Carbon nanostructures for neutrino physics, the Ptolemy experiment

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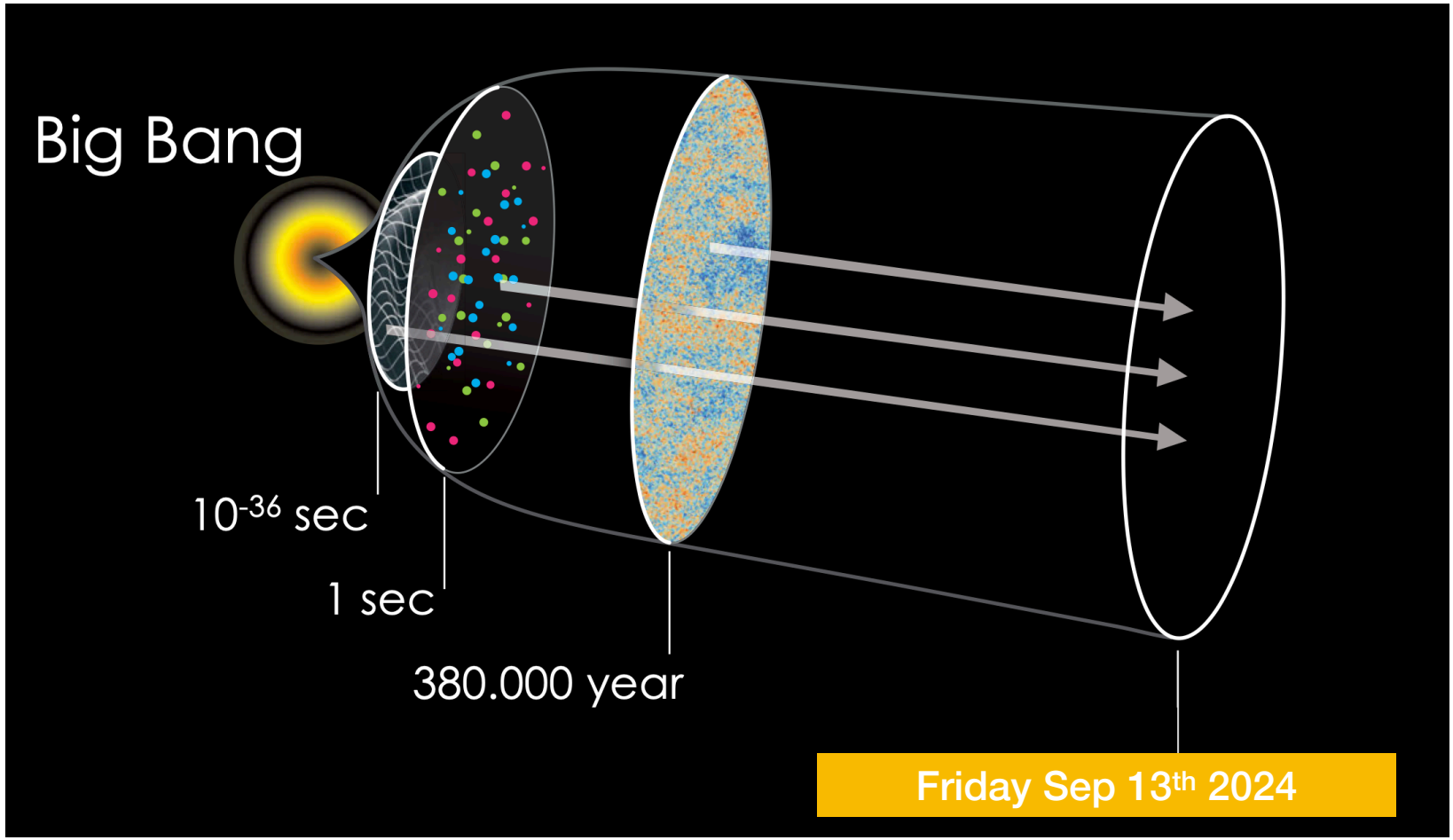
Channeling 2024 - Riccione

Outline

- The **neutrino cosmological background** (Cν**B**), the (absolute) neutrino **mass** measurement.

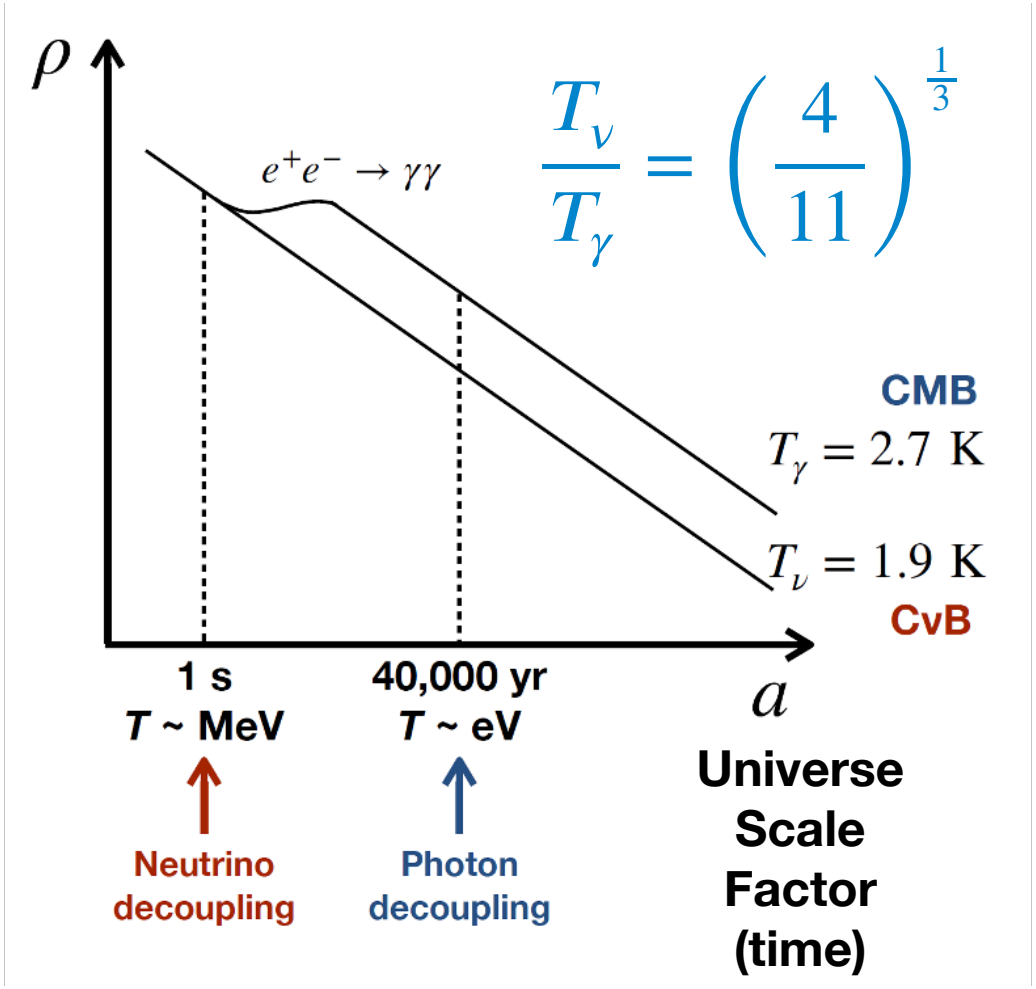
- The **Ptolemy** project
  - A novel type of electro-magnetic **filter**
  - **Advanced** detection concepts (nano-fabricated transition edge sensors, very low power radio-frequency detection)
  - A Tritium target based on **carbon nanostructure**

The history of Universe in short



- What happened 1 sec after the Big Bang??

