Transition-Edge Sensors to Detect Low-Energy Electrons: Chasing the CνB and the Neutrino Mass

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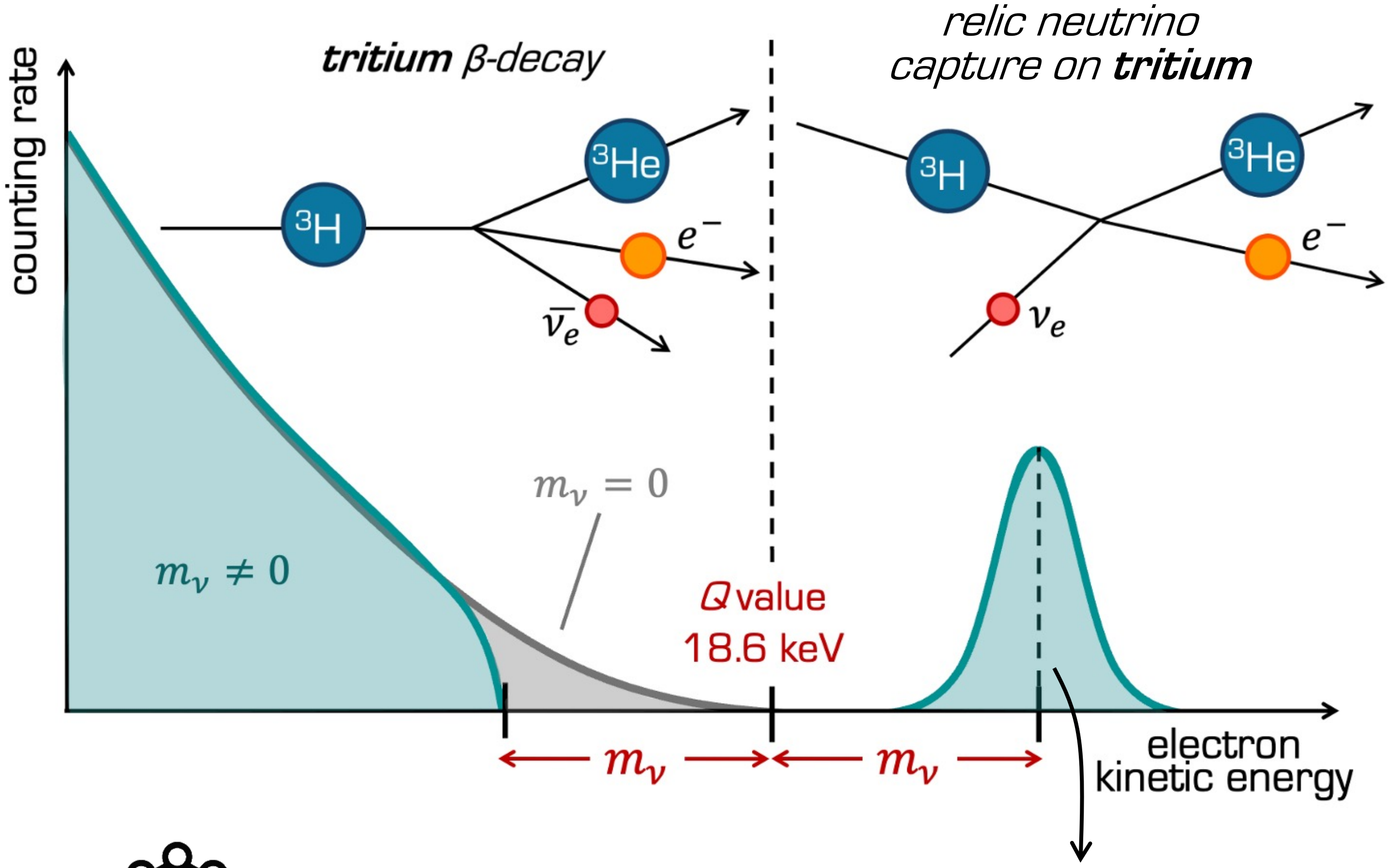
INFN Istituto Nazionale di Fisica Nucleare

Need Very Good Electron Energy Resolution

➢ **PTOLEMY** experiment: aims to **neutrino mass** and **Cosmic Neutrino Background** (relic neutrinos)



search for **bump** after spectrum endpoint

⇒ gap of $2m_\nu$

⇒ m_ν < eV

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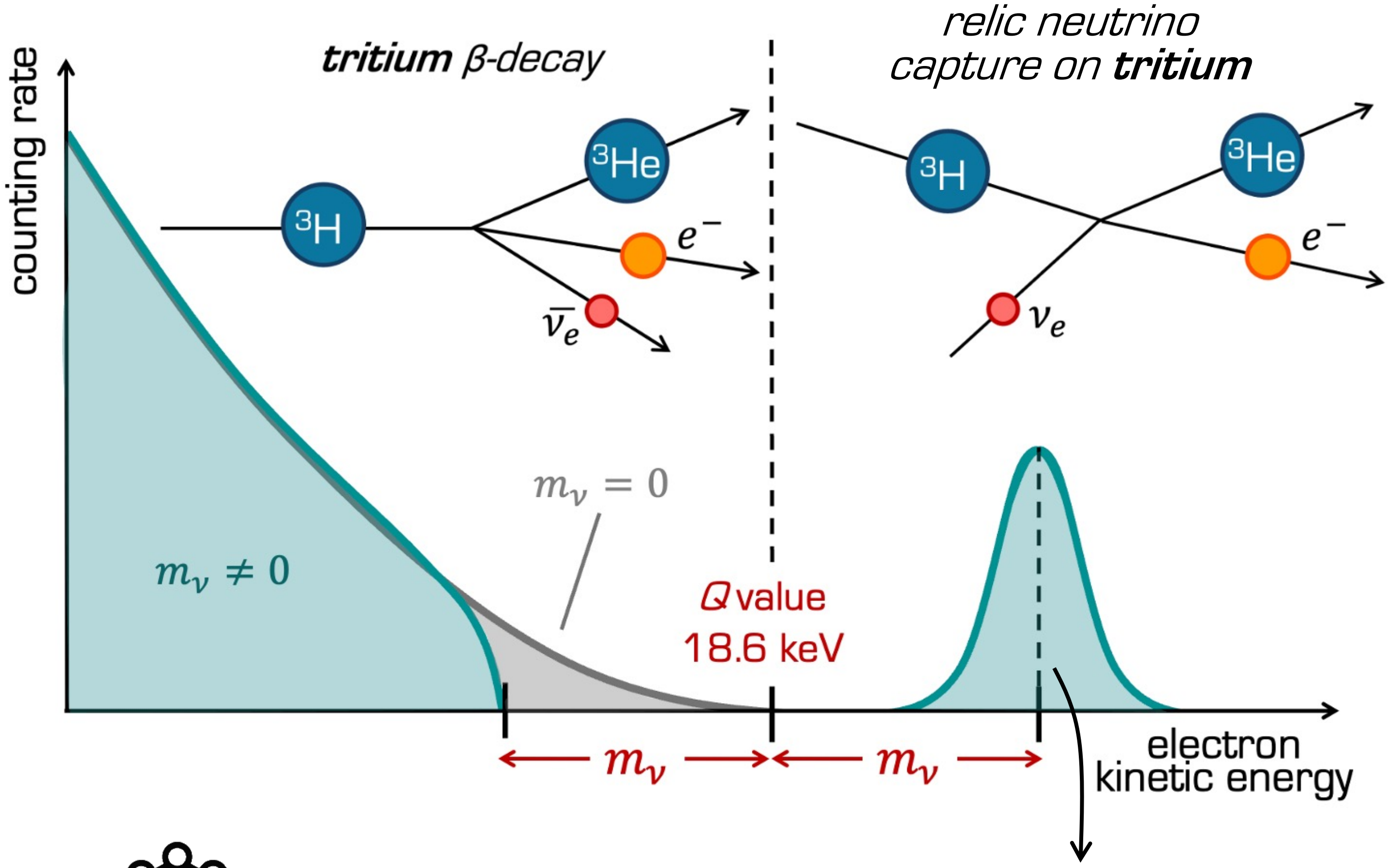

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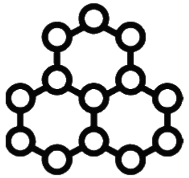
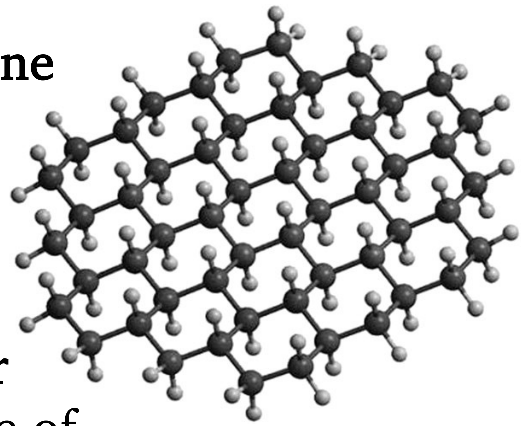


EXPERIMENT idea:

- ➢ tritium on **graphene** target
- ➢ electrons near endpoint slowed down by **EM filter** to an energy range of $\sim 0 - 10$ eV
- ➢ electrons energy measured with **TES microcalorimeters** (or electrostatic analyser)



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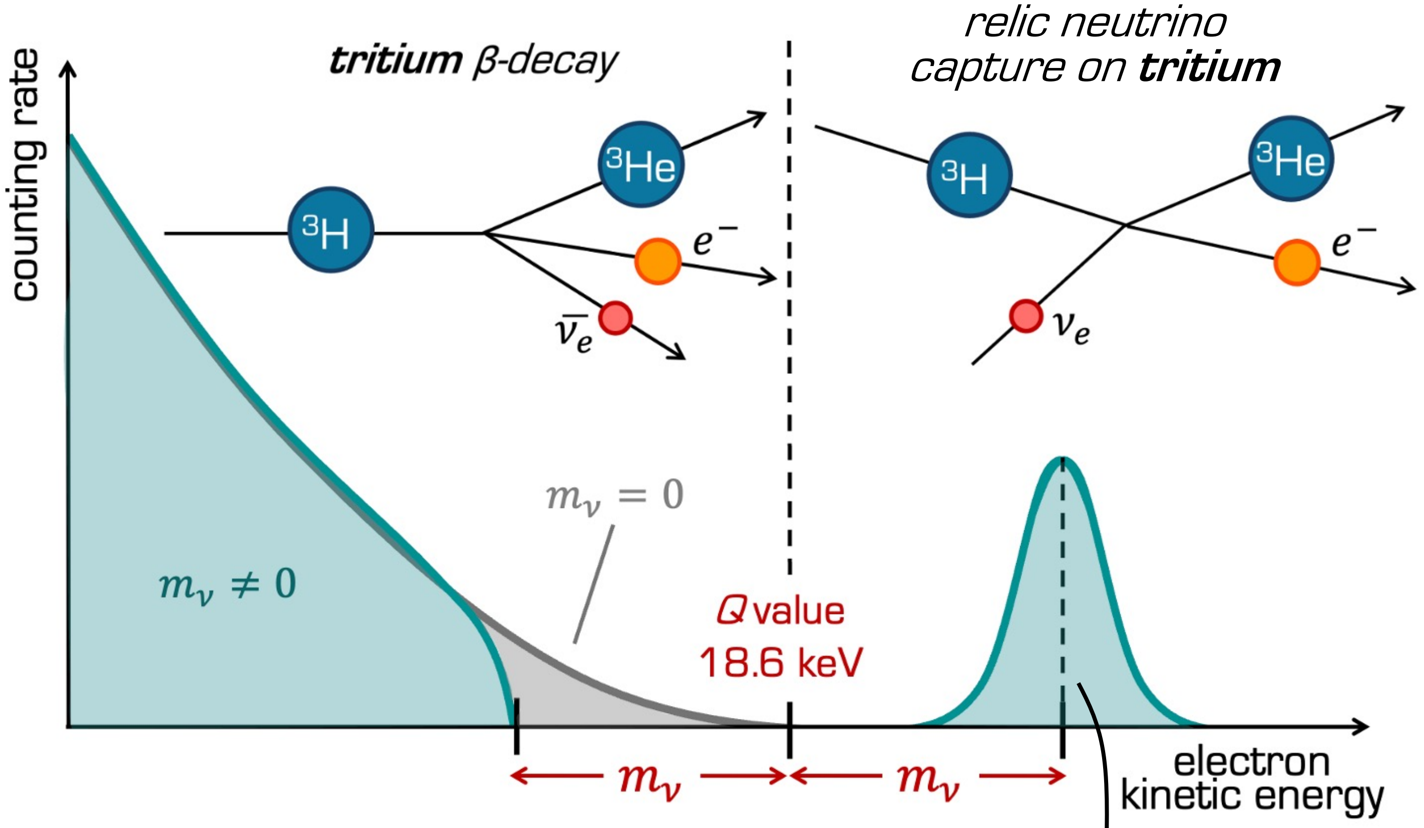

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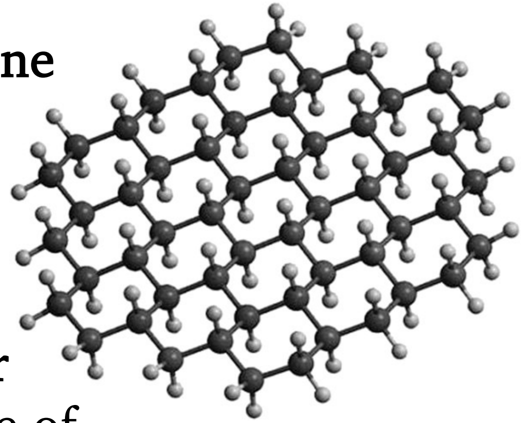

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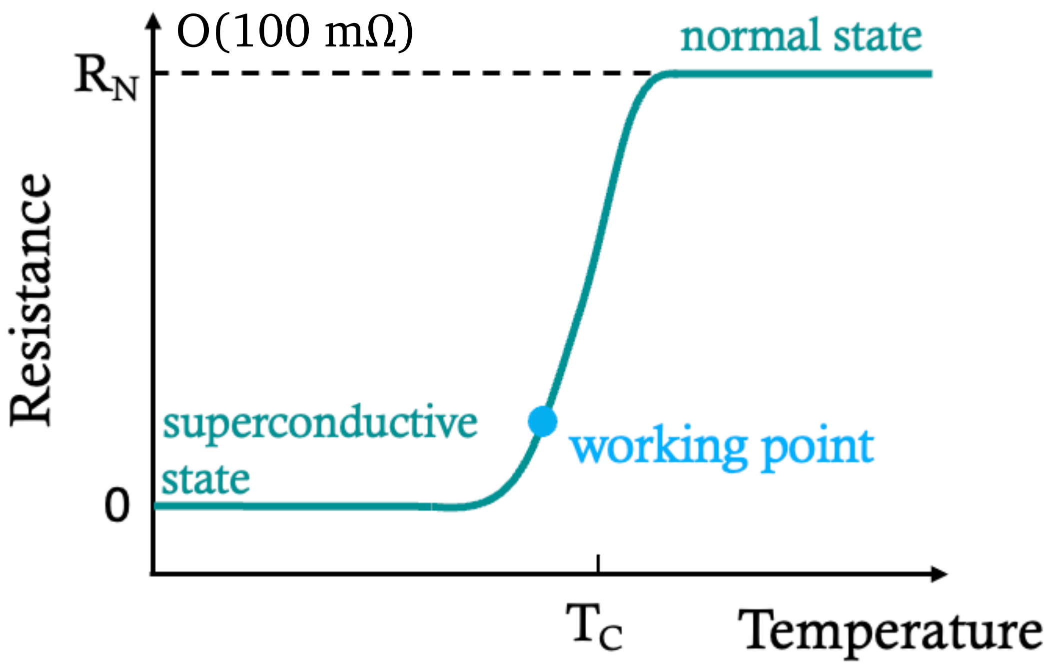
PTOLEMY goal:
$\sigma_e(E) = 50$ meV
for $E = 10$ eV

Transition-Edge Sensors: Operating Principle

- TES: superconductive film operated at its superconductive transition
- Critical temperatures of $\sim$ 100 mK $\Rightarrow$ **cryogenic** detector
- **Sharp** superconductive transition: typical width of few mK



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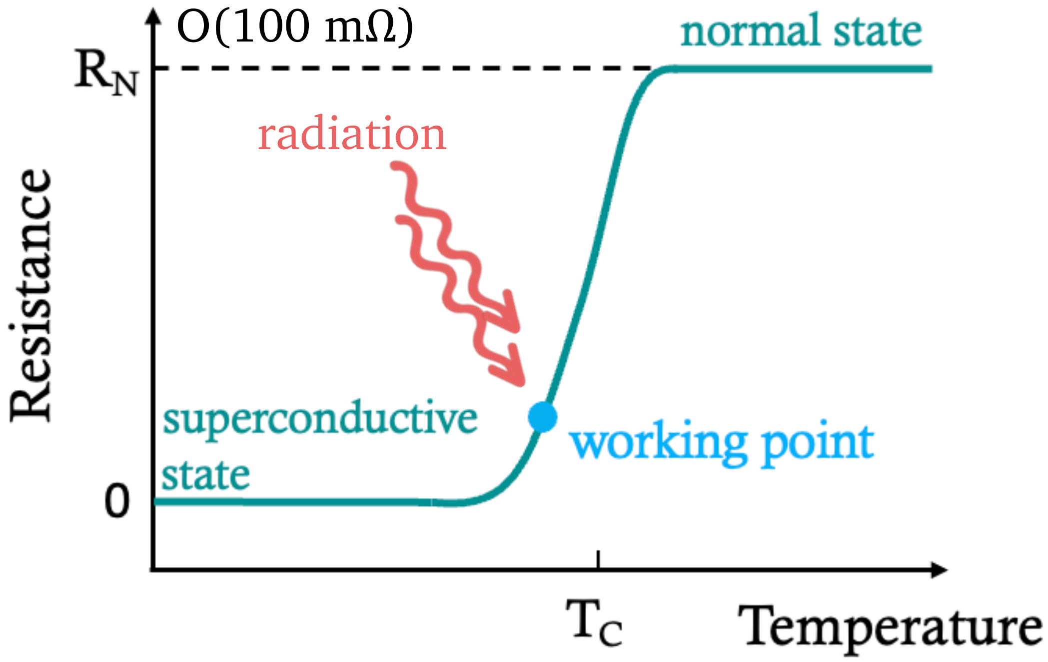

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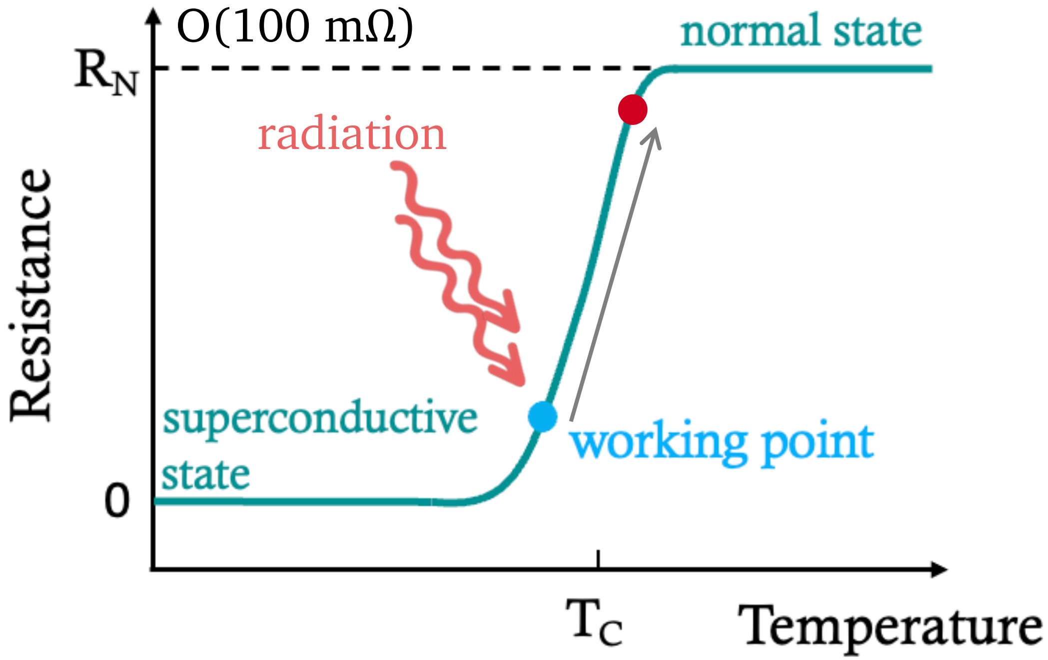

