Detecting Very Low Energy Electrons with Transition-Edge Sensors for the PTOLEMY Project

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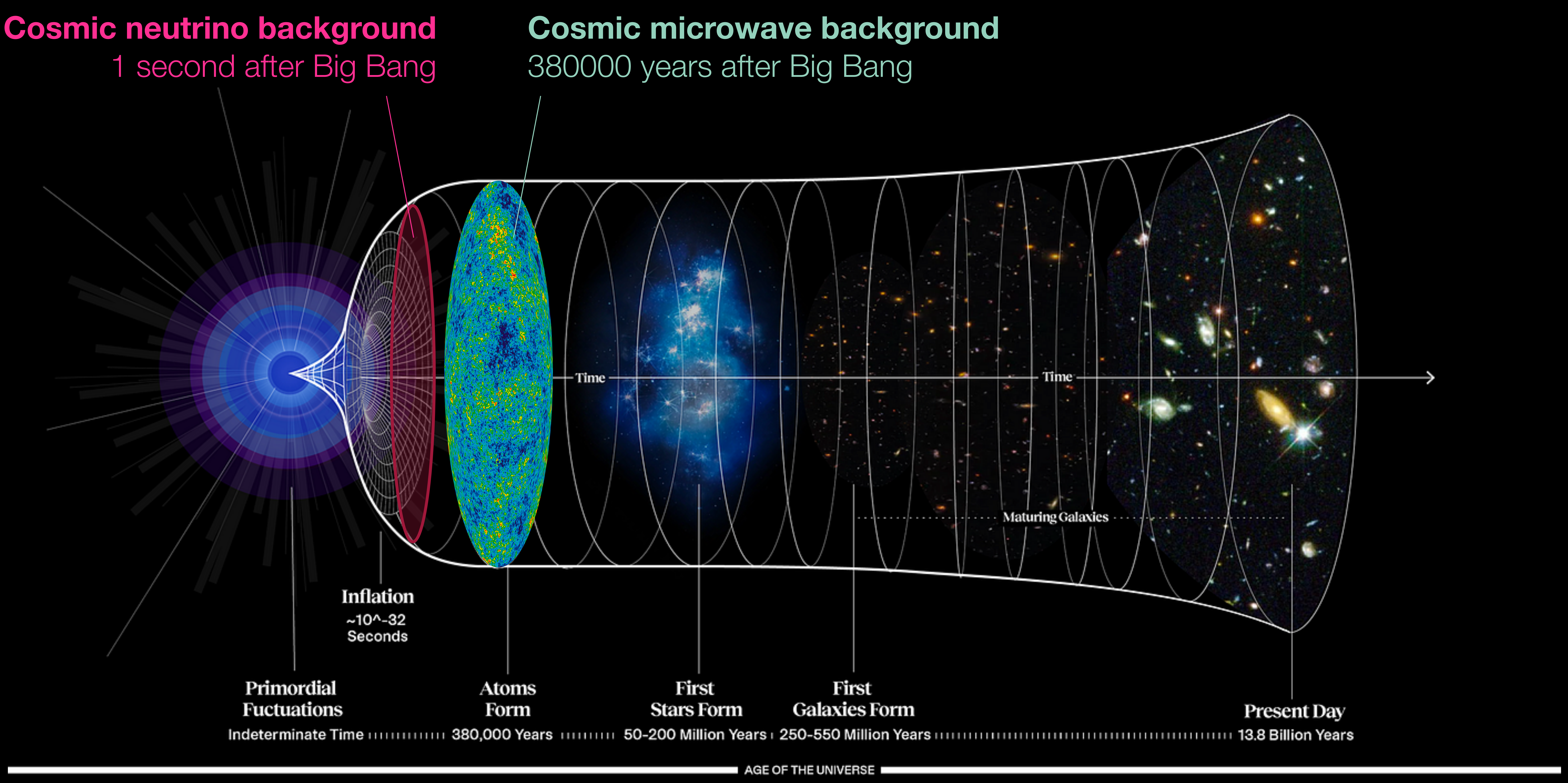
The Last Major Observable of the Hot Big Bang Model



Need Very Good Electron Energy Resolution

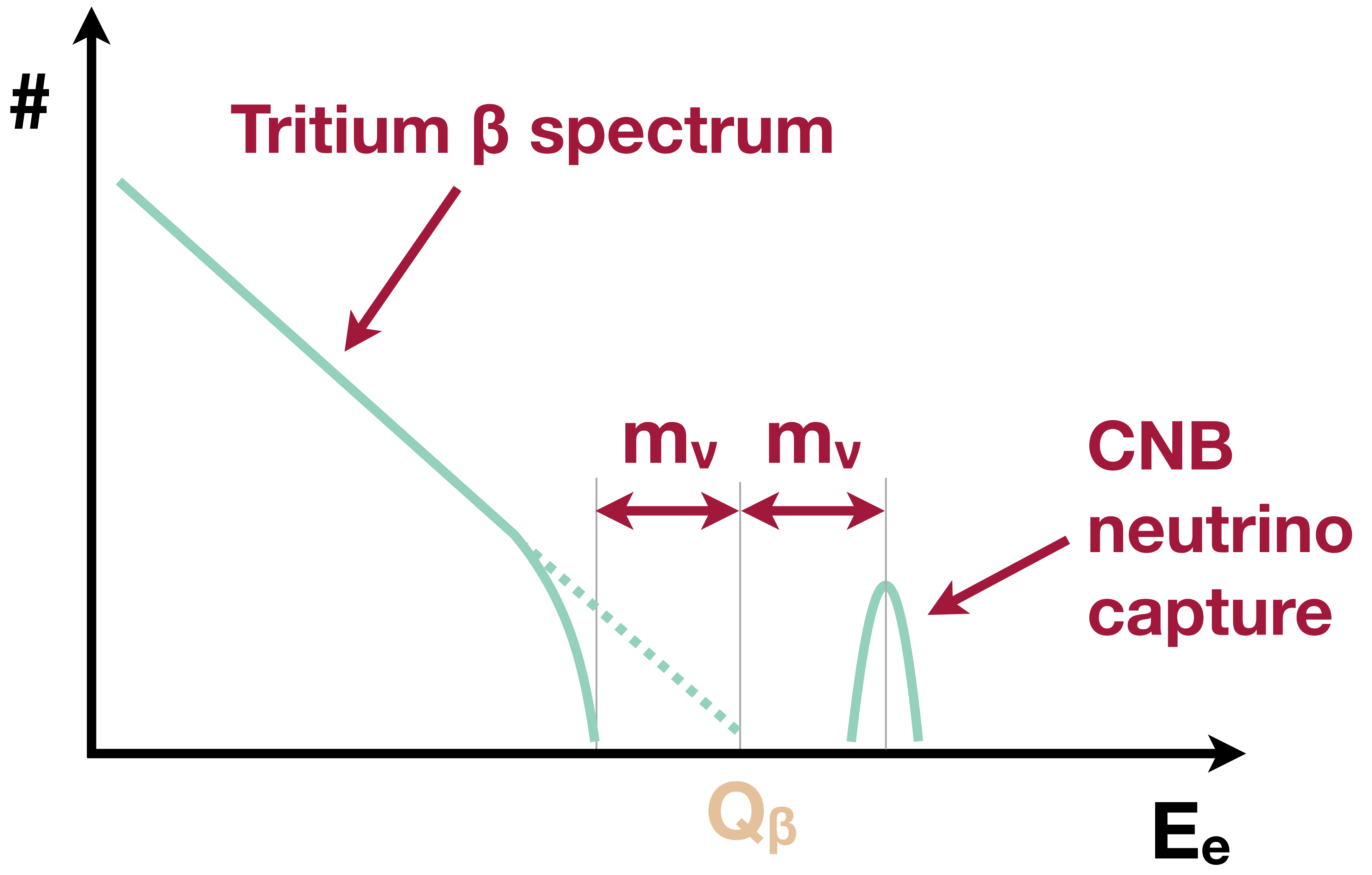
See talk by F. Virzi tomorrow

- PTOLEMY experiment: aims to measure the Cosmic Neutrino Background
  - Neutrino capture on **tritium**

    $\nu_e + {}^3H \rightarrow {}^3He + e^-$

PTOLEMY

- Tritium loaded on **graphene** target
  - Electrons **slowed down** by EM filter
- Smoking gun: **bump** after β endpoint
  - Gap = $2m_\nu$ and m_ν < eV



