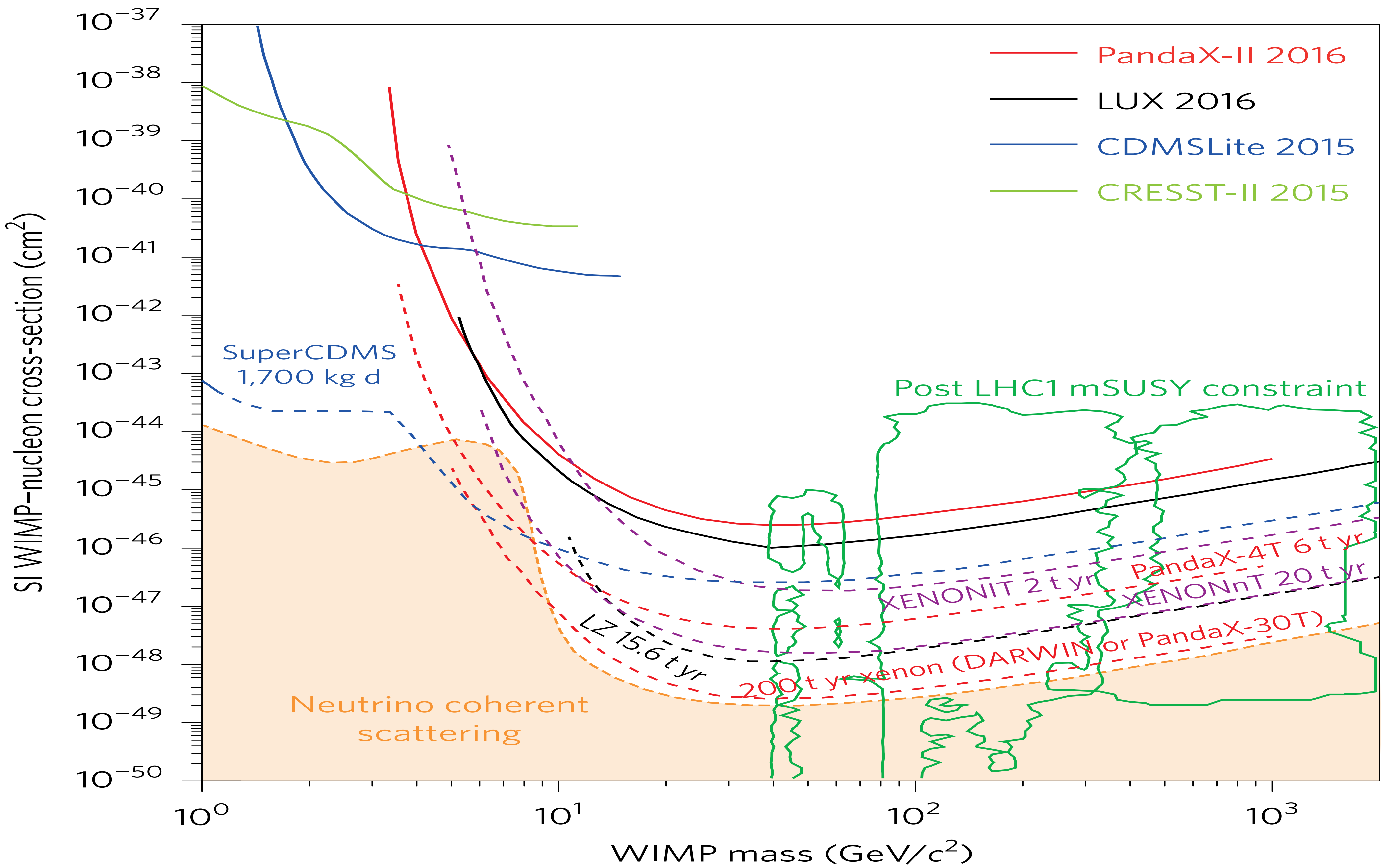
Discovering Dark Matter at High Nuclear Recoil

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

CERN-CKC, June 6th, 2017

simplest WIMP DM is running out of room



[Liu, Chen, Ji ’17]

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

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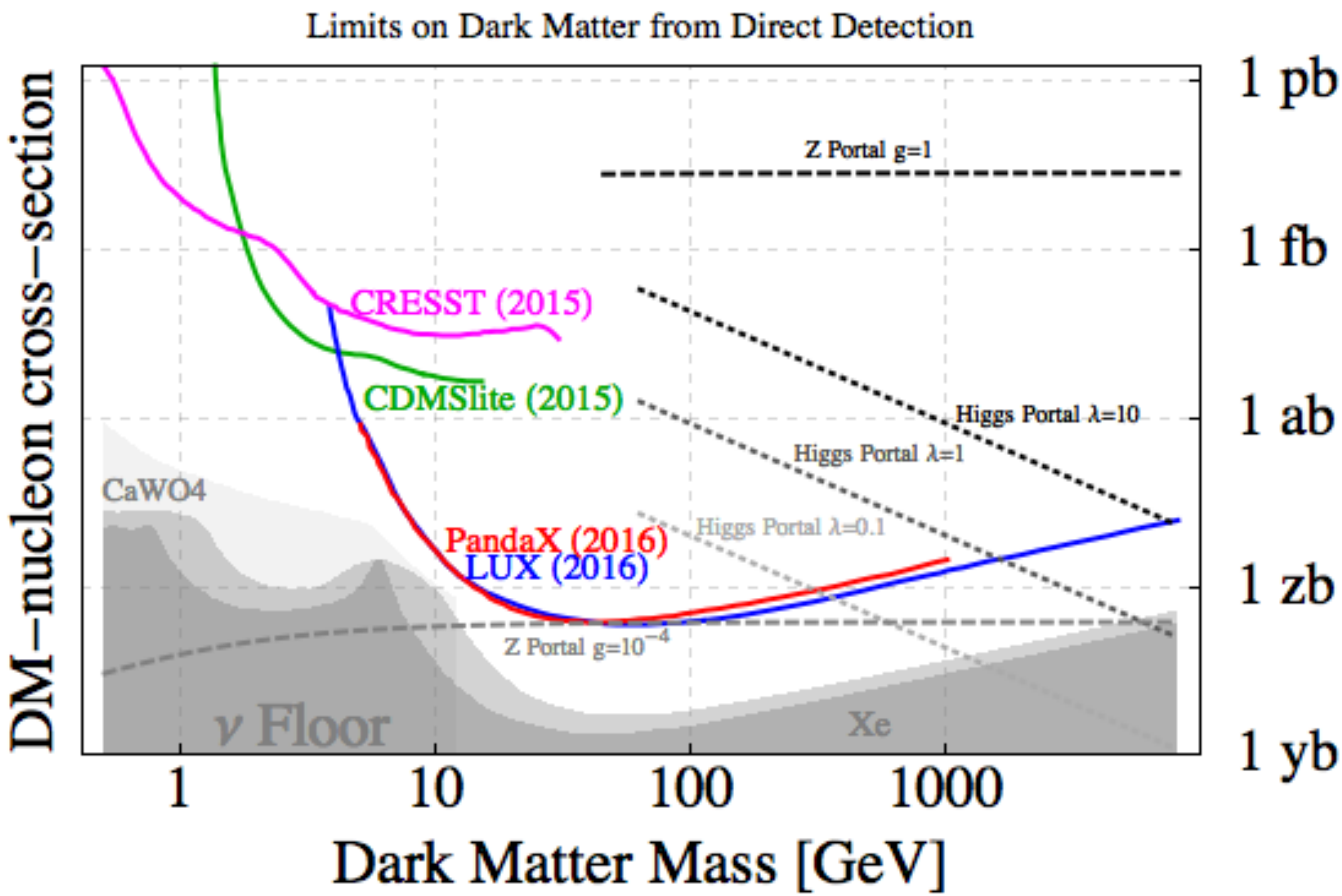
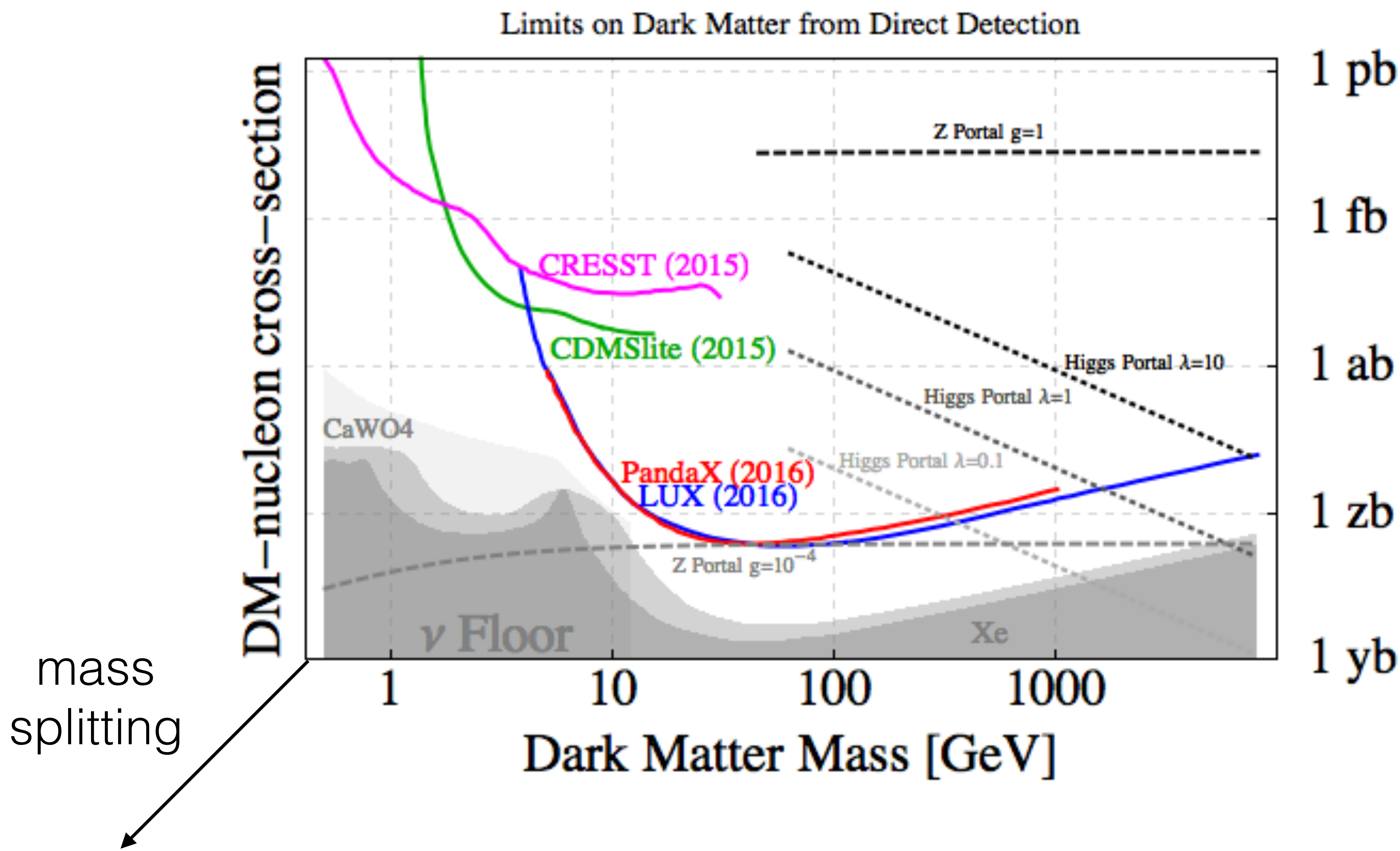


third direction: inelasticity



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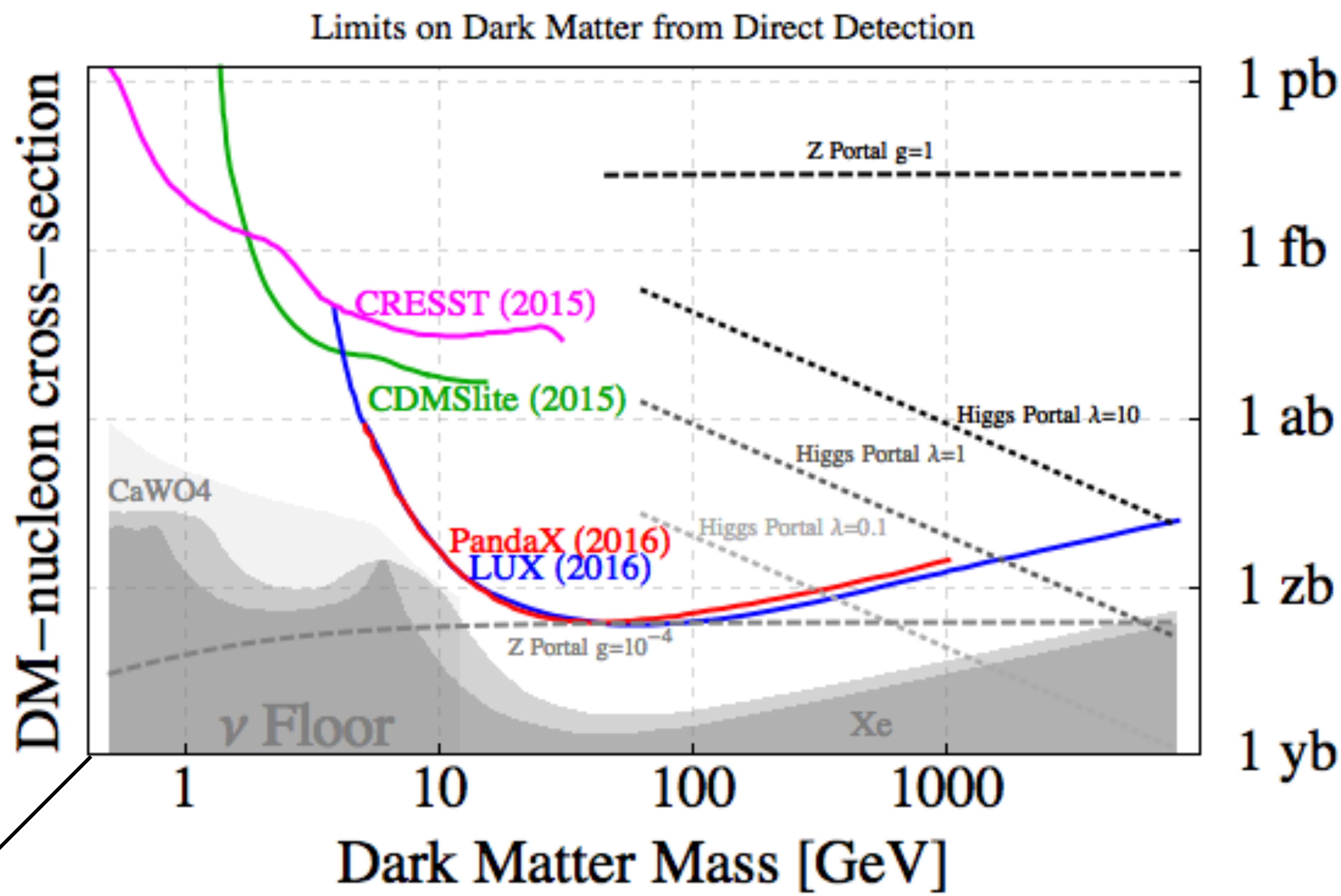

χ = DM

mass splitting

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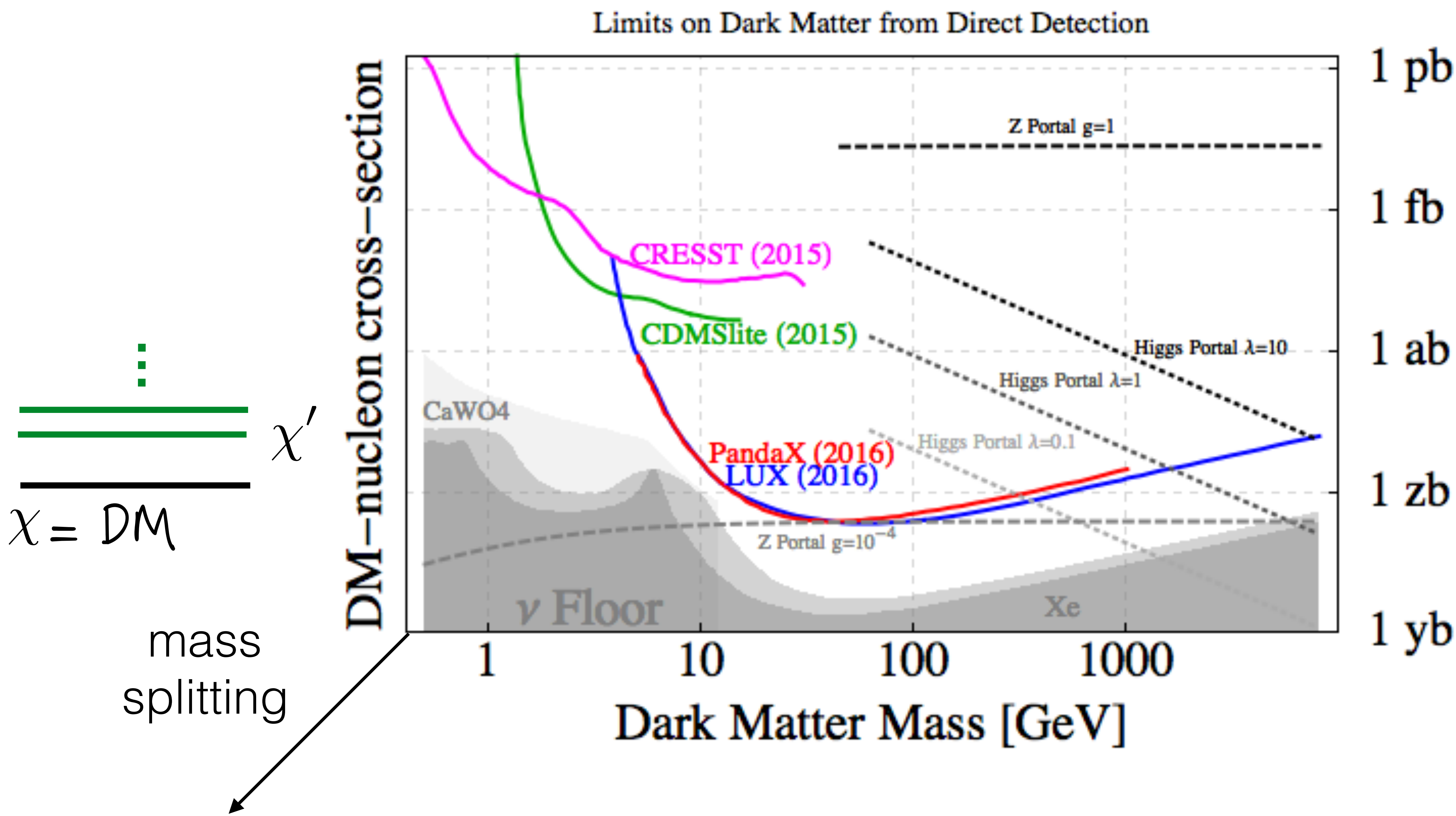

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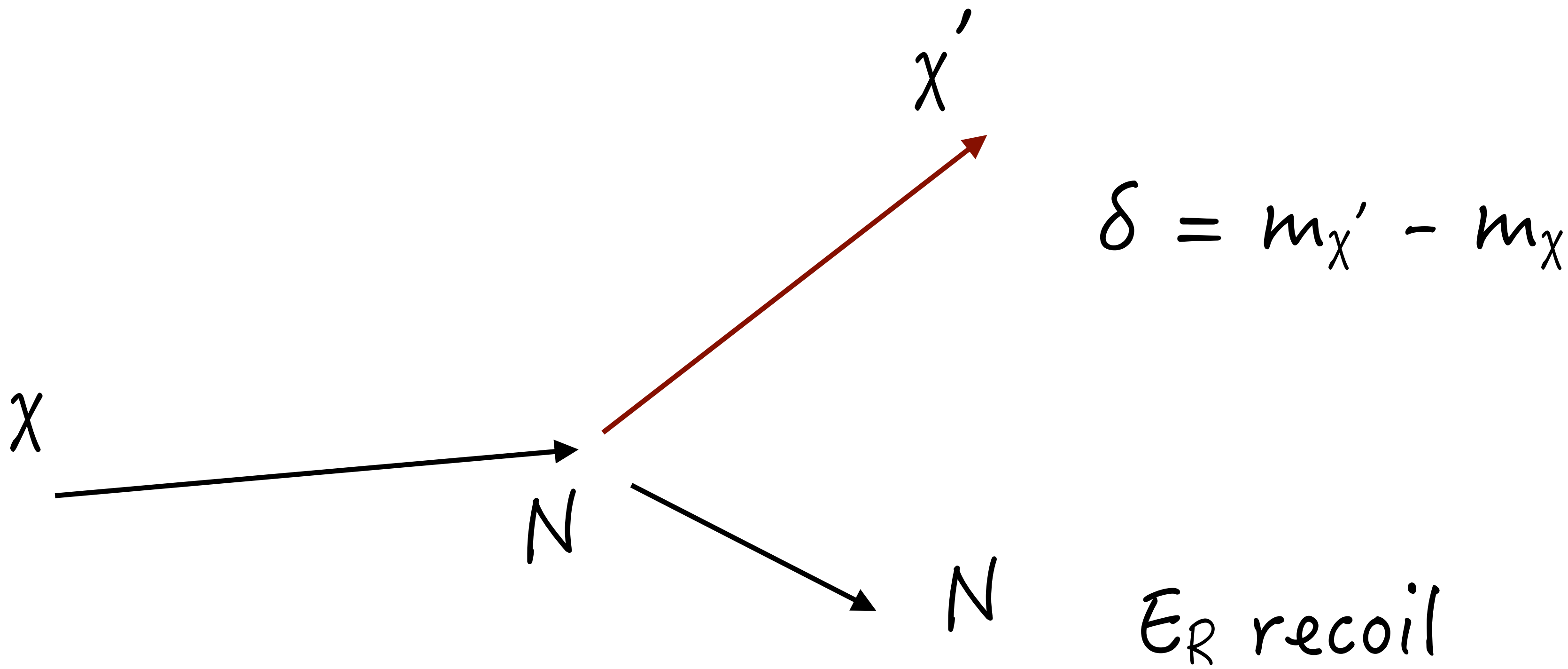

[L. J. Hall, T. Moroi and H. Murayama ’97, Tucker-Smith, Weiner ’01]

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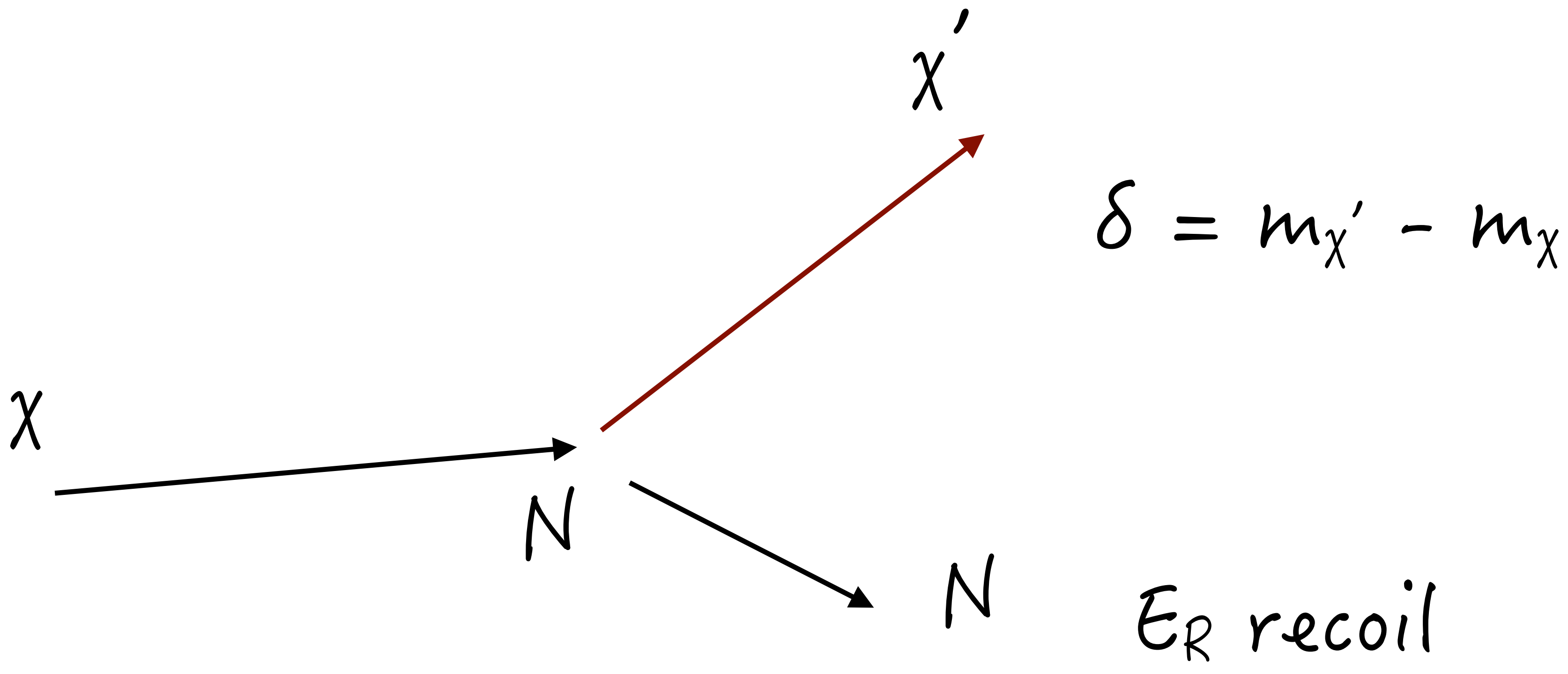


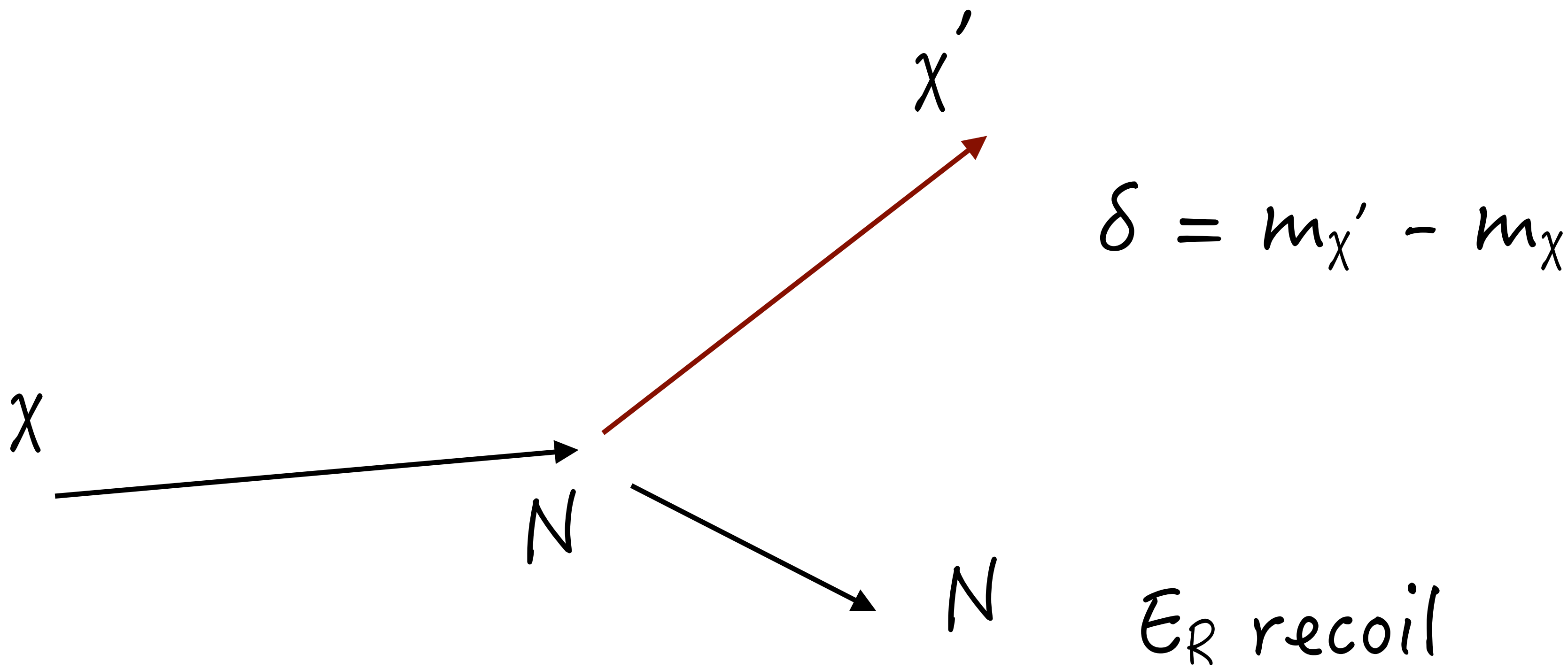
(target-dependent) minimum velocity required to scatter

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

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

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

Inelastic DM



popularized to reconcile DAMA with CDMS (2001-)

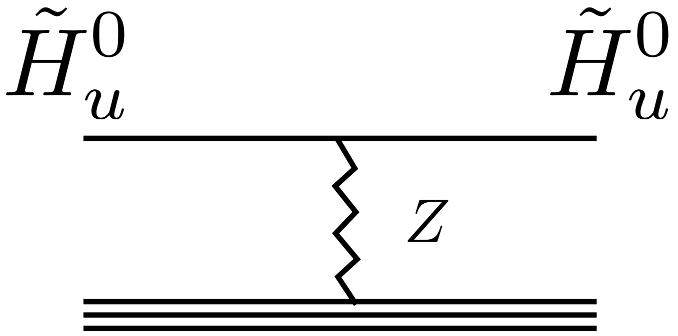
required $\delta \sim 100$ keV for $m_\chi \sim 100$ GeV

