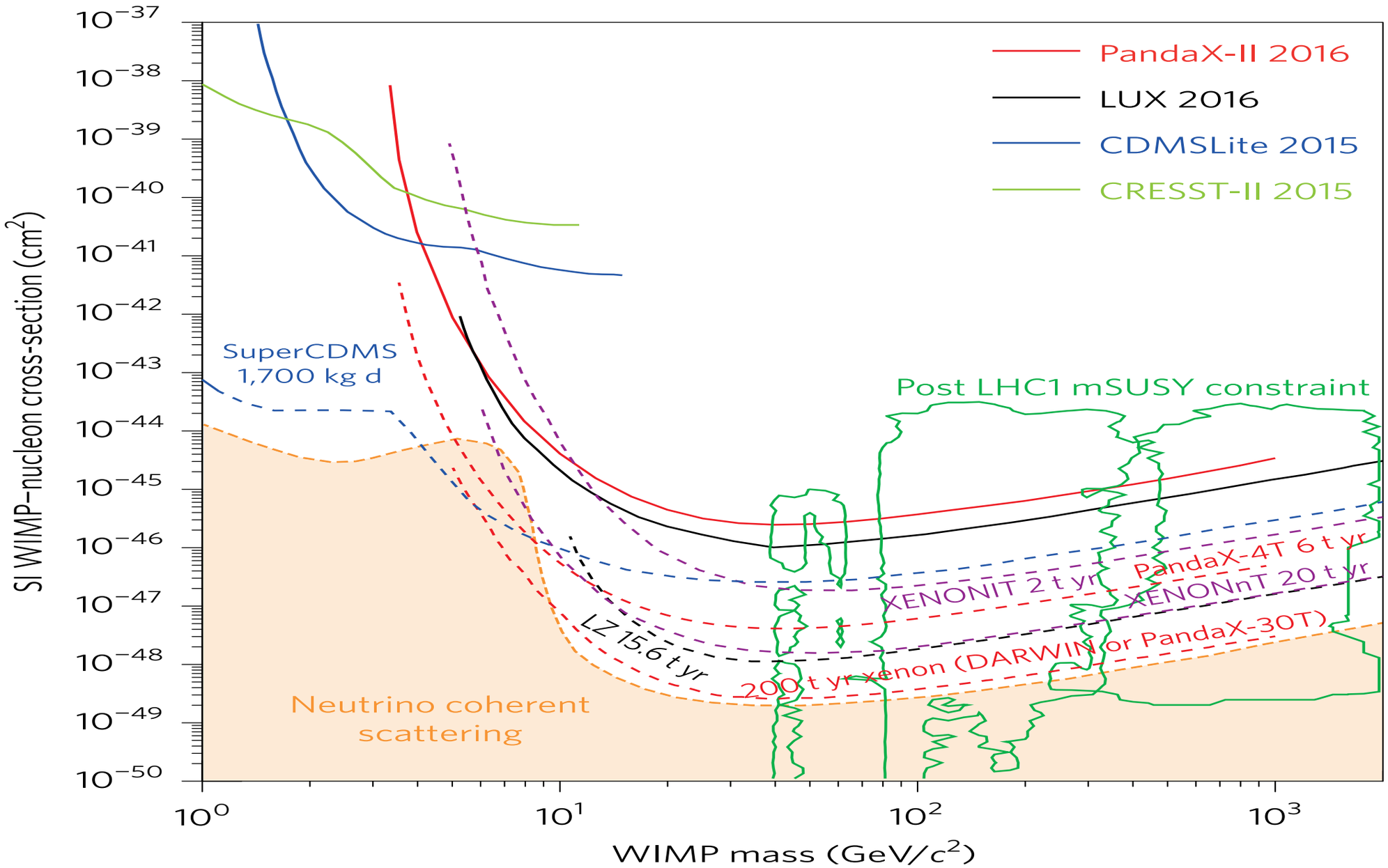
Discovering Dark Matter at High Nuclear Recoil

Adam Martin (amarti41@nd.edu)
University of Notre Dame

based off 1608.02662 with Joe Bramante (PI), Paddy Fox (FNAL) and Graham Kribs (Oregon)

PASCOS, June 20th, 2017

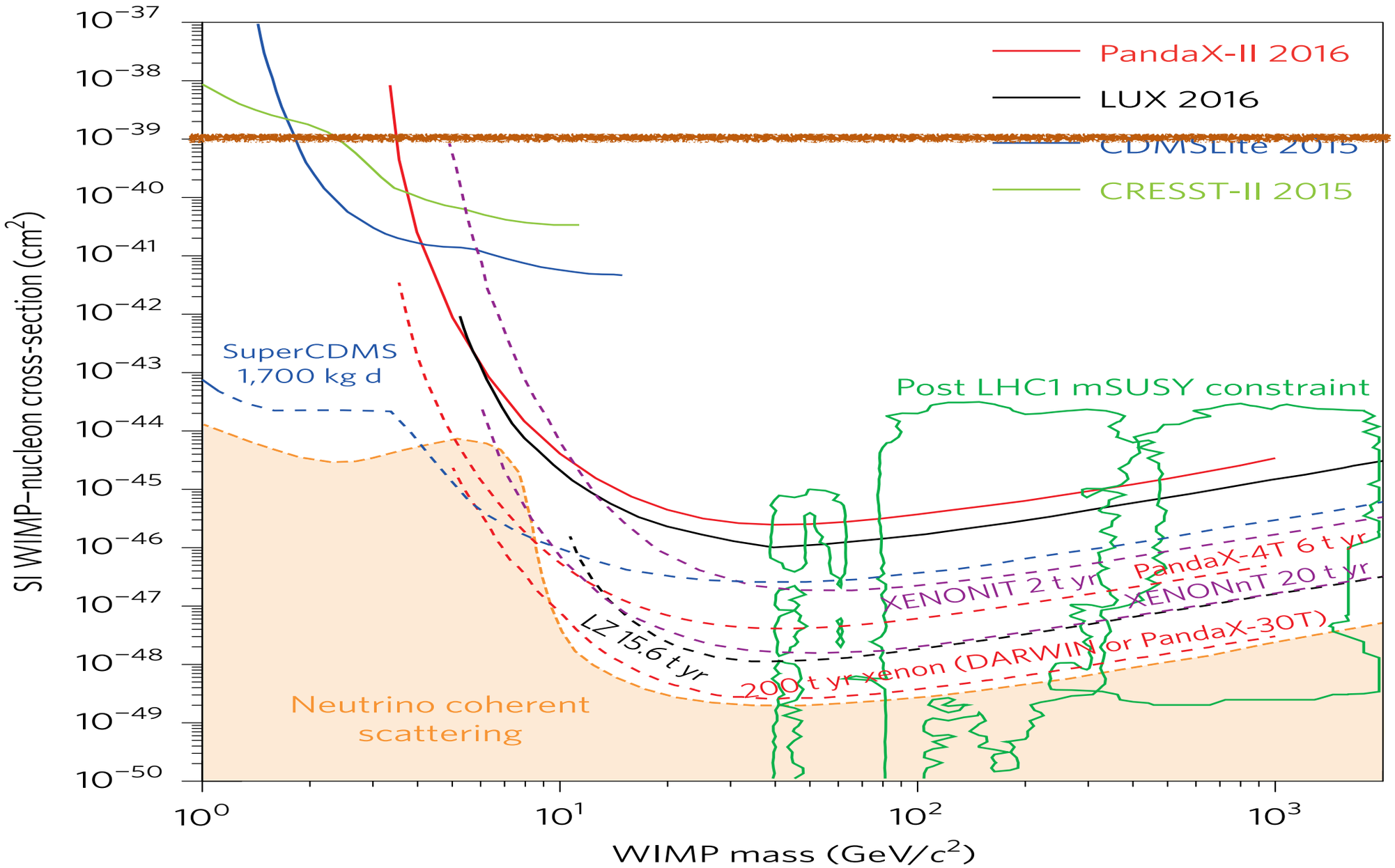
simplest WIMP DM is running out of room



[Liu, Chen, Ji '17]

(not shown: latest Xe100 (1609.06154) and XENON1T (1705.06655) results)

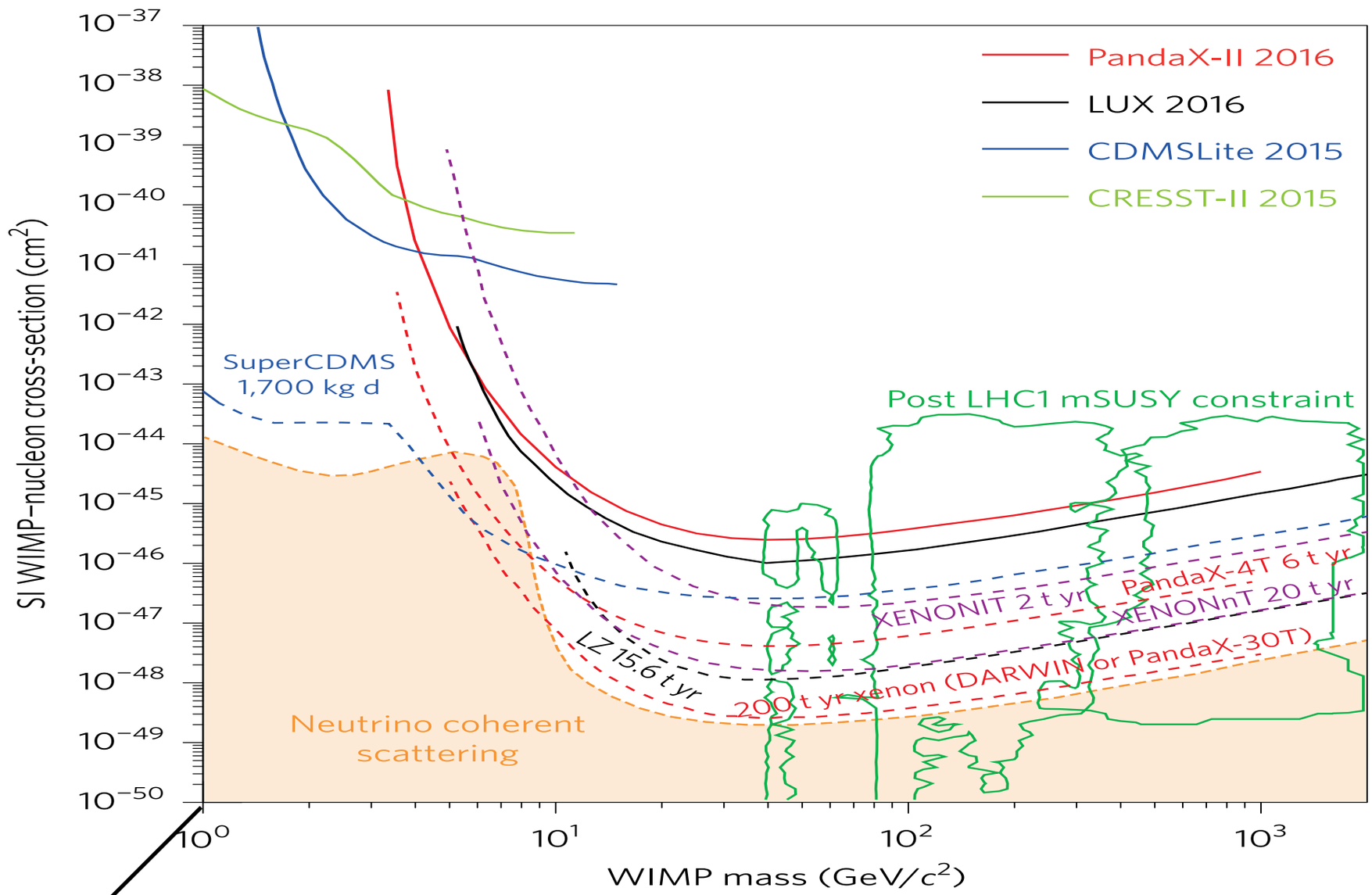
simplest WIMP DM is running out of room



[Liu, Chen, Ji '17]

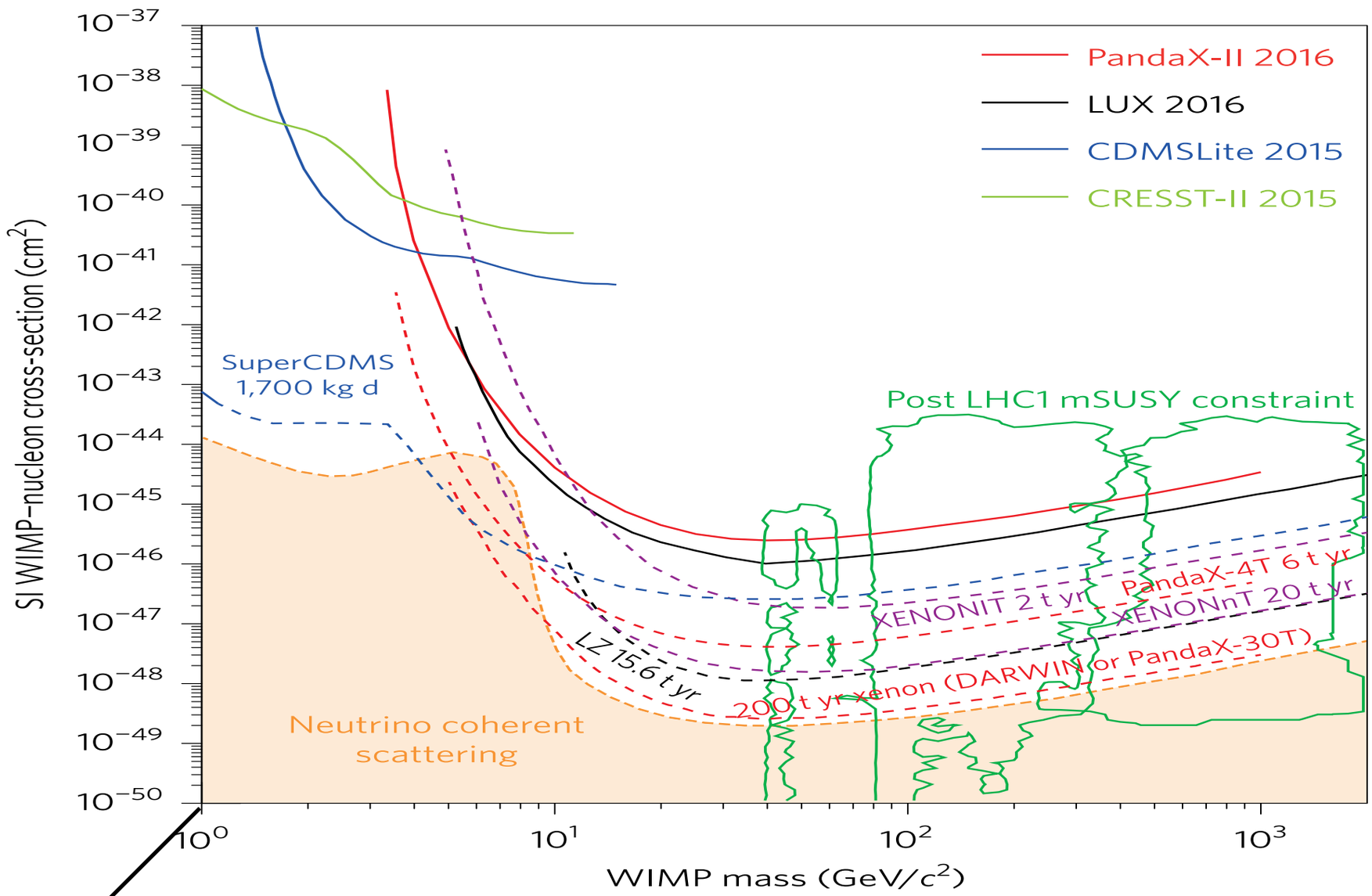
(not shown: latest Xe100 (1609.06154) and XENON1T (1705.06655) results)

