Modeling Interactions of MeV-Scale DM with Crystal Targets: Plasmons, Phonons, and Lattice Defects

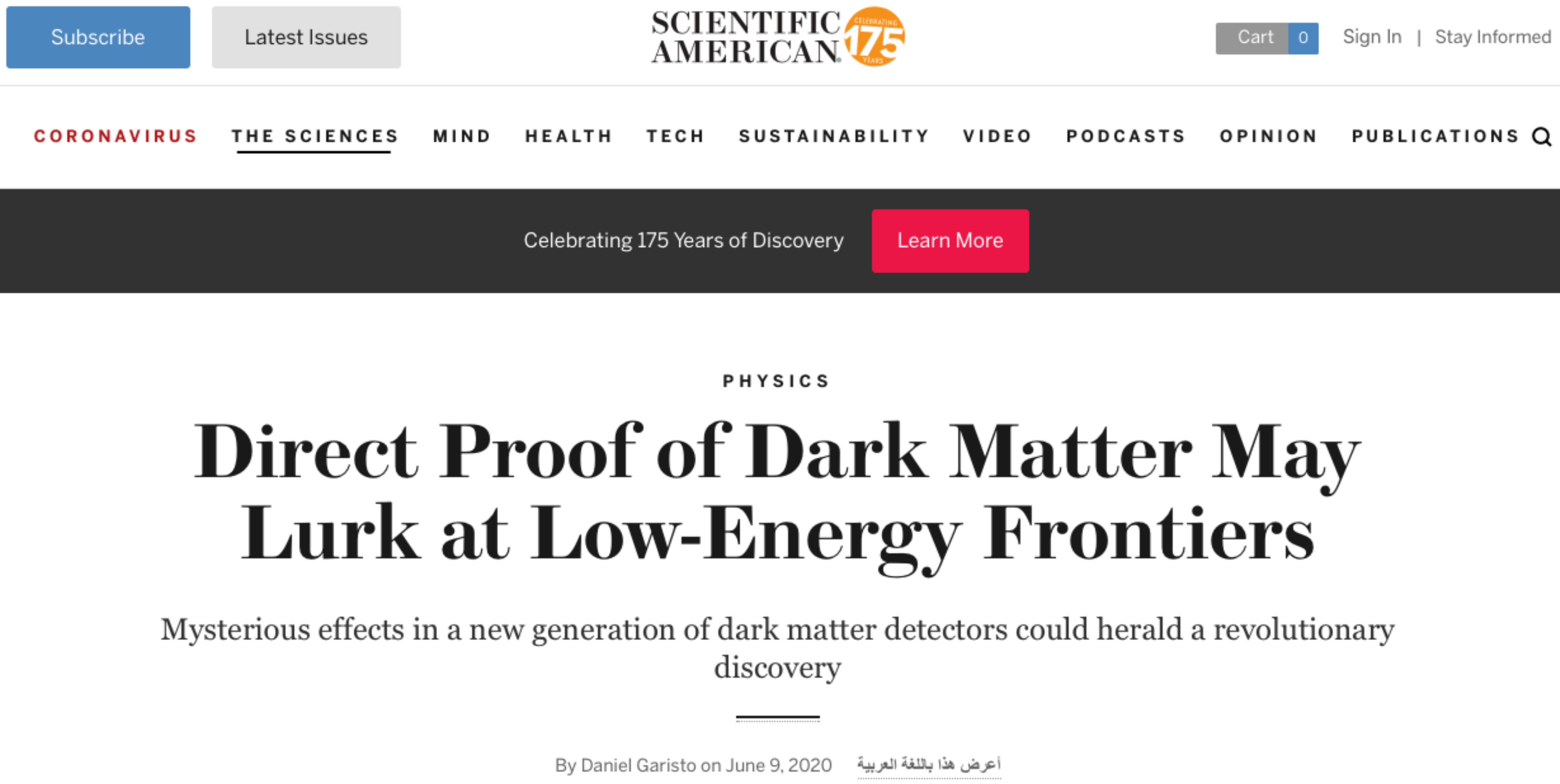
Noah Kurinsky

Physics Seminar, INFN-Roma

March 15, 2021

\+ Dan Baxter, Gordan Krnjaic, Yonatan Kahn arXiv:2002.06937
Phys. Rev. D 102, 015017 (2020)

Featured in Scientific American



PHYSICS

Direct Proof of Dark Matter May Lurk at Low-Energy Frontiers

Mysterious effects in a new generation of dark matter detectors could herald a revolutionary discovery

By Daniel Garisto on June 9, 2020 أعرض هذا باللغة العربية

Searching for Dark Matter in the Inelastic Regime

Daniel Baxter

HEP Seminar

University of California, Santa Barbara

September 28, 2020

THE UNIVERSITY OF CHICAGO

Photo Credit: Getty Images

Overview

- Kinematics of Sub-GeV DM

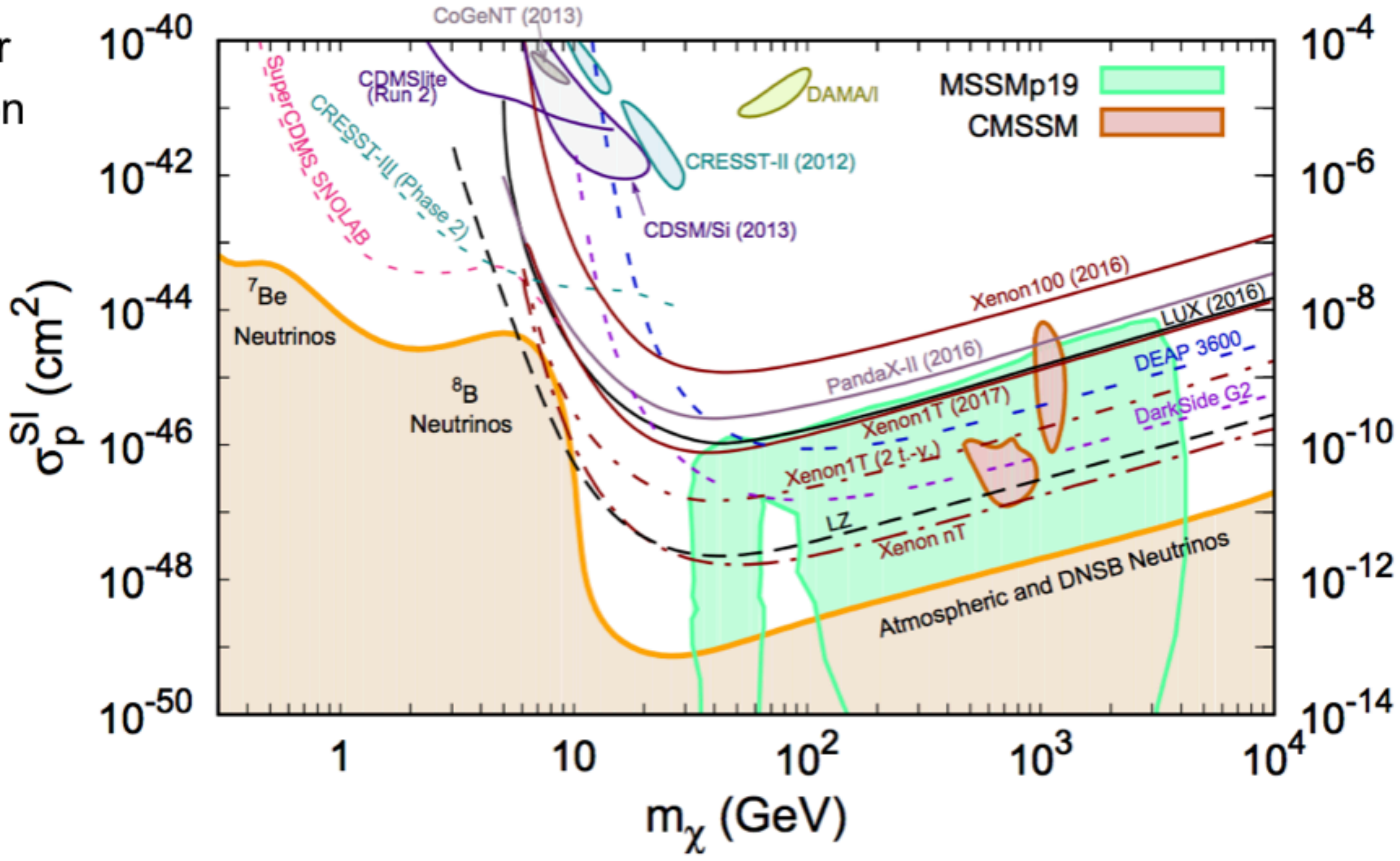
- Current Constraints
  - ER Searches
  - NR Searches
  - Summary of Excesses

- Modeling Excesses
  - Yield comparison
  - Elimination of SM Processes
  - Brief plasmon description

- Possible DM Interpretations

What Drives Low-Mass Detector Reach?

- Dark matter mass determines two quantities: local dark matter number density and recoil energy distribution
  - Mass density set by astrophysical constraints
- For low mass, sensitivity is limited by your energy threshold; lighter particles will transfer less energy to your target, and heavier nuclei will further suppress this transfer
- For high mass, increasing mass decreases number density; heavier target provides larger cross-section and therefore more exposure



$$\Delta E = \frac{m_T}{2}\left(\frac{m_\chi v_\chi}{(m_\chi + m_T)}\right)^2 \sim \frac{m_\chi^2 v_\chi^2}{2m_T} \quad (m_\chi << m_T)$$

$$\sim \frac{m_T v_\chi^2}{2} \quad (m_\chi >> m_T)$$

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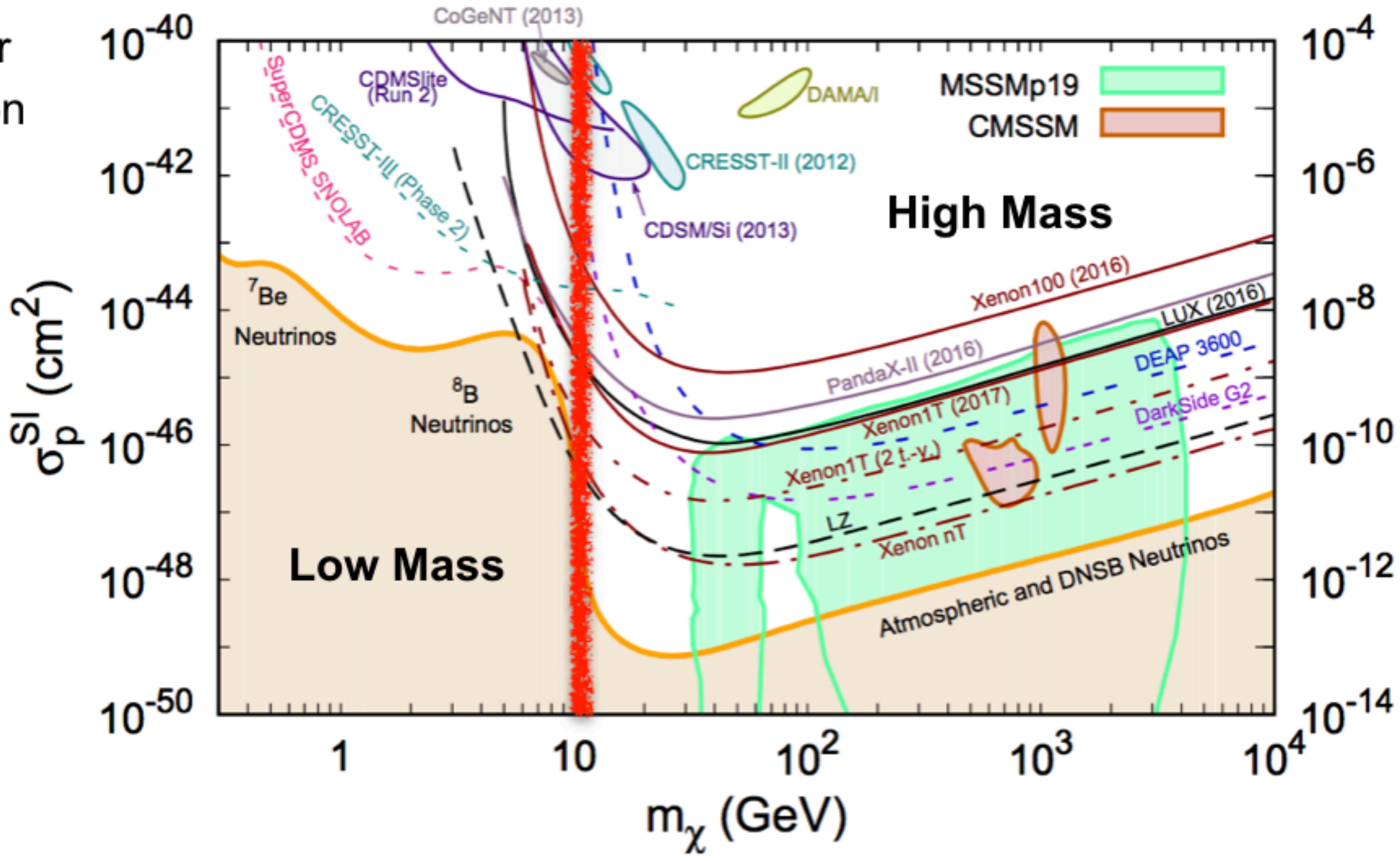
- Low mass detectors can be small, as long as they have low energy thresholds!



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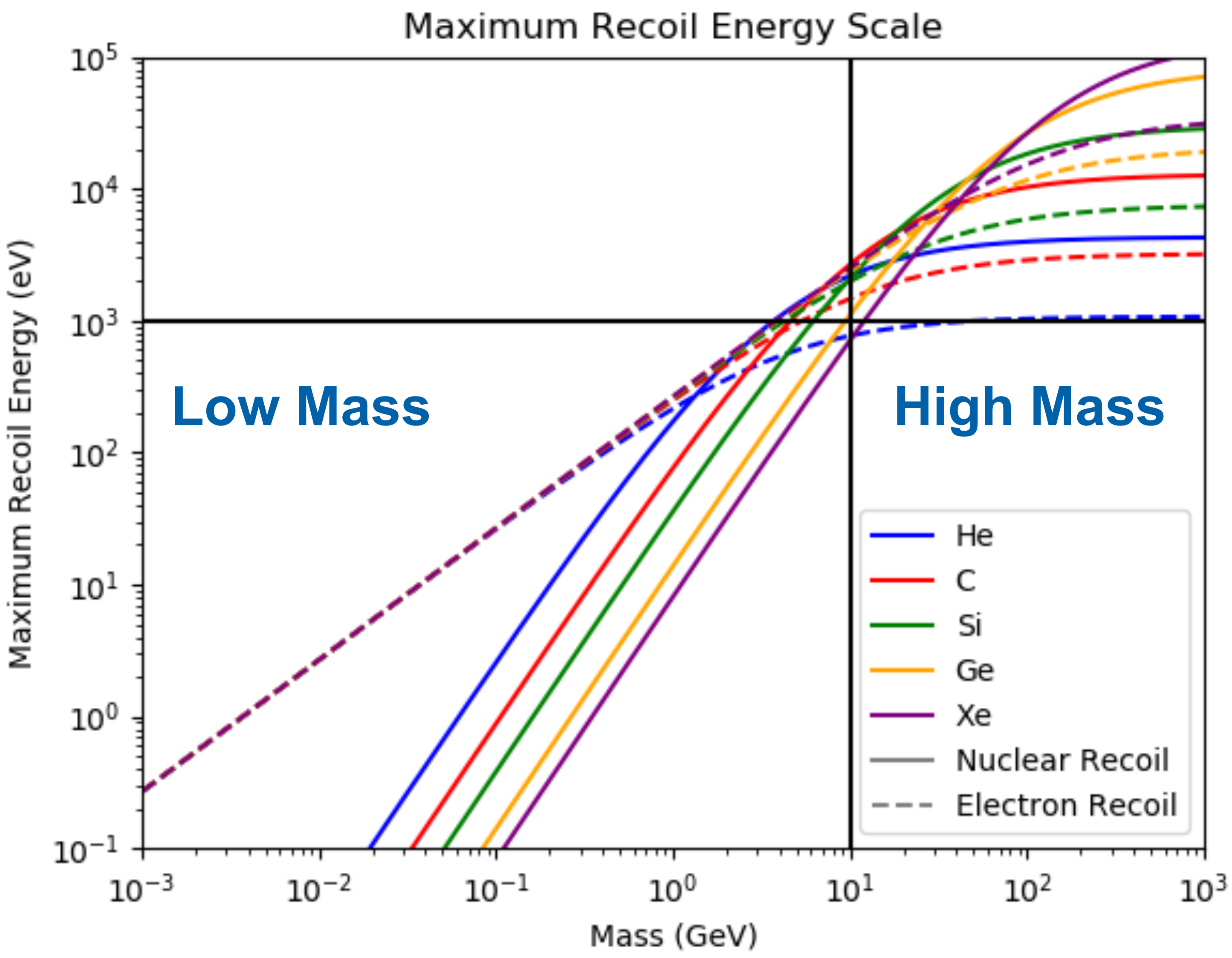
Collision Kinematics

- Recoil energy for typical DM velocity depends on target mass and recoil type
- Electron and nuclear recoils have different kinematics; nuclear recoils are simple elastic collisions, electron recoils are largely inelastic and depend on electron orbital and kinematics within the bound electron-atom system
- In addition to momentum transfer for a fixed velocity, using a velocity and angular distribution yields an expected energy spectrum



$$m_{\chi,NR} \geq \frac{\sqrt{2m_T\sigma_E}}{v}$$

$$m_{\chi,ER} \geq \frac{2\sigma_E}{v^2}$$

$$\Delta E_{NR} \leq \frac{1}{2m_N}q_{max}^2 = \frac{m_N v^2}{2}\left(\frac{2m_\chi}{m_\chi + m_N}\right)^2$$

$$\Delta E_{ER} \leq \frac{1}{2}\mu_{N\chi}v^2 = \frac{m_N v^2}{2}\left(\frac{m_\chi}{m_\chi + m_N}\right)$$

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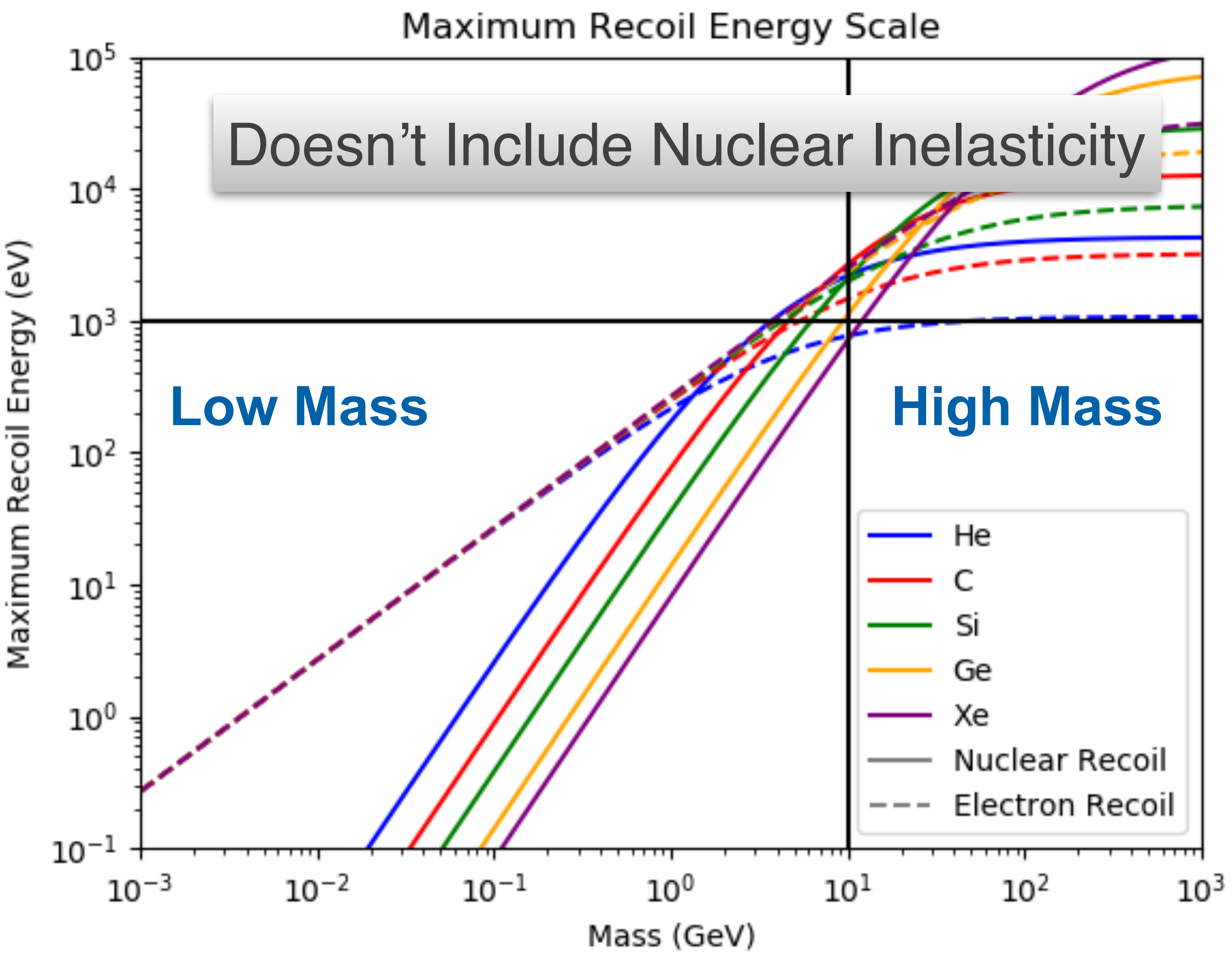

Doesn’t Include Nuclear Inelasticity

$$\Delta E_{NR} \leq \frac{1}{2m_N} q_{max}^2 = \frac{m_N v^2}{2} \left(\frac{2m_\chi}{m_\chi + m_N} \right)^2$$

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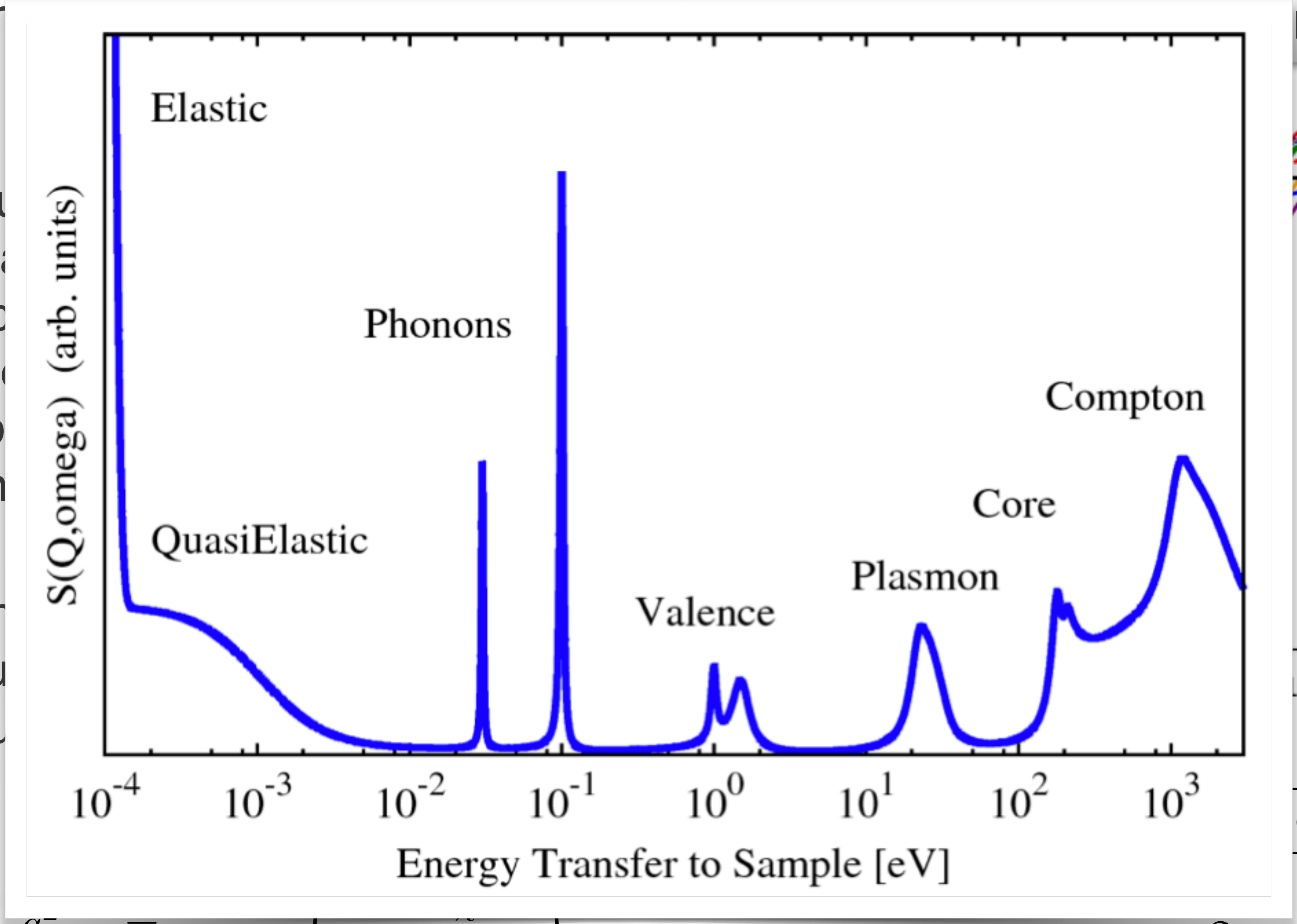
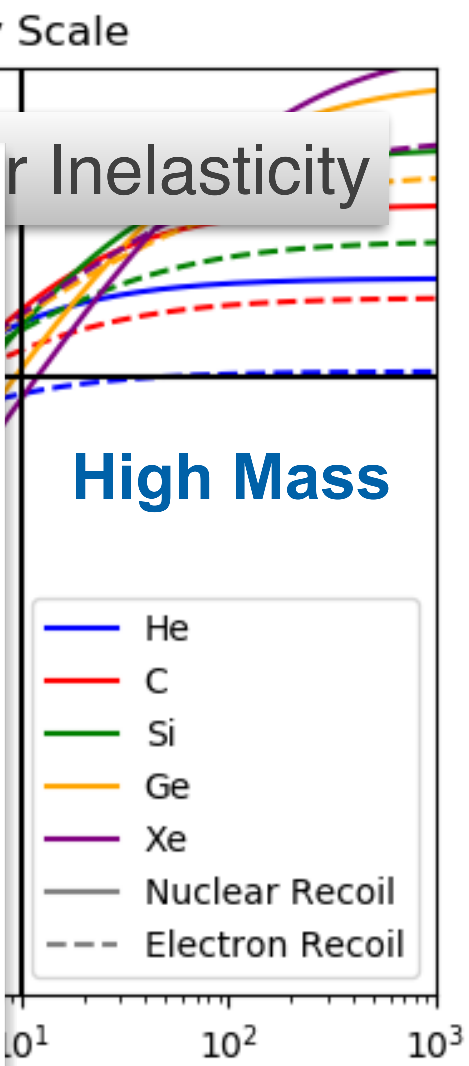




r Inelasticity

High Mass

$$\sigma_E$$

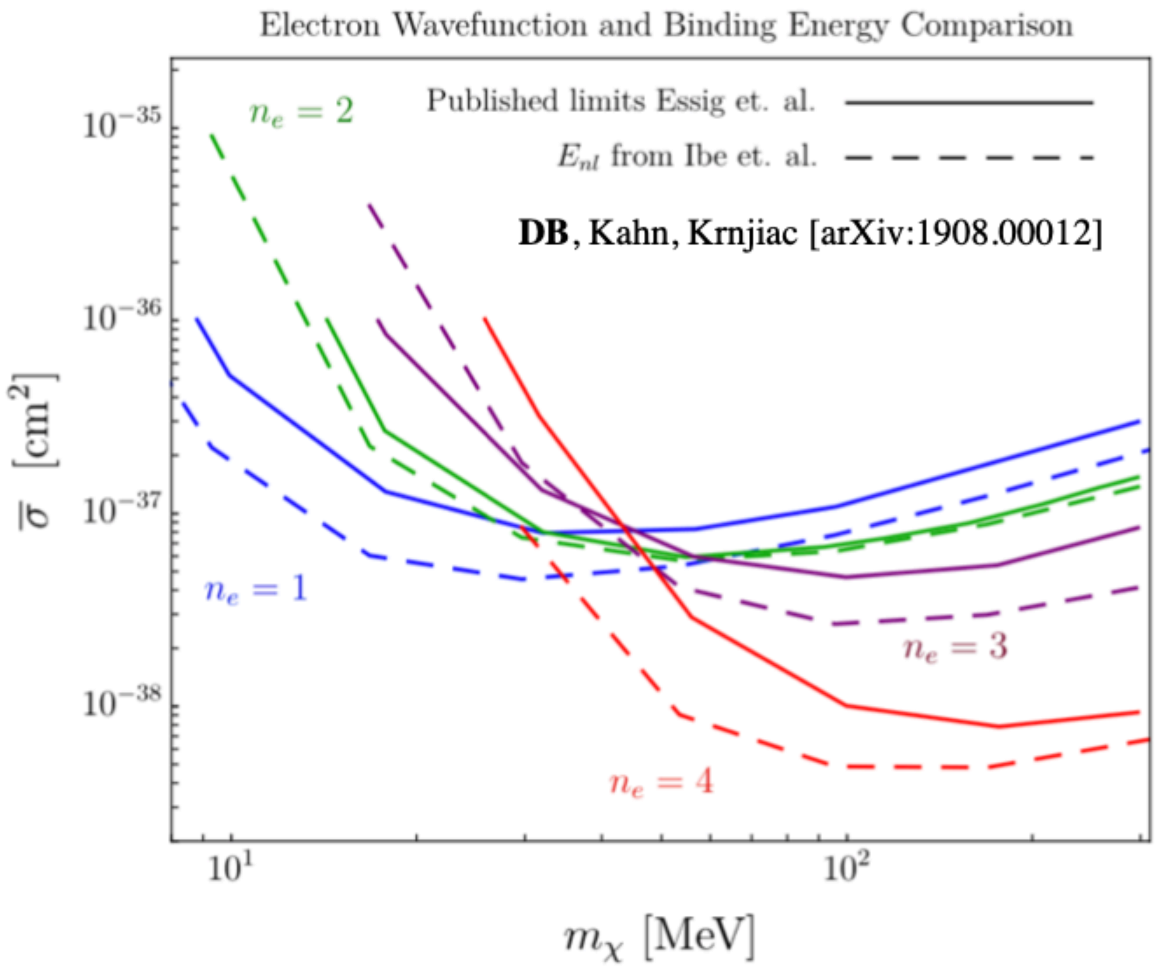
$$\Delta E_{NR} \leq \frac{1}{2m_N} q_{max} = \frac{\quad}{2}\left(\frac{\quad}{m_\chi + m_N}\right)$$

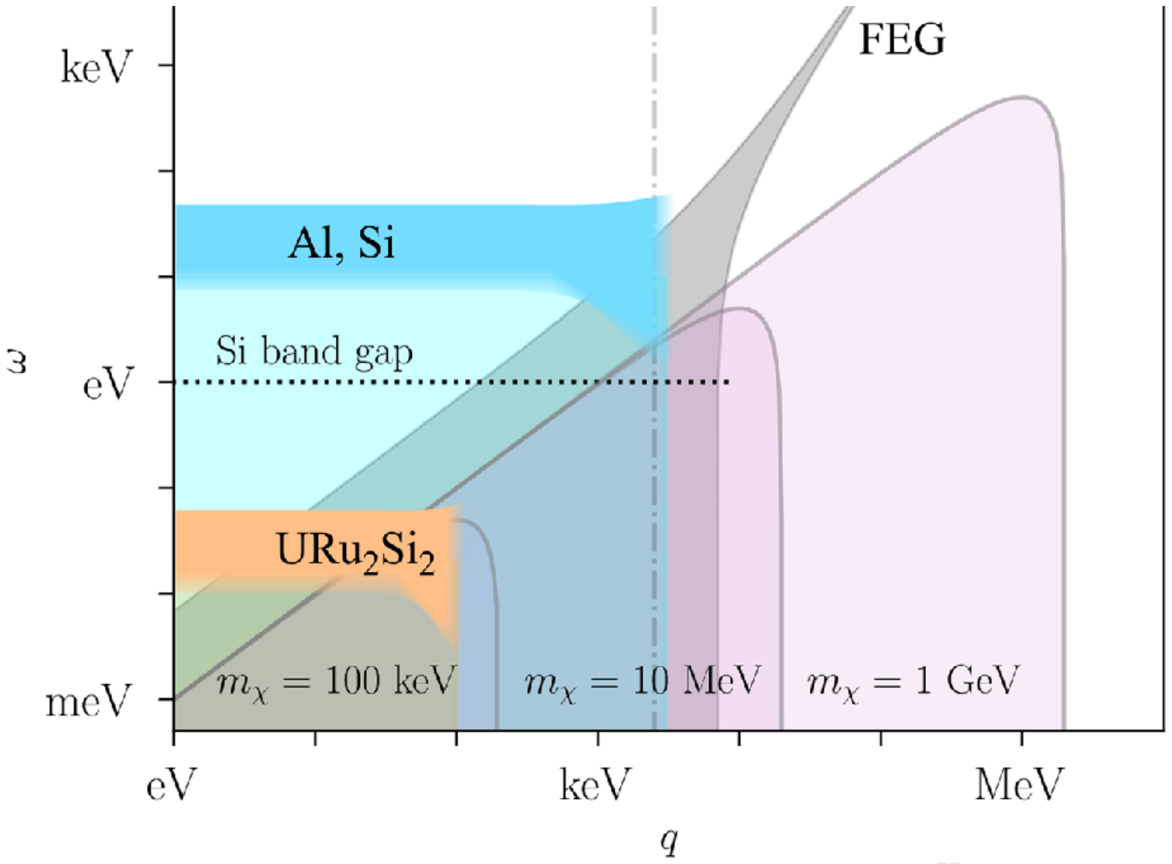
$$\Delta E_{ER} \leq \frac{1}{2}\mu_{N\chi} v^2 = \frac{m_N v^2}{2}\left(\frac{m_\chi}{m_\chi + m_N}\right)$$

$$m_{\chi,ER} \geq \frac{2\sigma_E}{v^2}$$

Revised DM Kinematics

- Free-particle regime (DM KE > keV):
  - DM interactions probe core electrons
  - DM will liberate nuclei with energies > 1keV),
  - Interaction can be treated pseudo-classically
- Bound-particle regime (DM KE < eV)
  - Electron interactions frozen out
  - Lattice defects can't be created
  - Only relevant processes are phonon creation in solid-state materials
- Collective Regime (DM KE > eV, < keV)
  - Corresponds to the MeV - GeV mass regime
  - Energy depositions *comparable to inelastic energy scales*
  - Detailed band structure important for electron recoils
  - Liberation of free nucleon from the lattice *not guaranteed*; energy loss mechanisms important





Berggren, Hochberg, Kahn, **NK**, Lehman, Yu, ArXiv:2101.08263

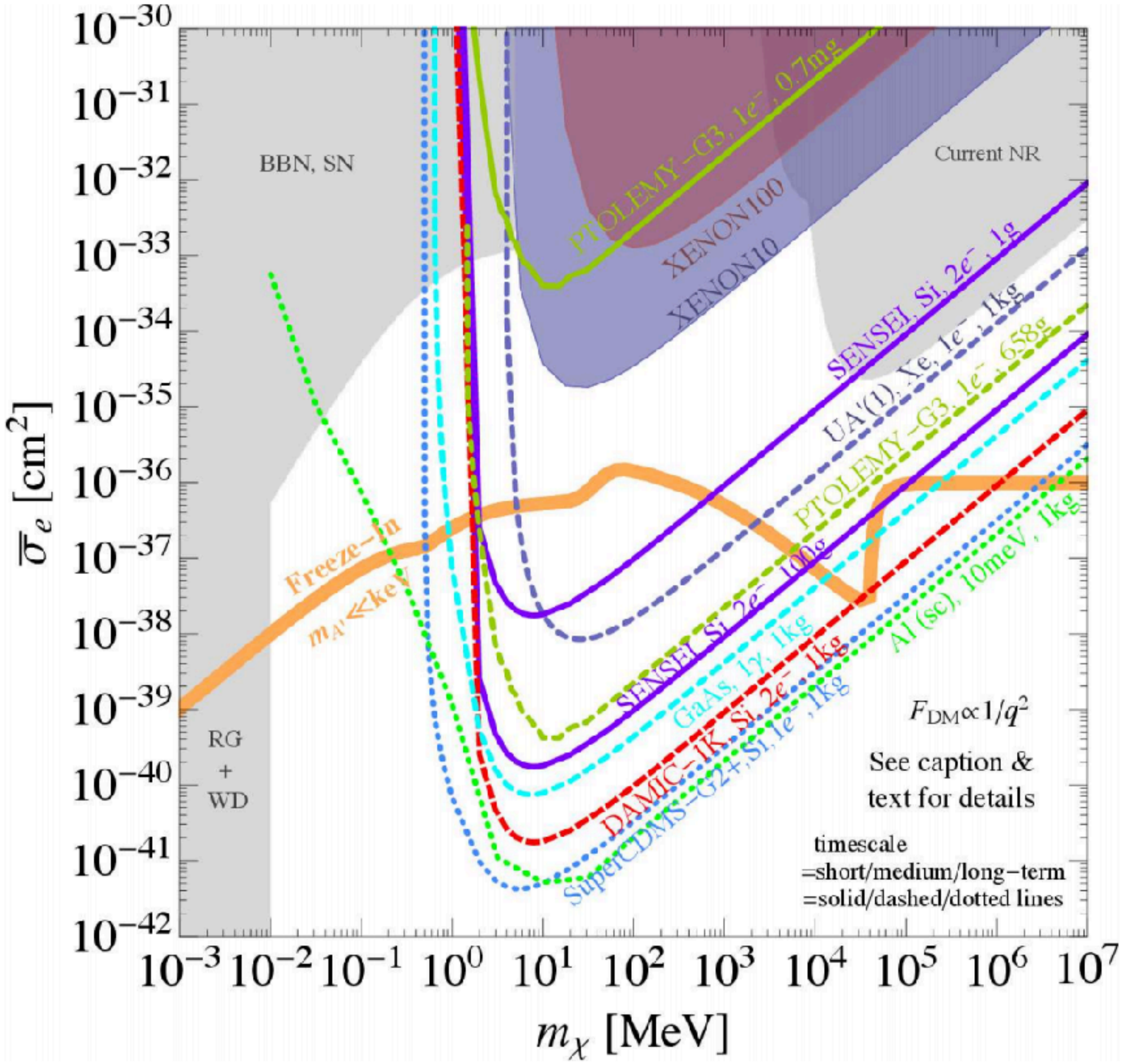
Low Mass (< GeV) Dark Matter

- Dark matter in the keV-GeV mass range can produce the correct DM relic density if we introduce a new mediator between the DM and SM

- Consider a massive 'dark photon' mediator coupled to a heavy particle which does not interact with SM as the only particles in a new 'dark sector'
  - If the mediator is heavier, dark matter can freeze out for the right coupling strengths in the same way as WIMP DM
  - If the dark photon is the lighter particle, it can 'freeze in' as the 'heavy' DM decays into dark photons and SM particles

- Much of the simplest parameter space completely unconstrained in the freeze-in scenario due to the momentum suppression

- Lots of theory work done on these models in the last few years and multiple workshop reports



$$\langle \sigma_A v \rangle \propto \frac{g_D^4}{m_\chi^2}$$

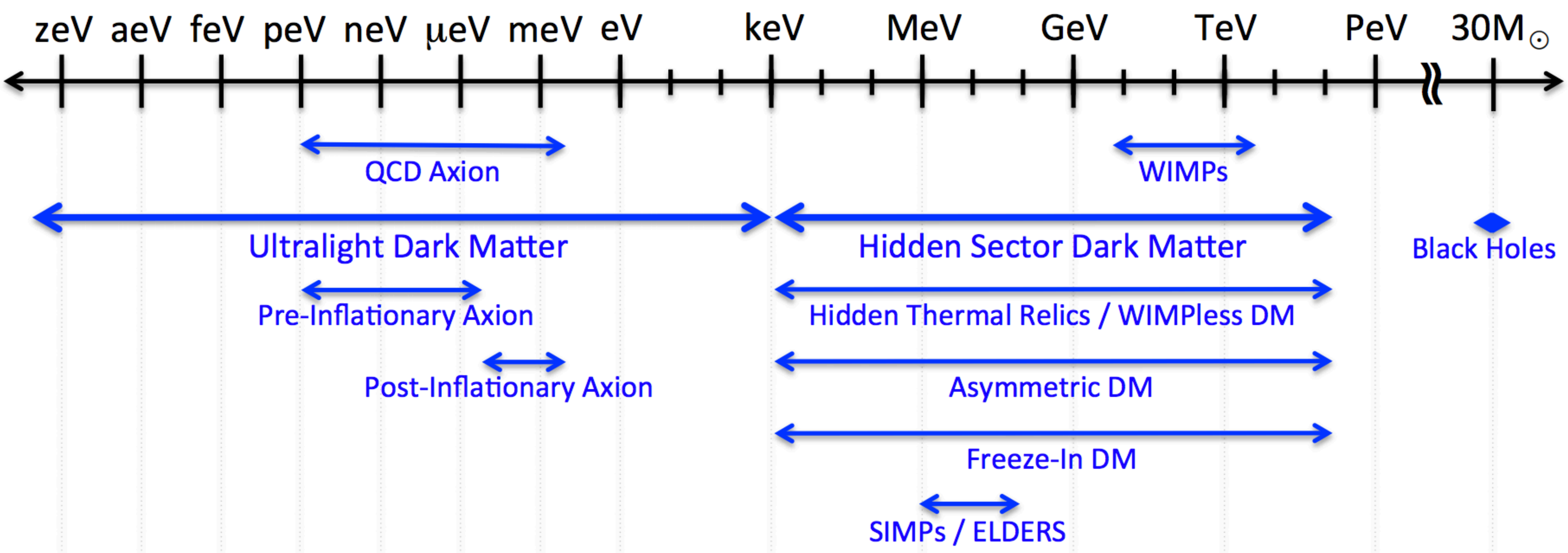
Secluded

$$\langle \sigma_A v \rangle \propto \frac{g_D^2 g_{SM}^2 m_\chi^2}{m_{med}^4}$$

Direct

DM Search Strategies

Dark Sector Candidates, Anomalies, and Search Techniques



zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M$_\odot$

QCD Axion

WIMPs

Ultralight Dark Matter

Hidden Sector Dark Matter

Black Holes

Pre-Inflationary Axion

Hidden Thermal Relics / WIMPless DM

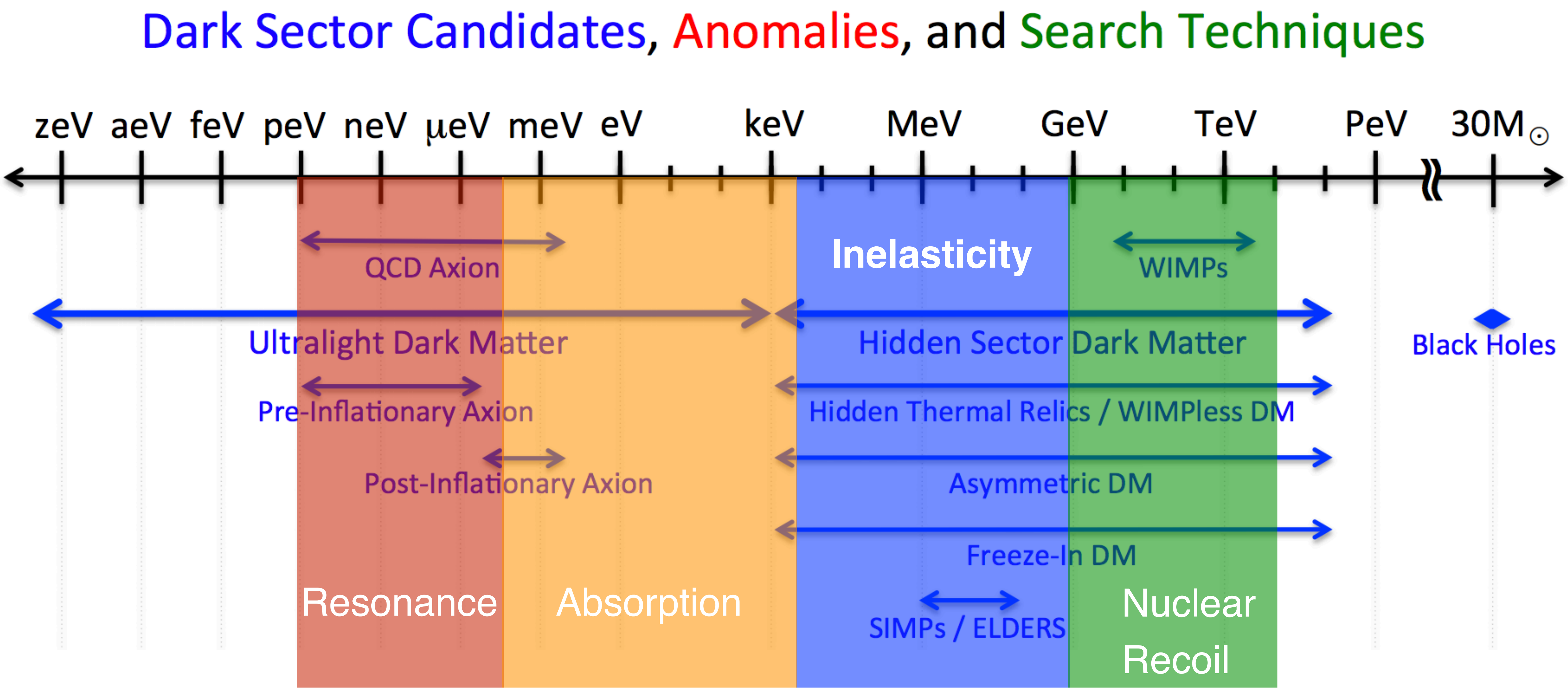
Post-Inflationary Axion

Asymmetric DM

Freeze-In DM

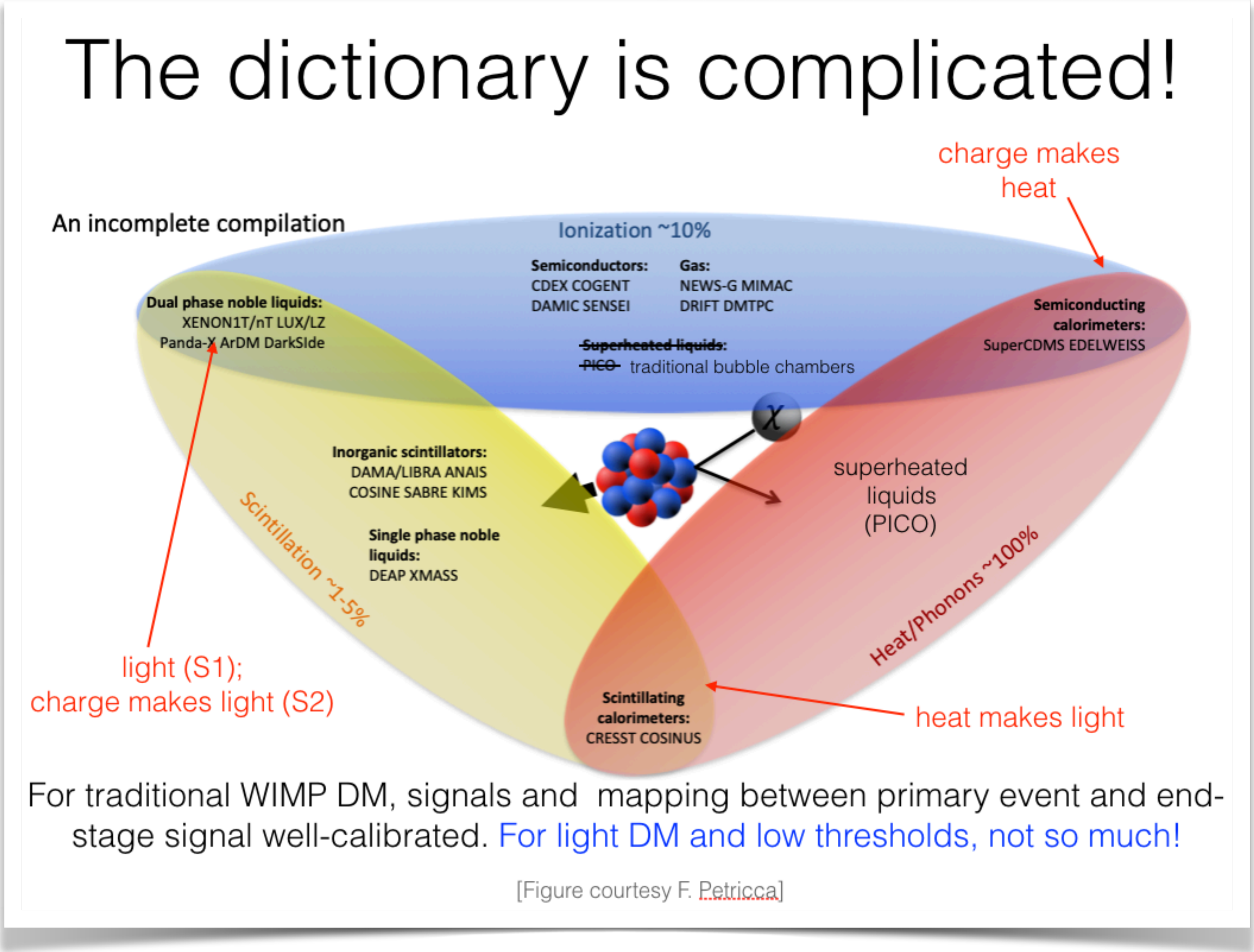
SIMPs / ELDERS

DM Search Strategies



- New mass ranges considered in dark-sector DM interactions are also where understanding material inelasticity becomes most important!

