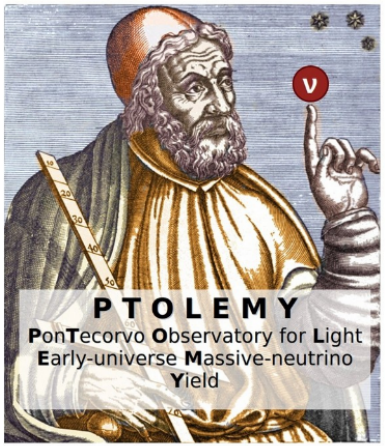
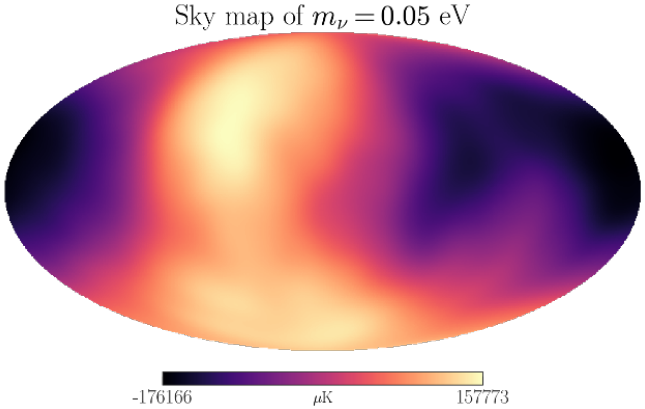


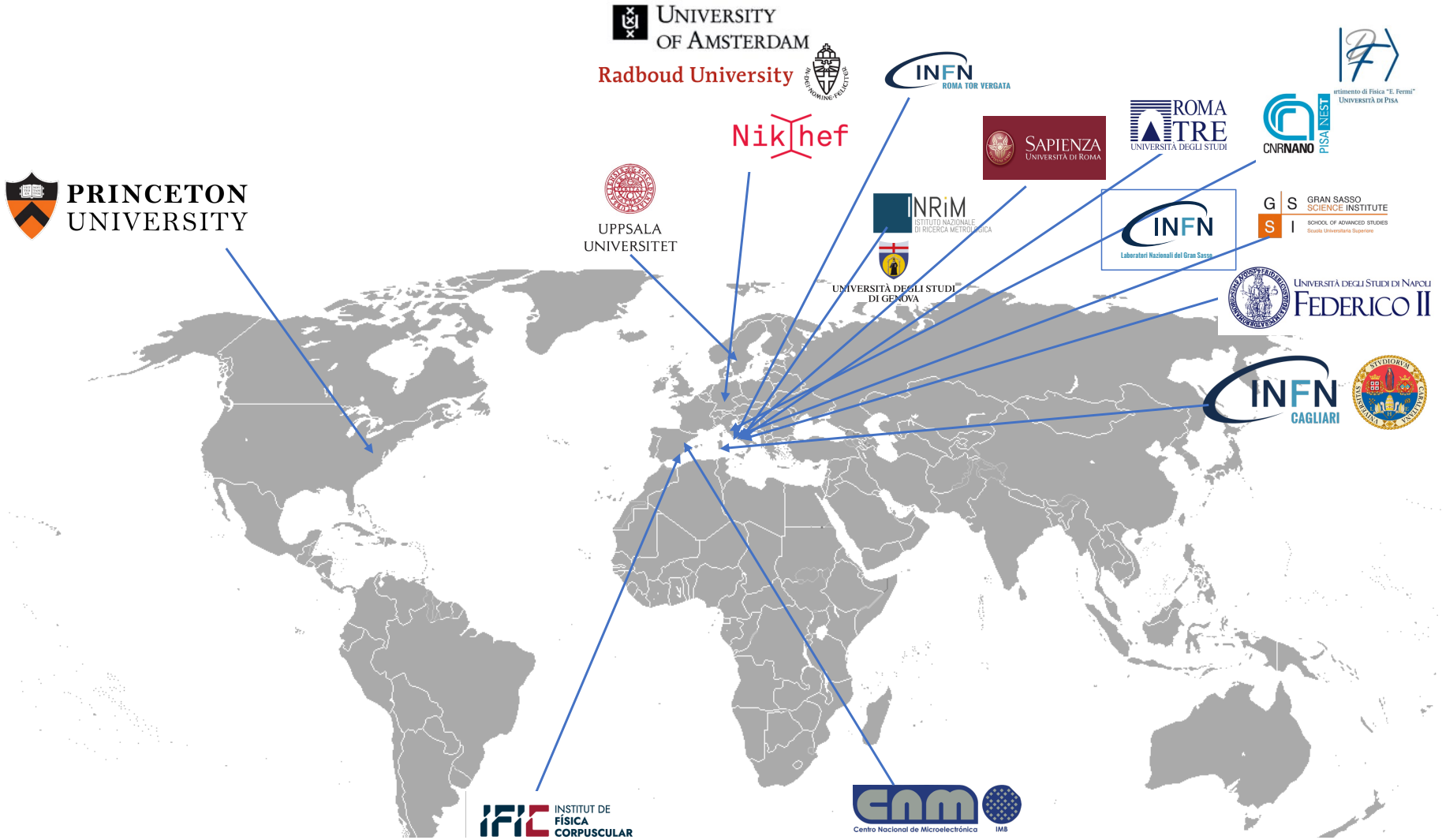


Neutrino sky

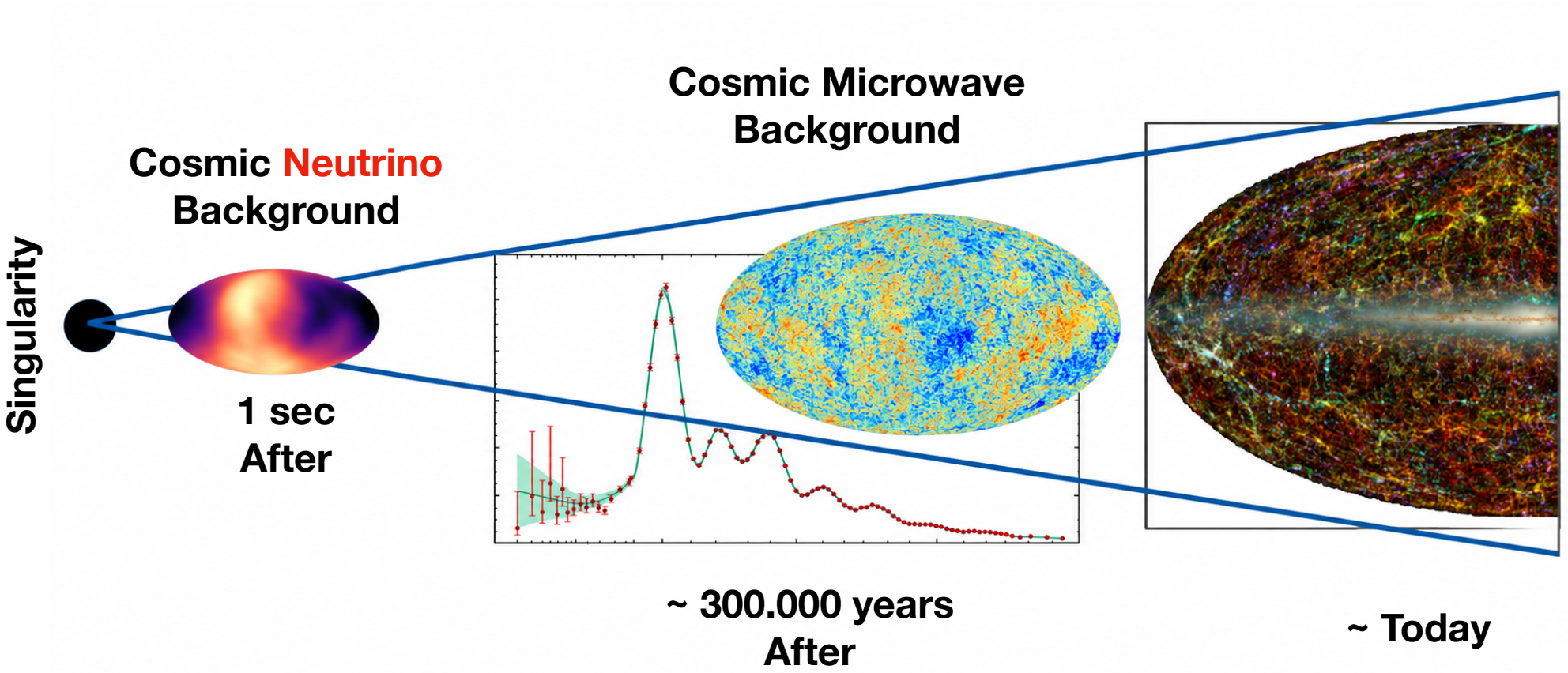
The Ptolemy project

Gianluca Cavoto - *Sapienza Univ Roma and INFN Roma*
On behalf of the ***Ptolemy*** *Collaboration*
30th Sep 2026 ***LNF Seminar***

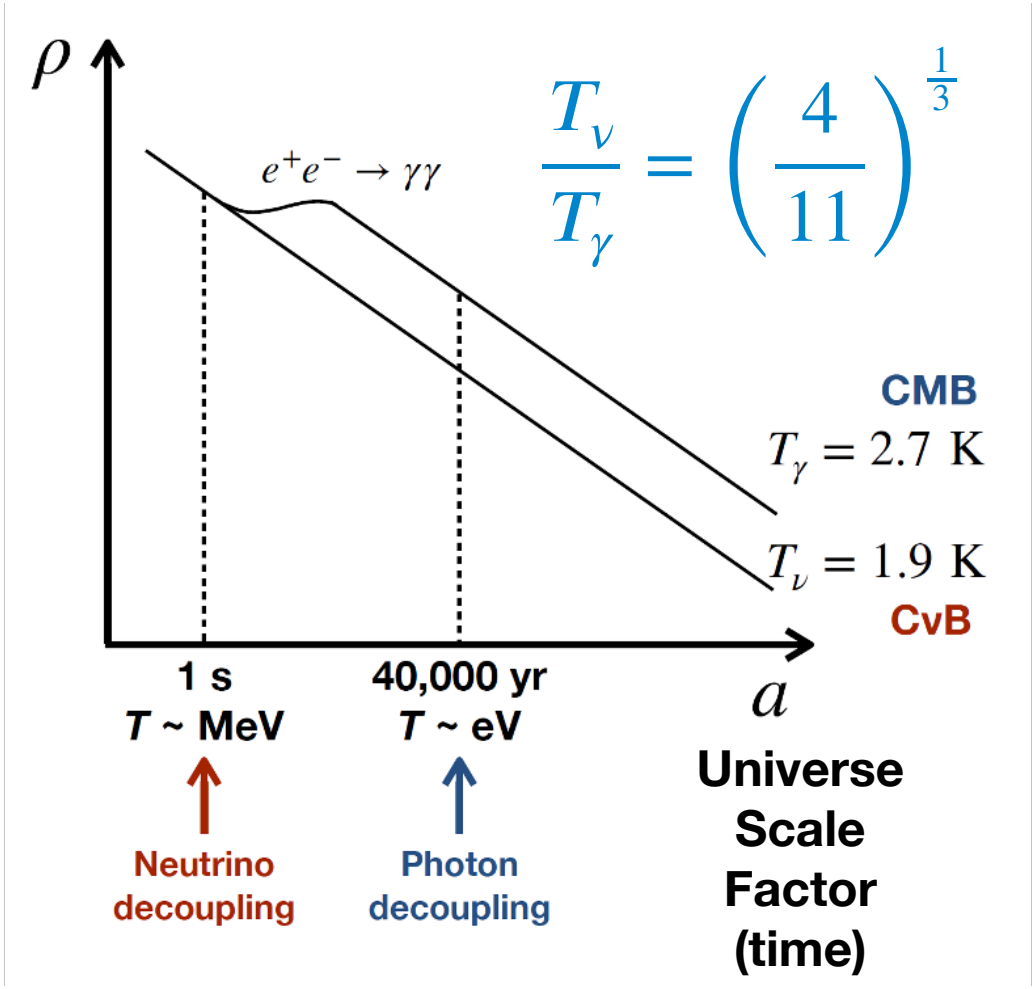
The Ptolemy collaboration



Looking at the Universe



Neutrinos decoupling

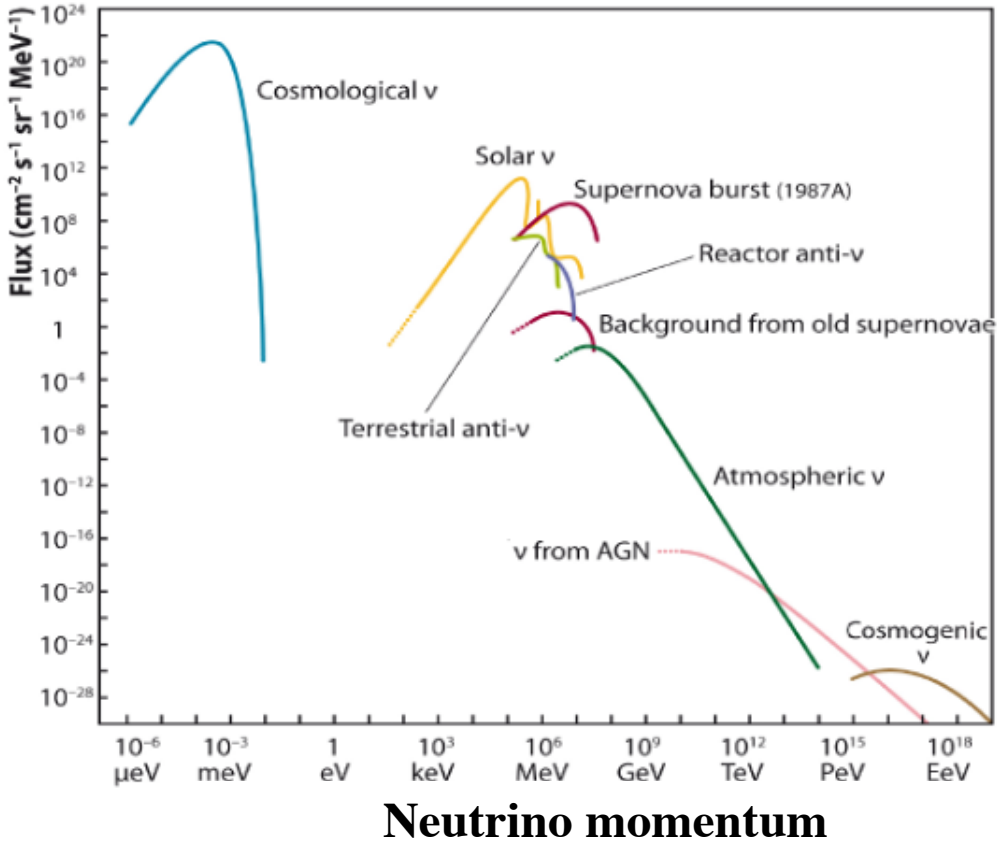


- Primordial universe in (local) thermal equilibrium
  - If a reaction rate **Γ** is *less* than Universe expansion rate **H**, a particle/radiation species can "decouple"
  - Spectrum determined by its temperature at that time

The cosmological neutrino background (CvB)

- **Cold** Matter (T ~ 1.9K)
- About **100/cm³** here and now
- Faint kinetic energy (< eV)

