The ultimate ionization threshold in semiconductor detectors
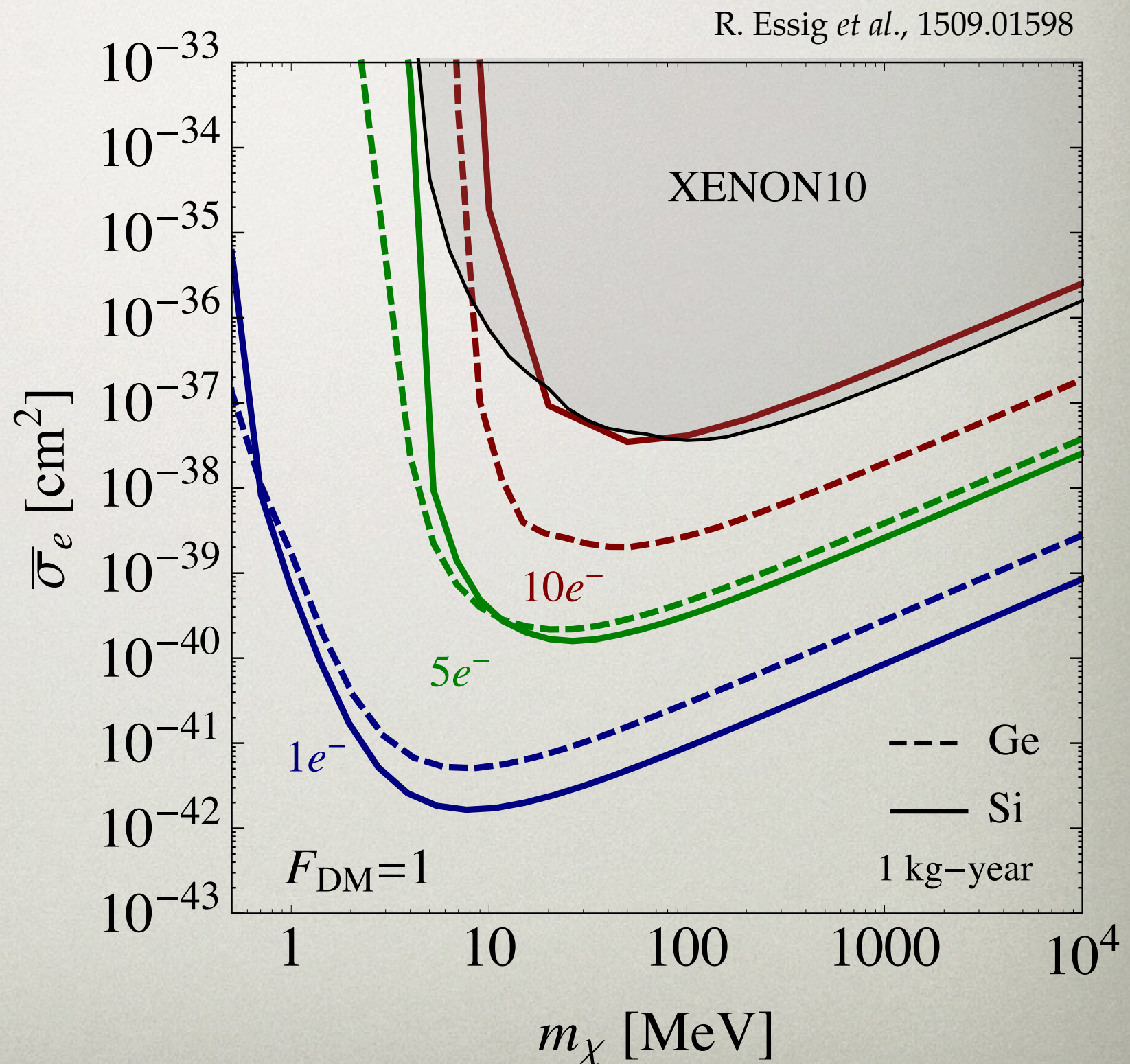
Aaron Manalaysay

UCDAVIS
UNIVERSITY OF CALIFORNIA

SLAC Workshop on Dark Sectors
29 April, 2016

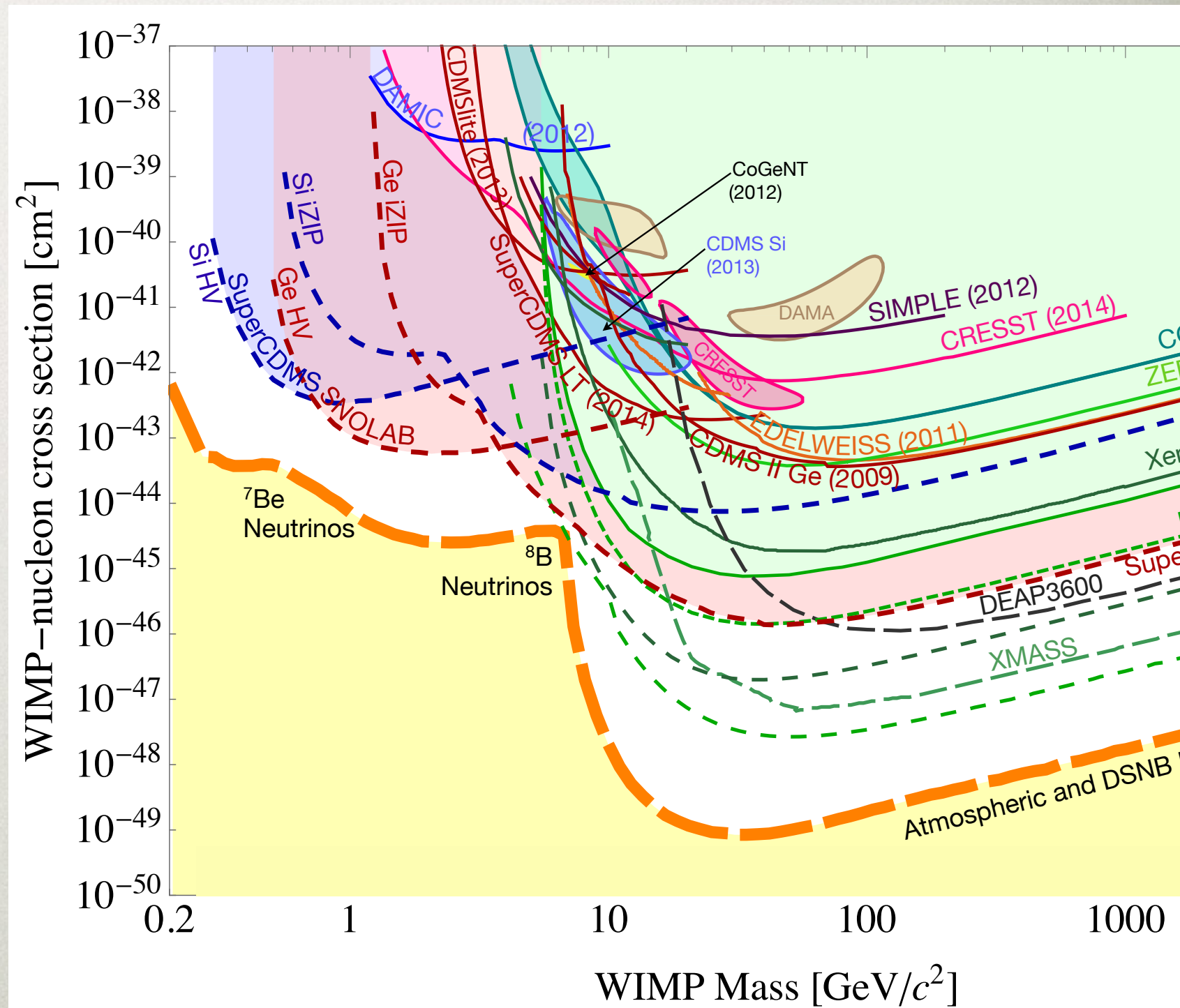# Low-threshold with semiconductors

- Strong motivation for future DM searches to push for semiconductors with <u>very</u> low ionization thresholds.

R. Essig *et al.*, 1509.01598

XENON10

$10e^-$

$5e^-$

$1e^-$

$F_{DM}=1$

1 kg−year

- - - Ge
——— Si

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

m_χ [MeV]
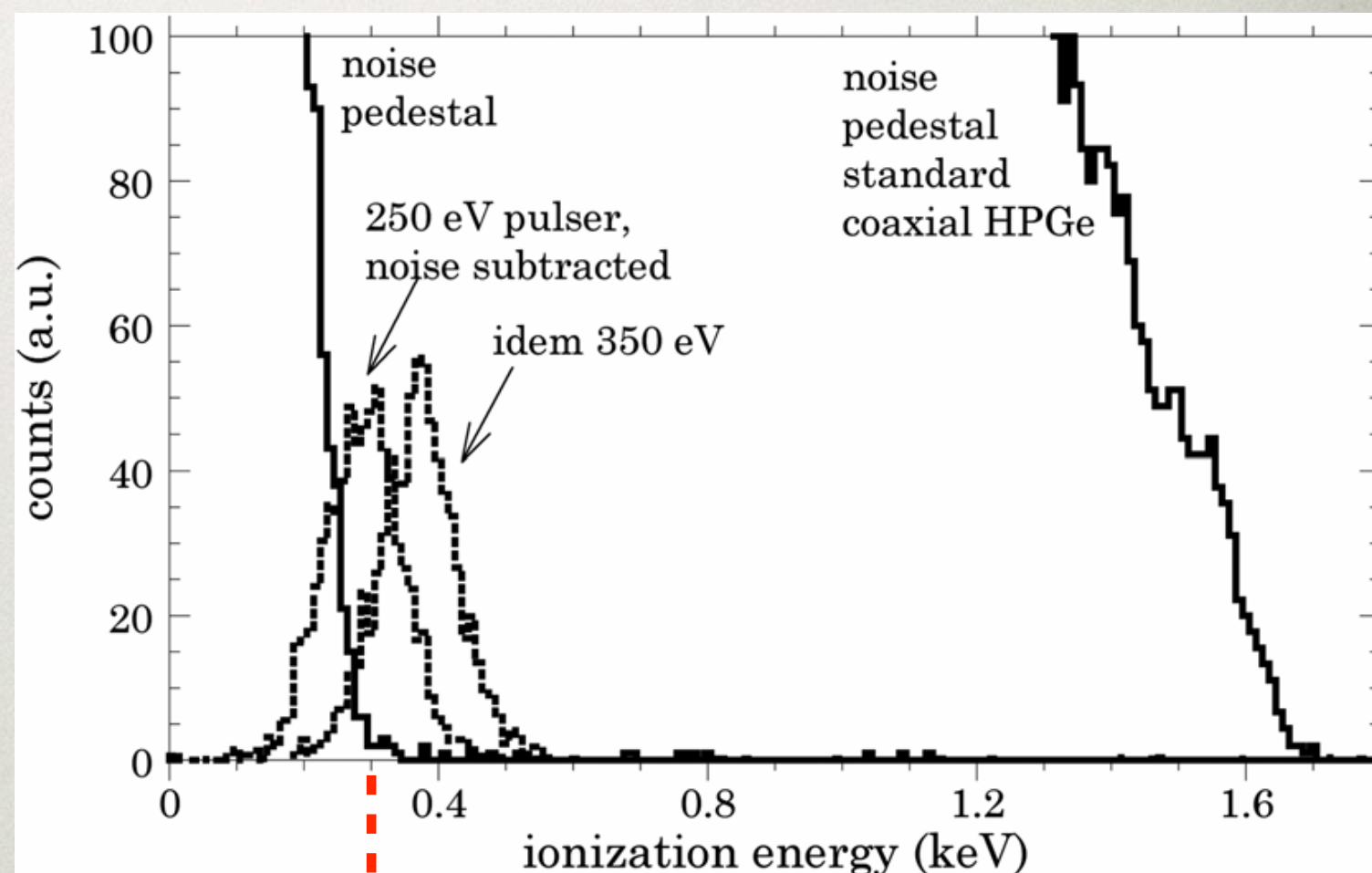
Lo... ...eshold SuperCDMS

- Indeed, SuperCDMS is taking the prospect for integer-electron counting very seriously.

Traditional charge readout

- Traditional charge readout in semiconductors, involving transistors and feedback, cannot approach thresholds of ~few electrons.

- Amplification is not the way to go.
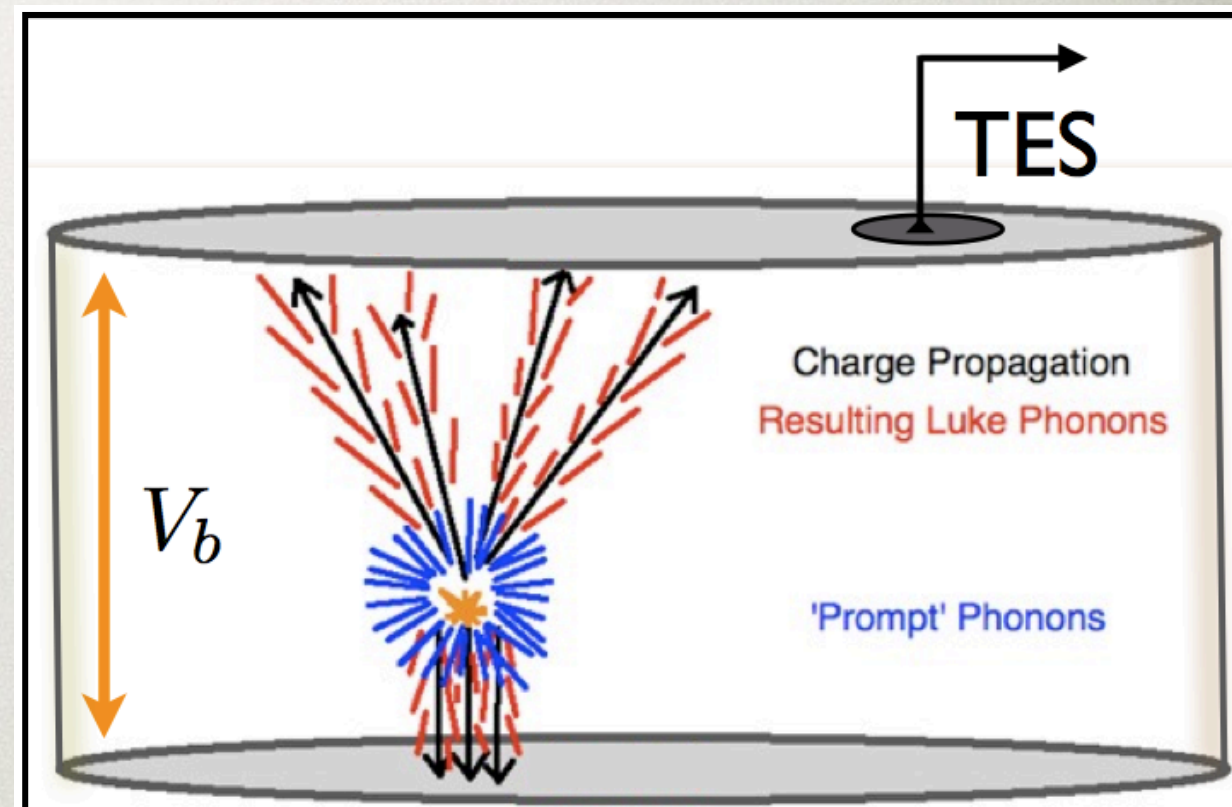
P.S.Barbeau, J.I.Collar, O.Trench, JCAP09 (2009)009

~100 e⁻

Paths to single-e⁻ sensitivity

- The CDMS approach involves using multiplication, instead of amplification.

- Drifting electrons each produce many phonons, which are detectable via TESs. Possibility to do n-γ discrimination.

- They are facing some hurdles to single-e⁻ sensitivity

  * Reducing noise requires reducing parasitic thermal power, which requires reducing T_c.

  * Observed noise scaling differs from ideal expectation ($\propto T_c^3$) —> the devil is in the details?

See next talk in this session by Lauren Hsu

From "Light Dark Matter at SuperCDMS" (J.Cooley, M.Pyle)
Beyond WIMPs (http://tomerv.wix.com/lightdm#!sessions/c3kh)

SuperC

TES

Charge Propagation
Resulting Luke Phonons

V_b

'Prompt' Phonons

"difficult" cryogenics

Luke energy scales as bias voltage and noise remains constant until breakdown

Paths to few-e⁻ sensitivity

- The DAMIC approach uses traditional CCDs

- Charge noise scales with the number of readouts, so they read out very infrequently (~8hr exposures)

- No timing information: one sees many tracks, reminiscent of emulsion or bubble chambers.

- Difficult to scale up in mass

- Noise floor limits sensitivity to ~10e⁻ threshold.

