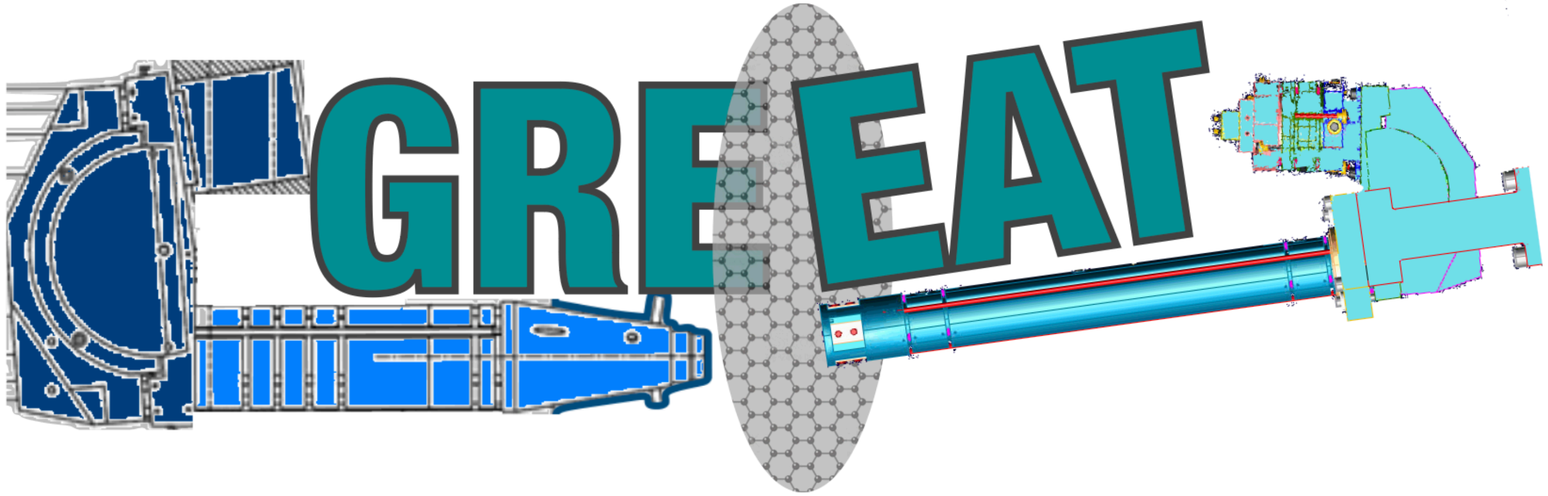


GRaphene to Electrons:
Energy and Angular resolved Transmission

Alice Apponi, Orlando Castellano, Martina Chirico, Alessandro Ruocco

Young Researcher Grant CSN5 - 2 years project 2025/2027

INFN Sezione di Roma Tre and

Dipartimento di Scienze, Università degli Studi Roma Tre

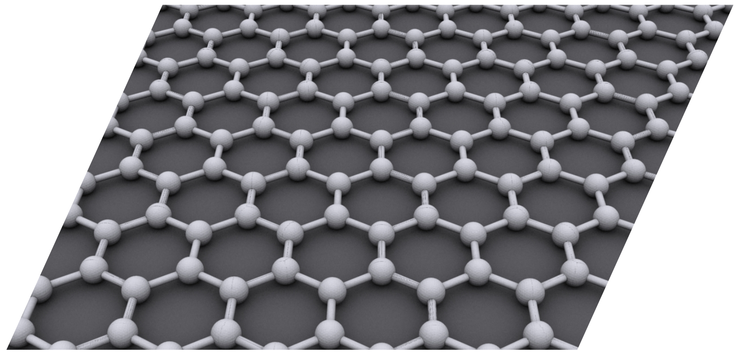
INFN Roma Tre topical afternoon:

The PTOLEMY programme - 18.06.2025

Graphene Transparency: a Growing Topic of Interest

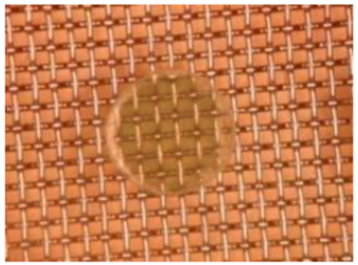
Graphene:

- Single sheet 1 atom thick
- C atoms arranged in honeycomb lattice

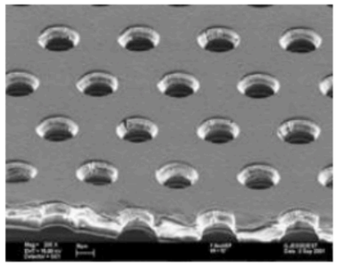


Integration of graphene in MPGD:

- Transparency to electrons
- Impermeability to atoms



MicroMegas



GEM

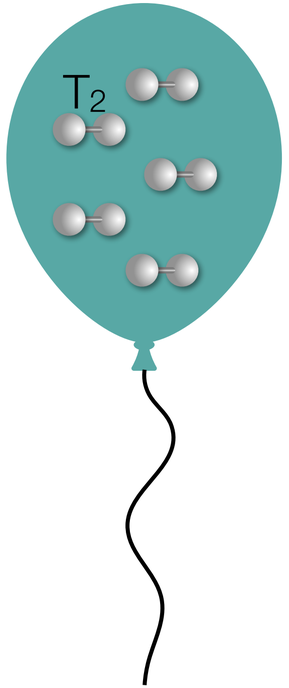
PTOLEMY experiment:

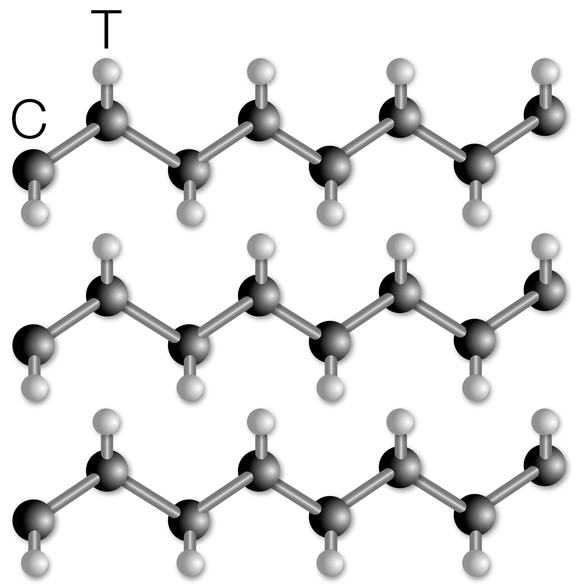
- Neutrino mass
- Tritiated graphene target

T on Graphene as Ptolemy Target

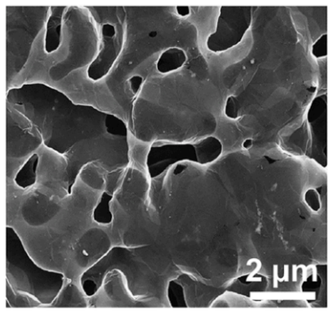
PTOLEMY experiment:

- Cosmic neutrino background and neutrino mass
- Measure the β-spectrum at end-point
- Tritium (T) in a solid-state target
- Carbon nanostructures main candidates
- Wrapped/Stacked configurations to improve density

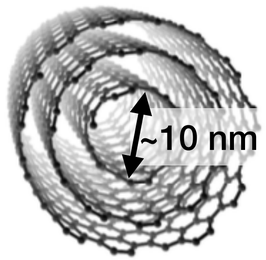




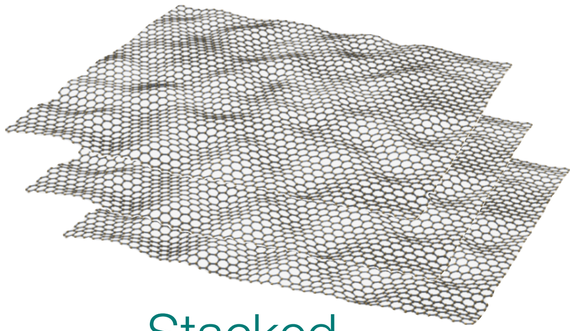
Graphene - electron transmission?



Nanoporous graphene



Carbon nanotubes

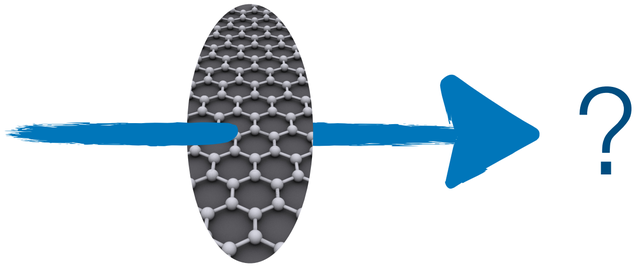


Stacked graphene

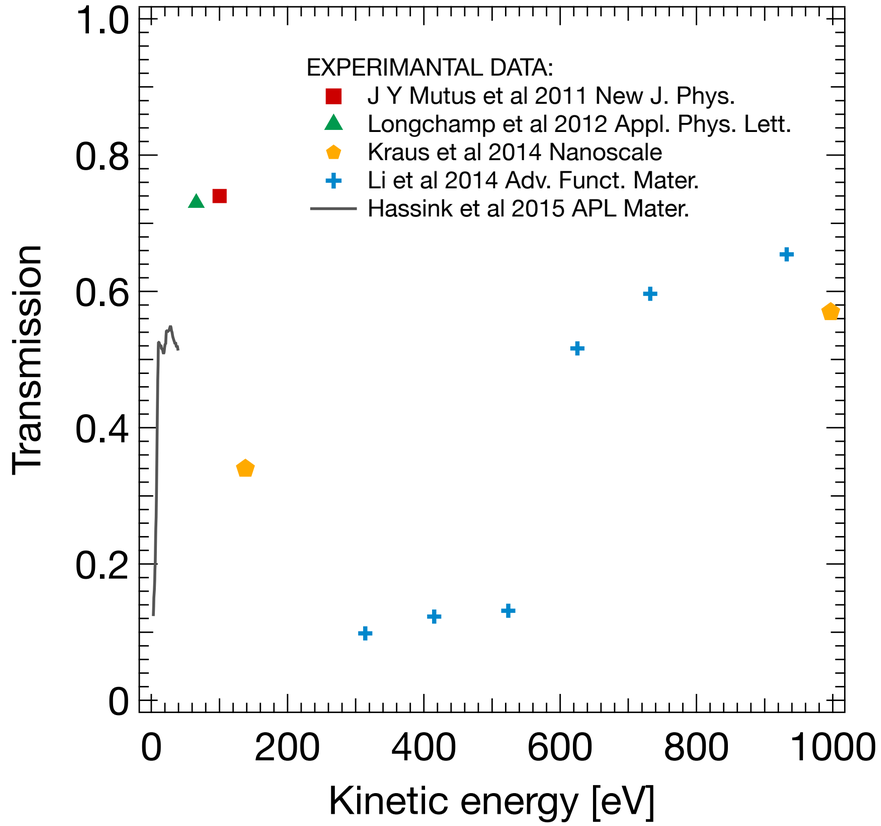
Graphene Transparency: Lots of Interest But Lack of Information

Transmission of low-energy electrons through graphene:

- Only a few data below 1 keV
- Clear lack of information
- Cross-section: still unknown



Quality? Cleannes?



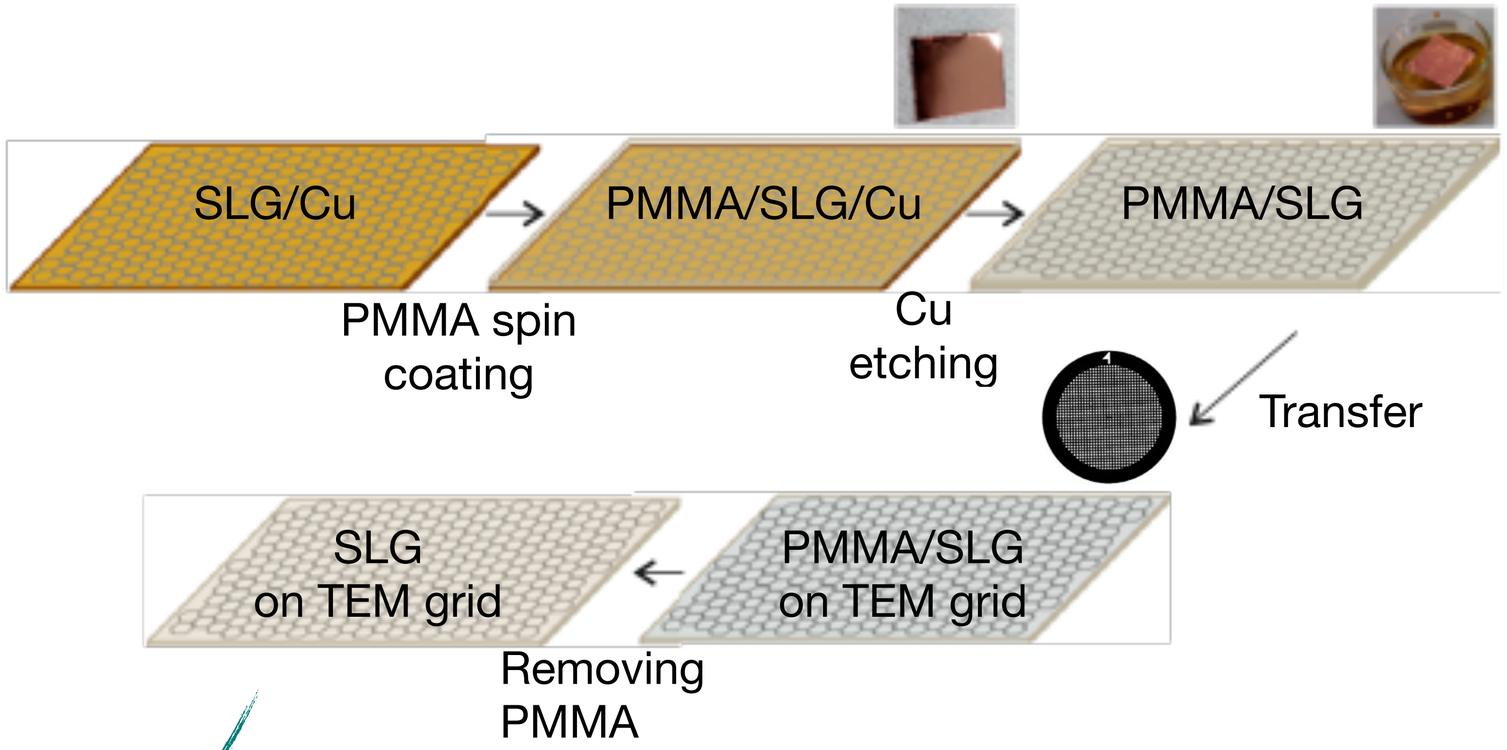
Our work included so far:

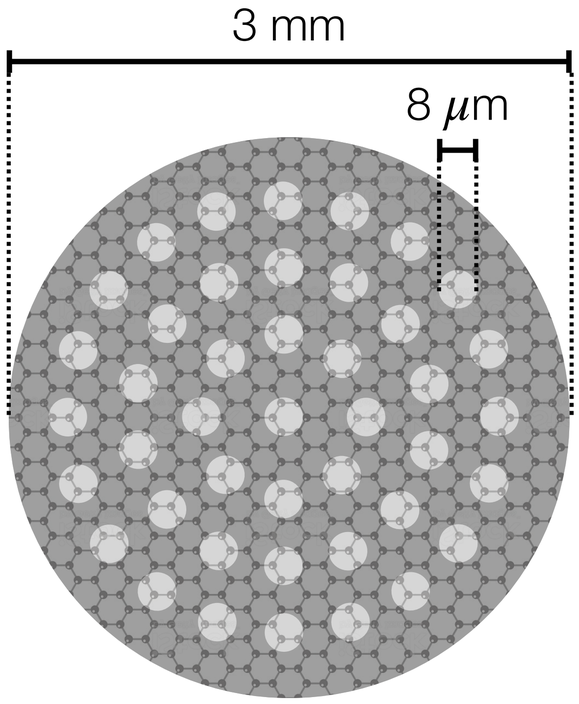
- Graphene thorough characterisation
- Transmission measurement in an extended energy range (30 - 900 eV)

Our Samples: Graphene Transferred Onto Metallic Grids

Monolayer graphene on nickel grids:

- Graphene grown on copper
- Transfer onto commercial nickel grids (Ted Pella Inc. - G2000HAN)
- Access to suspended graphene regions

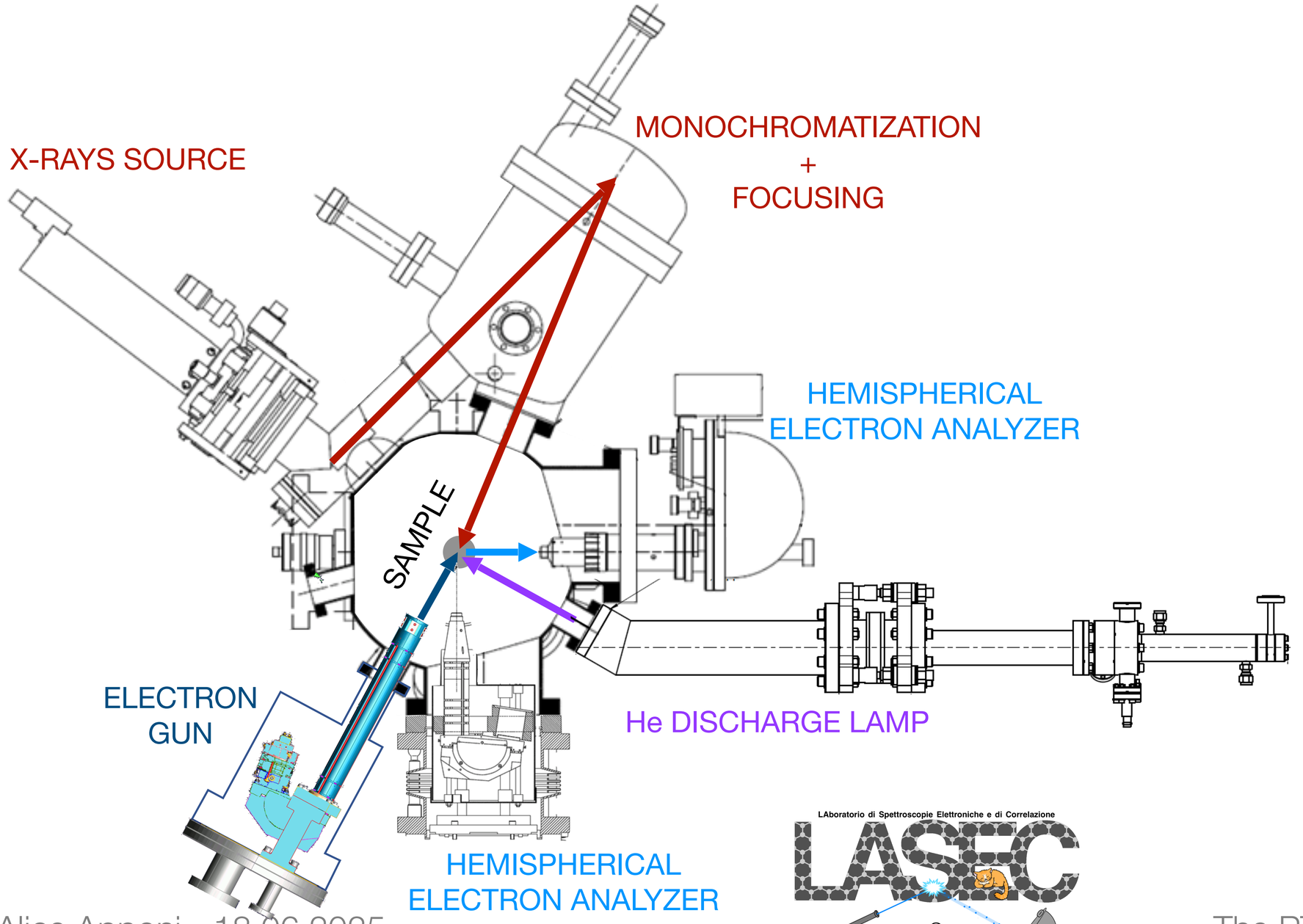




A. Apponi et al., Carbon (2024), https://doi.org/10.1016/j.carbon.2023.118502

UTMOST
UltraThin Materials fOr gaSeous deTectors

LASEC Lab: Electronic Spoctroscopies and More…



X-ray Al Kα source:

- hv = 1486.7 eV
- Monochromatized beam
- XPS resolution = 0.46 eV

Custom-made monochromatic electron gun:

- Continuous electron beam
- Tuneable energy 30 - 900 eV
- Resolution = 45 meV

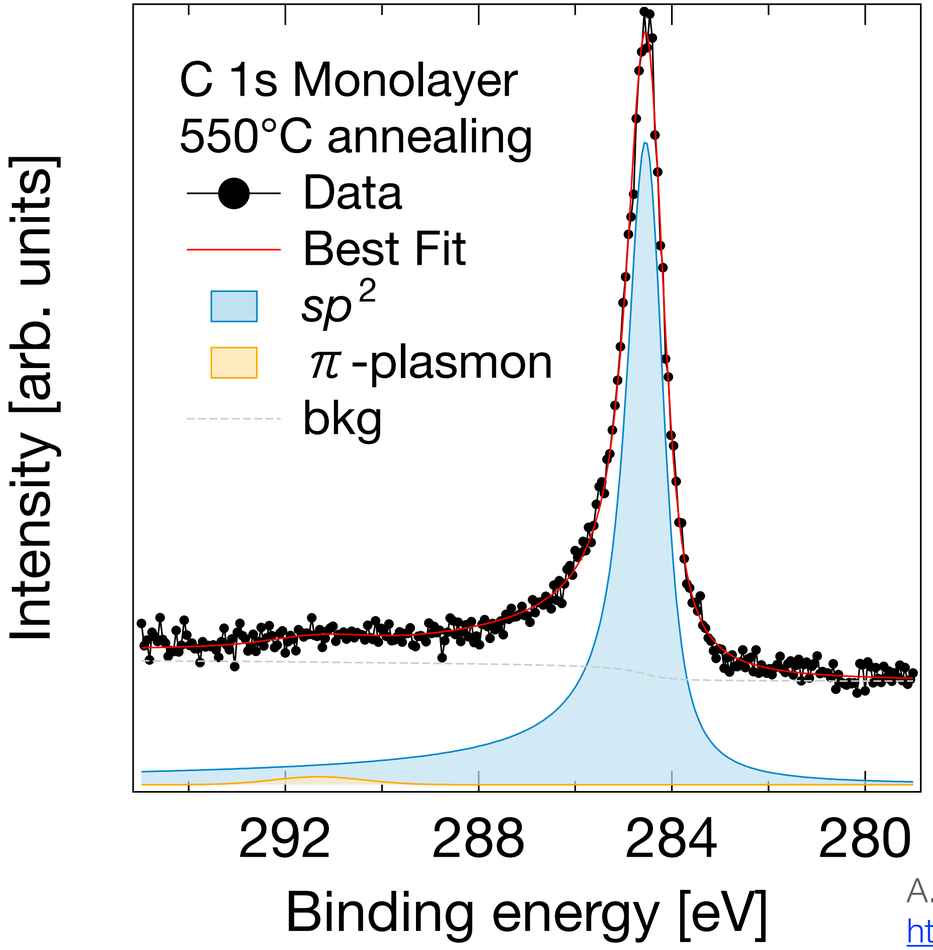
He discharge lamp:

- Spot diameter 300 μm

Spectroscopic Characterisation Reveals High Quality Graphene

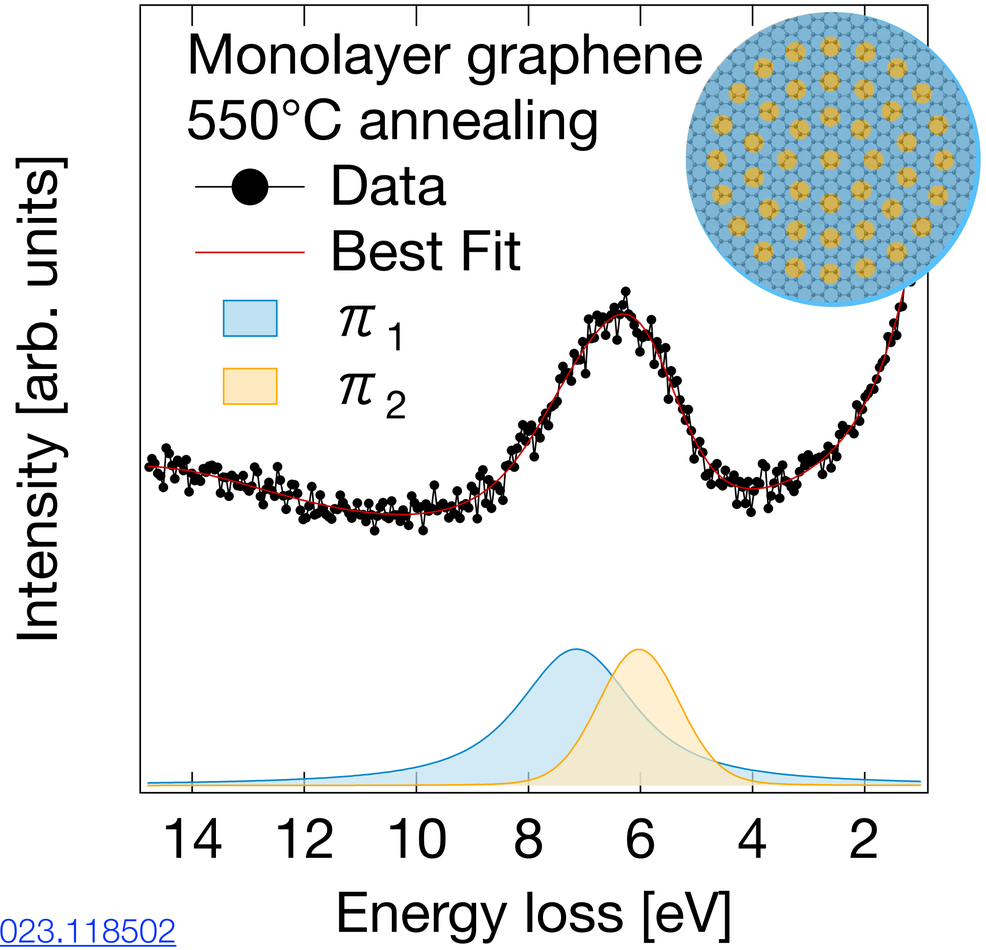
X-ray photoemission spectroscopy (XPS):

- C 1s core-level spectrum
- Pure sp^2 contribution —> **high quality** + **cleannes!**