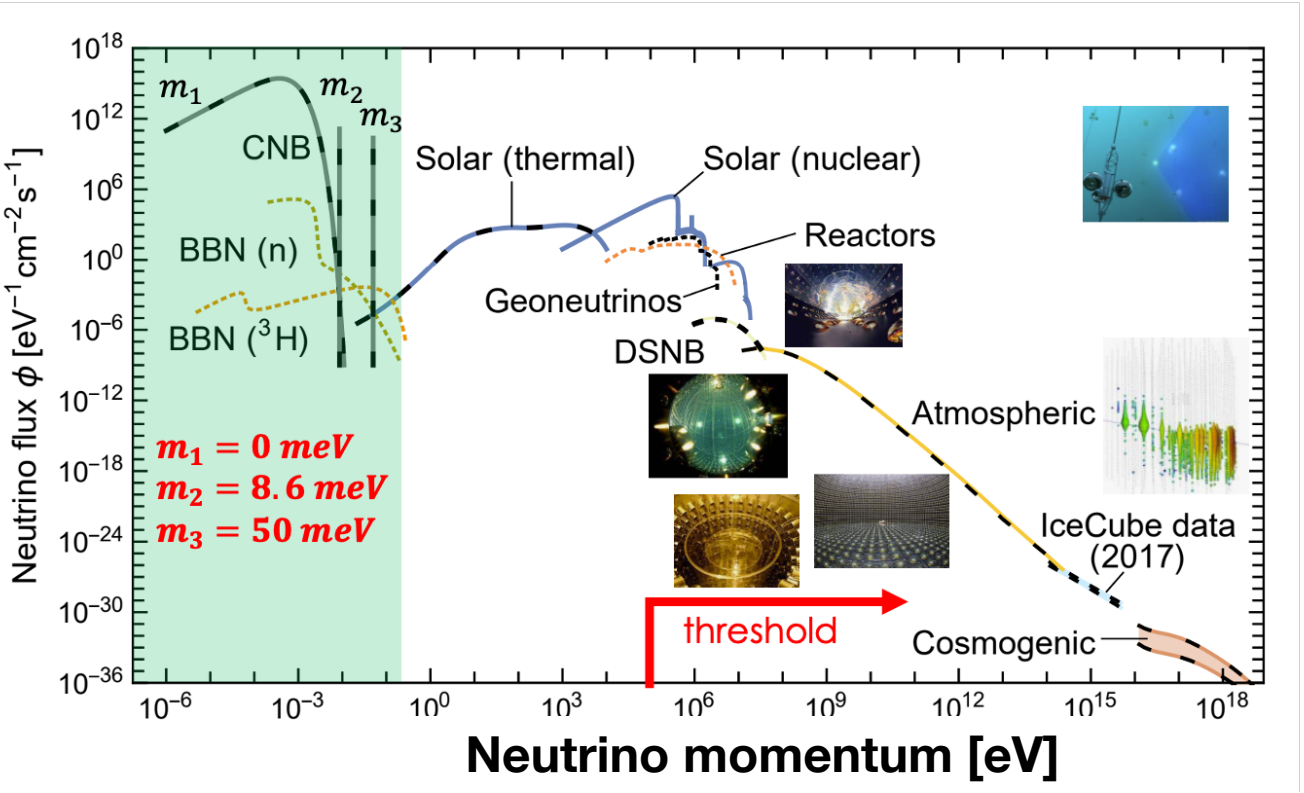
Neutrinos decoupling



- Primordial universe in (local) thermal equilibrium
  - If a reaction rate **Γ** is *less* than Universe expansion rate **H**, a particle/radiation species can "decouple"
  - Spectrum determined by its temperature at that time

The cosmological neutrino background

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

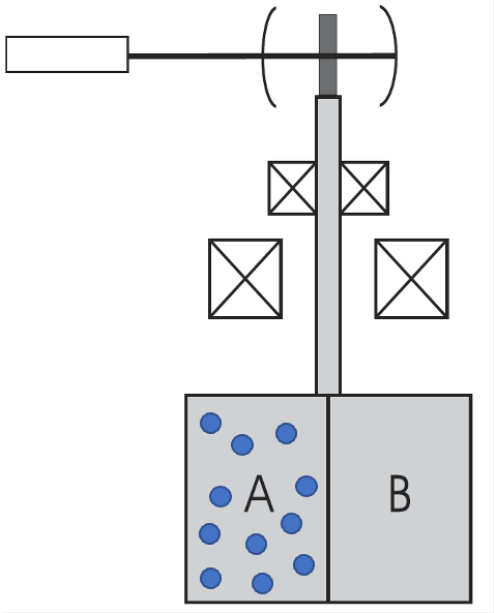


https://arxiv.org/pdf/1910.11878.pdf

A long sought messenger…

- Several **attempt** to **propose** a detection of (neutral) particle with minuscule momentum

Torsion balance



  - Neutrino wind: **coherent** scattering
    - Need to measure a very small acceleration
      $O(10^{-27}\ cm/s^2)$
      but with (GW) laser interferometry
      $\sim 10^{-16}\ cm/s^2$

