A DM Interpretation of Multiple Direct Detection Excesses

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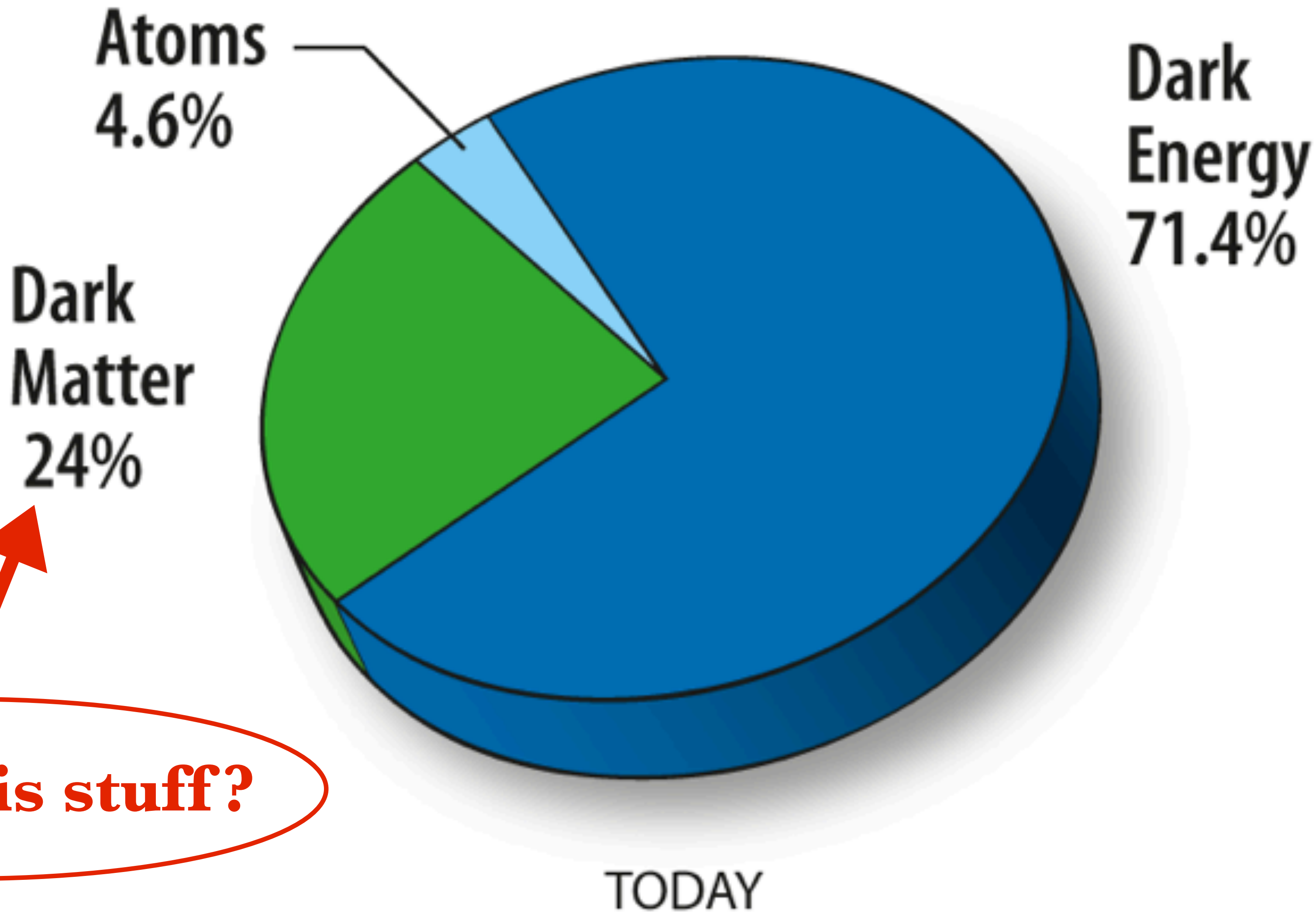
+ Noah Kurinsky, Dan Baxter, Yonatan Kahn

arXiv:2002.06937 Phys. Rev. D 102, 015017

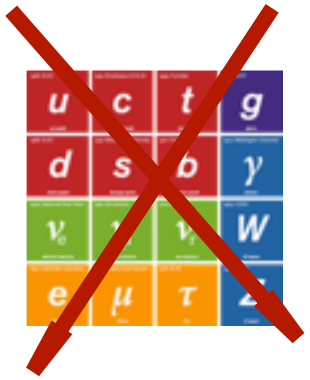
Lund University Seminar Sep 24, 2020

Open Questions in Fundamental Physics

Neutrino Masses
Matter Asymmetry
Inflation



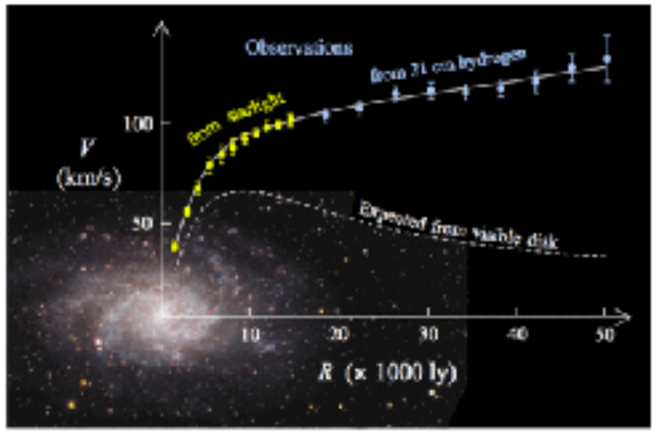
Accelerated Cosmic Expansion



What is this stuff?

Also Quantum Gravity

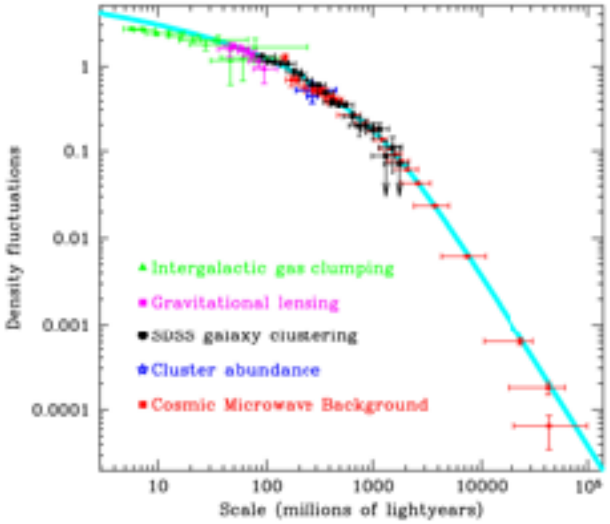
Remarkable Evidence for Dark Matter



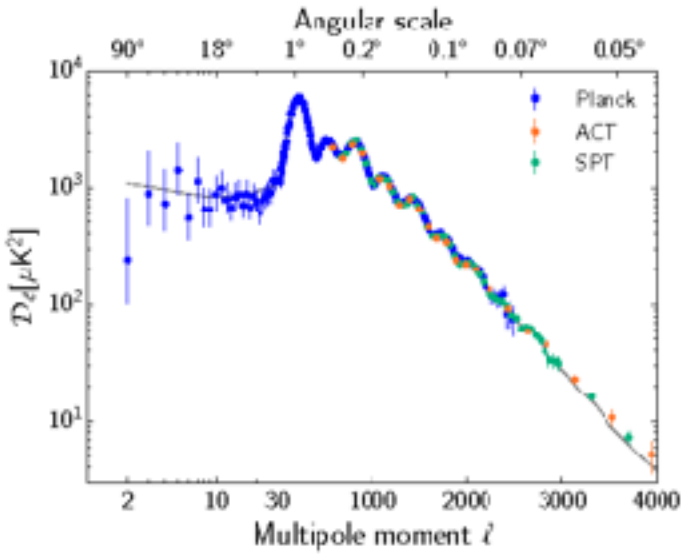
Rotation Curves

Gravitational Lensing

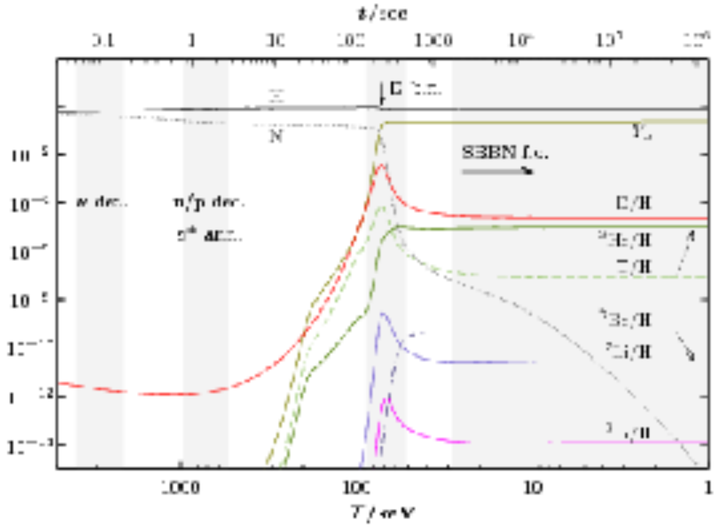
Cluster Collisions



Matter Power Spectrum



CMB Power Spectrum

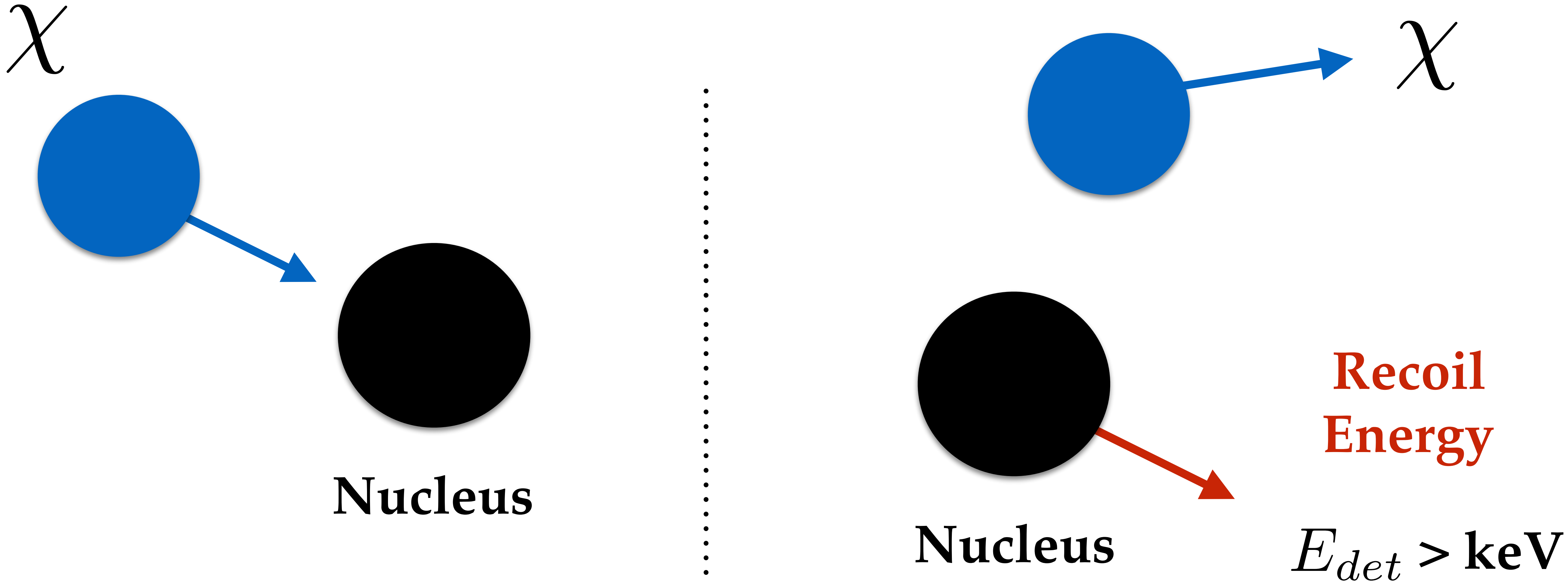


BBN Light Element Yields

Multiple independent, consistent observations
over **nearly** all of spacetime (!)

Holy Grail: extend our knowledge down to laboratory scales

Nuclear Recoil (NR) Direct Detection



χ

Nucleus

χ

Nucleus

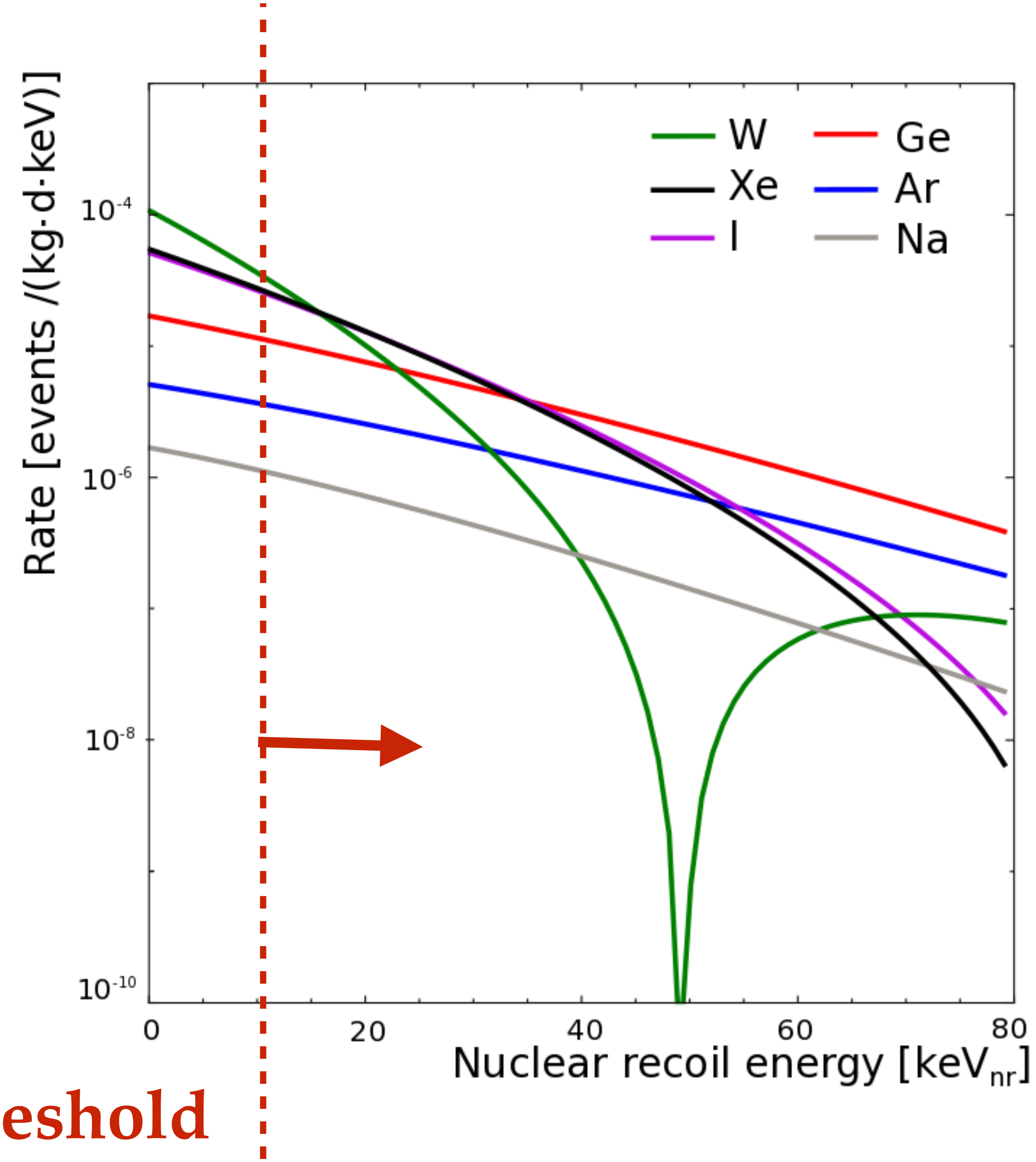
Recoil Energy

E_{det} **> keV**

$$|\vec{q}| \sim \mu v \qquad E_{det} = \frac{|\vec{q}|^2}{2m_N}$$

Insensitive to DM masses below < GeV

Nuclear Recoil Direct Detection



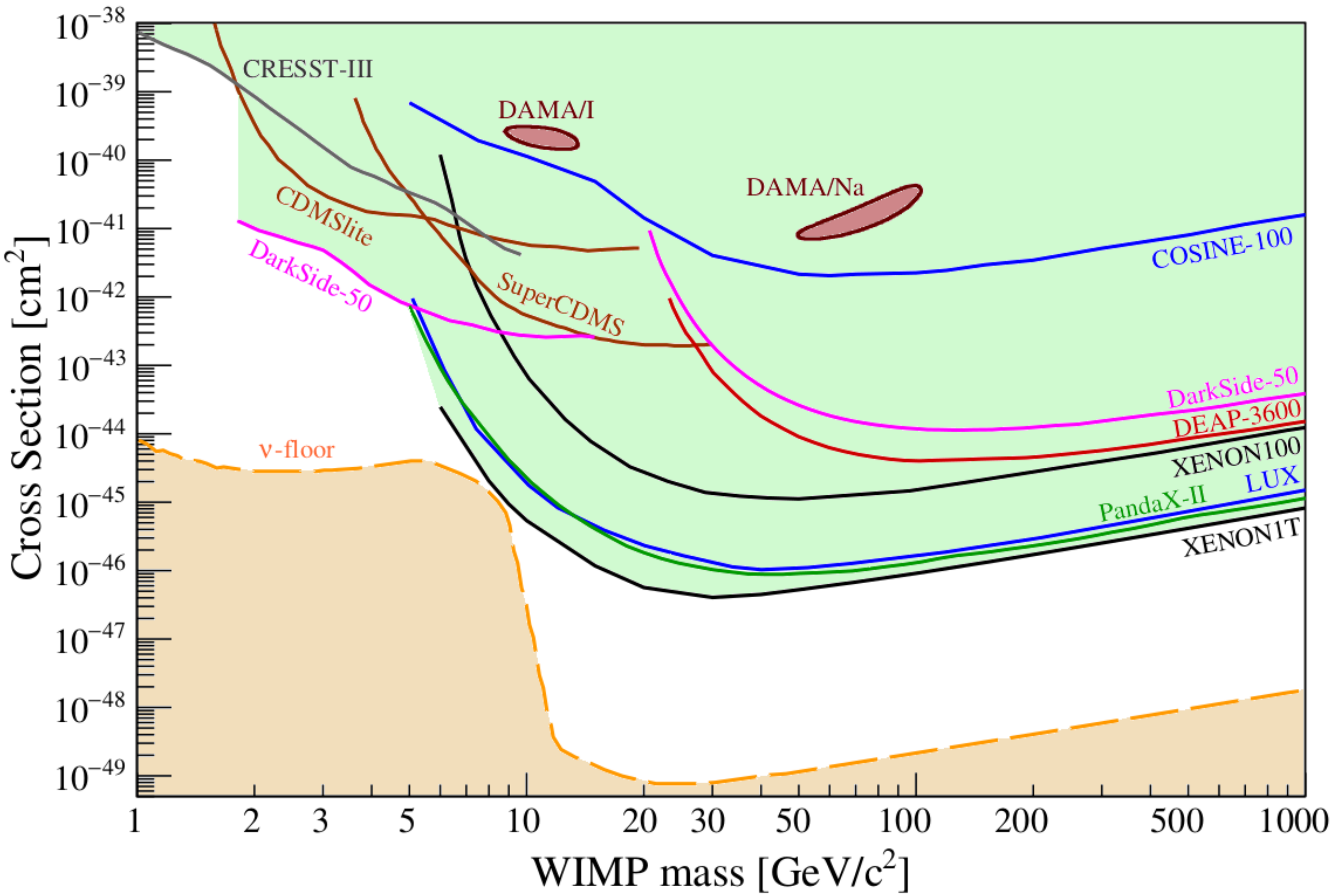
$$E_{det}$$

~ keV Threshold

Undagoitia, Rauch 1509.08767

*doesn't measure integrated rate

Nuclear Recoil Direct Detection



Current status: null results for weak scale DM

What about lighter DM (< GeV)?