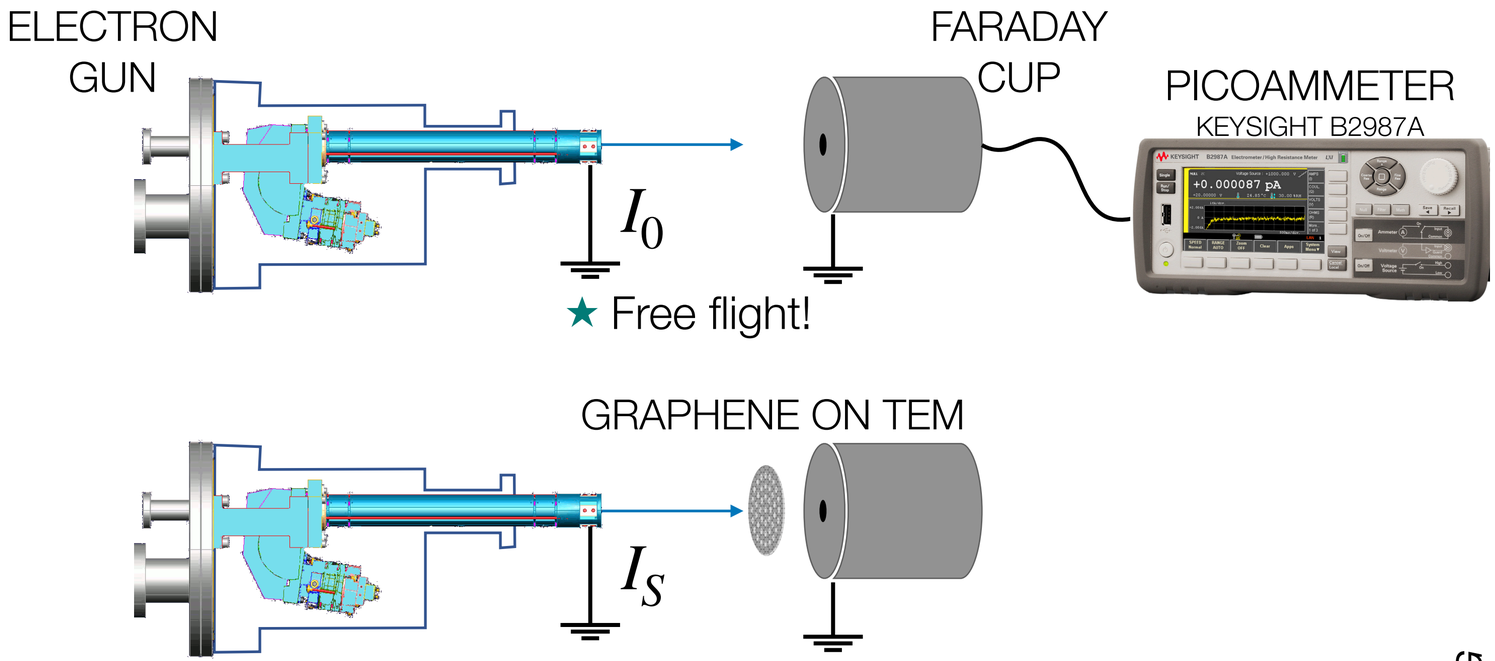
Electron energy loss spectroscopy (EELS):

- π-plasmon excitation
- **High quality** + suspended footprint



A. Apponi et al., Carbon (2024), https://doi.org/10.1016/j.carbon.2023.118502

Graphene Transmission Measured in the 30 - 900 eV Range

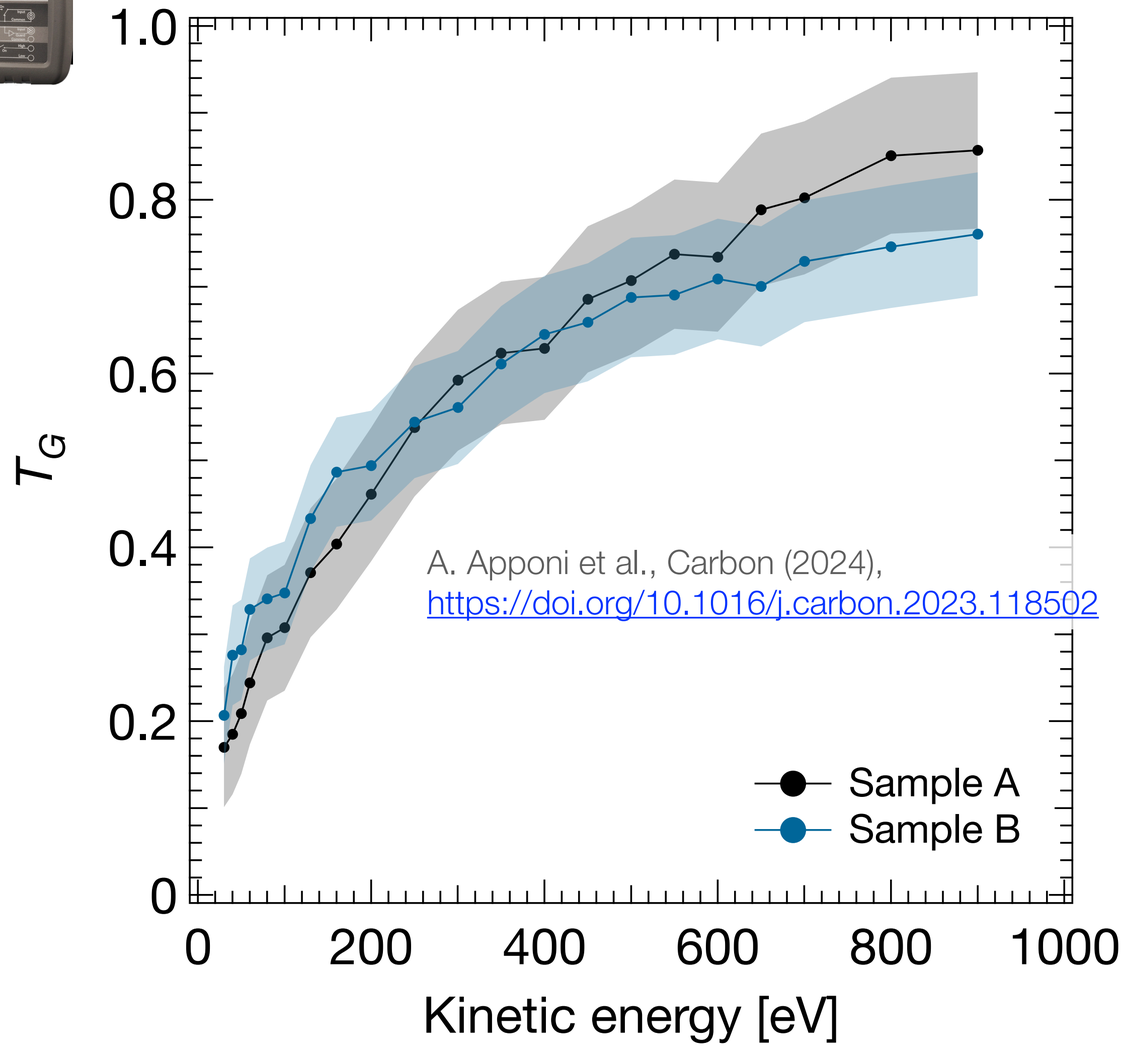


$$I_S(E) = a[I_0 T_{grid} T_G(E)] + b[I_0 T_{grid}]$$

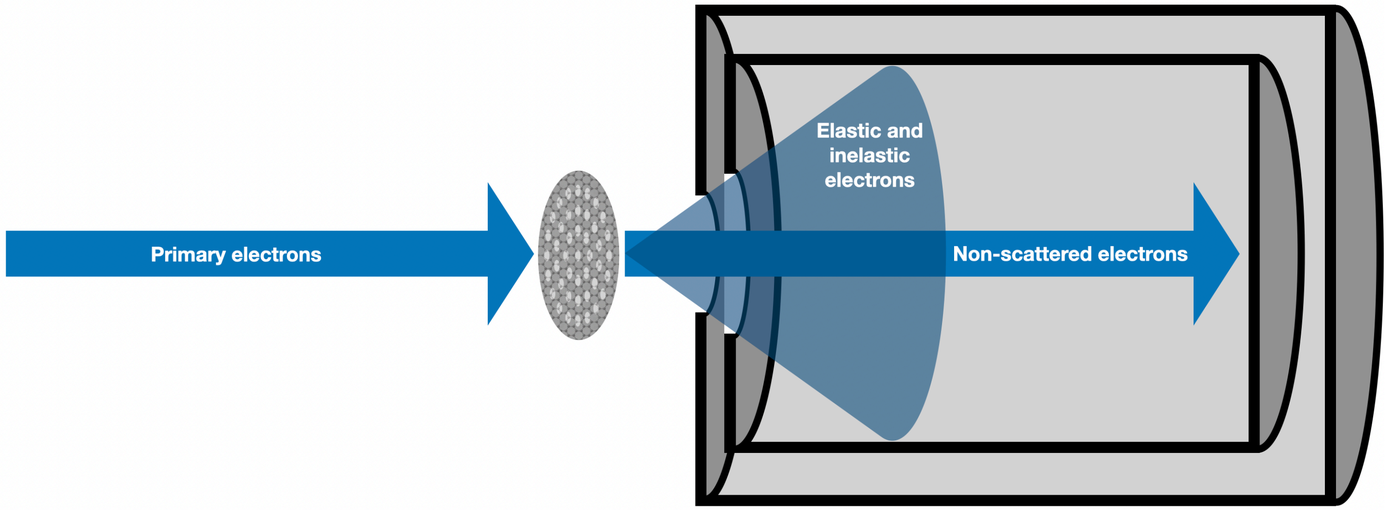
$a + b = 1$

a: Graphene coverage

$$T_G(E) = \frac{\frac{I_S}{I_0 T_{grid}} - b}{a}$$



Energy Resolution for Direct Measurement of Total Cross-Section

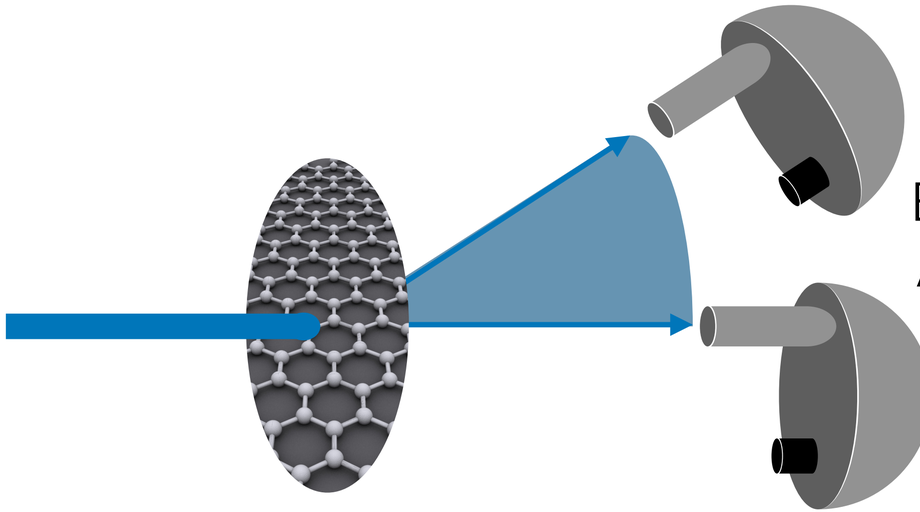


Integral measurement:

- No energy selection
- Current integrated within angular acceptance
- Result setup-dependent

Differential measurement:

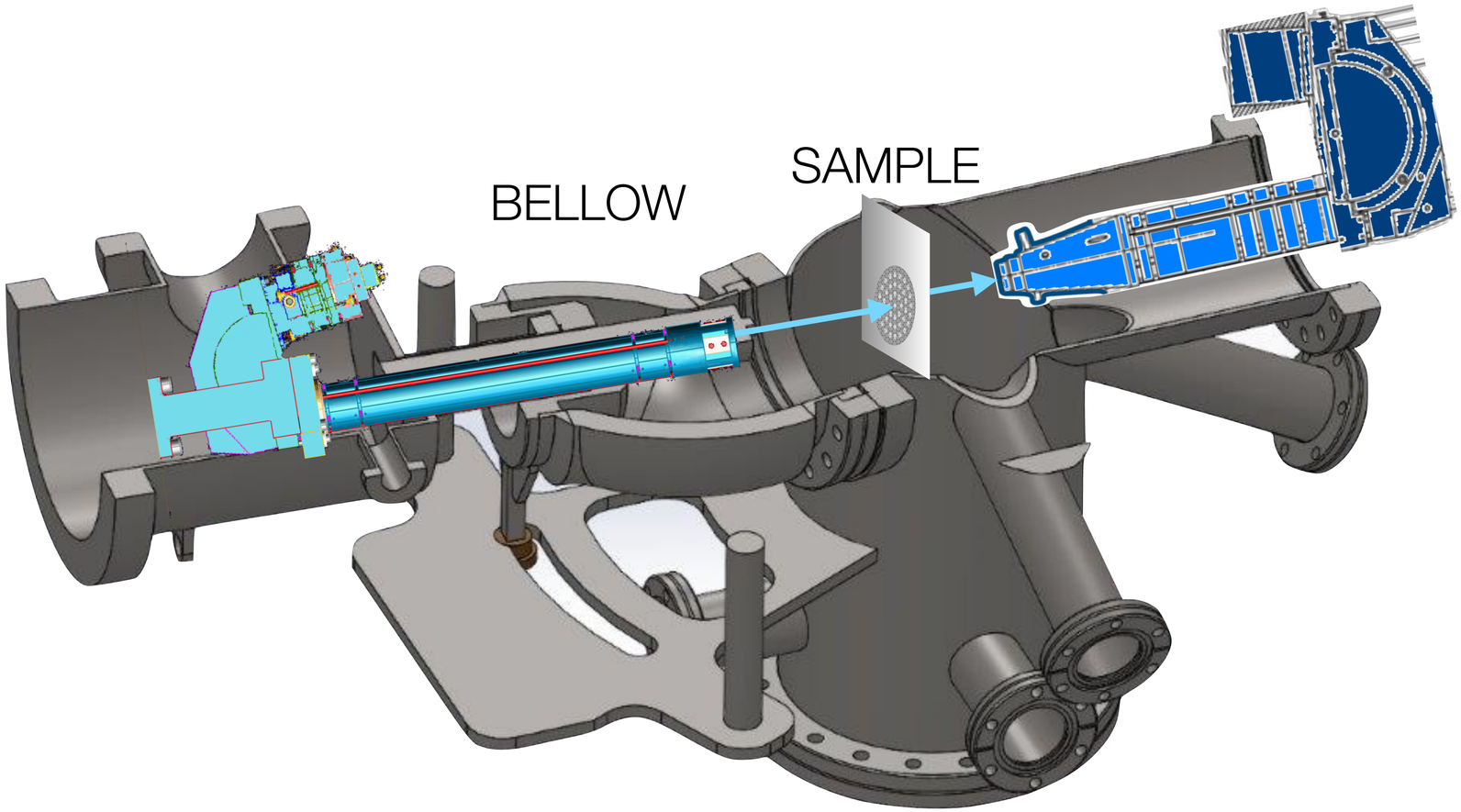
- Energy and momentum selection with hemispherical electron analyser
- Direct measurement of σ_{tot} = total cross-section
- Moveable setup for differential cross-section



