WIMPy Inelastic Dark Matter In Light Of Low-Background Experiments

Ningqiang Song

with Ben Broerman, Serge Nagorny and Aaron Vincent

Queen's University, McDonal Institute, Perimeter Institute

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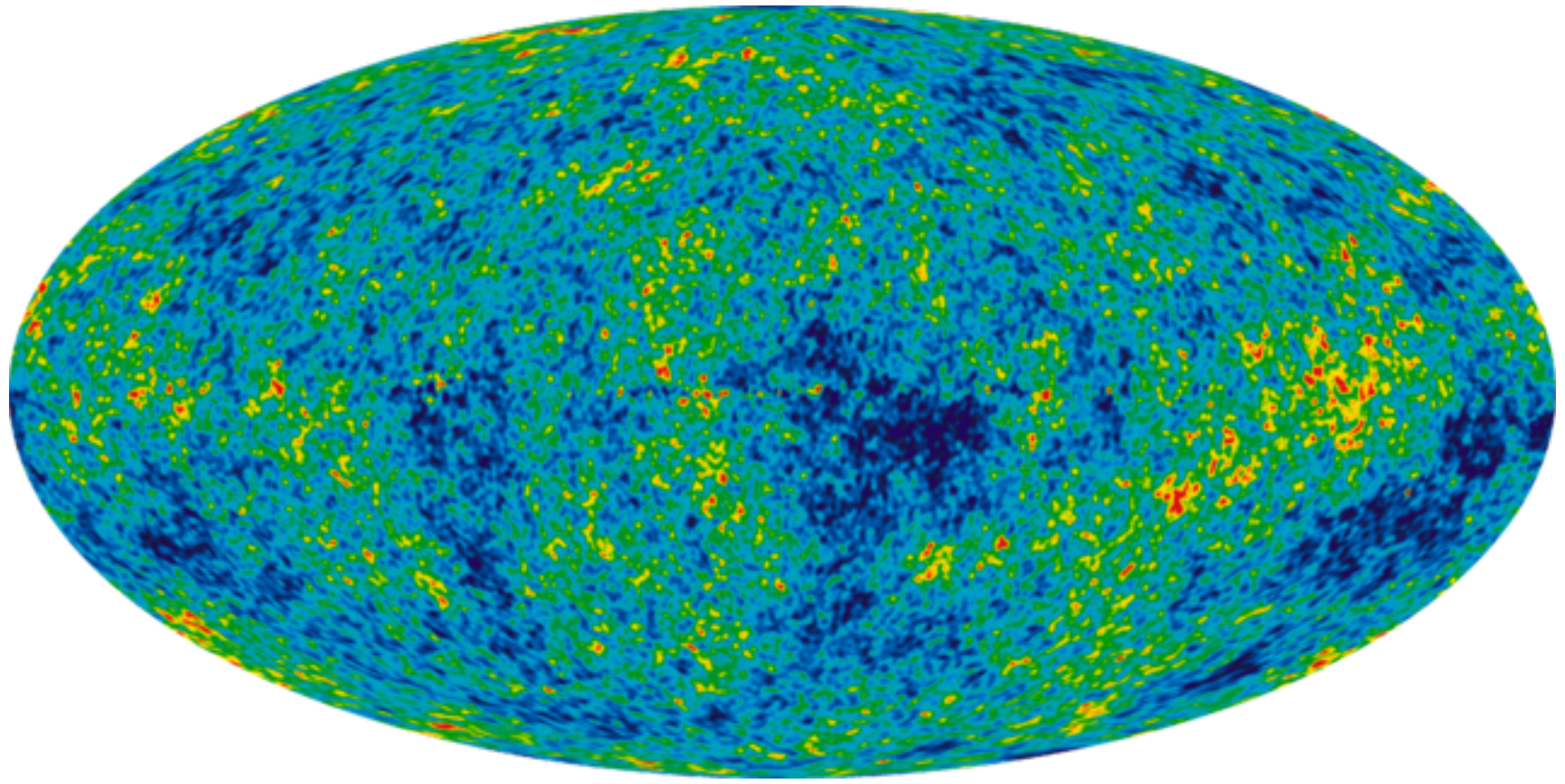
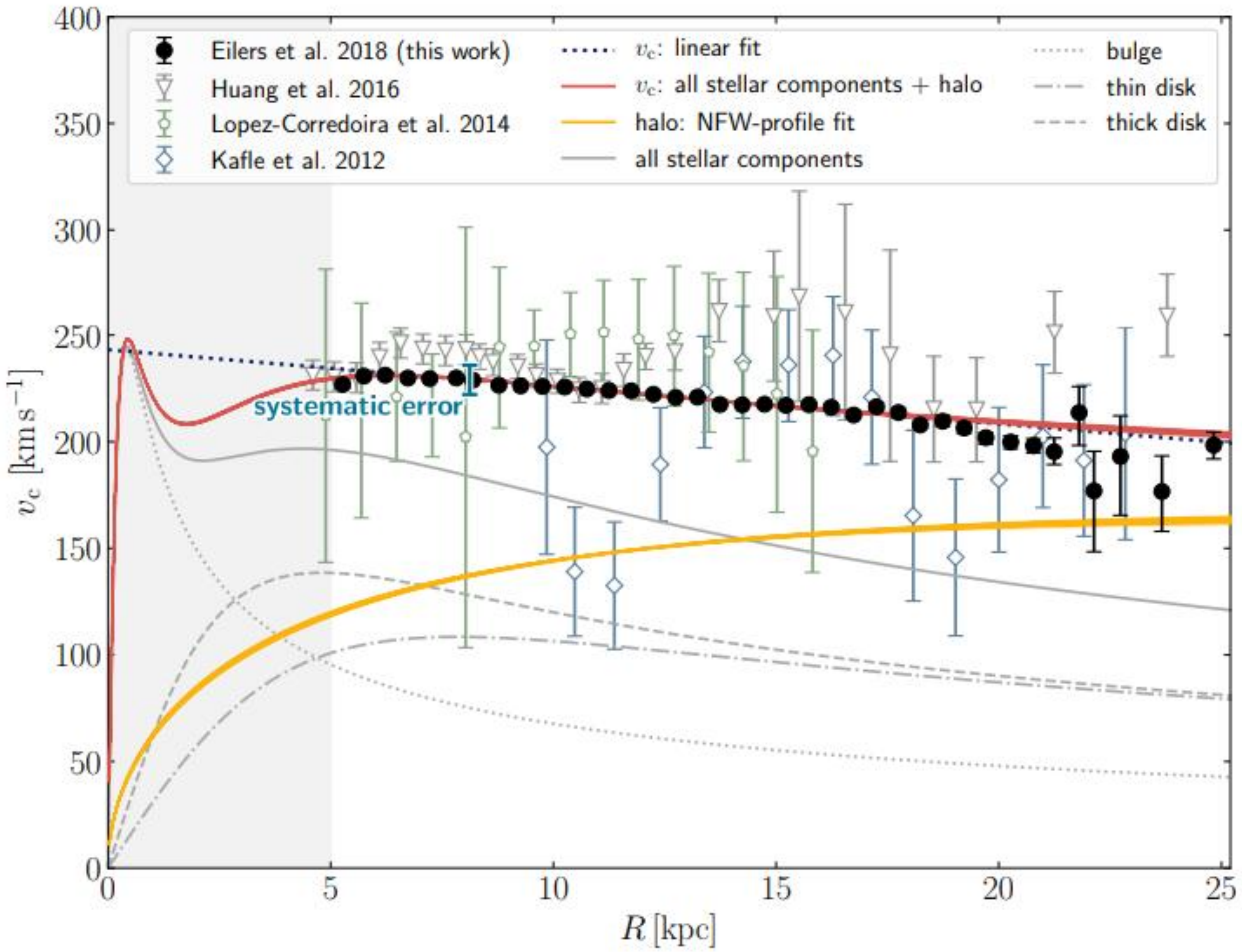
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's University



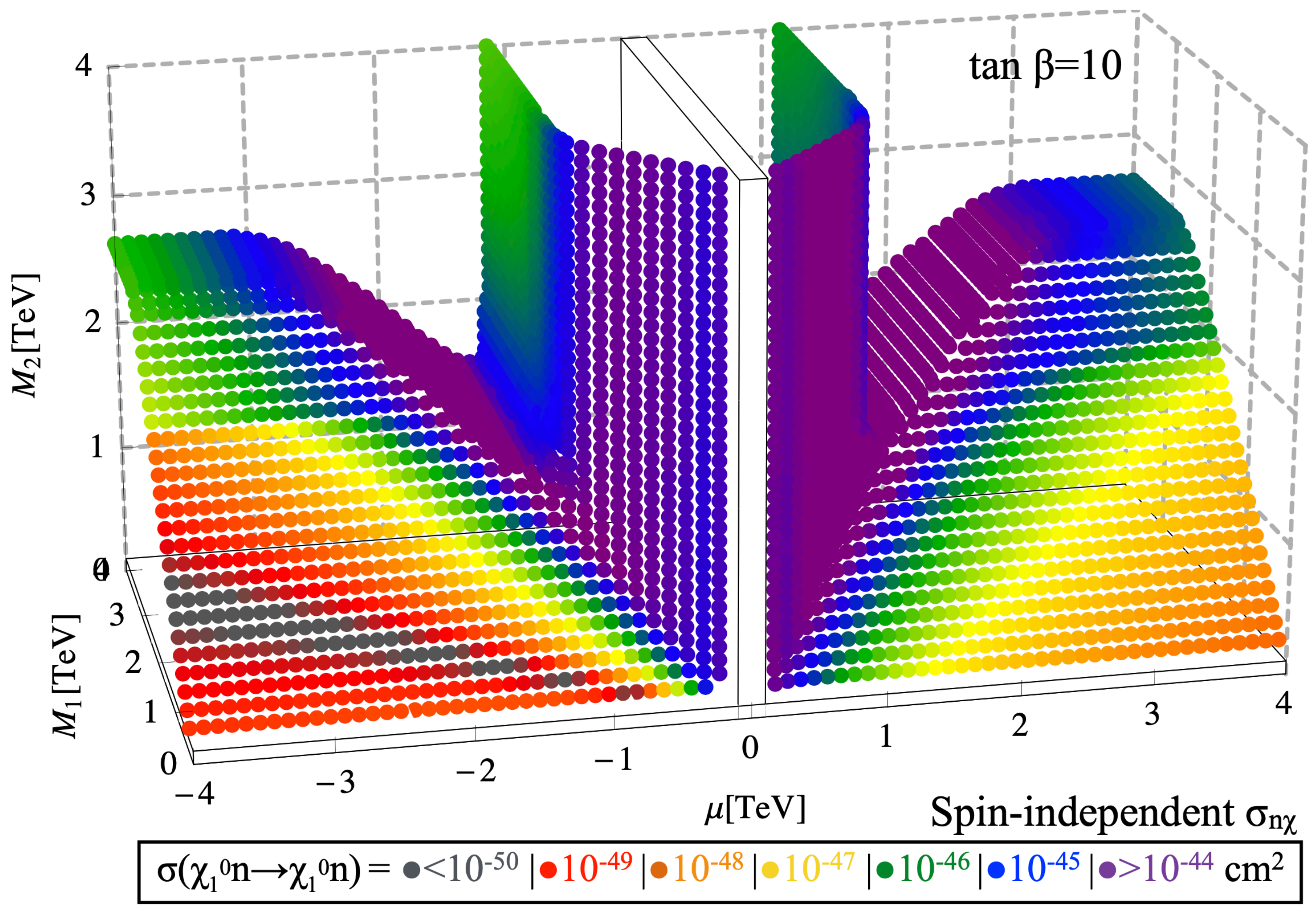


Dark matter is virialized in Milky Way

- Maxwellian distribution $v \sim 10^{-3}c$ (220 km/s)
- Escape velocity $v_{esc} \sim 500 - 600$ km/s (Gaia)
- Mass?
- Interactions?

Eilers *et al.*, 1810.09466

Inelastic Dark Matter

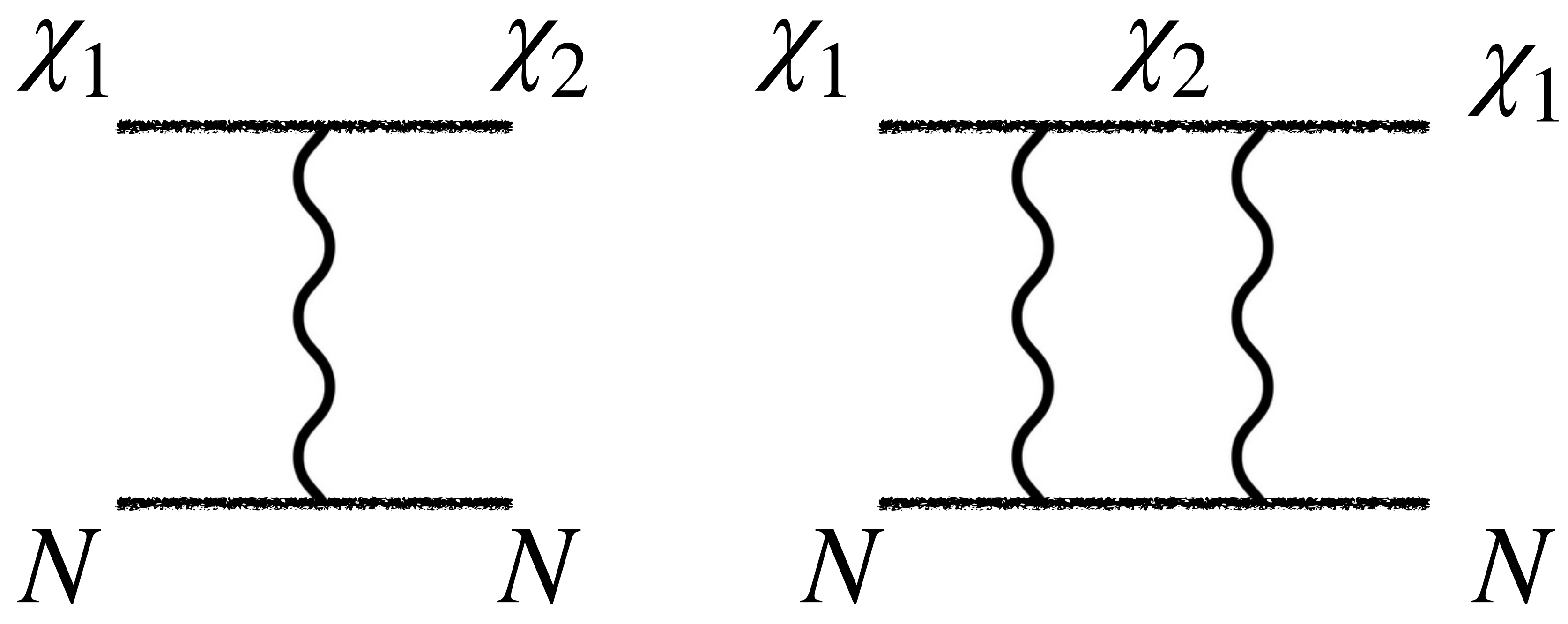


Neutralino DM, see Bramante et al, 1510.03460, 1412.4789

- Off-diagonal mass term $\begin{pmatrix} M & v \\ v & M \end{pmatrix}$
- After diagonalization $M_{\chi_1} = M + v$, $M_{\chi_2} = M - v$
- $\delta \equiv M_{\chi_2} - M_{\chi_1} \ll M_\chi$
- Example: dark photon-mediated DM

$$\mathscr{L} \supset \bar{\psi}(iD_\mu \gamma^\mu - m_\psi)\psi + (y\phi\bar{\psi}^T C^{-1}\psi + h.c.)$$