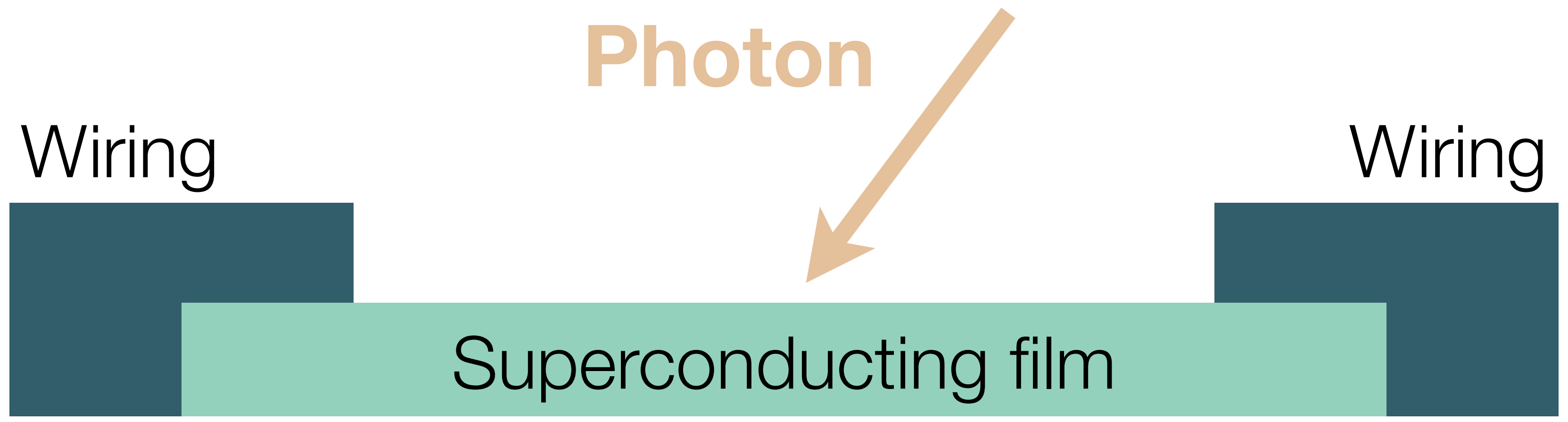
PTOLEMY goal

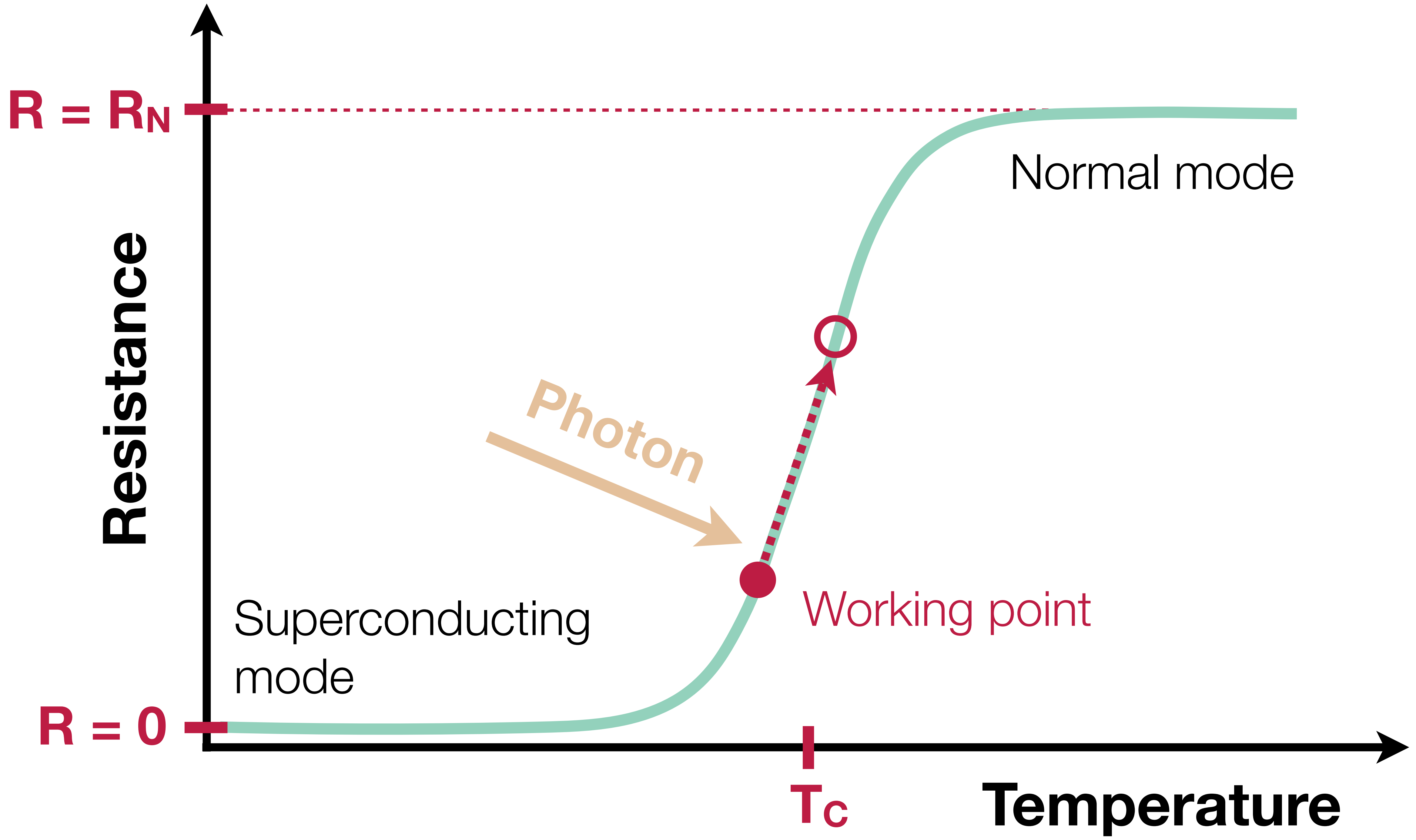
$\sigma_e(E)$ = 50 meV*
for E = 10 eV

* all resolutions in this talk are Gaussian, not FWHM

Transition-Edge Sensors: Operating Principle

- TES: superconducting film close to its T_C
  - Typical T_C ~ 100 mK
- **Cryogenic** photon detector
- Superconducting transition **very sharp!**
  - Typically ΔT ~ mK
- Photon absorbed → $\Delta T > 0$ → $\Delta R \gg 0$

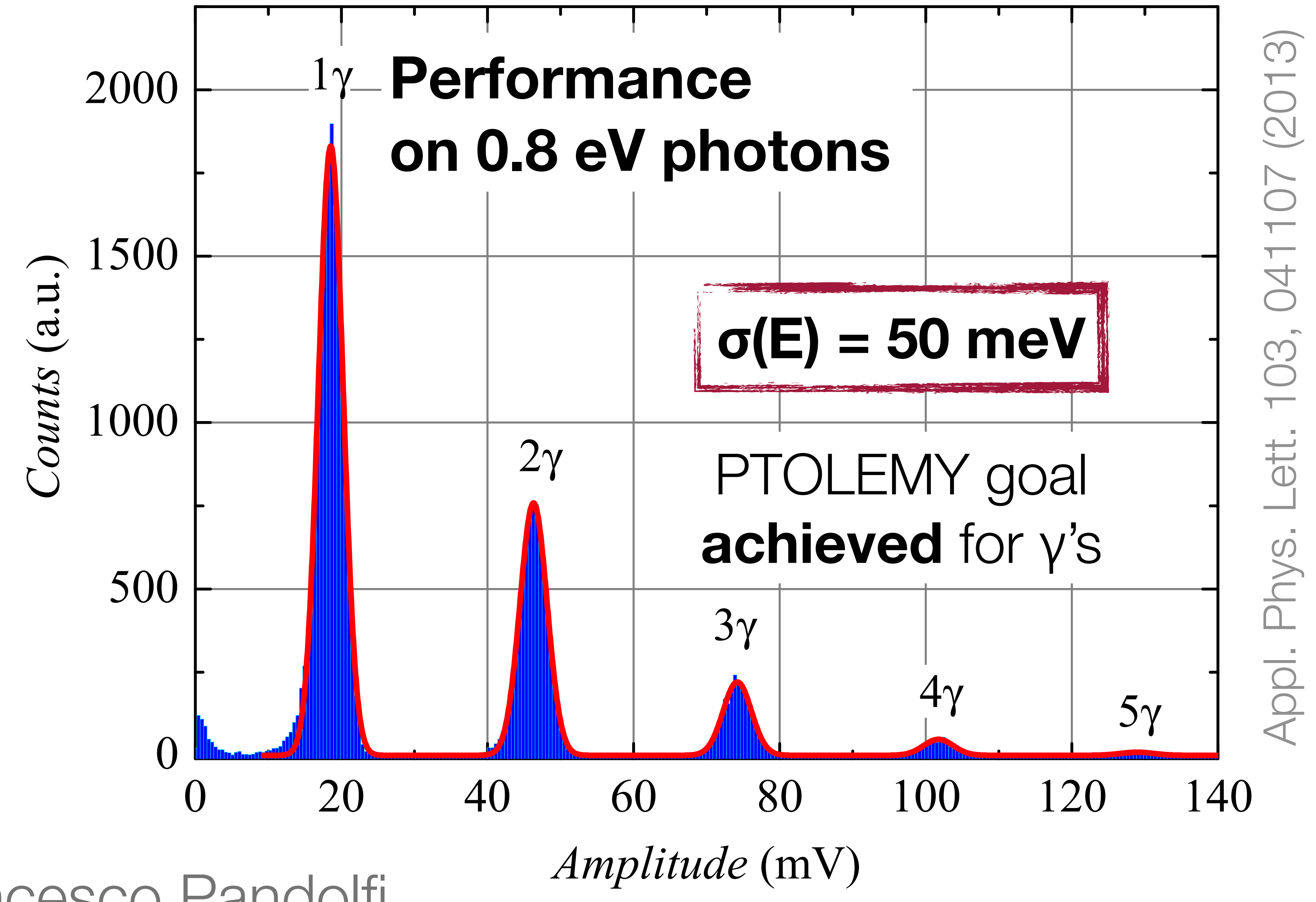




Great Resolution on Photons, But What About Electrons?

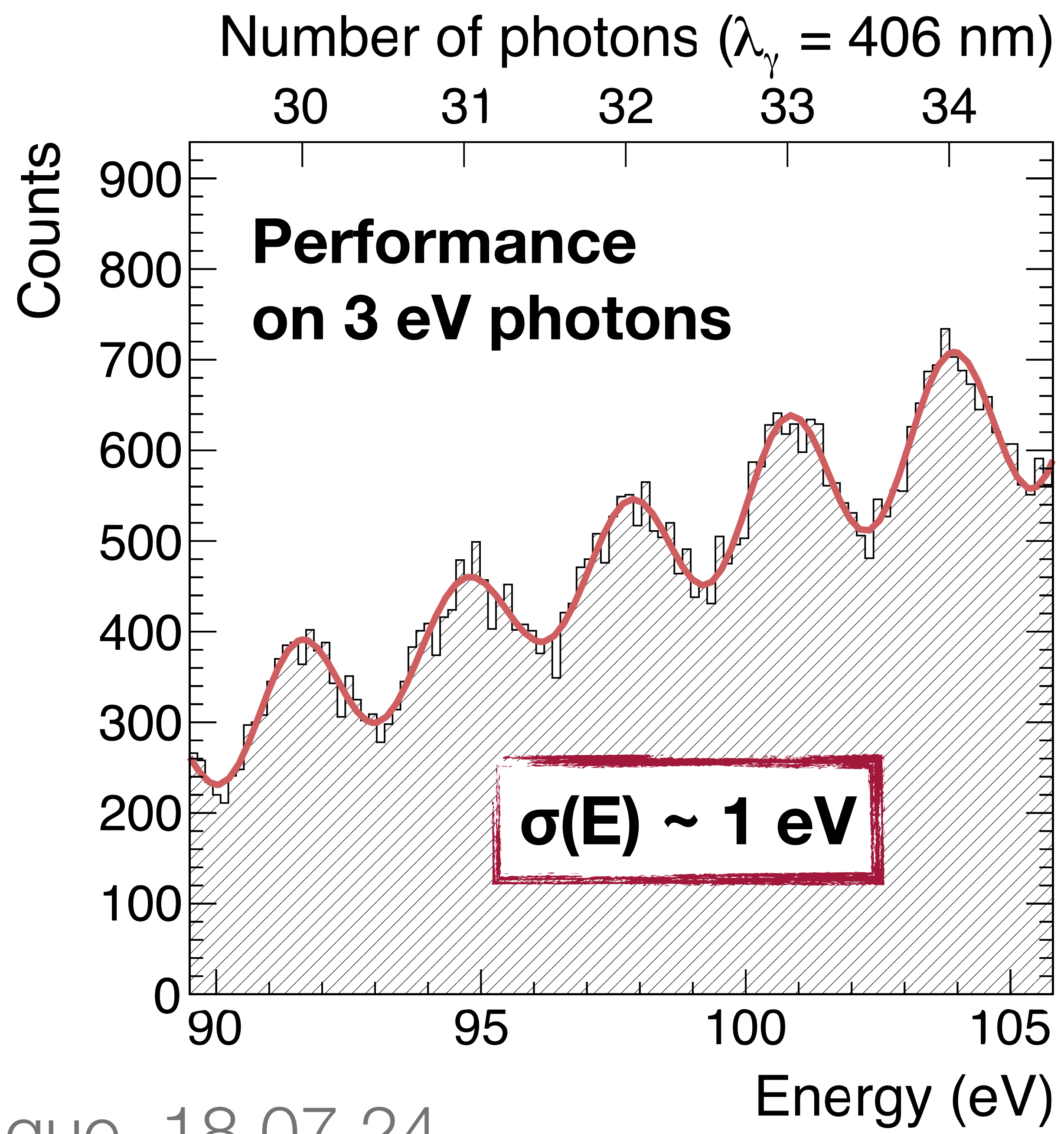
Best INRiM TES for photons (so far)