Detecting DM Recoils



The dictionary is complicated!

An incomplete compilation

Ionization ~10%

Semiconductors:
CDEX COGENT
DAMIC SENSEI

Gas:
NEWS-G MIMAC
DRIFT DMTPC

~~**Superheated liquids:**~~
~~PICO~~ traditional bubble chambers

Dual phase noble liquids:
XENON1T/nT LUX/LZ
Panda-X ArDM DarkSIde

Semiconducting calorimeters:
SuperCDMS EDELWEISS

charge makes heat

Inorganic scintillators:
DAMA/LIBRA ANAIS
COSINE SABRE KIMS

Single phase noble liquids:
DEAP XMASS

χ

superheated liquids (PICO)

Scintillation ~1-5%

Heat/Phonons ~100%

light (S1);
charge makes light (S2)

Scintillating calorimeters:
CRESST COSINUS

heat makes light

For traditional WIMP DM, signals and mapping between primary event and end-stage signal well-calibrated. For light DM and low thresholds, not so much!

[Figure courtesy F. Petricca]

Figure from Yonatan Kahn

High Resolution CCDs: DAMIC, SENSEI, DANAE*

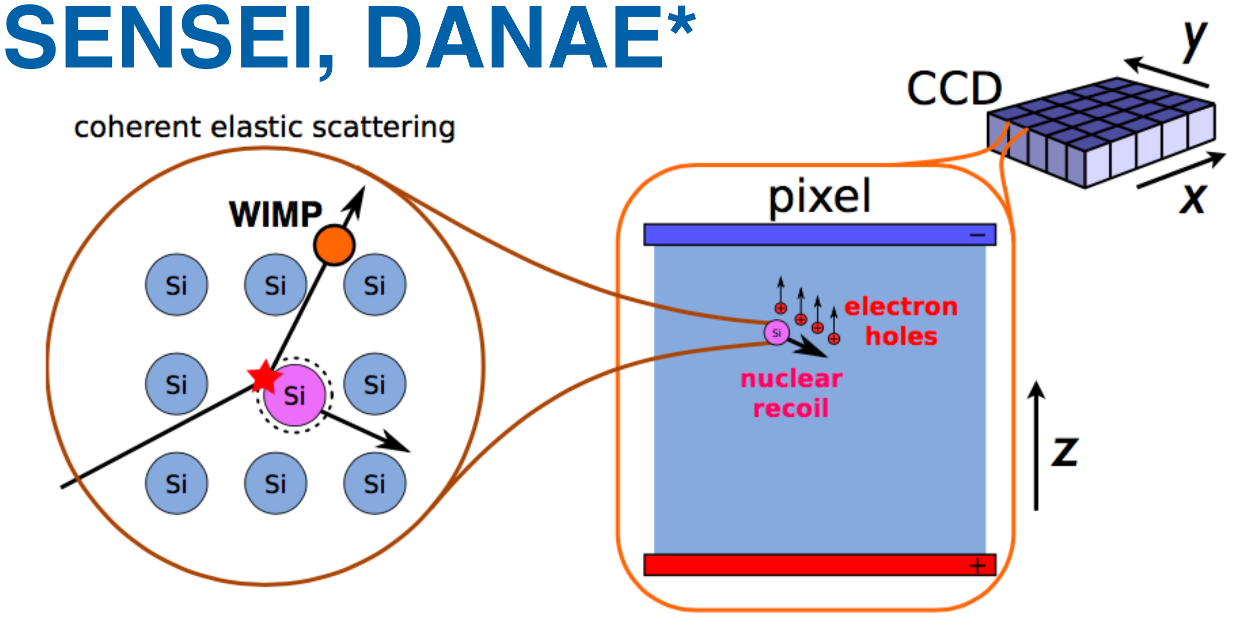
- Electron and nuclear recoils produce electron-hole pairs in Si, which are stored in pixels during the exposure

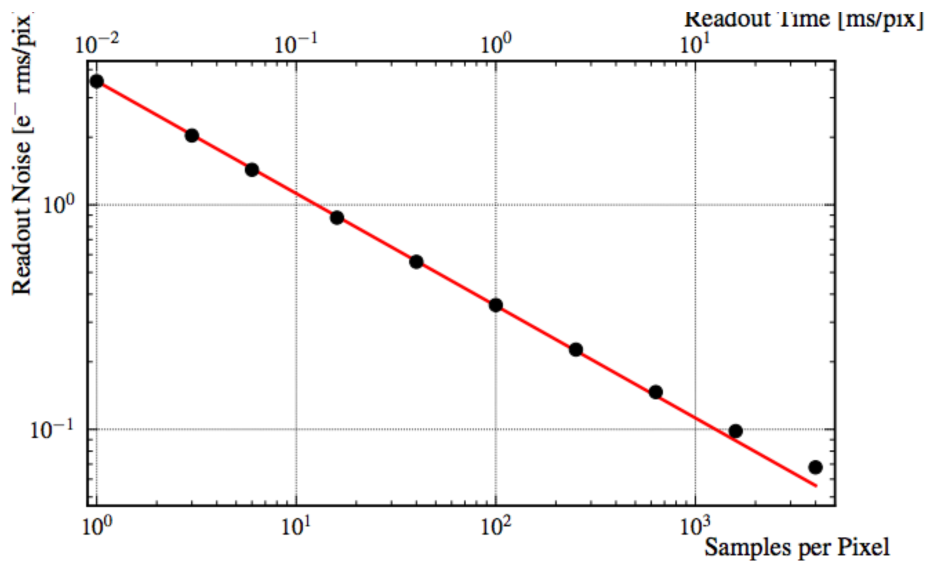
- Charges moved to set of charge amplifiers during readout
  - Single read noise limited by charge amplifier and electronics noise
  - Skipper CDDs capable of non-destructive read; can re-sample the same pixel and arbitrary number of times

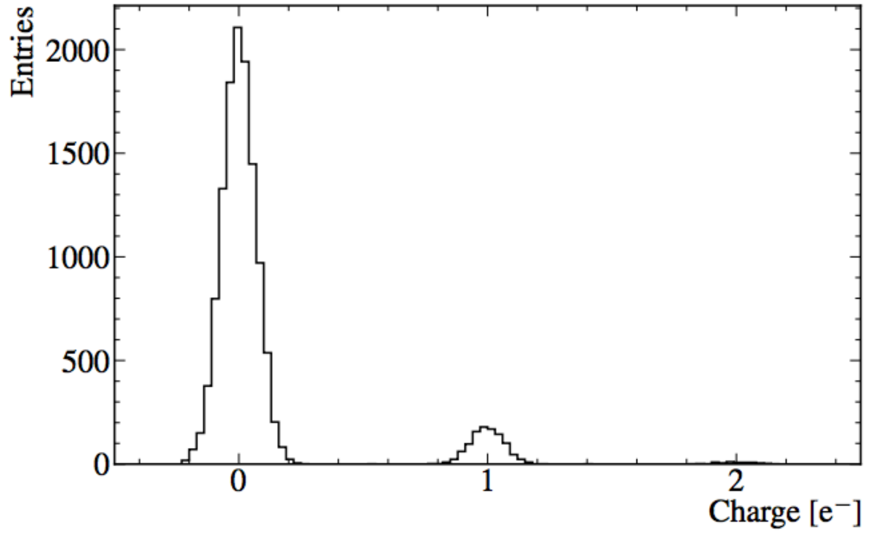
- Arbitrarily low resolution (in ideal case) at the expense of readout time. Very large dynamic range, excellent position resolution and event tracking

- No differentiation between paired and unpaired charge carrriers; operation at ~100K ensures some thermally generated carriers

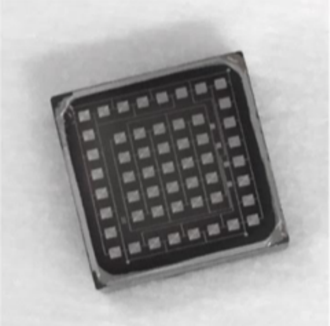
Tiffenberg et. al. 2017 (arXiv:1706.00028)







Athermal Phonon Sensors (SuperCDMS, EDELWEISS)

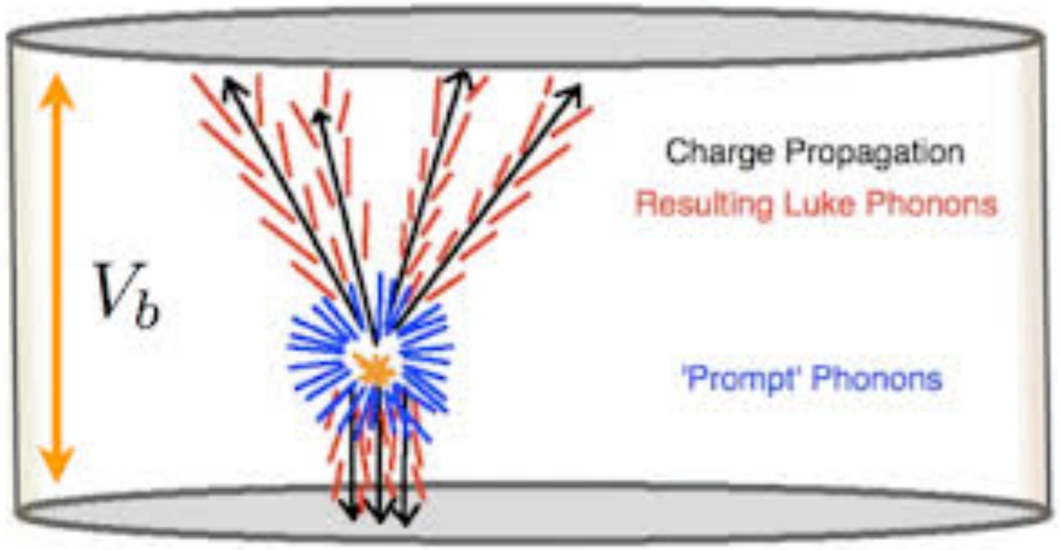


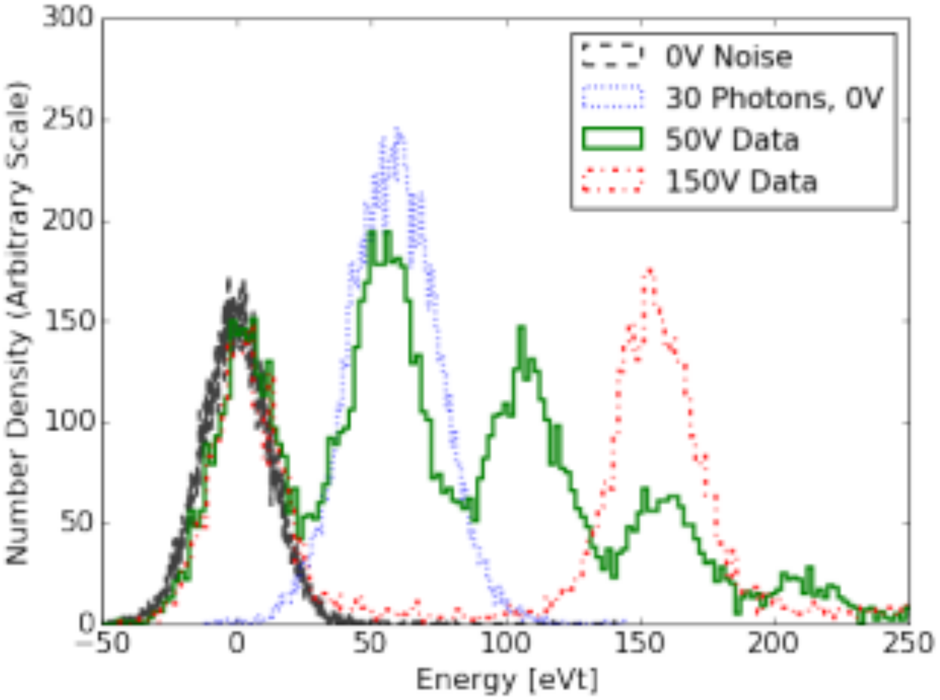
- In any recoil event, all energy eventually returns to the phonon system
  - Prompt phonons produced by interaction with nuclei
  - Indirect-gap phonons produced by charge carriers reaching band minima
  - Recombination phonons produced when charge carriers drop back below the band-gap
- Phonons are also produced when charges are drifted in an electric field; makes sense by energy conservation alone
- Total phonon energy is initial recoil energy plus Luke phonon energy, as shown at right

$$E_{phonon} = E_{recoil} + V * n_{eh}$$

$$= E_{recoil}\left[1 + V * \left(\frac{y(E_{recoil})}{\varepsilon_{eh}}\right)\right]$$

- Athermal phonons collected in superconducting aluminum fins and channeled into Tungsten TES, effectively decoupling crystal heat capacity from calorimeter (TES) heat capacity

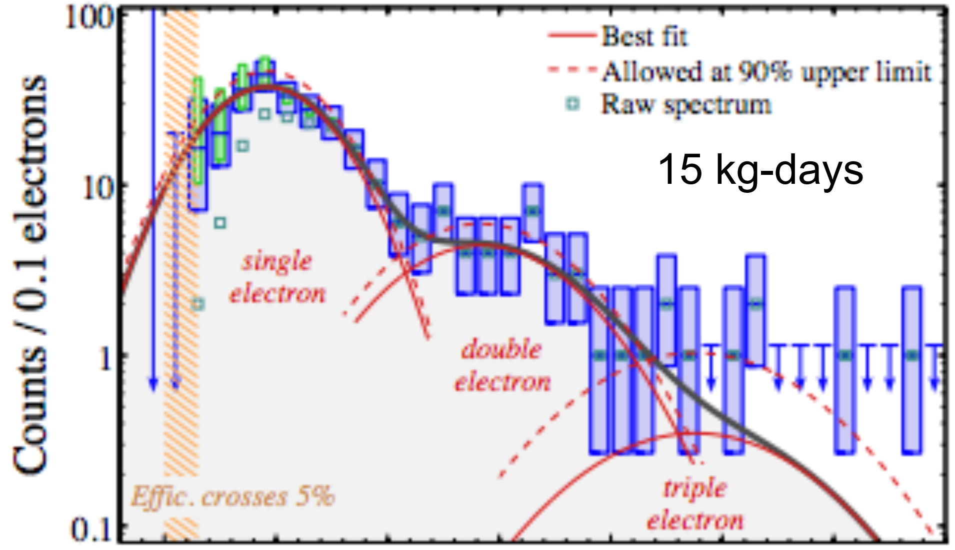


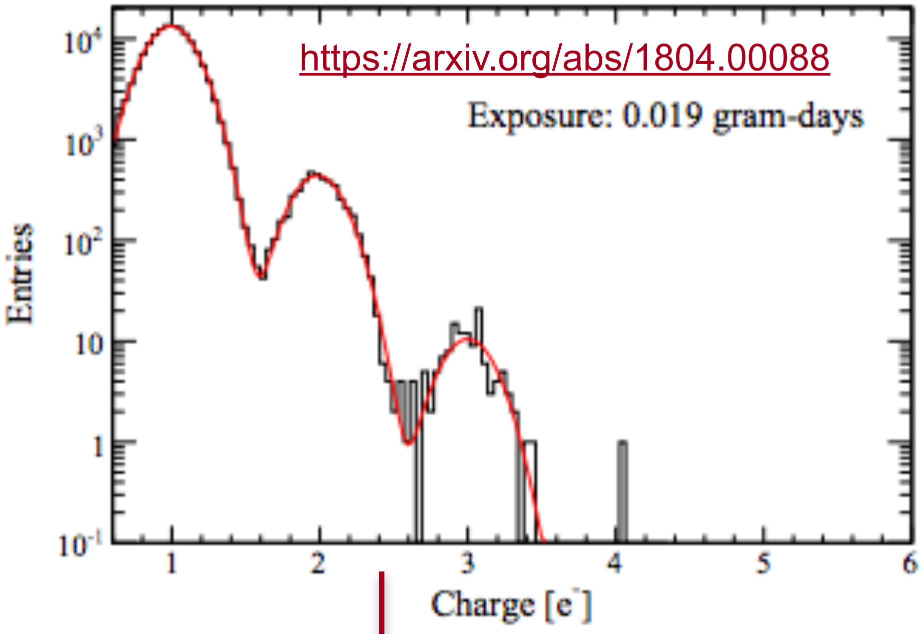


Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Comparison of ER Experiments (2018)

https://arxiv.org/abs/1206.2644

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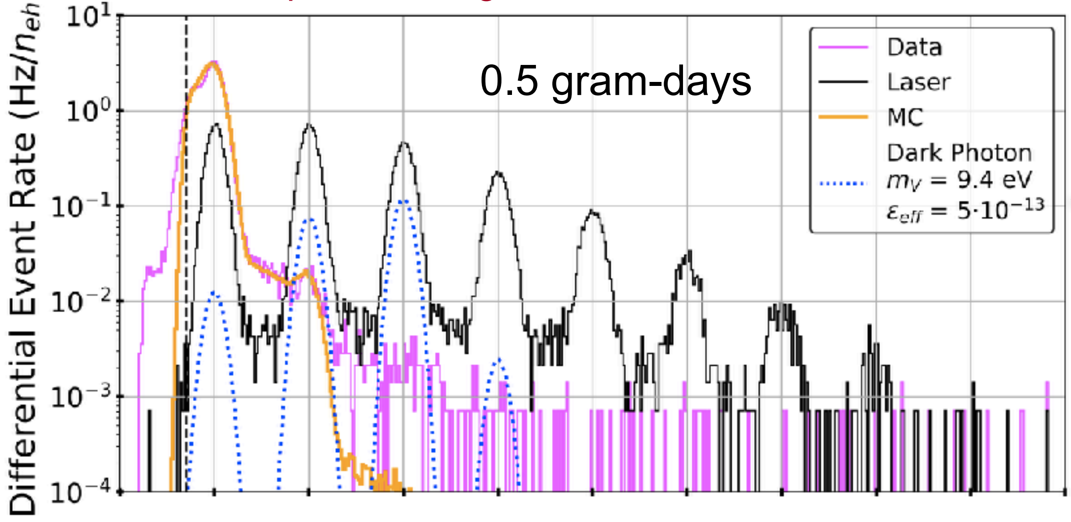

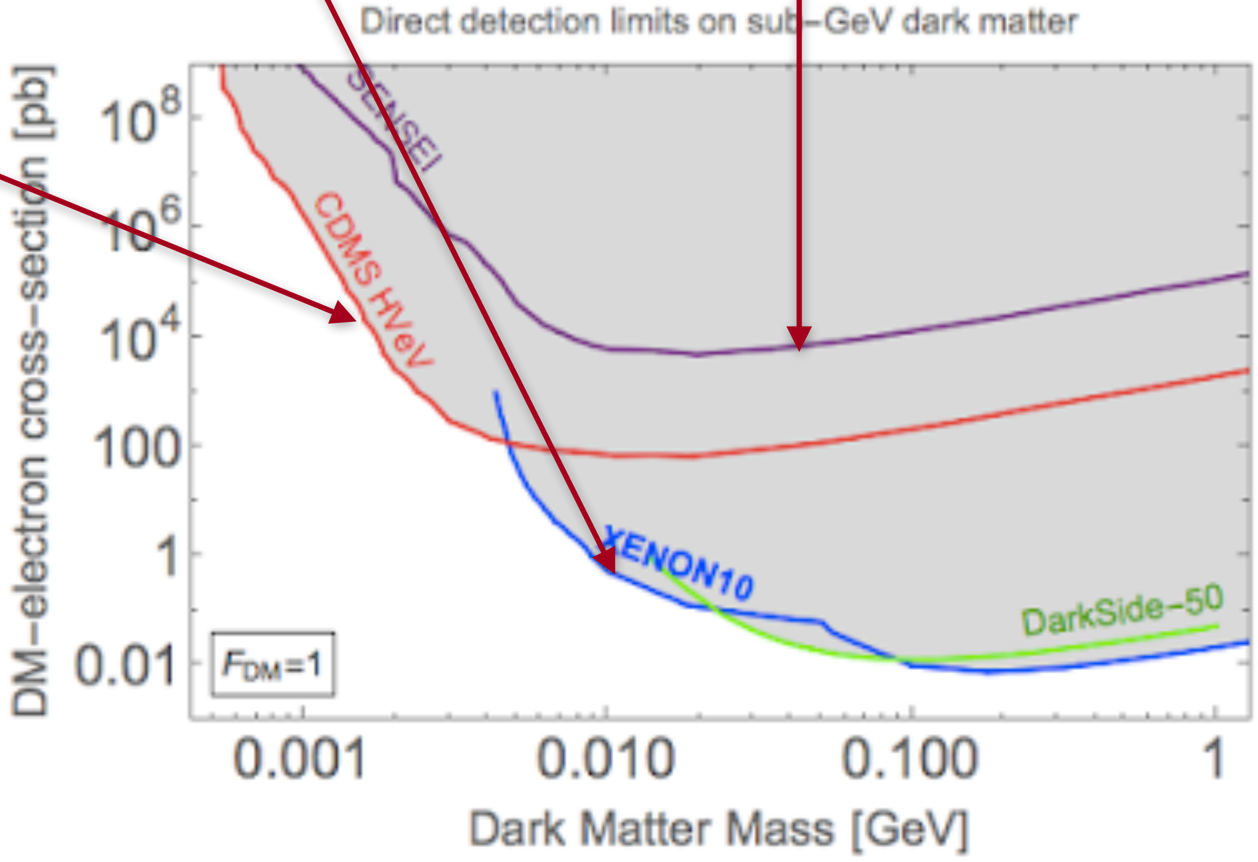

http://resonaances.blogspot.com/2018/05/dark-matter-goes-sub-gev.html

- Sensitivity determined by background, exposure, and resolution
- Pileup rejection important for IR-limited background

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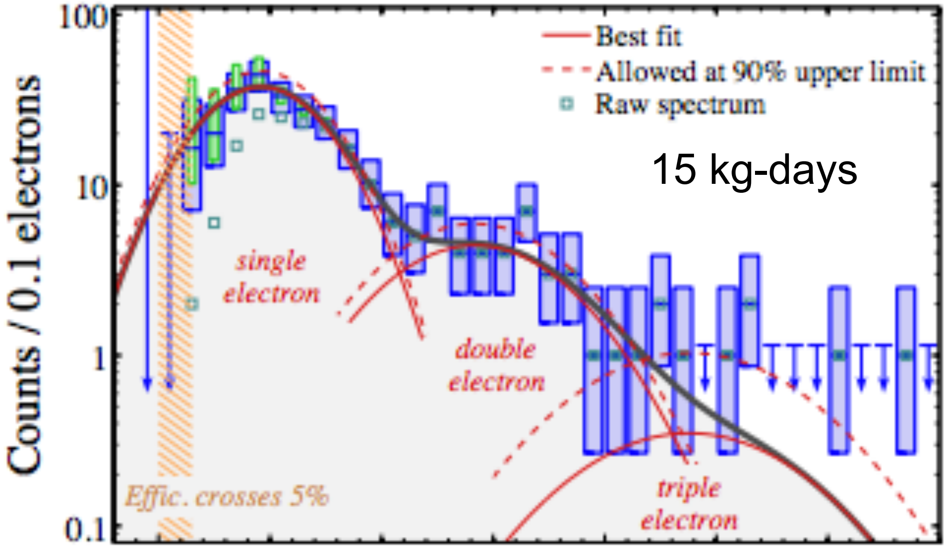
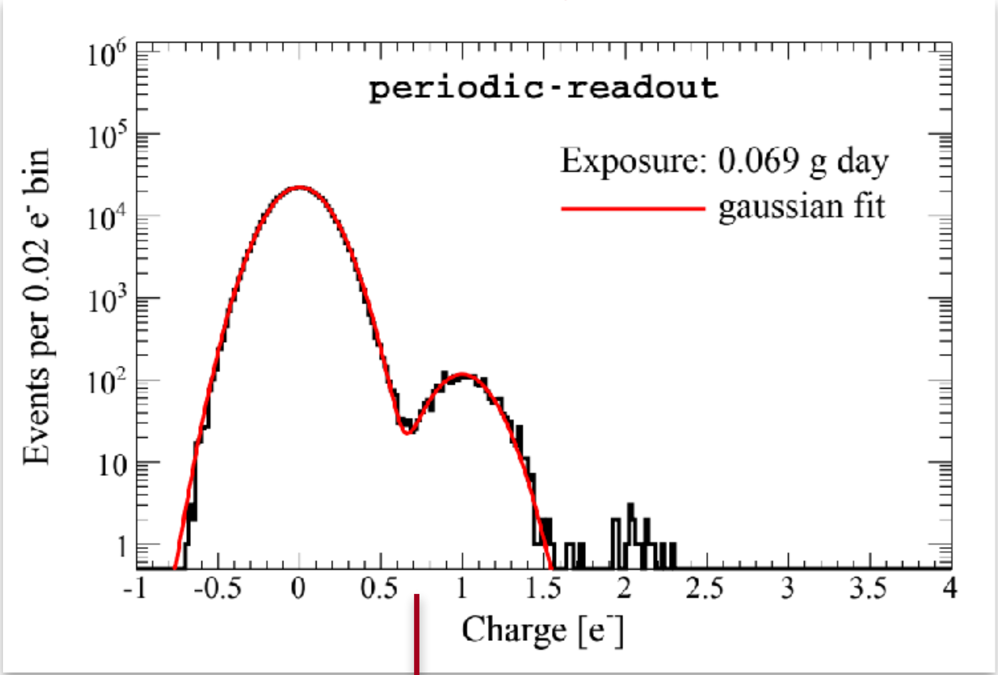


15 kg-days

https://arxiv.org/pdf/1901.10478.pdf



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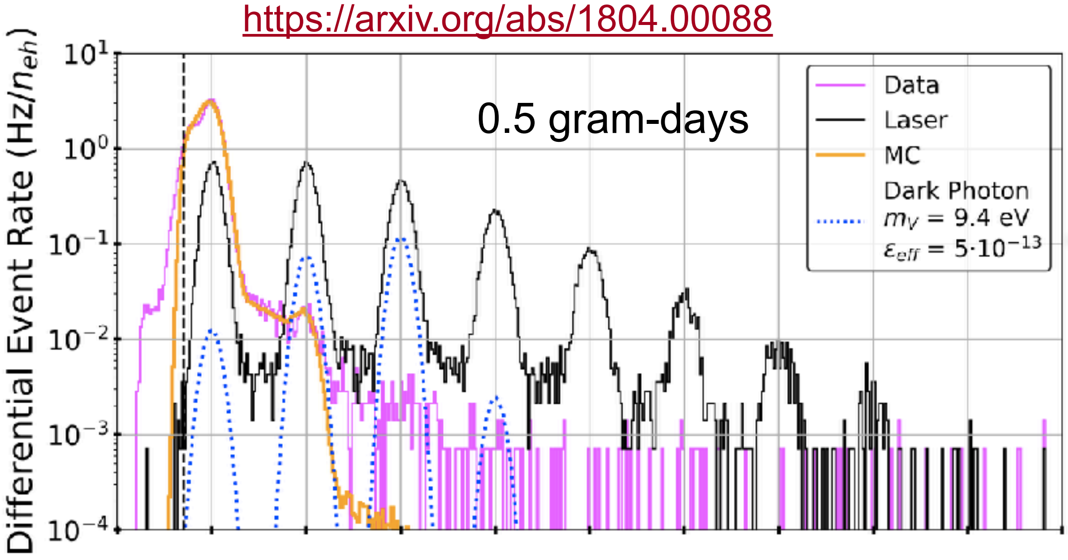

0.5 gram-days

- Sensitivity determined by background, exposure, and resolution
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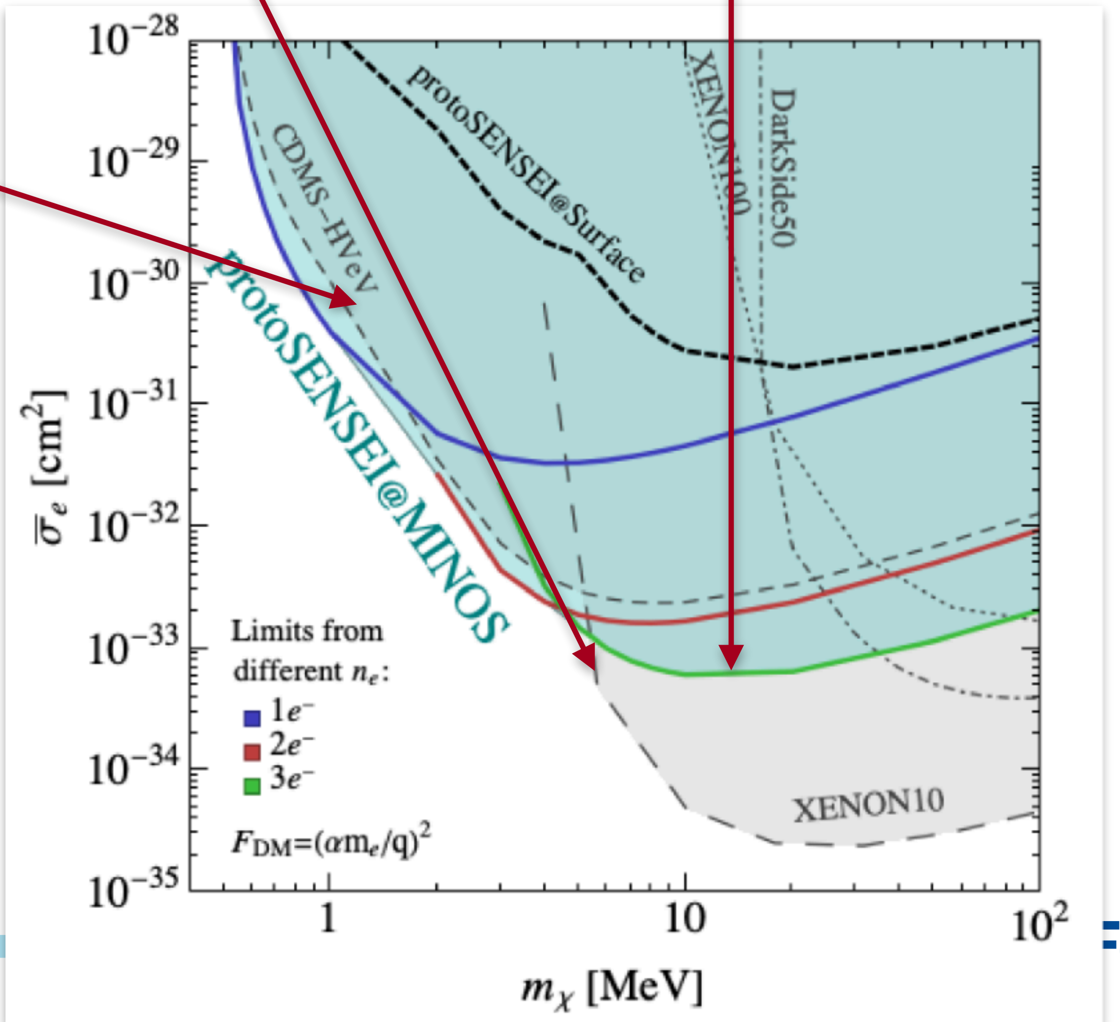
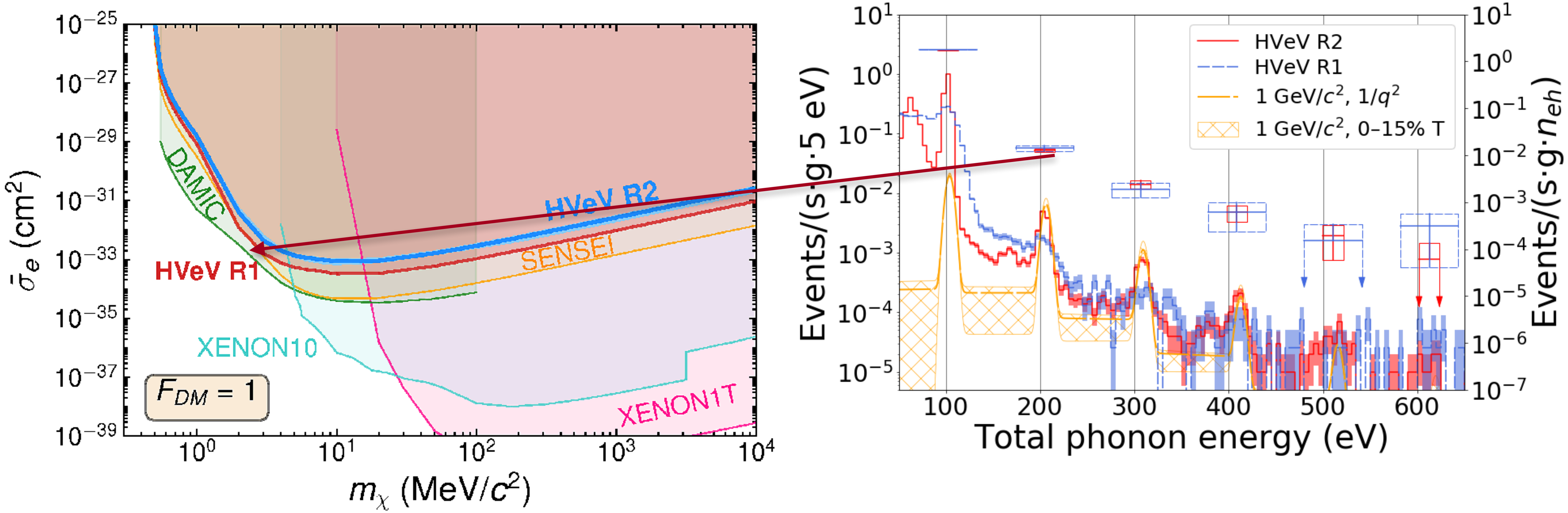


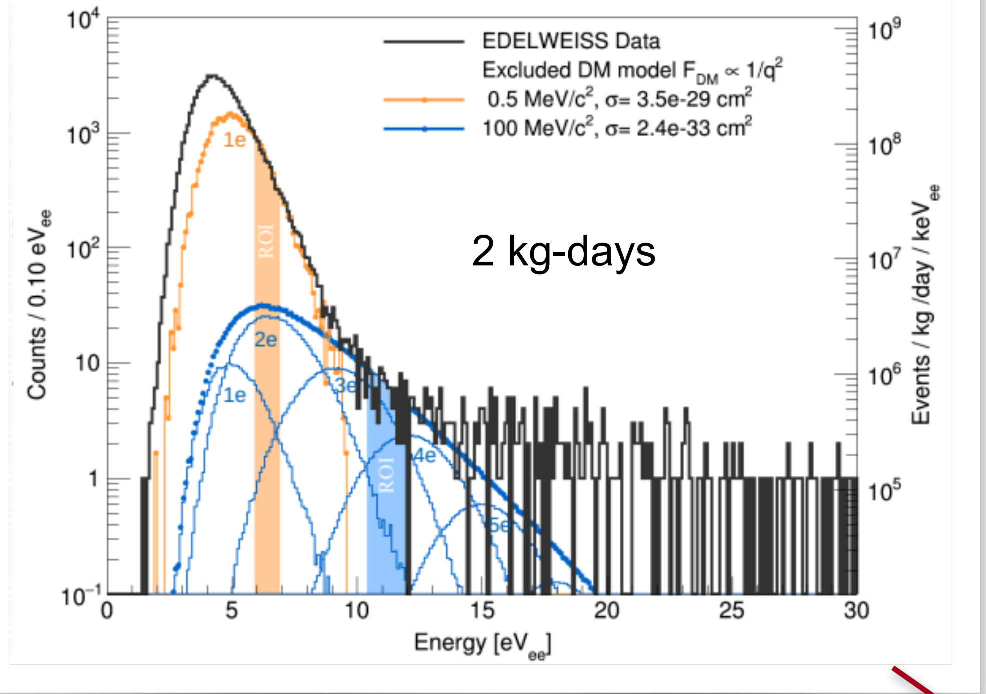
HVeV Run 2



- HVeV second run taken with 3 eV resolution detector over the course of 3 weeks:
  - 60V and 100V spectra show identical backgrounds; signal seen not voltage dependent
  - Different prototype, run in a different lab, in a different state
  - 0V data acquired with ~12 eV threshold, results still being analyzed
  - Rates in *every charge bin* consistent with Run 1…that is completely unexpected

