Theoretical Case for GeV+ Dark Matter

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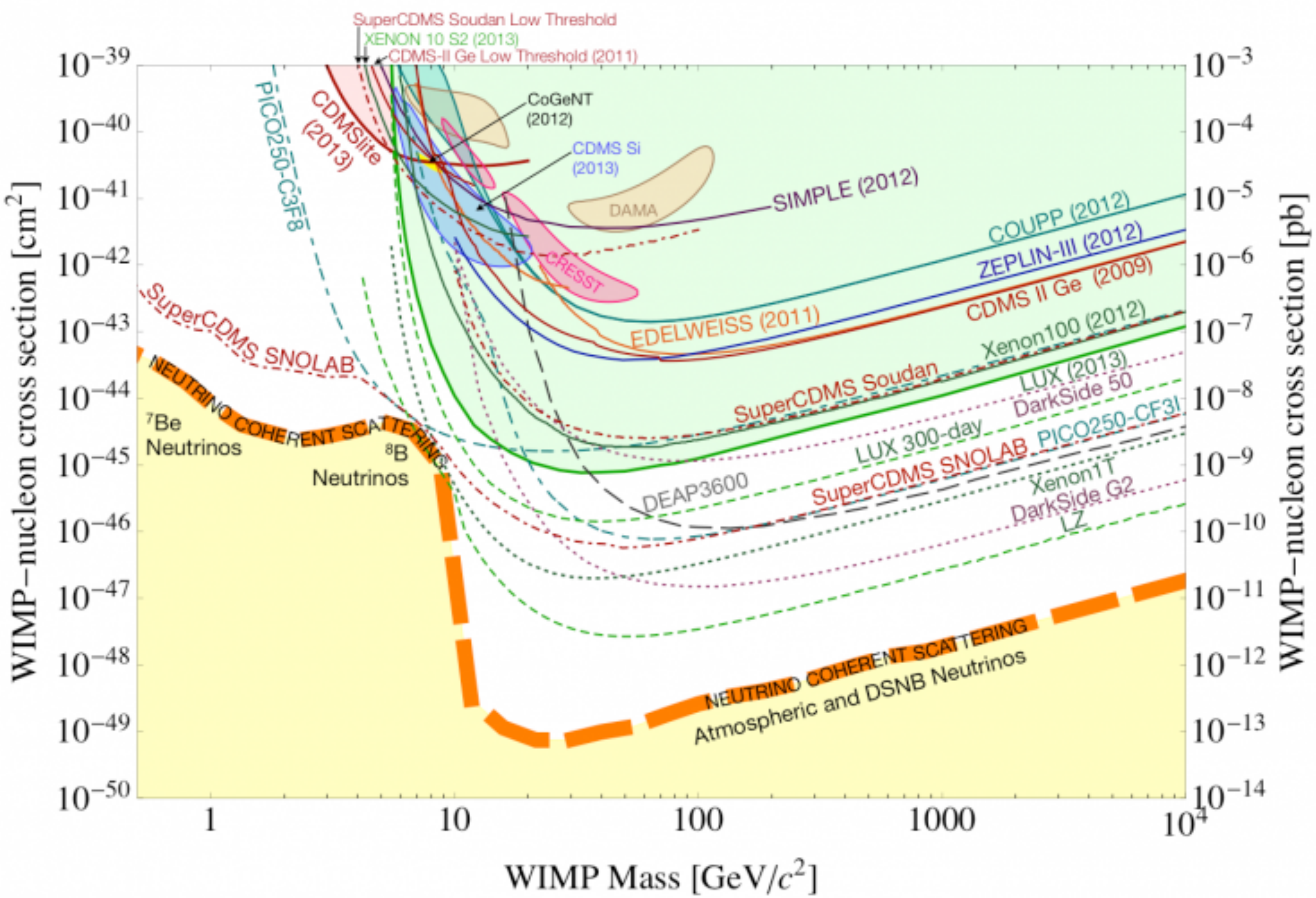
University of Oregon

3rd Berkeley Workshop on Direct Detection of Dark Matter | 5 December 2016

Let's agree on the issue

We've been searching for dark matter for nearly 30 years
with no (unambiguous) detection.



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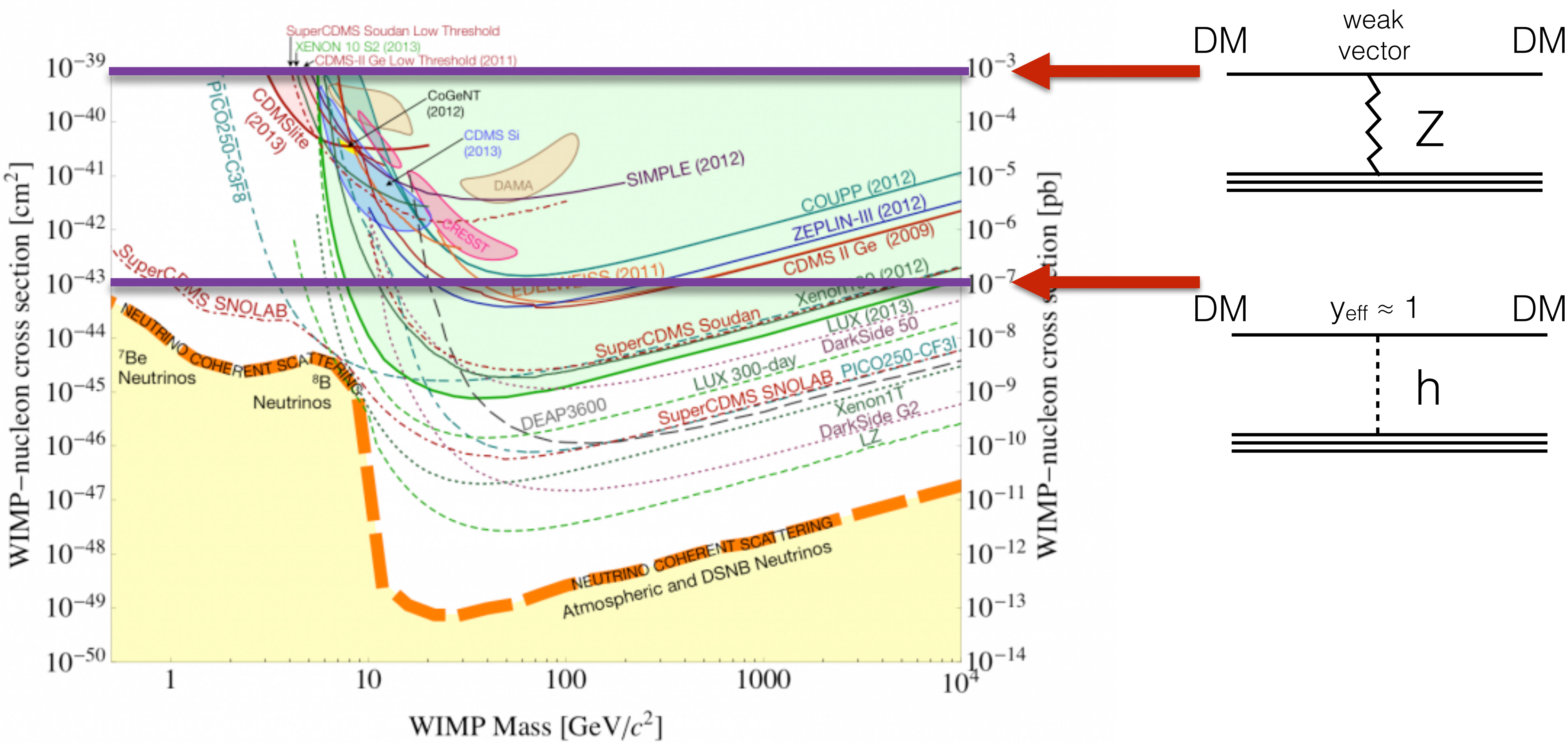
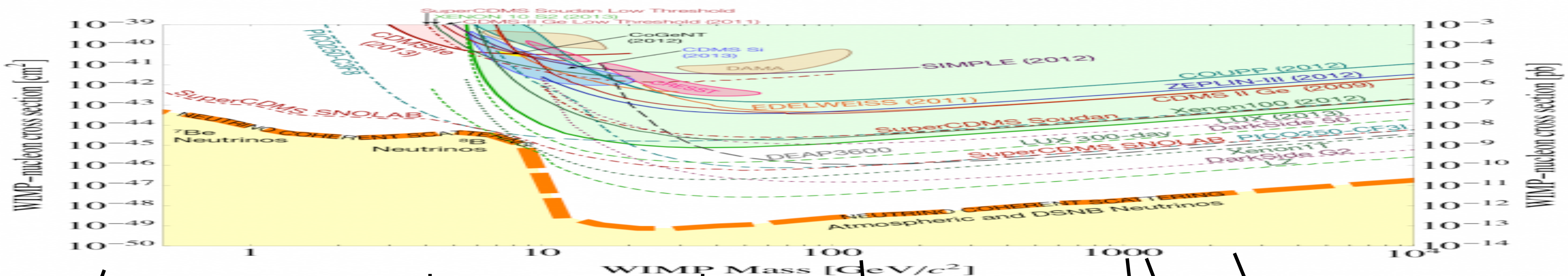


For theory, the remarkable ensemble of nuclear recoil detection technologies have pushed us far below Z exchange and seriously encroached extent Higgs exchange.

Scales



Λ_{QCD}

SIMP
(3->2 annihilation)

self-interacting DM
“too big to fail”, etc.

asymmetric with
$n_{DM} \sim n_{baryon}$

Fermi galactic
center excess
(if annihilation to bb)

weak
scale

asymmetric with
$n_{DM} \propto n_{baryon} \exp\left[-\frac{m_{DM}}{T_{EWPT}}\right]$

winos

Higgsinos

unitarity
bound

Theory Motivation for GeV+?

Of course!

The topic is so broad that I have no ability (or desire) to be exhaustive.

Instead, I'll focus on three theory "vignettes" that can focus our attention on the importance of the continued search for "heavy" ($m_{DM} > m_{Xe}$) dark matter.

In the process, we'll cover some old ground as well as explore some ideas that can differentiate various experiments and motivate new searches.

Three Vignettes

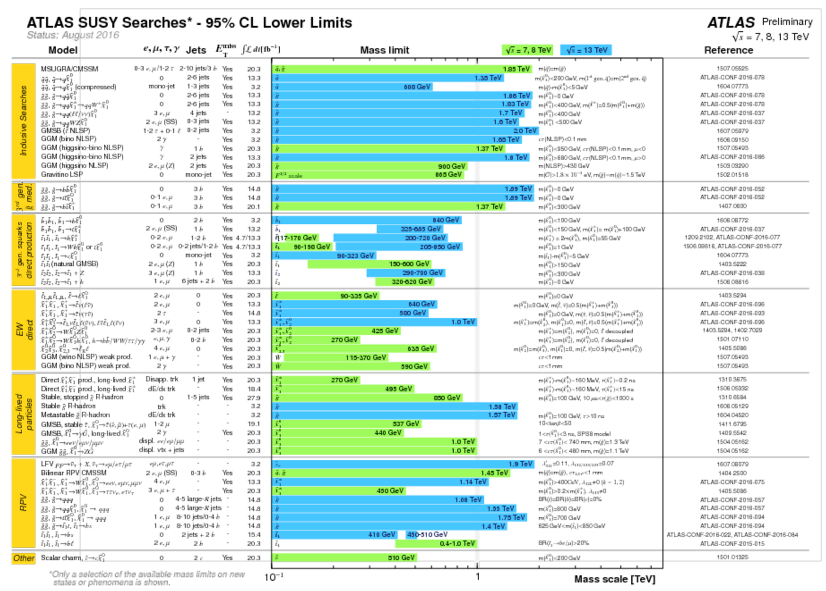
1. TeV supersymmetric dark matter
   (winos and Higgsinos)

2. Strongly-coupled composite dark matter
   (a.k.a., effective theories with high-dimension interactions with SM matter)

3. Inelastic dark matter

Vignette #1 — TeV Supersymmetry

The most naive interpretation of LHC bounds on superpartners



ATLAS

Combined with observation of Higgs mass ≈ 125 GeV
(i.e., heavy stops needed to give large positive radiative corrections to m_h)

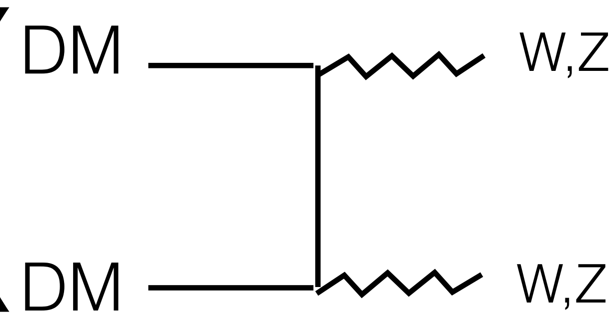
Suggests that, if superpartners exist at all, they are probably $\gtrsim O(\mathrm{TeV})$
(and theorists must live with some, at least 1 part in 100, fine-tuning)

TeV Supersymmetry Dark Matter Abundance

From a dark matter perspective this is not a problem and probably expected

Annihilation rates

$\langle \sigma_{\rm eff} v \rangle$ (



) $\sim \begin{cases} \dfrac{g^4}{24\pi m_{\rm DM}^2} & \text{Higgsinos} \\[2ex] \dfrac{3g^4}{16\pi m_{\rm DM}^2} & \text{Winos} \end{cases}$

e.g. Arkani-Hamed, Delgado, Giudice 0601041

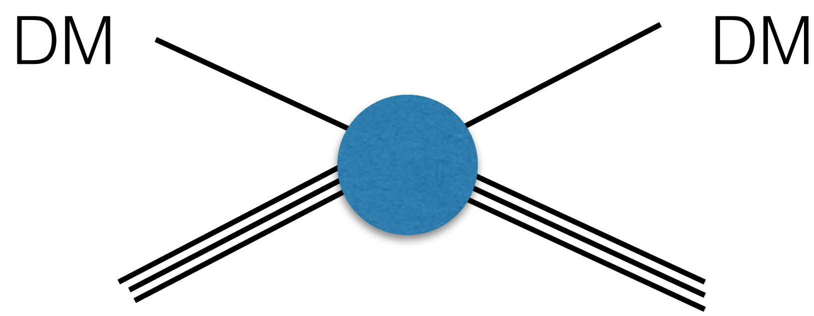
Thermal abundance

$$\Omega h^2 \sim \begin{cases} 0.12 \left(\dfrac{m_{\rm DM}}{1.1\ \rm TeV}\right)^2 & \text{Higgsinos} \\[2ex] 0.12 \left(\dfrac{m_{\rm DM}}{2.6\ \rm TeV}\right)^2 & \text{Winos} \end{cases}$$