https://arxiv.org/abs/hep-ph/0107027

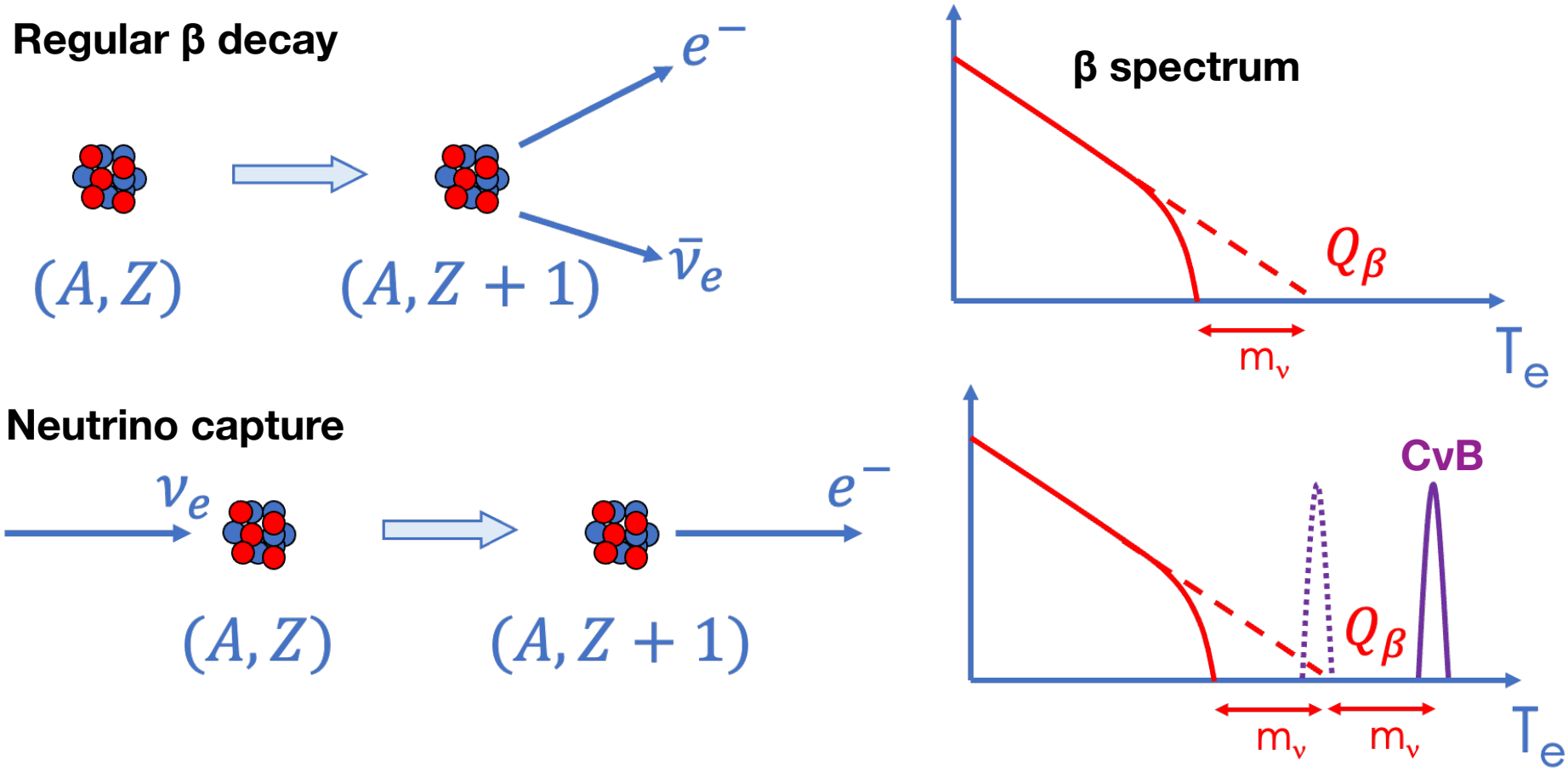
https://arxiv.org/abs/2109.07482

https://arxiv.org/abs/1703.08629

And more:
- Interaction with high energy neutrinos
- Ion storage ring
- Superconductors,
- ….

Capture on radioactive nuclei

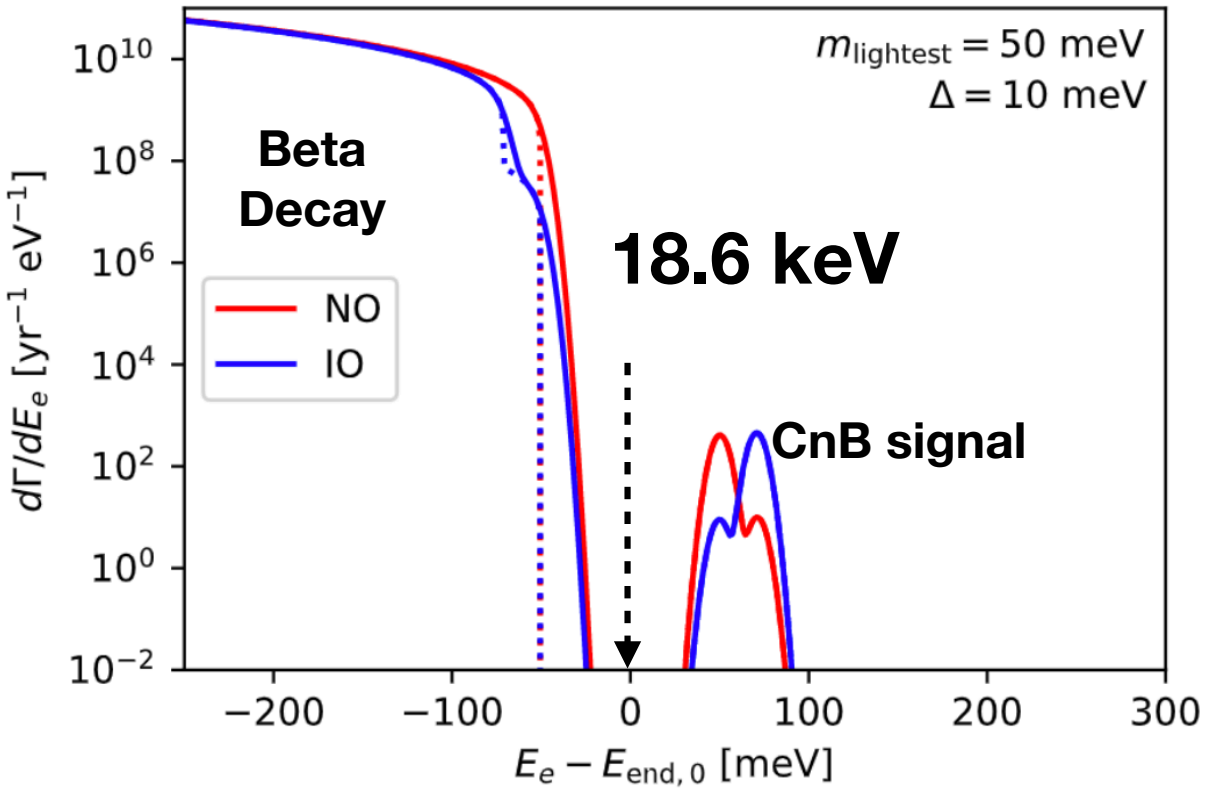
- Weinberg (1962)
- Revived more recently: Cocco, Mangano, Messina (2007)



The target, atomic tritium ^3H

Ptolemy Coll, M.G.Betti et al. JCAP 07 (2019), 047

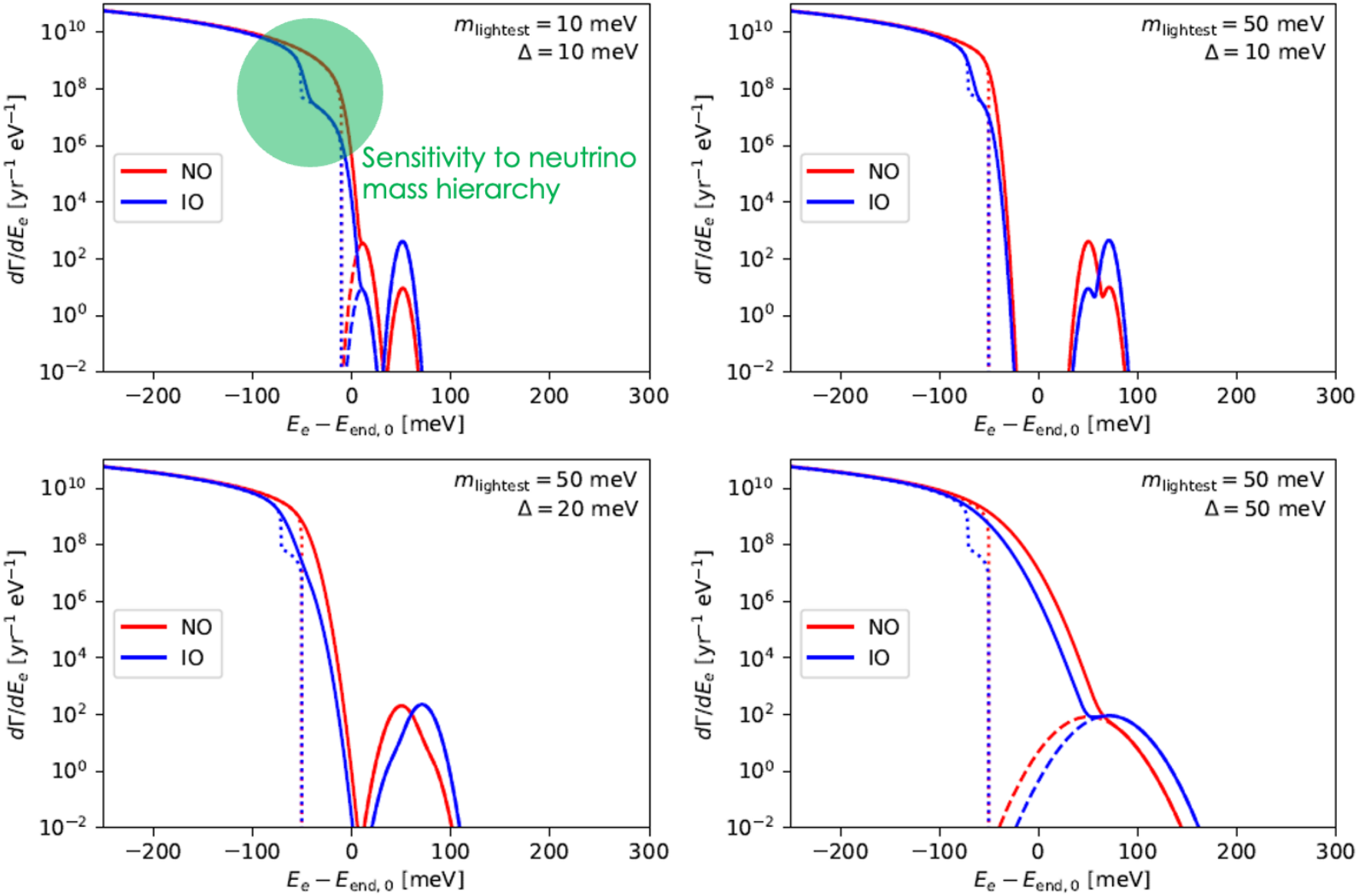
- Why **tritium**:
  - Relatively high cross section for capture
  - Relatively long lifetime (12 y)
  - Low Q value (18.6 keV)
- But
  - Need 100g ^3H for ~10 CνB events/y
  - And ^3H beta decay rate is ~0.2 THz/mg