third direction: inelasticity



mass
splitting

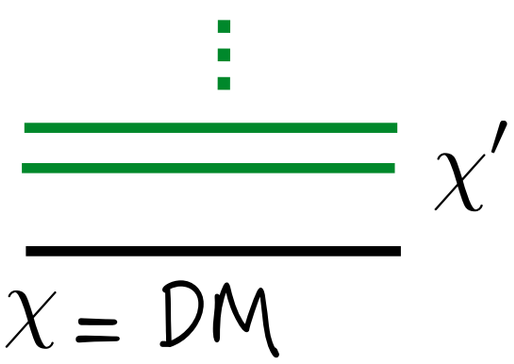
third direction: inelasticity



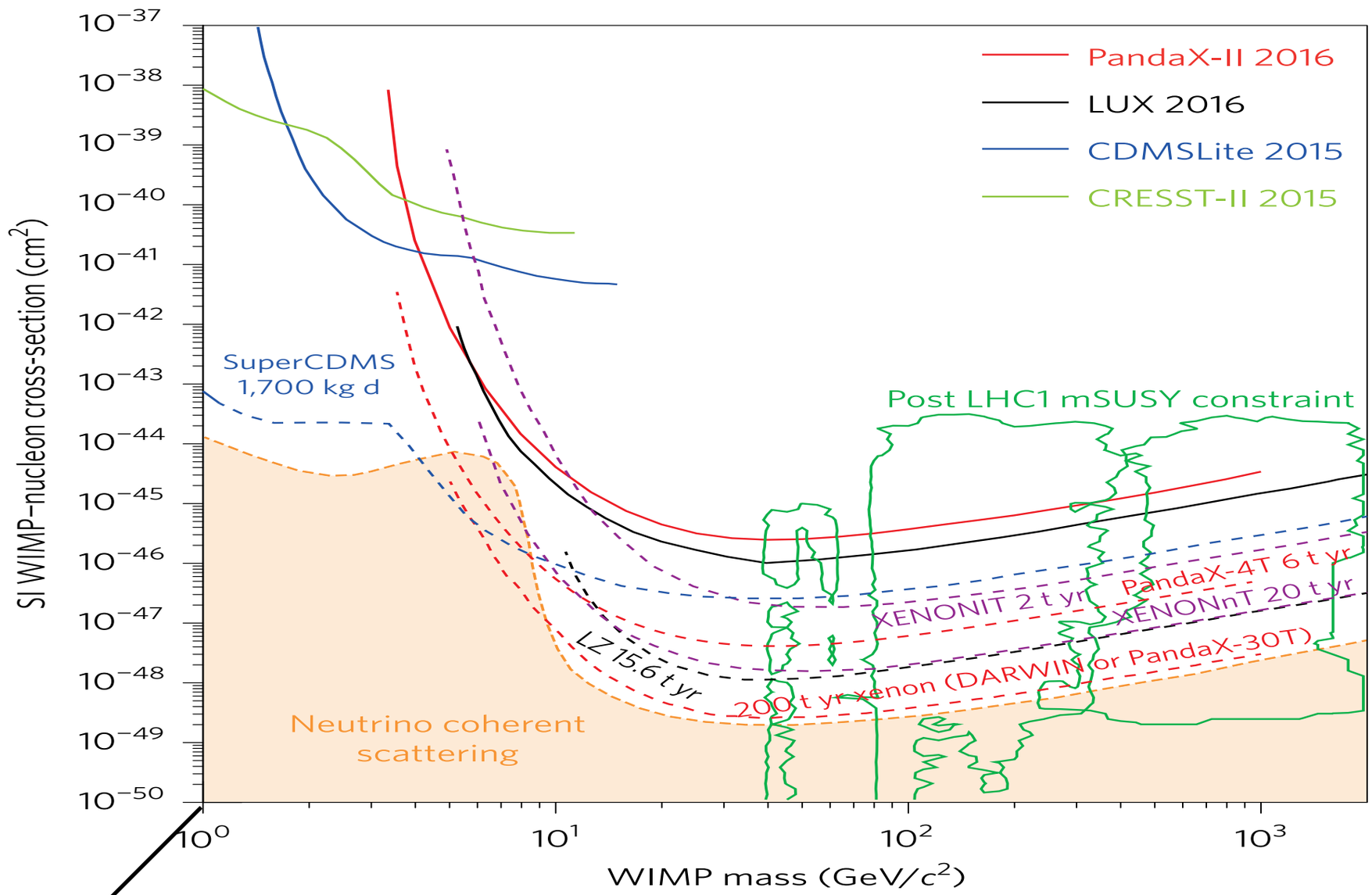
$\overline{\chi = DM}$

mass
splitting

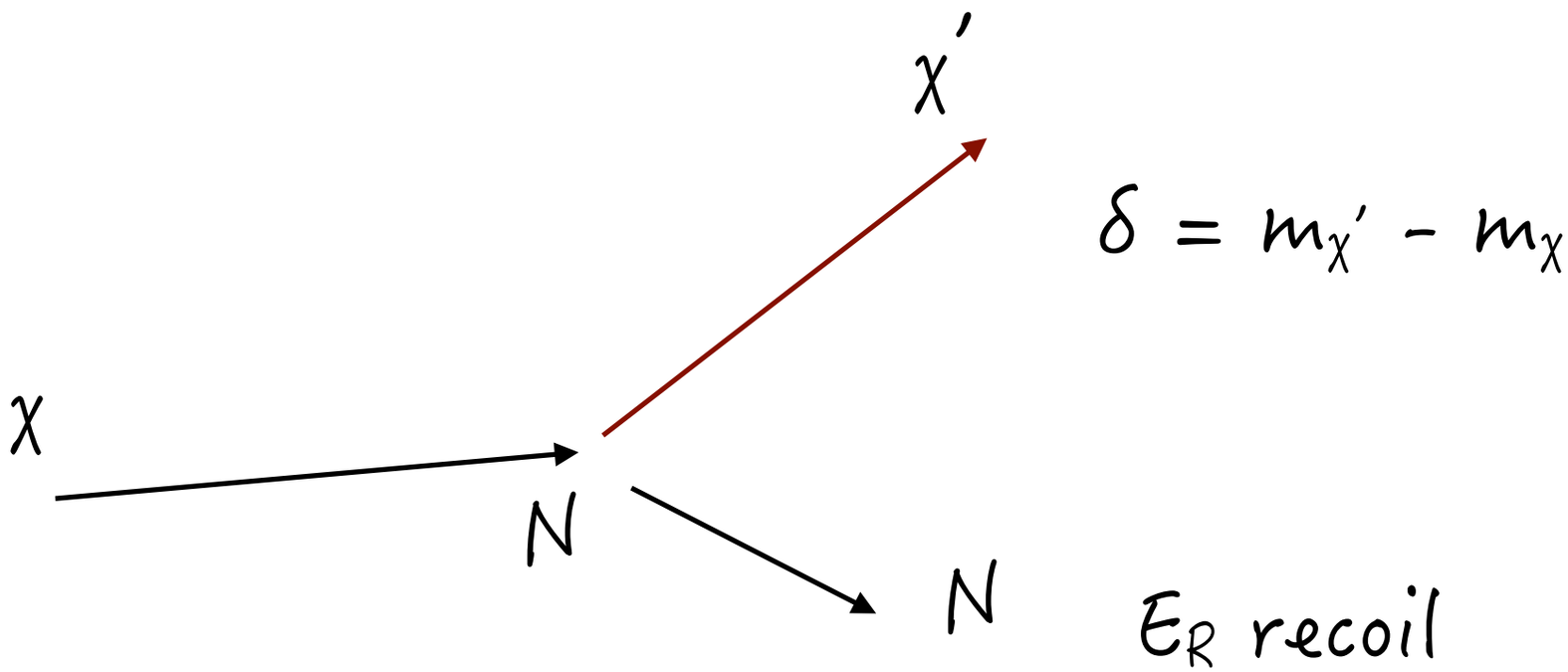
third direction: inelasticity



mass splitting

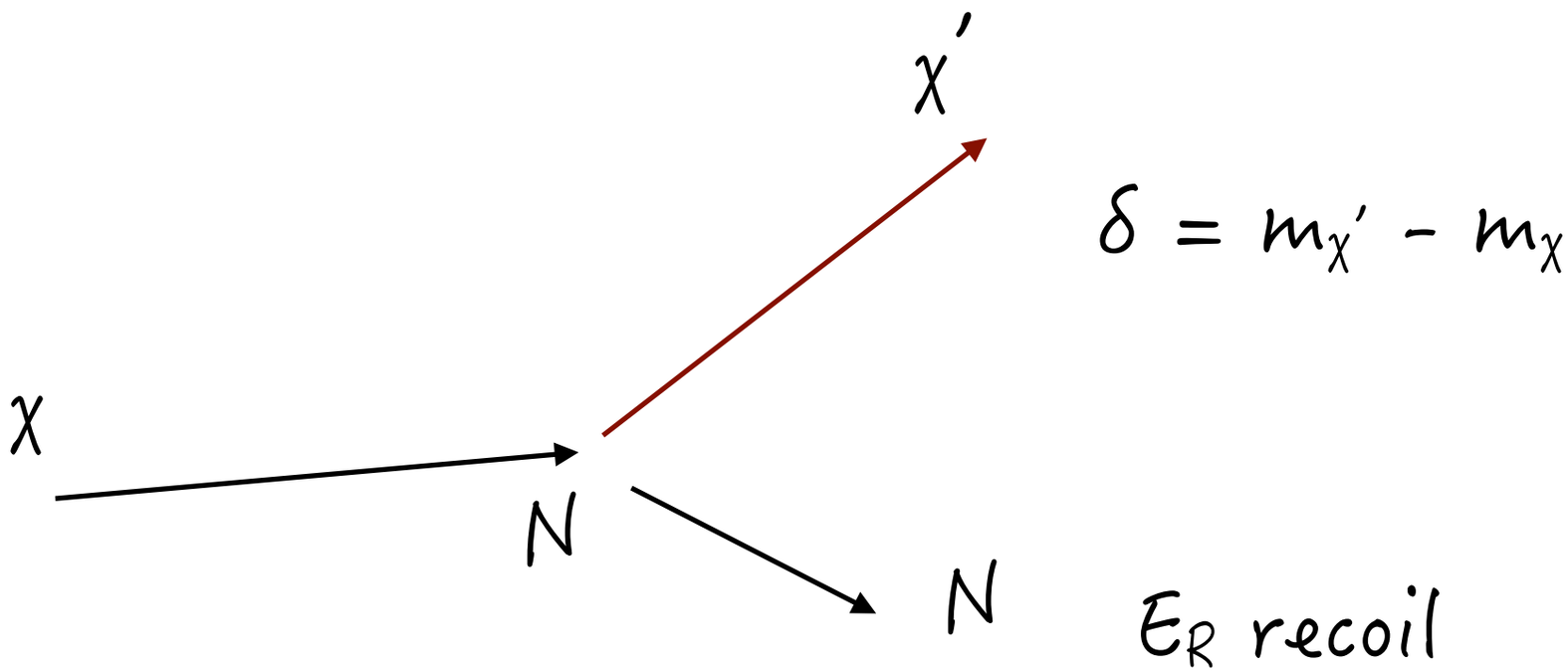


Inelastic DM



[L. J. Hall, T. Moroi and H. Murayama ’97, Tucker-Smith, Weiner ’01]

Inelastic DM



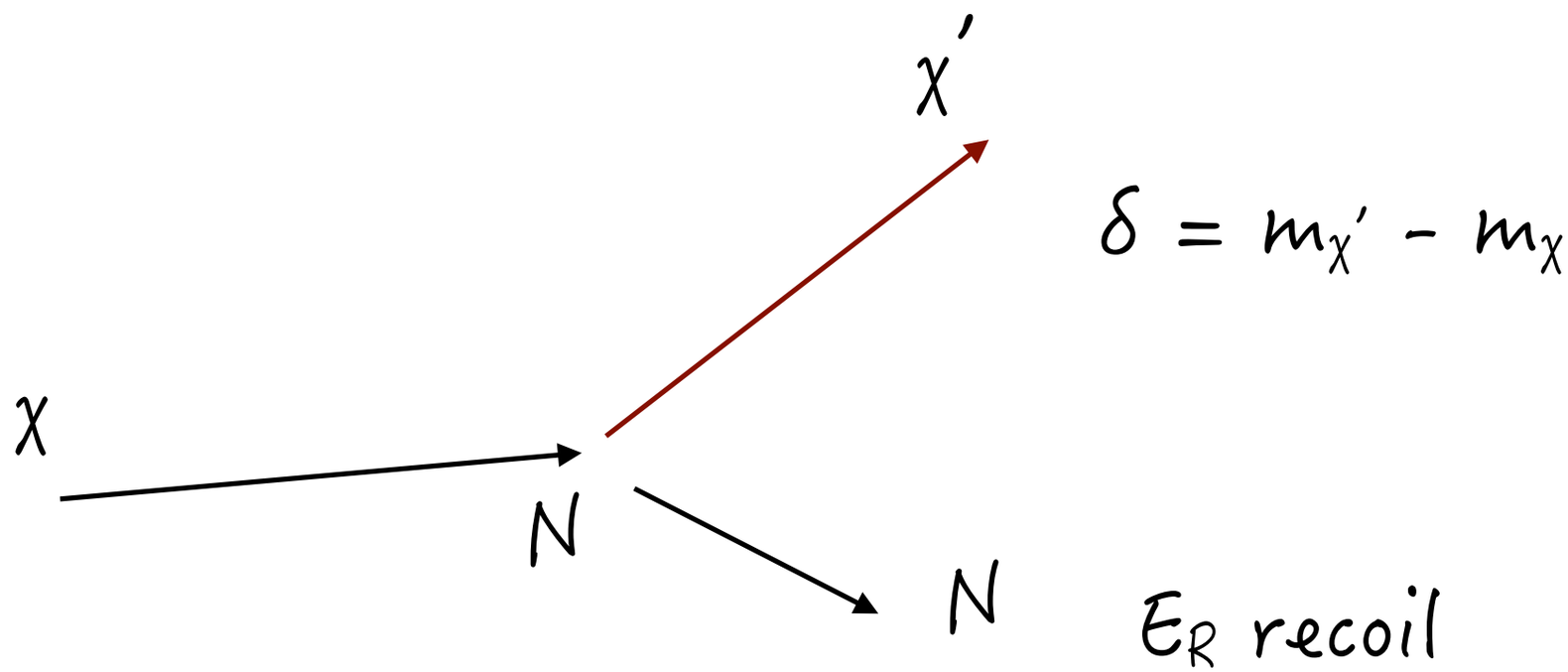
(target-dependent) minimum velocity required to scatter

$$KE_\chi \geq \delta \left(1 + \frac{m_\chi}{m_N}\right)$$

$$\sigma_{inelastic} = \sqrt{1 - \frac{2\,\delta}{\mu_{\chi N}\, v^2}}\,\sigma_{elastic}$$

[L. J. Hall, T. Moroi and H. Murayama '97, Tucker-Smith, Weiner '01]

Inelastic DM



popularized to reconcile DAMA with CDMS (2001-)

required $\delta \sim 100$ keV for $m_\chi \sim 100$ GeV

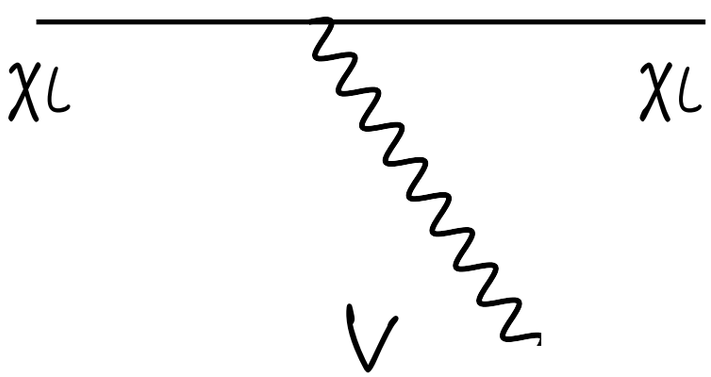
forgetting DAMA, range of m_χ, δ is wide open

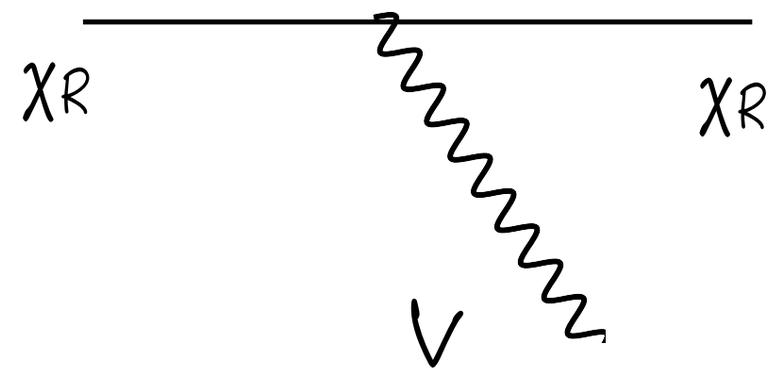
for canonical DM velocity distribution, available KE $\lesssim$ 650 keV

How to make an inelastic DM model

1.) Dirac fermion + some interaction that we can connect to SM

$$\mathcal{L} \supset V_\mu(\chi_L^\dagger \bar{\sigma}^\mu \chi_L + \chi_R^\dagger \sigma^\mu \chi_R) + M(\chi_R^\dagger \chi_L + h.c.)$$



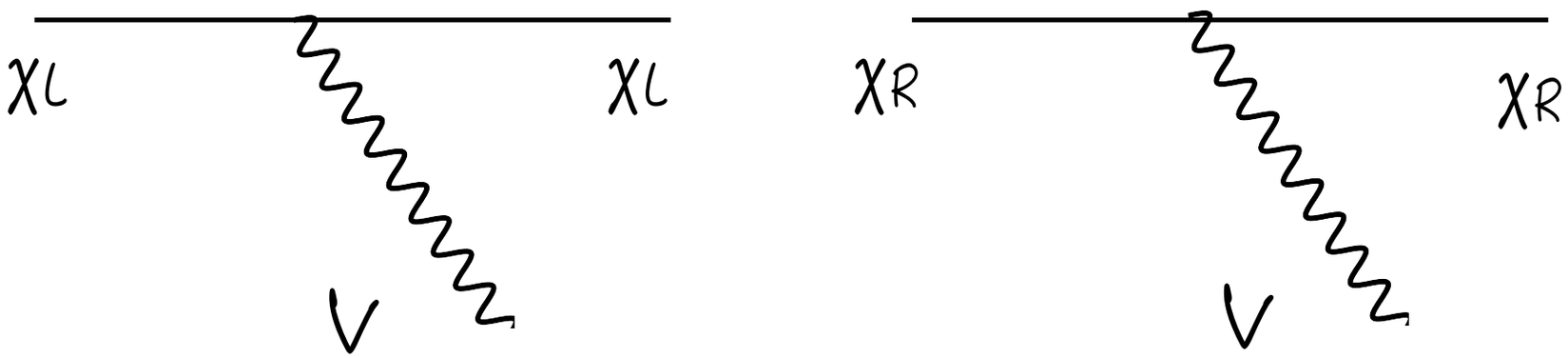


How to make an inelastic DM model

1.) Dirac fermion + some interaction that we can connect to SM

$$\mathcal{L} \supset V_\mu(\chi_L^\dagger \bar{\sigma}^\mu \chi_L + \chi_R^\dagger \sigma^\mu \chi_R) + M(\chi_R^\dagger \chi_L + h.c.)$$

$$\delta m(\chi_L \chi_L + h.c.)$$



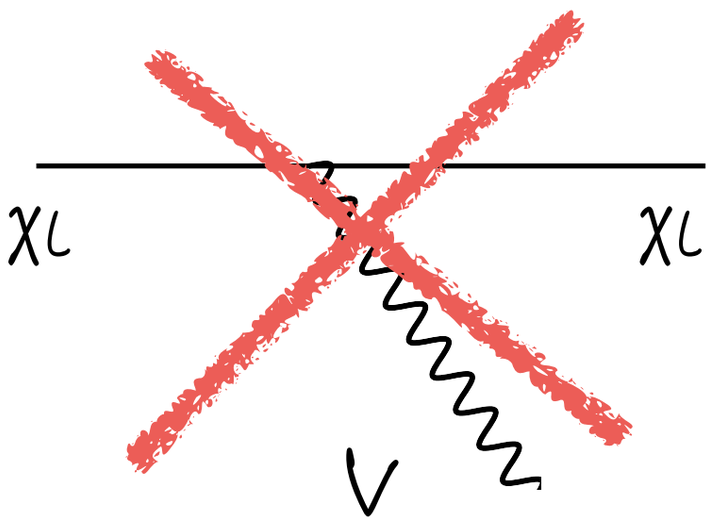
2.) add small Majorana mass, diagonalize: mass eigenstates χ, χ'

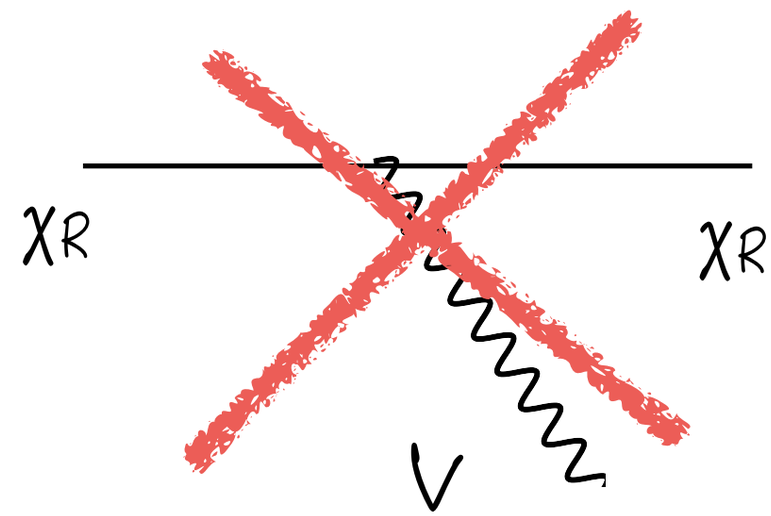
How to make an inelastic DM model

1.) Dirac fermion + some interaction that we can connect to SM

$$\mathcal{L} \supset V_\mu(\chi_L^\dagger \bar{\sigma}^\mu \chi_L + \chi_R^\dagger \sigma^\mu \chi_R) + M(\chi_R^\dagger \chi_L + h.c.)$$

$$\delta m(\chi_L \chi_L + h.c.)$$





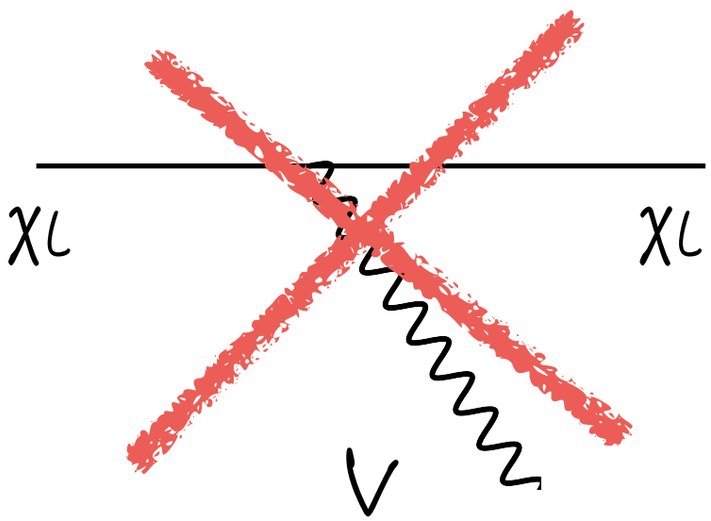
2.) add small Majorana mass, diagonalize: mass eigenstates χ, χ'

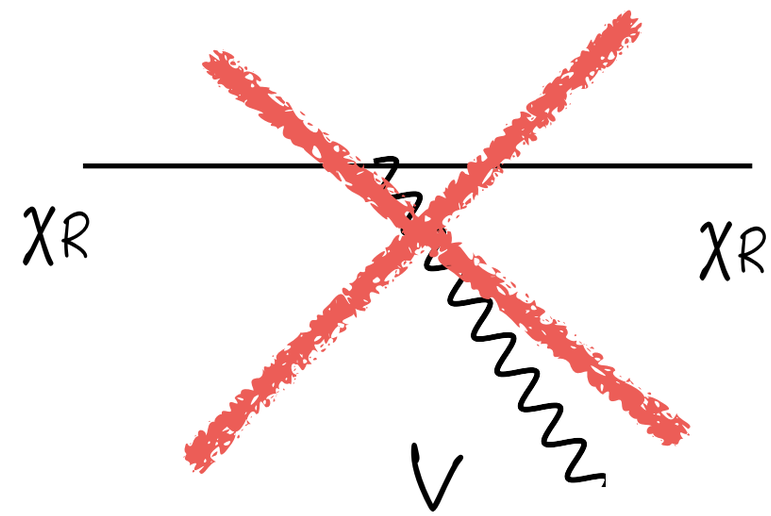
How to make an inelastic DM model

1.) Dirac fermion + some interaction that we can connect to SM

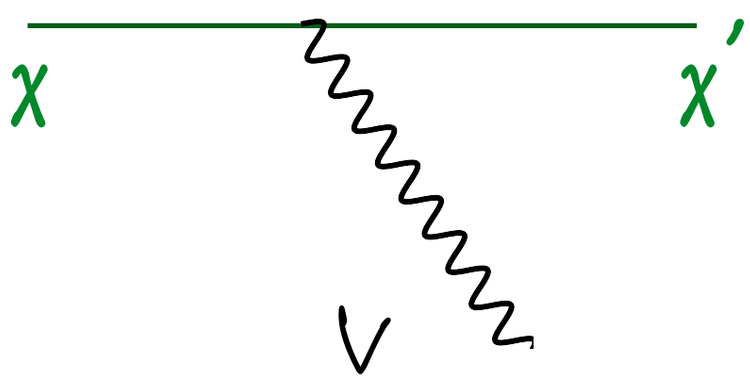
$$\mathcal{L} \supset V_\mu(\chi_L^\dagger \bar{\sigma}^\mu \chi_L + \chi_R^\dagger \sigma^\mu \chi_R) + M(\chi_R^\dagger \chi_L + h.c.)$$

$$\delta m(\chi_L \chi_L + h.c.)$$





2.) add small Majorana mass, diagonalize: mass eigenstates χ, χ'



inelastic vertex only

$$m_{\chi'} - m_\chi \sim \delta m$$

How to make an inelastic DM model

1.) Dirac fermion + some interaction that we can connect to SM

$$\mathcal{L} \supset V_\mu(\chi_L^\dagger \bar{\sigma}^\mu \chi_L + \chi_R^\dagger \sigma^\mu \chi_R) + M(\chi_R^\dagger \chi_L + h.c.)$$

Canonical example: MSSM higgsinos when μ ≪ M_1, M_2

connects to SM via Z boson

2.) ac

How to make an inelastic DM model

1.) Dirac fermion + some interaction that we can connect to SM

$$\mathcal{L} \supset V_\mu(\chi_L^\dagger \bar{\sigma}^\mu \chi_L + \chi_R^\dagger \sigma^\mu \chi_R) + M(\chi_R^\dagger \chi_L + h.c.)$$

Canonical example: MSSM higgsinos when μ ≪ M_1, M_2

connects to SM via Z boson

Many other examples, both for fermion and scalar DM

[C. Arina and N. Fornengo '07]

[Batell, Pospelov, Ritz '09]

[Y. Cui, D. E. Morrissey, D. Poland and L. Randall '09]

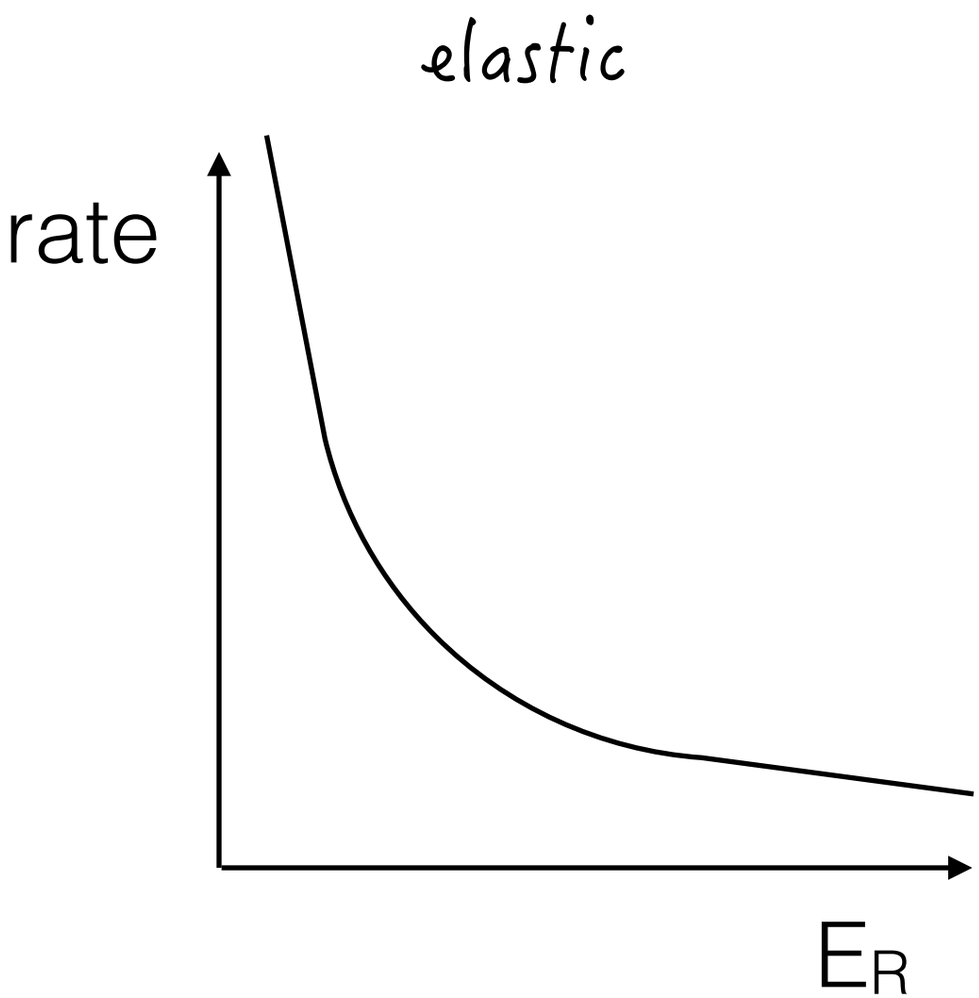
[H. An, P. S. B. Dev, Y. Cai and R. N. Mohapatra '10]

[K. R. Dienes, J. Kumar, B. Thomas and D. Yaylali '14] ....