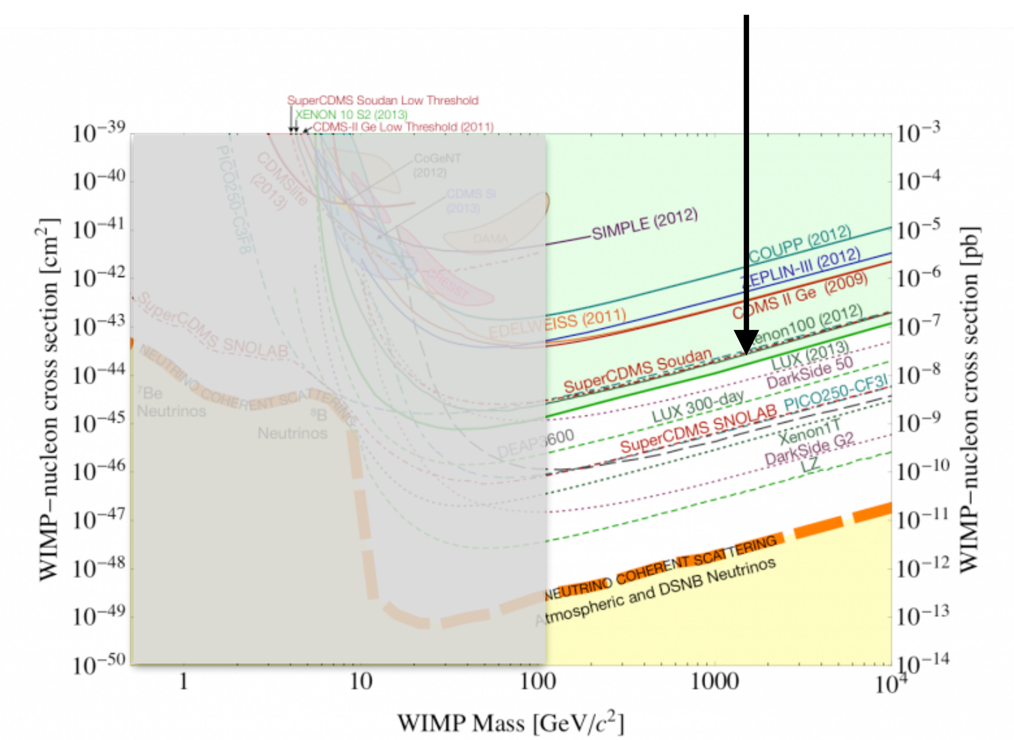
Emphasize: O(1) couplings to weak interaction leads to TeV mass dark matter (not 100 GeV scale)

Spin-Independent Direct Detection of TeV SUSY

Unlike the LHC, the kinematics of elastic spin-independent scattering

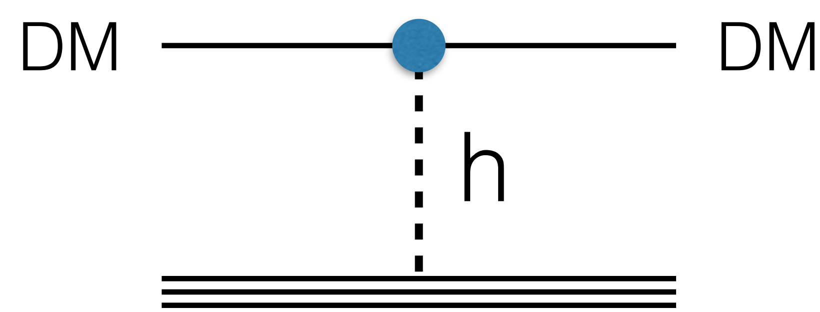


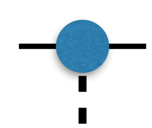
Depends (famously) on the reduced mass, providing sensitivity to scales far higher than LHC can probe (suffering only as $1/m_{DM}$ holding ρ_{local} constant).



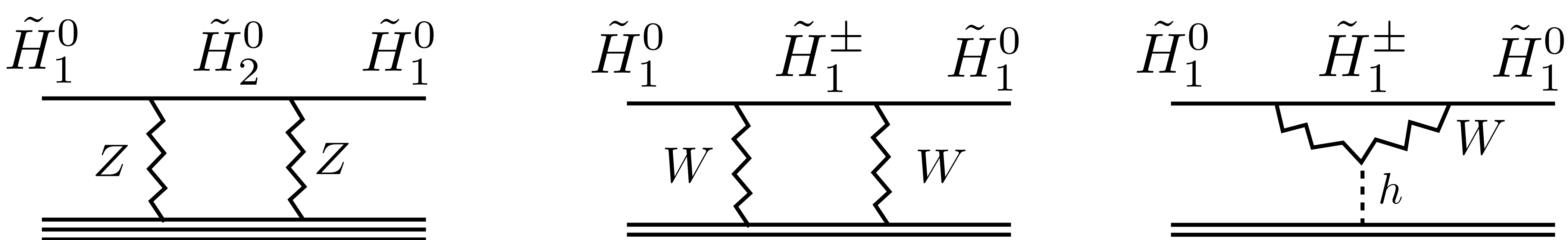
Spin-Independent Direct Detection of TeV SUSY

Majorana nature of SUSY dark matter implies leading interaction with SM through



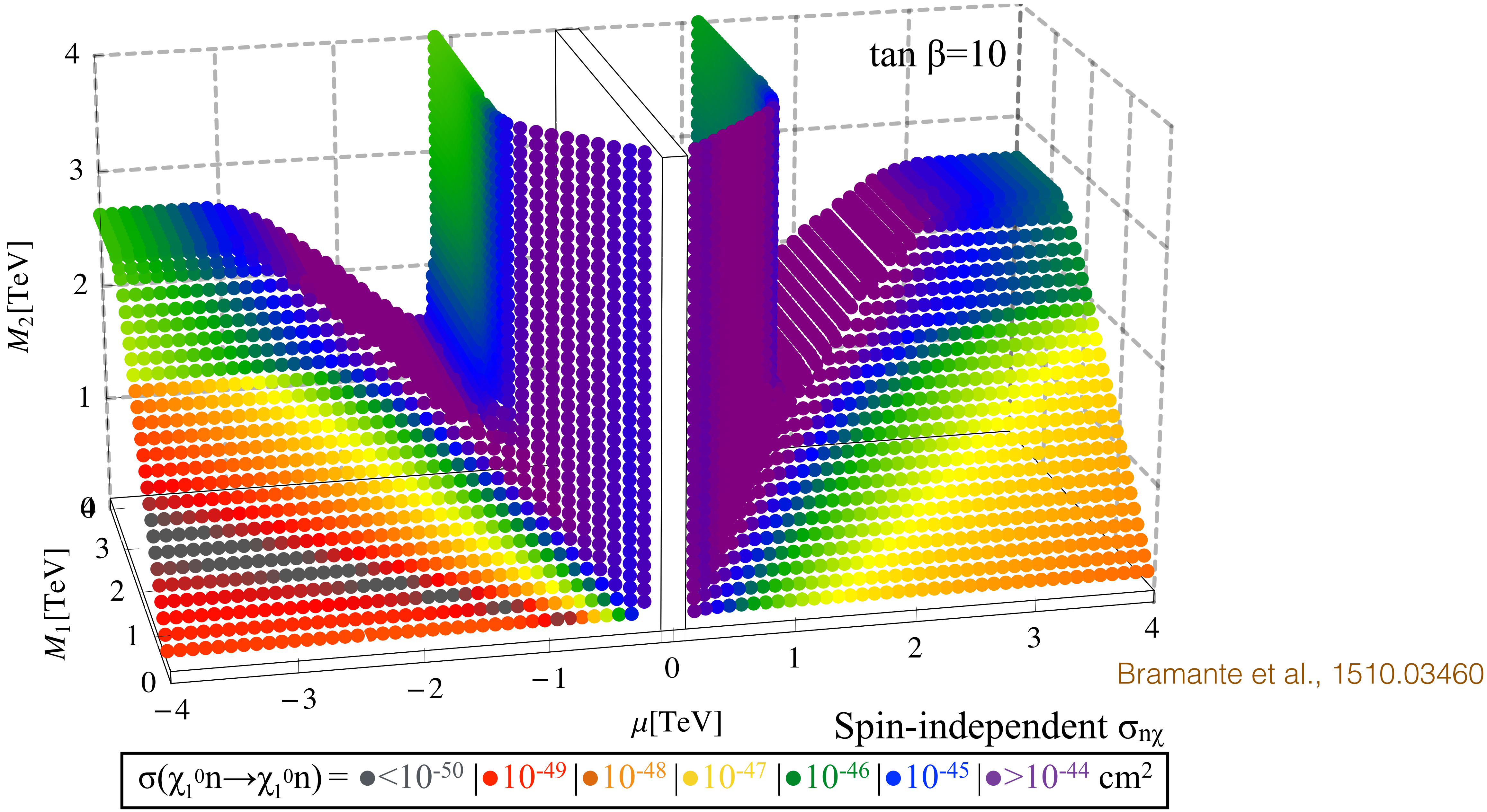
i.e., gaugino-Higgsino mixing  $\sim \frac{(gv)}{m_{\mathrm{DM}}}$ (if the other states are not too heavy)

Otherwise through EW loops (e.g., Higgsinos):



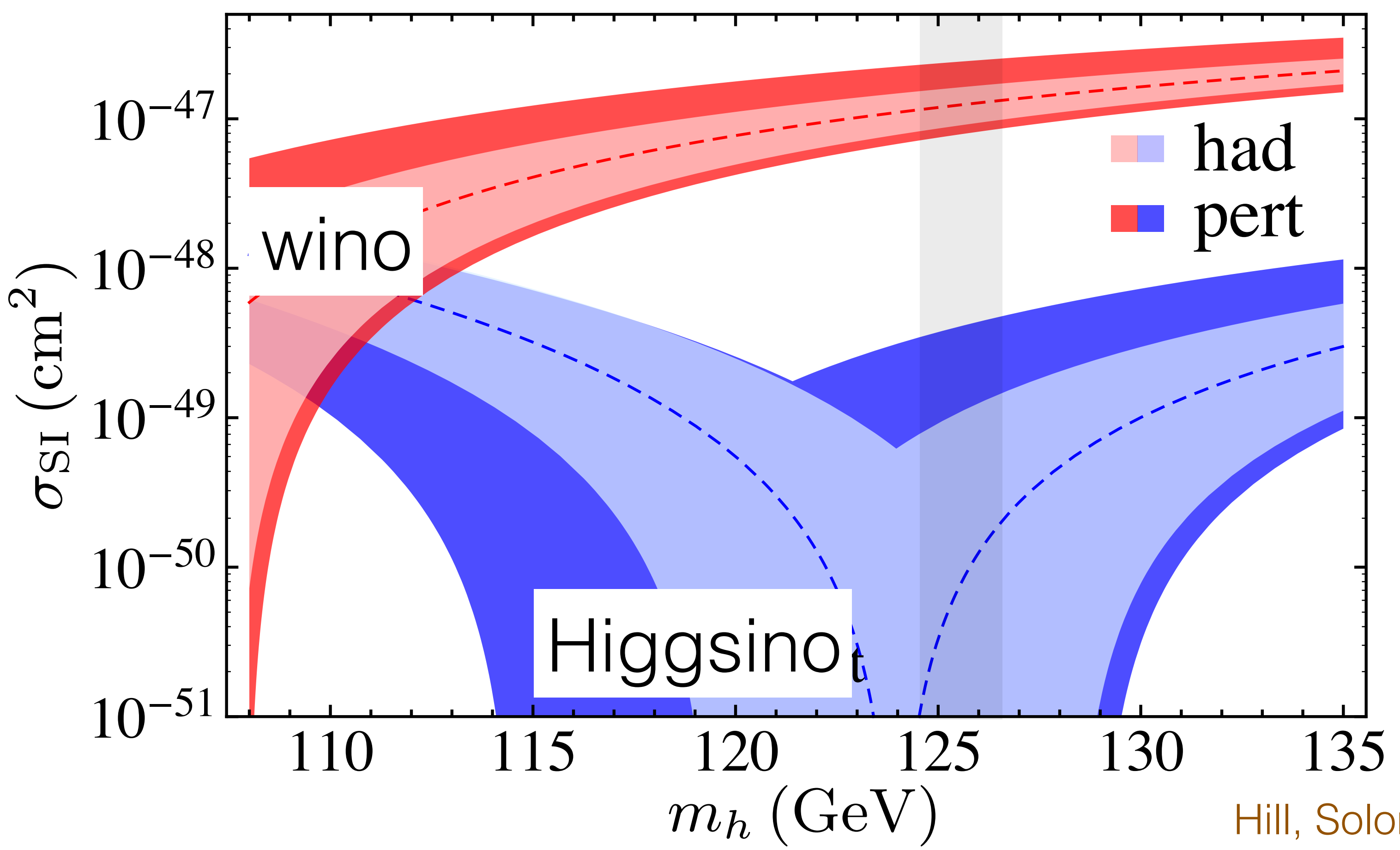
Spin-Independent Direct Detection Rates

Mixed wino / Higgsino states (requiring M_1,M_2,|μ| < 4 TeV)