$$^3\text{H} \rightarrow {}^3\text{He}^+ + e^- + \bar{\nu}_e$$

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

Access to several neutrino features



The experimental challenge

- How to get to **< 50 meV (β)** electron kinetic **energy** resolution at 18.6 keV (i.e. **< 3 ppm**)
- How to deal with a **10^{18} Bq** radioactivity ?

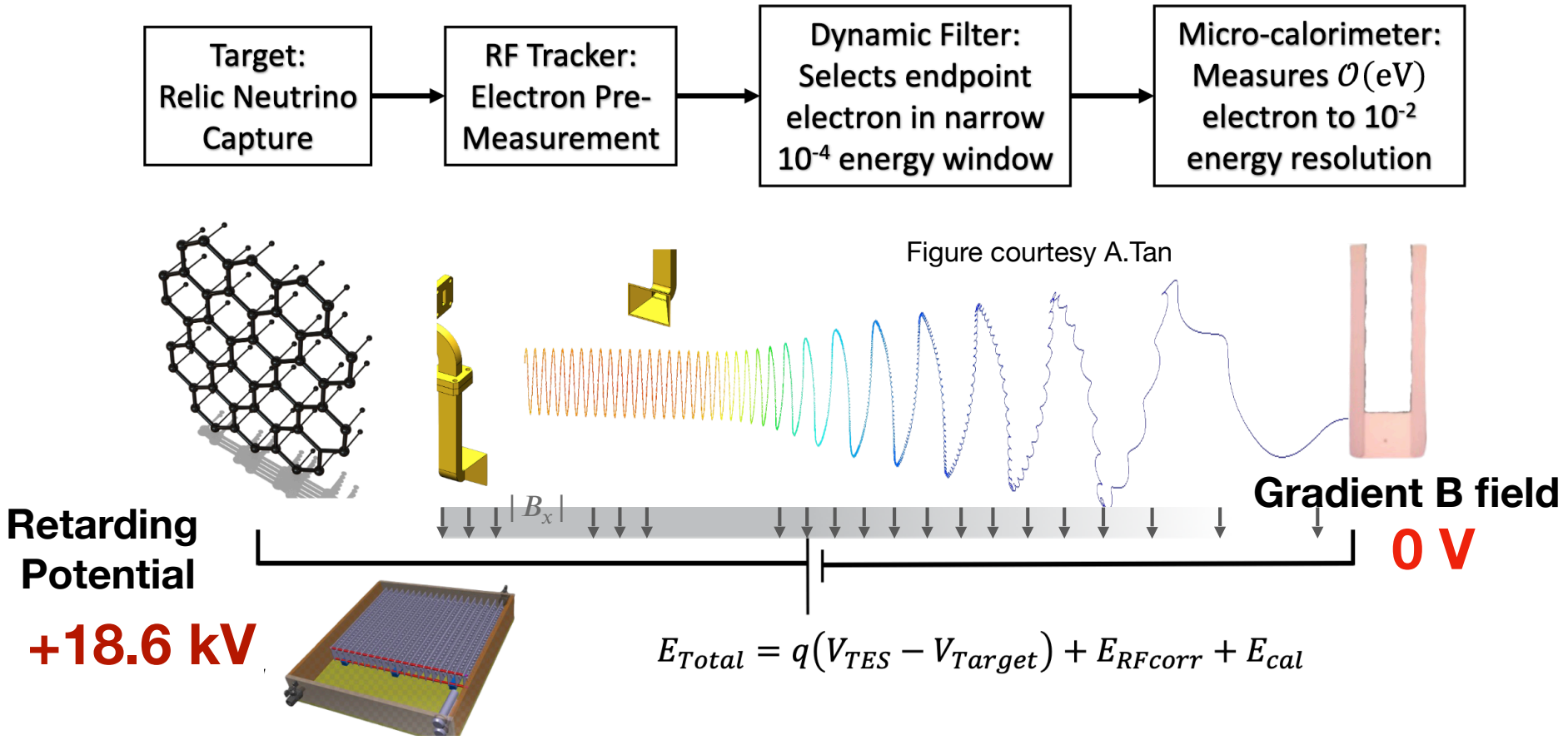
The Ptolemy project

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

An R&D project to demonstrate the detection concept

The Ptolemy concept

- Precisely defined (ppm) voltage difference: β-electron **slowed** down - and **removed** - to decimate the flux **unless** close to the **endpoint**
- Measure the electrons left with E ~1-10 eV (with 10^{-2} resolution)



The Ptolemy ingredients

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

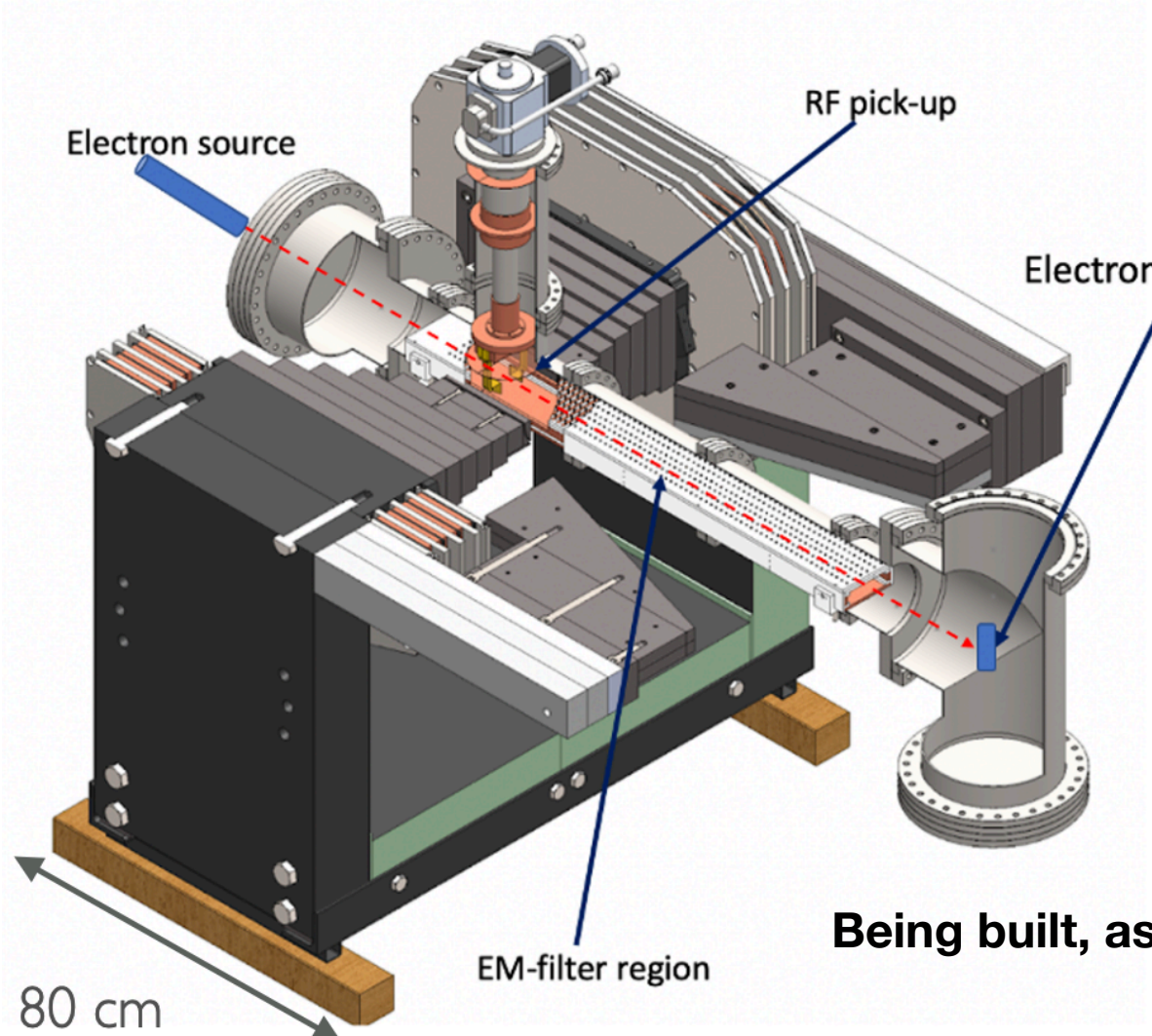
- Fast ~30 GHz radiation fast detection as *trigger*
  - cyclotron radiation emission (similar to Project-8)

