Ptolemy, a new detector for the cosmic neutrino background

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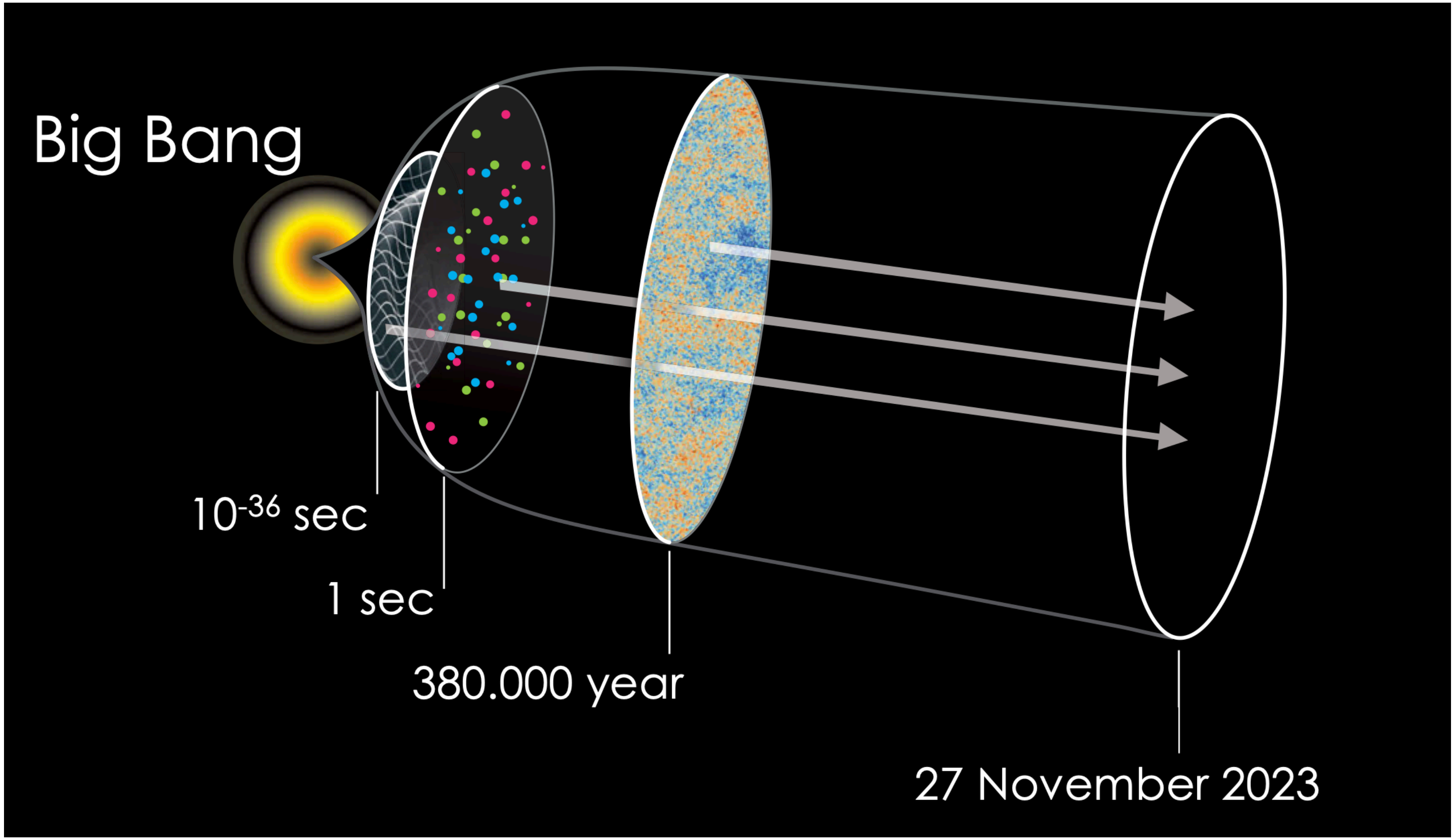
*On behalf of the **Ptolemy** Collaboration*
IJCLab Nov 27th 2023

Outline

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

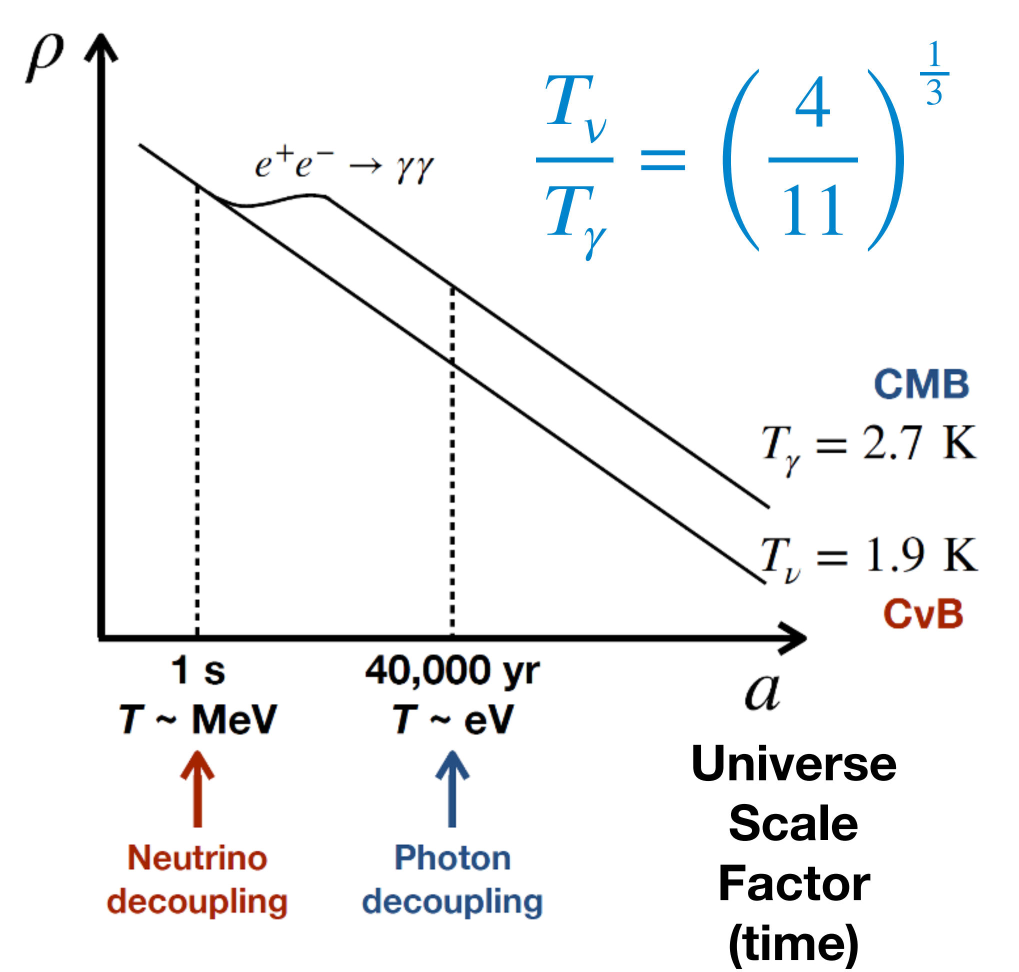
- The **Ptolemy** project
  - A novel type of electro-magnetic **filter**
  - **Advanced** detection concepts (nano-fabricated transition edge sensors, very low power radio-frequency detection)
  - A Tritium target based on **carbon nanostructure**

The history of Universe in short



- What happened 1 sec after the Big Bang??

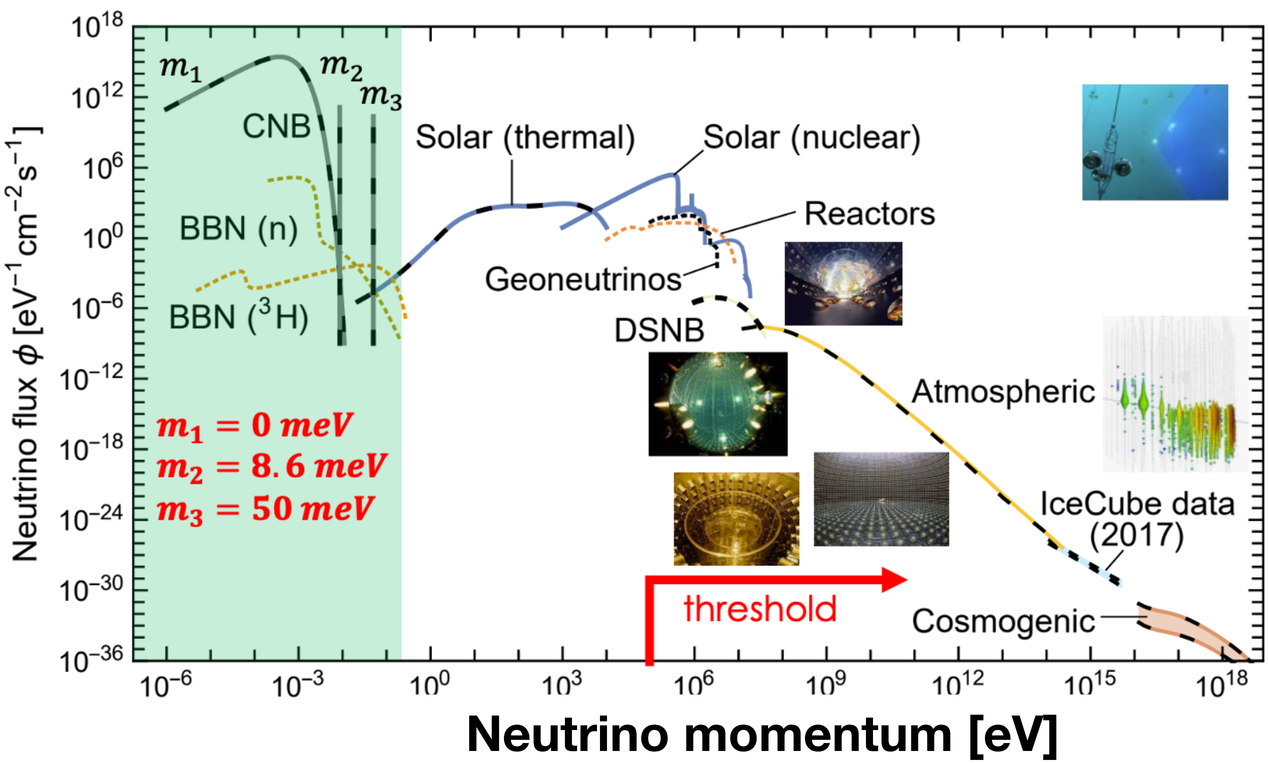
Neutrinos decoupling



- 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**

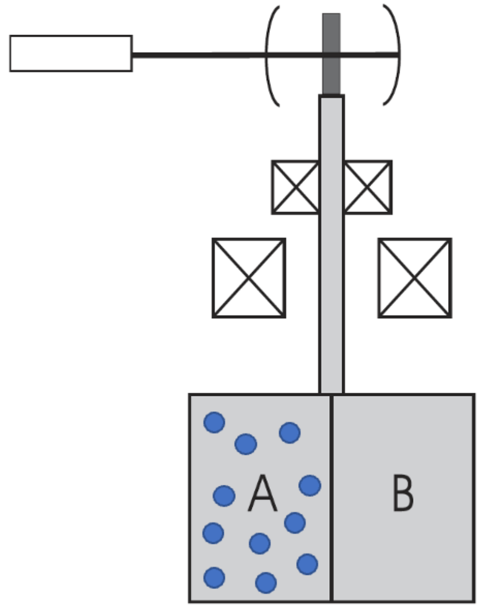


https://arxiv.org/pdf/1910.11878.pdf

A long sought messenger…

- Several **attempt** to **propose** a detection of (neutral) particle with minuscule momentum
  - Neutrino wind: **coherent** scattering
    - Need to measure a very small acceleration $O(10^{-27}\ cm/s^2)$ but with (GW) laser interferometry $\sim 10^{-16}\ cm/s^2$