Spin-Independent Direct Detection Rates

In the case of a nearly pure wino or Higgsino

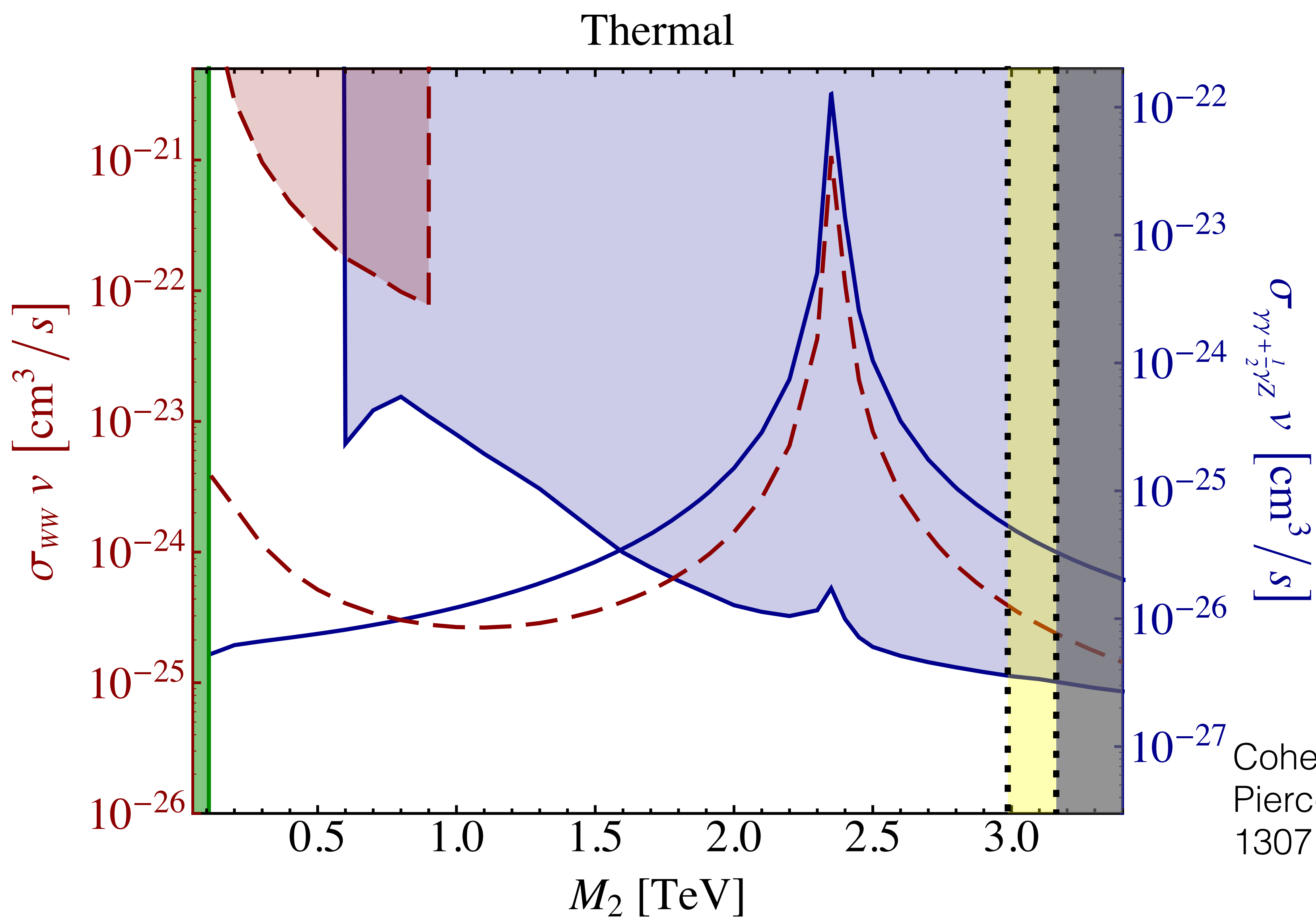


Hill, Solon 1309.4092

Cancellation with Higgs exchange with m_h = 125 GeV leads to a highly suppressed spin-independent elastic scattering rate for Higgsinos

Indirect Detection — Limits on Winos

Sommerfeld enhancement of annihilation disfavors 2.6 TeV winos



Cohen, Lisanti, Pierce, Slatyer 1307.4082

while no indirect detection bounds on 1.1 TeV Higgsinos.

Vignette #2 — Composite Dark Matter

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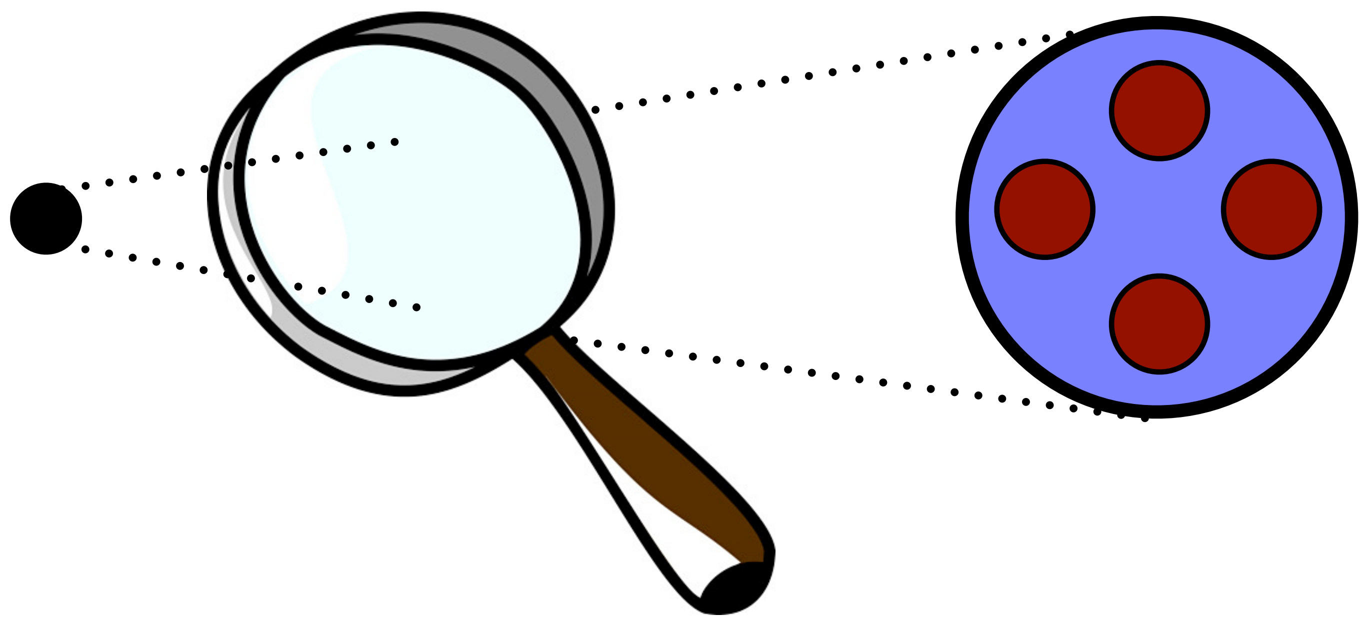


- New technically natural mass scales (Λ_{dark}, M_f)
- DM stability automatic (e.g., baryon number)
- Interactions with SM matter can be suppressed by powers of the compositeness scale
- Self-interactions can be naturally strongly-coupled
- Has a rich spectrum of states (e.g., baryons and mesons) leading to qualitative changes to experimental signals

Selected References

- Technibaryon dark matter (too bad, so sad) — Nussinov (1985); Chivukula, Walker (1990); Barr Chivukula, Farhi (1990)
- Quirky dark matter — GDK, Roy, Terning, Zurek 0909.2034
- Atomic dark matter — Kaplan, Krnjaic, Rehermann, Wells 0909.0753
- Composite Inelastic — Alves, Behbahani, Schuster, Wacker 0903.3945
- Weakly Interacting Stable Pions — Bai, Hill 1005.0008
- Dark SU(2) with $m_f \ll \Lambda_{dark}$ — Buckley, Neil 1209.6054
- Dark SU(3) with magnetic moment — LSD Collaboration 1301.1693
- Stealth Dark Matter 1 — GDK with LSD Collaboration 1402.6656
- Dark Nuclei [with SU(2)] — Detmold, McCullough, Pochinsky 1406.2276
- Glueball / glueballino ($\Lambda \ll M_{gluino}$) — Boddy, Feng, Kaplinghat, Shadmi, Tait 1408.6532
- SIMP dark pions — Hochberg, Kuflik, Murayama, Volansky, Wacker 1411.3727
- Stealth Dark Matter Model and polarizability — GDK with LSD Collaboration 1503.04203,1503.04205
- Accidental composite — Antipin, Redi, Strumia, Vigiani 1503.08749
- Non-abelian DM and dark radiation — Buen-Abad, Marques-Tavares, Schmaltz 1505.03542
- Chiral Dark Matter — Harigaya, Nomura 1603.03430 + Ko 1610.03848

Identity of Dark Matter

Dark matter is baryon or meson of new, confining gauge theory.

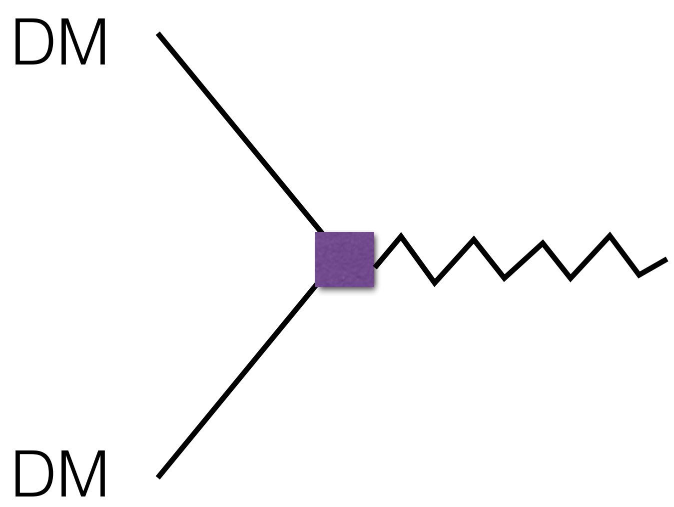
Dark quarks may transform under SM; or they may have their own gauged flavor symmetries (e.g., $U(1)_{dark}$) that mix with the SM.

Thermal freeze out, indirect detection, and direct detection, occur at non-relativistic velocities — hence these theories appear as if there is an elementary particle with higher dimensional interactions.

Which interactions dominate depends on the UV theory — that may be probed by the LHC.

Effective Interactions of Strongly Coupled Dark Matter

Effective interactions of strongly-coupled dark matter with SM mediators/matter is generically higher dimensional



$$\frac{1}{(\Lambda_{\rm dark})^n}$$

Effective interaction involves new, dynamical scale

e.g.:
magnetic moment:

$$\frac{\overline{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}}{\Lambda_{\rm dark}}$$

charge radius:

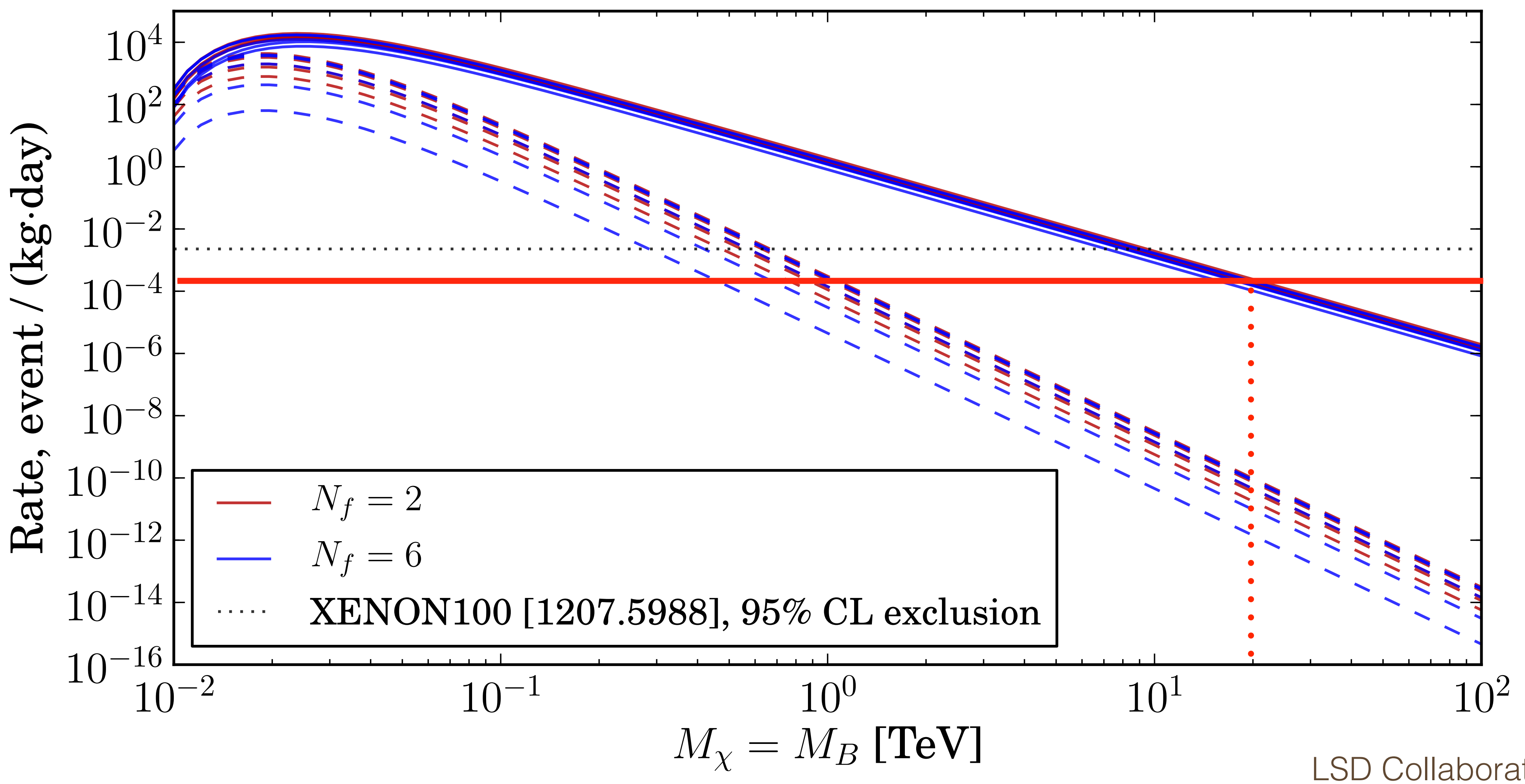
$$\frac{(\overline{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}}{(\Lambda_{\rm dark})^2}$$

polarizability:

$$\frac{(\overline{\psi}\psi)F_{\mu\nu}F^{\mu\nu}}{(\Lambda_{\rm dark})^3}$$

Strongly Coupled Dark Matter with an Magnetic Moment

E.g., “dark neutron” with electrically charged “dark quarks”; calculated using lattice gauge simulations.



