The ultimate ionization threshold in particle detectors

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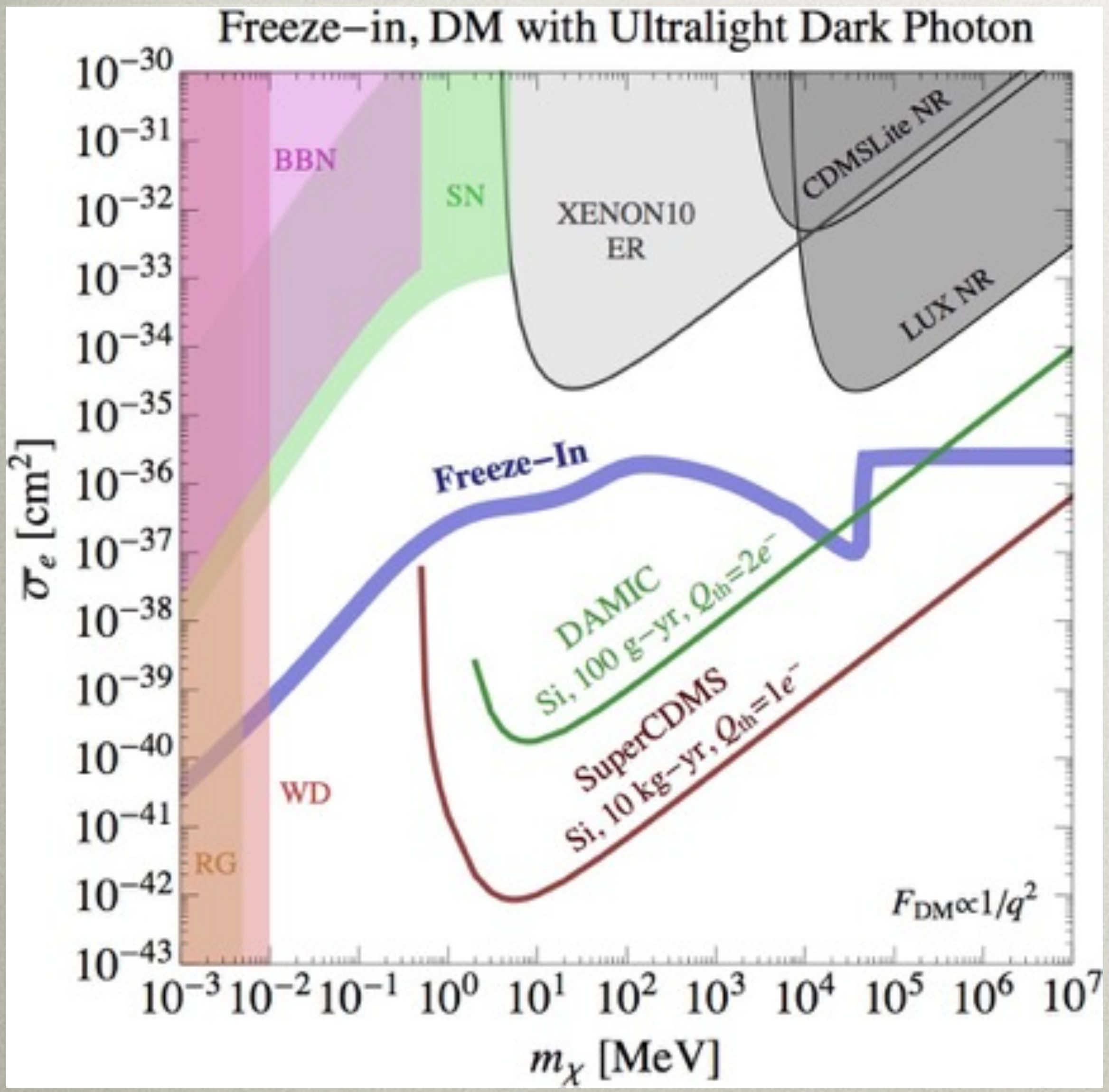
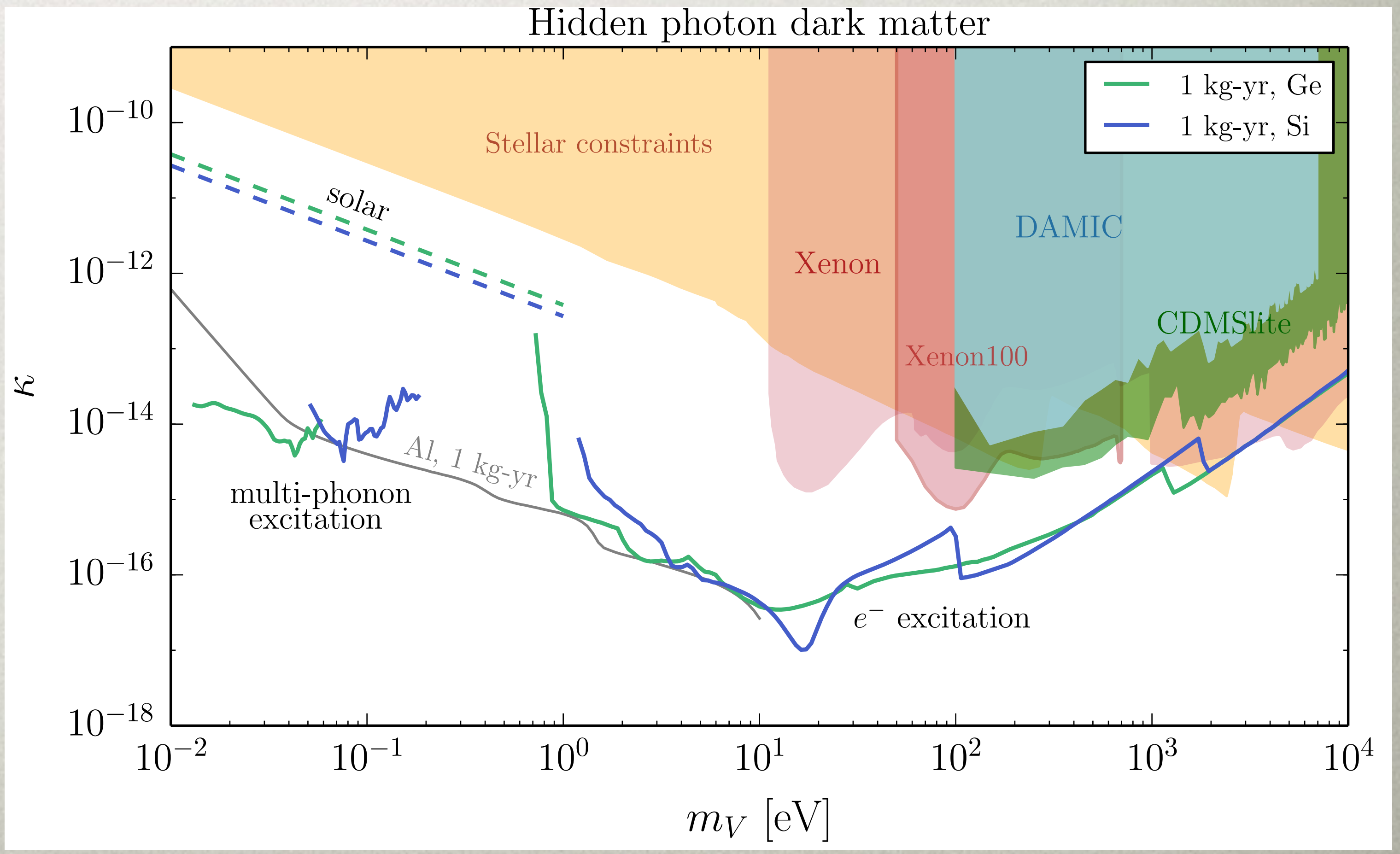
DM motivation for low thresholds

- Strong motivation for future DM searches to push for detectors with very low ionization thresholds.

R. Essig *et al.*, JHEP05 (2016) 046, 1509.01598

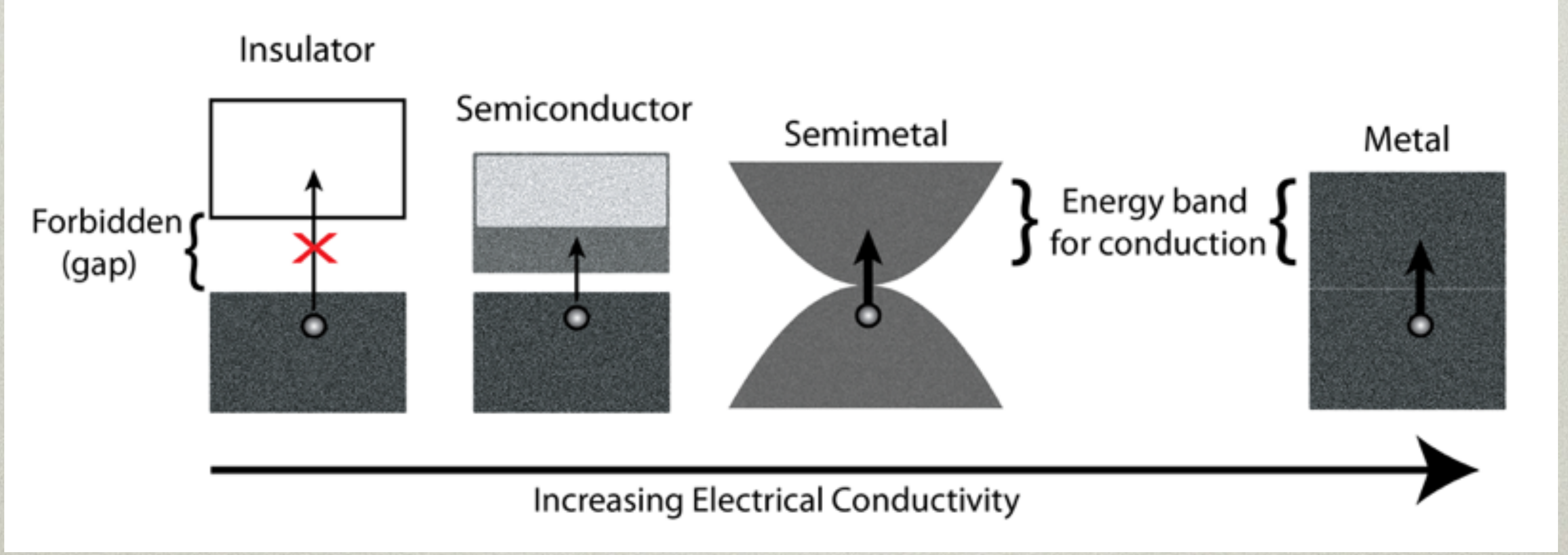


Y. Hochberg, T. Lin, K. Zurek, 1608.01994



DM motivation for low thresholds

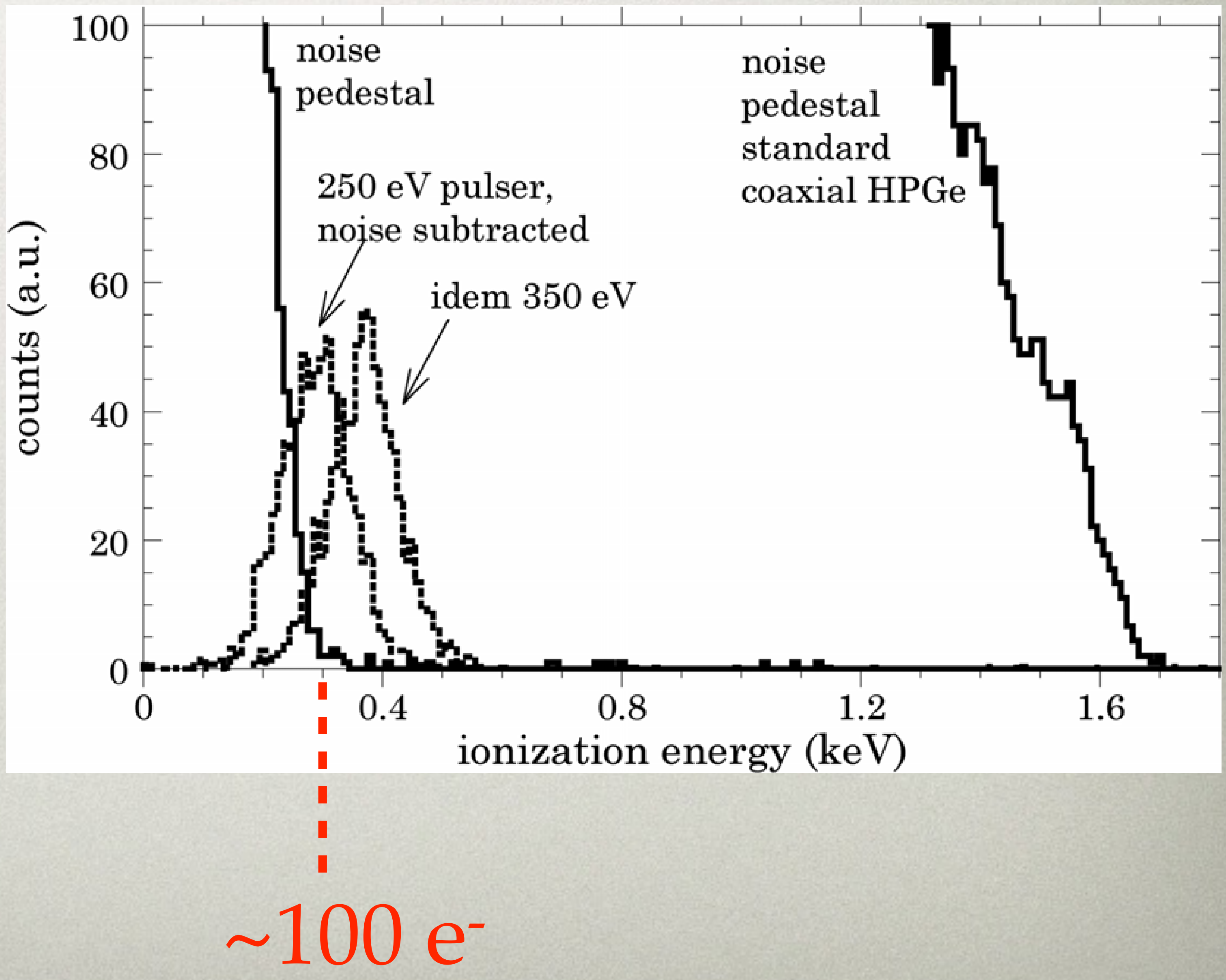
- Strong motivation for future DM searches to push for detectors with very low ionization thresholds.
- New materials with tunable gap energies could open a window into even lower-energy particle detection.



Traditional charge readout

- Traditional event-by-event charge readout involving transistors and feedback, cannot approach thresholds of ~few electrons.
- Amplification is not the way to go for reaching sensitivity to single electrons.

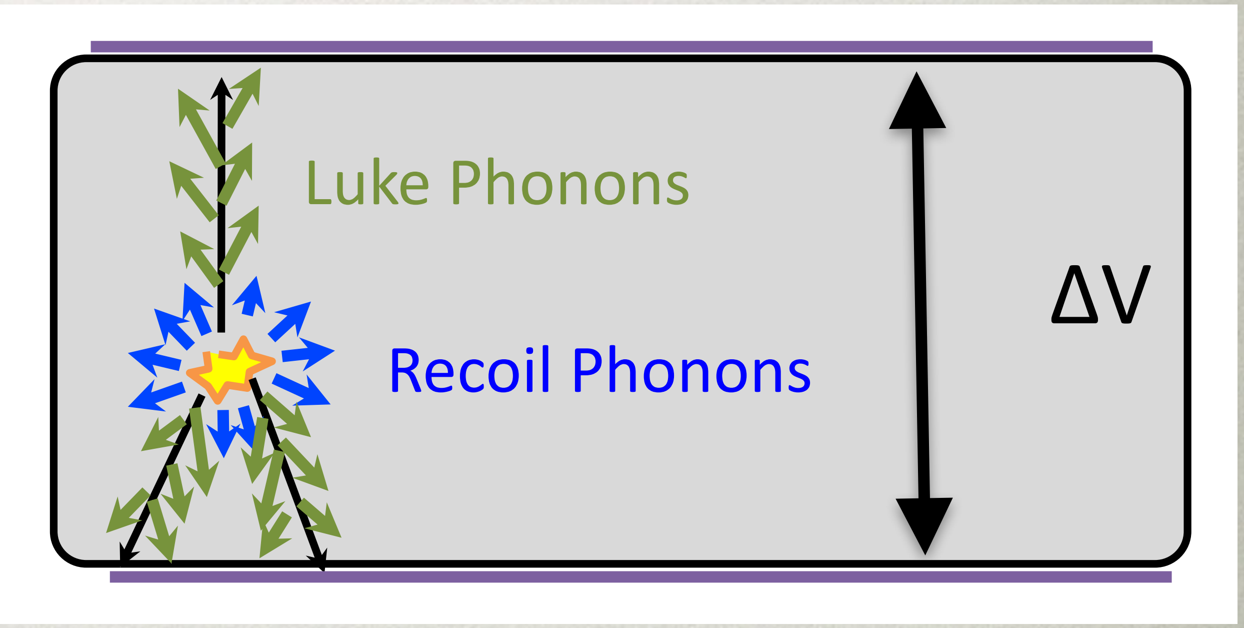
P.S.Barbeau, J.I.Collar, O.Trench, JCAP09 (2009)009



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.
- 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?

From Matt Pyle's talk earlier this week

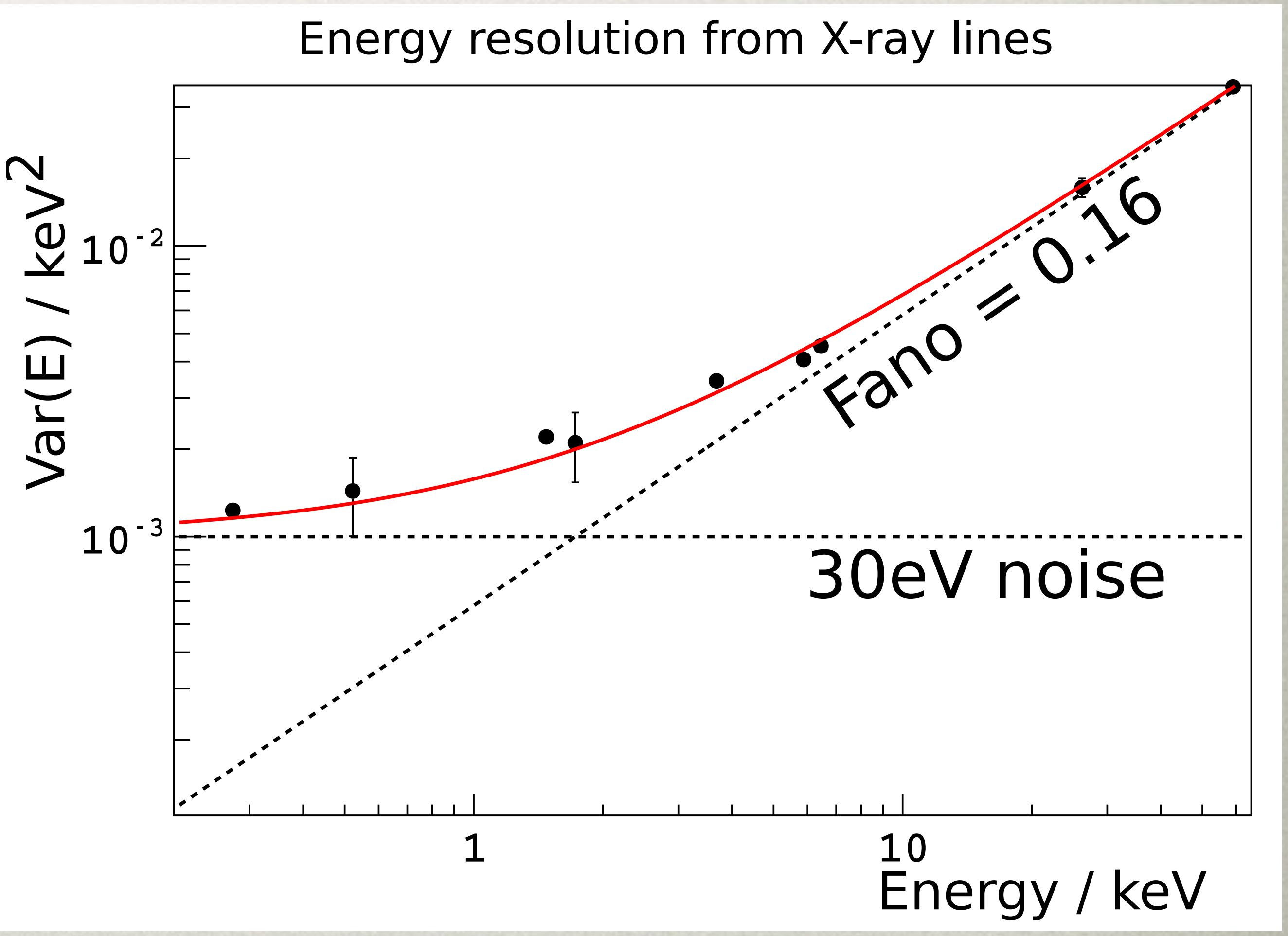


"difficult" cryogenics

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 $\mathcal{O}$(10 e$^-$) threshold, though new “SkipperCCD” tech might be able to push lower.

