Towards the ultimate ionization threshold in semiconductor detectors

Aaron Manalaysay
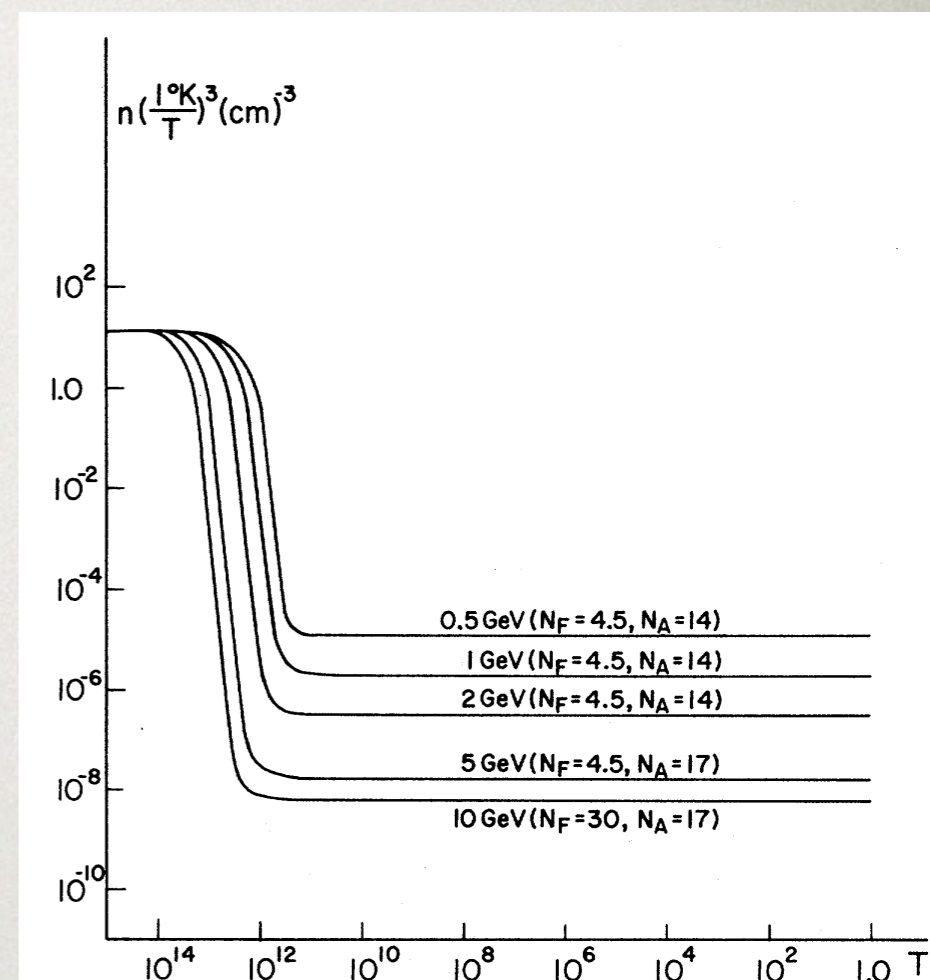
UC DAVIS
UNIVERSITY OF CALIFORNIA

Berkeley Workshop on Dark Matter Detection
9 June, 2015

To WIMP or not to WIMP

- For decades, we have hoped that the dark matter is related to EW naturalness.

- WIMPs would be a manifestation of that link.

- EW naturalness has been elusive, and we are being forced to invoke increasingly finely tuned models to describe WIMPs.

- Having to fine-tune the WIMP reduces its original motivation over other proposed DM candidates.

$n(\frac{1^\circ K}{T})^3 (cm)^3$

0.5 GeV ($N_F = 4.5$, $N_A = 14$)
1 GeV ($N_F = 4.5$, $N_A = 14$)
2 GeV ($N_F = 4.5$, $N_A = 14$)
5 GeV ($N_F = 4.5$, $N_A = 17$)
10 GeV ($N_F = 30$, $N_A = 17$)

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
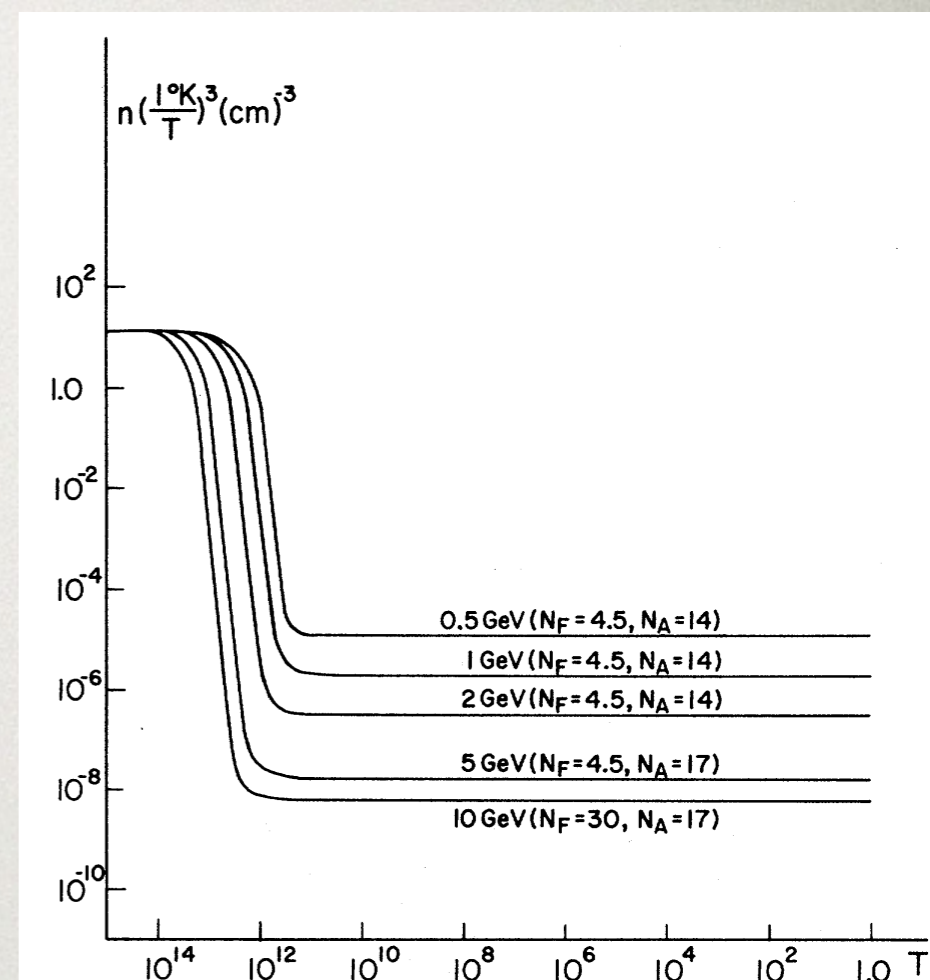Fermi National Accelerator Laboratory,[b] Batavia, Illinois 60510

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

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Where else might we look?

$n(\frac{1°K}{T})^3 (cm)^3$

10^2
1.0
10^2
10^{-4}

0.5 GeV ($N_F = 4.5$, $N_A = 14$)
1 GeV ($N_F = 4.5$, $N_A = 14$)
2 GeV ($N_F = 4.5$, $N_A = 14$)

10^{-6}

5 GeV ($N_F = 4.5$, $N_A = 17$)

10^{-8}

10 GeV ($N_F = 30$, $N_A = 17$)

10^{-10}

10^{14} 10^{12} 10^{10} 10^8 10^6 10^4 10^2 1.0 T

PHYSICAL REVIEW LETTERS

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
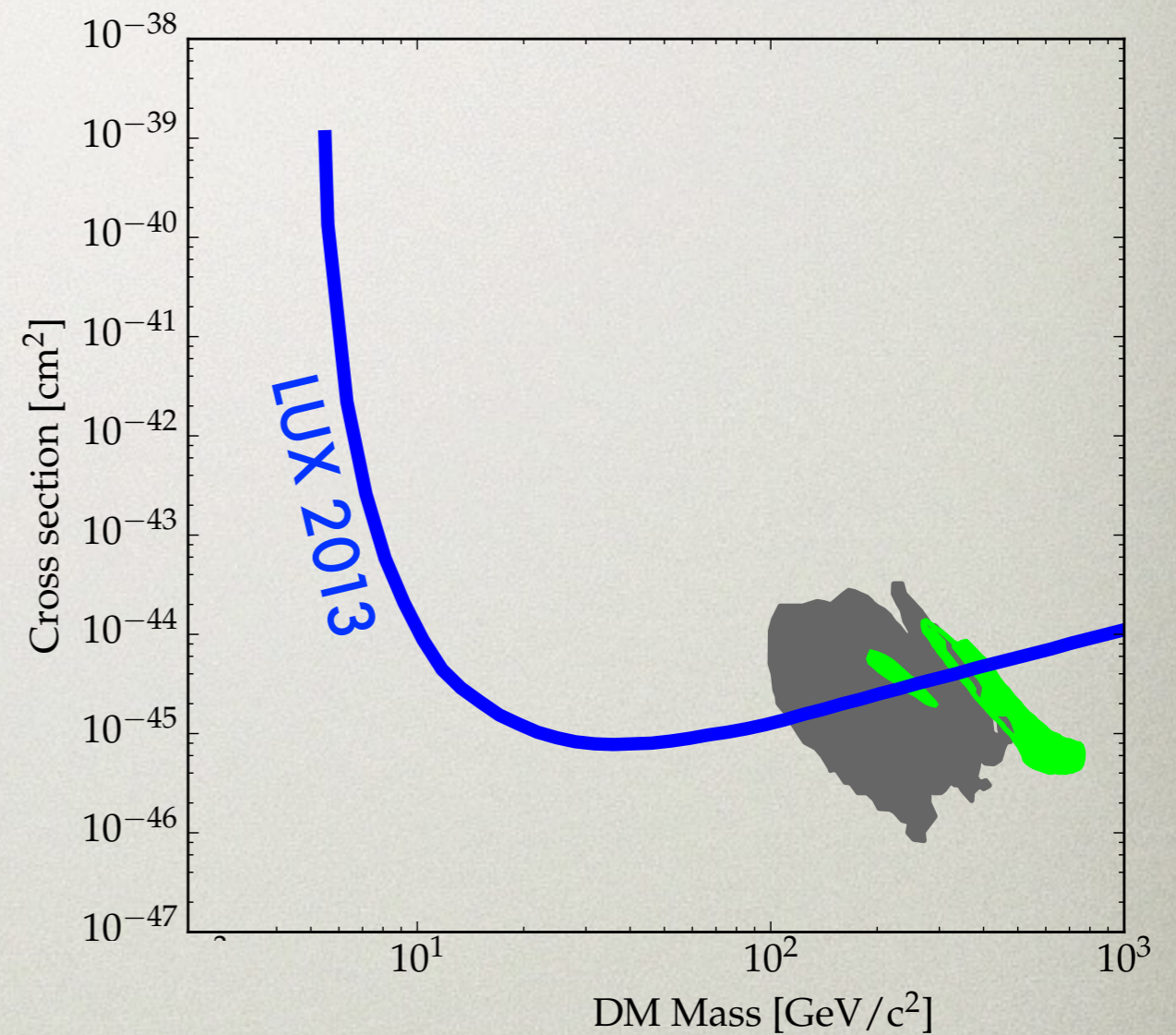*Fermi National Accelerator Laboratory*,[b] *Batavia, Illinois 60510*

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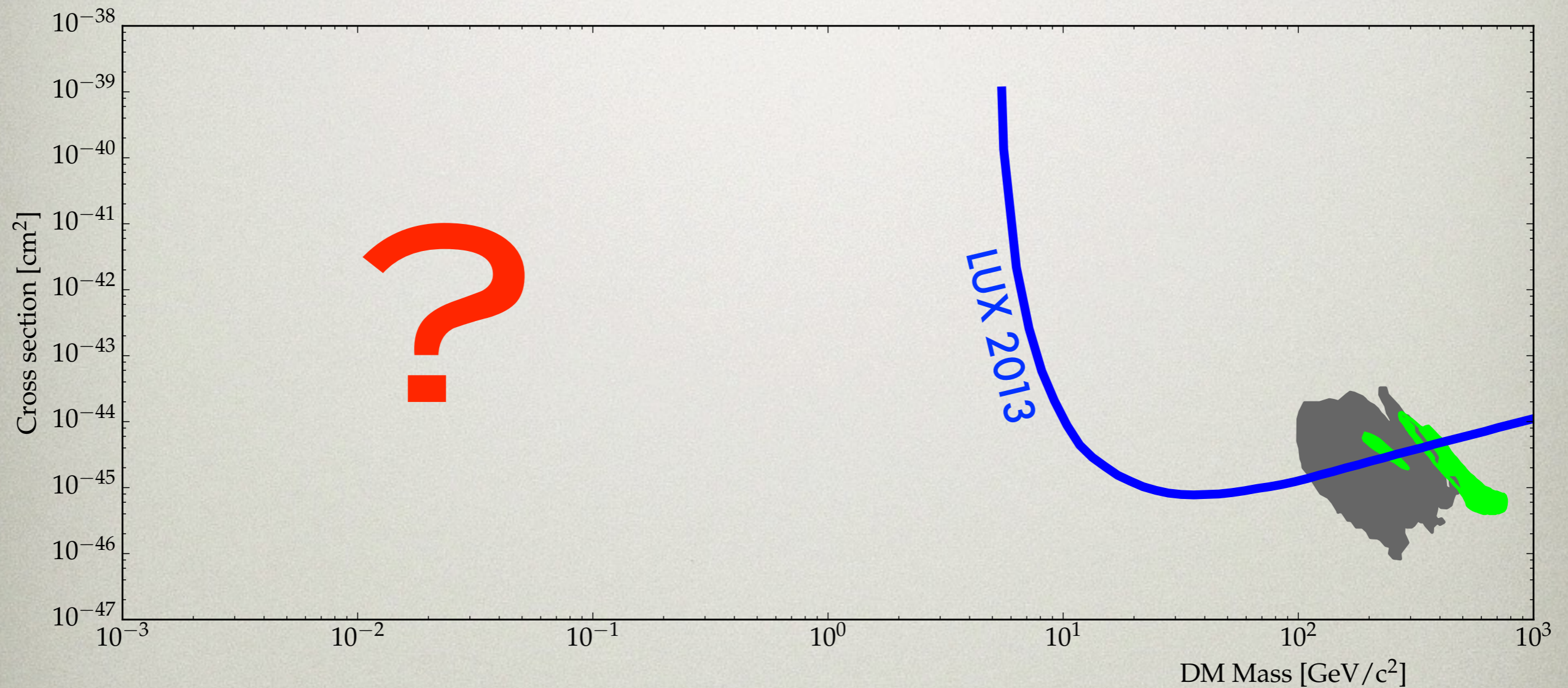*Stanford University, Physics Department, Stanford, California 94305*
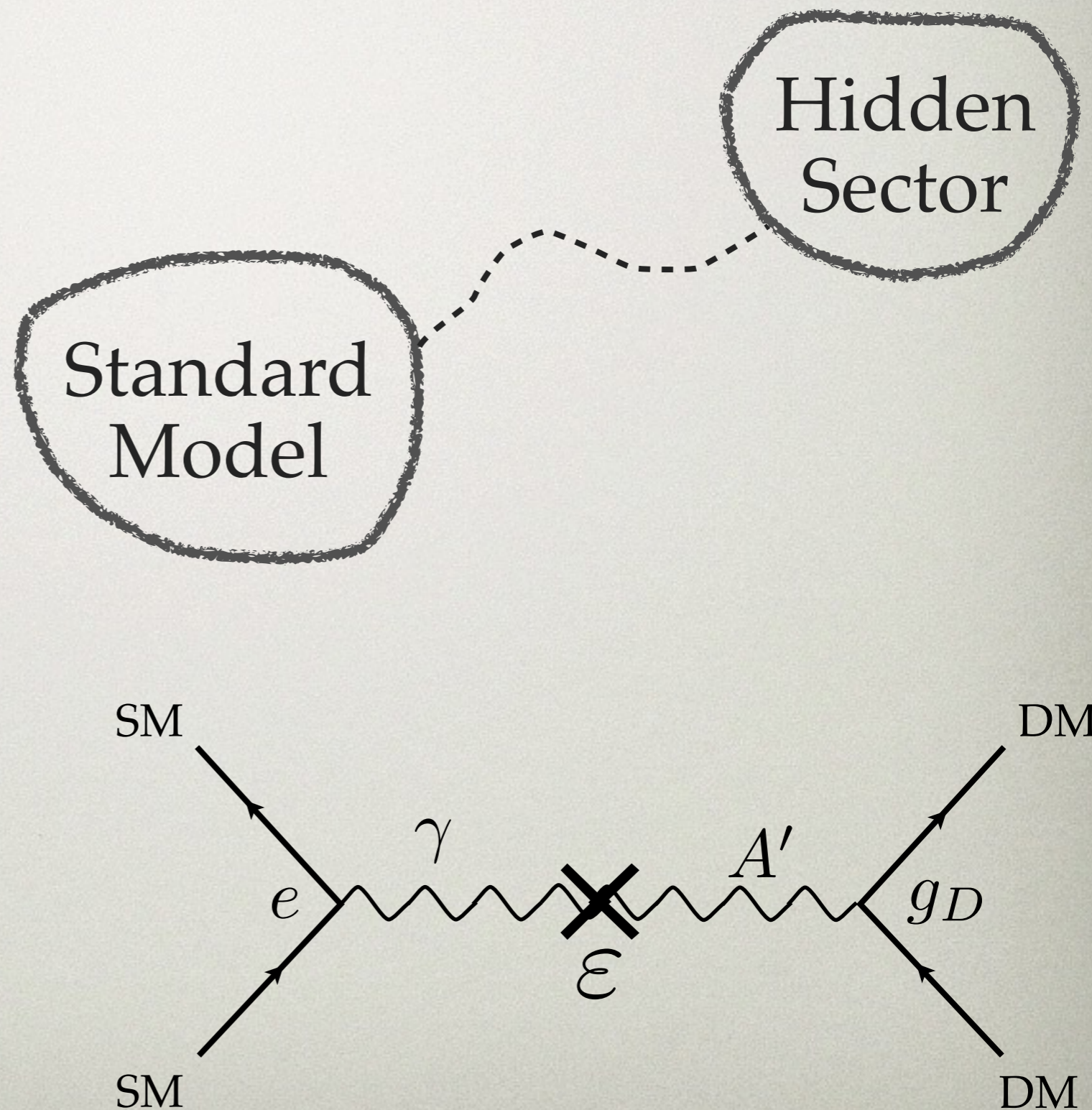(Received 13 May 1977)

Where else might we look?

Where else might we look?

The hidden sector

- See talk by R. Essig

- Many viable DM candidates in "hidden sector" models

- Additional fermions charged under a "hidden" U(1)′ gauge symmetry

- U(1)′ and U(1)$_{Y_W}$ can kinematically mix, giving a small coupling between DM and charge particles.
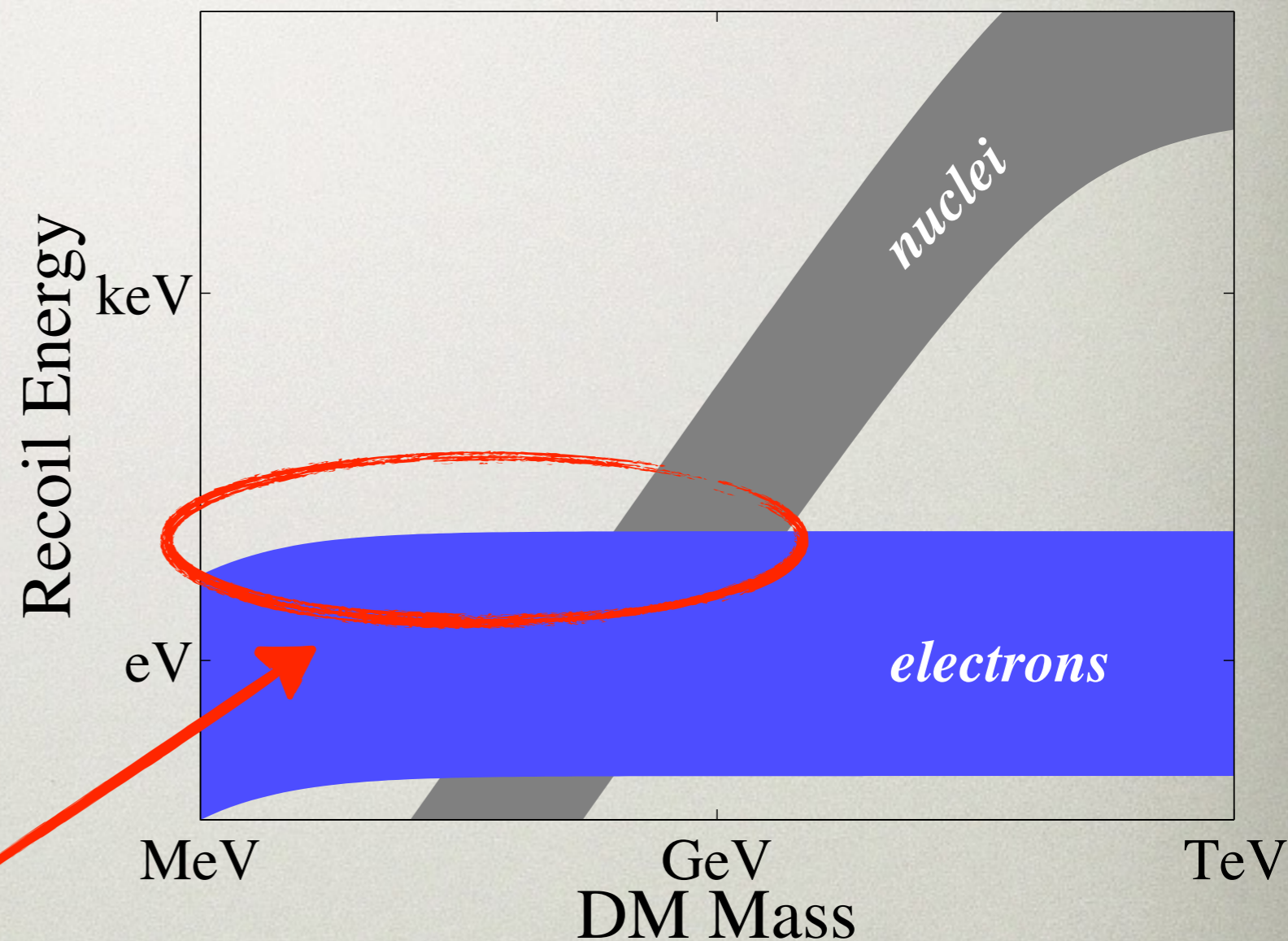
Electrons or nuclei?

DM target: electrons or nuclei?

