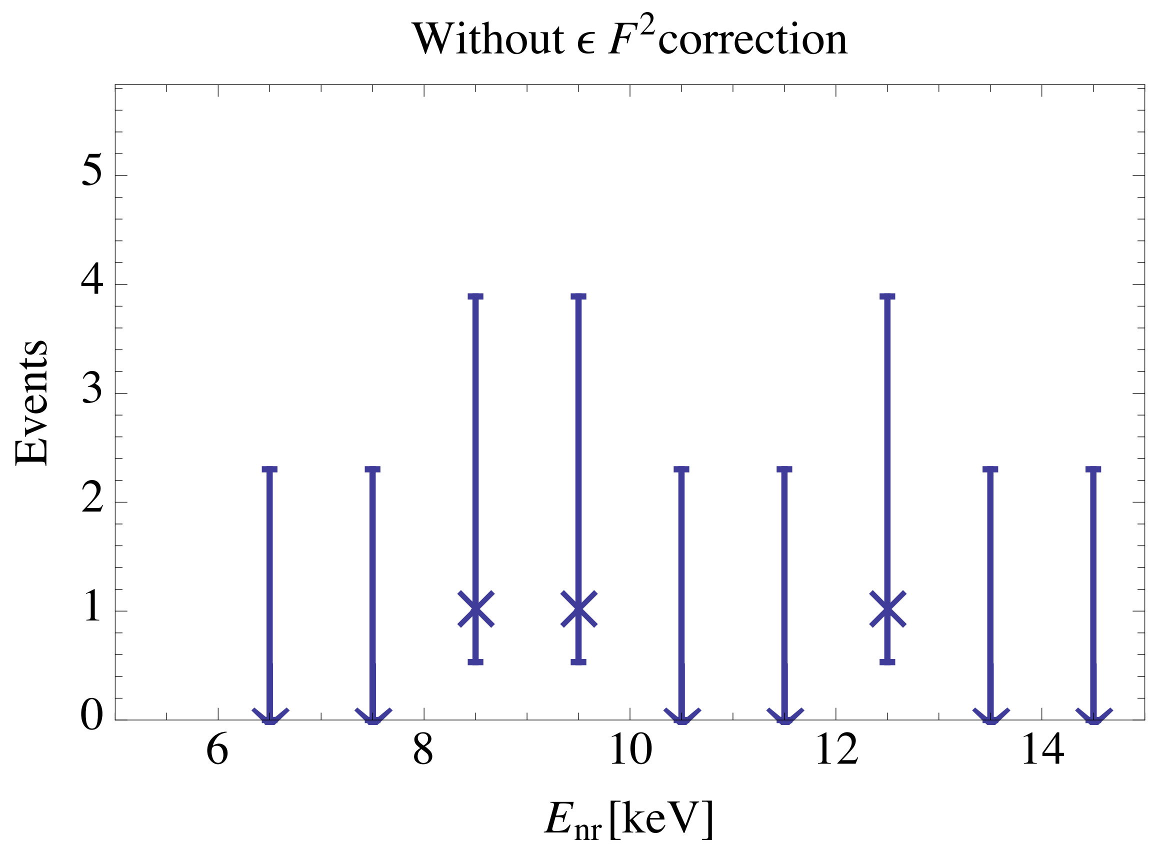
Thanks to Peter Sorensen, see 1208.5046

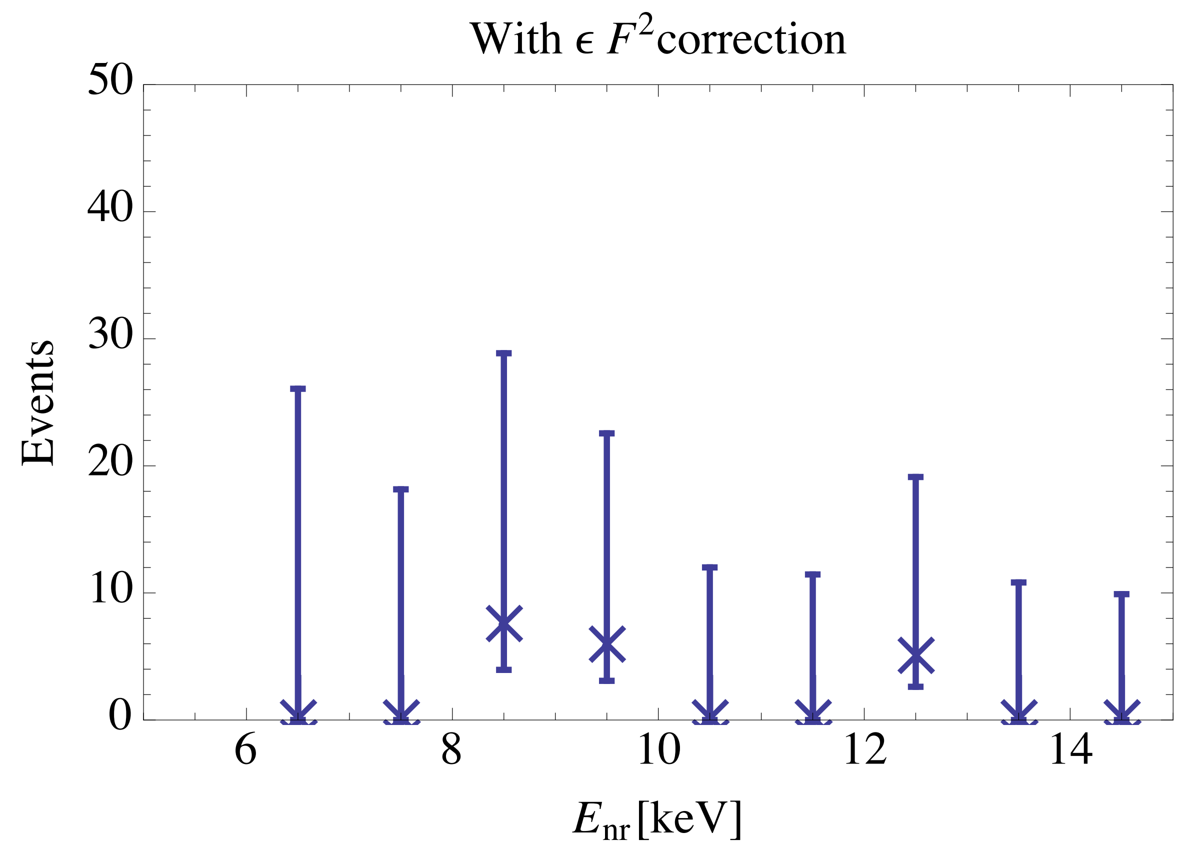




Thanks to Peter Sorensen, see 1208.5046



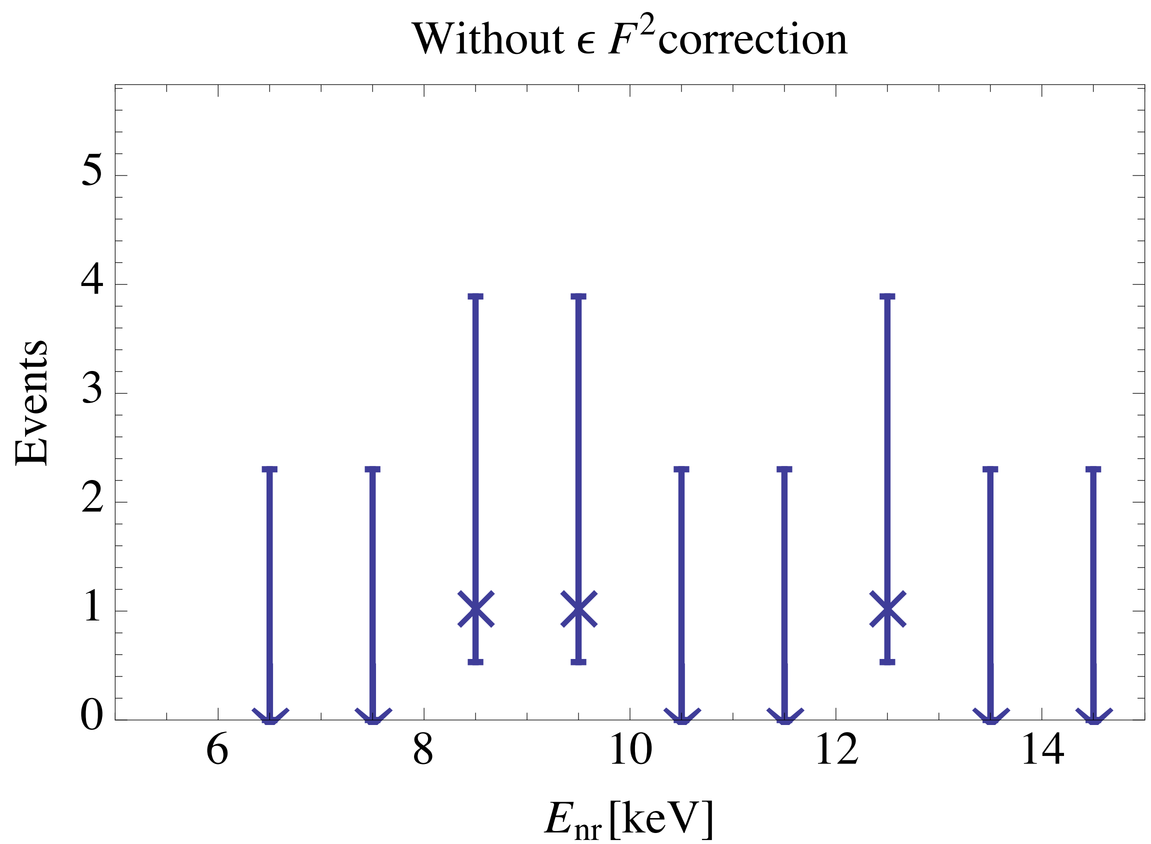