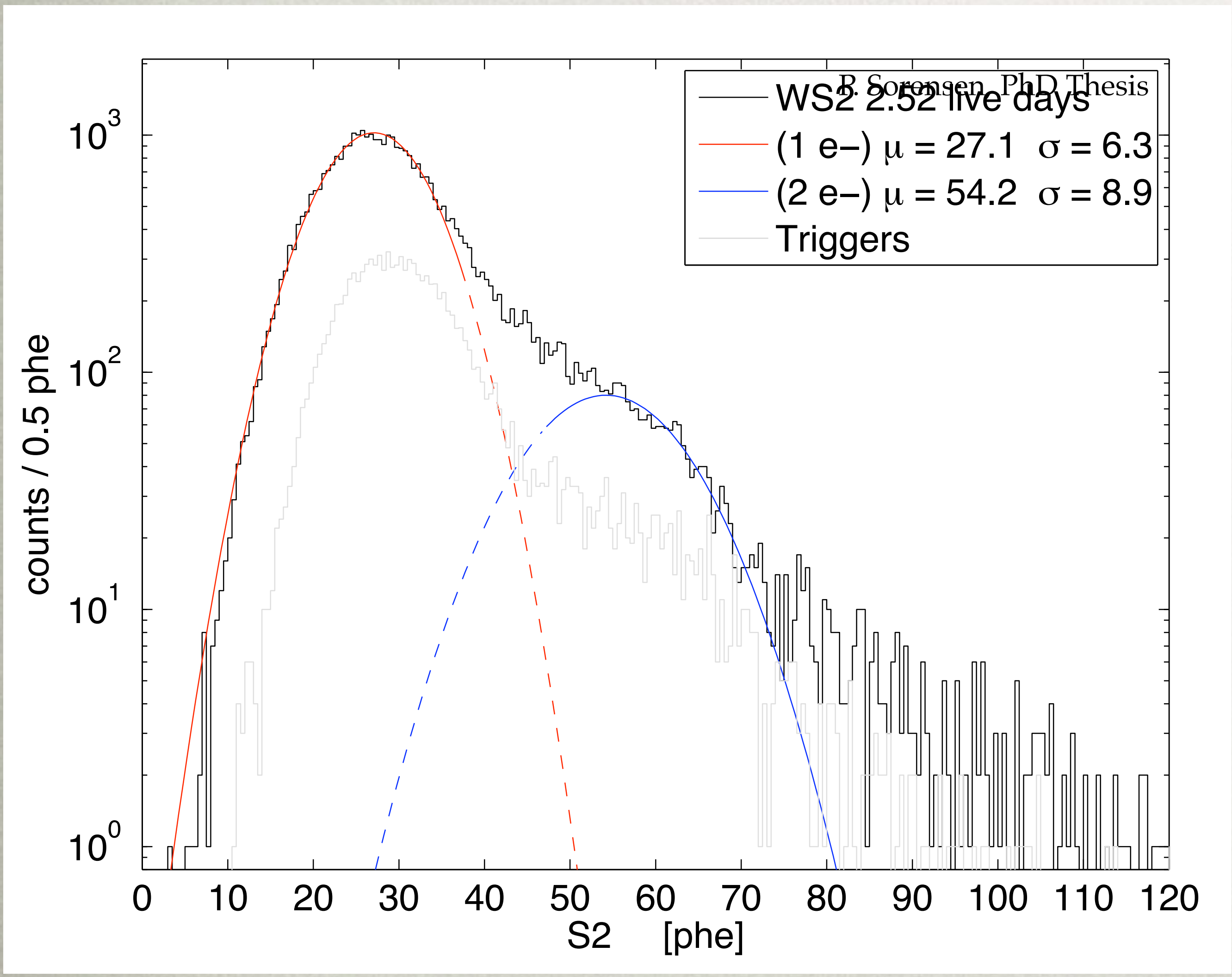
“Light DM at DAMIC” (J.Tiffenberg)
Beyond WIMPs (http://tomerv.wix.com/lightdm#!sessions/c3kh)

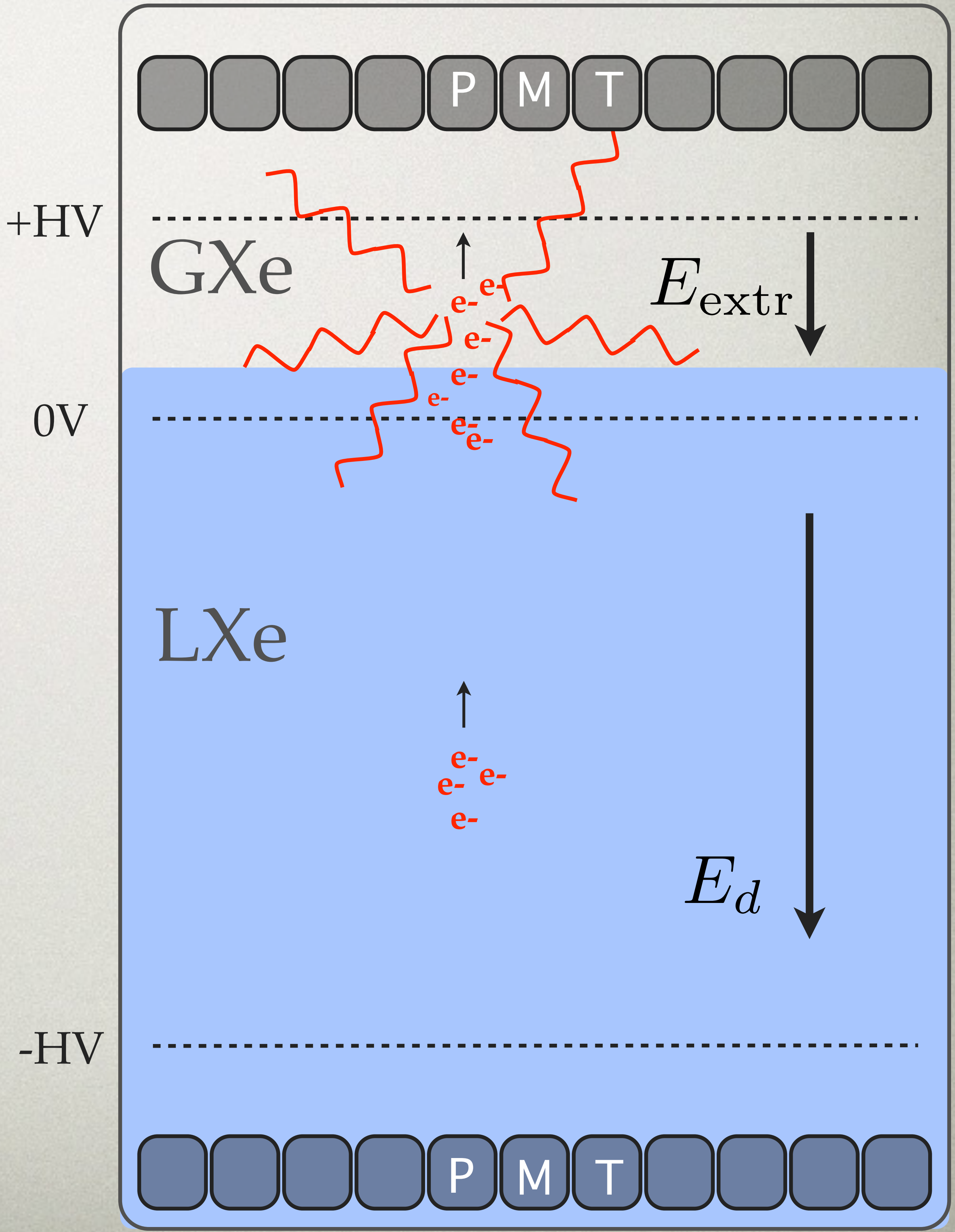


easy cryogenics

Single-e in noble liquids

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





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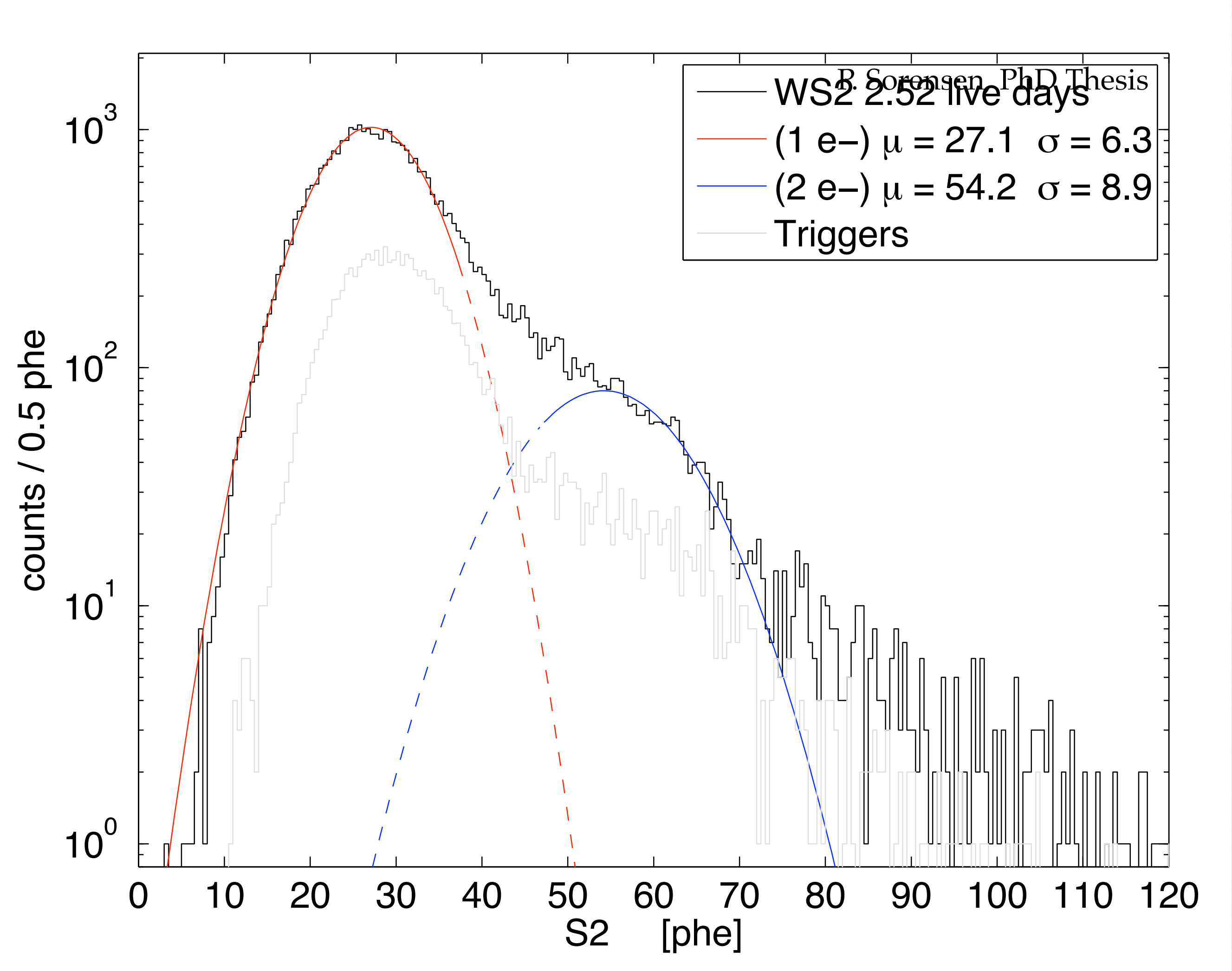
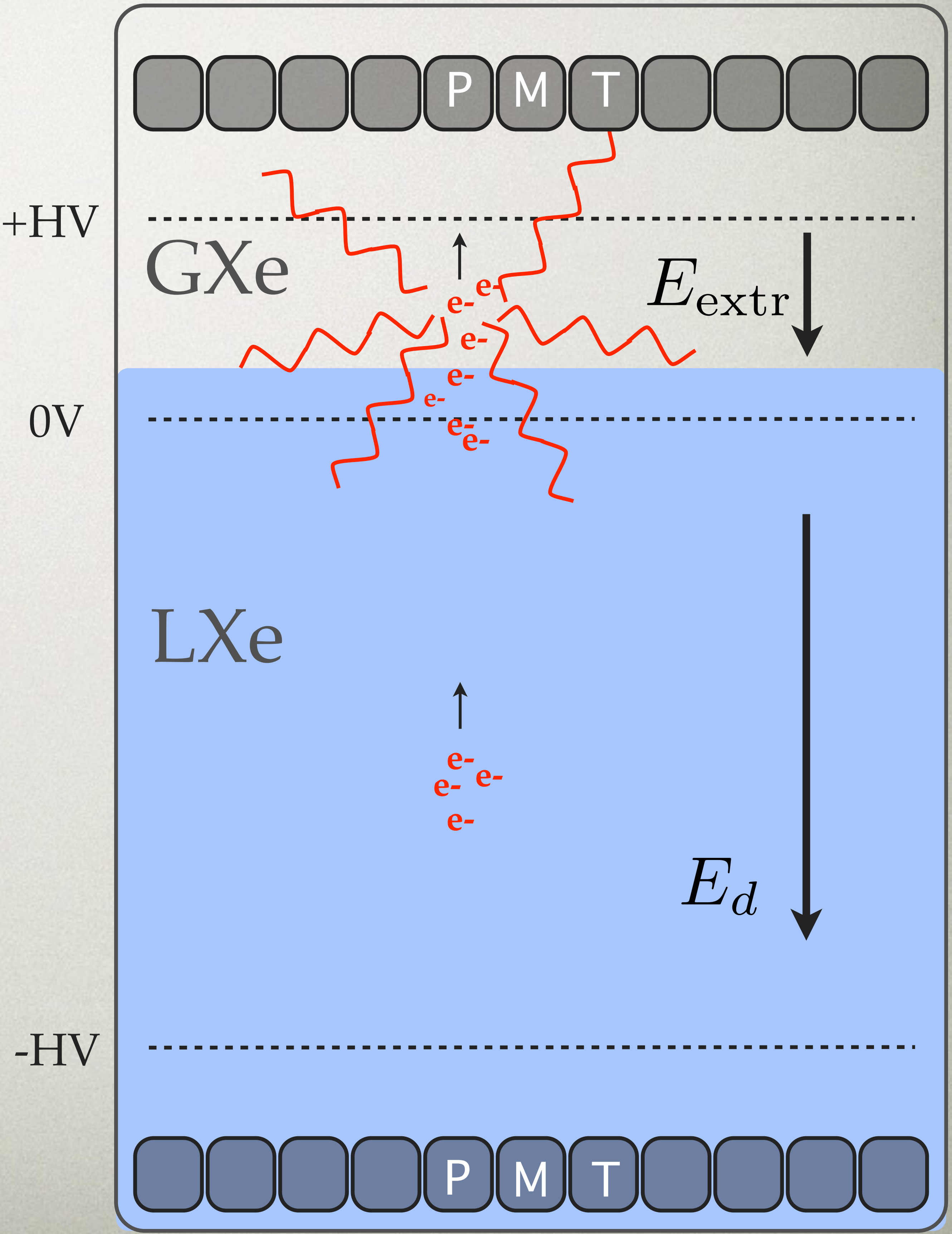
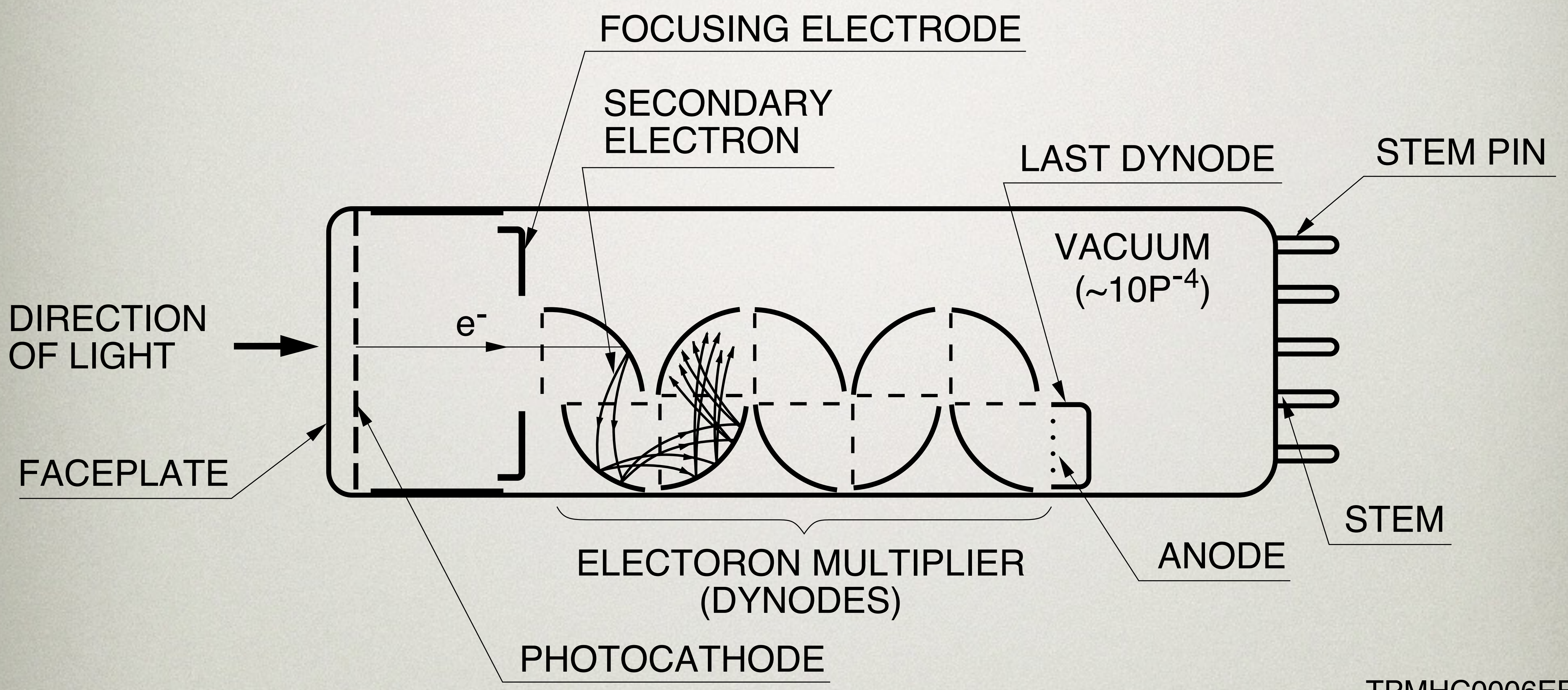




Can we extract electrons from other materials?

