Paleodetection at Queen’s

Aaron Vincent (et al.)

Kingston, Ontario
Traditional territory of the Anishinaabe, Haudenosaunee and Huron-Wendat

Queen’s Paleodetection Team

Queen's Centre for Understanding Minerals by Blasting them with Excessive Radiation (QCUMBER)

Physics

Yilda Boukhtouchen

Joe Bramante

Aaron Vincent

Audrey Fung

Next talk->

Mechanical and Materials Engineering

Levente Balogh

Talk tomorrow->

Thalles Lucas

Geological Sciences

Matt Leybourne

Sharlotte Mkhonto

Ongoing efforts at Queen’s

- **Geochemistry**: Identifying and characterizing candidate minerals for paleodetection
- **Physics theory**: predicting expected signals for WIMP and non-WIMP dark matter + other new physics
- **Materials Engineering**: producing track damage with proton accelerator beam to test theory against experiment.

Rocks

Looking for suitable candidates

- Should be stable against annealing over (at least) Myr time scales
    - e.g. halite, anything with H not great
- Should have very little U/Th content to mitigate fission track backgrounds

Two candidates

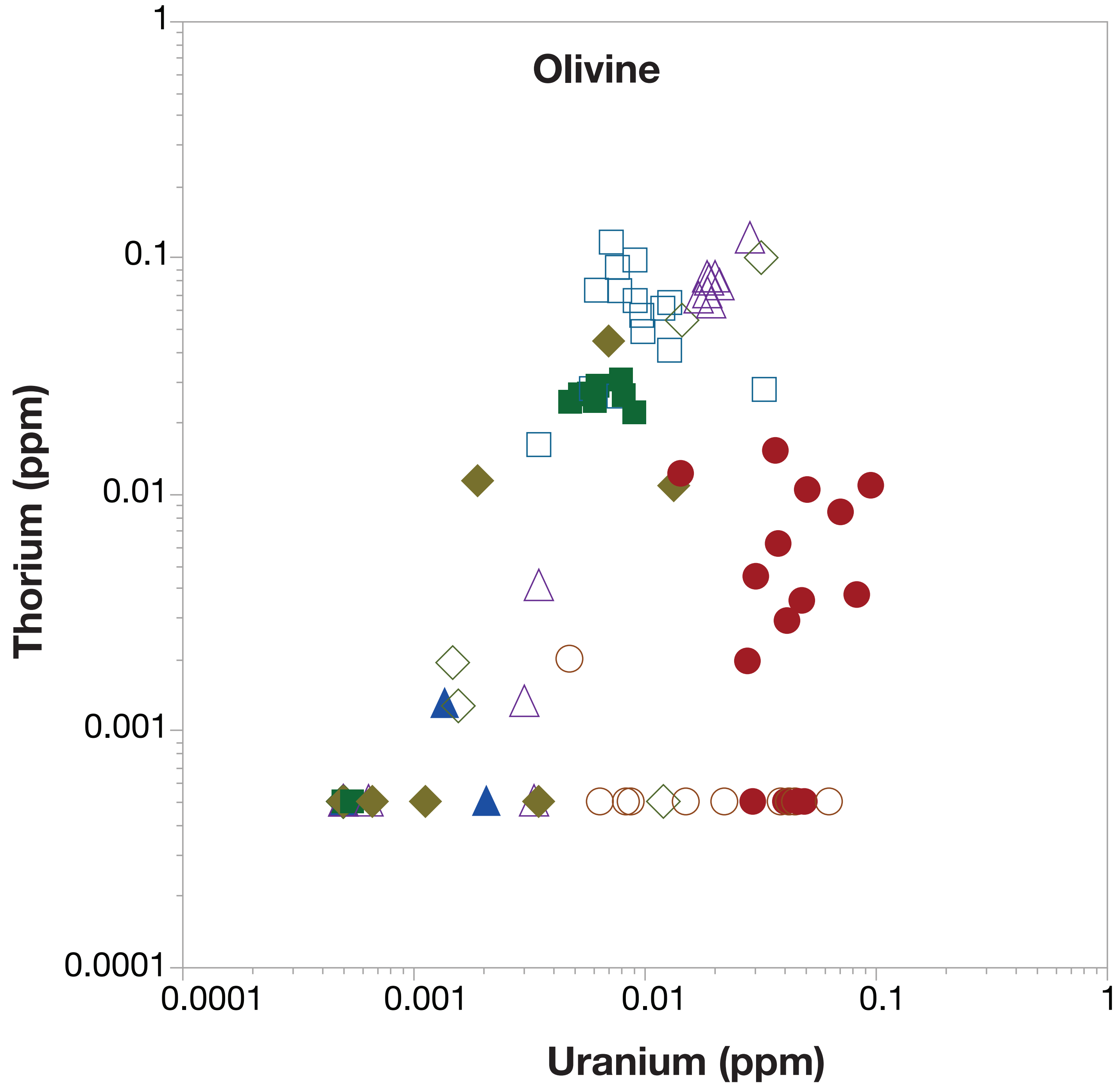
- Olivine $(Mg,Fe)_2SiO_4$
  - Has been suggested before (e.g.
  - Not expected to take up much uranium
  - “helps align the heart chakras” (source: the internet)

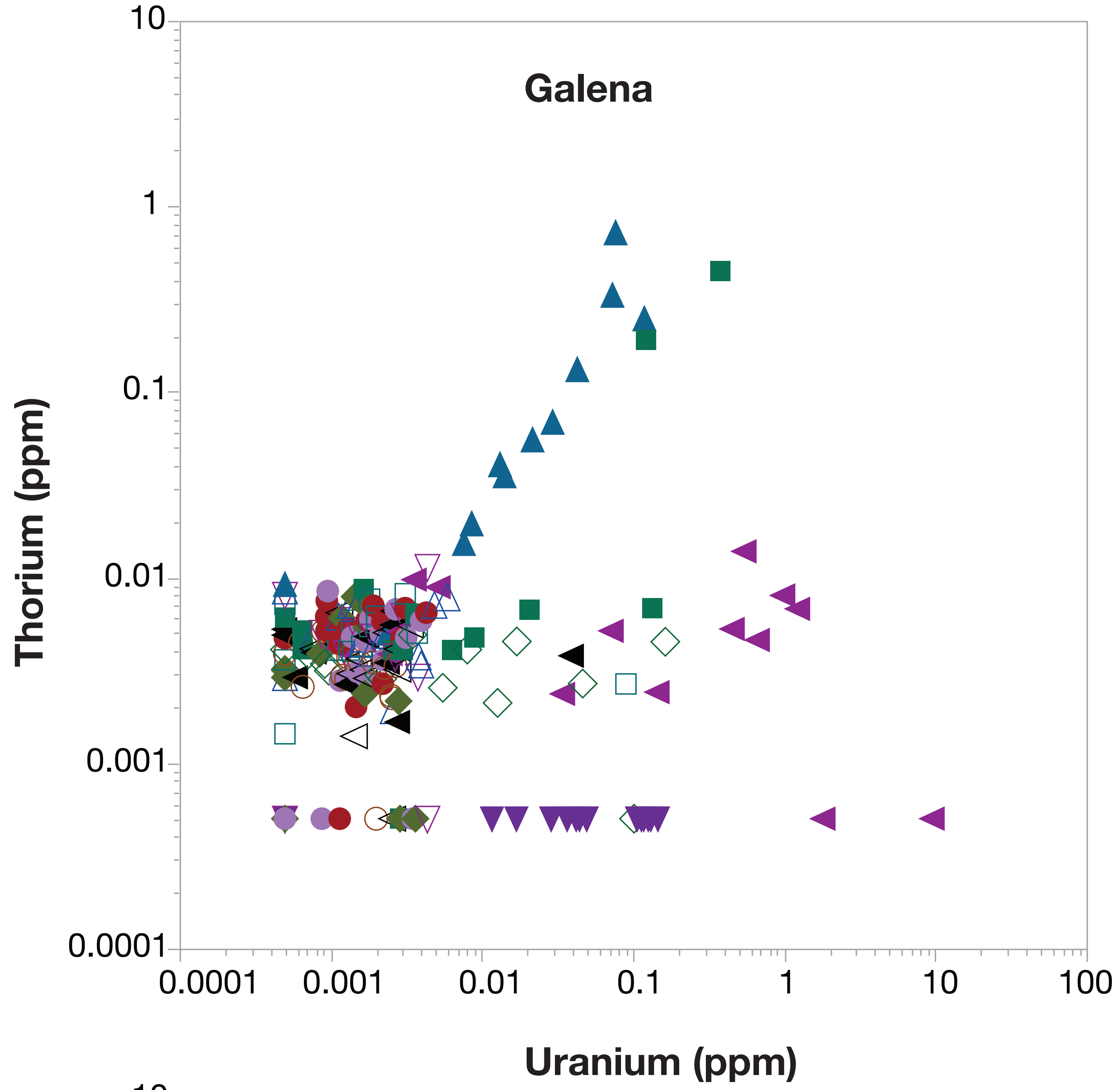
- Galena (PbS)
  - Not used before (as far as we know)
  - Not expected to take up much uranium
  - No healing properties :(

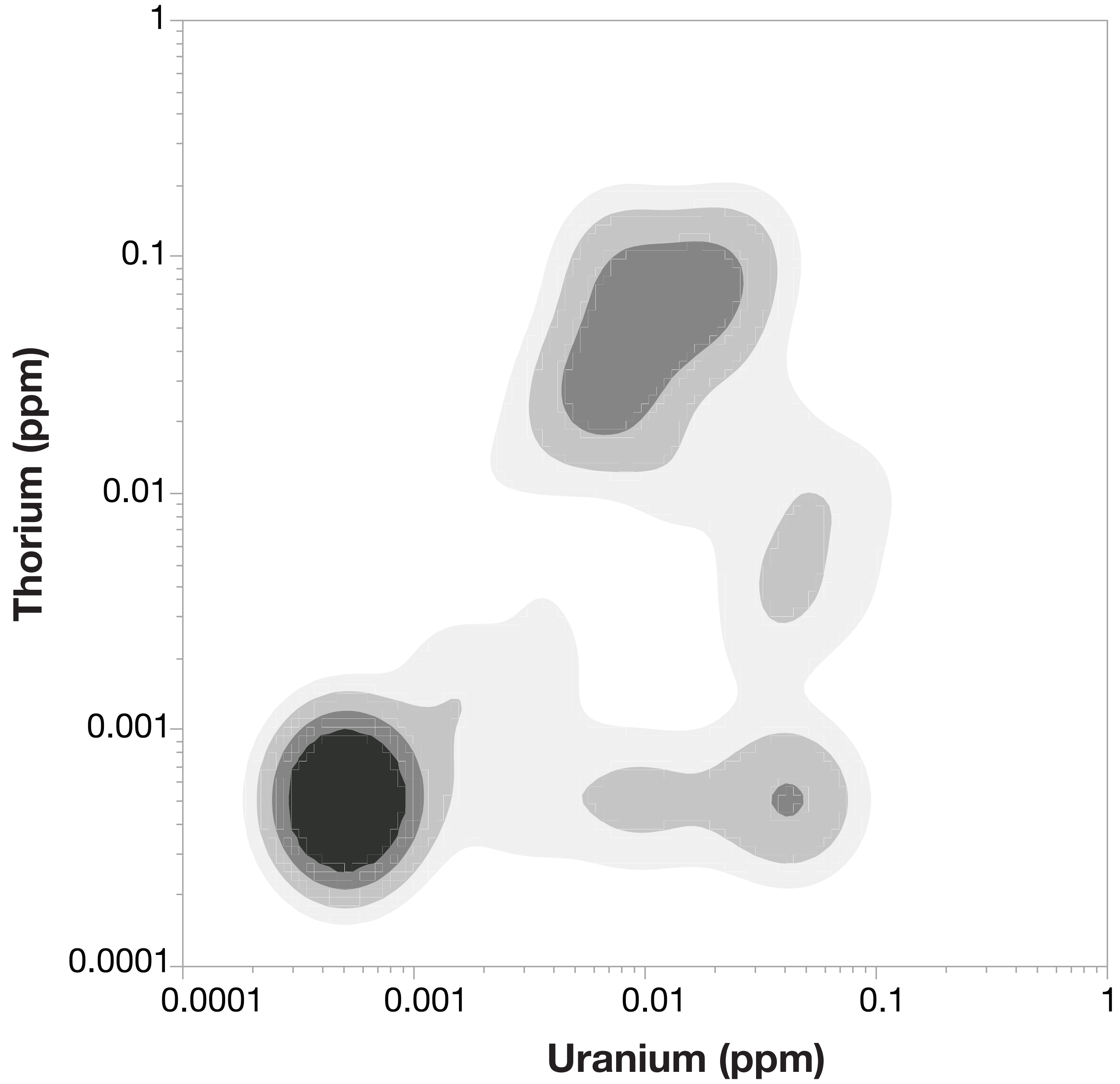
Annealing: we don’t know much; most work has been done on apatite since it’s used for fission track dating