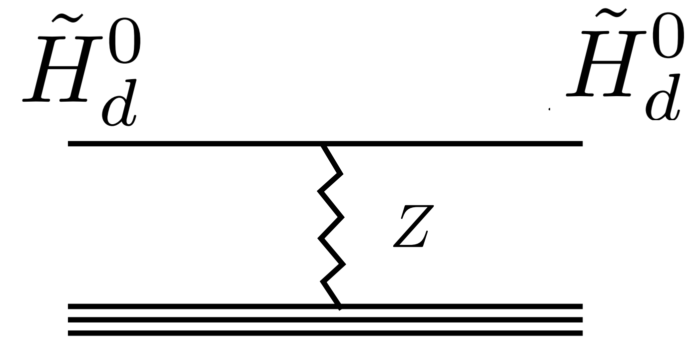
forgetting DAMA, range of δ is wide open

for canonical DM velocity distribution, available KE ≲ 650 keV

Inelastic DM: inelastic DM poster child

(nearly) pure Higgsinos: $\mu \ll M_1, M_2$





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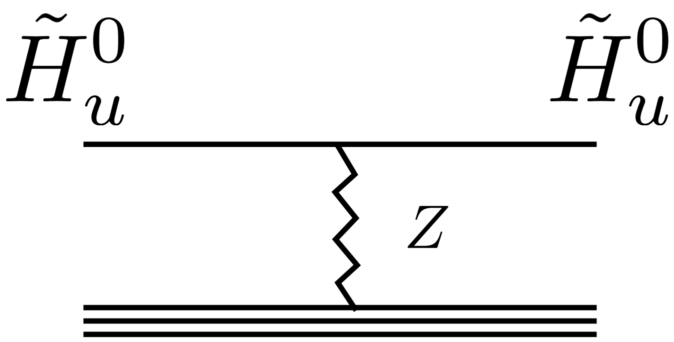

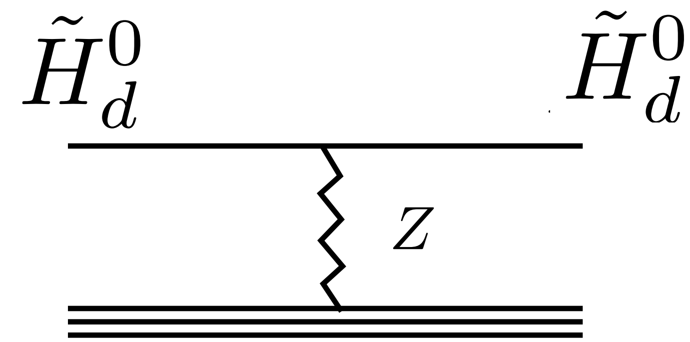

$\tilde{H}_u^0,\ \tilde{H}_d^0 \rightarrow \tilde{H}_1^0,\ \tilde{H}_2^0$ once we turn on EWSB

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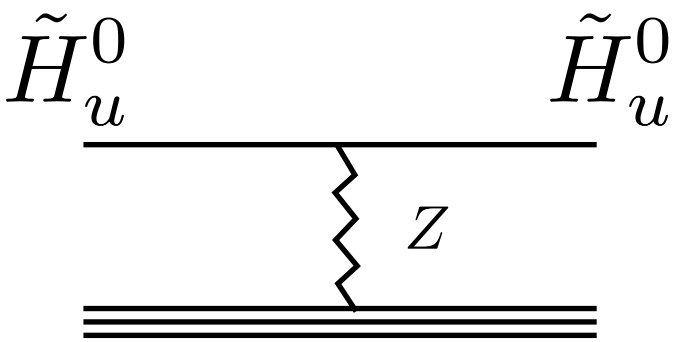

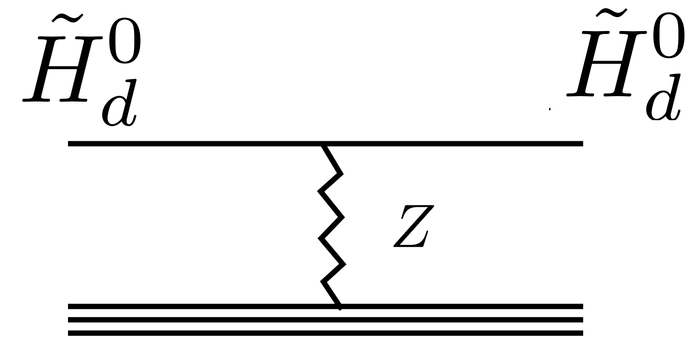

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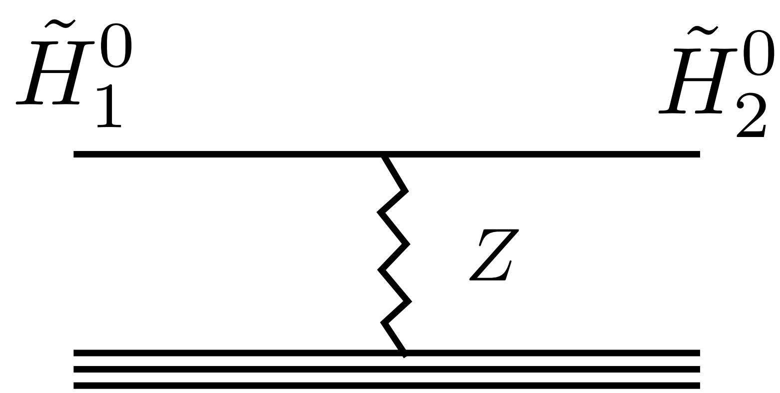

Z-exchange inelastic

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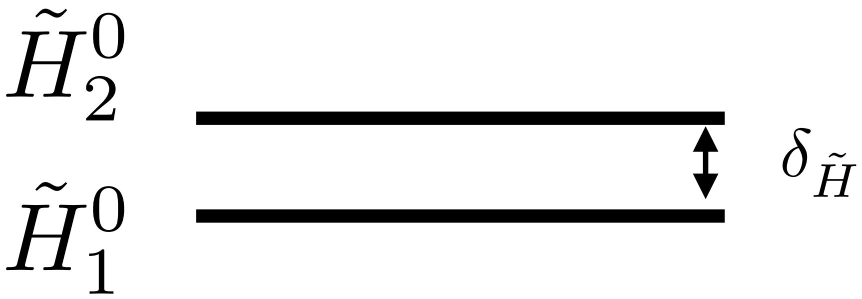

$$\delta_{\tilde{\mathrm{H}}} \simeq m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right) + \mathcal{O}\left(\frac{1}{M_{1,2}^2} \right) =$$

$$\begin{cases} 192\,\mathrm{keV} \left(\frac{10^7\ \mathrm{GeV}}{M_1} \right) & M_2 \gg M_1 \gg \mu \\ 640\,\mathrm{keV} \left(\frac{10^7\ \mathrm{GeV}}{M_2} \right) & M_1 \gg M_2 \gg \mu \end{cases}$$

(see 1405.3692)

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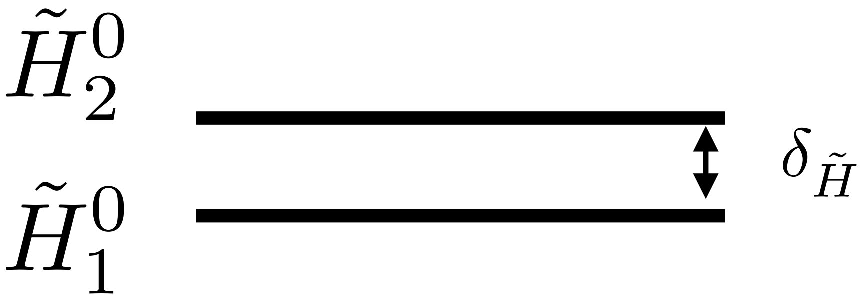

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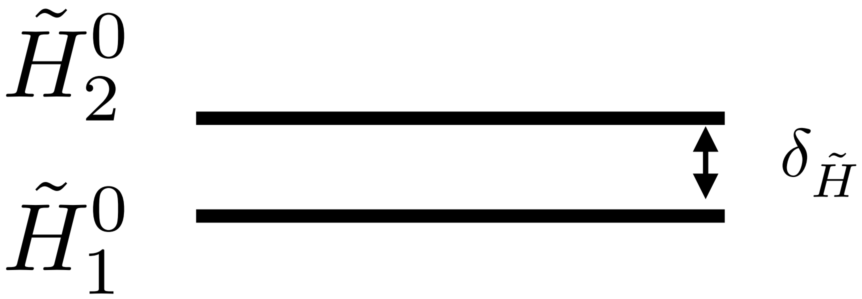

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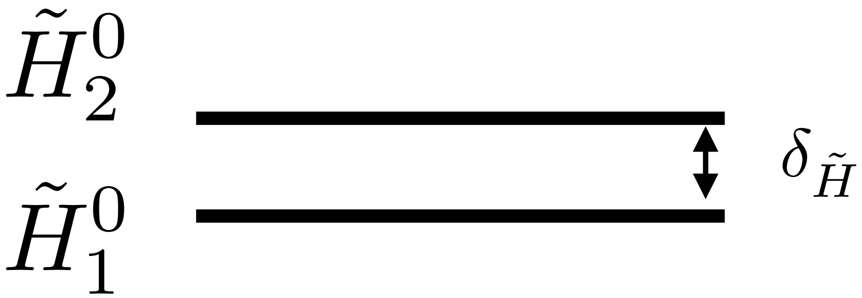

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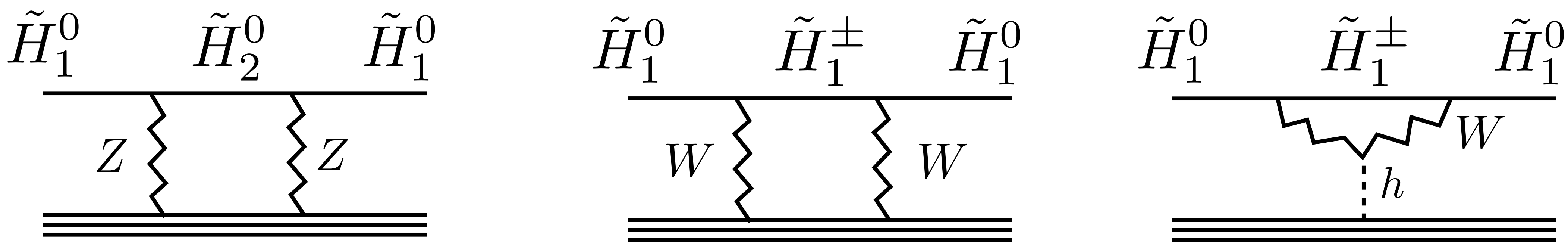
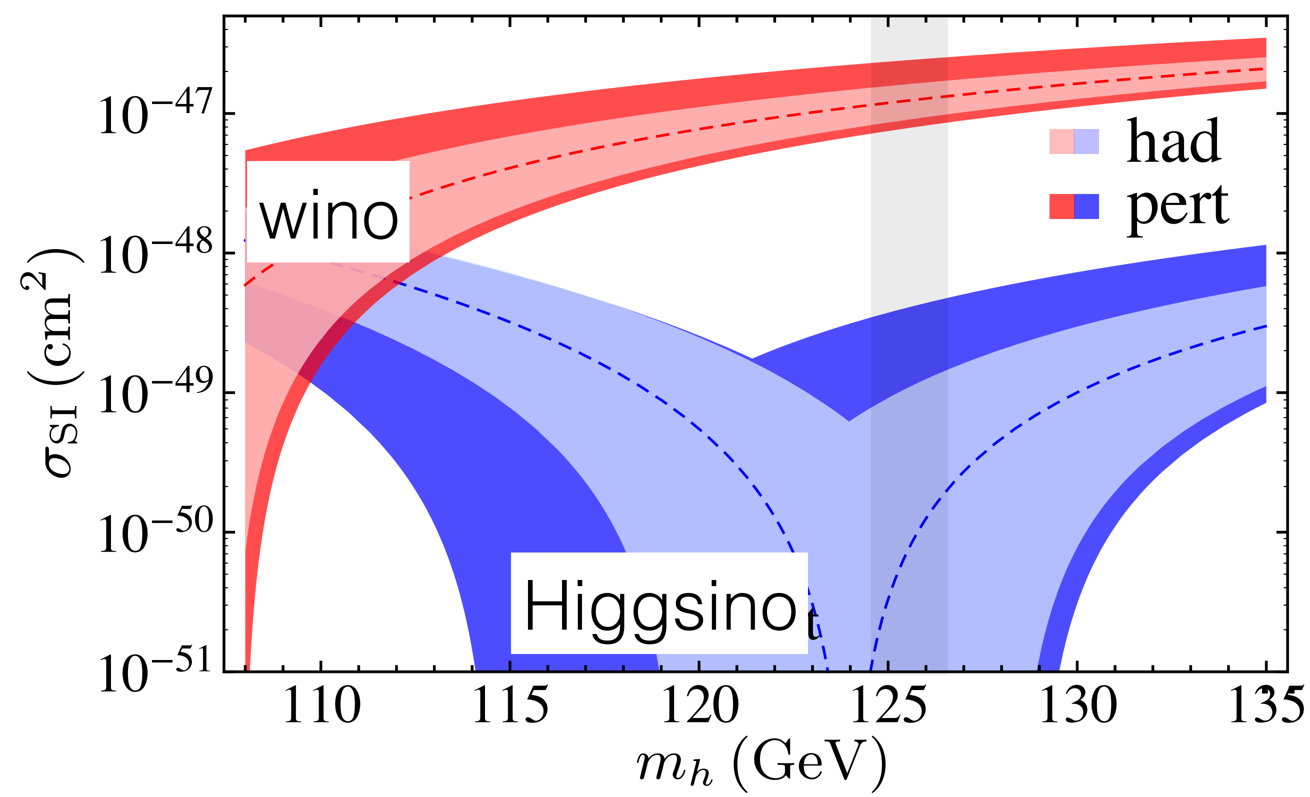
elastic scattering at loop level: suppressed by m_n or E_R



[Hisano et al ’11, Hill+Solon ’13]

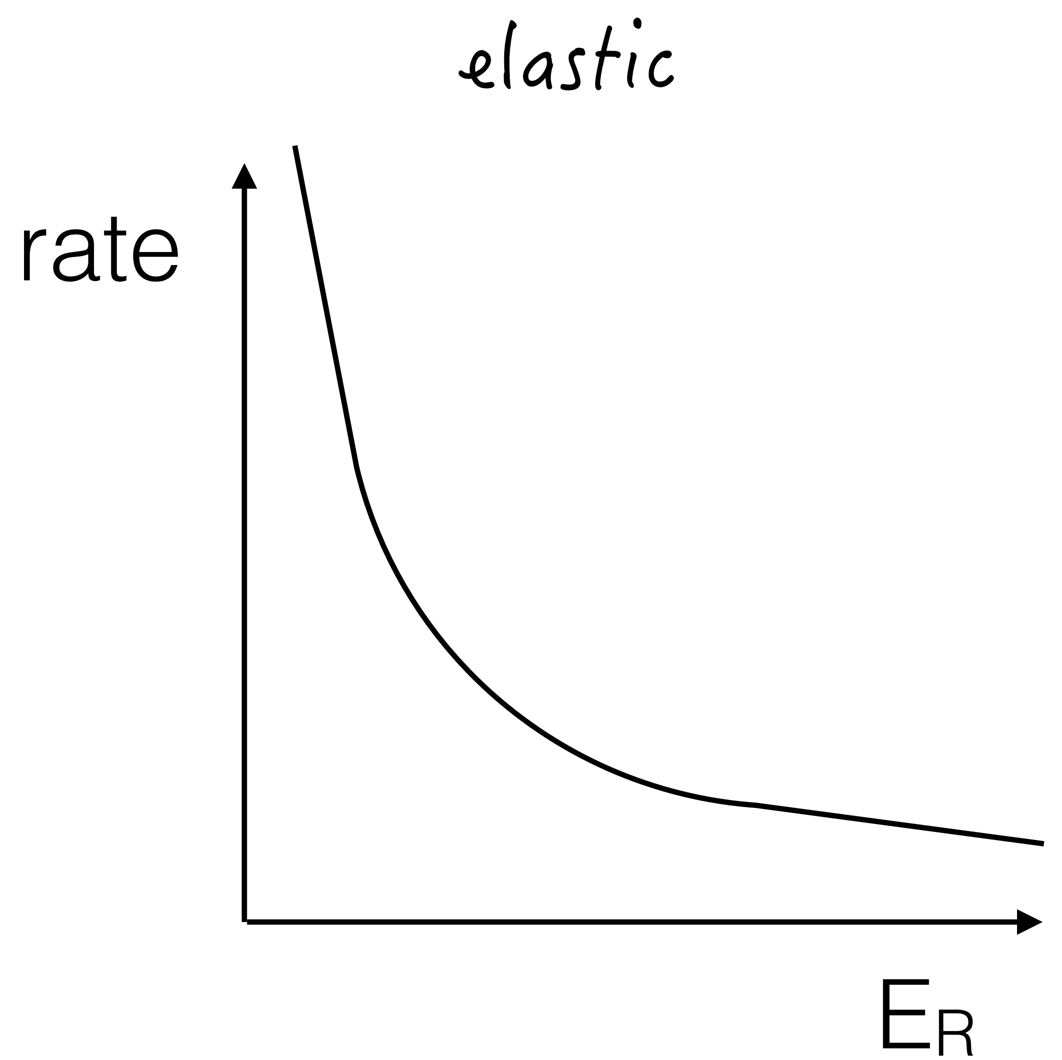
further suppressed by accidental cancellations



Hill, Solon 1309.4092

Direct Detection at High Recoil : Inelastic Kinematics

inelasticity changes nuclear recoil energy spectrum



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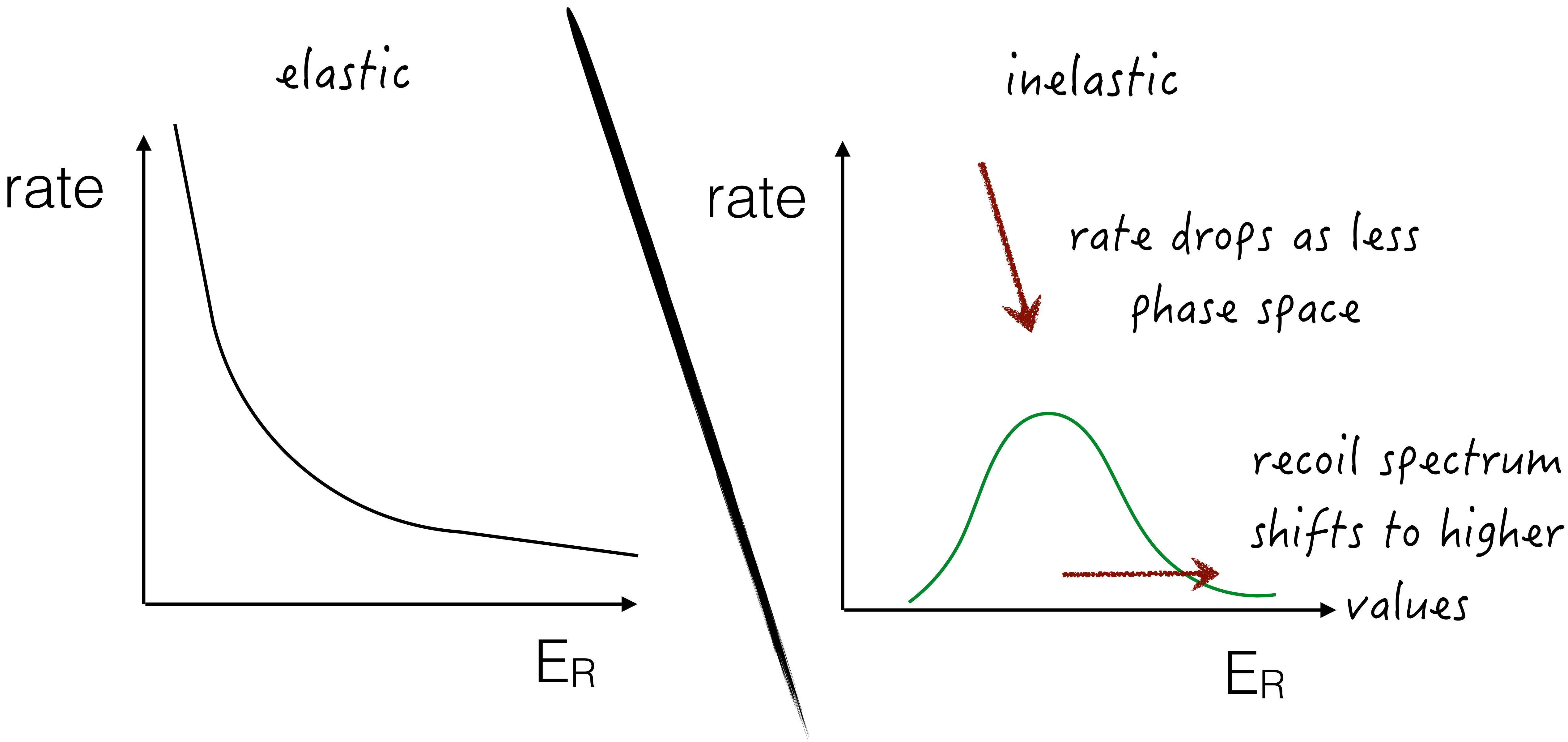
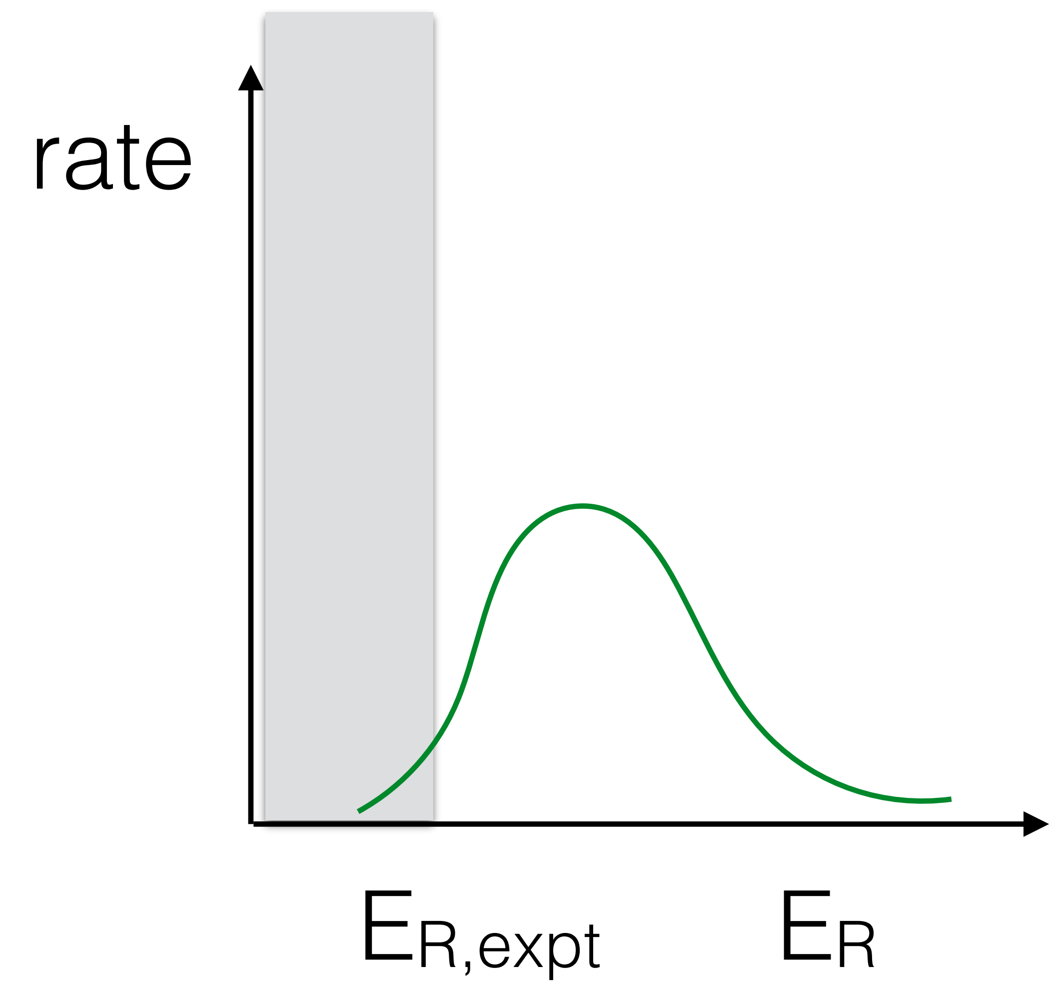


Direct Detection at High Recoil: Inelastic Kinematics

Experimental **signal windows** focused on low E_R



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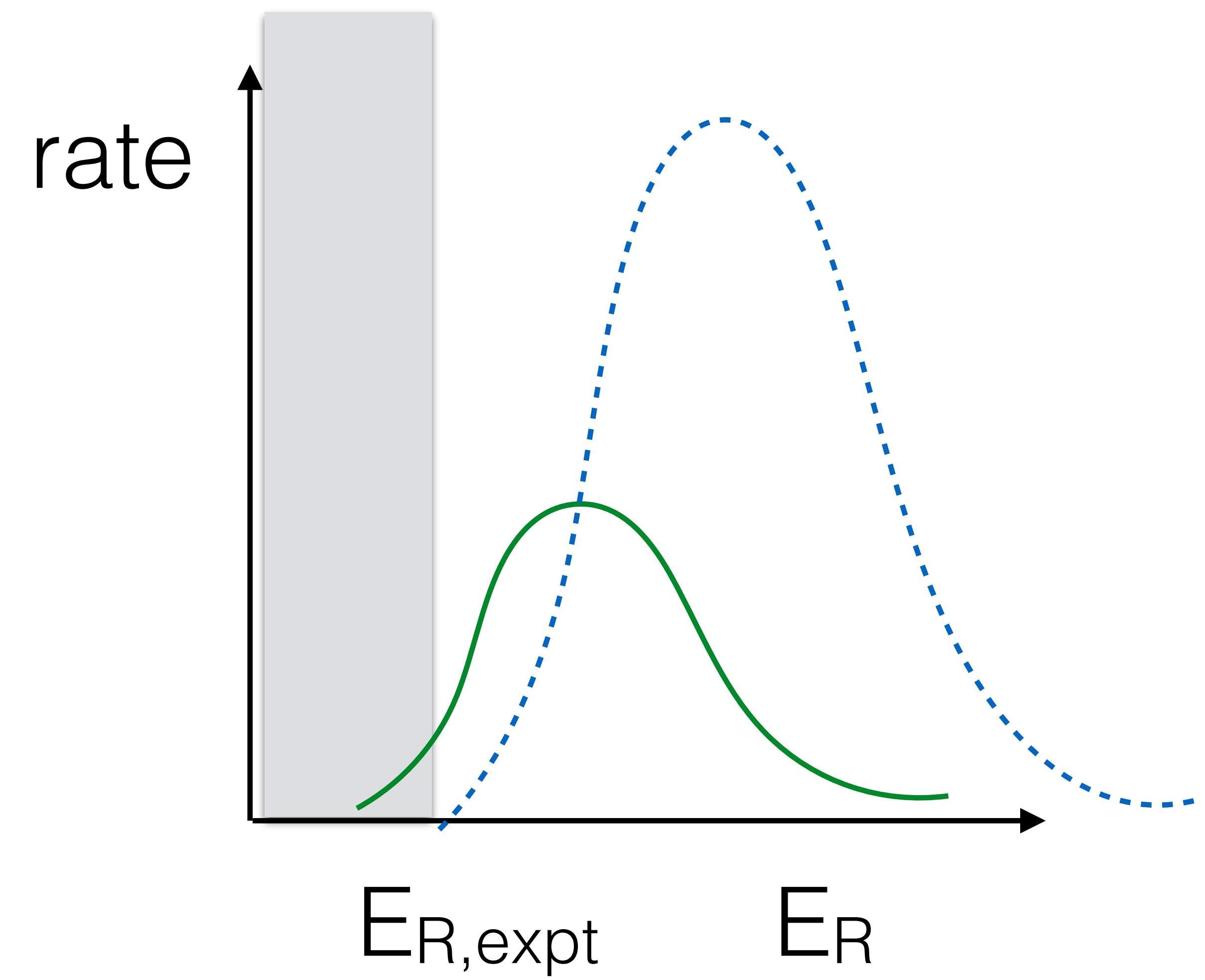