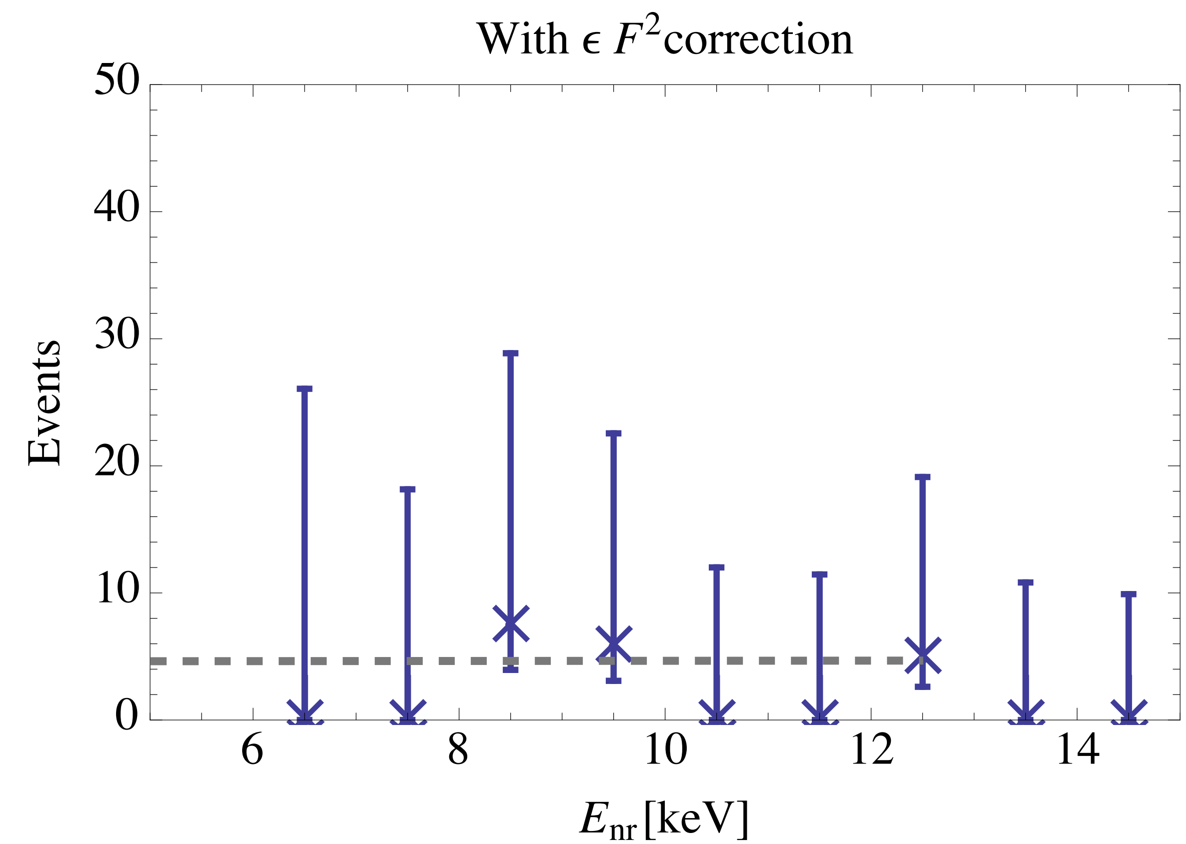


3 events could be upward fluctuation, 90% lower limit: 1.7

CDMS expects 0.7 background events, so perhaps 1 event is background. Best case is the highest event