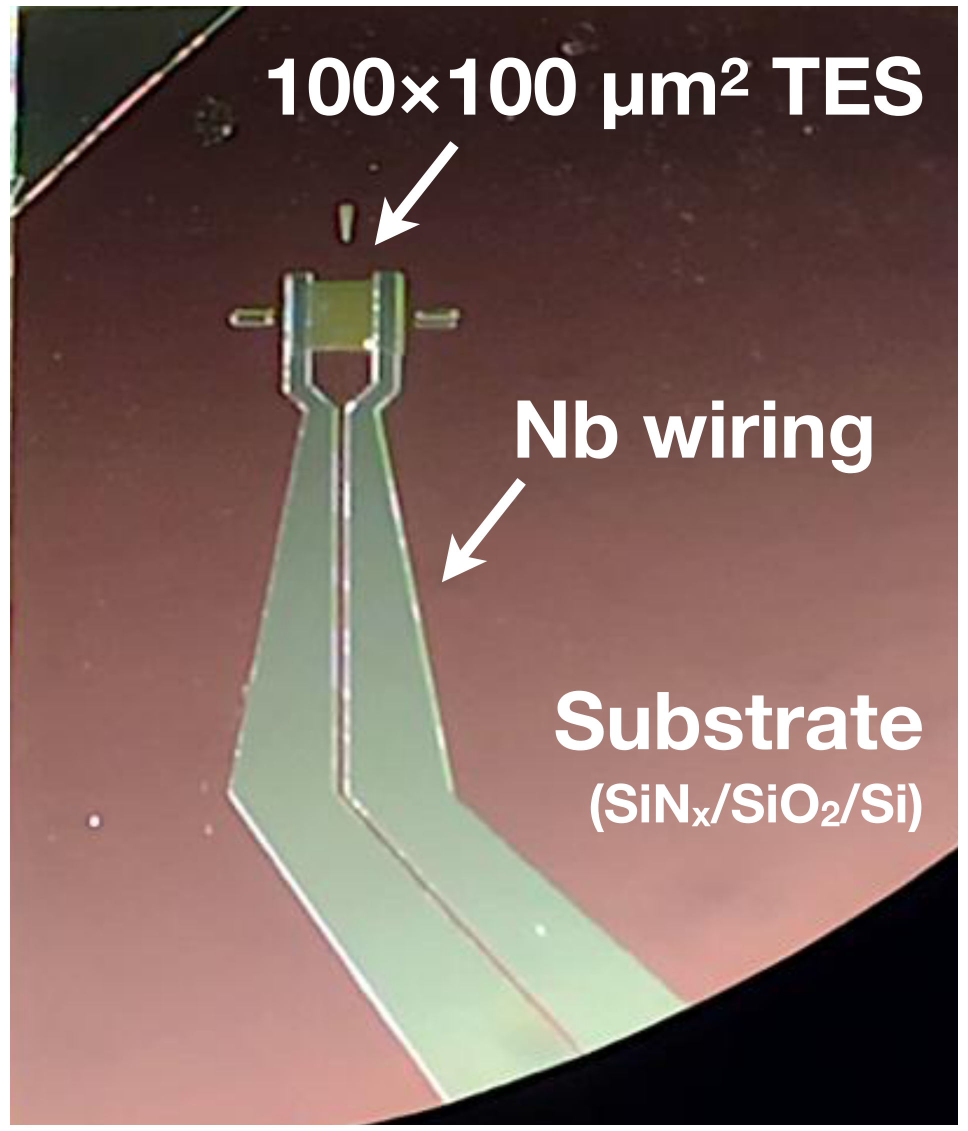
- 45 nm gold + 45 nm titanium
- Active area: 10×10 μm²
- T_C ~ 106 mK



TES designed for electron test (this talk)

- 30 nm gold + 15 nm titanium
- Active area: 100×100 μm²
- T_C ~ 84 mK

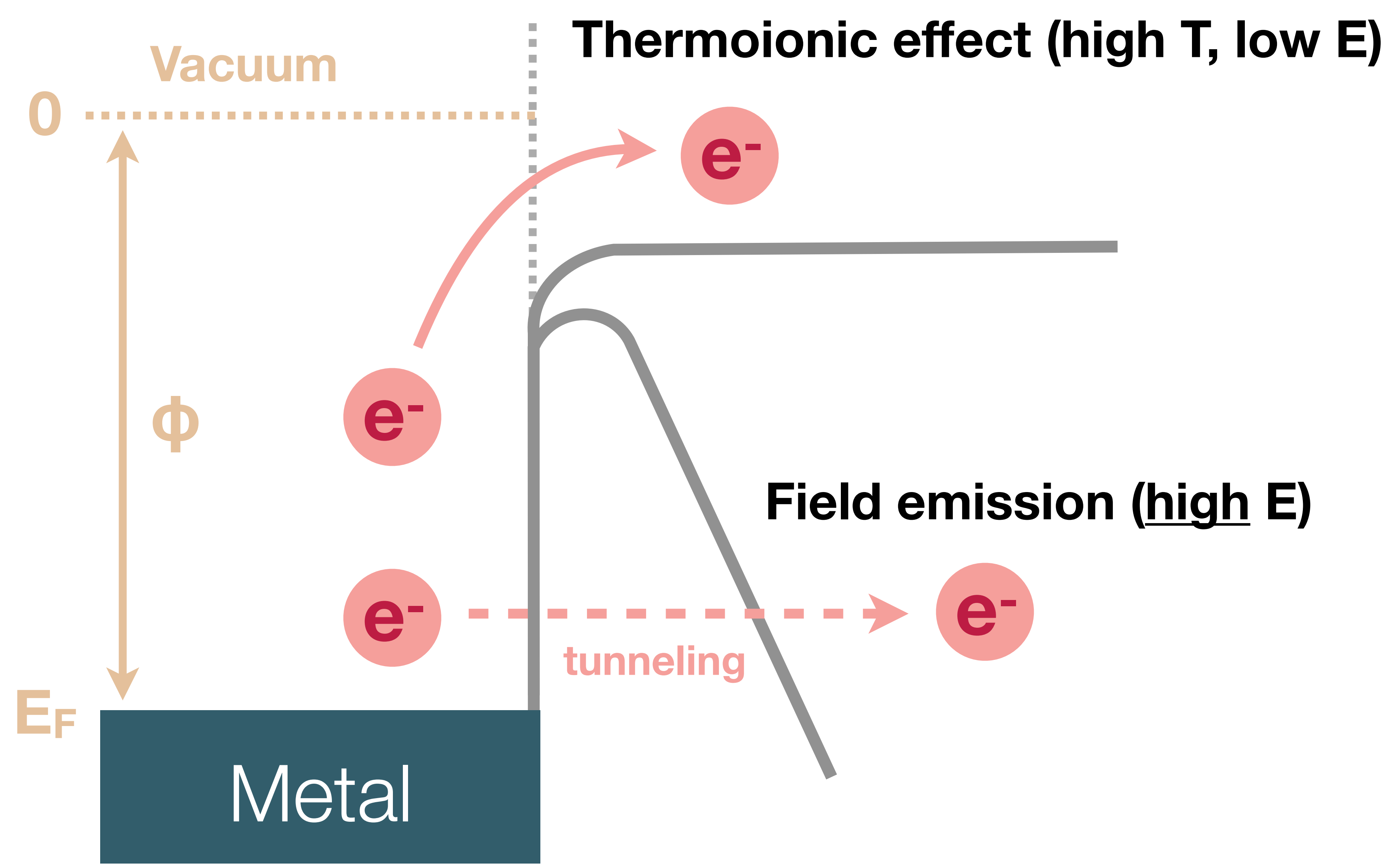




Can it detect electrons?

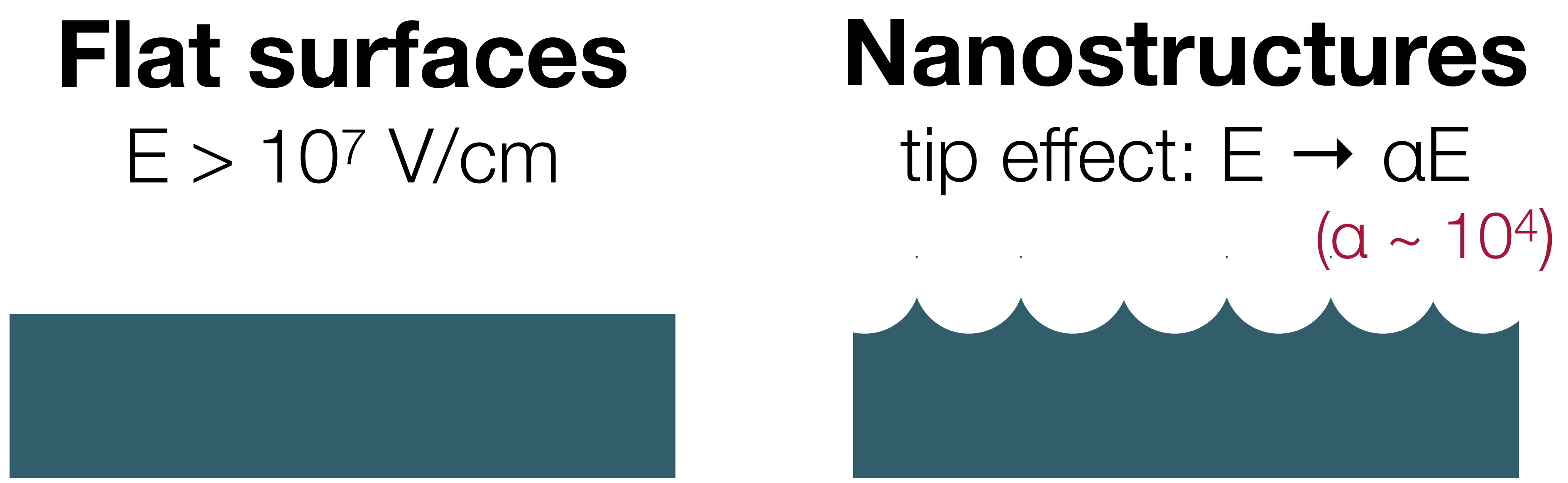
Cold Electron Source Through Field Emission

- ❖ **Problem:** electron sources are **hot**
  - E.g. **thermoionic** emission
  - **Cannot** be used in a cryostat