Torsion balance



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

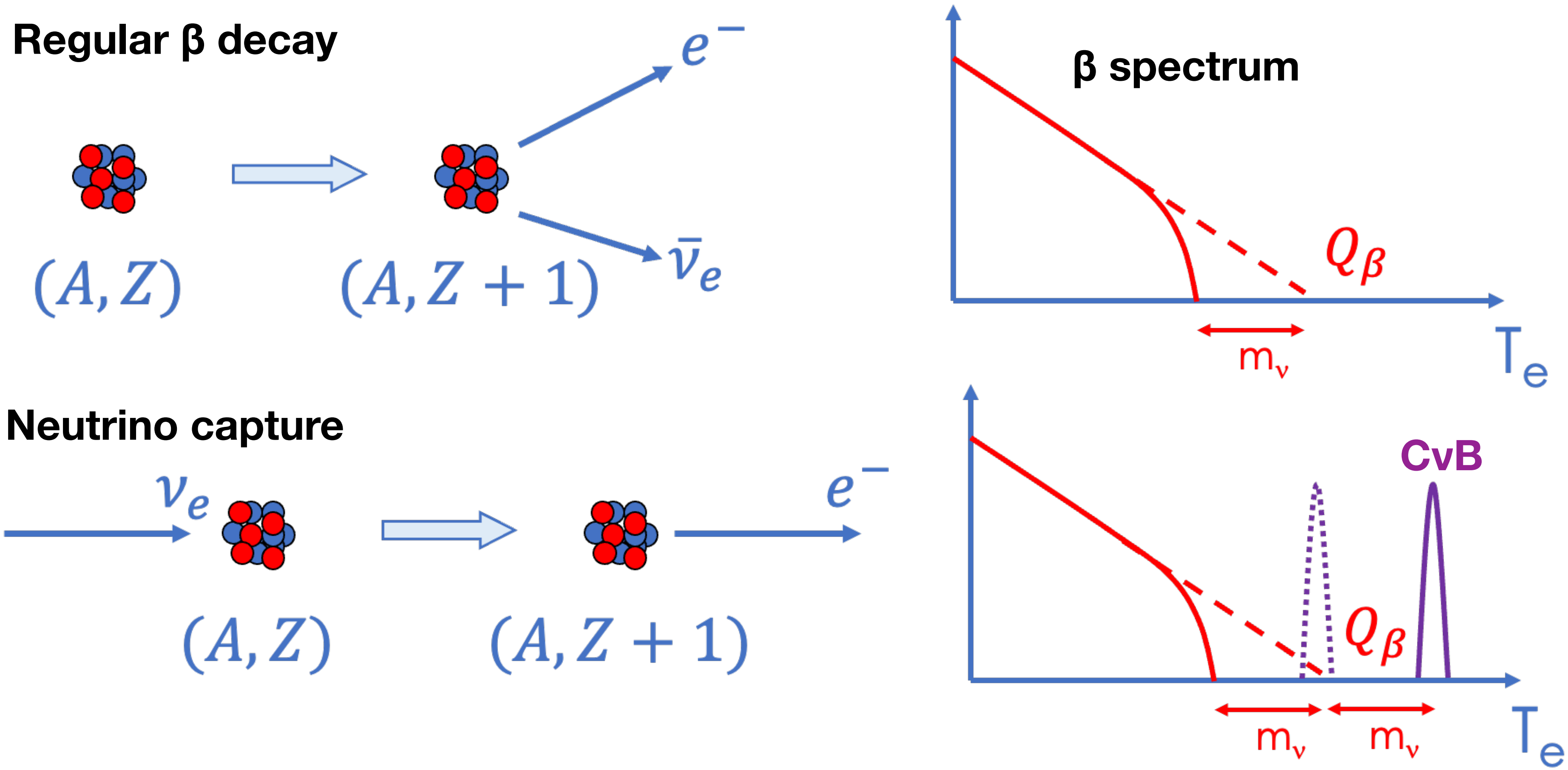
https://arxiv.org/abs/2109.07482

https://arxiv.org/abs/1703.08629

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

Capture on radioactive nuclei

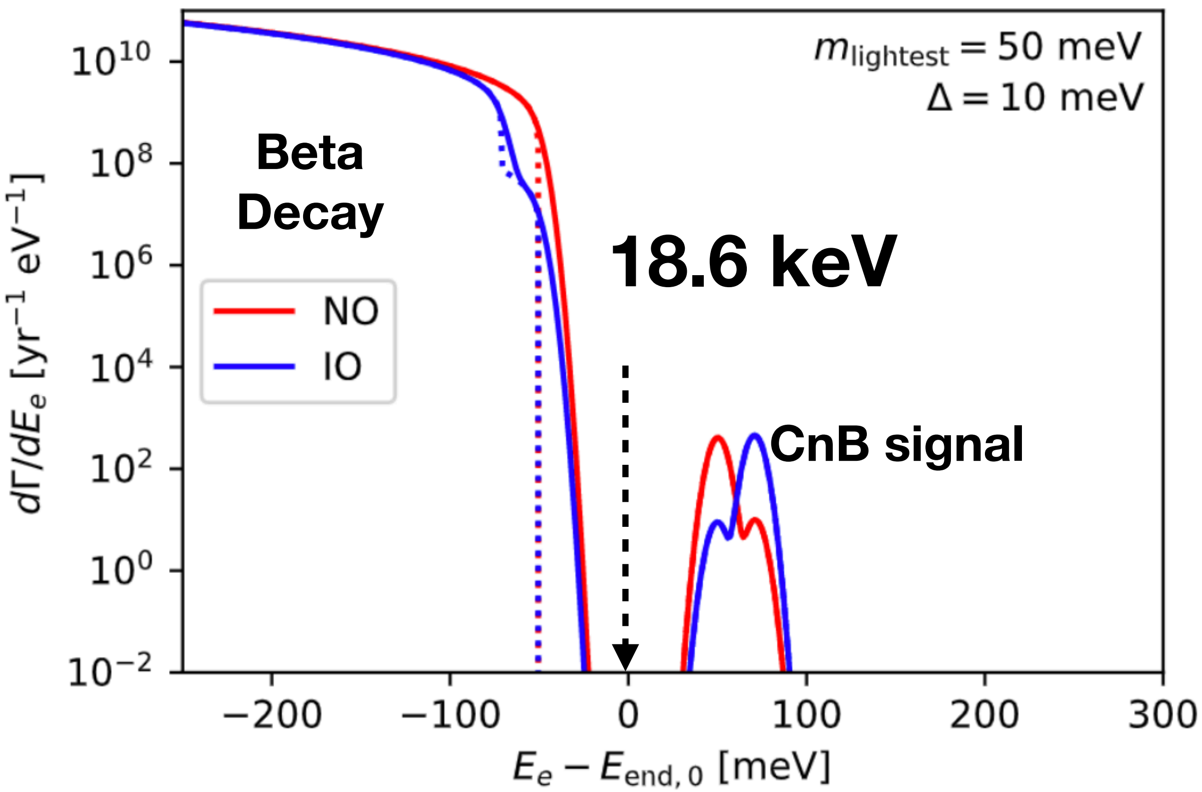
- Weinberg (1962)
- Revived more recently: Cocco, Mangano, Messina (2007)



The target, atomic tritium ^3H

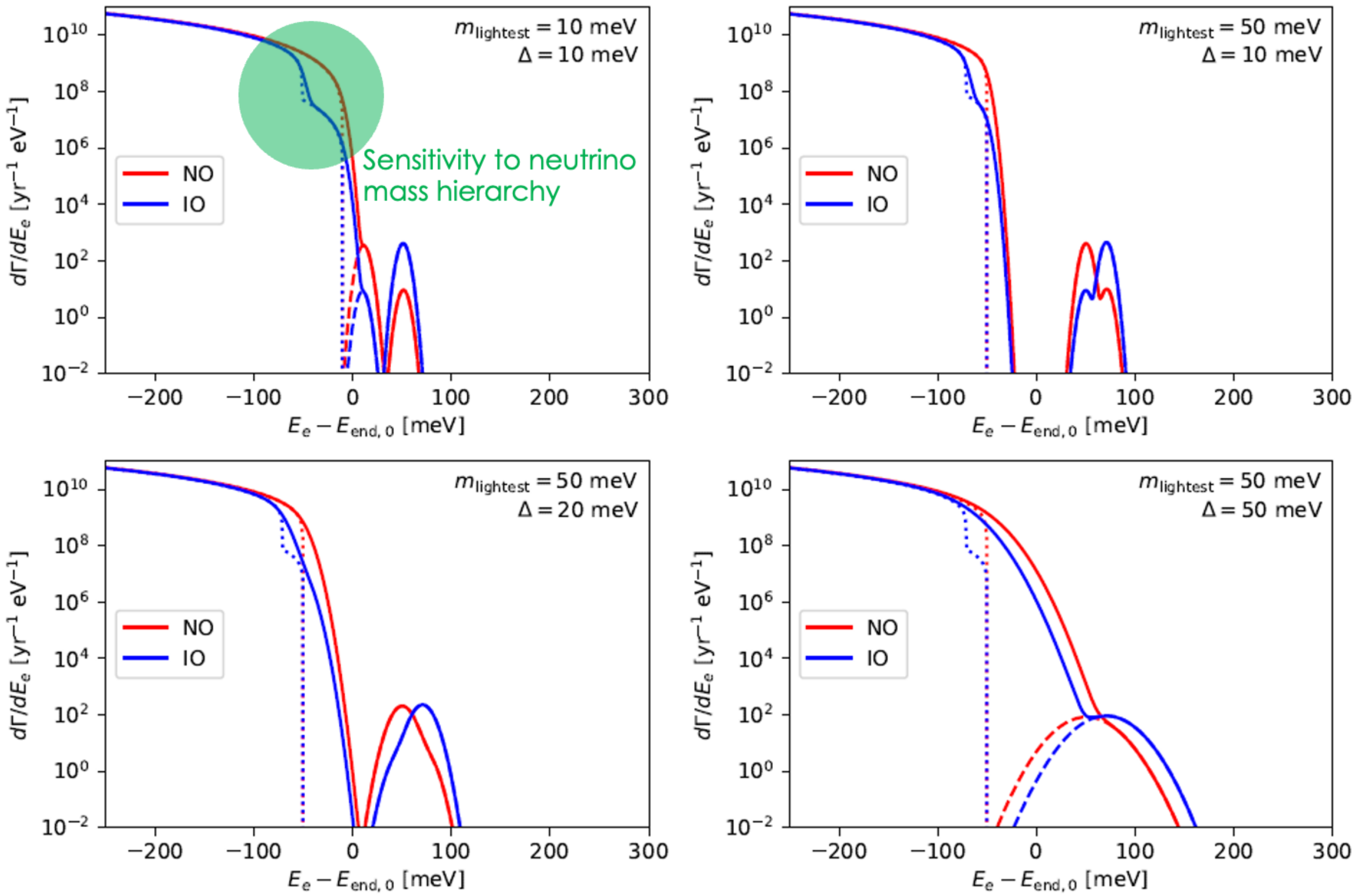
Ptolemy Coll, M.G.Betti et al. JCAP 07 (2019), 047