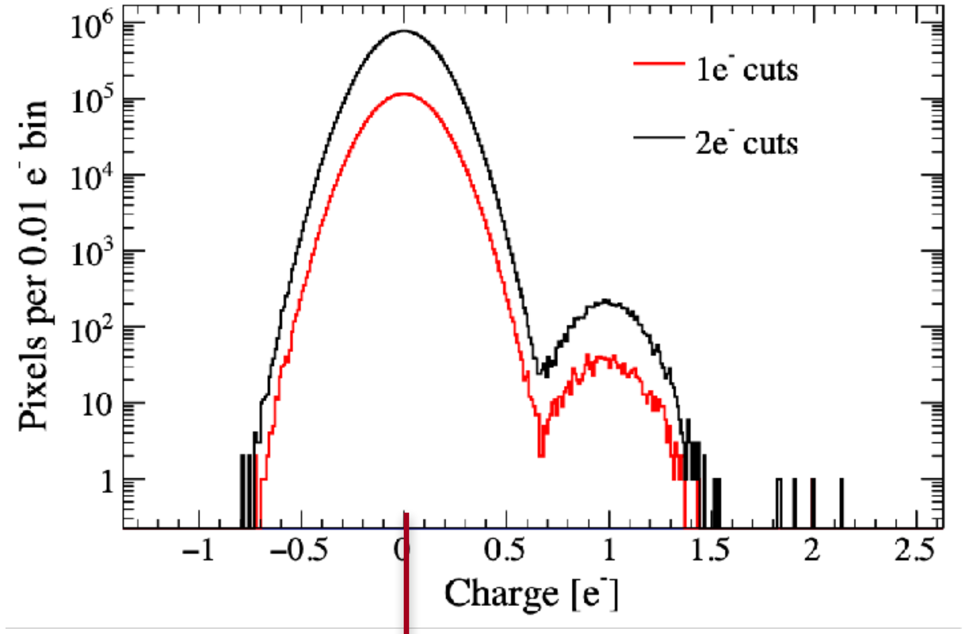
Comparison of ER Experiments (2020)

https://arxiv.org/abs/2003.01046

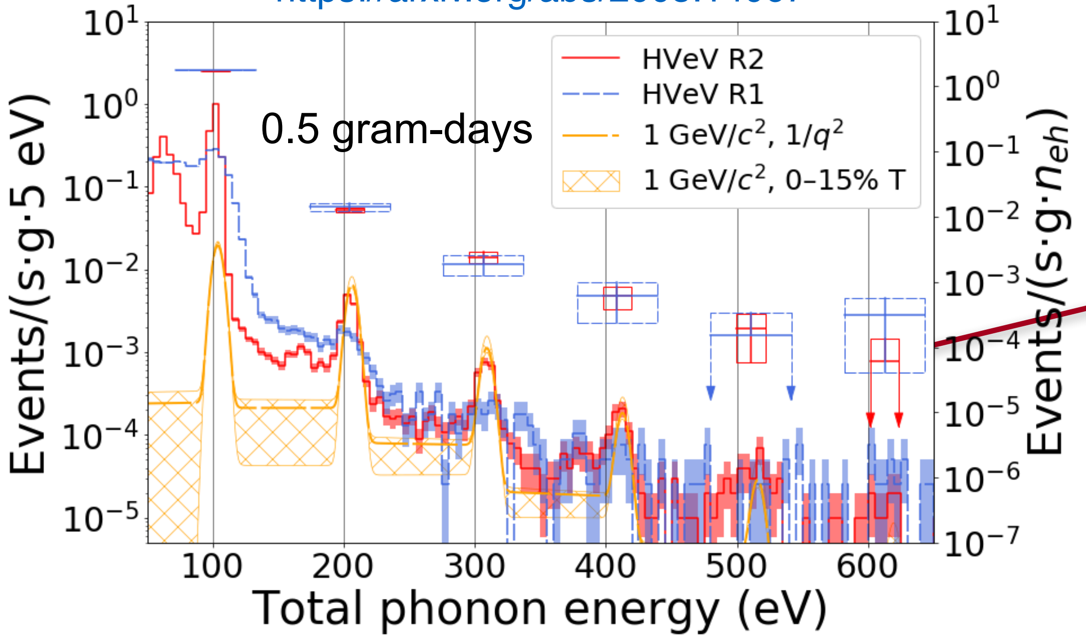


2 kg-days

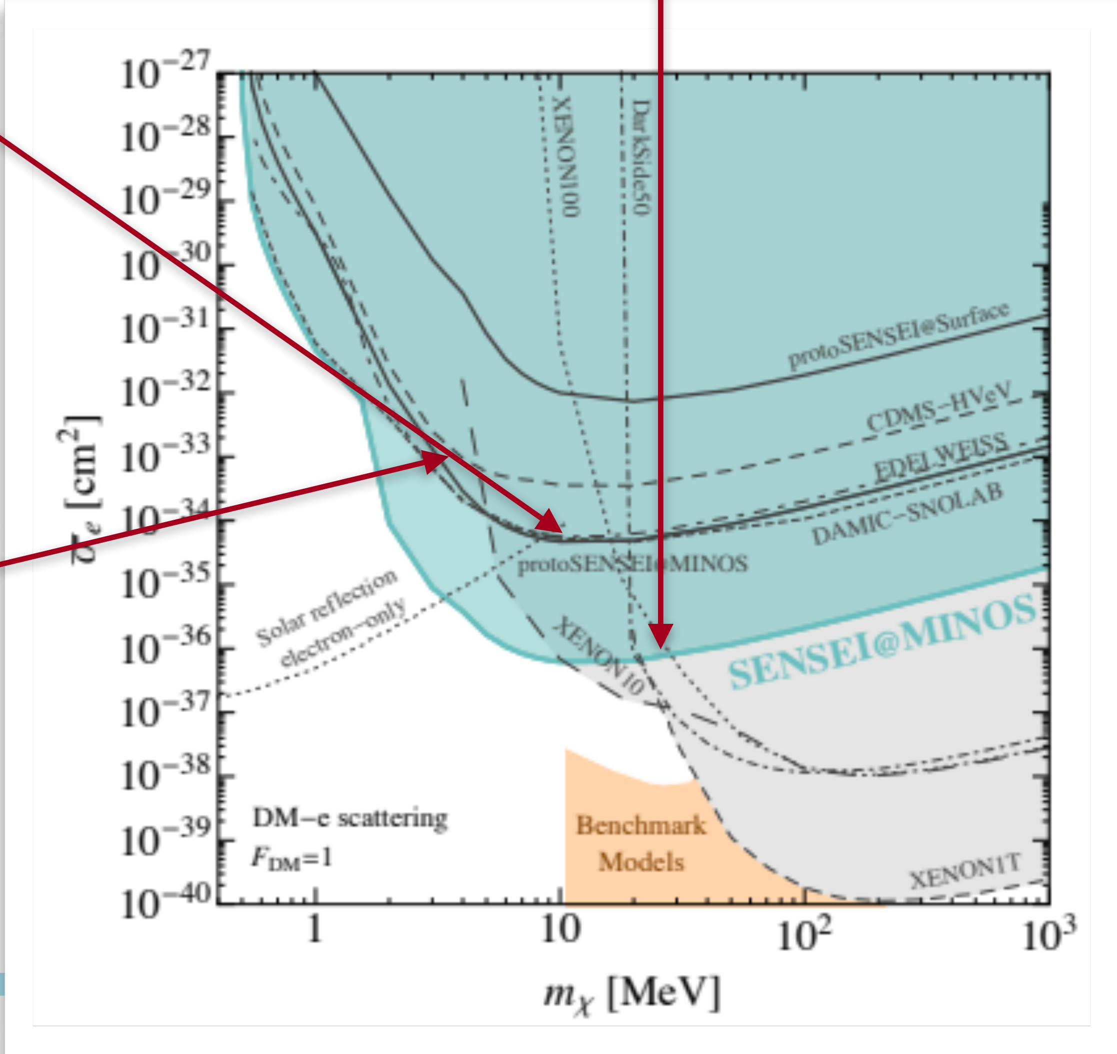
https://arxiv.org/abs/2004.11378



https://arxiv.org/abs/2005.14067

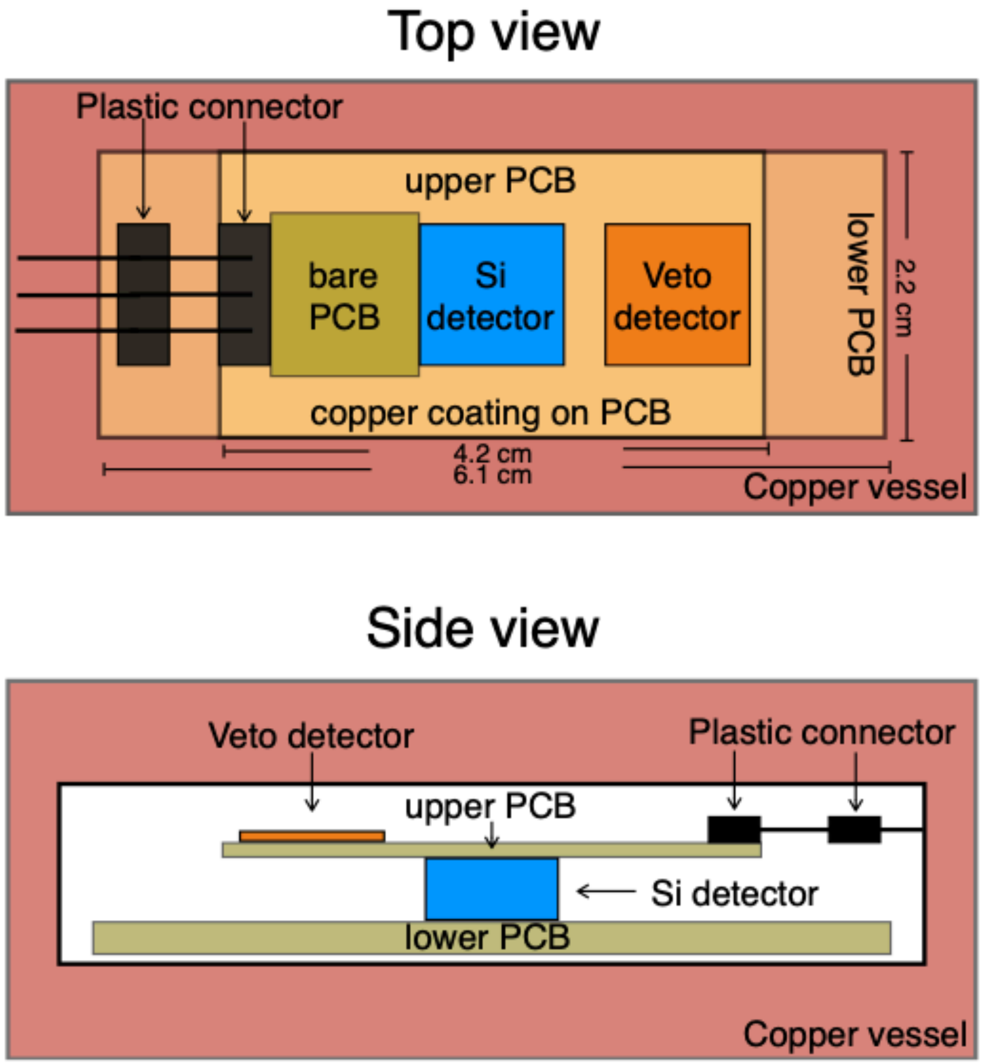


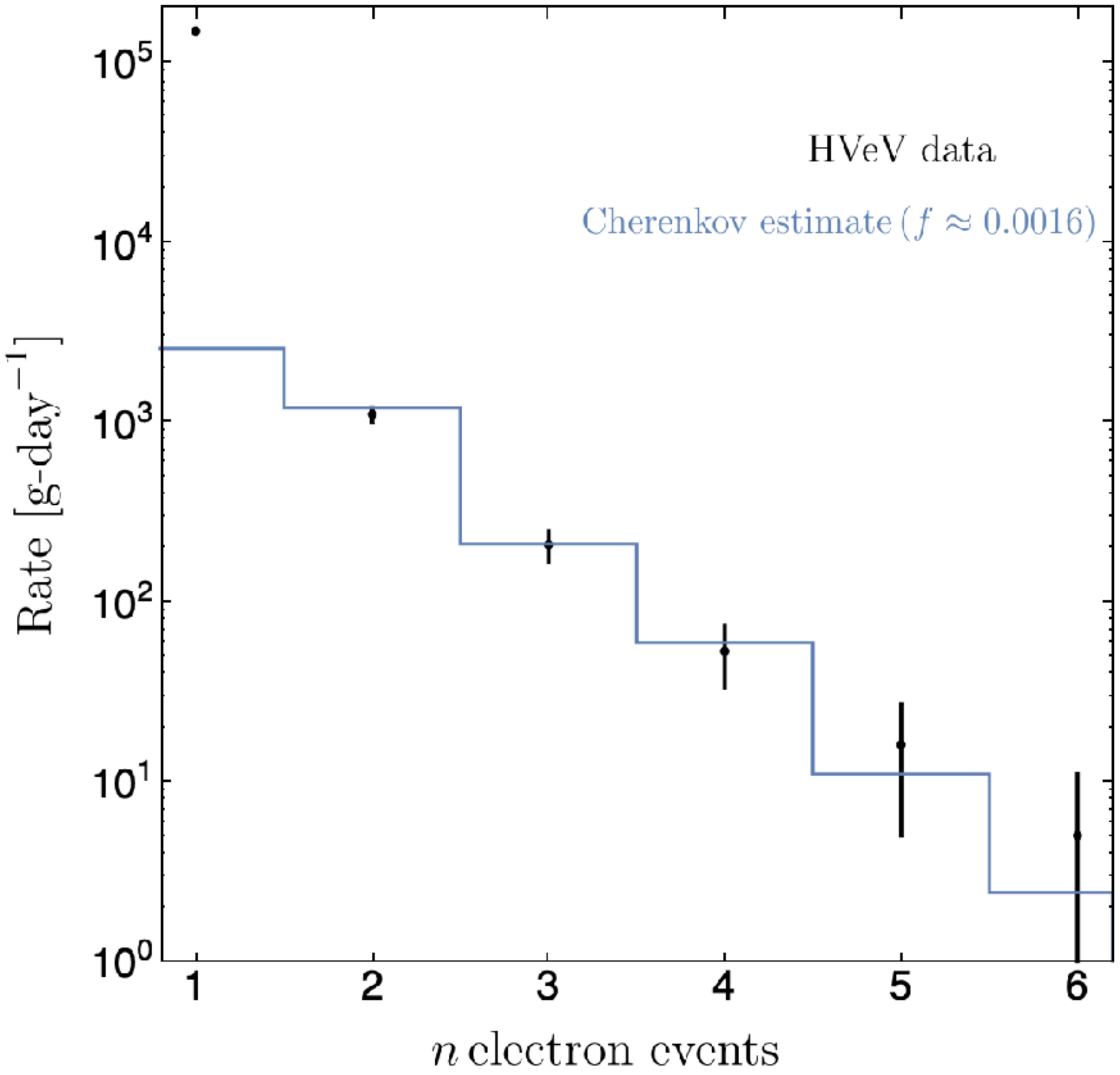
0.5 gram-days



Cerenkov Photon Backgrounds

Du et. al. 2020 (ArXiv:2011.13939)





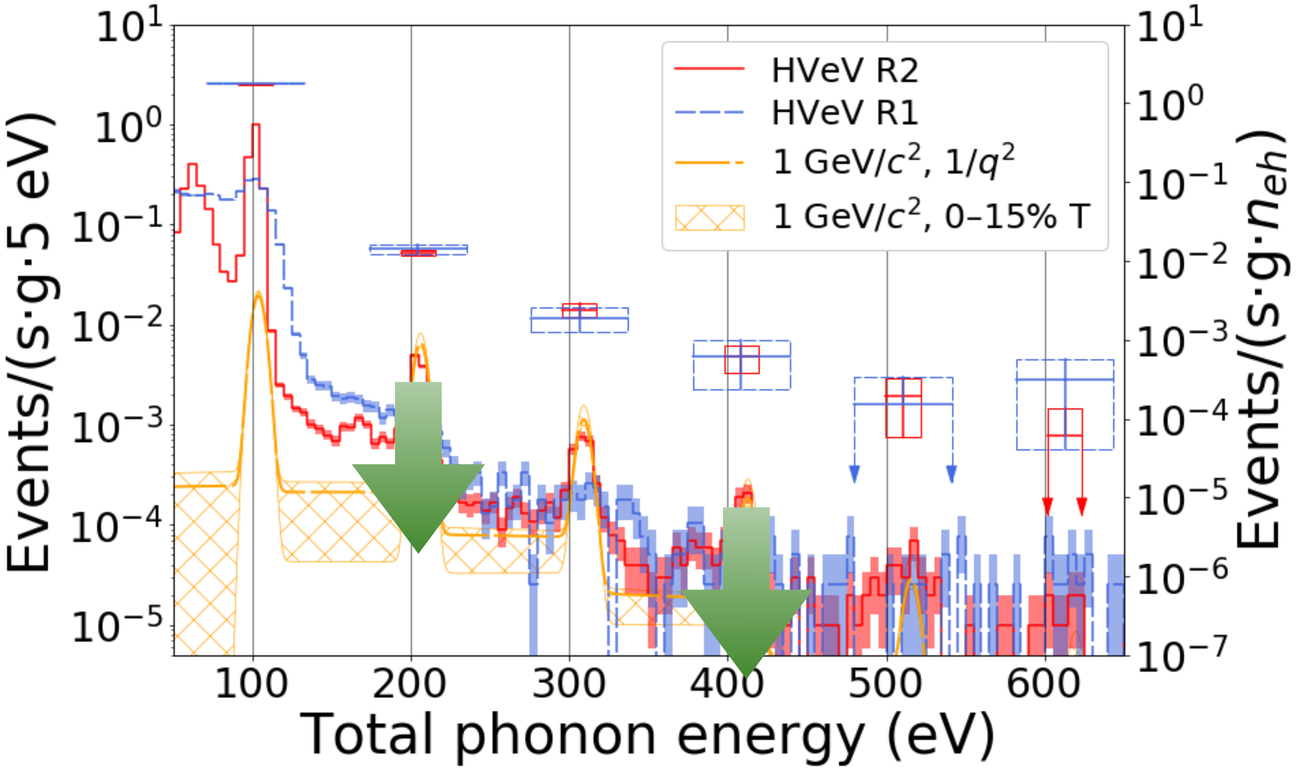
- Reduction of SENSEI background correlated with lower background and rejection of photons near high-energy tracks
- Recent paper demonstrated that the R1/R2 backgrounds can be explained by Cherenkov photons from mount PCBs
  - Also explored transition radiation, which is next leading background at the gram-day level

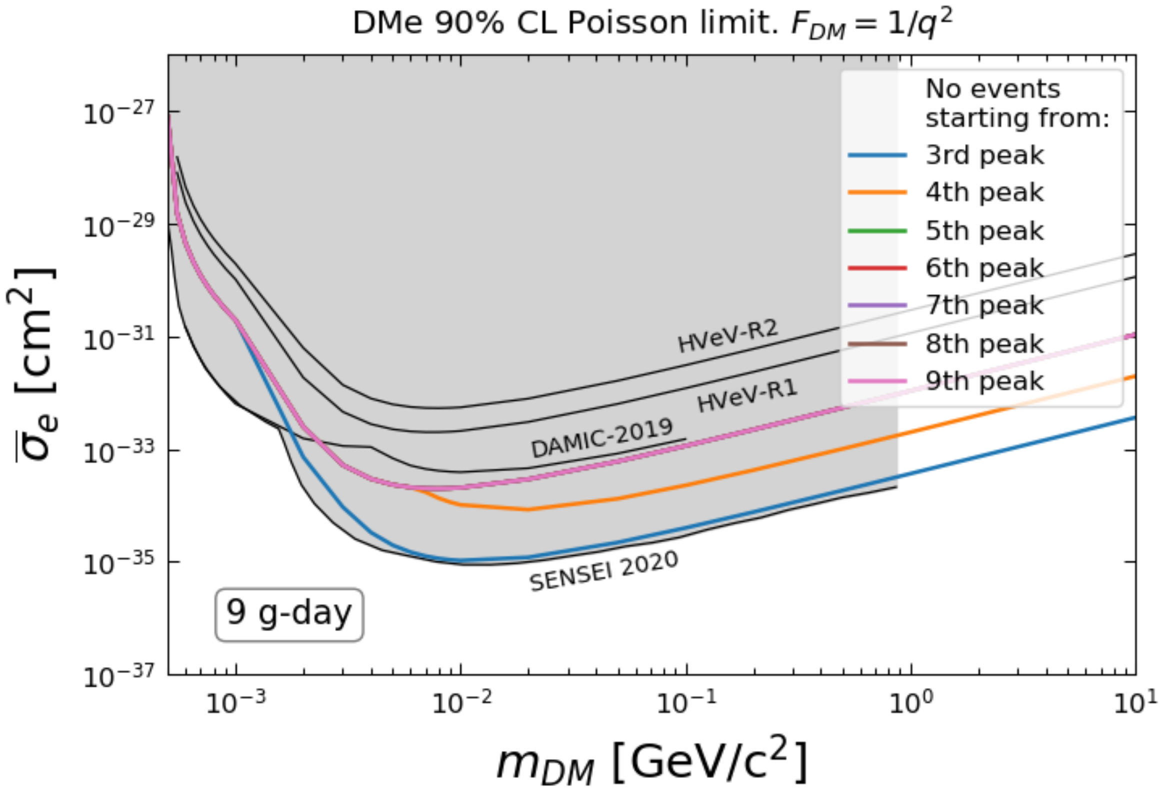
HVeV Run 3 Status

- Science run currently underway with 3 detectors (including detectors used for Runs 1-2, and a third new design)
  - Using coincidence in time to reject bursts of Cherenkov photons
  - Building model of leakage pileup to project component of single charge leakage in second electron-hole pair bin
  - Still expect single-electron bin is instrumental

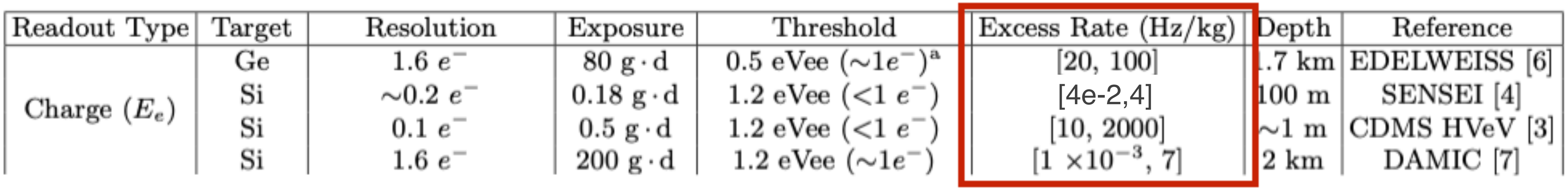
- Run started 12/23, officially ended 2/9
  - Accumulating ~1 g-days per calendar day
  - Estimate ~40 g-days of exposure by end of run

- Quick turn around expected on analysis, new results by June 2021
  - *Many* auxiliary science results to follow on 0V-HV correlations




DMe 90% CL Poisson limit. $F_{DM} = 1/q^2$

Semiconductors Summary



Readout Type	Target	Resolution	Exposure	Threshold	Excess Rate (Hz/kg)	Depth	Reference
Charge (E_e)	Ge	1.6 e^-	80 $\mathrm{g \cdot d}$	0.5 eVee ($\sim$1e^-)^a	[20, 100]	.7 km	EDELWEISS [6]
	Si	$\sim$0.2 e^-	0.18 $\mathrm{g \cdot d}$	1.2 eVee (<1 e^-)	[4e-2,4]	100 m	SENSEI [4]
	Si	0.1 e^-	0.5 $\mathrm{g \cdot d}$	1.2 eVee (<1 e^-)	[10, 2000]	$\sim$1 m	CDMS HVeV [3]
	Si	1.6 e^-	200 $\mathrm{g \cdot d}$	1.2 eVee ($\sim$1e^-)	[1 $\times10^{-3}$, 7]	2 km	DAMIC [7]

Intriguing coincidence of rates

Different Depths

Different Shielding

Different Exposures

Different Composition

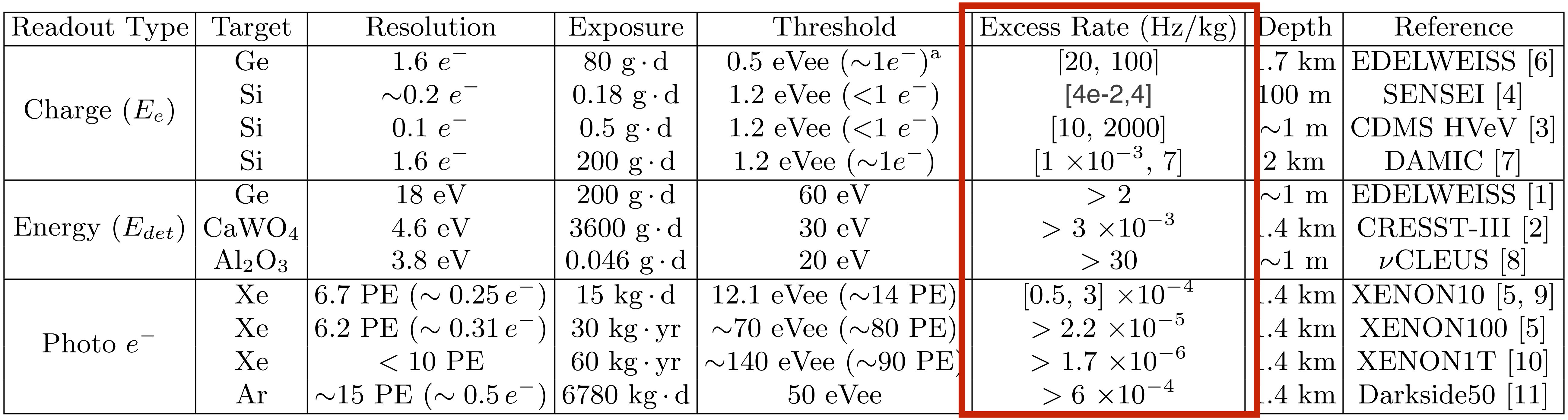
Different Temperatures

Different Pressures

Unlike nuclear recoil: these are integrated total rates!

Semiconductors have tiny thresholds

All Sub-GeV DM Searches



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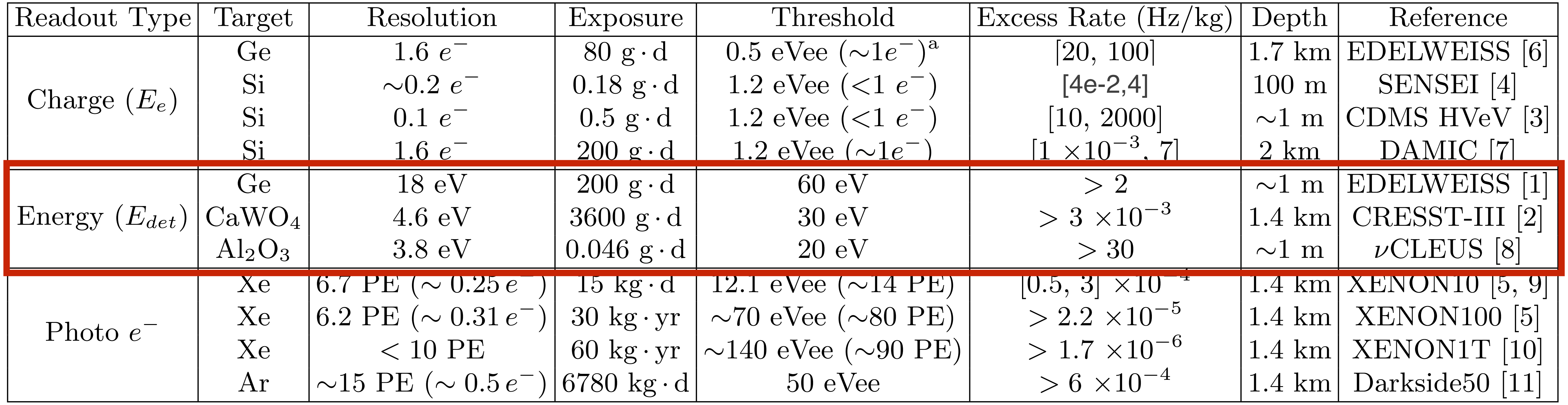
	Si	$\sim$0.2 e^-	0.18 g $\cdot$ d	1.2 eVee (<1 e^-)	[4e-2,4]	100 m	SENSEI [4]
	Si	0.1 e^-	0.5 g $\cdot$ d	1.2 eVee (<1 e^-)	[10, 2000]	$\sim$1 m	CDMS HVeV [3]
	Si	1.6 e^-	200 g $\cdot$ d	1.2 eVee ($\sim$1e^-)	[1 $\times 10^{-3}$, 7]	2 km	DAMIC [7]
Energy (E_{det})	Ge	18 eV	200 g $\cdot$ d	60 eV	> 2	$\sim$1 m	EDELWEISS [1]
	$CaWO_4$	4.6 eV	3600 g $\cdot$ d	30 eV	> 3 $\times 10^{-3}$	.4 km	CRESST-III [2]
	Al_2O_3	3.8 eV	0.046 g $\cdot$ d	20 eV	> 30	$\sim$1 m	νCLEUS [8]
Photo e^-	Xe	6.7 PE ($\sim$ 0.25 e^-)	15 kg $\cdot$ d	12.1 eVee ($\sim$14 PE)	[0.5, 3] $\times 10^{-4}$	.4 km	XENON10 [5, 9]
	Xe	6.2 PE ($\sim$ 0.31 e^-)	30 kg $\cdot$ yr	$\sim$70 eVee ($\sim$80 PE)	> 2.2 $\times 10^{-5}$	.4 km	XENON100 [5]
	Xe	< 10 PE	60 kg $\cdot$ yr	$\sim$140 eVee ($\sim$90 PE	> 1.7 $\times 10^{-6}$	.4 km	XENON1T [10]
	Ar	$\sim$15 PE ($\sim$ 0.5 e^-)	6780 kg $\cdot$ d	50 eVee	> 6 $\times 10^{-4}$	.4 km	Darkside50 [11]

Many others also observe excesses

All Sub-GeV DM Searches



Readout Type	Target	Resolution	Exposure	Threshold	Excess Rate (Hz/kg)	Depth	Reference
Charge (E_e)	Ge	1.6 e^-	80 $\mathrm{g \cdot d}$	0.5 eVee ($\sim$1e^-)^a	[20, 100]	1.7 km	EDELWEISS [6]
	Si	$\sim$0.2 e^-	0.18 $\mathrm{g \cdot d}$	1.2 eVee (<1 e^-)	[4e-2,4]	100 m	SENSEI [4]
	Si	0.1 e^-	0.5 $\mathrm{g \cdot d}$	1.2 eVee (<1 e^-)	[10, 2000]	$\sim$1 m	CDMS HVeV [3]
	Si	1.6 e^-	200 $\mathrm{g \cdot d}$	1.2 eVee ($\sim$1e^-)	[1 $\times 10^{-3}$, 7]	2 km	DAMIC [7]
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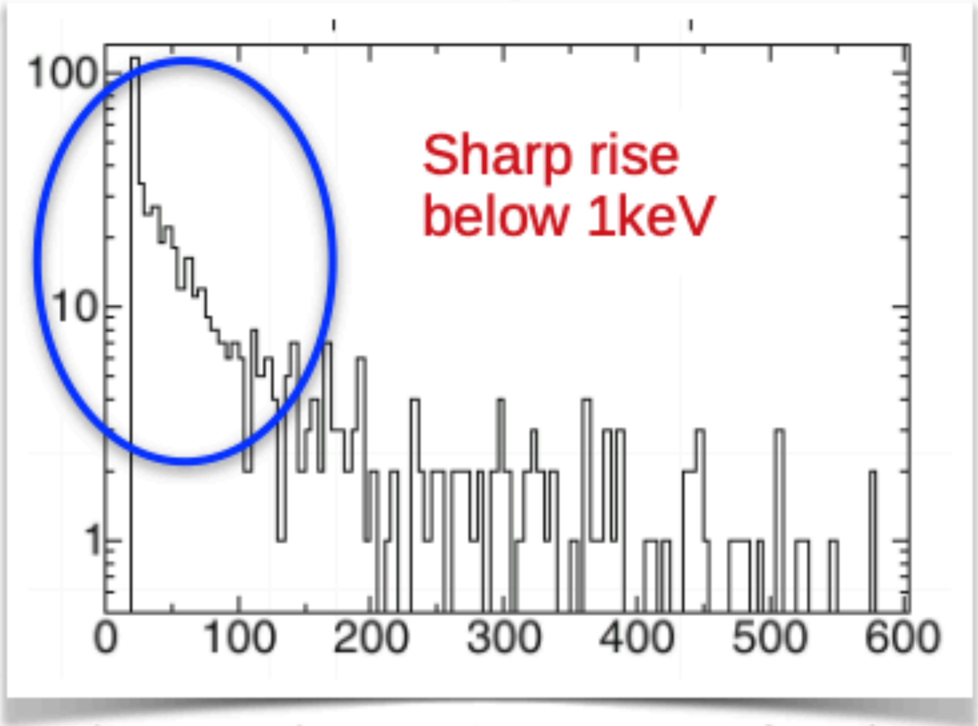
Many others also observe excesses

-*Edet* readout: total rate unknown, **hard to compare**

Excesses in NR Experiments (Early 2020)



NUCLEUS surface Al_2O_3 (2017

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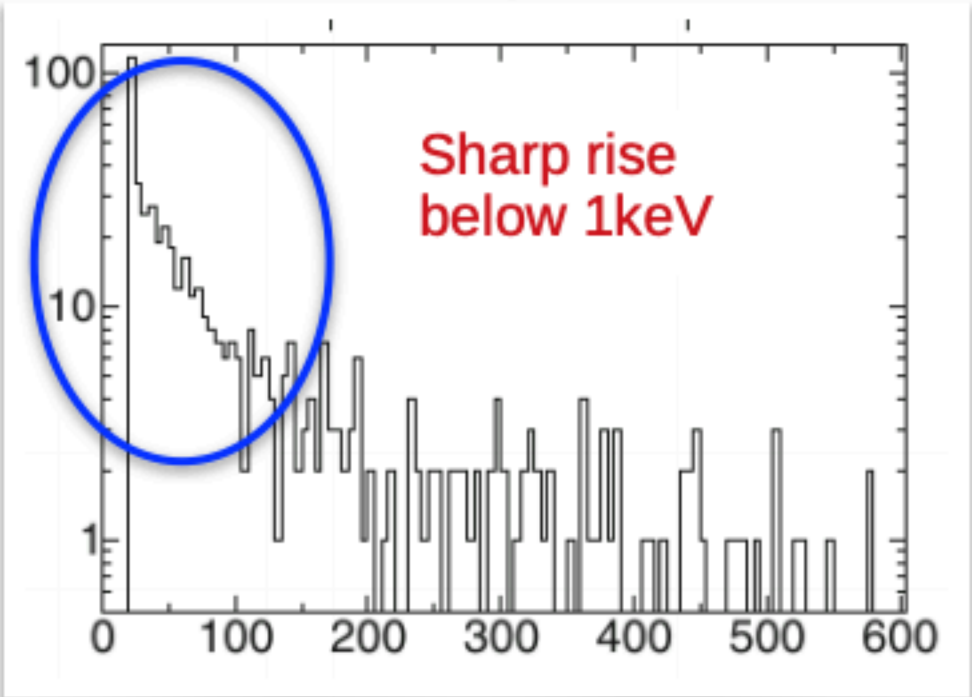

Sharp rise below 1keV

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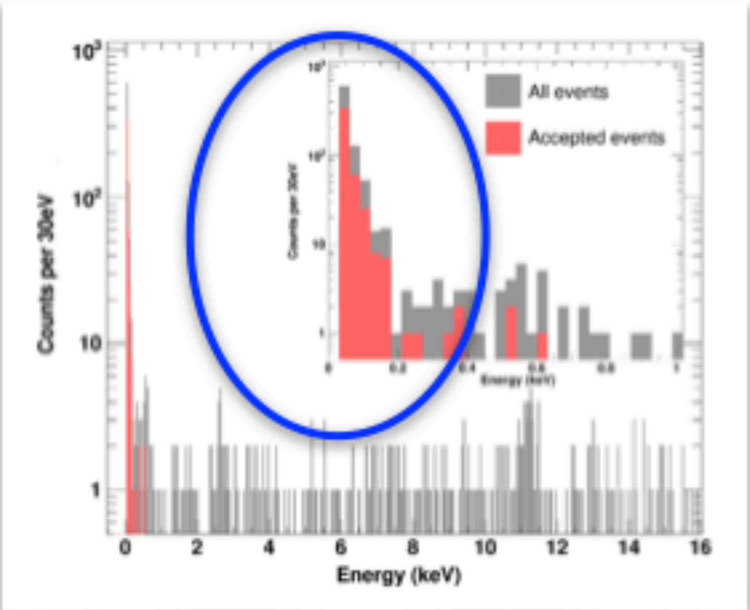

CRESST-III $CaWO_4$ (2019)

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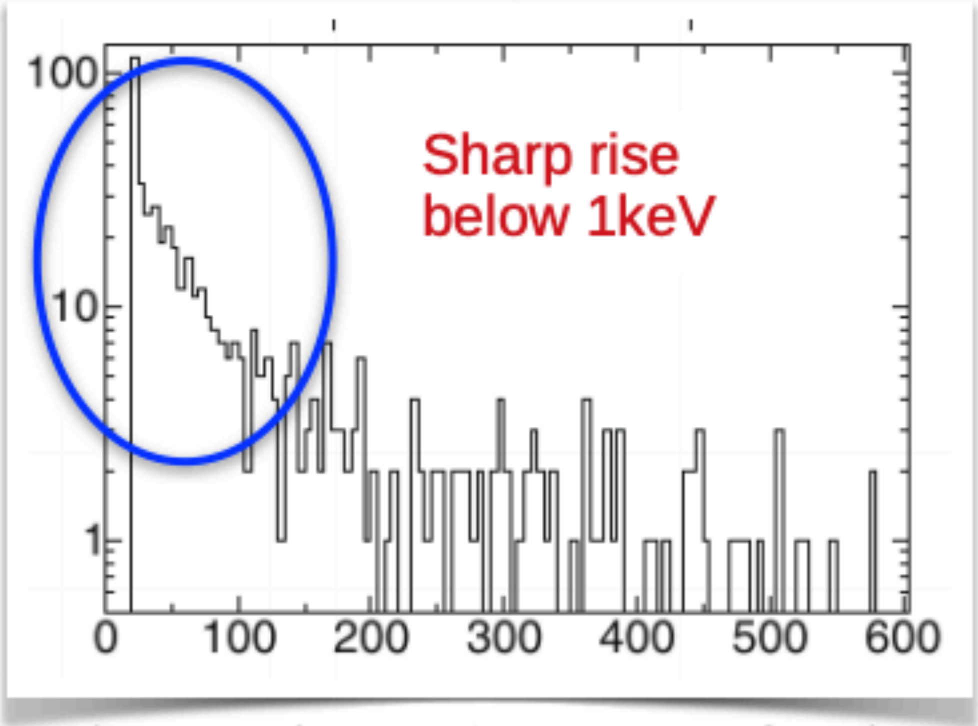

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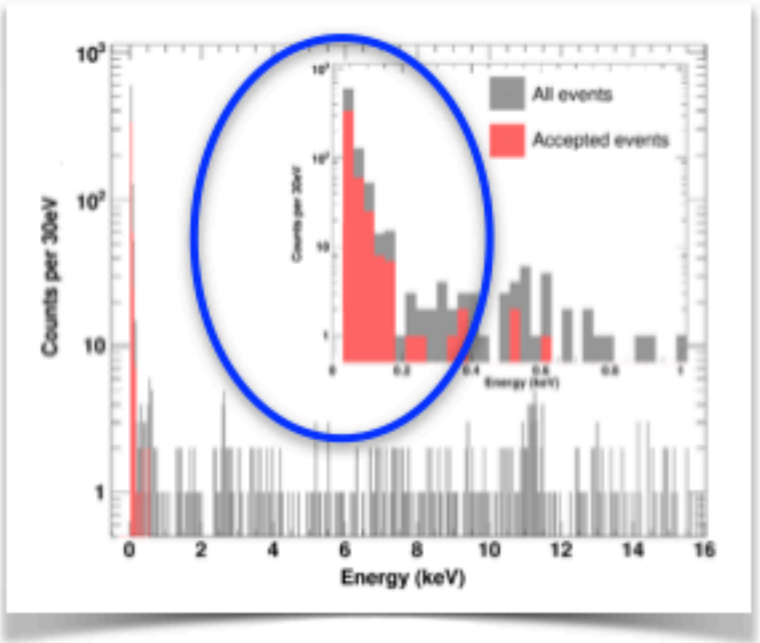

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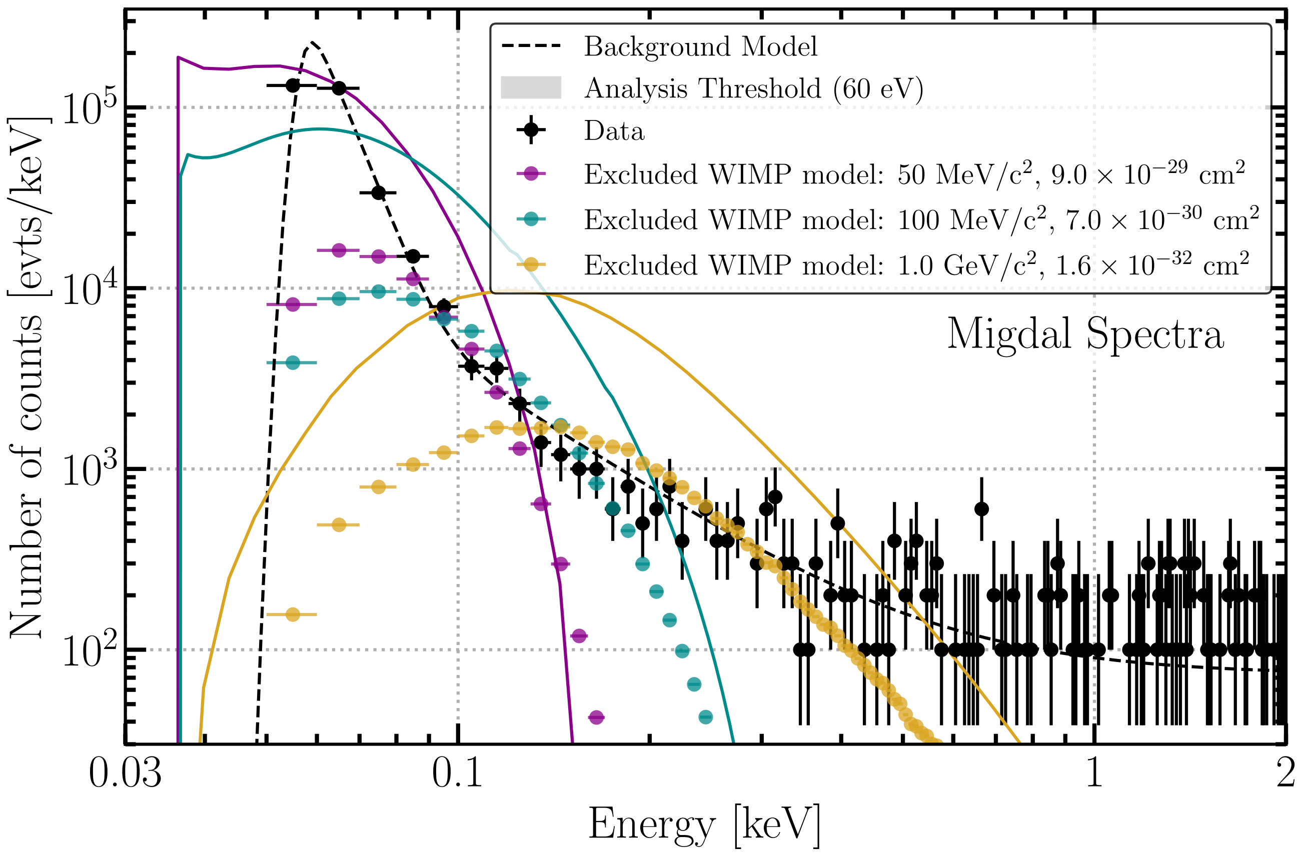

EDELWEISS surface (2019)
Germanium detector
(0V: heat readout)