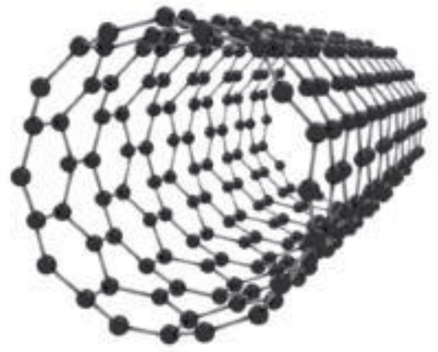


- ❖ **Solution:** field emission
  - Quantum **tunneling**
  - **No** heat

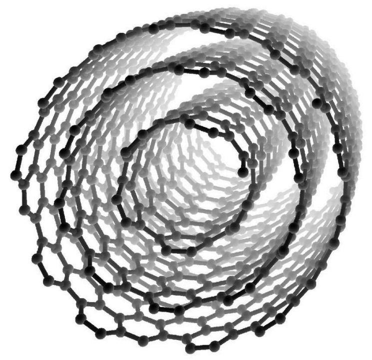
Need very high E for field emission



Single-wall nanotube

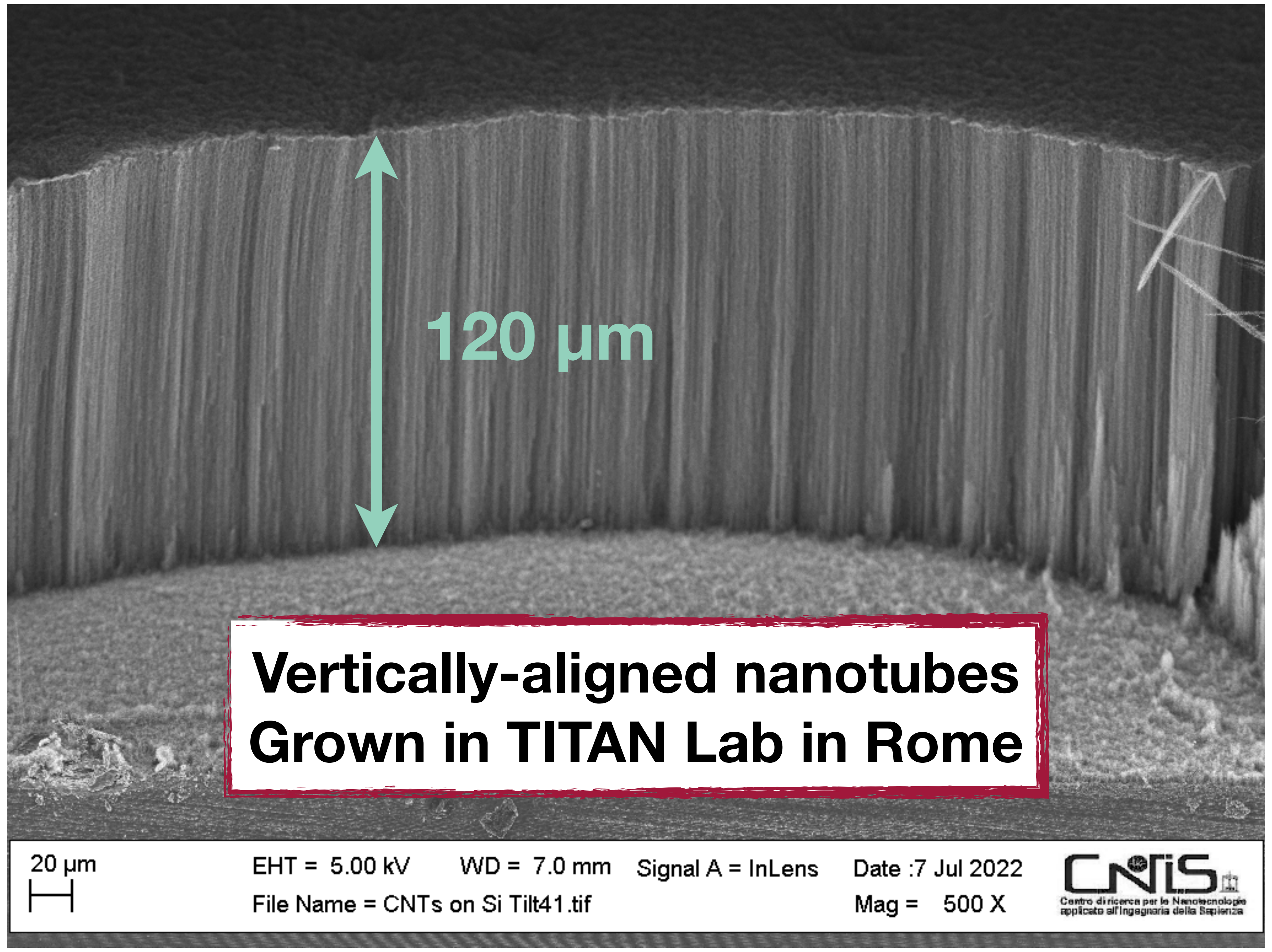


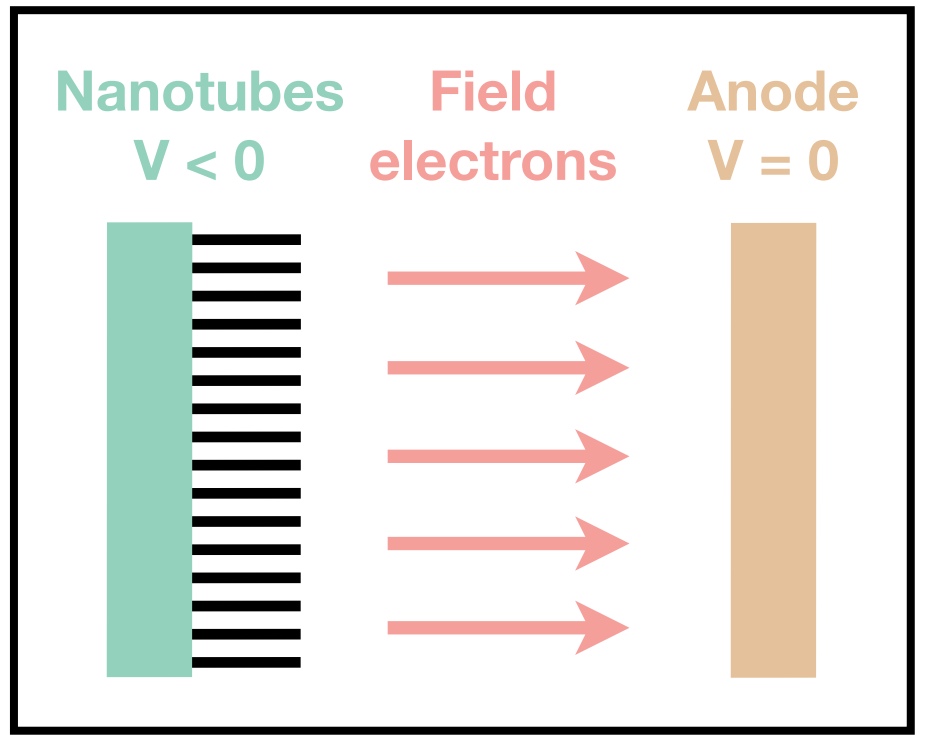
Multi-wall nanotube



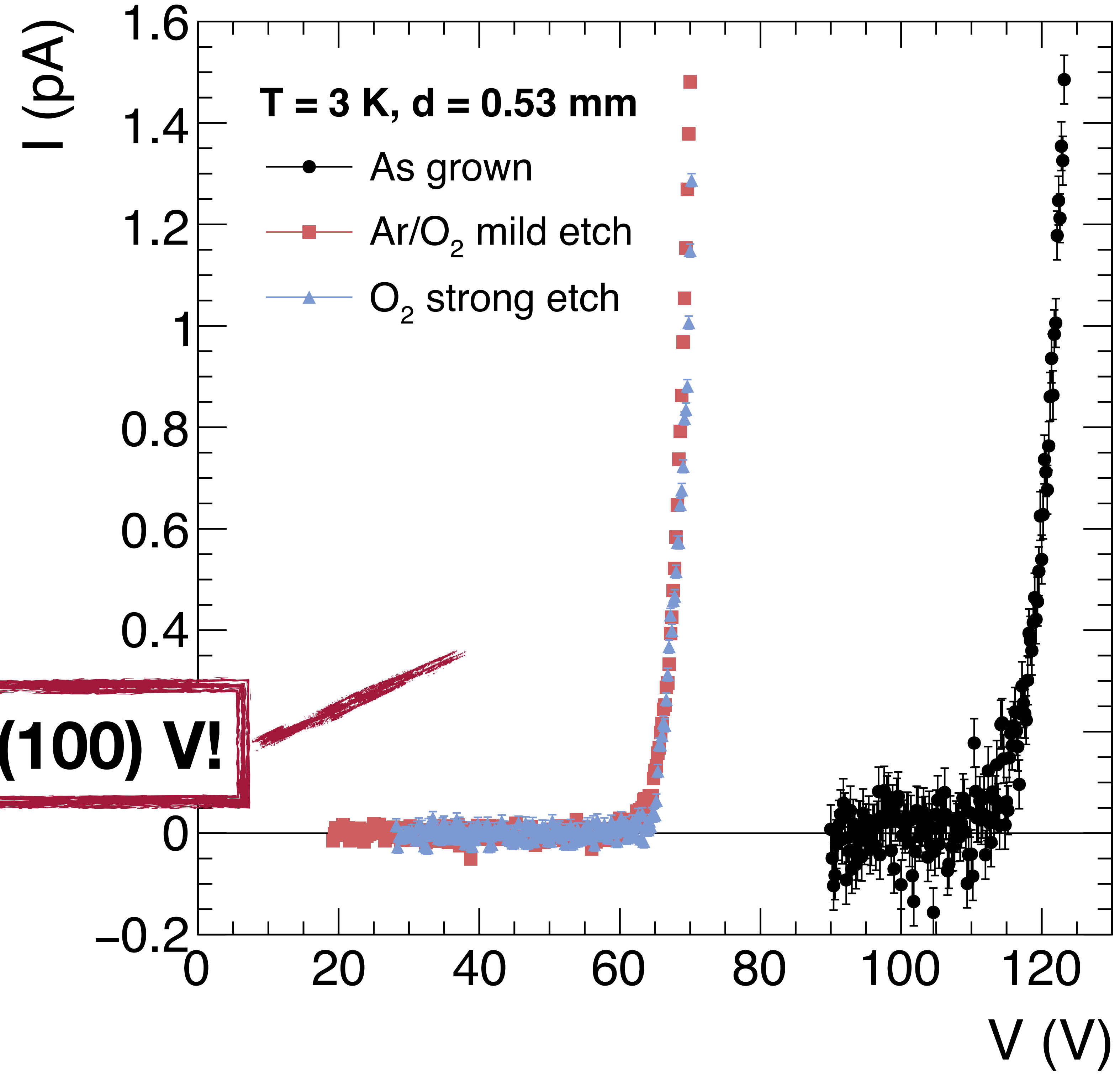
Field Emission from Carbon Nanotubes

- Carbon **nanotubes**: graphene ‘straws’
  - ⌀ ~ 20 nm, length ~ 100 μm
- Nanometric tips → tip effect
  - Field locally **amplified** by O(10^5) !