- Novel electromagnetic filter

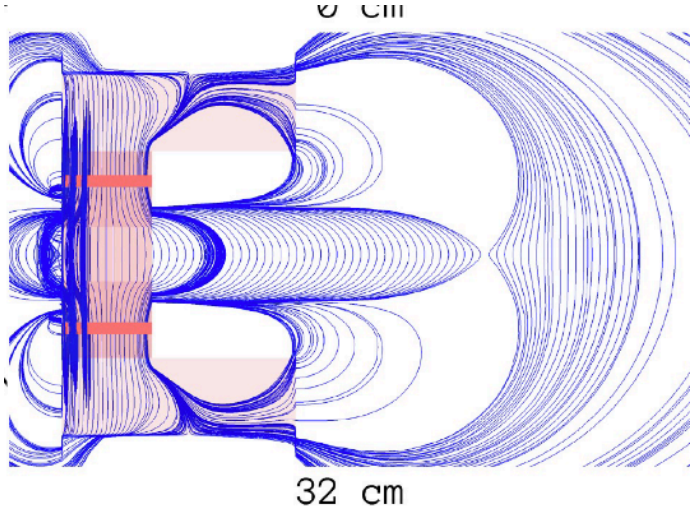
M.G.Betti et al,
Progress in Particle and Nuclear Physics,
106, (2019) 120-131

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

The demonstrator



A. Apponi et al 2022 JINST 17 P05021



An exponentially falling B field (fringe field)