$$I(E) = I_0 e^{-n_G \sigma_{tot}(E)}$$

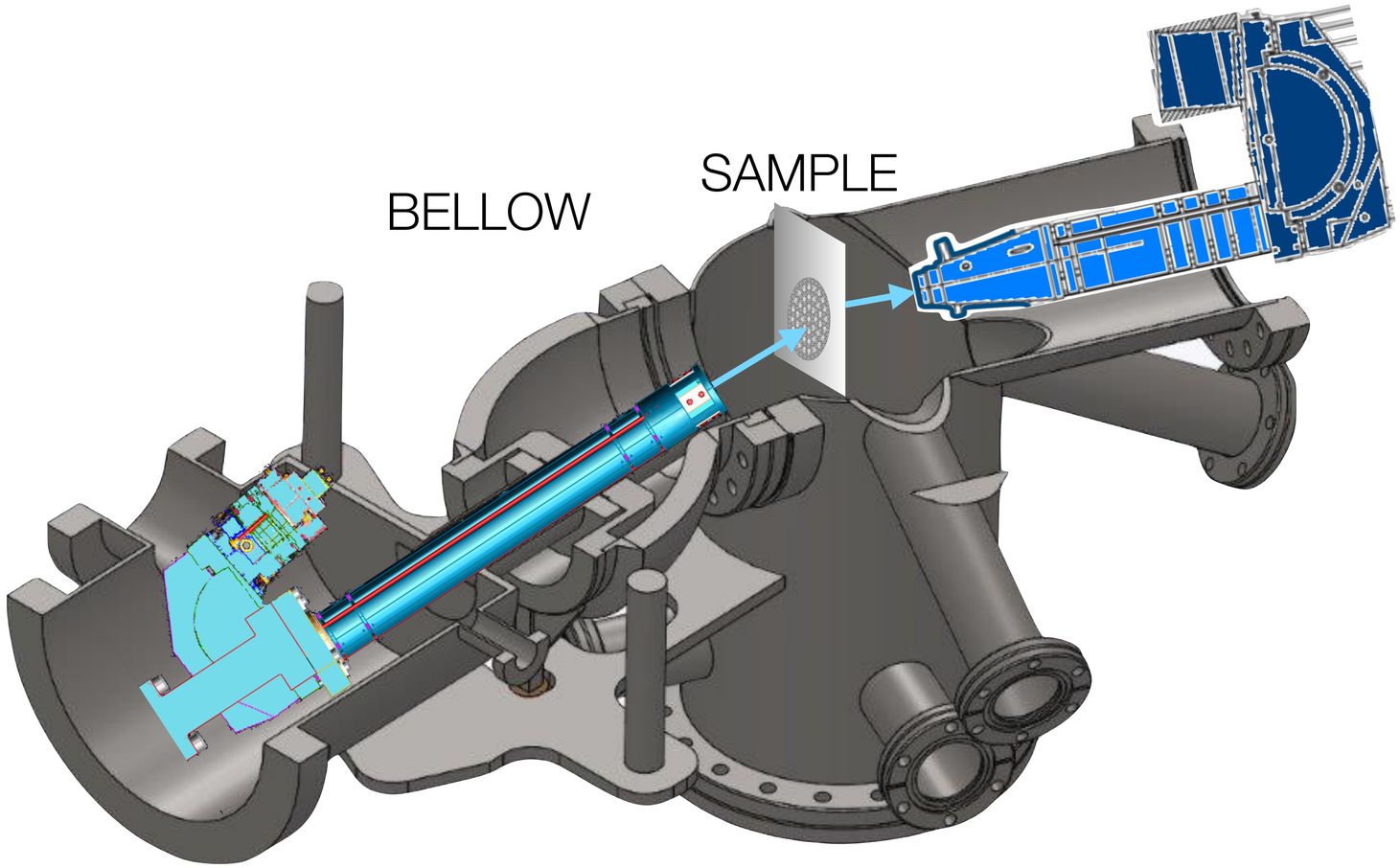
Moveable Electron Source for Angular Dependent Measurement

The TRAM-Chamber

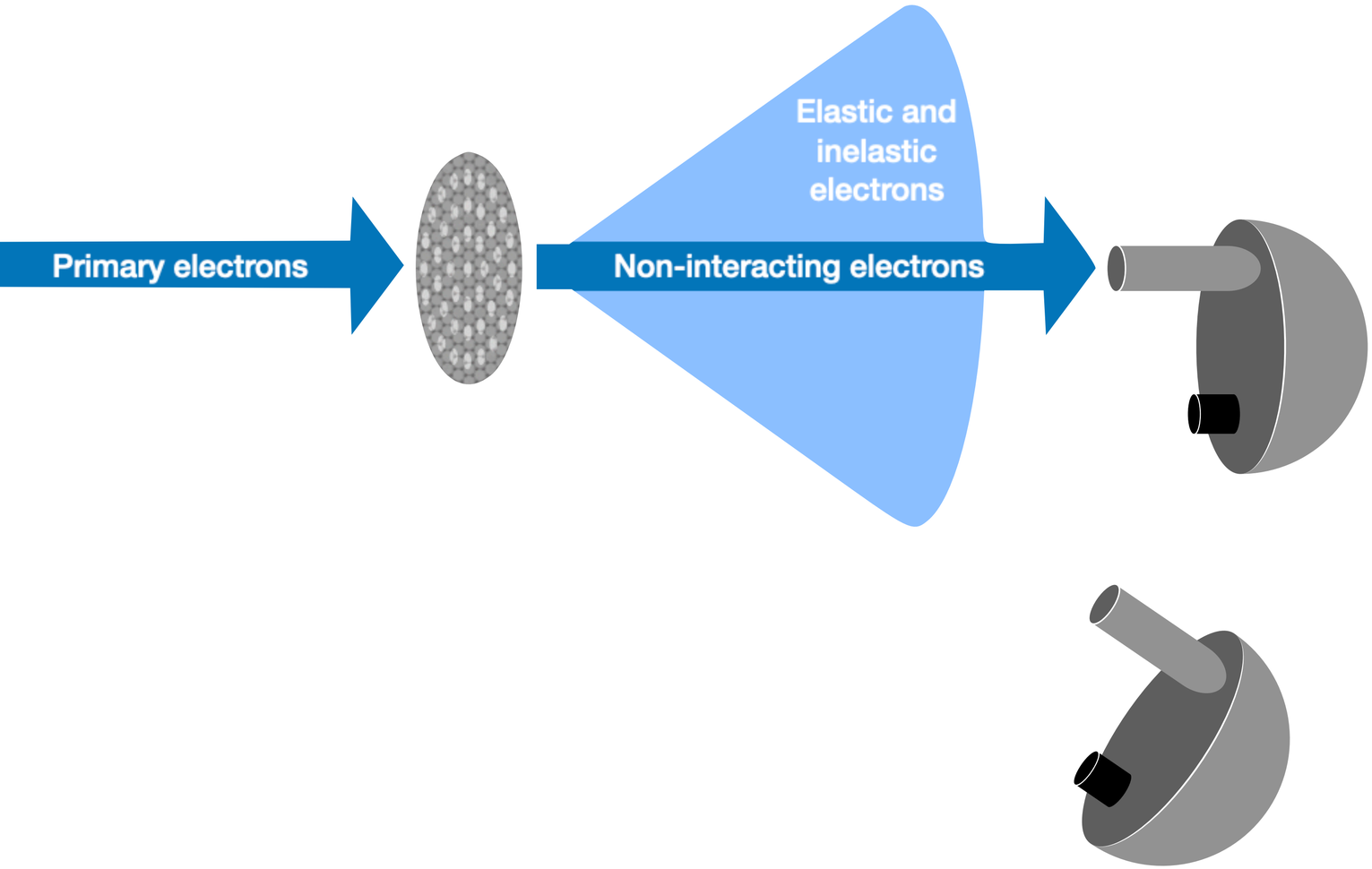


Moveable Electron Source for Angular Dependent Measurement

The TRAM-Chamber



Start With Non-Interacting e^- then Map Scattered e^-



Non-interacting electrons:

- Measure at fixed "0 angle" (1° angular acceptance)
- Total cross-section **I year goal**

Scattered electrons: **II year goal**

- Measure as a function of the angle and of the energy
- Differential and total cross-section

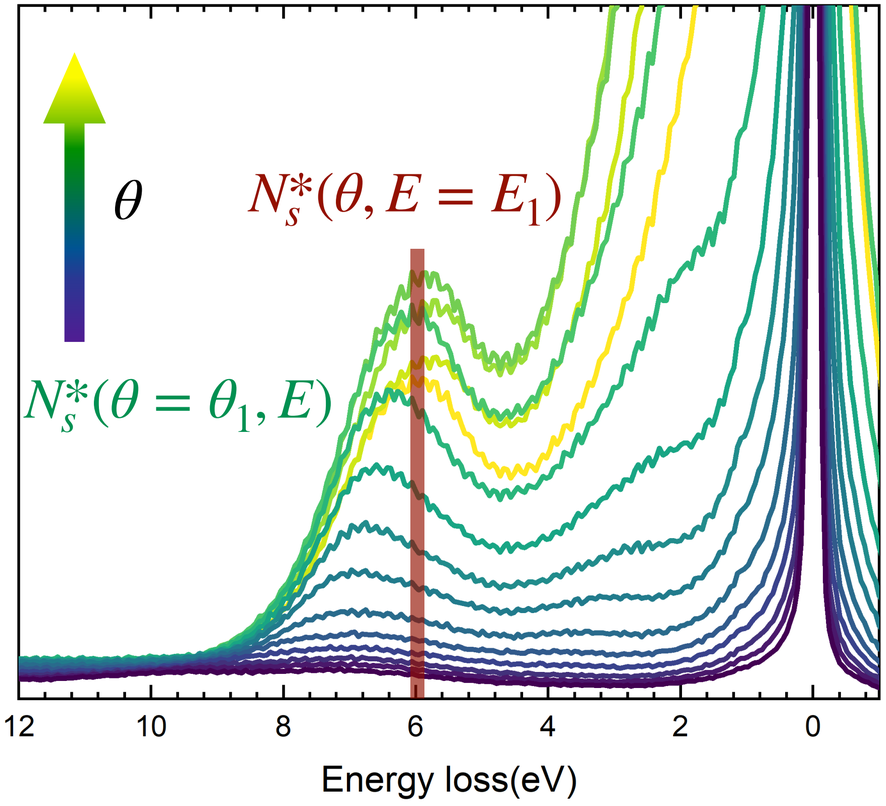
But How Do You Measure the Cross-Section?

$$\sigma = \frac{N_s}{N_0 n_G}$$

$n_G \sim 39\ nm^{-2}$

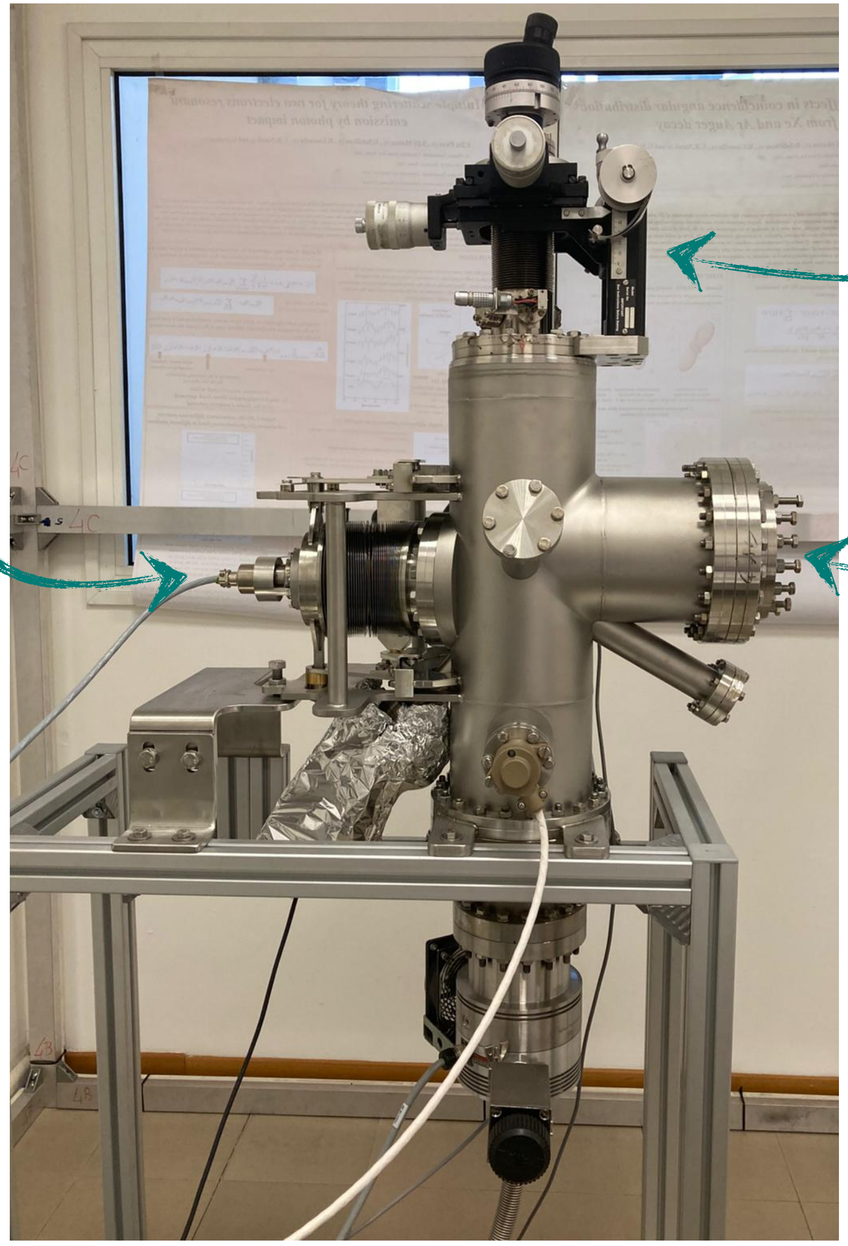
Energy loss measurement:

- Distribution of the transmitted electrons N_s^*
- Spectrum at a given angle —> $N_s^*(\theta = \theta_1, E)$
- Repeat for **different angles**
- Slice at a given energy loss —> $N_s^*(\theta, E = E_1)$
- Repeat for different primary energies

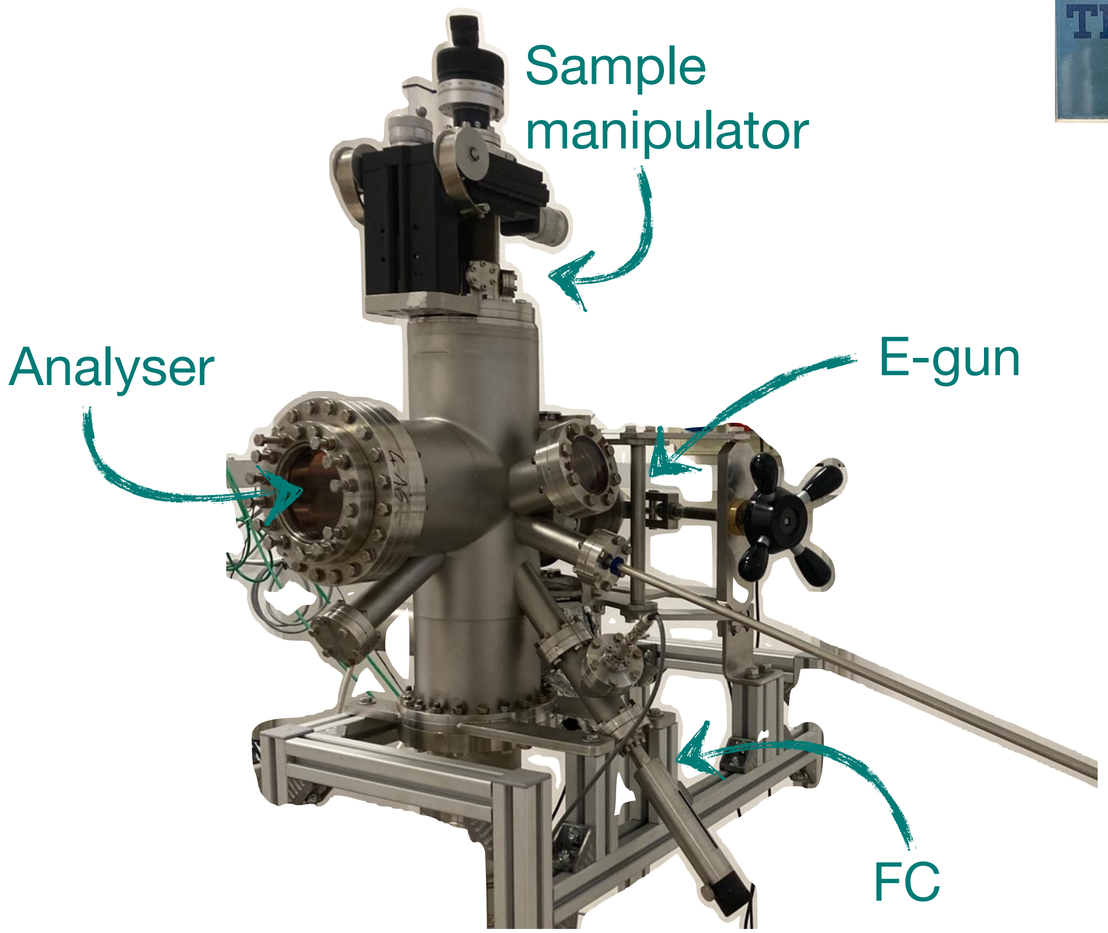


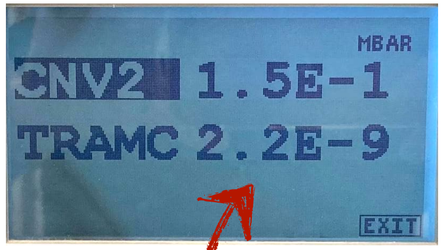
$N_s^* = N_s\ \epsilon$ (detector efficiency)

The TRAM-Chamber is Up and Running!

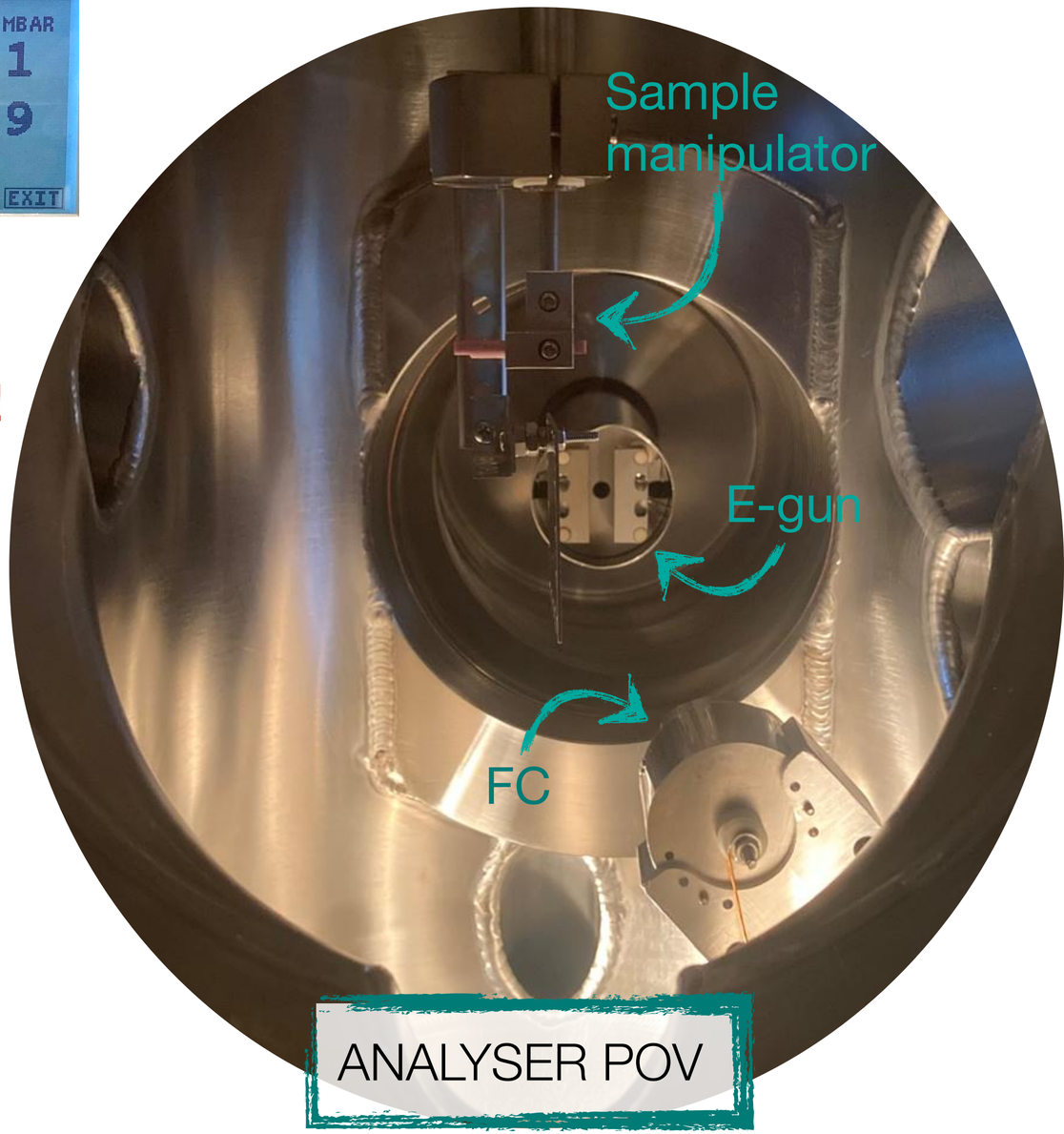


The TRAM-Chamber is Up and Running!

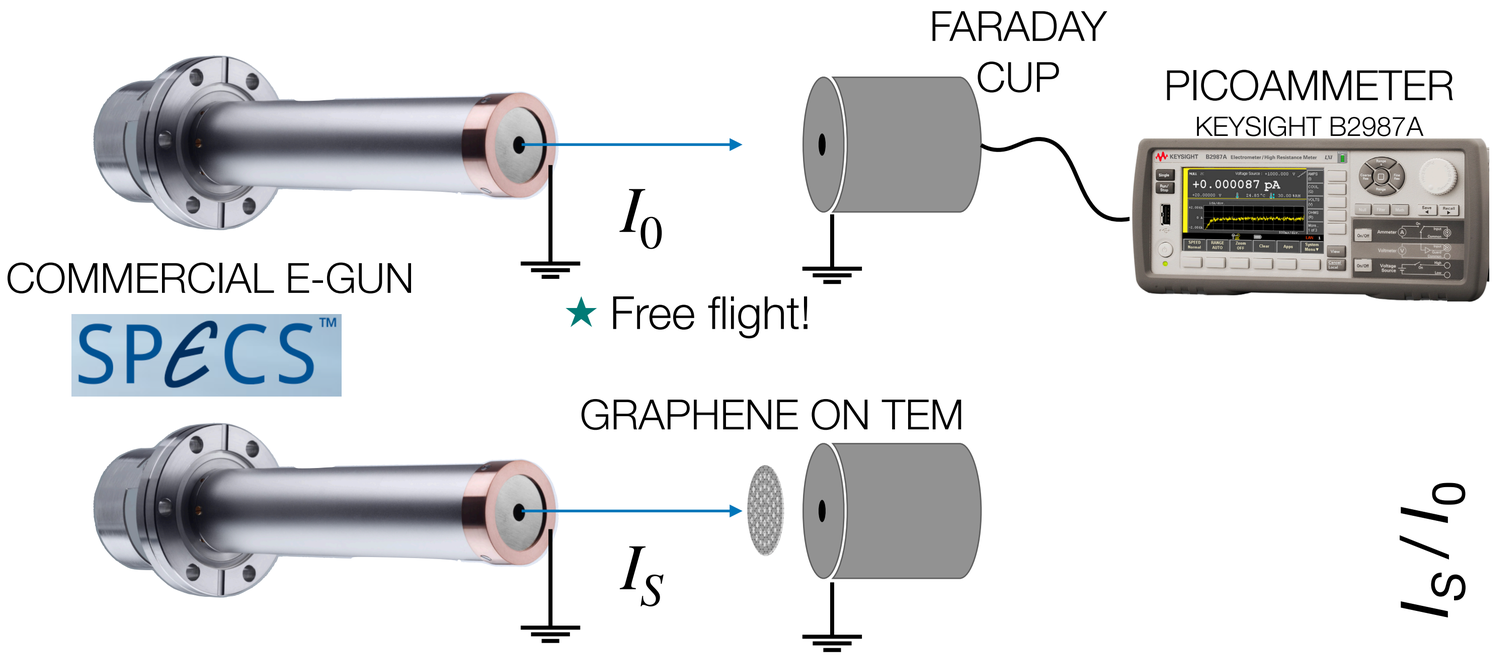




Without BAKE-OUT!