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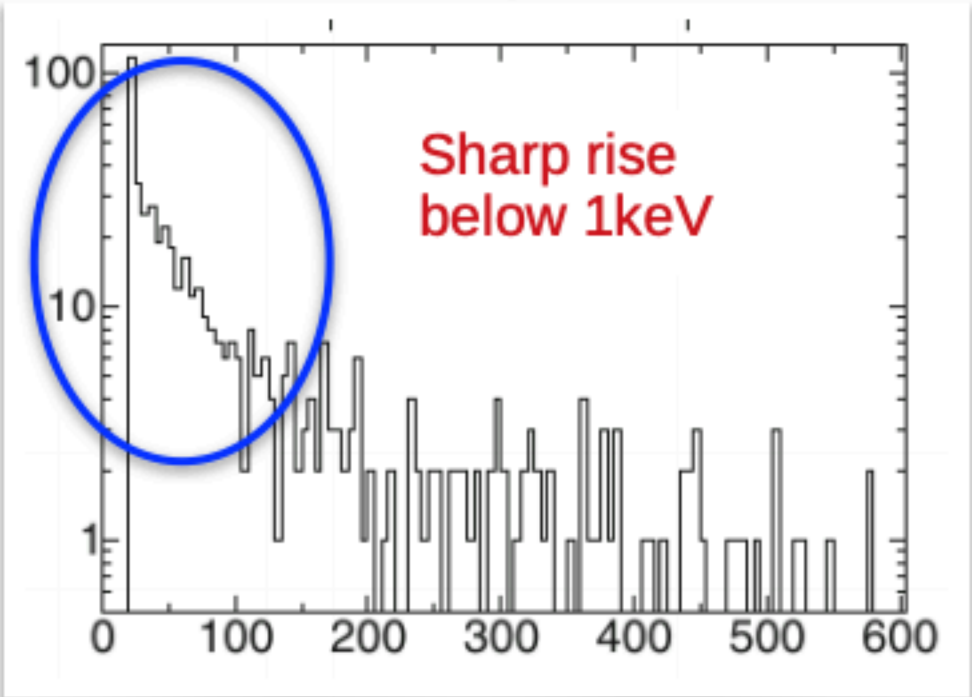

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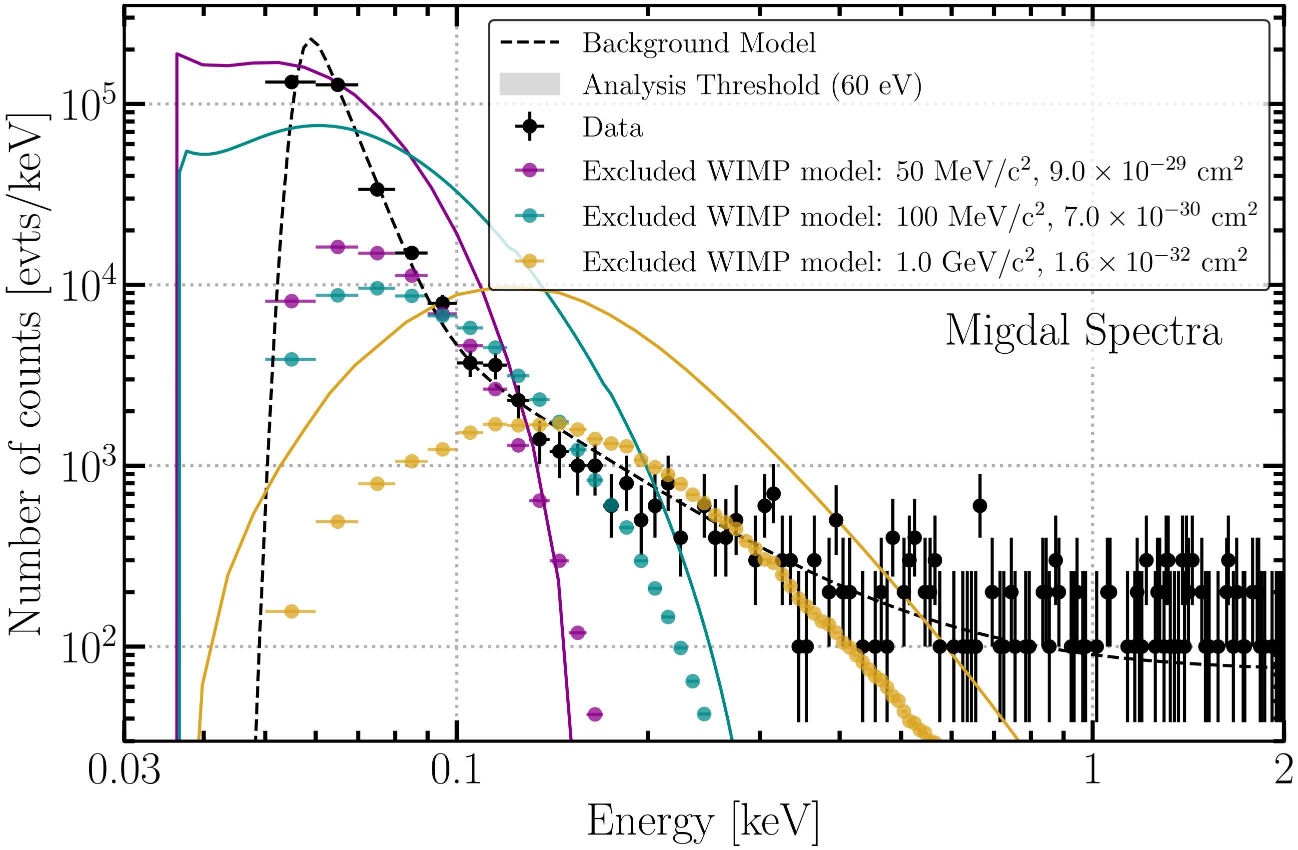

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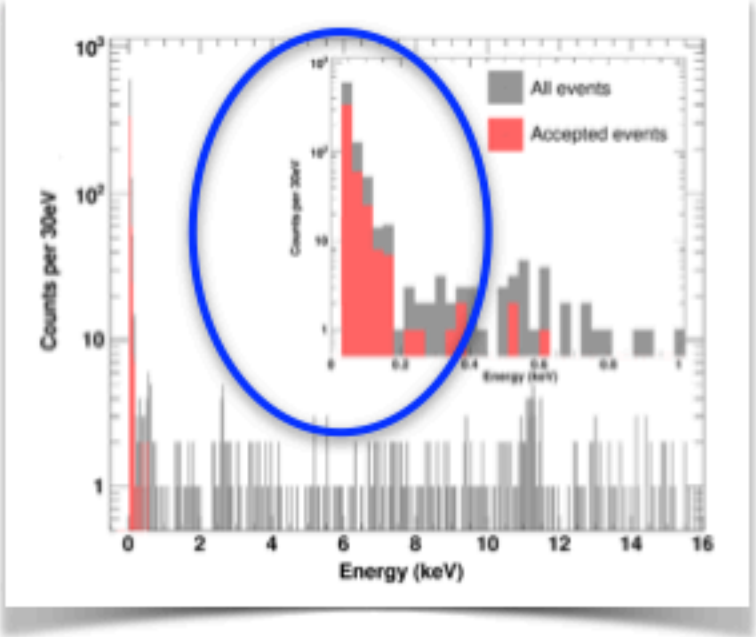
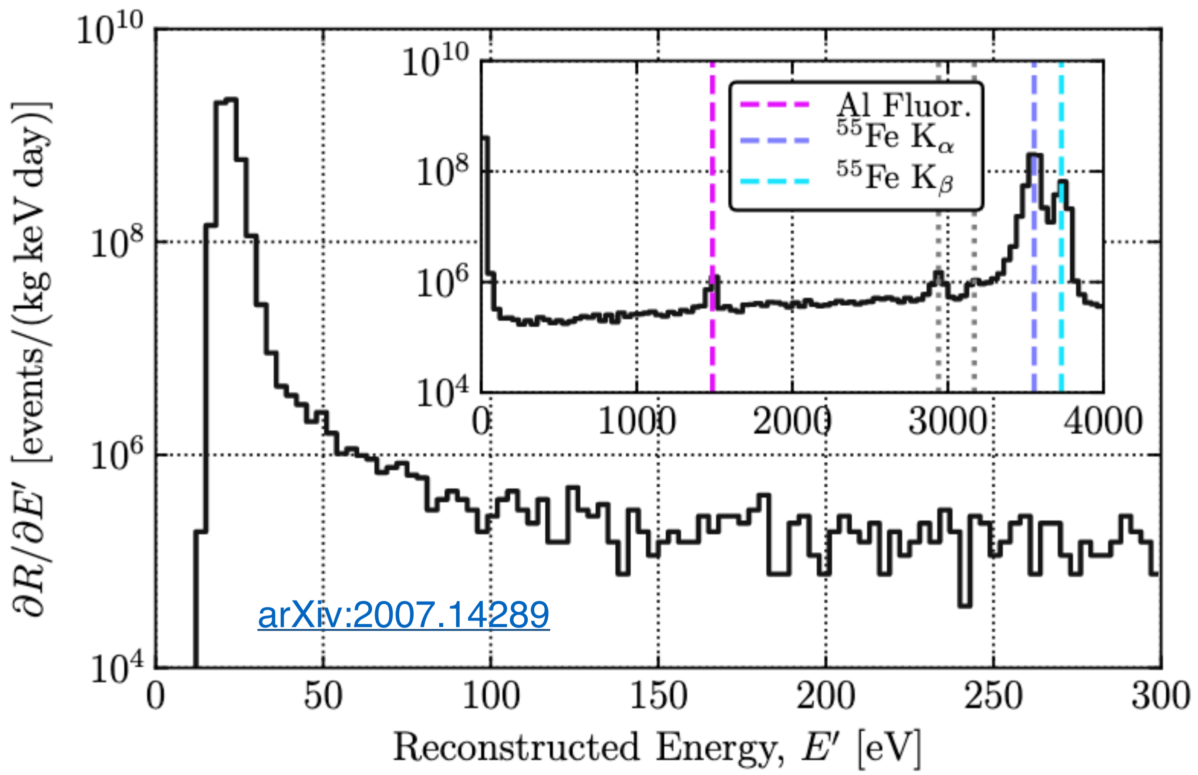


CRESST-III $CaWO_4$ (2019)

Expected soon:
DAMIC LT, SuperCDMS PD2, HVeV 0V

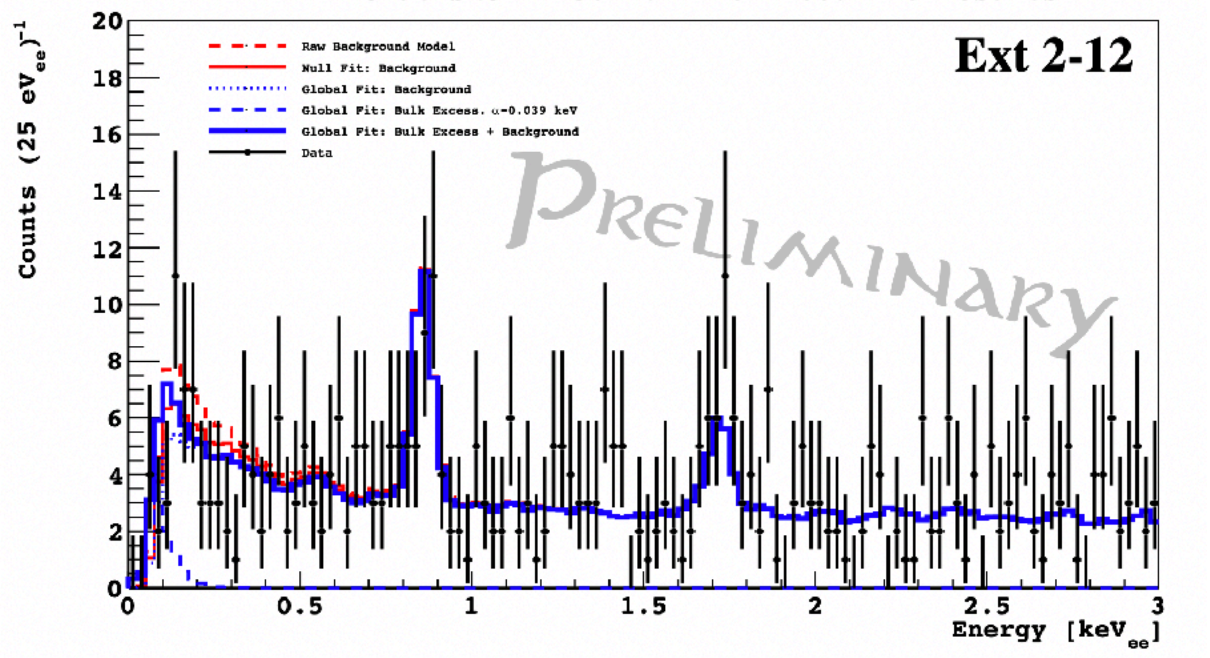
Excesses in NR Experiments (Mid 2020)

https://arxiv.org/abs/2007.15622

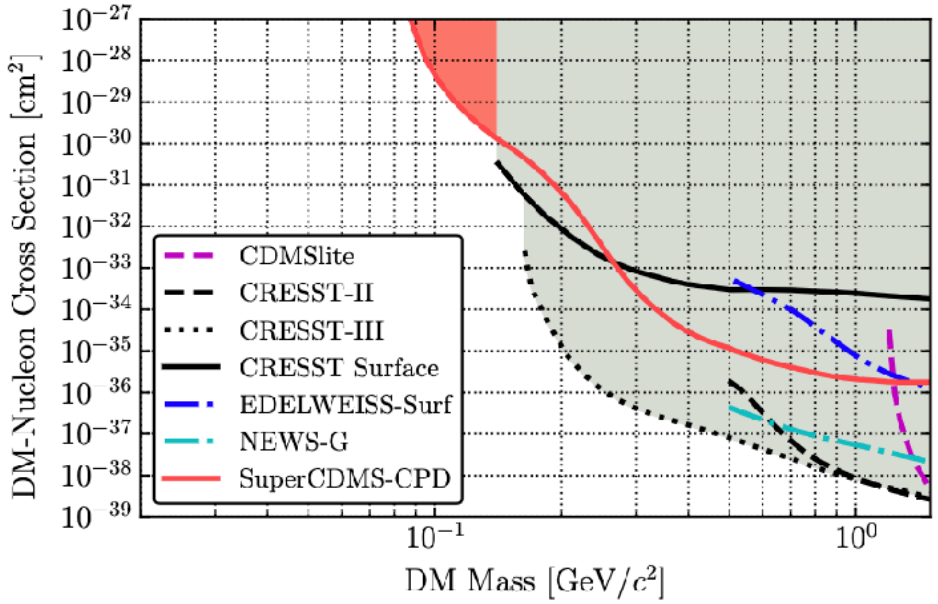


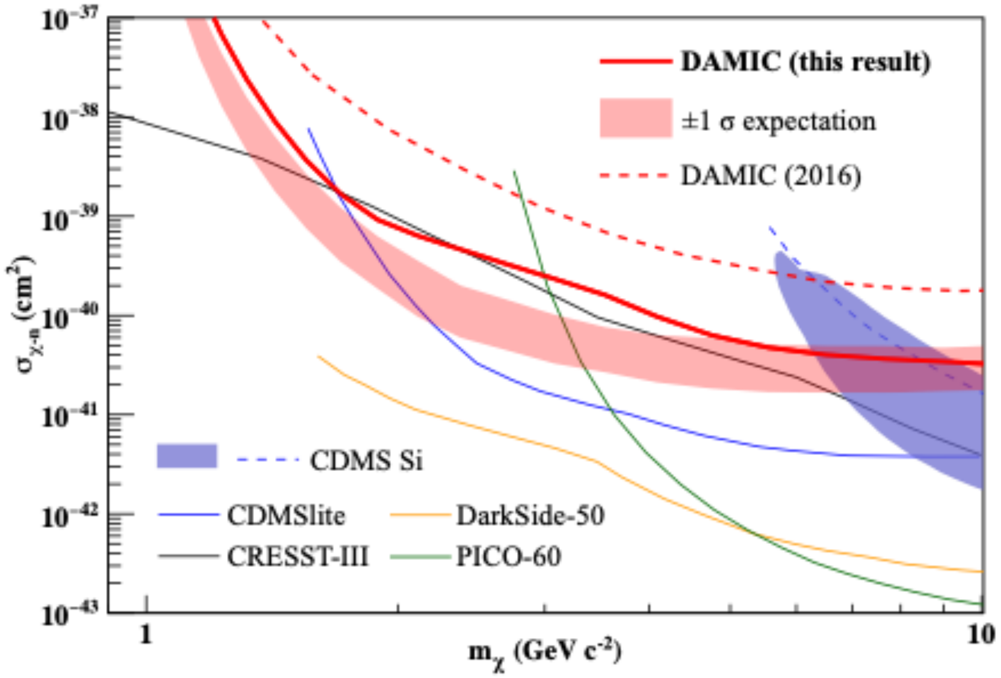
arXiv:2007.14289

SuperCDMS CPD @ SLAC
Si Phonon Calorimeter



DAMIC @ SNOLAB
Low-background Si CCD





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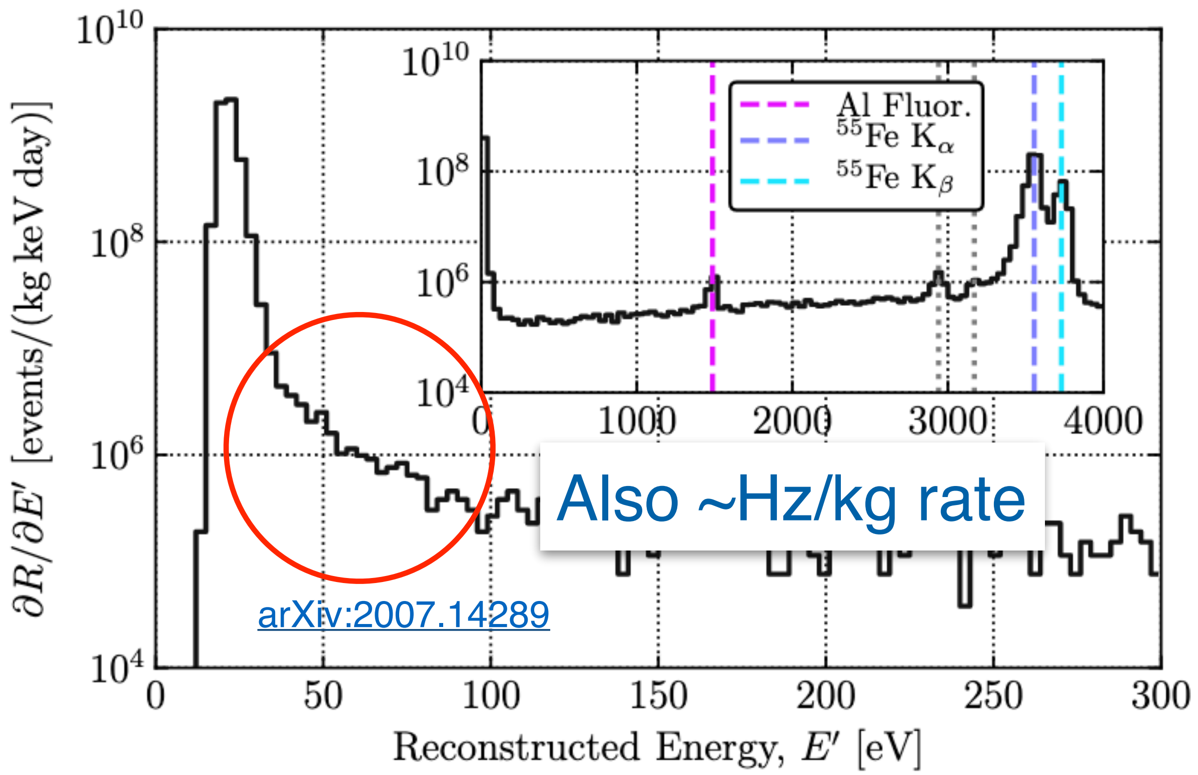

Also ~Hz/kg rate

arXiv:2007.14289

SuperCDMS CPD @ SLAC
Si Phonon Calorimeter

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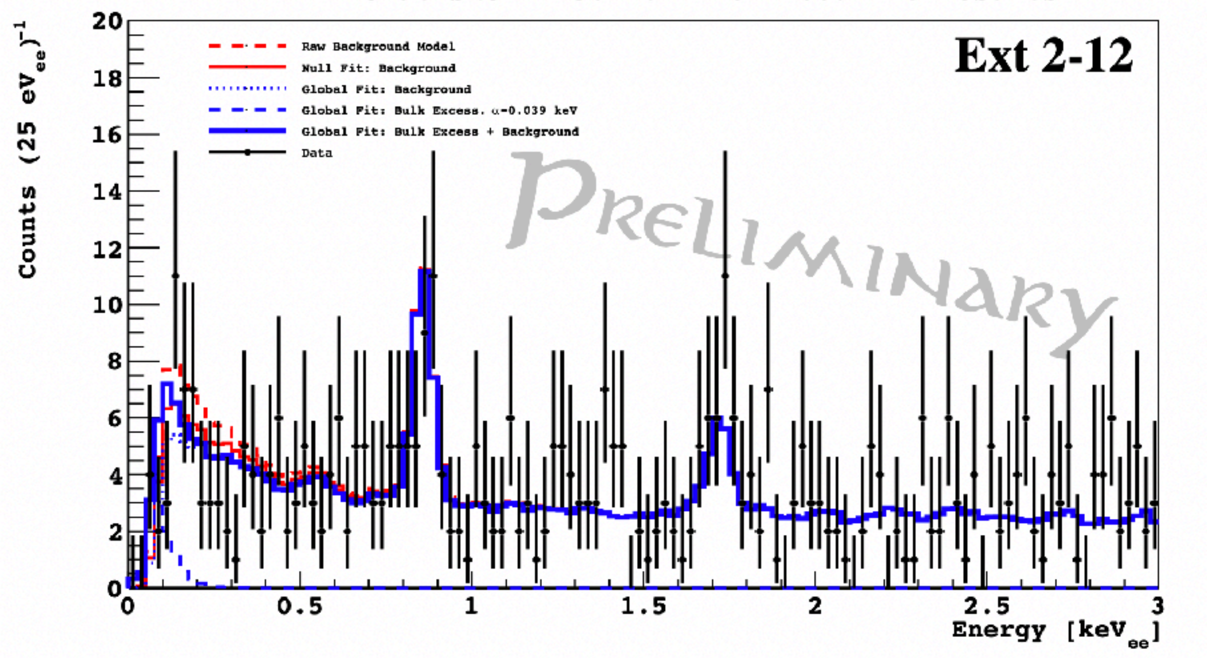

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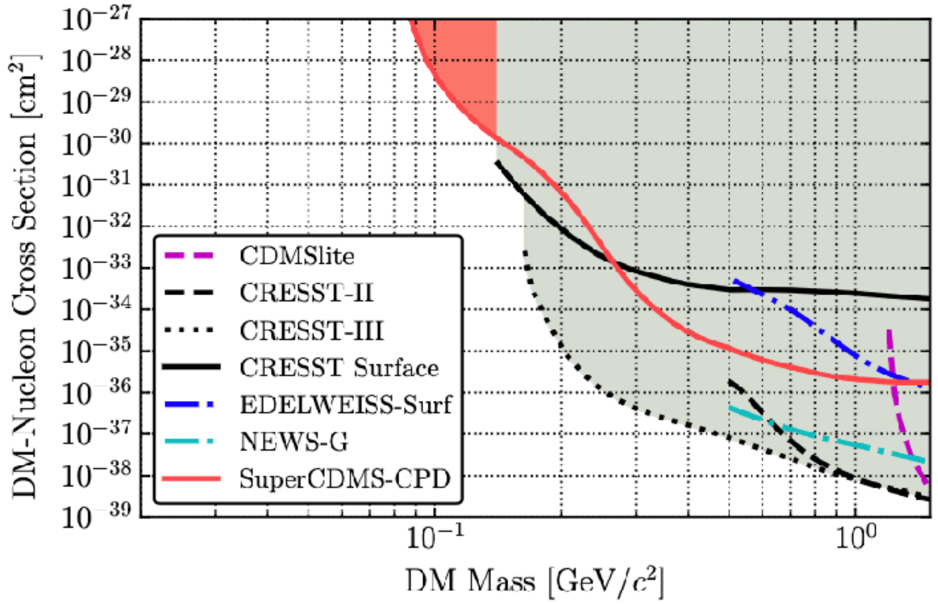

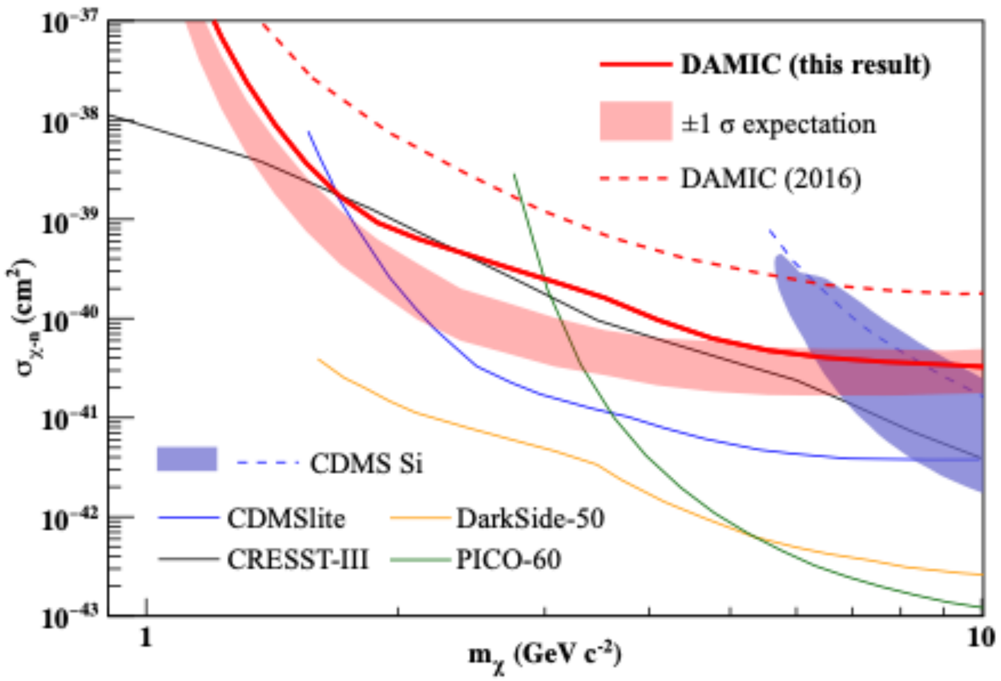

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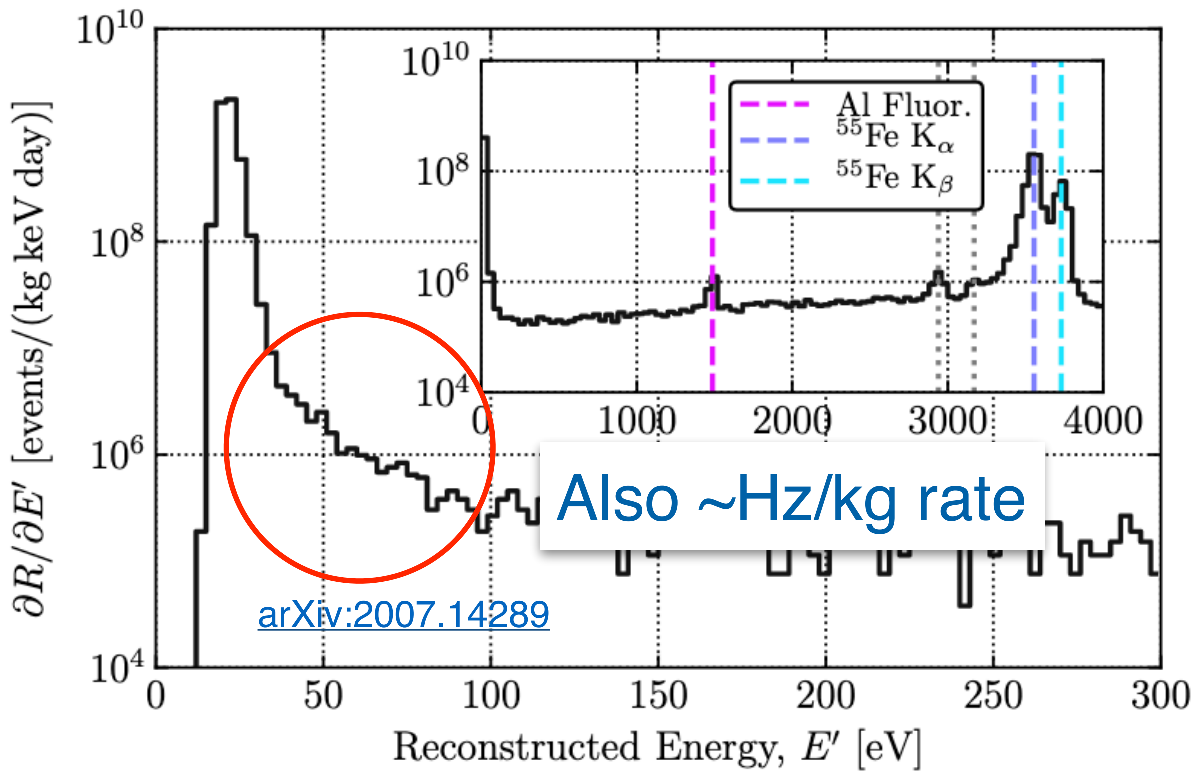

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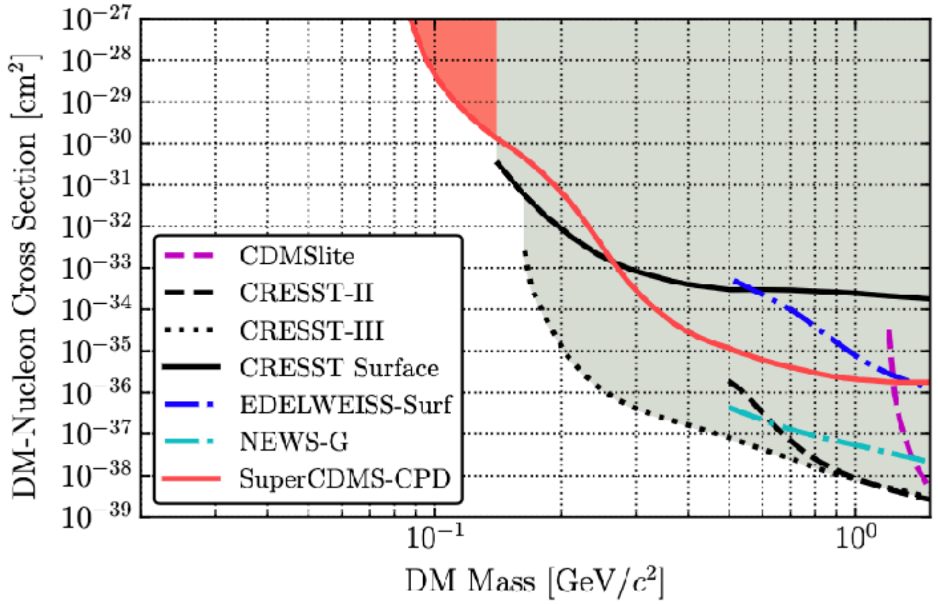

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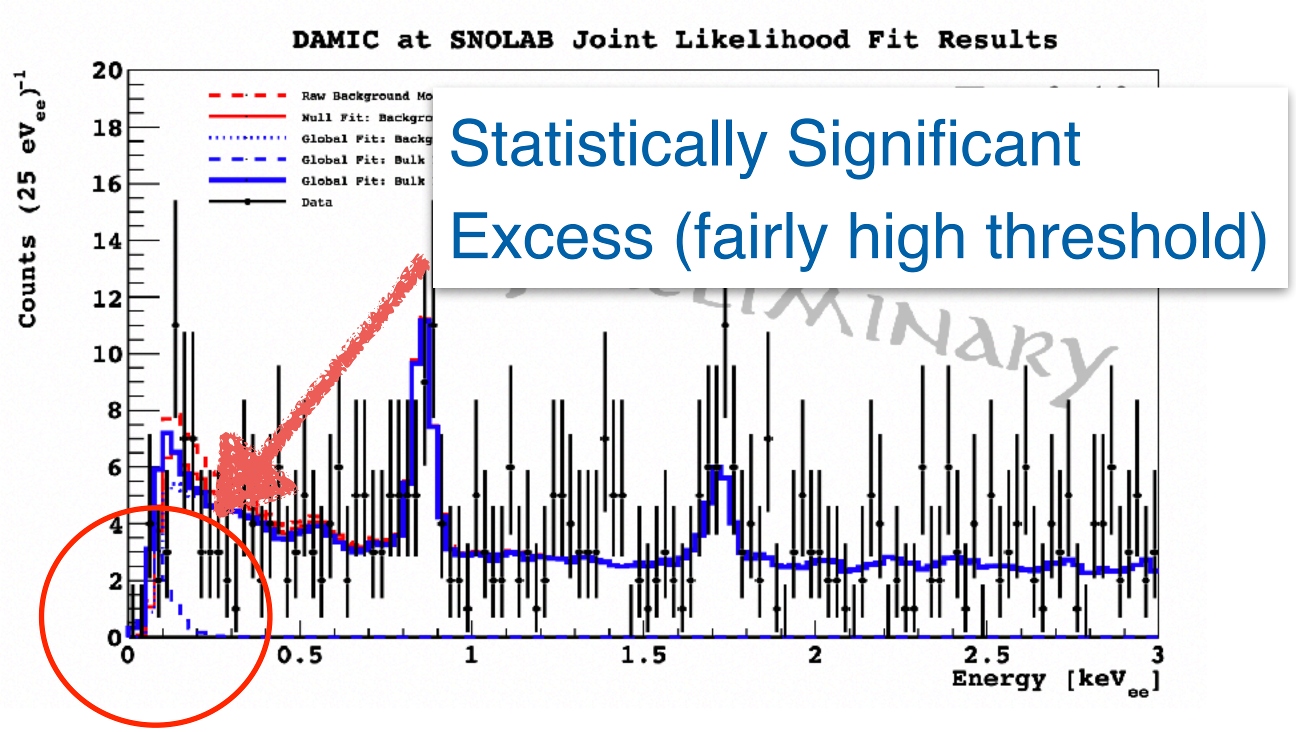
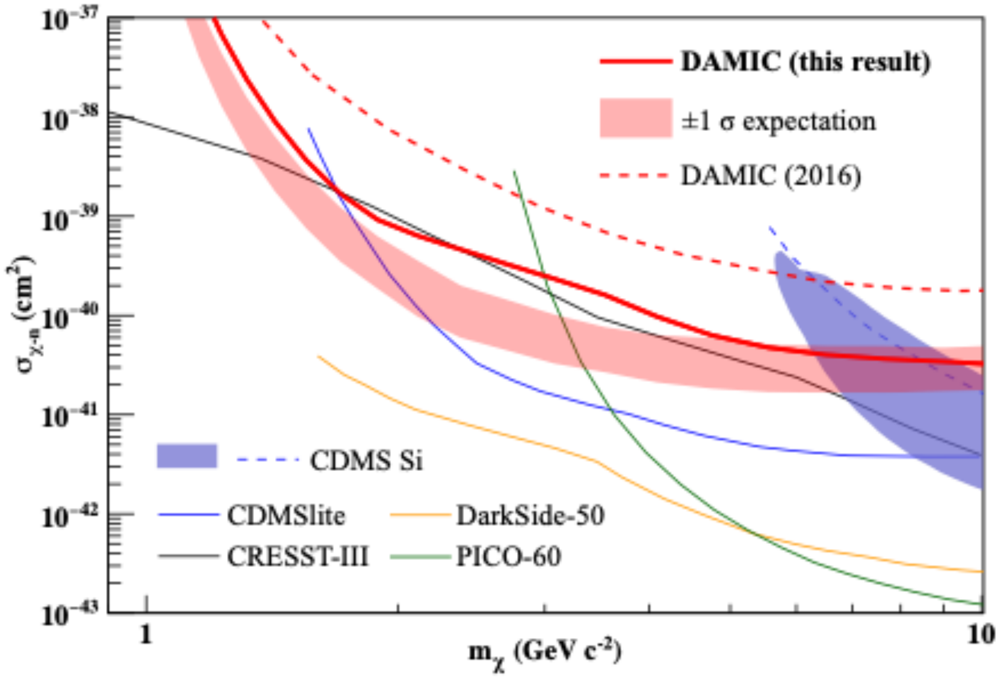


Statistically Significant Excess (fairly high threshold)

DAMIC @ SNOLAB
Low-background Si CCD

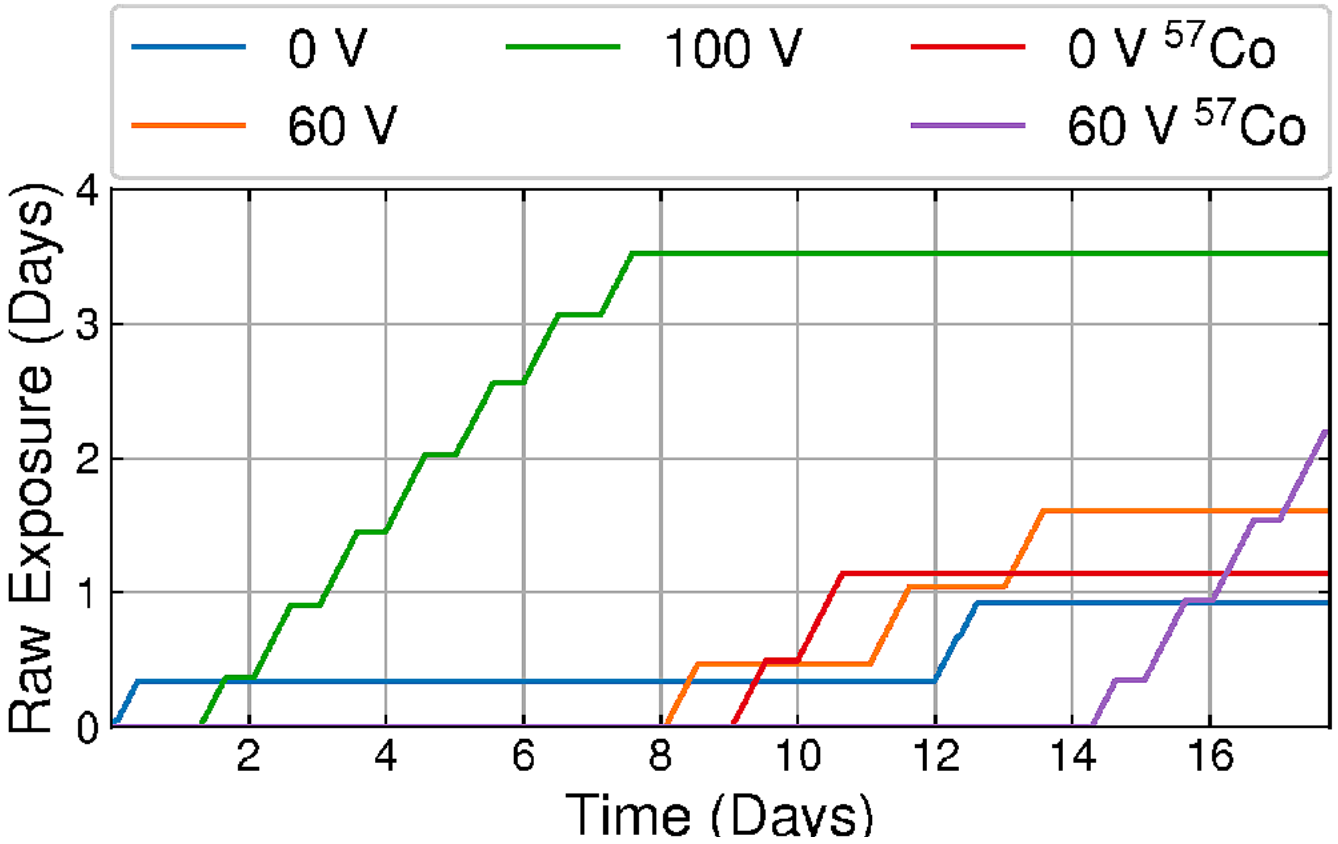


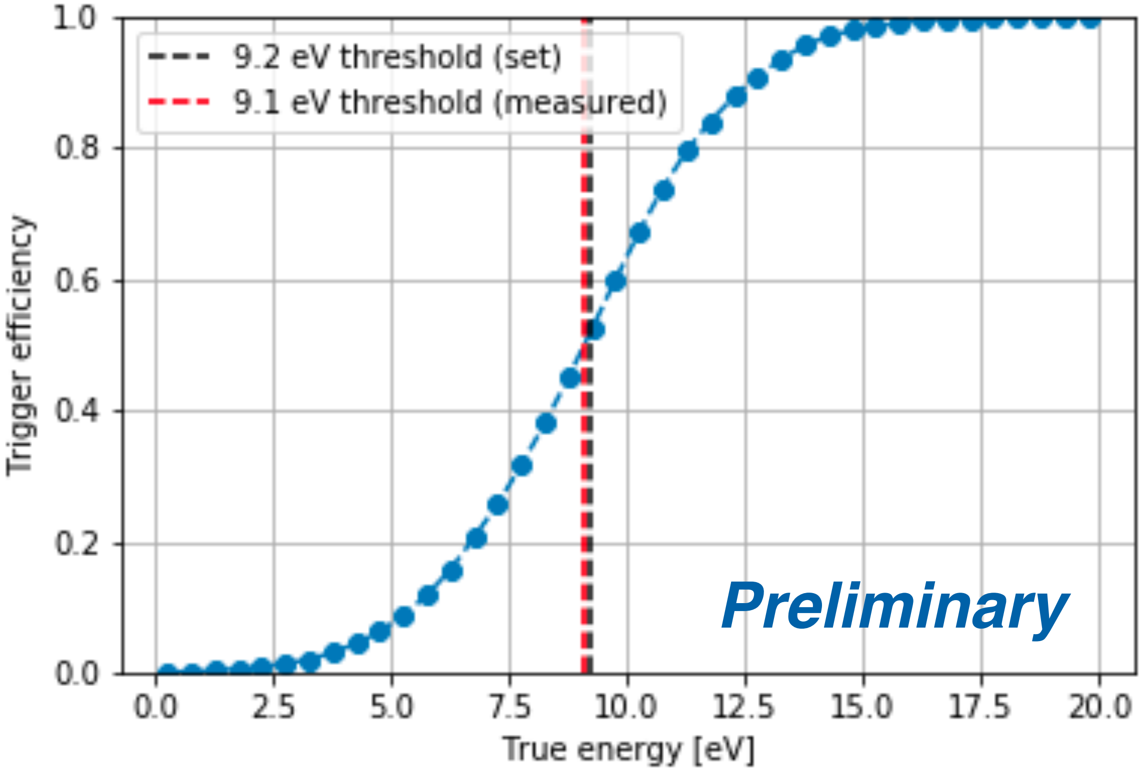
Plans ER/NR for Follow-up

- 1 gram-day of 0V data taken
  - Determine whether background is NR, ER, or detector-related
  - Continuous readout will allow NR limit with 9eV energy threshold
  - Coming late 2020

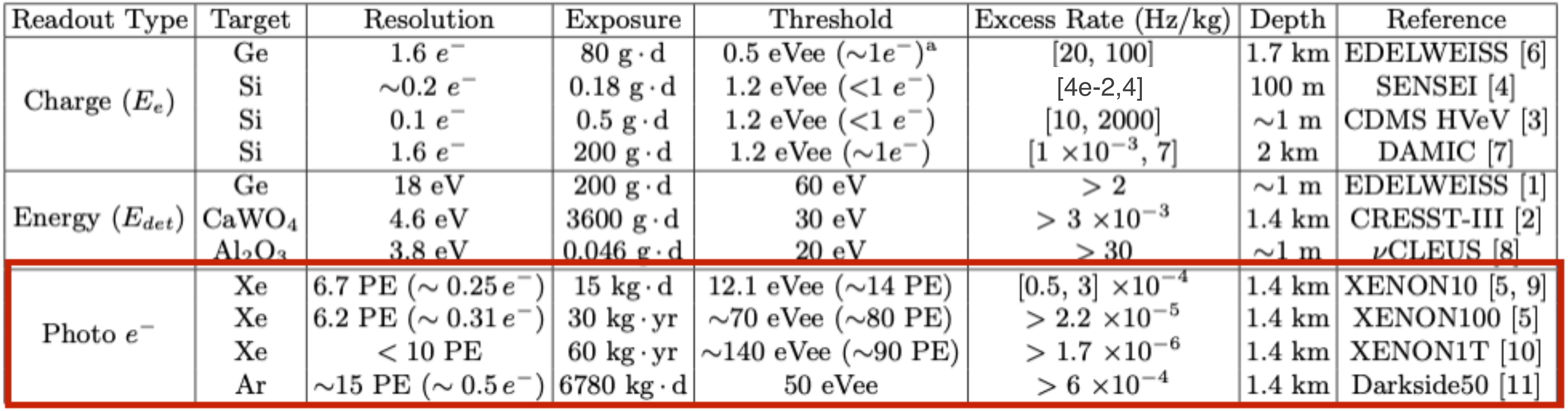
- More data taking at NEXUS
  - Currently operating underground, constructing lead shield
  - 3 eV resolution maintained in new facility