- Nuclei are great at searching for DM particles of mass roughly similar to the nuclear mass (that's just kinematics).

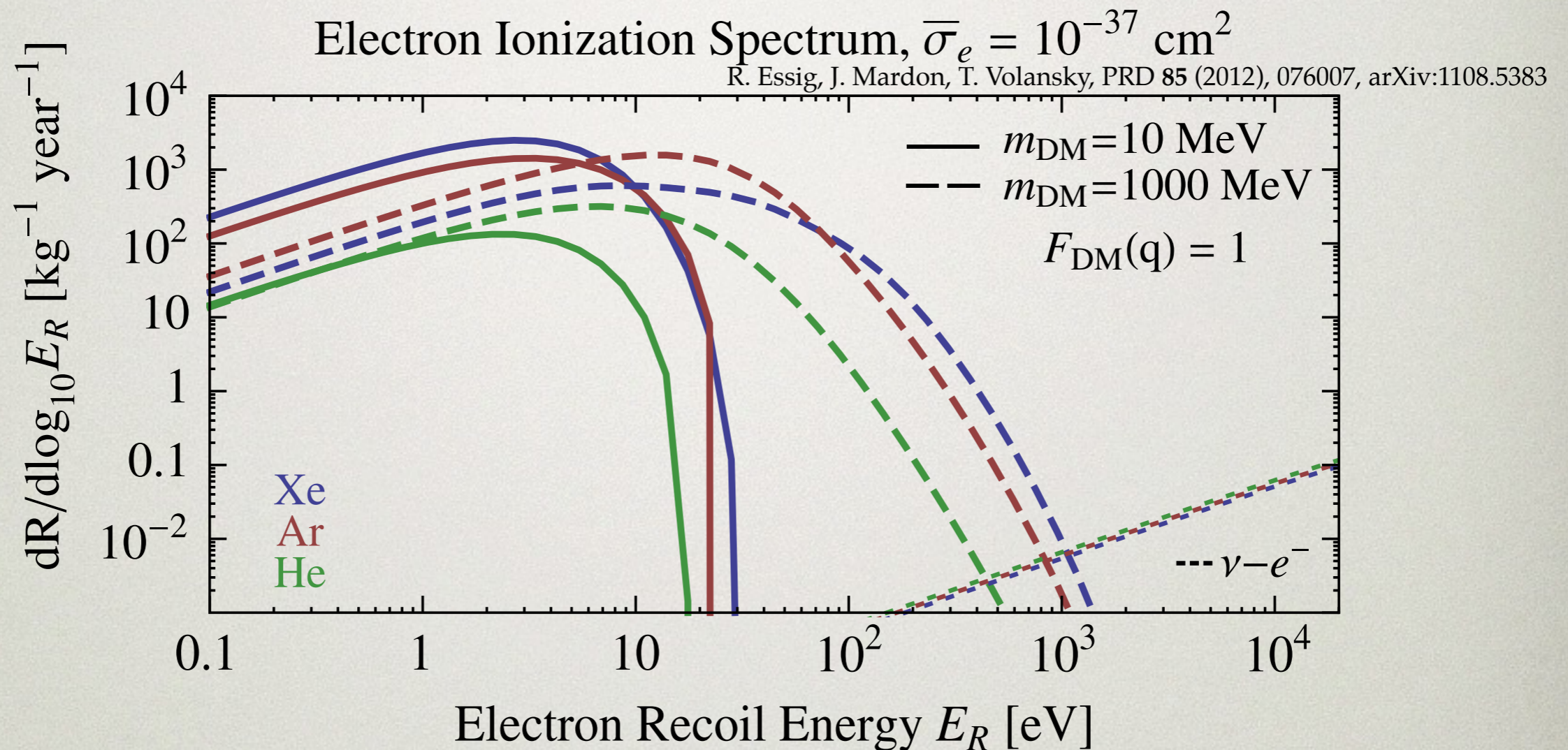- For DM masses of O(1-1000) MeV, electrons make a better target.
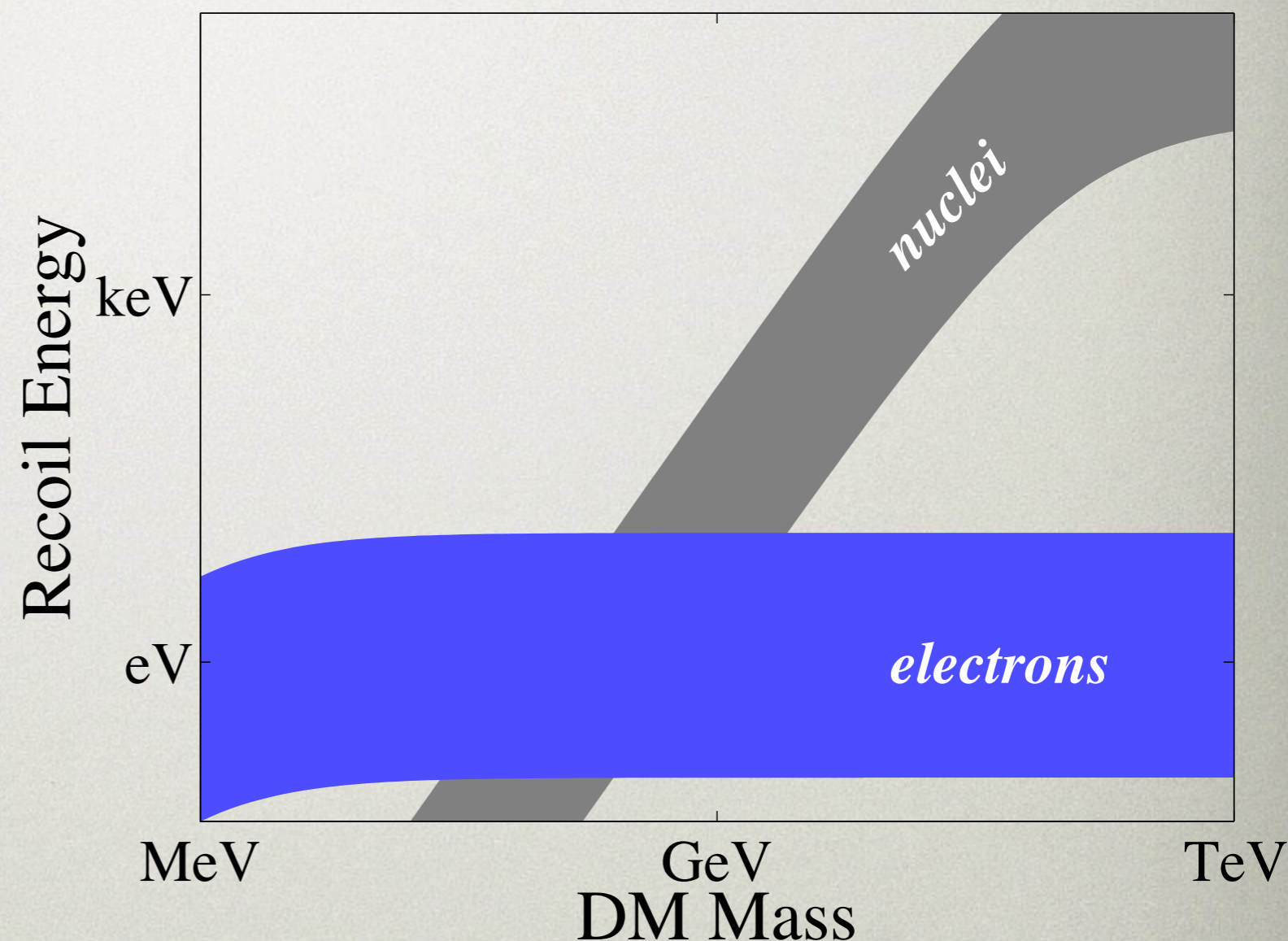
DM target: electrons or nuclei?

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atomic ionization range

Recoiling-electron energies

Electron Ionization Spectrum, $\overline{\sigma}_e = 10^{-37}$ cm^2

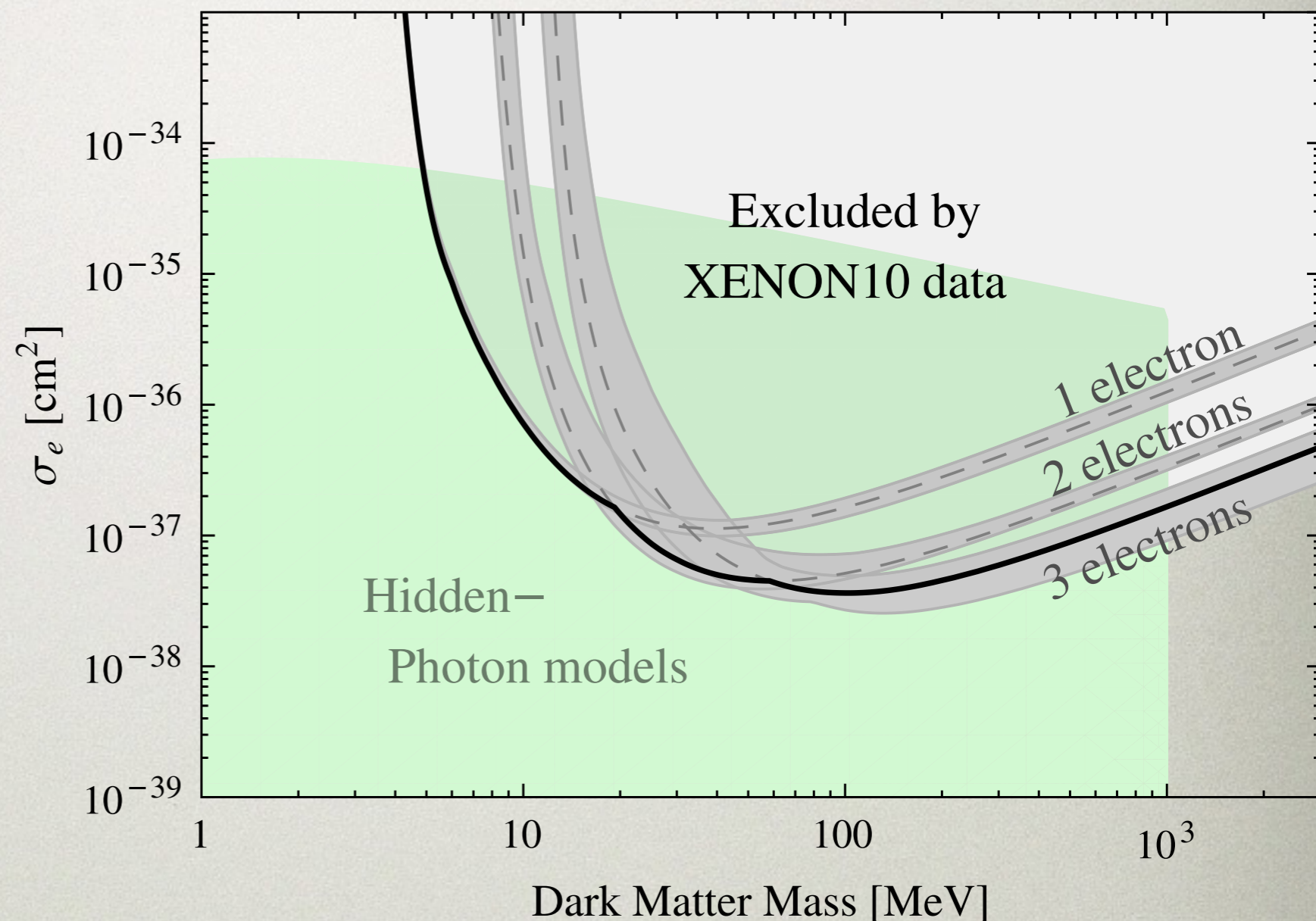R. Essig, J. Mardon, T. Volansky, PRD **85** (2012), 076007, arXiv:1108.5383

The previous slide is very cartoony; a more serious approach considers electron kinetic energy, binding energy, etc., e.g. by R. Essig, J. Mardon, and T. Volansky.

→ Electron recoil energies up to ~1 keV.

A XENON10 demonstration

- Here for $m_{A'} \approx 10$ MeV, $F(q) = 1$

- 12.5 live-day data set, 1.2 kg, no BG subtraction, can already probe un-touched parameter space.

Excluded by XENON10 data

1 electron

2 electrons

3 electrons

Hidden− Photon models
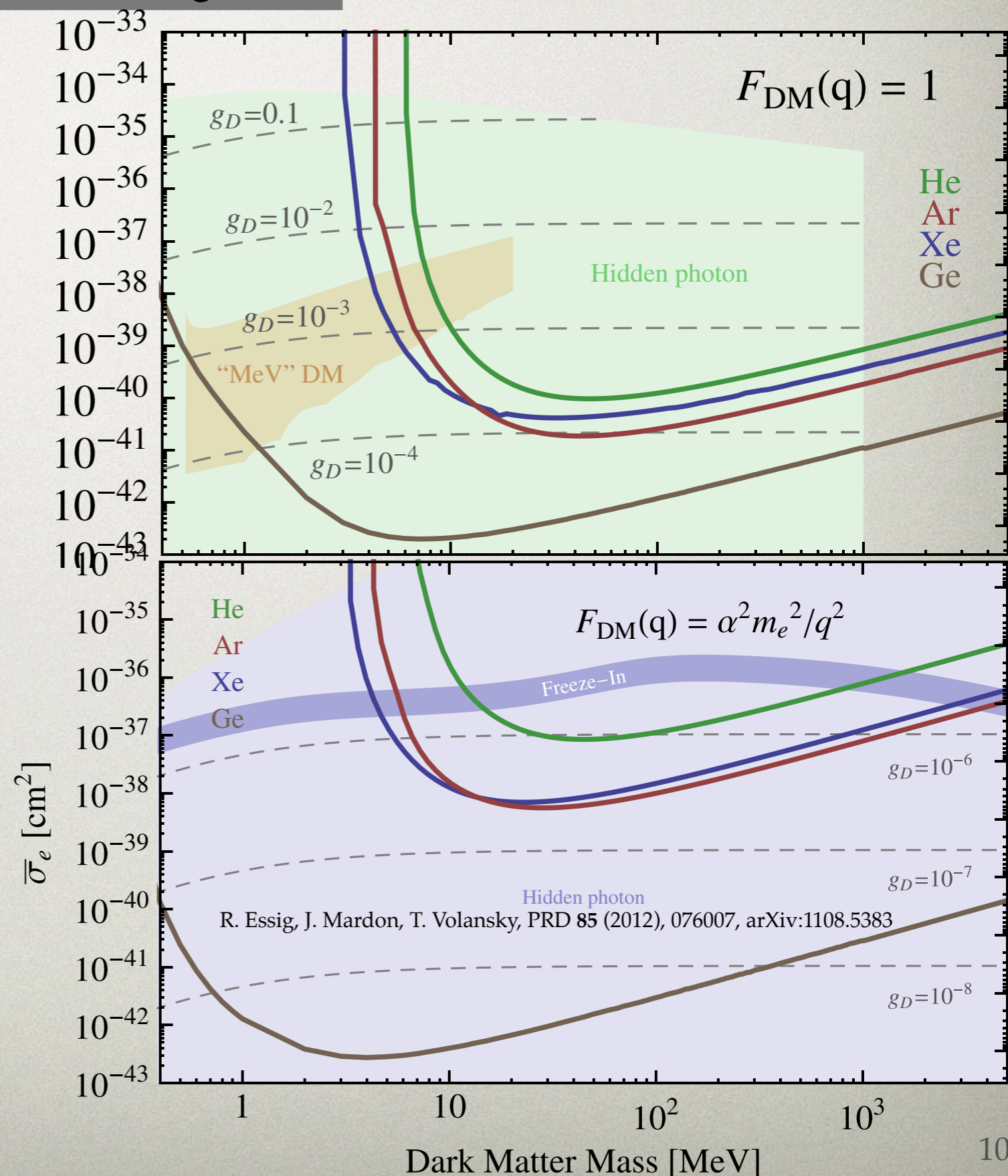
σ_e [cm^2]

Dark Matter Mass [MeV]

First Direct Detection Limits on Sub-GeV Dark Matter from XENON10

Rouven Essig,[1,2,*] Aaron Manalaysay,[3,†] Jeremy Mardon,[4,‡] Peter Sorensen,[5,§] and Tomer Volansky[6,‖]
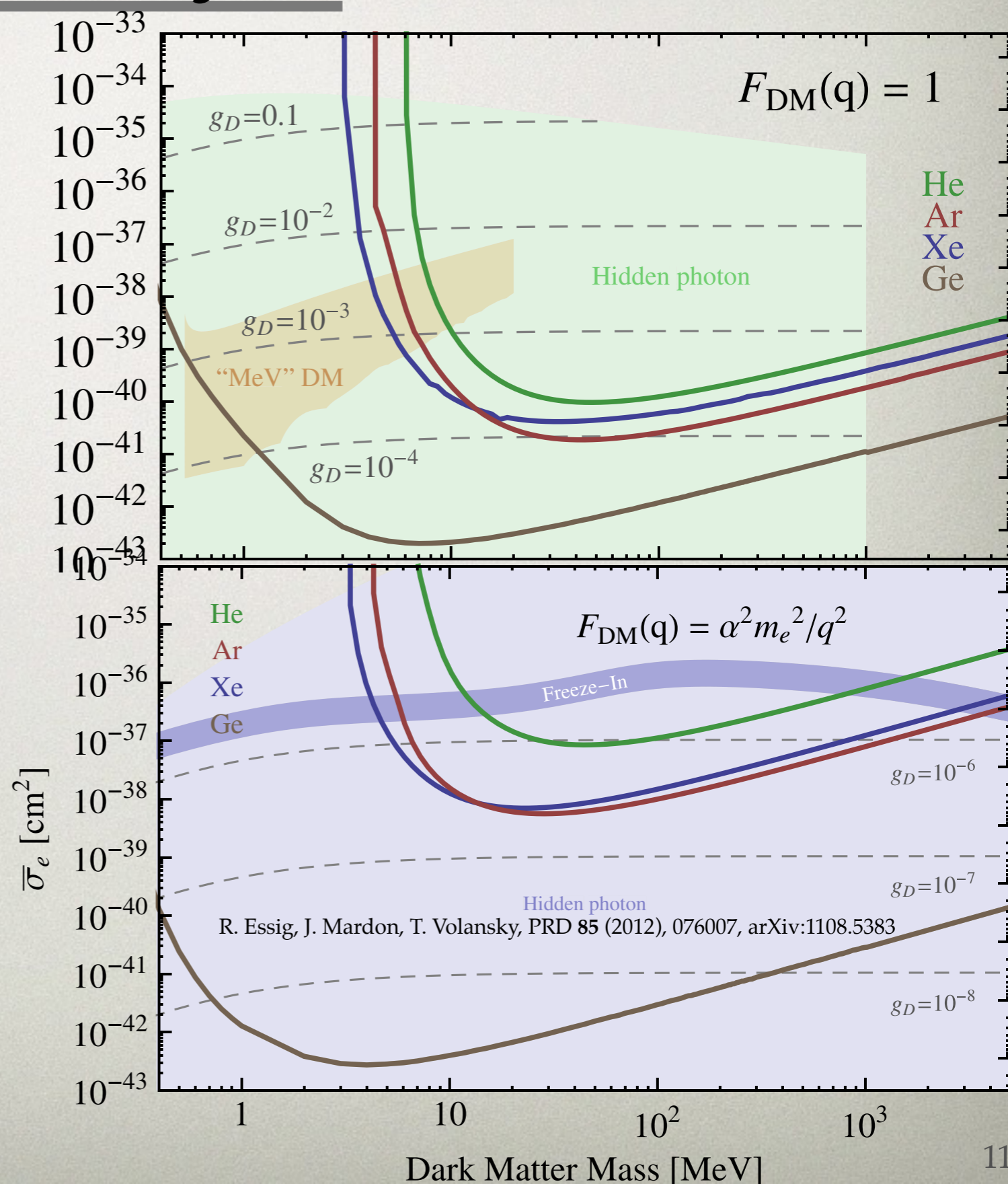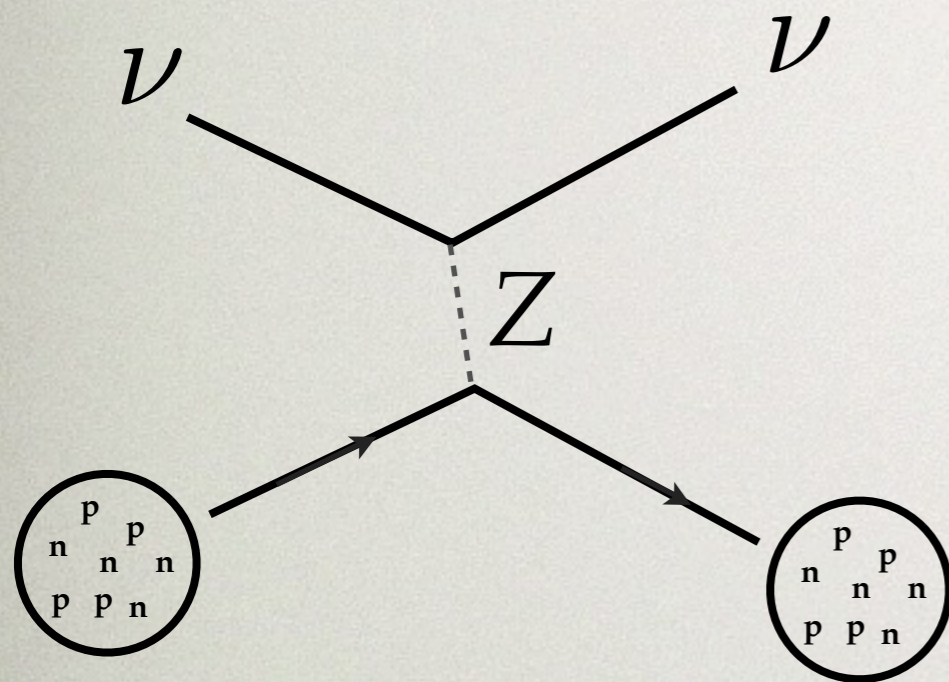
How far can we go in sensitivity?

Building sensitivity

- Sensitivity has been demonstrated in LXe.

- Semiconductor detectors appear to have a potential sensitivity that dwarfs that of noble liquids.