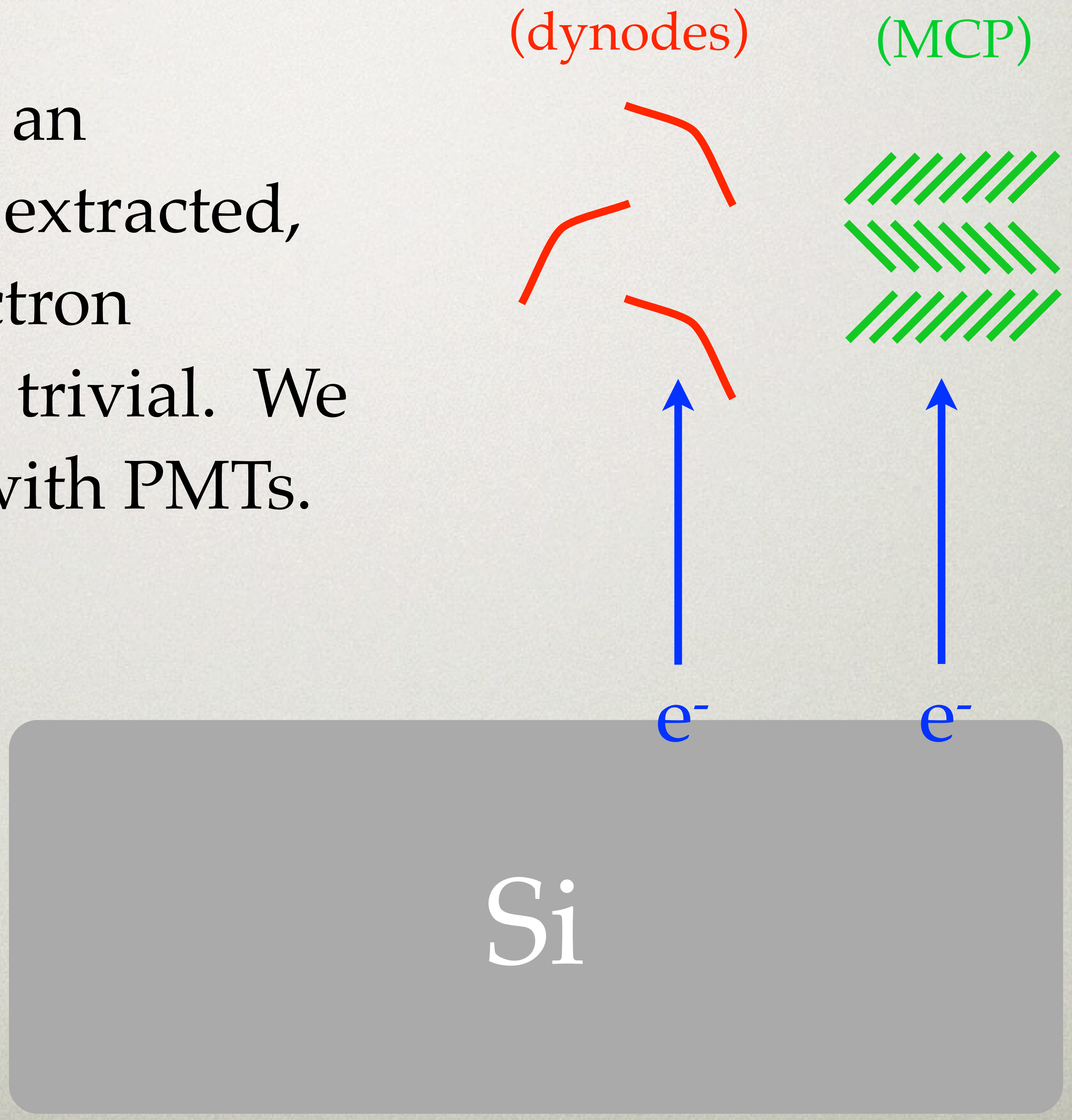
Single-e in a PMT



Photomultipler tubes easily see single photons (and hence, single electrons), through physical multiplication.

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.

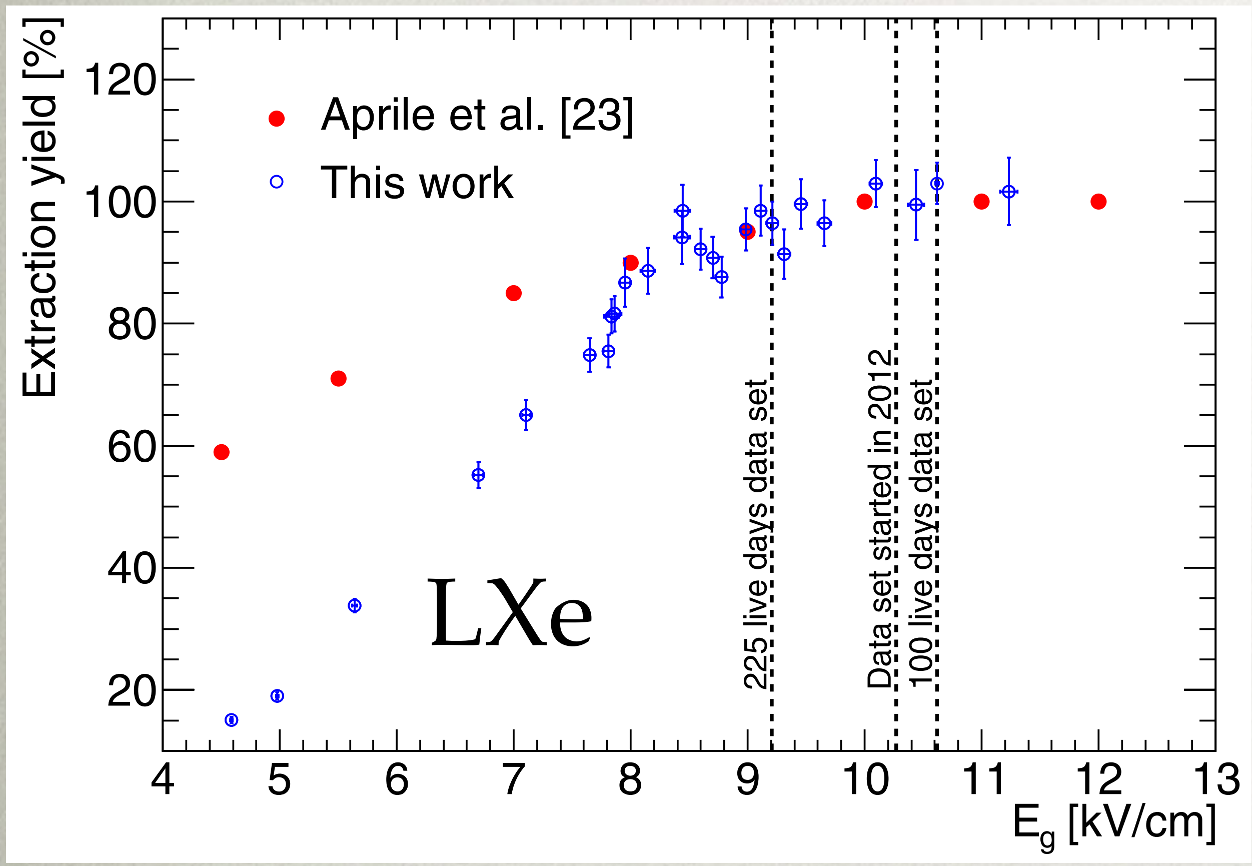


How can we extract electrons from the surface of a material?

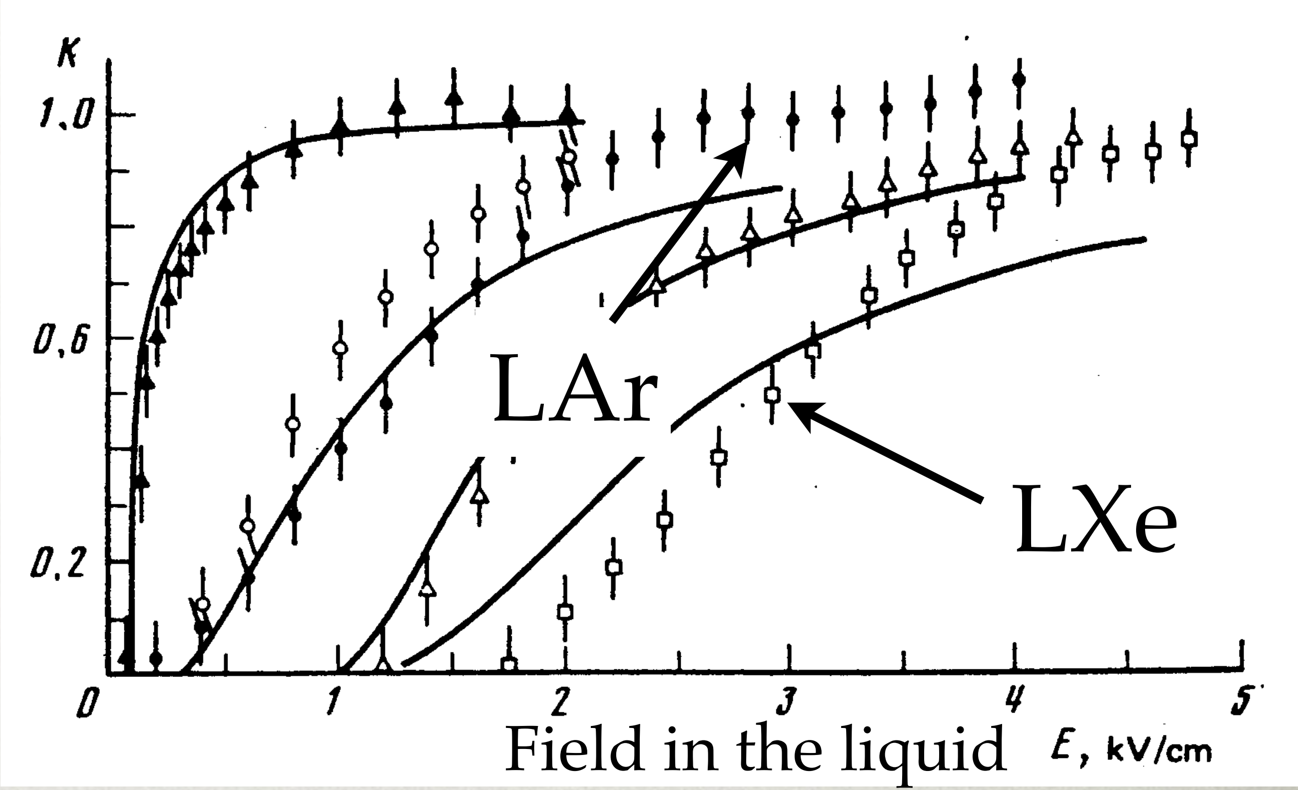
- Apply an electric field perpendicular to the surface.
- Crucial question: how strong of a field is necessary?

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)

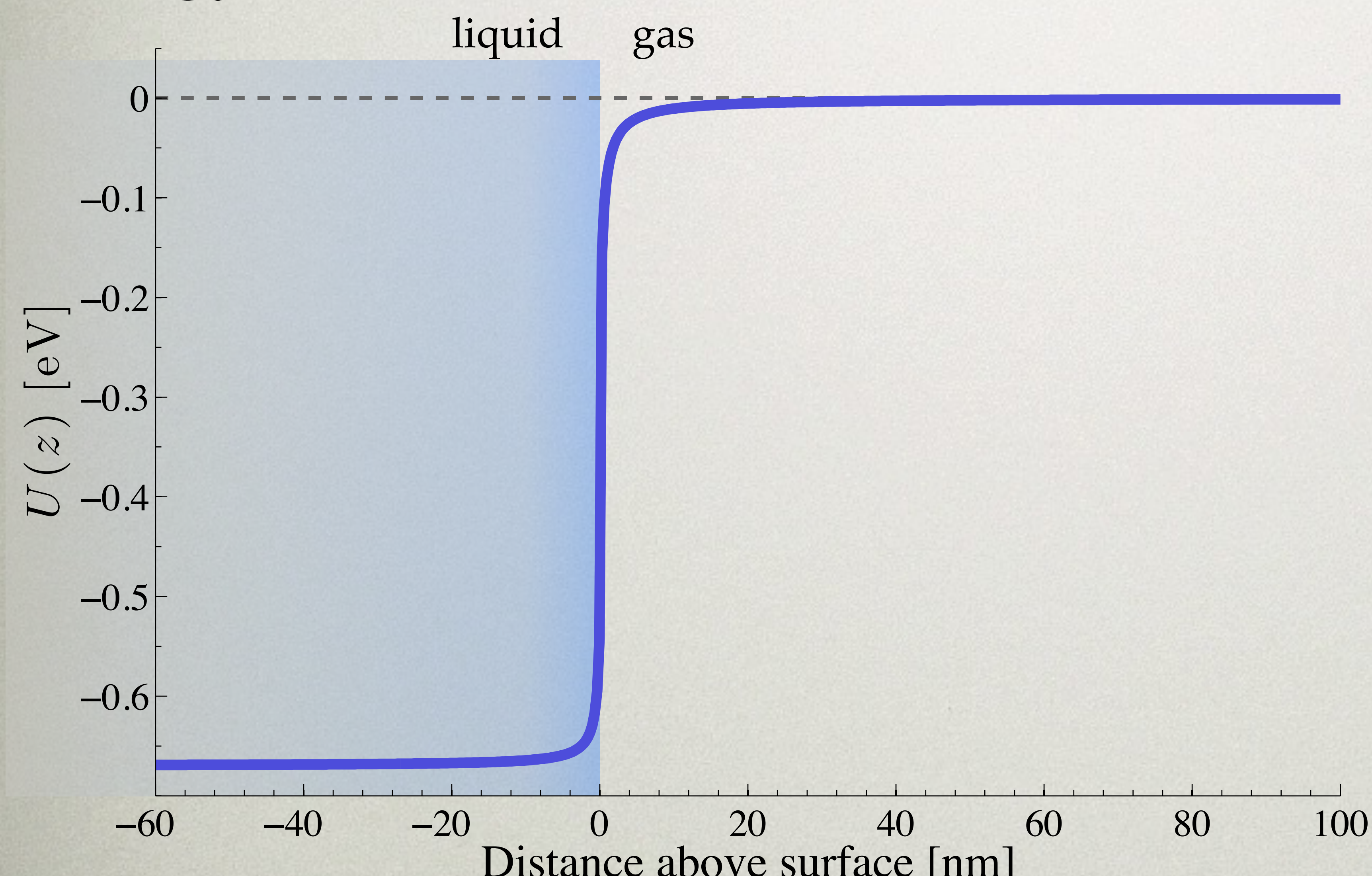
LAr: ~100% efficiency for electron extraction at ~4 kV / cm

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)

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

Understanding extraction in LXe

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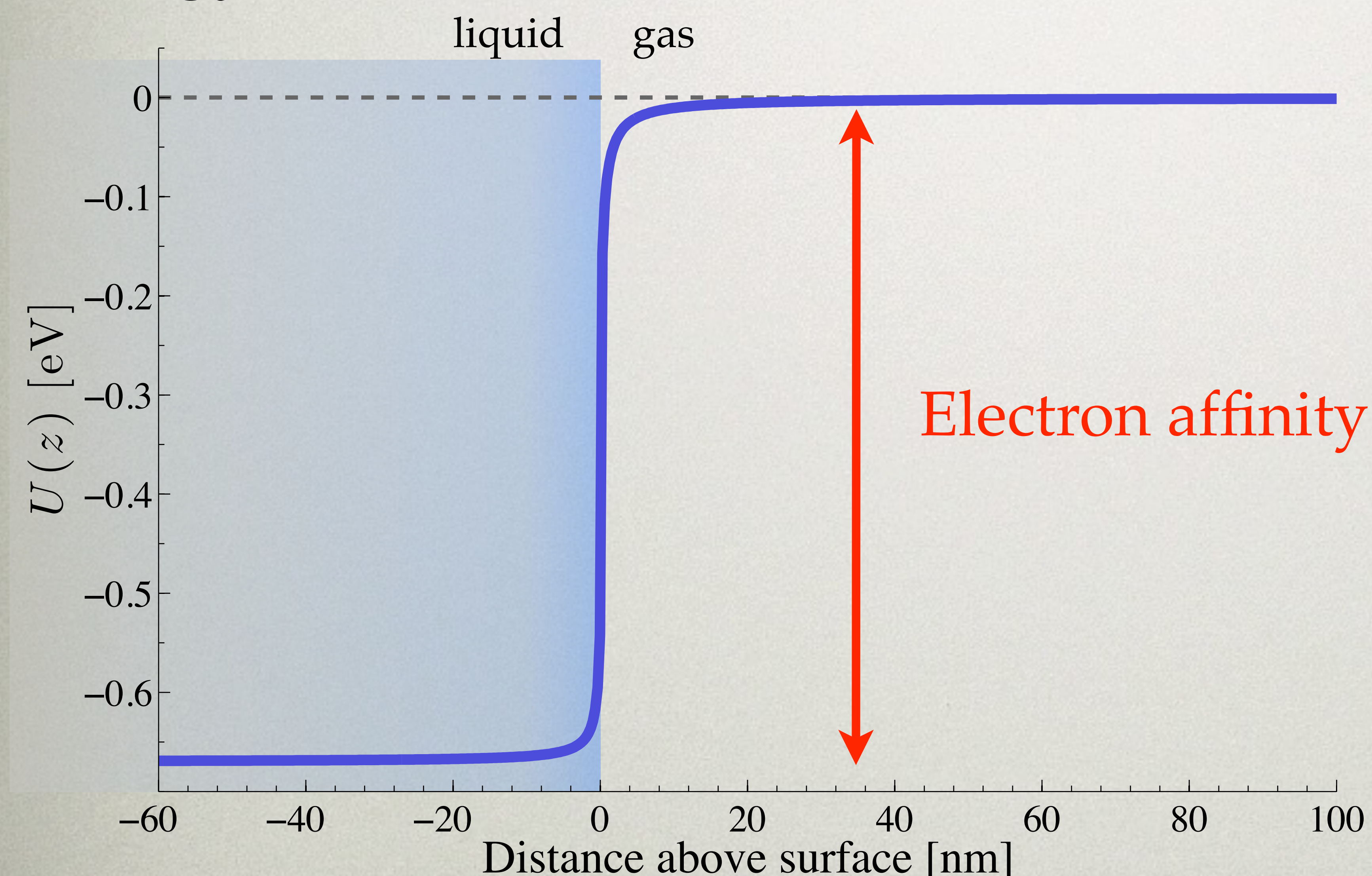

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Understanding extraction in LXe

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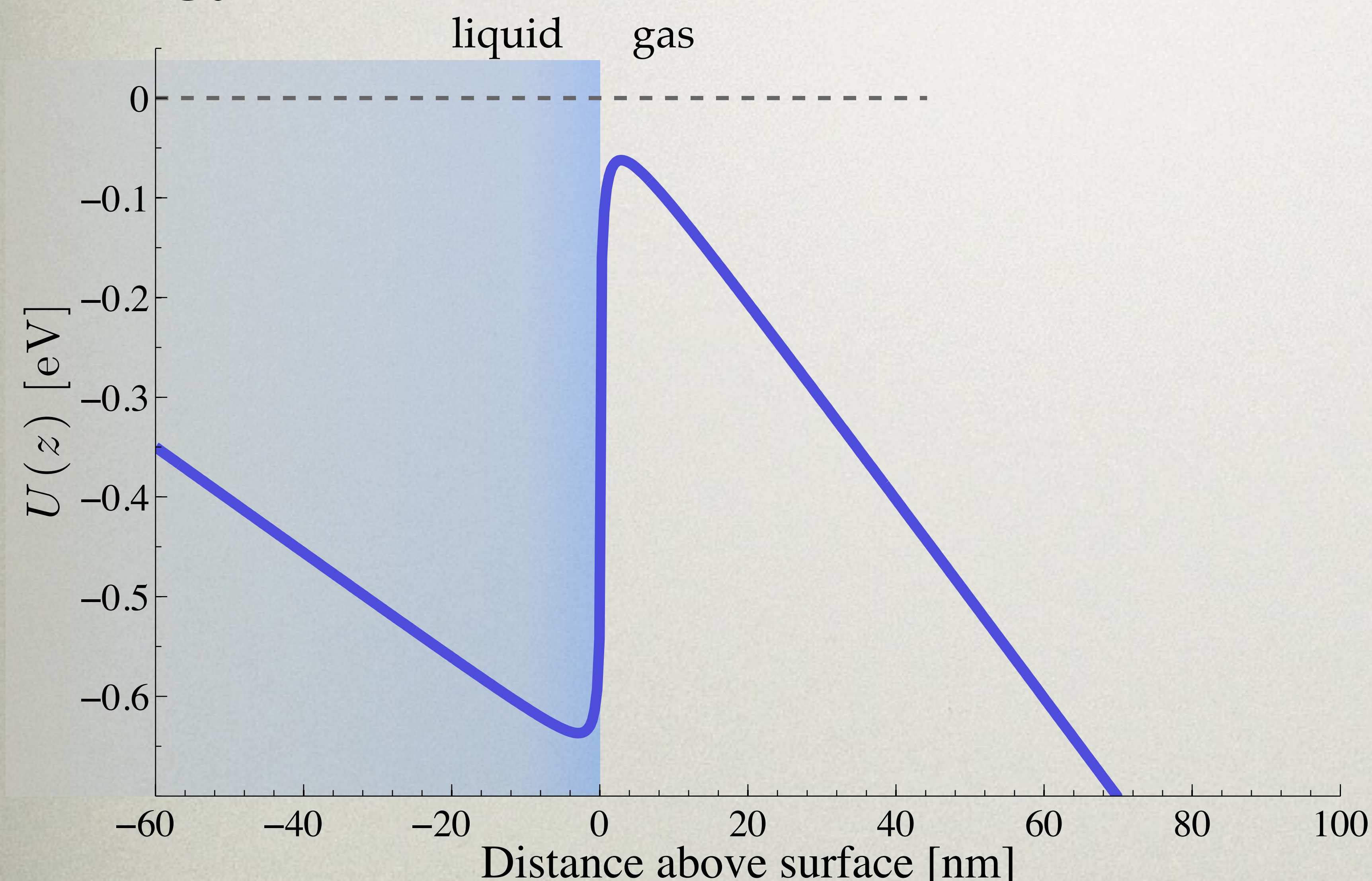

(with field)