- 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 CvB 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

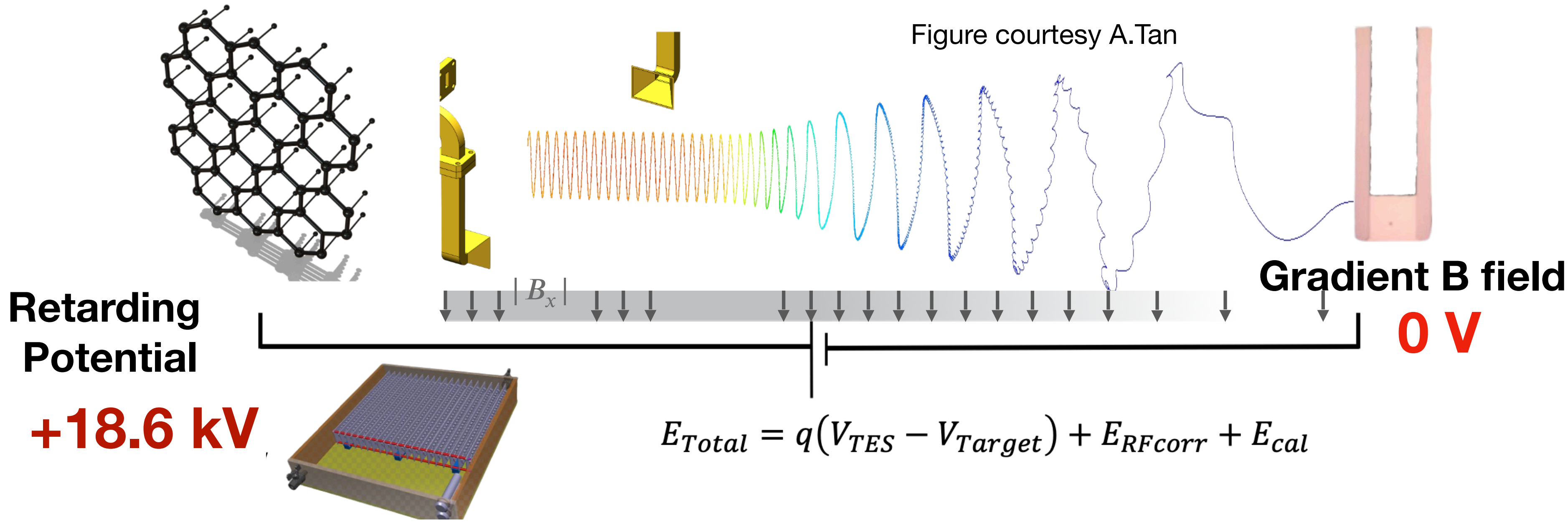
M.G. Betti et al JCAP07 (2019) 047

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)

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

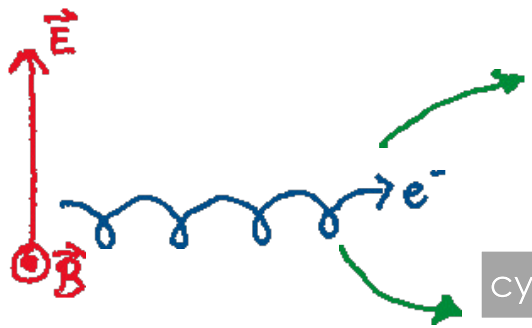
M.G.Betti et al,
Progress in Particle and Nuclear Physics,
106, (2019) 120-131

- Novel electromagnetic filter

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

Drifting electrons

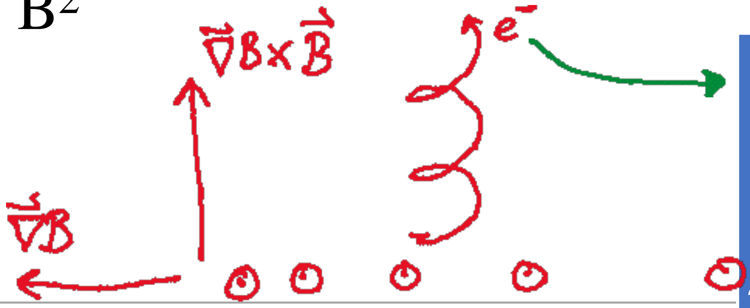
I: $\vec{E} \times \vec{B}$ drift



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 $\mu = \frac{m_e v_\perp^2}{2B}$

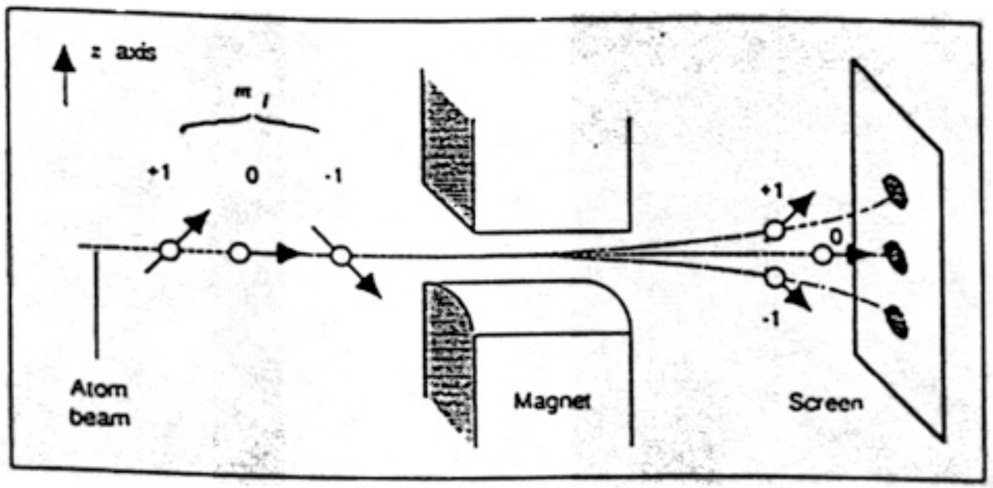


1. net drift, $v_{drift} = \mu \frac{|\vec{\nabla} B|}{B}$
2. Allows E field to work (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

- Switch on an additional vertical ***E*** field to select only the electrons close to the endpoint

Force due to gradient B field

- Remember *Stern-Gerlach* experiment
  - Select atoms according to their spin orientation thanks to (high) gradient magnetic field.



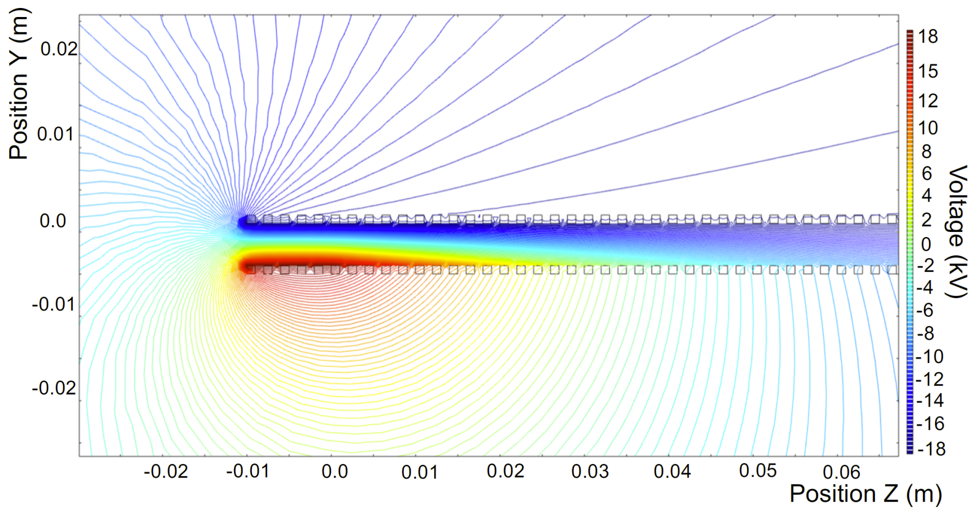
- The Ptolemy spinning β-electron has (conserved) magnetic moment

