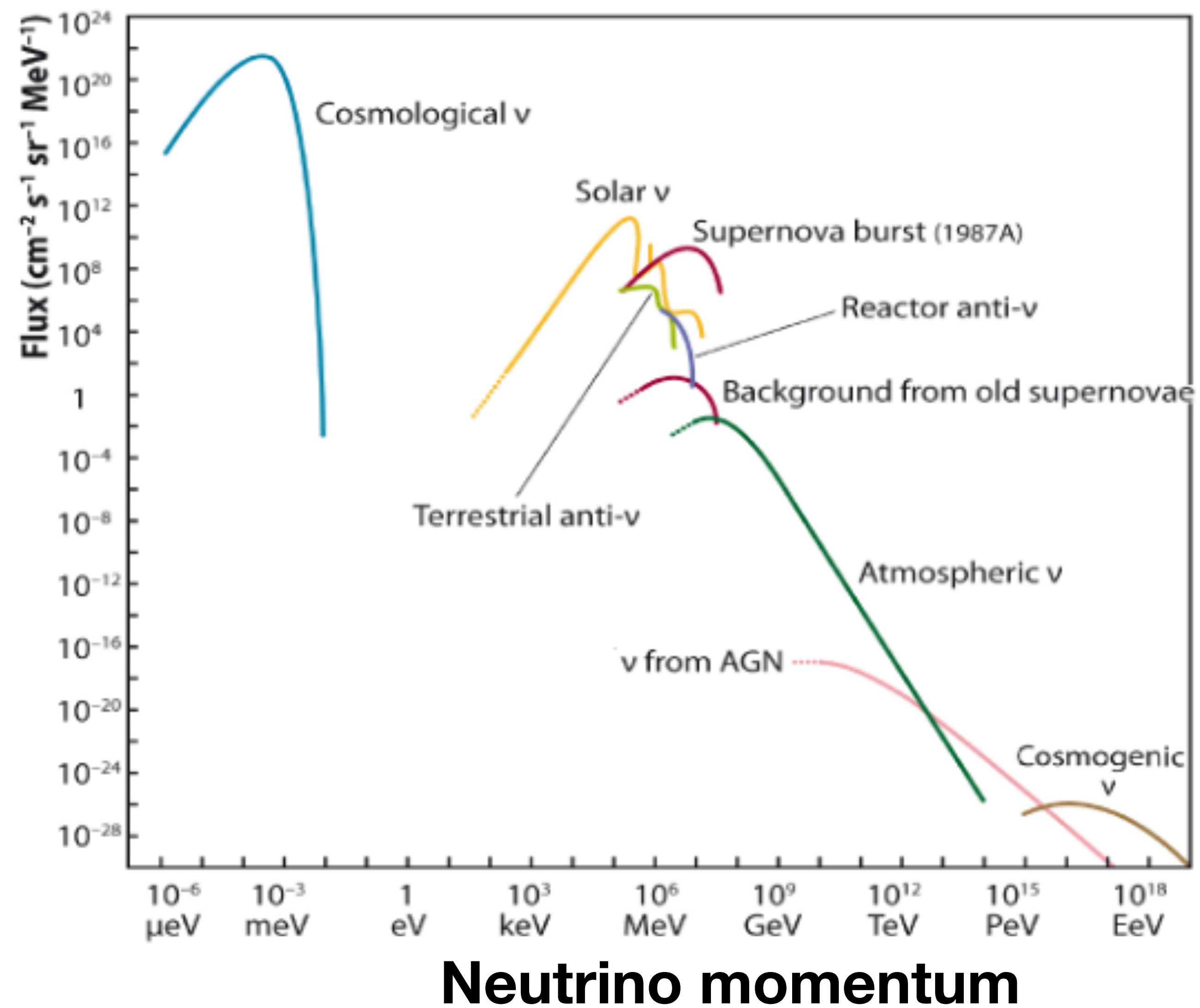
Development of detectors for ultra-low energy neutrinos

Gianluca Cavoto - *Sapienza Univ Roma and INFN Roma*
*On behalf of the **Ptolemy** Collaboration*
QT4HEP conference - ***CERN*** *1 Nov 2022*

Outline

- The **neutrino cosmological background** (CνB)
- The **Ptolemy** project
  - A novel type of electro-magnetic filter
  - Advanced detection concepts (**nano-fabricated transition edge sensors**, very low power radio-frequency detection)
  - A Tritium target based on **carbon nanostructure**
    - **Beta** decays and **quantum** uncertainty
- Use of (carbon) nanostructure as targets for particle physics

- Messengers from **1s** after the Big Bang
- **Cold** Matter (T ~ 1.9K)
- About **100/cm³** here and now
- Faint kinetic energy (< eV)

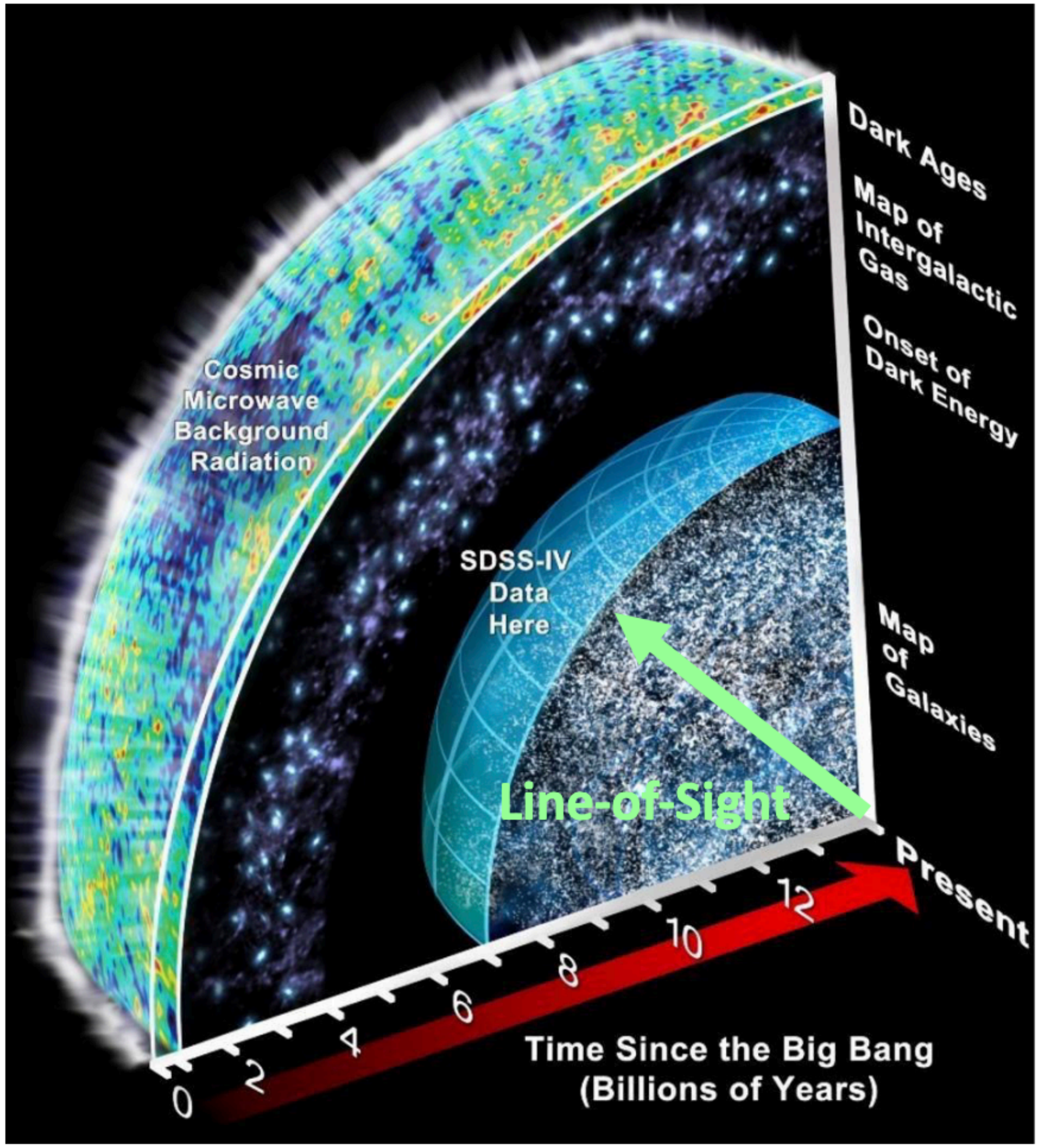


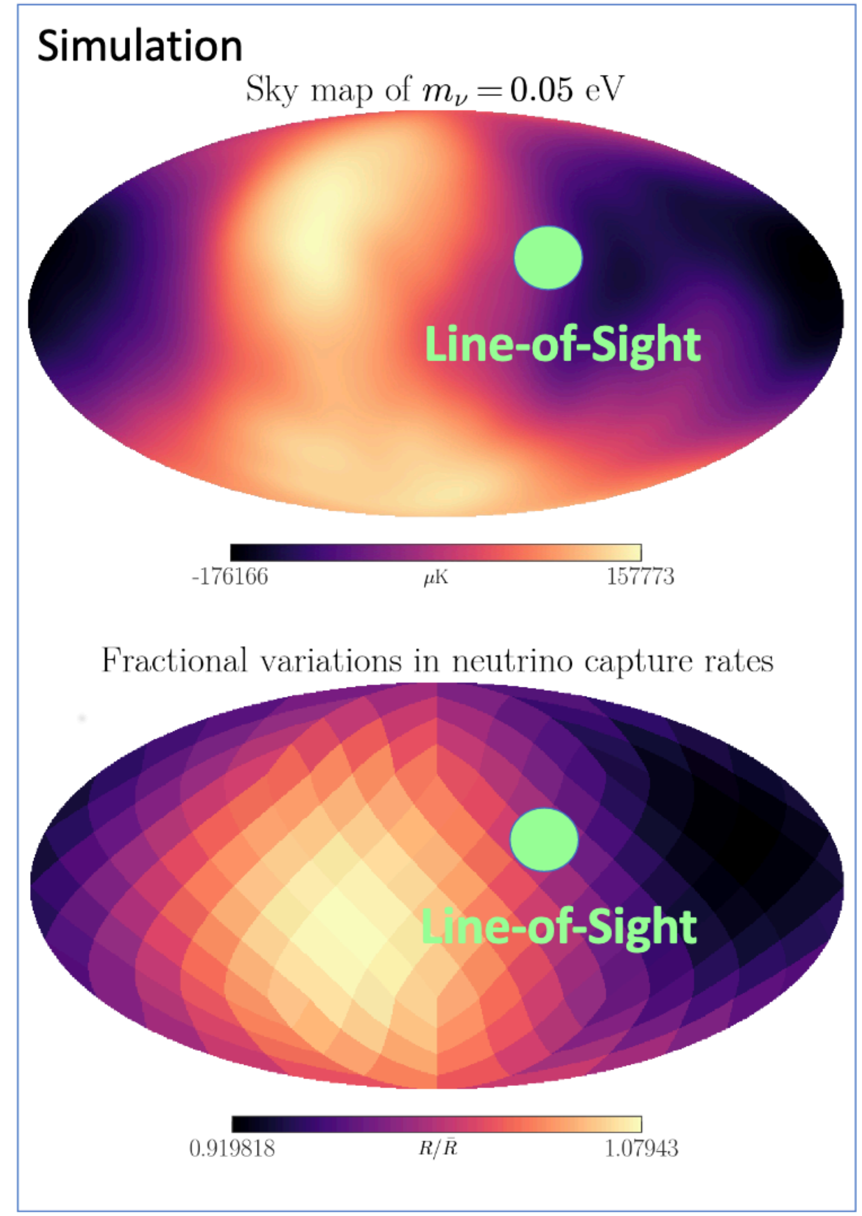
The Ptolemy project

M.G. Betti et al JCAP07 (2019) 047

An R&D project to demonstrate the detection concept

Relic neutrino sky map



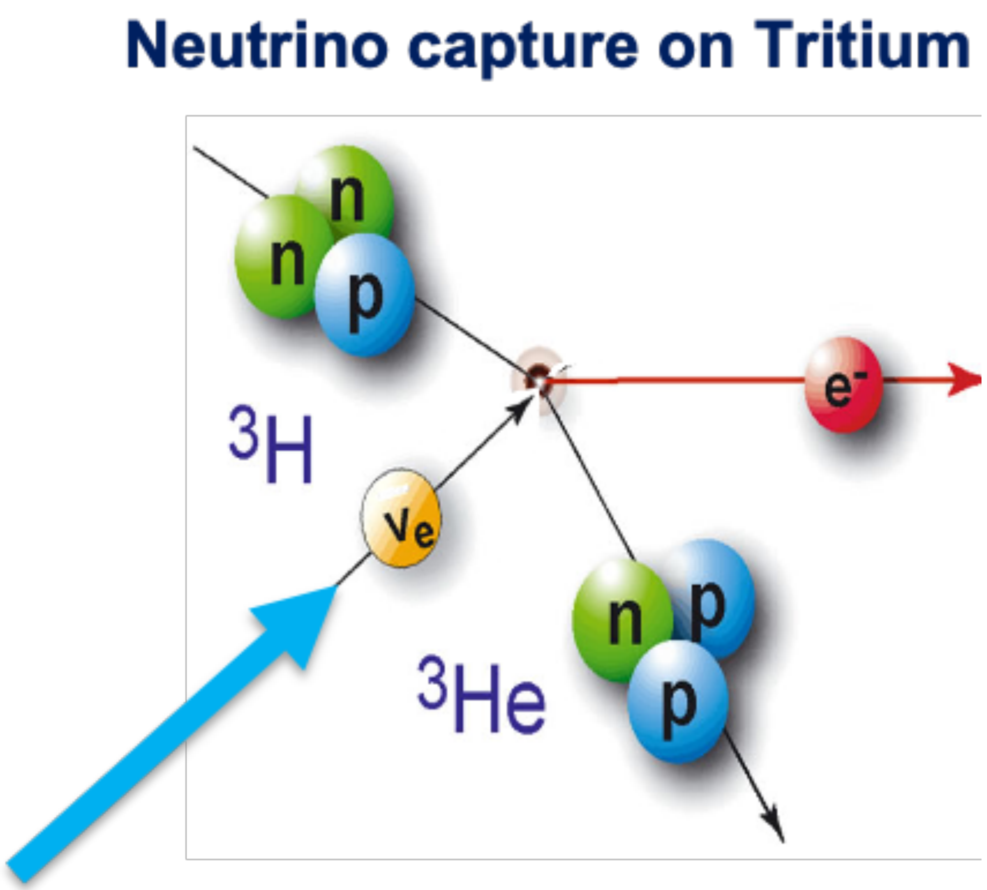


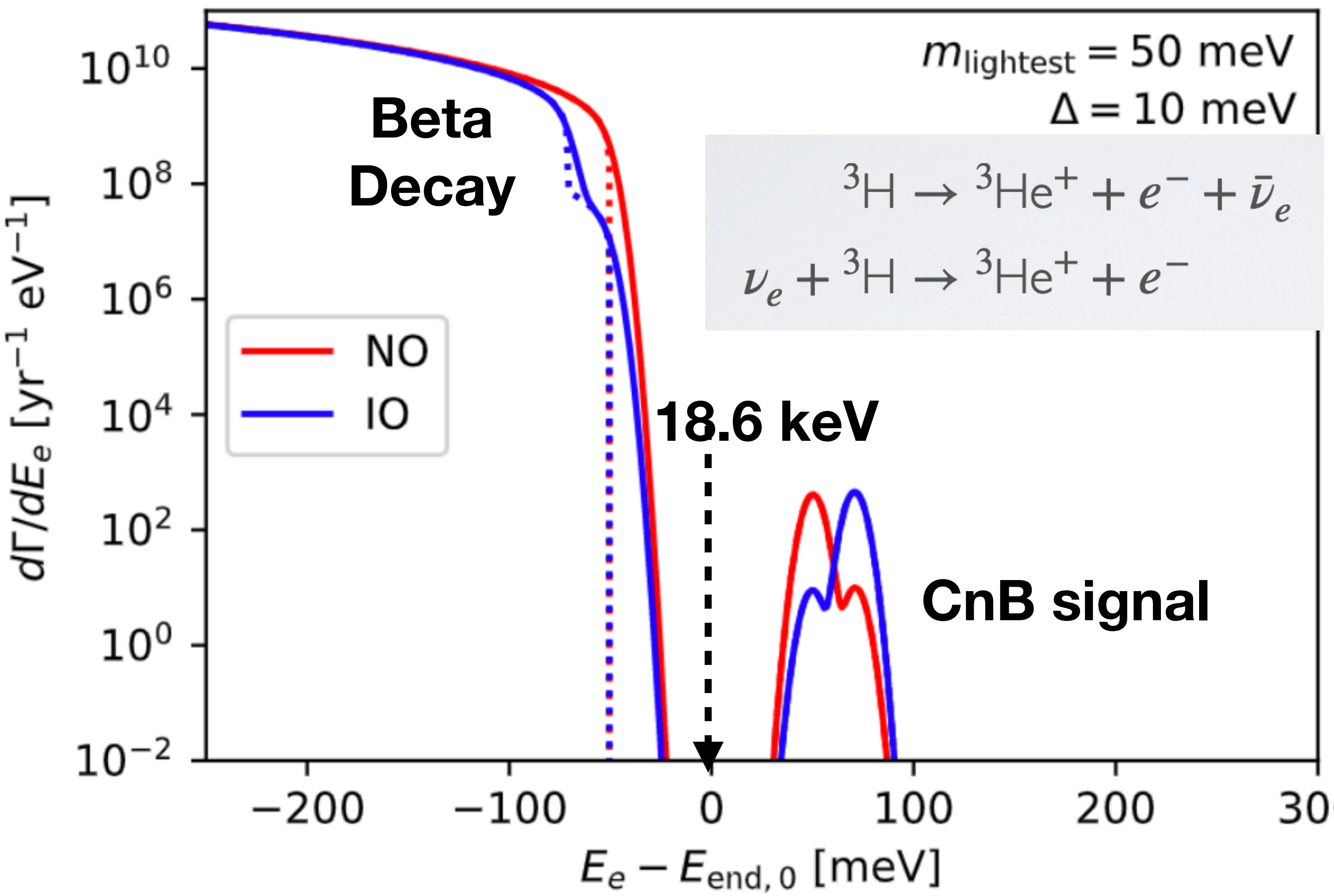
Multi-messenger astrophysics with the cosmic neutrino background, C.G. Tully and G. Zhang JCAP06(2021) 053

The target, atomic tritium ^3H

Cocco, Mangano & Messina, J Phys Conf Ser 110, 082014 (2008).