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

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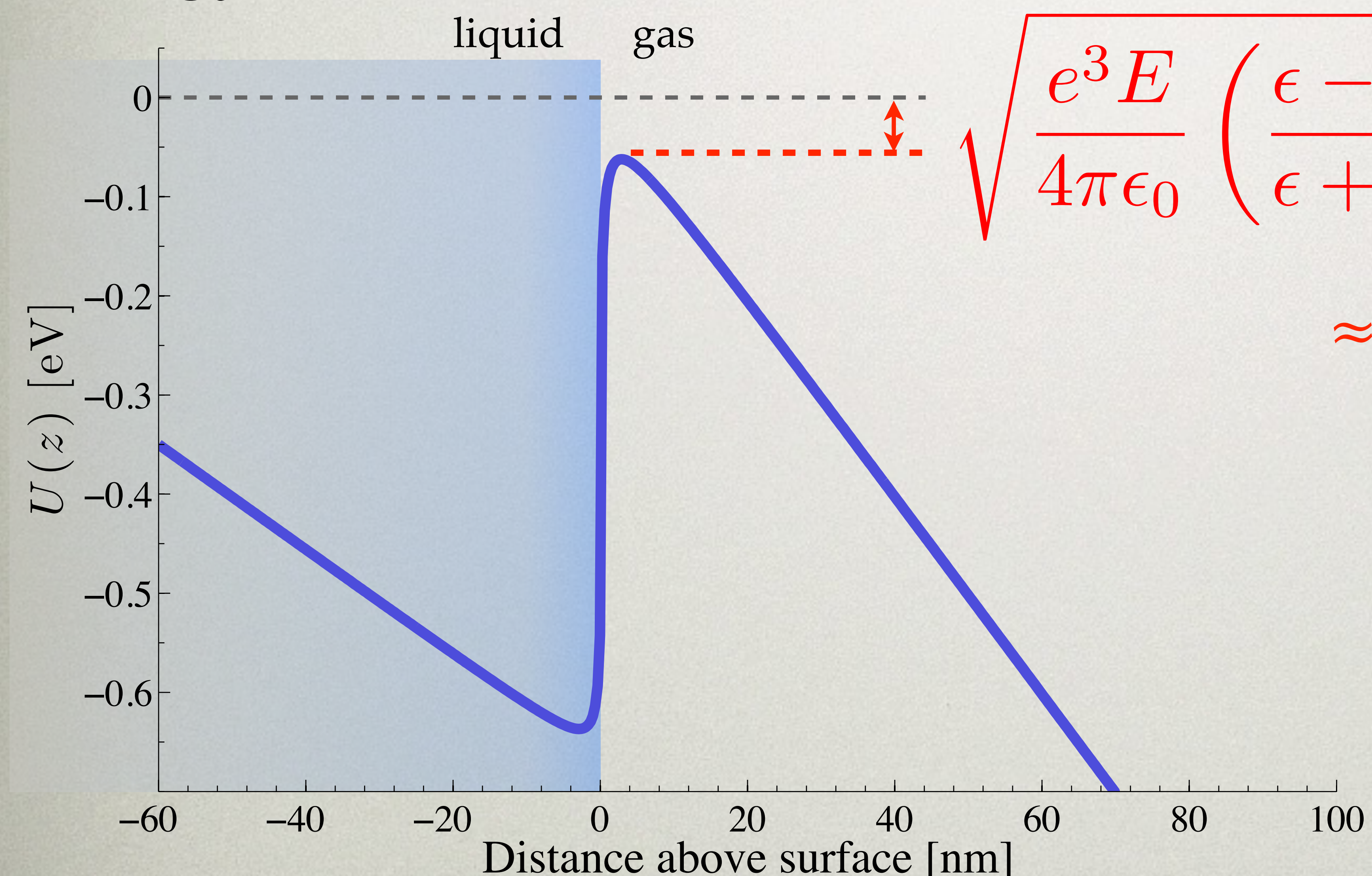

$$\sqrt{\frac{e^3E}{4\pi\epsilon_0}\left(\frac{\epsilon-\epsilon_0}{\epsilon+\epsilon_0}\right)}$$

≈ 0.02 eV at 10 kV / cm

(with field)

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

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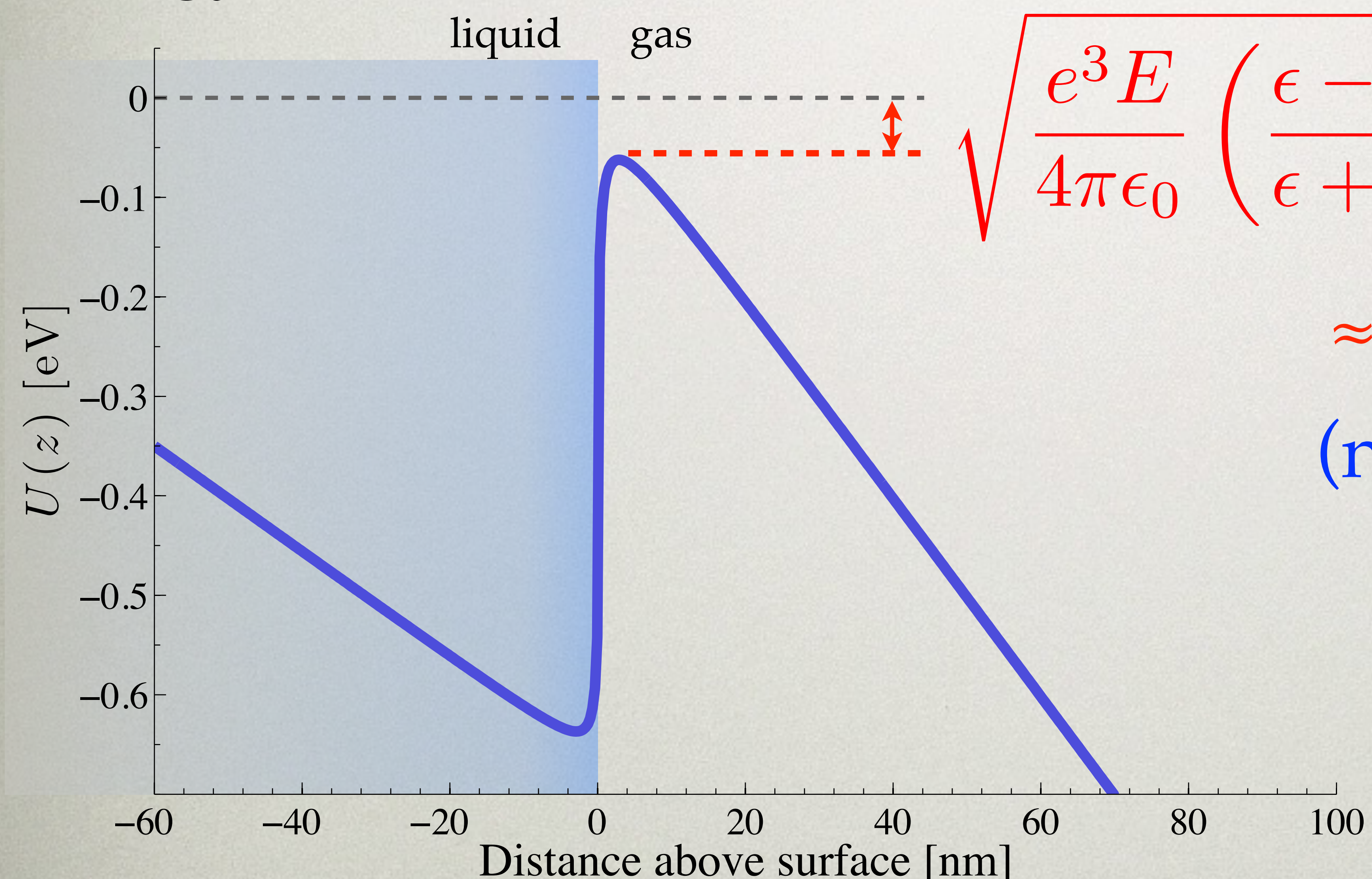


$$\sqrt{\frac{e^3E}{4\pi\epsilon_0}\left(\frac{\epsilon-\epsilon_0}{\epsilon+\epsilon_0}\right)}$$

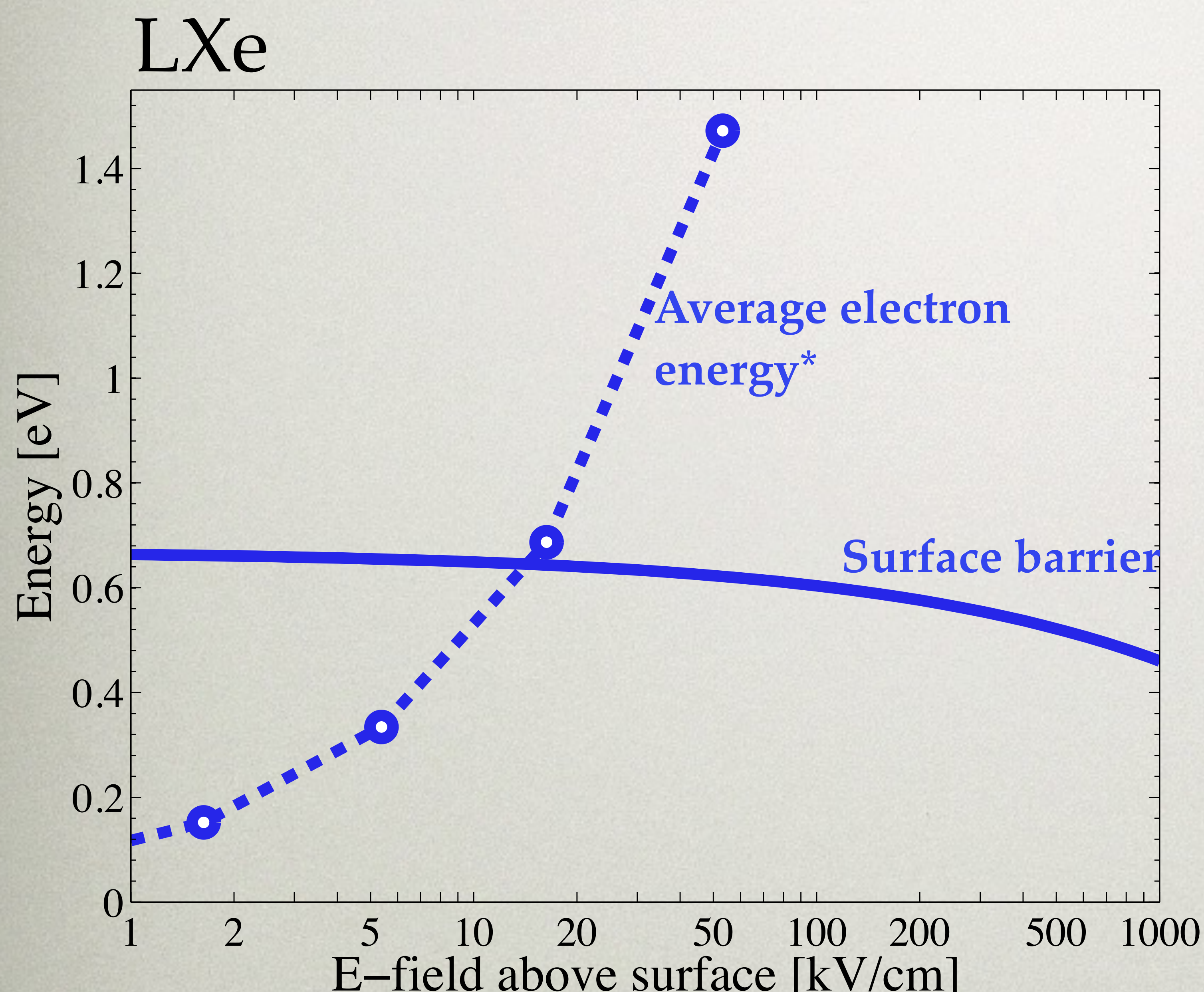
≈ 0.02 eV at 10 kV / cm

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

(with field)

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

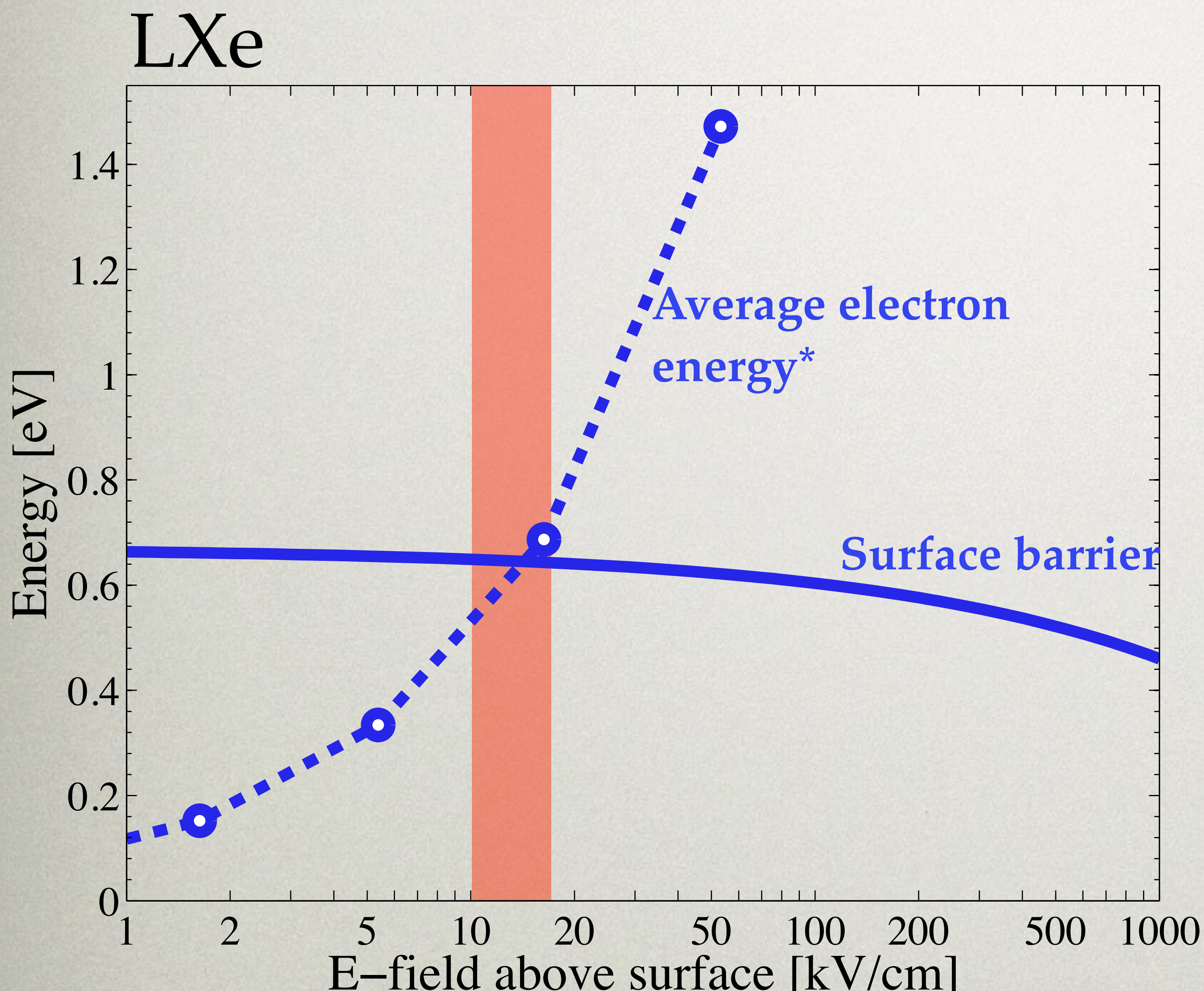
Electron heating



- 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



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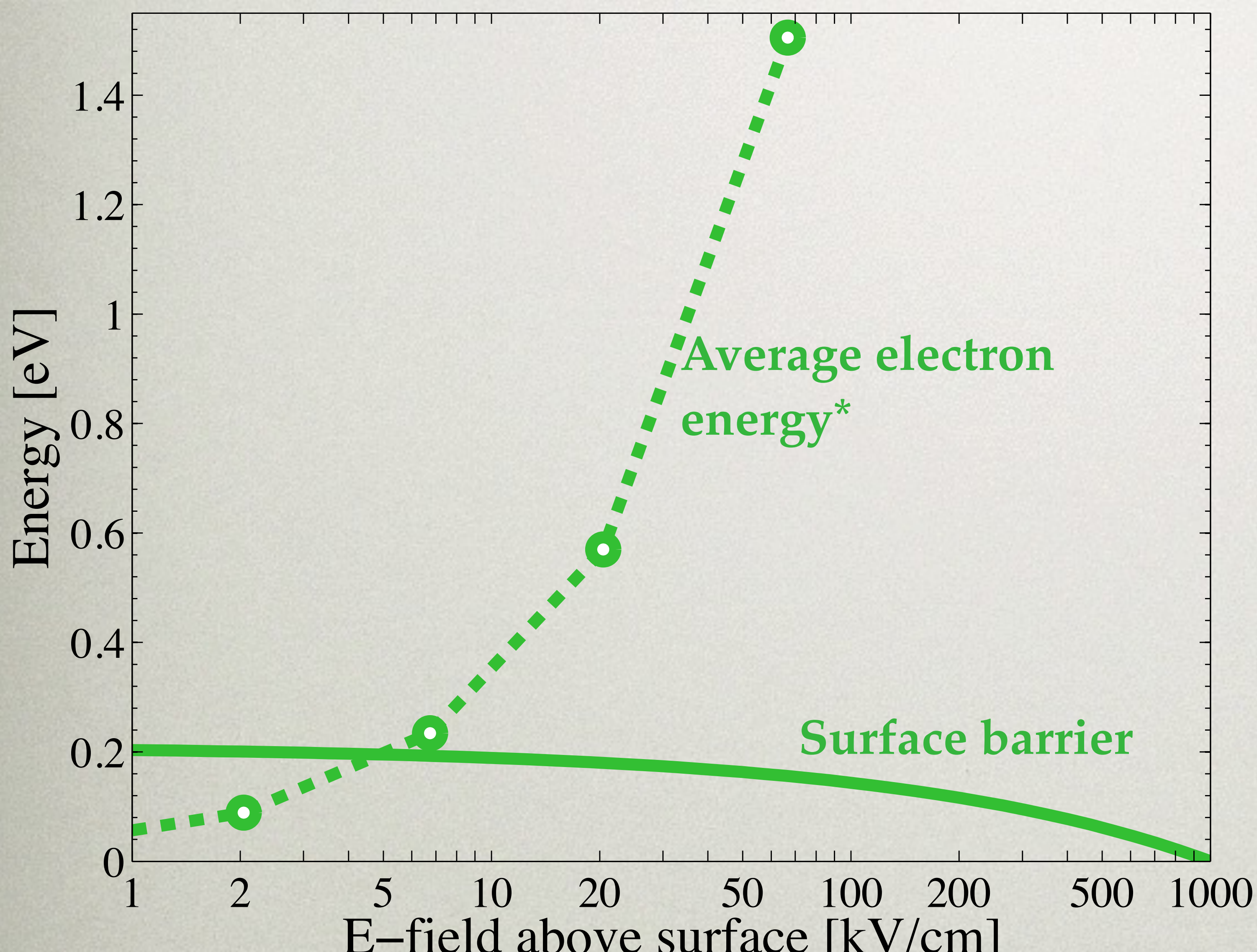
Electron heating