Schaumann 1903.02026

Overview

1) There are many weird direct-detection excesses

2) There is a candidate process to characterize these events

3) Currently no known plausible SM explanation

4) This process may originate from DM interactions

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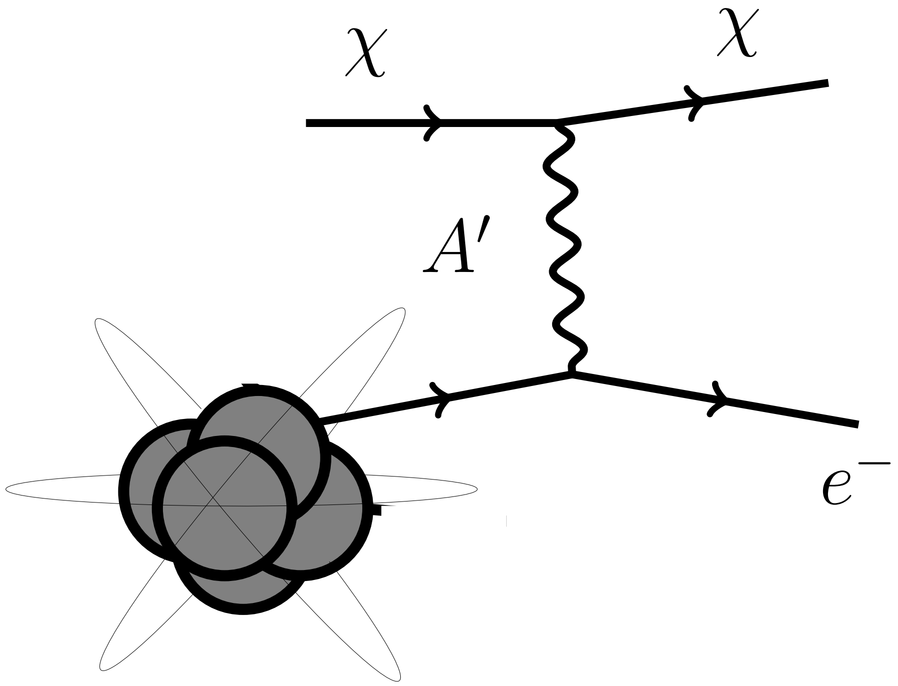
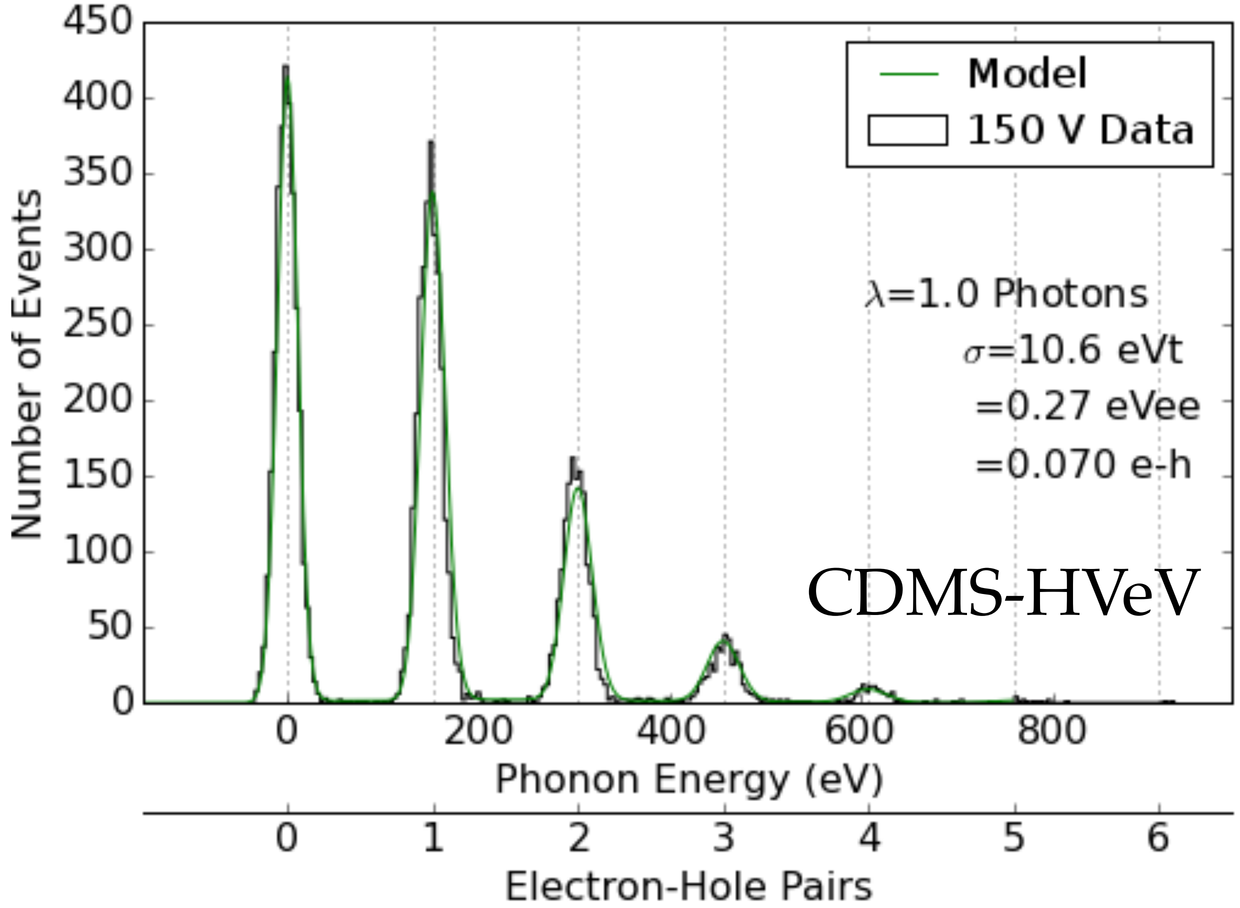
Low Threshold Revolution

Lighter DD targets probe sub-GeV DM





Scatter electrons, not nuclei

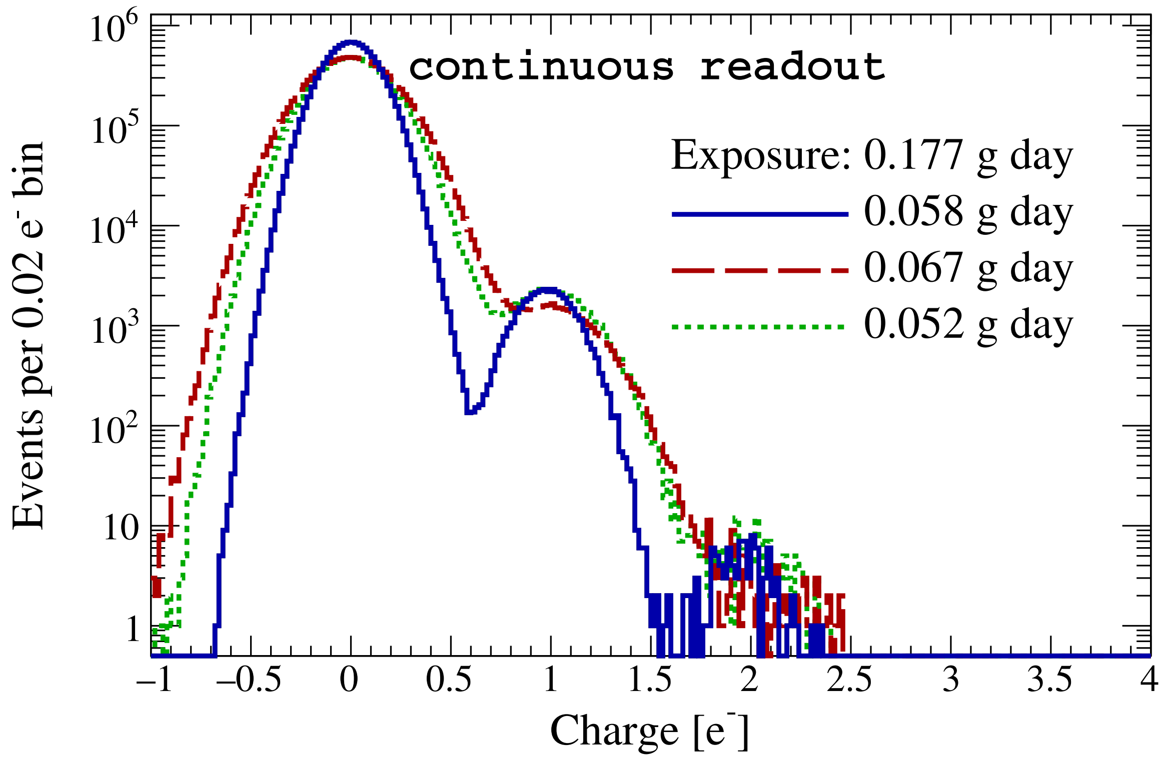
$$|\vec{q}| \sim m_e \alpha \quad , \quad E_e = \frac{|\vec{q}|^2}{2m_e}$$

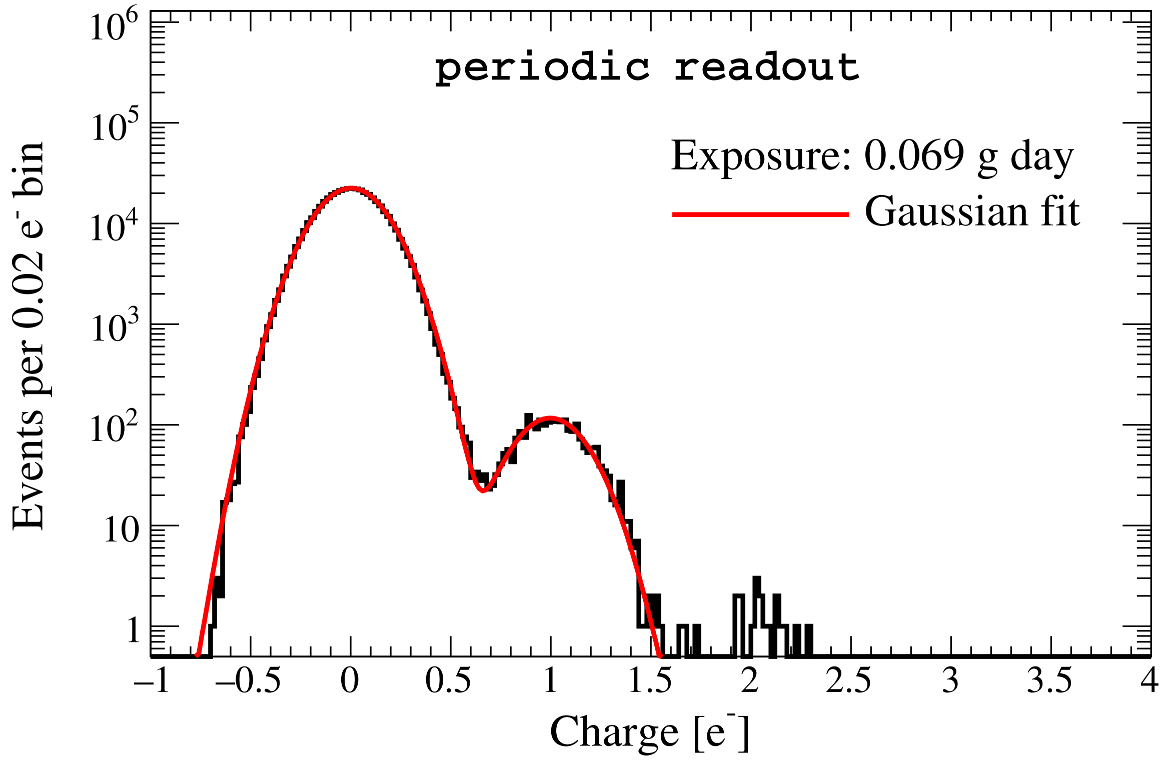
Measure *ionization*
1-electron sensitivity

See Rouven Essig's slides

SENSEI (Charge Readout)

Silicon semiconductor





100 m detector depth

100 K temperature

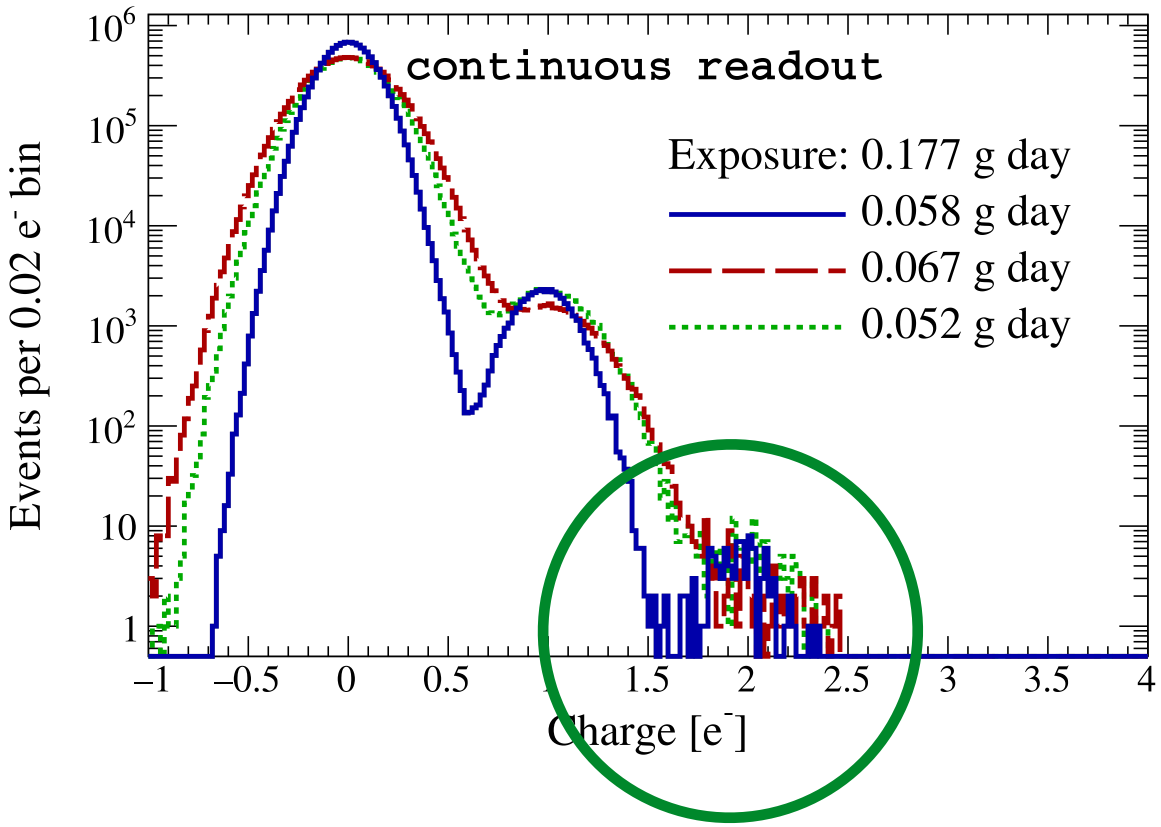
0.2 e resolution

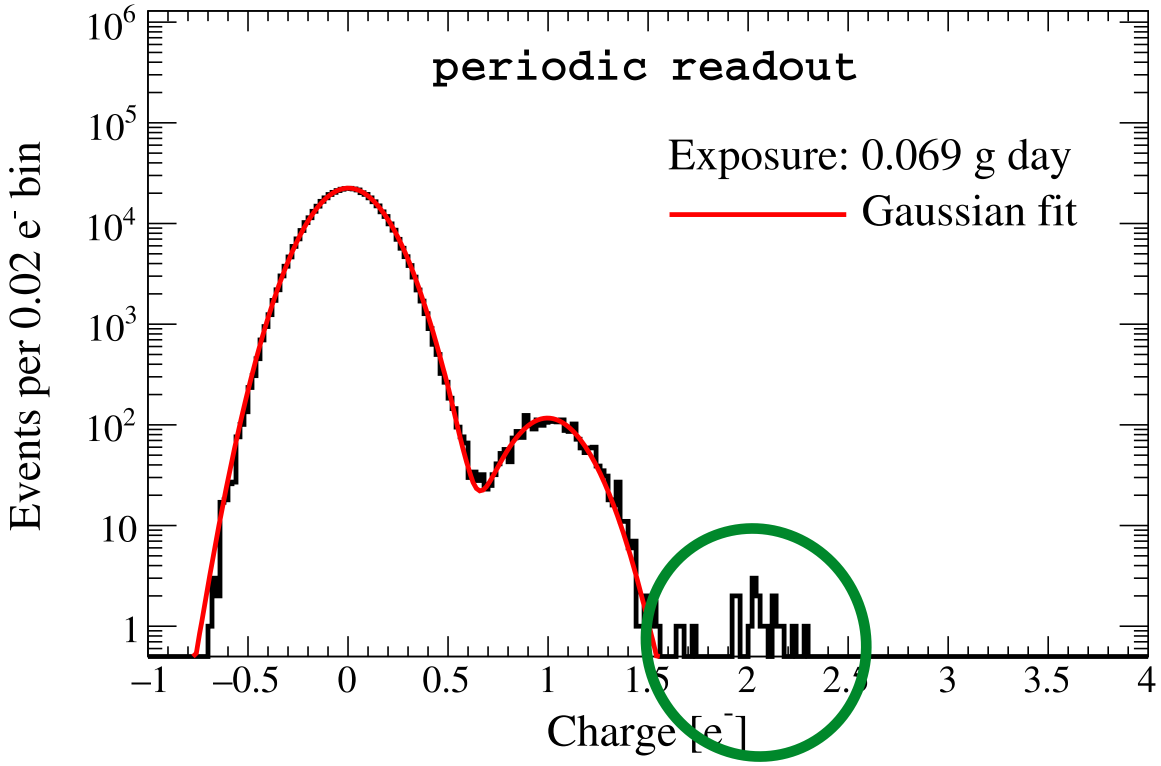
0.2 gram day exposure

SENSEI Collab. PRL 122, 161801 (2019)

SENSEI (Charge Readout)