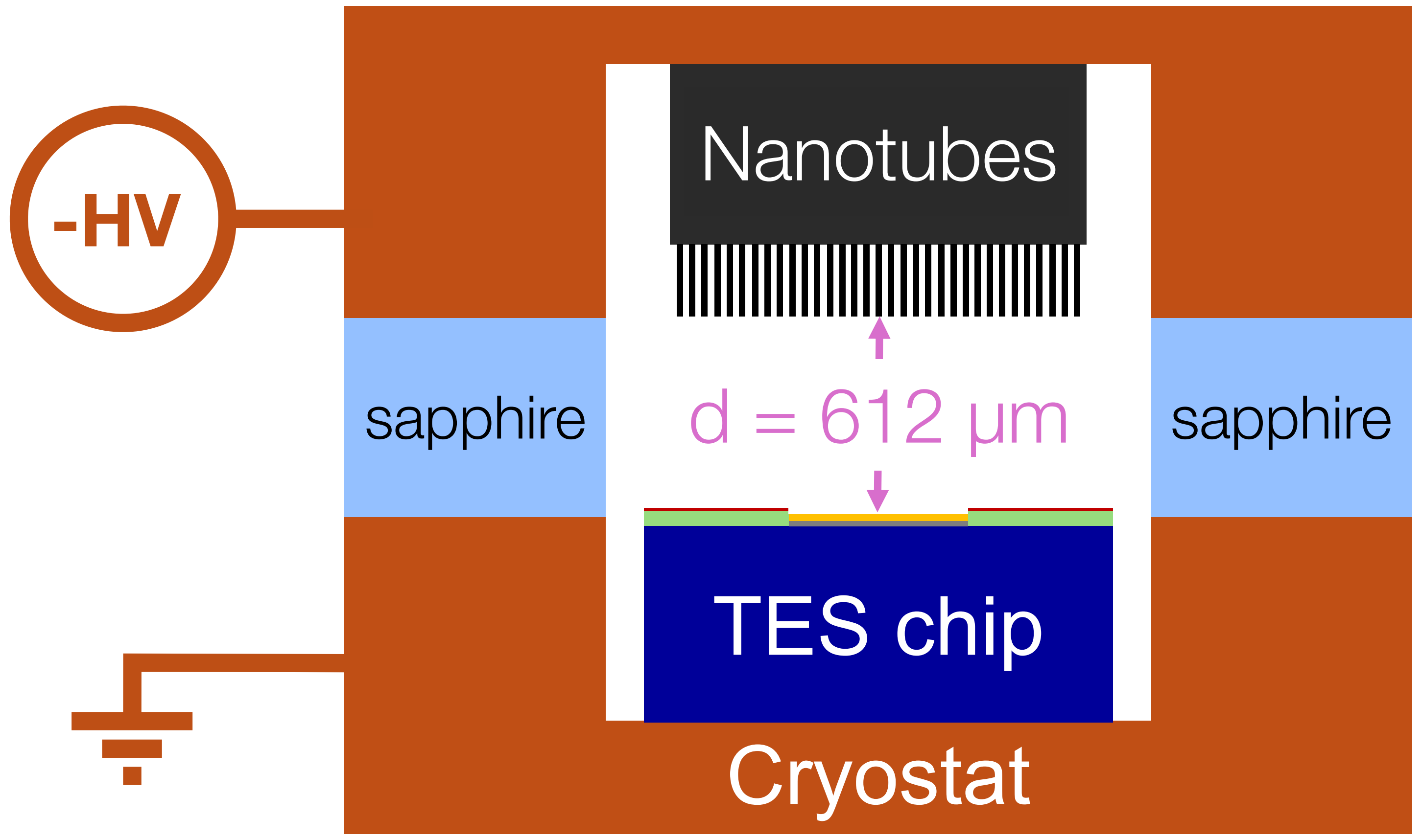


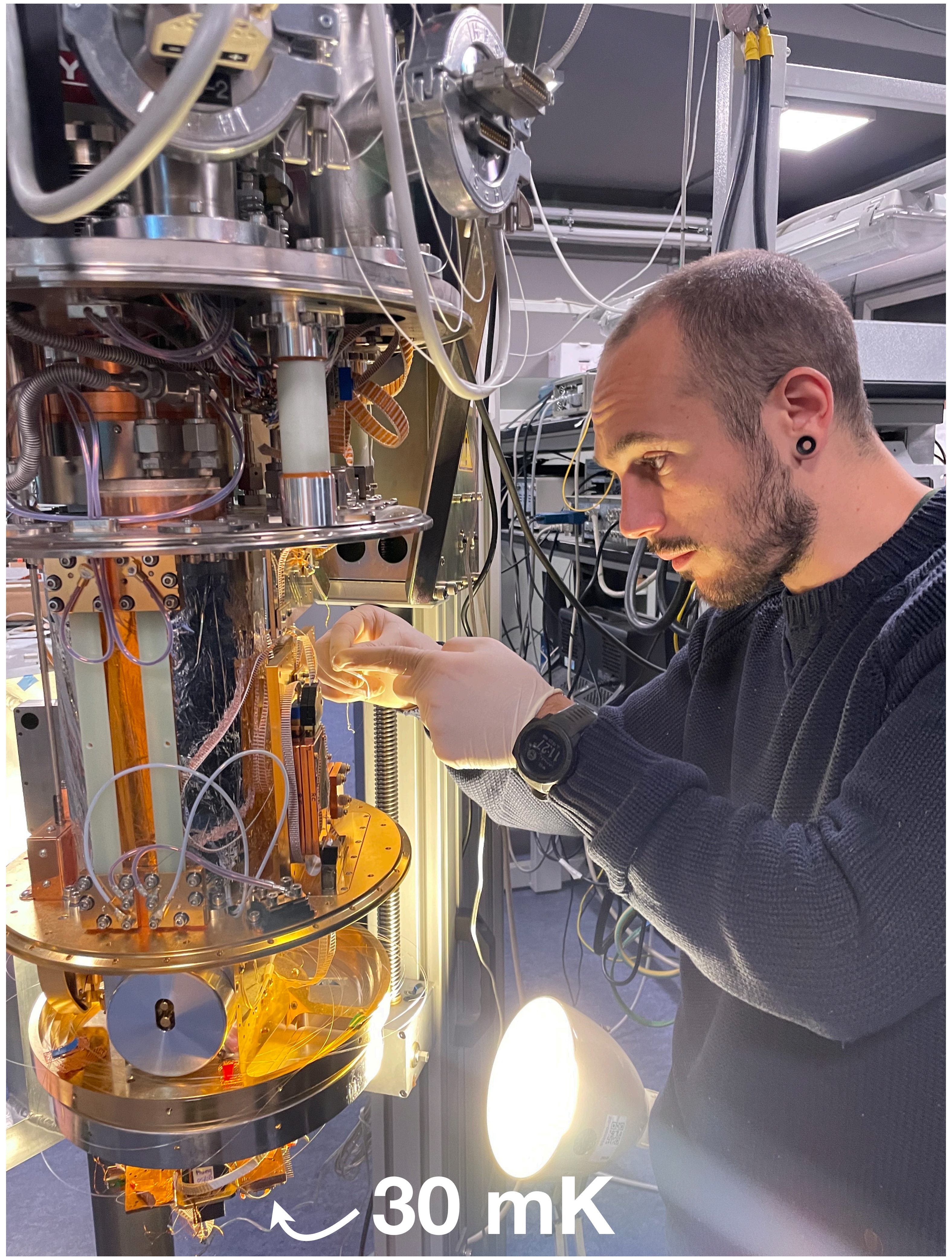
Emission with only O(100) V!

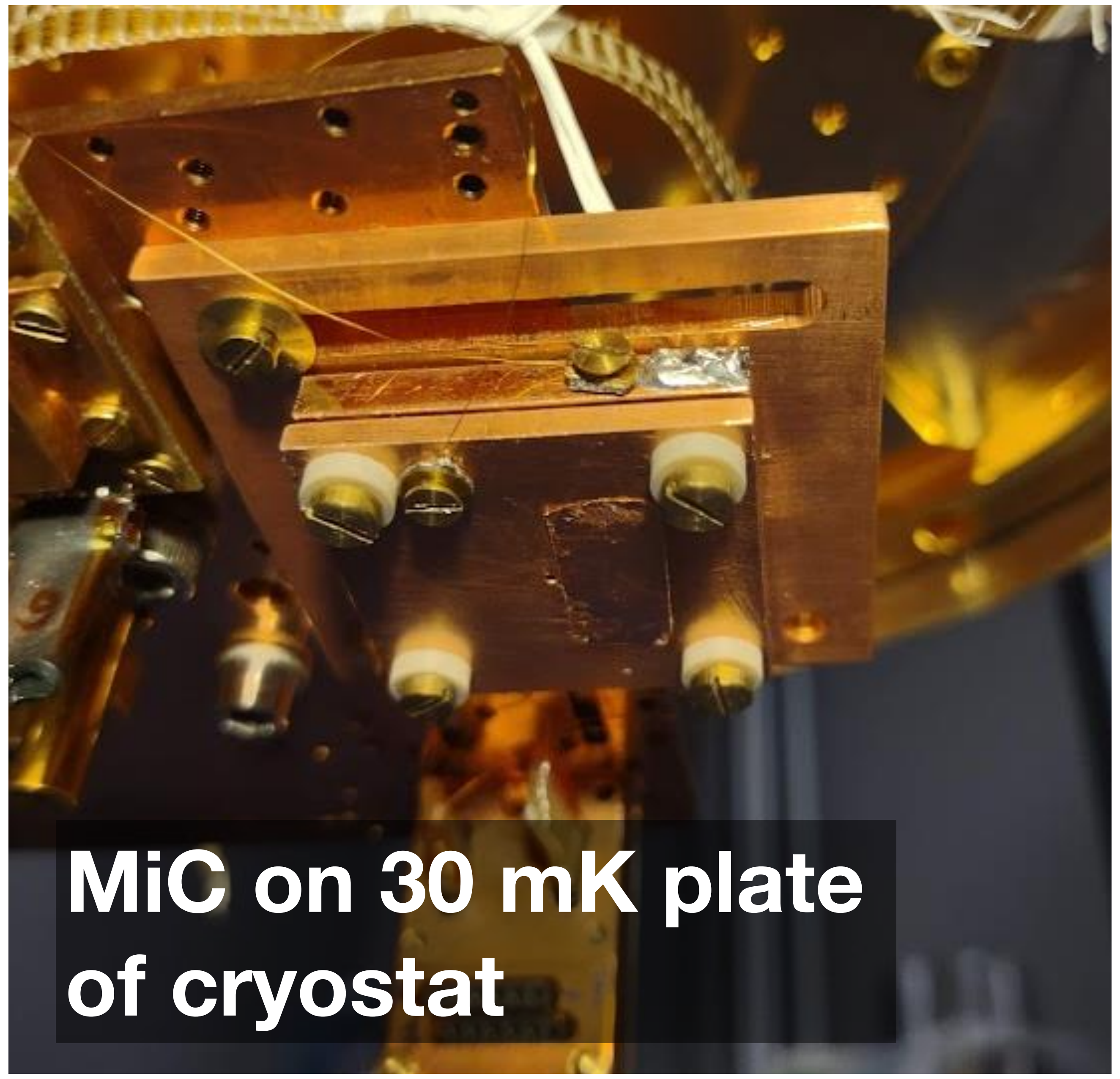


Nanotubes Coupled to TES in Compact 'MiC' Setup

Mozzarella in Carrozza (MiC)