Weinberg,. Phys Rev 128, 1457–1473 (1962).



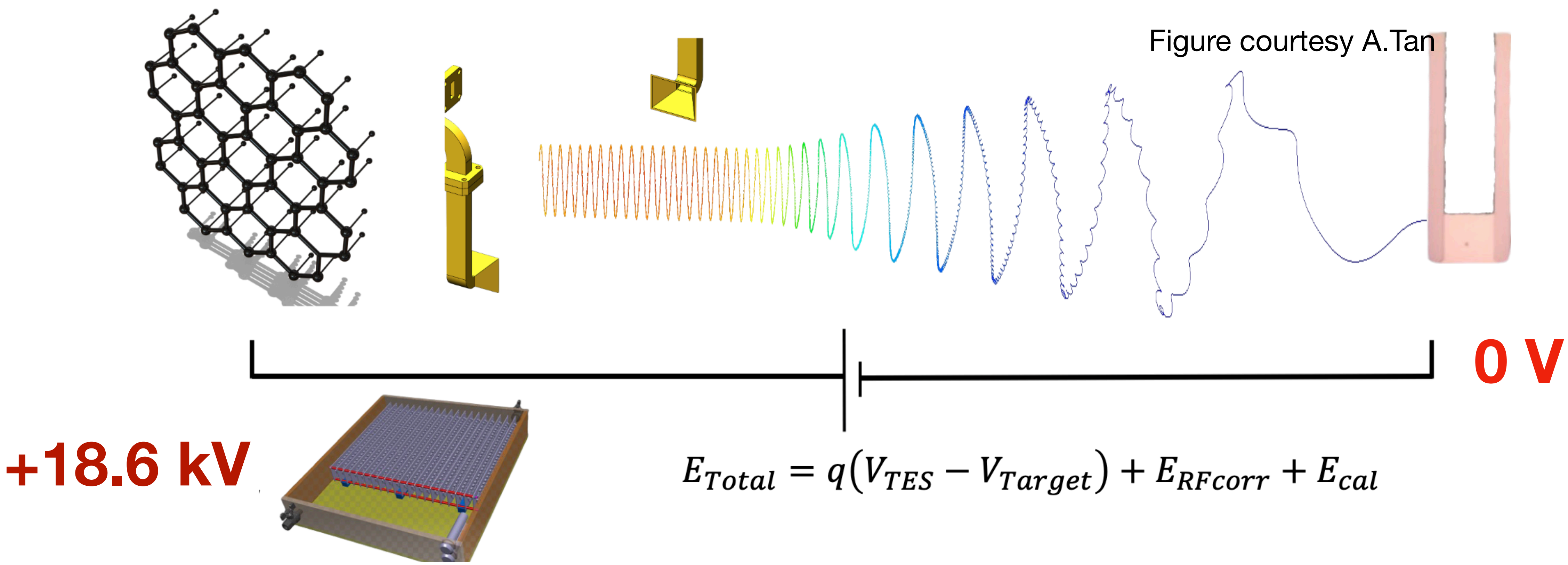


- < 50 meV (beta) electron kinetic energy resolution
- Need 100g ^3H for few CnB events/y
- But ^3H beta decay rate is ~0.2 THz/mg

The Ptolemy concept

- Precisely defined (ppm) voltage difference: beta electron slowed down - and removed - to decimate the flux.
- Measure a ~1-10 eV electron with 10^{-2} - 10^{-3} resolution

Target: Relic Neutrino Capture → RF Tracker: Electron Pre-Measurement → Dynamic Filter: Selects endpoint electron in narrow 10^{-4} energy window → Micro-calorimeter: Measures $\mathcal{O}(\mathrm{eV})$ electron to 10^{-2} energy resolution



The Ptolemy ingredients

- Tritium on **graphene**: atomic ${}^3H$ stored on a thin electrode

- Fast ~30 GHz radiation detection as *trigger*
  - cyclotron radiation emission (similar to Project-8)

- Novel electromagnetic filter

M.G.Betti et al,
Progress in Particle and Nuclear Physics,
106, (2019) 120-131

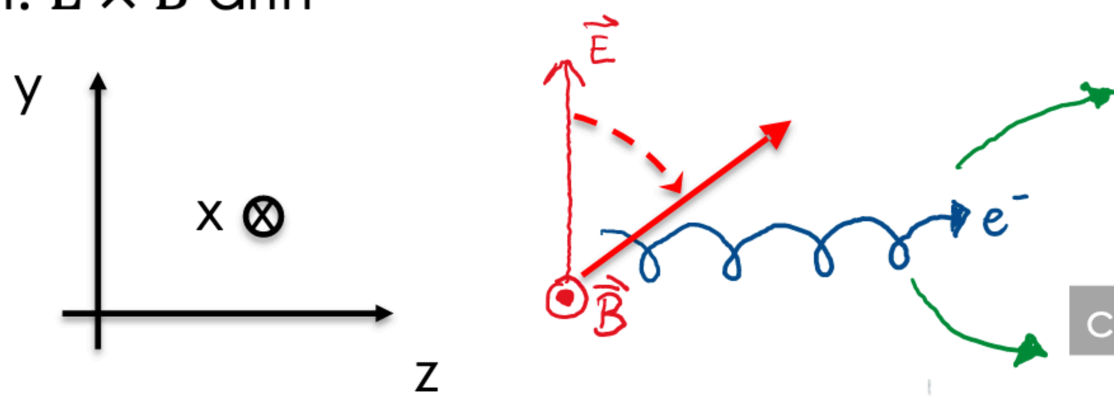
- Cryogenic **micro-calorimeter** based Transition Edge Sensors (**TES**) technology

Transverse (to the B field lines) velocity (Guiding Center System)

$$\boldsymbol{V}_D = \boldsymbol{V}_\perp = \left(q\boldsymbol{E} + \boldsymbol{F} - \mu \nabla B - m\frac{d\boldsymbol{V}}{dt} \right) \times \frac{\boldsymbol{B}}{qB^2}$$

Figure courtesy A.P.Colijn

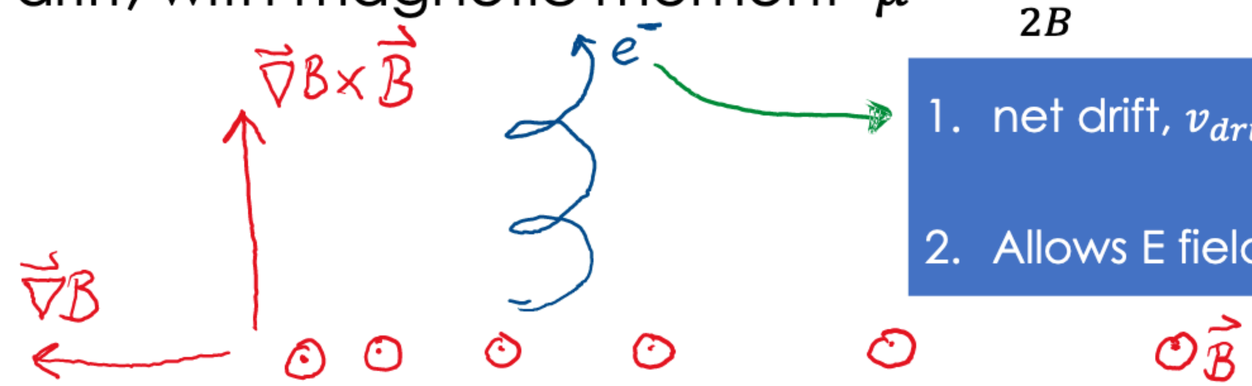
I: $\vec{E} \times \vec{B}$ drift



1. net drift, $v_{drift} = E/B$
2. no work, drift along equipotential planes

cyclotron motion – detectable RF

II: $\frac{\mu}{B^2}\vec{\nabla}B \times \vec{B}$ drift, with magnetic moment $\mu = \frac{m_e v_\perp^2}{2B}$



1. net drift, $v_{drift} = \mu\frac{|\vec{\nabla}B|}{B}$
2. Allows E field to work (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

MAC-E filter, collimating the electrons

MAC-E filter

Magnetic Adiabatic Invariance

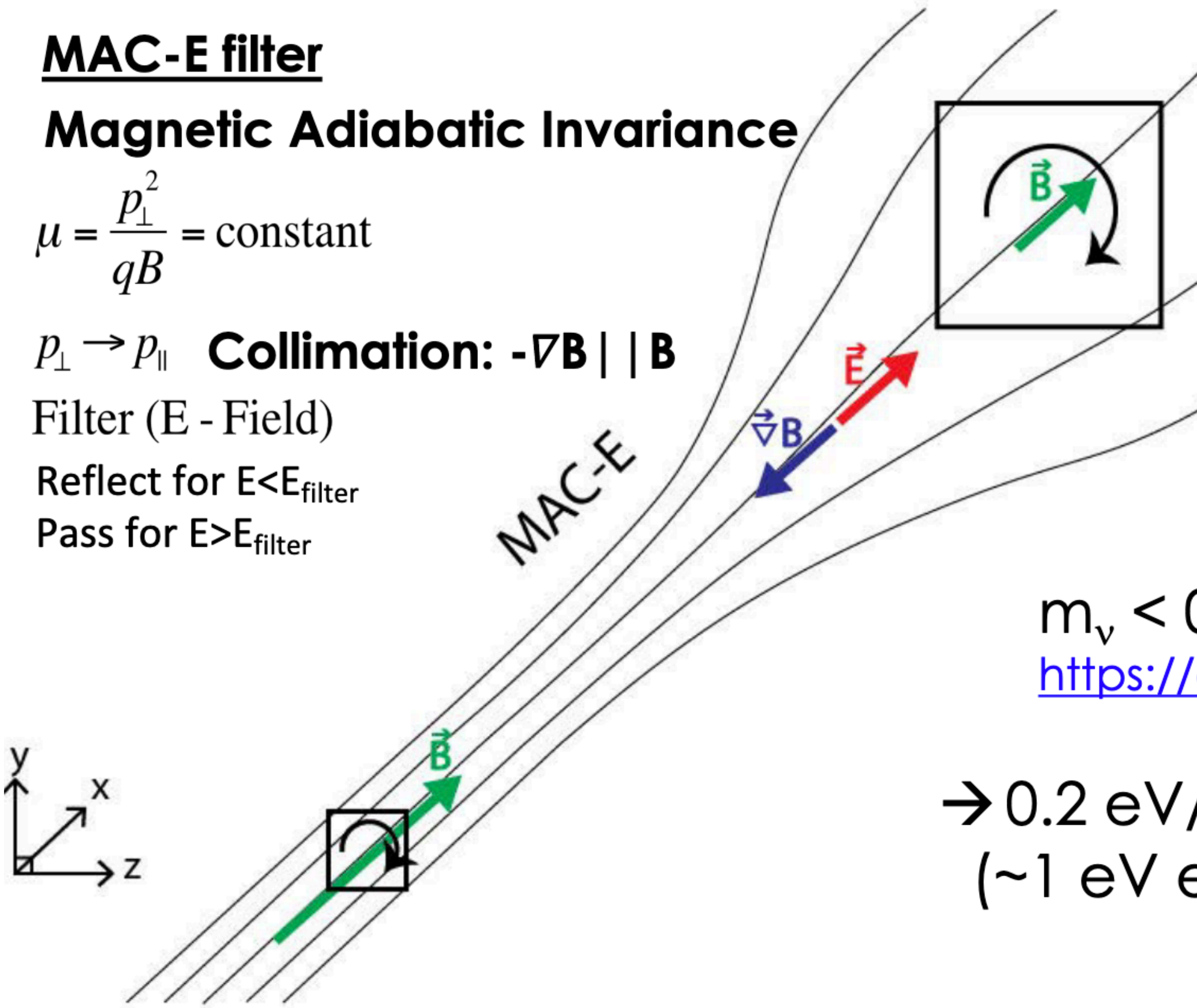
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$p_\perp \rightarrow p_\parallel$ **Collimation: $-\nabla B \,||\, B$**

Filter (E - Field)

Reflect for $E<E_{filter}$

Pass for $E>E_{filter}$



KATRIN

~1200m³

m_ν < 0.8 eV/c² (90% CL)

https://arxiv.org/abs/2105.08533

→ 0.2 eV/c² Sensitivity Goal (~1 eV energy resolution)

A transverse filter

Transverse Drift filter

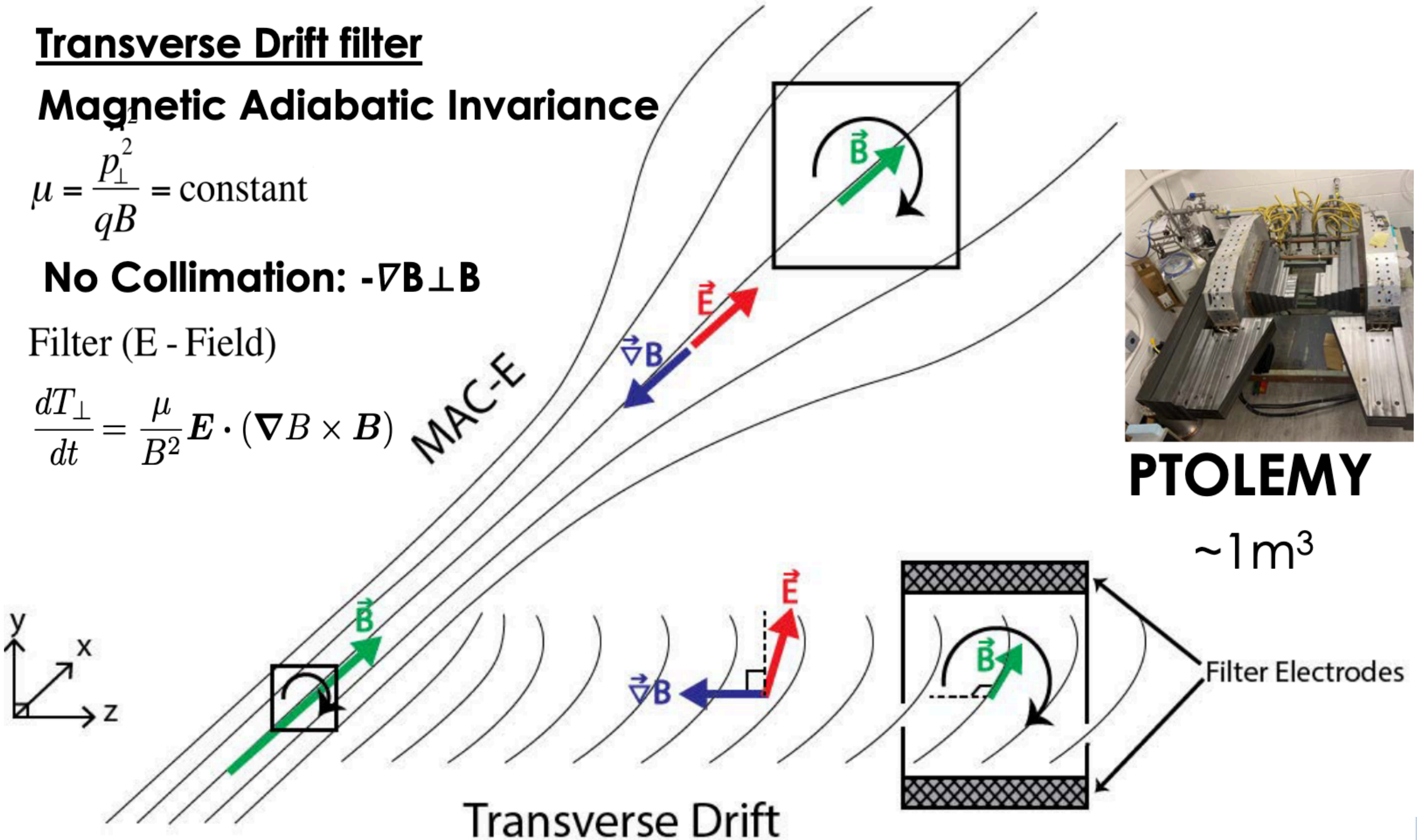
Magnetic Adiabatic Invariance

$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

No Collimation: $-\nabla B \perp B$

Filter (E - Field)