Silicon semiconductor





100 m detector depth

100 K temperature

0.2 e resolution

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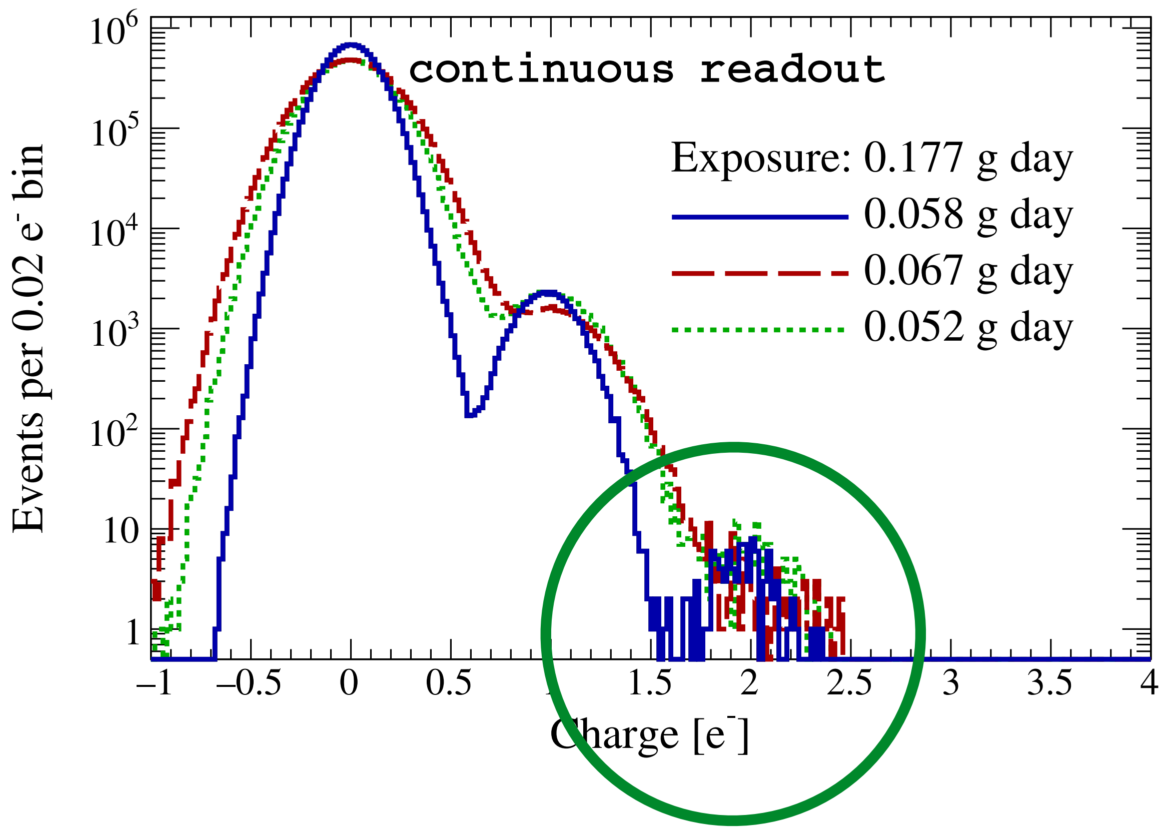
Excess Rate = 6 - 400 Hz/kg

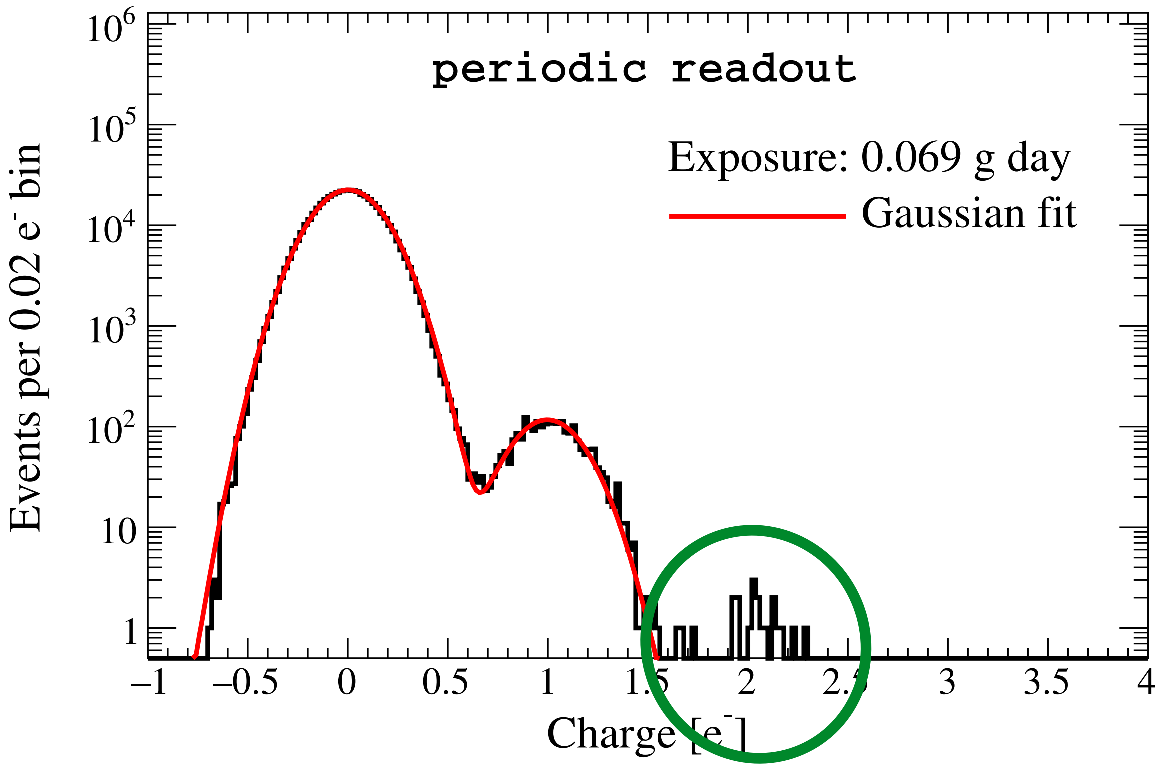
SENSEI Collab. PRL 122, 161801 (2019)

SENSEI Collaboration 2004.11378

SENSEI (Charge Readout)

Silicon semiconductor





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100 K temperature

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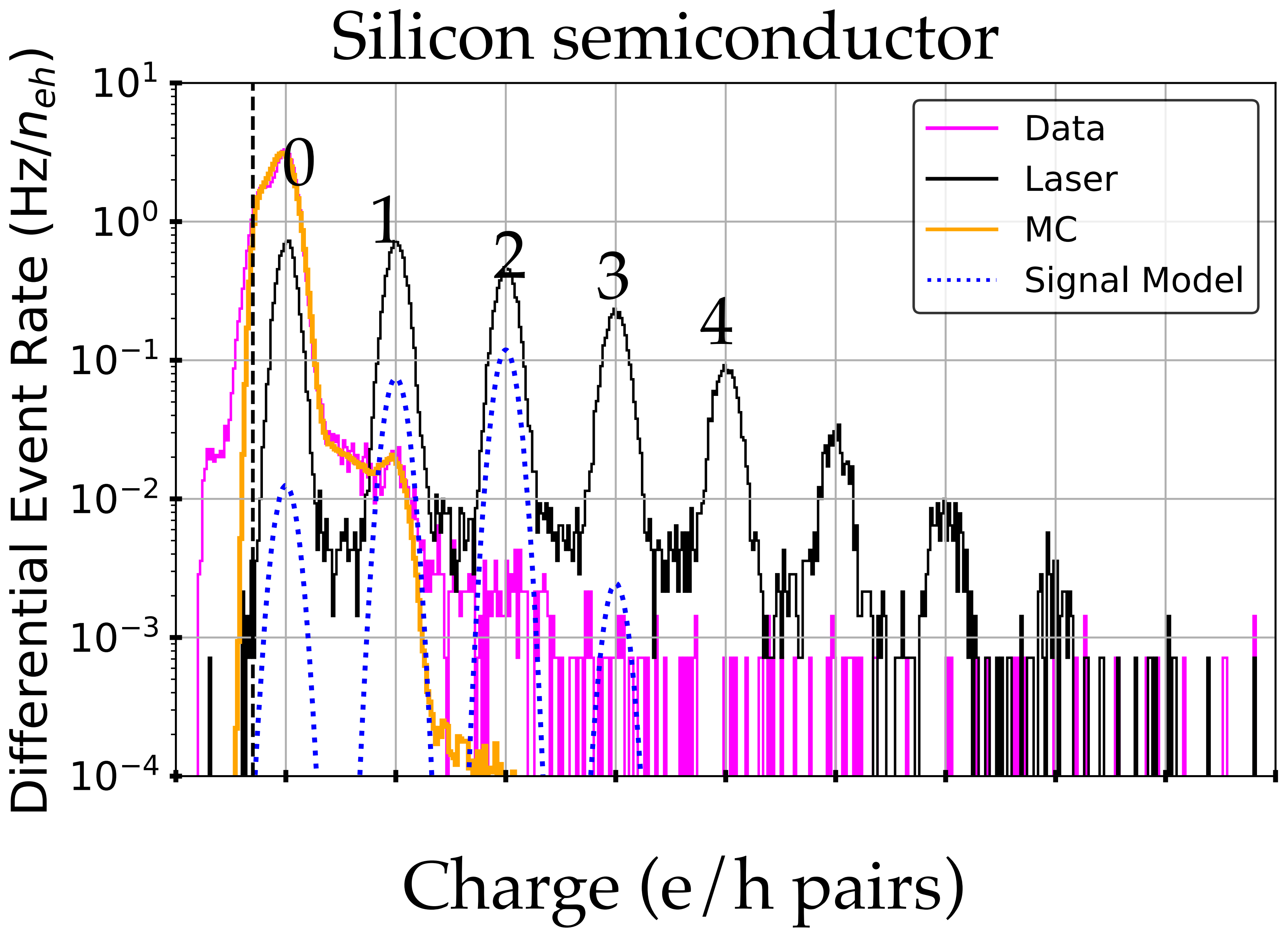
April 2020 Update: Excess* Rate ~ (0.01-1) Hz/kg

SENSEI Collab. PRL 122, 161801 (2019)

SENSEI Collaboration 2004.11378

CDMS-HVeV (Charge Readout)



1 m detector depth

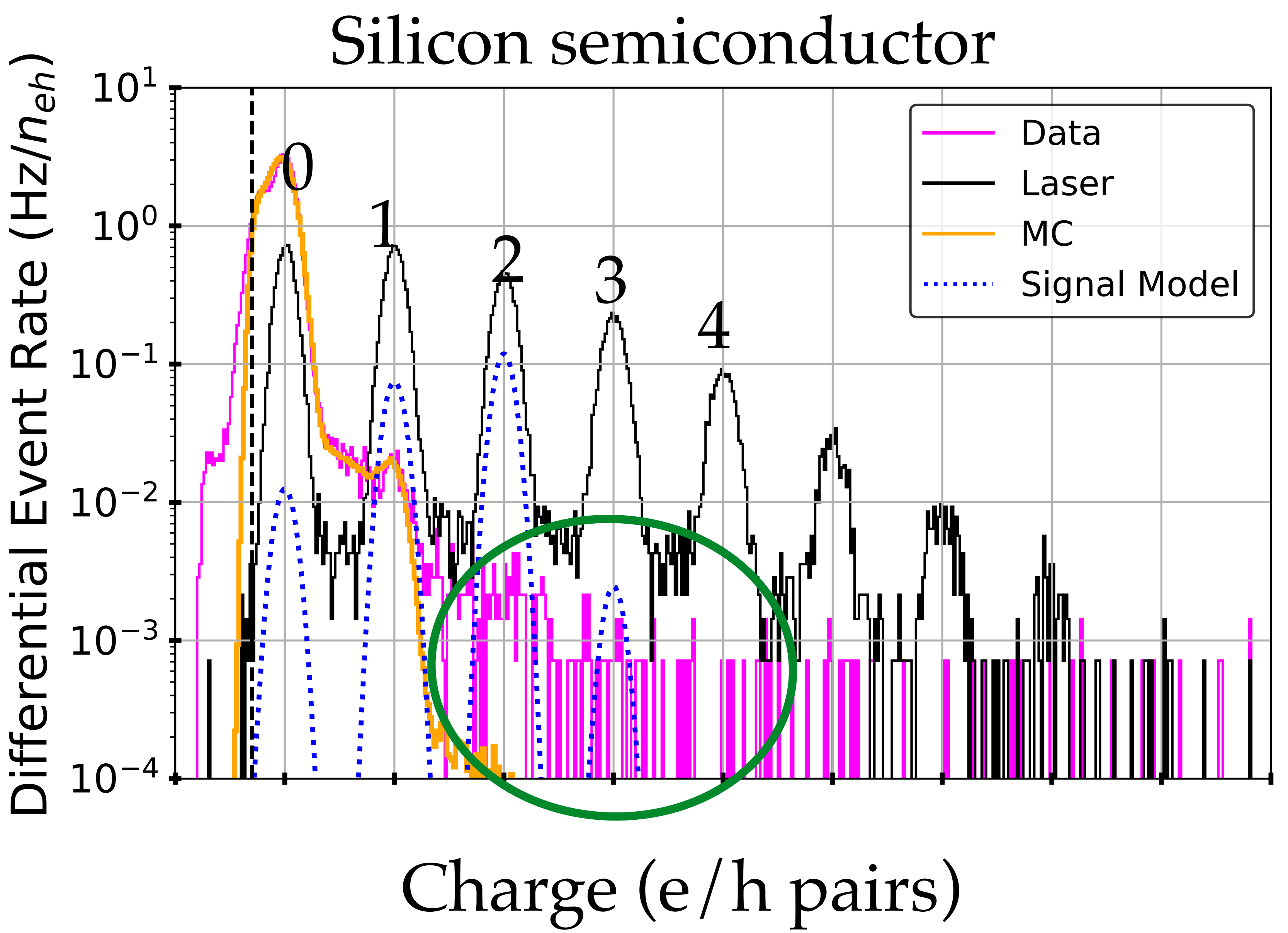
10 mK temperature

0.1 e resolution

0.5 gram day exposure

CDMS-HVeV 1804.10697

CDMS-HVeV (Charge Readout)



1 m detector depth

10 mK temperature

0.1 e resolution

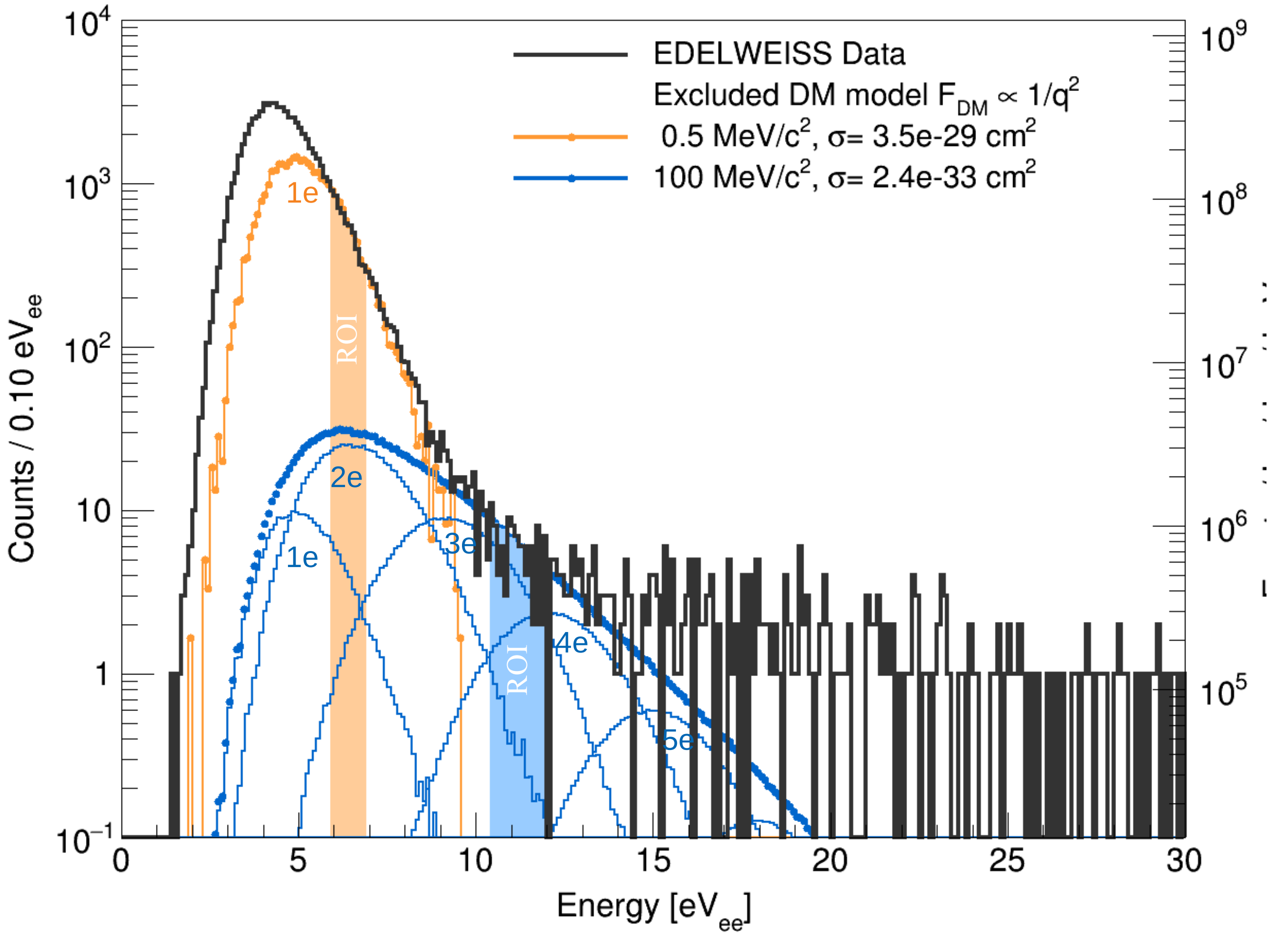
0.5 gram day exposure

Excess Rate = 10 - 2000 Hz/kg (without/with 1e bin)

CDMS-HVeV 1804.10697

EDELWEISS (Charge Readout)