Classical neutrino detectors unusable



The Ptolemy project

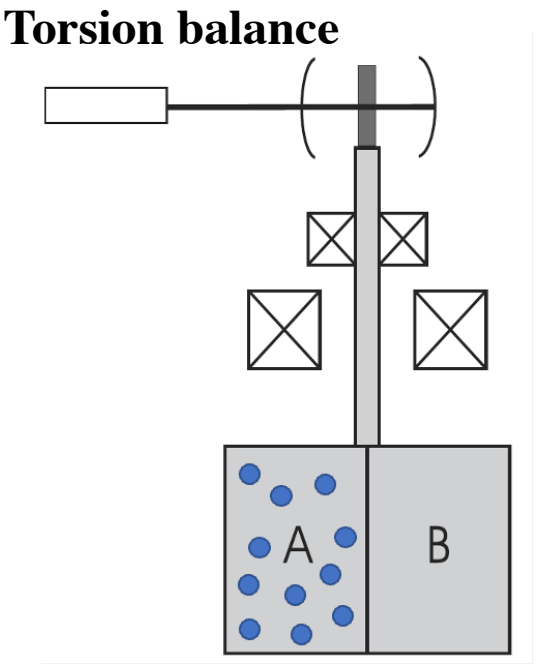
M.G. Betti et al JCAP07 (2019) 047

A novel compact spectrometer concept

Aiming to 0.02 - 0.2 eV neutrino mass range

A long sought messenger…

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



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

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

https://arxiv.org/abs/2109.07482

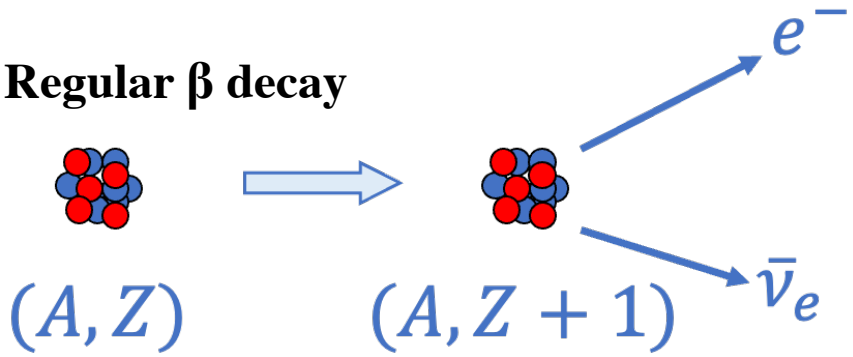
https://arxiv.org/abs/1703.08629

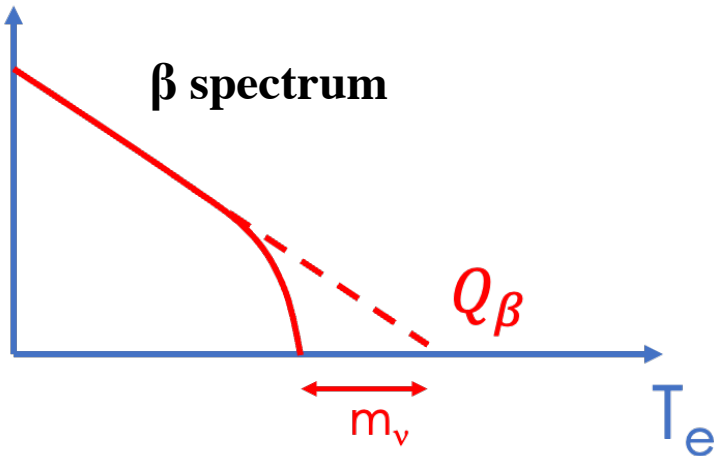
And more:
- Interaction with high energy neutrinos
- Ion storage ring
- Superconductors,
- ….

Capture on radioactive nuclei

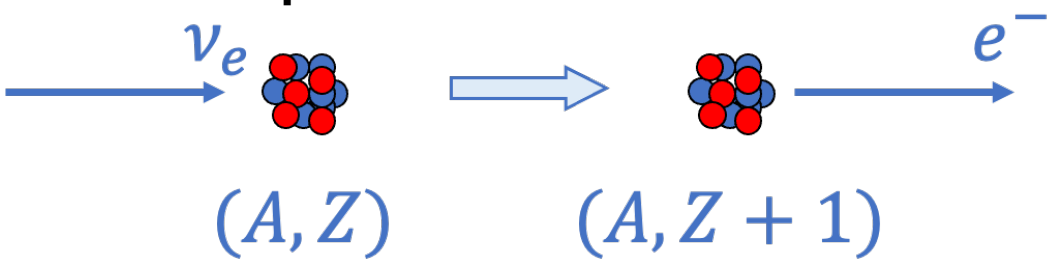
- Weinberg (1962) Weinberg,. Phys Rev 128, 1457–1473 (1962).
- Revived more recently: Cocco, Mangano, Messina (2007) JCAP 06(2007) 015

Regular β decay

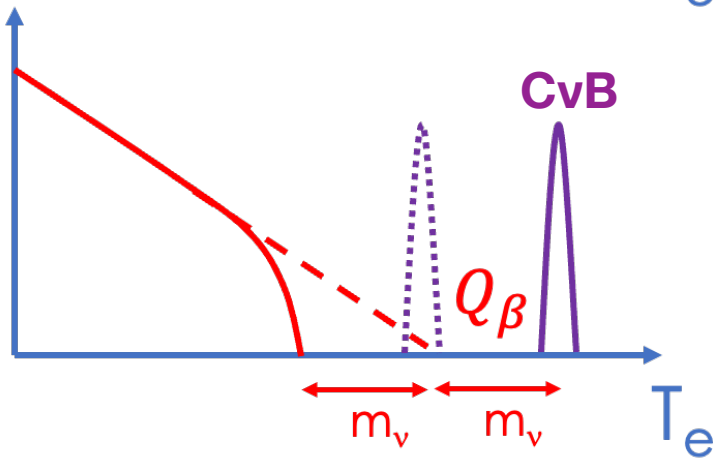




Neutrino capture



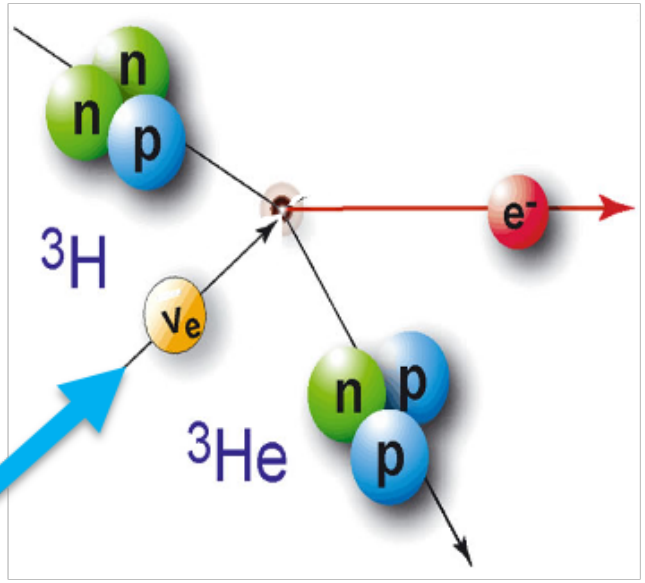
Non zero neutrino mass is critical



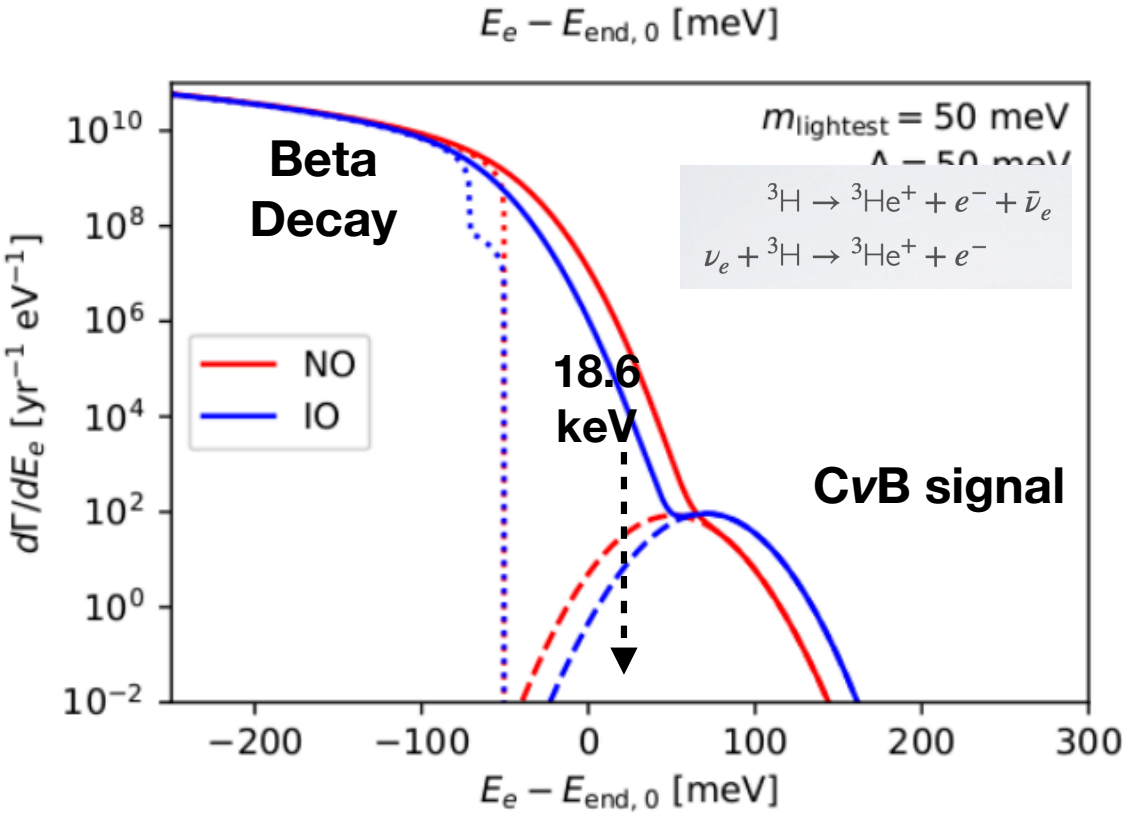
The target, atomic **tritium ^3H**

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

Neutrino capture on Tritium



No low threshold !

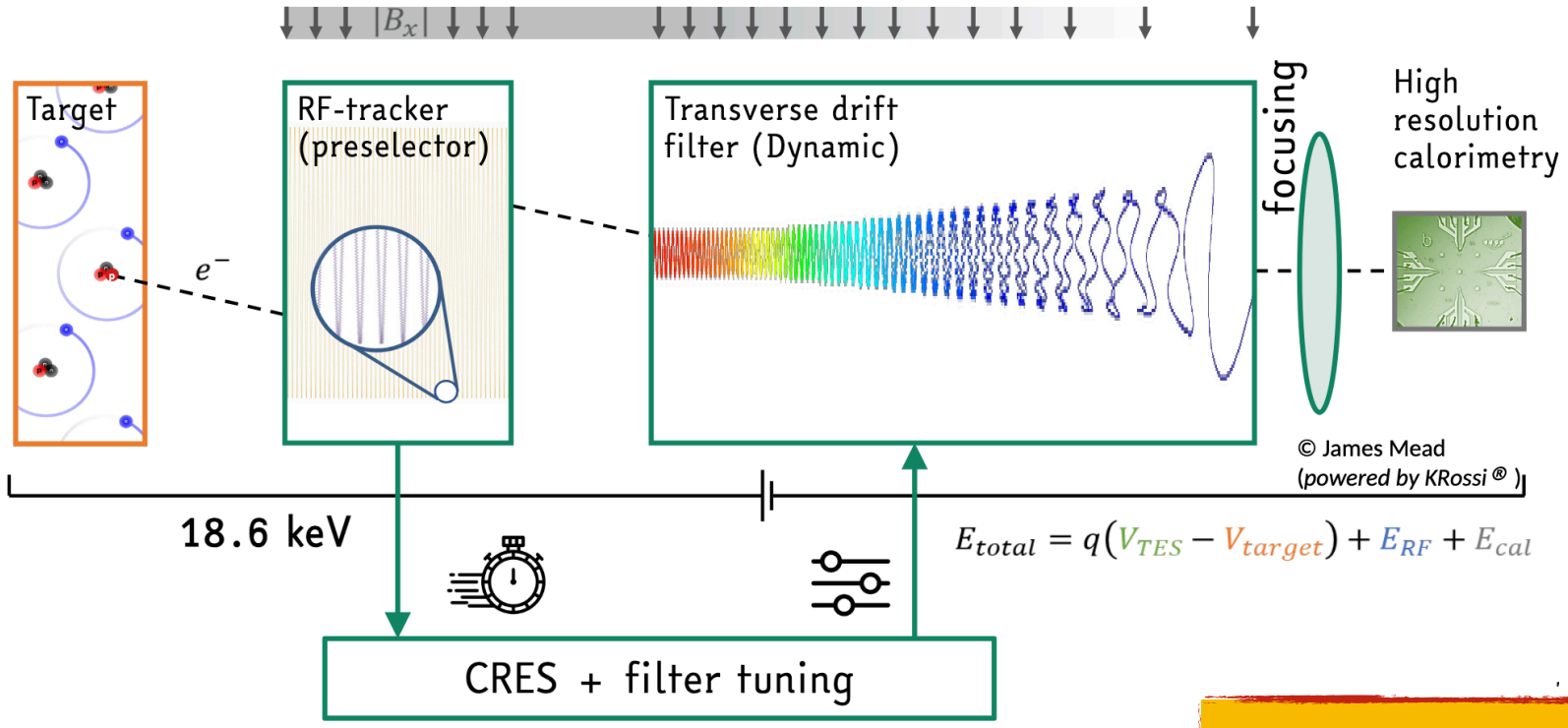


- Need 100g ^3H for few CνB events/y

First step is to measure neutrino mass from the endpoint

The Ptolemy concept

- Precisely defined (ppm) voltage difference: β electron slowed down from **18.6 keV** - and removed - to decimate the flux.
- Measure a E ~ 1-10 eV electron with 10^{-2} - 10^{-3} resolution



Detect β electrons at the end point 18.6 keV

Goal: 50 meV electron energy resolution

The Ptolemy ingredients

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

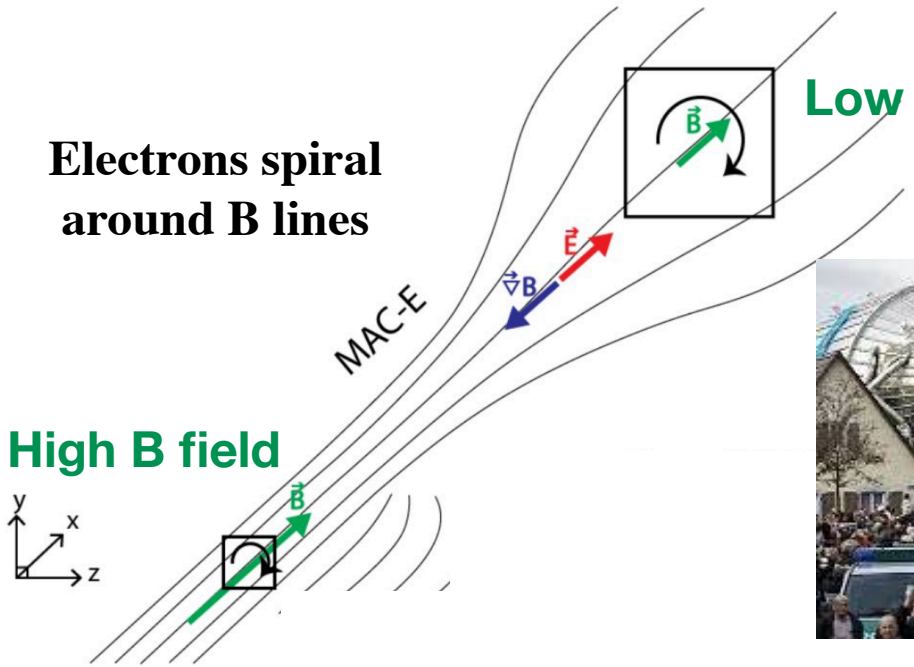
- Fast ~30 GHz radiation detection as *trigger*
  - **c**yclotron **r**adiation **e**mission **s**pectroscopy (**CRES** - see Project-8)

- **Novel electromagnetic (filter) spectrometer**

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

- Hemispherical electrostatic analyser
  - *In future* cryogenic **micro-calorimeter** based on Transition Edge Sensors (**TES**)

The MAC-E filter



$$\vec{B} \parallel \nabla B \parallel \vec{E}$$



Katrin @ KIT
Neutrino mass
measurement from ^3H
$m_\nu < 0.45$ eV (90% C.L.)