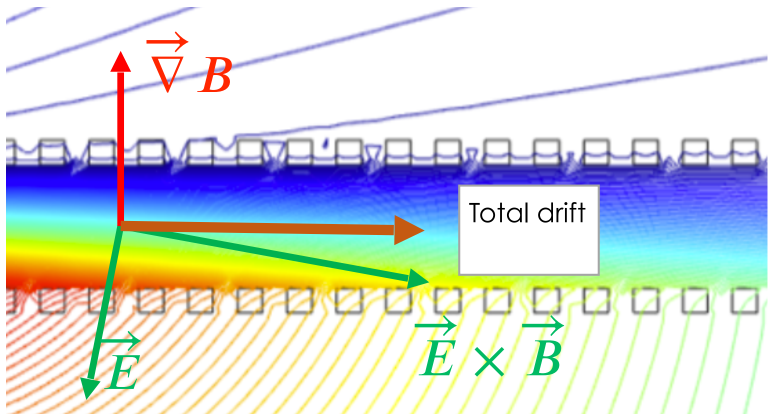
$$\mu = \frac{m_e v_\perp^2}{2B}$$

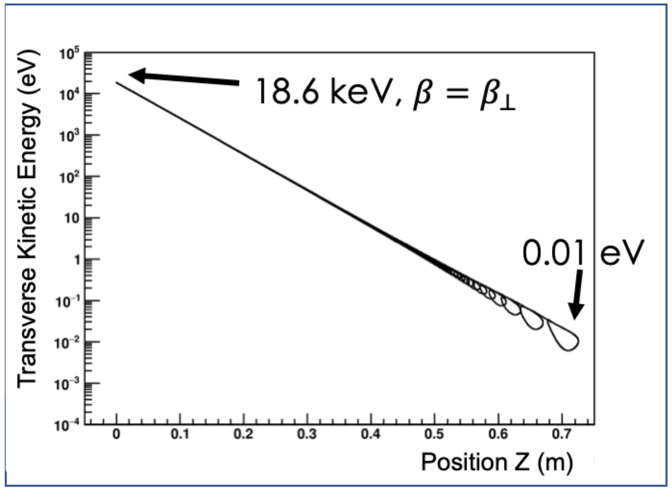
A transverse filter

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

- Switch on a “tuned” additional vertical ***E*** field to select only the electrons close to the endpoint

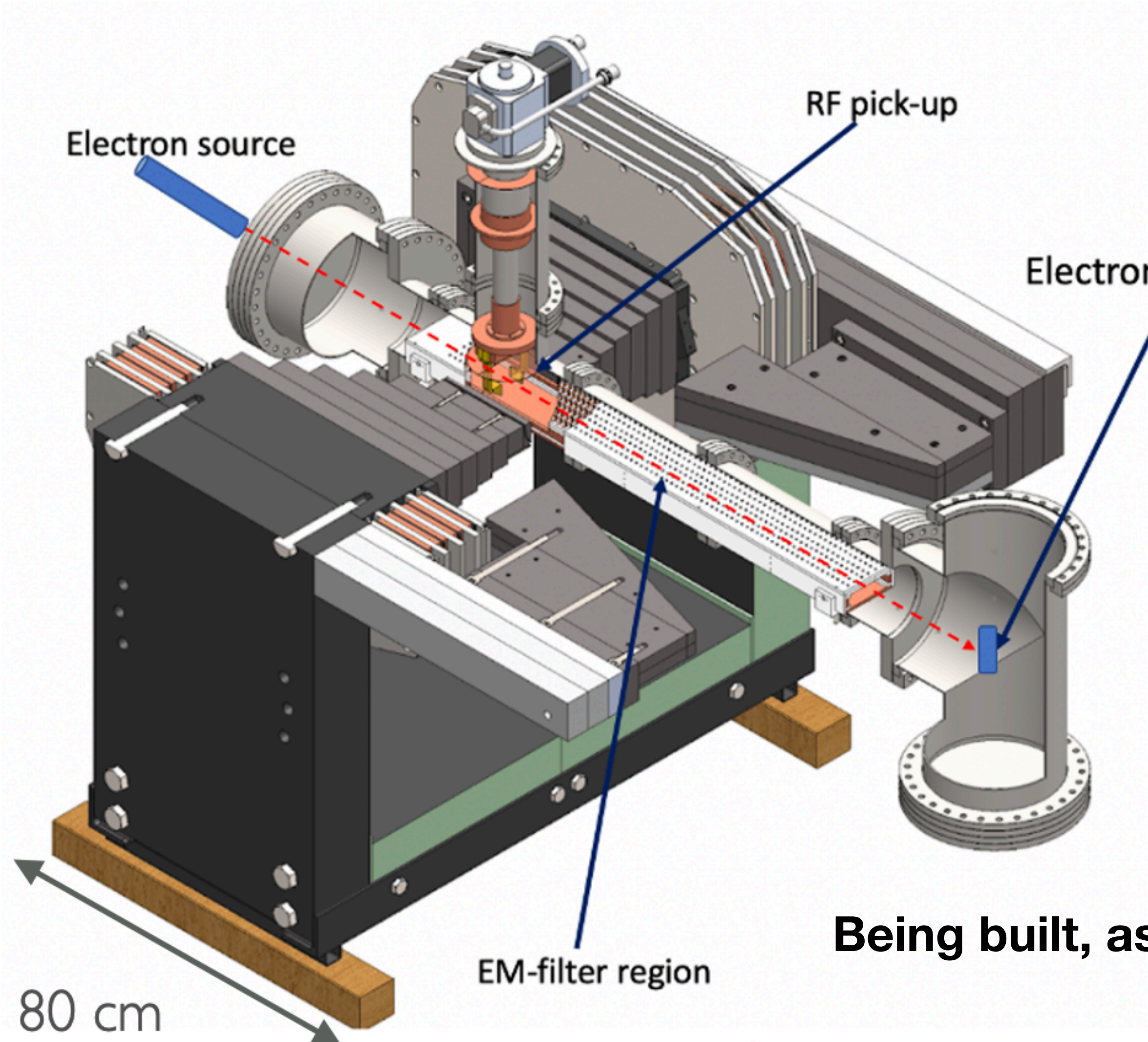




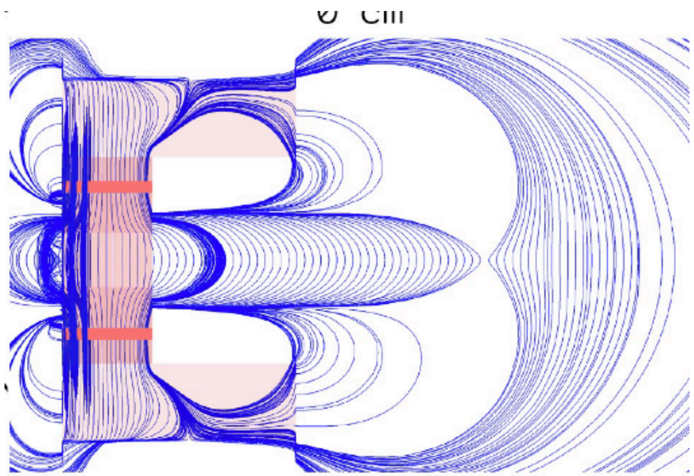


- Reduction of transverse (to ***B*** field) kinetic energy

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 2024

Cyclotron radiation as trigger

- First electrons pass in a high B field region, emission of radiation in RF range

$$f = \frac{1}{2\pi}\frac{eB}{m_e\gamma} \approx 27GHz$$

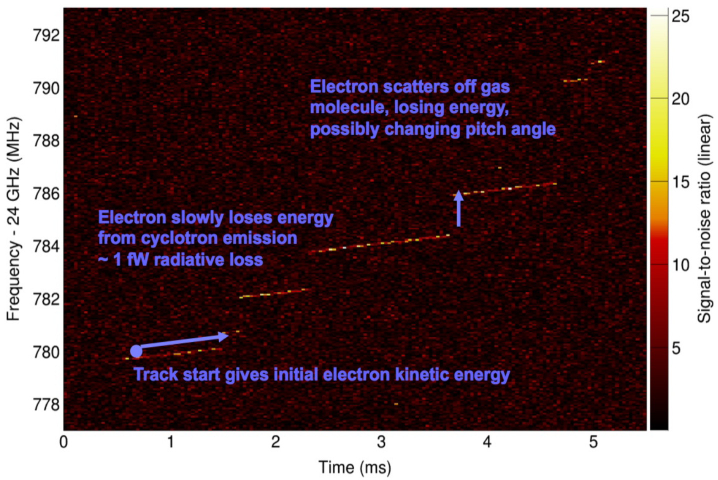
- From detected RF power (raw) sensitivity to transverse momentum

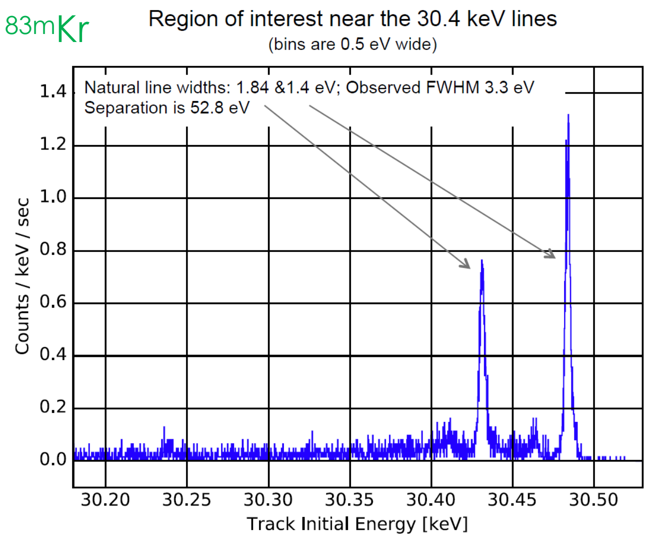
Rough O(eV) resolution (!) measurement of ***energy*** and ***pitch angle***

$$P = \frac{1}{4\,\pi\epsilon_0}\frac{2\,e^4B^2}{3m_e^2c}\left(\gamma^2-1\right)\sin^2\theta \approx 1\ fW \rightarrow \theta$$