Germanium semiconductor



2 km detector depth

10 mK temperature

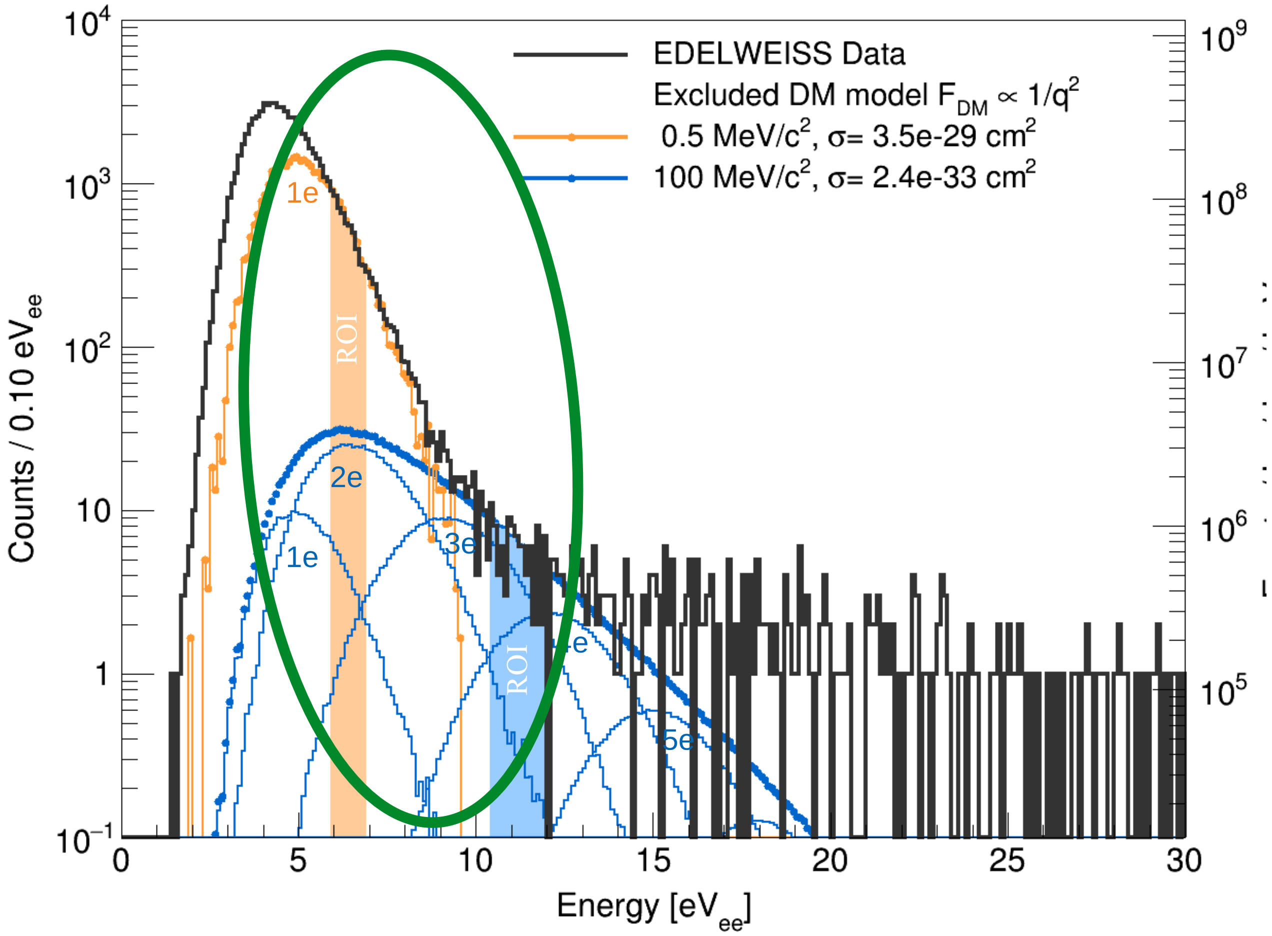
1.6 e resolution

80 gram day exposure

EDELWEISS Collaboration 2003.01046

EDELWEISS (Charge Readout)

Germanium semiconductor



2 km detector depth

10 mK temperature

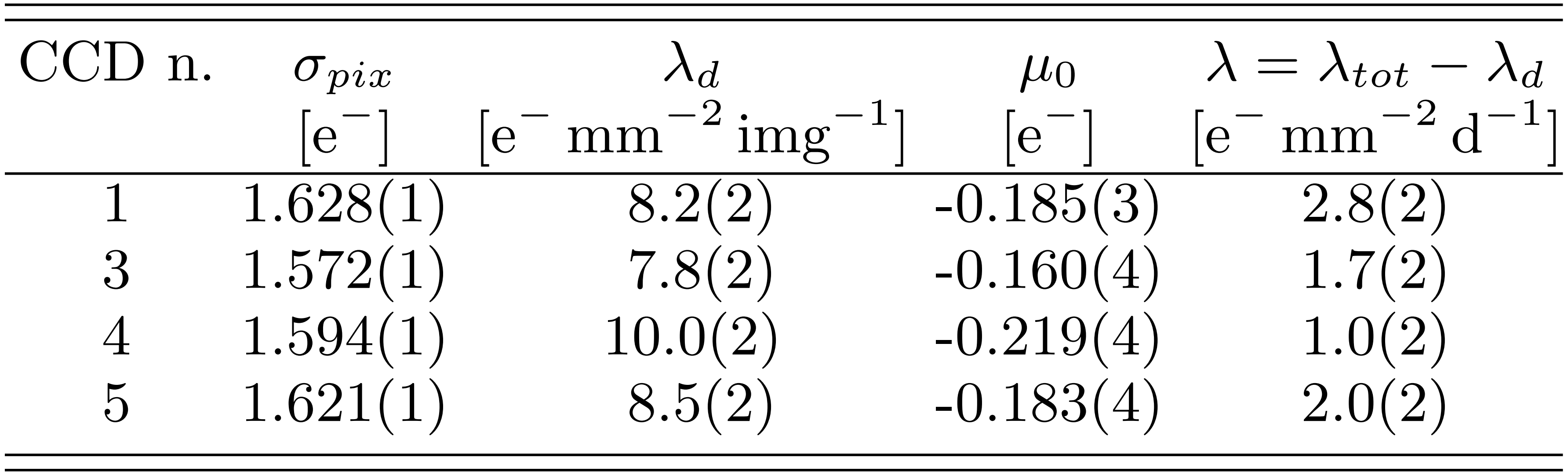
1.6 e resolution

80 gram day exposure

Excess Rate = 20 - 100 Hz/kg (without/with first bin)

EDELWEISS Collaboration 2003.01046

DAMIC (Charge Readout)



CCD n.	σ_{pix} [e$^-$]	λ_d [e$^-$ mm^{-2} img^{-1}]	μ_0 [e$^-$]	$\lambda = \lambda_{tot} - \lambda_d$ [e$^-$ mm^{-2} d^{-1}]
1	1.628(1)	8.2(2)	-0.185(3)	2.8(2)
3	1.572(1)	7.8(2)	-0.160(4)	1.7(2)
4	1.594(1)	10.0(2)	-0.219(4)	1.0(2)
5	1.621(1)	8.5(2)	-0.183(4)	2.0(2)

DAMIC Collaboration PRL 1907.12628

2 km detector depth

100 K temperature

1.2 e resolution

200 gram day exposure

They report a low "dark count" rate $\sim 10^{-3}\,\mathrm{Hz/kg}$

DAMIC (Charge Readout)

CCD n.	σ_{pix} $[\mathrm{e}^-]$	λ_d $[\mathrm{e}^-\ \mathrm{mm}^{-2}\ \mathrm{img}^{-1}]$	μ_0 $[\mathrm{e}^-]$	$\lambda = \lambda_{tot} - \lambda_d$ $[\mathrm{e}^-\ \mathrm{mm}^{-2}\ \mathrm{d}^{-1}]$
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DAMIC Collaboration PRL 1907.12628

1) Uses a different ionization model from others

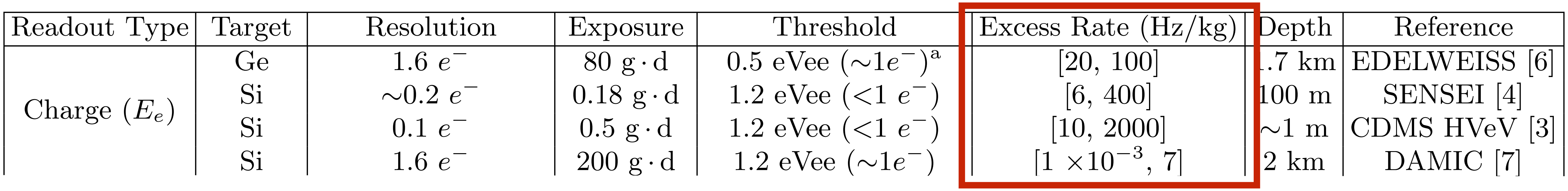
2) Reports “dark counts” based on likelihood analysis

Prior: all events treated as “dark count” BG

Could be misattributing would-be signal

Our interpretation: conservative upper bound ~ 7 Hz/kg

Semiconductor Summary



Readout Type	Target	Resolution	Exposure	Threshold	Excess Rate (Hz/kg)	Depth	Reference
Charge (E_e)	Ge	1.6 e^-	80 g · d	0.5 eVee ($\sim 1e^-$)[a]	[20, 100]	.7 km	EDELWEISS [6]
	Si	$\sim$0.2 e^-	0.18 g · d	1.2 eVee (<1 e^-)	[6, 400]	100 m	SENSEI [4]
	Si	0.1 e^-	0.5 g · d	1.2 eVee (<1 e^-)	[10, 2000]	$\sim$1 m	CDMS HVeV [3]
	Si	1.6 e^-	200 g · d	1.2 eVee ($\sim 1e^-$)	[1×10^{-3}, 7]	2 km	DAMIC [7]

Intriguing coincidence of rates

Different Depths

Different Shielding

Different Exposures

Different Composition

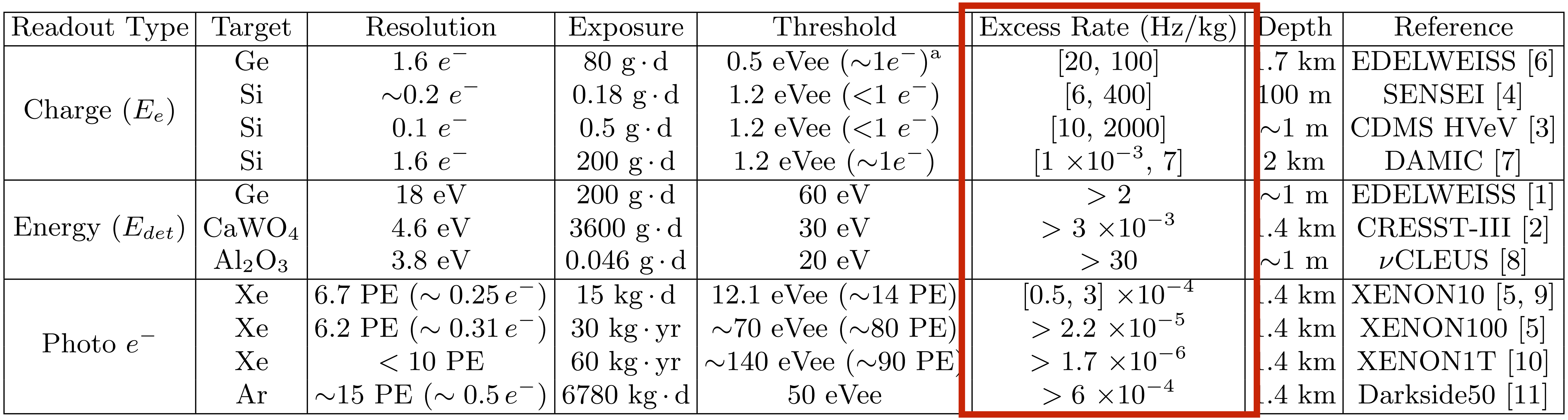
Different Temperatures

Different Pressures

Unlike nuclear recoil: these are integrated total rates!

Semiconductors have tiny thresholds

All sub-GeV Searches Summary



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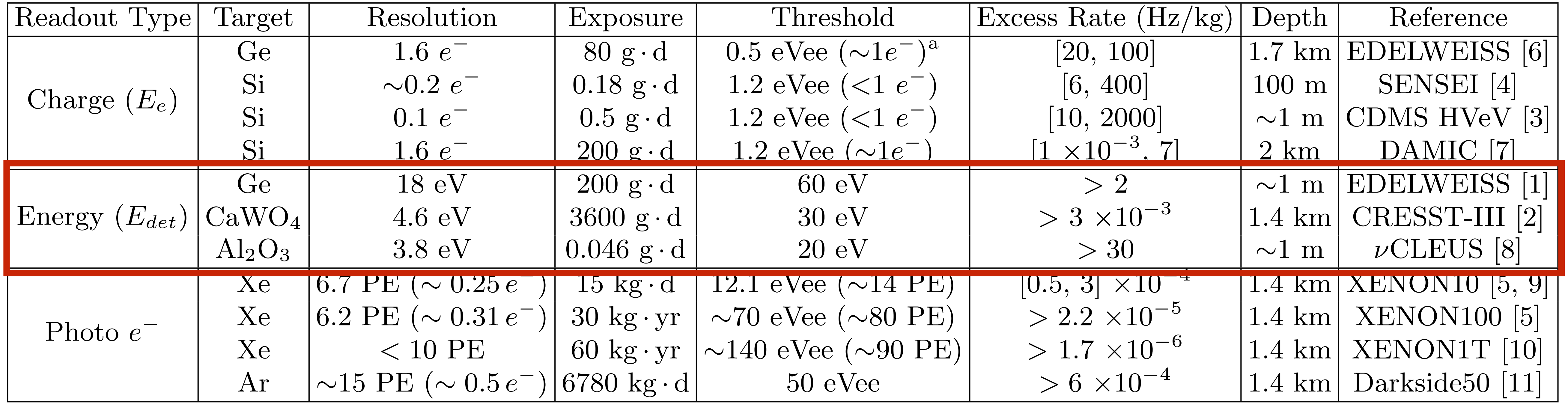
Energy (E_{det})	Ge	18 eV	200 g $\cdot$ d	60 eV	> 2	$\sim$1 m	EDELWEISS [1]
	$CaWO_4$	4.6 eV	3600 g $\cdot$ d	30 eV	$> 3 \times 10^{-3}$	.4 km	CRESST-III [2]
	Al_2O_3	3.8 eV	0.046 g $\cdot$ d	20 eV	> 30	$\sim$1 m	νCLEUS [8]
Photo e^-	Xe	6.7 PE ($\sim 0.25\, e^-$)	15 kg $\cdot$ d	12.1 eVee ($\sim$14 PE)	[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 Searches Summary



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

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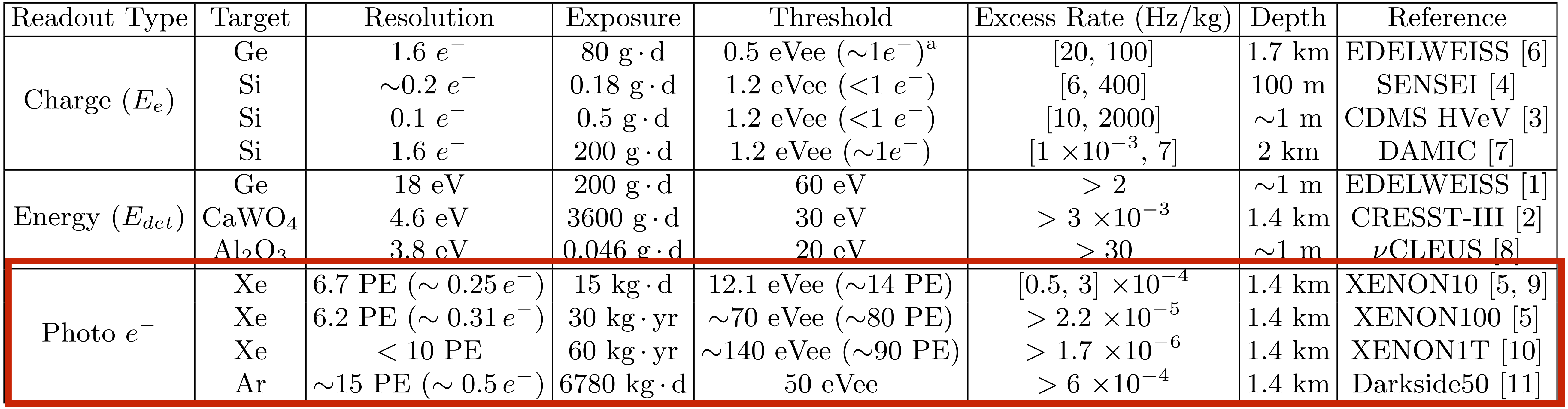

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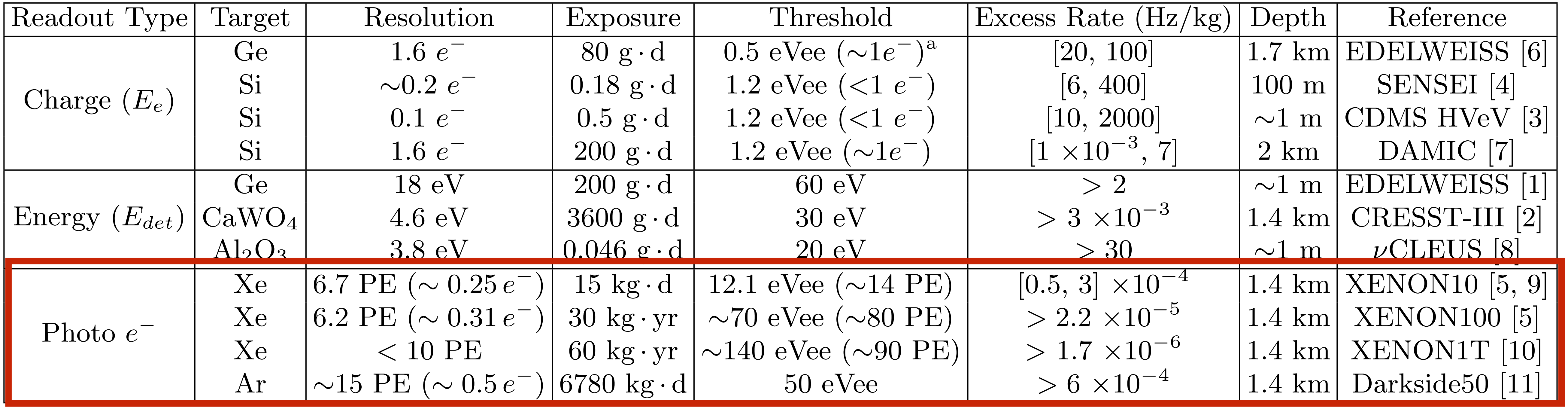

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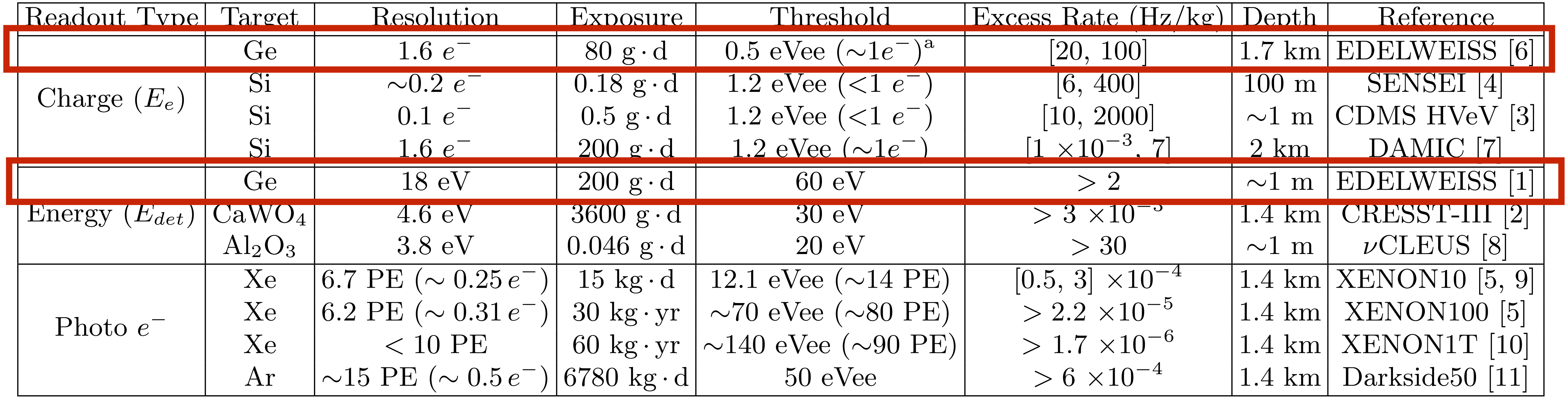
-XENON10/100/1T rates all **similar for same threshold**