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B \times \boldsymbol{B})$$



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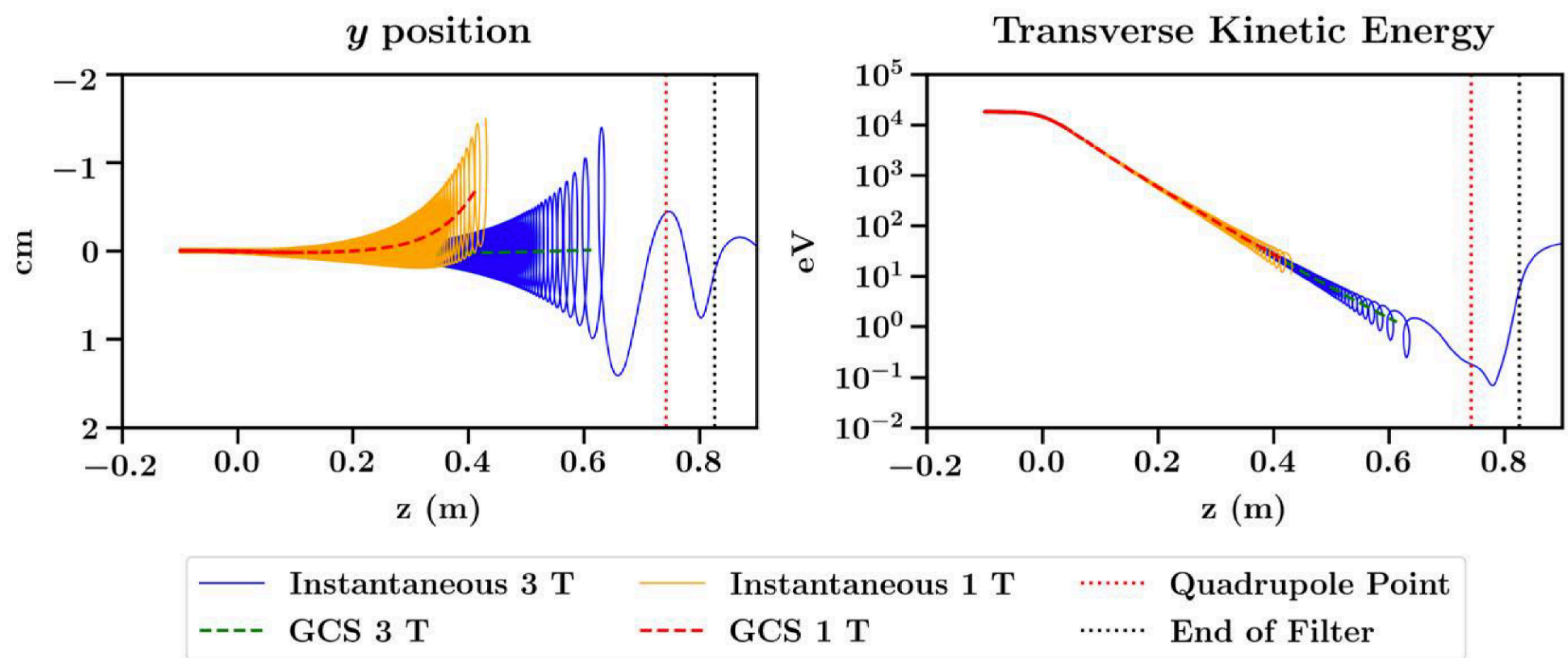
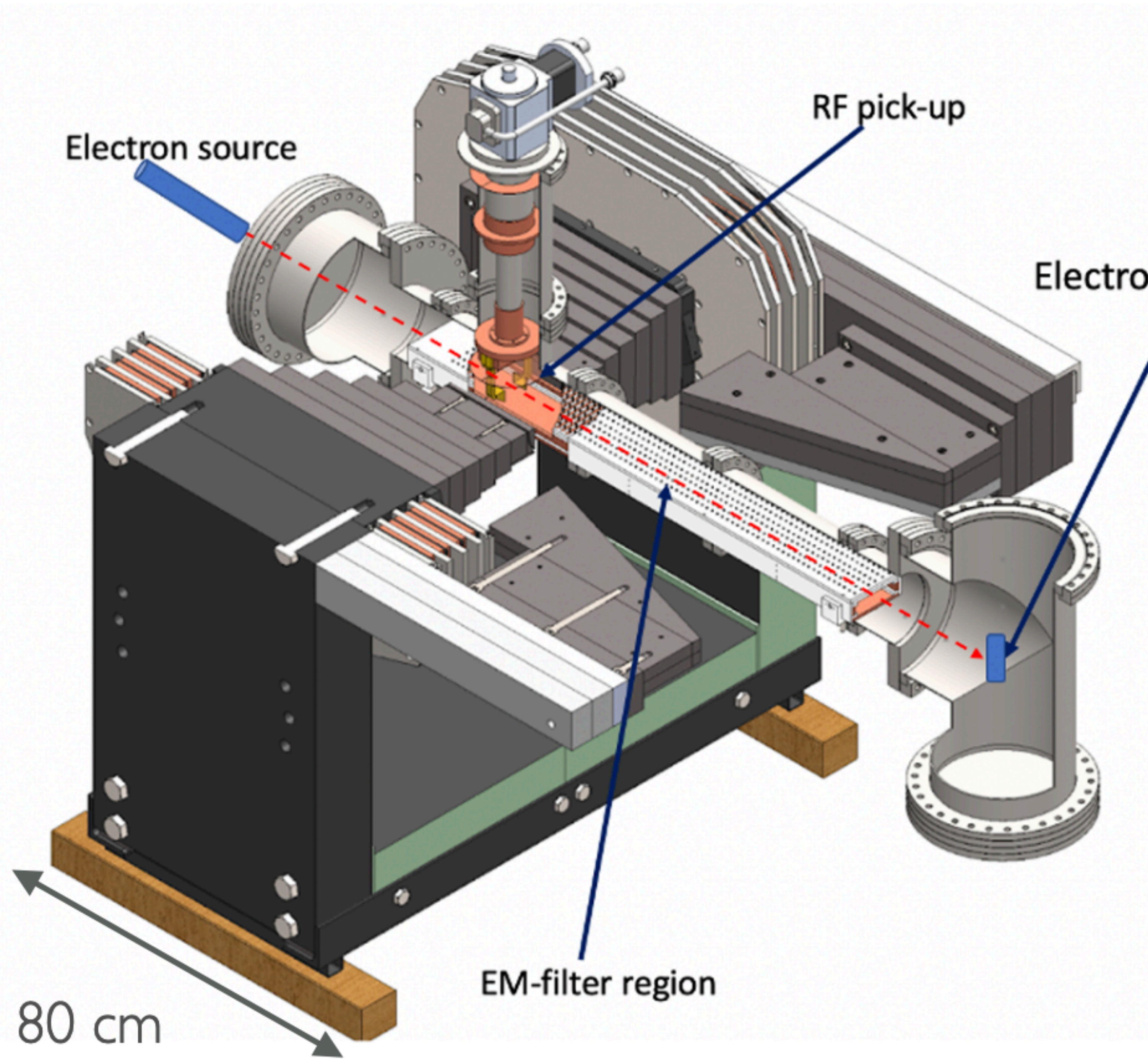
Transport simulation

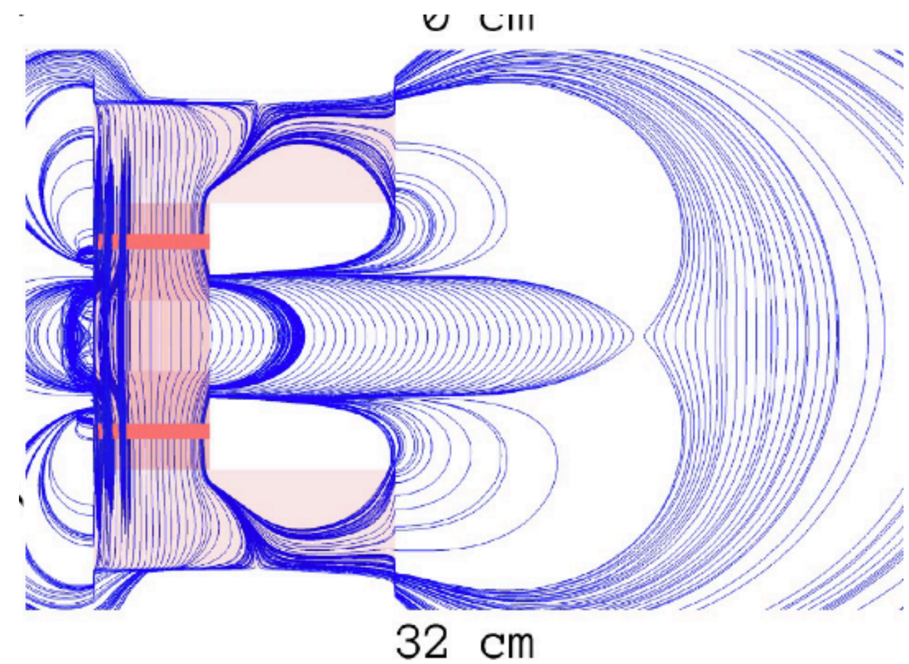


- Feasibility proved with simulation
- Need a real test

The demonstrator

A. Apponi et al 2022 JINST 17 P05021





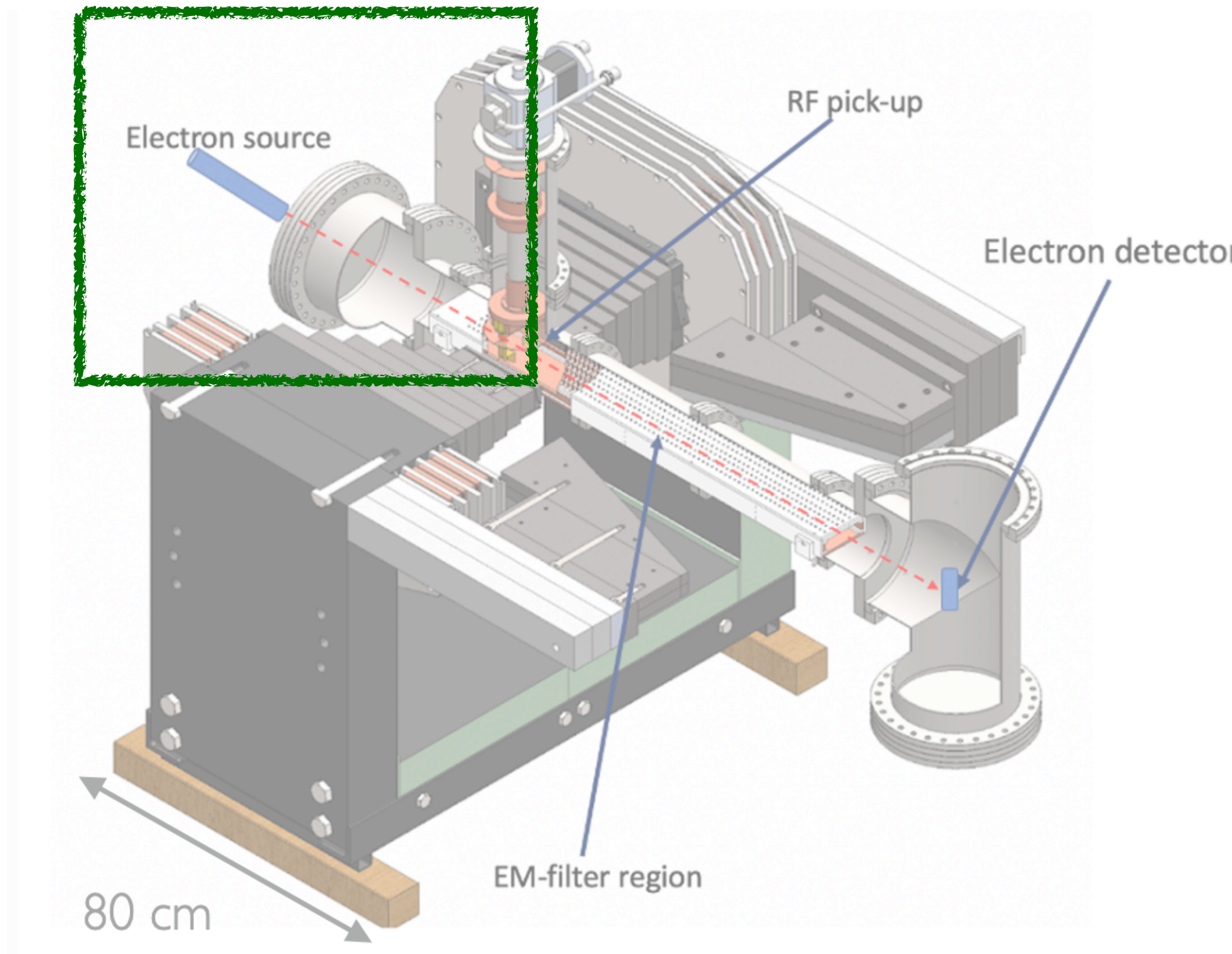
An exponentially falling B field (fringe field)
+
Non-uniform E field

Being built, assembled and operated at INFN LNGS

The source and the end of the filter

- Goal of the < 50 meV energy resolution:
  - **Preparare the initial state** on
    - A well defined spatial position (electrode)
    - Deal with intrinsic quantum spread of localisation of atomic ^{3}H (Heisenberg limit)
      - *Interplay with **condensed matter** physics*
  - **Detect** the electrons after the **end** of the filter
    - Kinetic energy much reduced to 10-100 eV
    - Deal with absorption of very slow electron in materials
      - **Superconduting** sensors, **surface** physics

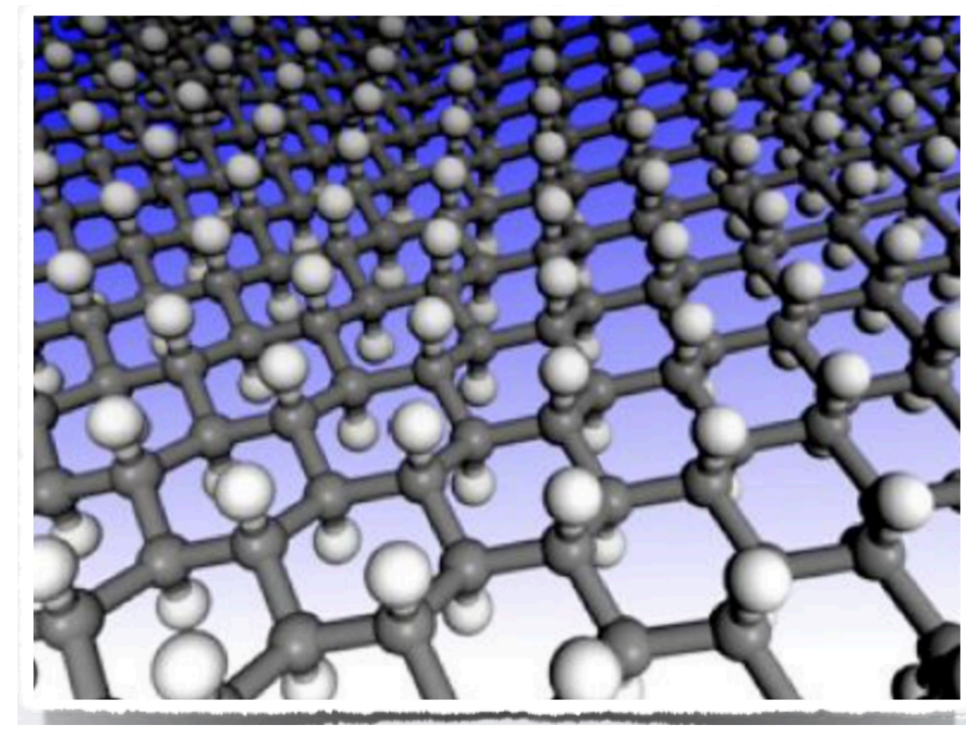
The target for neutrinos, source of electrons



Flat graphene ^3H storage

- ^3H ***H*** atom chemically bound to a ***C*** atom on a **flat graphene**

- **Solid** substrate
  - "Solid" tritium source, easily manageable
  - Well defined potential
  - Prevent molecule formation



- Can store (up to) 0.5 mg/cm^2
  - One ***^3H each C***

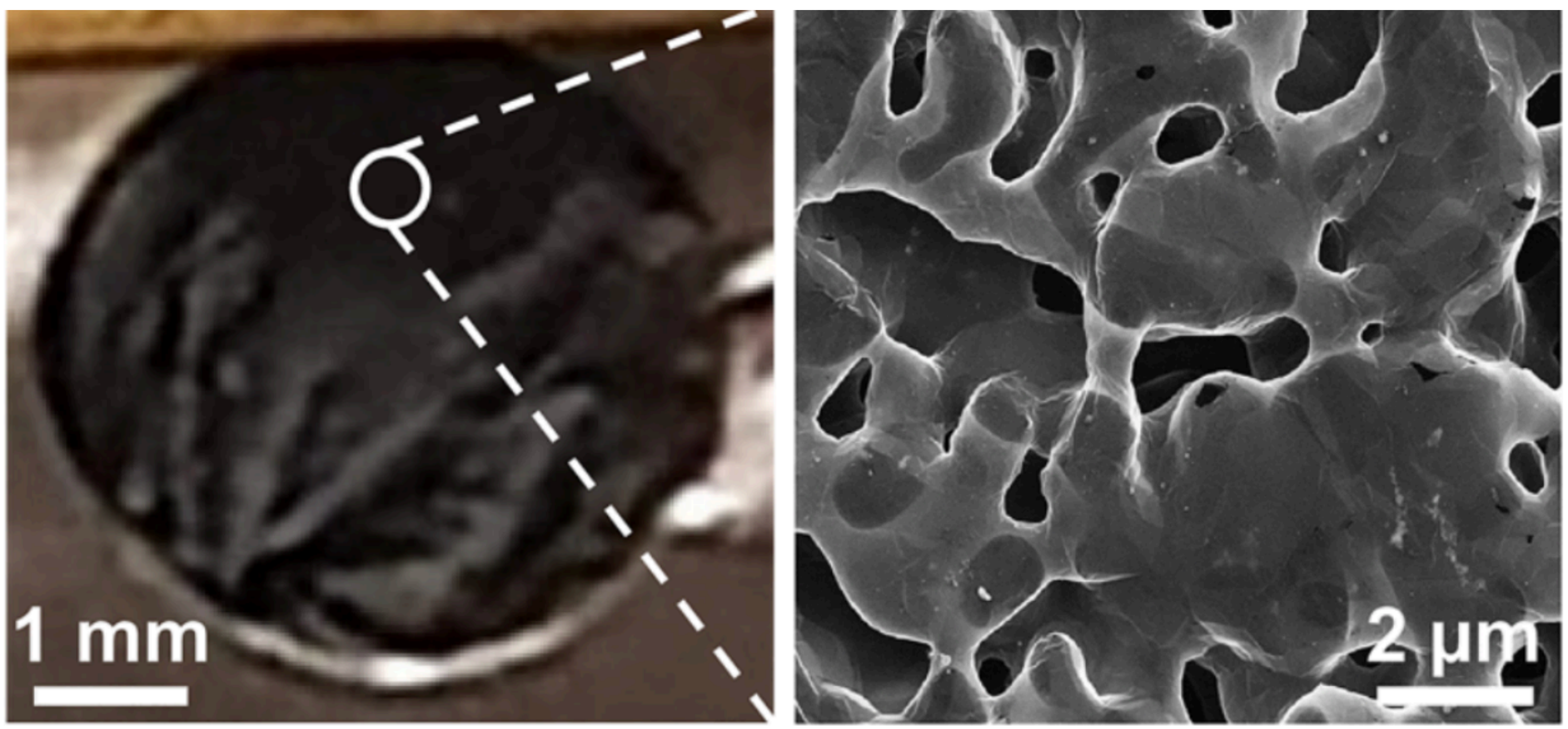
Mahmoud Mohamed Saad Abdelnabi et al 2021 Nanotechnology 32 035707