Bramante, **NS**, PRL/2006.14089
Batell, Pospelov, Ritz, 0903.3396

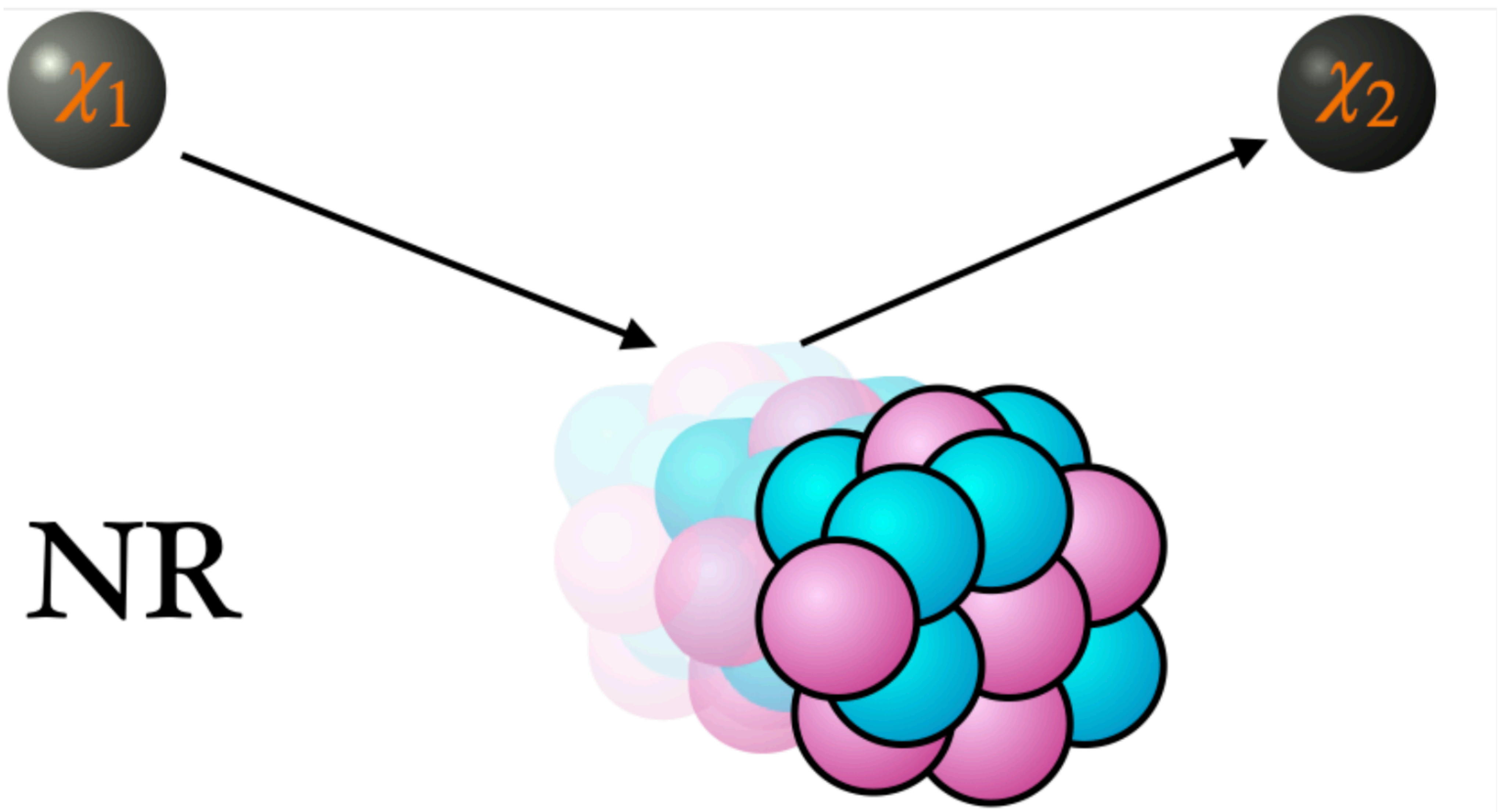


kinematically suppressed   loop suppressed

Kinematics in Nuclear Recoil

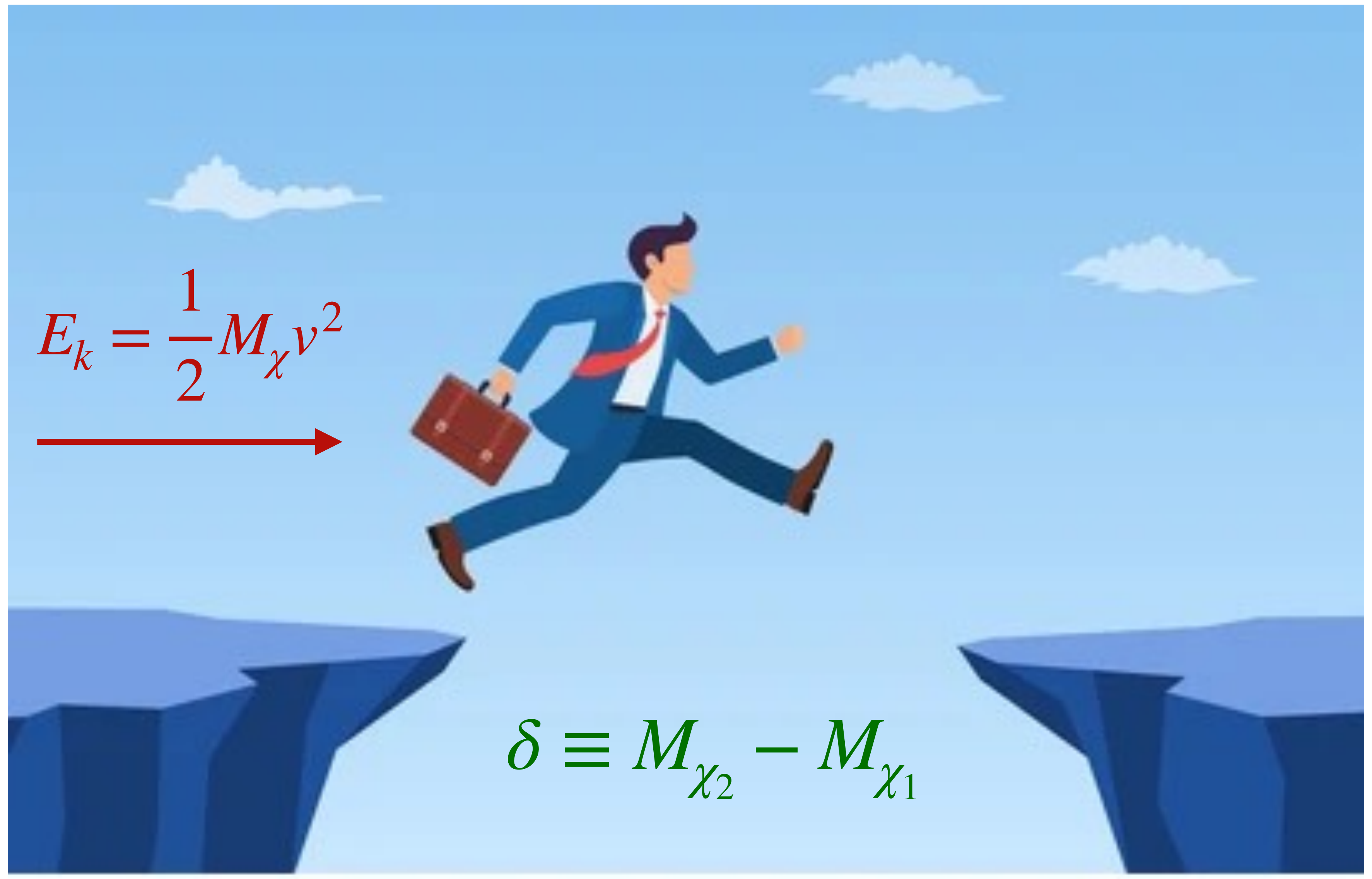
- $$\frac{\vec{q}_i^{\,2}}{2M_{\chi_1}} = \frac{\vec{q}_f^{\,2}}{2M_{\chi_2}} + \frac{\vec{q}^{\,2}}{2M_A} + \delta$$
- $$q_{\min/\max} = \mu_{\chi A} v \left[1 \mp \sqrt{1 - 2\frac{\delta}{\mu_{\chi A} v^2}} \right]$$
- Minimum velocity $v_{\min} = \sqrt{2\frac{\delta}{\mu_{\chi A}}}$

$\delta \equiv M_{\chi_2} - M_{\chi_1}$

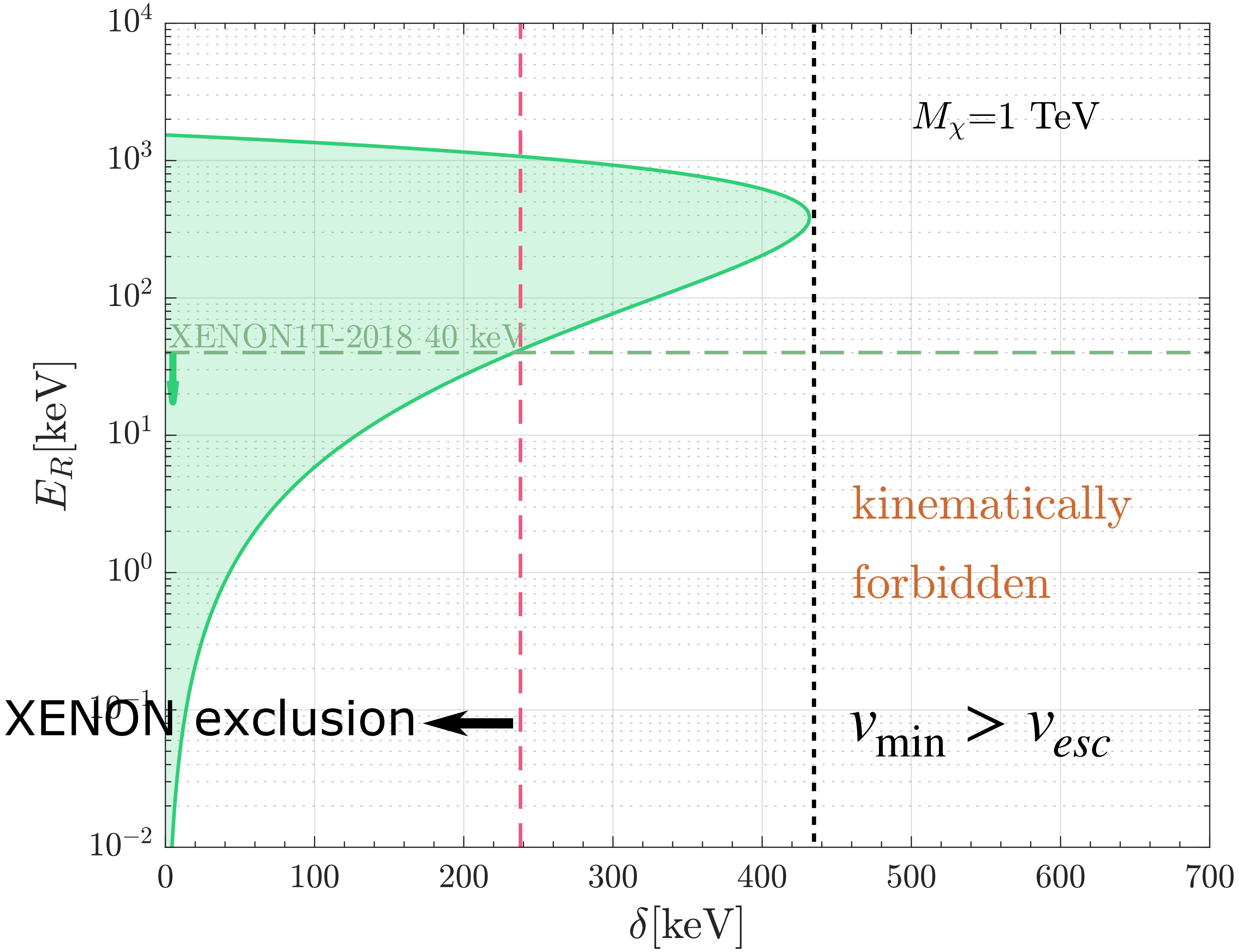


Why not XENON

- Xenon not heavy enough
- Xenon experiments only sensitive to low energy deposition ($E_R \lesssim 40$ keV)