LAr



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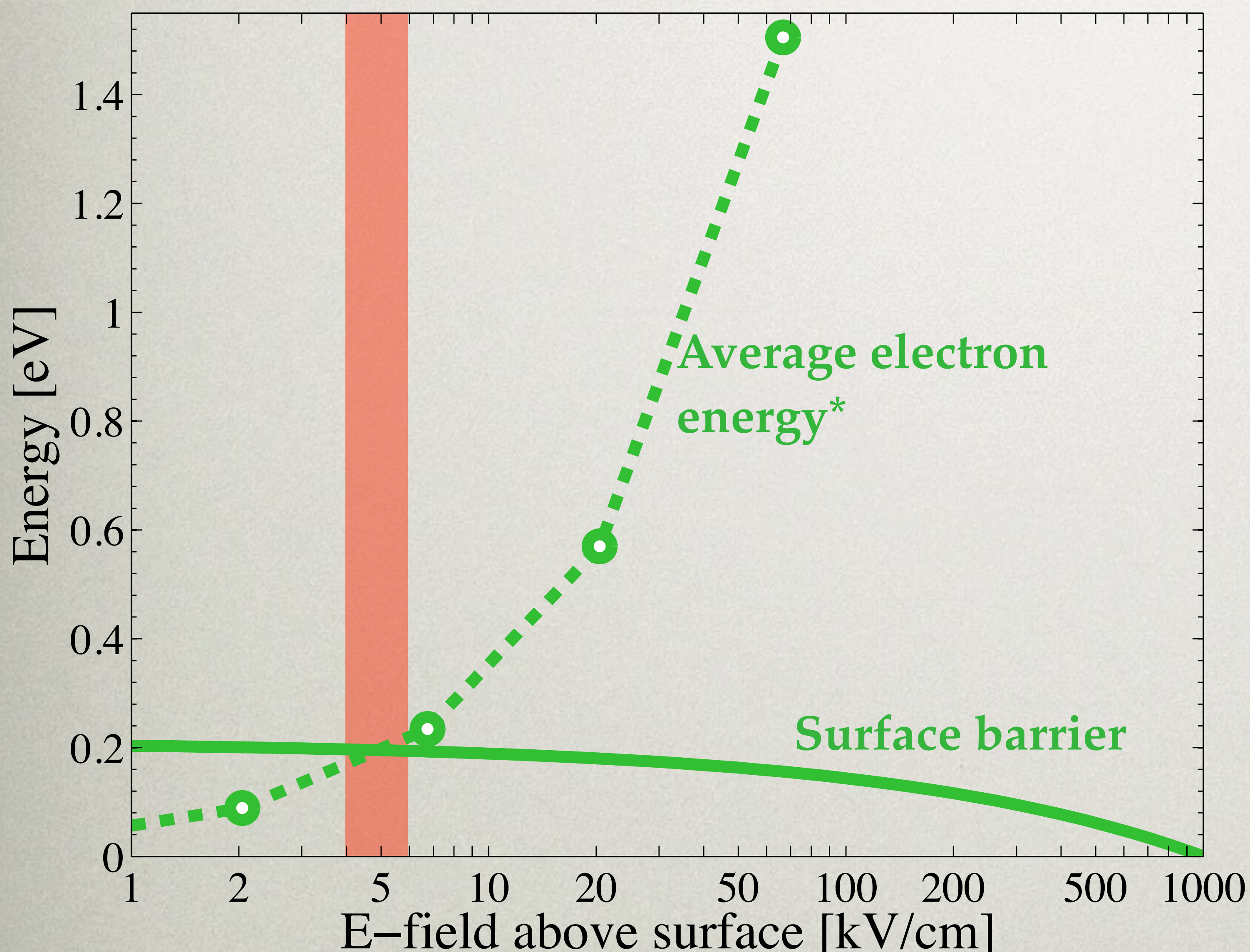

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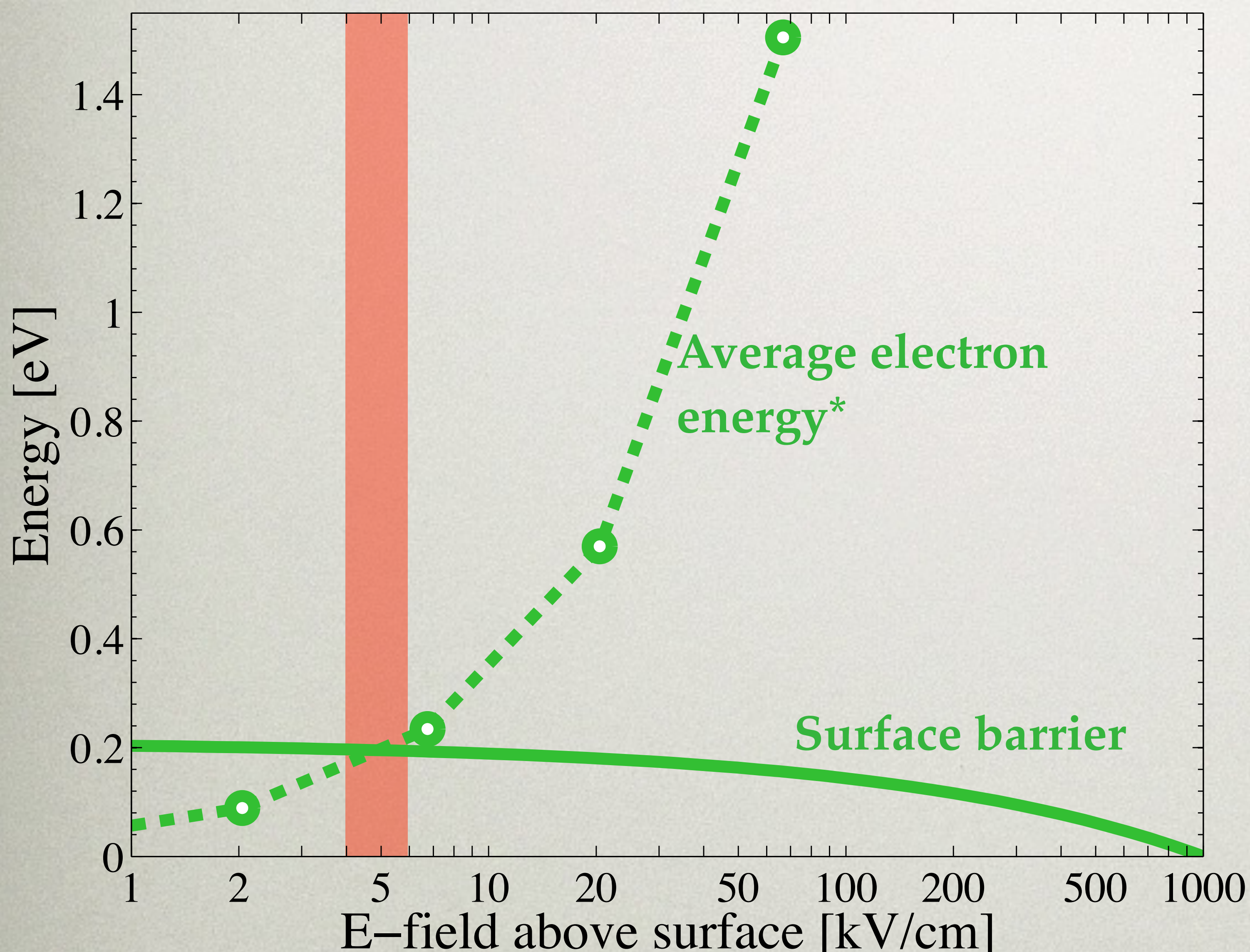

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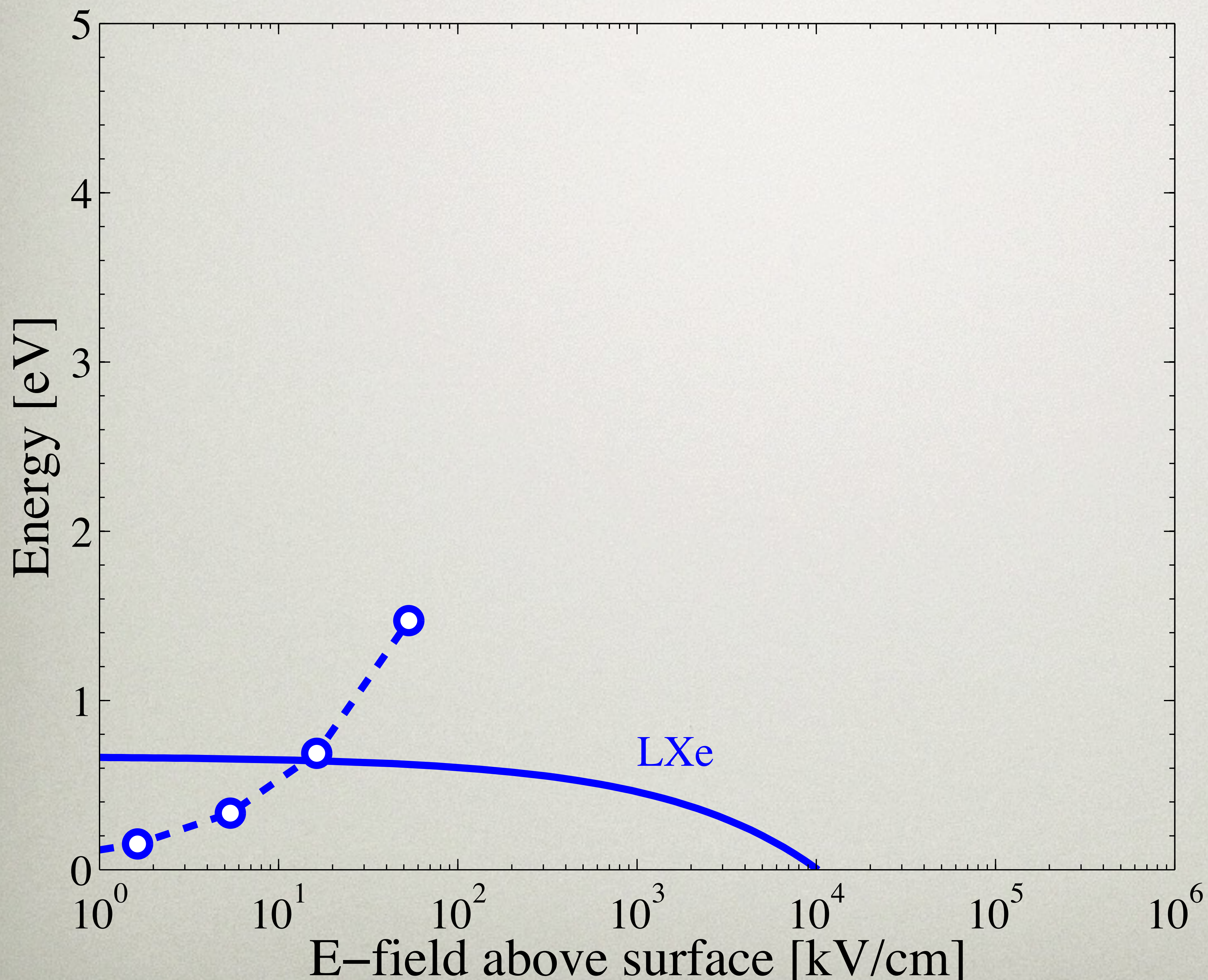
What does this plot look like for Si?

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

Electron heating (?)



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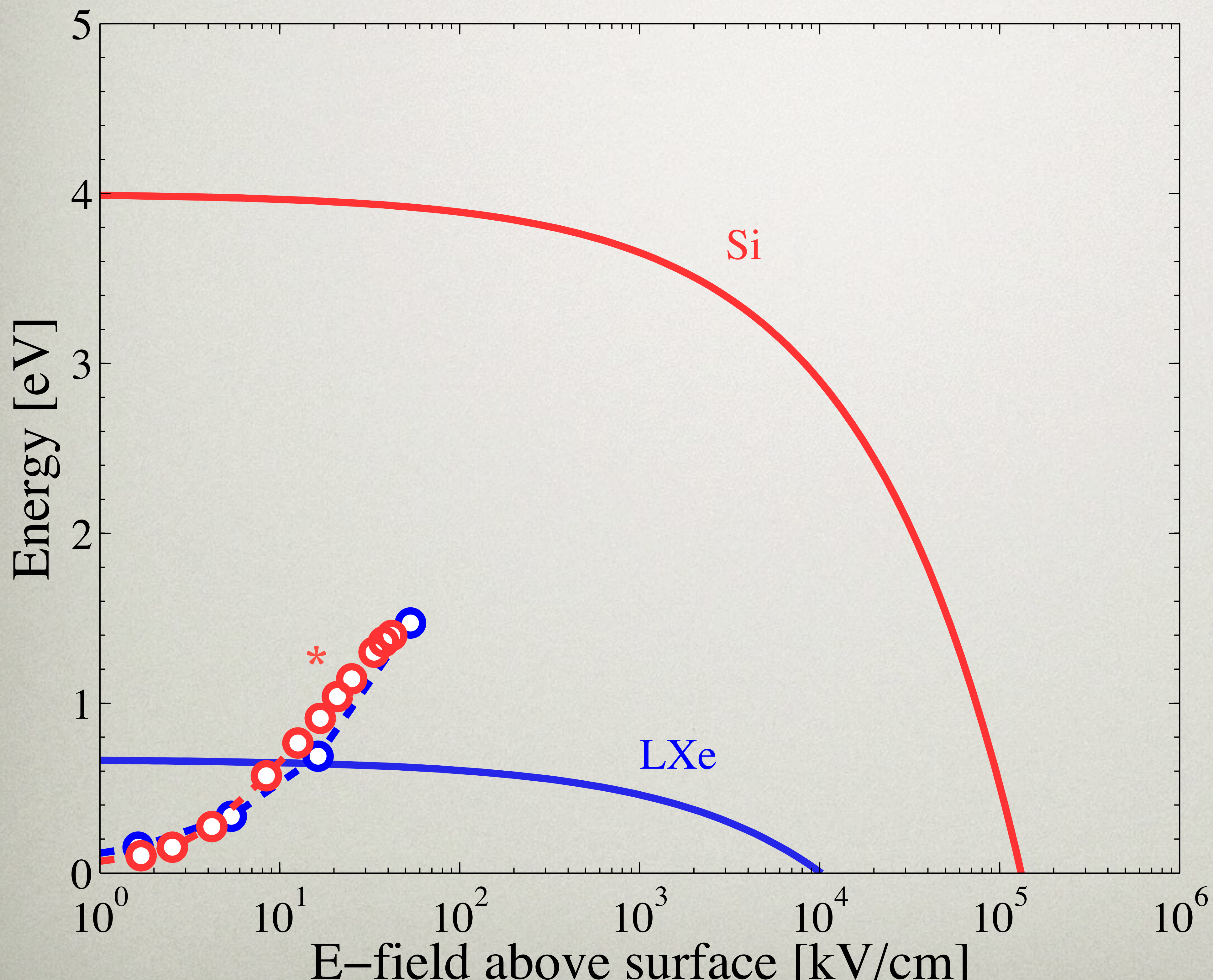
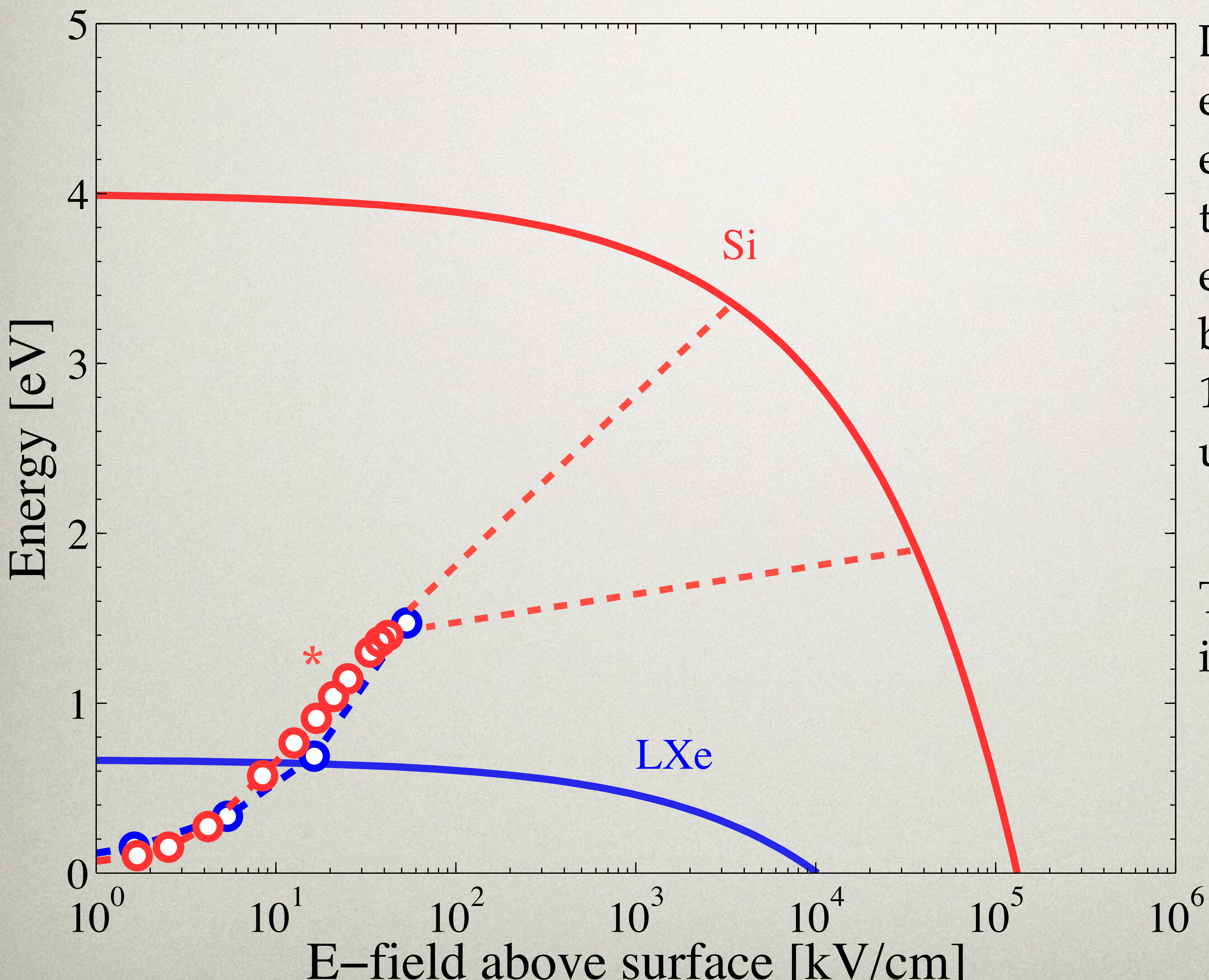


* M.J. Martín *et al.*, Semicond. Sci. Technol. 8 (1993) 1291

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?

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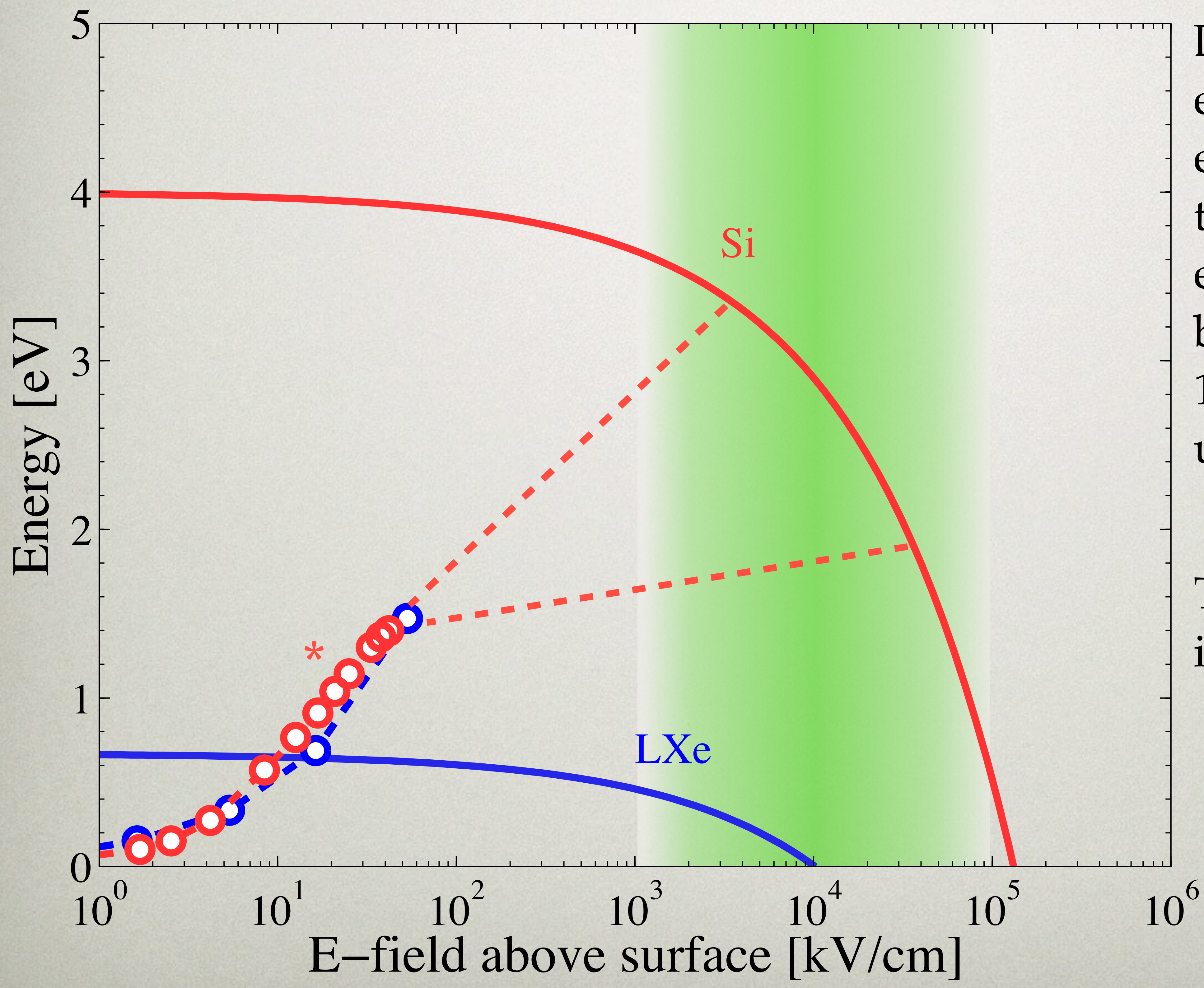