Aker et al., Science 388 (2025) 6743

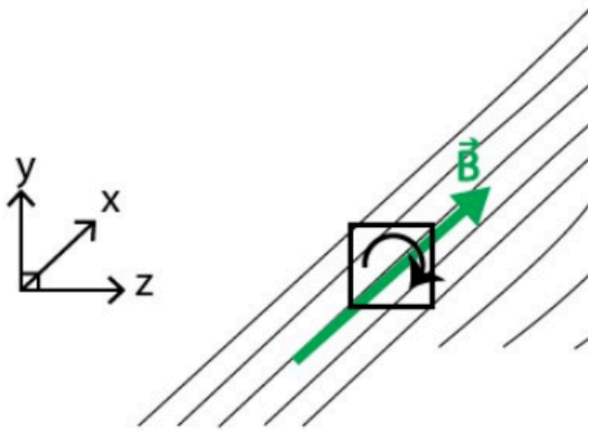
Transverse kinetic energy

Magnetic moment conservation $\mu = \dfrac{E_\perp}{B} = const$

Adiabatic collimation: $E_\perp \rightarrow E_\parallel$ + Parallel electric field $\vec{E}$ slows down electron

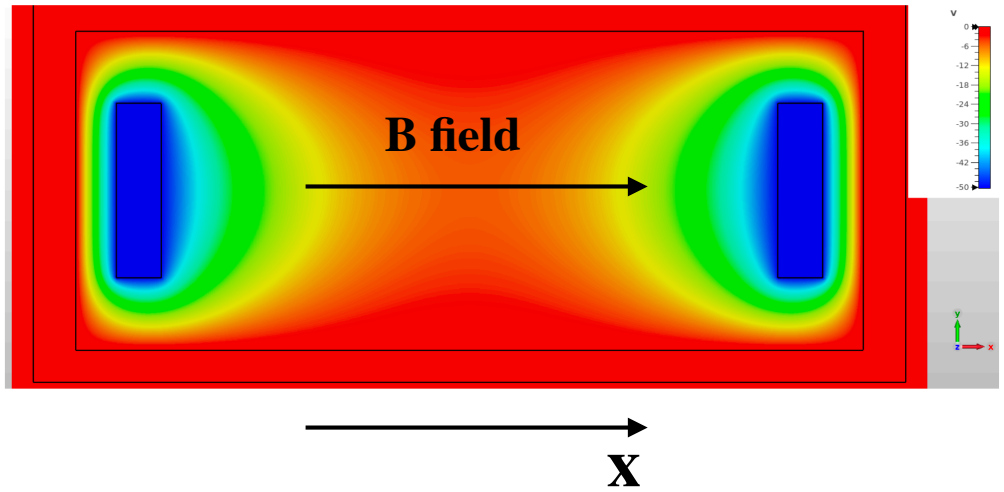
High pass filter: INTEGRAL measurement of the beta spectrum

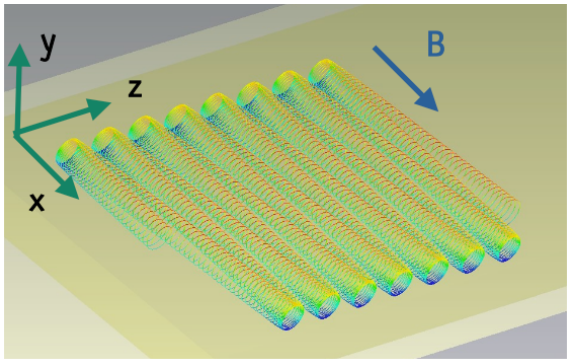
Trapping electrons



- In a high B field region electrodes to create a electric **potential well**
- Electrons are **spiralling** around the B field lines AND are **bouncing** back and forth

Potential values



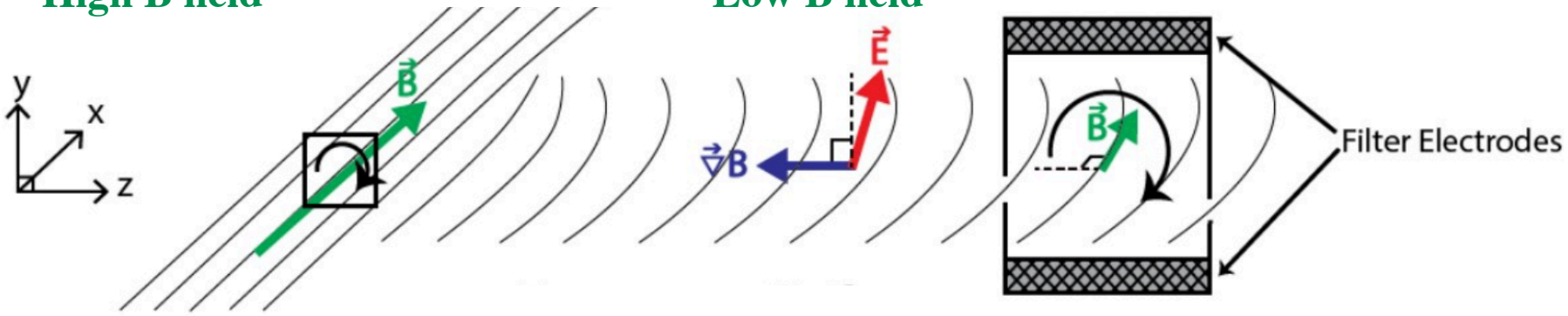


The Ptolemy filter: transverse!

$$\vec{B} \perp \nabla B \perp \vec{E}$$

Electrons spiral (fast) around B lines

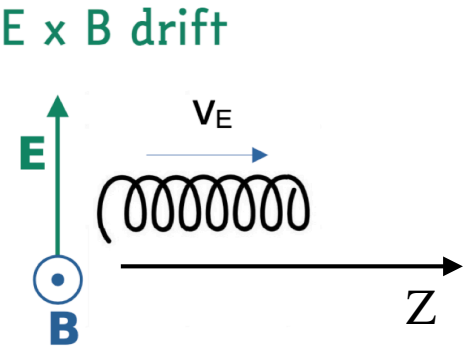
High B field **Low B field**



B field decreases (exponentially)

Electric field perpendicular to B field

$\vec{E} \times \vec{B}$ drift motion

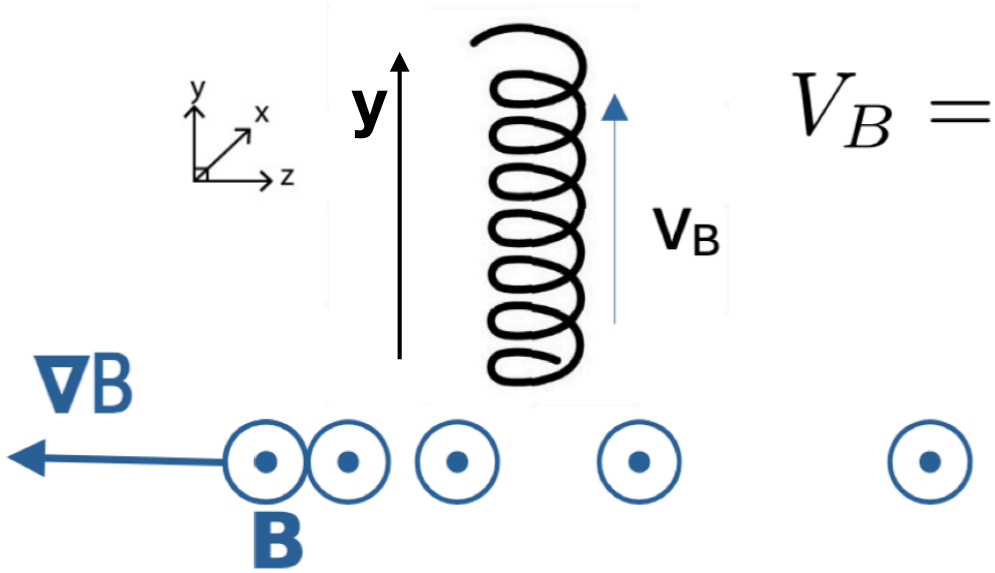


Electrons are spiralling along B lines (**x**)
AND
drifting along **z** (perpendicular to both $\vec{E}$ and $\vec{B}$)

$$V_E = \frac{E}{B}$$ **Drift velocity**

But gradient pushes electrons away!

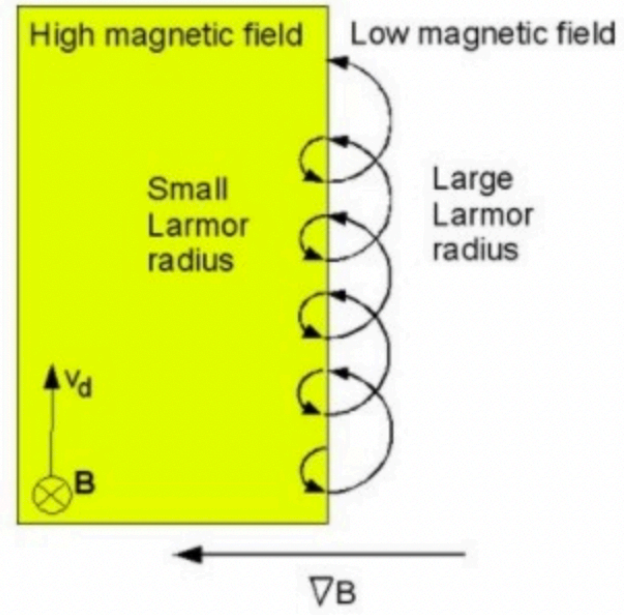
B x ∇B drift



$$V_B = \mu \frac{|\vec{\nabla} B|}{B}$$

Larmor Radius — **Transverse Velocity**

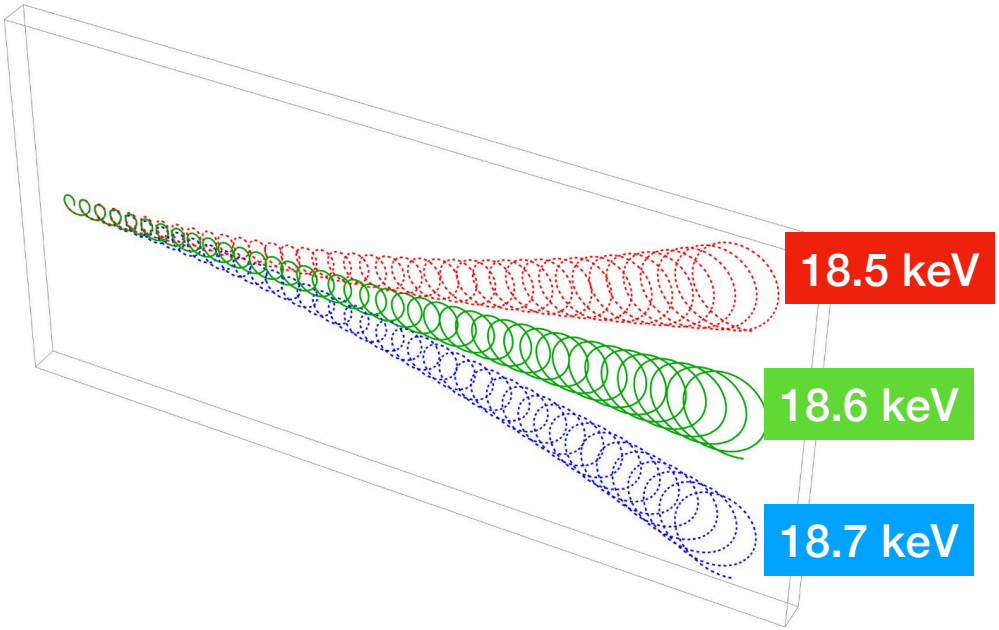
$$r_L = \frac{m v_\perp}{qB}$$

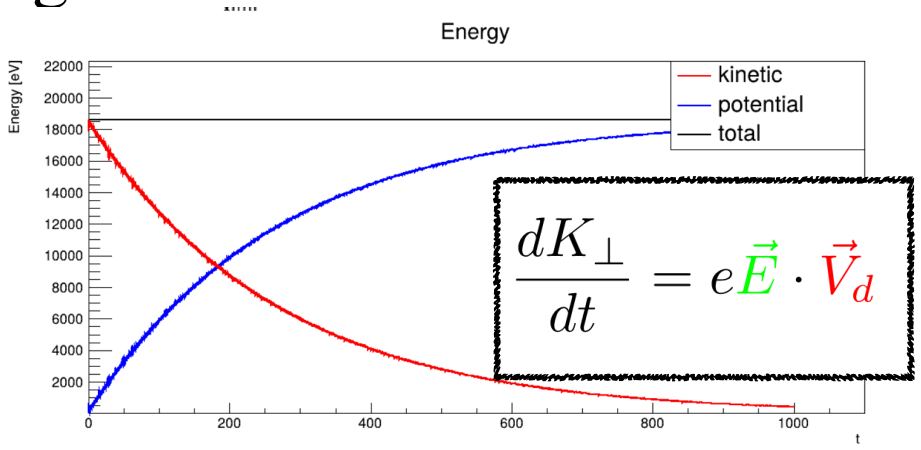


Electrons are (gently) pushed along y
WHILE
they are drifting along z AND
(fast) spiralling around the B field line (x)

The (dynamic) filtering

- While electrons are (fast) spiralling around B field lines they are "guided" with "*macroscopic*" velocity $\boldsymbol{V_d = V_E + V_B}$
- If the E field is properly **TUNED** only electrons with the desidered kinetic energy are exiting