- Plans for larger payload, additional studies w/ high-energy gamma sources, different detector packaging





All Sub-GeV Searches



Readout Type	Target	Resolution	Exposure	Threshold	Excess Rate (Hz/kg)	Depth	Reference
Charge (E_e)	Ge	1.6 e^-	80 $\text{g}\cdot\text{d}$	0.5 eVee ($\sim 1e^-$)[a]	[20, 100]	1.7 km	EDELWEISS [6]
	Si	$\sim$0.2 e^-	0.18 $\text{g}\cdot\text{d}$	1.2 eVee ($<1\ e^-$)	[4e-2,4]	100 m	SENSEI [4]
	Si	0.1 e^-	0.5 $\text{g}\cdot\text{d}$	1.2 eVee ($<1\ e^-$)	[10, 2000]	$\sim$1 m	CDMS HVeV [3]
	Si	1.6 e^-	200 $\text{g}\cdot\text{d}$	1.2 eVee ($\sim 1e^-$)	[1×10^{-3}, 7]	2 km	DAMIC [7]
Energy (E_{det})	Ge	18 eV	200 $\text{g}\cdot\text{d}$	60 eV	> 2	$\sim$1 m	EDELWEISS [1]
	$CaWO_4$	4.6 eV	3600 $\text{g}\cdot\text{d}$	30 eV	$> 3\times10^{-3}$	1.4 km	CRESST-III [2]
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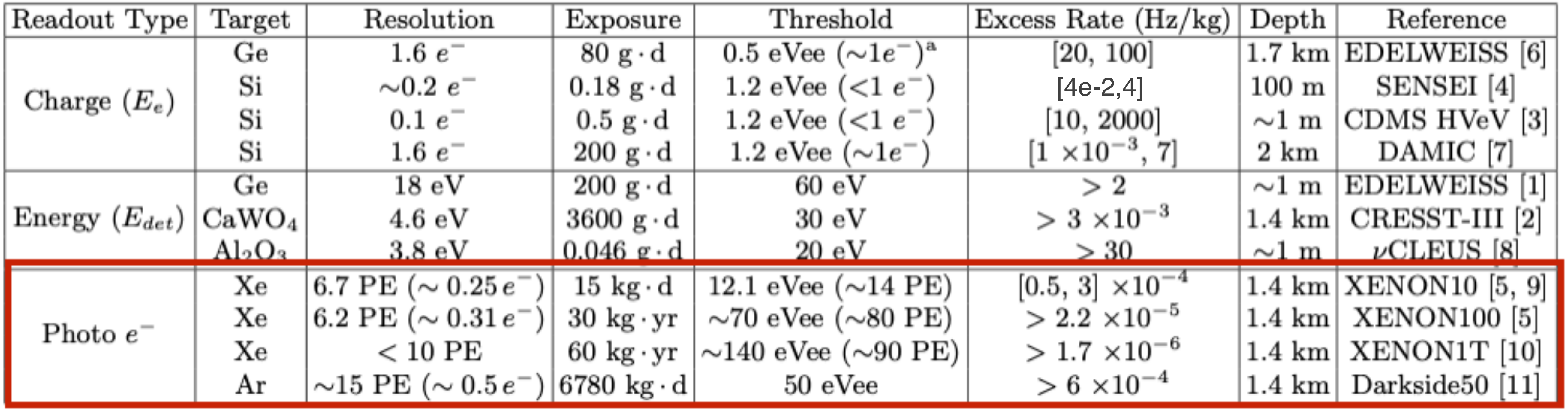
Photo e^-	Xe	6.7 PE ($\sim 0.25\,e^-$)	15 $\text{kg}\cdot\text{d}$	12.1 eVee ($\sim$14 PE)	[0.5, 3] $\times10^{-4}$	1.4 km	XENON10 [5, 9]
	Xe	6.2 PE ($\sim 0.31\,e^-$)	30 $\text{kg}\cdot\text{yr}$	$\sim$70 eVee ($\sim$80 PE)	$> 2.2\times10^{-5}$	1.4 km	XENON100 [5]
	Xe	$<$ 10 PE	60 $\text{kg}\cdot\text{yr}$	$\sim$140 eVee ($\sim$90 PE)	$> 1.7\times10^{-6}$	1.4 km	XENON1T [10]
	Ar	$\sim$15 PE ($\sim 0.5\,e^-$)	6780 $\text{kg}\cdot\text{d}$	50 eVee	$> 6\times10^{-4}$	1.4 km	Darkside50 [11]

Many others also observe excesses

-E_{det} readout: total rate unknown, **hard to compare**

-XENON10 measures total rate, but excess is **much smaller**

All Sub-GeV Searches



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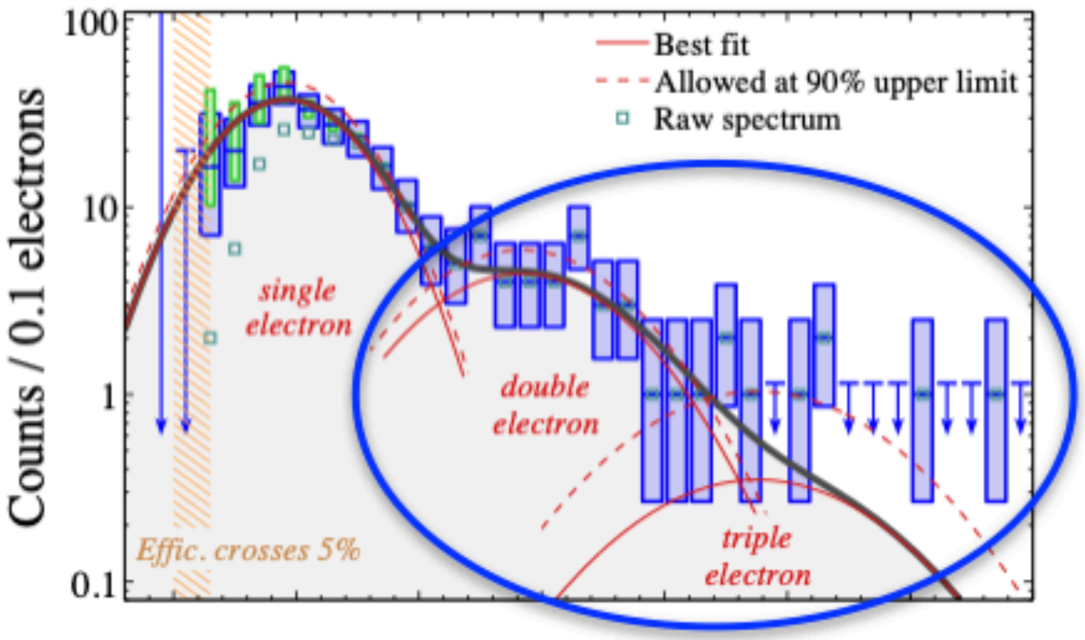
Many others also observe excesses

- *Edet* readout: total rate unknown, **hard to compare**

- XENON10 measures total rate, but excess is **much smaller**

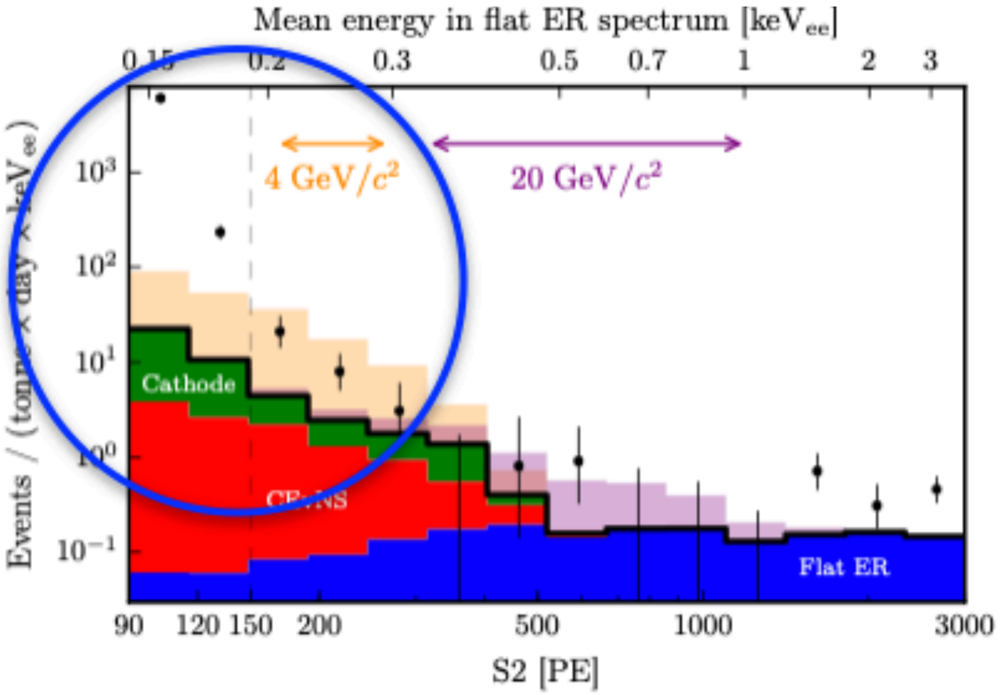
- XENON10/100/1T rates all **similar for same threshold**

Excesses in Liquid Nobles (Early 2020)



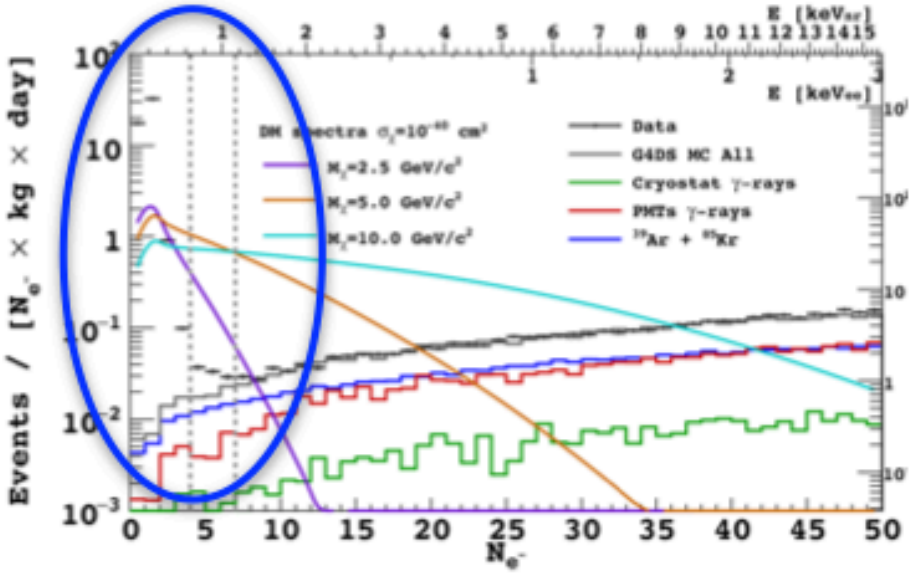
XENON10 S2 only

“likely to result from background processes”



XENON1T S2 only

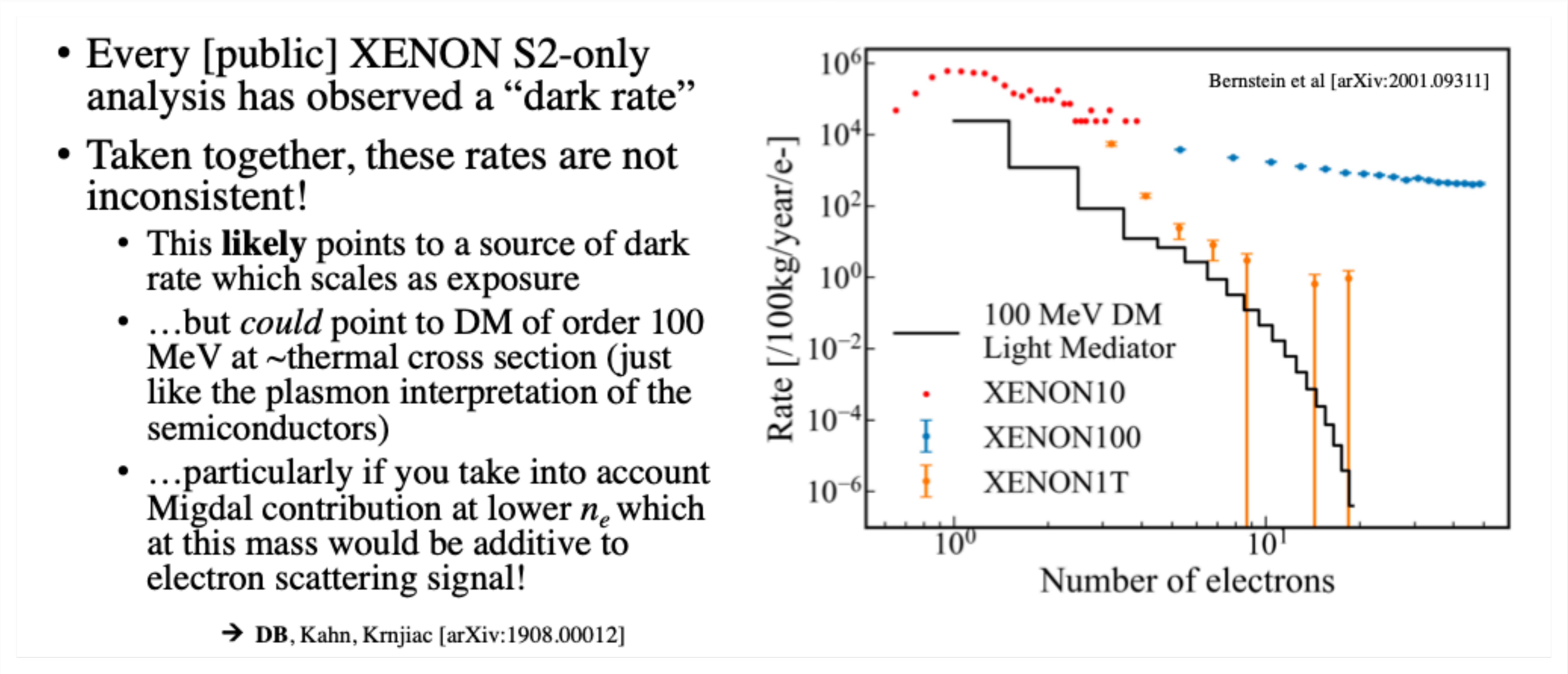
“likely due to unmodeled backgrounds”



Darkside-50 (Ar) S2 only

“believed to be from electrons trapped and subsequently released by impurities” (time correlation observed)

Also Earlier this Year…



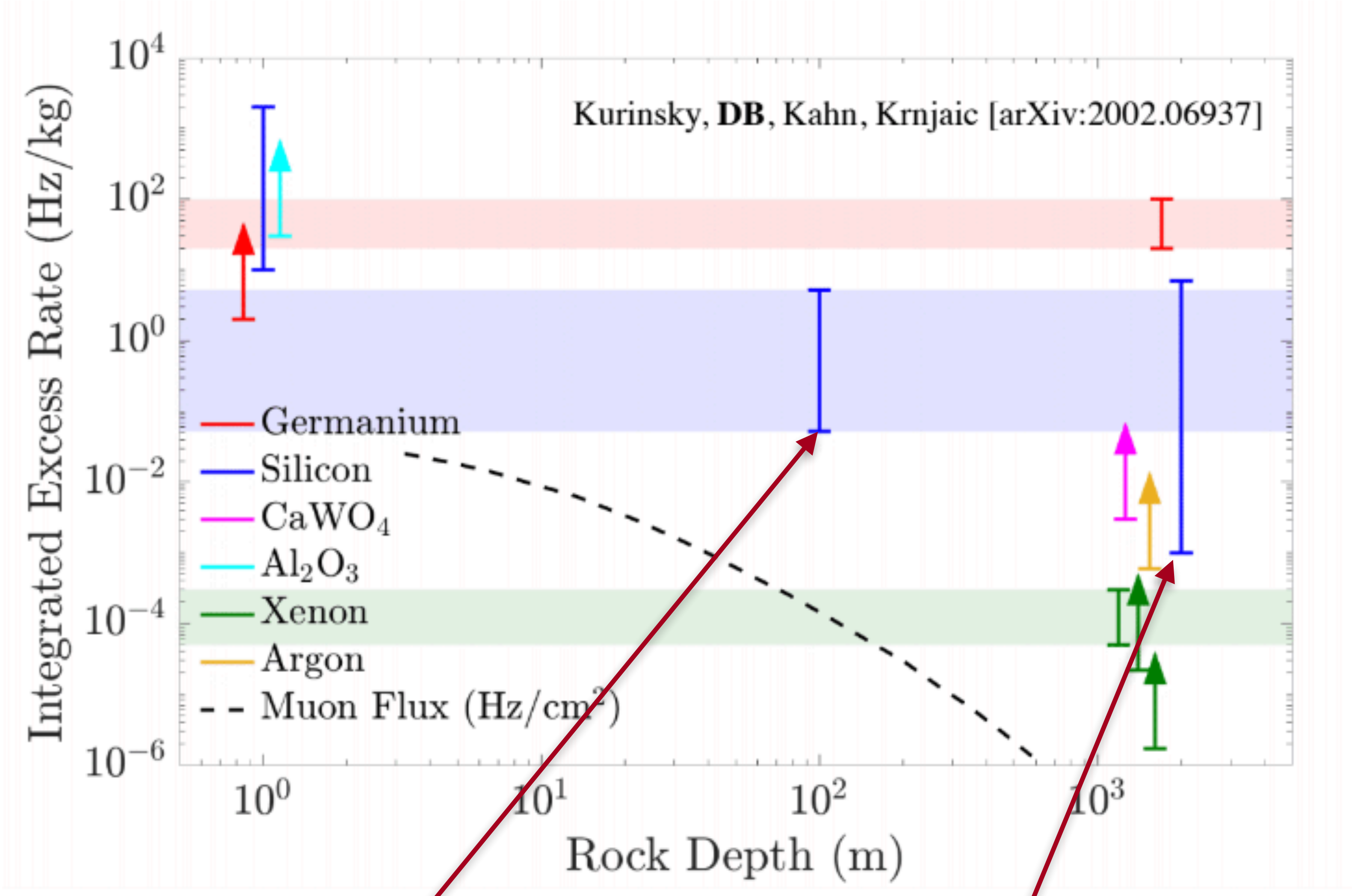
- Every [public] XENON S2-only analysis has observed a “dark rate”
- Taken together, these rates are not inconsistent!
  - This **likely** points to a source of dark rate which scales as exposure
  - …but *could* point to DM of order 100 MeV at ~thermal cross section (just like the plasmon interpretation of the semiconductors)
  - …particularly if you take into account Migdal contribution at lower n_e which at this mass would be additive to electron scattering signal!

→ **DB**, Kahn, Krnjiac [arXiv:1908.00012]

Slide Courtesy of Dan Baxter

Depth Dependence

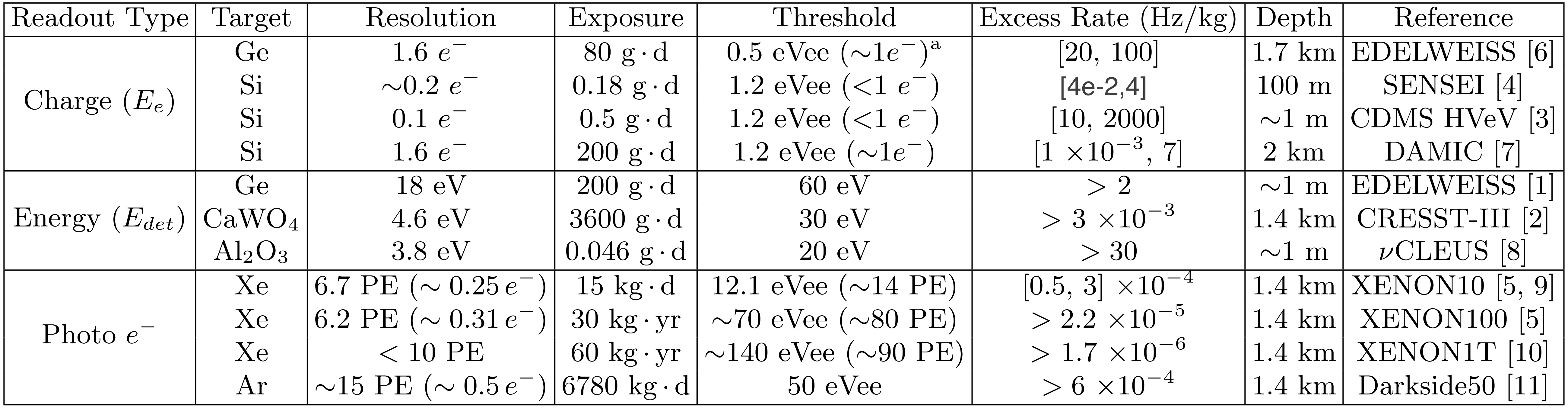
- Si/Ge Excesses show weak to no depth dependence
  - Upcoming datasets from SuperCDMS at SNOLAB (CUTE facility) and Fermilab @ MINOS (NEXUS facility and SENSEI) will add lower variance data points
- Sapphire detector is highest excess rate
- Lowest excess in LXe and LAr, intermediate rate in Ca2O3
- Rates correlate with material more than depth



MINOS Hall (SENSEI, SuperCDMS*)

SNOLAB/Gran Sasso/Modane (DAMIC, EDELWEISS, Xenon, DarkSide, SuperCDMS*)

Determining Signal Origin



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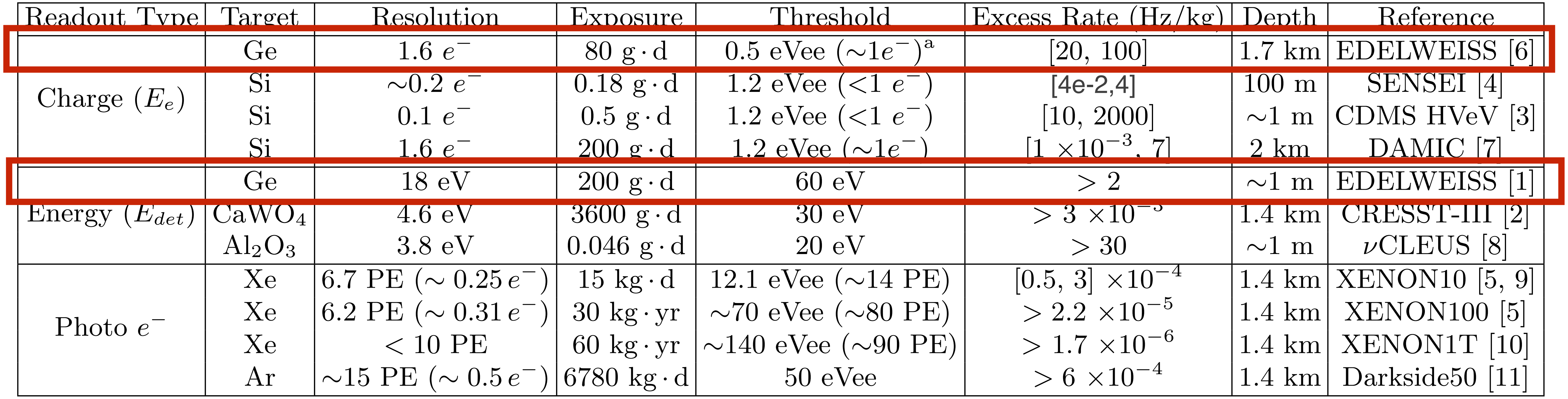
- First line of inquiry is to figure out if this is primarily an interaction with electrons or nucleons

Determining Signal Origin



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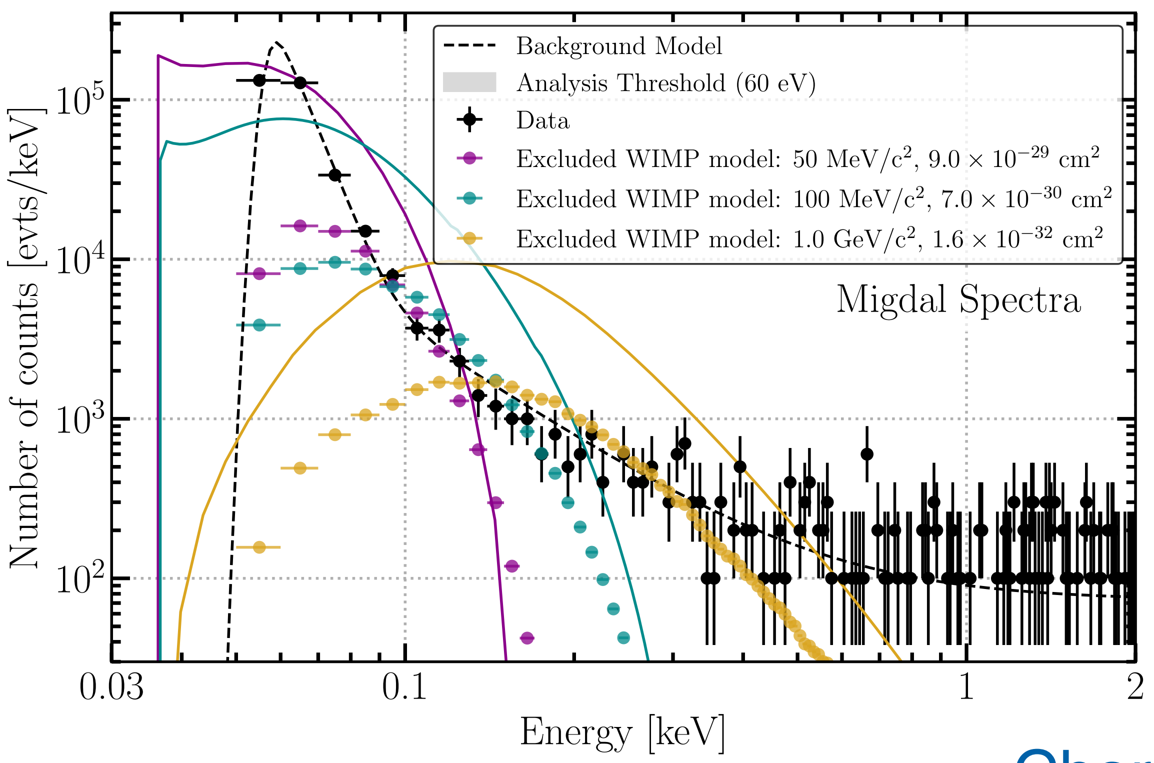
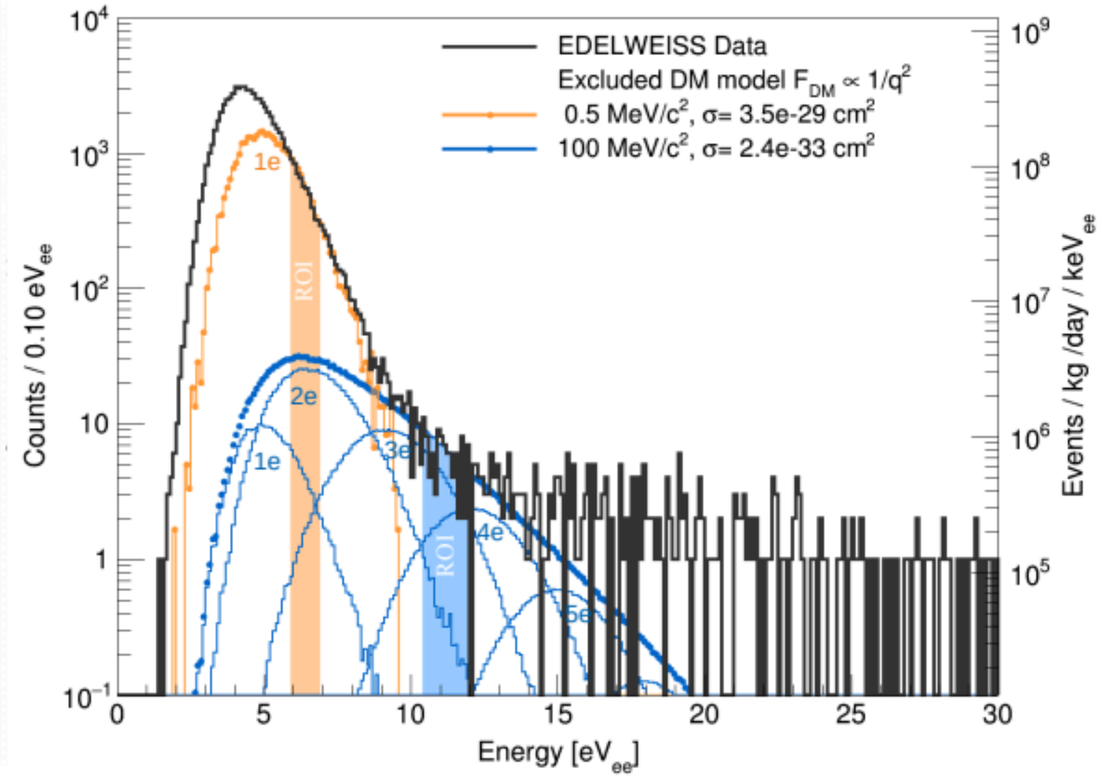
	$CaWO_4$	4.6 eV	$3600\ \text{g}\cdot\text{d}$	30 eV	$> 3\ \times 10^{-3}$	1.4 km	CRESST-III [2]
	Al_2O_3	3.8 eV	$0.046\ \text{g}\cdot\text{d}$	20 eV	> 30	$\sim$1 m	νCLEUS [8]
Photo e^-	Xe	6.7 PE ($\sim 0.25\, e^-$)	$15\ \text{kg}\cdot\text{d}$	12.1 eVee ($\sim$14 PE)	$[0.5, 3]\ \times 10^{-4}$	1.4 km	XENON10 [5, 9]
	Xe	6.2 PE ($\sim 0.31\, e^-$)	$30\ \text{kg}\cdot\text{yr}$	$\sim$70 eVee ($\sim$80 PE)	$> 2.2\ \times 10^{-5}$	1.4 km	XENON100 [5]
	Xe	$<$ 10 PE	$60\ \text{kg}\cdot\text{yr}$	$\sim$140 eVee ($\sim$90 PE)	$> 1.7\ \times 10^{-6}$	1.4 km	XENON1T [10]
	Ar	$\sim$15 PE ($\sim 0.5\, e^-$)	$6780\ \text{kg}\cdot\text{d}$	50 eVee	$> 6\ \times 10^{-4}$	1.4 km	Darkside50 [11]

- First line of inquiry is to figure out if this is primarily an interaction with electrons or nucleons

- The EDELWEISS data allows us to compare a total energy spectrum to a charge energy spectrum; the ratio of these values for a given energy helps identify the source of the events

Determining Signal Origin





$$Energy = E_{Det}$$

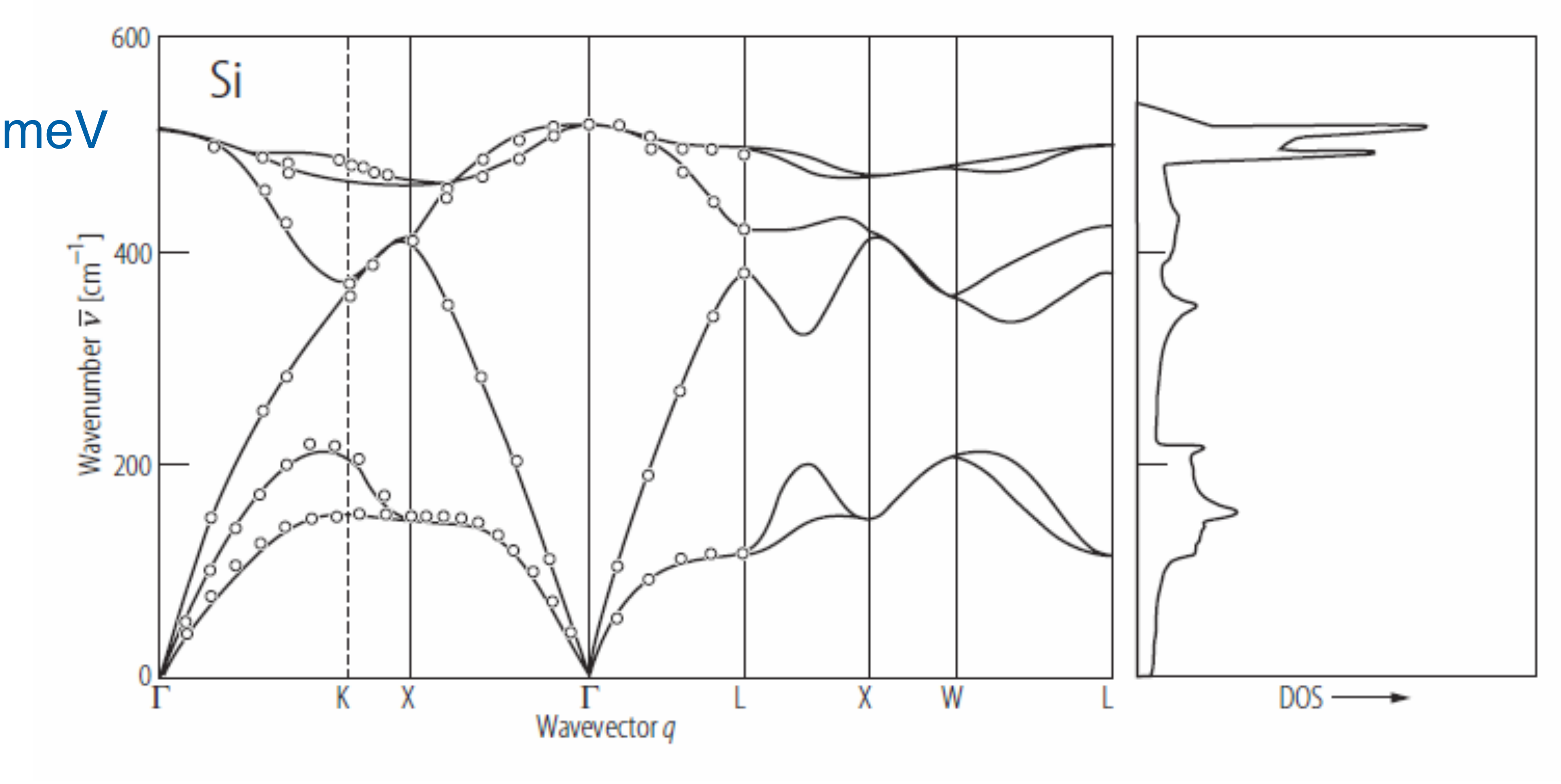
Charge Yield

$$E_e = E_{det}\left[y(E_{det}) + \frac{\epsilon_{eh}}{e \cdot V_{det}}\right]$$

- Conversion from total deposited energy (left) to charge production (right) will proceed differently depending on whether initial energy is given to electrons or nucleons

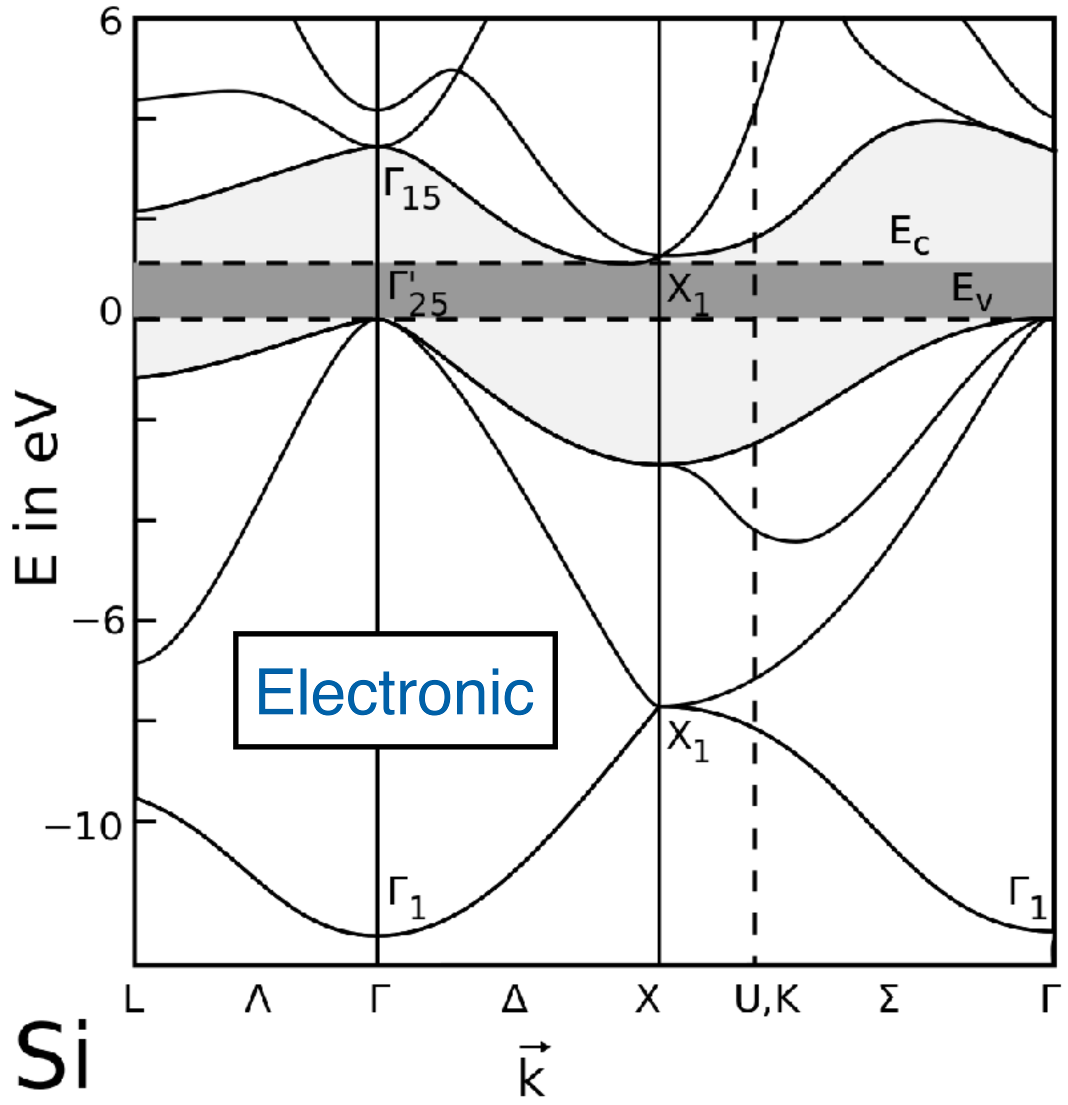
Relaxation via Phonons

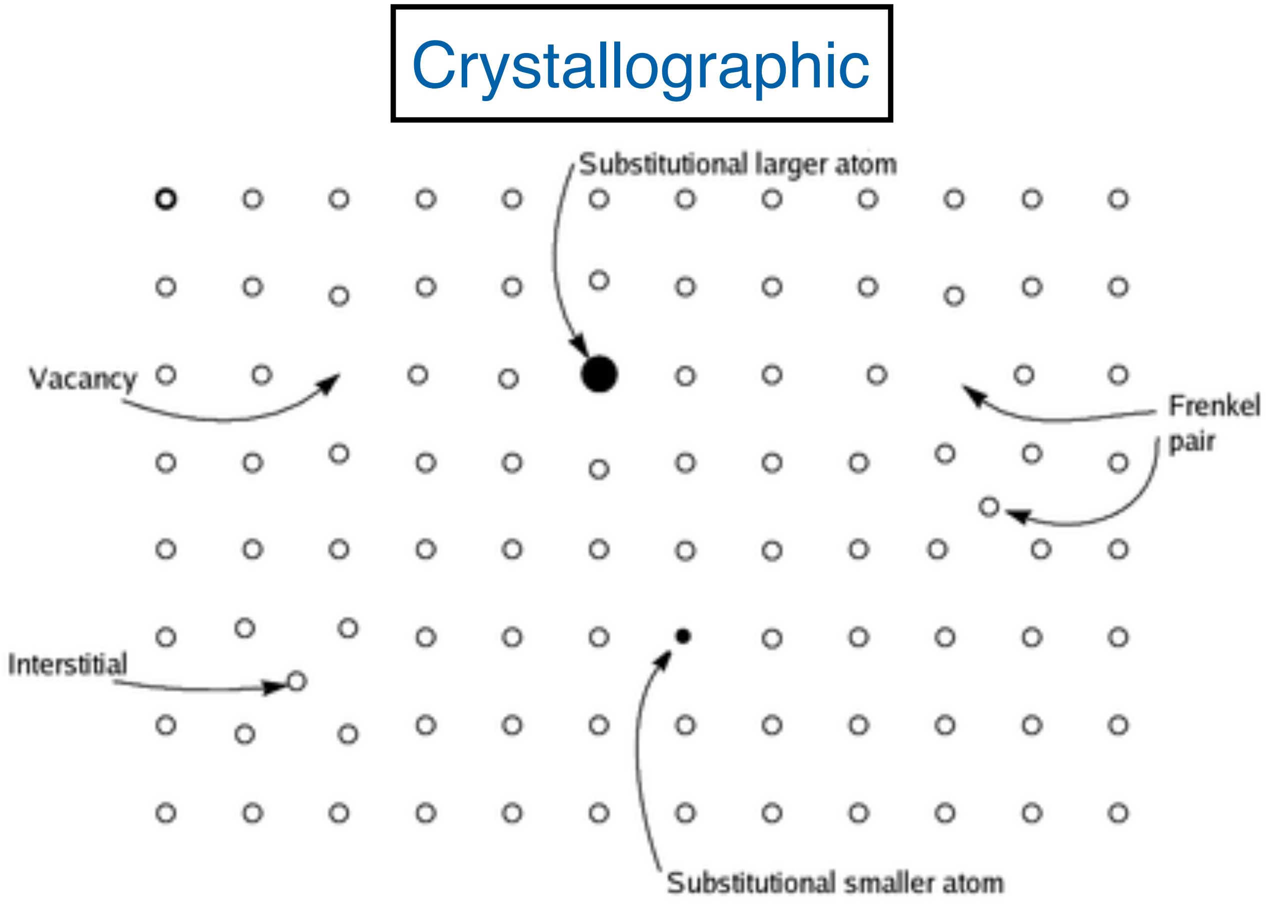
~60 meV



- Normal processes for hot carrier relaxation are impaction ionization (liberation of additional electrons) and phonon emission
  - Electon-phonon relaxation calculated via deformation potentials; high energy electrons always emit highest energy phonons
  - Electron energy cost finite and well characterized
  - Nucleon-phonon coupling more complex, energy cost of defects much less well understood (needs to be fit phenomenologically)
    - Not defined beyond the phonon limit; relaxation of 10 eV nucleon largely un-modeled