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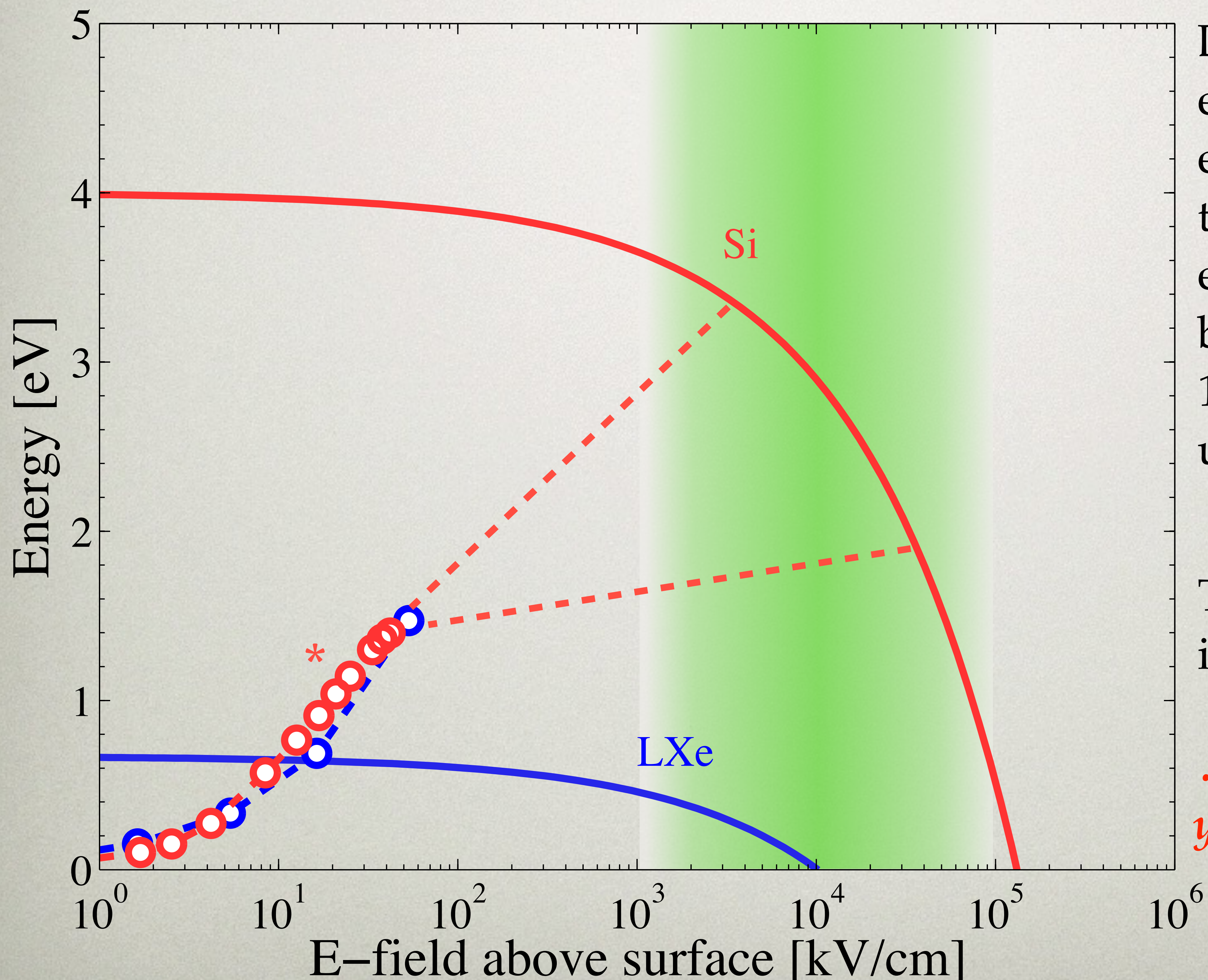


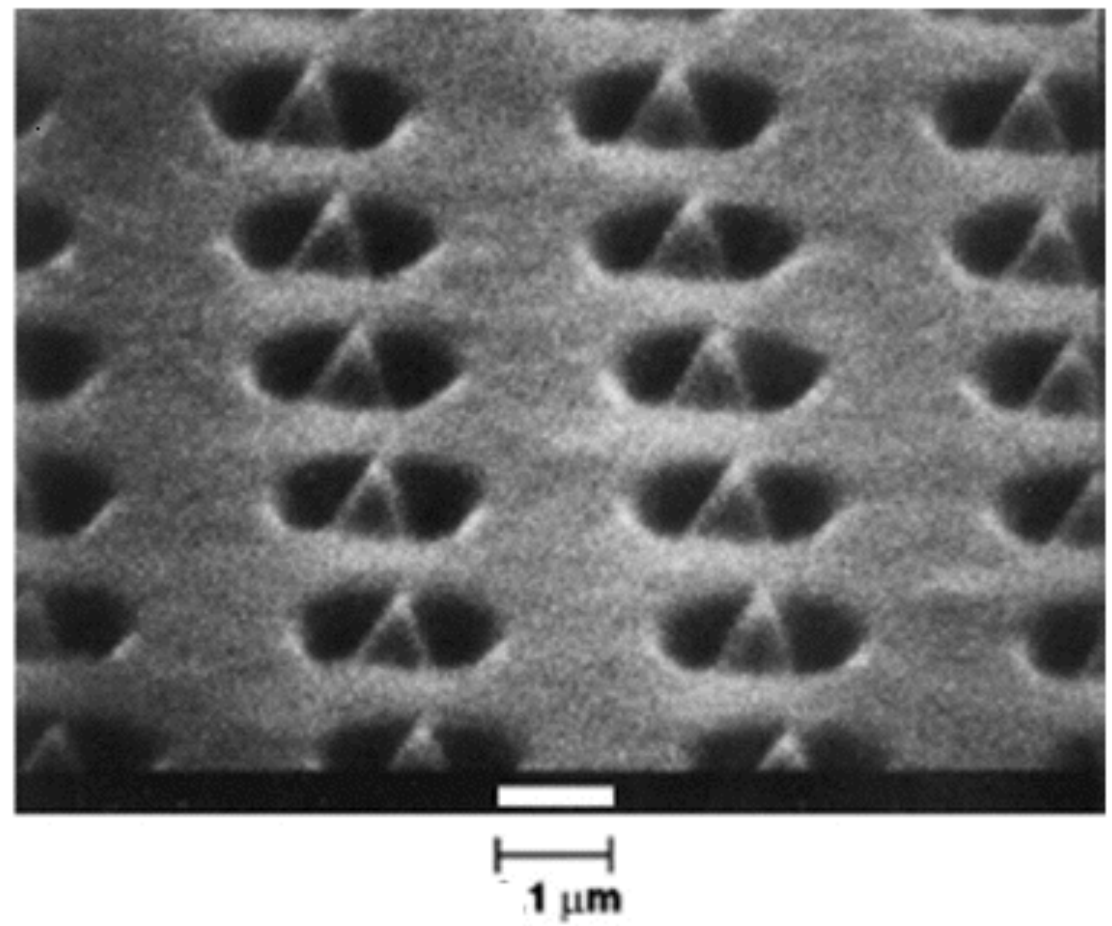
Depending on how I extrapolate the Si electron temp data, the necessary extraction field could be anywhere from 10^3 kV/cm or even up to 10^5 kV/cm.

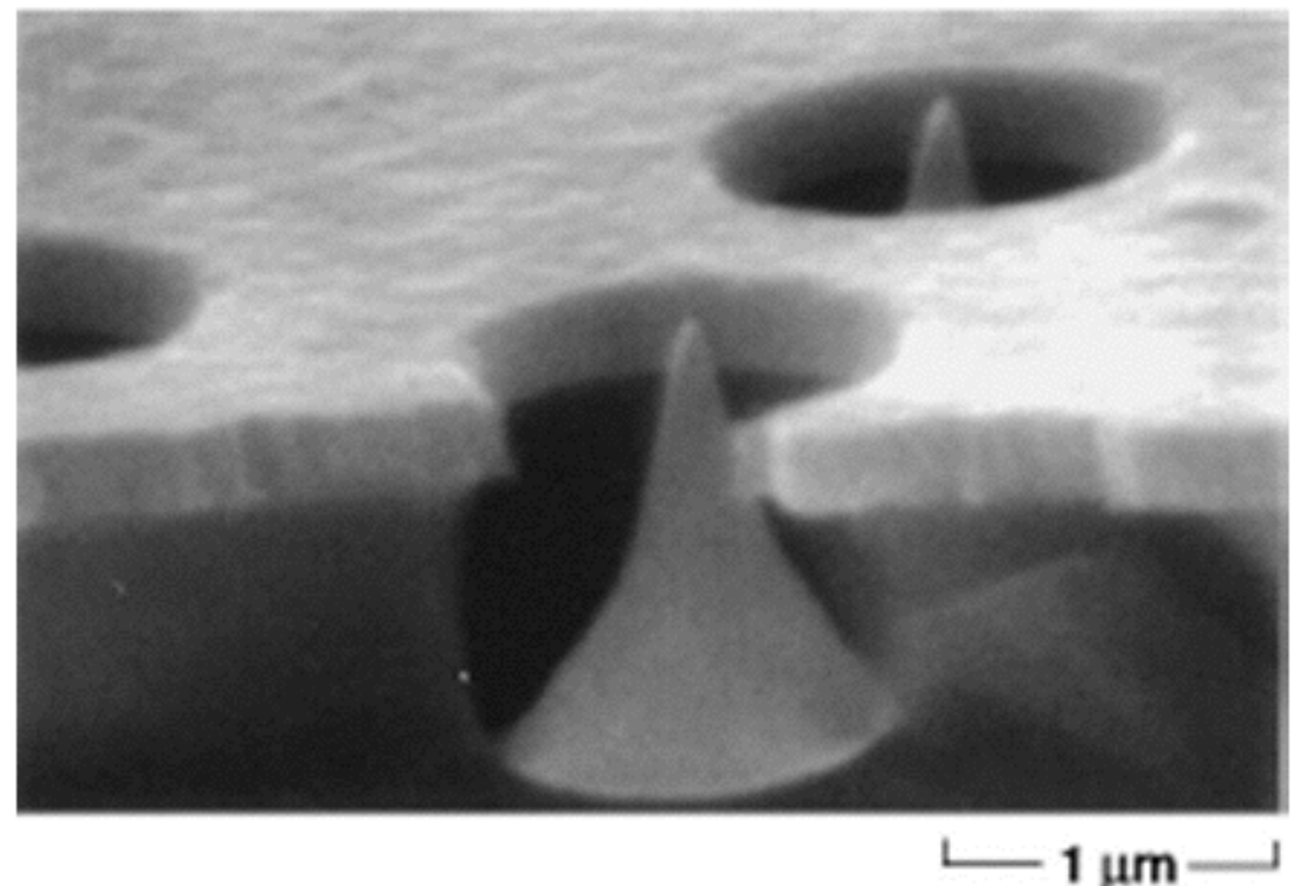
That's not feasible, is it?

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

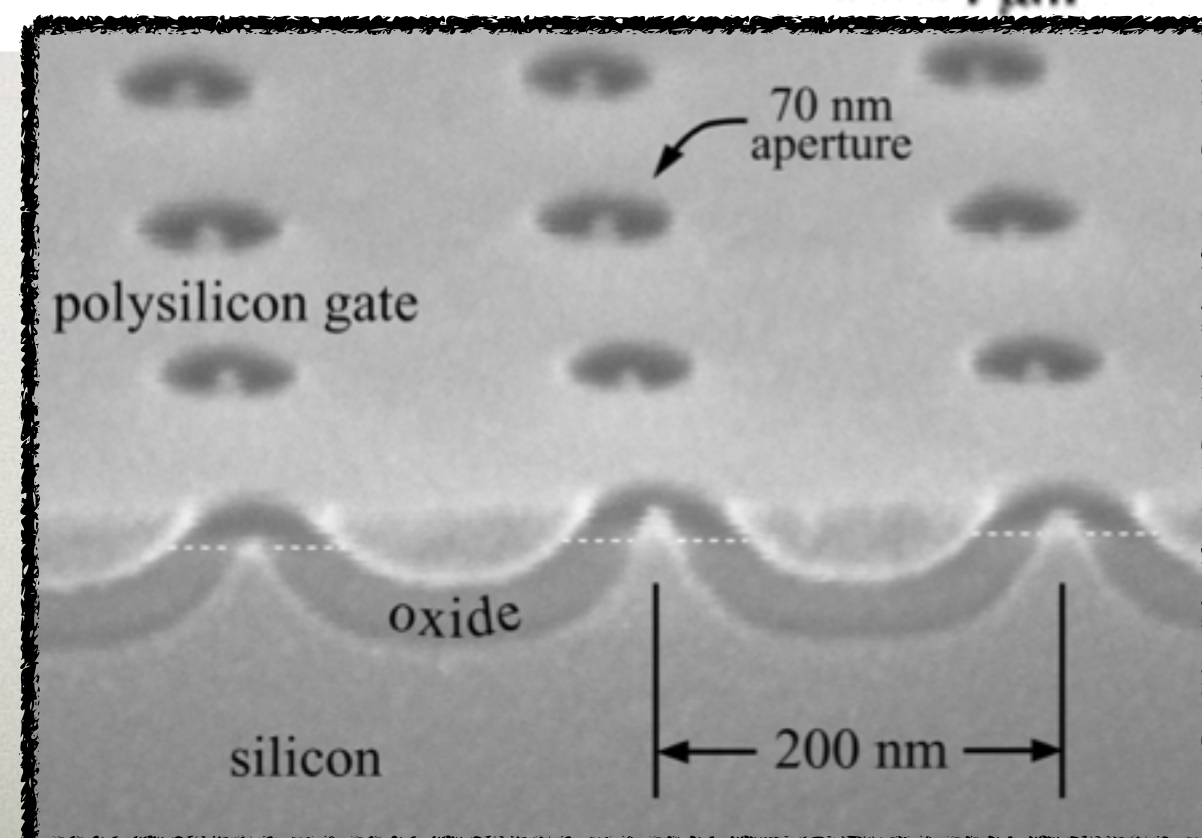
* M.J. Martín *et al.*, Semicond. Sci. Technol. 8 (1993) 1291

Field Emitter Arrays





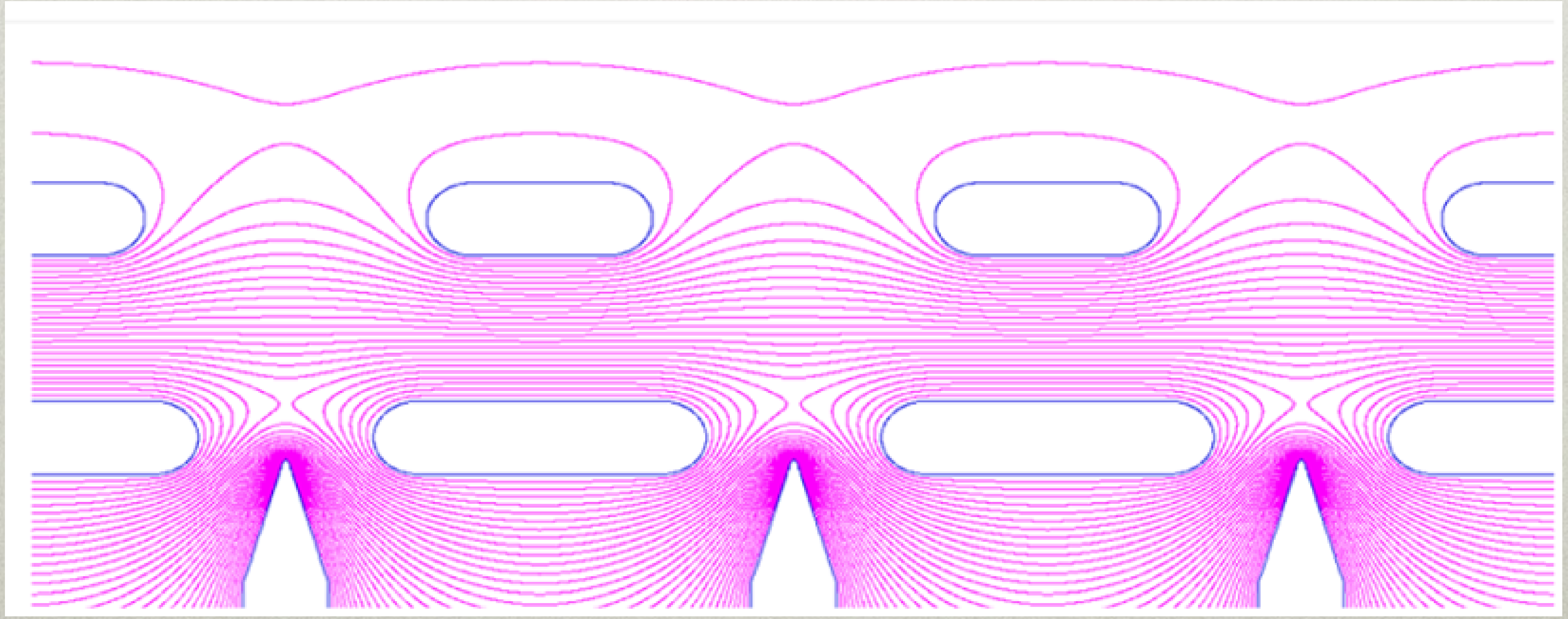
An array of microscopic tips is etched on the surface of the silicon (or other material). A conducting plate is held above the surface by an insulating layer. *Tips are* nm-*sharp!!!*



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 not 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 on a sapphire substrate having either a random or regular array