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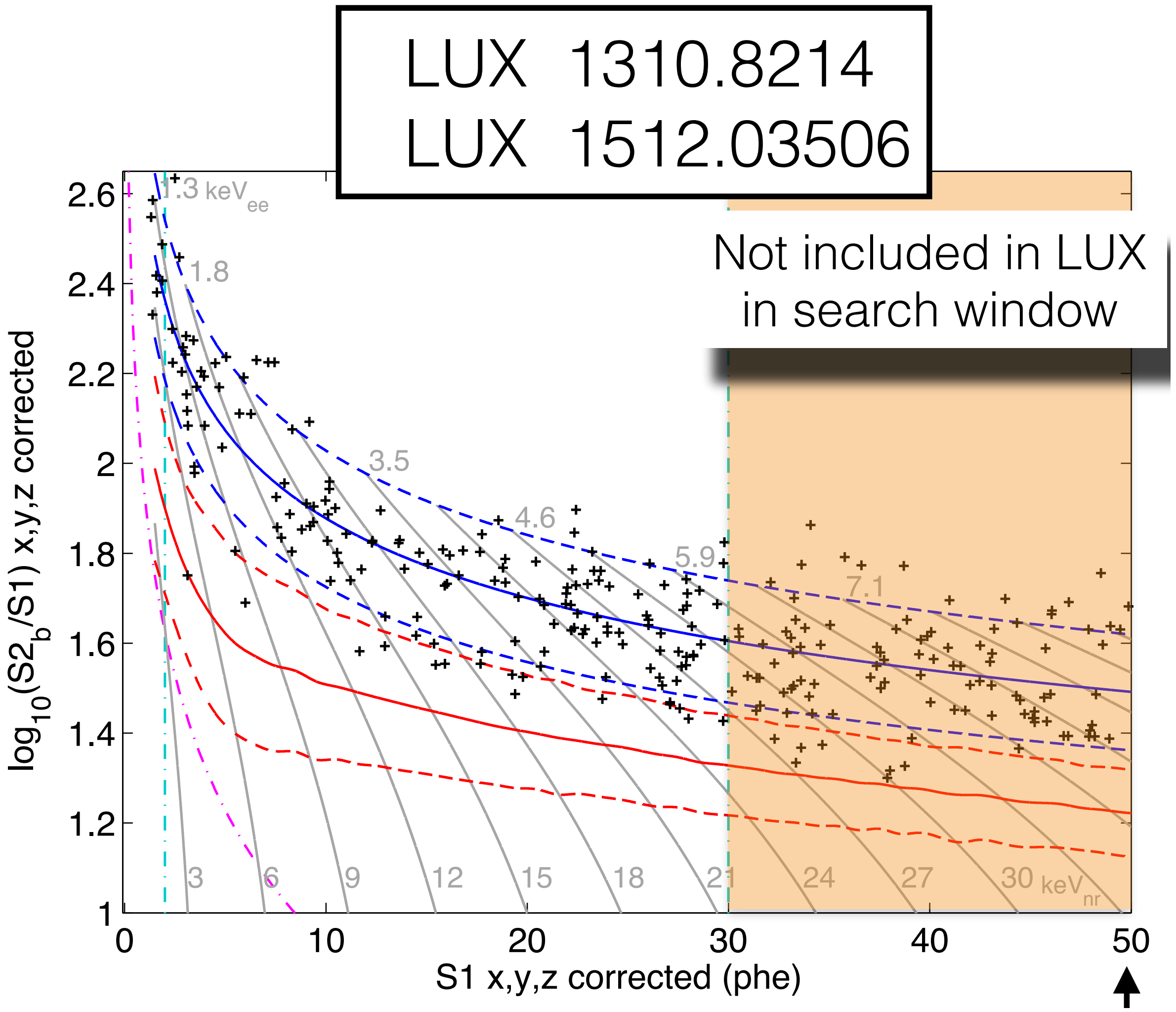
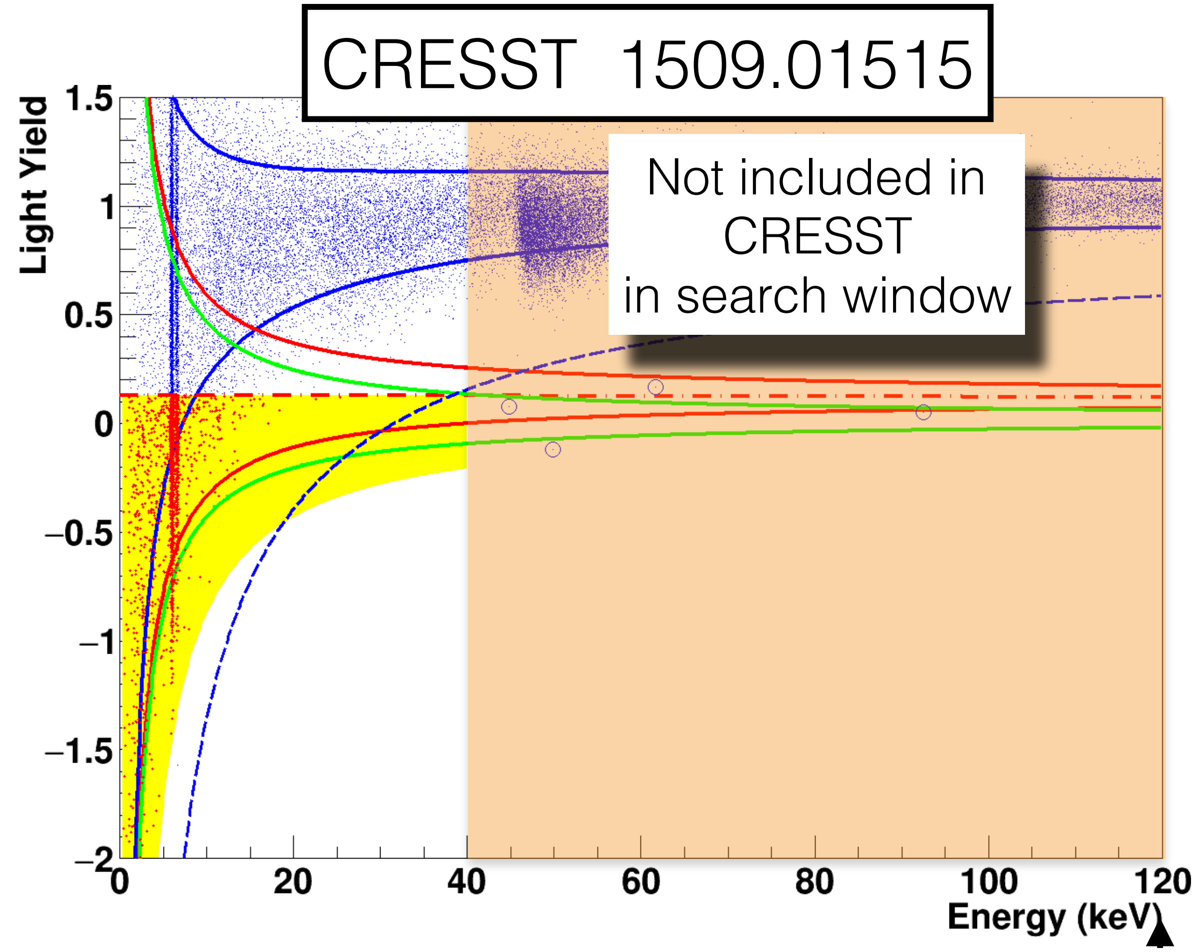
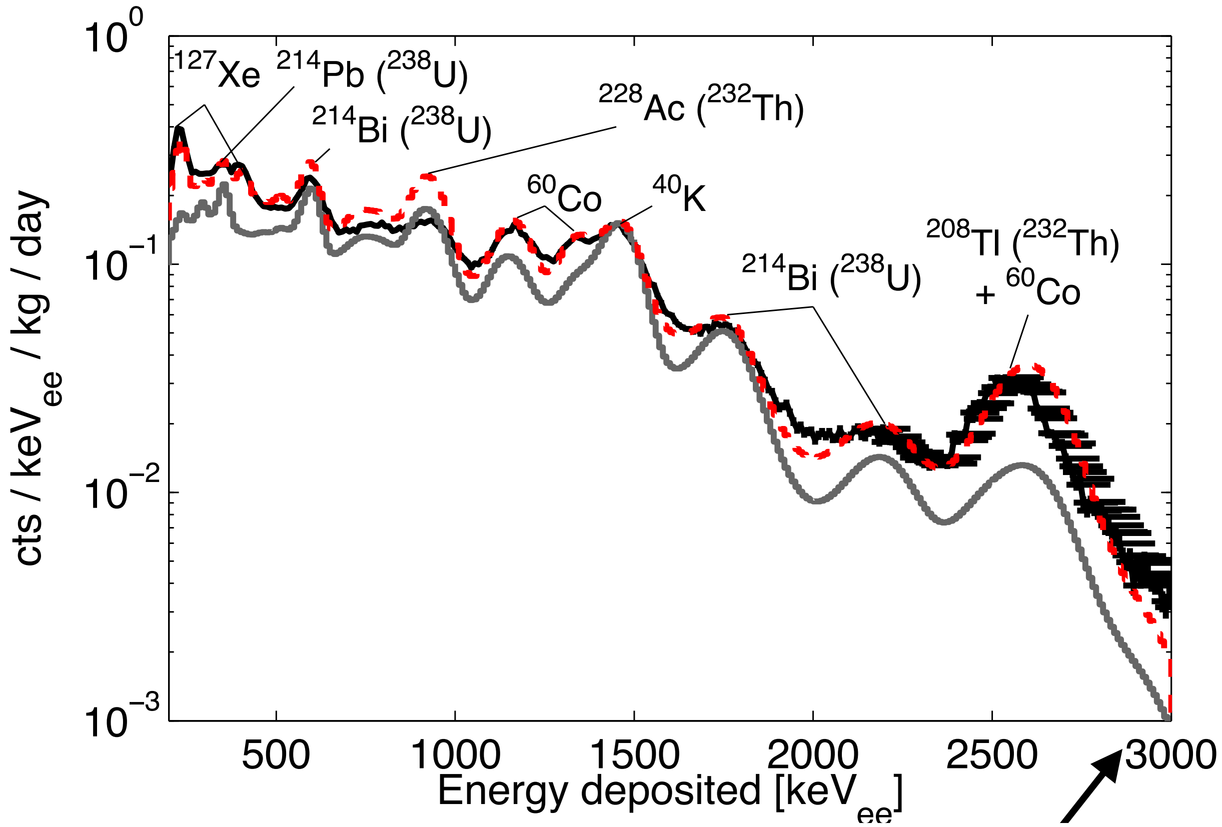


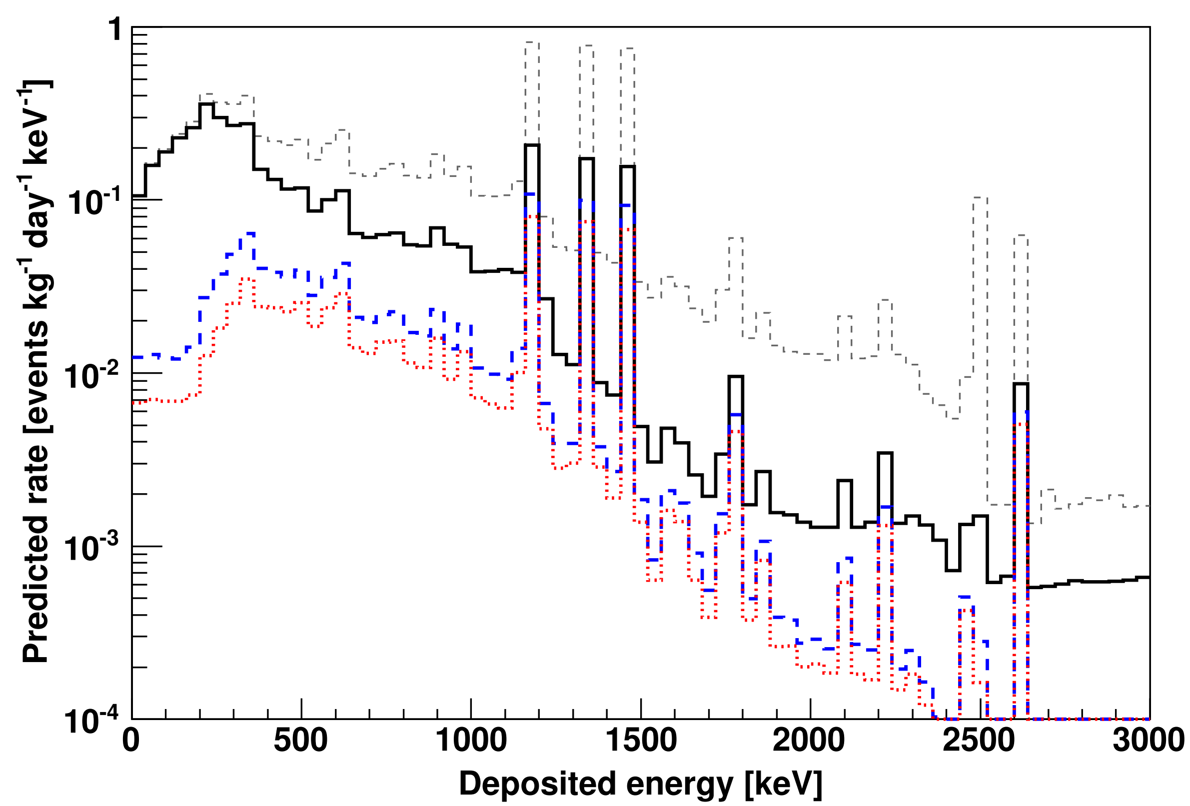


focus of current runs on low E_R

BUT: experiments are sensitive to high recoil events

ex. LUX 1403.1299 Xenon100 1101.3866





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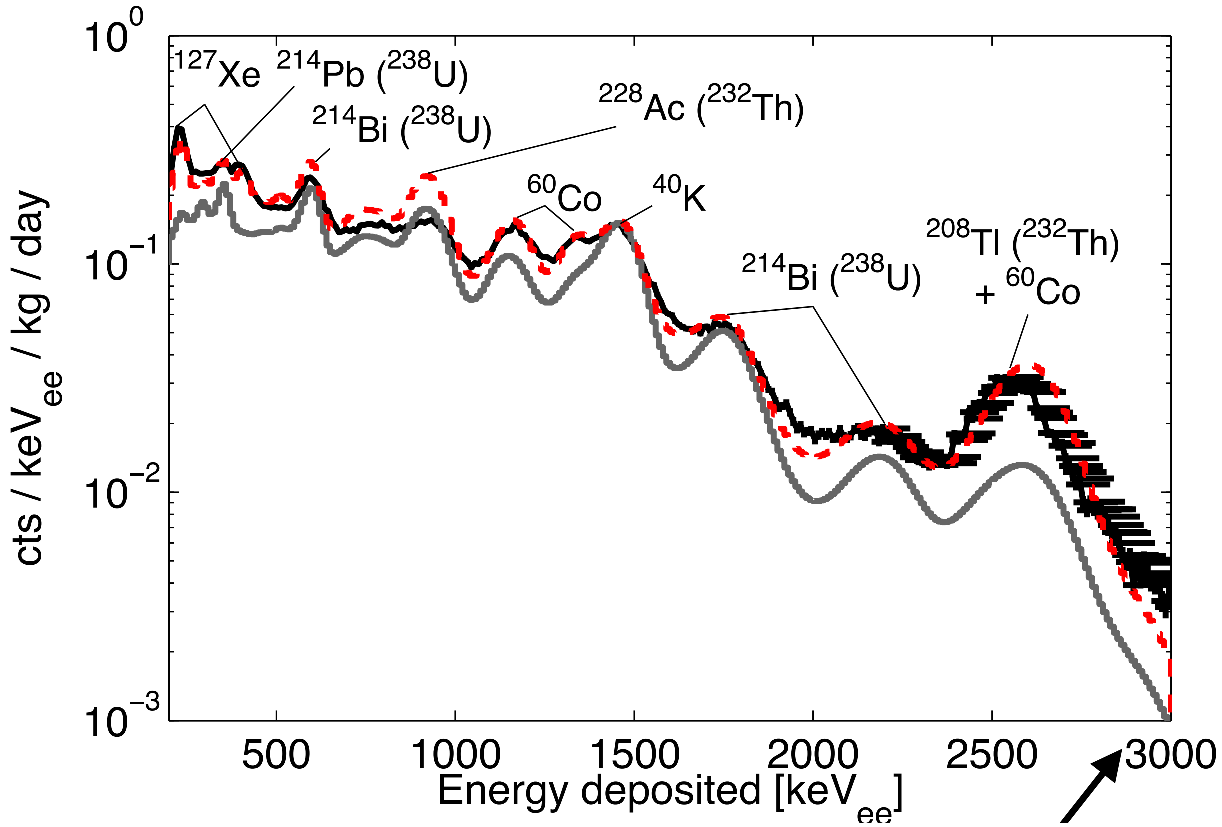
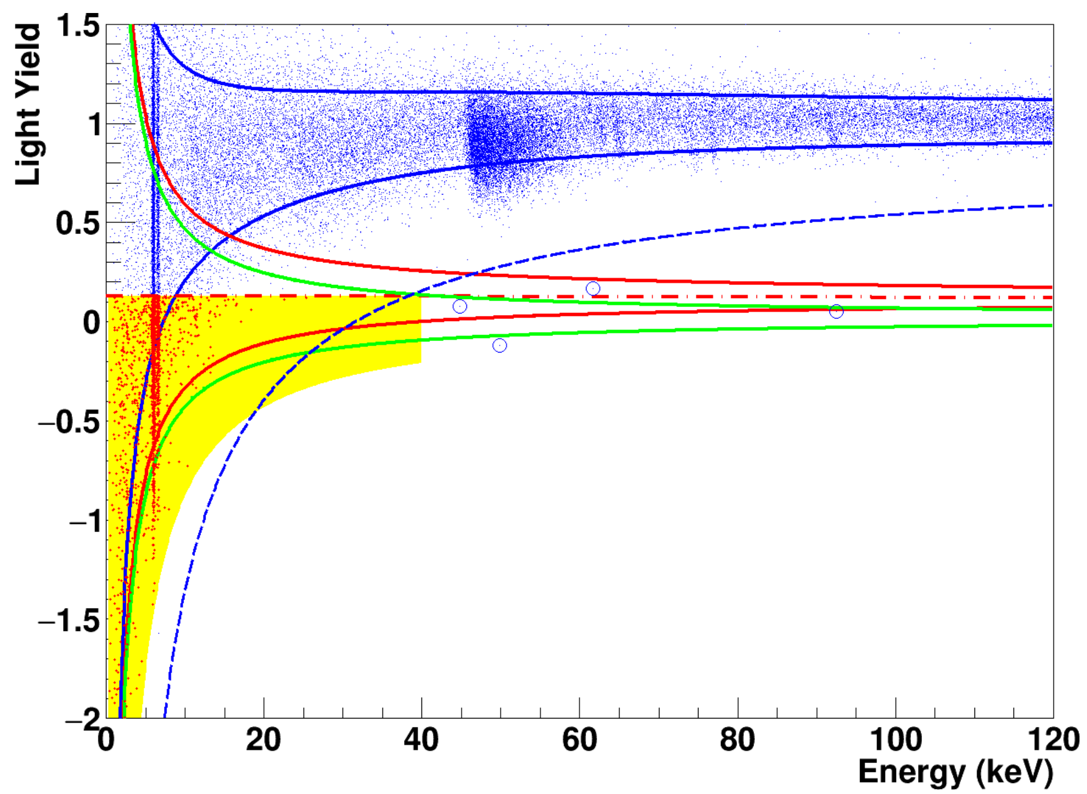


CRESST 1509.01515



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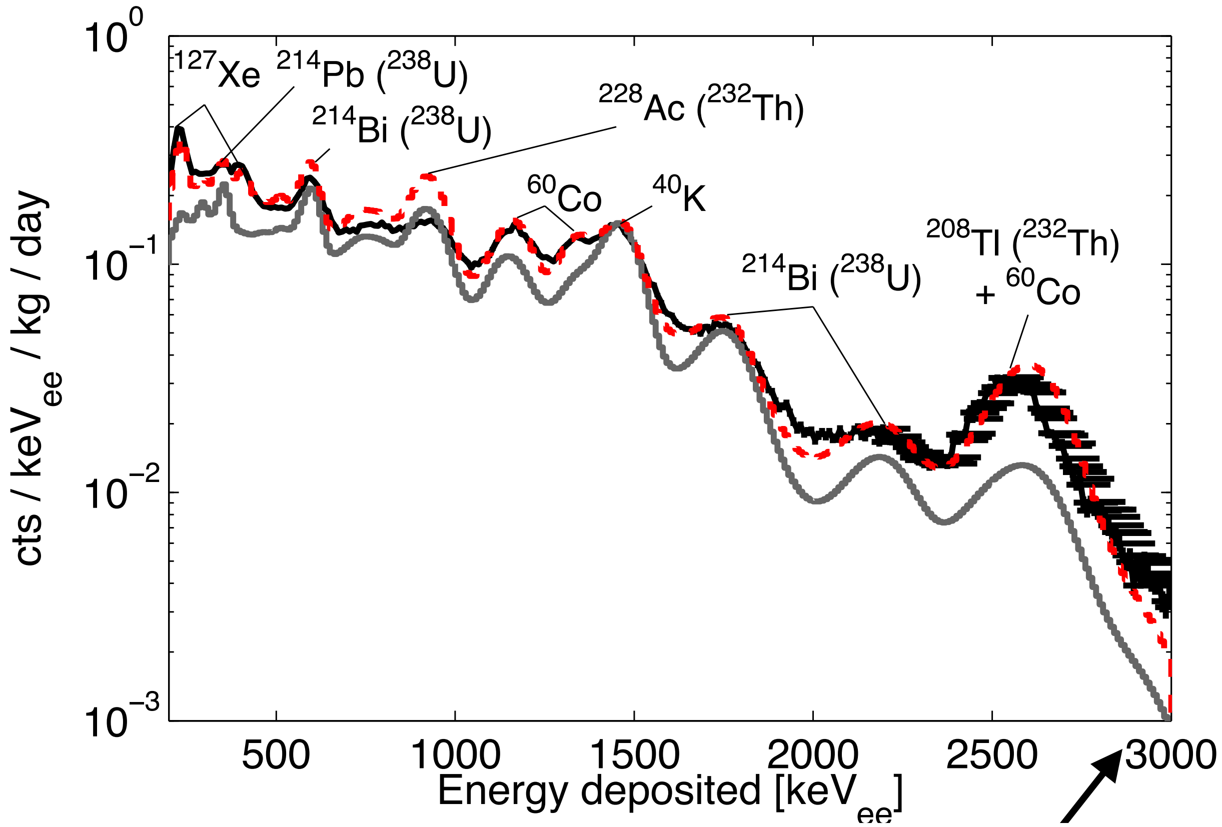

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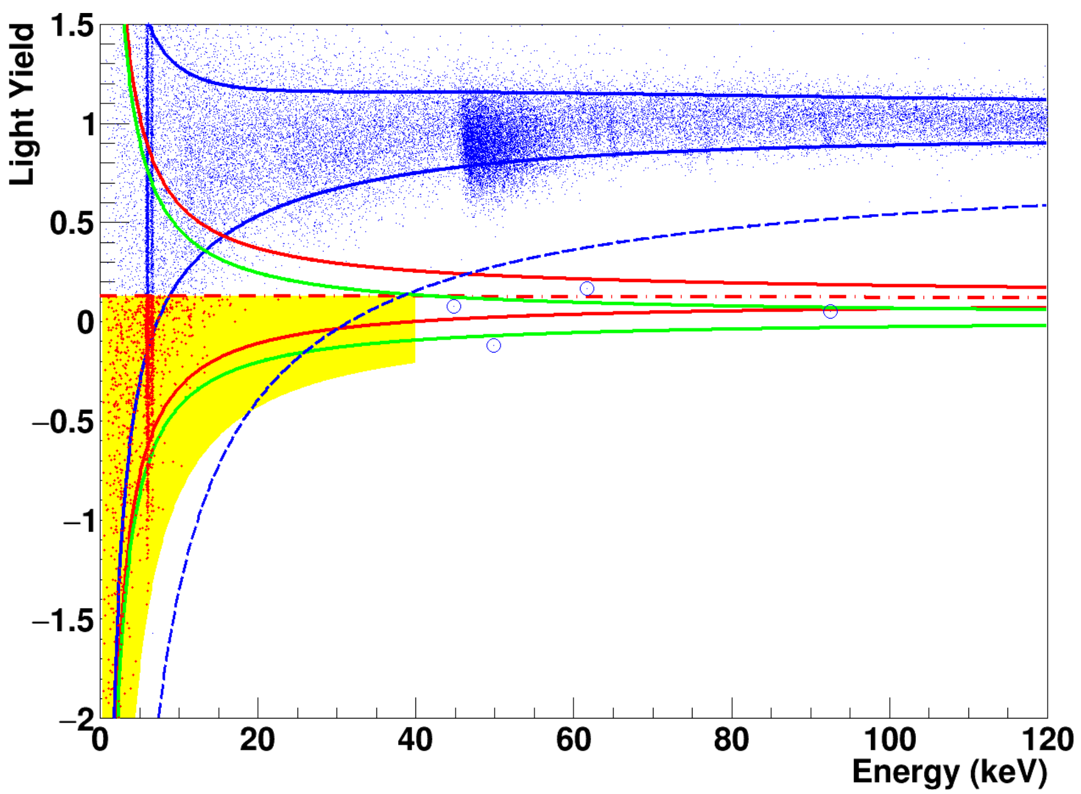

present: inelastic DM could be lurking in high nuclear recoil data of existing experiments: go and look!

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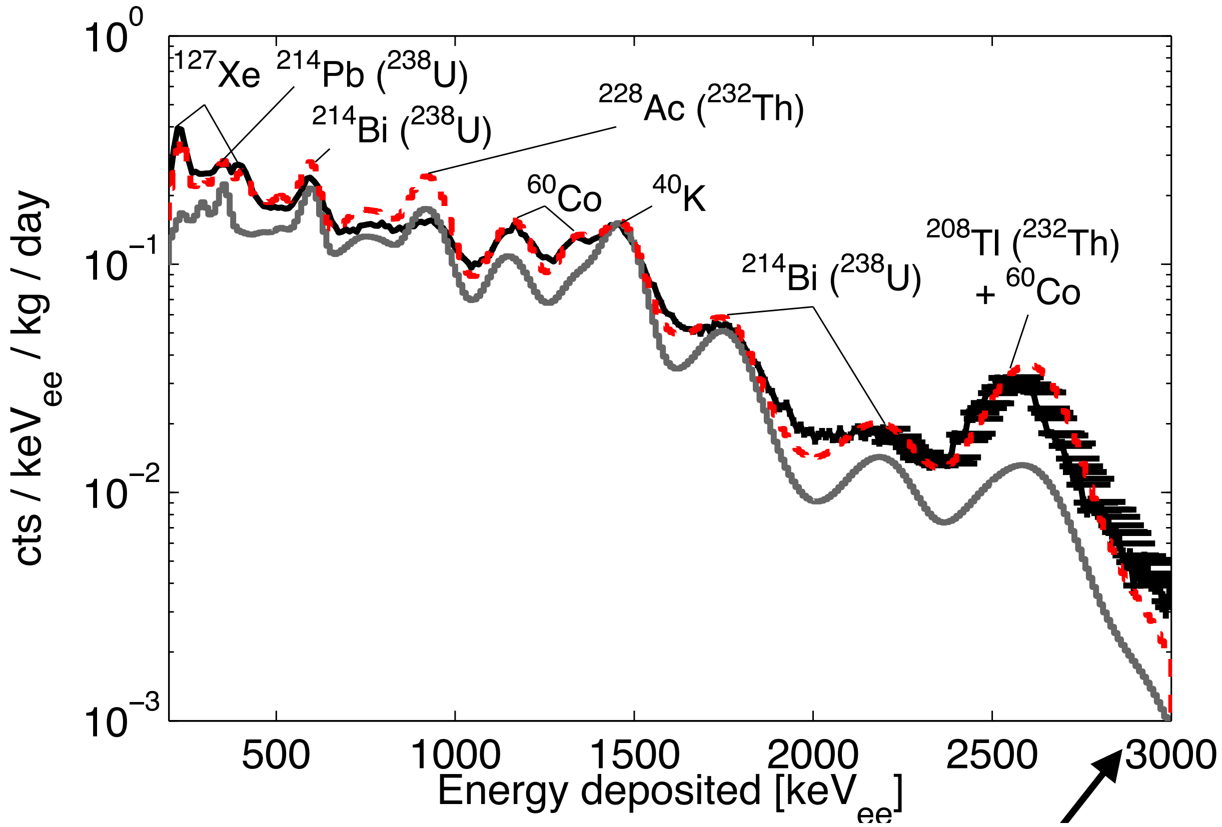

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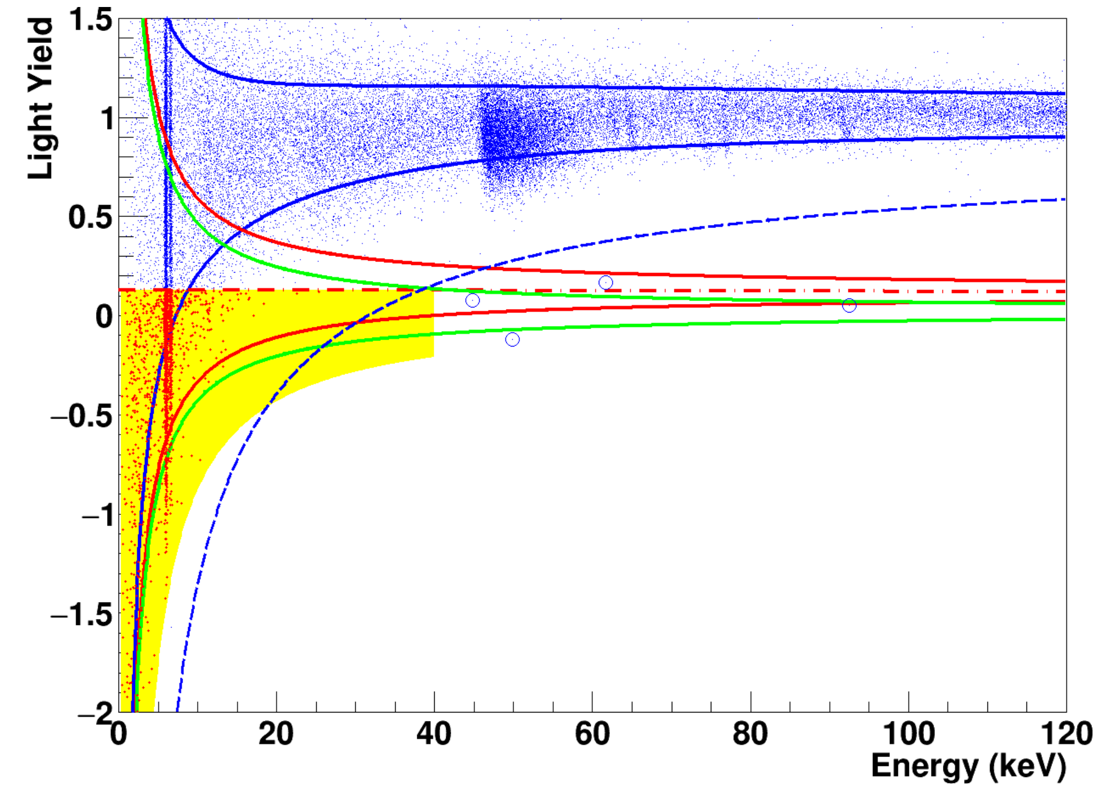