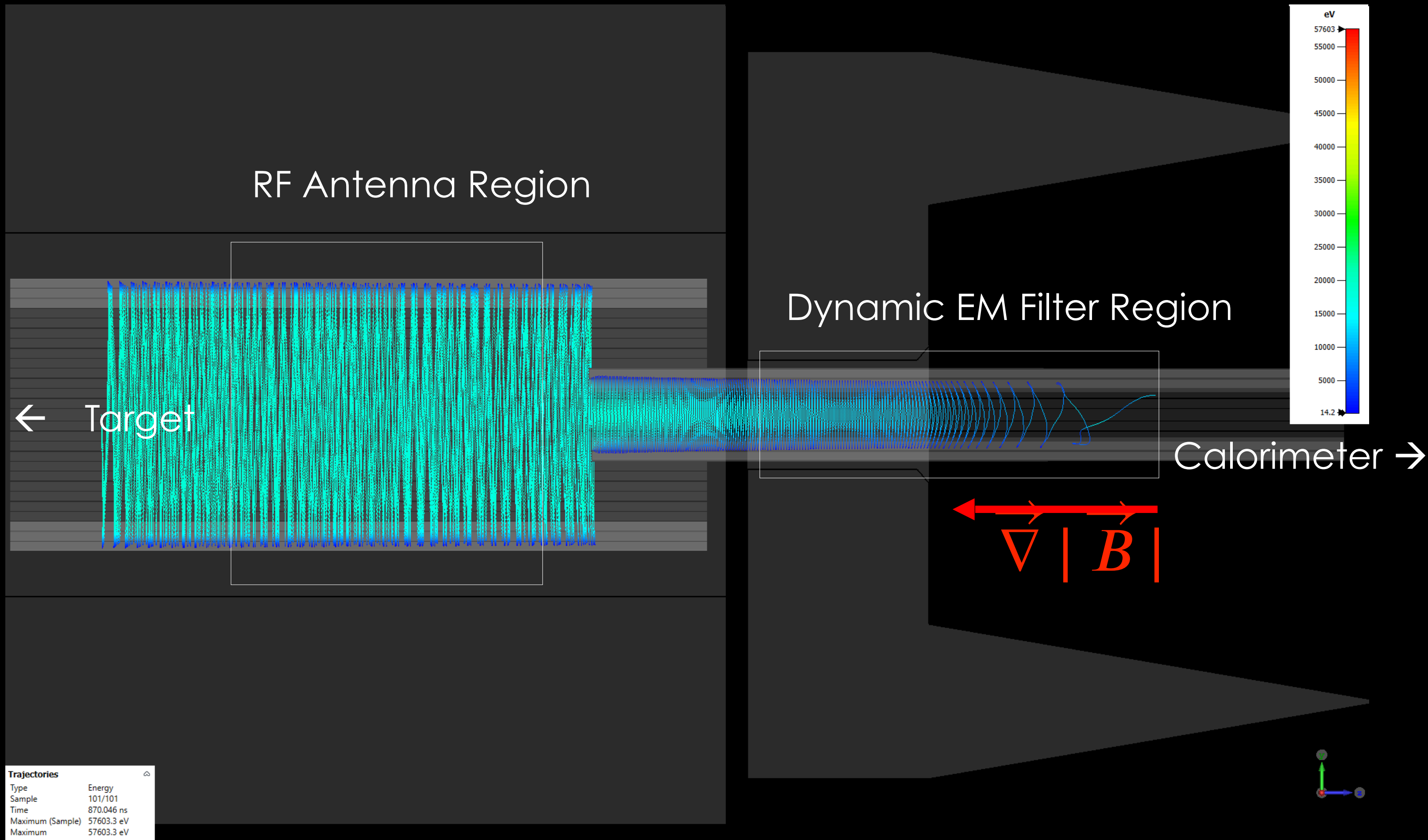
Pitch angle

Pioneering work by Project8 @ FNAL
A.Esfahani et. al, JPG Vol44,#5, 2017
https://arxiv.org/abs/1703.02037v1





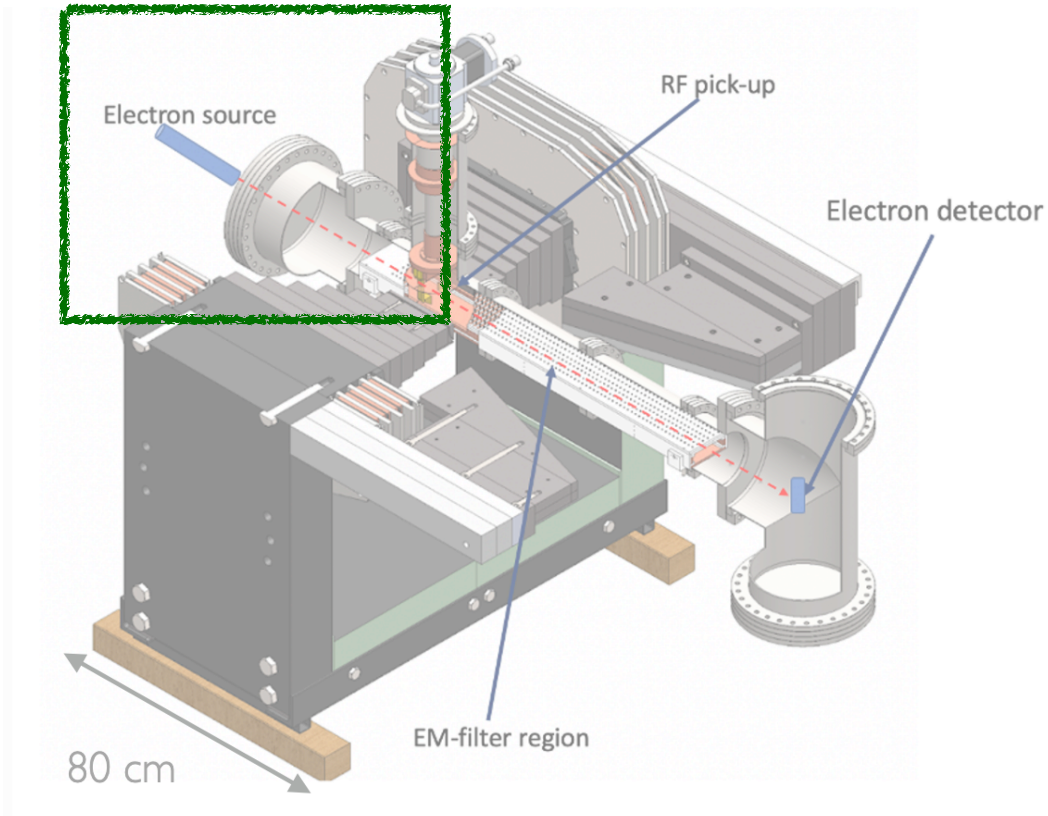
Electron Transport: RF pickup & Filter



The source and the end of the filter

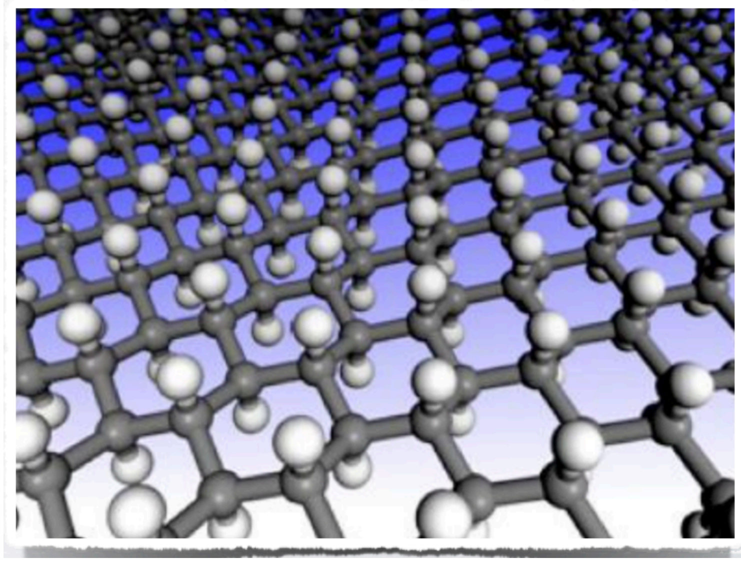
- Goal of the < 50 meV energy resolution:
  - **Preparare the initial state** on
    - A well defined spatial position (electrode)
    - Deal with intrinsic quantum spread of localisation of atomic ^3H (Heisenberg limit)
      - *Interplay with **condensed matter** physics*
  - **Detect** the electrons 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 ^3H storage

- ^3H 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***

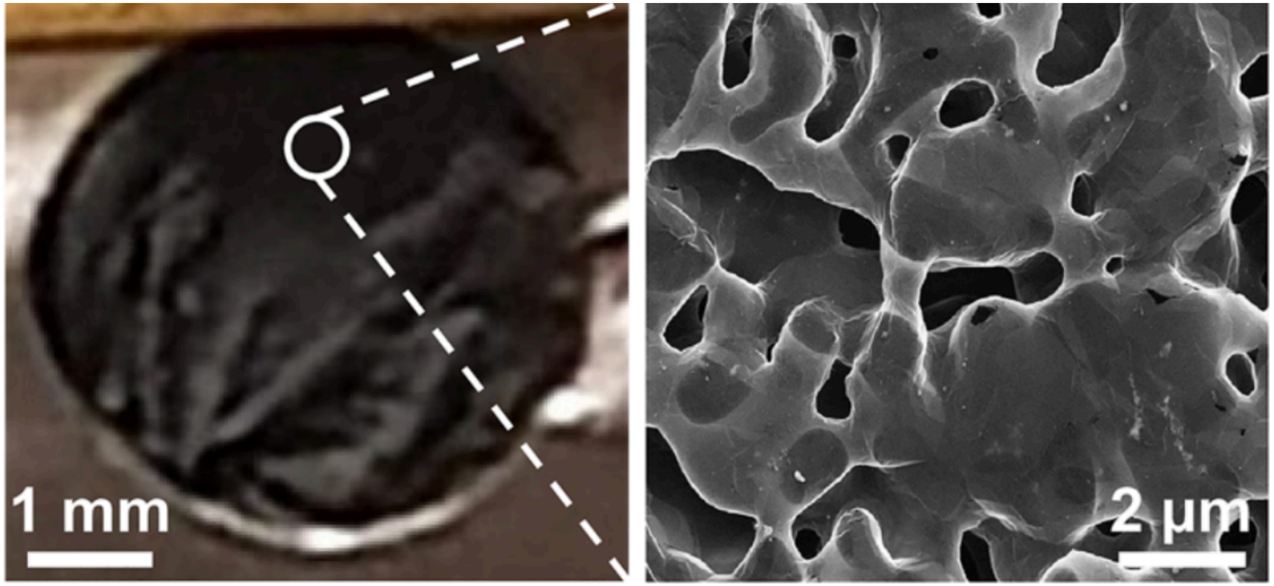
Mahmoud Mohamed Saad Abdelnabi et al 2021 Nanotechnology 32 035707

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**

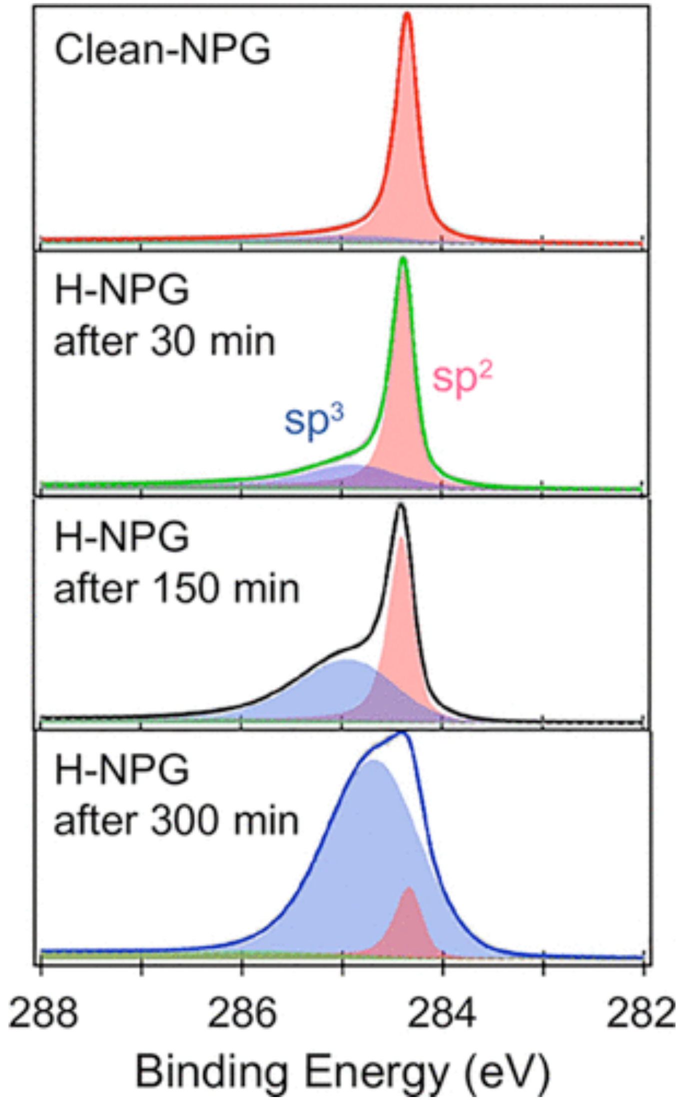


- Hydrogen chemi-sorbed on NPG (single or double layers continuous graphene surface)