shutterstock.com · 1808704210



Two Criteria

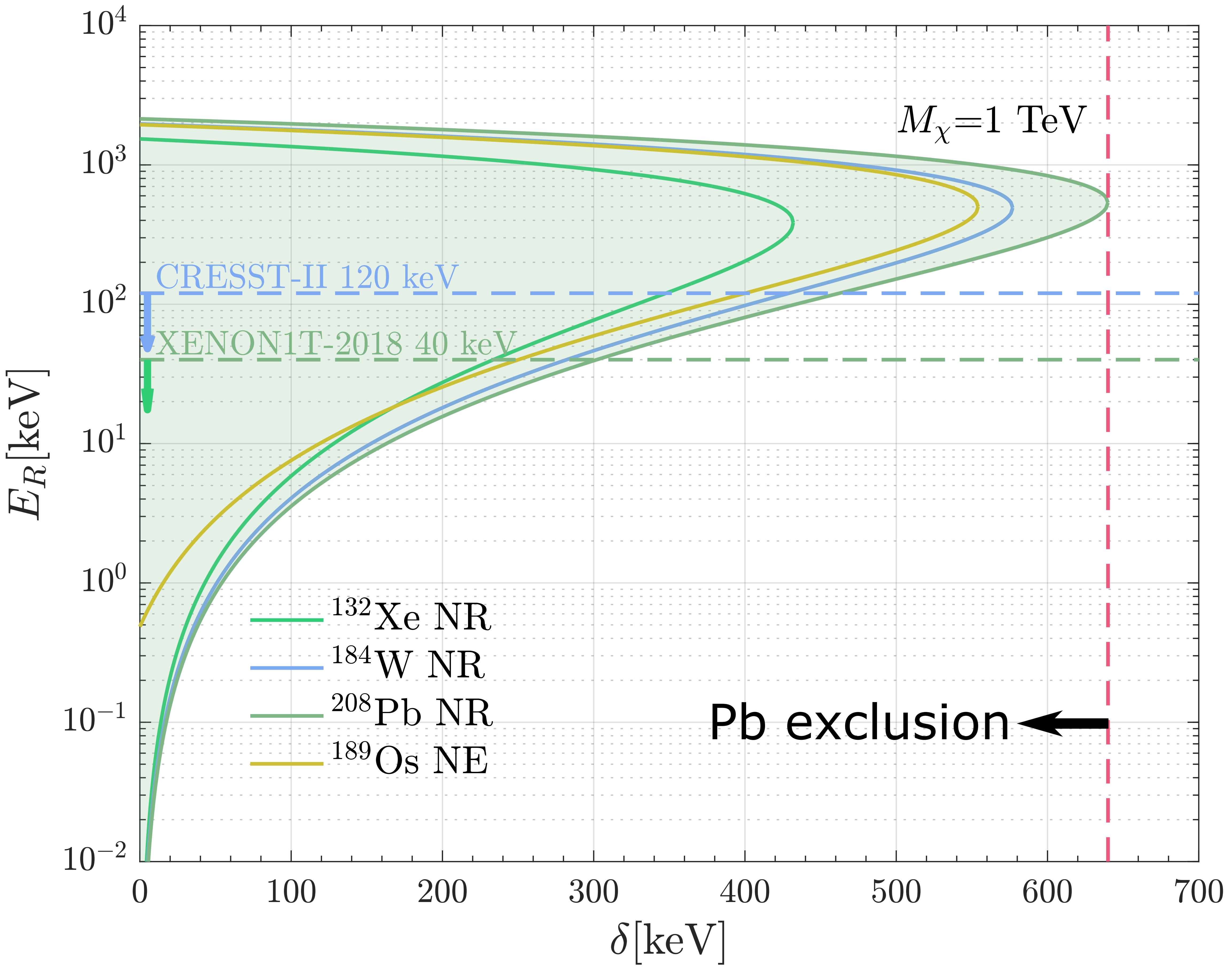
- Heavy nuclear target

$$\delta_{\max} = \frac{1}{2}\mu_{\chi A}(v_e + v_{esc})^2$$

- High energy deposition acceptance

$$E_{accept} > E_R^{\min} \sim \text{MeV}$$

Target nuclei with $A \sim 200$

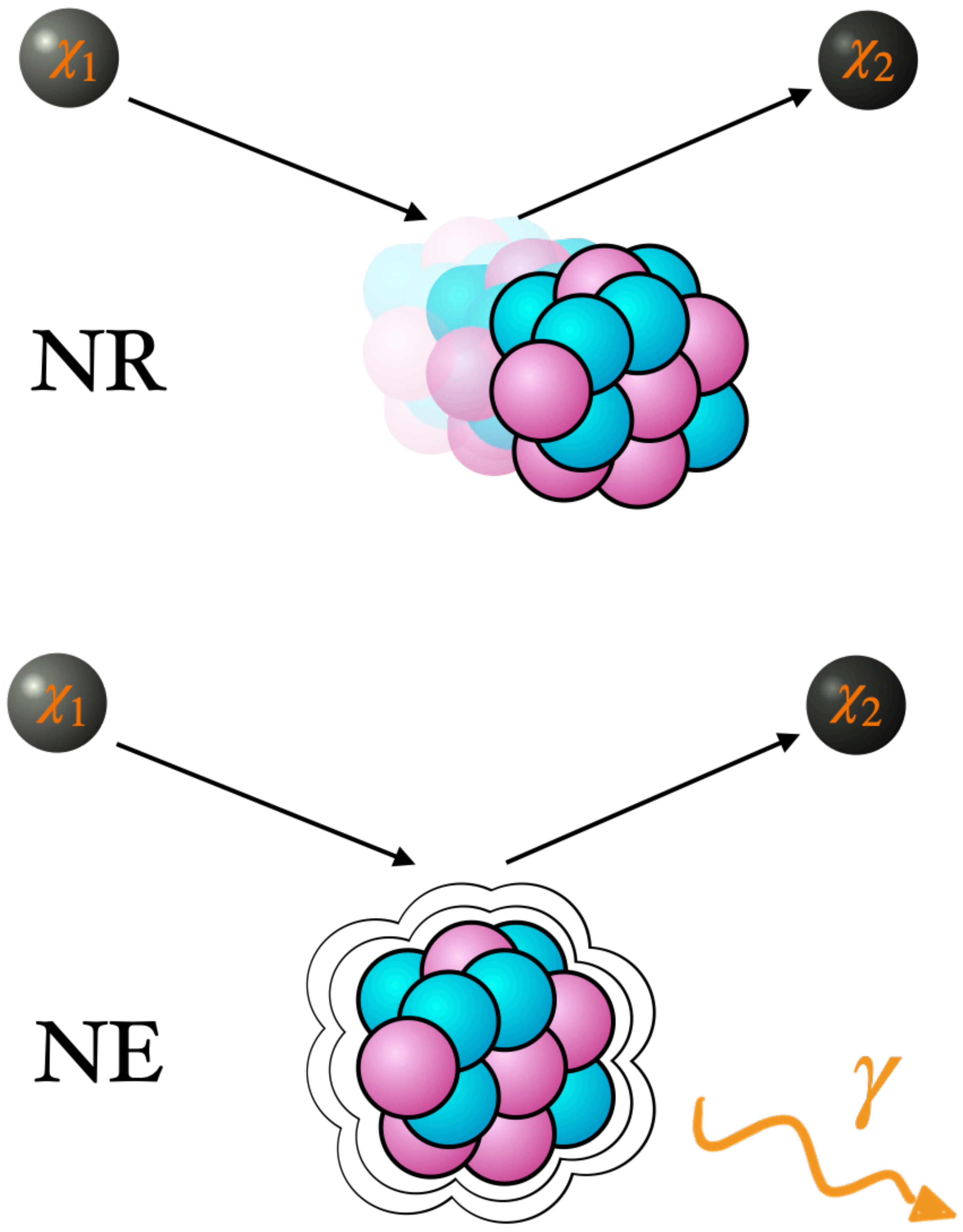


Ningqiang Song (ningqiang.song@queensu.ca)

Nuclear Excitation (NE)

$$\Delta \equiv \delta + E_{\text{excitation}}$$

- $$\frac{\vec{q}_i^{\,2}}{2M_{\chi_1}} = \frac{\vec{q}_f^{\,2}}{2M_{\chi_2}} + \frac{\vec{q}^{\,2}}{2M_A} + \Delta$$
- $$q_{\text{min / max}} = \mu_{\chi A} v \left[1 \mp \sqrt{1 - 2\frac{\Delta}{\mu_{\chi A} v^2}} \right]$$
- Minimum velocity $v_{\text{min}} = \sqrt{2\frac{\Delta}{\mu_{\chi A}}}$



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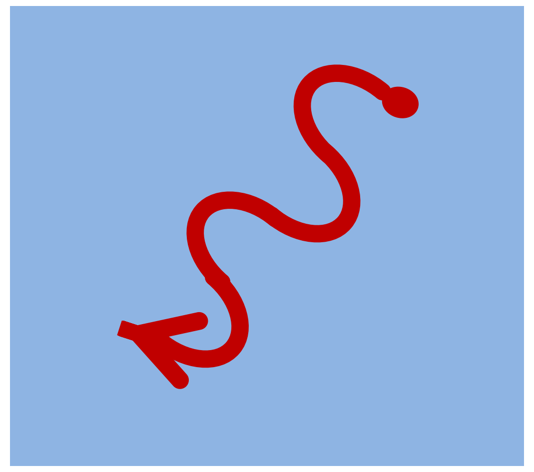
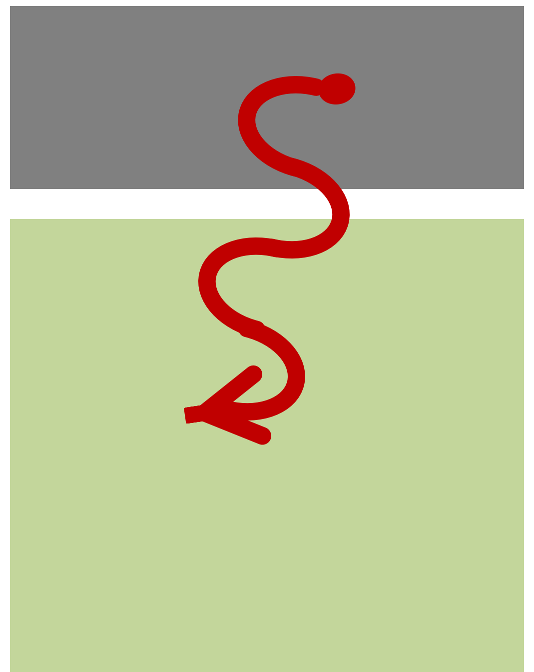
Nuclear Recoil vs Nuclear Excitation

detector ≠ source

detector = source



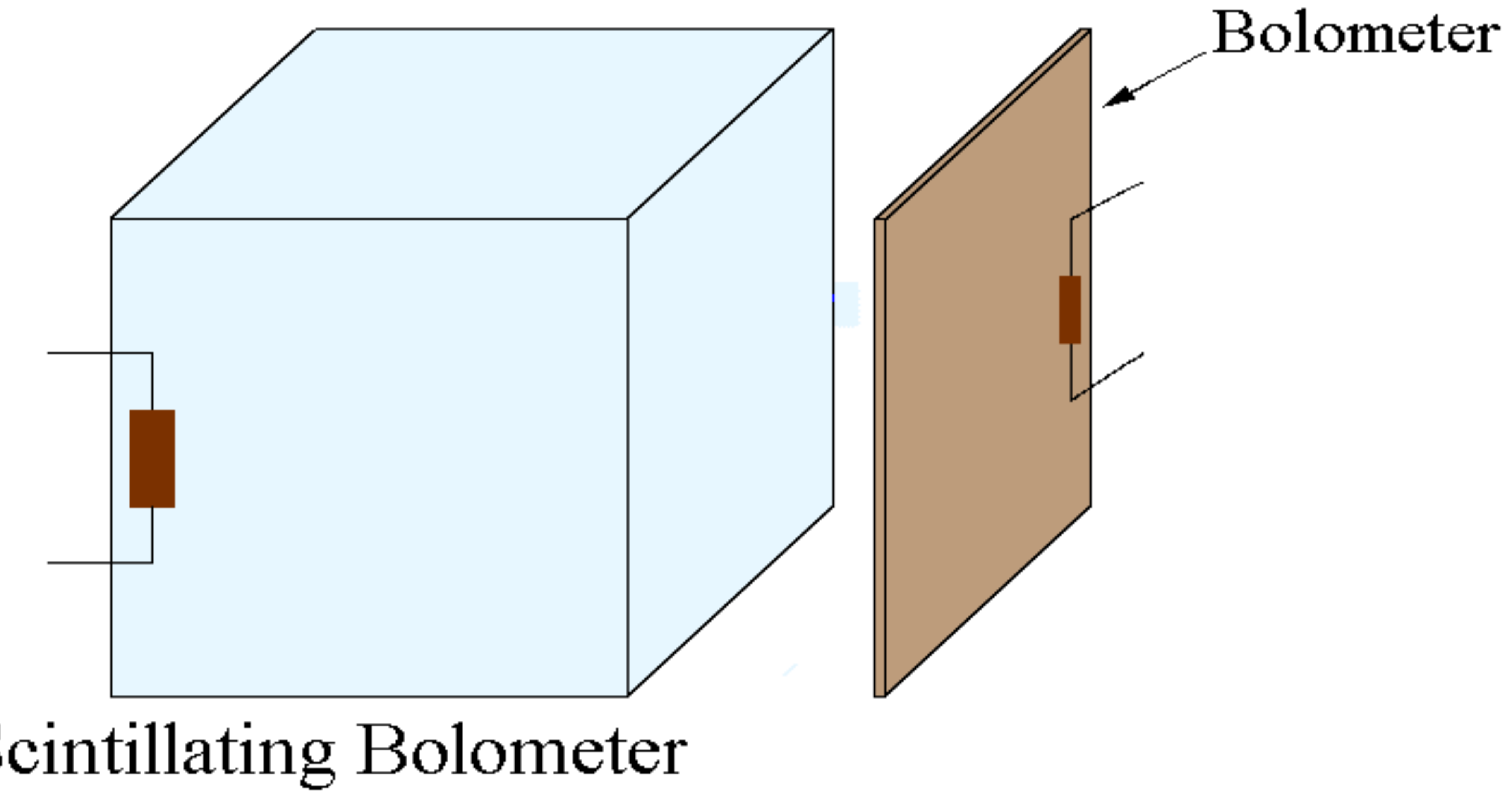


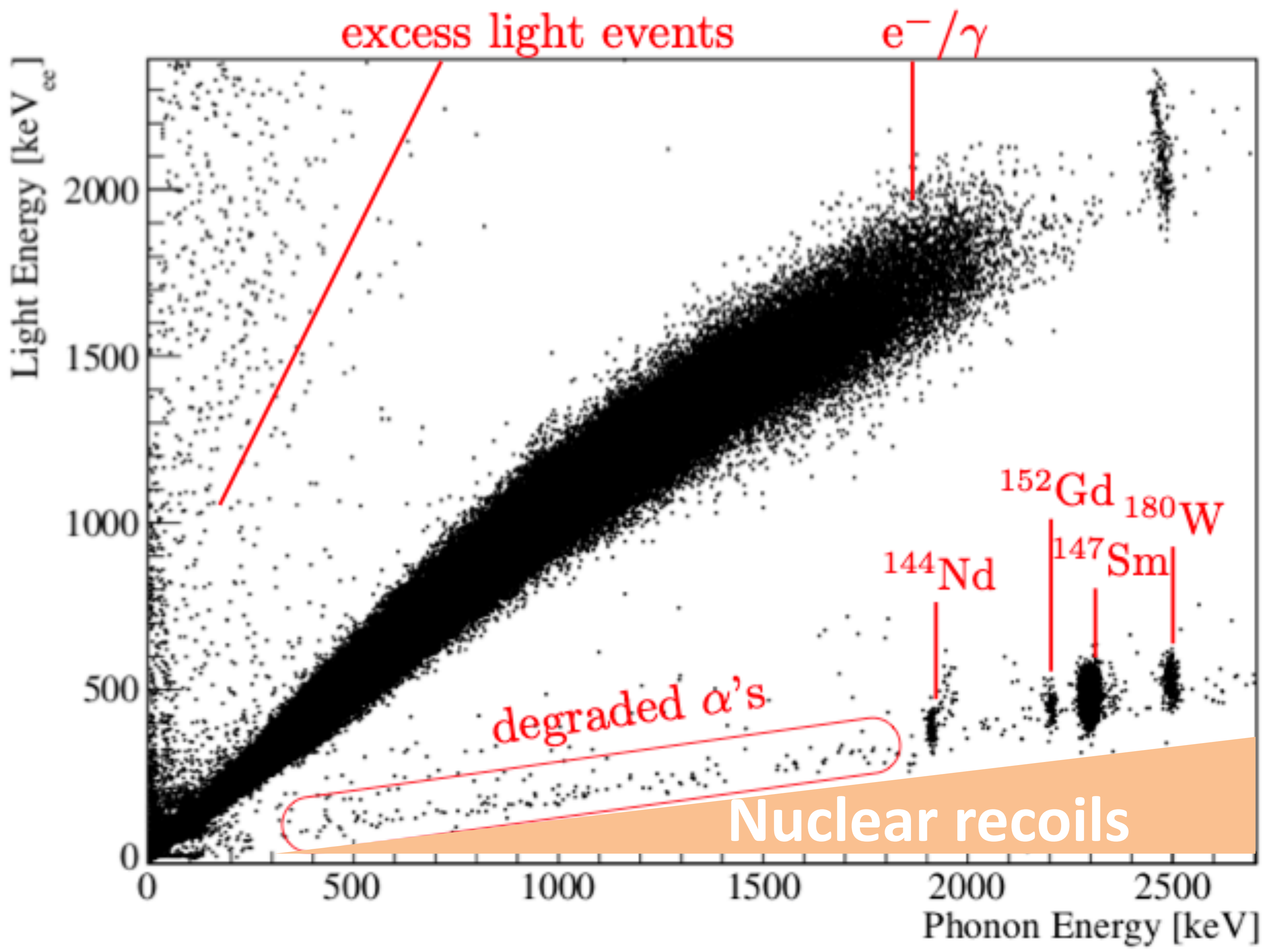
Nuclear Recoil	Type	Nuclear Excitation
Nuclear recoil	*Signal*	Deexcitation gamma
Scintillating bolometer	*Detection*	Gamma detector
Coherent $\propto A^2$	*Scattering*	Incoherent ~~$\propto A^2$~~
Helm form factor	*Form factor*	$S(\vec{q}) = \sum_L \lvert \langle J_f \lvert\lvert j_L(qr) Y_{LM}(\hat{r}) \rvert\rvert J_i \rangle \rvert^2$
Mass splitting	*Kinematical suppression*	Mass splitting+excitation

Engel, Vogel, hep-ph/9910409

Scintillating Bolometers

- Simultaneous double readout of heat (H) and scintillation light (L)
- Fraction of the deposited energy is converted into a scintillation (up to 25%)
- effective discrimination of e/γ from α events/DM by the difference in L/H ratio