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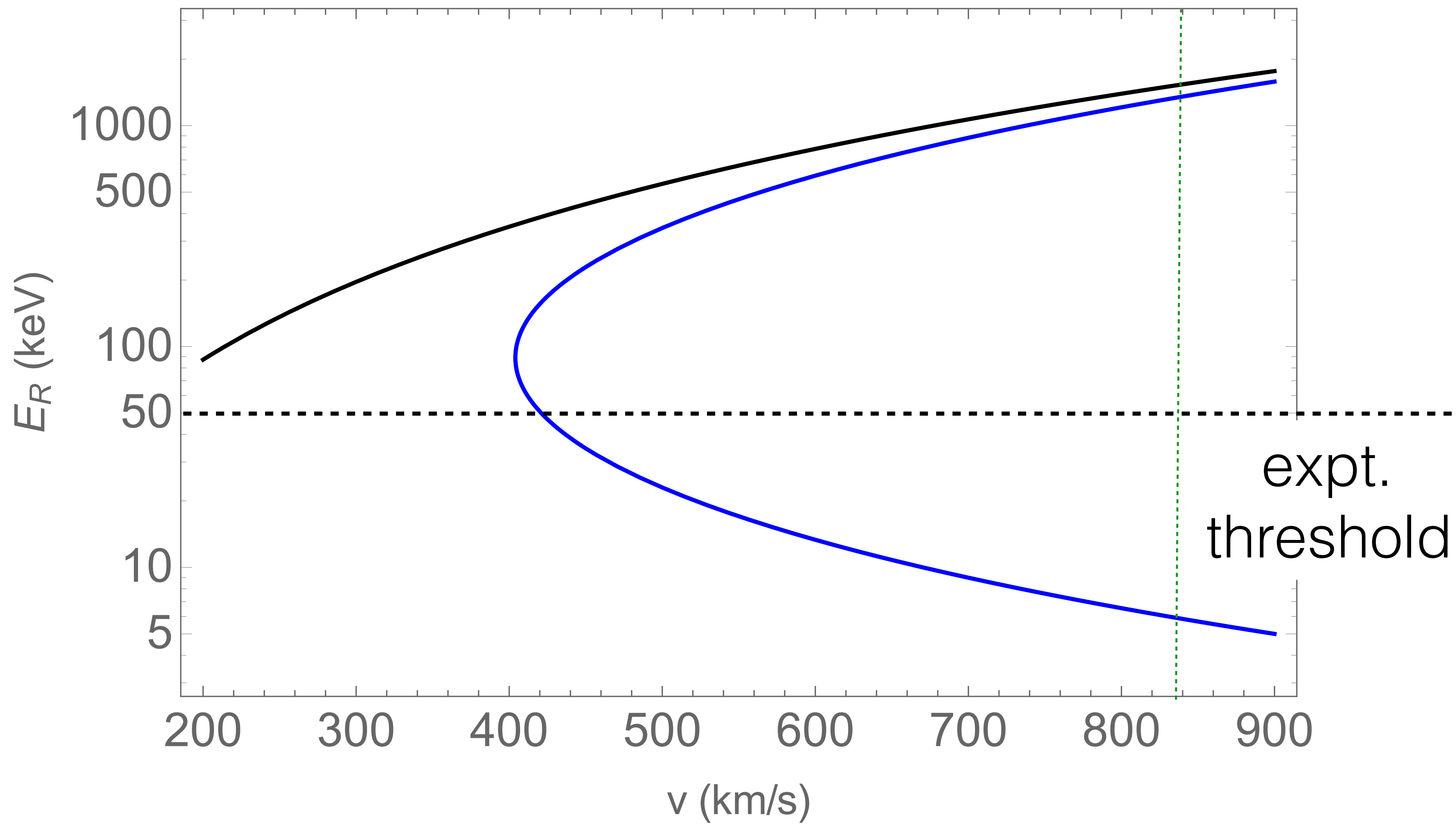
future: don't limit searches to low-recoil

Direct Detection at High Recoil: Inelastic Kinematics

mχ = TeV, δ = 100 keV



$$E_R = \frac{\mu_{\chi N}}{m_N}\left((\mu_{\chi N}\, v^2\ \cos^2\theta_{lab} - \delta) \pm (\mu_{\chi N}\, v^2\ \cos^2\theta_{lab})^{1/2}(\mu_{\chi N}\, v^2\ \cos^2\theta_{lab} - 2\delta)^{1/2}\right)$$

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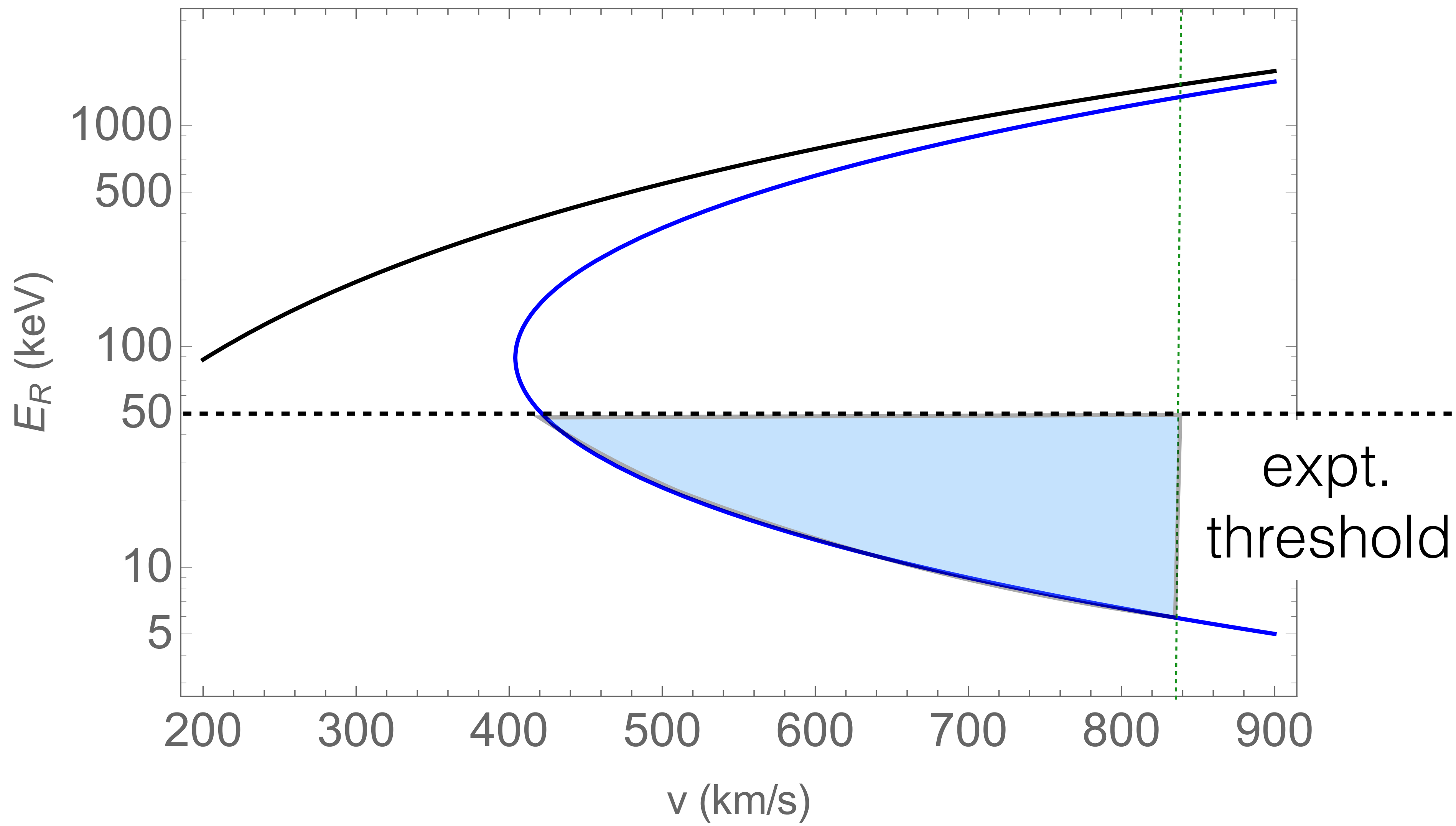

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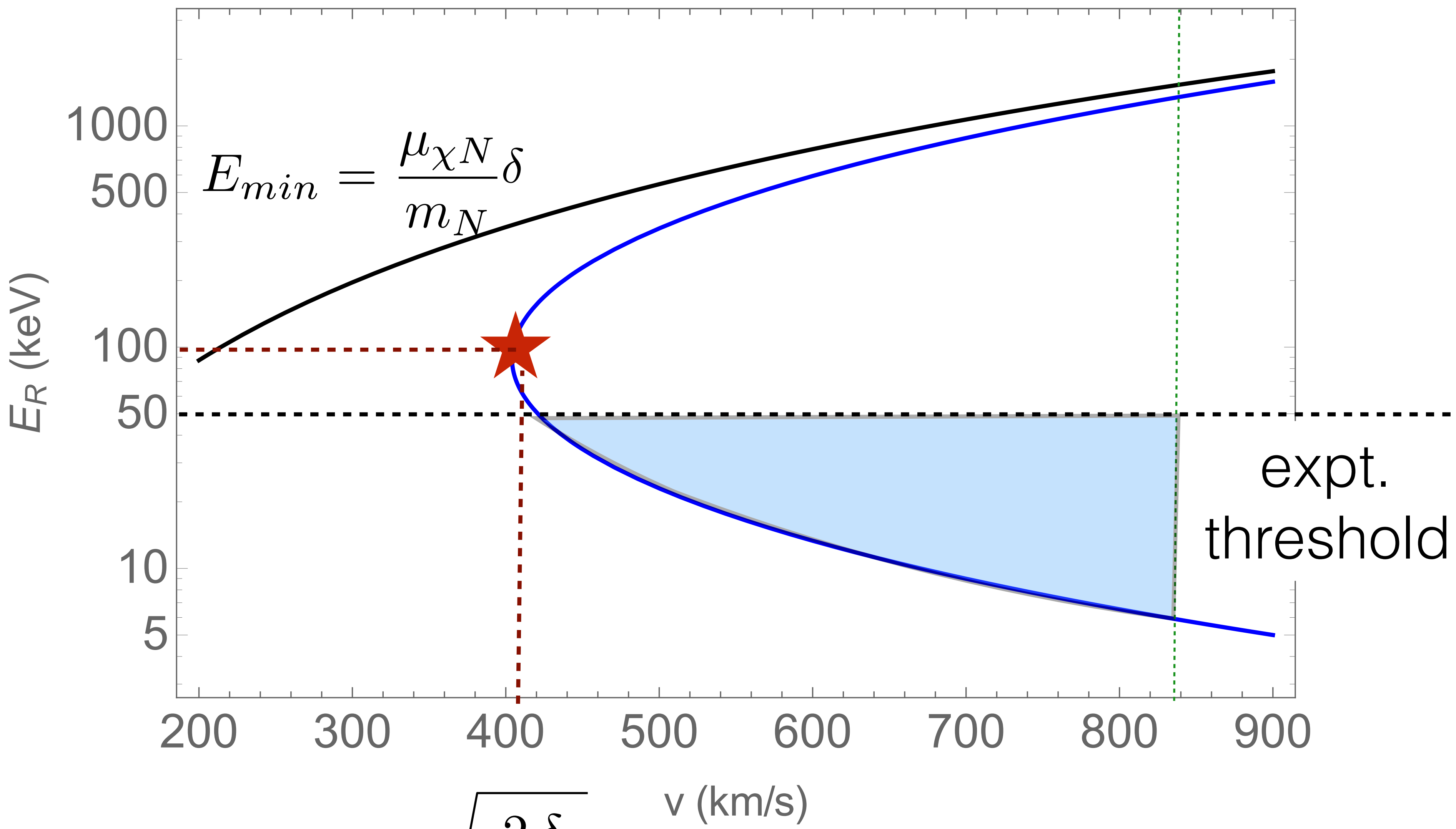

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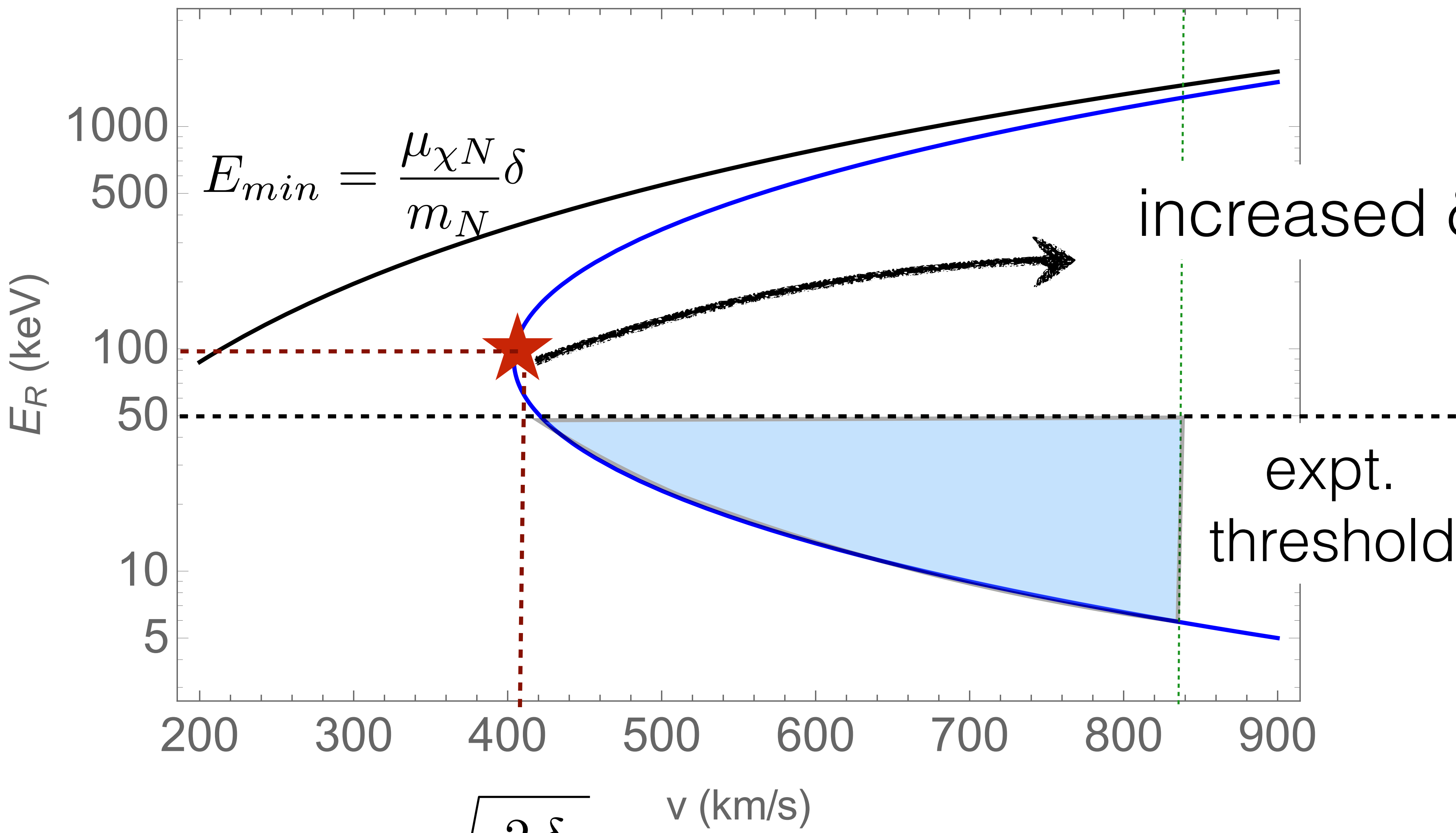

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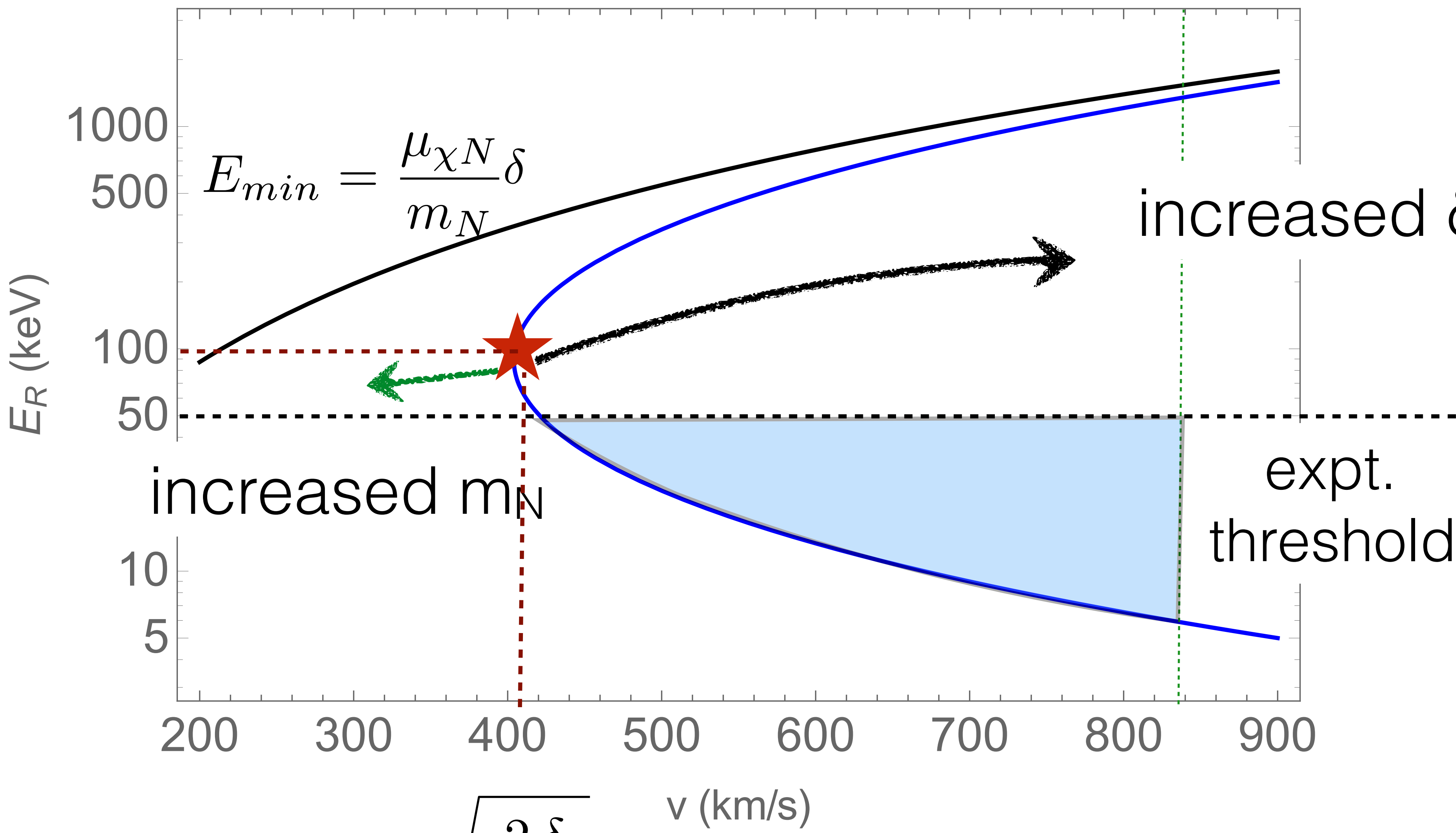

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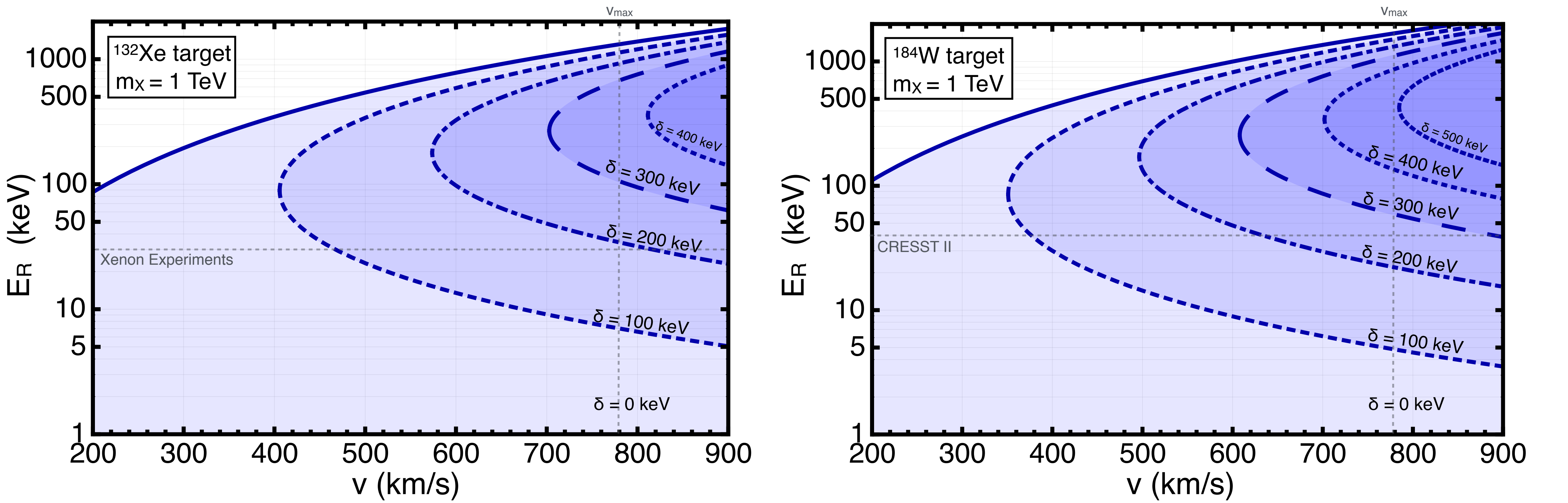

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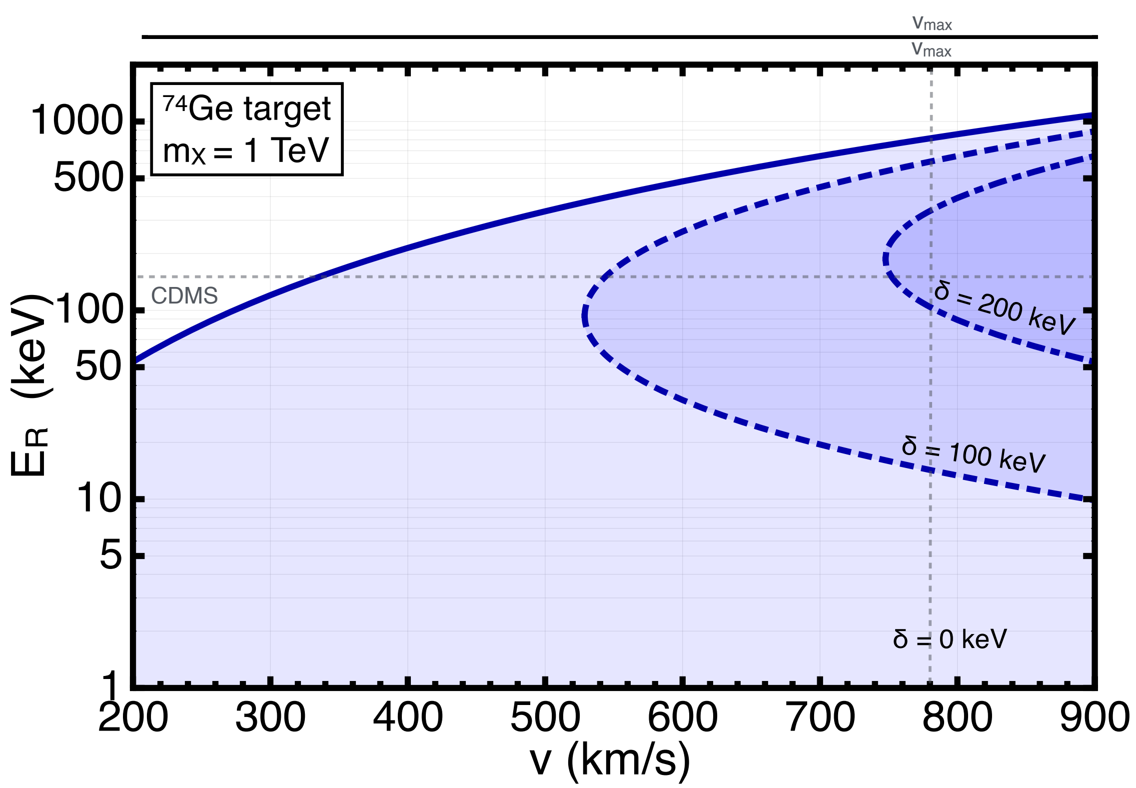

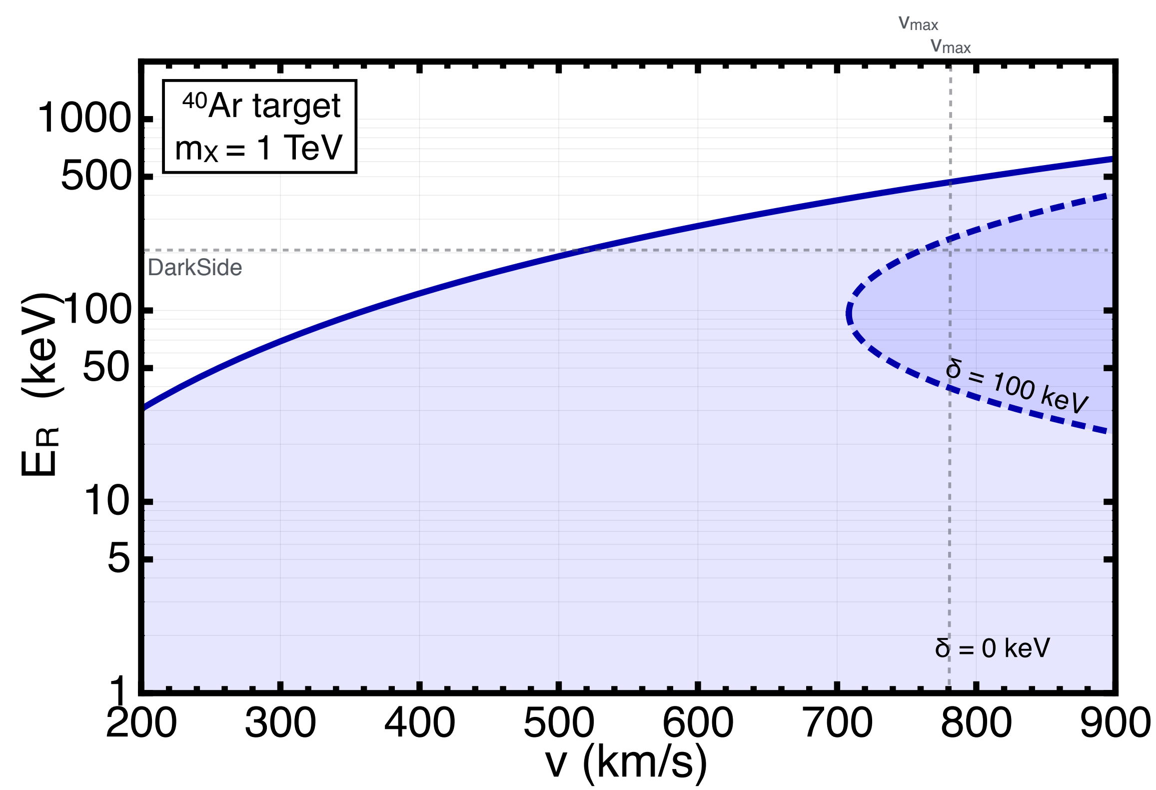

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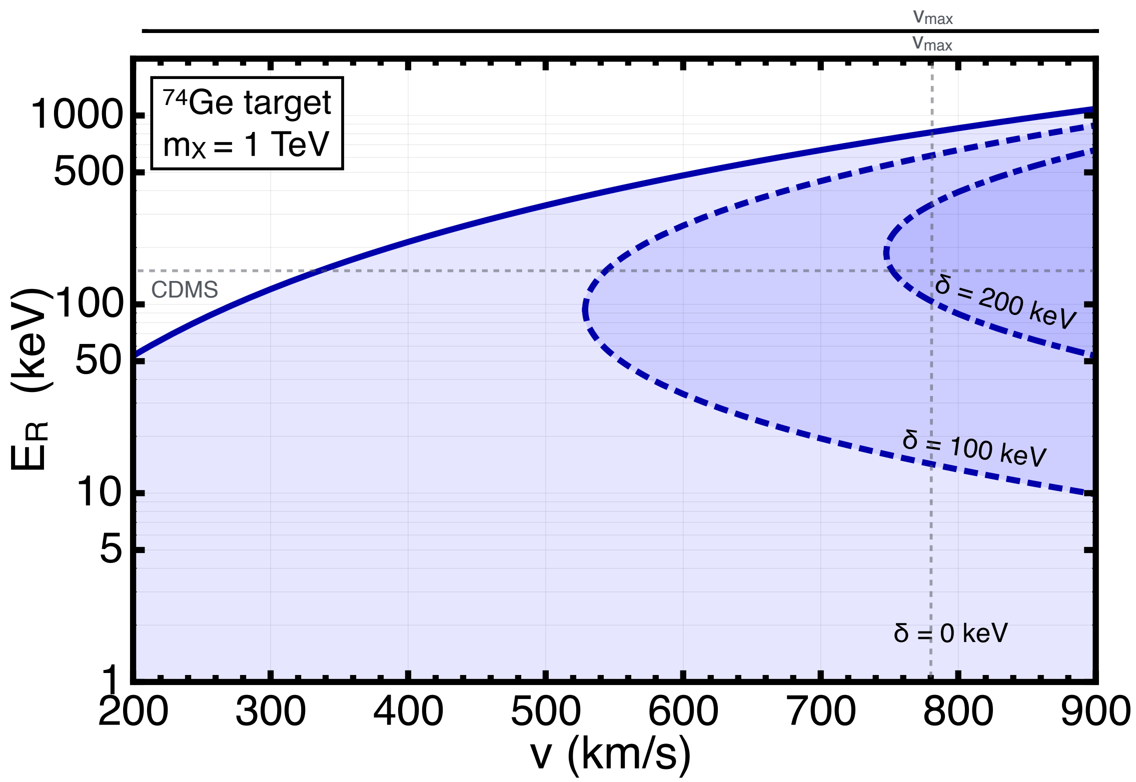