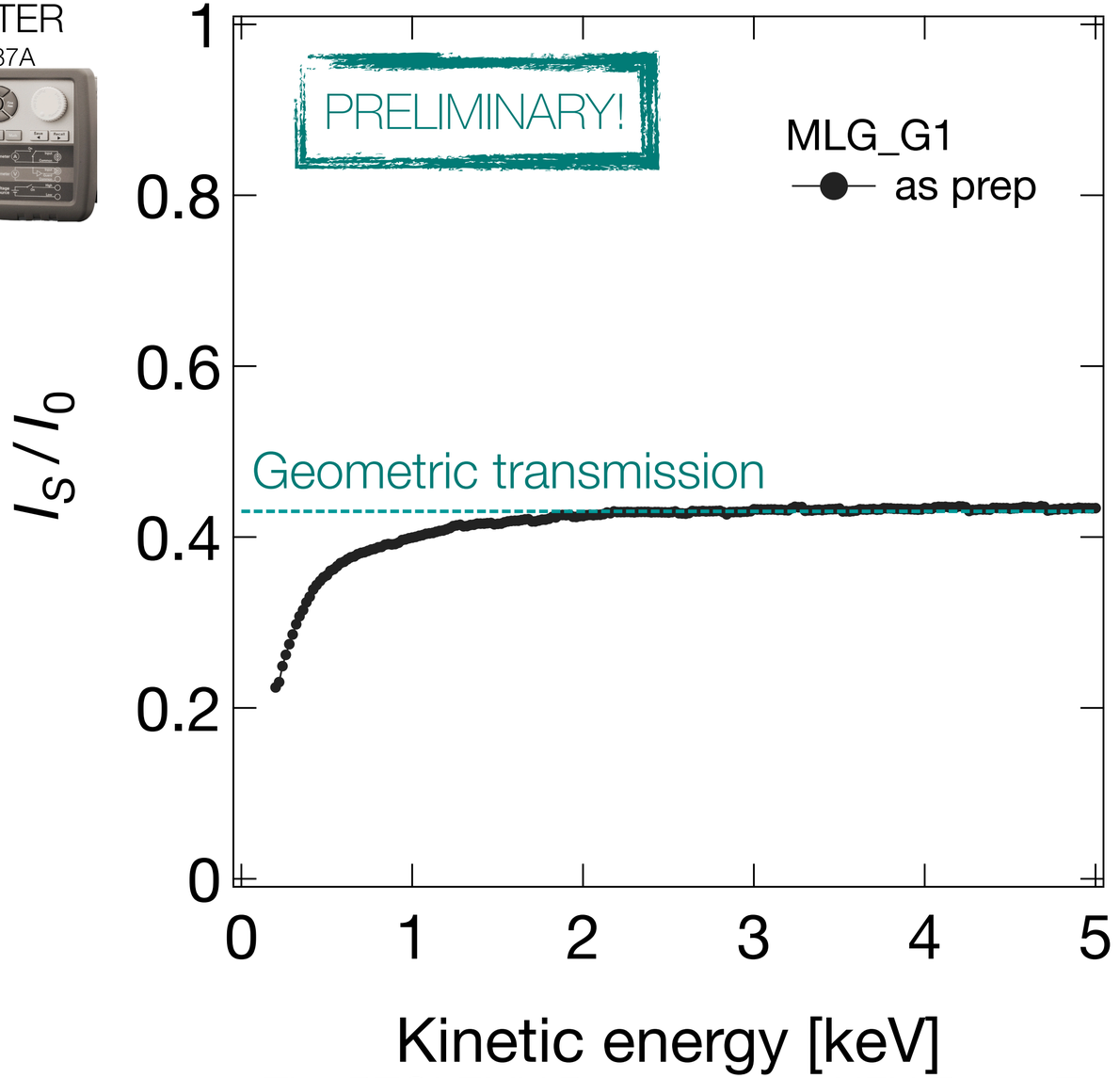


Integrated Transmission Extended Up To 5 keV



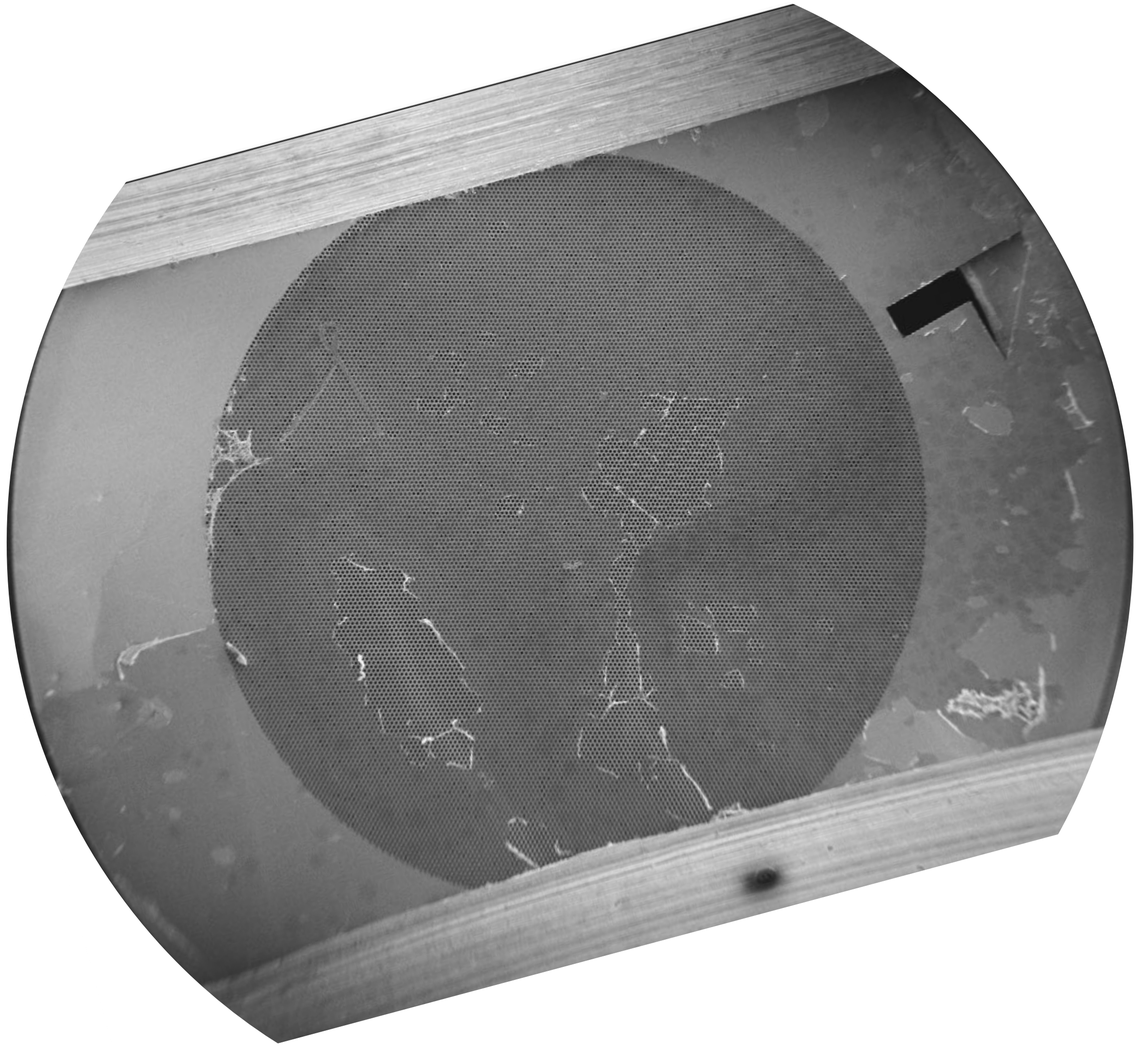
Commercial SPECS e-gun:

- Continuous electron beam
- Tuneable energy 0.2 - 5 keV

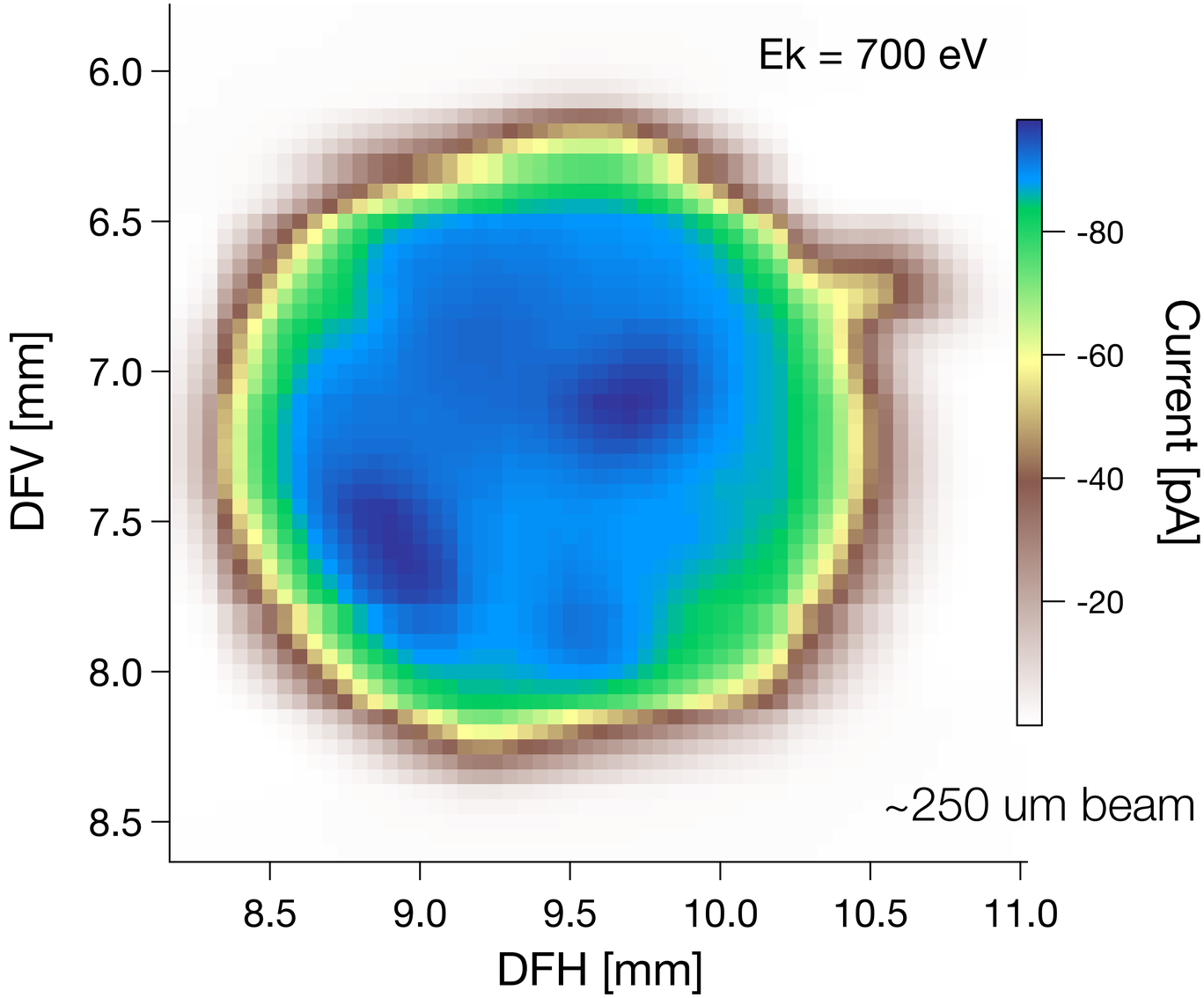


First Transmission Map with SPECS Gun

SCANNING ELECTRON MICROSCOPE



ELECTRON TRANSMISSION MAP



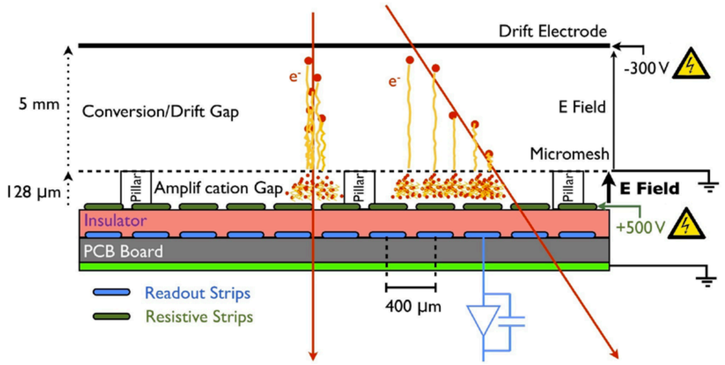
GREEAT project will measure the cross-section of electrons-graphene interaction (and any other 2D!)

UTMOST

UltraThin Materials fOr gaSeous deTectors

Design gas detectors with highly improved performances:

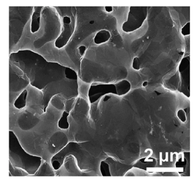
- Graphene on the mesh (or GEM)
- Conversion and avalanche gas(es) optimised in mixture and pressure
- Ion back-flow prevented



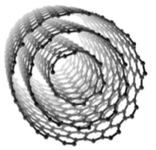
PTOLEMY

Development of novel neutrino detector PTOLEMY:

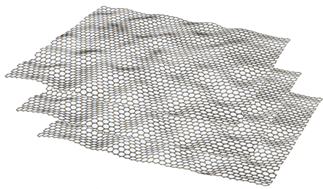
- Graphene-based target
- Transmission of electrons (higher energy) is crucial