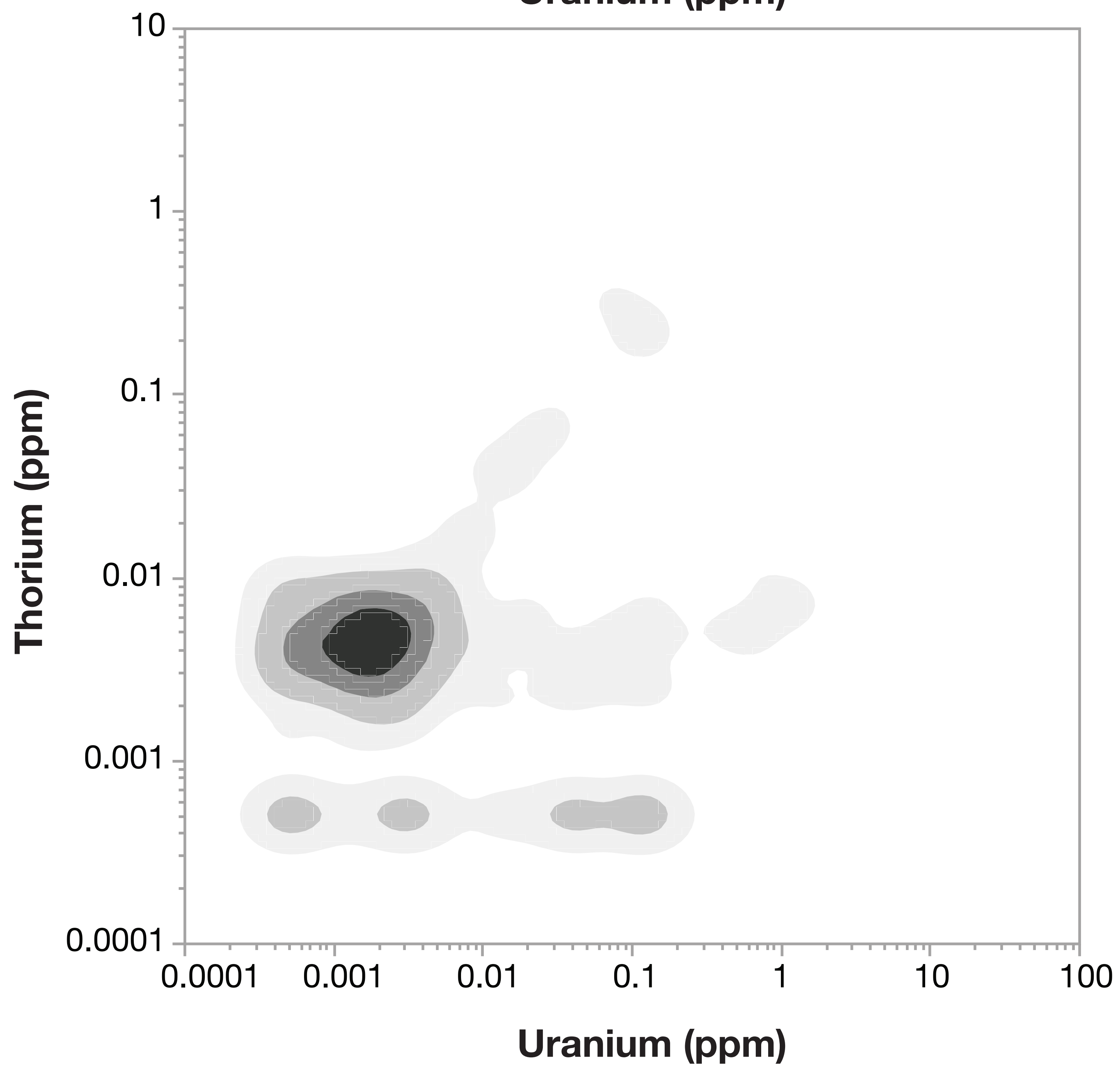
U/Th contents

- Leybourne lab laser ablation with ICP-MS





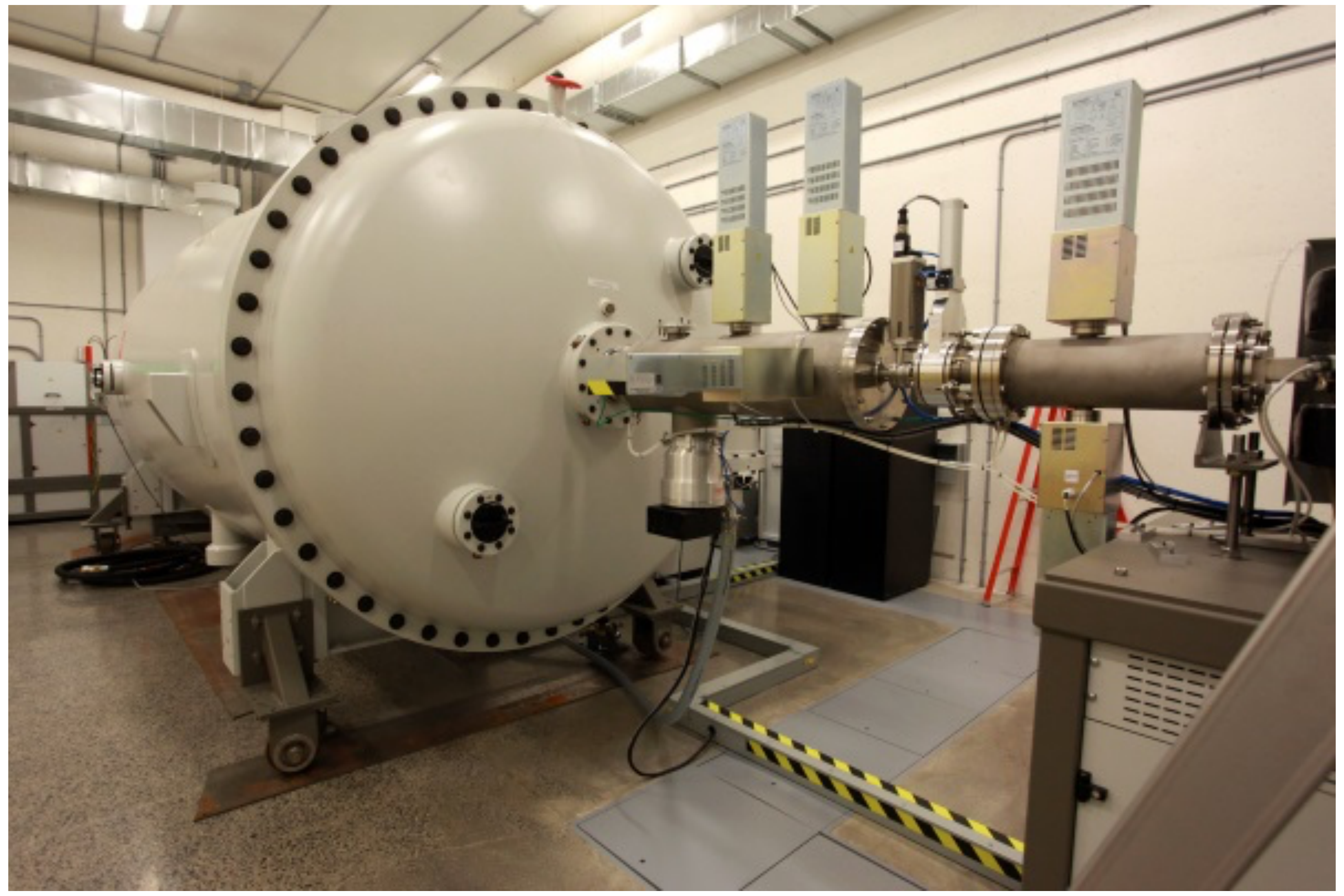




Data from Matt & Sharlotte

Calibrating

Talk by Levente tomorrow



Reactor materials testing laboratory (RMTL) @ Queen's

3 MeV proton beam

Dark matter is of course
-Non-relativistic
-Neutral

But

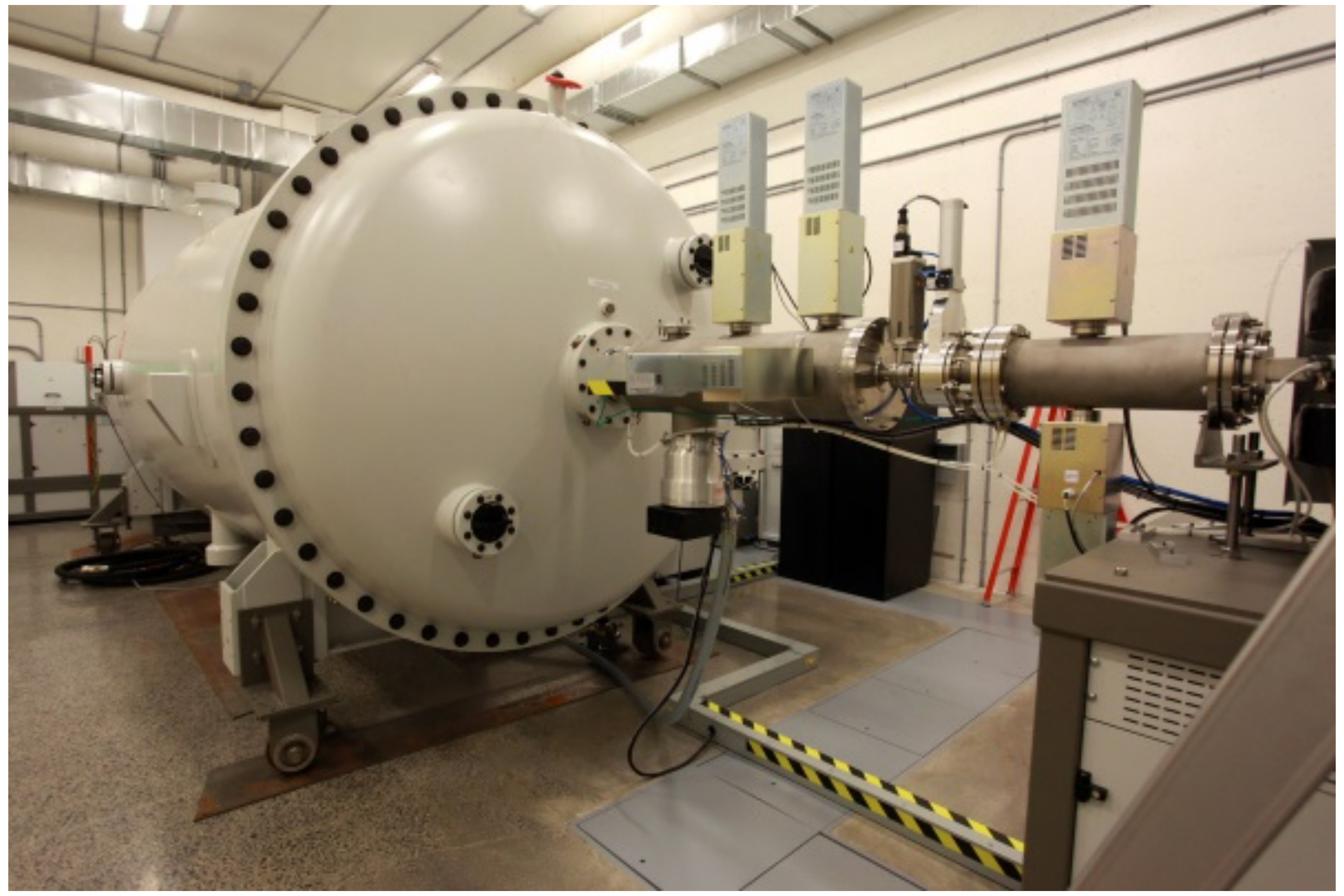
-we expect the atomic displacements following the primary interaction to behave in a similar way, regardless of the cause of the primary interaction.

-A neutron beam is hard to make, and leads to a lot of extra radioactivity

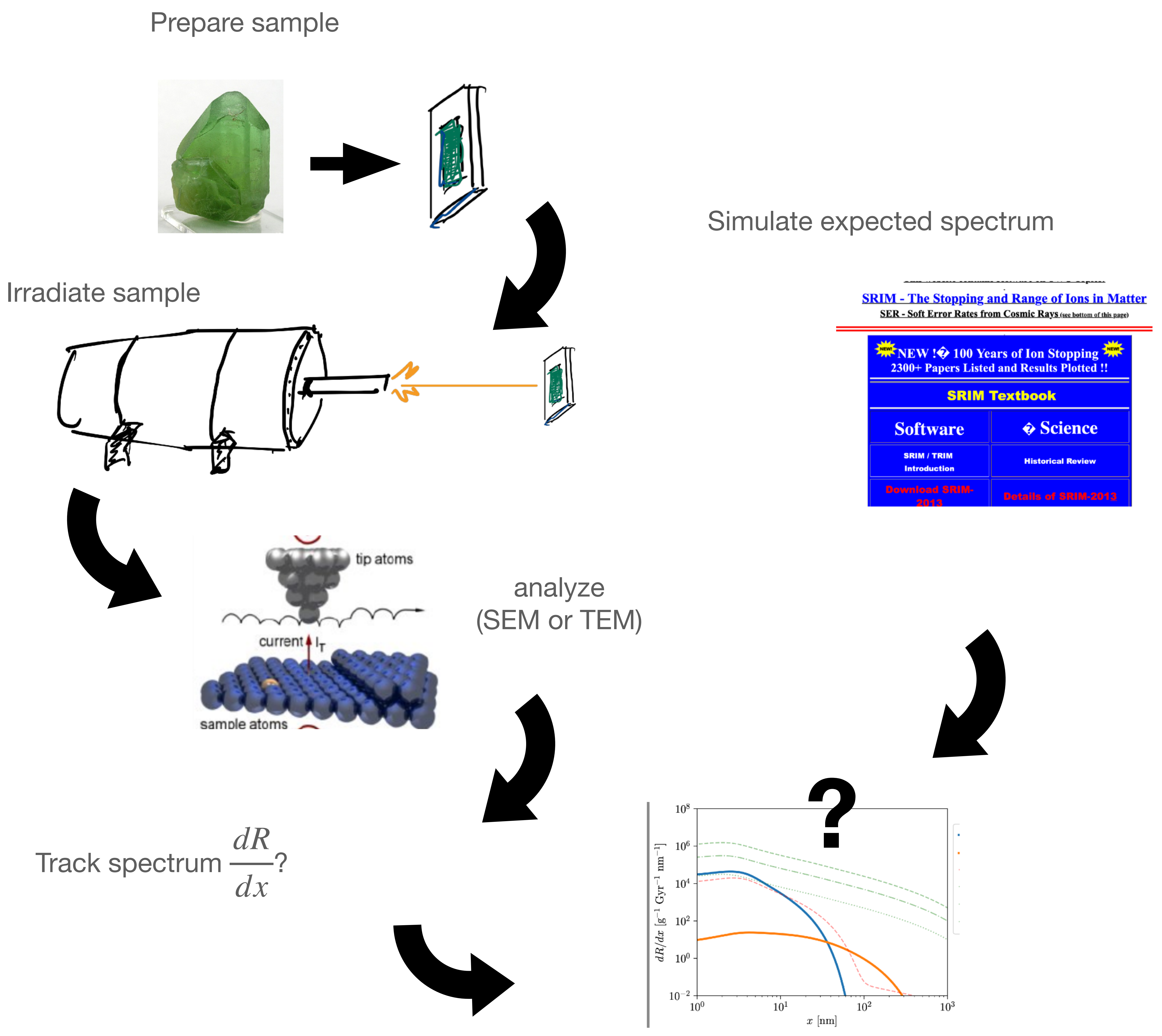
-If our measured vs modeled spectra match using the proton beam, we will have gained a measure of confidence in our approach