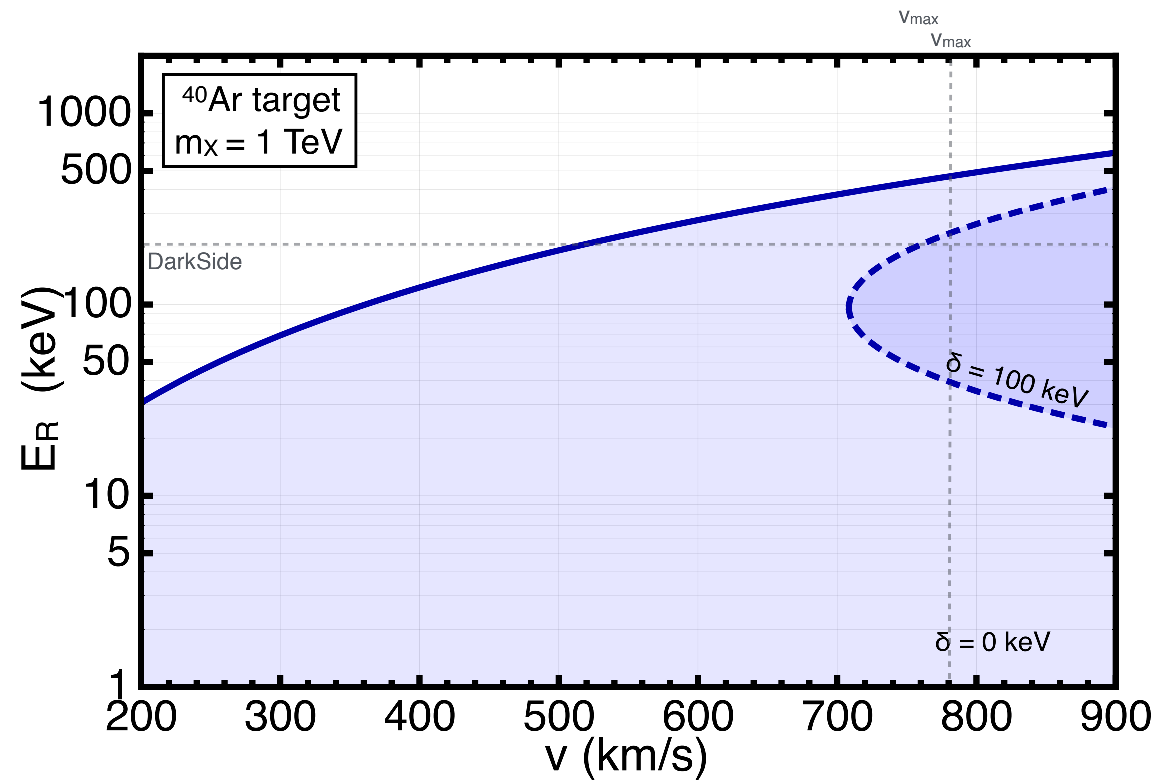

high recoil data can probe farthest in δ for heavy targets

and for $m_X \gg m_N$

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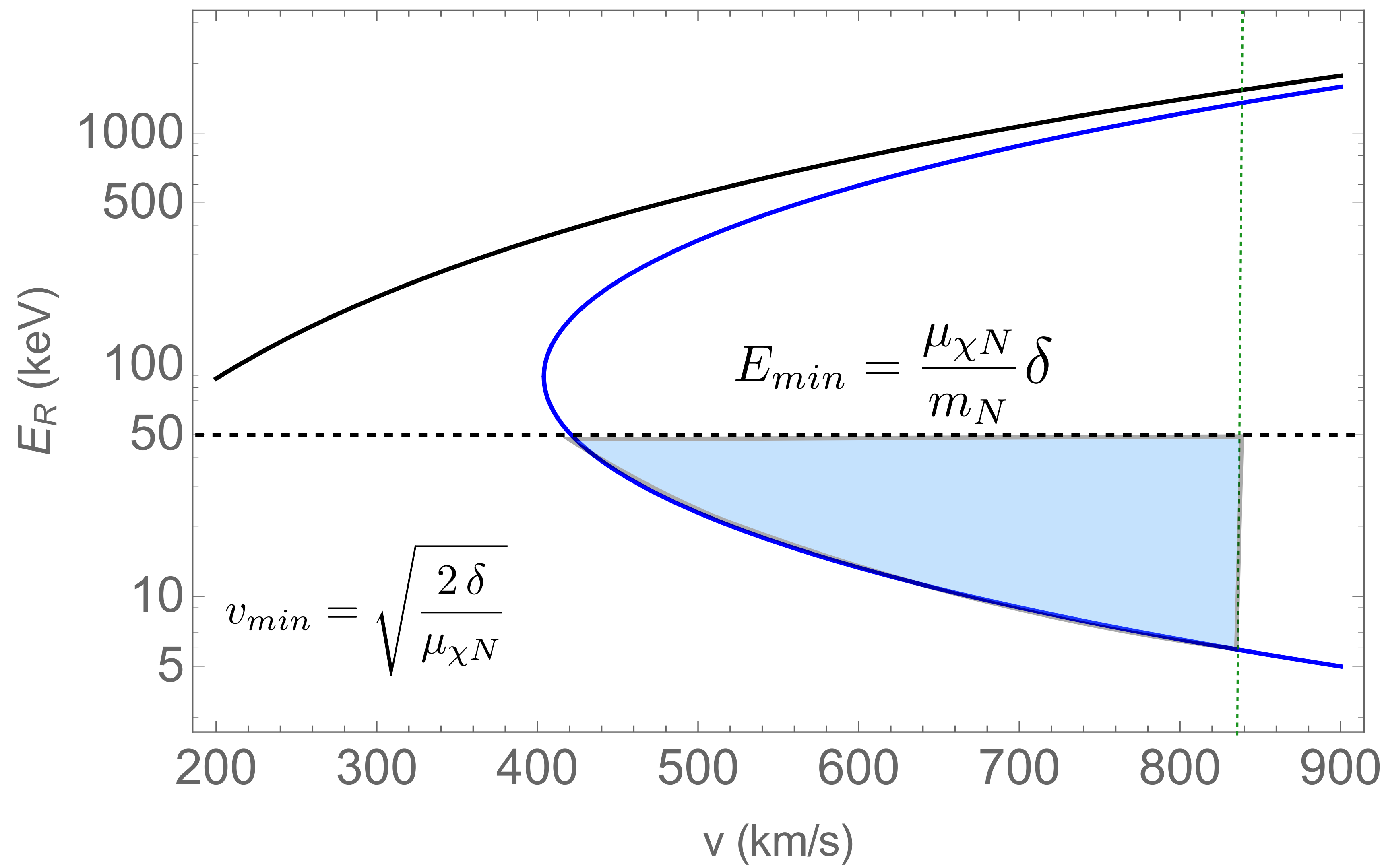

total rate is combines energy range, DM velocity spectrum (MB here), and nuclear form factors

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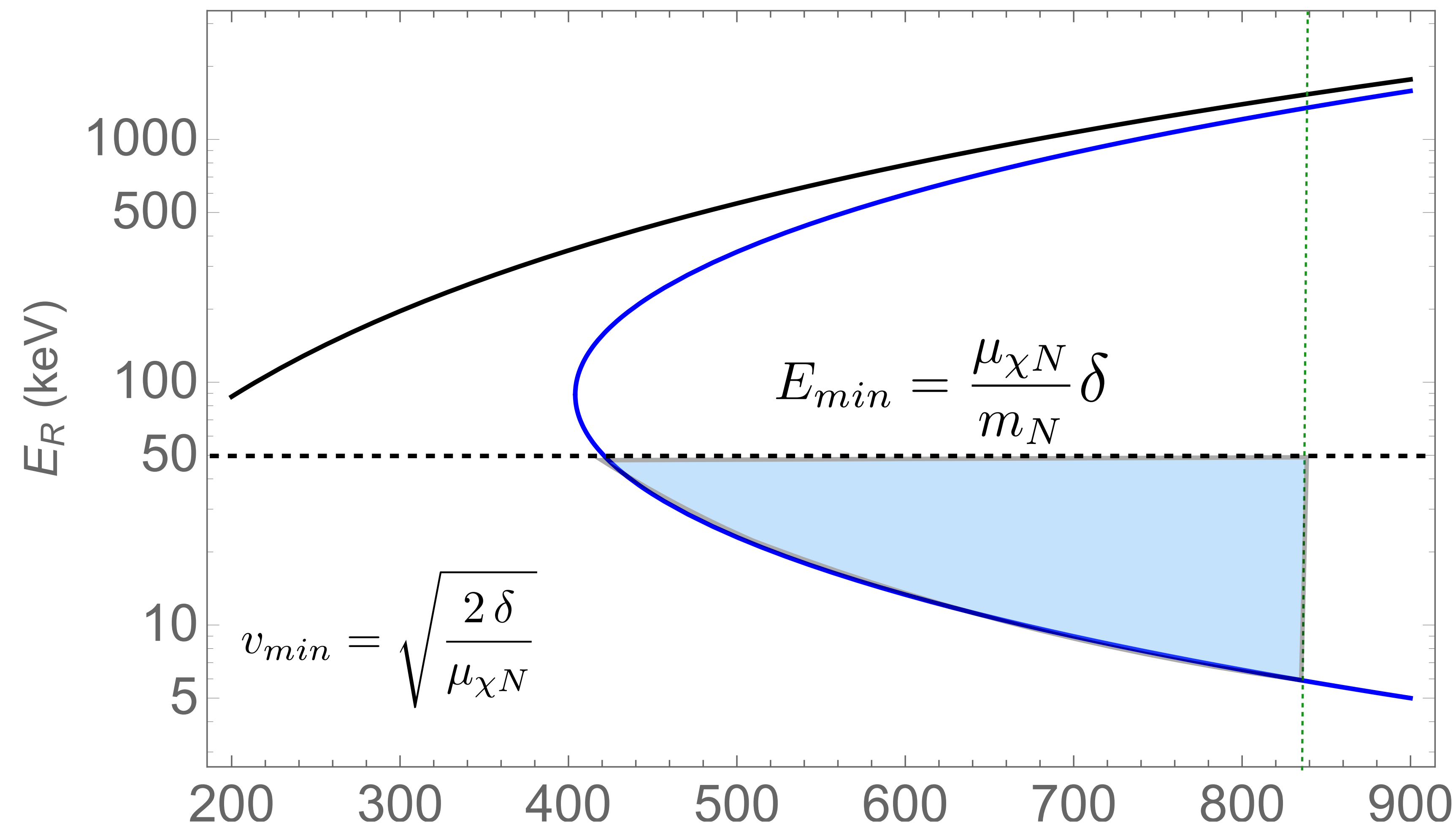

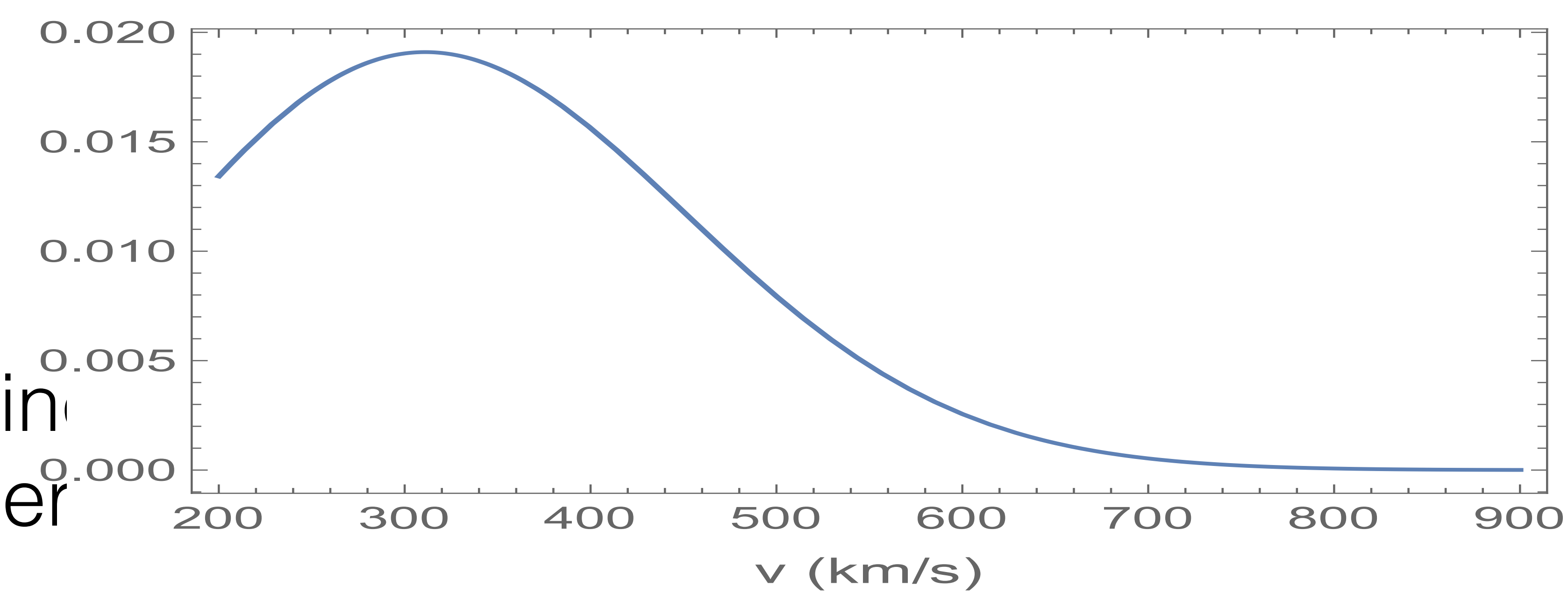

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(MB her

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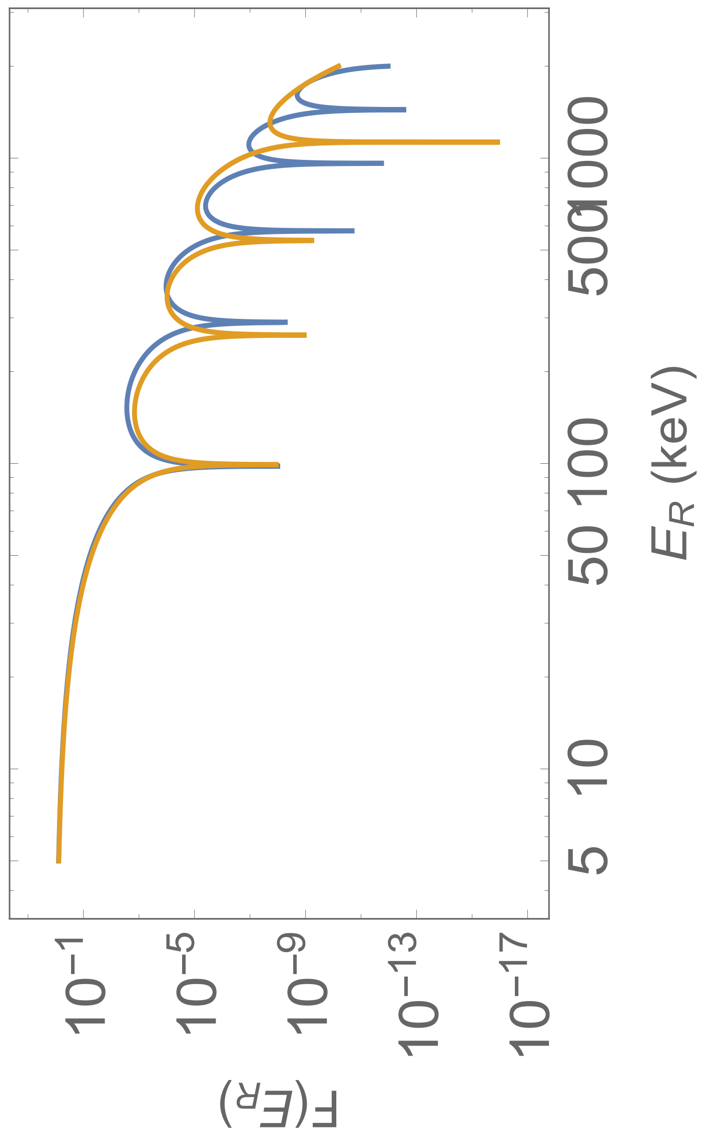

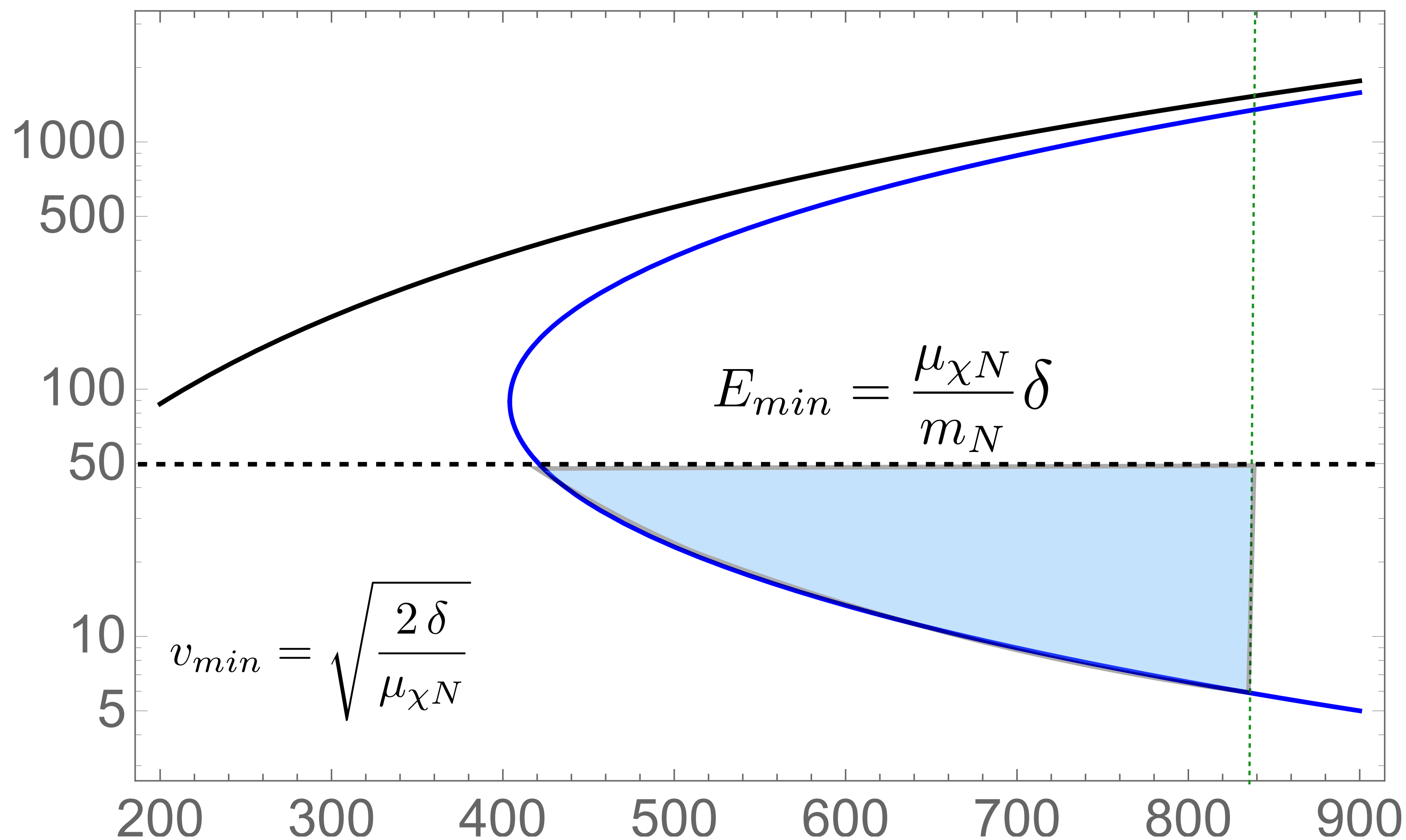

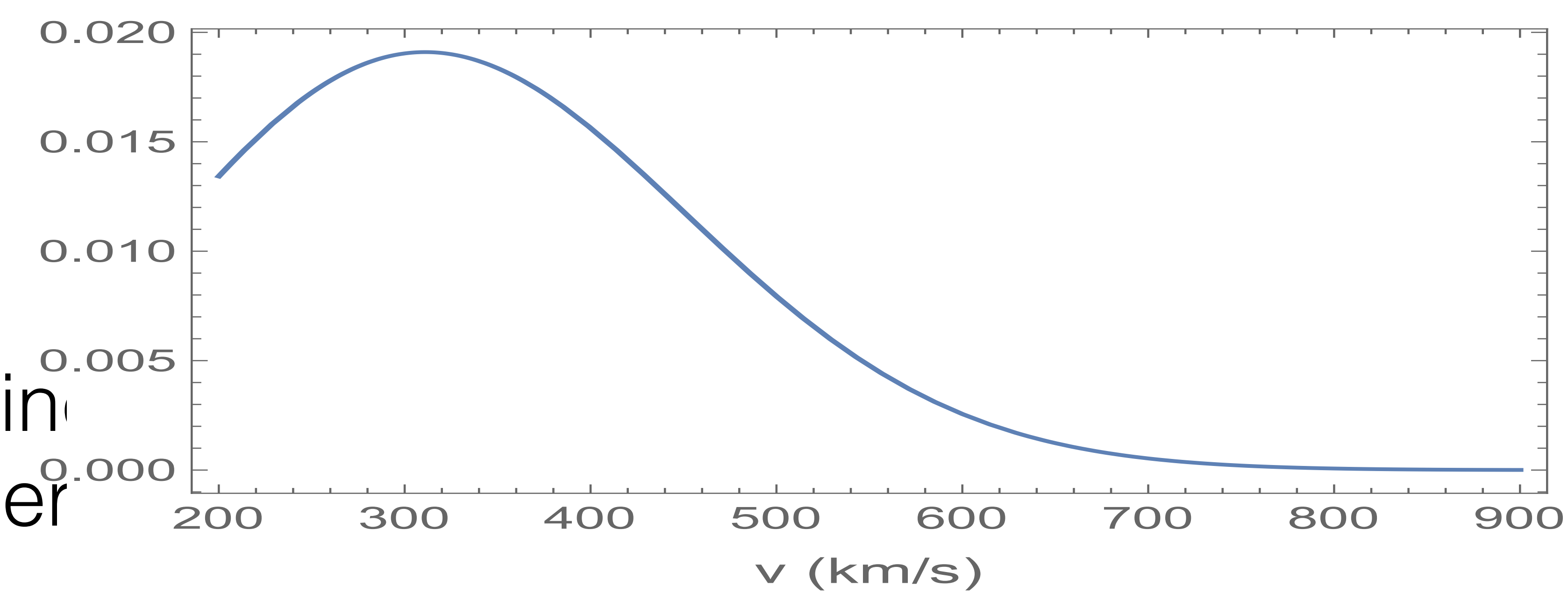

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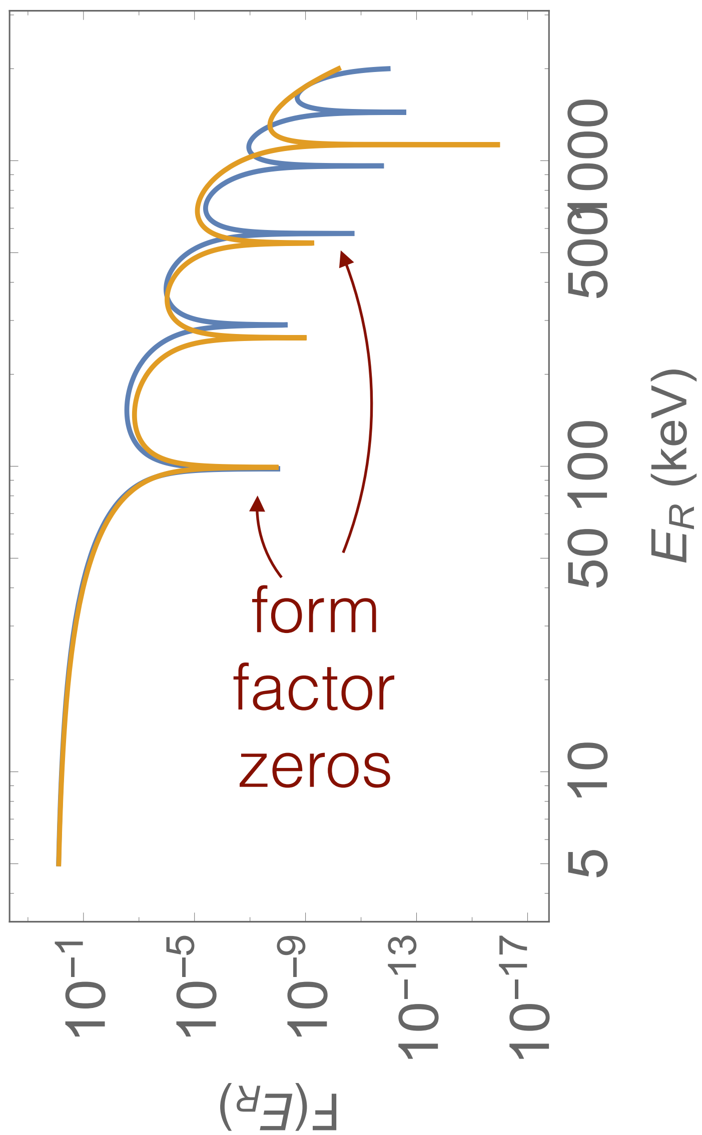
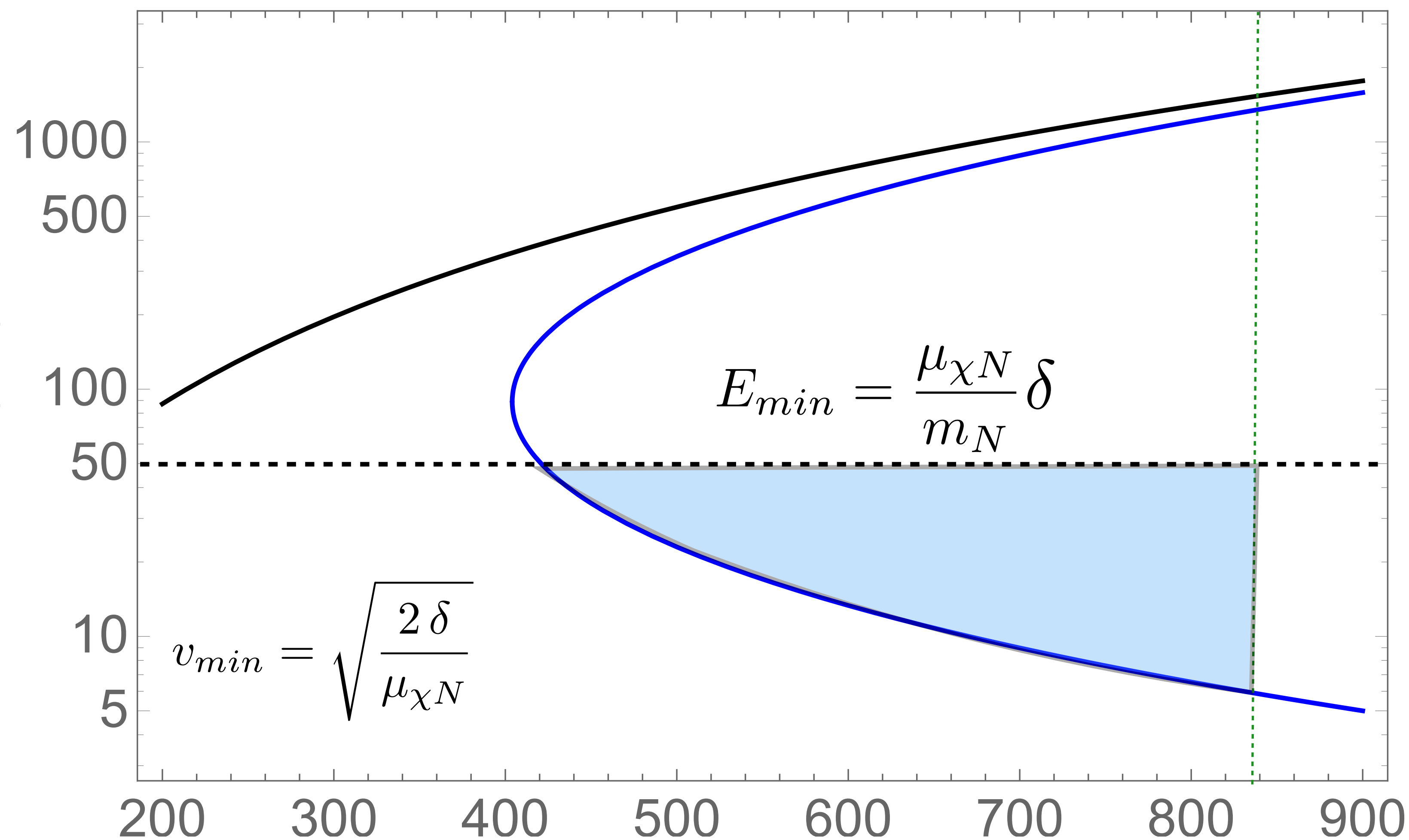
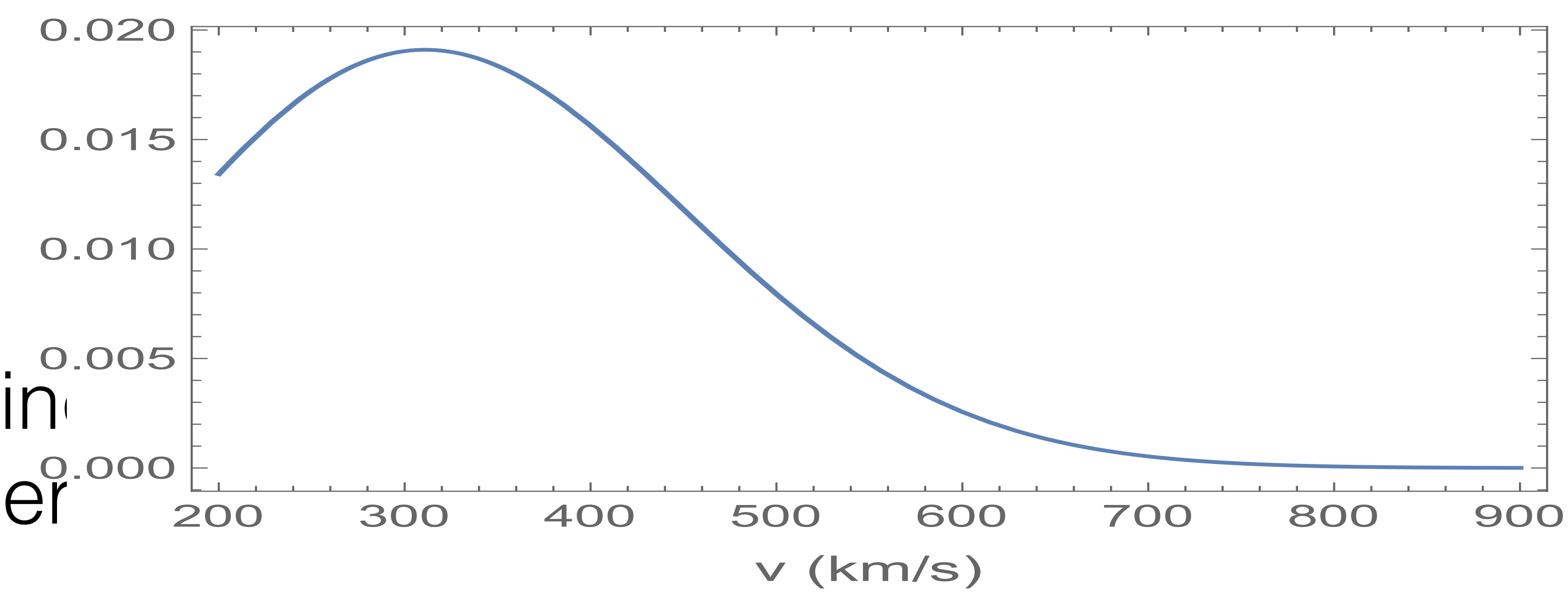
Direct Detection at High Recoil: Inelastic Kinematics