- Particle absorption $\Rightarrow$ small ΔT $\Rightarrow$ measurable ΔR

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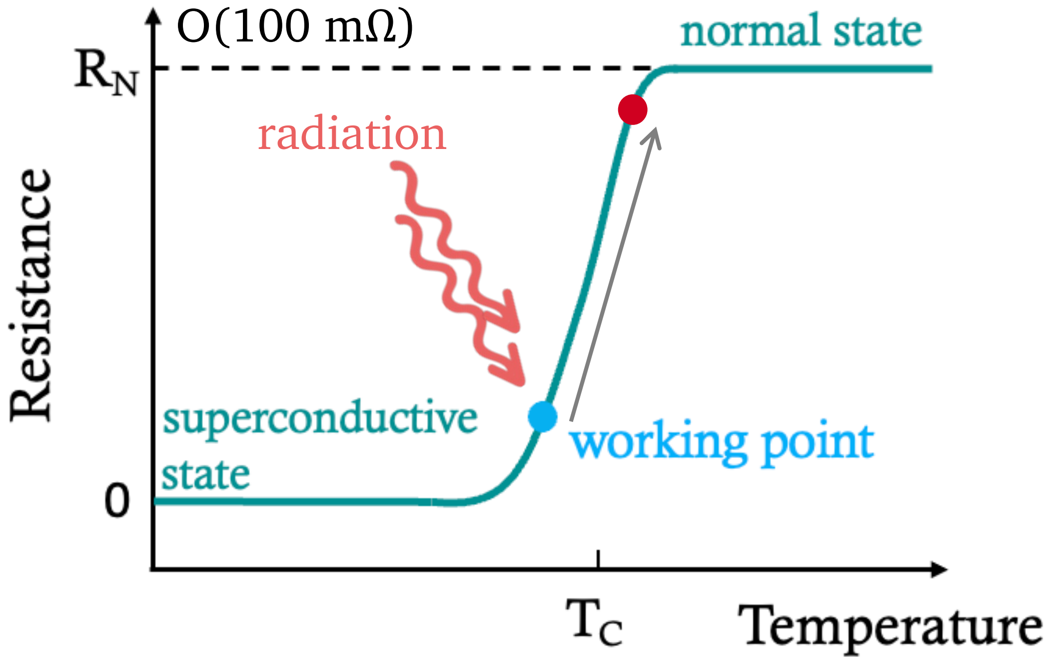
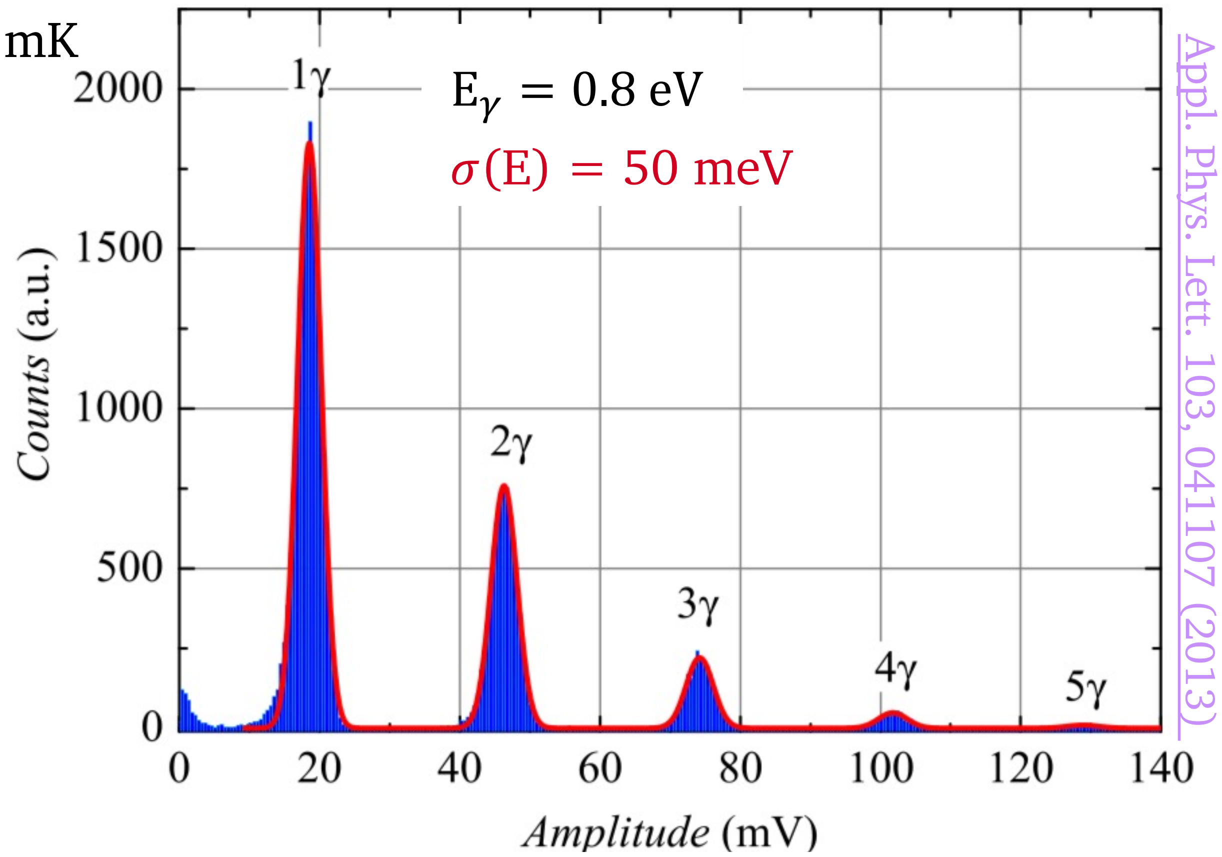


Photon-number resolving detector



Appl. Phys. Lett. 103, 041107 (2013)

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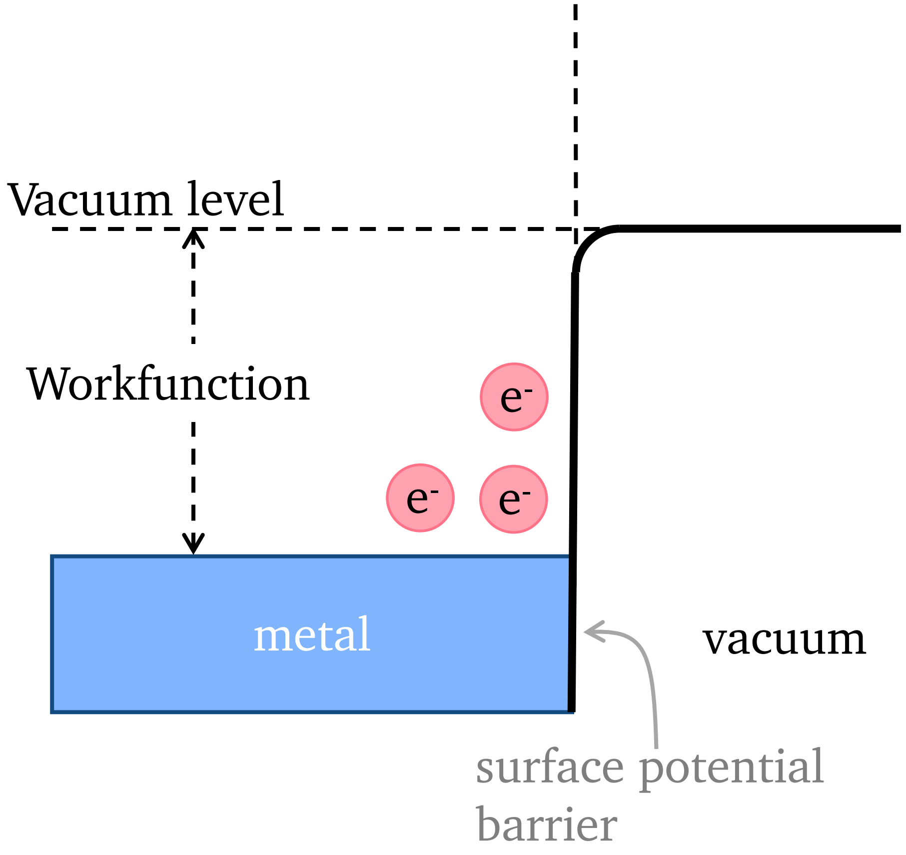
Can a TES detect electrons?

A Cold Electron Source

- Electron sources:



A Cold Electron Source

- Electron sources:
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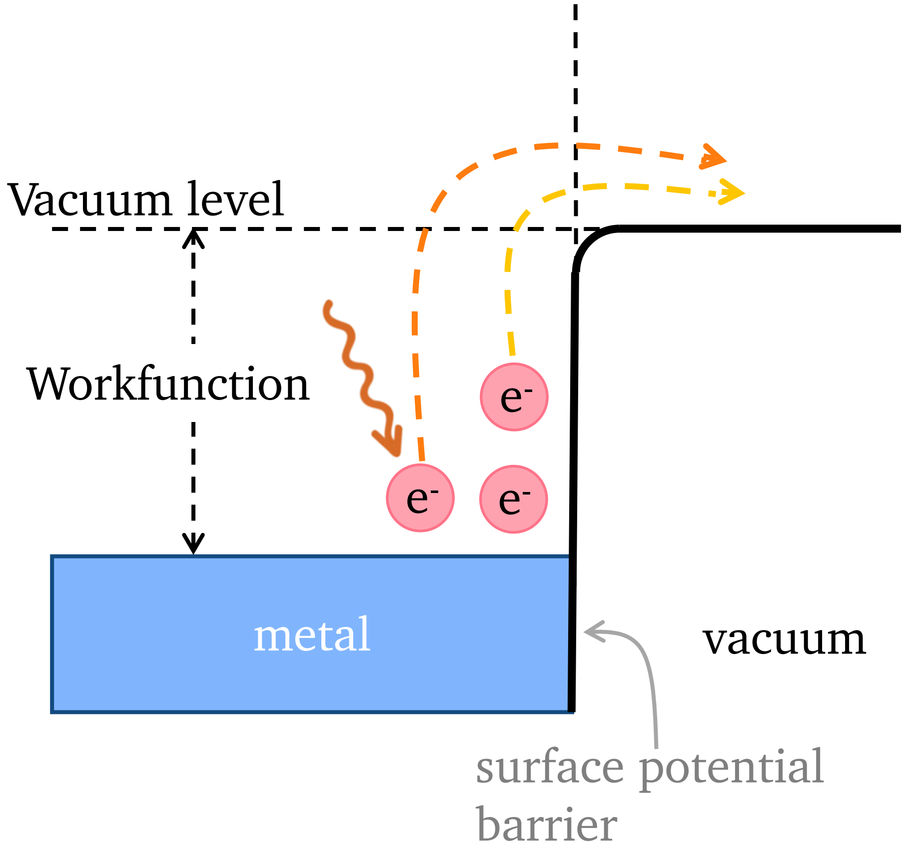
  - thermoionic emission



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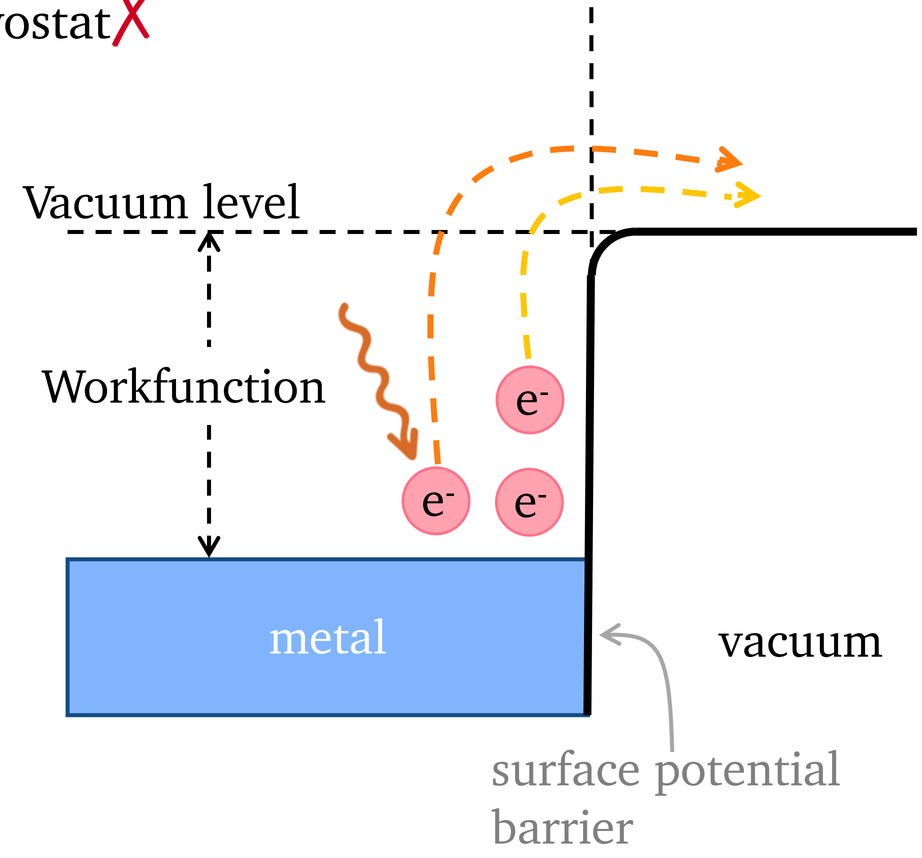
they generate **background/heat**
⇒ **cannot** be put inside a cryostat ✗



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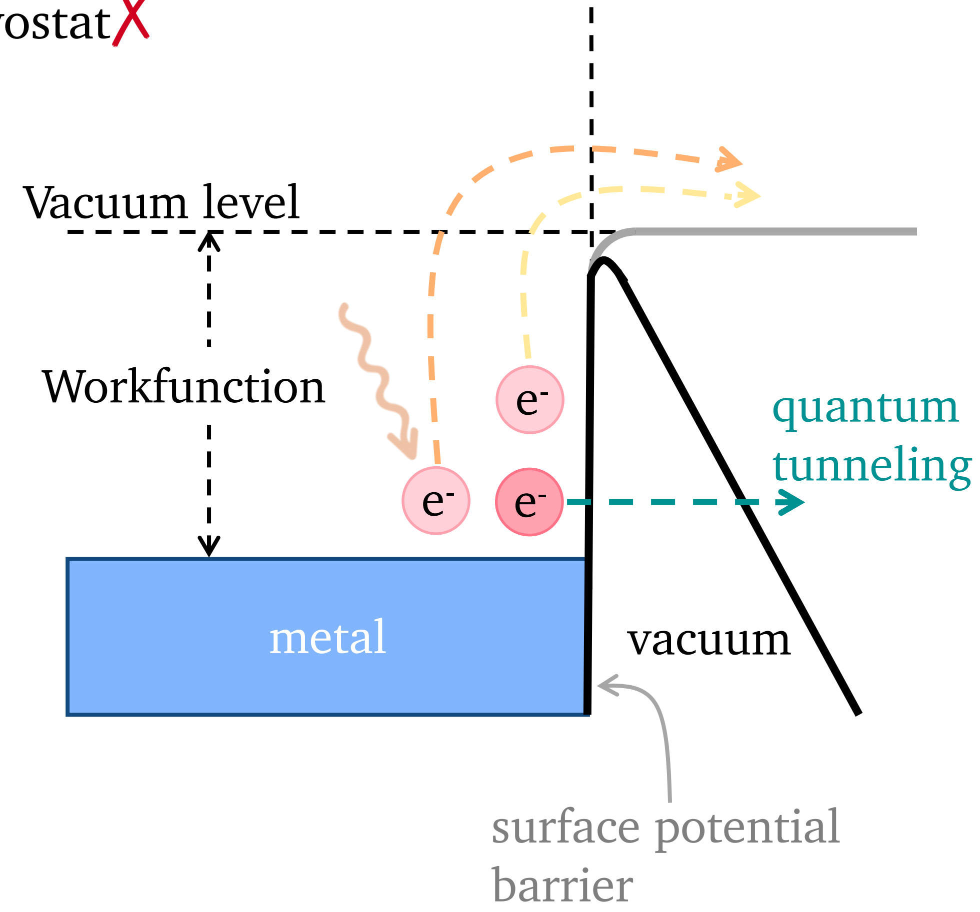

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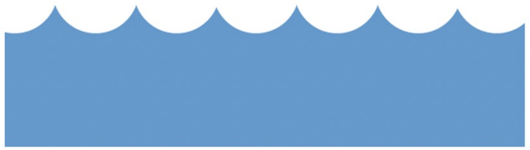
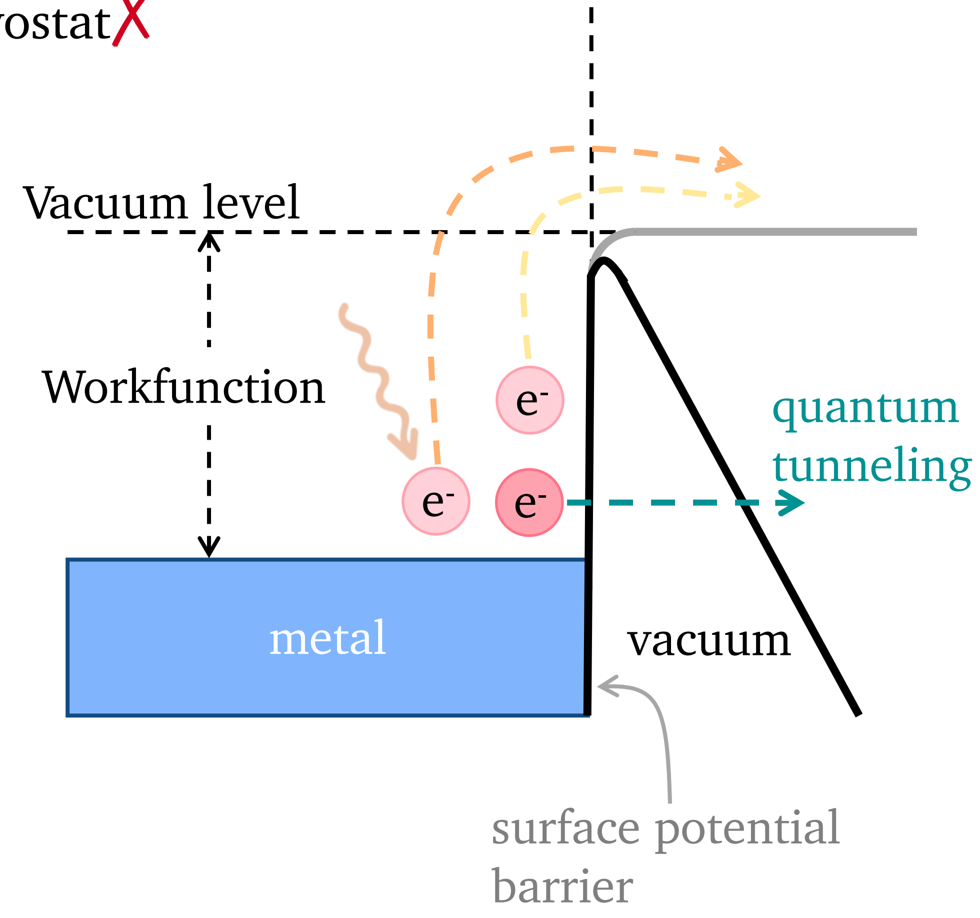
- Field emission needs very high **external electric fields**:

FLAT surfaces:
E > 10^7 V/cm

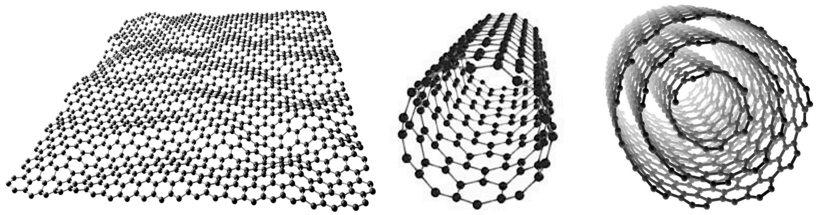
POINTY surfaces:
tip effect: E ⇒ γE



nanostructures: $\gamma \sim 10^4$

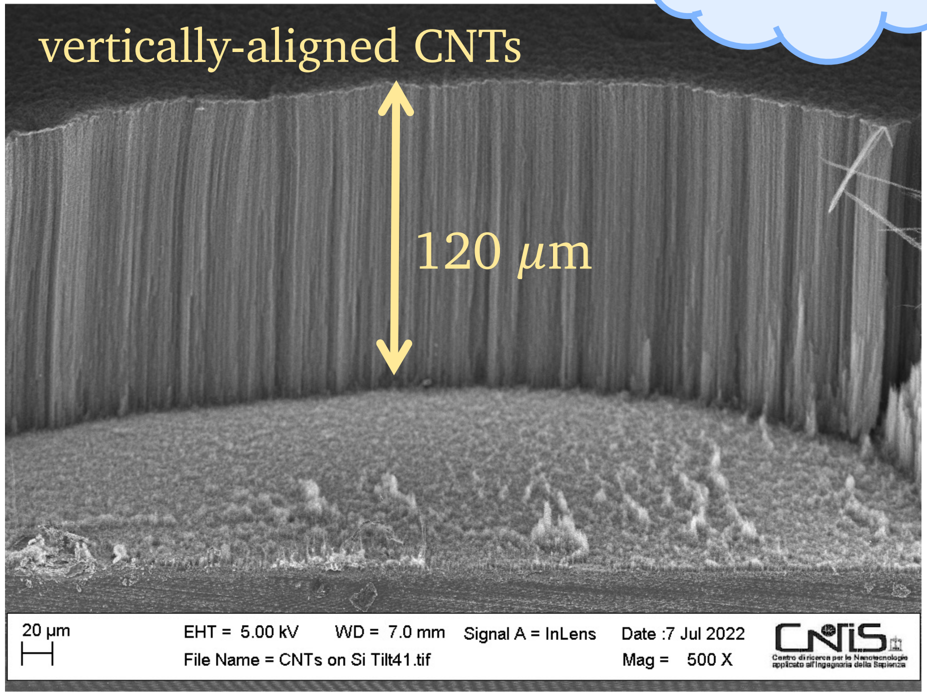


Carbon Nanotubes as Field Emitters



- Carbon **nanotubes** (**CNTs**): graphene 'straws'
  - diameter ~ 20 nm
  - lenght ~ 100 μm

original idea by **Alice Apponi (RomaTre)**



TITAN LAB
TECHNOLOGY INNOVATION THROUGH ADVANCED NANOSTRUCTURES

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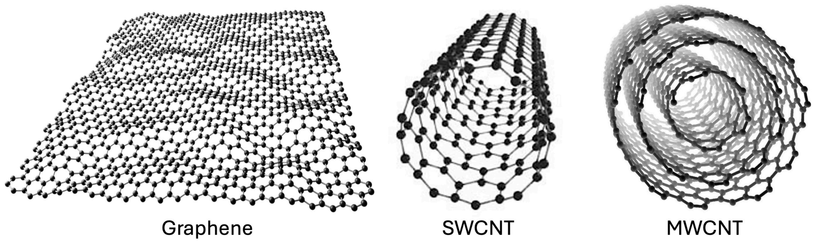

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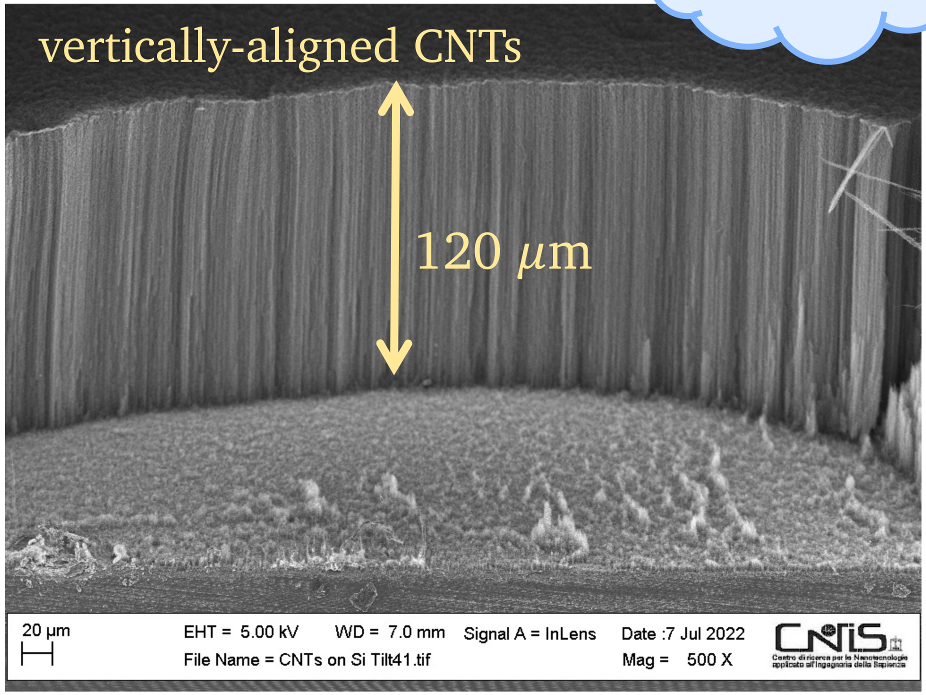

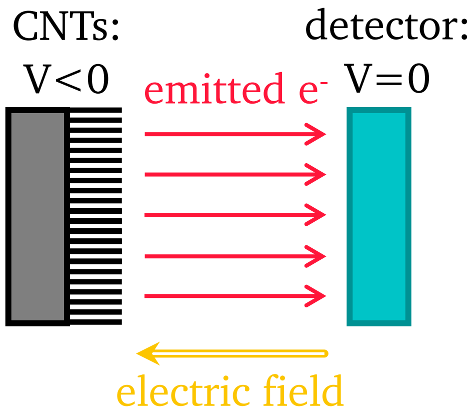

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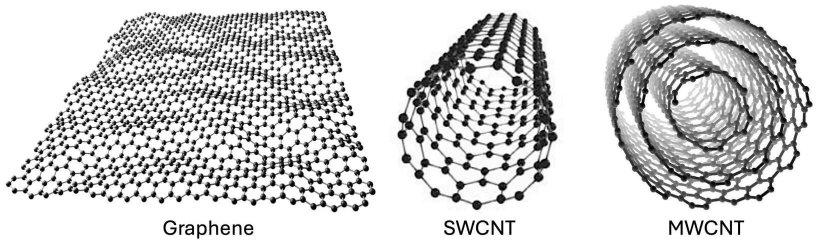

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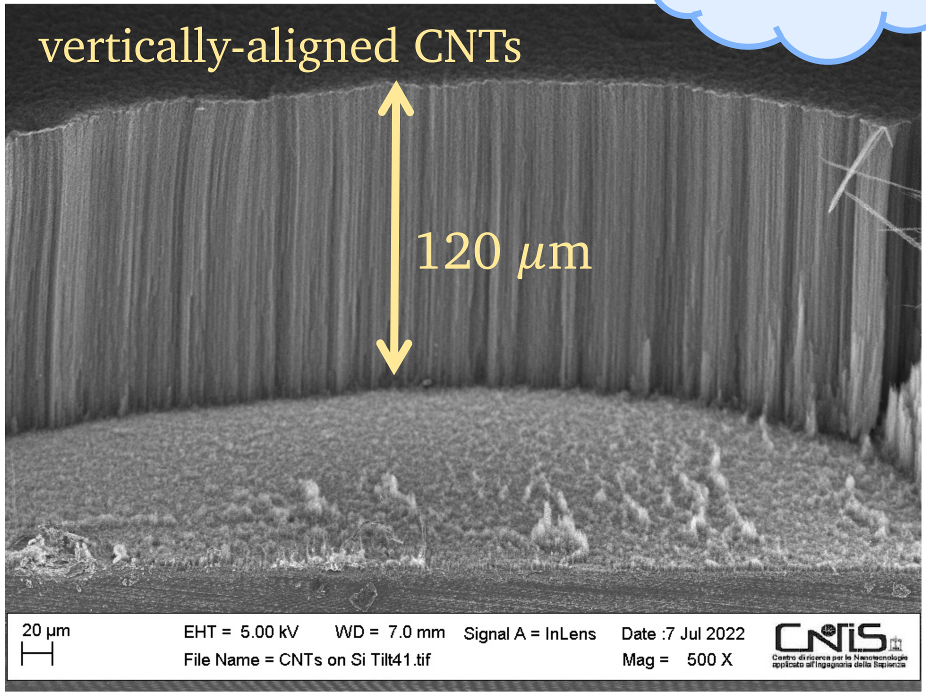

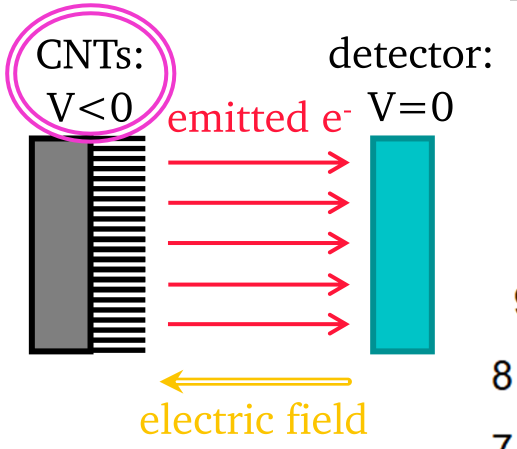

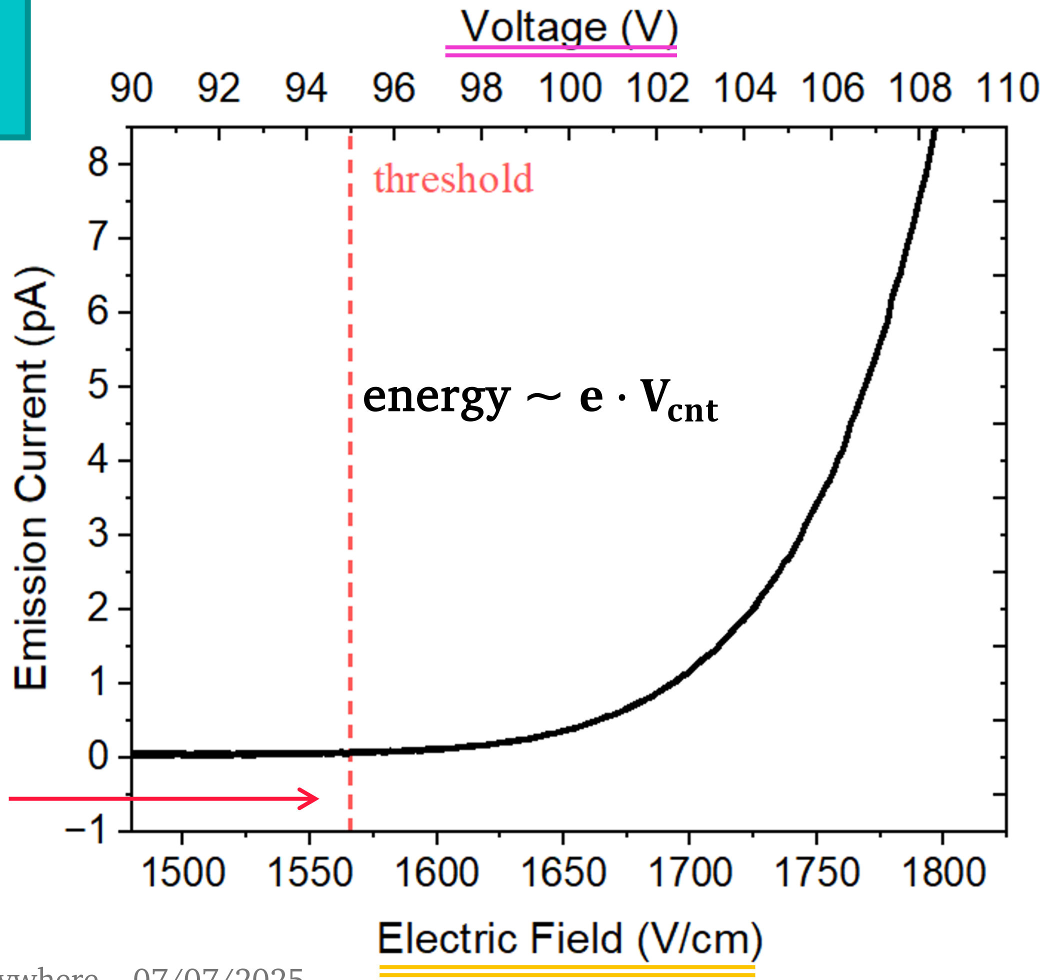

Threshold process
⇒ emission from
$\mathcal{O}$(100 V)!

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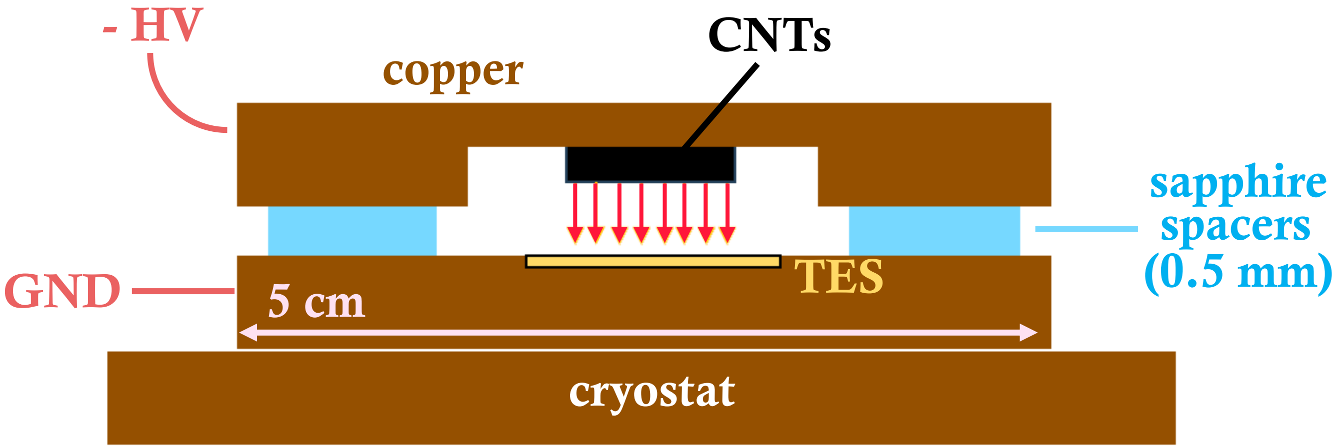
Mozzarella in Carrozza (MiC) Setup



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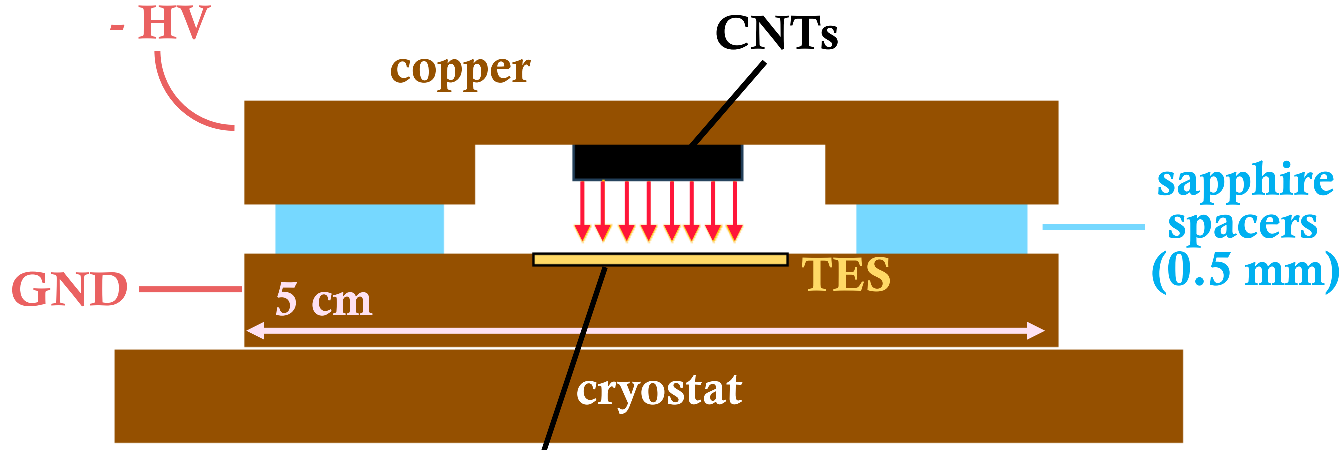

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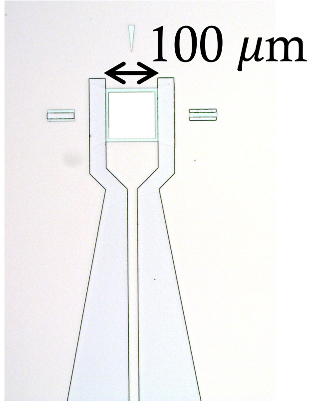
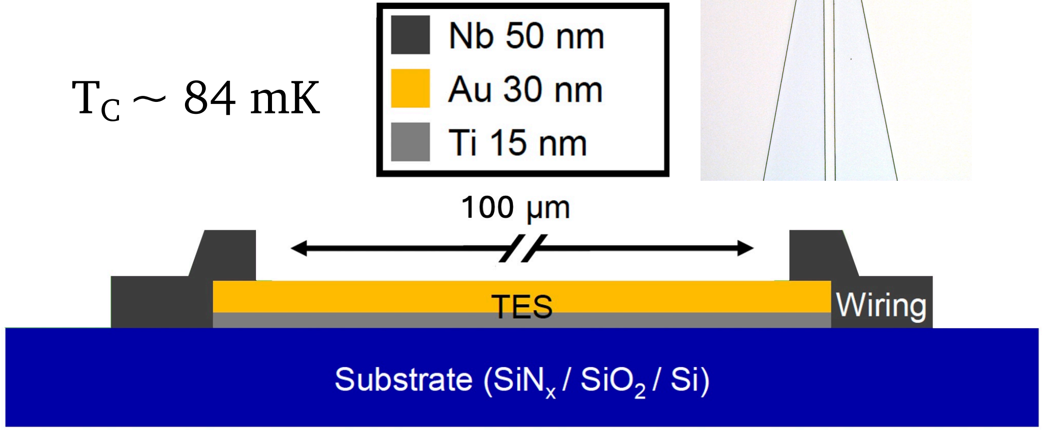
$T_C \sim 84$ mK