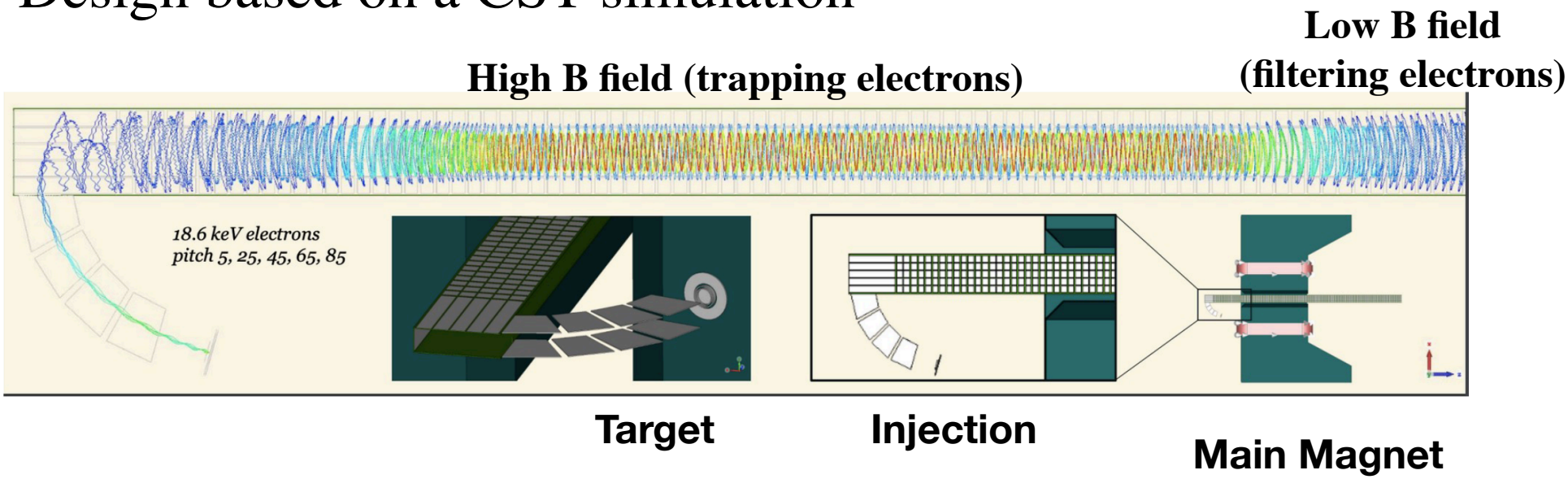




- Kinetic energy K drained in favour of potential energy

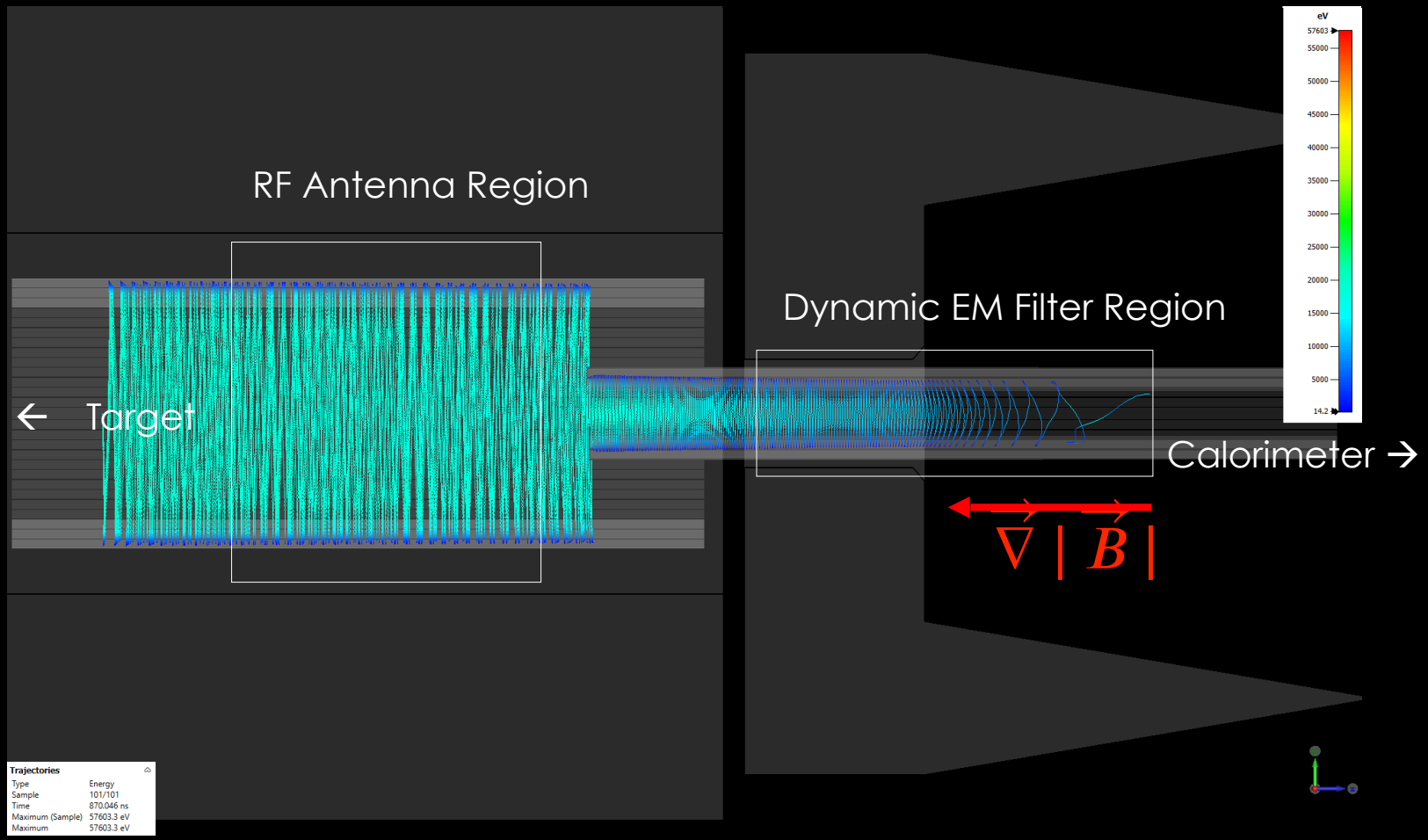
The Ptolemy spectrometer

Design based on a CST simulation

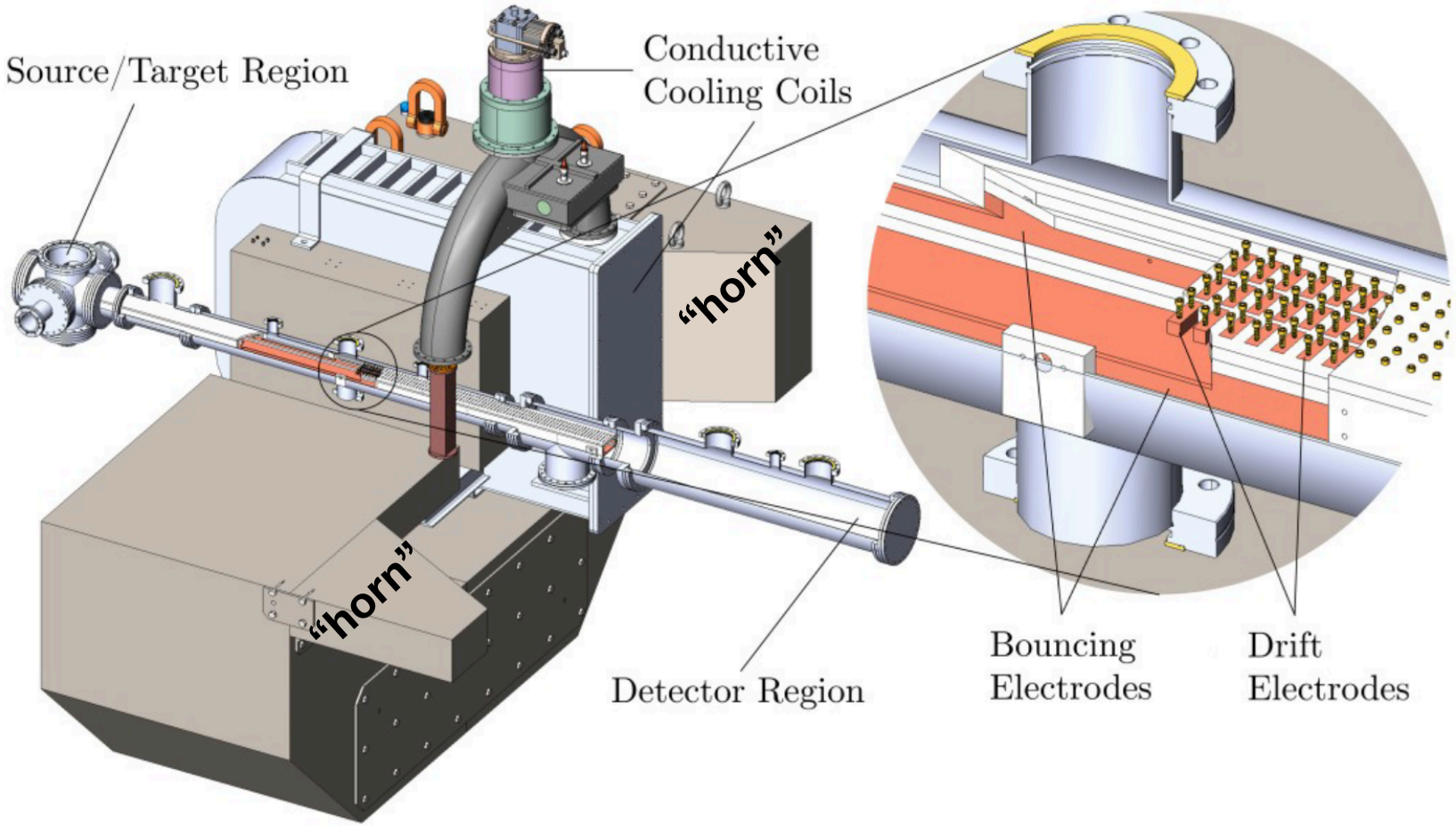


- Custom main magnet with a specially **shaped fringe field** (**exponentially** falling B field)
- Combined with a **gradient** electric field
  - **Electrodes optimization still going on**

Electron Transport: RF pickup & Filter



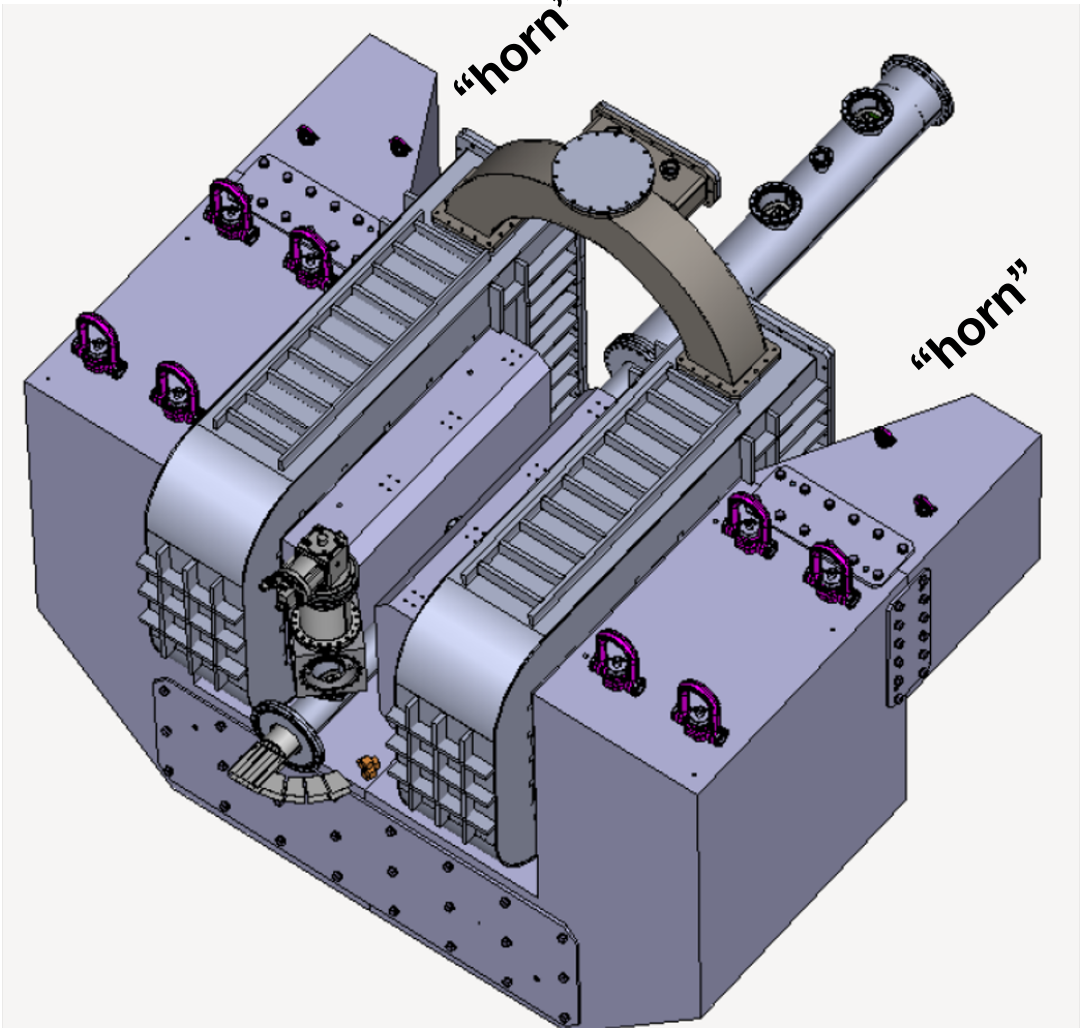
The demonstrator



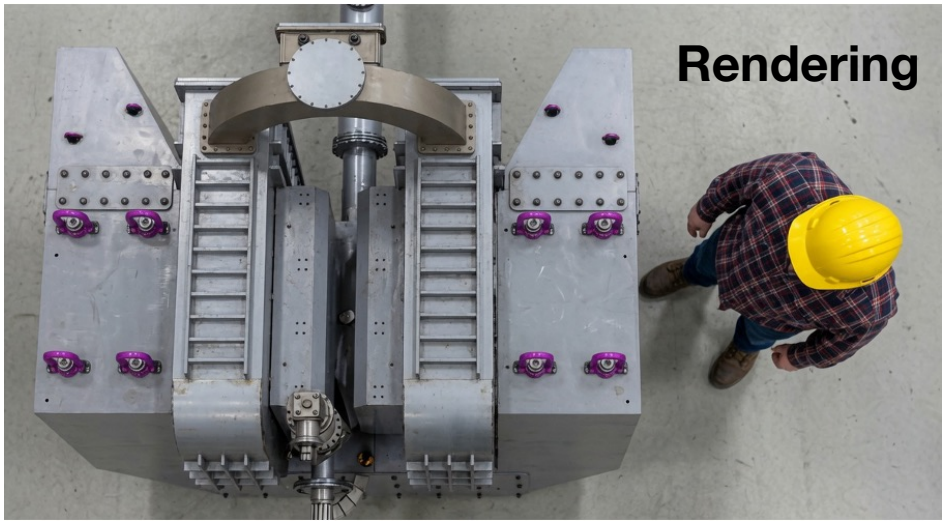
Apponi et al, JINST 17 (2022) 05, P05021

M.Farino et al, JINST 20 (2025) 08, P08025

MgB_2 magnet for LNGS



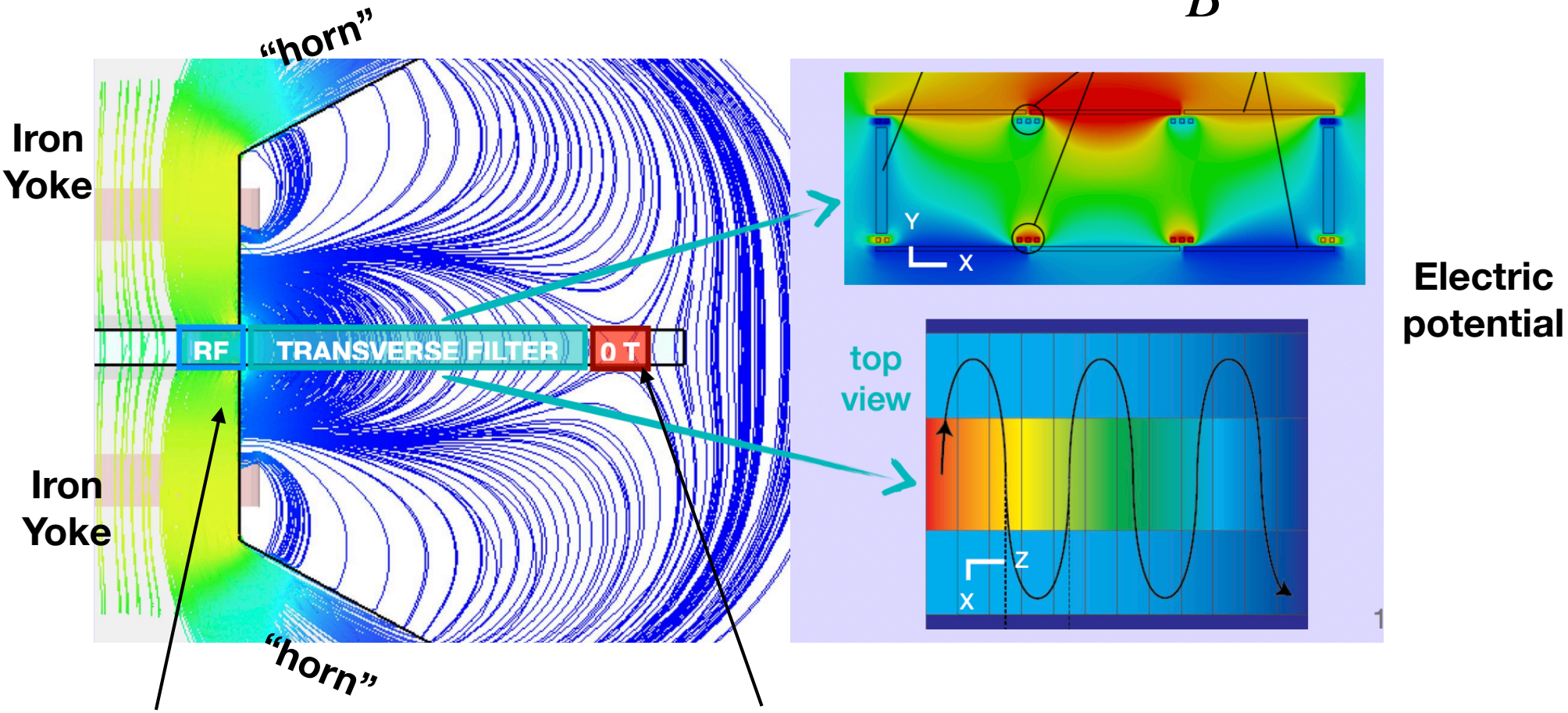
- Coils being built at ASG superconductors
- Iron properly shaped to produce gradient B field (fringe field)