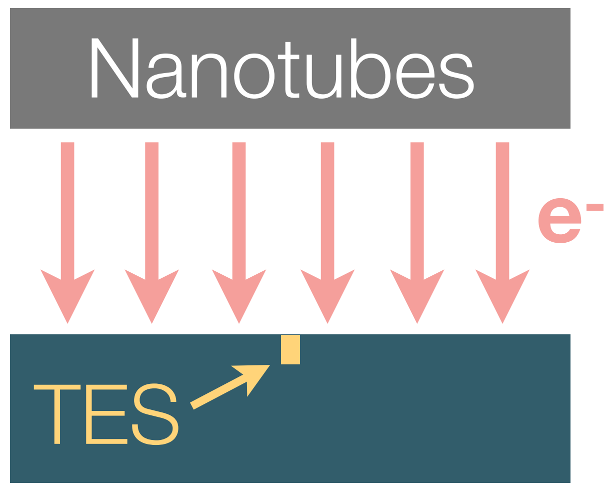


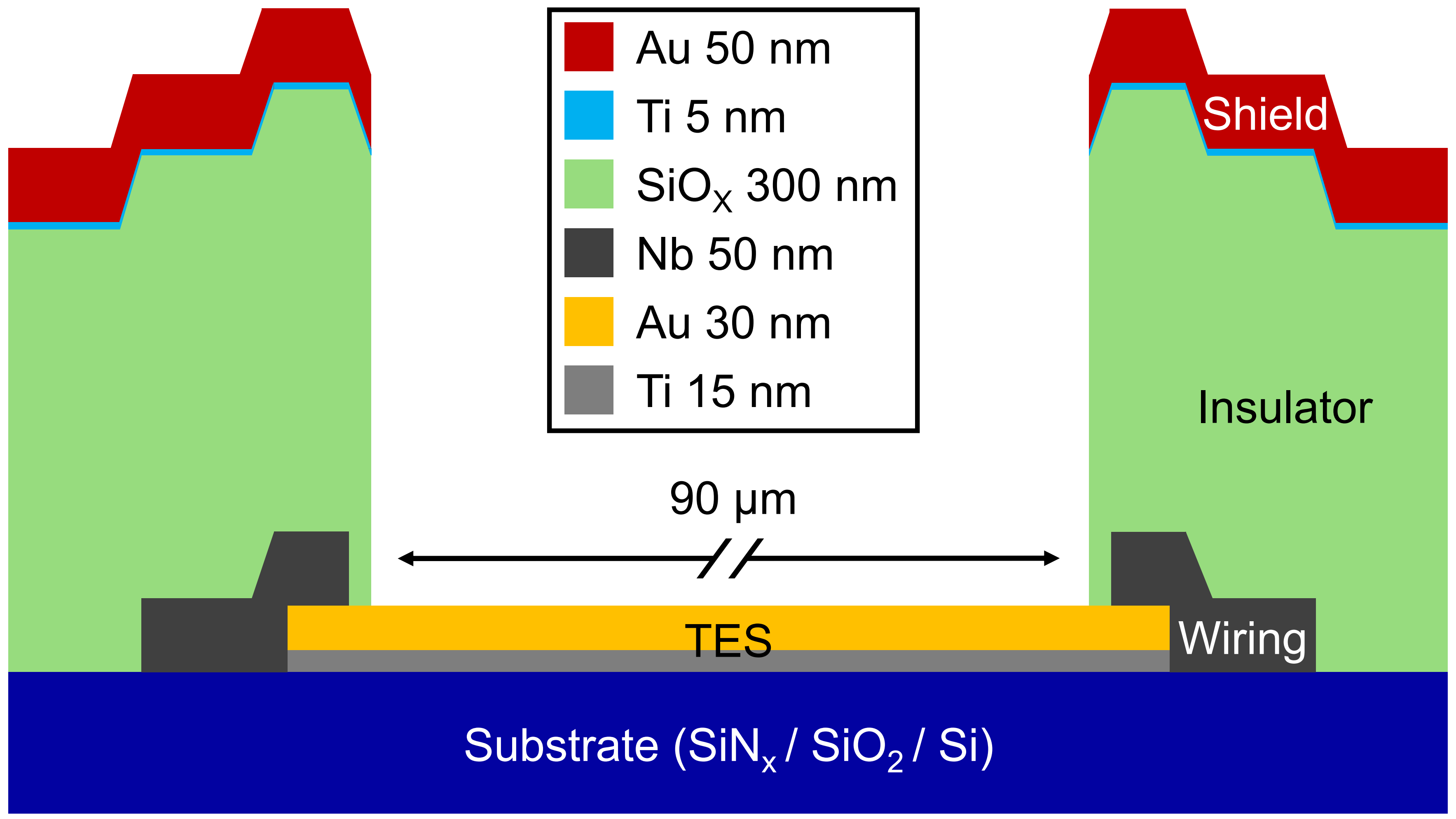


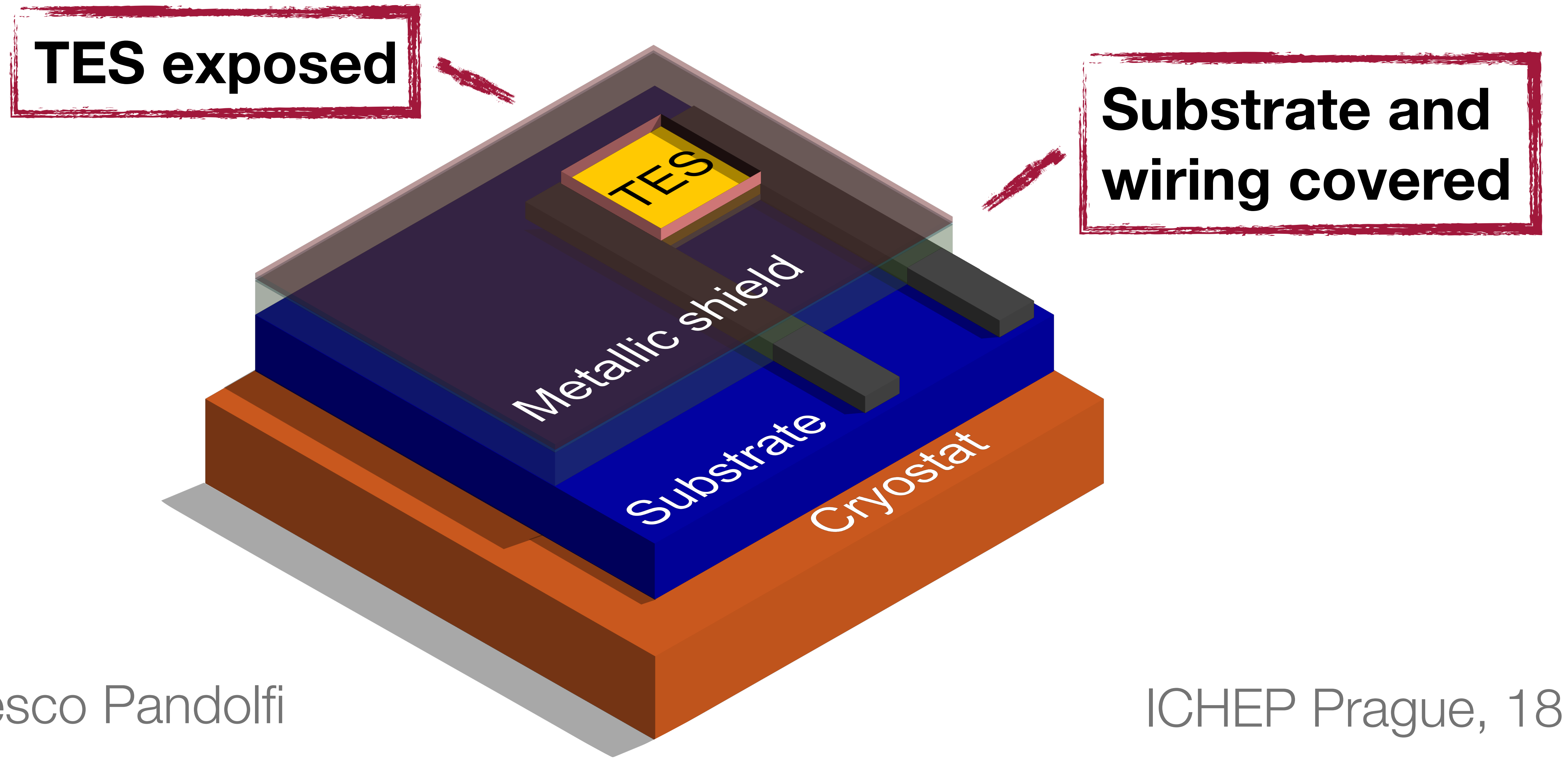


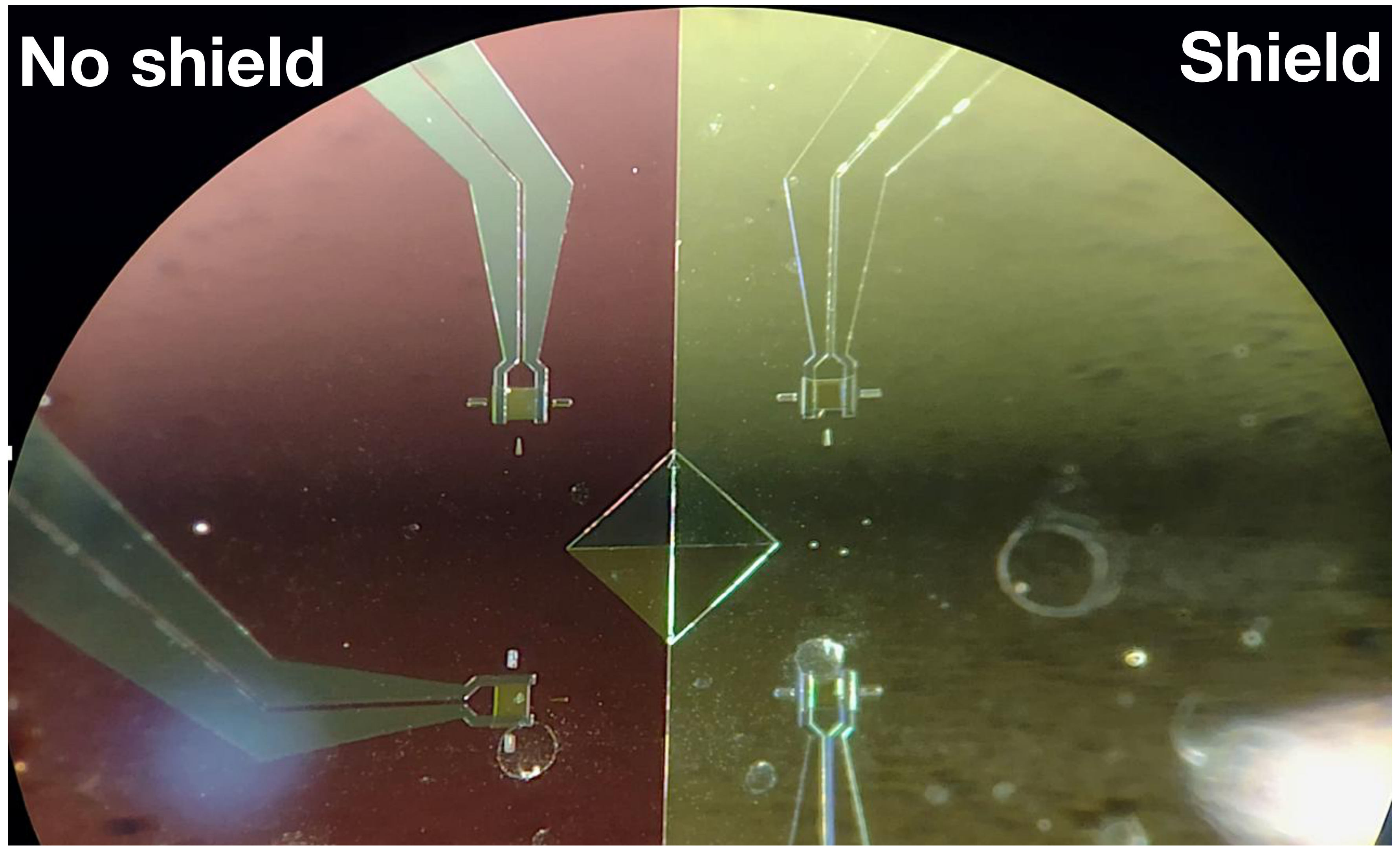
Shielding to Avoid Unwanted Electron Hits

- Nanotube surface (3×3 mm²) **much larger** than TES active area (100×100 μm²)
- Need to **avoid** electron hits on:
  - Wiring (spurious signals!)
  - Insulating substrate (charge build-up!)