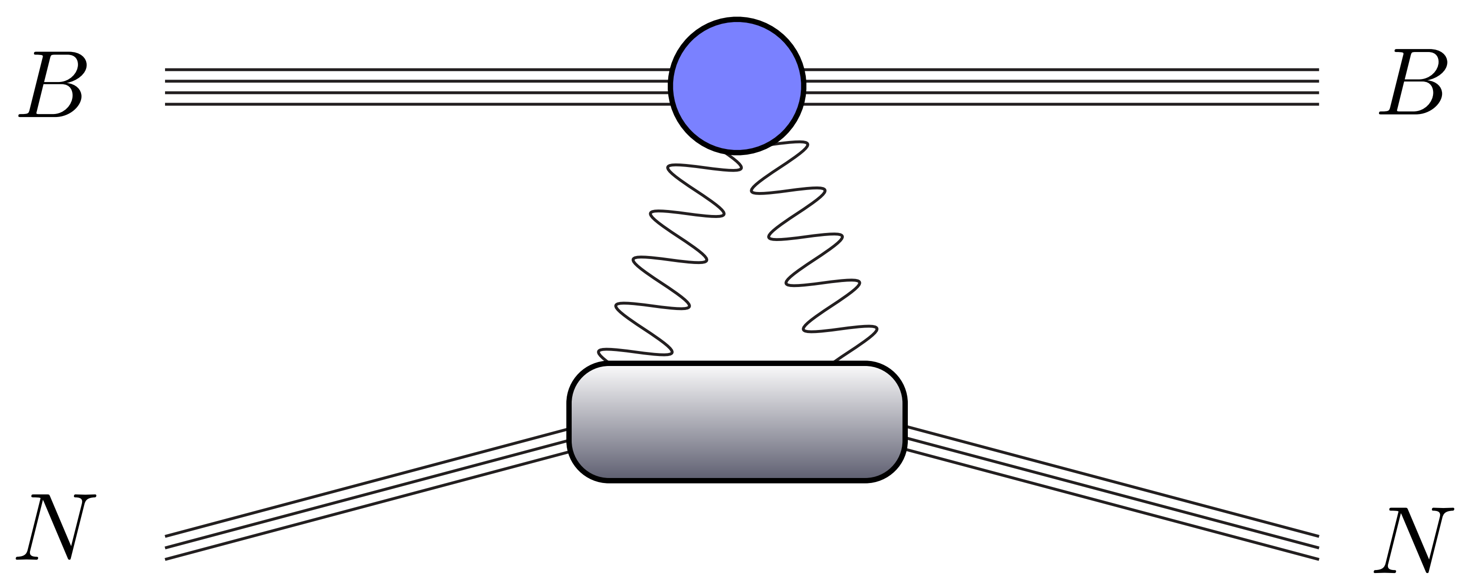
Estimated LUX 2016 bound

LSD Collaboration 1301.1693

Current bound: $m_{\rm DM} \gtrsim 20$ TeV

“Stealth Dark Matter” with EM Polarizability

For SU(N=even) theories, baryons are bosons, and the lightest can be a scalar.



This is the “stealthiest” theory in which dark quarks have EW charges.

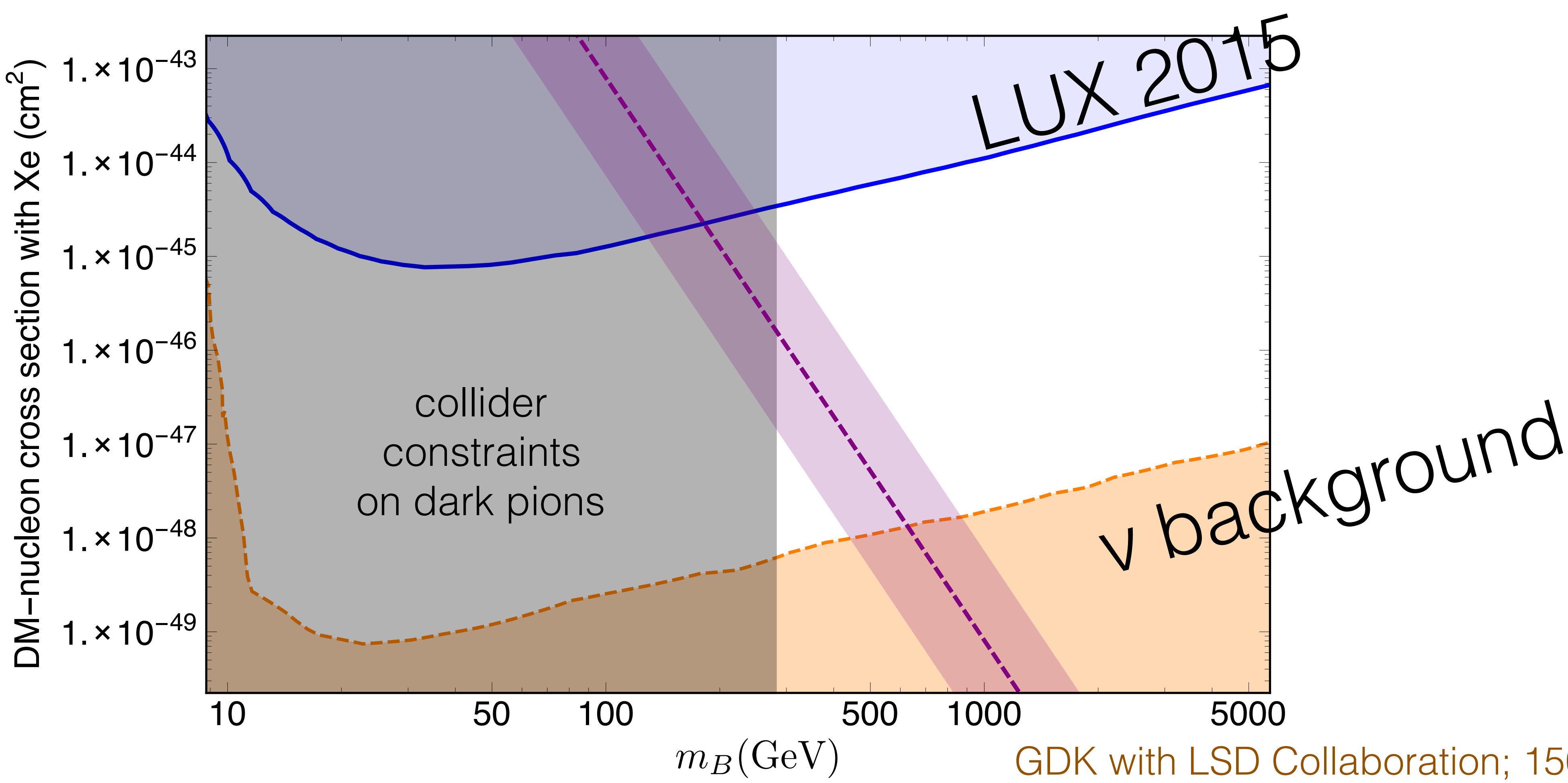
We considered SU(4) theories, and calculated the strongly coupled dark matter polarizability using lattice gauge simulations.

GDK with LSD Collaboration; 1503.04203, 1503.04205

"Stealth Dark Matter" with EM Polarizability

Note! $$\sigma_{\rm nucleon} = \frac{Z^4}{A^2} \frac{144\pi\alpha^4\mu_{nB}^2(M_F^A)^2}{m_B^6 R^2}[c_F^2]$$

Depends on (Z,A), since it doesn't have A^2-like (Higgs-like) scaling.
For Zenon, we obtain:

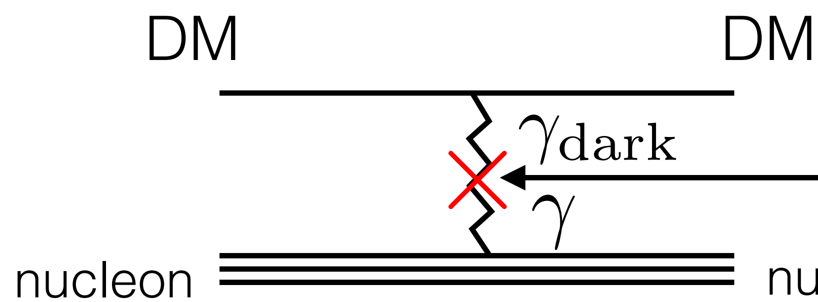


GDK with LSD Collaboration; 1503.04205

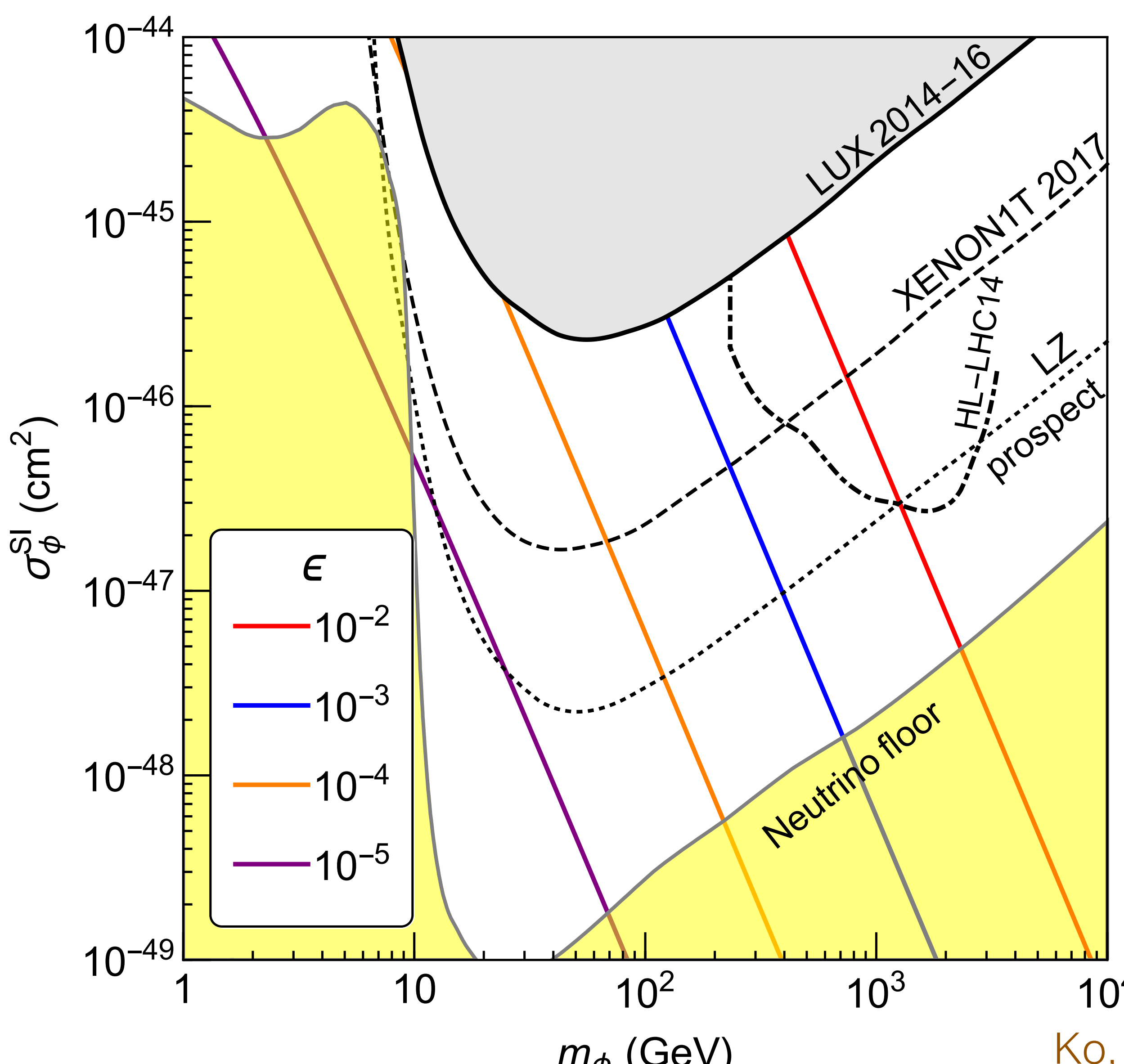
Confluence of collider and direct detection bounds, but for reasons completely different than ordinary (elementary) WIMPs.

Strongly Coupled “Chiral Dark Matter” through $U(1)_{dark}$

Dark pion dark matter; interactions through $U(1)_{dark}$ kinetic mixing



Dimensionless parameter
ϵ characterizes mixing



Ko, Harigara, Nomura; 1610.03848

Viable Origins for Abundance

1. Thermal freezeout

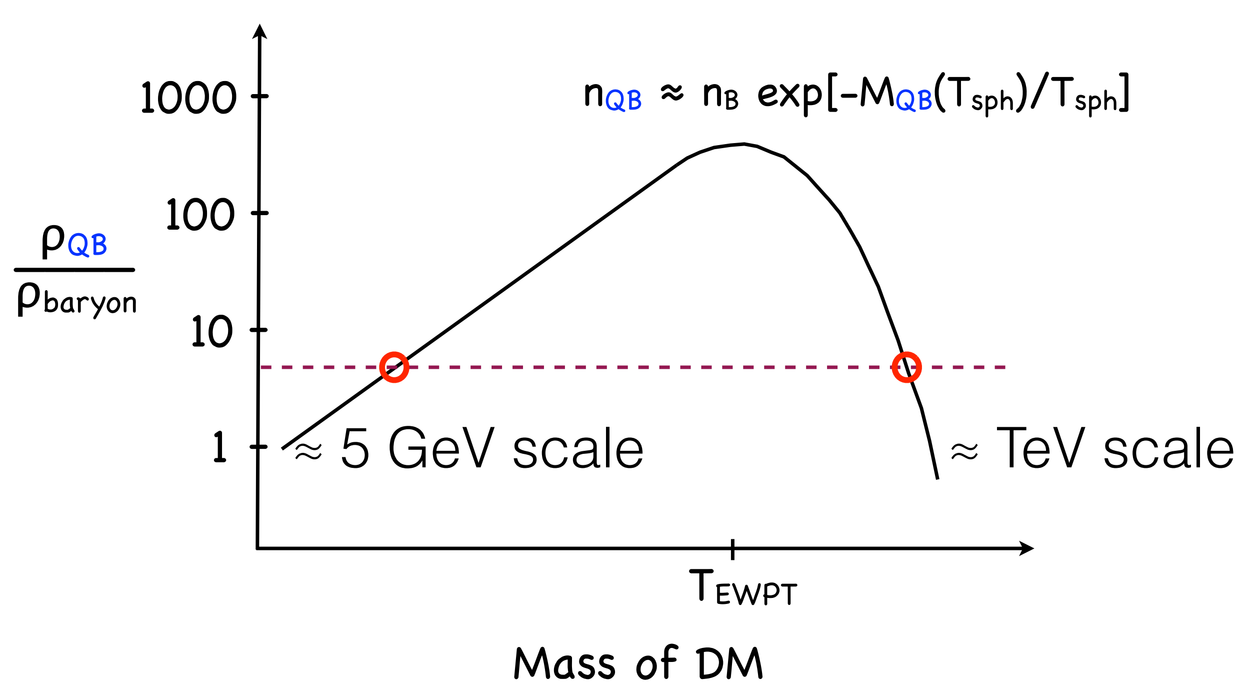
   For N_{dark} small, expect dark baryon annihilation to be strongly coupled (saturate unitarity bound — $m_{DM} \approx 100$ TeV).