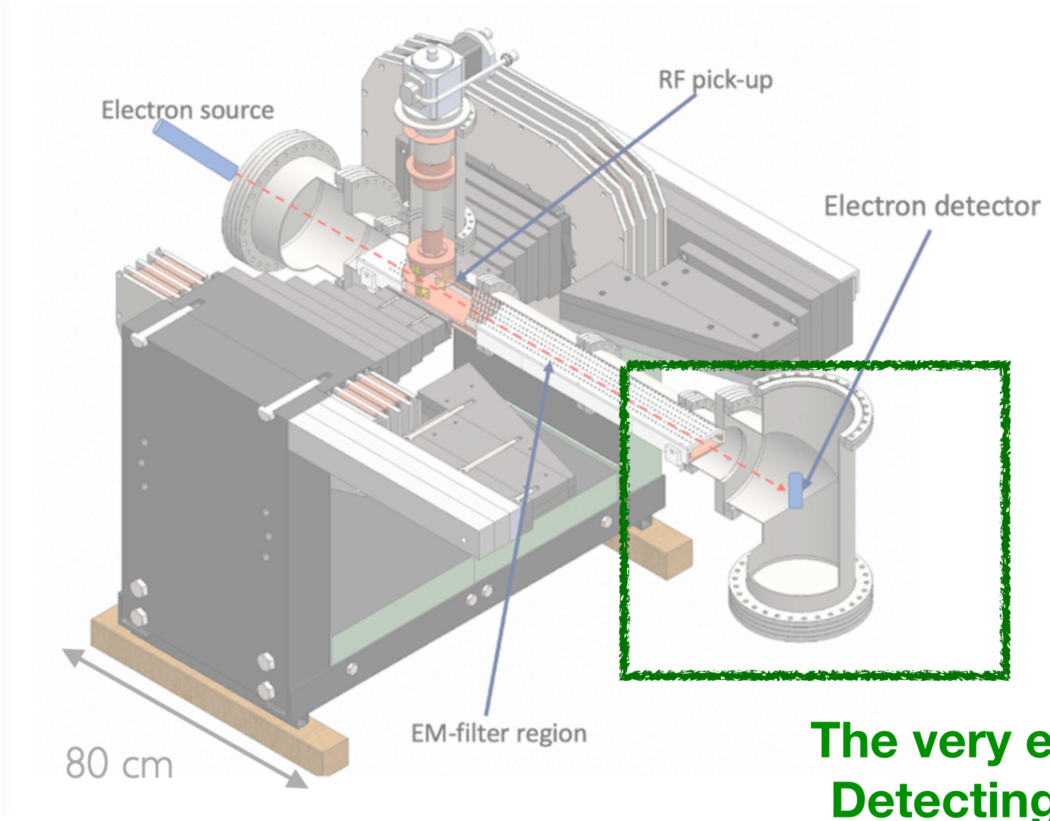
Graph**a**ne

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: semiconductor (graph**A**ne)

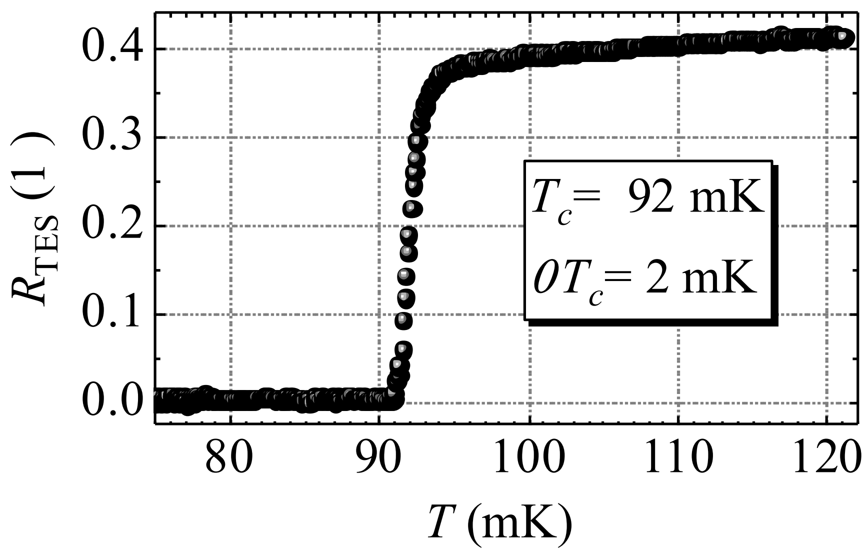


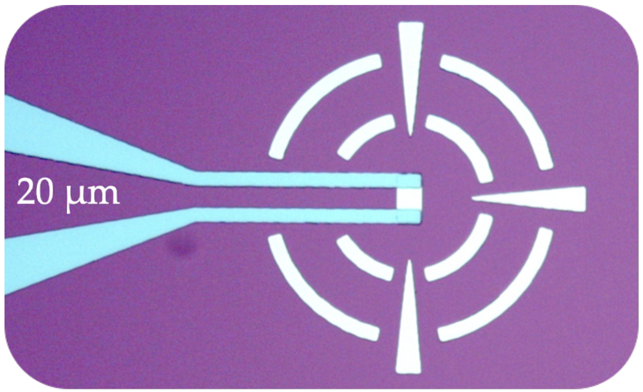
Next: put tritium on graphene and demonstrate it is a "solid" radioactive source



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

Superconductors detectors

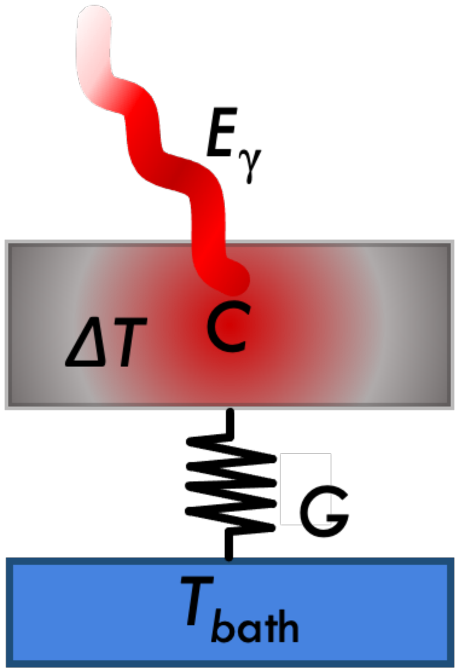




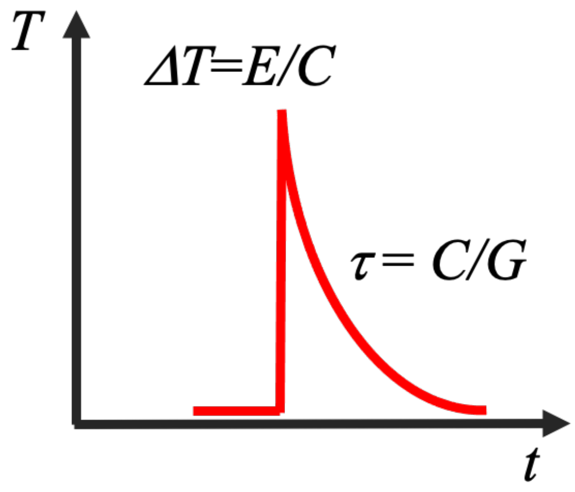
- Operate a **superconductive metallic nano-film** close to the phase-transition temperature
  - Small increase of the temperature, drop the bias large current, very **steep** response
  - SQUID current readout
  - Various applications: X-ray, telecom, astrophysics, QT, …