Calibrating

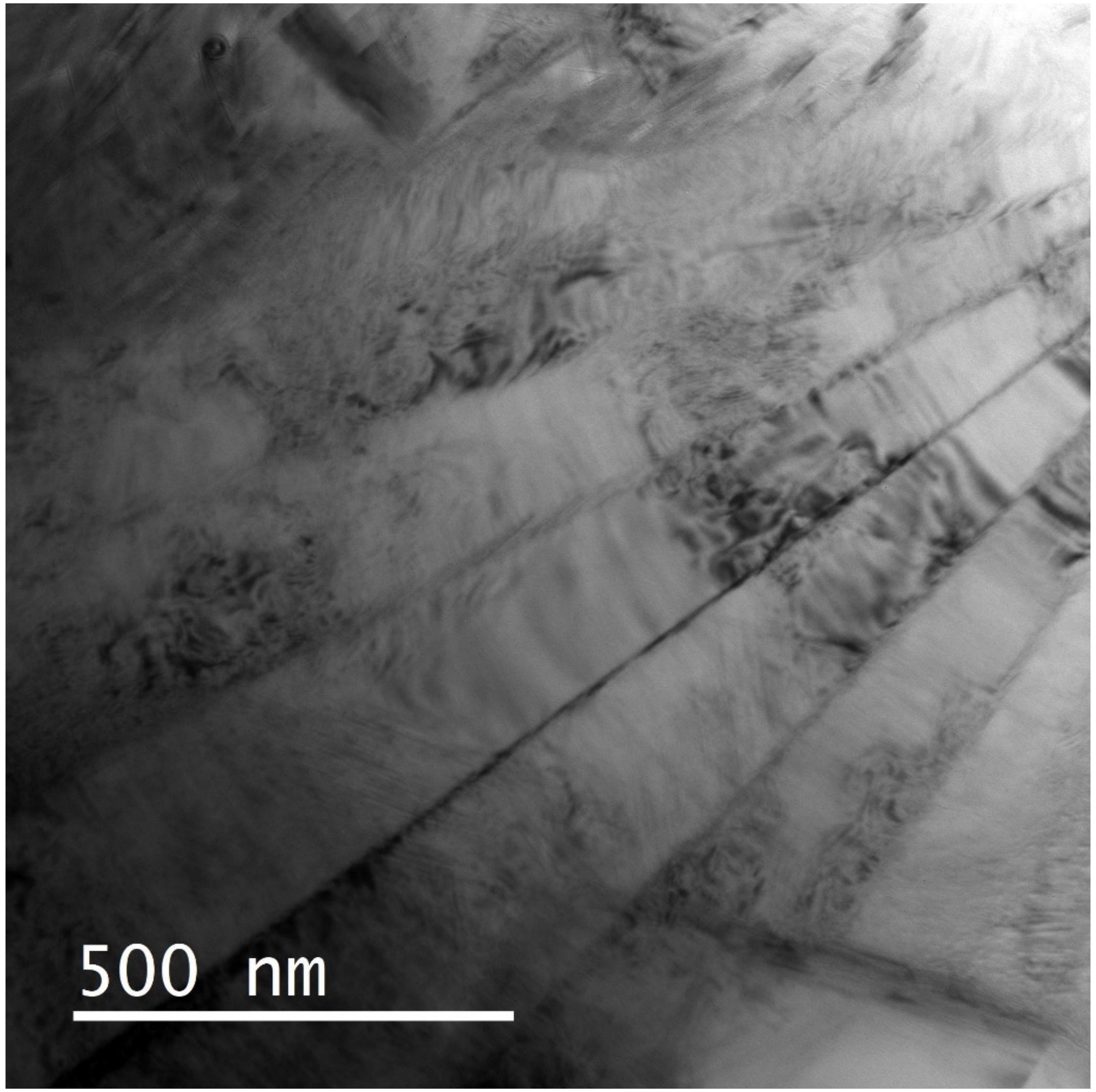
Talk by Levente tomorrow



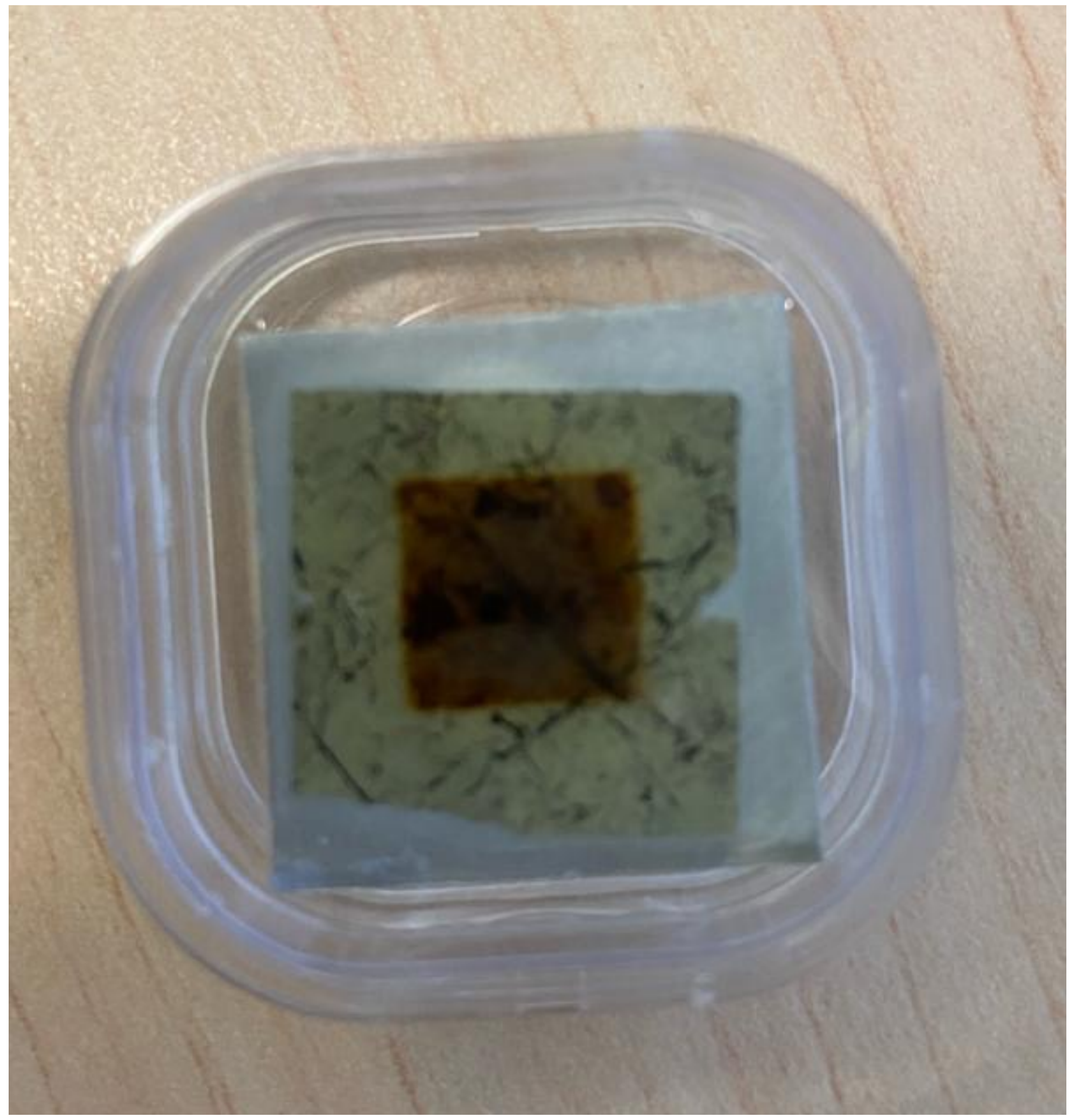
Reactor materials testing laboratory (RMTL) @ Queen's



Olivine non-irradiated

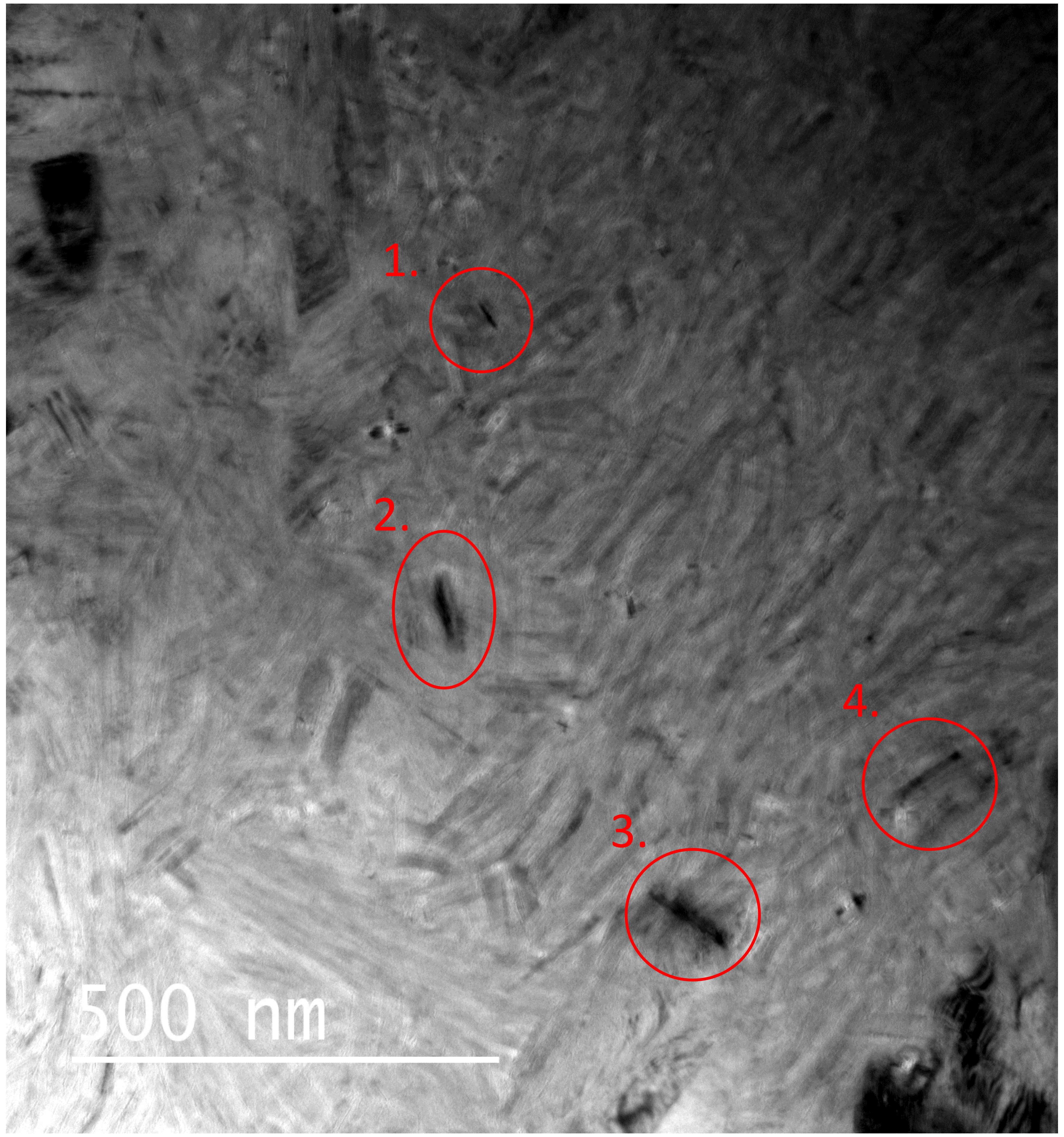


Large grains with Widmanstatten pattern



Thalles Lucas

Irradiated Olivine 5 MEV – 0.25 DPA



Thalles Lucas

- The irradiation induced the formation of nanostructures in the olivine. The SAED identified that these nanograins are crystalline in nature.
- Four regions with the possibility to be a amorphous track with length of: 32 nm, 62 nm, 85 nm and 108 nm respectively to 1,2,3,4.