All sub-GeV Searches Summary



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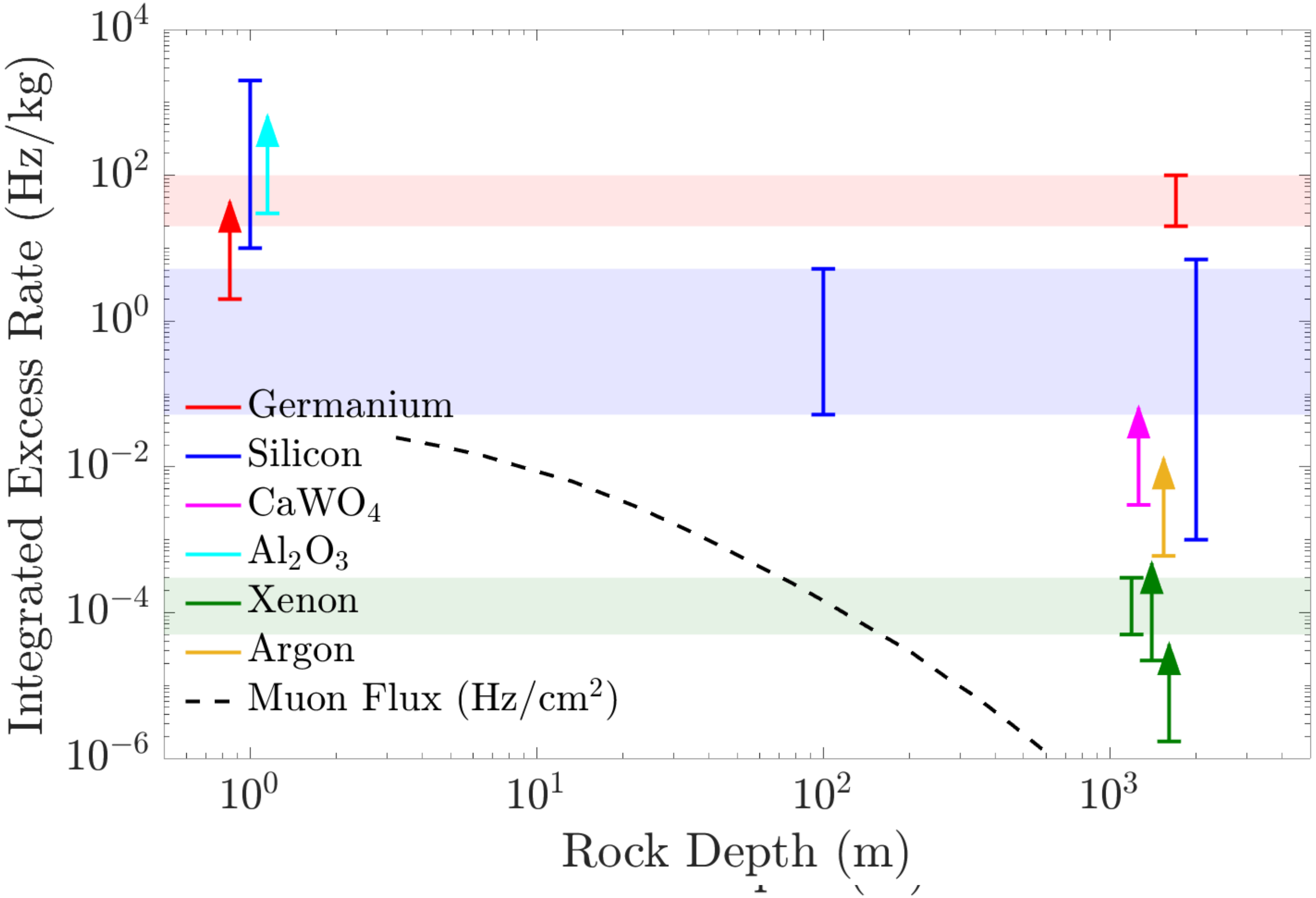
- *Edet* readout: total rate unknown, **hard to compare**

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

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

- EDELWEISS has excess in both *Ee* and *Edet* runs

Excesses vs. Depth



Includes new SENSEI 2020 result 2004.11378 (plot from FNAL wine/cheese seminar)

Overview

1) There are many weird direct-detection excesses

2) There is a candidate process to characterize these events

3) Currently no known plausible SM explanation

4) This process may originate from DM interactions

Why's Nobody Reporting a Signal?

EDELWEISS Case Study

EDELWEISS has data in both ER and NR

Both ER and NR runs observe excesses

Interpreting these as the *same process* implies a charge model

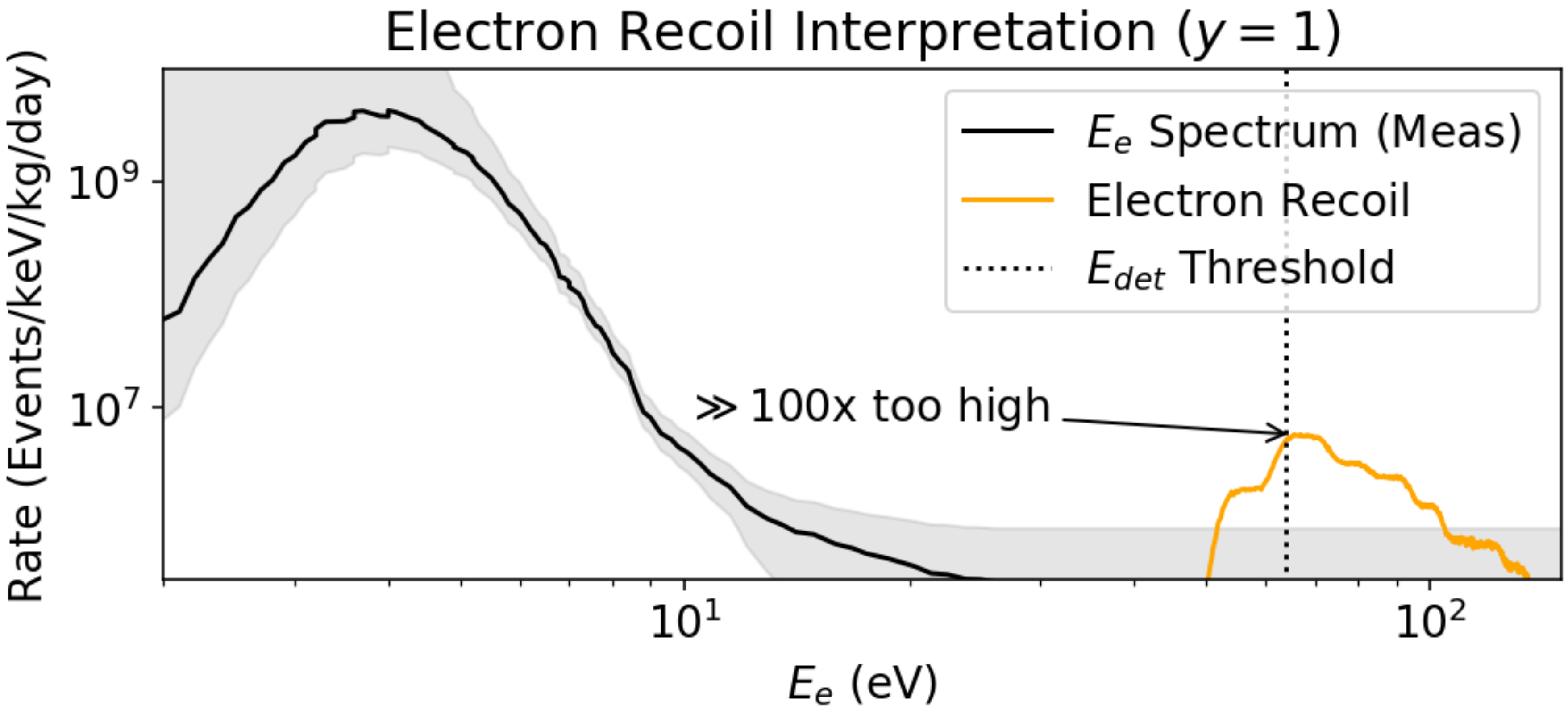
$$E_e = E_{det}\left[y(E_{det}) + \frac{\epsilon_{eh}}{e \cdot V_{det}}\right]$$

Can we find a consistent description?

J. Gascon http://vietnam.in2p3.fr/2020/tmex/transparencies/2_tuesday/2_afternoon/5_gascon.pdf

Electron Recoil Interpretation?

Assume EDELWEISS runs arise from DM-electron scattering

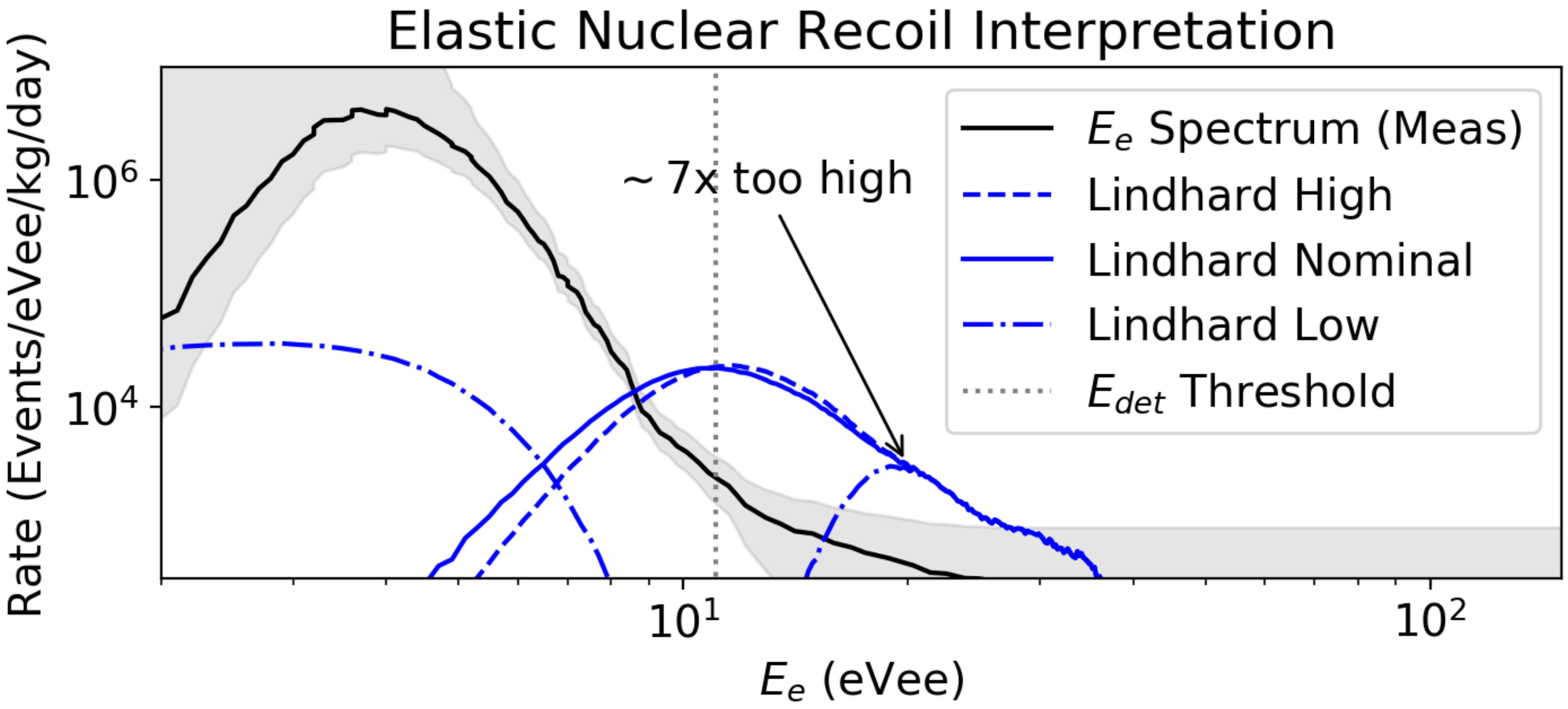


ER only prediction can’t fit under black curve: BAD FIT

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

Nuclear Recoil Interpretation?

Assume EDELWEISS runs arise from DM-nucleon scattering



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

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

Another Possibility?

Assume the excess is due to some inelastic* process

$$\langle E_e \rangle = \epsilon_{eh} \left(\lambda_{eh} + \frac{E_{det}}{e \cdot V_{det}} \right)$$

Total det energy

Electron/hole pair energy

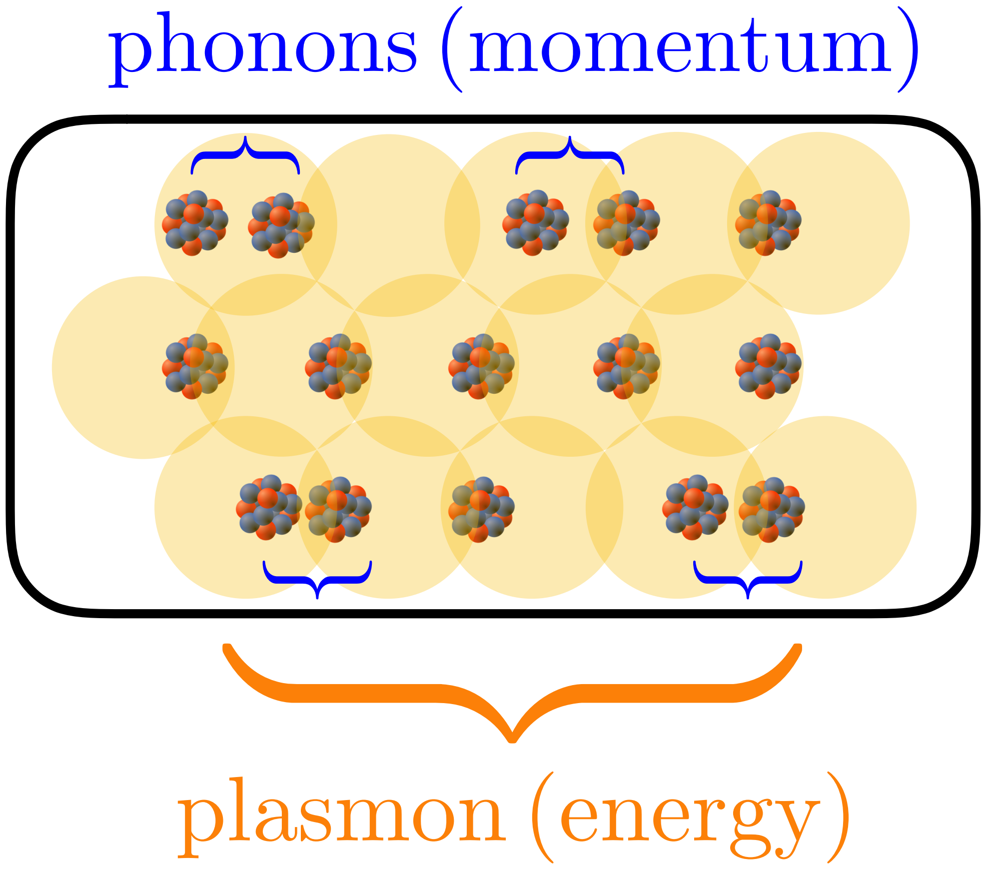
Average e/h yield per signal event

Key feature: constant piece independent of *Edet*

*Not to be confused with inelastic DM!

Consider Semiconductor Plasmons

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



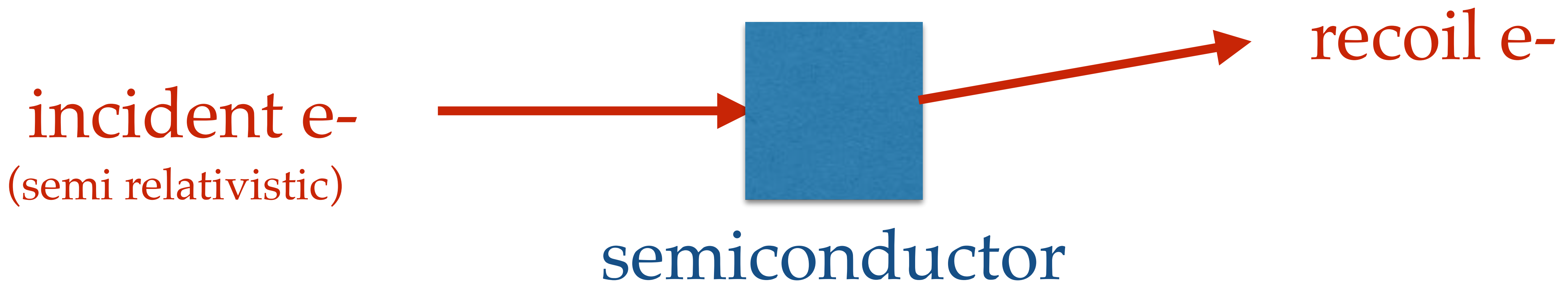
Plasmon excitation energy

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

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

Breaks usual charge heat yield relationship

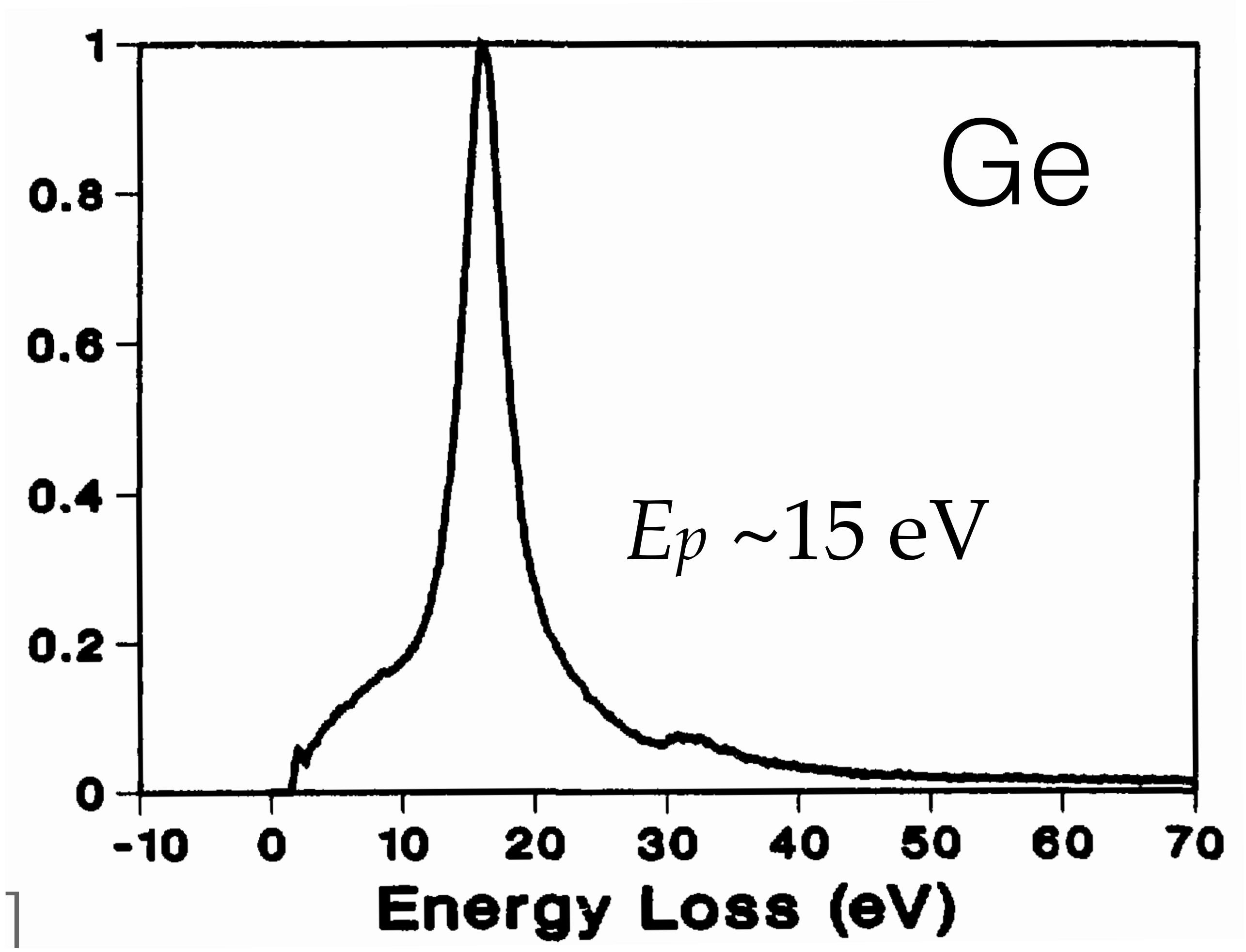
Analogy: Electron Energy Loss Spectroscopy (EELS)