"Light DM at DAMIC" (J.Tiffenberg)
Beyond WIMPs (http://tomerv.wix.com/lightdm#!sessions/c3kh)

Energy resolution from X-ray lines

$Var(E) / keV^2$

10^{-2}

10^{-3}

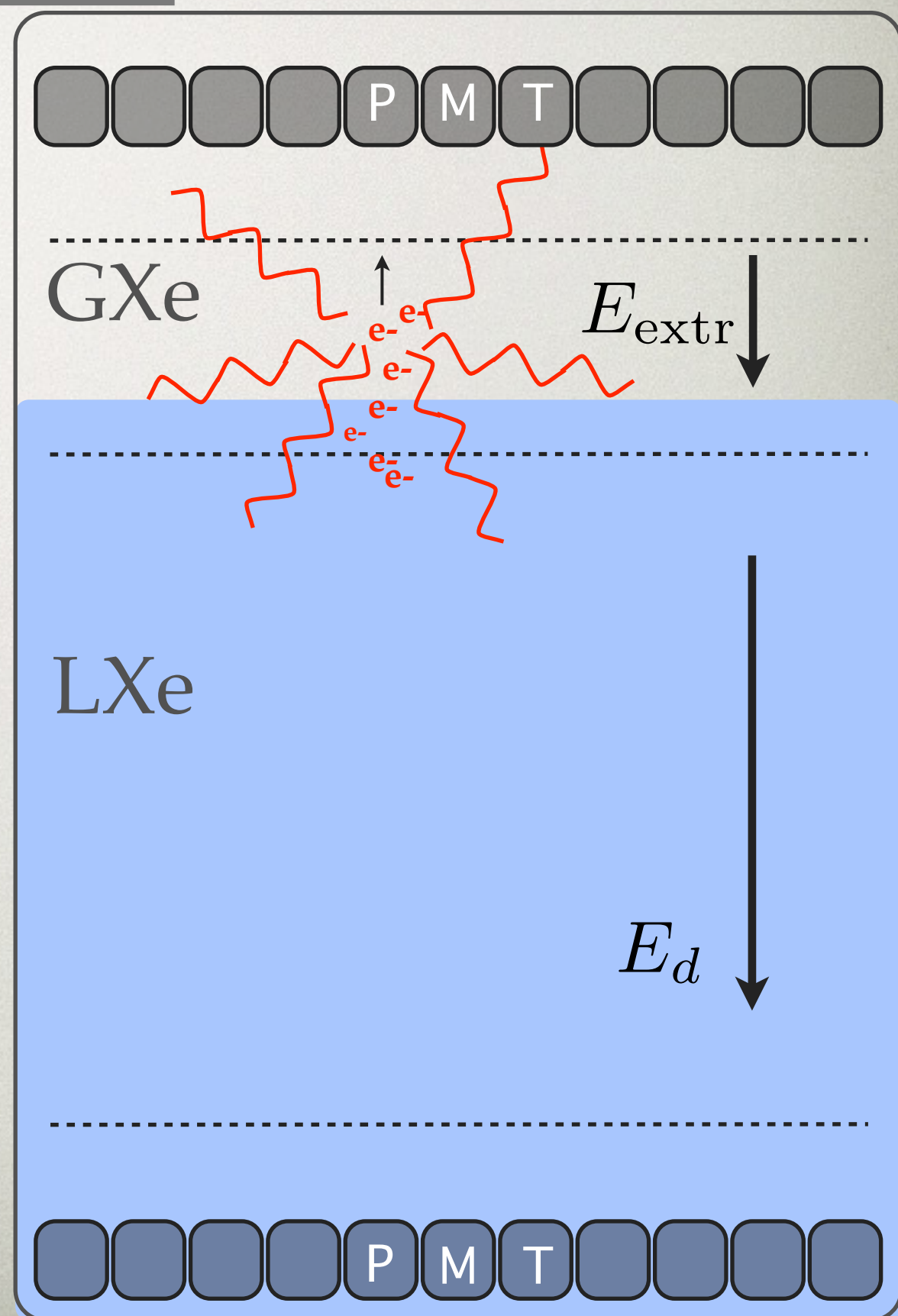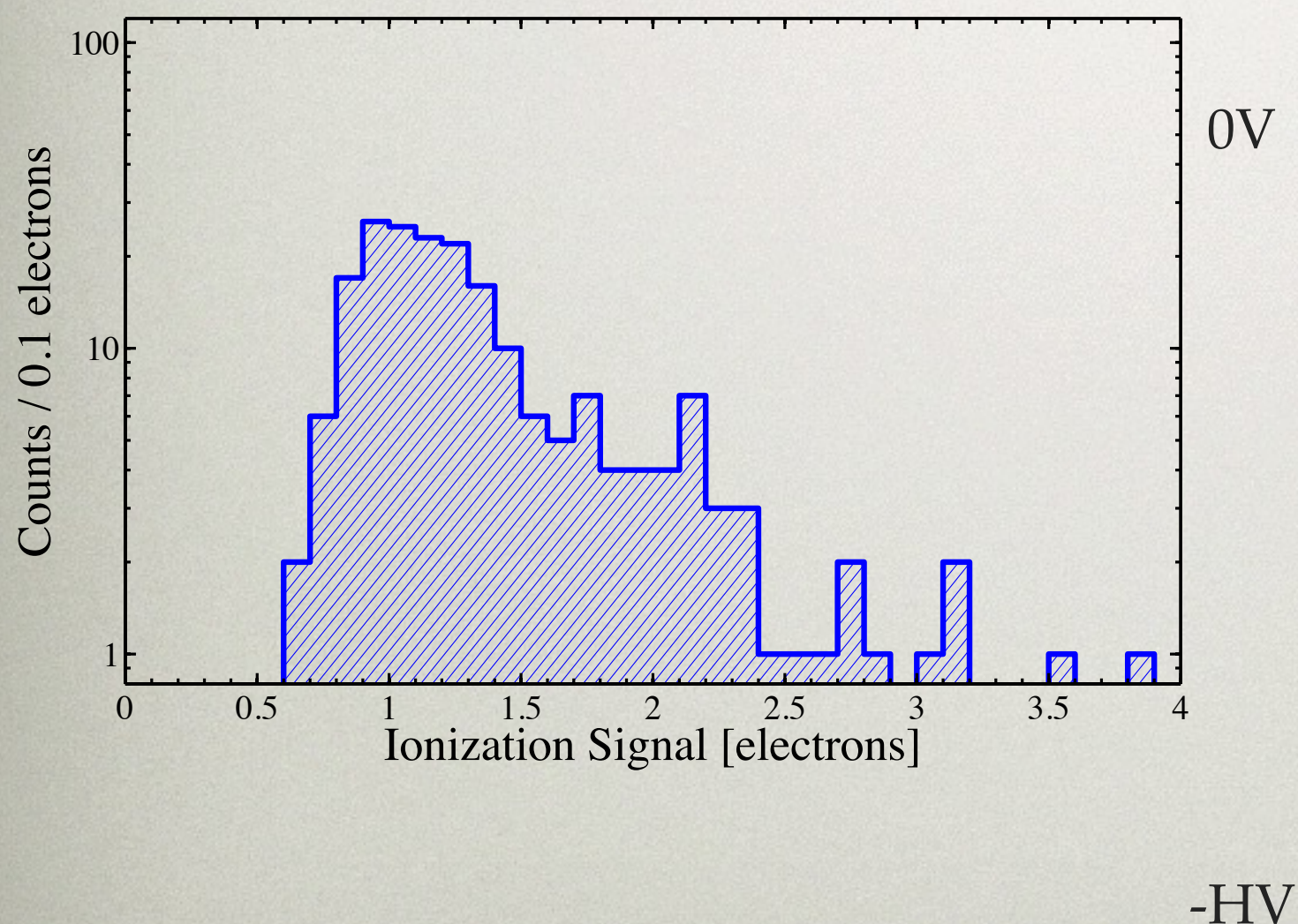Fano = 0.16

30eV noise

1

10
Energy / keV
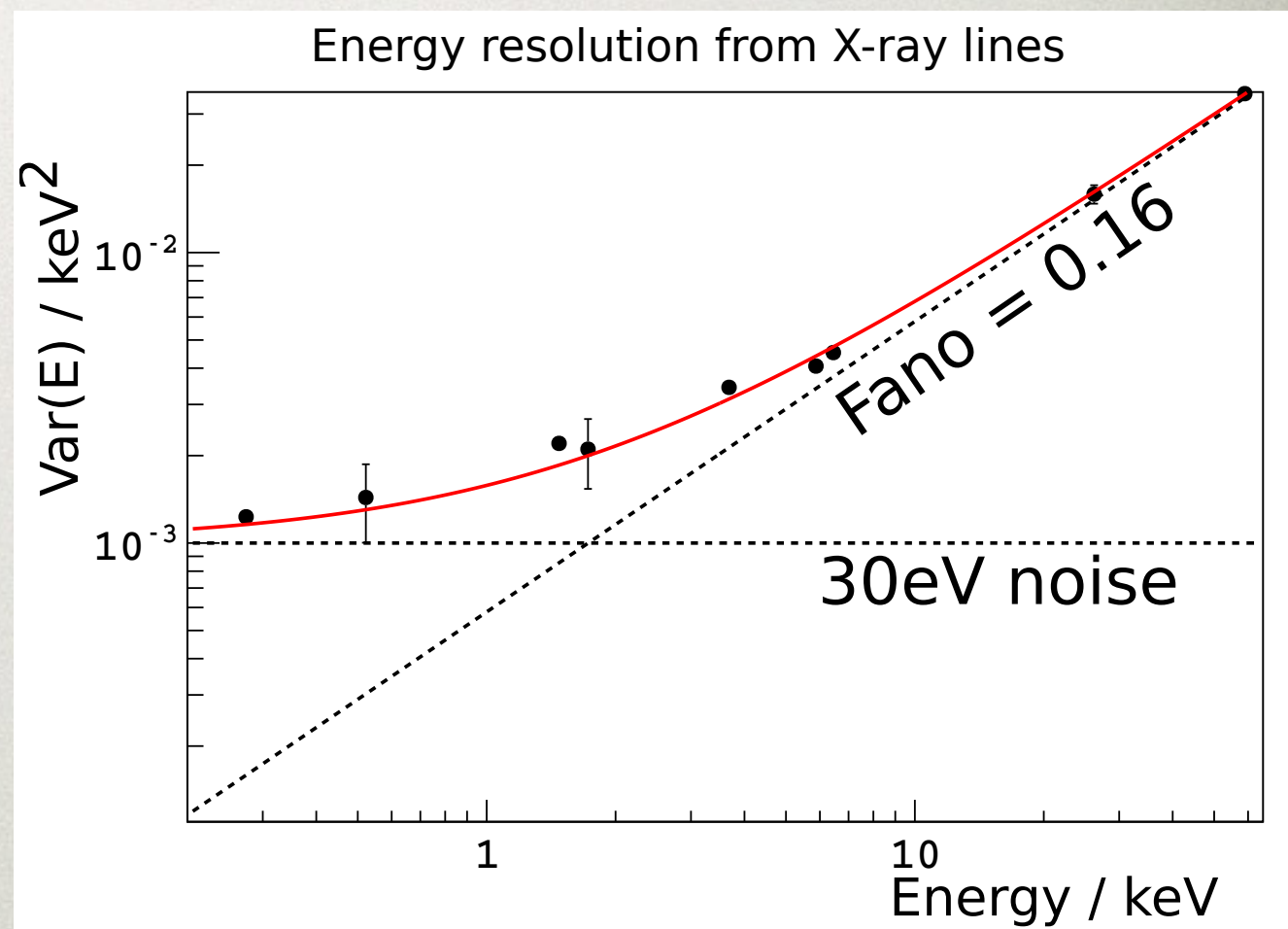
easy cryogenics

See talk by Juan Estrada

Single-e in noble liquids

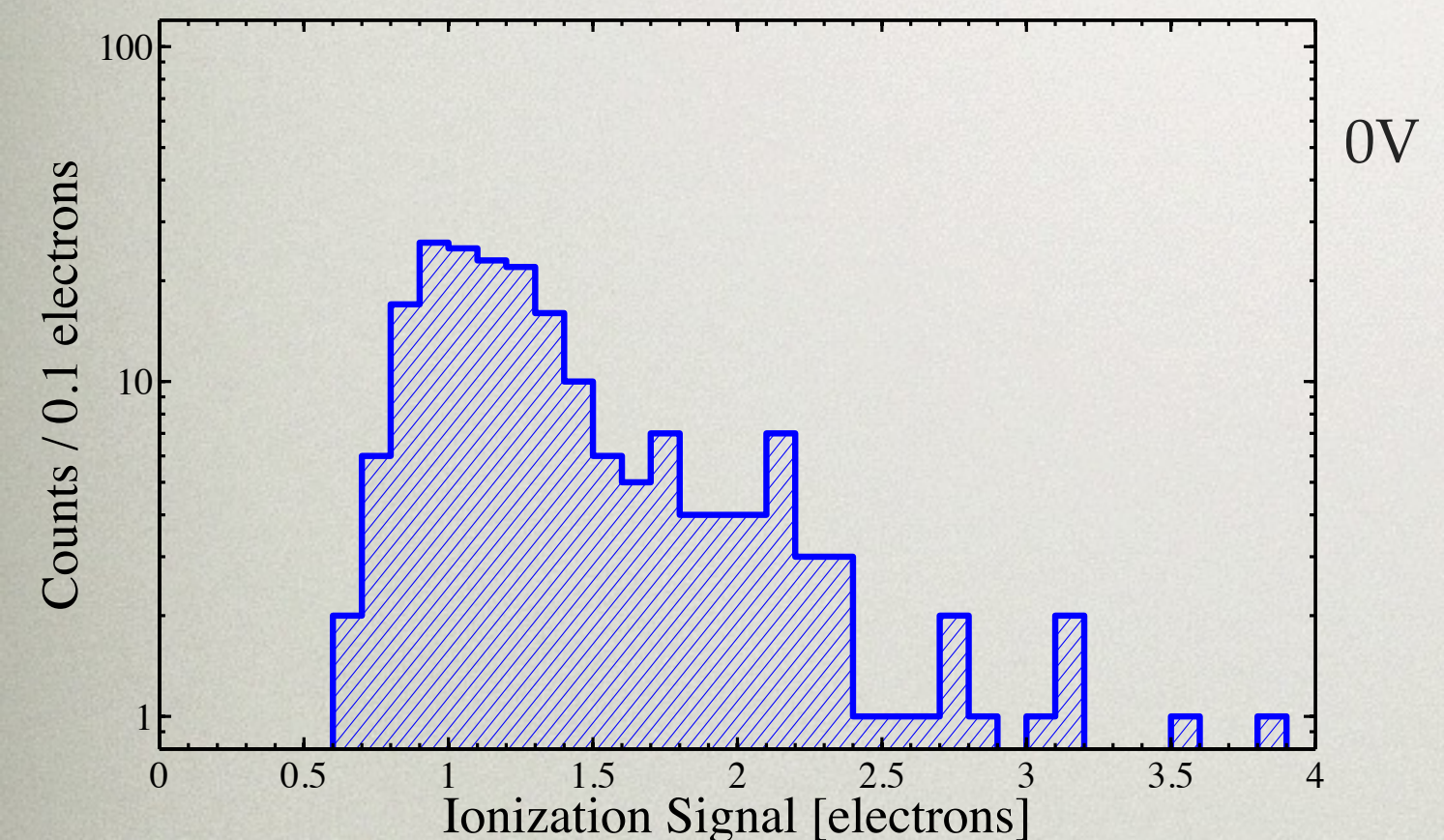Electron extraction works well for LXe and LAr:
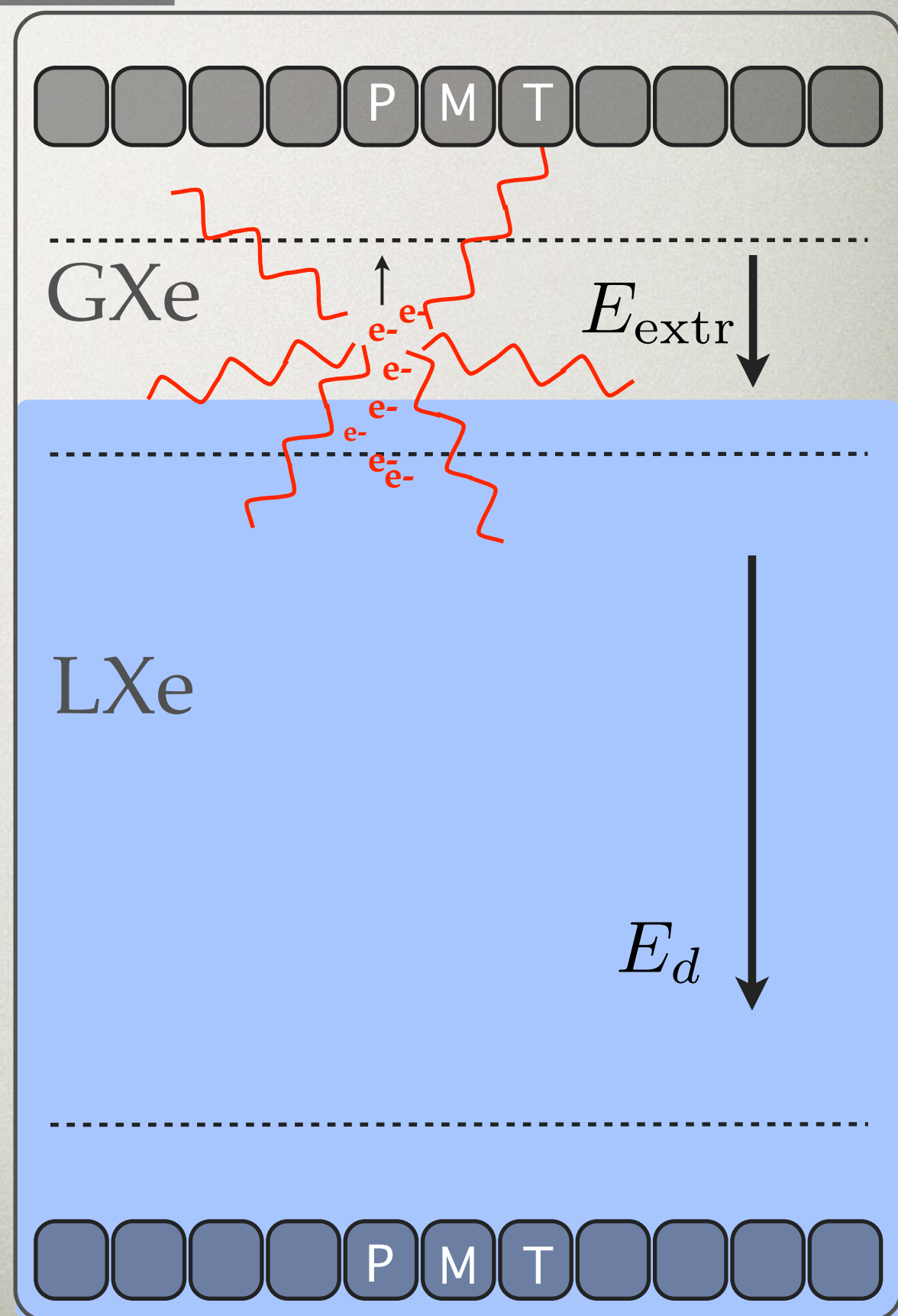*get the electrons out, then multiply them*