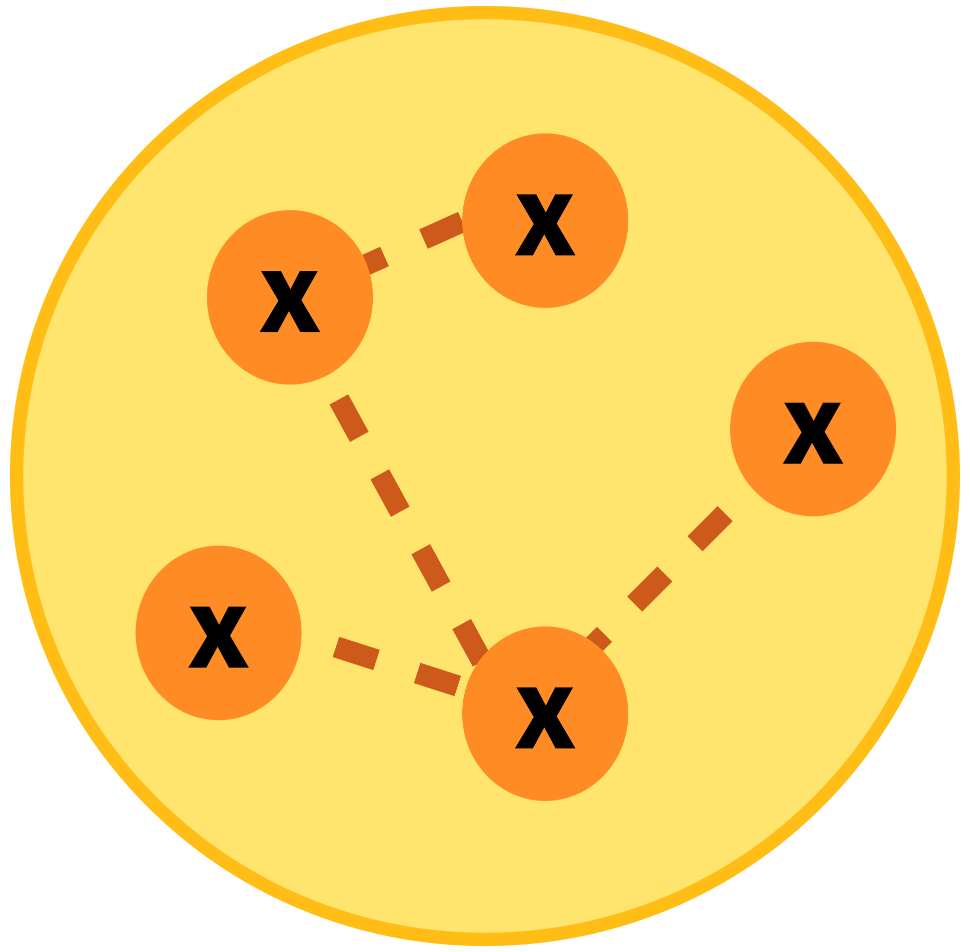
Theory work

Slides from Yilda Boukhtouchen

Fermionic DM Composite States

Dirac fermion X of mass m_χ, which has self-interactions through a light scalar field ϕ

$$\mathscr{L}_D = \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_\phi \bar{X}\phi X - \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$



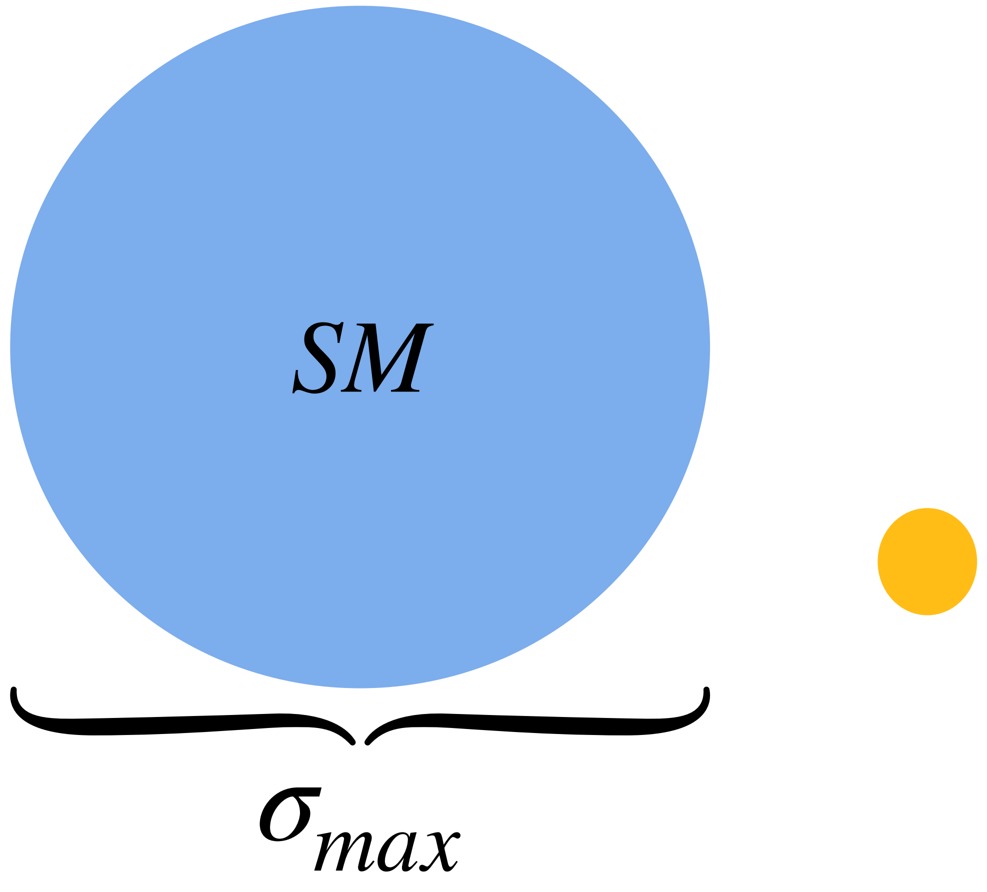
Attractive force due to ϕ

At large enough N, constituents form degenerate Fermi gas

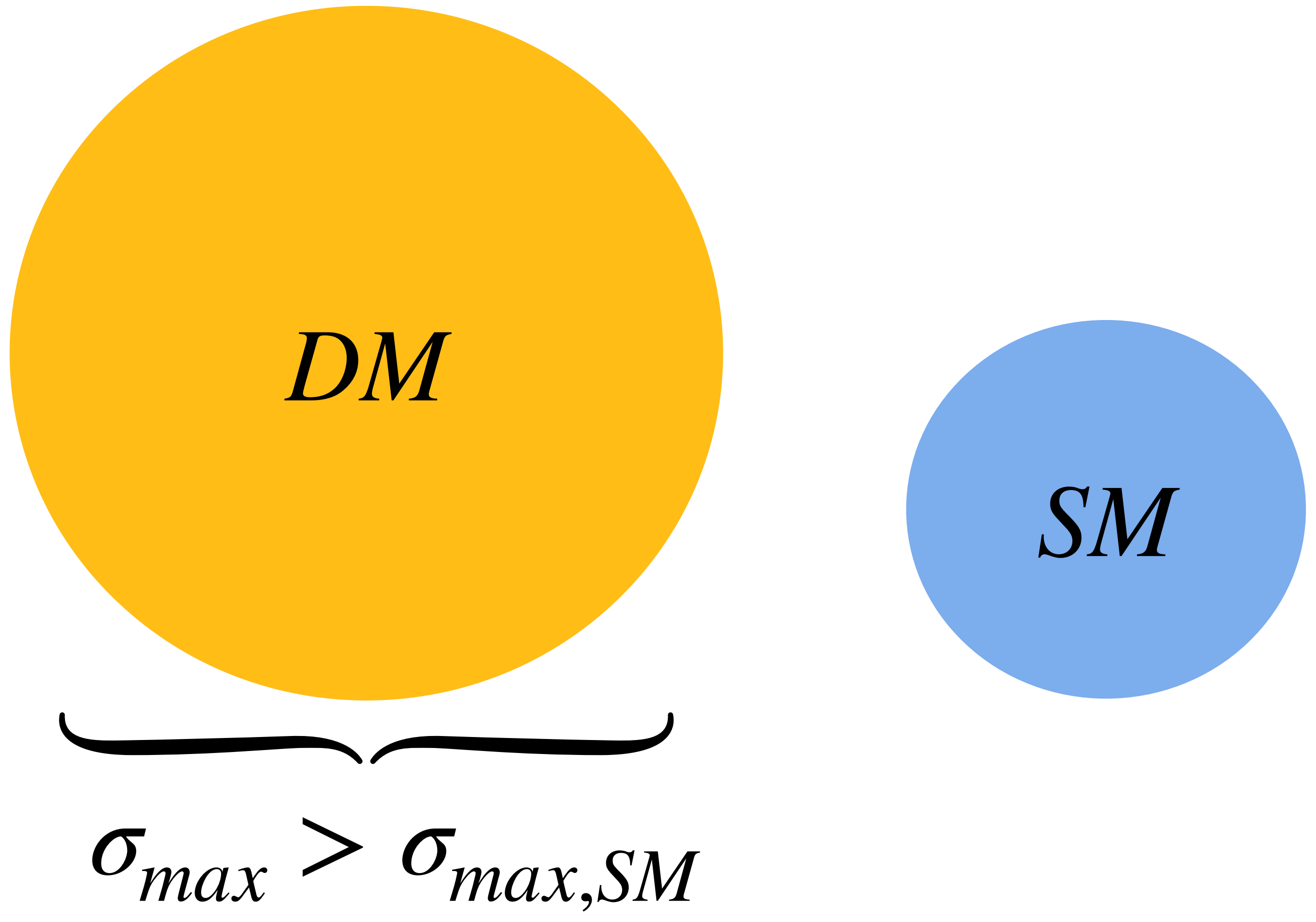
Solve system numerically for composite characteristics $(R, M, E_B \ldots)$

1707.02313 and others

Composites Larger than SM Nuclei



If $R_{DM} > R_{SM}$, we can extend the upper cross-section limit



Other groups have considered phenomenology of compact, tightly-bound composites ($E_B \sim m_X,\ R \sim N^{1/3}$)

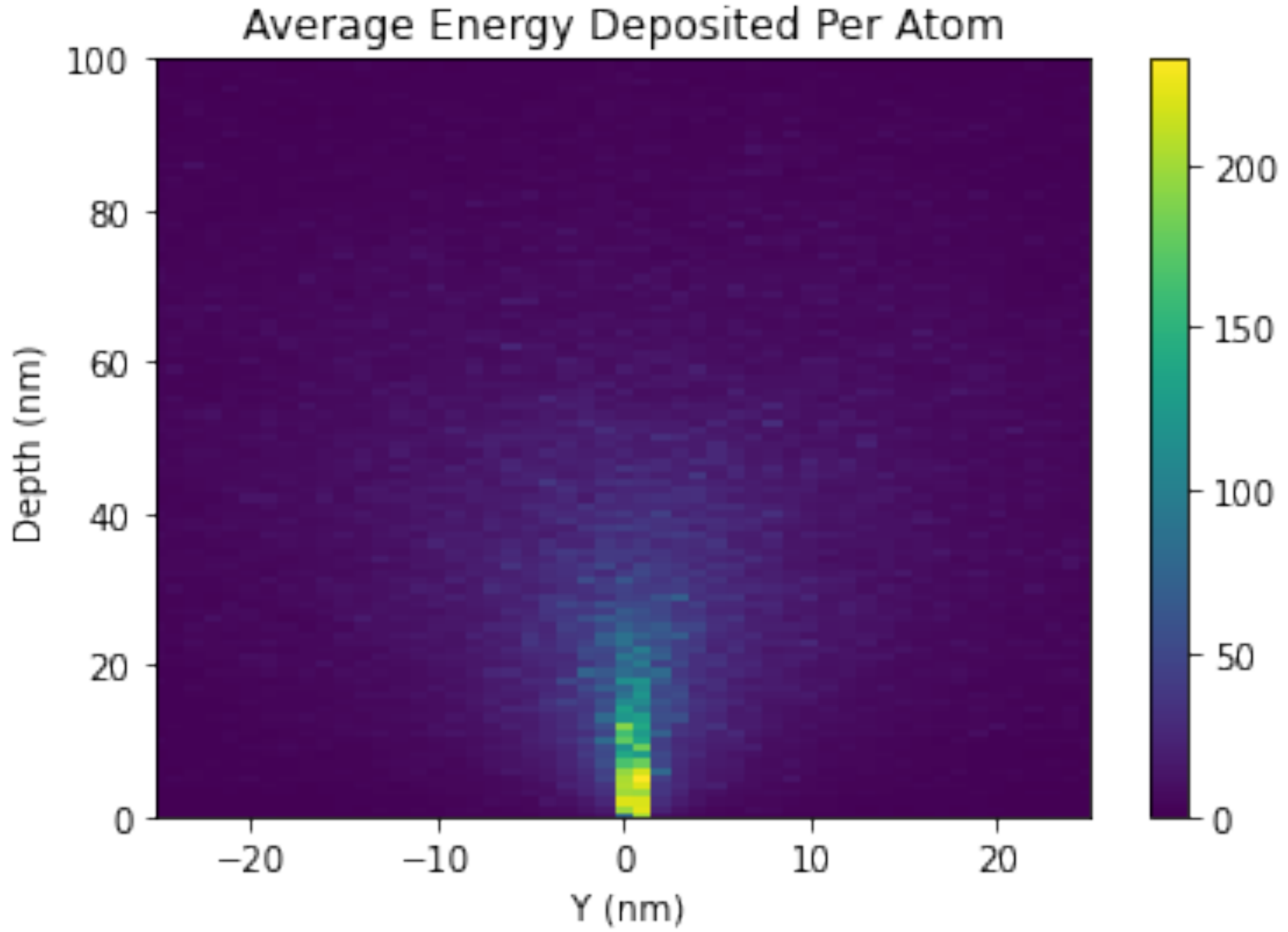
Loosely-bound composites ($E_B < m_X$) are also interesting:
$R \sim N^{2/3}$ so are larger at the same N