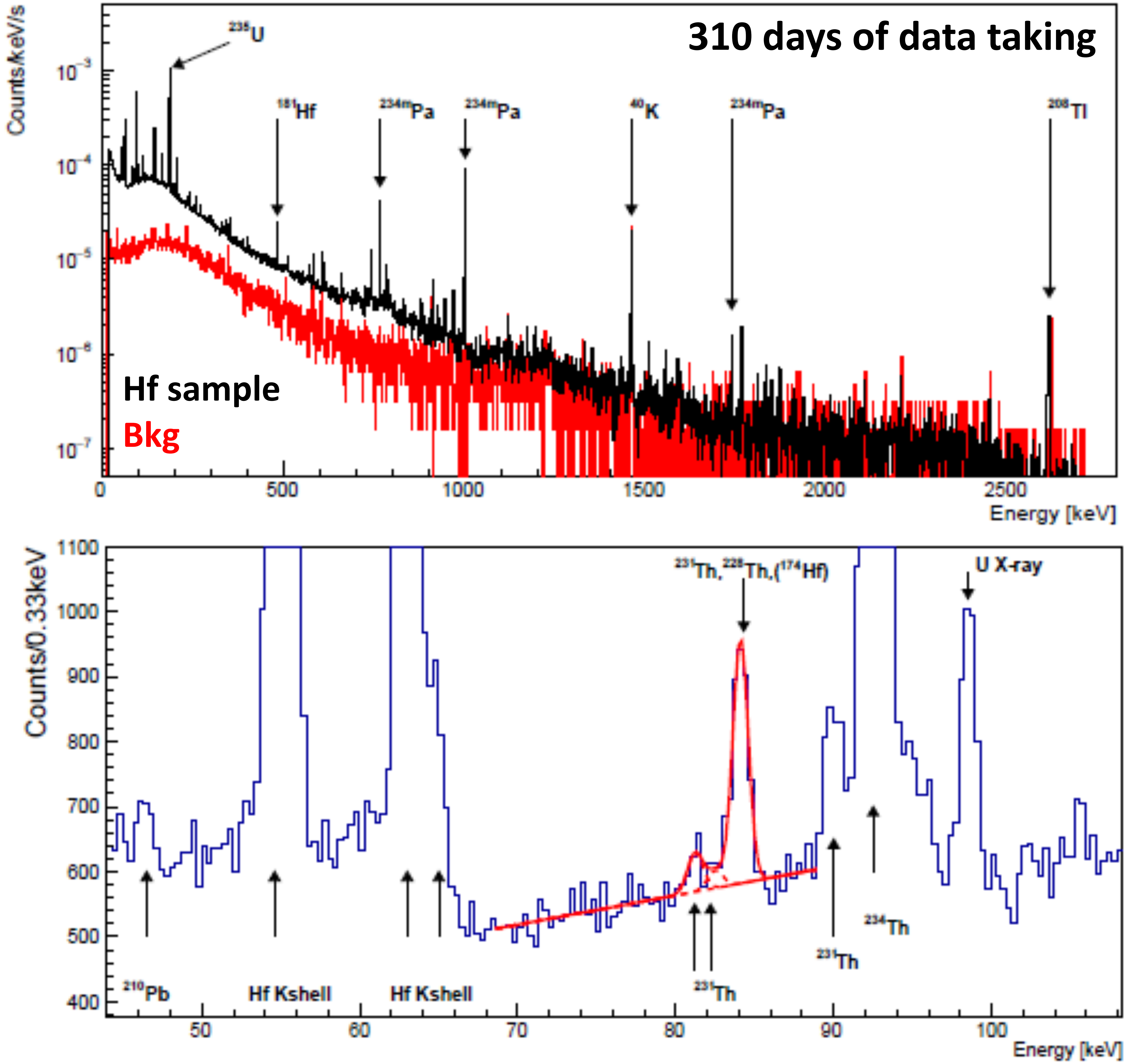


$CaWO_4$ scintillating bolometer

Munster *et al.*, arXiv:1403.5114

Gamma Detection

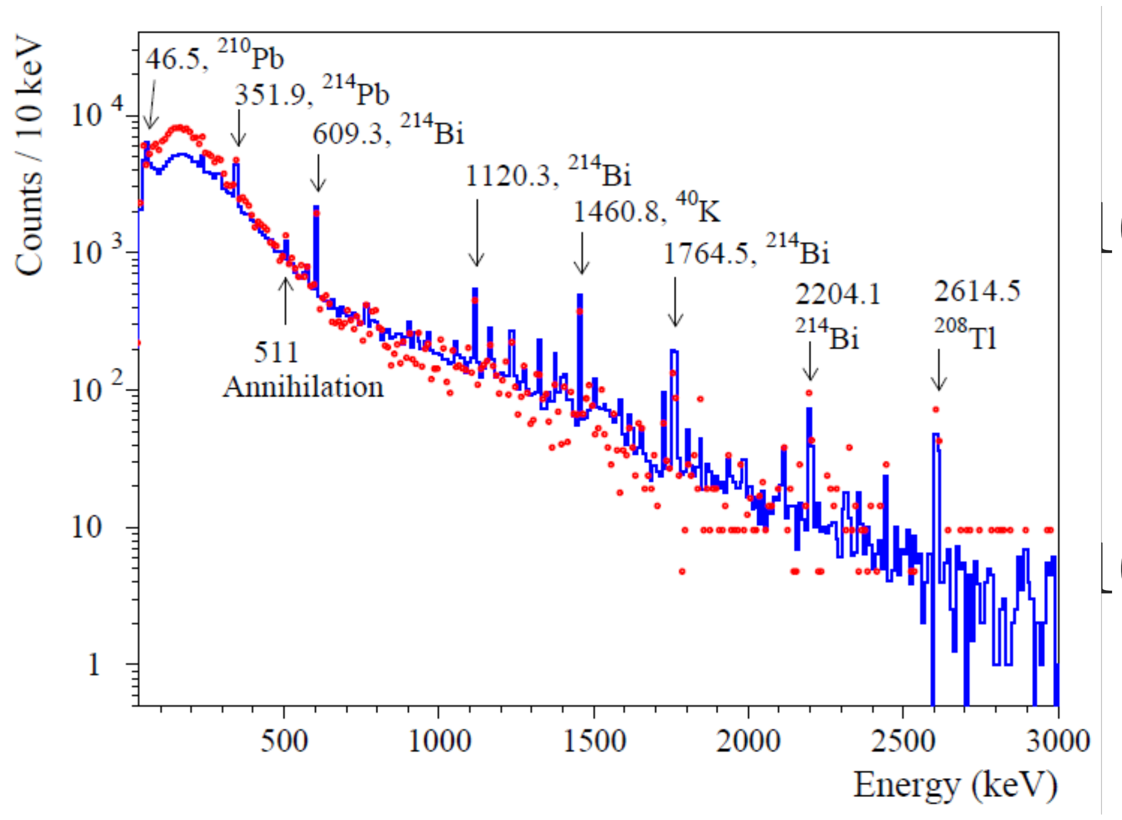
Broerman, Laubenstein, **SN**, **NS**, Vincent, 2012.08339



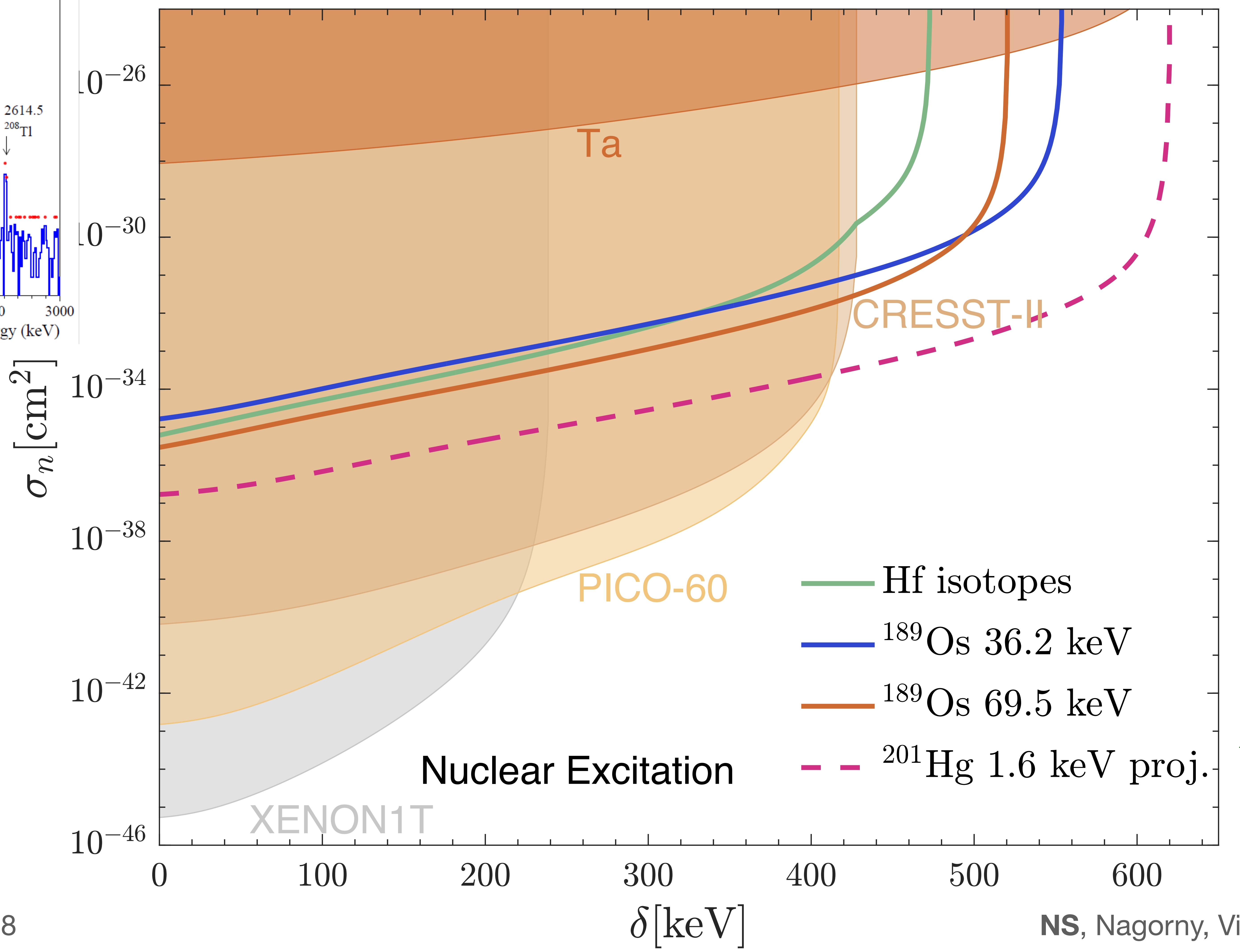
A(238U chain) = 11 Bq/kg
A(235U chain) = 0.5 Bq/kg
A(232Th chain) = 0.01 Bq/kg