- These projections assume:

  ‣ 1 kg-yr exposure

  ‣ Zero background

  ‣ Single-electron sensitivity

R. Essig, J. Mardon, T. Volansky, PRD **85** (2012), 076007, arXiv:1108.5383

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  ‣ Single-electron sensitivity

$F_{DM}(q) = 1$

$g_D = 0.1$

$g_D = 10^{-2}$

$g_D = 10^{-3}$

"MeV" DM

$g_D = 10^{-4}$

Hidden photon

He
Ar
Xe
Ge

$F_{DM}(q) = \alpha^2 m_e^2/q^2$

He
Ar
Xe
Ge

Freeze–In

$g_D = 10^{-6}$

$g_D = 10^{-7}$

Hidden photon

R. Essig, J. Mardon, T. Volansky, PRD **85** (2012), 076007, arXiv:1108.5383

$g_D = 10^{-8}$

$\overline{\sigma}_e$ [cm^2]

Dark Matter Mass [MeV]

Coherent neutrino scattering

$$\nu \qquad \nu$$

$$Z$$

- On a side note, detectors with ultra-low energy thresholds would also have applications at detecting coherent neutrino-nucleus interactions (never-before seen).
- There are many interesting things one could do with this process, but this is a dark-matter workshop, so I won't go into details here.

$$\frac{d\sigma}{d\Omega} = \left| \sum_{j=1}^{A} f_j(\mathbf{k}', \mathbf{k}) \exp[i(\mathbf{k}' - \mathbf{k}) \cdot \mathbf{x}_j] \right|^2$$

$$\frac{d\sigma}{dE_r} \simeq \frac{G_F^2 m_N}{4\pi \hbar^4 c^2} [N + Z(4\sin^2\theta_W - 1)]^2 \left[1 - \frac{m_N c^2 E_r}{2 E_\nu^2} \right] \rightarrow \sigma \propto N^2$$

How do we detect single-electron ionization signals in a semiconductor?

Low-threshold strategy

- Traditional signal amplification via transistor+feedback won't work (too much noise).

- Physical multiplication of electrons can provide virtually noise-free amplification: easily detect single electrons.

  ➡ <u>Avalanche-diode approach</u>: was tried, but no significant detector mass could be achieved

  ➡ <u>Phonon approach</u>: drifting electrons in a $O(10 \text{ mK})$ detector produce many phonons, which can be detected (see talk by M. Pyle). Probably possible, still a few years off, and will depend on new techniques. Also, dil. fridge > 500k$

  ➡ <u>CCD sensors</u>: can detect very small amounts of charge. Probably cannot achieve sensitivity to single electrons, but will get close. Requires very long charge-integration times.
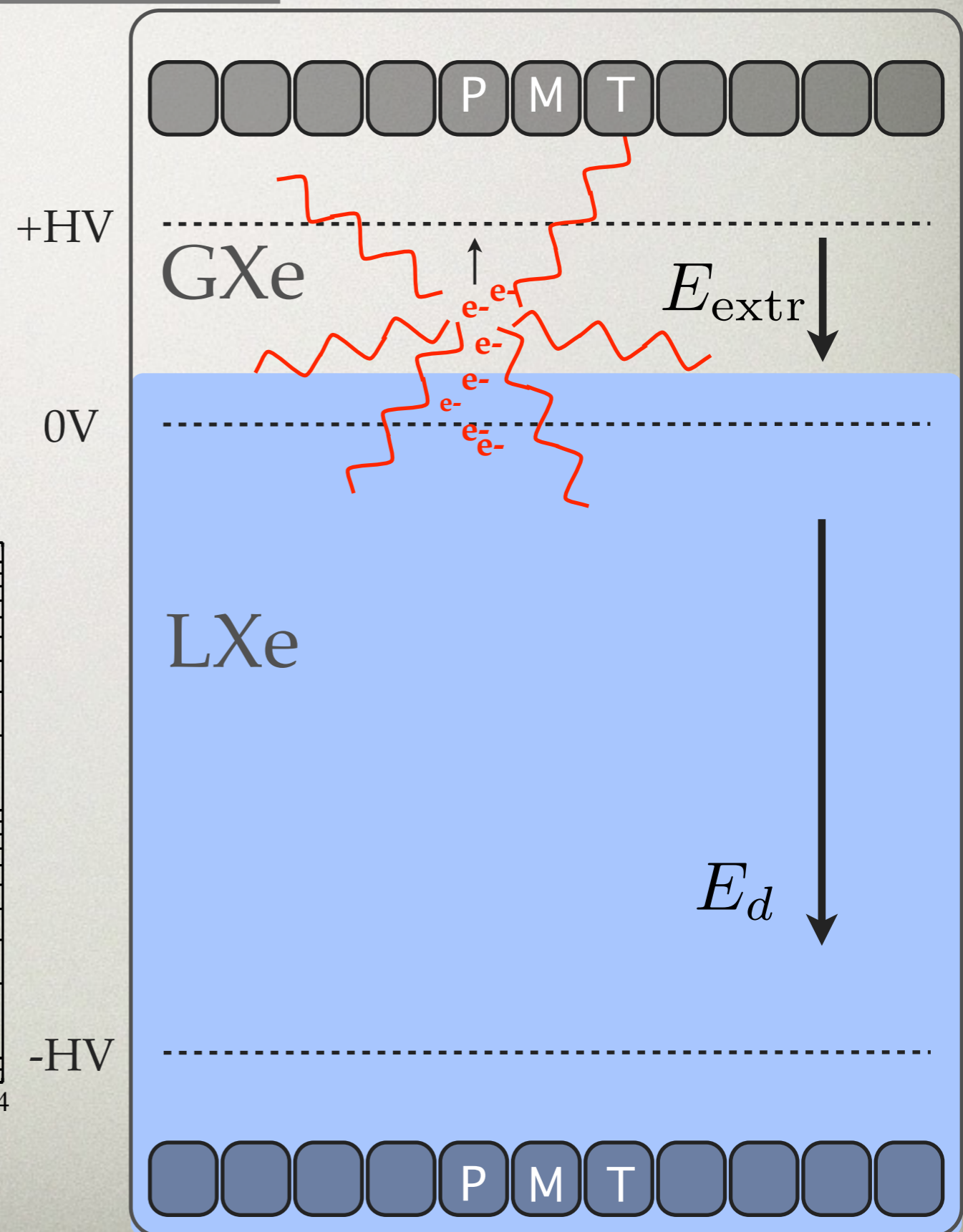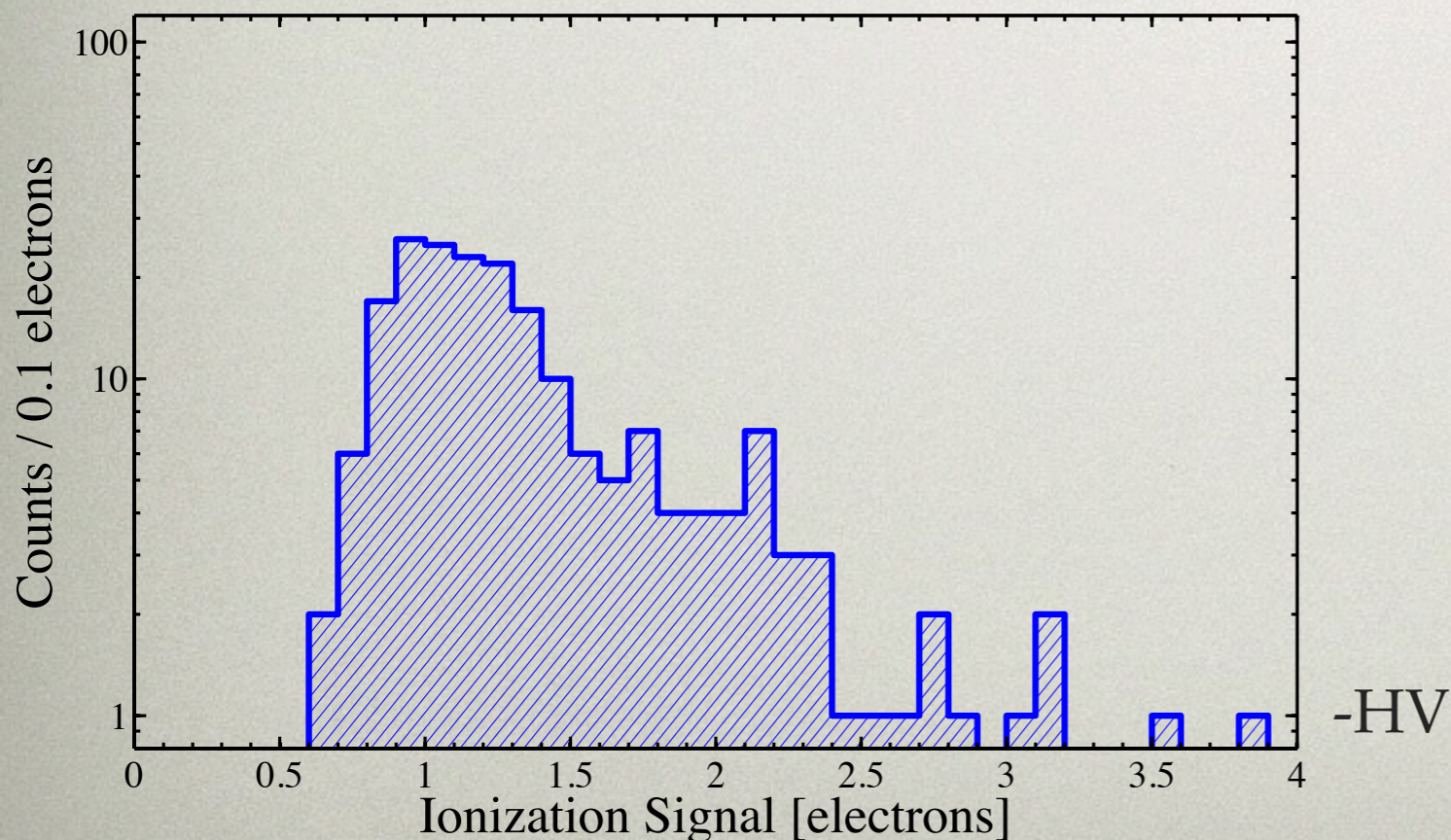
Single-e in noble liquids

Electron extraction works well for LXe and LAr.

+HV

GXe

E_{extr}

0V

LXe

E_d

-HV

P M T

P M T

Counts / 0.1 electrons

Ionization Signal [electrons]
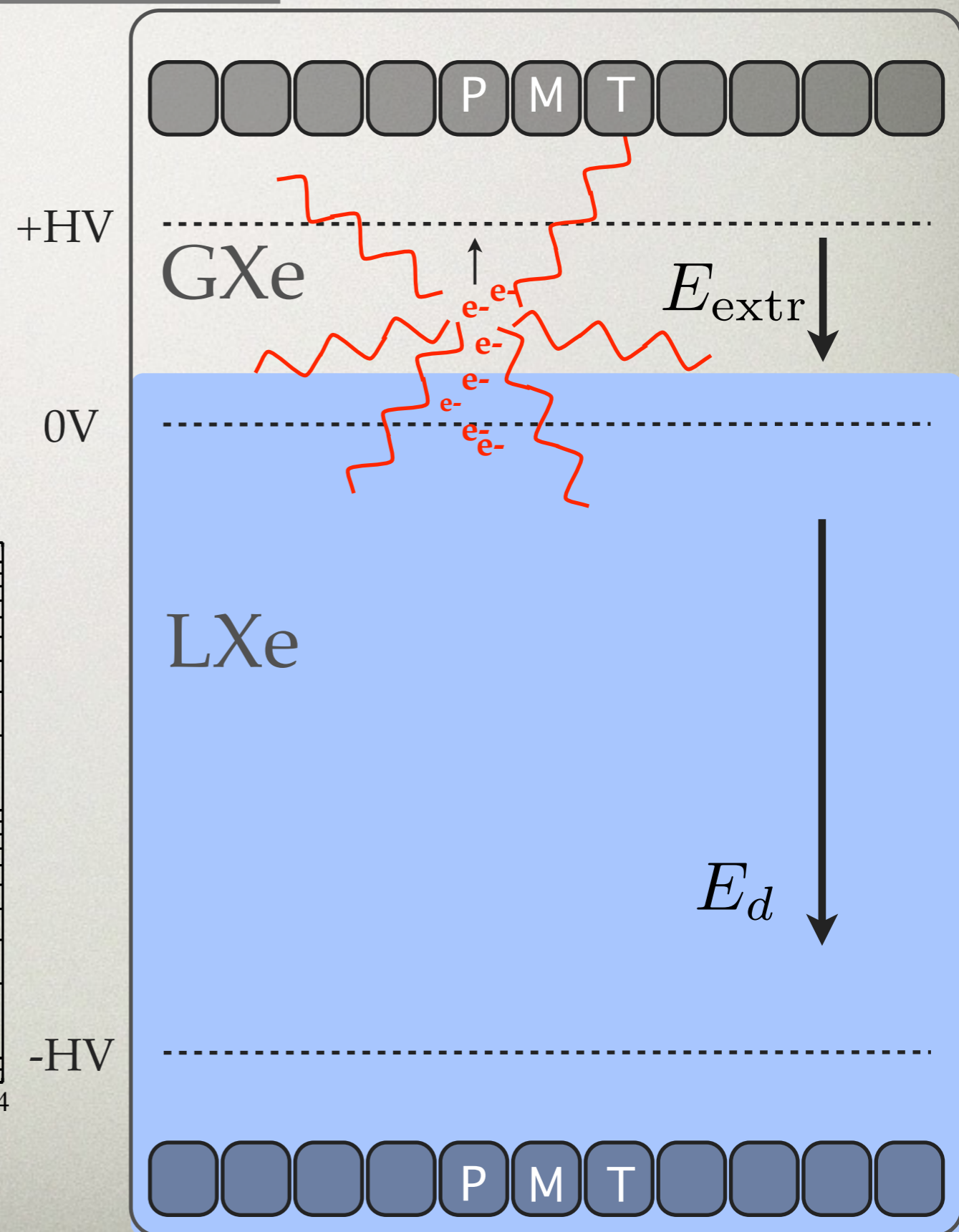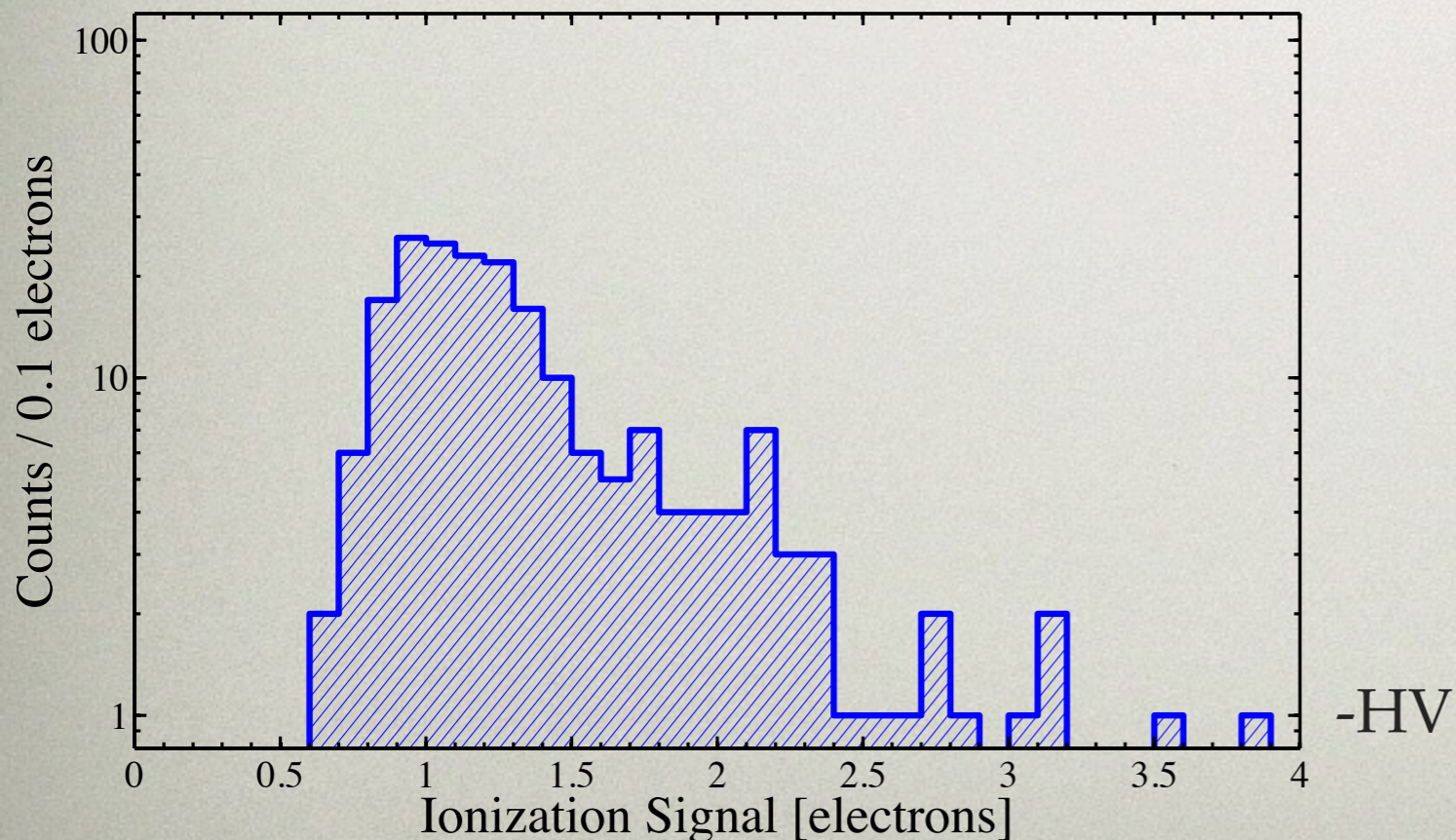
Single-e in noble liquids

Electron extraction works well for LXe and LAr.

What would be possible if we could extract electrons from a semiconductor?

$+\text{HV}$

GXe

E_{extr}

e- e-
e-
e-
e-
e-
e-
e-

0V

LXe

E_d

$-\text{HV}$

P M T

P M T

PMT without the P

If the electrons from an interaction could be extracted, obtaining single electron sensitivity would be trivial. We do this all the time with PMTs.
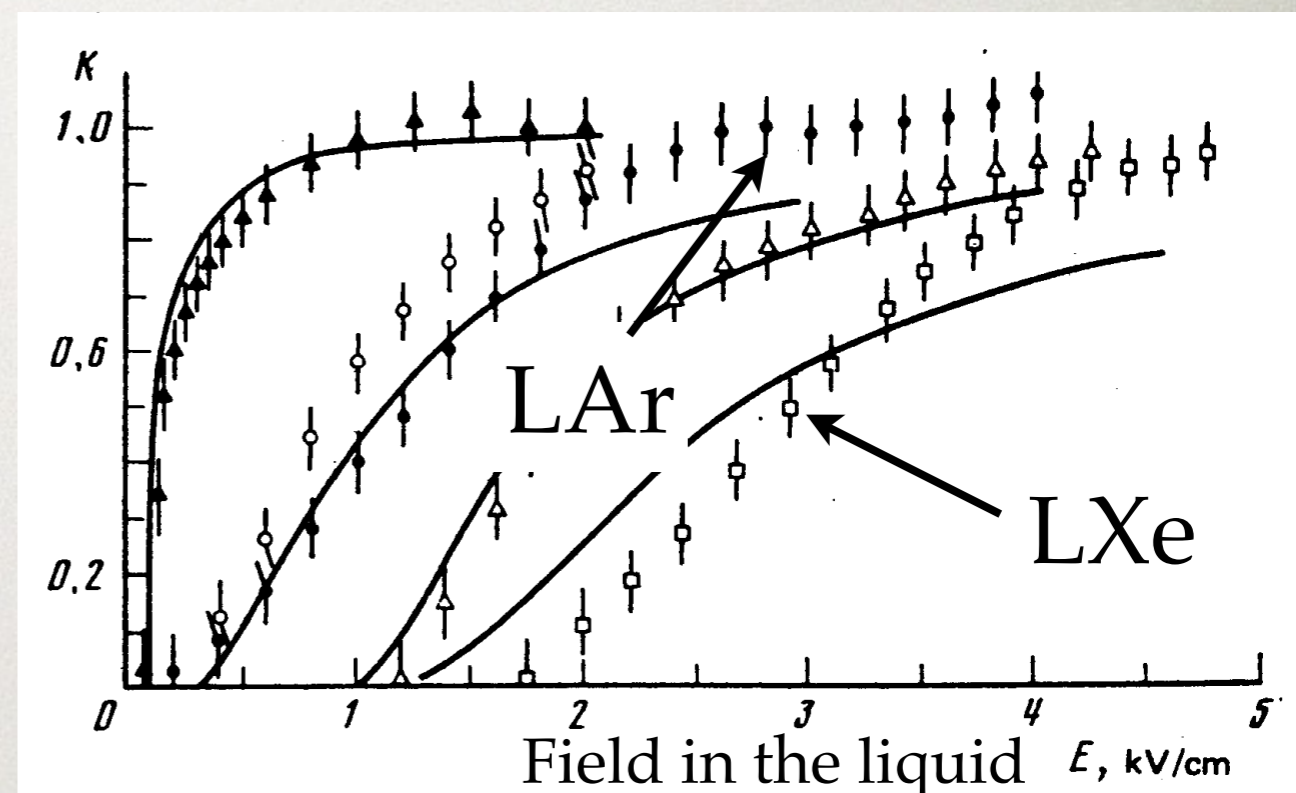
(dynodes)

(MCP)

e⁻

e⁻

Si
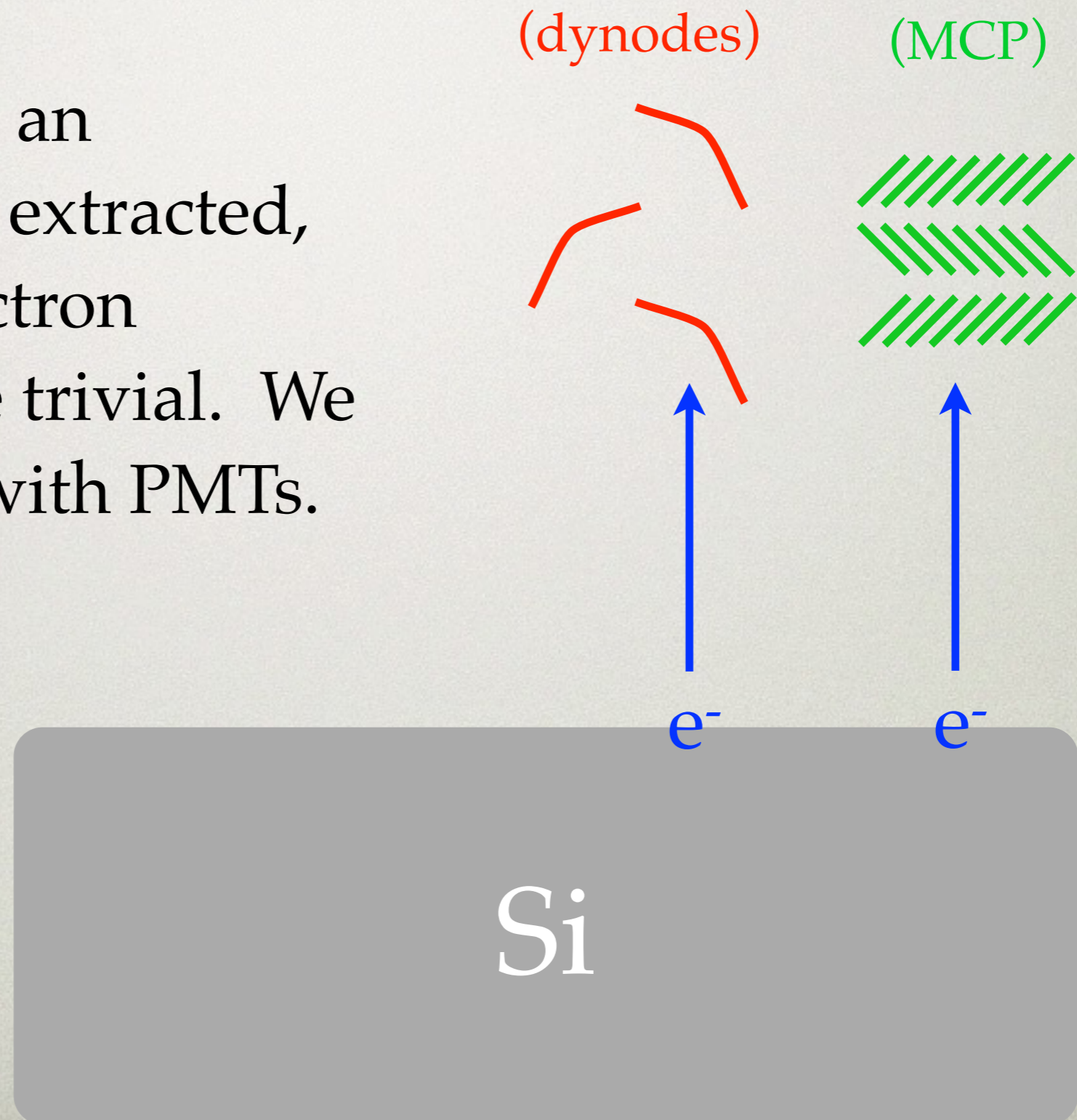
But I'm avoiding the question:
How?