Slides from Yilda Boukhtouchen

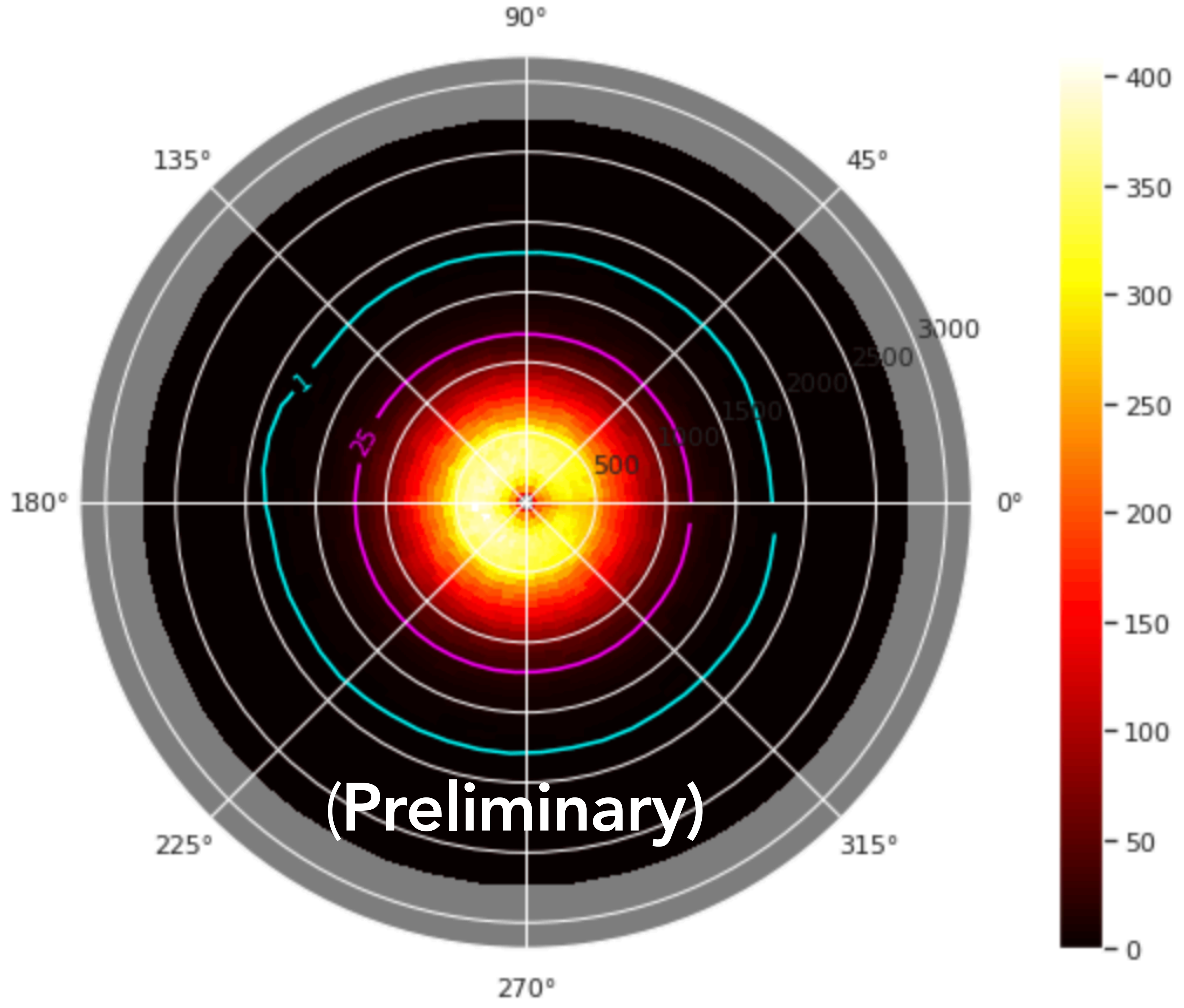
Detection Signature in Minerals

For large composite masses: Elastic, hard-sphere scattering with nuclei in mineral

Calculate single PKA's cascade of scatters in SRIM



All displaced nuclei are scattered radially outwards as composite passes, creating a cylindrical track



Energy deposition (eV) for DM radius of 50 Å

25 eV: displacement energy threshold

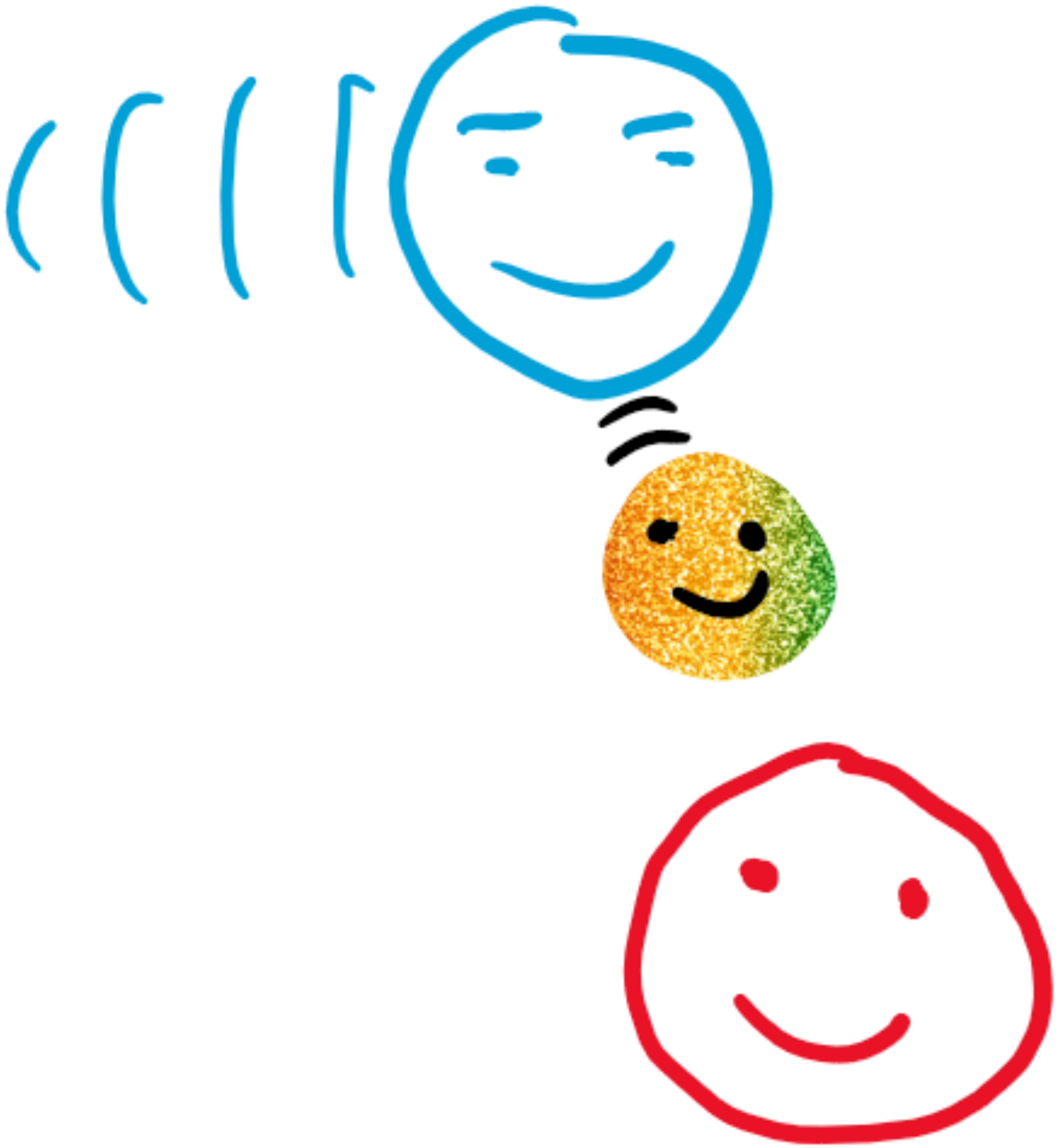
1 eV: energy required for melting (per atom)

New physics with solar neutrinos

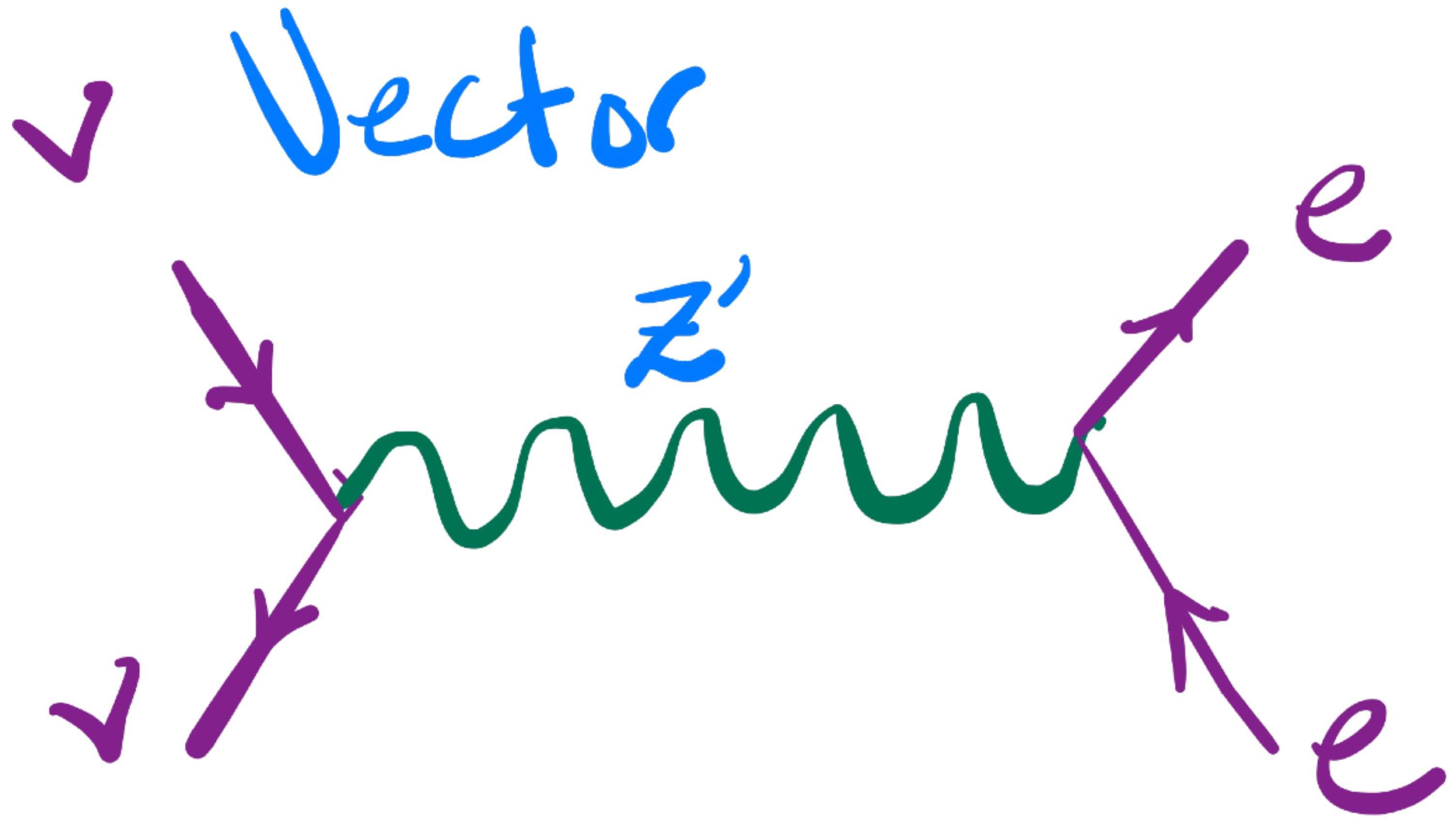
Low momentum: Coherent neutrino-nucleus scattering (CEvNS

Momentum exchanged for neutrino-nucleon events is around keV scale

Q^2 unstudied in those settings, can probe new interactions.

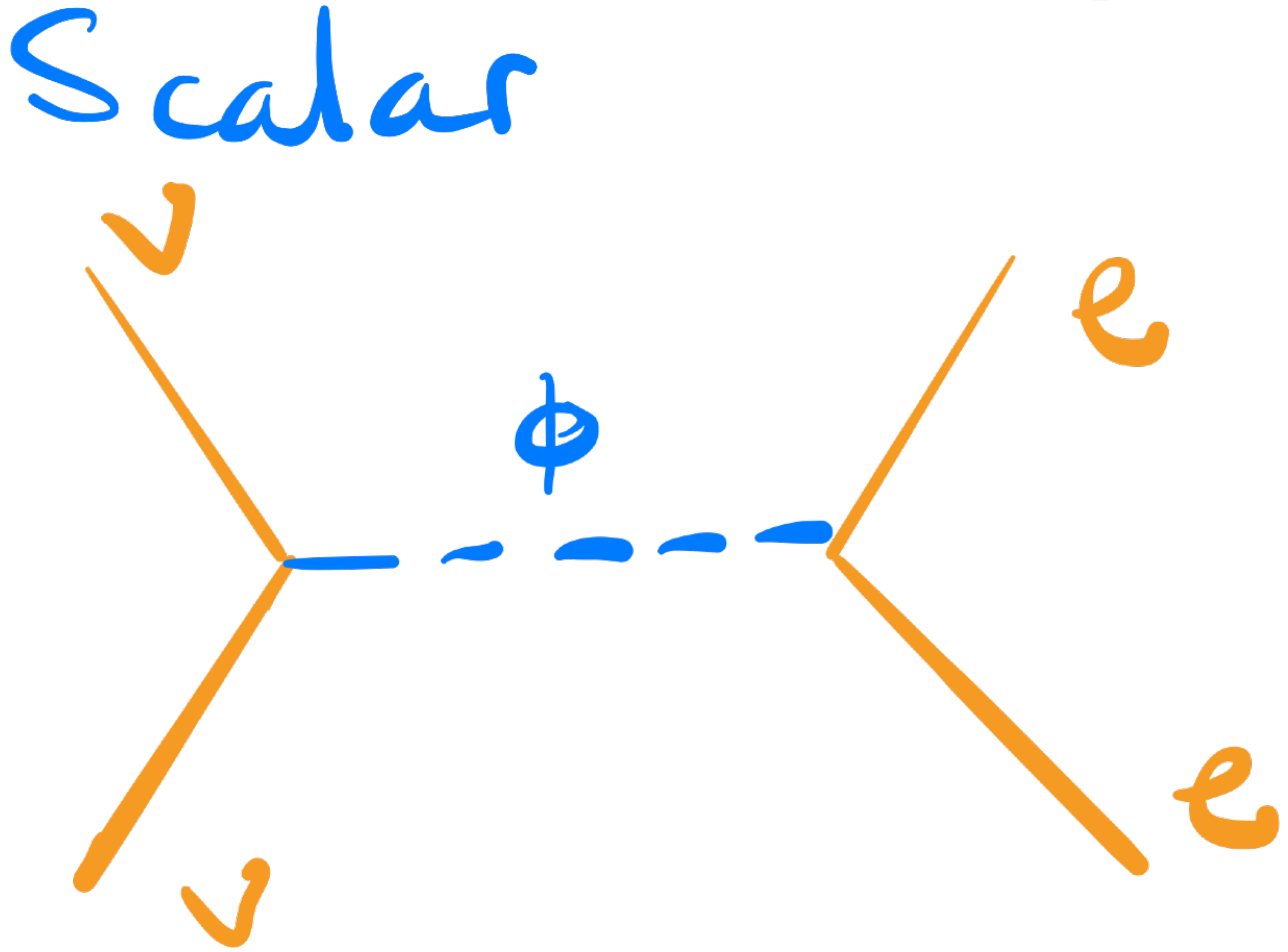


New physics: new light mediators? (Secret neutrino interactions/NSI)



$$\mathcal{L} = g_\nu Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{\ell} \gamma^\mu g_l \ell$$

$$\frac{d\sigma_{\nu e}}{dE_R} - \frac{d\sigma^{\rm SM}_{\nu e}}{dE_R} = \frac{\sqrt{2} G_F m_e g_v g_\nu g_e}{\pi\left(2E_R m_e + m^2_{Z'}\right)} + \frac{m_e g_\nu^2 g_e^2}{2\pi\left(2E_R m_e + m^2_{Z'}\right)^2}$$