2.) ac

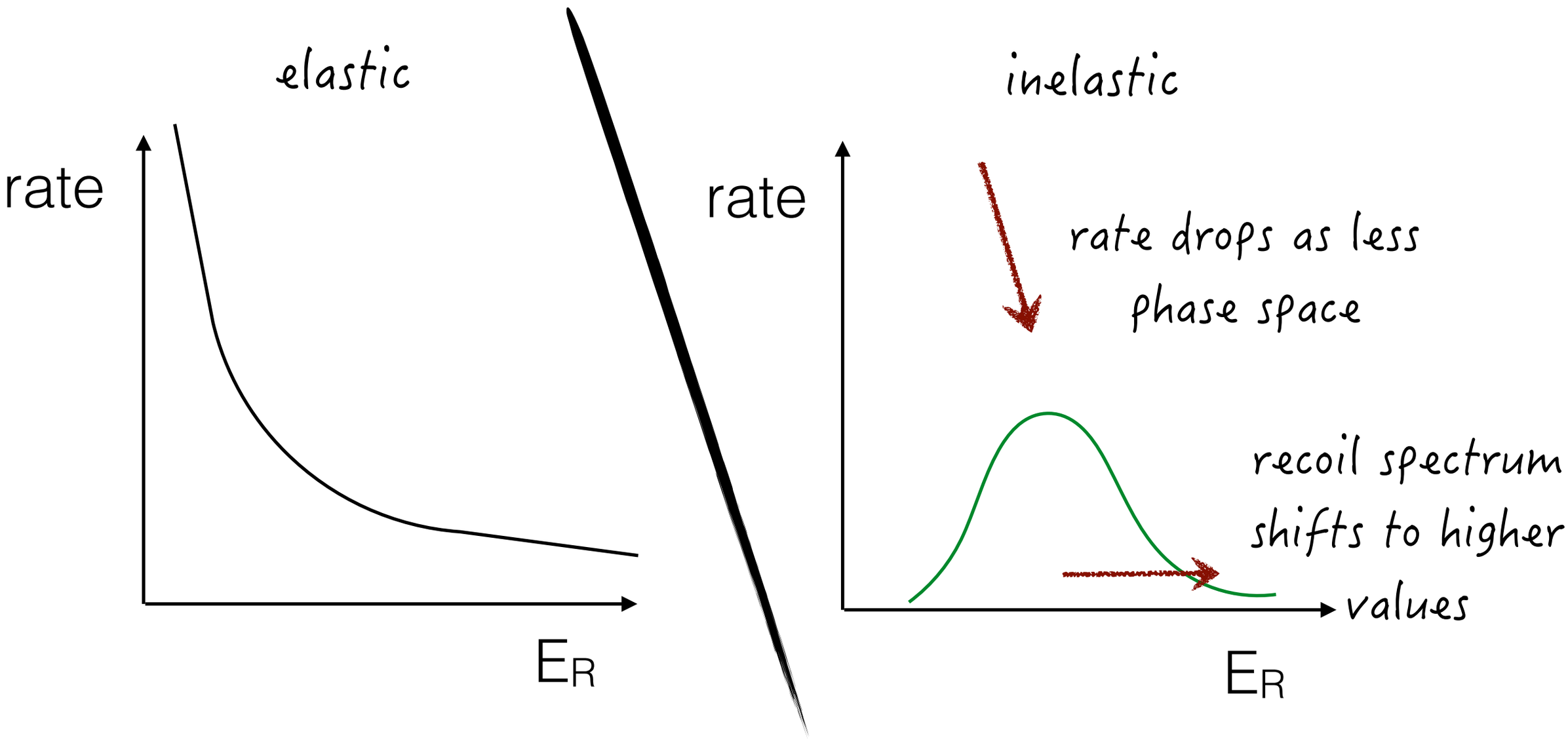
Direct Detection at High Recoil : Inelastic Kinematics

inelasticity changes nuclear recoil energy spectrum



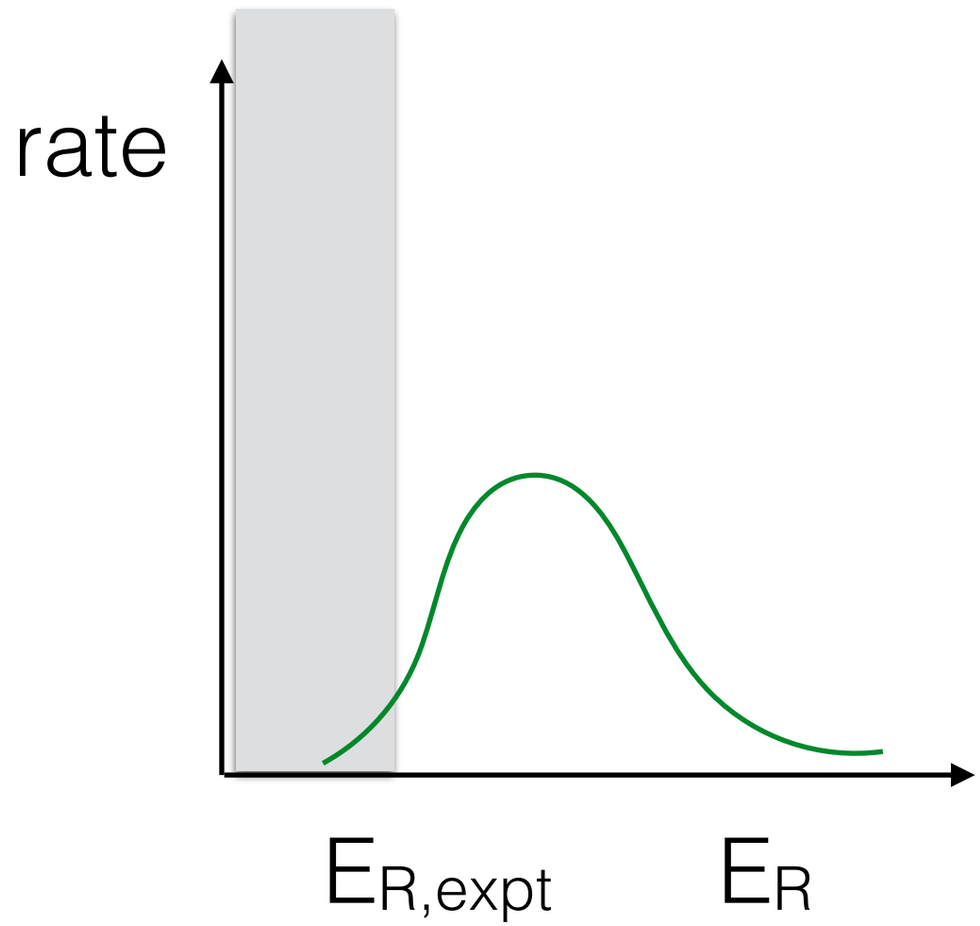
Direct Detection at High Recoil : Inelastic Kinematics

inelasticity changes nuclear recoil energy spectrum



Direct Detection at High Recoil: Inelastic Kinematics

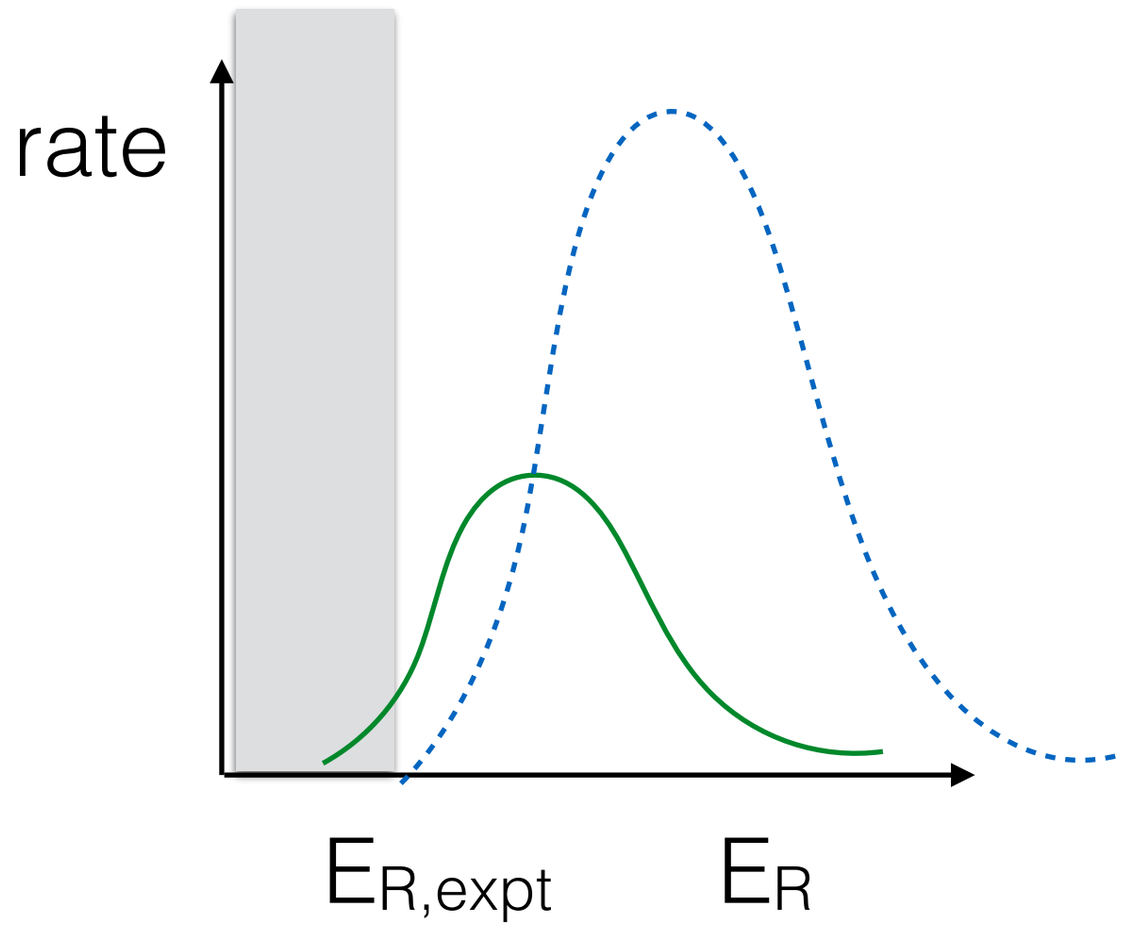
Experimental **signal windows** focused on low E_R



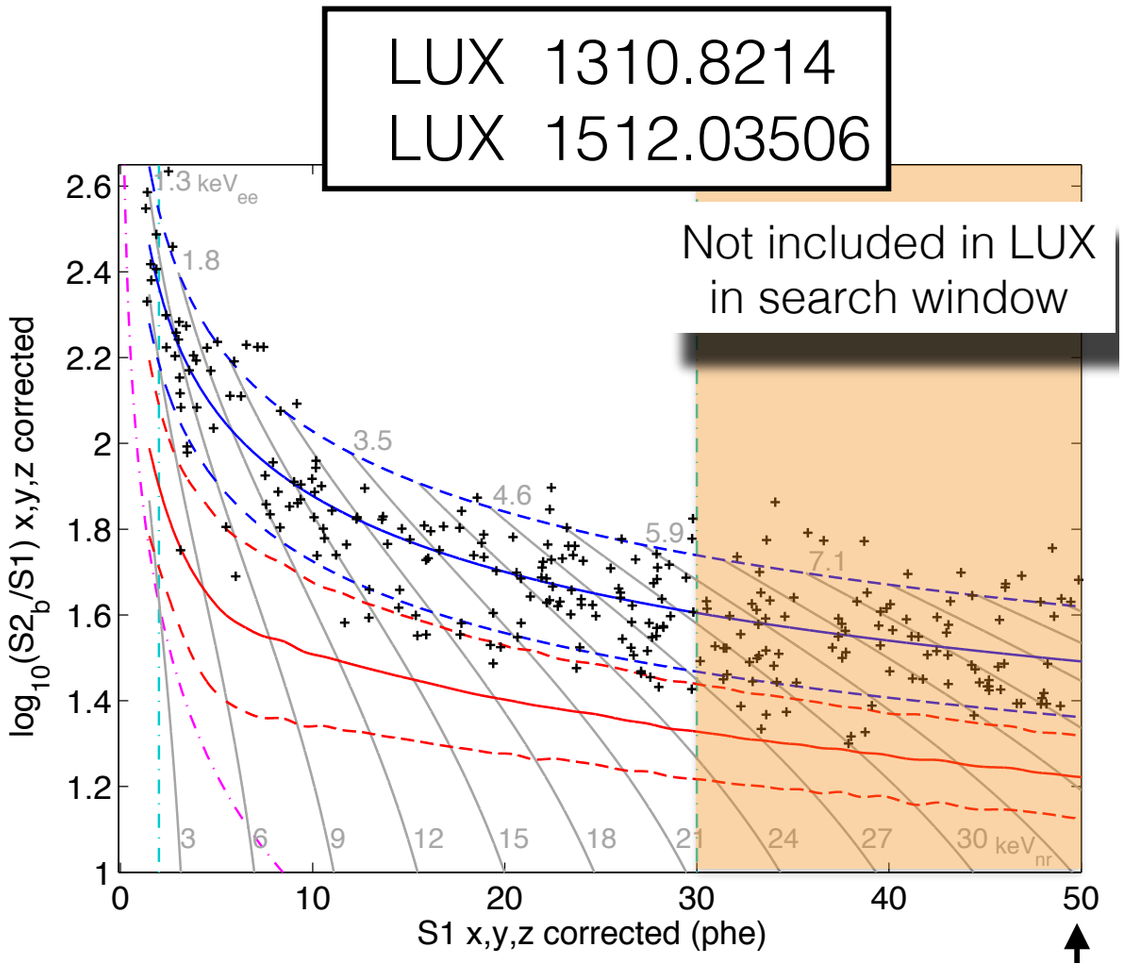
as a result, blind to sufficiently inelastic DM,
even if $\sigma_{\chi N}$ is large

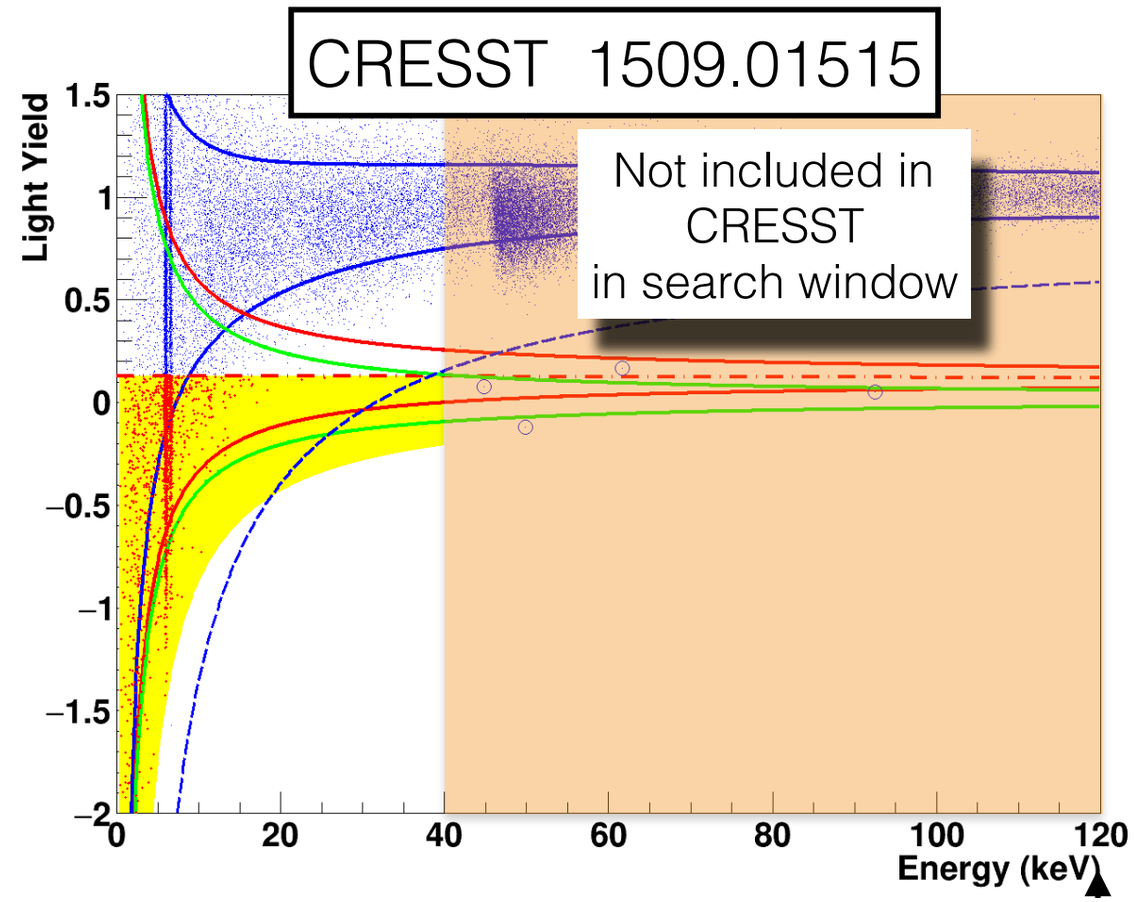
Direct Detection at High Recoil: Inelastic Kinematics

Experimental **signal windows** focused on low E_R



as a result, blind to sufficiently inelastic DM,
even if $\sigma_{\chi N}$ is large