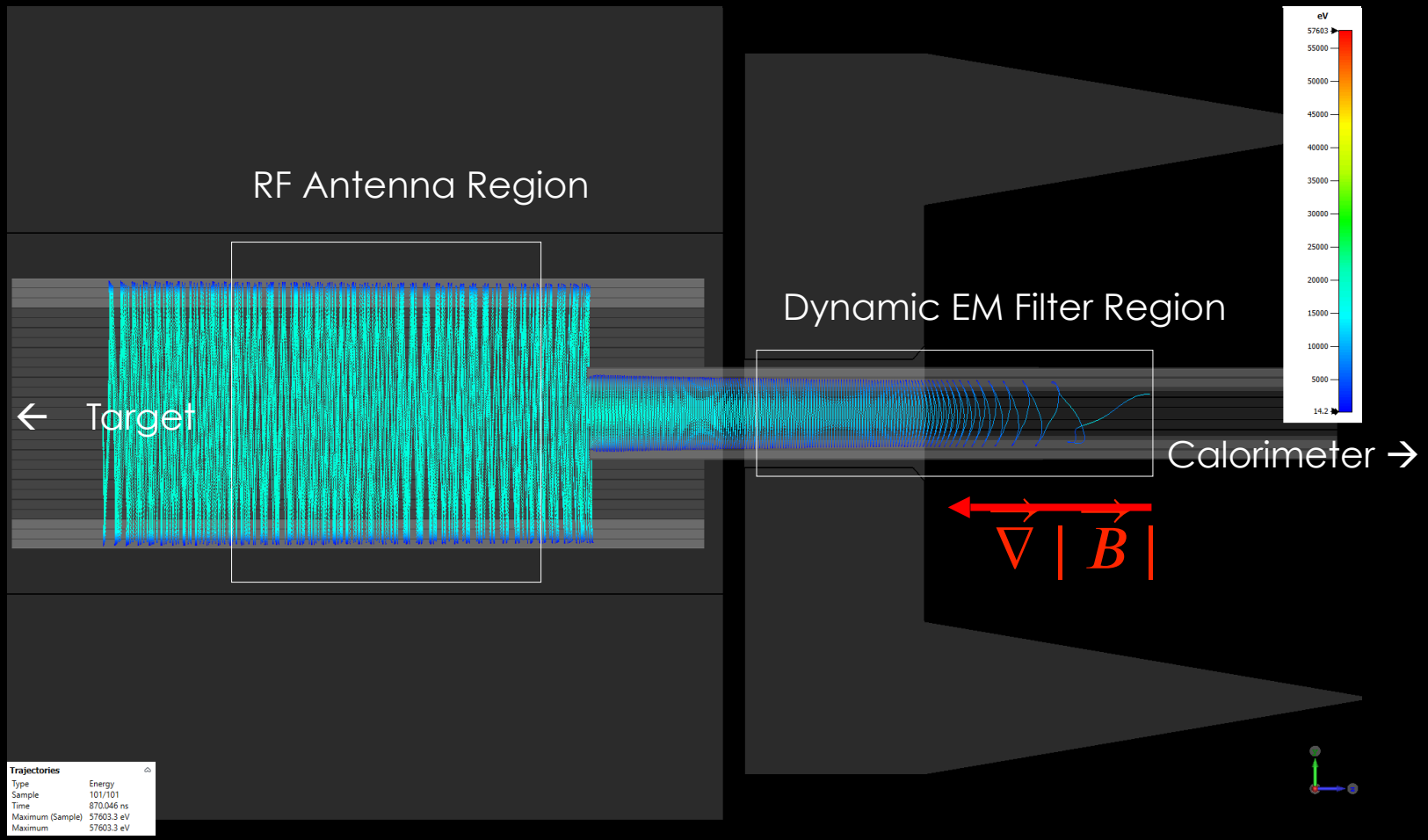
+

Non-uniform E field

Being built, assembled and operated at INFN LNGS

Being built, assembled and operated at INFN LNGS starting 2025

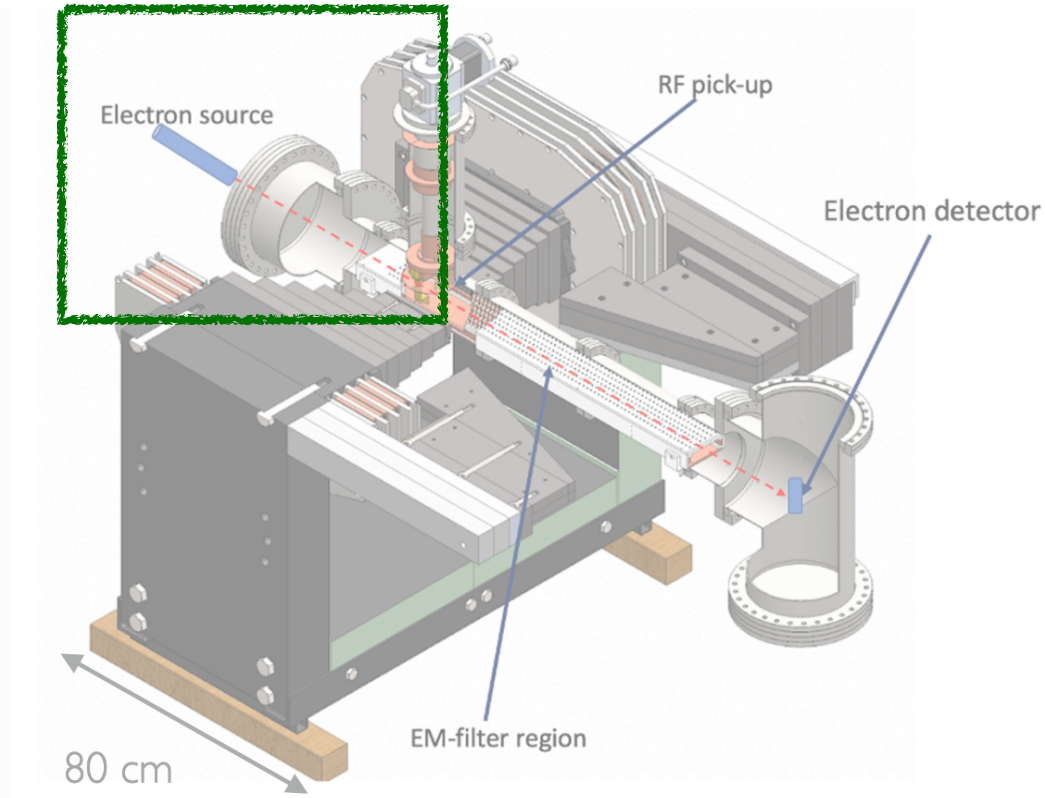
Electron Transport: RF pickup & Filter



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 ^3H (Heisenberg limit)
      - *Interplay with **condensed matter** physics*
  - **Detect** the electrons after the **end** of the filter
    - Kinetic energy much reduced (up to 10-100 eV)
    - Deal with absorption of very slow electron in materials
      - Transition Edge Sensors (**TES**) as micro-calorimeters

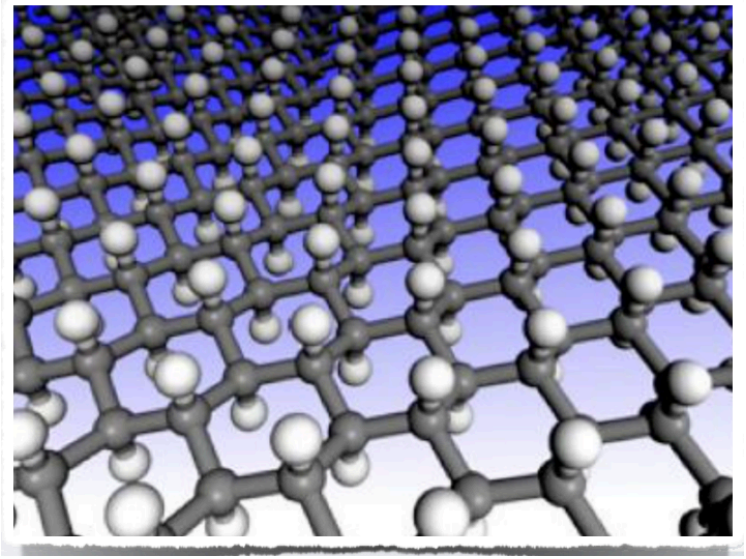
The target for neutrinos, source of electrons



Flat graphene **atomic** ^{3}H storage

- **^{3}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 ***^{3}H each C***

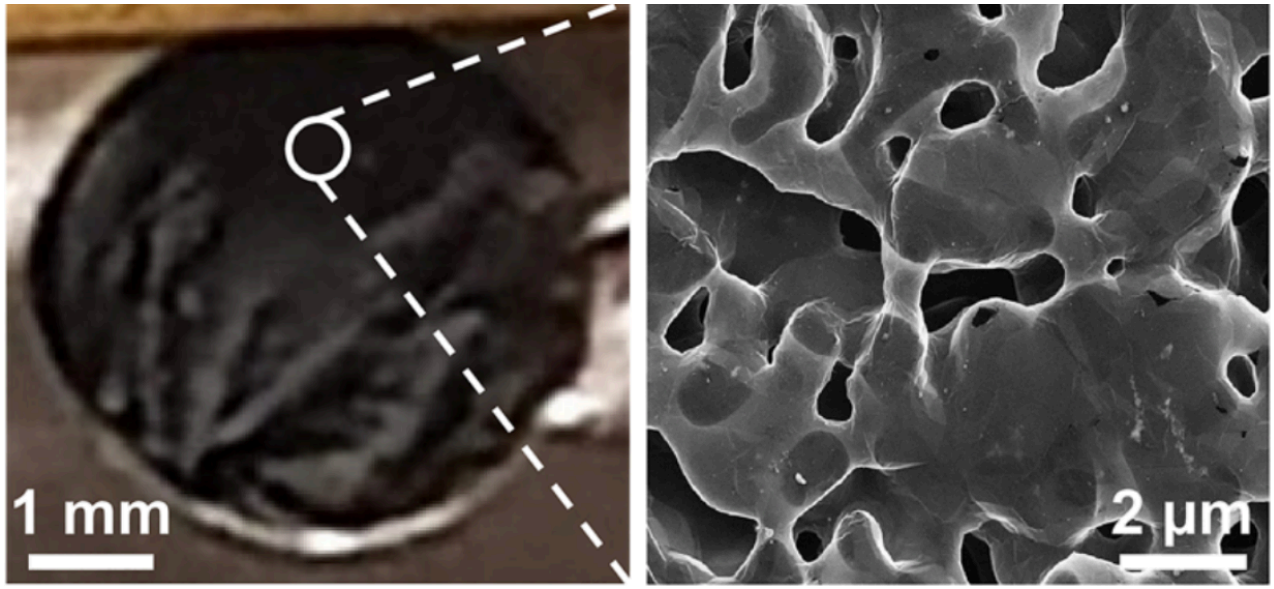
Mahmoud Mohamed Saad Abdelnabi et al 2021 Nanotechnology 32 035707

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**

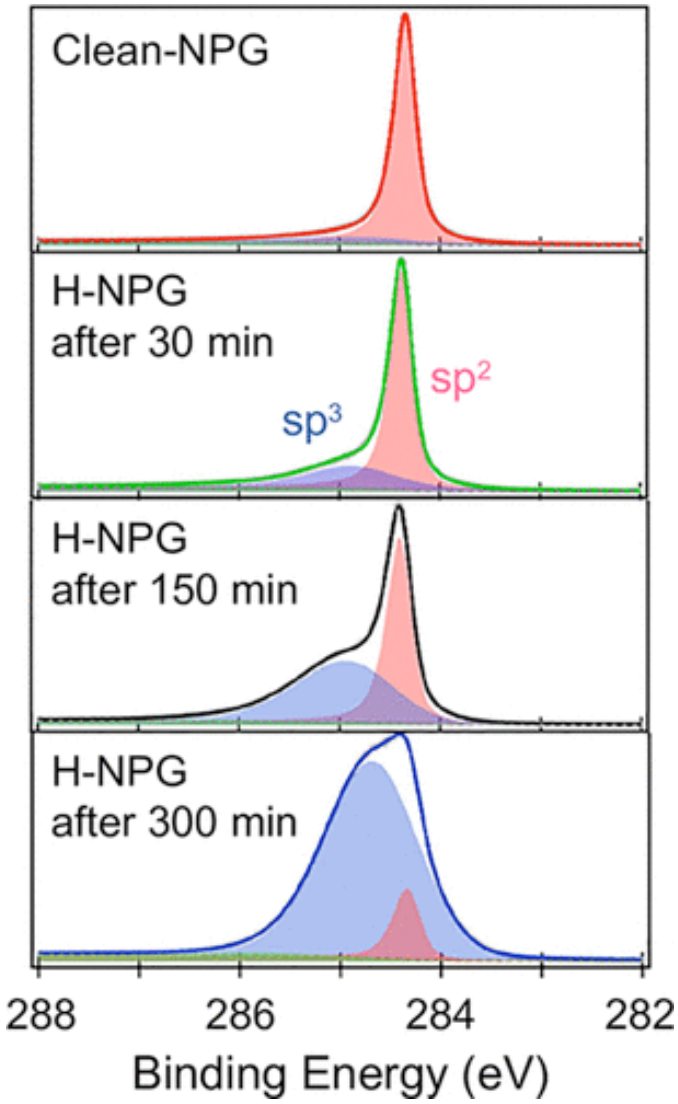


- Hydrogen chemi-sorbed on NPG (single or double layers continuous graphene surface)