   Kamionkowski, Griest; 1990

   For N_{dark} larger (in quarkonia limit), Witten showed that annihilation is exponentially suppressed — much smaller dark matter masses are possible.

   Witten; 1979

2. Asymmetric production - e.g. electroweak sphalerons connect dark and visible baryon numbers. Strong coupling ensures small symmetric component.



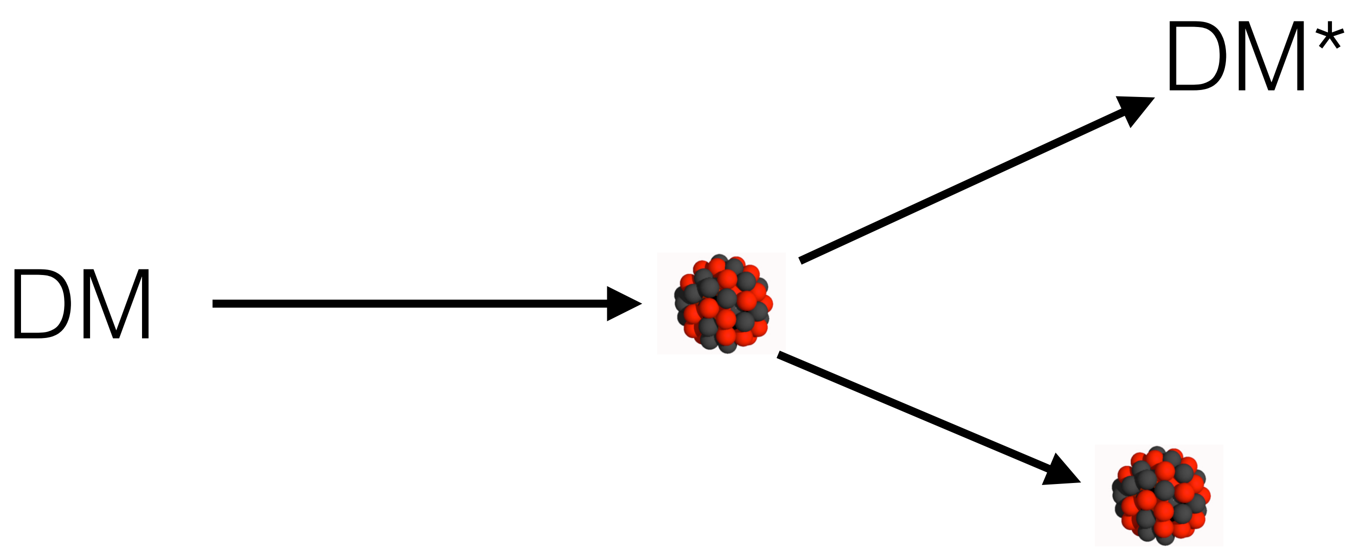
Barr, Chivukula, Farhi 1990; also GDK, Roy, Terning, Zurek 2009

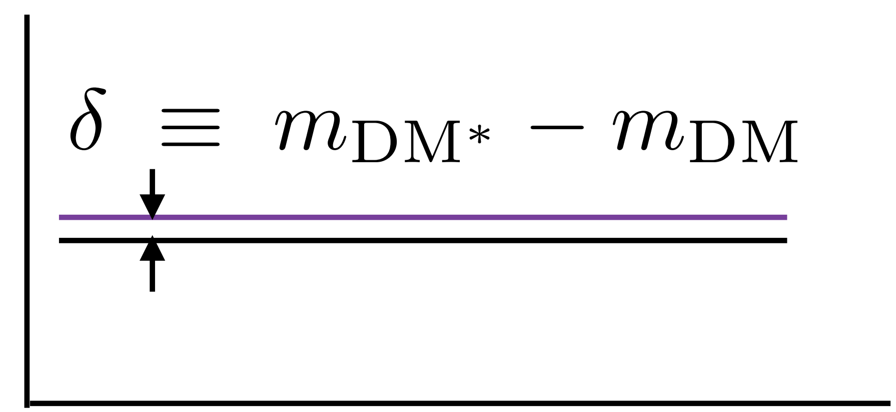
Vignette #3 — Inelastic Dark Matter

Vignette #3 — Inelastic Dark Matter

Hall, Moroi, Murayama, hep-ph/9712515
Tucker-Smith, Weiner 0101138, 0402065

The leading interaction with nuclei may proceed through an inelastic transition in which DM upstaters to an excited state DM*





This qualitatively changes the kinematics of dark matter scattering.

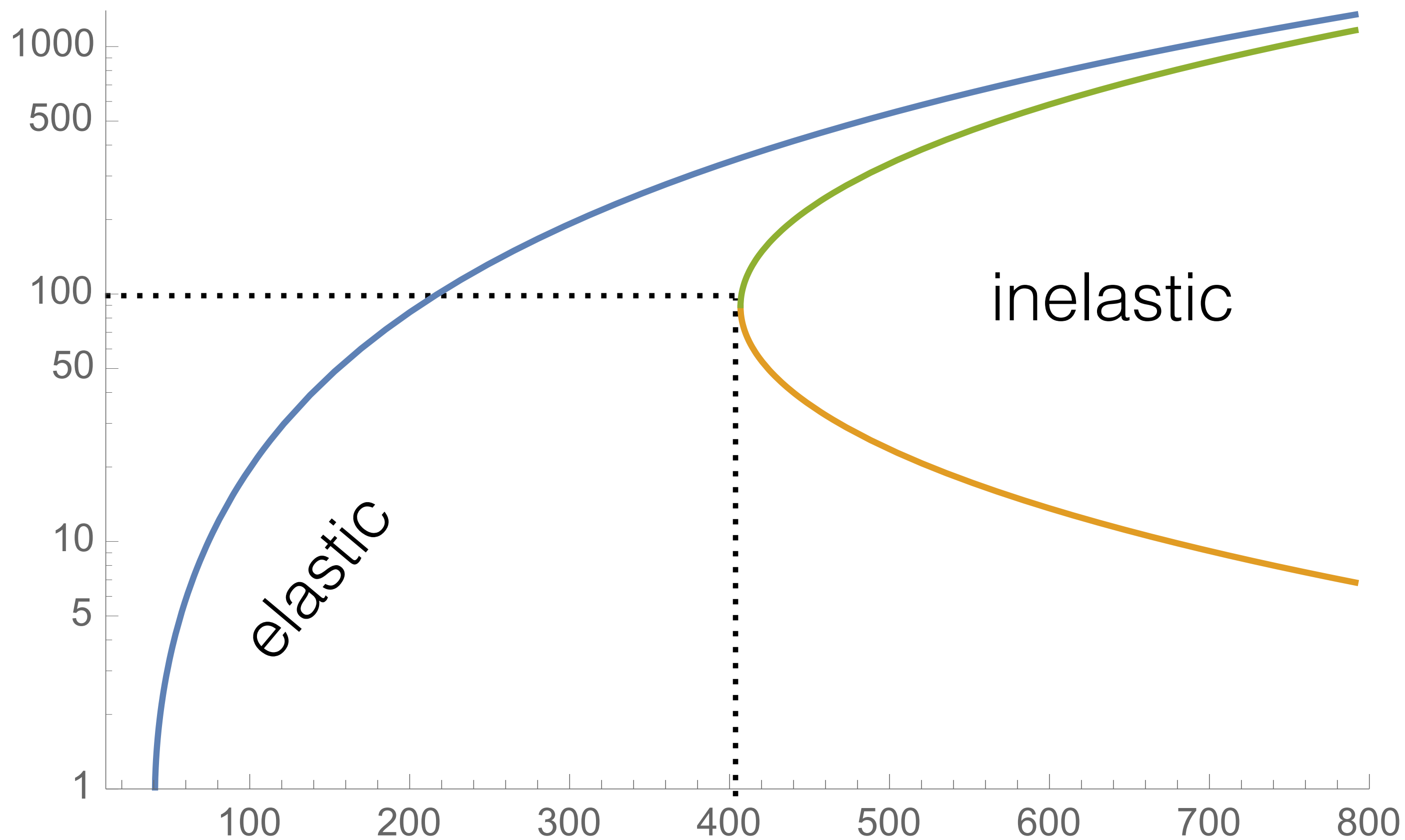
Since DM has $K.E. = \frac{1}{2}\mu v^2$ with $v_{\max} \lesssim v_{\mathrm{esc}} + v_{\mathrm{sun}}$, the max mass splitting

$$\delta \lesssim (400\ \mathrm{keV}) \frac{\mu}{m_{Xe}}$$

Inelastic Scattering Kinematics

E_R [keV]

$$E_R|_{\mathrm{v_{min}}} = \frac{\mu}{m_N}\delta$$



$m_{\mathrm{DM}} = 1$ TeV

$\delta = 100$ keV

v [km/s]

$$v_{\mathrm{min}}|_{E_{R,\mathrm{min}}} = \sqrt{\frac{2\delta}{\mu}}$$

Bramante, Fox, GK, Martin; 1608.02662

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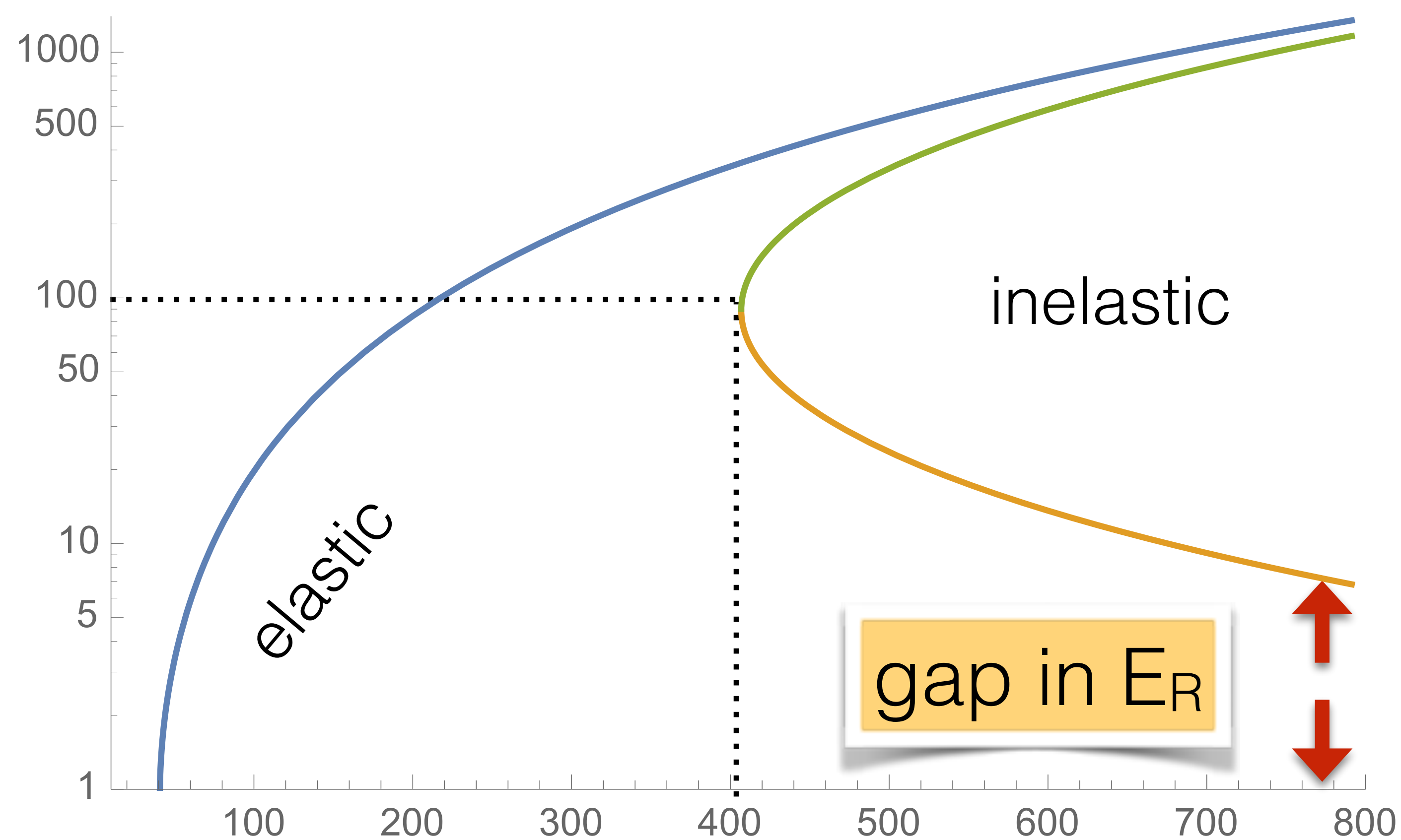