Similarly, perhaps XENON is downward fluctuation from 5.3



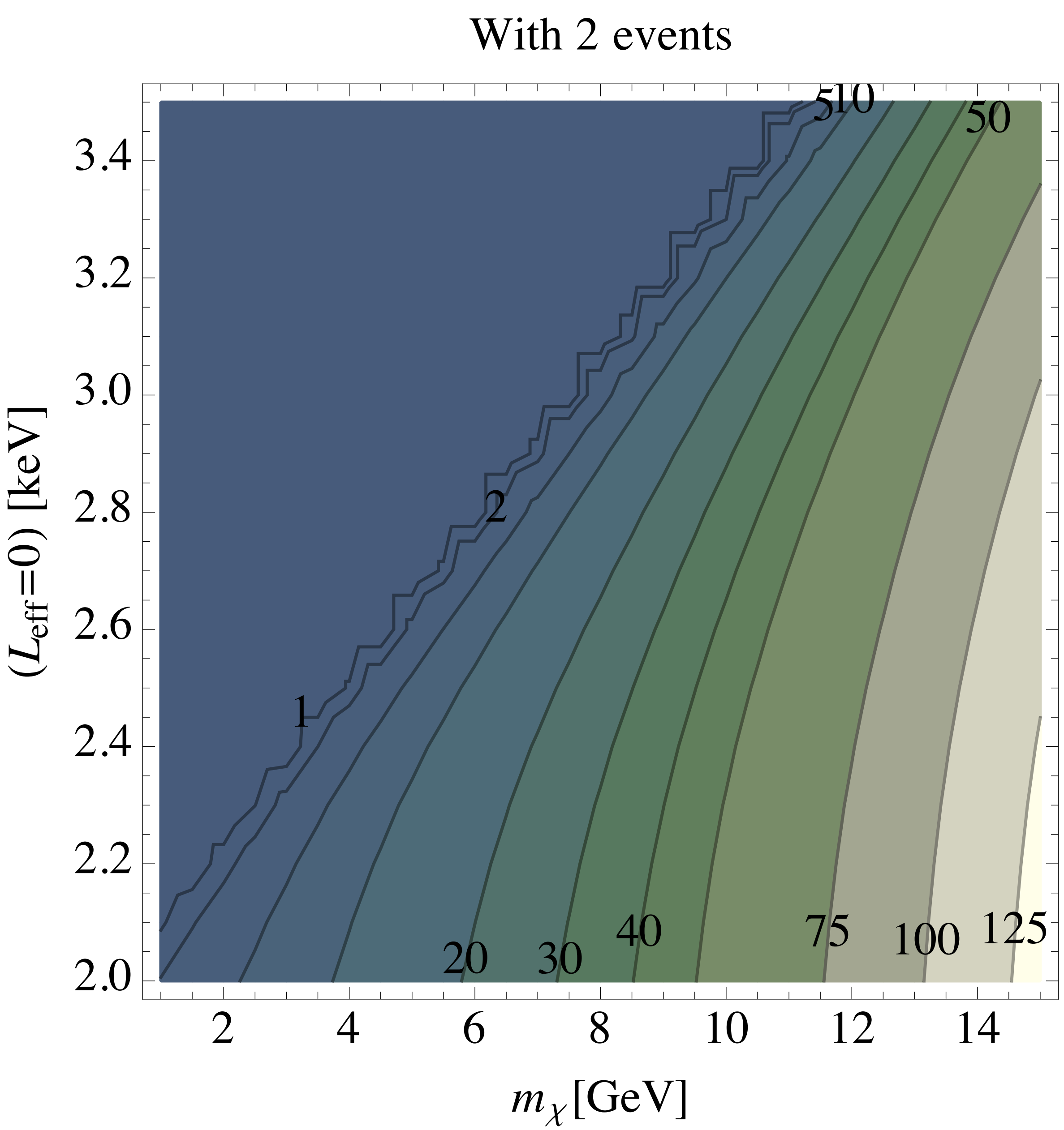


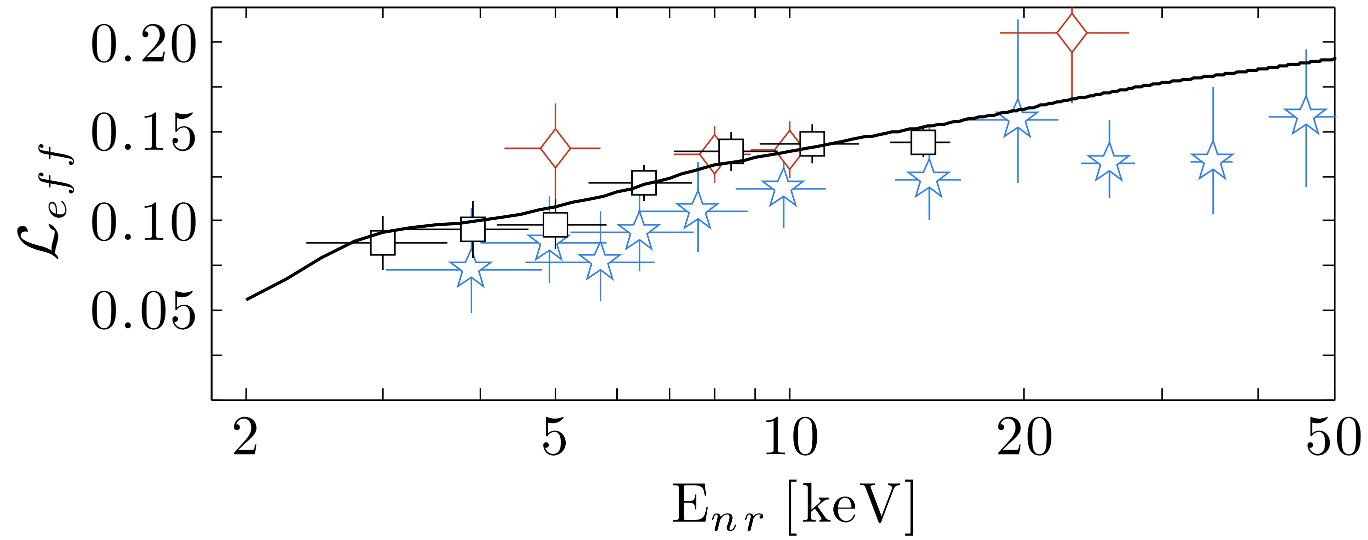
3 events could be upward