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

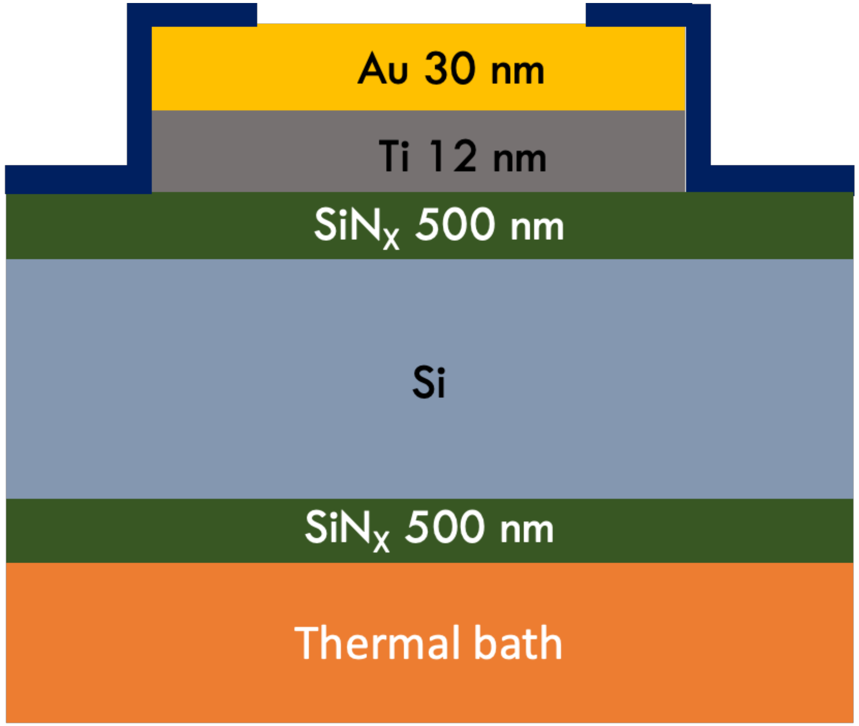


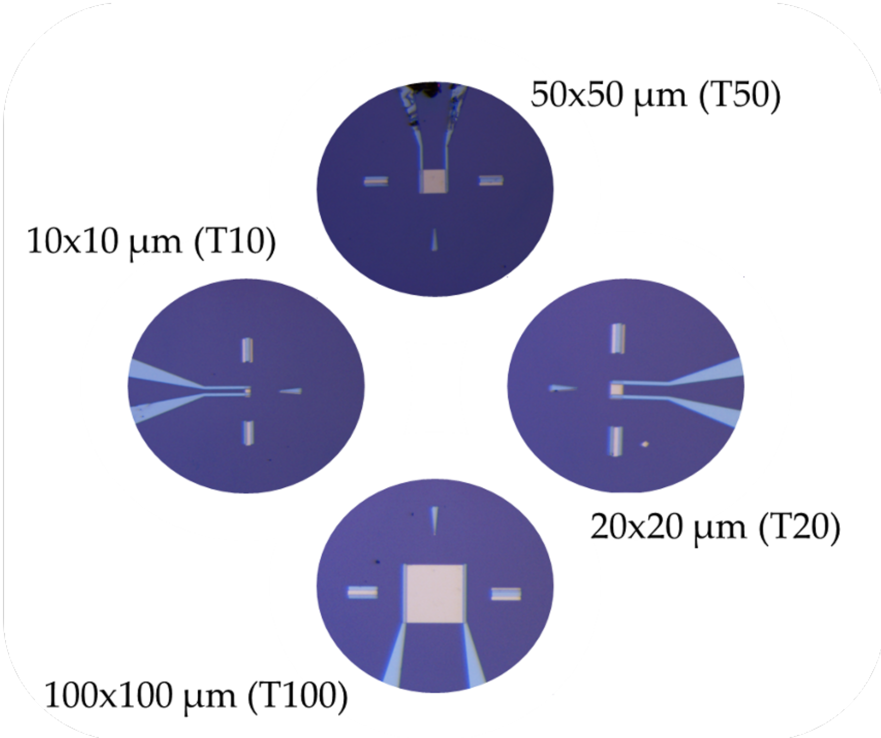
$$\Delta E \approx (k_B T^2 C\, B)^{\frac{1}{2}}$$

Energy resolution: better at low T and small C

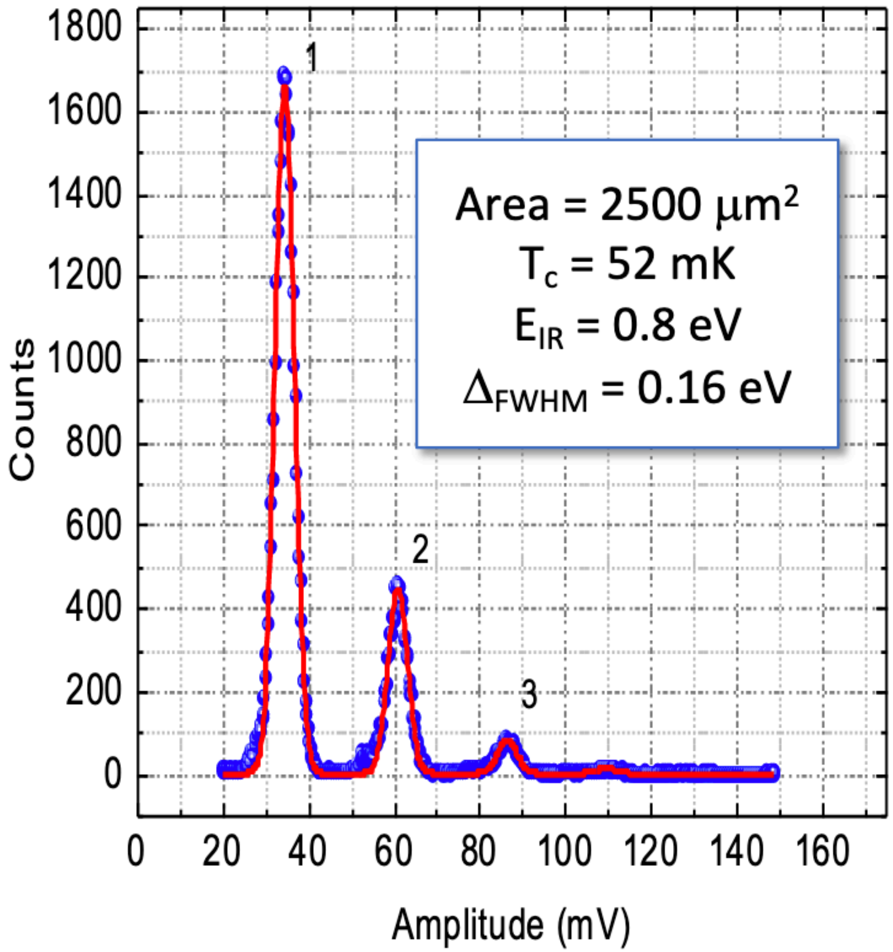
TES for Ptolemy

- Aim at **large** (~1 cm^2) sensors, array of TES sensors (with **multiplexed** readout)
- **Port** TES to detect very low energy <u>**electrons**</u>





TES tested with photons



- Counting of infra-red photons (0.8 eV) very successful
- Scaling to a smaller area 15x15 μm^2 (i.e. smaller capacitance) predicts 50 meV FWHM energy resolution

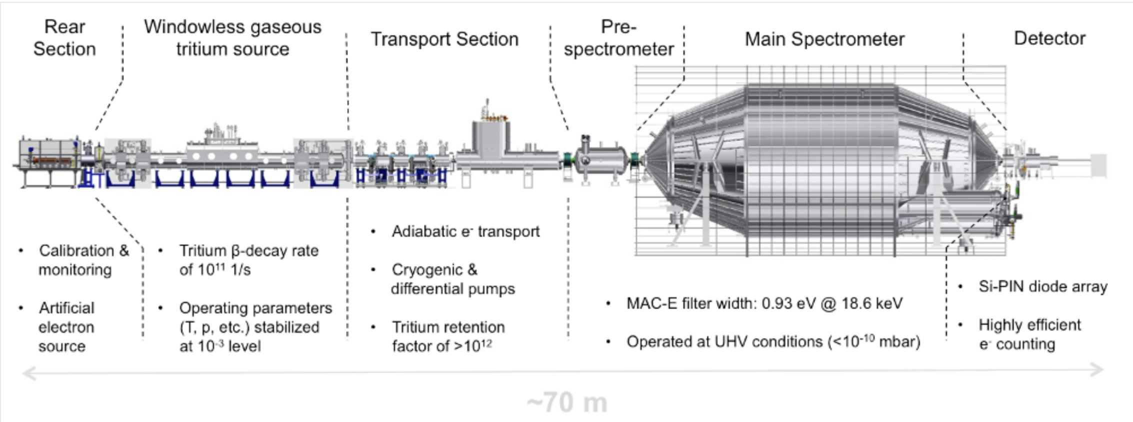
Next **challenge**: demonstrate **electrons** can be **absorbed** and detected