The right question: what field is necessary to extract electrons from silicon (for example)?

Extraction efficiency

E. Aprile *et al.*, IEEE Trans. Nucl. Sci. **51** (2004) 1986
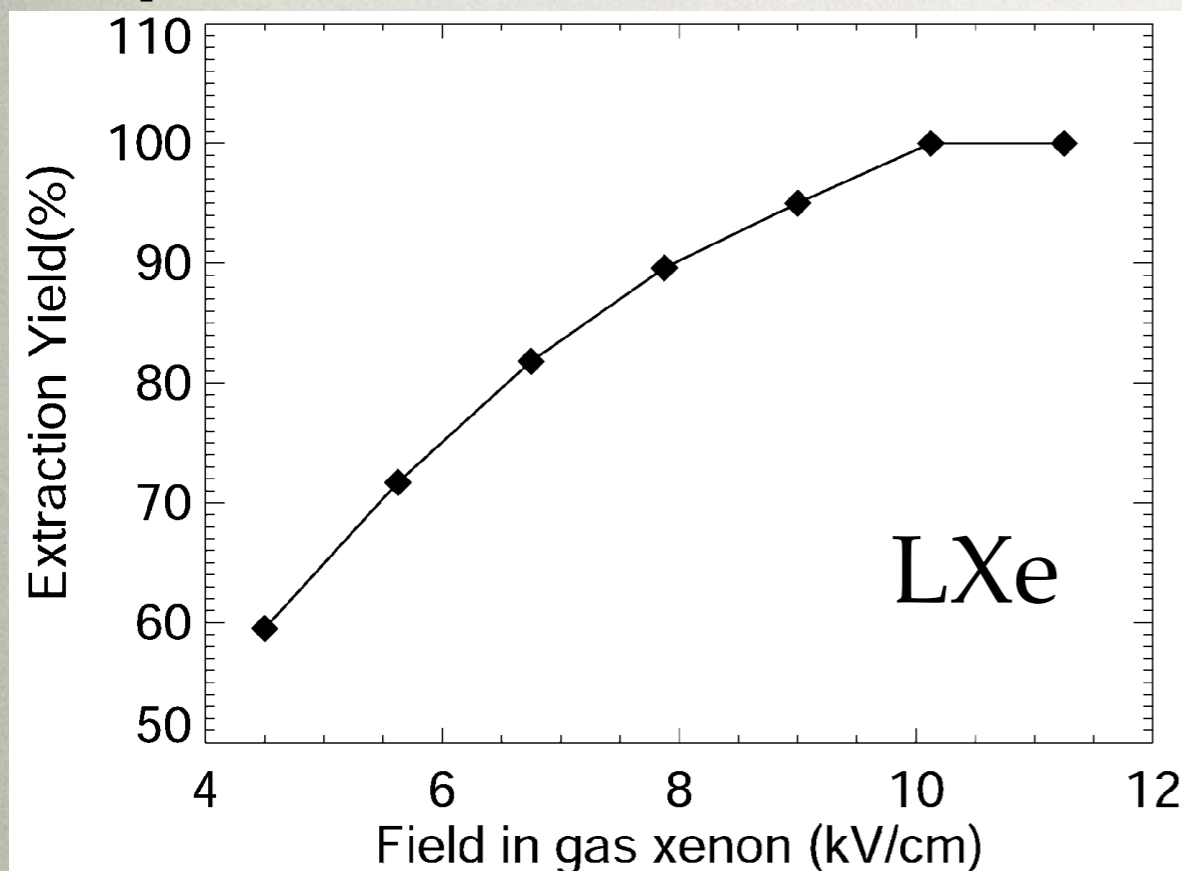
E.M.Gushchin *et al.*, Sov. Phys. JETP **55** (1982) 860

Different measurements support the same picture:

LXe: 100% efficiency for electron extraction at ~10 kV/cm (in the gas)

LAr: 100% efficiency for electron extraction at ~4 kV/cm

Can we understand these results and use them to predict what fields would be necessary in Si?

Understanding extraction in LXe

Electron potential
energy:
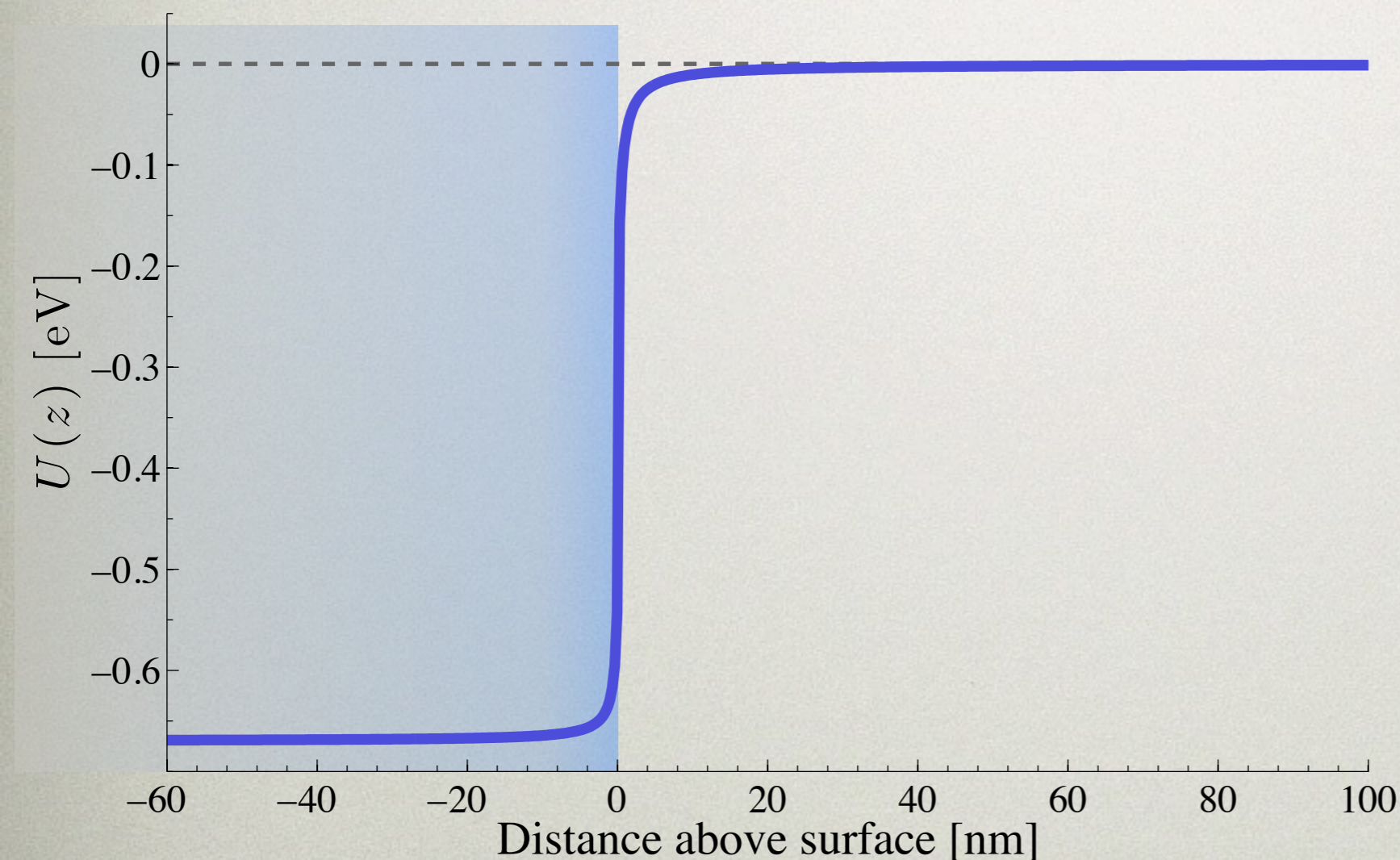
$$U(z) = \frac{1}{16\pi\epsilon_0} \frac{e^2}{z + \beta} \frac{\epsilon - \epsilon_0}{\epsilon + \epsilon_0}, \quad z > 0$$
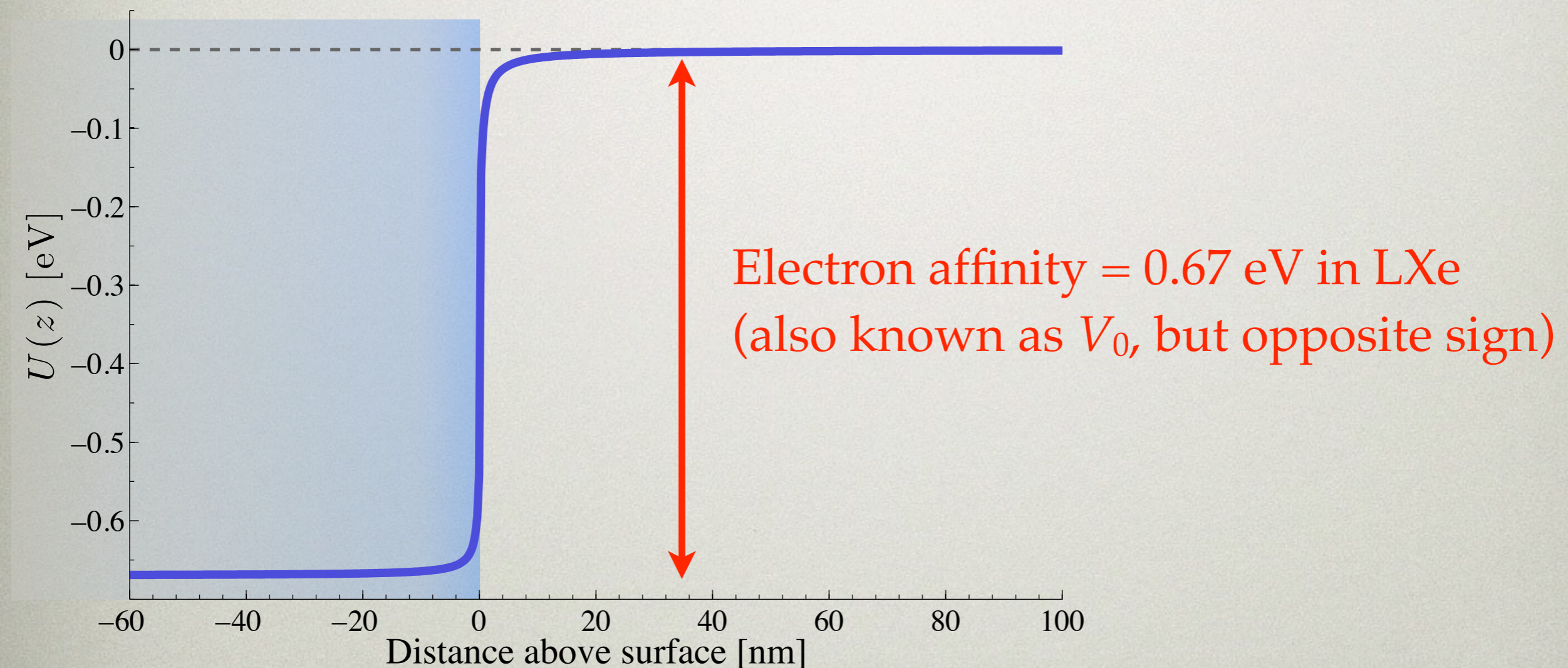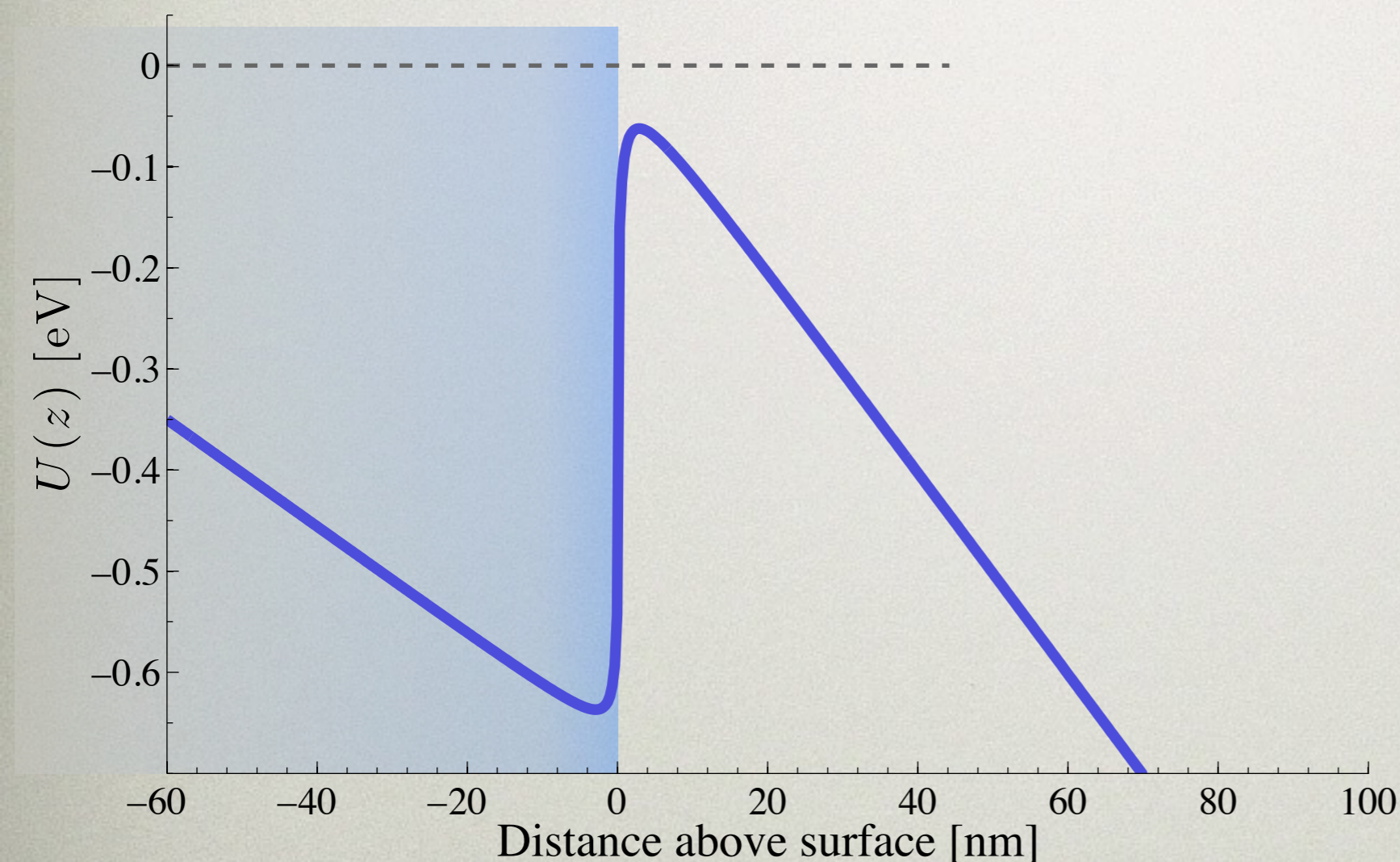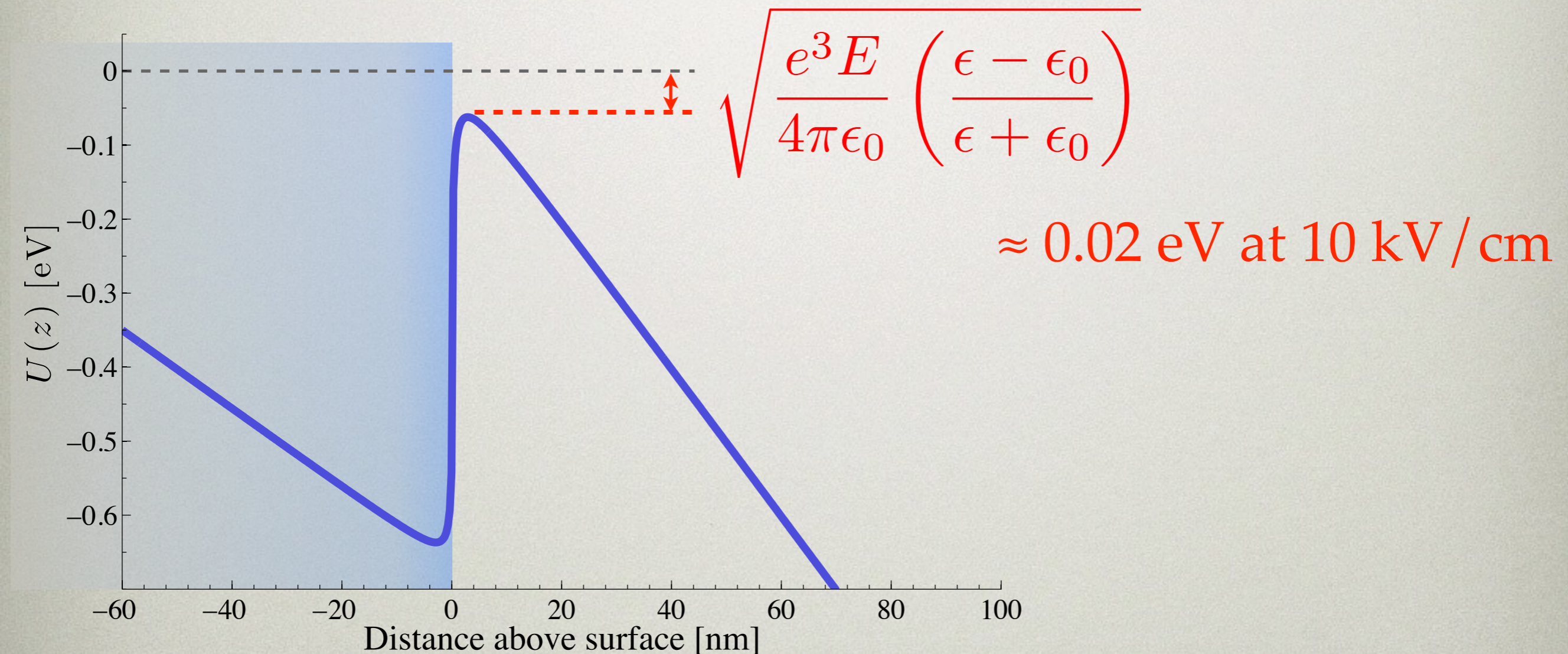

(no field)

Understanding extraction in LXe

Electron potential energy:

$$U(z) = \frac{1}{16\pi\epsilon_0} \frac{e^2}{z + \beta} \frac{\epsilon - \epsilon_0}{\epsilon + \epsilon_0}, \quad z > 0$$

Electron affinity = 0.67 eV in LXe
(also known as V_0, but opposite sign)

(no field)

20

Understanding extraction in LXe

Electron potential energy:

$$U(z) = \frac{1}{16\pi\epsilon_0} \frac{e^2}{z + \beta} \frac{\epsilon - \epsilon_0}{\epsilon + \epsilon_0} - eEz, \ z > 0$$
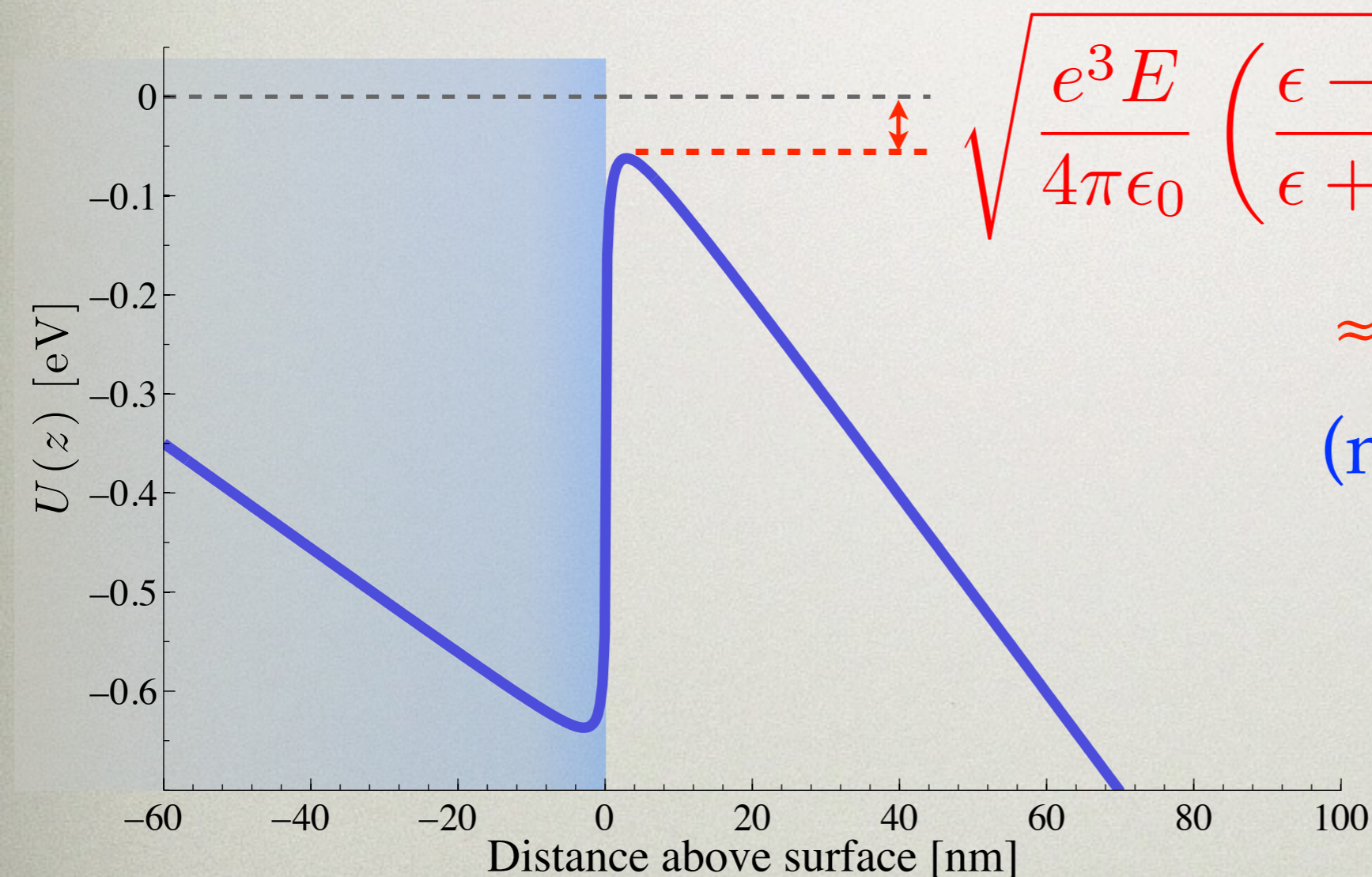