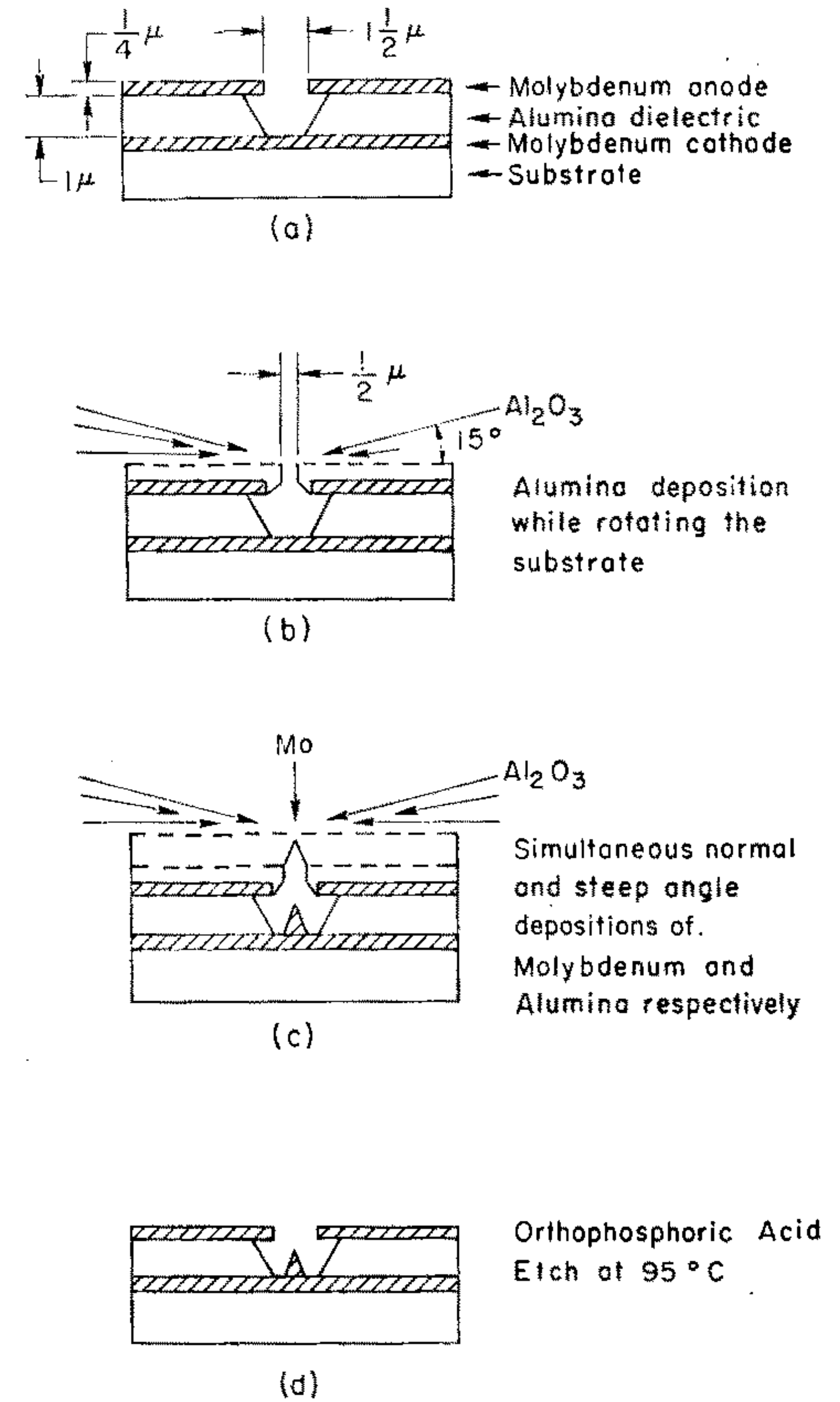
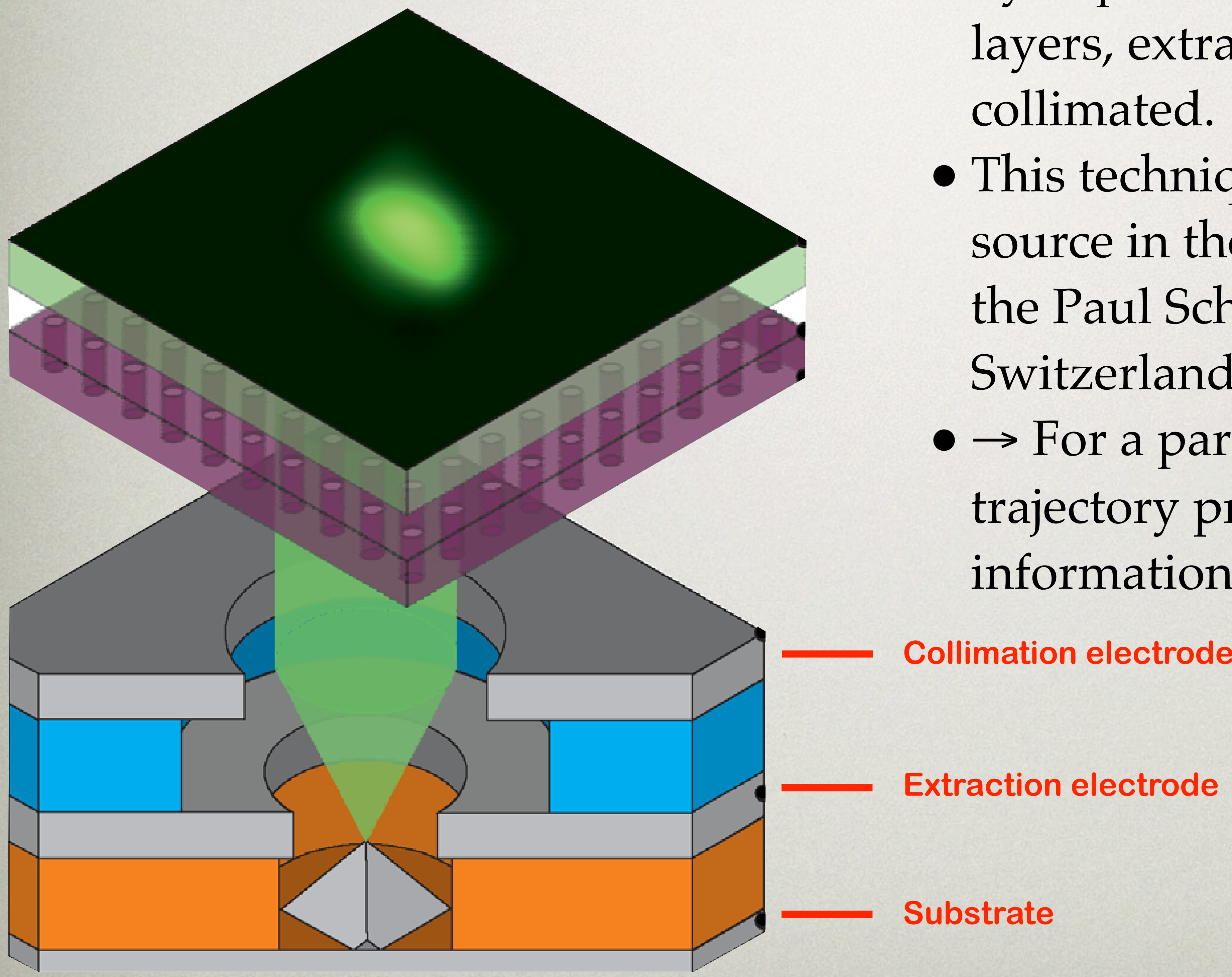


FIG. 2. Cathode formation by deposition from two sources.

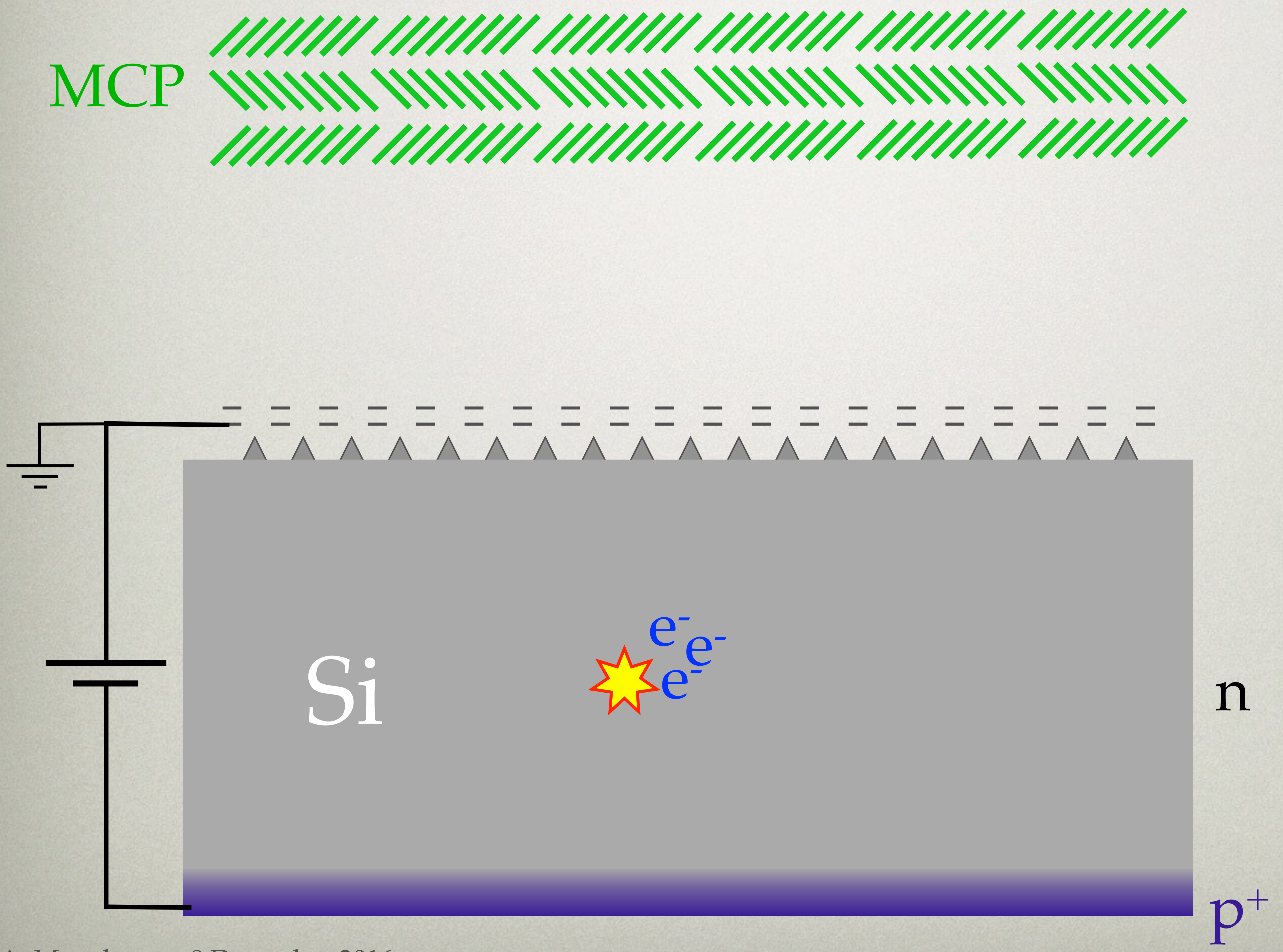
Electron collimation

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

Towards a detector concept



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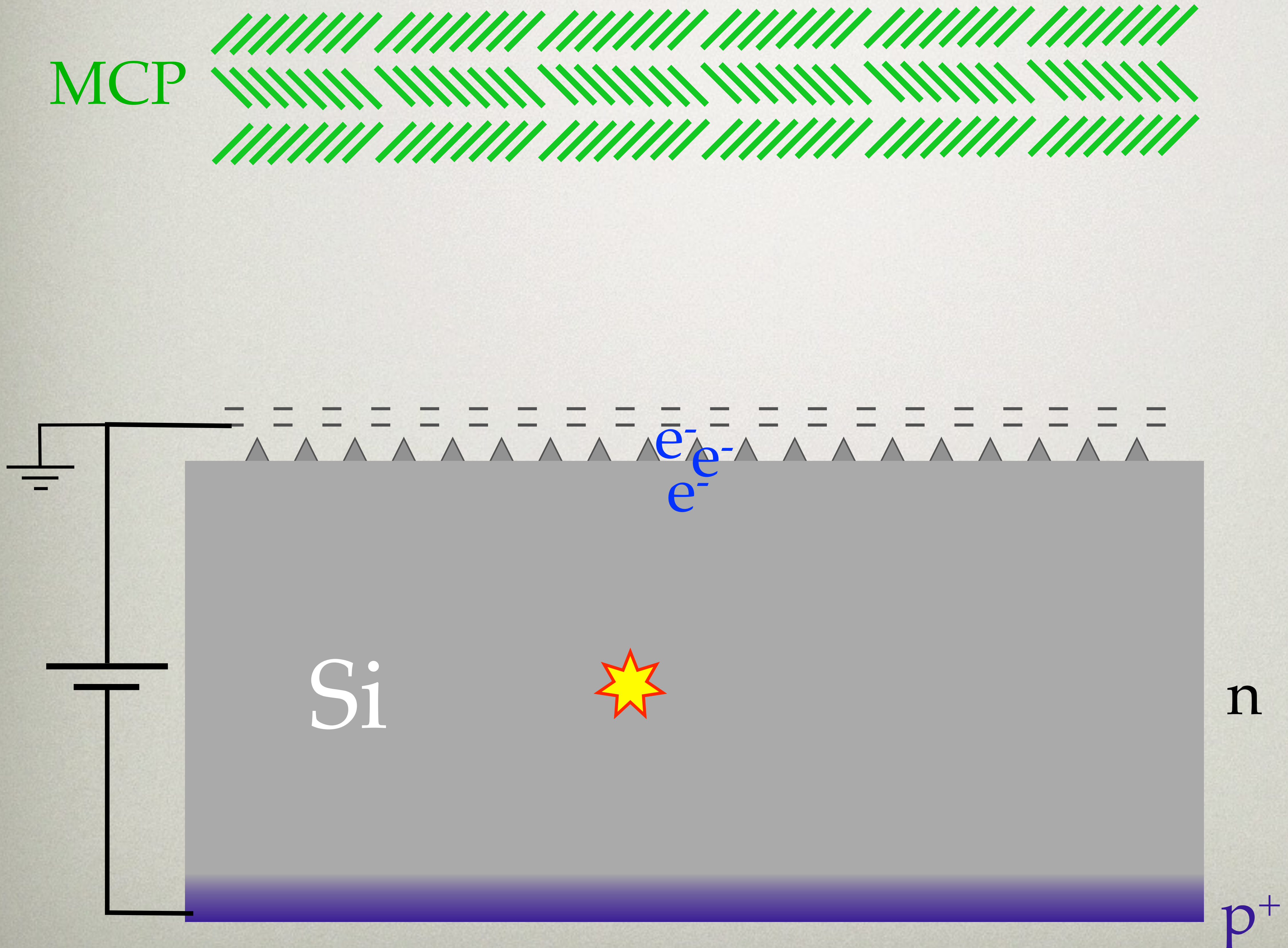

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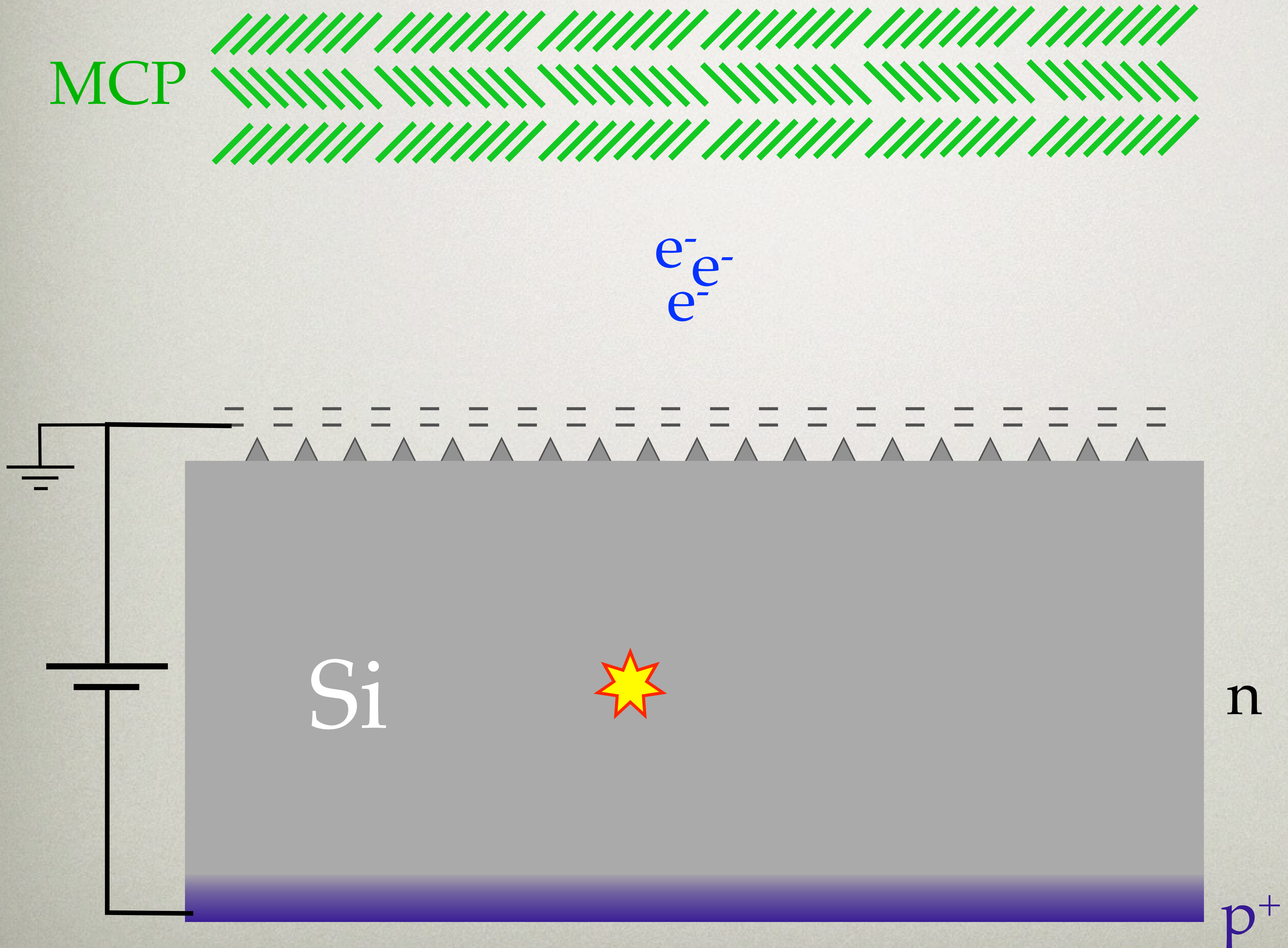

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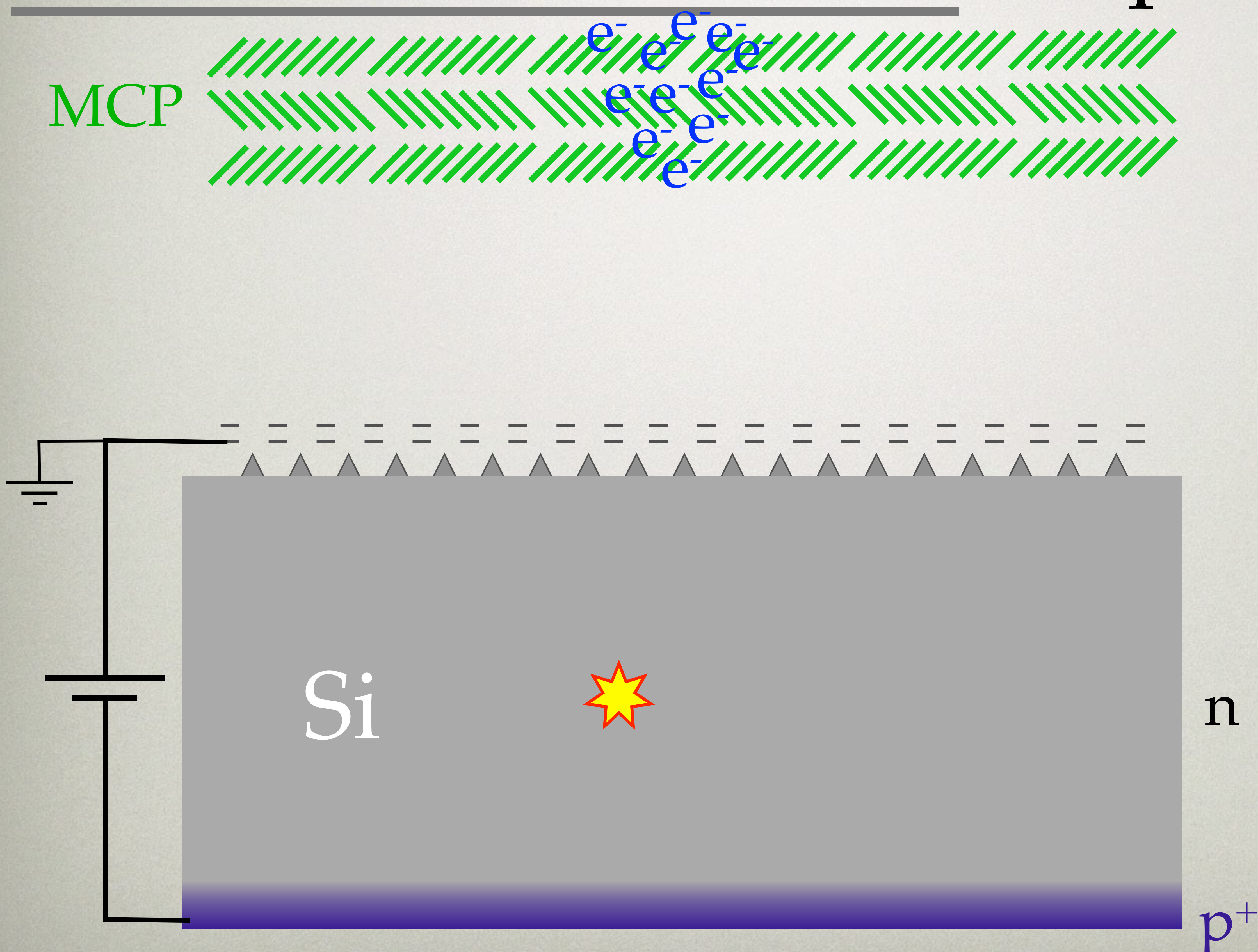