incident e-
(semi relativistic)

semiconductor

recoil e-



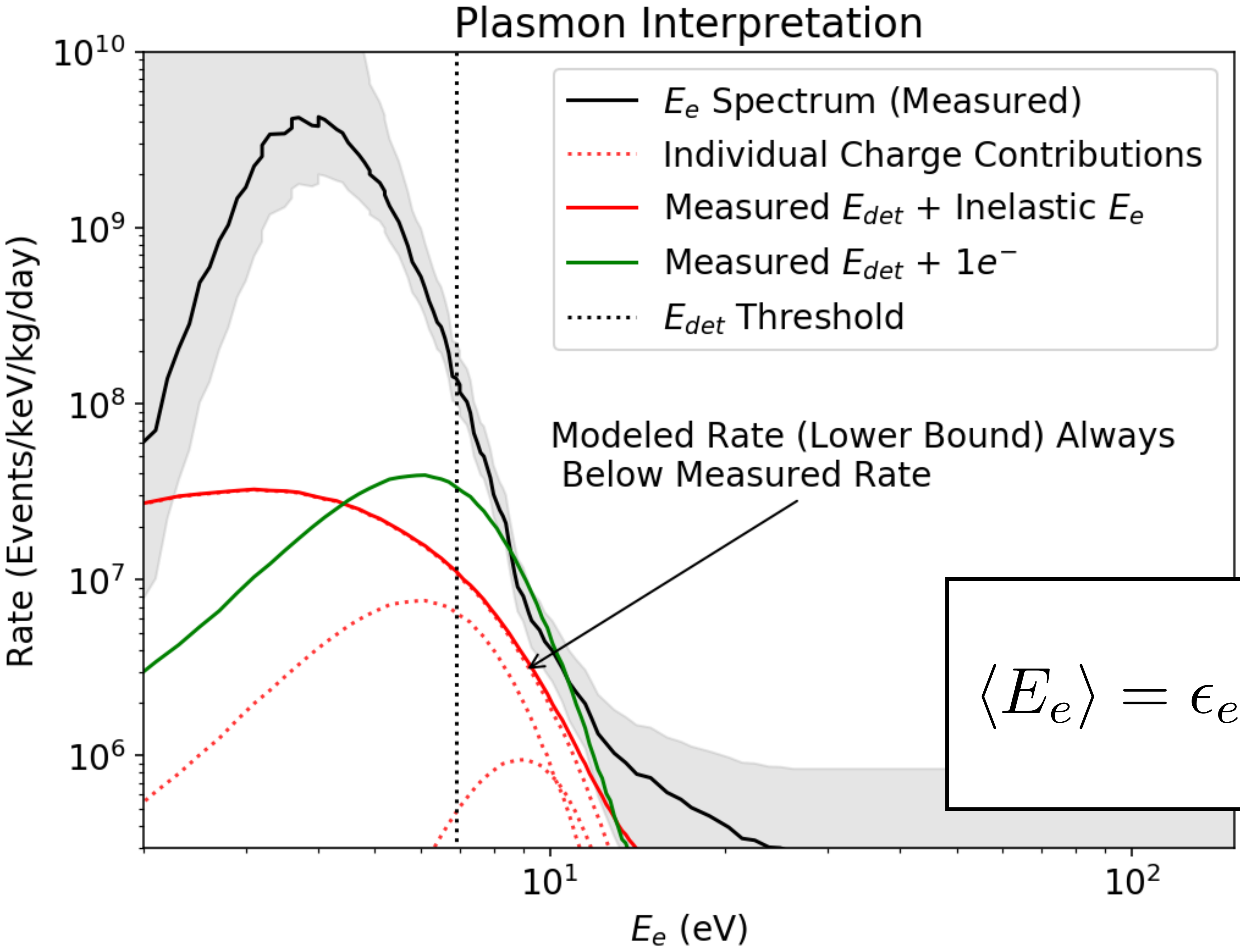
$E_{det} \sim E_p \sim 15$ eV

independent of initial velocity

Qualitatively different charge/heat yield relation

MK Kundmann PhD Thesis 1988

“Inelastic” Yield Model



Modeled Rate (Lower Bound) Always Below Measured Rate

$$\langle E_e \rangle = \epsilon_{eh} \left(\lambda_{eh} + \frac{E_{det}}{e \cdot V_{det}} \right)$$

Key point: model can now fit under black curve

General result not limited to plasmons

Overview

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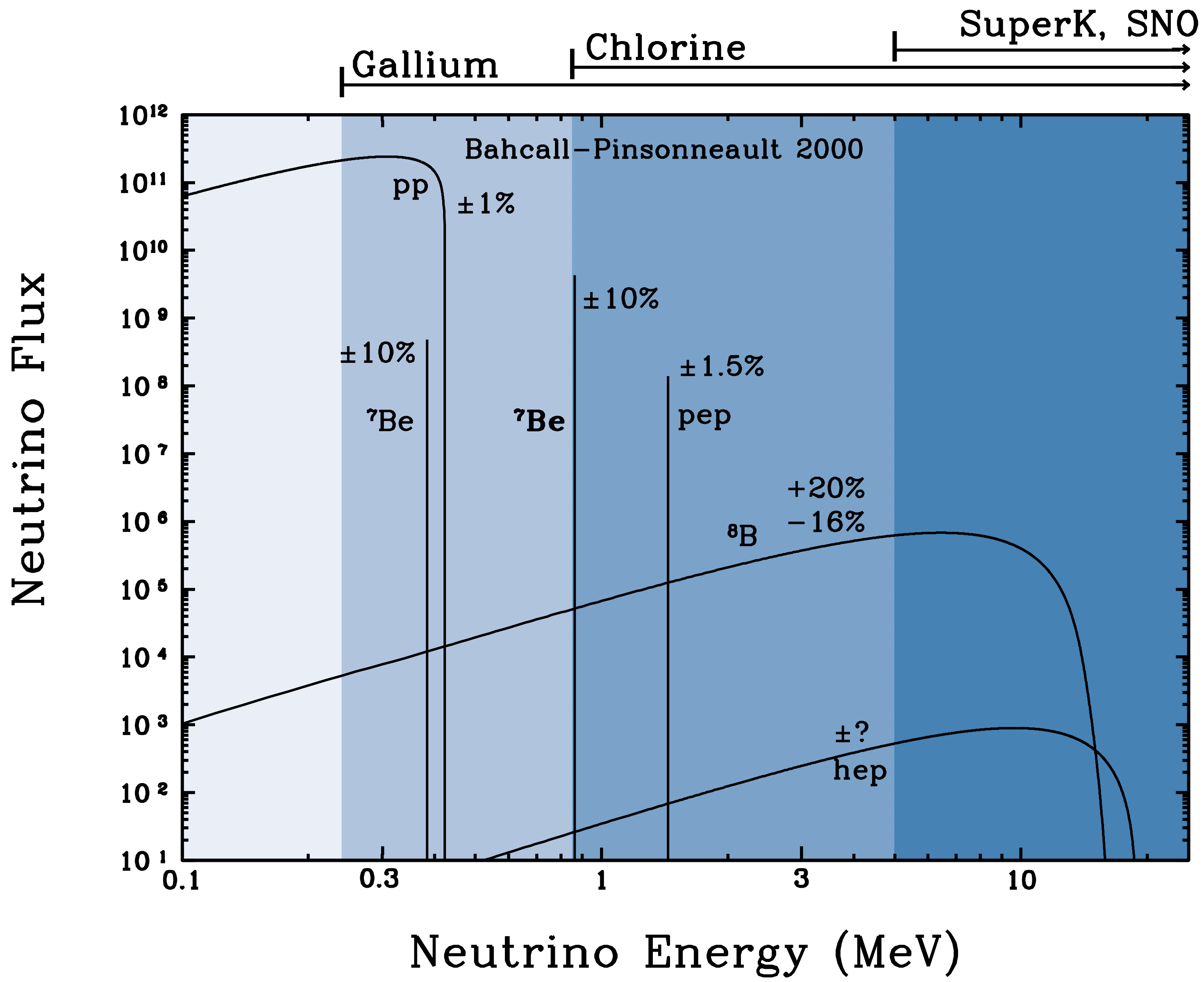
4) This process may originate from DM interactions

Solar *pp* Neutrinos?

Most abundant terrestrial neutrino flux



Can’t make plasmon

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

need ~ 16 eV in Ge

$$\mathcal{R}_{pp} = N_{\rm Ge}\Phi_{pp}\sigma_{pp}^{\rm coh} \simeq 2.3\times 10^{-6}\,\mathrm{Hz\,kg^{-1}}$$

… and flux too low

Photons / Electrons?

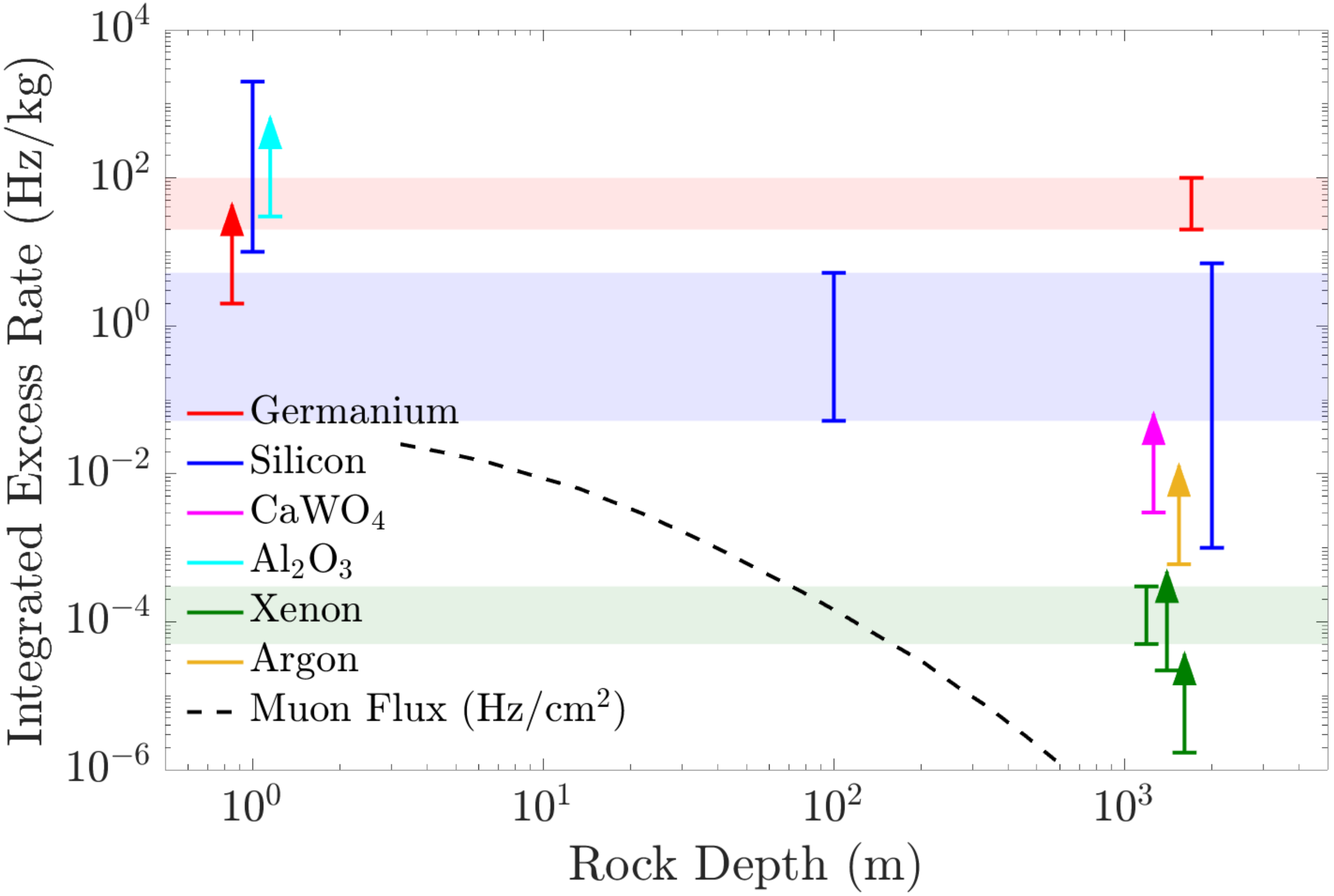
Photons: Transversely polarized & can’t source plasmons which are longitudinally polarized

Electrons: Mean free path ~ nm

Would multiple scatter and create many plasmons

Not observed: need single energy deposit < 100 eV

Muons?



Muon flux has known scaling with depth

Neutrons?

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?

Overview

1) There are many weird direct-detection excesses

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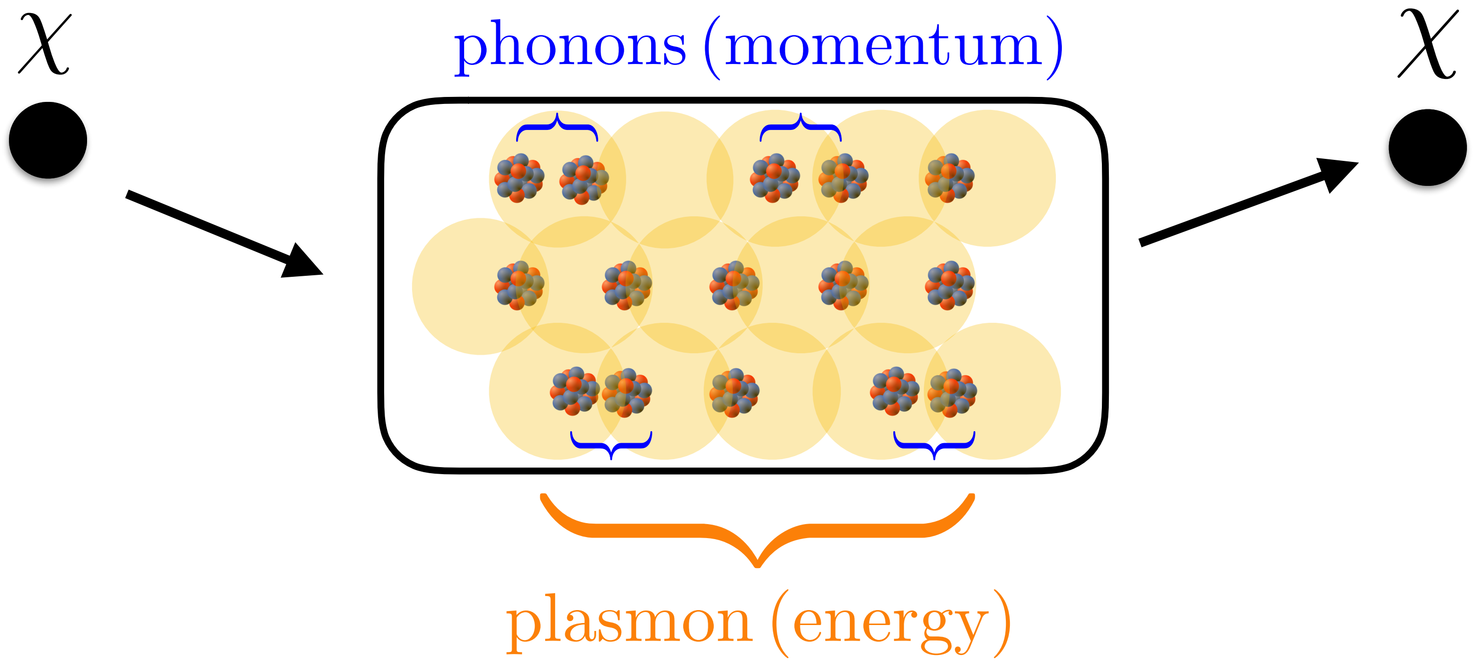
3) This process may originate from DM interactions

- **a) Direct Plasmon Excitation**
- b) Secondary Plasmon Excitation

a) Direct Plasmon Excitation Model

Extend EELS analogy: “millicharged” DM



DM excites plasmon directly through its own Coulomb field

Longer mean free path, << 1 interaction per crossing

a) Direct Plasmon Excitation Model

Can use measured EELS plasmon excitation prob.

$$\frac{dP}{dt\,d\omega} = \frac{e^2}{4\pi^3}\int d^3\mathbf{q}\,\frac{1}{q^2}\,\mathrm{Im}\left\{\frac{-1}{\epsilon(\omega,\mathbf{q})}\right\} \times \delta\left(\omega - \mathbf{q}\cdot\mathbf{v} + \frac{q^2}{2m_\chi}\right)$$

Need forward scatter (cos > 0) for low q-transfer

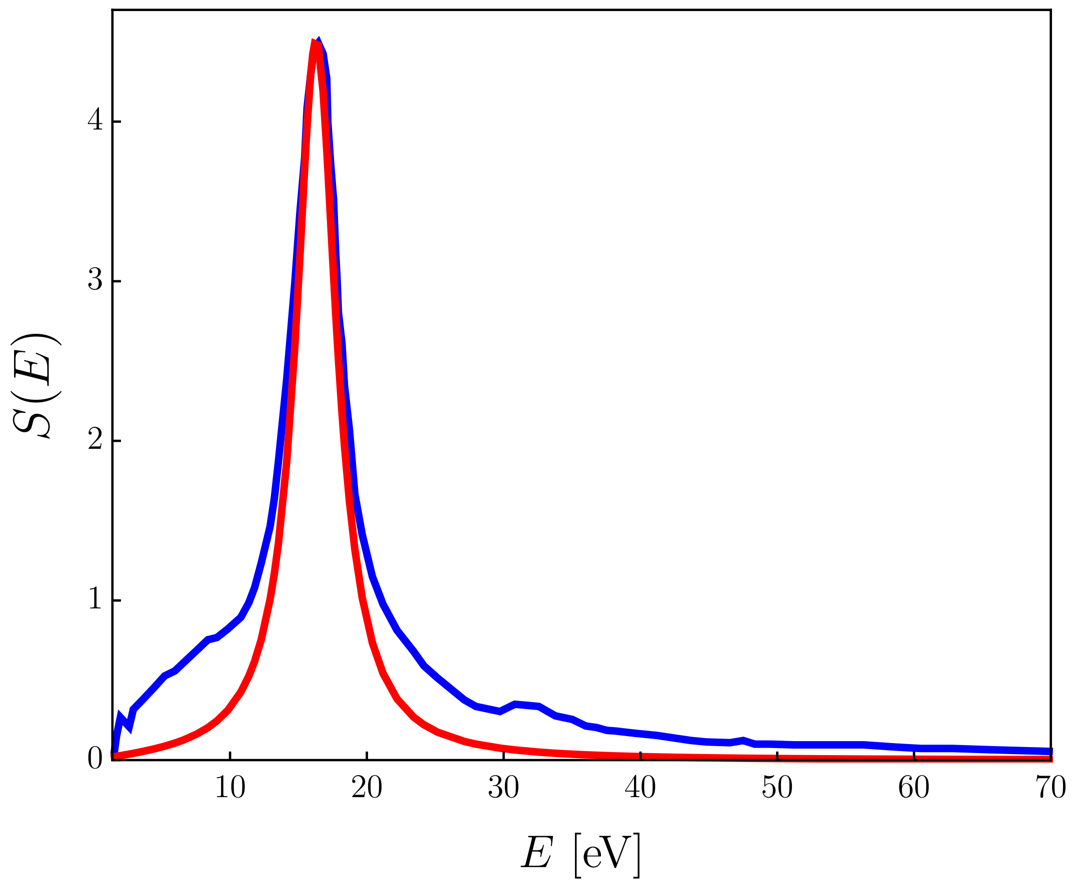
$$q = \frac{E}{v\cos\theta} + \frac{q^2}{2m_\chi v\cos\theta} \quad \longrightarrow \quad v \geq E_p/q_p = 6.5\times 10^{-3}\left(\frac{E_p}{16\ \mathrm{eV}}\right)$$