S. Nagorny et al., JINST 16 (2021) 03, P03027

Nuclear Excitation with Gamma Measurement



Belli *et al.*, 2009.01508

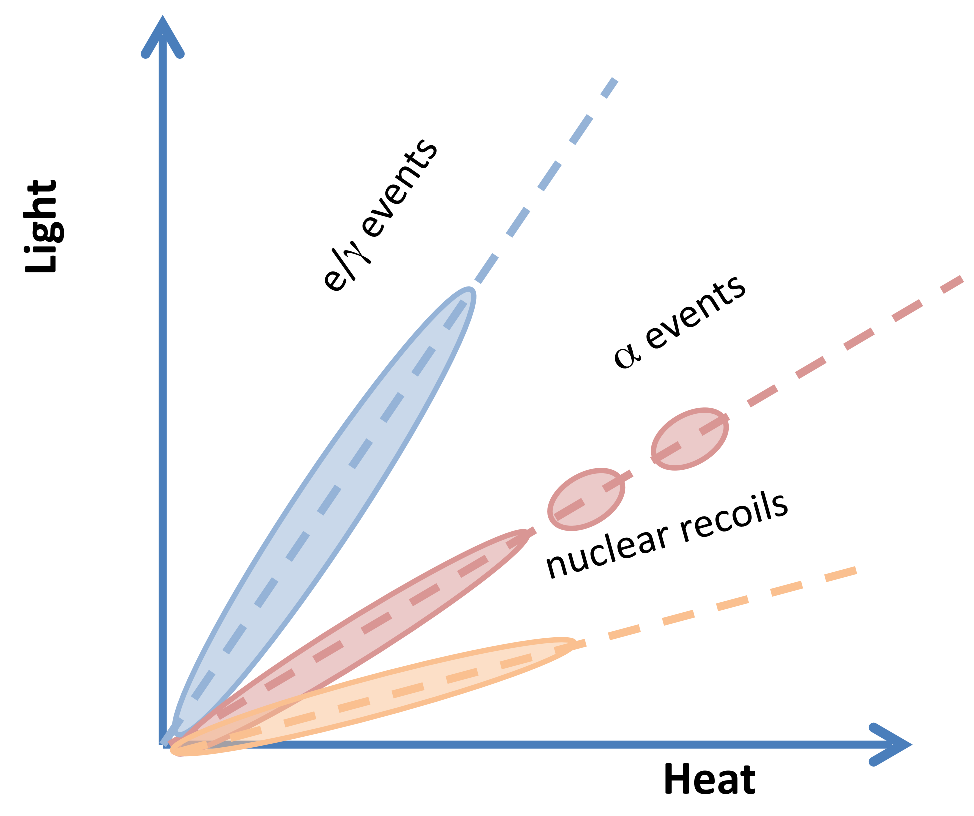


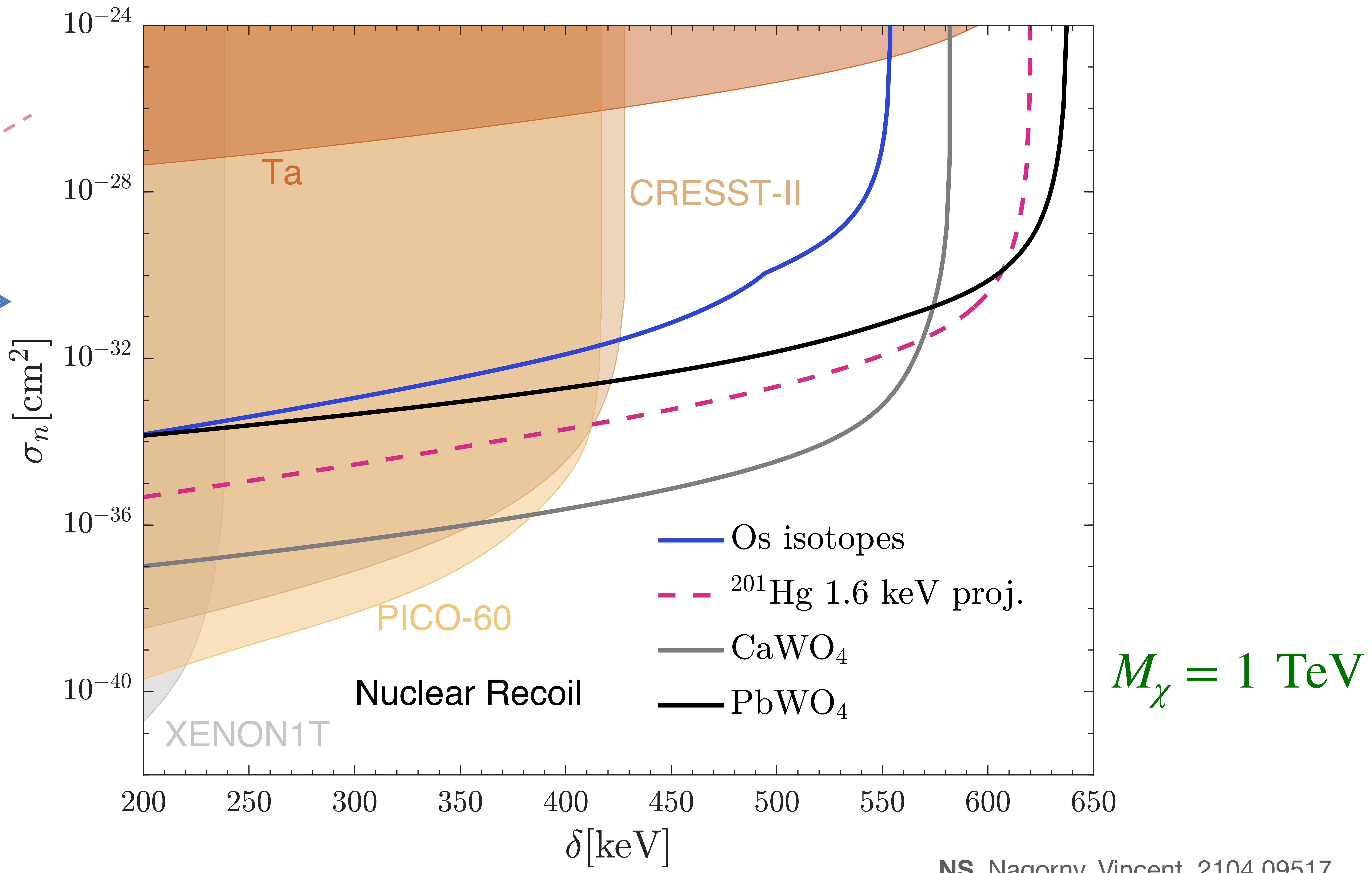
$M_\chi = 1$ TeV

NS, Nagorny, Vincent, 2104.09517

Broerman, Laubenstein, **NS**, Nagorny, Vincent, 2012.08339

Nuclear Recoil with Scintillating Bolometer



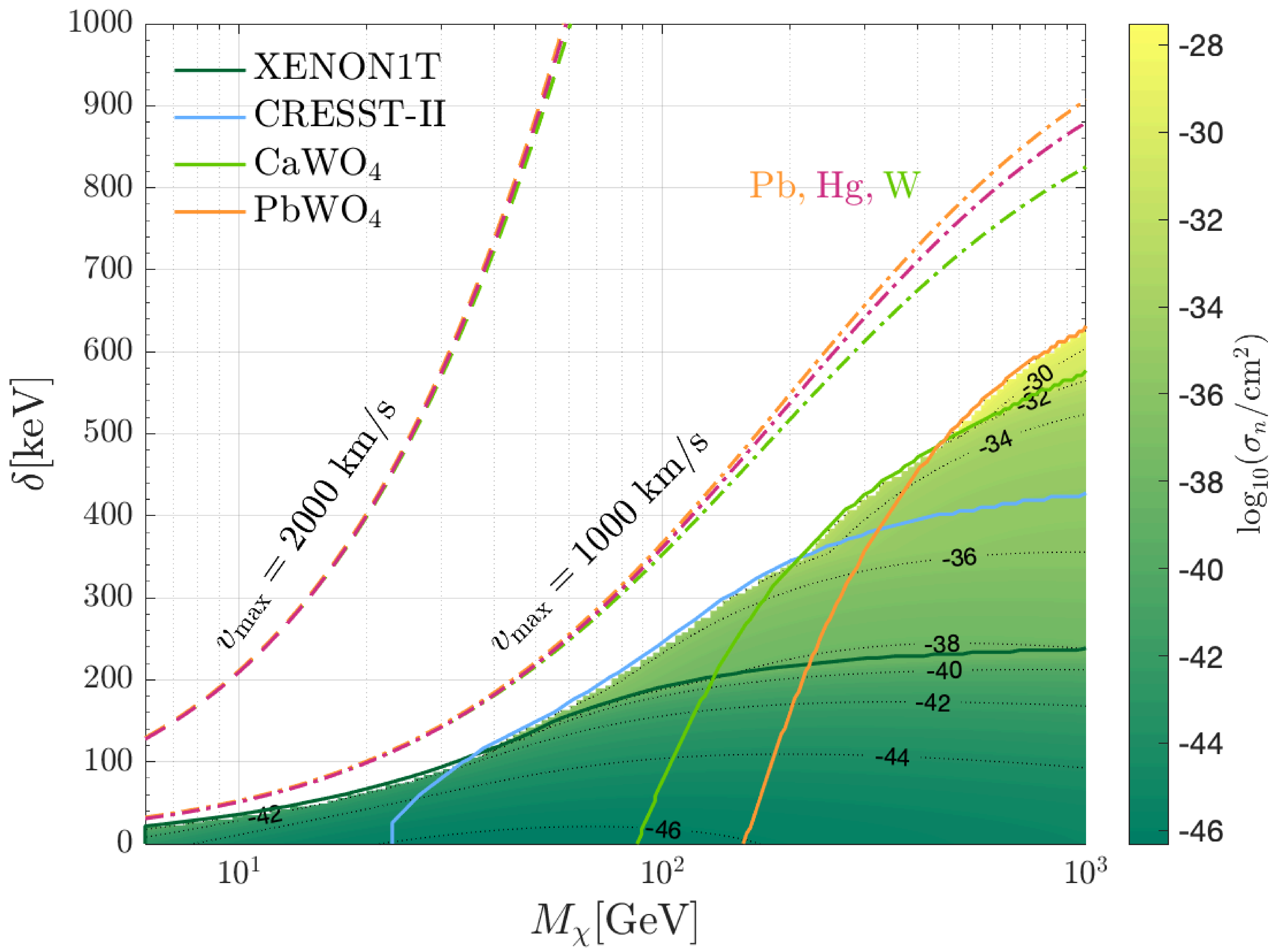


NS, Nagorny, Vincent, 2104.09517

Conclusions

- Inelastic dark matter detection challenged by kinematics
- Nuclear recoil search with $CaWO_4$, $PbWO_4$
- Nuclear excitation search with Hf, Os
- Boosted dark matter

$$\delta_{\max} = \frac{1}{2}\mu_{\chi A}(v_e + v_{esc})^2$$



Ningqiang Song (ningqiang.song@queensu.ca)

Backup Slides

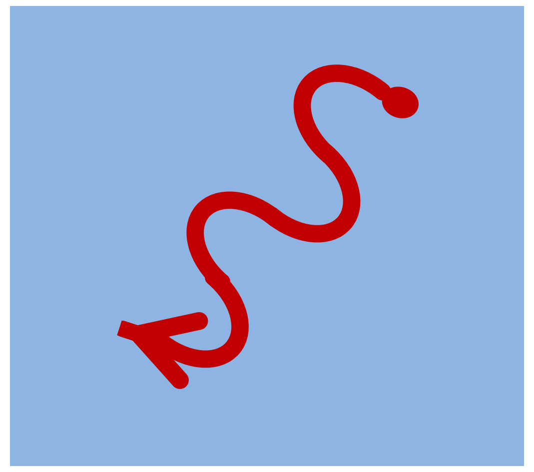
Nuclear Transition Table

Isotope	Abund.[%]	$J^p_{\text{g.s.}}$	$J^p_{\text{e.s.}}$	ΔE[keV]	B(E2)[$W.u.$]	E_γ[keV]	I_γ[%]	Bkg.[mBq/kg]
^{174}Hf	0.16	0^+	2^+	90.985	152(8) [105]	91.00	100	3.8
^{176}Hf	5.26	0^+	2^+	88.349	183(7) [106]	88.34	100	3.1
^{177}Hf	18.60	$7/2^-$	$9/2^-$	112.9500	282(8) [64]	112.9498	100	0.9
^{178}Hf	27.28	0^+	2^+	93.1803	160(3) [65]	93.1803	100	2.2
^{179}Hf	13.62	$9/2^+$	$11/2^+$	122.7904	245(14) [107]	122.793	100	0.9
^{180}Hf	35.08	0^+	2^+	93.3240	154.8(21) [66]	93.324	100	2.2
^{187}Os	1.8794	$1/2^-$	$3/2^-$	74.356	50^{+60}_{-50} [108]	74.30	100	0.25
		$1/2^-$	$5/2^-$	75.016	38(10) [108]	64.31	54.3	0.31
^{189}Os	16.152	$3/2^-$	$1/2^-$	36.17	27(7) [67]	36.17	100	0.40
		$3/2^-$	$5/2^-$	69.54	100(10) [67]	69.53	99.8	0.16
		$3/2^-$	$3/2^-$	95.27	14(3) [67]	59.06	75.5	0.20
^{201}Hg	13.17	$3/2^-$	$1/2^-$	1.5648	$\sim$ 34 [68]	1.5648	100	0.0056 (proj.)
		$3/2^-$	$5/2^-$	26.272	2.4(8) [68]	26.34	100	0.0060 (proj.)
		$3/2^-$	$3/2^-$	32.145	20(9) [68]	32.19	50.5	0.012 (proj.)

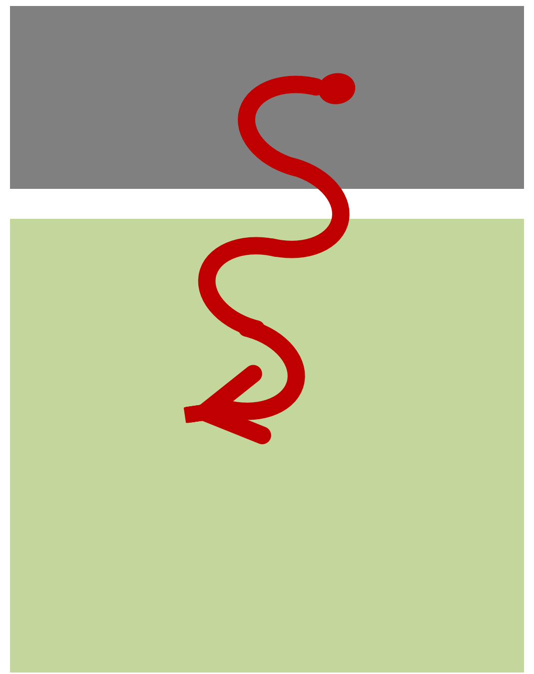
NS, Nagorny, Vincent, 2104.09517

Two different experimental approaches

detector = source



detector ≠ source

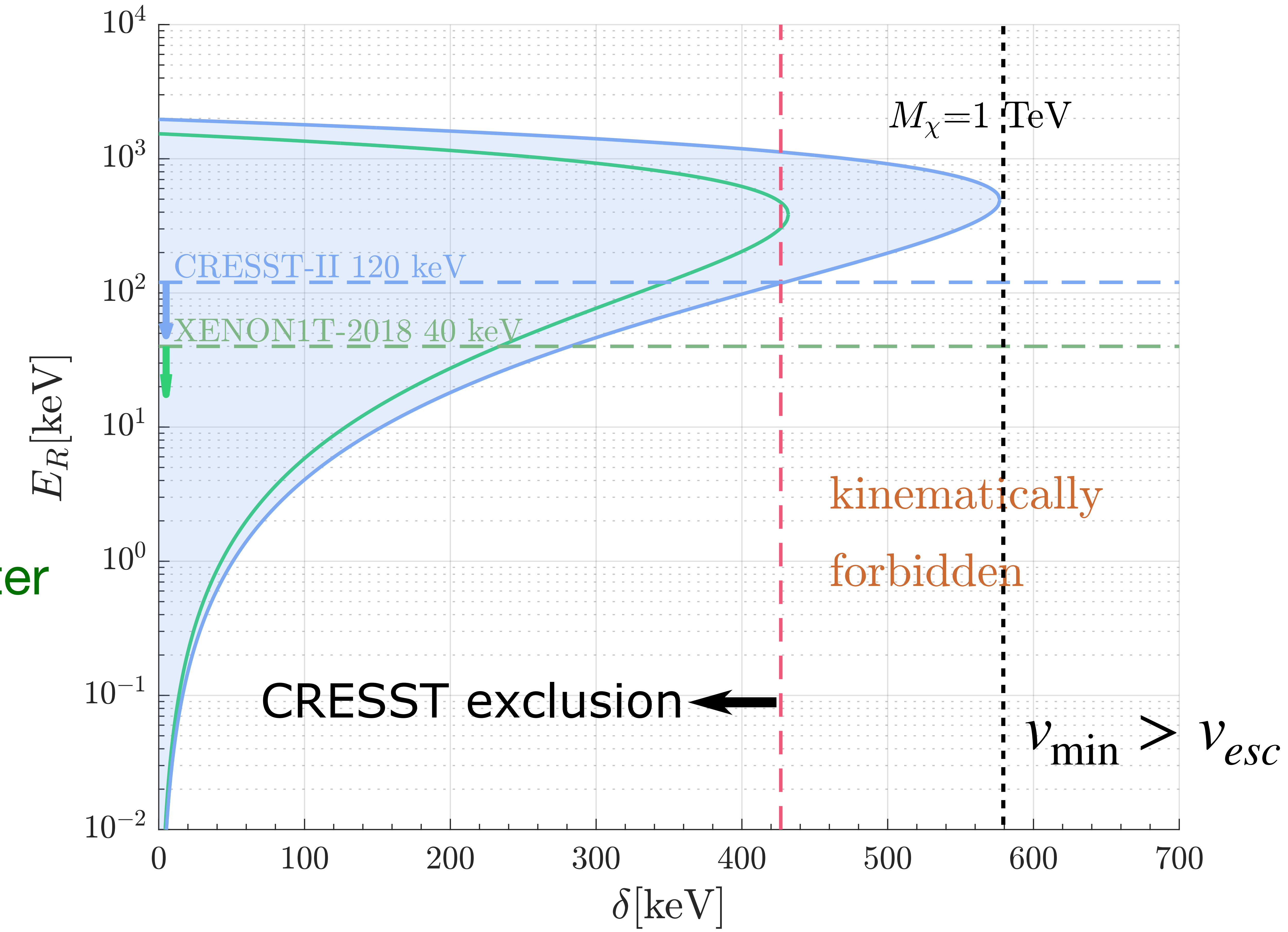


Light/Heat	*Possible channel/s*	**Charge**
Scintillating bolometer	*Detector type*	**HPGe**
Partially	*Material flexibility*	**Yes**
No limitation	*Energy limitation*	**> 300 keV (gamma)**
High (up to 100%)	*Detection efficiency*	**Low (few %)**
High (1/1000)	*Energy resolution*	**High (1/1000)**
Yes	*Particle discrimination*	**No**
$\leq 10^{24}$ y	*Sensitivity*	**$\leq 10^{22}$ y**

Why Not CRESST

- CRESST experiments sensitive to low energy deposition ($E_R < 120$ keV)

CaWO$_4$ scintillating bolometer



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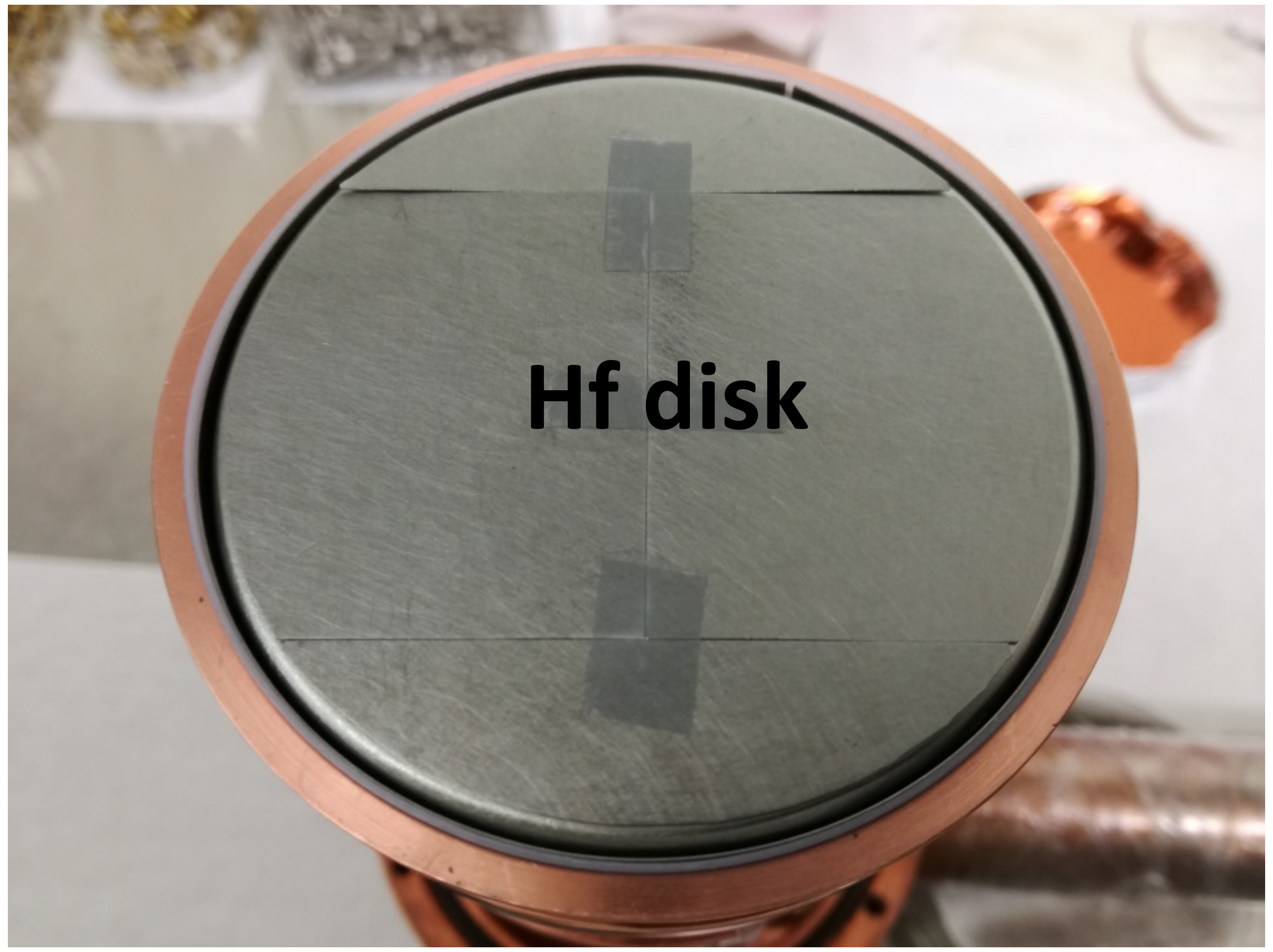
Hf-metal sample