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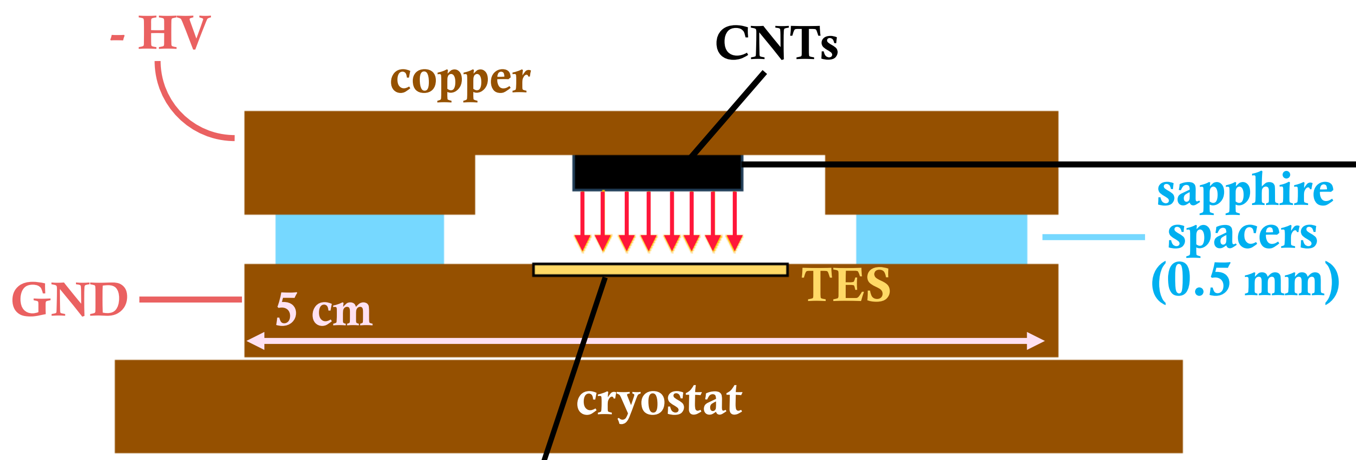
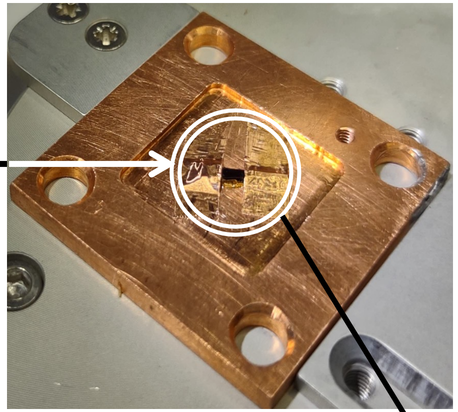
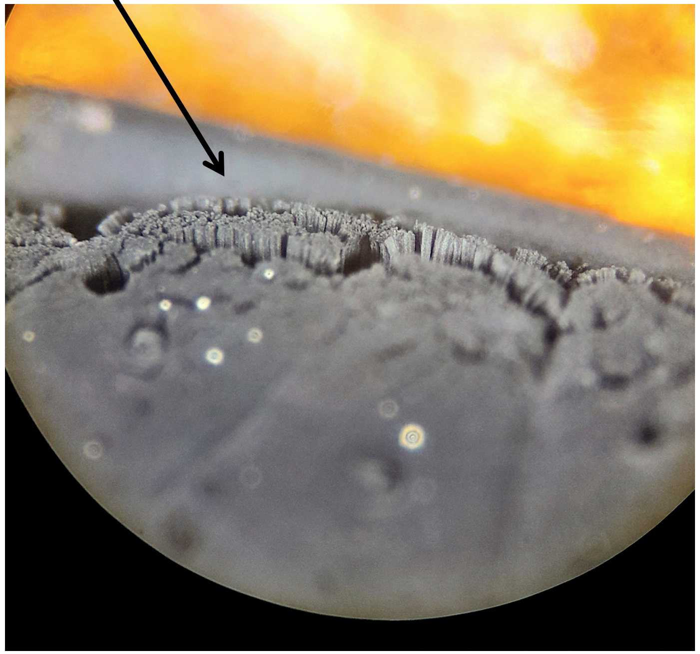
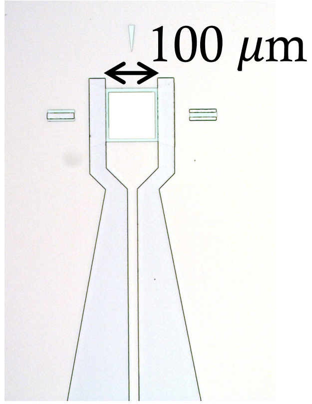




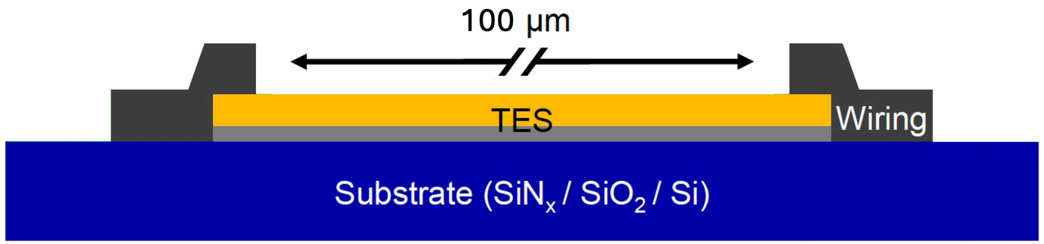


3 mm × 3 mm

$T_C \sim 84$ mK



Nb 50 nm
Au 30 nm
Ti 15 nm



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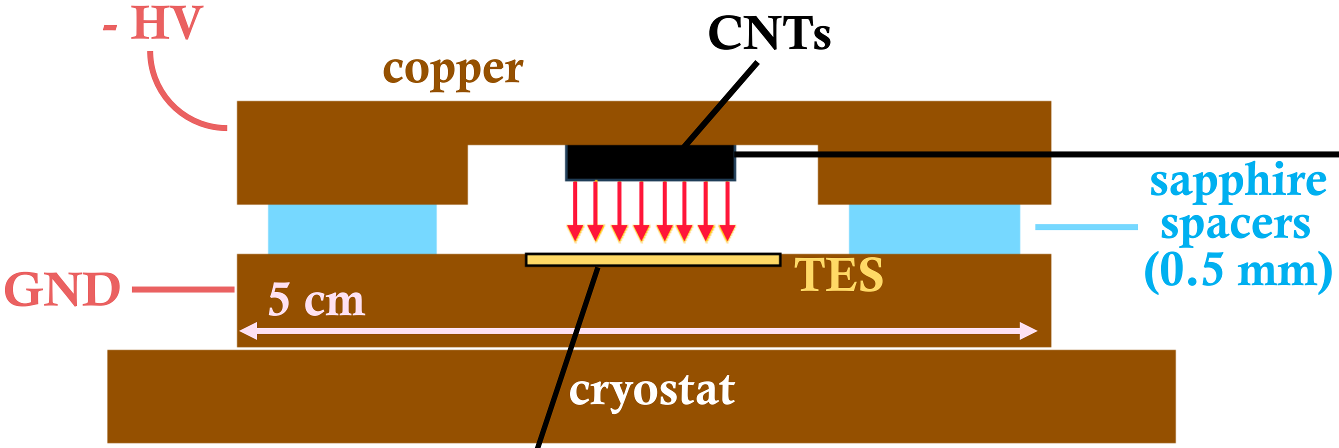

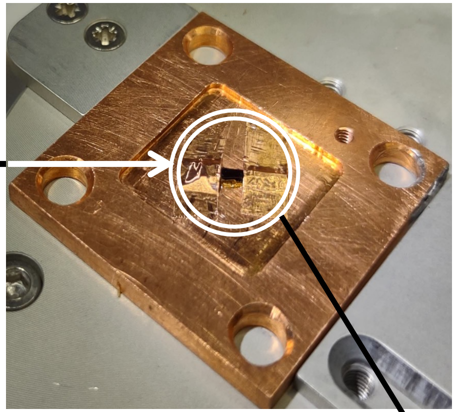

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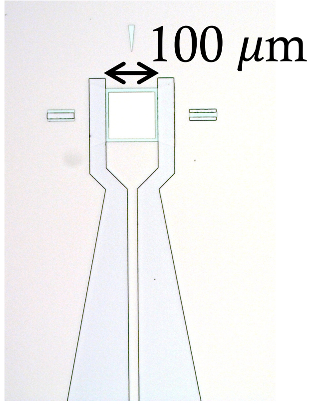

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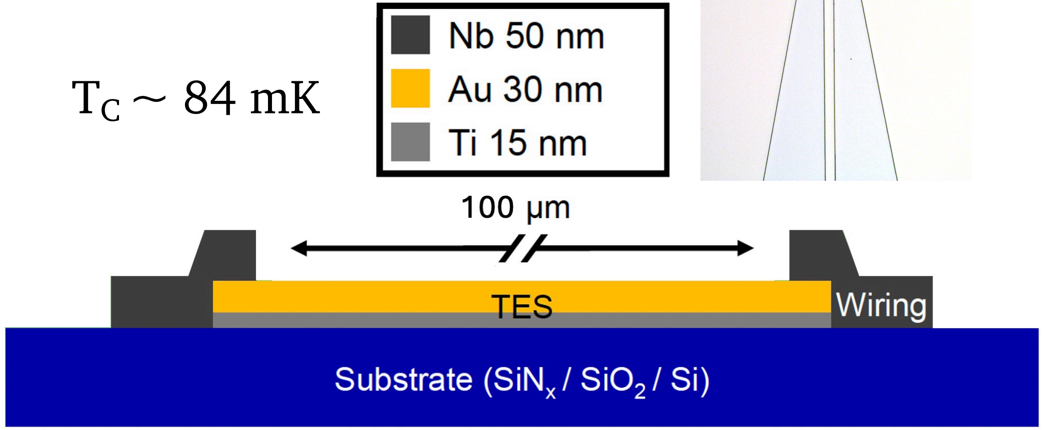
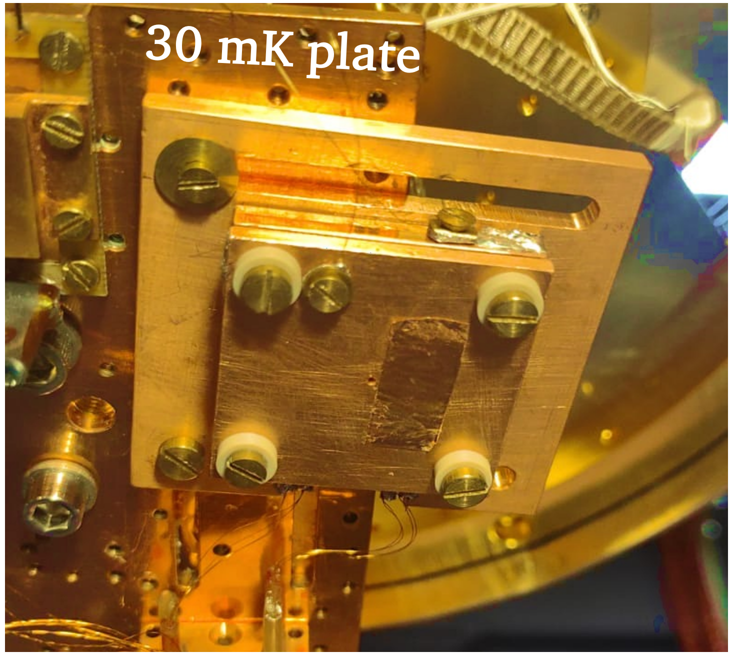
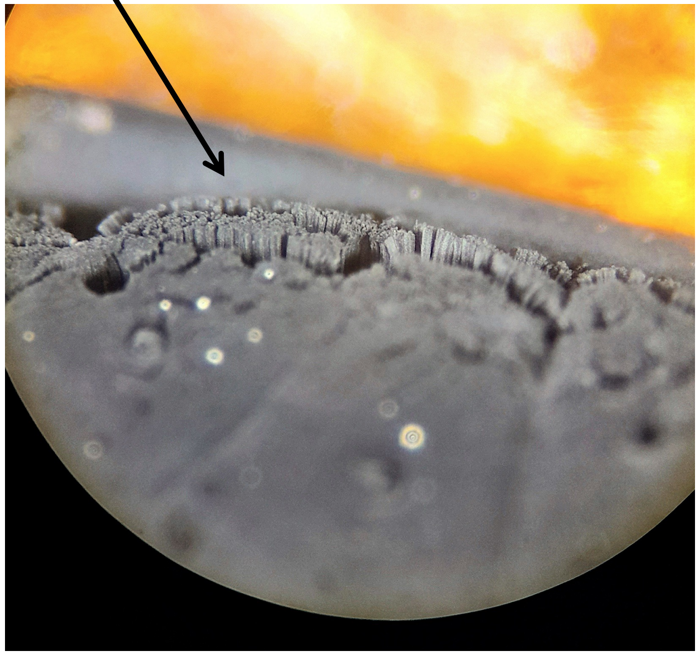
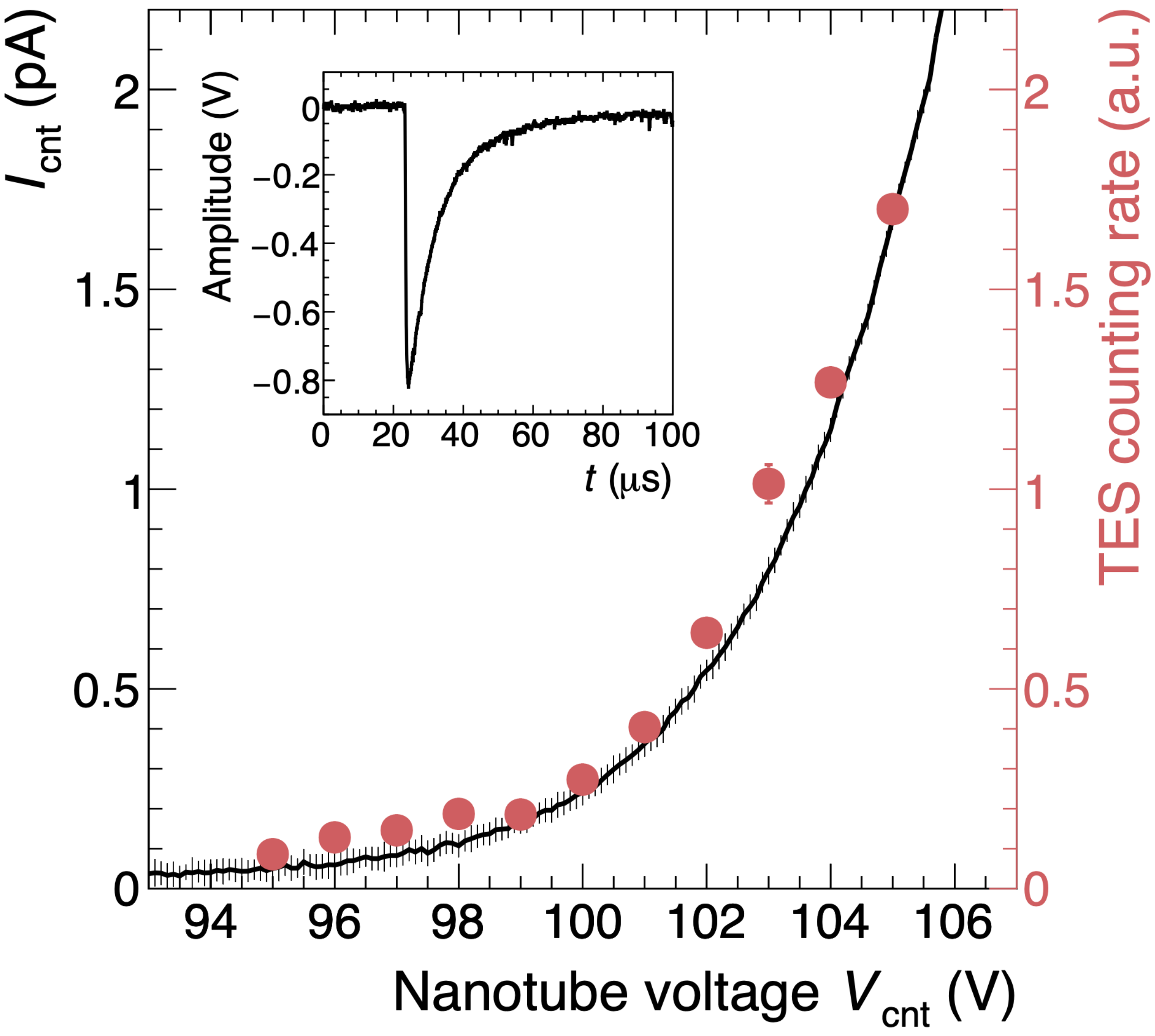