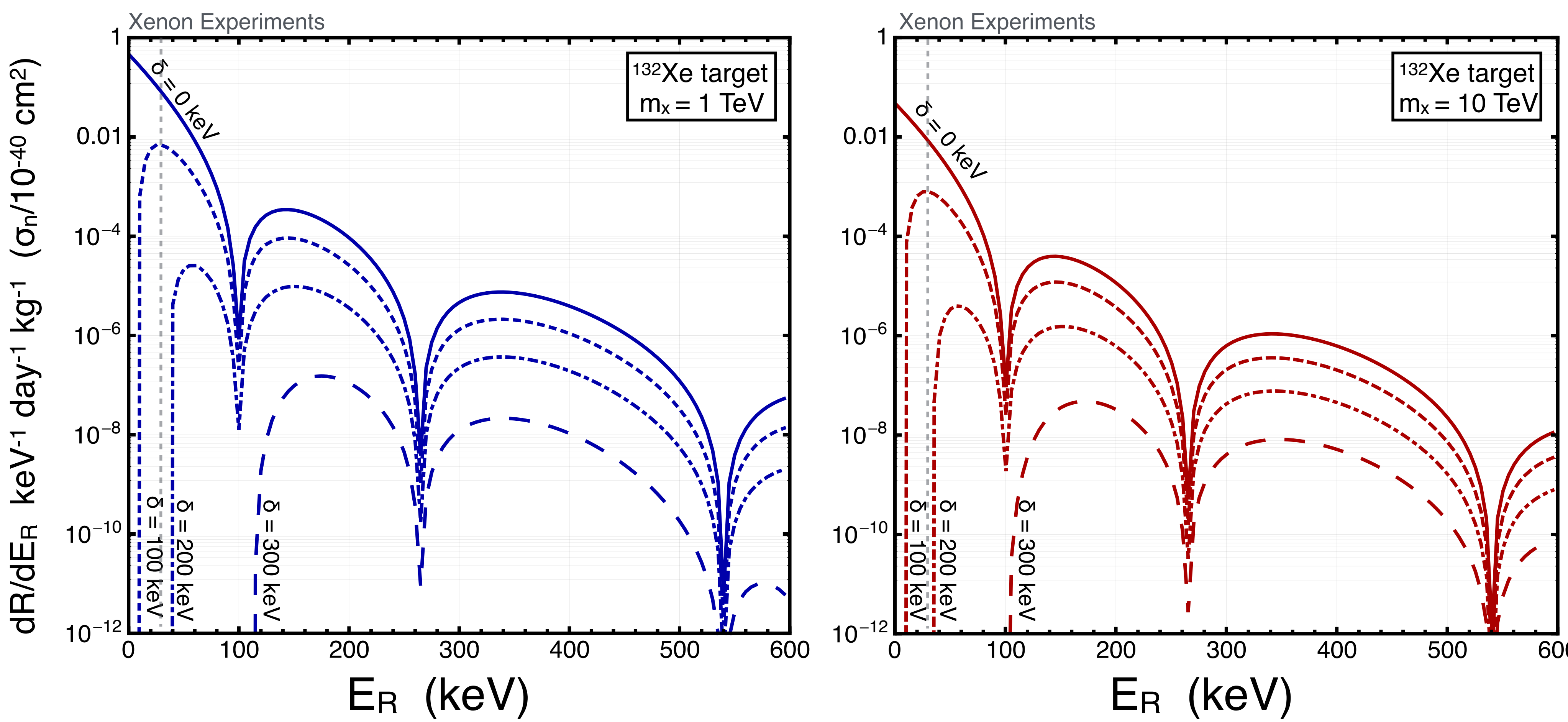






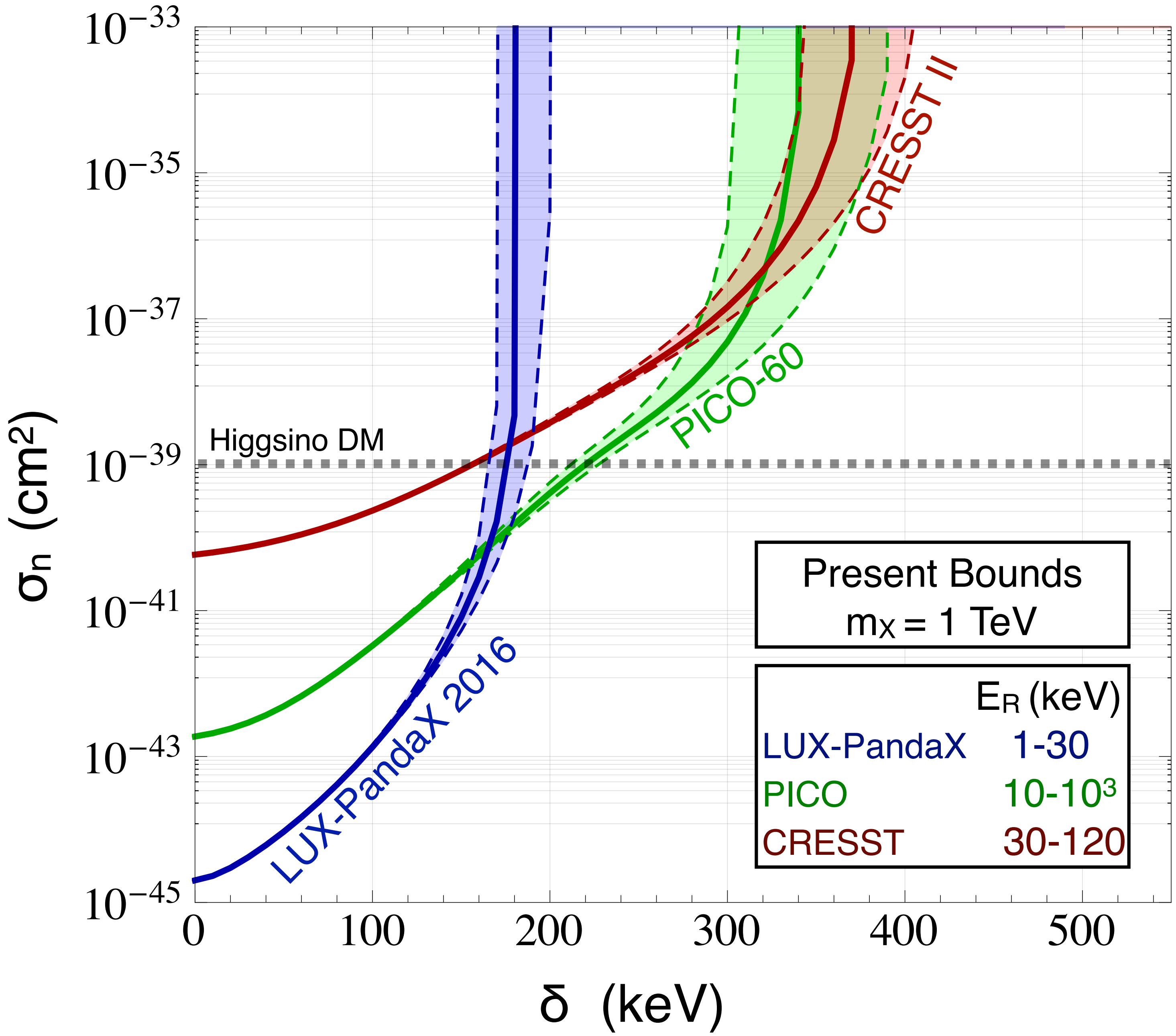
total rate is combin
(MB her

putting everything together



exact rate will be sensitive to the tail of the velocity distribution and large E_R part of form factors

bounds with current data, m_X = 1 TeV

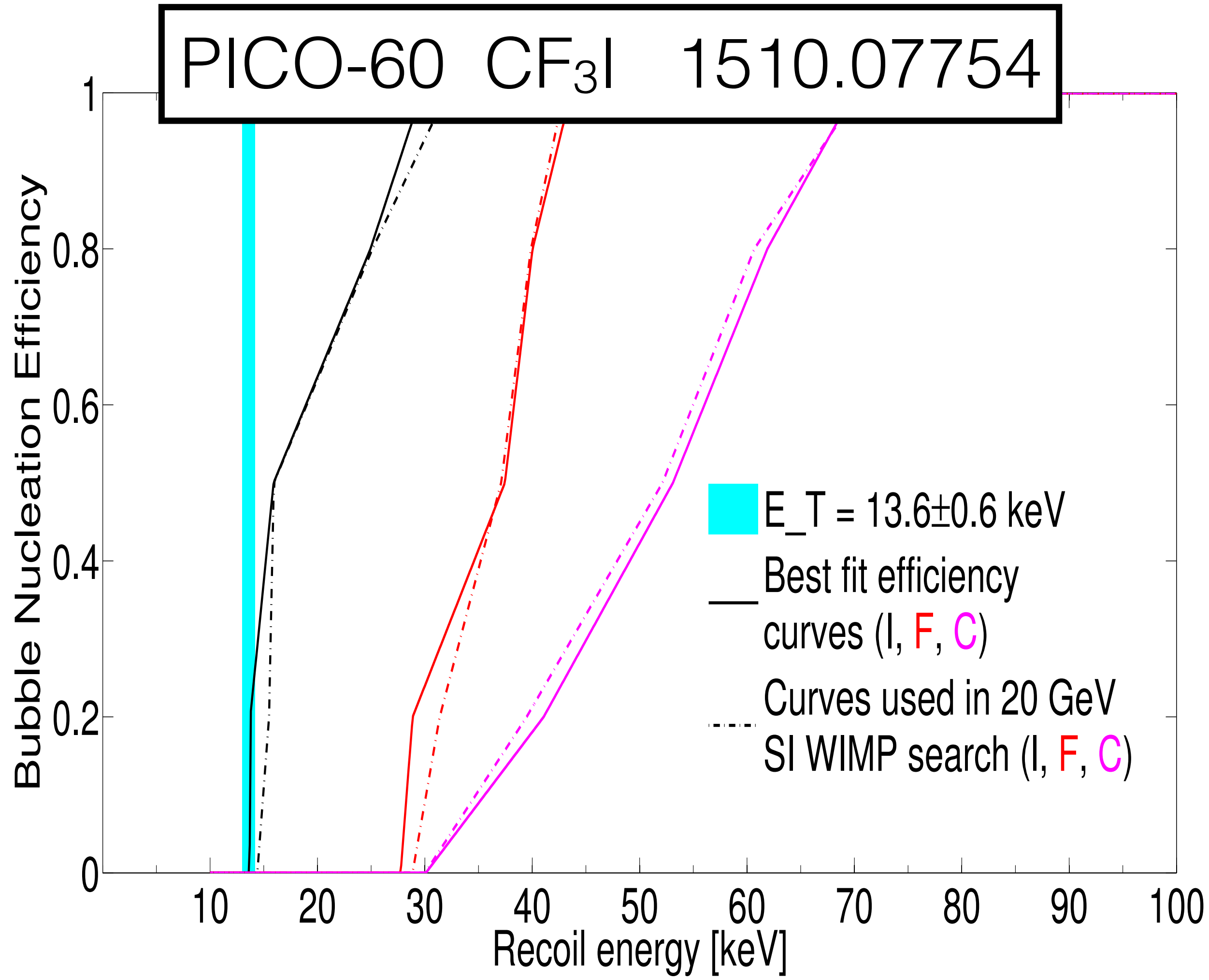


assuming spin-independent cross section, no v dependence

exposure (tonne-day)

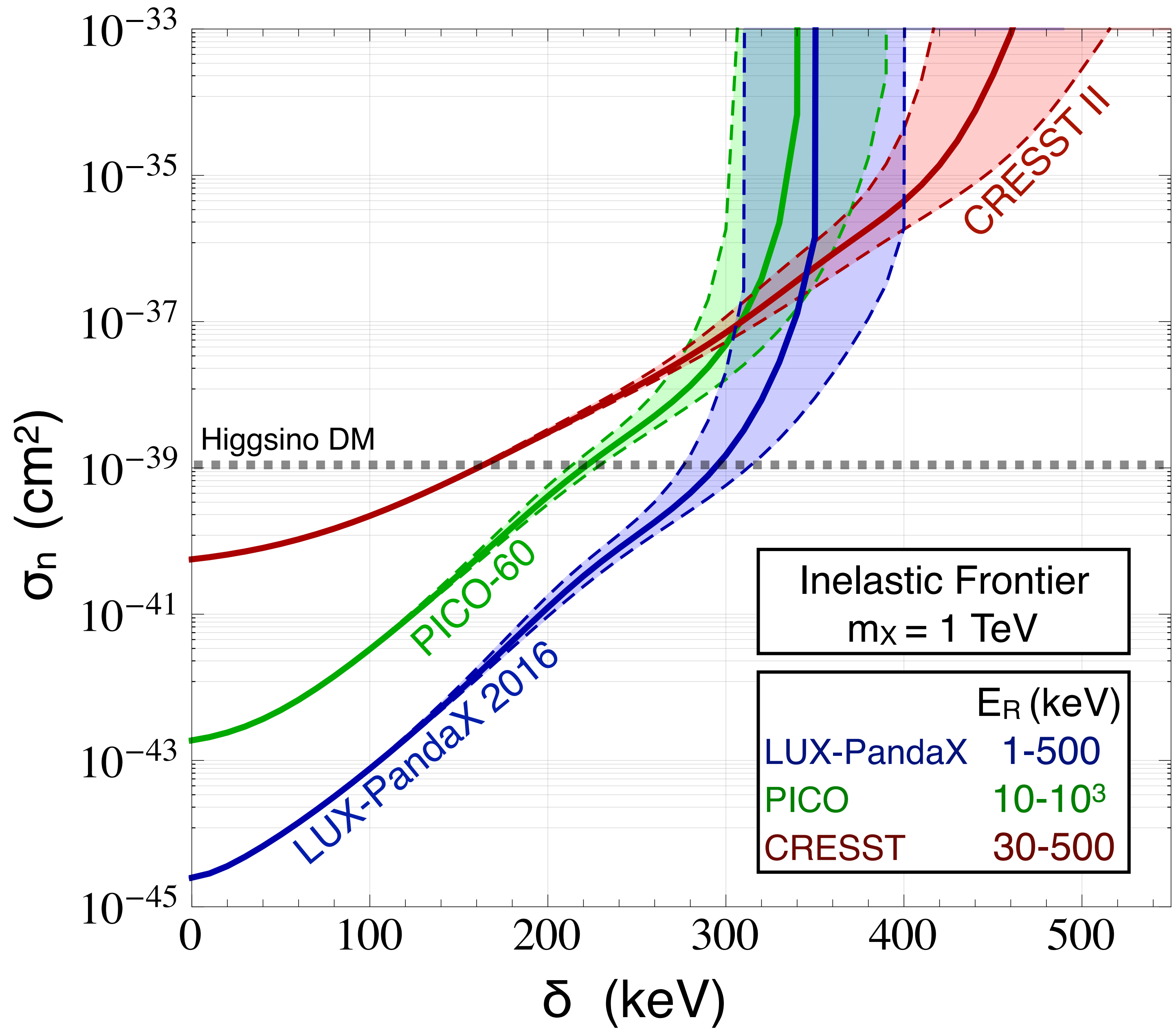
LUX: 1.4, PICO: 1.3, CRESST: 0.05

PICO?



smaller fiducial volume than Xe experiments (& similar mass element).. but NO upper limit on search window

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



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

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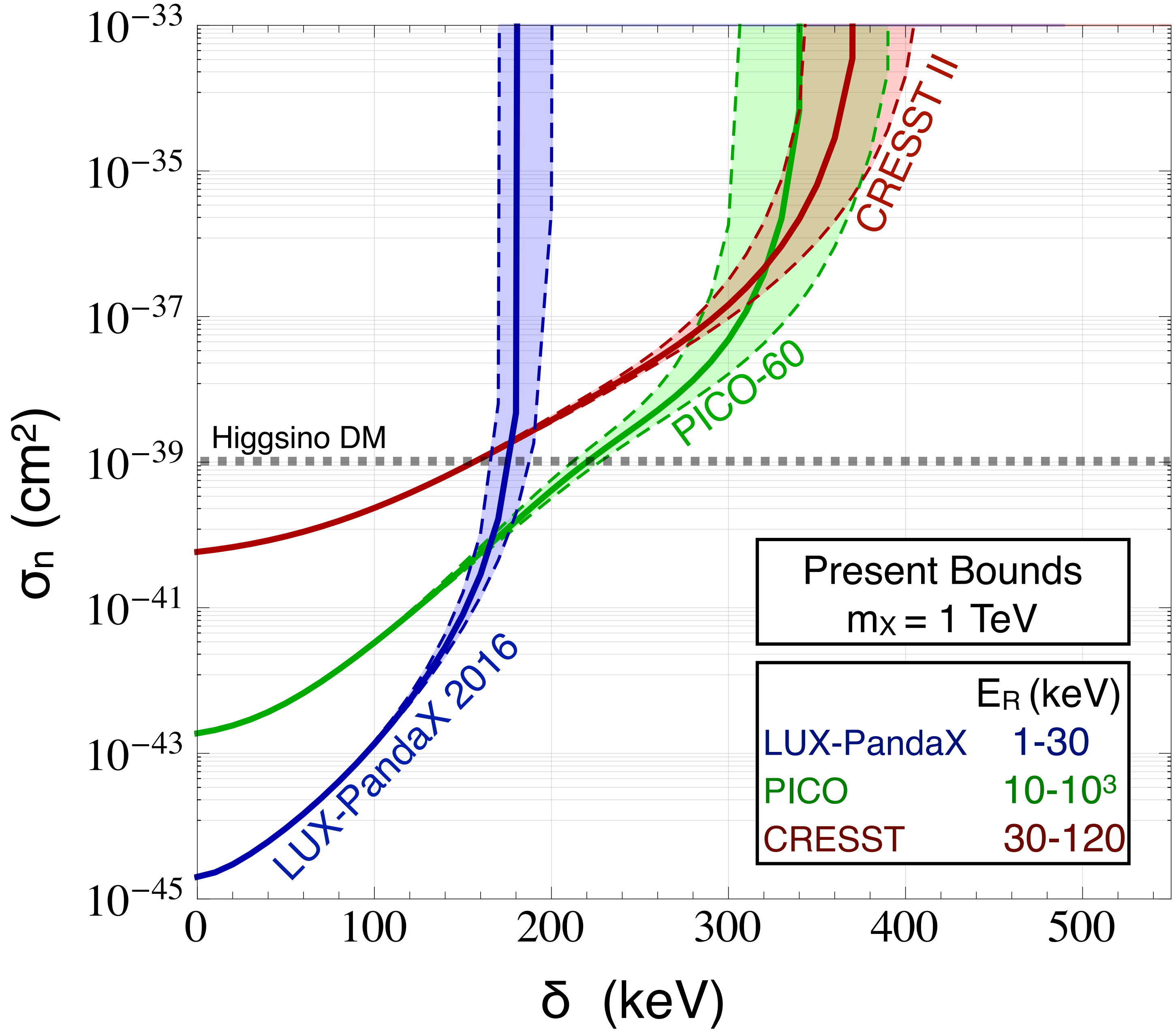

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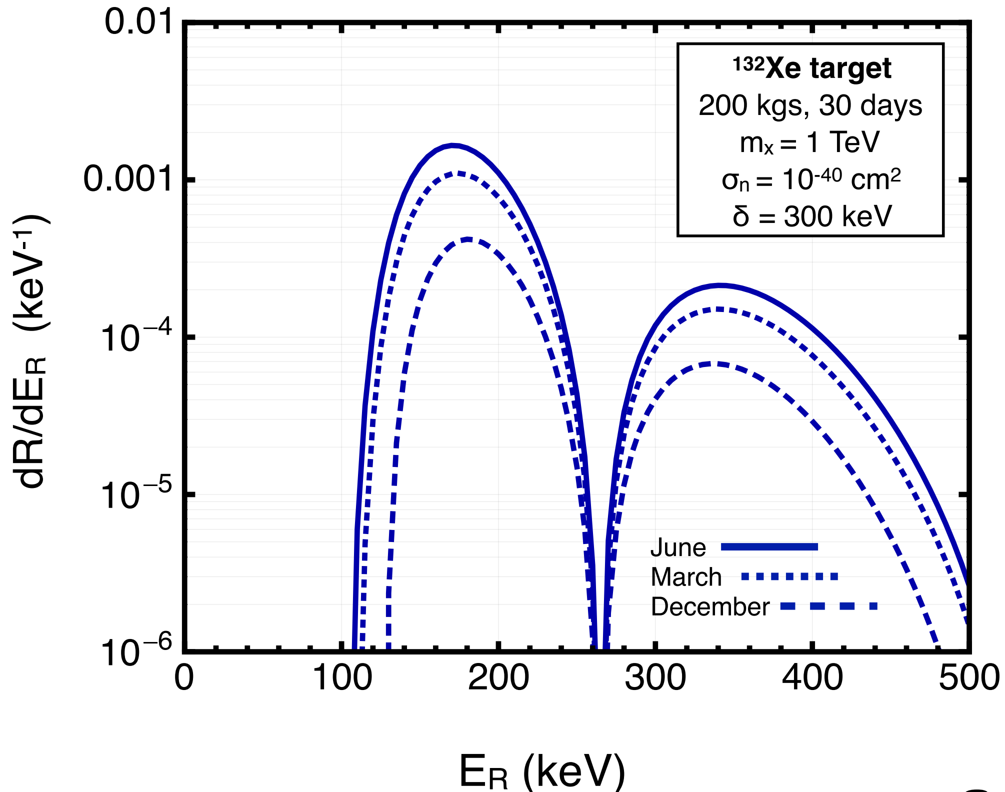
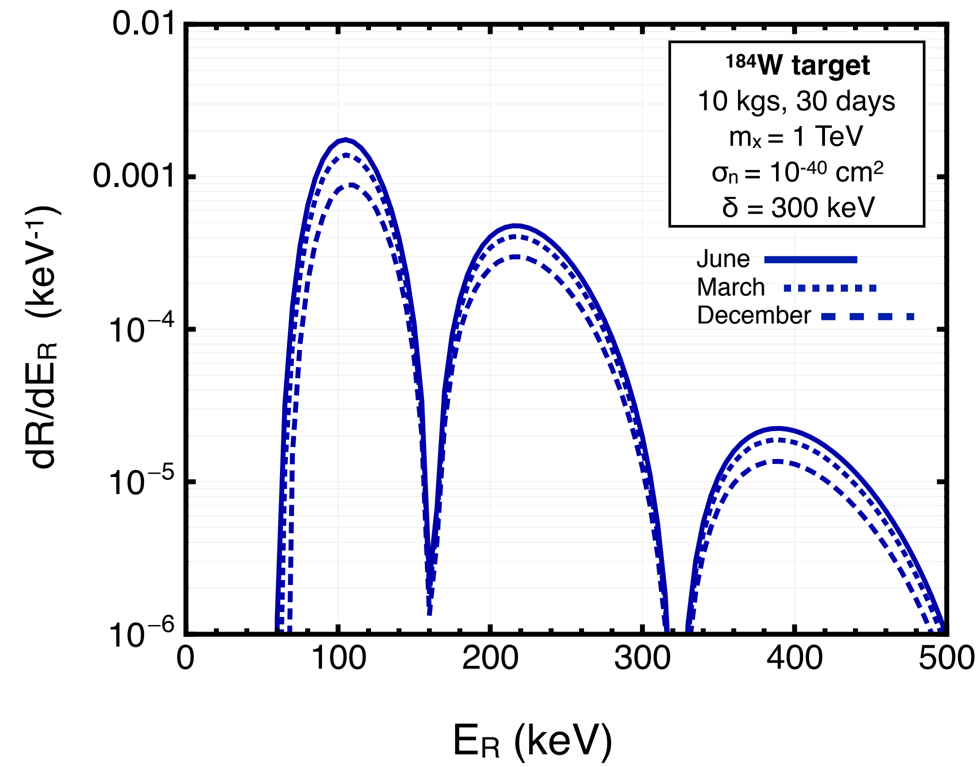
Modulation





ex: δ = 300 keV

velocity sensitivity → large modulation effects

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

What other models could lie in high recoil data?

Dark photon + dark charged DM:

[Batell, Pospelov, Ritz '09]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + |D_\mu \Phi|^2 - V(\Phi) - \frac{1}{4} V_{\mu\nu}^2 + \epsilon V_\mu \partial_\nu F^{\mu\nu} + \bar{\psi}(i D_\mu \gamma_\mu - m_\psi)\psi + (\lambda_{\rm D} \Phi \, \psi^T \, C^{-1} \, \psi + {\rm h.c.})$$

$U(1)_D$ breaking splits Dirac DM (ψ) -> 2 Majorana (χ_1, χ_2)

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$$\alpha_D \sim 0.04\left(\frac{m_{\chi_1}}{\rm TeV}\right)$$

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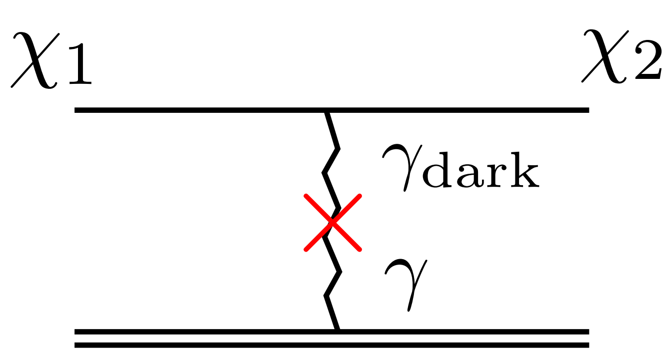
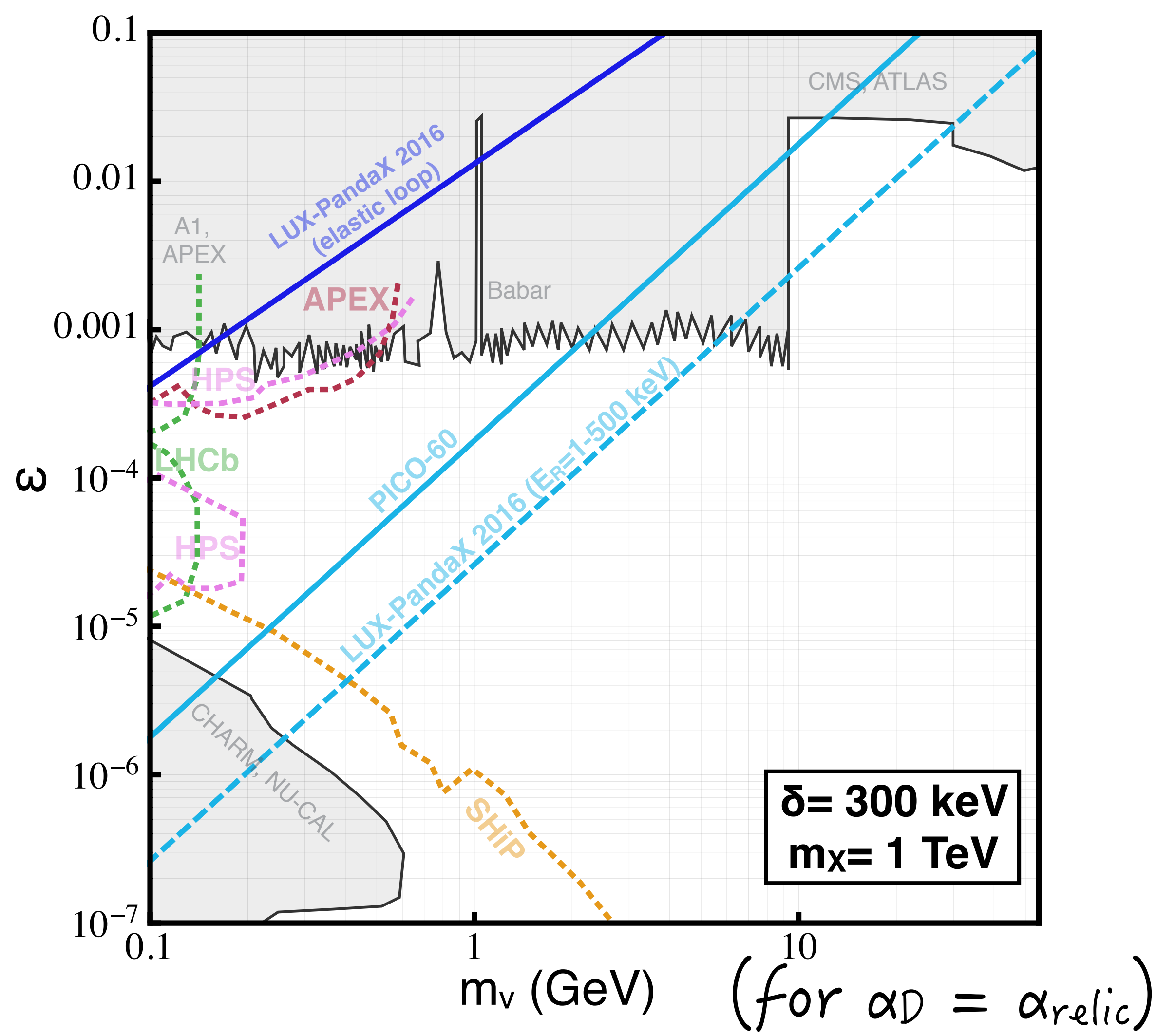


inelastic scattering via kinetic mixing

$$\sigma_{\chi,inelastic} \cong 10^{-30}\,{\rm cm}^2 \times \epsilon^2 \times \left(\frac{\rm m_\chi}{\rm TeV}\right)\left(\frac{\rm GeV}{\rm m_V}\right)^4$$

$$\times(\text{velocity factor}) \times {\rm A}^4$$

Dark photon + dark charged DM:



high recoil studies probe parameter space other methods can't (though more model dependent)