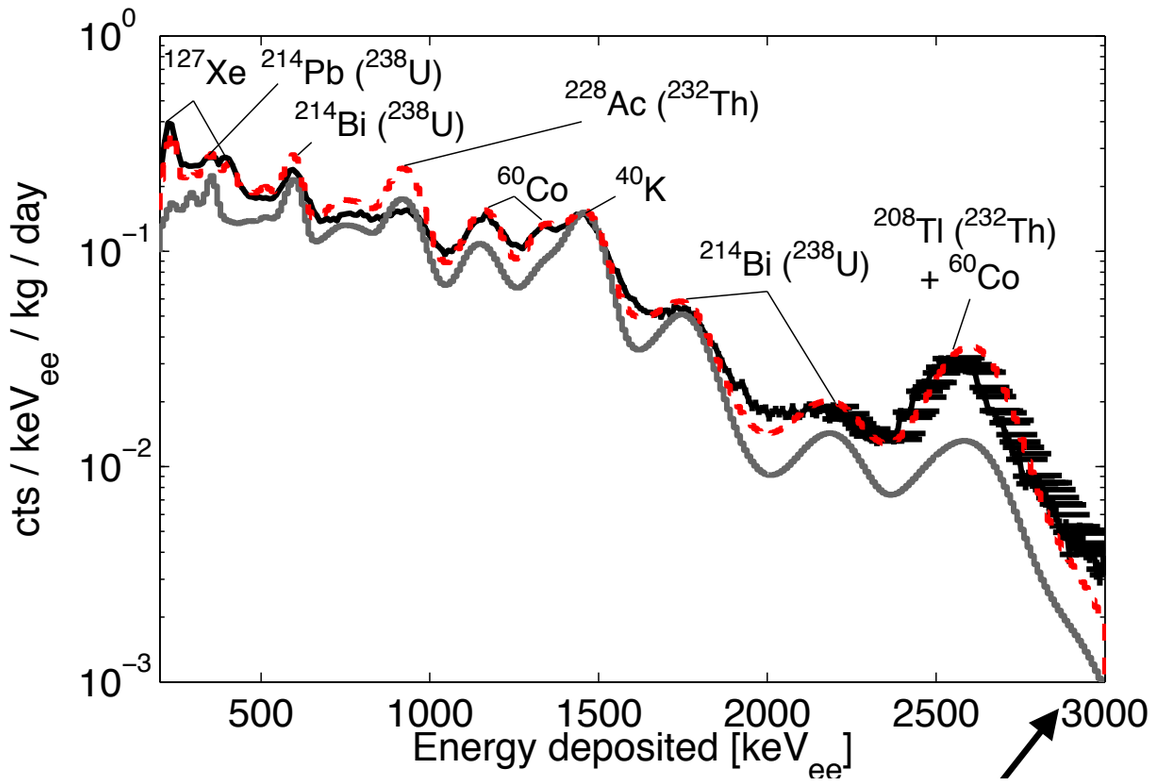




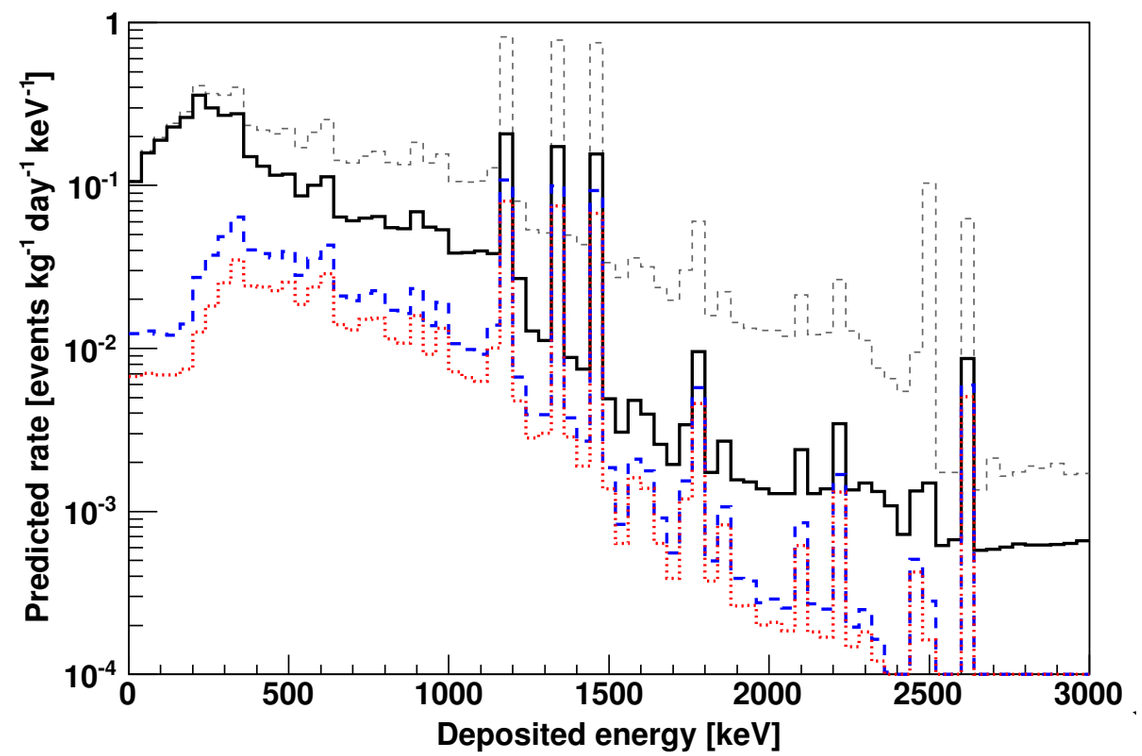
focus of current runs on low E_R

BUT: experiments are sensitive to high recoil events

ex. LUX 1403.1299

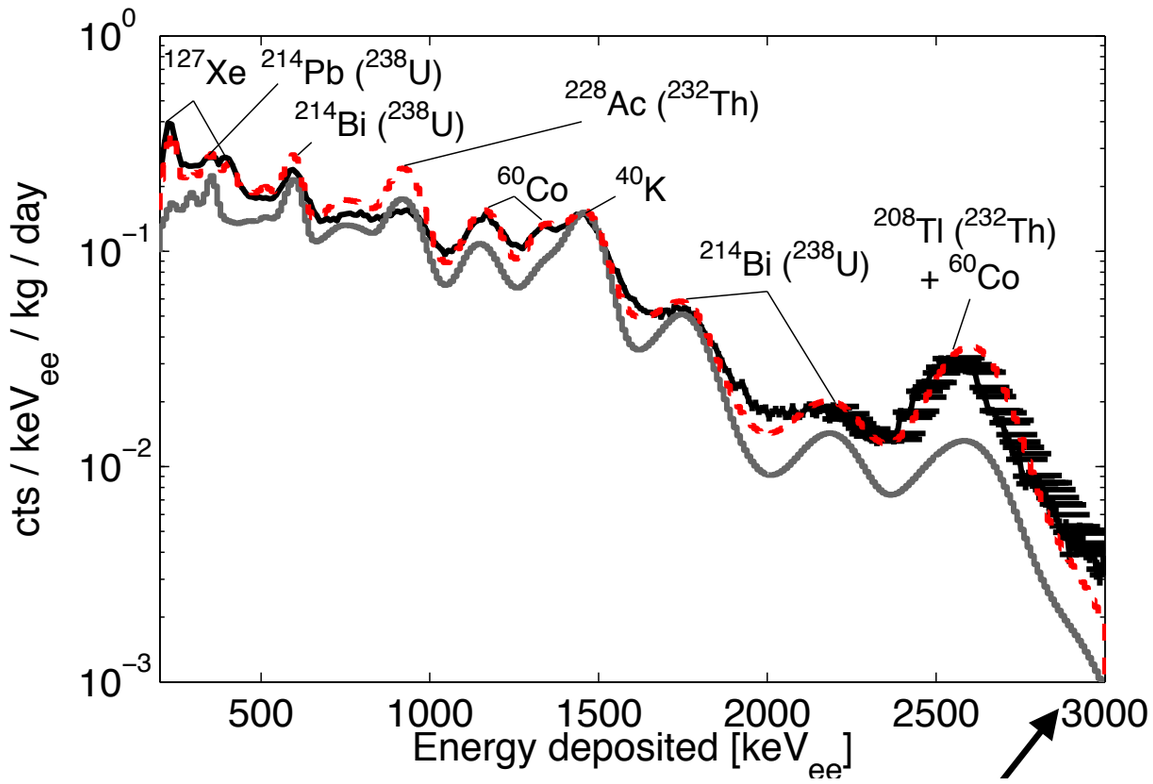


Xenon100 1101.3866

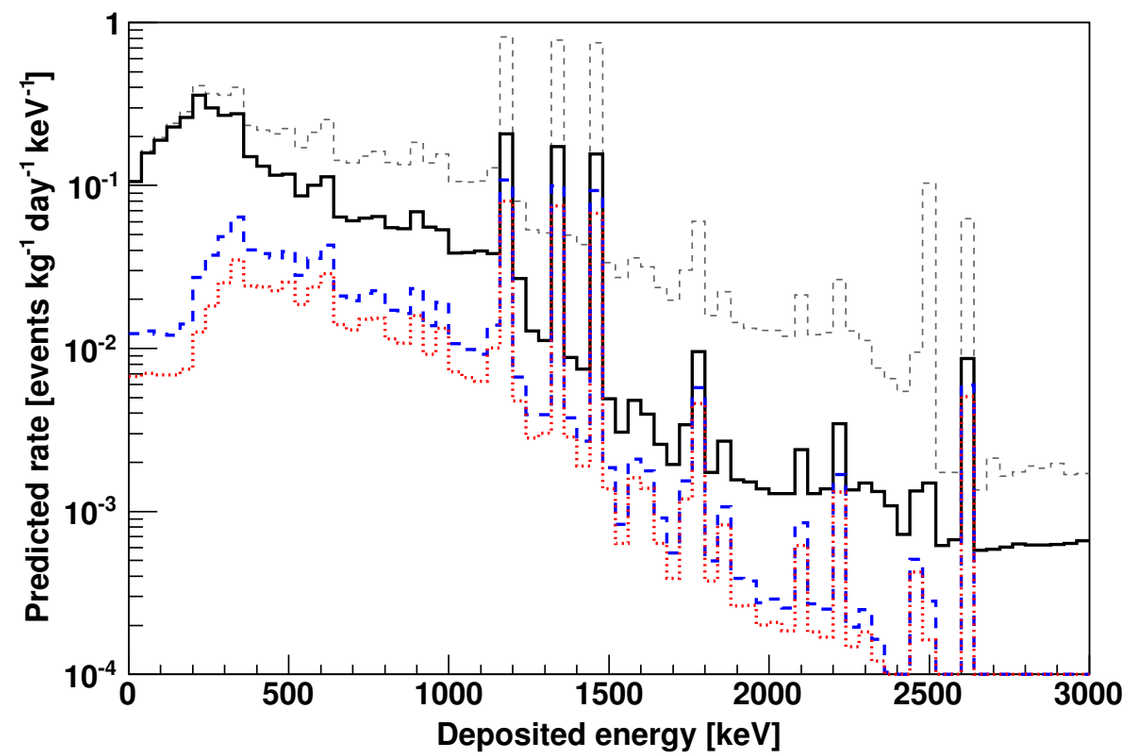


BUT: experiments are sensitive to high recoil events

ex. LUX 1403.1299



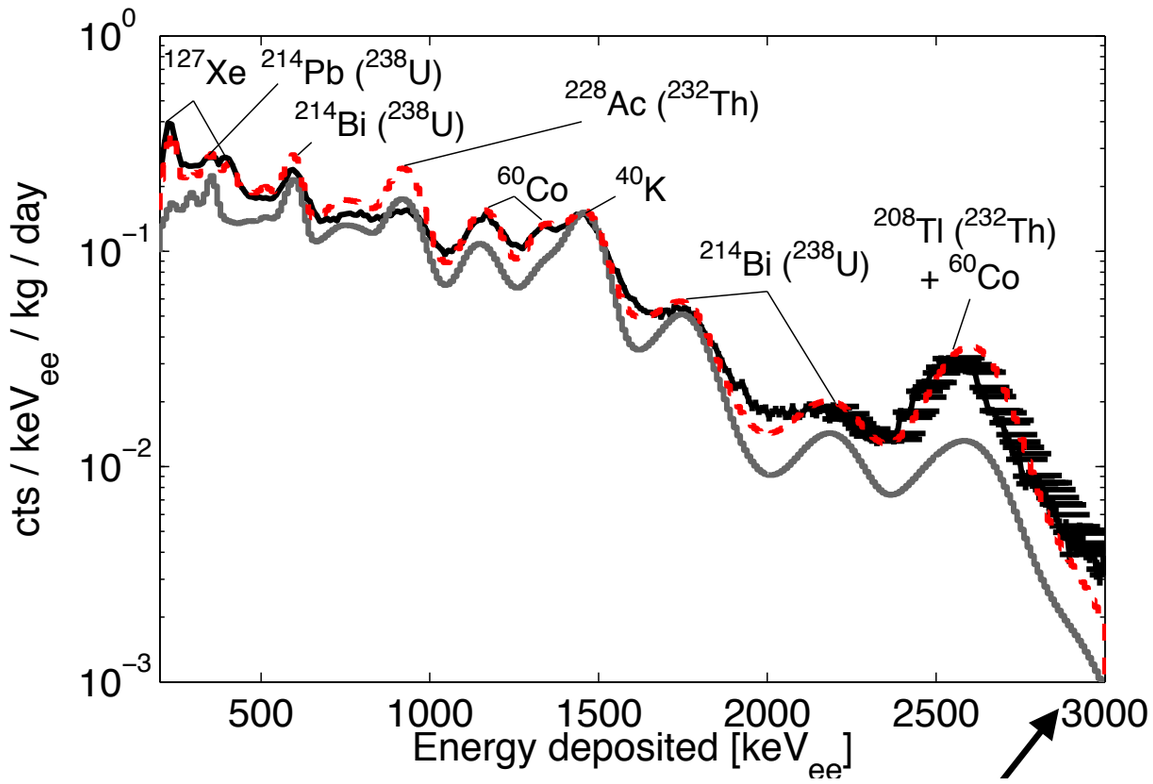
Xenon100 1101.3866



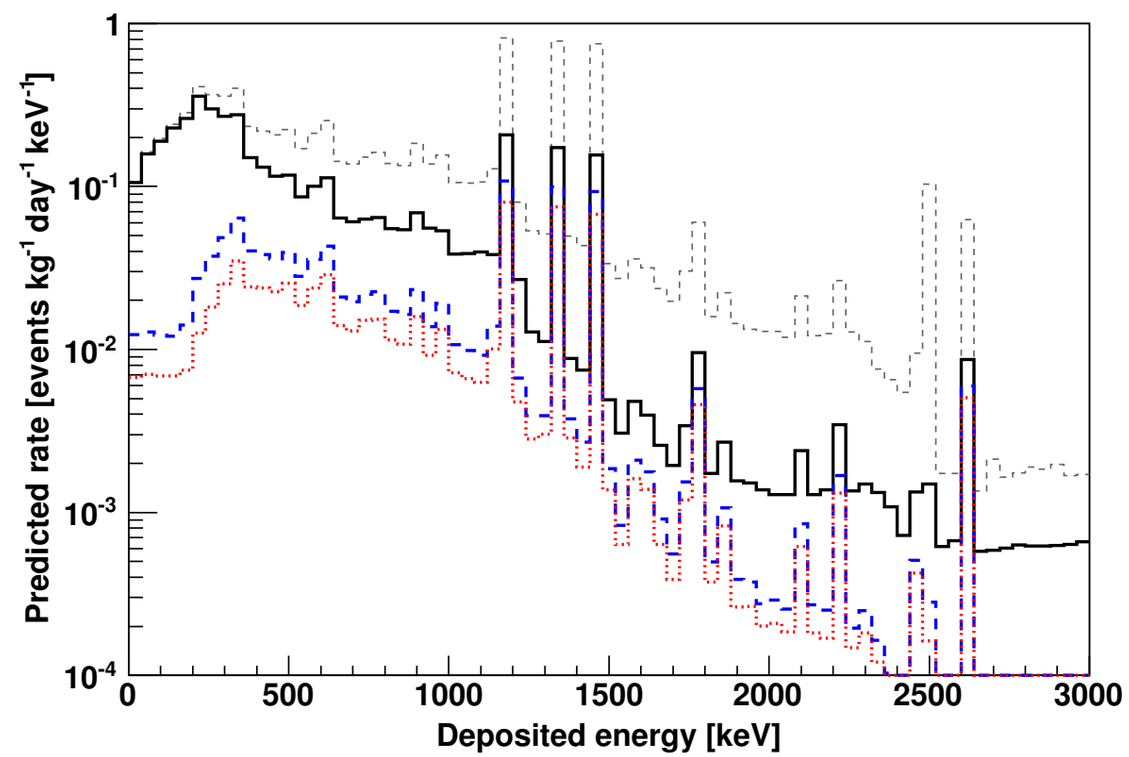
present: inelastic DM could be lurking in high nuclear recoil data of existing experiments: go and look!

BUT: experiments are sensitive to high recoil events

ex. LUX 1403.1299



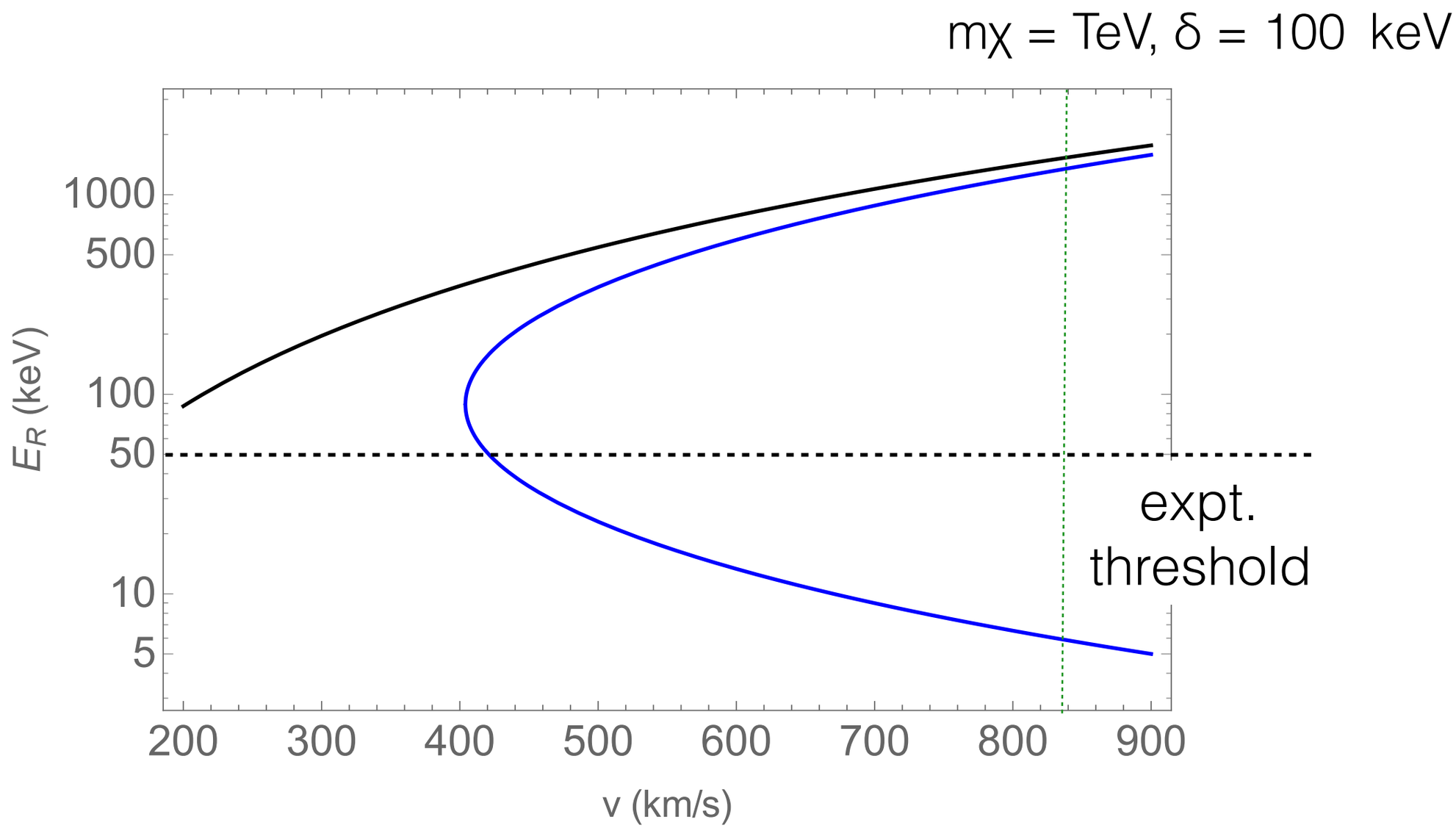
Xenon100 1101.3866



present: inelastic DM could be lurking in high nuclear recoil data of existing experiments: go and look!

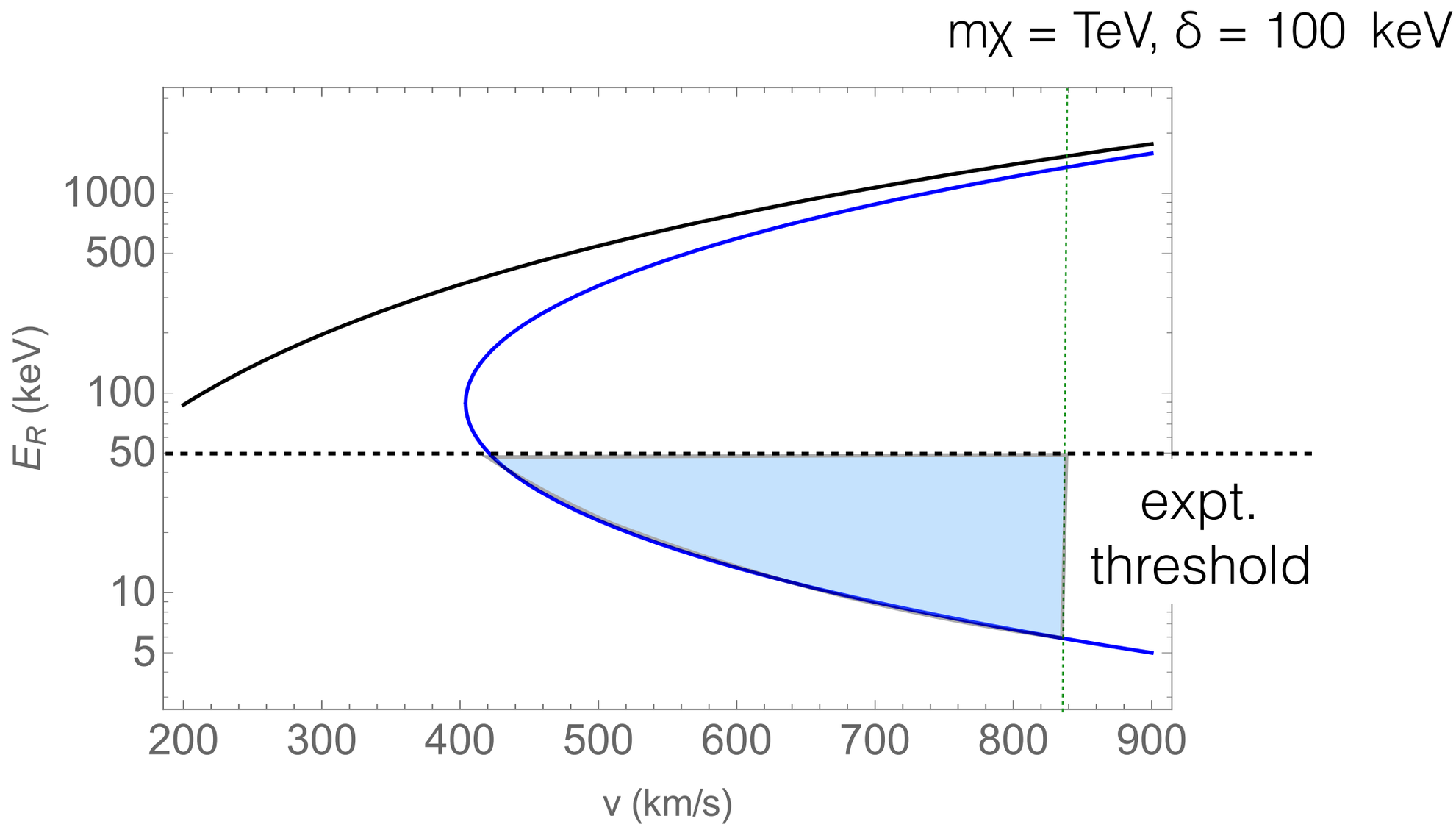
future: don't limit searches to low-recoil

Direct Detection at High Recoil: Inelastic Kinematics



total rate combines energy range, DM velocity spectrum and nuclear form factors

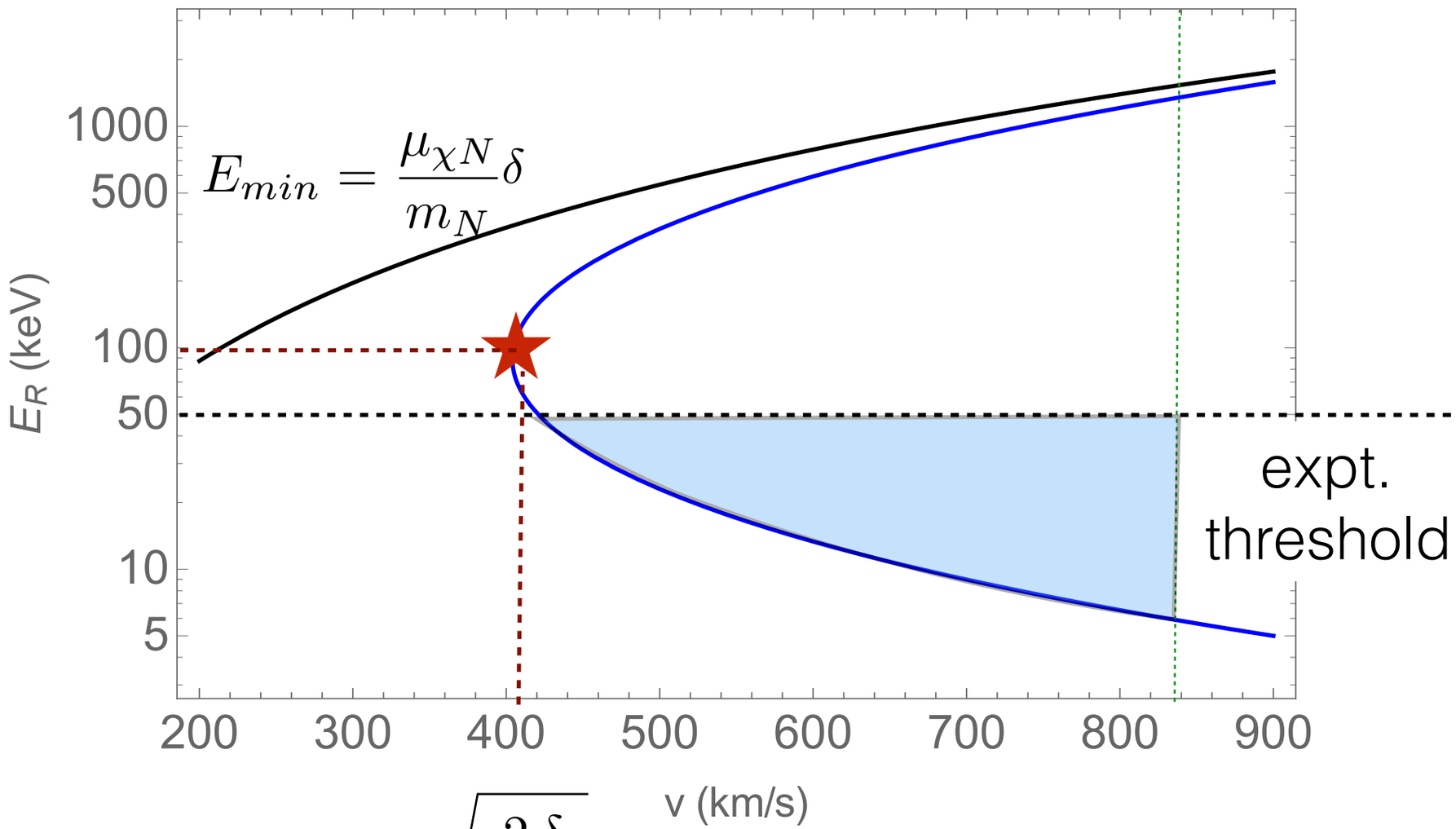
Direct Detection at High Recoil: Inelastic Kinematics