(with field)

Understanding extraction in LXe

Electron potential energy:

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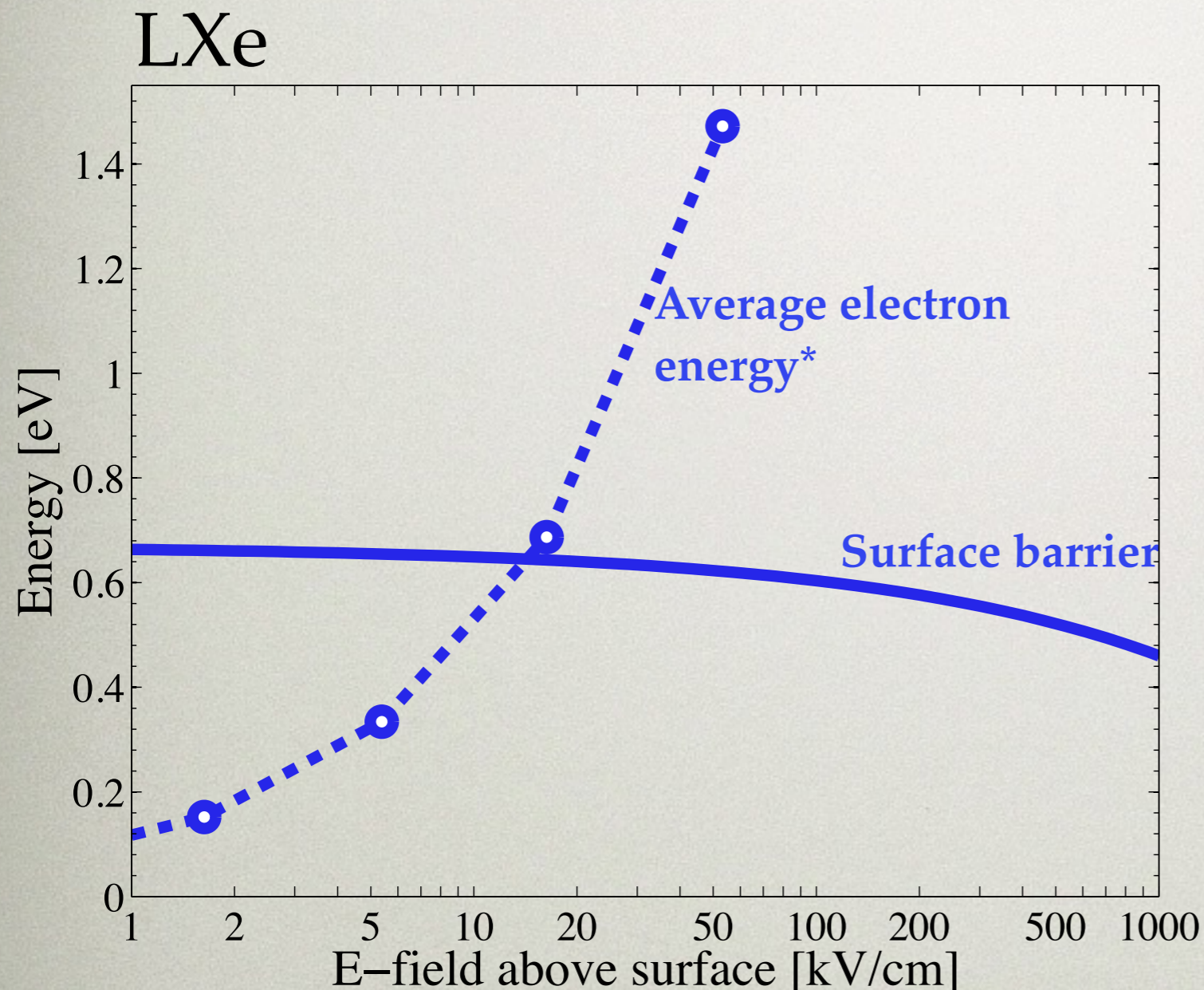
$$\sqrt{\frac{e^3 E}{4\pi\epsilon_0}\left(\frac{\epsilon - \epsilon_0}{\epsilon + \epsilon_0}\right)}$$

$$\approx 0.02 \text{ eV at } 10 \text{ kV/cm}$$

(with field)

Understanding extraction in LXe

Electron potential energy:

$$U(z) = \frac{1}{16\pi\epsilon_0} \frac{e^2}{z + \beta} \frac{\epsilon - \epsilon_0}{\epsilon + \epsilon_0} - eEz, \ z > 0$$

$$\sqrt{\frac{e^3 E}{4\pi\epsilon_0}\left(\frac{\epsilon - \epsilon_0}{\epsilon + \epsilon_0}\right)}$$

≈ 0.02 eV at 10 kV/cm
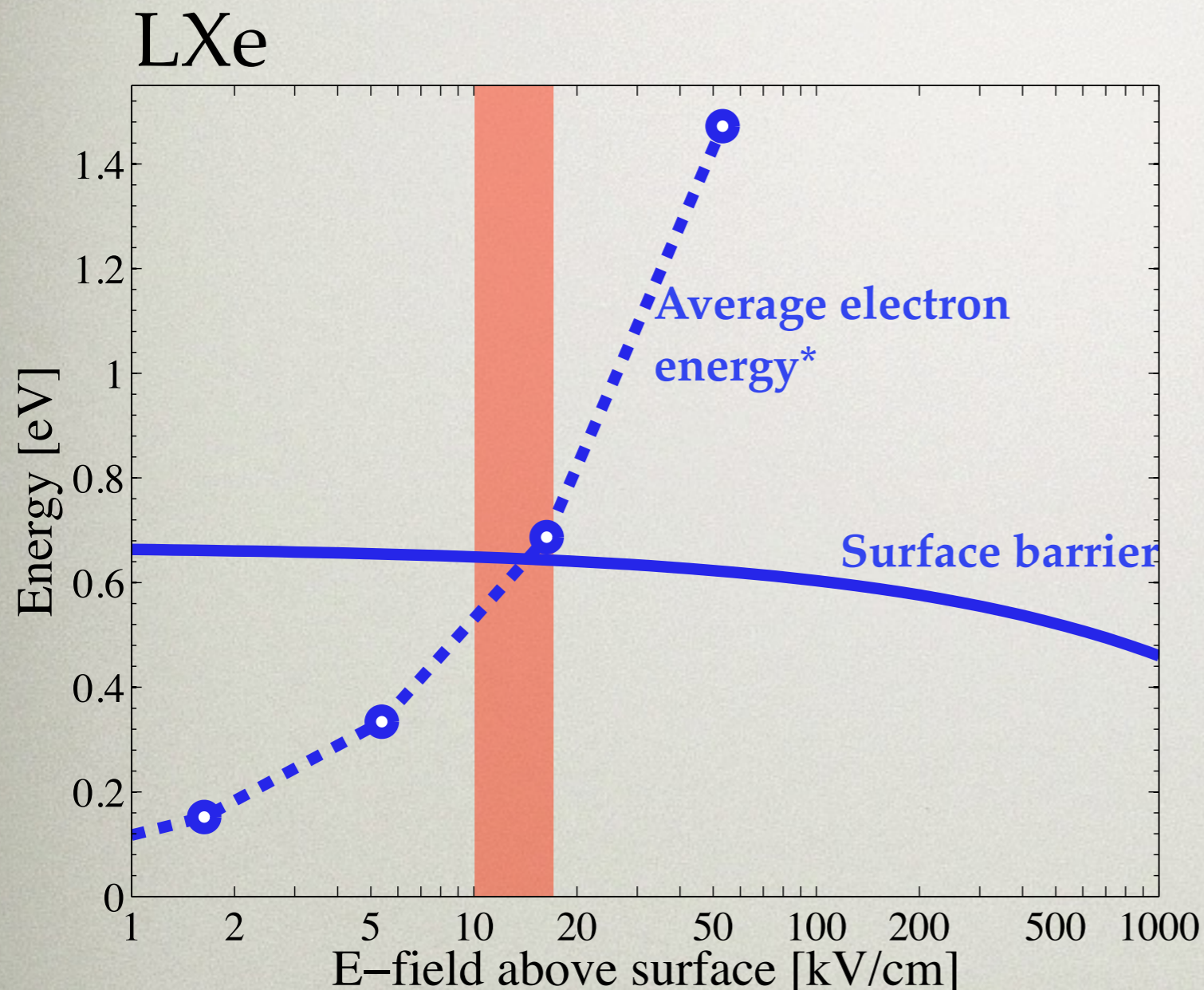
(not enough to explain 100% extraction...)

(with field)

Electron heating

LXe

- Electron temperature increases with applied field
- We can conclude that 100% extraction occurs when the electron temperature exceeds the potential barrier.
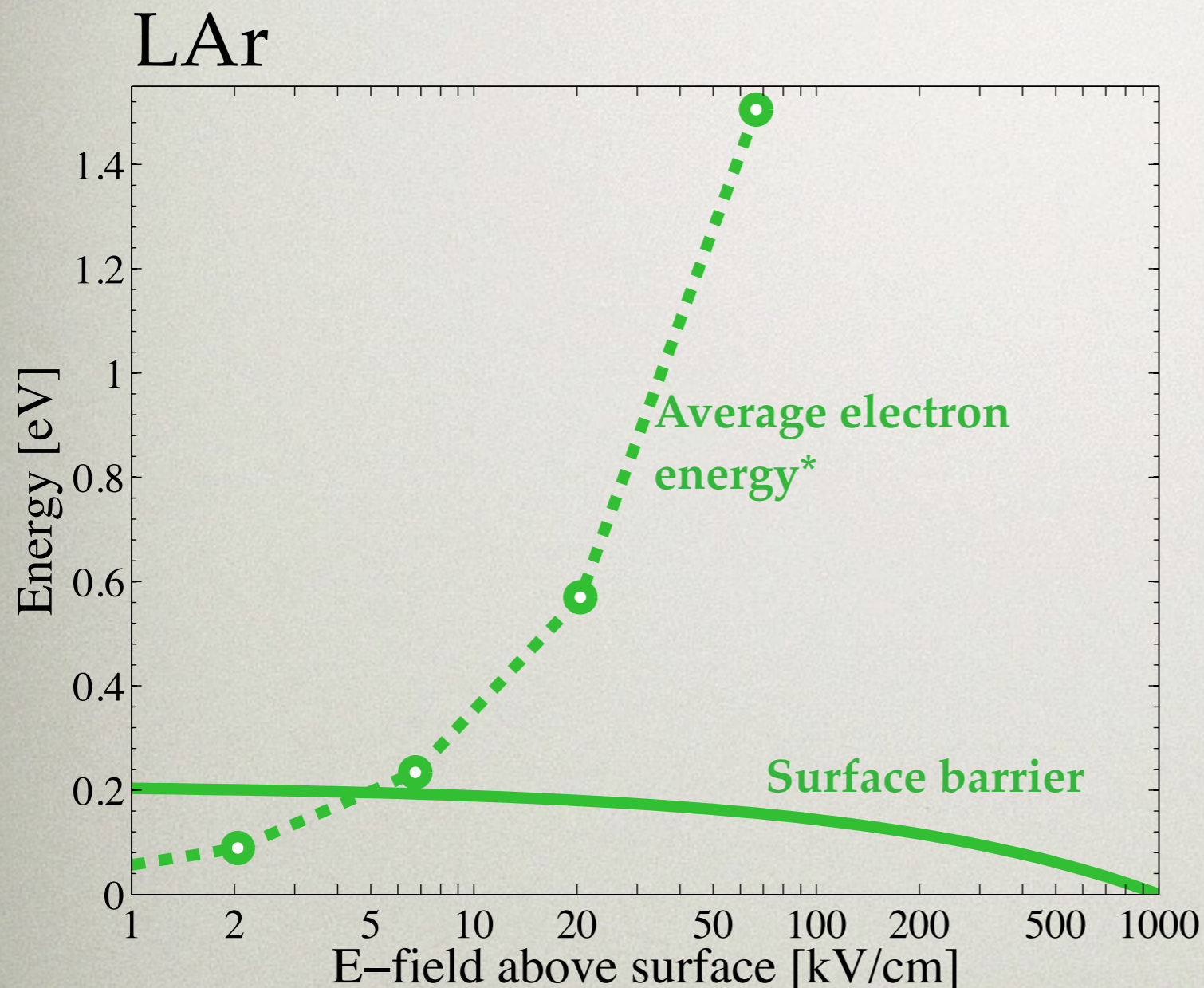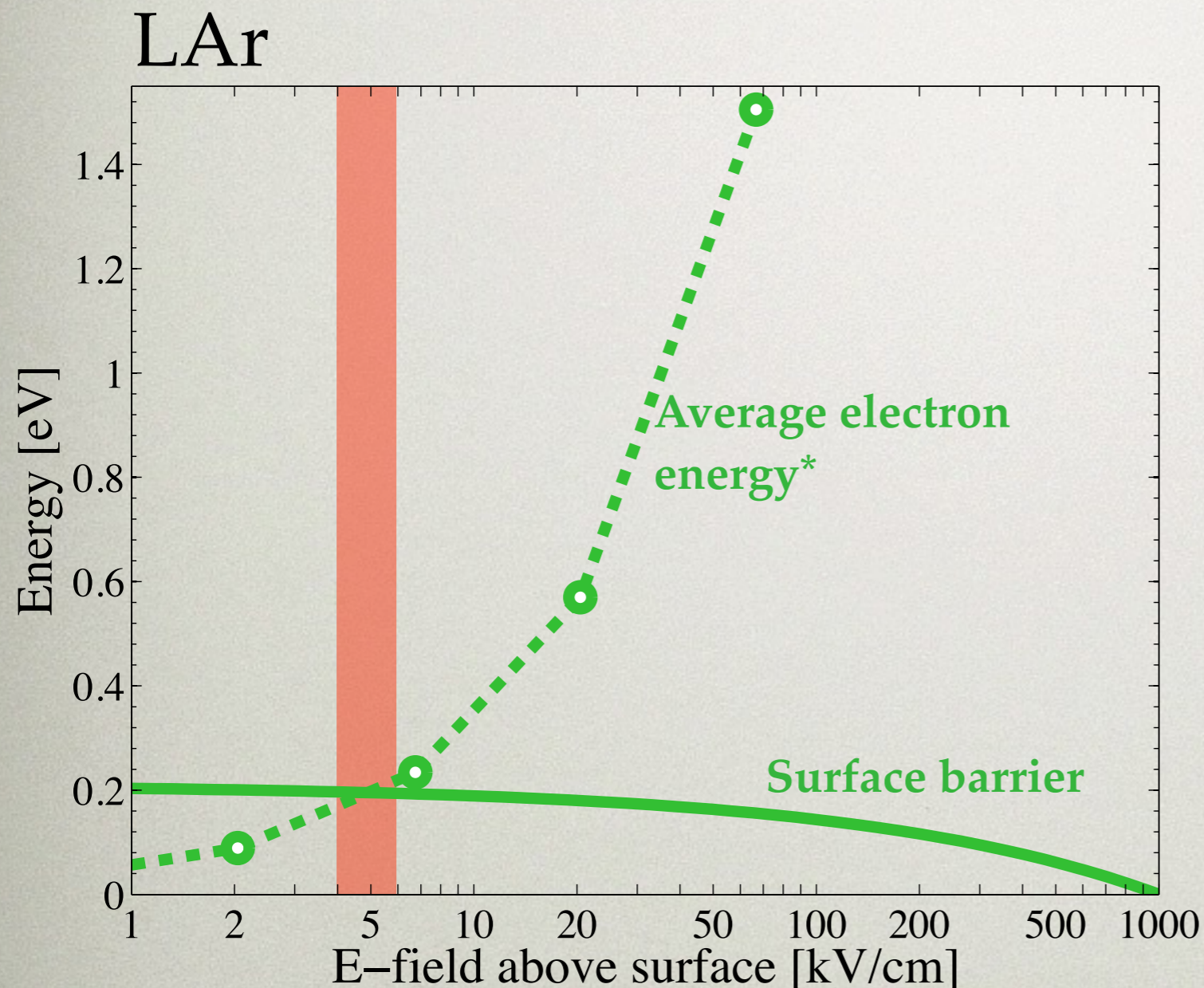
*U. Sowada *et al.*, Chem. Phys. Lett. **34** (1975) 466

Electron heating

LXe

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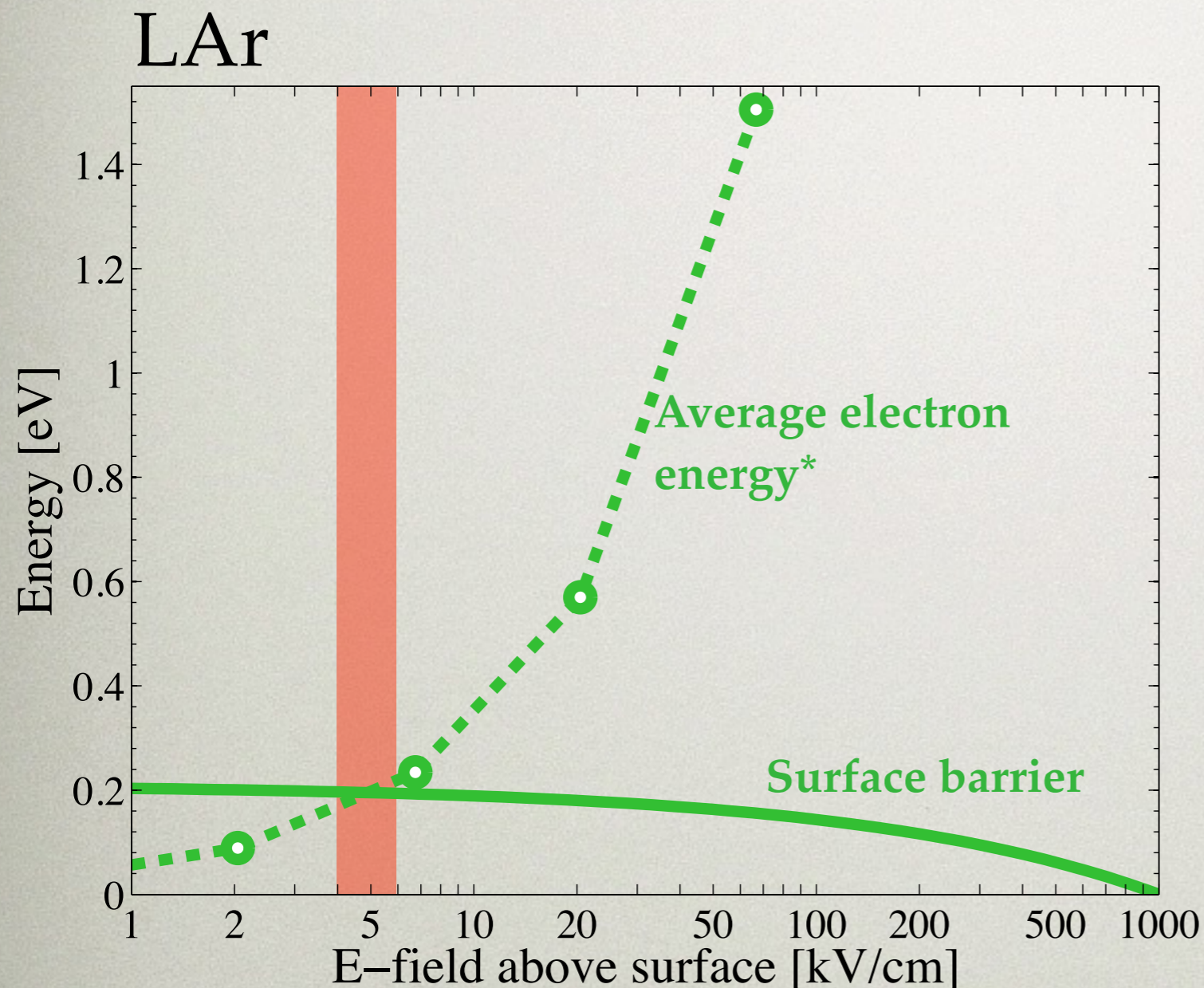
*U. Sowada *et al.*, Chem. Phys. Lett. **34** (1975) 466