fluctuation, 90% lower limit: 1.7

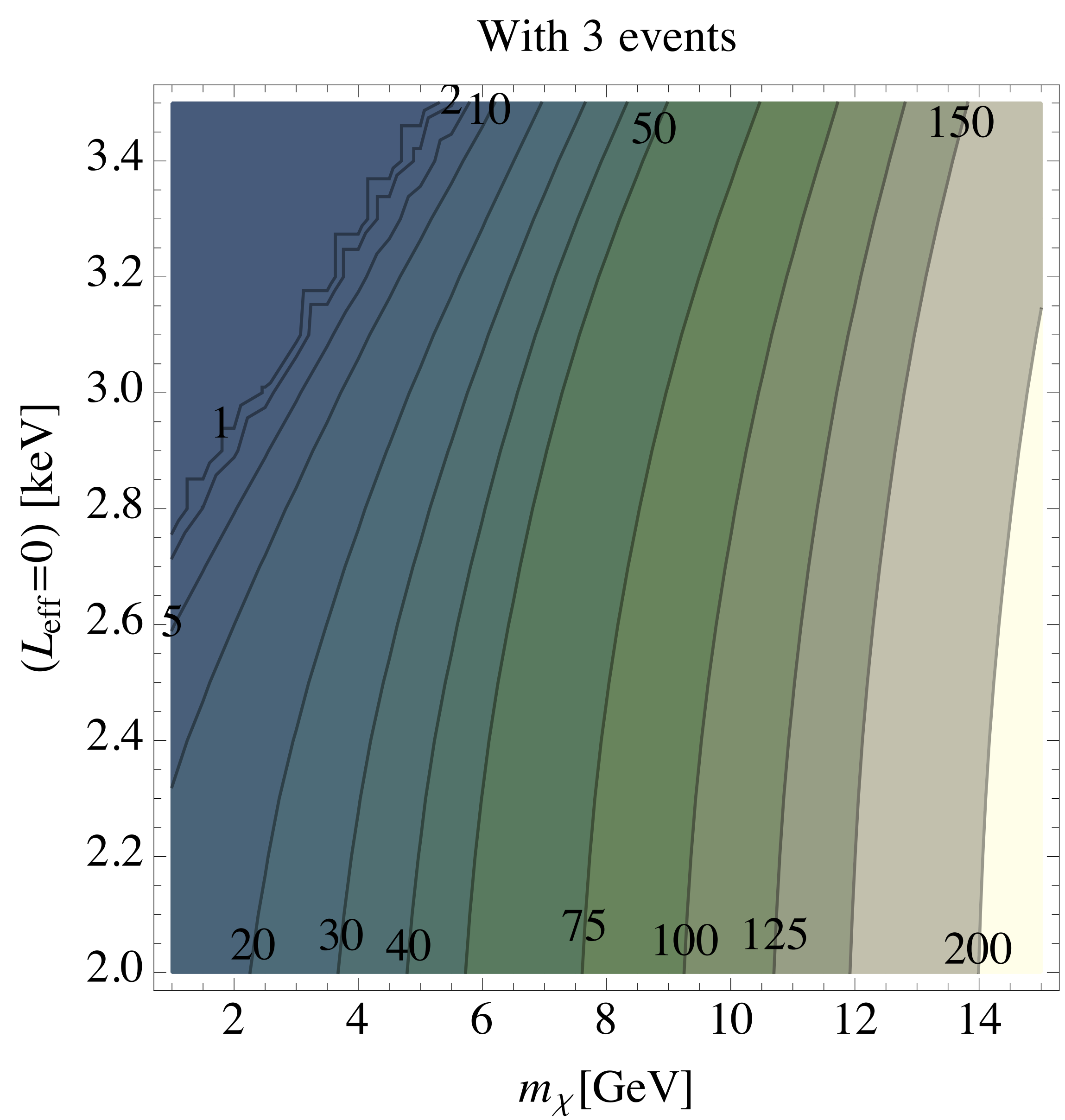
CDMS expects 0.7 background events, so perhaps 1 event is background. Best case is the highest event