Single-e in noble liquids

Electron extraction works well for LXe and LAr:
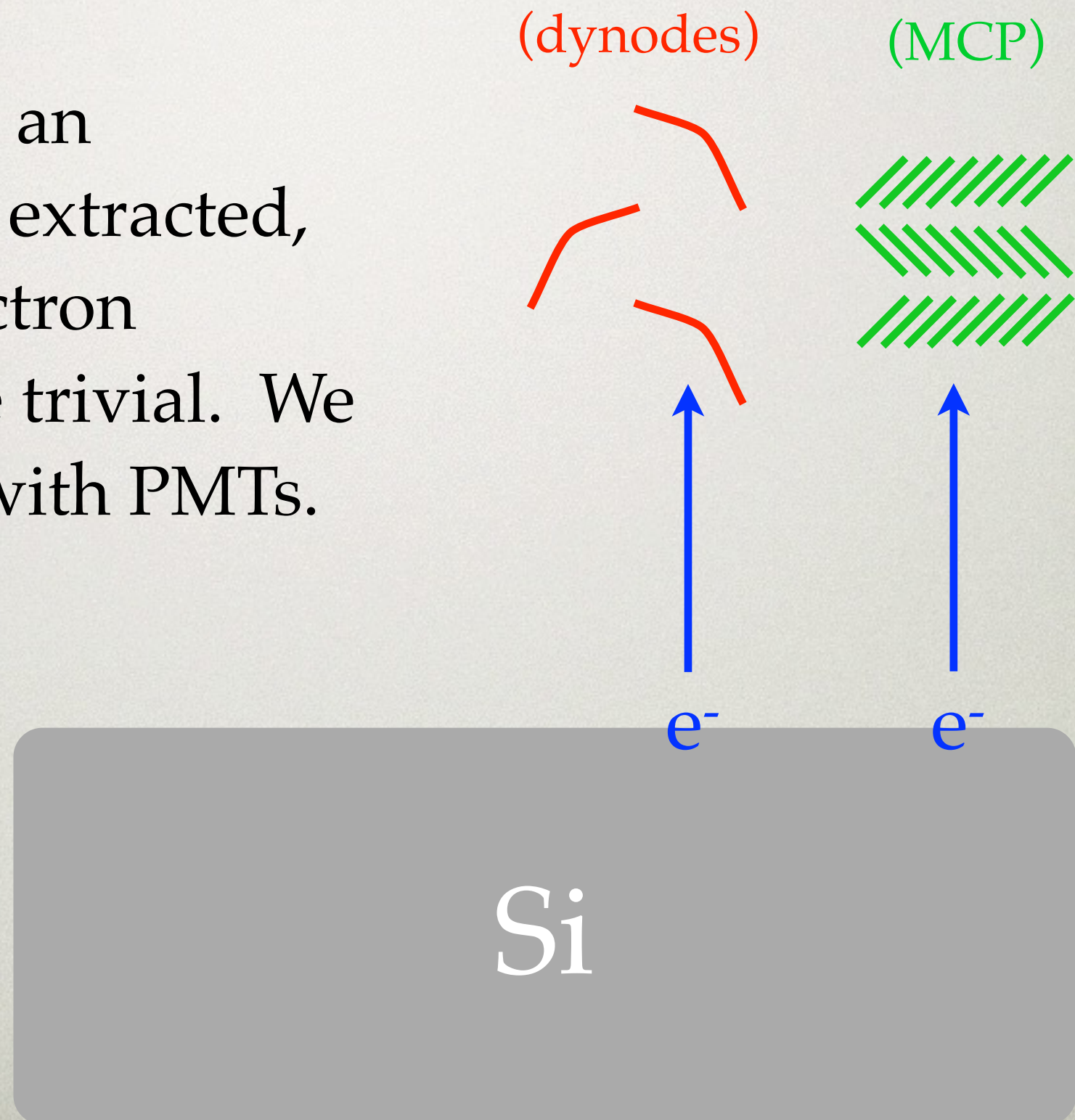*get the electrons out, then multiply them*

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

PMT without the P

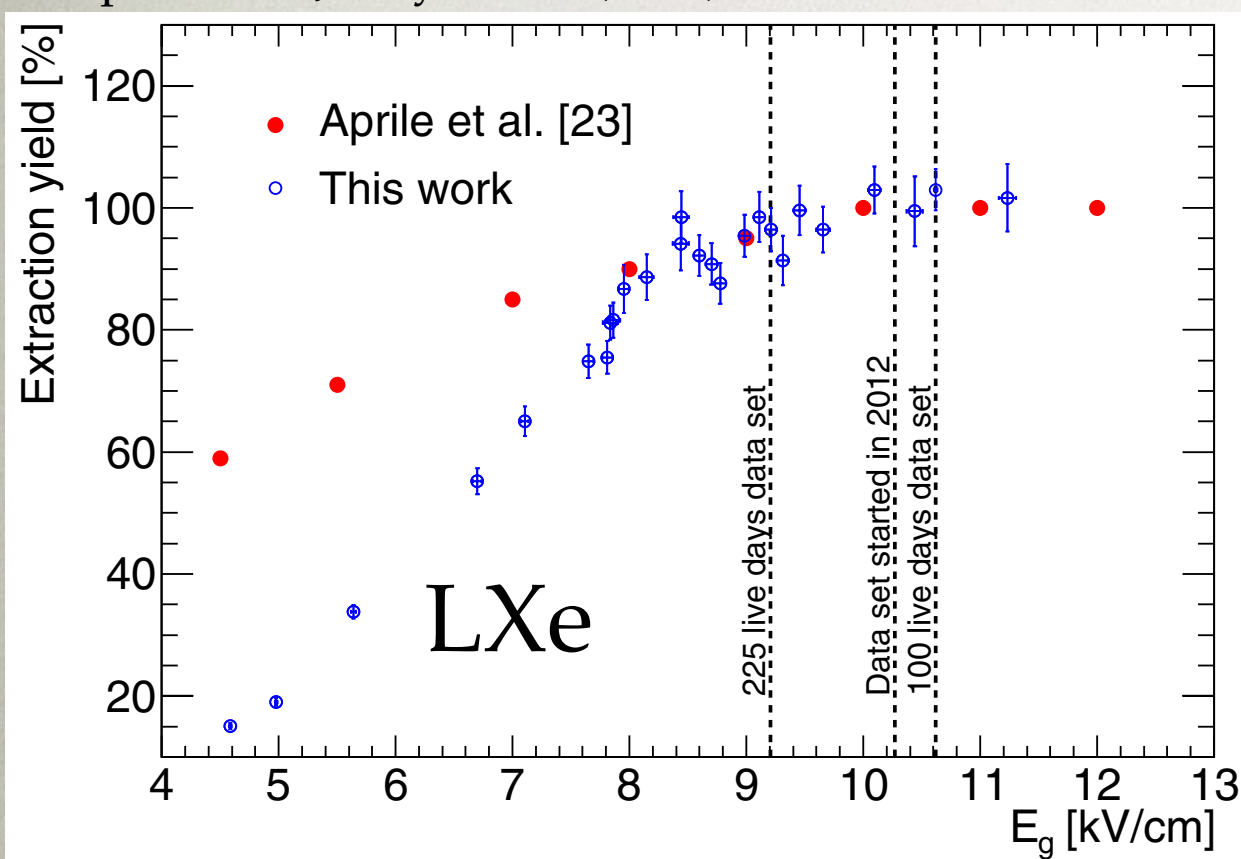If the electrons from an interaction could be extracted, obtaining single electron sensitivity would be trivial. We do this all the time with PMTs.
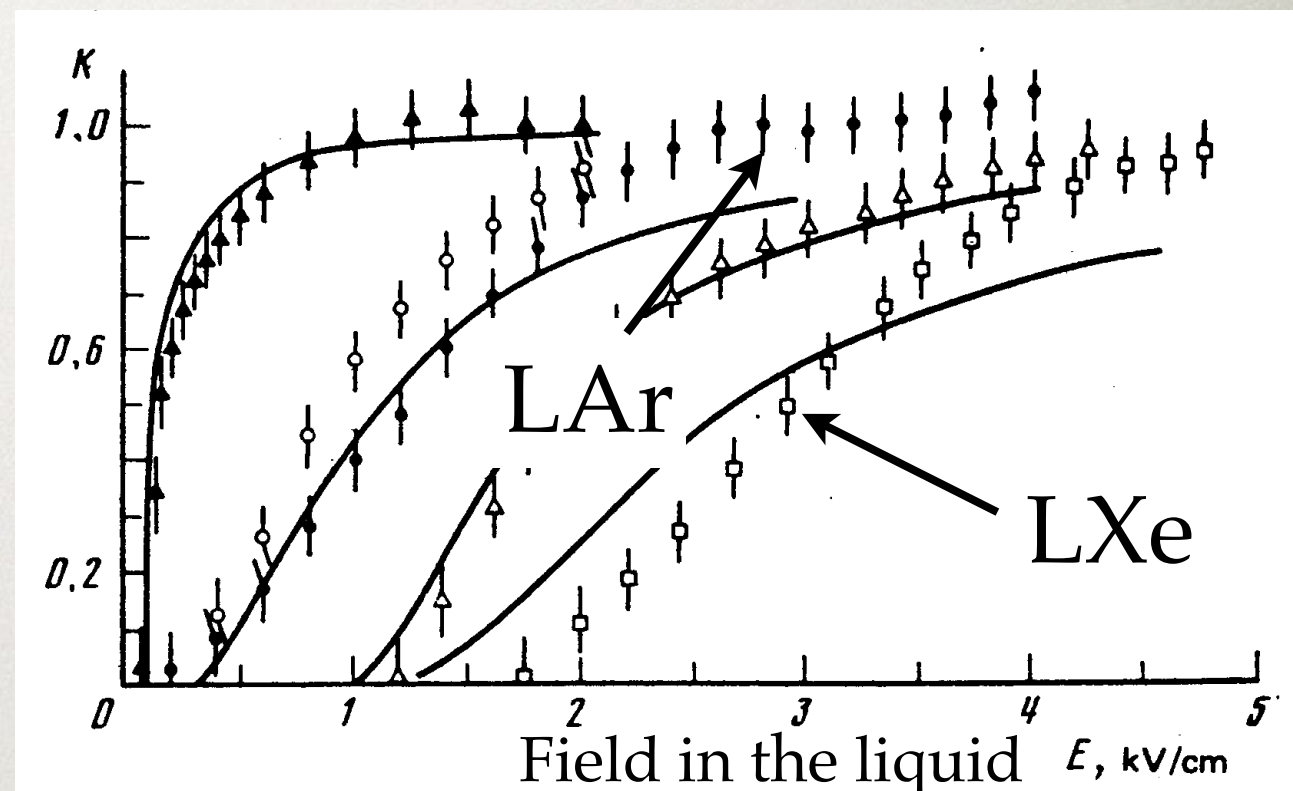
(dynodes)

(MCP)

e⁻

e⁻

Si

But I'm avoiding the question: How?

Extraction efficiency

E. Aprile *et al.* J. Phys. G **41** (2014) 035201

E.M.Gushchin *et al.*, Sov. Phys. JETP **55** (1982) 860

Different measurements support the same picture:

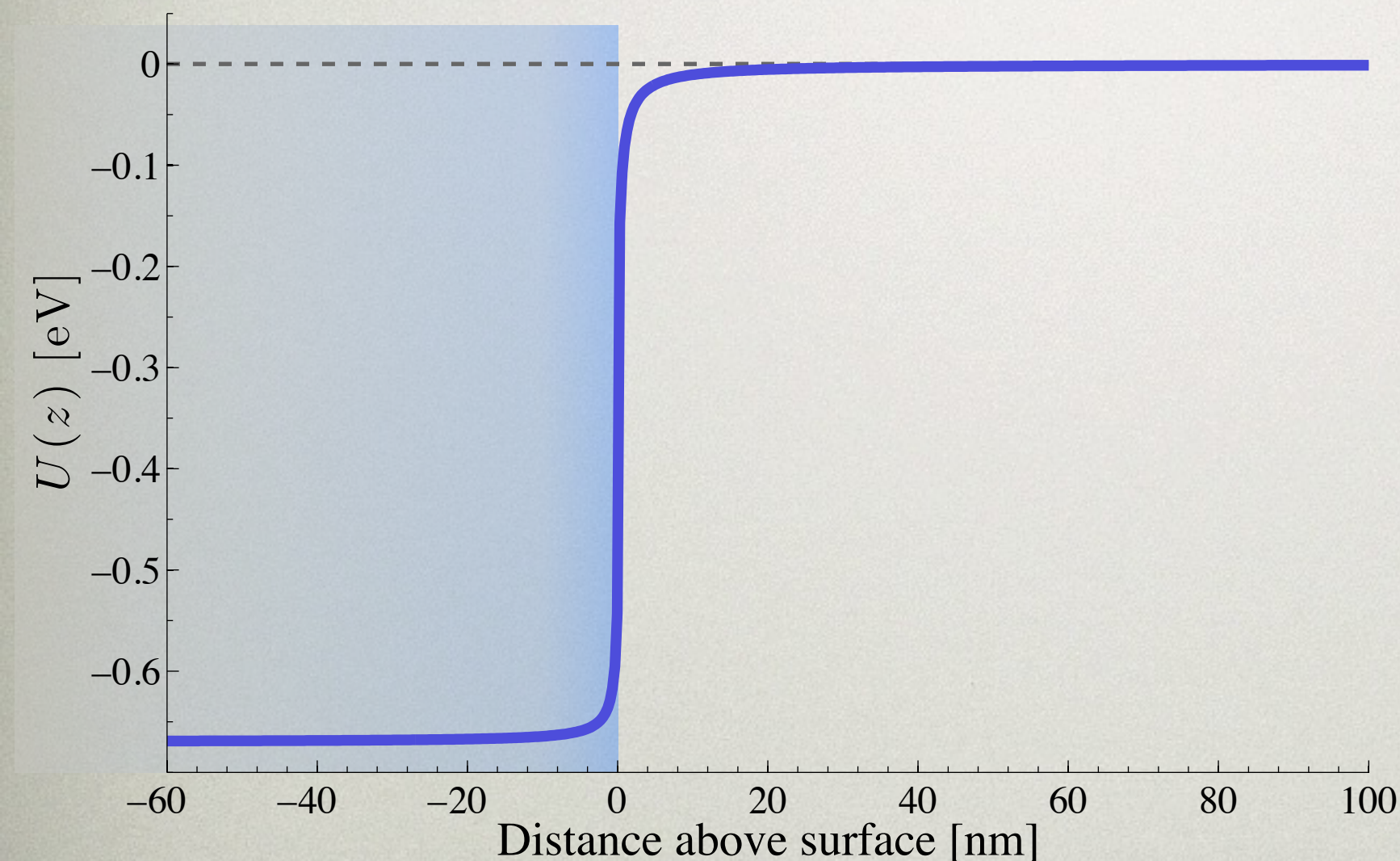LXe: 100% efficiency for electron extraction at ~10 kV/cm (in the gas)

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:

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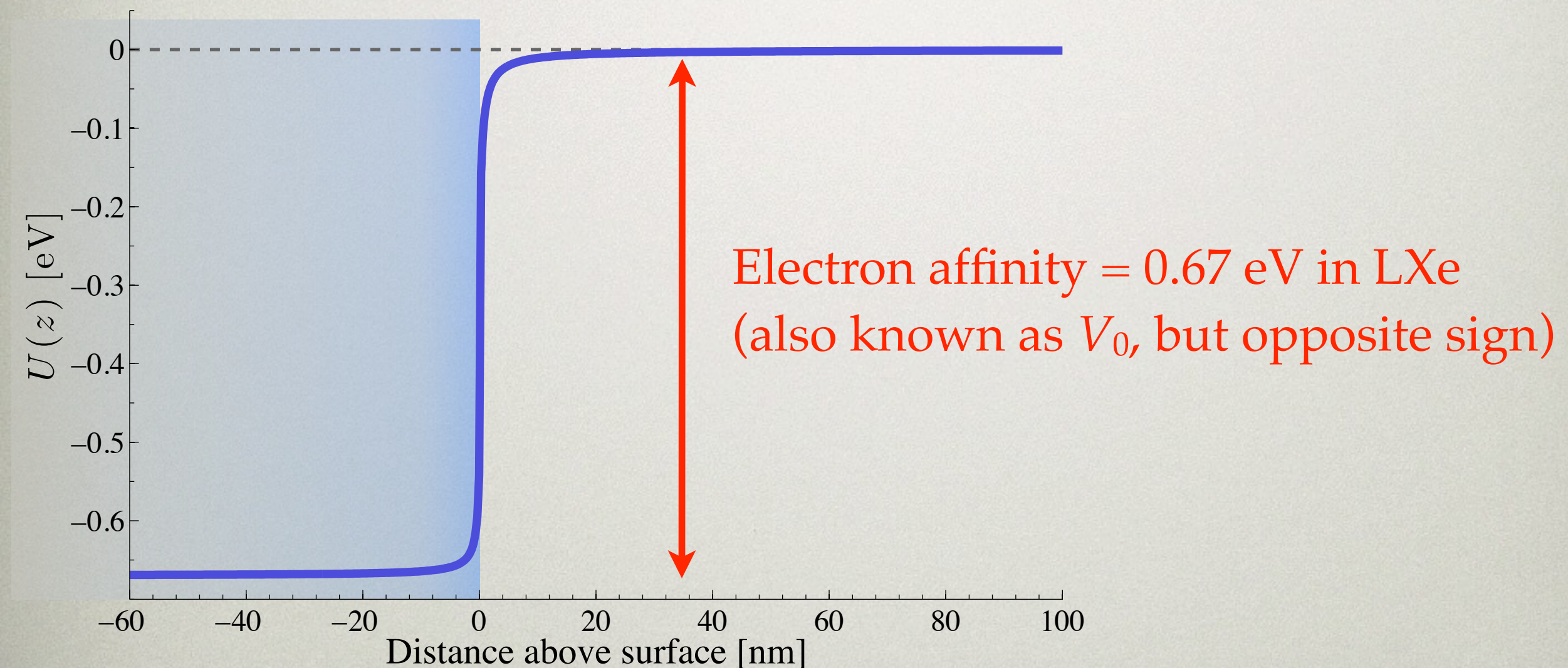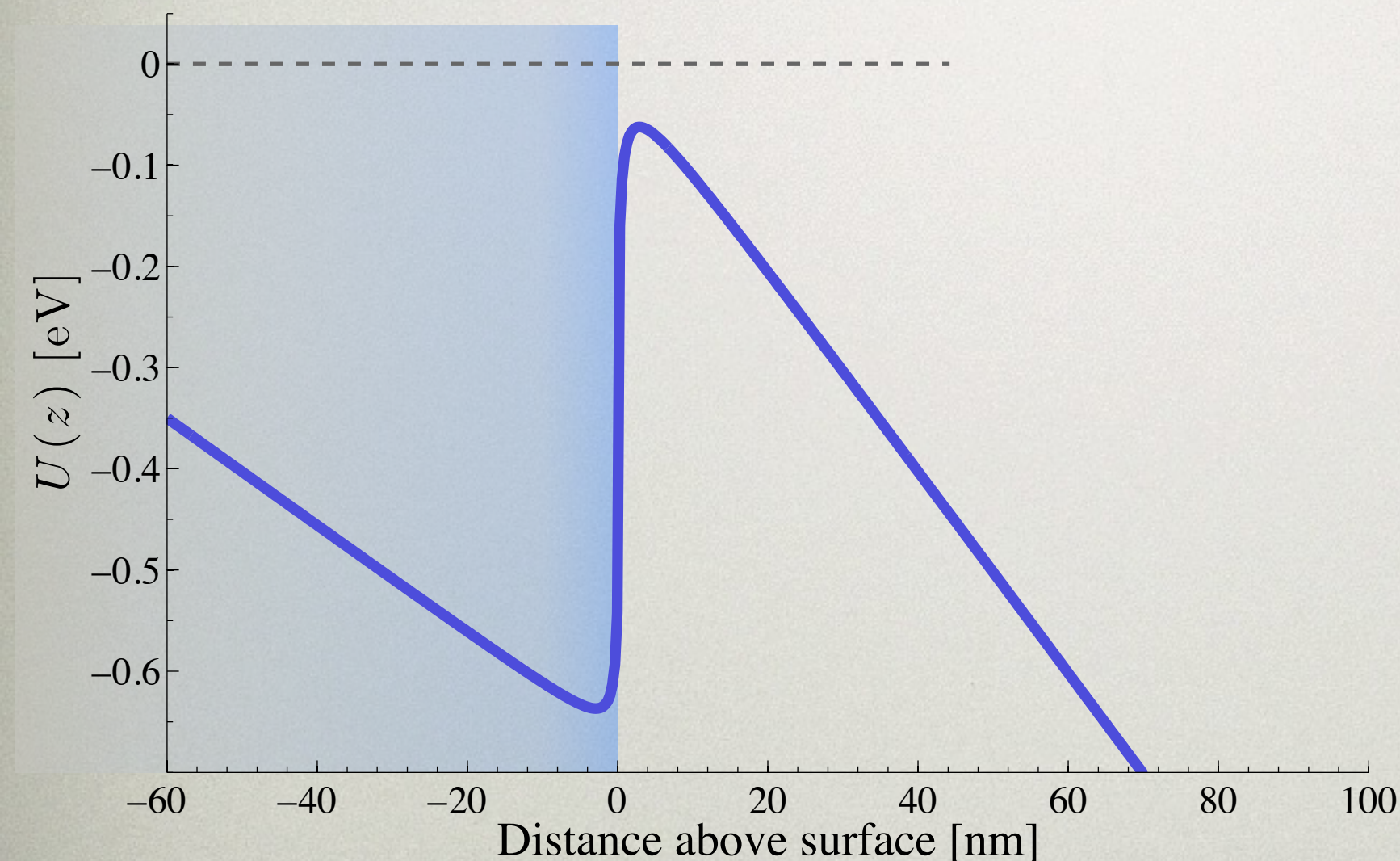