Electron heating

LAr

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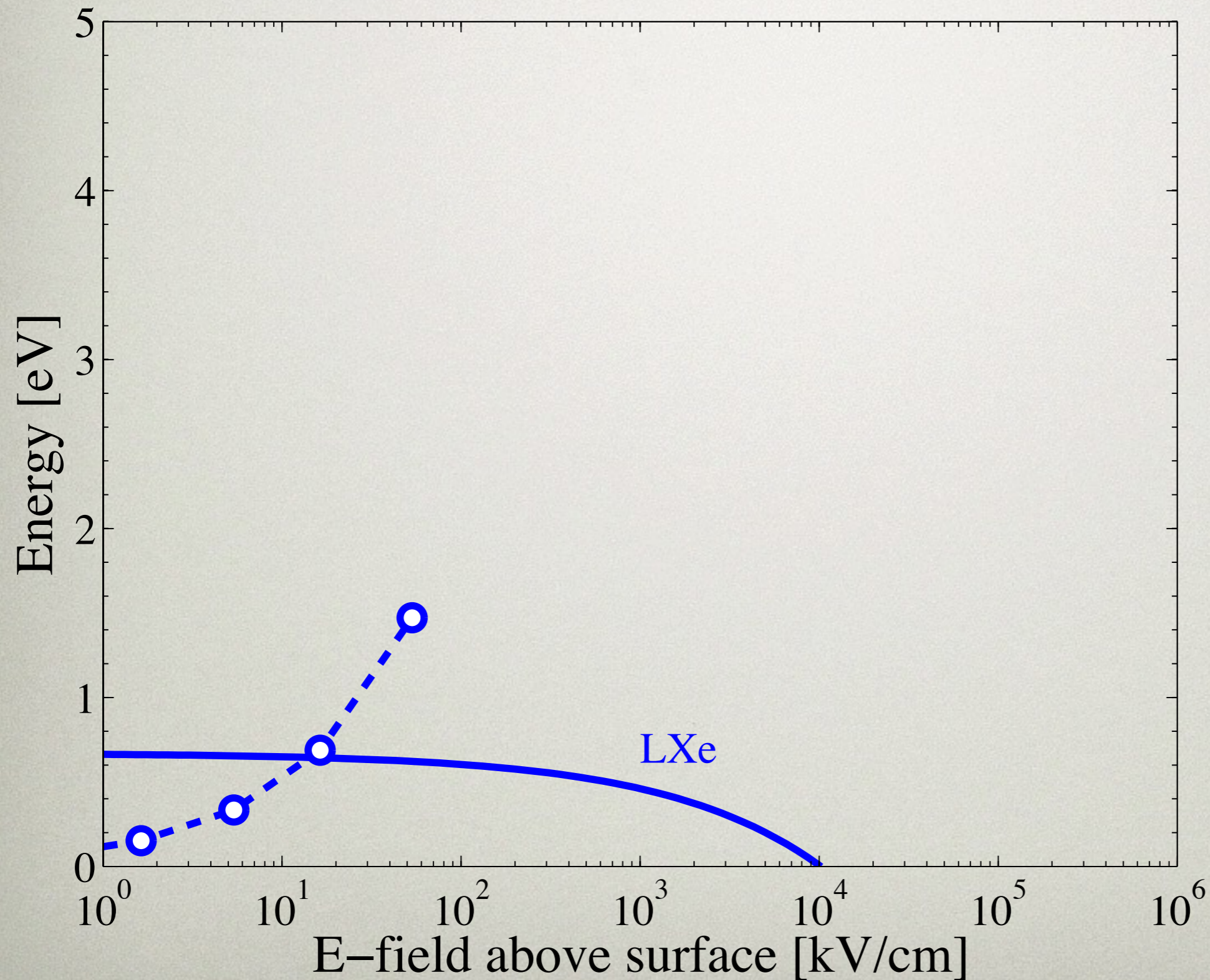
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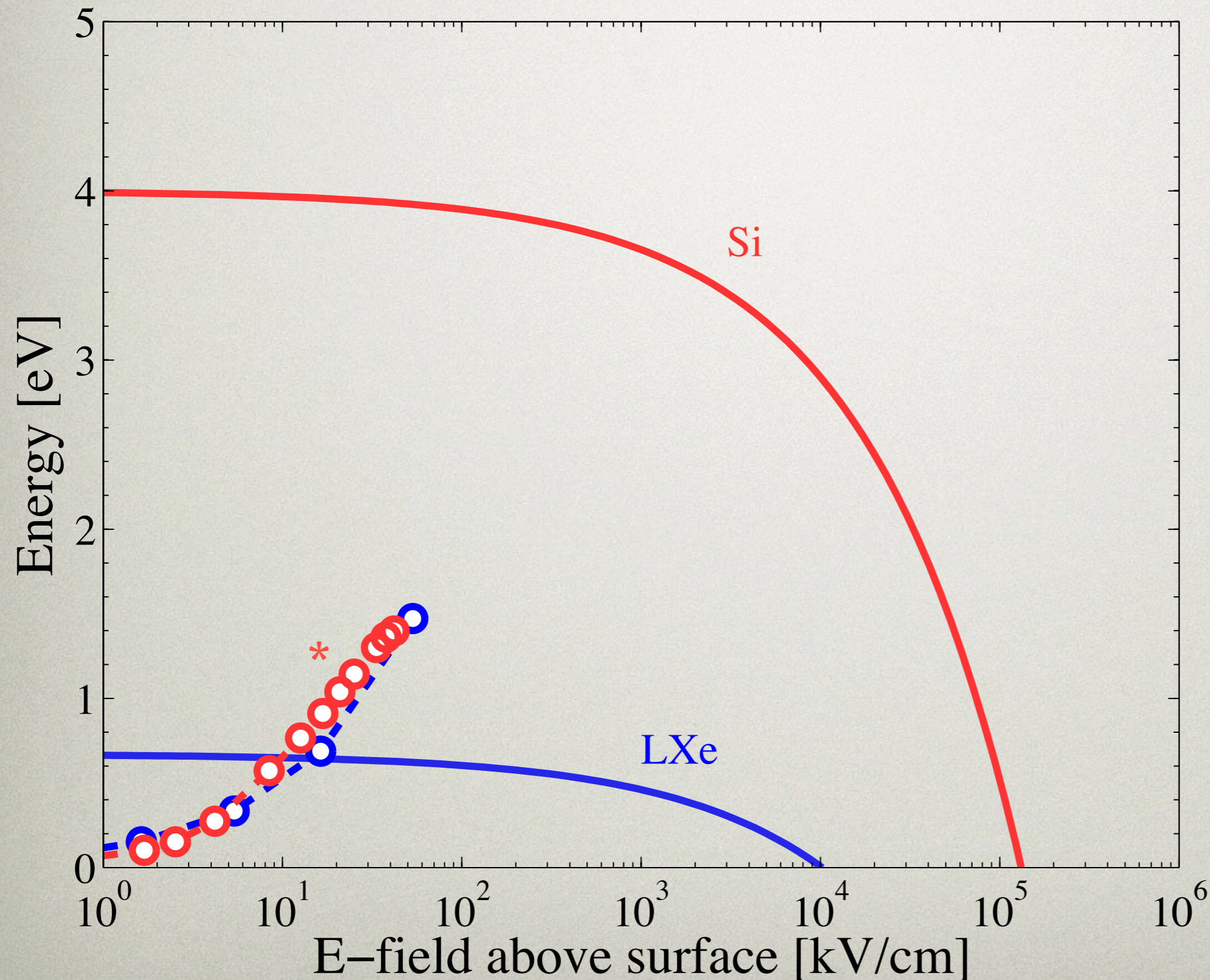
What does this plot look like for Si?
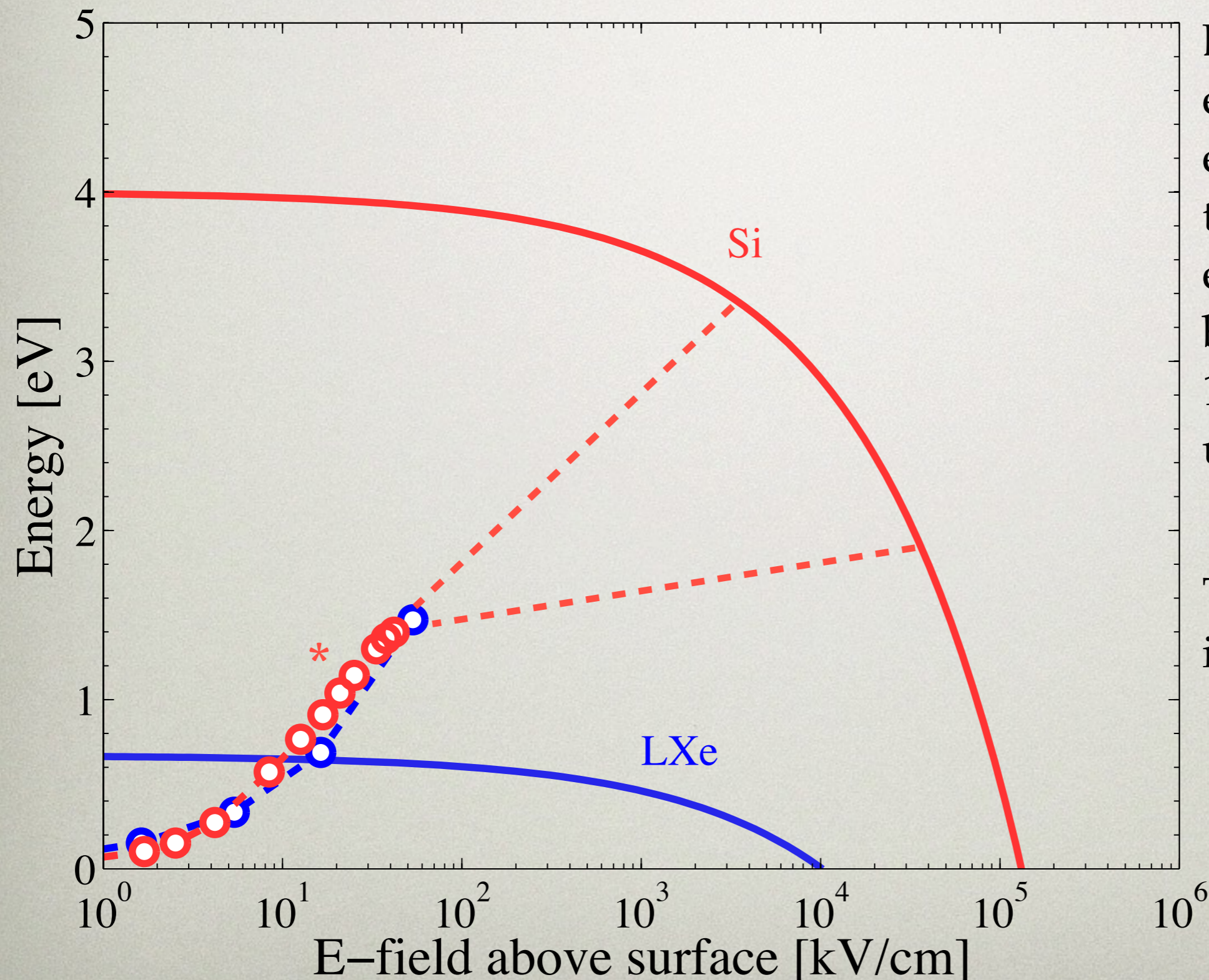
*U. Sowada *et al.*, Chem. Phys. Lett. **34** (1975) 466

Electron heating (?)

Electron heating (?)

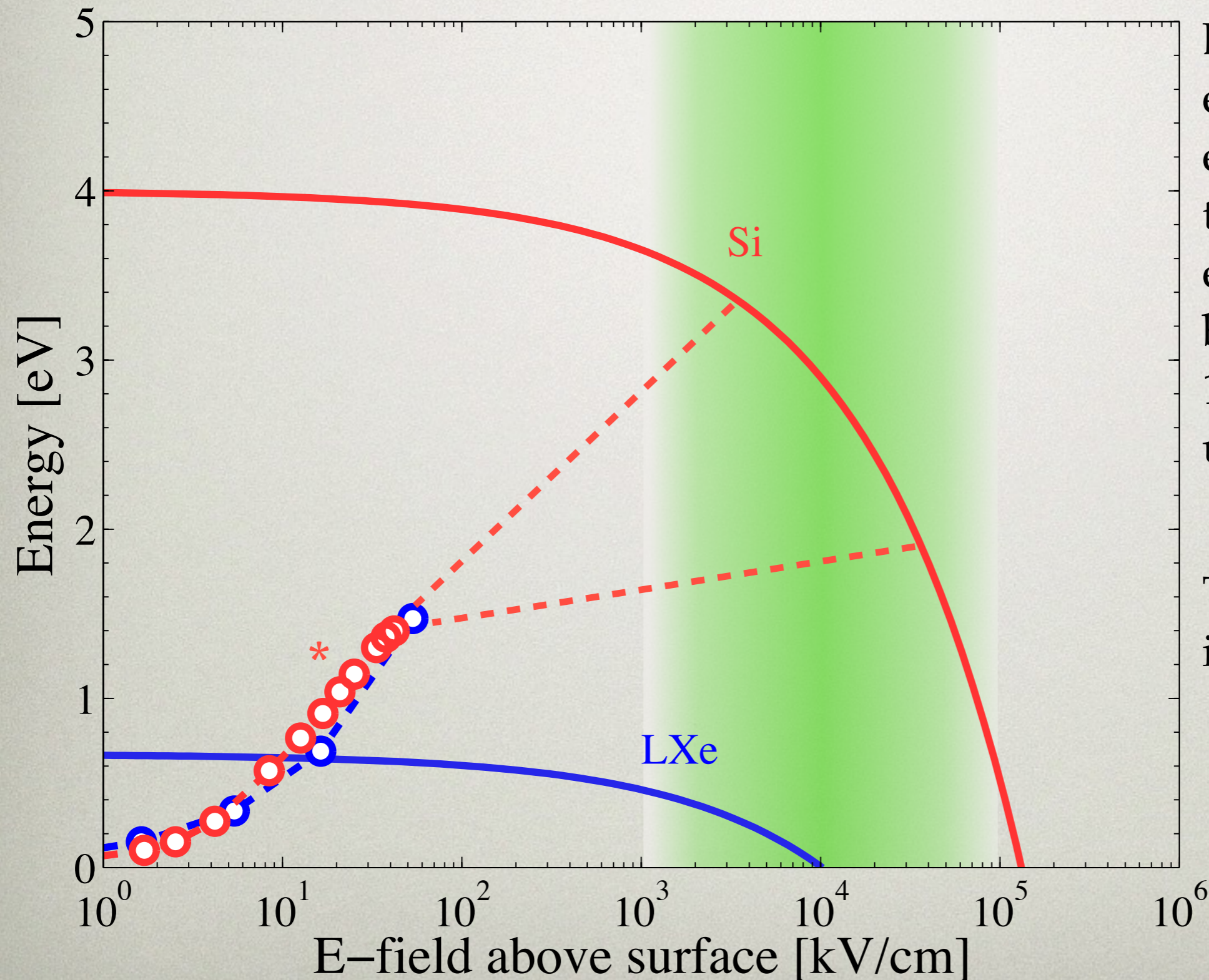* M.J. Martín *et al.*, Semicond. Sci. Technol. 8 (1993) 1291

Electron heating (?)

Depending on how I extrapolate the Si electron temp data, the necessary extraction field could be anywhere from 10^3 kV/cm or even up to 10^5 kV/cm.

That's not feasible, is it?

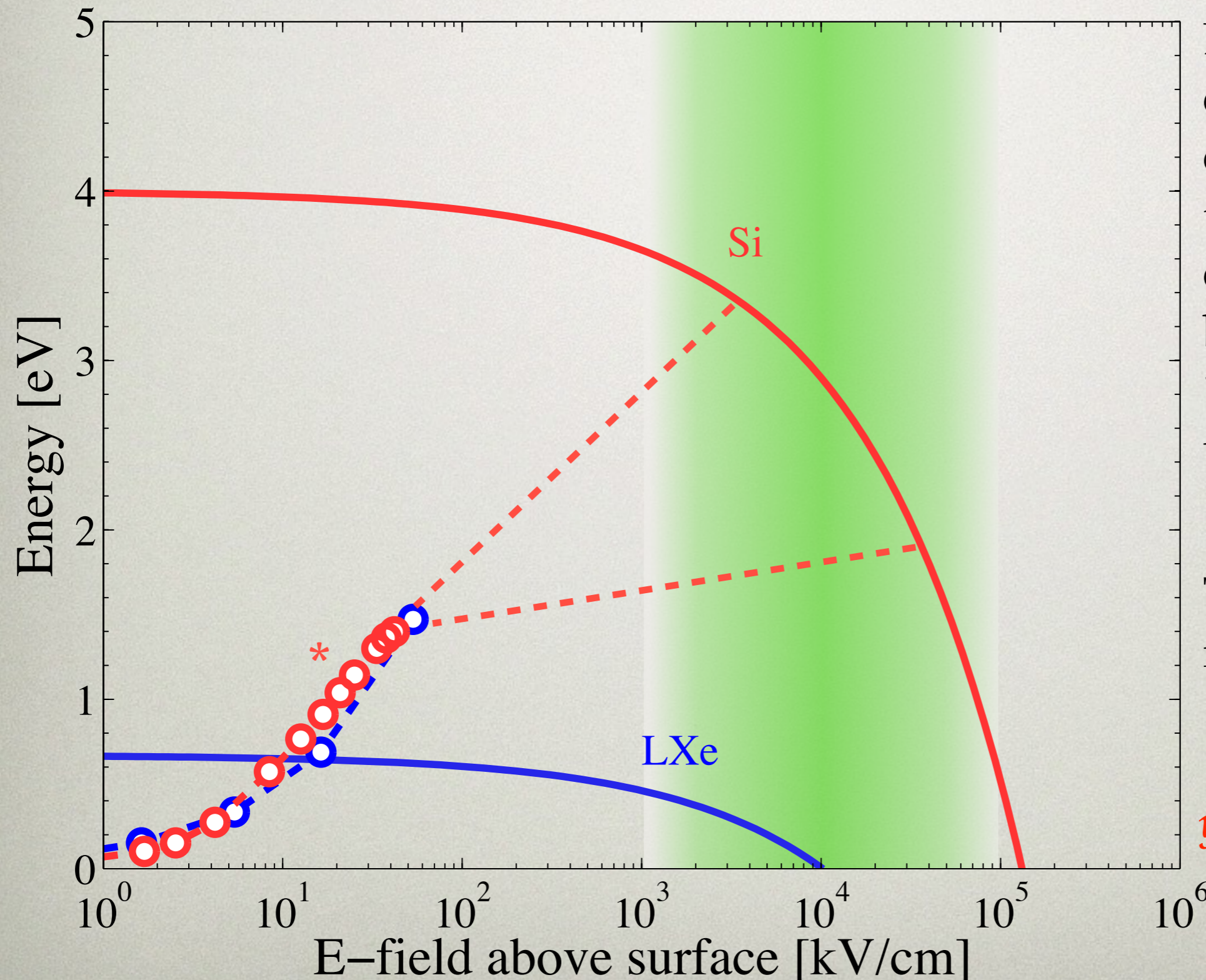* M.J. Martín *et al.*, Semicond. Sci. Technol. **8** (1993) 1291