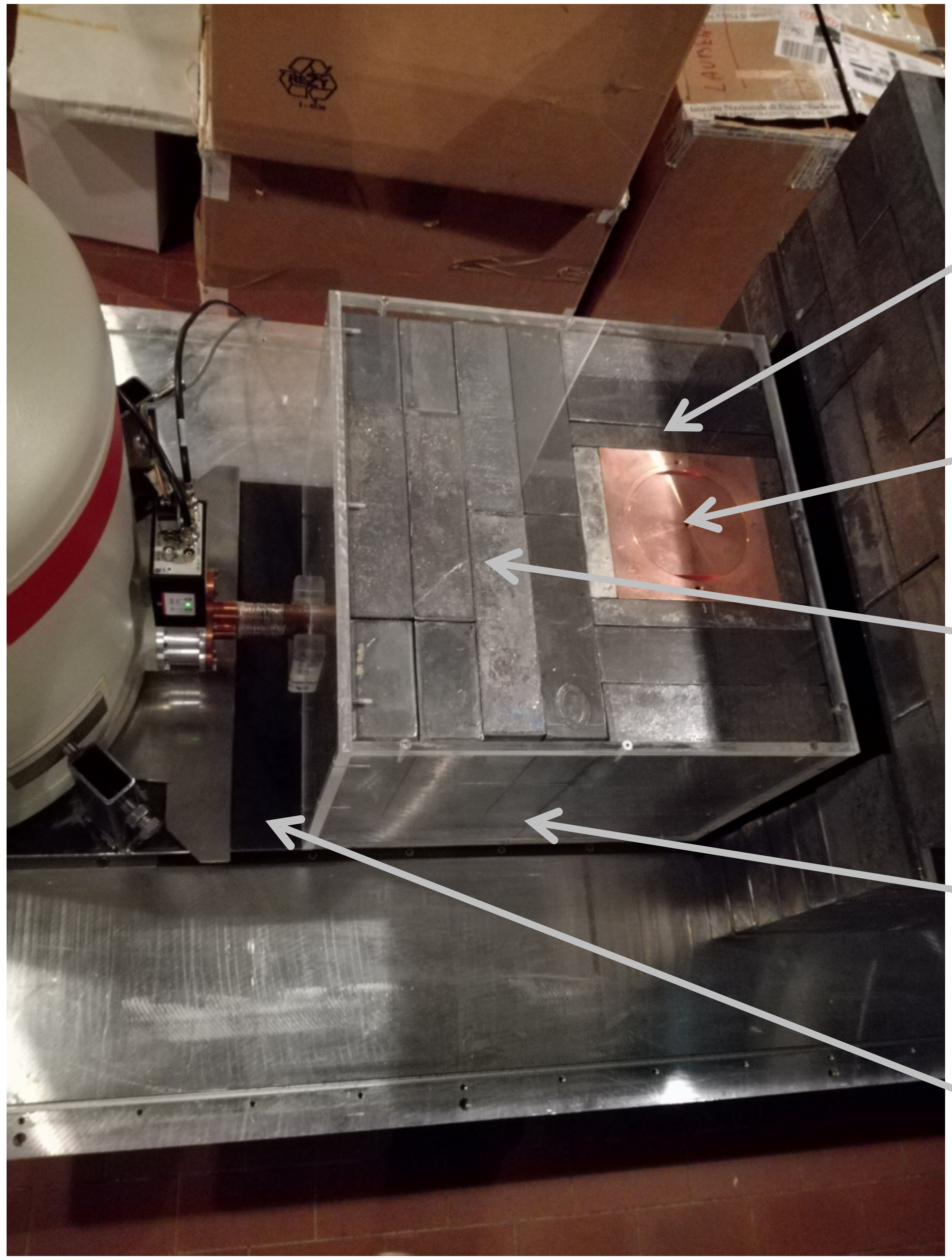
Total mass : **55.38 g** (99.5% grade)

Strip: 65 × 220 mm^2
thickness 0.25 mm

Disk: ∅65 mm
thickness 0.25 mm

B.Broerman et al., Nucl. Phys A, 10.1016/j.nuclphysa.2021.122212

Fast-movable part of passive shield



Roman lead (7 cm)

OFHC Copper shield (5 cm min)

Low-radioactivity lead (15 cm)

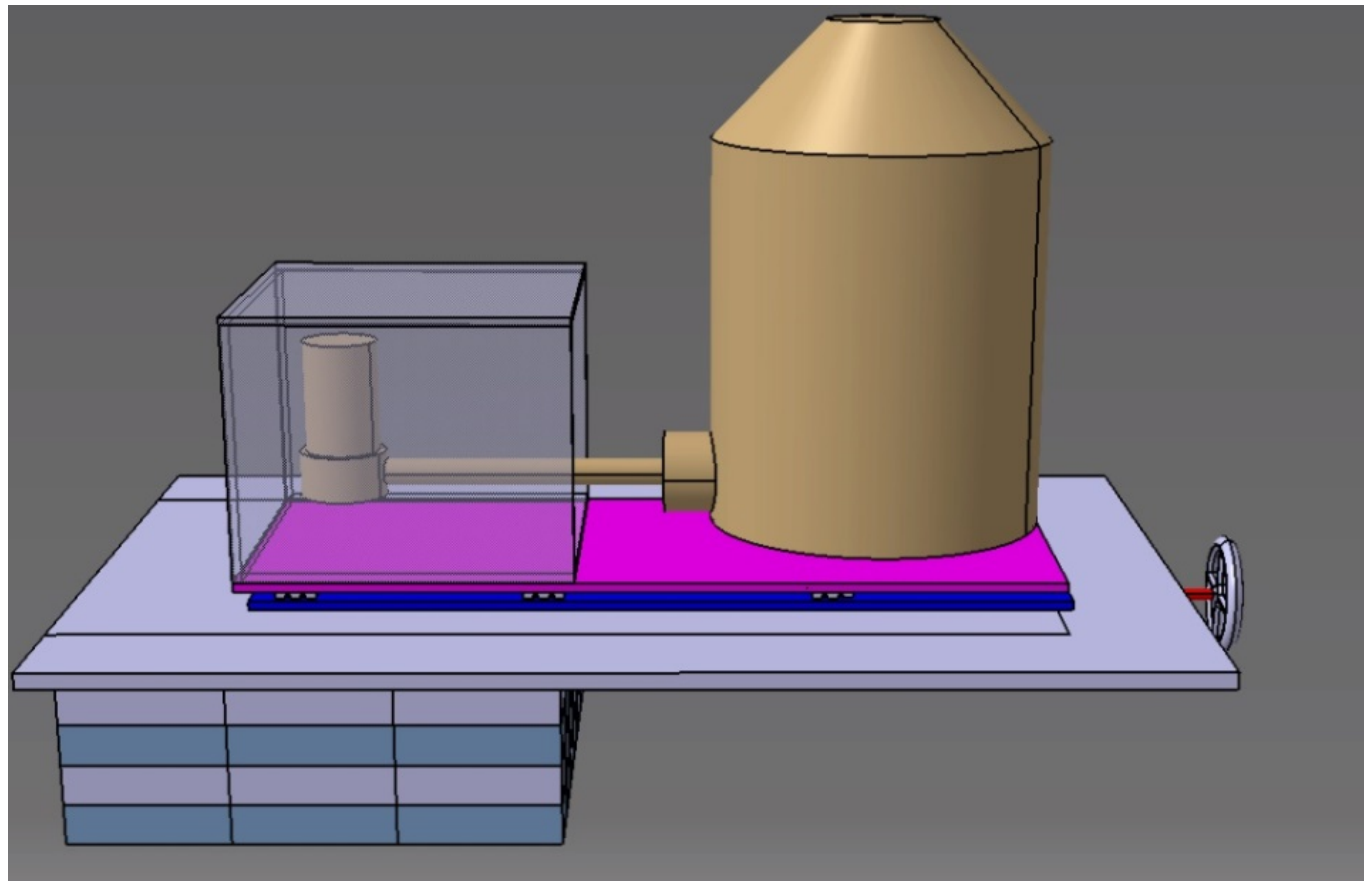
Plexiglas box 40×40×40 cm
continuously flushed by N_2

Stainless steel movable plate (1 cm)

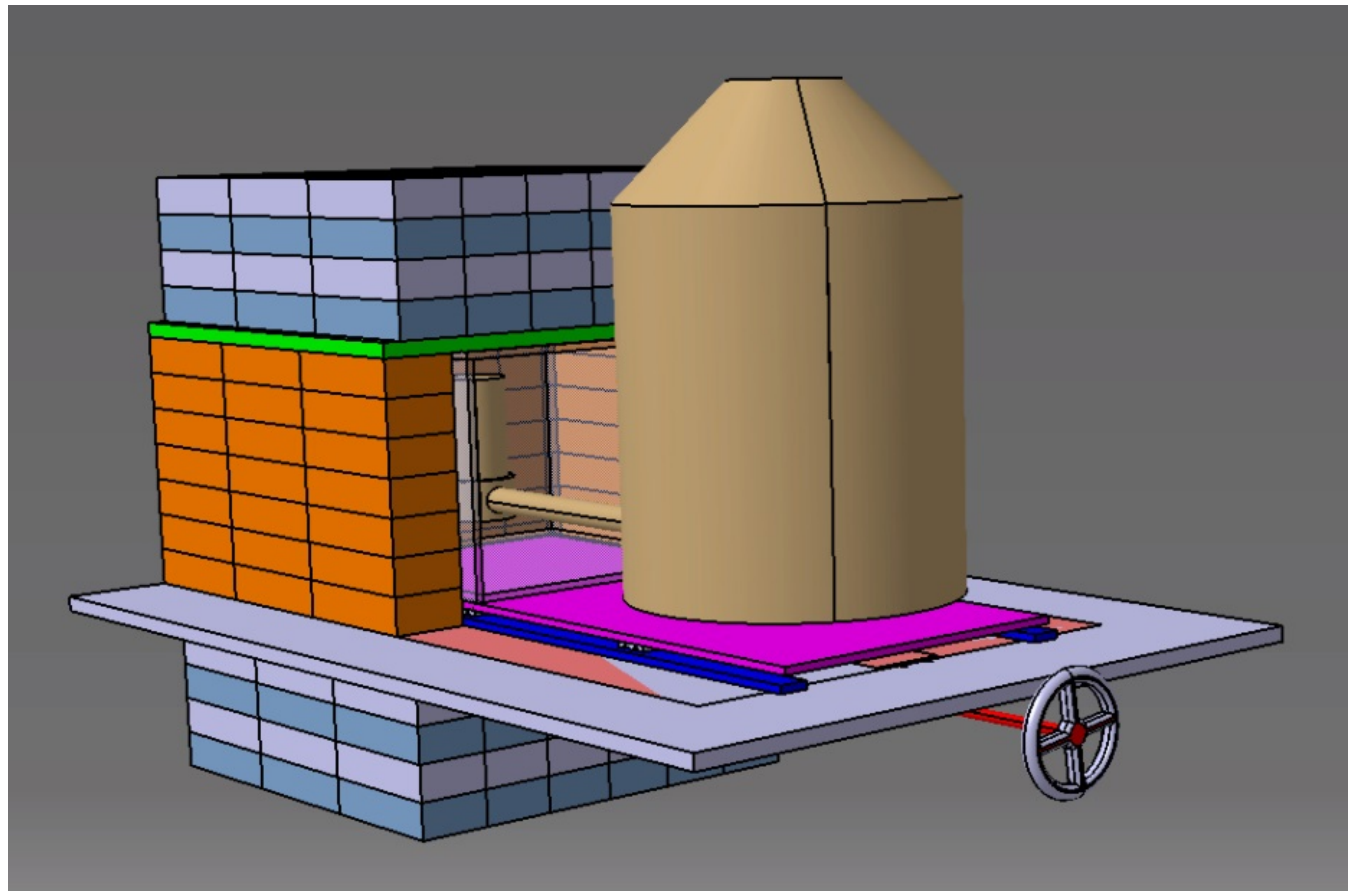
S. Nagorny et al., JINST 16 (2021) 03, P03027