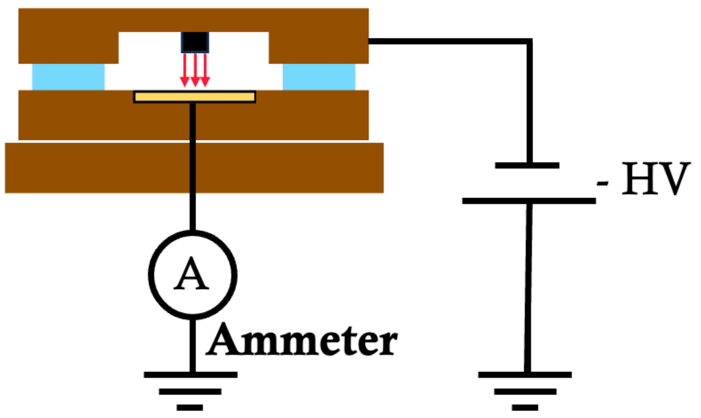




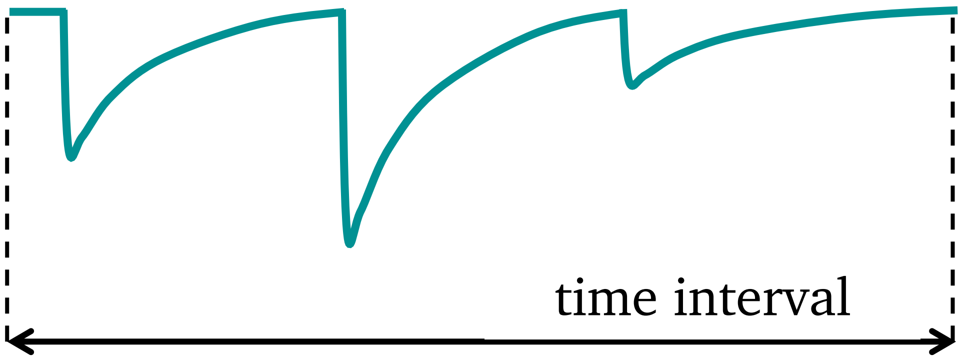
A Smoking Gun: the Signals are Electrons



field emission current measurement

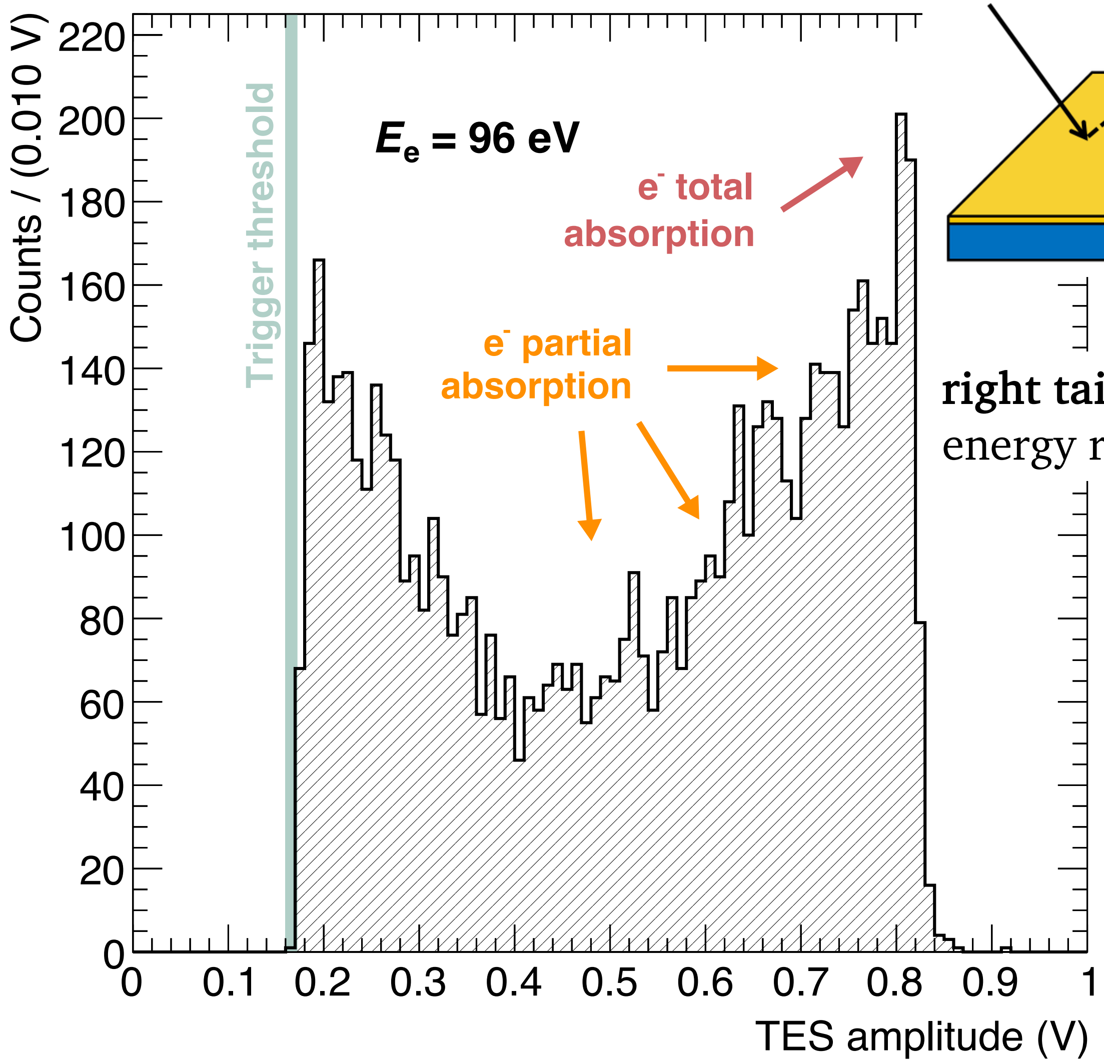


TES as electron counter

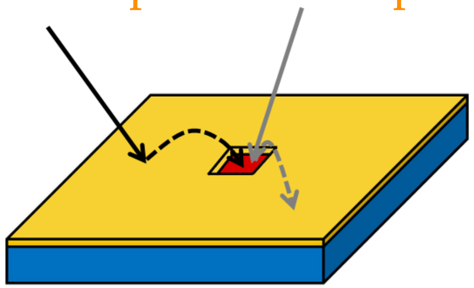


➢ the CNT current follows the same trend as the electron rate!

A Particular Signal Amplitude Spectrum



electron partial absorption:



right tail = TES energy resolution

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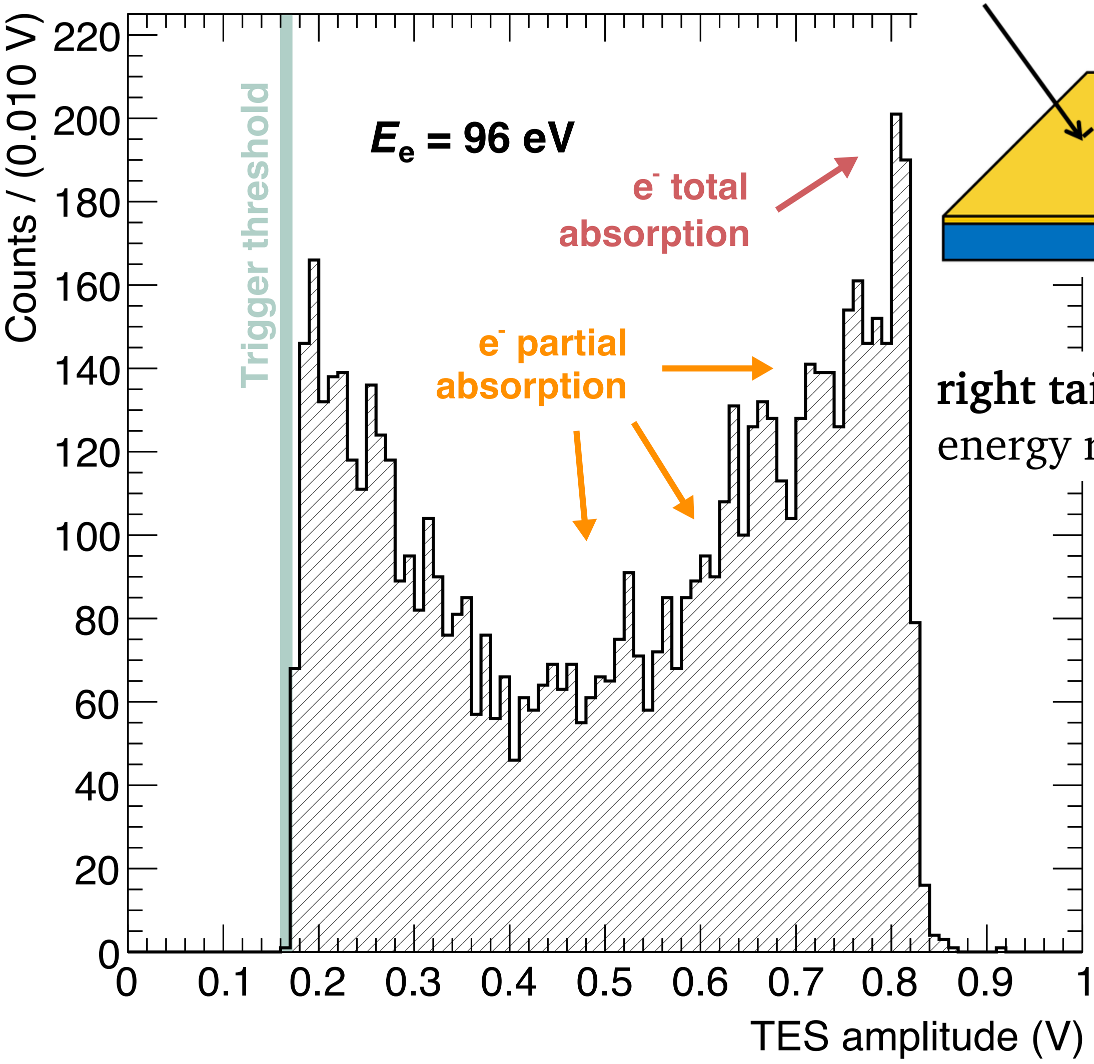

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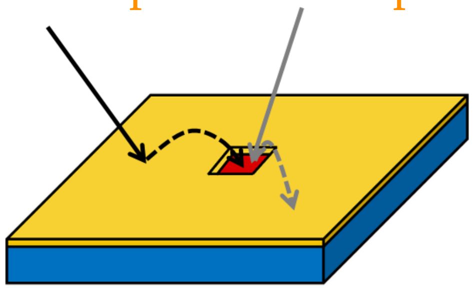

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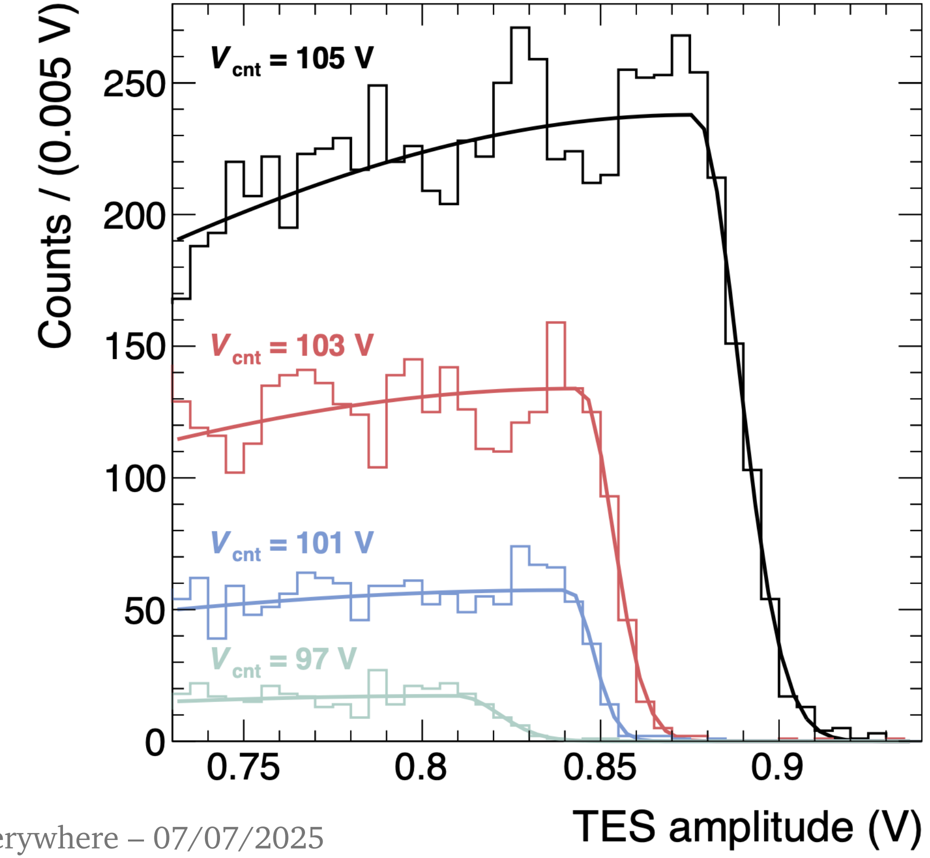
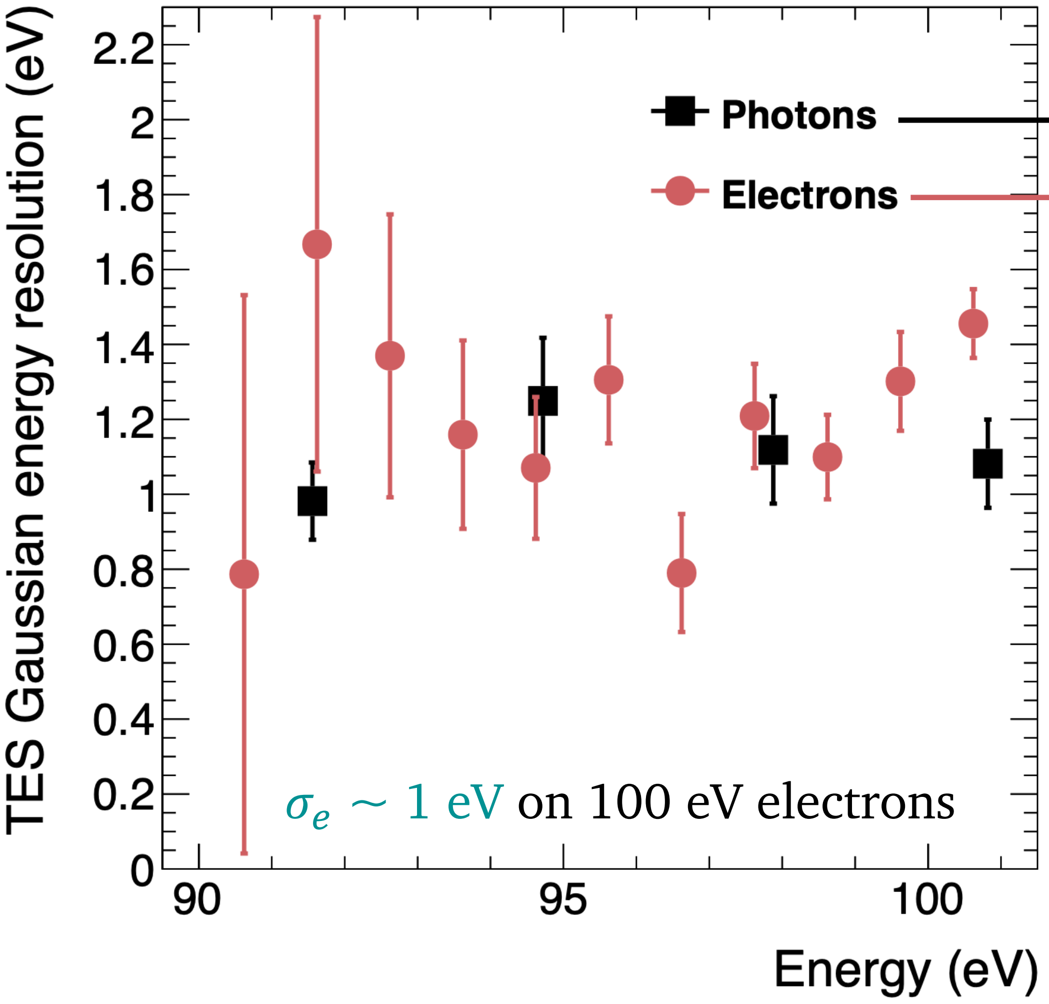
Asymmetric Gaussian fit function:

$$f(x) = \begin{cases} A \cdot exp\left(-\frac{(x-\boldsymbol{\mu})^2}{2\sigma_L^2}\right) & x < \mu \\ A \cdot exp\left(-\frac{(x-\boldsymbol{\mu})^2}{2\boldsymbol{\sigma}_R^2}\right) & x > \mu \end{cases}$$



Electron Resolution Compatible with Photons

Phys. Rev. Applied 22 (2024) L041007



optical calibration

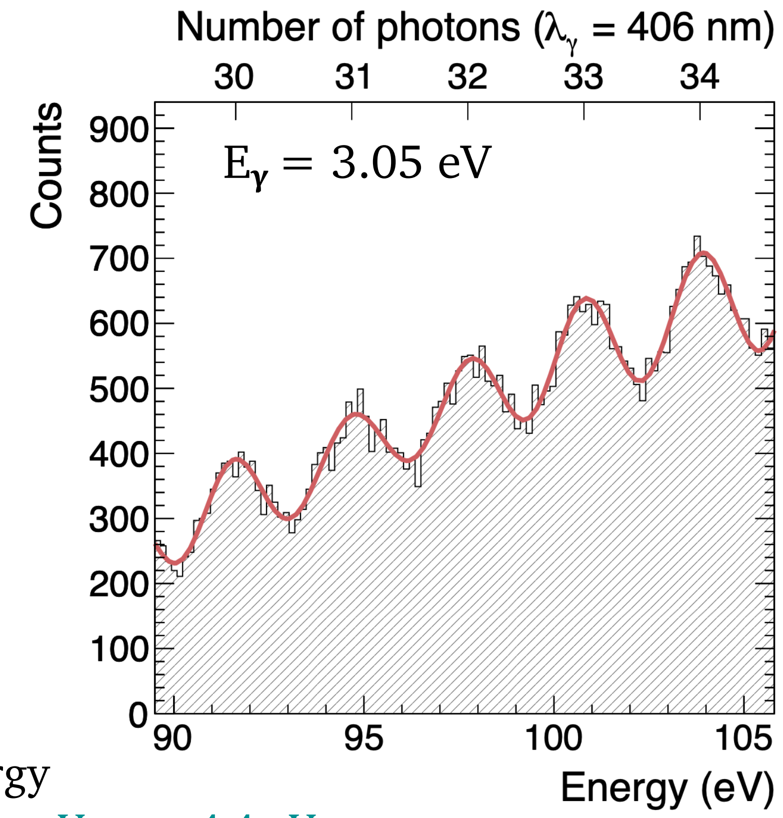
Electron energy resolution:

$$\sigma_e(E) = \frac{\sigma_{right}}{\mu} \boldsymbol{E_e}$$

fit parameters

electron nominal energy

$\boldsymbol{E_e} = eV_{cnt} - workfunction_{tes} = eV_{cnt} - 4.4\text{ eV}$



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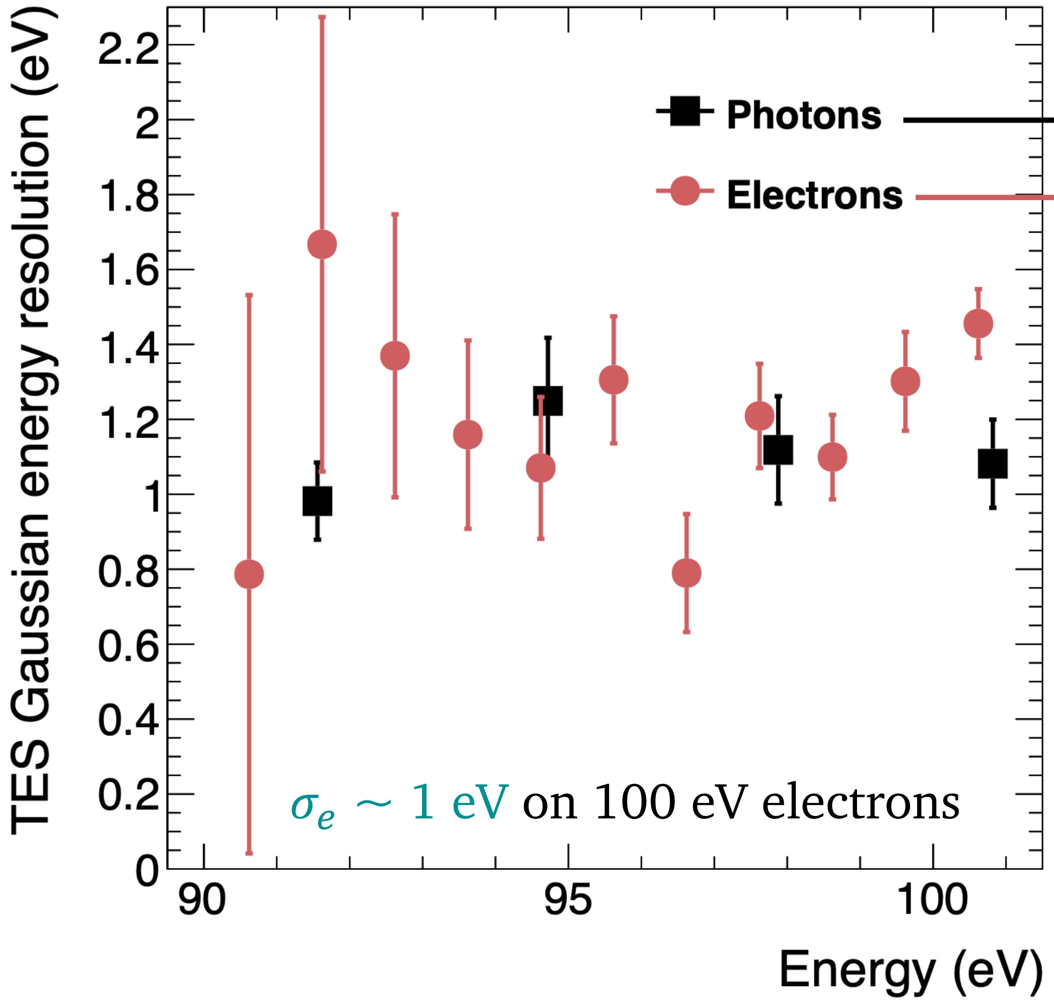
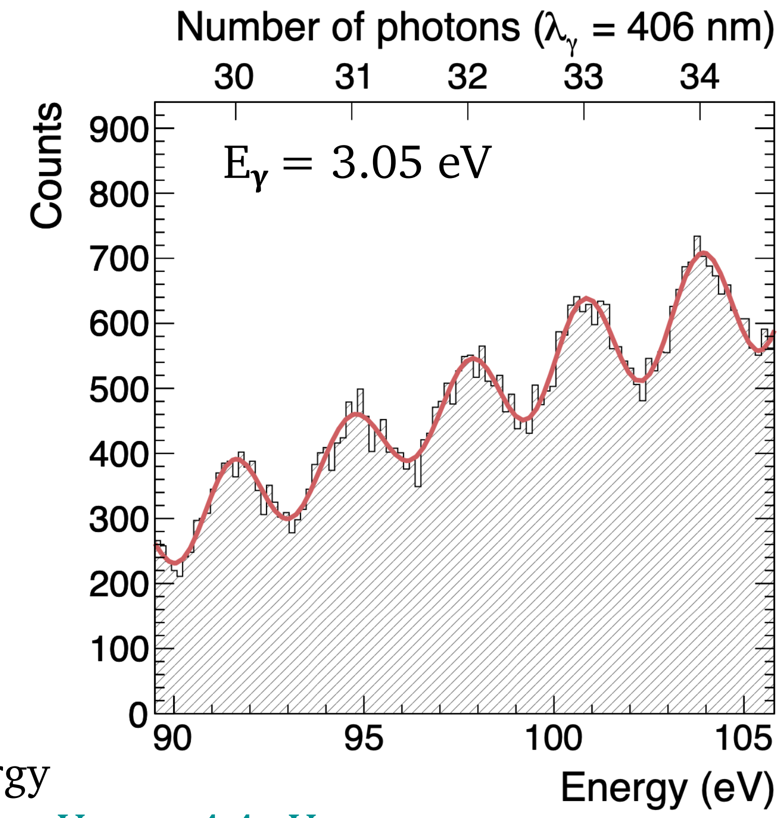