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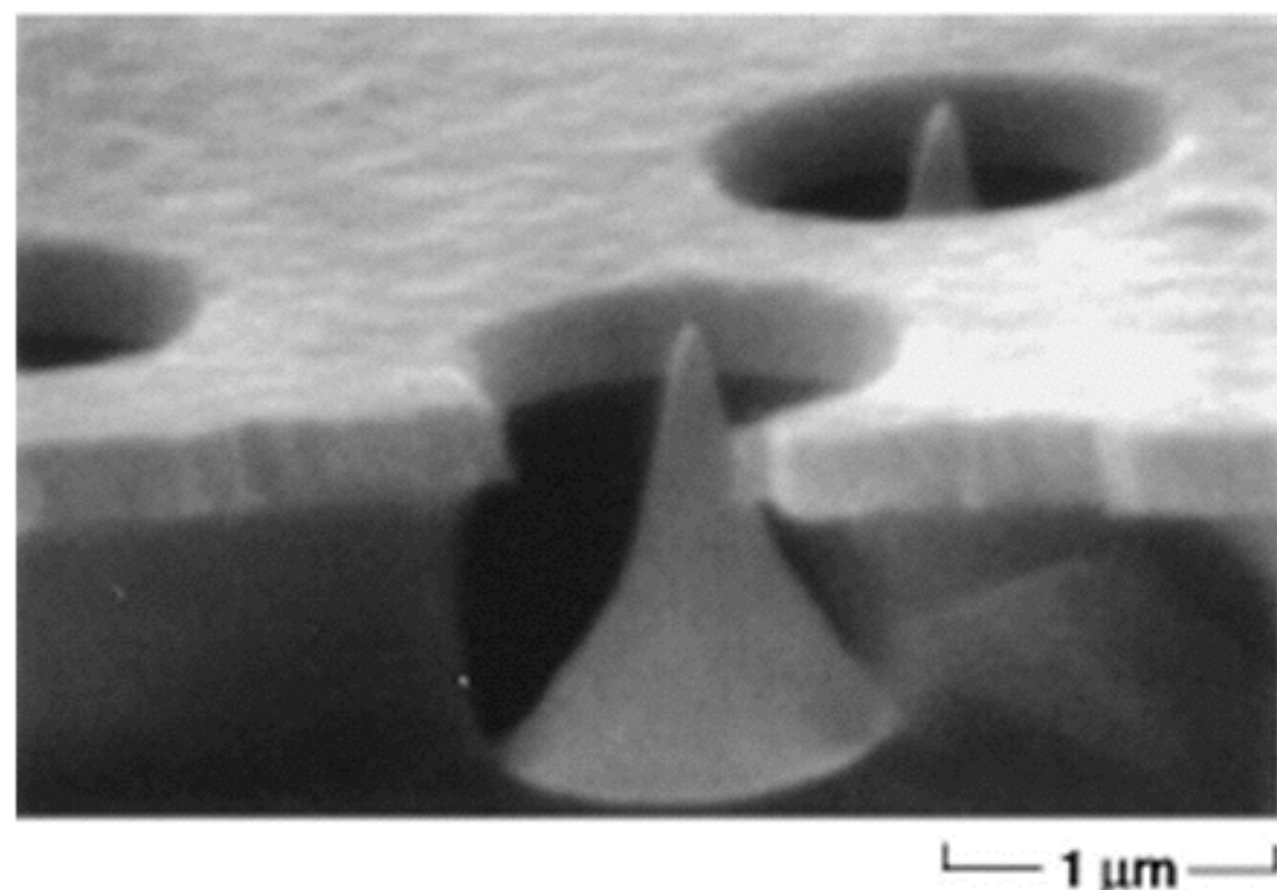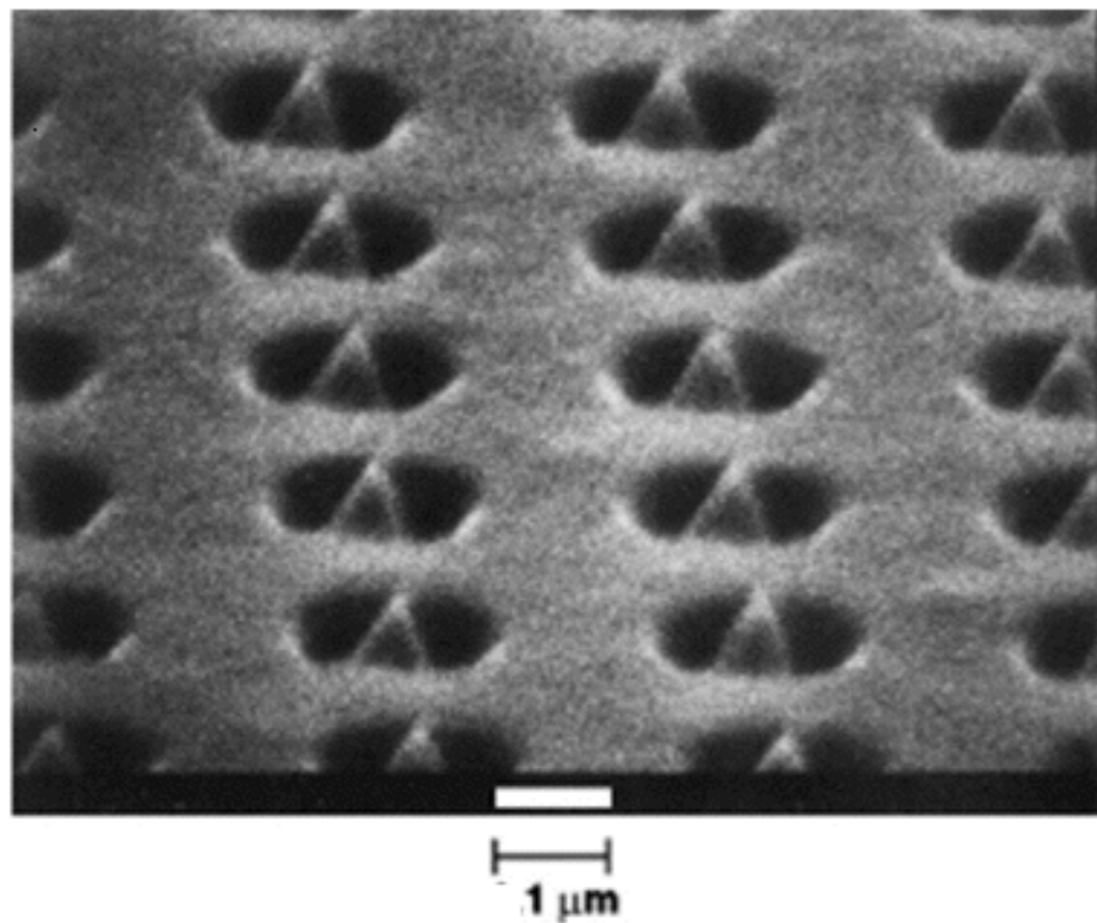
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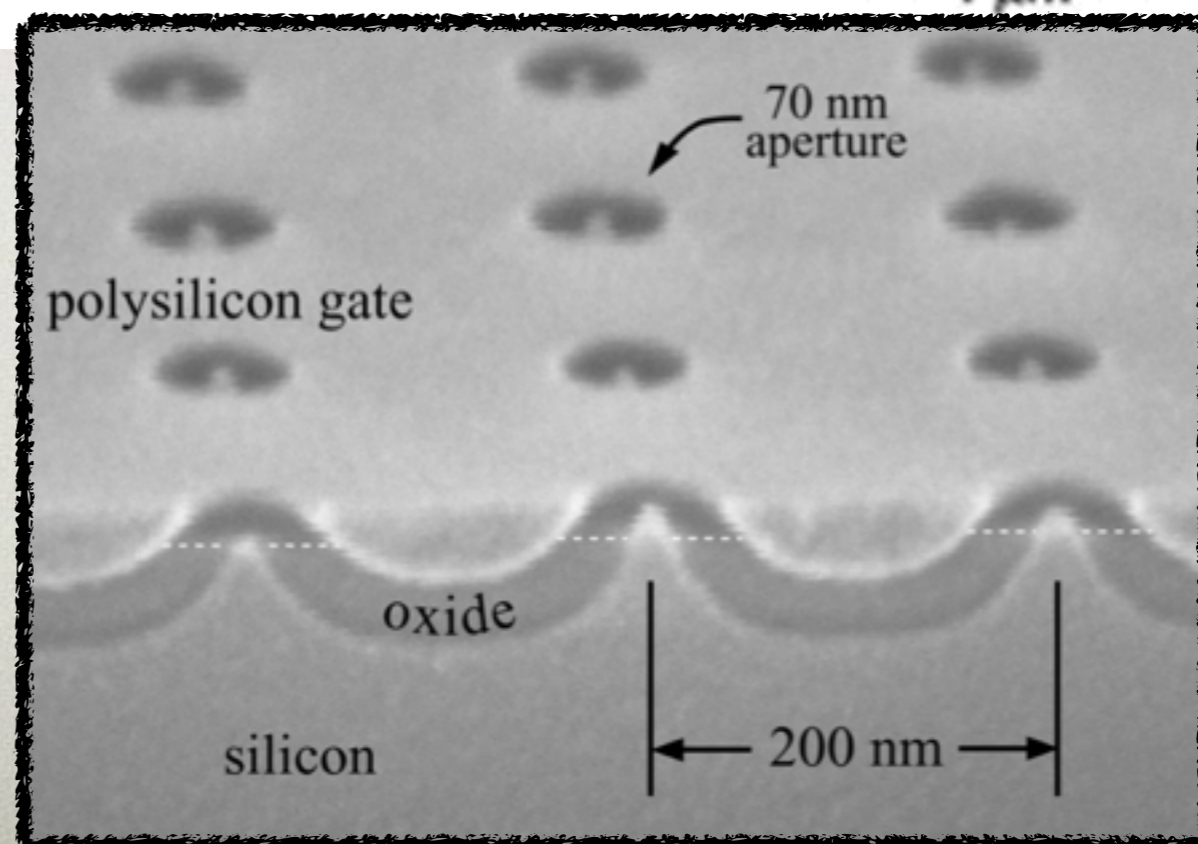
That's not feasible, is it?

...it depends on what you do to the surface!

* M.J. Martín *et al.*, Semicond. Sci. Technol. 8 (1993) 1291
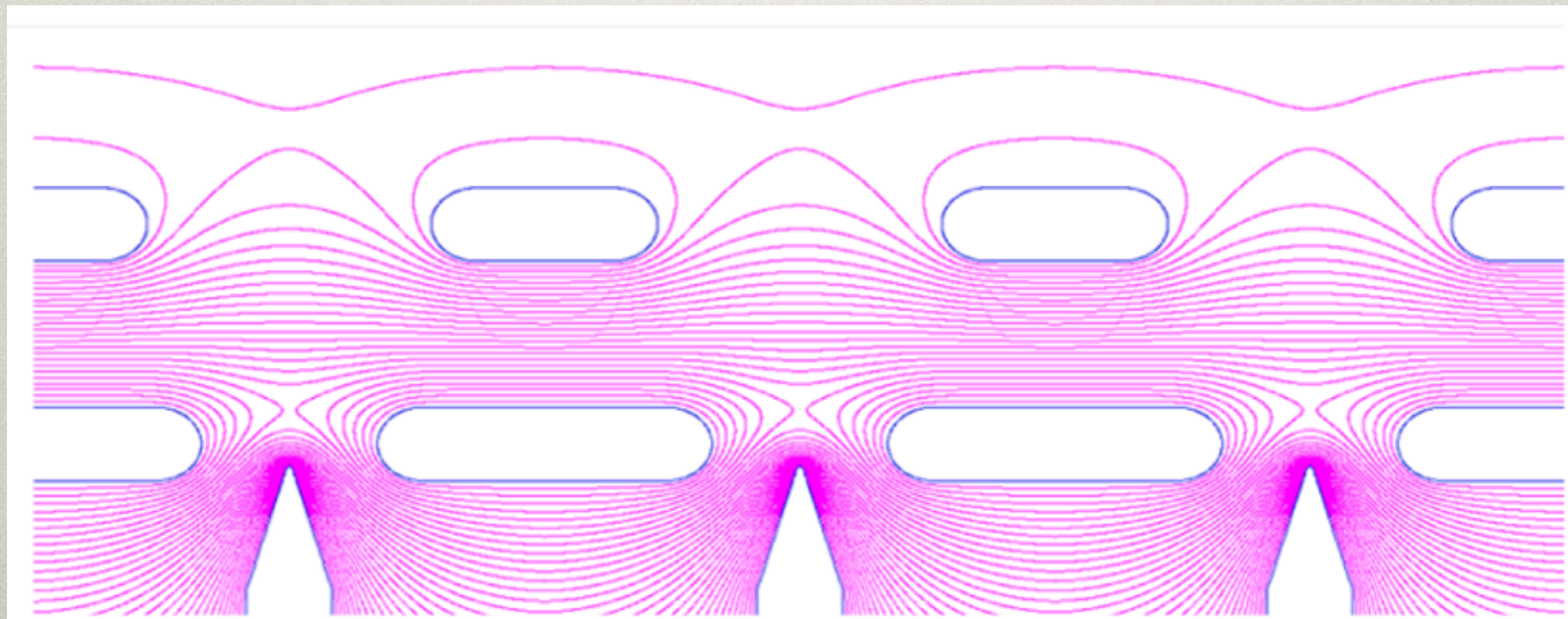
Field Emitter Arrays

An array of microscopic tips is etched on the surface of the silicon (or other material). A conducting plate is held above the surface by an insulating layer. *Tips are* nm-*sharp!!!*

HUGE field densities

Field densities of ~10^5 kV/cm at gate bias of ~30V!!

W.S. Graves *et al.*, PRL **108** (2012) 263904

This is <u>not</u> new technology

An important point about this technology is that it is very mature, involving standardized techniques. Many facilities easily have the necessary capabilities.

1968)

C.A. Spindt, J. Appl. Phys. **39** (1968) 3504

A Thin-Film Field-Emission Cathode

C. A. SPINDT

Applied Physics Laboratory, Stanford Research Institute, Menlo Park, California

(Received 19 February 1968)

Research on micron-size field-emission tubes[1,2] has recently led to the development of a novel low-voltage, high-current, field-emission cathode and relatively simple techniques for producing such cathodes in various forms. The basic cathode consists of a molybdenum–aluminum oxide–molybdenum thin-film sandwich

(a) Molybdenum anode / Alumina dielectric / Molybdenum cathode / Substrate

(b) Alumina deposition while rotating the substrate

(c) Simultaneous normal and steep angle depositions of. Molybdenum and Alumina respectively
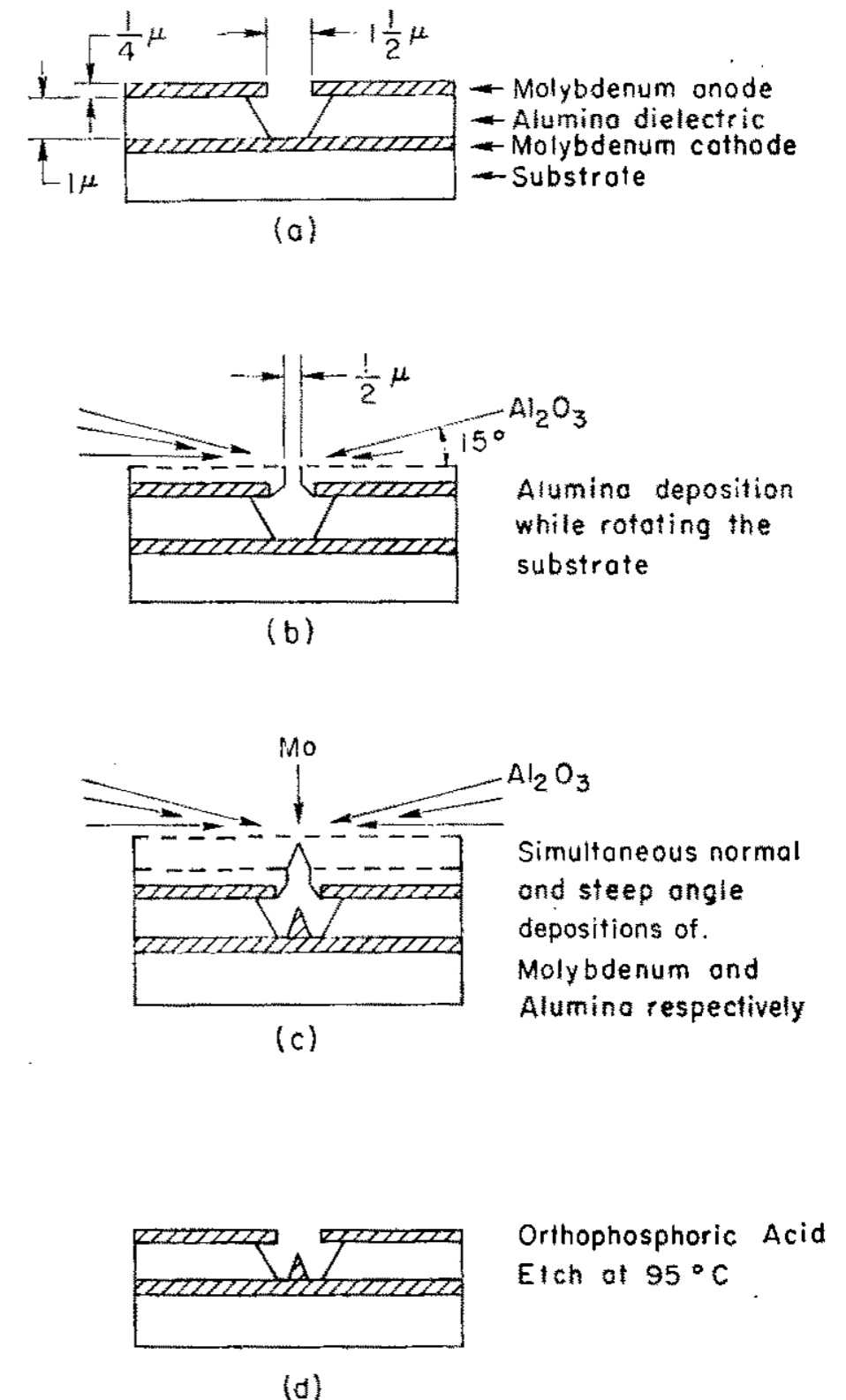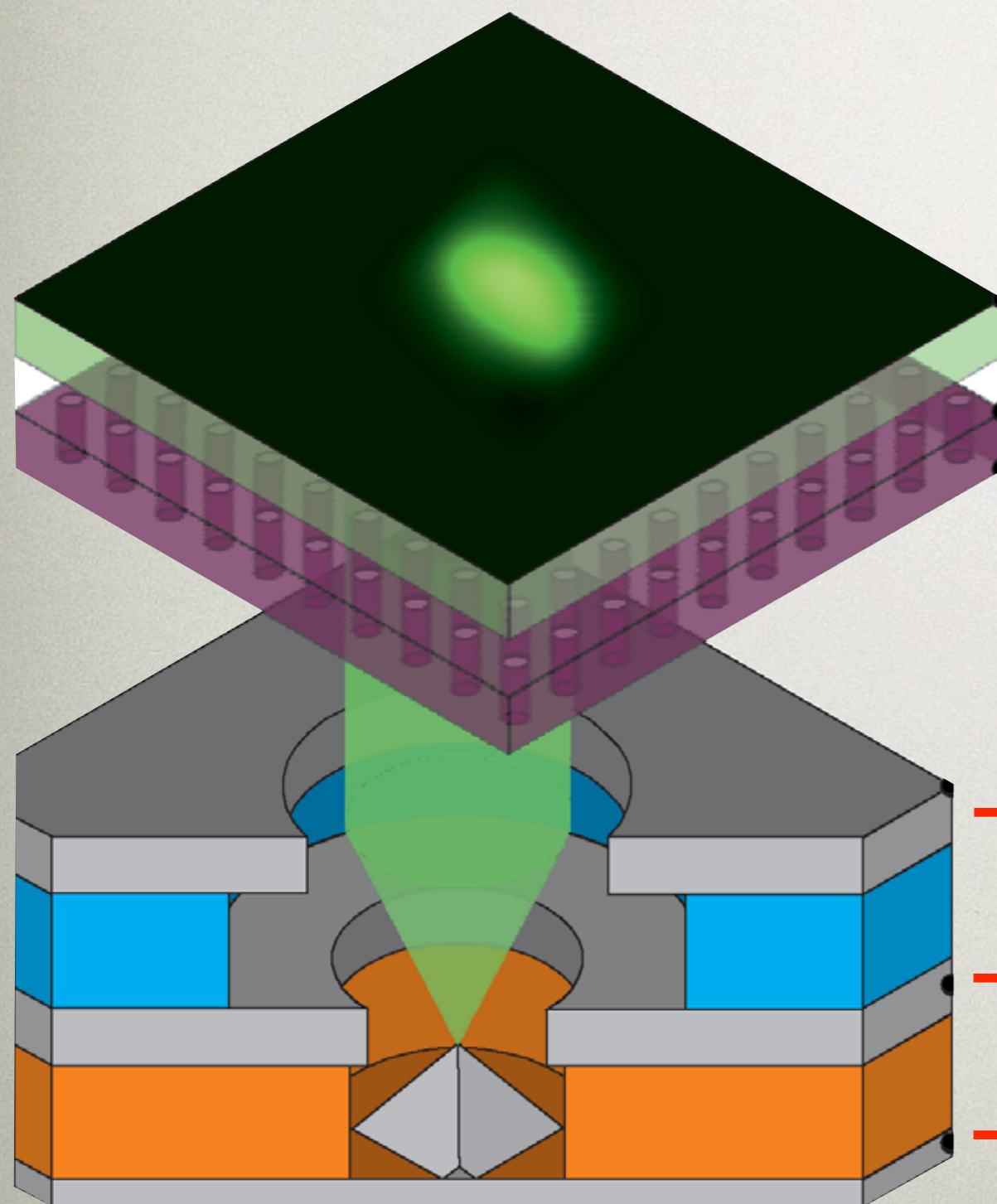
(d) Orthophosphoric Acid Etch at 95 °C

FIG. 2. Cathode formation by deposition from two sources.

Electron collimation

P. Helfenstein *et al.*, J. Appl. Phys. **112** (2012) 093307

- By depositing two conducting layers, extracted electrons can be collimated.
- This technique is used for the beam source in the free-electron laser at the Paul Scherrer Institute in Switzerland
- → For a particle detector, electron trajectory preserves the *x-y* information of the interaction vertex

— **Collimation electrode**
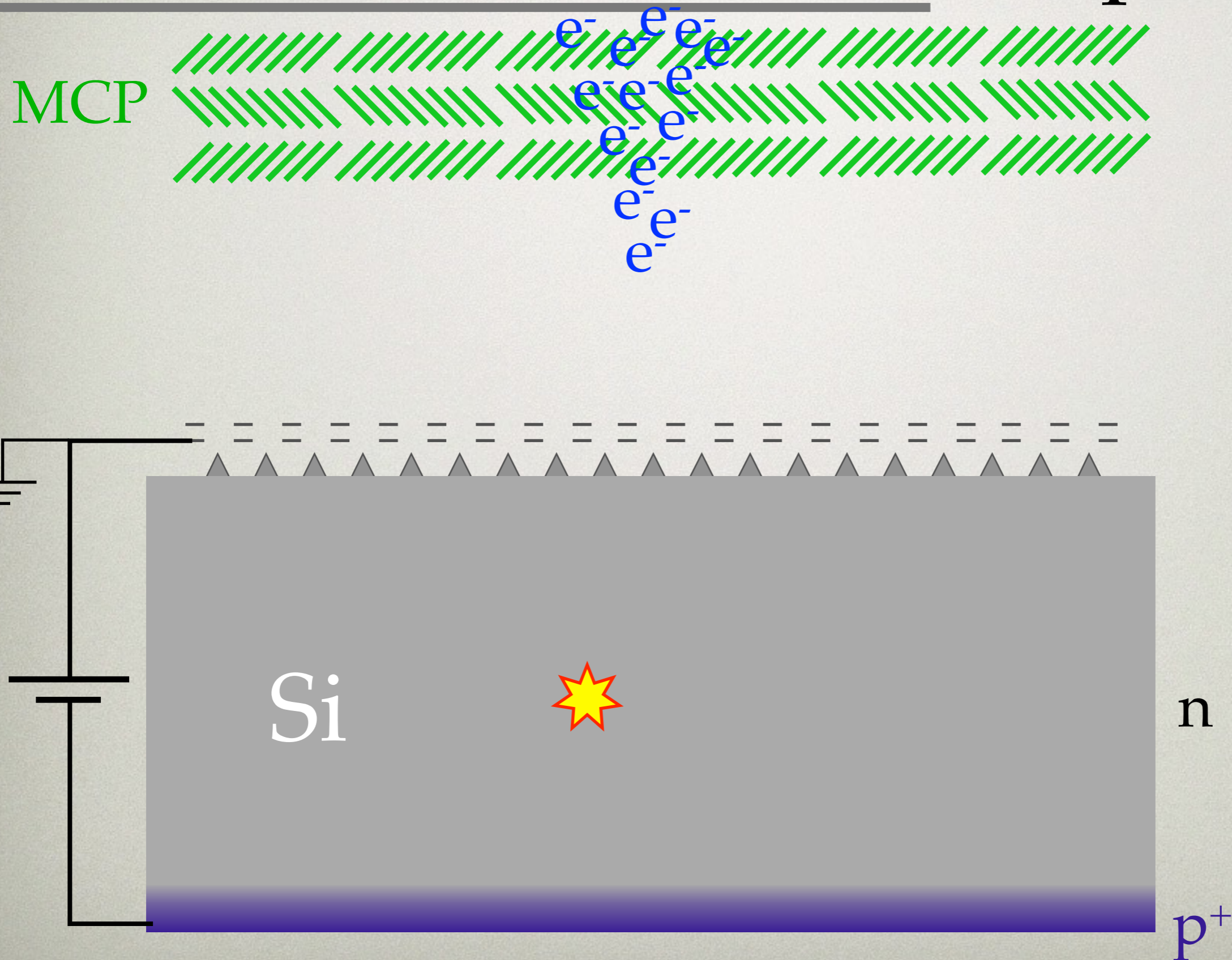
— **Extraction electrode**
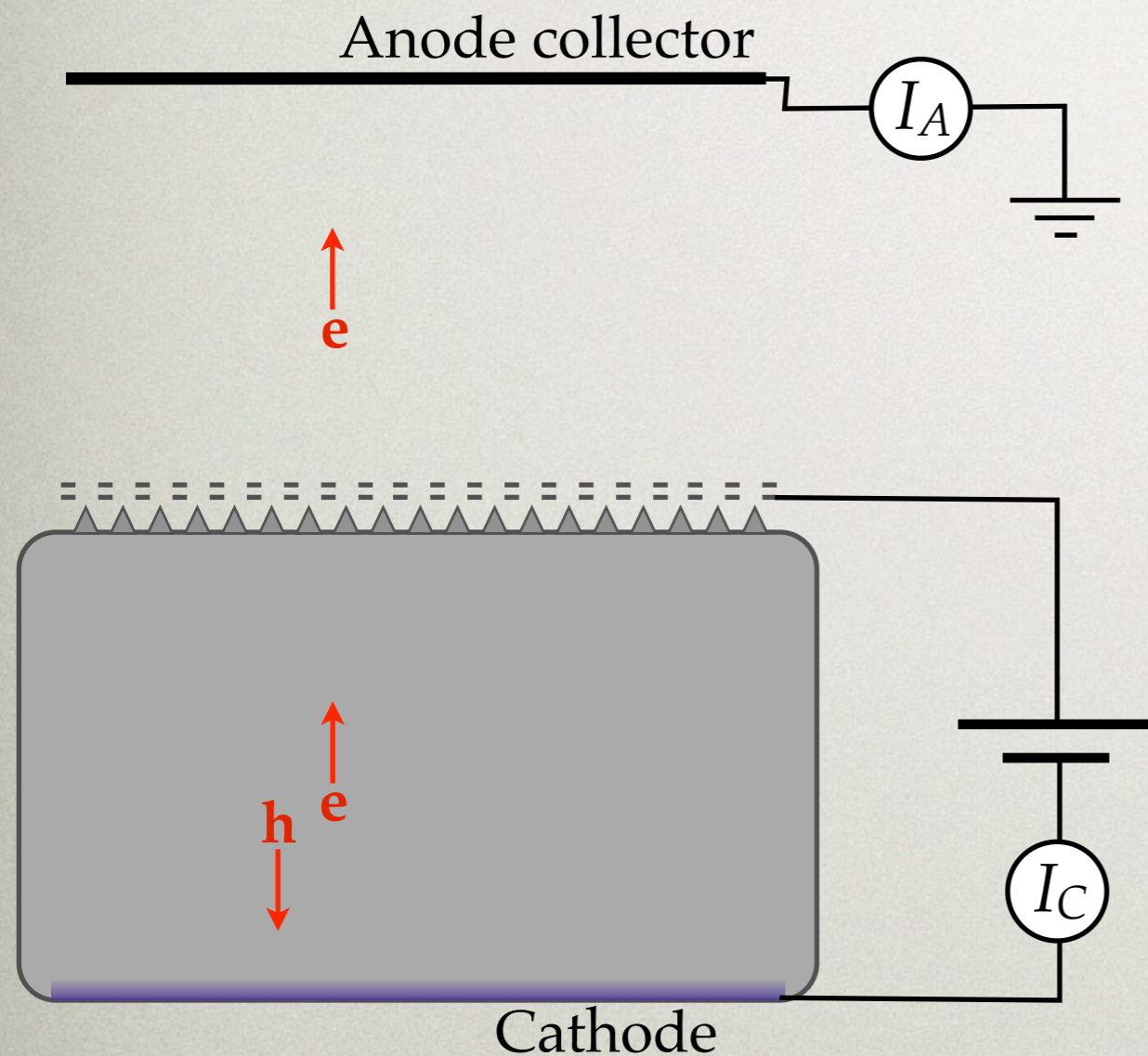
— **Substrate**

Towards a detector concept

MCP

Si

n

p⁺

Towards a detector concept

MCP

Si

e⁻ e⁻
e⁻

n

p⁺

Towards a detector concept

MCP

e⁻ e⁻ e⁻
e⁻ e
e⁻e⁻ e
e⁻e⁻e⁻
e⁻ e
e⁻ e⁻
e⁻
e⁻ e⁻
e⁻

Si

n

p⁺

What would be the easiest way to test the viability of this idea?