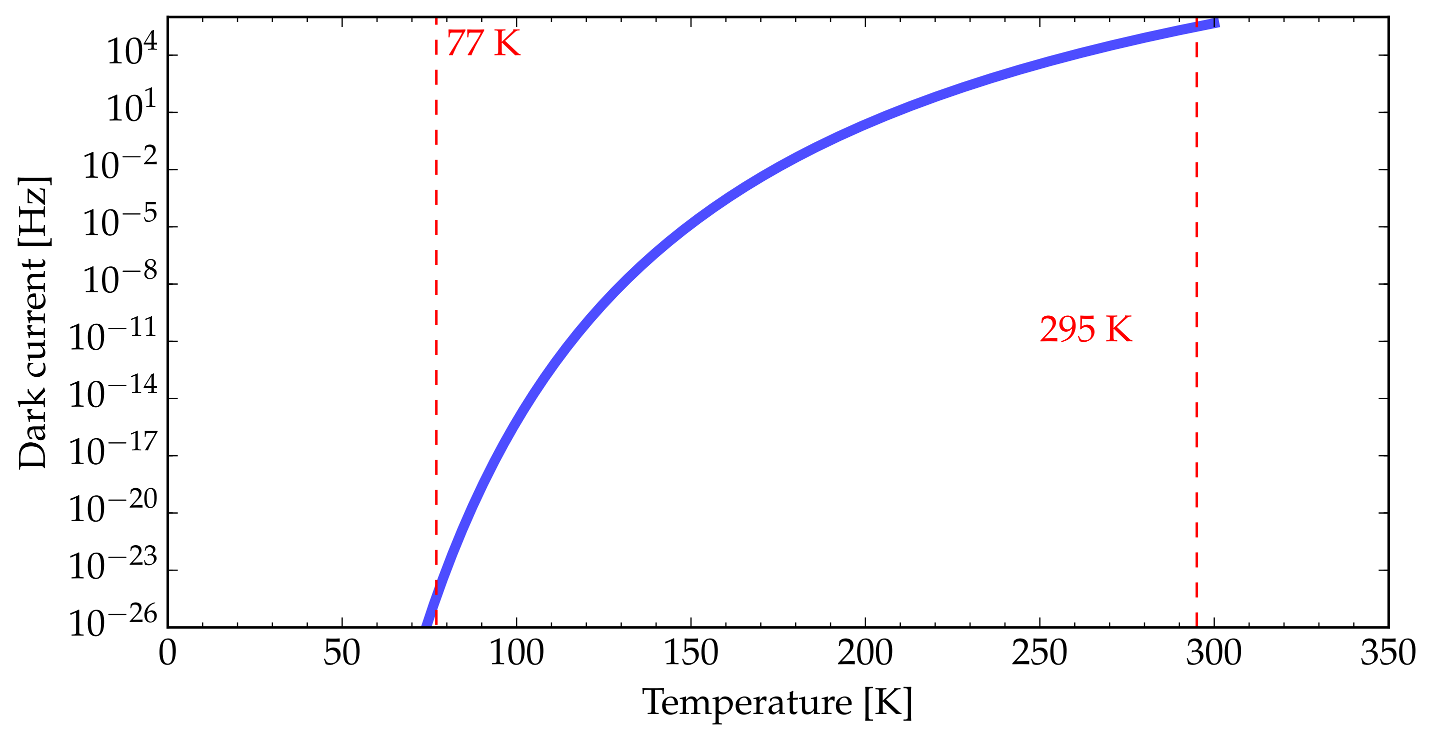
Someone else apparently had a similar idea…

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

Achieved 50 fA dark current at room temperature; given the carrier density scales as:

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

So naively:



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

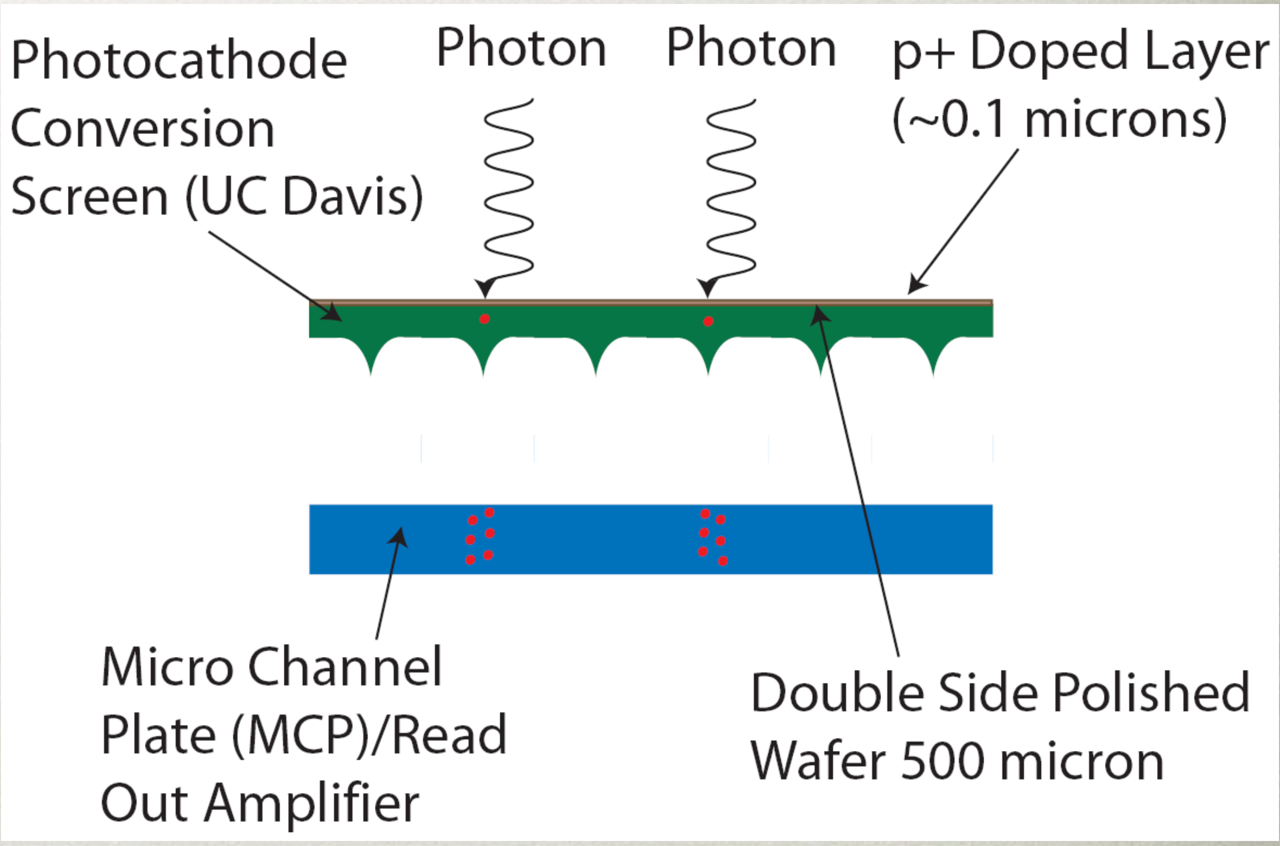


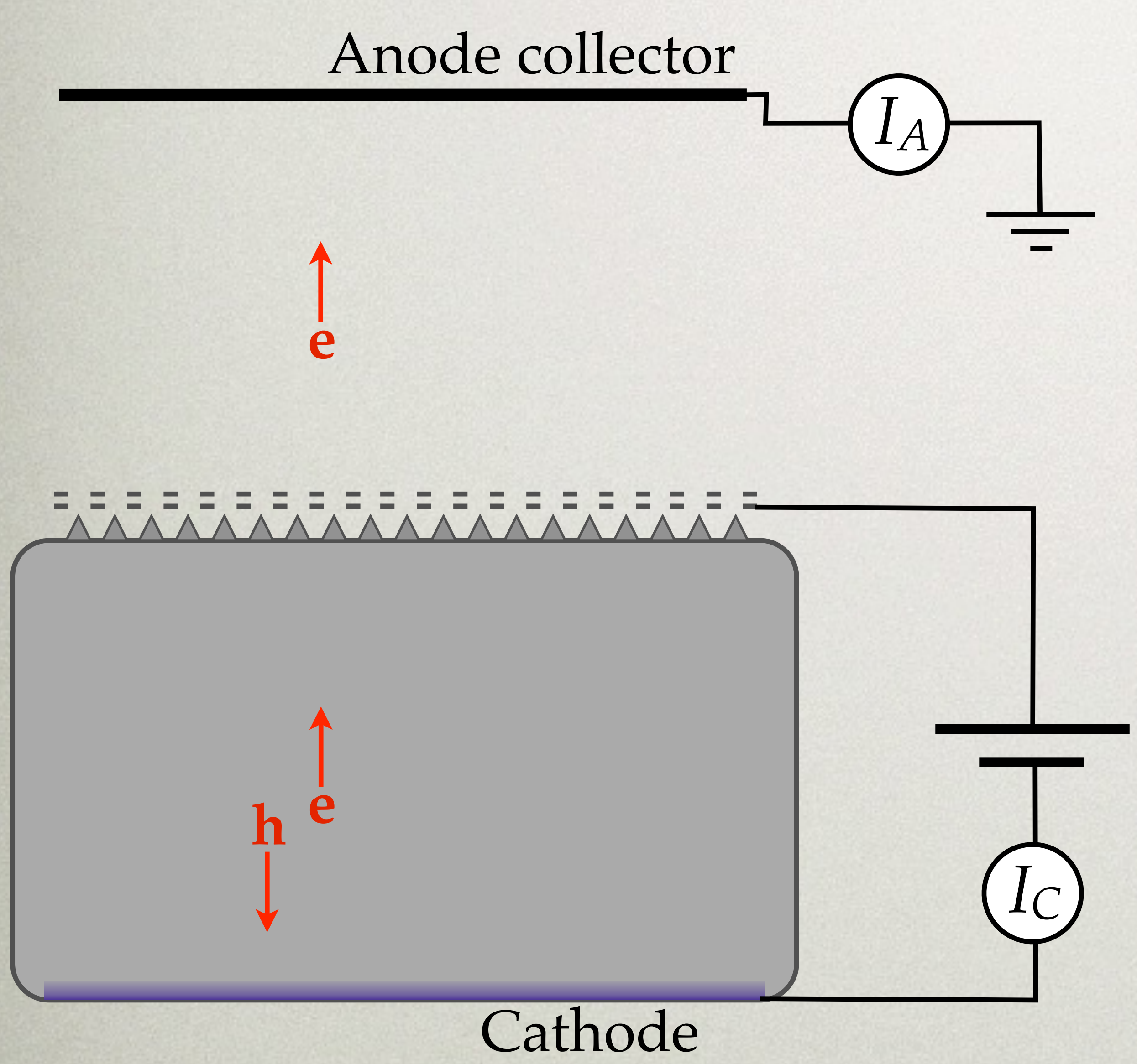
Figure 1: X-ray Imager and Energy Detector

Summary

- Searches for light DM provide good, well recognized motivations to build detectors with very low ionization thresholds
- Extracted electrons can easily be detected with the desired sensitivity
- High fields necessary to emit conduction electrons with high efficiency can be produced with microscopic tip arrays.
- Such a detector would be easy to operate, using simple, mature technologies.

Backup slides

Easy proof-of-principle

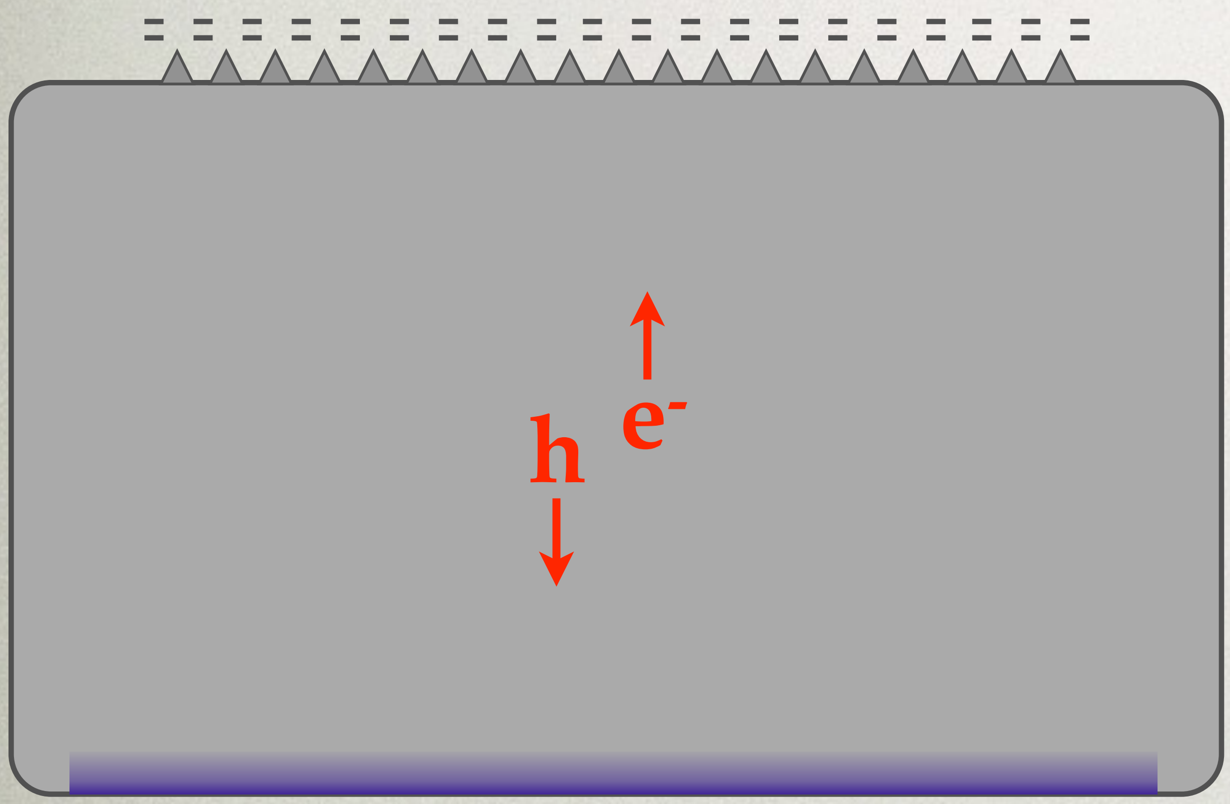


- To measure the extraction efficiency, one can measure the thermally induced current.
- The ratio of I_A to I_C should be equal to the extraction efficiency. It is essential to verify that this can be made something close to unity.
- The temp. can be varied to estimate which portion of I_C is due to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

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

Thoughts on potential backgrounds

Thermally induced electrons



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

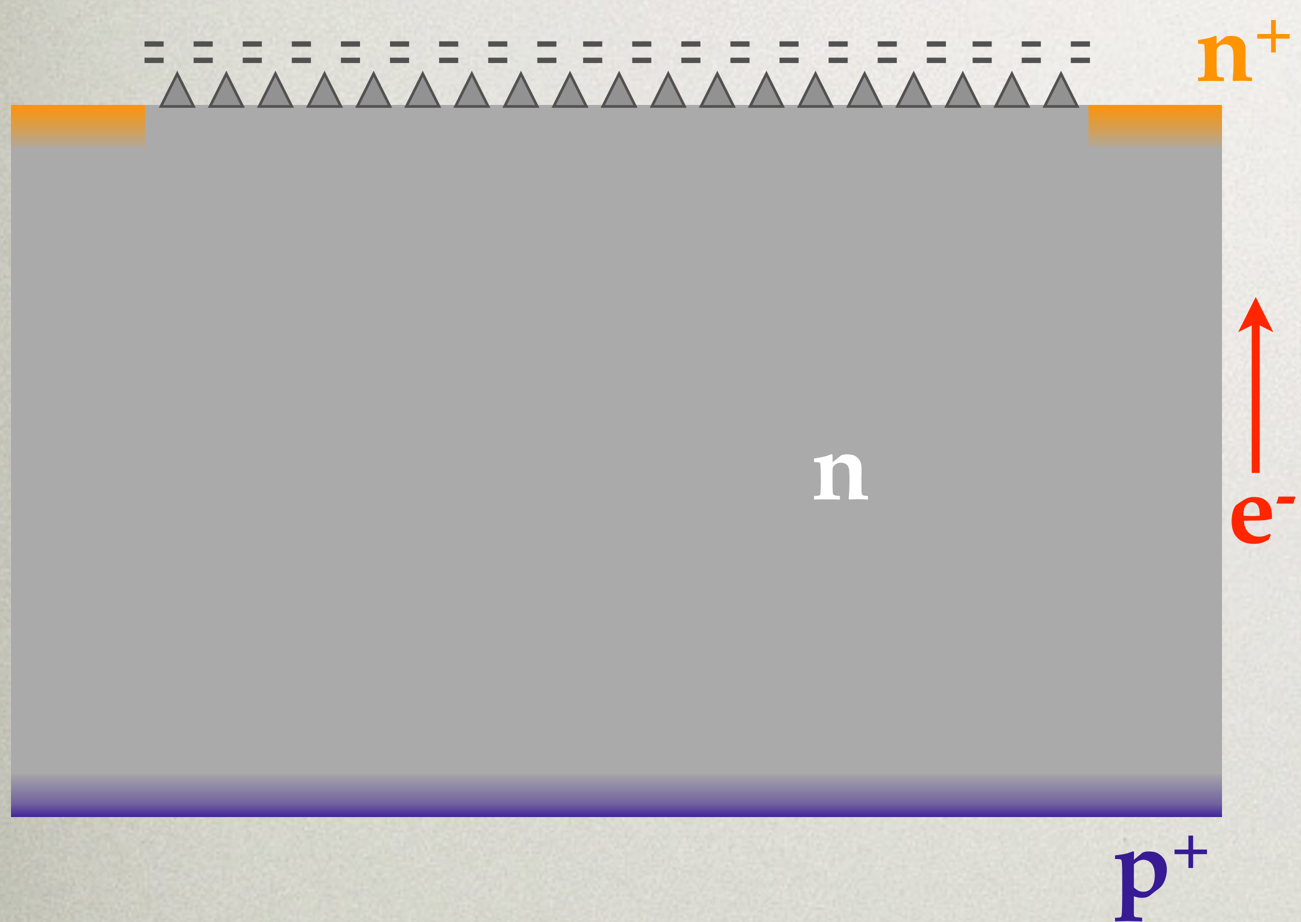
$E_g \approx 1.2$ eV (Silicon)

For example going from 77K to 4K suppresses the thermally induced current by over 700 orders of magnitude!!

Likely no difficult cryogenics needed (i.e. **no dilution fridge**).

Thoughts on potential backgrounds

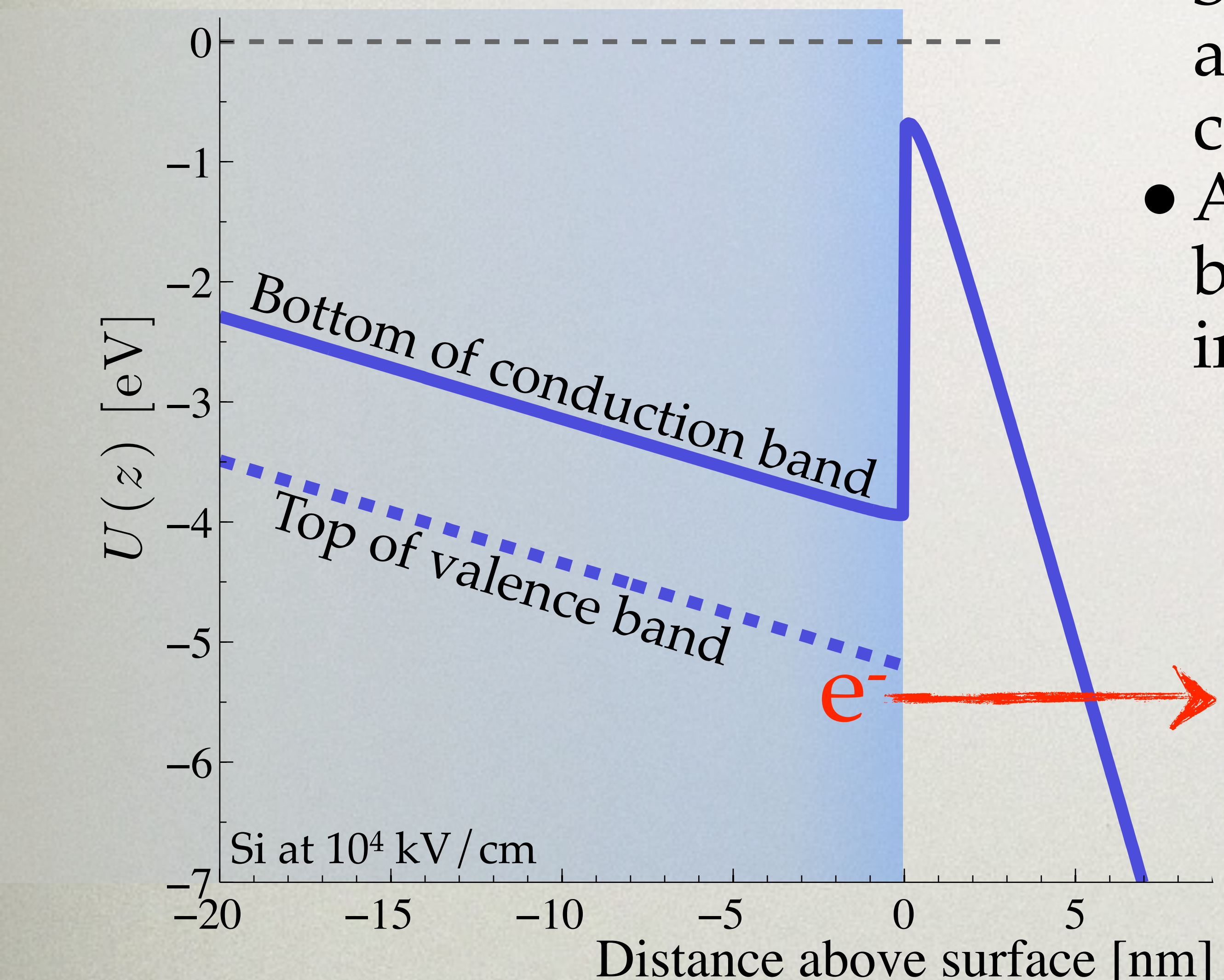
Surface currents



- 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)