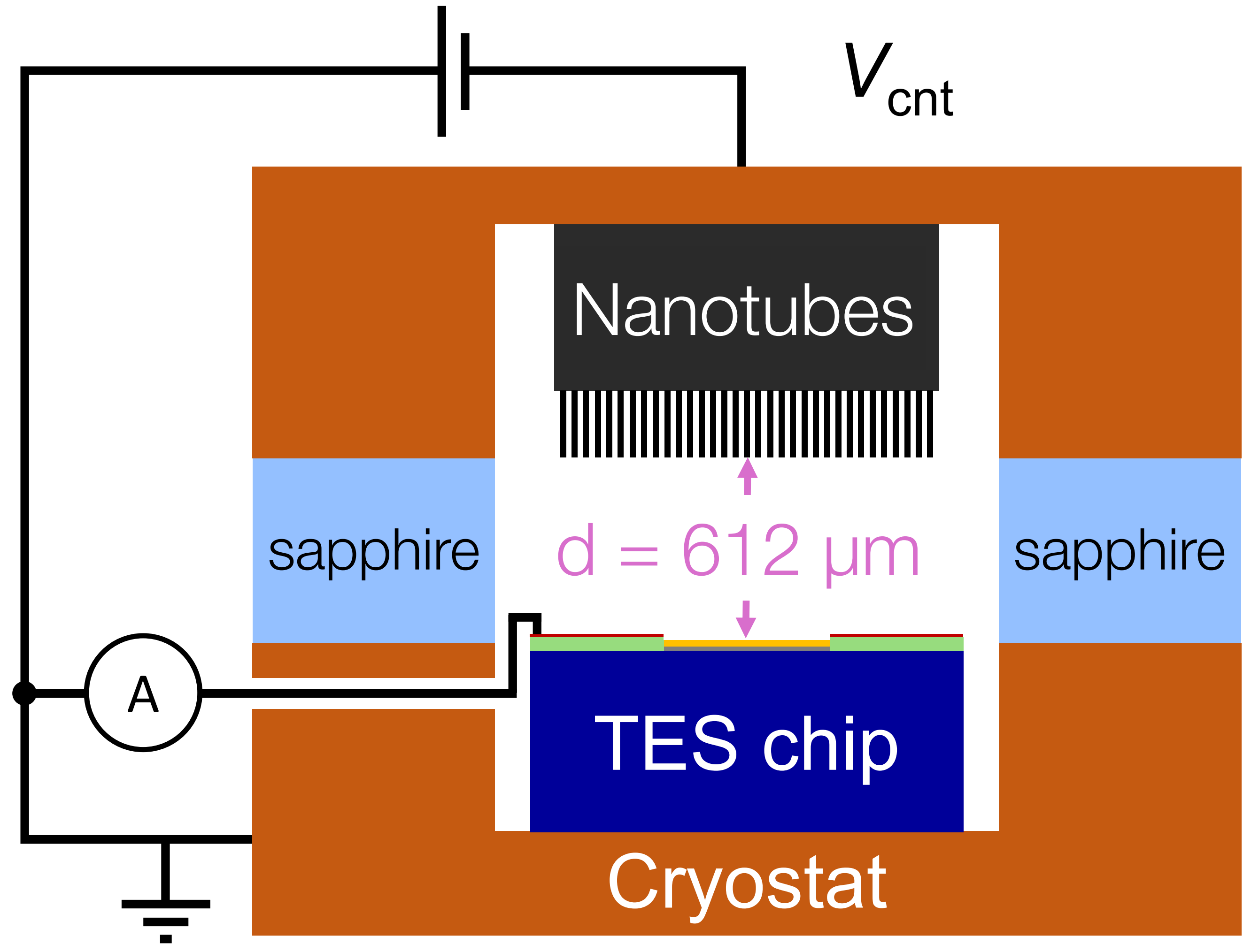


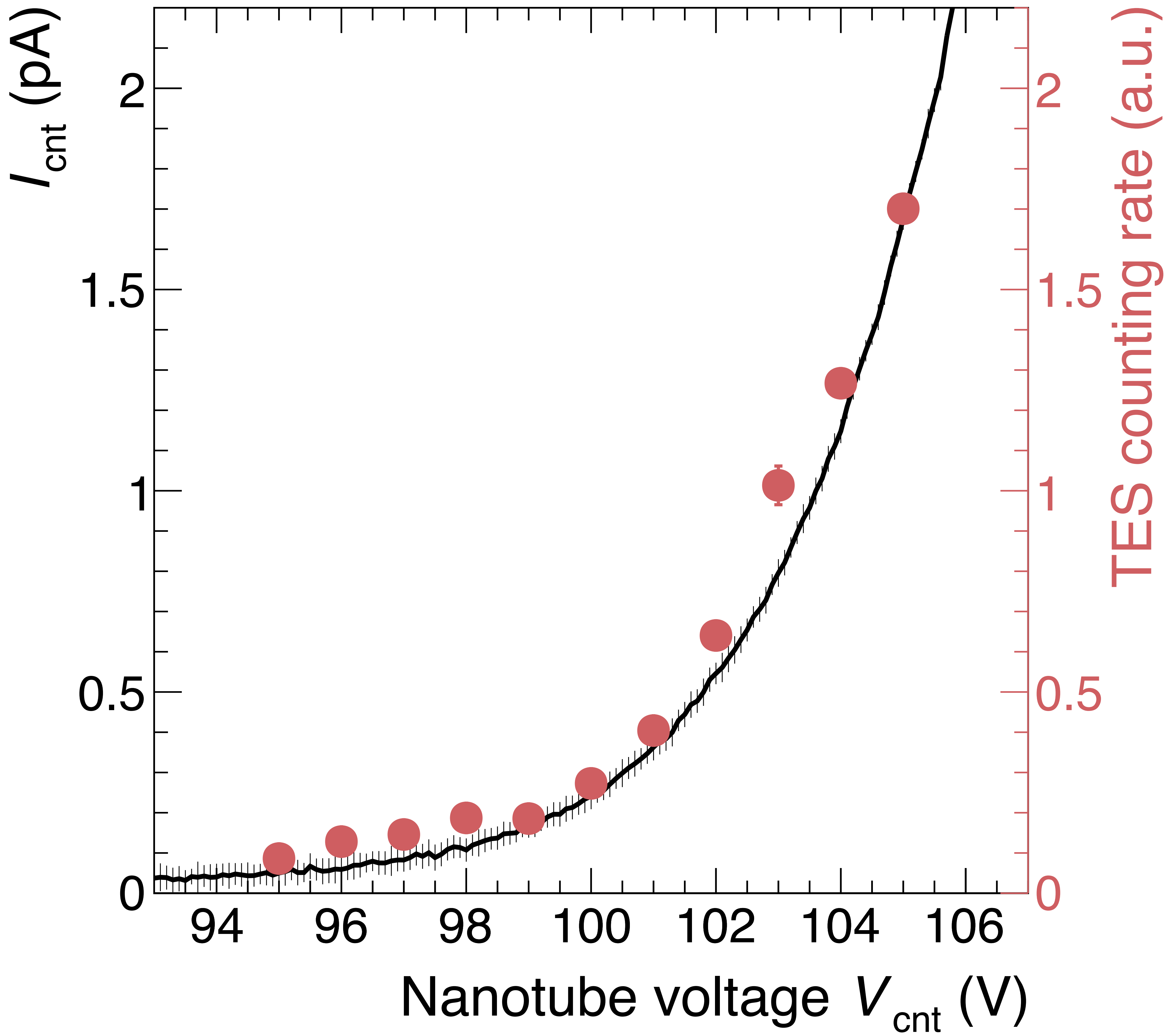




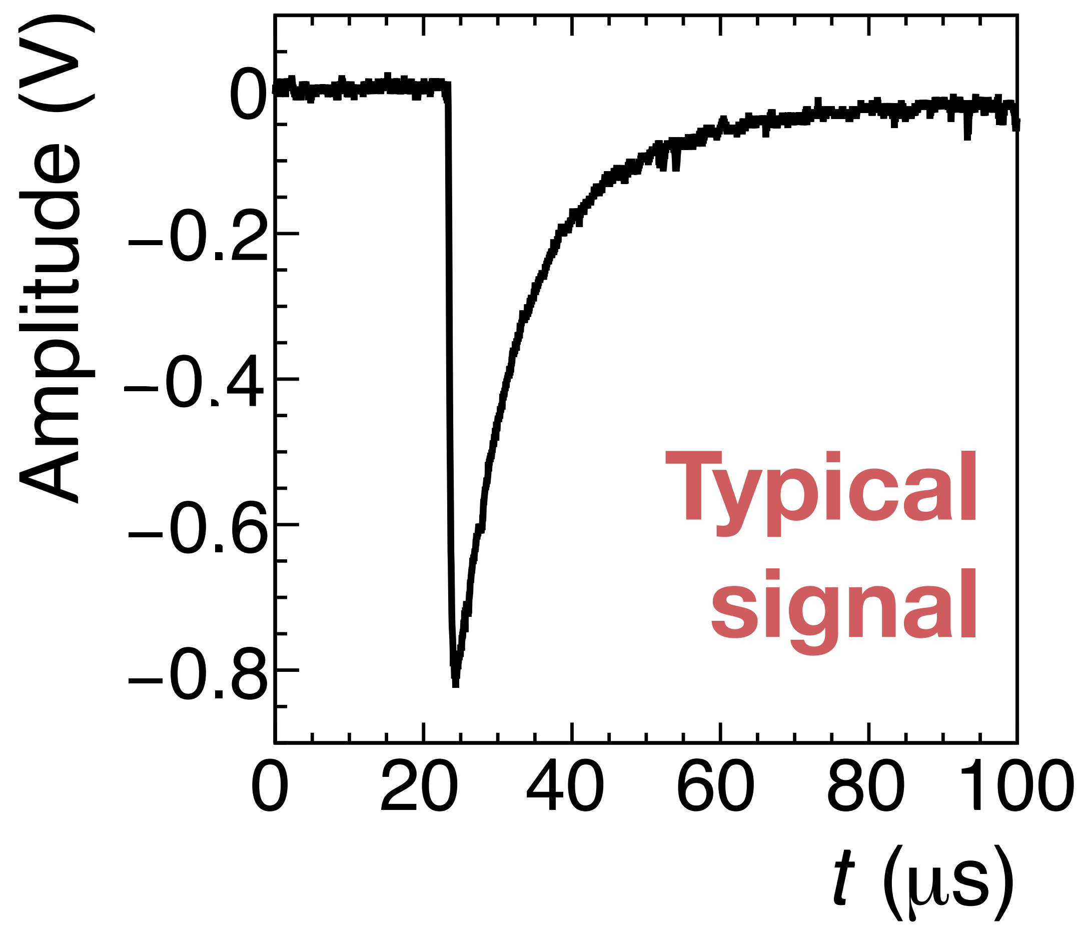
Smoking Gun: Nanotube Current Correlates with TES Rate