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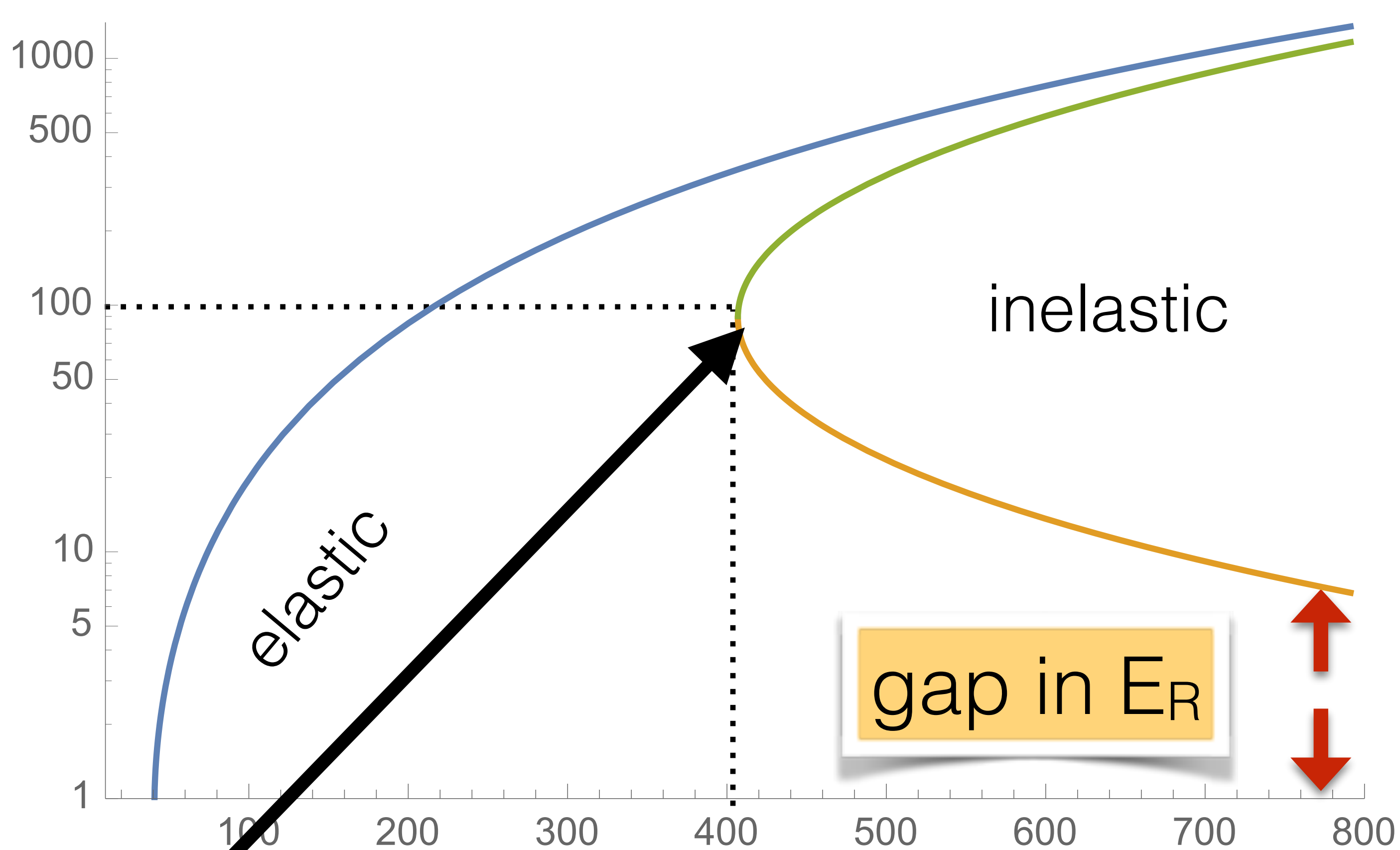


v [km/s]

$$m_{\mathrm{DM}} = 1\ \mathrm{TeV}$$

$$\delta = 100\ \mathrm{keV}$$

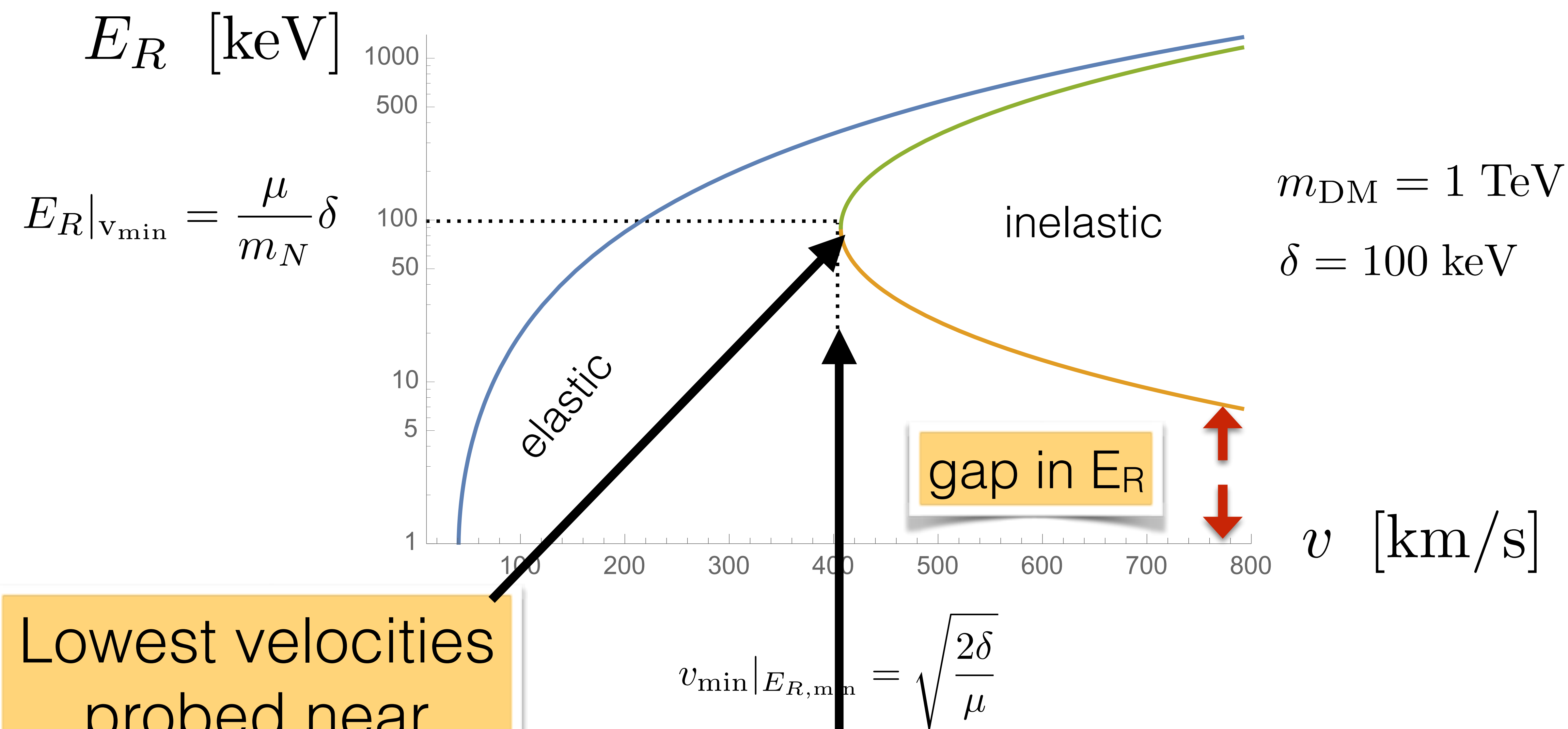
Lowest velocities probed near

$$E_R|_{\mathrm{v_{min}}} = \frac{\mu}{m_N}\delta$$

$$v_{\mathrm{min}}|_{E_{R,\mathrm{min}}} = \sqrt{\frac{2\delta}{\mu}}$$

Bramante, Fox, GK, Martin; 1608.02662

Inelastic Scattering Kinematics

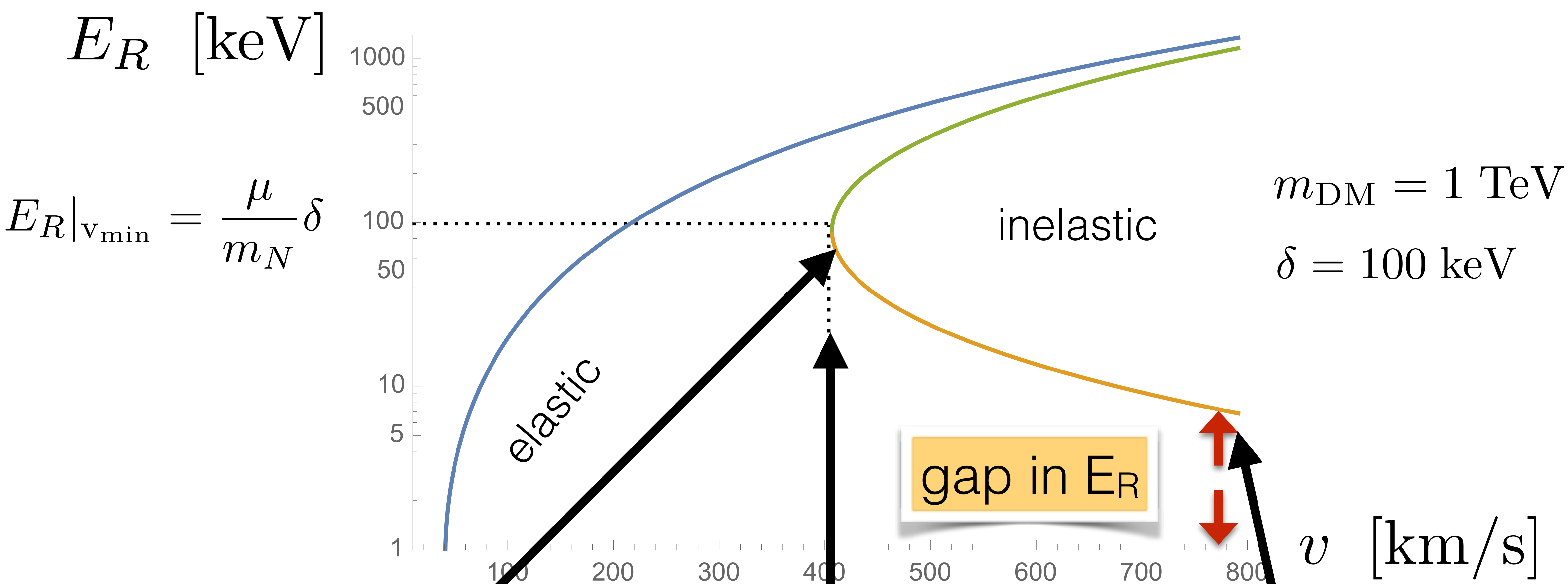


Lowest velocities probed near $E_R|_{v_{min}} = \frac{\mu}{m_N}\delta$

Min velocity to scatter

Bramante, Fox, GK, Martin; 1608.02662

Inelastic Scattering Kinematics



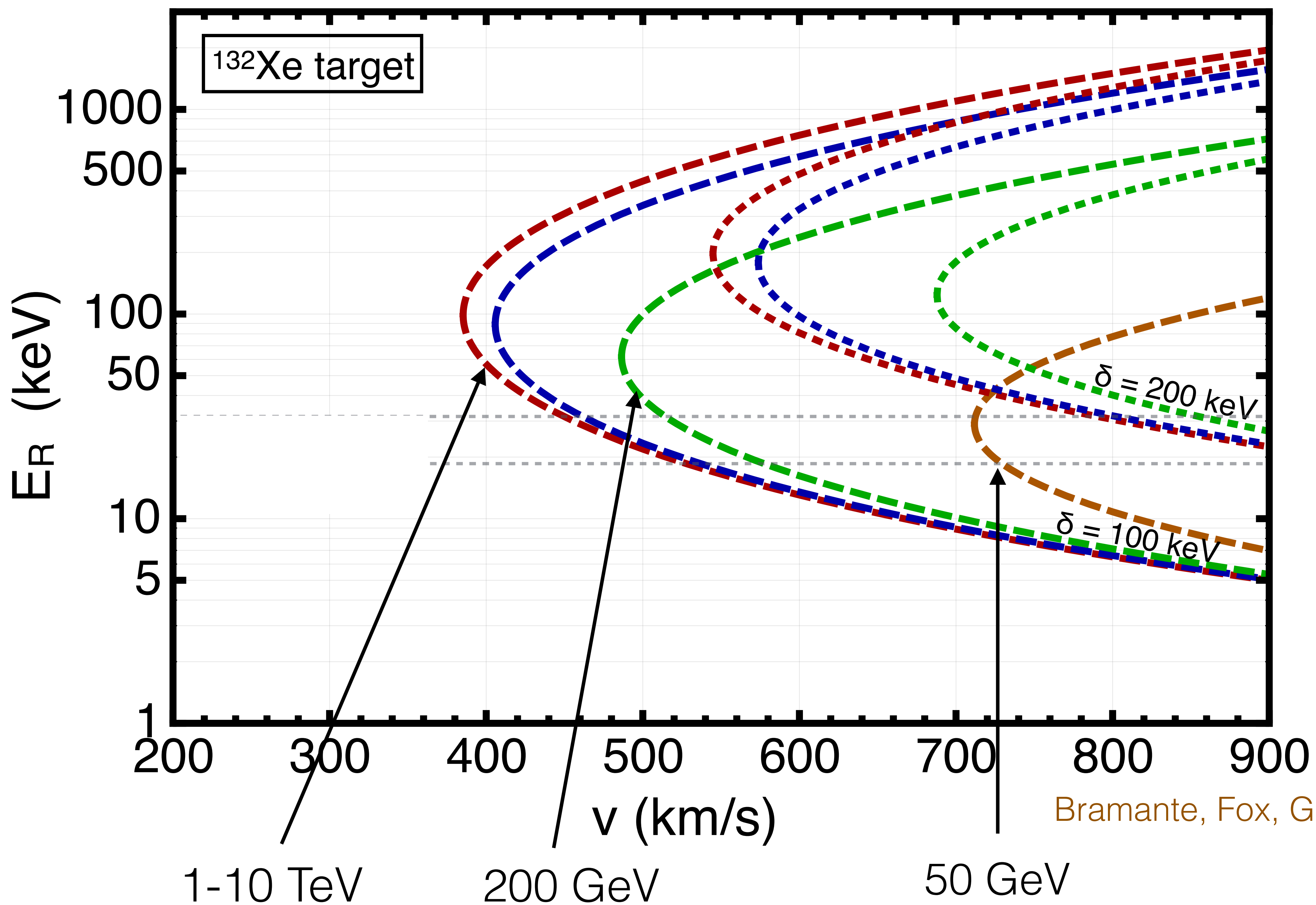
Lowest velocities probed near $E_R|_{\mathrm{v_{min}}} = \frac{\mu}{m_N}\delta$