Similarly, perhaps XENON is downward fluctuation from 5.3

Xenon efficiency







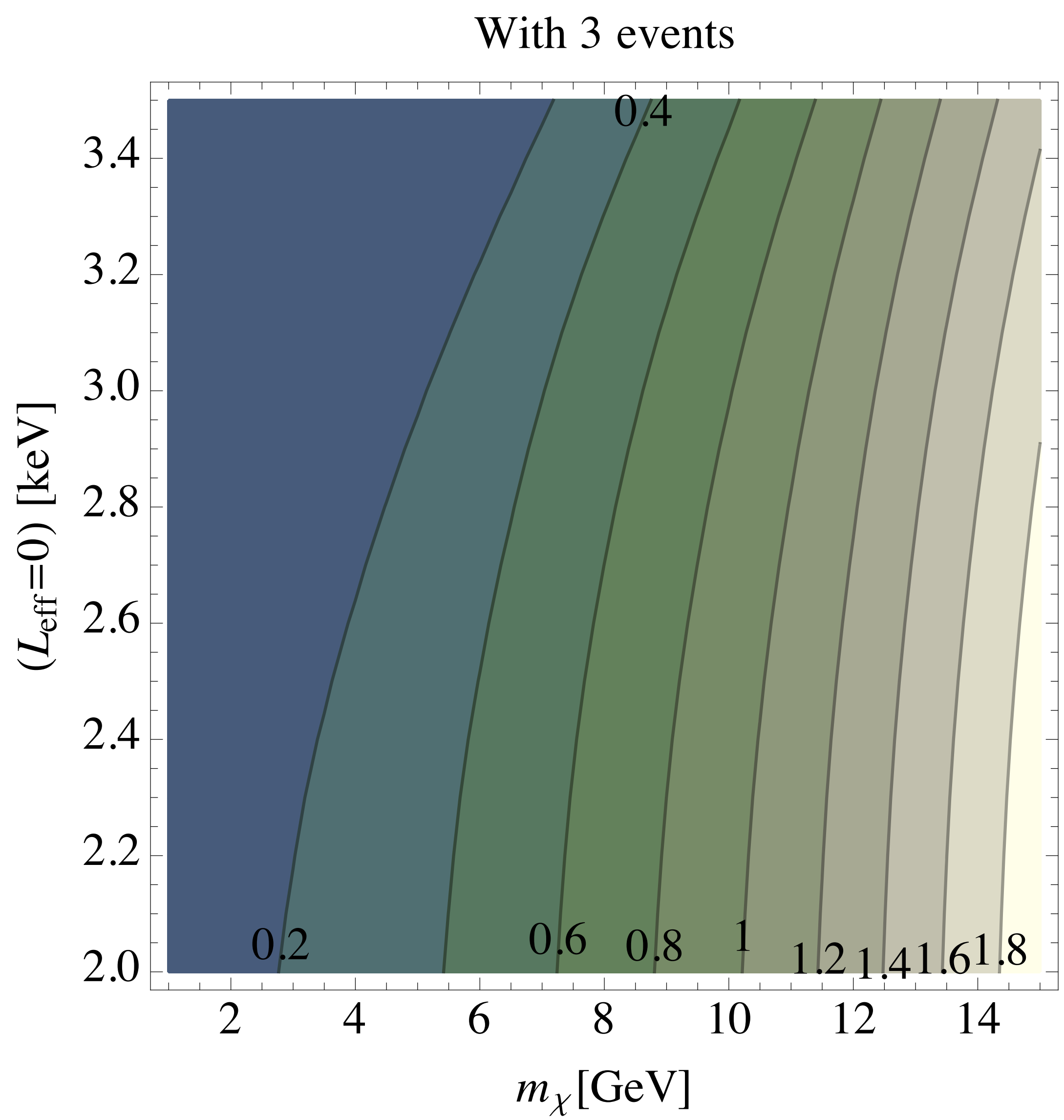
Isospin dependent couplings

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

In going from Si to Xe typically get ~20 enhancement in rate

$$\frac{f_n}{f_p} \approx -0.7$$

Suppression by ~170



Isospin dependent couplings

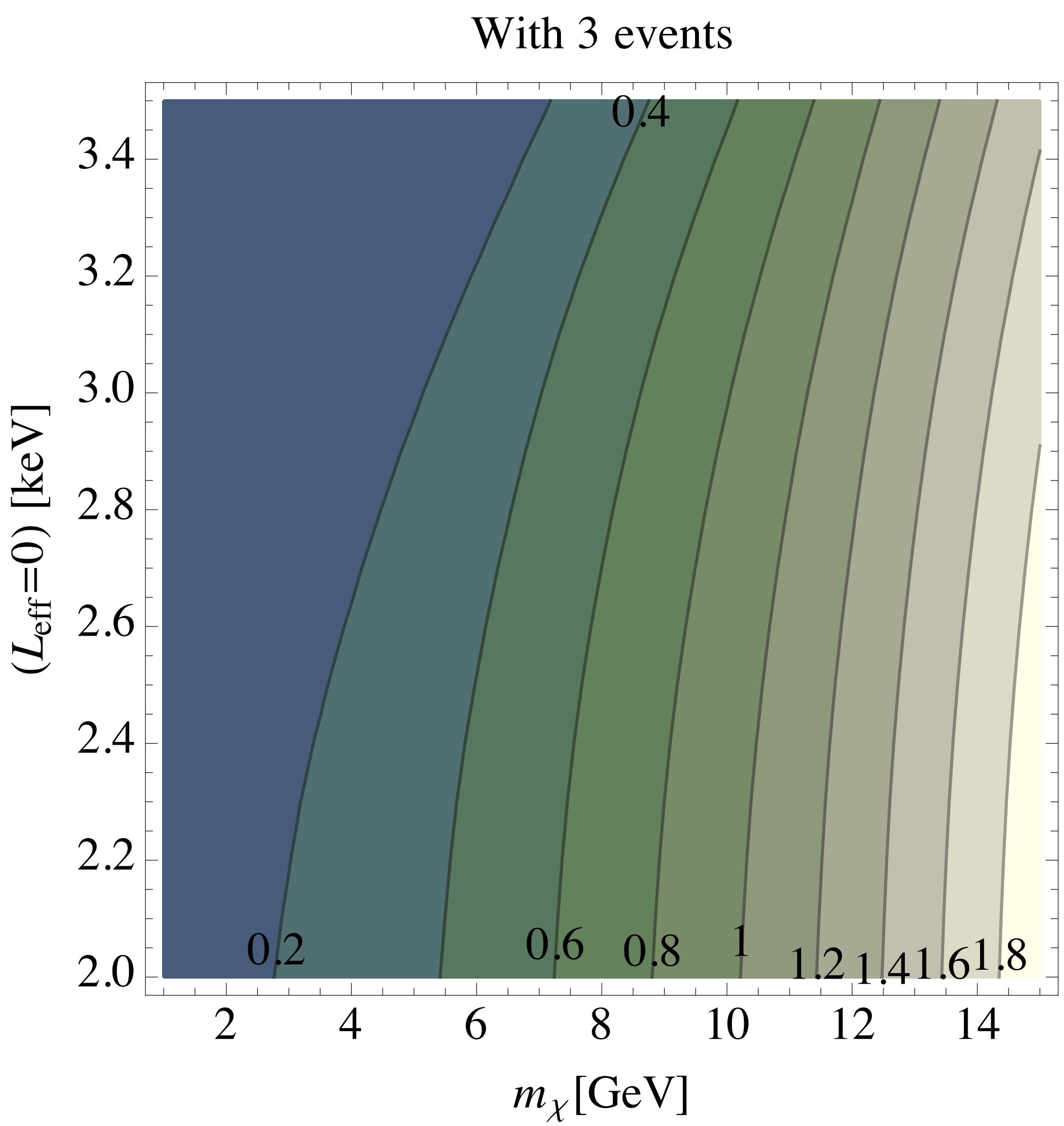