Meter long magnet (compare with Katrin)

Field in the filter region

B Field map - to be know with a precision of $\frac{\Delta B}{B} \sim 10^{-4}$

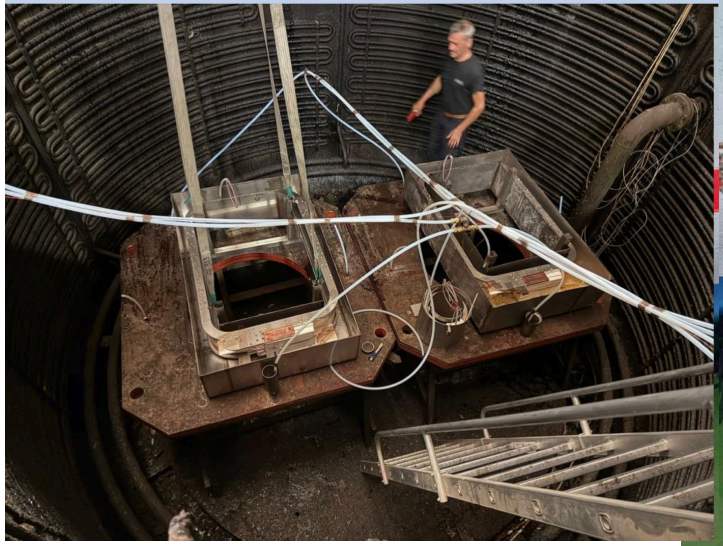


Magnet construction at ASG (Genova)

Yoke construction



SC Coil impregnation



Coil cold test facility

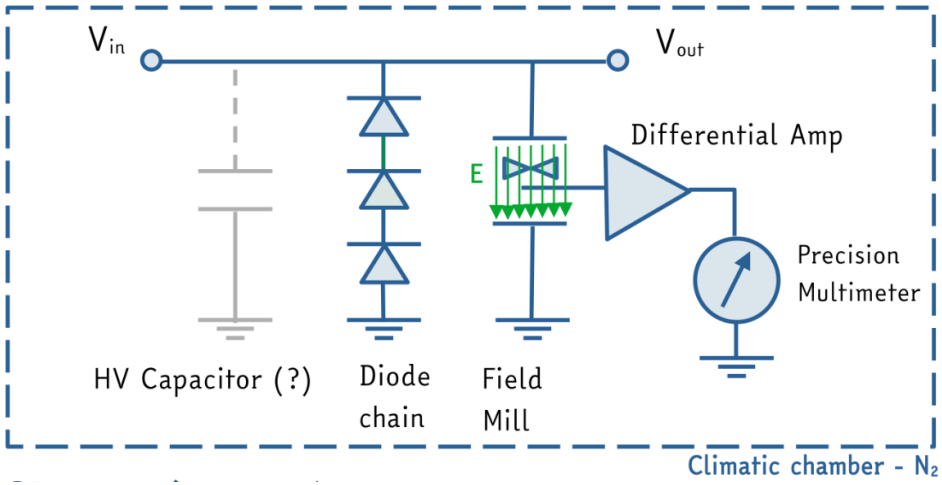


To be delivered to LNGS beginning of 2027

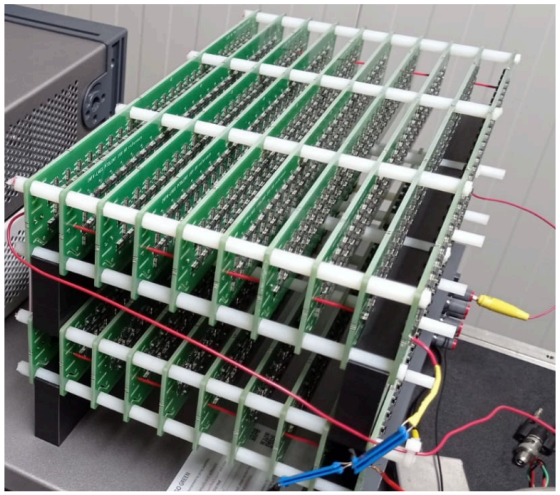
To be installed in Hall di Montaggio at LNGS (site preparation advanced)

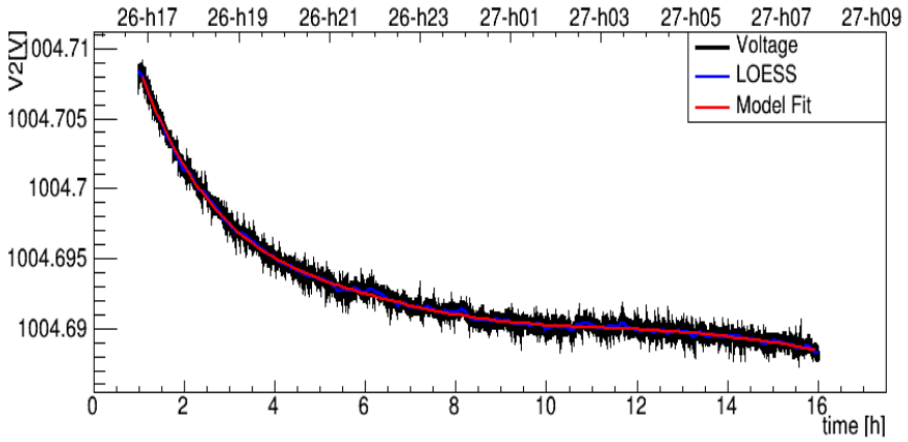
Ultra high precision high voltage

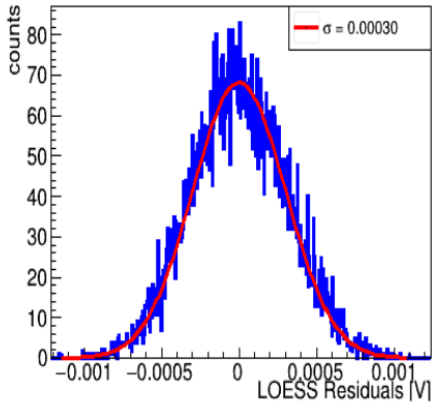
Field mill readout



20 board, 1 kV each







On a single board:
σ < 0.2 mV
0.2 ppm!

R.Ammendola et al., JINST 21 (2026)04, P04009

The Ptolemy ingredients

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

- Fast ~30 GHz radiation detection as *trigger*
  - cyclotron radiation emission spectroscopy (**CRES** - see Project-8)

- **Novel electromagnetic filter**

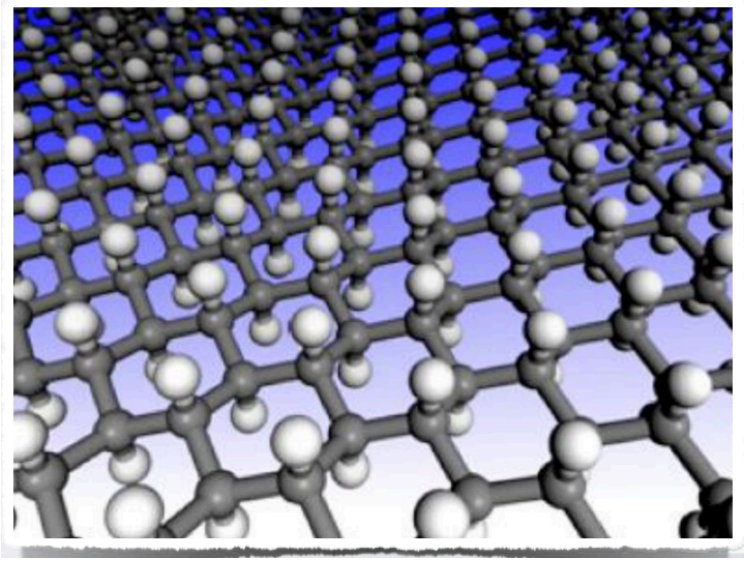
M.G.Betti et al,
Progress in Particle and Nuclear Physics,
106, (2019) 120-131

- Hemispherical electrostatic analyser
  - *In future* cryogenic **micro-calorimeter** based on Transition Edge Sensors (**TES**)

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

Use hydrogen (and deuterium) as a proxy of tritium

- **^{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) 0.02 μg/cm^2
  - One ***^{3}H each C atom***

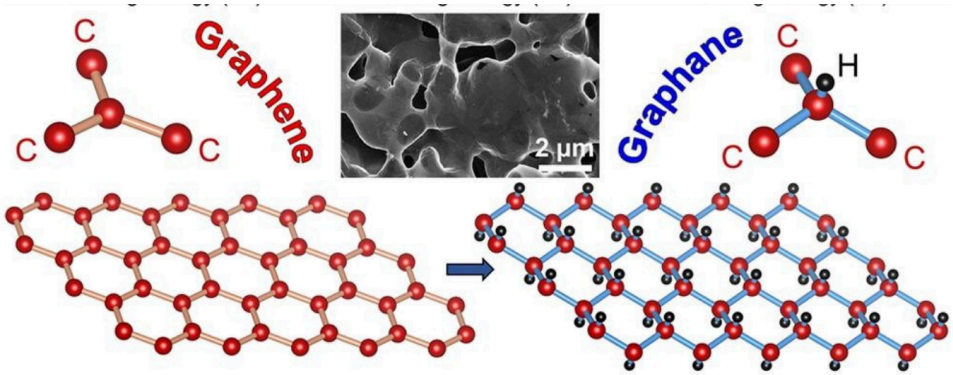
Mahmoud Mohamed Saad Abdelnabi et al 2021 Nanotechnology 32 035707

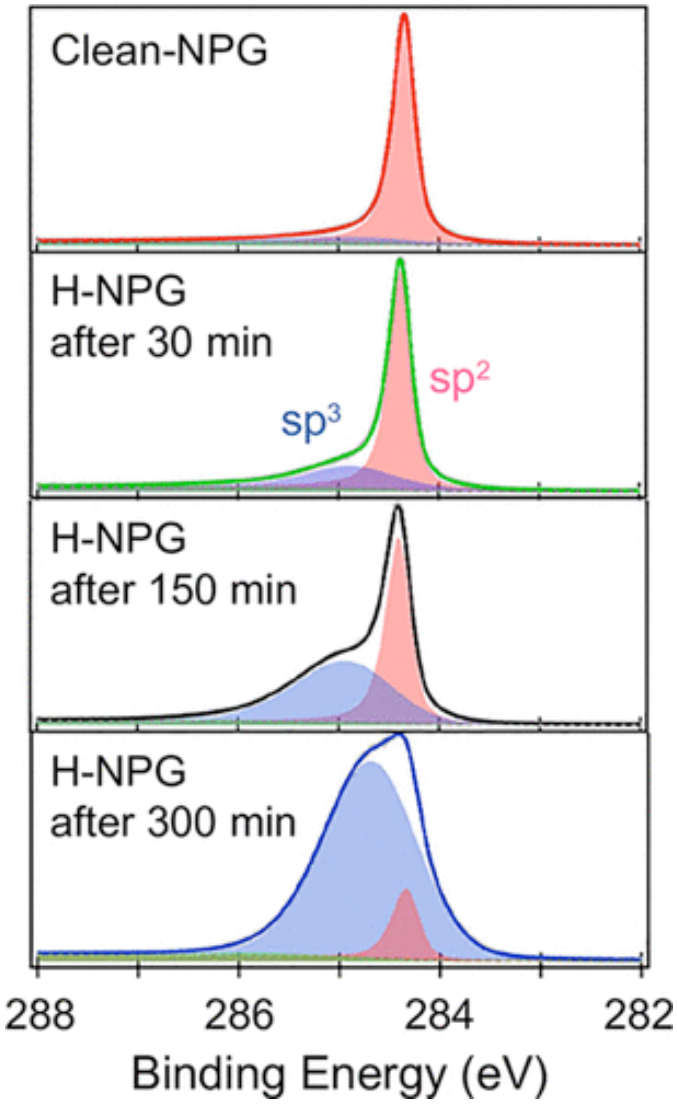
Mahmoud Mohamed Saad Abdelnabi et al Nanomaterials 2021, 11(1), 130

Graphane

M.G.Betti et al., Nano Lett. 2022, 22, 7, 2971–2977

- Larger than **90% hydrogen coverage**
  - In situ and in vacuum *H* thermal cracking
  - X-ray photoelectron spectroscopy on *C* 1s: amount of sp^3 coordinated *H*
- **Band-gap** observed: semiconductor (graph**A**ne)



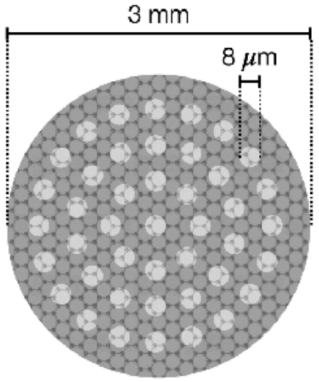


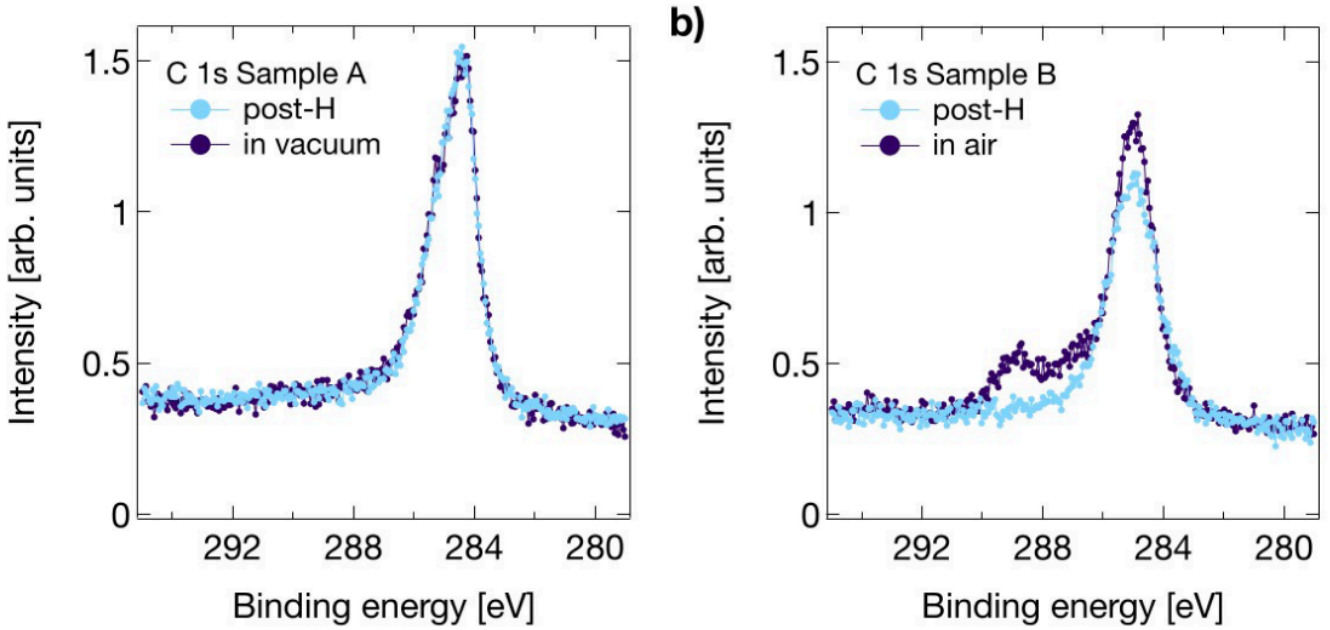
Next: put tritium on graphene and demonstrate it is a "solid" radioactive source