Easy proof-of-principle

Anode collector

I_A

e

h e

I_C

Cathode

- To measure the extraction efficiency, one can measure the thermally induced current.
- The ratio of I_A to I_C should be equal to the extraction efficiency. It is essential to verify that this can be made something close to unity.
- The temp. can be varied to estimate which portion of I_C is due to thermal excitation.

$$I_{\text{therm}} \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$

What about backgrounds?

Thoughts on potential backgrounds

Thermally induced electrons
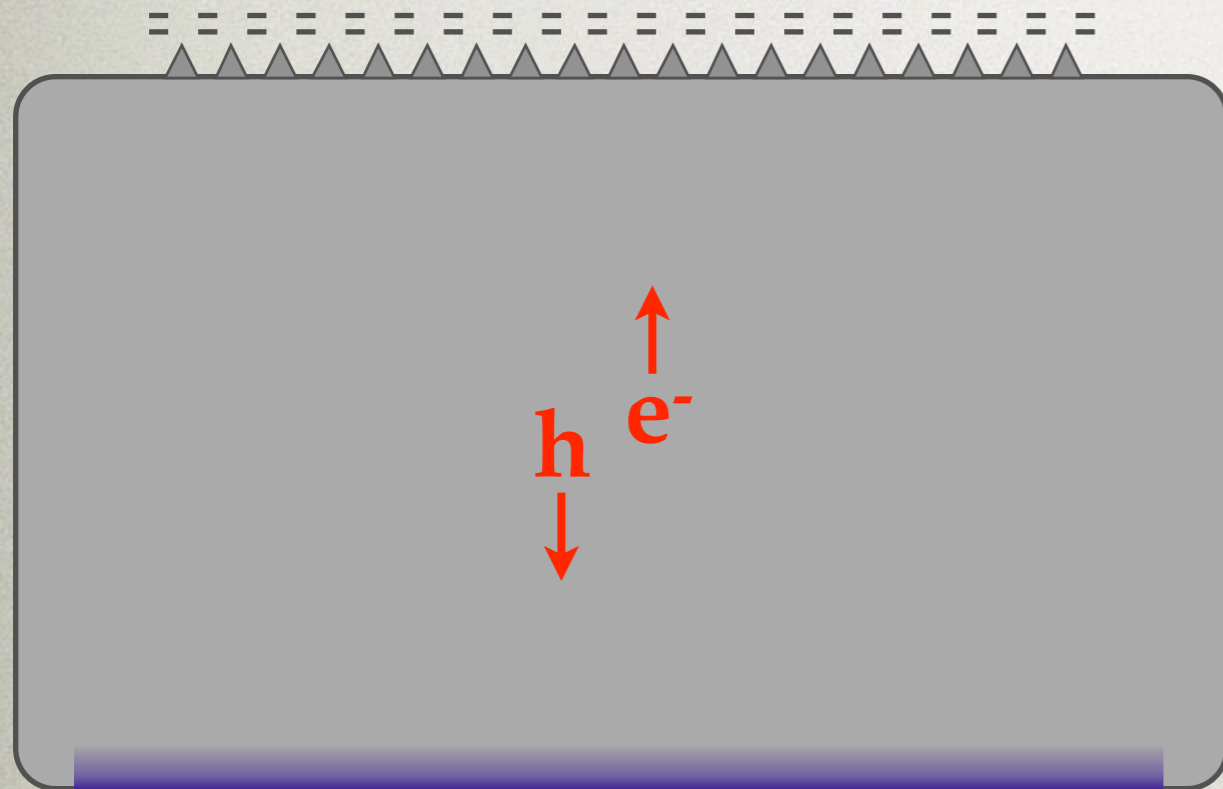
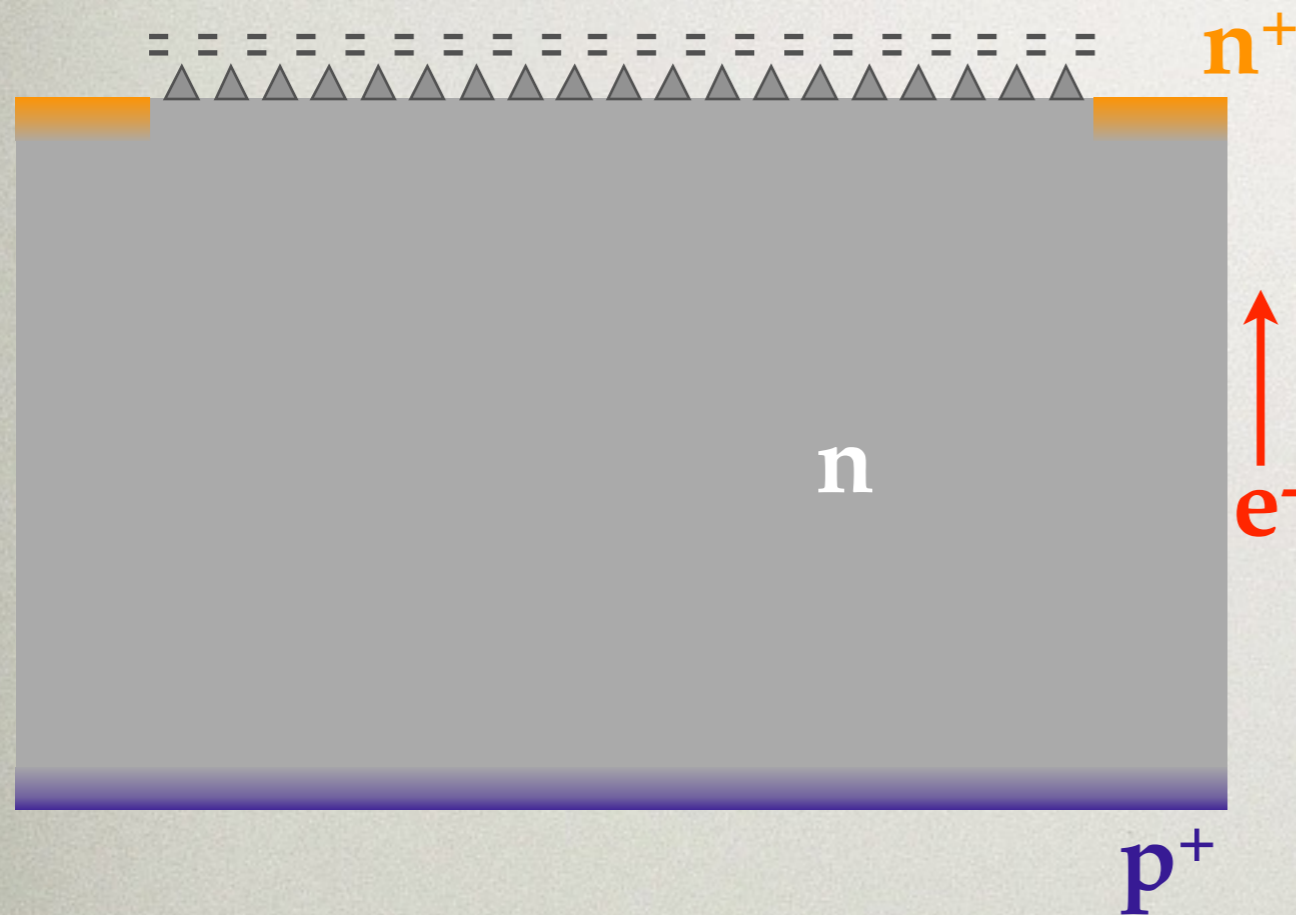$$I_{\mathrm{therm}} \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$

$E_g \approx 1.2$ eV (Silicon)

For example going from 77K to 4K reduces the thermally induced current by over 260 orders of magnitude!!

Likely no difficult cryogenics needed (i.e. **no dilution fridge**).
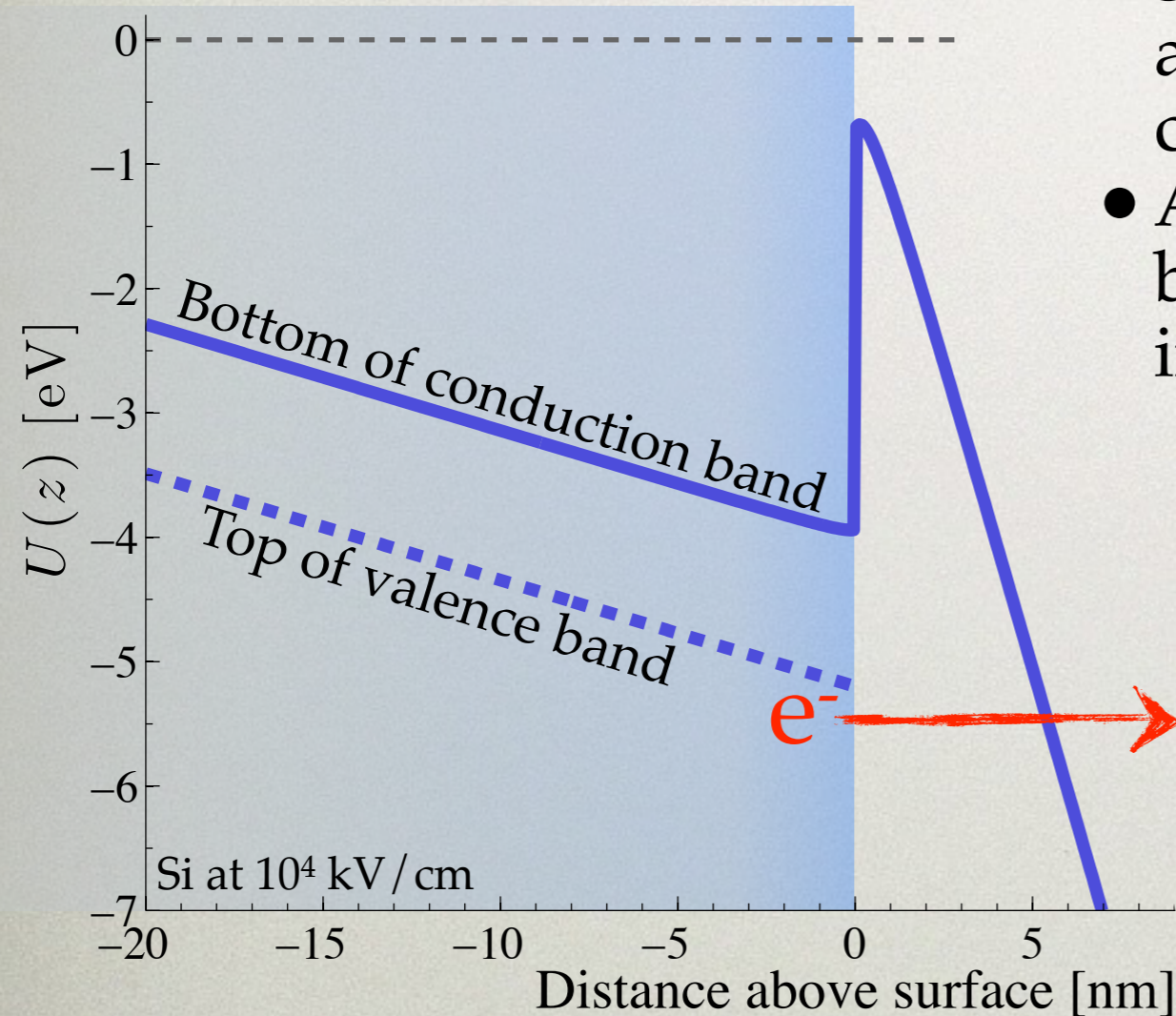
Thoughts on potential backgrounds

Surface currents

n^+

n

e^-

p^+

- A significant contribution to leakage current can be due to surface currents, unrelated to thermal excitation of the bulk
- These currents can be absorbed by depositing an n^+ contact on the periphery, outside the tip array, and coupling it to ground.

Thoughts on potential backgrounds

Valence tunneling

- Valence tunneling ("field emission") could spontaneously throw electrons off the surface
- Such electrons will leave the surface with a reduced kinetic energy (compared to conduction electrons)
- A retarding field, E_r, can kill electrons below a chosen energy (commonly done in emission spectroscopy)
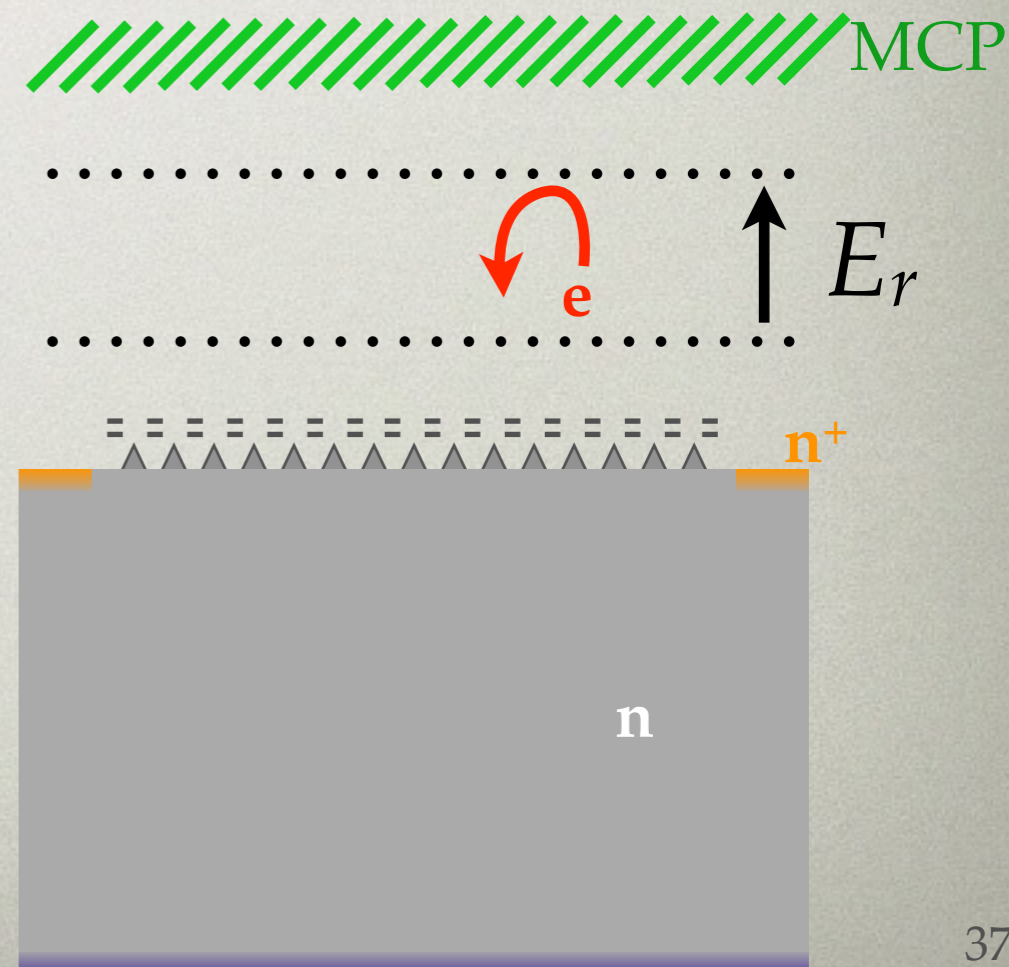
Lest you think this idea is crazy…

M. Wong, C.E. Hunt, Y. Diawara, Proc. of IEEE 20th Int. Vacuum Nanoelectronics Conf. (2007), pp. 195-196

A similar technique has been implemented in x-ray imaging.
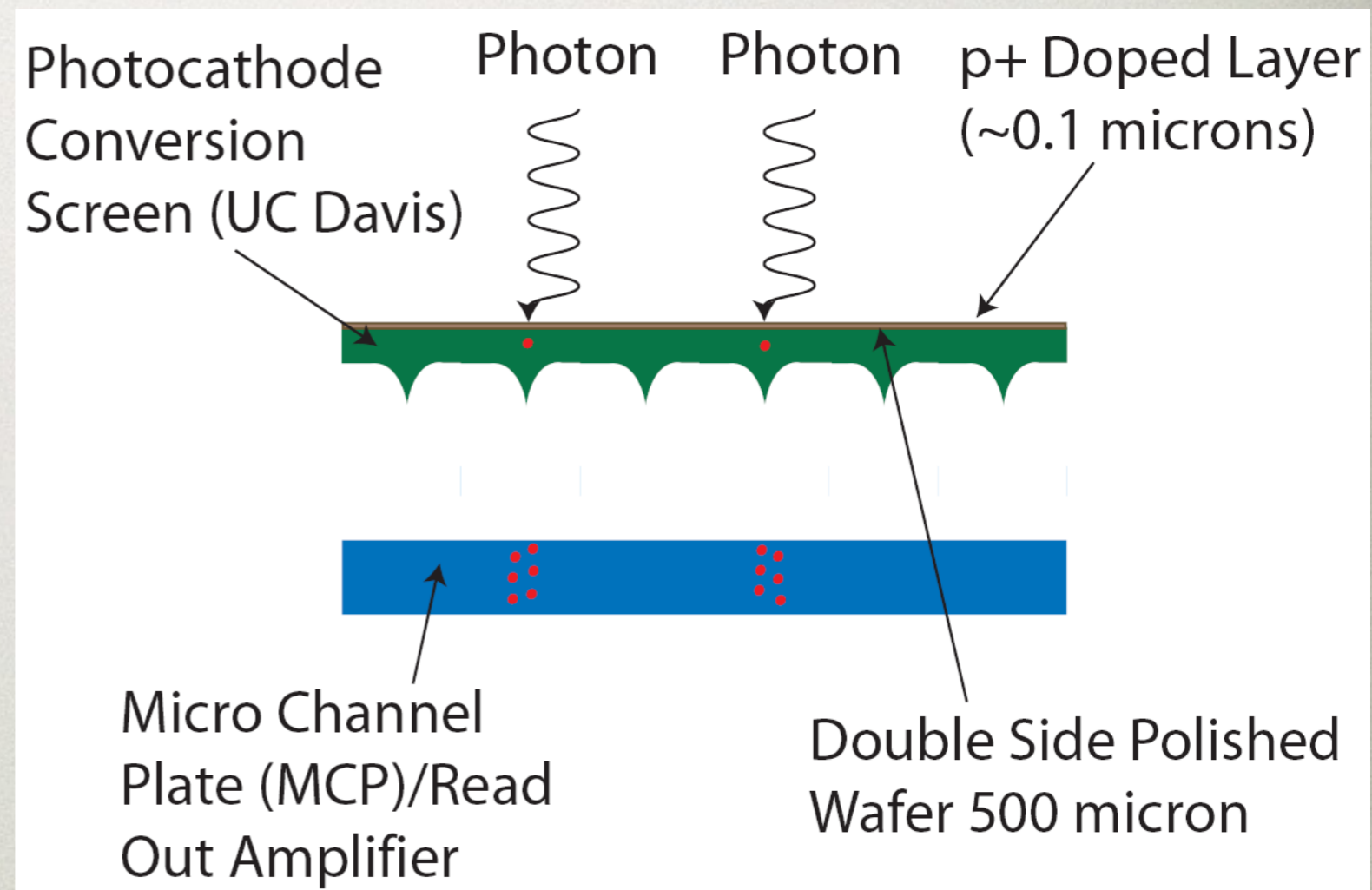

Figure 1: X-ray Imager and Energy Detector

…so stay tuned!

Summary

- Searches for sub-GeV DM and coherent neutrino scattering provide good, well recognized motivations to build a single-electron-threshold semiconductor calorimeter

- Extracted electrons can easily be detected with the desired sensitivity

- High fields necessary to emit conduction electrons from Si with ~100% efficiency can be produced with microscopic tip arrays.

- Such a detector would be easy to operate, using simple, mature technologies. Easy to reject/reduce many single-e backgrounds.