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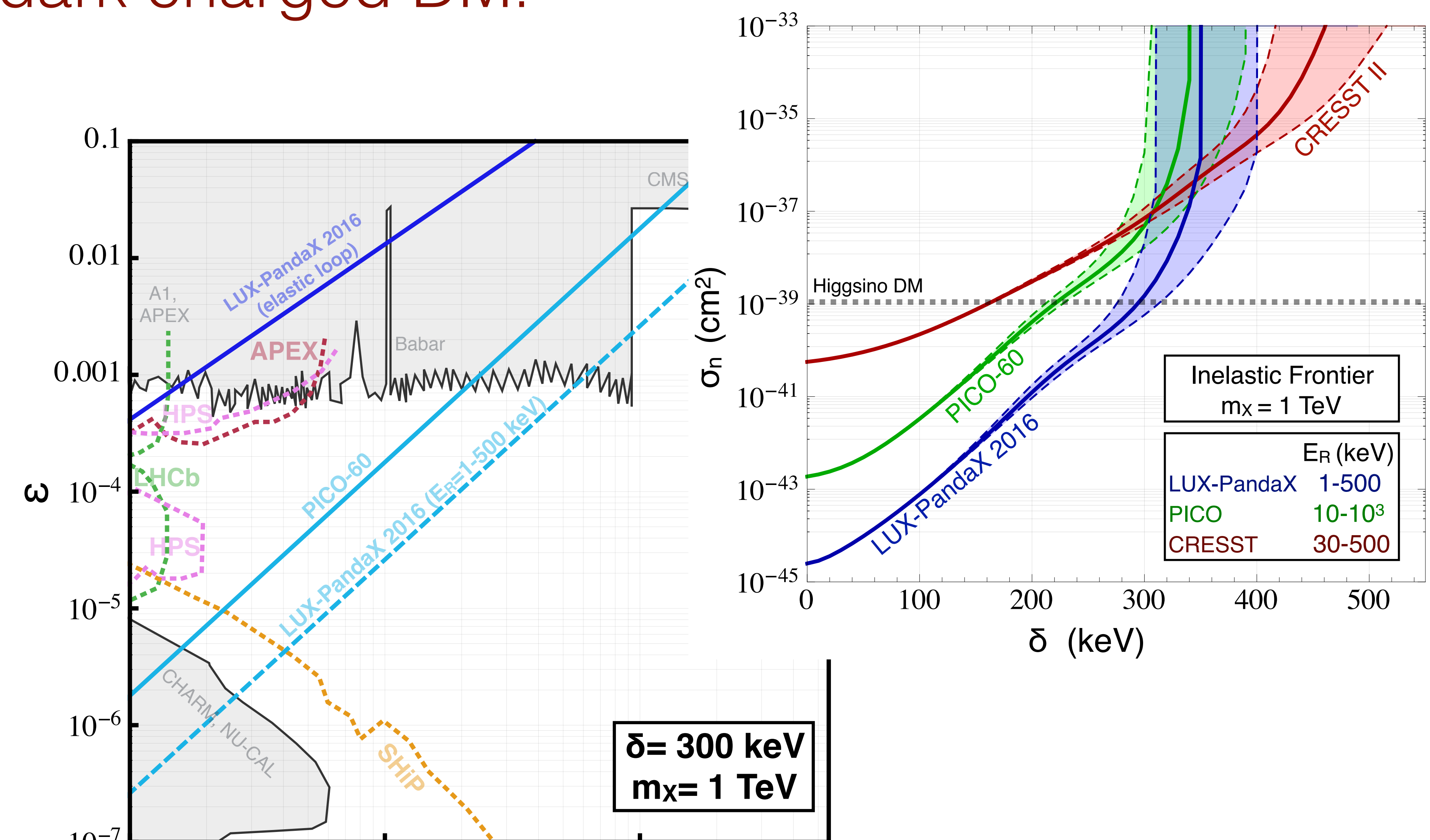

(for $\alpha_D = \alpha_{relic}$)

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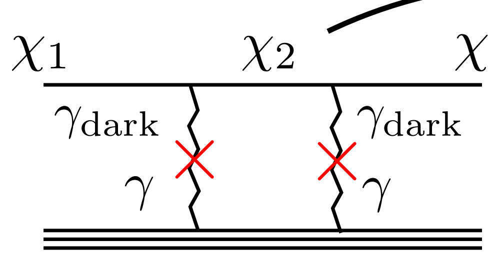

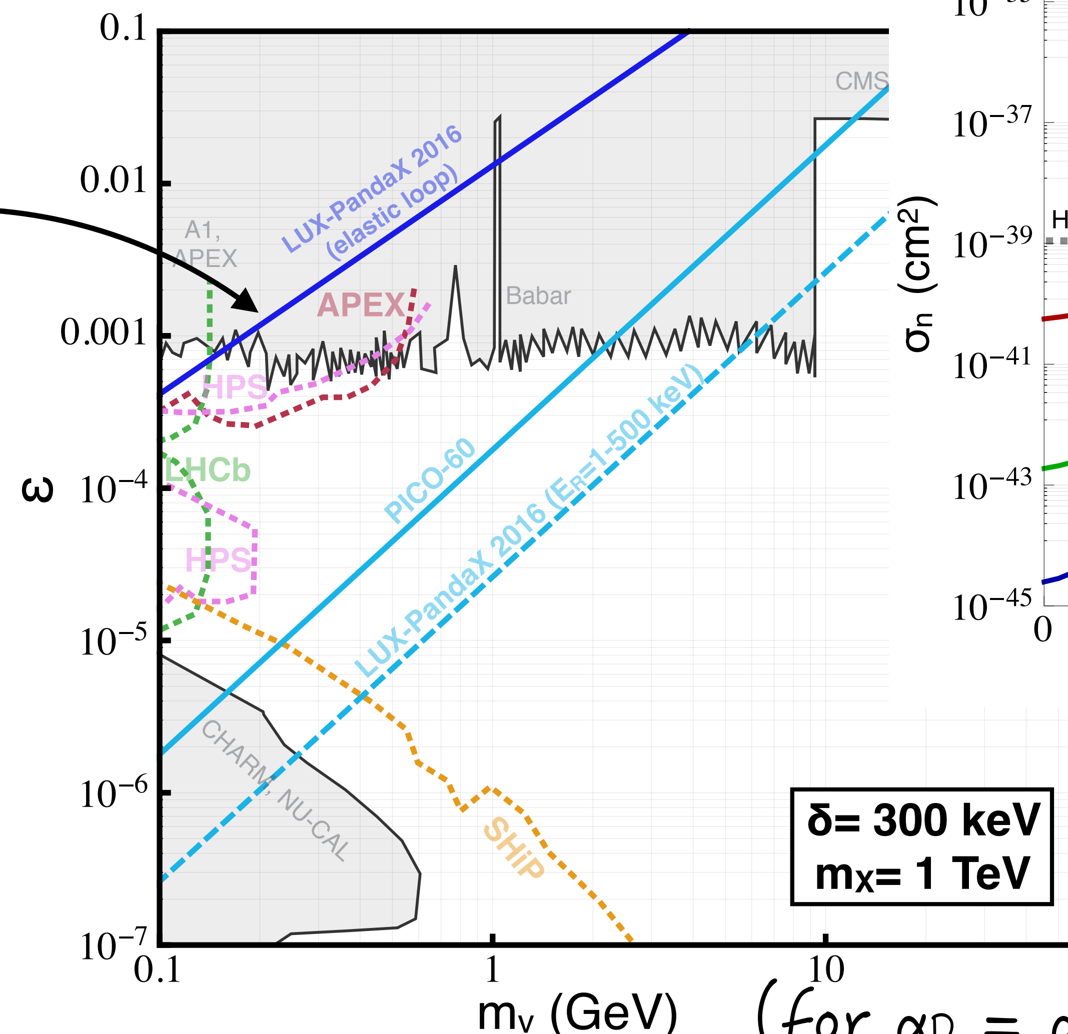

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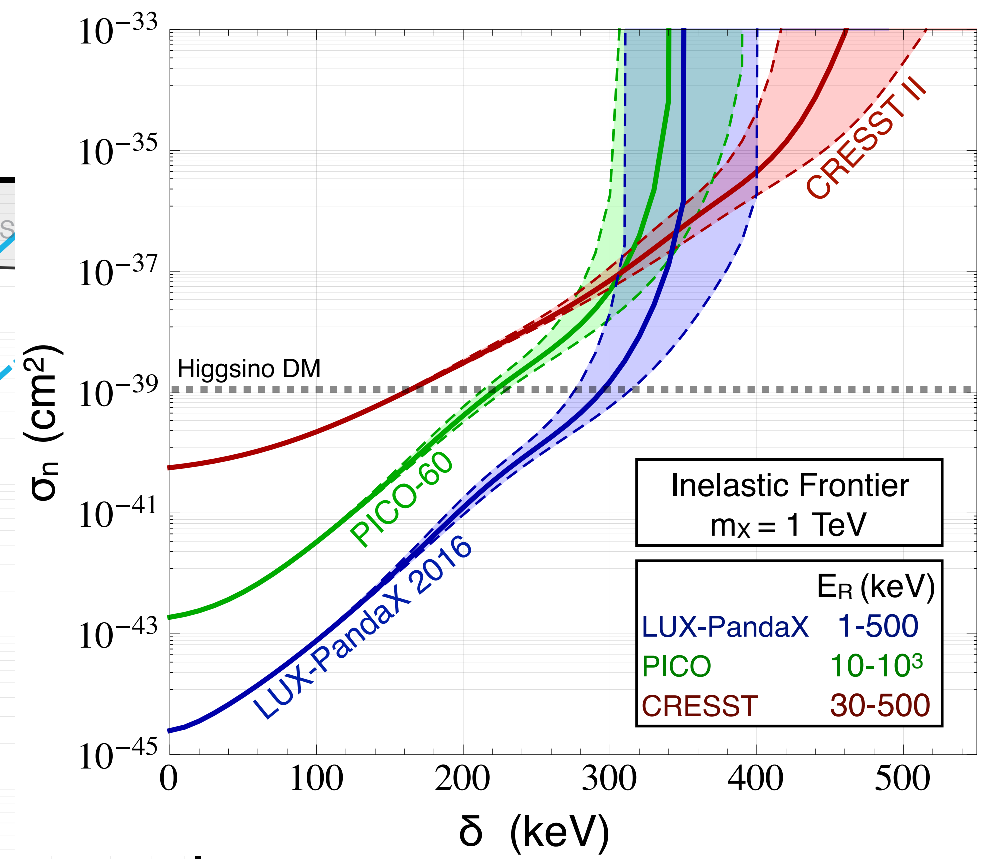

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(though more model dependent)

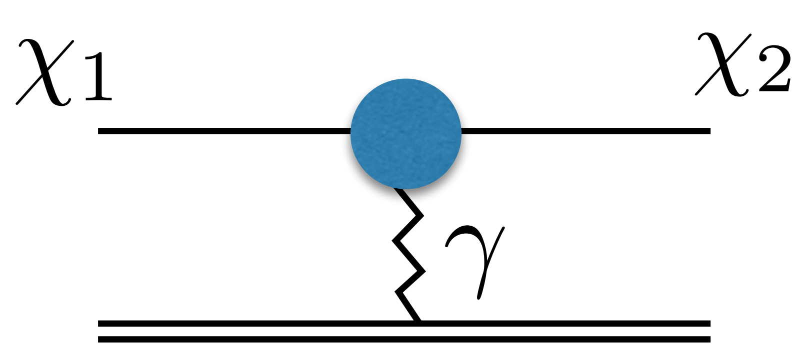
What other models could lie in high recoil data?

composite inelastic, i.e. magnetic inelastic:

$$\mathcal{L} \supset \left(\frac{g_M\, e}{8\, m_\chi}\right) \chi_2\, \sigma_{\mu\nu}\, \chi_1\, F^{\mu\nu}$$

[Chang, Weiner, Yavin ’10]

interaction with nuclei through photon exchange



momentum dependent

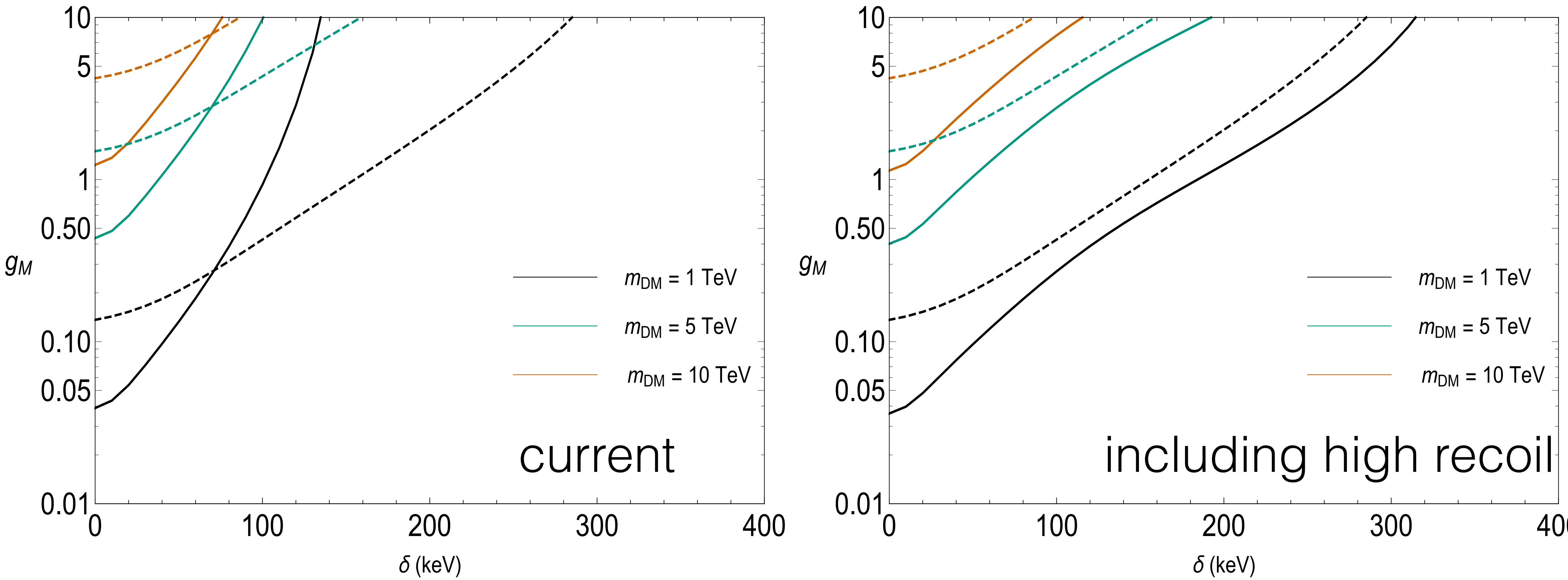
χ_2 lifetime: $\frac{10^{-4}\,\mathrm{s}}{g_M^2} \times \left(\frac{100\,\mathrm{keV}}{\delta}\right)^3 \times \left(\frac{m_X}{\mathrm{TeV}}\right)^2$

Relic abundance, UV completions explored in Weiner & Yavin 1209.1093

What other models could lie in high recoil data?

as interaction is energy dependent, no analog of σ_n

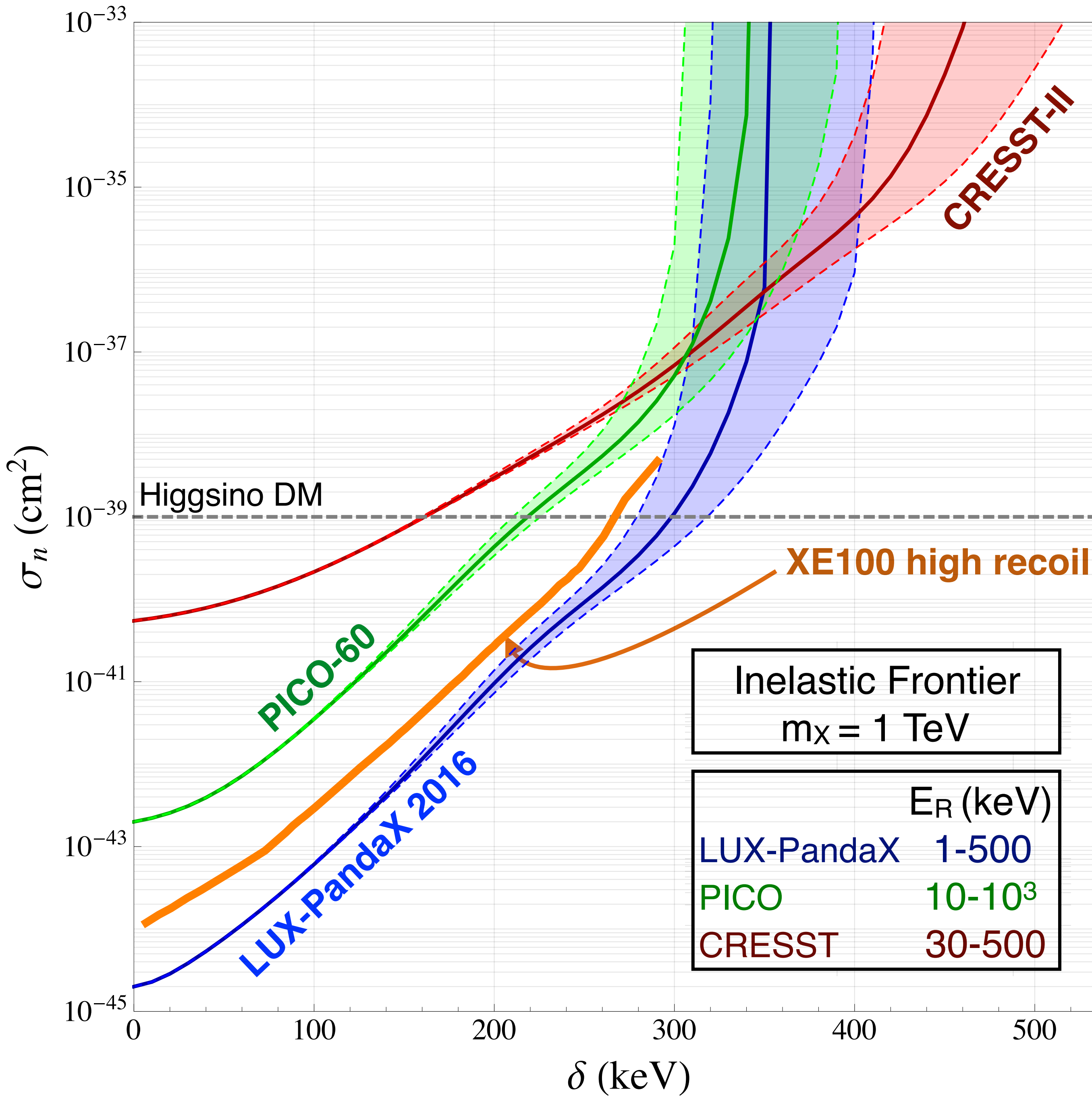
∴ bound g_M directly using nuclear response formalism of Fitzpatrick et al 1203.3542



dashed = PICO, **solid** = LUX/PandaX

strong bound from PICO due to large ^{127}I spin

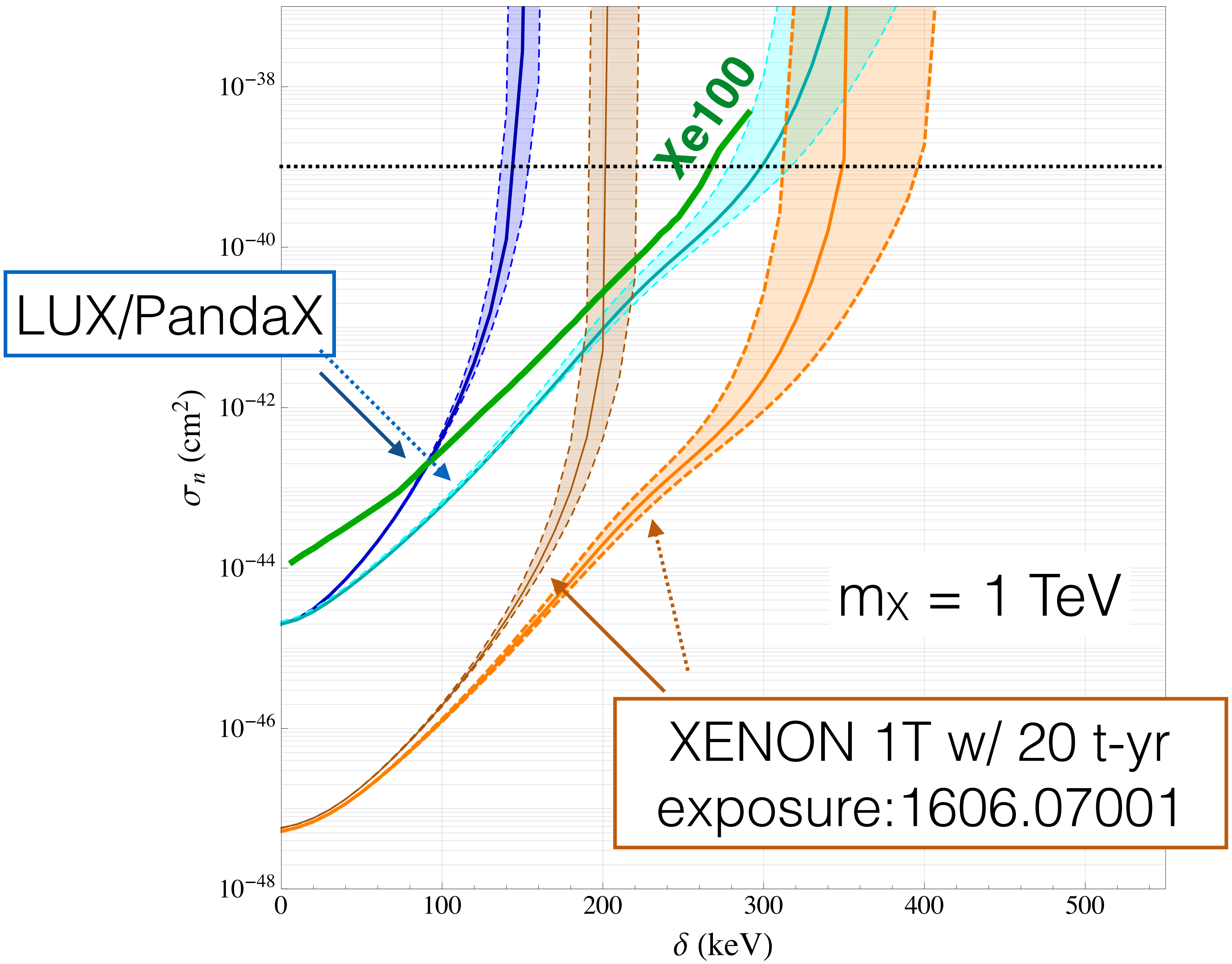
Recent progress at high recoil! : XE100 1705.02614



considered
recoil energies
out to 240 keVnr

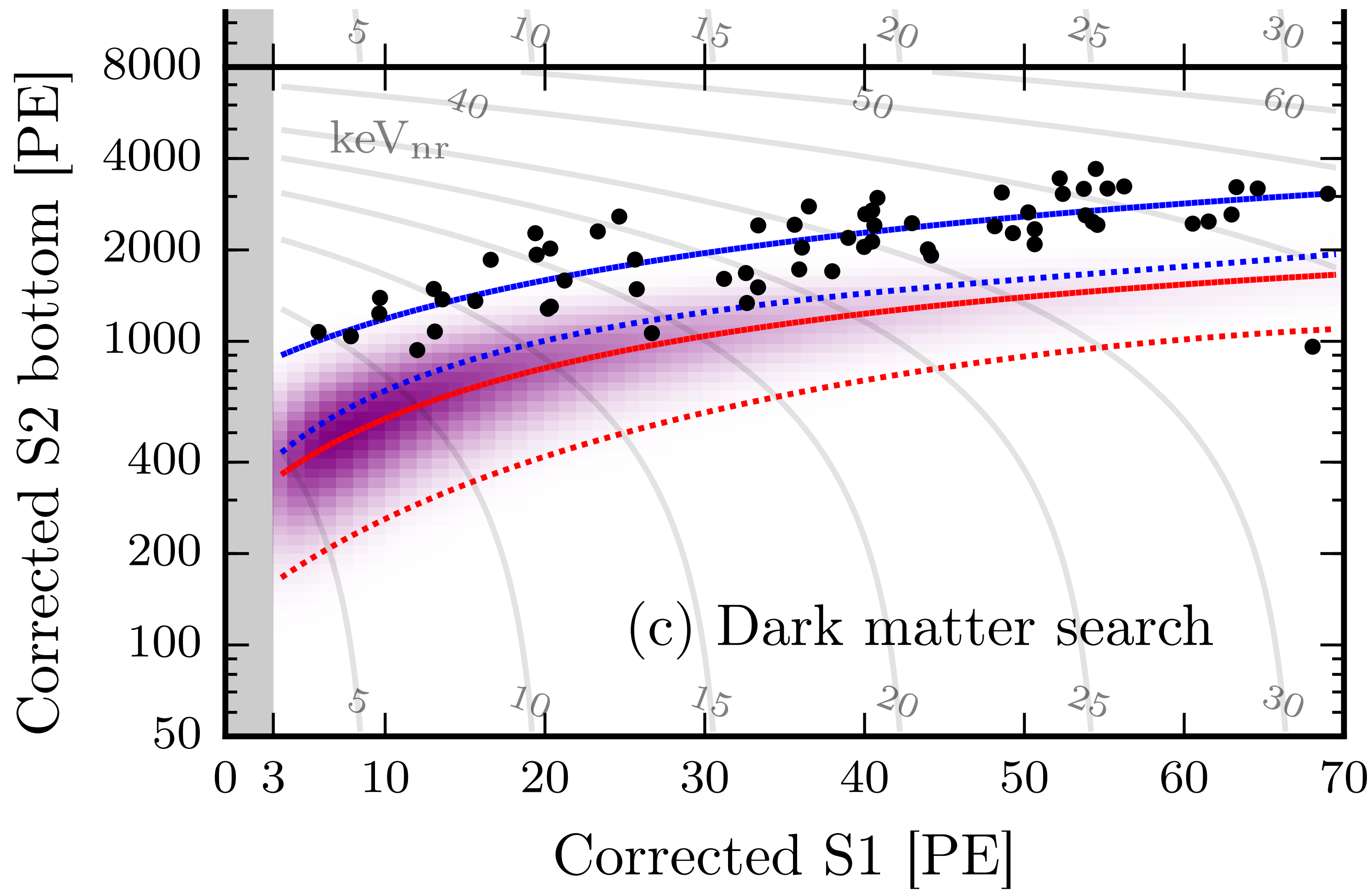
limit on ‘weak strength’
DM pushed out
to $\delta \gtrsim 260$ keV

Projections for future experiments



Perhaps the first signs of iDM?

from XENON1T 1705.06655



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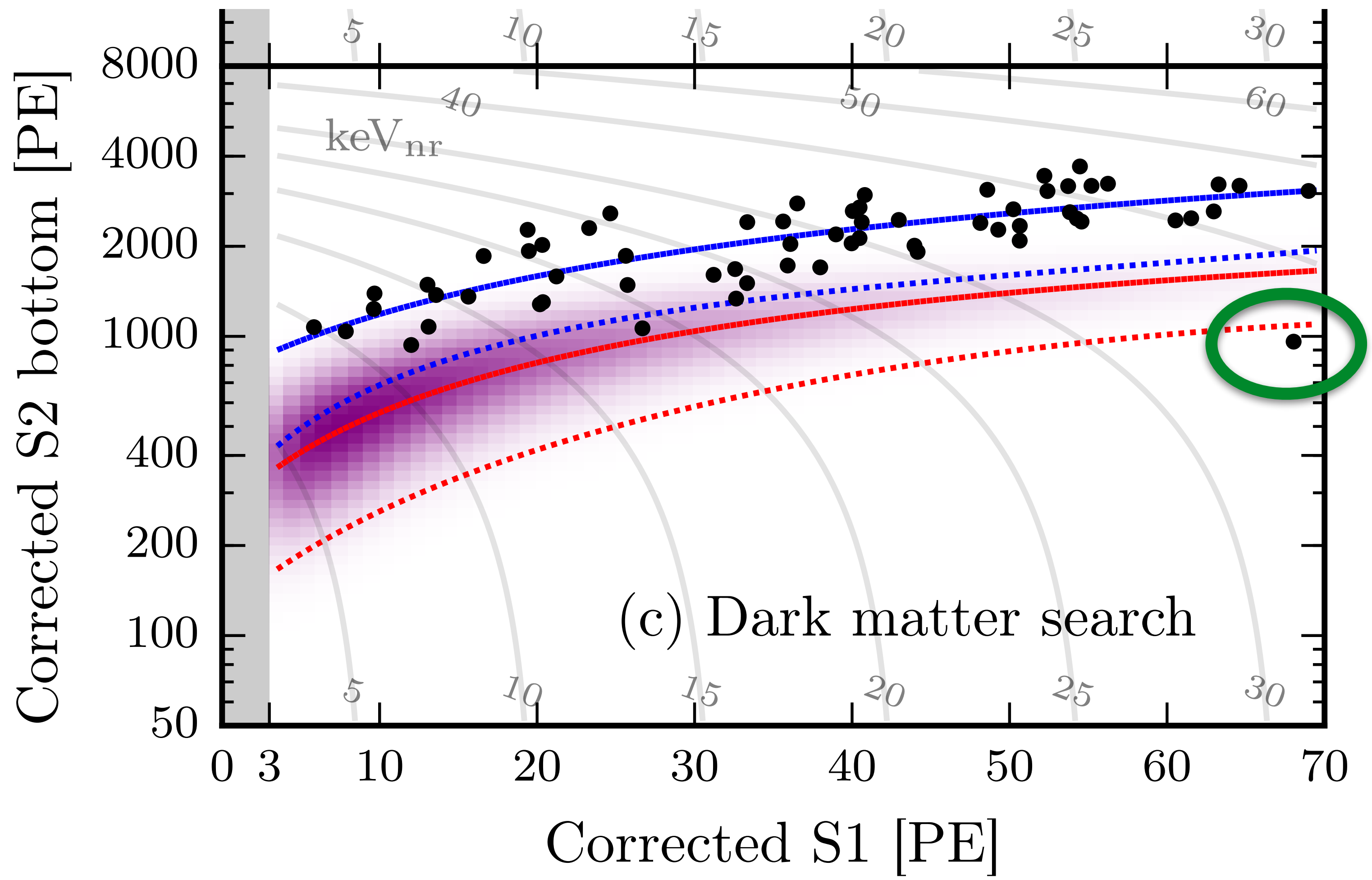


Conclusions

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

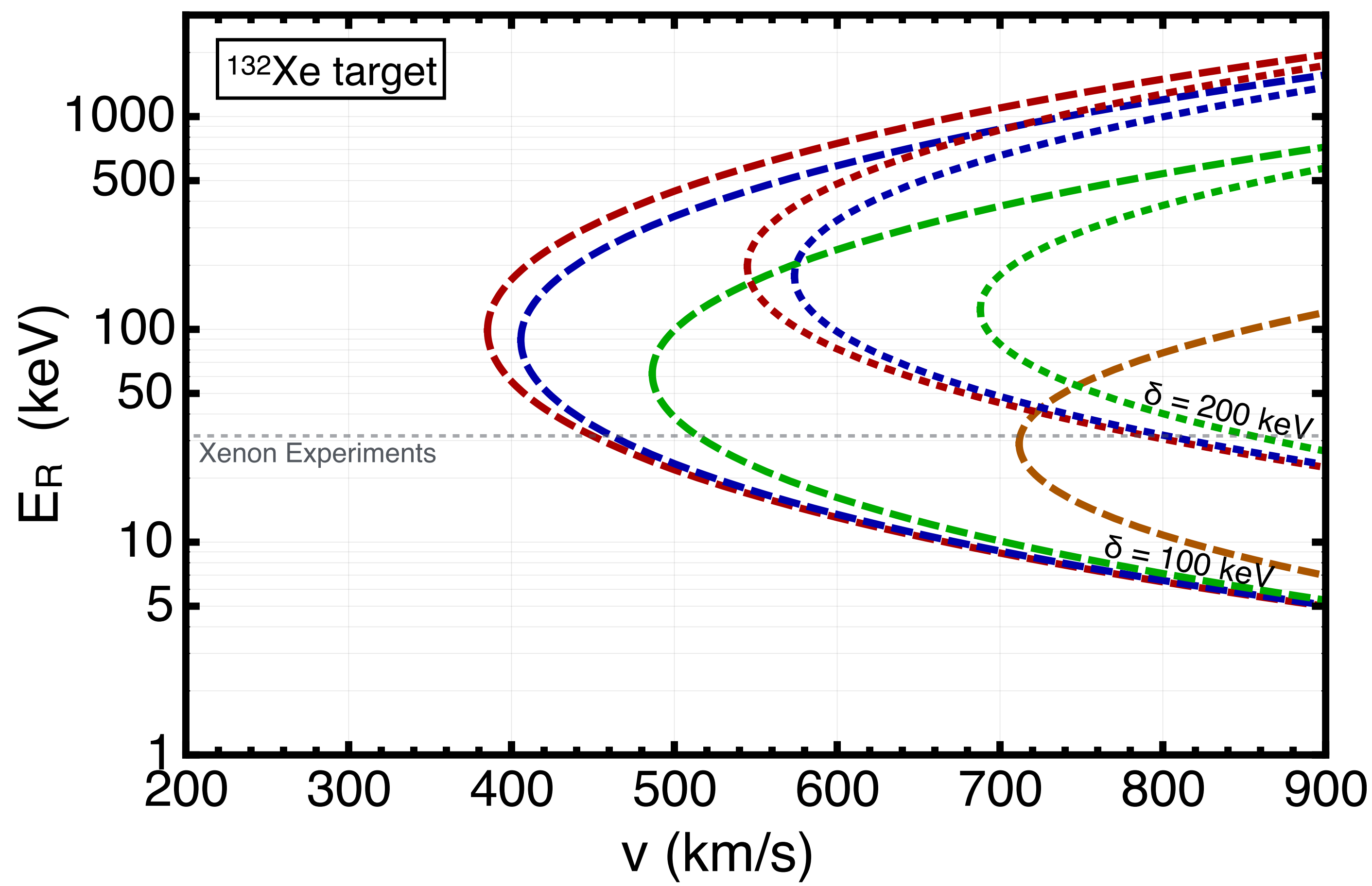
- current techniques work, just enlarge E_R signal regions;
  Xe100, LUX already looking into it
- most sensitive to heavy DM using heavy targets;
- sensitive to tails of DM velocity distribution, large modulation effects

what about $\delta \gtrsim$ MeV?