see talk by Jason Kumar

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

In going from Si to Xe typically get ~20 enhancement in rate

$$\frac{f_n}{f_p} \approx -0.7$$

Suppression by ~170



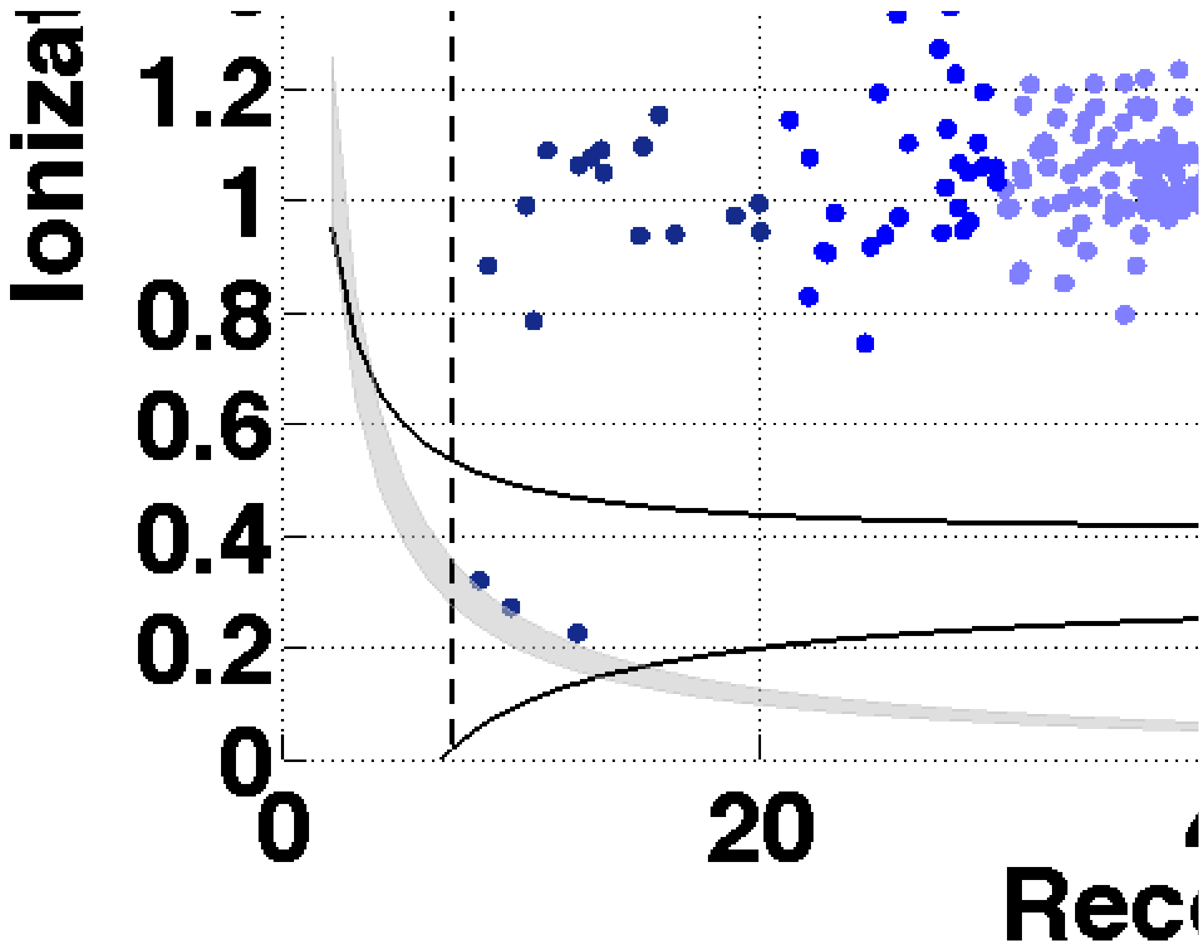
Isospin dependent couplings

$$\frac{f_n}{f_p} \approx -0.7$$

Predicted rate at DAMA~amplitude of modulation
DAMA ~100% modulated
Consistent with event timing in CDMS