Mahmoud Mohamed Saad Abdelnabi et al Nanomaterials 2021, 11(1), 130

Hydrogen on graphene

Nano Lett. 2022, 22, 7, 2971–2977

- Successfully tested various techniques to "*implant*" hydrogen (deuterium) to **Nano-Porous Graphene**

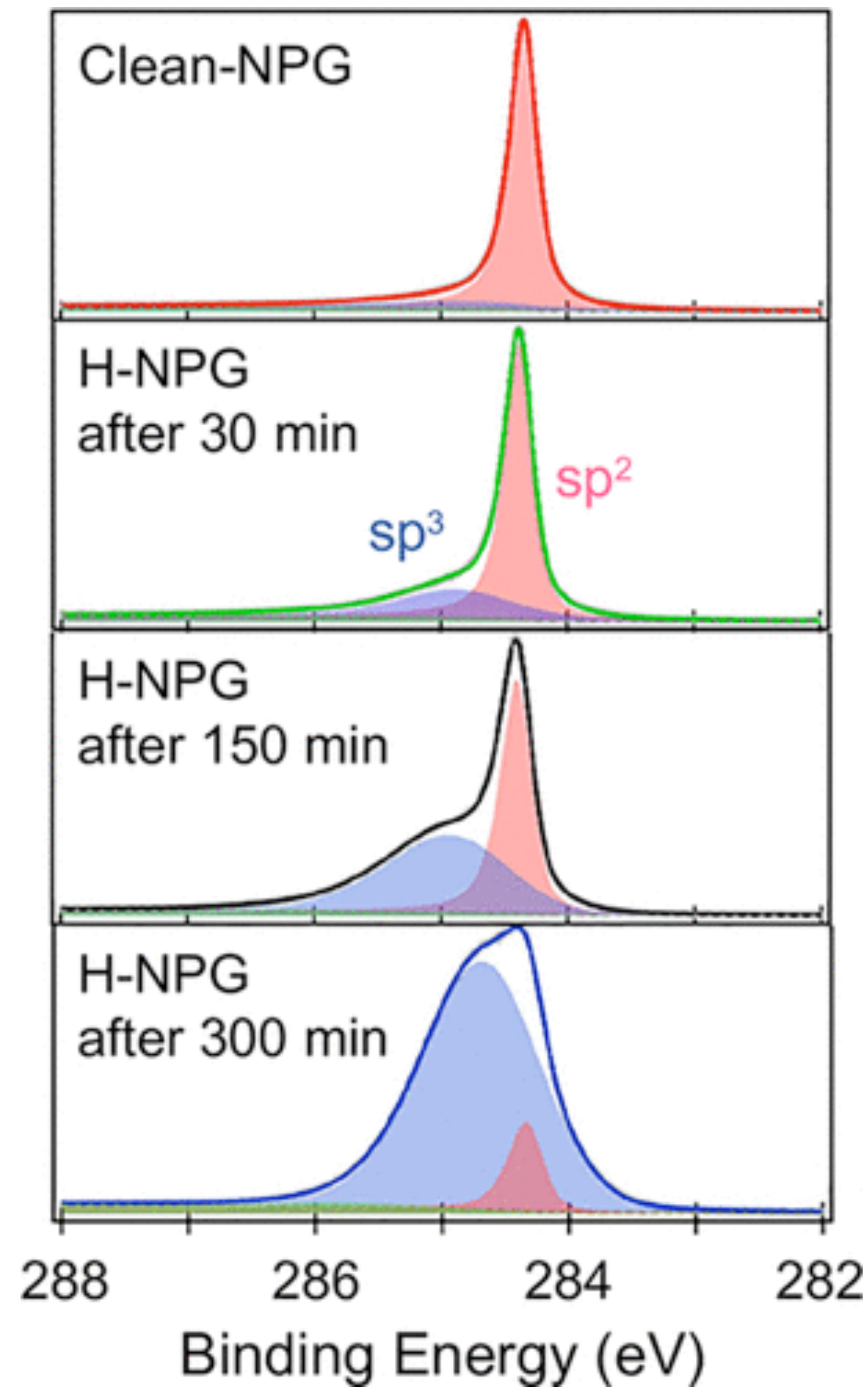


- Hydrogen chemi-sorbed on NPG (single or double layers continuous graphene surface)

Graph**a**ne

Nano Lett. 2022, 22, 7, 2971–2977

- Larger than **90% hydrogen coverage**
  - In situ *H* thermal cracking
  - *H* atoms diffuse in UHV to NPG
  - X-ray photoelectron spectroscopy on *C* 1s: amount of sp^3 coordinated *H*
- **Band-gap** observed: seminconductor.



Ye. Cheipesh, V. Cheianov, and A. Boyarsky Phys. Rev. D 104, 116004

- **Localization** of *³H* implies uncertainty on *³H* momentum: effect on the electron kinetic energy spread

$$^3\mathrm{H} \to {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

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

Fluctuating momenta

$$\mathbf{p}_T = \Delta\mathbf{p}_T$$

$$\mathbf{p}_{He} = \bar{\mathbf{p}}_{He} + \Delta\mathbf{p}_{He}$$

$$\mathbf{p}_e = \bar{\mathbf{p}}_e + \Delta\mathbf{p}_e$$

4-mom. conservation

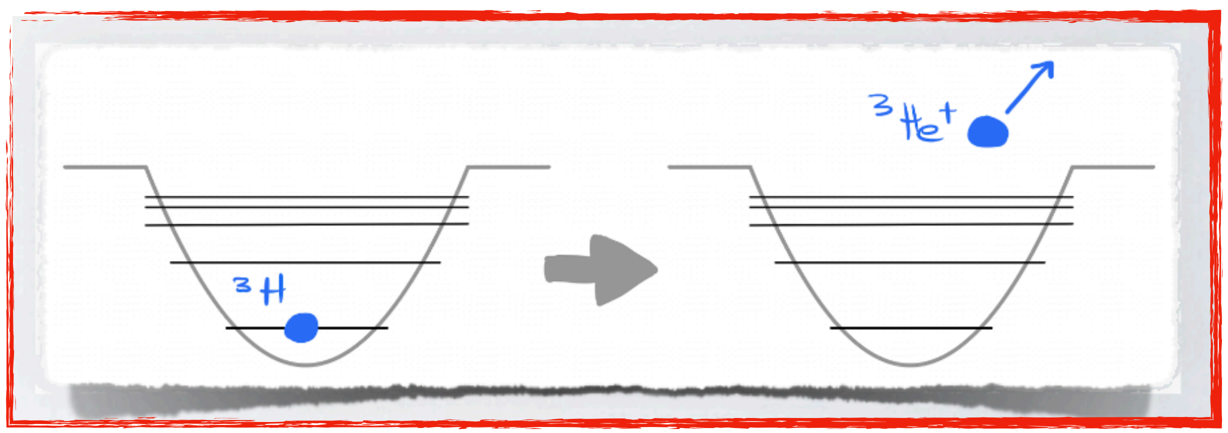
$$\Delta E_e \simeq \left| \frac{\mathbf{p}_e \cdot \Delta\mathbf{p}_T}{E_{He}} \right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T}$$

spread of initial tritium wave function $\left(\Delta x_T \sim 0.1\ \text{Å}\right)$

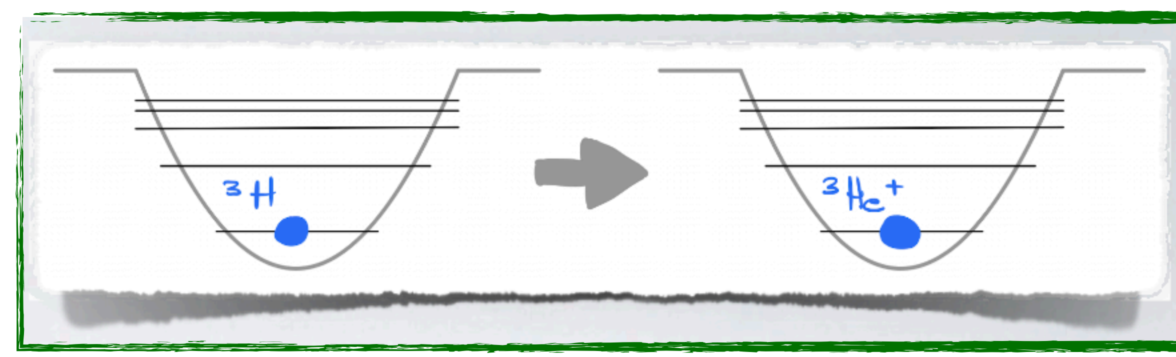
Can be as large as 500 meV

Inside the quantum spread

- Beta decays is very fast, no change in the Hamiltonian
- Two <u>*extreme*</u> cases for the fate of the ^3He (at the beta spectrum endpoint)



^{3}He is totally free



^{3}He stays in the ground state as ^{3}H

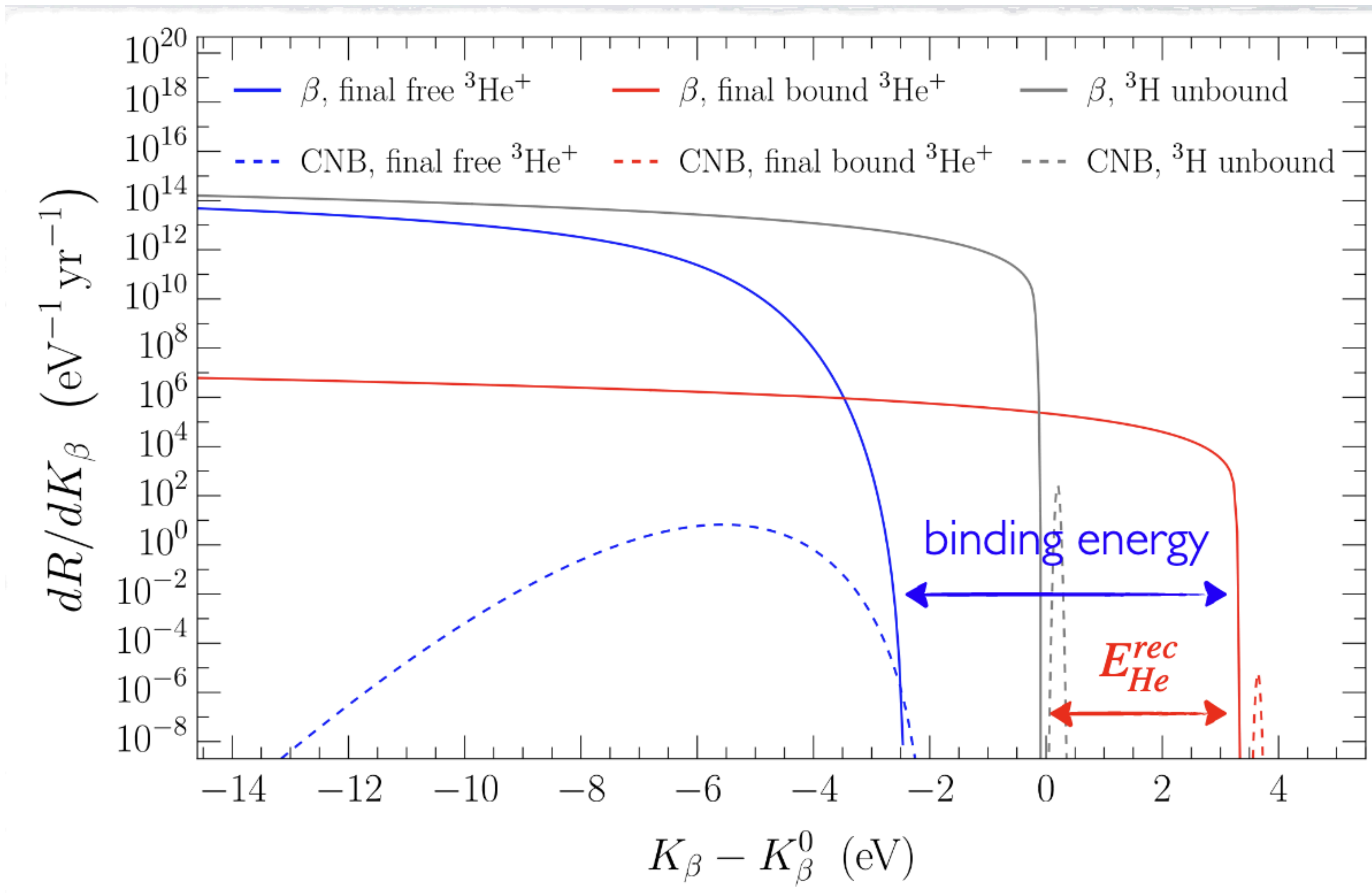
Amplitude process calculation predict momentum spread for the first and exponential suppression for the second

Rate at the endpoint

A.Apponi et al, Phys Rev D 106 (2022) 5,5

- ^3H decay in vacuum compared to the **two** extreme cases (starting with ^3H bound to graphene)

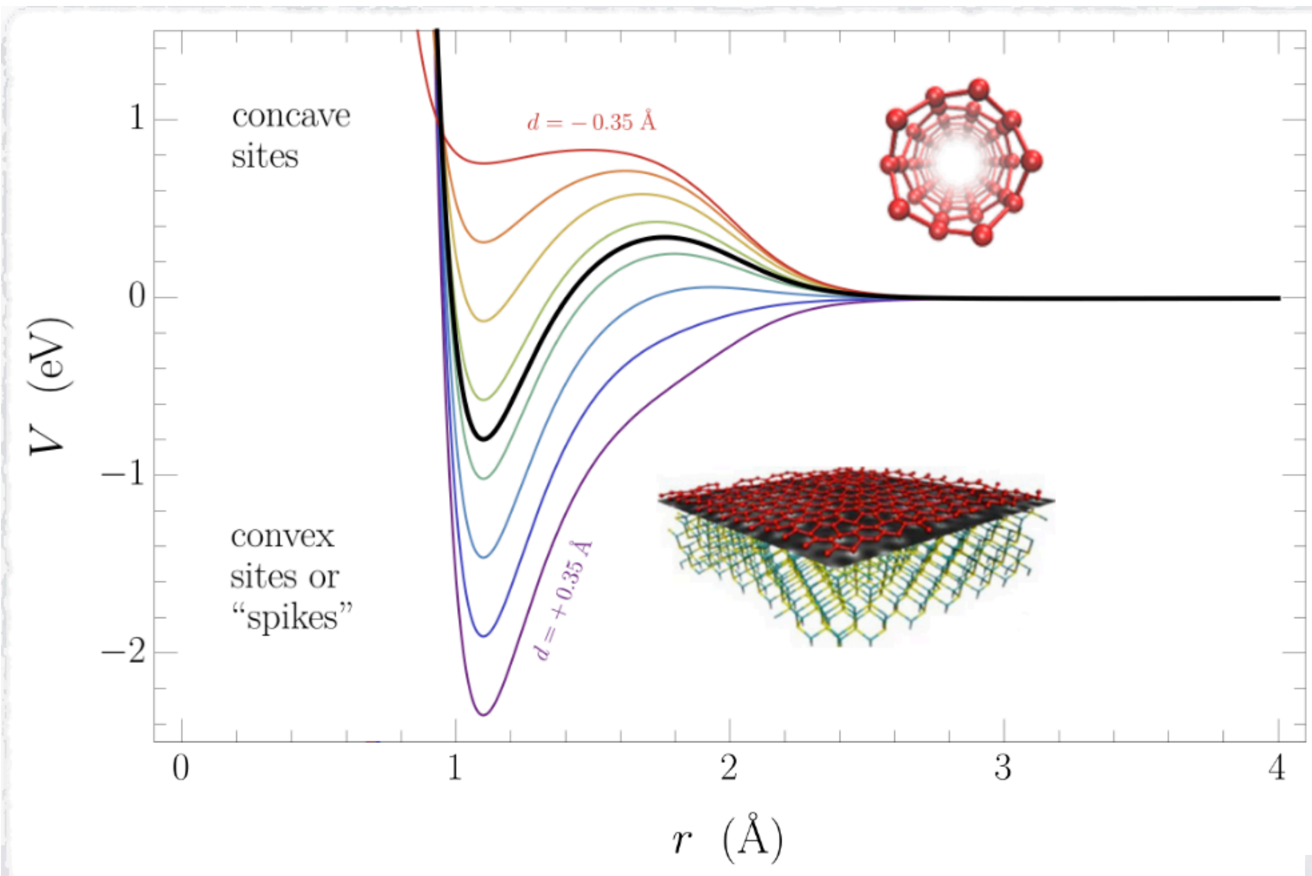
Shift and distortion of the spectrum close to the endpoint