$\sigma_e \sim 1$ eV on 100 eV electrons

optical calibration



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➢ **Compatible** resolution for electrons and photons!
⇒ noteworthy as $e^- \neq \gamma$ at such low energies
⇒ probably same heat absorption mechanism for e^- and γ

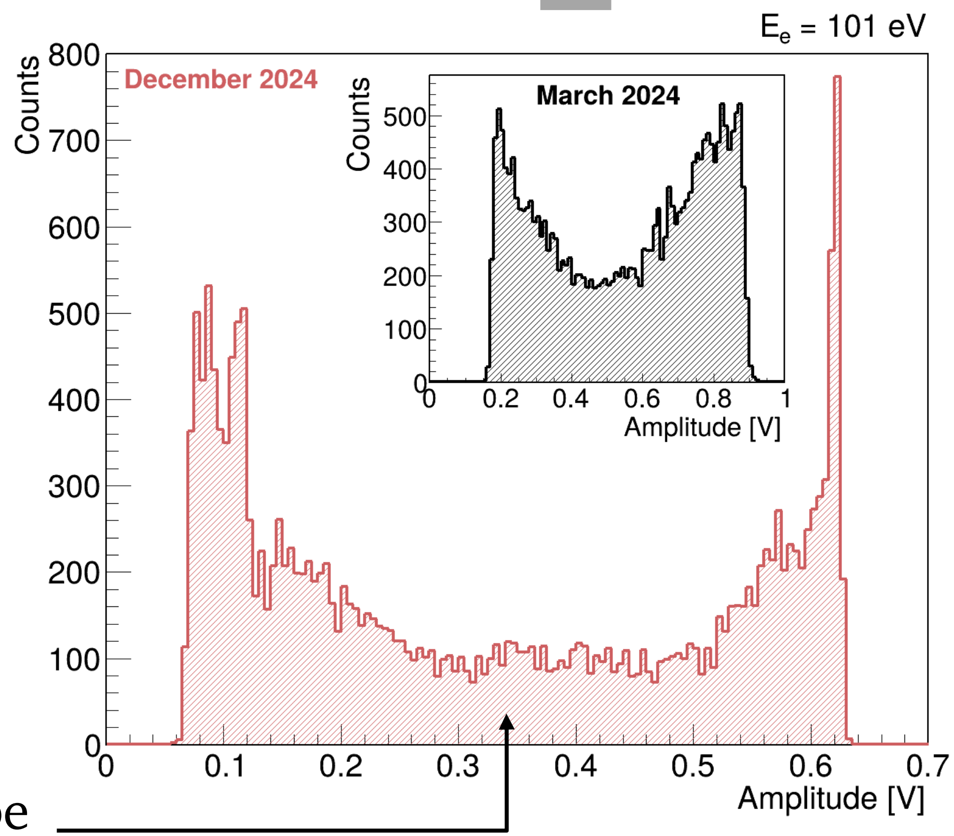
Conclusions

- **Detected** electrons with transition edge sensors!
  - resolution of $\sigma_e \sim 1$ eV on 100 eV
  - first time such low-energy electrons and such resolution
  - paper Phys. Rev. Applied 22 (2024) L041007

- Electron energy resolution **compatible** with photon one!
  - **optimism** on PTOLEMY goal of $\sigma_e(E) = 50$ meV for $E = 10$ eV!
    (50 meV for E = 0.8 eV achieved with photons)

- New results with important **improvements** on spectrum shape and energy resolution

paper in preparation

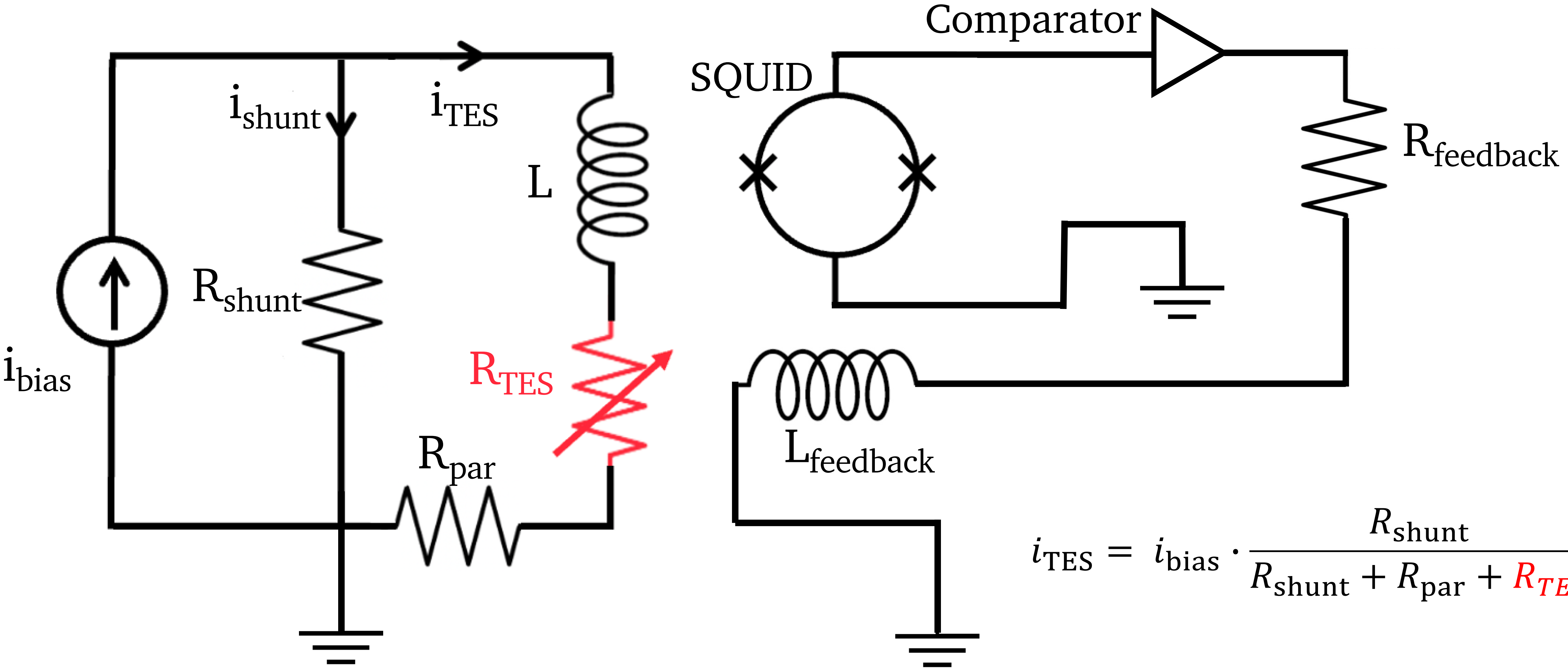


Thank you for your attention!

Backup Slides

TES Readout Circuit

A



$$i_{TES} = i_{bias} \cdot \frac{R_{shunt}}{R_{shunt} + R_{par} + R_{TES}}$$

TES Detection Performance

B

$$\tau_{eff} = \tau_{th}\left\{1 + \frac{\alpha}{n}\left(1 - \frac{T_{bath}^{n}}{T_c^{n}}\right)\right\}^{-1} \approx \frac{n}{\alpha}\tau_{th} \approx \frac{C}{G} \propto T_c^{-3}$$

effective time response

$$\Delta E_{FWHM} = 2.36\sqrt{4k_B T_c^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}} \propto T_c^{3/2}$$

energy FWHM

$$E_{sat} = C\Delta T_{sat} = \frac{C}{\alpha}\frac{\Delta R_{sat}}{R}T_c \propto T_c$$