Fast-movable passive shield

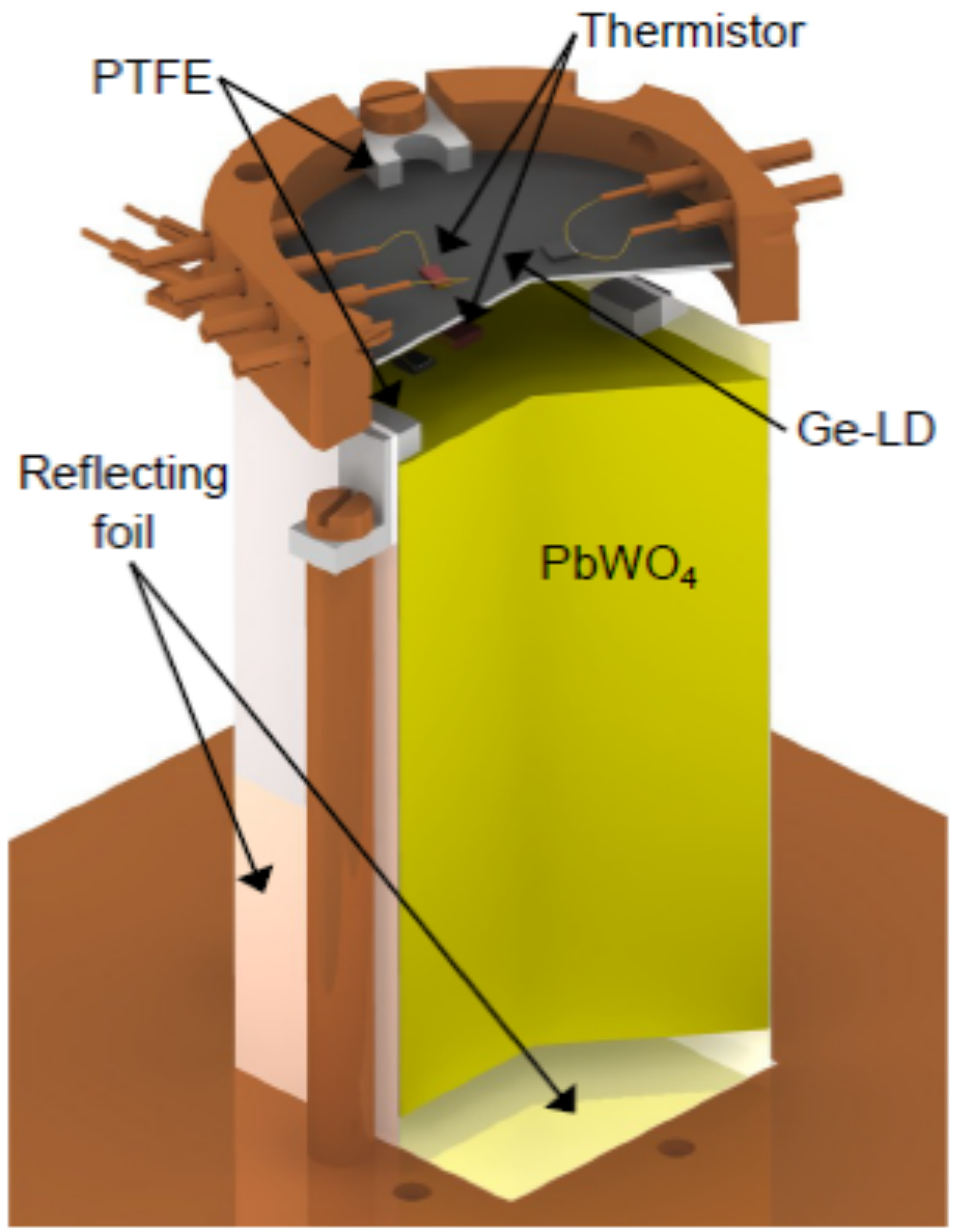
View of movable part



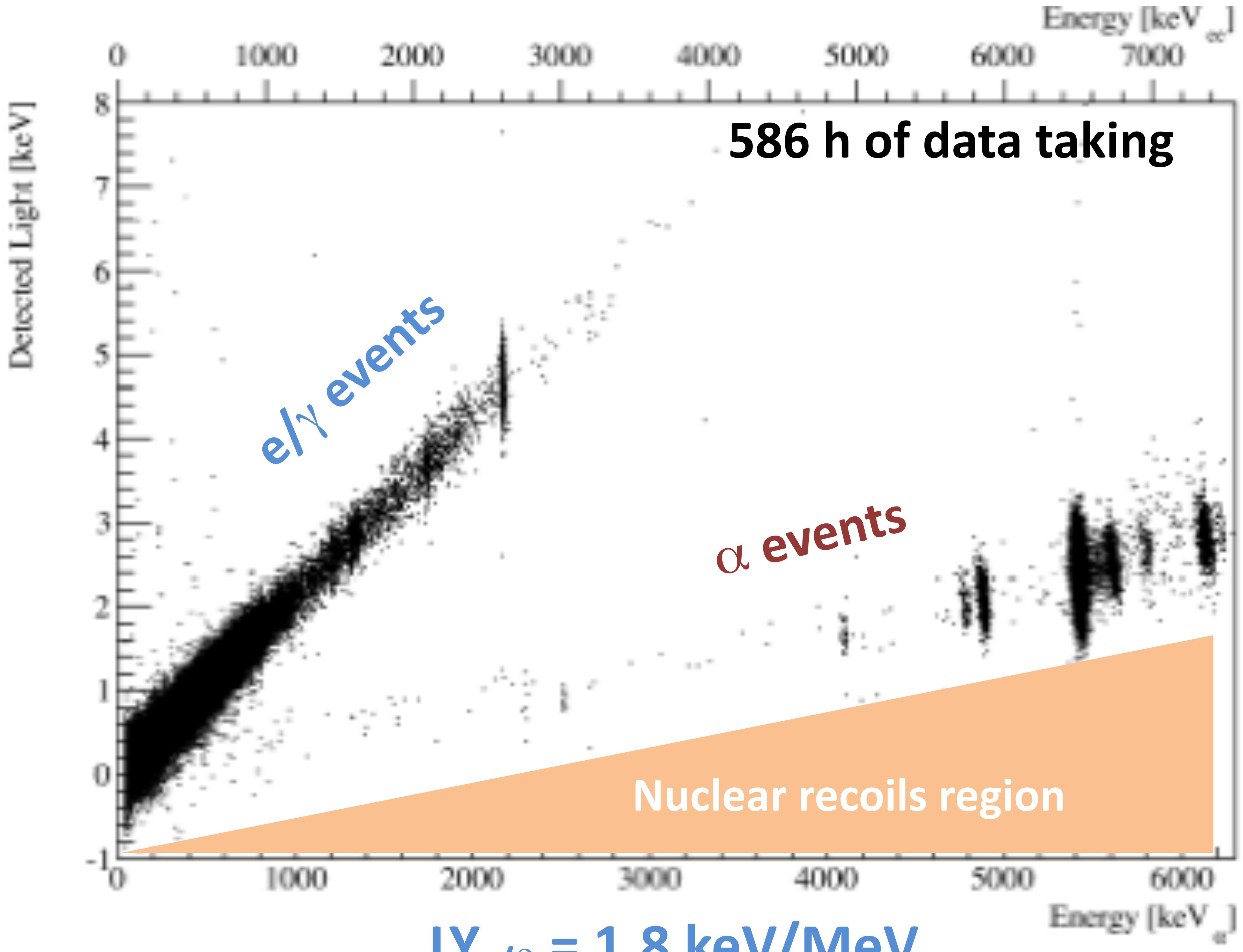
View of completed shield



Experiment with $^{arch}PbWO_4$ scintillating bolometer to search for alpha decay of natural lead isotopes