total rate combines energy range, DM velocity spectrum and nuclear form factors

Direct Detection at High Recoil: Inelastic Kinematics

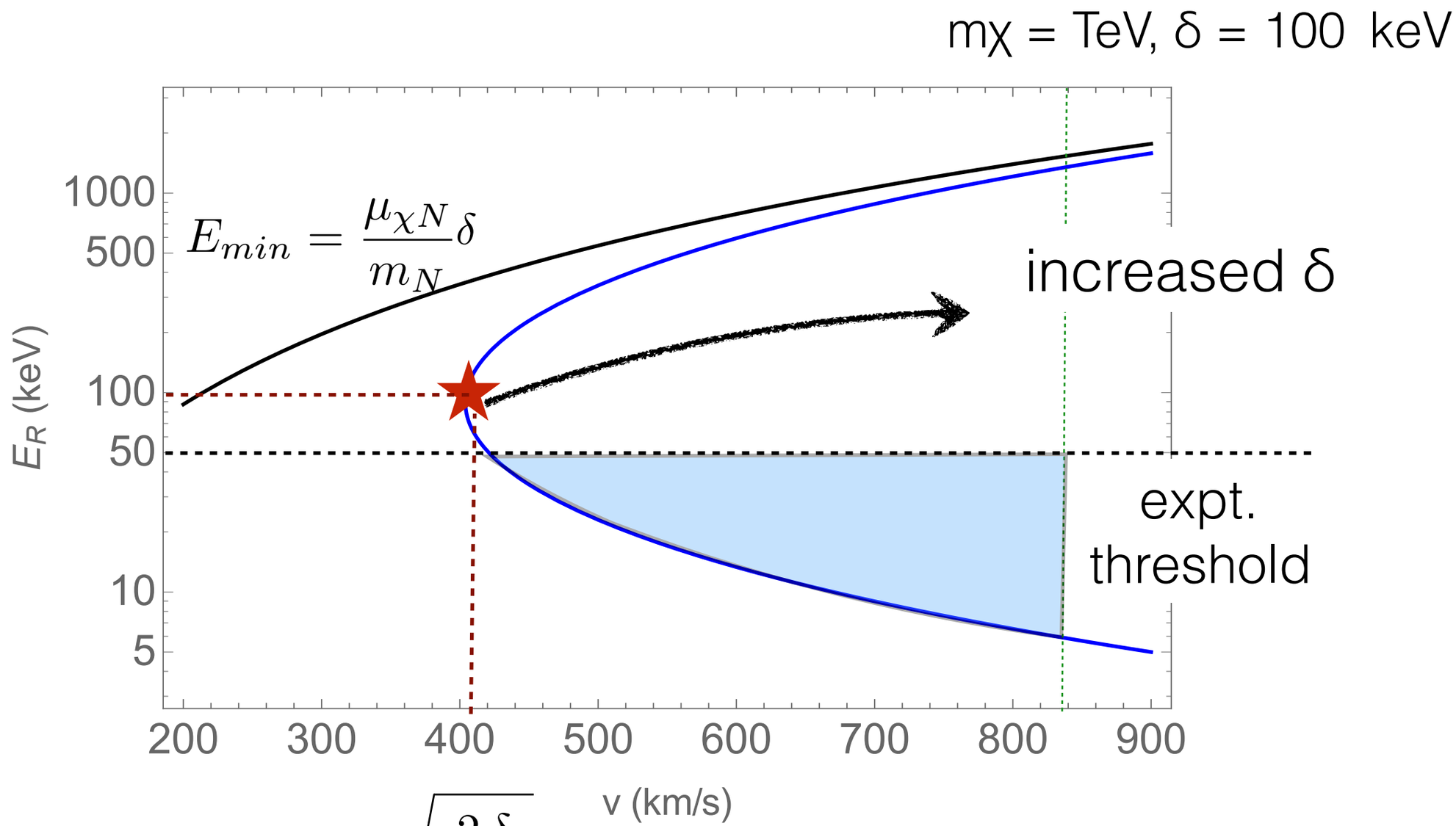
m_χ = TeV, δ = 100 keV



$$v_{min} = \sqrt{\frac{2\,\delta}{\mu_{\chi N}}}$$

total rate combines energy range, DM velocity spectrum and nuclear form factors

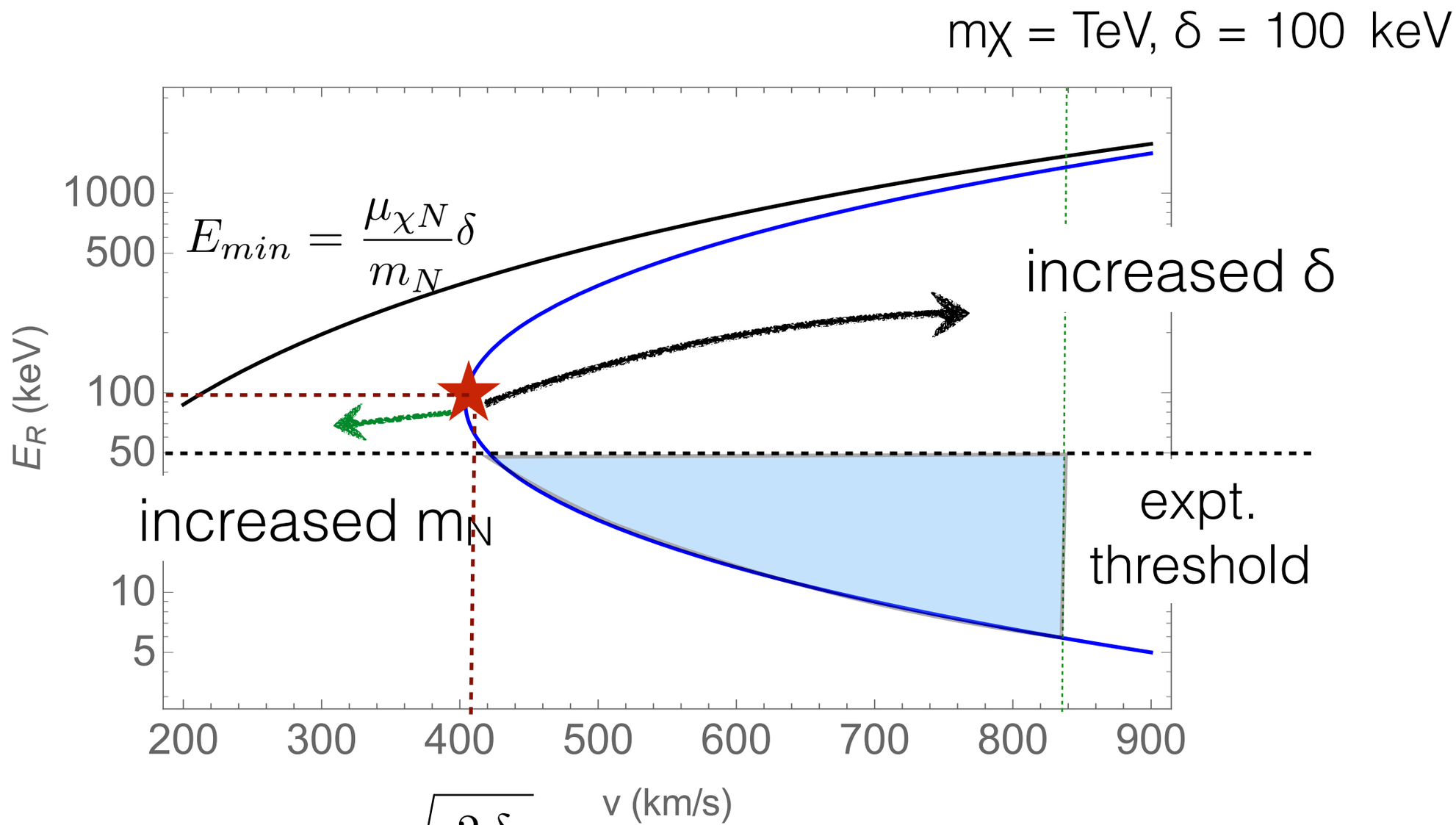
Direct Detection at High Recoil: Inelastic Kinematics



$$v_{min} = \sqrt{\frac{2\,\delta}{\mu_{\chi N}}}$$

total rate combines energy range, DM velocity spectrum and nuclear form factors

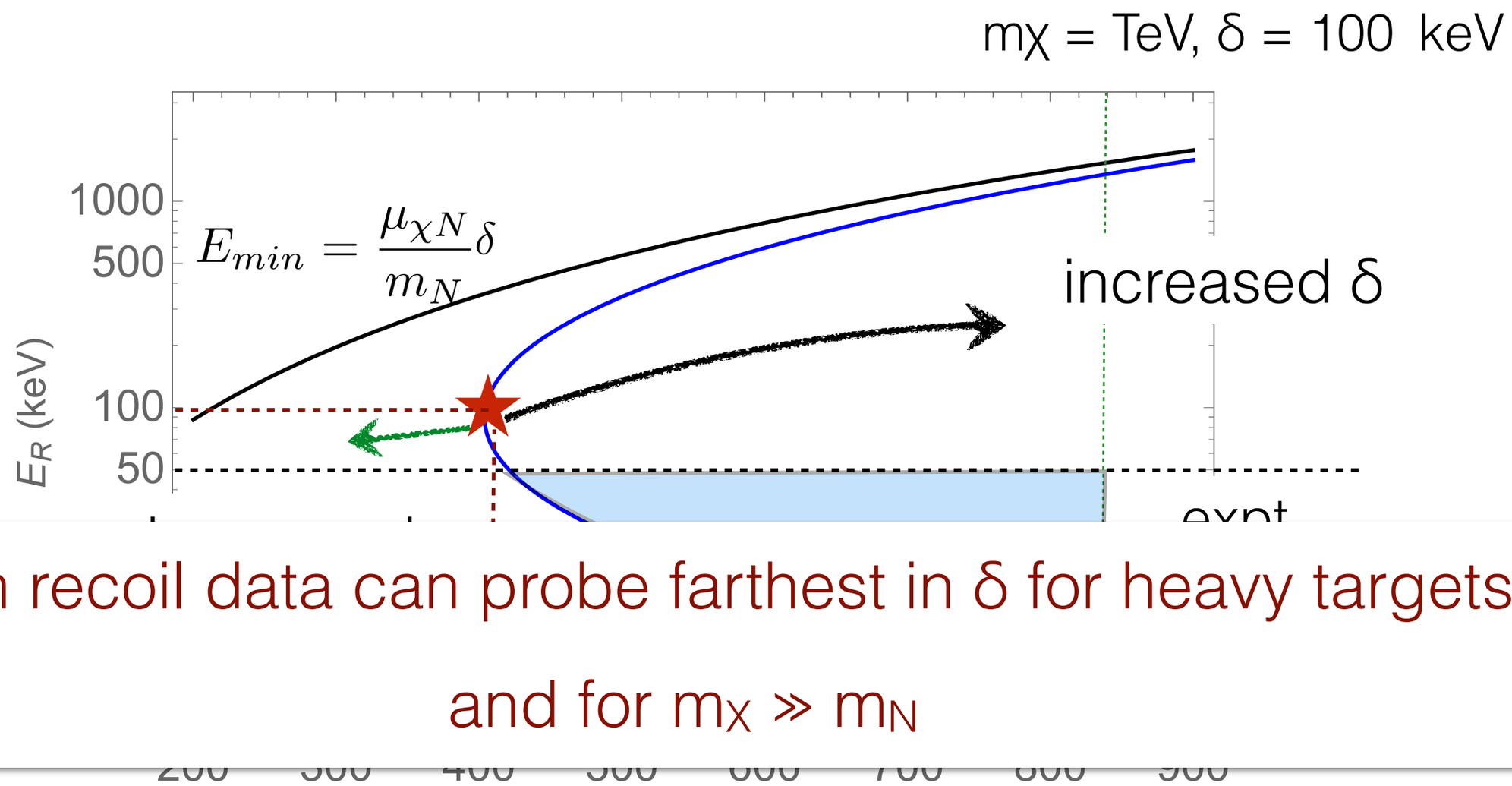
Direct Detection at High Recoil: Inelastic Kinematics



$$v_{min} = \sqrt{\frac{2\,\delta}{\mu_{\chi N}}}$$

total rate combines energy range, DM velocity spectrum and nuclear form factors

Direct Detection at High Recoil: Inelastic Kinematics



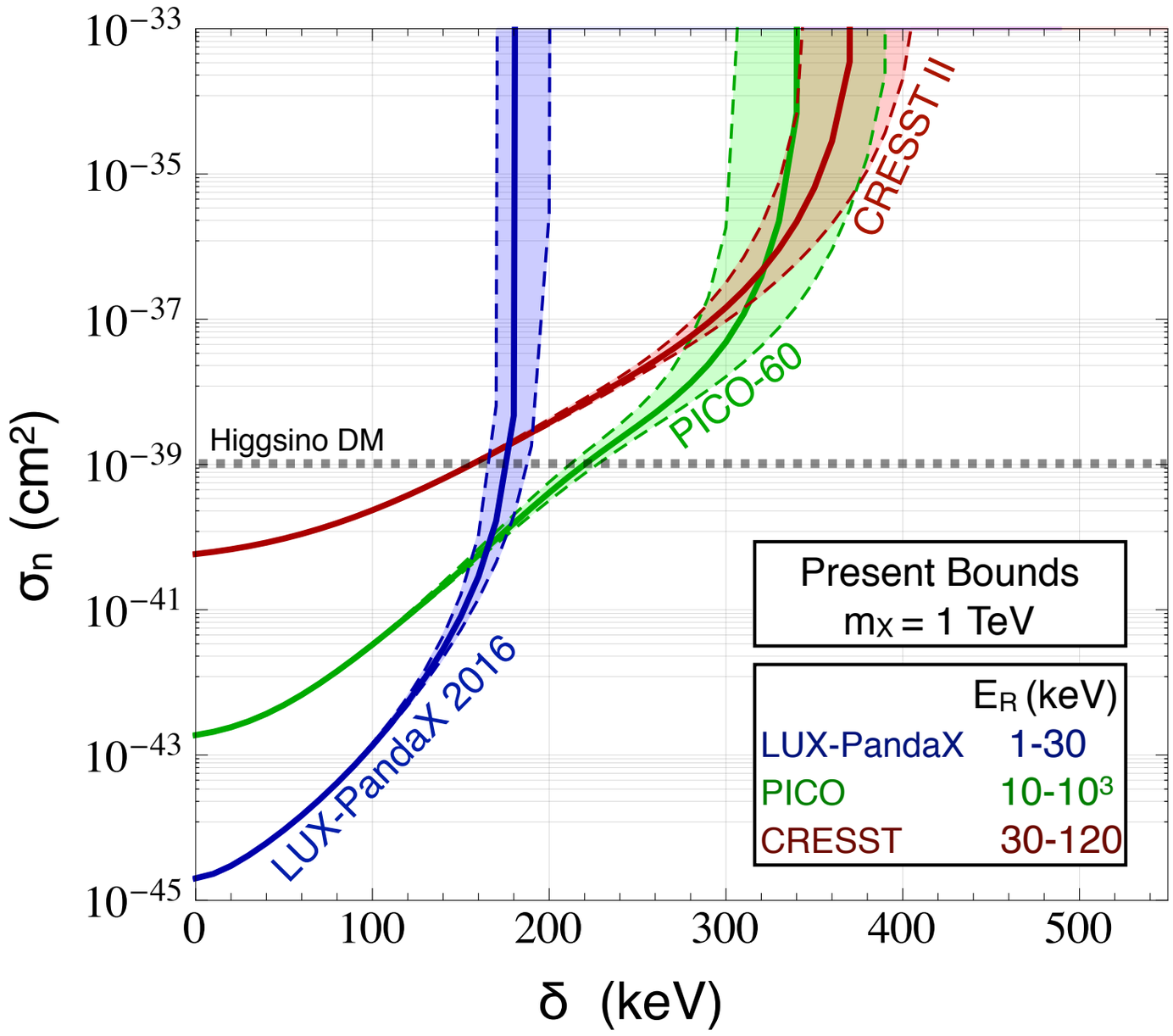
high recoil data can probe farthest in δ for heavy targets

and for $m_\chi \gg m_N$

$$v_{min} = \sqrt{\frac{2\,\delta}{\mu_{\chi N}}}$$

total rate combines energy range, DM velocity spectrum and nuclear form factors

bounds with current data, m_X = 1 TeV

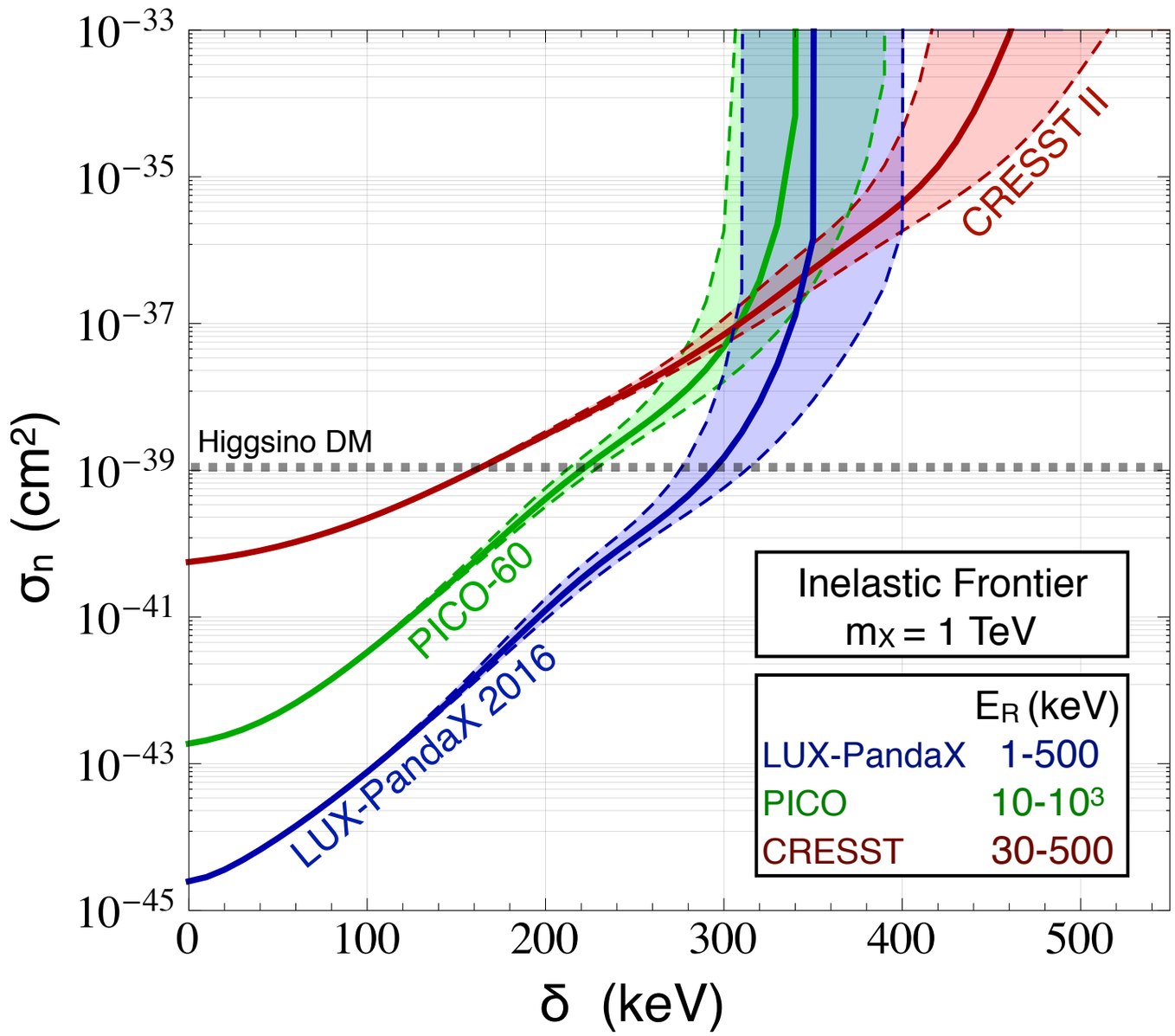


assuming spin-independent cross section, no v dependence

exposure (tonne-day)