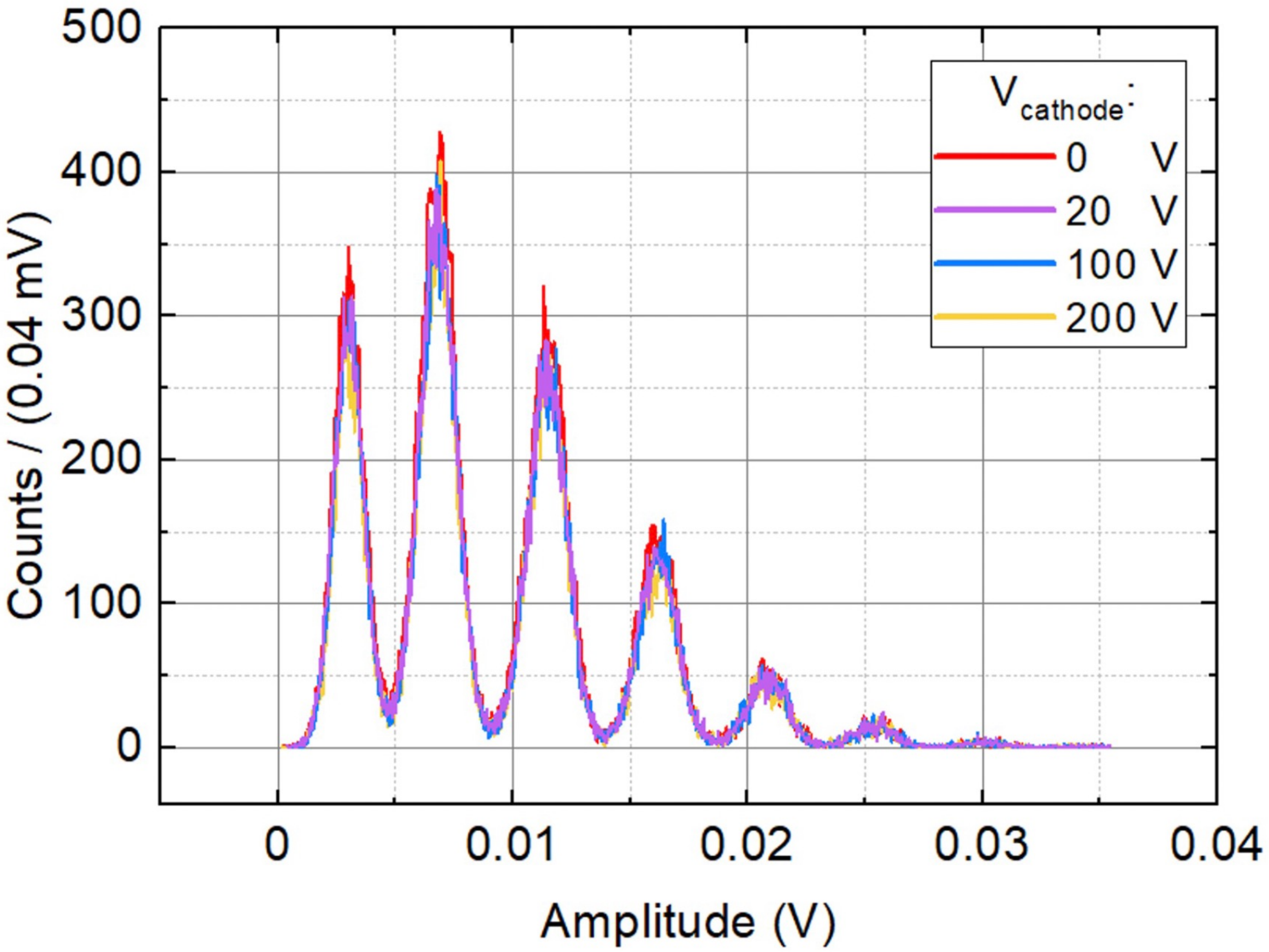
energy saturation

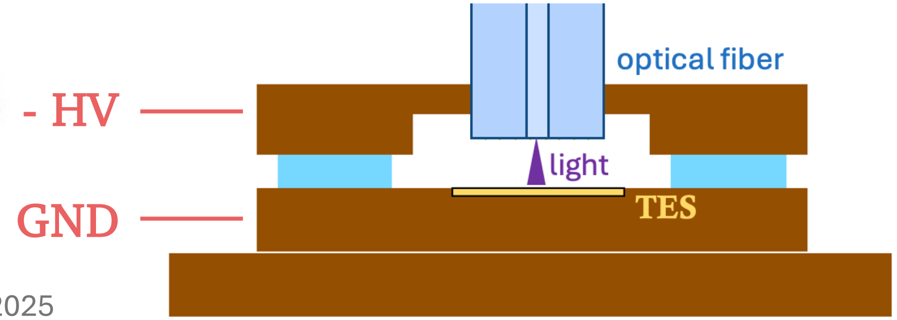
$$\alpha = \frac{T}{R}\frac{dR}{dT}$$

transition sharpness

Electric Field Does not Have Relevant Effects

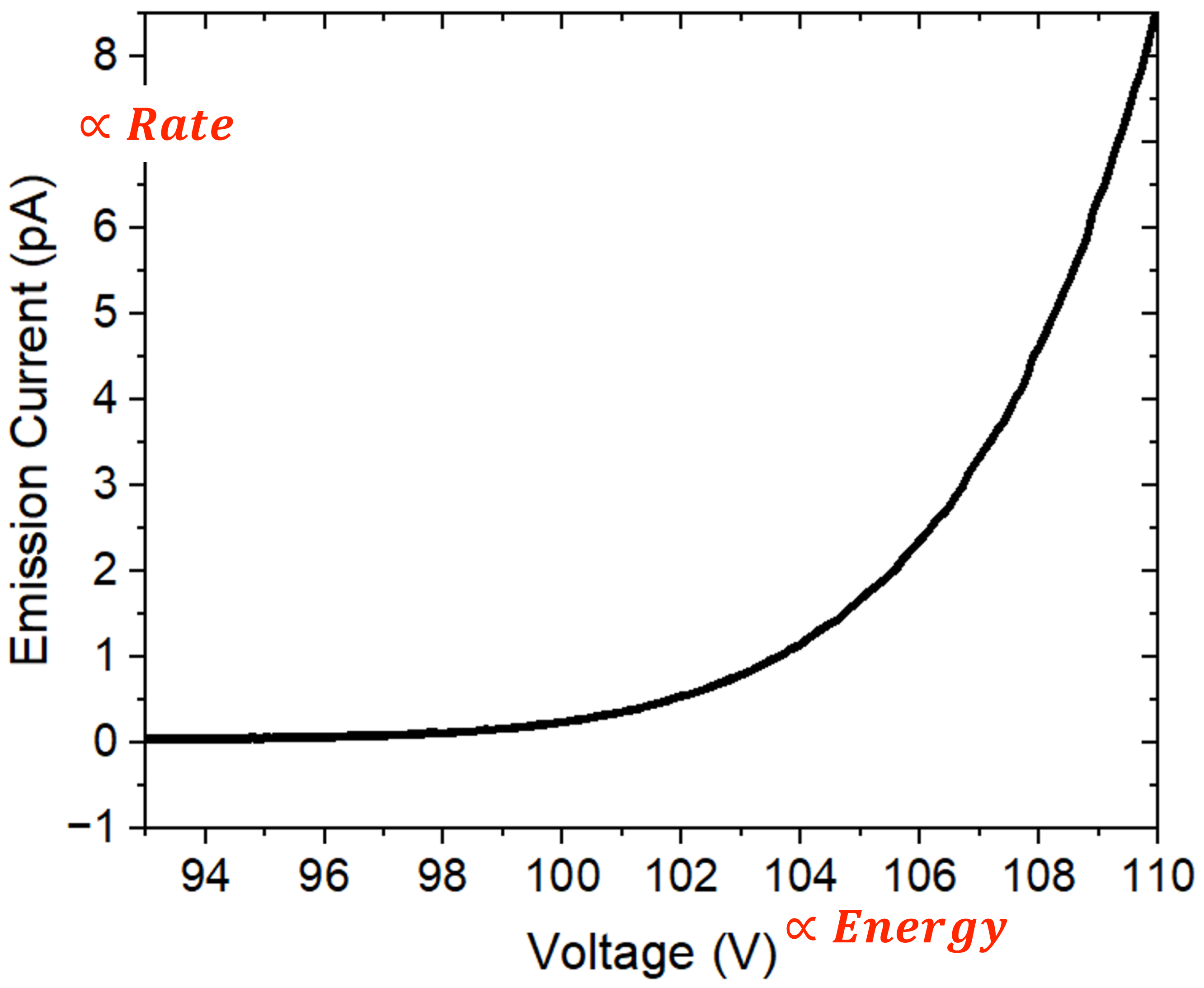
C

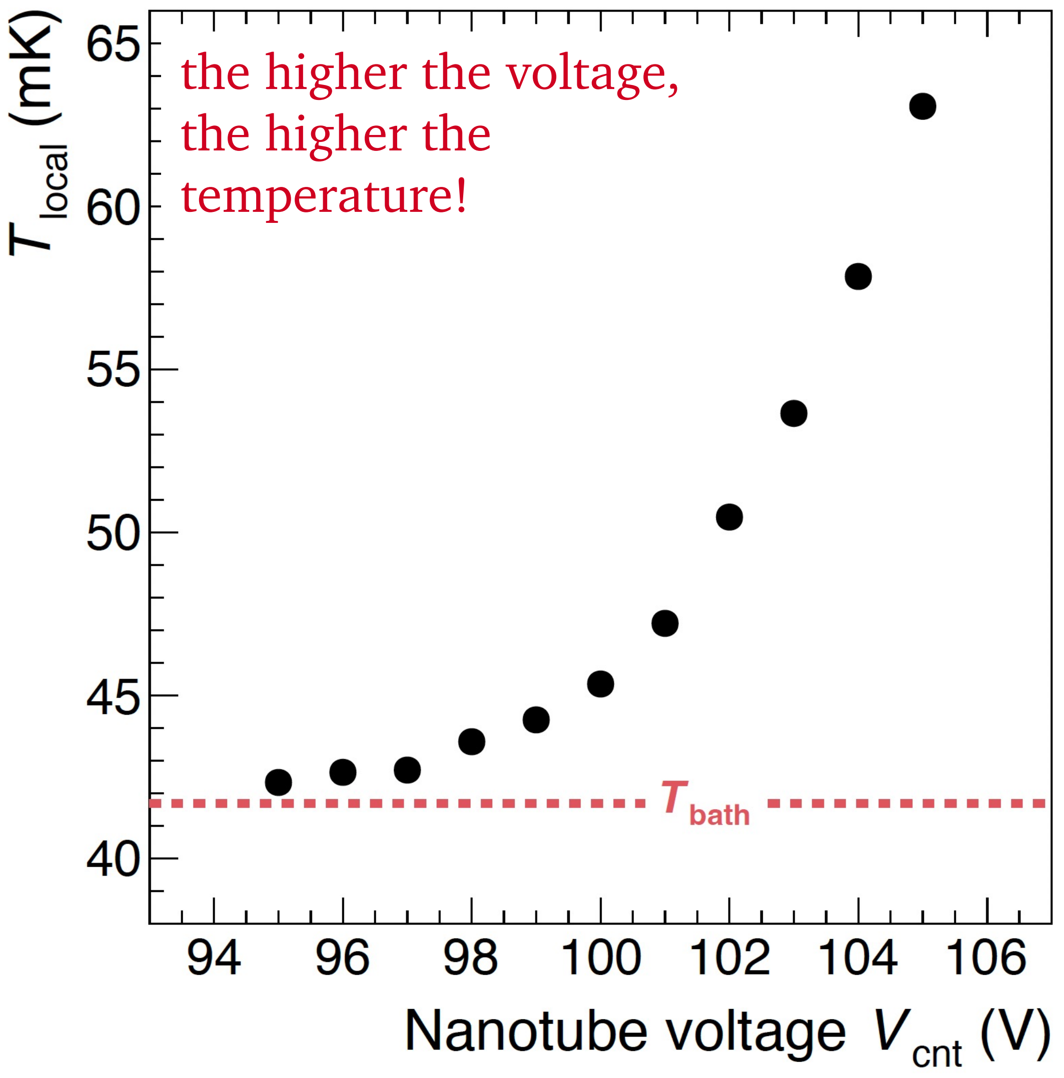




Field Emission Local Heating Effect

D

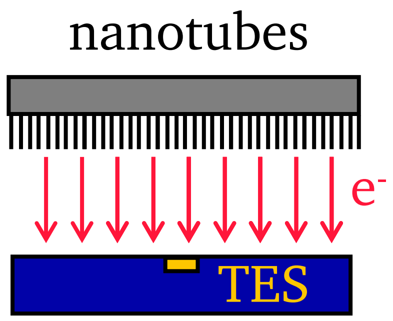


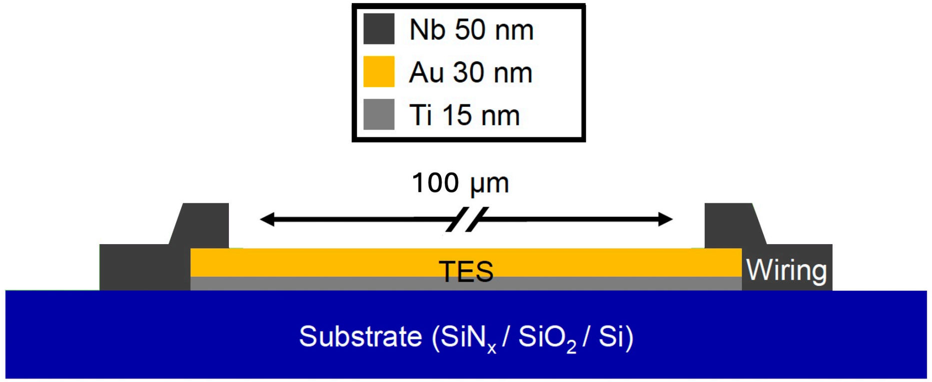


Shield against Unwanted Electron Hits

E

- CNTs surface (**3 mm × 3 mm**) ≫ TES active area (**100 μm × 100 μm**)
- Need to **avoid** electron hits on:
  - wiring (signal interferences)
  - insulating substrate (charge accumulation)





Shield against Unwanted Electron Hits

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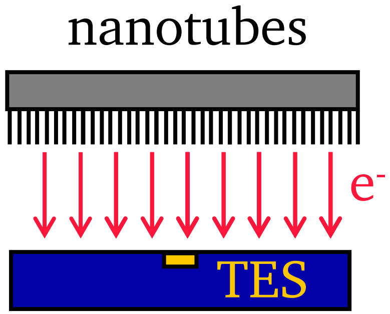
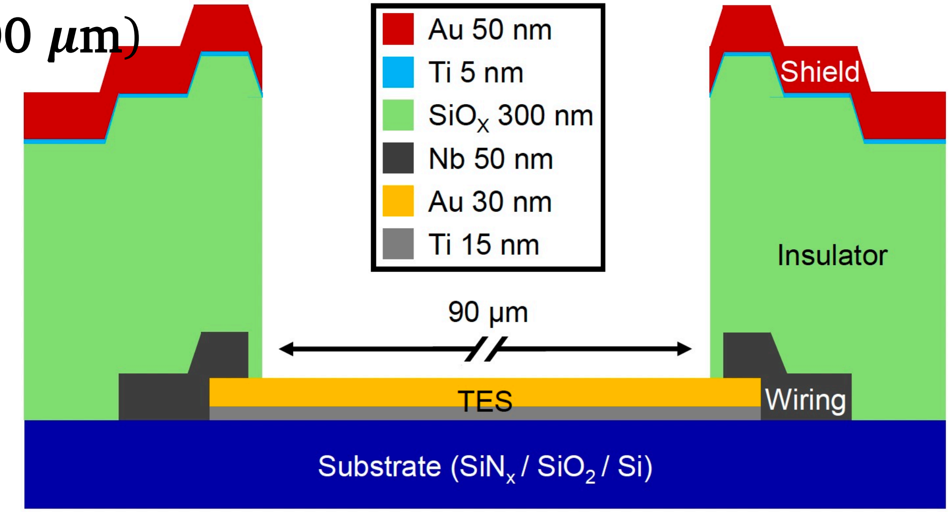
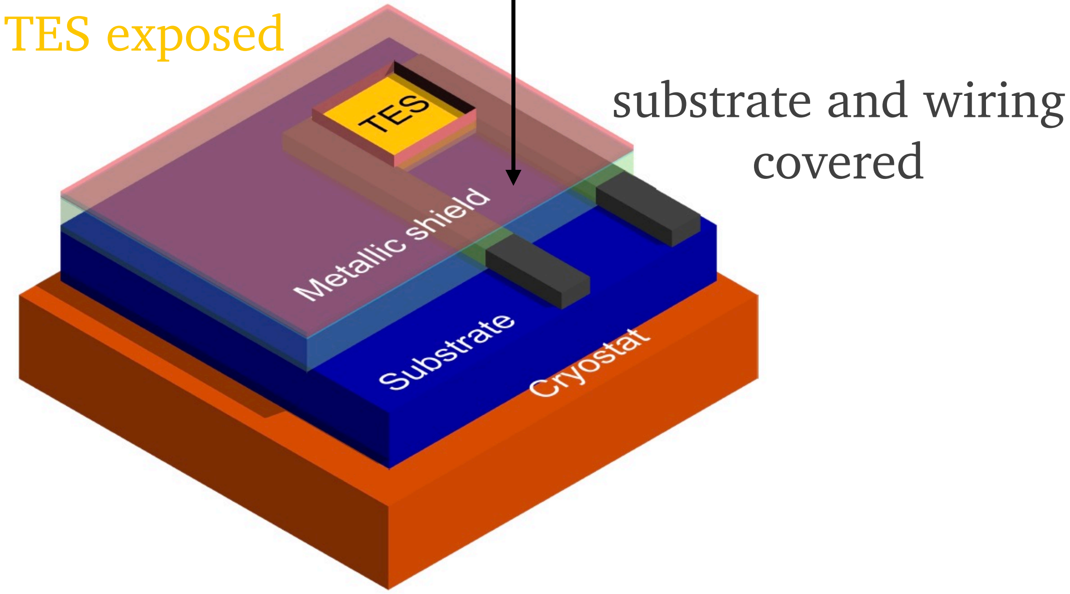
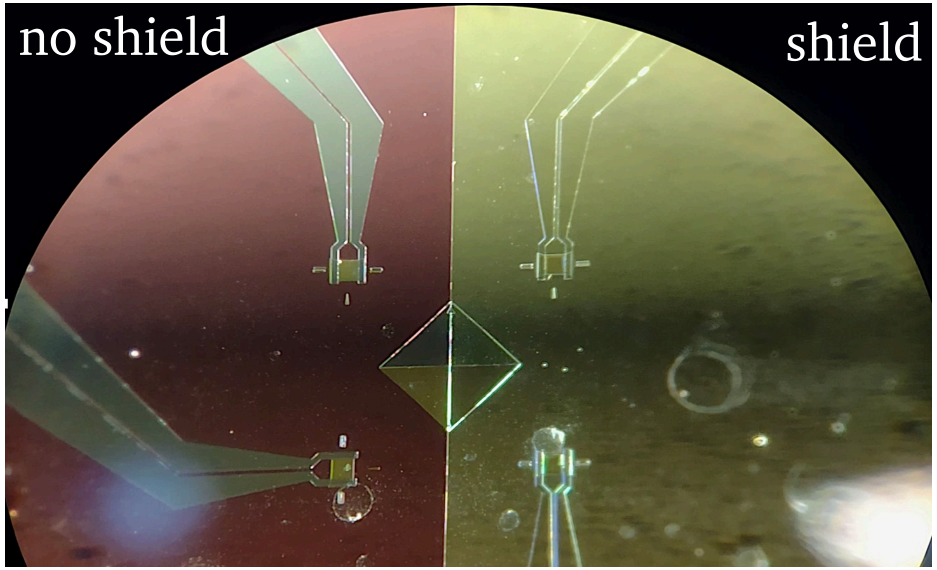
- ➢ CNTs surface (**3 mm × 3 mm**) ≫ TES active area (**100 μm × 100 μm**)
- ➢ Need to **avoid** electron hits on:
  - wiring (signal interferences)
  - insulating substrate (charge accumulation)

⇒ specifically designed gold <u>shield</u>









Electron Energy from Theory

F

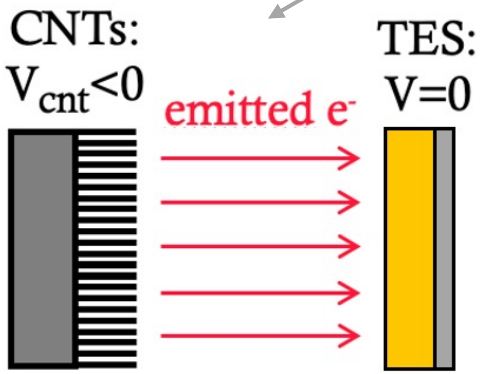
$$E_e = (eV_{\mathrm{cnt}} - \varphi_{\mathrm{cnt}}) + (\varphi_{\mathrm{cnt}} - \varphi_{\mathrm{tes}}) = eV_{\mathrm{cnt}} - \varphi_{\mathrm{tes}}$$

Electron Energy from Theory

F

$$E_e = (eV_{cnt} - \varphi_{cnt}) + (\varphi_{cnt} - \varphi_{tes}) = eV_{cnt} - \varphi_{tes}$$

accelerating voltage



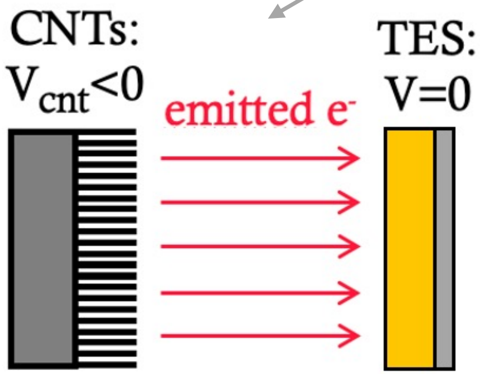
Electron Energy from Theory

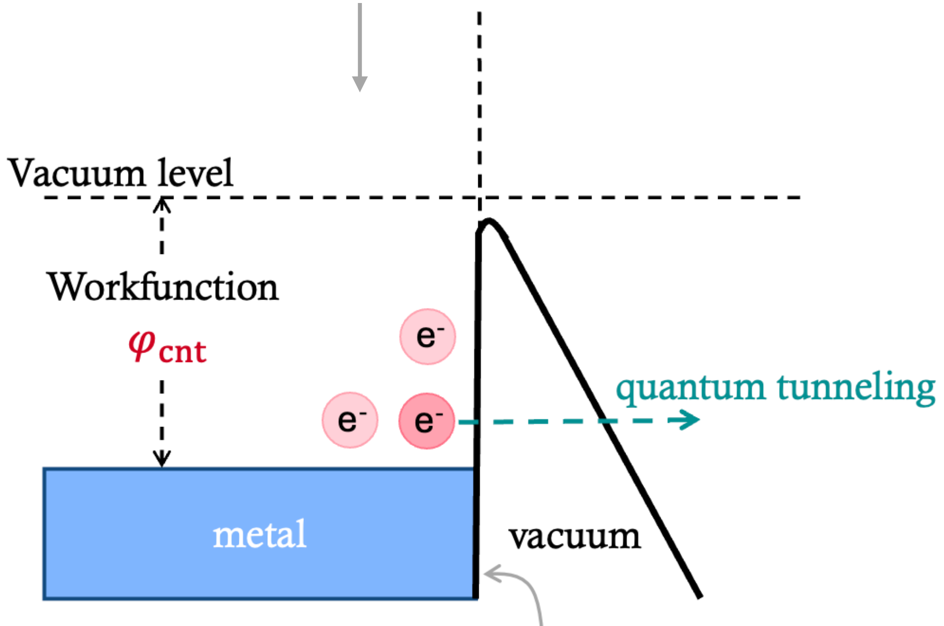
F

$$E_e = (eV_{cnt} - \varphi_{cnt}) + (\varphi_{cnt} - \varphi_{tes}) = eV_{cnt} - \varphi_{tes}$$

accelerating voltage

energy level al
emission





surface potential barrier

Electron Energy from Theory

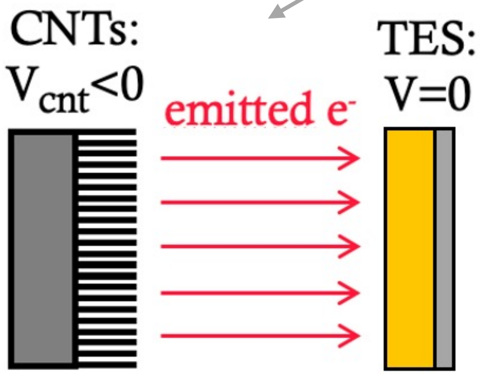
F

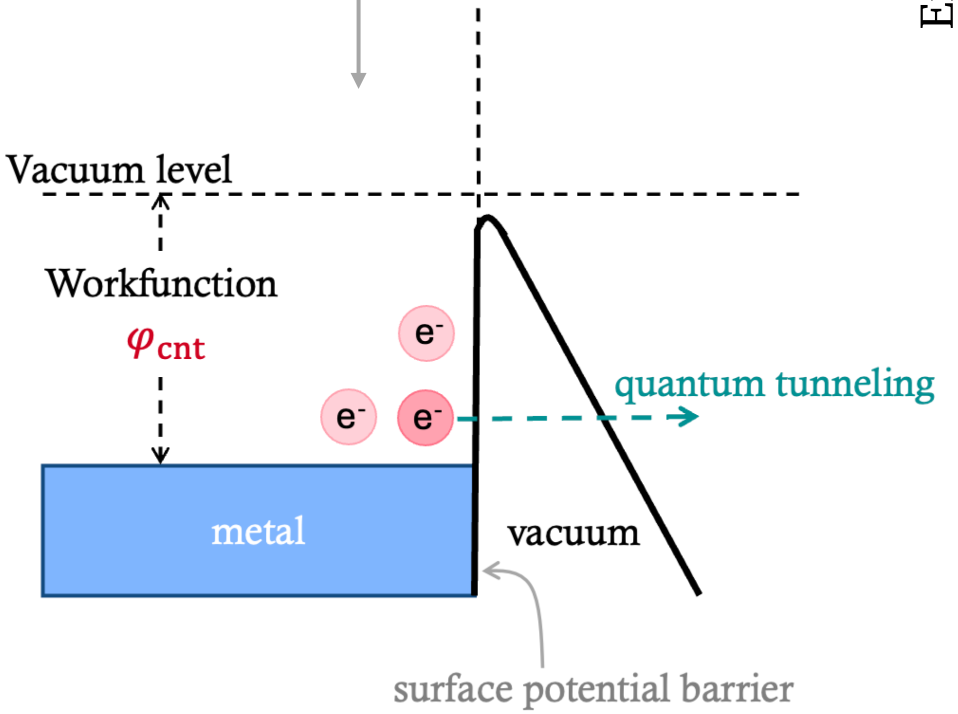
$$E_e = (eV_{cnt} - \varphi_{cnt}) + (\varphi_{cnt} - \varphi_{tes}) = eV_{cnt} - \varphi_{tes}$$