Stability in vacuum

Apponi et al, App. Surf.Sc., (2026) 165658 723

Graphene on TEM grid



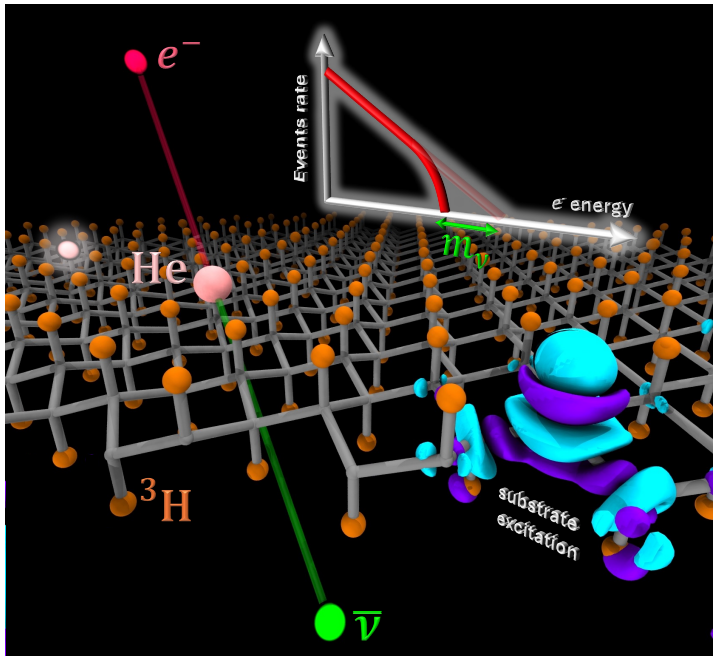


- Monolayer graphene hydrogenated and kept in vacuum
  No sign of loss of hydrogen after months
- Also study of graphene **transparency** to electrons
  (GREEAT project - CNS5 - A.Apponi)

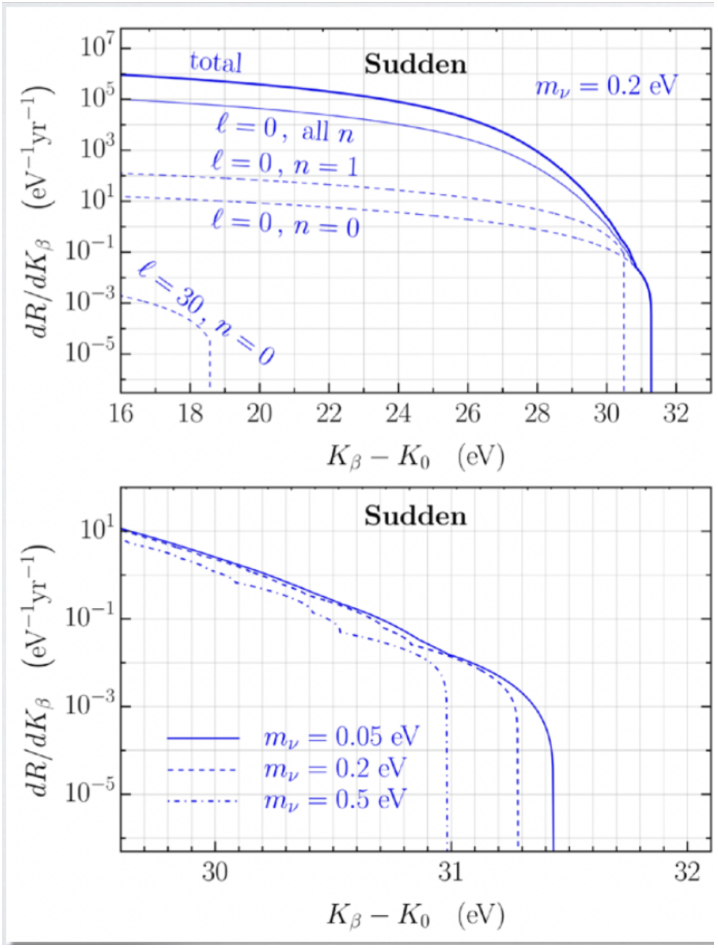
Our method here: Apponi et al, Carbon,216,2024,118502

Condensed matter and nuclear physics

- Graphene substrates with tritium:
  Density functional theory with quantum nuclear physics



A.Casale et al Phys. Rev. C 113, 054607 (2026)



Different timescale

Modelling Endpoint

The Ptolemy ingredients

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

- Fast ~30 GHz radiation detection as *trigger*
  - cyclotron radiation emission spectroscopy (**CRES** - see Project-8)

- **Novel electromagnetic filter**

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

- Hemispherical electrostatic analyser
  - *In future* cryogenic **micro-calorimeter** based on Transition Edge Sensors (**TES**)

Trigger with CRES

- Exploit the (fast) cyclotron motion around B lines
  - RF radiation emission (around 30 GHz in a 1 T field)

$$\text{power } P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{|q|^4 B^2}{m^2 c}(\gamma^2-1)\sin^2\theta \quad \text{Pitch angle}$$

$$\text{frequency } f_c = \frac{1}{2\pi}\frac{|q|B}{m}\frac{1}{K/m+1} \quad \text{Electron kinetic energy}$$

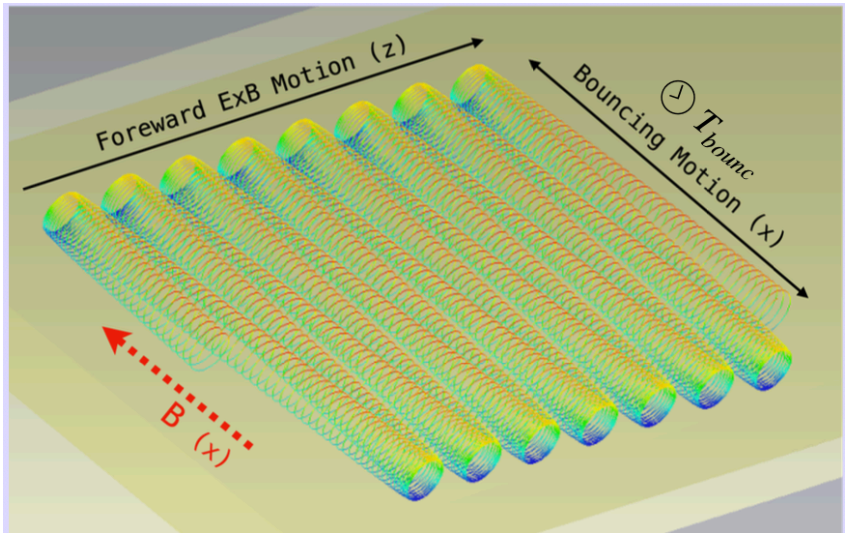
  - Relatively coarse **energy** measurement (~10 eV)
    - **Input** to the dynamic filter: switch ON the **electrodes**

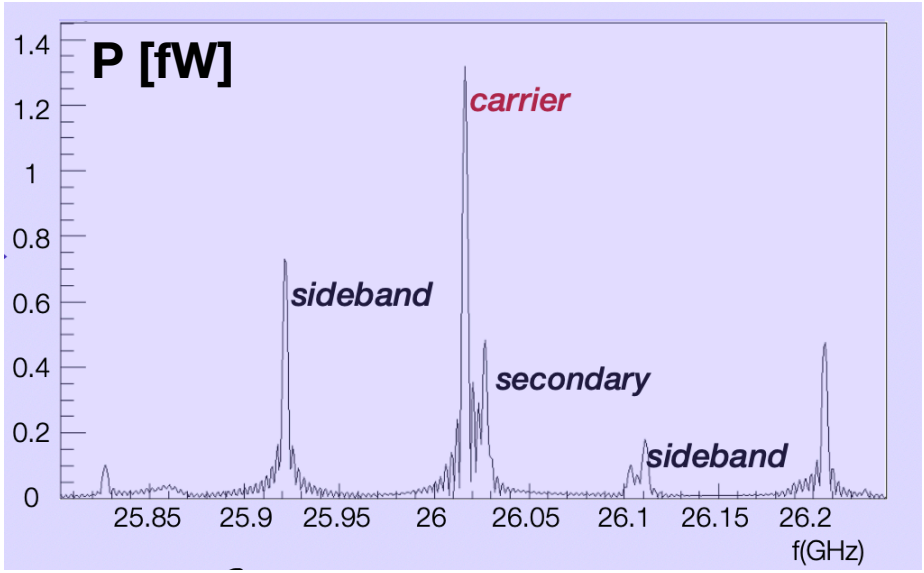
  - Information on the **pitch angle (wrt B field)**

RF radiation emission

In the high field region where electrons are transversely trapped

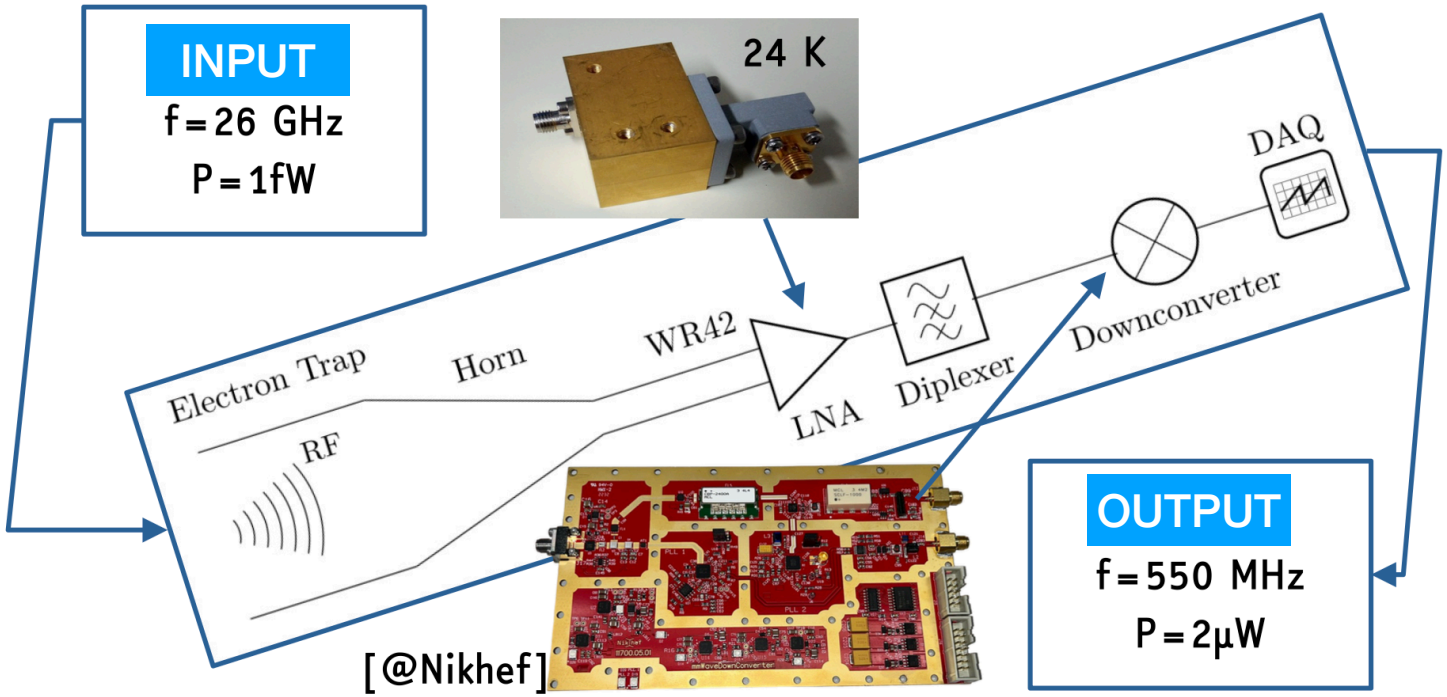
Main frequency (carrier) $\mathbf{f_c}$ + sideband frequencies $\mathbf{1/T_{bounc}}$





- Energy resolution ~10 eV in a 10-100 μs observation interval

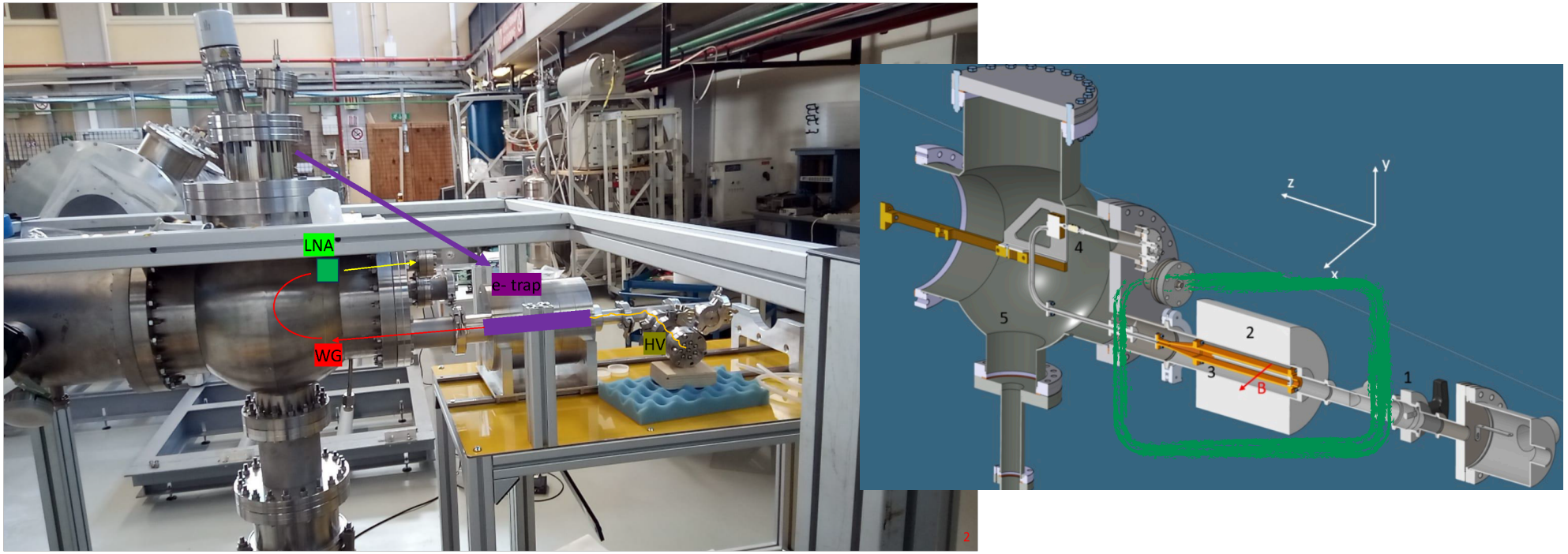
RF radiation detection



- Antenna collecting the radiation
- Cold amplifier + downconversion
- Custom FPGA