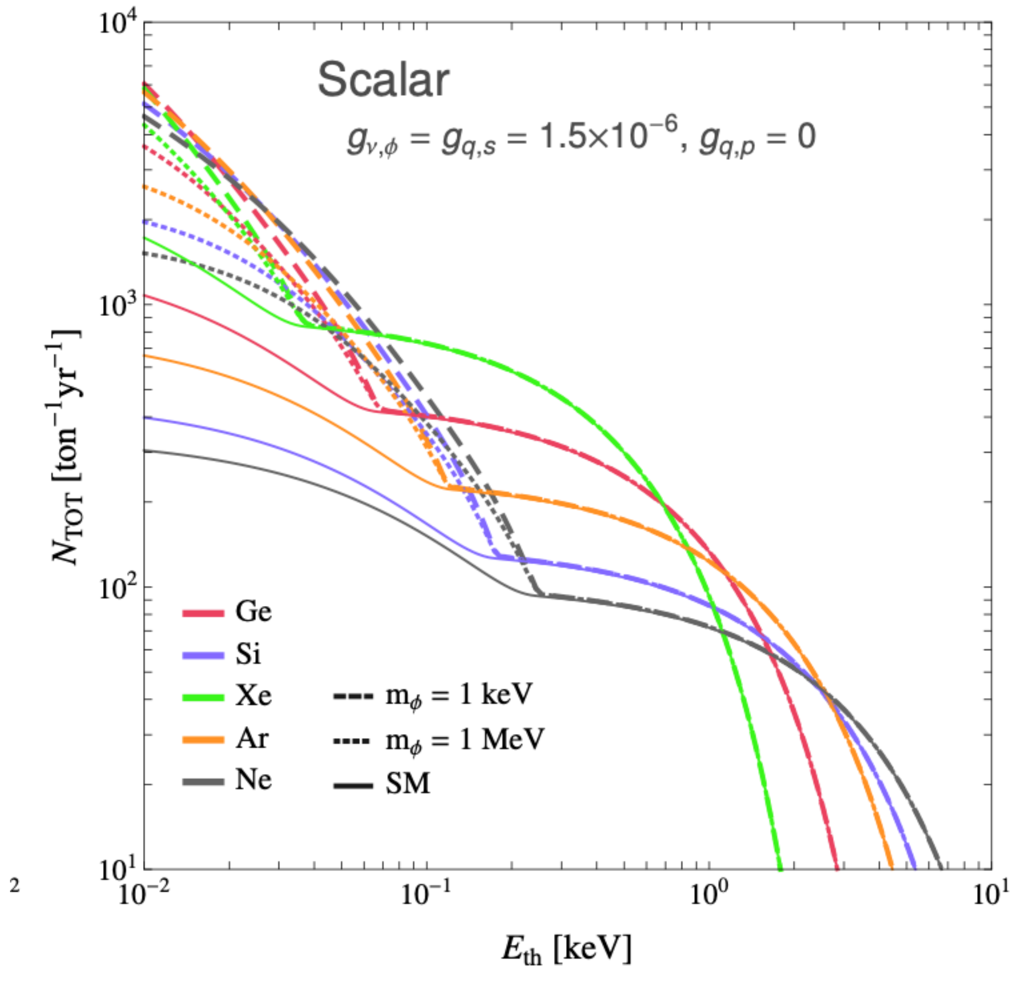
$$\mathcal{L} \supset \left(g_\nu\, \phi \bar{\nu}_R \nu_L + h.c.\right) + \phi \bar{\ell} g_l \ell$$

$$\frac{d\sigma_{\nu e}}{dE_R} - \frac{d\sigma^{\rm SM}_{\nu e}}{dE_R} = \frac{g_\nu^2 g_e^2 E_R m_e^2}{4\pi E_\nu^2 \left(2E_R m_e + m_\phi^2\right)^2} \,.$$