$$v_{\min}|_{E_{R,\min}} = \sqrt{\frac{2\delta}{\mu}}$$

Min velocity to scatter

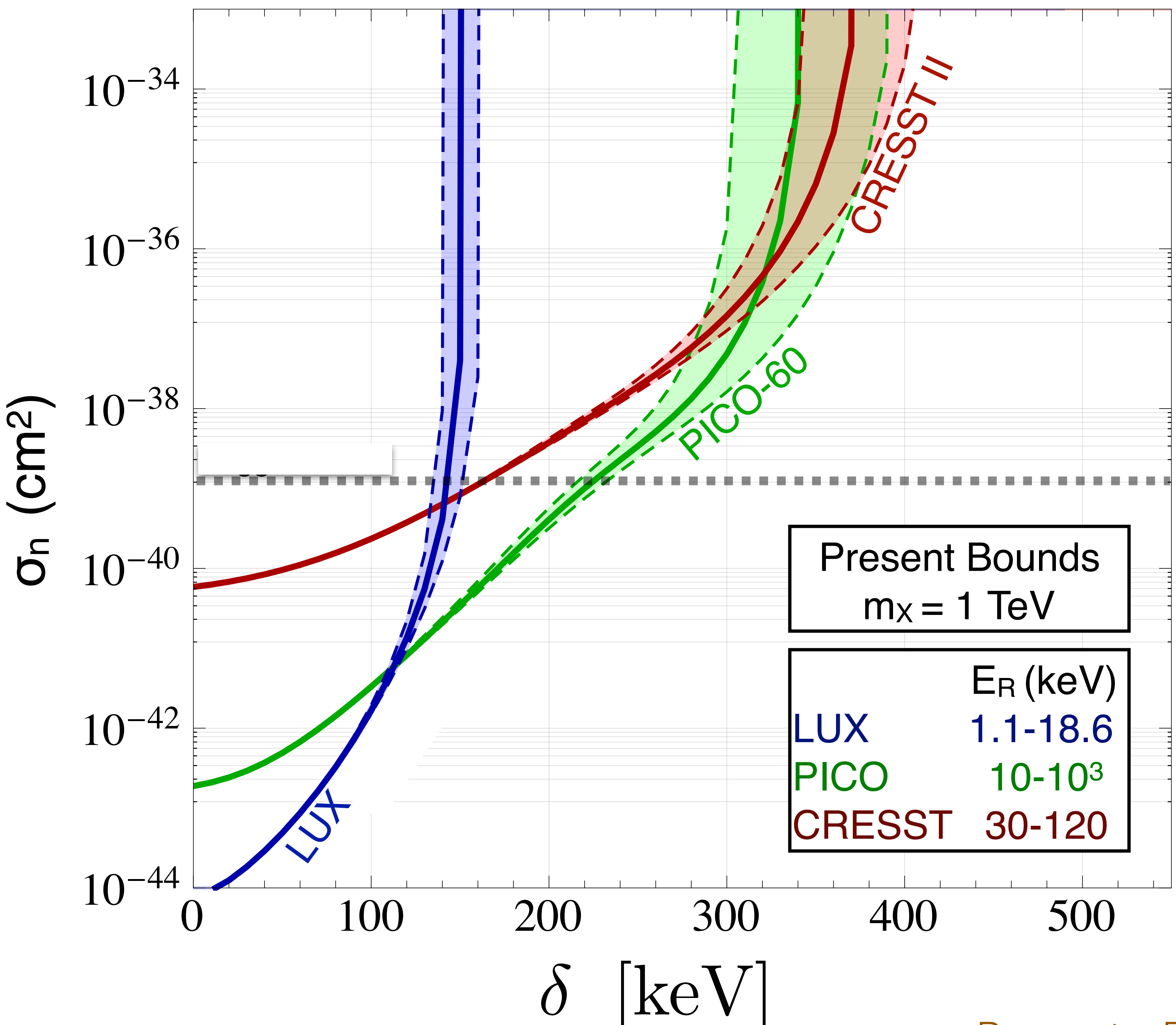
Smallest E_R at tail of velocity distribution

Inelastic Frontier maximzed with $m_{\mathrm{DM}} \gtrsim m_{\mathrm{Xe}}$



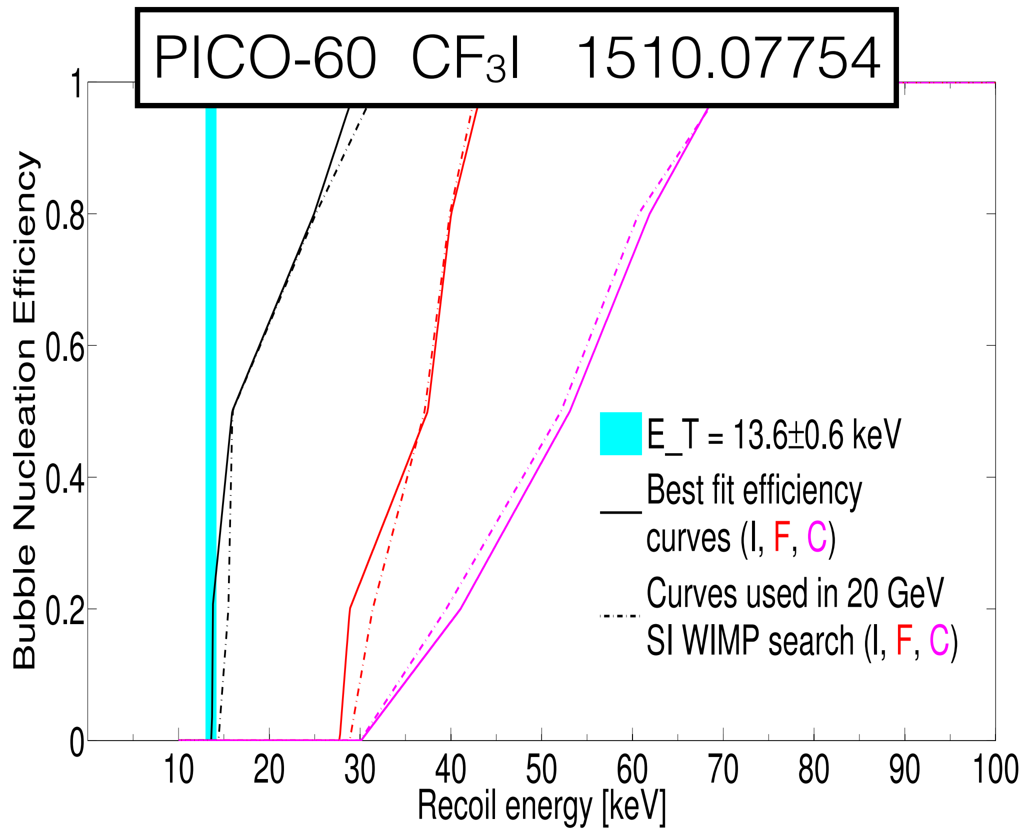
Bramante, Fox, GK, Martin; 1608.02662

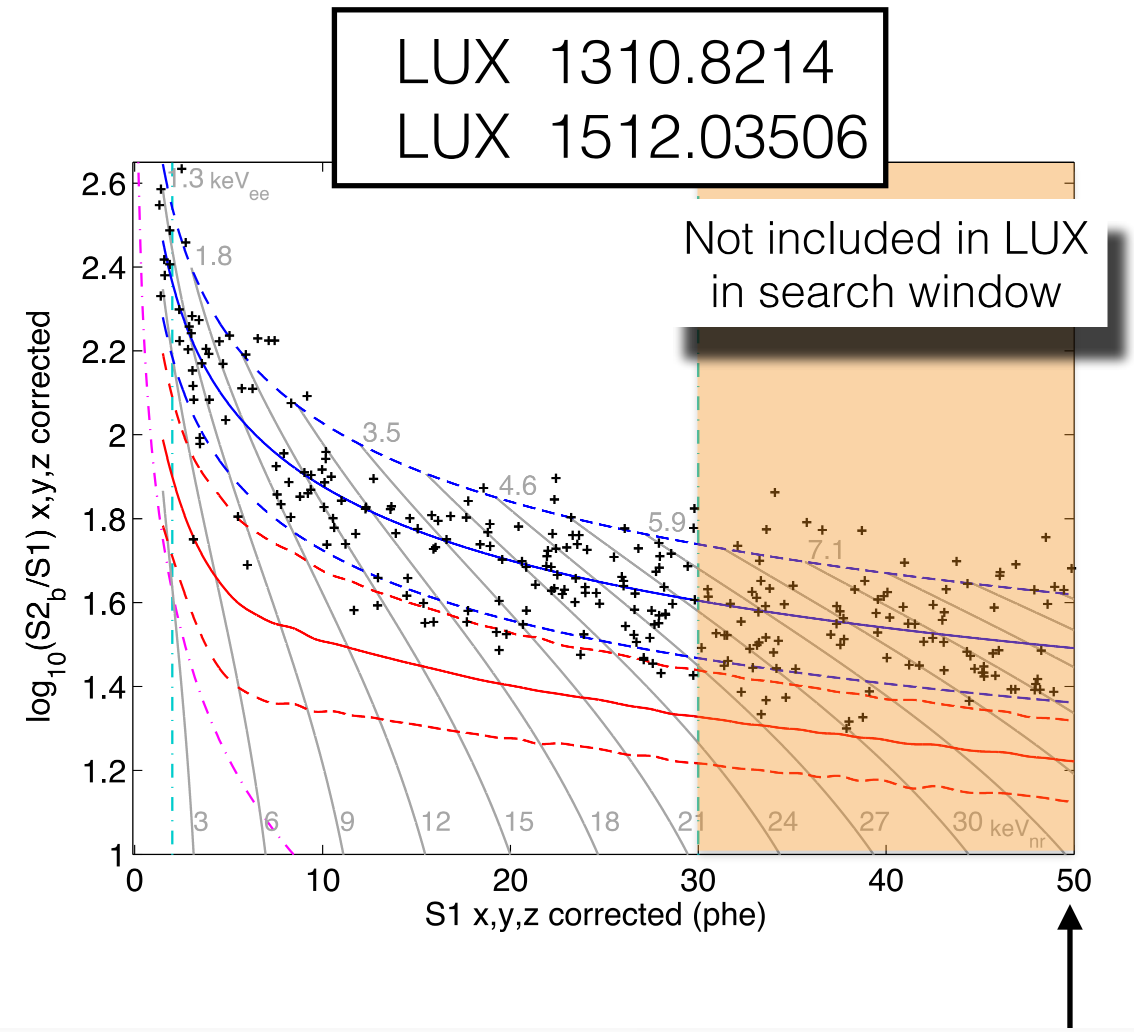
Inelastic Parameter Space



Bramante, Fox, GK, Martin; 1608.02662

Current Experimental Limitations



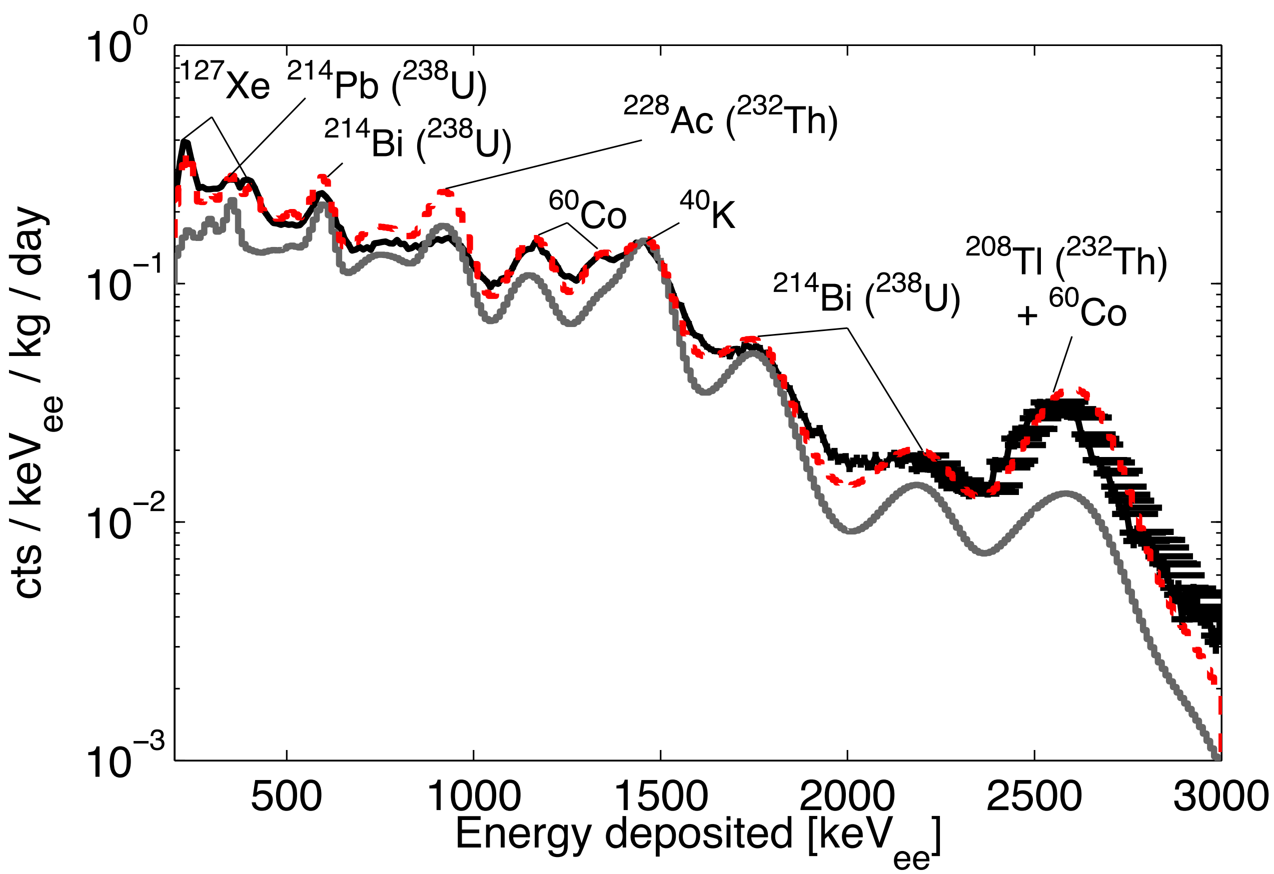


No upper bound on E_R!