Graphane

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: semiconductor (graph**A**ne)

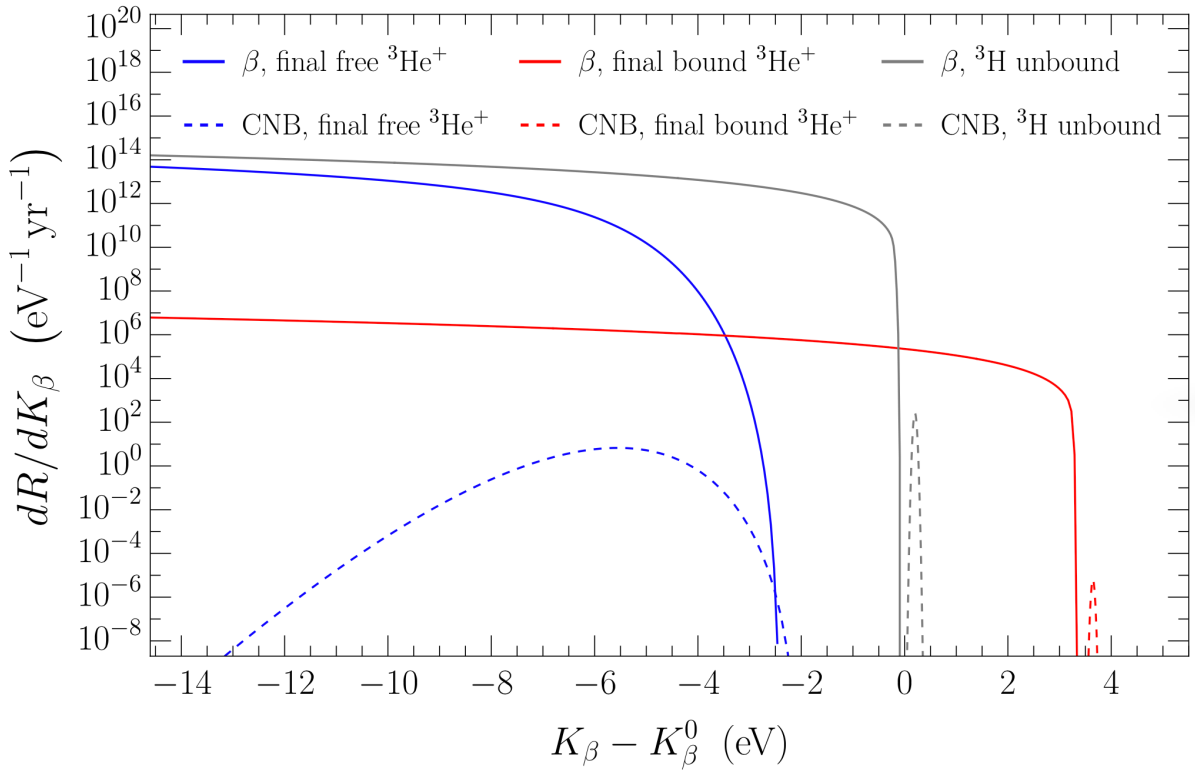


Next: put tritium on graphene and demonstrate it is a "solid" radioactive source

…hitting the Heisenberg limit??

- Spatially localised tritium (by covalent bond) implies an uncertainty on the tritium momentum

  - Effect on the electron energy resolution: ~500 meV (!?!)



Critical for endpoint Analysis (neutrino mass)

Quantum spread

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

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

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

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

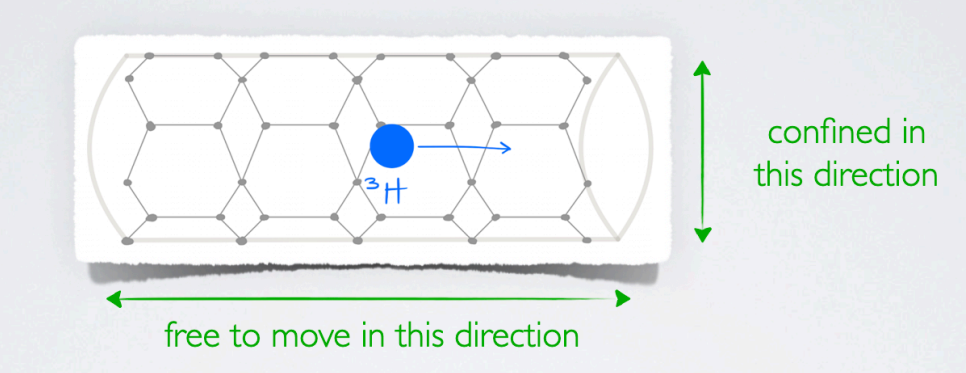
spread of initial tritium wave function $(\Delta x_T \sim 0.1\ \text{Å})$

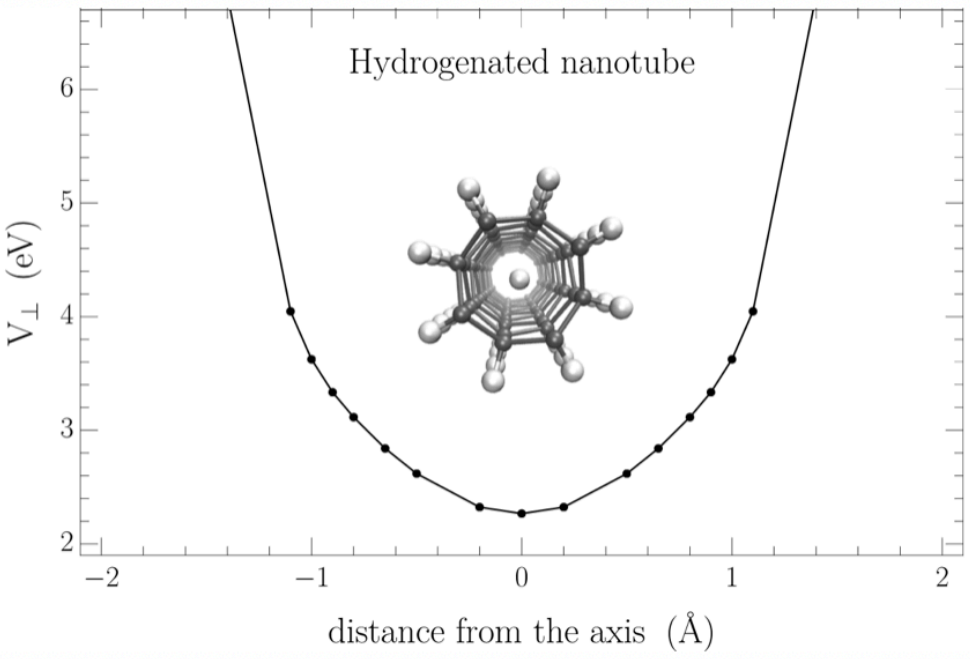
Can be as large as 500 meV

Carbon nanotubes a solution?