Electron affinity = 0.67 eV in LXe
(also known as V_0, but opposite sign)

(no field)

see e.g.: A.I. Bolozdynya, NIM **A422** (1999) 314

Understanding extraction in LXe

Electron potential energy:

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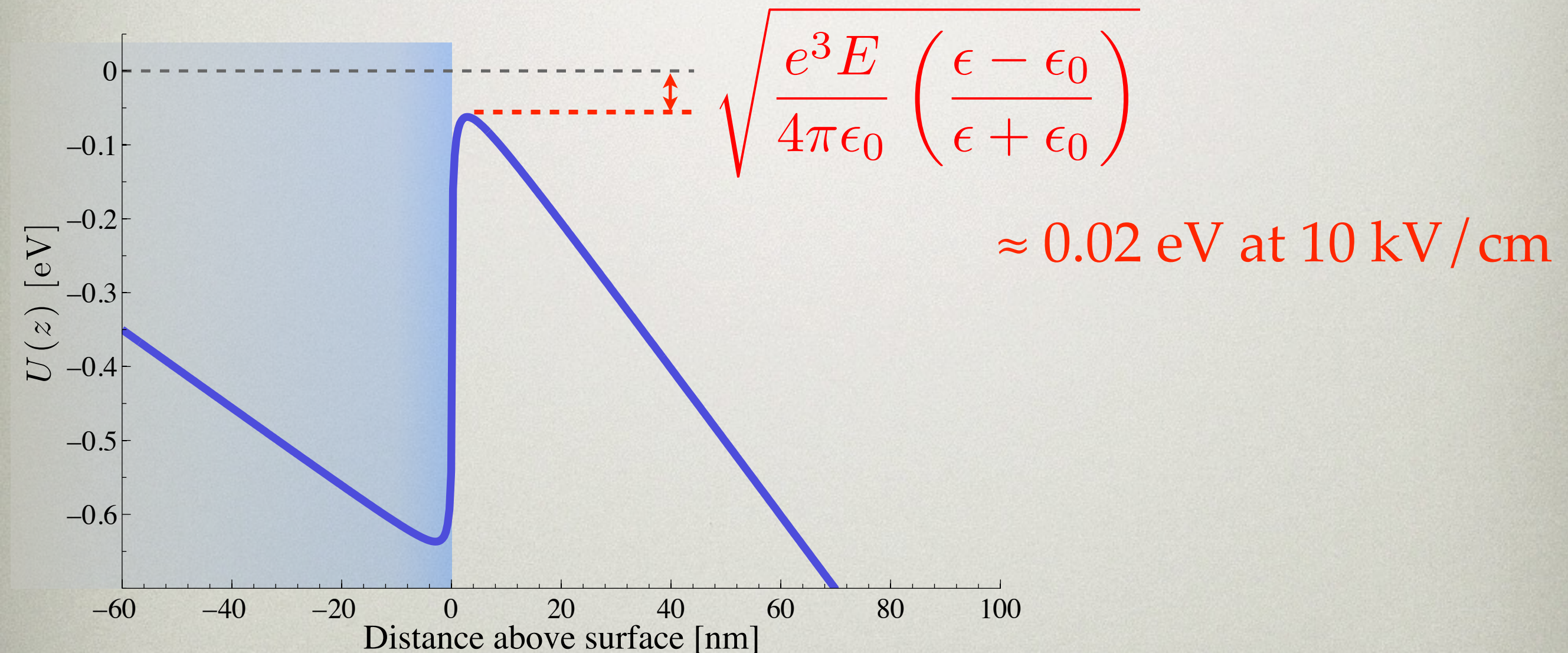

(with field)

Understanding extraction in LXe

Electron potential energy:

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

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

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

(with field)

Understanding extraction in LXe

Electron potential energy:

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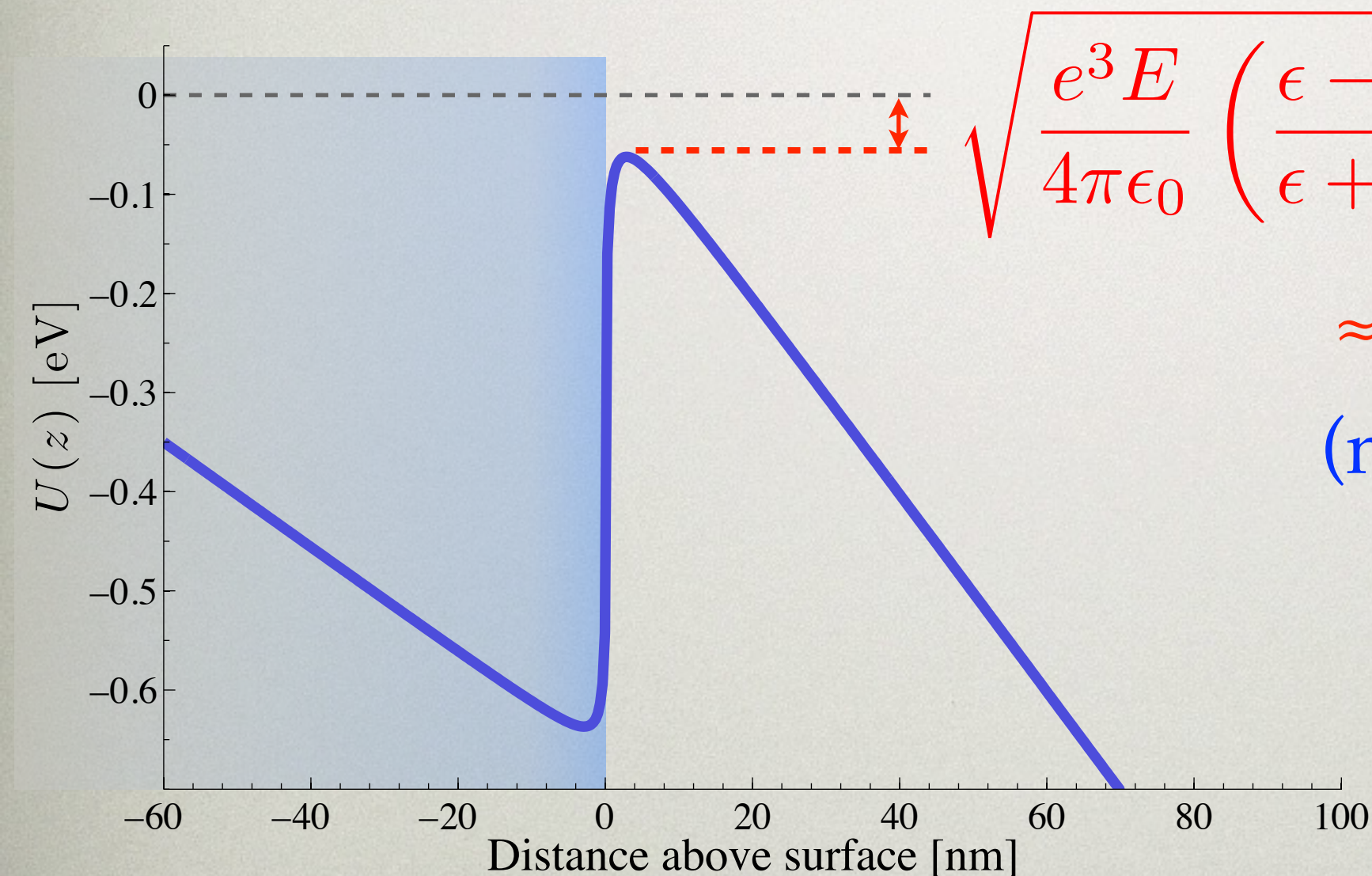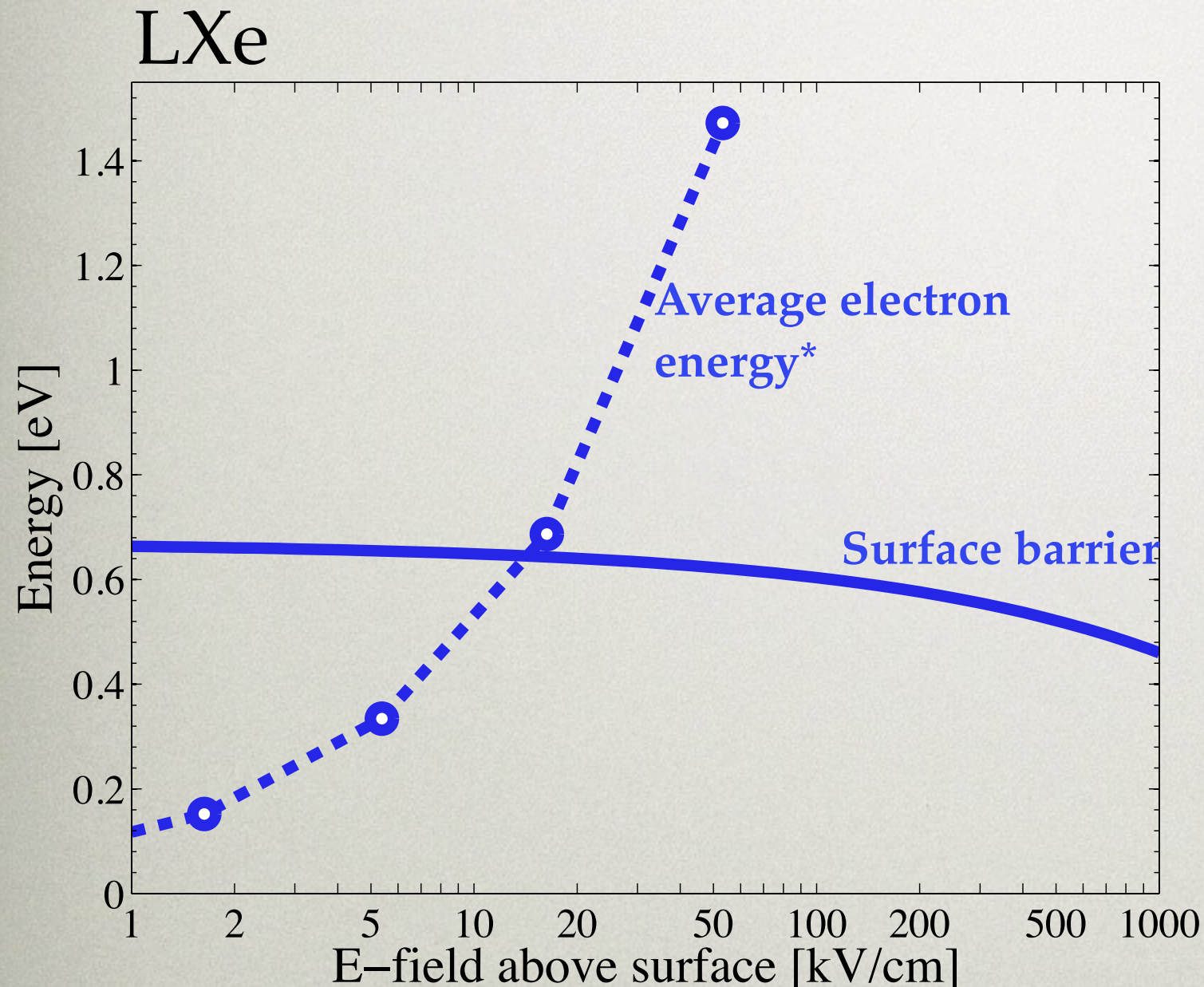
$$\sqrt{\frac{e^3 E}{4\pi\epsilon_0} \left(\frac{\epsilon - \epsilon_0}{\epsilon + \epsilon_0} \right)}$$

≈ 0.02 eV at 10 kV/cm

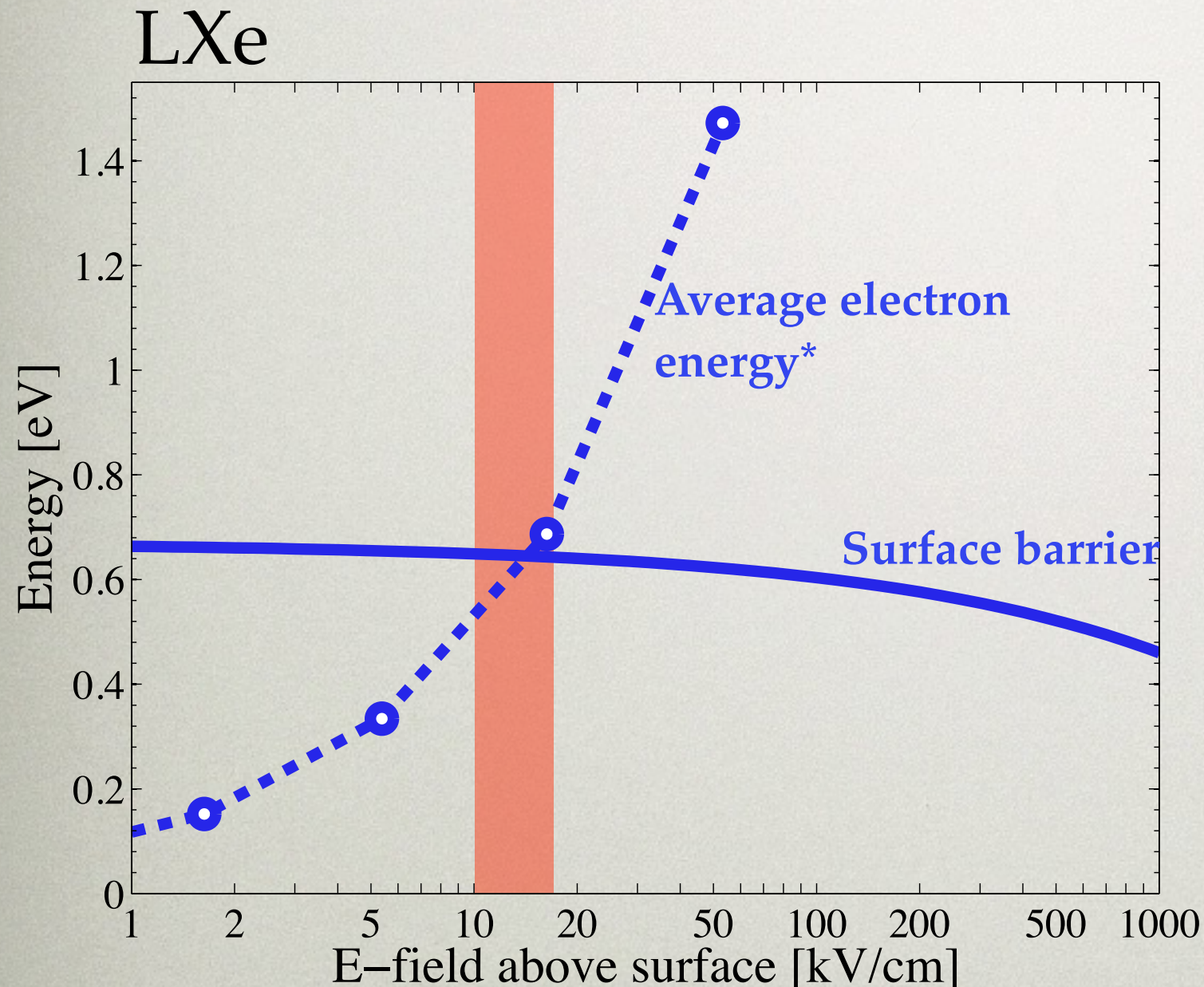(not enough to explain 100% extraction...)