Black line
current hitting shield



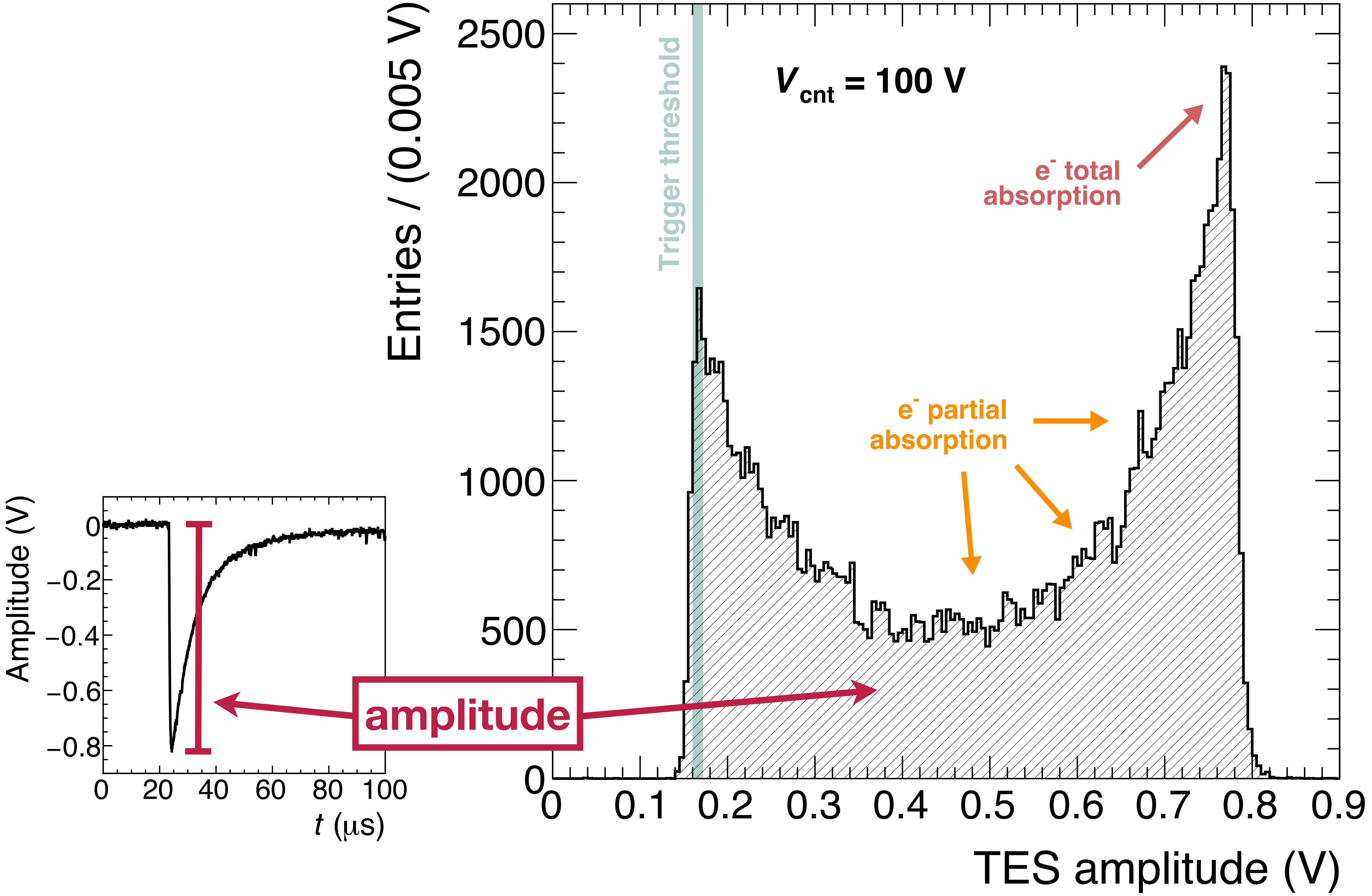


Red markers
rate of signals on TES

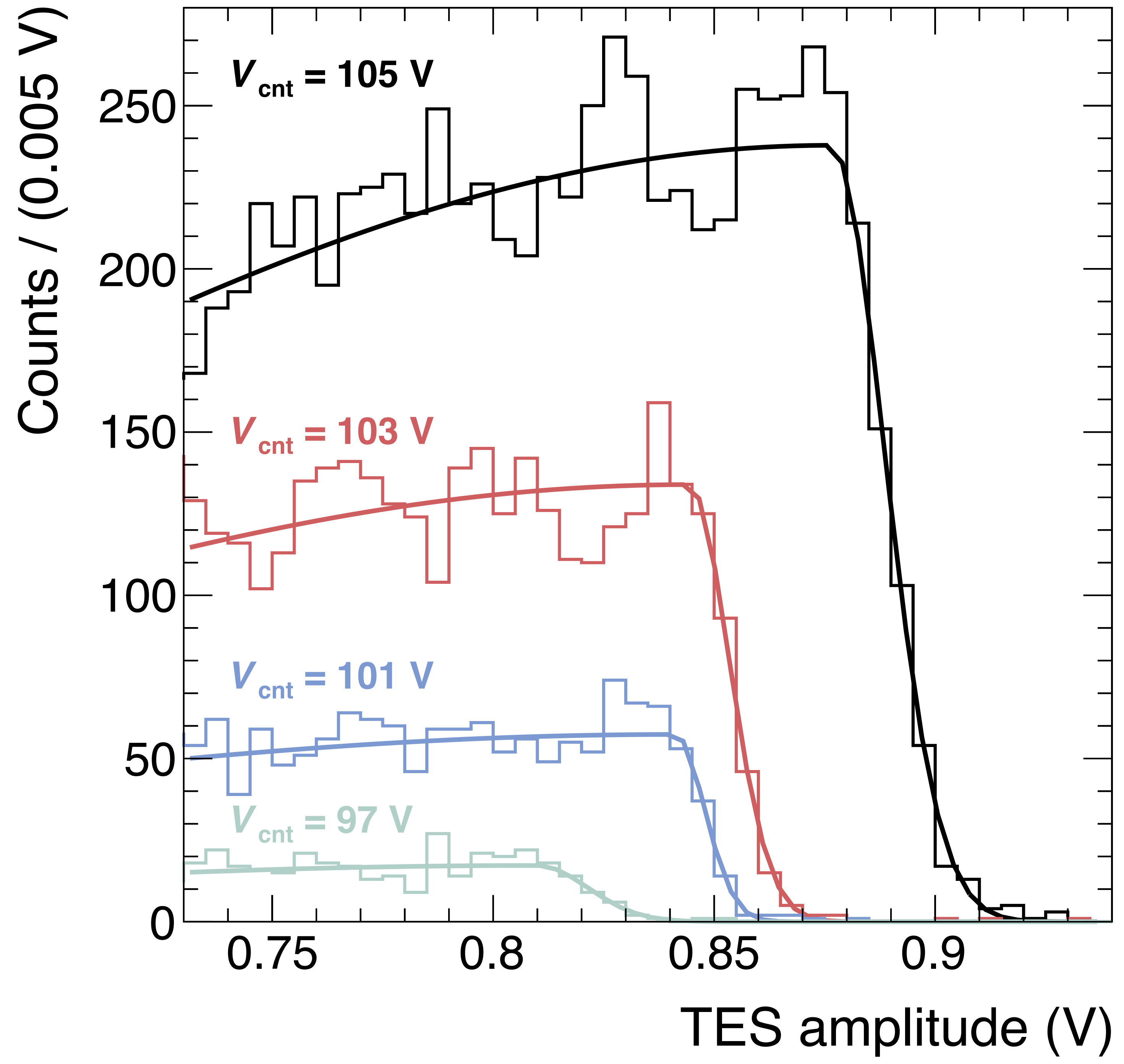


These are electrons!

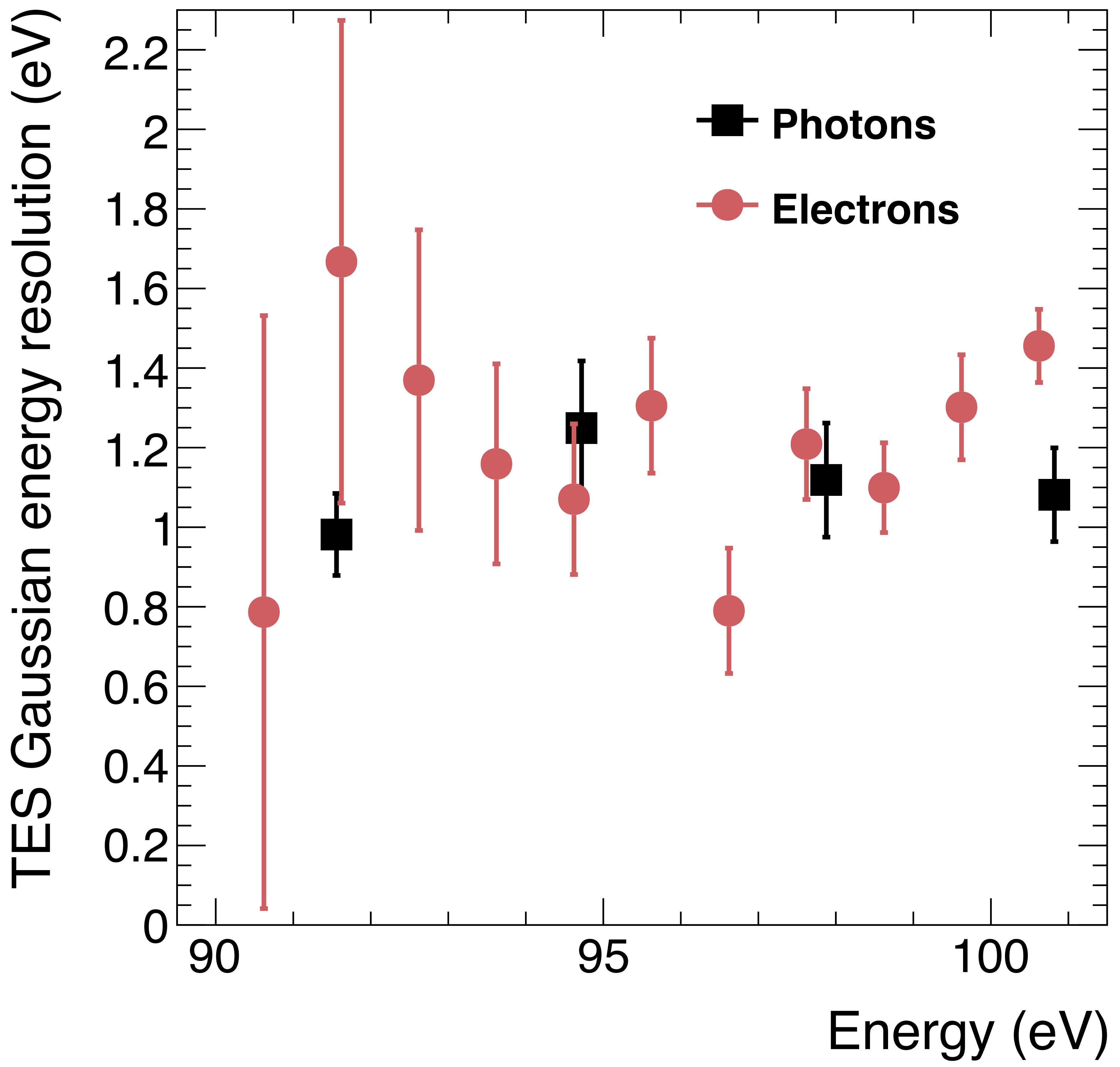
Fitting the Amplitude Distribution



- Fit peak with **asymmetric** Gaussian
  - σ_{left} = electron **partial** absorption
  - σ_{right} = electron energy resolution



Electron Energy Resolution Compatible with Photons!

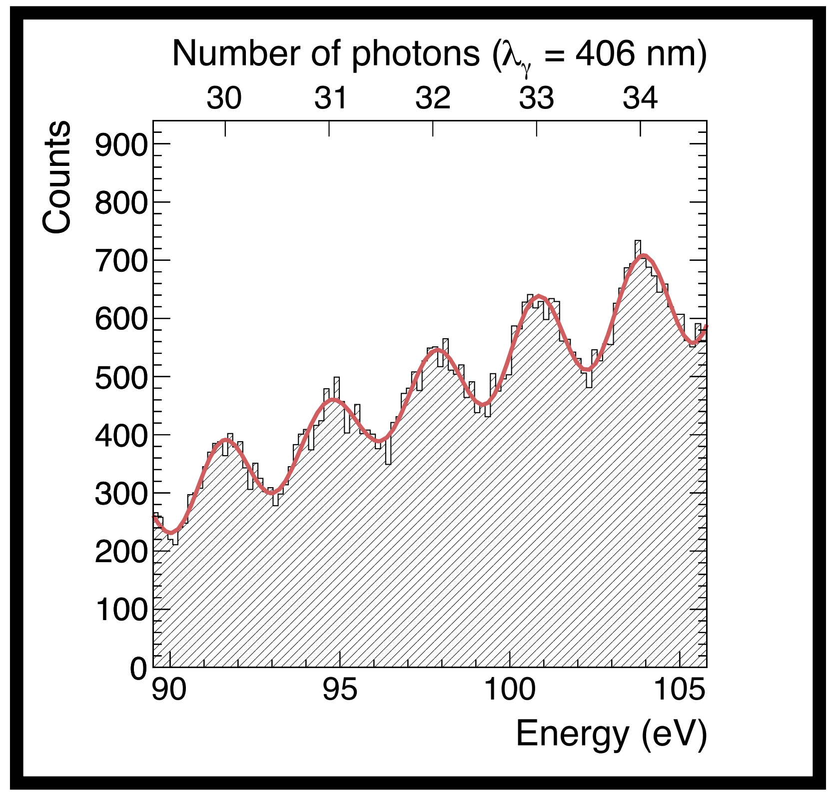


- e^- energy resolution defined as:

$$\sigma_e(E) = \frac{\sigma_{right}}{\mu} \cdot eV_{cnt}$$

from the fits

- Photon resolution taken from



- **Same** energy resolution for e^- and γ!
  - Same **heat** generation in TES

Not trivial!
e ≠ γ at low energy

- **Optimism** on PTOLEMY goal of $\sigma_e(E)$ = 50 meV @ 10 eV
  - If $\sigma_e(E) = \sigma_\gamma(E)$ at 100 eV ... probably also at 10 eV!

Paper on the arxiv: Go Check It Out!

arXiv:2405.19475

Detection of Low-Energy Electrons with Transition-Edge Sensors

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We present the first detection of electrons with kinetic energy in the 100 eV range with transition-edge sensors (TESs). This has been achieved with a (100×100) μm^2 Ti-Au bilayer TES, with a critical temperature of about 84 mK. The electrons are produced directly in the cryostat by an innovative cold source based on field emission from vertically-aligned multiwall carbon nanotubes. We obtain a Gaussian energy resolution between 0.8 and 1.8 eV for fully-absorbed electrons in the $(90 - 101)$ eV energy range, which is found to be compatible with the resolution of this same device for photons in the same energy range. This work opens new possibilities for high-precision energy measurements of low-energy electrons.

Conclusions

- **Detected** low-energy electrons with transition-edge sensor!
  - Obtained $\sigma_e(E)$ ~ 1 eV for E ~ 100 eV
  - **First time** such low energy, first time such good resolution

Only other paper on TES e^- detection: E > 300 eV, $\sigma_e(E)$ > 17 eV

- First time electron source **in proximity** of TES
  - ‘Cold’ field emission from **carbon nanotubes**
- Electron resolution **compatible** with photon resolution!
  - **Same** heat-based detection in TES
  - **Optimism** on PTOLEMY goal of $\sigma_e(E)$ = 50 meV for E = 10 eV

Already achieved for photons!