Relaxation via Quasiparticle Creation

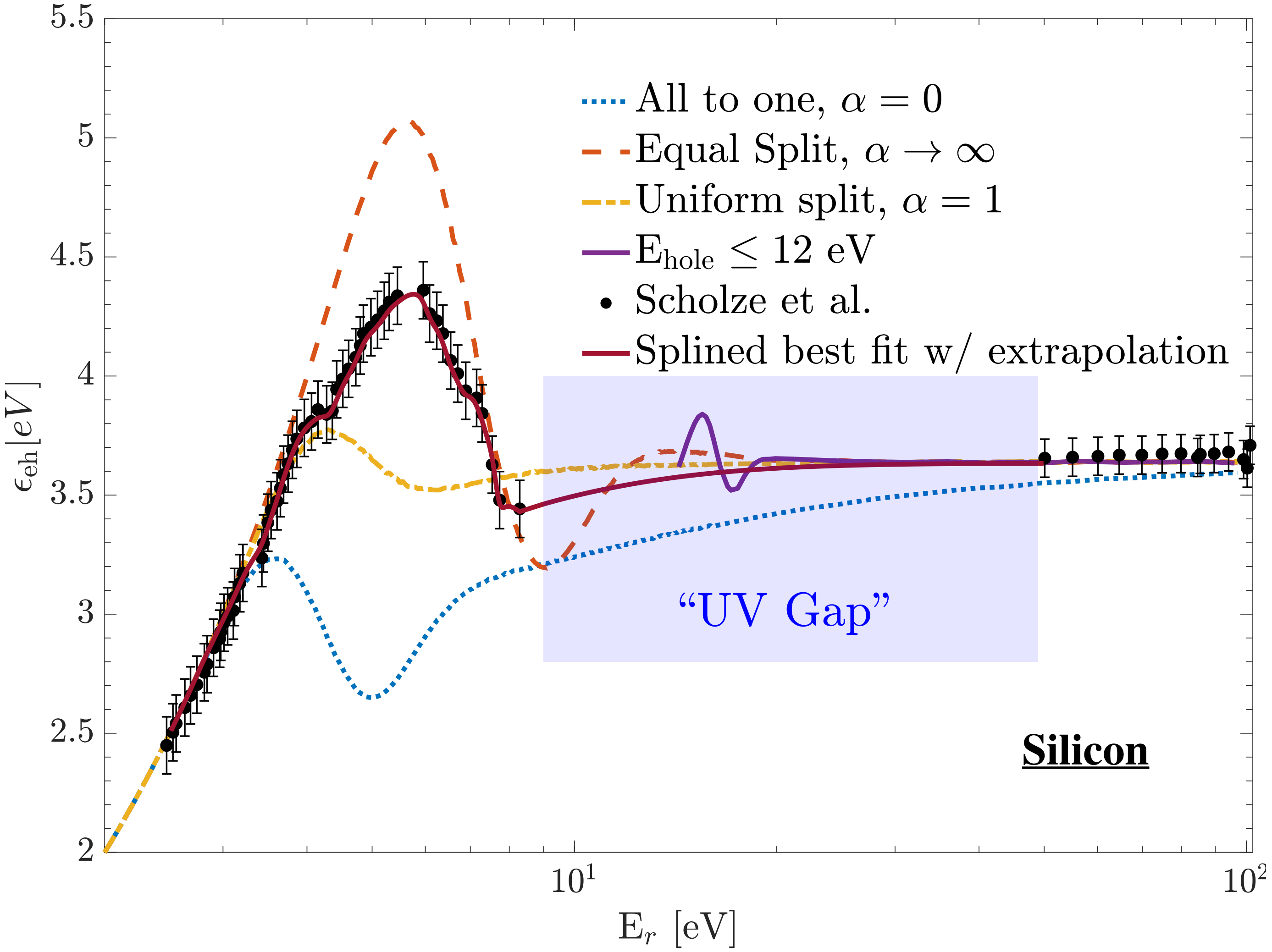




- Electronic excitations metastable in bulk material, energies and interactions well known
  - Electrons de-localized, strictly quantum mechanical
- Nuclear excitations myriad, energy highly dependent on momentum four-vector
  - some stable, some metastable, timescales poorly characterized
  - creation energy much greater than defect energy

Modeling Electron-Recoil Charge Yield

- For recoil energy Er, we expect a linear relationship between Ee and Er for electron-recoil processes
  - Poorly measured with photons below 100 eV (only one reference)
  - No measurements of charge yield for energy between ~5 eV and ~100 keV for electrons or protons
- Need this conversion to be able to compare Ee and Edet results.
  - If we believe it's linear across all energy scales, we can make some general observations
- Indirect measurements come from Electron Energy Loss Spectroscopy (EELS)

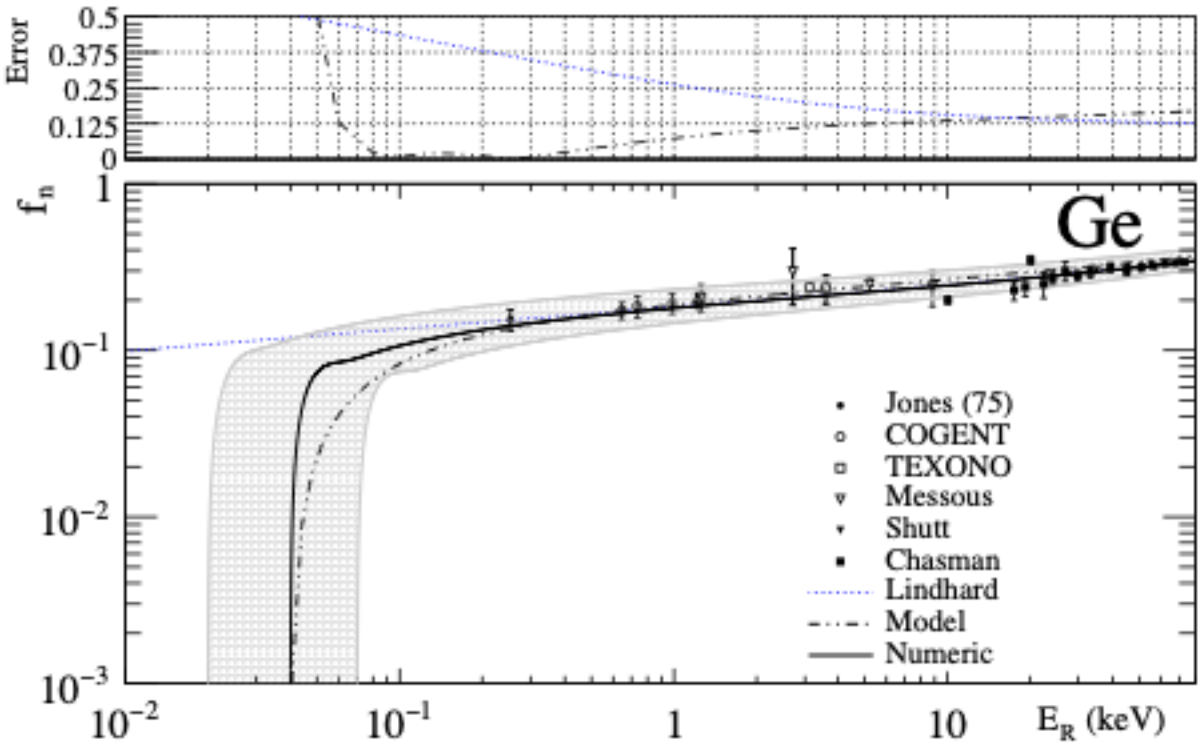


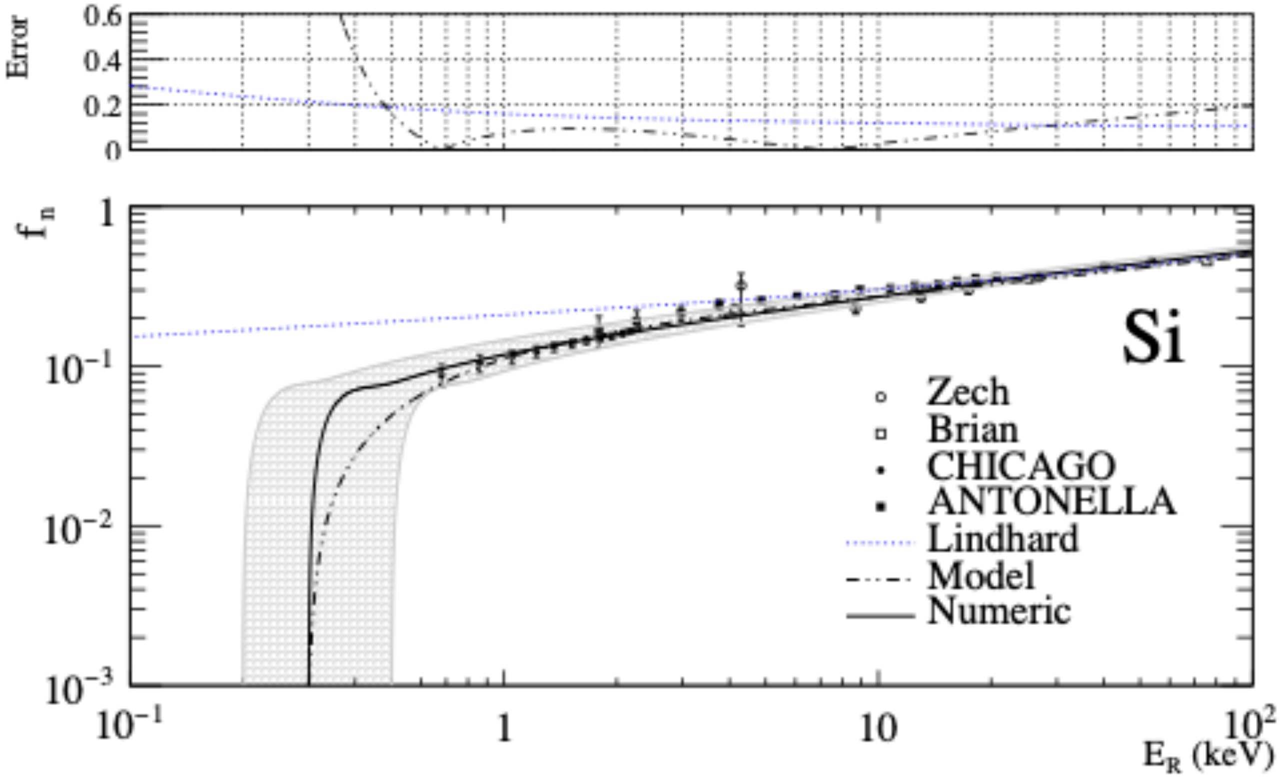
Ramanathan and Kurinsky, https://arxiv.org/abs/2004.10709

$$E_e = E_{det}\left[y(E_{det}) + \frac{\epsilon_{eh}}{e \cdot V_{det}}\right]$$

Understanding Low-Energy NR Yield

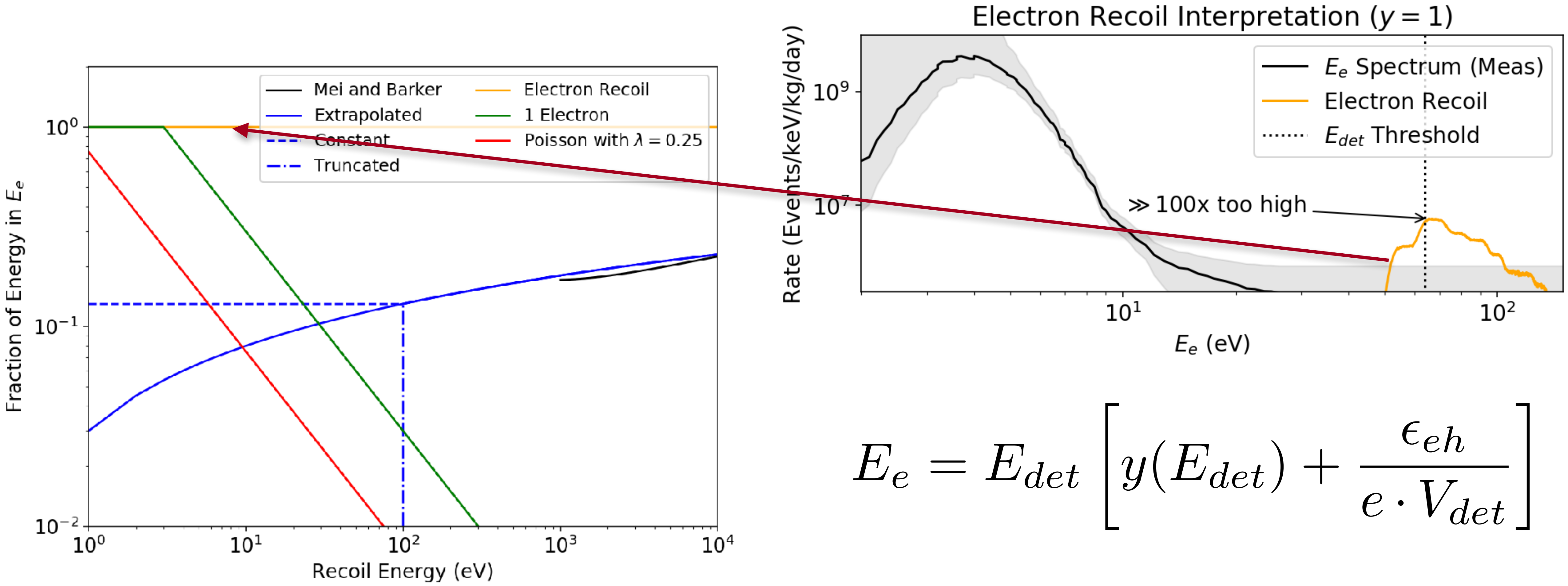
https://arxiv.org/pdf/2001.06503.pdf





- NR charge yield completely un-measured in Si below ~500 eV, very few measurements below 1 keV in Ge
  - LHe/LAr have a similar problem, but preliminary results suggest highly non-linear response in the low-energy region
- Consensus growing in the field that ~300 eV NR events will not generate charge in Si/Ge, similar effects for other solid-state detector technologies
  - Phenomenological model fits ~150 eV loss to nuclear lattice effects
- Displacement thresholds in Si/Ge are ~20-40 eV; at this scale, the picture off a recoiling nucleus is incorrect. Where between 20 eV and 1 keV does this really start to break down?
  - Plasmon has an energy of ~17 eV in both materials (24 eV in Al2O3)

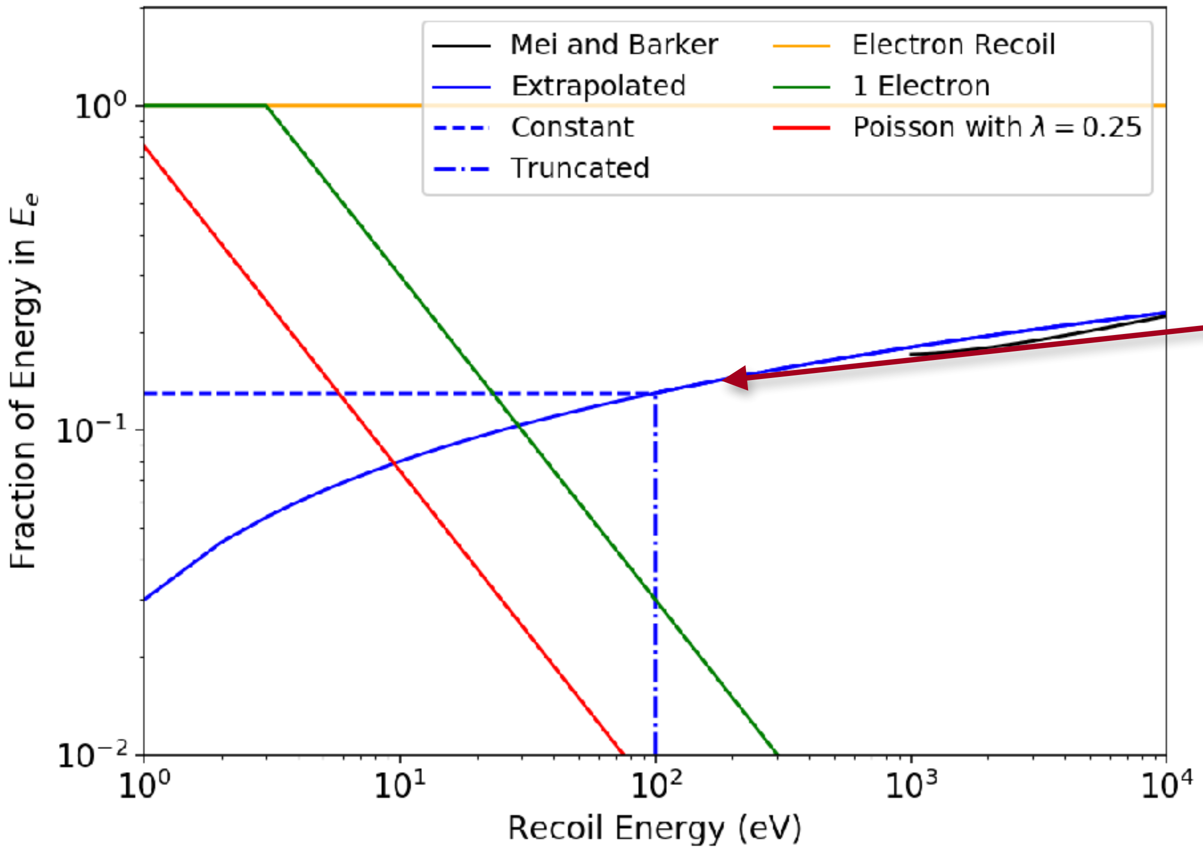
Electron Recoil Interpretation

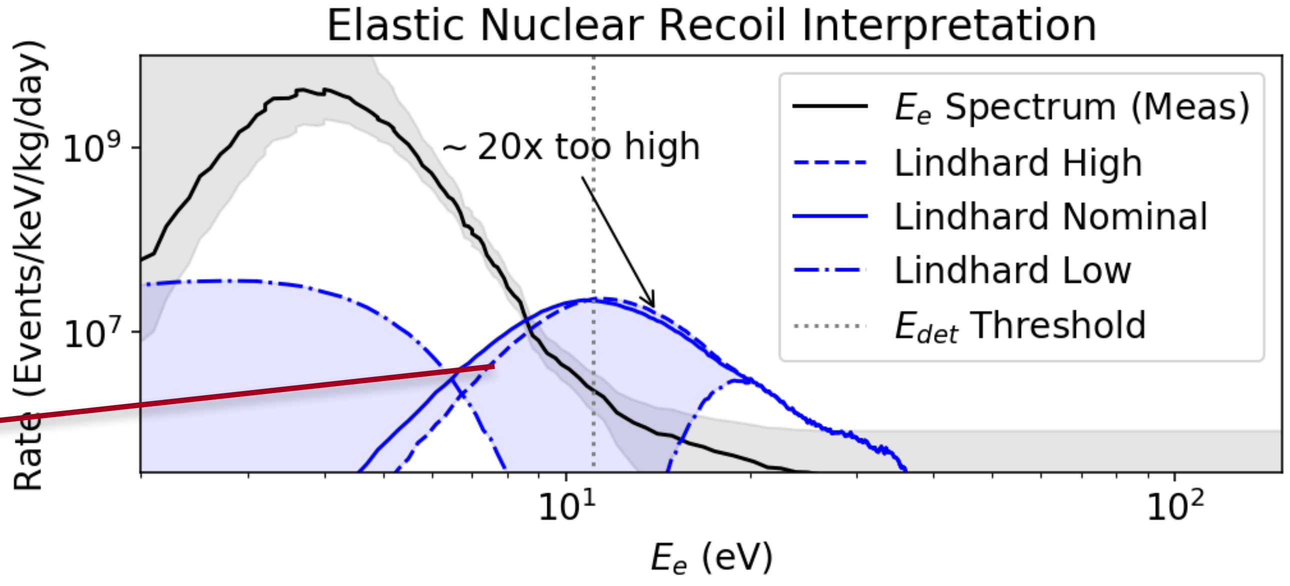


$$E_e = E_{det}\left[y(E_{det}) + \frac{\epsilon_{eh}}{e \cdot V_{det}}\right]$$

ER only prediction can’t fit under black curve: BAD FIT

Elastic Nuclear Recoil Interpretation





$$E_e = E_{det}\left[y(E_{det}) + \frac{\epsilon_{eh}}{e \cdot V_{det}}\right]$$

NR only prediction can’t fit under black curve: BAD FIT

Elastic Nuclear Recoil Interpretation

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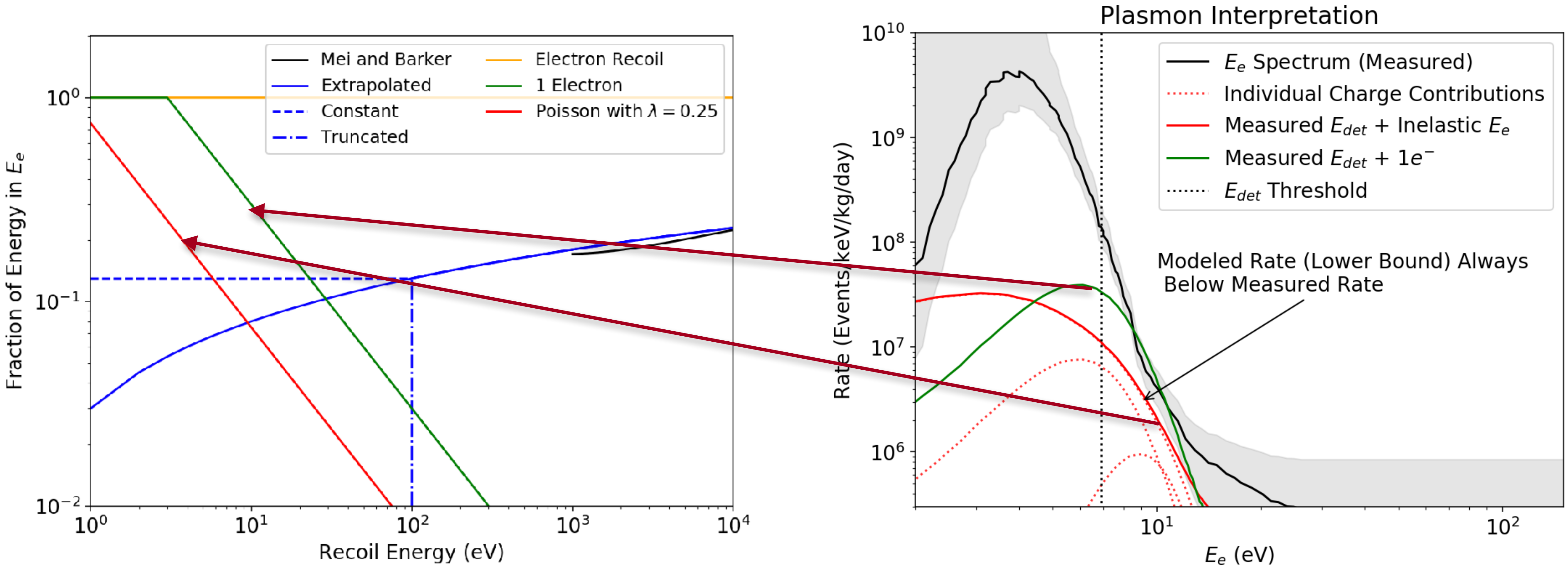
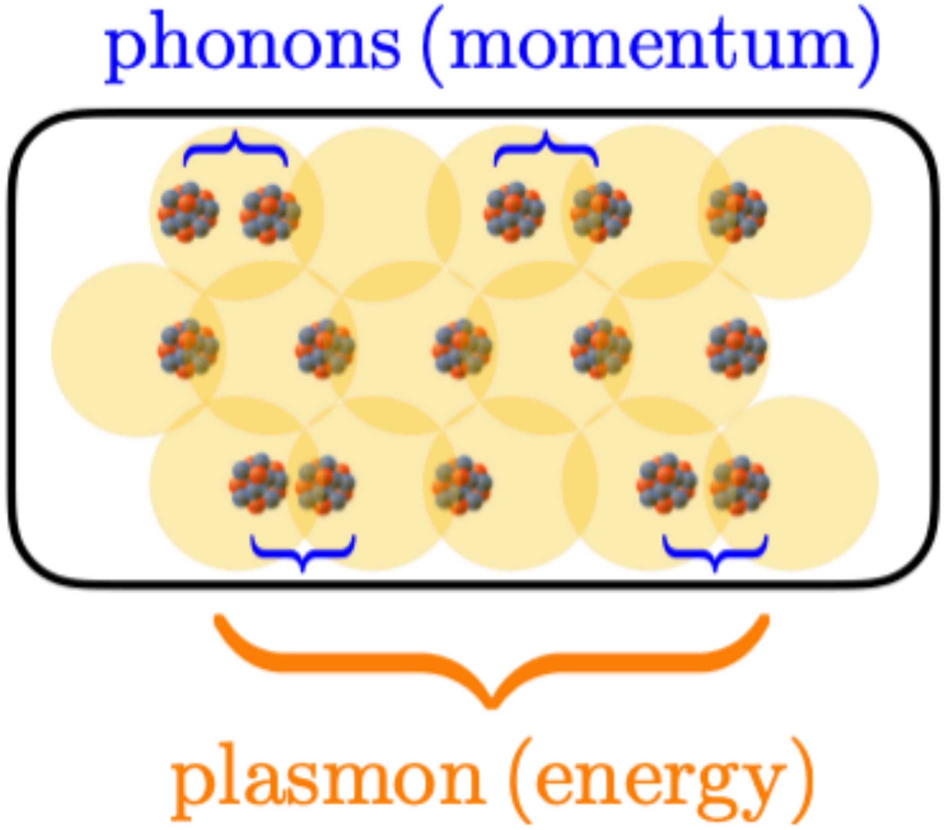


Model can fit under the black curve: 0V spectrum is consistent with HV spectrum only for highly inelastic yield curves

Consider Semiconductor Plasmons

Long wavelength charge oscillation between electrons/ions >> lattice spacing



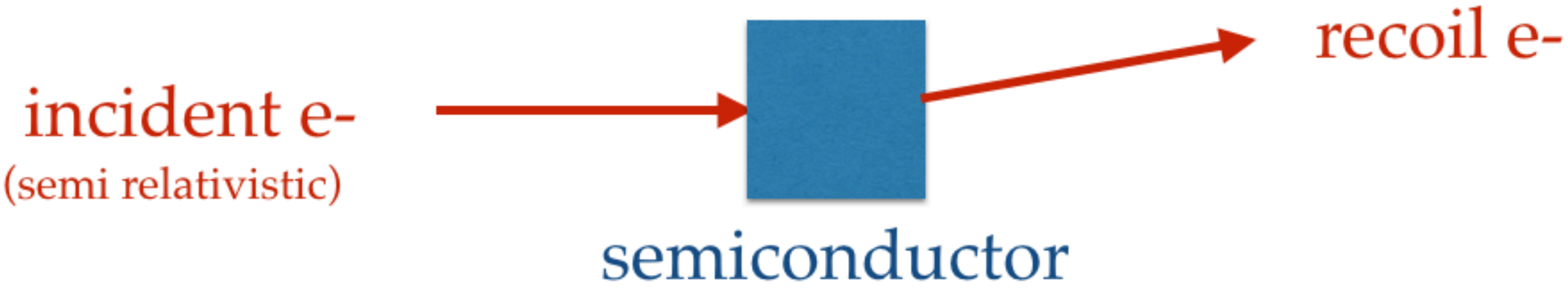
Plasmon excitation energy

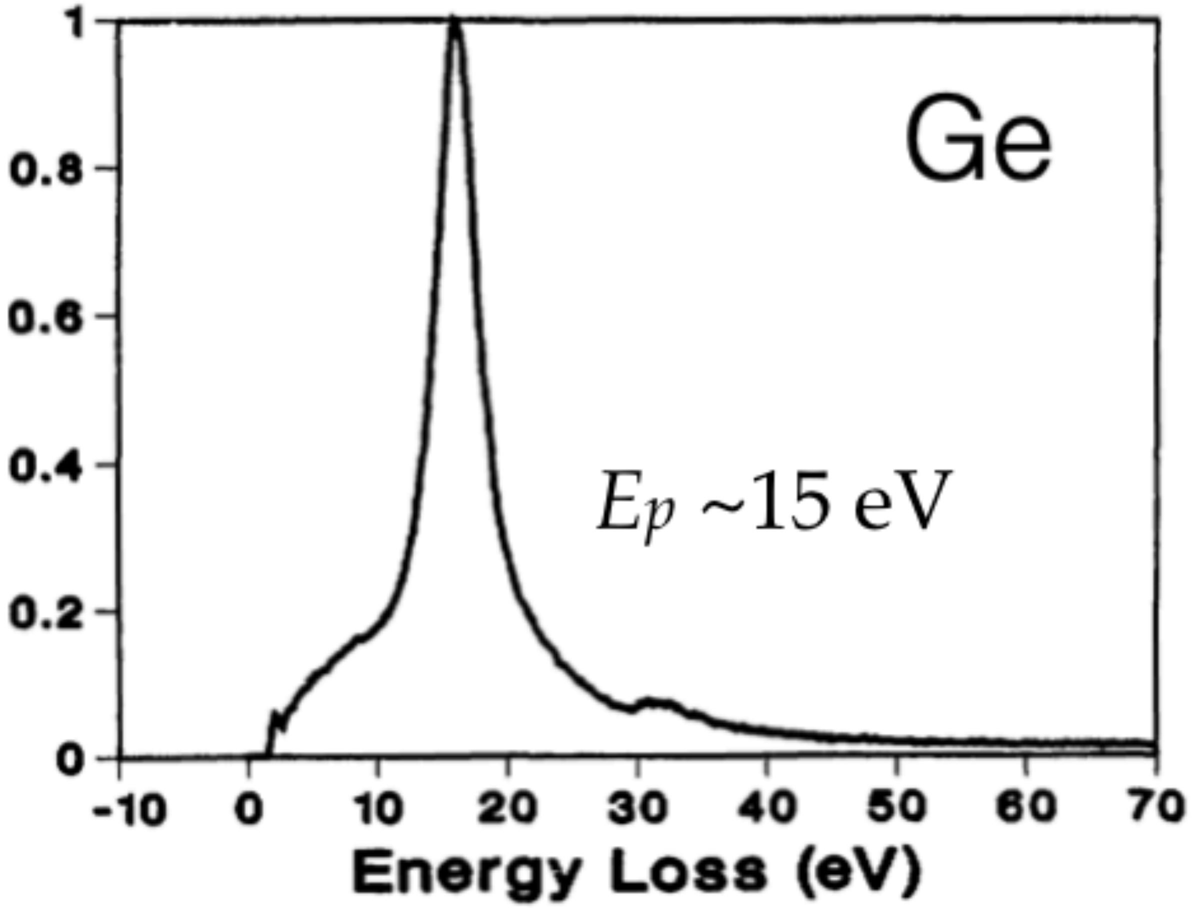
$$E_p \simeq \sqrt{\frac{4\pi\alpha n_e}{m_e}}$$

Low-P standing wave decays to e/h pairs or phonons

Breaks usual charge heat yield relationship

Electron Energy-Loss Spectroscopy (EELS)





$E_{det} \sim E_p \sim 15$ eV

independent of initial velocity

Qualitatively different charge/heat yield relation

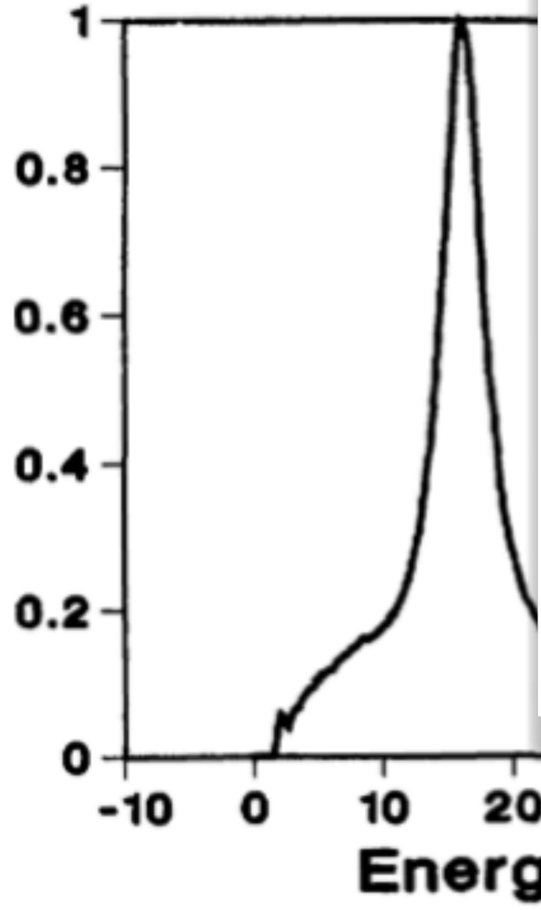
MK Kundmann PhD Thesis 1988

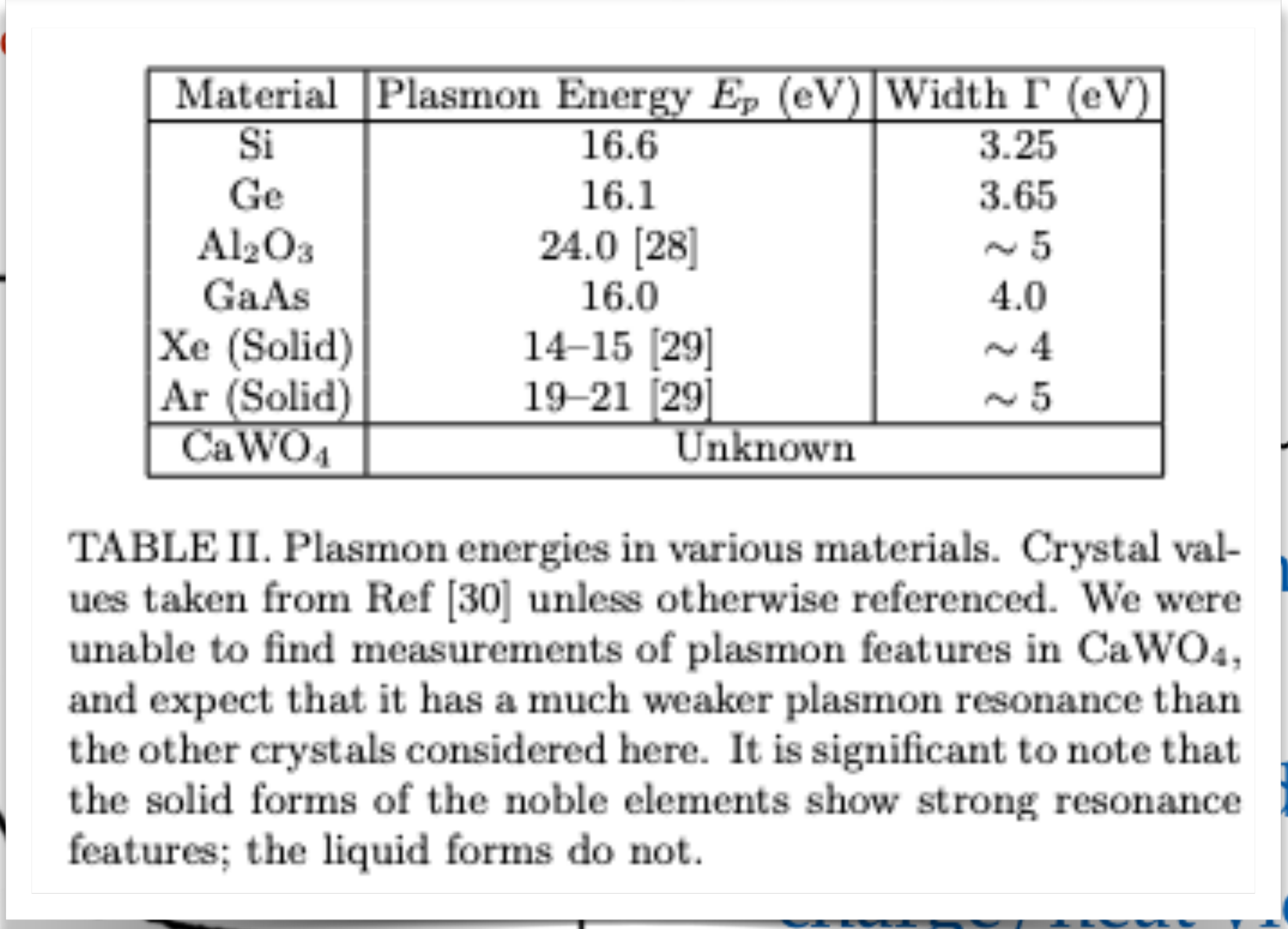
Electron Energy-Loss Spectroscopy (EELS)

incident e-

(semi relativisti

recoil e-





Material	Plasmon Energy E_p (eV)	Width Γ (eV)
Si	16.6	3.25
Ge	16.1	3.65
Al_2O_3	24.0 [28]	~ 5
GaAs	16.0	4.0
Xe (Solid)	14–15 [29]	~ 4
Ar (Solid)	19–21 [29]	~ 5
$CaWO_4$	Unknown	

TABLE II. Plasmon energies in various materials. Crystal values taken from Ref [30] unless otherwise referenced. We were unable to find measurements of plasmon features in $CaWO_4$, and expect that it has a much weaker plasmon resonance than the other crystals considered here. It is significant to note that the solid forms of the noble elements show strong resonance features; the liquid forms do not.

15 eV

itial velocity

ifferent

charge/heat yield relation

MK Kundmann PhD Thesis 1988

Possible Sources of Excesses at Low Energy

- SM Backgrounds?
  - Neutrinos
  - Photons
  - Protons/Electrons
  - Muons
  - Neutrons

- Experimental Effects?
  - Crystal Cracking
  - Non-poissonian leakage
  - Low-frequency noise
  - Earthquakes
  - Your Model Here

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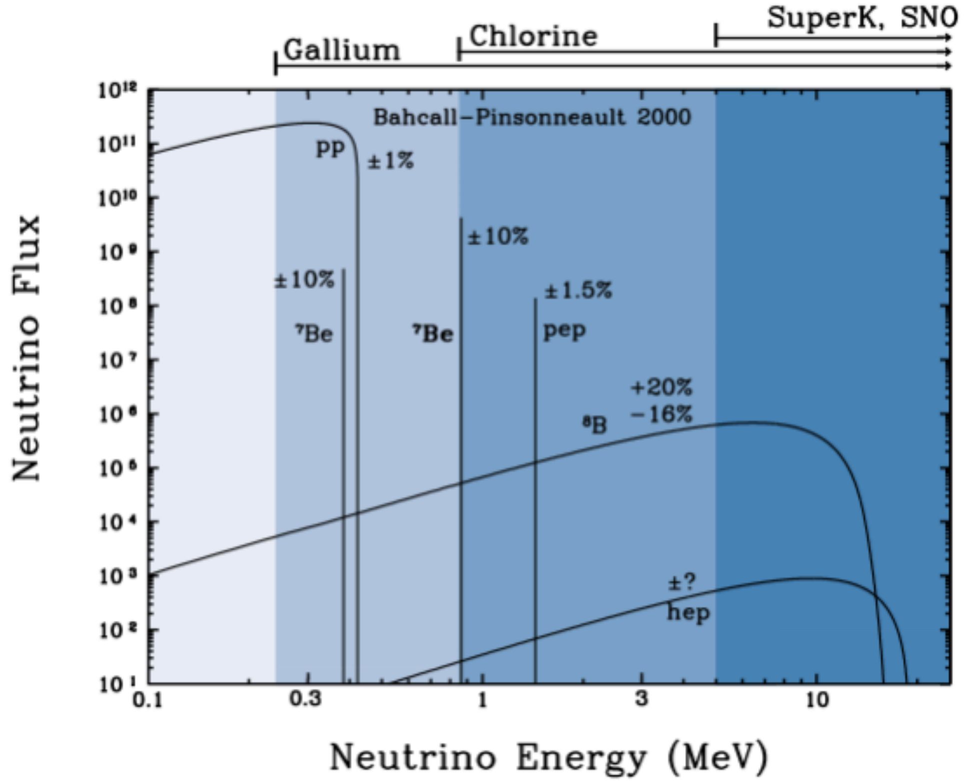
- New Physics?

Most abundant terrestrial neutrino flux



Can't make plasmon

$$E_R \sim \frac{2E_\nu^2}{M_{\mathrm{Ge}}} \sim 5\,\mathrm{eV}\left(\frac{E_\nu}{400\,\mathrm{keV}}\right)^2$$

need ~ 16 eV in Ge

$$\mathcal{R}_{pp} = N_{\mathrm{Ge}}\Phi_{pp}\sigma_{pp}^{\mathrm{coh}} \simeq 2.3\times10^{-6}\,\mathrm{Hz\,kg}^{-1}$$

… and flux too low

Figure from Gordan Krnjaic

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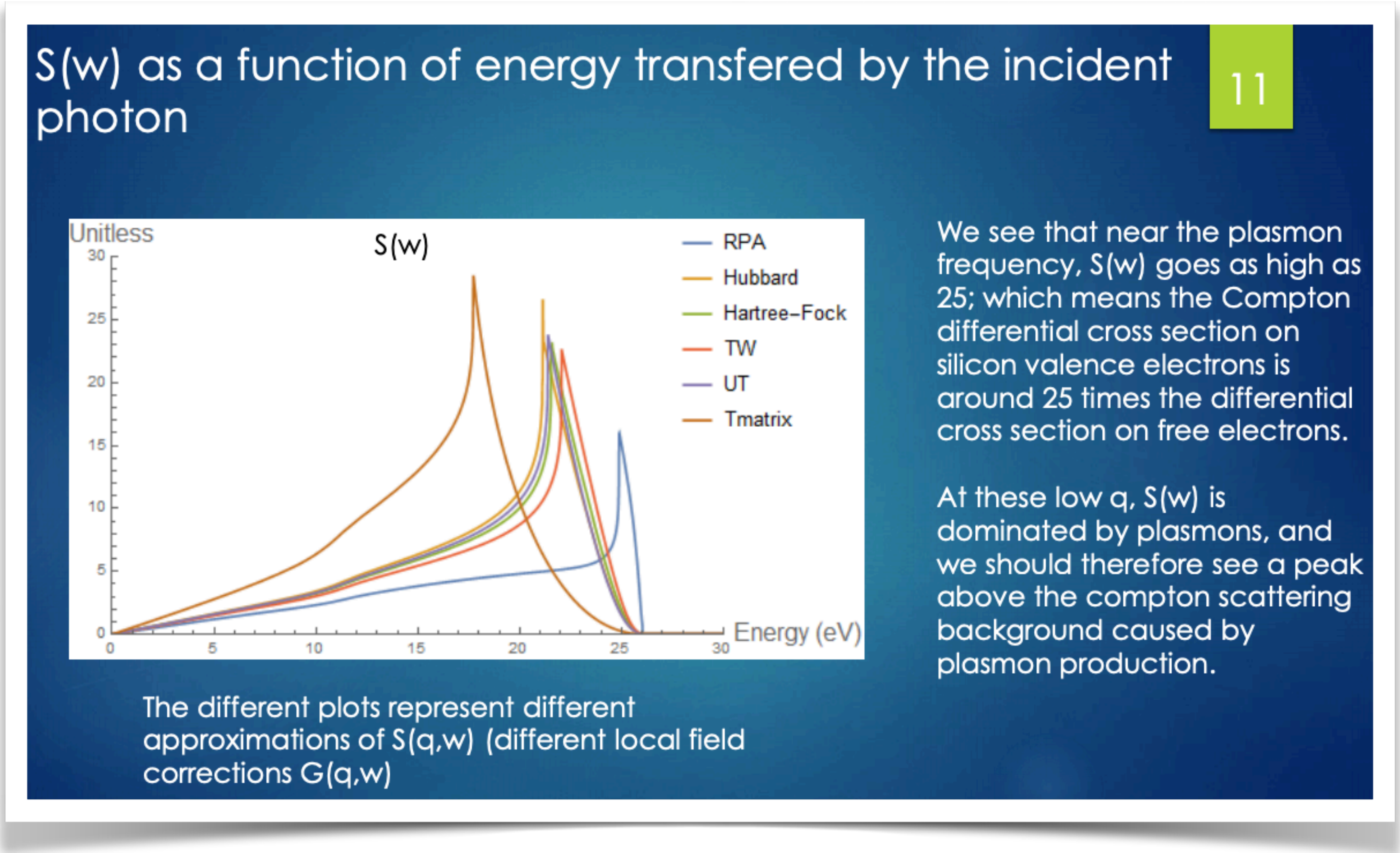
- New Physics?