Minimum (high!) velocity for direct plasmon excitation

MK Kundmann PhD Thesis 1988

a) Direct Plasmon Excitation Model

Approximate shape with Lorentzian fit (Frolisch model)



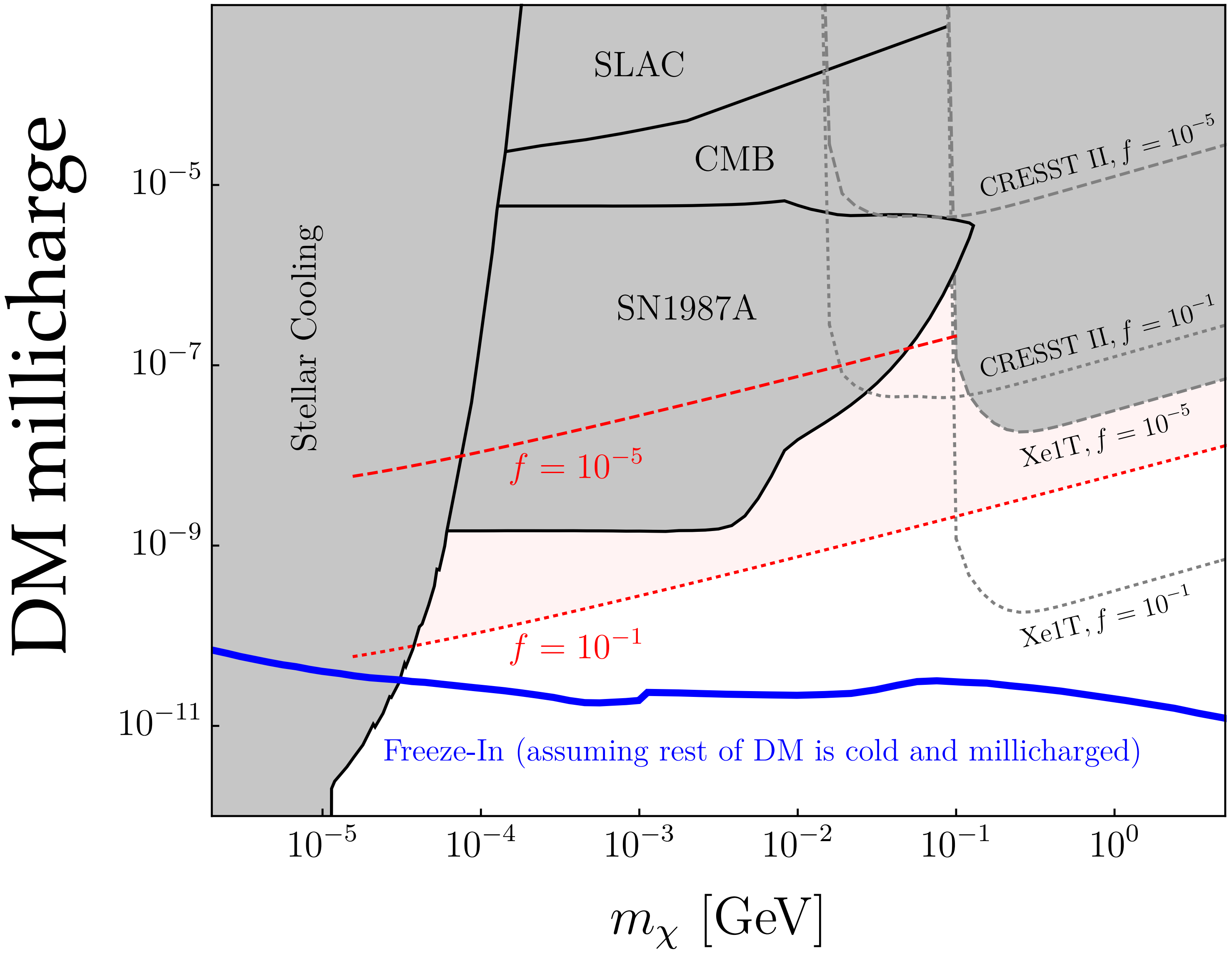
Completely calculable (rescale EELS rate by charge)

$$\frac{dR}{dE} = \frac{f\rho_\chi}{m_\chi \rho_T}\frac{2\kappa^2\alpha_D}{\pi} S(E)\int_0^{q_c}\frac{dq}{q}\eta(v_{\min}(q,E))$$

MK Kundmann PhD Thesis 1988

a) Direct Plasmon Excitation Model

Need fraction *f* of DM population with boosted velocity



Here

v~ 0.1

Shaded region ~ 10 Hz/kg in Ge

Overview

1) There are many weird direct-detection excesses

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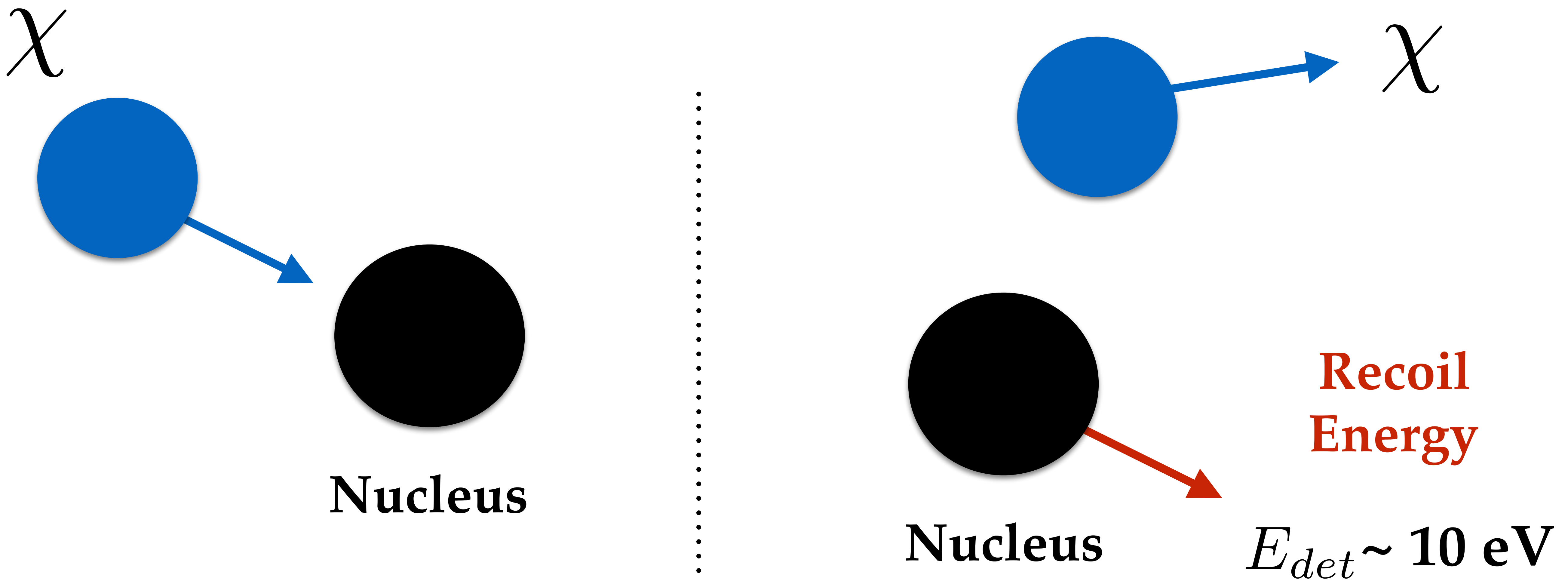
a) Direct Plasmon Excitation

b) Secondary Plasmon Excitation

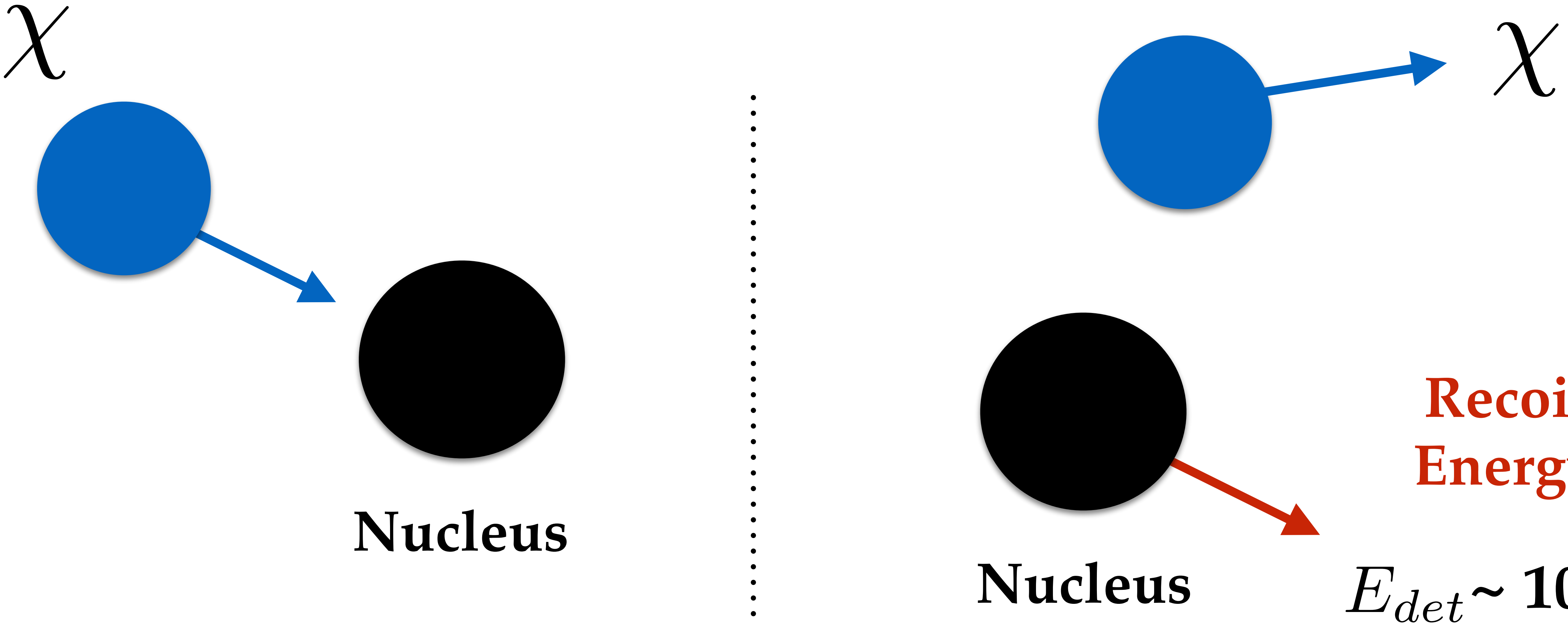
Secondary Plasmon Excitation Model



Step 1: DM induces a feeble nuclear recoil

Contact interaction, conventional DM velocity

Secondary Plasmon Excitation Model



χ

Nucleus

χ

Nucleus

Recoil Energy

E_{det} **~ 10 eV**

+ Plasmon & Phonons

Step 2: Nuclear recoil triggers plasmon excitation

See also Lin & Kozaczuk 2003.12077 for plasmon + single phonon study

Secondary Plasmon Excitation Model

Unlike millicharged scenario:

1) Use 100% of the DM population

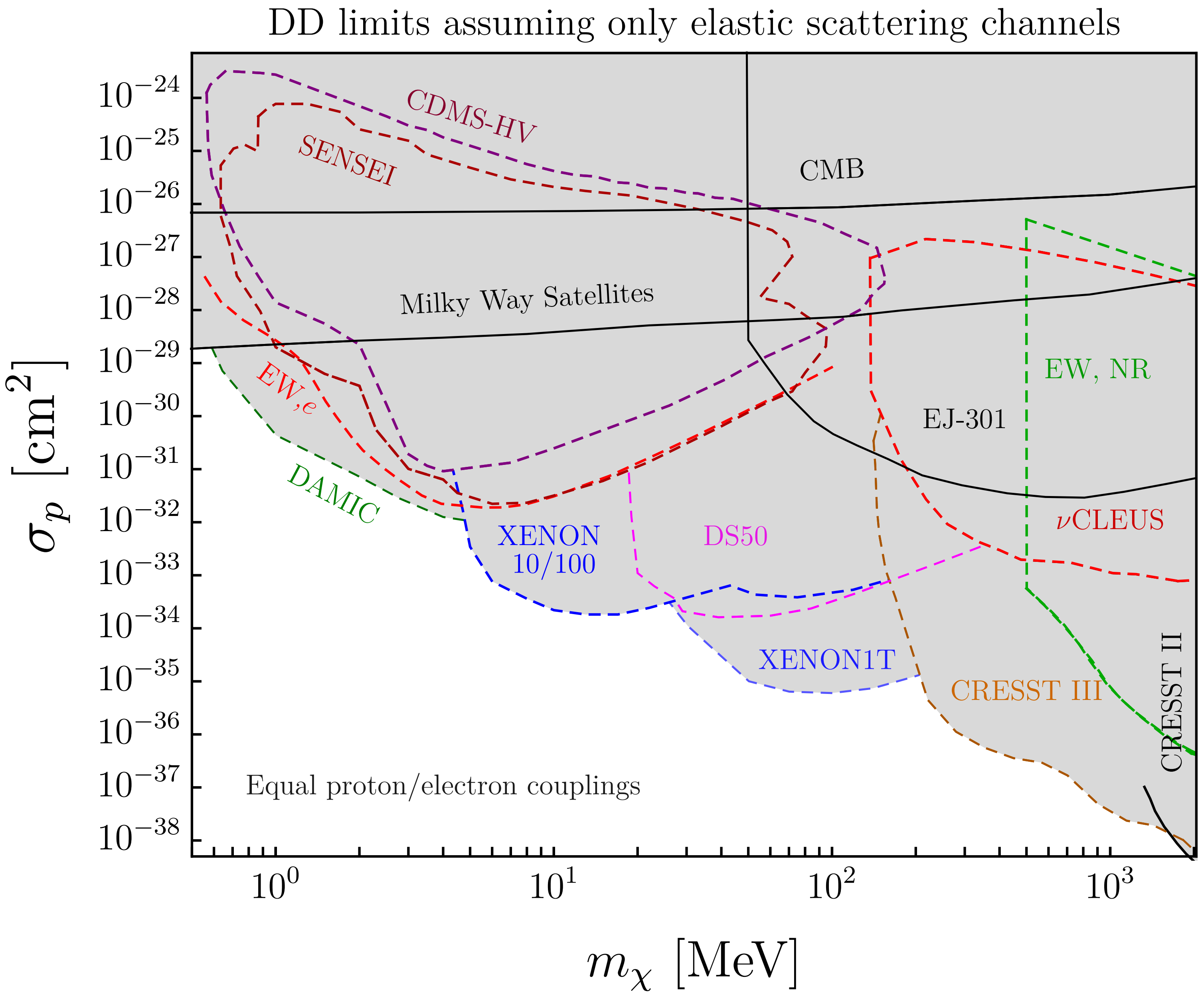
2) Use the usual DM velocity distribution