EXTRAS

Inelastic Kinematics

shifts in kinematically allowed region as we change m_{DM}



dashed: δ = 100 keV

dotted: δ = 200 keV

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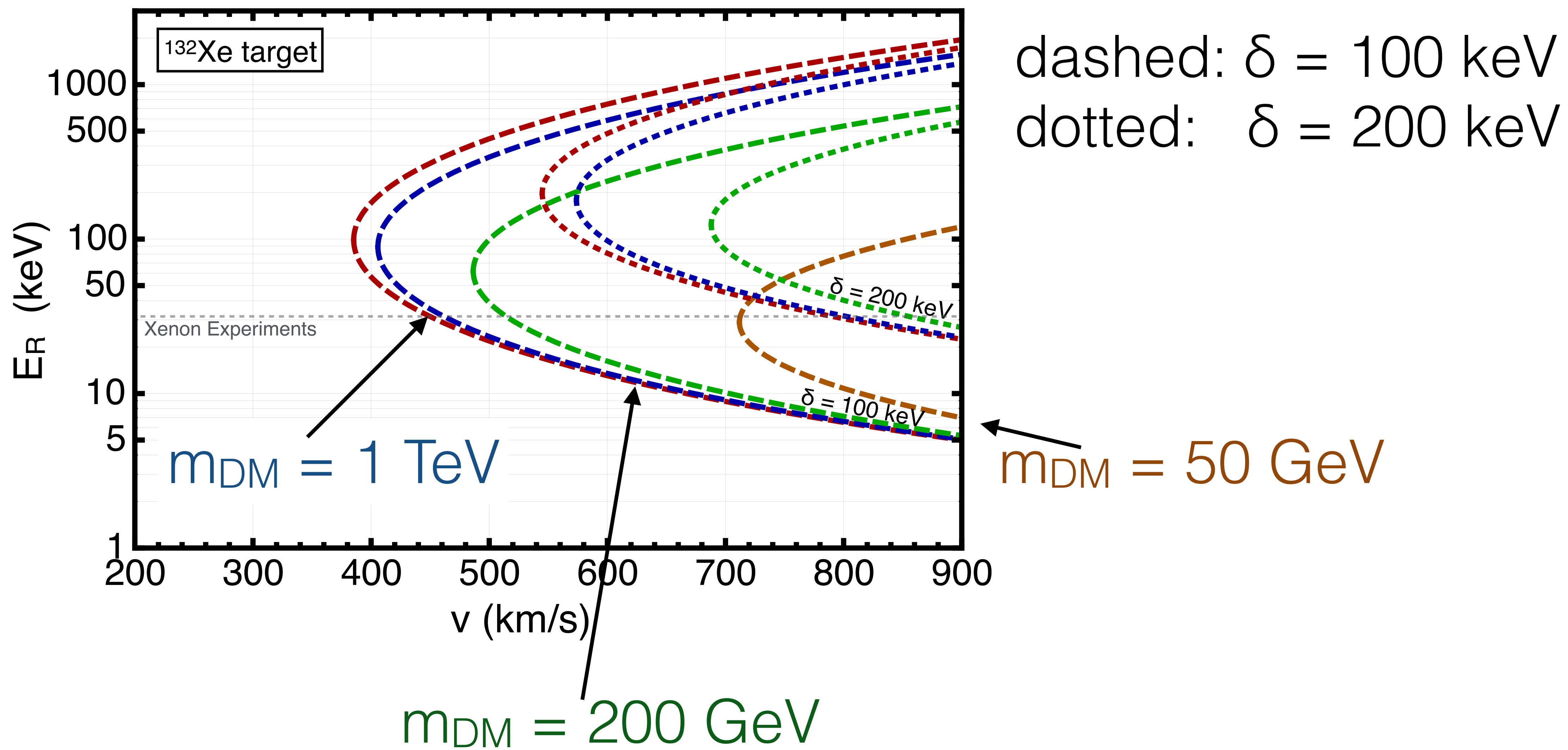

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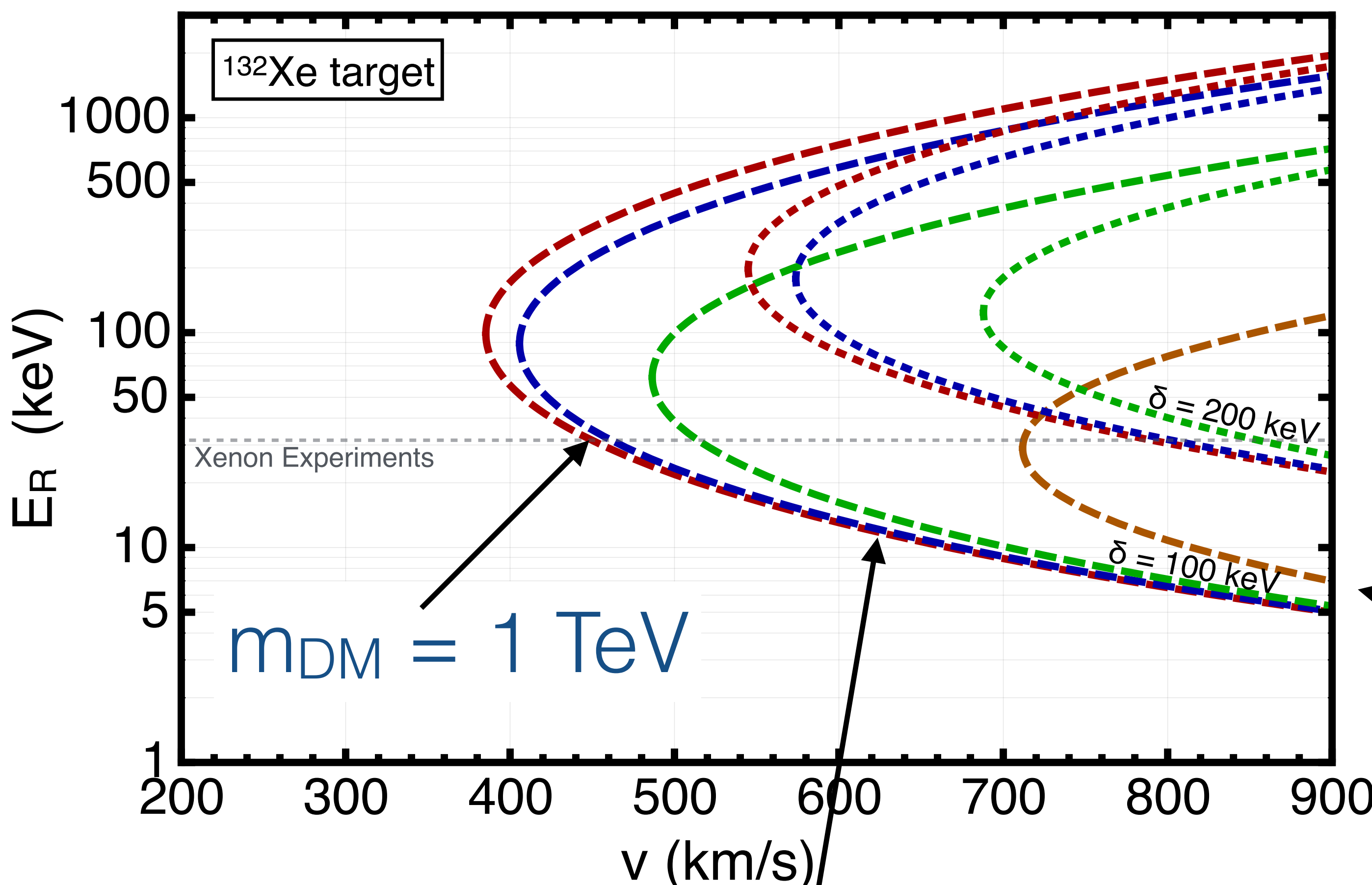


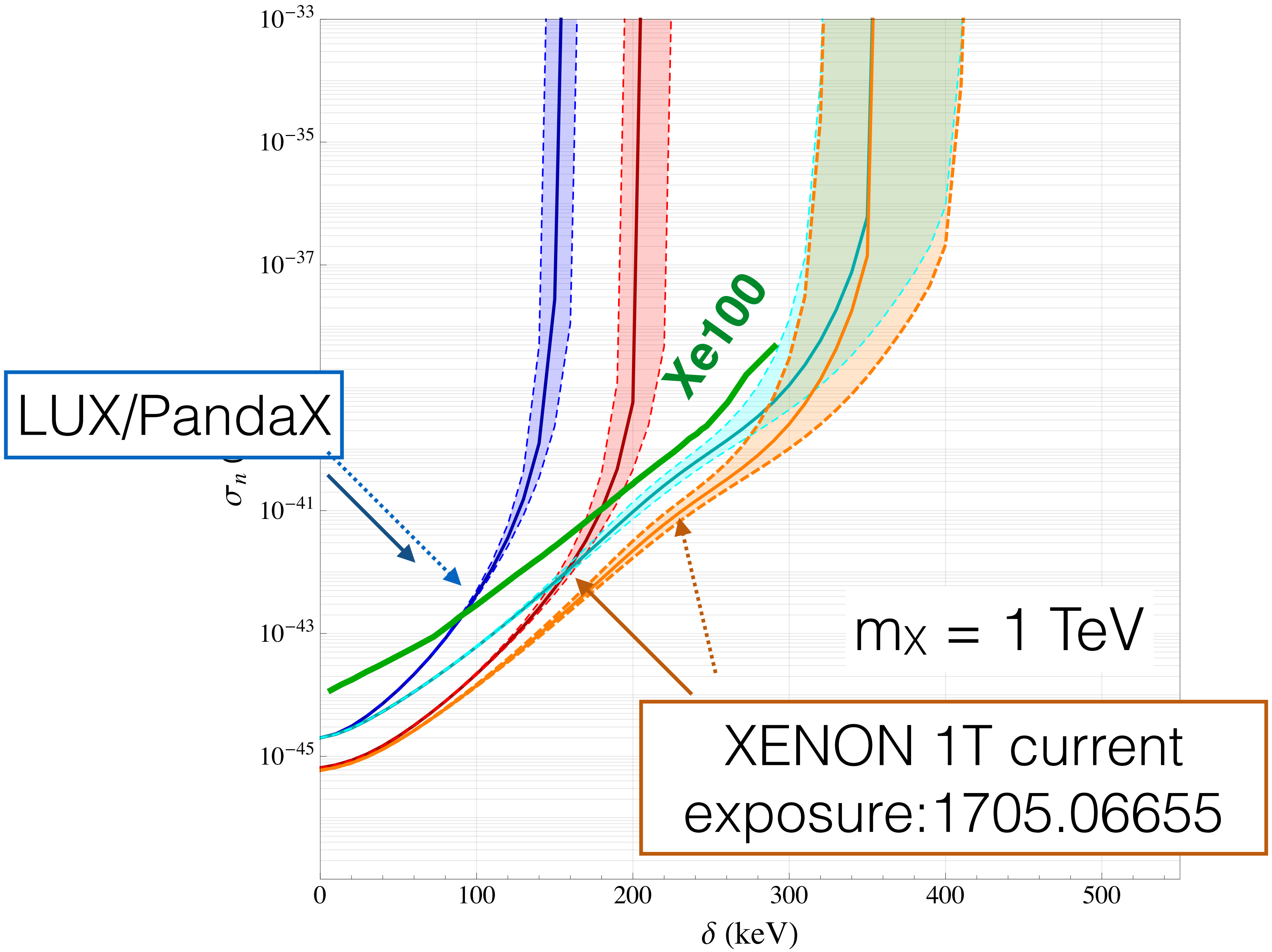
m_{DM} = 1 TeV

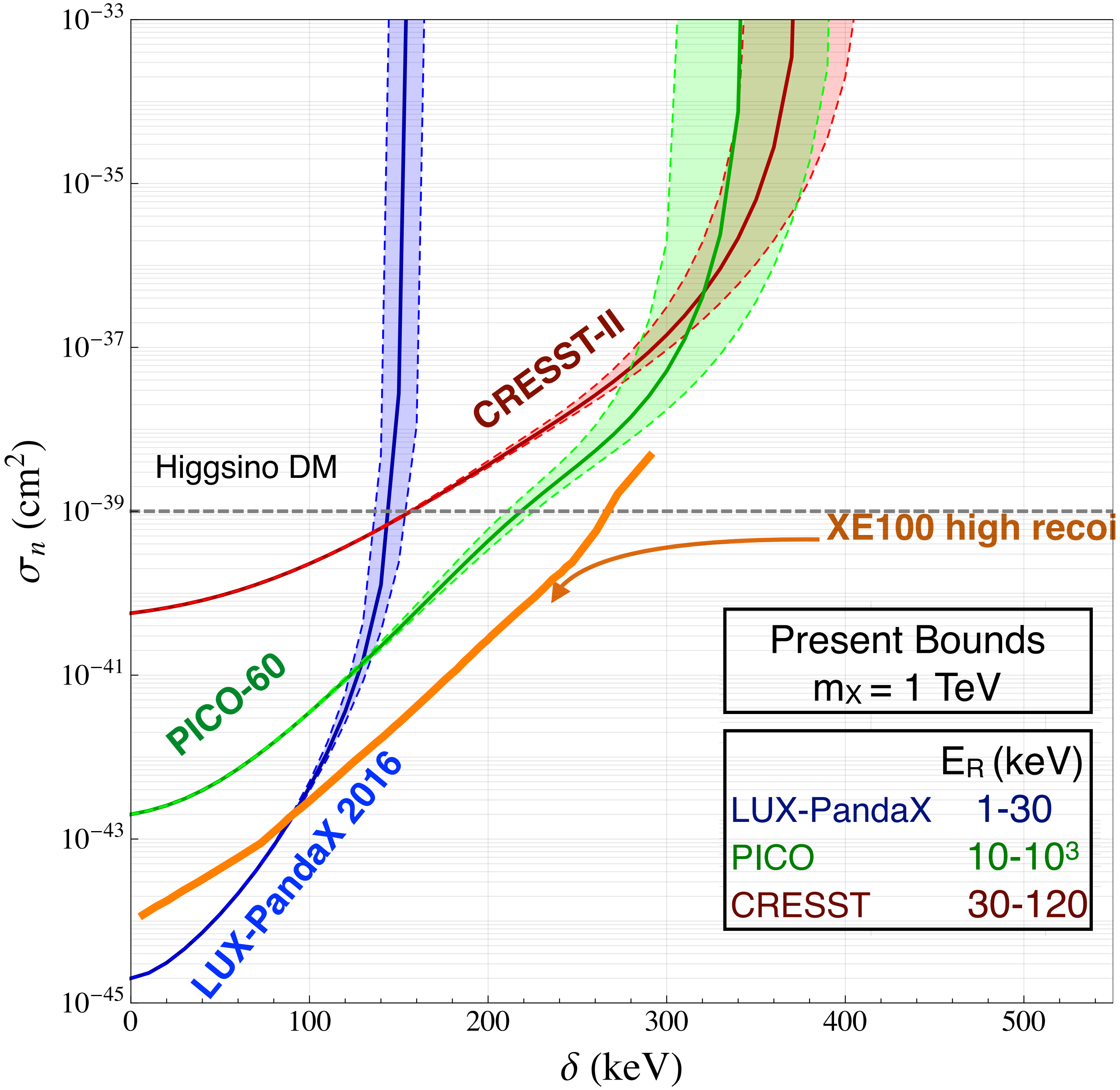
m_{DM} = 50 GeV

m_{DM} = 200 GeV

more parameter space
for **heavy DM**

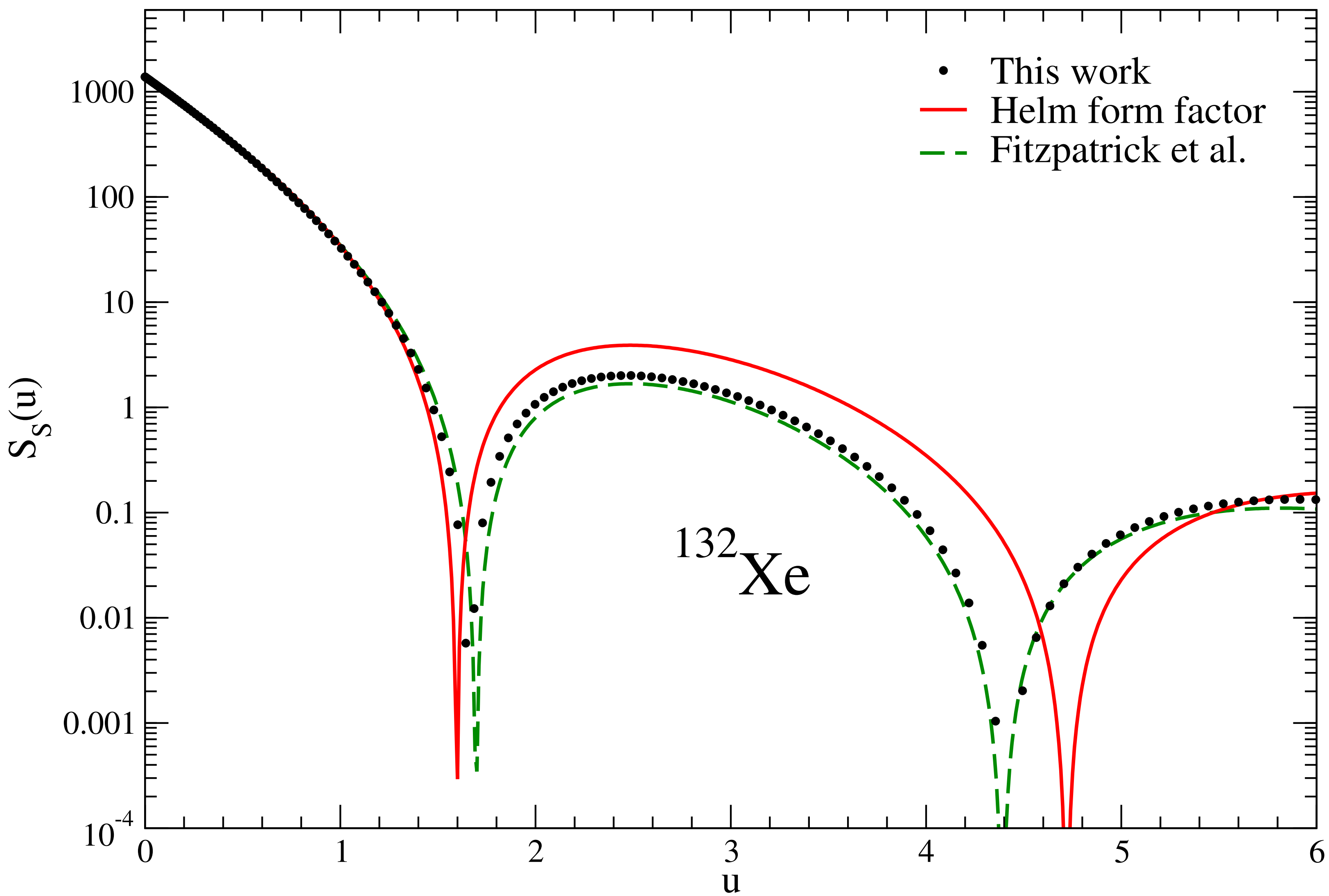
current XENON 1T comparison

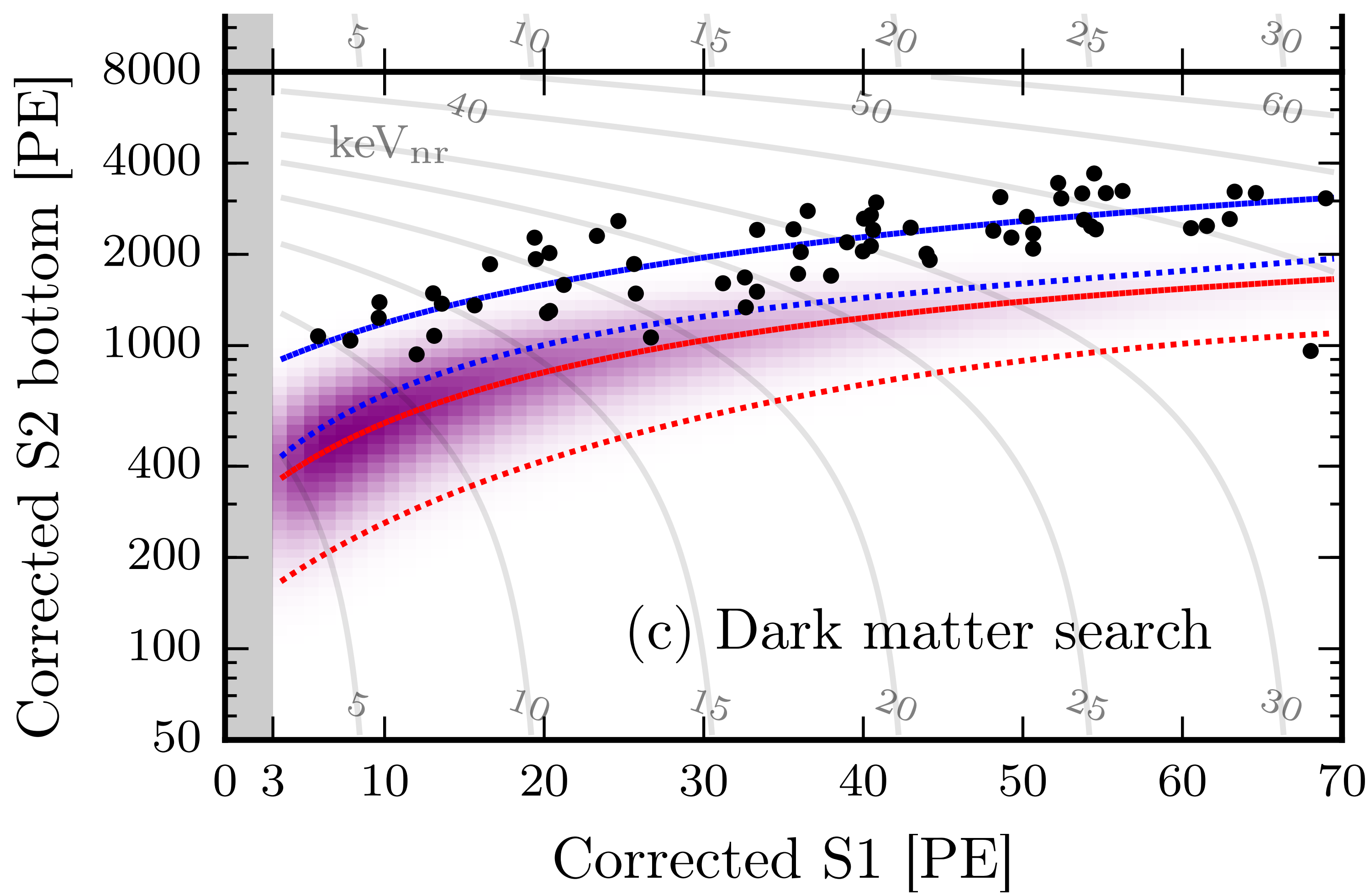




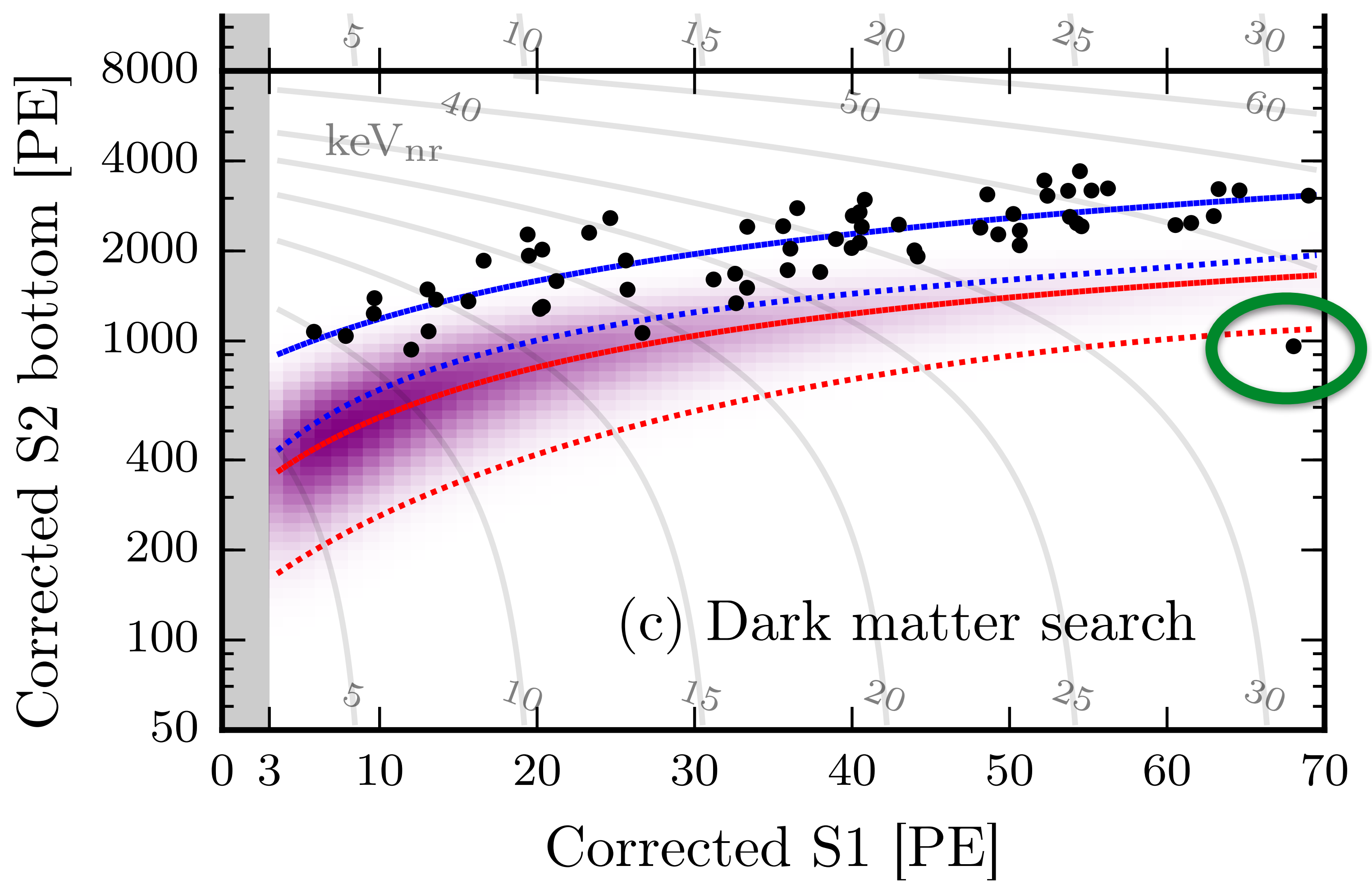
Higgsino DM
CRESST-II
PICO-60
LUX-PandaX 2016
XE100 high recoil
Present Bounds
$m_X = 1$ TeV
E_R (keV)
LUX-PandaX 1-30
PICO 10-10^3
CRESST 30-120
σ_n (cm^2)
δ (keV)
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
0
100
200
300
400
500

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



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