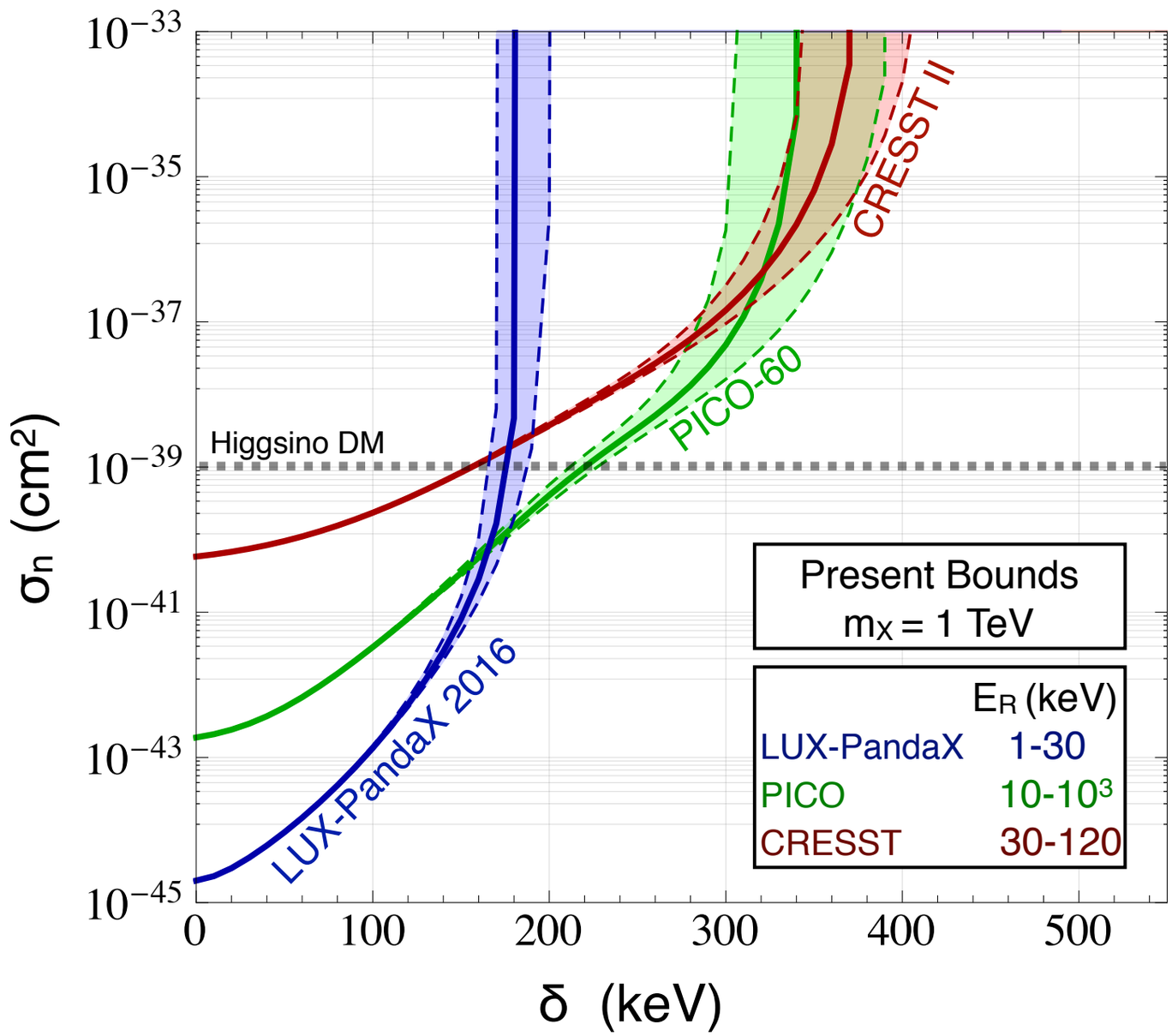
LUX: 1.4, PICO: 1.3, CRESST: 0.05

projected bounds including high recoil, current exposure: m_X = 1 TeV



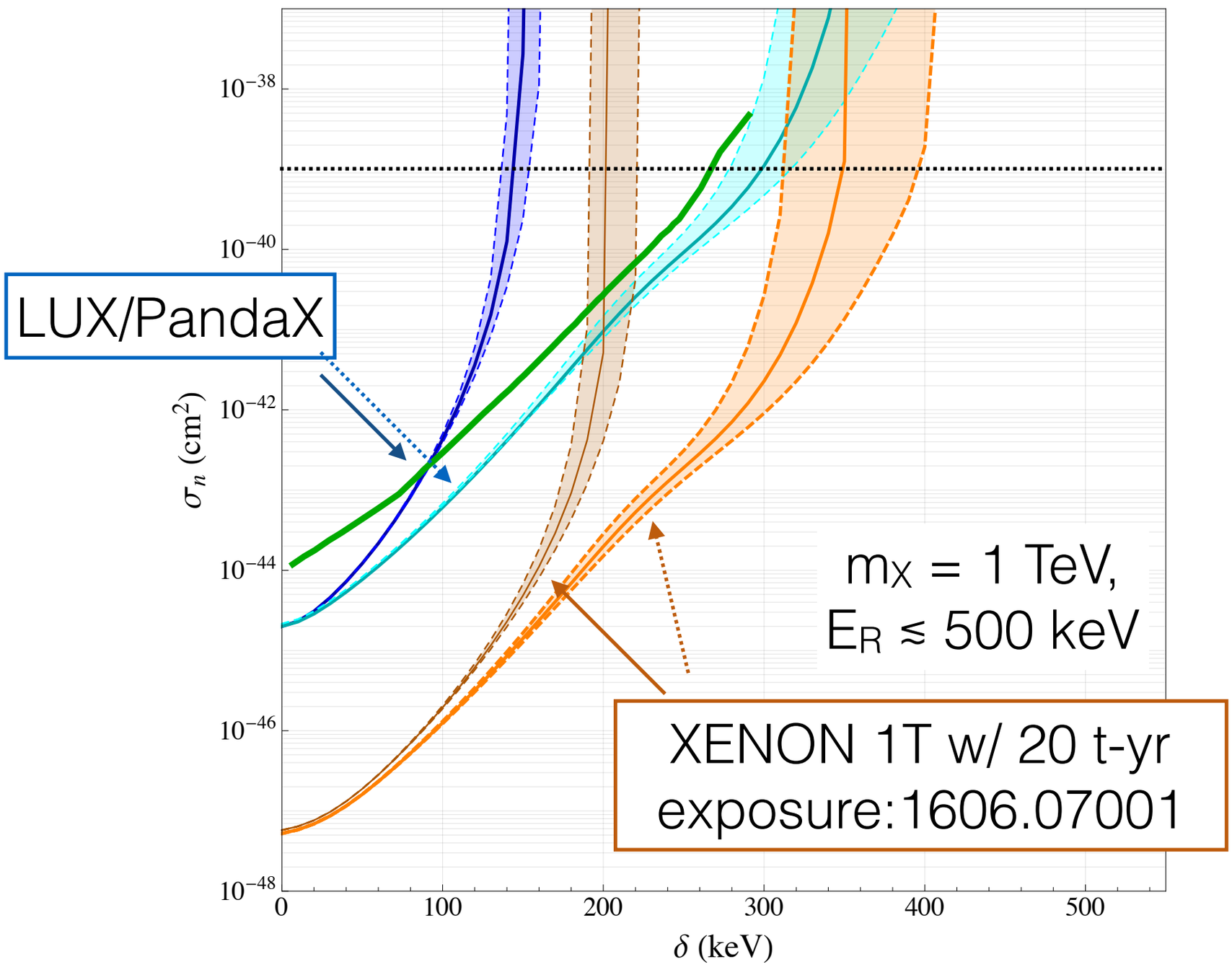
including data up to **500 keV**
(assuming no new observed events)

projected bounds including high recoil, current exposure: m_X = 1 TeV

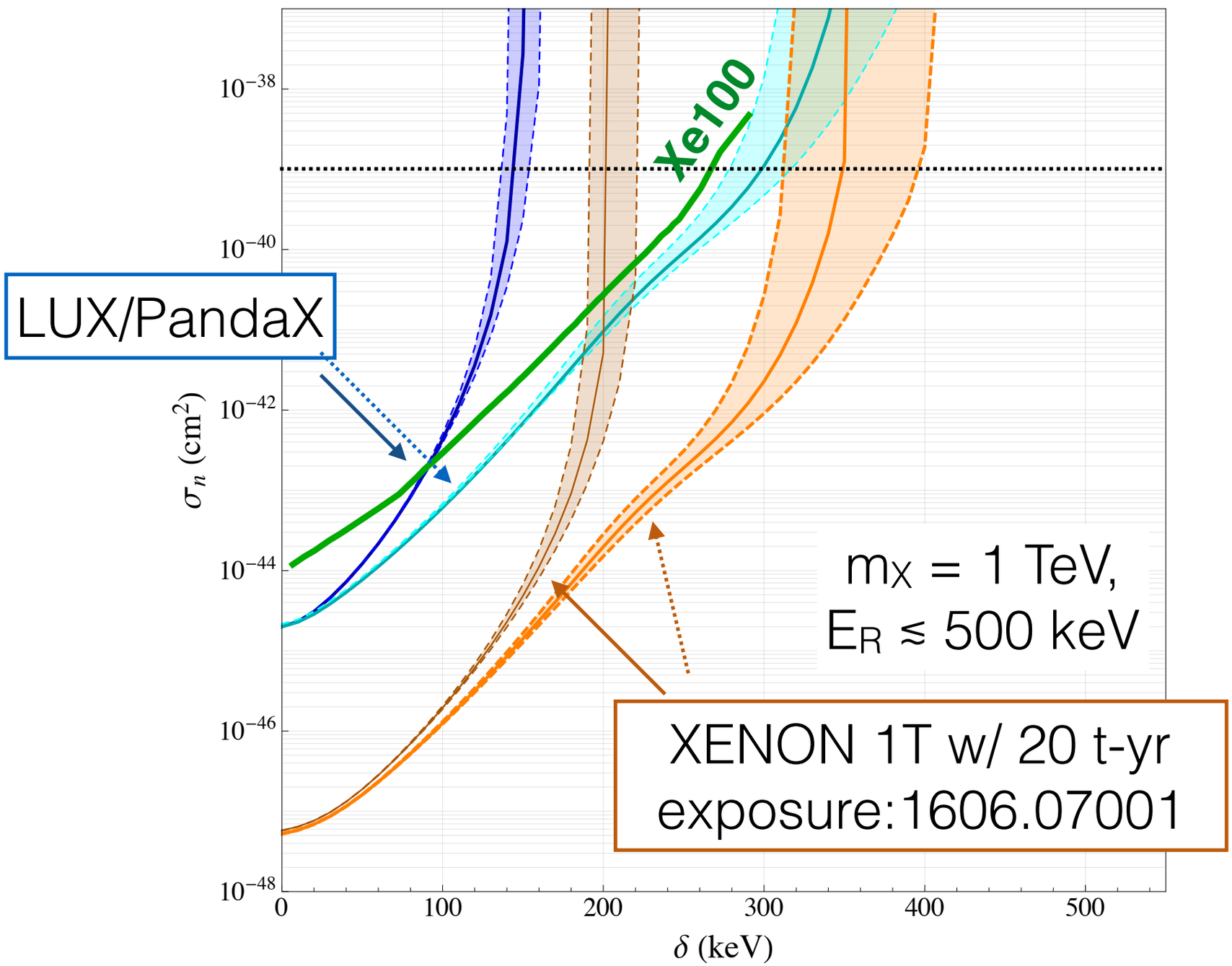


including data up to **500 keV**
(assuming no new observed events)

Projections for future experiments, recent results from Xe100



Projections for future experiments, recent results from Xe100

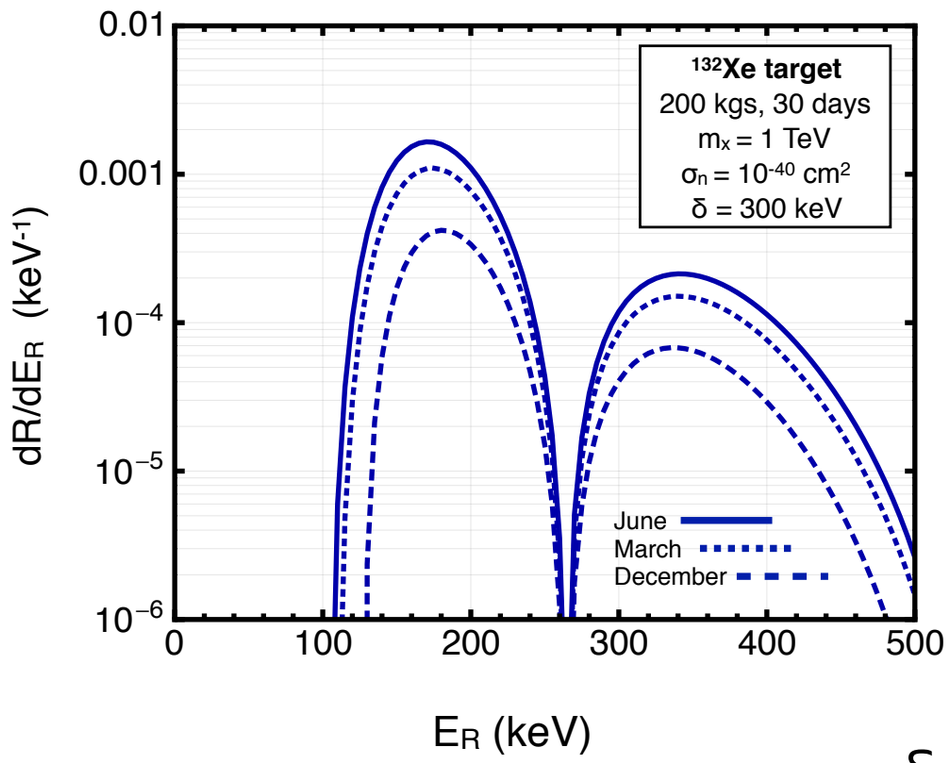


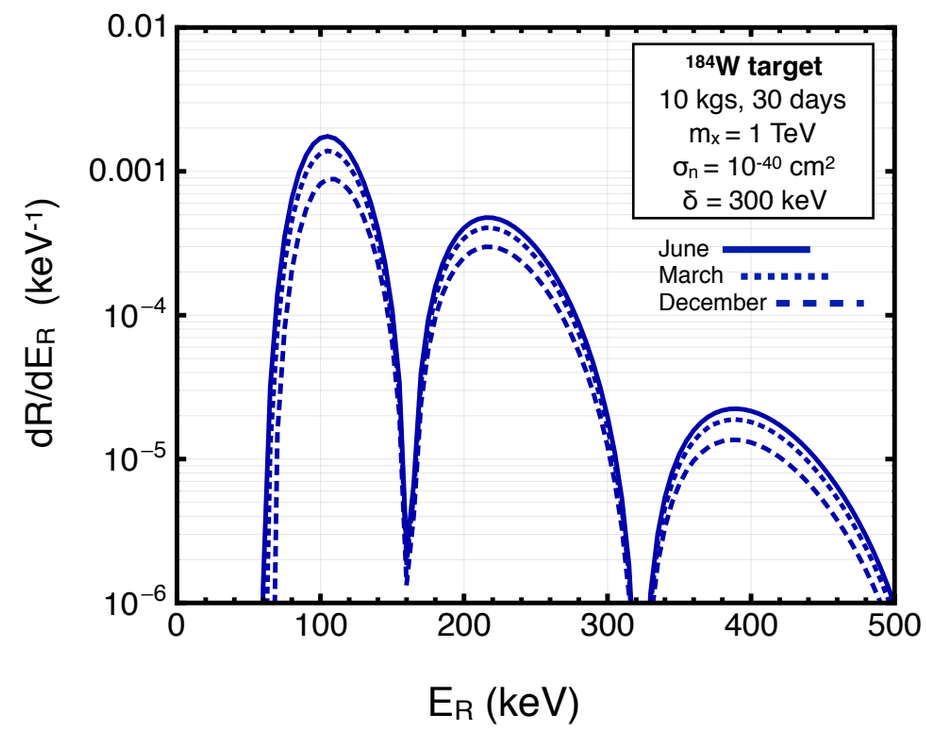
Xe100: 1705.02614

considered recoil energies out to 240 keVnr

limit on 'weak strength' DM pushed out to $\delta \gtrsim 260$ keV

Modulation





ex: δ = 300 keV

velocity sensitivity → large modulation effects

could be used to improve S/B and help pin down δ

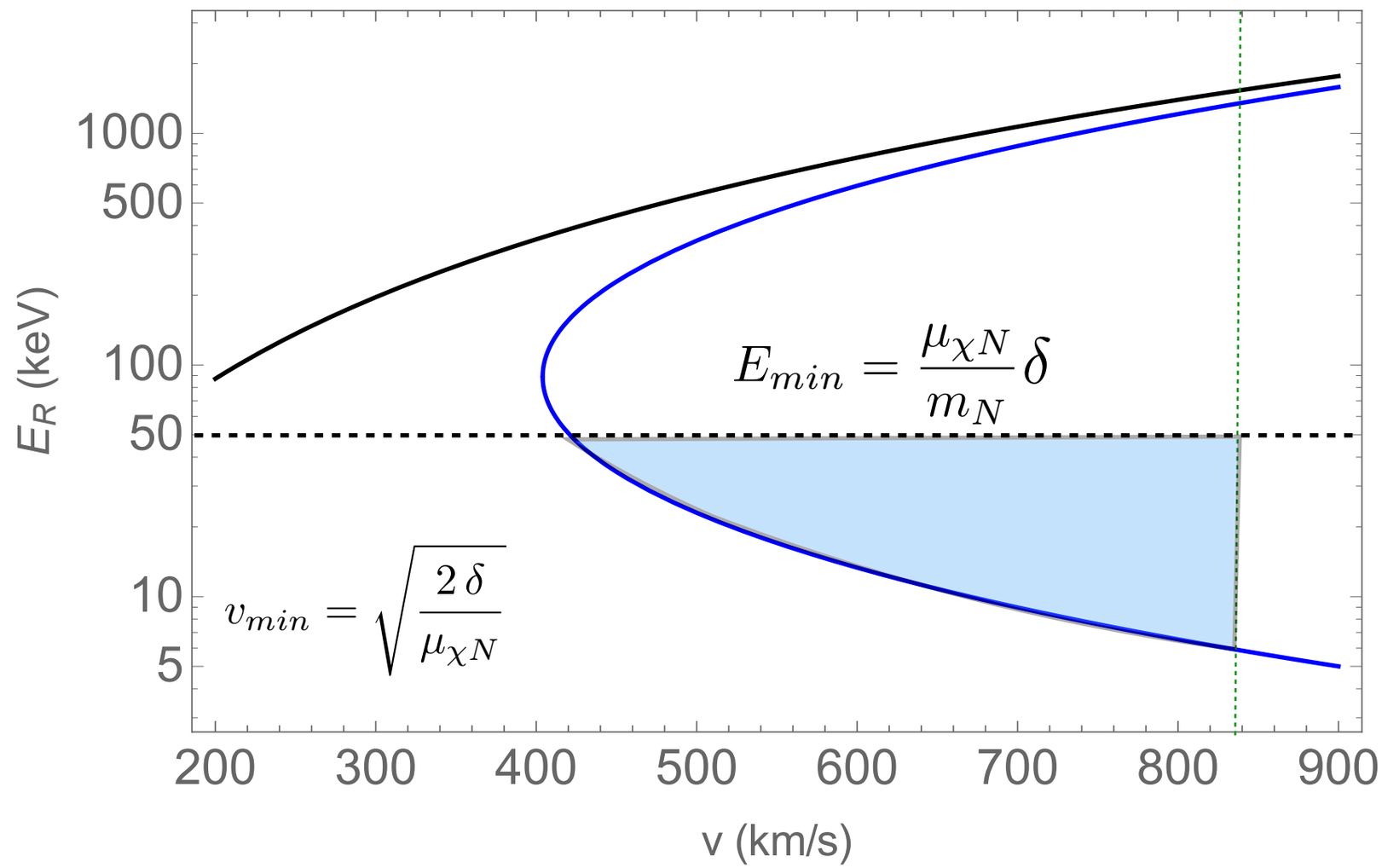
Conclusions

Explore the inelastic direction! Motivated models with sizable $\sigma_{\chi\text{-}N}$ within **easy** reach

- current techniques work, just enlarge E_R signal regions; Xe100, LUX already looking into it
- most sensitive to heavy DM using heavy targets;
- sensitive to tails of DM velocity distribution, large modulation effects

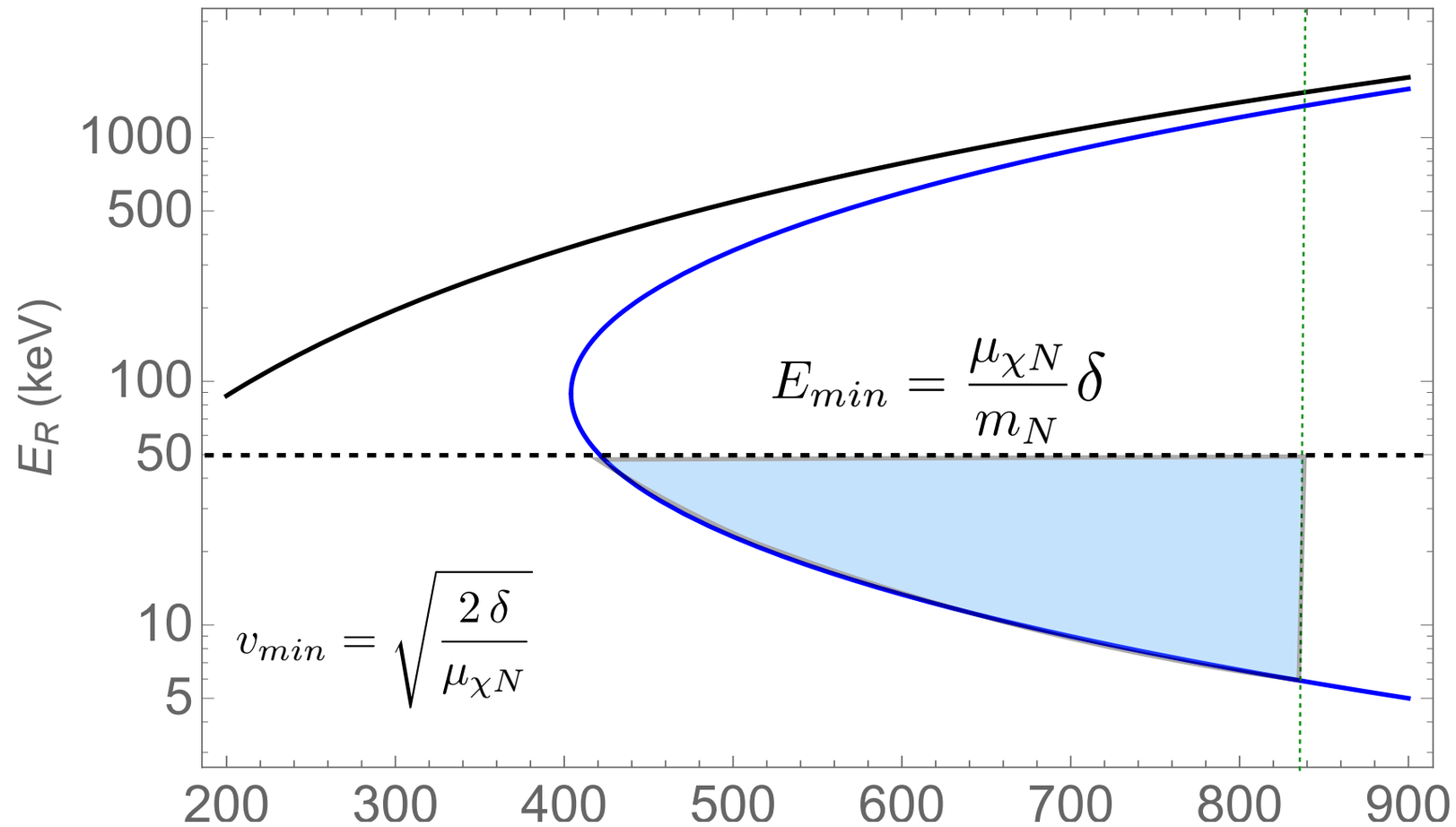
EXTRAS

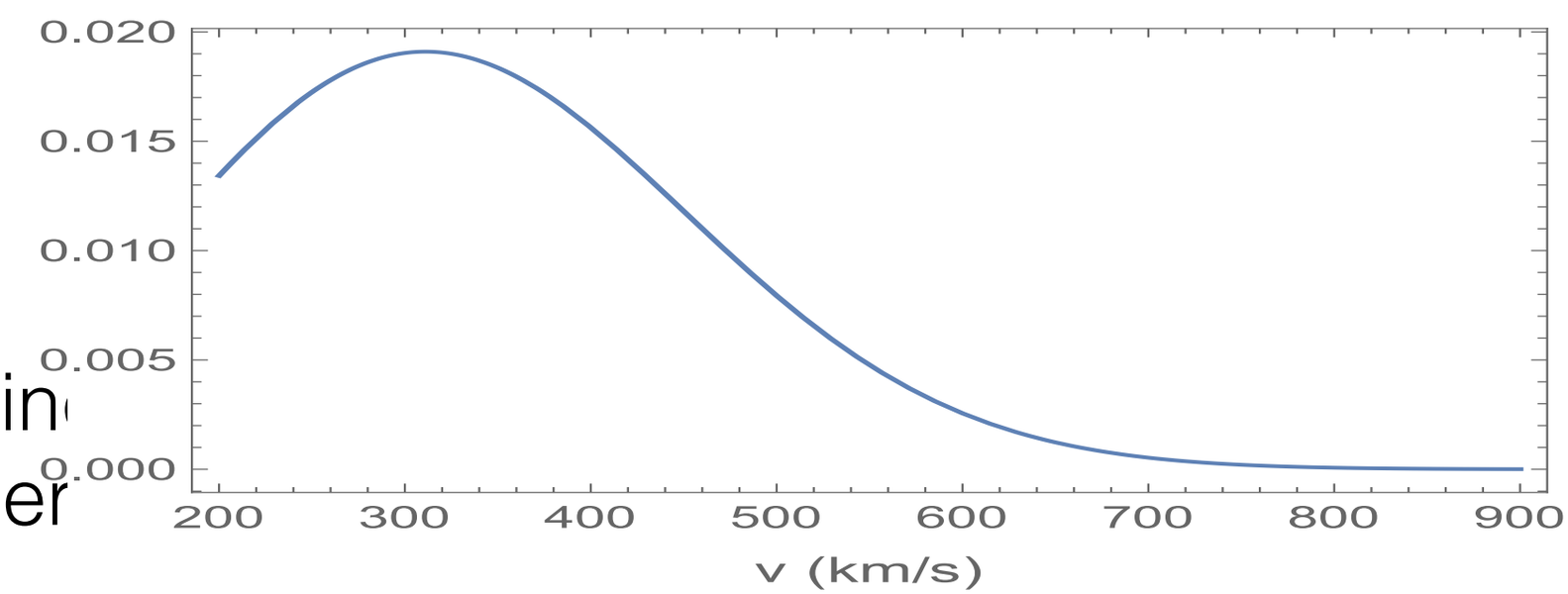
Direct Detection at High Recoil: Inelastic Kinematics



total rate is combines energy range, DM velocity spectrum (MB here), and nuclear form factors