Call for an optimised substrate for tritium

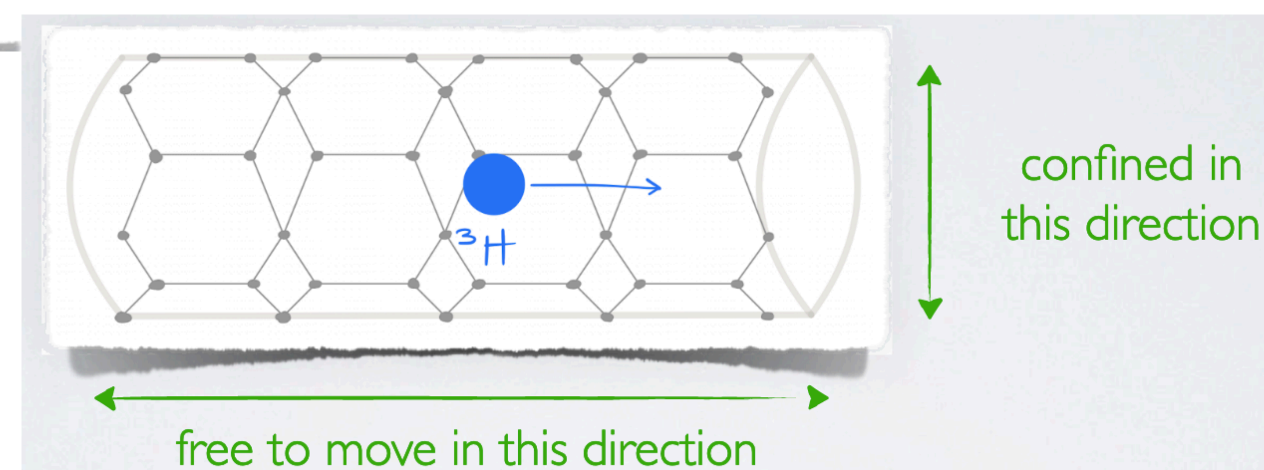
Look at the binding potential

Tritium - graphene potential



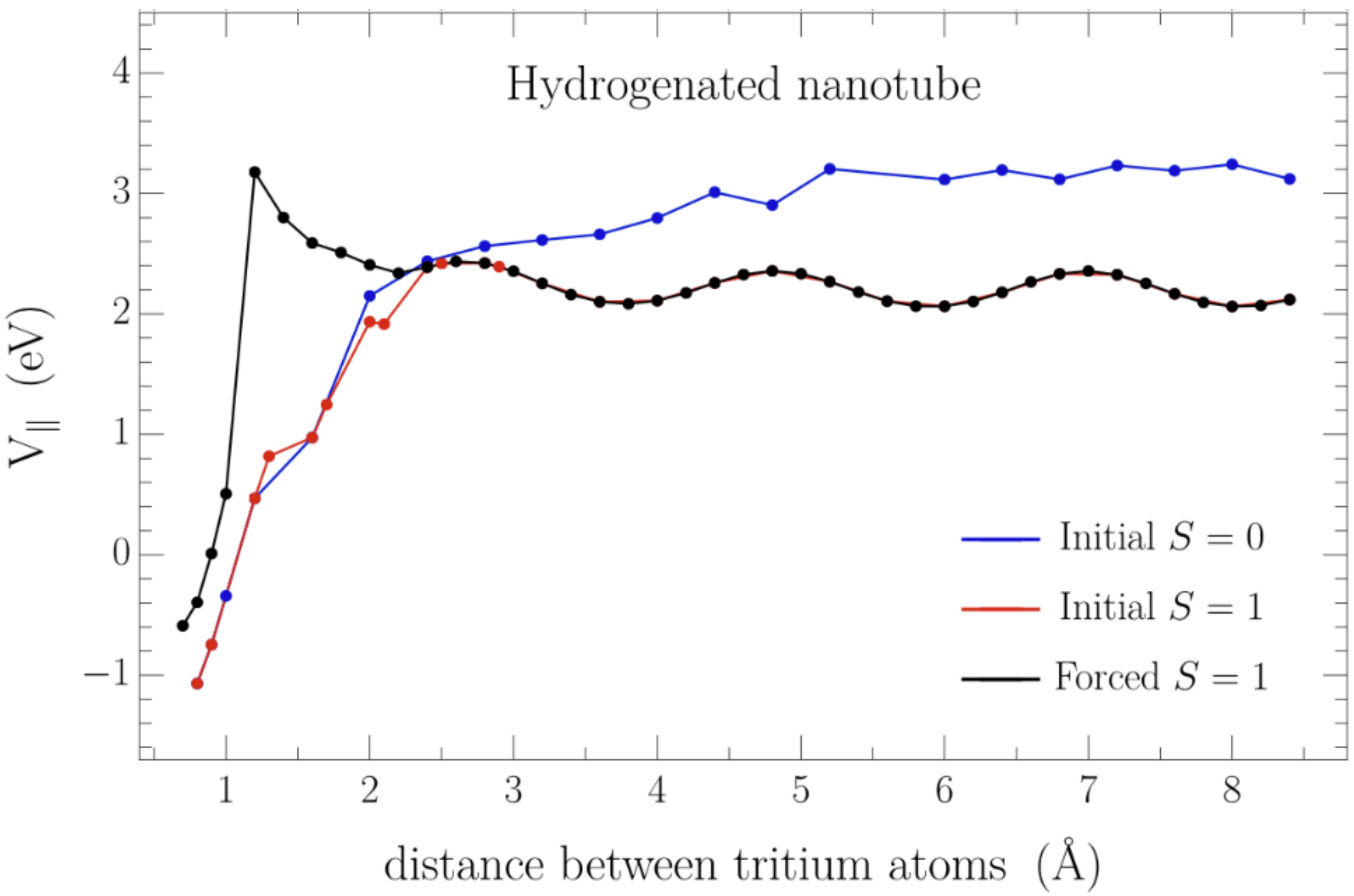
- **Shallower** potential if the binding site is **concave**

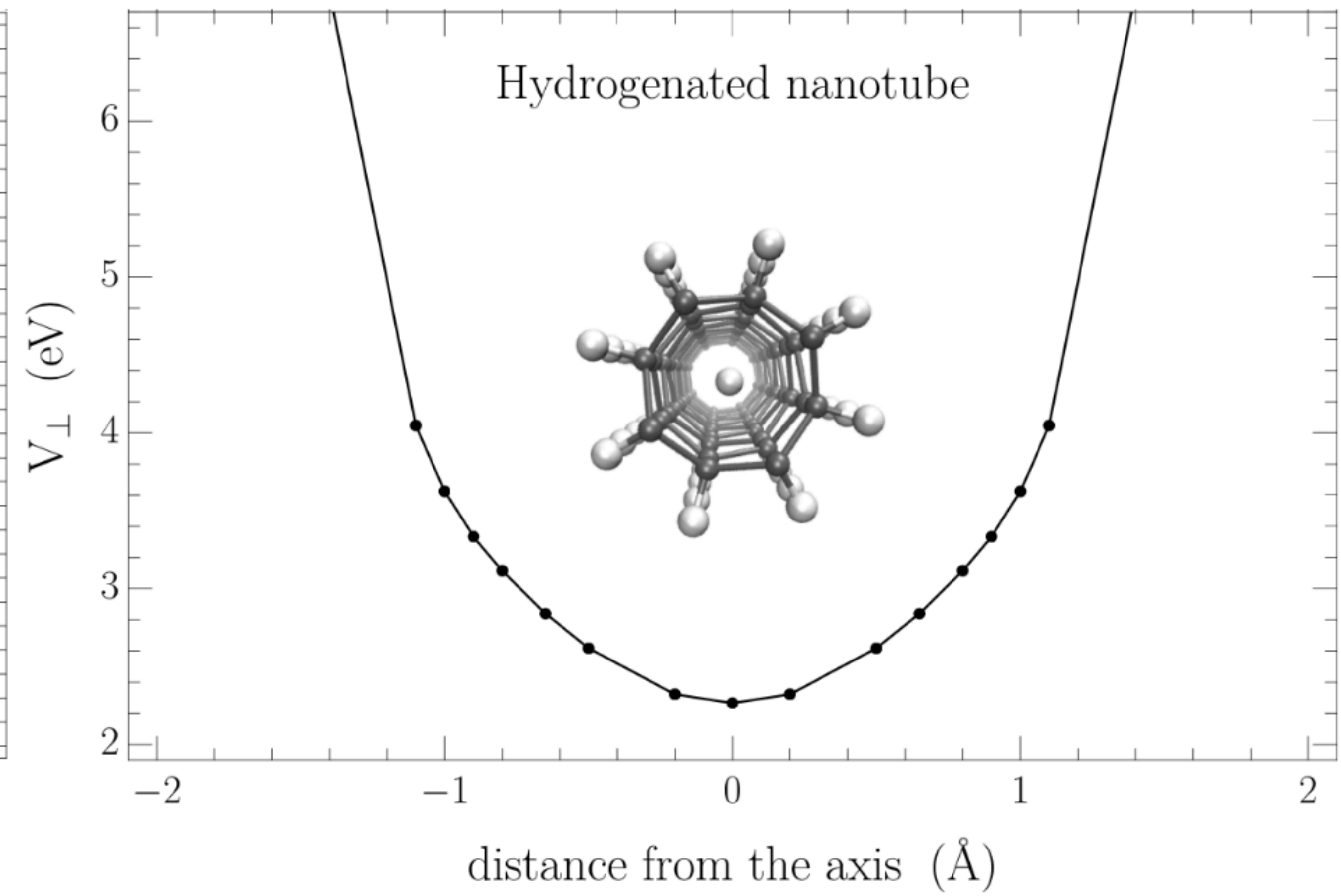
- Substrate with large concavity : a nanotube!



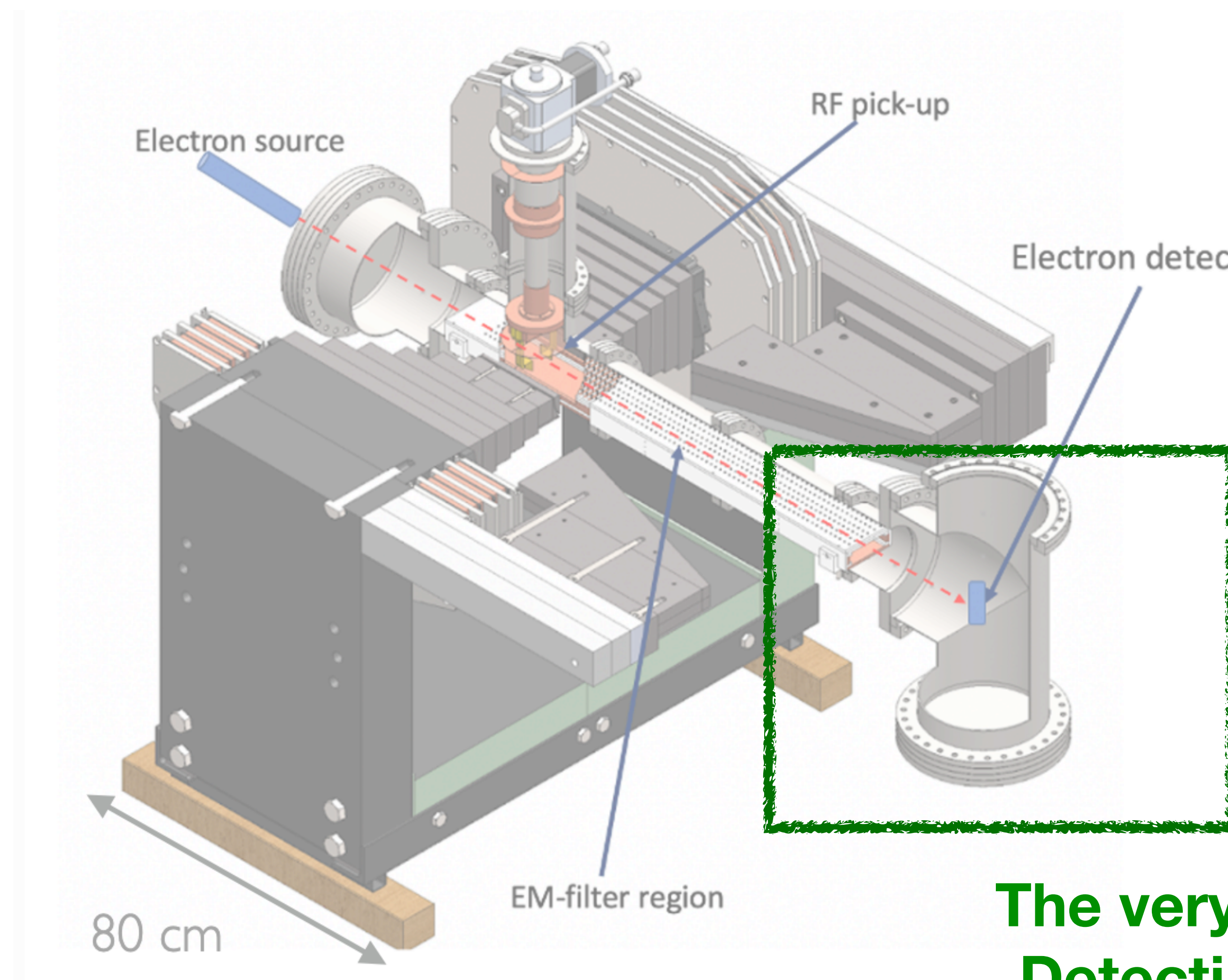
C nanotube for tritium storage

- Hydrogenate CNT to store ***^{3}H*** within the tube





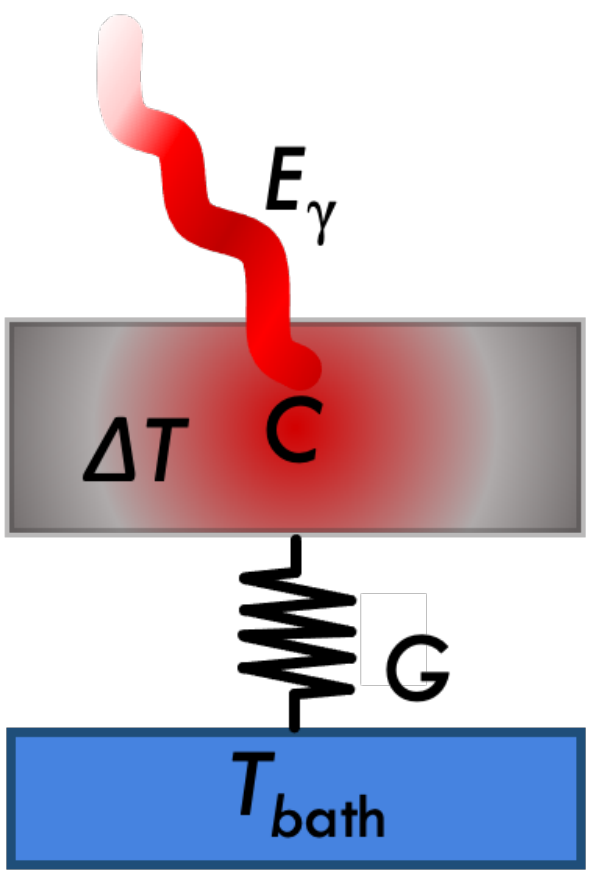
- Role of external B field to prevent dimerisation



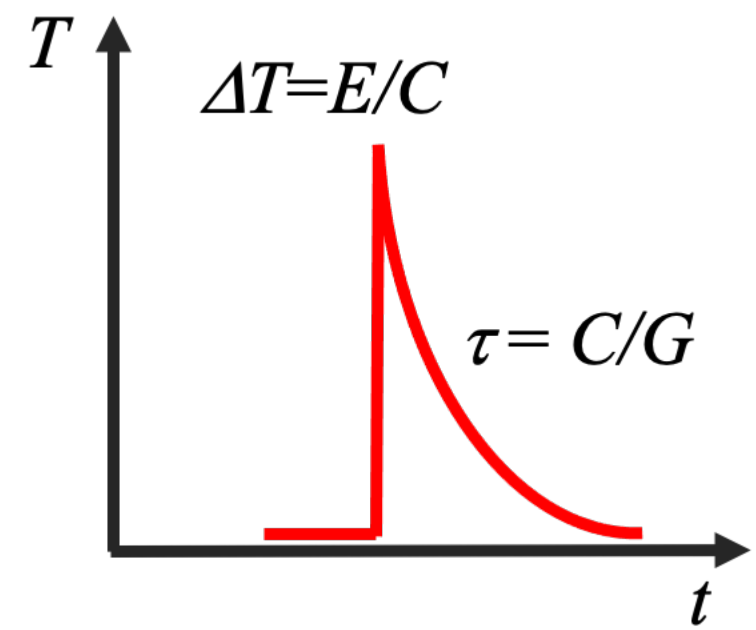
The very end of the filter, Detecting the surviving electrons (close to the endpoint)

Detection with cryo-micro-calorimeters

- Transition Edge Sensors (TES) technology
  - Developed for photon sensing
  - Increase in **temperature** measures **deposited energy**