(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

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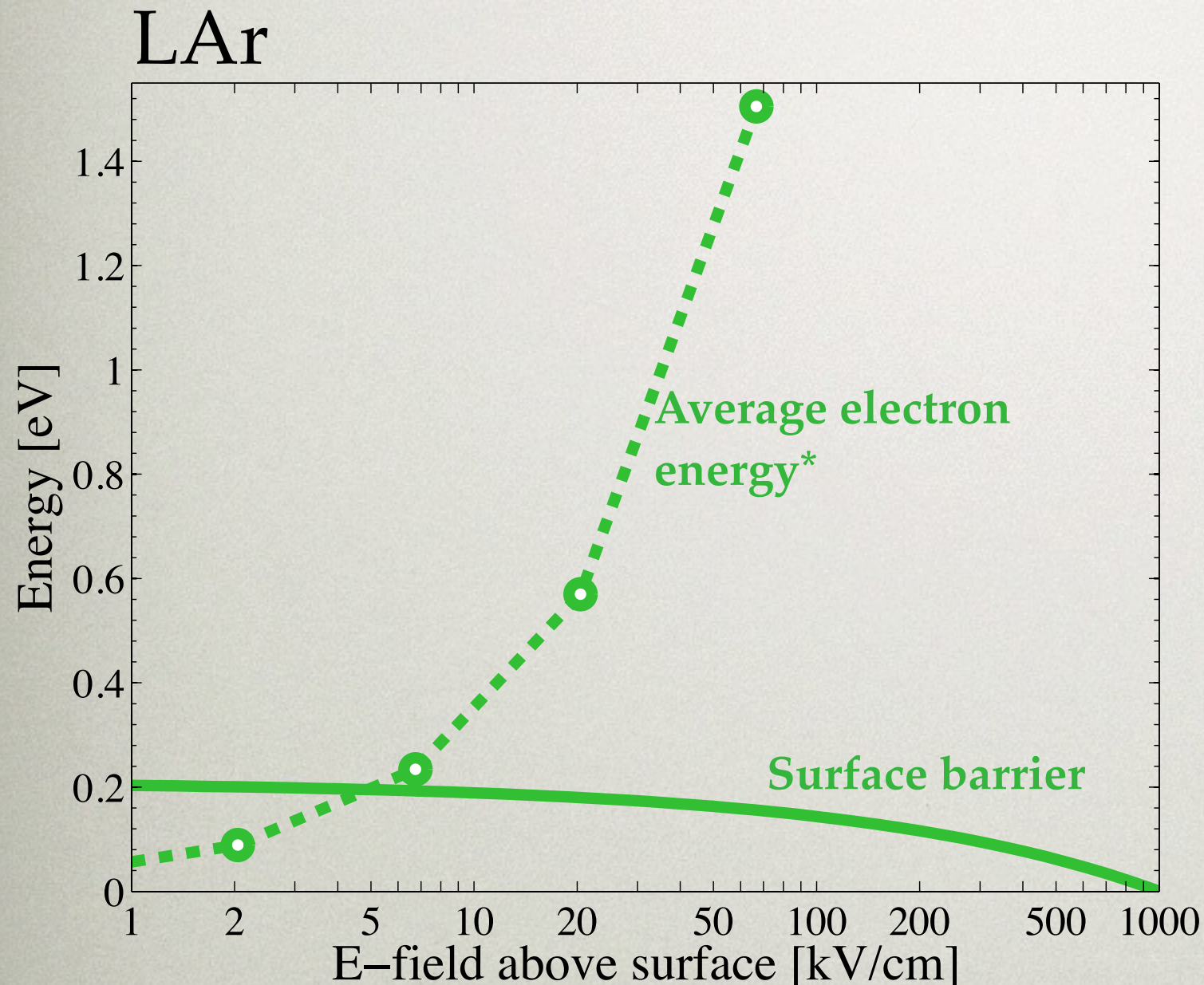*U. Sowada *et al.*, Chem. Phys. Lett. **34** (1975) 466

Electron heating

LAr

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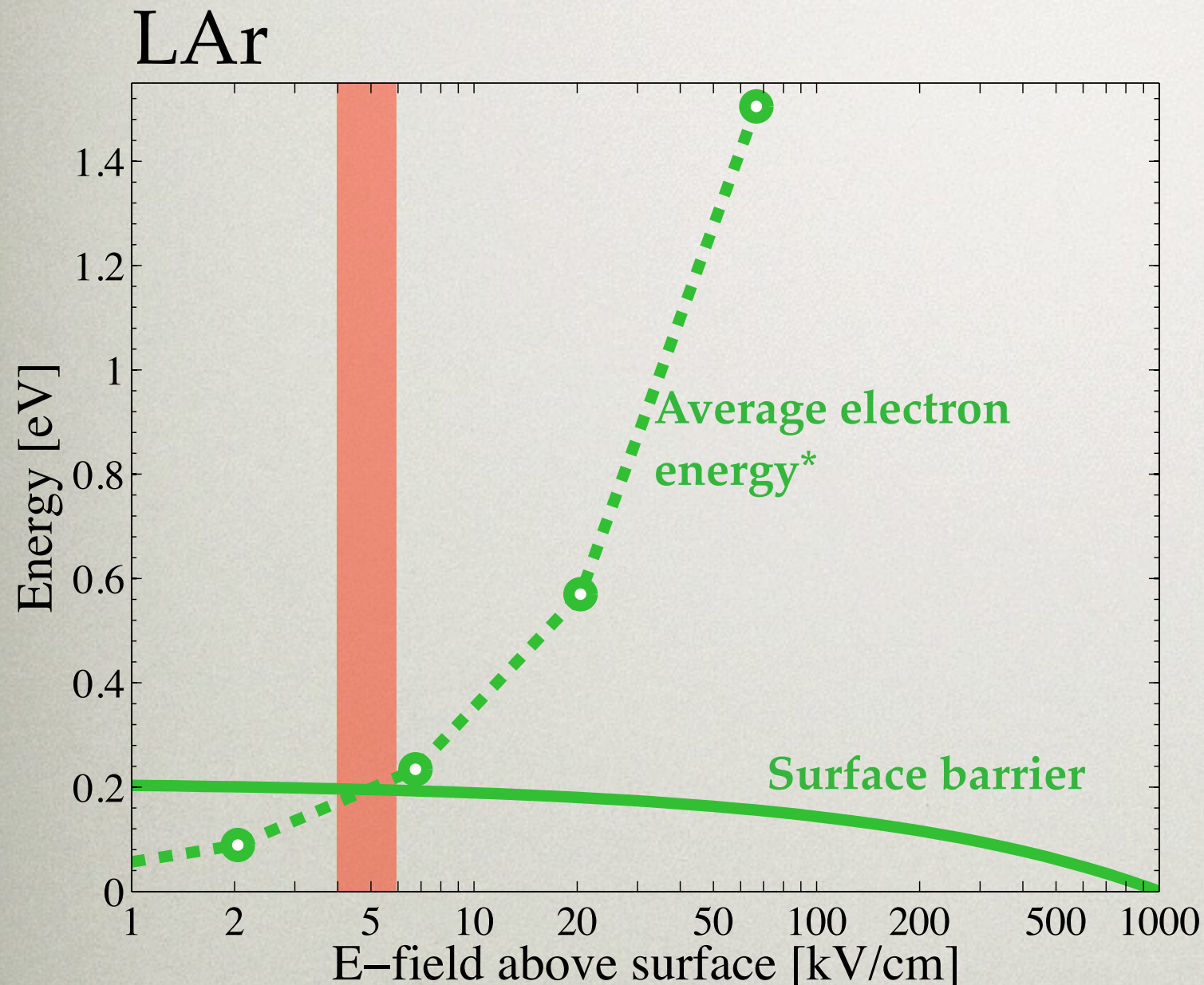*U. Sowada *et al.*, Chem. Phys. Lett. **34** (1975) 466

Electron heating

LAr

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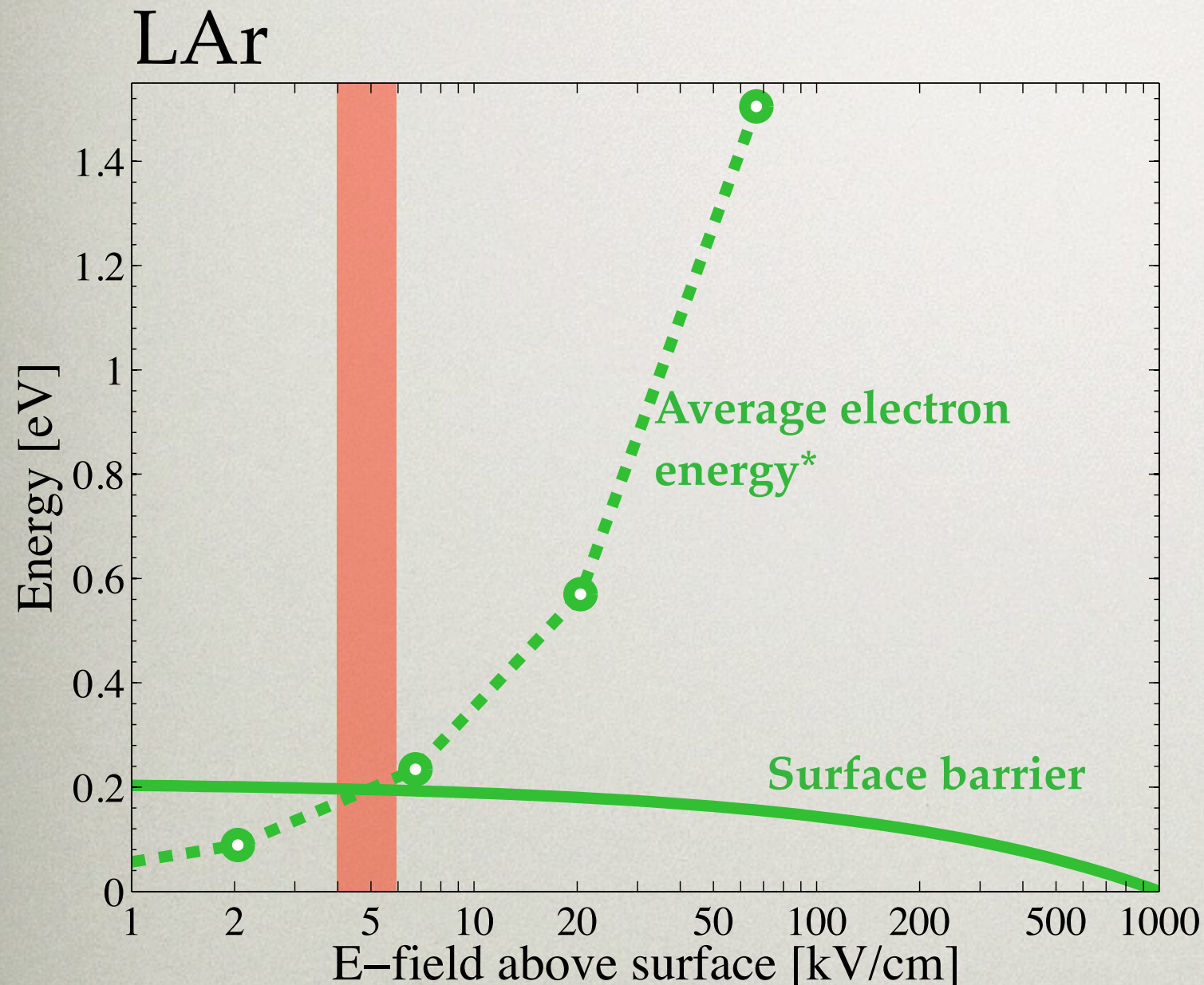*U. Sowada *et al.*, Chem. Phys. Lett. **34** (1975) 466
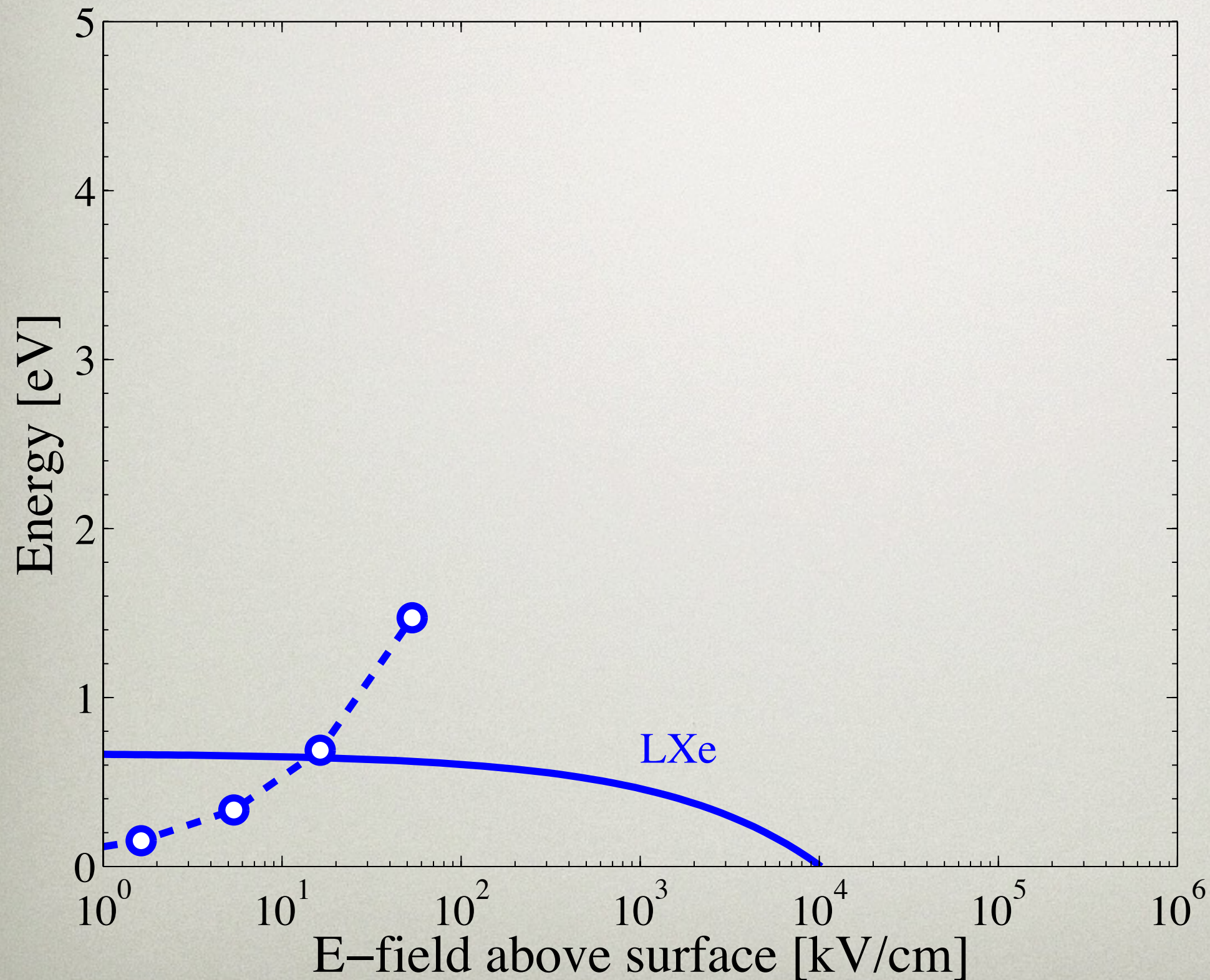
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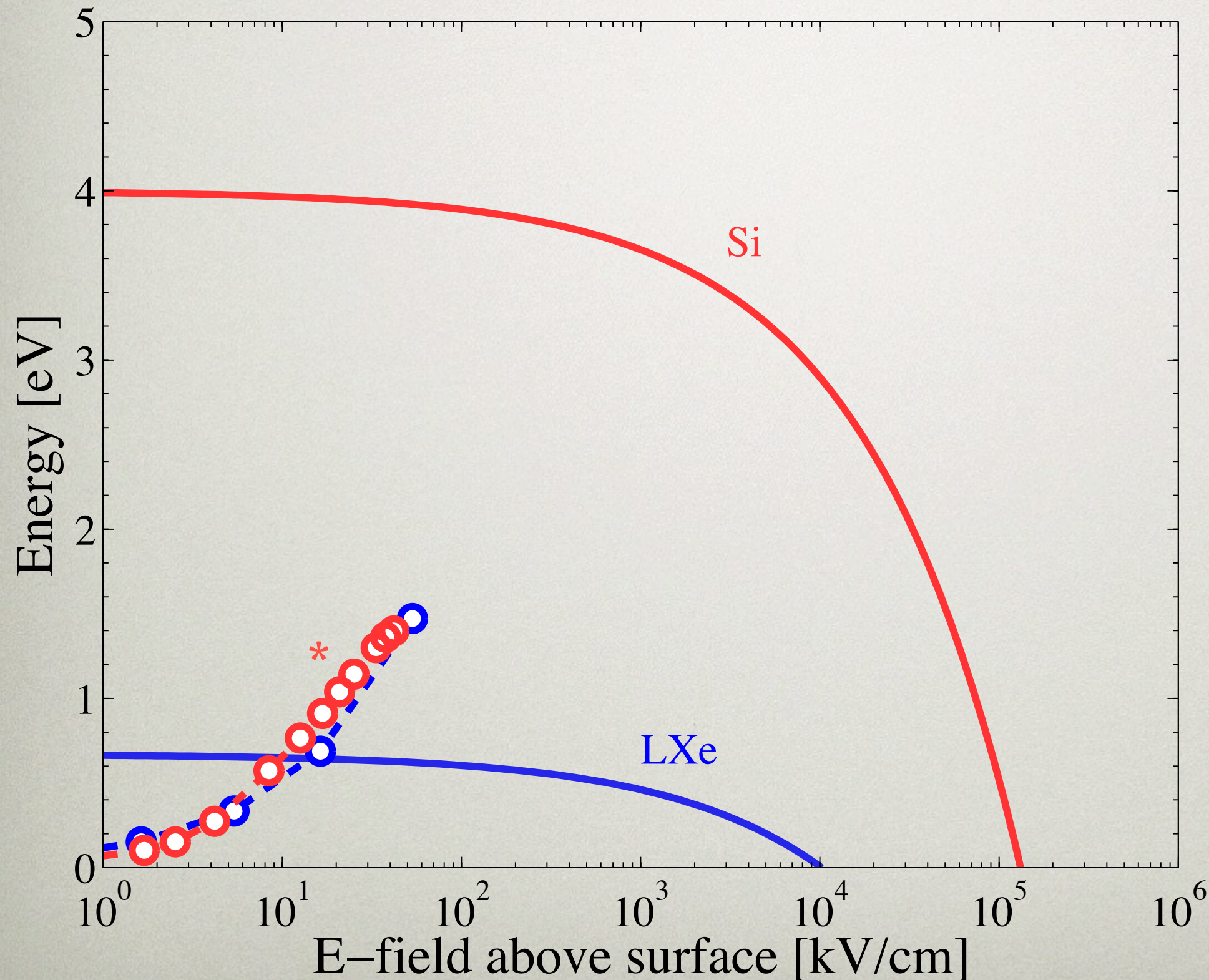
What does this plot look like for Si?

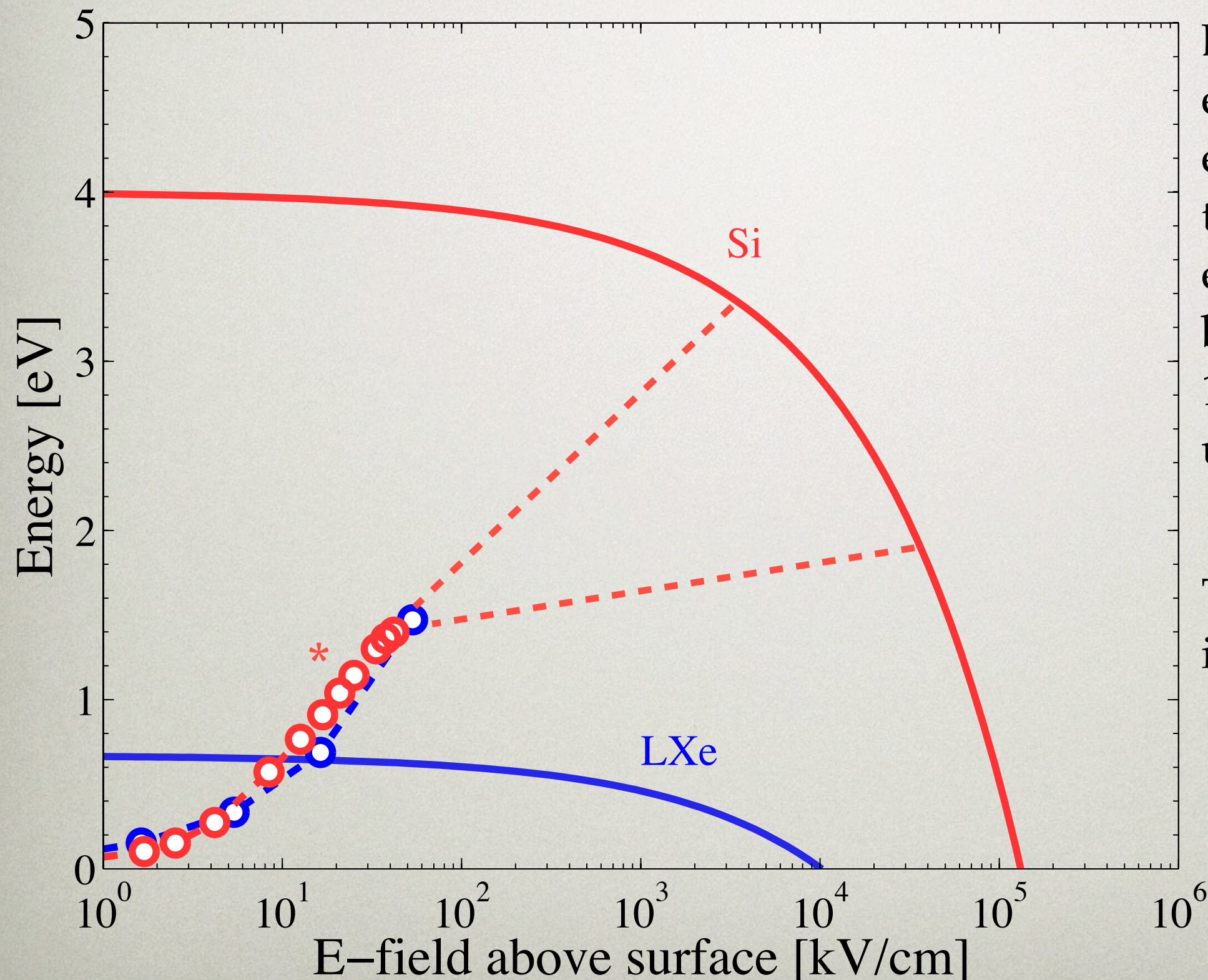*U. Sowada *et al.*, Chem. Phys. Lett. **34** (1975) 466

Electron heating (?)