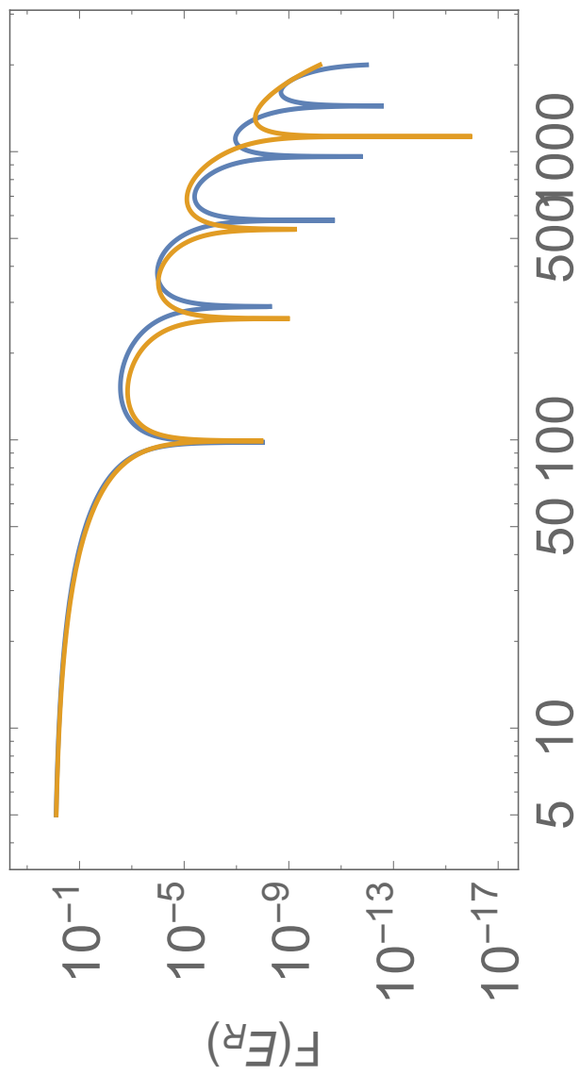
Direct Detection at High Recoil: Inelastic Kinematics