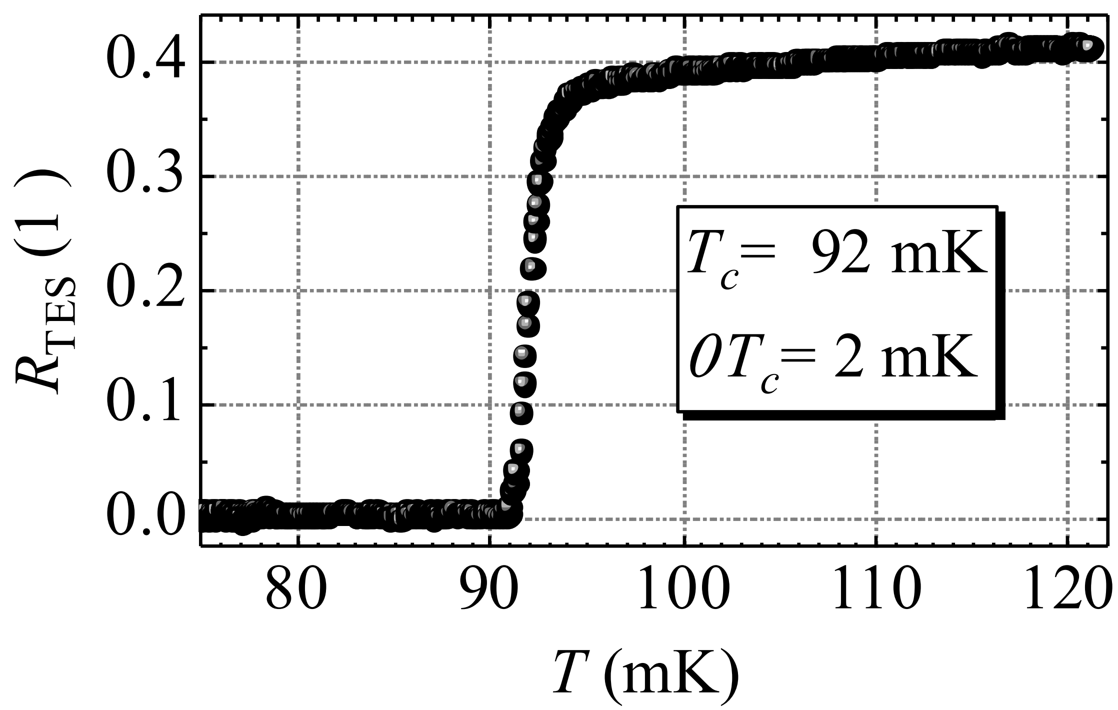
C: thermal capacitance
G: thermal conductance

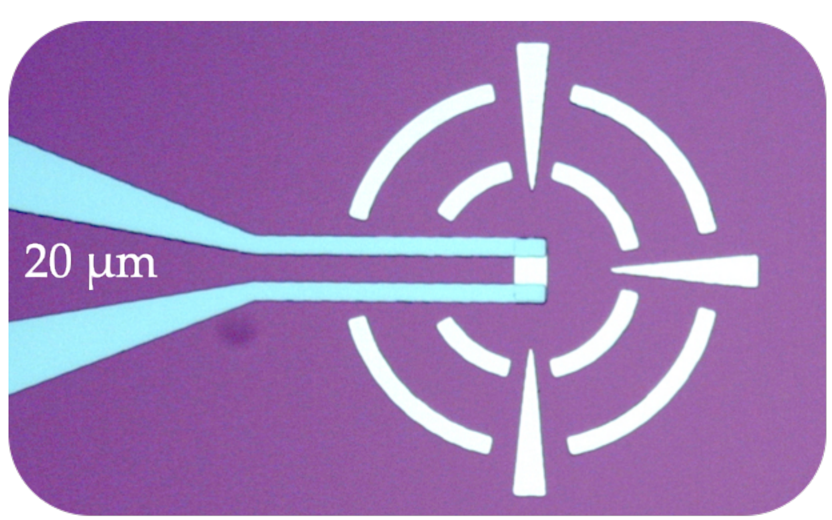


$$\Delta E \approx (k_B T^2 C\, B)^{\frac{1}{2}}$$

Energy resolution: better at low T and small C

Superconductors detectors

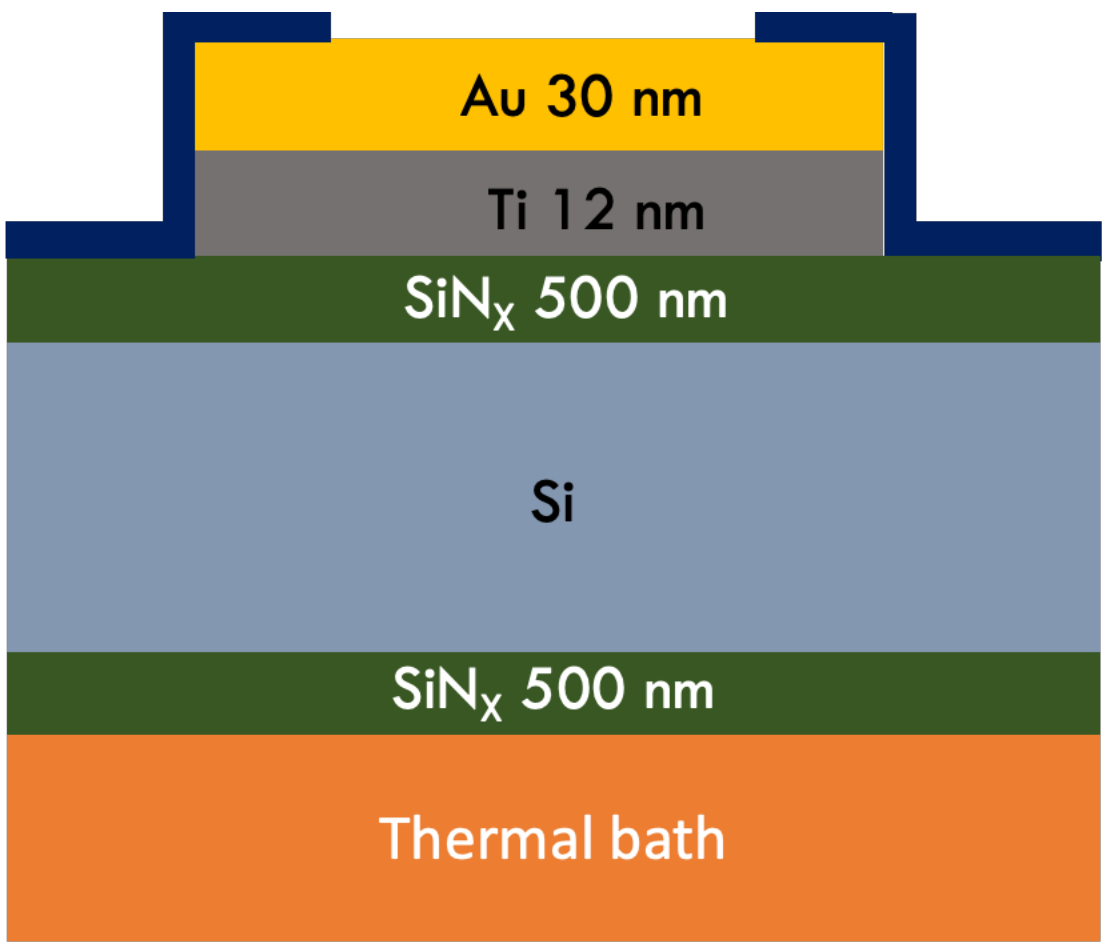


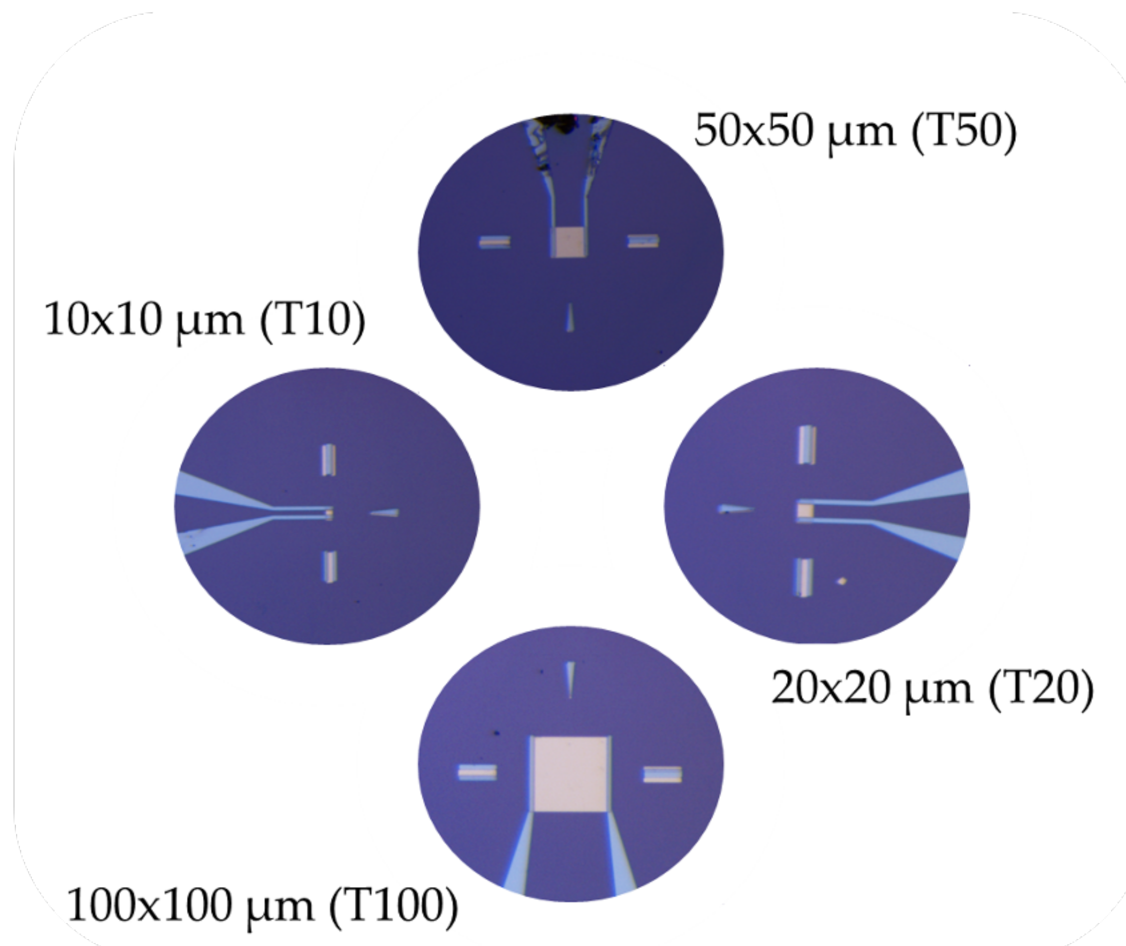


- Operate a **superconductive metallic nano-film** close to the phase-transition temperature
  - Small increase of the temperature, drop the bias large current, very **steep** response
  - SQUID current readout
  - Various applications: X-ray, telecom, astrophysics, QT, …

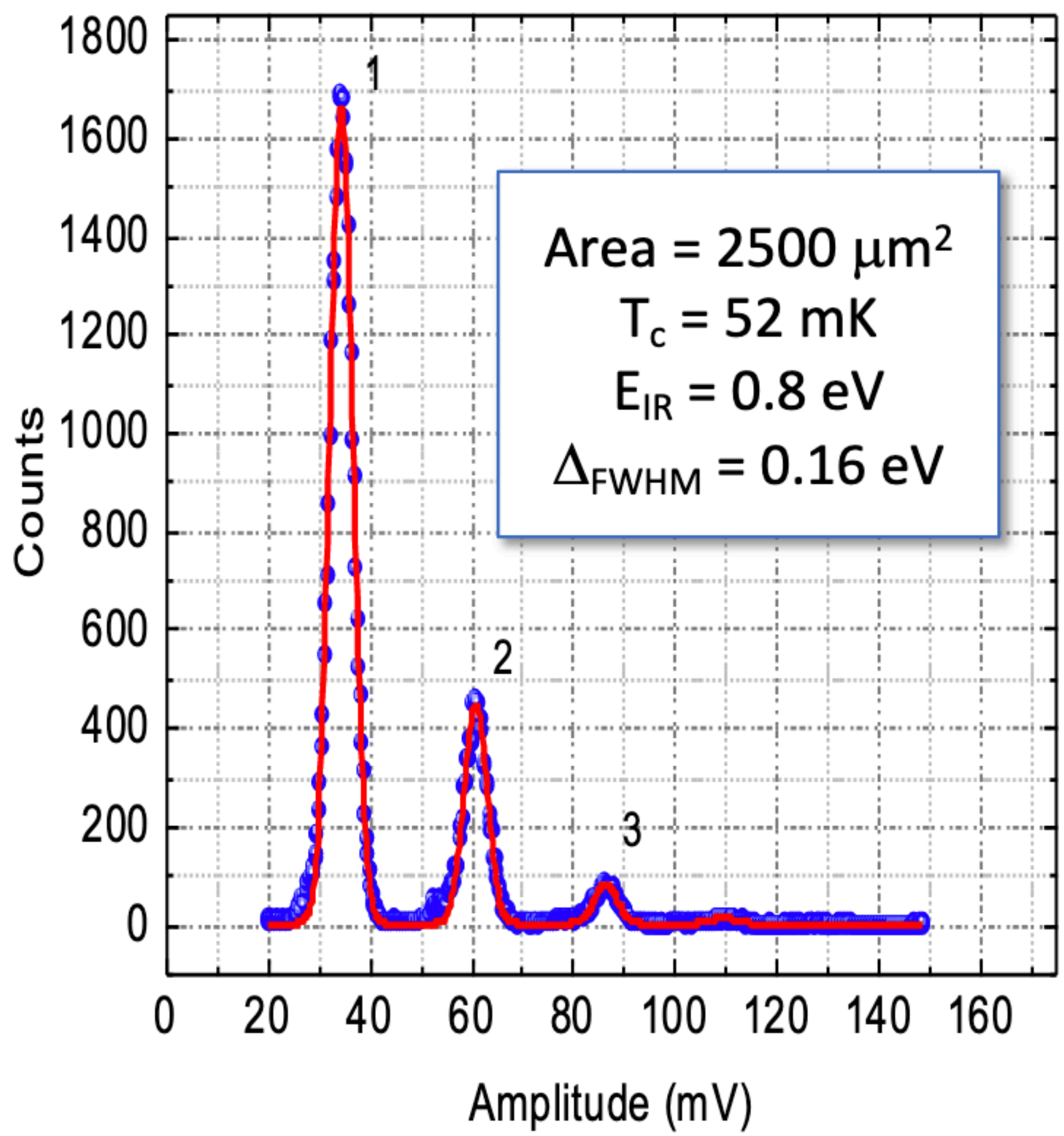
TES for Ptolemy

- Aim at **large** (~1 cm²) sensors, array of TES sensors (with **multiplexed** readout)
- **Port** TES to detect very low energy **electrons**



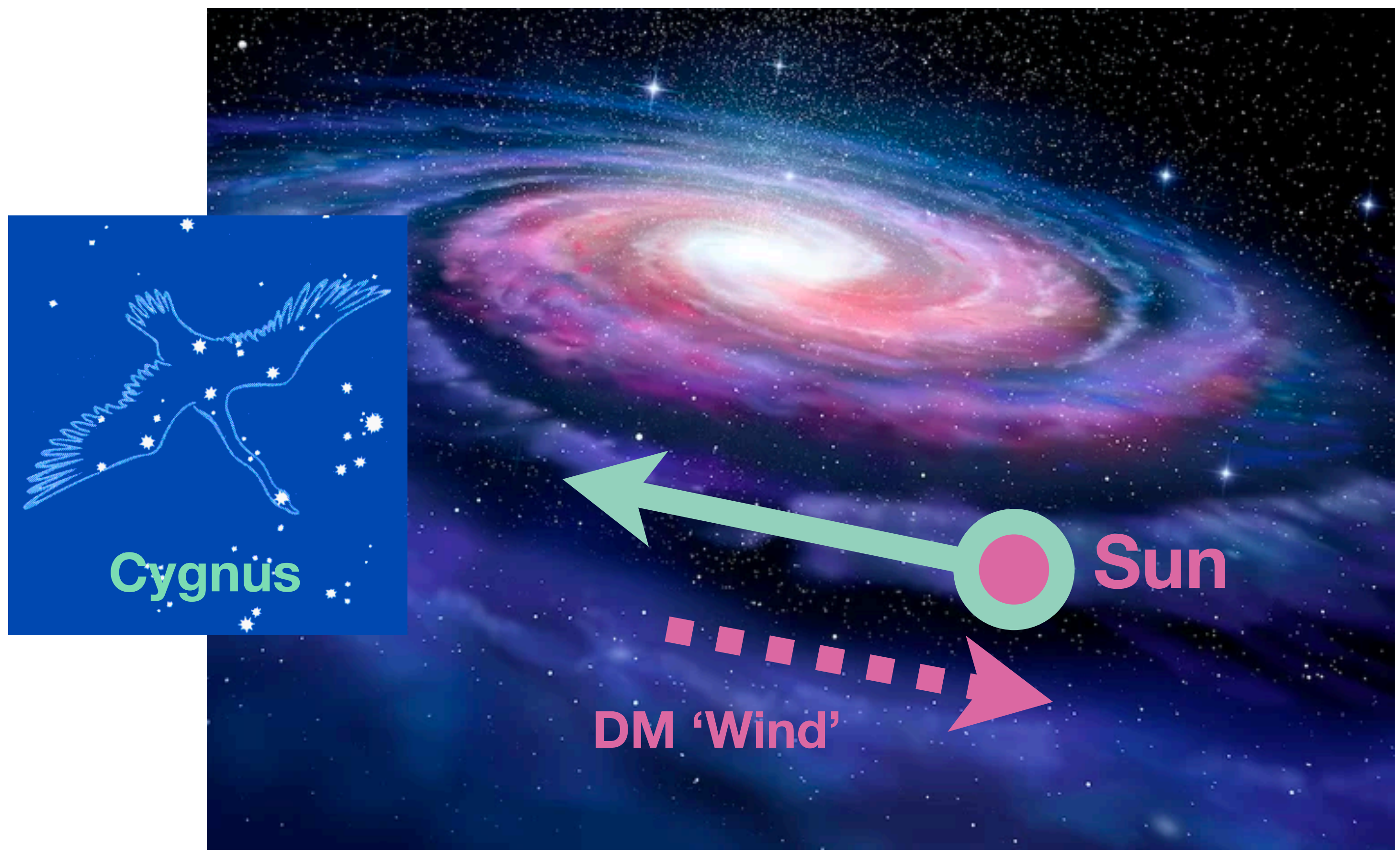


TES tested with photons



- Counting of infra-red photons (0.8 eV) very successful
- Scaling to a smaller area 15x15 μm² (i.e. smaller capacitance) predicts 50 meV FWHM energy resolution