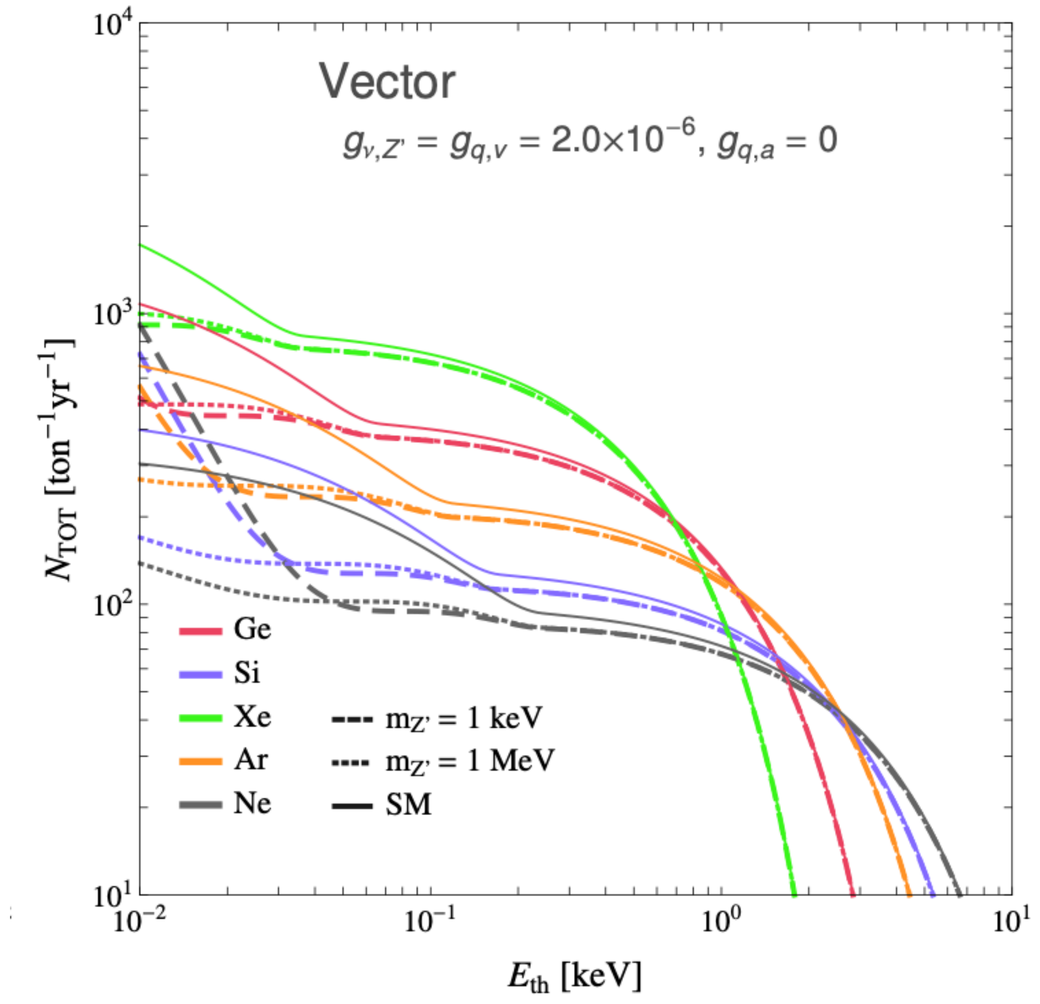
See arXiv : 1604.01025, 2006.11250

Solar neutrinos + new light mediator: recoil spectrum

1604.01025

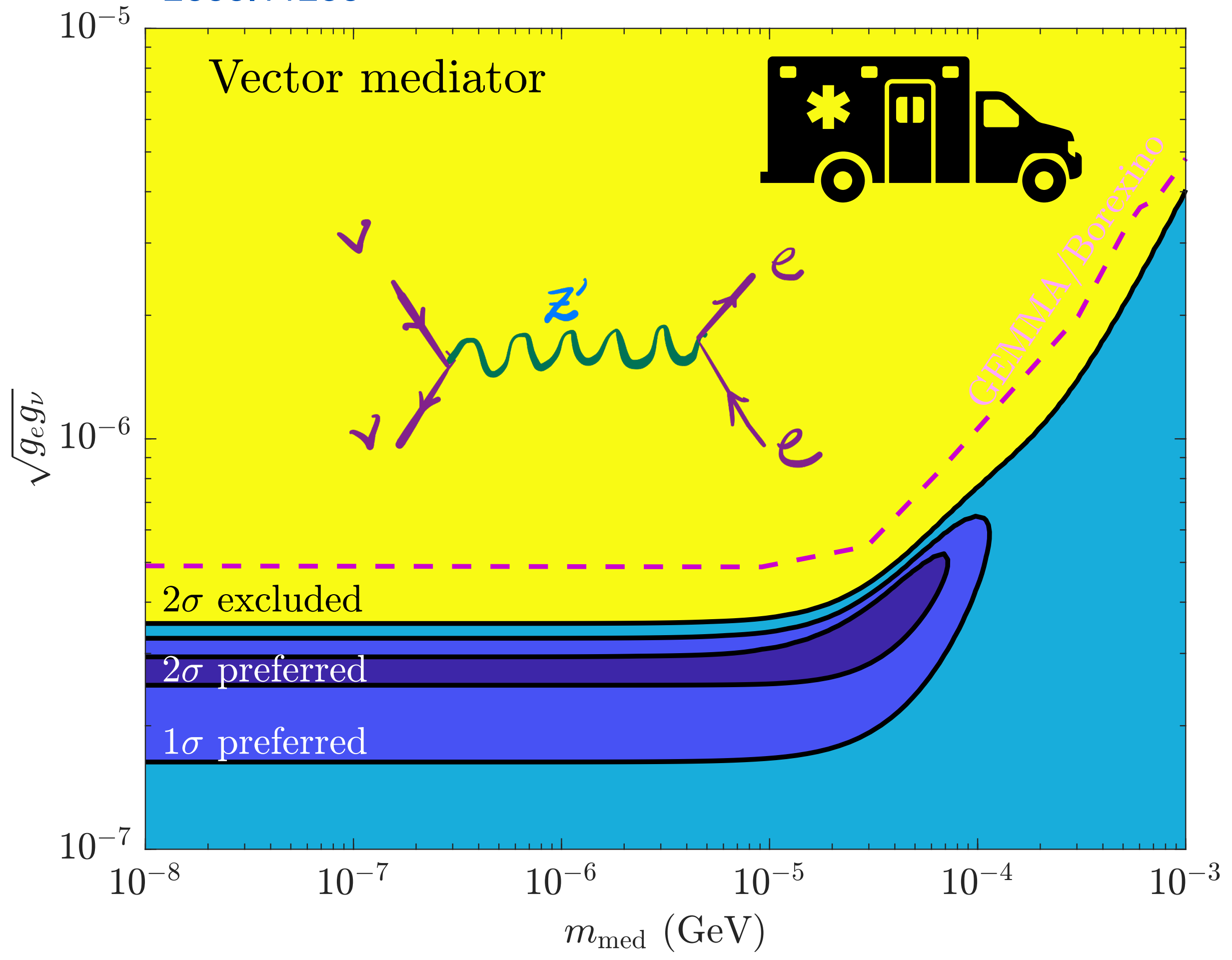


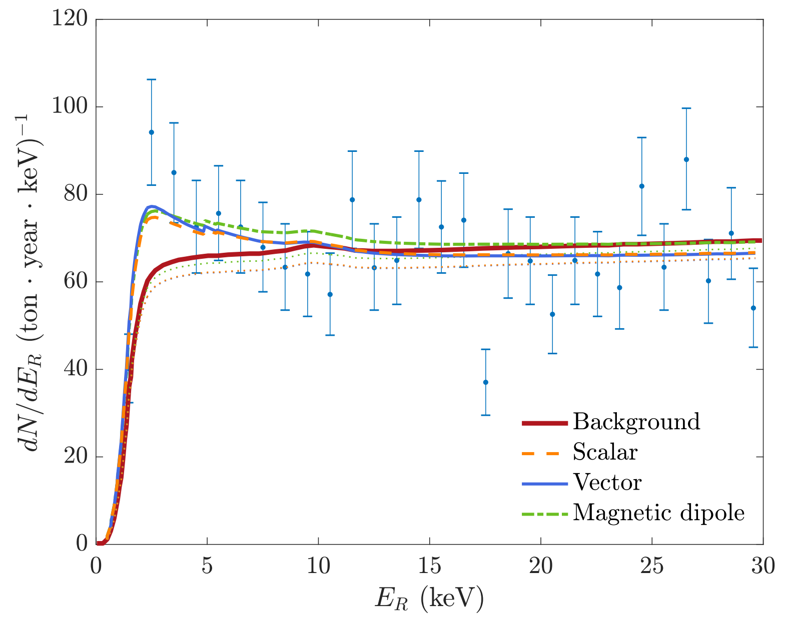
Enhancement at low q



Suppression due to interference with SM

2006.11250





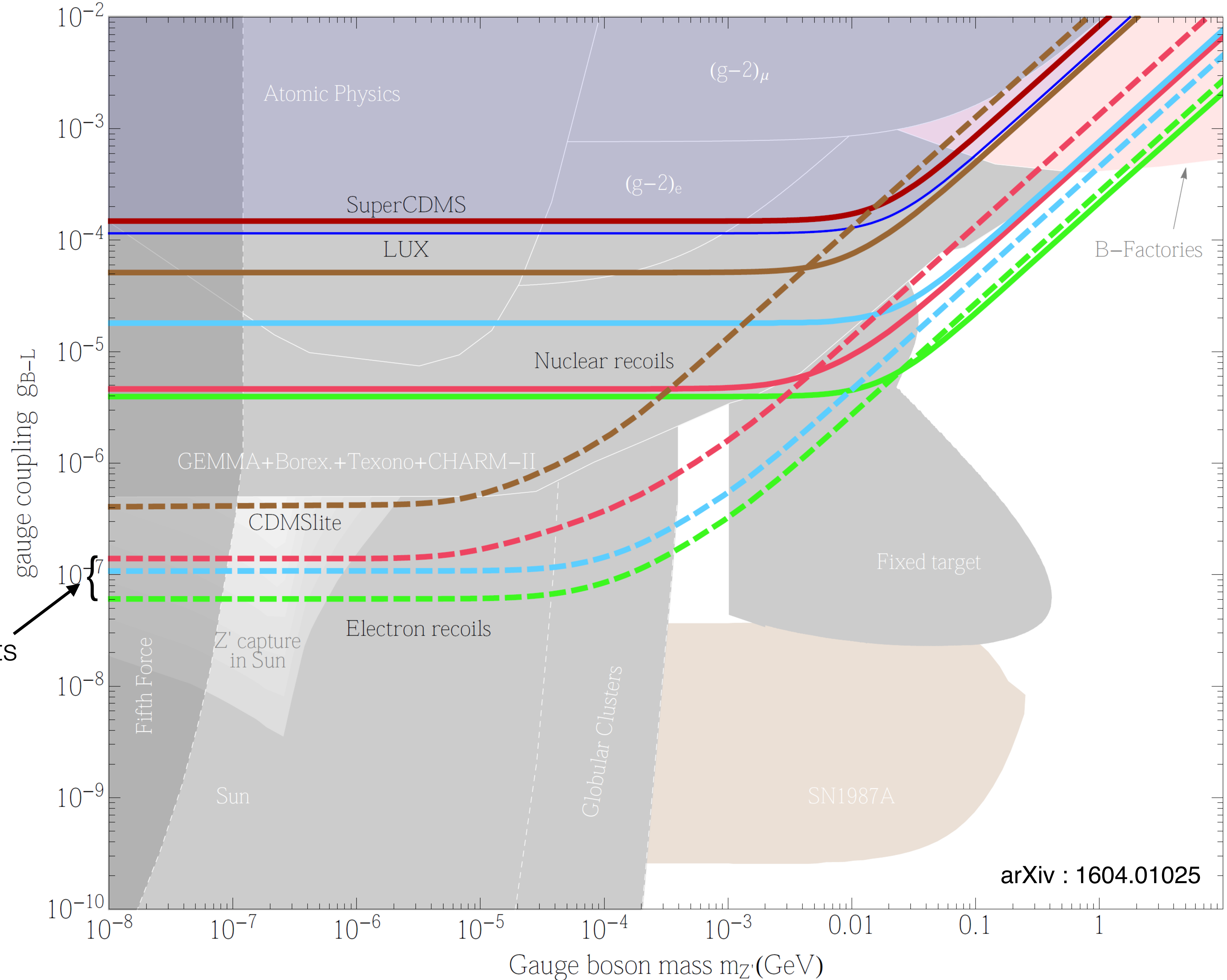
nu-e interactions could have explained the XENON1T excess (which was probably just tritium or something)

Reach of direct detection experiments + other constraints

Solid: scattering with nuclei

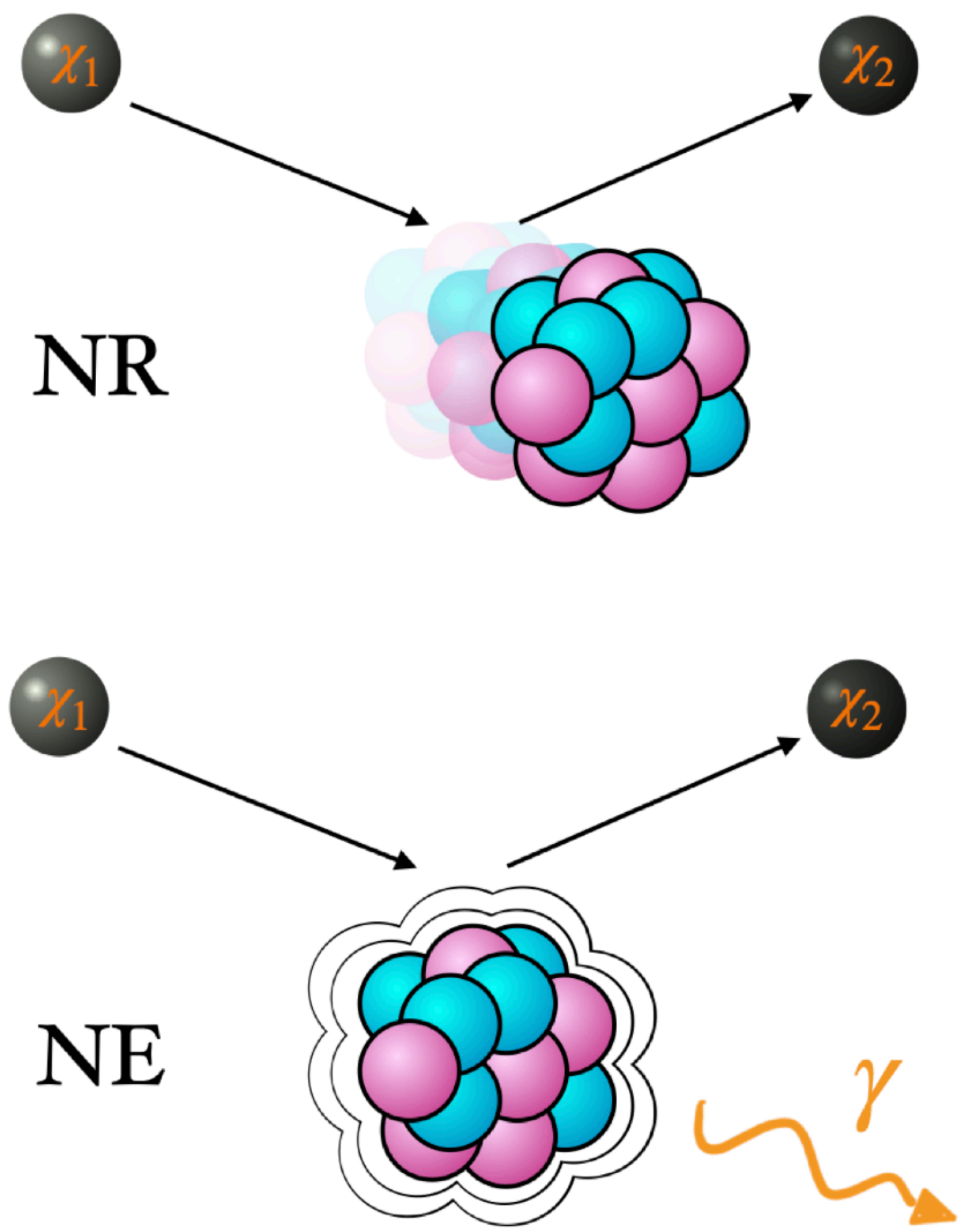
Dashed: scattering with electrons

future experiments



More in the next talk by Audrey!

Paleo-adjacent work: heavy elements



In many heavy elements, there are excited states in the few-keV range that can yield a deexcitation gamma ray

For inelastic dark matter, a heavy target nucleus is necessary to get the required momentum transfer q

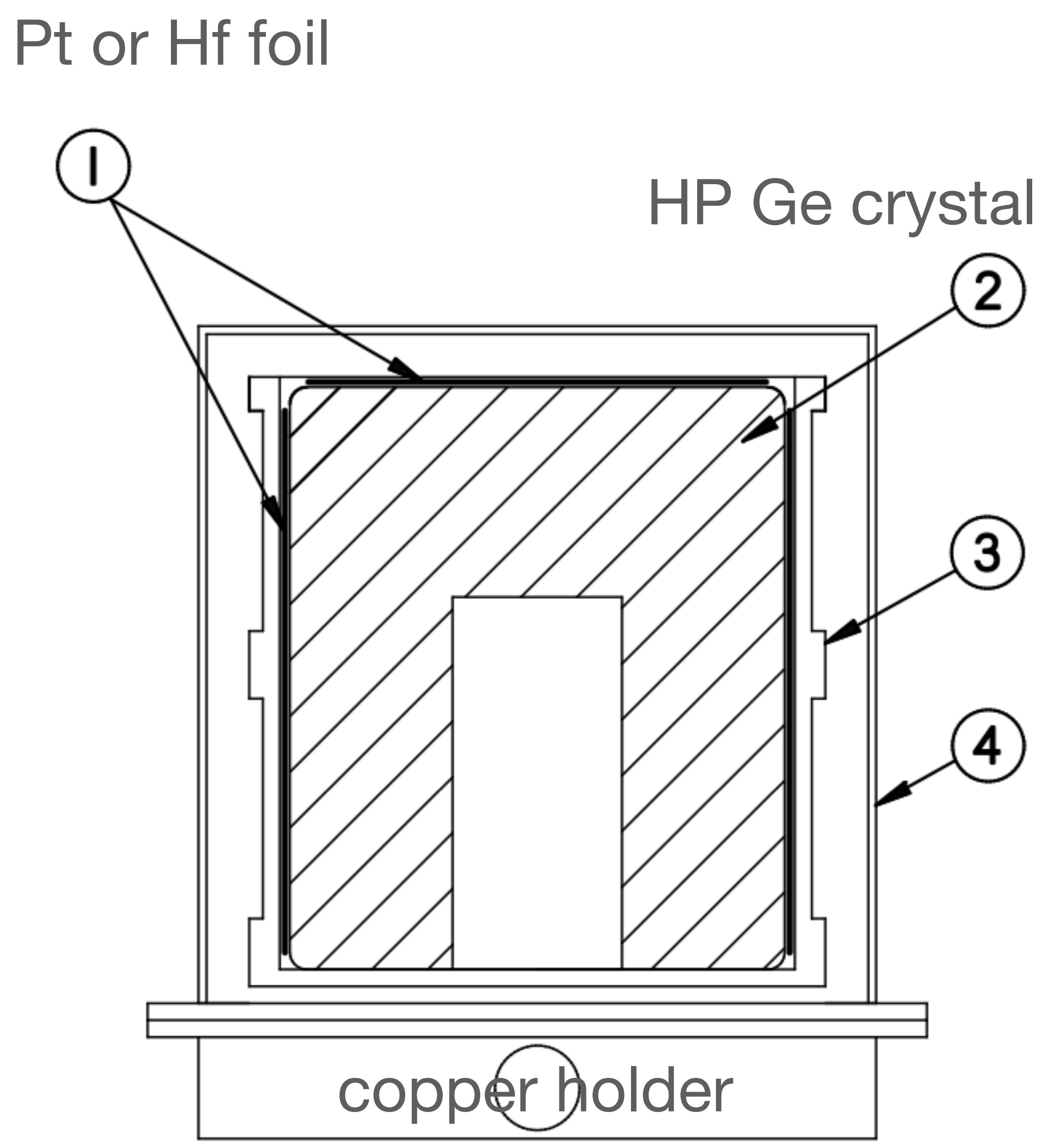
$$v_{\min}(E_R) = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N}{\mu_{\chi N}}E_R + \Delta\right) .$$

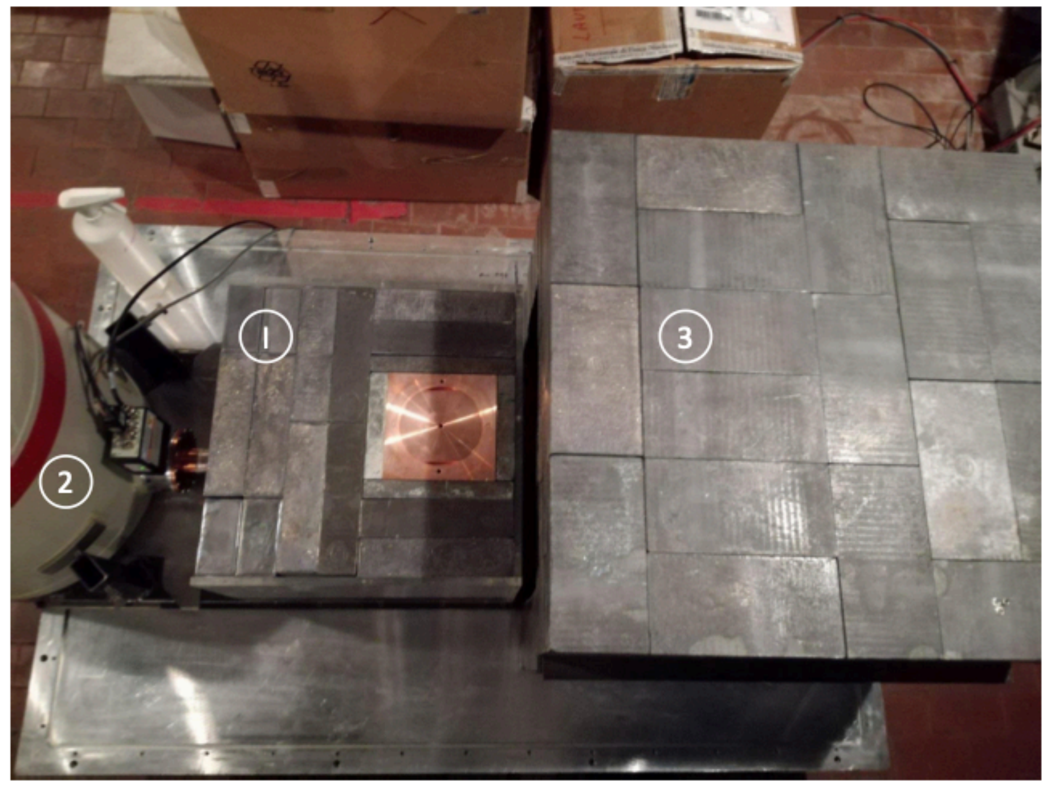
Isotope	Abund.[%]	$J^p_{\text{g.s.}}$	$J^p_{\text{e.s.}}$	ΔE[keV]	B(E2)[$W.u.$]	η[%]	Bkg.[mBq/kg]
^{177}Hf	18.60	$7/2^-$	$9/2^-$	112.9500	282(8) [68]	9.64	0.9
^{178}Hf	27.28	0^+	2^+	93.1803	160(3) [69]	7.37	2.2
^{180}Hf	35.08	0^+	2^+	93.3240	154.8(21) [70]	7.37	2.2
^{189}Os	16.15	$3/2^-$	$1/2^-$	36.17	27(7) [71]	0.695	0.40 (proj.)
		$3/2^-$	$5/2^-$	69.54	100(10) [71]	1.75	0.16
^{201}Hg	13.17	$3/2^-$	$1/2^-$	1.5648	~ 34 [72]	50	0.0056 (proj.)