S(w) as a function of energy transfered by the incident photon

11

We see that near the plasmon frequency, S(w) goes as high as 25; which means the Compton differential cross section on silicon valence electrons is around 25 times the differential cross section on free electrons.

At these low q, S(w) is dominated by plasmons, and we should therefore see a peak above the compton scattering background caused by plasmon production.

The different plots represent different approximations of S(q,w) (different local field corrections G(q,w)

[Emile Michaud Photon Production of Plasmon Talk]

Small Enhancement to Compton Rate

Possible Sources of Excesses at Low Energy

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  - ~~Photons~~
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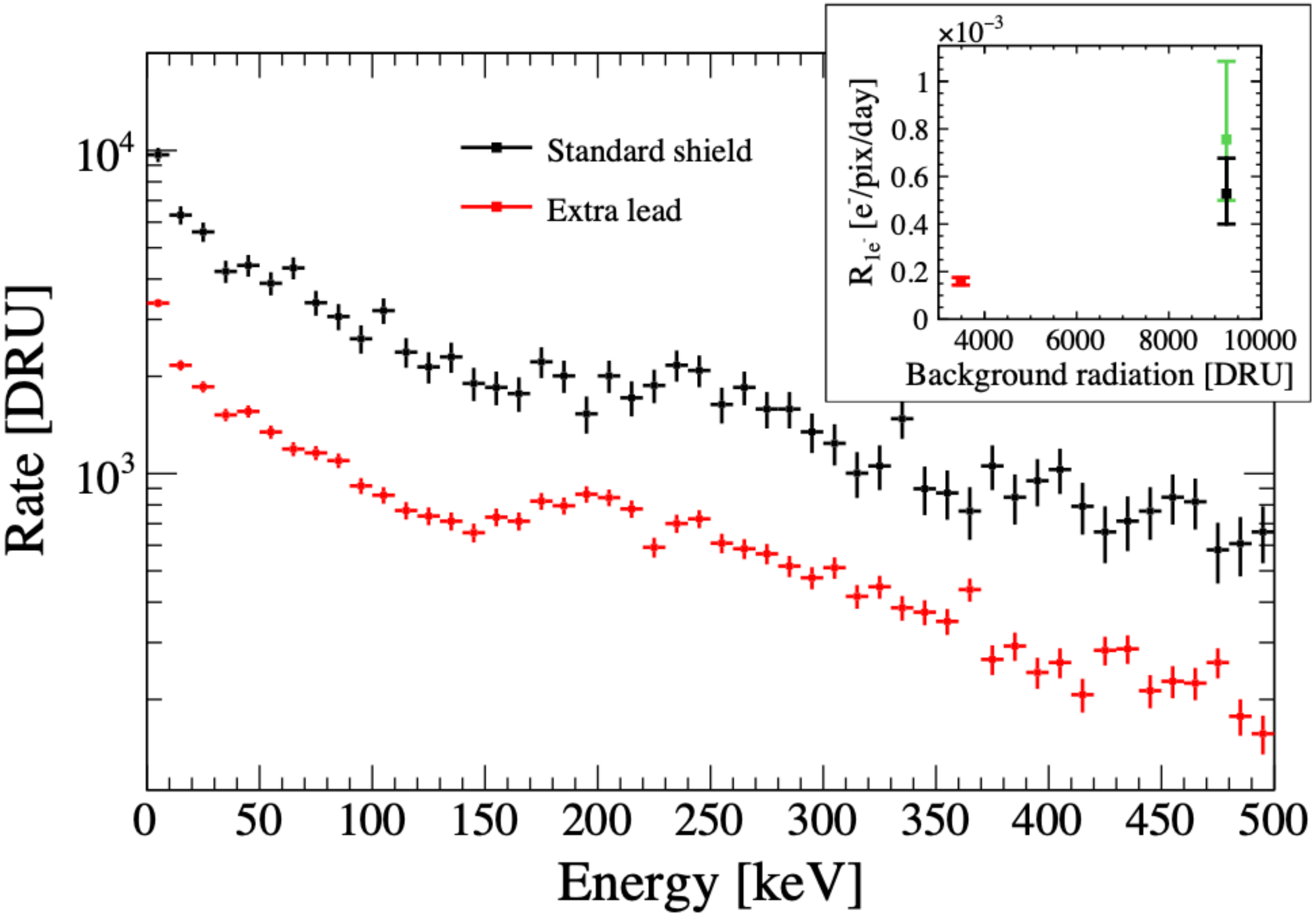

SENSEI Observes some reduction in low-energy charge excess with additional shielding, possibly indicative of gamma-induced secondary radiation (can't explain CRESST)

Possible Sources of Excesses at Low Energy

- SM Backgrounds?
  - ~~Neutrinos~~
  - ~~Photons~~
  - ~~Protons/Electrons~~
  - Muons
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- Experimental Effects?
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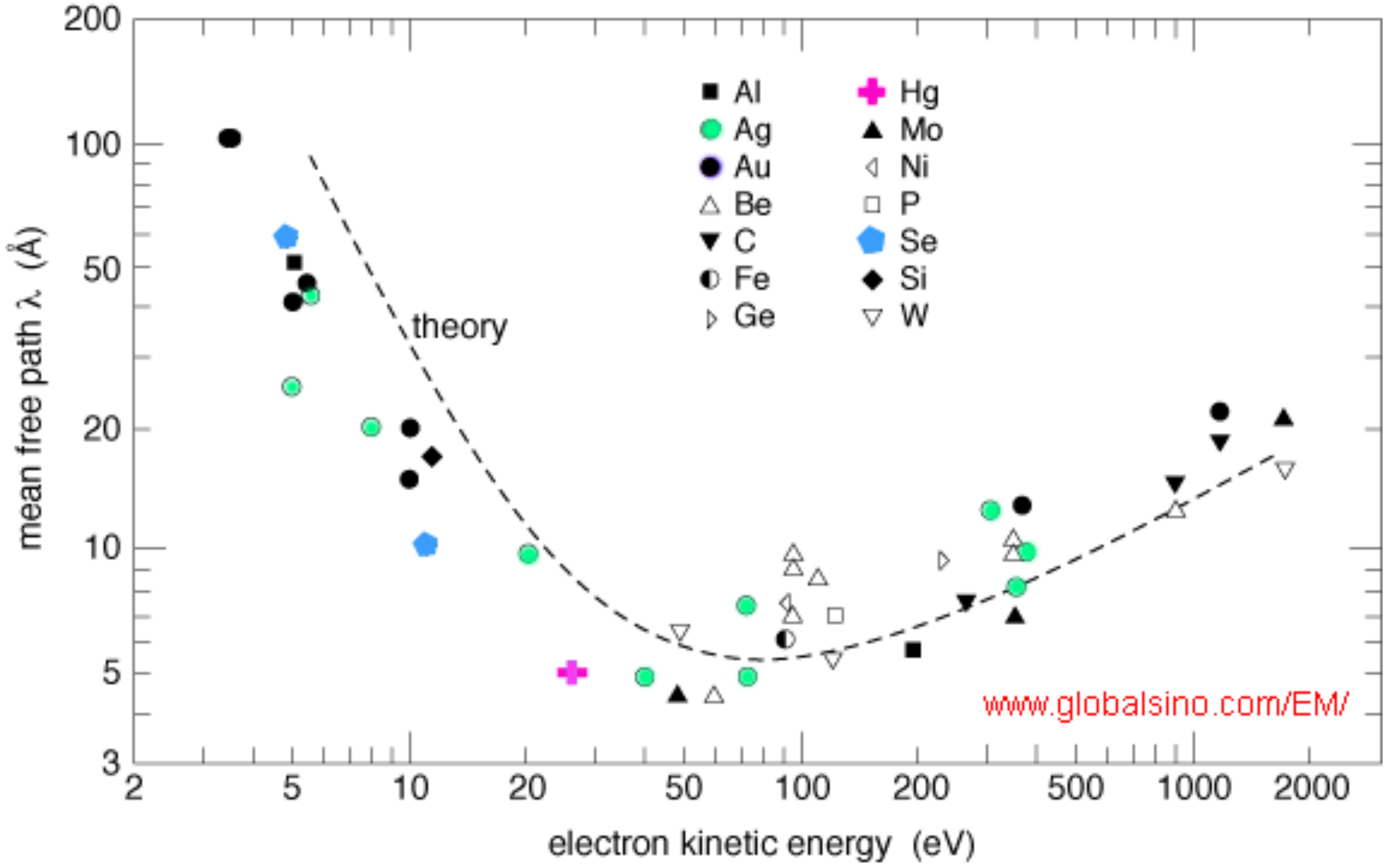

Protons/Electrons: mean free path too small, single scattering not possible for thick detectors (also true for < 1 keV photons)

Possible Sources of Excesses at Low Energy

- SM Backgrounds?
  - ~~Neutrinos~~
  - ~~Photons~~
  - ~~Protons/Electrons~~
  - ~~Muons~~
  - Neutrons

- Experimental Effects?
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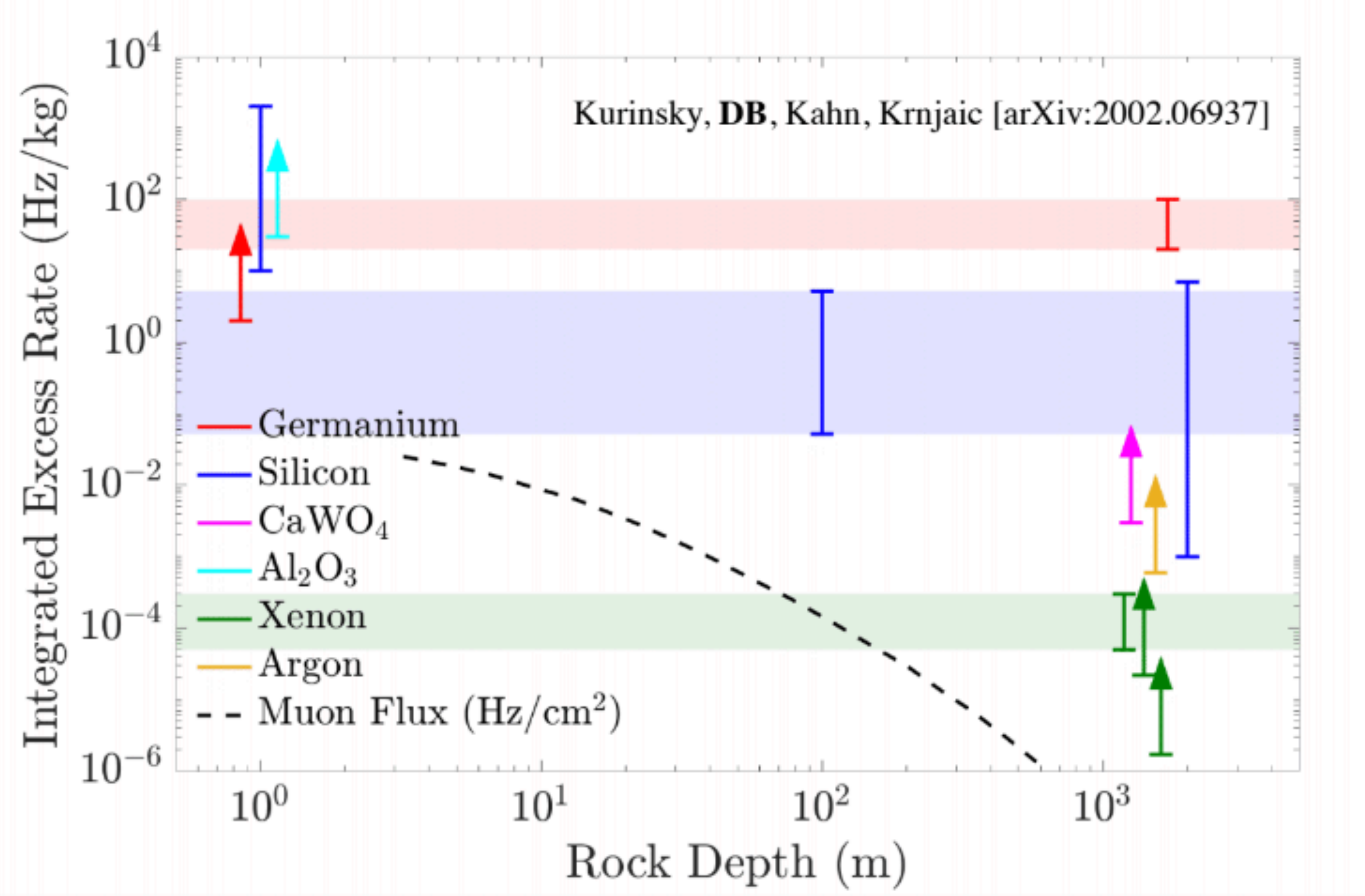

Direct Production by Muons not possible…has to be non-linear, metastable coupling. More data can fully rule out depth dependence.

Possible Sources of Excesses at Low Energy

- SM Backgrounds?
  - ~~Neutrinos~~
  - ~~Photons~~
  - ~~Protons/Electrons~~
  - ~~Muons~~
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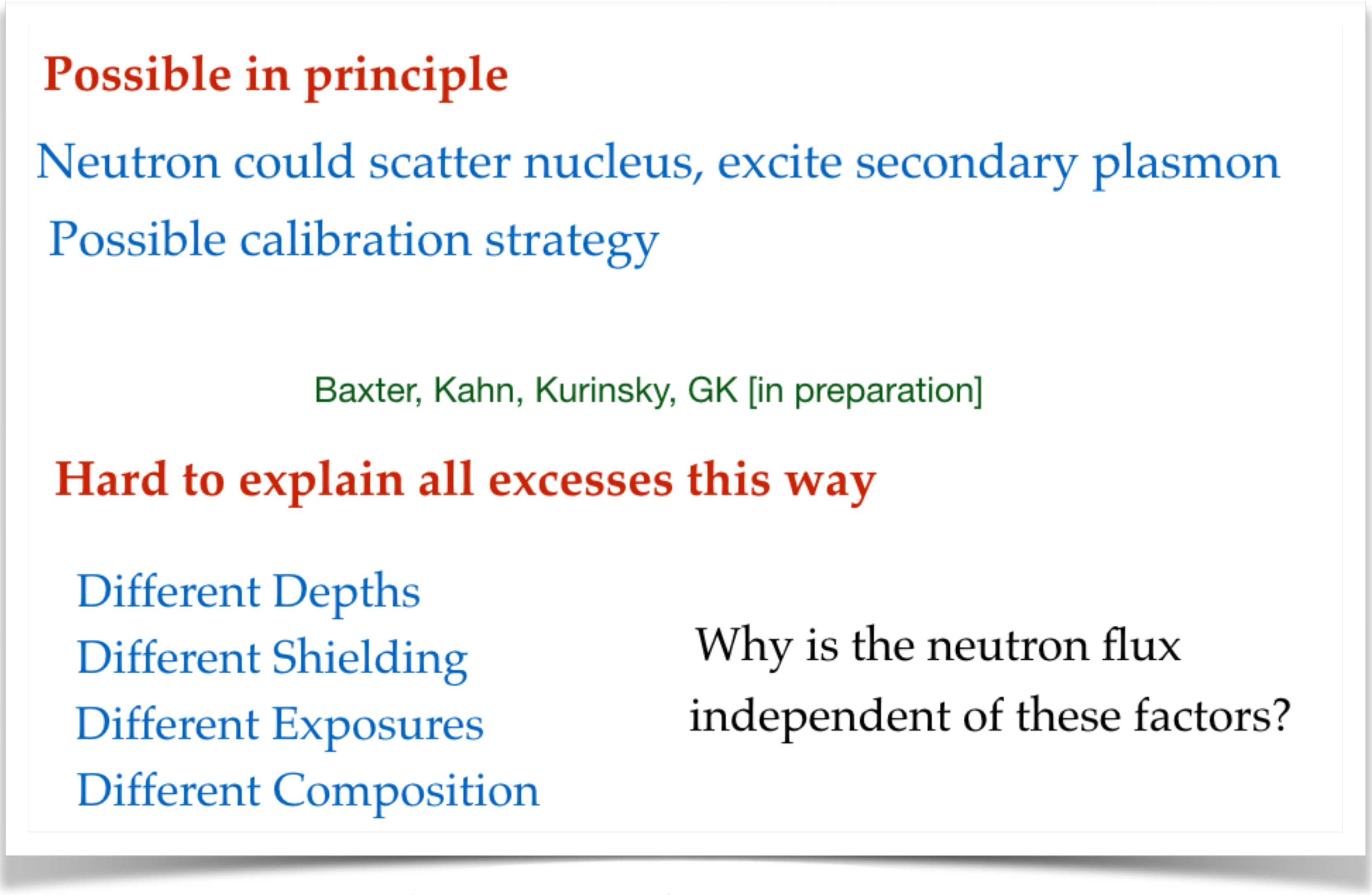

Possible in principle

Neutron could scatter nucleus, excite secondary plasmon

Possible calibration strategy

Baxter, Kahn, Kurinsky, GK [in preparation]

Hard to explain all excesses this way

Different Depths
Different Shielding
Different Exposures
Different Composition

Why is the neutron flux independent of these factors?

Slide from Gordan Krnjaic

Possible Sources of Excesses at Low Energy

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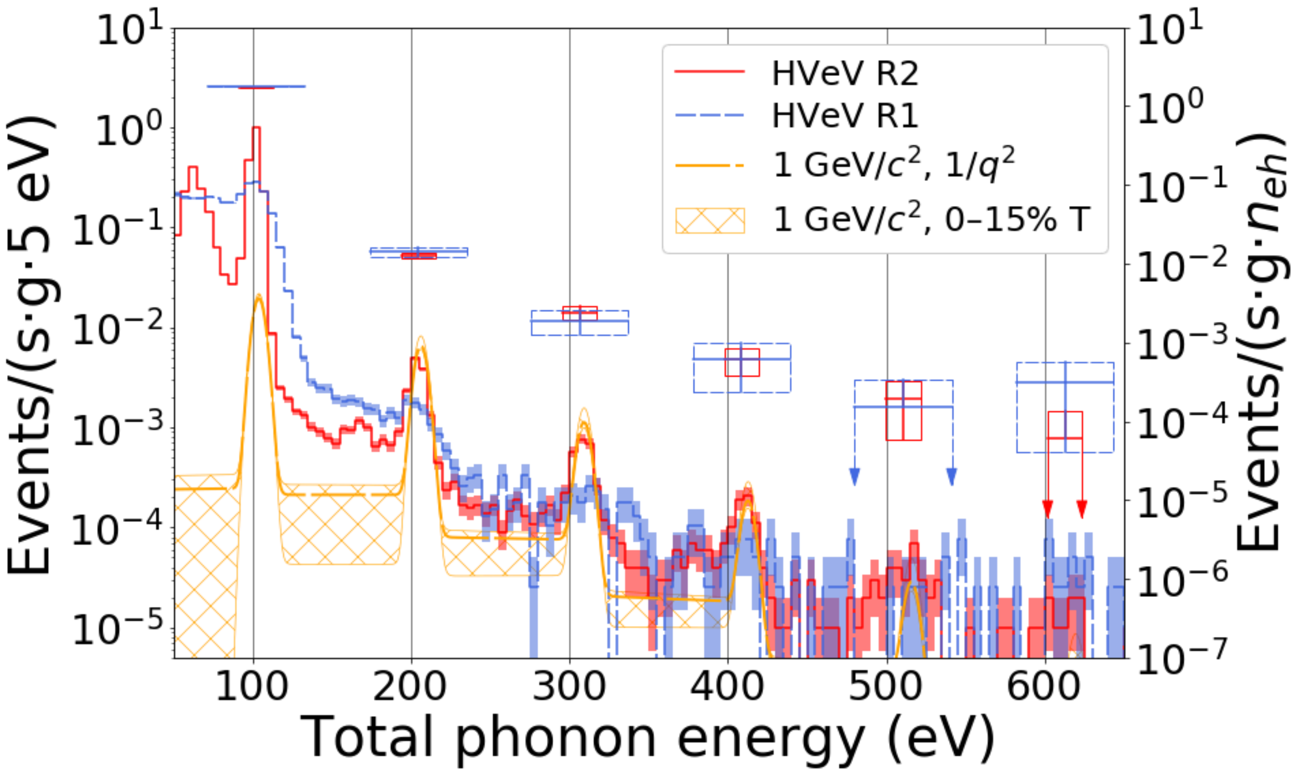

- Experimental Effects?
  - Crystal Cracking
  - Non-poissonian leakage
  - Low-frequency noise
  - Earthquakes
  - Your Model Here

Technology and detector dependent, Should not produce charge, could produce heat only signals

- New Physics?

Possible Sources of Excesses at Low Energy

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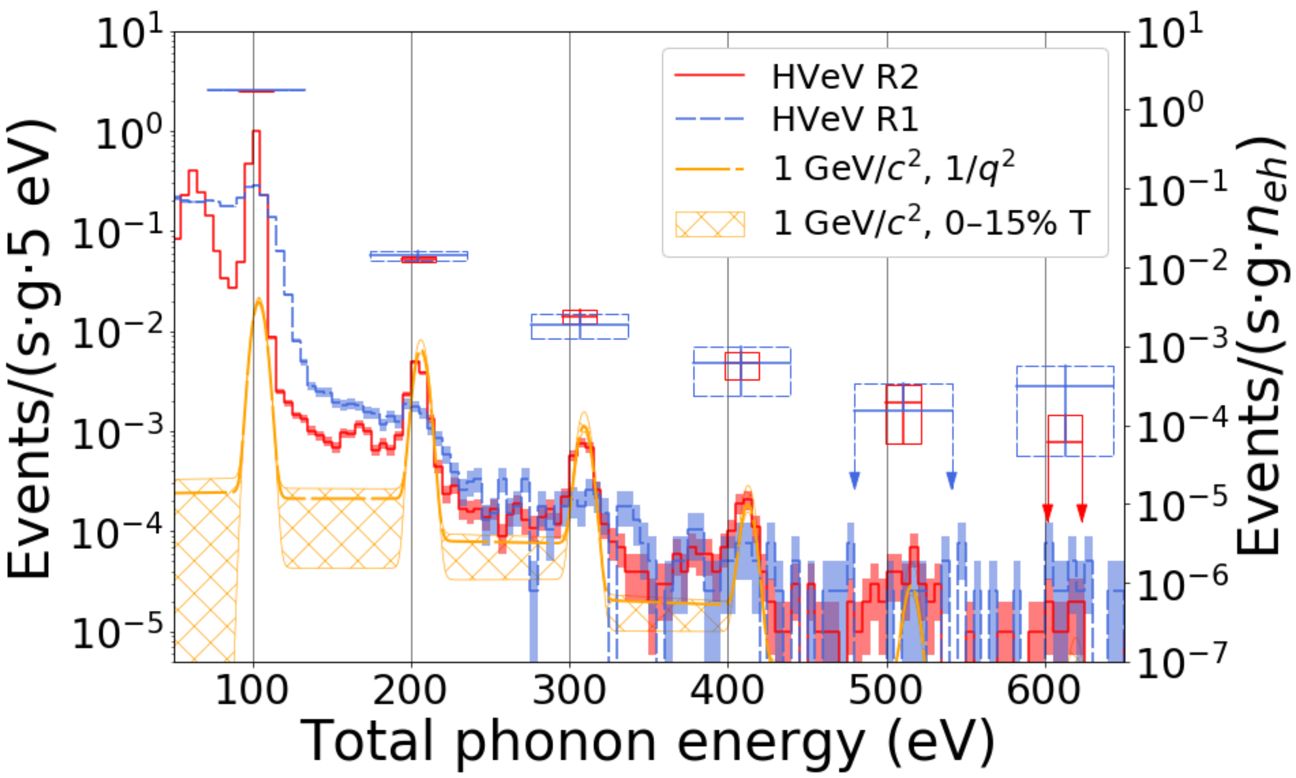

- Experimental Effects?
  - Crystal Cracking ?
  - Non-poissonian leakage
  - Low-frequency noise
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  - Your Model Here

No known mechanism for correlated leakage

Shouldn't be the same for CCDs (100K) and Calorimeters (10 mK)

- New Physics?

Possible Sources of Excesses at Low Energy

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  - ~~Neutrinos~~
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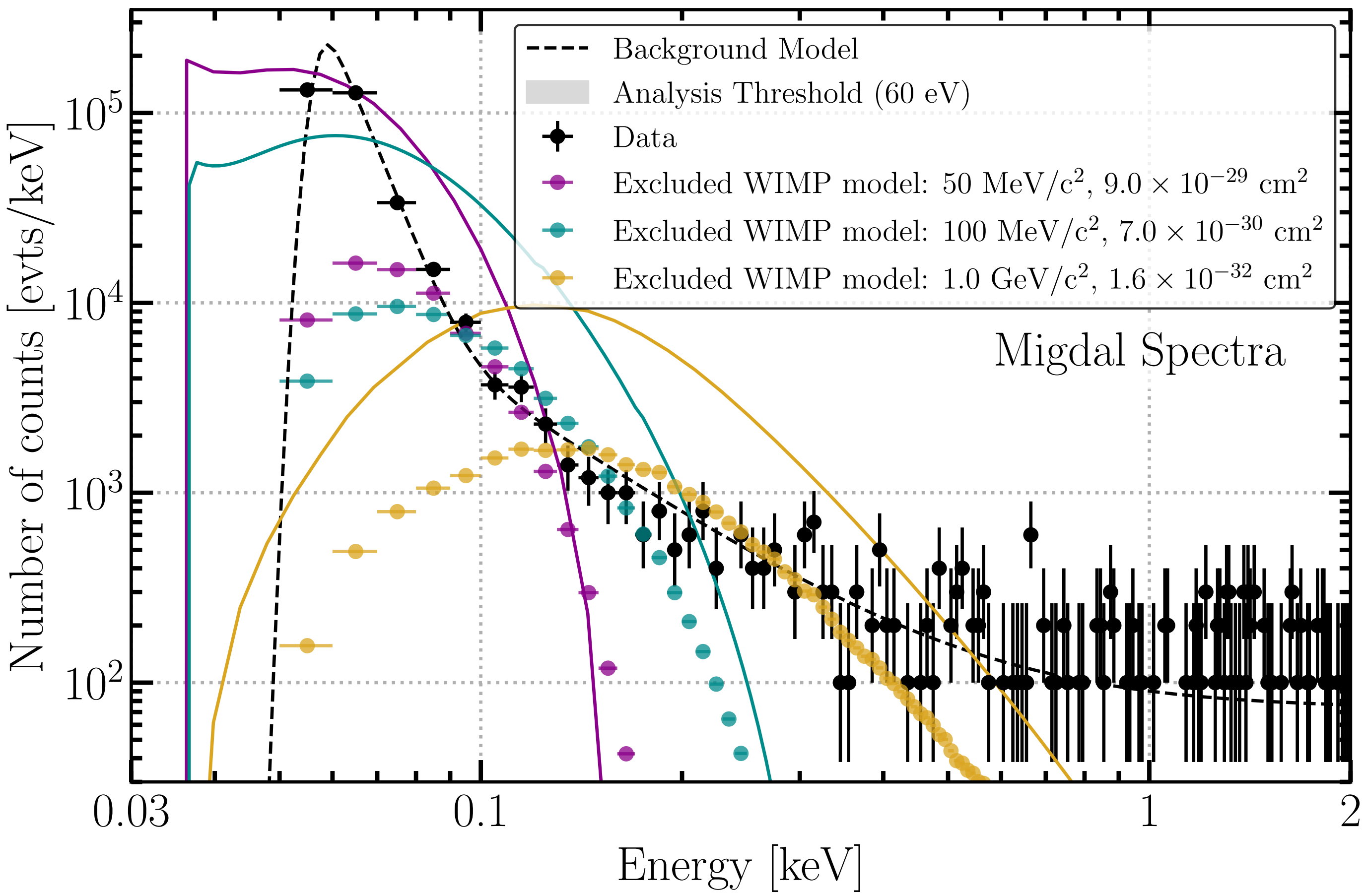


Far too many events, which looks like real pulses, too far above threshold (30-50 sigma)

Possible Sources of Excesses at Low Energy

- SM Backgrounds?
  - ~~Neutrinos~~
  - ~~Photons~~
  - ~~Protons/Electrons~~
  - ~~Muons~~
  - Neutrons ?

Remaining options are highly non-linear, metastable couplings, odd types of photon or neutron flux that do not respect shielding, or some new physics.

- Experimental Effects?
  - Crystal Cracking ?
  - ~~Non-poissonian leakage~~
  - ~~Low frequency noise~~
  - ~~Earthquakes~~
  - Your Model Here

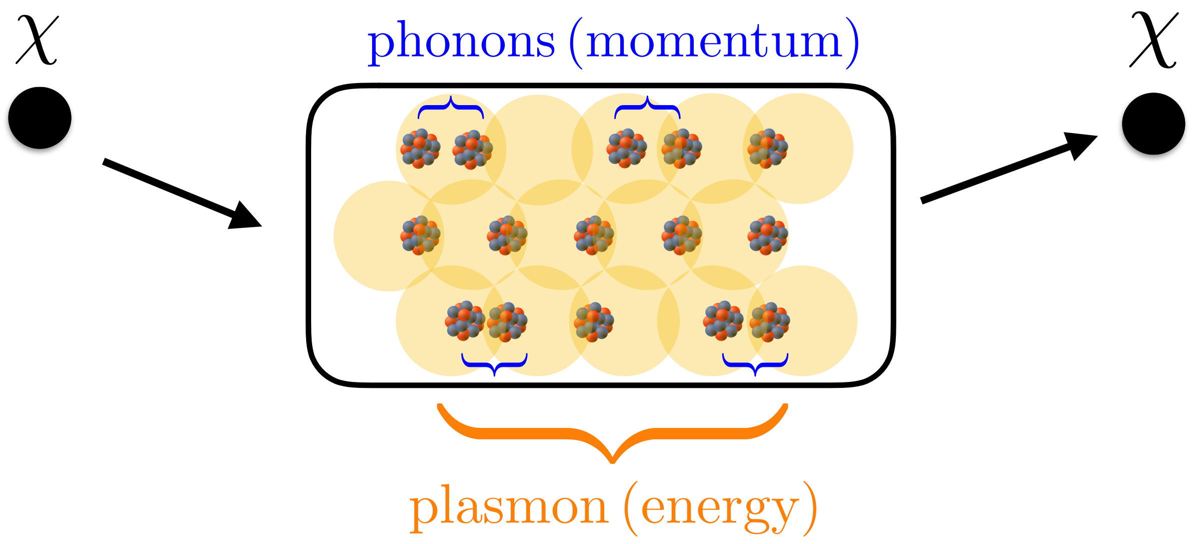
More background modeling encouraged…help us understand this!

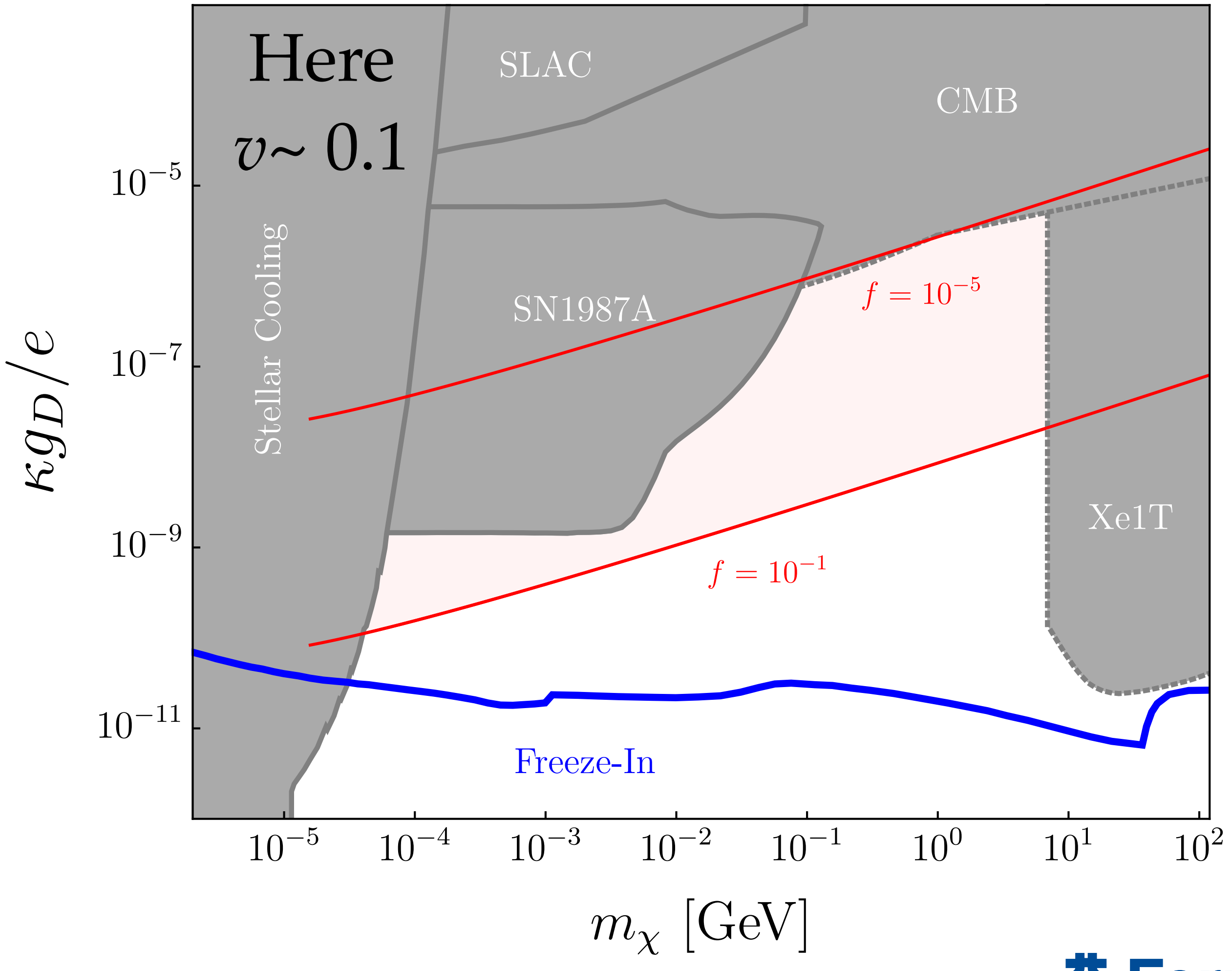
At what point do we start to decide that this really could be dark matter?

- New Physics?

Direct Plasmon Production DM Model

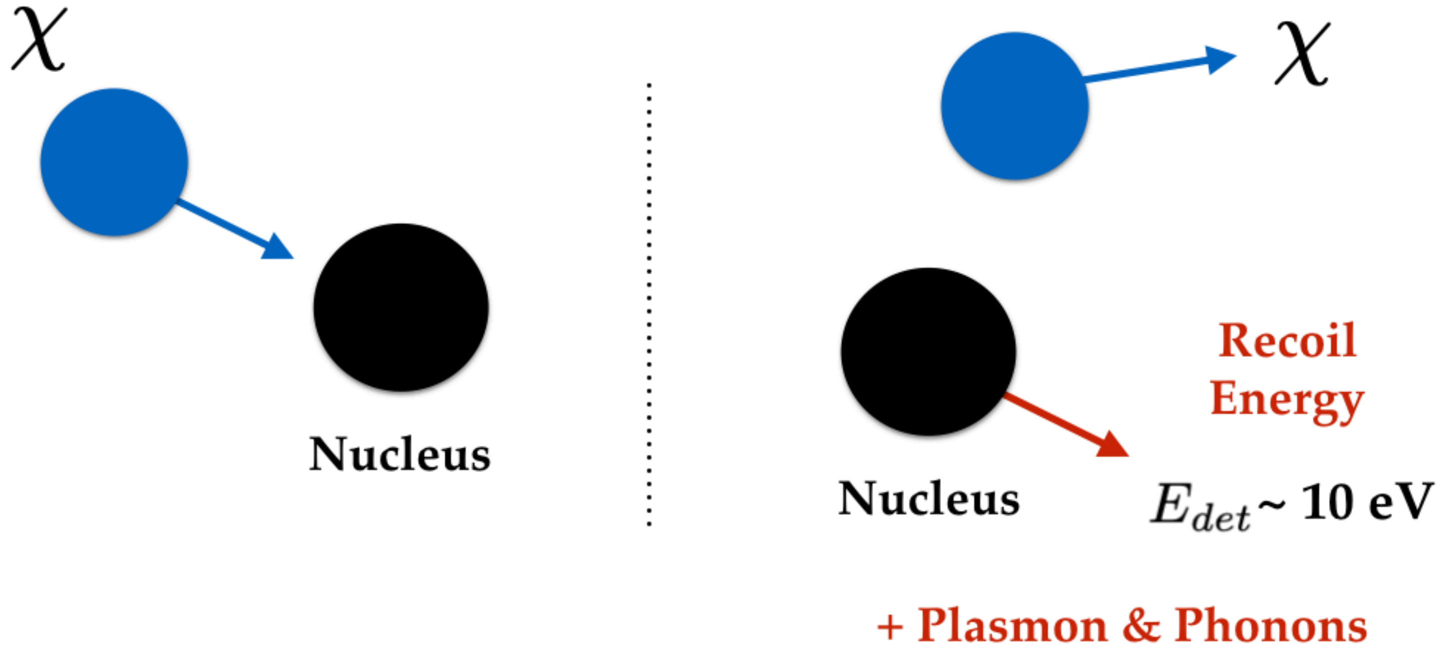
- DM couples to electrons.
- Direct plasmon production occurs as it does for electrons, but with a much longer mean free path
  - Calibrated by EELS…plasmon definitely produced
- DM has to be faster than the escape velocity
  - It should be an accelerated subcomponent, which can be produced in supernovae or in the sun





Nuclear Recoil DM Model

- DM couples to nucleons.
- Plasmons and phonons (and a little bit of charge) produced as nucleus relaxes
  - Defect energy cost is ~10-20 eV in Si/Ge, higher in sapphire



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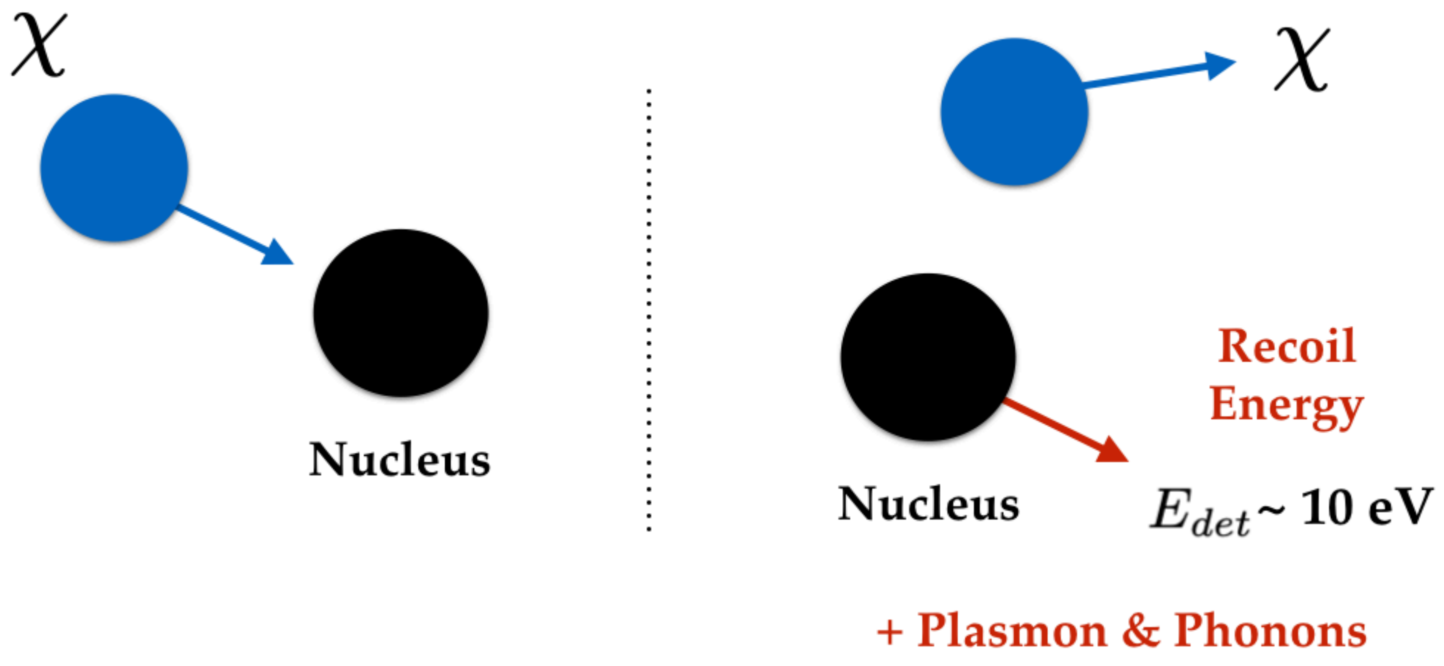

$$R \sim N_T \mathcal{P} \frac{\rho_\chi}{m_\chi} \sigma_n v,$$

Parametrize our ignorance

Nuclear Recoil DM Model

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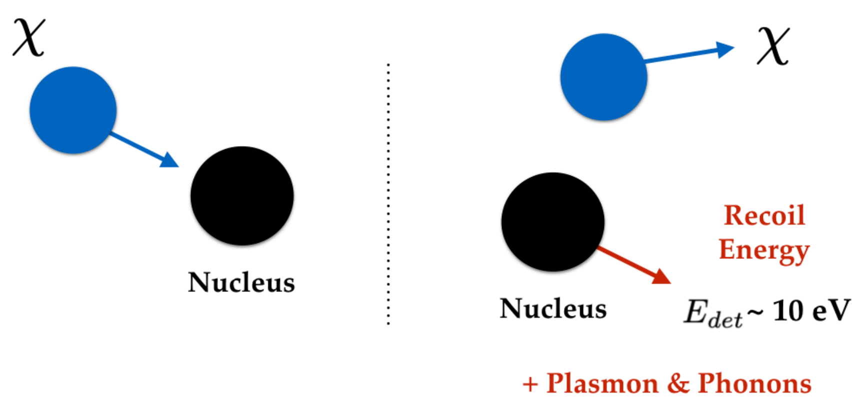
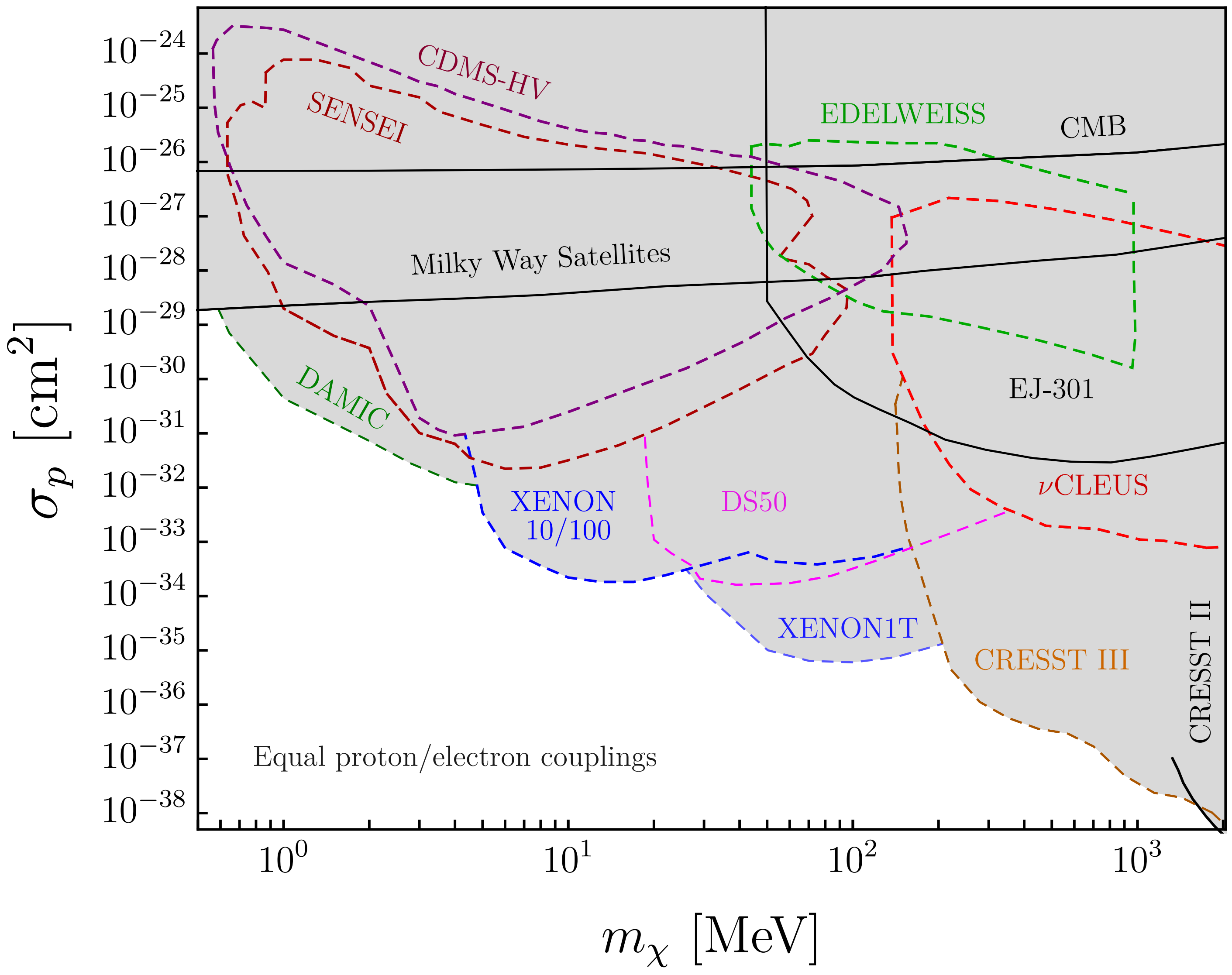
- Nucleon-plasmon cross-section has never been measured or calculated