Next **challenge**: demonstrate **electrons** can be **absorbed** and detected



G.Cavoto, et al., EPJC 76 (2016) 349

L.M. Capparelli, et al., Phys. Dark Universe, 9-10 (2015) 24

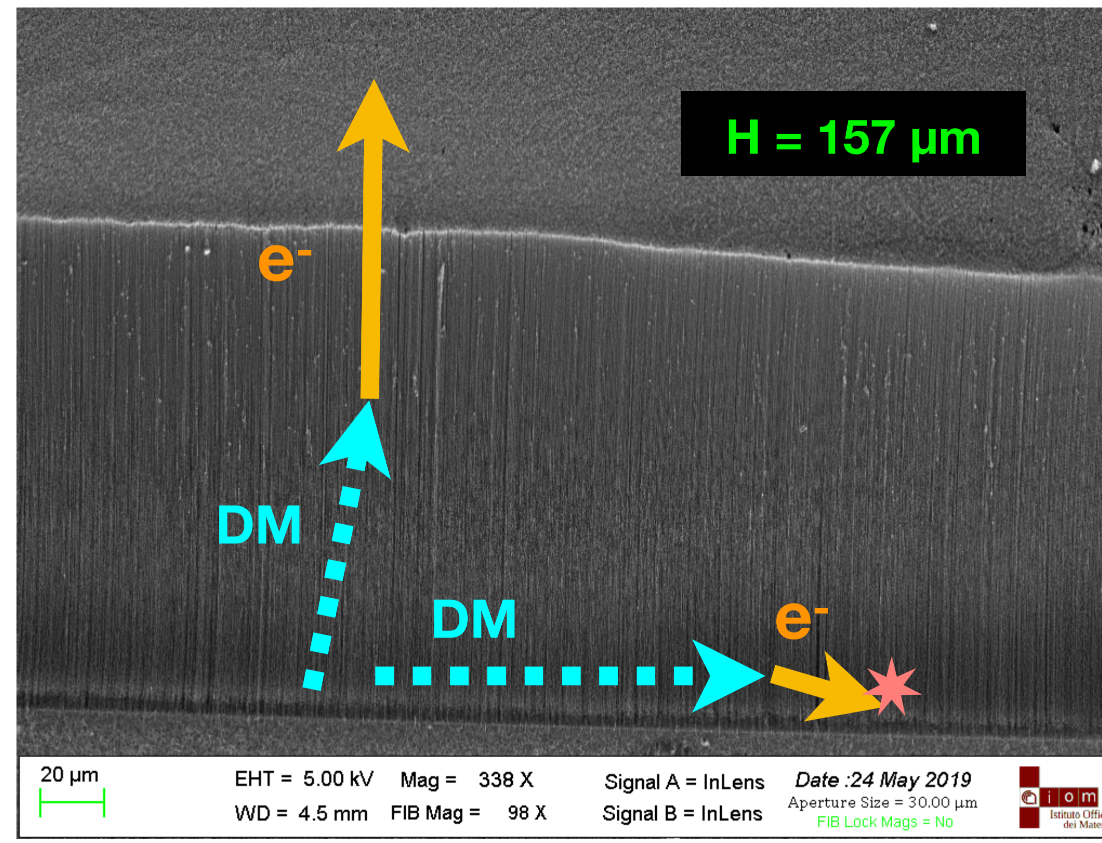
Vertically aligned CNT

G.D'Acunto et al, Carbon 139, 2018, 768-775

- Forests of CNT can be easily grown aligned
- They are naturally ***anisotropic***

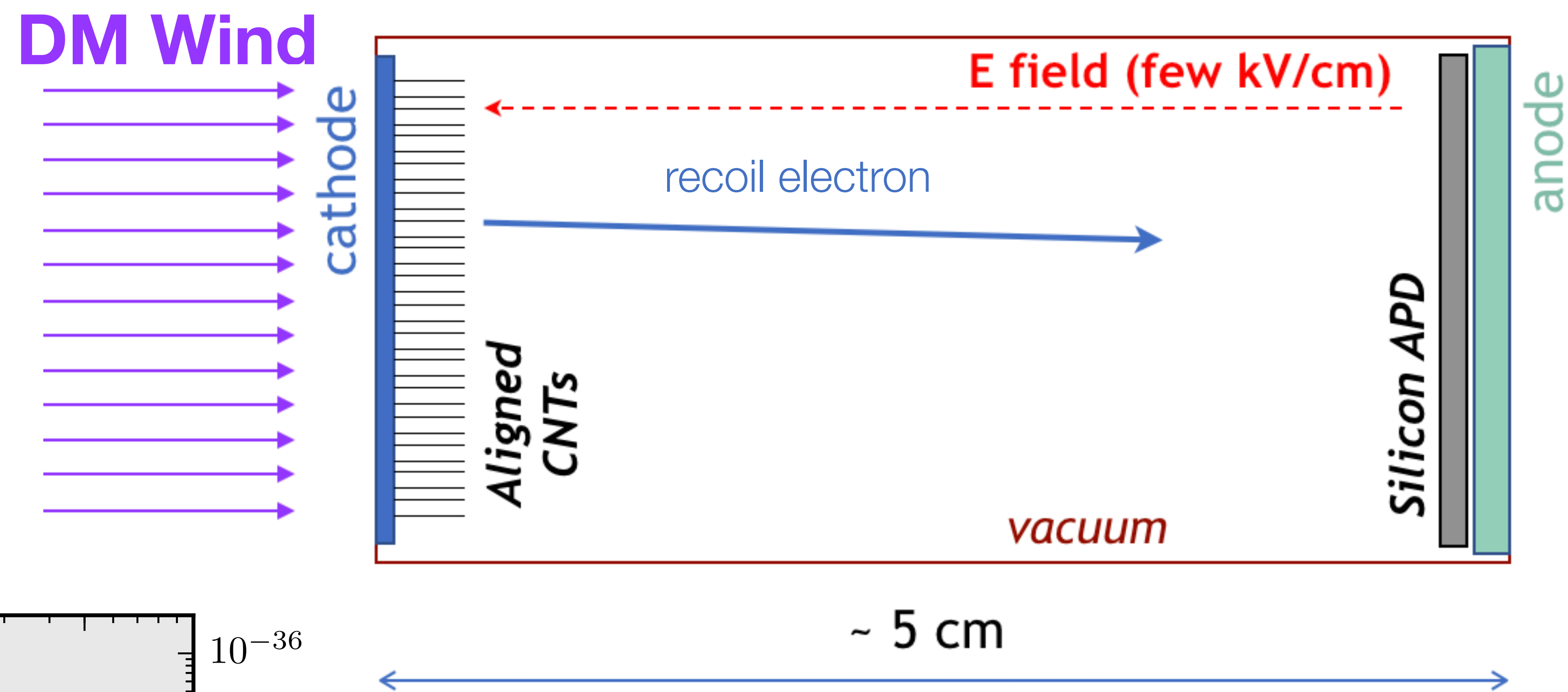
- DM can interact with electron
  - Kinematics favours $M_{DM} \ll$ GeV

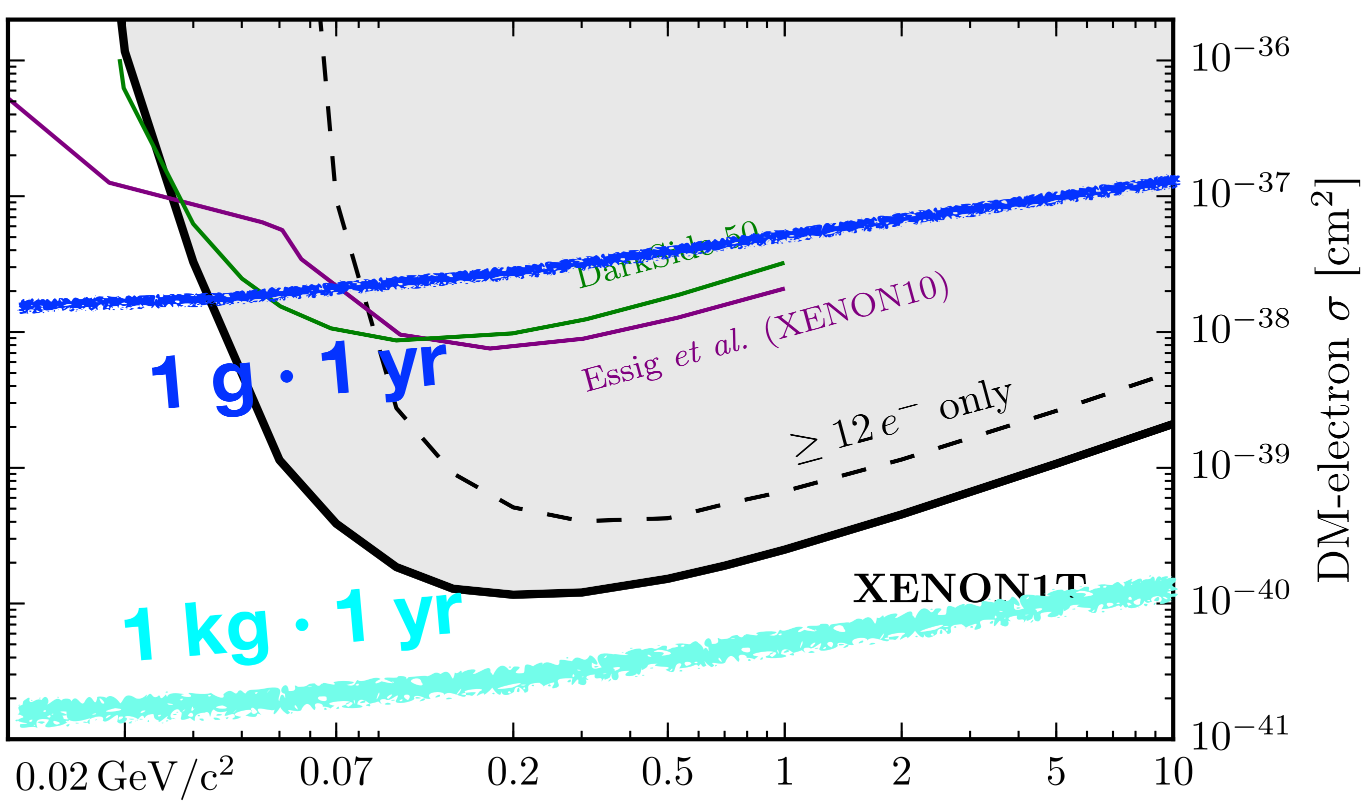
- Electron can be expelled by the forest if DM aligned with the tubes
- *Directionality*



The Andromeda project

- Build a prototype of a hybrid “dark-PMT” to detect electrons from CNT



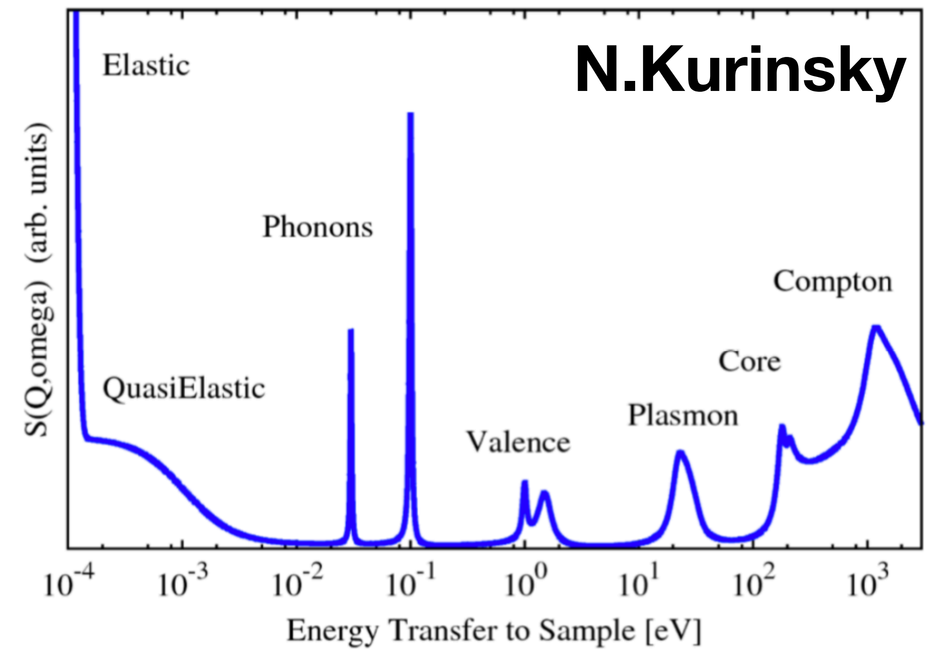


- Even 1g target mass competitive
- Background rejection with directionality

G. Cavoto, et al., PLB 776 (2018) 338

Some thoughts on new detectors

- Exchange between particle physics and condensed matter physics is a great opportunity in the realm of **new sensors** development.
- Especially true in the range of “low energy” particle physics
- Details of **physics at atomic-subatomic scale necessary** to understand a particle detector



Interaction with **theorists** is of paramount importance
Sometime you get difficult to implement) ideas

But out of 10 (?) crazy ideas you get a **bright bold one**

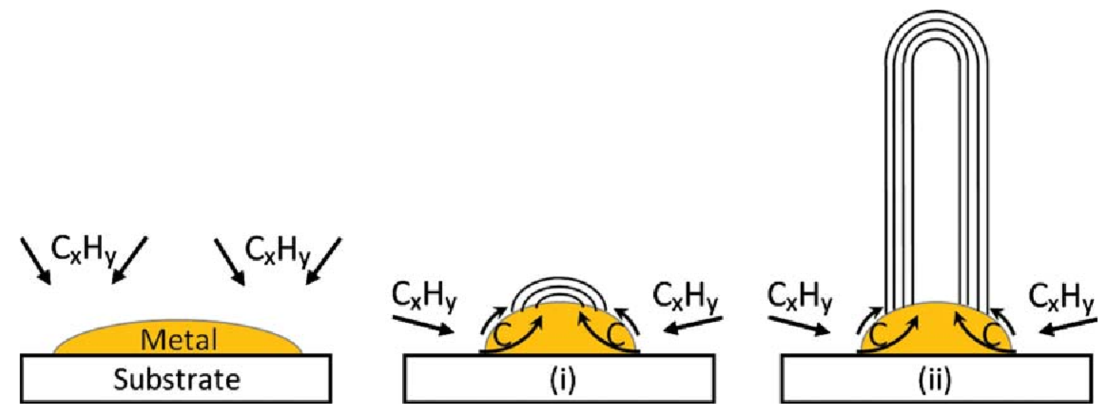
Outlook

- Cosmic neutrino background detection requires **bold** new ideas
  - Ptolemy aims at demonstrating a concept of a **compact** e.m. filter with **atomic** tritium on a **solid** substrate and cryogenic **calorimetry** to reach a **50 meV energy resolution.** Cyclotron radiation detection used as trigger
  - **Engineering** of the initial quantum state can be a way to store atomic tritium, **carbon nanostructure** seems promising
  - Advancing in nano-film fabrication and **surface** characterisation necessary for electron detection with TES
- **Scaling** of the detector concept to large masses still a challenge.
  - Superconducting magnets likely to be necessary

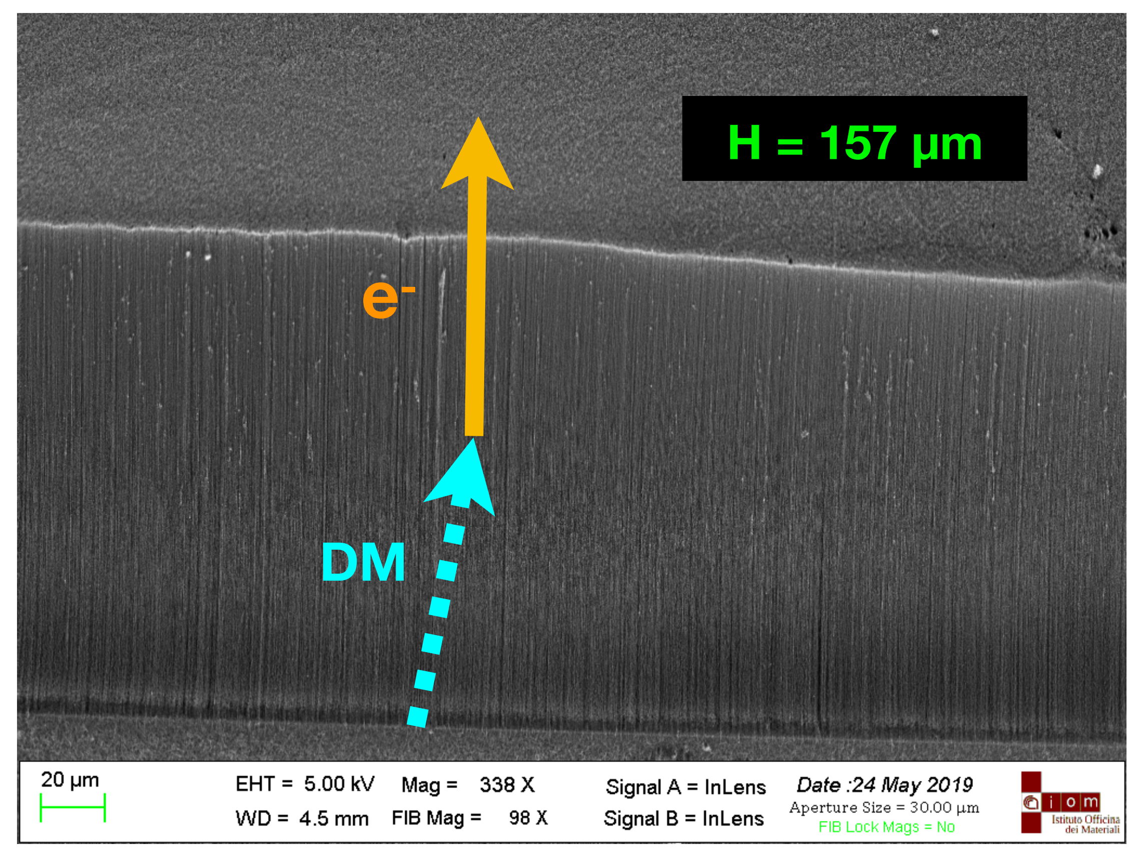
Additional slides

Growing vertically aligned CNT

- **Carbon nanotubes** synthesized through Chemical Vapor Deposition (CVD)
  - Internal diameter ~5 nm, length up to 300 µm
  - Single- or multi-wall depending on growth **technique**