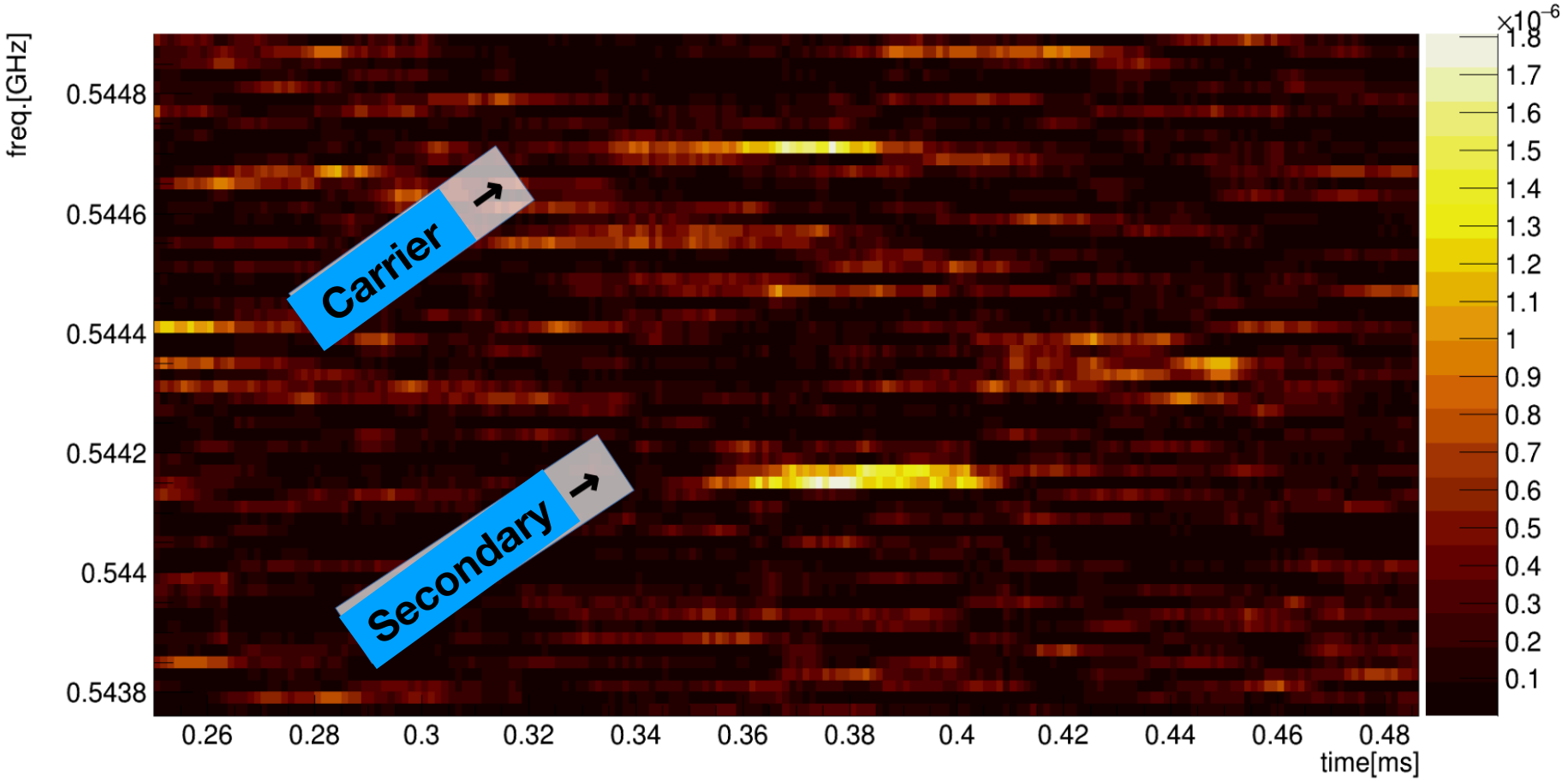
R&D at LNGS

- Small **dipole magnet** with a **waveguide** inside
- Electrodes inside the waveguide



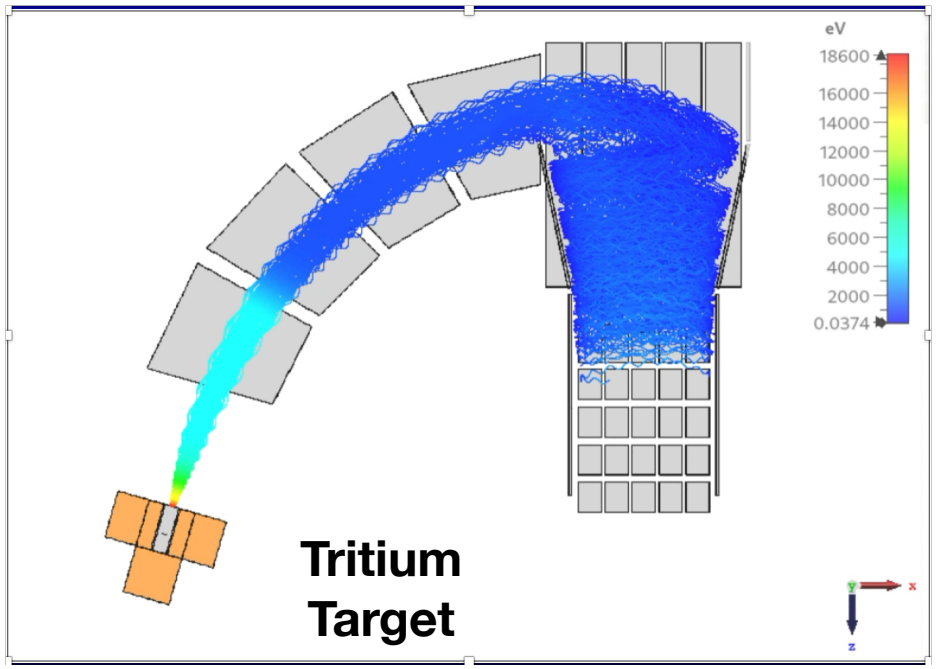
Calibration with ^{83}Kr atoms injected into the waveguide (~30 keV electrons)

Electron event (example)



Full simulation

- Based on COMSOL, **CST**, Kassiopeia,…
- Developed a custom code for particle tracking (**Lorentz4 -** open source code by Ptolemy)
- Currently working in injection into the magnet and collection after the filter



Recent results
Pitch angle compression
at the entrance of the
Main B field

Simulation will lead
the design of the electric field
Electrodes

The Ptolemy ingredients

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

- Fast ~30 GHz radiation detection as *trigger*
  - cyclotron radiation emission spectroscopy (**CRES** - see Project-8)

- **Novel electromagnetic filter**

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

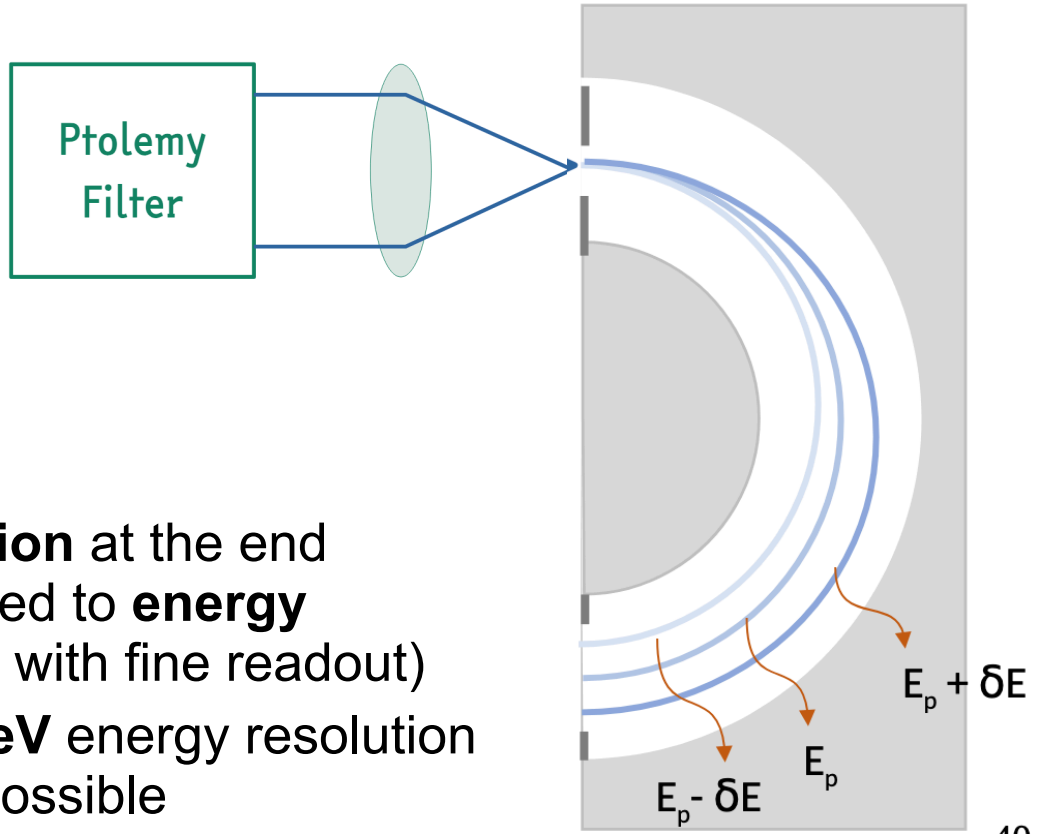
- Hemispherical electrostatic analyser
  - *In future* cryogenic **micro-calorimeter** based on Transition Edge Sensors (**TES**)

Final electron analyser

- Electrons with Ep ~10-100 eV are propagating within hemispherical electrodes.



Routinely used in synchrotron beam lines for condensed matter physics experiments

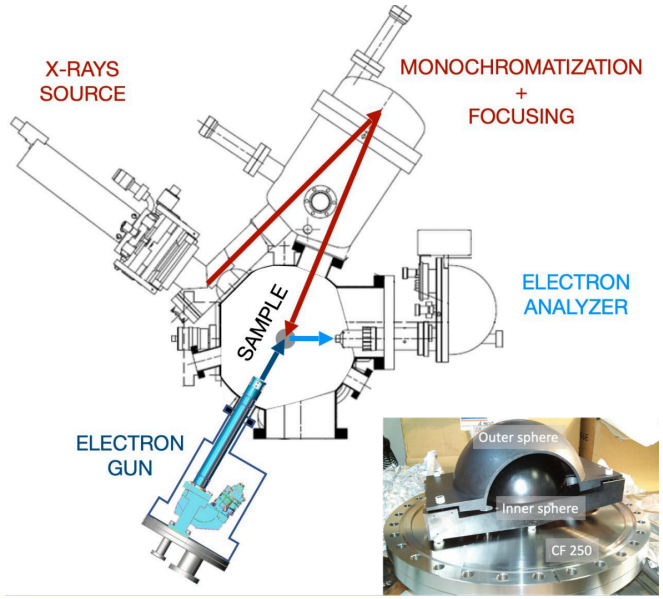


- **Position** at the end mapped to **energy** (MCP with fine readout)
- **10 meV** energy resolution well possible

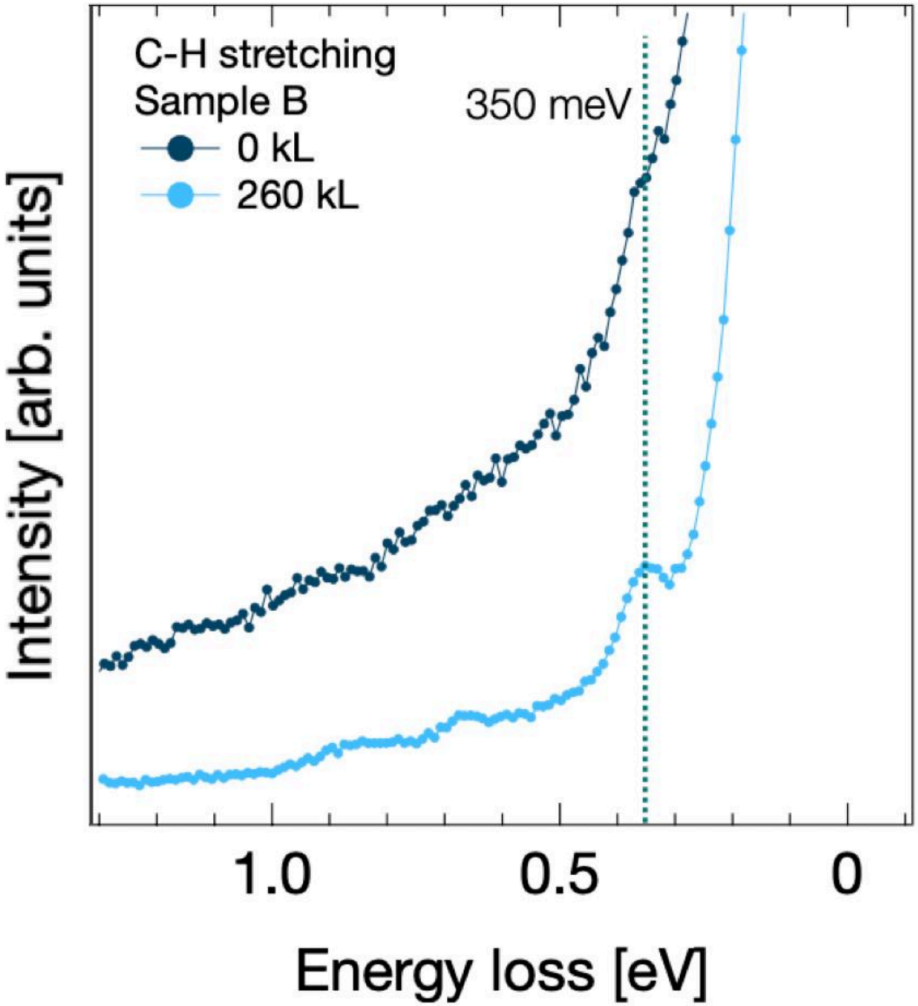
Detecting electrons with mV resolution

- Detecting **90 eV** electrons scattering on hydrogenated graphene with **60 meV** resolution
- C-H stretching energy (**350 meV**) visible!

Electron Energy Loss Spectroscopy
LASEC @ RomaTre

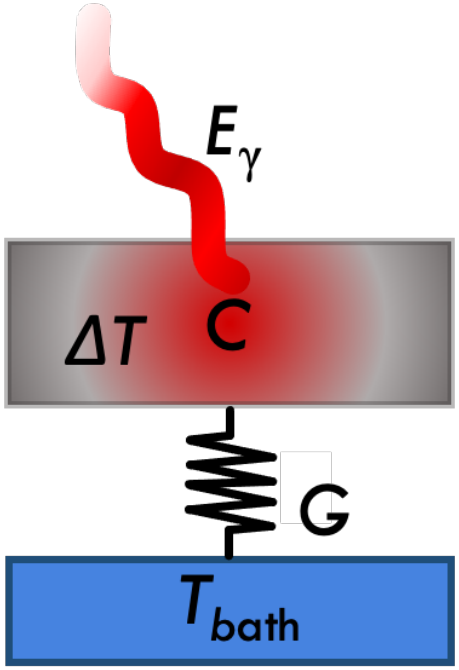


Apponi et al, App. Surf. Sc. 753 (2027) 168433

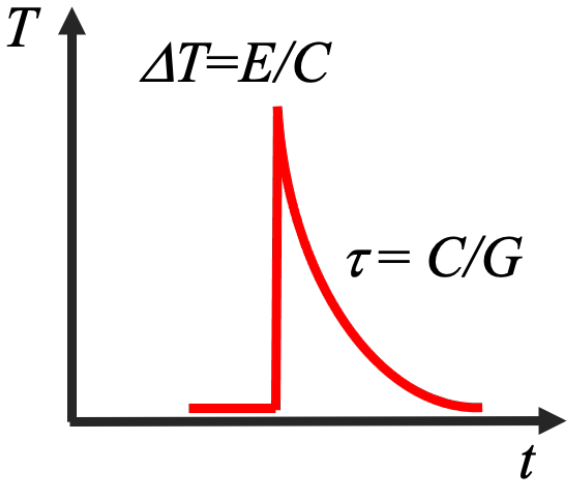


Detection with cryo-micro-calorimeters

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



C: thermal capacitance
G: thermal conductance

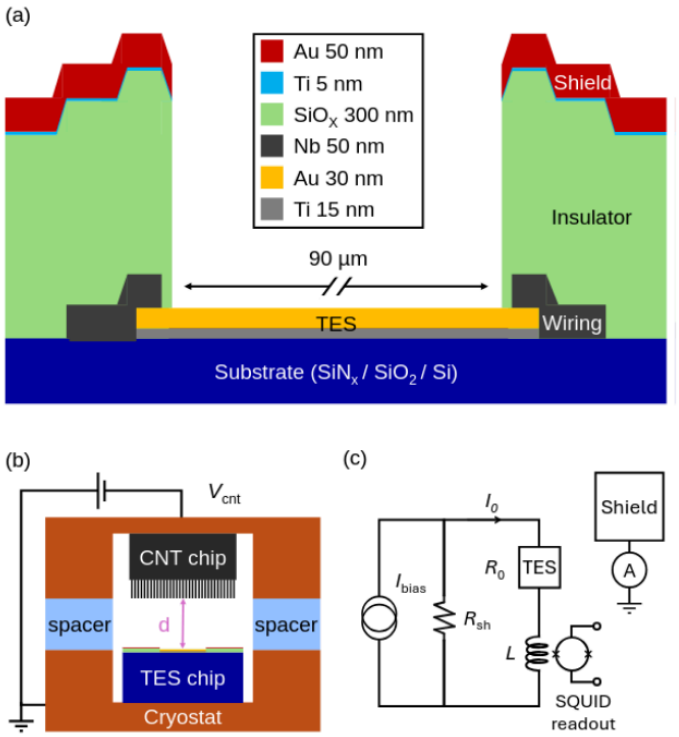


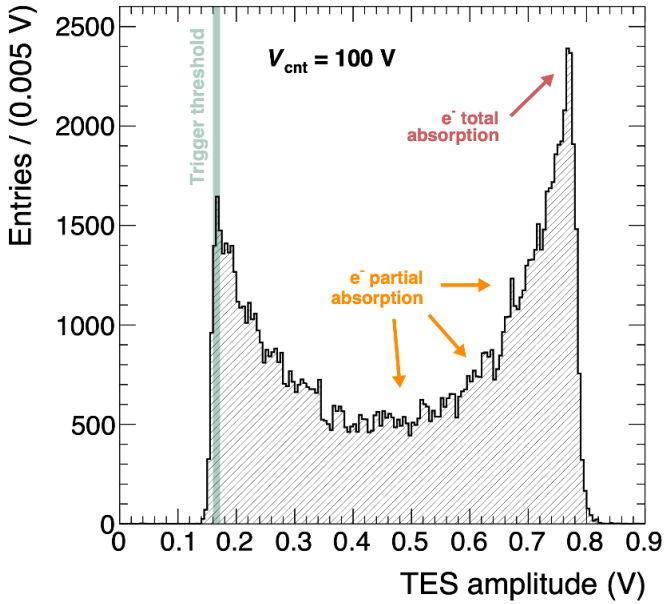
$$\Delta E \approx (k_B T^2 C B)^{\frac{1}{2}}$$