Electron heating (?)

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?

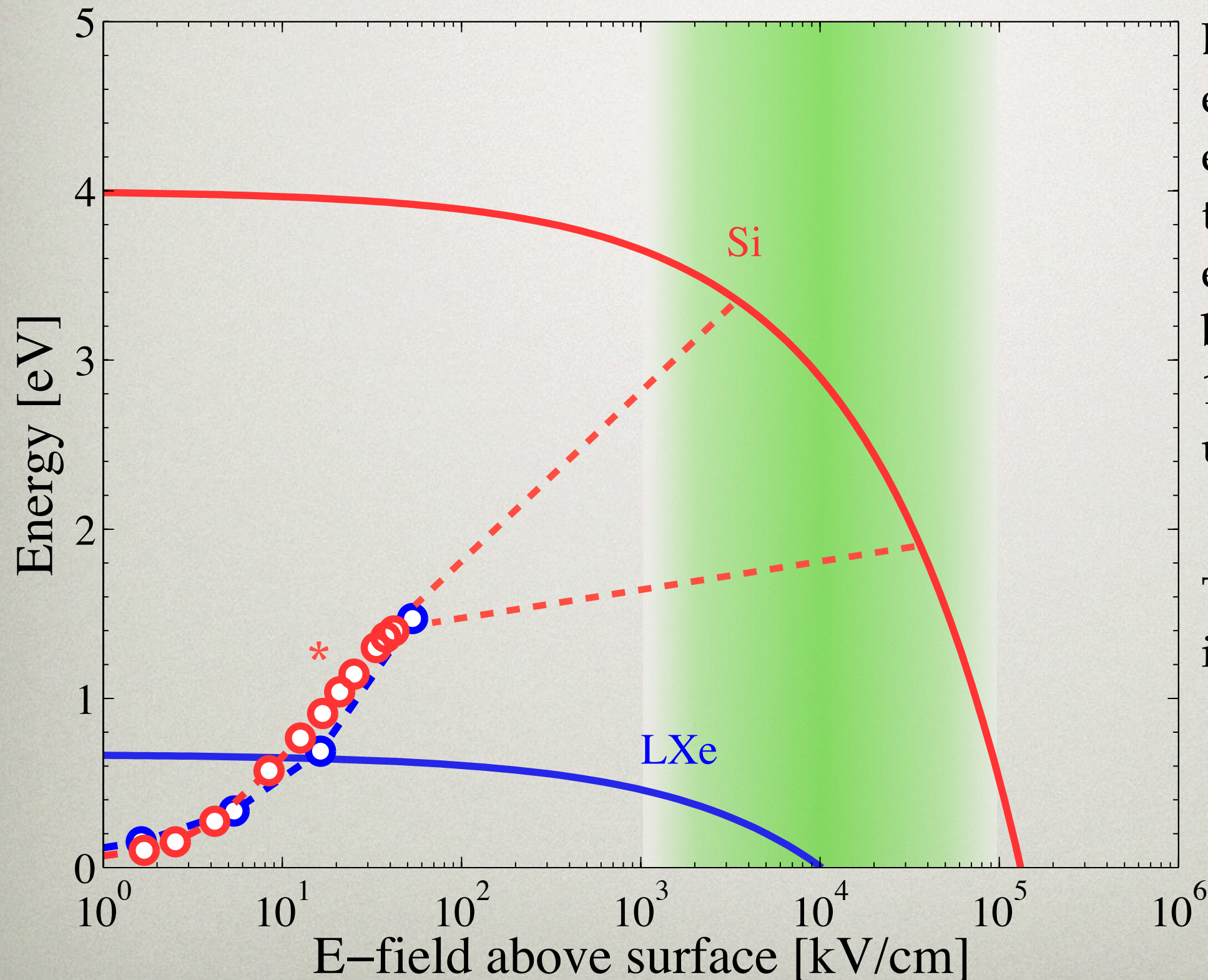* M.J. Martín *et al.*, Semicond. Sci. Technol. **8** (1993) 1291

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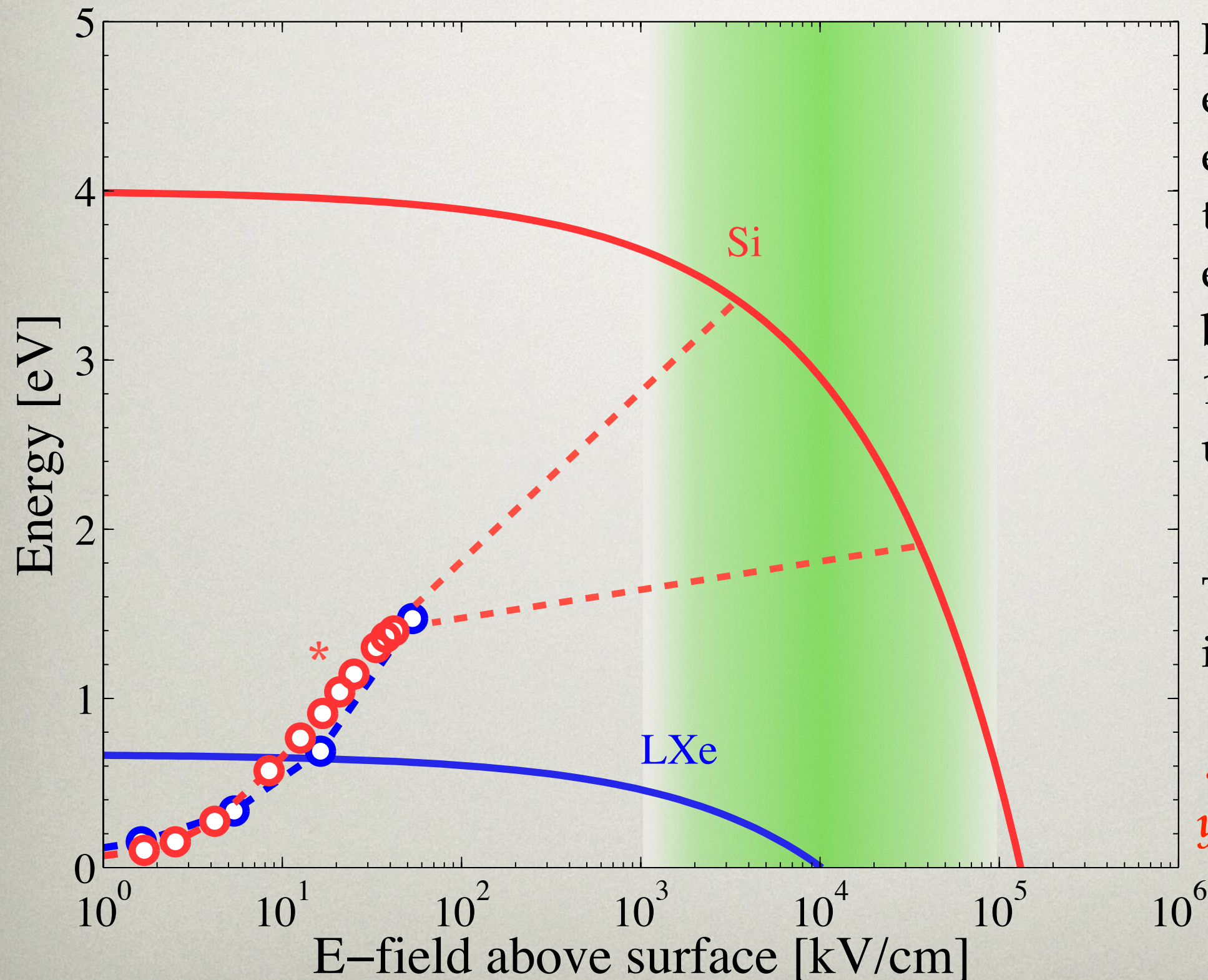* M.J. Martín *et al.*, Semicond. Sci. Technol. **8** (1993) 1291
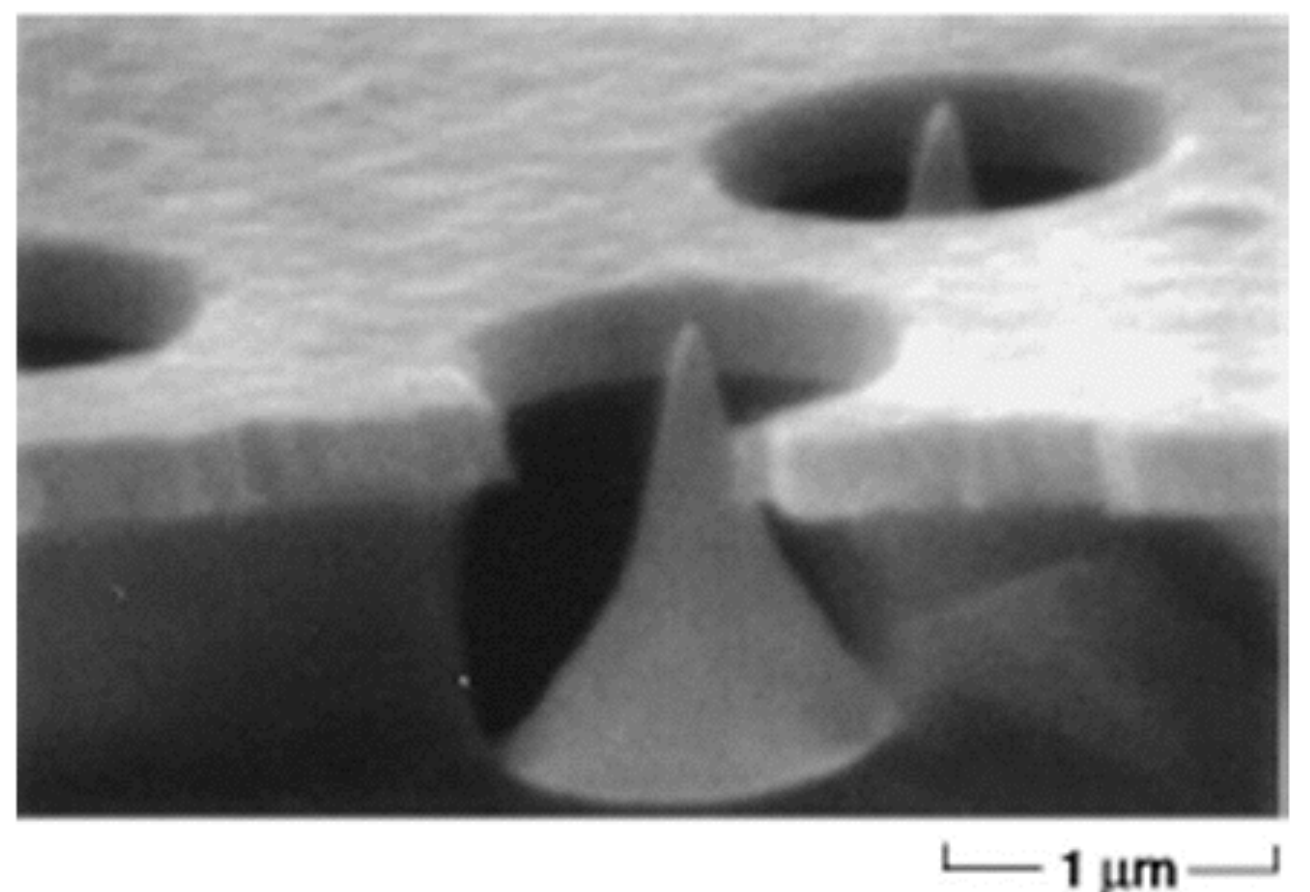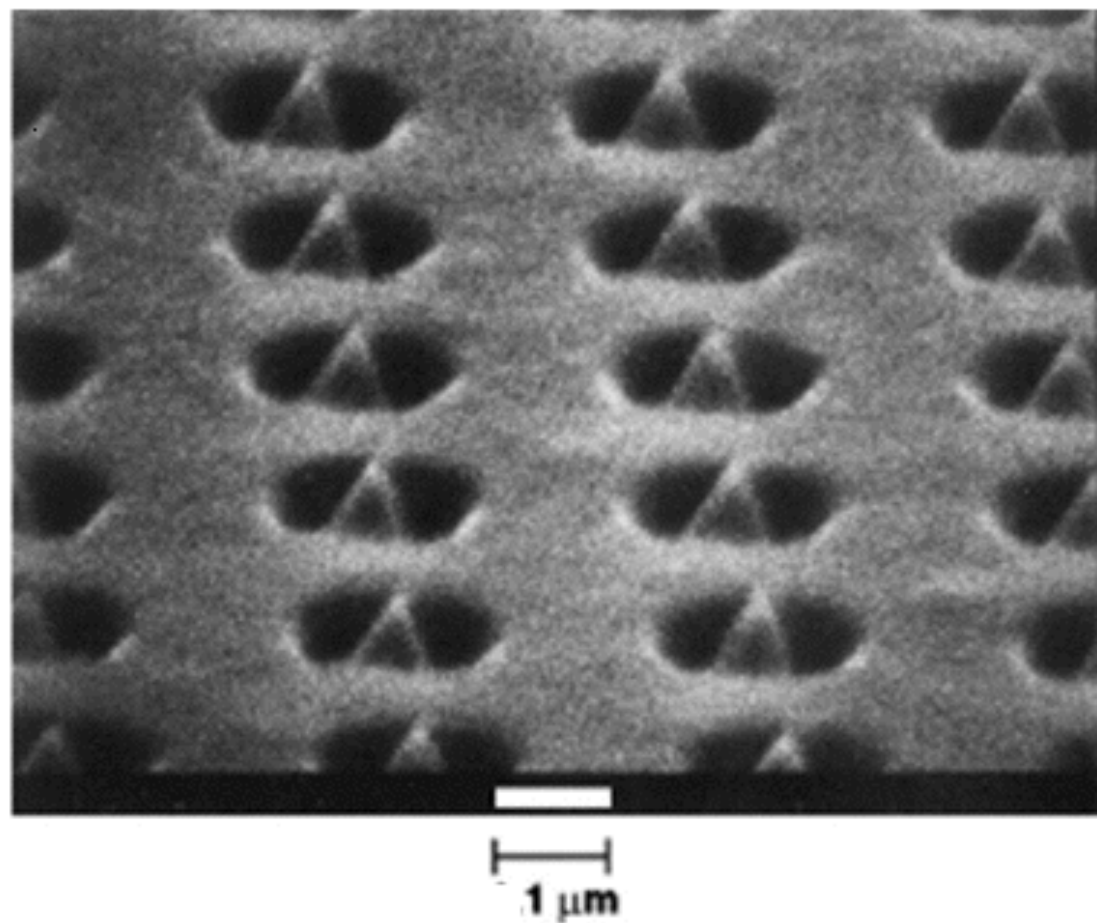
Electron heating (?)