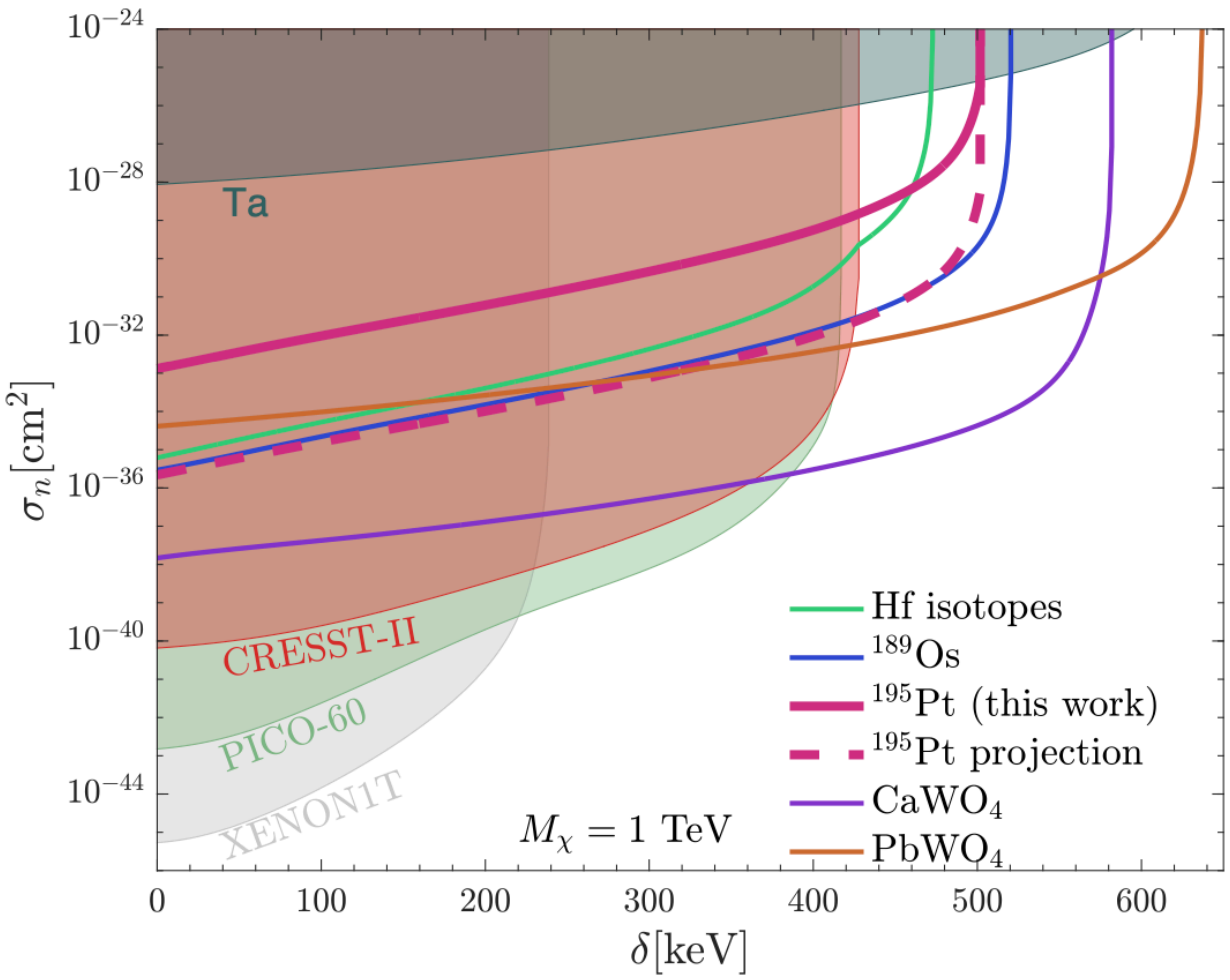
Serge Nagorni

Ningqiang Song

2104.09517







Gamma ray search at LNGS/analysis at Queen's:

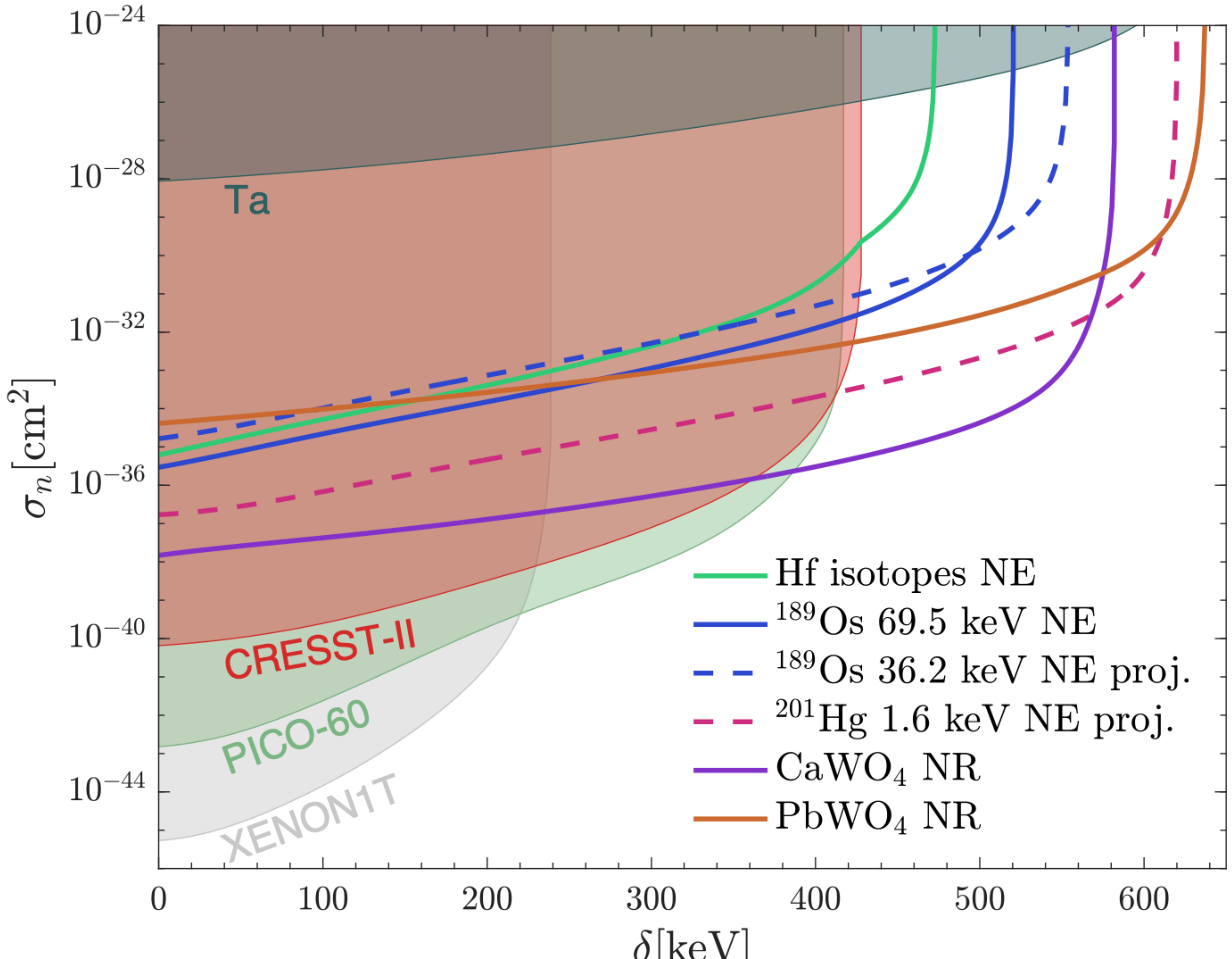
-55 g of Hafnium 2012.08339/Nuc Phys B

-45 g of platinum 2209.11106/Nuc Phys B

-new limits on rare decays

-+ new limits on dark matter-induced excitation

1 TeV inelastic dark matter

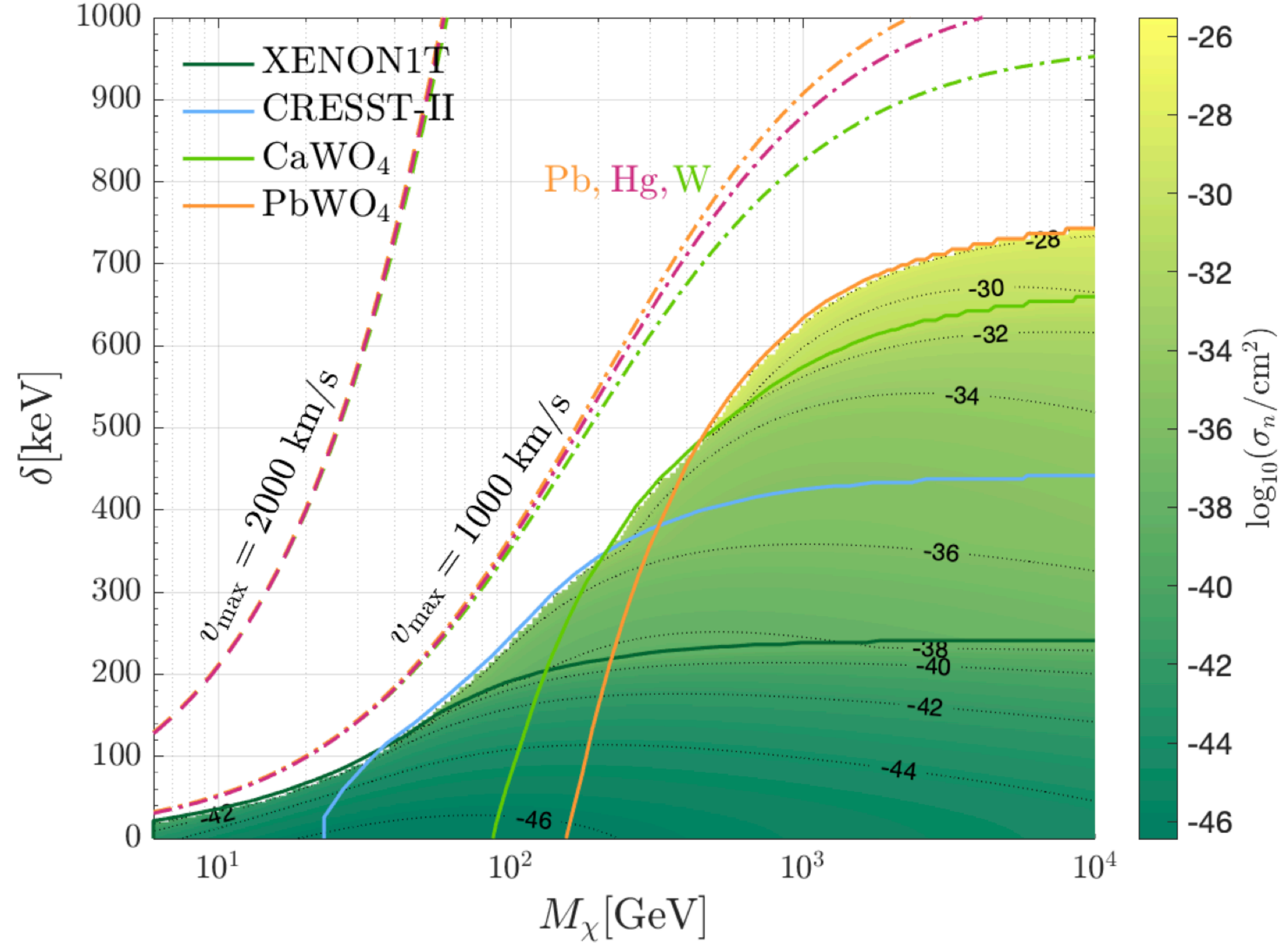


New limits using public calibration data

Pushing the frontier of WIMPy inelastic dark matter: journey to the end of the periodic table

Ningqiang Song,[1,2,3,*] Serge Nagorny,[1,2,†] and Aaron C. Vincent[1,2,3,‡]

2104.09517/PRD



Solid: existing data; dashed: potential reach for cosmic ray-boosted dark matter

Summary

- Ongoing analysis work on samples of olivine & galena
- Ongoing calibration work with 3 MeV proton beam
- Ongoing theory work looking at the WIMP & beyond!