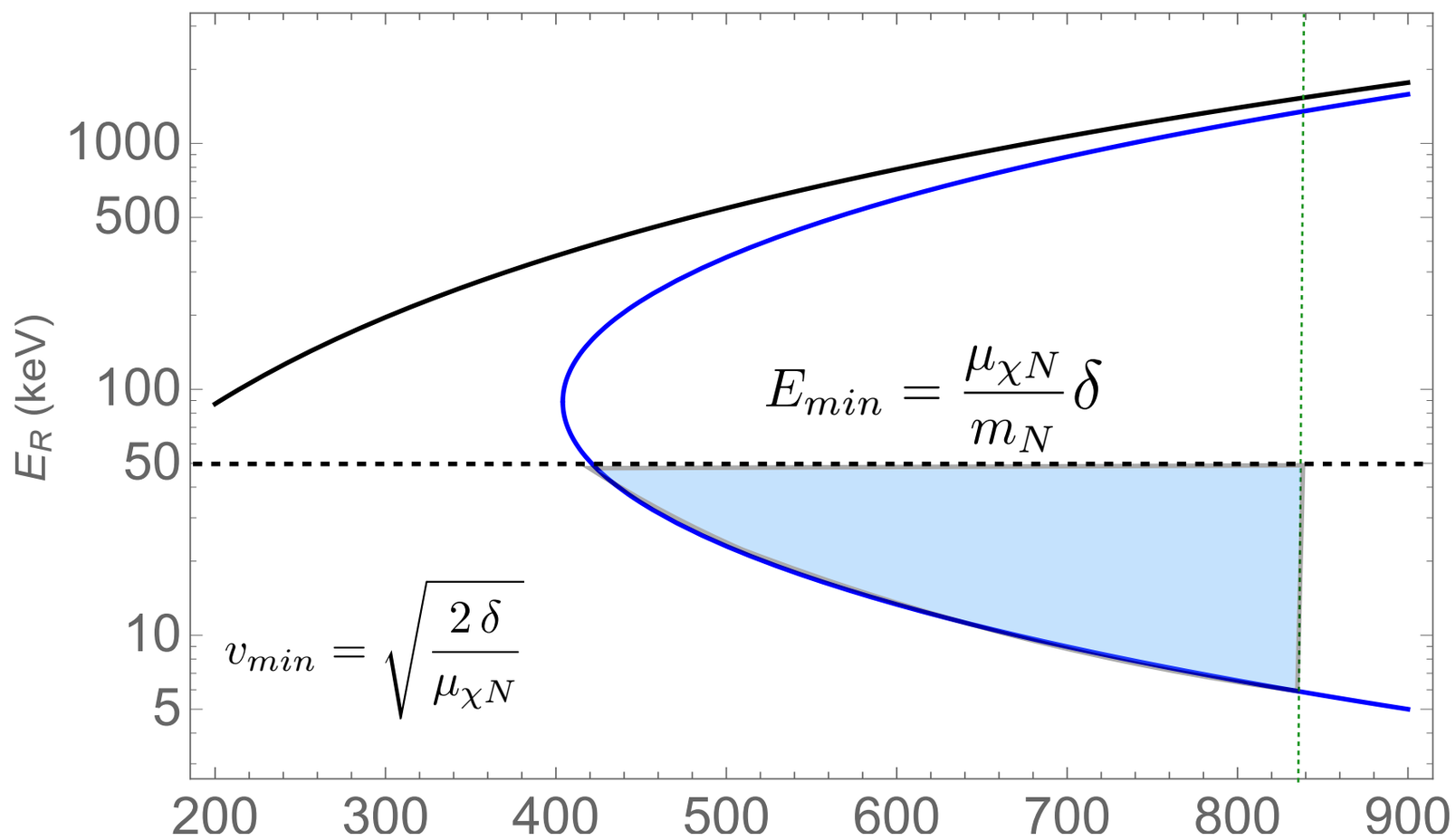


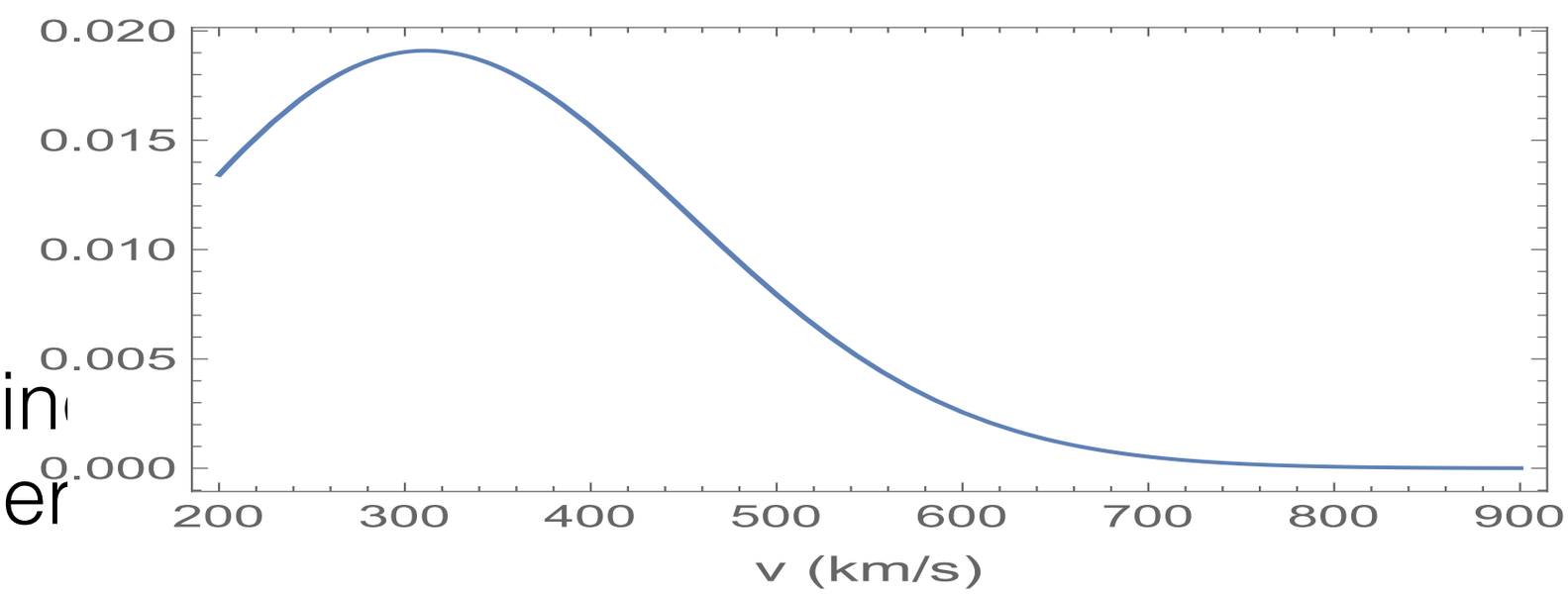


total rate is combin
(MB her

Direct Detection at High Recoil: Inelastic Kinematics

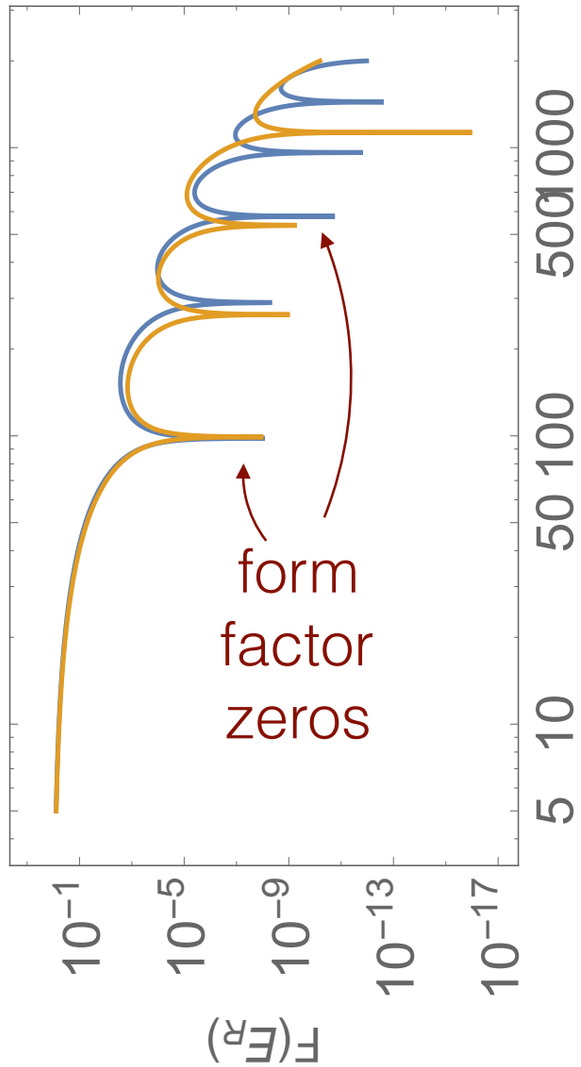


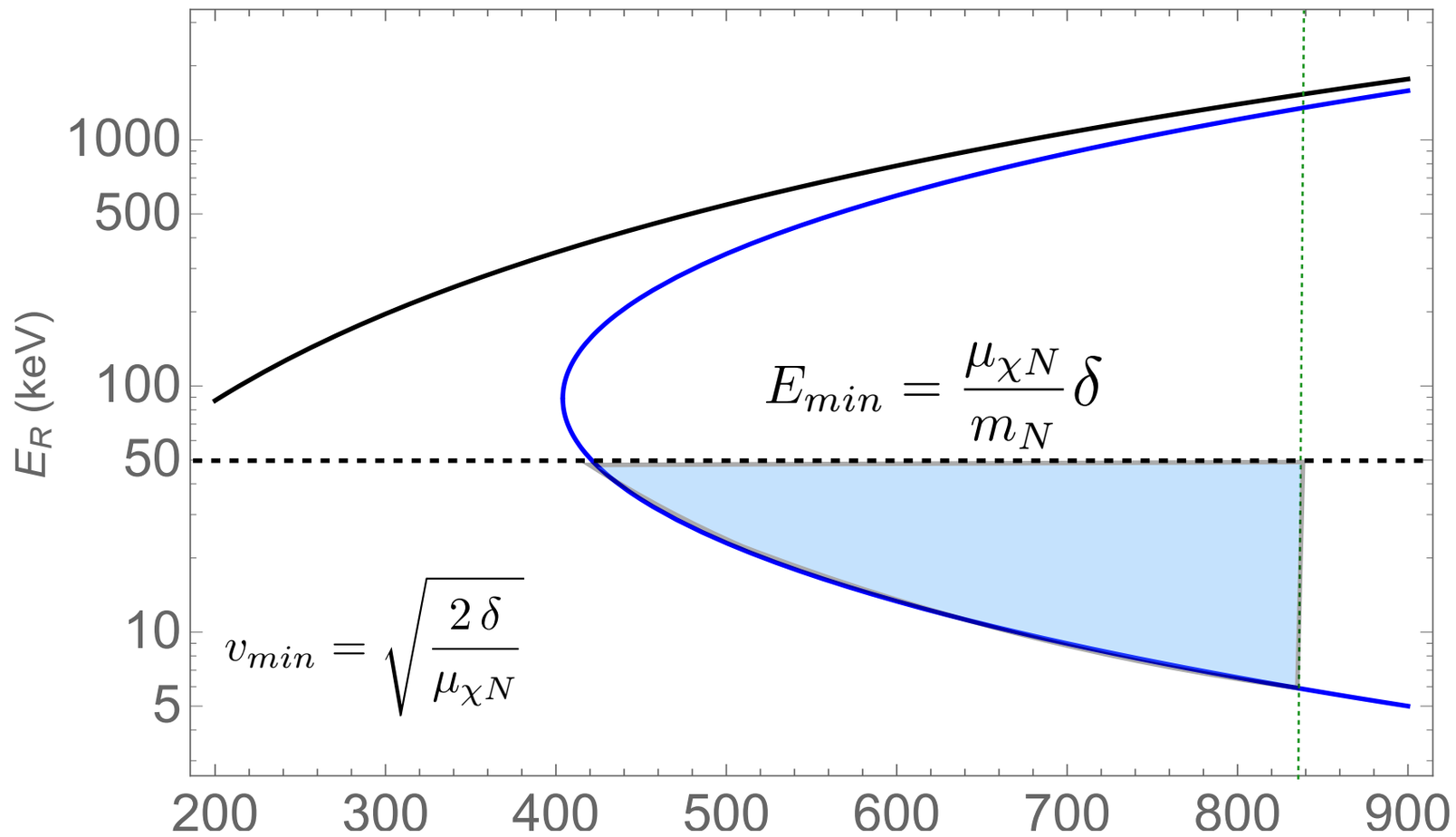


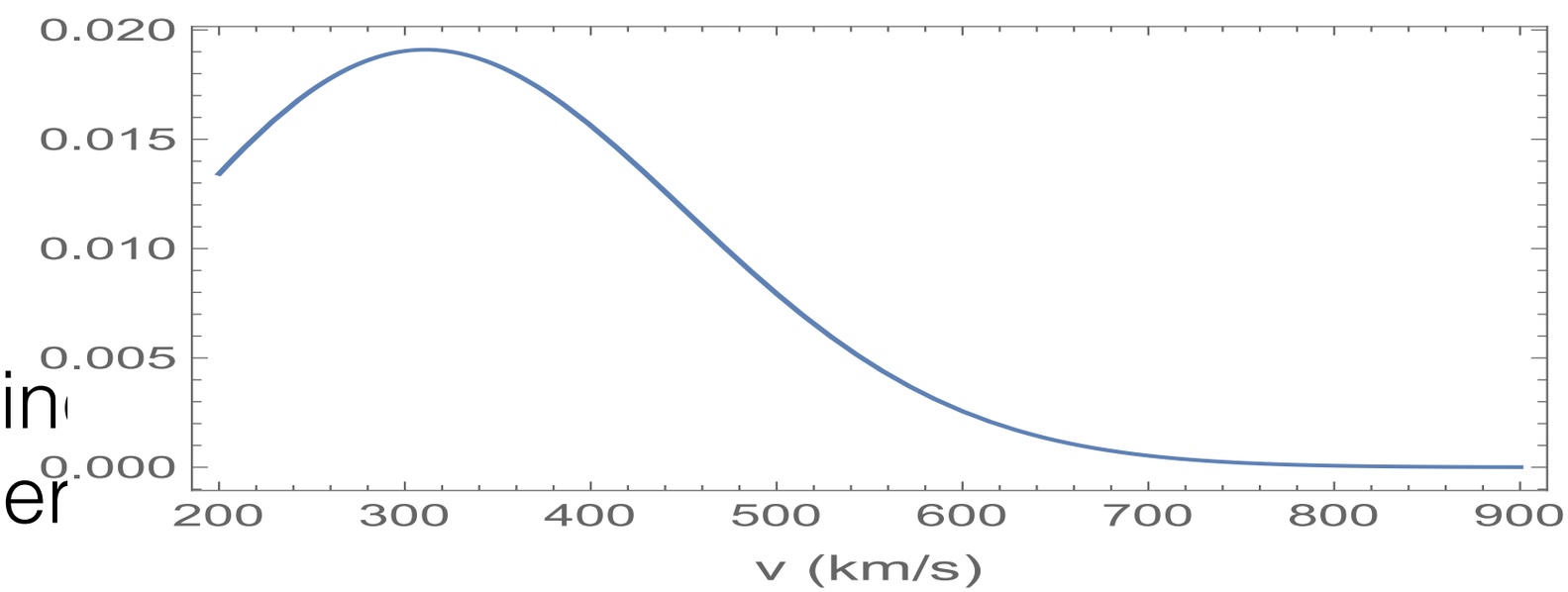


total rate is combin
(MB her

Direct Detection at High Recoil: Inelastic Kinematics

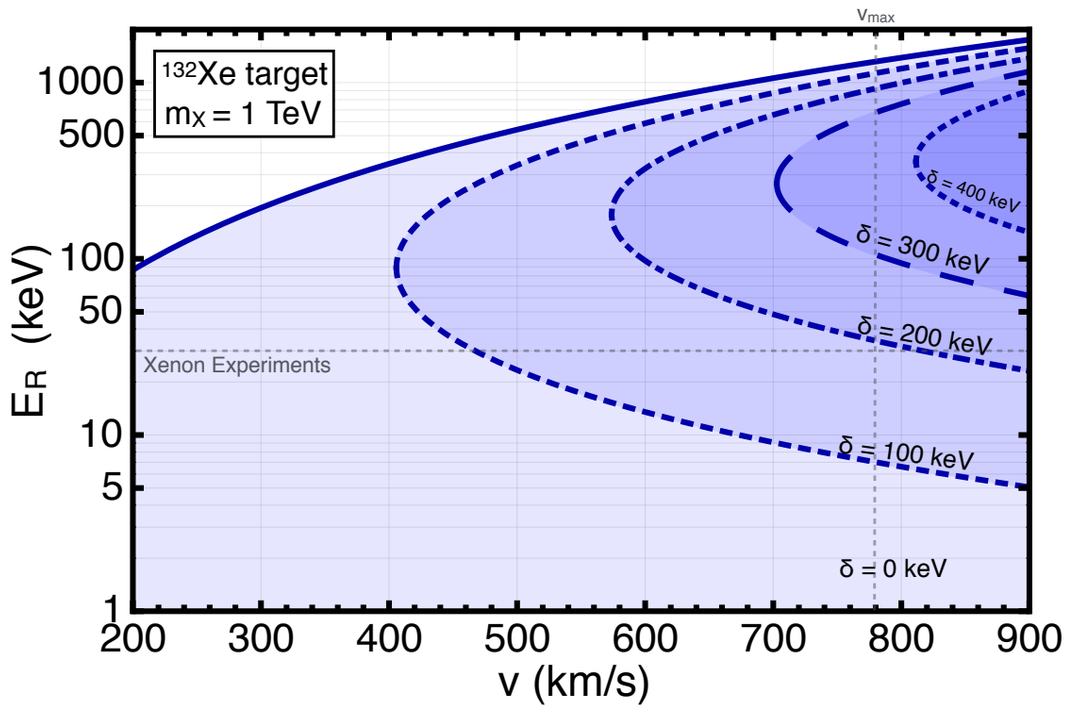


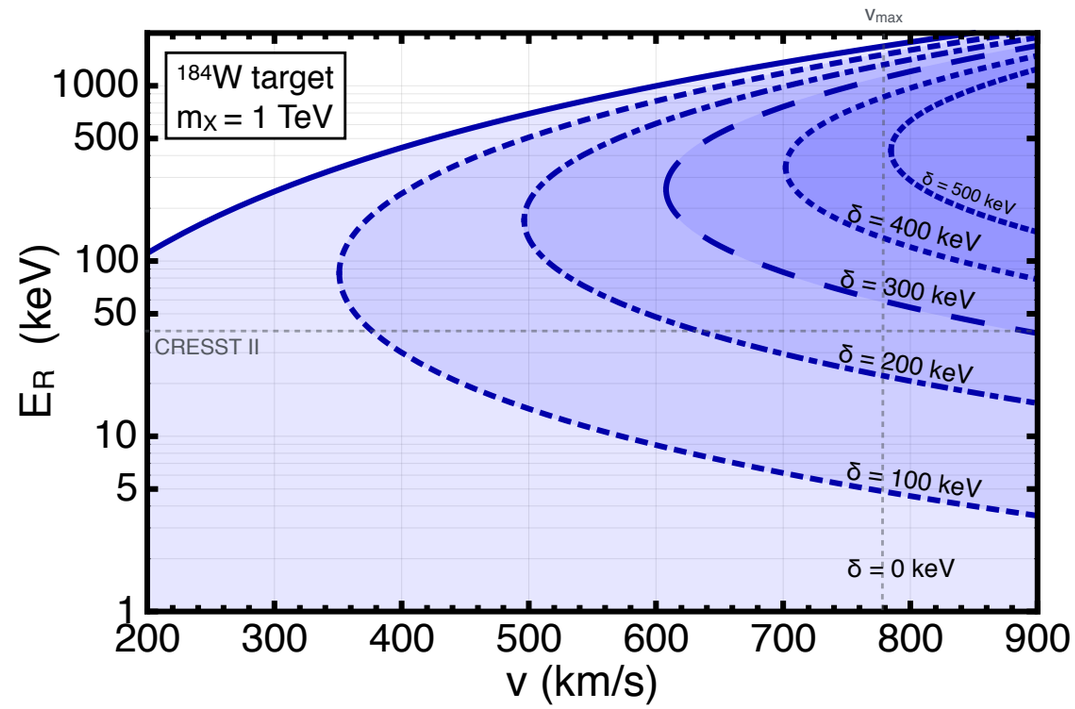




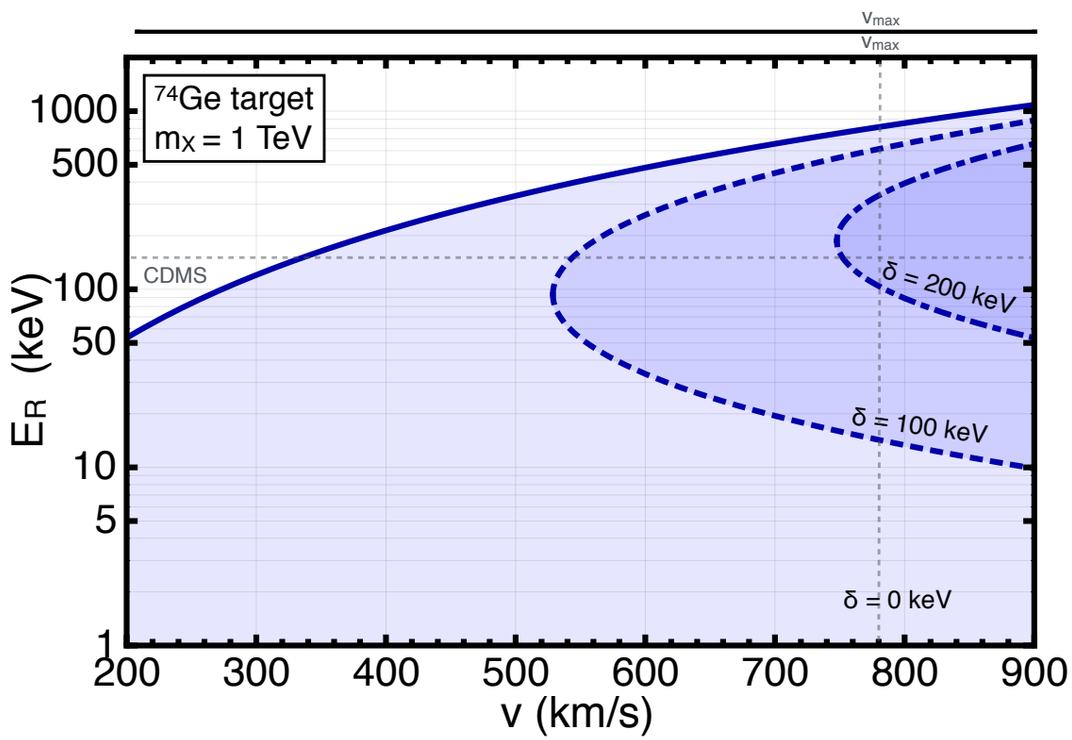
total rate is combin
(MB her

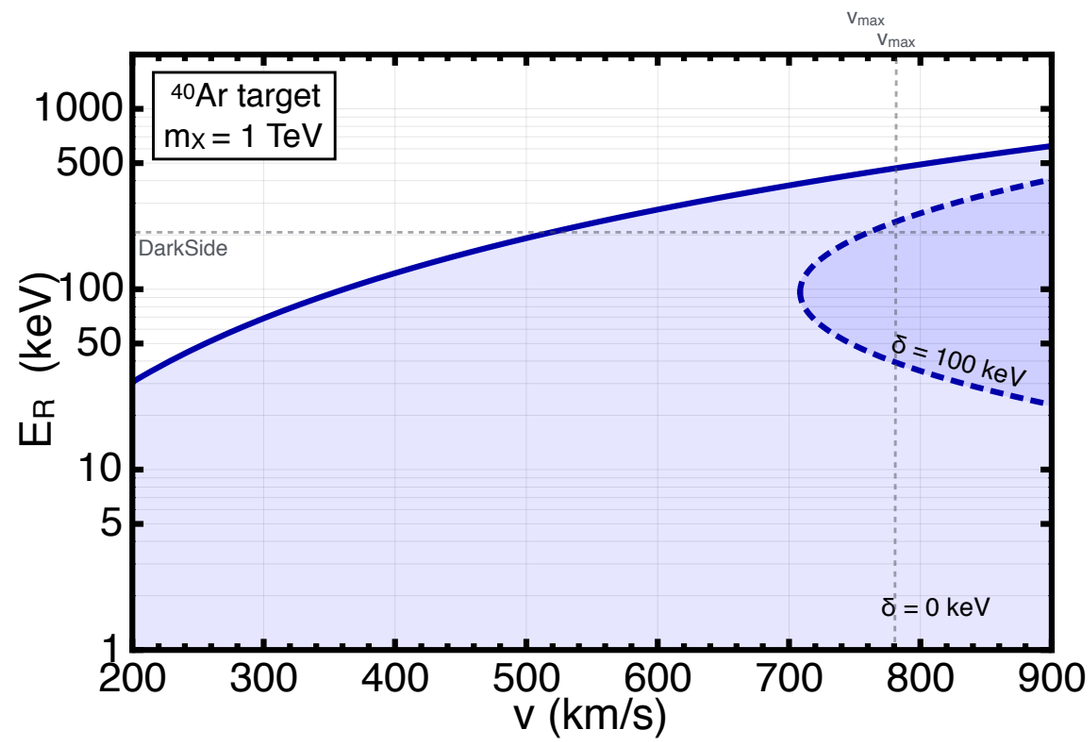
Direct Detection at High Recoil: Inelastic Kinematics



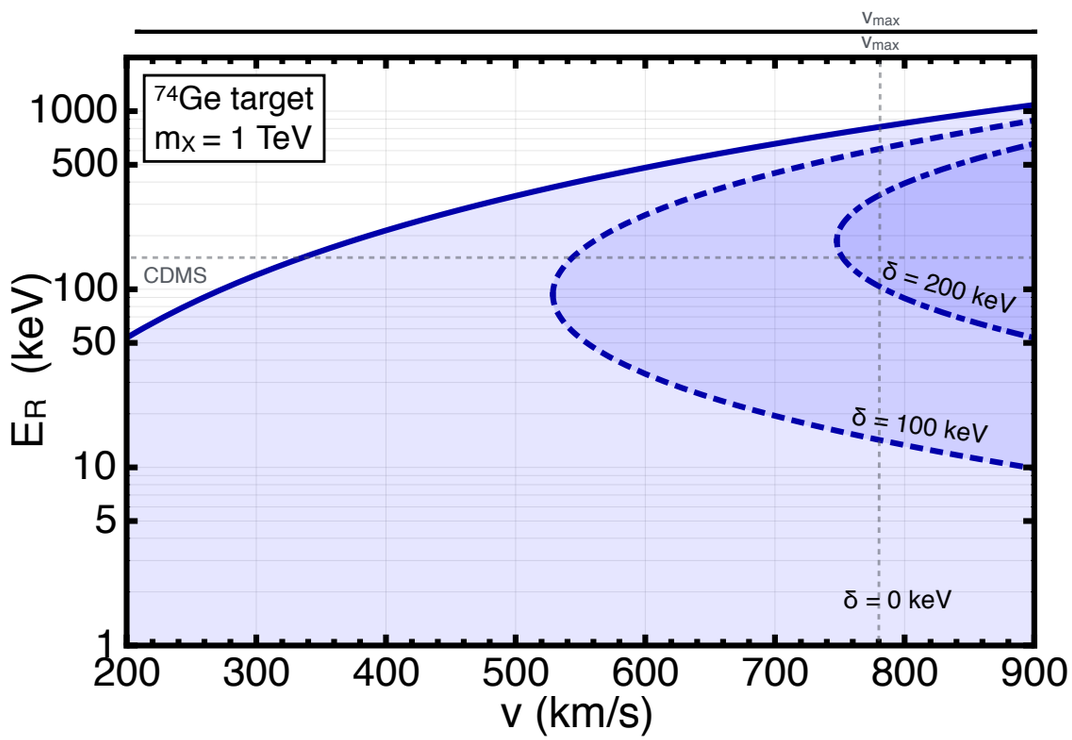


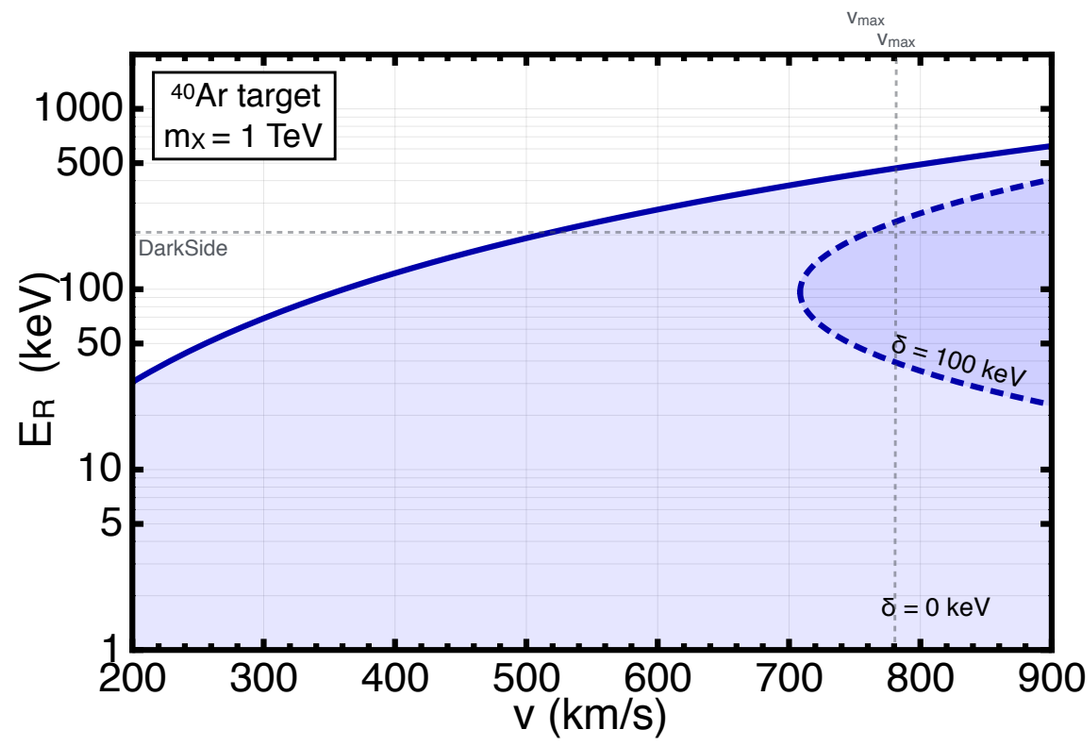
Direct Detection at High Recoil: Inelastic Kinematics





Direct Detection at High Recoil: Inelastic Kinematics

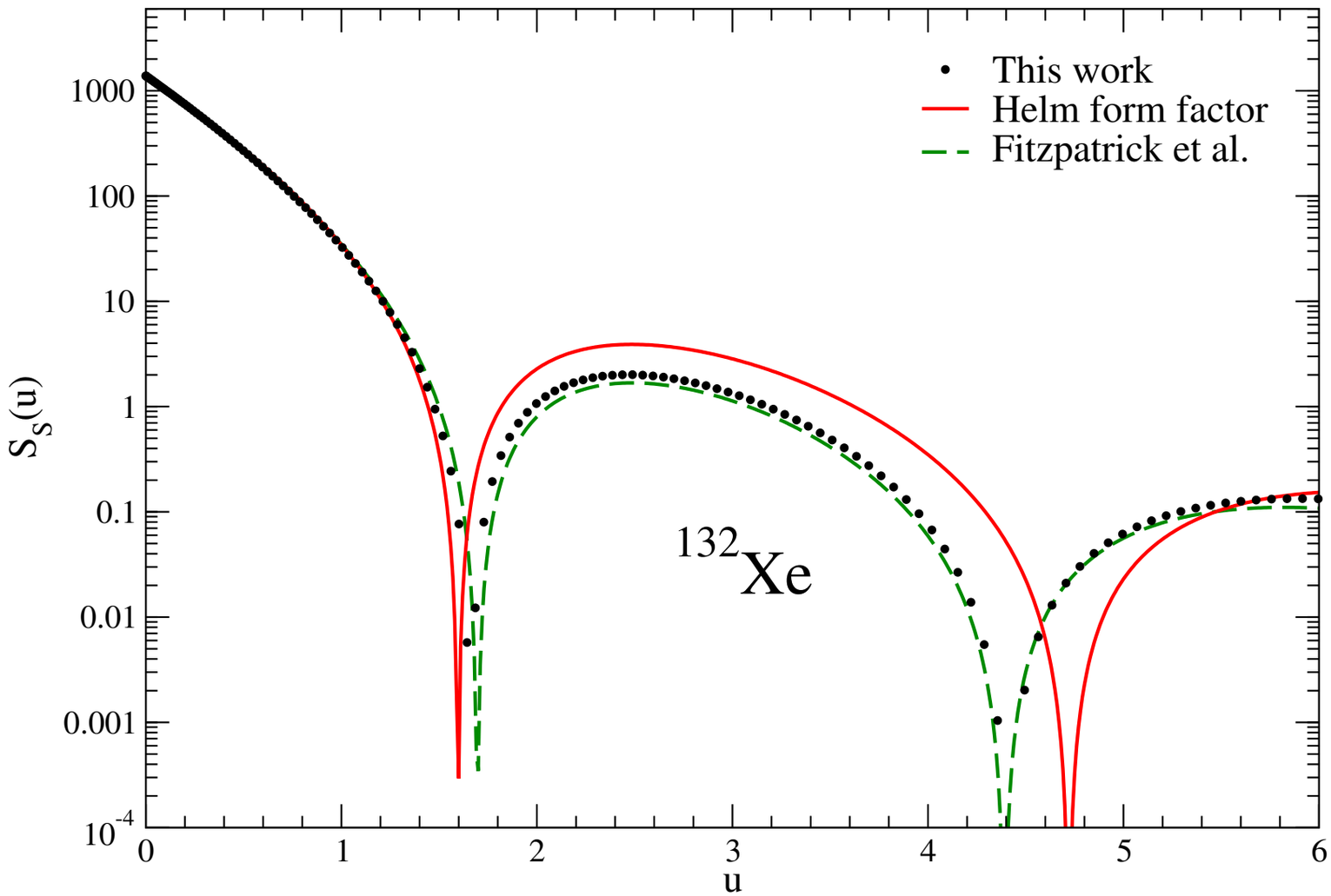


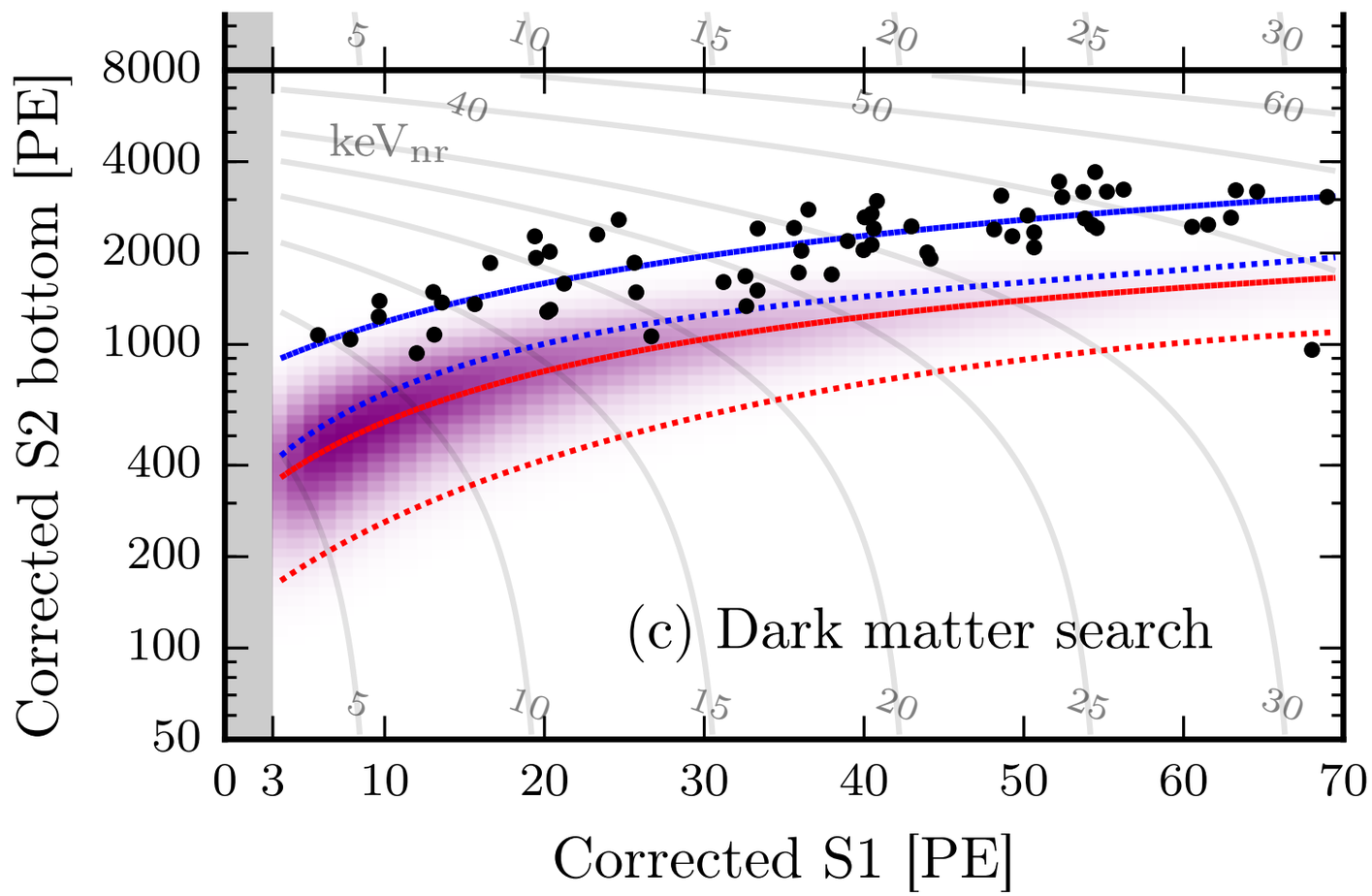


high recoil data can probe farthest in δ for heavy targets

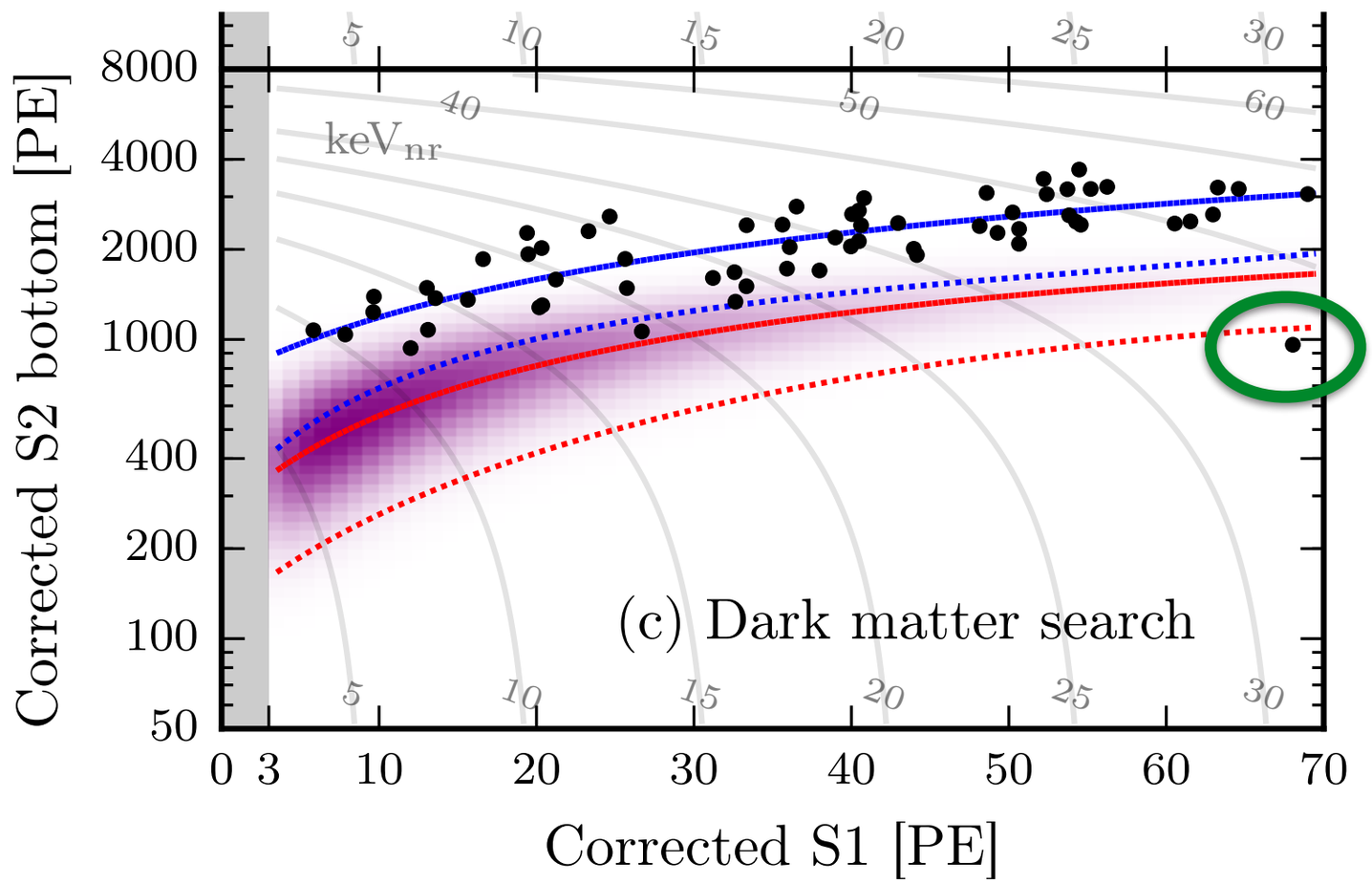
and for $m_X \gg m_N$

nuclear form factors





the lowest ER background ever achieved in a dark matter experiment. A single event far from the bulk distribution was observed at cS1 = 68.0 PE in the initial 4-day unblinding stage. This appears to be a *bona fide* event, though its location in $(\mathrm{cS1}, \mathrm{cS2_b})$ (see Fig. 2c) is extreme for all our physical background models and WIMP signal models. One event at cS1 = 26.7 PE is at the -2.4σ ER



the lowest ER background ever achieved in a dark matter experiment. A single event far from the bulk distribution was observed at cS1 = 68.0 PE in the initial 4-day unblinding stage. This appears to be a *bona fide* event, though its location in $(\mathrm{cS1}, \mathrm{cS2_b})$ (see Fig. 2c) is extreme for all our physical background models and WIMP signal models. One event at cS1 = 26.7 PE is at the -2.4σ ER