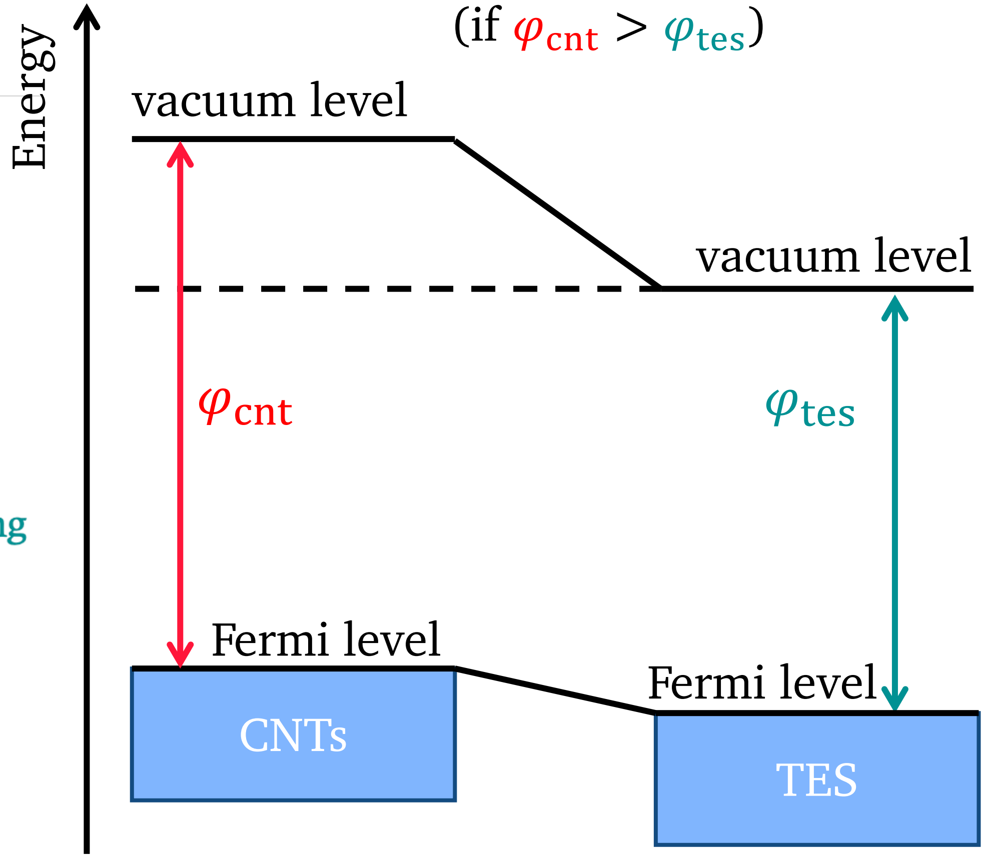
accelerating voltage

energy level al emission

different vacuum levels



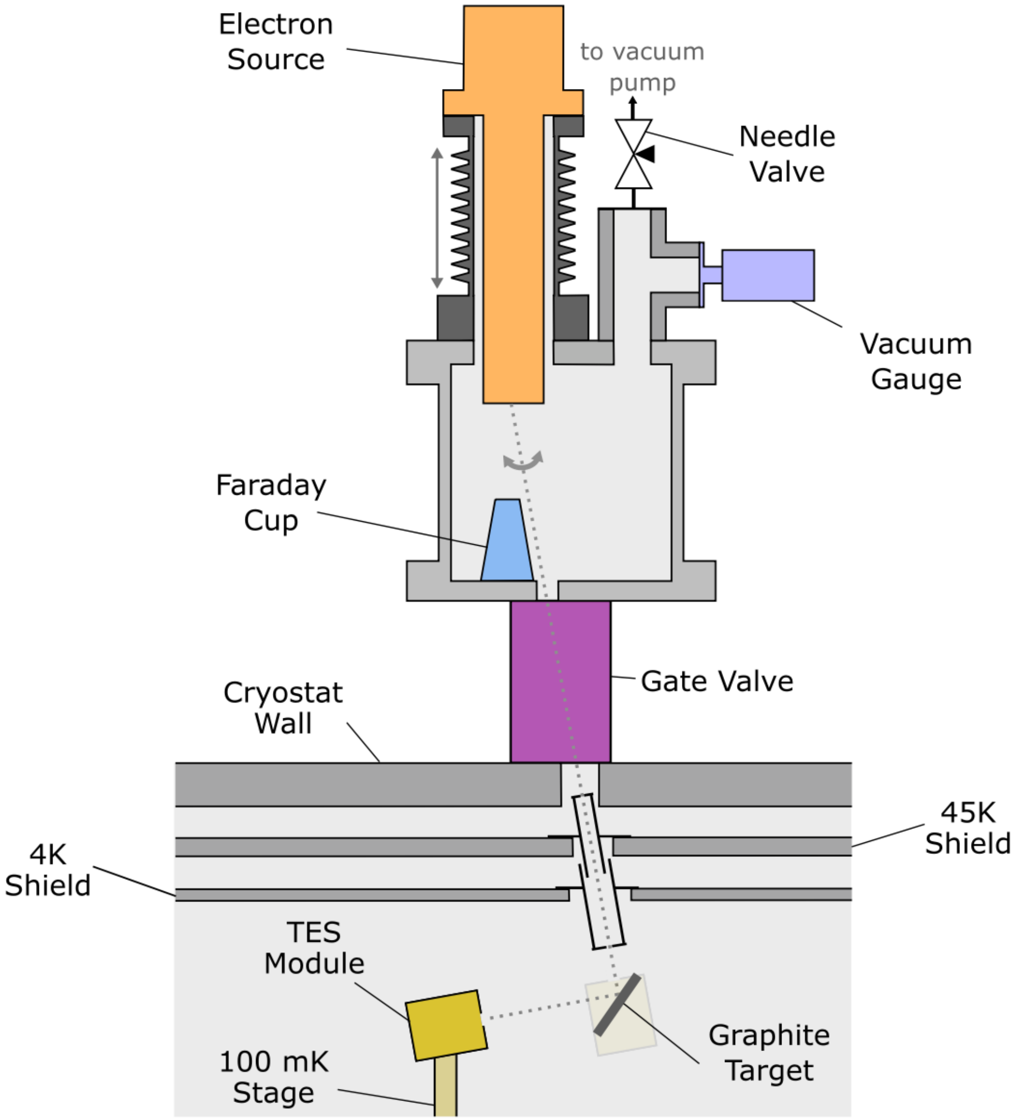


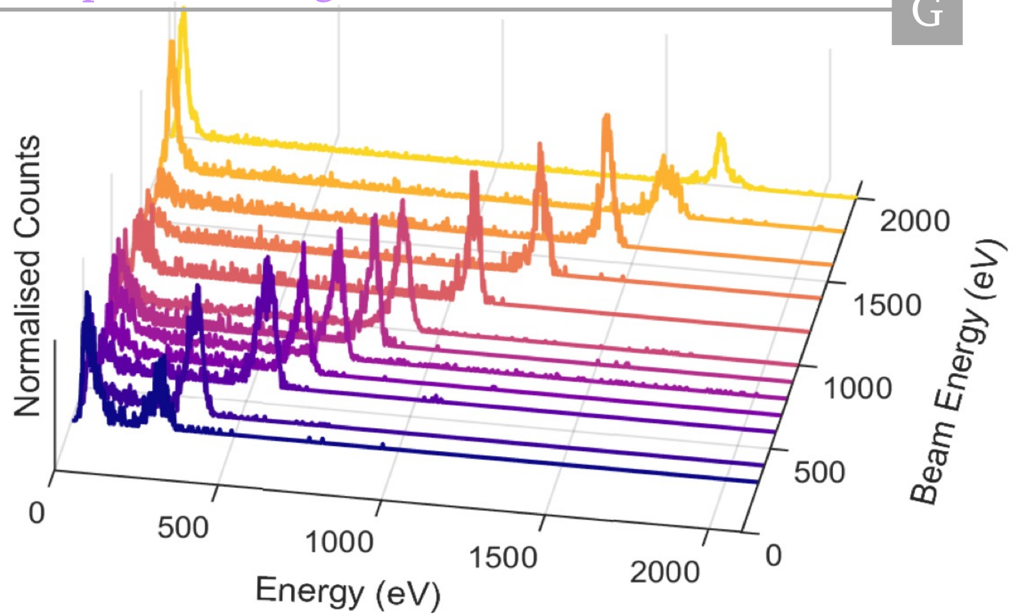


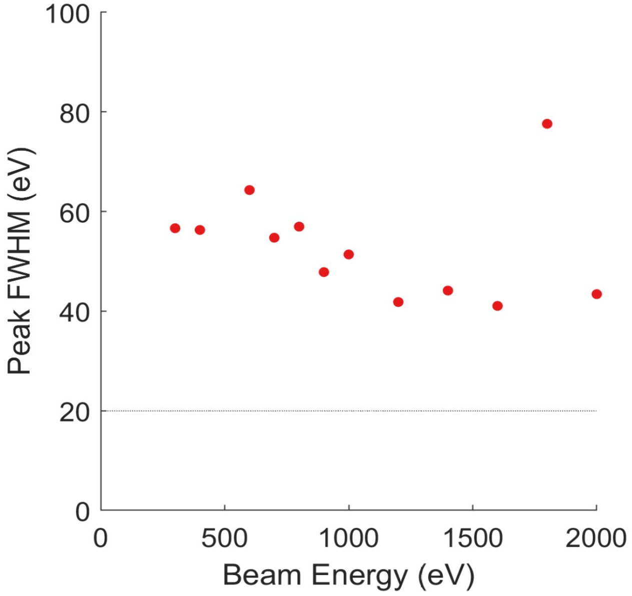
Cambridge Results

https://doi.org/10.17863/CAM.104850

G







Energy resolution:

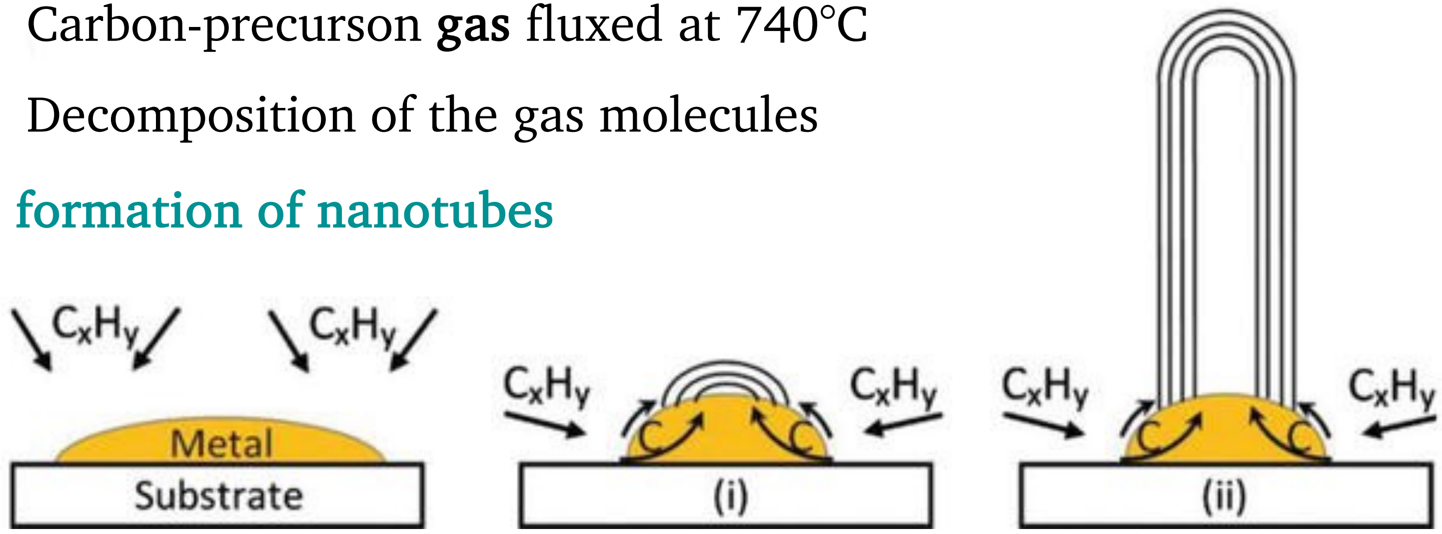
$$\sigma(eV) = \frac{FWHM(eV)}{2.35}$$

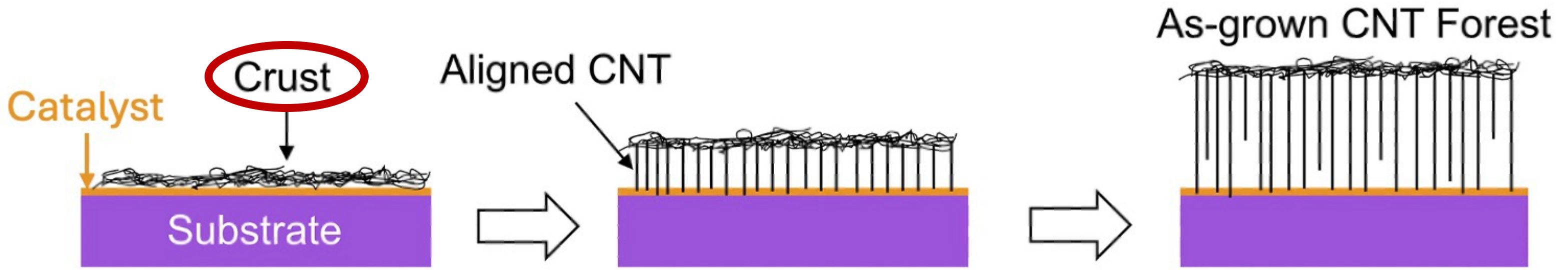
→ $\sigma > 17eV$

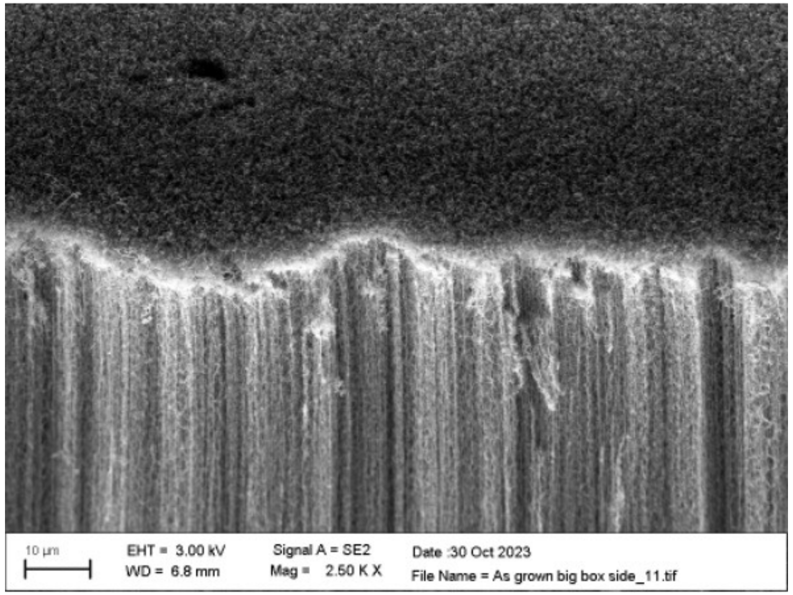
CNT Synthesis: Chemical Vapor Deposition

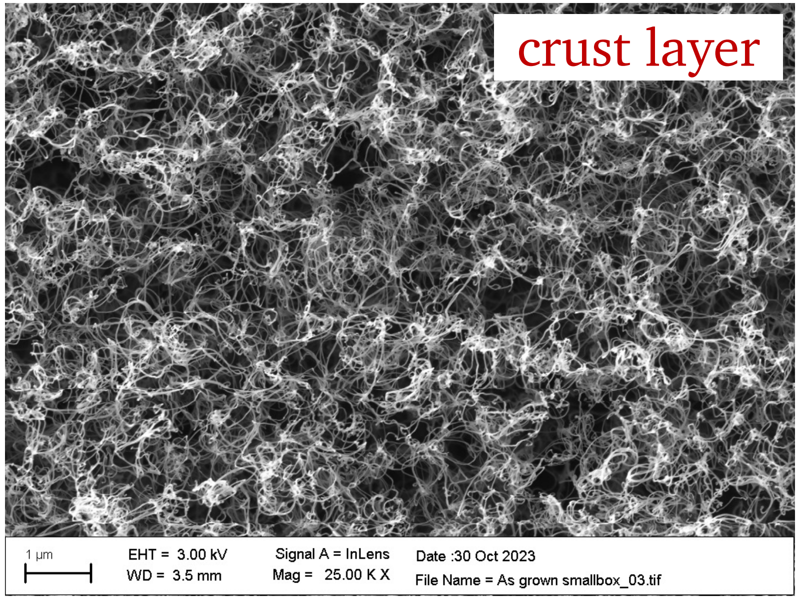
- ➢ Thin **catalyst** layer of iron deposited over silicon substrate
- ➢ **Annhealing** at 720°C in H_2 atmosphere
- ➢ Carbon-precurson **gas** fluxed at 740°C
- ➢ Decomposition of the gas molecules

⇒ formation of nanotubes



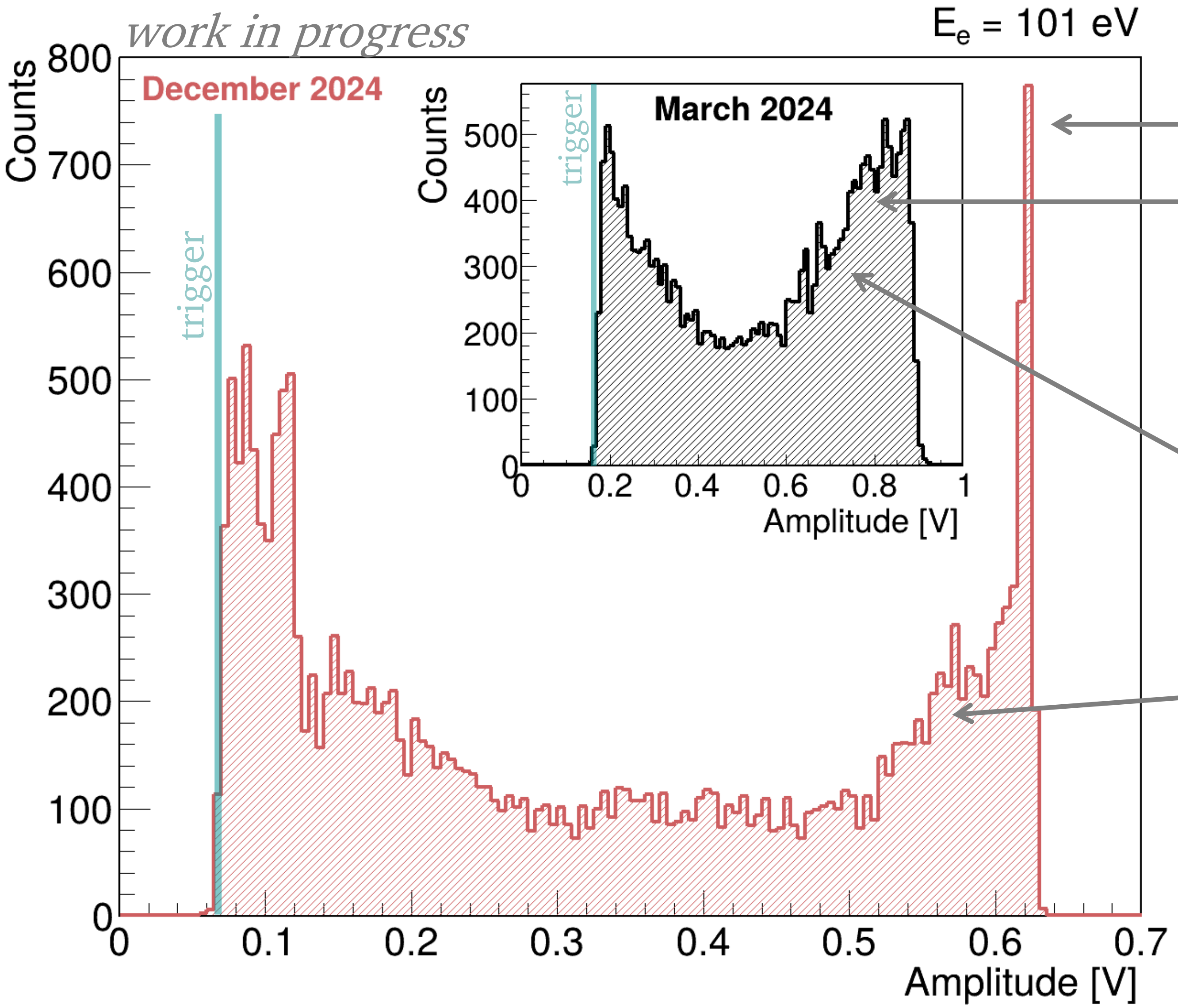




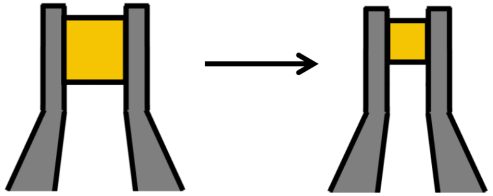


FWHM improved by a factor 30!

I



(1) total absorption peak:
improved energy resolution



$\sigma_e \propto \sqrt{Area_{TES}}$

100 μm × 100 μm → **60 μm × 60 μm**

expected resolution : ~ **0.60 eV**
measured resolution: ~ **0.45 eV**

(2) partial absorption shoulder:
less electrons hitting the TES from the shield