3) Can't calculate secondary plasmon excitation rate

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

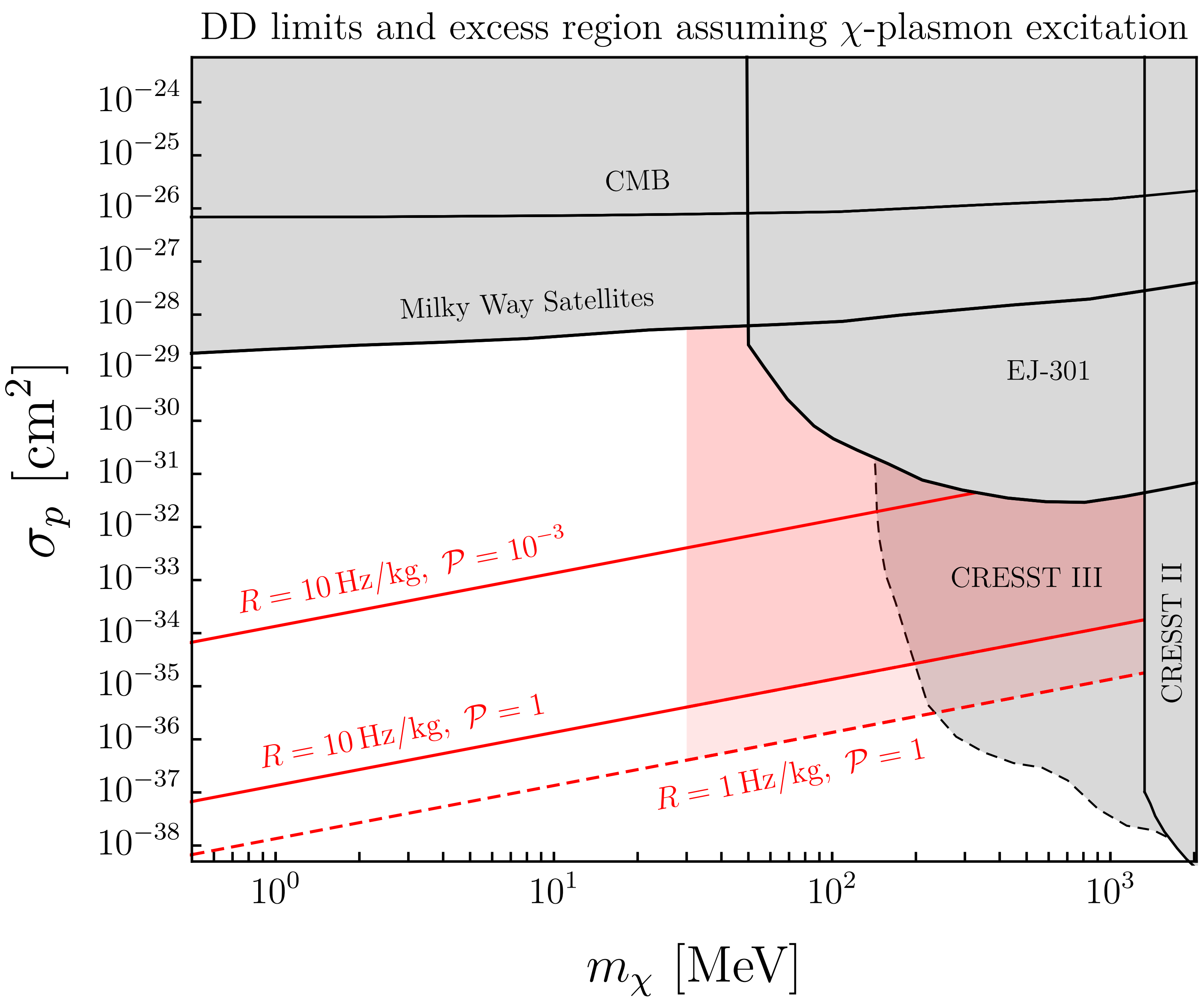
Parametrize our ignorance

Secondary Plasmon Excitation Model



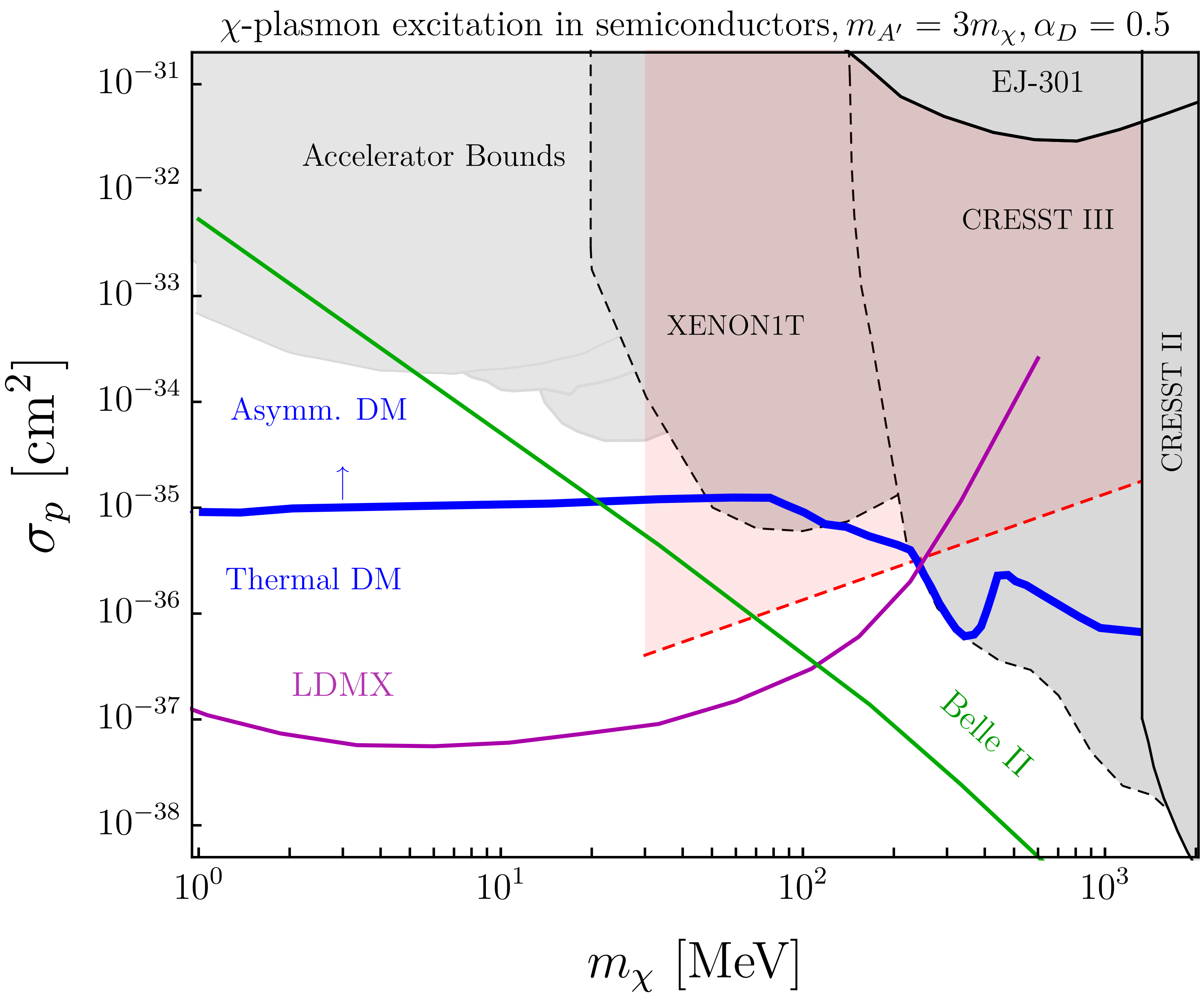
Naive limits for equal electron/proton couplings
Translated from DM-e scattering limits

Secondary Plasmon Excitation Model



Naive limits don't apply
Red = favored region

Secondary Plasmon Excitation Model



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

Dark photon mediator
Contact interaction

Predictions

1) Future results should continue to see ~ Hz/kg excesses

Despite improved shielding + BG rejection

2) Annual modulation (but weird!)

Large rates, should already be possible
No shift in signal shape, **only normalization**
Anisotropic crystals (daily modulation?)

3) Other materials should see this

Xenon crystal should see increased rate over liquid Xe, etc.

4) Neutron Scattering in Ge should see plasmon

Measures secondary excitation probability

Conclusion

1) There are many sub-GeV direct-detection excesses

2) There is a candidate process to explain these results

3) Currently no known plausible SM explanation

4) This process may originate from DM interactions

-direct plasmon excitation (fast millicharge DM fraction)

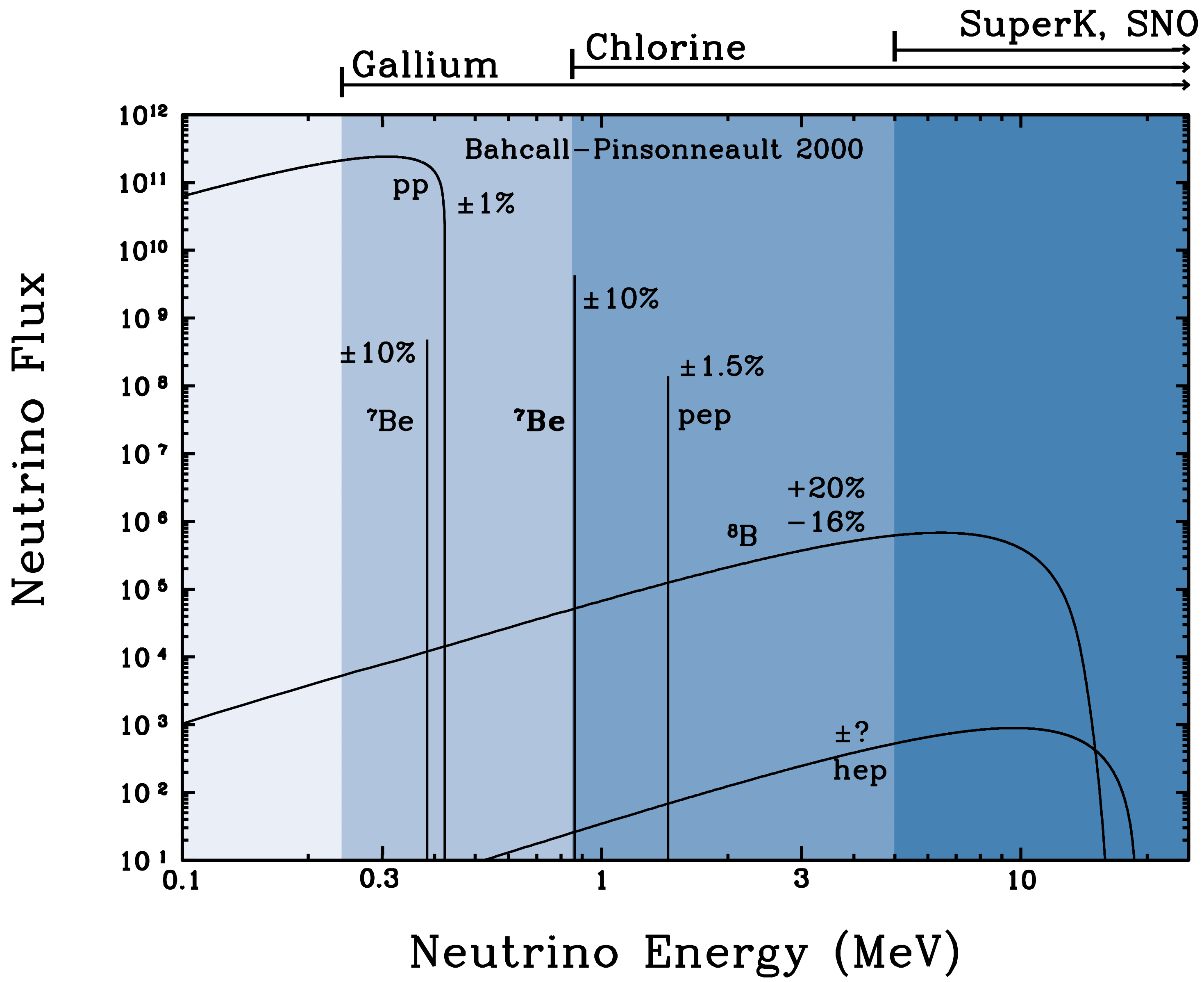
-secondary plasmon excitation (normal DM setup)

Thanks!

Backup

Solar *pp* Neutrinos?

Most abundant terrestrial neutrino flux



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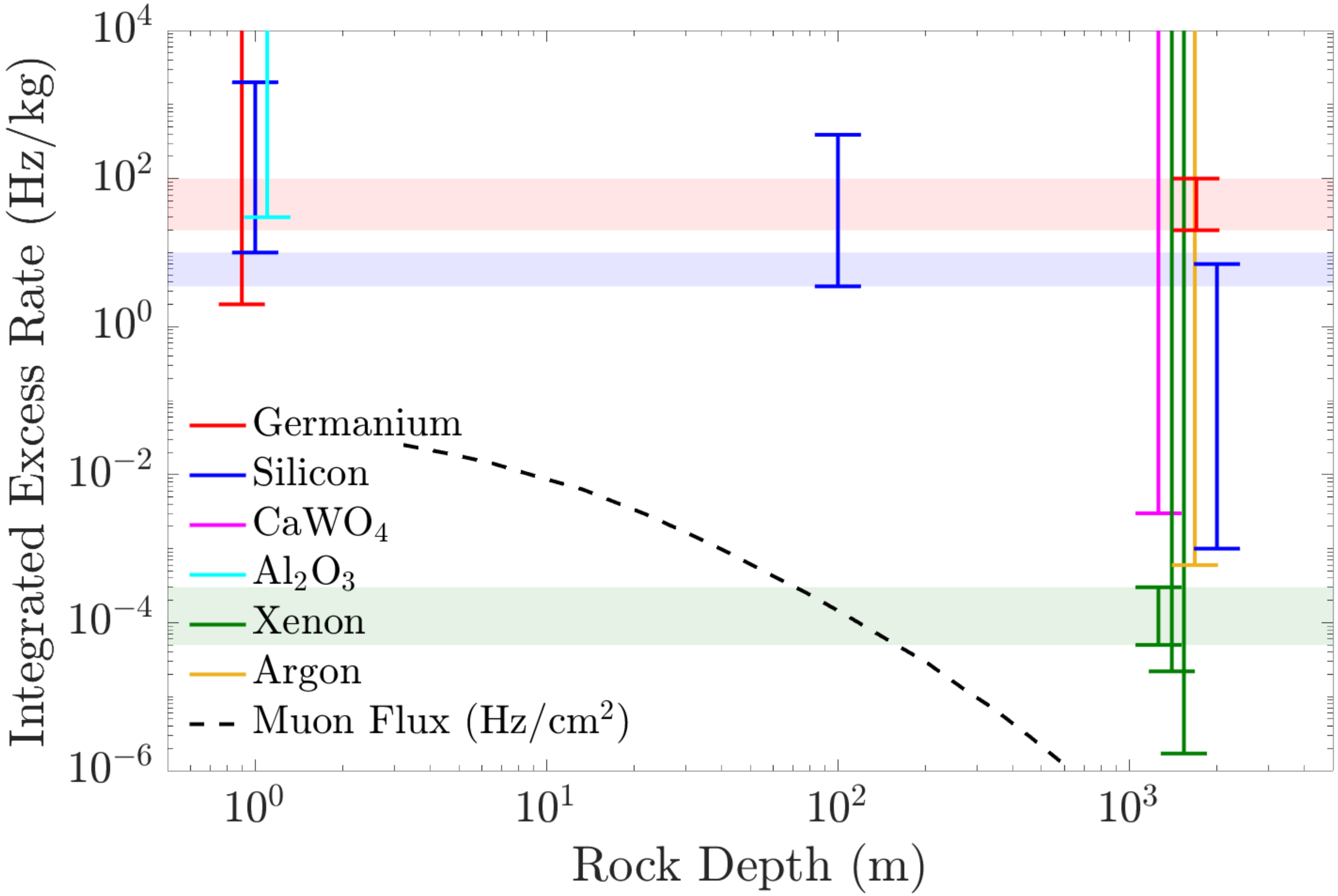

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Possible in principle

Neutron could scatter nucleus, excite secondary plasmon

Possible calibration strategy

Collar, Baxter, Kahn, Kavner, GK [in preparation]

Baxter, Kahn, Kurinsky, GK [in preparation]

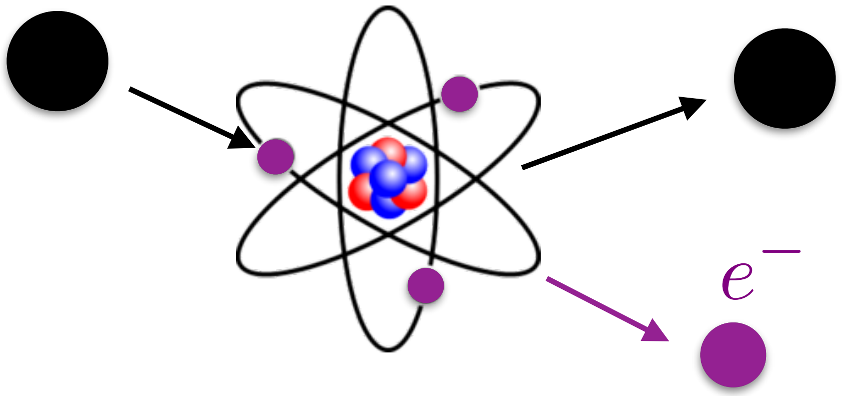
Hard to explain all excesses this way

Different Depths
Different Shielding
Different Exposures
Different Composition

Why is the neutron flux independent of these factors?

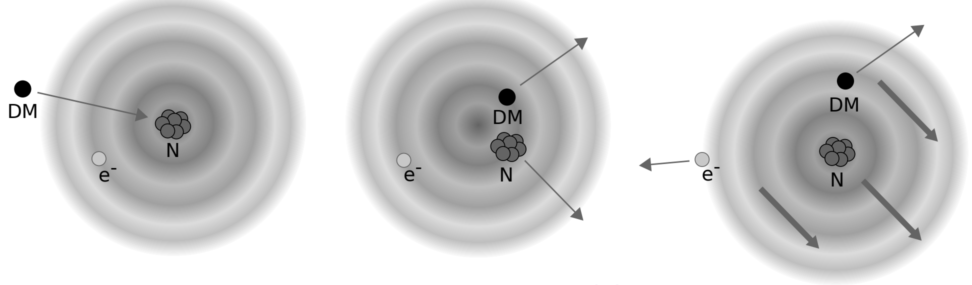
Q: Can the “Migdal effect” realize this?

If you hit the electron directly:

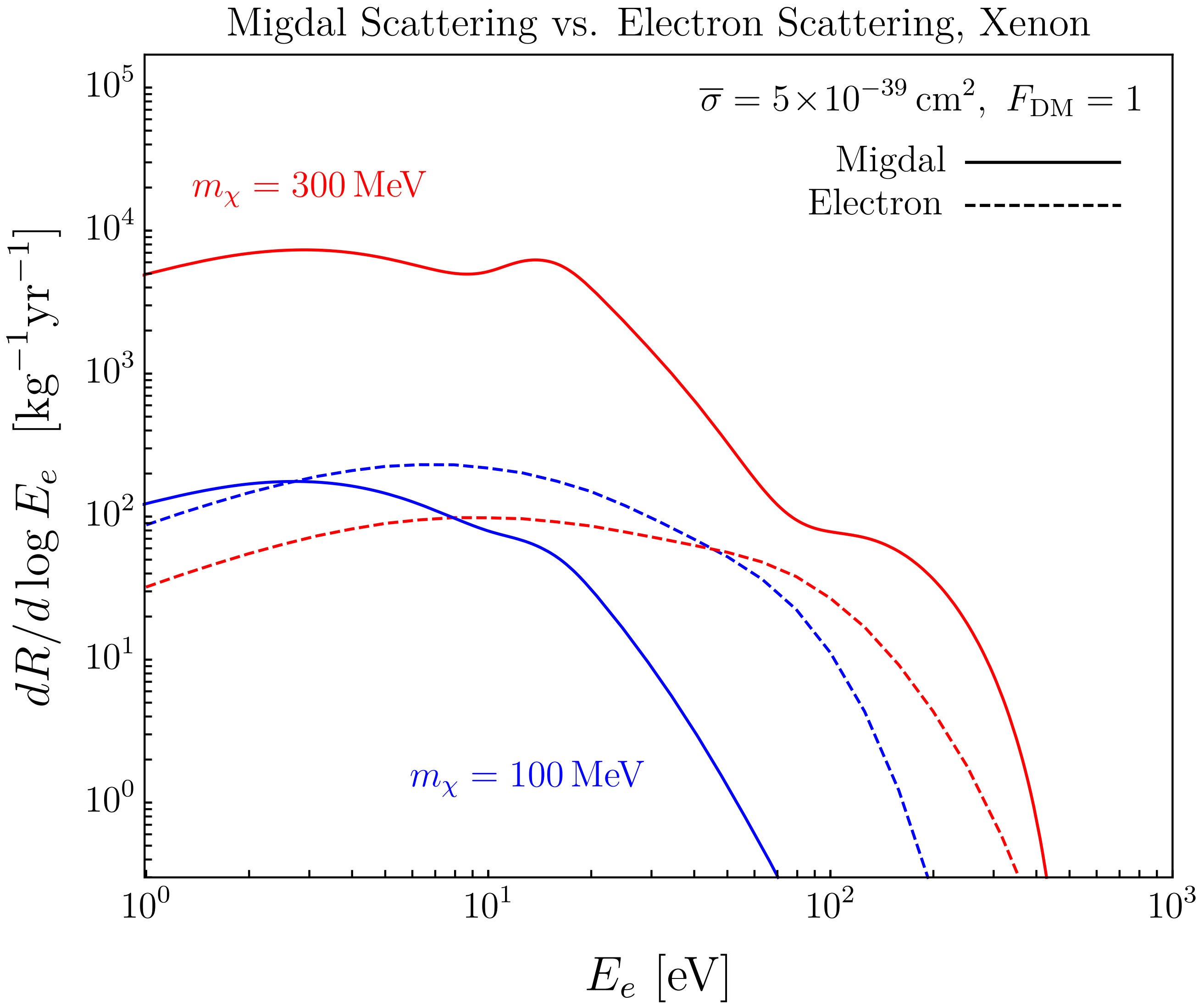


“electron recoil”

If you hit the nucleus:



“Migdal effect”



Same inelastic kinematics, vastly different dynamics!

Ibe, Nakano, Shoji, Suzuki 1707.07258

Baxter, Kahn, GK 1908.00012

Q: Can the "Migdal effect" realize this?

A: PROBABLY NOT

Migdal rates from Ibe et. al. too low, however:

Calculations assume single-atom systems

Also assume Hydrogenic wave functions

No treatment of multi-body physics (phonons etc)

See recent progress: Essig, Pradler, Sholapurkar, Yu 1908.10881

Ibe, Nakano, Shoji, Suzuki 1707.07258

Baxter, Kahn, GK 1908.00012