A. Apponi et al. Phys. Rev. D 106, 053002 (2022)

- Electric **Potential** binding tritium depends on the concavity of the surface !





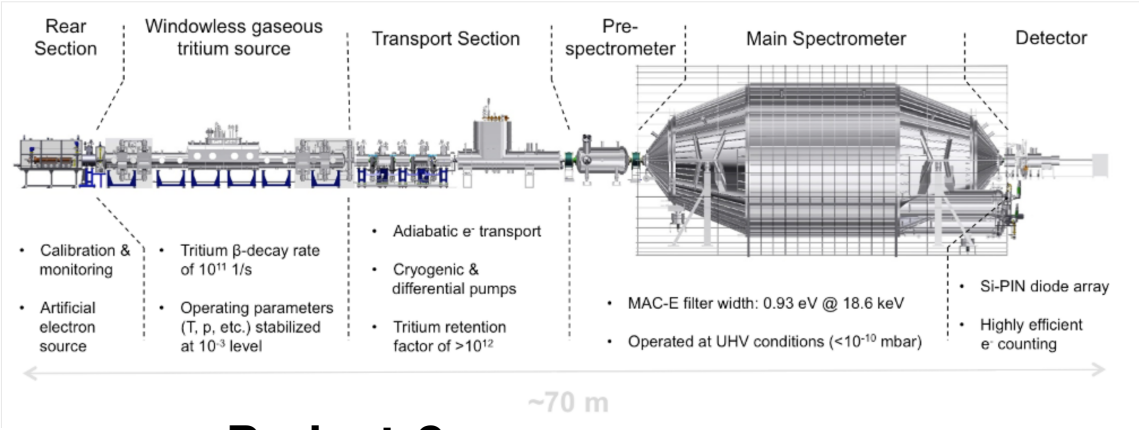
- "**Passivated**" CNT can host a tritium atom
- Prevent dimerization with **magnetic** field

Outlook

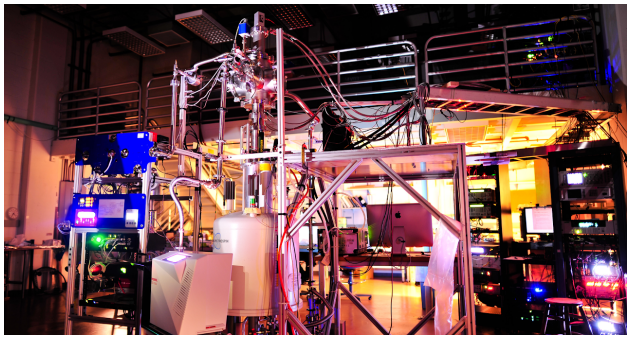
Neutrino mass determination

- End point of the β-spectrum of ^3H sensitive to neutrino mass.

KATRIN https://www.katrin.kit.edu/



Project-8 https://www.project8.org/



- Ptolemy aims at storing up to ~mg ^3H in a first phase
- More compact (~1 m long) apparatus

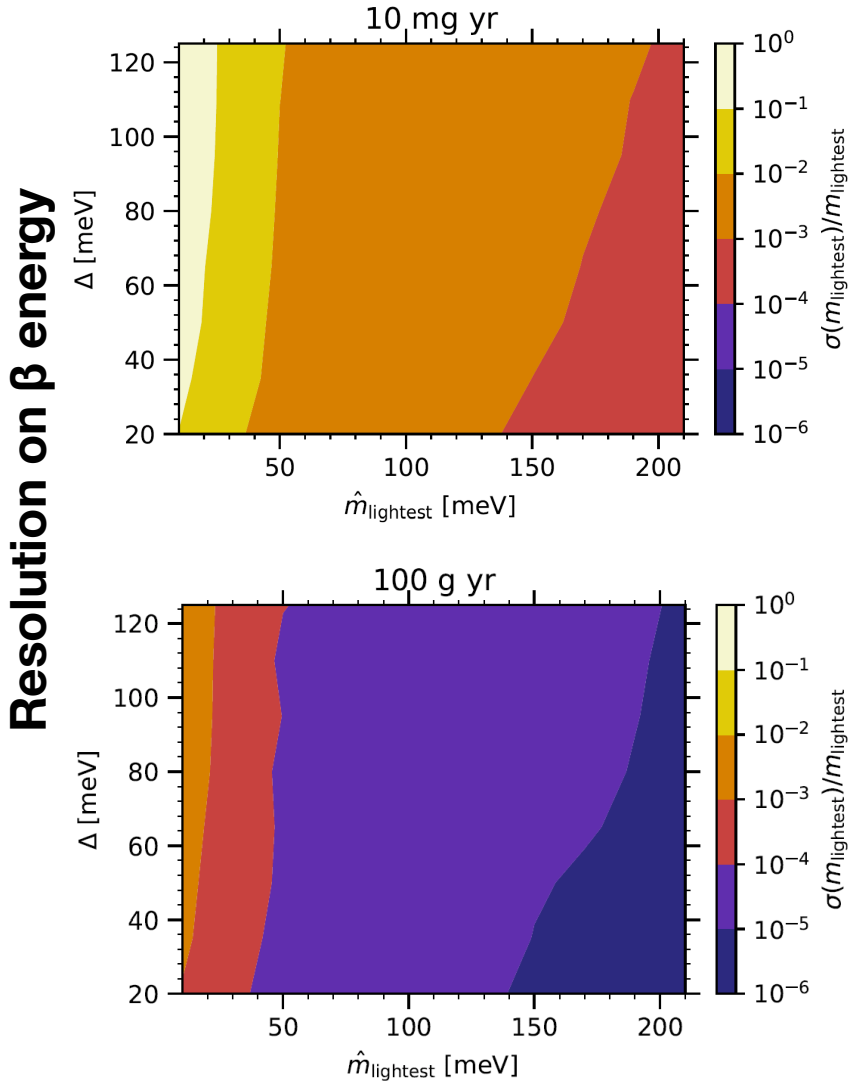
Range of sensitivity for m_ν

- Neutrino mass as first result

  1. Small exposure already gives sensitivity to O(10meV) m_ν

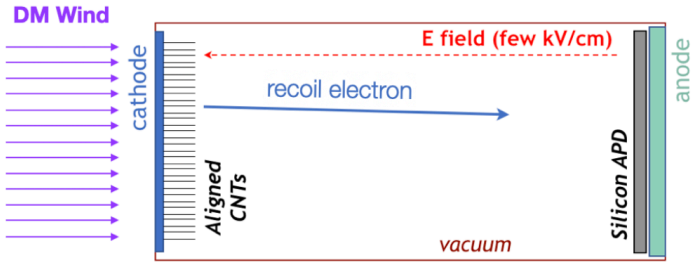
  2. Crucial for design of full scale $C\nu B$ PTOLEMY with 100g tritium

Working on a more realistic sensitivity estimante including initial and final state of ^{3}H and ^{3}He interaction with graphene



More than that

- INFN-Sapienza laboratories for technology with carbon nanostructure at Segrè.
  - Light dark matter directional detector (**Andromeda**)



See Luca Cecchini's talk

- Many other applications of carbon nanostructure
  - CNT-doped copper for additive manufacturing (with INFN): **Dragon** Cu, international patent
  - **UV light** detector based on VA-CNT - environment monitoring, astrophysics : NanoUV)
  - CNT for **anti-microbial** surface (with Biology dep.) and enhanced bio-sensors
  - **Composite** materials, CNT on basalt fibers (with DIMA at Sapienza)
  - …

Innovation

Looking for a game-changer for future experiments

When asked if he believed in asking customers what they want – Ford replied: **"If I had asked them what they had wanted, they would have said a faster horse."**