Outlook

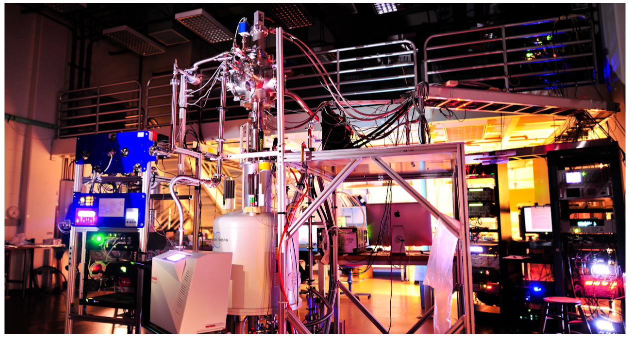
Neutrino mass determination

- 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

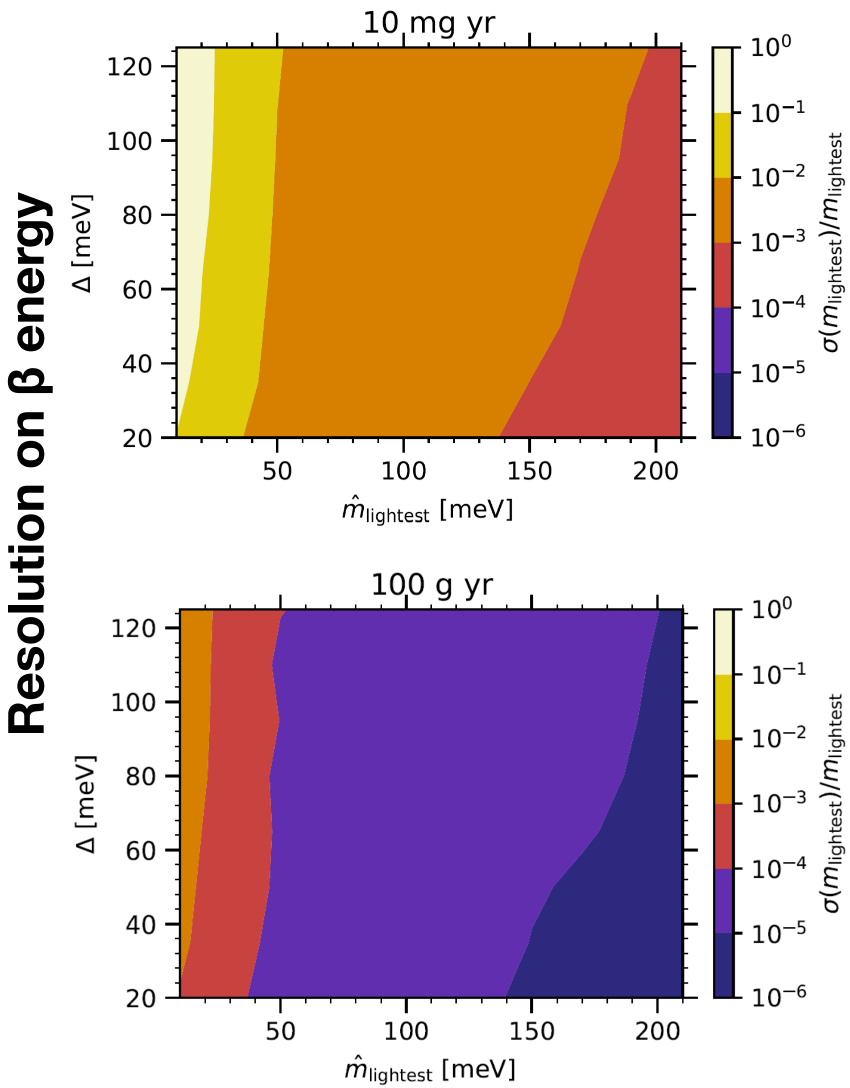
Range of sensitivity for m_ν

- Neutrino mass as first result

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

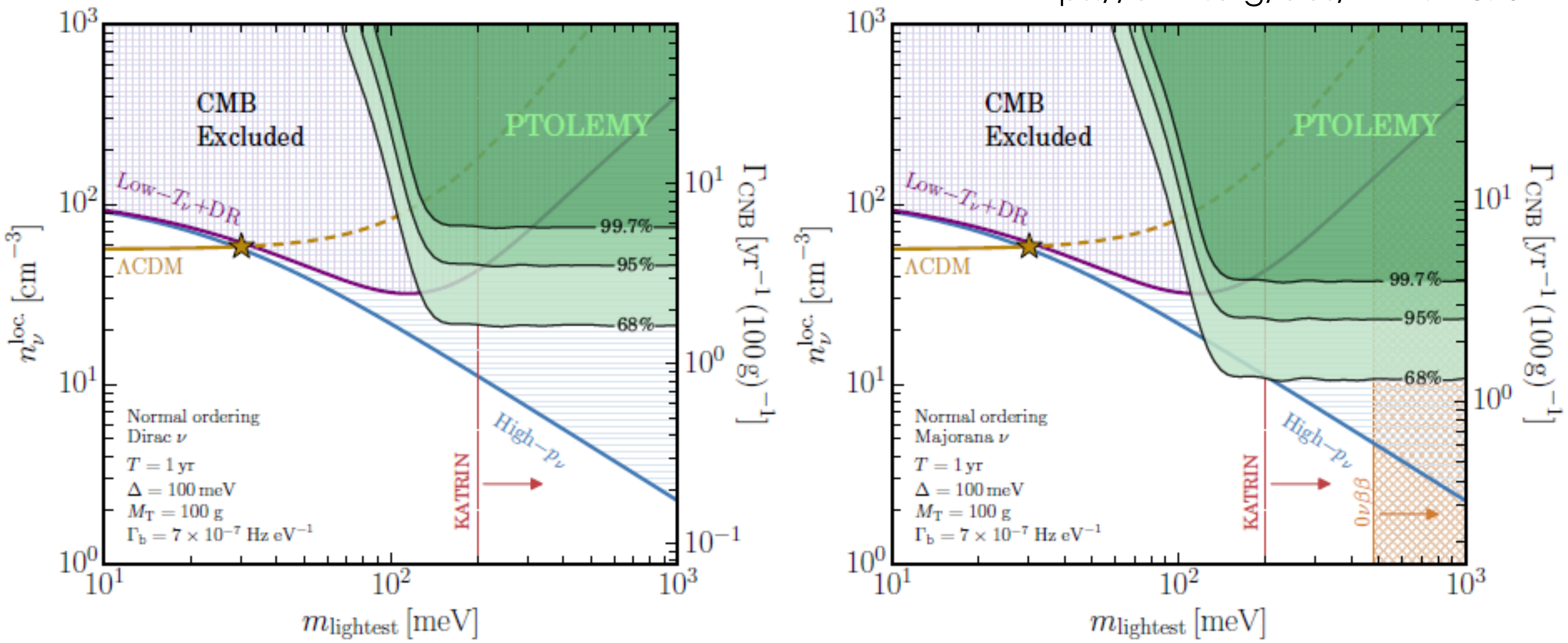
  2. Crucial for design of full scale $C\nu B$ PTOLEMY with 100g tritium

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



CνB sensitivity

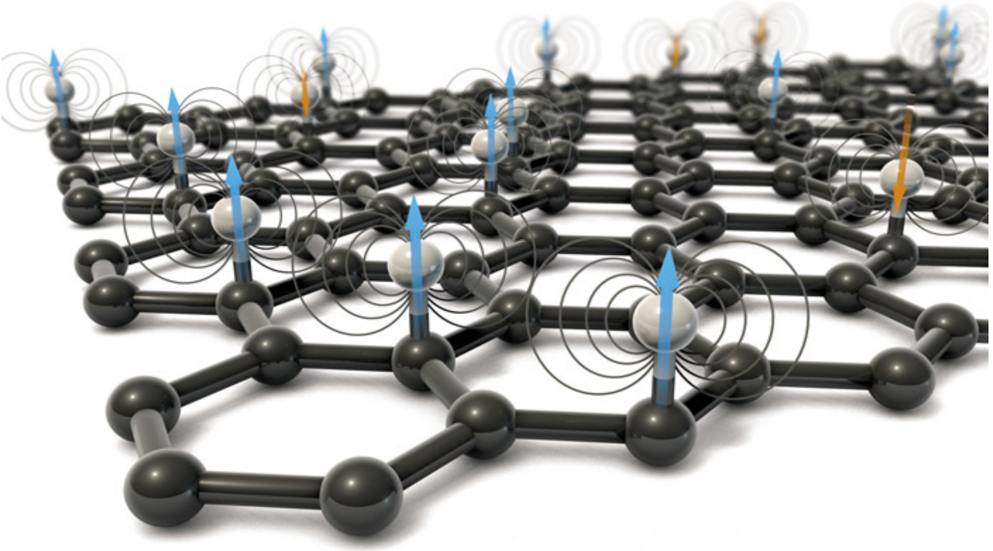
https://arxiv.org/abs/2111.14870



- Pushing energy resolution to low value crucial to cover cosmology prediction

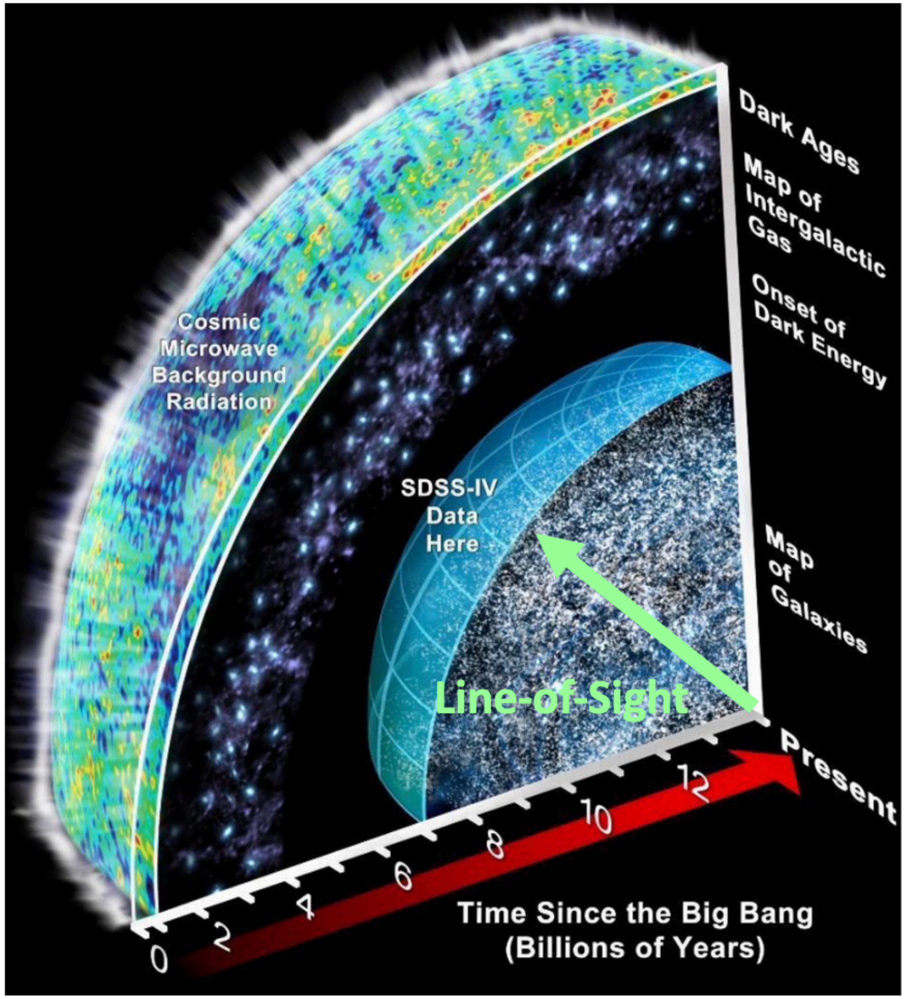
CvB astrophysics (!!!)

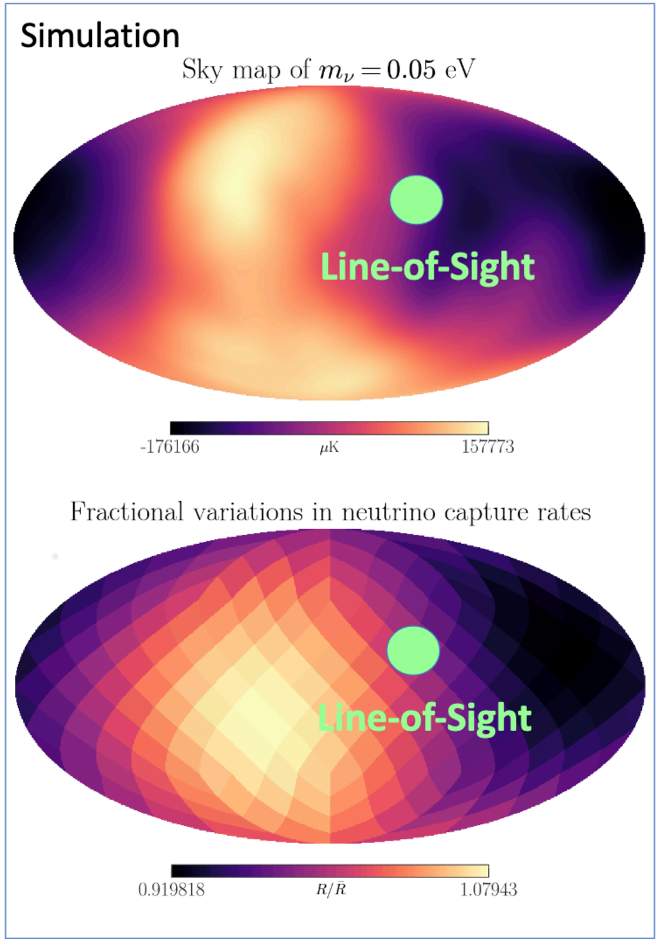
Graphene with polarized tritium nuclear spin



- Neutrino localisation
- Being non-relativistic they feel “near-by” large scale structure
- Becoming part of multi-messenger astronomy…

Relic neutrino sky map





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

Conclusion

- 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.**

  - Measurement of **neutrino mass** from beta spectrum endpoint might be done on a shorter term

- **Currently in active R&D phase**
  - **Carbon nanostructure** to store atomic tritium
    - Also a theoretical activity to understand condensed matter effect on tritium endpoint
  - **advanced detection concept** (low power fast **RF detection, electron detection with TES)**