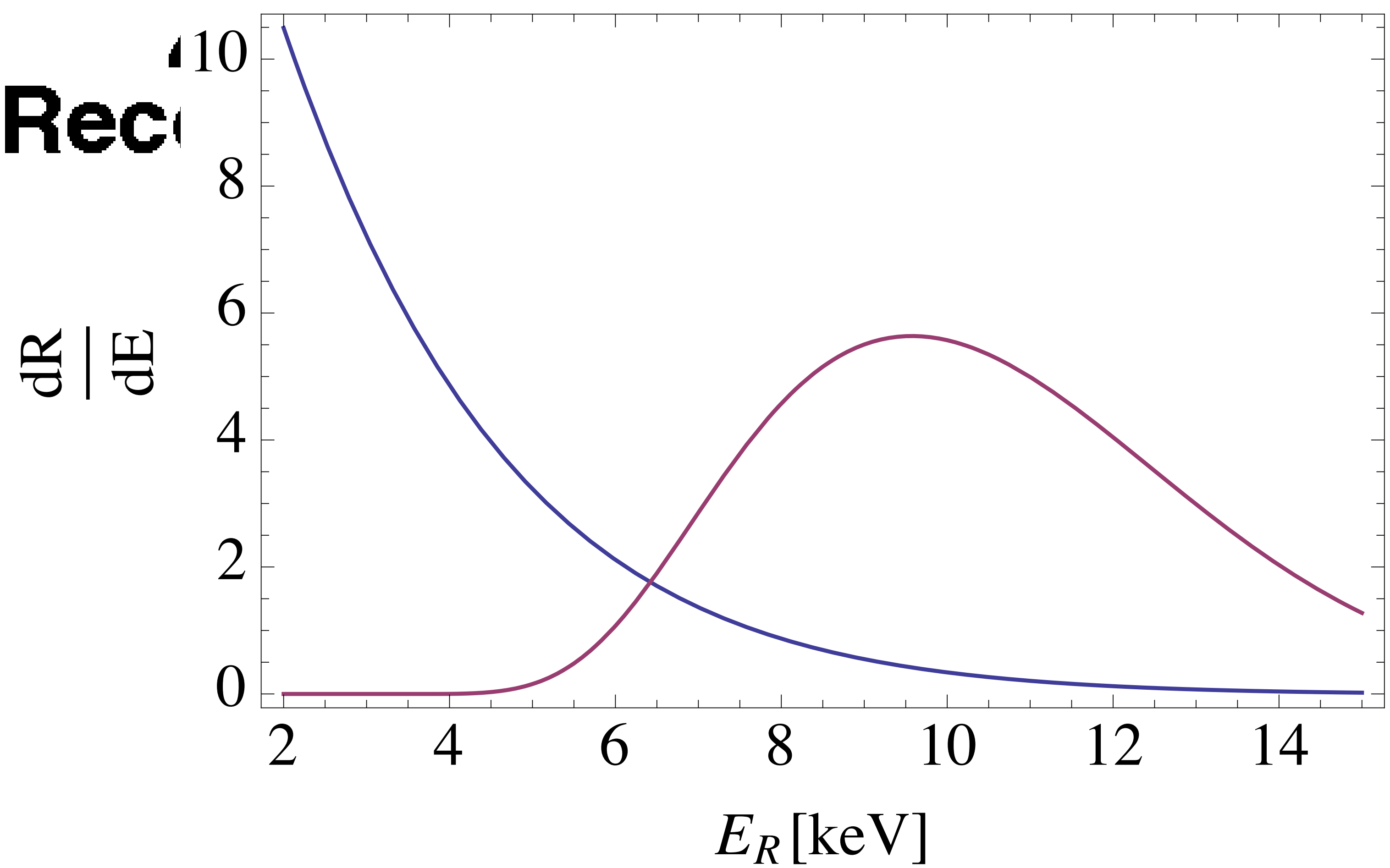
Rate too low to explain CoGeNT

Exothermic DM



Down scattering of WIMP to WIMP'
Favours light targets

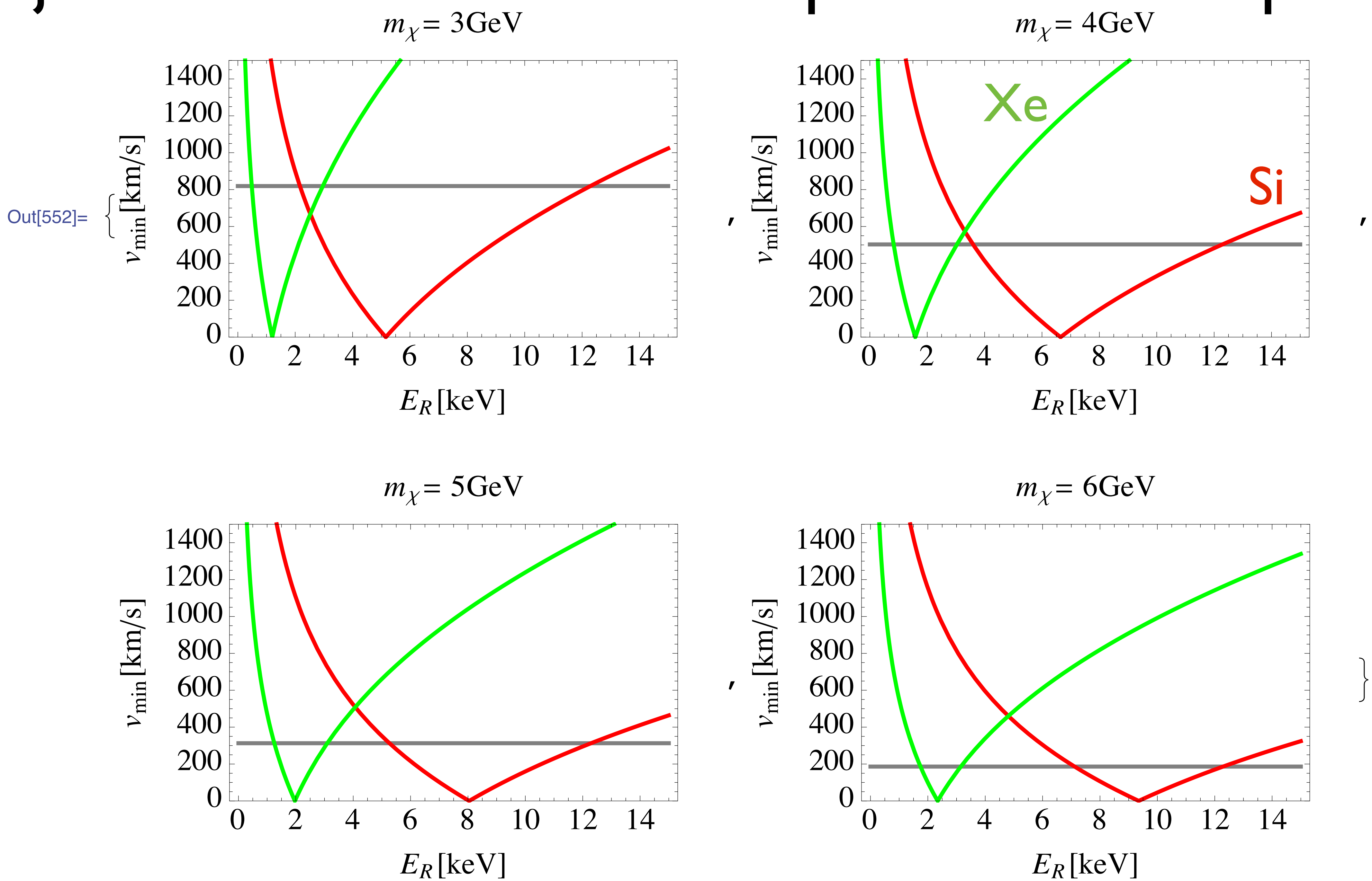
Out[539]=



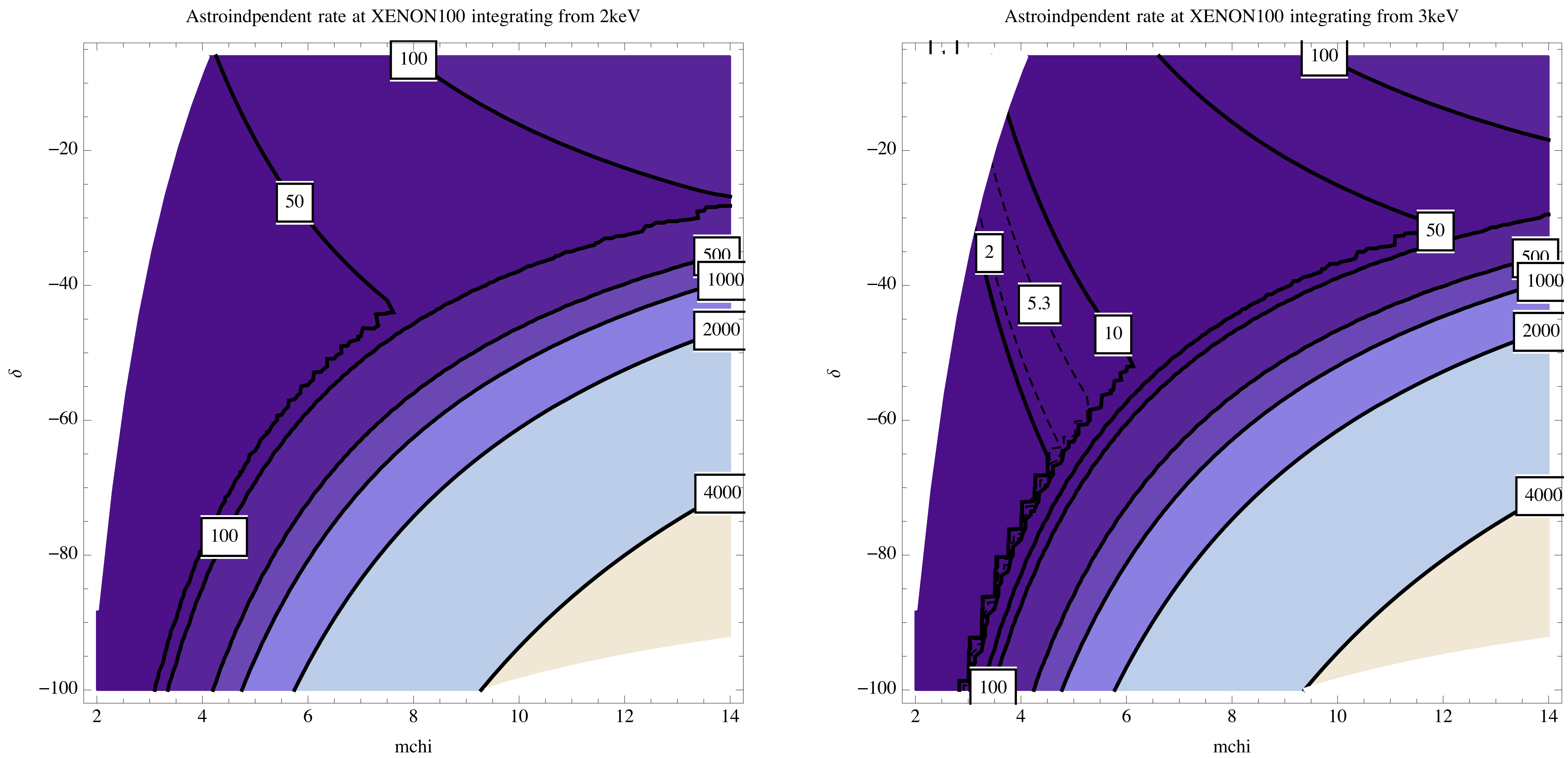
Exothermic DM

$$v_{\rm min} = \left| \delta + \frac{m_{\rm N}\, E_{\rm R}}{\mu} \right| \frac{1}{\sqrt{2\, E_{\rm R}\, m_{\rm N}}}$$

Projection to and from vmin space more complicated



Exothermic DM



Conclusions

- Should analyse data independent of astro uncertainties
- With only one experiment results are limited,
- Can extract f(v) by differentiating deconvoluted rate
- With multiple experiments should compare g(v)
- Under particle physics assumption can compare multiple experiments, test consistency
- Ultimately find region of consistent parameter space
- Independent of all astrophysics inputs, CDMS-Si is at odds with XENON100, for simple elastic WIMP
- XENON efficiency has to be a lot smaller, or non-standard WIMP