- All dashed experiments see excesses



DD limits assuming only elastic scattering channels



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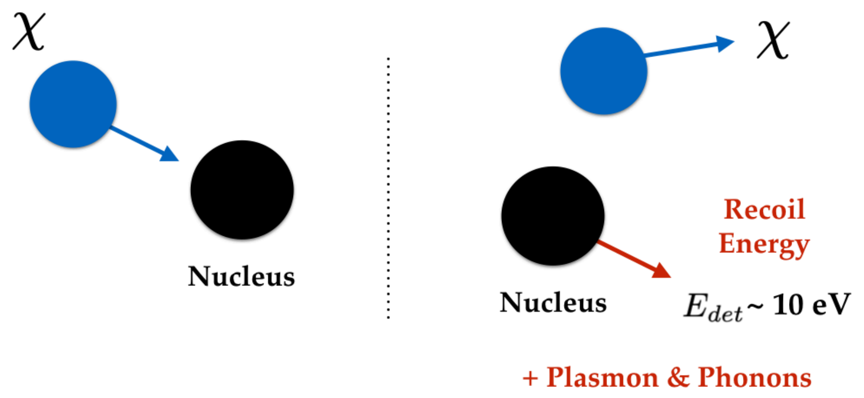
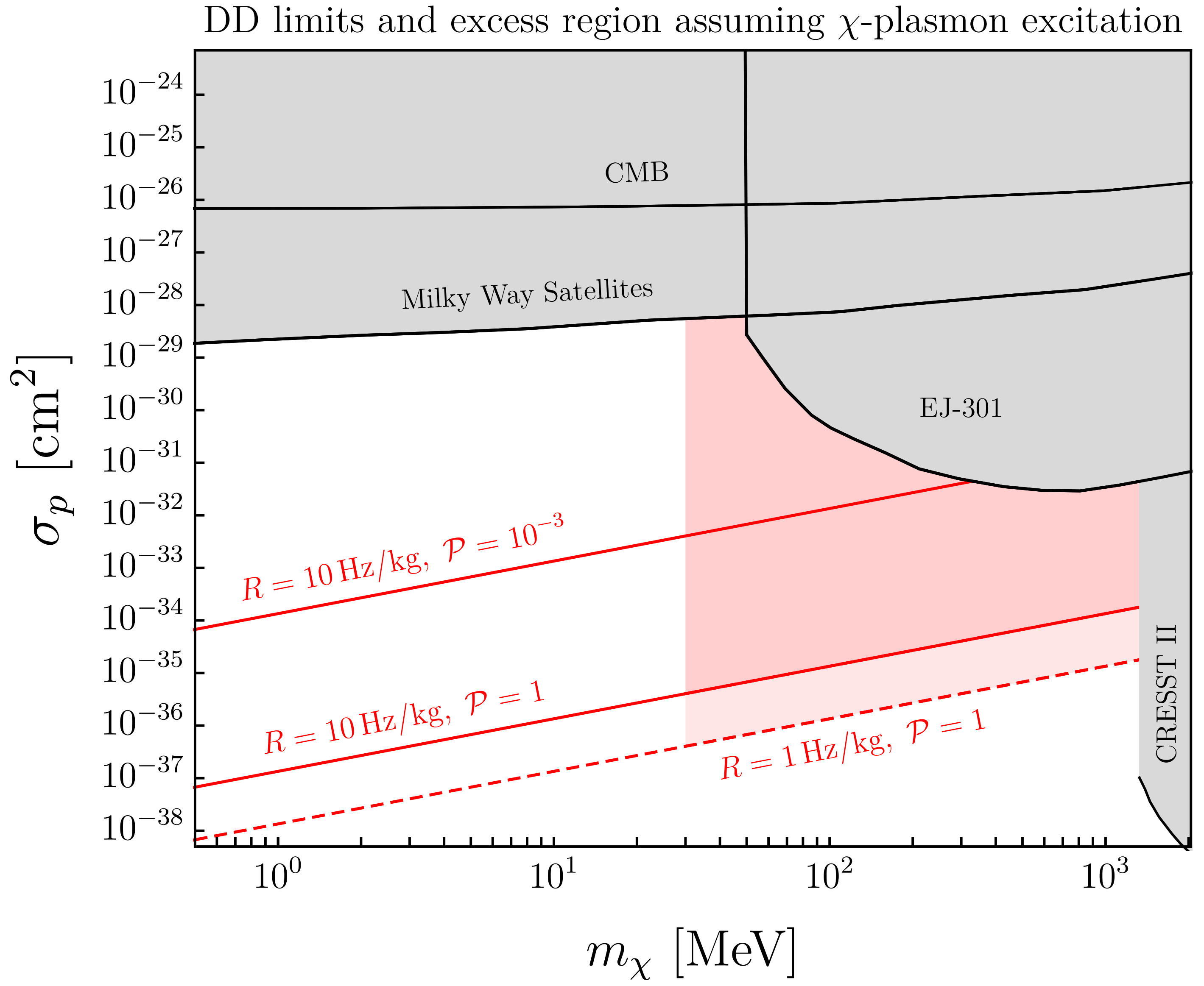
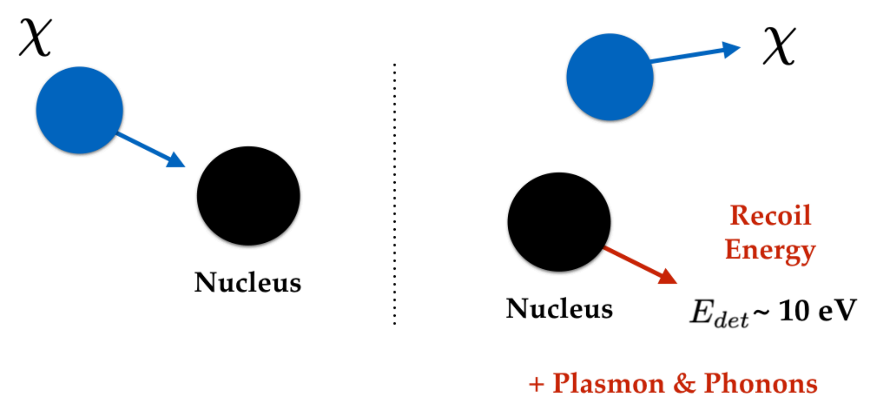
  - Preferred region at 30-1000 MeV





$$R \sim \frac{20\ \mathrm{Hz}}{\mathrm{kg}}\left(\frac{\mathcal{P}}{0.1}\right)\left(\frac{\sigma_p}{6\times10^{-34}\ \mathrm{cm}^2}\right)\left(\frac{100\ \mathrm{MeV}}{m_\chi}\right)$$

Nuclear Recoil DM Model



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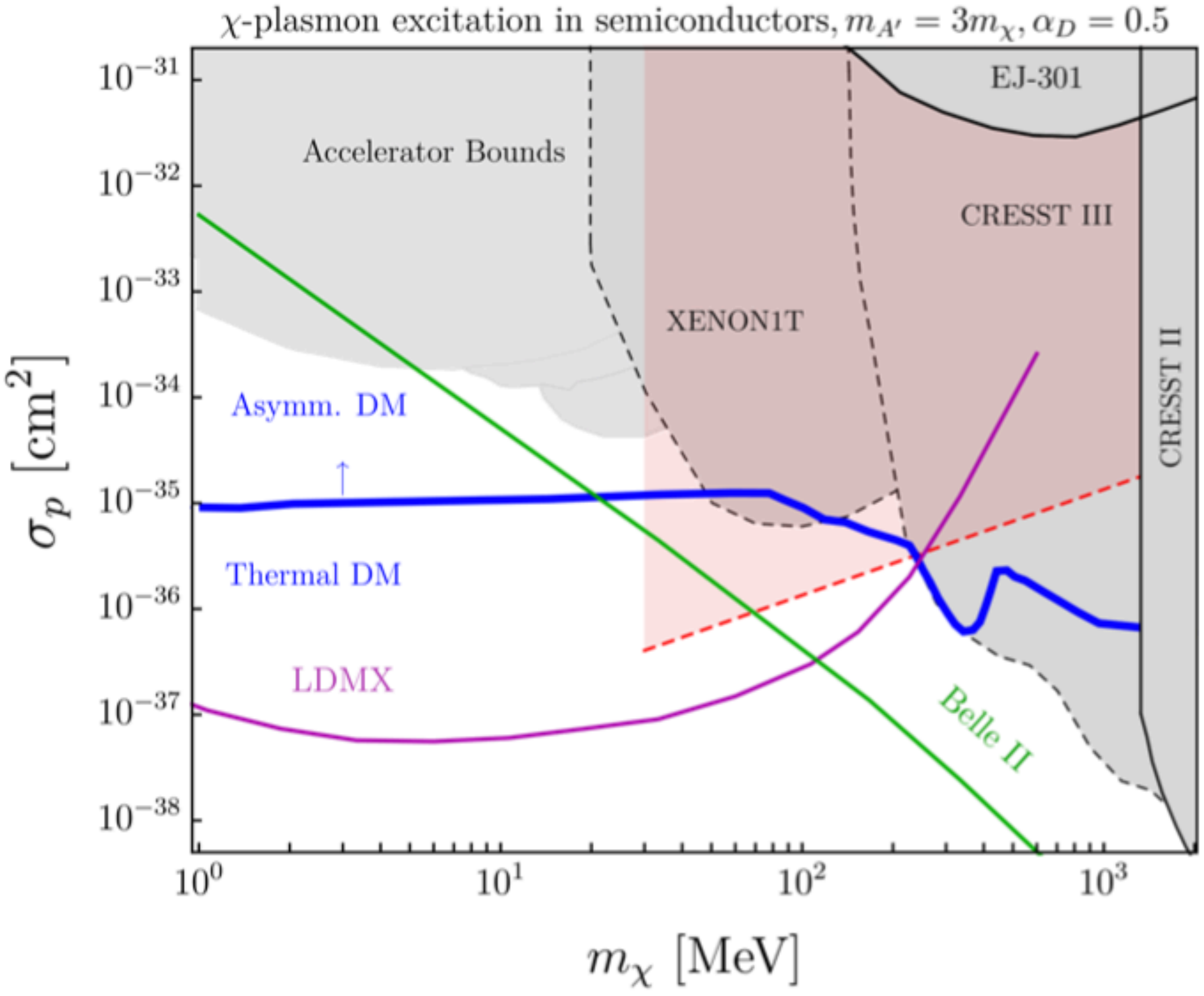
- All dashed experiments see excesses
  - Preferred region at 30-1000 MeV
  - Dark photon model viable!

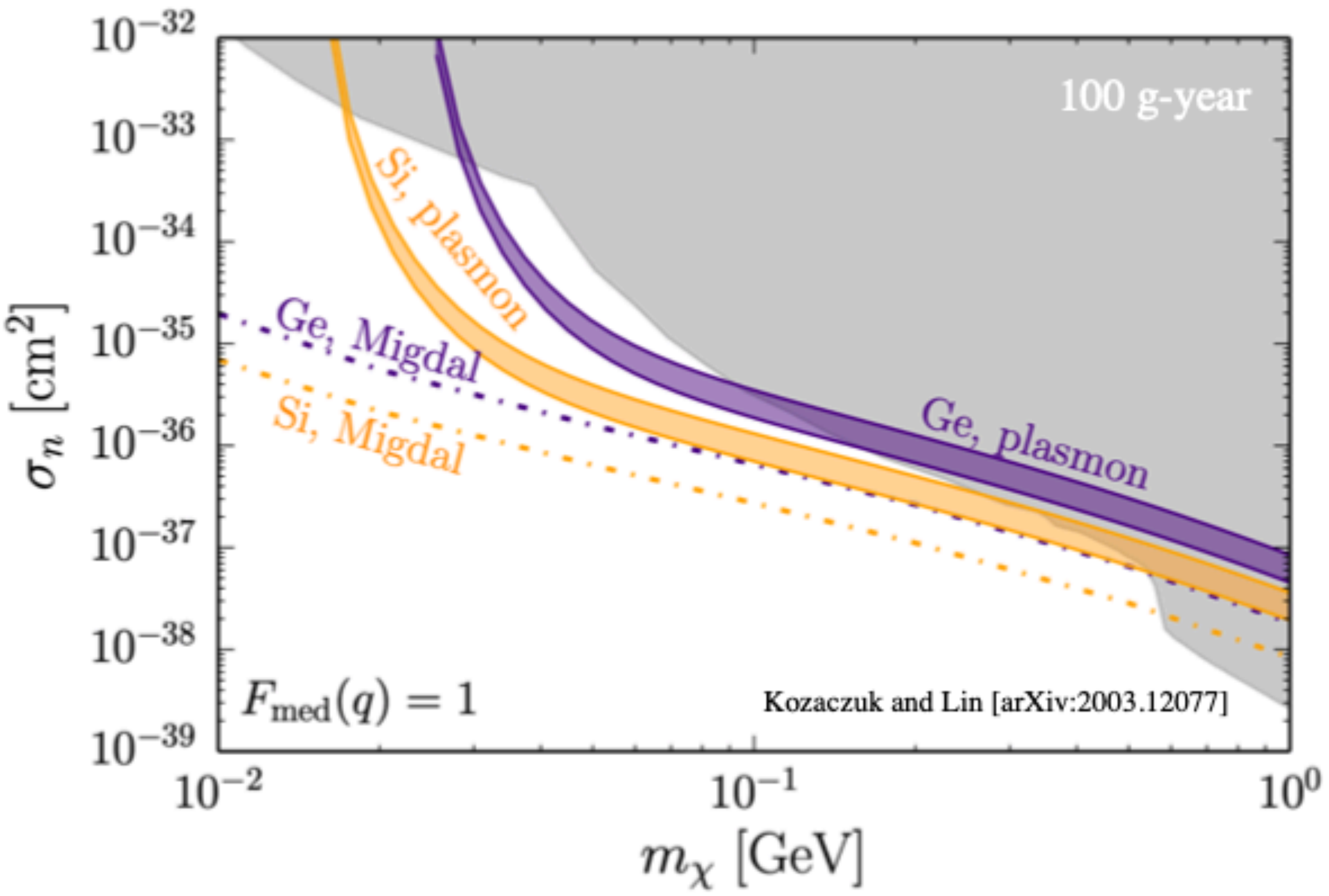


$$\mathcal{L} \supset -\frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu(\kappa e J^\mu_{\mathrm{EM}} + g_D J^\mu_D),$$

First-Principles Calculations: Plasmon Bremsstrahlung

- Follow-up study calculates plasmon production due to NR with a single phonon in the final state
  - Kinematics are distinct from those described previously, but set a lower bound on the total rate
  - Bound is already comparable to migdal, and suggests that total rate is much larger when accounting for multi-phonon scattering

- Sits at the opposite regime compared to the NR charge yield calculations, coming from NR-phonon scattering

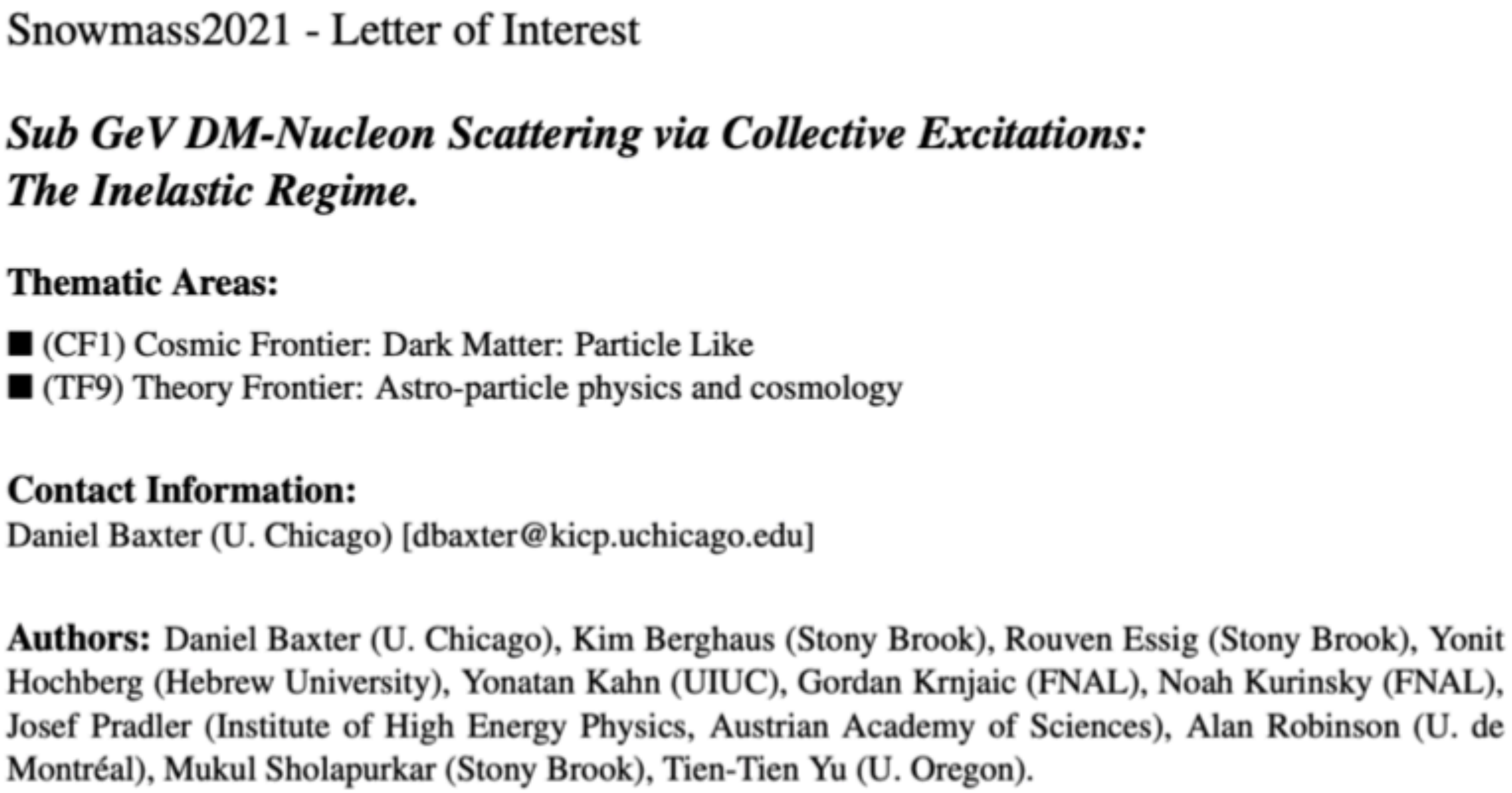


Kozaczuk and Lin [arXiv:2003.12077]

Moving Forward

Topic of EXCESS workshop, June 15/16, 2021

- Push forward calibration efforts to better under NR detector response and role of collective effects below 1 keV
- Building collaboration to push forward understanding of 10 eV to 1 keV ER/NR response in semiconductors



Snowmass2021 - Letter of Interest

Sub GeV DM-Nucleon Scattering via Collective Excitations: The Inelastic Regime.

Thematic Areas:

■ (CF1) Cosmic Frontier: Dark Matter: Particle Like
■ (TF9) Theory Frontier: Astro-particle physics and cosmology

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Authors: Daniel Baxter (U. Chicago), Kim Berghaus (Stony Brook), Rouven Essig (Stony Brook), Yonit Hochberg (Hebrew University), Yonatan Kahn (UIUC), Gordan Krnjaic (FNAL), Noah Kurinsky (FNAL), Josef Pradler (Institute of High Energy Physics, Austrian Academy of Sciences), Alan Robinson (U. de Montréal), Mukul Sholapurkar (Stony Brook), Tien-Tien Yu (U. Oregon).

Dielectric Function Formalism

- In the low-energy regime, we can express electromagnetic interactions in terms of the loss function:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_2 \mathrm{d}\hbar\omega_2} = r_0^2(\mathbf{e}_1 \cdot \mathbf{e}_2)^2 \left(\frac{\omega_2}{\omega_1}\right) S(\mathbf{q}, \omega), \quad r_0 = \frac{e^2}{mc^2}$$

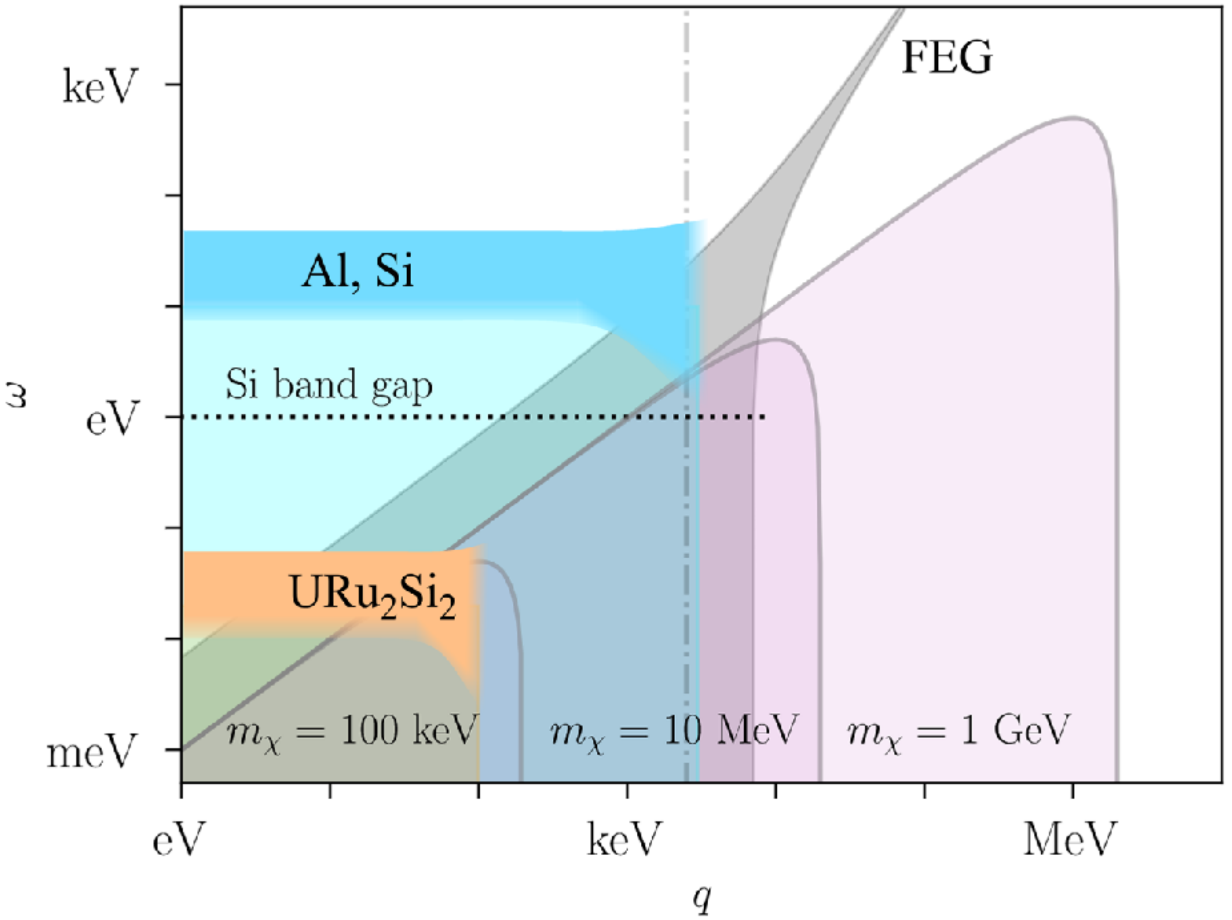
- This same language can be used to describe DM interactions, because the structure factor is only determined by interactions within the target material:

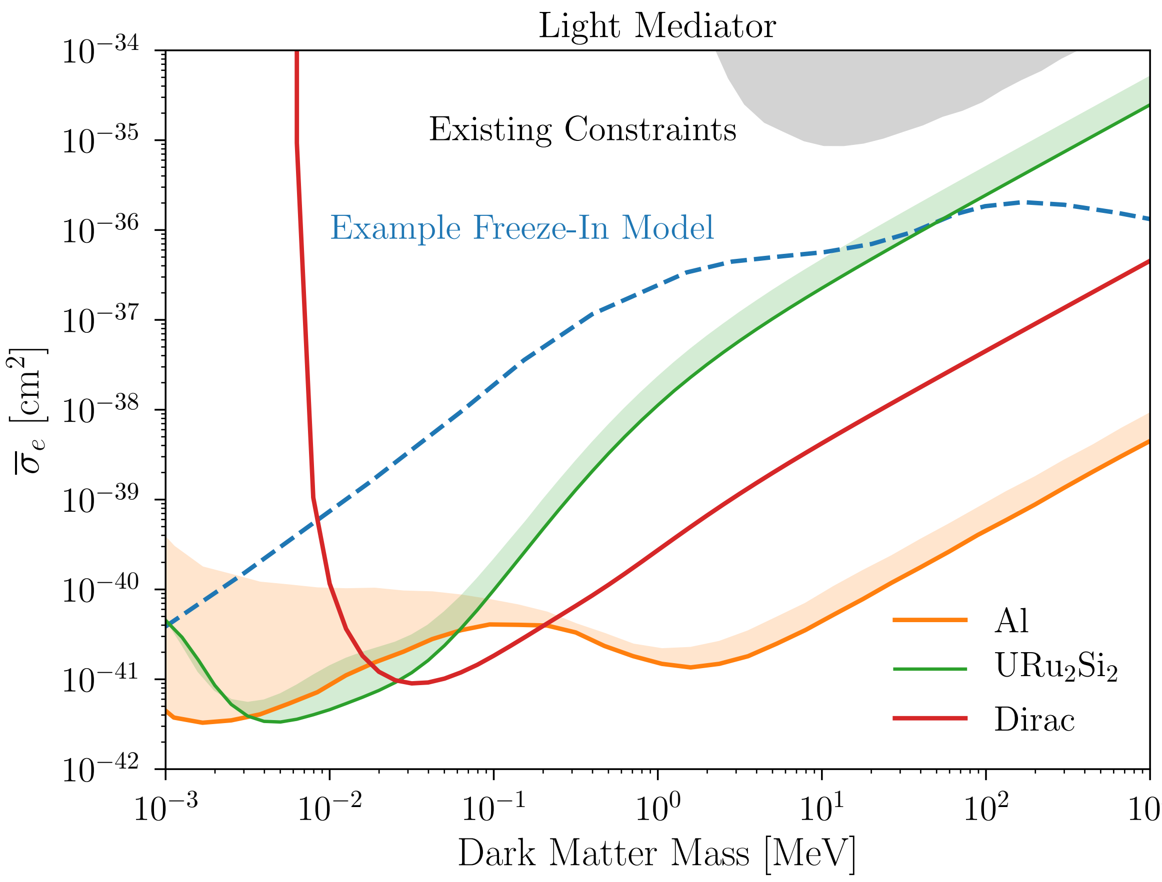
$$\Gamma(\mathbf{v}_\chi) = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[2\frac{q^2}{e^2} \operatorname{Im}\left(-\frac{1}{\epsilon(\mathbf{q}, \omega_\mathbf{q})}\right)\right]$$

- The loss function is well-characterized in the literature, and toy models exist for different types of materials - doesn't require detailed DFT calculations

- Upcoming paper explores a handful of new materials with data and toy models, reducing turnaround on material exploration from years to months
  - Also allows us to determine generic features of a material useful for DM detection in different models

Berggren, Hochberg, Kahn, **NK**, Lehman, Yu, ArXiv:2101.08263





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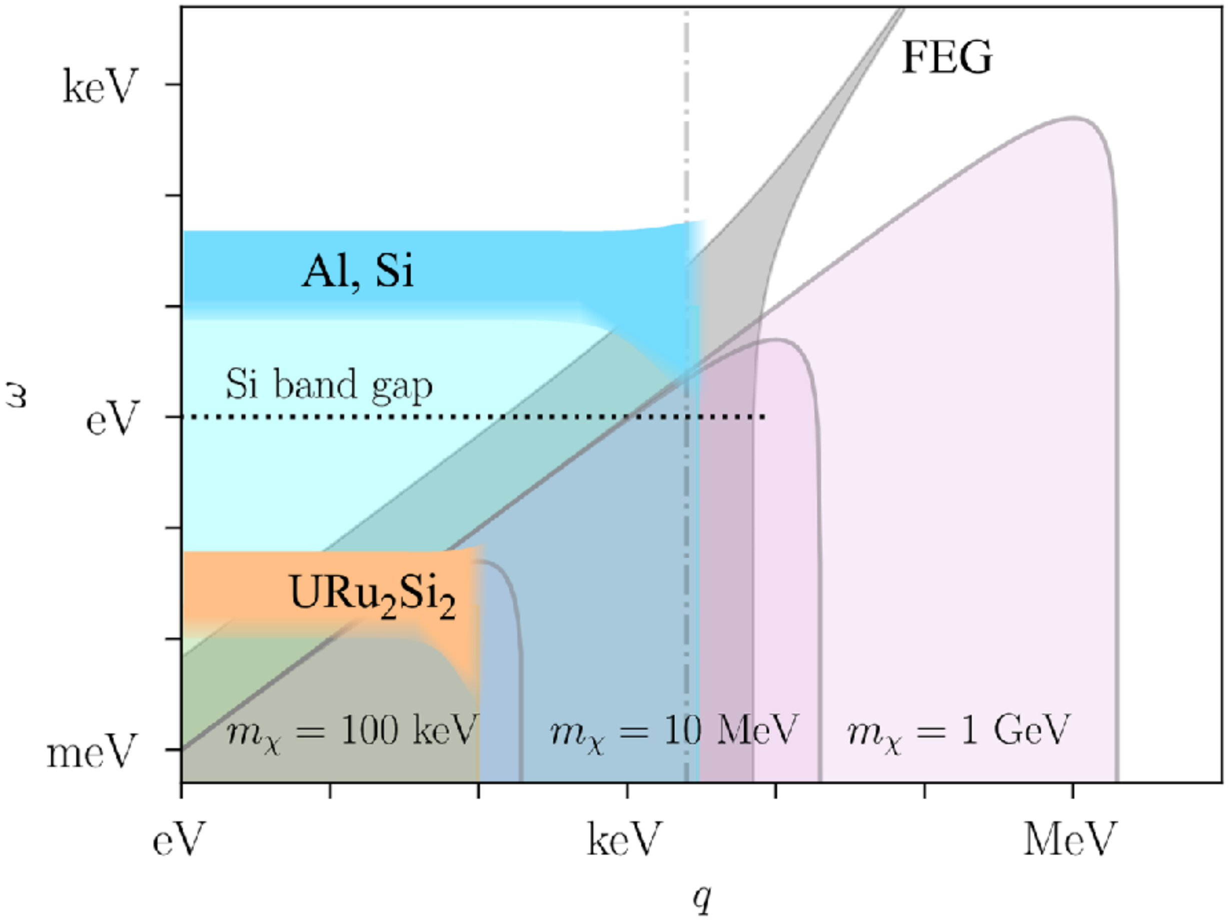

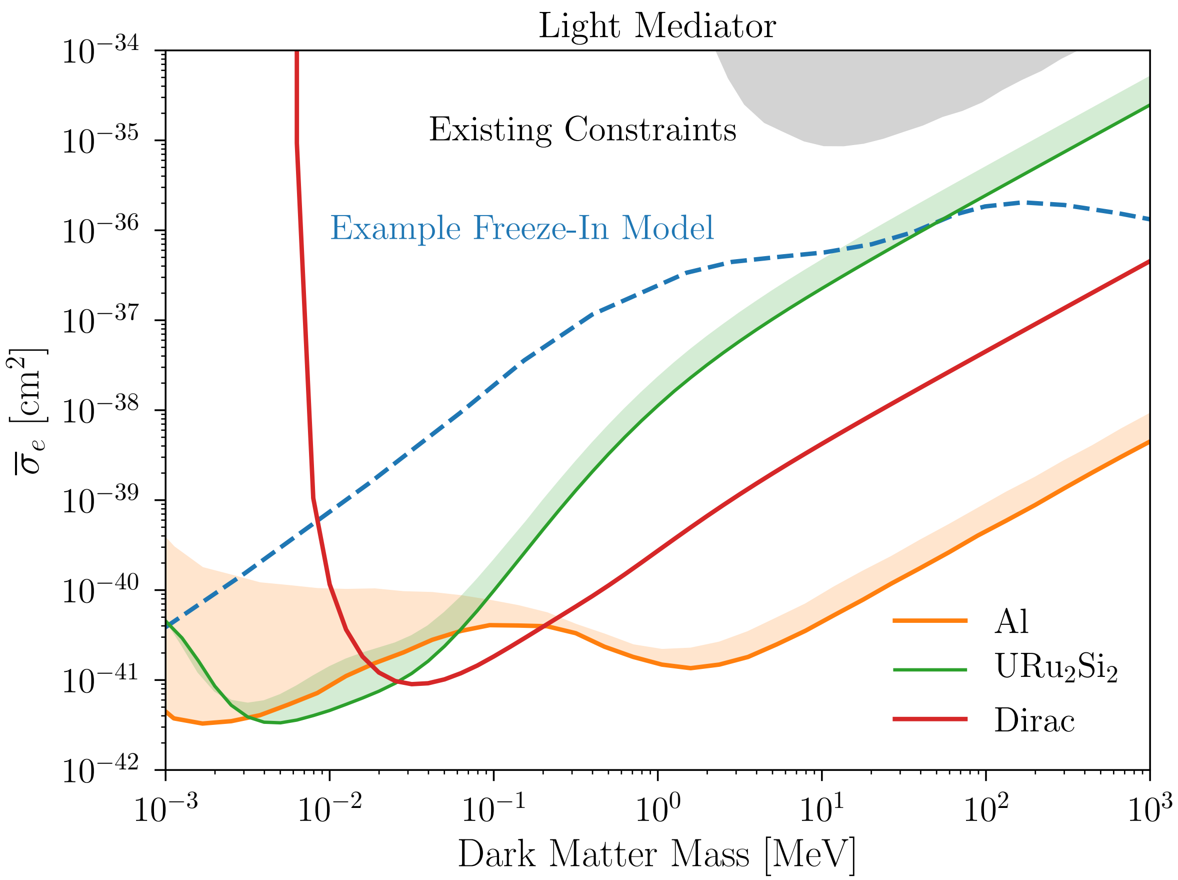

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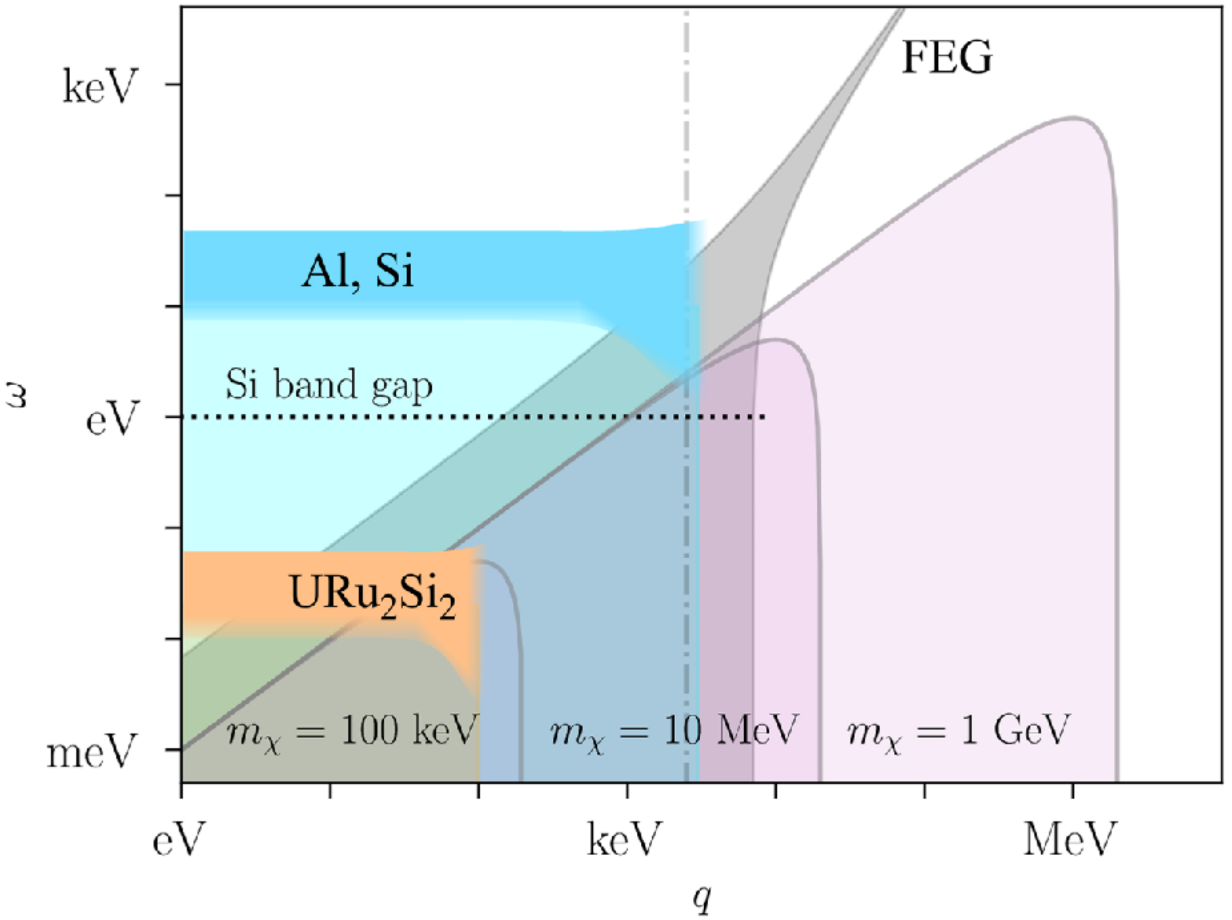

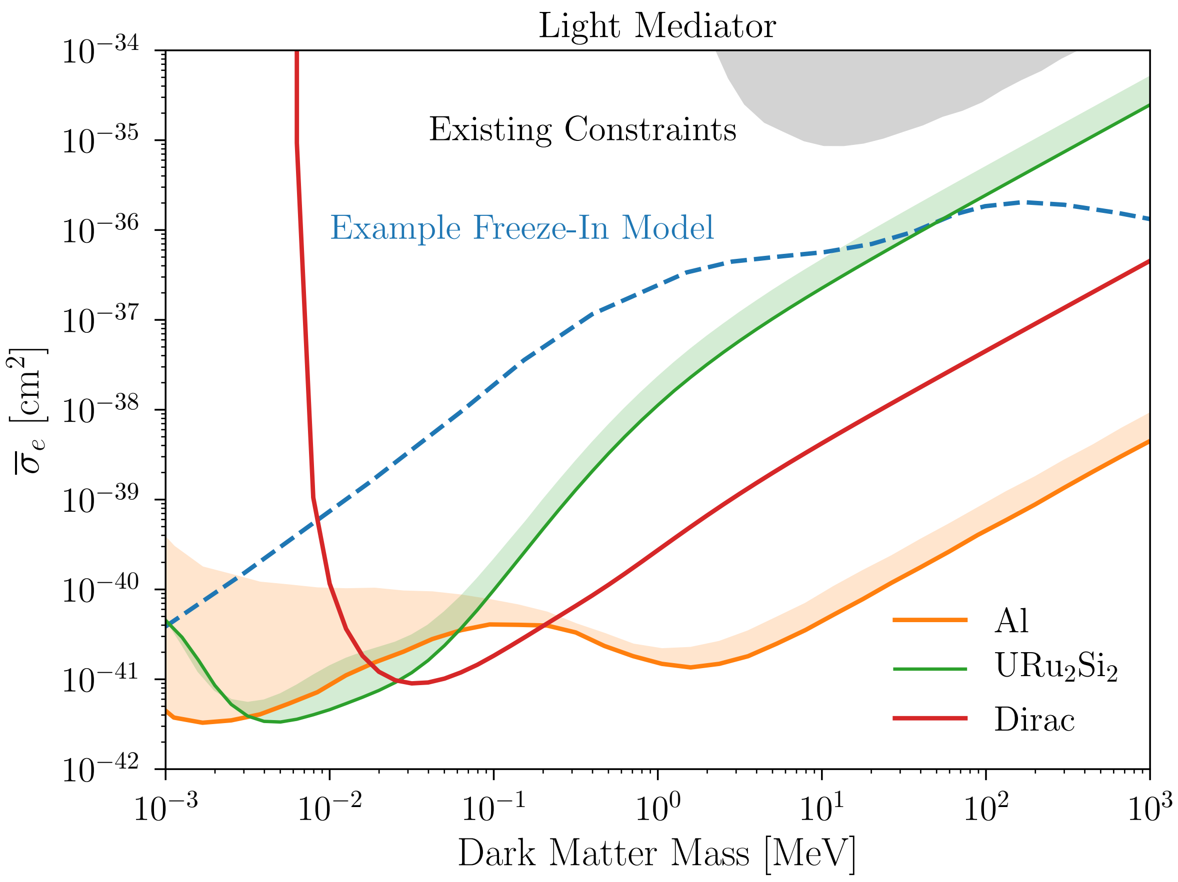

Conclusions

- Many experiments have begun to see low-energy excesses that are consistent with DM when inelasticity of the medium is accounted for.

- There is not a consistent story of a background or DM signal that can conclusively explain all excesses
  - Some excesses are likely un-modeled backgrounds related to secondary and tertiary production of low-energy photons and charged particles
  - Other excesses, which do not scale with shielding or environment, are harder to explain
  - Rates are strongly dependent on the medium used to detect events, and seem to correlate with the degree of regularity of the medium

- We are probing a regime in which DM is viable, and material responses are largely uncalibrated

- There is a ton of growth potential and discovery potential in these mass and energy regimes!