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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!!!*
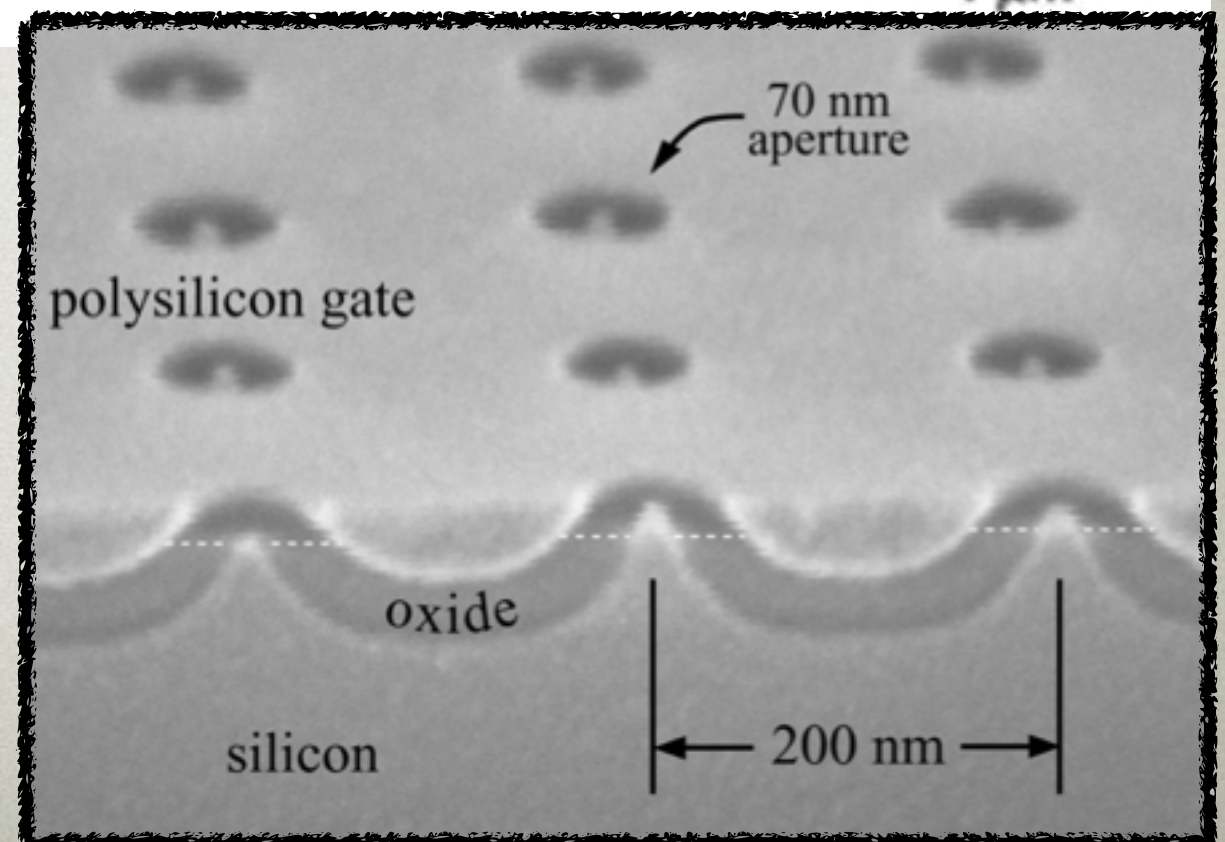
HUGE field densities

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

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

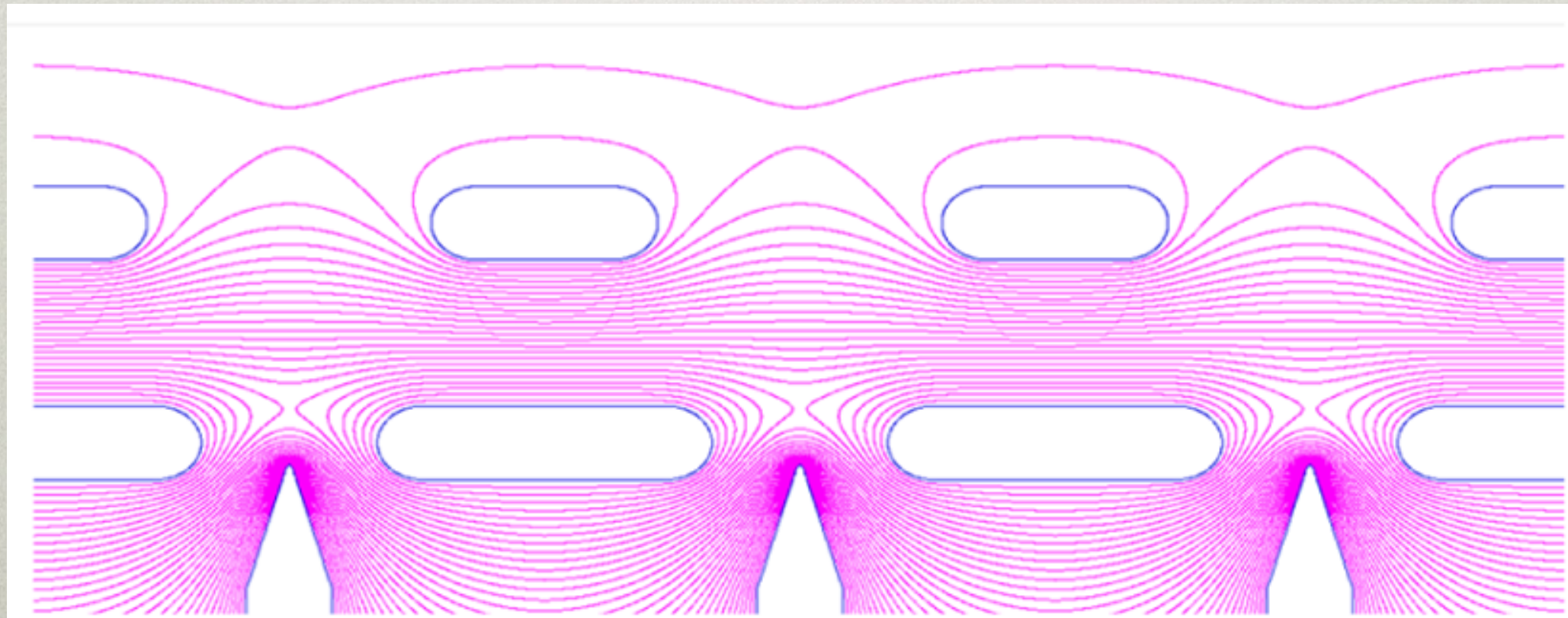# This is <u>not</u> new technology

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) Al_2O_3, $15°$ — Alumina deposition while rotating the substrate

(c) Mo, Al_2O_3 — Simultaneous normal and steep angle depositions of. Molybdenum and Alumina respectively
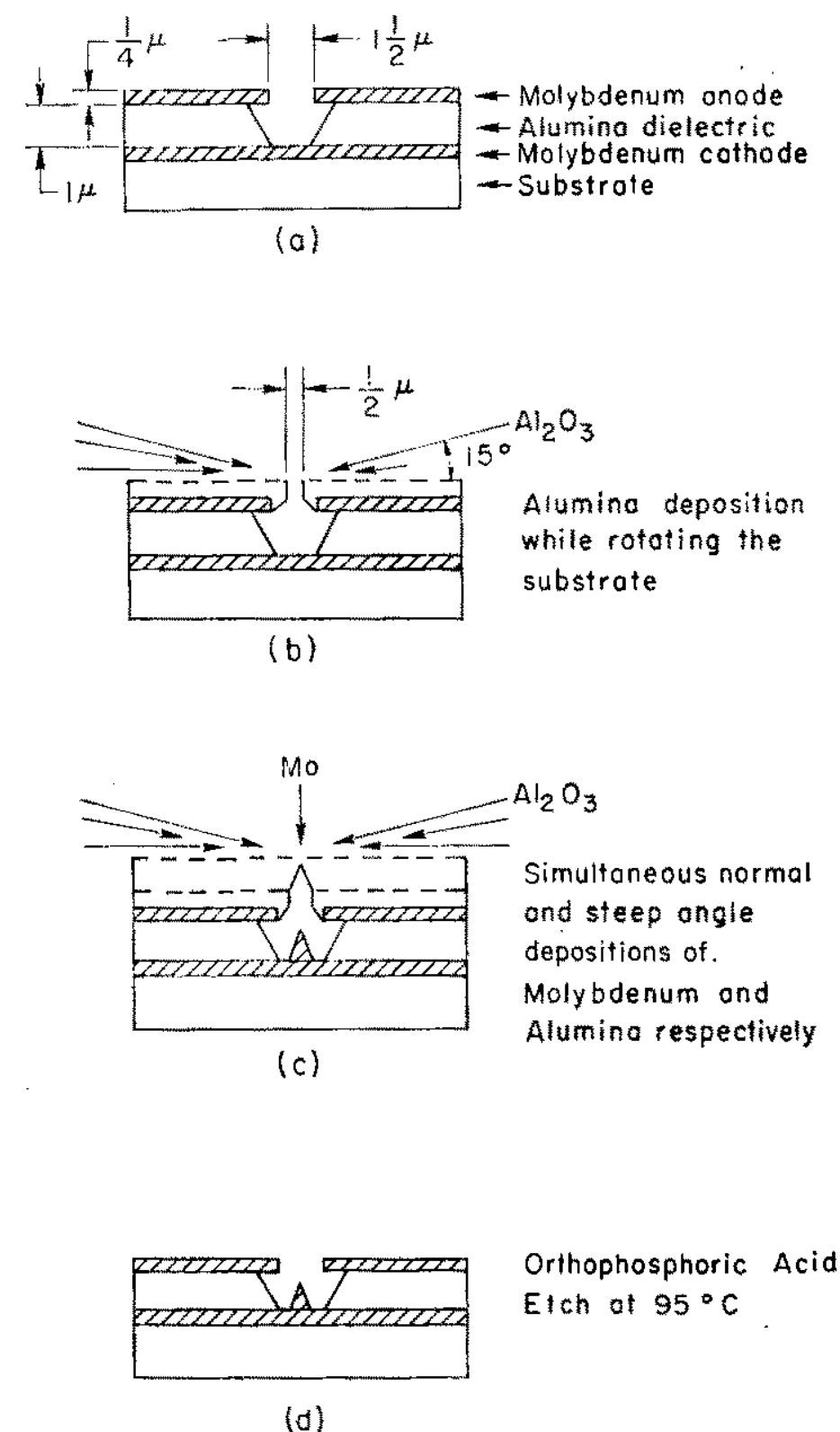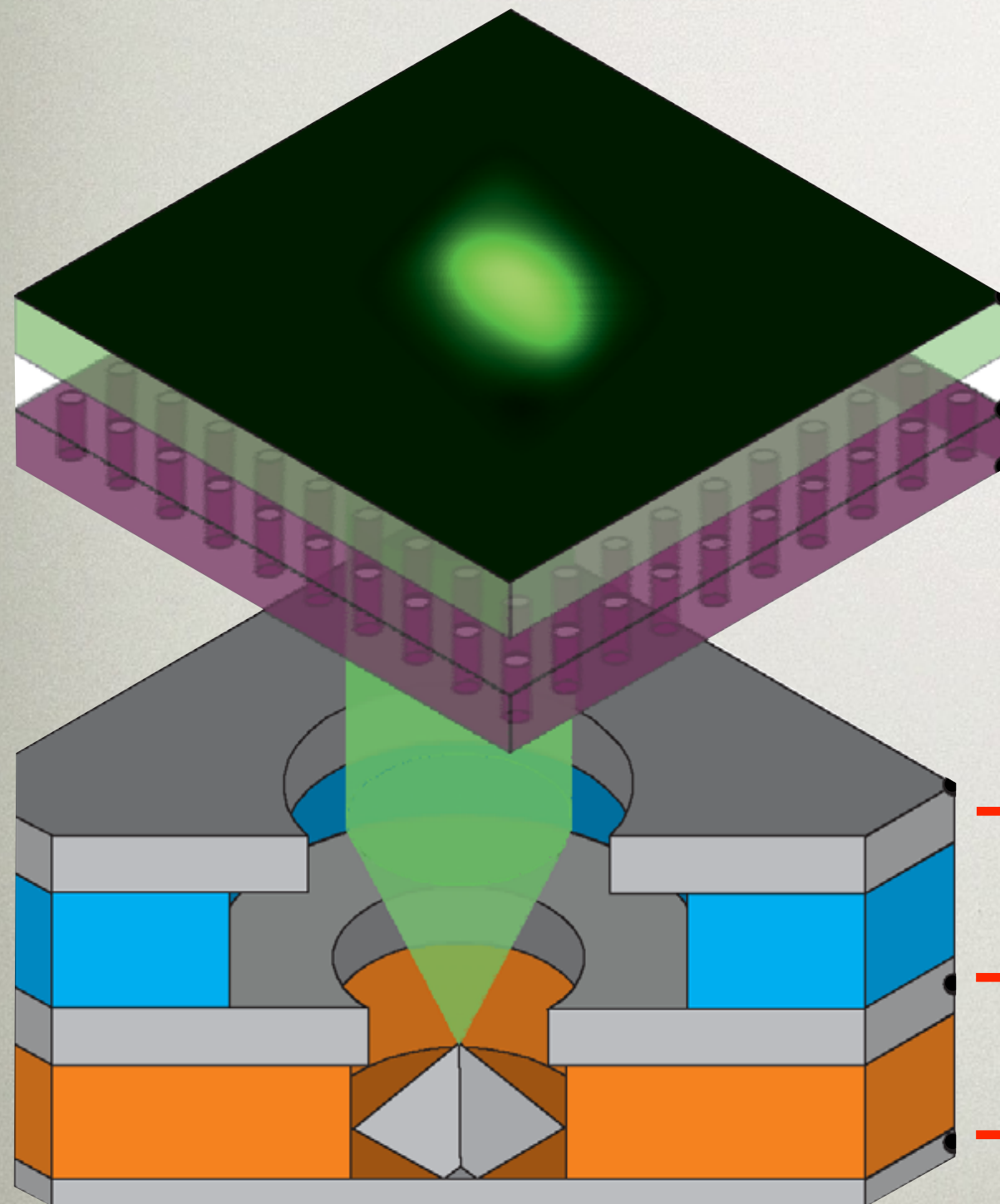
(d) Orthophosphoric Acid Etch at 95 °C

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

Electron collimation

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

Collimation electrode

Extraction electrode

Substrate

- 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
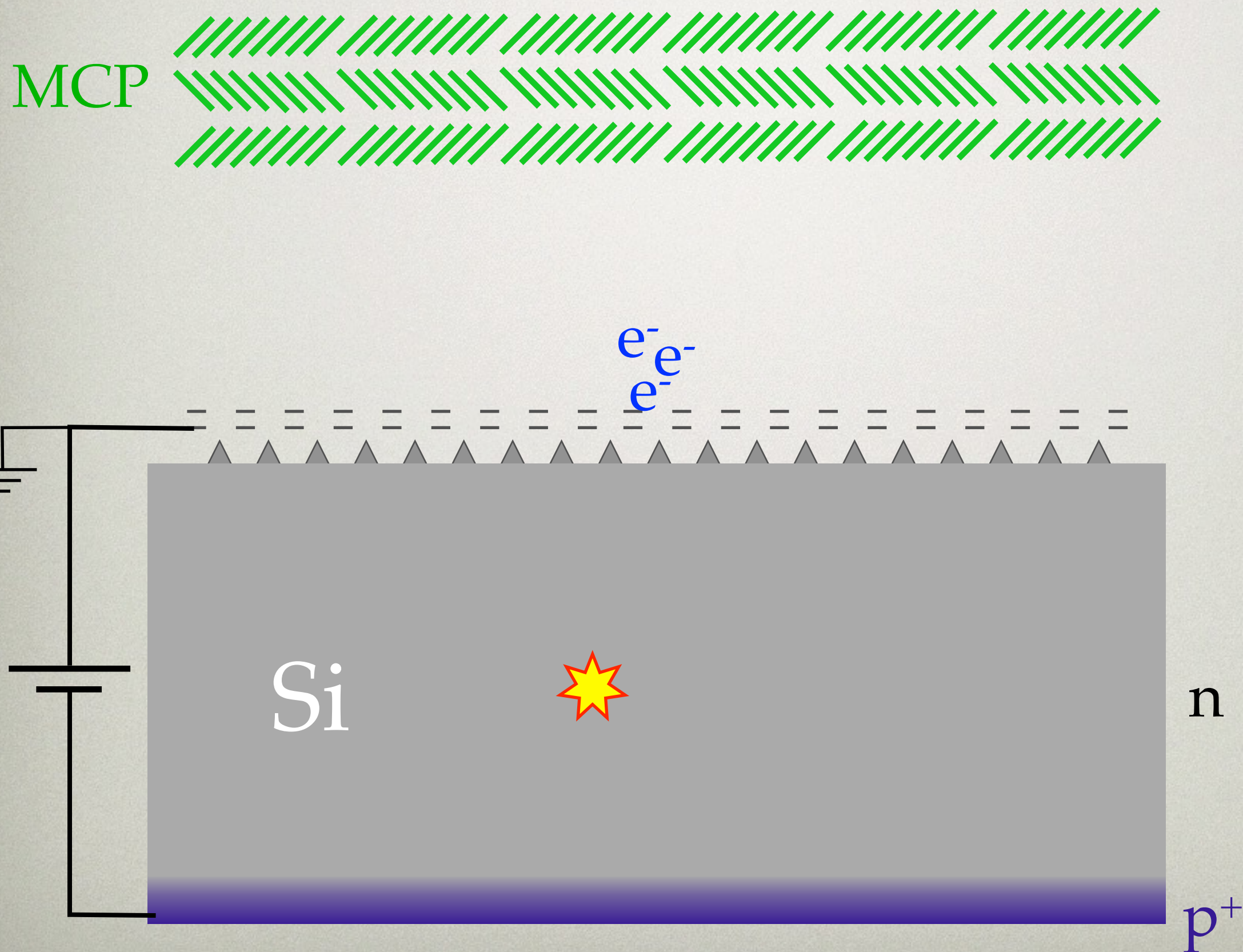
Towards a detector concept