$PbWO_4$ crystal
from archaeological lead
454.1 g, 3.0×3.0×6.1 cm³



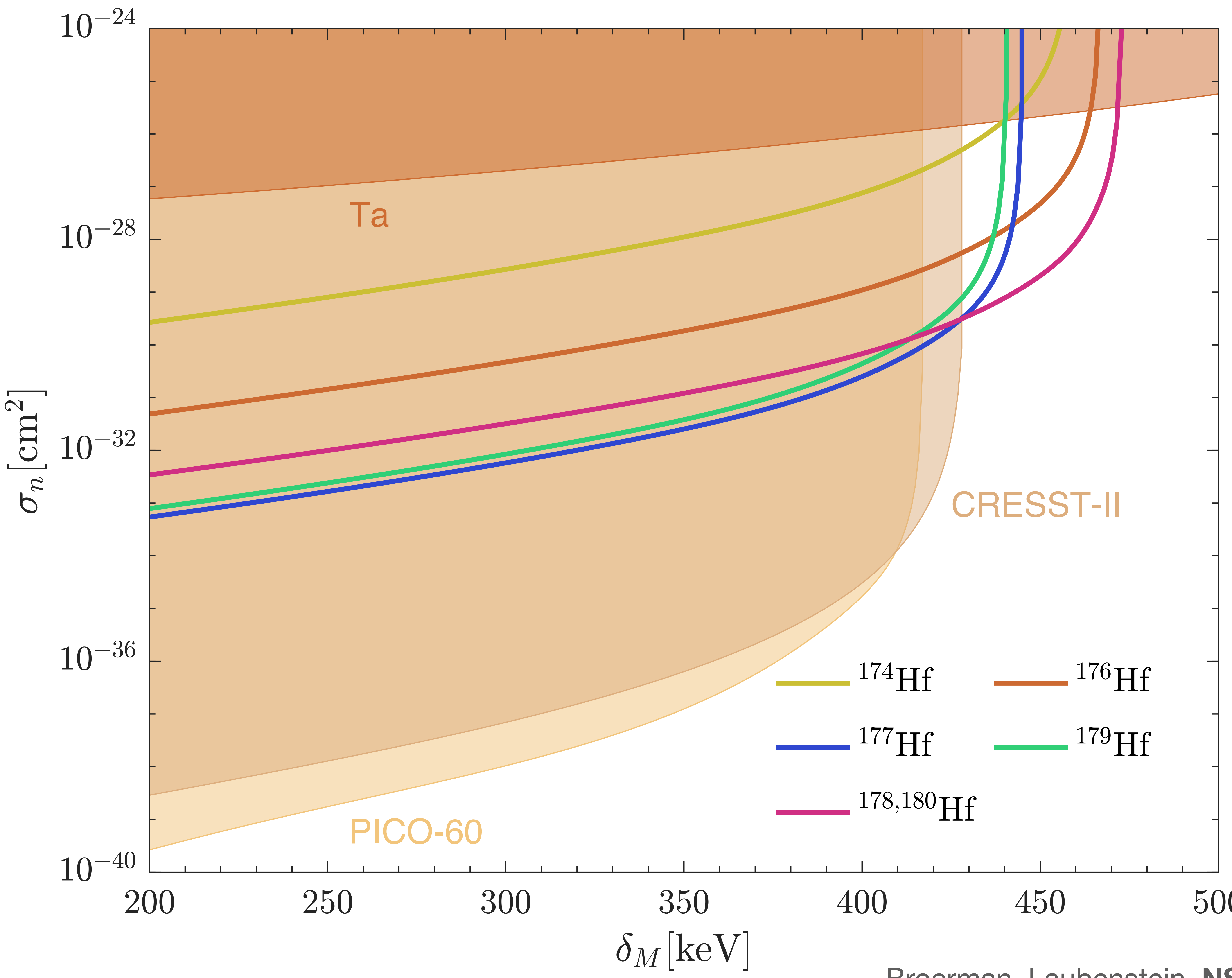
$LY_{\gamma/\beta}$ = 1.8 keV/MeV

$LY_{\alpha} = 0.3 + 2.9\times10^{-5} E_{\alpha}$ keV/MeV

7 events with $LY_{n.r.} < LY_{\alpha}$

J.W. Beeman et al., Eur. Phys. J. A 49 (2013) 50

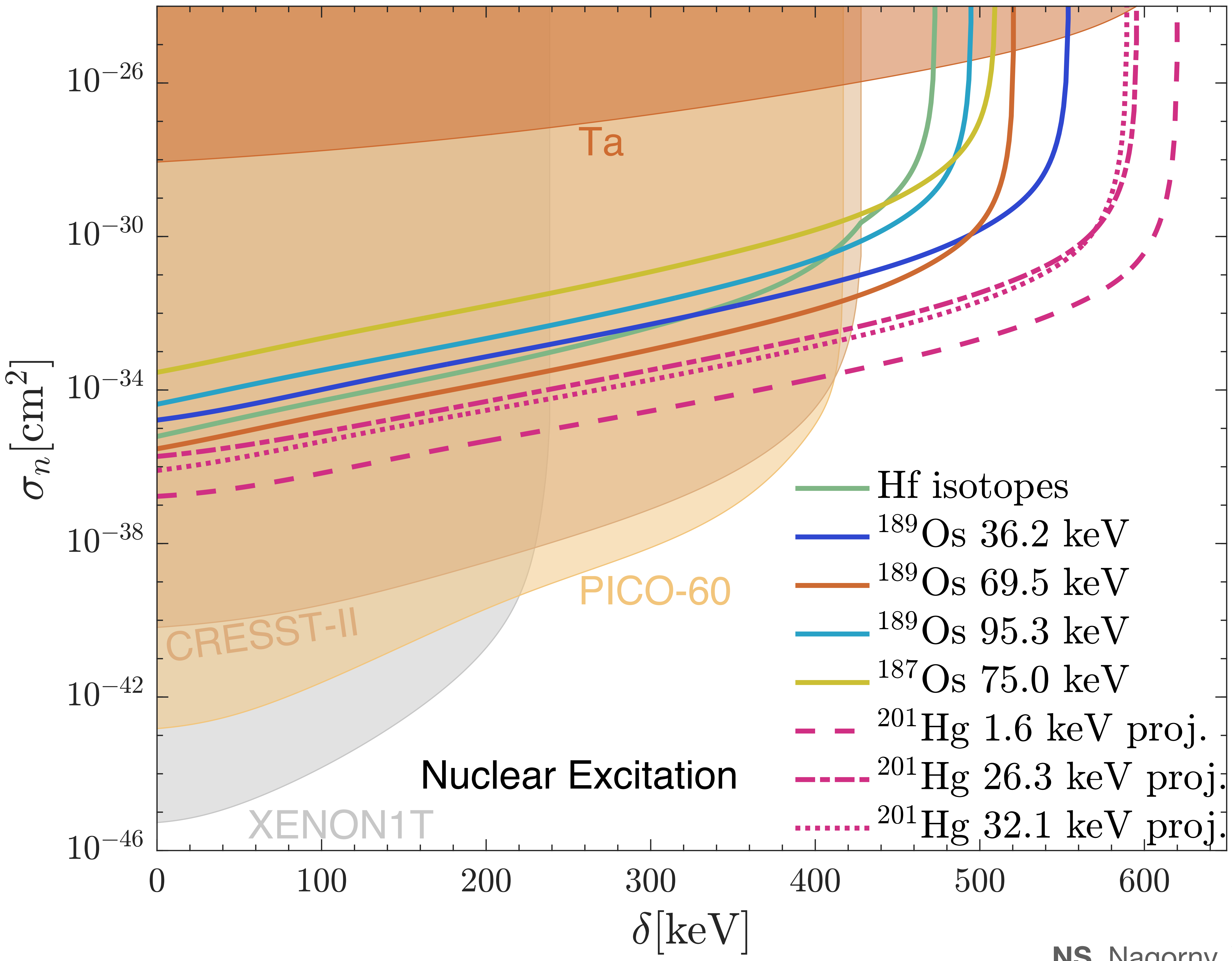
Hf Bounds



$M_\chi = 1$ TeV

Broerman, Laubenstein, **NS**, Nagorny, Vincent, 2012.08339

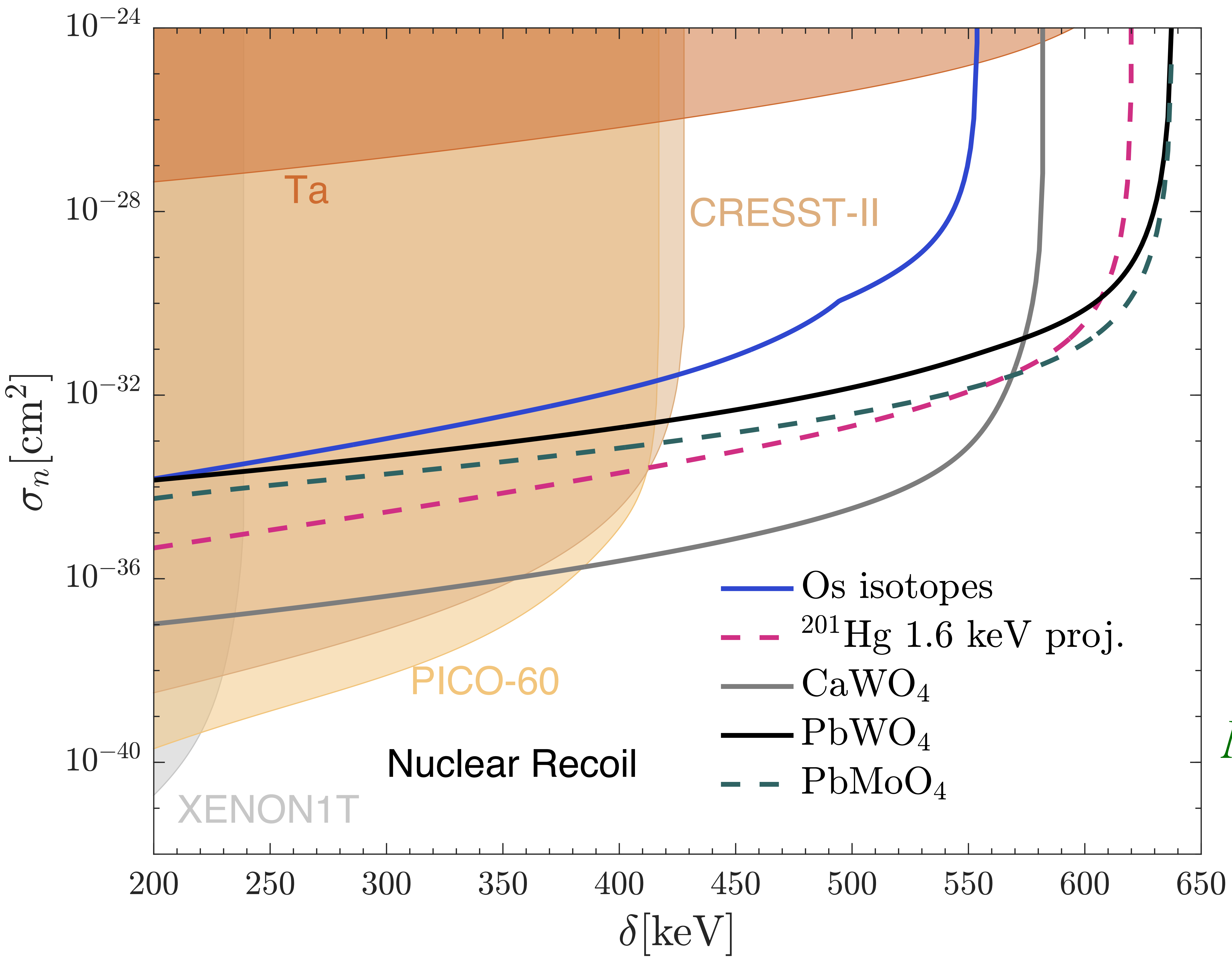
More Nuclear Transitions



$M_\chi = 1$ TeV

NS, Nagorny, Vincent, 2104.09517

$PbMoO_4$



$M_\chi = 1$ TeV

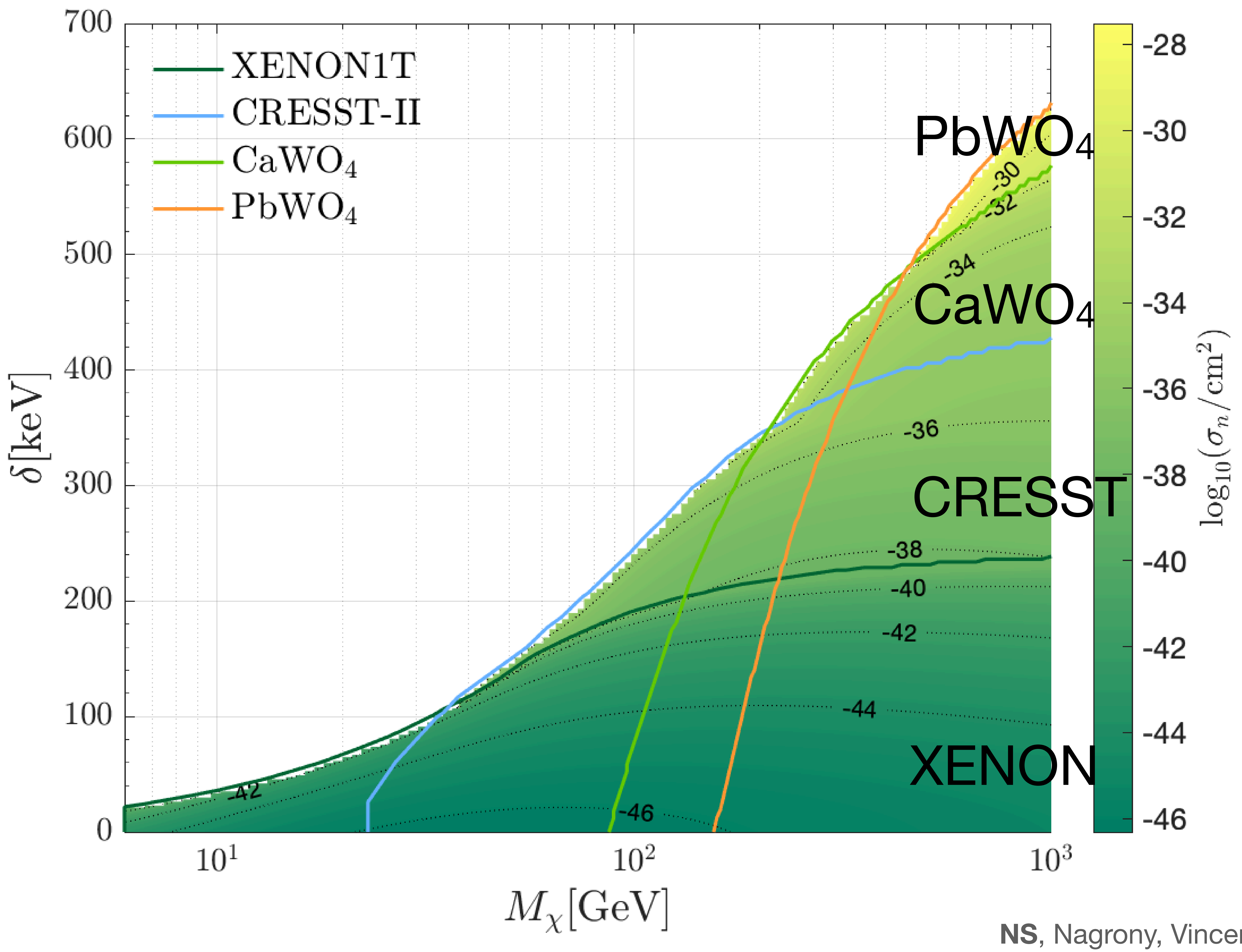
Event Rate for Nuclear Excitation

- $R = \sum_i N_{T_i} \frac{\rho_\chi}{M_\chi} \int_{v_{\min}}^{v_{\max}} dv v f(v) \int_{E_{R,\min}}^{E_{R,\max}} \frac{d\sigma_{\chi N}}{dE_R} dE_R$

$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{\sigma_n M_N}{2v^2\mu_{\chi n}^2} S(E_R)$$

- $S(\vec{q}) = \sum_L |\langle J_f || j_L(qr) Y_{LM}(\hat{r}) || J_i \rangle|^2$
- $B(E2) = \frac{1}{2J_i + 1} |\langle J_f || e r^2 Y_2 || J_i \rangle|^2$
- $S(\vec{q}) = \frac{A^2}{Z^2}(2J_i + 1) j_2(qR)^2 \frac{B(E2)}{e^2 R^4}$

WIMPy Inelastic Dark Matter Window

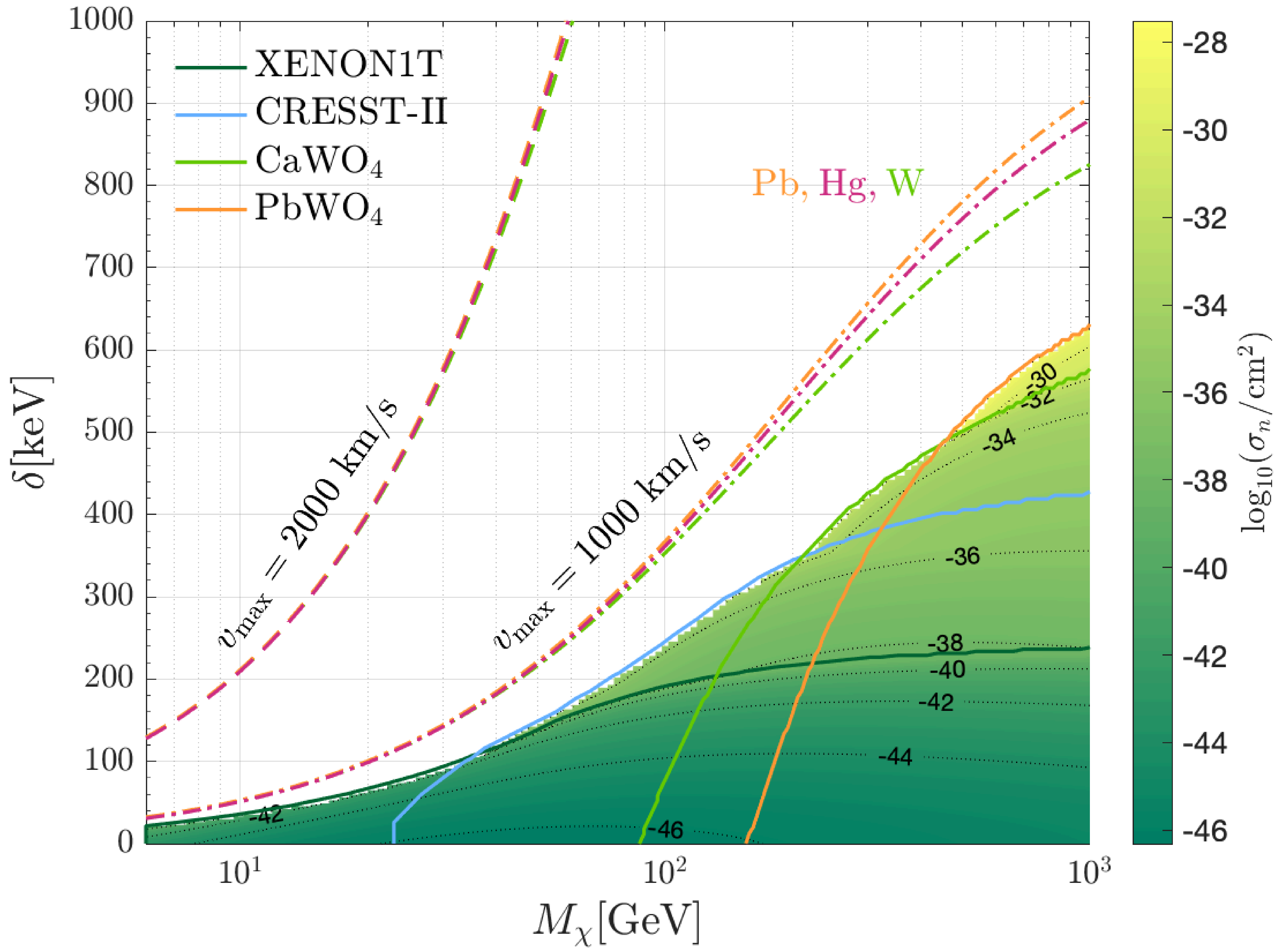


NS, Nagrony, Vincent, 2104.09517

Boosted Dark Matter

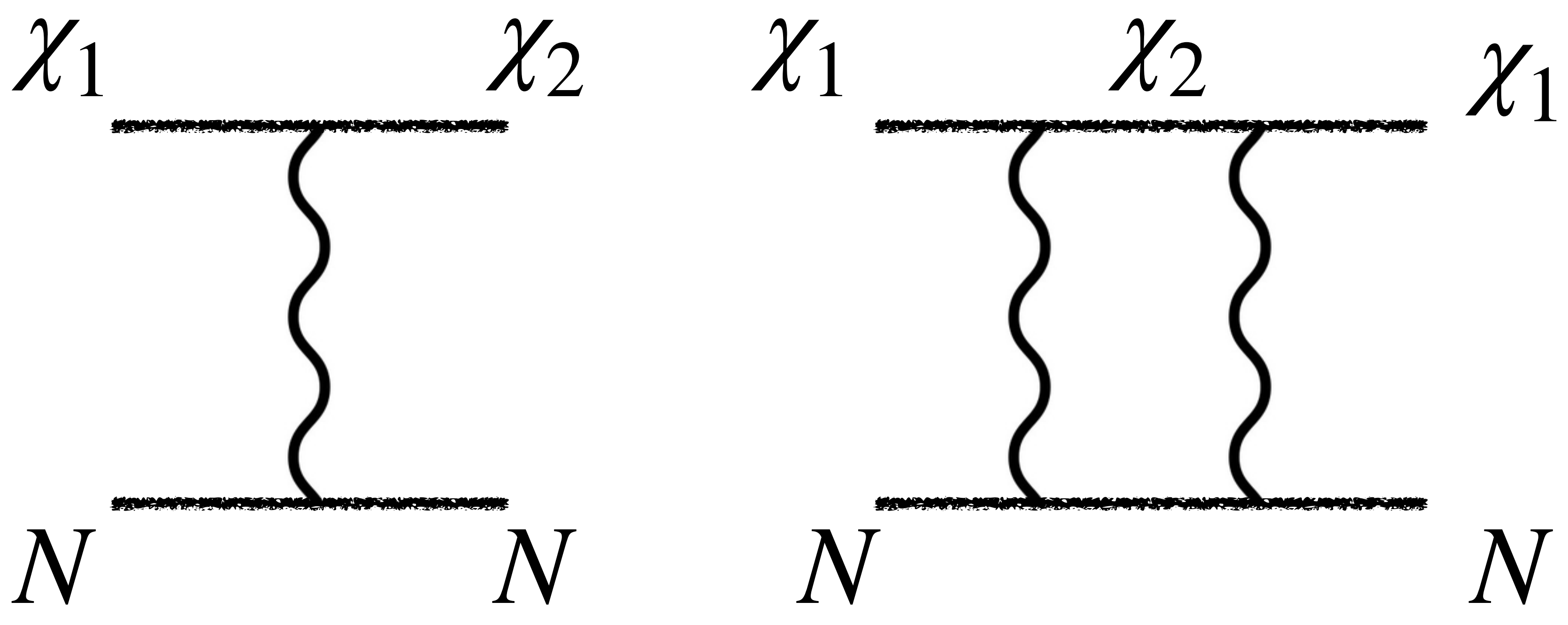
- Cosmic-ray, neutrino up-scattering
- Stellar acceleration
- Annihilation, semi-annihilation
- Heavy DM decay

$$\delta_{\max} = \frac{1}{2}\mu_{\chi A}(v_e + v_{esc})^2$$

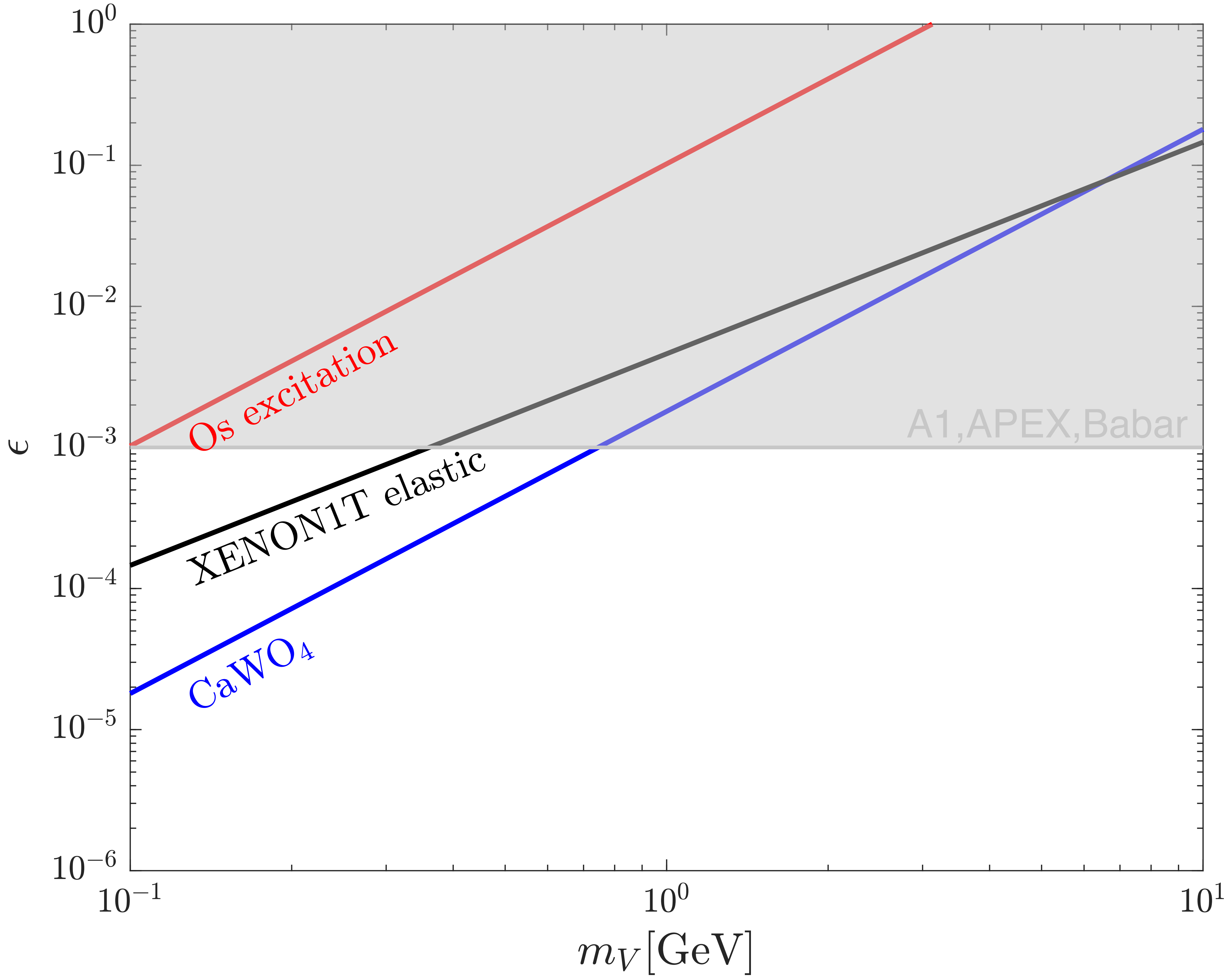


NS, Nagorny, Vincent, 2104.09517

Loop Elastic Scattering



- Dark photon mediated DM
- $$\sigma_{n,\mathrm{tree}} = \frac{16\pi\alpha\alpha_D\epsilon^2\mu_{\chi n}^2}{m_V^4}$$
- $$\sigma_{n,1\mathrm{loop}} \sim \frac{\alpha^2\alpha_D^2\epsilon^4\mu_{\chi n}^4}{\pi m_V^6}$$



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