Upper bound $E_{Rmax} \approx 33$ keVnr

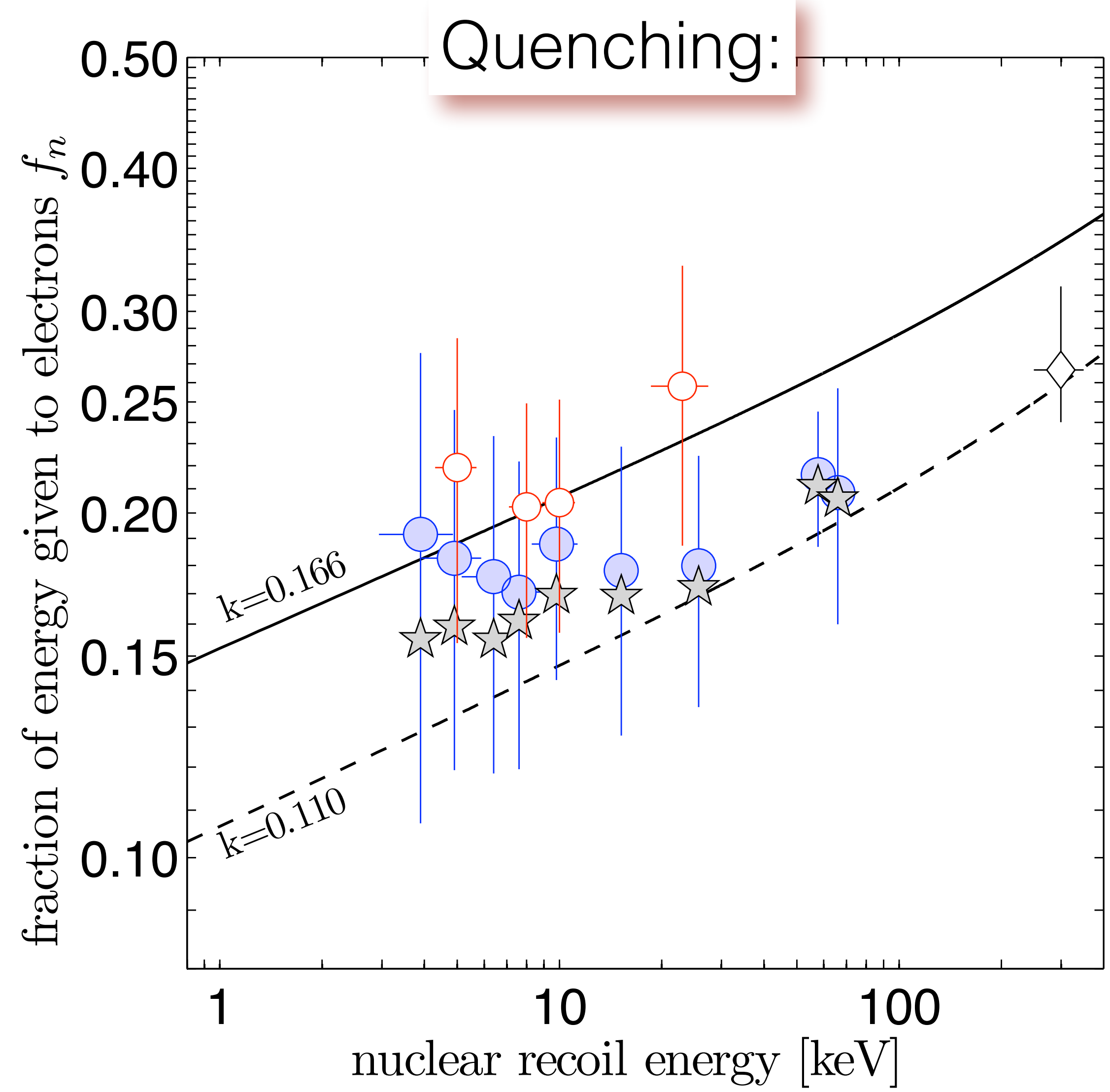
(due to neutron calibration max recoil energy of about 70 keVnr)

Xenon experiments are sensitive to much higher recoil energies



LUX 1403.1299

Quenching:

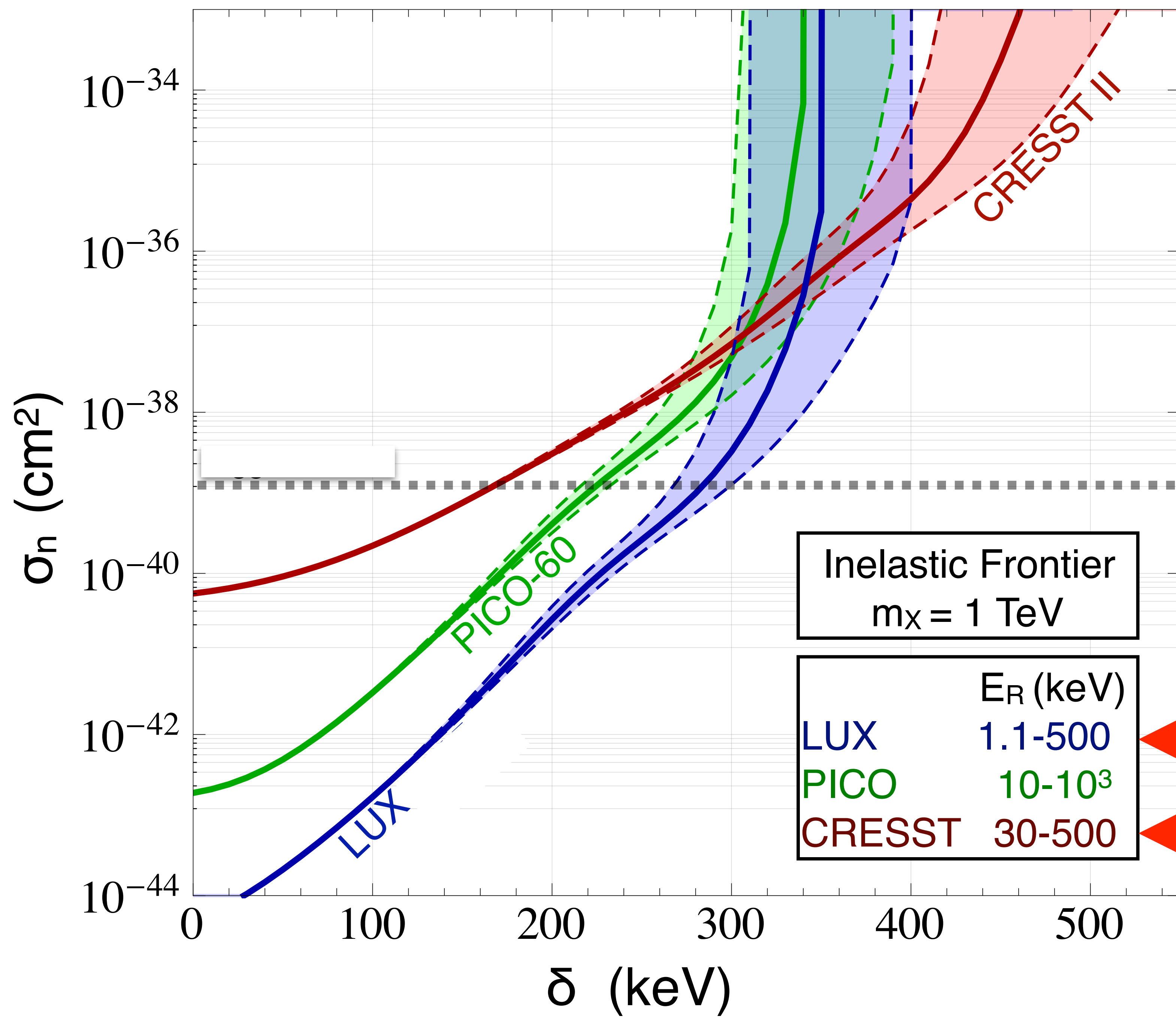


Sorensen, Dahl; 1101.6080

Up to 3 MeVee ≈ 10 MeVnr

(using AmBe source calibrated to 300 keVnr!)

Inelastic parameter space sensitivity improved!

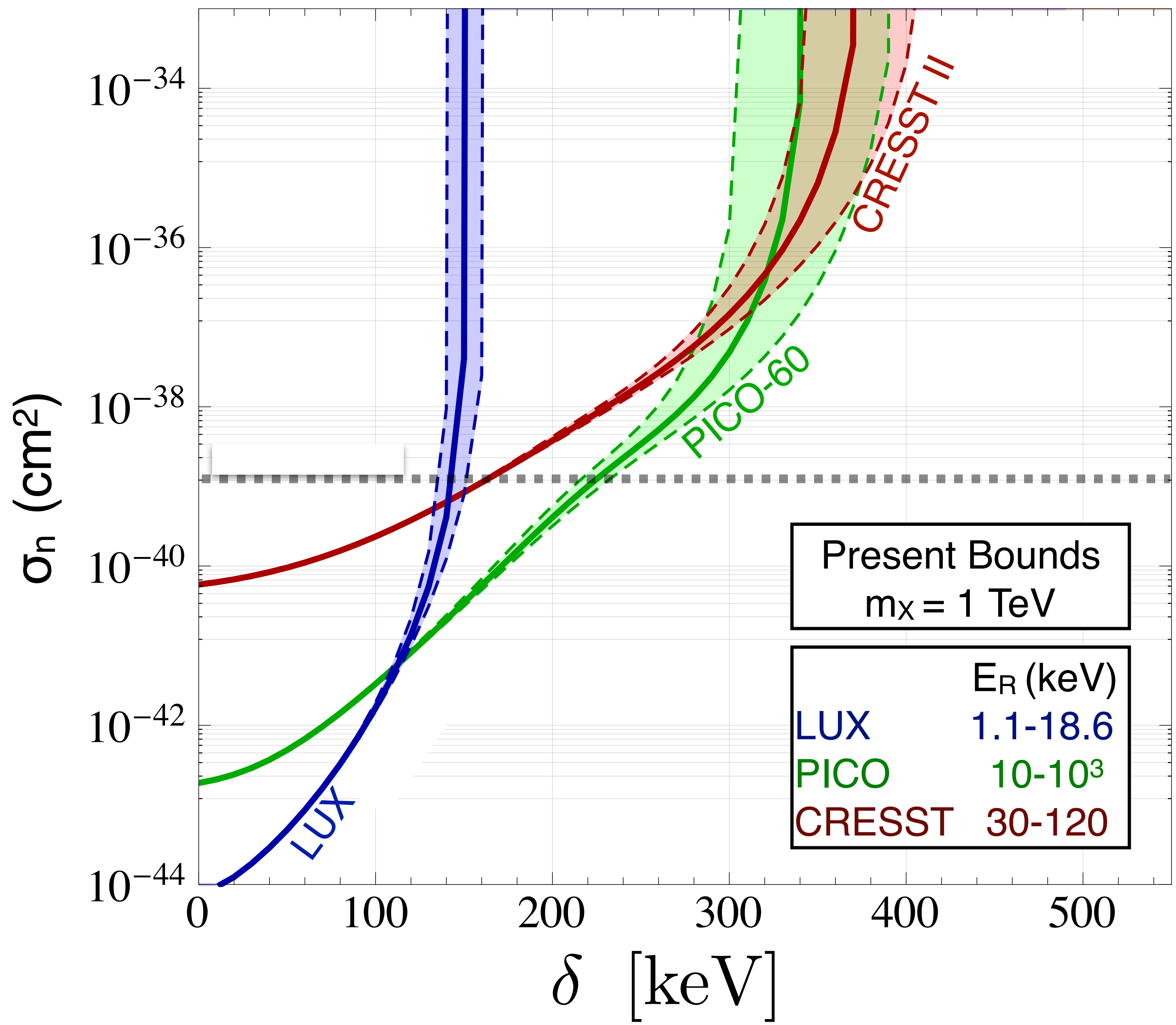


Extend to 500 keVnr

Projected sensitivity improvement using existing (2015) exposures.

Bramante, Fox, GK, Martin; 1608.02662

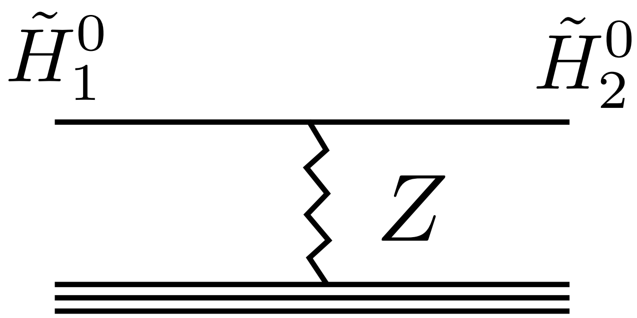
Inelastic Parameter Space



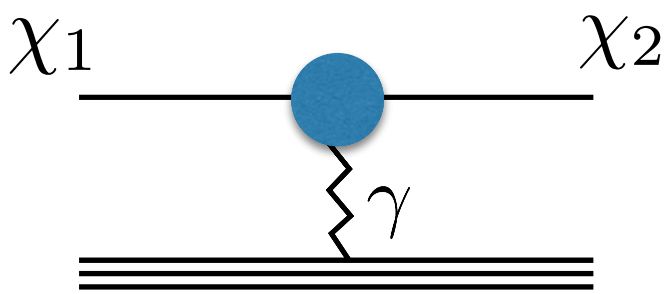
Bramante, Fox, GK, Martin; 1608.02662

Well Motivated Inelastic Models

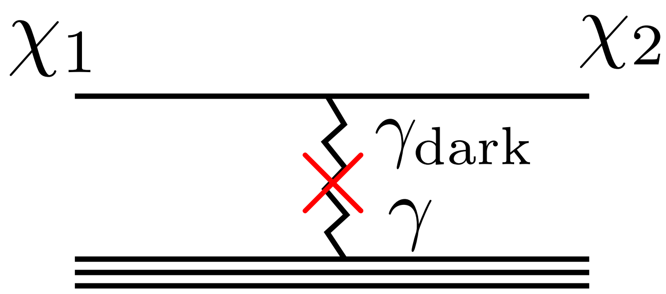
1. Nearly degenerate Higgsinos



2. Magnetic inelastic



3. Inelastic dark photon



Summary

- 3 theory vignettes are illustrative of the continued importance of searching for heavier dark matter

  (Near-GeV scale remains interesting and exciting; no time to discuss.)

- Higgsinos remain perfectly viable (if tuned) supersymmetry motivation;
  —> σ_n very small — below the neutrino floor

- Composite dark matter is a super interesting class of models that can obtain cosmological abundance and direct detection prospects
  —> effective interactions may not scale as A^2; provides method to distinguish interactions with different detectors

- Inelastic dark matter permits far larger effective cross sections;
  —> require analysis of high recoil data to maximize sensitivity