MCP

Si

e⁻ e⁻
e⁻

n

p⁺

Towards a detector concept

Towards a detector concept

MCP

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

Cathode

I_C
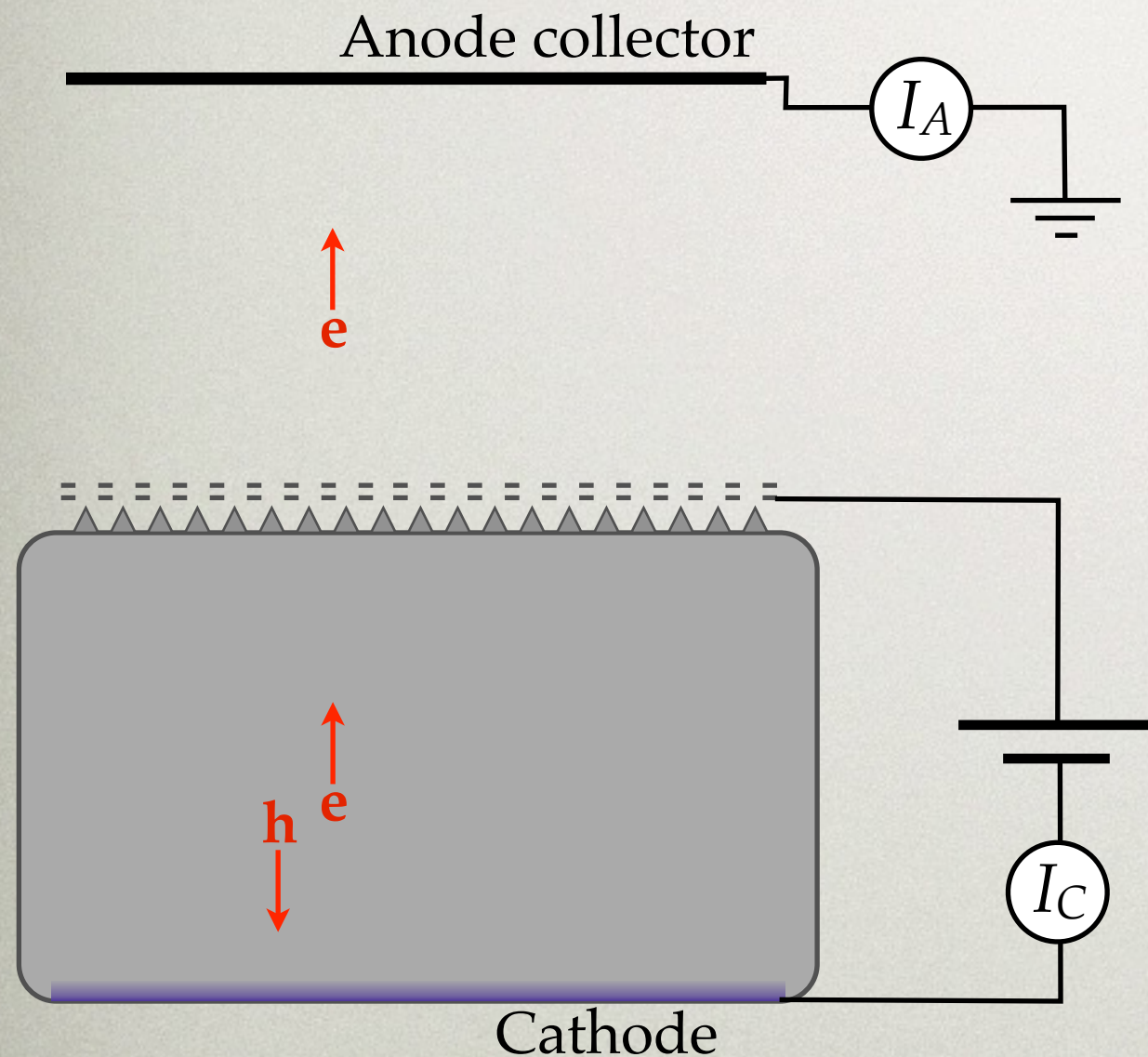
- To measure the extraction efficiency, one can measure the thermally induced current.
- The ratio of I_A to I_C should be equal to the extraction efficiency. It is essential to verify that this can be made something close to unity.
- The temp. can be varied to estimate which portion of I_C is due to 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
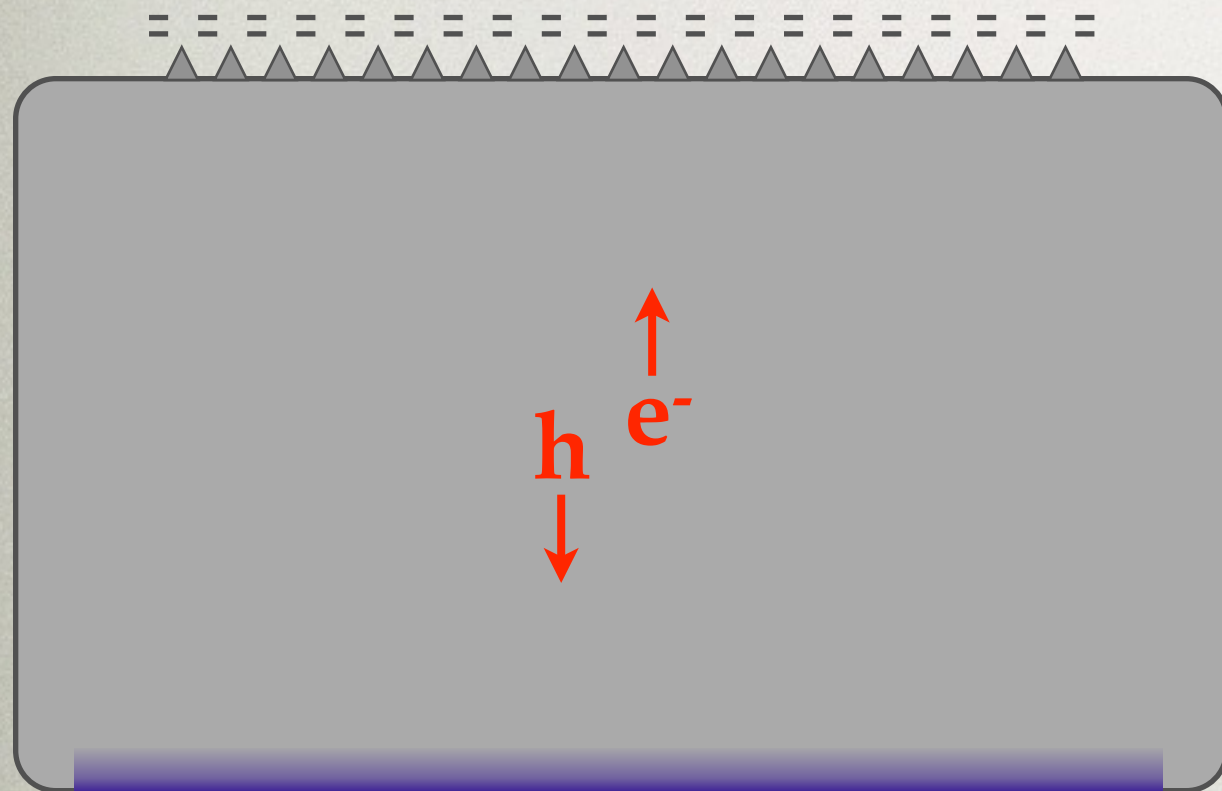
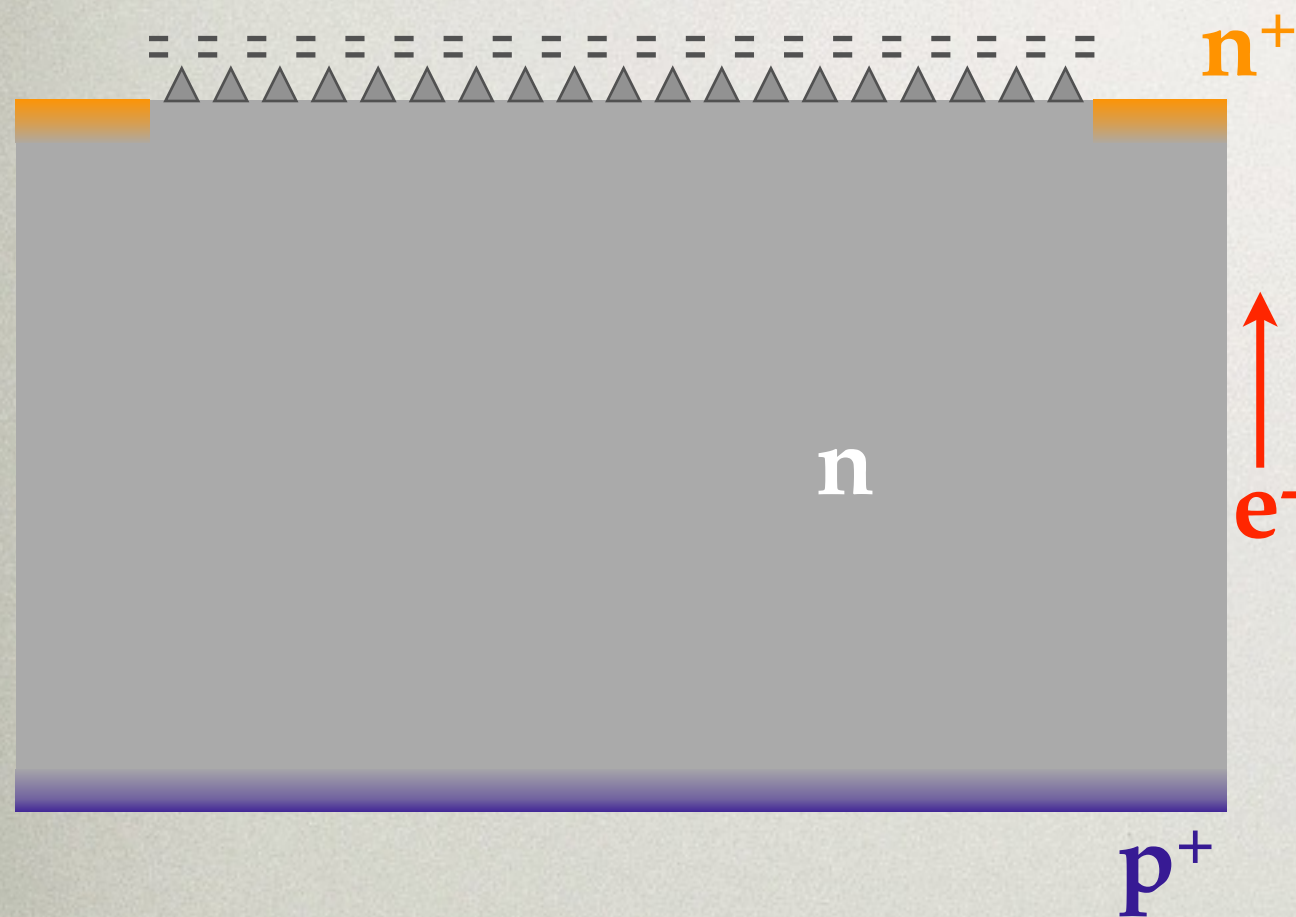$$I_{\mathrm{therm}} \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$

$E_g \approx 1.2$ 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**).
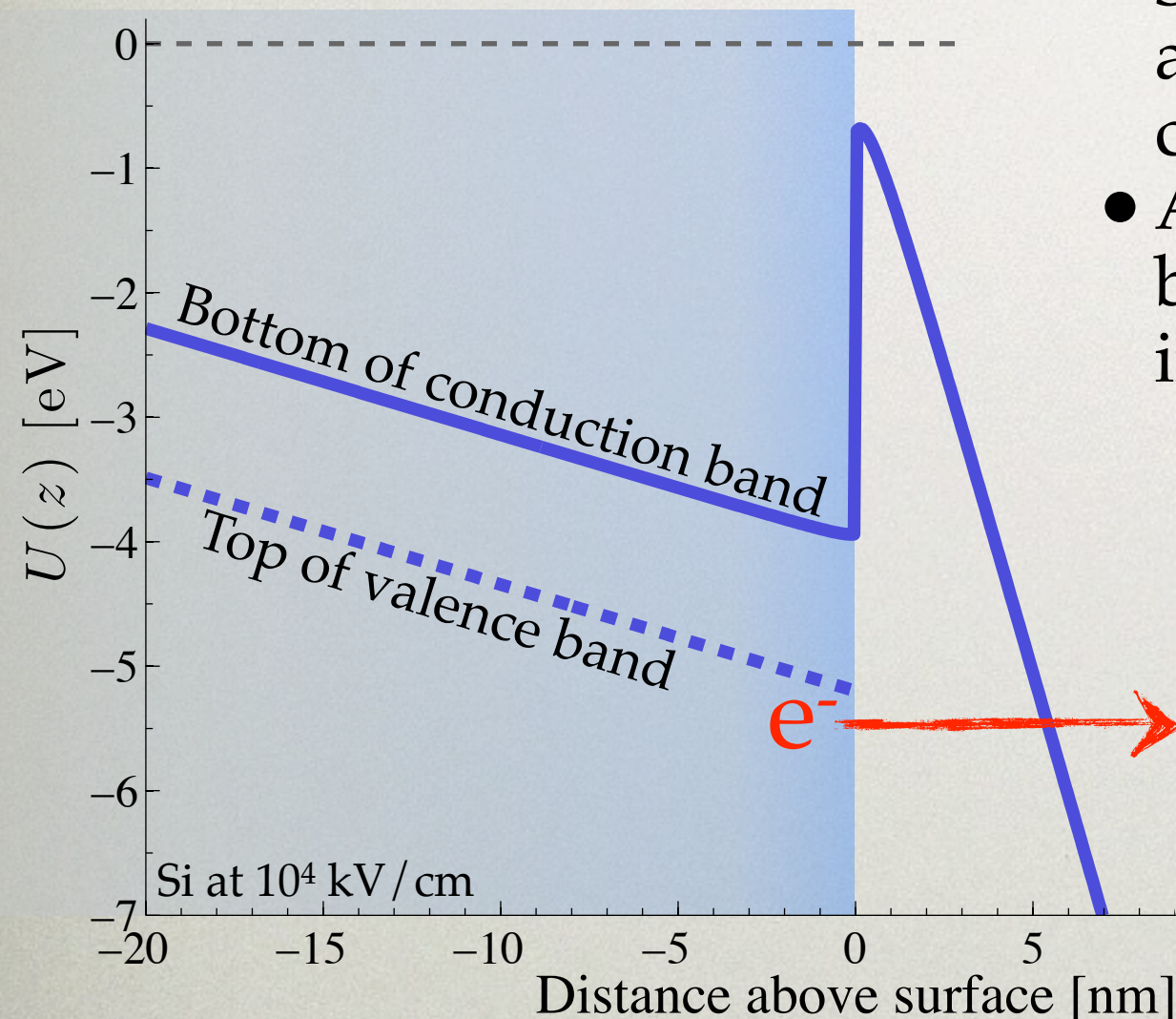
Thoughts on potential backgrounds

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

$U(z)$ [eV]

Bottom of conduction band

Top of valence band

e⁻

Si at 10^4 kV/cm

Distance above surface [nm]

- 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)

MCP

E_r

e

n⁺

n
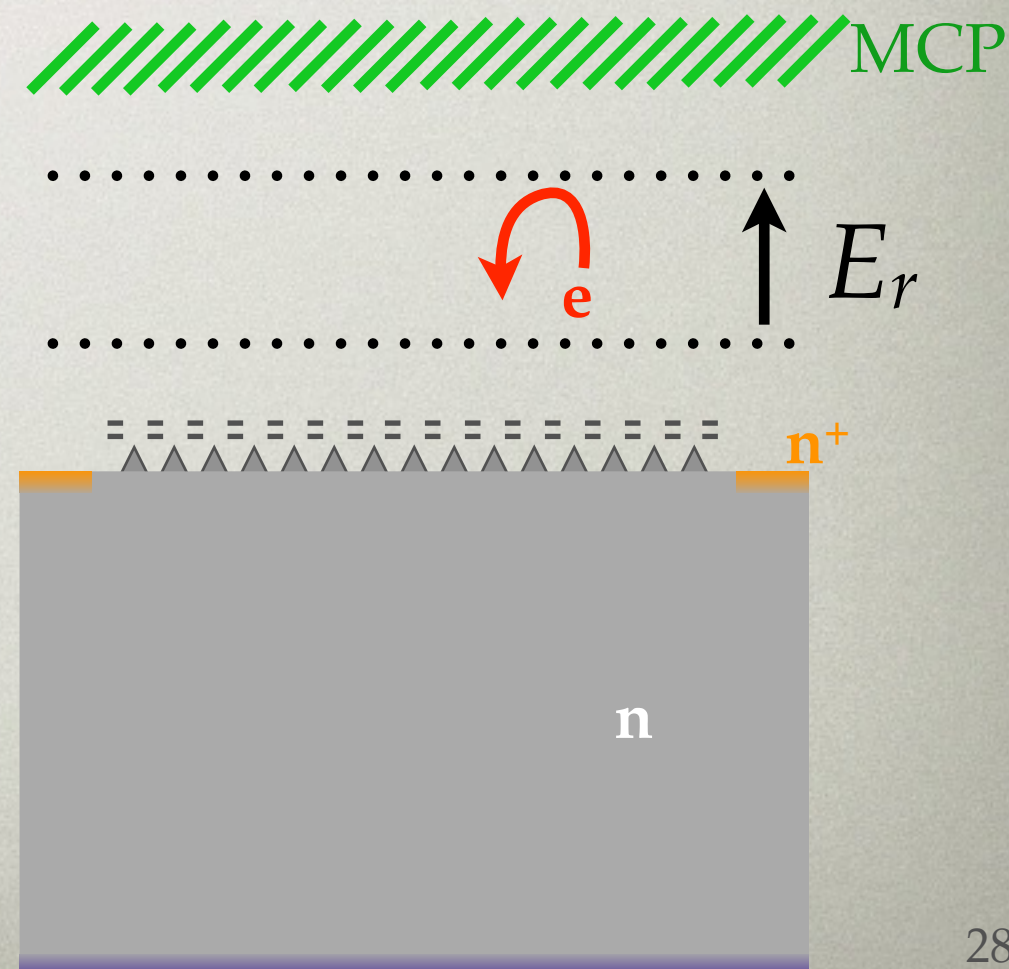
Someone else apparently had a similar idea…

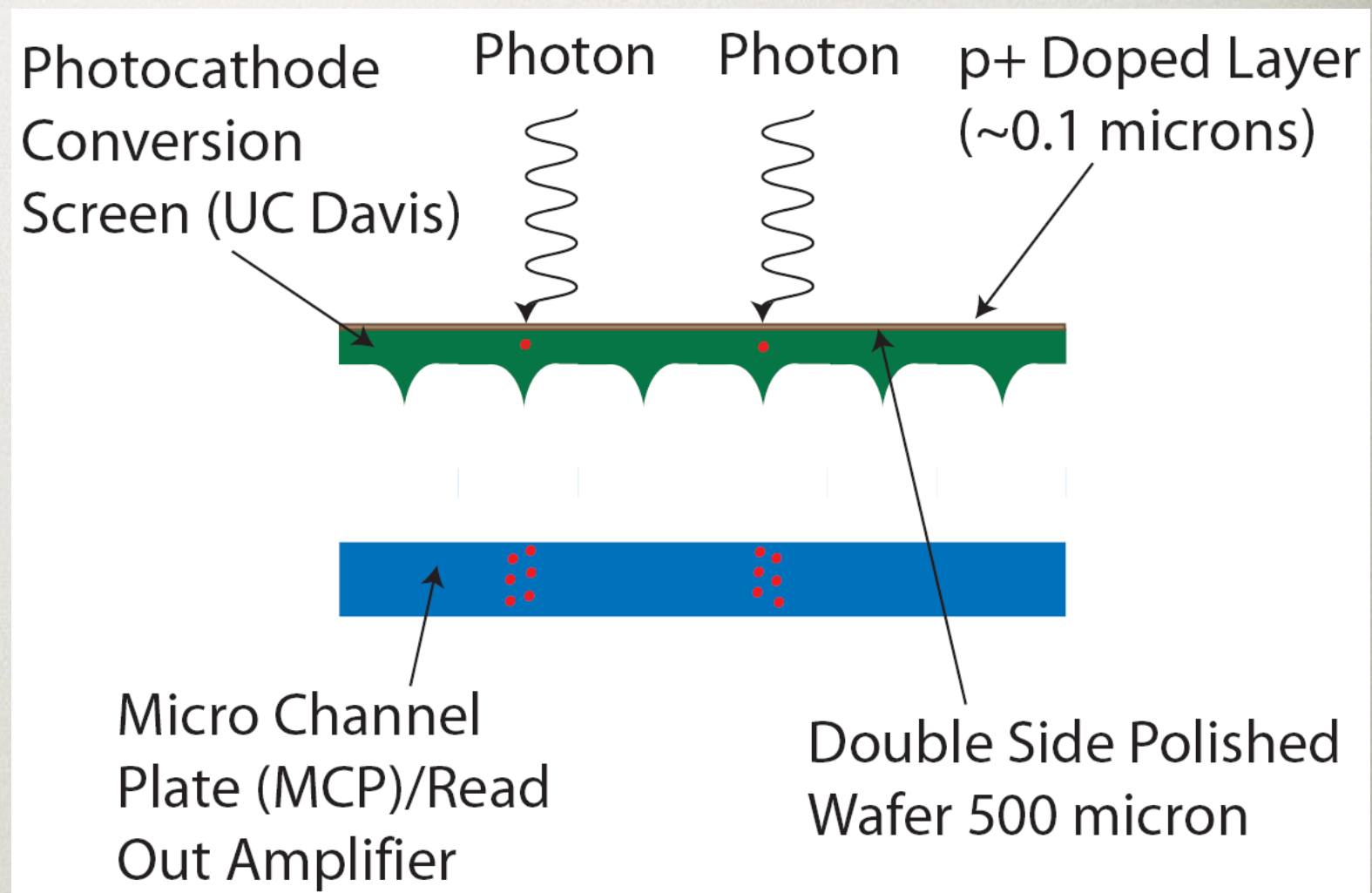As I recently discovered, a similar technique has been implemented in x-ray imaging.

Figure 1: X-ray Imager and Energy Detector

…so stay tuned!

Summary

- Searches for sub-GeV DM 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.