Nanoporous graphene

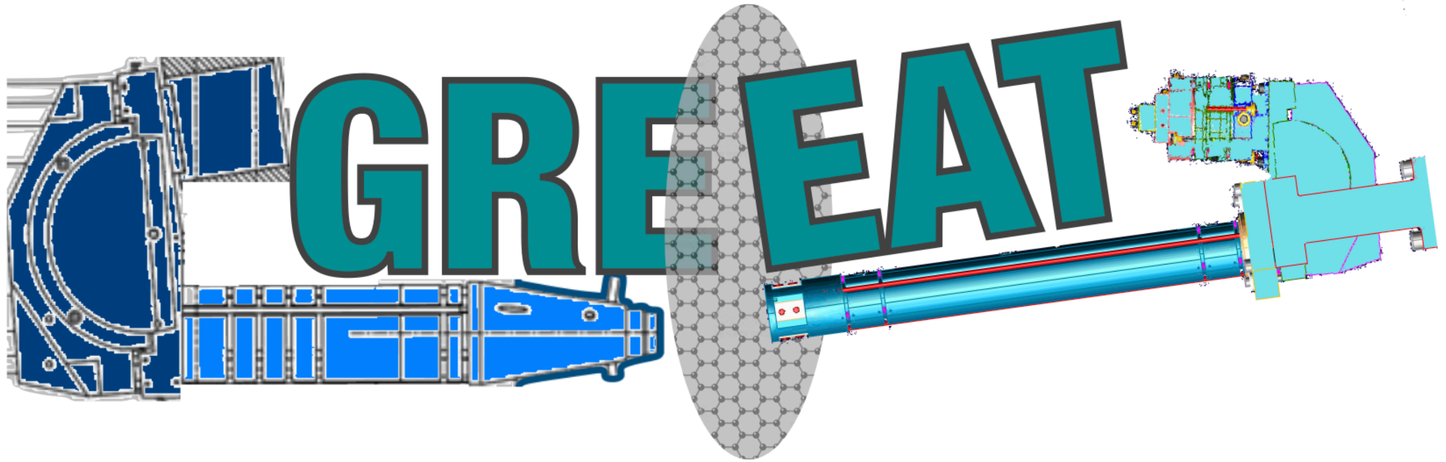


Carbon nanotubes



Stacked graphene

STAY TUNED, IT WILL BE

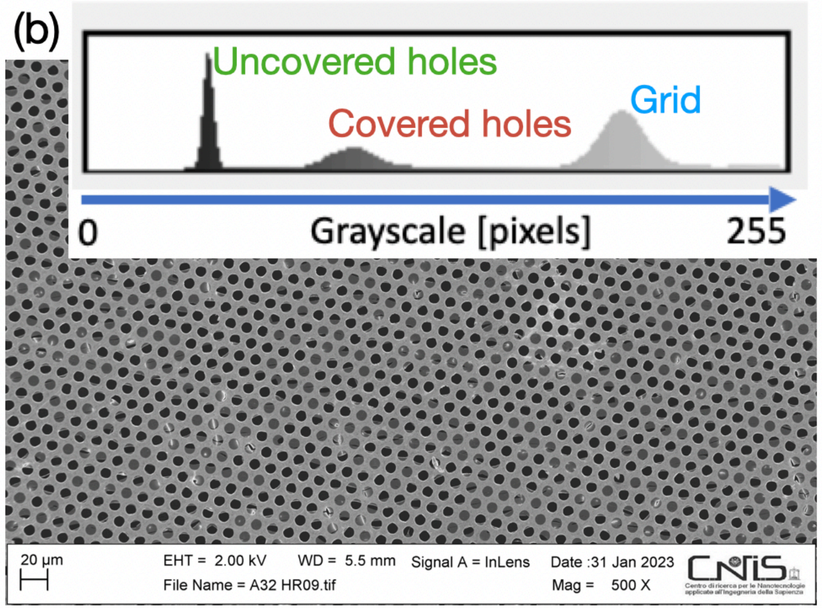


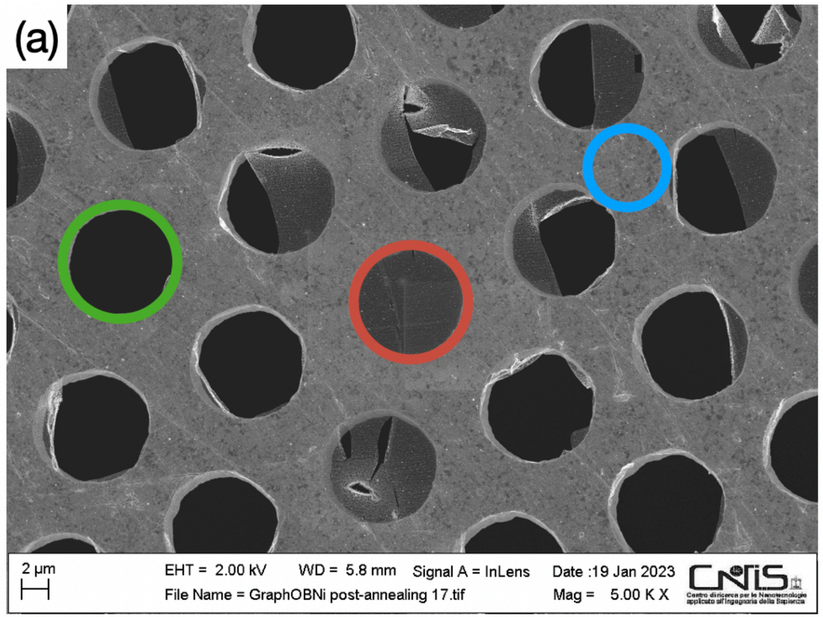
!

BACKUP

Greyscale Histogram for the Evaluation of Holes Coverage

- Software generates histogram based on pixels grey level
- Area of the covered holes, uncovered holes and grid regions
- Evaluate graphene coverage and geometrical transmission





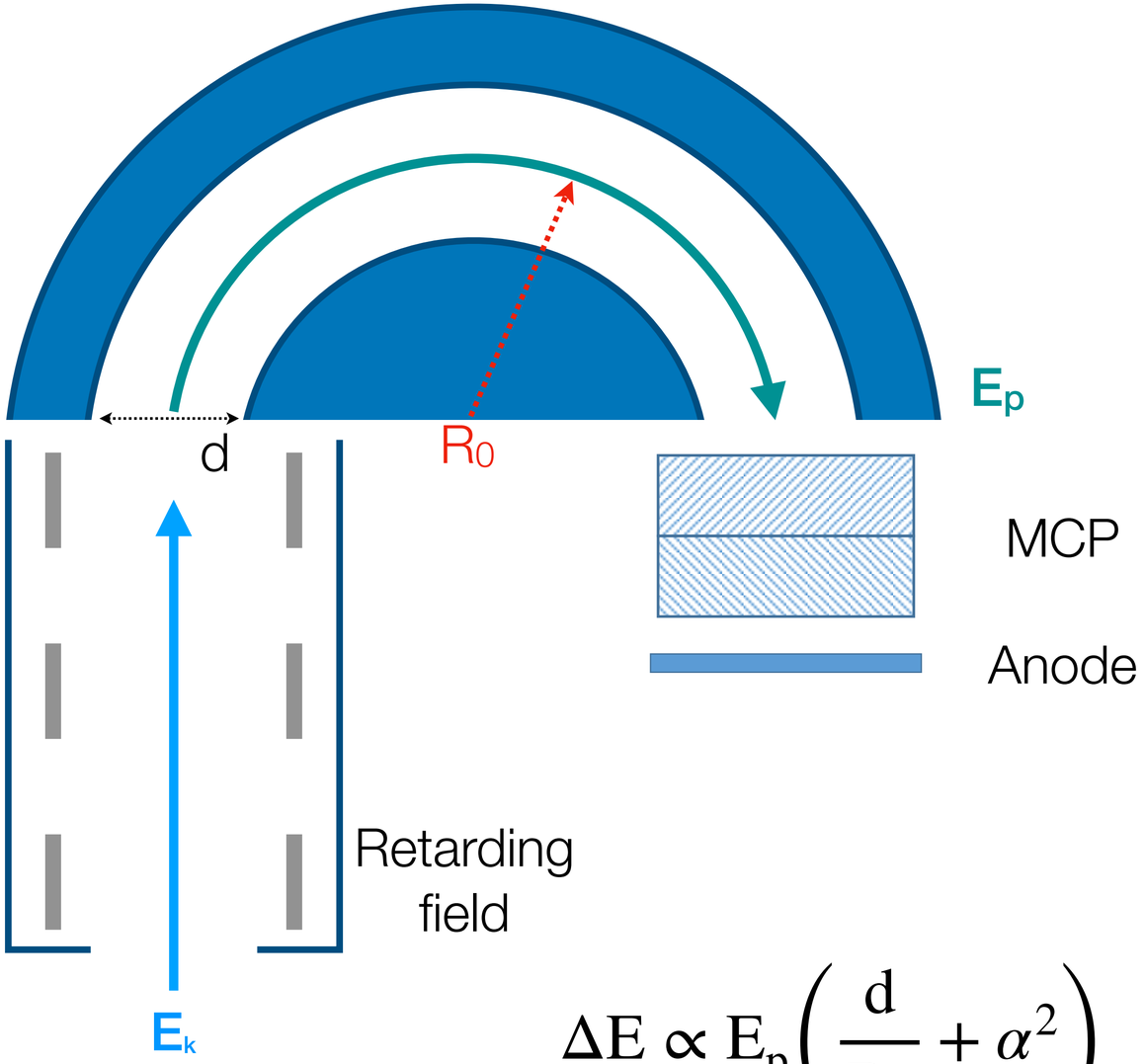
Grid geometrical transmission

- Sample A (37 ± 1)%
- Sample B (44 ± 1)%

Graphene coverage

- Sample A (38 ± 1)%
- Sample B (42 ± 1)%

Hemispherical Electron Analyser: an Electrostatic Filter for Electrons

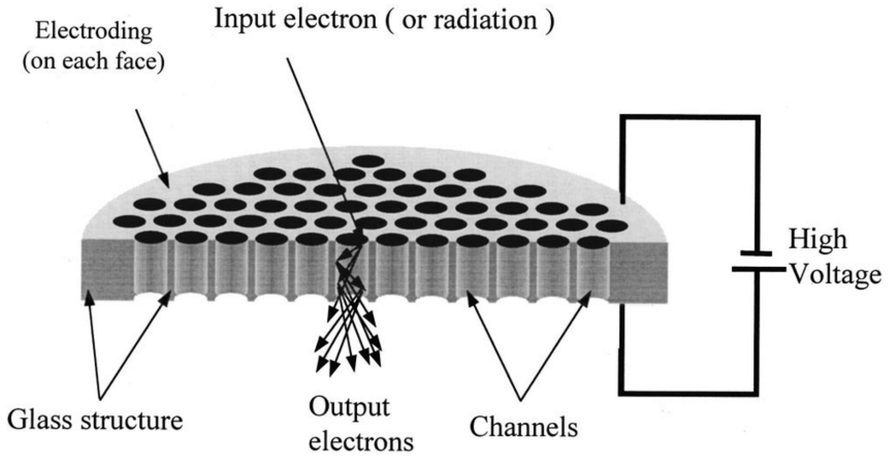


$$\Delta E \propto E_p\left(\frac{d}{R_0}+\alpha^2\right)$$

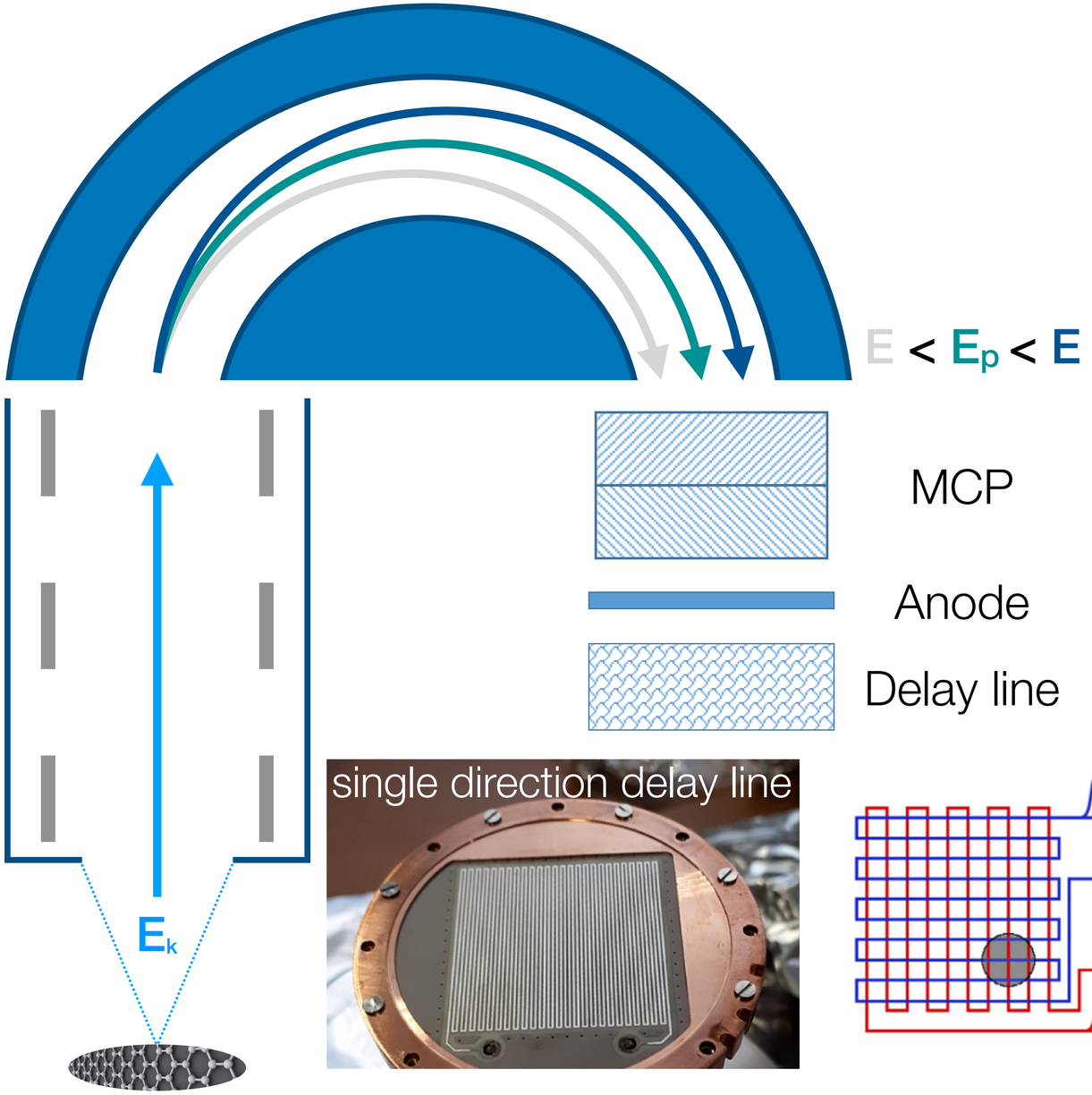
Hemispherical electron analyser:

- Electrostatic filter
- Electron detector at exit

Channeltron / microchannel plate (MCP)



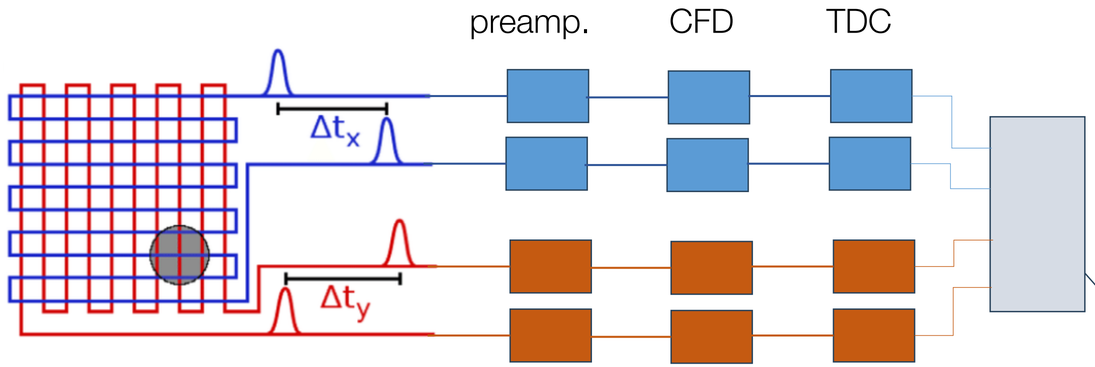
Hemispherical Electron Analyser: an Electrostatic Filter for Electrons

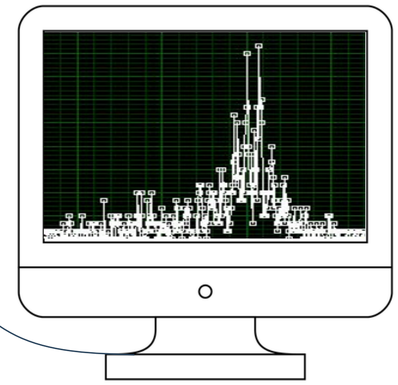


Hemispherical electron analyser:

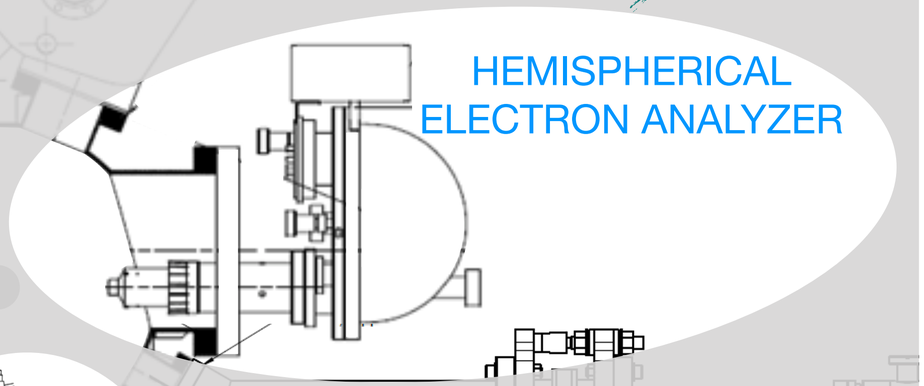
- Electrostatic filter
- Channeltron at exit
- Final electron position ∝ its energy

MCP+Delay line for parallel counting can be implemented



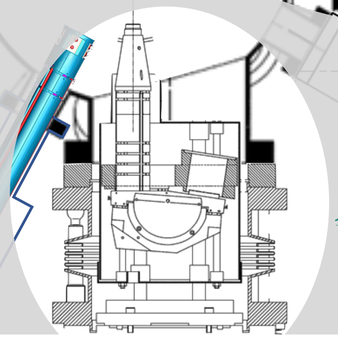


LASEC Lab: Electronic Spoctroscopies and More…



HEMISPHERICAL ELECTRON ANALYZER

Equipped with position sensitive detector for parallel acquisition



HEMISPHERICAL ELECTRON ANALYZER

"Twin" analayzer of the one we will use in the new chamber

LAboratorio di Spettroscopie Elettroniche e di Correlazione

Run the Experiment Backwards: Electron Currents of 10 - 100 fA

Electron detector side:

- Max rate ~600 kHz (~100 fA) for linear-mode operation
- Absolute efficiency of MCP measured with LASEC apparatus

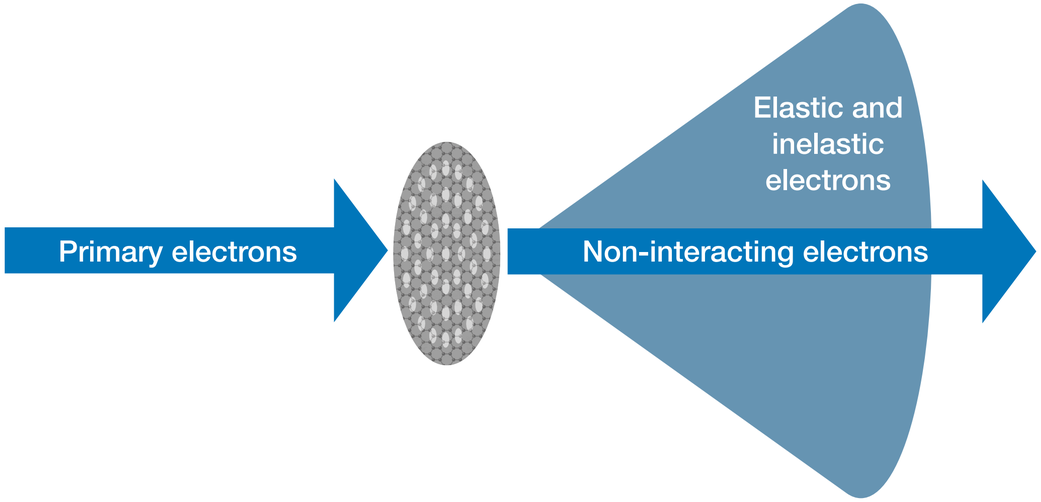
A. Apponi et al., Measur.Sci.Tech (2022), 10.1088/1361-6501/ac3d07

Monochromatic electron gun:

- Continuous beam ~1 fA - ~40 nA
- Tuneable energy within 30 - 900 eV
- Optimal stability even down to a few fA

We will run the experiments with electron currents in the 10 - 100 fA range

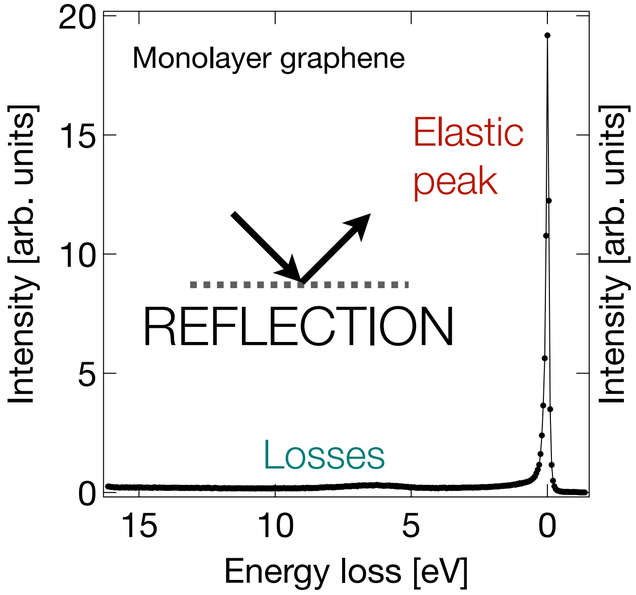
Start with Non-Interacting e$^-$, Boost with Parallel Acqisition for Scattered e$^-$

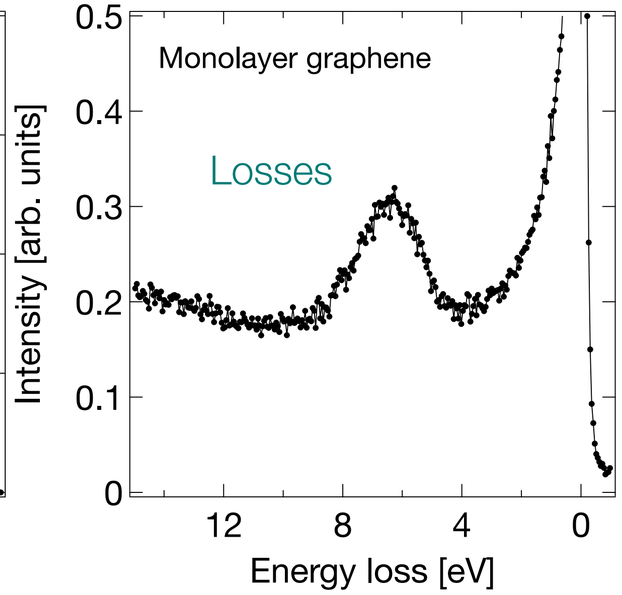


Non-interacting electrons:

- Measure at "0 angle" (1° angular acceptance)
- Total cross-section

I year goal



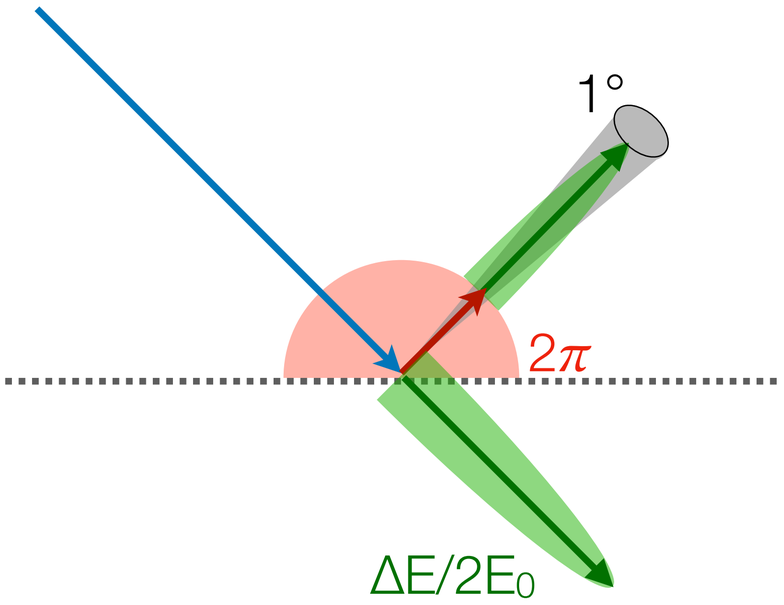


Scattered electrons:

- Reflection spectrum acquired in 30 hours with channeltron
- MCP+delay line for parallel acquisition gives a (*vital*) 10x boost
- Similar acquisition time in transmission
- Differential and total cross-section

II year goal

Reflection vs Transmission signal



REFLECTION PROCESS: EL+ANEL

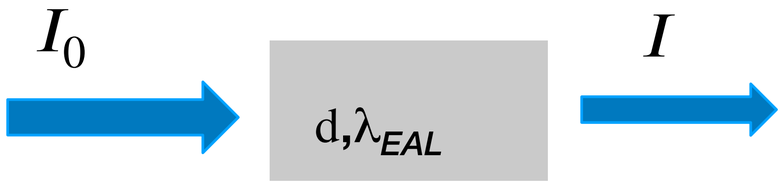
Electrons accepted within analyser

$$\frac{(0.5/57)^2\pi}{2\pi} \sim 4\text{x}10^{-5}$$

TRANSMISSION PROCESS: ANEL

TRANSMISSION = $4\text{x}10^5$ x REFLECTION

Thickness of a 2D material is an ill-defined quantity

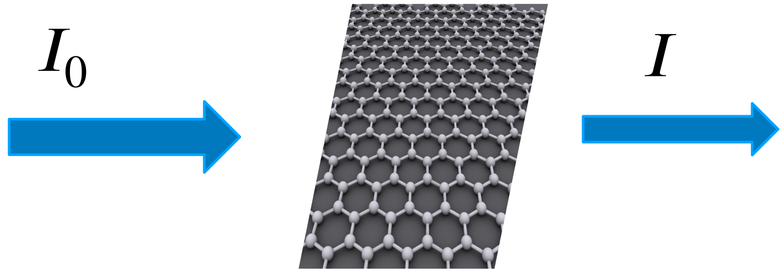


$$I(E) = I_0 e^{-\frac{d}{\lambda_{EAL}}}$$

Which thickness d should be used for ML graphene?

- Interplanar distance in graphite: 3.35 Å
- Twice the radius of covalent bond: 2.48 Å

The attenuation length affected by the arbitrariness of the thickness choice

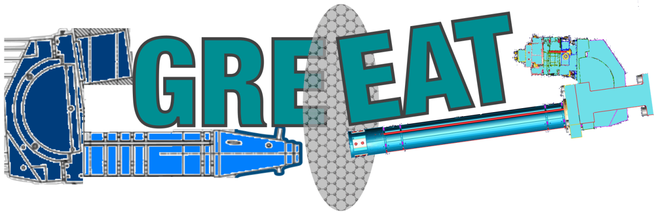


$$I(E) = I_0 e^{-n_G \sigma_{tot}(E)}$$

- n_G is the surface density of the carbon atom in graphene
- σ_{tot} is the total cross section

A correct measurement of the non scattered electrons I*(E)* allows to obtain the total cross section

To Conclude



GRaphene to Electrons:
Energy and Angular resolved Transmission

The GREEAT project:

- Graphene-electrons cross-section measured for the first time
- Fundamental for applications: MPGD, PTOLEMY

The GREEAT project reinforces the LASEC lab. (Univeristà Roma Tre) involvement in INFN activities