Energy resolution: better at low T and small C

Detection of electrons with TES

- 50 meV resolution obtained on 0.8 photons with TES
- **BUT**, Electron absorption mechanism **very** different from photons at 10-100 eV.





C.Pepe et al, PR App 22.4 (2024) L041007

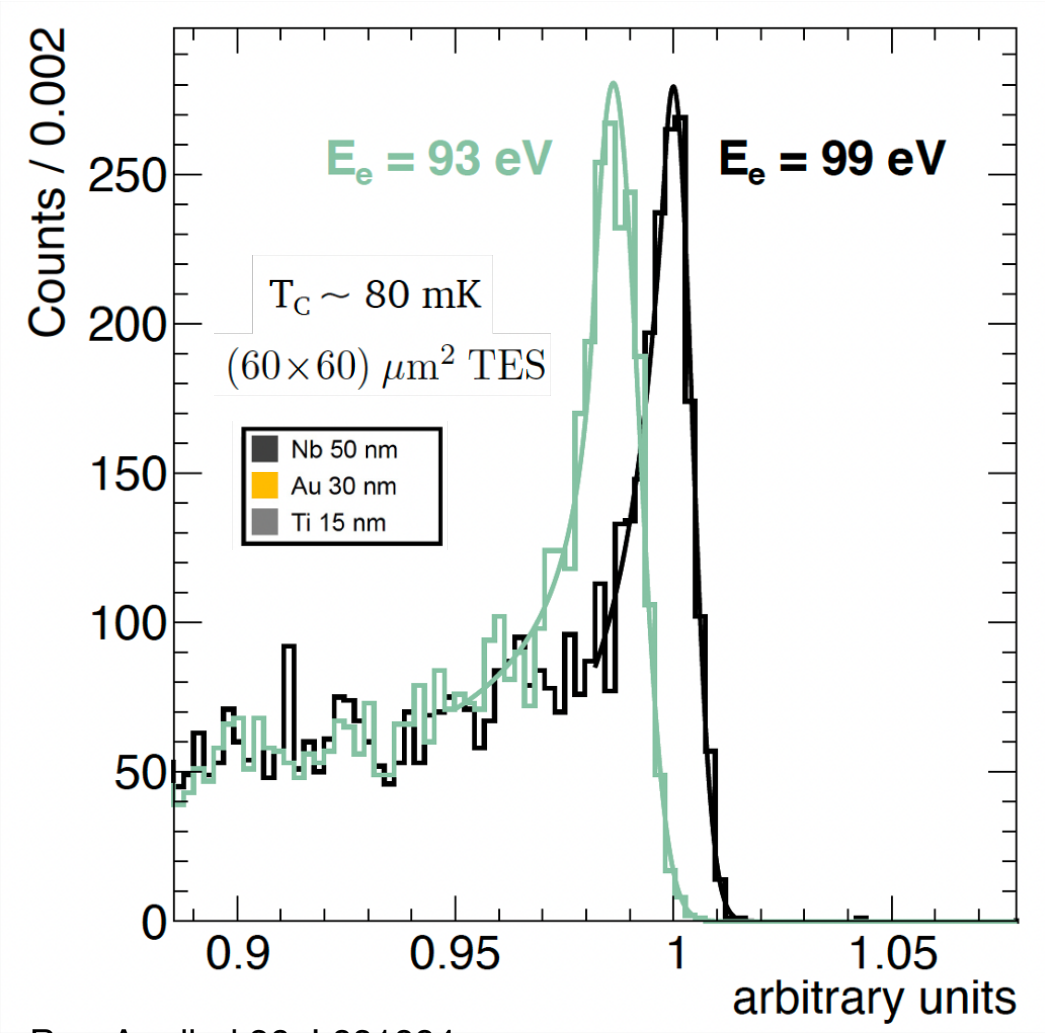
First demonstration electron and photon TES energy resolution is the same

Improving energy resolution

- Collaboration with INRIM - Sapienza
- Optimised calibration source and setup
  - CNT field emitting electrons in a cryostat
  - Better focusing on TES

Obtained $\Delta E \sim 0.5$ eV at 100 eV

Next step $\Delta E \sim 0.05$ eV at 10 eV



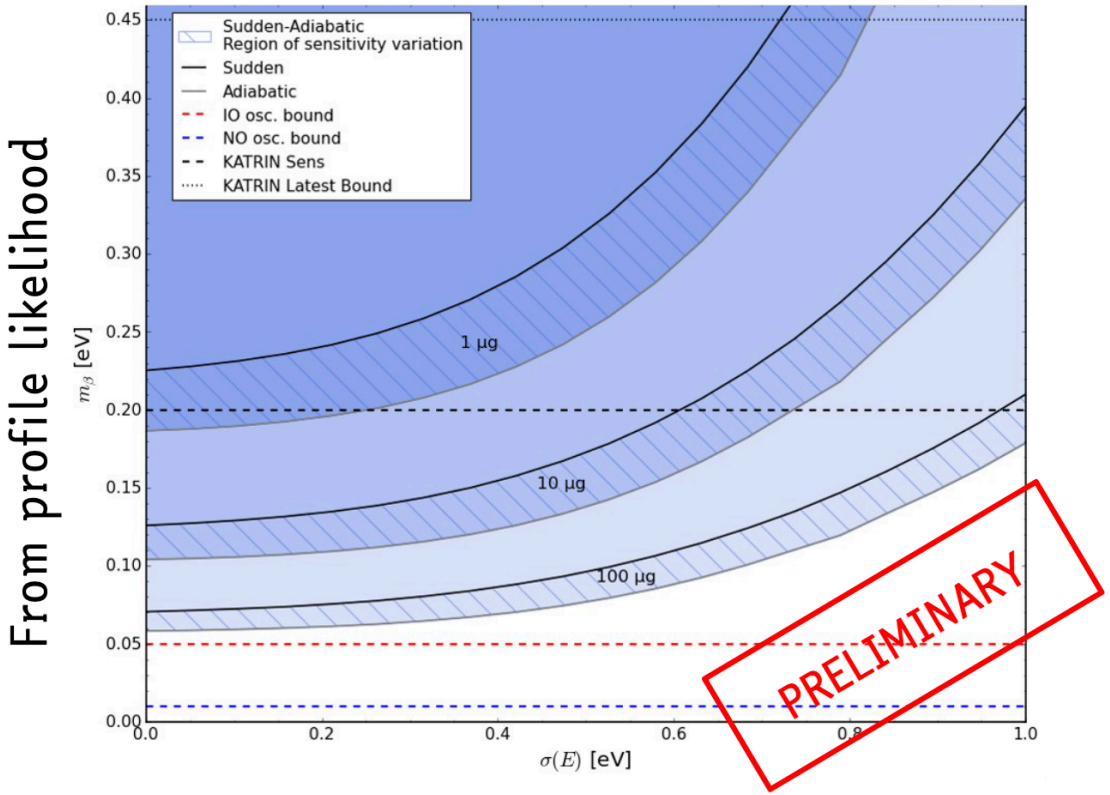
R.Ammendola et al, Phys. Rev. Applied 26, L031004



Outlook

Sensitivity to neutrino mass

- If demonstrated,
  the Ptolemy concept can then be used for a neutrino mass measurement with a 1-100 μg tritium mass



End point **theoretical systematic** (tritium bond to graphene) included

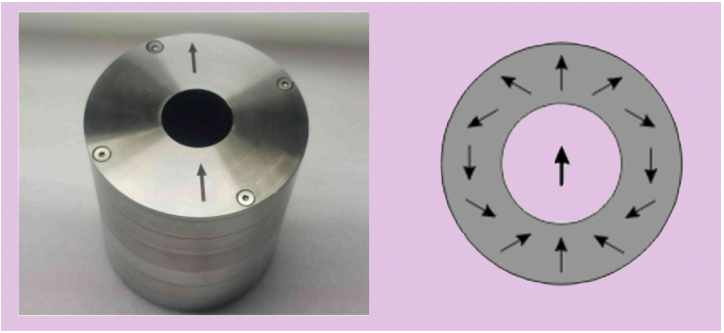
A.Casale et al Phys. Rev. C 113, 054607 (2026)

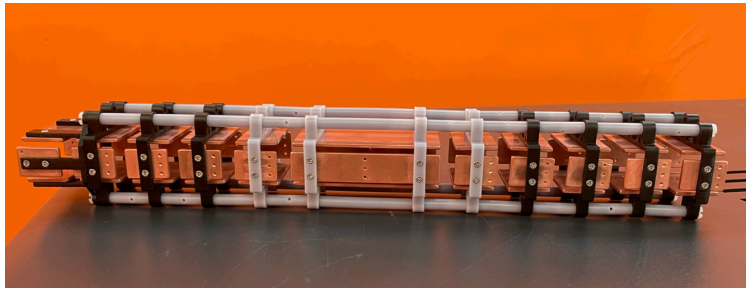
&

Apponi et al Phys. Rev. D 106, 053002

First small scale prototype at LNGS

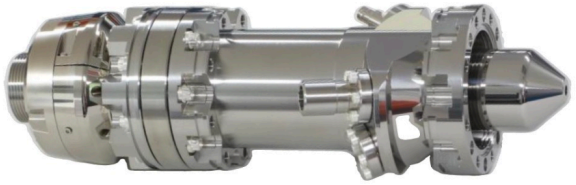
- Halbach cylinder permanent magnet (1 T, 5 cm diameter)





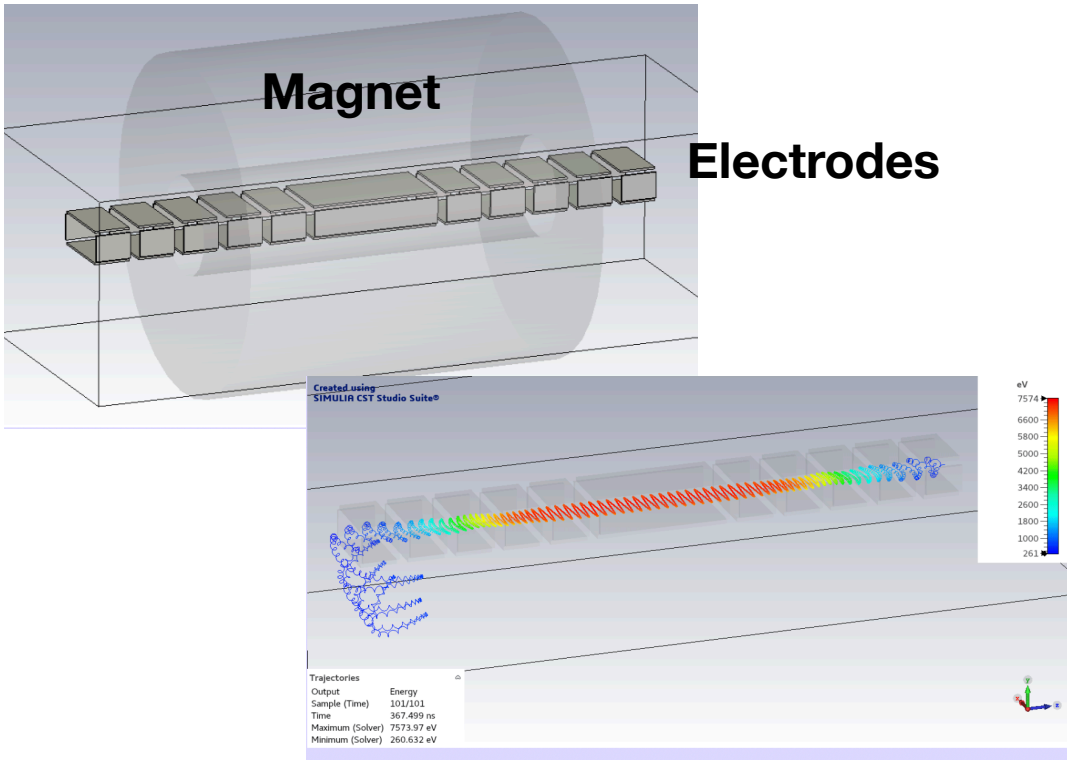
- Optimised electrodes

Kimball 1-20 keV electron gun



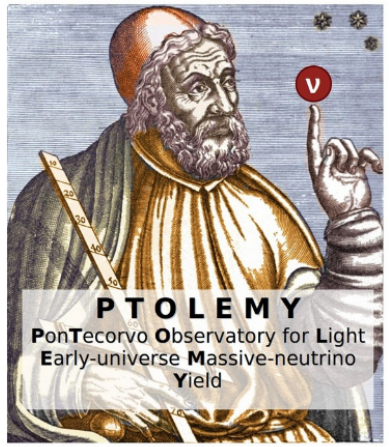
Injection of low energy particles+ acceleration + deceleration and detection

Work in progress



Summary

- Ptolemy project aims at developing a novel **small-sized** spectrometer for a future CvB detection
- A first step will be to measure the endpoint of tritium and make a competitive **neutrino mass** measurement



- **Filter demonstrator** being **assembled** in **2027** at INFN **LNGS**
  - First results from other prototypes coming soon
- *A neutrino mass experiment being proposed afterwards*

- **Feasibility** study to port **graphene** **hydrogenation** to **tritium**: now working with **UK AEA** at AGHS for JET at Culham (H3AT)

  - **Many advances in critical aspects** (low energy electron detection, graphene characterisations, theoretical uncertainty evaluation, high voltage measurement & monitoring,…)

Theoretical description of β spectrum

- Tritium atom bond to graphene carbon atom. *Condensed matter effect visibile at the endpoint* (^{3}He bound states vs. free ^{3}He state)
- Employing advanced condensed matter methods (**DFT**)
- Modelling of the **^{3}He potential**: theoretical uncertainty (See https://arxiv.org/pdf/2504.13259)