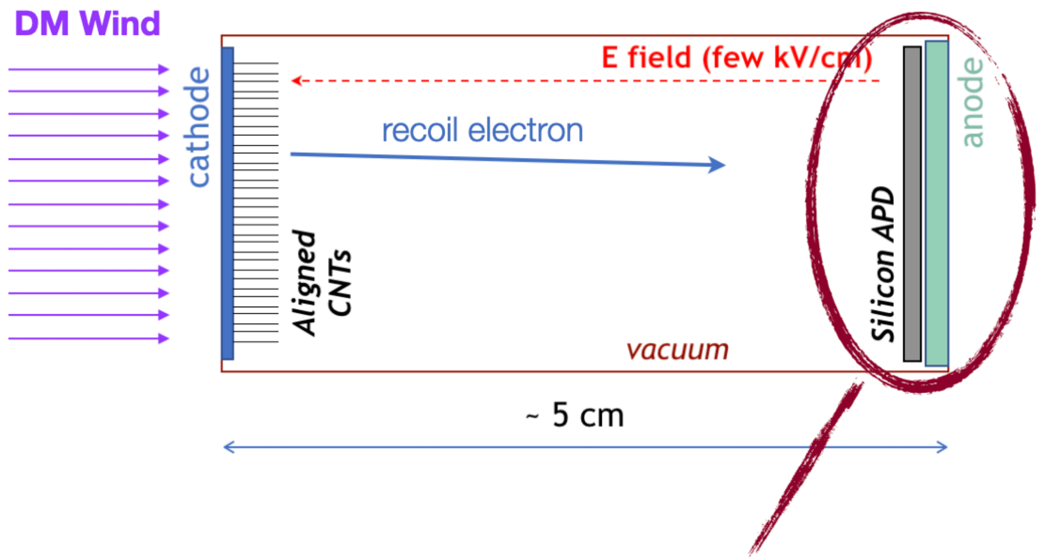


- Result: vertically-aligned nanotube 'forests' **(VA-CNT)**
  - **'Hollow'** in the direction of the tubes
  - Electrons can **escape** if **parallel** to tubes
  - Makes it an **ideal** light-DM target



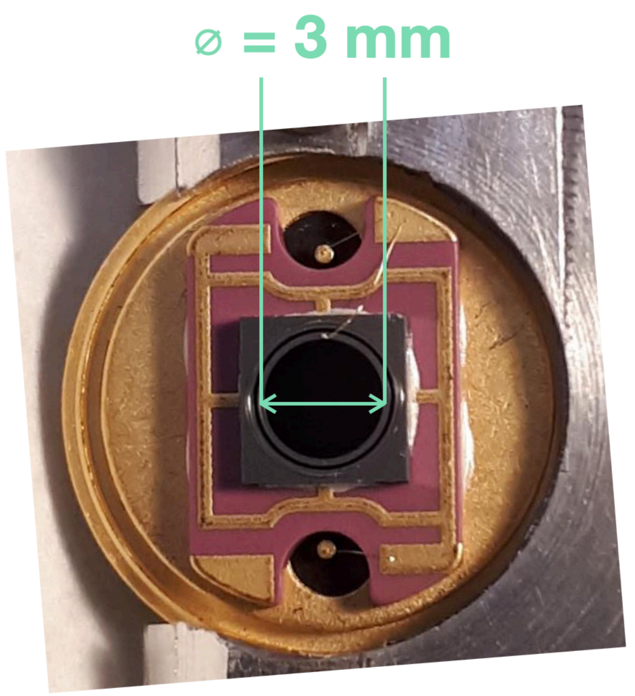
Silicon detectors for keV electrons

APDs and SDDs 'born' as photon detectors

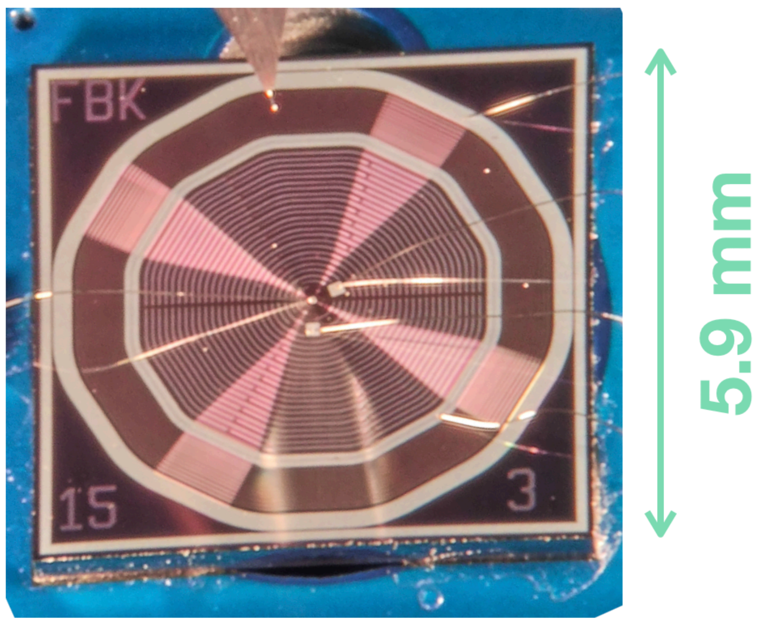


Challenge: detect keV electrons (with high efficiency)

- Benchmark: **Avalanche Photo-Diodes**
  - Simple, cost-effective
  - Hamamatsu windowless APD



- Possible upgrade: **Silicon Drift Detectors**
  - Ultimate resolution
  - FBK (SDD) + PoliMi (electronics)



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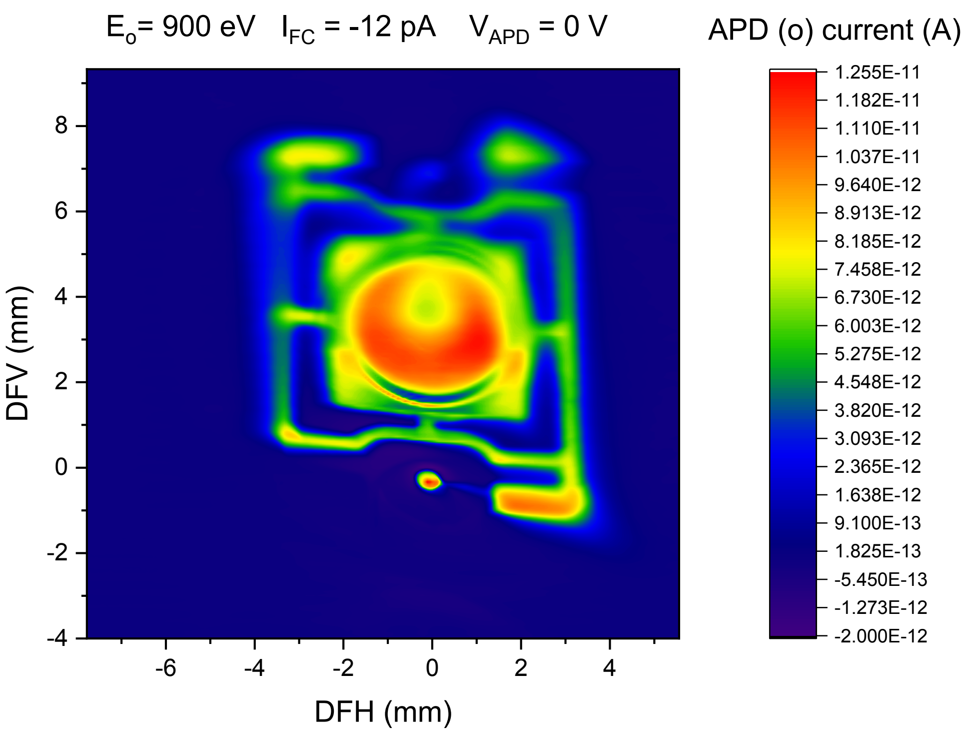
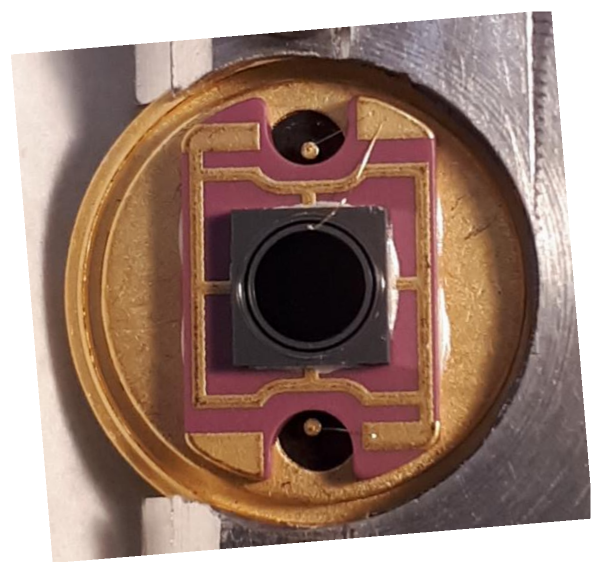
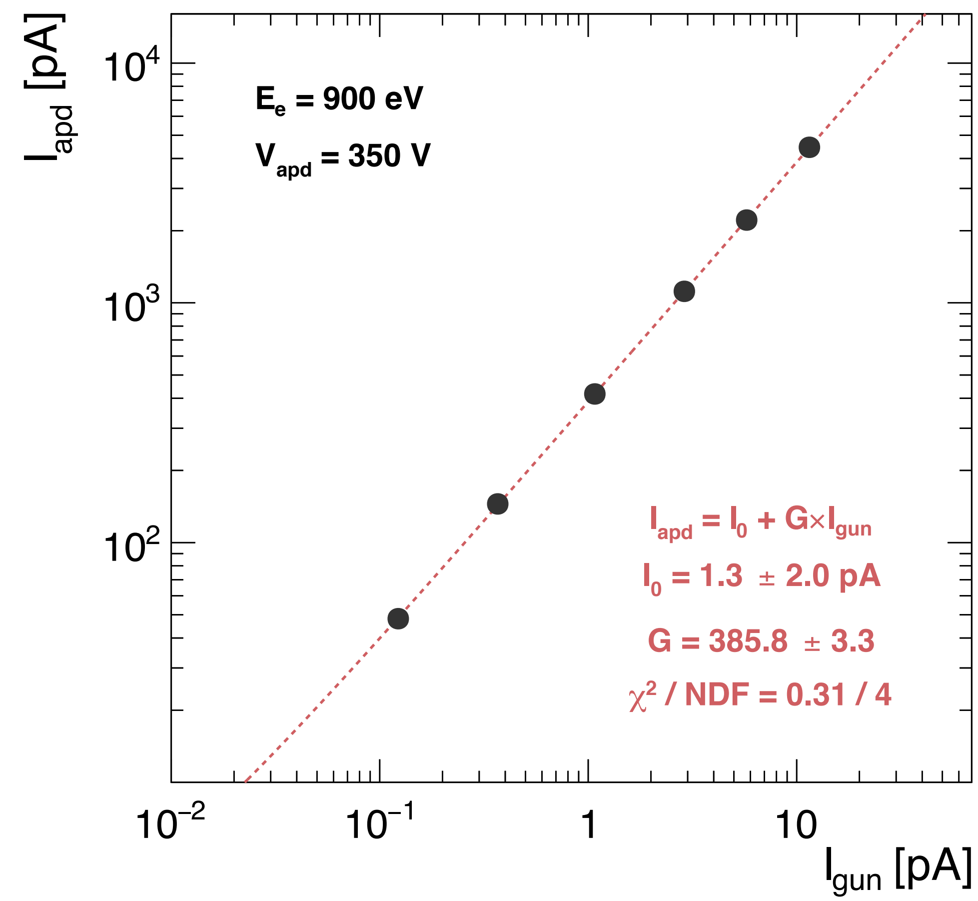
APD and 900 eV electrons

A. Apponi et al 2020 JINST 15 P11015

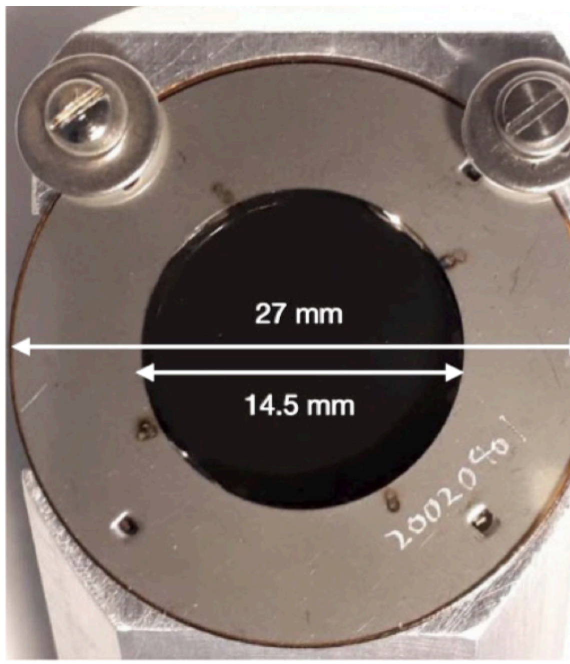






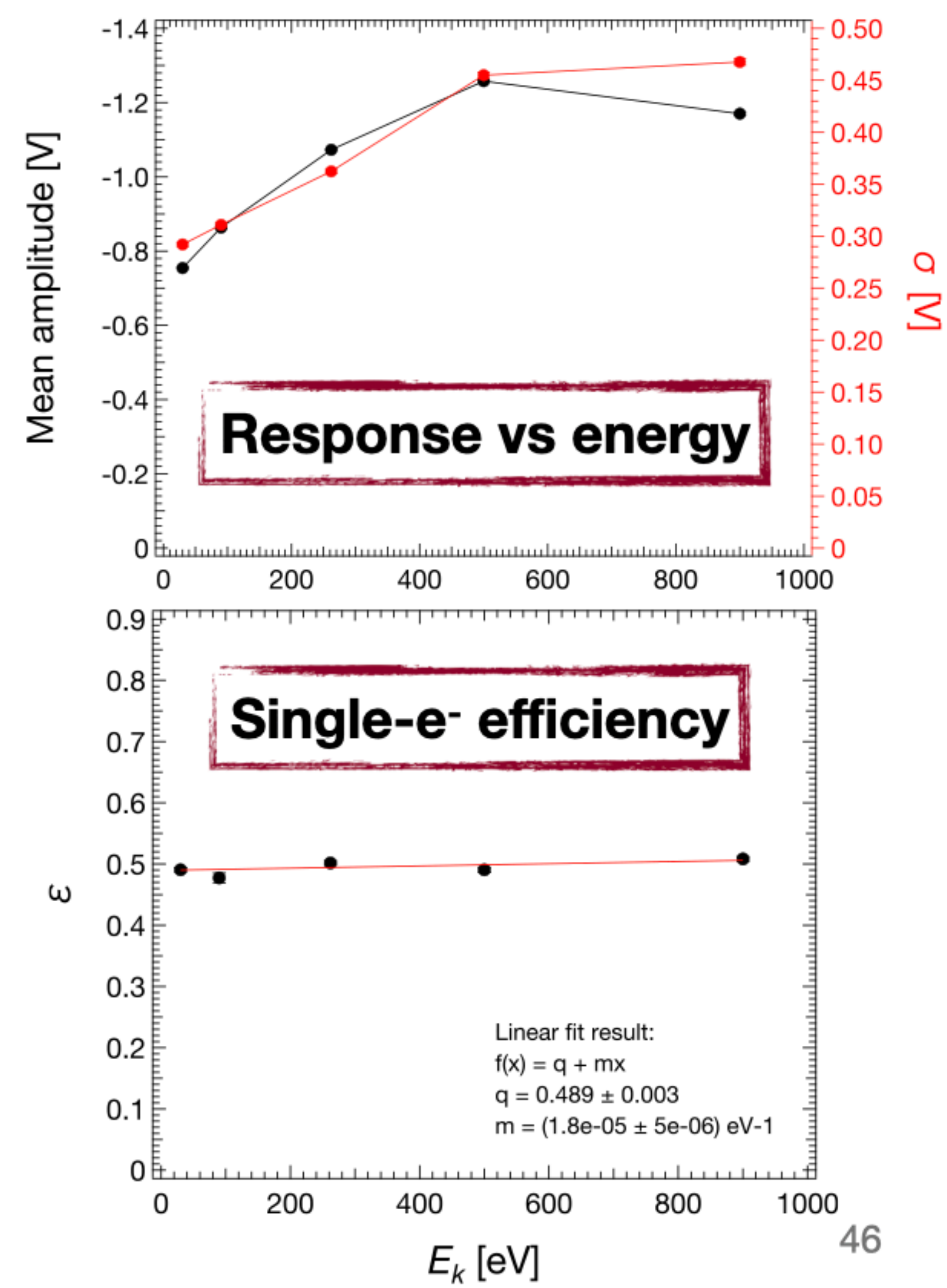
- Reading APD bias current when shooting gun on it
  - $V_{apd} = 0$: electronic ‘image’ of APD
  - $V_{apd} = 350$ V: I_{apd} **proportional** to I_{gun}

Alternative to silicon: Multi-channel plates



- **Established** detector for low-energy electrons
  - But **bad** energy resolution
- **Extensive** MCP characterization @ LASEC
  - $30 < E_e < 900$ eV
  - Very **mild** energy dependance
  - Single-e⁻ absolute **efficiency** ~ 49%

A. Apponi et al, Meas. Sci. Technol. **33** (2022) 025102



Gianluca Cavoto